

Peculiar galaxies – I. A catalogue of polar-ring galaxies from the TNG50 simulation

Josué G. López-Castillo,^{1★} Manuel Zamora-Avilés¹,^{1★} Gilberto C. Gómez¹,^{2★} Ivânio Puerari² and Divakara Mayya¹

¹*Instituto Nacional de Astrofísica, Óptica y Electrónica, Luis E. Erro 1, 72840, Tonantzintla, Puebla, México*

²*Universidad Nacional Autónoma de México, Instituto de Radioastronomía y Astrofísica, Apdo. postal 3-72, 58089 Morelia, Michoacán, México*

Accepted 2025 November 3. Received 2025 October 28; in original form 2025 June 3

ABSTRACT

The hydrodynamic cosmological simulation, TNG50, is employed to conduct an analysis of multispin galaxies that exhibit ringed structures composed of gas and stars that orbit nearly perpendicular around a host galaxy, known as polar ring galaxies (PRG). To ensure a robust sample, we select subhaloes based on the angle subtended by the angular momentum profiles, as well as on a visual inspection. The analysis is focused on galaxies with stellar masses greater than $10^9 M_{\odot}$. In addition, a dynamic decomposition is employed to separate the stellar and gaseous ring from the host galaxy. This results in a sample of 32 subhaloes with PRGs. This sample exhibits properties similar to those observed. These include colours typical of early-type galaxies (ETGs) or those transitioning toward blue systems. Most host galaxies are classified as ETGs, with 37.5 per cent exhibiting a disc-dominated morphology. The mean bulge-to-total (B/T) ratio is 0.64. Rings have average radii that are 2.36 and 3.41 times larger than their effective radii for the stellar and gaseous components, respectively, with star formation occurring predominantly within the rings. In contrast with observations, rings in the simulation tend to be less massive and slightly less perpendicular. The obtained sample displays a variety of host galaxy morphologies, including wide and narrow rings, providing a robust framework for studying the varied structural characteristics of PRG variants.

Key words: methods: numerical – catalogues – galaxies: evolution – galaxies: formation – galaxies: peculiar – galaxies: statistics.

1 INTRODUCTION

The study of peculiar galaxies enables us to test our models of the universe by examining objects that form and evolve under extreme environmental conditions. Polar ring galaxies (PRGs) are peculiar systems characterized by a central host galaxy encircled by an outer ring of stars, gas, and dust that orbits nearly perpendicular to the mid-plane of the host (B. C. Whitmore et al. 1990). The host galaxy in these objects is predominantly associated with early-type galaxies (ETGs, M. Arnaboldi et al. 1995; E. Iodice et al. 2002b; V. Reshetnikov & F. Combes 2015). The wide range of structures exhibited by PRGs makes them particularly valuable for studies of galaxy evolution. This diversity includes thin and compact structures, as well as very extended rings (V. Reshetnikov & N. Sotnikova 1997; I. Finkelman, J. G. Funes & N. Brosch 2012; Y. Ordenes-Briceño et al. 2016). Some of these structures are even disc-like, showing features such as spiral arms (e.g. NGC4650A, V. Reshetnikov & N. Sotnikova 1997; J. S. Gallagher et al. 2002; E. Iodice et al. 2002a, 2006). A significant fraction of polar ring structures appear bluer and fainter than their host galaxies, making them detectable only in deep galaxy surveys (V. Reshetnikov & F.

Combes 2015; A. V. Mosenkov et al. 2024). A possible correlation between PRGs and nuclear activity has also been suggested. While an excess of Seyfert and low-ionization nuclear emission-line region galaxies among PRGs has been reported, other observational studies find no significant correlation compared to ‘normal’ ETGs (V. P. Reshetnikov, M. Faúndez-Abans & M. de Oliveira-Abans 2001; I. Finkelman et al. 2012; D. V. Smirnov & V. P. Reshetnikov 2020).

In this context, PRGs have been used to better understand the distribution of dark matter in galaxies (O. N. Snaith et al. 2012; S. A. Khoperskov et al. 2014), the formation and evolution of galaxies, and the impact on the dark matter halo (A. V. Macciò, B. Moore & J. Stadel 2006), or the nature of the Tully–Fisher relation (E. Iodice et al. 2003). At the same time, the ring contains a substantial reservoir of gas comparable in mass to that of the host galaxy, and its colour indicates one or more recent episodes of star formation (G. Galletta, L. J. Sage & L. S. Sparke 1997; E. Iodice et al. 2002c; V. Reshetnikov & F. Combes 2015; A. V. Mosenkov et al. 2024). A connection between PRGs and active nuclei is also expected, although some observational results have not found a significant correlation compared to ‘normal’ ETGs (V. P. Reshetnikov et al. 2001; I. Finkelman et al. 2012). Moreover, PRGs tend to reside in low-density environments, which helps preserve their rings by reducing disruptive interactions with neighbouring galaxies (I. Finkelman et al. 2012; S. S. Savchenko & V. P. Reshetnikov 2017;

* E-mail: josue.gerardo@inaoep.mx (JGLC); mzamora@inaoep.mx (MZA); g.gomez@irya.unam.mx (GCG)

D. V. Smirnov & V. P. Reshetnikov (2020). Unfortunately, only a few dozen PRGs have been confirmed, largely due to their diffuse nature and orientation effects that complicate identification. These limitations, in turn, constrain the robustness of the derived results. B. C. Whitmore et al. (1990) estimated that about 5 per cent of nearby lenticular galaxies have or have had polar structures, while V. P. Reshetnikov et al. (2011) found a corresponding fraction of ~ 0.4 per cent for nearby galaxies on the *B* band. D. V. Smirnov & V. P. Reshetnikov (2022) reported a lower fraction (~ 0.01 per cent) in the *r* band, increasing with redshift. More recently, A. V. Mosenkov et al. (2024) estimated a PRG fraction of ~ 3 per cent in the *r* band, considering projection effects.

Several attempts have been made to understand the origin of these objects, with several scenarios proposed and tested using numerical simulations for comparison with observational data. One of the proposed scenarios, known as the merge scenario, consists of a head-on collision of two disc galaxies, similar to the formation of collisional ring galaxies but with low velocities, where the perturber galaxy ends as the host galaxy. K. Bekki (1997, 1998) demonstrated that PRGs formed by the merge scenario result in stable systems. For reference, AM 2229–735 has been classified as a PRG in formation through minor mergers (L. F. Quiroga et al. 2020). Another proposed scenario, the accretion scenario, consists of two galaxies undergoing a tidal interaction; one of them, the host galaxy, accretes gas from the donor galaxy that orbits almost perpendicular to the host galaxy. In this scenario, the interaction may or may not end in a merger (F. Schweizer, B. C. Whitmore & V. C. Rubin 1983; V. Reshetnikov & N. Sotnikova 1997; F. Bournaud & F. Combes 2003). A representative example of this formation scenario is NGC 3808B, which exhibits a tidal gas bridge being transferred from its companion NGC 3808A (V. P. Reshetnikov, V. A. Hagen-Thorn & V. A. Yakovleva 1996; Y. Ordenes-Briceno et al. 2016). Yet another model, the cosmological scenario, proposes that polar rings are formed by the accretion of cold gas from cosmological filaments onto the host galaxy. In this case, the accretion occurs perpendicular to the central galaxy (A. V. Macciò et al. 2006; C. B. Brook et al. 2008; O. N. Snaith et al. 2012). An observational signature of PRGs formed under this scenario is the low metallicity in their rings, indicative of the late infall of metal-poor gas, as is expected in cold accretion processes. This has been observed in systems such as NGC4650A (M. Spavone et al. 2010) and others (eg. UGC 7576, UGC 9796, or IIZw71; M. Spavone et al. 2011; O. V. Egorov & A. V. Moiseev 2019). There is no definite explanation for the origin of PRGs, as all of these scenarios likely occur in nature. Therefore, identifying observational features that can distinguish among the various formation mechanisms in individual galaxies would be important to assess the relative contributions of these different pathways.

Today, a variety of cosmological simulations have been performed, for example, EAGLE (R. A. Crain et al. 2015; J. Schaye et al. 2015), ILLUSTRISTNG (A. Pillepich et al. 2019; D. Nelson et al. 2019b), or HORIZON-AGN (Y. Dubois et al. 2014). These simulations can reproduce observational constraints such as star formation rates (SFRs), galaxy sizes, and dynamics (S. Genel et al. 2017; D. Nelson et al. 2018a; A. Pillepich et al. 2019). Thus, cosmological simulations have become a powerful tool for constraining the model of galaxy formation and evolution.

Historically, galaxies have been classified according to their apparent projected morphology, allowing us to catalogue them, for example, according to the distribution of the bulge and the disc (E. P. Hubble 1926; J. L. Sersic 1968). However, the advantage of numerical simulations is that they provide us with information about the morphological and dynamical parameters of galaxies over time.

In order to accurately study galaxies in cosmological simulations, it is necessary to use methods that split them into their constituent parts.

Recent studies have focused on clarifying the origins and evolutionary processes of these objects. D. V. Smirnov, A. V. Mosenkov & V. P. Reshetnikov (2023) conducted an analysis of PRGs selected through visual inspection of the TNG50 Infinite Gallery page,¹ at redshift 0.05. Six galaxies with the characteristics of PRGs were selected for further analysis. In these galaxies, the polar structure is formed by interaction with a gas-rich companion or satellite. The formed rings evolve and change their inclination with respect to the disc. Additionally, D. V. Smirnov et al. (2023) reported the relation of the formation of polar rings and temporary bursts of nuclear activity. Other types of annular structures have been identified in the EAGLE simulation by A. Elagali et al. (2018), who classified ring galaxies into two categories: O-type (resonance ring galaxies) and P-type (collisional ring galaxies). In contrast, as discussed in Section 2, our selection scheme specifically targets misaligned ring structures around galaxies.

The aim of this paper is the identification of PRGs in the hydrodynamic cosmological simulation TNG50 (A. Pillepich et al. 2019; D. Nelson et al. 2019b), which has the best resolution in the ILLUSTRISTNG simulations in an extended cosmological box. This allows us to identify and study a consistent sample of PRGs and compare it with the observational counterpart. The simulations also allow for the analysis of galaxy dynamics and the decomposition of galaxies into their different components, both in terms of their stellar and gaseous structure. Thus, the formation and evolution of the rings can be characterized. This sample of PRGs can be useful for future work to constrain the origin of these peculiar galaxies as well as their observables. The structure of this paper is as follows. A brief description of the cosmological simulation used, and the method used to select the PRGs as well as the decomposition method used to detect the ring structures is given in Section 2. Section 3 describes the general properties of the simulated PRGs and compares them with the observed PRGs. Sections 4 and 5 contain a discussion and summary and conclusions of the main results.

2 NUMERICAL METHODS

Modern cosmological simulations have become a powerful tool for statistically studying the impact of environment and interactions on the formation and evolution of galaxies from a statistical point of view. For this reason, we used the ILLUSTRISTNG simulation² (F. Marinacci et al. 2018; J. P. Naiman et al. 2018; V. Springel et al. 2018; D. Nelson et al. 2018a; A. Pillepich et al. 2018b), which reproduces key observational results such as the red sequence and blue cloud of Sloan Digital Sky Survey (SDSS) galaxies (D. Nelson et al. 2018b), the size evolution of galaxies (S. Genel et al. 2017), the structure and kinematics of gas and stellar discs (A. Pillepich et al. 2019), and the morphologies of galaxies in comparison to observations from the Pan-STARRS survey (V. Rodriguez-Gomez et al. 2019), among others. ILLUSTRISTNG is a magnetohydrodynamic cosmological simulation that is publicly available in all its versions, TNG50, TNG100, and TNG300, where the number in the label refers to the size of the simulation box in comoving Mpc. The simulations were calculated with the moving mesh code AREPO (V. Springel 2010) and the initial conditions were created using the N-GENIC code (V. Springel et al.

¹<https://www.tng-project.org/explore/gallery/rodriguezgomez19b/>

²<https://www.tng-project.org/>

2005) at redshift 127 using the Zeldovich approximation. The cosmological parameters used were those reported by Planck Collaboration XIII (2016), namely $\Omega_m = \Omega_{\text{dm}} + \Omega_b = 0.3089$, $\Omega_b = 0.0486$, and $\Omega_\Lambda = 0.6911$ (matter density, baryonic density, and cosmological constant, respectively), the Hubble constant used was $H_0 = 100h$ km s⁻¹ with $h = 0.6774$, normalization $\sigma_8 = 0.8159$, and spectral index $n_s = 0.9667$.

