

Understanding galaxy formation and evolution through kinematics and interstellar medium properties

Yifan Mai

A thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy (PhD)

Supervisor:

Scott Croom

Co-supervisors:

Emily Wisnioski, Sam Vaughan

The University of Sydney

Faculty of Science

School of Physics

*This research reported in this thesis was supported by the award of a Research
Training Program scholarship to the PhD Candidate.*

February 28, 2025

Declaration

This is to certify that to the best of my knowledge, the content of this thesis is my own work. This thesis has not been submitted for any degree or other purposes.

I certify that the intellectual content of this thesis is the product of my own work and that all the assistance received in preparing this thesis and sources have been acknowledged.

Yifan Mai

February 28, 2025

Authorship attribution statement

This thesis contains material that was previously published in the following sources. In both cases, I was the lead and corresponding author:

- Chapter 2 of this thesis is published as [Mai et al. \(2022\)](#). I designed the study, extracted the data, and wrote the drafts of the MS. A detailed and complete authorship attribution is presented at the beginning of this chapter.
- Chapter 3 of this thesis is published as [Mai et al. \(2024\)](#). I designed the study, extracted the data, and wrote the drafts of the MS. A detailed and complete authorship attribution is presented at the beginning of this chapter.
- I confirm that all of the work presented in this thesis is my own, except where indicated by specific reference in the text, and that this thesis has not been submitted in whole or in part for any other academic degree or professional qualification.

Yifan Mai

February 28, 2025

As supervisor for the candidature upon which this thesis is based, I can confirm that the authorship attribution statements above are correct.

Prof. Scott Croom

February 28, 2025

Abstract

In this thesis, we study the kinematics and interstellar medium properties of galaxies and how external and internal mechanisms influence their evolution. We start by connecting the rotational motion of galaxies to their large-scale environment. We then examine the turbulent motion of gas in galaxies. Finally, we build on our analysis of gas by measuring the heavy metal content within galaxies.

To understand the build-up of galaxy stellar angular momentum, we study the coherence between the projected stellar kinematic spin vectors and the line-of-sight motion of neighbouring galaxies using data from the SAMI Galaxy Survey. We find modest evidence of coherence signals ($\sim 2\sigma$) for neighbouring galaxies within 2 Mpc, i.e. the rotation of a galaxy is aligned with the average motion of neighbouring galaxies. The coherence signal might result from the interaction between paired or group galaxies. However, the coherence signals are consistent with zero or negative ($\sim 2\sigma$), i.e. the rotation of a galaxy is opposite to the average motion of neighbouring galaxies, for neighbours outside 3 Mpc, suggesting the positive signals we observed within 2 Mpc may be due to coincidental scatter or variance of large-scale structure.

We then analyse the gas kinematics and investigate the drivers of gas turbulence of the galaxies at $z \sim 0.3$, an epoch when the spatially resolved ionised gas kinematic is relatively unexplored, using data from the MAGPI survey. We use a Bayesian forward modelling technique, BLOBBY3D, which accounts for the effect of beam smearing, to model the ionised gas kinematics and flux distribution. The average ionised gas velocity dispersion (σ_{gas}) of galaxies at $z \sim 0.3$ is $26.1 \pm 8.7 \text{ km s}^{-1}$. We compare our results to the σ_{gas} of the SAMI ($z \sim 0$) and KROSS ($z \sim 1$) surveys, for which the σ_{gas} is also consistently measured using BLOBBY3D. We find that the average σ_{gas} is similar at the same star formation rate surface density (Σ_{SFR}) for the SAMI, MAGPI and KROSS galaxies, and Σ_{SFR} is the parameter that has the strongest correlation with σ_{gas} in both SAMI and MAGPI galaxies. This correlation suggests that the mechanisms related to Σ_{SFR} , such as stellar feedback and gas instability, may be the dominant drivers of gas turbulence from $z \sim 1$ to $z \sim 0$. We also find that the non-rotational motion of gas, which may be connected to gas transportation through the disc, is correlated with σ_{gas} for the galaxies at $z \sim 0.3$. The correlation between σ_{gas} and Σ_{SFR} at $z \sim 1$ is weaker compared to lower redshift, illustrating that other mechanisms, such as gas transportation and accretion, are relatively more important in driving gas turbulence at higher redshift galaxies.

We extend our BLOBBY3D analysis of the ionised gas distribution to measure the seeing-deconvolved gas-phase metallicity and metallicity gradient of the MAGPI galaxies. The median of the metallicity gradient ($\nabla[\text{O}/\text{H}]$) is $-0.028^{+0.031}_{-0.044}$ dex/kpc. Among 44 galaxies in our samples, 29 galaxies (66%) have significantly ($\geq 2\sigma$) negative metallicity gradients, 3 galaxies (7%) have significantly positive gradients and 12 galaxies (27%) have flat gradients. $\nabla[\text{O}/\text{H}]$ has significant positive correlations with σ_{gas} ($r = 0.48^{+0.10}_{-0.10}$) and Σ_{SFR} ($r = 0.37^{+0.12}_{-0.13}$). We find that galaxies with stronger gas turbulence (σ_{gas}) have flatter or positive metallicity gradients. Our results suggest that stellar feedback, gas accretion and transportation drive gas turbulence and enhance gas mixing, which flattens or inverts the metallicity gradients.

Acknowledgements

First and foremost, I would like to express my deepest gratitude to my supervisors, Scott Croom, Emily Wisnioski and Sam Vaughan, for their unwavering support, guidance, kindness and encouragement. They understood the difficulties and challenges I faced in research, language, culture, and life, and they were always there for me. In 2019, I came to Sydney to join a summer research program under Scott's supervision. He always praised me even when I made small progress. I felt happy and inspired and decided to apply for a PhD in his group. As such a dedicated supervisor, he continues to reflect on how to improve his supervision. I became more productive when we changed from one 1-hour meeting to two 30-minute meetings per week, and I really enjoyed our Wednesday group morning tea. I hope to be a great person like him—always positive, always encouraging.

I would like to thank my friends and colleagues in the SAMI/Hector team, the MAGPI team, and SIFA: Susie, Hillary, Tom, Di, Huimin, Liz, Madusha, Jesse, and Stefania... I probably would never have gone to the gym (or snorkelling) and become fit without Susie's company and being inspired by her as a role model. Thank you, Hillary, for being so warm-hearted and considerate. I thank all officemates in the 335A office: Purmortal, Mat, Alair, Pavadol and those mentioned above, for creating such a friendly and supportive environment. I would also like to thank Marie for all of her support.

I thank ASTRO3D for fostering a diverse, equitable, and inclusive (DEI) environment, which means so much to me. I also thank ASTRO3D for providing funding that allowed me to attend conferences, annual retreats, student workshops and writing retreats, through which I improved my academic skills, met so many wonderful people and built connections.

I thank Andre for all his listening, understanding and encouragement during our deep conversations. I also thank Andre for taking me on a flight around the Siding Spring Observatory—I will probably brag for the rest of my life that I flew a plane before I drove a car. I also thank Lei for his care and help. I thank Ling for our 15-year friendship.

Thanks to my lovely flatmates: Patricia, Linh, Pia and Xueqing. I enjoyed the time we spent together and our weekends of cooking and baking.

Finally, thanks to my family: my mum, grandma, Yuanyuan, aunts and uncles. Thank you for your love and support. To my grandpa, thank you for your love. I hope you'd be proud.

It has been a wonderful journey. I could not have finished it, nor been so happy without all of your love and support. Thank you!

Contents

Authorship attribution statement	iii
Abstract	iv
Acknowledgements	vi
List of Figures	x
List of Tables	xvii
1 Introduction	1
1.1 Galaxy angular momentum	3
1.2 Ionised gas kinematics	5
1.3 Metallicity distribution	8
1.4 Spectroscopic observations and techniques	10
1.4.1 Spectroscopy	10
1.4.2 The SAMI Galaxy Survey	11
1.4.3 The MAGPI survey	12
1.4.4 Galaxy modelling techniques	13
1.5 Thesis summary	15
2 The SAMI Galaxy Survey: The Relationship between Galaxy Rotation and the Motion of Neighbours	16
2.1 Abstract	17
2.2 Introduction	17
2.3 Data	19
2.4 Methods	21
2.4.1 Measurements of average velocities of neighbouring galaxies	21
2.4.2 Uncertainty estimation	25
2.5 Results	26
2.5.1 Results for neighbour galaxies within 1 Mpc	26
2.5.2 Large-scale results	29
2.5.3 Results for galaxies in 6 different regions	31
2.5.4 Galaxy subsamples	32
2.6 Discussion	35
2.6.1 Comparison to the results of Lee et al.	35

2.6.2	Implication of subsamples	36
2.6.3	Comparison to previous studies	36
2.7	Conclusions	39
3	The MAGPI survey: the evolution and drivers of gas turbulence in intermediate-redshift galaxies	41
3.1	Abstract	42
3.2	Introduction	42
3.3	Data	45
3.3.1	The MAGPI Survey	45
3.3.2	The SAMI Galaxy Survey	47
3.3.3	KROSS	48
3.4	Methods	49
3.4.1	Modeling the gas disc kinematics	49
3.5	Results	51
3.5.1	Velocity dispersions of MAGPI galaxies	51
3.5.2	Correlations between velocity dispersion and other galaxy properties	53
3.5.3	Non-rotational gas velocities	55
3.5.4	Comparison to the SAMI and KROSS surveys	56
3.6	Discussion	59
3.6.1	Gas velocity dispersion evolution through cosmic time	59
3.6.2	Drivers of gas turbulence	61
3.7	Conclusions	65
4	The MAGPI survey: forward modelled metallicity gradients in galaxies at $z \sim 0.3$	68
4.1	Abstract	69
4.2	Introduction	69
4.3	Data	71
4.3.1	Sample selection	72
4.4	Methods	72
4.4.1	Metallicity diagnostics	73
4.4.2	Modelling the flux distribution	74
4.4.3	Extinction correction	75
4.4.4	Metallicity gradient measurement	76
4.5	Results	77
4.6	Discussion	85
4.6.1	Drivers of the metallicity gradient	85
4.6.2	Evolution of metallicity gradient	88
4.6.3	The challenge of metallicity gradient measurement	89
4.7	Conclusions	90
5	Conclusions	92
5.1	Summary of the thesis	92
5.2	Future work	93
5.2.1	Molecular gas properties	93

5.2.2	Developing BLOBBY3D	94
5.2.3	The evolution of gas kinematics at $z > 1$	94

List of Figures

1.1	Figure from De Lucia & Blaizot (2007). The merger tree for a BCG. Symbols are colour-coded by B–V colour and their area scales with the stellar mass. Only progenitors more massive than $10^{10} M_{\odot} h^{-1}$ are shown with symbols. Galaxies that reside in the friends-of-friends (FOF) group inhabited by the main branch are shown as circles. Galaxies that have not yet joined this FOF group are shown as triangles.	2
1.2	Left: density map of a cross-section perpendicular to a given filament on a logarithmic scale (filament is going into the page). Right: projected vorticity within the filament within that section (towards the observer in red and away from the observer in blue) in units of $h \text{ km s}^{-1} \text{ Mpc}^{-1}$. The black lines show the contour of the density map. Circles are haloes with their corresponding virial radius. This figure is taken from Laigle et al. (2015).	3
1.3	The renormalized probability density function $(1 + \kappa\xi)$ of the angle between the kinematic axis of galaxies and their nearest filament (θ_{2D}) for galaxies in different stellar mass groups. The results show that galaxies with low stellar masses (in blue) tend to have the kinematic axis aligned with the nearest filament ($\theta_{2D} \sim 0^\circ$) and galaxies with higher stellar masses (in red) are more likely to have the kinematics axis perpendicular to the filament ($\theta_{2D} \sim 90^\circ$). This figure is taken from Welker et al. (2020).	4
1.4	A cartoon view of the circumgalactic medium (CGM) taken from Tumlinson et al. (2017). This plot shows the gas accretion from the IGM (blue), gas outflows (pink and orange) and gas recycling.	6
1.5	Intrinsic gas velocity dispersion as a function of redshift and cosmic time drawn from Übler et al. (2019). The average gas velocity dispersion of selected ionised gas measurements are shown in red. Local atomic and molecular averages and individual high- z molecular gas measurements are shown in black.	7
1.6	Redshift evolution of the MZR from Maiolino & Mannucci (2019) reproduced from Zahid et al. (2014). Blue, yellow, black and cyan points refer to $z = 0.08, 0.29, 0.78$, and 1.55 , respectively.	9
1.7	An image of a hexabundle front facet used in the SAMI instrument. This hexabundle consists of 61 optical fibres. This plot is taken from Croom et al. (2012).	12

1.8	Comparison of the MAGPI spatial resolution and redshift range with that of other IFS surveys focused on stellar (left panel) and gas (right panel) kinematics. The MAGPI samples are shown in primary samples and secondary samples separately. This plot is taken from Foster et al. (2021).	13
1.9	The 2D maps of the BLOBBY3D results for GAMA 485885 from the SAMI Galaxy Survey. These plots show from left to right the model built by BLOBBY3D, the model convolved with the PSF and LSF, single-component Gaussian fits to the data, and 2D residuals between the data and the convolved model. The first row shows the flux distribution of the H α emission line; the second row shows the velocity map; the third row shows the velocity dispersion map. This figure is taken from Varidel et al. (2019).	14
2.1	(a) Red points indicate the spatial distribution of GAMA galaxies, and black points show the spatial distribution of the SAMI galaxies. We divided the SAMI galaxies into 6 parts (as indicated by black numbers) in order to investigate the variance of large scale structure between different regions; (b) r -band absolute magnitude versus redshift diagram of SAMI and GAMA galaxies.	19
2.2	Uncertainty distribution of the position angles of the SAMI galaxies. The vertical line denotes 10° uncertainty.	21
2.3	The left panel (a) shows a SAMI galaxy and its neighbour galaxies. In the right panel (b) we have rotated the whole picture to make sure that the spin vector (PA) of SAMI galaxy is upward. The black ellipses in the middle of pictures demonstrate an example of SAMI galaxy and the black arrows show its spin vector. The neighbour circles illustrate the neighbour galaxies. The size of circles are proportional to the luminosity of galaxies and the color show the line-of-sight velocity of neighbour galaxies relative to the central SAMI galaxy.	22
2.4	We stack 1257 of the maps of neighbours of SAMI galaxies as shown in Figure 2.3(b). The point sizes are proportional to the luminosity of galaxies. The color of points shows the velocity offset between the SAMI galaxies and their neighbours. If there is a strong signal, the right side will be predominantly red, the left side will be predominantly blue.	23
2.5	Two methods of choosing neighbouring galaxies. (a) X-cut-10°: preserve the data of neighbour galaxies located between 10° and 170° or between 190° and 350° from north. (b) X-cut-45°: preserve the data of neighbour galaxies located between 45° and 135° or between 225° and 315° from north.	23

- 2.6 (a) The histogram shows the distribution of right-left-merged abs-L weighted average velocity offset between the randomized spin-axis of SAMI galaxies and the neighbouring galaxies within 1 Mpc. The standard deviation of the histogram (σ_{RAX}) is 5.4 km s^{-1} . The vertical dashed line marks the average velocity of the real data and the diagonally-shaded region shows its uncertainty using bootstrap estimates. (b) The same as (a), but for the neighbouring galaxies within 20 Mpc. The standard deviation of the histogram is 2.9 km s^{-1} 26
- 2.7 The black lines show radial profile of average velocity offset within 1 Mpc as a function of projected distance, D . The green lines show bootstrap uncertainties and the blue shades demonstrate RAX uncertainties. The green histograms show the number of galaxies which contribute to the bin. The left column is based on X-cut- 10° and the right column is based on X-cut- 45° . The top, middle and bottom rows are abs-luminosity-weighted, relative-luminosity-weighted and equal-weighted mean velocity, respectively. If the correlation between the direction of spin vector of the central galaxy and the motion of its neighbour galaxies exists, then the average velocity offset would be positive on the right side and negative on the left side of each panel. However, we do not detect significant signal of coherence for the neighbouring galaxies within 1 Mpc scales. 27
- 2.8 Right-left-merged radial profile of average velocity offset within 1 Mpc. The left column is based on X-cut- 10° and the right column is based on X-cut- 45° . The top, middle and bottom rows are abs-luminosity-weighted, relative-luminosity-weighted and equal-weighted mean velocity, respectively. The horizontal lines in (b) and (d) demonstrate the cumulative right-left-merged mean velocities for the neighbour galaxies within 800 kpc scales, in which blue lines represent the results of SAMI galaxies, red and yellow lines represent the results in (alias?). The uncertainties denoted by green lines are calculated using the bootstrapping method. The blue shades demonstrate RAX uncertainties. Note that the scale changes in (e) and (f). 28
- 2.9 We show 500-kpc-binned absolute-luminosity-weighted mean velocities within 20 Mpc scales in (a) and (b). Panel (c) and (d) show right-left-merged 500-kpc-binned mean velocities within 20 Mpc. The error bars represent σ_{RAX} 31
- 3.1 a) The SFR- M_* relation for SAMI (blue), MAGPI (orange) and KROSS (purple) galaxies in our sample. MAGPI galaxies that have $H\alpha$ -based SFR measurement but that are not in our final sample are shown in grey. b) The sSFR-redshift relation for galaxies in our sample. The black lines show the evolution of sSFR as a function of redshift drawn from Popesso et al. (2023) at three stellar mass values: 10^9 (dot-dashed line), 10^{10} (solid line) and $10^{11} M_\odot$ (dashed line). 49

- 3.2 The 2D maps of the BLOBBY3D results for MAGPI galaxy 1506106169. The first column shows the model made by BLOBBY3D; the second column shows the model convolved with the PSF and LSF of the data; the third column shows the results of the single Gaussian fit to the observed datacube; the fourth column shows the residuals between the data and the convolved model. The first row shows the flux distribution of the $H\alpha$ emission line; the second row shows the velocity map; the third row shows the velocity dispersion map. 50
- 3.3 The intrinsic gas velocity dispersion of MAGPI galaxies measured by BLOBBY3D as a function of SFR, colour-coded by stellar mass. Star-forming galaxies are shown as circles and galaxies with AGN at the centre are shown as stars. The upper limits of σ_{gas} for galaxies without reliable fits are shown as downward triangles. The black errorbars show the uncertainties on σ_{gas} 52
- 3.4 Intrinsic gas velocity dispersion (σ_{gas}) as a function of galaxy properties for MAGPI galaxies, including star-forming rate (SFR), specific star-formation rate (sSFR), star-formation rate surface density (Σ_{SFR}), stellar mass (M_*), half-light radius of $H\alpha$ flux (R_e), a proxy for the gravitational potential (M_*/R_e), stellar mass surface density (Σ_{M_*}), and the logarithmic offset in SFR from the star formation main sequence of MAGPI galaxies (ΔSFR). Pearson correlation coefficient, r , and p -value for each correlation are shown on each panel. The star-forming galaxies are shown as orange circles and the AGN-host galaxies are shown as dark red stars. We find that the σ_{gas} of MAGPI galaxies has the strongest correlation with Σ_{SFR} ($r = 0.65$). The σ_{gas} also has a strong correlation with SFR and ΔSFR 53
- 3.5 The partial correlations between gas velocity dispersion, SFR, M_* and R_e for the MAGPI sample. The Pearson correlation coefficient (r) and p -value are given in each box, which is colour-coded by its correlation coefficient. The partial correlation shows that SFR still has a strong correlation with gas velocity dispersion ($r = 0.598$) when we remove the effects from M_* and R_e . R_e has a negative partial correlation with σ_{gas} ($r = -0.407$), indicating that SFR and galaxy size have a combined effect on gas velocity dispersion. 55
- 3.6 a) Gas velocity dispersion versus Σ_{SFR} colour-coded by average velocity residual (Δv). The dashed line is the ordinary least squares regression line. b) The Pearson partial correlation between σ_{gas} , Σ_{SFR} , Δv and M_* . The Pearson correlation coefficient (r) and p -value are shown in each box, which is colour-coded by correlation coefficient. The result shows that in addition to Σ_{SFR} , gas velocity dispersion may also be related to non-circular motions of the gas. 57

3.7	The relationship between gas velocity dispersion and galaxy properties for MAGPI (orange), SAMI (blue) and KROSS (purple) survey. The lower panel of each plot shows the distribution of galaxy properties. The Pearson correlation coefficients (r) and p -values are shown on each plot. Both MAGPI and SAMI galaxies have the strongest correlation between σ_{gas} and Σ_{SFR} . KROSS galaxies also have a modest correlation between σ_{gas} and Σ_{SFR}	57
3.8	The $\sigma_{\text{gas}} - \Sigma_{\text{SFR}}$ relation for MAGPI (orange), SAMI (blue) and KROSS (purple) galaxies. The average σ_{gas} in each 0.5 dex bin for SAMI, MAGPI and KROSS are shown as black-edge triangles, circles and stars. The errorbars show the standard error of the mean.	58
3.9	The gas velocity dispersion of SAMI, MAGPI and KROSS galaxies as a function of lookback time. The data from KMOS ^{3D} (Übler et al., 2019) are shown as black triangles. The average σ_{gas} and the standard deviation of SAMI (Varidel et al., 2020), MAGPI, KROSS (Varidel et al. in prep), DEEP2 (Kassin et al., 2012), KMOS ^{3D} (Übler et al., 2019), GHASP (Epinat et al., 2010) and KROSS (Johnson et al., 2018) are shown as different black-edge markers. The black solid line shows the ordinary linear regression between gas velocity dispersion and lookback time for the combination of SAMI, MAGPI and KROSS data, for which gas velocity dispersions are measured with the same method. The black dot-dash line shows the ordinary linear regression between gas velocity dispersion and redshift for the combined data. The grey dashed line is a robust $\sigma_{\text{gas}} - z$ linear relation (Cappellari et al., 2013) from Figure. 6 in Übler et al. (2019), fitted using the ionised gas velocity dispersion data from literature at $0 < z < 4$. This plot shows that the gas velocity dispersions of SAMI, MAGPI and KROSS galaxies are consistent with the decreasing trend of gas velocity dispersion over cosmic time suggested by previous studies (Kassin et al., 2012; Wisnioski et al., 2015; Übler et al., 2019).	60
3.10	Four MAGPI galaxies that have $m = 3$ Fourier mode in the velocity residual maps. The first column shows the model made by BLOBBY3D; the second column shows the model convolved with the PSF and LSF of the data; the third column shows the results of the single Gaussian fit to the observed datacube; the fourth column shows the residuals between the data and the convolved model.	63

4.1	The metallicity and metallicity gradient measurement for an example galaxy (MAGPIID=1203195161). The first row shows the metallicity measured using the N2O2 diagnostic and the second row uses the N2H α diagnostic. The left panels show the metallicity map. The middle panels show the metallicity as a function of radius, where the metallicity in each 1 kpc bin is calculated using the sum flux method. The right panels demonstrate the metallicity of each spaxel as a function of radius (grey) and the average metallicity in each 1 kpc bin (spaxel average method) for three different weight methods (unweighted in blue, H α weighted in red and inverse variance weighted in yellow). We overplot the best linear fits for each method. The orange horizontal lines in the middle and right panels denote the valid metallicity range for each diagnostic (Kewley et al., 2019). The green vertical lines denote 1 R_e for this galaxy. We show the value of the metallicity gradient and central metallicity for each plot. We only show the value of the inverse variance weighted method for the spaxel average plots.	77
4.2	The radial metallicity distribution and metallicity gradient measured using the N2O2 diagnostic and the sum flux method for all galaxies in our sample. The orange horizontal lines denote the valid metallicity range for the N2O2 diagnostic (Kewley et al., 2019). The green vertical lines denote 1 R_e for each galaxy.	79
4.3	The comparison of the metallicity gradients measured using N2O2 and N2H α diagnostics (sum flux method). The correlation coefficient (r) and p -value are shown in top left.	82
4.4	Metallicity gradient (top two rows in the unit of dex/kpc, bottom two rows in the unit of dex/ R_e) as a function of a variety of galaxy properties, including stellar mass (M_*), R_e , a proxy for the gravitational potential (M_*/R_e), Σ_{M_*} , SFR, Σ_{SFR} , σ_{gas} and the logarithmic offset in SFR from the star formation main sequence (SFMS) of MAGPI galaxies (ΔSFR). We show the Pearson correlation coefficient, r , on each panel. The horizontal dashed lines denote the flat gradient. . . .	83
4.5	The Pearson partial correlation between $\nabla[\text{O}/\text{H}]$, SFR, M_* , R_e and σ_{gas} for MAGPI galaxies. The correlation coefficient (r) and p -value are shown in each box.	84

4.6	The $\nabla[\text{O}/\text{H}] - M_*$ relation for galaxies at $z \sim 0.3$ and $z \sim 0$. The galaxies of the MAGPI survey are shown as solid orange circles. The median $\nabla[\text{O}/\text{H}]$ in each 0.3 dex M_* bin are shown as black edge circles. The galaxies at the same redshift range as this study ($0.26 < z < 0.42$) measured by Carton et al. (2018) are shown as open purple diamonds. The galaxies of the SAMI survey are shown as grey triangles (N2O2 diagnostic) and their best fit (a broken linear-fit) is shown as a blue line and the 1σ uncertainty is shown as a blue band. The model prediction from Sharda et al. (2024) for the galaxies in the local Universe is shown as a pink band. The galaxies in the local Universe from the SAMI (Poetrodjojo et al., 2021), MaNGA (Belfiore et al., 2017) and CALIFA (Sánchez et al., 2014) surveys are shown as grey-edge markers, with seeing-correction made by Acharyya et al. (in preparation). Note that the metallicity of galaxies in the SAMI, MaNGA, and CALIFA survey shown as grey-edge markers is measured using the N2H α diagnostic.	87
4.7	The redshift evolution of the metallicity gradient from previous studies and this work (MAGPI). We compile simulation results from Gibson et al. (2013) and Hemler et al. (2021). We also include observational studies results from Gillman (2020), Carton et al. (2018), Wuyts et al. (2016), Belfiore et al. (2017), Jones et al. (2010, 2013), Yuan et al. (2011) and Queyrel et al. (2012). We note that the blue and pink shadows show the range of metallicity gradient and redshift in Belfiore et al. (2017) and Wuyts et al. (2016) separately.	88
4.8	Comparison of seeing-convolved ($\nabla[\text{O}/\text{H}]_{\text{gist}}$) and seeing-deconvolved ($\nabla[\text{O}/\text{H}]_{\text{blobby3d}}$) metallicity gradient of the MAGPI galaxies, colour-coded by the ratio between $R_{\text{e,H}\alpha}$ and the FWHM of PSF.	90

List of Tables

2.1	Cumulative right-left-merged mean velocity within a radius D , e.g. 0–0.8 Mpc. We also list the results in (alias?). In L19a($R \leq R_e$), the angular momentum of CALIFA galaxies is measured at $R \leq R_e$. In L19a($R_e < R \leq 2R_e$), the angular momentum of CALIFA galaxies is measured at $R_e < R \leq 2R_e$	30
2.2	The absolute-luminosity-weighted right-left-merged average velocity offset within 1 Mpc. The uncertainty of the right-left-merged average velocity is the RAX uncertainty (σ_{RAX}). The bottom of table shows the mean velocity of 6 different regions, the standard deviation and the standard error of the mean.	32
2.3	The absolute-luminosity-weighted right-left-merged average velocity offset within 20 Mpc. The uncertainty of the right-left-merged average velocity is the RAX uncertainty (σ_{RAX}). The bottom of table shows the mean velocity of 6 different regions, the standard deviation and the standard error of the mean.	32
2.4	The absolute-luminosity weighted right-left-merged mean velocity for the neighbouring galaxies within 1, 2, 6, 15 and 20 Mpc scales of different subsamples.	33
2.5	The equal weighted right-left-merged mean velocity for the neighbouring galaxies within 1, 2, 6, 15 and 20 Mpc scales of different subsamples.	34
4.1	The metallicity gradient (dex/kpc) and central metallicity ($12+\log(\text{O}/\text{H})$) measured using N2O2 and N2H α diagnostics and sum flux and spaxel average methods for 45 galaxies in Figure 4.2. *Note that galaxy MAGPIID=1533258059 is removed from our final sample due to its metallicity being lower than the valid range of the N2O2 diagnostic.	80
4.2	Same as Table 4.1, but the metallicity gradients are in the unit of dex/ R_e	81

Chapter 1

Introduction

A galaxy is a complex system that is made up of gravitationally bound stars, gas, dust and dark matter. Galaxies evolve within the framework of a cosmological model. The standard cosmological model is Lambda Cold Dark Matter (Λ CDM), where Lambda is a cosmological constant associated with dark energy, which drives accelerating expansion ([Riess et al., 1998](#); [Perlmutter et al., 1999](#)) and cold dark matter is the non-relativistic dark matter. The Λ CDM model can explain the accelerating expansion, the isotropy of the cosmic microwave background (CMB) and the flatness of the Universe (e.g. [Garnavich et al., 1998](#); [Perlmutter et al., 1999](#); [de Bernardis et al., 2000](#)). In this model, the structure of the Universe forms from primordial quantum fluctuations of a scalar field, which were amplified to cosmic scales by the expansion and evolved to the structure we see today (e.g. [Bardeen, 1980](#); [Guth, 1981](#); [Linde, 1982](#); [Calzetta & Hu, 1995](#)).

In the two-stage theory for galaxy formation ([White & Rees, 1978](#)), cold dark matter (CDM) collapses first and provides potential wells that facilitate the cooling and condensation of gas. The cosmic structures observed today could not have formed within 14 billion years without the influence of dark matter’s gravitational effects, underscoring the critical role of dark matter in galaxy formation.

During the 1980s, the standard explanation of the formation of galaxies and galaxy clusters in the CDM picture was developed ([Peebles, 1982, 1984](#); [Blumenthal et al., 1984](#); [Davis et al., 1985](#); [White & Frenk, 1991](#)). They proposed that the amplitude of baryonic matter fluctuations increases rapidly due to the gravitational influence of dark matter. Smaller mass fluctuations cluster hierarchically, forming bound systems where gas cools rapidly and galaxies are formed, while higher mass fluctuations give rise to galaxy clusters.

The dark matter (DM) haloes merge hierarchically. The galaxies within the haloes also merge following the DM merging. In the bottom-up scenario, larger haloes are formed by the merger of smaller haloes, leading to the growth of galaxies via mergers. The hierarchical models predict that galaxies build mass through mergers, and this process can be described by a galaxy’s merger tree. For example, Figure [1.1](#) is the merger tree for a brightest cluster galaxy (BCG; [De Lucia & Blaizot, 2007](#)). Mergers

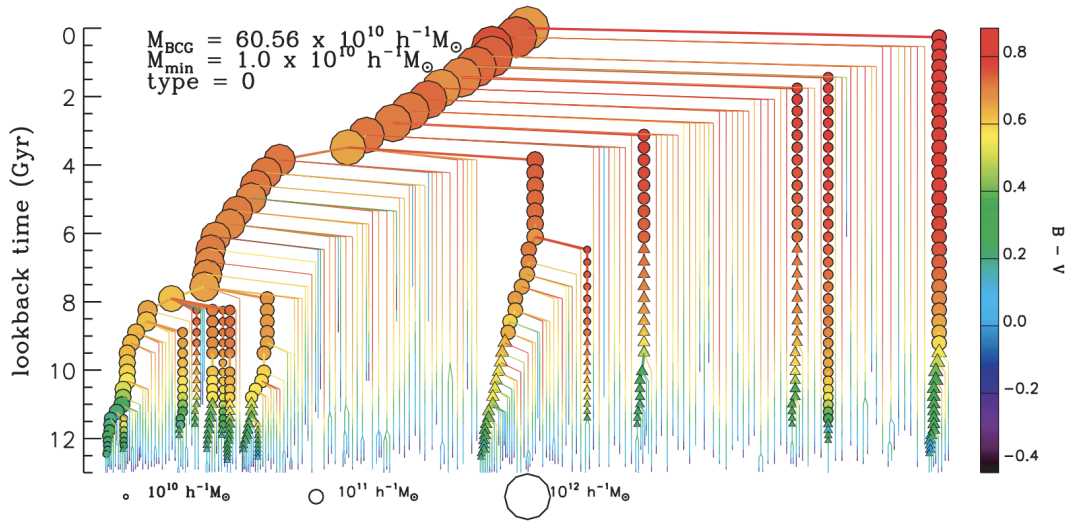


Figure 1.1: Figure from De Lucia & Blaizot (2007). The merger tree for a BCG. Symbols are colour-coded by B–V colour and their area scales with the stellar mass. Only progenitors more massive than $10^{10} M_{\odot} h^{-1}$ are shown with symbols. Galaxies that reside in the friends-of-friends (FOF) group inhabited by the main branch are shown as circles. Galaxies that have not yet joined this FOF group are shown as triangles.

significantly influence many galaxy properties, such as star formation rate (SFR), gas fraction and metallicity, which the hierarchical models can qualitatively predict (see the review by Somerville & Davé, 2015). Galaxies acquire angular momentum through the tidal torques from their neighbouring galaxies (Doroshkevich, 1970; Peebles, 1971; Efsthathiou & Jones, 1979). The galaxy interaction and mergers also influence the dynamical evolution of galaxies.

In addition to external processes such as merger and gas accretion, the internal feedback processes of galaxies also shape the evolution of galaxies. In cosmological models without feedback, the predicted star formation rates (SFRs) and the mass of galaxies are much higher than in observations (Katz et al., 1996; Somerville & Primack, 1999; Cole et al., 2000; Springel & Hernquist, 2003; Kereš et al., 2009). The disagreement between theory and observation suggests the need for mechanisms to reheat the gas to suppress star formation and remove baryons from galaxies. The internal process includes star-formation feedback (Ostriker & Shetty, 2011; Shetty & Ostriker, 2012; Faucher-Giguère et al., 2013; Krumholz & Burkhardt, 2016; Ceverino et al., 2017; Rupke, 2018; Krumholz et al., 2018; Bacchini et al., 2020; Sun et al., 2020; Ginolfi et al., 2020), such as energy injection from supernovae, stellar winds and radiation pressure from highly dense star clusters, and active galactic nuclei (AGN) feedback (Veilleux et al., 2005; Croton et al., 2006; Bower et al., 2006; Fabian, 2012; Ciccone et al., 2014). These feedback mechanisms are essential for regulating star formation and driving the evolution of galaxies.

Galaxy evolution is driven by the complex interplay of different internal and external processes. To quantify the evolution of galaxies and understand the rela-

tionship between galaxy properties and physical mechanisms, we measure the different properties of galaxies, such as stellar mass, SFR, age, bulge-to-total ratio and kinematics. We also study the environment of the galaxy and its relation to galaxy properties to learn how environmental effects impact the evolution of galaxies. Various metrics are used to quantify the environments, such as the density of the local environment (fields/groups/clusters), halo mass, and large-scale structure (voids/filaments/walls/nodes).

1.1 Galaxy angular momentum

The angular momentum of galaxies is a fundamental property that provides insights into their formation and evolution. Understanding how galaxies acquire and evolve their angular momentum is crucial for unravelling the complex evolution processes of galaxies.

The angular momentum of galaxies originates from the tidal interaction between the shape tensor of the galaxy and the tidal shear field from the neighbouring environment. This process, known as tidal torque theory (TTT), was originally proposed by [Hoyle \(1951\)](#) and further developed by [Peebles \(1969\)](#), [Doroshkevich \(1970\)](#) and [White \(1984\)](#). [Peebles \(1969\)](#) found that the growth rate of the angular momentum of galaxies in the early stages of protogalactic evolution is second order in the perturbation in the density (in proportion to $t^{5/3}$, where t is time). Protogalaxy refers to a cloud of gas that is forming into a galaxy. [White \(1984\)](#) presented detailed calculations for the analysis in [Doroshkevich \(1970\)](#) that the angular momentum of galaxies grows at first order (in proportion to t) during the linear phases of protogalaxies, when the density fluctuations in the universe are small and can be described by linear perturbation theory. [White \(1984\)](#) proved that [Peebles \(1969\)](#) is a special case where the *Lagrangian* volume, which initially contained the matter, is a sphere. In short, the initial density perturbations in the Universe not only drive galaxy formation but also contribute to the origin of the angular momentum of galaxies.

In the subsequent galaxy evolution, angular momentum is further affected by gas accretion, galaxy mergers and interactions with other galaxies and therefore deviates from the initial angular momentum set by TTT ([Bournaud & Combes, 2002](#); [Stewart et al., 2011](#); [López et al., 2019, 2021](#)). Simulation studies suggest that the vorticity of large-scale structures is predominately aligned with filaments ([Codis et al., 2012](#); [Dubois et al., 2014](#); [Welker et al., 2014](#); [Laigle et al., 2015](#)). Figure 1.2 shows the vorticity field across a filament. The low-mass galaxies that form in the vorticity-rich regions next to the filaments, accrete gas and build up angular momentum parallel to the filaments. Then low-mass galaxies move along the filaments towards the node of the cosmic web, acquire mass and angular momentum through mergers, and flip their spin from parallel to perpendicular to the filament ([Dubois et al., 2014](#); [Codis et al., 2018](#)).

The scenario of flipping galaxy angular momentum as they grow mass predicted in simulations was confirmed in observational studies ([Welker et al., 2020](#); [Barsanti](#)

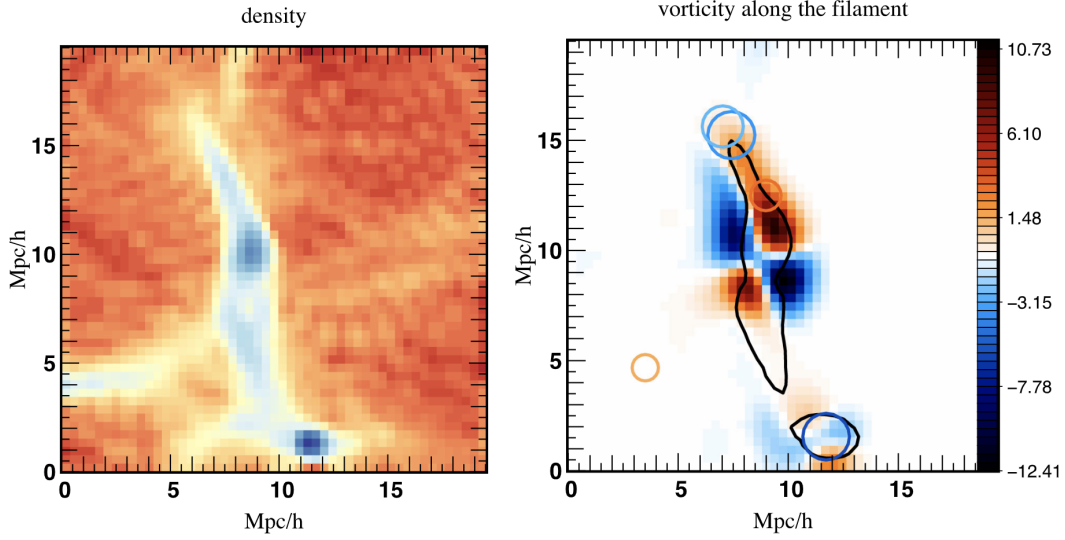


Figure 1.2: Left: density map of a cross-section perpendicular to a given filament on a logarithmic scale (filament is going into the page). Right: projected vorticity within the filament within that section (towards the observer in red and away from the observer in blue) in units of $h \text{ km s}^{-1} \text{ Mpc}^{-1}$. The black lines show the contour of the density map. Circles are haloes with their corresponding virial radius. This figure is taken from [Laigle et al. \(2015\)](#).

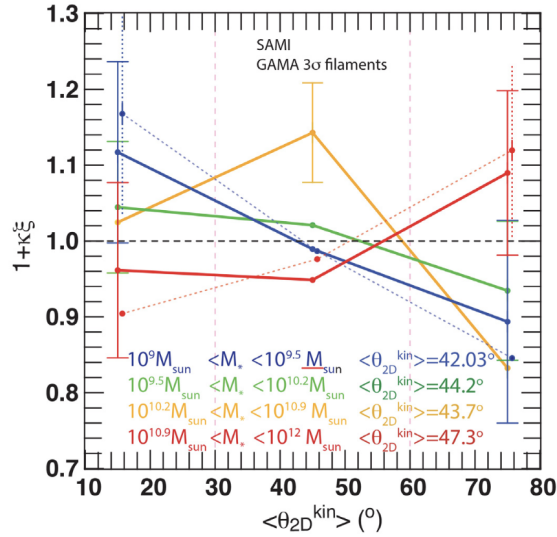


Figure 1.3: The renormalized probability density function ($1 + \kappa\xi$) of the angle between the kinematic axis of galaxies and their nearest filament (θ_{2D}) for galaxies in different stellar mass groups. The results show that galaxies with low stellar masses (in blue) tend to have the kinematic axis aligned with the nearest filament ($\theta_{2D} \sim 0^\circ$) and galaxies with higher stellar masses (in red) are more likely to have the kinematics axis perpendicular to the filament ($\theta_{2D} \sim 90^\circ$). This figure is taken from [Welker et al. \(2020\)](#).

et al., 2022). Welker et al. (2020) measured the spatially resolved stellar kinematics of 1418 galaxies from the SAMI Galaxy survey (Croom et al., 2012; Bryant et al., 2015) across GAMA fields (Driver et al., 2011), reconstructed the 3D network of cosmic filaments and estimated the alignment between the kinematic spin axis of galaxies and the direction of their nearest filament. As shown in Figure 1.3, they found that the spin axis of low-mass galaxies is preferentially aligned with the filament, while the spin of high-mass galaxies is more likely perpendicular to the filament, which is consistent with simulations. In addition to external processes like accretion and mergers, internal processes like AGN feedback also influence the angular momentum by preventing gas accretion and new gas inflow, which preserves the tendency of keeping the kinematic axis perpendicular to the filament (Dubois et al., 2014; Barsanti et al., 2023).

The connection between the angular momentum of a galaxy and its neighbouring galaxies has been found in both observation (Pestaña & Cabrera, 2004; Cervantes-Sodi et al., 2010; Mesa et al., 2014; Koo & Lee, 2018; Lee et al., 2018) and simulation studies (Capelo & Dotti, 2017; Choi et al., 2018). The spins of galaxies in pairs tend to align in the same direction (spin-spin alignment) possibly due to similar tidal field and/or galaxy interaction (Pestaña & Cabrera, 2004; Koo & Lee, 2018).

In addition to the spin-spin alignment, the spin-orbit alignment (SOA) in galaxy pairs, an alignment between the galaxy spin vector and the orbital angular momentum vector, has been found in simulation studies (An et al., 2021; Moon et al., 2021). These studies found that SOA is stronger for merging neighbours compared to the SOA for flybying ones. They suggested that SOA originates from the local cosmic flow along the filaments and is further influenced by galaxy interaction.

The coherence between the galaxy spin vector and the motion of neighbouring galaxies was detected first observationally by Lee et al. (2019a). Not limited to galaxy pairs, they investigated the coherence between galaxies and their neighbours within 1 Mpc. They found the signal of coherence is significant for the neighbouring galaxies within 800 kpc (3.5σ). In a further study, Lee et al. (2019b) extended the scope of neighbouring galaxies to 15 Mpc to examine if the coherence exists on a larger scale. They found a strong coherence signal for red neighbouring galaxies up to 6 Mpc (2.8σ). The coherence on large scales is not well understood. They suggested that it may come from the influence of the large-scale structure. These two studies indicated the influence of galaxy interaction and large-scale structure in shaping the angular momentum of the galaxies.

In summary, the build-up of galaxy angular momentum is a complex process influenced by tidal torques, gas accretion, mergers, interactions, and the impact of large-scale structures. Studying this process offers valuable insights into the dynamical evolution of galaxies and sheds light on the physical mechanisms that shape their diverse morphologies.

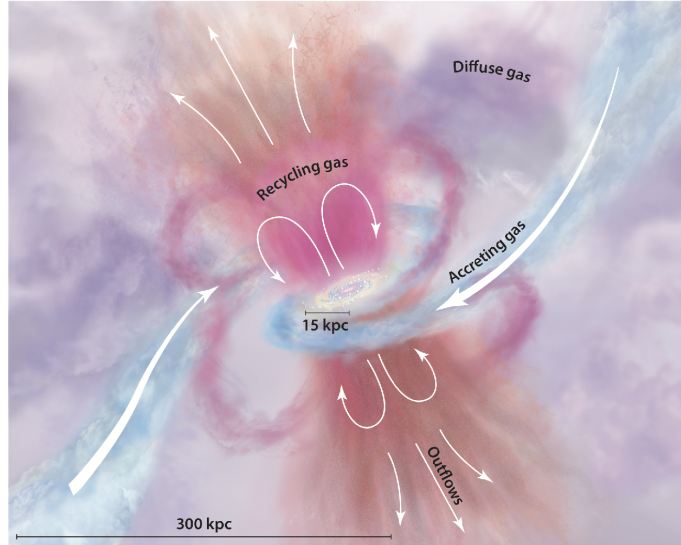


Figure 1.4: A cartoon view of the circumgalactic medium (CGM) taken from [Tumlinson et al. \(2017\)](#). This plot shows the gas accretion from the IGM (blue), gas outflows (pink and orange) and gas recycling.

1.2 Ionised gas kinematics

Gas plays a crucial role in the evolution of the galaxy. Figure 1.4 illustrates various gas-related processes within a galaxy. Galaxies accrete gas from the intergalactic medium (IGM), which fuels star formation and AGN activity. The star formation feedback, such as supernovae and stellar winds, returns gas back to the ISM. The star formation and AGN feedback also triggers gas outflow, part of which falls back to the galaxy (as a galactic fountain). These processes reshape the gas kinematics, enrich the gas metallicity and redistribute the metals throughout the galaxy.

The observation of gas kinematics, in turn, provides a crucial window that helps us understand the processes that drive galaxy evolution. In the 1910s, spectroscopic observations showed that nebulae, such as ‘Andromeda Nebula’ (Andromeda galaxy) and NGC 4594 (Sombrero galaxy), rotate rapidly about an axis ([Slipher, 1914](#)). In the 1920s-1930s, the measurement of motions of bright stars in the solar neighbourhood and globular clusters inspired the theory of the differential rotation of different sub-systems in the galaxy ([Lindblad, 1925](#); [Oort, 1926, 1927](#)). [Babcock \(1939\)](#) measured the rotation curve of Andromeda galaxy, which showed an unexpectedly large circular velocity at the outer parts of the galaxy. Further studies of galaxy rotation curves and the discrepancy between the visible matter and the total matter that needs to support the high rotational velocity suggested the need for dark matter ([Freeman, 1970](#); [Rubin & Ford, 1970](#)).

At the end of the 20th century, the development of Integral Field Spectroscopy (IFS) significantly advanced the study of galaxies by enabling the acquisition of spatially resolved, two-dimensional kinematics of galaxies ([Bacon et al., 2001](#); [Cappellari et al., 2011](#); [Sánchez et al., 2012](#); [Bryant et al., 2015](#)). This advancement provides unprecedented details about galaxies, such as the spin direction and kine-

matic distortion of gas, as revealed by their velocity fields.

Gas is present in a galaxy in multiple forms, including molecular gas (H_2), atomic gas (HI) and ionised gas (HII). Different phases of gas are studied using different observational techniques. The most common technique used to observe molecular gas in galaxies is radio observation using the carbon monoxide (CO) molecule as a tracer. Although molecular hydrogen is the most abundant form of molecular gas, it is difficult to observe. CO is the second most abundant molecule in the ISM and its rotational transition, CO(1-0), is easy to detect in radio observations. Radio telescopes like the Atacama Large Millimeter/submillimeter Array (ALMA; [ALMA Partnership et al., 2015](#)), and the Very Large Array (VLA; [Condon et al., 1998](#)) are used to measure radio emission. The primary observation technique used to study HI is the 21-centimetre line, or HI line, which is produced by a spin-flip transition of the electron in the neutral hydrogen atoms ([Ewen & Purcell, 1951](#); [Purcell, 1953](#)).

The properties of ionised gas can be investigated through detecting emission lines from spectroscopic observations. Instruments like SAMI ([Croom et al., 2012](#)), MUSE ([Bacon et al., 2010](#)), MaNGA ([Drory et al., 2015](#); [Blanton et al., 2017](#)), Fabry-Perot interferometers ([Epinat et al., 2008](#)) and Fourier Transform Spectrometers (FTS) ([Rousseau-Nepton et al., 2019](#)) collected spectroscopy of large samples of galaxies. The ionisation of gas can result from several processes, including photoionisation from massive young stars and AGN, and shock ionisation from supernovae and stellar winds. Emission line ratios can be used to determine gas temperature ([Osterbrock, 1989](#); [Hägele et al., 2006](#); [Binette et al., 2012](#)) and gas density ([Stanghellini & Kaler, 1989](#); [Kingsburgh & Barlow, 1992](#); [Wang et al., 2004](#)), provide diagnostics for the ionisation process (BPT; [Baldwin et al., 1981](#); [Kewley et al., 2001](#); [Kauffmann et al., 2003](#)) and metallicity measurement (see the review by [Kewley et al., 2019](#)).

