Collisional Relaxation Affects the Morphologies and Kinematics of Simulated Galaxies

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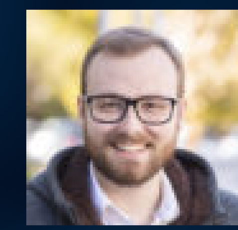

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Context

Simulations are a vital tool to the modern astronomer. They aid in interpreting observations and facilitate studying galaxies over a range of timescales. The recent success of cosmological hydrodynamical simulations (e.g. EAGLE, IllustriusTNG) in producing populations of galaxies that share similar distributions (sizes, velocities, number-counts, mass fractions, etc.) to observations has emboldened the community to investigate further. The predictive power of these simulations, however, can only be as reliable as the input physics. Simulations represent matter with point mass particles, so the gravitational force is equivalent to the sum of forces from all pairs of particles. This introduces a currently under-appreciated limitation – more massive particles cause greater gravitational deflections (scattering) during interactions (collisions). This effect can completely change both the kinematics and spatial distribution of particles in a gravitating system. We show to be (correctly) effectively collisionless, a galaxy needs to be resolved with a large number of particles, on the order of 10 .

Computational Experiments

Our main experiment was to evolve galaxies consisting of a Hernquist dark matter halo + exponential stellar disk with typical, identical initial properties (V200 = 200 km/s, c = 10, Rd = 0.02xR200, M*/MDM = 0.01) but resolved with different numbers of particles (or equivalently different particle masses). The only physics in these simulations is gravity. As seen in the projected dark matter density in Figure 1, higher resolutions galaxies' density fields are visually smoother (and, therefore, have smoother gravitational potential). It also shows the magnitude that a galaxy is affected by collisional heating depends on resolution. As gravity is scale-free (and also shown by our auxiliary experiments with different halo masses but similar numbers of particles), it is the number of perturbing particles that control the heating rate.

