Astrophysical observations preferring Modified Gravity

A natural approach to extended Newtonian gravity: tests and predictions across astrophysical scales.
Mon.Not.Roy.Astron.Soc. 411 (2011) 226-234
Wide binaries as a critical test of Classical Gravity. arXiv:1105.1873 [astro-ph.GA]
The outskirts of globular clusters as modified gravity probes. arXiv:1108.4021 [astro-ph.CO]

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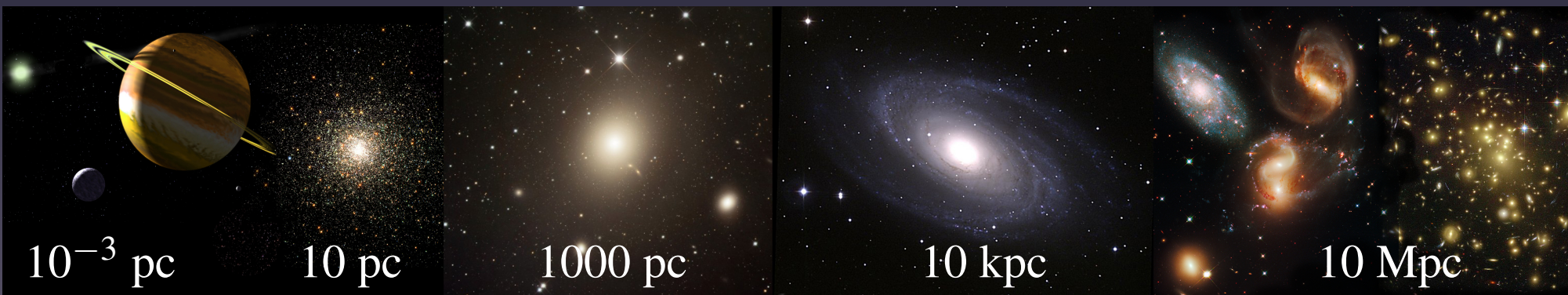
Where is Dark Matter required?

- Galactic rotation curves.
- Gravitational lensing and dynamics of clusters.
- Cosmological matter fraction requirements.

Where is gravity tested?

- Solar System dynamics
- Terrestrial experiments
- Particle accelerators



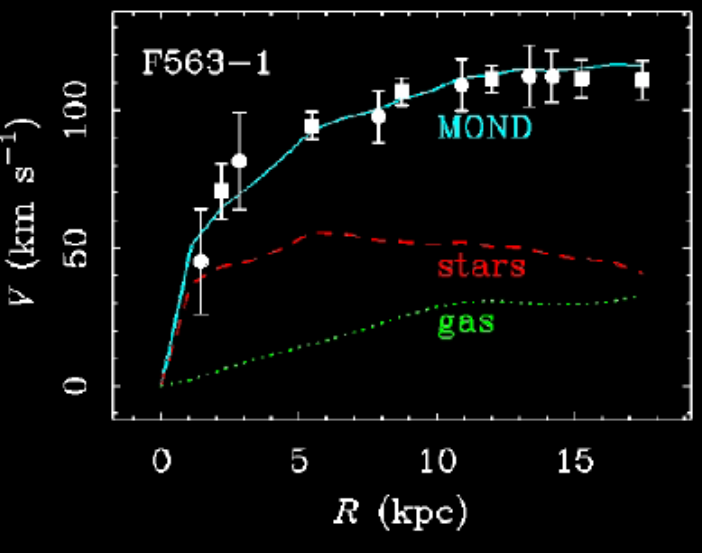
Room for alternatives

Modified Dynamics below $a_0 = 10^{-10}\,\mathrm{m/sec^2}$ (MoND)

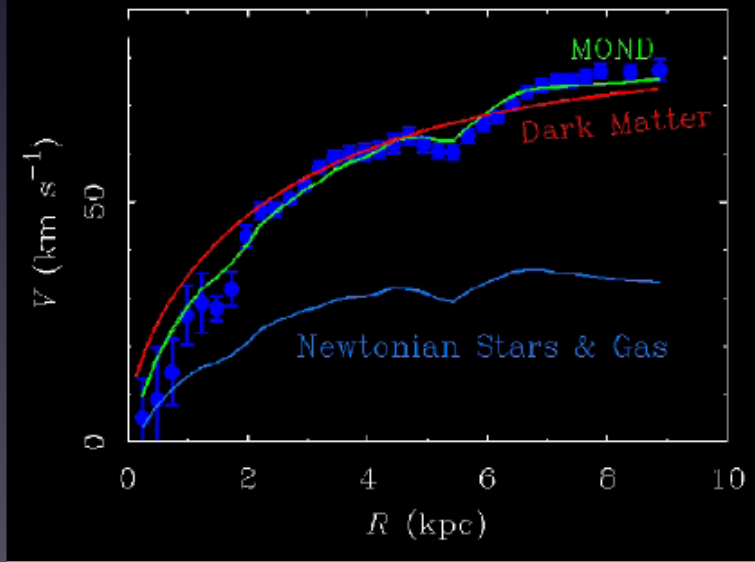
$$a \gg a_0. \quad \Rightarrow a = a_N, \qquad \frac{a}{a_0} = \left(\frac{GM}{a_0 r^2}\right),$$

$$a \ll a_0. \quad \Rightarrow a = (a_0 a_N)^{1/2}, \quad \frac{a}{a_0} = \left(\frac{GM}{a_0 r^2}\right)^{1/2},$$

