The Impact of Merging on The Origin of Kinematically Misaligned and Counter-rotating Galaxies in MaNGA

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ABSTRACT
Galaxy mergers and interactions are expected to play a significant role leading to offsets between gas and stellar motions in galaxies. Herein we crossmatch galaxies in MaNGA MPL-8 with the Dark Energy Spectroscopic Instrument (DESI) Legacy Surveys and identify 538 galaxies with merging/interacting features to investigate their position angle offsets ($\Delta PA$) between gas and stellar rotation. We find that there is a much higher merging/interacting fraction in misaligned galaxies ($30^\circ \leq \Delta PA < 150^\circ$) than that in co-rotators ($\Delta PA < 30^\circ$). This result corroborates that merging/interacting is one of the sources to produce misaligned galaxies and recent merging events can contribute to maximum 40% of such misalignment. Furthermore, the marginal merging/interacting fraction in star-forming (SF) counter-rotators ($\Delta PA \geq 150^\circ$) indicates the minor role of merging in the origin of SF counter-rotators. In addition, the slightly smaller merging/interacting fraction in non-star-forming (non-SF) counter-rotators ($0.14 \pm 0.039$) than that in non-SF misaligned galaxies ($0.22 \pm 0.031$) agrees with that counter-rotating is a stable state, where tidal features disappear. Finally, the ratio of co-rotators to counter-rotators in non-SF merging/interacting galaxies is about 8:1, much larger than the prediction from the isotropic merging (1:1), which supports the speculation that gas and stars prefer to be aligned during merging, as the orbital angular momentum transfers to gas and stellar spin.

Key words: galaxies: interactions - galaxies: kinematics and dynamics.

1 INTRODUCTION
The merging processes have profound influences on galaxy formation and evolution, such as enhancing star formation (SF) (Bournaud et al. 2011; Bloom et al. 2017; Pan et al. 2019), triggering active galactic nuclei (AGN) activity (Hopkins et al. 2008; Pu et al. 2018), transforming galaxy morphologies (Shi et al. 2009; Xu et al. 2012; Conselice 2014),

and causing chaos in the internal velocity fields of stars and gas.

Recently, benefiting from the developments of spatially-resolved integral field spectroscopy (IFS), it is possible to measure the position angles (PAs) of the stellar and ionized gas velocity fields directly, which are inferred from the doppler shifts of the absorption lines (for stars) and the emission lines (for gas), respectively. Some galaxies exhibit offsets in the PAs ($\Delta PA$) between the stellar and gas rotation. Galaxies with $30^\circ \leq \Delta PA < 150^\circ$ are called the misaligned
galaxies and those with ∆PA ≥ 150◦ are counter-rotators (Davis et al. 2011; Chen et al. 2016; Bryant et al. 2019).

Davis et al. (2011) investigated ionized, molecular and atomic gas in 260 early type galaxies (ETGs) in ATLAS3D (Cappellari et al. 2011), finding a large proportion of misaligned galaxies and underlining the importance of the externally acquired gas on the gas constituent in the ETGs. On the other hand, no striking differences in the kinematic PAs between gas and stars are found in non-interacting CALIFA galaxies (Sánchez et al. 2012), which are mainly late type galaxies (LTGs) (Barrera-Ballesteros et al. 2014). Moreover, Jin et al. (2016) and Chen et al. (2016) found younger stellar populations, enhanced star formation rates and higher metallicity in central regions of misaligned galaxies in MaNGA (Bundy et al. 2015) than their outer parts, which could be caused by misaligned gas accretion and its subsequent collision with in-situ gas. And Bryant et al. (2019) (hereafter B19) made use of galaxies in SAMI (Bryant et al. 2015) covering a broad range in morphological types, stellar masses and environments, proposing that not only gas accretion, but also the gas precession plays an important role in the apparent distributions of ∆PA. In addition, gas stripping and gas disc destruction induced by AGN feedback, merging and flyby events through groups or clusters make it easier to produce gas-stellar misalignment during subsequent gas re-accretion (van de Voort et al. 2015; Starkenburg et al. 2019; Duckworth et al. 2019b). Meanwhile lower stellar angular momentum inherited from halo spin exerts weaker torques on gas motion, leading to a longer time for misaligned gas precessing to align with stellar motion. As a result, galaxies with lower angular momentum are more likely to exhibit such misalignment (Duckworth et al. 2019a). All of this research shares a common sense that external processes, such as gas accretion and merging, play important roles in the formation of this kind of galaxies. In this case, the merging process could contribute to 30% of this misaligned gas (Brooks et al. 2009), and the others are from shocked and unshocked gas accretion.

