Can the observation of globular clusters in low-mass galaxies exclude the MOND modified gravity theory?

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How to distinguish MOND from dark matter?

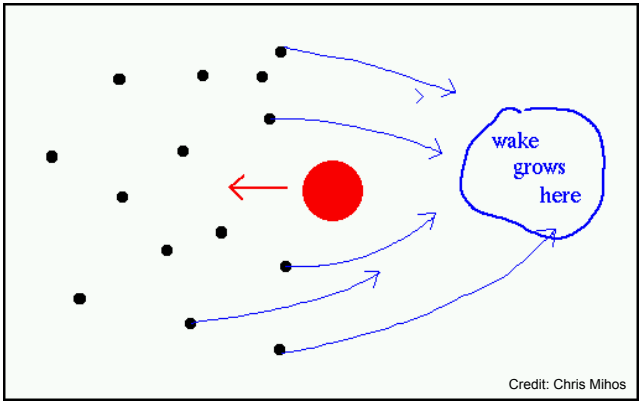
Strongest indication of MOND is its ability to model rotation curves. The same can be done with a suitable distribution of dark matter with Newtonian gravity (while not fully seen in simulations yet).

Additional discriminator tests are desirable:

- External field effect (e.g., satellites of galaxies), wide binary stars, relative velocities of galaxy clusters, growth of cosmological structure, efficiency of formation of tidal dwarf galaxies
- Here: test of modified gravity MOND (AQUAL/QUMOND) using dynamical friction

Dynamical friction: introduction

Massive body moving in the sea of lighter particles (satellite in a dark matter halo/stars of the host)



Dynamical friction: introduction

With Newtonian gravity, friction (de)acceleration given by Chandrasekhar formula (under certain circumstances):

$$a_{\mathrm{DF,NWT}} = \frac{2\pi \ln\Lambda G^2 \rho m}{\sigma^2 X^2}\left[\mathrm{erf}(X) - \frac{2X}{\sqrt{\pi}}\exp\left(-X^2\right)\right],$$

$$X = \frac{v}{\sqrt{2}\sigma}$$

$\ln\Lambda$ is **Coulomb logarithm**

CF breaks in some situations, e.g. satellite orbiting outside of a truncated galaxy

Dynamical friction in MOND - big perturbers

For big perturbers (major mergers of galaxies):

- Dynamical friction weaker with MOND than in equivalent Newton+DM system
- Major/intermediate galaxy mergers rare
- No problem with bulgeless galaxies
- No problem with fast galactic bars

Dynamical friction in MOND - small perturbers

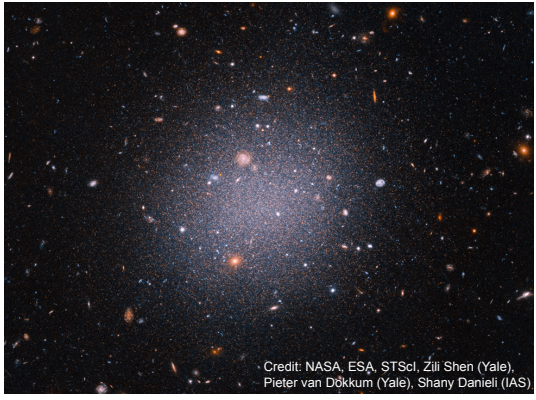
For small perturbers (e.g. GCs in galaxies):

- Dynamical friction is stronger for MOND than equivalent Newton+DM system
- Analytic expression for ratio of dynamical friction timescales: $\propto (a/a_0)^{-2}$ (MOND analog of Chandrasekhar formula = Sánchez-Salcedo formula, no mathematical derivation)
- GCs of low-surface-brightness galaxies experience extreme dynamical friction!
- GCs sink in the centers of the galaxies in ~ 1 Gyr (less than the age of GCs)
- MOND excluded (Ciotti & Binney 2004)?

Strong dynamical friction in ultra-diffuse galaxies?

- Mass of a dwarf, size of a giant $\rightarrow$ low acceleration, strong enhancement of dyn. frict.
- Some of them have old and very massive GCs ($10^6\,M_\odot$)
- Do they exclude MOND?

Let's do a simulation! (Bílek et al., 2021)