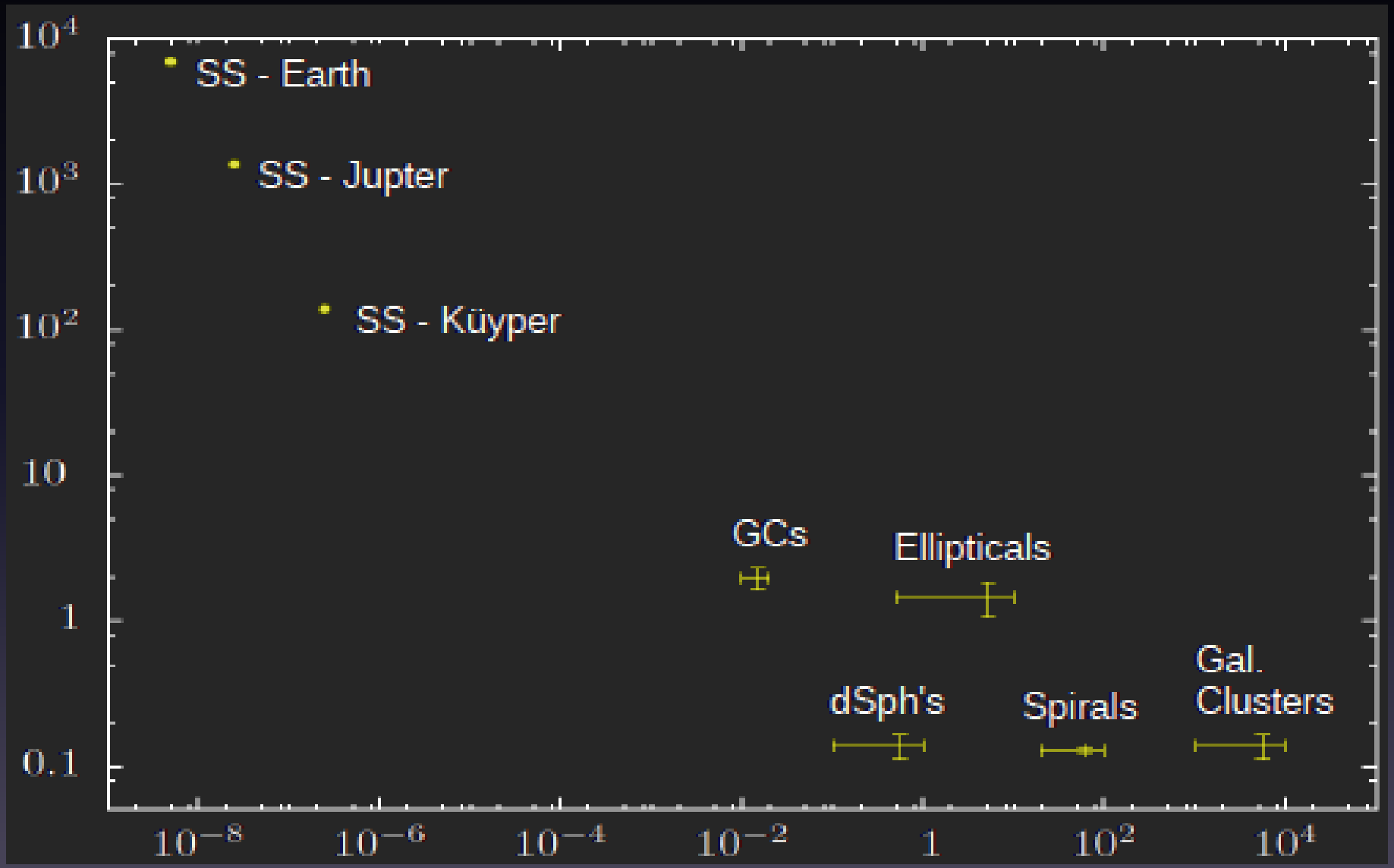
NGC 6946



NGC 1560



Astrophysical systems with $a \leq a_0$



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Modified gravity below a_0

Define $x \equiv \left(\frac{GM}{a_0 r^2}\right)^{1/2} \quad \Rightarrow \; g/a_0 = f(x)$

$$g \gg a_0,\; x \to \infty \;\Rightarrow\; g = g_{\rm N}, \qquad \frac{g}{a_0} = x^2,$$

$$g \ll a_0,\; x \to 0 \;\Rightarrow\; g = (a_0 g_{\rm N})^{1/2}, \qquad \frac{g}{a_0} = x,$$