While it may be expected the misaligned gas origins from external processes such as merging, there is not much observational evidence for this. Barrera-Ballesteros et al. (2015) used SDSS images to identify 103 interacting galaxies, and found a larger fraction of misalignments in interacting galaxies than in non-interacting galaxies. Furthermore, they highlighted that the misalignments correlate with merging stage. They separate the whole merging process into 4 stages (pre-merger, merger, post-merger and remnant) and found that the second and fourth stage have more misalignments. Despite a clear relationship between misalignment and galaxy interactions they found, they only have a sample of 66 interacting galaxies with well-defined ∆PA. Besides, the control sample, namely the non-interacting galaxies, is strongly biased to LTGs, while those with larger ∆PA are all ETGs. This relationship might spring from morphological dependency. A larger sample size is required for a higher statistical significance and a full estimation of star formation rate (morphological) dependency. On top of that, deeper images than SDSS are essential to look for faint structures of merging vestiges.

Mapping Nearby Galaxies at Apache Point Observatory (MaNGA) (Bundy et al. 2015) will finish observations of 10000 nearby galaxies designed to have a flat stellar mass distribution from 10^9 M⊙ to 10^{11} M⊙ with IFS data until 2020 (Wake et al. 2017). The latest internal data release MPL-8 contains 6505 unique galaxies. Meanwhile, there are plenty of methods to identify mergers, such as tidal features (Martínez-Delgado et al. 2010; Wen et al. 2014; Hood et al. 2018; Morales et al. 2018), morphological asymmetries (Richard et al. 2008; Shi et al. 2009; Lotz et al. 2010; Conselice 2014) or the galaxy pairs (Ellison et al. 2008; Li et al. 2008; Torrey et al. 2012). All of them can be extracted from the optical images. By combining MaNGA with imaging surveys, and looking for merger vestiges, we are able to directly examine the importance of the role that merger plays in kinematically misaligned galaxies.

The paper is organized as follows. In Section 2, we briefly introduce the MaNGA project, Legacy Surveys, sample selection and methodology. The observational results are shown in Section 3. We discuss the possible explanation for the ∆PA distribution of our sample in Section 4. A summary and conclusion are listed in section 5.

2 DATA AND METHODOLOGY

2.1 MaNGA

MaNGA, which started in 2014 July using the 2.5 meters telescope at Apache Point Observatory (APO) (Gunn et al. 2006), is one of three major programs in Sloan Digital Sky Survey IV (SDSS-IV, (Blanton et al. 2017)). This program aims to acquire integral field unit (IFU) spectra for 10000 nearby galaxies with redshift ranging from 0.01 to 1.0. Each target is observed to ensure the 5σ depth to reach 23 mag arcsec^{-2} (Law et al. 2015). The coverage of each galaxy is expected to be 1.5 effective radii (R_e) for primary sample and 2.5 R_e for secondary sample with typical angular resolution ~ 2.5 arcsec, corresponding to 1~2 kpc in such redshift range (Yan et al. 2016b). Thus the bundles are designed to contain 19 to 127 fibers to satisfy these coverages of galaxies with different angular size (Dory et al. 2015), with the mini-bundles with 7 fibers for flux calibration (Yan et al. 2016a). The dual-channel BOSS spectrographs cover a wavelength range of 3600~10300 Å with spectral resolution R~2000 (Smeke et al. 2013). The raw data is reduced through data reduction pipeline (DRP) (Law et al. 2016) and analyzed through Data Analysis Pipeline (DAP) (Westfall et al. 2019; Belfiore et al. 2019). In the latest internal data release MPL-8, there are 6505 unique galaxies with 3D data cubes and 2D data maps, which is the largest IFU survey sample to date.

