The Stability of Elliptical Galaxies in MOND

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Abstract

Galaxies are natural laboratories for testing the fundamental physics on the nature of dark matter. MOdified Newtonian Dynamics (MOND, Milgrom 1983) has been tested as a possible alternative for over 20 years on small and large scales. However, preciously little is known of MONDian elliptical galaxies accelerating in any galaxy cluster.

Following Schwarzschild's approach, we construct a series of Hernquist models embedded in external fields in the framework of MOND. These models represent medium-mass elliptical galaxies with mild cusps within a galaxy cluster, providing a MONDian external field on the order of $g_{ext}\approx a_0$. Using N-body simulations, we further test the stability of these models. We show here that initially axisymmetric elliptical galaxies become lopsided along the external field's direction, and that the centroid of the galaxy, defined by the outer density contours, is shifted by a few hundreds parsecs with respect to the densest point. Non-detection of such effects for large samples of galaxies with good photometry inside clusters could be used to falsify the modified gravity interpretation of the MOND phenomenology.

Introduction

MOND is essentially a dark matter theory with 100% conspiracy of dark matter with the baryons: the baryons dictate via the modified Poisson equation how much Dark Matter should be in a galaxy (Bekenstein & Milgrom 1984; Wu et al. 2007):

$$\vec{\nabla}\cdot\left[\frac{\vec{g}}{G_{\rm eff}}\right]=4\pi\rho_b,\quad G_{\rm eff}=\frac{G}{\mu\left(\frac{|\vec{g}|}{a_0}\right)},\quad \vec{g}=-\vec{\nabla}\Phi_{int}+\vec{g}_{ext}.$$

The acceleration constant a_0=1.2x10^{-10} m/s^2. The internal dynamical potential $\Phi_{\rm int}$ of a gravitating system in MOND depends on the baryon density ρ_b and its acceleration g_{ext} in the external background field, even if it is constant and uniform. Thus the internal potential is distorted by the external field even when the density is spherically symmetric. It means that spherical systems are not in exact equilibrium within the external field. Will these systems reach equilibrium states, or be completely destroyed?

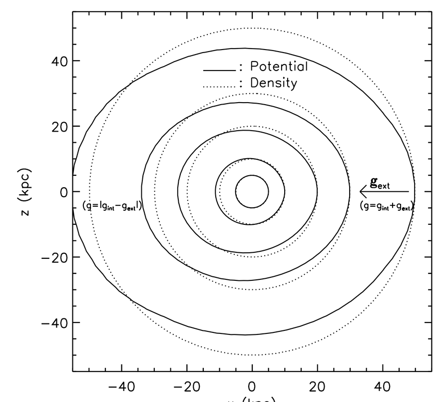
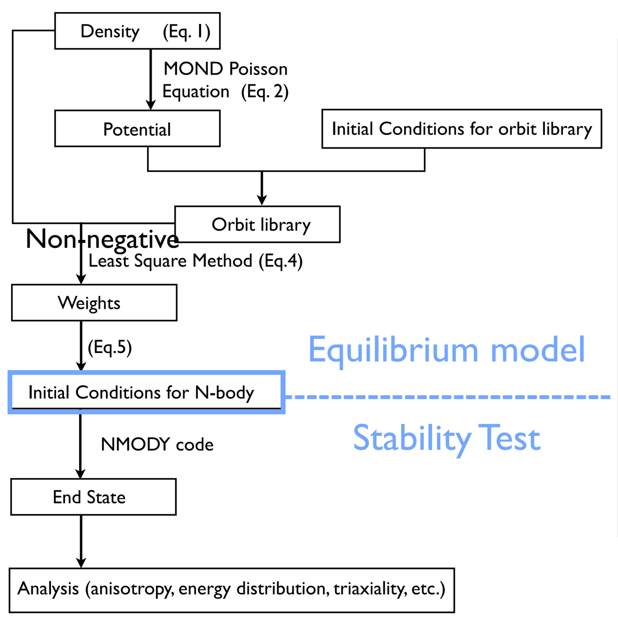


Fig 1: The asymmetric iso-potential contours (solid) of a spherically symmetric density distribution of the Plummer profile (dotted, for a galaxy of 5 x 10^{10} Msun with a 1 kpc core) due to a significant MOND external field g_{ext}=1a_0 (with the direction as indicated). Such asymmetry is not expected in Newtonian gravity.

