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Observational Evidence of Evolving Dark Matter Profiles at $z \leq 1$

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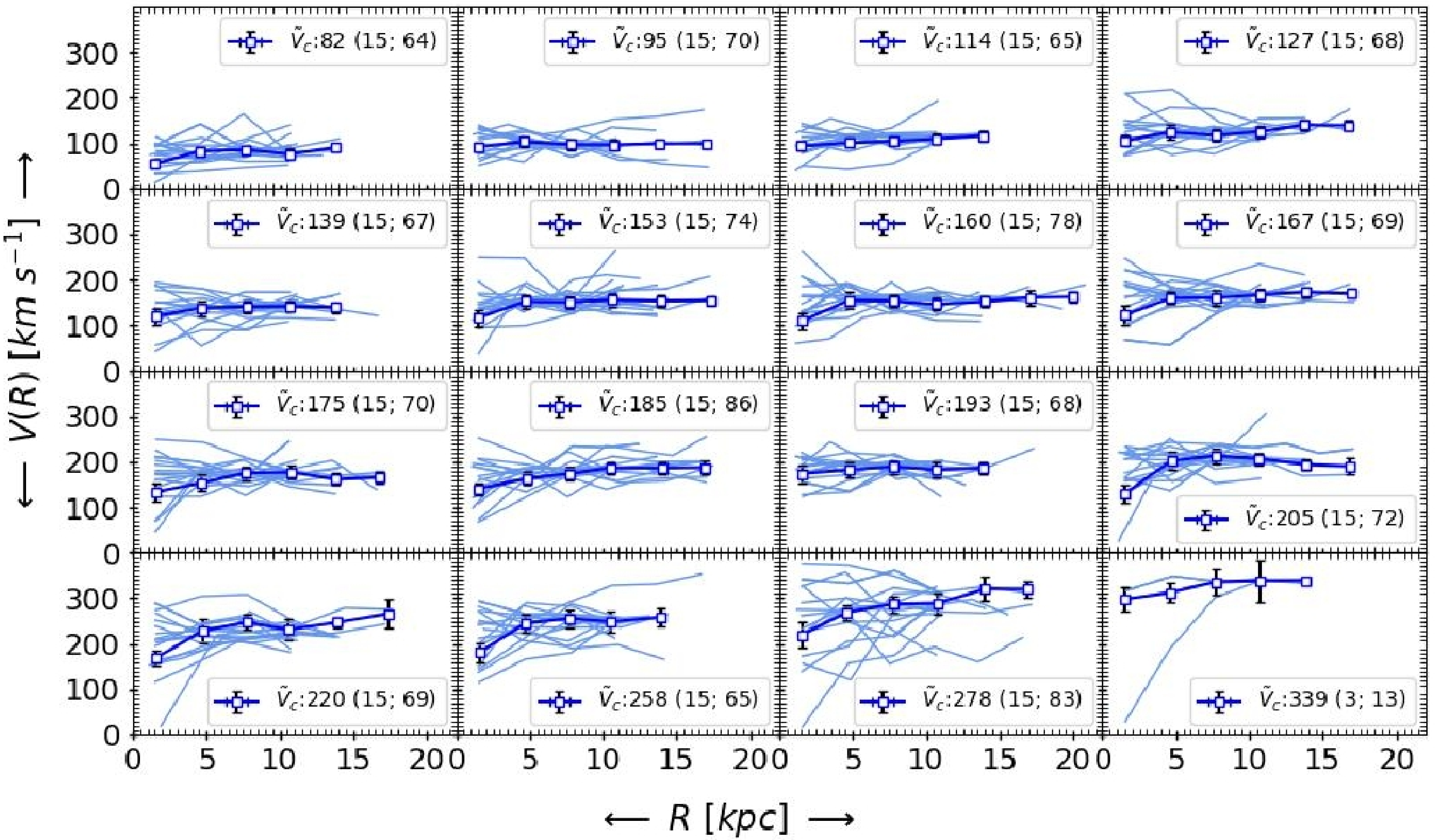
ABSTRACT