General Interpolation Function

$$g/a_0 = f(x) = x\frac{1 - x^{n+1}}{1 - x^n}, \qquad n \geq 1.$$

Check-ups of modified gravity

Newton's Theorems

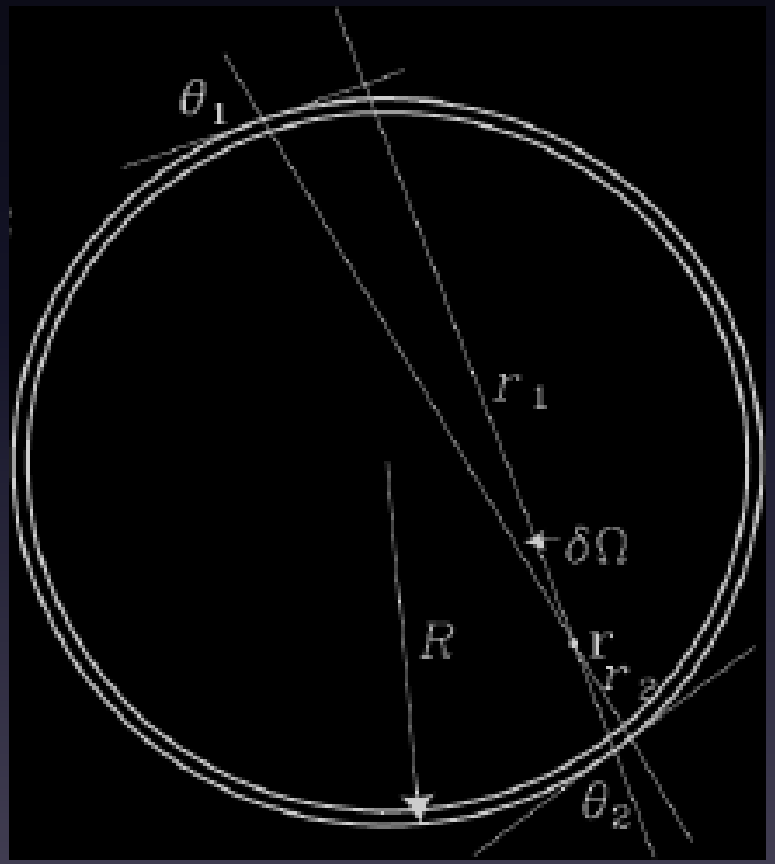
No net force from outer shells

$$\delta M_1/\delta M_2 = \rho r_1^2 \delta\Omega_1/\rho r_2^2 \delta\Omega_2 = r_1^2/r_2^2$$

$$\boxed{\left(\frac{\delta M_1}{\delta M_2}\right)^k = \left(\frac{r_1}{r_2}\right)^{2k}}$$

⋆ Accurate description of systems with spherical symmetry

⋆ Predictions for the outer radii of galactic systems



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Scaling laws in Equilibrium configurations

Tully-Fisher, Faber-Jackson and Fundamental Plane relations

Equilibrium Condition

$$\hat{P}_{\rm kin} = \rho(r)\sigma^2(r) = -g(r) = a_0 f(x)\Big|_r$$

- $\hat{P}_{\rm kin}$ Kinetic pressure per unit mass.
- $\sigma(r)$ – isotropic dispersion velocity (pressure supported sys.)
  – rotation velocity (angular momentum supported sys.)

Phenomenological description:

$$\sigma^2(r) = Cr^\beta M(r)^\gamma.$$

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Scaling laws in Equilibrium configurations

(Mendoza++,11) (Hernandez++,10)

Equilibrium Condition

$$\hat{P}_{\rm kin} = \rho(r)\sigma^2(r) = -g(r) = a_0 f(x)\Big|_r$$

$$\sigma^2(r) = C r^{\beta} M(r)^{\gamma} = (GMa_0)^{1/2}\,\frac{1-x^4}{1-x^3}$$

Theoretical prescription:

$$\beta = 2 - 4\gamma = \begin{cases} 1/2 & \text{if } g \gg a_0; \\ 0 & \text{if } g \ll a_0. \end{cases}$$

Fundamental plane + Tully-Fisher + Faber-Jackson + Scaling law for dSph.

