

On the origins of counterrotating stellar disks in TNG50. I

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ABSTRACT

Context. Understanding galaxy evolution is key to explaining the structures we observe today in the present-day Universe. Counter-rotating stellar disks, i.e. co-spatial stellar disks rotating with opposite angular momentum, have been proposed as signatures of past accretion events. Therefore, they constitute potentially valuable tracers of galactic assembly.

Aims. In this work, we aim to investigate the properties, formation channels, and significance of counterrotating stellar disks in a sample of Milky Way mass galaxies using the IllustrisTNG cosmological simulations.

Methods. We select an initial sample of 260 central late-type galaxies (i.e. $M_{\text{tot}} \approx 10^{12}$, $D/T > 0.5$, $N_{\text{star}} > 10^5$). For each galaxy, we measure the circularity of its stellar particles and we define the counterrotating disk by considering all stellar particles with circularity $\epsilon < -0.7$, which are located within the spatial extension of the main disk. We then characterize the mass fraction, spatial extent, and star formation history of the counterrotating disks.

Results. Out of the 260 central late-type galaxies, we find that 26 host significant counterrotating disks (i.e. contributing at least 1% of the total stellar mass of the disk). This means that counterrotating stellar disks (CRDs) are rare, consistent with the results from recent observations. We also find that the most of the CRDs are compact (i.e. 88%), in-situ dominated (i.e. 73%), and exhibit bursty SFHs whose peaks often coincide with external perturbations. This means that external perturbations are able to catalyze retrograde star formation, even when a majority of the CRD's star population is in-situ. Finally, we find that a variety of formation pathways can lead to CRDs, including interaction-induced in-situ bursts and smooth accretion of misaligned gas. This fuels star formation in the CRD component.

Conclusions. Overall, our results suggest that CRDs are rare but diverse in origin. In most cases, their formation is linked to the accretion of retrograde gas, either through mergers or environmental inflow, suggesting that these structures are sensitive tracers of the galaxy's past accretion history.

Key words. Galaxies: evolution - Galaxies: formation - Galaxies: kinematics and dynamics - Galaxies: star formation

1. Introduction

Present-day galaxies exhibit a wide variety of structural and kinematic properties (e.g., Monachesi et al. 2016; Rowlands et al. 2018), shaped by both internal and external processes such as minor mergers, ram-pressure stripping, and galaxy harassment (Boselli & Gavazzi 2006). Each of these mechanisms leaves long lasting features that can be used to characterize their evolution. A particularly revealing class of features are multiphase components (Rubin 1994), that is, kinematic stellar structures whose angular momentum is misaligned with respect to the main stellar disk. These components highlight the complexity of galactic dynamics, as present-day kinematics preserve the imprints of past accretion and interaction events (Monachesi et al. 2016; Rowlands et al. 2018; Monachesi et al. 2019; Dolfi et al. 2023). Among them, co-spatial counterrotating stellar disks (Braun et al. 1994) are of particular interest. These consist of two co-existing stellar components that are strongly misaligned in angular momentum but confined to the same plane. Their formation pathways and demographics provide unique constraints on the role of external accretion in shaping galaxy evolution.

The presence of counterrotating stellar disks (hereafter CRDs) is noteworthy because their high velocity amplitudes make it possible to distinguish their stellar populations from those of the main disk, thereby providing insights into the formation and evolution of their host galaxies. It has been argued that

CRDs originate from the retrograde acquisition of gas, which settles on misaligned orbits with respect to the pre-existing stellar disk and subsequently forms stars (Pizzella et al. 2004; Roškar et al. 2010; van de Voort et al. 2015; Starkenburg et al. 2019; Khoperskov et al. 2021, Bao et al. 2022; Bao et al. 2024; Gasyimov et al. 2025). CRDs are therefore direct evidence of past accretion events and constitute valuable tracers of galactic assembly. Several mechanisms have been proposed to explain the origin of the retrograde gas, including accretion from the cosmic web (Algorry et al. 2014), gas-rich mergers with dwarf galaxies (Thakar & Ryden 1996; Puerari & Pfenniger 2001; Algorry et al. 2014), tidal gas exchange between neighboring galaxies (Khim et al. 2021; Sil'chenko et al. 2023), and major mergers that preserve the stellar disk (Puerari & Pfenniger 2001; Crocker et al. 2009). Among these, the latter appears to be the least common in observed systems.

Observationally, CRDs appear to be rare, with only 1% of late-type galaxies presenting a CRD (Bao et al. 2022, Bevacqua et al. 2022, Gasyimov et al. 2025). At the same time, CRDs are also challenging to observe due to their low mass contribution (Rubino et al. 2021). Nevertheless, modern Integral Field Spectroscopy (IFS) instruments can be used to observe CRDs, which are typically identified from the presence of bimodal features in the velocity dispersion maps (Bao et al. 2022; Bao et al. 2024; Gasyimov et al. 2025). IFS instruments are also essential

to disentangle the two stellar disk components and study in detail the kinematics and stellar population properties of CRDs, allowing us to constrain their formation scenarios. Complementary techniques, such as SED fitting, are also used to extract physical and chemical properties of the CRDs. Some notable examples of CRDs include: NGC 4550 (Rubin et al. 1992; Rix et al. 1992; Coccato et al. 2013), NGC 7217 (Merrifield & Kuijken 1994), NGC 3593 (Bertola et al. 1996; Corsini et al. 1998; García-Burillo et al. 2000; Coccato et al. 2013), NGC 4138 (Jore et al. 1996) and NGC 5719 (Vergani et al. 2007; Coccato et al. 2011). These CRDs show a broad range of properties. They are generally observed to have younger stellar populations that co-rotate with the gas disk (Pizzella et al. 2004; Pizzella et al. 2014; Bao et al. 2022; Gasymov et al. 2025), steeper metallicity gradients and broader metallicity distributions than the main stellar disk (Coccato et al. 2013; Bevacqua et al. 2022; Gasymov et al. 2025). As previously mentioned, the presence of CRDs is typically linked to past accretion events that induce SF within the galaxy. Previous simulations (e.g. TNG100, EAGLE etc) have begun to explore the formation and evolution of CRD components (Lu et al. 2021; Santucci et al. 2024; Peirani et al. 2025). However, it is still unclear which are the dominant CRD formation mechanisms and under what conditions CRDs arise, particularly in late-type galaxies, which remains under-explored compared to the early-type galaxy counterparts, that are more common (Kuijken et al. 1996).

In this work we focus on the search, characterization and analysis of counter-rotating stellar disks (CRDs, hereafter) in central Milky Way (MW) type galaxies ($M_{\text{tot}} \approx 10^{12} M_{\odot}$) in TNG50 from the IllustrisTNG suite of cosmological hydrodynamical simulations. We aim to determine how common CRDs are in MW-type galaxies, as well as what are the dominant CRD formation mechanisms. In particular, we aim to confirm past formation channels proposed by observations of CRDs. The paper is organized as follows. In Section 2 we give an overview of the TNG50 simulation that is used, as well as define our sample of galaxies, and our definition of counterrotation. In Section 3, an initial characterization of counterrotating components in the galaxies is shown, afterwards, the selection of significant CRDs considered is defined. In Section 4, the structural properties and assembly of the significant CRDs is shown, ending with a classification of the CRDs. We analyze the possible formation channels for the CRDs in each classification in Section 5. We discuss our results in Section 6. Finally, we make a summary of our obtained results and conclude in Section 7.

2. Methodology

In this section we discuss the simulations employed in this paper, as well as the galaxy sample selection criteria and the definition of counterrotating stellar disks.

2.1. The IllustrisTNG: TNG50

The IllustrisTNG project (Nelson et al. 2015) is a set of gravitational magneto-hydrodynamics cosmological simulations, ran with the moving-mesh code AREPO (Springel 2010). The project is made up of three simulation volumes: TNG50 (Nelson et al. 2019, Pillepich et al. 2019), TNG100, and TNG300 (Pillepich et al. 2018, Springel et al. 2018, Nelson et al. 2018, Naiman et al. 2018, Marinacci et al. 2018). Each of these runs solves the coupled evolution of dark matter, gas, stars and super-massive blackholes from $z = 127$ to the present day, $z = 0$. All of the simulations of the IllustrisTNG project are governed by

a Λ CDM model, with a cosmology consistent with the Planck Collaboration et al. (2016) results. The IllustrisTNG set of simulations have been able to produce consistent results with observations in regimes beyond the ones used to calibrate the model (Nelson et al. 2015). This work makes use of the TNG50 run, and more specifically analyzes the baryonic simulation, TNG50-1 (TNG50, hereafter), which is the highest resolution simulation of the IllustrisTNG project. Its physical simulation box size is roughly 50 Mpc side in length, and the stellar and dark matter particle mass resolutions are $8.5 \times 10^4 M_{\odot}$ and $4.5 \times 10^5 M_{\odot}$, respectively. The softening length, at $z = 0$, are $\epsilon_{\text{DM},*} = 288$ pc and $\epsilon_{\text{gas},\text{min}} = 74$ pc. This simulation allows us to analyze components of galaxies in more detail than the other available simulations.

The TNG50 data provides the positions, velocities, mass, metallicity and metal abundances of the stellar particles as part of the complete snapshot data. Each stellar particle represents a single stellar population, with a given age and metallicity that is hereditary from the progenitor gas cell. Information about the galaxy and time where the stellar particle is born is provided in Rodríguez-Gomez et al. (2015) and is described in more detail in Section 2.3. The TNG50 simulation also gives information about the galaxies extracted from their member particles as a whole "classified according to a FoF algorithm, and subsequently Subfind", such as their total mass, total stellar mass, and virial radius. Information about the disk mass fraction according to the circularity of the particles is provided as an additional catalog by Genel et al. (2015).

2.2. Sample selection

In this study we decided to focus on a sample of MW-type galaxies. In a follow up study we will expand this sample to include a wider range of late-type galaxies. In particular, we select galaxies that fulfill the following criteria:

- A total mass range of $10^{11.5} - 10^{12.5} M_{\odot}$
- A Disk-to-Total mass ratio (D/T) larger than 0.5.
- A total number of stars $N_{\text{tot},\text{stars}} \geq 10^5$
- The galaxy must be the central galaxy in its group, meaning that it should be the most submassive halo according to the Friends-of-Friends(FOF) algorithm.