Context. 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 the former, instead, responds to the baryonic (feedback) processes by modifying its density distribution. These processes can be captured by comparing the inner dynamics of galaxies across the cosmic-time.
Aims. A pilot study of dynamical mass modelling of high redshift galaxy rotation curves, which is capable of constraining the structure of dark matter halos across cosmic time.
Methods. We investigate the dark matter halos of 256 star-forming disc-like galaxies at $z \sim 1$ using the KMOS redshift one spectroscopic survey (KROSS). This sample covers the redshifts $0.6 \leq z \leq 1.04$, effective radii $0.69 \leq R_e[\mathrm{kpc}] \leq 7.76$, and total stellar masses $8.7 \leq log(M_{\mathrm{star}}\ [\mathrm{M}_\odot]) \leq 11.32$. We present a mass modelling approach to study the rotation curves of these galaxies, which allow us to dynamically calculate the physical properties associated with the baryons and the dark matter halo. For the former we assume a Freeman disc, while for the latter we employ the NFW and the Burkert halo profiles, separately. At the end, we compare the results of both cases with state-of-the-art cosmological galaxy simulations (EAGLE, TNG100 and TNG50).
Results. We find that the *cored* dark matter halo emerged as the dominant quantity from a radius 1-3 times the effective radius. Its fraction to the total mass is in good agreement with the outcome of hydrodynamical galaxy simulations. Remarkably, we found that the dark matter core of $z \sim 1$ star-forming galaxies are smaller and denser than their local counterparts.

KROSS/VLT: 256 галактик



Приложили 3D-Barolo к кубам

Подгоняли кривые вращения суммой барионного вещества и темного гало (2 вида)

Here, we assume that the distribution of stars and gas in $z \sim 1$ star-forming disc galaxies are also in exponential discs, so that the surface densities:

$$\Sigma\_(R) \propto \frac{M\_}{R_{scale}} \exp(-R/R_{scale}), \quad (2)$$

where, $M\_$ and R_{scale} are the total mass and the scale length of the different components (stars, H2, HI), respectively. Note that stellar mass in the disc (without bulge) is denoted by $M_{\rm D}$, while the contribution of the total stellar mass is represented by $M_{\rm star} = M_{\rm D} + M_{\rm bulge}$. Given the density distribution of the stars and the gas, their contribution to the circular velocity of the disc can be expressed as follows:

$$V\_^2(R) = \frac{1}{2}\left(\frac{GM\_}{R_{scale}}\right)(x^2)\,[I_0K_0 - I_1K_1], \quad (3)$$

where, $x = R/R_{scale}$ and I_n and K_n are modified Bessel functions computed at $1.6x$ for stars and $0.53x$ for gas (c.f. Persic et al. 1996; Karukes & Salucci 2017).

Burkert Halo: Local spirals and low surface brightness galaxies indicate towards the existence of central DM *cores*, i.e. $\rho_{inner} \propto const$ (Salucci & Burkert 2000; de Blok et al. 2001). This observed DM-profile is well fitted by the Burkert (1995) halo, which possesses a double power law in the DM-density, i.e., at small radii $\rho \propto R^0$ and at larger radii $\rho \propto R^{-3}$. Such a DM-density distribution can be expressed as:

$$\rho(R) = \frac{\rho_0}{\left(1 + \frac{R}{r_0}\right)\left(1 + \frac{R^2}{r_0^2}\right)}, \quad (5)$$

where ρ_0 and r_0 are the central DM core density and core radius, respectively. Assuming spherical symmetry, the mass profile of Burkert DM halo follows as:

$$M_{\rm DM}^{\rm Burk}(R) = 4\pi\rho_0 r_0^3\left[\ln\left(1+\frac{R}{r_0}\right) - \arctan\left(\frac{R}{r_0}\right) + 0.5\,\ln\left(1+\frac{R^2}{r_0^2}\right)\right], \quad (6)$$

NFW Halo: In the standard collisionless cold dark matter paradigm, the current cosmological simulations predict a *cuspy* DM distribution in the center, i.e., $\rho_{inner} \propto R^{-1}$. This type of DM profile is well approximated by NFW halo, which is again a double power law but it has $\rho \propto R^{-1}$ at small radii and $\rho \propto R^{-3}$ at larger radii. Such a DM-density distribution can be expressed as:

$$\rho(R) = \frac{\rho_s}{\left(\frac{R}{r_s}\right)\left(1 + \frac{R}{r_s}\right)^2} \quad (7)$$

where ρ_s and r_s are, respectively, the characteristic density and scale radius of the DM distribution. Assuming spherical symmetry, the mass profile of NFW DM halo follows as:

