Shape asymmetries and lopsidedness-radial-alignment in simulated galaxies

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ABSTRACT
Galaxies are observed to be lopsided, meaning that they are more massive and more extended along one direction than the opposite. However, the galaxies generated in cosmological simulations are much less lopsided, inconsistent with observations. In this work, we provide a statistical analysis of the lopsided morphology of 2148 simulated isolated satellite galaxies generated by TNG50-1 simulation, incorporating the effect of tidal fields from halo centres. We study the radial alignment (RA) between the major axes of satellites and the radial direction of their halo centres within truncation radii of 3R_h, 5R_h and 10R_h. According to our results, RA is absent for all these truncations. We also calculate the far-to-near-side semi-axial ratios of the major axes, denoted by a_-/a_+, which measures the semi-axial ratios of the major axes in the hemispheres between backwards (far-side) and facing (near-side) the halo centres. If the satellites are truncated within radii of 3R_h and 5R_h with R_h being the stellar half mass radius, the numbers of satellites with longer semi-axes on the far-side are found to be almost equal to those with longer semi-axes on the near-side. Within a larger truncated radius of 10R_h, the number of satellites with axial ratios a_-/a_+ < 1.0 is about 10% more than that with a_-/a_+ > 1.0. Therefore, the tidal fields from halo centres play a minor role in the generation of lopsided satellites. The lopsidedness radial alignment (LRA), i.e., an alignment of long semi-major-axes along the radial direction of halo centres, is further studied. No clear evidence of LRA is found in our sample within the framework of ΛCDM Newtonian dynamics. In comparison, the LRA can be naturally induced by the external fields from the central host galaxy in Milgromian dynamics. Given that LRA is observed between the NGC 5055 in respect of Virgo axis, our results provide a new route to test gravity by exploring LRA in the further observations.

Key words: galaxies: interactions - galaxies: kinematics and dynamics - gravitation - methods: numerical - galaxies: statistics

1 INTRODUCTION
The mass distributions of gaseous and stellar components in many galaxies are observed to be lopsided. Since 1960s, optical or HI observations have revealed that some sprial galaxies are symmetric between their northern and southern sides (e.g., Dieter 1962; Arp 1966; Beale & Davies 1969; Rogstad 1971; Bosma 1978; Sancisi & Allen 1979). Baldwin et al. (1980) were the first to find that in a sample of about twenty lopsided galaxies, most of them are isolated galaxies. Later, systematic studies on the observed disc galaxies showed that about 1/3 of field disc galaxies are significantly lopsided with an azimuthal m = 1 Fourier amplitude A_1 ≥ 0.20 for the stellar light (Rix & Zaritsky 1995; Zaritsky & Rix 1997). In a sample of 54 early-type disc galaxies (S0 to Sab), 20% of them are lopsided, with A_1 ≥ 0.19 for the R-band surface brightness (Rudnick & Rix 1998). Conselice et al. (2000) and Bournaud et al. (2005b) found that the lopsidedness of galaxies strongly correlates with the morphological type, that late-type discs and irregulars are more asymmetric and elliptical and lenticular galaxies are less lopsided. However, Angiras et al. (2006) unveiled that the early-type galaxies are more lopsided than the late-type galaxies. Moreover, the lopsidedness of galaxies strongly correlates with stellar surface density, and tend to increase with radius, as revealed by a systematical study on the light distribution of 25,155 present-day galaxies from the Sloan Digital Sky Survey Data Release 4 (SDSS DR4, Reichard et al. 2008). It is also confirmed that the lopsidedness of stellar light distribution corresponds to the lopsided stellar mass distribution (Reichard et al. 2008). About 50% in the Westerbork HI sample of Spiral and Irregular Galaxies (WHISP) survey are observed to be strongly lopsided within small radii, R_25, (i.e., 2.5 times of disc scale lengths, van Eymeren et al. 2011), and there are 20% galaxies in this sample displaying noticeably increasing lopsidedness out to large radii. In a most recent study on the HI emission...
line of 29,958 nearby galaxies by Yu et al. (2022), 20% of the sample of galaxies are significantly asymmetric considering systematic bias due to S/N. Overall, a certain fraction of galaxies are morphologically lopsided in observations.

The lopsided morphologies of galaxies are presumably caused by a time-dependent non-equilibrium dynamical state. A number of mechanisms have been proposed to understand the morphological lopsidedness of galaxies within the framework of standard Newtonian dynamics. Such mechanisms are devised into two classes, namely internal and external ones (eg. a review of lopsided galaxies, Jog & Combes 2009). The internal mechanisms include the self-gravitational instability (Zaritsky et al. 2013), the offset centres between the disc and the dark matter halo in a galaxy (Levine & Sparke 1998; Noordermeer et al. 2001), and the lopsided dark matter host halo that provides a lopsided internal potential (Weinberg 1995; Jog 1997).

The external mechanisms include galaxies merger (Walker et al. 1996; Zaritsky & Rix 1997; Bok et al. 2019), asymmetric gas accretion from cosmological filaments (Bournaud et al. 2005b; Mapelli et al. 2008), close tidal encounters (Kornreich et al. 2002) and ram pressure stripping (Mapelli et al. 2008; Scott et al. 2010; Kenney et al. 2015). Bournaud et al. (2005a) showed that the lopsidedness induced by minor merger disappears when the companion is disrupted and most of the lopsided galaxies are not undergoing mergers. In a flyby interaction between a disc target galaxy and a companion galaxy (Mapelli et al. 2008), the lopsided feature can be produced in the target galaxy. Since the disc galaxy is rotating, the perturbation appears on the opposite side of the intruder galaxy after half rotating period (approximately 300 Myr) and this explains well the observed lopsided galaxy NGC 891. Moreover, Mapelli et al. (2008) indicated that the overall stellar component is not lopsided in the case of gas accretion, and that ram pressure only generates moderate tidal tails. The observational results of that a larger fraction of lopsided galaxies are early-type implies a tidal origin for the lopsidedness (Angras et al. 2006; van Eymeren et al. 2011). However, the lopsidedness does not correlate with the tidal parameter, $T_p$ (van Eymeren et al. 2011), which quantifies the effect of tidal force.

Within the framework of ΛCDM Newtonian dynamics, galaxies are supposed to be embedded in dark matter haloes. Ciotti & Dutta (1994) made the first prediction that the tidal force from a host halo causes an alignment between the major axes of satellites and radial direction of the central dark matter halo. This prediction appears to agree with the early observations that the projected major axes of galaxies preferentially align with the radial direction of the cluster centres (Hawley & Peebles 1975; Thompson 1976). The radial alignment (hereafter short for RA) between galaxies and cluster centres has been further confirmed in the SDSS observations (Pereira & Kuhn 2005; Faltenbacher et al. 2007; Wang et al. 2008) and in the cosmological simulations (Faltenbacher et al. 2008; Pereira et al. 2008; Knebe et al. 2020). However, some other observations (Hun & Ebeling 2012; Schneider et al. 2013; Chisari et al. 2014; Sifón et al. 2015) point towards the absence of RA in large samples of clusters at different redshifts. More recently, Singh et al. (2015) claimed to find an RA in a sample of early-type galaxies in the SDSS-III. Wang et al. (2019) also observed a strong signal for radial alignment in satellites orbiting host galaxy pairs in the SDSS I3. Since the lopsidedness and the RA can both be explained by the tidal force from a massive gravitational source, a natural question arises as to whether the long semi-major-axis of a lopsided galaxy aligns with the radial direction of the cluster centre. In principal, dark matter halo provides a deep gravitational potential. The lopsided shapes and the RA of satellite galaxies indicate that the semi-axial ratio of the major axis $a_-/a_+ < 1.0$, which means that the semi-axis facing to the halo centre is longer than that on the opposite side. The accurate definition of $a_-$ and $a_+$ are to be presented in §2.3. However, these problems have not yet been systematically addressed in the framework of ΛCDM cosmological simulations. The existing studies on the RA only focus on the alignment angles between the overall major axes and the radial direction to the cluster centres. We shall provide a more in-depth analysis below.