In particular, the D/T ratios are obtained from the publicly available database of IllustrisTNG as part of the additional catalogs¹, and are computed by considering as disk stellar particles the ones with circularity parameter (see Sec 2.3) larger than 0.7.

After applying the described selection criteria, we obtain a total of 260 late-type disk galaxies. As discussed, selected galaxies have a number of stellar particles of $\leq 5 \times 10^5$ stellar particles within them, thus ensuring enough particles to reasonably resolve the structure of the stellar disk and search for potential structures with small mass contributions, such as counterrotating stellar components.

2.3. Counterrotating disk definition

The goal of this work is to identify, quantify and analyze counterrotating stellar disks components (CRDs) in fully cosmological simulations of galaxy formation. Different methods for isolating particles associated to different galaxy components, such as counterrotating disks have been proposed. For example, Tissera et al. (2012) applies a criteria based on circularity and binding

¹ www.tng-project.org/data/docs/specifications/#sec5c

Table 1. Parameters of the sample of galaxies with a significant CRD component, as well as the six boundary cases. Column descriptions from the left to the right are: (1) internal name, (2) $z=0$ SubfindID from the TNG50 simulations, (3) total gravitationally bounded mass as defined by the Subfind algorithm, (4) stellar mass of the counterrotating disk, (5) total stellar disk mass, (6) half-mass radius of the stellar disk, (7) optical radius, (8) half-mass radius of the counterrotating stellar disk, (9) radius enclosing 95% of the counterrotating stellar disk mass, (10) stellar concentration of the counterrotating disk as defined in Sec. 4, (11) fraction of ex-situ stellar particles in the CRD.

Name	SubFindIDat99	M_{Bound}	M^{CRD}	M^{Disk}	R_{50}^{Disk}	R_{opt}	R_{50}^{CRD}	R_{95}^{CRD}	$R_{95}^{\text{CRD}}/R_{50}^{\text{CRD}}$	Exsitu CRD fraction
-	-	[$10^{10} M_{\odot}$]	[$10^8 M_{\odot}$]	[$10^{10} M_{\odot}$]	[kpc]	[kpc]	[kpc]	[kpc]	-	-
CR-0	501208	116.20	7.76	7.52	96.93	16.50	5.36	10.83	2.02	0.11
CR-1	394621	234.03	6.00	6.00	100.03	17.00	0.52	4.05	7.82	0.03
CR-2	526478	77.48	6.73	4.13	61.40	26.50	1.61	9.06	5.63	0.33
CR-3	531910	76.65	6.56	4.97	75.68	11.00	0.83	9.72	11.75	0.17
CR-4	559036	53.31	3.02	3.16	104.50	20.50	0.69	6.61	9.52	0.24
CR-5	547844	66.70	7.52	4.78	63.55	12.00	8.00	11.26	1.41	0.12
CR-6	552879	54.49	3.15	2.96	94.15	18.50	1.46	6.70	4.58	0.62
CR-7	557396	52.82	4.02	2.71	67.41	18.00	2.38	6.95	2.92	0.37
CR-8	557721	63.53	4.75	3.92	82.43	11.00	0.51	2.55	5.00	0.01
CR-9	563732	58.77	4.79	3.49	72.85	13.00	0.54	3.65	6.81	0.02
CR-10	570319	41.79	2.55	2.62	102.68	21.50	3.52	13.86	3.94	0.13
CR-11	587019	33.28	2.10	1.89	89.89	10.00	1.05	2.94	2.81	0.01
CR-12	597311	29.82	1.17	0.81	68.77	18.00	0.98	3.31	3.39	0.01
CR-13	601861	28.97	2.25	1.63	72.57	7.50	0.80	3.68	4.60	0.00
CR-14	610988	28.61	1.28	1.23	95.66	13.50	0.68	5.06	7.46	0.18
CR-15	616825	25.00	1.17	0.67	57.57	12.00	0.94	4.26	4.52	0.26
CR-16	617324	23.96	1.13	0.98	86.86	12.00	1.61	4.95	3.07	0.03
CR-17	619801	22.74	3.15	0.74	23.48	8.00	2.20	5.20	2.36	0.01
CR-18	626864	21.85	2.07	0.94	45.52	14.50	1.52	6.89	4.54	0.01
CR-19	627459	22.74	1.43	1.24	86.97	13.00	0.89	4.72	5.31	0.37
CR-20	627572	23.44	4.34	1.14	26.25	10.50	0.79	3.08	3.90	0.02
CR-21	628031	24.00	2.98	0.87	29.07	7.00	0.90	3.32	3.70	0.01
CR-22	594887	33.48	1.56	1.62	103.79	18.00	2.84	5.41	1.90	0.03
CR-23	603281	22.02	0.62	0.60	96.17	14.00	0.78	5.13	6.55	0.22
CR-24	617559	25.05	0.95	0.95	100.08	13.00	2.05	5.93	2.89	0.03
CR-25	623575	22.01	1.06	1.10	104.09	12.00	1.83	5.73	3.14	0.09

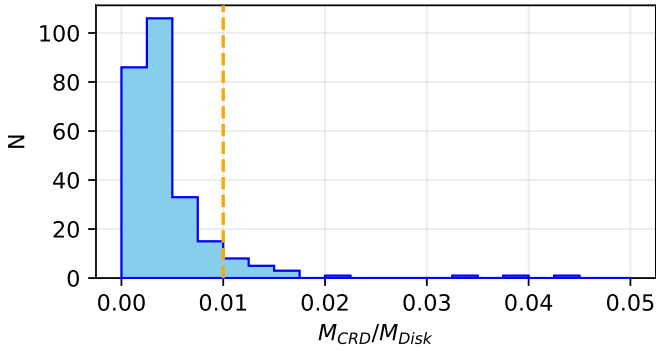


Fig. 1. Distribution of the counterrotating disk mass fraction for the full sample of 260 late-type disk galaxies. The vertical dashed orange line indicates a 1% mass fraction from the CRD. We see that only 10% of the galaxies (when including the boundary cases) have a CRD mass fraction greater than 1%.

energy to subdivide a late type galaxy on its different components. In this study, we follow an approach more closely related to the definitions used in Gómez et al. (2017) and Monachesi et al. (2019). We first rotate the galaxy so that the plane of the disk is co-planar with the xy -plane, i.e the angular momentum of

the galactic disk is parallel to the Z -axis direction. Afterwards, we identify particles that are counter-rotating in the galaxy using the circularity parameter, thus performing a kinematic decomposition. Following Abadi et al. (2003) this parameter is defined as:

$$\epsilon_{J_z} = \frac{J_z}{|\max(J_z(E))|}, \quad (1)$$

where J_z is the angular momentum in the z -axis and the term " $\max(J_z(E))$ " indicates the maximum angular momentum in the z -direction allowed for that orbital energy; i.e. that of a circular orbit.

In order to define the extension of the stellar disks we use the optical radius, R_{opt} . As in Varela-Lavin et al. 2023 and Dolfi et al. 2023, R_{opt} is defined as the radius at which the surface-brightness (SB) profile on the V -band of the galaxy, orientated on a face-on projection, reaches $\mu_V = 25 \text{ mag arcsec}^{-2}$. To estimate the optical radius, we measure the surface-brightness of the galaxy in cylindrical shells of width 0.5kpc and height 10kpc above and below the disk plane. The values of the R_{opt} obtained for each galaxy are listed on Table 1.

Having the circularity parameter computed for every stellar particle within R_{opt} . We define the counterrotating disk components by selecting stellar particles that fulfill the following criteria:

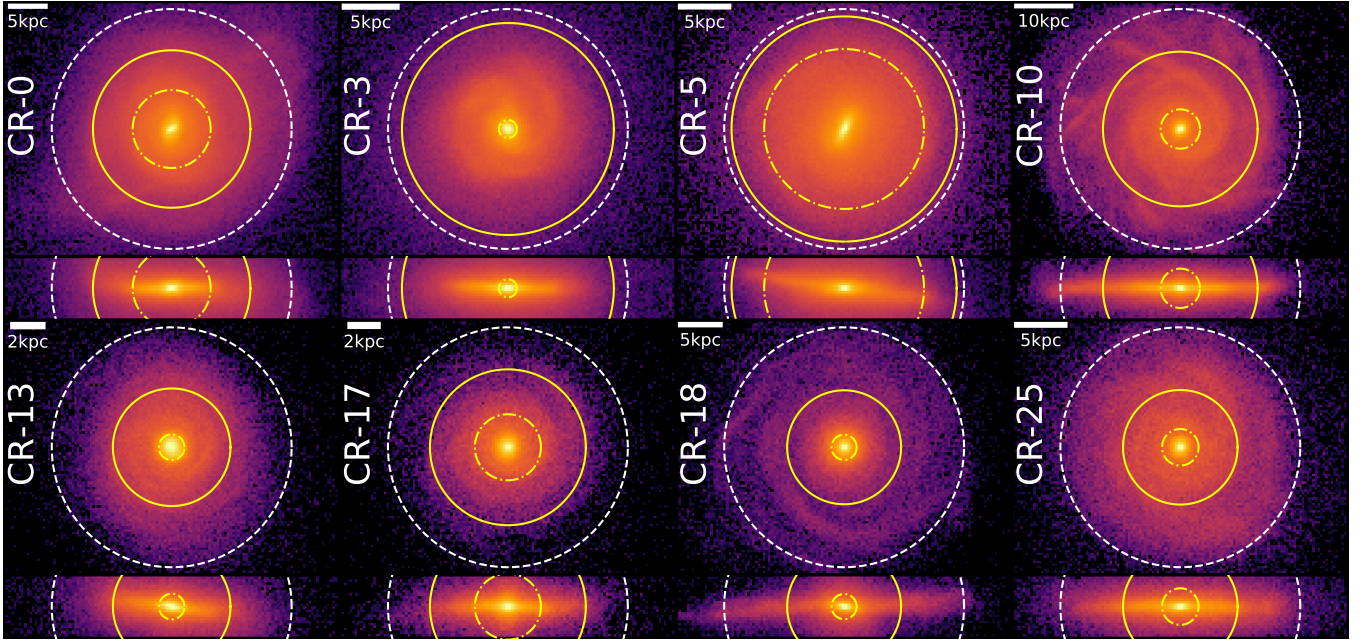


Fig. 2. The face-on and edge-on projections of the stellar mass surface density for a sub-sample of 8 galaxies with the most significant counterrotating stellar disks. The galaxies are sorted according to their total mass, from the most to the least massive. Here, we show all the stellar particles that belong to the host galaxy. The yellow solid and dot-dashed circle represent the radii, R_{95}^{CRD} and R_{50}^{CRD} , of the counterrotating disk, respectively, while the white dashed circle represents the optical radius, R_{opt} , of the galaxy.

