SDSS-IV MaNGA: Global Properties of Kinematically Misaligned Galaxies

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ABSTRACT
We select 456 gas-star kinematically misaligned galaxies from the internal Product Launch-10 of MaNGA survey, including 74 star-forming (SF), 136 green-valley (GV) and 206 quiescent (QS) galaxies. We find that the distributions of difference between gas and star position angles for galaxies have three local peaks at star-forming (SF), 136 green-valley (GV) and 206 quiescent (QS) galaxies. We find that the distributions of difference between the stellar and gaseous components. Furthermore, if the evolution of galaxies is primarily controlled by the internal process, we would expect kinematic alignment between the stellar and gaseous components. However, about two decades ago, long-slit spectroscopic observations have revealed that phenomenon of gas-star counter-rotation (Galletta 1987) is ubiquitous (20–24%) in elliptical and lenticular galaxies (Bertola et al. 1992; Kuijken et al. 1996; Kannappan & Fabricant 2001). Due to the development of integral-field spectroscopic (IFS) surveys, on the one hand, they confirm the universality of gas-star misalignment (20–50%) in early type galaxies ( Sarzi et al. 2006; Davis et al. 2011; Barrera-Ballesteros et al. 2015; Chen et al. 2016; Jin et al. 2016; Bryant et al. 2019). On the other hand, they find a fraction of 2–5% gas-star misalignment in blue star forming galaxies (Chen et al. 2016; Jin et al. 2016; Bryant et al. 2019). The misaligned gaseous components in these kinds of galaxies are believed to originate from external processes. They provide an ideal laboratory to investigate the influences of external processes on galaxy evolution. Whether the newly acquired gas triggers/enhances star formation or AGN activities? Whether the structure of the host galaxies is completely reshaped or merely perturbed?

In the last decade, series of work based on the IFS surveys are devoted to study the spatially resolved properties of gas-star kinematically misaligned galaxies, trying to understand their formation mechanisms. Galactic scale gas-star misalignment is believed to originate externally. Galaxy interaction, merger and gas accretion from dwarf companion or cosmic web are all proposed to be its possible origin. Based on ATLAS3D survey, Davis et al. (2011) discover 42 ± 5% of

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early-type galaxies in field showing kinematic misalignments while almost all the galaxies in Virgo cluster have gas-star alignment, which suggest a strong dependence on the environment. Barrera-Ballesteros et al. (2014, 2015) compare the ΔPA (ΔPA = |PA_{stellar} − PA_{gas}|, where PA_{stellar} is position angle of stellar velocity field and PA_{gas} is PA for gas) distribution between interacting galaxies (different stage of merger) and non-interacting galaxies in CALIFA survey, finding that galaxies with large ΔPA (≥ 50°) are dominated by early-type interacting galaxies, compared to small ΔPA (< 30°) in late-type interacting galaxies and non-interacting control samples, indicating merger is the main formation pathway for kinematic misalignment in early-type galaxies. Combining MaNGA survey with optical images from DESI Legacy survey, Li et al. (2021) find out that the merging remnant fraction is ~10% higher in quiescent misaligned galaxies with ΔPA > 30° than their co-rotating counterparts, while the fraction is nearly identical between star-forming misaligned galaxies (~10%) and co-rotators (~7%). Based on the MaNGA survey, the existence of blue counter-rotators has been discovered and they show younger stellar populations with more intense ongoing star formation in the central region (Chen et al. 2016; Jin et al. 2016), suggesting gas accretion in blue star-forming galaxies as an origin of kinematic misalignment. Chen et al. (2016) and Jin et al. (2016) propose the interaction between pre-existing and accreted gas as an angular momentum loss mechanism. Bryant et al. (2019) discover a similar environment dependence of misaligned fraction using SAMI survey, and point out that mergers are not the primary driver of gas-star misalignment in disc galaxies, while in clusters the misalignment is mainly driven by inner cluster process such as ram pressure stripping. As a summary, the literatures suggest different types of kinematically misaligned galaxies possess different formation mechanisms.

Following the development of observations, kinematically misaligned galaxies are also found and investigated based on cosmological simulations. Taylor et al. (2018) examine 3 gas-star counter-rotating galaxies among 82 galaxies with 10 < log(M_*/M_☉) < 11.8 and all of them experience gas accretion from cosmological filaments followed by gas inflow to the galaxy center. Starkenburg et al. (2019) find that ~73% of counter-rotating galaxies with 9.3 < log(M_*/M_☉) < 10.7 experience AGN feedback/lyby through group or cluster before the phenomenon of counter-rotation (ΔPA > 90°). Duckworth et al. (2020a,b) find that misaligned galaxies with log(M_*/M_☉) < 10.2 have enhanced black hole (BH) luminosity and BH growth in IllustrisTNG. Both Starkenburg et al. (2019) and Duckworth et al. (2020a,b) suggest gas removal followed by misaligned gas accretion is a key step to form low mass misaligned galaxies. However, Khoperskov et al. (2021) discover 25 star-star counter-rotating galaxies with 9.3 < log(M_*/M_☉) < 10.5, finding that they all display gas-star misalignments and experience gas accretion but without sudden gas removal by AGN feedback. Bassett et al. (2017) study gas-star counter-rotating S0 galaxies formed through minor merger finding that the key requirement for counter-rotation is the companion galaxy lying in the retrograde orbit with respect to the primary. From IllustrisTNG, Lu et al. (2021) concentrate on the dynamically hot star-forming disc galaxies with 9.7 < log(M_*/M_☉) < 10.3 and find out that the counter-rotating galaxies experience less mergers compared to normal disc galaxies. Using Horizon-AGN simulation, Khim et al. (2021) estimate relative contribution of different formation mechanisms to the emergence of gas-star misalignment in galaxies with log(M_*/M_☉) > 10 finding that mergers contribute ~35%, galaxy interactions (gas accretion from nearby galaxies) contribute ~23%, environmental interactions such as ram pressure stripping contribute ~21% and secular evolution (containing smooth gas accretion from filaments) contributes ~21%.