For this work, we used the TNG50-1 version (A. Pillepich et al. 2019; D. Nelson et al. 2019b) which, with a computational domain of 51.7 comoving Mpc, has a better spatial resolution than the larger versions, reaching 6.5 pc in the smallest gas cell of the simulation (at redshift 1) and masses of baryonic particles around $0.08 \times 10^6 M_\odot$ (A. Pillepich et al. 2019). This allows us to better resolve the morphology of galaxies. Stars are formed stochastically in cells where the gas number density exceeds the threshold $n_{\text{thr}} = 0.13 \text{ cm}^{-3}$ (see M. Vogelsberger et al. 2013, for details). ILLUSTRITNG is the continuation of the original simulation ILLUSTRIS (S. Genel et al. 2014; M. Vogelsberger et al. 2014) with the goal of reproducing with more precision properties of observed galaxies (D. Nelson et al. 2019a). The ILLUSTRITNG model for galaxy formation includes star formation, stellar evolution, primordial and metal-line cooling, stellar feedback, formation, growth, and feedback of supermassive black holes (R. Weinberger et al. 2017; A. Pillepich et al. 2018a). The star formation model was based on V. Springel & L. Hernquist (2003), where the stars are formed stochastically after the density overpasses a density threshold. Unresolved supernovae feedback was included for a star-forming gas using a two-phase, effective equation-of-state model. This galaxy formation model was calibrated on observational data to reproduce the statistical properties of galaxies. A more detailed description can be found in A. Pillepich et al. (2018a).

The galaxy sample was taken from the subhaloes of the snapshot corresponding to redshift zero. Subhaloes were defined as a group of gravitationally bound particles that belong to a given halo and were identified using the SUBFIND algorithm (V. Springel et al. 2001). The haloes were identified using the friends-of-friends algorithm introduced by M. Davis et al. (1985) using a link length of $b = 0.2$ times the mean particle separation. The algorithm was applied only to dark matter particles, and the other particle types were assigned to the same halo as the nearest dark matter particle. The TNG50 simulation is a combination of large volumes and high-resolution analogues to modern ‘zoom’ simulations of individual galaxies. This simulation generates $\sim 20\,000$ resolved galaxies with $M_\star \gtrsim 10^7 M_\odot$ (D. Nelson et al. 2019b). To ensure sufficient resolution for reliable morphological and kinematic analysis, we selected only subhaloes containing at least 10^4 stellar particles (Z. Penoyre et al. 2017), corresponding to a minimum stellar mass of $\sim 10^9 M_\odot$ (assuming a typical stellar particle mass of $10^5 M_\odot$). This criterion yields a sample of 4349 galaxies above the mass threshold.

To identify PRGs, we use the specific angular momentum of the stars. In an ideal PRG, the total angular momentum of the host galaxy’s disc and that of the ring should be perpendicular to each other (see Fig. 1 for a schematic representation).

To define the host galaxy’s reference frame, we considered the subhalo centre as the particle with the deepest gravitational potential. Additionally, particle velocities were measured in the reference frame of the centre of mass of the stellar particles within twice the subhalo stellar half-mass radius (r_{hm}). This approach prevents the inclusion of stellar particles from satellites or unbound high-speed particles.

Once the reference frame was established, we constructed the specific angular momentum (j) profile of the subhaloes using the particles contained within concentric spherical shells. The total

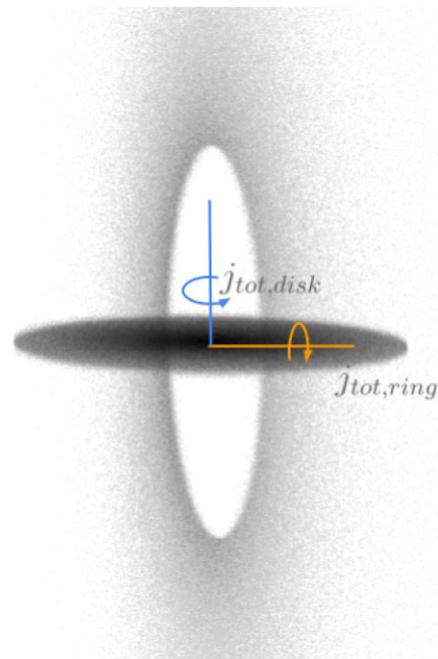


Figure 1. Representation of the vectors of the specific total angular momentum of the disc ($j_{\text{tot,disk}}$) and the ring ($j_{\text{tot,ring}}$) of an idealized model of a PRG.

specific angular momentum (j_{tot}) of each shell was computed as:

$$j_{\text{tot}} = \frac{\sum m_i \mathbf{r}_i \times \mathbf{v}_i}{\sum m_i}, \quad (1)$$

where m_i , \mathbf{r}_i , and \mathbf{v}_i represent the mass, position, and velocity of each particle i in the given shell. We took as a reference the j_{tot} of the stars within $0.5r_{\text{hm}}$ and compared its direction with the j_{tot} calculated in each shell. The same analysis was performed for the gaseous component, using the stellar j_{tot} as a reference.

Following V. Reshetnikov & F. Combes (2015), we considered a potential PRG if the inclination angle was between 30° and 150° . If the minimum inclination in the profile of the galaxy differed by more than 30° and less than 150° , the galaxy was considered a potential PRG as was found by V. Reshetnikov & F. Combes (2015) in their sample of observed PRG galaxies.

Fig. 2 shows, as an example, the subhalo 167392 at redshift zero. The galaxy was reoriented by aligning j_{tot} of the stellar particles within $0.1r_{200}^3$ with the z -axis. The lower panels show the resulting radial profiles of the specific angular momentum, its direction, and the magnitude of its components. In this example, it can be seen that the ring is roughly perpendicular to the pseudo-disc. However, the maximum inclination shown in the plot is approximately 50° . This difference is due to the extended bulge and stellar haloes around the host galaxy. This condition complicates the selection of PRGs. Therefore, a visual inspection was also performed using projections, profiles and line-of-sight velocity maps (see an example in Fig. 3).

The above described process yielded 44 PRG candidates in the entire computational box of the TNG50 simulation at redshift zero. Projections of the stellar and gaseous components of these PRGs candidates are shown in Figs 4 and 5. In the stellar projection, an extended spherical component is observed in all galaxies of the

³Radius at which the mean density is 200 times the critical density of the universe.

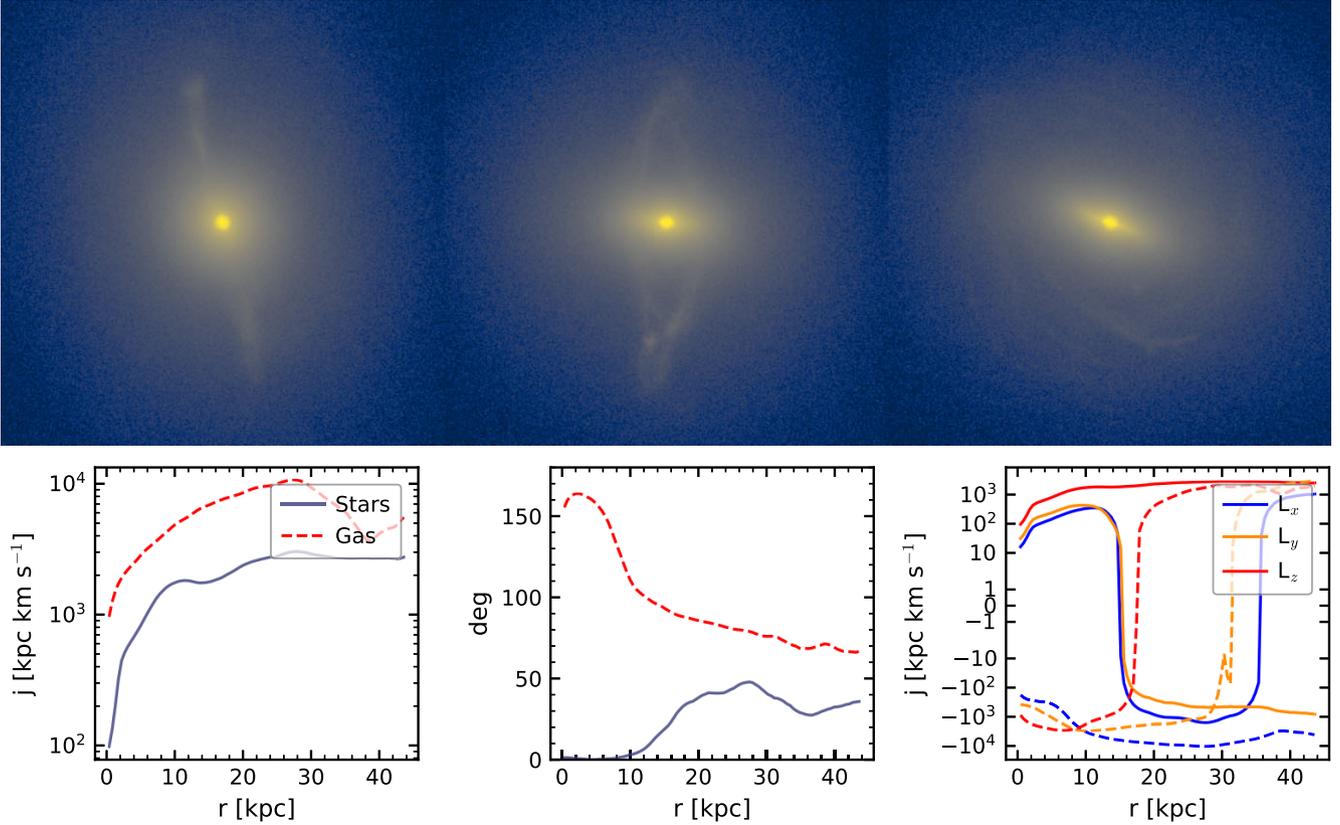


Figure 2. Stellar and gaseous structure and kinematics of a representative PRG candidate (subhalo 167392). Top row: surface mass density of the stellar component in the $x - y$ (left), $x - z$ (middle), and $y - z$ planes (right) for the subhalo 167392. The z -axis was defined as the direction of the total angular momentum of the stellar particles within $0.1r_{200}$ in the subhalo. Bottom row: radial profiles of the specific angular momentum (left), the relative angle of the specific angular momentum with the z -axis (middle), and the components of the specific angular momentum (right). In the three panels, both the angular momentum corresponding to the stellar (solid lines) and gaseous (dashed) galaxy components are shown.

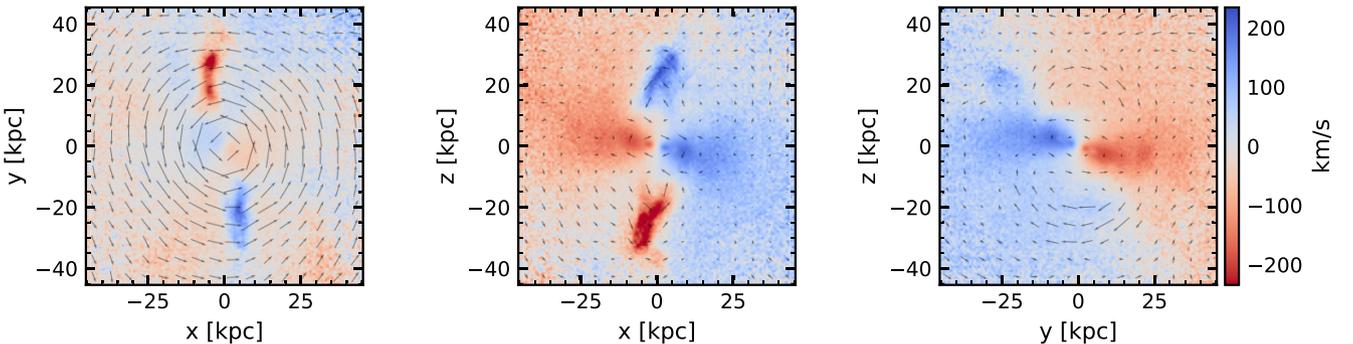


Figure 3. Mass weighted velocities of the stellar component in the line of sight along the main axes of the subhalo 167392. The rotating ring is clearly visible as polar structures in the left and middle panels, while the rotating host disc appears as an equatorial structure in the middle and right panels.

sample. This component makes it difficult to distinguish the ring or any other morphology. We note that the gas better traces the morphology of structures (Figs 4 and 5) and, interestingly, many of these galaxies exhibit a central gas deficiency, a characteristic commonly associated with late-type galaxies.