Different from Newtonian dynamics in which the tidal radius of a satellite is $\approx D \left[ \frac{M_{\text{sat}}}{3M_{\text{halo}}(D)} \right]^{1/3}$ (Binney & Tremaine 2008), the tidal radius is $\approx D \left[ \frac{M_{\text{sat,b}}}{3M_{\text{gal}}(D)} \right]^{1/3}$ (Zhao & Tian 2006) in the framework of Milgrom’s modified Newtonian dynamics (hereafter MOND, Milgrom 1983; Bekenstein & Milgrom 1984). Here $D$ is the distance between the satellite and the central galaxy, $M_{\text{sat}}$ and $M_{\text{sat,b}}$ are the overall and baryonic masses of satellite galaxy, $M_{\text{halo}}(D)$ and $M_{\text{gal}}$ are the total mass enclosed within the radius $D$ and the baryonic mass of the central brightest galaxy, respectively. The tidal radius is much smaller in Newtonian dynamics than in MOND. Consequently, the tidal effect is more significant in Newtonian dynamics, since $M_{\text{sat,b}} \gg M_{\text{halo}}(D) \gg M_{\text{gal}}$ (Niemiec et al. 2017) for a normal dwarf galaxy embedded in the dark matter halo of its host galaxy. External field effect takes the place of tidal field effect within the framework of MOND due to the violation of the strong equivalence principal (SEP) (Milgrom 1983). It was found that the internal gravitational potential is lopsided made by the homogeneous background gravitational field, which in turn leads to a lopsided shape of galaxies at the radii where external field is stronger than the internal gravitational field (Wu et al. 2010, 2017). In particular, the long semi-major-axes of galaxies aligns with the radial direction to the cluster centre (Wu et al. 2017). Moreover, the axial ratios between the semi-major axes along with and opposite to the cluster centre is larger than 1.0 (Wu et al. 2017), which hereafter is called lopsidedness-radial alignment (LRA). Recently, features of LRA have been observed in the NGC 5055-Virgo axis through weak lensing signals in Oria et al. (2021), although they did not used the terminology of LRA to describe such features.

As far as we know, the existence of LRA has not yet been investigated within the framework of Newtonian dynamics in the literature. If LRA cannot be produced by Newtonian dynamics, it would be feasible to distinguish Milgromian and Newtonian dynamics by exploring LRA in observations.

In this work, we present a detailed analyses of the asymmetric shapes of present-day satellite galaxies from the public data release of the cosmologically simulated galaxies, TNG50-1 (Nelson et al. 2019). We aim to examine whether LRA exists in these satellites. The manuscript is organised as follows. In §2, a sample of isolated satellite galaxies are selected. The major axes of the satellites are determined by calculating the eigenvectors of inertia tensor. Then the lopsidedness of satel-
lites are analysed based on the semi-major axial ratios \( a_- / a_+ \) §3. The existence of RA and LRA are investigated in §4. Furthermore, the existence of LRA in the TNG50-1 simulated galaxies are compared with that predicted in MOND. A table of strongly lopsided satellites in the TNG50-1 simulation is provided and the mechanisms to generate the lopsidedness are discussed in §5. In addition, the morphologies of tidal tails predicted in MOND and in Newtonian dynamics are briefly discussed in §5. Finally, our results are summarised in §6.

2 SIMULATED SATELLITE GALAXIES AND THEIR AXIAL RATIOS

The present-day “galaxies” studied here are obtained from the TNG50-1 simulation, which is part of the IllustrisTNG simulation suite (Marinacci et al. 2018; Naiman et al. 2018; Nelson et al. 2018, 2019; Springel et al. 2018; Pillepich et al. 2018). The IllustrisTNG project, using a moving-mesh code AREPO (Springel 2010), is the next generation of the magnetohydrodynamical (MHD) cosmological simulation, Illustris (Vogelsberger et al. 2014a,b). The TNG50-1 simulation is the highest resolution cosmological simulation run with a box size of 51.7 mpc in the TNG suite (Nelson et al. 2019). There are 2160^3 gas particles and also 2160^3 dark matter particles in the TNG50-1 simulation, and the mass resolutions for gas and dark matter are 8.5 \times 10^5 M_\odot and 4.5 \times 10^5 M_\odot, respectively. Such a high resolution allows us to extract satellite galaxies with high enough resolution to analyse their shapes.

2.1 Sample selection

We select the satellite galaxies at z=0 using the following criteria. First of all, the haloes at the boundary of the simulation box, i.e., if there are stellar particles in a halo travel through the periodic boundary and appear at the other side of the box, are excluded in our halo sample. The satellite galaxies are then selected from the haloes containing at least one satellite galaxy. Note that the central galaxies in the haloes are not included in our sample. The satellites studied in this work are restricted within a stellar mass range of \([10^8, 10^{11}] M_\odot / h\). In this mass range each satellite galaxy contains at least a hundred stellar particles. There are 3189 galaxies that satisfy the above selection constraints. Finally, in order to overcome the perturbation from recent mergers or collisions, we require the satellite galaxies to be isolated, which means that there are no nearby galaxies or substructures with a mass over 1% of a satellite within the virial radius of the subhalo, \( r_{\text{vir, sub}} \). The final sample contains 2148 isolated galaxies.\(^1\) We shall study the semi-axial ratio of the major axes and then analyse the LRA of the satellite galaxies in the following sections. We shall also provide a comparison between the isolated and non-isolated samples of satellites.

\(^1\) The isolated satellites do not refer to field galaxies, but satellites without any nearby galaxies within \( r_{\text{vir, sub}} \) of themselves, \( r_{\text{vir, sub}} \) is the truncation radius for the subhalo of a satellite, within which the mean overdensity of the subhalo mass is 200 times of the critical density of the Universe in the TNG50-1 simulation.

2.2 Intrinsic major axes of the satellites

To study the lopsidedness of satellite galaxies, we need to find out the intrinsic major axes. The position of deepest gravitational potential is defined as the centre of a satellite. The principal axes of a satellite are determined at truncation radii of 3 \( R_h \) (smaller radius), 5 \( R_h \) (intermediate radius) and 10 \( R_h \) (large radius) by the following approach. Here \( R_h \) is the half mass radius of the stellar component in a galaxy. At the beginning, we assume that the galaxy is a triaxially symmetric system whose isodensity surface can be described by the ellipsoidal equation, \((\frac{x}{a})^2 + (\frac{y}{b})^2 + (\frac{z}{c})^2 = r^2\). Initially, \((x, y, z)\) are the coordinates of stellar particles of a satellite obtained from the TNG50-1 simulation, and \(a, b\) and \(c\) are the characteristic scale lengths and take the value of unity. \(r\) is the distance to the satellite centre.

The moments of inertia tensor of stellar particles inside a sphere with a radius of \(r\) are calculated by

\[
I_{xx}(r) = \sum_i m_i (y_i'^2 + z_i'^2) / \sum_i m_i \tag{1}
\]

\[
I_{xy}(r) = \sum_i m_i x_i' y_i / \sum_i m_i \tag{2}
\]

and similar expressions for other components. The diagonalised inertia tensor are computed, and the eigenvalues of the system, \(I_x', I_y', I_z'\), are obtained. The principal axes of the satellite align with the eigenframe. The characteristic scale lengths are now updated to

\[
a'(r) = \sqrt{I_{x'y'} + I_{y'x'} - I_{y'y'}} / 2, \tag{3}
\]

\[
b'(r) = \sqrt{I_{x'x'} - I_{x'y'} - I_{y'y'}} / 2, \tag{4}
\]

\[
c'(r) = \sqrt{I_{x'x'} + I_{y'y'} - I_{x'y'}} / 2. \tag{5}
\]

The intrinsic major, intermediate and minor axes are the \(x'\), \(y'\) and \(z'\)-axes in the eigenframe of the inertia tensor, and the values of \(a'(r)\), \(b'(r)\) and \(c'(r)\) are the corresponding intrinsic characteristic scale lengths, respectively.