In this paper, we select 456 gas-star kinematically misaligned galaxies from the internal Product Launch-10 (MPL-10) in Mapping Nearby Galaxies at Apache Point Observatory (MaNGA, Bundy et al. 2015), a new fibre-optic integral field unit (IFU) survey. This is the largest gas-star kinematically misaligned sample so far. As a complementary work of Xu et al. (2022), we study the global properties of the misaligned galaxies. The paper is organized as follows. In Section 2 we give a short introduction on MaNGA survey and describe our data selection process. In Section 3 the global properties for kinematically misaligned galaxies are studied, including the distribution of ΔPA; the fraction of misaligned galaxies as a function of galaxy properties; gas kinematic asymmetry; H i-detection rate and molecular gas mass; size, morphology, the spin parameters of stars, and the environment. The flat ΛCDM cosmological model is applied with parameters H₀ = 70 km s⁻¹ Mpc⁻¹, Ωₘ = 0.3, and Ωₐ = 0.7 throughout this paper.

2 DATA

2.1 The MaNGA survey

MaNGA is a core program in the fourth-generation Sloan Digital Sky Survey (SDSS-IV, Blanton et al. 2017) started on July 1, 2014. The program uses the 2.5 m Sloan Foundation Telescope at the Apache Point Observatory (Gunn et al. 2006). Unlike previous SDSS surveys which obtain single fiber spectra at the centers of target galaxies, MaNGA applies 17 simultaneous hexagonal IFUs (Law et al. 2015) with the diameter ranging from 12′′ (19 fibers) to 32′′ (127 fibers) to explore detailed internal structure of nearby galaxies (Dory et al. 2015), while the mini-bundles with seven fibers are used for flux calibration (Yan et al. 2016a). It has finished the survey of an unprecedented sample of about 10,000 galaxies in early 2021 with a redshift coverage of 0.01 < z < 0.15 (Wake et al. 2017). The galaxies are selected to span a stellar mass interval of nearly 3 orders of magnitude with a flat distribution in between 9 ≤ log(M_*/M_☉) ≤ 11. The target selection procedure divides galaxies into “Primary” and “Secondary” which extend the radial coverage out to ~ 1.5 effective radius (R_e, Petrosian 50% light radius) and ~ 2.5R_e respectively (Yan et al. 2016b). Two dual-channel BOSS spectrographs provide a wavelength coverage of 3600-10,300Å with a spectral resolution of R ~ 2000 (Smee et al. 2013). Typical 3-hour dithered exposures ensure a per-fiber r-band continuum signal-to-noise ratio (S/N) per angstrom of 4 – 8 at 1.5R_e, with much higher S/N towards the center. The 2′′ fiber diameter corresponds to a spatial sampling of 1 – 2 kpc.

The Data Reduction Pipeline (DRP, Law et al. 2016) of MaNGA provides sky subtracted and flux calibrated 3D spectra for each galaxy. The Data Analysis Pipeline (DAP) is a survey-led software package for analyzing the spectra produced by the DRP to estimate physical properties. The DAP (Westfall et al. 2019) has been developed since 2014 and gone through several versions. In this work, we use the MaNGA sample and DAP products drawn from the MPL-10. The DAP heavily relies on penalized pixel-fitting (pPXF, Cappellari & Emsellem 2004) and a subset of stellar templates from MaStar library (Yan et al. 2019) to fit the stellar continuum and absorptions in each spaxel. The data products include the measurements of stellar kinematics, nebular emission-line properties (e.g., fluxes, equivalent widths, kinematics), spectral indices of absorption-line (e.g., Hδ) and bandhead/color (e.g., TiO, D$_n$4000).
Global Properties of Misaligned Galaxies

2.2 Sample selection

From the 9,456 unique galaxies in MPL-10, we first select 9,291 galaxies without faults and critical failure in DRP or DAP marked by DAPDONE and DAPQUAL keywords. To get the robust measurement of gas velocity field, we first discard 2,333 “lineless” galaxies. The “lineless” galaxies are defined as objects with Hα S/N lower than 3 for more than 90% spaxels within $1.5R_e$. The remaining 6,958 sources are referred as emission-line galaxies. We then use PaFit package in Python (Krajnović et al. 2006) to fit the position angle (PA) for stellar and gaseous velocity fields of each galaxy. Spaxels within $1.5R_e$ with median spectral S/N>3 per spaxel are used for fitting, where bad spaxels are removed based on the MaNGA DAP flag.

With the measurements of PA of stellar component ($PA_{\text{star}}$) and gaseous component ($PA_{\text{gas}}$), the position angle offset $\Delta PA = |PA_{\text{star}} - PA_{\text{gas}}|$ is calculated for each emission-line galaxy. We then select 723 candidates of misaligned galaxies defined as $\Delta PA > 30^\circ$ with robust PA measurements ($PA_{\text{error}} \leq 60^\circ$, where $PA_{\text{error}}$ is the 1$\sigma$ error of PAs).

Finally, we visually check the 723 sources and select 456 misaligned galaxies. On-going mergers, galaxies with irregular morphologies, groups within a single MaNGA bundle are removed through this process since it is hard to assign a major axis. In summary we obtain 456 misaligned galaxies from 6,958 emission-line galaxies in MPL-10.

Fig. 1 shows three examples of MaNGA galaxies. The left column gives the false color image. The middle and right column display the stellar and Hα velocity field respectively. The solid green lines mark the position angle (PA) of each component while the blue dashed lines mark the ±1$\sigma$ error of PAs. Top panel shows a galaxy in which stellar and ionized gas components are rotation in the same way. The middle panel shows a galaxy with gas-star perpendicularly rotating while the bottom panel displays a gas-star counter-rotator.