2.2 Legacy surveys

The Dark Energy Spectroscopic Instrument (DESI) Legacy Imaging Surveys (hereafter Legacy Surveys) (Dey et al. 2019) aim to provide targets for the DESI survey. The Legacy Surveys are a combination of three public projects covering about 14000 deg² of the sky visible from the northern hemisphere: the Beijing-Arizona Sky Survey (BASS) (Zou et al. 2017) observed by the 90Prime camera (Williams et al. 2004) on the Bok 2.3-meter telescope on Kitt Peak; the Mayall z-band Legacy Survey (MzLS) (Silva et al. 2016) observed by the Mosaic3 camera (Dey et al. 2016) on the
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4-meter Mayall telescope at Kitt Peak and the Dark Energy Camera Legacy Survey (DECaLS) (Blum et al. 2016) by the Dark Energy Camera (Flaugher et al. 2015) on the 4-meter Blanco telescope at the Cerro Tololo Inter-American Observatory. BASS covers about 5400 deg² in the north Galactic cap (dec>32°) providing g- and r-band images and MaLS complements the same region as BASS with z-band observations. In tandem, DECaLS surveys an equatorial area (dec<32°) of about 9000 deg² with g-, r- and z-band images. The surface brightness (SB) limits of BASS are $g=27.10$ and $r=26.76$ mag arcsec$^{-2}$ (5σ in 10×10 arcsec boxes). The SB limits of DECaLS are $g=27.77$ and $r=27.44$ mag arcsec$^{-2}$. They are about 1 mag deeper than those of SDSS. These deeper images will facilitate us to search for debris features of merging and strongly interacting galaxies.

2.3 Methods

Sample selection: We crossmatch the galaxies in MaNGA with legacy surveys (DECaLS and DR6 (BASS DR2)). Since the BASS data are independently processed by the BASS team and the image quality is better than sections provided from the Legacy Surveys data release, we use BASS images rather than DECaLS ones for those available in both surveys. Bad images including those with bad pixels across the galaxy, those with distortion during mosaic and those at the edge of an image segment, are eliminated from the sample. Finally we get 6217 galaxies (hereafter crossmatched MaNGA sample) with 3729 from BASS and 2488 from DECaLS. All of them have both g- and r-band images. For each galaxy we convolve one band images. For each galaxy we convolve one band with fluxes S/N of either Hα or O[III]λ5007 greater than 5; (2) for stellar rotation, we eliminate spaxels with velocity uncertainties > 30 km/s. As for gas, we only include spaxels with fluxes S/N of either Hα or O[III]λ5007 greater than 5; (3) the number of spaxels satisfying the above second criterion needs to be greater than 1/3 of spaxels with mask=0. We then visually check each map with the PA uncertainty >10° to ensure that the PA measurements are reasonable. At the end 4006 galaxies out of 6217 have both reliable stellar and gas PAs, while most of the rest don’t have enough gas to produce measurable emission lines. Among merging/interacting galaxies, 375 out of 538 have PA measurements available. The PAs are in the range from 0° to 360°, so we force the PA offsets between gas and stellar from 0° to 180°.

Stellar mass and star formation rate: The total stellar mass and SFR of the crossmatched MaNGA sample are obtained from two catalogs - GALEX-SDSS-WISE Legacy Catalog (GSLWC) from Salim et al. (2016) and MPA-JHU DR7 catalog. GSLWC derived physical properties from the UV/optical SED fitting, which is robust but only contains 5109 out of 6217 galaxies. In addition, we crossmatch the rest of them with MPA-JHU DR7 to add 840 more objects. The stellar mass and SFRs for star forming galaxies in this catalog are calculated following Kauffmann et al. (2003) and Brinchmann et al. (2004), respectively. For non-SF galaxies, the SFRs are estimated from D4000. The two catalogs agree with each other quite well in stellar mass and SFRs for SF galaxies, but the MPA catalog tends to overestimate the SFRs slightly for non-SF galaxies. Finally, there are 268 crossmatched MaNGA sample without stellar mass and SFR measurements. We don’t use them for the following investigations. Fig. 2 shows the SFR-M∗ diagram of our merging/interacting sample in MaNGA.