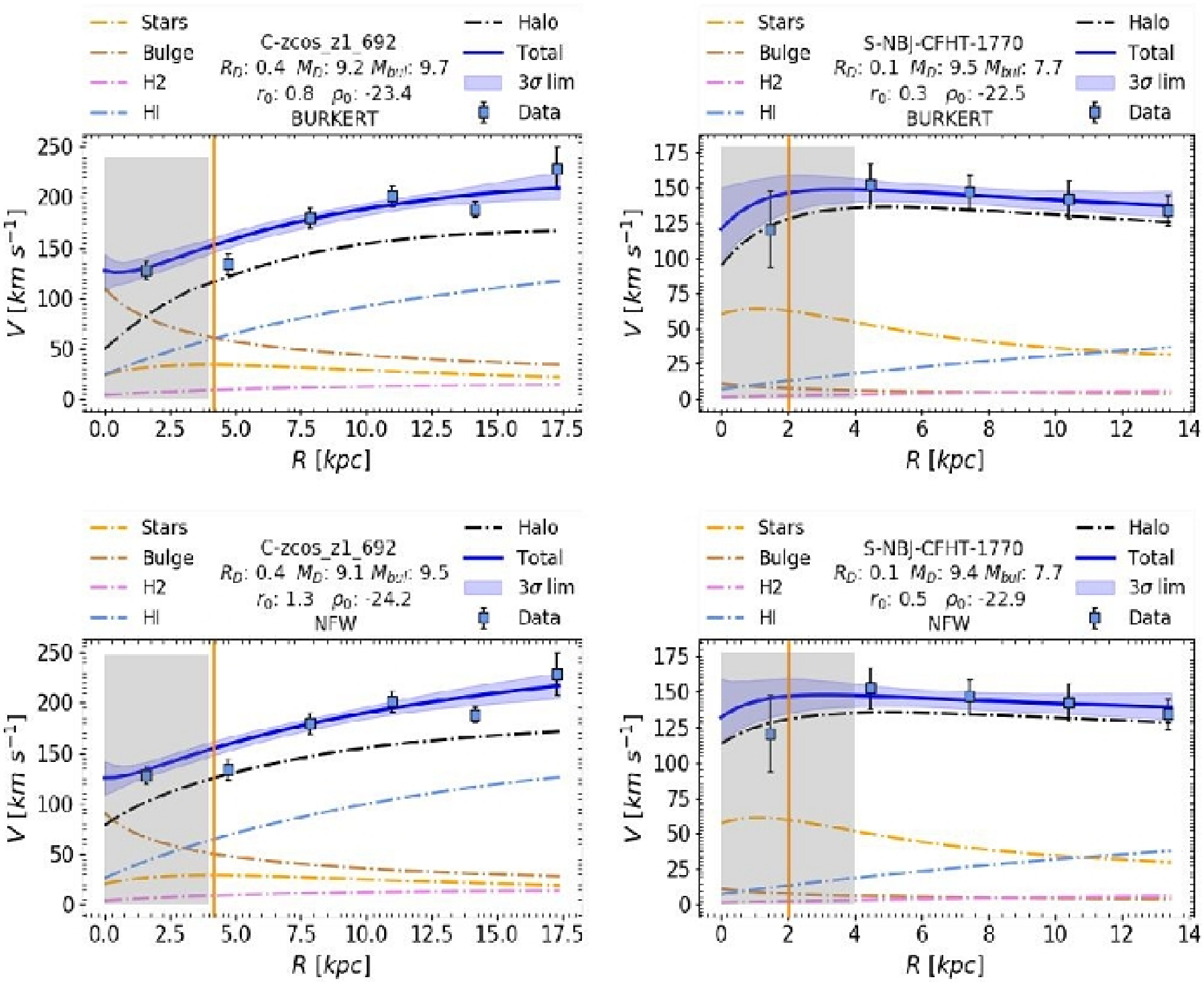
$$M_{\rm DM}^{\rm NFW}(R) = 4\pi\rho_s r_s^3\left[\ln\left(1 + \frac{R}{r_s}\right) - \frac{\frac{R}{r_s}}{1 + \frac{R}{r_s}}\right], \quad (8)$$