Figure 1. Examples of MaNGA galaxies with different types of kinematically misalignment. Each row corresponds to a MaNGA galaxy. The left column shows the SDSS $g$, $r$, $i$-band images with hexagons marking the regions of MaNGA bundle. The middle and right columns show stellar and gaseous velocity fields (traced by Hα) respectively. Red side moves away from us while blue side approaches us. The solid green lines mark the position angle (PA) of each component while the blue dashed lines mark the ±1$\sigma$ error of PAs. Top panel shows a galaxy in which stellar and ionized gas components are rotation in the same way. The middle panel shows a galaxy with gas-star perpendicularly rotating while the bottom panel displays a gas-star counter-rotator.
We cross match the MaNGA galaxies with catalog from Chang et al. (2015) and obtain the global stellar mass ($M_*$), star formation rate (SFR) for 6,217 emission-line galaxies and 416 out of 456 misaligned galaxies. The $M_*$ and SFR are estimated through photometric spectrum energy distribution (SED) fitting based on data from SDSS and WISE photometry with Chabrier initial mass function (IMF, Chabrier 2003). Fig. 2 shows the SFR vs. $M_*$ diagram with grey dots representing MaNGA galaxies and the red squares being the misaligned sample. The black contours depict galaxies from Chang et al. (2015). It is clear that there are two density peaks of these contours. The two black dashed lines (Jin et al. 2016) separate galaxies into three populations, where the upper line is the $\Delta p$ scatter of the star-forming main sequence and the lower line is log sSFR $\sim$ $-15$ (Chen et al. 2016). The top density peak with high SFR is defined as the star forming main sequence (SF), while the bottom peak with little star formation is the red quiescent sequence (QS). The population in between these two extremes is defined as green valley (GV). These 416 misaligned galaxies are divided into 74 SF, 136 GV and 206 QS galaxies. And the fractions of misaligned galaxies in emission-line galaxies with different galaxy types are 2.4% (SF), 7.3% (GV) and 15.6% (QS) respectively.

2.3 Control Samples

It is believed that the gas of the kinematically misaligned galaxies has an external origin like mergers and gas accretion. In order to quantify the influence of external gas acquisition on the following evolution of progenitor galaxies, we build ten non-misaligned control samples with $\Delta pA < 30^\circ$ for comparison. For each misaligned galaxy, we randomly select ten non-misaligned galaxies which are closely matched in the global $M_*$ and SFR, with $|\Delta \log M_*| < 0.1$ and $|\Delta \log \text{SFR}| < 0.2$. The motivation of choosing $M_*$ and SFR as matching parameters includes: (i) stellar mass is the most fundamental property of a galaxy and tightly correlates with many other physical parameters; (ii) requiring the control galaxies to have similar SFR is extremely important since the fraction of kinematically misaligned galaxies strongly depends on star formation activity (see Section 3.2). We show one of the control samples in Fig. 2 as blue squares. The right-hand panel gives the distribution of SFR for misaligned (blue) galaxies and control (red) samples while the top panel gives the distribution of $M_*$. The peak of each distribution is set to 1. It is clear that the sample and controls have similar distributions in $M_*$ and SFR.

3 RESULTS

3.1 $\Delta pA$ Distribution

Fig. 3 shows the $\Delta pA$ distribution for galaxies with robust gaseous and stellar PA measurements (black solid). The blue solid, green dashed and red dotted histograms represent the SF, GV and QS samples respectively. There are three local peaks at $\Delta pA \approx 0^\circ$, $90^\circ$ and $180^\circ$. To quantify the statistical significance of the peak at $90^\circ$, we perform the one-sample KS test with respect to a normal distribution which has a mean value of $90^\circ$ with standard deviation of $15^\circ$. The $p$-value for SF, GV, QS and all galaxies are 0.347, 0.192, 0.552 and 0.928 respectively. The $p$-value larger than 0.05 suggests that we cannot reject the hypothesis that they are drawn from the normal distribution at the peak of $90^\circ$. This triple peak distribution can be easily understood that the gas disks will feel a torque from stellar disks in case of $\Delta pA \neq 0^\circ$, $90^\circ$, $180^\circ$, which will pull the gas disk to co-rotating or counter-rotating with respect to stellar disks.

3.2 The fraction of misaligned galaxies

It is well known that the misaligned galaxies are ubiquitous in S0 and elliptical galaxies, but much fewer in blue star forming galaxies. This could be due to the large cross section between gaseous galaxies. If misaligned galaxies accrete external gas, the newly acquired gas will collide with the pre-existing gas in the progenitors, leading to the redistribution of angular momentum (Chen et al. 2016). Thus, in the gas-poor early type galaxies, the accreted gas would be easier to survive since the interaction with pre-existing gas is less important and the collisional cross-section between gas and star is too small to influence the angular momentum of the accreted gas, while in the gas-rich star forming galaxies, the misaligned phenomenon would only appear when the angular momentum of the accreted gas is larger than the pre-existing gas.

In the MaNGA target selection strategy (Wake et al. 2017), there is no cuts on size, inclination, morphology or environment. It provides an unprecedented IFU sample which is fully representative of the local galaxy population and the selection is well understood. Based on the largest misaligned sample from MaNGA, we analyze the dependence of kinematic misalignment fraction on galaxy physical parameters ($M_*$, SFR, sSFR $\equiv$ SFR/$M_*$) over all the galaxy populations.