2.1 Decomposition

To analyse the properties of our sample, it was necessary to identify the different dynamical components in galaxies. Visual inspection of

the angular momentum profiles was not sufficient to identify the ring due to the extended stellar spherical component present in almost all subhaloes, as shown in Figs 4 and 5. Therefore, to decompose the galaxies in the sample, we used the following procedure. First, we examine the κ parameter introduced by L. V. Sales et al. (2012),

$$\kappa = \frac{K_{\text{rot}}}{K}, \quad K_{\text{rot}} = \sum_i \frac{1}{2} m_i \left(\frac{j_{z,i}}{R_i} \right)^2, \quad (2)$$

where K_{rot} is the total kinetic energy associated with rotation around the z -axis, calculated with the stellar mass (m_i), the specific angular

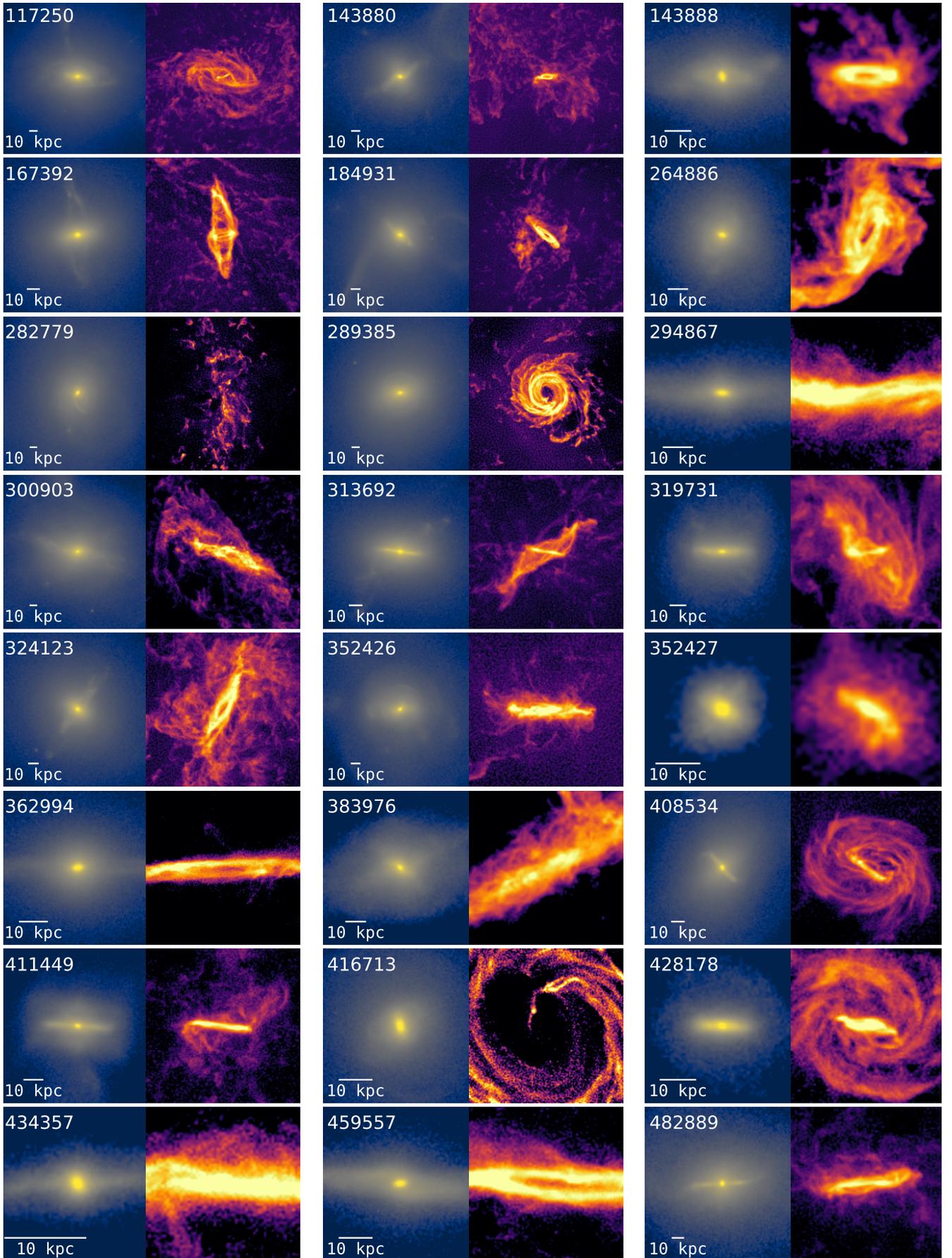


Figure 4. Surface mass density of the stellar (left) and gaseous (right) components of the first sample of galaxies listed in the Table 1.

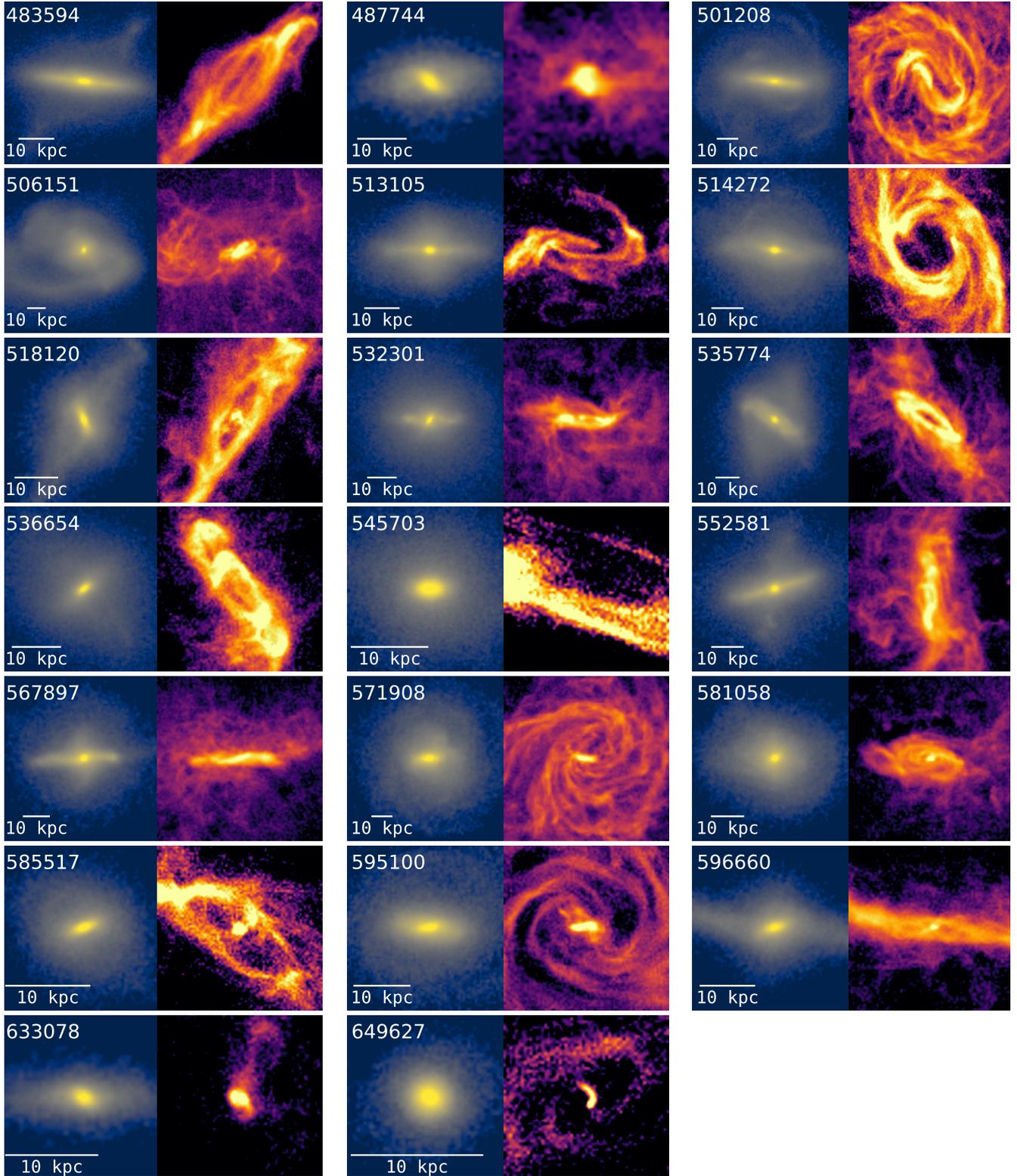


Figure 5. Continuation of Fig. 4.

momentum along the z -axis ($j_{z,i}$), and the cylindrical radius (R_i) of each particle; and K is the total kinetic energy of the galaxy. This parameter is used as an indicator of galaxy's shape, indicating whether it is more spherical or flat. For disc-dominated galaxies, $\kappa \sim 1$, while for bulge-dominated or elliptical galaxies $\kappa \sim 1/3$. The

values for our sample are around $1/3$, except for four of them that have values larger than 0.5 (see Table 1). This parameter classifies most of the galaxies in our sample as spherical or elliptical galaxies, due to the extended spherical component, as shown in Figs 4 and 5.

Table 1. (1) ID of the subhaloes in TNG50. (2) κ parameter described by equation (2). (3) Mass fraction of particles with $\epsilon > 0.7$. (4) Mass fraction of particles with $\epsilon < -0.7$.

Subhalo ID ⁽¹⁾	κ ⁽²⁾	$\epsilon_{07}^{(3)}$	$\epsilon_{-07}^{(4)}$
117250	0.298	0.199	0.036
143880	0.334	0.133	0.057
143888	0.418	0.256	0.064
167392	0.404	0.074	0.059
184931	0.300	0.074	0.061
264886	0.289	0.067	0.055
282779	0.290	0.080	0.046
289385	0.330	0.162	0.039
294867	0.339	0.226	0.073
300903	0.382	0.193	0.041
313692	0.388	0.335	0.033
319731	0.411	0.462	0.016
324123	0.338	0.117	0.044
352426	0.338	0.169	0.030
352427	0.361	0.163	0.032
362994	0.350	0.129	0.062
383976	0.395	0.200	0.026
408534	0.323	0.080	0.039
411449	0.330	0.285	0.030
416713	0.361	0.051	0.050
428178	0.562	0.549	0.010
434357	0.451	0.206	0.067
459557	0.261	0.229	0.139
482889	0.379	0.165	0.056
483594	0.217	0.389	0.023
487744	0.301	0.268	0.035
501208	0.606	0.509	0.014
506151	0.410	0.173	0.022
513105	0.363	0.222	0.088
514272	0.289	0.133	0.023
518120	0.317	0.051	0.065
532301	0.335	0.192	0.032
535774	0.457	0.072	0.085
536654	0.377	0.113	0.033
545703	0.302	0.092	0.053
552581	0.373	0.344	0.039
567897	0.445	0.348	0.025
571908	0.543	0.305	0.016
581058	0.401	0.163	0.048
585517	0.316	0.206	0.024
595100	0.637	0.436	0.008
596660	0.309	0.364	0.030
633078	0.255	0.245	0.093
649627	0.360	0.157	0.052

Circularity (ϵ) is a widely used parameter in the literature on dynamical decomposition, introduced by M. G. Abadi et al. (2003). In this work, we used the version of C. Scannapieco et al. (2009)⁴ which is defined as

$$\epsilon = \frac{\mathbf{j} \cdot \hat{\mathbf{z}}}{j_c(r)}, \quad (3)$$

where

$$j_c(r) = r v_c(r) = r \sqrt{\frac{GM(r)}{r}} \quad (4)$$

⁴Both definitions yield very similar results (F. Marinacci, R. Pakmor & V. Springel 2013).

is the angular momentum associated with a circular orbit. Values of $|\epsilon|$ greater than 0.7 correspond to the particles in a disc, with negative ϵ values corresponding to a counter-rotating disc. Particles with $|\epsilon| < 0.7$ belong to spherical components. Fig. 6 shows the distribution of particle circularities in the subhaloes of our sample. These distributions show that almost all galaxies are dominated by a spherical component except for the four galaxies with $\kappa \sim 0.6$ (IDs: 428178, 501208, 571908, and 595100) that exhibit right-skewed peaks. The remaining subhaloes show prominent peaks around $\epsilon \sim 0$, indicating the dominance of the spherical components in the systems.

The values obtained for κ and ϵ are consistent at different levels, but so far none of these provide much information about the rings. In order to separate the rings from the host galaxy, a variation of the method proposed by Y. Jagvaral et al. (2022) was used. This method consists in creating a $\cos(\alpha) - j_r$ diagram, where α is the angle subtended between the particle angular momentum vector and the total angular momentum of the stellar particles within $1r_{\text{hm}}$, and j_r is the ratio of the specific angular momentum of the particles (j_i) to its expected specific angular momentum for a circular orbit (j_c) at the same galactocentric distance, thus describing how circular the orbit of the particle is. Particles that fall in one of three categories are of particular interest: (i) particles with values of $\cos(\alpha) \sim 1$, which are commonly associated with a disc; (ii) particles with values of $\cos(\alpha) \sim -1$, which indicate a counter-rotating disc; and (iii) particles with $\cos(\alpha) \sim 0$, which indicate structures orbiting perpendicular to the plane of the galaxy, suggesting the presence of a polar ring. Fig. 7 shows the $\cos(\alpha) - j_r$ diagram for the subhalo 167392. Different groups are visible in reddish colours: a disc on the right ($\cos(\alpha) \sim 1$ and $j_r \sim 0.75$), a ring at the centre ($\cos(\alpha) \sim 0$, $j_r \sim 1$), and a counter-rotating component to the left ($\cos(\alpha) \sim -1$, $j_r \sim 1$).