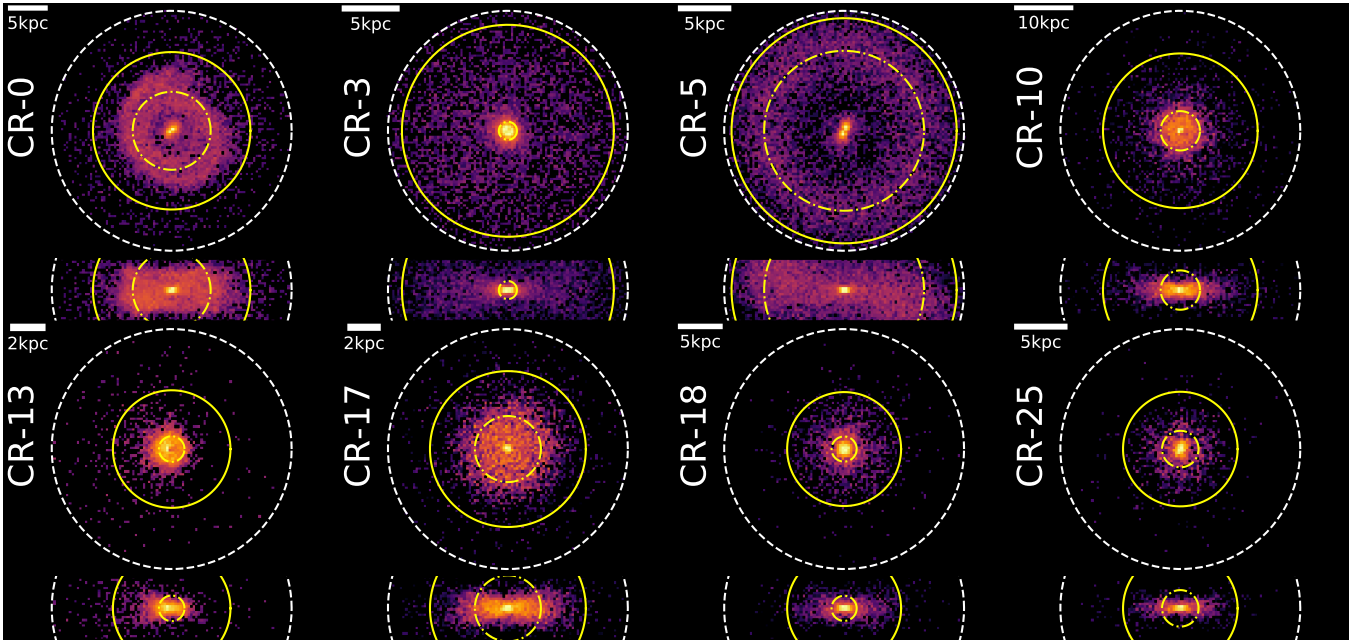


Fig. 3. Same as Fig. 2, but we show here only the stellar particles belonging to the CRDs.

- Circularity value in the range of $\epsilon < -0.7$.
- A distance from the galactic plane of under 5kpc ($|z| < 5 \text{ kpc}$).
- A galactocentric distance under R_{opt} .

These selection criteria allow us to select star particles in nearly circular orbits rotating in the opposite direction of the overall disk.

In this work we are also interested on characterizing the formation mechanisms of CRDs. Due to this, it is important to identify the origins of the different stellar particles associated to these components. In particular, we subdivide the counterrotating stellar particles as in-situ or ex-situ based on where the particle were

born. As discussed in [Rodríguez-Gomez et al. 2016](#), a particle is considered in-situ if the galaxy in which it formed is part of the main branch of the merger tree of the galaxy where the particle is at the present-day. In case the particle was born outside this main branch then the particle is tagged as ex-situ. Notice that particles that are formed within the potential well of the main progenitor from recently stripped gas from satellite galaxies are labeled as in-situ.

3. Identification of counterrotating disks

In this section we quantify and characterize the CRD components in the sample of 260 late-type galaxies. We then quantify the number of galaxies hosting a significant CRD. Once identified, CRD components are characterized based on three parameters:

- The counter-rotating disk mass fraction, $M_{\text{CRD}}/M_{\text{Disk}}$, which is given as the fraction of mass in the counterrotating component over the total disk stellar mass enclosed within R_{opt} and $|z| \leq 5$ kpc
- R_{50}^{CRD} , which quantifies the half-mass radius of the distribution of counterrotating stellar particles.
- R_{95}^{CRD} , which quantifies the radius at which the mass distribution of counterrotating stellar particles reaches 95% of the mass of the CRD.

Fig. 1 shows the distribution of the counterrotating disk mass fraction obtained from our full sample of late-type disks. Note that, for the majority of disk galaxies, the CRD components do not surpass the 1% threshold, highlighted by the vertical dashed line. We find that only $\approx 8\%$ of the galaxies host a CRD with a mass fraction larger than 1%. The sample of galaxies that host a significant CRD, i.e., $M_{\text{CRD}}/M_{\text{Disk}} \geq 0.01$ consists of 20 galaxies. In this study, we decided to include in our final sample 6 boundary cases with $0.0095 \leq M_{\text{CRD}}/M_{\text{Disk}} < 0.01$.

In Table 1 we list the internal properties of the galaxy sample with identified CRDs. In the left most column the label given to each identified CRD is shown. The corresponding Subfind ID at $z = 0$ is given in the second column.

Fig. 2 presents 8 examples of galaxies hosting a significant CRD. The figure shows their total stellar surface mass density both, in face-on and edge-on projections. We show the most extensive CRDs in terms of their R_{95}^{CRD} . The dashed white circle denotes the overall disk size in terms of R_{opt} , while the solid and dot-dashed yellow circles represent R_{95}^{CRD} and R_{50}^{CRD} , respectively. We note that the morphological diversity of the galactic disks, with some exhibiting well-defined bars (e.g., CR-5) and spiral structures (e.g., CR-10 and CR-18).

Fig. 3 shows the spatial distribution of the counterrotating stellar particles considered as members of the CRD, in the same order as in Fig. 2. By comparing the two figures, we observe that in some galaxies (e.g., CR-5 and CR-3), the CRDs extend to radial distances comparable to those of the overall stellar disk. In contrast, other cases (e.g., CR-25) exhibit much more compact CRDs. In addition, some cases such as CR-0 and CR-5 display an interesting torus like morphology. We will explore the origin of their structure in the following sections. The full set of 26 galaxies analyzed is shown in Fig. A.1 and A.2.

From this analysis it follows that, based on our criteria, approximately 10% (including the boundary cases) of the galaxies host a significant stellar CRD. Our results indicate that CRDs are relatively infrequent. This is consistent with previous observational studies, which report CRDs, specially stellar, as rare systems found in only $\approx 1\%$ of MaNGA galaxies (Bao et al. 2022, Gasymov et al. 2025).

4. Characterization of CRDs

In this section we characterize and quantify the main properties of the stellar CRDs. We focus on their radial distributions and the origin of their stellar particles.

Fig. 4 shows the relationship between the CRD mass fraction, $M_{\text{CRD}}/M_{\text{Disk}}$ and different measurements of the disk extension and mass distribution. In particular we focus on $R_{50}^{\text{CRD}}/R_{\text{opt}}$

(top), $R_{95}^{\text{CRD}}/R_{\text{opt}}$ (middle) and $R_{95}^{\text{CRD}}/R_{50}^{\text{CRD}}$ (bottom). Data points are color-coded according to the total stellar mass of the disk.

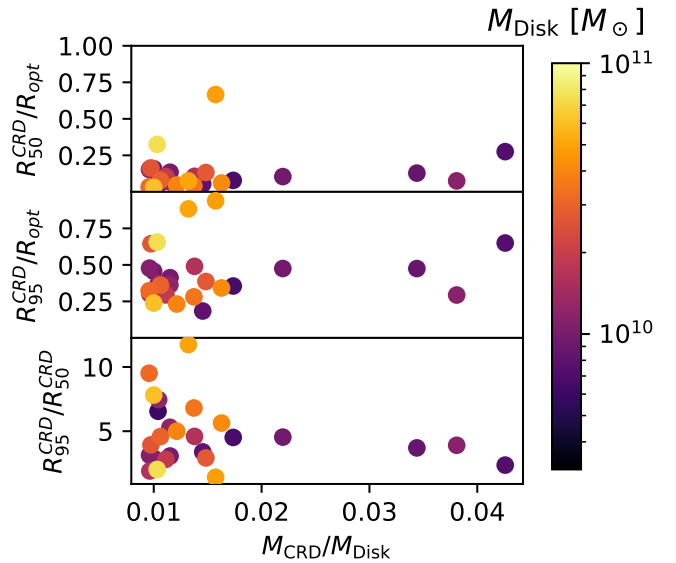


Fig. 4. The CRD mass fraction, $M_{\text{CRD}}/M_{\text{Disk}}$, as a function of different measurements of the counterrotating stellar disk extension and mass distribution for the sample of 26 significant CRD galaxies. Top & middle panels: the radius containing 50% and 95% of the counterrotating stellar disk mass normalized by the optical radius of the galaxy, respectively. Bottom panel: the stellar concentration of the counterrotating disk. All data points are color-coded by the total stellar disk mass. We see that, while most CRDs are compact with the majority having $R_{50}^{\text{CRD}}/R_{\text{opt}} < 0.25$, there are a few extended cases. Overall, we find that our sample of counter rotating galaxies show a variety of structural properties.

