Dynamics of disk and elliptical galaxies in Refracted Gravity

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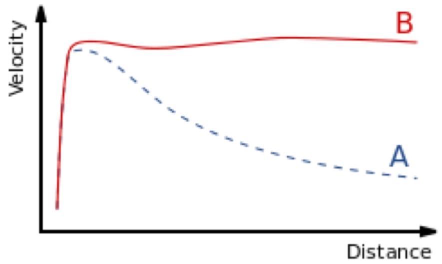
1. Introduction

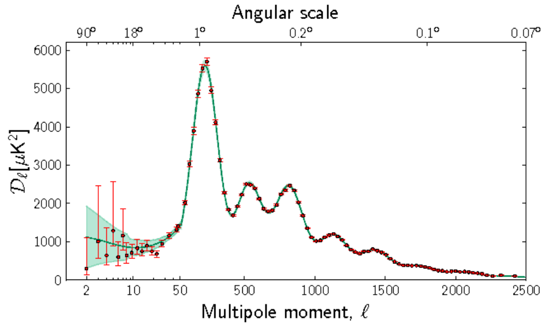
Coma cluster NASA's Spitzer Space Telescope.



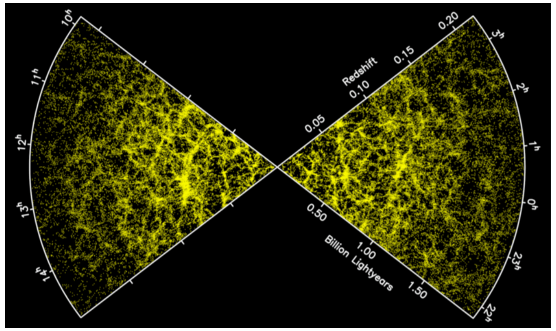
$v(R)$ trend expected (A, keplerian fall) and observed (B) wikipedia.org.

MASS DISCREPANCY PROBLEM

80—90%



CMB power spectrum physics.stackexchange.com.



Large scale structure roe.ac.uk.

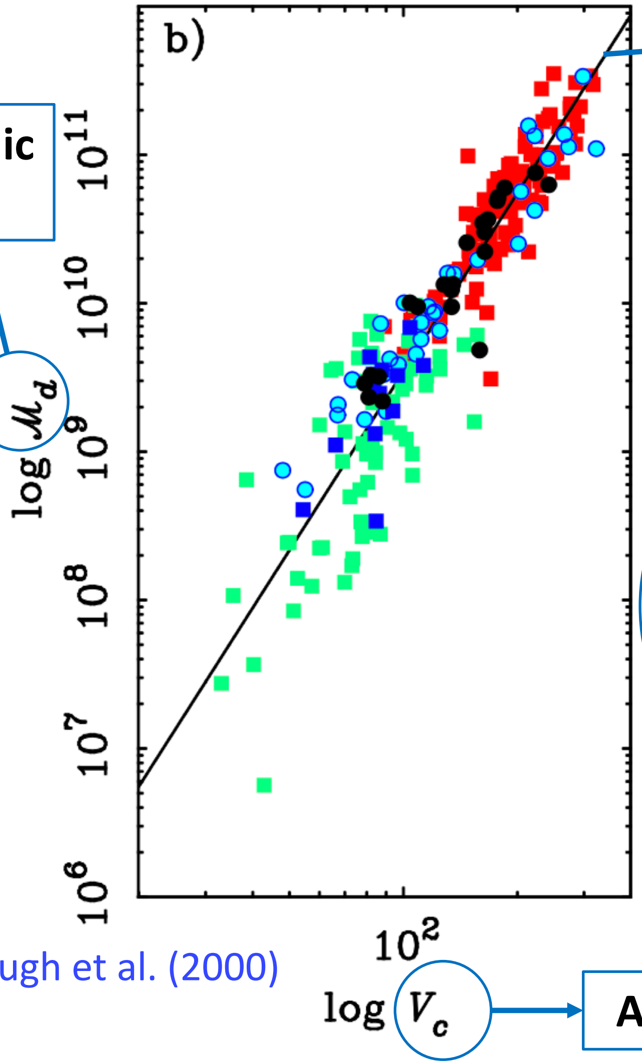
DARK MATTER

MODIFIED GRAVITY

WHY MODIFIED GRAVITY?

