Formation of early-type galaxies

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Introduction

Early-type galaxies (ETGs) are important tracers of the cosmic history of stellar mass assembly and galaxy evolution. Observational evidence suggests that the progenitors of ETGs underwent very rapid early formation, with the bulk of their stars forming in a short time-scale (Cowie et al. 1996; Thomas et al. 2005; Recchi et al. 2009; McDermid et al. 2015; Liu et al. 2016; Yan et al. 2021). However, the standard model of cosmology has not been able to reproduce ETGs with similarly short star-forming time-scales. This has led to the consideration of alternate theories of cosmology, such as based on the Milgromian dynamics (MOND), which corrects the theory of gravitation at low acceleration. In this poster, we compare the observational evidence for the rapid formation of ETGs and how MOND model galaxies reproduce the observed properties. MOND can provide insights into the formation of ETGs and improve our understanding of the Universe.

MOND

Milgrom proposed a modification to the theory of gravitation at low acceleration based on combining observational constraints on the dynamics in galaxies with constraints from the Solar system (Milgrom 1983a). This theory, called Modified Newtonian Dynamics (MOND), can be constructed by setting up a Lagrangian which yields a generalized Milgromian Poisson equation (Milgrom 2010). The Poisson equation includes a phantom dark matter density that is not real matter arising from the non-linearity of the equation, and a transition function characterizing the theory (Milgrom 2008, 2010, 2014; Famaey & McGaugh 2012; Banik & Zhao 2022). MOND predicts galaxy scaling relations such as the Baryonic Tully Fisher Relation (BTFR) and the Radial Acceleration Relation (RAR) (McGaugh et al. 2000; McGaugh 2005, 2012; Sanders 1990; Lelli et al. 2017).

Star-formation timescales and size

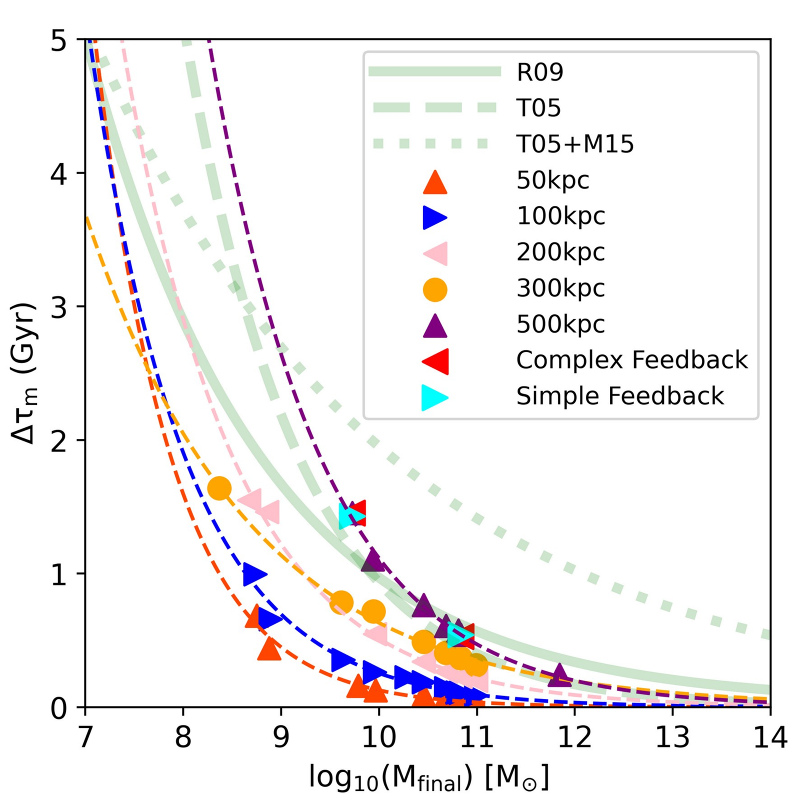

Figure 1. Eappen et al. (2022 their figure 3) shows the SFT-mass relation. The green curves are the observations and coloured markers are the model galaxies in this work. $\Delta\tau_m$ is the width of the star-formation history (SFH), i.e. the SFT.