Fig. 4 shows how the fraction of misaligned galaxies varies with $M_*$ (left), SFR (middle) and sSFR (right). We estimate the error bar by bootstrap method. The red circles are fractions of misaligned galaxies with respect to all galaxies (including emission-line and "lineless" galaxies) in a certain parameter bin, while black squares are fractions with respect to only emission-line galaxies. We find that the misaligned fraction peaks at $\log(M_*/M_\odot) \sim 10.5$ and declines to both low and high mass end. This fraction also decreases monotonically with increasing SFR and sSFR. In essence, this is the dependence on the amount of pre-existing gas. Galaxies with higher star formation activity are expected to contain larger amount of pre-existing gas, which makes it difficult for the newly accreted gas to maintain misaligned angular momentum. The decline of this fraction at the low mass end is primarily due to the fact that the low mass galaxies with $\log(M_*/M_\odot) < 10 \sim 10.5$ in the local universe are dominated by star-forming galaxies with higher sSFR. At the high mass end, the decrease of this fraction is consistent with Davis et al. (2011) and Jin et al. (2016). The low fraction of misalignment in the massive galaxies is suggested to be caused by galactic scale processes which suppress the accretion of external cold gas onto the galaxy, such as AGN feedback, existence of a hot X-ray gas halo, or a halo mass threshold.

3.3 Global properties of misaligned galaxies

3.3.1 Kinematic asymmetry

Considering that the misaligned galaxies have gone through gas accretion, external interaction or merging process, we would expect to find evidence of disturbance of gas velocity fields. In this section, we compare the asymmetry parameters ($V_{\text{asym}}$) of gas velocity fields between misaligned galaxies and their control samples. $V_{\text{asym}}$ used in this work is defined exactly the same as Equation (2) in Feng et al. (2020) and basically calculates higher-order coefficients of Fourier components normalized by the first-order coefficient, where the higher-order coefficients describe the asymmetric
Figure 2. SFR versus $M_*$ diagram for kinematically misaligned galaxies and one of the control samples. The black contours represent galaxies from Chang et al. (2015). The grey open circles represent MaNGA MPL-10 galaxies with $M_*$ and SFR measurements in Chang’s catalogue. Red squares represent misaligned galaxies while blue open squares represent control samples. Two dashed lines separate galaxies into star-forming, green-valley and quiescent. The top and right panels show distribution of stellar masses and SFR for the misaligned galaxies (red) and their control samples (blue) respectively. The peak of each distribution is set to 1.

pattern of the velocity fields and the first-order represents symmetric patterns of the velocity fields. Therefore higher value of $V_{\text{ asym}}$ means higher asymmetry. We refer readers to Feng et al. (2020) for more details of asymmetry parameter estimation.

Fig. 5 shows the distribution of kinematic asymmetry of gaseous component for the three galaxy types: SF (left), GV (middle) and QS (right). The red and blue histograms represent kinematically misaligned galaxies and their control samples, respectively. The peak of each distribution is set to 1. The dashed red and solid blue lines mark the median value of each distribution for misaligned galaxies and their controls, while the red and blue lines shown in top-right represent the median error of log $V_{\text{ asym}}$ for misaligned galaxies and control samples respectively. The diagram shows that in SF and GV galaxies, the asymmetry of gas velocity fields is higher in misaligned galaxies than their control samples, which is totally consistent with our expectation that the acquisition of external gas would cause larger asymmetry in gaseous components of misaligned galaxies. For QS misaligned galaxies, we do not have definite conclusion due to the larger error, which can be attributed to the S/N of H{$\alpha$} flux.

3.3.2 Gaseous content

It is suggested that misaligned galaxies acquire gas from external environments, which would lead to higher amount of gas in misaligned galaxies. On the other hand, the interaction between the pre-existing and accreted gas will cause redistribution of angular momentum and gas inflow, resulting in a rapid transformation of gas into stars. This process is especially important in the SF misaligned galaxies, in which their star-formation activity within central 1kpc is several times higher than the average of local star-forming galaxies (Chen et al. 2016). From this point of view, the cold gas fraction could be lower in the misaligned galaxies since they are transformed into stars efficiently. We do not have cold gas observations for the sample. However, HI-MaNGA program provide GBT H{$\alpha$} observation for a subsample. In this section, we compare the H{$\alpha$} detection rate and molecular gas mass fraction estimated from dust extinction (Barrera-Ballesteros et al. 2018) between misaligned galaxies and their control samples.

HI-MaNGA is a follow-up program to detect H{$\alpha$} for MaNGA galaxies using the Green Bank Telescope (GBT). The third data release of HI-MaNGA value-added catalogue contains 6,632 galaxies, where 3,358 of them are observed by GBT and the remaining...
galaxies are within ALFALFA catalogue (Haynes et al. 2018). The observation depth for GBT is about 1.5 mJy and velocity resolution is ~ 10 km s\(^{-1}\). We refer readers to Masters et al. (2019) & Stark et al. (2021) for more details about the HI-MaNGA project.

We cross-match the misaligned galaxies with HI-MaNGA value-added catalogue, finding 302 out of 416 matches and 90 of them are detected. Considering the beam size of GBT and ALFALFA is in the order of arcmin, the HI detection could be contaminated by nearby galaxies. Stark et al. (2021) flag potential confused sources which are located within 1.5 times the half-power beam width (HPBW) and at similar redshift of the primary target. They also estimate the probability \( P_{R=0.2} \) where \( R \) represents the fraction of contribution to the total measured flux from the companions. In this work, we remove 44 sources in which HI flux is contaminated by limiting confusion flag = 1 and \( P_{R>0.2} > 0.1 \) (Stark et al. 2021). We build 10 control samples from HI-observed galaxies for the 258 (= 302 – 44) misaligned galaxies. The control samples are selected in a similar way as described in Section 2.3 but with an additional requirement: \( |\Delta z| < 0.001 \). Fig. 6 shows the HI-detection rate \( (N_{\text{detected}}/N_{\text{observed}}) \) for the misaligned galaxies and control samples, where \( N_{\text{observed}} \) is the number of galaxies matched in HI-MaNGA catalogue and \( N_{\text{detected}} \) is the number of galaxies detected in HI. Red histograms in Fig. 6 are for the misaligned sample and blue for their controls. It is clear that the HI-detection rate is significantly lower in misaligned galaxies than their controls for SF, GV and QS.