BARYONIC TULLY-FISHER RELATION

Baryonic mass



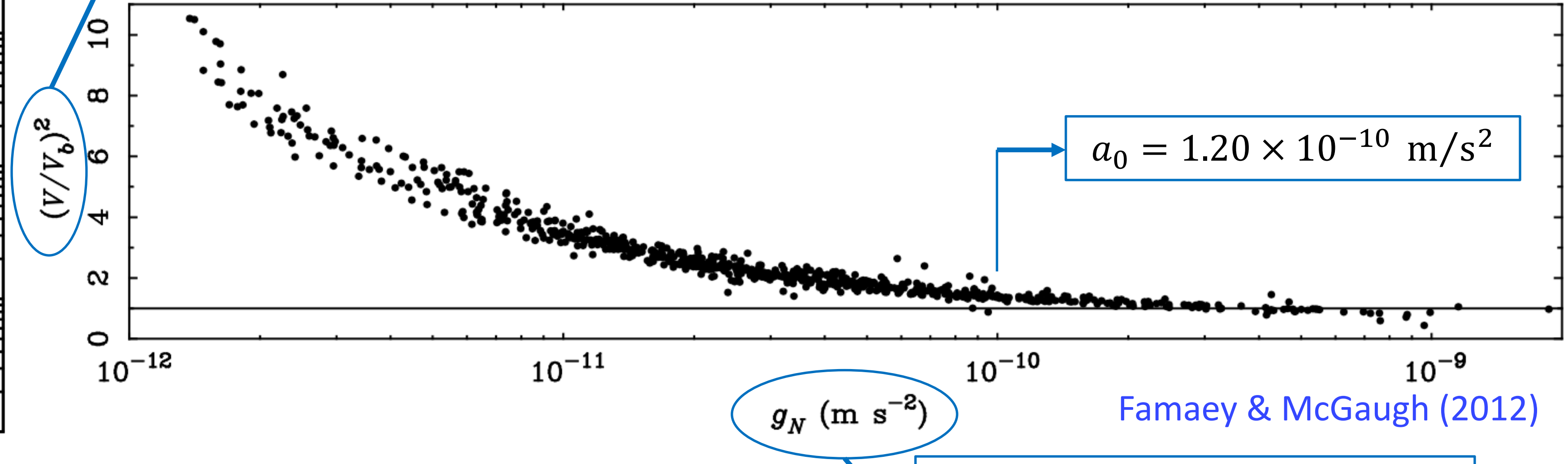
McGaugh et al. (2000)

Asymptotic flat rotation velocity

$$M_{\mathrm{d}} = A V_{\mathrm{c}}^4$$
$$A = 47 \pm 6 \frac{M_{\odot}\mathrm{s}^4}{\mathrm{km}^4} \sim (G a_0)^{-1}$$
$$a_0 = 1.20 \times 10^{-10}\ \mathrm{m/s^2}$$

Mass discrepancy $= \left(\frac{v_{\mathrm{observed}}}{v_{\mathrm{baryonic}}}\right)^2$