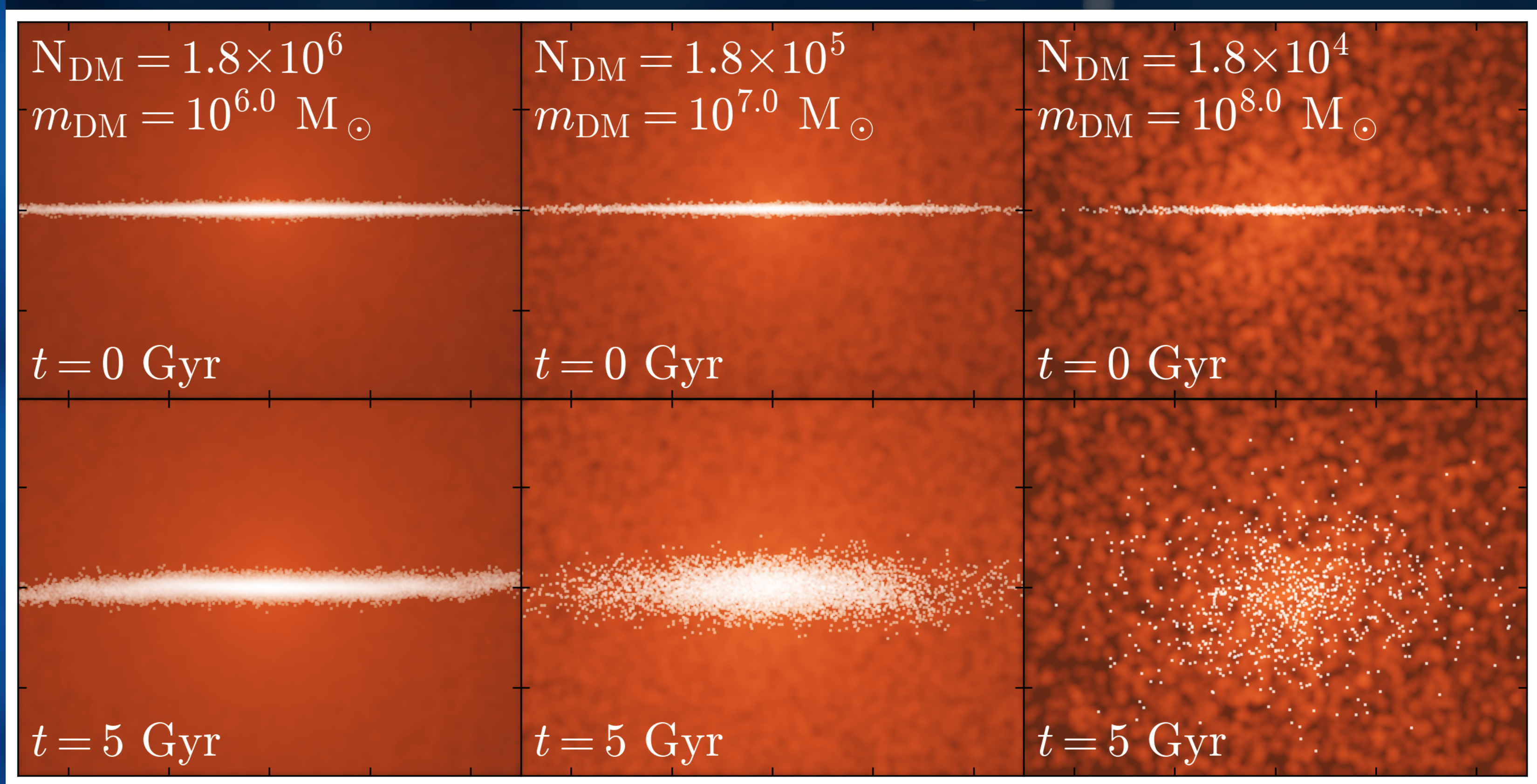


Figure 1: Two snapshots (rows) at the same physical time showing the edge-on projected distribution of stars (white points) in three of our differently resolved (parameterised by number of particles, NDM, and dark matter particle mass, mDM) but otherwise identical Milky Way mass, stable disk galaxies (columns). Lighter background colours correspond to higher projected dark matter densities. The galaxy disks become visually thicker due to gravitational scattering events. Scattering is stronger at lower resolutions.

Morphology

We measure a variety of morphological indicators as our test galaxies evolve. The galaxies start with stars on nearly circular orbits (κrot≈1) in the plane of the disk (c/a≈0), but collisions perturb those orbits making the lower resolution galaxies harbour stars with increasingly random orientations (κrot≈1/3) and more spherical (less flattened) spatial distributions (c/a≈1). In the literature, it is typical to prescribe a threshold in a morphological indicator to designate galaxies as either disk or bulge dominated. The lowest resolution galaxy in our main experiment rapidly (~4 Gyr depending on the indicator and threshold) passes from the disk to the bulge kinematic classification. We extended the models in Ludlow et al. (2021) to predict the evolution of kinematic morphological indicators. Although trickier to model, the spatial distribution mirrors kinematics as expected.