2.3 Semi-axial ratios of the satellites

For a system that has rotated into its eigenframe of the inertia tensor, the positive \(x'\)-axis is defined as the major axis pointing to the halo centre. Thus the far- and near-side hemispheres are the hemispheres backwards and facing the cluster centre, respectively, segmented by a plane perpendicular to the major axis at the centre of the satellite. The characteristic scale lengths of the major axis on the far- and near-sides are described by the root mean square semi-axes, \(a_-\) and \(a_+\), which are

\[
a_- (r) = \left( \frac{\sum_i m_i x_i'^2}{\sum_i m_i} \right)^{1/2}, \quad x_i' < 0, \tag{6}
\]

\[
a_+ (r) = \left( \frac{\sum_i m_i x_i'^2}{\sum_i m_i} \right)^{1/2}, \quad x_i' > 0. \tag{7}
\]

respectively. For a perfectly triaxially symmetric system, \(a_-\) and \(a_+\) should be equal. However, as aforementioned, the galaxies are lopsided in nature, i.e. \(a_-\) and \(a_+\) can be different. Here we use the semi-axial ratio, \(a_- + a_+\), to quantify the lopsidedness of a satellite galaxy. The semi-axial ratios

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are calculated within the truncation radii of 3Rh, 5Rh and 10Rh for the sample of isolated galaxies.

In addition, in the whole sample of satellite galaxies, the non-isolated galaxies strongly influenced by the tidal fields from the nearby massive galaxies, i.e., locating within 10Rhom of the satellite galaxy. For non-isolated galaxies, the tidal fields come from both the halo centres and the nearby galaxies. Thus the definition of positive x'-axis is different from that of the isolated galaxies. For a non-isolated satellite, the near-side is defined by the direction of the object, be it a nearby massive galaxy or the halo centre, along which the tidal field is stronger. To make a comparison to the isolated sample, the semi-axial ratios of the non-isolated galaxies are also computed within the truncation radii of 3Rh, 5Rh and 10Rh.

| Mass (M⊙/h) | Samples | Radius (Rh) | N− | N+ | μ | σ |
|-------------|---------|-------------|-----|-----|---|---|
| 10^8 − 10^9 | Isolated | 3 | 772 | 777 | 1.000 | 0.061 |
| | 5 | 791 | 758 | 1.000 | 0.110 |
| | 10 | 838 | 711 | 0.994 | 0.140 |
| | Non-isolated | 3 | 343 | 306 | 0.997 | 0.141 |
| | 5 | 381 | 268 | 0.995 | 0.207 |
| | 10 | 399 | 250 | 0.983 | 0.269 |
| 10^9 − 10^10 | Isolated | 3 | 234 | 240 | 1.004 | 0.052 |
| | 5 | 217 | 257 | 1.004 | 0.065 |
| | 10 | 230 | 235 | 1.000 | 0.075 |
| | Non-isolated | 3 | 155 | 138 | 0.997 | 0.059 |
| | 5 | 158 | 135 | 0.999 | 0.084 |
| | 10 | 180 | 113 | 0.985 | 0.105 |
| 10^10 − 10^11 | Isolated | 3 | 73 | 52 | 0.996 | 0.039 |
| | 5 | 69 | 56 | 1.001 | 0.069 |
| | 10 | 68 | 57 | 1.010 | 0.086 |
| | Non-isolated | 3 | 48 | 51 | 0.999 | 0.043 |
| | 5 | 59 | 40 | 0.991 | 0.052 |
| | 10 | 61 | 38 | 0.981 | 0.085 |

3 LOPSIDENESS OF THE SATELLITES

For a self-gravitationally bound system embedded in a static potential of a dark halo and deviating from the halo centre, the tidal field from the dark halo may change the shape of the self-bound system. The semi-axis facing the halo centre is expected to be longer than the semi-axis backwards the halo centre. This implies that the system is lopsided and the semiaxial ratio a−/a+ < 1.0. However, previous studies on tidal effect mainly focused on galaxies interactions such as minor mergers (Walker et al. 1996; Bok et al. 2019) or close encounters (Kornreich et al. 2002). Considering the tidal force decays with distance as a power law of D−3, the tidal effect caused by halo centres is a minor effect. It is still unknown whether such effect produces detectable lopsidedness in satellites.

Moreover, apart from the tidal interactions due to minor mergers or close encounters, lopsidedness can be produced by a number of other mechanisms, including such external effects as asymmetric gas accretion (Bournaud et al. 2005b; Mapelli et al. 2008) and ram pressure stripping (Mapelli et al. 2008; Kenney et al. 2015) and such internal effects as self-gravitational instability (Zaritsky et al. 2013), offset centres between the disc and the dark matter halo (Levine & Sparke 1998; Noordermeer et al. 2001), and the lopsided dark matter host halo (Weinberg 1995; Jog 1997). On the other hand, for a large sample of galaxies, if the tidal fields from the halo centres are not taken into account, the above effects do not produce a preferred alignment for the long semi-major axes in respect to the radial directions of halo centres. The directions of the long semi-major axes are random for a large sample of galaxies. Therefore, the numbers of galaxies with a−/a+ < 1.0 and a−/a+ > 1.0 are expected to be approximately equal. However, it remains unclear whether the number of galaxies with long semi-major axes on the near-side of halo centres is larger than that on the far-side in case the tidal field from the halo centres are incorporated.

An analysis to a large sample of 1912 disc galaxies in Illustris-TNG100 simulation (Lokas 2022) has unveiled that only 8% of discs are moderately lopsided with the Fourier amplitude A1 ≥ 0.10, and that only 0.37% are strongly lopsided galaxies with A1 ≥ 0.2, which is a substantially lower fraction compared to the observations (e.g., 30% in Jog & Combes 2009). In this work, we analyse lopsidedness of satellite galaxies generated the TNG50-1 simulation, of which the resolution is higher. It is thus possible to include the low mass satellite galaxies in our sample. Moreover, we study the orientations of the long semi-major axes of the satellites in respect of the radial directions to halo centres (i.e., the LRA), which have not yet been systematically explored.

3.1 Distribution of the semi-axial ratios

To examine the distribution of a−/a+ near the value of 1.0, we calculate a−/a+ of the stellar components of all galaxies in two samples of isolated and non-isolated satellites. Each sample is further divided into three subsamples according to their stellar mass, including low mass satellites, intermediate mass satellites and massive satellites with stellar masses being in ranges of [10^8, 10^9]M⊙/h, [10^9, 10^10]M⊙/h and [10^10, 10^11]M⊙/h, respectively. The fractions of galaxies as a function of semi-axial ratios, a−/a+, in bins of 0.02, of the stellar components are shown in Fig. 1, truncated at radii of 3Rh (red curves), 5Rh (golden) and 10Rh (purple). In the inner regions of lower mass satellites, there are larger fractions of symmetric galaxies whose a−/a+ ≈ 1.0, while in large radii, there are more lopsided satellites. This is because the tidal field plays a more important role in the outer regions of a satellite, especially for low mass satellites. There are more satellites with a−/a+ < 1.0 in the non-isolated galaxies sample (lower panels). Obviously, the tidal field effect from a close encounter or a minor merger influence the orientation of semi-major axis of a satellite more significantly. Since the samples of galaxies are large enough, below we introduce a Gaussian distribution function to fit the dependence of fractions of satellites on the varying ratio a−/a+.
We show how the peak of \( a_-/a_+ \) in a Gaussian fitting deviates from 1.0 in Table 1, which quantifies the systematical tidal effect from the halo centres. The numbers of galaxies with \( a_-/a_+ < 1 \) and \( a_-/a_+ > 1 \), denoted as \( N_- \) and \( N_+ \), are listed in the forth and fifth columns of Table 1 for the samples of isolated and non-isolated satellite galaxies in three mass bins. For subsample of the low mass satellites in mass range of \( 10^8 - 10^9 M_\odot/h \), the values of \( N_- \approx N_+ \) at 3\( R_h \). As the radius grows, \( N_- \) increases slightly. At 5\( R_h \), \( N_- \) is about 4% larger than \( N_+ \), while in large radii, \( N_- \) is about 18% larger than \( N_+ \). Moreover, the mean values of \( a_-/a_+ \) at 3\( R_h \) and 5\( R_h \) are 1.000. Thus the tidal effects from the halo centres can be ignored in the inner regions of the isolated galaxies. In the outer regions of the satellites, although there are more galaxies with \( a_-/a_+ < 1.0 \), the mean value of \( a_-/a_+ \) is 0.994, only slightly deviating from 1.0.