MASS DISCREPANCY-ACCELERATION RELATION



$a_0 = 1.20 \times 10^{-10}\ \mathrm{m/s^2}$

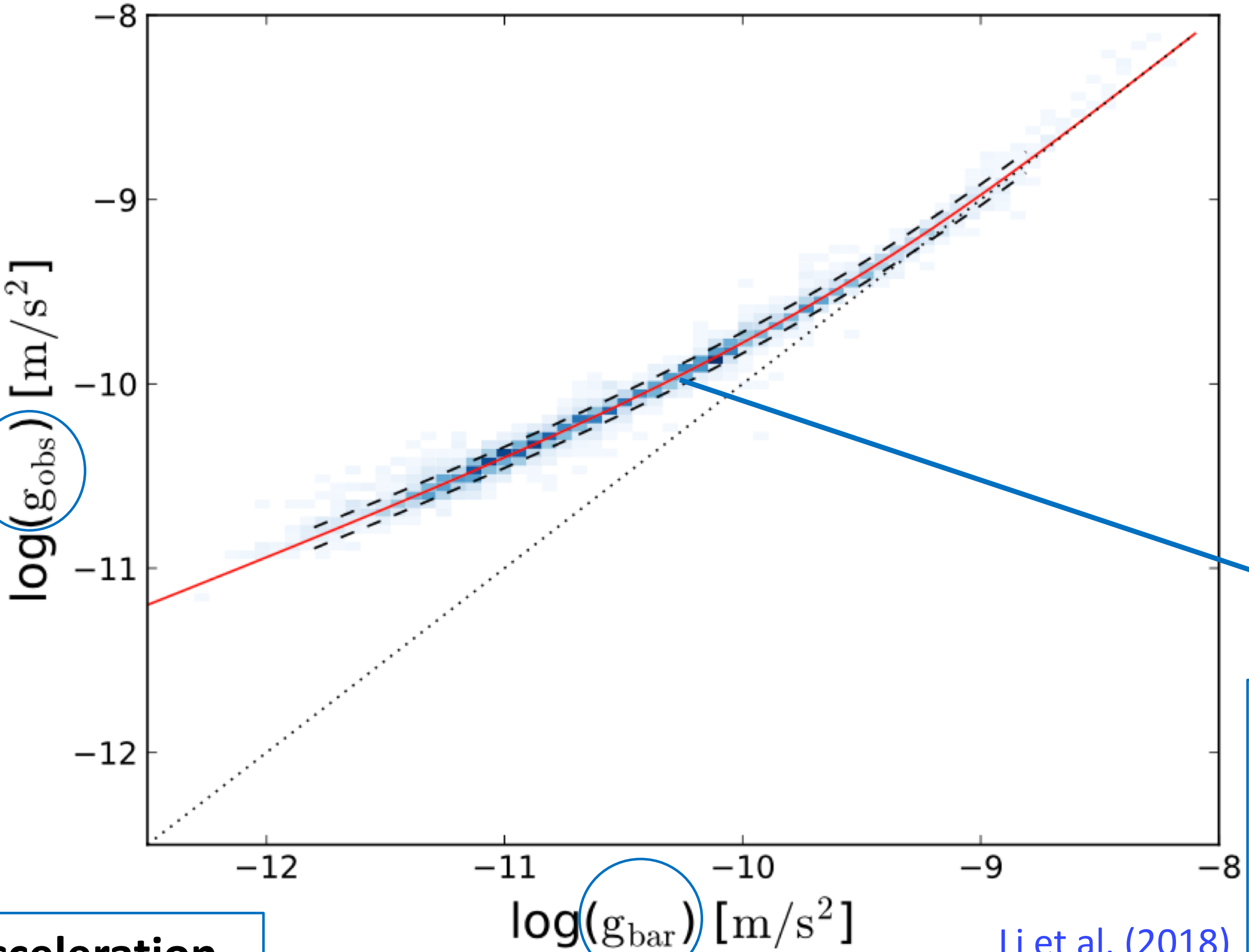
Famaey & McGaugh (2012)

Newtonian acceleration due to baryons

$$\frac{\partial \phi_{\mathrm{N}}}{\partial R} \leftarrow \nabla^2 \phi_{\mathrm{N}} = 4\pi G \rho$$

RADIAL ACCELERATION RELATION

Centripetal acceleration $= \dfrac{v_{\rm obs}(R)^2}{R}$



Li et al. (2018)

$$g_{\rm obs}(R) = \frac{g_{\rm bar}(R)}{1 - \exp\left(-\sqrt{g_{\rm bar}(R)/g_\dagger}\right)}$$

$$g_\dagger = 1.20 \times 10^{-10}\ \mathrm{m/s^2} \simeq a_0$$

McGaugh et al. (2016)