To separate the particles of each component in the $\cos \alpha - j_r$ diagram, we used the CUPID⁵ clump finding algorithm (D. S. Berry et al. 2007). First, the background was removed from the $\cos \alpha - j_r$ diagram using a method similar to that used for clumpiness (C. J. Conselice 2003). It was removed by smoothing the original image with a median filter, where the filter size was set to half the square root of the number of bins and then subtracted from the original image. Finally, the clump finding algorithm was applied to the background-subtracted image. The method was initially applied to the stellar particles as these provide a better sample of the dynamic behaviour exhibited by the different galactic components. It was then repeated for the gaseous component, with the orientation of the stellar disc serving as the reference direction. Fig. 8 shows the different components obtained by this method for the stellar component. The orange area in the $\cos \alpha - j_r$ diagram corresponds to the main disc of the host galaxy. The components depicted by the green and purple colours correspond to a counter-rotating disc, the first with very circular orbits and the second with more dispersion. While these three regions are coplanar, a fourth structure is visible near the centre of the $\cos \alpha - j_r$ diagram. This area, marked in red colour, corresponds to a ring comprised of particles in very circular orbits, in contrast to the host galaxy, which shows a larger dispersion similar to ETGs. The individual components are also shown in Fig. 8.

Dynamic decomposition allows for a better understanding of the different components and their relation to counter-rotating discs and PRGs (S. Khoperskov et al. 2020). This method reveals the different dynamical components and allows the identification and classification of structures in the subhaloes. From the initial sample

⁵<http://starlink.eao.hawaii.edu/starlink/CUPID>

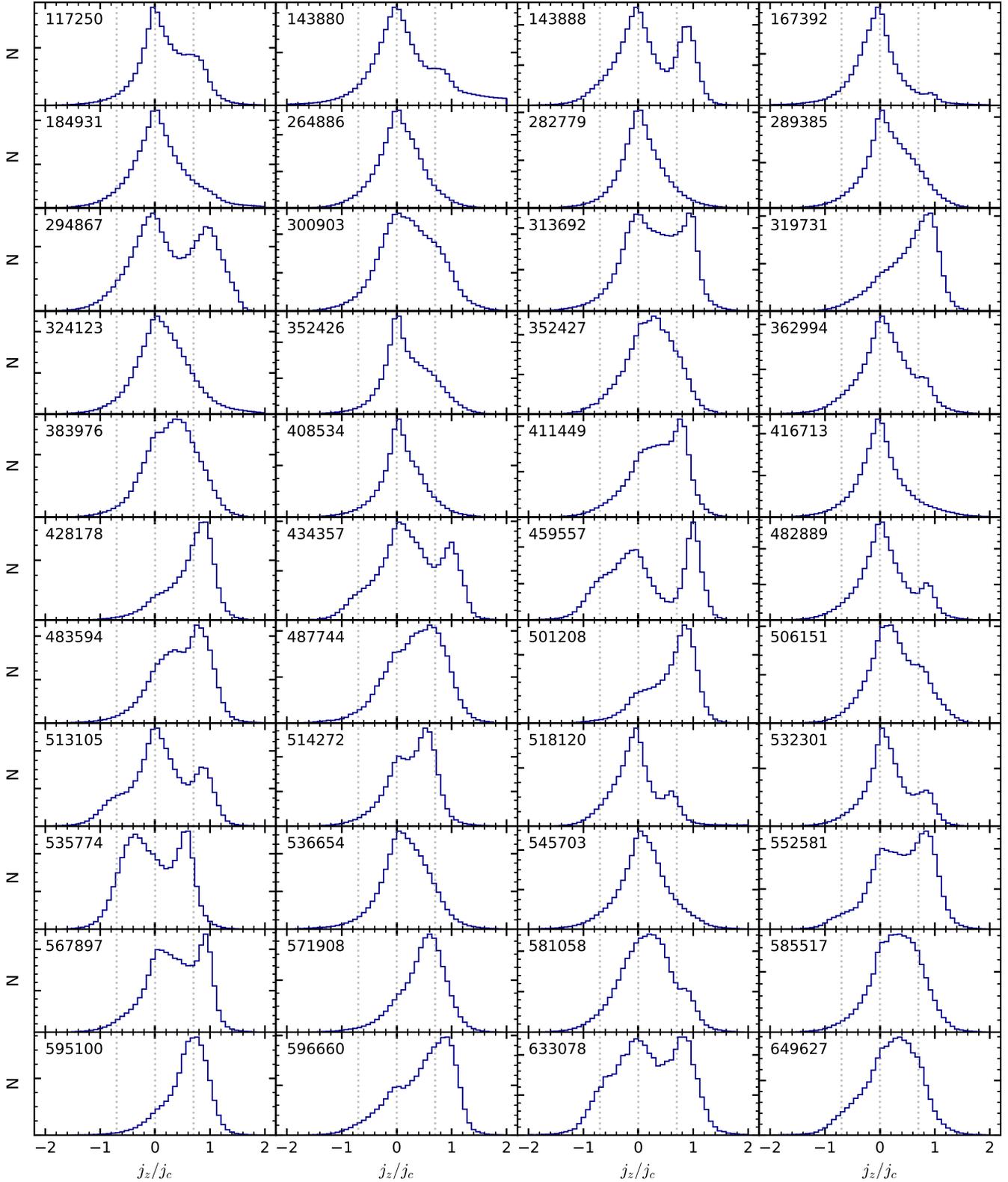


Figure 6. Circularities distribution of the complete first sample from Table 1. For each panel, the subhalo ID is indicated as the number in the upper left corner. Dotted vertical lines correspond to values of -0.7 , 0 , and 0.7 respectively.

of 44 galaxies, 12 were excluded (143880, 184931, 282779, 294867, 300903, 352426, 362994, 459557, 482889, 506151, 567897, and 581058), as the decomposition did not show a clear polar structure in these subhaloes. Some of these galaxies have structures resembling

a merger remnant, while others, such as subhalo 362994, resemble a ring around an extended bulge, but not in a polar orientation (similar to the Sombrero galaxy). As shown in Figs 4 and 5, galaxies in this sample often exhibit extended spherical components or tidal streams,

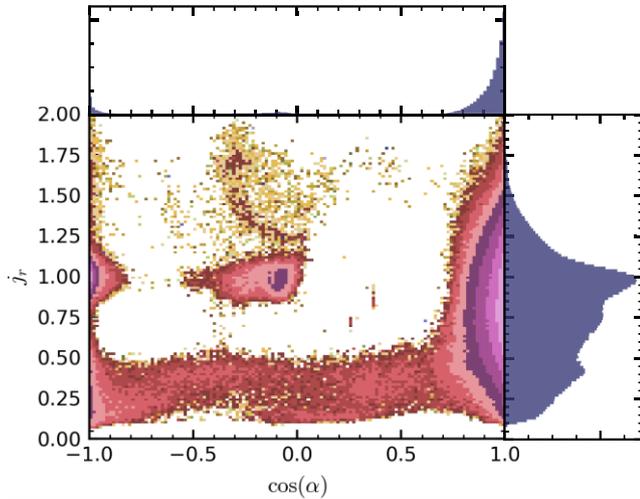


Figure 7. $\cos \alpha - j_r$ diagram of the subhalo 167392. The colours indicate the density of particles. The upper and right histograms are the projections of the diagram along the $\cos \alpha$ and j_r axes.

likely associated with violent formation events or past interactions. These structures add noise to the analysis, which may obscure faint polar features or even lead to misidentifications. Particles in stellar haloes or interaction remnants that have a similar dynamic as rings may produce spurious measurements. Such contamination could artificially increase the number of PRG candidates or, conversely, hide genuine faint polar structures. Although our method aims to minimize this contamination and incorporates multiple filters, we acknowledge that residual non-rotational components may still bias the estimated properties of both the rings and their host galaxies.

3 RESULTS

The final sample of PRG in the TNG50 simulation is conformed by 32 subhaloes. The decomposition allows for the selection of the particles that belong to individual structures in the subhaloes. This decomposition method was also applied to the gaseous component of the galaxy. Due to the lack of gas in the inner part of many subhaloes in the sample, we take as reference the total angular momentum of the stellar particles inside $1r_{\text{hm}}$. The PRG sample in TNG50 is listed in Table 2 with the masses of the stellar and gaseous components in the whole galaxy within a radius of $5r_{\text{hm}}$.

Individual and statistical analyses have been performed on PRGs since they were first observed (B. C. Whitmore 1991; E. Iodice et al. 2002c; V. Reshetnikov & F. Combes 2015). Taking advantage of the number of galaxies from cosmological simulations, it is possible to compare the similarity of our sample against the observed properties. In this work, we compared our sample of simulated PRG with the observational PRG sample of V. Reshetnikov & F. Combes (2015), composed of 46 objects from the SDSS-based Polar Ring Catalogue (A. V. Moiseev et al. 2011) and 4 from the catalogue presented in B. C. Whitmore et al. (1990).

3.1 Fraction of galaxies with polar ring

PRGs are uncommon objects. B. C. Whitmore et al. (1990) estimated that 5 per cent of nearby lenticular galaxies have or had some polar structure. V. P. Reshetnikov et al. (2011) estimated that ~ 0.4 per cent of nearby galaxies, with absolute magnitudes in the range of -17 to -22 mag in the B band, have polar-ring features. Also, D. V.

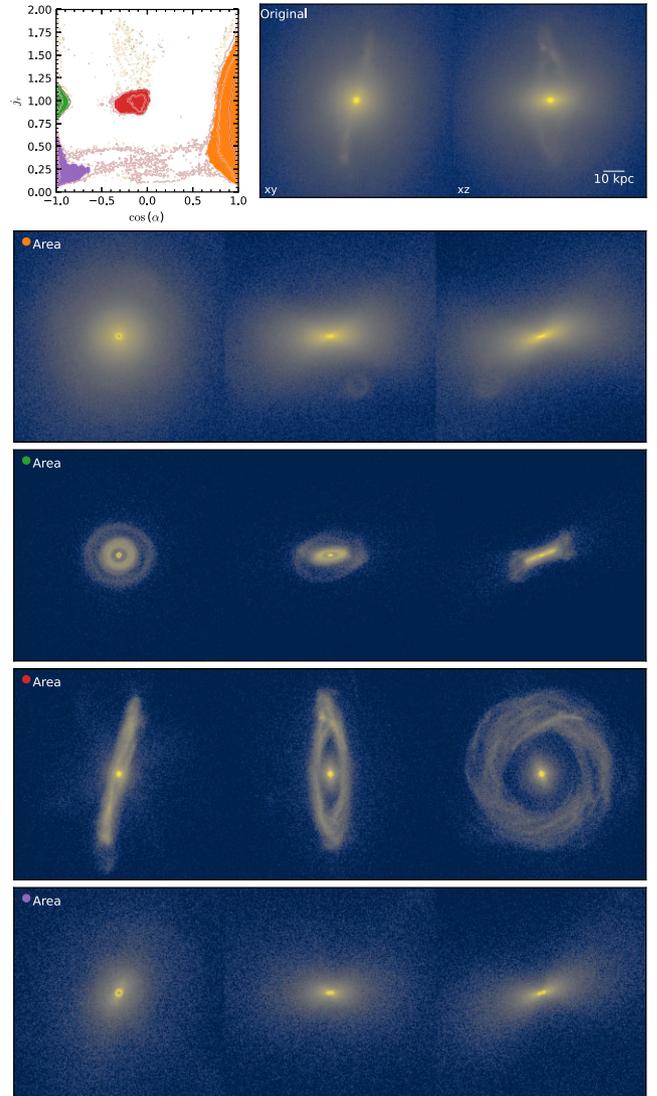


Figure 8. Decomposition of the subhalo 167392. The upper left panel shows the $\cos \alpha - j_r$ diagram, with the coloured areas indicating the individual components of the subhalo. The upper right panel shows the original subhalo before the decomposition. The remaining panels display the projections of the stellar particles that fall within the shaded regions of the $\cos \alpha - j_r$ diagram. Each component is marked by a coloured dot in the upper left corner of its respective panel: orange for the host galaxy disc, green and purple for the counter-rotating disc component, and red for the polar ring.

Smirnov & V. P. Reshetnikov (2022) found ~ 0.01 per cent of PRG in a sample of galaxies in the r band with $M_r = -17$ to -22 mag, concluding that this fraction increases with redshift up to ~ 1 . Recently, A. V. Mosenkov et al. (2024) reported that the fraction of PRG in the r -band is ~ 1.1 per cent or ~ 3 per cent when projection effects are taken into account.

To compare our sample with observations, we used the synthetic multiwavelength photometry catalogue presented by A. Trčka et al. (2022). This catalogue was produced using data from the TNG50 simulation and the radiative transfer code SKIRT (P. Camps & M. Baes 2020). It contains subhaloes magnitudes for 14 broad-band filters, ranging from UV to submillimetre wavelengths. For a direct comparison, we used the Johnson_B and SDSS_r filters. The fraction of galaxies with a polar ring in the TNG50 was calculated using the mean magnitude of the subhaloes in the three orientations within

Table 2. Total and component masses of the PRGs in TNG50. All the values were calculated within $5 r_{\text{hm}}$.

