Testing QUMOND theory with Galactic globular clusters in a weak external field**

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We dedicate this poster to the memory of our dear friend and colleague Antonio Sollima, who passed away prematurely a few months ago. Antonio was a generous and witty person, and a creative and brilliant scientist, whom we miss deeply. Antonio conceived, developed and carried out most of this work, which we have had the honour to finalize.

Abstract

We developed self-consistent dynamical models of stellar systems in the framework of quasi-linear modified Newtonian dynamics (QUMOND), constructed from the anisotropic distribution function of Gunn & Griffin (1979), combined with the modified Poisson equation defining this gravitation theory, and taking into account the external field effect. We have used these models, and their Newtonian analogues, to fit the projected density and the velocity dispersion profiles of a sample of 18 Galactic globular clusters, using the most updated datasets of radial velocities and Gaia proper motions. We have thus obtained, for each cluster, estimates of the dynamical mass-to-light ratio (M/L) for each theory of gravity.

The selected clusters have accurate proper motions and a well sampled mass function down to the very low mass regime. This allows us to constrain the degree of anisotropy and to provide, from comparison with stellar evolution isochrones, a dynamics-independent estimate of the minimum mass-to-light ratio $(M/L)_{min}$. Comparing the best-fitting dynamical M/L with $(M/L)_{min}$, we find that for none of the analyzed clusters the two tested gravity theories are significantly incompatible with the observational data, although for one of them (NGC 5024) the dynamical M/L predicted by QUMOND lies at 2.8σ below $(M/L)_{min}$. Our results suggest that the kinematics of globular clusters in a relatively weak external field can be a powerful tool to prove alternative theories of gravitation.

Framework

Globular clusters can be used as powerful laboratories to test alternative gravity theories (e.g. Sollima & Nipoti 2010, Sollima et al. 2012)

Observational data

- 18 Galactic globular clusters with heliocentric distances $1.8 < R_{\odot}/\,\mathrm{kpc} < 18.5$ and Galactocentric distances $2.5 < R_{GC}/\,\mathrm{kpc} < 18.5$
- Cluster proper motions provided by the 3rd data release of the Gaia survey (Gaia Collaboration et al. 2021)
- Radial velocities from Baumgardt & Hilker (2018)
- Density profiles from Miocchi et al. (2013) and Trager, King, & Djorgovski (1995)
- External accelerations $0.32 < a_{ext}/a_0 < 4.88$, where $a_0 \approx 1.2 \times 10^{-10}$ m s^{-2}.
- Mass function (Baumgardt et al. 2023) & isochrones (Cassisi et al. 2000) → dynamics-independent minimum M/L

