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Dark Matter Halos of Disk-like Galaxies at $z \sim 1$

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Abstract. In the concordance cosmological scenario, the cold collisionless dark matter component dominates the mass budget of galaxies and interacts with baryons only via gravity. However, there is growing evidence that dark matter responds to baryonic processes by modifying its density distribution, which can be captured by comparing the inner dynamics of galaxies across cosmic time. We present a pilot study of dynamical mass modeling of high redshift galaxy rotation curves, which is capable of constraining the structure of dark matter halos across cosmic time.

Key words. galaxies: galaxy evolution – Halos: galaxy halos – Cosmology: dark matter

1. Introduction

The structure of dark matter halos and their evolution through cosmic time is one of the most intriguing open questions of modern astrophysics and cosmology, especially as it could unveil the fundamental nature of dark matter. Cosmological hydrodynamical simulations (e.g., Schaye et al. 2015; Pillepich et al. 2018) assuming the Lambda Cold Dark Matter (ΛCDM) model of structure formation are remarkably able to reproduce various non-trivial observables, such as galaxy morphology and scaling relations, that relate the interplay between dark and luminous matter (e.g., Vogelsberger et al. 2020). Moreover, recent results of these simulations predict that baryonic feedback processes could impact the dark matter distribution over a few Giga years (e.g., Pontzen & Governato 2012; Pontzen & Governato 2014). However, due to the lack of high-resolution data at high-redshift, until recently, it was not possible to test simulations in this regard at a high-redshift Universe. Thanks to the development of new generation integral field spectrographs (e.g., Eisenhauer et al. 2003; Bacon et al. 2010; Sharples 2014), it is now possible to observe and resolve distant galaxies. That is, now, we can peer into the heart of distant galaxies and study the fundamental physical processes that govern their evolution, thus helping us to solve some of the biggest mysteries of the Universe such as the nature of dark matter (see, Price et al. 2021; Sharma et al. 2022).

We have recently analyzed star-forming galaxies of the KMOS Redshift One Spectroscopic Survey (KROSS Stott et al. 2016), in particular disk-like systems. We investigated the shape of their velocity profiles (Sharma et al. 2021a), their dark matter fraction (Sharma et al. 2021b), and the shape of their dark matter halos (Sharma et al. 2022). We presented the aforementioned studies at EAS2022, and we review them here. Section 2 discusses the velocity profiles, shows the dark matter fraction, and compares it with state-of-the-art simulations. In section 3, we present the observational evidence of evolving dark matter halos and provide a possible theoretical interpretation. Lastly, section 4 provides the conclusions.

2. Dark Matter Fraction

In Sharma et al. (2022), we investigated the shape of 256 rotation curves employing beam smearing and pressure support correction, which yielded flat rotation curves till the last point of observations. We co-added these rotation curves in five velocity bins and compared them with their local counterparts. We noticed that velocity profiles, i.e., rotation curves, of disk-like galaxies at $z \approx 0$ and $z \sim 1$ are statistically the same. This information allowed us to investigate the dark matter content of these galaxies, by computing the dark matter fraction ($f_{\rm DM}$) of individual and co-added galaxies. We notably estimated the $f_{\rm DM}$ (1) through a halo-model independent approach and (2) through a halo-model dependent approach.

In the halo-model independent approach, we estimated the total mass of stars and gas using SED-fitting and scaling relations, respectively. Assuming that stars and gas follow a Sérsic profile (see Sharma et al. 2021b for details), we estimated their masses within a scale radius. Then, the dark matter fraction was computed as:

$$f_{{\rm DM}(<R)} = 1 - \frac{M_{bar}(< R)}{M_{dyn}(< R)} \quad (1)$$

where M_{bar} is the baryonic mass (stars and gas) and M_{dyn} the dynamical mass estimated directly from the rotation curves. Note that we accounted for stars in the bulge component; see Sharma et al. (2021b) for details. In Figure 1a and Figure 1b, we show the resulting $f_{\rm DM}$ for individual and co-added rotation curves, within R_{out}[1] and R_e[2], respectively. We notice that the majority of star-forming galaxies in our sample have dark-matter dominated outer disks ($\sim 5-10$ kpc), which is in agreement with local disk galaxies (Persic et al. 1996; Martinsson et al. 2013). At $z \sim 1$, only a small fraction ($\sim 5\%$) of our sample has low ($< 20\%$) dark matter fraction within R_{out} and R_e. We find a large scatter in the fraction of dark matter at a given stellar mass (or circular velocity) with respect to local star-forming galaxies, suggesting that galaxies at $z \sim 1$ span a wide range of stages in the formation of their stellar discs (e.g., see Puech et al. 2010; Kassin et al. 2012; Simons et al. 2016) which may lead to diverse dark matter halo properties that are coupled with baryons. Our results agree with previous high-redshift studies (e.g., Genzel et al. 2017; Genzel et al. 2020) in the range between $9.0 \le \log(M_*) \le 10.6$ and $z \sim 1$, the rest of their sample being biased towards more massive galaxies than the intermediate-mass galaxies of our sample.