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Probes for gravity

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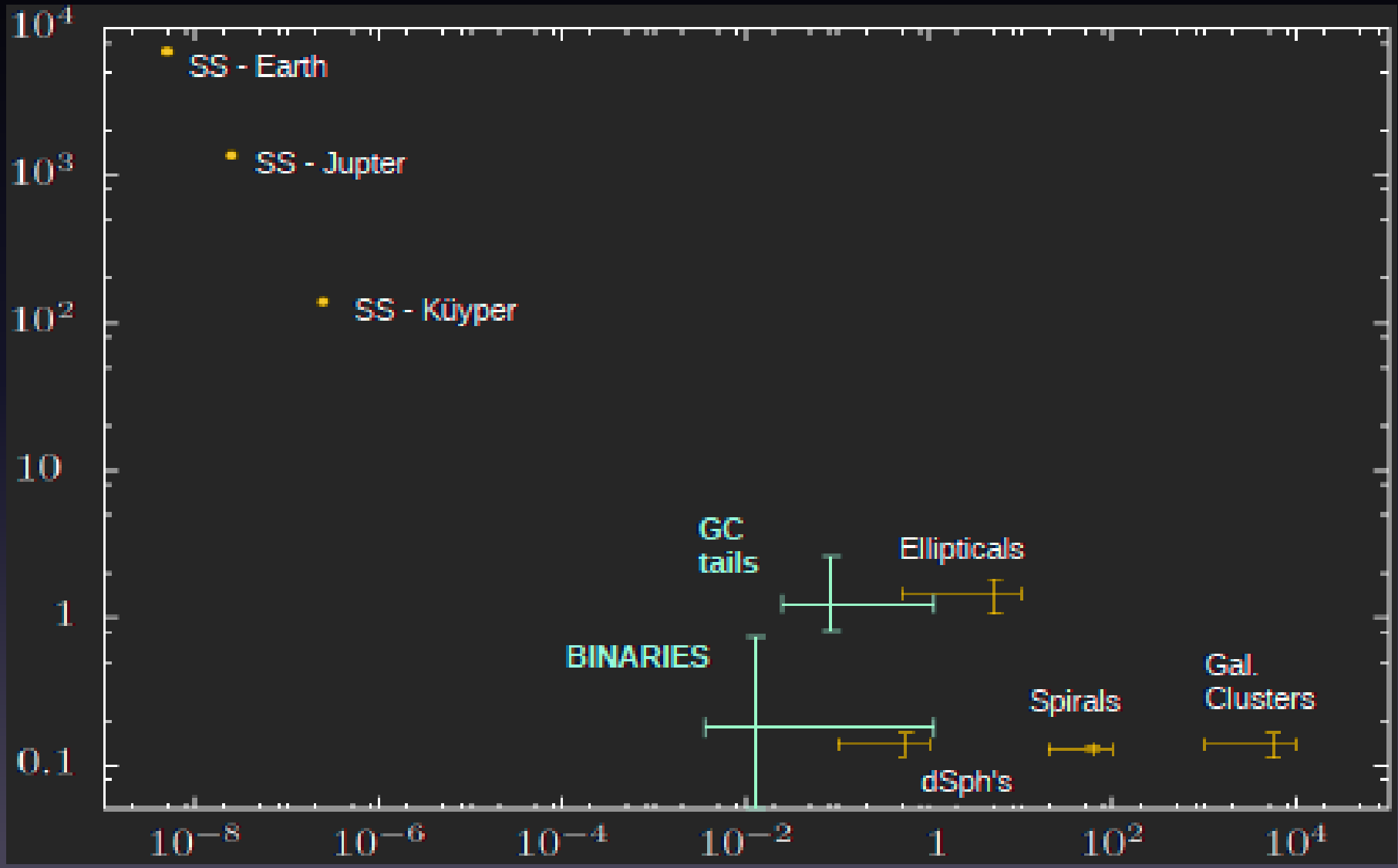
New probes for gravity



$\log(a/a_0)$

$\log(\text{Size}/1\text{kpc})$

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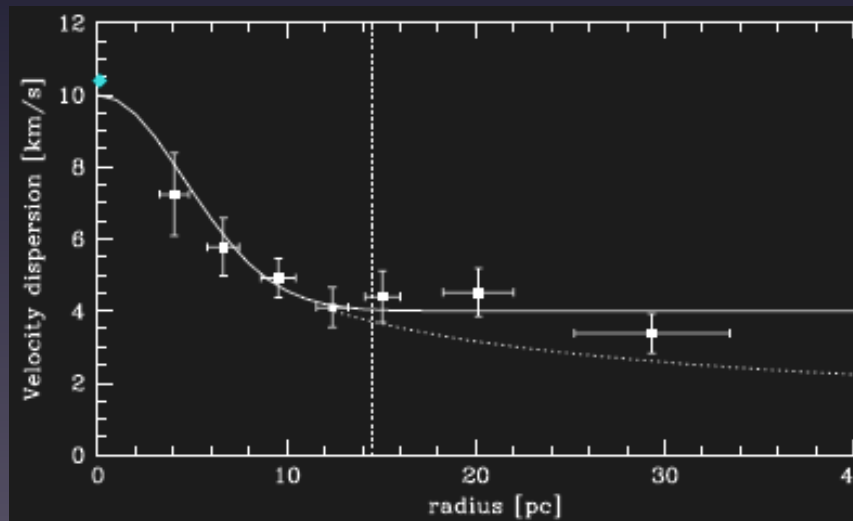
Scaling law for Globular Clusters