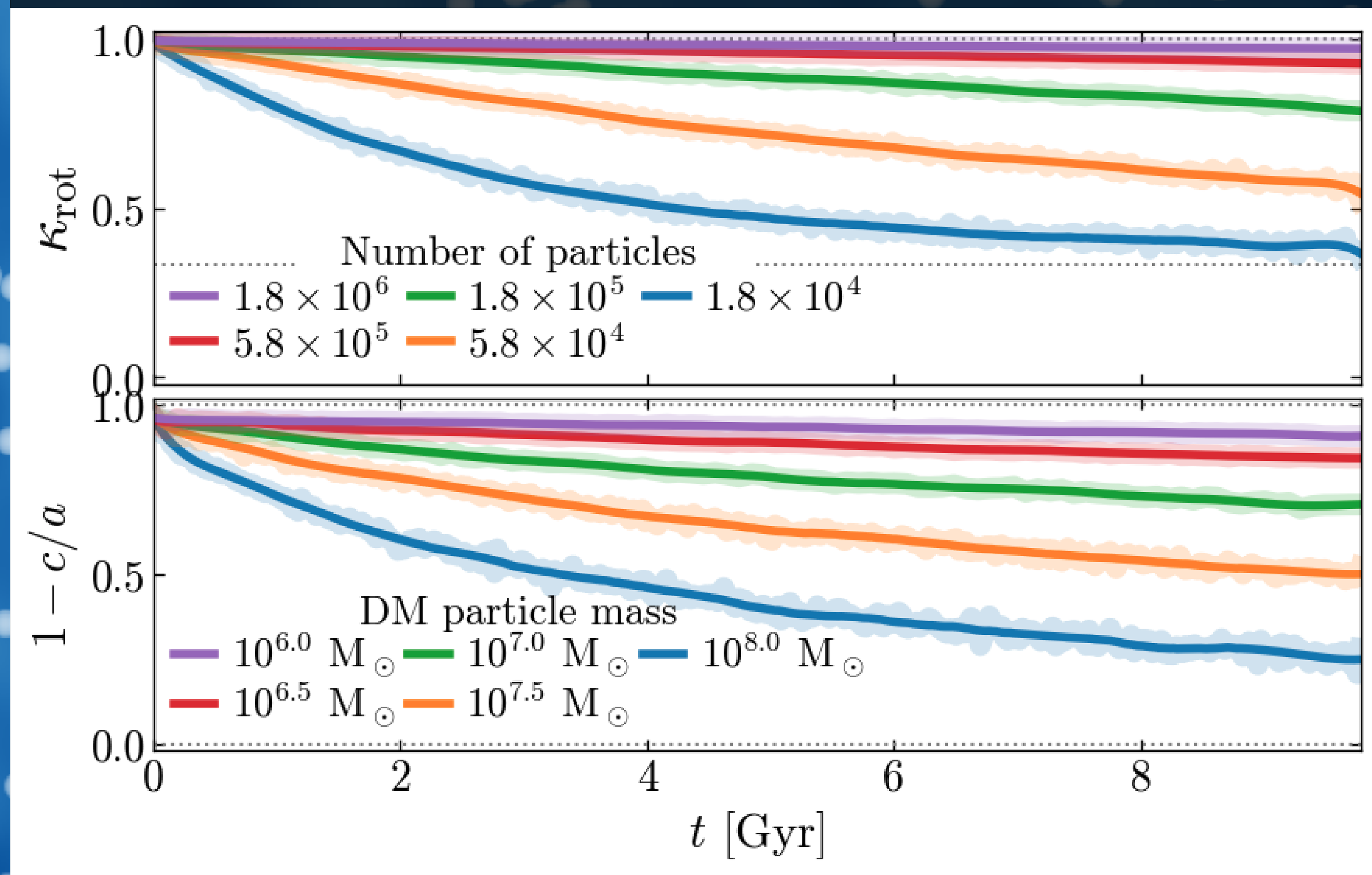