Subhalo ID	Stellar mass ($10^{10} M_{\odot}$)	Gas mass ($10^{10} M_{\odot}$)	Baryonic mass ($10^{10} M_{\odot}$)	Stellar ring mass ($10^{10} M_{\odot}$)	Stellar host mass ($10^{10} M_{\odot}$)	Ring-to-host mass ratio
117250	97.835	19.385	117.220	3.740	94.216	0.040
143888	9.544	0.711	10.255	2.681	7.232	0.371
167392	44.133	5.955	50.088	1.075	43.127	0.025
264886	7.911	2.093	10.004	0.806	7.135	0.113
289385	63.499	5.119	68.617	1.248	62.291	0.020
313692	43.780	6.769	50.548	0.545	43.250	0.013
319731	7.167	2.483	9.650	0.256	6.924	0.037
324123	29.857	8.790	38.647	1.667	28.303	0.059
352427	0.198	0.140	0.338	0.027	0.171	0.160
383976	6.745	2.856	9.601	0.449	6.327	0.071
408534	17.409	1.993	19.402	0.912	16.535	0.055
411449	15.673	0.912	16.586	0.918	14.801	0.062
416713	11.149	0.218	11.367	0.550	10.833	0.051
428178	1.867	0.717	2.584	0.081	1.795	0.045
434357	0.832	0.254	1.086	0.254	0.683	0.371
483594	8.606	0.703	9.309	0.540	8.178	0.066
487744	0.388	0.175	0.563	0.060	0.331	0.182
501208	8.355	2.378	10.733	0.331	8.056	0.041
513105	4.335	0.219	4.553	0.538	3.801	0.141
514272	3.503	0.898	4.401	0.123	3.388	0.036
518120	1.795	0.841	2.636	0.233	1.637	0.142
532301	4.750	1.852	6.601	0.289	4.551	0.063
535774	4.921	2.710	7.631	0.365	4.586	0.080
536654	3.172	0.488	3.661	0.211	3.003	0.070
545703	2.705	0.004	2.710	0.191	2.546	0.075
552581	4.384	1.299	5.684	0.124	4.262	0.029
571908	2.381	2.031	4.412	0.358	2.076	0.172
585517	1.238	0.161	1.399	0.136	1.119	0.122
595100	1.969	0.420	2.389	0.145	1.880	0.077
596660	1.453	0.297	1.750	0.205	1.321	0.155
633078	0.270	0.060	0.329	0.097	0.190	0.510
649627	0.757	0.041	0.798	0.061	0.713	0.086

$5r_{\text{hm}}$ to account for any orientation-related issues. For the range of $M_{\text{B}} = -17$ to -22 mag, the fraction is 1.01 ± 0.20 per cent and for the range of $M_r = -17$ to -22 , it is 0.53 ± 0.11 per cent (bootstrap estimated errors). The results obtained in TNG50 are approximately one order of magnitude larger than those reported by V. P. Reshetnikov et al. (2011) and D. V. Smirnov & V. P. Reshetnikov (2022), but smaller than the result obtained by A. V. Mosenkov et al. (2024). However, the fraction of PRGs in TNG50 filtered by stellar mass within $5r_{\text{hm}}$ between $10^9 - 10^{12}$ is 1 per cent.

Using the synthetic catalogue from A. Trčka et al. (2022), we plotted our PRGs in the colour–magnitude diagram (see Fig. 9). The three orientations reported by A. Trčka et al. (2022) are shown for comparison (face-on, edge-on, and randomly oriented).⁶ We compared the position of our PRG sample with galaxies from the Legacy area of the SDSS Data Release Seven reported by L. Simard et al. (2011). As expected, while some PRGs lie in the red sequence, most of them are scattered in the Green Valley and the upper region of the blue cloud.

3.2 Bulge-to-total mass ratio in host galaxies

The bulge-to-total mass ratio (B/T) is a widely used parameter for classifying galaxy morphology. Galaxies having $B/T \geq 0.5$ are

⁶Note, however, that aligning a PRG solely based on its angular momentum is imprecise due to contributions from both the host galaxy and the polar ring.

classified as early- and late-type otherwise. To estimate the bulge mass, we used a criterion similar to that described in the catalogue by S. Genel et al. (2015), where the circularity parameter described in Section 2.1 is used. For this analysis, the parameter ϵ was calculated excluding the particles associated with the ring to minimize their influence on the results. We estimated the bulge mass using particles with $\epsilon < 0$, multiplied by 2, assuming that the bulge symmetry is around 0 in the circularity plot. This helps minimize the contribution of particles in the disc.

The results must be interpreted with caution, given the presence of counter-rotating components in our PRG sample. Although these components are not significant in most galaxies (see Table 1), they are prominent in some, such as in the 459 557 subhalo. Our analysis shows that most host galaxies have B/T values greater than 0.5, with an average of 0.64, indicating that PRG in the TNG50 simulation are predominantly bulge-dominated systems (see Fig. 10). Subhaloes with B/T values below 0.5, such as 428178, 501208, and 595100, were also classified as disc-dominated galaxies based on the κ parameter and the original ϵ values prior to decomposition. These results suggest a diverse range of morphologies within the PRG sample.

3.3 Ring-to-host mass ratio

Observations have shown that the baryonic mass of the ring in PRGs is not negligible, sometimes comparable to or even exceeding the

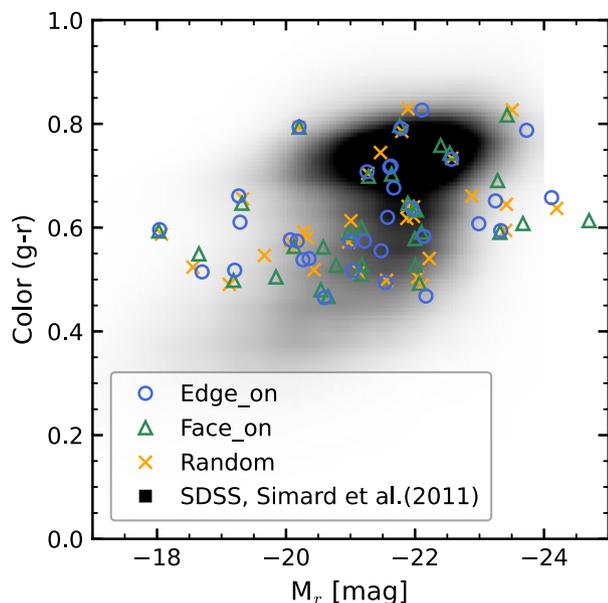


Figure 9. Colour–magnitude diagram for galaxies on this catalogue. The grey-scale background represents the point density of galaxies taken from the Legacy area of the SDSS Data Release Seven taken from the catalogue of L. Simard et al. (2011, with darker areas indicating higher concentrations). Markers are the values of the TNG50 PRGs. Magnitudes are taken from the catalogue of A. Trčka et al. (2022) in three orientations inside $5r_{\text{hm}}$: edge-on (circles), face-on (triangles), and random orientation (crosses).

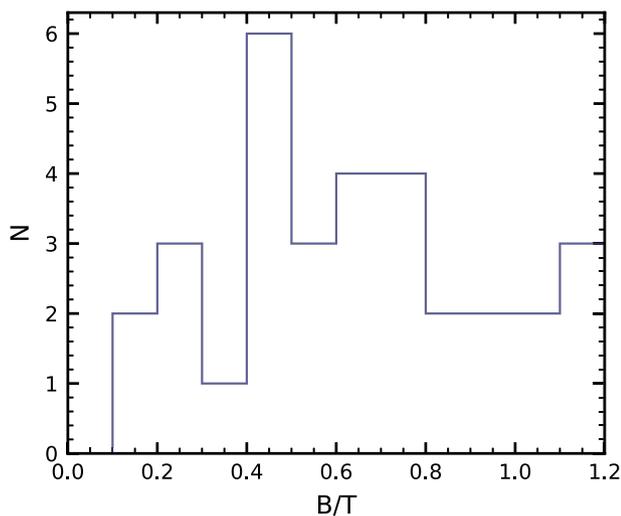


Figure 10. B/T histogram of the PRG galaxies using circularities in the range $-0.7 < \epsilon < 0.7$ and the mass inside $5r_{\text{hm}}$.

mass of the host galaxy (E. Iodice et al. 2002c; V. Reshetnikov & F. Combes 2015). In this study, since the subhaloes have been dynamically decomposed into their individual components, estimating the masses of the ring and host galaxy was straightforward. The mass of each was calculated by summing the mass of the stellar particles assigned to either the ring or the host galaxy. Ring particles were identified as those falling within the central shaded regions in the $\cos \alpha - j_r$ diagram, while the host galaxy consists of the remaining stellar particles. These masses were computed for all stellar particles within a radius of $5r_{\text{hm}}$.

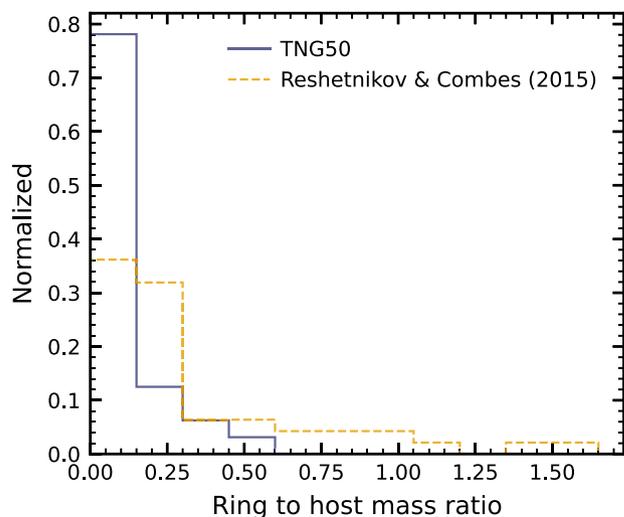


Figure 11. Ring-to-host mass ratio for the TNG50 PRG sample (solid line) and the observed PRG (dashed line) from V. Reshetnikov & F. Combes (2015).

From the distribution of the ring-to-host mass ratios in Fig. 11, it is clear that the rings in our TNG50 sample are less massive than those observed in real PRGs. Most of the subhaloes in the sample exhibit ring-to-host mass ratios below 0.2 (none exceed 0.6). The mean value of this distribution is ~ 0.11 , indicating that in the TNG50 simulation, rings are typically much less dominant in terms of mass compared to the host galaxy.

3.4 Ring inclinations

By definition, polar rings are expected to have an inclination close to 90° from the plane of the host galaxy. However, observations have shown a wide range of inclinations, with many rings nearly perpendicular to the host galaxy. Some cases have reported ring inclinations as low as $\sim 35^\circ$ from the plane of the host galaxy (B. C. Whitmore 1991; V. Reshetnikov & F. Combes 2015). Simulations have also shown that ring inclinations can change over time (D. V. Smirnov et al. 2023).

In this work, we computed the ring inclination by comparing the angular momentum vectors of the host galaxy and the selected ring. The resulting ring inclinations are presented in Table 3. The top panel of Fig. 12 shows the perpendicularity of stellar and gas rings, i.e. how far the components are from perpendicularity, where 0° indicates an orthogonal ring and 90° is a coplanar component with respect to the host galaxy. For the stellar component, there is no clear trend; the distribution shows two peaks at bins 15° – 20° and 45° – 50° (blue bars), while gas rings show a trend with a peak at bin 10° – 15° (green bars). This tendency for gas rings is more similar to the perpendicularity of observed PRGs. Angles measured from host discs show the distribution of rings in more detail (bottom panel, Fig. 12). No clear pattern is observed in the angles of stellar rings, whereas gas rings show a trend centred on the 70° – 80° bin. The lower panel of Fig. 12 also shows that two gas discs are almost antiparallel to their corresponding stellar discs, which may suggest a link between the evolution of PRGs and counter-rotating galaxies (S. Khoperskov et al. 2020). Differences in the angles of the stellar and gaseous rings could be due to dynamical evolution and perturbations outside the subhaloes.

The discrepancy between the observed inclinations and our results may be due to observational biases, such as selection effects, pro-

Table 3. Parameters estimated for the gas components: (1) ID of the subhalo in TNG50, (2) mean ring radius, (3) relation of the mean ring radius and the half-mass radius, (4) percentile 20 of the radii distribution, (5) percentile 80 of the radii distribution, (6) angle between the specific angular momentum of the central disc and the ring, and (7) distance from the perpendicularity of the ring.