Модель с 5-тью свободными параметрами

Parameter Range (log scale, Units)	**Case-1 (Individual RCs)** Prior: central value, σ (dex)	**Case-2 (Co-added RCs)** Prior: central value, σ (dex)
$8.0 \leq \log(M_{\rm D}\ [{\rm M_\odot}]) \leq 12.5$	Gaussian Prior: $0.9M_{\rm star}$, $\sigma_{M_{\rm star}}$	Gaussian Prior: $0.9\tilde{M}_{\rm star}$, $\sigma_{\tilde{M}_{\rm star}}$
$-1.7 \leq \log(R_{\rm D}\ [{\rm kpc}]) \leq 1.7$	Gaussian Prior: R_D, σ_{R_D}	Gaussian Prior: $\tilde{R}_D$, $\sigma_{\tilde{R}_D}$
$5.0 \leq \log(M_{\rm bulge}\ [{\rm M_\odot}]) \leq 11.5$	Gaussian Prior: $0.1M_{\rm star}$, $\sigma_{M_{\rm star}}$	Flat Prior
$-2.0 \leq \log(r_{0/s}\ [{\rm kpc}]) \leq 2.0$	Flat Prior	Flat Prior
$-26 < \log(\rho_{0/s}\ [{\rm gm\ cm^{-3}}]) < -18$	Flat Prior	Flat Prior

Table 1. Mass modelling parameter range and their prior details. Note that Gaussian prior keep true photometric uncertainty (or dispersion σ) around the central value, where central values are computed from the high-resolution photometric data (see Harrison et al. 2017; Sharma et al. 2021a). In case of co-added RCs, quantities are represented by tilde over-head (e.g. $\tilde{R}_D$).

Примеры подгонки индивидуальных кривых



Примеры подгонки сложенных кривых вращения (бины по массе)