The ionised gas velocity dispersion, measured using the width of emission lines, reveals the ionised gas turbulence within the galaxy. The integrated velocity dispersion measured from the spectrum integrated across a galaxy combines the random (or turbulent) motion of gas and rotational velocity, as both of them contribute to the broadening of the emission line of the integrated spectrum. Using IFS, we can obtain the spatially resolved gas velocity dispersion, also called intrinsic gas velocity dispersion or local gas velocity dispersion, which represents the random motion of gas around the mean rotational velocity at each spatial location.

The ionised gas velocity dispersion is found to be decreased with cosmic time, from $\sim 50 \text{ km s}^{-1}$ at $z \sim 2$ to $\sim 20 \text{ km s}^{-1}$ at $z \sim 0$ ([Kassin et al., 2012](#); [Wisnioski et al., 2015](#); [Übler et al., 2019](#)). Figure 1.5 shows the intrinsic gas velocity dispersion as a function of redshift from [Übler et al. \(2019\)](#). The evolution of ionised gas velocity dispersion is shown in red, which shows a decreasing trend of dispersion with cosmic time.

Ongoing energy inputs are required to sustain the ionised gas velocity dispersion we observed at all epochs. The thermal broadening of ionised gas traced by the $\text{H}\alpha$ emission line due to a characteristic temperature of 10^4 K is estimated to be 11.7 km s^{-1} ([Bland-Hawthorn et al., 2024](#)). Simulation studies show that the gas turbulence above the thermal contribution dissipates within a few megayears ([Mac](#)

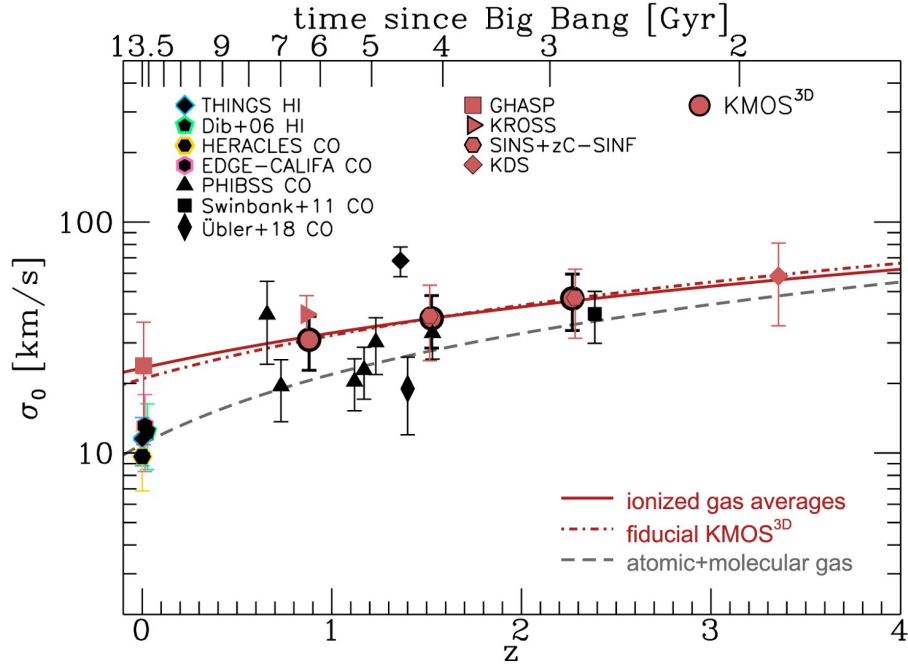


Figure 1.5: Intrinsic gas velocity dispersion as a function of redshift and cosmic time drawn from [Übler et al. \(2019\)](#). The average gas velocity dispersion of selected ionised gas measurements are shown in red. Local atomic and molecular averages and individual high- z molecular gas measurements are shown in black.

[Low et al., 1998](#); [Stone et al., 1998](#)). Therefore, additional energy sources are needed to explain the observation.

Previous studies identified several mechanisms that may contribute to the gas turbulence. These mechanisms can be categorized into external and internal mechanisms. External mechanisms include gas accretion ([Klessen & Hennebelle, 2010](#); [Aumer et al., 2010](#)) and minor mergers ([Bournaud et al., 2009](#)). Internal mechanisms include star-formation feedback ([Green et al., 2010](#); [Faucher-Giguère et al., 2013](#); [Green et al., 2014](#)), gravitational instability ([Krumholz & Burkhardt, 2016](#); [Krumholz et al., 2018](#)) and interactions between different galaxy components ([Aumer et al., 2010](#); [Oliva-Altamirano et al., 2018](#)).

The degree of importance of these mechanisms in driving gas turbulence at different redshifts is debated. The gas velocity dispersion of IFS data has not been measured in a consistent manner for galaxies at $z = 0$ to 1. Therefore, a consistent measurement of gas velocity dispersion is needed to constrain the evolution of gas turbulence and to understand the mechanisms that drive gas turbulence.

The gas velocity dispersion measured using different emission lines may vary, especially for the galaxies with relatively low gas velocity dispersion (smaller than 30 km s^{-1}) (e.g. [Law et al., 2021, 2022](#); [Übler et al., 2024](#)). Various lines may be sensitive to different mechanisms. Therefore, using the same emission line to measure the gas velocity dispersion is also important for the consistency of the results.

1.3 Metallicity distribution

Metallicity is the abundance of elements that are heavier than hydrogen and helium. Big bang nucleosynthesis results in mass abundances of about 75% hydrogen, about 25% helium, and about 0.01% heavier elements. Most of the heavy elements in the present Universe are created in the following stellar nucleosynthesis. Therefore, metallicity reflects the imprint of star formation history.

By studying the metallicity and metallicity distribution of galaxies, we can learn how gas is accreted, consumed, recycled and redistributed. Stellar winds and supernovae blow the metals synthesized in stars into the ISM. Galaxies lose metals through outflows and stripping. Metals that are blown out may fall back into the galaxy in the so-called "galactic fountain" process. Gas from the IGM accretes into galaxies and dilutes the metallicity. In summary, many internal and external processes influence the metallicity of galaxies. Therefore, the analysis of metallicity can help us understand the processes that regulate the evolution of galaxies.

Normally, the gas-phase metallicity is expressed by the oxygen abundance ($12 + \log_{10}(\text{O}/\text{H})$), as oxygen is the most abundant heavy element by mass. The gas-phase metallicity can be inferred by a variety of methods (see the reviews by [Kewley et al., 2019](#); [Maiolino & Mannucci, 2019](#)).

- The direct method uses temperature-sensitive auroral lines, such as $[\text{O III}]\lambda 4363$ and $[\text{O II}]\lambda 7320, \lambda 7330$, to measure the electron temperature and then derive chemical abundance. The limitation of this direct method is the auroral lines are typically faint. Therefore, it does not work well for high redshift galaxies (e.g. [Dinerstein, 1990](#); [Pilyugin et al., 2006](#); [Pérez-Montero, 2017](#)).
- Empirical calibrations are derived by fitting the auroral metallicity and optical strong-line ratios using the observed data. This method enables us to measure the metallicity of faint galaxies using the strong line diagnostics. However, systematic differences exist between different auroral strong-lines diagnostics ([Pagel et al., 1979](#); [Edmunds & Pagel, 1984](#); [Dopita & Evans, 1986](#); [Pilyugin & Thuan, 2005](#)).
- Theoretical metallicity calibrations are calculated by combining stellar population synthesis and photoionisation models ([McGaugh, 1991](#); [Charlot & Longhetti, 2001](#); [Kewley & Dopita, 2002](#)).

The gas-phase metallicity has correlations with many galaxy properties. The first relation that has been observed is the mass-metallicity relation (MZR; [Peimbert & Spinrad, 1970](#); [Lequeux et al., 1979](#); [Tremonti et al., 2004](#)). The MZR could be influenced by several mechanisms. Star formation feedback expels metals through metal-rich gas outflows. This process removes metals more efficiently for smaller galaxies with shallower potential wells, and vice versa ([Tremonti et al., 2004](#); [Tumlinson et al., 2011](#); [Chisholm et al., 2018](#)). Similarly, [Vaughan et al. \(2022\)](#) used galaxy stellar mass divided by galaxy size (M/R) as a proxy of the gravitational potential and found it gave a better correlation with metallicity for both star-forming and quenched galaxies. As shown in Figure 1.6, MZR evolves monotonically with

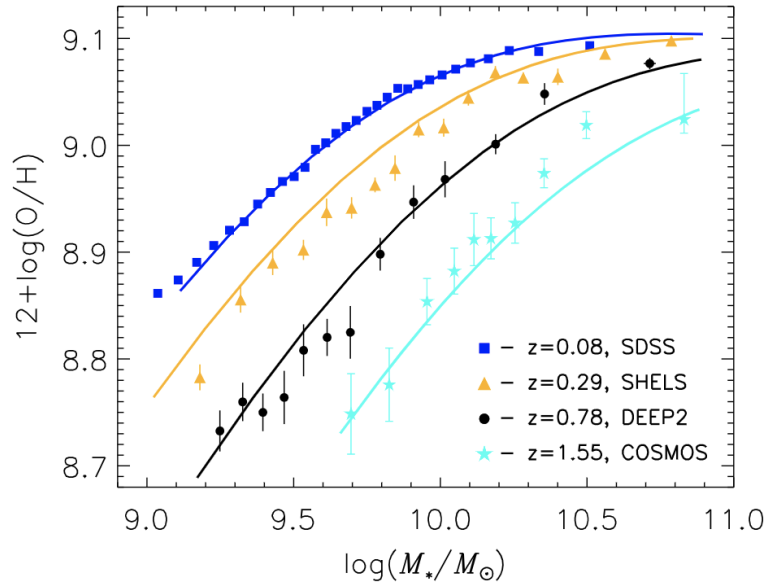


Figure 1.6: Redshift evolution of the MZR from Maiolino & Mannucci (2019) reproduced from Zahid et al. (2014). Blue, yellow, black and cyan points refer to $z = 0.08$, 0.29 , 0.78 , and 1.55 , respectively.

redshift (Gallazzi et al., 2014; Faisst et al., 2016). At fixed stellar mass, galaxies at higher redshift have lower metallicity.

Metallicity also correlates with SFR (Ellison et al., 2008). To describe the inter-correlation between mass, metallicity and SFR, Mannucci et al. (2010) introduced the fundamental metallicity relation (FMR). They found that high-redshift galaxies followed the FMR defined by local galaxies, i.e. there is no redshift evolution for FMR up to $z \sim 2.5$. It suggests that the evolution of MZR is due to galaxies at high redshift having higher SFRs.

The radial distribution of metals provides insights into gas accretion and star formation processes. Observational studies show that the metallicity of low-redshift galaxies decreases exponentially with radius (Sánchez et al., 2012; Belfiore et al., 2017). The negative metallicity gradient conforms with the galactic discs' inside-out formation scenario (Portinari & Chiosi, 1999; Sánchez et al., 2014). The metallicity gradient correlates with morphology (Sánchez et al., 2014), mass (Belfiore et al., 2017; Poetrodjojo et al., 2021), size (Sánchez-Menguiano et al., 2018; Boardman et al., 2021) and environment (Lian et al., 2019), which reflects a tight connection between metallicity gradient and galaxy evolution. By comparing observation data with theoretical predictions, we can have a better understanding of the impact of physical processes on the metallicity distribution (Taylor & Kobayashi, 2017; Kobayashi & Taylor, 2023).

Different to local galaxies, the metallicity gradients of high-redshift galaxies are mostly flat (Wuyts et al., 2016), suggesting a need for strong feedback mechanisms to flatten the gradient in high-redshift galaxies. The scatter of metallicity gradients of high-redshift galaxies is larger than that of low-redshift galaxies. Carton et al.

(2018) found 8% of high-redshift galaxies in their sample have positive metallicity gradients. This may result from strong metal-poor gas accretion that dilutes the metallicity at the galaxy centre. The accreted metal-poor gas acts as the fuel of star formation, resulting in a correlation between metallicity gradient and specific star formation rate (sSFR; Stott et al., 2014).

1.4 Spectroscopic observations and techniques

Unlike other branches of physics where controlled experiments can be performed on Earth, the Universe itself serves as the laboratory for astrophysics. Each advance in observational techniques improves our understanding of the Universe and brings new discoveries. Among these techniques, spectroscopy enables us to obtain unprecedented details in the wavelength direction by measuring features such as gas emission lines and stellar continuum, unveiling physical processes and properties of galaxies, such as star formation, feedback, gas motion, metallicity, etc.

1.4.1 Spectroscopy

Early spectroscopy was based on slits, which isolated the light from a single object. While multi-slit systems were developed to observe multiple objects at once, they are less flexible compared to modern fibre-based systems. The optical fibre can direct light to the spectrograph, enabling the observation of multiple objects simultaneously, significantly increasing the efficiency of building large samples.

The single-fibre spectroscopy enables us to obtain the spectra of galaxies within the aperture of the fibre. Multi-object single-fibre galaxy surveys like the 2dF Galaxy Redshift Survey (2dFGRS; Colless et al., 2001) that obtained spectra for $\sim 220,000$ galaxies, provided redshift of each galaxy and mapped the large-scale structure of the Universe; the Sloan Digital Sky Survey (SDSS) obtained the spectra of over three million galaxies (Stoughton et al., 2002; Abazajian et al., 2009; Alam et al., 2015). However, galaxies are complex objects whose structure and properties vary spatially, requiring a more comprehensive approach to fully capture their structure.

Fabry-Perot interferometers were used to collect spectroscopy of galaxies since 1980 (Taylor & Atherton, 1980). Many studies used the Fabry-Perot technique to obtain three-dimensional (two spatial dimensions and one wavelength dimension) information about galaxies, such as the GHASP survey (Epinat et al., 2008). While Fabry-Perot interferometry was an early approach to integral field spectroscopy (IFS), modern IFS systems using fibre bundles and image slicers have significantly advanced the field by enabling more efficient and higher-resolution observations.

The development of IFS overcomes the limitations of single-fibres and long-slit spectroscopy, providing two-dimensional spectroscopy. The first large IFS project was SAURON (Bacon et al., 2001), which obtained the stellar kinematics of 48 galaxies (Emsellem et al., 2004). The two-dimensional stellar kinematics fostered a new analysis of stellar angular momentum, which revealed that the early-type galaxies can be classified into two distinct groups, slow-rotator and fast rotator (Emsellem

et al., 2007; Cappellari et al., 2007). Based on the SAURON project, the ATLAS^{3D} project obtained spatially-resolved spectra of ~ 260 early-type galaxies, furthering our understanding of the evolution of early-type galaxies (Cappellari et al., 2011). The Calar Alto Legacy Integral Field Area (CALIFA) survey collected spectra of 667 galaxies that cover all types of galaxies. (Sánchez et al., 2012, 2016).

The early IFS projects mentioned above were based on single-object instruments, which had monolithic optics, i.e. they can only observe one galaxy at a time, limiting their efficiency in building large samples. To build large samples that cover a wide range of galaxy properties and environments, increasing the observation efficiency is necessary. Multi-object IFS surveys addressed this limitation by observing multiple galaxies in one exposure. By gathering statistically significant samples, multi-object IFS surveys, such as the SAMI Survey (Croom et al., 2012; Bryant et al., 2015) and the MaNGA Survey (Bundy et al., 2015; Blanton et al., 2017), allow us to investigate trends and correlations that were previously inaccessible with smaller datasets. Surveys like HUDF (Bacon et al., 2017), MAGIC (Epinat et al., 2024) and MEGAFLOW (Bouché et al., 2024) observed galaxies over a large environment and redshift range using MUSE, the Multi Unit Spectroscopic Explorer (Bacon et al., 2010).

1.4.2 The SAMI Galaxy Survey

The Sydney-AAO (Australian Astronomical Observatory) Multi-object IFS (SAMI) Survey (Croom et al., 2012; Bryant et al., 2015) is the pioneer of multi-object IFS surveys. While FLAMES (Pasquini et al., 2002; Flores et al., 2006) was the first multi-object IFS instrument, it featured smaller fibre bundles and was used to target relatively small samples. The SAMI instrument (Croom et al., 2012) was designed for use on the 3.9-m Anglo-Australian Telescope (AAT). The SAMI survey employed revolutionary new imaging fibre bundles, *hexabundles* (Bland-Hawthorn et al., 2011; Bryant et al., 2011, 2014), which employed 61 optical fibres, covering 15 arcsec diameter in total with a filling fraction of 73%, as shown in Figure 1.7. There are 13 hexabundles in SAMI, which can observe 12 target galaxies and one calibration star simultaneously. SAMI covers wavelength between 3750-5750 Å in the blue arm and 6300-7400 Å in the red arm, with spectral resolution $R = 1804$ and 4303 respectively. This wavelength coverage ensures that SAMI has access to important spectral features, such as $H\alpha$, $H\beta$, $[N\ II]$, $[O\ II]$, $[O\ III]$ and D4000. The high resolution in the red arm allows analysis on ionised gas velocity dispersion.

One of the science goals of the SAMI survey is to understand how both mass and angular momentum build in galaxies. To achieve this goal, the SAMI survey collected the spatially resolved spectroscopy of over 3000 galaxies at $0.004 < z < 0.115$, spanning a broad range of stellar mass and environment. In addition, the SFR and metallicity typically vary spatially. The hexabundles cover $2\ R_e$ for 40% of galaxies in the sample, enabling us to capture the variation of galaxy properties up to larger radius than previous studies.

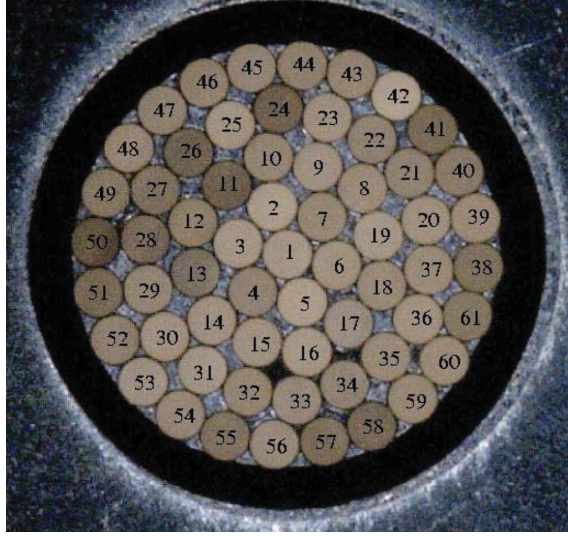


Figure 1.7: An image of a hexabundle front facet used in the SAMI instrument. This hexabundle consists of 61 optical fibres. This plot is taken from [Croom et al. \(2012\)](#).

1.4.3 The MAGPI survey

To have a deeper understanding of galaxy evolution, it is important to investigate galaxies at different evolution stages. The Middle Ages Galaxy Properties with Integral Field Spectroscopy (MAGPI) survey ([Foster et al., 2021](#)) is designed to study the physical drivers of galaxy transformation at $z \sim 0.3$ (3 – 4 Gyr lookback time), when galaxy properties are predicted to evolve significantly. Previous IFS surveys mostly focused on low-redshift, like SAMI ($0.004 < z < 0.115$; [Bryant et al., 2015](#)) and MaNGA ($0.01 < z < 0.15$; [Blanton et al., 2017](#)), and high-redshift, like KROSS ($0.8 < z < 1.0$; [Stott et al., 2016](#)) and KMOS^{3D} ($0.7 < z < 2.7$; [Wisnioski et al., 2015](#)). As shown in Figure 1.8, the MAGPI survey provides a linkage between low and high-redshift galaxies, helping us constrain the evolution of galaxies.

Nature vs. *Nurture* is a long debating topic in galaxy evolution. *Nature* refers to the internal processes, such as gas transportation and stellar feedback. On the contrary, *Nurture* refers to the environmental effect. It is unclear which mechanism plays a more important role in shaping the evolution of the galaxies and how these processes influence each other. The challenges of tackling this question include the complexity of the interplay of different processes, combined effects from local and global mechanisms and the variety of these processes across cosmic time.

The science goal of the MAGPI survey is to disentangle the influence of external and internal processes on galaxy evolution. To break the degeneracy between processes, detailed measurements of galaxy properties like stellar and gas kinematics, spatially resolved metallicity distribution and SFR are necessary, which can be obtained by high-resolution integral field spectroscopy. As shown in Figure 1.8, the MAGPI survey is the first observational survey that obtains both spatially resolved stellar and ionised gas kinematics beyond 2 Gyr lookback time, which provides new constraints on the evolution of galaxies.

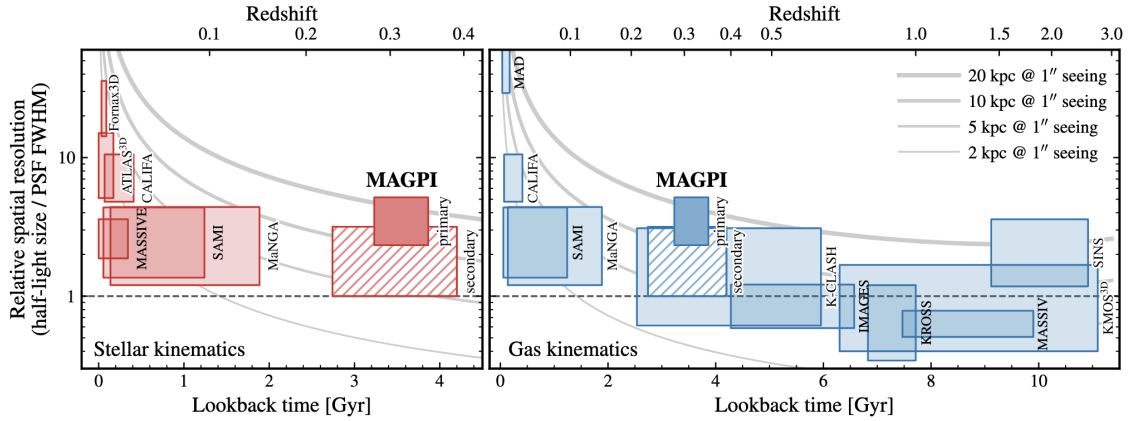


Figure 1.8: Comparison of the MAGPI spatial resolution and redshift range with that of other IFS surveys focused on stellar (left panel) and gas (right panel) kinematics. The MAGPI samples are shown in primary samples and secondary samples separately. This plot is taken from [Foster et al. \(2021\)](#).

The MAGPI survey employs the Multi Unit Spectroscopic Explorer (MUSE; [Bacon et al., 2010](#)) instrument, with Ground Layer Adaptive Optics (GLAO) at the Very Large Telescope (VLT) of the European Southern Observatory. Operating in wide-field mode, MUSE provides a 1×1 arcmin² field of view (FOV) sampled at 0.2×0.2 arcsec². The MAGPI observations cover a wavelength range of 4700 to 9351 Å, with a spectral resolution of $R = 2728$ at 7025 Å, covering multiple emission lines that can be used for the measurement of kinematics and metallicity, such as H α , H β , [N II], [O II], [O III].

The MAGPI survey selected galaxies from a broad range of environments. The primary samples include 60 massive central galaxies with 20 each in isolated, group and cluster environments (full sample halo mass range $11.35 \leq \log(M_{\text{halo}}/M_{\odot}) \leq 15.35$). The secondary samples include neighbouring galaxies within the MUSE FOV around the central galaxies.

1.4.4 Galaxy modelling techniques

The spatial resolution of ground-based spectroscopy is fundamentally constrained by the Earth’s atmosphere, a phenomenon commonly referred to as seeing or beam smearing. Beam smearing spreads the light over a larger area, normally described by the point spread function (PSF). This effect impacts the observed properties of galaxies, such as the distribution of flux and the kinematic measurements. For example, it can smooth out the flux distribution and inferred metallicity distribution ([Yuan et al., 2013](#); [Mast et al., 2014](#); [Stott et al., 2014](#); [Belfiore et al., 2017](#)), flatten the observed velocity gradients, and broaden the velocity dispersion ([Epinat et al., 2010](#); [Davies et al., 2011](#); [Varidel et al., 2016](#)).

The spectral resolution of the spectrograph, normally described by the line spread function (LSF), and spaxel grid also impacts our measurements. Therefore, to study the intrinsic properties of galaxies, techniques that can mitigate or account for the instrumental and atmospheric factors are necessary.

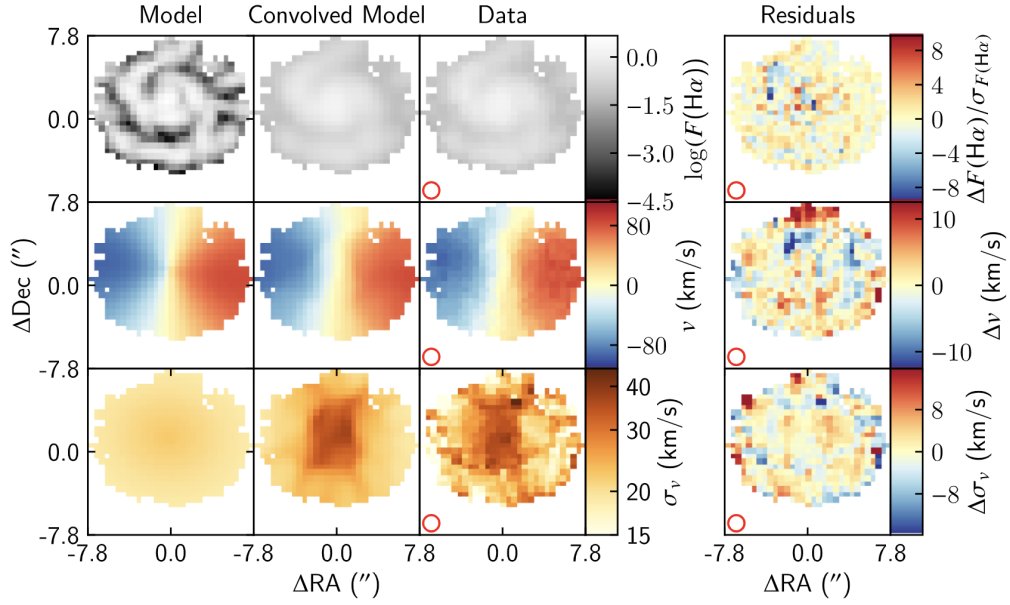


Figure 1.9: The 2D maps of the BLOBBY3D results for GAMA 485885 from the SAMI Galaxy Survey. These plots show from left to right the model built by BLOBBY3D, the model convolved with the PSF and LSF, single-component Gaussian fits to the data, and 2D residuals between the data and the convolved model. The first row shows the flux distribution of the H α emission line; the second row shows the velocity map; the third row shows the velocity dispersion map. This figure is taken from [Varidel et al. \(2019\)](#).

Many efforts have been made to recover the intrinsic galaxy properties, such as applying a correction on velocity dispersion and building a galaxy model that accounts for the instrumental factors. [Davies et al. \(2011\)](#) built a simple disk model assuming an exponential radial profile of flux, accounting for the beam smearing and instrumental broadening. [Johnson et al. \(2018\)](#) built models similar to [Davies et al. \(2011\)](#) and convolved the models with a range of seeing conditions to simulate the effects of beam smearing. [Di Teodoro & Fraternali \(2015\)](#) built a tilted-ring model (^{3D}BAROLO), which assumed a galaxy consists of concentric rings with different rotational velocities and flux. Similarly, GBKFIT ([Bekiaris et al., 2016](#)) and GALPAK3D ([Bouché et al., 2015](#)) also assumed parametric radial flux distributions and velocity profiles in their model.

However, the above models cannot fully capture the non-parametric variation of flux distribution of galaxies. Some galaxies may have complex substructures, such as spiral arms, rings and clumps. The effect of beam smearing also depends on the flux distribution. Therefore, a modelling technique that can model the flux substructures is able to recover the intrinsic flux distribution and kinematics better than other modelling techniques.

The method we used to measure the intrinsic flux distribution and gas kinematics is a code called BLOBBY3D ([Varidel et al., 2019](#)). It is a Bayesian inference method which accounts for PSF and LSF and forward models the gas kinematics and substructures simultaneously. BLOBBY3D does not assume any given gas structure, but

decomposes the gas distribution into a number of Gaussian ‘blobs’. The number, shape and brightness of blobs are flexible and depend on the complexity of the observed gas substructure. Figure 1.9 shows an example of the BLOBBY3D results, which demonstrates its ability to model the complex flux substructures and intrinsic gas velocity dispersion.

1.5 Thesis summary

In this thesis, we aim to examine the impacts of internal and external mechanisms on galaxy kinematics and ISM properties. In Chapter 2, we focus on the environmental impact on galaxy stellar angular momentum. Specifically, we investigate the relation between galaxy rotation and the relative motion of neighbouring galaxies. In Chapter 3 and Chapter 4, we use BLOBBY3D to build models for intermediate-redshift star-forming galaxies to obtain the intrinsic (seeing-deconvolved) galaxy properties. In Chapter 3, we measure the ionised gas velocity dispersion of 110 star-forming galaxies from the MAGPI survey and investigate the mechanisms that drive gas turbulence. We also compare our results to galaxies at low and high redshifts to investigate the evolution of gas velocity dispersion. In Chapter 4, we extend our BLOBBY3D analysis to allow the measurement of the seeing-deconvolved gas-phase metallicity and metallicity gradient of the MAGPI galaxies. We investigate the correlation between galaxy properties and metallicity gradient to understand the mechanisms that influence metal distribution. In Chapter 5, we summarise the main conclusions of this thesis and discuss potential future work.

Chapter 2

The SAMI Galaxy Survey: The Relationship between Galaxy Rotation and the Motion of Neighbours

This chapter is based on the paper *The SAMI Galaxy Survey: The Relationship between Galaxy Rotation and the Motion of Neighbours*, which was published in the *Monthly Notices of the Royal Astronomical Society* in Volume 515, Issue 1, Pages 984-997. The authors are Yifan Mai, Sam P. Vaughan, Scott M. Croom, Jesse van de Sande, Stefania Barsanti, Joss Bland-Hawthorn, Sarah Brough, Julia J. Bryant, Matthew Colless, Michael Goodwin, Brent Groves, Iraklis S. Konstantopoulos, Jon S. Lawrence, Nuria P. F. Lorente, and Samuel N. Richards.

I was responsible for data analysis, interpretation and paper writing. The data analysis includes calculating the relative velocity between SAMI galaxies and their neighbouring galaxies using the GAMA catalogue, generating the stacked maps based on the PA measurements from [van de Sande et al. \(2017b\)](#) and all of the following analysis of average velocities of neighbouring galaxies. My supervisors, Scott M. Croom and Sam P. Vaughan, provided guidance on methodology, reviewed drafts, and provided feedback. Other authors are founders and team members of the SAMI Galaxy Survey. They contributed to the observing and data reduction and provided comments on the paper.

2.1 Abstract

Using data from the SAMI Galaxy Survey, we investigate the correlation between the projected stellar kinematic spin vector of 1397 SAMI galaxies and the line-of-sight motion of their neighbouring galaxies. We calculate the luminosity-weighted mean velocity difference between SAMI galaxies and their neighbours in the direction perpendicular to the SAMI galaxies' angular momentum axes. The luminosity-weighted mean velocity offsets between SAMI and neighbours, which indicates the signal of coherence between the rotation of the SAMI galaxies and the motion of neighbours, is $9.0 \pm 5.4 \text{ km s}^{-1}$ (1.7σ) for neighbours within 1 Mpc. In a large-scale analysis, we find that the average velocity offsets increase for neighbours out to 2 Mpc. However, the velocities are consistent with zero or negative for neighbours outside 3 Mpc. The negative signals for neighbours at distance around 10 Mpc are also significant at $\sim 2\sigma$ level, which indicate that the positive signals within 2 Mpc might come from the variance of large-scale structure. We also calculate average velocities of different subsamples, including galaxies in different regions of the sky, galaxies with different stellar masses, galaxy type, λ_{Re} and inclination. Although low-mass, high-mass, early-type and low-spin galaxies subsamples show $2\text{--}3\sigma$ signal of coherence for the neighbours within 2 Mpc, the results for different inclination subsamples and large-scale results suggest that the $\sim 2\sigma$ signals might result from coincidental scatter or variance of large-scale structure. Overall, the modest evidence of coherence signals for neighbouring galaxies within 2 Mpc needs to be confirmed by larger samples of observations and simulation studies.

2.2 Introduction

The environment in which a galaxy resides plays an important role in its formation and evolution. For example, it is well known that star formation rate is dependent on local galaxy density at low-redshift (e.g. Hashimoto et al., 1998; Kauffmann et al., 2004; Lewis et al., 2002). Likewise, there is evidence that a galaxy's morphology is also dependent on environment. The morphology-density relation, first presented by Dressler (1980), shows that the fraction of elliptical and S0 galaxies increases with increasing density while the fraction of spiral galaxies decreases. Cappellari et al. (2011) found the existence of a kinematic morphology-density relationship, which showed that slow-rotator galaxies are more likely to be found in high density environments. van de Sande et al. (2021b) also found that environmental density correlates with the fraction of slow rotators after accounting for the effect of stellar mass (but see also Brough et al., 2017; Greene et al., 2017; Veale et al., 2017).

A key question that relates to morphology is how galaxies acquire their angular momentum. Tidal torque theories state that protogalaxies acquire angular momentum through torquing moments exerted by nearby large-scale structure. The angular momentum of protogalaxies is conserved during collapse (Doroshkevich, 1970; White, 1984; Porciani et al., 2002; Schäfer, 2009). However, tidal torque theories are not enough to give a full picture of the build up of angular momentum of present-day galaxies. The spin of a galaxy may deviate from the original direction due to non-

linear effects such as mergers (Welker et al., 2014).

A different and novel investigation into the relationship between a galaxy and its local environment was conducted by Welker et al. (2020). They used data from the SAMI Galaxy Survey to find how a galaxy’s spin axis is related to the nearest galaxy filament. Welker et al. (2020) found that the spin of low-mass galaxies tended to be aligned with the nearest filament while the spin of high-mass galaxies was more likely to be orthogonal to their nearest filament. Their results are consistent with other observational studies (Tempel & Libeskind, 2013; Kraljic et al., 2021) and numerical simulation results (Codis et al., 2012; Dubois et al., 2014; Wang et al., 2018; Ganeshiah Veena et al., 2019; Kraljic et al., 2020). Most recently, Barsanti et al. (submitted), using the SAMI Galaxy Survey, find that the mass of the bulge is the primary parameter of correlation with spin-filament alignments.

Lee et al. (2019a, hereafter L19a) took a different approach, examining whether the rotation of a galaxy is correlated with the motion of its neighbours. Their results can be considered as observational evidence that the direction of galaxy rotation is influenced by the interaction of the neighbouring galaxies through adding new angular momentum during flybys and/or mergers. They estimated the angular momentum vectors of 445 galaxies from the Calar Alto Legacy Intergral Field Area survey (CALIFA; Sánchez et al., 2012) whilst also measuring the relative motion of their neighbouring galaxies by comparing the galaxy redshifts. Then, they built a composite map of the velocity distribution of each galaxy’s neighbours and calculated the luminosity-weighted mean velocity as a function of radius from the central galaxy. They found that coherence between the rotations of CALIFA galaxies and the motion of neighbouring galaxies is significant for the neighbours up to 800 kpc in projected distance on the sky. They also found hints that the coherence signal between galaxies and their neighbours was stronger when they only studied the outskirts of each galaxy, rather than when they studied the central regions, and that the spin of low-mass galaxies tended to be more aligned with their neighbours than the rotation of high-mass galaxies.

Lee et al. (2019b, hereafter L19b) investigated this coherence on larger scales. They extended the scope of neighbour galaxies to 15 Mpc, and found that this coherence exists out to several Mpc scales, especially between the central rotation of CALIFA galaxies and the neighbouring galaxies with red optical colours. This result might indicate a correlation between the long-term motion of the large-scale structure and the direction of a galaxy’s rotation. L19b found that the absolute-luminosity-weighted velocity for central rotation ($30.6 \pm 10.9 \text{ km s}^{-1}$) is slightly larger than that for outskirts rotation ($25.9 \pm 11.2 \text{ km s}^{-1}$) when measured using the neighbours at distance $1 \text{ Mpc} < D < 6 \text{ Mpc}$. On the contrary, L19a found that the coherence signal is stronger for the outskirts rotation of CALIFA galaxies when considering the neighbours within 1 Mpc. L19b also analysed the subsamples of CALIFA galaxies and found that the high Sérsic index galaxies (Sérsic index $n > 2$) or internally-well-aligned galaxies (position angle difference between the central and outskirts angular momentum vectors is smaller than 5.0°) have slightly stronger coherence.

The L19a and L19b results are intriguing, but the relatively small sample size of

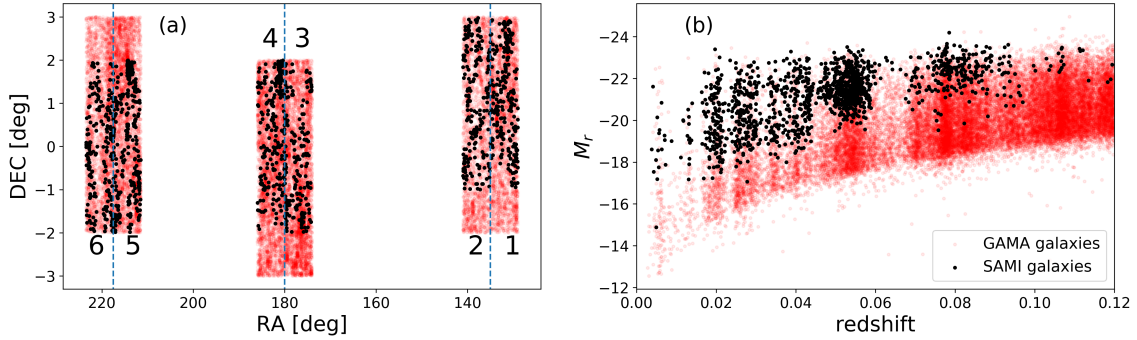


Figure 2.1: (a) Red points indicate the spatial distribution of GAMA galaxies, and black points show the spatial distribution of the SAMI galaxies. We divided the SAMI galaxies into 6 parts (as indicated by black numbers) in order to investigate the variance of large scale structure between different regions; (b) r -band absolute magnitude versus redshift diagram of SAMI and GAMA galaxies.

CALIFA galaxies hampers the ability to draw any firm conclusions about the size of the coherence signal. In this study, we investigate the existence of coherence between the angular momentum vectors of galaxies and the motion of their neighbours, carrying out analysis similar to [L19a](#) and [L19b](#), using a sample that is three times as large from the SAMI Galaxy Survey. The plan of the paper is as follows: in [Section 2.3](#) and [Section 2.4](#), we describe the data and methods of this study; in [Section 2.5](#) and [Section 2.6](#), we analyse the data and discuss our results; in [Section 2.7](#), we present our conclusions. Throughout this paper, we adopt the concordance cosmology: $(\Omega_\Lambda, \Omega_m, h) = (0.7, 0.3, 0.7)$.

2.3 Data

We use data of galaxies observed by the Sydney-AAO (Australian Astronomical Observatory) Multi-object Integral field spectrograph (SAMI; [Croom et al., 2012](#)) as part of the SAMI Galaxy Survey ([Bryant et al., 2015](#)). SAMI has collected spatially resolved spectroscopy for 3068 galaxies between a redshift of 0.004 and 0.115, with wavelength coverage between 3700–5700 Å in the blue and 6300–7400 Å in the red. The SAMI integral field units are hexabundles ([Bryant et al., 2014](#); [Bland-Hawthorn et al., 2011](#)) with radius 7.5 arcsec, consisting of 61 individual fibres, whose radii are 0.8 arcsec. SAMI fibres are fed to the double-beam AAOmega spectrograph ([Sharp et al., 2006](#)). 40 percent of the galaxies are observed to more than twice their effective radius (R_e), and the R_e of 17 percent of the galaxies are larger than the SAMI bundle. We use data from the third public SAMI data release (DR3; [Croom et al., 2021](#)), which presents fully reduced data-cubes as well as catalogues of galaxy properties and maps of spatially resolved kinematics ([Sharp et al., 2015](#); [Bryant et al., 2015](#); [Owers et al., 2017](#)). The SAMI galaxies are distributed in three $4 \times 12 \text{ deg}^2$ fields, as shown in [Figure 2.1\(a\)](#). [Figure 2.1\(b\)](#) shows the r -band absolute magnitude versus redshift diagram of the SAMI galaxies we use in this study (black points) and the neighbouring galaxies (red points). We do not include SAMI cluster galaxies in this sample.

The SAMI survey reached $> 80\%$ completeness (the ratio between the number of observed galaxies and the number of good targets) for primary targets. The SAMI survey includes four volume limited samples which consist of a stepped series of stellar mass limits, i.e. samples at higher redshift have higher stellar mass limits (see Fig 4. of [Bryant et al., 2015](#)).

This work defines the “neighbour galaxies” as the galaxies that have line-of-sight velocity differences with respect to the given SAMI galaxies less than 500 km s^{-1} and projected distances smaller than 20 Mpc. The neighbour galaxies database comes from the Galaxy and Mass Assembly (GAMA) survey ([Driver et al., 2011](#)), which is a spectroscopic survey carried out using the AAOmega multi-object spectrograph on the Anglo-Australian Telescope (AAT). The GAMA survey consists of five individual regions. We used the data of galaxies in three equatorial regions called G09, G12 and G15 each of 60 deg^2 ([Baldry et al., 2018](#); [Liske et al., 2015](#)), within which the SAMI Galaxy Survey has been observed.

Three GAMA regions used in this study reach $> 98\%$ completeness. The limit of r -band magnitude of the GAMA survey is 16 to 19.4 for G09 and G15, and 16 to 19.8 for G12. We only include galaxies that have the normalized redshift quality, $nQ \geq 3$, i.e. the probability that the redshift found for this spectrum is greater than 0.9. The redshift error for galaxies with $nQ \geq 3$ is $\sigma_v = 65 \text{ km s}^{-1}$ (see more details in [Driver et al., 2011](#)).

In this study, the main quantity of interest is the stellar kinematic position angle (PA) of each galaxy. The kinematic PA is less affected by the projection effect and generally more accurate than PA inferred from morphology, as it better traces the angular momentum of the galaxy. We use the measurements of PA from [van de Sande et al. \(2017b\)](#), and briefly outline the measurement method below. PA represents the angle between the negative velocity peak (with respect to the systematic velocity of the galaxy) of the kinematic map and North. For example, a kinematic PA of 90° represents the negative velocity part of that galaxy aligned to the east. PA is measured using the FIT_KINEMATIC_PA code, based on the method presented in Appendix C of [Krajinović et al. \(2006\)](#). PAs are obtained from the two-dimensional stellar velocity kinematic maps using spaxels that have uncertainties in stellar velocity less than 30 km s^{-1} . Other than the limit on uncertainty, we do not place any further constraints on which spaxels are used, in contrast with [L19a](#). They measured the PA of CALIFA galaxies from the central ($R \leq R_e$) and outskirt regions ($R_e < R \leq 2R_e$) respectively. Because the bundles used in SAMI survey only cover up to $1.5 R_e$ for most of SAMI targets, we are not able to perform the measurement for $R_e < R \leq 2R_e$. Therefore, we use all spaxels to measure PA. Our results are comparable to the " $R \leq R_e$ " subsample on [L19a](#), where they only use spaxels within R_e to measure PA.

The SAMI DR3 includes 1559 galaxies with PA data in the GAMA regions. In order to decrease the negative effects of position angle uncertainties, we only use data where the error on PA is smaller than 10° , resulting in a sample of 1257 galaxies. In order to compare our results with [L19a](#), we also process the data using an error limit of $< 20^\circ$. This sample contains 1397 galaxies. Figure 2.2 demonstrates the

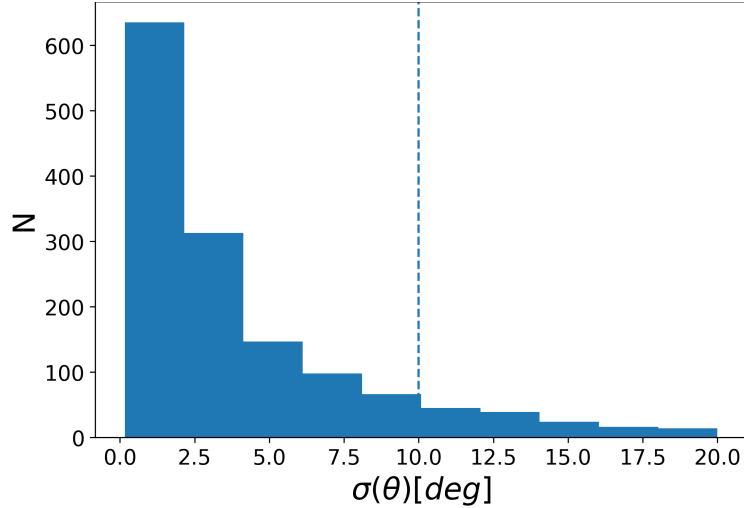


Figure 2.2: Uncertainty distribution of the position angles of the SAMI galaxies. The vertical line denotes 10° uncertainty.

uncertainty distribution of the position angles of the SAMI galaxies that match criteria. Though the target selection of SAMI survey aims to cover a broad range in stellar mass, galaxies with poor measurement of stellar kinematic position angle tend to be faint.

The stellar mass of SAMI galaxies are measured using a method described in [Bryant et al. \(2015\)](#). The morphologies of SAMI galaxies have been visually classified by SAMI team members ([Cortese et al., 2016](#)). The measurements of the spin parameter approximation (the flux-weighted ratio of ordered to random motion of stars within a galaxy), λ_{Re} , are conducted by [van de Sande et al. \(2017b\)](#) with aperture correction ([van de Sande et al., 2017a](#)) and seeing correction from [Harborne et al. \(2020\)](#) (optimised for SAMI in [van de Sande et al. 2021a](#)). The measurement of photometric ellipticity ([D'Eugenio et al., 2021](#)) is based on r -band SDSS and VLT Survey Telescope (VST) ([Shanks et al., 2015](#)) images using Multi Gaussian Expansion (MGE, [Cappellari, 2002](#)). We obtain an r -band axis ratio (b/a) from ellipticity and determine the inclination as follows ([Hubble, 1926](#)):

$$\cos(i) = \sqrt{\frac{(b/a)^2 - (b/a)_{\min}^2}{1 - (b/a)_{\min}^2}}, \quad (2.1)$$

with $(b/a)_{\min} = 0.15$ (following [Sargent et al. 2010](#) and [Leslie et al. 2018](#) and based on [Guthrie 1992](#) and [Yuan & Zhu 2004](#)).

In order to investigate the relative motion between the SAMI galaxies and their neighbours, we calculate the line-of-sight velocity offset (Δv) for each neighbouring galaxy as

$$\Delta v = \frac{z_{\text{nei}} - z_{\text{SAMI}}}{1 + z_{\text{SAMI}}} \cdot c, \quad (2.2)$$

where z_{nei} is the heliocentric redshift of neighbour galaxies around SAMI galaxies, z_{SAMI} is the heliocentric redshift of SAMI galaxies and c is the speed of light. Both

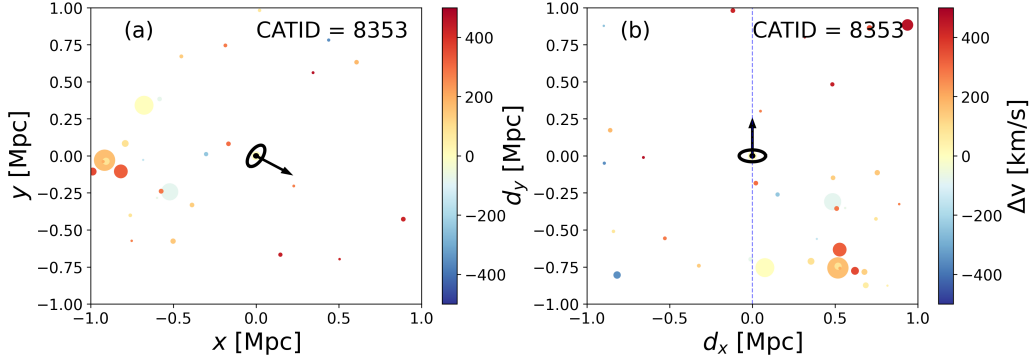


Figure 2.3: The left panel (a) shows a SAMI galaxy and its neighbour galaxies. In the right panel (b) we have rotated the whole picture to make sure that the spin vector (PA) of SAMI galaxy is upward. The black ellipses in the middle of pictures demonstrate an example of SAMI galaxy and the black arrows show its spin vector. The neighbour circles illustrate the neighbour galaxies. The size of circles are proportional to the luminosity of galaxies and the color show the line-of-sight velocity of neighbour galaxies relative to the central SAMI galaxy.

redshifts of neighbour galaxies and SAMI galaxies are from the GAMA catalogue, as galaxies observed by SAMI are drawn from the GAMA survey.