Considering that there are only 46 (= 90 – 44) HI-detected misaligned galaxies, this sample is hardly to give a robust statistics on HI mass distribution. We estimate the molecular gas mass \( M_{\text{gas}} \) based on the method described in Barrera-Ballesteros et al. (2018). The molecular gas mass is estimated as \( \Sigma_{\text{gas}} = 30M_\odot\text{pc}^{-2}A_V \), where optical extinction \( A_V \) is from the Balmer decrement. We construct 10 control samples with the same criteria as we construct control samples for HI-observed misaligned galaxies. Fig. 7 shows the distribution of molecular gas mass fraction defined as \( M_{\text{gas}}/M_* \) between misaligned galaxies (red) and control samples (blue). It is clear that misaligned galaxies have lower molecular gas mass fraction than the control samples.

A similar result is reported in Duckworth et al. (2020a) based on a sample of ~4500 galaxies in MaNGA MPL-8, where the gas mass is estimated in exactly the same way. Based on IllustrisTNG simulation, Lu et al. (2021) show that low mass counter-rotating disc galaxies possess smaller H\(_i\) mass fraction within twice the half stellar mass radius \( 2R_{\text{hsm}} \). The evidence of lower H\(_i\) detection rate and molecular gas mass fraction in the SF and GV misaligned sample could be the consequence of high star-formation efficiency (SFE = SFR/M\(_{\text{gas}}\)). Based on the MaNGA survey, Chen et al. (2016) compare the star-formation activity parameter \( \alpha_{\text{SF}} = 1/(sSFR \times (\tau_{\text{H}}(z) - 1\text{Gyr}) \) between SF counter-rotators and the average of local SF galaxies, where \( \tau_{\text{H}}(z) \) is the Hubble time at redshift \( z \) and \( \alpha_{\text{SF}} \) compares the current SFR and the past average. They show that the central star-formation activity of SF misaligned galaxies is several times higher than the average of local SF galaxies within central 1kpc. Based on a larger sample, Xu et al. (2022) discover that the central region of misaligned SF galaxies have higher SFR in comparison with their control samples, and the misaligned galaxies shows smaller central D\(_e\)4000 indicating younger stellar populations in SF and GV misaligned galaxies. For the QS misaligned galaxies, the H\(_i\) and molecular gas deficiency could be due to a selection bias that progenitors with lower gaseous contents are easier to show kinematic misalignments, since the lack of interaction between accreted and pre-existing gas.

### 3.3.3 Size

As suggested by Chen et al. (2016), gas-gas collision leads to fast gas inflow, triggering the central star formation. These newly formed stars may lead to the change of stellar light/mass distribution, especially for the gas-rich SF galaxies. In this section, we compare \( r\)-band effective radius \( R_e \), which is defined as a radius containing 50% emission of a galaxy, between misaligned galaxies and their control samples.

In this work, we take \( R_e \) from NASA-Sloan Atlas (NSA)\(^1\) (Blanton et al. 2011) and convert it to physical scale in unit of kpc. Fig. 8 shows the distribution of \( R_e \) for the misaligned galaxies (red) and control samples (blue). The red and blue vertical lines mark the median value of each distribution. There is a clear trend that misaligned galaxies have smaller \( R_e \) than the control samples for all the three types of galaxies. It is about 1.5 – 2 kpc smaller for SF and GV misaligned galaxies than their controls and 1 kpc smaller for QS misaligned galaxies.

This result is within our expectation under the picture of angular momentum loss due to gas-gas collision for the SF galaxies, and then the in-falling gas gathering in the central region triggering star formation, which increases the brightness at the galaxy center. Since \( R_e \) quantifies the radius at which half of light is emitted, the central star formation would be manifested as the decline of \( R_e \). Similar results are also found in simulation. Starkenburg et al. (2019) find that counter-rotating galaxies with \( \Delta PA > 90^\circ \) have smaller half stellar mass radius compared to the whole sample with 9.3 < log\((M_*/M_\odot)\) < 10.7. Lu et al. (2021) discover the star-forming counter-rotators with 9.7 < log\((M_*/M_\odot)\) < 10.3 also have smaller half stellar mass radius compared to normal disc galaxies. The difference in \( R_e \) between GV misaligned galaxies and their controls indicates that similar process happen in GV galaxies. The

\(^1\) http://nsatlas.org/
difference in $R_e$ between QS misaligned galaxies and their controls is smaller, we will discuss this difference in Section 4.1.

3.3.4 Morphology

Galaxy morphology can be characterized by the Sérsic index. The surface brightness profile can be described as:

$$ I(R) = I_0 \cdot \exp \left[ -\beta_n \cdot \left( \frac{R}{R_e} \right)^{1/n} \right], $$

where $I(R)$ is surface brightness at radius $R$, $I_0$ is central surface brightness and $n$ is called Sérsic index. The case of $n = 2$ is used as the demarcation for disc dominated versus bulge dominated galaxies. The value of Sérsc index for MaNGA galaxies is taken from the NASA-Sloan Atlas catalogue. Fig. 9 shows the distribution of Sérsc index for the misaligned galaxies (red) and their control samples (blue). The red and blue vertical lines mark the median value of each distribution.