**PAs of stellar and gas rotations:** The velocity maps of both stellar and ionized gas are extracted from the output of data analysis pipeline (DAP) in MaNGA (Westfall et al. 2019; Belfiore et al. 2019). The pipeline first bins adjacent spaxels and stacks the spectra in those spaxels using Voronoi binning procedure (Cappellari, & Copin 2003) to ensure the pseudo-r-band S/N bigger than 10. Then the continuum of each bin is fitted using penalized pixel-fitting routing (pPXF) (Cappellari, & Emsellem 2004; Cappellari 2017) and hierarchically clustered MILES templates (MILES-BC) (MILES stellar library: Sánchez-Blázquez et al. 2006) to determine the stellar kinematics. After performing stellar-continuum fit, the pipeline fixes the stellar kinematics and fits the emission lines by adopting Gaussian emission-line models and continuum simultaneously, providing best fit continuum models and fluxes and equivalent widths of emission lines, as well as velocities and velocity dispersions. The PAs of stellar and gas rotations are measured using FIT_KINEMATIC_PA code, which is developed by Cappellari et al. (2007) based on algorithms proposed in Appendix C of Krajnović et al. (2006). To obtain robust PAs of both stellar and gas, we apply following criteria: (1) only spaxels with mask=0 in DAP output are used, which means there are no significant issues of the data quality and the fit is reasonable; (2) for stellar rotation, we eliminate spaxels with velocity uncertainties > 30 km/s. As for gas, we only include spaxels with fluxes S/N of either Hα or O[III]λ5007 greater than 5; (3) the number of spaxels satisfying the above second criterion needs to be greater than 1/3 of spaxels with mask=0. We then visually check each map with the PA uncertainty >10° to ensure that the PA measurements are reasonable. At the end 4006 galaxies out of 6217 have both reliable stellar and gas PAs, while most of the rest don’t have enough gas to produce measurable emission lines. Among merging/interacting galaxies, 375 out of 538 have PA measurements available. The PAs are in the range from 0° to 360°, so we force the PA offsets between gas and stellar from 0° to 180°.

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1. http://legacysurvey.org
2. http://batc.bao.ac.cn/BASS/doku.php?id=home
3. https://wwwmpa.mpa-garching.mpg.de/SDSS/DR7/
3 RESULTS

Fig. 3(a) shows the merging/interacting fractions in three $\Delta$PA groups. Following the classification in Chen et al. (2016), galaxies with $\Delta$PA < 30° are co-rotators or aligned galaxies; those with $\Delta$PA $\geq$ 150° are counter-rotators and the rest (30° $\leq$ $\Delta$PA <150°) are misaligned galaxies (Here the definition is a little bit different with Chen et al. (2016), where counter-rotators are also misaligned galaxies). As showed in Table 1, 289 of merging/interacting galaxies are co-rotators; 73 of them are misaligned galaxies and only 13 of them are counter-rotators. The intrinsic fractions satisfy $\beta$ distributions, so the errors in Table 1 are the square roots of variances of $\beta$ distributions. In Fig. 3(a), there is a remarkable enhancement for misaligned galaxies to have merging/interacting signatures against the fraction in co-rotators group. This result is an important evidence to support the merging origin of this misaligned gas. On the other hand, we don’t see striking differences of the merging/interacting fractions between co-rotators and counter-rotators.

We further divide our sample into star-forming (SF) and non star-forming (non-SF) galaxies as the dashed line in Fig. 2. Fig. 3(b) illustrates the merging/interacting fraction for SF galaxies (blue) and non-SF galaxies (red). In total 2648 out of 3010 SF galaxies satisfy our PA measurement criterion, but only 1187 out of 2939 non-SF galaxies do as the rest of them either don’t have enough ionized gas to produce detectable emission lines or are slow rotators, which are less likely to have coherent stellar motion (Cappellari 2016). The numbers of merging galaxies and the merging/interacting fractions are listed in Table 1. In Fig. 3(b), the merging/interacting fractions in non-SF galaxies are higher than those in SF galaxies in every group of $\Delta$PA. This is because total merging/interacting fraction in non-SF galaxies (133/1187 $\sim$ 0.11) is larger than that in SF galaxies (207/2648 $\sim$ 0.08). As discussed above, we adopt several criteria to ensure that our PA measurements are robust. These criteria force selected galaxies to have enough ionized gas to produce detectable emission lines. For non-SF galaxies, mergers are an efficient way for those quenched galaxies to acquire external gas to meet those criteria. As a result, we tend to overestimate the merging/interacting fraction. In fact, the original merging/interacting fraction of non-SF galaxies is about 0.09, showing no significant difference with SF galaxies. In non-SF galaxies, the misaligned galaxies show the highest merging/interacting fraction, and the counter-rotator has an intermediate value while the co-rotator shows the lowest fraction. In contrast, in SF galaxies, while the mis-aligned galaxies still have the highest fraction, the counter-rotator even has a smaller fraction than the co-rotator.

Fig. 4 illustrates the $\Delta$PA distribution of SF galaxies (Fig. 4(a)) and non-SF galaxies (Fig. 4(b)) along with the numbers and relative frequencies listed in Table 2. In non-SF galaxies, it is obvious that merging/interacting galaxies have much higher possibility to be misaligned than the whole non-SF sample. The difference between merging/interacting galaxies and total sample in the counter-rotator fraction is marginal. Whereas in SF galaxies, although we still find the misalignment enhancement in merging/interacting galaxies, there are rarer counter-rotators in merging/interacting galaxies than the whole SF sample. We will discuss the possible physical explanations of these results in Section 4.