2.4 Methods

2.4.1 Measurements of average velocities of neighbouring galaxies

In order to investigate the relationship between galaxies' rotation and the motion of their neighbours, we compare the direction of the projected angular momenta of SAMI galaxies with the line-of-sight velocity offset of their neighbour galaxies. This method is based on that of [L19a](#). We rotate all the galaxies in a 20 Mpc by 20 Mpc box around each SAMI galaxy so that the SAMI galaxy has its angular momentum axis pointing vertically (North). This means that rotation towards the observer (negative velocity) is to the East and rotation away from the observer (positive velocity) is to the West. Figure 2.3(a) shows an example of a SAMI galaxy and the relative motion of its neighbour galaxies, while Figure 2.3(b) shows the map after rotation. The arrow indicates the direction of the projected angular momentum of the SAMI galaxy. Then, we stacked these maps for all 1257 SAMI galaxies in our sample to investigate the overall trend of neighbour galaxies motion, as shown in Figure 2.4. If a correlation between the angular momentum vector of galaxies and the motion of their neighbours is sufficiently strong, the left side of Figure 2.4 would be predominantly blue and the right side would be predominantly red.

We then select which neighbouring galaxies would form part of our quantitative analysis in two different ways:

1. X-cut-10°: we form this subsample by removing neighbouring galaxies which are located $\pm 10^\circ$ from the North and South directions, as shown in Figure

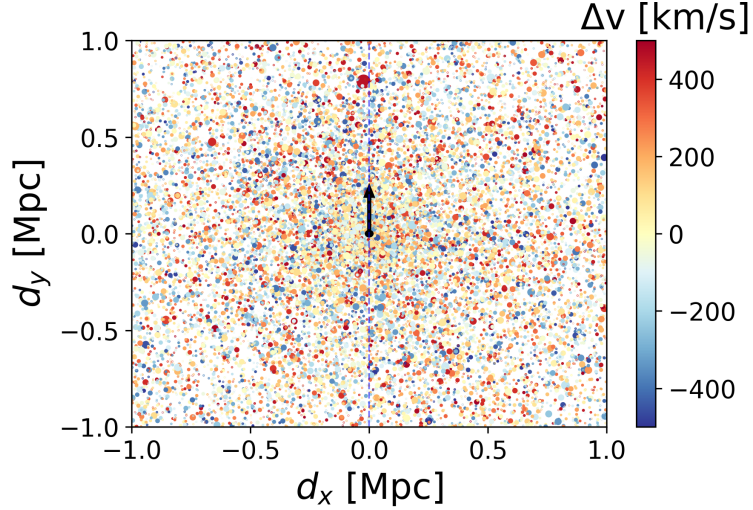


Figure 2.4: We stack 1257 of the maps of neighbours of SAMI galaxies as shown in Figure 2.3(b). The point sizes are proportional to the luminosity of galaxies. The color of points shows the velocity offset between the SAMI galaxies and their neighbours. If there is a strong signal, the right side will be predominantly red, the left side will be predominantly blue.

2.5(a).

2. X-cut-45°: In order to compare our results with L19, we preserved the galaxies with PA uncertainty smaller than 20° and removed neighbouring galaxies which are located $\pm 45^\circ$ from the North and South directions, as shown in Figure 2.5(b).

The selection (ii) is the same as used by L19, but the PA uncertainty of SAMI data is smaller. The PA uncertainty cuts are 10° in (i) and 20° in (ii), whilst L19a used 45°.

We then calculate the average line-of-sight velocity of the neighbouring galaxies as a function of projected comoving distance d for both (i) and (ii),

$$d = \text{sign}(d_x) \cdot \sqrt{d_x^2 + d_y^2}, \quad (2.3)$$

where d_x is projected comoving distance perpendicular to the direction of angular momentum of the given target SAMI galaxy and d_y is projected comoving distance parallel to the direction of angular momentum.

We use three kinds of luminosity-weighted average to calculate the mean line-of-sight velocity offset of neighbour galaxies. The first method is absolute-luminosity (abs-L) weighting, which averages the velocity of neighbouring galaxies weighted by their r -band luminosity. This method does not take into account the luminosity of the SAMI galaxies from which we measured angular momentum vectors. Secondly, we use a relative-luminosity (rel-L) weighting, which weights each neighbour galaxy's line-of-sight velocity by the ratio between the r -band luminosity of the neighbouring galaxy

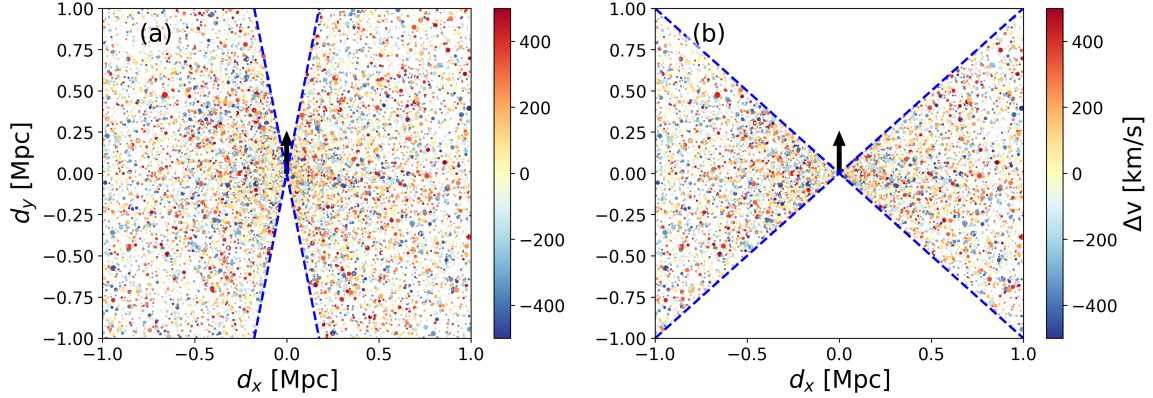


Figure 2.5: Two methods of choosing neighbouring galaxies. (a) X-cut-10°: preserve the data of neighbour galaxies located between 10° and 170° or between 190° and 350° from north. (b) X-cut-45°: preserve the data of neighbour galaxies located between 45° and 135° or between 225° and 315° from north.

and the r -band luminosity of the SAMI galaxy. These two kinds of luminosity-weighted methods are the same as that in L19a, which helps us to compare our results with theirs. Finally, we also calculated an unweighted average, treating each of the neighbouring galaxies equally. This is equivalent to thinking of the galaxies as tracer particles in the overall dark matter distribution. In contrast, the luminosity weighting approach implies that higher luminosity galaxies are associated with higher mass, potentially leading to higher torques of the SAMI galaxies.

Following equations 2, 3 and 4 in L19a, we calculate the mean velocity offset at D , where D is the distance for a bin instead of individual galaxies. This method of finding the average velocity difference of galaxies in a 100 kpc window is used to smooth the profile, which is otherwise dominated by scatter, such that

$$\langle \Delta v \rangle^{d100}(D) = \begin{cases} \frac{\sum_{Rd(D,100)} \Delta v L_w}{\sum_{Rd(D,100)} L_w} & \text{if } D > 0 \\ 0 & \text{if } D = 0 \\ \frac{\sum_{Ld(D,100)} \Delta v L_w}{\sum_{Ld(D,100)} L_w} & \text{if } D < 0. \end{cases} \quad (2.4)$$

We take L_w to be the absolute luminosity of the neighbouring galaxy in the abs-L case, and the ratio of luminosity of the SAMI galaxies and their neighbours in the rel-L case ($L_w = L_{\text{nei}}/L_{\text{SAMI}}$). For the equal-weight case, L_w is identical for all galaxies. The right-side distance range R_d is

$$R_d(D, 100) = \begin{cases} D - 100 \text{ kpc} < d \leq D & \text{if } D > 100 \text{ kpc} \\ 0 < d \leq D & \text{if } 0 < D \leq 100 \text{ kpc}, \end{cases} \quad (2.5)$$

and the left-side distance range L_d is

$$L_d(D, 100) = \begin{cases} D \leq d < D + 100 \text{ kpc} & \text{if } D < -100 \text{ kpc} \\ D \leq d < 0 & \text{if } -100 \text{ kpc} \leq D < 0. \end{cases} \quad (2.6)$$

This is the approach used by [L19a](#). However, note that when calculated like this, individual points are not independent of each other.

Furthermore, we simplify the radial profile by merging the left and right hand side mean velocities using

$$\langle \Delta v \rangle_{R-L}^{d100}(D) = \frac{\left(\sum_{R_d(D,100)} \Delta v L_w \right) - \left(\sum_{L_d(-D,100)} \Delta v L_w \right)}{\left(\sum_{R_d(D,100)} L_w \right) + \left(\sum_{L_d(-D,100)} L_w \right)} \quad (2.7)$$

where $D > 0$. Figuratively speaking, we fold the profiles from the positive and negative D directions together by flipping the sign and combining. If the coherence exists, the right-left-merged mean velocities would be positive.

We also create cumulative right-left-merged mean velocities according to:

$$\langle \Delta v \rangle_{R-L}^{cumu}(D) = \frac{\left(\sum_{0 < d \leq D} \Delta v L_w \right) - \left(\sum_{-D \leq d < 0} \Delta v L_w \right)}{\left(\sum_{0 < d \leq D} L_w \right) + \left(\sum_{-D \leq d < 0} L_w \right)}. \quad (2.8)$$

$\langle \Delta v \rangle_{R-L}^{cumu}$ can be interpreted as coherence signal within given projected distance D .

2.4.2 Uncertainty estimation

We use two different methods to estimate the uncertainties on our measurements, and hence analyse the significance of any velocity offsets. The first one is a bootstrapping method, which randomly resamples the neighbour galaxies with replacement 1000 times and calculates the standard deviation of the mean velocity of resamples (σ_{BST}). The size of resamples is the same as the original samples.

In the second method, we randomize the spin-axis of each SAMI galaxy, build a new composite map and obtain the right-left-merged average velocity. Following [L19a](#), we call these data "RAX", for "random spin-axis". As we have randomized the PAs, we expect the RAX data to have a mean of zero velocity offset. The scatter about this zero gives us another estimate of the uncertainty on the measurement. We repeat this process 100 times.

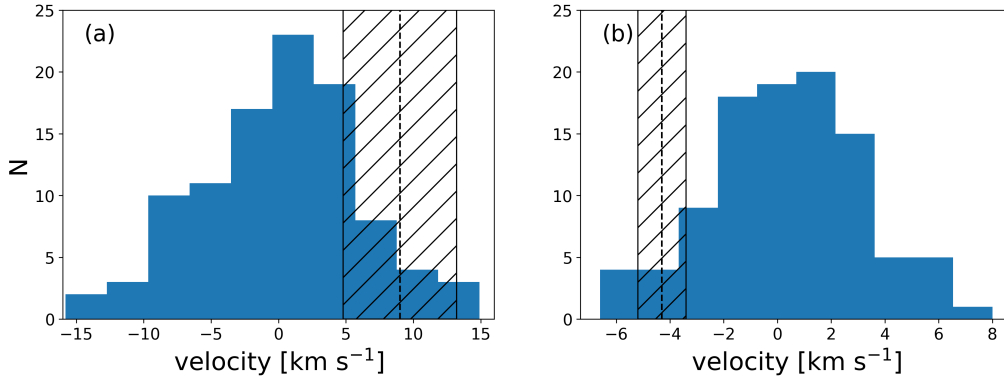


Figure 2.6: (a) The histogram shows the distribution of right-left-merged abs-L weighted average velocity offset between the randomized spin-axis of SAMI galaxies and the neighbouring galaxies within 1 Mpc. The standard deviation of the histogram (σ_{RAX}) is 5.4 km s^{-1} . The vertical dashed line marks the average velocity of the real data and the diagonally-shaded region shows its uncertainty using bootstrap estimates. (b) The same as (a), but for the neighbouring galaxies within 20 Mpc. The standard deviation of the histogram is 2.9 km s^{-1} .

Figure 2.6 shows the distribution of average velocities for 100 RAX samples, where the vertical dash lines mark the average velocities of the real data. The diagonal-line-shaded regions are the bootstrap uncertainty estimates. The uncertainties using RAX methods are 6.0 km s^{-1} for the neighbour galaxies within 1 Mpc and 2.9 km s^{-1} for the neighbour galaxies within 20 Mpc. The RAX uncertainty for the abs-L weighting is 1.4 times as large as bootstrap uncertainty (4.2 km s^{-1}) for the neighbours within 1 Mpc and 3.2 times as large as bootstrap uncertainty (0.9 km s^{-1}) for neighbours within 20 Mpc. Considering the other weighting schemes, we find the RAX uncertainty is 3 times and 5 times greater than bootstrap uncertainties for the rel-L and unweighted cases respectively, which indicates that the bootstrap method may underestimate the variance caused by large-scale structure. When resampling the data for the bootstrap analysis, we select data from mostly the same structures. Bootstrapping, therefore, does not capture the cosmic variance between different patches of sky.

In the following Sections, we will use σ_{RAX} as main value of uncertainty, as we consider they give more robust estimation of uncertainty than bootstrapping.

2.5 Results

2.5.1 Results for neighbour galaxies within 1 Mpc

We present average line-of-sight velocity of neighbouring galaxies as function of projected distance D in Figure 2.7. If the coherence between the rotation of SAMI galaxies and the motion of neighbouring galaxies exists, we expect the average velocity offset to be positive on the right side of the profile and negative on the left. Figure 2.7 shows the derived profiles based on X-cut- 10° and X-cut- 45° for abs-L, rel-L and equal weighting within 1 Mpc.

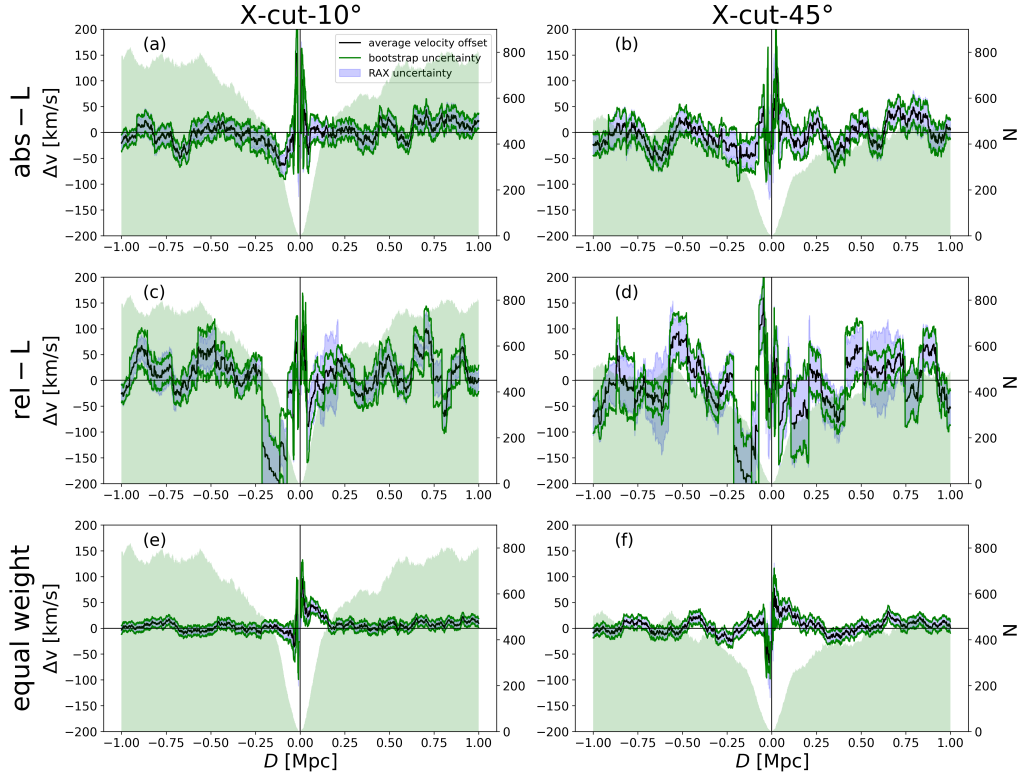


Figure 2.7: The black lines show radial profile of average velocity offset within 1 Mpc as a function of projected distance, D . The green lines show bootstrap uncertainties and the blue shades demonstrate RAX uncertainties. The green histograms show the number of galaxies which contribute to the bin. The left column is based on X-cut-10° and the right column is based on X-cut-45°. The top, middle and bottom rows are abs-luminosity-weighted, relative-luminosity-weighted and equal-weighted mean velocity, respectively. If the correlation between the direction of spin vector of the central galaxy and the motion of its neighbour galaxies exists, then the average velocity offset would be positive on the right side and negative on the left side of each panel. However, we do not detect significant signal of coherence for the neighbouring galaxies within 1 Mpc scales.

The extremely high velocity offset when the distance is smaller than 20 kpc is due to the small number of galaxies at this separation, leading to large uncertainty on the velocity. The number of galaxies contributing to the given bin is denoted by the green histograms in Figure 2.7.

The profiles using the three different weighting scheme show broadly similar trends. However, the profile using the rel-L weighting fluctuates more than the abs-L weighting and equal weighting, because the mean velocity can be influenced by individual bright galaxies. The equal-weighted profile shows the least variance.

In Figure 2.7(a), the velocity offset at negative values of D ranges from ≈ -50 to 20 km s^{-1} , and ≈ -20 to 30 km s^{-1} for positive values of D . There are large outliers at $D = -0.15 \text{ Mpc}$ in Figure 2.7(c), caused by a single bright galaxy ($M_r = -21.6 \text{ mag}$) nearby a faint SAMI galaxy ($M_r = -14.9 \text{ mag}$). Their rel-L weight counts nearly half the weight in that bin. The velocity offset between them is -256.5 km s^{-1} .

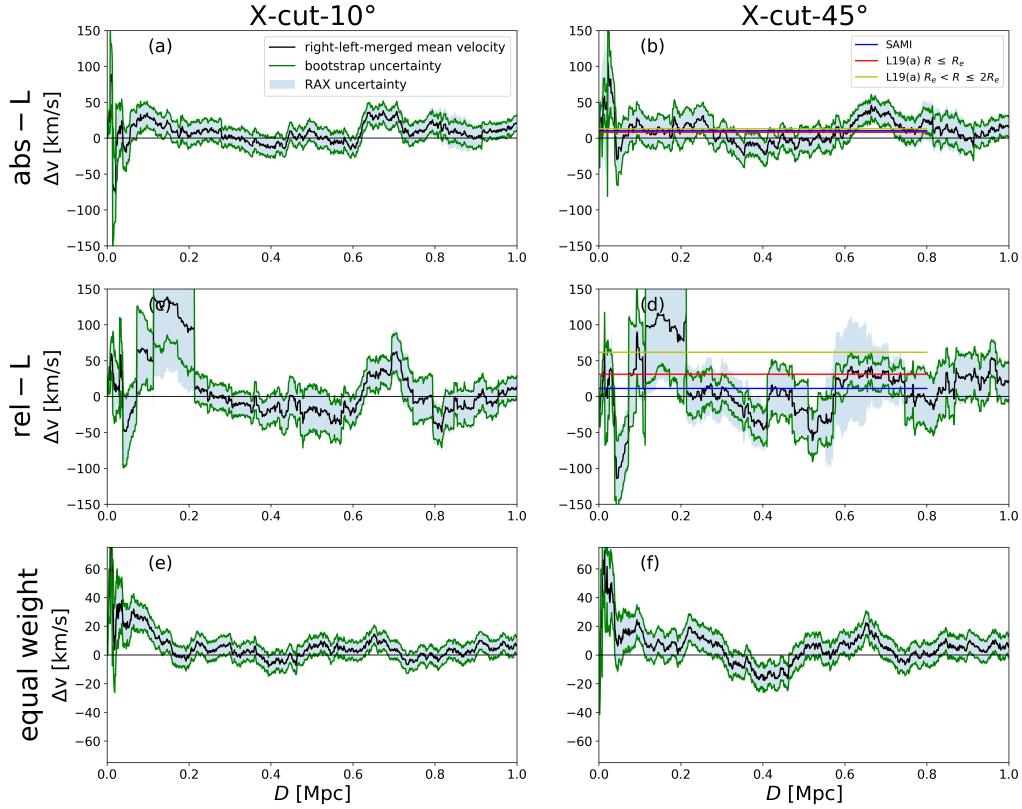


Figure 2.8: Right-left-merged radial profile of average velocity offset within 1 Mpc. The left column is based on X-cut-10° and the right column is based on X-cut-45°. The top, middle and bottom rows are abs-luminosity-weighted, relative-luminosity-weighted and equal-weighted mean velocity, respectively. The horizontal lines in (b) and (d) demonstrate the cumulative right-left-merged mean velocities for the neighbour galaxies within 800 kpc scales, in which blue lines represent the results of SAMI galaxies, red and yellow lines represent the results in L19a. The uncertainties denoted by green lines are calculated using the bootstrapping method. The blue shades demonstrate RAX uncertainties. Note that the scale changes in (e) and (f).

s^{-1} . These outliers are much smaller in abs-L weighting and disappear in equal weighting figures. Apart from these outliers, no significant signal of the coherence can be seen in Figure 2.7(c). The equal-weighted average velocity in Figure 2.7(e) is smaller than those in abs-L and rel-L. The average velocity profiles in X-cut-45° are similar to those in X-cut-10°.

Figure 2.8 presents the right-left-merged radial profile of velocity within 1 Mpc, calculated using Equation 2.7. Within a given interval, the right-left-merged average velocity is the average velocity from the positive D directions minus the average velocity from the negative D directions, and then normalized by the luminosity. If the coherence exists, the right-left-merged velocity would be positive. The uncertainties denoted by green lines are calculated by the bootstrapping method. The blue shading demonstrates RAX uncertainties. Note that the bootstrap uncertainties are similar to RAX uncertainties in Figure 2.8 because we use small bins (100 kpc) when

Weighting	D (Mpc)	X-cut-10° $\langle \Delta v \rangle_{R-L}^{cumu} \pm \sigma_{RAX}$ (km s ⁻¹)	X-cut-45° $\langle \Delta v \rangle_{R-L}^{cumu} \pm \sigma_{RAX}$ (km s ⁻¹)	L19a ($R \leq R_e$) $\langle \Delta v \rangle_{R-L}^{cumu} \pm \sigma_{BST}$ (km s ⁻¹)	L19a ($R_e < R \leq 2R_e$) $\langle \Delta v \rangle_{R-L}^{cumu} \pm \sigma_{BST}$ (km s ⁻¹)
abs-L	0.2	13.8 ± 12.0 (1.1σ)	13.6 ± 16.1 (0.8σ)	57.3 ± 35.9 (1.6σ)	68.8 ± 37.3 (1.8σ)
	0.5	4.6 ± 7.2 (0.6σ)	2.1 ± 9.4 (0.2σ)	30.1 ± 19.1 (1.6σ)	38.5 ± 20.9 (1.8σ)
	0.8	8.6 ± 5.8 (1.5σ)	10.4 ± 8.6 (1.2σ)	8.3 ± 12.8 (0.6σ)	13.1 ± 14.2 (0.9σ)
	1	9.0 ± 5.4 (1.7σ)	9.6 ± 7.5 (1.3σ)	-	-
	2	12.5 ± 4.4 (2.8σ)	13.2 ± 5.4 (2.4σ)	-	-
	6	2.2 ± 3.0 (0.7σ)	-2.6 ± 3.6 (-0.7σ)	21.2 ± 7.9 (2.7σ)	-
	15	-4.2 ± 2.7 (-1.5σ)	-7.1 ± 4.2 (-1.7σ)	-	-
	20	-4.3 ± 2.9 (-1.5σ)	-6.6 ± 4.0 (-1.7σ)	-	-
rel-L	0.2	82.4 ± 64.5 (1.3σ)	71.1 ± 60.1 (1.2σ)	57.9 ± 46.0 (1.3σ)	109.5 ± 58.9 (1.9σ)
	0.5	21.0 ± 24.8 (0.8σ)	17.3 ± 29.2 (0.6σ)	25.2 ± 23.4 (1.1σ)	61.1 ± 27.8 (2.2σ)
	0.8	12.7 ± 17.2 (0.7σ)	17.1 ± 23.9 (0.7σ)	31.1 ± 15.6 (2.0σ)	61.7 ± 17.6 (3.5σ)
	1	11.1 ± 14.4 (0.8σ)	18.6 ± 21.1 (0.9σ)	-	-
	2	10.5 ± 10.5 (1.0σ)	27.9 ± 15.9 (1.8σ)	-	-
	6	2.7 ± 6.2 (0.4σ)	-0.9 ± 7.8 (-0.1σ)	-	-
	15	-0.6 ± 6.5 (-0.1σ)	-2.9 ± 7.9 (-0.4σ)	-	-
	20	-1.5 ± 5.9 (-0.2σ)	-3.1 ± 7.2 (-0.4σ)	-	-
equal weight	0.2	7.9 ± 6.7 (1.2σ)	10.4 ± 7.9 (1.3σ)	-	-
	0.5	3.7 ± 3.9 (0.9σ)	1.2 ± 4.7 (0.3σ)	-	-
	0.8	2.8 ± 2.9 (1.0σ)	2.7 ± 3.9 (0.7σ)	-	-
	1	3.5 ± 2.7 (1.3σ)	3.6 ± 3.5 (1.0σ)	-	-
	2	7.3 ± 2.3 (3.1σ)	6.6 ± 2.7 (2.5σ)	-	-
	6	3.3 ± 2.4 (1.4σ)	0.6 ± 2.7 (0.2σ)	-	-
	15	-1.7 ± 2.4 (-0.7σ)	-3.9 ± 3.7 (-1.1σ)	-	-
	20	-2.8 ± 2.5 (-1.1σ)	-4.0 ± 3.6 (-1.1σ)	-	-

Table 2.1: Cumulative right-left-merged mean velocity within a radius D , e.g. 0–0.8 Mpc. We also list the results in L19a. In L19a($R \leq R_e$), the angular momentum of CALIFA galaxies is measured at $R \leq R_e$. In L19a($R_e < R \leq 2R_e$), the angular momentum of CALIFA galaxies is measured at $R_e < R \leq 2R_e$.

smoothing and plotting the profile. As a result the uncertainties are dominated by random scatter rather than systematic effects.

Figure 2.8(a) shows the abs-L weighted average velocity in X-cut-10°. Even though there are some deviations away from zero at the level of up to $\sim 2\sigma$, there is no obvious coherent signal. The velocity is consistent with zero at $200 < D < 600$ kpc. The outliers at $D = 150$ kpc in rel-L (Figure 2.8c and 2.8d) are caused by bright neighbour galaxy nearby a single faint SAMI galaxy, as discussed above. The uncertainties when using rel-L is also larger than for the abs-L and equal weight cases. The dynamic range in weights is larger for the relative luminosity than the absolute luminosity. Therefore, the rel-L weighted average velocity is more likely driven by single galaxy and the bootstrap uncertainty is larger. Similarly, for the equal weighted panel in Figure 2.8(e), we find the average velocity is 10–30 km s⁻¹ and is significant at 2σ level at $D < 100$ kpc. The average velocity is consistent with zero at $200 < D < 1000$ kpc. Table 2.1 shows the cumulative right-left-merged mean velocity within a radius D , which is chosen to display the coherence signal. The signals of coherence for the neighbour galaxies within 1 Mpc are around the 1σ level for all three kinds of weighting cases.

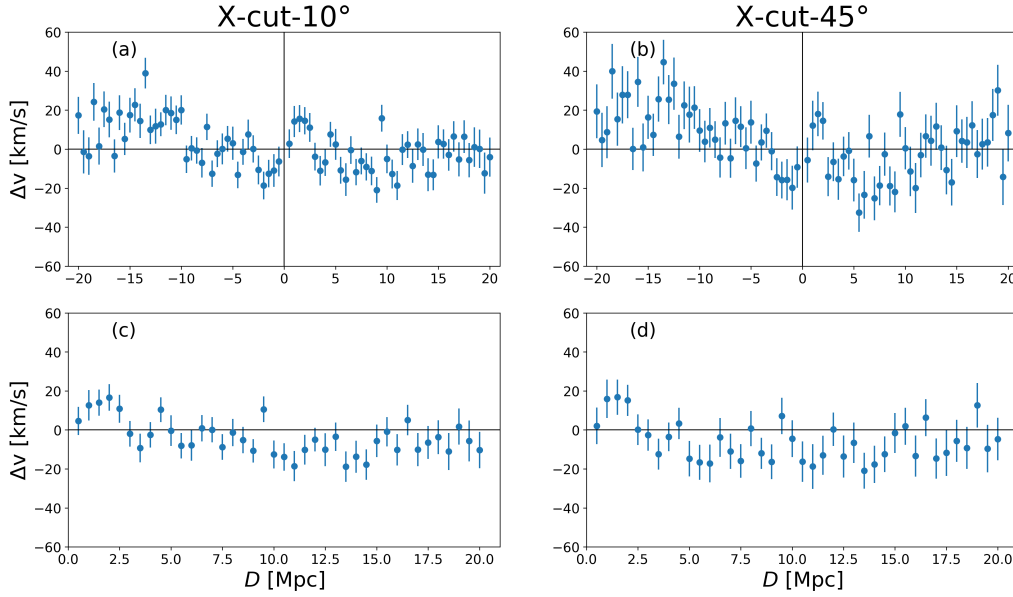


Figure 2.9: We show 500-kpc-binned absolute-luminosity-weighted mean velocities within 20 Mpc scales in (a) and (b). Panel (c) and (d) show right-left-merged 500-kpc-binned mean velocities within 20 Mpc. The error bars represent σ_{RAX} .

2.5.2 Large-scale results

We also extend our study to a projected neighbour distance of 20 Mpc in order to investigate the velocity offset on larger scales. We calculate all three kinds of weightings, which qualitatively behave similarly to each other. Results for all three weightings are listed in Table 2.1, but to give an example of our results we only plot the results of the abs-L weighted analysis. The average velocity profile of relative luminosity weighting and equal weighting have similar trends to the profile of absolute luminosity weighting.

When studying larger scale results we use 500-kpc-binned mean velocities, with no smoothing, so that each point is independent. The 500-kpc-binned mean velocities and right-left-merged 500-kpc-binned mean velocities are shown in Figure 2.9. The 500-kpc-binned mean velocities show that there is a weak signal of coherence within 2 Mpc scales. The average velocities increase from 0–0.5 Mpc bin ($4.6 \pm 7.2 \text{ km s}^{-1}$) to 1.5–2.0 Mpc bin ($16.6 \pm 6.8 \text{ km s}^{-1}$) in the X-cut-10° case. Table 2.1 also shows that the right-left-merged average velocity for the neighbour galaxies within 2 Mpc scales is $12.5 \pm 4.4 \text{ km s}^{-1}$ in the X-cut-10° case, which is significant at the $\sim 3\sigma$ level (RAX errors).

The right-left-merged velocities are consistent with zero for the neighbouring galaxies at 3–8 Mpc distance. There is an “anti-correlation” between spin vector of SAMI galaxies and their neighbours’ motion for the neighbour galaxies outside 10 Mpc, i.e. the average velocity is positive on the left-side and negative on the right-side, as shown in Figure 2.9(a) and (b). The right-left-merged average velocity is negative at 10 to 20 Mpc, both in X-cut-10° and X-cut-45°, but their signals are also only significant at $\sim 2\sigma$ level, as shown in Figure 2.9(c) and (d).

Region	abs-L		rel-L		equal weight	
	X-cut-10°	X-cut-45°	X-cut-10°	X-cut-45°	X-cut-10°	X-cut-45°
	$\langle \Delta v \rangle_{R-L}^{cumu}$ (km s ⁻¹)	$\langle \Delta v \rangle_{R-L}^{cumu}$ (km s ⁻¹)	$\langle \Delta v \rangle_{R-L}^{cumu}$ (km s ⁻¹)	$\langle \Delta v \rangle_{R-L}^{cumu}$ (km s ⁻¹)	$\langle \Delta v \rangle_{R-L}^{cumu}$ (km s ⁻¹)	$\langle \Delta v \rangle_{R-L}^{cumu}$ (km s ⁻¹)
1	-2.7 ± 18.7	-0.2 ± 21.9	-3.0 ± 12.3	0.4 ± 14.6	7.7 ± 7.2	-0.0 ± 9.3
2	15.6 ± 14.2	-0.9 ± 20.3	-4.5 ± 22.1	-4.3 ± 42.4	-8.0 ± 10.6	-12.7 ± 11.5
3	18.6 ± 16.8	24.3 ± 20.5	22.6 ± 27.7	49.7 ± 64.4	3.9 ± 7.9	4.8 ± 11.9
4	18.8 ± 14.2	17.5 ± 18.1	20.6 ± 40.4	32.1 ± 47.2	7.4 ± 7.5	10.4 ± 8.2
5	1.2 ± 9.9	2.8 ± 11.7	-2.2 ± 12.0	-6.1 ± 14.2	1.7 ± 4.9	3.6 ± 6.0
6	6.6 ± 14.2	6.1 ± 17.0	17.2 ± 20.8	2.5 ± 26.5	1.9 ± 7.1	1.0 ± 10.4
mean	9.7	8.3	8.4	12.4	2.4	1.2
standard deviation	9.3	10.3	12.9	23.0	5.7	7.7
standard error on mean	3.8	4.2	5.3	9.4	2.3	3.2

Table 2.2: The absolute-luminosity-weighted right-left-merged average velocity offset within 1 Mpc. The uncertainty of the right-left-merged average velocity is the RAX uncertainty (σ_{RAX}). The bottom of table shows the mean velocity of 6 different regions, the standard deviation and the standard error of the mean.

2.5.3 Results for galaxies in 6 different regions

We divide the SAMI galaxies into 6 different regions on the sky, as shown in Figure 2.1(a), in order to investigate the variation between different regions and see if the signal of coherence is stronger in any region. Table 2.2 and Table 2.3 list the right-left-merged average velocities for the different weights in each of these subsamples. We will focus on abs-L in the rest of this Section, but the results are qualitatively similar for the other weights.

The average velocity offset varies between different regions. The standard errors on the mean of the right-left-merged velocities between 6 regions are 3.8 km s⁻¹ for X-cut-10° and 4.2 km s⁻¹ for X-cut-45° within 1 Mpc; 2.8 km s⁻¹ for X-cut-10° and 4.3 km s⁻¹ for X-cut-45° within 20 Mpc. The scatter between regions is similar to the bootstrap uncertainty and RAX uncertainty of average velocity of the whole sample, when considering neighbouring galaxies within 1 Mpc. The scatter between regions is similar to the RAX uncertainty, but three times larger than the bootstrap uncertainty when considering neighbouring galaxies within 20 Mpc, which also suggests that the bootstrap uncertainty of average velocity is an underestimate, particularly on large scales.

In the abs-L case, Region 1 is a relative outlier at both 1 and 20 Mpc, which reflects the difference in large-scale structure of different regions. The average velocities in other regions are consistent with each other. Within 20 Mpc scales, the right-left-merged average velocities are negative in Region 1, 2, 4, 5 and 6. However, the velocity offsets are significant at 2σ level in Region 1 and consistent with zero in others.

Region	abs-L		rel-L		equal weight	
	X-cut-10°	X-cut-45°	X-cut-10°	X-cut-45°	X-cut-10°	X-cut-45°
	$\langle \Delta v \rangle_{R-L}^{cumu}$ (km s ⁻¹)	$\langle \Delta v \rangle_{R-L}^{cumu}$ (km s ⁻¹)	$\langle \Delta v \rangle_{R-L}^{cumu}$ (km s ⁻¹)	$\langle \Delta v \rangle_{R-L}^{cumu}$ (km s ⁻¹)	$\langle \Delta v \rangle_{R-L}^{cumu}$ (km s ⁻¹)	$\langle \Delta v \rangle_{R-L}^{cumu}$ (km s ⁻¹)
1	-14.2 ± 7.0	-22.0 ± 8.4	-16.2 ± 10.3	-13.9 ± 12.3	-10.8 ± 6.1	-15.6 ± 7.3
2	-0.7 ± 7.9	2.8 ± 9.9	3.1 ± 9.8	0.7 ± 12.2	-1.7 ± 6.9	2.8 ± 8.4
3	4.7 ± 7.4	4.8 ± 10.1	11.8 ± 13.3	7.7 ± 18.4	6.6 ± 6.1	5.7 ± 8.2
4	-8.9 ± 8.9	-10.2 ± 10.6	0.8 ± 12.2	8.6 ± 16.2	-3.3 ± 6.7	-4.7 ± 7.2
5	-0.8 ± 6.1	-4.3 ± 7.5	2.1 ± 6.1	-6.0 ± 8.6	0.7 ± 5.7	-1.8 ± 6.8
6	-0.2 ± 8.3	4.5 ± 9.0	7.7 ± 14.4	7.3 ± 17.0	-2.4 ± 6.8	-0.7 ± 6.9
mean	-3.3	-4.1	1.6	0.8	-1.8	-2.4
standard deviation	6.9	10.5	9.6	9.1	5.7	7.4
standard error on mean	2.8	4.3	3.9	3.7	2.3	3.0

Table 2.3: The absolute-luminosity-weighted right-left-merged average velocity offset within 20 Mpc. The uncertainty of the right-left-merged average velocity is the RAX uncertainty (σ_{RAX}). The bottom of table shows the mean velocity of 6 different regions, the standard deviation and the standard error of the mean.

	1 Mpc (km s ⁻¹)	2 Mpc (km s ⁻¹)	6 Mpc (km s ⁻¹)	15 Mpc (km s ⁻¹)	20 Mpc (km s ⁻¹)
$9 < \log(M_*/M_\odot) < 10.2$	-1.0 ± 9.4 (-0.1σ)	14.6 ± 6.9 (2.1σ)	3.0 ± 5.0 (0.6σ)	1.6 ± 5.5 (0.3σ)	-0.7 ± 5.7 (-0.1σ)
$10.2 < \log(M_*/M_\odot) < 10.9$	7.4 ± 7.4 (1.0σ)	6.9 ± 5.0 (1.4σ)	-0.3 ± 3.7 (-0.1σ)	-5.4 ± 4.3 (-1.2σ)	-3.9 ± 4.4 (-0.9σ)
$10.9 < \log(M_*/M_\odot) < 12$	29.9 ± 13.2 (2.3σ)	21.1 ± 9.0 (2.3σ)	6.2 ± 4.8 (1.3σ)	-9.1 ± 5.8 (-1.6σ)	-10.2 ± 5.9 (-1.7σ)
early-type	16.1 ± 8.2 (2.0σ)	22.2 ± 6.4 (3.5σ)	9.1 ± 4.8 (1.9σ)	-1.7 ± 5.1 (-0.3σ)	-3.0 ± 5.1 (-0.6σ)
late-type	6.4 ± 7.2 (0.9σ)	5.5 ± 5.2 (1.1σ)	-3.4 ± 4.3 (-0.8σ)	-8.9 ± 4.3 (-2.1σ)	-8.5 ± 4.3 (-2.0σ)
$\lambda_{Re} < 0.409$	19.9 ± 8.1 (2.5σ)	18.0 ± 7.4 (2.4σ)	9.6 ± 5.2 (1.8σ)	-1.3 ± 5.4 (-0.2σ)	-2.0 ± 5.9 (-0.3σ)
$0.409 < \lambda_{Re} < 0.586$	6.5 ± 10.3 (0.6σ)	10.8 ± 8.9 (1.2σ)	-0.1 ± 6.1 (-0.0σ)	-4.2 ± 6.3 (-0.7σ)	-2.4 ± 6.3 (-0.4σ)
$\lambda_{Re} > 0.586$	9.8 ± 11.0 (0.9σ)	12.3 ± 8.0 (1.5σ)	1.6 ± 4.5 (0.4σ)	-5.5 ± 4.8 (-1.1σ)	-7.3 ± 5.3 (-1.4σ)
$0^\circ < i < 30^\circ$	8.6 ± 13.6 (0.6σ)	16.8 ± 9.4 (1.8σ)	3.9 ± 5.9 (0.7σ)	-5.6 ± 5.2 (-1.1σ)	-10.0 ± 5.7 (-1.7σ)
$30^\circ < i < 60^\circ$	7.6 ± 6.4 (1.2σ)	14.4 ± 5.1 (2.8σ)	5.7 ± 3.8 (1.5σ)	-1.3 ± 3.7 (-0.4σ)	0.4 ± 3.9 (0.1σ)
$60^\circ < i < 90^\circ$	14.7 ± 13.1 (1.1σ)	7.9 ± 8.4 (0.9σ)	-5.7 ± 5.6 (-1.0σ)	-8.4 ± 6.0 (-1.4σ)	-9.0 ± 5.7 (-1.6σ)

Table 2.4: The absolute-luminosity weighted right-left-merged mean velocity for the neighbouring galaxies within 1, 2, 6, 15 and 20 Mpc scales of different subsamples.

2.5.4 Galaxy subsamples

We also divide SAMI galaxies by galaxy mass, galaxy type, stellar spin parameter (quantified via λ_{Re}) and inclination (i) to find out if any subsample gives a more significant signal of coherence between the spin of SAMI galaxies and the motion of neighbours. We note that this classification is only applied to the SAMI galaxies, while the full sample of neighbouring galaxies is retained without subdivision. Table 2.4 shows the absolute-luminosity weighted right-left-merged mean velocity for the neighbouring galaxies within 1, 2, 6, 15 and 20 Mpc scales using X-cut-10°.

We detect signals at the 2σ level for low-mass ($9 < \log(M_*/M_\odot) < 10.2$) galaxies and high-mass ($10.9 < \log(M_*/M_\odot) < 12$) galaxies, but only 1.4σ signal at intermediate masses ($10.2 < \log(M_*/M_\odot) < 10.9$) for neighbouring galaxies within 2 Mpc. It is not obvious what would cause this particular trend as a function of mass, although we note that the difference is not significant. The high-mass galaxies subsample gives $\sim 2\sigma$ significance for the neighbouring galaxies within 1 Mpc and 2 Mpc. The average velocity of low-mass galaxies subsample is consistent with zero for the neighbours within 1 Mpc, but is significant at 2σ level for the neighbours within 2 Mpc. However, the intermediate-mass galaxies subsample does not have any signal of coherence on any scale.

The early-type galaxy subsample has a 3.5σ signal for the neighbouring galaxies within 2 Mpc, which is the strongest detection in all of the subsamples. The signals of the late-type galaxies subsample are consistent with zero for the neighbouring galaxies within 1 and 2 Mpc.

For the λ_{Re} case, we split the sample into 3 equally sized subsamples. The low-spin galaxies ($\lambda_{Re} < 0.409$) have a stronger signal than the high-spin ($\lambda_{Re} > 0.586$) and intermediate-spin ($0.409 < \lambda_{Re} < 0.586$) for the neighbours within 1 Mpc and 2 Mpc scales.

We expect the edge-on galaxies ($60^\circ < i < 90^\circ$) to have a stronger signal than the face-on galaxies ($0^\circ < i < 30^\circ$), because the coherent motion of neighbours of face-on galaxies will be perpendicular to the line-of-sight, thus can not be measured by line-of-sight velocity offset. However, the edge-on galaxies subsample only has a 1.1σ significance signal for neighbouring galaxies within 1 Mpc scales, which is not significantly larger than the face-on galaxies (0.6σ). For the neighbours within 2 Mpc scales, both the face-on galaxies subsample and the galaxies with inclination between 30° and 60° subsample have stronger signals (1.8σ and 2.8σ , respectively) than the edge-on galaxies subsample (0.9σ).

When looking at large scales, we see the average velocity for the neighbouring galaxies within 20 Mpc of high-mass SAMI galaxies is negative and significant in 1.7σ , which indicates that the average velocity of neighbours between distance 10-20 Mpc is negative and significant at the same level with positive signal for neighbours within 2 Mpc. The negative signals may point to even the RAX errors underestimating the variance due to large-scale structure, so the significance of the positive signals might also be less than formally measured.

The equal weighted results are a little different compared to the abs-L weighted

	1 Mpc (km s ⁻¹)	2 Mpc (km s ⁻¹)	6 Mpc (km s ⁻¹)	15 Mpc (km s ⁻¹)	20 Mpc (km s ⁻¹)
$9 < \log(M_*/M_\odot) < 10.2$	1.4 ± 5.2 (0.3 σ)	8.8 ± 4.2 (2.1 σ)	6.3 ± 3.8 (1.7 σ)	1.7 ± 4.4 (0.4 σ)	-0.8 ± 4.7 (-0.2 σ)
$10.2 < \log(M_*/M_\odot) < 10.9$	6.6 ± 4.3 (1.6 σ)	4.4 ± 3.3 (1.4 σ)	0.6 ± 2.8 (0.2 σ)	-2.1 ± 3.8 (-0.6 σ)	-2.1 ± 4.0 (-0.5 σ)
$10.9 < \log(M_*/M_\odot) < 12$	1.6 ± 6.6 (0.2 σ)	7.0 ± 6.6 (1.1 σ)	2.0 ± 4.6 (0.4 σ)	-8.6 ± 5.2 (-1.7 σ)	-9.9 ± 5.5 (-1.8 σ)
early-type	4.7 ± 4.8 (1.0 σ)	13.0 ± 4.0 (3.3 σ)	7.6 ± 4.3 (1.8 σ)	-0.1 ± 4.6 (-0.0 σ)	-2.0 ± 4.8 (-0.4 σ)
late-type	2.0 ± 4.8 (0.4 σ)	3.5 ± 3.8 (0.9 σ)	0.1 ± 3.5 (0.0 σ)	-5.2 ± 3.6 (-1.4 σ)	-6.4 ± 3.7 (-1.7 σ)
$\lambda_{Re} > 0.586$	9.2 ± 6.0 (1.5 σ)	9.1 ± 4.7 (2.0 σ)	1.4 ± 3.3 (0.4 σ)	-3.3 ± 4.3 (-0.8 σ)	-5.7 ± 4.9 (-1.2 σ)
$0.409 < \lambda_{Re} < 0.586$	2.2 ± 5.7 (0.4 σ)	6.2 ± 5.4 (1.2 σ)	0.2 ± 5.2 (0.0 σ)	-2.8 ± 5.8 (-0.5 σ)	-1.7 ± 5.9 (-0.3 σ)
$\lambda_{Re} < 0.409$	4.8 ± 4.5 (1.1 σ)	6.5 ± 4.4 (1.5 σ)	9.7 ± 4.2 (2.3 σ)	0.8 ± 4.7 (0.2 σ)	-0.7 ± 5.2 (-0.1 σ)
$0^\circ < i < 30^\circ$	0.8 ± 8.1 (0.1 σ)	11.1 ± 6.2 (1.8 σ)	7.8 ± 5.4 (1.4 σ)	-0.5 ± 5.3 (-0.1 σ)	-5.3 ± 5.8 (-0.9 σ)
$30^\circ < i < 60^\circ$	1.4 ± 3.8 (0.4 σ)	6.7 ± 3.5 (1.9 σ)	5.4 ± 2.9 (1.8 σ)	0.9 ± 3.0 (0.3 σ)	1.5 ± 3.2 (0.5 σ)
$60^\circ < i < 90^\circ$	8.6 ± 5.8 (1.5 σ)	5.7 ± 4.7 (1.2 σ)	-3.2 ± 4.4 (-0.7 σ)	-6.8 ± 5.1 (-1.3 σ)	-8.2 ± 5.0 (-1.6 σ)

Table 2.5: The equal weighted right-left-merged mean velocity for the neighbouring galaxies within 1, 2, 6, 15 and 20 Mpc scales of different subsamples.

results, as shown in Table 2.5. The high-mass galaxies subsample does not have a signal for neighbours within 1 and 2 Mpc. The high-spin galaxies have slightly stronger signal than the low-spin galaxies, which is different to the abs-L weighted case. None of the differences between different subsamples is particularly convincing and the underlying mechanism of these differences is not clear.

Finally, we apply our method to galaxy groups and galaxy pairs to see if the coherence signal is stronger for central galaxies and their satellites or galaxy pairs. 97.9% of satellite galaxies are within 1 Mpc from their central galaxies and the distance between all galaxy pairs are smaller than 160 kpc. Since galaxies in a group or pair tend to have more interactions, we might expect to see a stronger coherence signal here. However, the right-left-merged average velocity offset for group galaxies is -1.3 ± 4.8 km s⁻¹ and for paired galaxies is 9.3 ± 6.1 km s⁻¹, which do not show stronger signal than the other subsamples.

To summarise, we do not find strong evidence that a specific subsample of galaxies shows a strong coherence signal. Our tentative results for high and low-mass galaxies (although not intermediate mass galaxies) and early-type galaxies would need to be confirmed with more observational data and studies using cosmological simulations.