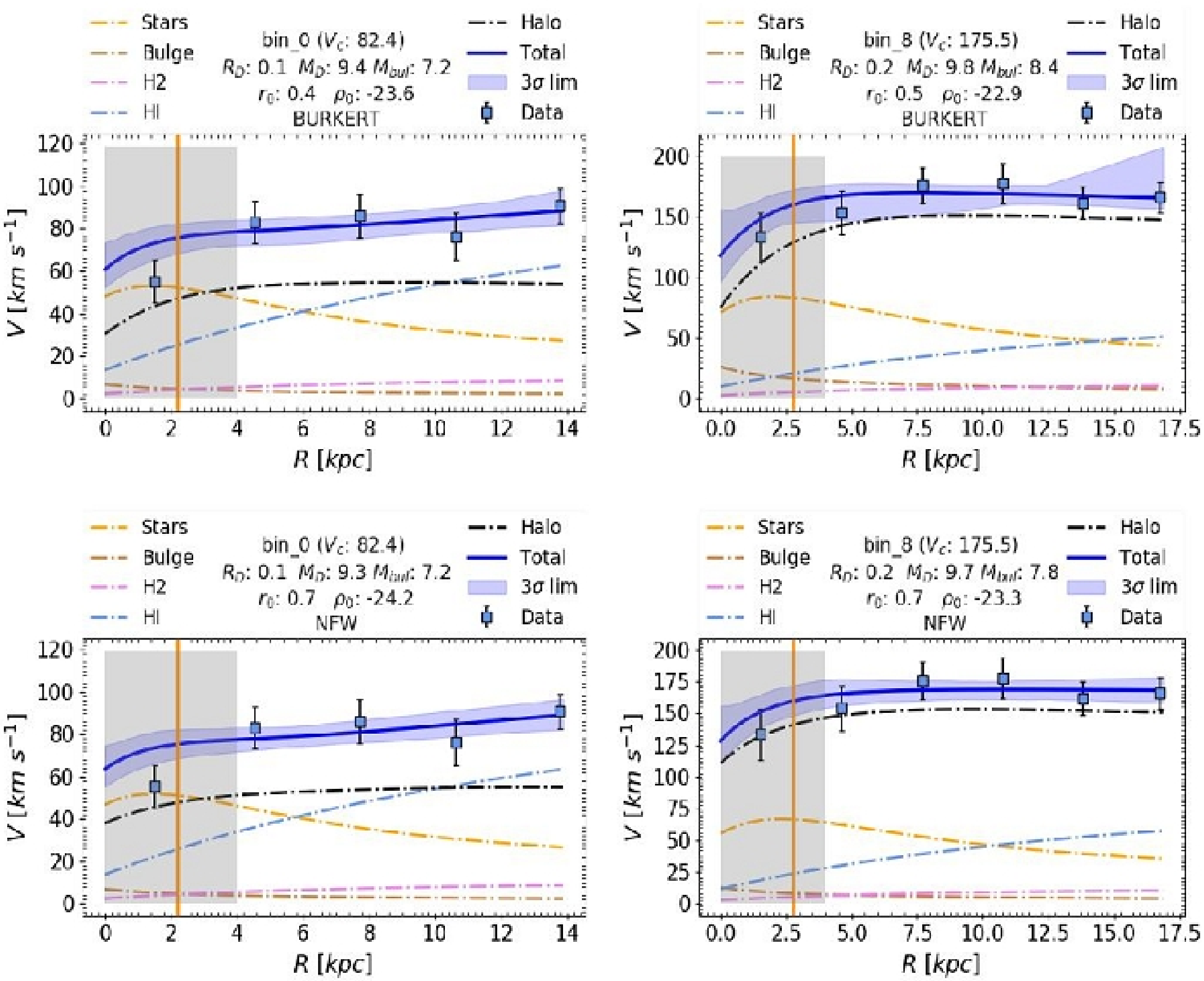


Fig. 3. Co-added RC mass modelling. *Row-1:* Posterior distributions (MCMC output) of the estimated parameters: $r_{0/s}$, $\rho_{0/s}$ and M_{bulge}, for Burkert