In the subsample of low mass isolated satellites, the tidal fields from halo centres do not lead to clearly visible lopsidedness. Such a conclusion still holds in the subsamples of intermediate mass isolated satellites with mass of \( 10^9 - 10^{10} M_\odot/h \). In the subsample of massive isolated satellites with mass of \( 10^{10} - 10^{11} M_\odot/h \), although the values of \( N_- > N_+ \) for the three truncation radius, the number (125) of massive isolated satellites is significantly smaller than the numbers of other two subsamples. In addition, the mean values of \( a_-/a_+ \) deviate from 1.0 only by less than 1\% (as seen in Table 1). Overall, we have found no obvious evidence of lopsidedness in this subsample.

Further, if we consider the whole sample (including the above three subsamples) of isolated satellites, we find only 162 significantly lopsided galaxies whose semi-axial-scale-length deviation to the near-side semi-axis, \( \Delta a \equiv |a_- - a_+| > \Delta a > 0.1 \), within 3\( R_h \). That means among the isolate sample of satellites, only 7.5\% are significantly lopsided.

In the above analysis, \( a_-/a_+ \) is used to define the lopsidedness, which is different from that adopted in the previous analysis based on disc galaxies obtained from the TNG100-1 simulation by Lokas (2022). It is helpful to make a comparison between our results with theirs. To directly compare the lopsidedness with that in the discs sample (Lokas 2022) in TNG-100 simulation, we also calculated the Fourier \( m=1 \) mode values, \( A_1 \), for the isolated satellites on the \( x'-y' \) planes in their eigenframes of inertia tensor. In the calculations of
\( A_1 \), the centre of a satellite is defined by the densest region of the stellar component. The \( A_1 \) values of satellites are calculated at around 3 \( \text{R}_h \) in a radial bin within 2.5 – 3.5 \( \text{R}_h \). Note that in Łokas (2022) \( A_1 \) is calculated at 2 \( \text{R}_h \). We show the accumulative fraction of satellites with growing \( A_1 \) values in Fig. 2 and also in Table 2. The fraction of strongly lopsided satellites with \( A_1 > \) 0.2 are 7.8\%, which is an order of magnitude larger than that (0.37\%) in Łokas (2022). One of the possible reasons might be that the sample selections are different. Our sample includes all isolated satellites in a broader stellar mass range of \( 10^9 \) – \( 10^{11} \) \( M_{\odot} / h \), whereas the sample of Łokas (2022) contains only disc galaxies with stellar masses beyond \( 10^{10} \) \( M_{\odot} \). Another possible reason is that we calculate \( A_1 \) in a radius larger than that in Łokas (2022).

Although the fraction of strongly lopsided satellites obtained by us for \( A_1 > \) 0.2 is one order of magnitude larger than that of Łokas (2022), it is still much smaller than the observed one (van Eymeren et al. 2011; Yu et al. 2022).

Furthermore, we find that the variances of the Gaussian fittings for \( a_- / a_+ \) are always the largest for the low mass satellites. Therefore the low mass satellites are more lopsided, and the intermediate and massive satellites are more symmetric.

Next we turn to consider the sample of non-isolated satellites. In this case, the values of \( N_\pm \) are significantly larger than those of \( N_\mp \). Moreover, \( \Delta a \) is further enhanced. In addition, we find 115 significantly lopsided satellites with \( \Delta a > 0.1 \) at the truncation radius of 3 \( \text{R}_h \) out of 1041 non-isolated satellites. The fraction of significantly lopsided non-isolated satellites is about 11.0\% under the criteria of \( a_- / a_+ > 0.1 \), slightly larger than the fraction in the isolated sample. If \( A_1 \) is used instead of \( \Delta a \), 18.1\% of the non-isolated satellites are strongly lopsided with \( A_1 > 0.2 \). The larger fraction measured by \( A_1 \) can be attributed to the usage of a locally radial range of [2.5, 3.5 \( \text{R}_h \)] in calculations.

It is the asymmetric distribution of stars within the range of [2.5, 3.5 \( \text{R}_h \)] that makes \( A_1 \) larger. All stellar particles within 3 \( \text{R}_h \) are included in the calculation of \( \Delta a \), so the global asymmetry is weakened if the central regions are symmetric.

In a word, the non-isolated satellites are made more lopsided by the perturbations from a close encounter or a minor merger (see §5.2). The fraction of strongly lopsided satellites in our non-isolated sample is much higher than that obtained by Łokas (2022), but is also lower than that in observations van Eymeren et al. (e.g., 2011); Yu et al. (e.g., 2022), as in the case of isolated satellites.

### 3.2 Shape correlations

As aforementioned, the three subsamples of isolated galaxies display weak lopsidedness in their shapes. The long semi-axes of satellites do not obviously face the direction of halo centres. This implies that the lopsided shapes of satellites are not mainly caused by the tidal fields from the halo centres. To examine the tidal field effects from the halo centres more carefully, we further check the inner and outer semi-axial ratios, \( a_- / a_+ \), in different environments of the haloes, and show the results in Figs. 3-4.

The histograms of \( a_- / a_+ \) for the inner (Fig. 3) and outer (Fig. 4) regions of satellites show that the asymmetry of the galaxies is weak. The values of \( a_- / a_+ \) for most of the satellites are between 0.9 – 1.1, which agrees with the conclusion in Table 1. In the dense regions of satellites, i.e., within 3 \( \text{R}_h \) of the satellites, the fraction of satellites with \( a_- / a_+ < 1.0 \)
The Jacobi radius of a satellite on a circular orbit is approximately (Binney & Tremaine 2008)

\[ r_t = D \left( \frac{M_{\text{sat}}}{\zeta M_{\text{halo}}} \right)^{1/3}, \quad \zeta = 3 \]

and the tidal radii on other kinds of orbits has the same form but with different values of \( \zeta \). The lopsidedness is not directly related to the tidal force from halo centres for most of the satellites outside \( 0.2R_{\text{vir}} \). An implication is that there are little correlations between the physical quantities appearing in Eq. 8 (\( M_{\text{sat}} \), \( M_{\text{halo}} \) and \( D \)) and the lopsidedness. We use the results shown in Fig. 5 to confirm that in all truncation radii of satellites, the semi-axial ratios \( a_-/a_+ \) do not correlate with the halo masses nor the satellite masses.

Observations have revealed that the HI distribution in galaxies are typically asymmetric (e.g., Watts et al. 2020a). In simulations, the HI distribution of satellite galaxies in TNG100-1 are generally asymmetric (Watts et al. 2020b). Recently, Łokas (2022) pointed out the lack of a direct relation between the global asymmetries of the stellar and of the gaseous components in TNG100 simulation. Below, we study the relation between the gas fractions and the lopsidedness of satellite galaxies. The values of \( a_-/a_+ \) for satellites

**Figure 4.** The lower left panel: The correlation between semi-axial ratios, \( a_-/a_+ \) at \( 10R_{\text{vir}} \), for the 2148 present-day isolated satellites in 3\( \sigma \) variance of Gaussian fitting and the distances, \( D \), of satellites to their host halo centres. The binning method is the same as that in Fig. 3. The fractions of satellites with \( a_-/a_+ < 1.0 \) at all distances is presented in the upper left panel. A histogram of satellites with different values of \( a_-/a_+ \) is given in the right panel.

**Figure 5.** The relation between the semi-axial ratios in the inner (upper panel), intermediate (middle panel) and outer (lower panel) regions of the overall sample of 3189 satellites and their host halo masses. The satellites are presented in colour filled circles. Different colours and sizes of the circles show the masses and the sizes of the satellites. The axial ratios \( a_-/a_+ = 1.0 \) are plotted as black dashed lines. The red dashed lines and pink shadows show the areas of 1\( \sigma \) and 3\( \sigma \) variance of \( a_-/a_+ \) in the Gaussian fitting.
truncated at $3 R_h$ versus the fraction of gas, $f_{\text{gas}}$ in a satellite, are plotted in Fig. 6 for isolated (upper panel) and non-isolated (lower panel) satellites. The fraction of gas is defined by $f_{\text{gas}} = m_{\text{sat,gas}} / m_{\text{sat,b}}$, where $m_{\text{sat,gas}}$ and $m_{\text{sat,b}}$ are the masses of gas and baryons of a satellite galaxy. In both samples, there is a clear signal that more massive satellites tend to be less gas-rich, and the dispersion of $a_- / a_+$ are smaller around 1.0. More massive satellites are more symmetric with smaller values of $\Delta a$. As satellite mass decreases, $\Delta a$ becomes larger. Satellites with a larger fraction of gaseous component appear to be more lopsided.