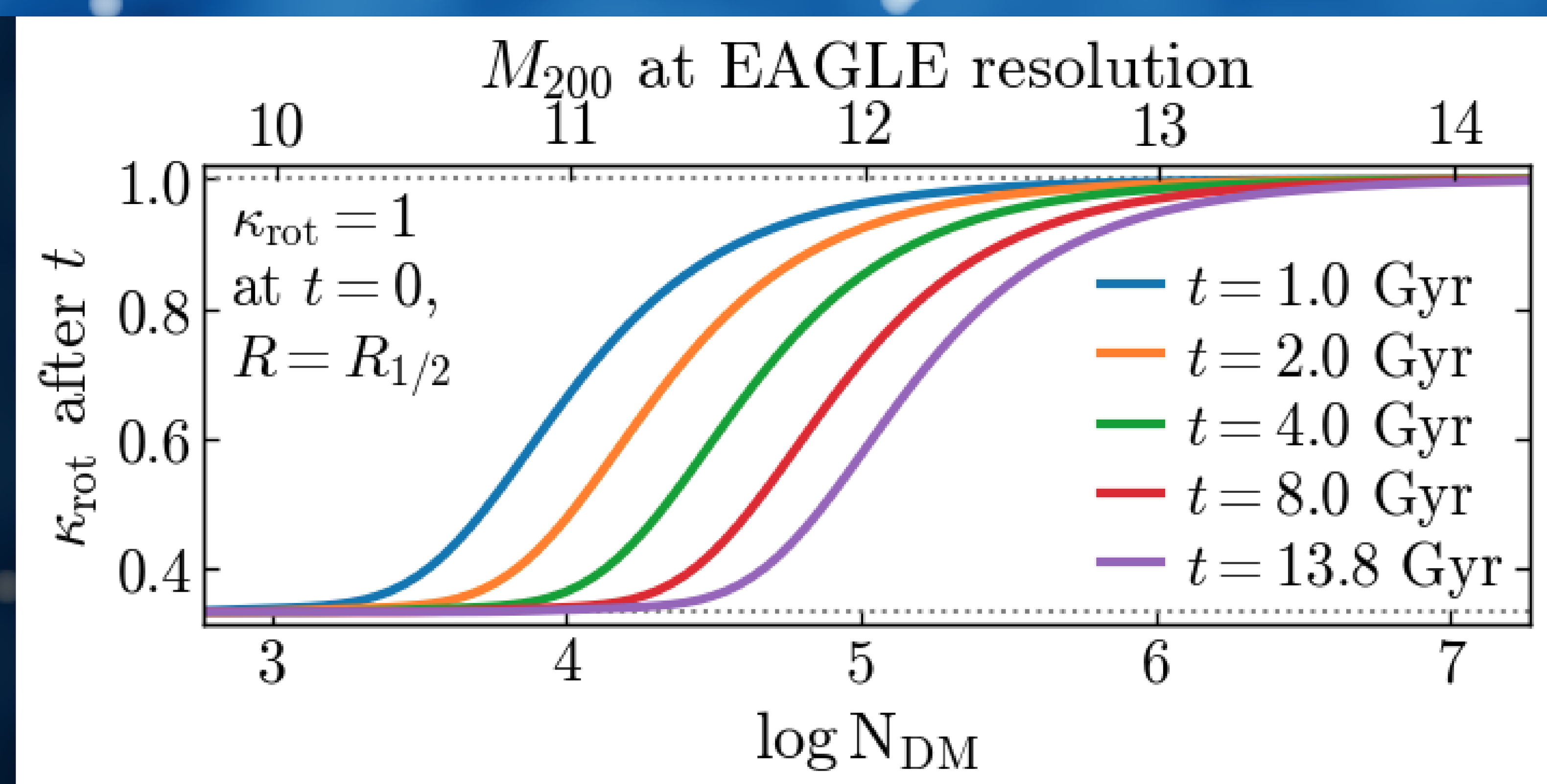