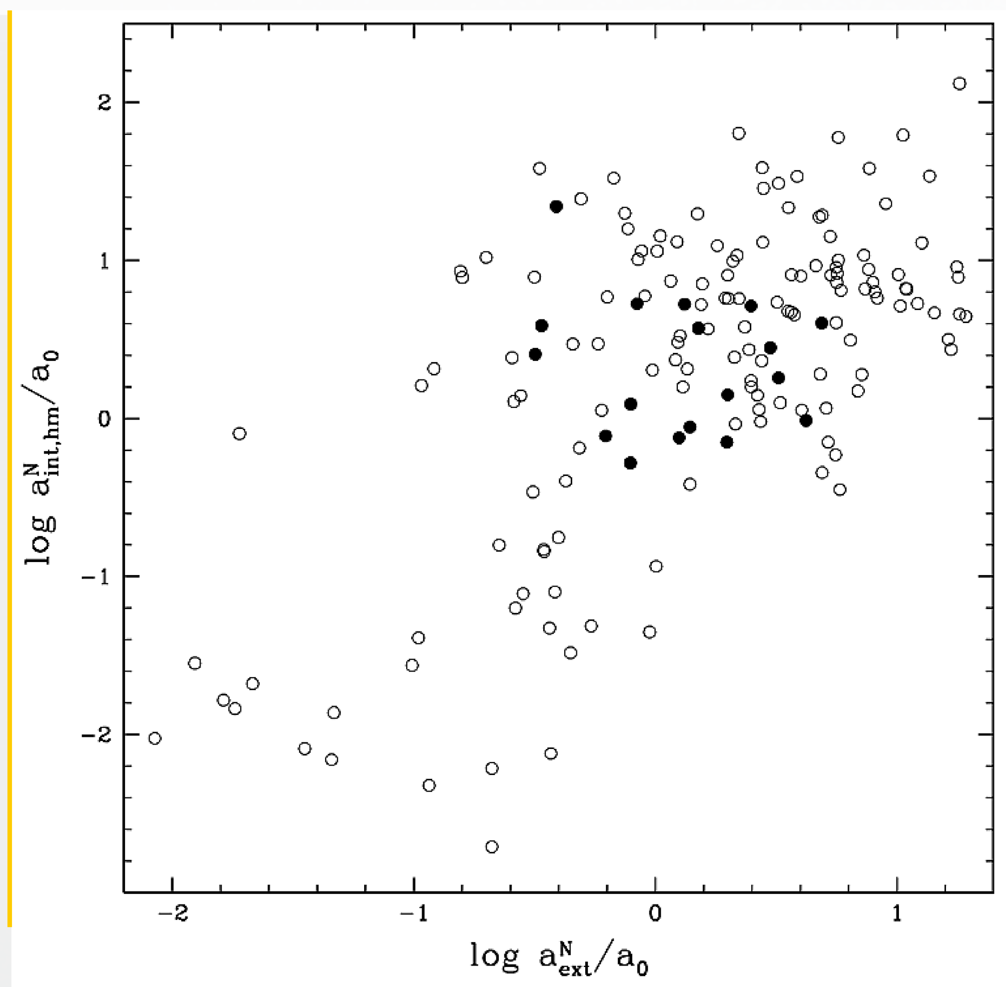

Figure 1: Internal vs. external acceleration (normalized to the MOND characteristic acceleration a_0) of the 160 GCs of the Baumgardt & Hilker (2018) database (open dots). The 18 globular clusters analysed in this work are marked by full dots.

Models

Gunn & Griffin (1979) radially anisotropic distribution function:

$$\boxed{f(E,L) = \exp\left(-\frac{L^2}{2\sigma_K^2 r_a^2}\right)\left[\exp\left(-\frac{E}{\sigma_K^2}\right)-1\right]}$$

E = energy, L = angular-momentum magnitude, r_a = anisotropy radius, σ_K = characteristic speed

MOND models: Milgrom (2010) QUMOND gravity + external field $\mathbf{a}_{ext}$

$$\nabla^2\phi_M = \nabla\cdot[\nu(y)\nabla\phi_N] \qquad \nu(y) = 1 + \frac{2}{y+\sqrt{y^2+4y}} \qquad y = \|\nabla\phi_N\|/a_0$$

$$\lim_{r\to\infty}\nabla\phi_N = -\mathbf{a}^N_{ext}$$

$$\lim_{r\to\infty}\nabla\phi^M = -\mathbf{a}^M_{ext}$$

ϕ_M = MOND potential, ϕ_N = Newtonian potential, $\nu(y)$ = interpolating function

Analogous Newtonian models for comparison

Density profiles and individual kinematic data of the clusters are fitted with both QUMOND and Newtonian models.

The best-fitting dynamical mass-to light ratio $(M/L)_{dyn}$ of QUMOND and Newtonian models are compared with the dynamics-independent minimum M/L estimated with stellar evolution models $(M/L)_{min}$.

10^6 pairs $[(M/L)_{dyn}, (M/L)_{min}]$ have been extracted and the fraction of the occurance $(M/L)_{dyn} > (M/L)_{min}$ has been taken as probability P of the model.

		Newtonian		QUMOND	
NGC	$(M/L_V)_{min}$	M/L_V	P	M/L_V	P
288	0.988	2.931	1.000	1.400	0.997
1261	0.811	1.896	1.000	1.097	0.965
1851	0.887	2.132	1.000	2.069	1.000
4590	1.187	2.960	1.000	1.883	0.984
4833	0.872	1.348	1.000	1.069	0.844
5024	1.232	2.028	1.000	0.927	0.005
5897	1.329	2.393	1.000	1.339	0.591
6101	1.329	2.568	1.000	1.386	0.640
6121	1.059	1.895	1.000	1.549	0.977
6171	0.953	2.078	1.000	1.518	1.000
6254	0.900	1.749	1.000	1.485	0.983
6352	0.943	2.067	0.999	3.198	1.000
6362	0.868	1.965	1.000	1.274	1.000
6366	0.720	1.564	1.000	1.077	0.994
6496	1.151	1.643	0.981	1.270	0.754
6723	0.927	2.232	1.000	1.697	1.000
6779	0.844	3.147	1.000	3.063	1.000
6838	0.725	1.207	1.000	1.191	1.000