4 ALIGNMENTS

The existence of RA is still controversial. The RA between the major axis of a satellite and the radial direction of its central halo was found in observations in 1970s (Hawley & Peebles 1975; Thompson 1976). More recently, some observations further confirmed the existence of the RA in large samples of galaxies (Pereira & Kuhn 2005; Faltenbacher et al. 2007; Wang et al. 2008, 2019), but there are also other observations that do not find the evidence of RA at different redshifts (Hung & Ebeling 2012; Schneider et al. 2013; Chisari et al. 2014; Sifón et al. 2015). On the other hand, RA was discovered in the cosmological simulations by Faltenbacher et al. (2008); Pereira et al. (2008); Knebe et al. (2020). Especially, it is more pronounced on the small scale of $1.5 R_{\text{vir}}$ (Faltenbacher et al. 2008). The mean value of the alignment angle, $\phi$, i.e., the angle between the major axis of a satellite and the radial direction of the halo centre, is adopted to determine the existence of RA in Faltenbacher et al. (2008). The long and short semi-major axes are not distinguished in the above studies, thus the values of $\phi$ are taken to lie in $[0^\circ, 90^\circ]$. For a sample of satellites radially aligned with their halo centres, the mean value of $\phi$ is less than $45^\circ$. In addition, besides the radial alignment of satellites, Wang et al. (2019) observed a tangential alignment in the satellites around bound primary galaxy pairs in the SDSS DR13. There is a clear trend that the major axes of satellites located in the area between two primary galaxies are perpendicular to the radial direction of its host halo. The tangential alignment is beyond the scope of this work, and we will not discuss more on this issue.

The RA of isolated satellites with mass of $10^8 - 10^9 M_\odot / h$ in the most massive halo (Halo 0) in TNG50-1 is qualitatively shown in Fig. 7. These satellites are the ones most substantially perturbed by the tides from their host halo. The three panels present the RA in all chosen truncation radii of satellites. The orientations of long semi-major axes of satellites are plotted with blue (inwards) and red (backwards) arrows on the circles of satellites. We observe no significant RA at the truncation radii of $3 R_h$, $5 R_h$ and $10 R_h$ at the first glance of the figure. To examine whether RA exists or not, below we perform a more careful analysis.

4.1 RA and LRA

As aforementioned, it remains unclear whether LRA can be produced in the simulated galaxies within the $\Lambda$CDM framework. Here we provide the first systematical analysis of the existence of LRA in the sample of satellite galaxies generated from TNG50-1 simulation.

We need to consider the RA before analysing LRA. For this purpose, here we define a new alignment angle, $\theta$, as follows,

$$\cos \theta = \mathbf{x}_{\text{sat}}' \cdot \mathbf{D},$$

where $\mathbf{x}_{\text{sat}}'$ is the eigenvector of long semi-major axis of a satellite, and $\mathbf{D}$ is the radial direction to the halo centre. The values of $\theta$ are calculated for the sample of isolated satellites. Given that the long and short semi-major axes are distinguished in this work, $\theta$ takes all the possible values within $[0^\circ, 180^\circ]$. For $\theta \in [0^\circ, 90^\circ]$, the long semi-major axis of the satellite is radially aligned with the direction of halo centre, and for $\theta \in [90^\circ, 180^\circ]$, the short semi-major-axis is radially aligned. The values of $\theta$ can be used to determine the existence of RA and the LRA. It is convenient to use $\theta_1$ and $\theta_2$ to denote the mean values of $\theta$ for the ranges of $[0^\circ, 90^\circ]$ and $[90^\circ, 180^\circ]$, respectively. An RA emerges when $\theta_1 < 45^\circ$ or $\theta_2 > 135^\circ$.

Moreover, LRA refers to the special case in which the long semi-major axis of a lopsided satellite radially aligns with the halo centre, corresponding to $\theta < 90^\circ$. The existence of
LRA can be determined by the $\theta$-dependence of number of satellites.

### 4.1.1 Absence of RA

In Fig. 8, the values of $\theta$ are binned in $5^\circ$ in the inner, intermediate and outer regions for the overall sample of isolated galaxies with flavogreen histogrammes. For satellites truncated at $3R_h$, the numbers of galaxies in bins reach maximal and are nearly $\theta$-independent for the range $\theta \in [60^\circ, 120^\circ]$. The major axes of these satellites are almost perpendicular to the radial direction of their halo centres. For satellites truncated at $5R_h$, the situation is rather similar. In contrast, in the case of $10R_h$, there appear two peaks at approximately $30^\circ$ and $130^\circ$ in the histogram. We compute the values of $\bar{\theta}_1$ and $\bar{\theta}_2$ at all truncation radii for the isolated galaxies. We find that $\bar{\theta}_1 = 53.3^\circ$ and $\bar{\theta}_2 = 125.3^\circ$ for $3R_h$, $\bar{\theta}_1 = 51.1^\circ$ and $\bar{\theta}_2 = 125.8^\circ$ for $5R_h$ and $\bar{\theta}_1 = 45.0^\circ$ and $\bar{\theta}_2 = 130.3^\circ$ for $10R_h$. There is no signature of RA. Our findings are at odds with previous results obtained in cosmological simulations (Faltenbacher et al. 2008; Pereira et al. 2008; Knebe et al. 2020). Such an inconsistency might result from the difference in the selected samples. The samples of galaxies considered by (Pereira et al. 2008; Knebe et al. 2008, 2020) are supposed to be triaxial. Our sample includes both triaxially and axially symmetric satellites.

For an oblate elliptical satellite or a disc satellite, the major and intermediate axes are indistinguishable. For such an oblate/disc galaxy, when $\theta \approx 90^\circ$, it might be because the intermediate axis is determined as major axis, and therefore a well aligned galaxy is artificially classified as misaligned. To avoid this problem, we remove the nearly axially symmetric satellites (with an axial ratio $b : a \in [0.9, 1.0]$) from our sample, following the strategy used by Pereira et al. (2008); Knebe et al. (2008) and Knebe et al. (2010). After doing so, the rest subsample contains only triaxial systems.\(^2\) The alignment angle, $\theta$, of the triaxial satellites are computed, with results presented in Fig. 8 with green histogrammes. Once again, RA is not seen within $3R_h$ and $5R_h$. $\bar{\theta}_1 = 52.8^\circ$ and $\bar{\theta}_2 = 125.9^\circ$ within $3R_h$, and $\bar{\theta}_1 = 46.8^\circ$ and $\bar{\theta}_2 = 125.5^\circ$ within $5R_h$. Therefore the absence of RA is not caused by the axial symmetry of satellite galaxies at $3R_h$ and $5R_h$. Only in the outer regions of the triaxial satellites ($10R_h$) are there two tiny peaks in the $\theta$-dependent number of galaxies. It is hard to judge whether RA really exist from such a weak signal. In conclusion, we do not find any clear signature of RA in the case of triaxially symmetric subsample of satellites. Our findings agree well with the observatons by Hung & Ebeling (2012); Schneider et al. (2013); Chisari et al. (2014) and Sifón et al. (2015).

In addition, although no RA is found, there could be another kind of alignment for the whole isolated sample that includes axially symmetric satellites. To describe this new alignment, we use a symbol $\alpha$ to denote the angle between the short axes of satellites and the direction to their halo centres. As can be seen from Fig. 9, shown in bins of $5^\circ$, the number of satellites is strongly $\alpha$ dependent at different truncation radii. The numbers of galaxies linearly increase as $\alpha$ rises in all the three cases, and reach maxima as $\alpha$ approaches $90^\circ$. Therefore, the short axes of the satellite galaxies tends to align with the tangential direction of their halo centres.