In the halo-model dependent approach, we dynamically mass modelled the individual and co-added rotation curves and disentangled the baryonic and dark matter components. Here, we discuss only co-added rotation curves, for which we have used a Freeman (1970) disc to model stars and gas components. Since the bulge is unresolved in the data, it was considered a point mass. The dark matter halo was modelled using two halo profiles: the cuspy NFW (Navarro et al. 1997) and the cored Burkert (Burkert 1995) profile, which can be characterized by an inner density and a radius ($\rho^{\rm inner}_{s/0}$, $r^{\rm inner}_{s/0}$). For details about the dynamical

[1] R_{out} is the scale radius, namely $2.95\times R_e$.

[2] R_e is the half-light radius of the galaxy, estimated using high-resolution HST images.

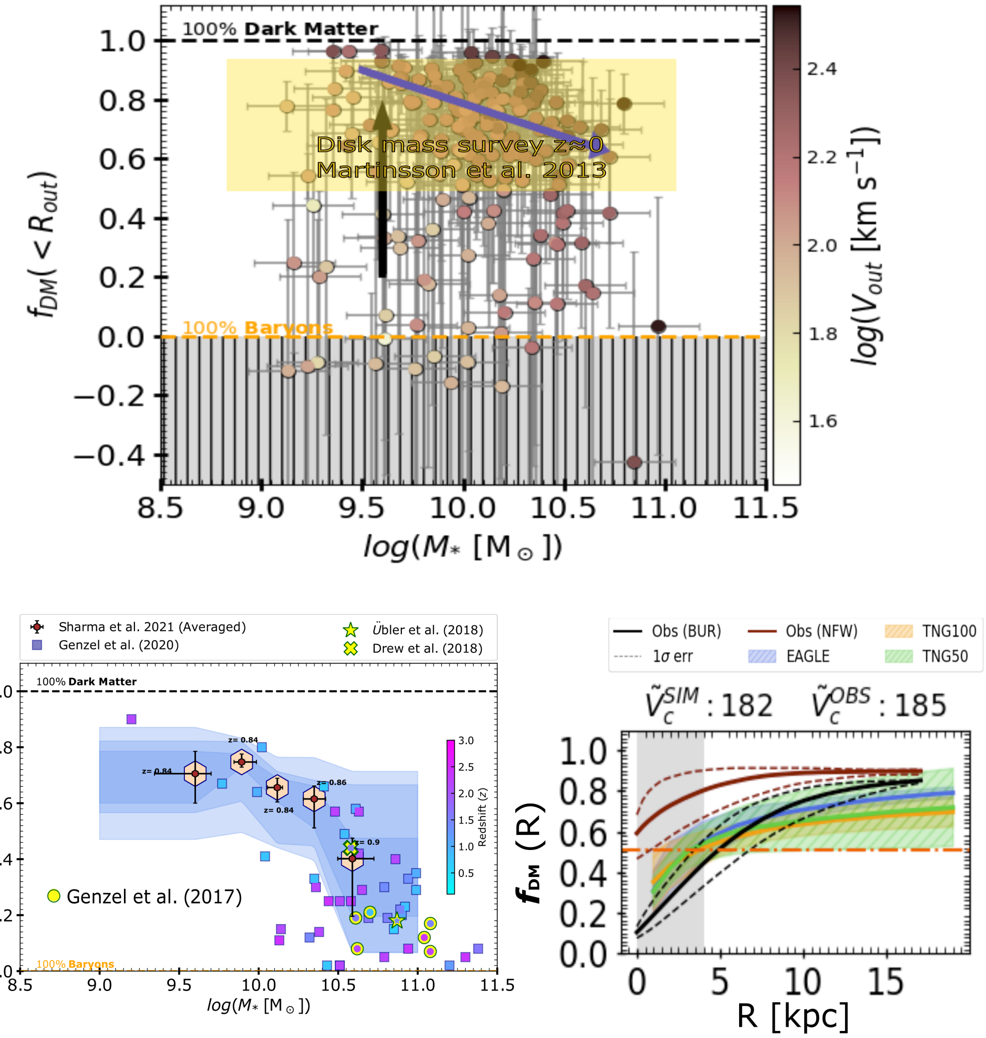

Fig. 1. Dark matter fraction ($f_{\rm DM}$) of star-forming disk-like galaxies at $z \sim 1$. *Upper panel:* Halo model independent $f_{\rm DM}$ of individual galaxies. Each data point is colour-coded with the circular velocity of the galaxy. The grey-shaded area represents the forbidden region. *Lower panel:* In left, Halo-model independent $f_{\rm DM}$ of co-added galaxies. The colour code of each data point is given in the legend. In right, Halo-model dependent $f_{\rm DM}$ of co-added galaxies lying between $182 \le V_c \le 185$km/s velocity bin. The colour codes are given in the legend, and a full figure can be found in Sharma et al. (2022).

modelling, see Sharma et al. (2022). In this case, we estimated the dark matter fraction as:

$$f_{\rm DM(<R)} = \frac{V_{DM}^2(R)}{V_{tot}^2(R)}, \qquad (2)$$

where V_{DM} is the dark matter component of the velocity and V_{tot} is the total rotation velocity, i.e., the best-fit rotation curve. In Figure 1c, we show an example of the resolved $f_{\rm DM}$ in the velocity bin ∼185 km/s, for both halo models (Burkert: black; NFW: brown). We also compare the results with state-of-the-art simulations (EAGLE: blue; TNG100: green; and TNG50: orange). We notice that $f_{\rm DM}$ estimated using the Burkert halo model is consistent with the simulations, from the inner region to the outskirts. In comparison, the NFW halo overestimates the dark matter fraction, especially in the inner region. This analysis suggests that dark matter dominates the $z \sim 1$ galaxies from the inner region to the outskirts and, most importantly, that dark matter halos of disk-like galaxies appear to be cored at $z \sim 1$.

3. Dark Matter Halos