For all the three types of galaxies, the misaligned galaxies show larger Sérsc index than their control samples, with smallest difference in $n$ for QS galaxies. The median value for SF misaligned galaxies is $n \sim 3$, while the median value for control sample is less than 2, implying SF misaligned galaxies are more bulge dominated compared to the disc nature of their controls. The GV misaligned galaxies (median $n \sim 4$) also show a more bulge dominated feature than controls (close to disc dominated, with median $n \sim 2$). Both QS misaligned galaxies and their controls display bulge dominated feature with median of $n$ for misaligned galaxies is a little bit higher than controls. As suggested by Chen et al. (2016), for SF misaligned galaxies, the redistribution of angular momentum happens during the interaction between accreted and pre-existing gas, leading to gas inflow and central star formation. The central star-formation will alter the light distribution, leading to higher Sérsc index of SF misaligned galaxies. The higher Sérsc index of GV galaxies could be attributed to a similar process.
3.3.5 Spin parameter $\lambda_R$

Based on the picture described in the previous sections, the interaction between accreted and pre-existing gas will lead to the loss of angular momentum. The newly formed stellar components from the gas will have lower angular momentum. To explore the kinematic state of stellar component of a galaxy, we calculate the spin parameter $\lambda_R$, as a proxy for the specific angular momentum of stars in the galaxy (Emsellem et al. 2007). This parameter is similar to $V/\sigma$ but incorporates spatial information, which is defined as

$$\lambda_R = \frac{\sum_{i=1}^{N_p} F_i R_i |V_i|}{\sum_{i=1}^{N_p} F_i R_i \sqrt{V_i^2 + \sigma_i^2}}$$

where $R$ is the radius within which the summation has been made, $F_i$, $V_i$, $\sigma_i$ are the $r$-band flux, stellar velocity and stellar velocity dispersion of the $i$th spaxel, $R_i$ is the distance between the $i$th spaxel and the galaxy center.

Fig. 10 show the distribution of $\lambda_R$ for the stellar components between misaligned galaxies (red) and control samples (blue). The two vertical lines mark the median value of each distribution. As $\lambda_R$ is a projected quantity, we add an additional control parameter inclination $\varphi_{\text{incl}}$ with $|\Delta \varphi_{\text{incl}}| < 5^\circ$. Clearly, all the three types of misaligned galaxies tend to rotate slower than the control samples. Similar results are reported in both observations and simulations. Duckworth et al. (2020a) find that misaligned galaxies with different morphological types in MaNGA survey are all have lower angular momentum in stellar components compared to their aligned counterparts, consistent with their results from IllustrisTNG simulation. Starkenburg et al. (2019) show that gas-star counter-rotating galaxies display smaller stellar spin compared to a whole sample with $9.3 < \log(M_*/M_\odot) < 10.7$. For SF misaligned galaxies, the lower $\lambda_R$ in misaligned galaxies is due to the loss of angular momentum during the interaction between accreted and pre-existing gas, leading to the newly formed stellar components with lower angular momentum. For GV misaligned galaxies, similar formation can be applied.

3.3.6 Environment

In the gas accretion scenario, we would expect the misaligned galaxies reside in environments which could provide the convenience for cold gas accretion. In dense environment, the gas stripping or halo heating mechanism may inhibit such process. From ATLAS3D survey, Davis et al. (2011) show early-type galaxies in dense group and cluster are more likely displaying kinematic alignments between gas and stars, while misalignments tend to exist in field galaxies. Based on 66 misaligned galaxies with different star-formation types in MaNGA survey, Jin et al. (2016) show that they all reside in more isolated environment. With a ~10 times larger sample size, we revisit the environmental dependence of different types of misaligned galaxies in this section. We compare the environmental parameters between misaligned galaxies and their control samples.

We use two parameters to characterize the environment of misaligned galaxies, the neighbour count ($N_{\text{neigh}}$) and the tidal strength parameter ($Q_{\text{lss}}$). $N_{\text{neigh}}$ is defined as the number of neighbours with $r$-band absolute magnitude brighter than $-19.5$ within $500$ km s$^{-1}$ line-of-sight velocity and $5$ Mpc projected distance in a volume limited sample with $z < 0.15$. The tidal strength parameter $Q_{\text{lss}}$ is a description of the total gravitational interaction strength by all the neighbours within a fixed volume. The estimation method is described in Argudo-Fernández et al. (2015) and the result is released in the GEMA-VAC catalogue. It is defined as:

$$Q_{\text{lss}} = \log \left[ \sum_i \frac{M_i}{M_p} \left( \frac{D_p}{d_i} \right)^3 \right]$$

where $M_i$ and $M_p$ are the stellar mass of the $i$th galaxy and the primary galaxy, $d_i$ is the projected distance between the primary galaxy and the $i$th neighbour with $D_p$ being the diameter of the primary galaxy.

Fig. 11 shows $N_{\text{neigh}}$ versus $Q_{\text{lss}}$ diagram for SF (top-left), GV (top-right) and QS (bottom-left) misaligned galaxies (red) and their control samples (blue). The top left and bottom right insets of each panel are the distribution of $Q_{\text{lss}}$ and $N_{\text{neigh}}$ respectively. The two vertical lines mark the median value of each distribution.

As we can see from all the three types of galaxies, misaligned galaxies tend to reside in more isolated environment with lower value of $Q_{\text{lss}}$ than their control samples. Similar trend is also found in $N_{\text{neigh}}$, but with much less significance.

4 DISCUSSION

4.1 Formation mechanisms of misaligned galaxies

It is believed that misaligned galaxies mainly form through external process, but the origin of external gas is still under debate. Galaxy interaction (Casanueva et al. 2021), major/minor merger (Khim et al. 2021) and gas accretion (Taylor et al. 2018; Starkenburg et al. 2019; Duckworth et al. 2020a,b; Khoperskov et al. 2021) are all suggested to be the driver of kinematic misalignments.