### 4.1.2 On the existence of LRA

For a sample of satellites, LRA exists if there is a significantly larger number of satellites with $\theta < 90^\circ$ than that with $\theta > 90^\circ$. Note that the existence of LRA is determined by $\bar{\theta} < 90^\circ$ rather than $\bar{\theta} < 45.0^\circ$ for the whole sample, since a dominant fraction of the satellites are axial-symmetric (as seen from Fig. 8). Fig. 8 shows mirror-symmetric distributions, centred at $\theta = 90^\circ$, of the numbers of isolated satellites (flavogreen histogrammes) at $3R_h$ and $5R_h$. This indicates that the long semi-major axes of the satellites in these radii do not prefer to point towards the direction facing their halo centres, i.e., the
4.2 LRA in Milgromian Dynamics

In the framework of Milgrom’s modified Newtonian dynamics (Milgrom 1983, MOND), the asymmetric shapes for the cluster galaxies have been predicted (Wu et al. 2010, 2017) as an effect of the violation of SEP. When the size of a satellite is much smaller than the distance of the satellite with respect to the host galaxy, the gravitational field generated by the host galaxy can be considered as a constant field for the satellite. In the presence of a constant external gravitational acceleration, $g_{\text{ext}}$, the Poisson’s equation in MOND reads (Bekenstein & Milgrom 1984)

$$\nabla \cdot \left[ \mu \left( \frac{|\mathbf{g}|}{a_0} \right) \mathbf{g} \right] = 4\pi G \rho_b, \quad \mathbf{g} = \nabla \phi_{\text{int}} + g_{\text{ext}}, \tag{10}$$

Here $a_0 \approx 3700 \text{ km s}^{-2}\text{ Mpc}^{-1}$ is Milgrom’s gravitational acceleration constant. $\phi_{\text{int}}$ is the internal gravitational potential introduced by the baryonic matter density $\rho_b$. The interpolating function, $\mu(X)$, approaches 1 in the strong gravitational field with acceleration $|\mathbf{g}| \gg a_0$, and approaches $X$ in the weak field with $|\mathbf{g}| \ll a_0$. By introducing the $\mu$ function, the285(370,580),(540,675) in the strong gravitational field, which is less than $90^\circ$. All these results imply a weak LRA in the outer regions of satellite galaxies.

Figure 8. The histogrammes of the aligned angles between the long semi-major-axes of satellites and their halo centres in the inner regions within $3R_h$ (upper panel), intermediate regions within $5R_h$ (middle panel) and outer regions within $10R_h$ (lower panel). The angles are binned in $5^\circ$ for the overall sample of isolated satellites (the flavogreen histogrammes) and for the triaxial isolated satellites with intermediate-to-long axial ratios $b:a < 0.9$ (the green histogrammes).

Figure 9. The histogrammes of the alignment angles between the minor axes of satellites and their halo centres, $\alpha$, for the isolated satellites in bins of $5^\circ$ in the inner regions within $3R_h$ (gray histogrammes), intermediate regions within $5R_h$ (black histogrammes) and outer regions within $10R_h$ (red histogramme).
The violation of SEP leads to a lopsided shape of the internal gravitational potential for a galaxy embedded in an external field. A self-bound gravitational system with perfect symmetry in shape generates a lopsided potential in the external field dominated regions. The symmetric mass distribution then self-evolves to a lopsided shape (Wu et al. 2017). The galaxies considered in Wu et al. (2017) are embedded in an external field of \( \approx 1\sigma_0 \), which is comparable to the strength of the background gravitational acceleration in a rich cluster. The self-evolution quickly relaxed within dozens of Kelperian times at a inner radius of \( r = a \), where \( a \) is a characteristic scale of the stellar component. The ratio \( a_-/a_+ \) increases with radius and reaches down to about [0.93, 0.95] at the radius enclosed 90% mass, \( \approx 5R_h \) for a galaxy (Wu et al. 2017). \(^3\) Recently, features of LRA have been observed in the NGC 5055-Virgo axis through weak lensing signals in Oria et al. (2021), although they did not use LRA to describe their observation. The lopsided shape of a galaxy tightly aligns with the direction of a cluster centre in MOND. There is always a clear LRA in MOND when the external field effect is taken into account. In comparison, recall that the LRA is absent in isolated satellites of the TNG50-1 simulation.

The difference in predictions made by two frameworks originates from the fact that the external field effect is much stronger than the tidal effect at any given distance to the cluster centre, \( D \). In the framework of MOND, the external acceleration for a satellite from a cluster central galaxy decays following \( \propto (GM_{\text{gal}}a_0)^{1/2}D^{-1} \), while the acceleration from the tidal field of the same central galaxy decays as \( \propto M_{\text{gal}}D^{-3} \). Thus the external field effect plays a dominant role in MOND. As for the tidal field effect in the framework of \( \Lambda \)CDM, the acceleration for a satellite from a tidal field of its host halo centre is \( \propto M_{\text{host}}D^{-3} \). Here the \( M_{\text{host}} \) includes the baryonic mass and the dark matter halo mass of the central galaxy. Although \( M_{\text{host}} \geq M_{\text{gal}} \) for the central galaxy, the tidal fields decay much more rapidly with growing distance. In §4.1.2, we have already illustrated that the tidal fields from halo centres do not result in an LRA for a large sample of satellite galaxies. Thus the different predictions on the existence of LRA provide a new probe to test gravity.

5 DISCUSSIONS

5.1 Extremely lopsided satellites and absence of LRA

The extremely lopsided galaxies with an \( a_-/a_+ \) beyond the 3\( \sigma \) variance of the Gaussian fitting are listed in Table 3 for the isolated sample (the upper sub-tabular) and the non-isolated sample (the lower sub-tabular).

Seven out of twenty extremely isolated satellites are strongly influenced by the tidal fields from the halo centres as the distances to the halo centres \( \leq 0.14R_{\text{vir}} \). As a result, the tidal radius \( r_t \) is smaller than \( 3R_h \). There are five satellites with \( a_-/a_+ < 1.0 \) and two with \( a_-/a_+ > 1.0 \) among the satellites close to halo centres. These galaxies are listed in the \( 1_{st} - 7_{th} \) rows of the upper sub-tabular in Table 3. Note that the above seven satellites cannot be considered as standard ‘isolated’ satellites, since they are very close to their halo centres, with \( r_t < 3R_h \). The situation is more severe for the twenty non-isolated galaxies, out of which are there eighteen satellites strongly influenced by the nearby massive galaxies with \( r_t < 3R_h \) (the \( 1_{st} - 18_{th} \) rows in the lower sub-tabular of Table 3). There are eight non-isolated satellites with \( a_-/a_+ < 1.0 \) and ten with \( a_-/a_+ > 1.0 \). Moreover, isolated and non-isolated satellites within \( 10R_h < r_t \) are shown in the \( 8_{th} - 12_{th} \) rows of upper sub-tabular and in the \( 19_{th} - 20_{th} \) rows of the lower sub-tabular, respectively. Interestingly, there is only one satellite with \( a_-/a_+ < 1.0 \) in each sub-tabular. Obviously, interactions from the halo centres or nearby massive galaxies are responsible for the lopsidedness of the satellites close to the halo centres or massive galaxies. However, the LRA is not found even in these strongly tidally disrupted satellites.

At the bottom of the two sub-tabulars of Table 3, there are eight isolated and five non-isolated satellites extremely lopsided and with \( r_t > 10R_h \). Apparently, tidal stripping is not the driving force for the lopsidedness of these satellites.

5.2 Other mechanisms to produce lopsided satellites

The external perturbations and internal dynamics accounting for the lopsidedness of galaxies have been extensively studied (e.g., Bournaud et al. 2005b; Mapelli et al. 2008; Kenney et al. 2015; Zaritsky et al. 2013; Levine & Sparke 1998; Noordermeer et al. 2001; Weinberg 1995; Jog 1997). We briefly discuss the possible origins of lopsidedness below.

5.2.1 External origins

As aforementioned, the interactions from the halo centres or massive galaxies make a small part of satellites become extremely lopsided, as summarised in Table 3. These satellites reside in the central regions of their host haloes or in the vicinity of nearby massive galaxies. The tidal radii of these galaxies are smaller than \( 3R_h \). Moreover, there are a large number of satellites in Table 3 that do not have a dark matter subhalo.