As indicated in Section 2, dark matter halos of disk-like galaxies at $z \sim 1$ are consistent with being cored. This information allows us to investigate their structural properties, such as their inner density and radius ($\rho_0^{\rm inner}$, $r_0^{\rm inner}$ respectively). In Figure 2, we show these two quantities as a function of the circular velocity and compare this relationship with local disk galaxies. We notice that dark matter cores at $z \sim 1$ are, on average, three times smaller and an order of magnitude denser than their local counterparts, which suggests an expansion of the dark matter halos over 6.5 Gyrs. We also notice that the structural properties of the halo are strongly correlated with the circular velocity of galaxies, which could be due to angular momentum exchange between dark matter halo and baryonic matter at the time of galaxy formation. In other words, it reflects an interplay between dark and luminous matter, which can be interpreted theoretically.

In particular, the expansion of the inner region of dark matter halos could be due to baryonic feedback process, such as stellar winds, supernova explosions and active galactic nuclei (AGN), the latter being expected to play a role when $M_\star \geq 10^{10}$ $M_\odot$ (Juneau et al. 2013; Kocevski et al. 2017; Lapiner et al. 2021, 2023). These different processes not only regulate star formation, but also induce powerful gas ouflows and mass fluctuations that affect the gravitational potential and thereby dark matter particles (Pontzen & Governato 2012; Pontzen & Governato 2014). On one hand, small gas density fluctuations induced by stellar winds and supernova explosions in the interstellar medium can cumulatively heat up dark matter particles, as in a diffusion process, and lead to the formation of a core (El-Zant et al. 2016; Hashim et al. 2022). On the other hand, bulk outflows from stellar feedback episodes or AGNs can lead halos to expand as they relax to their new equilibrium after the sudden change in gravitational potential (Peirani et al. 2017; Freundlich et al. 2020b; Li et al. 2023). These processes can further act in concert with dynamical friction, which can also dynamically heat up dark matter halos and contribute to core formation (El-Zant et al. 2001; Dekel et al. 2021).

Both our observations and these theoretical arguments corroborated by hydrodynamical simulations (e.g. Pontzen & Governato 2012; Peirani et al. 2017; Freundlich et al. 2020a; Hashim et al. 2022) suggest that dark matter halos may be initially cuspy, as arising from dark-matter-only simulations, and evolve into cores throughout cosmic time due to baryonic feedback processes. It is however still necessary to quantify the strength of the feedback processes, their relative importance, the associated time scales, and the importance of other phenomena, such as mergers, in the formation of dark matter halo cores over the last 6.5 Gyrs. We also note that the observed shape of dark matter halos may also result from the nature of dark matter itself, e.g. self-interacting or fuzzy dark matter, or even modified gravity rather than baryonic processes within the ΛCDM paradigm.