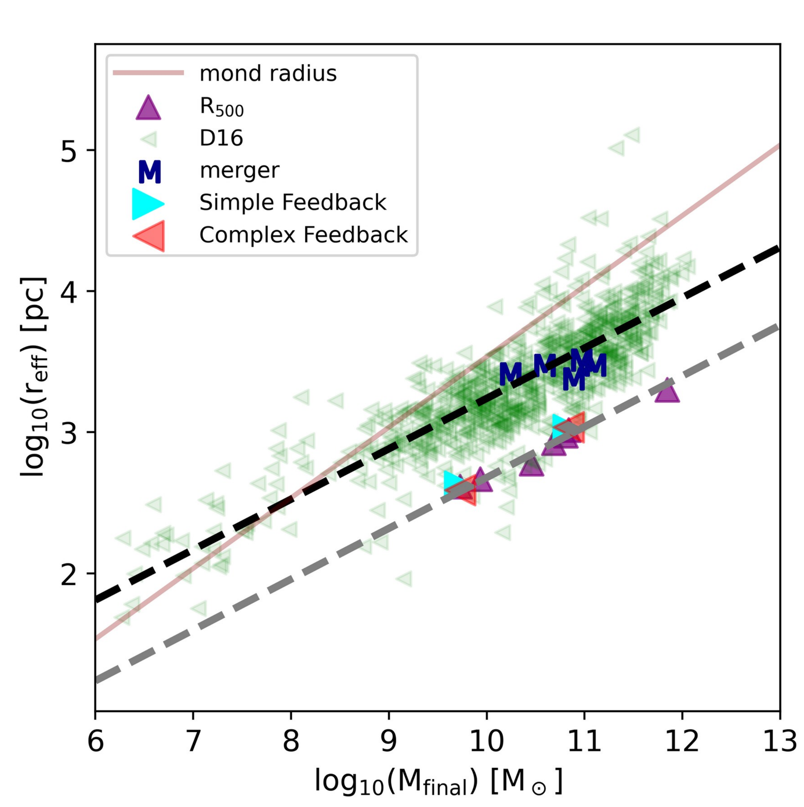

Figure 2. Eappen et al. (2022, their figure 7) shows the effective-radius - mass relation. Dashed black line is the observational result, dashed grey line is the size-mass relation for model galaxies and $M_\odot$ are the single merger models.

- The monolithic collapse of post-Big-Bang gas clouds of different initial radii with no initial rotation, set-up using Phantom of RAMSES (POR), form model galaxies.
- The model galaxies are found to follow a similar downsizing behavior as documented in Thomas et al. (2005, 2010). That is, the star-formation timescales (SFTs) are found to be similar to the observed ETGs.
- The addition of complex feedback mechanisms does not affect the SFTs of the model galaxies.
- The model galaxies fall slightly below the observed size - mass relation.
- The single merger model which is formed through the merger of two comparable mass model galaxies reaches the size-mass relation.
- These mergers could take place in the densest part of the Universe (e.g. central regions of galaxy clusters).

Bibliography

- **Milgrom M., 1983a, ApJ, 270, 365 (Paper on MOND)**
- **Lüghausen F., Famaey B., Kroupa P., 2015, Canadian Journal of Physics, 93, 232 (Paper on the numerical code used)**
- **Eappen R., Kroupa P., Wittenburg N., Haslbauer M., Famaey B., 2022, MNRAS, 516, 1081**

Forming too early?