Table 1: properties of the Newtonian and QUMOND best-fit models. Column 1: name of the globular clusters. Column 2: minimum V-band mass-to-light ratio. Columns 3 and 4: V-band mass-to-light ratio and probability of the Newtonian model. Columns 5 and 6: V-band mass-to-light ratio and probability of the best QUMOND model. Mass-to-light ratios are in solar units.

Results

None of the analysed clusters has been found with a dynamical M/L significantly incompatible (P < 0.003, corresponding to 3σ) with the predicted lower limit. For one of them (NGC5024) the QUMOND prediction lies at 2.8σ below such a lower limit (P = 0.005).

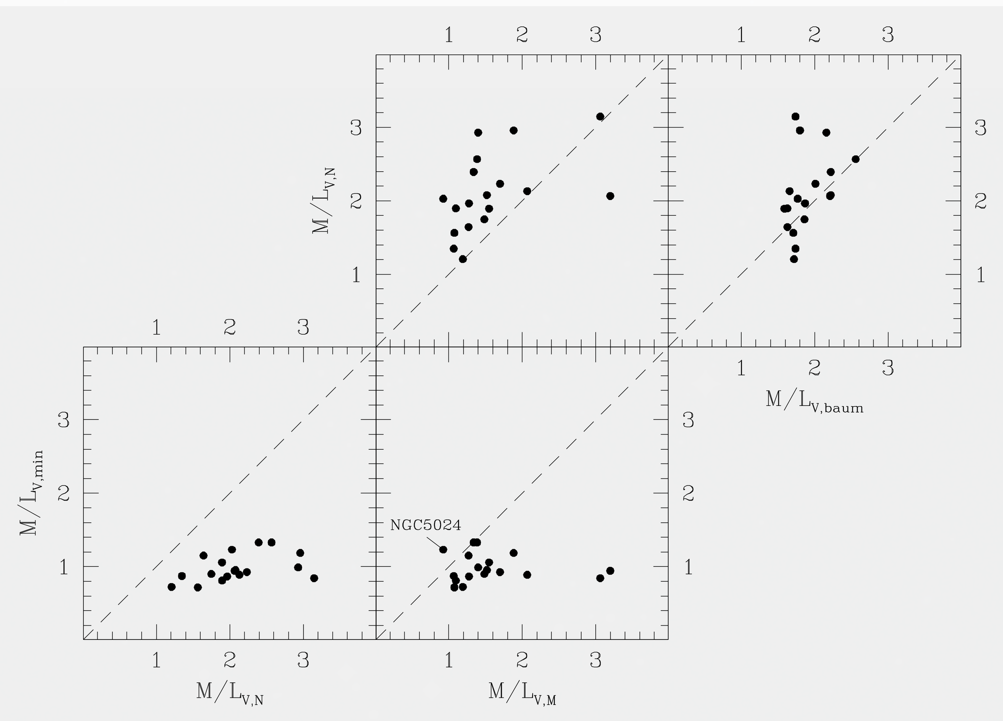

Figure 2: Comparison among different estimates of M/L (in solar units) for our sample of globular clusters (dots). In the upper panels we compare the best-fitting Newtonian M/L with that of QUMOND (left panel) and that of Baumgardt & Vasiliev (2021) (right panel). In the lower panels we compare the minimum $(M/L)_{min}$ with the best-fitting M/L of Newtonian (left panel) and QUMOND (right panel) models.