(Scarpa++,07)

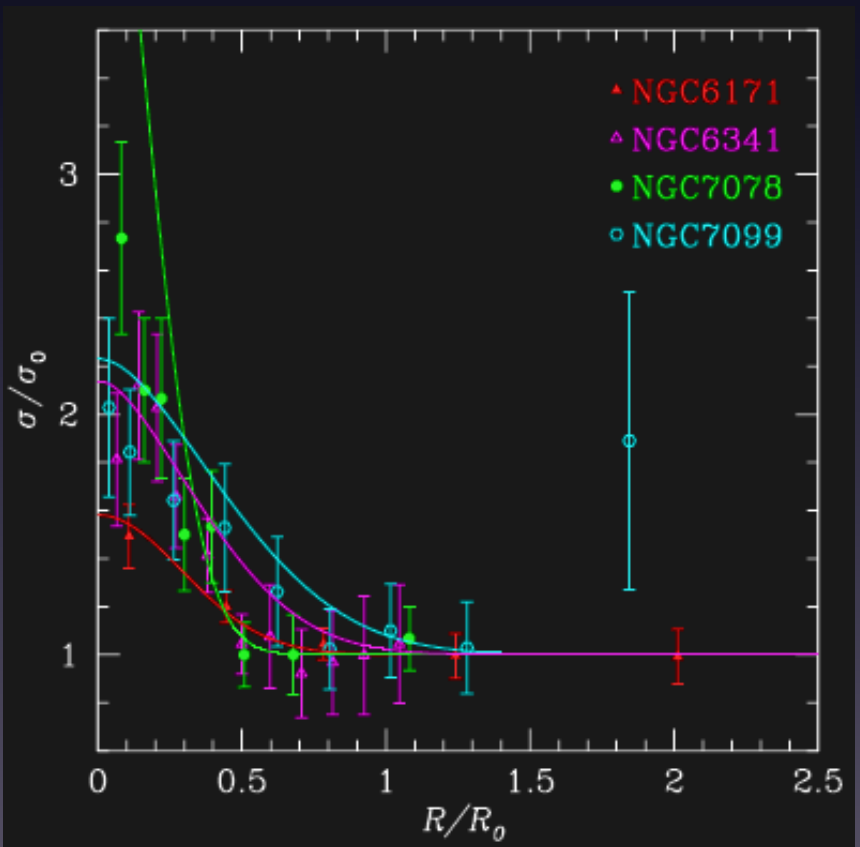
- Keplerian fall not observed

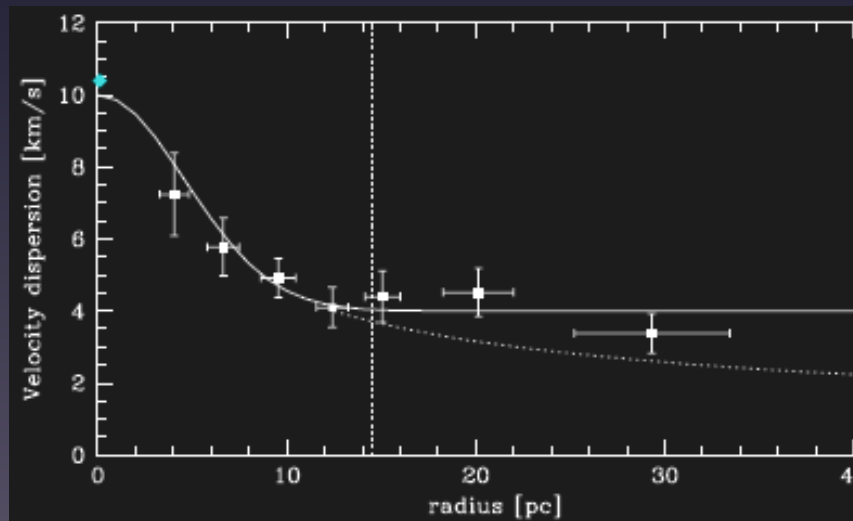


Modified Dynamics for Globular Clusters

(Scarpa++,11)...