Several dark-matter-free (DM-free) galaxies have been recently observed by Oh et al. (2015); van Dokkum et al. (2018b,a, 2019). The existence of DM-free galaxies is at odds with the standard stellar-to-halo mass relation, which challenges the standard \( \Lambda \)CDM framework (Haslbauer et al. 2019). On the other hand, some research groups claimed that the DM-free galaxies are the remnants of a dwarf galaxy undergone tidal disruptions through close encounters (e.g., Jing et al. 2019; Moreno et al. 2022). Since the dark matter particles are dynamically hotter than the stellar particles in a dwarf galaxy, the dwarf galaxy loses its dark matter halo by the tidal shocks as the consequence of a close encounter with another galaxy (Jing et al. 2019). Below, we shall show that the extremely lopsided DM-free satellites, including subID 198267, subID 509096 and subID 535781 in Table 3, can be explained by this scenario. Such satellites are passing through...
or have just passed through the disc planes of their central host galaxies. The dark matter subhaloes of these satellites have been tidally disrupted by the central galaxy or a nearby massive galaxy. The ratio \((a_-/a_+)\) for the above three example satellites are all less than 1.0, implying a tidal origin for the lopsidedness.

The lopsidedness may result from multiple origins. For instance, in the central regions of a cluster, satellites are perturbed by tidal interaction caused by the central galaxy. At the meanwhile, the satellites are interacting with each other due to the fact that the number density of galaxies are larger in the cluster centre. Let us take the DM-free satellite subID 566663 in Table 3 as an example galaxy. The distance between this satellite and its halo centre is 0.14\(R_{\text{vir}}\).

The halo-centric position of the satellite is \((x', y', z') = (13.0, 11.5, 0.6)\) kpc/h and the relative velocity to the halo

| subID   | haloID | \(m_{\text{sat},*}\) (10^8\(M_\odot/h\)) | \(m_{\text{sat,gas}}\) (10^8\(M_\odot/h\)) | \(m_{\text{sat, dm}}\) (10^8\(M_\odot/h\)) | \(R_h\) (kpc) | \(D\) (kpc) | \(r_1\) (kpc) | \((a_-/a_+)\) | \((A_1)\) | \(3R_h\) |
|---------|--------|----------------------------------|----------------------------------|----------------------------------|-------------|-------------|-------------|---------------|------------|-----------|

Table 3. Extremely lopsided satellites with semi-axial ratios truncated within 3\(R_h\), \((a_-/a_+)3R_h\), out of 3\(\sigma\) of the Gaussian fitting. The information of isolated and non-isolated satellites are shown in the upper and the lower sub-tabulars, respectively. The IDs of the subhaloes within which the satellites are embedded are listed in the first column. The IDs of the host haloes for the satellites are listed in the second column. The masses of the stellar, gaseous and dark matter of the satellites are provided in the third to the fifth columns. The

\* There are no stellar particles within 2.5 – 3.5\(R_h\). Thus \(A_1\) cannot be measured in this galaxy.
Figure 10. The projected stellar mass densities of satellite subID 566663 are exhibited on $x' - z'$ (upper left), $x' - y'$ (lower left) and $z' - y'$ (lower right) planes of inertia tensor’s eigenframe, with black dotted circles showing the radii of $3R_h$. The radial phase-space density distribution of this satellite, $r$ versus $v_r$, is displayed in the upper right panel.

centre is $(v_x', v_y', v_z') = (-107.3, 133.4, -8.6)\,\text{km}\,\text{s}^{-1}$, when the whole halo is rotated to the eigenframe of inertia tensor of the central galaxy. The orbit of this satellite on the scale of cluster of galaxies implies that it is passing through the stellar plane of its host halo. Thus the tidal shocking from the close encounter may account for the lack of dark matter. However, the ratio $\left(a_+/a_-\right)\,R_h = 1.84 > 1.0$. Therefore, the long semi-major axis is in the far-side to its central galaxy, indicating that the lopsidedness is not due to tidal shocking. Other physical origins are required. To find out the ture mechanism, we examine the stellar surface density of this satellite in the left two panels as well as the lower-right one of Fig. 10. There is a clear structure located outside $3R_h$. Moreover, an infalling clump at the same radius is found in the phase-space density distribution of subID 566663 displayed in the upper right panel of Fig. 10. Since the particles within the clump are identified as part of the satellite subID 566663, that the clump is infalling shows that the satellite is a nonfully relaxed merger remnant.

Early studies have demonstrated that asymmetric gas accretion with subsequent star formation is responsible for the lopsidedness of galaxies (e.g., Bournaud et al. 2005b; Mapelli et al. 2008). The cold gas accreted from the cosmic filaments could form new stars and thus lead to an asymmetric shape of the stellar component in a satellite galaxy (Kereš et al. 2005). A typical example satellite galaxy, subID 455296, is presented in Fig. 11. The phase-space density distribution (left panel) reveals that there is a substructure falling into the satellite centre. The gas distribution in this satellite is examined (middle panel) to exclude other physical process such as merger of galaxies. On the scale of $\approx 1\,\text{kpc}$, the projected stellar density appears to be quite symmetric on the $x' - z'$ plane of its own eigenframe of inertia tensor. There are extended structures on the upper left corner of the projected densities of both stellar and gaseous components. The gas is accreted into the satellite centre. The metallicity of stars in this satellite is studied in the right panel. The metallicity of stars in the regions of infalling gas appears to be higher, which suggests that young stars form through the accretion of cold gas. We deduce from these results that the cold gas accretion and the subsequent star formation can generate the lopsidedness of satellite subID 455296 at the radius near $10\,R_h$ and of the subID 455296-like satellites.

Ram pressure stripping from the diffuse intergalactic medium (IGM) plays only a minor role in producing the lopsidedness of galaxies (Mapelli et al. 2008). The gaseous component in a satellite is compressed by the IGM in the leading side and is stretched in the opposite direction of the orbit (e.g., a recent review by Boselli et al. 2022). The gaseous component can be stripped outside the stellar component by ram pressure (Smith et al. 2012). As a consequence, the stellar and dark matter components would be influenced by the drag force imposed by the gas, which in turn leads to an offset of a few $kpc$ between the disc and the dark matter halo (Smith et al. 2012). The satellite subID 313700 displayed in Fig. 12 is a representative example of ram pressure stripped lopsided galaxy. In the eigenframe of inertia tensor of the host central galaxy, the galactocentric distance and relative speed between subID 313700 and the central galaxy are 74 $kpc$/h and 765.3 $kms^{-1}\text{h}^{-1}$, respectively. This satellite is on an incoming orbit to the central galaxy. The gaseous component of the satellite has been stripped out and left behind the stellar disc. In view of the large gas fraction ($f_{gas} = 82\%$) in this satellite, the gravitational force introduced by the gaseous component is significant. The gravitation from the stripped gas then drags the stars in the direction opposite to the direction of motion. We therefore draw a conclusion that the lopsidedness of the stellar component is caused by ram pressure in the subID 313700-like satellites.

5.2.2 Internal origins

Apart from the external origins for the lopsidedness of galaxies, internal dynamics can also produce significantly lopsided galaxies. For instance, the gravitational instability of disc galaxies may result in a significantly lopsided shape of a galaxy (Zaritsky et al. 2013). The extremely lopsided satellite subID 494710, listed in Table 3, is a typical disc galaxy with spiral arms. This stellar disc is thin, with $c: a = 0.19$. In addition, this satellite is far away to the central galaxy and to other satellite galaxies. Moreover, there is neither asymmetric gas accretion nor recent minor merger events in this satellite. Thus the gravitational instability of the thin disc might be the mechanism of the lopsidedness. The origins of lopsidedness is irrelevant to our conclusions, thus will not be discussed further.

5.3 Asymmetric tidal tails

For the outskirts of the cluster satellite galaxies where $r > 5R_h$ or even further out, $g_{int} \gg g_{ext}$ in MOND. In these regions, the dominant gravity is the external field. Thus MOND
that in the far-side. Hence, LRA is expected only within \( r_1 \) of the satellites or star clusters. In the outskirts of a self-bound system where \( r > r_1 \), the stars are believed to be unbound.