Subhalo ID ⁽¹⁾	$R^{(2)}$ [kpc]	$R/r_{hm}^{(3)}$	Percentile 20 ⁽⁴⁾ [kpc]	Percentile 80 ⁽⁵⁾ [kpc]	Ring-disc angle ⁽⁶⁾ [°]	Perpendicularity ⁽⁷⁾ [°]
117250	17.137	1.224	15.633	40.593	36.301	53.699
143888	7.976	1.817	6.122	13.435	140.040	50.040
167392	20.603	2.269	18.210	31.044	99.547	9.547
264886	15.521	2.685	10.839	39.612	98.251	8.251
289385	18.928	1.294	15.148	34.922	75.318	14.682
313692	21.361	2.456	17.587	30.349	43.468	46.532
319731	22.145	3.117	18.580	28.753	54.914	35.086
324123	22.582	2.023	17.938	103.737	101.505	11.505
352427	6.116	2.327	5.297	23.401	13.597	76.403
383976	18.363	3.212	13.651	35.424	63.083	26.917
408534	25.673	2.943	23.220	40.728	75.610	14.390
411449	8.661	1.458	7.832	160.217	6.524	83.476
416713	22.766	6.513	28.488	61.080	142.888	52.888
428178	14.684	4.536	12.752	38.408	58.711	31.289
434357	6.635	4.617	5.734	10.623	63.373	26.627
483594	15.187	4.292	12.666	20.940	50.624	39.376
487744	4.559	1.787	3.719	24.075	152.850	62.850
501208	19.658	3.331	14.768	34.979	116.466	26.466
513105	11.234	3.148	9.582	21.412	160.003	70.003
514272	18.679	4.732	18.205	170.190	118.096	28.096
518120	13.532	4.661	13.320	119.252	125.765	35.765
532301	6.898	1.607	5.531	10.925	30.448	59.552
535774	10.145	1.932	7.878	16.333	133.017	43.017
536654	9.020	3.517	7.224	13.677	102.098	12.098
545703	12.225	7.508	15.186	28.912	72.119	17.881
552581	9.921	2.550	7.907	15.616	105.577	15.577
571908	23.231	3.867	19.022	43.732	76.548	13.451
585517	8.942	6.025	10.517	126.354	49.919	40.081
595100	12.850	5.796	11.164	23.478	85.376	4.624
596660	12.122	5.325	11.002	17.541	32.258	57.742
633078	1.355	0.997	1.060	45.044	4.096	85.904
649627	5.262	5.517	8.147	23.230	79.605	10.395

jection angles, or resolution limits. The dynamical decomposition of the galaxies allows us to identify those with inclinations with respect to the disc. Fig. 12 shows the distribution of the angles between the selected rings and the dominant discs. The mean inclination for the stellar rings is $\sim 82.61^\circ$, while ~ 50 per cent of the objects have inclinations greater than 90° and ~ 50 per cent less than 90° . This suggests a relatively uniform distribution of the angles and their evolution. For gaseous rings, ~ 0.56 per cent have inclinations less than 90° , with an average inclination of 80.44° .

3.5 Ring radii

The mean radius (R) of the rings was calculated using:

$$R = \frac{\int_{0.5r_{hm}}^{10r_{hm}} r^2 \rho(r) dr}{\int_{0.5r_{hm}}^{10r_{hm}} r \rho(r) dr}, \quad (5)$$

as described in D. V. Smirnov et al. (2023), where $\rho(r)$ is the density profile of the stellar ring. The radii of the rings vary significantly depending on the size of the host galaxies, with an average radius of ~ 10.19 kpc in this sample. To put this in perspective, we compared the mean radius of the rings with the stellar half-mass radius of the subhalo (r_{hm}). Most of the rings are extended, between $\sim 2r_{hm}$ and

$\sim 4r_{hm}$ (see Fig. 13 and Table 4). However, a considerable number of PRGs have ring radii smaller than $2r_{hm}$, indicating that some rings could be embedded within the central structures of their host galaxies. Additionally, it is worth noting that the rings in the TNG50 simulation appear to be thick.

However, the mean radius of the gaseous rings shows a more extended distribution compared to the stellar counterpart, with an average value of ~ 13.87 kpc, more than ~ 3 kpc larger than that of the stellar rings. This is more noticeable when comparing the mean radius with r_{hm} , as some gaseous rings extend beyond ~ 6 times r_{hm} (Fig. 13). The width of the rings was estimated using the 20th and 80th percentiles of the stellar particle distribution, within a range of $0.5-10r_{hm}$. These results show that the stellar rings are more compact than their gaseous counterparts. When comparing the 80th percentile of both components, the stellar rings have an extension of ~ 18.21 kpc, while the gas rings extend up to ~ 45.25 kpc. Figs 14 and 15 compare the mean radius, 20th, and 80th percentiles of the stellar and gaseous rings, highlighting the differences in their spatial distributions.

3.6 Star formation rate

The SFR in PRGs is expected to be low, though higher than in typical ETGs. The bluer colour of the rings suggests the presence of ongoing star formation. Observationally, these galaxies fall in the green valley

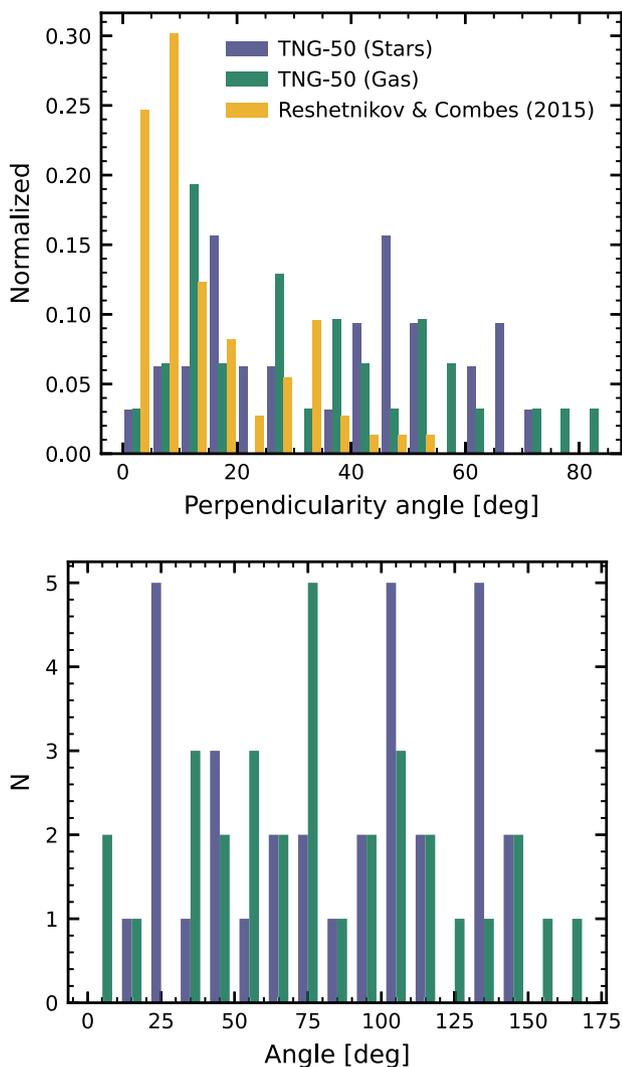


Figure 12. Angular distribution of the ring–disc orientation in the PRG sample. Top: perpendicularity of the ring measured from the disc plane, shown separately for the stellar (blue) and gaseous (green) components. The yellow histogram is the perpendicularity estimated from observations of B. C. Whitmore (1991) and V. Reshetnikov & F. Combes (2015). Bottom: distribution of the estimated angles between the angular momentum vector of the stellar disc and the stellar (blue) and gaseous (green) ring.

in the colour–magnitude diagram, due to the combination of the red host galaxy and the blue star-forming rings (V. Reshetnikov & F. Combes 2015). The SFRs of the TNG50 sample are mostly low (see Fig. 16), consistent with observational data. However, a few galaxies exhibit higher SFRs, ranging from ~ 10 and $\sim 30 M_{\odot} \text{yr}^{-1}$. The highest SFR in our sample is $\sim 65.91 M_{\odot} \text{yr}^{-1}$ (beyond the limits of Fig. 16) corresponding to subhalo 117250, which is also the most massive subhalo in the sample.

These SFR values were measured within a radius of $5r_{\text{hm}}$ and reflect the instantaneous SFR in the gas cells⁷ (Table 5) When

⁷The instantaneous SFR is provided for the TNG50 simulation as a parameter of each gas cell. This star formation follows the model of V. Springel & L. Hernquist (2003). Gas cells are designated as star forming when their density exceeds a specified threshold and stochastically convert to stars on a

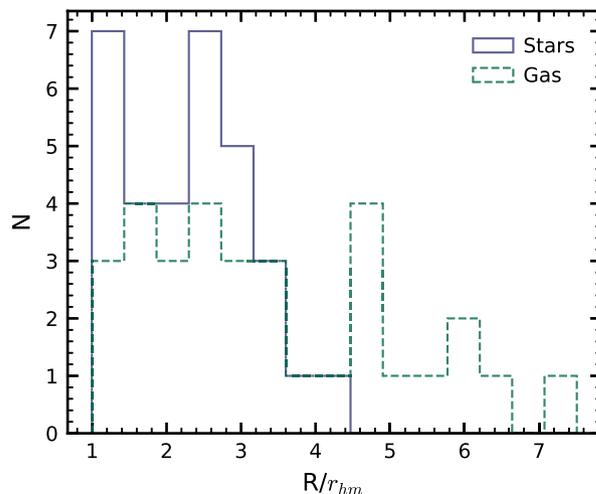


Figure 13. Distribution of the mean ring radius over the r_{hm} of the PRG sample.

comparing the SFR of the subhalo with that of the ring, we find that the contribution of the ring to the overall star formation varies significantly. In many cases, the SFR in the rings constitutes a substantial fraction of the total, suggesting that the rings are the primary sites of star formation. However, also a notable number of PRGs show rings with minimal contribution to the total SFR, indicating that star formation may be occurring in other parts of the galaxy. This low star formation in some of the rings could be due to the variety of evolutionary stages present in the PRG sample from TNG50.

To build a control sample for comparison with the SFRs of our PRG sample, we selected 100 bulge-dominated and 100 disc-dominated subhaloes from the full TNG50 sample at redshift zero. This selection was based on the κ criterion described in Section 2.1 applied to all galaxies containing more than 10^4 stellar particles. Fig. 17 shows violin plots of the logarithmic SFR for PRGs and the two control groups, considering only systems with non-zero SFRs. The shaded regions indicate the distribution of values for each sample, while the horizontal lines mark, from top to bottom, the maximum, mean, and minimum SFRs. For PRGs, these values are 69.42 , 6.20 , and $0.04 M_{\odot} \text{yr}^{-1}$; for the bulge-dominated control sample, 3.22 , 0.25 , and $0.00018 M_{\odot} \text{yr}^{-1}$; and for the disc-dominated control sample, 7.08 , 0.86 , and $0.00073 M_{\odot} \text{yr}^{-1}$. PRGs exhibit systematically higher SFRs than both control groups. This is consistent with previous observational studies, which indicate that PRGs often sustain active star formation comparable to that of star-forming discs (M. Spavone et al. 2010; I. Finkelman et al. 2012). The elevated SFRs in PRGs may reflect their dynamical state. Systems with recently formed rings are expected to exhibit enhanced star formation, whereas more evolved PRGs may show reduced activity due to gas depletion or expulsion.

4 DISCUSSION

The analysis of our PRG sample from the TNG50 simulation provides valuable insight into the physical properties and the underlying

predetermined time-scale. The SFR of a gas cell is inversely proportional to the density-dependent time-scale for star formation and is proportional to the subgrid estimate of cold gas mass (M. Donnari et al. 2019).

Table 4. (1) ID of the subhalo in TNG50, (2) absolute magnitude in the r band, (3) bulge-to-total mass fraction, (4) mean ring radius, (5) relation of the mean ring radius and the half-mass radius, (6) percentile 20 of the radii distribution, (7) percentile 80 of the radii distribution, (8) angle between the specific angular momentum of the central disc and the ring, and (9) distance from the perpendicularity of the ring.

Subhalo ID ⁽¹⁾	$M_r^{(2)}$	$B/T^{(3)}$	$R^{(4)}$ [kpc]	$R/r_{hm}^{(5)}$	Percentile 20 ⁽⁶⁾ [kpc]	Percentile 80 ⁽⁷⁾ [kpc]	Ring-disc angle ⁽⁸⁾ [°]	Perpendicularity ⁽⁹⁾ [°]
117250	-24.117	0.719	25.325	1.808	19.881	36.896	18.675	71.325
143888	-21.609	1.003	9.175	2.090	6.748	19.901	136.646	46.646
167392	-23.247	1.149	24.290	2.675	21.319	32.802	107.407	17.407
264886	-22.136	0.946	8.145	1.409	5.868	14.888	106.658	16.658
289385	-23.730	0.656	16.621	1.137	13.824	26.987	27.439	62.561
313692	-22.988	0.545	12.188	1.401	7.837	26.047	23.789	66.211
319731	-21.574	0.297	15.153	2.133	10.382	25.522	24.000	66.000
324123	-23.329	0.748	15.170	1.359	11.693	28.473	107.574	17.574
352427	-18.039	0.409	4.068	1.548	3.143	7.310	135.438	45.438
383976	-21.671	0.543	10.331	1.807	7.242	23.146	37.555	52.445
408534	-22.567	0.808	12.128	1.390	8.745	25.334	72.436	17.564
411449	-22.107	0.427	7.438	1.252	6.393	10.488	102.870	12.870
416713	-21.782	0.974	11.611	3.322	9.468	41.894	141.607	51.607
428178	-20.357	0.188	9.737	3.008	7.527	15.295	49.335	40.665
434357	-19.287	0.788	5.120	3.562	3.609	9.852	62.127	27.873
483594	-21.626	0.368	11.152	3.152	8.223	20.729	40.526	49.474
487744	-19.204	0.585	6.158	2.414	4.753	9.757	28.139	61.861
501208	-21.952	0.208	17.011	2.882	12.962	26.606	119.271	29.271
513105	-21.256	0.828	5.757	1.613	4.630	7.974	54.388	35.612
514272	-21.217	0.469	10.078	2.553	8.758	15.219	132.557	42.557
518120	-20.597	1.110	9.332	3.214	7.084	17.157	137.414	47.414
532301	-21.475	0.610	5.020	1.170	3.742	8.796	105.852	15.852
535774	-22.168	1.109	10.895	2.075	9.209	18.359	91.196	1.196
536654	-21.000	0.656	6.470	2.523	5.402	14.193	96.317	6.317
545703	-20.203	0.757	4.957	3.044	4.030	8.559	142.385	52.385
552581	-21.540	0.437	9.274	2.384	7.450	13.936	114.152	24.152
571908	-21.038	0.280	15.573	2.592	11.532	29.203	67.490	22.510
585517	-20.067	0.482	4.012	2.703	3.009	6.674	43.076	46.924
595100	-20.263	0.162	9.392	4.236	8.023	13.457	83.319	6.681
596660	-20.172	0.470	9.015	3.960	6.855	14.762	22.729	67.271
633078	-18.698	1.068	2.564	1.886	1.779	6.820	131.861	41.861
649627	-19.266	0.644	2.959	3.102	2.070	5.731	79.238	10.762

mechanisms driving the formation and evolution of these peculiar objects. Our procedure successfully separated the polar structure from the host galaxy in both stellar and gaseous components. This separation allowed us to potentially study the distinct physical properties and infer the evolutionary stages of PRGs.