The top panel shows that most CRDs are relatively compact in nature, with approximately 88% having half-mass radii (R_{50}^{CRD}) smaller than a quarter of their optical radii (R_{opt}). However, the middle panel reveals that around 89% of CRDs have $R_{95}^{\text{CRD}}/R_{\text{opt}}$ values greater than 0.25, and approximately 19% exceed half the optical radii. This indicates that, while most CRDs are compact in terms of their half-mass radii, many have a reasonably extended radial distribution. The bottom panel of Fig. 4 shows a measure of the CRDs concentration, which is defined as the ratio $R_{95}^{\text{CRD}}/R_{50}^{\text{CRD}}$. CRDs with $R_{95}^{\text{CRD}}/R_{50}^{\text{CRD}} \leq 2$ enclose approximately significant of their mass in thin ring-like structure. We identify 3 of these torus-like CRDs, which are CR-0, CR-5, and CR-22. Indeed, this can be appreciated on Fig. 3. CRDs with higher concentration values, such as CR-3 and CR-10, exhibit less compact profiles. The wide spread in the CRDs concentration highlights the structural diversity within the sample. Overall, we find that our sample of counter rotating galaxies shows a variety of structural properties. Three CRDs show a ring like structure, some display an extended CRD, while others have a more compact nature with values of R_{95}^{CRD} below half of the disk's R_{opt} .

We now characterize the origin of the stellar particles that conform each CRD. We recall the reader that stellar particles formed from the gas distribution bound to the potential well of the main host galaxy are defined as in-situ. This includes gas that may be recently stripped from closely interacting satellite galaxies. In Fig. 5 we show the fractions of in-situ and ex-situ stellar particles in each significant CRD. The light blue (bottom) fraction of each bar indicates the contribution from in-situ stellar

particles, while the other colored fractions indicate the contribution to the ex-situ from different satellite galaxies. Interestingly, a majority of the CRDs present a dominant in-situ contribution, with 19 out of 26 (73%) cases displaying fractions above 80%. The remaining 7 CRDs present a more significant ex-situ contribution; i.e. $> 20\%$. We find only one CRD dominated by the ex-situ component (CR-6). In general, CRDs with significant ex-situ contributions have only one significant progenitor that contributes over 90% of the ex-situ particles, with CR-2 being the only exception. We will further explore these cases in Section 5.

In general, we find that CRDs have a very significant in-situ contribution and, in most cases, present a compact distribution. We note however, that some show extended configurations. As we will show in Section 5, even though most CRDs stellar particles are born within the host potential well, the corresponding star formation bursts are typically associated to significant interaction with massive nearby satellites.

In Fig. 6 we show the distribution of CRDs in a space defined by the fraction of ex-situ material and the extension of the CRD with respect to the overall stellar disk, $R_{95}^{\text{CRD}}/R_{\text{opt}}$. Each symbol represents a single CRD. The top histogram in the figure highlights that a significant fraction of CRDs ($\approx 80\%$) fall into a compact configuration, with values of $R_{95}^{\text{CRD}}/R_{\text{opt}} < 0.5$. Indeed, the median value of the distribution is $R_{95}^{\text{CRD}}/R_{\text{opt}} \sim 0.37$. Note however the presence of the five interesting cases with very extended in-situ discs; i.e. $R_{95}^{\text{CRD}}/R_{\text{opt}} > 0.6$ (see also Fig. 4). As previously discussed, the histogram on the right panel of the figure shows that most CRDs ($\approx 73\%$) have an ex-situ fraction < 0.2 . Indeed, the median value of the ex-situ mass fraction is ~ 0.06 .

Based on this space we classify CRDs in different categories using a threshold $R_{95}^{\text{CRD}}/R_{\text{opt}} = 0.5$ and an ex-situ fraction of 20%. The different categories are defined as *i)* compact in-situ, *ii)* compact ex-situ and *iii)* extended in-situ. These categories reflect both their spatial extent and whether the ex-situ mass fraction is significant. The classification scheme is highlighted with different colored regions in Fig. 6. Using this scheme, we find that compact in-situ CRDs are the most common, with 14 cases, followed by 7 compact ex-situ and 5 extended in-situ CRDs. Note that no CRDs with a significant ex-situ fraction are found to be extended.

This analysis indicates that CRDs are not only rare in TNG50, but they also predominantly exhibit compact spatial distributions. Interestingly, despite being less frequent, it is the extended types that are more likely to be detected observationally, providing context for the $\approx 1\%$ occurrence reported in the MaNGA survey (Bao et al. 2022, Gasymov et al. 2025). Using this CRD classification as foundation, in the next Section we proceed to analyze each type individually, examining their star formation histories and merger activity to characterize the nature of their formation.

5. Formation channels for CRDs

In this Section we explore the different formation channels of the 26 significant CRDs, subdivided according to the three categories defined in Section 4. In our analysis we incorporate information about the stellar ages as well as the properties of infalling satellites.

Fig. 7 shows the star formation histories (SFHs) of all 26 significant CRDs. Each panel represents a galaxy from our sample. Here, the orange and the light blue lines represent the SFH of the CR ($\epsilon < -0.7$) and the co-rotating ($\epsilon > 0.7$) disk component, respectively. The vertical dashed lines indicate the median

of each distribution. Additionally, the gray dashed line represents the SFH of all stellar particles confined within a cylinder of radius $R = R_{\text{opt}}$ and height $|z| \leq 5$ kpc. All SFHs are normalized to the peak value of the corresponding distribution. We can clearly see that, with respect to the full disks, CRDs typically have a more bursty history. In most cases, these bursts are also noticeable in the overall disk's SFH. Additionally, we also notice that CRDs are significantly older than the corotating counterparts. Indeed, this is the case for $\approx 93\%$ of the identified CRDs. The two exceptions are CR-0 and CR-11. We will further study these cases later in this section.

Fig. 7 also highlights the more significant interaction events each galaxy has undergone. We focus on interactions associated with satellites that have at least a total peak mass of $5 \times 10^9 M_{\odot}$ and that, at the corresponding peak mass time, the satellite to host mass ratio was larger than 20%. The first pericenter passage of such interactions are indicated with arrows, color coded according to each satellite's peak mass. For CRDs with an ex-situ fraction $\geq 10\%$, we highlight the arrow associated with the most significant ex-situ contributor. As expected, we observe in all cases a higher frequency of significant mergers at early times. Nonetheless, significant interactions can take place at any time. Such interactions are commonly associated with star-formation (SF) bursts in the overall stellar disk (see also Gargiulo et al. 2017).

5.1. Compact in-situ CRDs

Compact CRDs are the most frequent type in our sample. By definition, these systems are not very extended (their values of R_{95}^{CRD} lying under half of the optical radius of the overall disk), meaning the counterrotating stars are largely confined to the spatial limits of the galaxy's bulge or bar. Within this category, we first consider those CRDs that formed predominantly in-situ (ex-situ fraction $< 20\%$). There are 14 such cases in our sample. Compact in-situ CRDs are indicated by blue boxes, as well as an upward-pointing blue triangle symbols on the top right corner of each panel in Fig. 7.

Among the compact in-situ CRDs, one galaxy, CR-14, stands out as a borderline case: about 18% of its CRD stellar particles are ex-situ (accreted). CR-14 lies just below our threshold for the "ex-situ" category; its counterrotating component can be mainly associated to a significant accretion event. Indeed, Fig. 7 shows that a merger with a satellite of peak mass of the order of $\approx 8 \times 10^{10} M_{\odot}$ induces a SF burst that gives rise to most of the co-rotating component. Furthermore, the assembly information shown in Fig. 5 for CR-14's CRD shows that the majority of its few accreted stars came from this single infalling satellite (see Fig. 7, blue highlighted arrow), which contributed both stars and gas, as well as inducing a burst of star formation.

Many of the compact in-situ CRDs show clear signs of interaction-triggered star formation in their histories, even though the stars themselves formed in-situ. For example, CR-11, CR-12, CR-14, CR-18, CR-20 and CR-25 all exhibit enhanced star formation in their CRDs that was preceded by an interaction event either at intermediate (e.g CR-12 and CR-20) or at late times (CR-11). In these galaxies, a passing or merging satellite disturbed the gas in the host, inducing a burst of star formation in the inner galactic region contributing with stellar particles on retrograde orbits. In each of these cases the CRD's stellar mass is almost entirely in-situ; the interactions served as a catalyst for star formation rather than directly depositing a large number of stars.

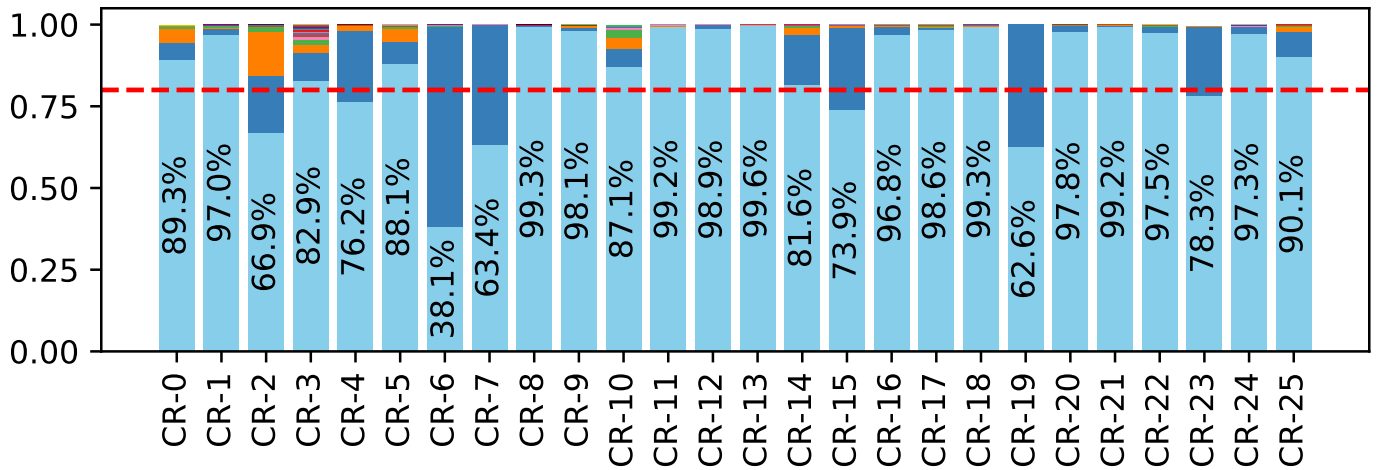


Fig. 5. The fraction of the in-situ and ex-situ stellar particles in the counterrotating disk for the sample of 26 significant CRD galaxies. Light blue bars represent the fraction of in-situ stellar particles in the CRD, while the remaining colors represent the contribution to the ex-situ fraction in the CRD from different satellite galaxies. Each color refers to a different satellite. The red dashed line indicates an in-situ contribution equals to 80%.