The morphologies of the tidal tails of star clusters, including in Palomar 5-like globular clusters (Thomas et al. 2018) and open clusters (Kroupa et al. 2022), have been studied. A comparison has been made by Thomas et al. (2018) between an external field in MOND and a tidal field in Newtonian dynamics concerning the morphologies of the leading and trailing tails of a Palomar 5-like GC embedded in a Milky Way-like potential. The leading tail obtained by MOND is significantly shorter and more fluffy than the trailing tail, which is due to that the escaping stars need to overcome a deeper potential well from the GC in the near-side (Thomas et al. 2018). These predictions by Thomas et al. (2018) agree well with the observed Palomar 5 stream (Bernard et al. 2016).

Very recently, there are more asymmetric tidal tails observed in star clusters, including Hyades, Praesepe, Coma Berenices, COIN-Gaia 13 and NGC 752 (Kroupa et al. 2022). The numerical simulations for the formation of tidal tails in open clusters were performed in both Newtonian and Milgromian dynamics (Kroupa et al. 2022). The authors found that the tidal tails are nearly symmetric within the framework of Newtonian dynamics, but are asymmetric in MOND with more stars in the leading tails than trailing tails within a globular cluster-centric distance of 50 pc. Thus an asymmetry is found in the simulated tidal tails in MOND, which agrees well with the observations.

In distinction to MOND, the tidal tails of satellites are found to be extremely symmetric in a smooth and static host halo potential in previous studies of Newtonian dynamics (Dehnen et al. 2004). The sole tidal field from the Milky Way cannot reproduce the asymmetric tidal tails of Palomar 5 (Dehnen et al. 2004), unless other consequences of gravitational interactions are introduced, such as perturbations induced by giant molecular clouds (Amorisco et al. 2016), subhaloes (Erkal et al. 2017), spiral arms (Banik & Bovy 2019) or a prograde Galactic bar (Pearson et al. 2017). Bonaca et al. (2020) emphasised that none of the currently existing scenarios can explain all the observational features of the stellar streams of Palomar 5. To explain all the observational results...
of Palomar 5 within one scenario is out of the scope of this work.

We see from the above discussion that the different predictions on asymmetry of tidal tails provide another efficient method to verify or falsify gravity. However, in this work, we do not focus on the tidal structures of cosmologically simulated satellites in TNG50-1, since their resolution is not high enough, especially in the low mass satellites.

6 SUMMARIES AND CONCLUSIONS

In this work, we have presented a detailed analysis of the semi-major axial ratios \( (a_-/a_+) \) of the satellite galaxies generated by the TNG50-1 simulation. We have found that the distribution of \( a_-/a_+ \) is almost symmetric around the central value of \( a_-/a_+ = 1.0 \). This result indicates that the probabilities for the long semi-major axes of satellites to point towards and outwards the halo centres are nearly equal. We have adopted two criteria to define the lopsidedness of a satellite. More concretely, a satellite galaxy is regarded as lopsided if \( \Delta > 0.1 \) or \( A_1 > 0.2 \). Under the former criterion, the fractions of strongly lopsided satellites are 7.5% and 11% for the isolated and non-isolated satellites truncated at 3 \( R_h \), respectively. Under the latter criterion, the two numbers become 7.8% and 18.1%, respectively. While the fractions of strongly lopsided satellites in our analysis are at least one order of magnitude larger than those reported in Lokas (2022), they are still smaller than observations (e.g., Jog & Combes 2009; van Eymeren et al. 2011; Yu et al. 2022).

The correlations between \( a_-/a_+ \) and other physical parameters have been further studied. We have shown that \( a_-/a_+ \) does not correlate with the distance to the halo centres, \( D \), in both the inner and outer regions of the satellites. The fraction of galaxies with long semi-major axes in the near-side to halo centres, \( f_{N_S} \), is almost equal to 50%. These findings imply that the tidal fields from the halo centres do not lead to the lopsidedness of satellites. Moreover, we have found that neither the masses of the host haloes \( M_{\text{halo}} \) nor the satellite masses \( M_{\text{sat}} \) correlate with \( a_-/a_+ \). However, we have revealed a correlation between the values of \( a_-/a_+ \) and the fractions of gas, \( f_{\text{gas}} \), in the satellites. In both isolated and non-isolated samples of satellites, more massive galaxies tend to be more gas-poor. Moreover, the more gas-rich galaxies are more lopsided, with a larger \( \Delta a \).

We have known from the above analysis that the lopsidedness of satellites is not mainly induced by the tidal fields from the halo centres. Although this result provides us with evidence that LRA is unlikely present in the simulated satellites within the framework of ΛCDM. More careful investigation is required to reach a conclusive answer. This model provides us with the chance to examine the existence of such a new alignment in the TNG50-1 simulation. The alignment angle \( \theta \) defined in Eq. 9 has been systematically analysed. In the inner (3 \( R_h \)) and intermediate (5 \( R_h \)) regions, no LRA has been observed. Only in the outer region (10 \( R_h \)) of the satellites is there a very weak LRA.

In contrast, LRA was shown (Wu et al. 2010, 2017) to be a natural prediction of MOND as a consequence of the violation of SEP caused by the external fields. This conclusion is supported by the values of ratio \( a_-/a_+ < 1.0 \) for cluster galaxies truncated at \( \approx 5 R_h \) predicted in Wu et al. (2017). The LRA has been observed quite recently in the NGC 5055 galaxy with respect to the Virgo axis (Oria et al. 2021). Since the predictions on the LRA are so different in MOND and in the ΛCDM framework, the existence of LRA in future observations will provide a discriminating test of gravity.

Another promising way to test gravity is to observe the morphologies of tidal tails of star clusters. In modified gravity, the leading and trailing tails are asymmetric due to the galactic external fields (Thomas et al. 2018; Kroupa et al. 2022), while in Newtonian dynamics, these two tails are nearly symmetric even when the galactic tidal field is taken into account (Dehnen et al. 2004). The asymmetric morphologies of tidal tails, as the extended part of satellites or star clusters, stem from the same physical mechanism as that for LRA in MOND.

Finally, we have briefly discussed the possible origins for the lopsidedness of satellites in the TNG50-1 simulation. The lopsidedness could be induced by the tidal stripping from the nearby central galaxies or massive satellite galaxies, the recent mergers, the asymmetric accretion of cold gas from cosmic filaments, the ram pressure stripping and internal dynamics of the disc galaxies.

ACKNOWLEDGEMENTS

The authors acknowledge the public release of Illustris-TNG data. XW is financially supported by the Natural Science Foundation of China (Number NSFC-12073026, NSFC-11421303) and “the Fundamental Research Funds for the Central Universities”. YZ is financially supported by “Fund for Fostering Talents in Basic Science of the National Natural Science Foundation of China NO.J1310021”.

XW motivated and supervised the project. JS analysed the released TNG50-1 data with assistance of BG. YZ contribute to the early analysis to Illustris-1 data as an undergraduate thesis project. XW and JS wrote the manuscript with contributions from BG and YZ.

REFERENCES

Amorisco N. C., Gómez F. A., Vegetti S., White S. D. M., 2016, MNRAS, 463, L17
Angriss A. R., Jog C. J., Omar A., Dwarkanath K. S., 2006, MNRAS, 369, 1849
Arp H., 1966, Atlas of peculiar galaxies. Pasadena: California Inst. Technology
Bai L., Zhong J., Chen L., Li J., Hou J., 2022, Research in Astronomy and Astrophysics, 22, 055022
Baldwin J. E., Lynden-Bell D., Sancisi R., 1980, MNRAS, 193, 313
Bank N., Boyy J., 2019, MNRAS, 484, 2009
Beale J. S., Davies R. D., 1969, Nature, 221, 531
Bekenstein J., Milgrom M., 1984, ApJ, 286, 7
Bernard E. J., et al., 2016, MNRAS, 463, 1759
Binney J., Tremaine S., 2008, Galactic Dynamics: Second Edition. Princeton University Press
Bok J., Blyth S. L., Gilbank D. G., Elson E. C., 2019, MNRAS, 484, 582
Bonaca A., et al., 2020, ApJ, 889, 70
Boselli A., Fossati M., Sun M., 2022, A&ARv, 30, 3
Bosma A., 1978, PhD thesis, University of Groningen, Netherlands
Bournard F., Jog C. J., Combes F., 2005a, A&A, 437, 69
Bournard F., Combes F., Jog C. J., Puerari I., 2005b, A&A, 438, 507

MNRAS 000, 1–16 (0000)