2.6 Discussion

2.6.1 Comparison to the results of Lee et al.

Table 2.1 compares the coherence signals between our results and those in L19a. The limit of PA uncertainty in L19a is 45° and they used X-cut-45°. The σ_{RAX} in our results are smaller, as the SAMI sample we use has a three times larger sample size compared to L19a. Also, the GAMA sample used to define environment reaches 2 magnitudes fainter than SDSS as well as having high completeness. Using abs-L weighting, the average velocities of our results are lower than those in L19a, except for average velocity for neighbours within 0.8 Mpc. In L19a the right-left-merged mean velocities are 57.3 ± 35.9 km s⁻¹ for the neighbour galaxies within 0.2 Mpc and 30.1 ± 19.1 km s⁻¹ for 0.5 Mpc, when they measured the PA of CALIFA galaxies using spaxels in centre regions. In our results, the velocities are 13.6 ± 16.1 km s⁻¹

for 0.2 Mpc and $2.1 \pm 9.4 \text{ km s}^{-1}$ for 0.5 Mpc on X-cut-45°. Although the RAX uncertainty in our results are smaller than L19a, the significance of velocity offset in our results is formally consistent with zero.

In the rel-L case, the right-left-merged mean velocity for neighbour galaxies within 0.2 Mpc for X-cut-45° is as large as $71.1 \pm 60.1 \text{ km s}^{-1}$, which is similar with results in L19a. However, as we discussed in Section 2.5.1, this signal is dominated by a single bright galaxy (r -band magnitude = -21.6 mag) nearby a faint SAMI galaxy (r -band magnitude = -14.9 mag). Therefore, the uncertainties in rel-L case are larger than those of abs-L case. The significance of signal in the rel-L case is also around the 1σ level. The equal weighted cases generally have smaller velocity offsets, and are formally consistent with zero.

Thus, for scales less than 1 Mpc we do not find convincing evidence of a signal. While the measurements are not formally in statistical disagreement with those of L19a, we typically find a lower signal with a smaller uncertainty than L19a.

L19b finds that abs-L weighted right-left-merged mean velocity is $21.2 \pm 7.9 \text{ km s}^{-1}$ at $D \leq 6.20 \text{ Mpc}$ for central rotation and their 1-Mpc-binned right-left-merged mean velocity is positive up to 8 Mpc. However, we do not detect the same signal. Table 2.1 shows that the abs-L weighted velocities are $2.2 \pm 3.0 \text{ km s}^{-1}$ for X-cut-10° and $-2.6 \pm 3.6 \text{ km s}^{-1}$ for X-cut-45° at $D \leq 6 \text{ Mpc}$. Comparing the most similar measurements at 6 Mpc (X-cut-45°) the difference between L19b and our results is 2.7σ . Figure 2.9 also shows that the 500-kpc-binned right-left-merged mean velocity is positive up to 3 Mpc, but only significant in $1-3\sigma$. The average velocity in 10.5–11.0 Mpc bin is $-18.6 \pm 7.8 \text{ km s}^{-1}$, which is negative and significant at the same level as the average velocities for neighbours within 2 Mpc. As the signal within 2 Mpc has the same amplitude and significance as the negative signal in 10 Mpc, it is hard to distinguish the signal of coherence from the variance due to large-scale structure.

2.6.2 Implication of subsamples

We divide SAMI galaxies into 6 different regions on the sky and also divide SAMI galaxies by galaxy mass, galaxy type, λ_{Re} and inclination to find out if any subsample has a stronger signal of coherence.

The mean velocity in region 1 at 20 Mpc is a relative outlier (see Table 2.3). This difference may be caused by large-scale structure near the SAMI galaxies. For instance, if the neighbours on the left side of the angular momentum of a SAMI galaxy are closer to us, while on the right side are far away, this will lead to positive mean velocity and vice versa. L19b also found that 2 out of 6 regions in CALIFA galaxies have relatively strong coherence, while the other regions have ambiguous or no coherence signal. They suggested that large-scale coherence may be related to specific structure instead of being a universal property.

Although we expect the edge-on galaxies subsample to have the strongest signal among three inclination subsamples due to projection effects, it only has a 1.1σ signal within 1 Mpc and is consistent with zero within 2 Mpc (see Table 2.4). However,

the subsample of galaxies with inclination between 30° to 60° shows a 2.8σ signal within 2 Mpc and the face-on galaxies subsample also has a 1.8σ signal. These signals are more likely coming from coincidental scatter instead of arising from a particular physical property. We also notice that the average velocities of the edge-on and face-on galaxies subsamples for the neighbours within 20 Mpc are negative and significant at 1.6σ and 1.7σ level, which suggests that large-scale structure can also impact results.

The results of the three inclination subsamples imply that the $2\text{--}3\sigma$ signal of low-mass, high-mass, early-type and low-spin galaxies subsamples are not enough to provide compelling evidence for a correlation between rotation of particular type of SAMI galaxies and the motion of neighbouring galaxies. However, if these signals are indeed real and confirmed by more observational results, there must be a physical explanation for this. We discuss the possible explanation in the following subsection.

As shown in Figure 2.1, some SAMI galaxies are close to the edge of GAMA fields. Therefore, only neighbour galaxies on one side are selected for some SAMI galaxies, which may bias our results. However, the right-left-merged method we used can mitigate the edge effect.

2.6.3 Comparison to previous studies

It is natural to think that the spin of galaxies could be influenced by the effects of galaxy-galaxy interactions over time. Using the IllustrisTNG simulation (Nelson et al., 2019), Moon et al. (2021) proposed that the alignment between the spin vector of a galaxy and the orbital motion of its neighbours results from the long-term interactions between paired galaxies. Their results showed that $\sim 10\%$ more galaxies have their spin vector aligned with the orbital angular momentum vector of pair galaxies than a random isotropic sample. They found the alignment is stronger for low-mass central galaxies and galaxies in low-density environments.

Taking the findings of Moon et al. (2021) we build a toy model to compare to our findings in Section 2.5. To make their results quantitatively comparable to ours, we map their results from the percentage of alignment to average right-left-merged velocity offset. We assume we have 1400 pairs of central galaxies and neighbouring galaxies, in which the spin vectors of 770 of the central galaxies are aligned with the orbital angular momentum vector of pair galaxies and for 630 pairs the vectors are anti-aligned (i.e., 10% more galaxies are aligned with their pair galaxies than random sample). The pairwise velocity dispersion or relative motion of galaxies varies with galaxy properties. On average, the three dimensional velocity dispersion between pair galaxies is around 500 km s^{-1} (Li et al., 2006). We now assume that this 500 km s^{-1} velocity is a reasonable estimation of the relative motion between galaxies and that all galaxies have this relative motion. This is, no doubt, an oversimplification, but allows us to make a semi-quantitative comparison between our results and the simulations of Moon et al. (2021).

We next consider the projection effects of galaxy inclinations and line-of-sight veloc-

ities by randomizing the viewing angle in our model and calculating the equivalent of the equal-weighted velocity offset from Section 2.4. We build this toy model 1000 times by drawing the viewing angle from random distribution. Our model shows that the average right-left-merged velocity offset is $20.3 \pm 6.6 \text{ km s}^{-1}$ (where the uncertainty is standard deviation on the mean).

The equal weighted average right-left-merged velocity offset for SAMI galaxies and their pair galaxies is $9.3 \pm 6.1 \text{ km s}^{-1}$. Our result on the observational data in Section 2.5 is a little smaller than the above simulated results, but not significantly so, particularly given the simple assumptions used. We note, however, that our model ignores the effect of large-scale structure on the evolutionary history of our sample.

It has recently become clear that the spin vector of galaxies is correlated with large-scale structure by both simulations and observations (Codis et al., 2012, 2018; Dubois et al., 2014; Welker et al., 2020; Blue Bird et al., 2020; Kraljic et al., 2020, 2021; Tudorache et al., 2022, Barsanti et al. submitted). Low-mass galaxies form in the neighbourhood of filaments, where the vorticity field is predominantly aligned with the filament (Laigle et al., 2015). Then galaxies migrate towards filaments, accrete gas and merge with other low-mass galaxies along filaments. High-mass galaxies largely build their mass through mergers, so the spin axis tends to be dominated by angular momentum from the merger (Codis et al., 2018). Barsanti et al.’s (submitted) finding that the flip of spin-alignment is most strongly correlated with the mass of galaxy’s bulge also supports that mergers are the main drivers of the flip as the bulges of galaxies accrete mass through mergers. Codis et al. (2012) used the Horizon 4 π dark matter simulation and showed that dark matter flows towards filaments, forming low-mass dark matter haloes in the filaments. Galaxies in these halos tend to have their spin vector parallel to the filaments. Low-mass haloes merge with other haloes in the filaments and convert the orbital angular momentum into spin. Thus the high-mass haloes tend to spin perpendicular to the filaments. Hydrodynamical simulations (e.g. Dubois et al., 2014) also showed that low-mass blue galaxies tends to align with filaments, while the alignment of high-mass red galaxies is more likely orthogonal to the filaments. Their results suggest that the tentative positive signal of coherence within 2 Mpc scales for the low-mass and high-mass galaxies might result from different physical mechanisms.

The spin alignment trends suggested by Dubois et al. (2014) and Codis et al. (2018) have been detected in a recent observational study by Welker et al. (2020). They investigated the kinematic spin-axis of the SAMI galaxies and their nearest cosmic filament in projection. They found that the spin-axis of low-mass SAMI galaxies tend to align with their nearest filament, whilst the spin-axis of high-mass galaxies tend to be orthogonal to their nearest filament. This pattern is consistent with that found in the Horizon-AGN simulation (Dubois et al., 2014; Codis et al., 2018) and SIMBA simulation (Kraljic et al., 2020). This scenario suggests that low-mass galaxies are more likely to be aligned with cosmic web, and so they might be expected to show a stronger signal of coherence between galaxy spin and cosmic filament. We find some hints that low-mass galaxies have a stronger correlation between spin and the motion of neighbours (e.g. within 2 Mpc - see Table 2.4 and 2.5). These two

results could be consistent with each other, but we caution that our measurement is different to that of [Welker et al. \(2020\)](#). We measure how the spin of galaxies is related to the motion of neighbouring galaxies, whilst [Welker et al. \(2020\)](#) measured how the spin of galaxies is related to the location of neighbouring galaxies. Detailed simulations of the two measurements would be needed to confirm that picture is consistent.

[Xia et al. \(2021\)](#) used the Millennium simulation ([Springel et al., 2005](#)), a dark-matter cosmological simulation to measure the angular momentum around filaments. They found dark matter rotates around the filament axis, implying that large-scale coherent motion exists in this simulation. Their result shows that the rotational velocity of dark matter haloes as a function of distance to the filament axis increases from 0 to 2 Mpc, peaking at around 55 km s^{-1} and then decreasing. The trend of this velocity profile is similar with the trend in [Figure 2.9\(c\)](#) within 3 Mpc scales. However, the average velocities in [Figure 2.9\(c\)](#) are no more than 20 km s^{-1} . Note that our measurement is different to theirs: we measure the line-of-sight velocity offsets of neighbouring galaxies of each SAMI galaxy, whilst they measured the rotation of dark matter along the filaments in 3-dimensional space. Again, simulations of our specific measurements are needed to confirm any agreement.

An observational study using data from SDSS DR12 galaxy survey ([Wang et al., 2021](#)) also studies the spin of filaments. The spin of filaments seems to couple with the finding that the spin vector of low-mass galaxies tends to align with filaments. This can partially explain the tentative coherence signal we find of low-mass SAMI galaxies for the neighbouring galaxies within 2 Mpc.

Early-type galaxies, typically with higher mass and lower spin, have undergone on average ~ 1 merger since $z \sim 1$ ([López-Sanjuan et al., 2012](#)), which may influence the spin of galaxies. In addition, early-type galaxies are more likely to live in denser environments ([Dressler, 1980](#); [Park et al., 2007](#)), which exert stronger tidal force on galaxies and impact their spin. Both mergers and environment could potentially explain our tentative signal of coherence which is stronger in early-type galaxies than late-type galaxies, but we stress that a larger sample is required to confirm this finding and detailed simulations would demonstrate this in a quantitative way. Specifically, it would be valuable to make measurements of the coherence of spin and cosmic flows in both large N-body simulations, looking at the effect on halos, and in recent large-volume hydrodynamical simulations such as EAGLE ([Schaye et al., 2015](#)) or IllustrisTNG ([Pillepich et al., 2018](#)).

2.7 Conclusions

We use data from the SAMI Galaxy Survey to investigate the relationship between the direction of a galaxy’s rotation and the average motion of its neighbours. We perform a similar analysis as [L19a](#), but with a sample with three times as many galaxies and a neighbour population that reaches 2 magnitudes fainter than SDSS. When we calculate the average line-of-sight velocity offset between a SAMI galaxy and its neighbours, we weight them using three different methods: the first one con-

siders the absolute luminosity of neighbour galaxies; the second considers the ratio of absolute luminosity between a neighbouring galaxy and a given SAMI galaxy; the third one is equal weighted. In addition, we calculate the velocity of different subsamples, including investigating subsets of the data in different regions of the sky and galaxies with different stellar mass, morphological type, λ_{Re} and inclination.

We find only very small velocity offsets that are significant up to 2σ level for the neighbouring galaxies within 1 Mpc, most of which are smaller than those found by [L19a](#). When we extend the scope of neighbouring galaxies up to 20 Mpc, we find the average velocities increase up to 2 Mpc scales. The average velocity is 12.5 ± 4.4 km s⁻¹ (2.8σ) for the neighbouring galaxies within 2 Mpc (X-cut-10° case), but the average velocities for neighbours outside 3 Mpc are consistent with zero or negative. Some negative signals are also significant at 2σ level. Therefore, we suggest that the deviations at the $\sim 2\sigma$ level could be caused by differences in large-scale structure in the different observational regions from GAMA, and may not originate from a global relation between spin and neighbour motion.

We find modest evidence that low-mass, high-mass, early-type and low-spin galaxies subsamples have stronger signal of coherence for the neighbours within 2 Mpc. However, the results of different inclination subsamples and the large-scale results suggest that the $2\text{--}3\sigma$ signals of some subsamples are not strong enough to distinguish coherence signals from coincidental scatter or variance of large-scale structure.

We propose that the coherence signals in our results may result from the combined effect of galaxy interactions and large-scale structure. However, simulation studies including N-body simulations and hydrodynamical simulations, as well as larger samples of IFS observations (e.g., the MaNGA survey [Bundy et al. 2015](#); the forthcoming Hector survey [Bryant et al. 2020](#)) are needed to test our measurements and confirm these findings.

Acknowledgements

The SAMI Galaxy Survey is based on observations made at the Anglo-Australian Telescope. The Sydney-AAO Multi-object Integral field spectrograph (SAMI) was developed jointly by the University of Sydney and the Australian Astronomical Observatory. The SAMI input catalogue is based on data taken from the Sloan Digital Sky Survey, the GAMA Survey and the VST ATLAS Survey. The SAMI Galaxy Survey is supported by the Australian Research Council Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D), through project number CE170100013, the Australian Research Council Centre of Excellence for All-sky Astrophysics (CAASTRO), through project number CE110001020, and other participating institutions. The SAMI Galaxy Survey website is <http://sami-survey.org/>.

JvdS acknowledges support of an Australian Research Council Discovery Early Career Research Award (project number DE200100461) funded by the Australian Government. Sarah Brough acknowledges funding support from the Australian Research Council through a Future Fellowship (FT140101166). JBH is supported by

an ARC Laureate Fellowship FL140100278. The SAMI instrument was funded by Bland-Hawthorn’s former Federation Fellowship FF0776384, an ARC LIEF grant LE130100198 (PI Bland-Hawthorn) and funding from the Anglo-Australian Observatory. JJB acknowledges support of an Australian Research Council Future Fellowship (FT180100231). B.G. is the recipient of an Australian Research Council Future Fellowship (FT140101202).

Data availability

All observational data presented in this paper are available from Astronomical Optics’ Data Central service at <https://datacentral.org.au/> as part of the SAMI Galaxy Survey Data Release 3.

Chapter 3

The MAGPI survey: the evolution and drivers of gas turbulence in intermediate-redshift galaxies

This chapter is based on the paper *The MAGPI Survey: the evolution and drivers of gas turbulence in intermediate-redshift galaxies*, which was published in the *Monthly Notices of the Royal Astronomical Society* in Volume 533, Issue 4, Pages 3878-3892. The authors are Yifan Mai, Scott M. Croom, Emily Wisnioski, Sam P. Vaughan, Mathew R. Varidel, Andrew J. Battisti, J. Trevor Mendel, Marcie Mun, Takafumi Tsukui, Caroline Foster, Katherine E. Harborne, Claudia D. P. Lagos, Di Wang, Sabine Bellstedt, Joss Bland-Hawthorn, Matthew Colless, Francesco D'Eugenio, Kathryn Grasha, Yingjie Peng, Giulia Santucci, Sarah M. Sweet, Sabine Thater, Lucas M. Valenzuela, and Bodo Ziegler.

I was responsible for data analysis, interpretation and paper writing. The data analysis includes generating a BPT diagram for each galaxy and sample selection, generating the inputs for BLOBBY3D (continuum-subtracted data, PSF and LSF, OPTIONS to optimise the CPU time in running BLOBBY3D for each galaxy), testing different model options of BLOBBY3D, applying BLOBBY3D to the data from the MAGPI survey and analysing the correlation between different parameters. My supervisors, Scott M. Croom, Emily Wisnioski and Sam P. Vaughan, provided guidance on methodology, reviewed drafts, and provided feedback. Mathew R. Varidel is the developer of BLOBBY3D. Other authors are founders and team members of the MAGPI Survey. They contributed to the data reduction and provided comments on the paper.

3.1 Abstract

We measure the ionised gas velocity dispersions of star-forming galaxies in the MAGPI survey ($z \sim 0.3$) and compare them with galaxies in the SAMI ($z \sim 0.05$) and KROSS ($z \sim 1$) surveys to investigate how the ionised gas velocity dispersion evolves. For the first time, we use a consistent method that forward models galaxy kinematics from $z = 0$ to $z = 1$. This method accounts for spatial substructure in emission line flux and beam smearing. We investigate the correlation between gas velocity dispersion and galaxy properties to understand the mechanisms that drive gas turbulence. We find that in both MAGPI and SAMI galaxies, the gas velocity dispersion more strongly correlates with the star-formation rate surface density (Σ_{SFR}) than with a variety of other physical properties, and the average gas velocity dispersion is similar, at the same Σ_{SFR} , for SAMI, MAGPI and KROSS galaxies. The results indicate that mechanisms related to Σ_{SFR} could be the dominant driver of gas turbulence from $z \sim 1$ to $z \sim 0$, for example, stellar feedback and/or gravitational instability. The gas velocity dispersion of MAGPI galaxies is also correlated with the non-rotational motion of the gas, illustrating that in addition to star-formation feedback, gas transportation and accretion may also contribute to the gas velocity dispersion for galaxies at $z \sim 0.3$. KROSS galaxies only have a moderate correlation between gas velocity dispersion and Σ_{SFR} and a higher scatter of gas velocity dispersion with respect to Σ_{SFR} , in agreement with the suggestion that other mechanisms, such as gas transportation and accretion, are relatively more important at higher redshift galaxies.

3.2 Introduction

The evolution of the bulk gas motions within galaxies with cosmic time is governed by the complex interplay of different internal and external physical processes such as gravity, feedback, cooling, gas accretion and galaxy interactions (e.g. [Bower et al., 2006](#); [Dekel et al., 2009](#); [Bouché et al., 2010](#); [Davé et al., 2012](#); [Genel et al., 2012](#); [Lilly et al., 2013](#); [Gabor & Bournaud, 2014](#); [Schaye et al., 2015](#); [Sillero et al., 2017](#); [Bird et al., 2021](#); [Forbes et al., 2023](#)). Galaxy kinematic properties are important tools to help us understand the evolution of galaxies from the early Universe to the present time and to constrain galaxy evolution models (e.g. review by [Cappellari, 2016](#)).

The velocity dispersion of ionised gas within disk galaxies decreases with cosmic time ([Kassin et al., 2012](#); [Wisnioski et al., 2015](#); [Johnson et al., 2018](#); [Übler et al., 2019](#)), from $\sim 50 \text{ km s}^{-1}$ in galaxies at $z > 1$ to $\sim 20 \text{ km s}^{-1}$ in the local universe ([Genzel et al., 2006](#); [Epinat et al., 2008](#); [Law et al., 2009](#); [Green et al., 2014](#); [Moiseev et al., 2015](#); [Varidel et al., 2020](#); [Law et al., 2022](#)). The thermal broadening of star-forming gas traced by the $\text{H}\alpha$ emission line due to a characteristic temperature of 10^4 K is estimated to be 11.7 km s^{-1} ([Bland-Hawthorn et al., 2024](#))¹. However, the ionised gas velocity dispersion observed at all epochs is greater than this value. The

¹This value assumes a mean molecular weight made up of 74% H, 24% He and 2% for all other metals, typical of the modern day ISM.

gas velocity dispersion above the thermal contribution must arise from other local or global processes which induce turbulence in the gas. Two questions thus arise: What are the main drivers of turbulence in ionised gas and how do the physical processes that induce turbulence evolve with cosmic time?

The main drivers of high gas velocity dispersion over cosmic time are not well constrained. Disk galaxies in a state of equilibrium must maintain a balance between the energy loss by turbulent dissipation and energy injection from other local and global mechanisms (Krumholz et al., 2018). Global or external mechanisms that may induce higher turbulence include gas accretion (Klessen & Hennebelle, 2010; Aumer et al., 2010) and minor mergers (Bournaud et al., 2009). Possible internal mechanisms of gas turbulence include star-formation feedback (e.g. Green et al., 2010; Faucher-Giguère et al., 2013; Green et al., 2014; Moiseev et al., 2015; Bacchini et al., 2020; Egorov et al., 2023), gravitational instability (e.g. Krumholz & Burkhardt, 2016; Krumholz et al., 2018; Molina et al., 2020) and interactions between different galaxy components (Aumer et al., 2010; Oliva-Altamirano et al., 2018).

Star-formation feedback is widely considered to be a significant source of gas turbulence, both theoretically (Ostriker et al., 2010; Ostriker & Shetty, 2011; Faucher-Giguère et al., 2013; Krumholz & Burkhardt, 2016; Krumholz et al., 2018; Bacchini et al., 2020) and in simulations (e.g. Shetty & Ostriker, 2012; Rathjen et al., 2023; Hung et al., 2019). Stellar feedback injects energy and momentum into the interstellar medium through supernovae, stellar winds, radiation pressure and ionising radiation. A correlation between star formation rate (SFR) and gas velocity dispersion has been found in many observational studies (e.g. Green et al., 2010, 2014; Zhou et al., 2017; Varidel et al., 2020; Law et al., 2022), providing evidence for the role of stellar feedback in increasing the local turbulence in disks and therefore the measured disk velocity dispersion.

However, the degree of importance of stellar feedback in driving gas turbulence is debated. Some studies proposed that star formation alone can explain the gas velocity dispersion we observe (Bacchini et al., 2020; Faucher-Giguère et al., 2013; Egorov et al., 2023), while other studies suggested that stellar feedback can only drive part of the gas velocity dispersion, thus other mechanisms are needed (Zhou et al., 2017; Bik et al., 2022; Forbes et al., 2023; Kim et al., 2013; Dib et al., 2006; Shetty & Ostriker, 2012). Gravitational instability (Krumholz & Burkhardt, 2016; Krumholz et al., 2018), gas accretion (Klessen & Hennebelle, 2010) and galaxy interaction (Bournaud et al., 2009) have been suggested as possible sources of the additional gas turbulence.

The importance of different mechanisms may vary with redshift and environment. Gas accretion at high redshift was more efficient in converting bulk kinetic energy into turbulent kinetic energy than at low redshifts (Klessen & Hennebelle, 2010; Ginzburg et al., 2022). A simulation study by Jiménez et al. (2023) showed that stellar feedback is more important for galaxies in lower halo masses and at lower redshift. Krumholz et al. (2018) predicts that the relation between gas velocity dispersion and SFR changes with the fraction of the interstellar medium that is in the star-forming molecular phase, which in turn depends on redshift.

The measurement of intrinsic gas velocity dispersion is challenging. Ionised gas velocity dispersion is normally measured based on the width of emission lines, such as the $H\alpha$ emission line. However, the measurement of line width within a dynamic system like a disk is complicated by observational and instrumental factors including the line spread function (LSF), spaxel grid, and the size and shape of the point spread function (PSF) (Davies et al., 2011; Oh et al., 2022). The beam smearing caused by the Earth’s atmosphere blurs light between neighbouring spaxels. If there is a velocity difference between neighbouring spaxels, the beam smearing artificially broadens emission lines, thus increasing the apparent gas velocity dispersion. The beam smearing is the strongest at the centre of galaxies, where the velocity gradient is the largest.

Several different methods have been applied to minimise or account for the beam smearing. Johnson et al. (2018) applied a correction to gas velocity dispersion based on galaxy size, seeing PSF and velocity gradient. ^{3D}BAROLO (Di Teodoro & Fraternali, 2015), GalPaK^{3D} (Bouché et al., 2015) and GBKFIT (Bekiaris et al., 2016) use model-fitting techniques to model the flux and kinematics of galaxy three-dimensional data cubes, including beam smearing effects. ^{3D}BAROLO uses a tilted-ring model that assumes a galaxy is a thin disc and consisting of concentric rings with different rotational velocity and flux. GalPaK^{3D} and GBKFIT assume parametric radial flux distributions and velocity profiles.

In this study, we use the code BLOBBY3D (Varidel et al., 2019) which employs a forward modelling technique that models the gas kinematics and substructures simultaneously. The advantage of BLOBBY3D is that it does not assume any given gas structure, but decomposes the gas distribution into a number of Gaussian ‘blobs’. The number of blobs is flexible and depends on the complexity of the observed gas substructure. BLOBBY3D has been shown to recover the intrinsic gas velocity dispersion better than other modelling techniques where there is sufficient signal-to-noise (S/N). More constrained techniques, such as ^{3D}BAROLO and GalPaK^{3D}, may work better where S/N is poor.

Different surveys have employed various measurement techniques to measure the intrinsic gas velocity dispersion in galaxies across cosmic epochs. For example, Übler et al. (2019) measured the gas velocity dispersion of galaxies at $z > 0.6$ by forward-modelling the one-dimensional velocity and velocity dispersion profile. Law et al. (2022) corrected for the effects of beam smearing using estimates derived from a three-dimensional model that is constructed based on the observed velocity field of each galaxy for low redshift galaxies ($z \sim 0.05$). The systematic difference between the surveys makes it difficult to constrain the evolution of gas velocity dispersion.

The most rapid change in gas velocity dispersion seems to occur from $z \sim 1$ to $z \sim 0$ (Wisnioski et al., 2015; Übler et al., 2019; Kassin et al., 2012). Previous studies measured the ionised gas velocity dispersion for many local galaxies from the Integral Field Spectroscopy (IFS) survey such as SAMI (Varidel et al., 2020) and MaNGA (Yu et al., 2019; Law et al., 2022) and high redshift galaxies at $z > 0.6$ such as KMOS^{3D} (Übler et al., 2019). Kassin et al. (2012) used the slit-based

DEEP2 survey to investigate the evolution of gas velocity dispersion of galaxies at $0.2 < z < 1.2$. However, the gas velocity dispersion from IFS data between $0 < z < 1$, at which most of the change of gas velocity dispersion happens, has not been investigated in a self-consistent manner.

In this study, we will measure the ionised gas velocity dispersion of galaxies from the Middle Ages Galaxy Properties with Integral Field Spectroscopy (MAGPI) survey (Foster et al., 2021) at $z \sim 0.3$, to fill the gap of the IFS measurement of gas velocity dispersion at intermediate redshift, and to link SAMI galaxies (Bryant et al., 2015) at $z \sim 0.05$ and KROSS galaxies (Stott et al., 2016) at $z \sim 1$. We measure the gas velocity dispersion from these three surveys in a consistent manner, enabling a detailed exploration of how gas kinematics evolved over the past 8 billion years. In Section 3.3, we describe the MAGPI survey, data reduction and our sample selection. In Section 3.4, we describe the methods used to measure the gas velocity dispersion. In Section 3.5, we present our results for MAGPI gas velocity dispersions, investigate their relations with galaxy properties and compare them with other surveys. In Section 3.6, we discuss the evolution of gas velocity dispersion and drivers of gas turbulence. In Section 3.7, we summarise our results.

Throughout this paper, we adopt the concordance cosmology ($\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$, $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$).

3.3 Data

3.3.1 The MAGPI Survey

Data used in this work are drawn from the MAGPI survey (Foster et al., 2021). MAGPI makes use of the ground layer adaptive optics (GLAO) aided, wide-field optical integral field spectrograph, the Multi Unit Spectroscopic Explorer (MUSE; Bacon et al., 2010), mounted at the European Southern Observatory Very Large Telescope (VLT). MUSE has a $1 \times 1 \text{ arcmin}^2$ field-of-view (FOV) sampled at $0.2 \times 0.2 \text{ arcsec}^2$. The typical full width at half maximum (FWHM) of MUSE PSF is $\sim 0.6 \text{ arcsec}$. The spectroscopic observations from the MAGPI survey cover the wavelength ranges 4700-9351 Å with a spectral resolution of $R = 2728$ at 7025 Å.

The MAGPI survey targets 60 massive central galaxies (primary galaxies) and their neighbouring galaxies (secondary galaxies) within the MUSE FOV. The targets are selected from G12, G15 and G23 fields in the Galaxy And Mass Assembly (GAMA) survey (Driver et al., 2011). At the time of writing, the MAGPI survey has completed the observation of 48 fields, among which 35 fields have been fully reduced with relevant data products. There are 780 passive and star-forming galaxies in the redshift range of interest ($0.22 < z < 0.42$), of which 223 have $\text{H}\alpha$ -based SFR measurement.

Galaxy properties

We use the Galaxy Integral Field Unit (IFU) Spectroscopy Tool (GIST; [Bittner et al., 2019](#)) to fit emission lines and continuum spectra in MAGPI galaxies (Battisti et al. in prep). GIST is a Python wrapper designed to run the Penalized PiXel-Fitting (pPXF; [Cappellari & Emsellem, 2004](#); [Cappellari, 2017](#)) method on IFS data. GIST can extract stellar kinematics, conduct emission-line analysis, and deduce stellar population properties through spectral fitting. We use the $H\alpha$ flux map in GIST to calculate the half-light radius (R_e) of MAGPI galaxies as the tracer of star-forming R_e , inside which half the stars are currently forming. However, we note that $H\alpha$ R_e can be different to star-forming R_e if extinction significantly varies across the galaxy. At low surface brightness $H\beta$ may not have sufficient S/N to get a reliable extinction correction, so we use non-extinction corrected $H\alpha$ R_e . We generate the inclination corrected curve of growth of $H\alpha$ flux as a function of radius and define the radius enclosing 50% of the flux as R_e , to clarify that this is effectively the major axis R_e , not circularly averaged. Throughout this paper, R_e represents the half-light radius of $H\alpha$ flux unless specified otherwise.

BLOBBY3D requires stellar continuum-subtracted data. We subtract the stellar continuum from the MUSE spectrum using the stellar continuum fitting products from GIST. The stellar continuum fits were done on a spaxel level. Initial estimates of the stellar continuum were performed with the emission line masked, and those initial estimates were then used to fit the stellar continuum and emission line using templates from flexible stellar population synthesis (FSPS; [Conroy et al., 2009, 2010](#); [Conroy & Gunn, 2010](#)). The multiplicative Legendre polynomial is set to 12 (Battisti et al. in prep), which is a commonly adopted value for MUSE data to match the stellar templates reliably and account for residual flux calibration uncertainty.

We use the Baldwin, Phillips & Terlevich (BPT; [Baldwin et al., 1981](#); [Kewley et al., 2001](#); [Kauffmann et al., 2003](#)) ionisation diagnostics to identify star-forming (SF), active galactic nucleus (AGN) and composite spaxels in galaxies and to classify galaxies. We use the line ratios $[NII]\lambda 6584/H\alpha$ and $[OIII]\lambda 5007/H\beta$, including only spaxels that have $S/N > 3$ in all emission lines. The flux and error of these four emission lines are estimated using GIST ([Bittner et al., 2019](#), Battisti et al. in prep) from 50 Monte Carlo realisations of the input data. We remove galaxies that are dominated by AGN and/or composite spaxels ($\geq 50\%$) from our sample. However, we keep the galaxies with AGN and/or composite centre (> 10 spaxels) and star-forming disc (≥ 50 SF spaxels), and identified them as AGN-host galaxies. We mask the AGN and/or composite centres and keep the SF discs for these galaxies. Galaxies that are dominated by SF spaxels are classified as SF galaxies. Some SF galaxies may have a few spaxels at the edge of galaxies classified as composite spaxels due to the low S/N of the $[NII]\lambda 6584$, $[OIII]\lambda 5007$ or $H\beta$ emission lines.

SFRs are estimated using the dust-corrected $H\alpha$ luminosity ([Kennicutt, 1998](#)). $H\alpha$ flux is corrected for extinction using the Balmer decrement on a spaxel by spaxel basis. The extinction curve from [Fitzpatrick et al. \(2019\)](#) is adopted with $R_V = 3.1$. The SFRs are first calculated on a spaxel-by-spaxel basis. The integrated SFRs are then calculated from a sum of the SFRs of all SF spaxels to avoid contamination

from AGN (see Mun et al. 2024 for more details). The fraction of SFR missed due to ignoring the AGN/composite spaxels is small. The upper limit on the flux missed (assuming all $H\alpha$ flux is from star formation) is on average only 25% (0.12 dex) for AGN-host galaxies. The SFR surface density (Σ_{SFR}) is calculated as $\Sigma_{\text{SFR}} = \text{SFR}/(2\pi R_e^2)$, in which R_e from $H\alpha$ is used.

The stellar masses are calculated using PROSPECT (Robotham et al., 2020), a package used to analyse star formation history and spectral energy distributions (SED). Photometry over the *ugriZJHK* bands from GAMA imaging is used to perform PROSPECT SED fitting, assuming a Chabrier (2003) stellar initial mass function (IMF). The stellar population templates by Bruzual & Charlot (2003) are adopted and the dust attenuation law by Charlot & Fall (2000) is applied to correct stellar light attenuation by dust, as outlined in Bellstedt et al. (2020). The stellar mass surface density (Σ_{M_*}) is calculated as $\Sigma_{M_*} = M_*/(2\pi R_e^2)$.

PSF and LSF

The spatial PSF for the MAGPI survey is reconstructed from information generated by the adaptive optics system (Fusco et al., 2020). The advantage of the reconstructed PSF is that it can be obtained for any given time and field, instead of strongly depending on the availability of bright stars. It agrees well with an in-field PSF estimate when a bright star is present (Mendel et al., in prep).

The PSF convolution kernel in BLOBBY3D is a sum of multiple 2D concentric circular Gaussian profiles. We fit the reconstructed PSF with the two-component Gaussian model, which is enough to adequately model the PSF profile. We also test a PSF model using three Gaussian profiles, however this results in just a 1% change in the measured velocity dispersions (i.e., it does not significantly affect our results), but requires 30% more CPU time in running BLOBBY3D.

The spectral LSF is measured from fitting Gaussian profiles to isolated bright sky-lines, both for a collapsed spectrum of the full field and for every spaxel individually (Bacon et al., 2017, Mendel et al. in prep). The spatial variation of the MUSE LSF is small, so we use the LSF derived from an average spectrum of the full field. The variation of instrumental resolution (σ_{LSF}) between different fields is $0.135 \pm 0.006 \text{ km s}^{-1}$. When we build the BLOBBY3D model for different galaxies, we use the σ_{LSF} based on their field and redshift.

Sample selection

In our preliminary selection, we choose galaxies that have more than 50 spaxels with $H\alpha$ $S/N > 3$. Galaxies with fewer spaxels have less robust resolved kinematics due to beam smearing. Given the typical PSF of MAGPI data (FWHM ~ 0.6 arcsec), 50 pixels correspond to ~ 7 independent resolution elements within the galaxy. The galaxies chosen have redshifts between 0.22 and 0.42. We remove galaxies with clearly disturbed gas kinematics and galaxies with inclination greater than 60° . The intrinsic gas velocity dispersion of high-inclination galaxies is hard to constrain due to the beam smearing (Varidel et al., 2019). Furthermore, BLOBBY3D assumes

galaxies have a thin disc and so is not able to model very edge-on galaxies, as the thickness of the galaxy disc becomes prominent for edge-on galaxies so the thin disc model does not work well. There are 110 galaxies in our preliminary sample after applying the above cuts.

3.3.2 The SAMI Galaxy Survey

The Sydney–AAO Multi-object Integral field spectrograph (SAMI; [Croom et al., 2012](#)) uses 13 hexabundles ([Bland-Hawthorn et al., 2011](#)) over 1° diameter field-of-view, mounted on the Anglo-Australian Telescope. The SAMI galaxy survey ([Bryant et al., 2015](#); [Scott et al., 2018](#)) collected spatially resolved spectra for 3068 galaxies at $0.004 < z < 0.115$ with a broad range in galaxy stellar mass ($\log(M_*/M_\odot) = 8$ to 12). The integral field units were hexabundles ([Bland-Hawthorn et al., 2011](#)) that contained 61 fibres that cover 15 arcsec diameter regions on the sky. The SAMI survey observed each galaxy with 7 dithers/pointings. The data were resampled to $0.5''$ per spaxel. The wavelength range of SAMI is 3750–5750 Å ($R = 1808$) and 6300–7400 Å ($R = 4304$) for the blue and red arms respectively. Stellar masses are estimated from the rest-frame i -band absolute magnitude and $g-i$ colour, following the method of [Taylor et al. \(2011\)](#) and assuming a [Chabrier \(2003\)](#) IMF.

[Varidel et al. \(2020\)](#) used BLOBBY3D to measure the ionised gas velocity dispersion of 383 star-forming SAMI galaxies. They removed AGN and low-ionisation nuclear emission-line region (LINER) galaxies from their sample. They removed galaxies with an inclination greater than 60° . They also removed mergers or galaxies with clearly disturbed gas kinematics. They applied a mask to spaxels with $H\alpha$ S/N < 3 and retained galaxies that had at least 300 unmasked spaxels. They rounded the gas velocity dispersion to the nearest whole number.

Given that both [Varidel et al. \(2020\)](#) and this work employ spatially resolved spectroscopic observational data and utilize the same dispersion measurement methods, we adopt the gas velocity dispersions measured by [Varidel et al. \(2020\)](#) as a source of low-redshift dispersion measurements for comparison. For the SAMI galaxies, we use R_e measured from the $H\alpha$ emission line (SAMI DR3; [Croom et al., 2021](#)) as discussed for MAGPI galaxies in Section 3.3.1, and dust-corrected $H\alpha$ -based SFRs ([Kennicutt, 1998](#)), using the dust extinction law of [Cardelli et al. \(1989\)](#)², for better comparisons. We note that [Varidel et al. \(2020\)](#) used R_e measured using r -band images ([Bryant et al., 2015](#)) and SFRs measured by MAGPHYS ([da Cunha et al., 2008](#)) using full spectral energy distribution fits to 21 photometric bands spanning the UV, optical and far-infrared. We note that the choice of R_e does not change the results.

3.3.3 KROSS

The KMOS Redshift One Spectroscopic Survey (KROSS; [Stott et al., 2016](#)) observed 795 star-forming galaxies at $z=0.8$ –1.0 using the K -band Multi Object Spectrograph

²We note that the dust extinction law of [Cardelli et al. \(1989\)](#) and [Fitzpatrick et al. \(2019\)](#) provide comparable results over the considered wavelength ranges.

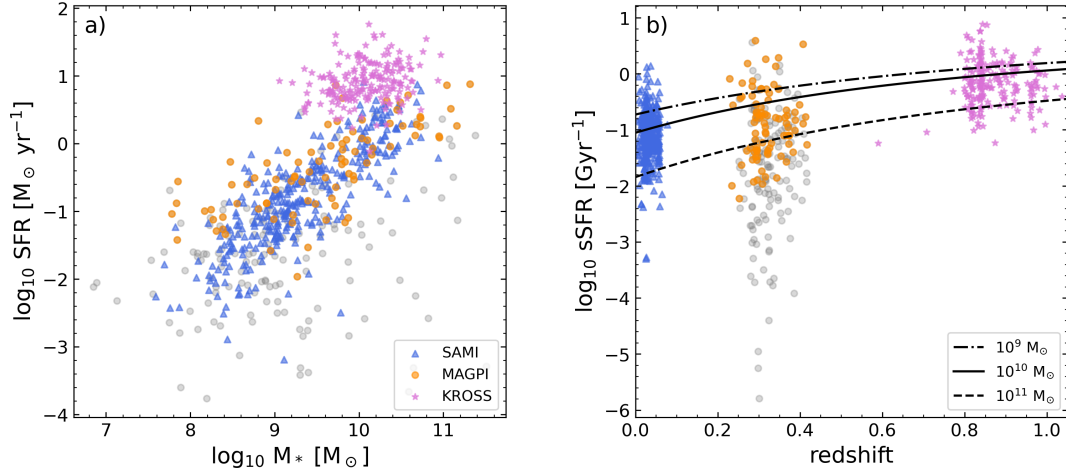


Figure 3.1: a) The SFR- M_* relation for SAMI (blue), MAGPI (orange) and KROSS (purple) galaxies in our sample. MAGPI galaxies that have $H\alpha$ -based SFR measurement but that are not in our final sample are shown in grey. b) The sSFR-redshift relation for galaxies in our sample. The black lines show the evolution of sSFR as a function of redshift drawn from [Popesso et al. \(2023\)](#) at three stellar mass values: 10^9 (dot-dashed line), 10^{10} (solid line) and $10^{11} M_{\odot}$ (dashed line).

(KMOS; [Sharples et al., 2013](#)) on the VLT. Each IFU of KMOS covers a $2.8'' \times 2.8''$ field with $0.2'' \times 0.2''$ spatial pixels. The $H\alpha$ line in this redshift range is observed within the YJ -band with spectral resolution $R = 3400$. We use R_e measured from the $H\alpha$ flux.

Varidel et al. (in prep)³ measure the gas velocity dispersion of 315 KROSS galaxies using BLOBBY3D. They remove AGN galaxies and highly-inclined galaxies ($i > 60^\circ$) and galaxies where the mode of the gas velocity dispersion in the posterior distribution is smaller than the thermal contribution of the gas, 9 km s^{-1} (which might be caused by the variation in spectral resolution on KMOS). They also removed major mergers, i.e. galaxies with clearly disturbed kinematics. This leaves 193 galaxies for further analysis.

We use the redshift, SFR, stellar mass, and inclination angle from the publicly available KROSS catalogue ([Harrison et al., 2017](#)). The SFRs are calculated using the integrated $H\alpha$ luminosity with dust correction applied ([Wuyts et al., 2011](#)). Stellar masses are estimated by scaling the H -band AB magnitude by a constant mass-to-light ratio for all galaxies, assuming a [Chabrier \(2003\)](#) IMF. [Harrison et al. \(2017\)](#) adopted the median mass-to-light ratio for the KROSS sample, $\gamma_H = 0.2$.

We show the SFR- M_* relation for SAMI, MAGPI and KROSS galaxies in our sample in Figure 3.1(a). This shows that galaxies in the SAMI and MAGPI samples have similar mass and SFR distribution, while the galaxies in the KROSS sample have higher mass and SFR. The MAGPI galaxies that have $H\alpha$ -based SFR measurement but that are not in our final sample are shown as grey circles. In Figure 3.1(b), we

³This work has been published in PhD thesis: <https://hdl.handle.net/2123/25670>

show the sSFR as a function of redshift for galaxies in the surveys. The evolution of sSFR of the galaxies in our sample aligns with the result in [Popesso et al. \(2023\)](#), which captured the evolution of the star formation main sequence (SFMS).

3.4 Methods

3.4.1 Modeling the gas disc kinematics

We use the forward-modelling technique, BLOBBY3D⁴ ([Varidel et al., 2019](#)), to infer the spatial distribution and kinematics of the gas simultaneously. BLOBBY3D is a Bayesian inference code for gas disc kinematics, using a Gaussian mixture model for the spatial distribution of the gas but assuming a thin regularly rotating galaxy. BLOBBY3D does not impose a specific spatial gas structure, but instead decomposes the gas distribution into a sum of positive-definite Gaussian basis functions (blobs), which gives it more flexibility in modelling the gas distribution. BLOBBY3D constructs a 3D (position-position-wavelength) cube that is convolved by the PSF in the spatial direction and the LSF in the wavelength direction. The convolved model is compared to the observed data cube. BLOBBY3D uses a diffusive nested sampling algorithm ([Skilling, 2004](#)), DNEST4 ([Brewer et al., 2011](#); [Brewer & Foreman-Mackey, 2018](#)), to run Markov Chain Monte Carlo (MCMC) chains to explore the posterior distribution. The advantage of DNEST4 over other sampling algorithms is in its application to high dimensional parameter spaces and multimodal distributions, which is essential to model the gas distribution and kinematics of galaxies. DNEST4 allows BLOBBY3D to jump to different models with varying numbers of blobs. For all parameters fitted in BLOBBY3D, see more details in Table 1 of [Varidel et al. \(2019\)](#). The results we use in this work are the median value over the gas velocity dispersion in the posterior samples. The uncertainty of the gas velocity dispersion is the standard deviation of the posterior samples.

We measure the ionised gas velocity dispersion of MAGPI galaxies using the H α emission line. An example set of 2D maps, showing the results of using BLOBBY3D on a MAGPI galaxy 1506106169, is displayed in Figure 3.2. This galaxy is a median-size galaxy in our sample, which has 329 spaxels with H α S/N greater than 3. The 2D maps are generated using PYBLOBBY3D, which is part of the code BLOBBY3D. PYBLOBBY3D basically performs single component Gaussian fit to the pre-convolved datacube, convolved datacube and observed datacube. Both pre-convolved datacube and convolved datacube are the outputs of BLOBBY3D.

Velocity profile

BLOBBY3D assumes a continuous velocity profile for the galaxy, based on an empirical model proposed by [Courteau \(1997\)](#)

$$v(r, \theta) = v_c \frac{(1 + r_t/r)^\beta}{(1 + (r_t/r)^\gamma)^{1/\gamma}} \sin(i) \cos(\theta) + v_{\text{sys}}, \quad (3.1)$$

⁴<https://github.com/SpaceOdyssey/blobby3d>

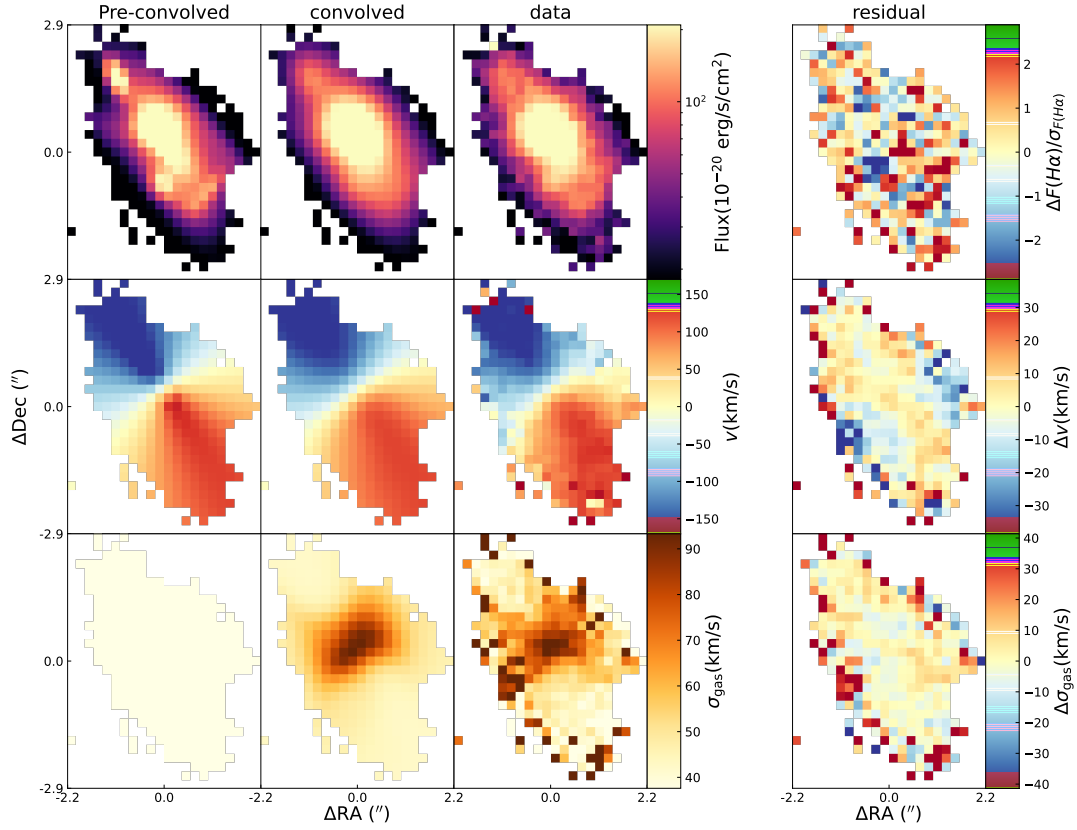


Figure 3.2: The 2D maps of the BLOBBY3D results for MAGPI galaxy 1506106169. The first column shows the model made by BLOBBY3D; the second column shows the model convolved with the PSF and LSF of the data; the third column shows the results of the single Gaussian fit to the observed datacube; the fourth column shows the residuals between the data and the convolved model. The first row shows the flux distribution of the $H\alpha$ emission line; the second row shows the velocity map; the third row shows the velocity dispersion map.

where v_c is the asymptotic velocity, r is the distance to the kinematic centre, r_t is the turnover radius, β is a parameter that controls the gradient of the velocity profile, γ is a parameter that controls the sharpness of the velocity profile turnover point, v_{sys} is a systemic velocity term, i is the inclination of the galaxy and θ is the polar angle in the plane of the disc. We calculate inclinations from the axis ratio (b/a) of the white-light image of MAGPI MUSE data, which are estimated using the tool PROFOUND (Robotham et al., 2018), as

$$\cos(i) = \sqrt{\frac{(b/a)^2 - q_0^2}{1 - q_0^2}}, \quad (3.2)$$

where q_0 is the intrinsic axial ratio of an edge-on galaxy (Weijmans et al., 2014); here we adopt $q_0 = 0.2$, following Cortese et al. (2016). We note that the adopted value of q_0 may influence the estimation of v_c , but the fit gas velocity dispersion is insensitive to q_0 . The emission line broadening caused by beam smearing is related to line-of-sight velocity, which is the combination of inclination and rotational velocity. Therefore, the underestimation or overestimation of i can be balanced by v_c in Eq. 3.1.