In this work, we suggest different types of misaligned galaxies have undergone different formation mechanisms. For SF and GV misaligned galaxies, we propose a scenario that the progenitor galaxy accretes gas from gas-rich dwarf or cosmic web, followed by angular momentum redistribution through gas-gas interactions, leading to the star-formation in the central region. This toy model can naturally explain all of our observation results in section 3. On the one hand, a large amount of SF and GV misaligned galaxies show S0-like morphologies. Numerical simulation from Barnes (1992) suggest that merger, especially major merger could hardly keep the disk structure.

Figure 6. HI detection rate ($N_{\text{detected}}/N_{\text{observed}}$) for misaligned galaxies (red) and their control samples (blue) classified into three galaxy types (SF, GV and QS).
in spiral or S0 galaxies thus merger could not be a primary formation pathway for SF and GV misaligned galaxies. Casanueva et al. (2021) study galaxies with log(M*/M⊙) > 9 in EAGLE simulation, finding that contribution from mergers, including minor mergers, for the formation of misaligned galaxies is less than 5%. Therefore, gas accretion is a more preferred mechanism in the formation of kinematic misalignments in SF and GV galaxies. On the other hand, both SF and GV misaligned galaxies show lower Dn4000 (younger stellar population) and higher specific SFR in the central regions (Chen et al. 2016; Xu et al. 2022), indicating enhanced central star-formation activities.

We propose three possibilities to explain the origin of QS misaligned galaxies: (i) the QS misaligned galaxy is an evolutionary result of the GV misaligned galaxy. But this should not be the dominant formation mechanism because the number of GV misaligned galaxies is much less than their QS counterparts; (ii) mergers. Li et al. (2021) find that the fraction of galaxies with the merging remnant features is ~18% in quiescent misaligned galaxies and ~8% in their co-rotating counterparts, while the remnant fractions for misaligned star-forming galaxies and their co-rotating counterpart are almost identical. Khim et al. (2021) study galaxies with log(M*/M⊙) > 10 in Horizon-AGN simulation and point out the 35% misaligned galaxies form through major and minor mergers; (iii) misaligned gas accretion. The observed differences in Section 3 between misaligned QS galaxies and their controls could be due to selection bias. An old progenitor galaxy tends to have higher possibility to be more bulge dominated and contain less cold gas fraction. It is easier for them to be observed as misaligned galaxies because the interaction between accreted and pre-existing gas can be neglected.

If we assume every galaxy has the same chance to accrete external gas, a misaligned fraction of 456/6958 = 7% suggests that the kinematic misaligned phenomenon can last for ~Gyr timescale (1 Gyr/13.7 Gyr ≈ 7%). Based on the FIRE simulation, van de Voort et al. (2015) show that successive gas accretion can make the phenomenon of gas-star kinematic misalignments to last ~Gyr, which is totally consistent with our observations.
4.2 Lower gaseous content in misaligned galaxies

The misaligned galaxies show lower H\textsc{i} detection rate and molecular gas mass fraction. Similar results have been found for galaxies with different morphological types (ETGs, S0-Sas, Sb-Sd) in MaNGA survey (Duckworth et al. 2020a), also in simulations for galaxies with $9.3 < \log(M_*/M_\odot) < 10.8$ (Starkenburg et al. 2019), dynamically hot disc galaxies with $9.7 < \log(M_*/M_\odot) < 10.3$ (Lu et al. 2021).

One explanation for the lower gaseous content in SF and GV misaligned galaxies is that the cold gas is transformed into stars through higher star formation efficiency (SFE $\equiv$ SFR/$M_{\text{gas}}$). Using star-formation activity parameter $\alpha_{\text{SF}}$, Chen et al. (2016) show SF counter-rotators have several times higher star-formation activity in the central region compared to the average of local SF galaxies. Based on a larger sample, Xu et al. (2022) show that the SF misaligned galaxies have higher $s$SFR and lower $D_{\alpha}4000$ (younger stellar population) in the central region than the control samples. Both Chen et al. (2016) and Xu et al. (2022) describe a picture that the interaction between the pre-existing gas and the accreted gas leads to the angular momentum loss of gas. Thus the gas falls to the central region and triggers the star-burst/star-formation. The observed global properties in Section 3, such as higher Sérsic index, smaller $R_e$, lower spin parameter $\lambda_{R_e}$, can naturally fit into this picture for the SF and GV misaligned galaxies.

Based on the Illustris simulation, Starkenburg et al. (2019) and Duckworth et al. (2020a,b) propose the low gaseous content for misaligned galaxies is due to gas loss from AGN feedback and flyby through group or cluster. Starkenburg et al. (2019) discover 73% galaxies show BH activity or flyby through a massive system like group or cluster within 1 Gyr before emergence of counter-rotation ($\Delta PA > 90^\circ$). Duckworth et al. (2020a) find that no gas rotation galaxies (NGR galaxies, which cannot fit position angle for H\textsc{i} velocity fields due to gas depletion or dispersion dominated feature) and misaligned galaxies have similar stellar spin parameter ($J_1/R_e$), which is lower than aligned galaxies, suggesting the progenitor galaxies experience gas removal (stage of no gas) and then re-accretion (stage of misalignment). Duckworth et al. (2020b) show misaligned
galaxies with $\log(M_*/M_\odot) < 10.2$ have boosted AGN luminosity, which leads to outflows and gas removal.