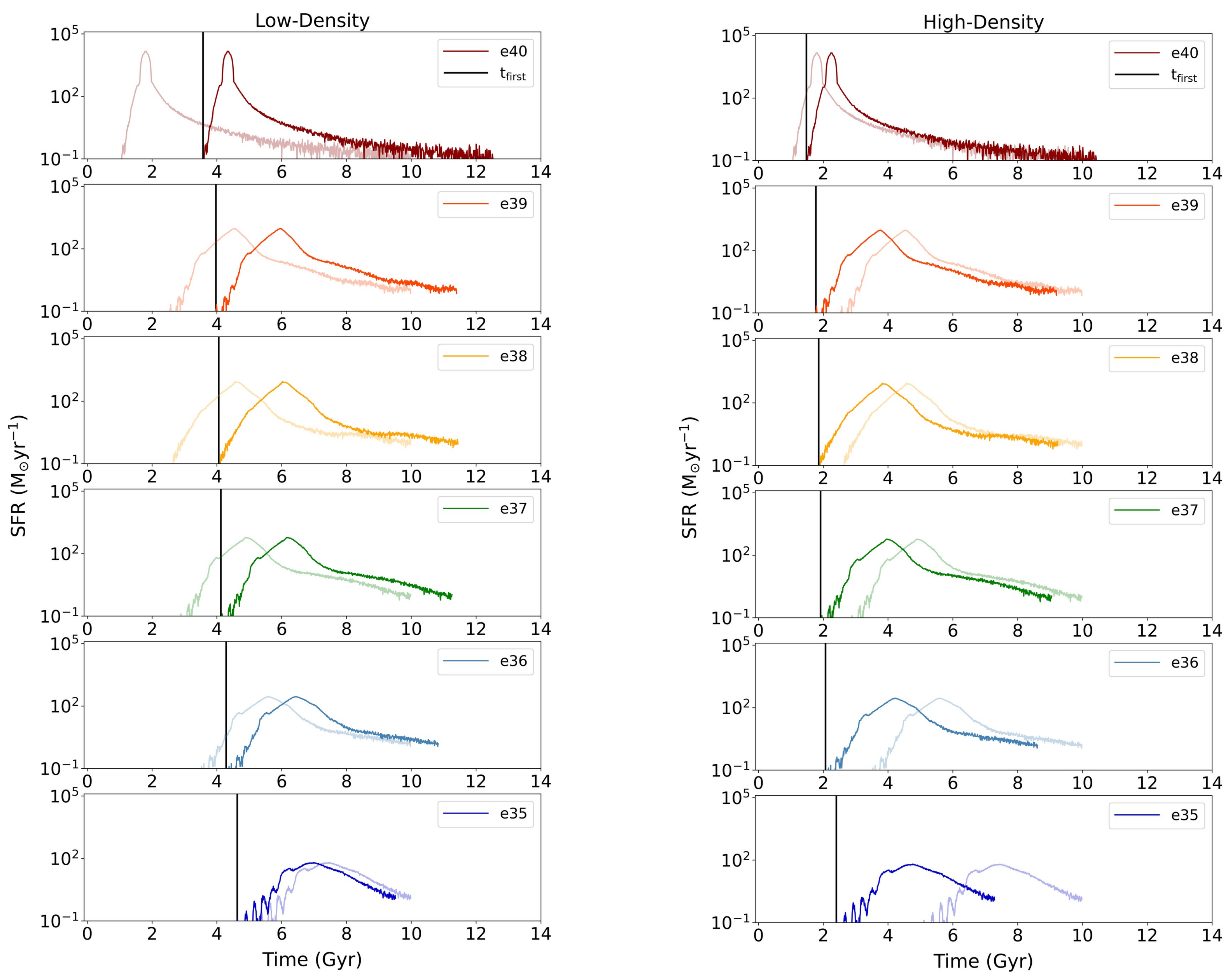

Figure 3. Eappen et al. (2022, their figure 6) show the SFH in the low and high – density environments. The transparent SFHs are relative to the start of computation at *t=0.* The thick curves represent the SFH relative to the Big Bang. The black line is the time when the first star is formed in the model galaxy.

Assuming the standard age of the Universe is 13.8 Gyr and the age-dating deduced by Thomas et al. (2005) for ETGs is valid, the SFH of the model galaxies are shifted to calculate the time when the first stars would have formed in the observed Universe.