Figure 2: The evolution of the fraction of stellar kinetic energy in the azimuthal direction for the stars at the half mass radius (krot, top row) and 1 - the ratio of the minor to major axis of the stars (1 – c/a, bottom row) for 5 galaxies resolved at different resolutions. Poorer resolutions result in a greater kinematic and morphological change.



Scaling Relations

In Figure 3, we show the evolution of scaling relations for galaxies with different stellar mass. We generated the galaxies with the same particle mass – similar to those produced by cosmological simulations – to emphasise that relations derived from simulations are susceptible to being affected by collisional heating. The projected size increases as the stellar population net gains kinetic energy from its interactions with dark matter particles. The total mass profile is negligibly affected by collisional relaxation, so the circular velocity profile only increases from the change in the half mass radius. Most concerning, however, is the loss of the stellar mean streaming velocity and the transfer of angular momentum to the dark matter.

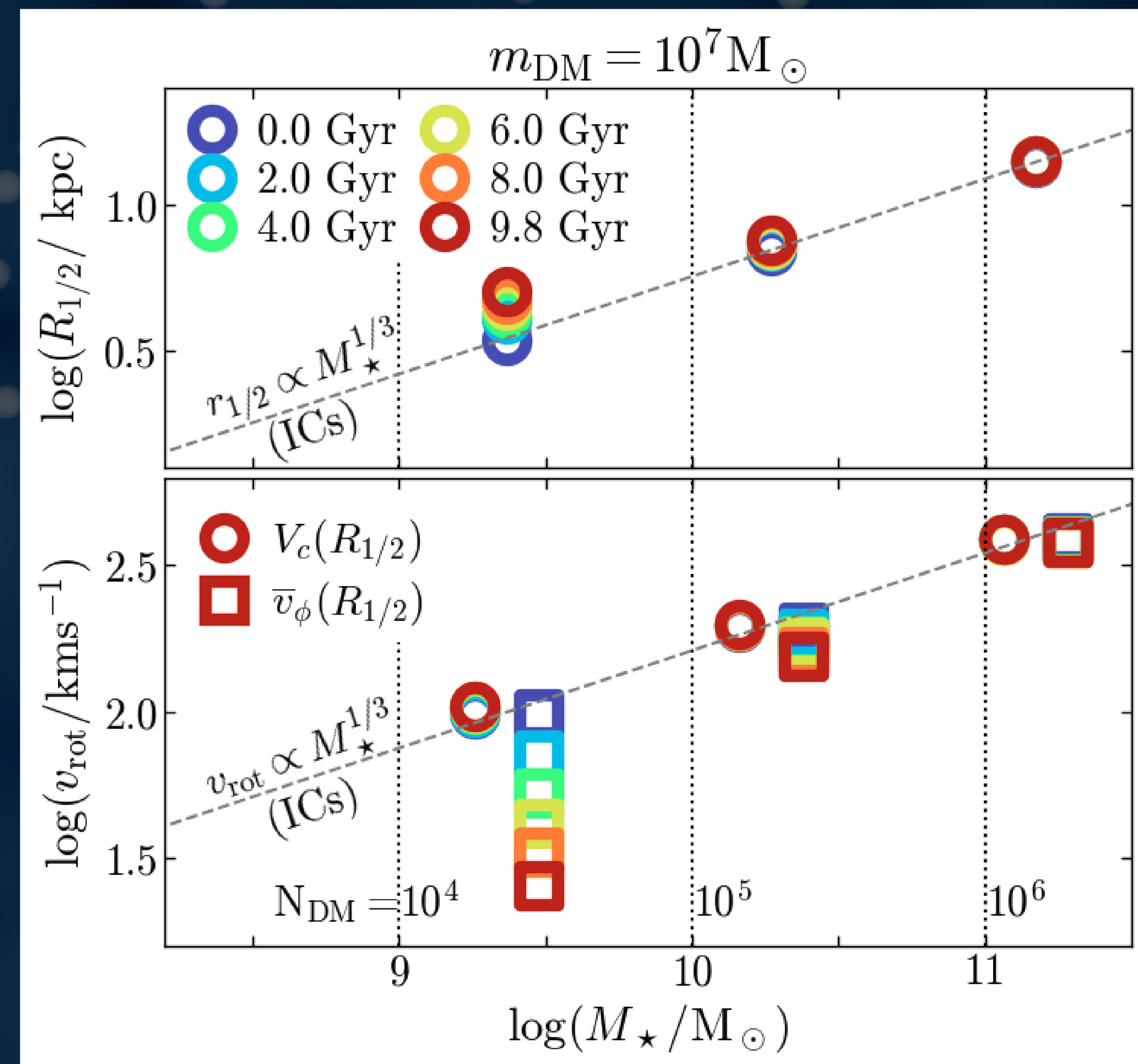


Figure 3: The evolution of the size-mass and Tully-Fisher relations for 3 galaxies generated with the same particle masses. We show two measurements of velocity: the circular velocity, Vc, and the mean azimuthal velocity of the stars, v̄ϕ. As we fixed the baryon fraction to 0.01, the stellar mass sets the total number of particles in each galaxy and hence controls the heating rate. As expected, the greatest deviations from the ICs (diagonal lines) occur in galaxies with the fewest particles.

Caution!

Figure 4: The predicted κrot after a given time for an initially pure disk galaxy only affected by N-body physics. We show the change as both a function of the number of particles and the halo mass adopting EAGLE's particle mass resolution (9.70x10^6 M$_\odot$). The predictions rely on the models we developed that describe the kinematics. At Milky Way masses in EAGLE, gravitational scattering significantly affects the energies of stellar orbits.

Poor resolution affects galaxy kinematics. The community was always aware that simulations require a given resolution for the results to be reliable, but now it's clear that collisional relaxation in disk galaxies is a strong limitation: especially for the kinematics. Figure 4 shows that EAGLE's resolution is not sufficient to suppresses the evolution of kinematics from gravitational scattering at Milky Way masses. From this work, we can make more educated estimates of the resolution requirements for future simulations.