On the other hand, some compact in-situ CRDs appear to have formed very early, alongside the initial assembly of the galaxy’s bulge, and without any later significant interactions. Galaxies such as CR-1, CR-8, CR-9, CR-21, CR-22, and CR-24 exhibit strong early bursts of star formation, occasionally correlated with the high merger rates characteristic of that epoch. During this early phase of galaxy assembly, star formation occurred in a more irregular and turbulent environment, resulting in a pressure-supported stellar population. The more isotropic kinematics of these stellar particles are associated with broad circularity distributions, contributing to both the co-rotating and counterrotating components of the final stellar disk. Accordingly, the stellar ages of these CRDs trace back to the formation of the galaxies’ primordial inner regions. These structures are therefore old and centrally concentrated.

The two remaining cases have peculiar formation mechanisms. CR-16 formed over a prolonged period during which the co-rotating component experienced minimal star formation; until the merger of an infalling satellite, the galaxy lacked a dynamically cold stellar disk. The CRD is thus a remnant of this earlier evolutionary stage, when the galaxy was pressure-supported rather than rotation-supported. Finally, CR-13’s formed within a short time window following the smooth accretion of misaligned cold gas. The accreted gas triggered a burst of SF in the central region giving rise to the CRD.

In summary, the compact in-situ CRDs encompass a variety of formation paths. Some (e.g., CR-1, CR-8, CR-9, CR-21, CR-22, CR-24) formed at the earliest times of their host galaxy, essentially as part of the old bulge formation. Others (e.g., CR-11, CR-12, CR-18, CR-20) formed later, with their counterrotating stars born during one or more bursts triggered by satellite interactions (but without significant stellar accretion). A particular case (e.g., CR-14) shows a minor contribution from accreted stars in addition to in-situ star formation. CR-16’s CRD is the remnant of a pre-disk stellar population formed prior to the development of a dynamically cold disk, while CR-13’s CRD originated from the accretion of misaligned gas that fueled central star formation.

From these results, we can broadly categorize the origins of compact in-situ CRDs into three scenarios: (i) formation at early times together with the galaxy’s bulge, (ii) interaction-induced star formation without substantial stellar accretion, (iii) pecu-

liar cases associated with smooth misaligned cold gas accretion and pre-stellar disk irregular star formation. The first two mechanisms being the most frequent. In practice, some CRDs may involve a combination of these mechanisms. Overall, however, the common theme is that the compact in-situ CRDs were built by star formation within the galaxy, often triggered or influenced by interactions, rather than by direct deposition of stars from mergers.

5.2. Compact ex-situ CRDs

This subtype of CRD is compact in extent but contains a significant fraction of ex-situ stellar particles. By definition, compact ex-situ CRDs have more than 20% of their counterrotating stars accreted from satellite galaxies. We identify 7 galaxies in this category (CR-14, discussed earlier, falls just below the 20% threshold). These are marked with red rhombus symbols in Figures 6 and 7 (see also Appendix Figures A.1 and A.2).

As shown on Fig. 5, past mergers are of great importance in the assembly of compact ex-situ CRDs. In several cases, a single satellite merger provided the bulk of the accreted stellar particles for the CRD. For example, CR-4, CR-6, CR-7, CR-15, CR-19 and CR-23 each have one dominant progenitor galaxy contributing the majority of the ex-situ component in the CRD. Only one case, CR-2, has two significant contributors to its ex-situ stellar mass. Often, these mergers also enhanced in-situ star formation in the host. As a result, the infalling satellites not only donated stars but also triggered new star formation in retrograde orbits, as evidenced by the star formation histories. Indeed, Fig. 7 shows clear star formation peaks coincident with the merger times for these galaxies. We recall the reader that, in all panels, the most significant contributor is shown with a highlighted arrow.

Notably, some of the most massive satellite interactions in our entire sample are associated with compact ex-situ CRDs. CR-2, CR-4, CR-6, and CR-7 experienced some of the highest-mass merger events (in terms of total satellite-to-host mass ratio) of all the galaxies with CRDs (mass ratio > 40%). These massive satellites are strongly affected by dynamical friction, rapidly sinking to the host galactic center. The fact that these major interactions resulted in relatively compact counterrotating disks (confined to the bulge region) indicates that the stars brought in by the merger, and those induced by associated star

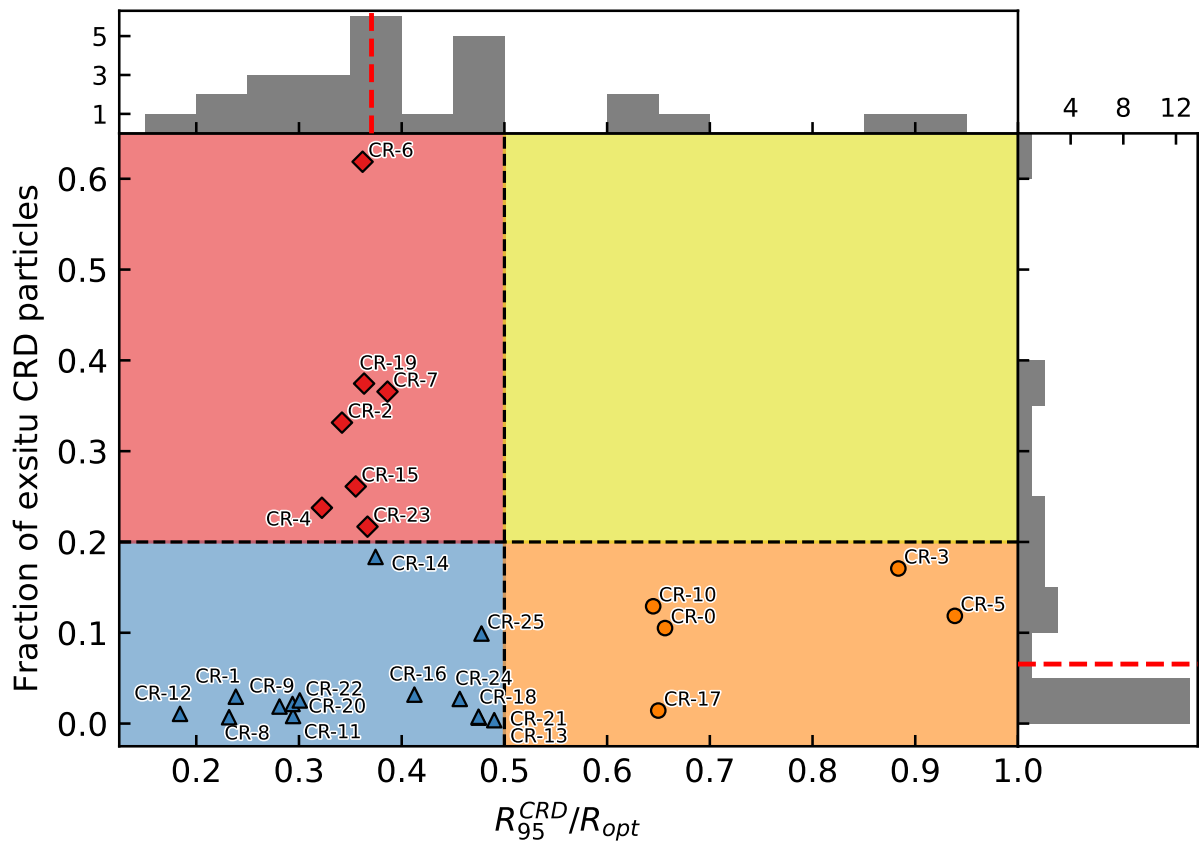


Fig. 6. Classification of the sample of 26 significant CRDs according to their counterrotating stellar disk extension ($R_{95}^{\text{CRD}}/R_{\text{opt}}$), and to their ex-situ fraction of stellar particles. We classify the CRDs into four different types, namely extended ex-situ CRDs (yellow quadrant), compact ex-situ (red rombus quadrant), compact in-situ (blue triangle quadrant) and extended in-situ (orange circle quadrant).

formation bursts, remained concentrated in the central regions of the galaxy. It is also worth noting that, as in the compact in-situ cases, these CRDs contain an old significant in-situ component tracing back to the formation of the galaxy’s primordial inner regions.

In observational terms, compact CRDs like those identified in TNG50 may be difficult to detect, as their small radial extent, and dominance of the central bulge light, limits their visibility in standard kinematic analyses. Observationally confirmed CRDs, such as those reported by Bao et al. (2022), typically correspond to more extended structures, likely due to selection biases or resolution constraints. According to our analysis, if a compact ex-situ CRD were to be observed, its formation would be strongly influenced by one or two significant merger events. In all eight cases of this subtype in our sample, an interaction or merger can be linked to the emergence of the counterrotating component. While in simulations the ex-situ mass fraction provides a clear discriminator of the CRD formation channel, such quantity is inaccessible observationally. In practice, distinguishing in-situ from ex-situ CRDs would rely on indirect indicators such as differences in stellar age, metallicity, or α -element abundance relative to the host disc. In addition, compact CRDs could still produce detectable features in the stellar velocity dispersion field, such as double peaks (i.e., 2σ or σ -elongated profiles), which

do not require spatial separation of the co- and counterrotating components. We defer this to a follow-up analysis.