Recently, D. V. Smirnov et al. (2023) identified six PRGs from 2D synthetic images of galaxies in TNG50. This sample overlaps with ours, further validating the completeness of our PRG catalogue.

The analysis of our PRG sample showed similarities and differences with respect to the observational data. First, our sample of 32 PRGs showed that the simulated fraction of such systems is slightly higher than the observational estimates. This discrepancy could be attributed to the broader selection criteria used in our simulations or projection effects that can complicate observational identification. Our sample was defined using dynamical criteria, which produced a wide range of relative angles. Some of these are very small with respect to the host plane, making observational distinctions challenging due to projection effects, limited spatial resolution, and low surface brightness. These factors may further explain the differences observed in the properties of the rings, such as their relative inclination with respect to their host galaxies.

Our sample also exhibited a systematic difference in the inclination between stellar and gaseous rings, a result that is consistent with the variations reported by D. V. Smirnov et al. (2023) and S. Khoperskov et al. (2020). Rings are formed with an initial inclination relative to

their host galaxy and change their inclinations as they evolve, with some systems developing counter-rotating components (J. G. López-Castillo, in preparation). This can be seen in Table 1 with some galaxies showing a significant fraction of mass with ϵ_{-07} or Fig. 8 with components marked green and purple indicating a counter-rotating component.

The morphological difference between the stellar and gaseous rings, particularly in their radial extent and thickness, could offer some insight into the physical processes at play within these structures. This variation suggests that the formation of polar rings is likely driven by multiple mechanisms rather than by a single process. For example, the more extended and diffuse nature of the gaseous rings could be indicative of continuous gas accretion. The capacity of the simulation to track these changes reinforces its value in exploring scenarios where polar rings are formed through different mechanisms, such as mergers or accretion events, providing a broader understanding of the life cycles of PRGs. Meanwhile, the discrepancy in the ring-to-host ratio is a noteworthy result. It may provide insight into the formation scenario, or alternatively reflect the impact of the physical prescriptions in the simulation, such as stellar and/or black hole feedback. Further analysis is necessary to clarify this point.

The SFRs in our sample were consistent with the expected behaviour of observed PRGs, particularly those in ETGs, where low but sustained star formation is observed. The few cases of higher star formation activity in the rings provide important insights for

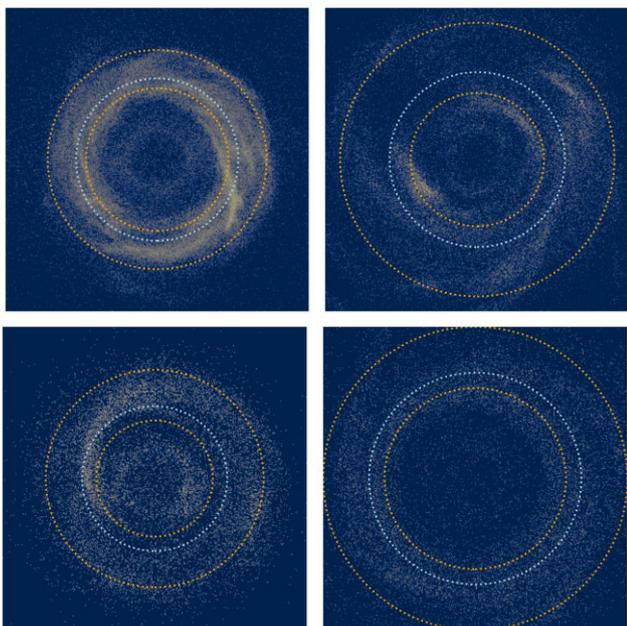


Figure 14. Example images showing the mean radius (middle dotted circle) and 20th and 80th percentiles (inner and outer dotted circles) of the stellar ring’s surface mass density for subhaloes 167392 (upper left), 501208 (upper right), 552581 (lower left), and 595100 (lower right).

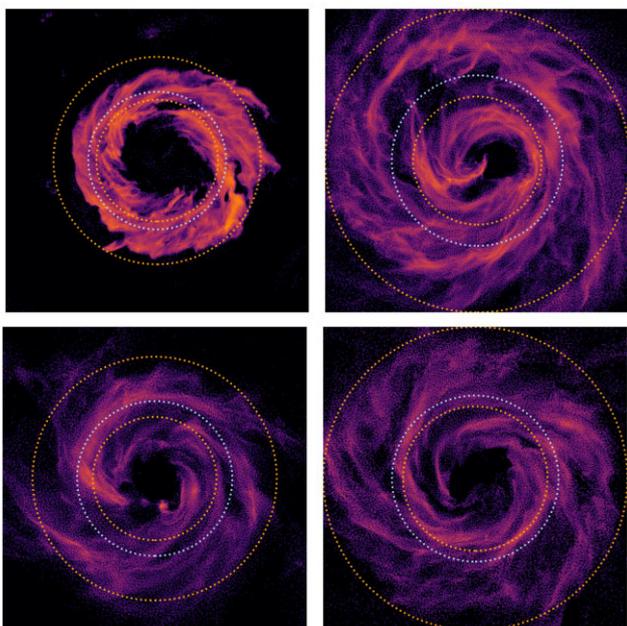


Figure 15. Mean radius (middle dotted circle) and 20th and 80th percentiles (inner and outer dotted circles) for the surface mass density of the gaseous rings in subhaloes 167392 (upper left), 501208 (upper right), 552581 (lower left), and 595100 (lower right).

understanding the role of PRGs in galaxy evolution, as these systems may contribute to the rejuvenation of their host galaxies.

The use of cosmological simulations such as TNG50 offers complementary insights to observational studies by effectively capturing the distribution and morphology of PRGs over a wide range of dynamical conditions. Although some discrepancies persist between the simulated and observed PRGs, these simulations are useful tools

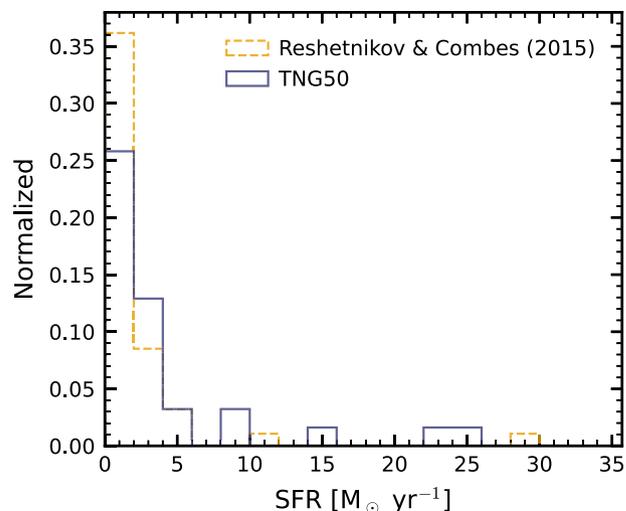


Figure 16. Distribution of the SFR. The dashed line is the SFR of observed galaxies (V. Reshetnikov & F. Combes 2015). The solid line is the instantaneous SFR of our PRG sample, estimated within $5r_{\text{hm}}$.

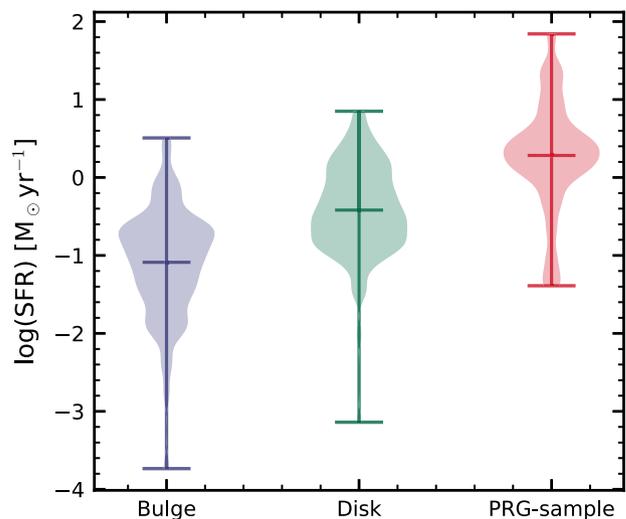


Figure 17. Comparison of the SFRs among bulge-dominated subhaloes, disc-dominated subhaloes, and the PRG sample. Shaded areas represent the probability density distributions, while horizontal lines indicate, from top to bottom, the maximum, mean, and minimum values.

for exploring the underlying physical processes that govern the formation and evolution of PRGs, giving some clues about related unresolved problems.

5 SUMMARY AND CONCLUSIONS

This paper presents a catalogue of PRGs extracted from the cosmological simulation TNG50. The resolution of this simulation allows for a detailed characterization of the objects’ morphologies. In subhaloes with more than 10^4 stellar particles, we applied some filters to separate the PRG sample. First, we computed the angular momentum and inclination profiles for these subhaloes, selecting those with an inclination difference exceeding 30° (up to 150°). Then, a visual inspection of the stellar projections and line-of-sight velocity maps yielded a preliminary sample of 44 candidate PRGs.

Table 5. (1) ID of the subhalo in TNG50, (2) mass of the gaseous ring inside $5r_{\text{hm}}$, (3) instantaneous SFR, (4) instantaneous SFR of the gaseous ring, and (5) percentage of the SFR in the gaseous ring.

Subhalo ID ⁽¹⁾	Gas ring mass ⁽²⁾ [$10^{10} M_{\odot}$]	SFR total ⁽³⁾ [$M_{\odot} \text{ yr}^{-1}$]	SFR ring ⁽⁴⁾ [$M_{\odot} \text{ yr}^{-1}$]	SFR [per cent] ⁽⁵⁾
117250	10.147	69.420	52.559	75.711
143888	0.686	2.450	2.428	99.082
167392	2.694	23.327	11.395	48.851
264886	1.924	5.365	5.070	94.502
289385	2.809	2.934	2.668	90.958
313692	3.605	24.344	11.063	45.442
319731	1.208	3.025	0.821	27.137
324123	6.519	15.044	13.980	92.928
352427	0.129	0.041	0.038	93.506
383976	2.495	4.915	3.794	77.202
408534	0.670	1.685	0.128	7.581
411449	0.559	1.811	1.764	97.391
416713	0.177	1.393	0.079	5.667
428178	0.330	1.390	0.470	33.784
434357	0.192	1.230	0.546	44.359
483594	0.609	1.237	0.855	69.135
487744	0.118	0.550	0.360	65.563
501208	2.013	2.920	2.715	92.967
513105	0.143	0.095	0.061	63.722
514272	0.478	1.609	0.788	48.962
518120	0.414	3.436	1.106	32.202
532301	1.118	8.495	7.425	87.410
535774	1.947	9.466	8.952	94.568
536654	0.320	1.021	0.779	76.344
545703	0.002	0.054	0.000	0.000
552581	0.886	3.110	2.396	77.038
571908	1.396	2.316	1.049	45.272
585517	0.023	0.818	0.065	7.970
595100	0.225	2.198	0.574	26.109
596660	0.198	1.990	0.494	24.840
633078	0.018	0.421	0.121	28.693
649627	0.029	0.218	0.076	34.922

The resulting sample was then dynamically analysed. The 1D parameters κ (L. V. Sales et al. 2012) and the circularity (M. G. Abadi et al. 2003, ϵ) in Section 2.1 show that the majority of the subhaloes in the sample are dominated by spherical components (bulge, and stellar halo), which limits the extraction of information related to the ring. To overcome this, we employed a 2D method. Our approach uses the cosine of the angle between the vectors of the angular momentum of the particles and the angular momentum of the central part of the subhalo ($\cos \alpha$) and the relation of the orbit and the circular orbit of the particles (Y. Jagvaral et al. 2022). This results in a 2D plane that clearly distinguishes the main dynamic structures within the subhaloes. By applying a clump-finding algorithm to this plane, we were able to isolate regions of high density corresponding to the main components. Using this method, we confirmed 32 subhaloes as genuine PRGs from our initial sample.