- Keplerian fall not observed

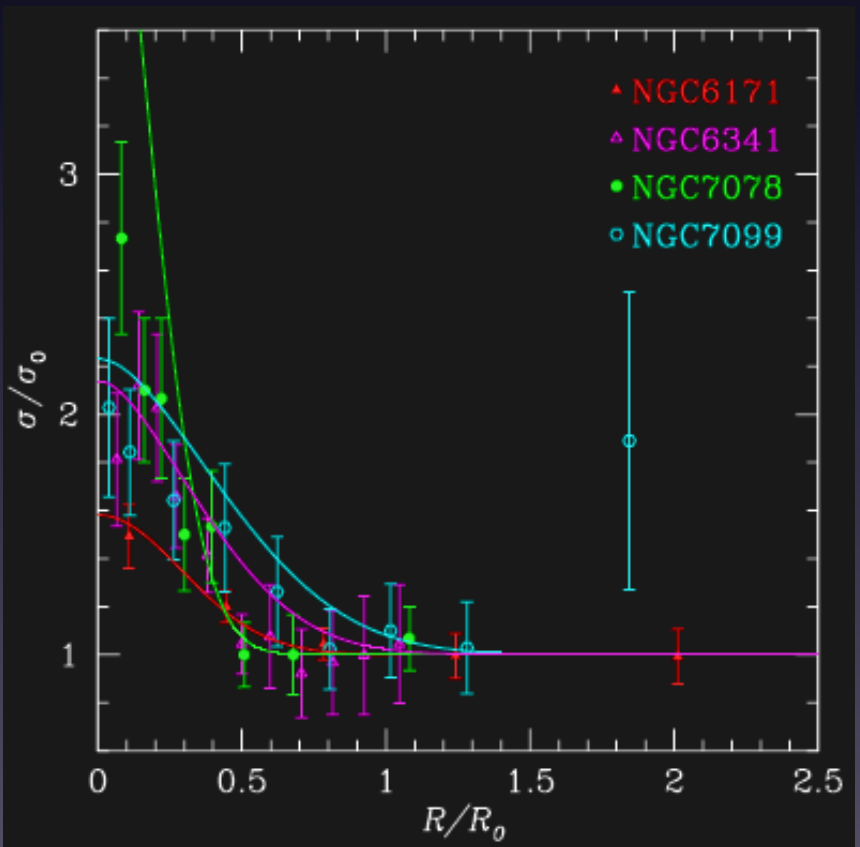


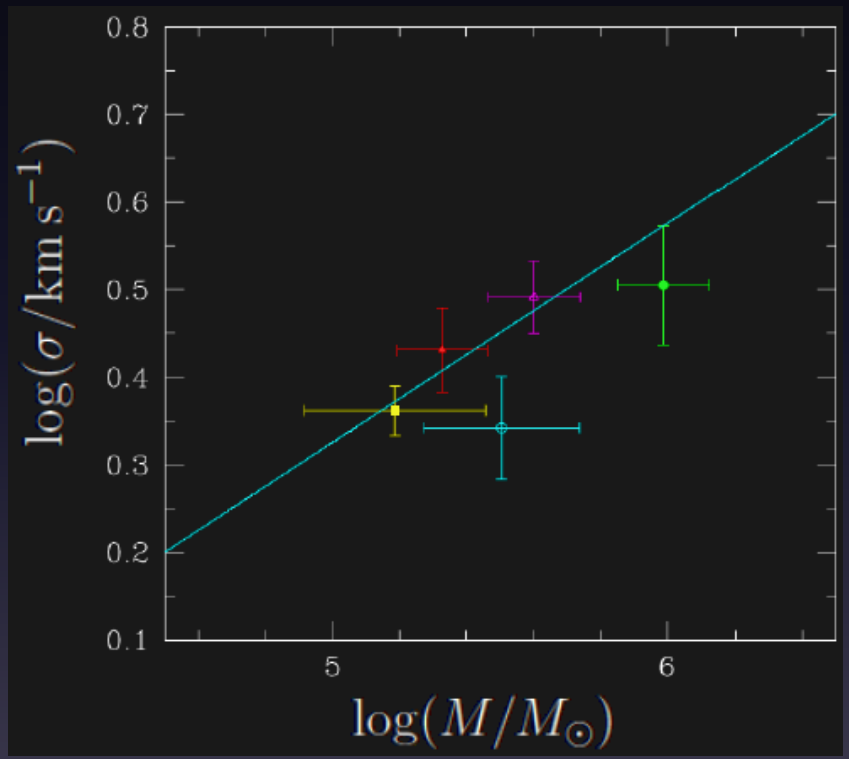


Scaling law for Globular Clusters

(Hernandez+Jimenez,11)