5.3. Extended In-situ CRDs

Extended CRDs are the minority in our TNG50 sample. By definition, these systems have $R_{95}^{\text{CRD}}/R_{\text{opt}} > 0.5$, indicating that their counterrotating stellar disks extend beyond half the optical radius of the host galaxy. Among the 26 identified CRDs, only five meet this criterion. All five of these are predominantly of in-situ origin and are marked with orange circle symbols in Fig. 6 and 7 (see also Fig. A.1 and A.2).

The extended in-situ CRDs, CR-0, CR-3, CR-5, CR-10, and CR-17, formed the bulk of their counterrotating stars within the main galaxy, with relatively low ex-situ stellar mass fractions. Specifically, CR-0, CR-3, CR-5, and CR-10 each have approximately 11 – 17% of their CRD stellar mass contributed by satellites, while CR-17 is almost entirely in-situ, with less than 2% ex-situ material. Despite their in-situ dominance, all five systems show clear signs that interactions played a pivotal role in their formation, either by supplying retrograde gas or perturbing the host. As illustrated in Fig. 7, which traces the stellar age distributions and merger events for each CRD, these galaxies experienced one or more significant interactions around the epoch of their main counterrotating star formation. Notably, and in con-

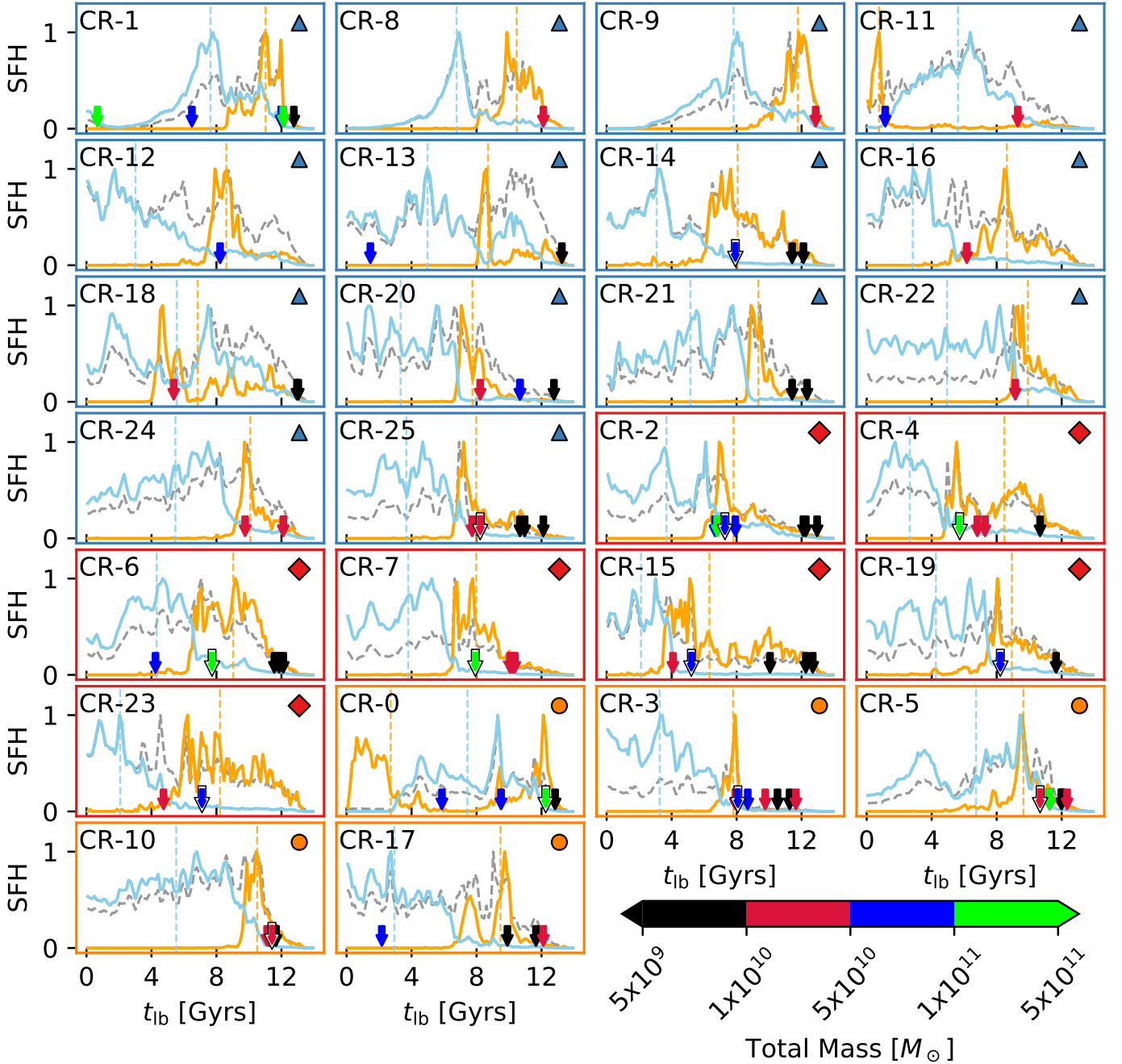


Fig. 7. The star formation histories (SFHs) of all 26 significant CRDs, grouped according to the classification type, namely compact in-situ, compact ex-situ, extended in-situ (see Sec.4). Here, the orange and the light blue lines represent the SFH of the counterrotating and the co-rotating disk component belonging, respectively. The vertical dashed lines indicate the peak value of each distribution. The gray line represents the SFH of all stellar particles belonging to the disk. All SFHs are normalized to the peak value of the corresponding distribution. For each CRD, we also label the time of the first pericenter for the most significant interactions experienced by the galaxy, considering only satellites with a peak total mass $>5 \times 10^9 M_\odot$ and a satellite-to-host mass-ratio $>20\%$. The most significant interaction of the CRD is identified by an arrow outlined in black and white.

trast to the majority of CRDs in our sample, the stellar distribution in these five systems is significantly extended.

Examples of this CRD type are shown in Fig. 3. Two peculiar cases are CR-0 and CR-5, which present a torus-like spatial distribution of the CRD component. Both present a concentration $R_{95}^{\text{CRD}}/R_{50}^{\text{CRD}} \leq 2$ (see Sec. 4). In the CR-0 case, its CRD's star formation history (Fig. 7) shows at least three distinct peaks. The oldest peak, around 12 Gyr ago (lookback time), corresponds to the very early assembly of the galaxy and is associated with both gas accretion during these early times and a burst associated to a

very significant merger, highlighted with a green arrow. The next peak, near 9 Gyr ago, is associated with the infall of a second significant satellite (blue arrow in Fig. 7). This interaction induced a burst star formation, contributing to the CRD in the inner galactic region, as seen in the previous CRD type. The most recent rise in CR-0's counterrotating star formation begins ~ 3 Gyr ago and continues toward the present day. Interestingly, CR-0 is experiencing an ongoing interaction with a massive satellite that had its first pericentric passage ≈ 4 to 5 Gyr ago. The satellite has not fully merged at $z = 0$ and continues to orbit the host.

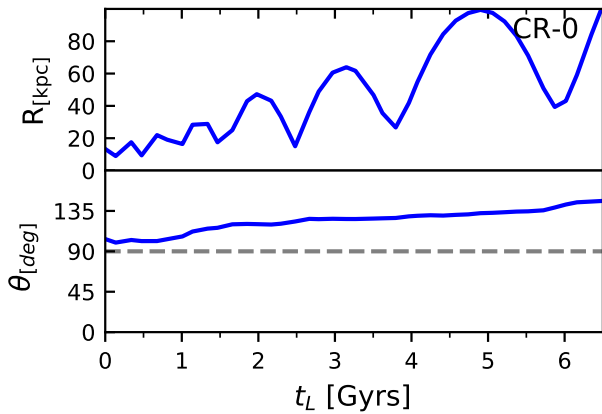


Fig. 8. The orbit of the satellite that is continuing its interaction with CR-0 at $z=0$. We follow the evolution of the satellite orbit to a lookback time of 6 Gyr. Top panel: evolution of the satellite galactocentric distance from the host. Bottom panel: evolution of the angle between the angular momentum of the disk and the satellite’s orbital angular momentum. Orbits near 180° are counterrotating, while those near 0° are co-rotating.

In Fig. 8, we analyze the orbit of this infalling satellite. The top panel shows the time evolution of the satellite’s galactocentric distance, while the bottom panel the evolution of the angle between the angular momentum of the disk and the satellites’s orbital angular momentum. Orbits near 180° are counterrotating, those near 90° are polar, and those near 0° are co-rotating. The figure clearly shows that the satellite is accreted in a counterrotating orbit with respect to the main disc. The satellite is relatively gas rich, with a gas-to-total mass fraction at infall of 17%. The gas stripped on this counterrotating orbit fuels the more recent star formation episode of its CRD.

CR-5 also presents a torus-like CRD structure. Its star formation peak occurred around 9.5 Gyr ago and coincides with a major interaction involving a massive gas-rich satellite. This satellite had its first pericentric passage at ~ 11 Gyr ago and deposited a significant amount of co-rotating gas at the outermost pre-existing disk region, that subsequently formed the stellar torus-like structure. Interestingly, after the formation of this structure, CR-5 experienced a significant accretion of gas, counterrotating with respect to the pre-existing structure, giving rise to the present-day overall disk. This is shown in the top panel of Fig. 9. Here we show, with blue lines, the time evolution of the disk’s angular momentum vector orientation with respect to its orientation at the present-day, J_{disk}^0 . In addition, we show with an orange line, the time evolution of the CRD angular momentum vector orientation with respect to J_{disk}^0 . We can clearly see that the CRD and the overall disk remain well aligned until $t_L = 7.5$ Gyr. After this time, both component become progressively more misaligned. This is due to the later accretion of misaligned, as shown by the black line which follows the time evolution of the gas angular momentum vector orientation, J_{gas} , with respect to J_{disk}^0 . To compute J_{gas} we considered, at every snapshot, all gas cells enclosed within a sphere of radius equal to the present-day R_{opt} . This clearly indicates the significant accretion of misaligned cold gas within $4.5 \lesssim t_L \lesssim 7.5$ Gyr. Within this period of time the increasing misalignment of the gas component is subsequently followed by what results in the present-day corotating disk.