4. Conclusions

We presented an observational study of disk-like galaxies at $z \sim 1$. In particular, we estimated their dark matter fraction and investigated the structural properties of their dark matter halos compared to local star-forming galaxies. We dynamically mass modelled these galaxies to disentangle their baryonic and dark matter components, and noticed that star-forming galaxies at $z \sim 1$ are dark matter dominated till the last point of observation, typically $R \sim 1 - 3 \times R_e$. This dynamical mod-

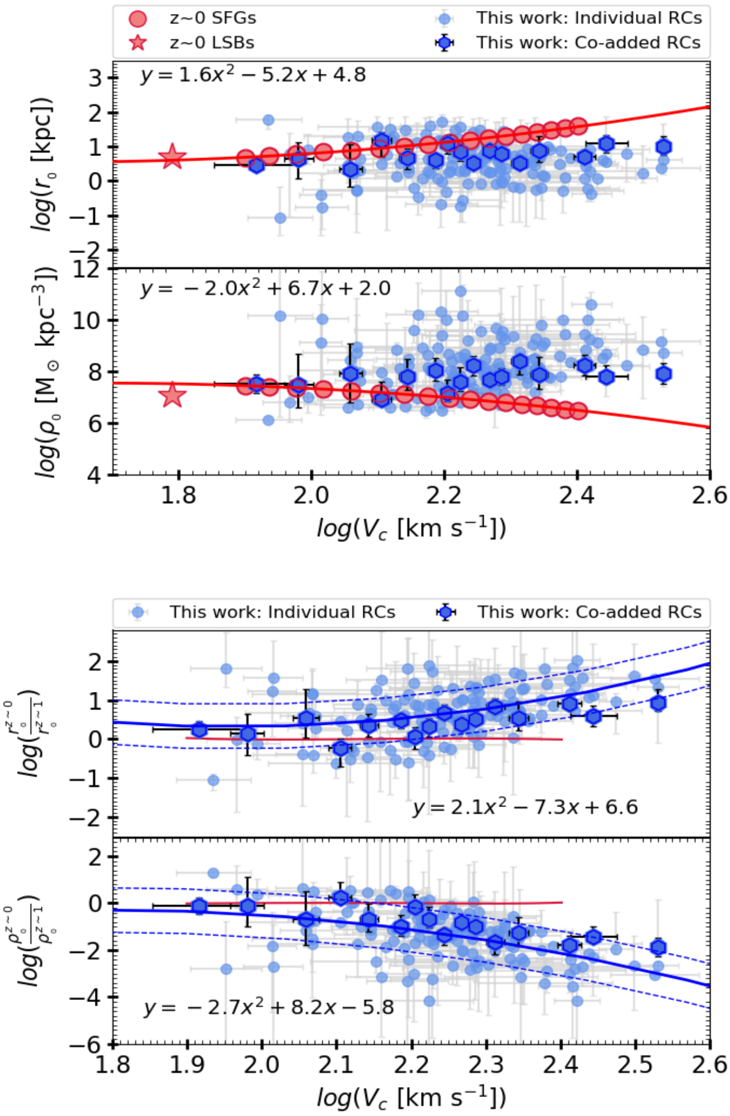

Fig. 2. Structural properties of dark matter halos at $z \sim 1$. *Upper panel:* dark matter core radius and core density as a function of the circular velocity in the upper and lower panels, respectively. The colour codes are given in the legend of the plot. A comparison sample of local SFGs (Persic et al. 1996) is represented by the coral red circles. The best-fit line of the local SFGs is shown in red, and its polynomial equation is printed in the upper left corner of each panel. *Lower panel:* Ratio of dark matter core radius and density at $z \approx 0$ to $z \sim 1$ as a function of the circular velocity. This plot shows the expansion factor of dark matter cores at $z \sim 1$ with respect to local SFGs. The colour codes for data points are similar to those in the left panel. The solid blue line is the best-fit second-order polynomial function, whose expression is printed on both panels. The dashed blue lines show the 1σ intrinsic scatter in the relations.

elling suggested that star-forming galaxies at $z \sim 1$ have constant inner dark matter density cores, as also seen in local star-forming galaxies. The data allowed us to compare the size and density of $z \sim 1$ dark matter halos with their local counterparts: dark matter cores at $z \sim 1$ appear to be, on average, three times smaller and an order of magnitude denser than their local counterparts. In other words, there seems to be an expansion of dark matter halos over cosmic time, which could be due to dark matter response to baryonic feedback processes (e.g., stellar winds, supernova explosions, AGNs) over a few Gyrs. These observational finding may have strong implications for cross-checking simulations and galaxy evolution models, as well as for determining the nature of dark matter.

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