- Keplerian fall not observed
- A Faber-Jackson-like scaling law





$$\sigma/\sigma_0 = (M/M_\odot)^{1/4}$$

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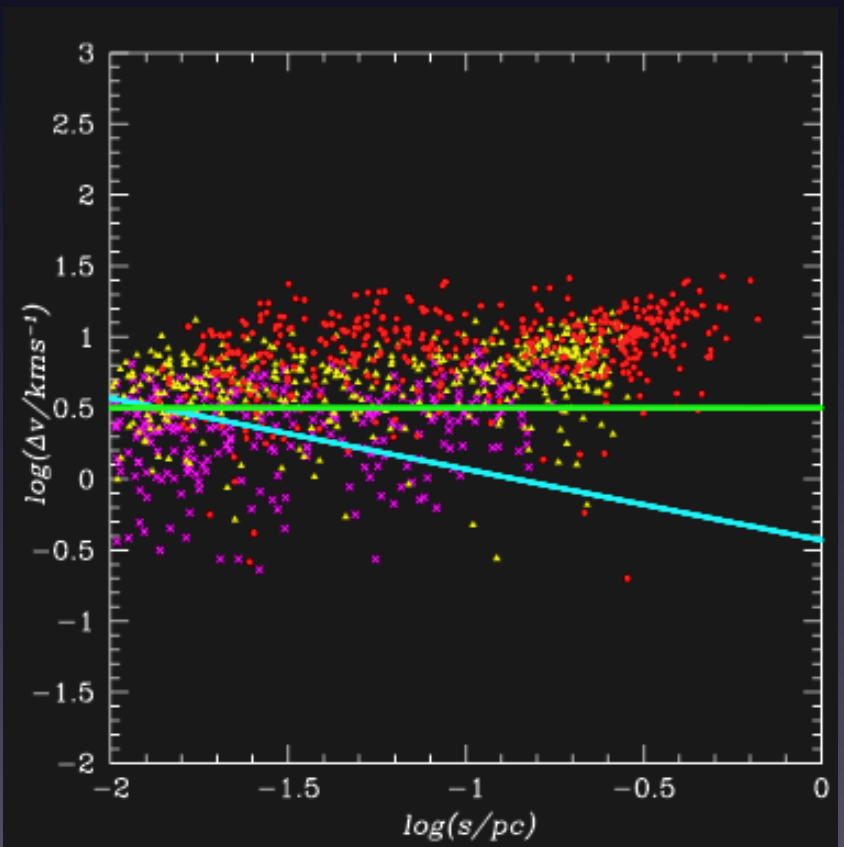
Projected velocity of wide binaries

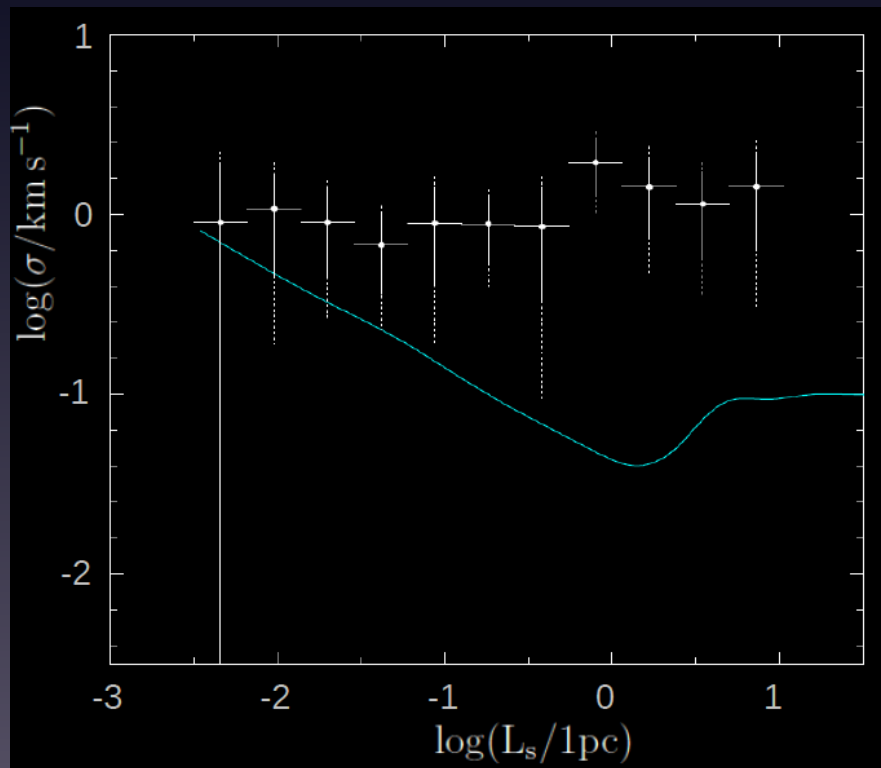
Tidal stability of binaries under the galactic field (Jiang+Tremaine,10)

Stability criterion

$$\frac{dF_{\rm gal}}{dR}\Delta r = F_{\rm int} = GM_{\rm sat}^2/\Delta r^2$$

- Δr Separation of binary stars
- $M_{\rm sat}$ Mass of binary stars
- $\rho_{\rm sat} \equiv (4\pi/3)M_{\rm sat}(\Delta r)^{-3}$