Compact relic galaxies

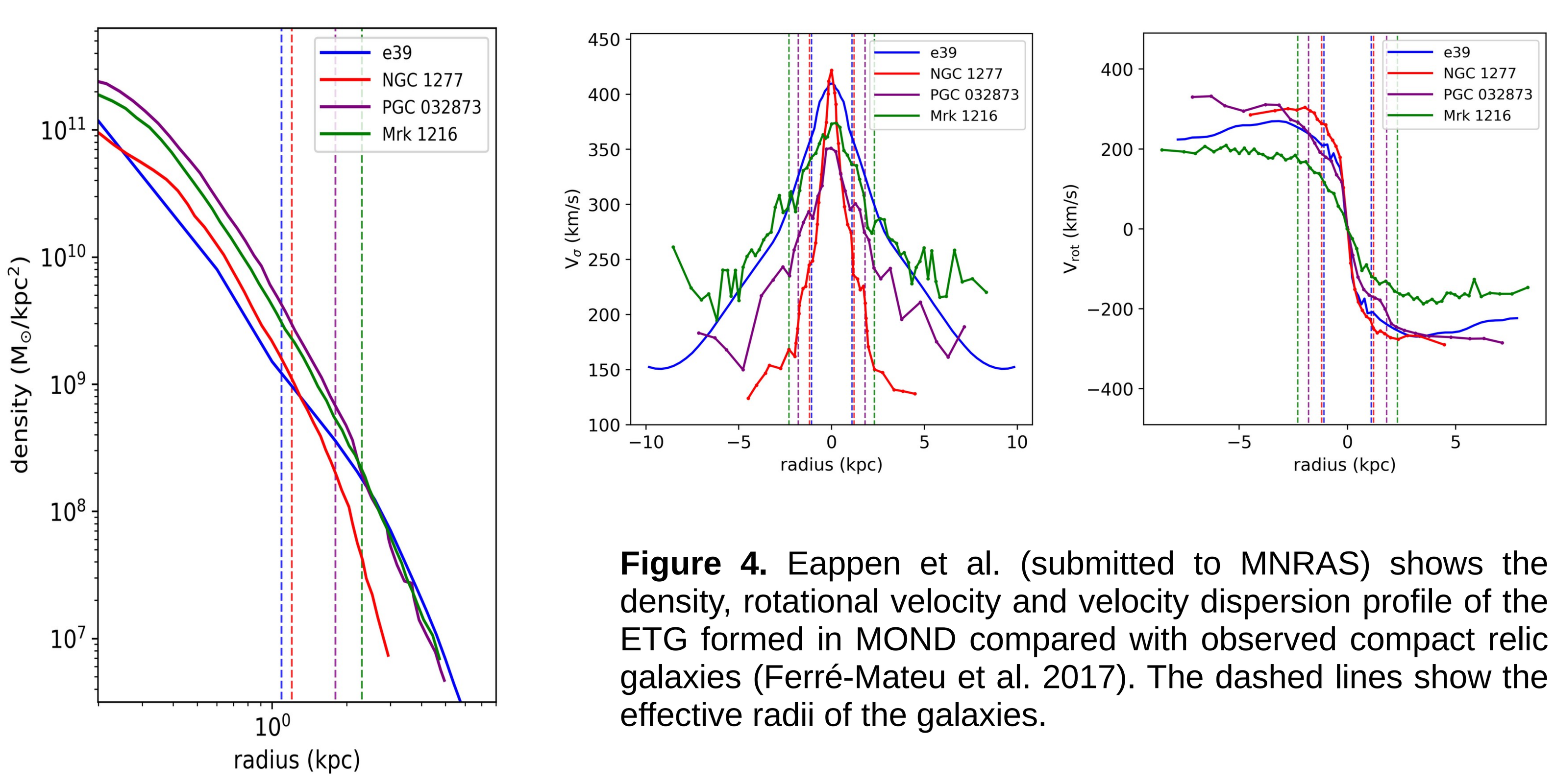

Figure 4. Eappen et al. (submitted to MNRAS) shows the density, rotational velocity and velocity dispersion profile of the ETG formed in MOND compared with observed compact relic galaxies (Ferré-Mateu et al. 2017). The dashed lines show the effective radii of the galaxies.

The monolithic collapse of a post-Big-Bang non-rotating gas cloud in MOND produces galaxies that closely resembles compact relic galaxies, with a fast rotation and high central velocity dispersion. Our findings support the idea that the Milgromian law of gravitation naturally yields objects resembling real galaxies. The recent discovery of very high redshift galaxies, some of which reached almost 10^{11} M_{sun} only about 0.5 Gyr after the Big Bang (see Labbe et al. 2022; Haslbauer et al. 2022), suggests that galaxies could form even faster in the real Universe. This may be achieved by denser gas clouds with a smaller initial radius compared to the model galaxy. These results highlight the potential of MOND in explaining the properties of observed galaxies and offer insight into the formation of galaxies in the early Universe.

Conclusions

- This work for the first time shows that the SFTs observed for ETGs are a natural occurrence in MOND.
- The size-mass relation is found to be consistent with observations.
- The kinematical and structural properties of the model galaxies shows that they are good candidates for compact relic galaxies.

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