The final sample represents 1.01 per cent of all galaxies in the B band and 0.53 per cent in the r band in the TNG50 simulation, which is consistent with observational estimates (B. C. Whitmore et al. 1990; V. P. Reshetnikov et al. 2011; D. V. Smirnov & V. P. Reshetnikov 2022; A. V. Mosenkov et al. 2024). Furthermore, the PRGs of the sample occupy a region on the colour–magnitude diagram that lies between the red sequence and the transition to the blue cloud, a distribution that reflects the contrast between the early-type host galaxy and the blue young rings.

The host galaxies in the PRG sample exhibit a pronounced bulge component, with a mean B/T ratio of 0.64, suggesting that most host galaxies are bulge dominated, consistent with observations. However, a notable number of host galaxies are disc-dominated, indicating a diverse range of morphologies. This diversity makes our PRG sample a valuable resource for understanding galaxy evolution pathways, particularly those driven by interactions and accretion processes.

The rings in our sample exhibit average radii of 2.36 and 3.41 times the effective radius for the stellar and gaseous components, respectively. The comparatively more extended structure of the gaseous rings may suggest distinct formation or accretion histories relative to the stellar rings. Furthermore, while the rings are relatively stable and well defined, they tend to be less massive and less perpendicular than those observed in some PRGs.

A distinctive result from our study is the difference in inclinations between the stellar and gaseous rings, with the latter often exhibiting a higher degree of perpendicularity relative to the host galaxy disc. This behaviour is consistent with the findings of D. V. Smirnov et al. (2023) and S. Khoperskov et al. (2020), who report that polar structures adjust their inclination over time due to dynamical processes. Some rings evolve into configurations resembling counter-rotating discs, emphasizing the dynamic nature of PRGs and pointing to complex formation scenarios that may involve gas accretion, satellite interactions, or minor mergers.

The ring-to-host mass ratios in TNG50 are typically lower than those reported in observed PRGs, with most rings accounting for less than 20 per cent of the host galaxy's stellar mass. This reduced mass, combined with a relatively low but steady SFR concentrated in the rings, supports the idea that PRGs can retain gas and sustain star formation at moderate levels. Consequently, the rings may play a significant role in the rejuvenation of their host galaxies.

Analysing the colour–magnitude distribution of PRGs, we found that while some fall along the red sequence, the majority occupy the green valley or the upper region of the blue cloud. This distribution suggests that PRGs represent a transitional phase between early-type, red galaxies and actively star-forming, blue galaxies, a shift driven by star formation events within the rings that significantly affect the overall colours of the host galaxies.

This study highlights the role of cosmological simulations as indispensable complements to observational studies of PRGs. Our findings suggest that PRGs are versatile and dynamic structures shaped by multiple formation mechanisms, making them powerful probes of galaxy evolution. In particular, the interplay of gas accretion and galactic interactions significantly influences their morphology and star formation histories. Our catalogue lays a robust foundation for future studies to further assess the relative contributions of different formation scenarios and to refine theoretical models of polar-ring dynamics in evolving cosmic environments.

ACKNOWLEDGEMENTS

We thankfully acknowledge a useful and constructive report by an anonymous referee. JGLC acknowledges the Secretaría de Ciencia, Humanidades, Tecnología e Innovación (SECIHTI) for his PhD grant. MZA acknowledges support from SECIHTI grant no. 320772. GCG acknowledges support from UNAM's Programa de Apoyo a Proyectos de Investigación e Innovación Tecnológica (PAPIIT) grant no. IN110824. The authors thankfully acknowledge computer resources, technical advice, and support provided by National Supercomputing Laboratory of Southeast Mexico, a member of the SECIHTI network of national laboratories. The ILLUSTRISTNG simulations were undertaken with compute time awarded by the Gauss Centre for Supercomputing (GCS) under GCS Large-Scale Projects GCS-ILLU and GCS-DWAR on the GCS share of the supercomputer Hazel Hen at the High Performance Computing Center Stuttgart (HLRS), as well as on the machines of the Max Planck Computing and Data Facility (MPCDF) in Garching, Germany.

DATA AVAILABILITY

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

REFERENCES

Abadi M. G., Navarro J. F., Steinmetz M., Eke V. R., 2003, *ApJ*, 597, 21
 Arnaboldi M., Freeman K. C., Sackett P. D., Sparke L. S., Capaccioli M., 1995, *Planet. Space Sci.*, 43, 1377
 Bekki K., 1997, *ApJ*, 490, L37
 Bekki K., 1998, *ApJ*, 499, 635
 Berry D. S., Reinhold K., Jenness T., Economou F., 2007, in Shaw R. A., Hill F., Bell D. J., eds, ASP Conf. Ser., Vol. 376, *Astronomical Data Analysis Software and Systems XVI*. Astron. Soc. Pac., San Francisco, p. 425
 Bournaud F., Combes F., 2003, *A&A*, 401, 817
 Brook C. B., Governato F., Quinn T., Wadsley J., Brooks A. M., Willman B., Stilp A., Jonsson P., 2008, *ApJ*, 689, 678

Camps P., Baes M., 2020, *Astron. Comput.*, 31, 100381
 Conselice C. J., 2003, *ApJS*, 147, 1
 Crain R. A. et al., 2015, *MNRAS*, 450, 1937
 Davis M., Efstathiou G., Frenk C. S., White S. D. M., 1985, *ApJ*, 292, 371
 Donnari M. et al., 2019, *MNRAS*, 485, 4817
 Dubois Y. et al., 2014, *MNRAS*, 444, 1453
 Egorov O. V., Moiseev A. V., 2019, *MNRAS*, 486, 4186
 Elagali A., Lagos C. D. P., Wong O. I., Staveley-Smith L., Trayford J. W., Schaller M., Yuan T., Abadi M. G., 2018, *MNRAS*, 481, 2951
 Finkelman I., Funes J. G., Brosch N., 2012, *MNRAS*, 422, 2386
 Gallagher J. S., Sparke L. S., Matthews L. D., Frattare L. M., English J., Kinney A. L., Iodice E., Arnaboldi M., 2002, *ApJ*, 568, 199
 Galletta G., Sage L. J., Sparke L. S., 1997, *MNRAS*, 284, 773
 Genel S. et al., 2014, *MNRAS*, 445, 175
 Genel S. et al., 2017, *MNRAS*, 474, 3976
 Genel S., Fall S. M., Hernquist L., Vogelsberger M., Snyder G. F., Rodriguez-Gomez V., Sijacki D., Springel V., 2015, *ApJ*, 804, L40
 Hubble E. P., 1926, *ApJ*, 64, 321
 Iodice E. et al., 2006, *ApJ*, 643, 200
 Iodice E., Arnaboldi M., Bournaud F., Combes F., Sparke L. S., van Driel W., Capaccioli M., 2003, *ApJ*, 585, 730
 Iodice E., Arnaboldi M., De Lucia G., Gallagher III J. S., Sparke L. S., Freeman K. C., 2002a, *AJ*, 123, 195
 Iodice E., Arnaboldi M., Sparke L. S., Freeman K. C., 2002c, *A&A*, 391, 117
 Iodice E., Arnaboldi M., Sparke L. S., Gallagher J. S., Freeman K. C., 2002b, *A&A*, 391, 103
 Jagvaral Y., Campbell D., Mandelbaum R., Rau M. M., 2022, *MNRAS*, 509, 1764
 Khoperskov S. A., Moiseev A. V., Khoperskov A. V., Saburova A. S., 2014, *MNRAS*, 441, 2650
 Khoperskov S. et al., 2020, *MNRAS*, 500, 3870
 Macciò A. V., Moore B., Stadel J., 2006, *ApJ*, 636, L25
 Marinacci F. et al., 2018, *MNRAS*, 480, 5113
 Marinacci F., Pakmor R., Springel V., 2013, *MNRAS*, 437, 1750
 Moiseev A. V., Smirnova K. I., Smirnova A. A., Reshetnikov V. P., 2011, *MNRAS*, 418, 244
 Mosenkov A. V., Bahr S. K. H., Reshetnikov V. P., Shakespear Z., Smirnov D. V., 2024, *A&A*, 681, L15
 Naiman J. P. et al., 2018, *MNRAS*, 477, 1206
 Nelson D. et al., 2018a, *MNRAS*, 475, 624
 Nelson D. et al., 2018b, *MNRAS*, 477, 450
 Nelson D. et al., 2019a, *Comput. Astrophys. Cosmol.*, 6, 2
 Nelson D. et al., 2019b, *MNRAS*, 490, 3234
 Ordenes-Briceño Y., Georgiev I. Y., Puzia T. H., Goudfrooij P., Arnaboldi M., 2016, *A&A*, 585, A156
 Penoyre Z., Moster B. P., Sijacki D., Genel S., 2017, *MNRAS*, 468, 3883
 Pillepich A. et al., 2018a, *MNRAS*, 473, 4077
 Pillepich A. et al., 2018b, *MNRAS*, 475, 648
 Pillepich A. et al., 2019, *MNRAS*, 490, 3196
 Planck Collaboration XIII, 2016, *A&A*, 594, A13
 Quiroga L. F., Muñoz-Cuartas J. C., Rodrigues I., Libeskind N. I., 2020, *MNRAS*, 491, 1887
 Reshetnikov V. P., Faúndez-Abans M., de Oliveira-Abans M., 2001, *MNRAS*, 322, 689
 Reshetnikov V. P., Faúndez-Abans M., de Oliveira-Abans M., 2011, *Astron. Lett.*, 37, 171
 Reshetnikov V. P., Hagen-Thorn V. A., Yakovleva V. A., 1996, *A&A*, 314, 729
 Reshetnikov V., Combes F., 2015, *MNRAS*, 447, 2287
 Reshetnikov V., Sotnikova N., 1997, *A&A*, 325, 933
 Rodriguez-Gomez V. et al., 2019, *MNRAS*, 483, 4140
 Sales L. V., Navarro J. F., Theuns T., Schaye J., White S. D. M., Frenk C. S., Crain R. A., Dalla Vecchia C., 2012, *MNRAS*, 423, 1544
 Savchenko S. S., Reshetnikov V. P., 2017, *Astron. Lett.*, 43, 146
 Scannapieco C., White S. D. M., Springel V., Tissera P. B., 2009, *MNRAS*, 396, 696
 Schaye J. et al., 2015, *MNRAS*, 446, 521
 Schweizer F., Whitmore B. C., Rubin V. C., 1983, *AJ*, 88, 909

- Sersic J. L., 1968, Atlas de Galaxias Australes. Observatorio Astronómico, Argentina
- Simard L., Mendel J. T., Patton D. R., Ellison S. L., McConnachie A. W., 2011, *ApJS*, 196, 11
- Smirnov D. V., Mosenkov A. V., Reshetnikov V. P., 2023, *MNRAS*, 527, 4112
- Smirnov D. V., Reshetnikov V. P., 2020, *Astron. Lett.*, 46, 501
- Smirnov D. V., Reshetnikov V. P., 2022, *MNRAS*, 516, 3692
- Snaith O. N., Gibson B. K., Brook C. B., Knebe A., Thacker R. J., Quinn T. R., Governato F., Tissera P. B., 2012, *MNRAS*, 425, 1967
- Spavone M., Iodice E., Arnaboldi M., Gerhard O., Saglia R., Longo G., 2010, *ApJ*, 714, 1081
- Spavone M., Iodice E., Arnaboldi M., Longo G., Gerhard O., 2011, *A&A*, 531, A21
- Springel V. et al., 2005, *Nature*, 435, 629
- Springel V. et al., 2018, *MNRAS*, 475, 676
- Springel V., 2010, *MNRAS*, 401, 791
- Springel V., Hernquist L., 2003, *MNRAS*, 339, 289
- Springel V., White S. D. M., Tormen G., Kauffmann G., 2001, *MNRAS*, 328, 726
- Trčka A. et al., 2022, *MNRAS*, 516, 3728
- Vogelsberger M. et al., 2014, *MNRAS*, 444, 1518
- Vogelsberger M., Genel S., Sijacki D., Torrey P., Springel V., Hernquist L., 2013, *MNRAS*, 436, 3031
- Weinberger R. et al., 2017, *MNRAS*, 465, 3291
- Whitmore B. C., 1991, in Casertano S., Sackett P. D., Briggs F. H., eds, *Warped Disks and Inclined Rings around Galaxies*. Cambridge Univ. Press, Cambridge, p. 60
- Whitmore B. C., Lucas R. A., McElroy D. B., Steiman-Cameron T. Y., Sackett P. D., Olling R. P., 1990, *AJ*, 100, 1489

This paper has been typeset from a $\text{\TeX}/\text{\LaTeX}$ file prepared by the author.