Simulation process : Schwarzschild modeling + N-body



Eq.1 $$\rho=\frac{M}{2\pi abc}\frac{1}{r(r+1)^3}$$

Eq.2 $$\nabla\cdot[\mu(x)\nabla\Phi]=4\pi G\rho$$

Eq.3 $$\mu(x)=\frac{x}{1+x}$$

Eq.4 $$\chi^2=\frac{1}{N_{cells}}\sum_{i=1}^{N_{cells}}\left(\sum_{j=1}^{N_{orbits}}W_jO_{ij}-M_i\right)^2+\lambda\sum_{j=1}^{N_{orbits}}\omega_j^2$$

Eq.5 $$n_j=W_jN_{total}$$

We constructed three Hernquist models for cuspy elliptical galaxies:

Model 1: Axis-symmetric, isolated system;

Model 2: Axis-symmetric (the same density as used in Model 1), embedded in a -- for simplicity -- uniform external field.

Model 3: Triaxial, embedded in a uniform external field.

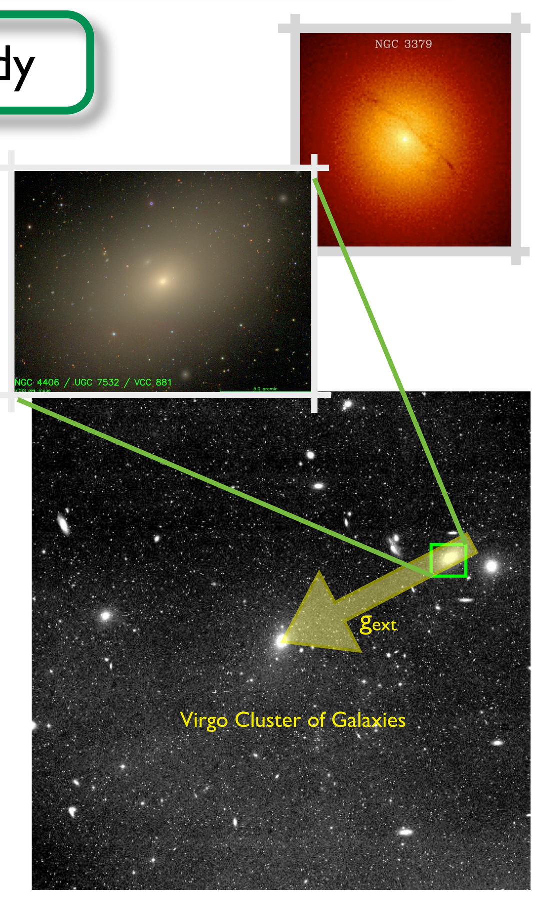
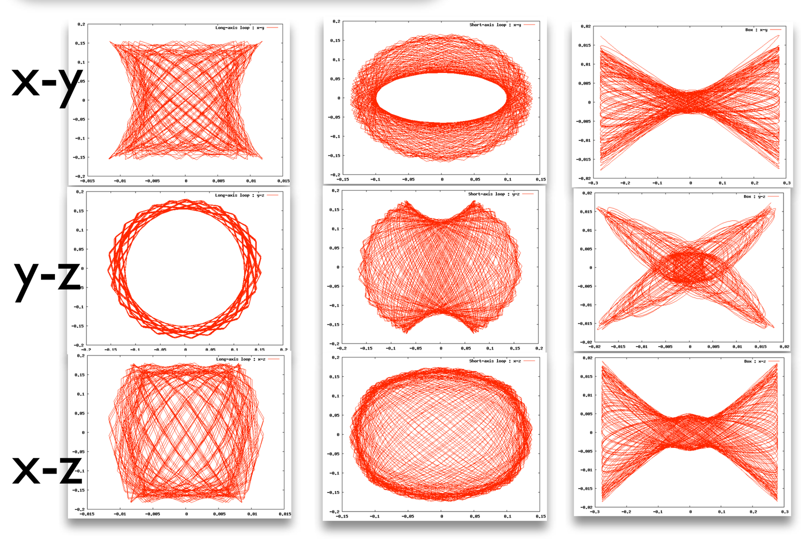


Fig 2: Isolated field elliptical NGC3379 (upper panel), cluster elliptical galaxy NGC4406 (middle panel) and centre region of Virgo Cluster of Galaxies (lower panel), the arrow shows the direction of external field, which is pointing to the centre of Virgo Cluster, the giant elliptical NGC4486.

Orbital structure



The Schwarzschild technique generates most of the orbits for a given potential (Fig. 3 show the regular orbits).

Bottom panels (Fig 4) are the integration of mass as a function of energy for the three models. There are more chaotic orbits within an external field (models 2, 3) because of less symmetries.