4 DISCUSSION

In this work, we find that misaligned galaxies have higher merging/interacting fraction than co-rotators (Fig. 3) and meanwhile, merging/interacting galaxies are more likely to be misaligned against total sample (Fig. 4). This result provides us a direct observational evidence that merging is one way to produce kinematically misaligned galaxies. As demonstrated in Jin et al. (2016) and B19, misalignment also holds a secondary correlation with stellar mass. We now examine that such a higher merging/interacting fraction in misaligned galaxies is not related to different stellar mass distributions in co-rotators and misaligned galaxies. Fig. 5 shows the stellar mass distributions of the co-rotators and misaligned galaxies & counter-rotators of total cross-matched MaNGA sample. We find that misaligned galaxies & counter-rotators tend to have smaller stellar mass than co-rotators in both SF and non-SF sample, with the KS test p-value = 1.62 x 10^-8 for SF galaxies and 3.11 x 10^-5 for non-SF galaxies. We then subsample from the co-rotators to create a sample with a consistent mass distribution as the misaligned & counter-rotators. We find that the merging/interacting fractions are 0.060 for SF galaxies and 0.075 for non-SF galaxies, showing more difference against other two groups. Hence we confirm that the misalignment enhancement in the merging/interacting sample is really attributed to mergers but not stellar mass. Simulations account for this enhancement as companions could provide external misaligned gas and the original gas disc disruption and gas expelling induced by merging make it easier to form and keep misaligned gas discs (Crocker et al. 2009; van de Voort et al. 2015).

In this study we use SF and non-SF galaxies to represent the LTGs and ETGs, respectively. As shown in Fig. 4 and Table 2, in the whole non-SF sample, the ratio of misaligned galaxies to counter-rotators is about 2:1, smaller than the ratio of $\Delta$PA coverages between these two groups (4:1). B19 use gas precession scenario to explain this counter-rotator excess. Due to the lack of in situ gas in ETGs, the incoming gas will not experience dissipating processes but form a rotating disk with angular momentum along the initial direction. Further gas precession due to gravitational dynamical settling leads such gas to be stabilized in either counter-rotating or co-rotating with stellar motion (Stevens et al. 2016; Davis, & Bureau 2016), thus resulting in more counter-rotators in ETGs. In contrast, in the whole SF sample, only 8% have $\Delta$PA $\geq$ 30° and only 2% exhibit counter-rotating. According to B19, the interaction between existing co-rotating gas and incoming gas rapidly disrupts the latter when the incoming gas mass is smaller than that of in situ gas. Even if a larger amount of gas is accreted, the incoming gas is still not prone to settle to counter-rotating, but rather to co-rotating. Moreover, simulations of halo accretion (Danovich et al. 2015) show that the accreted gas in LTGs is tilted rapidly toward to stellar rotation outside 0.1 virial radii, such that the external gas in the region covered by MaNGA is more likely to already align with stellar rotation. Both co-rotating settling and preferentially aligned
Then the maximum merging fraction in misaligned galaxies is about 4\%, thus sharing a common view with the assumption of ETGs containing such misalignments. In our sample, the total fraction of non-SF co-rotators and counter-rotators in LTGs and the co-rotating preference in LTGs. Furthermore, the gas precession scenario also predicts the same role to produce SF counter-rotators. Finally, the ratio of co-rotators to counter-rotators in non-SF merging/interacting galaxies is about 8:1, much larger than the prediction from the isotropic merging (1:1), which supports the speculation that gas and stars prefer to be aligned during merging, as the orbital angular momentum transfers to gas and stellar spin.

5 SUMMARY

In 6217 MaNGA galaxies crossmatched with Legacy Surveys, we find 538 galaxies with merging features or strong interaction with companions. They can be roughly separated into four groups - isolated galaxies with tidal streams (219); distorted galaxies with companions (184); galaxies with shells (36) and galaxies with extended asymmetric halo (99).