Comparison of models and observational data for the globular cluster NGC5024:

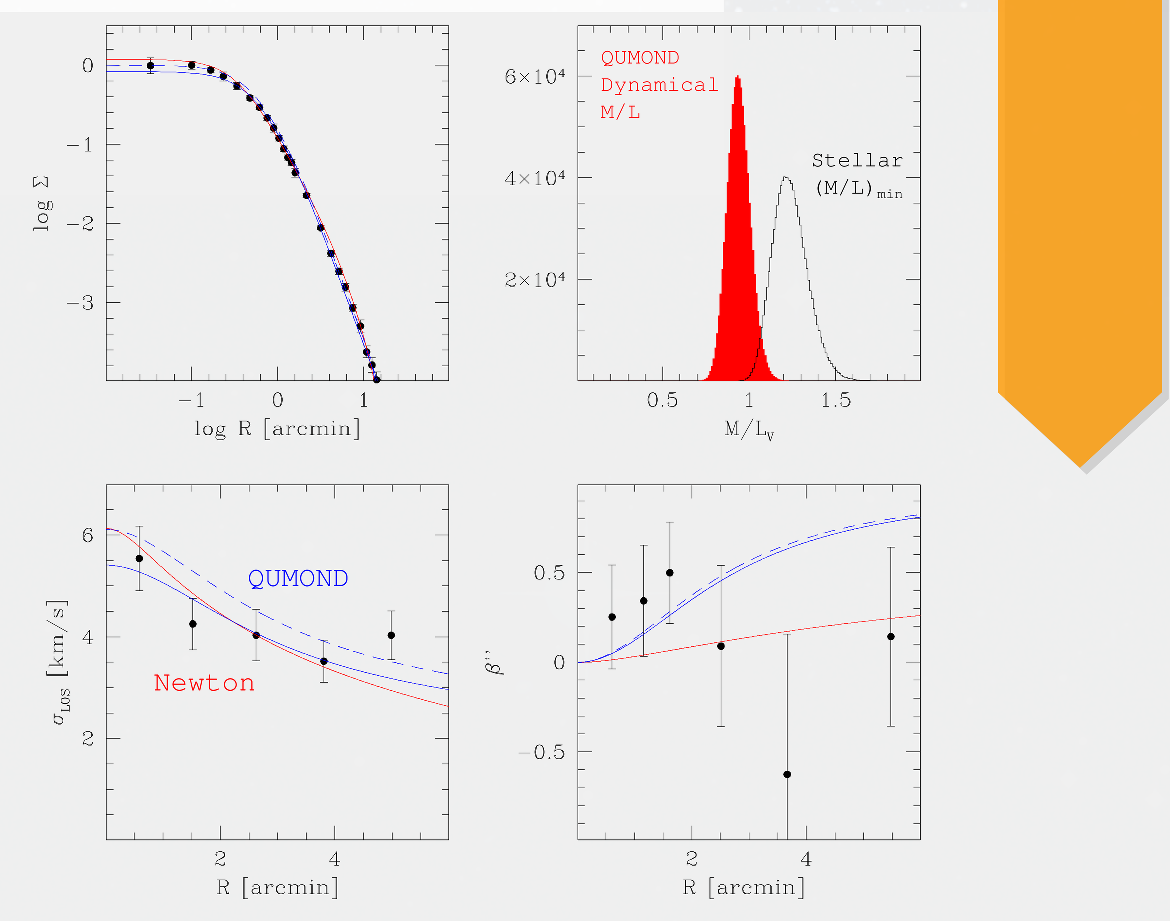

Figure 3: Projected density (upper left panel), LOS velocity dispersion (lower left panel), projected anisotropy parameter (lower right panel) profiles of the best-fitting Newtonian (red solid curves) and QUMOND (blue solid curves) models of NGC 5024. The dashed blue curve indicates the best-fitting QUMOND model assuming the minimum mass-to-light ratio $(M/L)_{min}$ = 1.232. The black dots mark binned observational data for comparison, but the analysis has been conducted using unbinned data. The probability distributions of M/L for QUMOND models and of $(M/L)_{min}$ are shown in the upper right panel with red and empty histograms, respectively. Mass-to-light ratios are in solar units.

Conclusions

None of the analysed globular clusters has a dynamical M/L formally incompatible (> 3σ) with the minimum $(M/L)_{min}$ prediction of stellar evolution models, although only one of them (NGC 5024) reaches a disagreement with the QUMOND prediction at 2.8σ.

Our results suggest that the kinematics of globular clusters in a relatively weak external field can be a powerful tool to prove alternative theories of gravitation.

Future modelling should also take mass segregation into account to obtain more accurate estimates and stronger constraints on the models.

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