Fig 3: Orbit examples of Long-axis loop (left), short-axis loop (middle) and box (right) orbits on x-y (upper), y-z (middle) and x-z (bottom) planes.

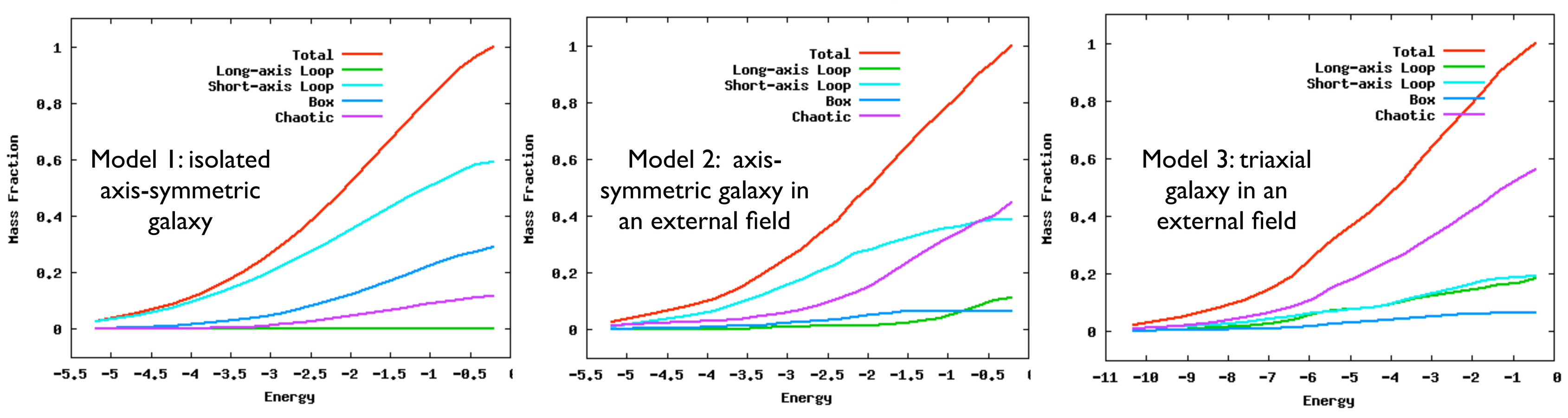


Fig 4: Orbital structures of three models as shown in the labels.

Model Stability

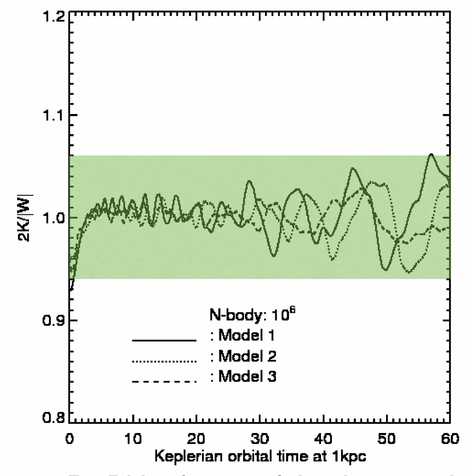


Fig 5:Virial ratio of the three models

In our simulations, we have 10^6 particles for each model and each model evolves 60 Keplerian orbital times at the scale of 1kpc.

The scalar Virial theorem, W +2K=0, is valid for systems in equilibrium, where W is the Clausius integral, and K is the kinetic energy of the system. In the Fig. 5, we show that the evolution of -2K/W for all models is always about unity, as expected for an equilibrium system. Fig. 6 shows the evolution of axis-symmetric systems, without (i.e. model 1) and with (model 2) an external field.

Fig. 5 and Fig. 6 demonstrate that our N-body ICs start off in quasi-equilibrium and after approximately five Keplerian times (1 kpc) can be considered fully relaxed and appear stable.