CR-10 and CR-17 present a similar formation mechanism of the CRD component. In the case of CR-10, its CRD formed

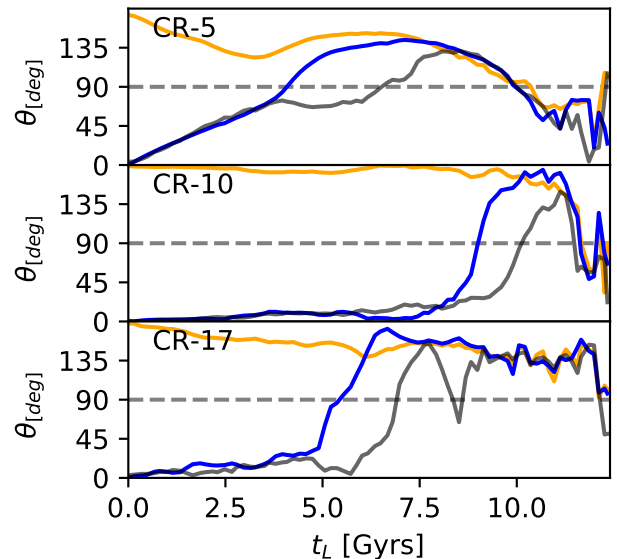


Fig. 9. Time evolution of the angle between the angular momentum of the disk at $z=0$ and the disk (blue), CRD (orange) and gas within R_{opt} (black). The angles are obtained using the dot product between the angular momentum vectors as the bottom panel of Fig. 8.

through multiple nearly simultaneous satellite interactions at early time. Four different satellites (2 of them with mass ratios over 25%, other 2 being 12%) interact in a narrow time window with the host. The most massive interacting satellites are indicated by the red arrows in Fig. 7. A central burst of star formation, associated with these interactions, contributed to both the corotating and counterrotating components of the final disc. These satellites also contributed with both, stellar particles and extended gas component that gives rise to the present-day CRD. Interesting, as shown in the middle panel of Fig. 9, the present-day CRD arises as a corotating component. However, the posterior accretion of misaligned gas, starting at $t_L \approx 11.5$ Gyr gives rise to a new rotating component that, at the present-day, represents the corotating disk. CR-17 CRD, instead, almost entirely formed in-situ (only 2% ex-situ) within two early burst of SF; a first episode at a lookback time $t_L \approx 10$ Gyr and a second episode 7 Gyr ago. We note that during that period of time, the SF activity of the present-day co-rotating component was almost negligible. Indeed, as shown in Fig. 7, the present-day co-rotating disk starts to grow in mass after $t_L \approx 7$ Gyr. In the bottom panel of Fig. 9 we can clearly see that the CRD is born as a corotating component. However, after $t_L \approx 7.5$ Gyr, significant accretion of counterrotating gas gives rise the present-day corotating disc.

Finally, CR-3 is an outlier in several aspects. It’s the closest extended CRD to being ex-situ; about 17% of its stellar mass is directly accreted from satellites. CR-3 also extends unusually far into the outer disk (high $R_{95}^{\text{CRD}}/R_{\text{opt}}$). Its formation history (Fig. 7) shows a prominent star formation peak around 8 Gyr ago, coinciding with the infall of multiple significant satellites in rapid succession. Two of these satellites were fairly massive ($\approx 40\%$ mass ratio). The ex-situ stellar component of this CRD originates from these satellites. The interactions not only deposited stars into the CRD but also funneled gas into the host, which subsequently formed stars on retrograde orbits (hence the substantial in-situ contribution).

In summary, all four extended in-situ CRDs can trace their formation to interactions: CR-5 and CR-10 each formed during a major burst of multiple simultaneous minor mergers, CR-0’s

CRD grew through a combination of early accretion and an ongoing major interaction, and CR-17's CRD was built via a single low mass merger. However the reasons for counterrotation vary, CR-0 is due to the ongoing accretion of the infalling satellite in a counterrotating orbit. CR-5, CR-10 and CR-17 all have later accretion of misaligned gas that gives rise to a younger stellar disk that ends up dominating over the older CRD. Finally, CR-3 is mainly associated with the simultaneous accretion of significant satellites that contributed with both stars and gas in counterrotating orbits. The accretion of counterrotating gas that gives rise to some of these CRDs will be studied in detail in a follow-up article.

6. Discussion

Our study, based on fully cosmological simulations, indicates that counterrotating stellar disks (CRDs) are rare but present in $\lesssim 10\%$ of MW-mass galaxies at $z = 0$. And only $\lesssim 1\%$ host an extended CRD. These CRDs contribute only a small fraction of their hosts' stellar mass (typically $\lesssim 2\%$) and tend to be spatially compact (confined well within the optical radius). A key result is that all but one of these CRDs are dominated by in-situ star formation, with the majority of stars in each counterrotating disk having formed within the galaxy's potential well rather than being accreted. This is true even in cases with a non-negligible ex-situ stellar contribution. In line with this, most CRDs have distinctly timed star formation episodes in their history – sharp bursts that coincide with some perturbation. This is in agreement with observations, where CRDs are a rare occurrence, encompassing only $\approx 1\%$ of galaxies with ionized gas in MaNGA (Bao et al. 2022, Bevacqua et al. 2022). Interestingly, we find that the simulated CRDs are older, on average, than their present-day corotating stellar disks. This is in contrast with observational studies, where they find that CRDs are mostly younger than the main stellar disk (Pizzella et al. 2014, Gasymov et al. 2025). We also find that, typically, galaxy models with CRDs have the gas and the younger stellar disk component (typically dominant) co-rotating with respect to each other. This is in agreement with observations of CRDs in late-type galaxies (Bao et al. 2022, Bao et al. 2024, Gasymov et al. 2025).

Our analysis reveals multiple formation channels for CRDs with varying degrees of external influence. The simulated galaxies exhibit a spectrum of CRD types, from significant merger-driven structures to more internal early star forming episodes. For example, one notable CRD involves an extended retrograde disk (CR-3) built primarily by the accretion of multiple satellite galaxies in quick succession. This event contributed with both stellar particles and a significant amount of gas mass in retrograde orbits, producing one of the most extended CRDs in the sample. There are other four extended in-situ CRDs which, despite having nearly all their counterrotating stars formed in-situ, can each be traced to at least one significant encounter that induced their formation. One of these cases is currently forming stars in its CRD as a result of the prolonged accretion of a satellite on a retrograde orbit. In contrast, the other three, older CRDs are remnants of a previous accretion of misaligned gas that gave rise to the currently dominant younger co-rotating stellar disk. Episodes of gas misalignment giving rise to a younger stellar disk has been observed in past studies (Pizzella et al. 2004; Vergani et al. 2007; Gasymov et al. 2025). Similarly, we identify compact ex-situ CRDs (eight cases); i.e., compact and retrograde disk components with a significant ex-situ contribution. In general, these ex-situ star particles are associated to one significant progenitor. The associated interactions often enhanced

in-situ star formation in the inner regions of the host (Barnes & Hernquist 1996, Tissera et al. 2002, Rupke et al. 2010, Bustamante et al. 2018), contributing to both the overall and the CR stellar distribution. Finally, the most common variety in TNG50 are compact in-situ CRDs. These 14 cases are diverse in origin: roughly half formed at very early times, coeval with the galaxy's initial bulge formation and without any clear external trigger. A few others in this category show evidence of accretion events that induced bursts of in-situ star formation within the central region, that contributed to both the co-rotating and counterrotating components of the final stellar disk.

Despite the variety of formation channels, the in-situ stars' dominance indicates that gas with a misaligned (retrograde) angular momentum was accreted into the galaxy's disk along its history. In some cases, this can be directly associated with interactions. Indeed, for the merger-induced CRDs, infalling satellites delivered not just stars but also fresh gas that was subsequently funneled into the host on retrograde orbits. In other cases, we find that misaligned gas accretion takes place after the present-day CRD formation, resulting in a younger stellar disk that ends up dominating over the older CRD. The mechanism behind such accretion will be further studied in a follow-up work.

In summary, nearly all (all but one) simulated CRDs are dominated by stars formed in-situ, even in systems shaped by mergers. Importantly, 'in-situ' here includes stars formed within the host from gas stripped or supplied by companions. Interactions often play a role in triggering or shaping the CRD. However, they are not strictly required in all cases. A small fraction of CRDs, especially compact ones, appear to arise naturally during the early phases of galaxy formation, without any recent accretion event. Thus, our results indicate that, although most counterrotating stellar disks are dominated by in-situ star formation, their emergence is frequently linked to external processes. Interactions and the accretion of misaligned gas are common triggers that supply the conditions for retrograde star formation.

7. Summary and conclusions

In this work we have identified and analyzed the formation mechanisms of counterrotating stellar disks in galaxies selected from the Illustris TNG50 simulation. The sample focused only on central MW-mass galaxies, ranging in mass from $10^{11.5}$ to $10^{12.5} M_{\odot}$. We characterized these counterrotating components by selecting particles with circularities < -0.7 and located within the spatial extension of the stellar disc. Within the sample of 260 MW-mass galaxies, we identified 26 cases with counterrotating stellar disk. Their CRDs contribute with, at least, 1 percent of the stellar mass of the galaxy. Our main results can be summarized as follows:

- **Statistics:** CRDs are rare. Only $\approx 10\%$ host a significant stellar counterrotating disk (CRD) when adopting a threshold of $M_{\text{CRD}}/M_{\text{Disk}} \geq 0.01$. CRDs represent a minor fraction of the overall stellar disk mass.
- **Structure:** CRDs are predominantly compact. Quantitatively, $\approx 88\%$ have $R_{50}^{\text{CRD}} < 0.25 R_{\text{opt}}$, and the distribution of sizes peaks at median $R_{95}^{\text{CRD}}/R_{\text{opt}} \sim 0.37$, although a minority are more extended; three systems display torus-like morphologies.
- **Stellar origin:** Nearly all CRDs are in-situ dominated. This definition includes stars formed inside the host from gas that may have been stripped from satellites. Ex-situ contributions are typically small ($\approx 73\%$ of CRDs have ex-situ < 0.2 ; median ex-situ fraction ≈ 0.06).