We investigate the gas-stellar rotation misalignments extracted from stellar and ionized gas velocity maps. We find that misaligned galaxies tend to have higher possibility to experience merging/interacting (Fig. 3) and merging/interacting galaxies are prone to be misaligned (Fig. 4). We confirm that this misalignment enhancement is not due to different stellar mass distributions between the whole MaNGA sample and merging/interacting sample but directly relating to mergers, and this reveals a direct connection between the misaligned gas and external origins. In this case, recent merging events can contribute to maximum 40\% of such misalignment.

We then consider the morphological dependency, using SF galaxies and non-SF galaxies to represent LTGs and ETGs. Our results corroborate the gas precession scenario in ETGs and the co-rotating preference in LTGs. In addition, the slightly smaller merging/interacting fraction in counter-rotators than in misaligned galaxies infers that counter-rotating is a stable state as predicted by the precession scenario and could last for such a long time that tidal features disappear. The marginal merging/interacting fraction in SF counter-rotators means that mergers tend to play a minor role to produce SF counter-rotators. Finally, the ratio of co-rotators to counter-rotators in non-SF merging/interacting galaxies is about 8:1, much larger than the prediction from the isotropic merging (1:1), which supports the speculation that gas and stars prefer to be aligned during merging, as the orbital angular momentum transfers to gas and stellar spin.

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Table 1. The fractions of merging/interacting galaxies (the numerators) in parent MaNGA sample (the denominators) in different kinematic groups. The errors are the square roots of variances of $\beta$ distributions.

| groups            | co-rotators (0°-30°) | misaligned galaxies (30°-150°) | counter-rotators (150°-180°) |
|-------------------|----------------------|---------------------------------|-------------------------------|
| total             | (289/3519)±0.0046    | (73/358)±0.021                  | (13/129)±0.026               |
| SF-galaxies       | (184/2451)±0.0053    | (24/153)±0.029                  | (2/44)±0.031                 |
| non-SF galaxies   | (83/932)±0.0093      | (39/177)±0.031                  | (11/78)±0.039                |

Table 2. The numbers of different kinds of galaxies in different $\Delta$PA groups. The numbers in the brackets show the relative frequency.

| groups             | co-rotators (0°-30°) | misaligned galaxies (30°-150°) | counter-rotators (150°-180°) |
|--------------------|----------------------|---------------------------------|-------------------------------|
| SF merging/interacting | 184 (0.88)         | 24 (0.11)                       | 2 (0.01)                     |
| the whole SF       | 2451 (0.92)         | 153 (0.06)                      | 44 (0.02)                    |
| non-SF merging/interacting | 83 (0.63)        | 39 (0.29)                       | 11 (0.08)                    |
| the whole non-SF   | 932 (0.78)          | 177 (0.15)                      | 78 (0.07)                    |
Figure 1. Four examples from different groups of our sample. These are: (1) isolated galaxies with tidal features (top left); (2) distorted galaxies with companions (top right); (3) galaxies with shells (bottom left) and (4) galaxies with extended asymmetric halo (bottom right). The plate-ifu IDs in MaNGA are showed on the top of each panel. Red plus symbol marks the center of each galaxy. The MaNGA IFU footprint is also overlaid in red.
Figure 2. (a): The distribution of our sample in SFR-M∗ diagram. Red dots are 485 of merging galaxies having both SFR and stellar mass measurements from literatures. Shadows in the background show the distribution of 100 thousand galaxies from GSWLC catalog. The dashed line is the 1σ lower boundary of star forming main sequence from Chen et al. (2016).

Figure 3. (a): The fractions of merging galaxies in parent MaNGA sample in three kinematic groups. co-rotators are those with ΔPA<30°; misaligned galaxies are those with 30°≤ΔPA<150°; and counter-rotators are those with ΔPA≥150°. The error bars illustrate the square roots of the variances of the β distributions. (b): The same as (a). The blue bars are fractions of SF galaxies and the red ones are fractions of non-SF galaxies.
Figure 4. The $\Delta$PA distribution in SF merging/interacting galaxies (red bars in (a)), the whole SF sample (blue bars in (a)), non-SF merging/interacting galaxies (red bars in (b)) and the whole non-SF sample (blue bars in (b)). The $\Delta$PA classification is the same as that in Fig. 3. And the error bars illustrate the square roots of the variances of the $\beta$ distributions.

Figure 5. The stellar mass distributions of the whole SF galaxies (a) and non-SF galaxies (b) in MaNGA sample. The red lines illustrate misaligned galaxies & counter-rotators and the blue lines illustrate the co-rotators. The vertical dashed lines are the median value of each distribution. Error bars show the square roots of the variances of the $\beta$ distributions in each bin.