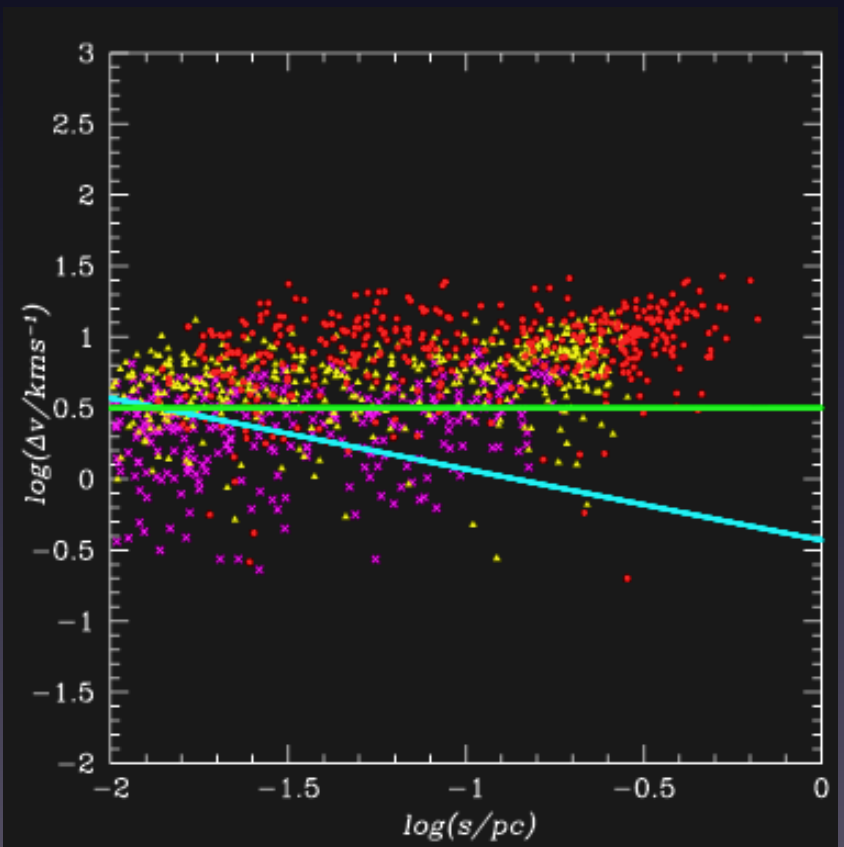
Projected velocity of wide binaries

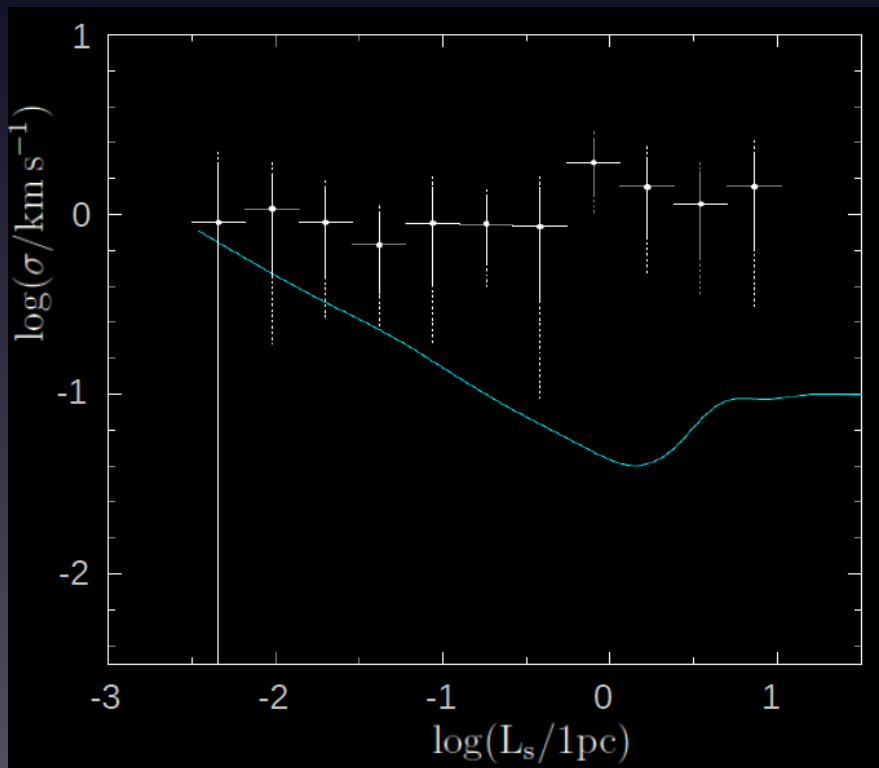
Modified gravity signature (Hernandez++,11)

Stability criterion

$$\frac{dF_{\rm gal}}{dR}\Delta r = F_{\rm int} = GM_{\rm sat}^2/\Delta r^2$$

- Newtonian stability for the system
  $\rho_{\rm sat} > \bar{\rho}$, $(\Delta_v \propto (\Delta r)^{-1/2})$
- Under modified gravity
  $\rho_{\rm sat} > (\Delta r/R)\,\bar{\rho}$, $(\Delta_v = \text{const.})$





Modified (Extended) Gravity

Features

- Valid and testable theory (e.g. no *dark matter above* a_0).
- Consistent description of galactic dynamics.
- Sensible explanation of phenomena in binary systems and globular clusters where no DM is expected.

Shortcomings

- No covariant relativistic counterpart to account for lensing or cosmology.
- No easy prescription for a universal gravitational potential (no simple n-body simulations).
- Description of Galaxy Clusters requires neutrino dark matter.

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