Почему гало Буркерта лучше гало Наварро-Френк-Вайта

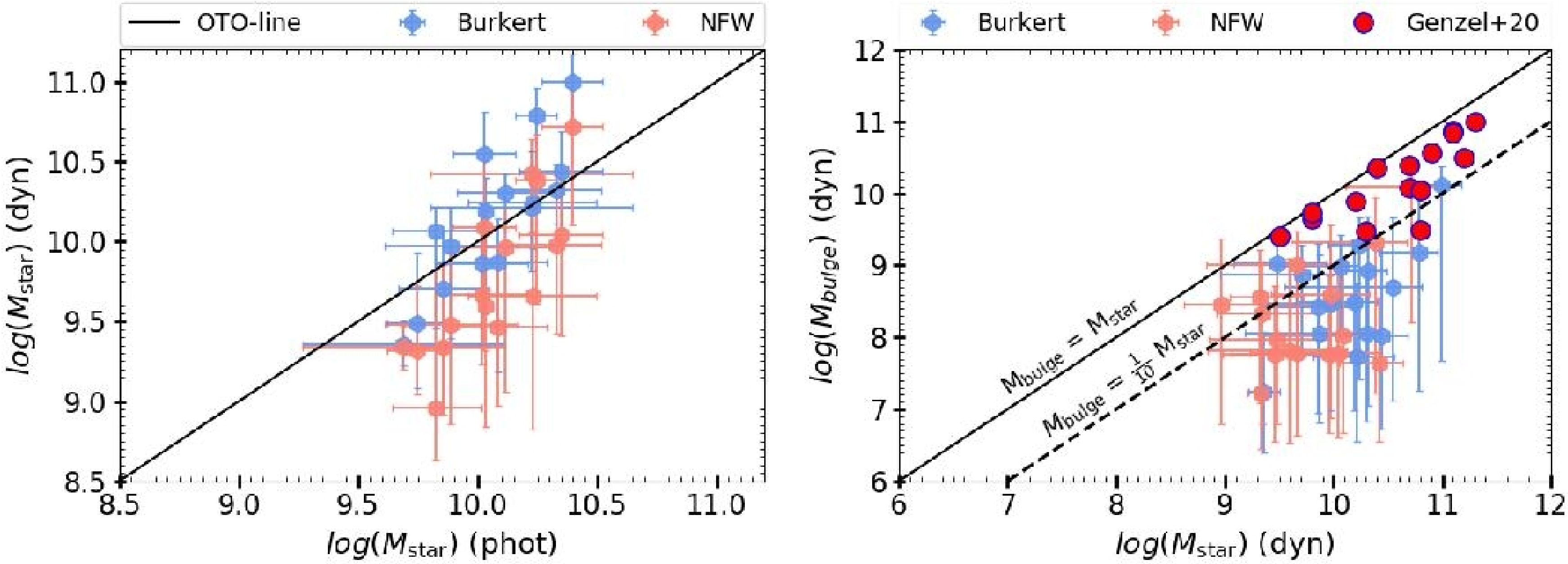


Fig. 4. *Left panel:* Comparison of the photometric and dynamical stellar masses in Burkert (blue) and NFW (pink) halo profiles for co-added RCs. The black solid line shows the one-to-one relations. We note that the dynamical stellar masses obtained in the possession of the Burkert halo agree very well with the photometric stellar masses. In contrast, the dynamical stellar masses obtained with the NFW halo are lower than the photometric stellar masses by a factor of 0.5. *Right panel:* Dynamically derived bulge masses versus stellar masses, in the case of Burkert (blue) and NFW (pink) halo profiles for co-added RCs. We compare our results with a pioneering study in this field: Genzel et al. (2020, : red filled circles), and we find that in our sample B/T is never higher than ~ 0.3, which is different from what is reported by Genzel et al. (2020) for the same redshift range ($z = 0.6 - 1.2$) and similar stellar mass sample.