Velocity dispersion gradient

BLOBBY3D allows flexibility to assume different forms for the velocity dispersion as a function of radius. We adopt a flat velocity dispersion profile to simplify the inference following Varidel et al. (2020)’s analysis for SAMI galaxies. However, other surveys have shown that velocity dispersion can be radially variant (e.g. Genzel et al., 2017; Yu et al., 2019). We therefore tested using a log-linear profile and fit all spaxels with $S/N > 3$ in $H\alpha$. We have 11 AGN-host galaxies in our preliminary sample. These galaxies tend to have a higher central velocity dispersion, which forces a steep velocity dispersion slope and leads to an under-estimate of the outer dispersion. For this reason, we mask central AGN regions based on the BPT maps (Kewley et al., 2001; Kauffmann et al., 2003). We note that the small number of high-dispersion pixels at the edges of the velocity maps in some galaxies (as seen in Figure 3.2) are likely spurious artifacts caused by low $H\alpha$ S/N in these regions. This was also the case in the Varidel et al. (2020) analysis for SAMI galaxies.

For comparison, we run the model fits using both a constant velocity dispersion across the entire galaxy and a gradient in the dispersion. Overall, we find flat gradients and mean velocity dispersions that do not change significantly across the galaxies in either fit. We therefore choose the simpler constant velocity dispersion model.

3.5 Results

3.5.1 Velocity dispersions of MAGPI galaxies

Of 110 selected galaxies in our preliminary sample, 87 have a unimodal posterior distribution in gas velocity dispersion (σ_{gas}) with a peak at a realistic velocity (i.e.

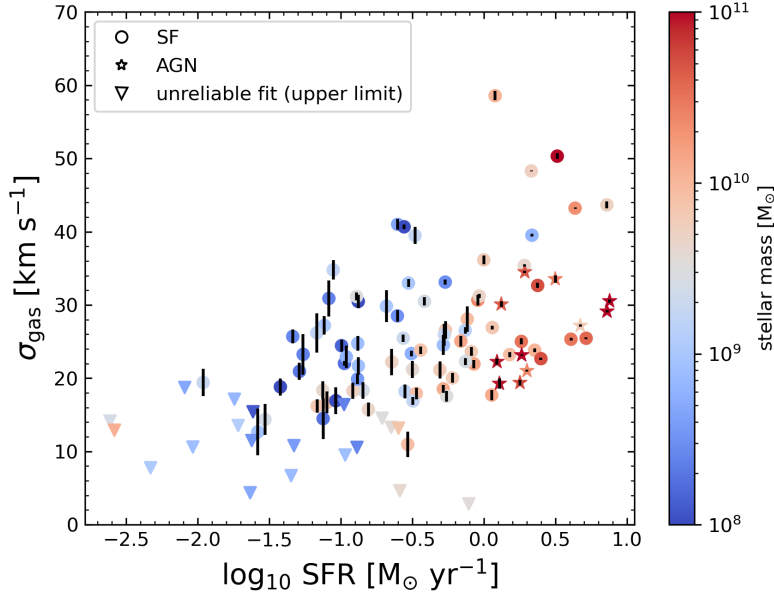


Figure 3.3: The intrinsic gas velocity dispersion of MAGPI galaxies measured by BLOBBY3D as a function of SFR, colour-coded by stellar mass. Star-forming galaxies are shown as circles and galaxies with AGN at the centre are shown as stars. The upper limits of σ_{gas} for galaxies without reliable fits are shown as downward triangles. The black errorbars show the uncertainties on σ_{gas} .

$> 10 \text{ km s}^{-1}$). The mode of the posterior distribution of the remaining 23 galaxies is at 0 km s^{-1} , which is unrealistic. This may result from an intrinsic dispersion much lower than the spectral resolution of MUSE, which BLOBBY3D is not able to resolve. The galaxies that do not have reliable velocity dispersion fits have low SFR and low gas velocity dispersion, and typically have large uncertainties in gas velocity dispersion. For those galaxies without reliable fit, the 95 percentile of σ_{gas} of posterior samples is taken as the upper limit.

The average σ_{gas} for the 87 MAGPI galaxies that have reliable fit is $26.1 \pm 8.7 \text{ km s}^{-1}$, where $\pm 8.7 \text{ km s}^{-1}$ represents the standard deviation. When we include the upper limit of σ_{gas} for galaxies without reliable fits, the average σ_{gas} for the 110 galaxies is $23.4 \pm 9.8 \text{ km s}^{-1}$. Figure 3.3 shows SFR versus gas velocity dispersion for 110 MAGPI galaxies, colour-coded by stellar mass. This includes 76 star-forming galaxies (circles) and 11 AGN-host galaxies (stars). The standard deviations of the posterior effective samples are shown as error bars. We show the upper limits of σ_{gas} for galaxies without a reliable fit (downward triangles). Note that we remove those galaxies with unreliable fits from any further analysis.

The spectral resolution for the $\text{H}\alpha$ line of MAGPI galaxies corresponds to $\sim 38 \text{ km s}^{-1}$. The minimum velocity dispersion that converges in the galaxies we selected is 11.0 km s^{-1} , about $1/3$ of the instrumental resolution. It is difficult to measure the intrinsic velocity dispersion if it is much lower than the instrumental resolution (Wisnioski et al. in prep).

Most of the galaxies with AGN sit at high SFR in Figure 3.3. These galaxies also

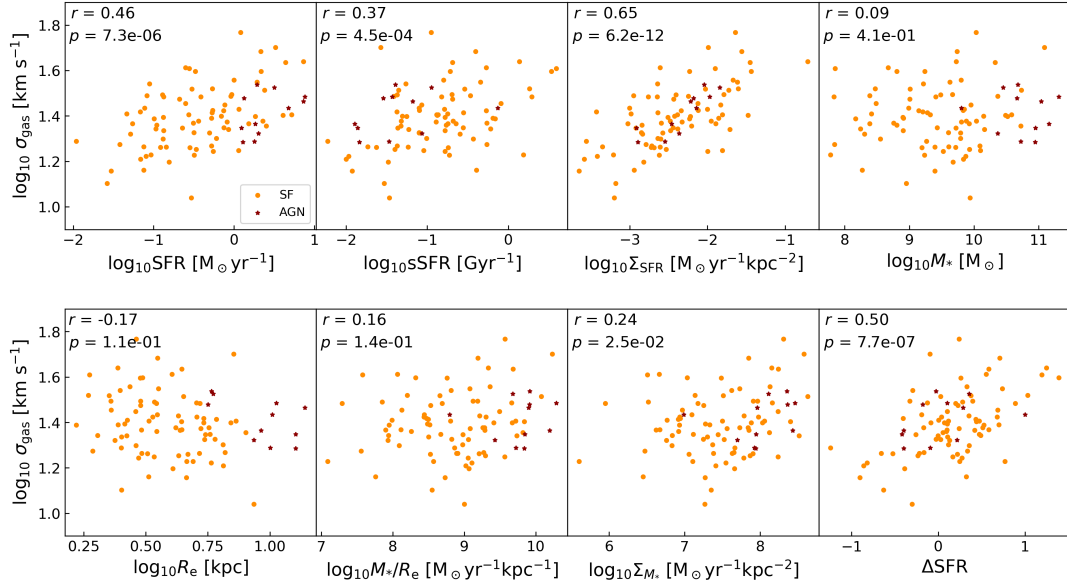


Figure 3.4: Intrinsic gas velocity dispersion (σ_{gas}) as a function of galaxy properties for MAGPI galaxies, including star-formation rate (SFR), specific star-formation rate (sSFR), star-formation rate surface density (Σ_{SFR}), stellar mass (M_*), half-light radius of H α flux (R_e), a proxy for the gravitational potential (M_*/R_e), stellar mass surface density (Σ_{M_*}), and the logarithmic offset in SFR from the star formation main sequence of MAGPI galaxies (ΔSFR). Pearson correlation coefficient, r , and p -value for each correlation are shown on each panel. The star-forming galaxies are shown as orange circles and the AGN-host galaxies are shown as dark red stars. We find that the σ_{gas} of MAGPI galaxies has the strongest correlation with Σ_{SFR} ($r = 0.65$). The σ_{gas} also has a strong correlation with SFR and ΔSFR .

have larger sizes and higher stellar masses (see Section 3.5.2), which are positively correlated with SFR. However, it is noteworthy that they tend to have lower dispersion than other galaxies of the same SFR. We test whether the masking of the centres of the AGN galaxies influences our measurements by selecting 9 SF galaxies, masking their centres and then refitting for σ_{gas} . This test shows that the differences of σ_{gas} between the centre-masked and no-mask versions are a few km s^{-1} and the average offset is 0.4 km s^{-1} . This suggests that our approach of masking the central region in AGN-host galaxies does not bias the σ_{gas} measurements.

Galaxies with AGN at the centre do not have higher dispersion than the galaxies with similar SFR, which indicates that the AGN in our sample, though they may have high gas velocity dispersion in the central AGN region, do not influence the global gas velocity dispersion of the star-forming disc of their host galaxies. AGN-host galaxies are closer to the average values of dispersion at fixed Σ_{SFR} (see Section 3.5.2 below).

3.5.2 Correlations between velocity dispersion and other galaxy properties

To investigate what factors can impact gas velocity dispersion, we calculate the Pearson correlation coefficient (r) between gas velocity dispersion and galaxy properties, such as total SFR, specific SFR (sSFR), Σ_{SFR} , stellar mass, R_e , a proxy for the gravitational potential (M_*/R_e), Σ_{M_*} , and the logarithmic offset in SFR from the SFMS of MAGPI galaxies (ΔSFR). The SFMS is defined as the best linear fit to the MAGPI galaxies located at $0.25 \leq z \leq 0.424$ that have SFRs measured from H α (Mun et al., 2024). We plot all these correlations in Figure 3.4, with the Pearson correlation coefficient (r) and p -value on each plot. The Pearson correlation coefficient measures the linear correlation between two variables. The p -value helps determine whether the observed correlation is statistically significant. A p -value of 0.05 or lower is generally considered statistically significant. We use PINGOUIN (Vallat, 2018) to calculate r and p -values.

We find that the gas velocity dispersion of MAGPI galaxies is strongly correlated with SFR, as already shown in Figure 3.3, with correlation coefficient $r = 0.46$. We look at properties derived using SFR to see if they reduce the scatter in the $\sigma_{\text{gas}} - \text{SFR}$ relation. When SFR is combined with R_e , the Σ_{SFR} gives a stronger correlation with σ_{gas} ($r = 0.65$) than SFR, while R_e has no significant correlation with σ_{gas} ($r = -0.17$). This result is consistent with galaxies at $z \sim 0.05$ (SAMI; Varidel et al., 2020). This trend may arise from star-formation feedback, mainly from the supernova, which injects energy into neighbouring gas, leading to turbulence and increasing the gas velocity dispersion (e.g. Faucher-Giguère et al., 2013; Krumholz et al., 2018). The rate of energy injection per unit area, traced by Σ_{SFR} , is more correlated with gas velocity dispersion than the global SFR of galaxies, which indicates that the star formation on small scales within the disc may be more important than the global SFR of the galaxy.

We also calculate the $\Sigma_{\text{SFR},i\text{-band}}$ using $R_{e,i\text{-band}}$ ($\Sigma_{\text{SFR},i\text{-band}} = \text{SFR}/(2\pi R_{e,i\text{-band}}^2)$). The $R_{e,i\text{-band}}$ is the half-light radius of i -band image of MAGPI galaxies that is estimated by fitting a single Sérsic profile using Galfit (Peng et al., 2010). We find that the Σ_{SFR} using R_e of the H α flux gives a higher correlation coefficient ($r = 0.65$) than $\Sigma_{\text{SFR},i\text{-band}}$ ($r = 0.61$). As we might expect, Σ_{SFR} calculated by H α R_e has a tighter correlation, because it more accurately portrays the Σ_{SFR} of star-forming regions within the galaxies.

We incorporate SFR with stellar mass in two different ways, i.e. sSFR and ΔSFR . ΔSFR has a slightly stronger correlation ($r = 0.50$) with σ_{gas} than SFR. sSFR does not reduce the scatter in $\sigma_{\text{gas}} - \text{SFR}$ relation, with $r = 0.37$ for sSFR. Also, we find that M_* have no significant correlation with σ_{gas} ($r = 0.09$). There is no significant correlation between σ_{gas} and M_*/R_e ($r = 0.16$), in contrast to stellar velocity dispersion correlating with potential, which indicates that the gas velocity dispersion is more easily influenced by local power sources (Oh et al., 2022). We note that $M_*/R_{e,i\text{-band}}$ is a better proxy for gravitational potential, but the correlation coefficient does not change when we use $M_*/R_{e,i\text{-band}}$. We use H α R_e for all parameters in Figure 3.4 for consistency. Σ_{M_*} is weakly correlated with σ_{gas} ($r = 0.24$).

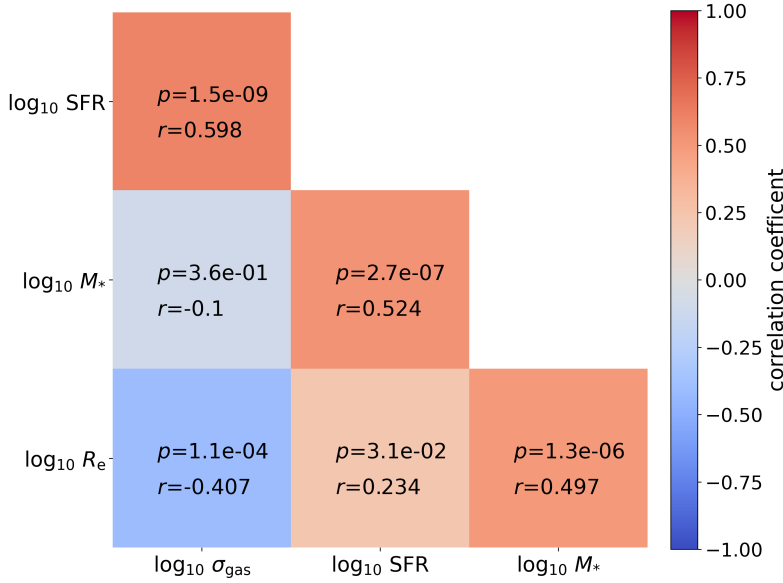


Figure 3.5: The partial correlations between gas velocity dispersion, SFR, M_* and R_e for the MAGPI sample. The Pearson correlation coefficient (r) and p -value are given in each box, which is colour-coded by its correlation coefficient. The partial correlation shows that SFR still has a strong correlation with gas velocity dispersion ($r = 0.598$) when we remove the effects from M_* and R_e . R_e has a negative partial correlation with σ_{gas} ($r = -0.407$), indicating that SFR and galaxy size have a combined effect on gas velocity dispersion.

From the galaxy SFMS, we know that galaxies with higher mass tend to have higher SFR. To disentangle the correlation between these parameters, we carry out a partial correlation analysis as shown in Figure 3.5 using PINGOUIN (Vallat, 2018). Partial correlation measures the correlation between two variables, with the effect of other variables removed (Whittaker, 2009). The partial correlations between σ_{gas} , SFR, M_* and R_e show that SFR has the strongest correlation with σ_{gas} ($r = 0.598$) when we take M_* and R_e into account. M_* has no significant partial correlation with σ_{gas} ($r = -0.1$). Though no significant correlation has been found between σ_{gas} and R_e in Figure 3.4, R_e has a negative partial correlation with σ_{gas} ($r = -0.407$), indicating that SFR and galaxy size have a combined effect on gas velocity dispersion. It provides further evidence that Σ_{SFR} is more important than total SFR on σ_{gas} , as demonstrated in Figure 3.4.

3.5.3 Non-rotational gas velocities

We also want to investigate other mechanisms that might influence gas turbulence, such as gas accretion and gas transportation through a disc. We use the velocity residual between the observed MAGPI velocity map, derived using single Gaussian component fit, and the convolved model as an indicator of non-regular rotational velocity. The model velocity profile in BLOBBY3D only contains rotation. Therefore, the deviation of the observed velocity map from the model velocity map can be considered as non-rotational motion (or at least deviations from regular rotation). We

calculate the average velocity residual (Δv) weighted by H α line S/N of each spaxel to reduce the impact of the low S/N spaxels at the edge of galaxy, as follows:

$$\Delta v = \frac{\sum_{i \in \Omega} |v_{\text{con}} - v_{\text{data}}|_i \cdot sn_i}{\sum_{i \in \Omega} sn_i}, \quad (3.3)$$

where Ω includes all spaxels with H α S/N greater than 10, v_{con} is the velocity in the convolved model of each spaxel, v_{data} is the velocity in the data, sn is the S/N of each spaxel. Then we investigate its correlation with gas velocity dispersion.

Since the $\sigma_{\text{gas}} - \Sigma_{\text{SFR}}$ is the strongest correlation we find ($r = 0.65$), we colour-coded the galaxies in our sample in the $\sigma_{\text{gas}} - \Sigma_{\text{SFR}}$ plane by their average velocity residual (shown in Figure 3.6a), to see whether non-rotational velocity contributes to the scatter of this relation. The dashed line in Figure 3.6a is fitted by ordinary least squares regression. We find that the galaxies above the line tend to have slightly (but non-negligible) higher velocity residuals. The average velocity residual is $4.54 \pm 0.28 \text{ km s}^{-1}$ for the galaxies above the line and is $3.67 \pm 0.16 \text{ km s}^{-1}$ for the galaxies under the line. The velocity residual difference is small compared to the rotational velocity of the galaxy ($\sim 100 \text{ km s}^{-1}$). When we look at the large-scale velocity residual in individual galaxies, the velocity residual in some regions could be up to $\sim 40 \text{ km s}^{-1}$ (e.g. see Figure 3.10 below).

We further investigate the partial correlation between σ_{gas} , Σ_{SFR} , Δv and M_* , as shown in Figure 3.6b. The correlation coefficient between σ_{gas} and Σ_{SFR} is $r = 0.71$. The correlation coefficient between σ_{gas} and Δv is $r = 0.424$. The result shows that in addition to Σ_{SFR} , our measurement of gas velocity dispersion may also be related to non-circular motions of the gas. We test an alternative method to find asymmetry, by rotating the seeing convolved velocity map by 180° , but this approach has more noise (the velocity residuals are consistently larger), likely because a non-uniform flux distribution plus beam smearing can generate kinematic asymmetries. This method reduces the significance of the signal we see, but we do not consider it reliable.

We find Δv also has a strong correlation with M_* . This correlation may arise from the larger velocity amplitudes in high-mass galaxies, which could lead to greater residuals. Possible contributing factors include slight inaccuracies in the model (e.g. velocity profile, the position of blobs), and deviations induced by bars or spiral arms. Further analysis is needed to investigate the impact of these factors.

Among all MAGPI galaxies in our sample, we find that four galaxies with high Δv show an interesting Fourier $m = 3$ pattern in the velocity residual maps. We will further discuss this in Section 3.6.2.

3.5.4 Comparison to the SAMI and KROSS surveys

We compare the MAGPI sample with the SAMI ($z \sim 0.05$) and KROSS ($z \sim 1$) samples, of which the σ_{gas} is measured in a consistent method. As the SAMI and KROSS samples only include SF galaxies, we remove the AGN-host galaxies from our MAGPI sample in the following comparison. We note that removing AGN-host

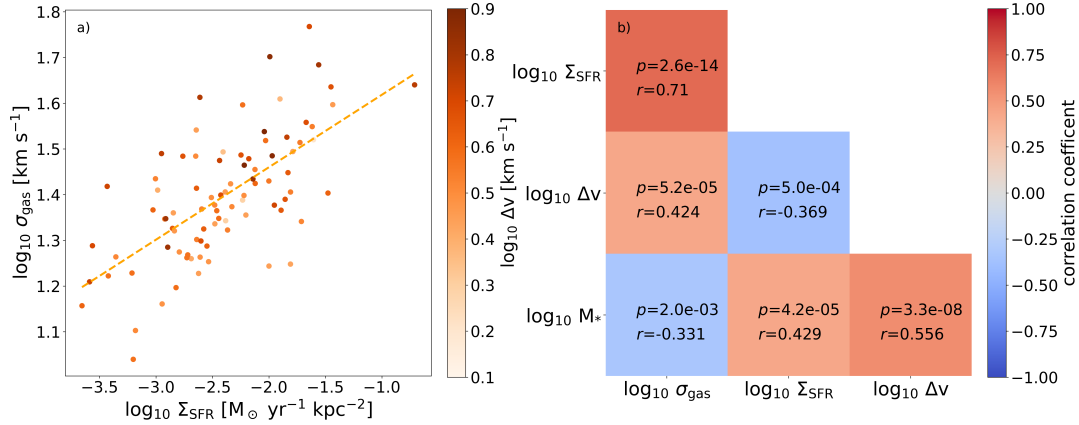


Figure 3.6: a) Gas velocity dispersion versus Σ_{SFR} colour-coded by average velocity residual (Δv). The dashed line is the ordinary least squares regression line. b) The Pearson partial correlation between σ_{gas} , Σ_{SFR} , Δv and M_{*} . The Pearson correlation coefficient (r) and p -value are shown in each box, which is colour-coded by correlation coefficient. The result shows that in addition to Σ_{SFR} , gas velocity dispersion may also be related to non-circular motions of the gas.

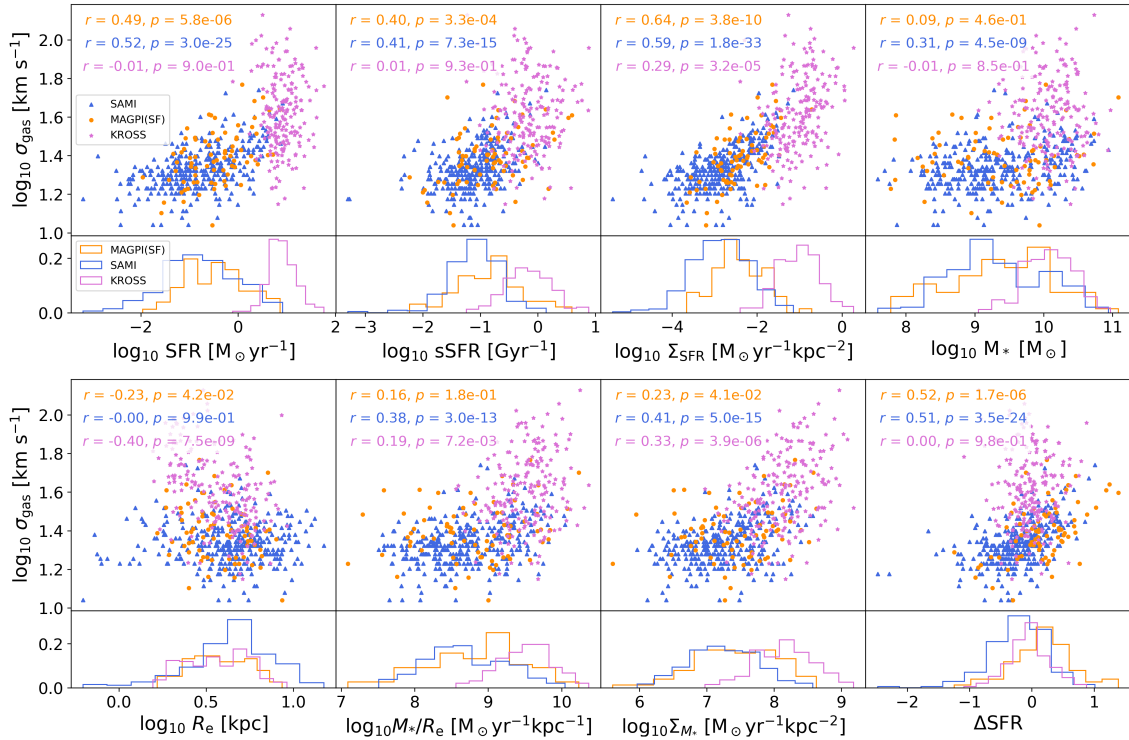


Figure 3.7: The relationship between gas velocity dispersion and galaxy properties for MAGPI (orange), SAMI (blue) and KROSS (purple) survey. The lower panel of each plot shows the distribution of galaxy properties. The Pearson correlation coefficients (r) and p -values are shown on each plot. Both MAGPI and SAMI galaxies have the strongest correlation between σ_{gas} and Σ_{SFR} . KROSS galaxies also have a modest correlation between σ_{gas} and Σ_{SFR} .

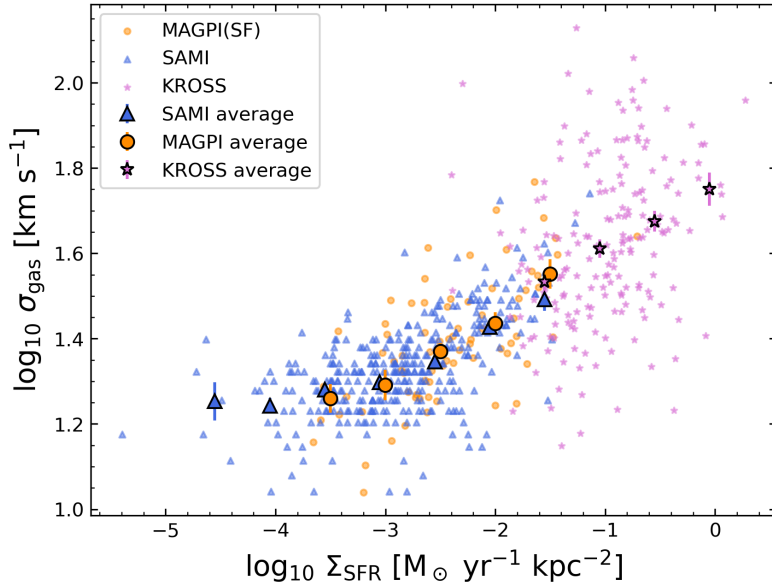


Figure 3.8: The $\sigma_{\text{gas}} - \Sigma_{\text{SFR}}$ relation for MAGPI (orange), SAMI (blue) and KROSS (purple) galaxies. The average σ_{gas} in each 0.5 dex bin for SAMI, MAGPI and KROSS are shown as black-edge triangles, circles and stars. The errorbars show the standard error of the mean.

galaxies does not change our results. Figure 3.7 compares the MAGPI, SAMI and KROSS velocity dispersions against several other galaxy properties. The Pearson correlation coefficients, r , and the p -values are shown for each survey separately. The histograms illustrate that the distribution of galaxy properties of MAGPI and SAMI galaxies are similar, although MAGPI galaxies have slightly higher stellar mass and higher SFR than SAMI galaxies. KROSS galaxies have ~ 2 dex higher SFR and ~ 1 dex higher stellar mass.

We find that both MAGPI and SAMI data show that σ_{gas} is strongly correlated with SFR and Σ_{SFR} . Also, both MAGPI and SAMI data show that Σ_{SFR} has a higher correlation coefficient than SFR, which may indicate that higher energy injection per unit area by star-formation feedback, rather than total SFR of the galaxy, drives higher σ_{gas} . We also find ΔSFR has a strong correlation ($r \sim 0.5$) with σ_{gas} for SAMI and MAGPI galaxies.

Similar to Figure 3.5, the partial correlations between σ_{gas} , SFR, M_* and R_e for SAMI galaxies show that there is no partial correlation between σ_{gas} and M_* , indicating that the relation between stellar mass and dispersion is driven by SFR for SAMI galaxies. There is no partial correlation between σ_{gas} and M_* for KROSS galaxies. The progenitors of SAMI galaxies, at the redshifts of MAGPI and KROSS, will have lower stellar masses. However, the stellar mass has no partial correlation with σ_{gas} for SAMI, MAGPI and KROSS galaxies, indicating that mass-related progenitor bias is unlikely to be significant for our σ_{gas} analysis. However, it would be interesting to analyse the low-mass high-redshift galaxies in future studies.

Interestingly, although there is no correlation between σ_{gas} and SFR found for

KROSS galaxies, there is a significant correlation between σ_{gas} and Σ_{SFR} . This result suggests Σ_{SFR} is also more important than SFR for high redshift galaxies. However, we note that the range of SFR for KROSS galaxies is narrower (on a log-scale) than SAMI and MAGPI, which limits our ability to detect a correlation. The negative correlation between R_e and σ_{gas} may indicate that BLOBBY3D does not perfectly account for the beam smearing in the high-redshift galaxies, which makes smaller galaxies have higher σ_{gas} . Varidel et al. (2019) used toy models to test the ability of BLOBBY3D in recovering the intrinsic velocity dispersion in different galaxy size-seeing ratios (see Figure 4 in Varidel et al., 2019). However, further tests on how well can BLOBBY3D recover the intrinsic σ_{gas} in more realistic cases could be valuable.

As Σ_{SFR} has the strongest correlation with σ_{gas} for MAGPI and SAMI galaxies, and a moderate correlation with KROSS galaxies, we calculate the average σ_{gas} in each 0.5 dex bin for MAGPI, SAMI and KROSS galaxies separately. Figure 3.8 shows that the average σ_{gas} is similar for SAMI, MAGPI and KROSS galaxies at the fixed Σ_{SFR} and the average σ_{gas} lines up for galaxies from three surveys at different redshifts, which may suggest that the mechanism that relates to Σ_{SFR} is the main driver of gas turbulence at different redshifts.

3.6 Discussion

3.6.1 Gas velocity dispersion evolution through cosmic time

We show the intrinsic gas velocity dispersion of SAMI, MAGPI and KROSS galaxies as a function of lookback time (t_{lookback}) in Figure 3.9. The velocity dispersion of these galaxies is all measured using BLOBBY3D. Previous observational studies have shown gas velocity dispersion decreases with cosmic time, so that galaxies have higher gas velocity dispersion when the Universe was younger (Kassin et al., 2012; Wisnioski et al., 2015; Übler et al., 2019). With the addition of the MAGPI data, a large IFS dataset at this epoch, we can explore the different mechanisms which may drive turbulence and their evolution.

Two versions of the ordinary linear regression fitting of the gas velocity dispersions of SAMI, MAGPI and KROSS galaxies are shown in Figure 3.9. The linear relation between gas velocity dispersion and lookback time (line 1) is shown as a black solid line and is given by

$$\sigma_{\text{gas}}[\text{km s}^{-1}] = 3.4(\pm 0.2) \cdot t_{\text{lookback}} + 20.1(\pm 0.8) . \quad (3.4)$$

The relation between gas velocity dispersion and redshift (line 2) is shown as a black dot-dash line and is given by

$$\sigma_{\text{gas}}[\text{km s}^{-1}] = 27.5(\pm 1.4) \cdot z + 21.0(\pm 0.7) . \quad (3.5)$$

Our results show a decreasing trend of gas velocity dispersion from $z = 1$ to $z = 0$, which is consistent with previous studies. Both Wisnioski et al. (2015) and Übler et al. (2019) showed clear decreasing trends of gas velocity dispersion over cosmic

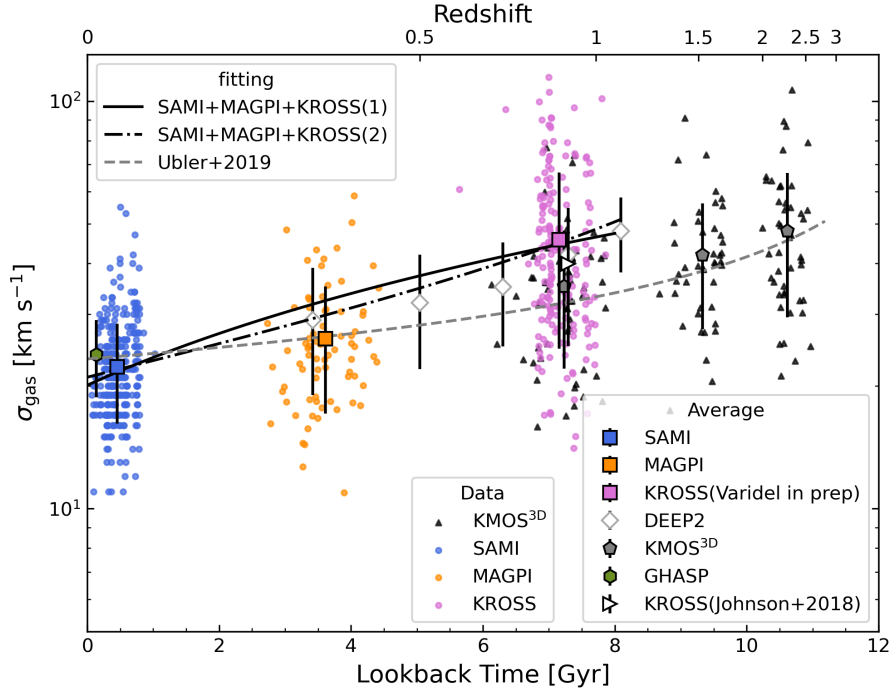


Figure 3.9: The gas velocity dispersion of SAMI, MAGPI and KROSS galaxies as a function of lookback time. The data from KMOS^{3D} (Übler et al., 2019) are shown as black triangles. The average σ_{gas} and the standard deviation of SAMI (Varidel et al., 2020), MAGPI, KROSS (Varidel et al. in prep), DEEP2 (Kassin et al., 2012), KMOS^{3D} (Übler et al., 2019), GHASP (Epinat et al., 2010) and KROSS (Johnson et al., 2018) are shown as different black-edge markers. The black solid line shows the ordinary linear regression between gas velocity dispersion and lookback time for the combination of SAMI, MAGPI and KROSS data, for which gas velocity dispersions are measured with the same method. The black dot-dash line shows the ordinary linear regression between gas velocity dispersion and redshift for the combined data. The grey dashed line is a robust $\sigma_{\text{gas}} - z$ linear relation (Cappellari et al., 2013) from Figure. 6 in Übler et al. (2019), fitted using the ionised gas velocity dispersion data from literature at $0 < z < 4$. This plot shows that the gas velocity dispersions of SAMI, MAGPI and KROSS galaxies are consistent with the decreasing trend of gas velocity dispersion over cosmic time suggested by previous studies (Kassin et al., 2012; Wisnioski et al., 2015; Übler et al., 2019).

time using data of KMOS^{3D} in the redshift range $0.6 < z < 2.6$. [Übler et al. \(2019\)](#) did a linear regression of gas velocity dispersion and redshift using the gas velocity dispersion of KMOS^{3D} galaxies and ionised gas velocity dispersion from the literature at $0 < z < 4$. The fit in [Übler et al. \(2019\)](#) is described by the equation

$$\sigma_{\text{gas}}[\text{km s}^{-1}] = 9.8(\pm 3.5) \cdot z + 23.3(\pm 4.9) . \quad (3.6)$$

The gas velocity dispersion of SAMI, MAGPI and KROSS in our results are consistent with $\sigma_{\text{gas}} - z$ linear fitting in [Übler et al. \(2019\)](#). The gas velocity dispersion of MAGPI galaxies at $z \sim 0.3$ is in good agreement with the results in the slit based DEEP2 survey ([Kassin et al., 2012](#)). The average velocity dispersion of KROSS galaxies measured with BLOBBY3D agrees with [Johnson et al. \(2018\)](#), who measured the gas velocity dispersion of KROSS galaxies fitting a single Gaussian component with beam smearing correction applied. The KROSS galaxies at $z \sim 1$ have higher gas velocity dispersion than the KMOS^{3D} galaxies at a similar redshift. This difference may be due to differences in sample selection; [Übler et al. \(2019\)](#) applied strict criteria to select only settled-disc galaxies, which may exclude the most turbulent galaxies and thus lower the average gas dispersion of the sample. We remark that we did not apply the strict selection criteria of [Übler et al. \(2019\)](#) to our sample of KROSS galaxies, but we removed galaxies with clear indications of ongoing major mergers.

The evolution of gas velocity dispersion fits in a consistent picture with the evolution of star formation and gas fraction. Previous studies have found that the sSFR decreases over cosmic time ([Madau et al., 1998](#); [Hopkins & Beacom, 2006](#); [Madau & Dickinson, 2014](#); [Leslie et al., 2020](#); [Popesso et al., 2023](#)). The decreasing global averages of gas velocity dispersion is consistent with decreasing sSFR, which is an important galaxy property that correlates with gas velocity dispersion. The evolution in sSFR is fairly flat from $z \sim 5$ to $z \sim 1$, only slightly decreasing. Most of the change appears to have happened between $z \sim 1$ to 0. Galaxy gas content, which is the fuel of star formation, also evolves with cosmic time. Star-forming galaxies in earlier cosmic epochs held more molecular gas compared to the present time (e.g. [Tacconi et al., 2020](#)). The gas fractions of star-forming galaxies have decreased from $z = 3$ to $z = 0$ at a roughly constant rate ([Wiklind et al., 2019](#)).

3.6.2 Drivers of gas turbulence

We discussed the correlation between SFR and σ_{gas} ($r = 0.46$) and between Σ_{SFR} and σ_{gas} ($r = 0.65$) for MAGPI galaxies in Section 3.5.2. There is also a strong correlation between Σ_{SFR} and σ_{gas} for SAMI galaxies and a moderate correlation for KROSS galaxies. The average σ_{gas} is similar for SAMI, MAGPI and KROSS galaxies at the fixed Σ_{SFR} , as shown in Figure 3.8.

Star-formation feedback is considered to be an important source of gas turbulence since it injects energy into the interstellar medium ([Ostriker & Shetty, 2011](#); [Shetty & Ostriker, 2012](#); [Faucher-Giguère et al., 2013](#); [Krumholz & Burkhardt, 2016](#); [Krumholz et al., 2018](#); [Bacchini et al., 2020](#); [Sun et al., 2020](#); [Ceverino et al., 2017](#)). Some analytical models and theories proposed that the energy from star-formation

feedback sweeps up gas, then the shell of gas breaks up and merges with the interstellar medium, generating turbulence. The rate of energy injection per unit area, which is determined by the momentum injected per unit mass, star-formation surface density and gas velocity dispersion, balances the energy loss rate by turbulent dissipation (Krumholz et al., 2018; Faucher-Giguère et al., 2013; Krumholz et al., 2017). Given the importance of stellar feedback on driving turbulence, we expect a positive correlation between gas velocity dispersion and Σ_{SFR} .

The strong correlations between σ_{gas} and SFR, and between σ_{gas} and Σ_{SFR} have been observed by many observational studies (Green et al., 2010; Lehnert et al., 2013; Green et al., 2014; Moiseev et al., 2015; Zhou et al., 2017; Johnson et al., 2018; Yu et al., 2019; Varidel et al., 2020; Law et al., 2022) and simulation studies (Shetty & Ostriker, 2012; Hung et al., 2019; Jiménez et al., 2023; Rathjen et al., 2023), that can be considered as the evidence of star-formation feedback driving gas turbulence. In particular, Egorov et al. (2023) using high-resolution observations of gas superbubbles, showed a dependence of the kinetic energy of ionised gas velocity dispersion on energy input from stellar feedback, which provided further support for the star-formation feedback energy injection theory.

The degree of star-formation feedback in increasing gas velocity dispersion is controversial. Some studies proposed that star-formation feedback is the dominant factor driving gas turbulence. Faucher-Giguère et al. (2013) and Bacchini et al. (2020) built theoretical models to show that star-formation feedback alone is enough to sustain gas turbulence in local and high-redshift star-forming galaxies without other energy sources. On the contrary, some studies suggested a need for additional sources of gas turbulence (Zhou et al., 2017; Bik et al., 2022; Forbes et al., 2023).

Another possible explanation for the strong correlation between σ_{gas} and Σ_{SFR} is that gravitational instability drives gas velocity dispersion (Krumholz & Burkhardt, 2016; Krumholz et al., 2018; Molina et al., 2020). The Toomre-Q parameter (Toomre, 1964), or gravitational stability parameter, can be approximated by

$$Q \approx \sqrt{2} \frac{v_c \sigma_{\text{gas}} f_g}{\pi G r \Sigma_{\text{gas}}} , \quad (3.7)$$

where Q is the total Toomre-Q parameter for both gas and stars, v_c is the galaxy rotation curve velocity (assuming a flat rotation curve), f_g is the gas fraction, Σ_{gas} is the gas surface density. The gravitational instability creates turbulence to keep the galaxy disc in marginally stable status, i.e. $Q \approx 1$. The energy source for this mechanism is gas inward transportation through the disc. If instability arises in the disc, it will break the axisymmetry, causing the subsequent torques that drive gas inward motion until marginal stability is restored (Bertin & Lodato, 1999; Krumholz & Burkert, 2010; Forbes et al., 2012, 2014; Krumholz et al., 2018). The Kennicutt-Schmidt relation shows us that Σ_{SFR} is proportional to Σ_{gas} (Kennicutt, 1998; Kennicutt & Evans, 2012). Therefore, the strong correlation we find between σ_{gas} and Σ_{SFR} may be a correlation between σ_{gas} and Σ_{gas} to keep the galaxy disc marginally stable, $Q \approx 1$. Further observations of f_{gas} and Σ_{gas} are needed to test this idea. For example, Krumholz & Burkhardt (2016) showed that the σ_{gas} -SFR

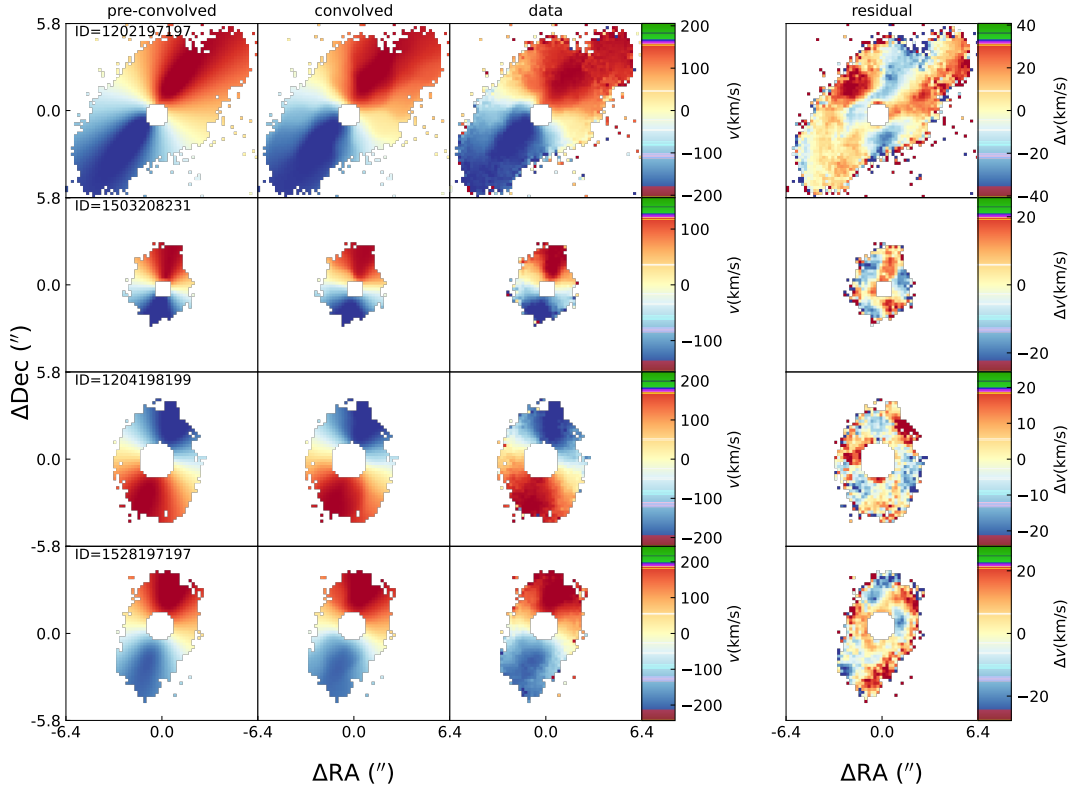


Figure 3.10: Four MAGPI galaxies that have $m = 3$ Fourier mode in the velocity residual maps. The first column shows the model made by BLOBBY3D; the second column shows the model convolved with the PSF and LSF of the data; the third column shows the results of the single Gaussian fit to the observed datacube; the fourth column shows the residuals between the data and the convolved model.

relation is different for gravity-driven and star formation feedback-driven models. In the gravity-driven model, f_g changes the slope of the σ_{gas} -SFR relation.

Gravitational instabilities can also be induced by external influences like galaxy-galaxy interactions or accretion. In Section 3.5.3, we find some galaxies have large Δv values, indicating non-circular motions. Four galaxies with high Δv ($\Delta v = 8.6 \pm 2.0 \text{ km s}^{-1}$) show an interesting Fourier $m = 3$ pattern in their velocity residual maps, which means there are three approaching and three receding regions in velocity residual maps. Figure 3.10 shows the four MAGPI galaxies with this pattern. These galaxies are AGN-host galaxies. We mask the AGN spaxels in these galaxies. We rule out the possibility of simple gas inflows for this pattern, as the simple gas inflow model only creates an axisymmetric pattern on the line-of-sight velocity residual map (Genzel et al., 2023; Tsukui et al., 2024). The $m = 3$ patterns we see may be caused by an interaction with a satellite galaxy, which disturbs the galaxy disc and triggers the bending wave or disc corrugation, which wraps up with differential rotation (e.g. Bland-Hawthorn & Tepper-García, 2021; Tepper-García et al., 2022). A warp can be also caused by misaligned gas accretion and can provide kinetic energy to gas, increasing the velocity dispersion (Khachaturyants et al., 2022; Jiménez et al., 2023). One galaxy (ID=1204198199) shows evidence of interaction with neighbouring high

mass galaxies in the white light image from MUSE. The other three galaxies do not have clear features indicating interactions with other galaxies, but they live in groups that might have interaction with neighbouring low-mass galaxies.

Another explanation for this $m = 3$ pattern is spiral-arm related gas flows (Kawata et al., 2014; Grand et al., 2016). Grand et al. (2016) showed that spiral arms induce large-scale streaming motion so that the gas behind the arm moves azimuthally backwards and radially outwards, while the gas at the front of the arm moves azimuthally forward and radially inward. The radial velocity in their model is $\sim 20 \text{ km s}^{-1}$ and the azimuthal velocity is $\sim 10 \text{ km s}^{-1}$ relative to the mean rotational velocity. Although the line-of-sight velocity depends on the inclination of the galaxy and the location in the galaxy, the velocity residual we find is of the same order of magnitude as the combined effect of radial and azimuthal gas flows in Grand et al. (2016). Therefore, the $m = 3$ pattern may be due to these galaxies having three spiral arms. Bland-Hawthorn et al. (2024) showed that the gas-rich galaxies have a relatively shortlived feature of 3-arm ($m = 3$) spirals using hydrodynamics simulations. They suggested that this feature is indicative of large-scale instability in the disc's early lifecycle. Two galaxies (ID=1202197197, 1204198199) with $m = 3$ pattern are identified as three-armed spiral galaxies in Chen et al. (2023). Based on the white light MUSE image, another one (ID=1528197197) has some features of spiral arms, but the number of arms is uncertain. The remaining $m = 3$ galaxy (ID=1503208231) does not have a clear feature of arms. Finally, for these $m = 3$ featured galaxies, the possible influence of AGN-driven turbulence cannot be ruled out completely.