- **Star-formation histories and triggers:** CRDs are generally older than their co-rotating counterparts and exhibit bursty SFHs whose peaks frequently coincide with satellite pericenters or interactions. Thus, external perturbations often trigger star formation. These episodes may occur in retrograde or prograde orbits, which are subsequently transformed into a CRD through the later accretion of cold gas, giving rise to the present-day disk.
- **Formation channels:** Compact in-situ CRDs arise through multiple pathways: (i) early formation alongside bulge assembly; (ii) interaction-induced in-situ bursts; and (iii) rarer cases linked to smooth misaligned gas accretion. Extended in-situ CRDs, although fewer, can usually be traced to interactions and late accretion of misaligned gas that gives rise to a younger dominant corotating stellar disk. Ex-situ rich cases typically originate from one dominant (occasionally two) progenitor(s); these mergers often coincide with enhanced in-situ star formation in retrograde orbits.

In a follow-up work we will characterize the mechanism that drives the late accretion of misaligned cold gas, giving rise to preferentially extended CRDs. We will also explore whether the identification of compact in-situ CRDs can be achieved through the characterization of the stellar population abundances.

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Appendix A: Spatial distribution of components for galaxies hosting a significant CRD.

Figures A.1 and A.2 show the face-on and edge-on projections of the stellar mass surface density for the 26 significant CRD galaxies.

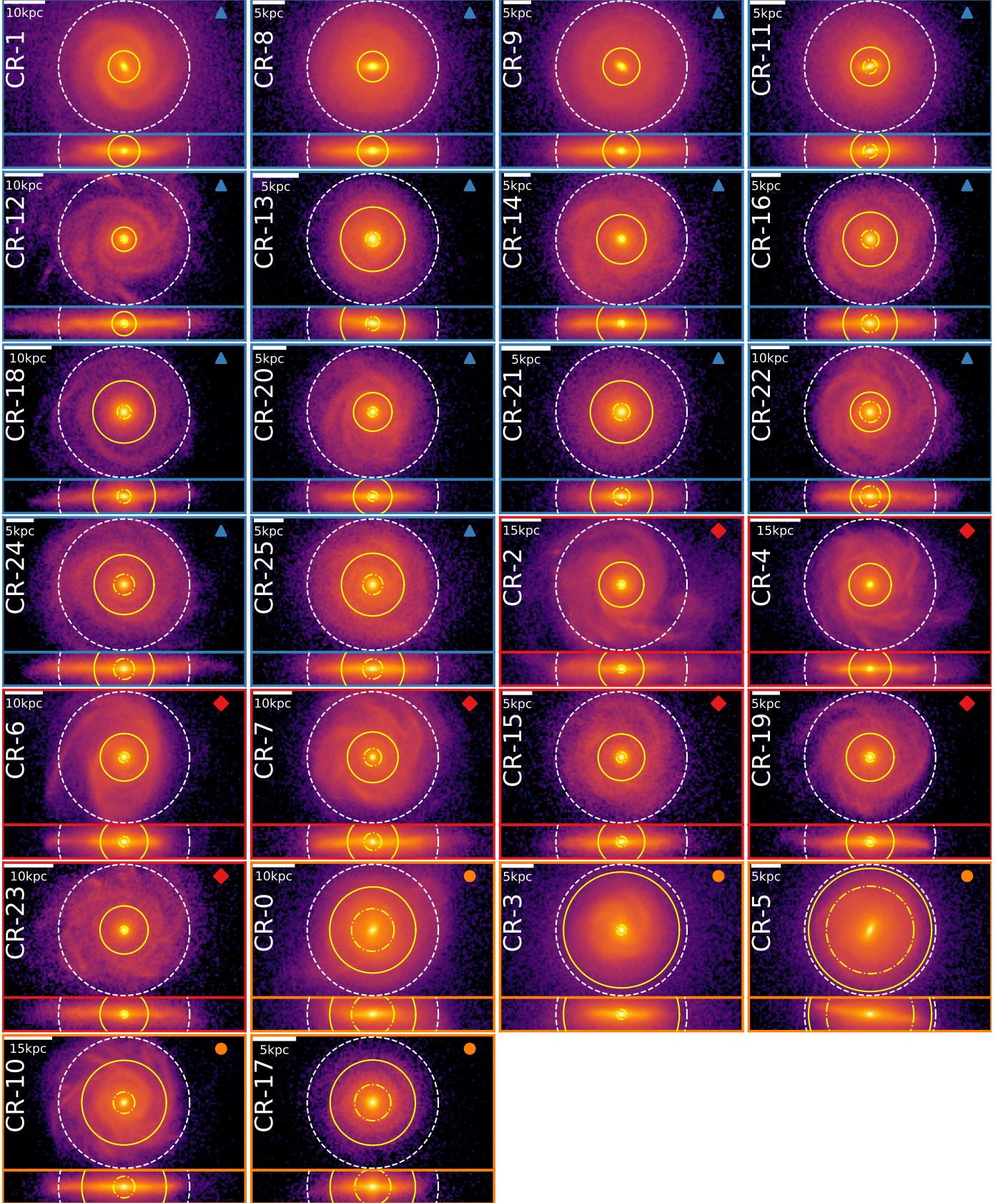


Fig. A.1. The face-on and edge-on projections of the stellar mass surface density for the 26 significant CRD galaxies. The galaxies are sorted as in figure 7. Here, we show all the stellar particles that belong to the host galaxy. The yellow solid and dotted-dashed circle represent the radii, R_{95}^{CRD} and R_{50}^{CRD} , of the counterrotating disk, respectively, while the white dashed circle represents the optical radius, R_{opt} , of the galaxy. In the top right corner of each panel the type is shown which are, Extended exsitu CRDs, Compact exsitu CRDs, Compact insitu CRDs, Extended insitu CRDs which are represented as yellow star, red rombus, blue triangles, and orange circles respectively.

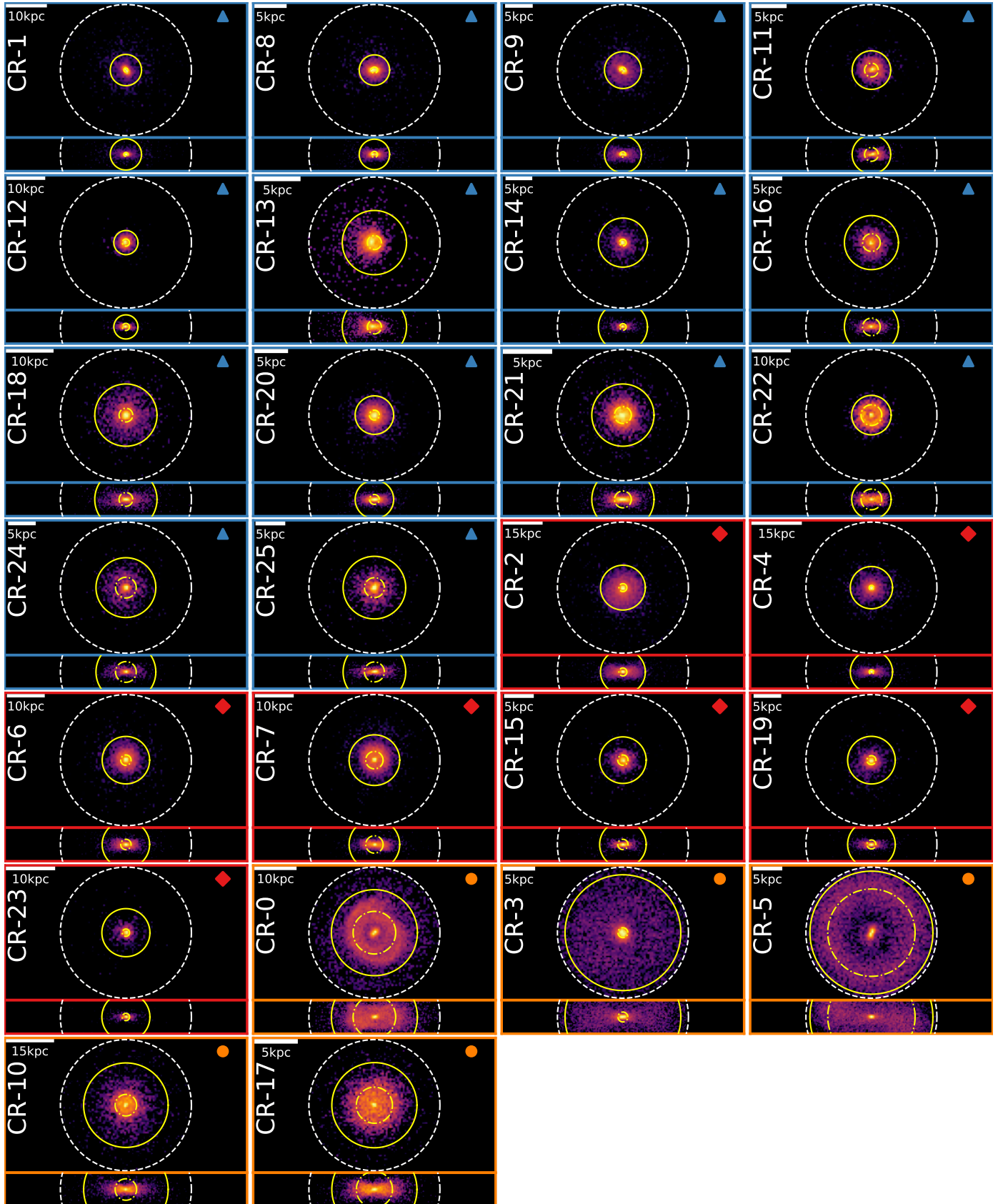


Fig. A.2. As in A.1 but for only counterrotating stellar disk particles, as described in Section 2.3