Как ни странно, и с LCDM-симуляциями Буркерт сходится лучше

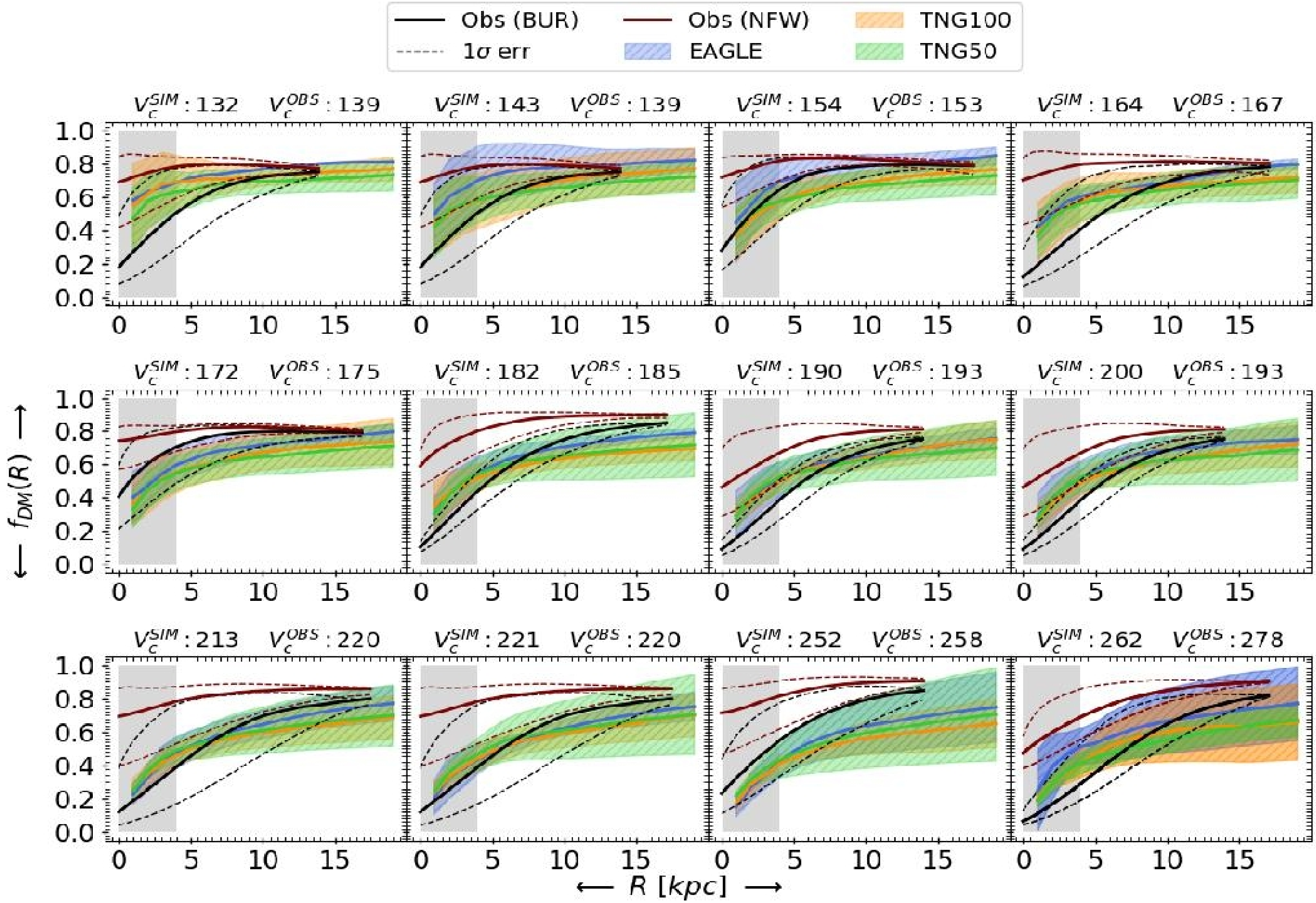


Fig. 8. Dark matter fraction as a function of radius in various velocity bins of observed and simulated galaxies. The central value of $f_{DM}(R)$ is