Mechanisms acting on different scales, such as stellar feedback, gas transportation and accretion, may contribute to the gas turbulence at the same time. However, simulating physical processes at different scales at the same time is difficult and simulations on different scales give different results. Using magnetohydrodynamic simulations of the star-forming interstellar medium in galaxy discs, Rathjen et al. (2023) showed the correlation between gas velocity dispersion and SFR vanished if they turned off stellar feedback. In contrast, Jiménez et al. (2023) showed that the correlation is weaker but still exists in their EAGLE cosmological simulations without star-formation feedback. Note that these two studies investigate the relation in different scales. Rathjen et al. (2023) focused on a galactic scale and did not include the impact of cosmological accretion on turbulence. On the contrary, Jiménez et al. (2023) studied the impact of several mechanisms on turbulence on cosmological scales, but their results were limited by the spatial resolution of cosmological simulations and the sub-grid physics that was employed for stellar feedback.

The importance of different mechanisms may also vary with redshift and halo mass (Ginzburg et al., 2022; Jiménez et al., 2023). Ginzburg et al. (2022) built an analytical model to show that the contributions from three mechanisms to gas turbulence, including stellar feedback, gas transportation and gas accretion, evolved with cosmic time and were different for galaxies in different halo masses, but the relative contributions between them (the ratio of turbulent energy injection rates between different processes) were within a factor of ~ 2 in all discs at all redshifts. Their model predicts that stellar feedback is relatively more important for galaxies in lower halo mass and at lower redshift. The importance of gas transportation increases with

redshift. Accretion is the most important mechanism for galaxies at $z > 3$. Similarly, Kohandel et al. (2020) used zoom-in simulations of galaxies to show accretion and mergers are the major sources of gas velocity dispersion for galaxies at $6 < z < 8$ and stellar feedback is sub-dominant.

Our results support a multi-drivers scenario. Both MAGPI and SAMI galaxies have a strong correlation between gas velocity dispersion and Σ_{SFR} , agreeing with Ginzburg et al. (2022)’s model that the gas velocity dispersion is predominantly supported by stellar feedback at low redshift. They also showed that the importance of transportation and accretion slowly increases with redshift, which is consistent with our result in Figure 3.6 that the gas velocity dispersion is correlated with the non-rotational motion of gas (Δv) for MAGPI galaxies and the correlation coefficient between Δv and σ_{gas} ($r = 0.424$) is smaller than that of Σ_{SFR} and σ_{gas} ($r = 0.71$). Ginzburg et al. (2022) also showed that for galaxies at $z \sim 1$, the contribution of gas transportation is similar to stellar feedback. Stellar feedback is relatively more important for galaxies in haloes with a halo mass $\log M_{h,0} \lesssim 12.5$ at $z = 0$, while gas transportation is more important for galaxies in haloes with $\log M_{h,0} \gtrsim 12.5$. KROSS galaxies have ~ 1 dex higher stellar mass on average than MAGPI and SAMI galaxies, which implies that they tend to live in higher mass haloes. This fact may be why we see a weaker correlation ($r = 0.29$) between gas velocity dispersion and Σ_{SFR} for the KROSS galaxies and the scatter of gas velocity dispersion in the Σ_{SFR} bin is higher than SAMI and MAGPI. However, we note that the range of Σ_{SFR} of KROSS galaxies on a log-scale is ~ 1 dex narrower than SAMI and MAGPI, which may limit our ability to detect the correlation. It is worth exploring the gas velocity dispersion of low mass high redshift galaxies.

3.7 Conclusions

We studied the intrinsic H α kinematic properties of 110 galaxies at $z \sim 0.3$ from the MAGPI survey using a 3D Bayesian inference forward-modelling technique, BLOBBY3D, which can model gas kinematics and gas substructure simultaneously. It assumes a regular rotating disc and decomposes the ionised gas distribution into a number of blobs with a positive definite Gaussian basis function. The constructed 3D cubes are convolved by the PSF and LSF to account for the beam smearing and instrumental broadening. The average gas velocity dispersion at $z \sim 0.3$ is found to be $26.1 \pm 8.7 \text{ km s}^{-1}$, where $\pm 8.7 \text{ km s}^{-1}$ represents the standard deviation.

We investigate the correlation between the gas velocity dispersion of MAGPI galaxies and galaxy properties. We find that the gas velocity dispersion of MAGPI galaxies has the strongest correlation with Σ_{SFR} ($r = 0.65$). The gas velocity dispersion also has a strong correlation with SFR ($r = 0.46$) and with ΔSFR ($r = 0.50$). The partial correlation analysis between gas velocity dispersion, SFR, stellar mass and galaxy size shows that dispersion has a positive partial correlation with SFR and a negative partial correlation with size and an insignificant correlation with stellar mass. Using the residual between the regular rotating velocity map in the model and the velocity map of galaxies as an indicator of the non-rotational motion of the gas, we find that the galaxies with higher velocity residual tend to have higher gas

velocity dispersion.

We compare our results of MAGPI galaxies ($z \sim 0.3$) with SAMI ($z \sim 0.05$) and KROSS ($z \sim 1$) survey, for which the gas velocity dispersion is also measured using BLOBBY3D. The σ_{gas} –lookback time relation shows a decreasing trend of gas velocity dispersion over cosmic time. Both SAMI and MAGPI galaxies have a strong correlation between σ_{gas} and Σ_{SFR} . KROSS galaxies have a moderate correlation between σ_{gas} and Σ_{SFR} . We find that σ_{gas} is similar at fixed Σ_{SFR} for SAMI, MAGPI and KROSS galaxies, which suggests that the mechanisms related to Σ_{SFR} may be the dominant factor that drives gas turbulence from $z \sim 1$ to $z \sim 0$. The possible mechanisms that can explain this σ_{gas} – Σ_{SFR} correlation are stellar feedback and gravitational instability.

When compared with theoretical models, our results support a multi-drivers scenario. At $z \sim 0.05$ and $z \sim 0.3$, the star-formation feedback is the dominant driver of gas turbulence. The correlation between Δv and σ_{gas} suggests that the non-rotational motion of the gas, such as gas transportation through the disc or gas accretion, also contributes to the gas turbulence for MAGPI galaxies at $z \sim 0.3$. For KROSS galaxies at $z \sim 1$, the importance of gas transportation may be higher than at low redshift, resulting in the moderate correlation between dispersion and Σ_{SFR} and higher scatter of σ_{gas} in the Σ_{SFR} bin.

Acknowledgements

We wish to thank the ESO staff, and in particular the staff at Paranal Observatory, for carrying out the MAGPI observations. MAGPI targets were selected from GAMA. GAMA is a joint European-Australasian project based around a spectroscopic campaign using the Anglo-Australian Telescope. GAMA was funded by the STFC (UK), the ARC (Australia), the AAO, and the participating institutions. GAMA photometry is based on observations made with ESO Telescopes at the La Silla Paranal Observatory under programme ID 179.A-2004, ID 177.A-3016. The MAGPI team acknowledge support by the Australian Research Council Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D), through project number CE170100013. YM is supported by an Australian Government Research Training Program (RTP) Scholarship. CF is the recipient of an Australian Research Council Future Fellowship (project number FT210100168) funded by the Australian Government. CL, JTM and CF are the recipients of ARC Discovery Project DP210101945. KG is supported by the Australian Research Council through the Discovery Early Career Researcher Award (DECRA) Fellowship (project number DE220100766) funded by the Australian Government. Y.P. acknowledges the support from the National Science Foundation of China (NSFC) grant Nos. 12125301, 12192220, 12192222, and the science research grants from the China Manned Space Project with No. CMS-CSST-2021-A07. GS and KH acknowledge funding from the Australian Research Council (ARC) Discovery Project DP210101945. SMS acknowledges funding from the Australian Research Council (DE220100003). LMV acknowledges support by the German Academic Scholarship Foundation (Studienstiftung des deutschen Volkes) and the Marianne-Plehn-Program of the Elite Network

of Bavaria. M.V. was supported by philanthropic funding from The Johnston Fellowship and from other donor(s) who are families affected by mental illness who wish to remain anonymous.

Data Availability

The MUSE data used in this work are available on the ESO public archive. The reduced MAGPI datacubes and the emission line data products will be public in the MAGPI team data release (Mendel et al. in prep and Battisti et al. in prep).

Chapter 4

The MAGPI survey: forward modelled metallicity gradients in galaxies at $z \sim 0.3$

This chapter is based on work that has not yet been submitted for publication. I was responsible for data analysis, interpretation and paper writing. The data analysis includes generating a BPT diagram for each galaxy and sample selection, generating the inputs for BLOBBY3D, testing different constraints on kinematics in model options of BLOBBY3D, applying BLOBBY3D to the data from the MAGPI survey, dust correction, calculating the N2O2 and N2H α metallicity and metallicity gradients, and analysing the correlation between different parameters. My supervisors, Scott M. Croom, and Emily Wisnioski, provided guidance on methodology, reviewed drafts, and provided feedback.

4.1 Abstract

We measure the seeing-deconvolved metallicity gradients of 44 star-forming galaxies at $z \sim 0.3$ from the MAGPI survey and investigate their relationship with galaxy properties to understand the mechanisms that influence the distribution of metals and shape the evolution of the galaxies. We use a Bayesian modelling technique which takes the seeing into account and can model the substructures of the flux distribution. The median of the metallicity gradient ($\nabla[\text{O}/\text{H}]$) is $-0.028^{+0.031}_{-0.044}$ dex/kpc. Among these galaxies, 66% have negative metallicity gradients (2σ significance), 7% have positive gradients and 27% have flat gradients. The $\nabla[\text{O}/\text{H}]-M_*$ relation of the MAGPI galaxies generally agrees with theoretical predictions and the metallicity gradients vary significantly for the galaxies with $M_* < 10^{10} M_\odot$. We find that galaxies with stronger gas turbulence and higher star formation rate density tend to have flatter or even positive metallicity gradients, which indicates that mechanisms like star formation feedback, gas accretion and transportation enhance gas-mixing, which flatten or invert the metallicity gradient.

4.2 Introduction

Metals, as the product of stellar nucleosynthesis, provide insight into star formation history and galaxy evolution. The metallicity of galaxies is affected by multiple mechanisms simultaneously. Gas accretion from the intergalactic medium (IGM) provides fuel for star formation and dilutes the metallicity. Gas outflows driven by stellar feedback or active galactic nucleus (AGN) feedback expel metals from galaxies and redistribute the metallicity across galaxies. The enhancement of metallicity is aligned with star formation and the growth of the stellar mass of galaxies.

The metallicity distribution provides insight into star formation and feedback. The metallicity gradient of low-redshift galaxies is on average negative (Sánchez et al., 2012; Belfiore et al., 2017), in agreement with galactic discs' inside-out formation scenario. In the inside-out formation scenario, the cooling time of the inner region of galaxies is shorter, the gas condenses into cold clumps and forms stars quickly, while the gas of the outer region has a longer cooling time (Larson, 1976; K  pner, 1999; Portinari & Chiosi, 1999; S  nchez et al., 2014; Pezzulli & Fraternali, 2016).

The metallicity gradient is also influenced by gas accretion. The accreted gas triggers gas radial inflows when the specific angular momentum is not equal to that of the accreted point (Mayor & Vigroux, 1981), resulting in metallicity dilution and redistribution. Therefore, the measurement of the metallicity gradient provides an indirect tracer of gas radial motion (Pezzulli & Fraternali, 2016).

While we have good measurements of the metallicity gradient of galaxies in the local Universe, our understanding of the metallicity gradient in higher redshift galaxies is limited. Simulations and analytical models are used to predict the evolution of the metallicity gradient (Chiappini et al., 2001; Moll   & D  az, 2005; Fu et al., 2009; Kobayashi & Nakasato, 2011; Pilkington et al., 2012; Gibson et al., 2013). However, the results in these studies are inconsistent due to their different treatments of

star formation and feedback (Pilkington et al., 2012; Gibson et al., 2013). In the ‘enhanced’ feedback models, star formation feedback injects a lot of energy into the interstellar medium (ISM) that redistributes metal-enriched gas over large scales and flattens the metallicity gradient. The strong feedback can also move the gas and metals into the halo. On the contrary, the ‘conventional’ feedback models result in a steep metallicity gradient (Gibson et al., 2013).

Observations of higher redshift galaxies are necessary to provide constraints to metallicity gradient evolution (Queyrel et al., 2012). However, there is no clear picture of the evolution of metallicity gradients. Carton et al. (2018) showed that the scatter of the metallicity gradient in higher redshift galaxies is larger than local galaxies. They analysed 84 star-forming galaxies at $0.08 < z < 0.84$ and found the median of the metallicity gradient is $-0.039^{+0.007}_{-0.009}$ dex/kpc and 8% of galaxies have significantly (2σ) positive gradients, 38% have significantly negative gradients and 31% have gradients consistent with zero. Wuyts et al. (2016) found the metallicity gradients are on average flat over their sample of 419 star-forming galaxies at $z = 0.6 - 2.7$, with 15% of galaxies having significantly (3σ) negative or positive gradients.

The variation of metallicity gradients at high redshift suggests the impact of mechanisms that are different to local galaxies. The positive gradient, which is rare at low redshift, may result from strong gas accretion that dilutes the metallicity at the galaxy centre (Queyrel et al., 2012; Stott et al., 2014). The flatter gradient at high redshift may also result from metal-poor gas inflows or strong feedback that redistributes metallicity. Studies on gas kinematics showed that the gas turbulence in higher redshift galaxies is higher than at lower redshift, which might result from stronger star formation feedback and gas accretion (Wisnioski et al., 2015; Übler et al., 2019; Mai et al., 2024). Therefore, the metallicity distribution is likely connected with the gas kinematics.

The measurement of the metallicity gradient is limited by spatial resolution (Yuan et al., 2013; Acharyya et al., 2020). The systematic flattening of the metallicity gradient is caused by beam smearing (also called seeing), which results from Earth’s atmospheric turbulence and blurs the light and flattens the flux distribution of the galaxies. The systematic flattening is stronger for the galaxies at higher redshift and marginally resolved galaxies (Yuan et al., 2013; Mast et al., 2014; Belfiore et al., 2017).

The measurement of metallicity gradients is also influenced by the clumpiness of gas and the non-uniform flux distribution of different emission lines (Belfiore et al., 2017). Models like GALPAK3D (Bouché et al., 2015) that assumes a smooth radial flux distribution cannot fully capture the spatial variance of the metallicity distribution for galaxies with complex substructures.

Therefore, to obtain a seeing-deconvolved metallicity distribution which captures the substructures of flux, we need a modelling technique with more flexibility in the flux distribution. The method we use is a code called BLOBBY3D (Varidel et al., 2019), which employs a forward modelling technique that accounts for beam smearing and models the gas kinematics and substructures simultaneously. Instead of assuming a pre-determined flux profile, BLOBBY3D decomposes the gas distribution into a

number of Gaussian ‘blobs’. The number of blobs is flexible and the shape and flux of each blob are also flexible and depend on the complexity of the observed gas substructure.

In this study, we aim to measure the gas-phase metallicity gradients of star-forming galaxies and understand the mechanisms related to metallicity distribution at $z \sim 0.3$, an epoch in which the metallicity gradient is relatively unexplored. In Section 4.3, we describe the MAGPI survey and our sample selection. In Section 4.4, we describe the method we use to model the flux distribution and calculate the metallicity and metallicity gradients. In Section 4.5, we demonstrate the results for the metallicity gradients for galaxies in the MAGPI survey and the correlation between metallicity gradients and other galaxy properties. In Section 4.6, we discuss the evolution of metallicity gradients and the mechanisms that relate to metallicity distribution. In Section 4.7, we summarise our results.

Throughout this paper, we adopt a concordance cosmology ($\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$, $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$).

4.3 Data

The Middle Ages Galaxy Properties with Integral Field Spectroscopy (MAGPI) survey (Foster et al., 2021) focuses on galaxies at a lookback time of 3 – 4 Gyr ($z \sim 0.3$) when the galaxy properties are predicted to evolve significantly. The survey uses the Multi Unit Spectroscopic Explorer (MUSE; Bacon et al., 2010) with Ground Layer Adaptive Optics (GLAO), mounted at the European Southern Observatory Very Large Telescope (VLT). MAGPI uses the wide-field mode of MUSE, which has a $1 \times 1 \text{ arcmin}^2$ field-of-view (FOV) sampled at $0.2 \times 0.2 \text{ arcsec}^2$. The typical full width at half maximum (FWHM) of the MUSE point-spread function (PSF) is $\sim 0.6 \text{ arcsec}$. The MAGPI survey covers a wavelength range between 4700 and 9351 Å with a spectral resolution of $R = 2728$ at 7025 Å.

The MAGPI survey targets 60 massive central galaxies (primary galaxies) and their neighbouring galaxies (secondary galaxies) within the MUSE FOV. The selection of MAGPI primary galaxies requires that galaxies uniformly sample a range of environments (isolated, groups and clusters), covering a halo mass range $11.35 \leq \log(M_{\text{halo}}/M_\odot) \leq 15.35$. 56 primary galaxies are selected from the Galaxy And Mass Assembly survey (GAMA; Driver et al., 2011) G12, G15 and G23 fields. The remaining 4 primary galaxies are drawn from MUSE archival observations of Abell 370 and Abell 2744. At the time of writing, the survey has completed the observation of 53 fields, which have been fully reduced with relevant data products. There are 332 star-forming galaxies that have $\text{H}\alpha$ -based star formation rate (SFR) measurement at redshift $0.26 < z < 0.42$.

We utilize the Galaxy Integral Field Unit (IFU) Spectroscopy Tool (GIST; Bittner et al., 2019) to fit the observed (seeing-convolved) emission lines and continuum spectra in MAGPI galaxies (Battisti et al. in prep). GIST is a Python wrapper that implements the Penalized PiXel-Fitting (pPXF; Cappellari & Emsellem, 2004; Cappellari, 2017) method on IFS data. The stellar continuum fits are conducted

on a spaxel level. Initial estimates of the stellar continuum are made with the emission lines masked. These estimates are then used to fit the stellar continuum and emission lines using templates from flexible stellar population synthesis (FSPS; Conroy et al., 2009, 2010; Conroy & Gunn, 2010) and the multiplicative Legendre polynomial is set to 12 to account for uncertainties in flux calibration across the spectral range.

The effective radius (R_e) of the galaxies is estimated from the i -band image of MAGPI MUSE data using the tool PROFIT (Robotham et al., 2017). PROFIT accounts for the PSF and models the 2-dimensional surface brightness distribution assuming a single Sérsic profile.

The stellar masses are determined using PROSPECT (Robotham et al., 2020), which is an energy balance spectral energy distribution (SED) fitting code. Photometry from GAMA imaging over the $ugriZJHK$ bands is employed for PROSPECT SED fitting, assuming a Chabrier (2003) stellar initial mass function (IMF). The stellar population templates from Bruzual & Charlot (2003) are utilized to create an unattenuated stellar SED, and the dust attenuation law by Charlot & Fall (2000) is applied to correct for dust attenuation, following the methodology outlined in Bellstedt et al. (2020). The stellar mass surface density (Σ_{M_*}) is calculated as $\Sigma_{M_*} = M_*/(2\pi R_e^2)$.

The ionised gas velocity dispersion (σ_{gas}), which traces the strength of gas turbulence, is measured using BLOBBY3D in Mai et al. (2024). The beam smearing due to the atmosphere broadens the gas velocity dispersion we observed, especially for the galaxies with a steep velocity gradient. BLOBBY3D can measure the intrinsic σ_{gas} by forward-modelling the gas kinematics and spatial gas distribution simultaneously accounting for the beam smearing from the PSF.

We use the dust-corrected $\text{H}\alpha$ flux maps to derive SFR using the calibration of Kennicutt (1998). We correct the dust extinction using the Balmer decrement on a spaxel by spaxel basis (see details in Mun et al., 2024). The extinction curve from Fitzpatrick et al. (2019) is adopted with $R_V = 3.1$. The SFR surface density (Σ_{SFR}) is calculated as $\Sigma_{\text{SFR}} = \text{SFR}/(2\pi R_{e,\text{H}\alpha}^2)$, in which SFR is the total integrated SFR, $R_{e,\text{H}\alpha}$ is the half-light radius of $\text{H}\alpha$ map, which is used to better trace the star formation region. The star formation main sequence (SFMS) is defined as the best linear fit to the MAGPI galaxies located at $0.25 \leq z \leq 0.424$ (Mun et al., 2024).

4.3.1 Sample selection

To select galaxies for which we can measure robust metallicities, we select galaxies that have more than 50 spaxels with a $\text{S/N} > 5$ for $\text{H}\alpha$, $\text{H}\beta$ and $[\text{O II}]\lambda 3727, \lambda 3729$. We select galaxies in the redshift range $0.26 < z < 0.42$, which ensures the emission lines we used as diagnostic of the gas-metallicity are within the wavelength range that the MAGPI survey covers. These emission lines include $[\text{O II}]\lambda 3727, \lambda 3729$, $\text{H}\beta$, $\text{H}\alpha$ and $[\text{N II}]\lambda 6584$. We remove galaxies with evidence of an active galactic nucleus (AGN) activity to avoid AGN contamination in our metallicity measurement. We

use the Baldwin, Phillips & Terlevich (BPT; [Baldwin et al., 1981](#); [Kewley et al., 2001](#); [Kauffmann et al., 2003](#)) ionisation diagnostics to identify star-forming (SF), AGN and composite spaxels in galaxies and remove galaxies with AGN and/or composite centre. There are 82 galaxies in our preliminary sample after applying the above cuts.

4.4 Methods

We use BLOBBY3D¹ ([Varidel et al., 2019](#)) to model the spatial flux distribution of the emission lines we used for metallicity diagnostics. BLOBBY3D is designed to perform Bayesian inference on gas kinematics from emission line observations of galaxies using Integral Field Spectroscopy. It can model the gas spatial substructure and kinematics simultaneously, accounting for the PSF and line spread function (LSF). BLOBBY3D decomposes the gas distribution into a number of Gaussian ‘blobs’, without having a pre-determined flux distribution profile of the galaxy. This method can model complex gas substructures such as rings, spiral arms and individual clumps, which are difficult to model by methods such as GALPAK3D ([Bouché et al., 2015](#)) that implement a parametric radial flux distribution.

BLOBBY3D uses a diffusive nested sampling algorithm, DNEST4 ([Brewer et al., 2011](#); [Brewer & Foreman-Mackey, 2018](#)), which is an effective variant of nested sampling ([Skilling, 2004](#)). DNEST4 uses Markov Chain Monte Carlo (MCMC) to explore the complex posterior distribution and compute the normalization constant. The key advantage of DNEST4 over other sampling algorithms is its effectiveness in handling high-dimensional parameter spaces and multimodal distributions, which is a useful feature for modelling complex gas substructures.

An inference problem with a varying number of components is normally difficult to explore. DNEST4 has an in-built reversible jump object that allows varying the number of blobs/components. BLOBBY3D uses the reversible jump to add or remove blobs from the model, which enables the number of blobs to be a flexible parameter depending on the complexity of the galaxy flux distribution. The flux, position and shape (width, axis ratio and orientation angle) of each blob are also flexible parameters. See Table 1 in [Varidel et al. \(2019\)](#) for more details about all hyperparameters and parameters used in the model.

4.4.1 Metallicity diagnostics

We use the $[\text{N II}]/[\text{O II}]$ ratio (N2O2), based on $[\text{N II}]\lambda 6584$ and $[\text{O II}]\lambda 3727, \lambda 3729$ lines, as our primary gas-phase metallicity diagnostic. The N2O2 is the most reliable metallicity diagnostic in the optical spectrum as it is less sensitive to ionisation parameter and insensitive to the ISM pressure (see the review in [Kewley et al., 2019](#)).

We use the metallicity diagnostic calibrations outlined in [Kewley et al. \(2019\)](#). The gas-phase metallicity is calculated as

¹<https://github.com/SpaceOdyssey/Blobby3D>

$$\begin{aligned}
z = & 9.4772 + 1.1797 \cdot x + 0.5085 \cdot y + 0.6879 \cdot x \cdot y \\
& + 0.2807 \cdot x^2 + 0.1612 \cdot y^2 + 0.1187 \cdot x \cdot y^2 + 0.1200 \cdot y \cdot x^2 \\
& + 0.2293 \cdot x^3 + 0.0164 \cdot y^3,
\end{aligned} \tag{4.1}$$

where z is the gas-phase metallicity, $\log(\text{O}/\text{H}) + 12$. x is the metallicity diagnostic ratio $\log(R)$, where $R = F_{\text{int}}([\text{N II}]\lambda 6584)/(F_{\text{int}}([\text{O II}]\lambda 3727) + F_{\text{int}}([\text{O II}]\lambda 3729))$ for the N2O2 diagnostic. F_{int} is the intrinsic flux after extinction correction of a given emission line (see Section 4.4.3 for more details). y is the ionisation parameter $\log(U)$. Here we adopt $\log(U) = -3.17$.

We also use the $[\text{N II}]\lambda 6584/\text{H}\alpha$ ratio (N2H α) to measure the metallicity as a comparison. The advantage of this diagnostic is the separation between $[\text{N II}]$ and $\text{H}\alpha$ emission lines is small, thus there is no need to make a dust correction for the line ratio calculation, which may introduce more uncertainty, especially when the $\text{H}\beta$ line is weak. The gas-phase metallicity using N2H α is calculated as

$$\begin{aligned}
z = & 10.526 + 1.9958 \cdot x - 0.6741 \cdot y + 0.2892 \cdot x \cdot y \\
& + 0.5712 \cdot x^2 - 0.6597 \cdot y^2 + 0.0101 \cdot x \cdot y^2 + 0.0800 \cdot y \cdot x^2 \\
& + 0.0782 \cdot x^3 - 0.0982 \cdot y^3,
\end{aligned} \tag{4.2}$$

where $R = F_{\text{int}}([\text{N II}]\lambda 6584)/(F_{\text{int}}(\text{H}\alpha))$. Note that this diagnostic is more sensitive to ionisation parameter and ISM pressure.

4.4.2 Modelling the flux distribution

BLOBBY3D requires a single, continuous wavelength range for input spectra. It does not support the inclusion of multiple disjoint wavelength intervals, meaning that any analysis requiring non-contiguous spectral regions must be performed separately. BLOBBY3D is computationally expensive, making it impractical to fit a large wavelength range that simultaneously includes $\text{H}\alpha$, $[\text{N II}]$, and $[\text{O II}]$. To optimize computational efficiency, we first fit the spectrum covering $\text{H}\alpha$ and $[\text{N II}]$, as these lines are close in wavelength. Although $[\text{N II}]$ is relatively weak, $\text{H}\alpha$ provides a strong constraint on the kinematics. We then fit a separate spectral range that includes $[\text{O II}]$.

To model the flux of $\text{H}\alpha$ and $[\text{N II}]$, we choose the rest-frame wavelength range [6535,6595] Å of the cube, which covers $\text{H}\alpha$ and $[\text{N II}]\lambda 6548, \lambda 6584$. We subtract the stellar continuum from the spectrum using the output from GIST, as BLOBBY3D requires the input datacube to be continuum subtracted. The blobs for $\text{H}\alpha$ and $[\text{N II}]$ are the same. BLOBBY3D performs inferences for the $\text{H}\alpha$ flux and the $[\text{N II}]/\text{H}\alpha$ flux ratio for each blob (spatial Gaussian flux profile). The flux ratio between two $[\text{N II}]$ lines is assumed to be $F_{6584}/F_{6548} = 3$. The gas kinematics of $\text{H}\alpha$ and $[\text{N II}]$ are assumed to be consistent.

We then model the flux of $[\text{O II}]\lambda 3727, \lambda 3729$ using the data in the rest-frame wavelength range [3718,3738] Å. The flux ratio between $[\text{O II}]\lambda 3727$ and $[\text{O II}]\lambda 3729$ is set

to be flexible for each blob. We constrain the kinematic model of [O II] to have the same position angle (PA) as H α using the average PA we obtain from the inference of H α . This PA constraint is under the assumption that all gas components rotate in the same direction. The flux distribution (the number, position and shape of blobs) in the BLOBBY3D model of [O II] is similar to, but does not necessarily the same as the H α and [N II] flux distribution, as it depends on the observed [O II] flux.

BLOBBY3D requires the full width at half maximum (FWHM) of PSF and LSF as the inputs. We use the PSF of the z -band when we model the H α and [N II] lines, as the z -band is close to the wavelength of H α at $z \sim 0.3$. We use the PSF of the g -band when we model the [O II] line. We adopt the FWHM of LSF at $6563 \cdot (1 + z)$ Å when we model the H α and [N II] lines, where z is the redshift of the galaxy. We adopt the FWHM of LSF at $3728 \cdot (1 + z)$ Å when we model the [O II] line.

We also test other different levels of constraints on the kinematics for [O II] modelling, including (1) no constraints on the kinematics; (2) constraining both the PA and the velocity profile of [O II] to be the same as H α ; (3) constraining the PA, velocity profile and velocity dispersion to be the same as H α . The results show that the [O II] flux distribution does not vary significantly between different constraints and they do not change the results on the metallicity gradient. Previous studies suggested that the velocity and the velocity dispersion measured from different emission lines are different (e.g. [Levy et al., 2018](#); [Law et al., 2022](#); [Übler et al., 2024](#)). We therefore choose the simplest constraint, constraining the PA only, to improve our modelling and allow the flexibility of the velocity profile and velocity dispersion.

Different kinematics for various emission lines may indicate that they are not emitted from the same regions, which may influence the accuracy of the metallicity measurement. Therefore, measuring the metallicity using multiple diagnostics is crucial for assessing systematic differences and ensuring consistency across different methods.

4.4.3 Extinction correction

The flux of emission lines is attenuated by the dust in the ISM in the Milky Way and the source galaxy. The strength of dust attenuation is wavelength dependent, which causes a biased flux ratio if two emission lines are widely separated. To get the intrinsic flux of emission lines, we perform two steps of dust attenuation correction to correct the extinction from the Milky Way and the source galaxy using the DUST_EXTINCTION Python package ([Gordon, 2024](#)).

Firstly, we correct the foreground extinction from the dust in the Milky Way using

$$F_{\text{MWcorr}}(\lambda_{\text{red}}) = F_{\text{obs}}(\lambda_{\text{red}}) \cdot 10^{0.4 \cdot k(\lambda_{\text{red}}) \cdot E(B-V)_{\text{MW}}}, \quad (4.3)$$

where F_{MWcorr} is the flux of a given emission line after Milky Way dust correction, λ_{red} is the redshifted wavelength of the emission line, F_{obs} is the observed flux of the emission line, k is the extinction curve from [Fitzpatrick et al. \(2019\)](#) with $R_V = 3.1$,

and $E(B - V)_{\text{MW}}$ is the reddening value due to the dust in Milky Way (Schlafly & Finkbeiner, 2011).

Then we correct the intrinsic extinction due to the dust from the source galaxy using

$$F_{\text{int}}(\lambda_{\text{res}}) = F_{\text{MWcorr}}(\lambda_{\text{res}}) \cdot 10^{0.4 \cdot k(\lambda_{\text{res}}) \cdot E(B-V)_{\text{int}}} , \quad (4.4)$$

where F_{int} is the intrinsic flux of a given emission line, λ_{res} is the rest-frame wavelength of the emission line, and $E(B - V)_{\text{int}}$ is the intrinsic reddening value due to the dust in the source galaxy. We calculate $E(B - V)_{\text{int}}$ for each spaxel, as follows

$$E(B - V)_{\text{int}} = \log_{10} \left(\frac{(\text{H}\alpha/\text{H}\beta)_{\text{MWcorr}}}{(\text{H}\alpha/\text{H}\beta)_{\text{int}}} \right) / (0.4 (k(\text{H}\beta) - k(\text{H}\alpha))) , \quad (4.5)$$

where $(\text{H}\alpha/\text{H}\beta)_{\text{MWcorr}}$ is the ratio of observed $\text{H}\alpha$ and $\text{H}\beta$ flux (Balmer decrement) after foreground extinction correction, $(\text{H}\alpha/\text{H}\beta)_{\text{int}}$ is the intrinsic ratio of $\text{H}\alpha$ and $\text{H}\beta$ and we adopt $(\text{H}\alpha/\text{H}\beta)_{\text{int}} = 2.86$ for case B recombination (Osterbrock, 1989). $k(\text{H}\beta)$ and $k(\text{H}\alpha)$ are the k value from the extinction curve from Fitzpatrick et al. (2019) for $\text{H}\alpha$ and $\text{H}\beta$, respectively.

We calculate the Balmer decrement using the $\text{H}\alpha$ and $\text{H}\beta$ flux measurement from the GIST output. We note that it would be better to implement the Balmer decrement into the prior in BLOBBY3D to take the seeing-deconvolved structure of dust into account. However, such an implementation involves complex modifications of BLOBBY3D and a detailed investigation of dust attenuation effects, which is beyond the scope of this paper.

4.4.4 Metallicity gradient measurement

When measuring the radial metallicity gradient, we first correct the inclination of the galaxy using its position angle and ellipticity measured from the white-light image of MAGPI MUSE data, which are estimated using the tool PROFOUND. Then we sum the flux from the BLOBBY3D model fit in each 1 kpc annular bin and calculate the metallicity for each bin. We call this the ‘sum flux’ method hereafter. We fit the metallicity gradient and central metallicity using the ordinary least squares linear regression method. We normalized the gradient by the R_e of the galaxy to remove the size dependence of metallicity gradients (Sánchez et al., 2014; Ho et al., 2015; Sánchez-Menguiano et al., 2016; Poetrodjojo et al., 2021).

To test the robustness of the above method, we also measure the metallicity gradient in a different way. In this method, we measure the metallicity of each spaxel and then calculate the average metallicity in each 1 kpc bin. We call this the ‘spaxel average’ method hereafter. We only include the spaxels with S/N of $[\text{N II}]$, $[\text{O II}]$, $\text{H}\alpha$ and $\text{H}\beta$ emission lines greater than 3 to ensure a reliable metallicity measurement on each spaxel. We note that this method cannot estimate metallicity to as great a radius as

the sum flux method, due to the per-spaxel S/N requirements. When we calculate the average metallicity in each 1 kpc bin, three different weight methods are used: (1) unweighted: the metallicity of each spaxel is weighted equally; (2) H α weighted: the metallicity is weighted by the H α flux at that spaxel; (3) inverse variance weighted: the metallicity is weighted by the inverse variance of the metallicity at that spaxel. The H α weighted method can lower the weights on the spaxels that have low flux and therefore larger uncertainty in the metallicity measurement. However, it can potentially bias the average metallicity to a higher value. Similarly, the inverse variance weighted method can increase the weights of the spaxels with more accurate metallicity measurement.

All galaxies have metallicity gradients measured out to at least $1 R_e$ using the sum flux method. However, in the spaxel average method, some galaxies have metallicity gradients measured over a smaller extent due to per-spaxel S/N requirements. Therefore, we adopt the sum flux method as our primary approach for metallicity gradient measurement.

4.5 Results

Figure 4.1 is an example of the metallicity and metallicity gradient measurement for a galaxy (MAGPIID=1203195161). We show the metallicity gradient measured using the sum flux method (middle panels) and the gradient measured using the spaxel average method (right panels). The right panels show the metallicity gradients measured using three different weighted methods. The uncertainty on the metallicity gradient was determined from the linear fitting process, performed using the `curve_fit` function from the Python library `SciPy` (Virtanen et al., 2020). This fitting routine accounts for the uncertainties in the average metallicity of individual bins, which were propagated through the fitting procedure to yield the uncertainty on the gradient.

We also find that the metallicity gradient fitting the unweighted average metallicity is slightly steeper than other weighted methods in some galaxies, possibly due to those low flux and high uncertainty spaxels at large radius normally having low metallicity measurements that lower the unweighted average metallicity.

To ensure the robustness of the metallicity gradient measurement, we only keep the galaxies with at least 6 data points for the sum flux method and at least 3 data points for the spaxel average method. We show the radial metallicity gradients measured using the N2O2 diagnostic and the sum flux method for all galaxies that match this criterion in Figure 4.2. There is one galaxy (MAGPIID=1533258059) that has a metallicity lower than the valid range of the N2O2 diagnostic. We remove this galaxy from further analysis. The final sample includes 44 galaxies.

Table 4.1 and Table 4.2 show the metallicity gradient and central metallicity for all galaxies in our sample. We list the results for N2O2 and N2H α diagnostics and the sum flux and spaxel average method (inverse variance weighted). For the metallicity gradients measured using different weighted methods, 38 out of 44 galaxies are consistent within 1σ ; 43 out of 44 galaxies are consistent within 2σ . We compare

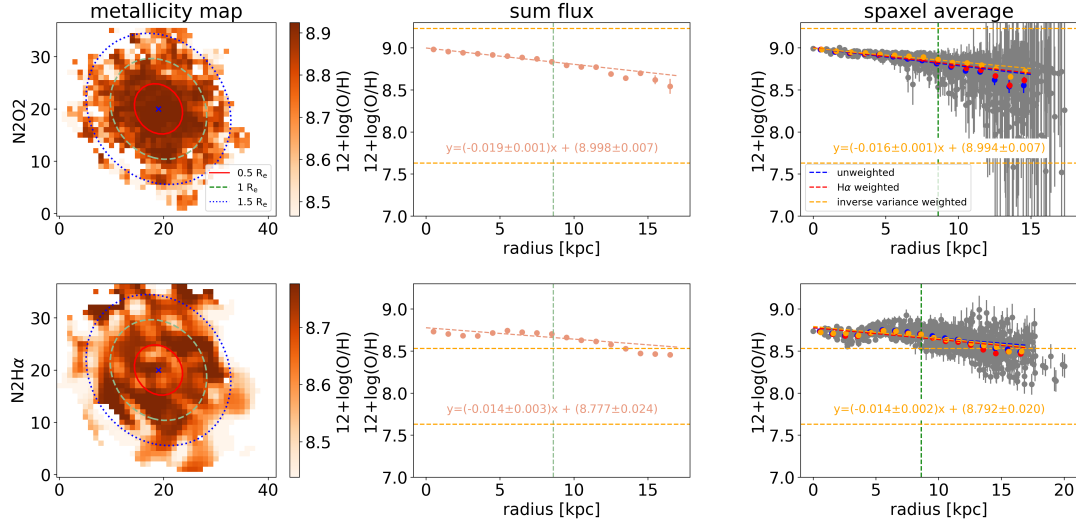


Figure 4.1: The metallicity and metallicity gradient measurement for an example galaxy (MAGPIID=1203195161). The first row shows the metallicity measured using the N2O2 diagnostic and the second row uses the N2H α diagnostic. The left panels show the metallicity map. The middle panels show the metallicity as a function of radius, where the metallicity in each 1 kpc bin is calculated using the sum flux method. The right panels demonstrate the metallicity of each spaxel as a function of radius (grey) and the average metallicity in each 1 kpc bin (spaxel average method) for three different weight methods (unweighted in blue, H α weighted in red and inverse variance weighted in yellow). We overplot the best linear fits for each method. The orange horizontal lines in the middle and right panels denote the valid metallicity range for each diagnostic (Kewley et al., 2019). The green vertical lines denote $1 R_e$ for this galaxy. We show the value of the metallicity gradient and central metallicity for each plot. We only show the value of the inverse variance weighted method for the spaxel average plots.

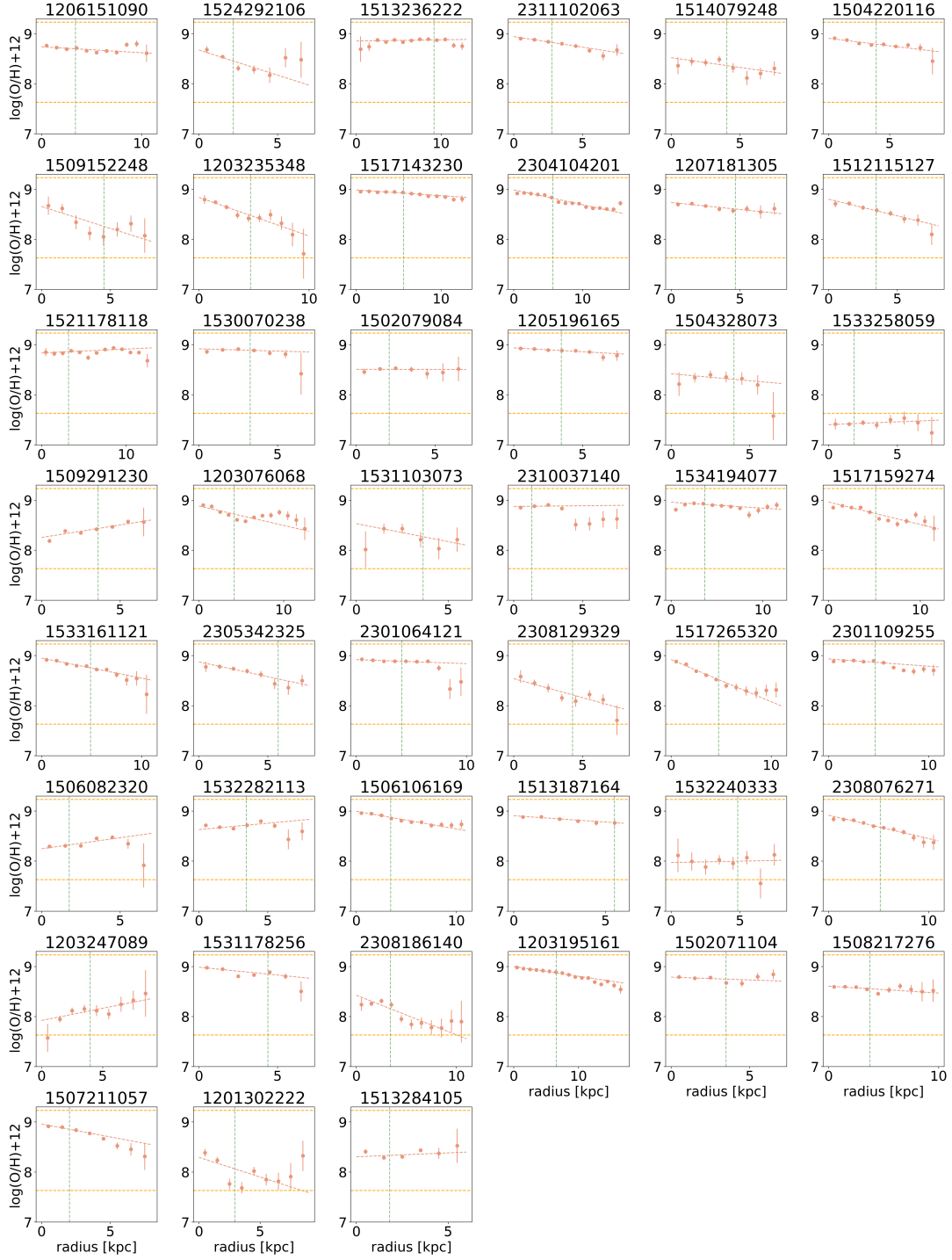


Figure 4.2: The radial metallicity distribution and metallicity gradient measured using the N2O2 diagnostic and the sum flux method for all galaxies in our sample. The orange horizontal lines denote the valid metallicity range for the N2O2 diagnostic (Kewley et al., 2019). The green vertical lines denote $1 R_e$ for each galaxy.

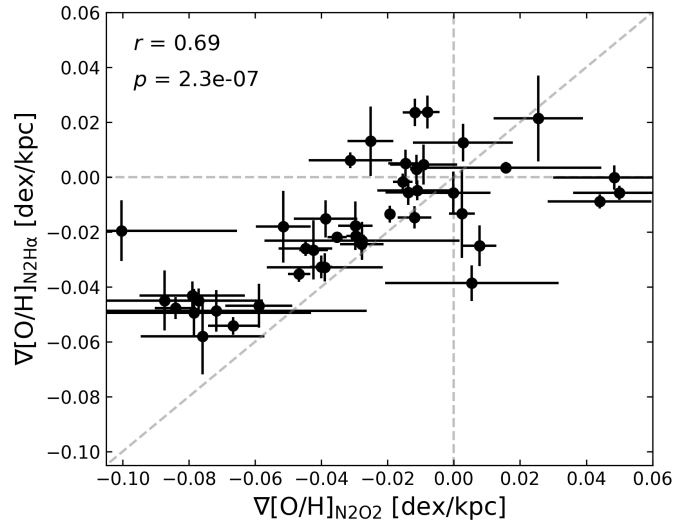


Figure 4.3: The comparison of the metallicity gradients measured using N2O2 and N2H α diagnostics (sum flux method). The correlation coefficient (r) and p -value are shown in top left.

the N2O2 and N2H α metallicity gradients in Figure 4.3. The metallicity gradients measured using these two diagnostics are strongly correlated ($r = 0.69$, $p = 2.3 \cdot 10^{-7}$). We use the metallicity measured using the N2O2 diagnostic and sum flux method for the following analysis.

The median of the metallicity gradient is $-0.028^{+0.031}_{-0.044}$ dex/kpc. Among 44 galaxies in the final sample, there are 29 galaxies (66%) that have significantly (2σ) negative metallicity gradients, 3 galaxies (7%) that have significantly positive metallicity gradients and 12 galaxies (27%) that have flat gradients (i.e. are less than 2σ from zero). The majority of the galaxies in our sample (24 galaxies, 55%) have a metallicity gradient between -0.05 dex/kpc and 0 dex/kpc. The galaxies with steeper gradient (< -0.05 dex/kpc) normally have larger uncertainty in the gradient measurement and lower stellar mass (see Figure 4.4 below).

To understand the mechanisms that influence the metallicity gradients, we investigate the relation between the metallicity gradient and several galaxy properties, including stellar mass (M_*), R_e , a proxy for the gravitational potential (M_*/R_e), Σ_{M_*} , SFR, Σ_{SFR} , σ_{gas} and the logarithmic offset in SFR from the SFMS of MAGPI galaxies (ΔSFR).