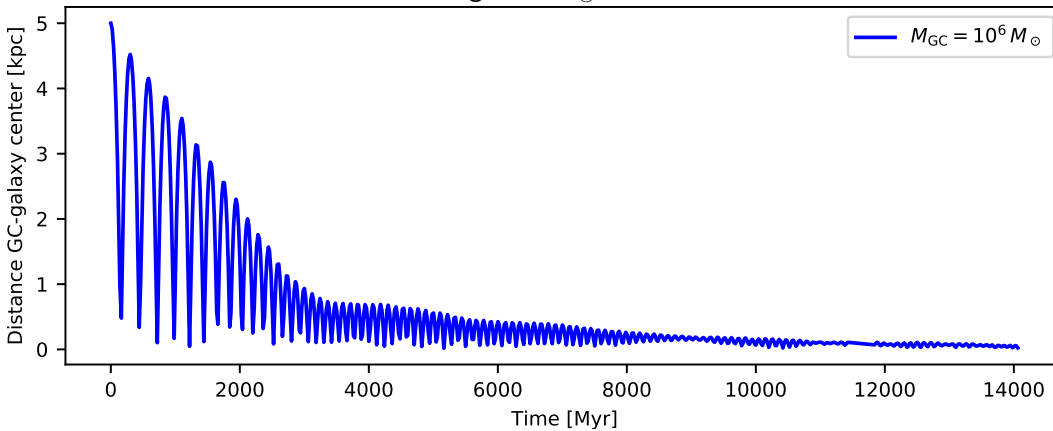


Simulation setup

- Phantom of RAMSES adaptive-mesh refinement code
- Spheroidal galaxy $M = 2 \times 10^8\, M_\odot$, $R_e = 2\,\mathrm{kpc}$, **in isolation** (otherwise EFE)
- Stars: 10^7 particles, $20\, M_\odot$ per particle
- Maximum resolution 50 pc
- GCs modeled as point masses

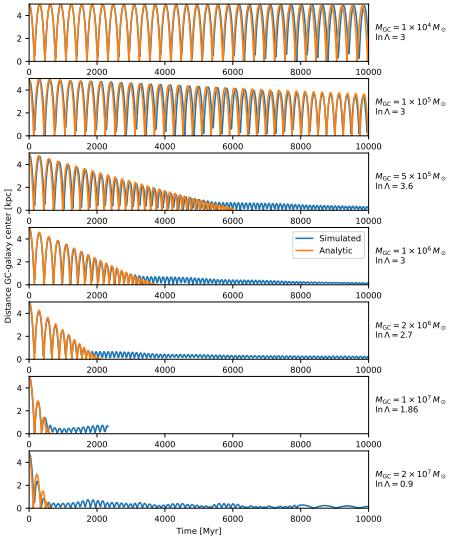
Core stalling

Free fall of a singe $10^6\ M_\odot$ GC to a UDG:

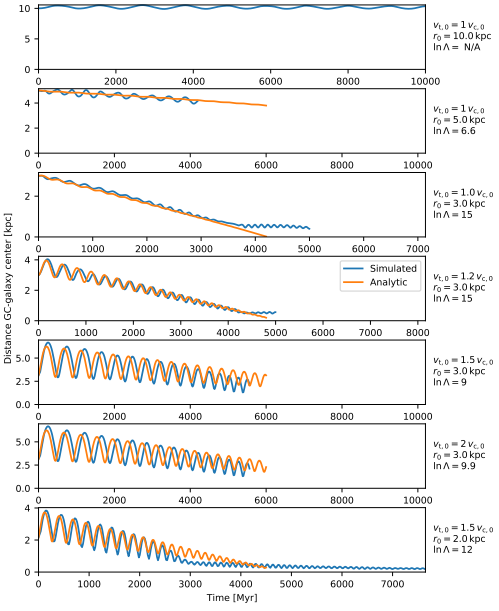


Dynamical friction not effective in the central half kpc! (core stalling)

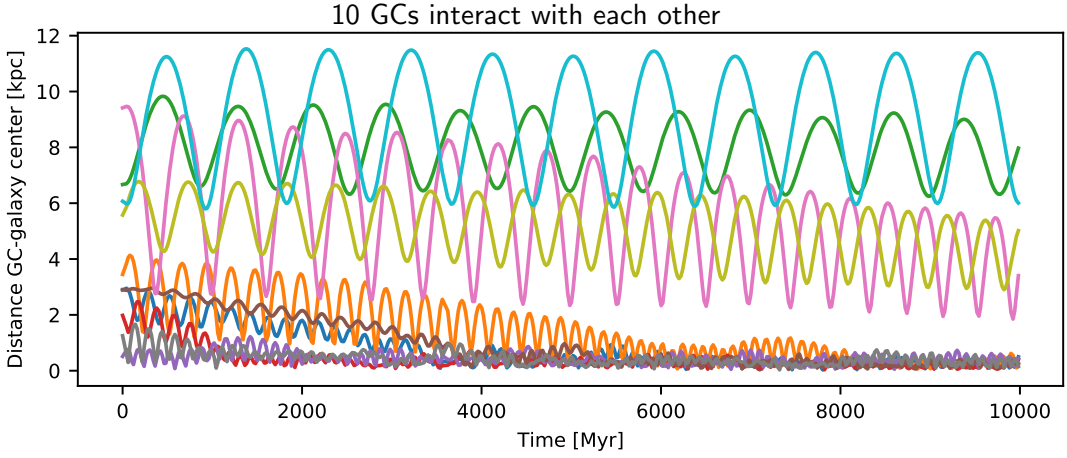
Test of the Sánchez-Salcedo formula (masses)



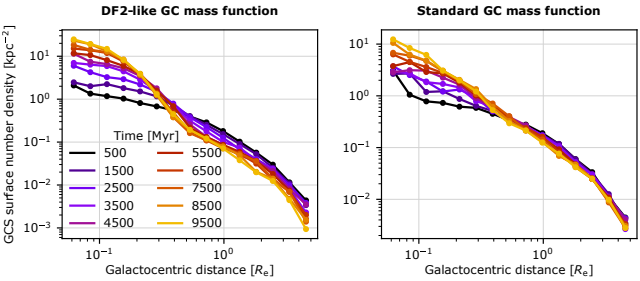
Test of the Sánchez-Salcedo formula (eccentities)