Результат: на z=1 гало компактнее и плотнее

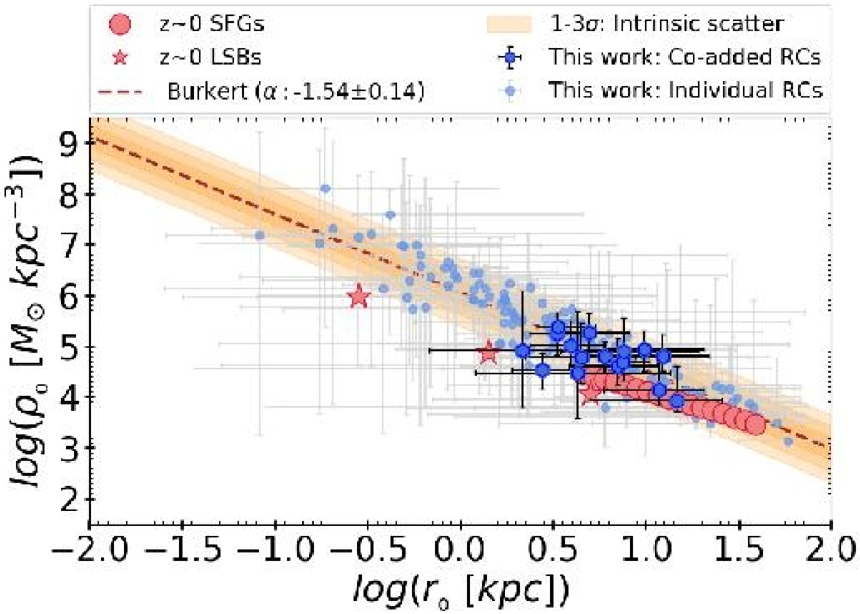
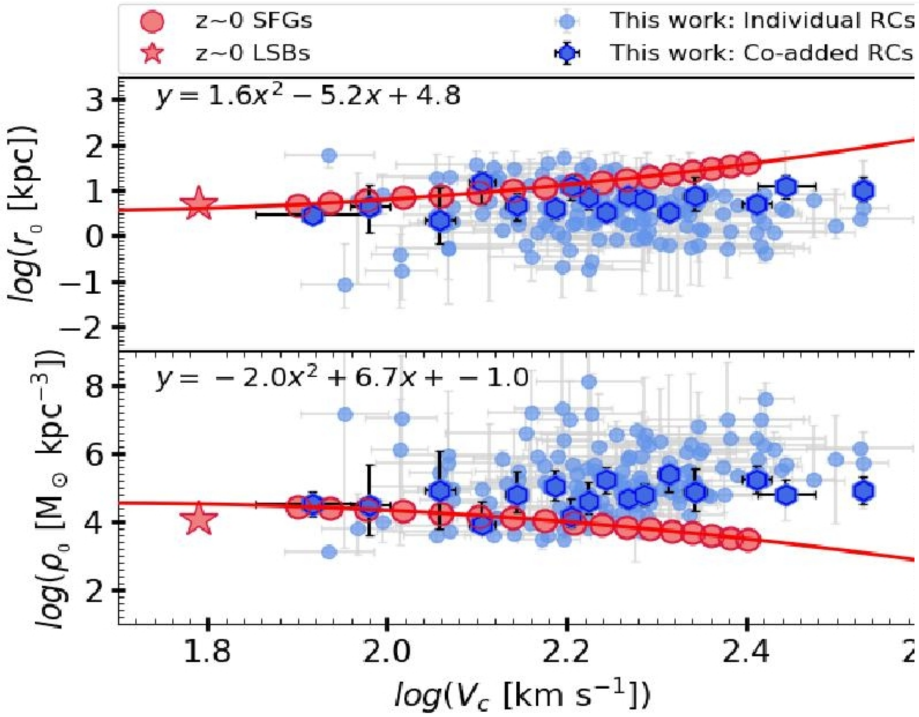
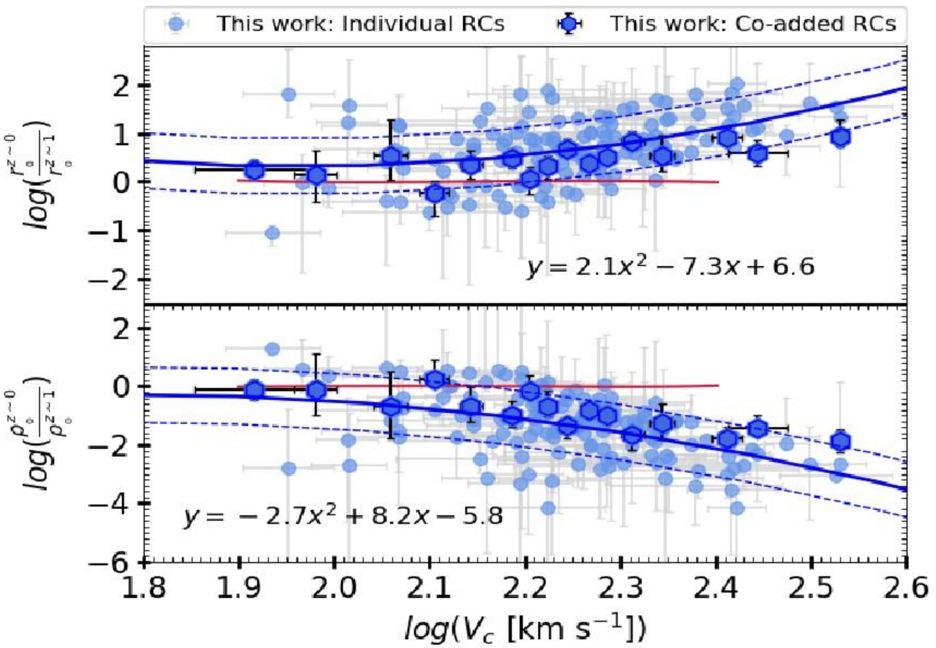


Fig. 7. DM core density vs. core radius relation of local and high-z galaxies. The blue circles and hexagons represent the $z \sim 1$ individual and co-added RCs, respectively. The coral circles and stars represent the local star-forming and low surface brightness galaxies (Persic et al. 1996; Di Paolo et al. 2019), respectively. The brown dashed line is the best fit $\rho_0 \propto r_0^{\alpha}$ to $z \sim 1$ data with slope $\alpha = -1.54$, and the orange shaded area represents the $1 - 3\sigma$ intrinsic scatter in the relation.

Эволюция сильнее в массивных галактиках





Идея:

- Вспоминая главную последовательность, можно предположить, что в массивных галактиках сильнее звездообразование, и наблюдаемая в последние 7 млрд лет эволюция параметров темных гало – это feedback от барионов (??)