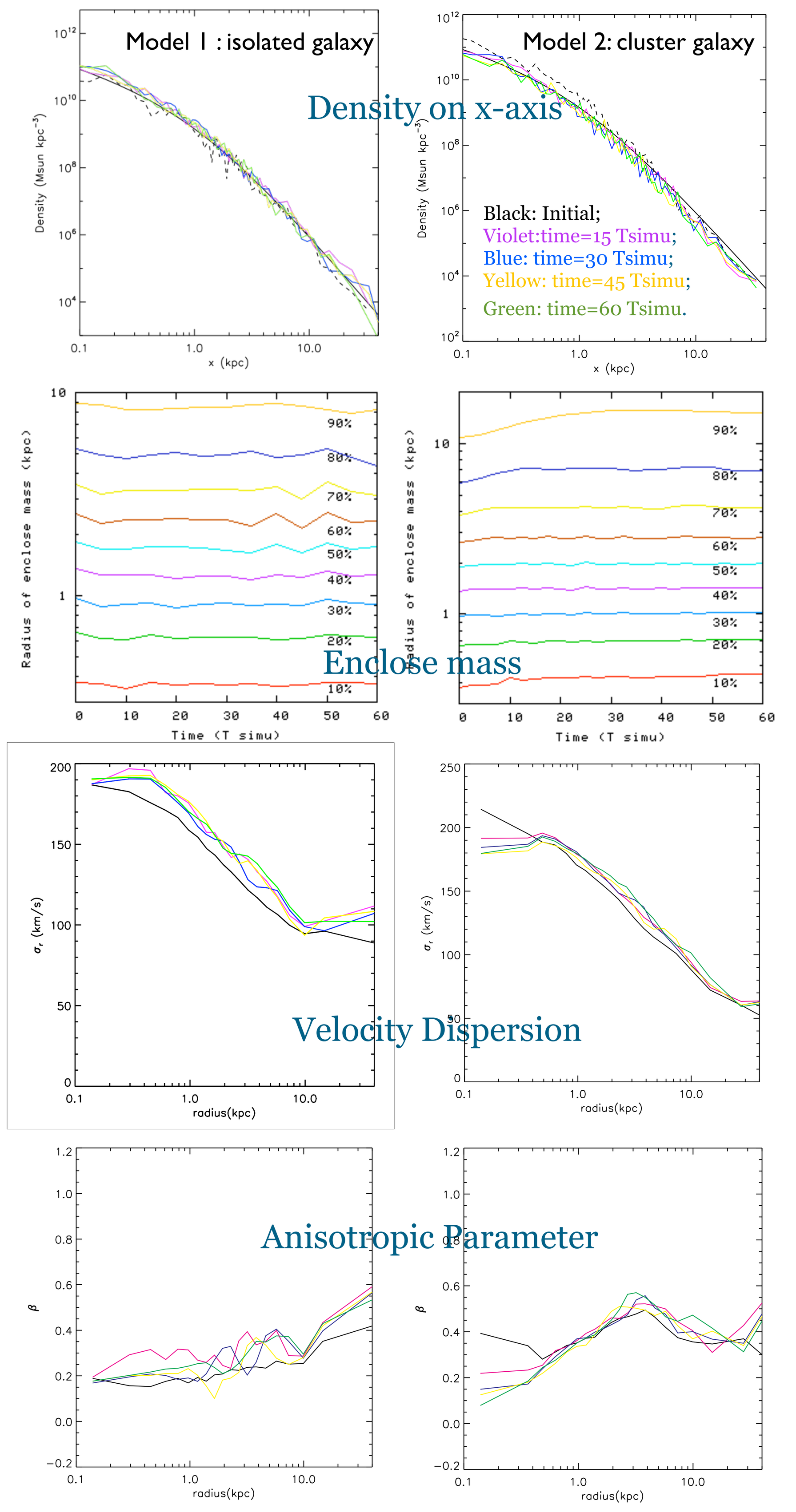


Fig 6: Evolutions of density on x-axis (uppermost panels), radii of enclosed mass fraction (upper middle panels), radial velocity dispersion (lower middle panel) and anisotropic parameters (bottom panels) for the same axis-symmetric density distribution, but without (model 1, left panels) and with (model 2, right panels) an external field. After the systems virialised to equilibrium, the models appear stable.