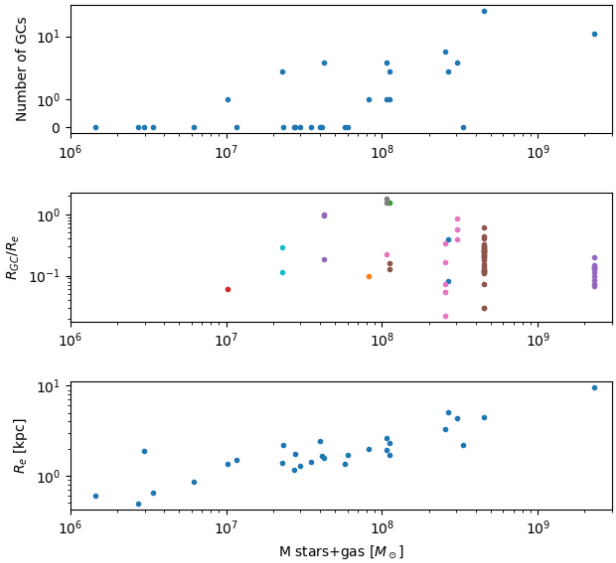
Simulations with many GCs

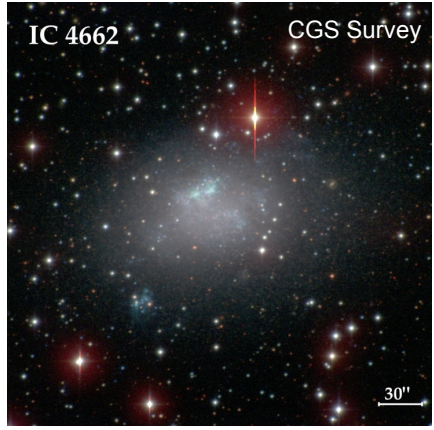


Simulations with many GCs



GCs of isolated dwarfs (in progress)





Simulation setup

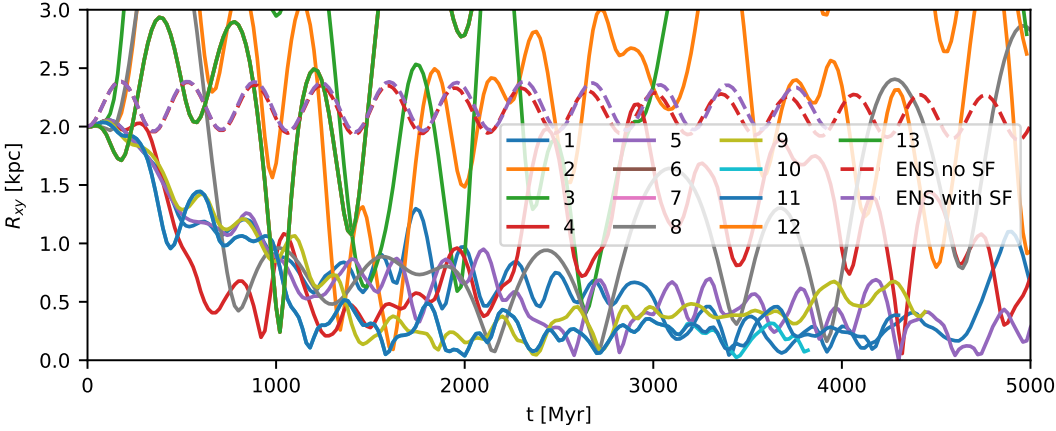
- Mass $10^8\,M_\odot$ (or $0.2 \times 10^8\,M_\odot$)
- 90% gas
- 2 kpc scale length gas, 1 kpc stars
- GC $10^5\,M_\odot$

Start at $z = 2$. **Does GC survive for 10 Gyr?**

Simulations

- Prograde, no SNe
- Retrograde, no SNe
- Radial, no SNe
- Prograde, SNe included

Effect of supernovae



Less massive GC

- GC $10^4\ M_\odot$ – survives even without SNe

Fornax dwarf (very preliminary)

- EFE from the MW is low (pericenter: $g_{\rm ext}/g_{\rm int} \approx 0.5$)
- We made simulation in isolation, no EFE, resolved GCs
- $\rightarrow$ GCs sink in ca. 3 Gyr
- Fornax needs parameters hitting borders of allowed ranges, or a special solution (e.g. a merger of dwarfs), or another MOND theory (not QUMOND)

Summary

- Formula for dynamical friction in MOND exists, works only sometimes!
- GCs of spheroidal UDGs prevented from full sinking by core stalling
- Massive GCs of isolated disk dwarfs without star formation sink fast if co-rotate, slow if counterrotate
- SNe in gas-rich dwarfs prevent GCs from settling in the galaxy center
- Fornax Dwarf seems to require a special solution
- Case of non-isolated dwarfs remains to be explored