We show the relationship between the metallicity gradient ($\nabla[\text{O}/\text{H}]$) and galaxy properties in Figure 4.4. We use the bootstrap method to resample the data 1000 times and calculate the Pearson correlation coefficient, r , for each resample. The size of the resample is the same as the original sample. We show the median of r and 16th and 84th of r on each panel. We show the metallicity gradient in the unit of dex/kpc at the top two rows, and in the unit of dex/ R_e at the bottom two

MAGPIID	N2O2				N2H α			
	sum flux		spaxel average		sum flux		spaxel average	
	gradient	central metal	gradient	central metal	gradient	central metal	gradient	central metal
1206151090	-0.012 $\pm$ 0.005	8.738 $\pm$ 0.016	-0.008 $\pm$ 0.002	8.760 $\pm$ 0.004	-0.015 $\pm$ 0.004	8.581 $\pm$ 0.011	-0.021 $\pm$ 0.004	8.582 $\pm$ 0.012
1524292106	-0.100 $\pm$ 0.035	8.674 $\pm$ 0.077	-0.179 $\pm$ 0.035	8.804 $\pm$ 0.059	-0.020 $\pm$ 0.011	8.438 $\pm$ 0.023	-0.011 $\pm$ 0.007	8.410 $\pm$ 0.012
1513236222	0.002 $\pm$ 0.004	8.853 $\pm$ 0.030	0.005 $\pm$ 0.002	8.889 $\pm$ 0.019	-0.013 $\pm$ 0.016	8.840 $\pm$ 0.116	-0.024 $\pm$ 0.017	8.891 $\pm$ 0.116
2311102063	-0.042 $\pm$ 0.004	8.942 $\pm$ 0.011	-0.026 $\pm$ 0.005	8.915 $\pm$ 0.013	-0.027 $\pm$ 0.011	8.738 $\pm$ 0.032	-0.014 $\pm$ 0.013	8.709 $\pm$ 0.036
1514079248	-0.039 $\pm$ 0.017	8.521 $\pm$ 0.070	0.068 $\pm$ 0.007	8.330 $\pm$ 0.015	-0.033 $\pm$ 0.005	8.440 $\pm$ 0.024	-0.012 $\pm$ 0.003	8.375 $\pm$ 0.006
1504220116	-0.030 $\pm$ 0.005	8.907 $\pm$ 0.017	-0.018 $\pm$ 0.005	8.904 $\pm$ 0.017	-0.018 $\pm$ 0.009	8.681 $\pm$ 0.035	-0.024 $\pm$ 0.010	8.677 $\pm$ 0.037
1509152248	-0.087 $\pm$ 0.030	8.653 $\pm$ 0.112	-0.056 $\pm$ 0.041	8.741 $\pm$ 0.073	-0.045 $\pm$ 0.011	8.422 $\pm$ 0.048	0.019 $\pm$ 0.005	8.391 $\pm$ 0.010
1203235348	-0.077 $\pm$ 0.010	8.835 $\pm$ 0.035	-0.085 $\pm$ 0.042	8.924 $\pm$ 0.085	-0.045 $\pm$ 0.004	8.560 $\pm$ 0.019	-0.056 $\pm$ 0.003	8.596 $\pm$ 0.006
1517143230	-0.011 $\pm$ 0.002	8.984 $\pm$ 0.010	-0.007 $\pm$ 0.001	8.975 $\pm$ 0.008	0.003 $\pm$ 0.005	8.666 $\pm$ 0.034	0.004 $\pm$ 0.004	8.660 $\pm$ 0.029
2304104201	-0.030 $\pm$ 0.003	8.986 $\pm$ 0.014	-0.028 $\pm$ 0.004	8.989 $\pm$ 0.018	-0.021 $\pm$ 0.002	8.744 $\pm$ 0.012	-0.018 $\pm$ 0.003	8.724 $\pm$ 0.027
1207181305	-0.028 $\pm$ 0.007	8.733 $\pm$ 0.020	-0.012 $\pm$ 0.024	8.732 $\pm$ 0.046	-0.024 $\pm$ 0.004	8.653 $\pm$ 0.012	-0.031 $\pm$ 0.007	8.658 $\pm$ 0.016
1512115127	-0.067 $\pm$ 0.008	8.800 $\pm$ 0.026	-0.055 $\pm$ 0.009	8.800 $\pm$ 0.027	-0.054 $\pm$ 0.003	8.651 $\pm$ 0.014	-0.048 $\pm$ 0.004	8.630 $\pm$ 0.014
1521178118	0.008 $\pm$ 0.005	8.833 $\pm$ 0.040	0.010 $\pm$ 0.002	8.878 $\pm$ 0.013	-0.025 $\pm$ 0.007	8.991 $\pm$ 0.058	-0.020 $\pm$ 0.007	8.936 $\pm$ 0.055
1530070238	-0.009 $\pm$ 0.010	8.916 $\pm$ 0.026	0.020 $\pm$ 0.009	8.868 $\pm$ 0.017	0.004 $\pm$ 0.007	8.698 $\pm$ 0.020	-0.007 $\pm$ 0.003	8.718 $\pm$ 0.005
1502079084	-0.000 $\pm$ 0.011	8.507 $\pm$ 0.028	0.048 $\pm$ 0.022	8.493 $\pm$ 0.042	-0.006 $\pm$ 0.008	8.411 $\pm$ 0.018	-0.011 $\pm$ 0.005	8.432 $\pm$ 0.008
1205196165	-0.015 $\pm$ 0.003	8.935 $\pm$ 0.010	0.002 $\pm$ 0.003	8.917 $\pm$ 0.011	-0.002 $\pm$ 0.003	8.693 $\pm$ 0.012	-0.001 $\pm$ 0.003	8.695 $\pm$ 0.013
1504328073	-0.028 $\pm$ 0.029	8.418 $\pm$ 0.093	0.103 $\pm$ 0.012	8.179 $\pm$ 0.024	-0.023 $\pm$ 0.007	8.395 $\pm$ 0.021	-0.004 $\pm$ 0.002	8.360 $\pm$ 0.004
1533258059*	0.011 $\pm$ 0.010	7.401 $\pm$ 0.028	0.082 $\pm$ 0.028	7.258 $\pm$ 0.068	-0.011 $\pm$ 0.003	7.805 $\pm$ 0.008	-0.004 $\pm$ 0.001	7.789 $\pm$ 0.001
1509291230	0.050 $\pm$ 0.014	8.253 $\pm$ 0.043	0.049 $\pm$ 0.031	8.253 $\pm$ 0.074	-0.006 $\pm$ 0.003	8.305 $\pm$ 0.007	-0.006 $\pm$ 0.003	8.304 $\pm$ 0.008
1203076068	-0.039 $\pm$ 0.010	8.881 $\pm$ 0.036	-0.068 $\pm$ 0.009	8.953 $\pm$ 0.026	-0.015 $\pm$ 0.007	8.649 $\pm$ 0.028	-0.002 $\pm$ 0.010	8.574 $\pm$ 0.043
1531103073	-0.072 $\pm$ 0.045	8.530 $\pm$ 0.129	0.055 $\pm$ 0.126	8.298 $\pm$ 0.253	-0.049 $\pm$ 0.008	8.467 $\pm$ 0.022	-0.019 $\pm$ 0.004	8.407 $\pm$ 0.007
2310037140	0.003 $\pm$ 0.015	8.873 $\pm$ 0.030	0.018 $\pm$ 0.006	8.847 $\pm$ 0.011	0.013 $\pm$ 0.007	8.694 $\pm$ 0.012	0.003 $\pm$ 0.004	8.710 $\pm$ 0.006
1534194077	-0.012 $\pm$ 0.004	8.957 $\pm$ 0.015	-0.003 $\pm$ 0.007	8.945 $\pm$ 0.024	0.024 $\pm$ 0.005	8.610 $\pm$ 0.018	0.017 $\pm$ 0.004	8.622 $\pm$ 0.015
1517159274	-0.045 $\pm$ 0.008	8.961 $\pm$ 0.032	-0.031 $\pm$ 0.007	8.941 $\pm$ 0.031	-0.026 $\pm$ 0.003	8.723 $\pm$ 0.014	-0.030 $\pm$ 0.003	8.729 $\pm$ 0.015
1533161121	-0.040 $\pm$ 0.003	8.949 $\pm$ 0.012	-0.032 $\pm$ 0.004	8.946 $\pm$ 0.012	-0.033 $\pm$ 0.004	8.730 $\pm$ 0.020	-0.020 $\pm$ 0.003	8.691 $\pm$ 0.012
2305342325	-0.059 $\pm$ 0.010	8.873 $\pm$ 0.034	-0.024 $\pm$ 0.028	8.896 $\pm$ 0.067	-0.047 $\pm$ 0.008	8.659 $\pm$ 0.033	-0.009 $\pm$ 0.004	8.564 $\pm$ 0.011
2301064121	-0.008 $\pm$ 0.004	8.918 $\pm$ 0.013	0.006 $\pm$ 0.006	8.908 $\pm$ 0.017	0.024 $\pm$ 0.006	8.573 $\pm$ 0.024	0.028 $\pm$ 0.008	8.551 $\pm$ 0.030
2308129329	-0.076 $\pm$ 0.019	8.538 $\pm$ 0.072	-0.088 $\pm$ 0.007	8.617 $\pm$ 0.012	-0.058 $\pm$ 0.014	8.453 $\pm$ 0.062	-0.093 $\pm$ 0.016	8.568 $\pm$ 0.032
1517265320	-0.084 $\pm$ 0.006	8.918 $\pm$ 0.020	-0.082 $\pm$ 0.007	8.952 $\pm$ 0.021	-0.048 $\pm$ 0.004	8.628 $\pm$ 0.019	-0.046 $\pm$ 0.005	8.607 $\pm$ 0.023
2301109255	-0.015 $\pm$ 0.005	8.933 $\pm$ 0.020	0.010 $\pm$ 0.002	8.888 $\pm$ 0.006	0.005 $\pm$ 0.005	8.701 $\pm$ 0.021	-0.007 $\pm$ 0.004	8.729 $\pm$ 0.017
1506082320	0.044 $\pm$ 0.016	8.246 $\pm$ 0.044	0.002 $\pm$ 0.023	8.314 $\pm$ 0.051	-0.009 $\pm$ 0.003	8.296 $\pm$ 0.006	-0.004 $\pm$ 0.003	8.260 $\pm$ 0.006
1532282113	0.026 $\pm$ 0.013	8.628 $\pm$ 0.042	0.034 $\pm$ 0.030	8.621 $\pm$ 0.081	0.021 $\pm$ 0.016	8.419 $\pm$ 0.041	-0.002 $\pm$ 0.008	8.421 $\pm$ 0.021
1506106169	-0.035 $\pm$ 0.003	8.994 $\pm$ 0.009	-0.035 $\pm$ 0.003	9.003 $\pm$ 0.008	-0.022 $\pm$ 0.001	8.803 $\pm$ 0.007	-0.020 $\pm$ 0.001	8.799 $\pm$ 0.009
1513187164	-0.025 $\pm$ 0.007	8.905 $\pm$ 0.013	-0.009 $\pm$ 0.014	8.900 $\pm$ 0.023	0.013 $\pm$ 0.013	8.599 $\pm$ 0.020	-0.001 $\pm$ 0.005	8.615 $\pm$ 0.007
1532240333	0.005 $\pm$ 0.026	7.971 $\pm$ 0.113	0.011 $\pm$ 0.031	7.988 $\pm$ 0.094	-0.039 $\pm$ 0.006	8.224 $\pm$ 0.027	-0.064 $\pm$ 0.012	8.275 $\pm$ 0.037
2308076271	-0.047 $\pm$ 0.003	8.917 $\pm$ 0.014	-0.041 $\pm$ 0.006	8.921 $\pm$ 0.019	-0.035 $\pm$ 0.003	8.696 $\pm$ 0.015	-0.033 $\pm$ 0.003	8.694 $\pm$ 0.018
1203247089	0.048 $\pm$ 0.018	7.922 $\pm$ 0.067	0.231 $\pm$ 0.046	7.594 $\pm$ 0.095	-0.000 $\pm$ 0.004	8.130 $\pm$ 0.016	-0.003 $\pm$ 0.002	8.124 $\pm$ 0.004
1531178256	-0.031 $\pm$ 0.013	8.985 $\pm$ 0.033	-0.018 $\pm$ 0.013	8.969 $\pm$ 0.034	0.006 $\pm$ 0.003	8.588 $\pm$ 0.010	0.002 $\pm$ 0.004	8.594 $\pm$ 0.014
2308186140	-0.079 $\pm$ 0.016	8.425 $\pm$ 0.061	0.034 $\pm$ 0.038	8.163 $\pm$ 0.075	-0.043 $\pm$ 0.005	8.298 $\pm$ 0.020	-0.016 $\pm$ 0.008	8.252 $\pm$ 0.014
1203195161	-0.019 $\pm$ 0.001	8.998 $\pm$ 0.007	-0.016 $\pm$ 0.001	8.994 $\pm$ 0.007	-0.014 $\pm$ 0.003	8.777 $\pm$ 0.024	-0.014 $\pm$ 0.002	8.792 $\pm$ 0.020
1502071104	-0.011 $\pm$ 0.012	8.786 $\pm$ 0.026	0.012 $\pm$ 0.005	8.781 $\pm$ 0.009	-0.005 $\pm$ 0.004	8.613 $\pm$ 0.006	-0.002 $\pm$ 0.002	8.609 $\pm$ 0.003
1508217276	-0.014 $\pm$ 0.007	8.606 $\pm$ 0.022	-0.001 $\pm$ 0.005	8.598 $\pm$ 0.009	-0.006 $\pm$ 0.005	8.499 $\pm$ 0.014	-0.007 $\pm$ 0.009	8.499 $\pm$ 0.020
1507211057	-0.052 $\pm$ 0.008	8.958 $\pm$ 0.017	-0.043 $\pm$ 0.011	8.983 $\pm$ 0.021	-0.018 $\pm$ 0.013	8.703 $\pm$ 0.031	-0.001 $\pm$ 0.002	8.689 $\pm$ 0.004
1201302222	-0.079 $\pm$ 0.035	8.293 $\pm$ 0.123	-0.232 $\pm$ 0.101	8.536 $\pm$ 0.147	-0.049 $\pm$ 0.009	8.231 $\pm$ 0.029	-0.019 $\pm$ 0.017	8.206 $\pm$ 0.024
1513284105	0.016 $\pm$ 0.029	8.303 $\pm$ 0.070	-0.030 $\pm$ 0.042	8.374 $\pm$ 0.096	0.003 $\pm$ 0.002	8.202 $\pm$ 0.005	0.000 $\pm$ 0.000	8.194 $\pm$ 0.000

Table 4.1: The metallicity gradient (dex/kpc) and central metallicity (12+log(O/H)) measured using N2O2 and N2H α diagnostics and sum flux and spaxel average methods for 45 galaxies in Figure 4.2. *Note that galaxy MAG-PIID=1533258059 is removed from our final sample due to its metallicity being lower than the valid range of the N2O2 diagnostic.

MAGPIID	N2O2				N2H α			
	sum flux		spaxel average		sum flux		spaxel average	
	gradient	central metal	gradient	central metal	gradient	central metal	gradient	central metal
1206151090	-0.040 $\pm$ 0.017	8.738 $\pm$ 0.016	-0.028 $\pm$ 0.006	8.760 $\pm$ 0.004	-0.050 $\pm$ 0.014	8.581 $\pm$ 0.011	-0.072 $\pm$ 0.015	8.582 $\pm$ 0.012
1524292106	-0.219 $\pm$ 0.076	8.674 $\pm$ 0.077	-0.391 $\pm$ 0.076	8.804 $\pm$ 0.059	-0.043 $\pm$ 0.024	8.438 $\pm$ 0.023	-0.024 $\pm$ 0.015	8.410 $\pm$ 0.012
1513236222	0.022 $\pm$ 0.035	8.853 $\pm$ 0.030	0.047 $\pm$ 0.023	8.889 $\pm$ 0.019	-0.123 $\pm$ 0.147	8.840 $\pm$ 0.116	-0.219 $\pm$ 0.152	8.891 $\pm$ 0.116
2311102063	-0.117 $\pm$ 0.012	8.942 $\pm$ 0.011	-0.072 $\pm$ 0.014	8.915 $\pm$ 0.013	-0.074 $\pm$ 0.030	8.738 $\pm$ 0.032	-0.038 $\pm$ 0.037	8.709 $\pm$ 0.036
1514079248	-0.158 $\pm$ 0.071	8.521 $\pm$ 0.070	0.277 $\pm$ 0.029	8.330 $\pm$ 0.015	-0.133 $\pm$ 0.021	8.440 $\pm$ 0.024	-0.049 $\pm$ 0.011	8.375 $\pm$ 0.006
1504220116	-0.116 $\pm$ 0.020	8.907 $\pm$ 0.017	-0.072 $\pm$ 0.020	8.904 $\pm$ 0.017	-0.069 $\pm$ 0.035	8.681 $\pm$ 0.035	-0.093 $\pm$ 0.039	8.677 $\pm$ 0.037
1509152248	-0.397 $\pm$ 0.135	8.653 $\pm$ 0.112	-0.256 $\pm$ 0.185	8.741 $\pm$ 0.073	-0.204 $\pm$ 0.050	8.422 $\pm$ 0.048	0.087 $\pm$ 0.024	8.391 $\pm$ 0.010
1203235348	-0.361 $\pm$ 0.048	8.835 $\pm$ 0.035	-0.397 $\pm$ 0.195	8.924 $\pm$ 0.085	-0.211 $\pm$ 0.021	8.560 $\pm$ 0.019	-0.262 $\pm$ 0.012	8.596 $\pm$ 0.006
1517143230	-0.063 $\pm$ 0.010	8.984 $\pm$ 0.010	-0.039 $\pm$ 0.008	8.975 $\pm$ 0.008	0.016 $\pm$ 0.030	8.666 $\pm$ 0.034	0.020 $\pm$ 0.025	8.660 $\pm$ 0.029
2304104201	-0.168 $\pm$ 0.016	8.986 $\pm$ 0.014	-0.157 $\pm$ 0.020	8.989 $\pm$ 0.018	-0.122 $\pm$ 0.009	8.744 $\pm$ 0.012	-0.100 $\pm$ 0.017	8.724 $\pm$ 0.027
1207181305	-0.130 $\pm$ 0.031	8.733 $\pm$ 0.020	-0.055 $\pm$ 0.114	8.732 $\pm$ 0.046	-0.114 $\pm$ 0.020	8.653 $\pm$ 0.012	-0.143 $\pm$ 0.034	8.658 $\pm$ 0.016
1512115127	-0.231 $\pm$ 0.026	8.800 $\pm$ 0.026	-0.191 $\pm$ 0.033	8.800 $\pm$ 0.027	-0.188 $\pm$ 0.011	8.651 $\pm$ 0.014	-0.166 $\pm$ 0.013	8.630 $\pm$ 0.014
1521178118	0.025 $\pm$ 0.016	8.833 $\pm$ 0.040	0.032 $\pm$ 0.006	8.878 $\pm$ 0.013	-0.080 $\pm$ 0.024	8.991 $\pm$ 0.058	-0.063 $\pm$ 0.022	8.936 $\pm$ 0.055
1530070238	-0.030 $\pm$ 0.033	8.916 $\pm$ 0.026	0.065 $\pm$ 0.028	8.868 $\pm$ 0.017	0.015 $\pm$ 0.024	8.698 $\pm$ 0.020	-0.022 $\pm$ 0.008	8.718 $\pm$ 0.005
1502079084	-0.000 $\pm$ 0.024	8.507 $\pm$ 0.028	0.100 $\pm$ 0.046	8.493 $\pm$ 0.042	-0.012 $\pm$ 0.016	8.411 $\pm$ 0.018	-0.023 $\pm$ 0.010	8.432 $\pm$ 0.008
1205196165	-0.053 $\pm$ 0.010	8.935 $\pm$ 0.010	0.006 $\pm$ 0.011	8.917 $\pm$ 0.011	-0.006 $\pm$ 0.011	8.693 $\pm$ 0.012	-0.004 $\pm$ 0.011	8.695 $\pm$ 0.013
1504328073	-0.111 $\pm$ 0.118	8.418 $\pm$ 0.093	0.412 $\pm$ 0.046	8.179 $\pm$ 0.024	-0.093 $\pm$ 0.028	8.395 $\pm$ 0.021	-0.016 $\pm$ 0.009	8.360 $\pm$ 0.004
1533258059*	0.021 $\pm$ 0.018	7.401 $\pm$ 0.028	0.151 $\pm$ 0.052	7.258 $\pm$ 0.068	-0.020 $\pm$ 0.006	7.805 $\pm$ 0.008	-0.007 $\pm$ 0.001	7.789 $\pm$ 0.001
1509291230	0.180 $\pm$ 0.050	8.253 $\pm$ 0.043	0.175 $\pm$ 0.111	8.253 $\pm$ 0.074	-0.021 $\pm$ 0.009	8.305 $\pm$ 0.007	-0.023 $\pm$ 0.010	8.304 $\pm$ 0.008
1203076068	-0.161 $\pm$ 0.040	8.881 $\pm$ 0.036	-0.282 $\pm$ 0.039	8.953 $\pm$ 0.026	-0.063 $\pm$ 0.028	8.649 $\pm$ 0.028	-0.007 $\pm$ 0.041	8.574 $\pm$ 0.043
1531103073	-0.261 $\pm$ 0.165	8.530 $\pm$ 0.129	0.199 $\pm$ 0.459	8.298 $\pm$ 0.253	-0.177 $\pm$ 0.027	8.467 $\pm$ 0.022	-0.070 $\pm$ 0.013	8.407 $\pm$ 0.007
2310037140	0.004 $\pm$ 0.020	8.873 $\pm$ 0.030	0.023 $\pm$ 0.008	8.847 $\pm$ 0.011	0.016 $\pm$ 0.009	8.694 $\pm$ 0.012	0.005 $\pm$ 0.005	8.710 $\pm$ 0.006
1534194077	-0.043 $\pm$ 0.014	8.957 $\pm$ 0.015	-0.013 $\pm$ 0.026	8.945 $\pm$ 0.024	0.087 $\pm$ 0.018	8.610 $\pm$ 0.018	0.063 $\pm$ 0.014	8.622 $\pm$ 0.015
1517159274	-0.231 $\pm$ 0.042	8.961 $\pm$ 0.032	-0.161 $\pm$ 0.038	8.941 $\pm$ 0.031	-0.134 $\pm$ 0.014	8.723 $\pm$ 0.014	-0.153 $\pm$ 0.015	8.729 $\pm$ 0.015
1533161121	-0.196 $\pm$ 0.016	8.949 $\pm$ 0.012	-0.158 $\pm$ 0.018	8.946 $\pm$ 0.012	-0.160 $\pm$ 0.020	8.730 $\pm$ 0.020	-0.099 $\pm$ 0.014	8.691 $\pm$ 0.012
2305342325	-0.339 $\pm$ 0.058	8.873 $\pm$ 0.034	-0.136 $\pm$ 0.159	8.896 $\pm$ 0.067	-0.270 $\pm$ 0.046	8.659 $\pm$ 0.033	-0.053 $\pm$ 0.025	8.564 $\pm$ 0.011
2301064121	-0.033 $\pm$ 0.015	8.918 $\pm$ 0.013	0.023 $\pm$ 0.023	8.908 $\pm$ 0.017	0.098 $\pm$ 0.025	8.573 $\pm$ 0.024	0.117 $\pm$ 0.032	8.551 $\pm$ 0.030
2308129329	-0.324 $\pm$ 0.080	8.538 $\pm$ 0.072	-0.376 $\pm$ 0.029	8.617 $\pm$ 0.012	-0.248 $\pm$ 0.059	8.453 $\pm$ 0.062	-0.398 $\pm$ 0.070	8.568 $\pm$ 0.032
1517265320	-0.398 $\pm$ 0.029	8.918 $\pm$ 0.020	-0.387 $\pm$ 0.034	8.952 $\pm$ 0.021	-0.227 $\pm$ 0.019	8.628 $\pm$ 0.019	-0.218 $\pm$ 0.022	8.607 $\pm$ 0.023
2301109255	-0.068 $\pm$ 0.024	8.933 $\pm$ 0.020	0.045 $\pm$ 0.009	8.888 $\pm$ 0.006	0.023 $\pm$ 0.023	8.701 $\pm$ 0.021	-0.033 $\pm$ 0.018	8.729 $\pm$ 0.017
1506082320	0.077 $\pm$ 0.028	8.246 $\pm$ 0.044	0.003 $\pm$ 0.040	8.314 $\pm$ 0.051	-0.016 $\pm$ 0.004	8.296 $\pm$ 0.006	-0.008 $\pm$ 0.005	8.260 $\pm$ 0.006
1532282113	0.088 $\pm$ 0.046	8.628 $\pm$ 0.042	0.116 $\pm$ 0.105	8.621 $\pm$ 0.081	0.074 $\pm$ 0.054	8.419 $\pm$ 0.041	-0.005 $\pm$ 0.028	8.421 $\pm$ 0.021
1506106169	-0.121 $\pm$ 0.010	8.994 $\pm$ 0.009	-0.120 $\pm$ 0.009	9.003 $\pm$ 0.008	-0.075 $\pm$ 0.004	8.803 $\pm$ 0.007	-0.069 $\pm$ 0.005	8.799 $\pm$ 0.009
1513187164	-0.138 $\pm$ 0.038	8.905 $\pm$ 0.013	-0.048 $\pm$ 0.077	8.900 $\pm$ 0.023	0.072 $\pm$ 0.069	8.599 $\pm$ 0.020	-0.003 $\pm$ 0.026	8.615 $\pm$ 0.007
1532240333	0.026 $\pm$ 0.127	7.971 $\pm$ 0.113	0.053 $\pm$ 0.149	7.988 $\pm$ 0.094	-0.187 $\pm$ 0.031	8.224 $\pm$ 0.027	-0.310 $\pm$ 0.058	8.275 $\pm$ 0.037
2308076271	-0.242 $\pm$ 0.017	8.917 $\pm$ 0.014	-0.212 $\pm$ 0.030	8.921 $\pm$ 0.019	-0.183 $\pm$ 0.014	8.696 $\pm$ 0.015	-0.169 $\pm$ 0.018	8.694 $\pm$ 0.018
1203247089	0.193 $\pm$ 0.073	7.922 $\pm$ 0.067	0.918 $\pm$ 0.184	7.594 $\pm$ 0.095	-0.001 $\pm$ 0.018	8.130 $\pm$ 0.016	-0.012 $\pm$ 0.007	8.124 $\pm$ 0.004
1531178256	-0.137 $\pm$ 0.055	8.985 $\pm$ 0.033	-0.078 $\pm$ 0.056	8.969 $\pm$ 0.034	0.027 $\pm$ 0.013	8.588 $\pm$ 0.010	0.009 $\pm$ 0.017	8.594 $\pm$ 0.014
2308186140	-0.268 $\pm$ 0.054	8.425 $\pm$ 0.061	0.116 $\pm$ 0.128	8.163 $\pm$ 0.075	-0.147 $\pm$ 0.018	8.298 $\pm$ 0.020	-0.055 $\pm$ 0.026	8.252 $\pm$ 0.014
1203195161	-0.127 $\pm$ 0.008	8.998 $\pm$ 0.007	-0.105 $\pm$ 0.008	8.994 $\pm$ 0.007	-0.089 $\pm$ 0.020	8.777 $\pm$ 0.024	-0.093 $\pm$ 0.016	8.792 $\pm$ 0.020
1502071104	-0.039 $\pm$ 0.042	8.786 $\pm$ 0.026	0.043 $\pm$ 0.018	8.781 $\pm$ 0.009	-0.017 $\pm$ 0.013	8.613 $\pm$ 0.006	-0.006 $\pm$ 0.007	8.609 $\pm$ 0.003
1508217276	-0.051 $\pm$ 0.026	8.606 $\pm$ 0.022	-0.004 $\pm$ 0.019	8.598 $\pm$ 0.009	-0.021 $\pm$ 0.017	8.499 $\pm$ 0.014	-0.027 $\pm$ 0.032	8.499 $\pm$ 0.020
1507211057	-0.105 $\pm$ 0.017	8.958 $\pm$ 0.017	-0.087 $\pm$ 0.022	8.983 $\pm$ 0.021	-0.037 $\pm$ 0.027	8.703 $\pm$ 0.031	-0.001 $\pm$ 0.004	8.689 $\pm$ 0.004
1201302222	-0.231 $\pm$ 0.104	8.293 $\pm$ 0.123	-0.681 $\pm$ 0.297	8.536 $\pm$ 0.147	-0.145 $\pm$ 0.025	8.231 $\pm$ 0.029	-0.056 $\pm$ 0.051	8.206 $\pm$ 0.024
1513284105	0.029 $\pm$ 0.052	8.303 $\pm$ 0.070	-0.054 $\pm$ 0.076	8.374 $\pm$ 0.096	0.006 $\pm$ 0.004	8.202 $\pm$ 0.005	0.001 $\pm$ 0.000	8.194 $\pm$ 0.000

Table 4.2: Same as Table 4.1, but the metallicity gradients are in the unit of dex/ R_e .

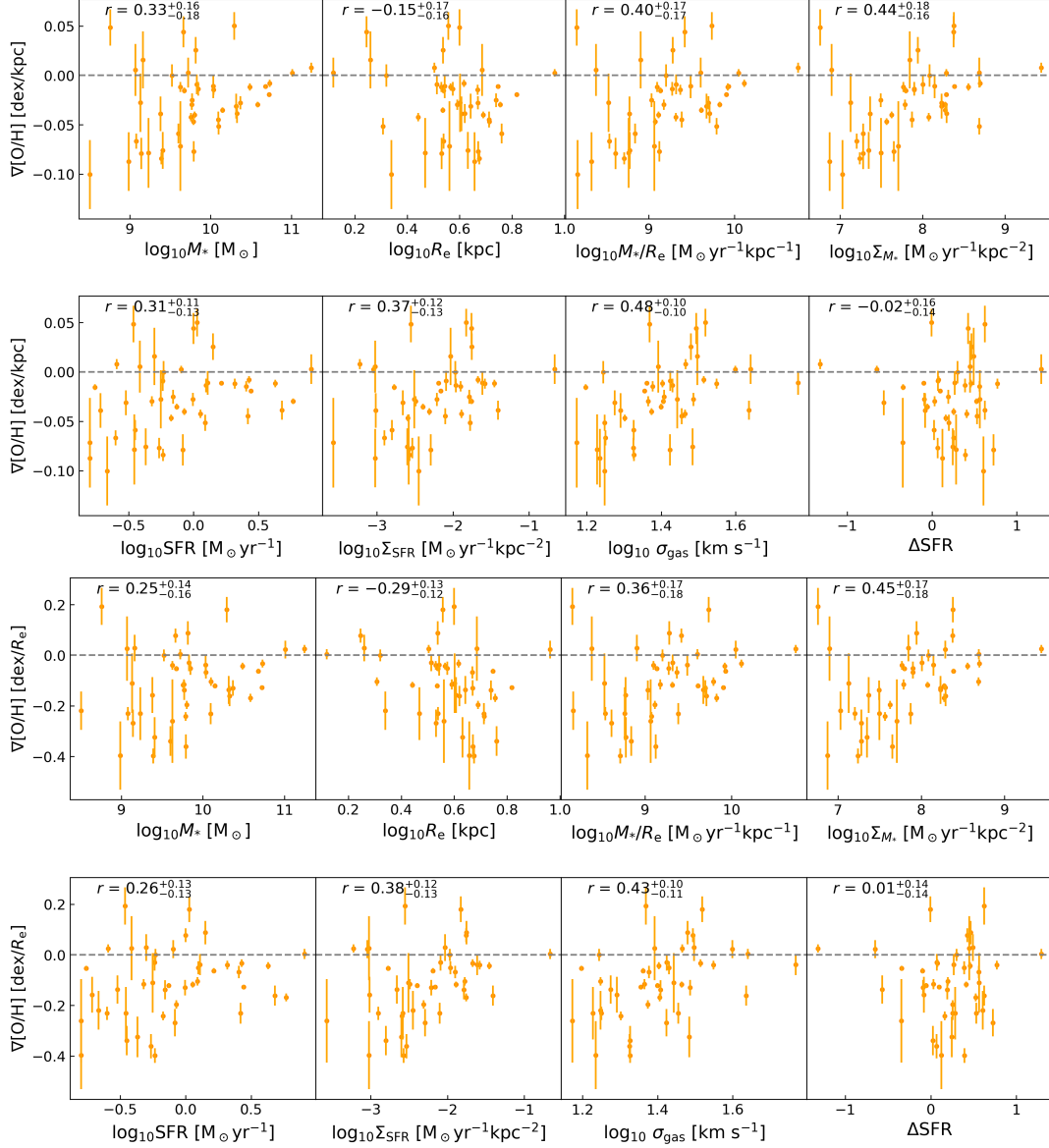


Figure 4.4: Metallicity gradient (top two rows in the unit of dex/kpc, bottom two rows in the unit of dex/ R_e) as a function of a variety of galaxy properties, including stellar mass (M_*), R_e , a proxy for the gravitational potential (M_*/R_e), Σ_{M_*} , SFR, Σ_{SFR} , σ_{gas} and the logarithmic offset in SFR from the star formation main sequence (SFMS) of MAGPI galaxies (ΔSFR). We show the Pearson correlation coefficient, r , on each panel. The horizontal dashed lines denote the flat gradient.

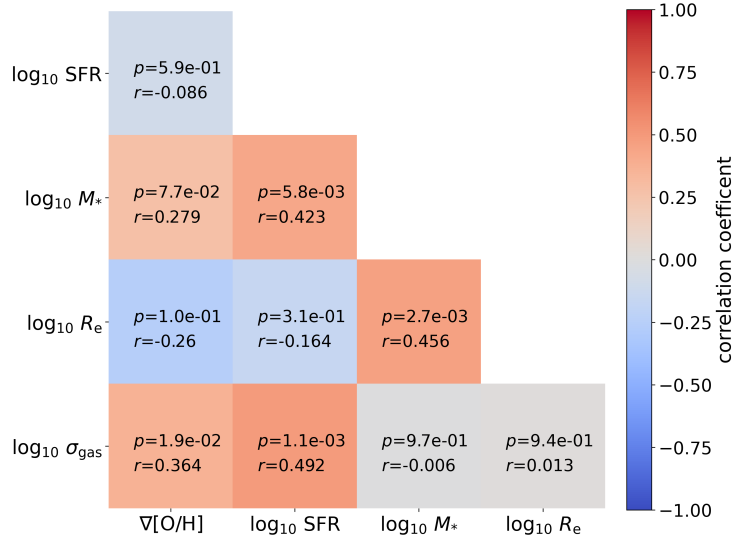


Figure 4.5: The Pearson partial correlation between $\nabla[\text{O}/\text{H}]$, SFR, M_* , R_e and σ_{gas} for MAGPI galaxies. The correlation coefficient (r) and p -value are shown in each box.

rows.

The results are similar for metallicity gradients in different units. We discuss the relation for metallicity gradient in the unit of dex/kpc here. We find the $\nabla[\text{O}/\text{H}]$ of MAGPI galaxies has a significant positive correlation with σ_{gas} ($r = 0.48^{+0.10}_{-0.10}$) and a moderate positive correlation with Σ_{SFR} ($r = 0.37^{+0.12}_{-0.13}$). M_* , M_*/R_e , Σ_{M_*} and SFR have weak to moderate correlations with $\nabla[\text{O}/\text{H}]$, but the significance is lower than 3σ . We also find that $\nabla[\text{O}/\text{H}]$ in the unit of dex/kpc has no significant correlation with R_e . However, $\nabla[\text{O}/\text{H}]$ in the unit of dex/ R_e has a weak correlation with R_e .

To disentangle the intercorrelation between different parameters, we also analyse the partial correlation between $\nabla[\text{O}/\text{H}]$, SFR, M_* , R_e and σ_{gas} , i.e. the correlation between two parameters when the effects of other parameters are removed (Whitaker, 2009). We calculate the Pearson partial correlation coefficient for each pair parameter and p -value using PINGOUIN (Vallat, 2018). We consider the correlation to be significant when $p < 0.05$. As shown in Figure 4.5, $\nabla[\text{O}/\text{H}]$ has the strongest partial correlation with σ_{gas} . M_* may contribute to the residual of the $\sigma_{\text{gas}}-\nabla[\text{O}/\text{H}]$ relation, but the correlation between M_* and $\nabla[\text{O}/\text{H}]$ is not significant.

The $\nabla[\text{O}/\text{H}]$ of MAGPI galaxies has the most significant correlation with σ_{gas} , i.e. the galaxies with higher σ_{gas} tend to have flatter or even positive metallicity gradients. This correlation has been observed in galaxies at $z \sim 1.2$ (Queyrel et al., 2012). The correlation in our sample at $z \sim 0.3$ is stronger than in Queyrel et al. (2012). Similarly, Sharda et al. (2021b) found most of the dispersion-dominated galaxies ($v_\phi/\sigma_{\text{gas}} \leq 1$, where v_ϕ is the rotational velocity) have flat gradients, while the rotation-dominated galaxies have both flat gradients and steep negative gradients. However, we find the relation between $\nabla[\text{O}/\text{H}]$ and $v_\phi/\sigma_{\text{gas}}$ is insignificant in the MAGPI sample.

Sharda et al. (2024) built an analytical model to investigate the impact of star formation feedback, advection (bulk flow of gas), cosmic accretion and diffusion (turbulent mixing of gas) on the metallicity gradient. The model in Sharda et al. (2024) shows that the metallicity gradient of low-mass galaxies varies significantly with the extent of newly produced metals mixing with the interstellar medium (described by the yield reduction factor, ϕ_y ²).

The $\nabla[\text{O}/\text{H}]-M_*$ relation for galaxies in our MAGPI sample generally agrees with the model in Sharda et al. (2024). The metallicity gradient spans a wide range for the low-mass galaxies. The high-mass galaxies have flatter metallicity gradients than the low-mass galaxies, as shown in the $\nabla[\text{O}/\text{H}]-M_*$ panel in Figure 4.4.

We find galaxies with higher Σ_{SFR} tend to have flatter metallicity gradients, suggesting that the mechanisms driving enhanced SFR may also contribute to the flattening of the metallicity gradient. Carton et al. (2018) found a slight trend that galaxies with higher SFR tend to have a more negative metallicity gradient. However, their sample includes galaxies in a wide range of redshift ($0.1 \lesssim z \lesssim 0.8$). Therefore, the trend they observed may be dominated by redshift evolution. As shown in Figure 7 in Carton et al. (2018), higher redshift galaxies tend to have higher SFR and more negative metallicity gradient.

Our result shows that different metallicity diagnostics predict different metallicity distributions in some galaxies. For example, in galaxy MAGPIID=1203195161 the metallicity decreases with radius smoothly in the N2O2 diagnostic. While in the N2H α diagnostic, the metallicity decreases within 4 kpc and then slightly increases between 4 – 7 kpc and decreases again in the larger radius, as shown in Figure 4.1. The variation of ionisation parameter and ISM pressure across the galaxy may play a role in the increase of the metallicity profile, as the N2H α diagnostic is sensitive to ionisation parameter. Therefore, assuming a constant $\log(U)$ limits the accuracy of the N2H α diagnostic. This finding aligns with Poetrodjojo et al. (2021), who showed that the metallicity gradients derived using different diagnostics present systematic discrepancies.

Easeman et al. (2022) also investigated the impact of different diagnostics on the dips in radial metallicity profiles. However, they found no clear connection between the dips and the variation of ionisation parameter within galaxies. Their results suggested that central quenching may be a possible reason for the dips.

Some galaxies in our sample have elevated N2H α metallicity in galaxies centre or outer disc. This may link to central quenching or outside-in quenching, which depends on the environment (Wang et al., 2022). Further studies are needed to investigate how the variation of ionisation parameter and quenching scenarios influence the metallicity measured using different diagnostics.

While details of the metallicity gradients measured using different diagnostics are different, the global trends are partially similar. The N2H α metallicity gradient in

² $0 \leq \phi_y \leq 1$. $\phi_y \sim 1$ means the newly produced metals from supernovae are fully mixed with ISM before ejected and $\phi_y \sim 0$ means the newly produced metals are ejected from the galaxy without mixing with ISM.

the unit of dex/kpc also has a positive correlation with σ_{gas} ($r = 0.37^{+0.11}_{-0.12}$) and Σ_{SFR} ($r = 0.63^{+0.06}_{-0.08}$). Compared with the N2O2 metallicity gradient, the N2H α gradient has a more significant correlation with M_* ($r = 0.38^{+0.11}_{-0.12}$), M_*/R_e ($r = 0.47^{+0.12}_{-0.12}$), Σ_{M_*} ($r = 0.52^{+0.12}_{-0.13}$) and SFR ($r = 0.48^{+0.10}_{-0.12}$). The difference in metallicity gradient measured using different diagnostics is consistent with the results in [Poetrodjojo et al. \(2021\)](#), which showed large systematic discrepancies between them.

4.6 Discussion

4.6.1 Drivers of the metallicity gradient

The MAGPI galaxies in our sample have negative metallicity gradients on average. The negative metallicity gradient results from the galactic disc's inside-out growth. The star formation history in the central regions is longer than the outer disc, leading to more enrichment of metals in the core ([Larson, 1976](#); [Matteucci & Francois, 1989](#); [Boissier & Prantzos, 1999](#)).

The galaxy can have a steep metallicity gradient if the metals stay undisturbed in the galactic disc ([Gibson et al., 2013](#)). However, mechanisms like gas inflows, outflows, accretion and galaxy interaction play a role in redistributing the metals in the galaxy, which flattens the metallicity gradient or even inverts the gradient ([Cresci et al., 2010](#); [Kewley et al., 2010](#); [Rupke et al., 2010](#); [Marinacci et al., 2014](#); [Chisholm et al., 2018](#)).

The positive correlation between $\nabla[\text{O}/\text{H}]$ and σ_{gas} of the MAGPI galaxies (Figure 4.4) suggests a connection between gas turbulence and metallicity gradient flattening. [Mai et al. \(2024\)](#) found that the main driver of gas turbulence in the MAGPI galaxies is stellar feedback or gas instability. Gas accretion and transportation also contribute to the gas turbulence in the MAGPI galaxies. This result agrees with the model in [Sharda et al. \(2024\)](#), which showed that stellar feedback, gas accretion and transportation are important to drive gas turbulence and metal-mixing and only models that include those mechanisms can reproduce the $M_* - \nabla[\text{O}/\text{H}]$ relation in the local galaxies. [Sharda et al. \(2024\)](#) found the relative importance of different mechanisms varies with stellar mass. Stellar feedback and gas accretion play a more important role in massive galaxies.

Some observations ([Belfiore et al., 2017](#); [Poetrodjojo et al., 2021](#)) show that the mass-metallicity gradient relation bends at $\sim 10^{10.5}M_\odot$, i.e. the metallicity gradient decreases with increasing stellar mass when $M_* \lesssim 10^{10.5}M_\odot$ and increases with increasing stellar mass when $M_* \gtrsim 10^{10.5}M_\odot$. The possible physical mechanism that causes this break is that galaxies transform from accretion-dominated to advection-dominated at $\sim 10^{10.5}M_\odot$, where both metallicity redistribution mechanisms, accretion and advection, are the weakest ([Sharda et al., 2021a](#)). Therefore, galaxies have the steepest metallicity gradient at $\sim 10^{10.5}M_\odot$.

We compare the $\nabla[\text{O}/\text{H}] - M_*$ relation of the MAGPI galaxies with galaxies at the

same redshift³ ($z \sim 0.3$; Carton et al., 2018), galaxies at $z \sim 0$ from the SAMI Galaxy Survey (N2O2) (Poetrodjojo et al., 2021) and the theoretical predictions for local galaxies from Sharda et al. (2024), with the mass-loading factor in the model estimated from the EAGLE cosmological simulations (Mitchell et al., 2020), as shown in Figure 4.6. The metallicity gradients (N2H α) of the SAMI (Poetrodjojo et al., 2021), MaNGA (Belfiore et al., 2017) and CALIFA (Sánchez et al., 2014) surveys galaxies shown as grey-edge markers are taken from Sharda et al. (2024) and have seeing-correction by Acharyya et al. (in preparation)⁴. The seeing-corrected metallicity gradient of low-mass SAMI galaxies from Acharyya et al. (in preparation) is flatter than the observed (seeing-convolved) metallicity gradient of SAMI galaxies in Poetrodjojo et al. (2021). This is possibly due to the different diagnostics they used.

The $\nabla[\text{O}/\text{H}] - M_*$ plane of the MAGPI galaxies qualitatively agree with the prediction in Sharda et al. (2024). The low-mass MAGPI galaxies have steeper metallicity gradients on average than the galaxies in the SAMI, MaNGA and CALIFA samples (all at $z \sim 0$), suggesting the strength of metallicity flattening processes is relatively weaker in $z \sim 0.3$ low-mass galaxies than local galaxies. However, the scatter and uncertainty of the metallicity gradient are large in our low-mass bins. A larger sample is needed to confirm this result. The median metallicity gradient in the $10^{10.3} M_\odot$ bin is lower than in the neighbouring bins. However, the bending of $\nabla[\text{O}/\text{H}] - M_*$ relation in the MAGPI sample is not as obvious as in the SAMI, MaNGA and CALIFA samples.

Our result shows that galaxies with higher Σ_{SFR} have flatter metallicity gradients (Figure 4.4). This is consistent with the scenario that the accretion of pristine gas or gas transportation from the outskirts to the inner regions flattens the metallicity gradient and triggers star formation (Stott et al., 2014). The galaxies with positive metallicity gradients might result from metal-poor intergalactic medium accreting directly to the centre of the galaxy, which dilutes the central metallicity and inverts the metallicity gradient (Cresci et al., 2010).

The interaction between galaxies might trigger gas transportation throughout the disc. A mild correlation has been observed between the metallicity gradient and environment (Boardman et al., 2023). The galaxies in denser environments tend to have a flatter metallicity gradient (Franchetto et al., 2021; Lara-López, M. A. et al., 2022). It would be interesting to analyse the impact of the environment with the full MAGPI sample.

4.6.2 Evolution of metallicity gradient

There is no consistent picture of the metallicity gradient within high redshift galaxies in both observational and simulation studies. Some observation studies showed that the metallicity gradient of high redshift galaxies is flatter than low redshift galaxies;

³Note that the redshift range of the galaxies in Carton et al. (2018) is $0.1 \lesssim z \lesssim 0.8$. We only select galaxies that are in the same redshift range as this study ($0.26 < z < 0.42$).

⁴This work has been published in PhD thesis: https://openresearch-repository.anu.edu.au/bitstream/1885/258981/1/Ayan_thesis_2022.pdf

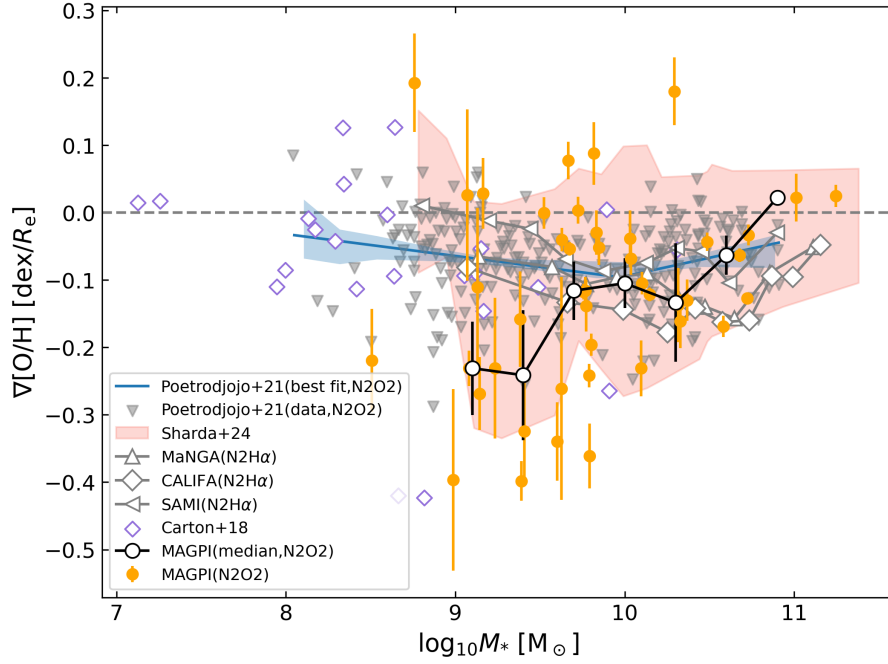


Figure 4.6: The $\nabla[\text{O}/\text{H}] - M_*$ relation for galaxies at $z \sim 0.3$ and $z \sim 0$. The galaxies of the MAGPI survey are shown as solid orange circles. The median $\nabla[\text{O}/\text{H}]$ in each 0.3 dex M_* bin are shown as black edge circles. The galaxies at the same redshift range as this study ($0.26 < z < 0.42$) measured by Carton et al. (2018) are shown as open purple diamonds. The galaxies of the SAMI survey are shown as grey triangles (N2O2 diagnostic) and their best fit (a broken linear-fit) is shown as a blue line and the 1σ uncertainty is shown as a blue band. The model prediction from Sharda et al. (2024) for the galaxies in the local Universe is shown as a pink band. The galaxies in the local Universe from the SAMI (Poetrodjojo et al., 2021), MaNGA (Belfiore et al., 2017) and CALIFA (Sánchez et al., 2014) surveys are shown as grey-edge markers, with seeing-correction made by Acharyya et al. (in preparation). Note that the metallicity of galaxies in the SAMI, MaNGA, and CALIFA survey shown as grey-edge markers is measured using the N2H α diagnostic.

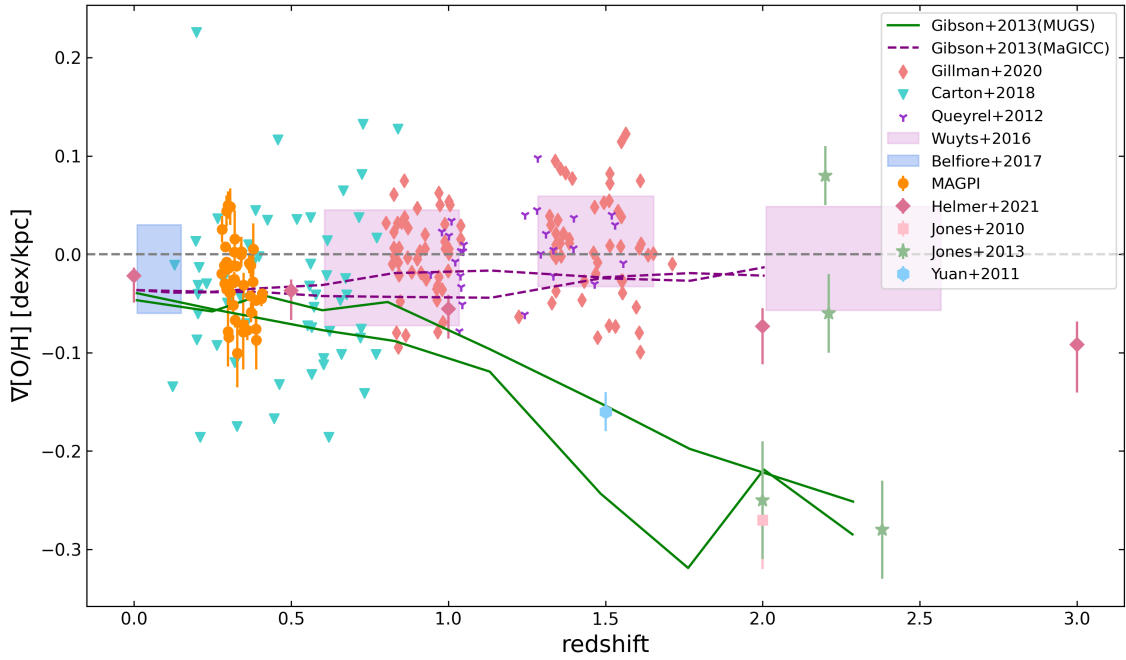


Figure 4.7: The redshift evolution of the metallicity gradient from previous studies and this work (MAGPI). We compile simulation results from [Gibson et al. \(2013\)](#) and [Hemler et al. \(2021\)](#). We also include observational studies results from [Gillman \(2020\)](#), [Carton et al. \(2018\)](#), [Wuyts et al. \(2016\)](#), [Belfiore et al. \(2017\)](#), [Jones et al. \(2010, 2013\)](#), [Yuan et al. \(2011\)](#) and [Queyrel et al. \(2012\)](#). We note that the blue and pink shadows show the range of metallicity gradient and redshift in [Belfiore et al. \(2017\)](#) and [Wuyts et al. \(2016\)](#) separately.

some high redshift galaxies even have inverted metallicity gradients ([Cresci et al., 2010](#); [Wuyts et al., 2016](#); [Gillman, 2020](#)). On the contrary, other observation studies found the metallicity gradient is steeper for high redshift galaxies ([Jones et al., 2010](#); [Yuan et al., 2011](#); [Jones et al., 2013](#)). Simulation studies also show an inconsistent picture of the redshift evolution of the metallicity gradient due to the different feedback implementations ([Gibson et al., 2013](#); [Hemler et al., 2021](#)). [Gibson et al. \(2013\)](#) showed that galaxies at high redshift have relatively flat metallicity gradients in the enhanced feedback model and have steep gradients in the conservative feedback model.