Lopsidedness and offset

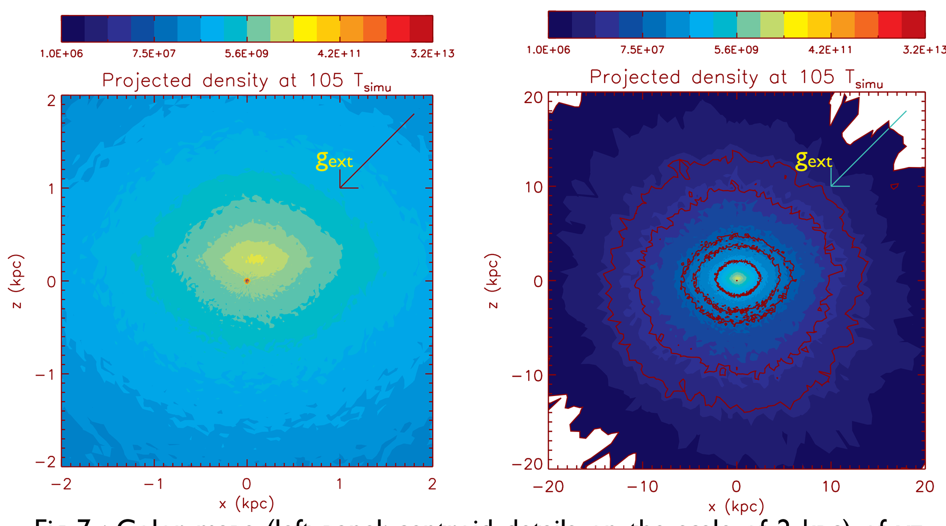


Fig 7 : Color maps (left panel: centroid details on the scale of 2 kpc) of xz-projected density for model 2 (left panel) and at t~100 T_{simu} later.
The dark dot in the centre shows the origin point (i.e. center of mass), roughly corresponding to the centroid defined by the outer surface density contours. It is clearly offset from the central density distribution. The arrows indicate the direction of the external field. The right panel shows xz-projected density on the scale of 20 kpc show the twist of isophotes between and inner and outer density distribution.

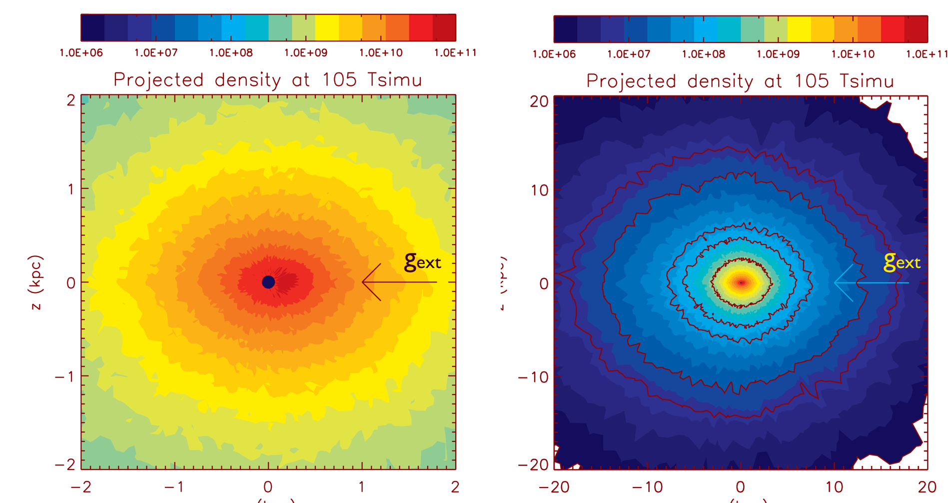


Fig 8 : Color maps (left panel: centroid details on the scale of 2 kpc) of xz-projected density for model 3 (left panel) and at t~100 T_{simu} later.

Fig. 7 and Fig. 8 show the evolution of projected density of the model after 0, and ~100 Keplerian time at the typical scale of 1 kpc (i.e., ~0.5 Gyr), this is longer than the stability test.

One can see clearly an offset of 200 pc of the central densest point from the centroids defined by the outer projected density contours. The outer parts of the model is distorted by the external field. By and large this live N-body simulation confirms our expectation that the axisymmetry is broken in the presence of an external field, which shows up as a twist of the isophotes and an offset of the density peaks.

If real elliptical galaxies in rich clusters show perfectly symmetric light with no significant offsets between the centroids of the inner and outer contours, the classical version of MOND is likely excluded. This predicted lopsidedness of galaxies inside distant rich clusters should be falsifiable with photometry only, using, e.g. the VLTI. To resolve a centroid offset of ~200pc in an elliptical galaxy in a rich cluster of typical internal gravity 10^{-8} cms^{-2} at a distance of 160-210 Mpc (e.g., Abell 1983, Abell 2717, MKW9 Pointecouteau et al. 2005, Sanders 2003) would require a minimum angular resolution of 0.2 arcsec.

Conclusions

1. The broken of symmetry of the light profiles of galaxies in clusters presents a stringent test of gravity.

2. Following the N-body simulation of an elliptical galaxy built by the Schwarzschild's approach, we find that the galaxy's internal potential is distorted along the direction of the galaxy's acceleration in a cluster. The peak of the baryon density is shifted gradually to a stable point ~200pc away from the geometric center determined by the outer contours computed from the N-body simulation.

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