However, the gas removal scenario faces difficulties in explaining the enhanced central star formation and the global properties like smaller $R_e$, lower spin parameter, higher Sérsic index observed in this work. On the other hand, Khoperskov et al. (2021) study 25 star-star counter-rotating galaxies with $\log(M_*/M_\odot) > 10.5$ in IllustrisTNG, finding that they all display gas-star misalignments due to gas accretion but without sudden gas loss by AGN feedback. We prefer the scenario that interaction between pre-existing and accreted gas triggers gas inflow, leading to enhanced central star formation and also fuelling the black hole, therefore displaying higher incidence of AGNs and boosted BH luminosity in misaligned galaxies than their controls. Both the activities of central BH and star-formation consume the cold gas, leading to lower cold gas content compared to their aligned counterparts.

For QS misaligned galaxies, the lower gaseous contents can be due to a selection bias, since progenitors with lower gas fraction would be easier to show kinematic misalignments.

4.3 Beam smearing and inclination correction of $\lambda_{R_e}$

Fig. 10 shows a large amount of SF misaligned galaxies with $\lambda_{R_e} < 0.1$, indicating that they could be slow rotators. This result is totally out of our expectation. On the one hand, galaxies with higher Sérsic index and smaller $R_e$ suffer larger beam smearing effect (Harborne et al. 2020), leading to a lower $\lambda_{R_e}$ estimation. On the other hand, as $\lambda_{R_e}$ is a projected identity, the inclination will affect our measurement to a lower value. In this section, we check how the beam smearing and inclination effect influence our results on $\lambda_{R_e}$.

We correct the beam smearing effect based on Eqn. (16) and Eqn. (18) in Harborne et al. (2020). They provide the corrections of $\lambda_{R_e}$ for galaxies with different $\sigma_{PSF}/R_e$ and Sérsic index using a series of mock observations, where $\sigma_{PSF}$ is the point spread function.
\( \delta \) of the observation. For SF galaxies, we adopt the inclination correction method described in Fraser-McKelvie et al. (2021). The inclination correction assumes that the intrinsic axial ratio is \( \alpha_0 = 0.2 \) and the anisotropy parameter is \( \beta = 0.3 \) for an edge-on disc galaxy, since SF galaxies are dominated by disc galaxies. The deprojected \( \lambda_{R_e} \) satisfies

\[
\lambda_{R_e}^{\text{deproj}} = \frac{\lambda_{R_e}}{\sqrt{C^2 - \lambda_{R_e}^2 (C^2 - 1)}} ,
\]

where \( C = \frac{\sin \theta}{\sqrt{1 - \beta \cos^2 \psi}} \), \( \cos \psi = \frac{(b/a)^2 - \alpha_0^2}{1 - \alpha_0^2} \) and \( b/a \) is the observed axial ratio.

Before any correction is applied, Fig. 3 of Fraser-McKelvie et al. (2021) shows the \( \lambda_{R_e} \) of SF galaxies ranges from 0.3 to 0.5 depending on their locations on the SF main-sequence. A median value of \( \lambda_{R_e} \sim 0.4 \) for our SF control samples is consistent with Fraser-McKelvie’s result. Once the beam smearing and inclination corrections are applied, the median value of \( \lambda_{R_e} \) in SF control sample increases to \( \sim 0.6 \) as shown in Fig. 12, which is totally consistent with Fraser-McKelvie’s result. The \( \lambda_{R_e} \) of misaligned galaxies are smaller than their control samples in all the three galaxy types (SF, GV and QS), suggesting our conclusions remain unchanged.

### 5 CONCLUSIONS

We identify 456 gas-star kinematically misaligned galaxies from MPL-10 of MaNGA survey. We cross-match them with Chang’s catalogue to obtain the global \( M_e \) and SFR measurements, identifying 74 star-forming, 136 green-valley and 206 quiescent galaxies. We find that \( \Delta \Phi_a \) distribution has three local peaks around 0°, 90° and 180°. The misaligned fraction peaks at log(\( M_e / M_{\odot} \)) \( \sim 10.5 \) and declines to both low and high mass end. This fraction decreases monotonically with increasing SFR and sSFR. Through comparing the physical properties between misaligned galaxies and their control samples, we find that:

i) For SF and GV galaxies, the asymmetry of gas velocity fields is higher in misaligned galaxies than their control samples.

ii) The \( \text{H}_i \)-detection rate is lower in misaligned galaxies than their control samples in all the three types. The estimated molecular gas fraction based on the optical extinction is also lower for misaligned galaxies.

iii) Misaligned galaxies are smaller in effective radius for all the three types of galaxies. It is about 1–2 kpc smaller for SF and GV misaligned galaxies than their controls, while it is 1 kpc smaller for QS misaligned galaxies.

iv) Misaligned galaxies in all the three types show larger Sérsic index than their control samples, with the smallest difference in \( n \) for QS galaxies. The median for SF misaligned galaxies is \( n \sim 3 \), while the median value for control sample is less than 2. The GV misaligned galaxies (median \( \sim 4 \)) also show a more bulge dominated feature than controls (close to disc dominated, with median \( \sim 2 \)). Both QS misaligned galaxies and their controls display bulge dominated feature with the smallest difference in Sérsic index.

v) All the three types of misaligned galaxies have lower spin parameters \( \lambda_{R_e} \) of stellar components compared to the control samples.

vi) Misaligned galaxies in all the three types have lower tidal strength parameter \( (Q_{\text{gas}}) \) and similar trend is also found in neighbour count (Nneigh) with much less significance, suggesting that they tend to reside in more isolated environment.

Combining those observational results, we suggest that misaligned SF and GV galaxies form through gas accretion. The angular momentum experiences redistribution during the interaction between pre-existing and misaligned accreted gas, leading to gas inflow to the center which triggers central star formation. We propose three possible origins of the misaligned QS galaxies: (1) external gas accretion; (2) merger; (3) GV galaxies evolve into QS galaxies.

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### DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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Figure 12. The $\lambda R_e$ distribution between misaligned galaxies and control sample in three galaxy types (SF, GV and QS) after beam smearing and inclination correction.

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