We compile the metallicity gradient measurement from previous studies in [Figure 4.7](#). The metallicity gradients for the MAGPI galaxies are shown as orange circles. The metallicity gradients of the MAGPI galaxies generally agree with previous observation ([Carton et al., 2018](#)) and simulation ([Gibson et al., 2013](#)) results at the same redshift. The scatter of the metallicity gradient of our result is smaller than the results in [Carton et al. \(2018\)](#). The difference might come from different modelling techniques, metallicity diagnostic and observation depth. [Carton et al. \(2018\)](#) directly included the metallicity gradient in their model and assumed a radial log-linear profile of the metallicity distribution, while our model fits the different emission lines flux distribution individually and allows flexibility in the spatial flux substructures. The metallicity diagnostics used in [Carton et al. \(2018\)](#) depended on

the galaxy. They chose the two strong forbidden lines and two Balmer lines with the highest S/N, typically $H\beta$, $[O\text{ III}]\lambda 5007$, $H\alpha$ and $[S\text{ II}]\lambda 6717, 6731$ for galaxies at $z \lesssim 0.4$. In contrast, we use N2O2 as our primary metallicity diagnostic. The metallicity gradients measured using different diagnostics possess systematic discrepancies (Poetrodjojo et al., 2021). Different observational depths may also influence the measured metallicity gradient, as the metallicity gradient might be different in the inner and outer regions (Mott et al., 2013; Belfiore et al., 2017).

The divergence of the metallicity gradient predictions is obvious for galaxies at $z \gtrsim 1$. Gibson et al. (2013) demonstrated the evolution of the metallicity gradient of two types of feedback models, as shown in Figure 4.7. The MaGICC (Making Galaxies in a Cosmological Context; Brook et al., 2012) is the ‘enhanced’ feedback model, which is efficient in redistributing the metals over large scales and flattening the metallicity gradient at high redshift. The MUGS (McMaster Unbiased Galaxy Simulations; Stinson et al., 2010) is the ‘conventional’ feedback model, which employed a weaker feedback scheme than MaGICC, returning much steeper metallicity gradients for galaxies at high redshift. We note that the stellar mass range of the galaxies in MaGICC and MUGS simulation is comparable to the MAGPI data we use.

The discrepancy of metallicity gradients for these two feedback models is not obvious at $z \sim 0.3$. Therefore, it is difficult to constrain the stellar feedback model using the galaxies at this redshift. However, our result shows that the galaxies with higher Σ_{SFR} have flatter metallicity gradient, suggesting a connection between the strength of feedback and metallicity gradient flattening. The metallicity gradient may coevolve with Σ_{SFR} . The driver of higher Σ_{SFR} and the flattening of the metallicity gradient may be the same. The gas inflows feed metal-poor molecular gas to the centre of the galaxies, which triggers star formation and flattens the metallicity gradient.

Most of the observations of high redshift galaxies showed shallow-to-flat metallicity gradient (Figure 4.7), which agrees with higher gas velocity dispersion and stronger gas transportation and accretion in higher redshift galaxies (Wisnioski et al., 2015; Übler et al., 2019; Mai et al., 2024). However, the flat gradients at high redshift may result from the limit of resolution and the flattening of seeing (Yuan et al., 2013; Belfiore et al., 2017), which we will discuss in the following subsection.

4.6.3 The challenge of metallicity gradient measurement

The angular resolution of observation influences the accuracy of metallicity gradient measurement (Yuan et al., 2013; Stott et al., 2014; Belfiore et al., 2017; Acharyya et al., 2020). Yuan et al. (2013) showed that the flattening of the metallicity gradient increases with FWHM of angular resolution. Stott et al. (2014) tested the effect of atmospheric seeing and inclination of the galaxy for galaxies at $z \sim 1$. They found the metallicity gradient is ~ 80 per cent of the true value when the galaxy is face-on and the FWHM of seeing is 0.7 arcsec for galaxies at $z \sim 1$ ($R_e \sim 5$ kpc). The metallicity gradient is ~ 70 per cent of the true value if the galaxy has 50° inclination. At the fixed angular resolution, the effect of seeing flattening is stronger for smaller galaxies and galaxies at higher redshift. Therefore, it is challenging to

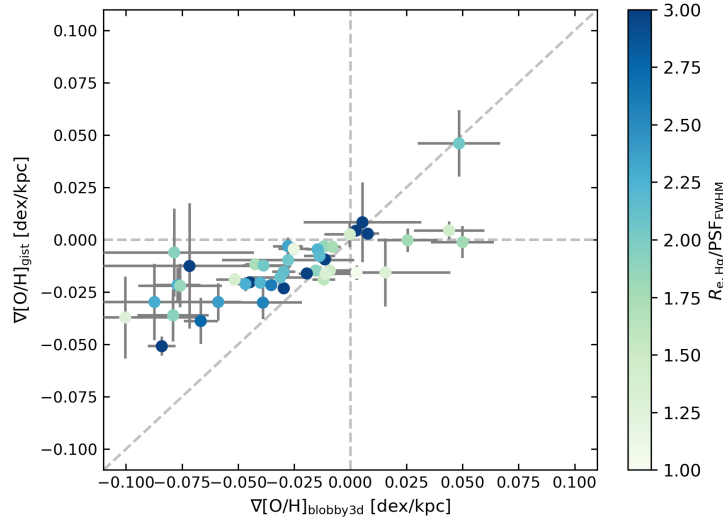


Figure 4.8: Comparison of seeing-convolved ($\nabla[\text{O}/\text{H}]_{\text{gist}}$) and seeing-deconvolved ($\nabla[\text{O}/\text{H}]_{\text{blobby3d}}$) metallicity gradient of the MAGPI galaxies, colour-coded by the ratio between $R_{\text{e,H}\alpha}$ and the FWHM of PSF.

measure the true metallicity gradient for higher redshift galaxies.

The substructures of the emission line flux distribution, such as clumps, spiral arms and rings, also influence the metallicity gradient (Belfiore et al., 2017). Most modelling techniques assume a radial profile of flux or metallicity without considering the substructures (e.g. Carton et al., 2018).

The modelling technique we used accounts for the effect of seeing and has a large flexibility in the flux distribution. We compare the seeing-deconvolved metallicity gradient measured from the flux map output of BLOBBY3D with the seeing-convolved metallicity gradient measured from the flux map output of GIST, in Figure 4.8. We see that the seeing-convolved metallicity gradients are flatter than the seeing-deconvolved gradients.

Although we note that the largest galaxies are closest to the one-to-one line, smaller galaxies (relative to seeing) are typically further from the one-to-one line, but some (with small BLOBBY3D gradients) still lie near the one-to-one line. The potential reason is that the low S/N cut we chose induces large uncertainty on metallicity measurement. Also, if a galaxy has a true gradient that is flat, it will not change much. The flattening- $R_{\text{e,H}\alpha}/\text{PSF}_{\text{FWHM}}$ relation may be stronger if a higher S/N cut is applied (Acharyya et al., 2020).

4.7 Conclusions

We measured the seeing-deconvolved gas-phase metallicity of 44 star-forming galaxies at $z \sim 0.3$ from the MAGPI survey. We used a Bayesian inference method, BLOBBY3D, to model the flux distribution of different emission lines. This method takes the effect of seeing into account and has high flexibility with regard to the flux

distribution. We calculated the metallicity using the N2O2 and N2H α diagnostics (Kewley et al., 2019). We summarise the main findings below.

- (i) The median of the metallicity gradient of galaxies in our sample is $-0.028^{+0.031}_{-0.044}$ dex/kpc. The majority of the galaxies (66%) have significant ($\geq 2\sigma$) negative metallicity gradients. A small fraction of galaxies (7%) have significant positive gradients. And 27% of galaxies have relatively flat metallicity gradients.
- (ii) The $\nabla[\text{O}/\text{H}]-M_*$ relation of the MAGPI galaxies is generally consistent with the theoretical prediction of Sharda et al. (2024), which suggests that multiple mechanisms, including stellar feedback, gas transportation and gas accretion, contribute to the shaping of the metallicity profile, and the relative importance of these mechanisms varies with the stellar mass of galaxies. The metallicity gradients of low-mass MAGPI galaxies are steeper on average than galaxies at $z \sim 0$. However, the scatter and uncertainty of metallicity gradients of low-mass galaxies are large in our sample. Further study with a large sample is needed to understand the variation of metallicity gradients at $z \sim 0.3$.
- (iii) The metallicity gradient is positively correlated with σ_{gas} ($r = 0.48$) and Σ_{SFR} ($r = 0.37$). Galaxies with higher gas turbulence tend to have flatter or even positive metallicity gradients. Our results suggest that stellar feedback, gas accretion and transportation are important to drive gas turbulence and enhance gas-mixing, leading to flatter or inverted metallicity gradients.
- (iv) The metallicity gradients measured using N2O2 and N2H α diagnostics are broadly consistent. The difference between them may result from the variation of ionisation parameter and ISM pressure.

Acknowledgements

We wish to thank the ESO staff, and in particular the staff at Paranal Observatory, for carrying out the MAGPI observations. MAGPI targets were selected from GAMA. GAMA is a joint European-Australasian project based around a spectroscopic campaign using the Anglo-Australian Telescope. GAMA was funded by the STFC (UK), the ARC (Australia), the AAO, and the participating institutions. GAMA photometry is based on observations made with ESO Telescopes at the La Silla Paranal Observatory under programme ID 179.A-2004, ID 177.A-3016. The MAGPI team acknowledge support by the Australian Research Council Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D), through project number CE170100013. YM is supported by an Australian Government Research Training Program (RTP) Scholarship.

Data availability

The MUSE data used in this work are available on the ESO public archive. The reduced MAGPI datacubes and the emission line data products will be public in the MAGPI team data release (Mendel et al. in prep and Battisti et al. in prep).

Chapter 5

Conclusions

5.1 Summary of the thesis

In this thesis, we have studied the spatially resolved stellar and gas kinematics and metallicity distribution to understand what drives their evolution. Different properties of galaxies are interconnected, offering multiple perspectives on understanding the evolutionary pathways of galaxies. In this chapter, we summarise our conclusions from each previous chapter and discuss potential future directions.

In Chapter 2, we focused on the connection between galaxy rotation and the motion of neighbouring galaxies. We obtained the projected spin vectors of stellar kinematics of 1397 galaxies from the SAMI Galaxy Survey and the redshifts of neighbouring galaxies from the GAMA survey. We measured the relative motion between the SAMI galaxies and their neighbours by calculating the average velocity offset between them as a function of the distance from the SAMI galaxies. We only found modest evidence of the coherence between galaxy rotation and the motion of neighbouring galaxies within 2 Mpc (2.8σ). This coherence might arise from galaxy interaction, flybys and mergers. Another possible explanation is that the coherence may link to the alignment between low-mass galaxy spin vectors relative to their nearest filament (Welker et al., 2020) and the spin of the filament itself (Xia et al., 2021; Wang et al., 2021). However, we also found the coherence signals were consistent with zero or even negative ($\sim 2\sigma$) for galaxies outside 3 Mpc, which suggested the modest signal within 2 Mpc may result from coincidental scatter or variation of large-scale structure. The tentative evidence we found for neighbouring galaxies within 2 Mpc needs to be confirmed by larger samples of IFS observations, such as the MaNGA survey (Bundy et al., 2015) and the forthcoming Hector survey (Bryant et al., 2020).

In Chapter 3, we forward modelled the ionised gas distribution and kinematics of 110 star-forming galaxies at $z \sim 0.3$ (the MAGPI survey) and compared our results to the galaxies at $z \sim 0$ (the SAMI survey) and $z \sim 1$ (the KROSS survey), for which the gas kinematics is measured using a consistent method. The gas velocity dispersion (σ_{gas}) decreases from $z \sim 1$ to $z \sim 0$, which is consistent with the finding in previous studies (e.g. Übler et al., 2019). We explored the correlation between

σ_{gas} and a variety of galaxy properties. We found the σ_{gas} of the MAGPI and SAMI galaxies has the strongest correlation with star-formation rate surface density (Σ_{SFR}) and a modest correlation with Σ_{SFR} for the KROSS galaxies. The average σ_{gas} is similar at the same Σ_{SFR} for galaxies at different redshifts, suggesting that the mechanisms related to Σ_{SFR} , such as stellar feedback or gas instability, may be the dominant driver of gas turbulence from $z \sim 1$ to 0. We also used the difference in velocity between the observed data and the model (Δv) to trace the non-rotational motion of the gas. Using a partial correlation analysis, We found Δv has a modest correlation with σ_{gas} at fixed Σ_{SFR} and stellar mass, indicating that the non-rotational motion of the gas, such as gas transportation, also contributes to gas turbulence. We found the correlation between σ_{gas} and Σ_{SFR} is relatively weaker at $z \sim 1$ than lower redshifts, which is consistent with the suggestion that the importance of stellar feedback decreases with redshift and other mechanisms, such as gas transportation and accretion are more important in driving gas turbulence at higher redshift.

In Chapter 4, we extended our analysis of the ionised gas distribution to the metallicity distribution. We measured the seeing-deconvolved gas-phase metallicity gradient of 44 star-forming galaxies from the MAGPI survey. The median of the metallicity gradient of galaxies at $z \sim 0.3$ is $-0.028^{+0.031}_{-0.044}$ dex/kpc. 29 out of 44 galaxies (66%) have significant ($\geq 2\sigma$) negative metallicity gradients. The overall negative metallicity gradient is consistent with the inside-out growth of the galactic disc. We found that the $\nabla[\text{O}/\text{H}]-M_*$ relation of the MAGPI galaxies is generally consistent with the theoretical prediction of [Sharda et al. \(2024\)](#), which includes gas accretion, transportation and stellar feedback in the model. We found that galaxies with higher σ_{gas} and Σ_{SFR} tend to have flatter metallicity gradients. The $\nabla[\text{O}/\text{H}]-\sigma_{\text{gas}}$ relation may result from the stellar feedback, gas accretion and transportation processes, which drive gas turbulence, mix gas and flatten the metallicity gradient.

The results in Chapter 3 and Chapter 4 illustrate the connection between different galaxy properties, revealing that the underlying physical mechanisms drive the correlation between them. The non-rotational motion of gas, such as inflows and outflows, increases the gas turbulence and flattens the metallicity gradient. Both $\nabla[\text{O}/\text{H}]$ and σ_{gas} have strong correlation with Σ_{SFR} . Gas accretion and transportation may trigger star formation, drive gas turbulence, mix gas at different radii and flatten the metallicity gradient.

5.2 Future work

5.2.1 Molecular gas properties

In Chapter 3, we analysed the ionised gas kinematics and its relation to galaxy properties. We found the ionised gas velocity dispersion has a strong correlation with Σ_{SFR} . This correlation can be explained by the stellar feedback-driven gas turbulence. However, [Krumholz & Burkhardt \(2016\)](#) proposed that the disc of a galaxy tends to stay in marginally stable status and the $\sigma_{\text{gas}}-\Sigma_{\text{SFR}}$ relation could be produced by gravitational instability in the gas. Their theory predicts a rela-

tion between σ_{gas} and SFR and the steepness of the relation changes with the gas fraction. The gravitational stability parameter of the disc depends on the gas surface density. Therefore, to test the robustness of their theory, the measurement of the gas fraction and gas surface density, for example using the Atacama Large Millimeter/submillimeter Array (ALMA) is needed.

We could use ALMA data to investigate the difference between molecular and ionised gas velocity dispersion for the MAGPI sample in a further study. Molecular and ionised gas velocity dispersion trace different phases of the interstellar medium. Multiple molecular gas tracers (e.g. multi-J CO, HCO⁺, C[I], HCN, H₂O) can provide us with plenty of information on molecular gas properties and their physical conditions (e.g. [Caldú-Primo et al., 2013](#); [Caldú-Primo & Schrubba, 2016](#); [Mogotsi et al., 2016](#); [Koch et al., 2019](#)).

5.2.2 Developing BLOBBY3D

In Chapter 3, we found 4 AGN-host MAGPI galaxies have interesting kinematic distortion patterns. The gas velocity maps of these galaxies deviate from simple regular rotation discs. After subtracting the symmetric rotational velocity from the velocity map, the residual velocity maps of these four galaxies show a clear $m = 3$ Fourier mode. The underlying physical mechanisms are still unclear. We explored several possible explanations, including interaction with a satellite galaxy that disturbs galaxy disc, and spiral arms induced large-scale streaming motion of the gas. It would be interesting to use hydrodynamic N-body simulation to have a further analysis on this kind of pattern (e.g. [Bland-Hawthorn & Tepper-García, 2021](#); [Tepper-García et al., 2022](#)).

We plan to develop BLOBBY3D code to make it able to model more complex kinematics and have a further investigation of this kind of kinematic distortion on larger samples of galaxies to understand its physical mechanisms and the role of AGN in this kinematic distortion. It is also interesting to investigate the relation between kinematics distortion and bar/spiral arms structure and its impact on local star formation activity.

BLOBBY3D assumes a log-linear profile of the velocity dispersion. However, the gas velocity dispersion may vary in different regions of galaxies. A possible way to improve the model is to allow each blob in BLOBBY3D has its own velocity dispersion, which gives more flexibility in the distribution of gas velocity dispersion. We can use it to investigate how stellar feedback influences local gas turbulence. However, implementing individual velocity dispersions per blob introduces additional free parameters into the model, which may increase the risk of parameter degeneracy. This could complicate the fitting process and reduce the reliability of parameter estimates, particularly in cases where the observational data lack sufficient resolution or S/N. Estimating the valid range of velocity dispersion and using priors in the model might mitigate these issues.

5.2.3 The evolution of gas kinematics at $z > 1$

Gas velocity dispersion is found to be decreased over cosmic time, i.e. gas in the galaxy settles down, from pressure-dominated to rotation-dominated. The pivotal epoch of galaxy disc settle down is $z \sim 1$. However, the epoch of this transformation is still not well understood. Current analysis on gas velocity dispersion in high redshift galaxies is biased to relatively massive, high SFR galaxies, which also have high gas velocity dispersion (Übler et al., 2024). It would be interesting to investigate the gas velocity dispersion of lower mass galaxies at $z > 1$ using BLOBBY3D on data observed by the Giant Magellan Telescope (GMT) and Extremely Large Telescope (ELT) in the future. Analysing the high redshift galaxies with relatively low Σ_{SFR} can fill the lower Σ_{SFR} end in the current analysis. The results can be compared to the research of gas velocity dispersion at $z < 1$ in this thesis to further our understanding of the evolution of different physical processes that drive gas turbulence.

Bibliography

- ALMA Partnership et al., 2015, [ApJ](#), 808, L3
- Abazajian K. N., et al., 2009, [ApJS](#), 182, 543
- Acharyya A., et al., 2020, [MNRAS](#), 495, 3819
- Alam S., et al., 2015, [ApJS](#), 219, 12
- An S.-H., et al., 2021, [ApJ](#), 914, 86
- Aumer M., et al., 2010, [ApJ](#), 719, 1230
- Babcock H. W., 1939, [Lick Observatory Bulletin](#), 498, 41
- Bacchini C., et al., 2020, [A&A](#), 641, A70
- Bacon R., et al., 2001, [MNRAS](#), 326, 23
- Bacon R., et al., 2010, in McLean I. S., Ramsay S. K., Takami H., eds, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series Vol. 7735, Ground-based and Airborne Instrumentation for Astronomy III. p. 773508, [doi:10.1117/12.856027](#)
- Bacon R., et al., 2017, [A&A](#), 608, A1
- Baldry I. K., et al., 2018, [MNRAS](#), 474, 3875
- Baldwin J. A., Phillips M. M., Terlevich R., 1981, [PASP](#), 93, 5
- Bardeen J. M., 1980, [Phys. Rev. D](#), 22, 1882
- Barsanti S., et al., 2022, [MNRAS](#), 516, 3569
- Barsanti S., et al., 2023, [MNRAS](#), 526, 1613
- Bekiaris G., et al., 2016, [MNRAS](#), 455, 754
- Belfiore F., et al., 2017, [MNRAS](#), 469, 151
- Bellstedt S., et al., 2020, [MNRAS](#), 498, 5581
- Bertin G., Lodato G., 1999, [A&A](#), 350, 694
- Bik A., et al., 2022, [A&A](#), 666, A161
- Binette L., et al., 2012, [A&A](#), 547, A29

- Bird J. C., et al., 2021, [MNRAS](#), 503, 1815
- Bittner A., et al., 2019, [A&A](#), 628, A117
- Bland-Hawthorn J., Tepper-García T., 2021, [MNRAS](#), 504, 3168
- Bland-Hawthorn J., et al., 2011, [Optics Express](#), 19, 2649
- Bland-Hawthorn J., et al., 2024, [ApJ](#), 968, 86
- Blanton M. R., et al., 2017, [AJ](#), 154, 28
- Blue Bird J., et al., 2020, [MNRAS](#), 492, 153
- Blumenthal G. R., et al., 1984, [Nature](#), 311, 517
- Boardman N. F., et al., 2021, [MNRAS](#), 501, 948
- Boardman N., et al., 2023, [Monthly Notices of the Royal Astronomical Society](#), 520, 4301
- Boissier S., Prantzos N., 1999, [Monthly Notices of the Royal Astronomical Society](#), 307, 857
- Bouché N., et al., 2010, [ApJ](#), 718, 1001
- Bouché N., et al., 2015, [AJ](#), 150, 92
- Bouché N. F., et al., 2024, [arXiv e-prints](#), p. arXiv:2411.07014
- Bournaud F., Combes F., 2002, [A&A](#), 392, 83
- Bournaud F., Elmegreen B. G., Martig M., 2009, [ApJ](#), 707, L1
- Bower R. G., et al., 2006, [MNRAS](#), 370, 645
- Brewer B. J., Foreman-Mackey D., 2018, [Journal of Statistical Software](#), 86, 1–33
- Brewer B. J., Pártay L. B., Csányi G., 2011, [Statistics and Computing](#), 21, 649
- Brook C. B., et al., 2012, [MNRAS](#), 424, 1275
- Brough S., et al., 2017, [ApJ](#), 844, 59
- Bruzual G., Charlot S., 2003, [MNRAS](#), 344, 1000
- Bryant J. J., et al., 2011, [MNRAS](#), 415, 2173
- Bryant J. J., et al., 2014, [MNRAS](#), 438, 869
- Bryant J. J., et al., 2015, [MNRAS](#), 447, 2857
- Bryant J. J., et al., 2020, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series. p. 1144715, doi:10.1117/12.2560309
- Bundy K., et al., 2015, [ApJ](#), 798, 7
- Caldú-Primo A., Schrubba A., 2016, [AJ](#), 151, 34
- Caldú-Primo A., et al., 2013, [AJ](#), 146, 150

- Calzetta E., Hu B. L., 1995, [Phys. Rev. D](#), 52, 6770
- Capelo P. R., Dotti M., 2017, [MNRAS](#), 465, 2643
- Cappellari M., 2002, [MNRAS](#), 333, 400
- Cappellari M., 2016, [ARA&A](#), 54, 597
- Cappellari M., 2017, [MNRAS](#), 466, 798
- Cappellari M., Emsellem E., 2004, [PASP](#), 116, 138
- Cappellari M., et al., 2007, [MNRAS](#), 379, 418
- Cappellari M., et al., 2011, [MNRAS](#), 413, 813
- Cappellari M., et al., 2013, [MNRAS](#), 432, 1709
- Cardelli J. A., Clayton G. C., Mathis J. S., 1989, [ApJ](#), 345, 245
- Carton D., et al., 2018, [MNRAS](#), 478, 4293
- Cervantes-Sodi B., Hernandez X., Park C., 2010, [MNRAS](#), 402, 1807
- Ceverino D., et al., 2017, [MNRAS](#), 467, 2664
- Chabrier G., 2003, [PASP](#), 115, 763
- Charlot S., Fall S. M., 2000, [ApJ](#), 539, 718
- Charlot S., Longhetti M., 2001, [MNRAS](#), 323, 887
- Chen Q.-H., et al., 2023, [arXiv e-prints](#), p. arXiv:2310.20073
- Chiappini C., Matteucci F., Romano D., 2001, [ApJ](#), 554, 1044
- Chisholm J., Tremonti C., Leitherer C., 2018, [MNRAS](#), 481, 1690
- Choi H., et al., 2018, [ApJ](#), 856, 114
- Cicone C., et al., 2014, [A&A](#), 562, A21
- Codis S., et al., 2012, [MNRAS](#), 427, 3320
- Codis S., et al., 2018, [MNRAS](#), 481, 4753
- Cole S., et al., 2000, [MNRAS](#), 319, 168
- Colless M., et al., 2001, [MNRAS](#), 328, 1039
- Condon J. J., et al., 1998, [AJ](#), 115, 1693
- Conroy C., Gunn J. E., 2010, [ApJ](#), 712, 833
- Conroy C., Gunn J. E., White M., 2009, [ApJ](#), 699, 486
- Conroy C., White M., Gunn J. E., 2010, [ApJ](#), 708, 58
- Cortese L., et al., 2016, [MNRAS](#), 463, 170
- Courteau S., 1997, [AJ](#), 114, 2402

- Cresci G., et al., 2010, [Nature](#), 467, 811
- Croom S. M., et al., 2012, [MNRAS](#), 421, 872
- Croom S. M., et al., 2021, [MNRAS](#), 505, 991
- Croton D. J., et al., 2006, [MNRAS](#), 365, 11
- D'Eugenio F., et al., 2021, [MNRAS](#), 504, 5098
- Davé R., Finlator K., Oppenheimer B. D., 2012, [MNRAS](#), 421, 98
- Davies R., et al., 2011, [ApJ](#), 741, 69
- Davis M., et al., 1985, [ApJ](#), 292, 371
- De Lucia G., Blaizot J., 2007, [MNRAS](#), 375, 2
- Dekel A., Sari R., Ceverino D., 2009, [ApJ](#), 703, 785
- Di Teodoro E. M., Fraternali F., 2015, [MNRAS](#), 451, 3021
- Dib S., Bell E., Burkert A., 2006, [ApJ](#), 638, 797
- Dinerstein H. L., 1990, in Thronson Harley A. J., Shull J. M., eds, *Astrophysics and Space Science Library* Vol. 161, *The Interstellar Medium in Galaxies*. pp 257–285, [doi:10.1007/978-94-009-0595-5_10](#)
- Dopita M. A., Evans I. N., 1986, [ApJ](#), 307, 431
- Doroshkevich A. G., 1970, [Astrophysics](#), 6, 320
- Dressler A., 1980, [ApJ](#), 236, 351
- Driver S. P., et al., 2011, [MNRAS](#), 413, 971
- Drory N., et al., 2015, [AJ](#), 149, 77
- Dubois Y., et al., 2014, [MNRAS](#), 444, 1453
- Easeman B., et al., 2022, [MNRAS](#), 511, 371
- Edmunds M. G., Pagel B. E. J., 1984, [MNRAS](#), 211, 507
- Efstathiou G., Jones B. J. T., 1979, [MNRAS](#), 186, 133
- Egorov O. V., et al., 2023, [arXiv e-prints](#), p. [arXiv:2307.10277](#)
- Ellison S. L., et al., 2008, [ApJ](#), 672, L107
- Emsellem E., et al., 2004, [MNRAS](#), 352, 721
- Emsellem E., et al., 2007, [MNRAS](#), 379, 401
- Epinat B., Amram P., Marcelin M., 2008, [MNRAS](#), 390, 466
- Epinat B., et al., 2010, [MNRAS](#), 401, 2113
- Epinat B., et al., 2024, [A&A](#), 683, A205
- Ewen H. I., Purcell E. M., 1951, [Nature](#), 168, 356

- Fabian A. C., 2012, [ARA&A](#), 50, 455
- Faisst A. L., et al., 2016, [ApJ](#), 822, 29
- Faucher-Giguère C.-A., Quataert E., Hopkins P. F., 2013, [MNRAS](#), 433, 1970
- Fitzpatrick E. L., et al., 2019, [ApJ](#), 886, 108
- Flores H., et al., 2006, [A&A](#), 455, 107
- Forbes J., Krumholz M., Burkert A., 2012, [ApJ](#), 754, 48
- Forbes J. C., et al., 2014, [MNRAS](#), 438, 1552
- Forbes J. C., et al., 2023, [ApJ](#), 948, 107
- Foster C., et al., 2021, [PASA](#), 38, e031
- Franchetto A., et al., 2021, [The Astrophysical Journal](#), 923, 28
- Freeman K. C., 1970, [ApJ](#), 160, 811
- Fu J., et al., 2009, [ApJ](#), 696, 668
- Fusco T., et al., 2020, [A&A](#), 635, A208
- Gabor J. M., Bournaud F., 2014, [MNRAS](#), 437, L56
- Gallazzi A., et al., 2014, [ApJ](#), 788, 72
- Ganeshaiah Veena P., et al., 2019, [MNRAS](#), 487, 1607
- Garnavich P. M., et al., 1998, [ApJ](#), 493, L53
- Genel S., Dekel A., Cacciato M., 2012, [MNRAS](#), 425, 788
- Genzel R., et al., 2006, [Nature](#), 442, 786
- Genzel R., et al., 2017, [Nature](#), 543, 397
- Genzel R., et al., 2023, [ApJ](#), 957, 48
- Gibson B. K., et al., 2013, [A&A](#), 554, A47
- Gillman S. R., 2020, Doctoral thesis, Durham University, <https://etheses.dur.ac.uk/13573/>
- Giolfi M., et al., 2020, [A&A](#), 633, A90
- Ginzburg O., et al., 2022, [MNRAS](#), 513, 6177
- Gordon K., 2024, dust_extinction, doi:10.5281/zenodo.11235336, <https://doi.org/10.5281/zenodo.11235336>
- Grand R. J. J., et al., 2016, [MNRAS](#), 460, L94
- Green A. W., et al., 2010, [Nature](#), 467, 684
- Green A. W., et al., 2014, [MNRAS](#), 437, 1070
- Greene J. E., et al., 2017, [ApJ](#), 851, L33

- Guth A. H., 1981, [Phys. Rev. D](#), **23**, 347
- Guthrie B. N. G., 1992, [A&AS](#), **93**, 255
- Hägele G. F., et al., 2006, [MNRAS](#), **372**, 293
- Harborne K. E., et al., 2020, [MNRAS](#), **497**, 2018
- Harrison C. M., et al., 2017, [MNRAS](#), **467**, 1965
- Hashimoto Y., et al., 1998, [ApJ](#), **499**, 589
- Hemler Z. S., et al., 2021, [MNRAS](#), **506**, 3024
- Ho I. T., et al., 2015, [MNRAS](#), **448**, 2030
- Hopkins A. M., Beacom J. F., 2006, [ApJ](#), **651**, 142
- Hoyle F., 1951, in Problems of Cosmical Aerodynamics. p. 195
- Hubble E. P., 1926, [ApJ](#), **64**, 321
- Hung C.-L., et al., 2019, [MNRAS](#), **482**, 5125
- Jiménez E., et al., 2023, [MNRAS](#), **524**, 4346
- Johnson H. L., et al., 2018, [MNRAS](#), **474**, 5076
- Jones T., et al., 2010, [ApJ](#), **725**, L176
- Jones T., et al., 2013, [ApJ](#), **765**, 48
- Kassin S. A., et al., 2012, [ApJ](#), **758**, 106
- Katz N., Weinberg D. H., Hernquist L., 1996, [ApJS](#), **105**, 19
- Kauffmann G., et al., 2003, [MNRAS](#), **346**, 1055
- Kauffmann G., et al., 2004, [MNRAS](#), **353**, 713
- Kawata D., et al., 2014, [MNRAS](#), **443**, 2757
- Kennicutt Robert C. J., 1998, [ARA&A](#), **36**, 189
- Kennicutt R. C., Evans N. J., 2012, [ARA&A](#), **50**, 531
- Kepner J. V., 1999, [ApJ](#), **520**, 59
- Kereš D., et al., 2009, [MNRAS](#), **396**, 2332
- Kewley L. J., Dopita M. A., 2002, [ApJS](#), **142**, 35
- Kewley L. J., et al., 2001, [ApJ](#), **556**, 121
- Kewley L. J., et al., 2010, [The Astrophysical Journal Letters](#), **721**, L48
- Kewley L. J., Nicholls D. C., Sutherland R. S., 2019, [ARA&A](#), **57**, 511
- Khachaturyants T., et al., 2022, [MNRAS](#), **512**, 3500
- Kim C.-G., Ostriker E. C., Kim W.-T., 2013, [ApJ](#), **776**, 1

- Kingsburgh R. L., Barlow M. J., 1992, [MNRAS](#), **257**, 317
- Klessen R. S., Hennebelle P., 2010, [A&A](#), **520**, A17
- Kobayashi C., Nakasato N., 2011, [ApJ](#), **729**, 16
- Kobayashi C., Taylor P., 2023, [arXiv e-prints](#), p. [arXiv:2302.07255](#)
- Koch E. W., et al., 2019, [MNRAS](#), **485**, 2324
- Kohandel M., et al., 2020, [MNRAS](#), **499**, 1250
- Koo H., Lee J., 2018, [ApJ](#), **858**, 51
- Krajnović D., et al., 2006, [MNRAS](#), **366**, 787
- Kraljic K., Davé R., Pichon C., 2020, [MNRAS](#), **493**, 362
- Kraljic K., et al., 2021, [MNRAS](#), **504**, 4626
- Krumholz M., Burkert A., 2010, [ApJ](#), **724**, 895
- Krumholz M. R., Burkhardt B., 2016, [MNRAS](#), **458**, 1671
- Krumholz M. R., Kruijssen J. M. D., Crocker R. M., 2017, [MNRAS](#), **466**, 1213
- Krumholz M. R., et al., 2018, [MNRAS](#), **477**, 2716
- Laigle C., et al., 2015, [MNRAS](#), **446**, 2744
- Lara-López, M. A. et al., 2022, [A&A](#), **660**, A105
- Larson R. B., 1976, [MNRAS](#), **176**, 31
- Law D. R., et al., 2009, [ApJ](#), **697**, 2057
- Law D. R., et al., 2021, [AJ](#), **161**, 52
- Law D. R., et al., 2022, [ApJ](#), **928**, 58
- Lee J. C., Hwang H. S., Chung H., 2018, [MNRAS](#), **477**, 1567
- Lee J. H., et al., 2019a, [ApJ](#), **872**, 78
- Lee J. H., et al., 2019b, [ApJ](#), **884**, 104
- Lehnert M. D., et al., 2013, [A&A](#), **555**, A72
- Lequeux J., et al., 1979, [A&A](#), **80**, 155
- Leslie S. K., et al., 2018, [A&A](#), **615**, A7
- Leslie S. K., et al., 2020, [ApJ](#), **899**, 58
- Levy R. C., et al., 2018, [ApJ](#), **860**, 92
- Lewis I., et al., 2002, [MNRAS](#), **334**, 673
- Li C., et al., 2006, [MNRAS](#), **368**, 37
- Lian J., et al., 2019, [MNRAS](#), **489**, 1436

- Lilly S. J., et al., 2013, [ApJ](#), **772**, 119
- Lindblad B., 1925, *Arkiv for Matematik, Astronomi och Fysik*, **21**, 1
- Linde A. D., 1982, [Physics Letters B](#), **108**, 389
- Liske J., et al., 2015, [MNRAS](#), **452**, 2087
- López-Sanjuan C., et al., 2012, [A&A](#), **548**, A7
- López P., Merchán M. E., Paz D. J., 2019, [MNRAS](#), **485**, 5244
- López P., et al., 2021, [MNRAS](#), **502**, 5528
- Mac Low M.-M., et al., 1998, [Phys. Rev. Lett.](#), **80**, 2754
- Madau P., Dickinson M., 2014, [ARA&A](#), **52**, 415
- Madau P., Pozzetti L., Dickinson M., 1998, [ApJ](#), **498**, 106
- Mai Y., et al., 2022, [MNRAS](#), **515**, 984
- Mai Y., et al., 2024, [MNRAS](#), **533**, 3878
- Maiolino R., Mannucci F., 2019, [A&A Rev.](#), **27**, 3
- Mannucci F., et al., 2010, [MNRAS](#), **408**, 2115
- Marinacci F., et al., 2014, [Monthly Notices of the Royal Astronomical Society](#), **442**, 3745
- Mast D., et al., 2014, [A&A](#), **561**, A129
- Matteucci F., Francois P., 1989, [MNRAS](#), **239**, 885
- Mayor M., Vigroux L., 1981, [A&A](#), **98**, 1
- McGaugh S. S., 1991, [ApJ](#), **380**, 140
- Mesa V., et al., 2014, [MNRAS](#), **438**, 1784
- Mitchell P. D., et al., 2020, [MNRAS](#), **494**, 3971
- Mogotsi K. M., et al., 2016, [AJ](#), **151**, 15
- Moiseev A. V., Tikhonov A. V., Klypin A., 2015, [MNRAS](#), **449**, 3568
- Molina J., et al., 2020, [A&A](#), **643**, A78
- Mollá M., Díaz A. I., 2005, [MNRAS](#), **358**, 521
- Moon J.-S., An S.-H., Yoon S.-J., 2021, [ApJ](#), **909**, 34
- Mott A., Spitoni E., Matteucci F., 2013, [Monthly Notices of the Royal Astronomical Society](#), **435**, 2918
- Mun M., et al., 2024, [MNRAS](#),
- Nelson D., et al., 2019, [Computational Astrophysics and Cosmology](#), **6**, 2
- Oh S., et al., 2022, [MNRAS](#), **512**, 1765

- Oliva-Altamirano P., et al., 2018, [MNRAS](#), **474**, 522
- Oort J. H., 1926, PhD thesis, -
- Oort J. H., 1927, Bull. Astron. Inst. Netherlands, **3**, 275
- Osterbrock D. E., 1989, Astrophysics of gaseous nebulae and active galactic nuclei
- Ostriker E. C., Shetty R., 2011, [ApJ](#), **731**, 41
- Ostriker E. C., McKee C. F., Leroy A. K., 2010, [ApJ](#), **721**, 975
- Owers M. S., et al., 2017, [MNRAS](#), **468**, 1824
- Pagel B. E. J., et al., 1979, [MNRAS](#), **189**, 95
- Park C., et al., 2007, [ApJ](#), **658**, 898
- Pasquini L., et al., 2002, The Messenger, **110**, 1
- Peebles P. J. E., 1969, [ApJ](#), **155**, 393
- Peebles P. J. E., 1971, [A&A](#), **11**, 377
- Peebles P. J. E., 1982, [ApJ](#), **263**, L1
- Peebles P. J. E., 1984, [ApJ](#), **277**, 470
- Peimbert M., Spinrad H., 1970, [A&A](#), **7**, 311
- Peng C. Y., et al., 2010, [AJ](#), **139**, 2097
- Pérez-Montero E., 2017, [PASP](#), **129**, 043001
- Perlmutter S., et al., 1999, [ApJ](#), **517**, 565
- Pestaña J. L. G., Cabrera J., 2004, [MNRAS](#), **353**, 1197
- Pezzulli G., Fraternali F., 2016, [MNRAS](#), **455**, 2308
- Pilkington K., et al., 2012, [A&A](#), **540**, A56
- Pillepich A., et al., 2018, [MNRAS](#), **473**, 4077
- Pilyugin L. S., Thuan T. X., 2005, [ApJ](#), **631**, 231
- Pilyugin L. S., Vílchez J. M., Thuan T. X., 2006, [MNRAS](#), **370**, 1928
- Poetrodjojo H., et al., 2021, [MNRAS](#), **502**, 3357
- Popesso P., et al., 2023, [MNRAS](#), **519**, 1526
- Porciani C., Dekel A., Hoffman Y., 2002, [MNRAS](#), **332**, 325
- Portinari L., Chiosi C., 1999, [A&A](#), **350**, 827
- Purcell E. M., 1953, Proceedings of the American Academy of Arts and Sciences, **82**, 347
- Queyrel J., et al., 2012, [A&A](#), **539**, A93

- Rathjen T.-E., et al., 2023, [MNRAS](#), 522, 1843
- Riess A. G., et al., 1998, [AJ](#), 116, 1009
- Robotham A. S. G., et al., 2017, [MNRAS](#), 466, 1513
- Robotham A. S. G., et al., 2018, [MNRAS](#), 476, 3137
- Robotham A. S. G., et al., 2020, [MNRAS](#), 495, 905
- Rousseau-Nepton L., et al., 2019, [MNRAS](#), 489, 5530
- Rubin V. C., Ford W. Kent J., 1970, [ApJ](#), 159, 379
- Rupke D. S. N., 2018, [Galaxies](#), 6, 138
- Rupke D. S. N., Kewley L. J., Barnes J. E., 2010, [The Astrophysical Journal Letters](#), 710, L156
- Sánchez-Menguiano L., et al., 2016, [A&A](#), 587, A70
- Sánchez-Menguiano L., et al., 2018, [A&A](#), 609, A119
- Sánchez S. F., et al., 2012, [A&A](#), 538, A8
- Sánchez S. F., et al., 2014, [A&A](#), 563, A49
- Sánchez S. F., et al., 2016, [A&A](#), 594, A36
- Sargent M. T., et al., 2010, [ApJ](#), 714, L113
- Schäfer B. M., 2009, [International Journal of Modern Physics D](#), 18, 173
- Schaye J., et al., 2015, [MNRAS](#), 446, 521
- Schlaflly E. F., Finkbeiner D. P., 2011, [ApJ](#), 737, 103
- Scott N., et al., 2018, [MNRAS](#), 481, 2299
- Shanks T., et al., 2015, [MNRAS](#), 451, 4238
- Sharda P., et al., 2021a, [MNRAS](#), 504, 53
- Sharda P., et al., 2021b, [MNRAS](#), 506, 1295
- Sharda P., et al., 2024, [MNRAS](#), 528, 2232
- Sharp R., et al., 2006, in McLean I. S., Iye M., eds, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series Vol. 6269, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series. p. 62690G ([arXiv:astro-ph/0606137](#)), doi:10.1117/12.671022
- Sharp R., et al., 2015, [MNRAS](#), 446, 1551
- Sharples R., et al., 2013, [The Messenger](#), 151, 21
- Shetty R., Ostriker E. C., 2012, [ApJ](#), 754, 2
- Sillero E., et al., 2017, [MNRAS](#), 472, 4404

- Skilling J., 2004, in Fischer R., Preuss R., Toussaint U. V., eds, American Institute of Physics Conference Series Vol. 735, Bayesian Inference and Maximum Entropy Methods in Science and Engineering: 24th International Workshop on Bayesian Inference and Maximum Entropy Methods in Science and Engineering. pp 395–405, [doi:10.1063/1.1835238](https://doi.org/10.1063/1.1835238)
- Slipher V. M., 1914, Lowell Observatory Bulletin, **2**, 66
- Somerville R. S., Davé R., 2015, *ARA&A*, **53**, 51
- Somerville R. S., Primack J. R., 1999, *MNRAS*, **310**, 1087
- Springel V., Hernquist L., 2003, *MNRAS*, **339**, 312
- Springel V., et al., 2005, *Nature*, **435**, 629
- Stanghellini L., Kaler J. B., 1989, *ApJ*, **343**, 811
- Stewart K. R., et al., 2011, *ApJ*, **738**, 39
- Stinson G. S., et al., 2010, *MNRAS*, **408**, 812
- Stone J. M., Ostriker E. C., Gammie C. F., 1998, *ApJ*, **508**, L99
- Stott J. P., et al., 2014, *MNRAS*, **443**, 2695
- Stott J. P., et al., 2016, *MNRAS*, **457**, 1888
- Stoughton C., et al., 2002, *AJ*, **123**, 485
- Sun J., et al., 2020, *ApJ*, **892**, 148
- Tacconi L. J., Genzel R., Sternberg A., 2020, *ARA&A*, **58**, 157
- Taylor K., Atherton P. D., 1980, *MNRAS*, **191**, 675
- Taylor P., Kobayashi C., 2017, *MNRAS*, **471**, 3856
- Taylor E. N., et al., 2011, *MNRAS*, **418**, 1587
- Tempel E., Libeskind N. I., 2013, *ApJ*, **775**, L42
- Tepper-García T., Bland-Hawthorn J., Freeman K., 2022, *MNRAS*, **515**, 5951
- Toomre A., 1964, *ApJ*, **139**, 1217
- Tremonti C. A., et al., 2004, *ApJ*, **613**, 898
- Tsukui T., et al., 2024, *MNRAS*, **527**, 8941
- Tudorache M. N., et al., 2022, *MNRAS*, **513**, 2168
- Tumlinson J., et al., 2011, *Science*, **334**, 948
- Tumlinson J., Peebles M. S., Werk J. K., 2017, *ARA&A*, **55**, 389
- Übler H., et al., 2019, *ApJ*, **880**, 48
- Übler H., et al., 2024, *MNRAS*, **527**, 9206

- Vallat R., 2018, [Journal of Open Source Software](#), 3, 1026
- Varidel M., et al., 2016, [PASA](#), 33, e006
- Varidel M. R., et al., 2019, [MNRAS](#), 485, 4024
- Varidel M. R., et al., 2020, [MNRAS](#), 495, 2265
- Vaughan S. P., et al., 2022, [MNRAS](#), 516, 2971
- Veale M., et al., 2017, [MNRAS](#), 471, 1428
- Veilleux S., Cecil G., Bland-Hawthorn J., 2005, [ARA&A](#), 43, 769
- Virtanen P., et al., 2020, [Nature Methods](#), 17, 261
- Wang W., et al., 2004, [A&A](#), 427, 873
- Wang P., et al., 2018, [ApJ](#), 866, 138
- Wang P., et al., 2021, [Nature Astronomy](#),
- Wang D., et al., 2022, [MNRAS](#), 516, 3411
- Weijmans A.-M., et al., 2014, [MNRAS](#), 444, 3340
- Welker C., et al., 2014, [MNRAS](#), 445, L46
- Welker C., et al., 2020, [MNRAS](#), 491, 2864
- White S. D. M., 1984, [ApJ](#), 286, 38
- White S. D. M., Frenk C. S., 1991, [ApJ](#), 379, 52
- White S. D. M., Rees M. J., 1978, [MNRAS](#), 183, 341
- Whittaker J., 2009, Graphical models in applied multivariate statistics. Wiley Publishing
- Wiklind T., et al., 2019, [ApJ](#), 878, 83
- Wisnioski E., et al., 2015, [ApJ](#), 799, 209
- Wuyts S., et al., 2011, [ApJ](#), 738, 106
- Wuyts E., et al., 2016, [ApJ](#), 827, 74
- Xia Q., et al., 2021, [MNRAS](#), 506, 1059
- Yu X., et al., 2019, [MNRAS](#), 486, 4463
- Yuan Q.-r., Zhu C.-x., 2004, , 28, 127
- Yuan T. T., et al., 2011, [ApJ](#), 732, L14
- Yuan T. T., Kewley L. J., Rich J., 2013, [ApJ](#), 767, 106
- Zahid H. J., et al., 2014, [ApJ](#), 791, 130
- Zhou L., et al., 2017, [MNRAS](#), 470, 4573

- da Cunha E., Charlot S., Elbaz D., 2008, [MNRAS](#), 388, 1595
- de Bernardis P., et al., 2000, [Nature](#), 404, 955
- van de Sande J., et al., 2017a, [MNRAS](#), 472, 1272
- van de Sande J., et al., 2017b, [ApJ](#), 835, 104
- van de Sande J., et al., 2021a, [MNRAS](#), 505, 3078
- van de Sande J., et al., 2021b, [MNRAS](#), 508, 2307