Newtonian acceleration due to baryons

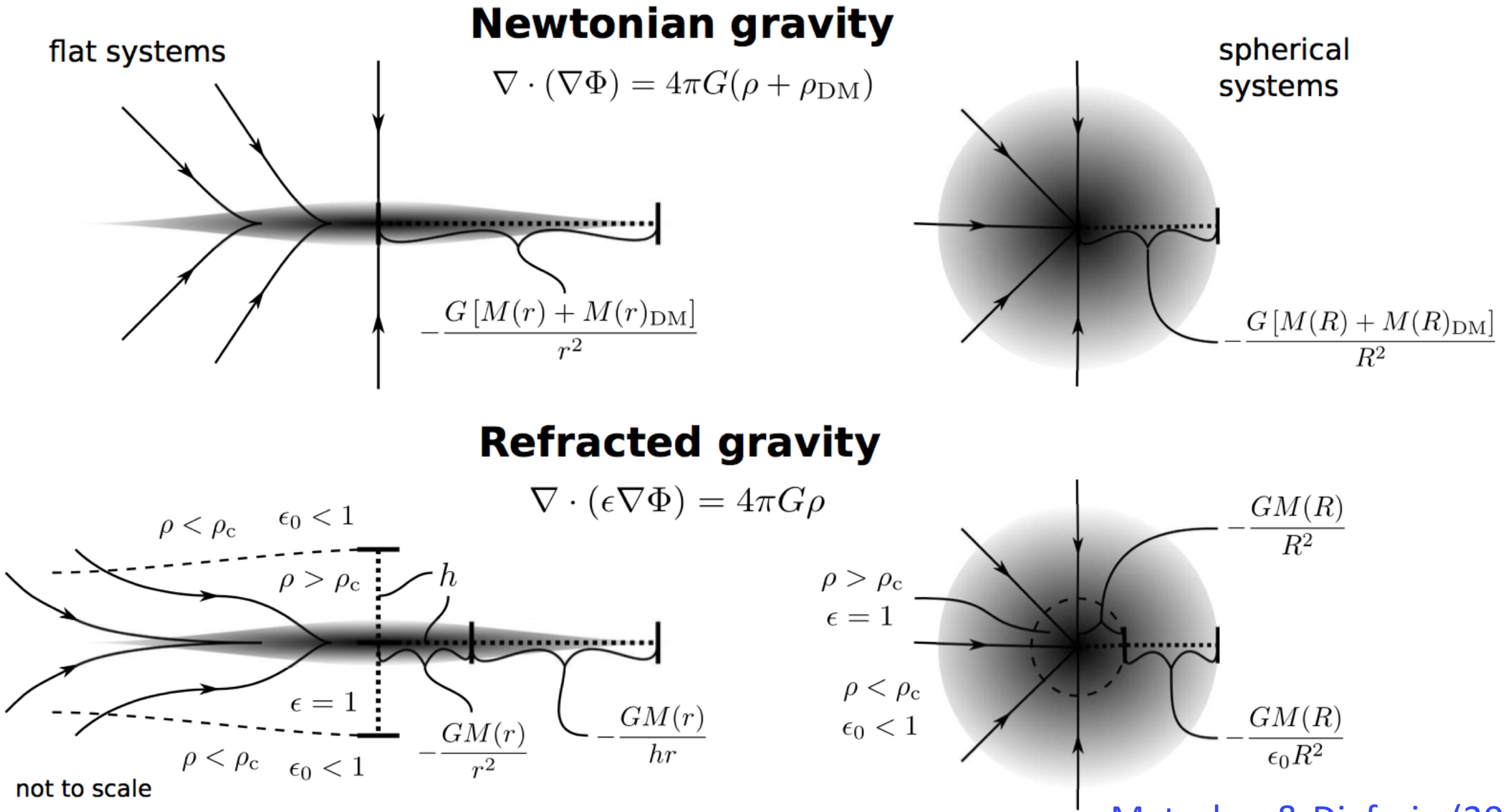
$$\frac{\partial \phi_{\rm N}}{\partial R} \leftarrow \nabla^2 \phi_{\rm N} = 4\pi G \rho$$

2. Refracted Gravity (RG)

Classic theory of gravity inspired to electrodynamics in matter not resorting to dark matter

DARK MATTER PRESENCE

FIELD LINES FOCUSSING



Matsakos & Diaferio (2016)

MODIFIED POISSON EQUATION

$$\nabla \cdot [\epsilon(\rho)\nabla\phi] = 4\pi G\rho$$

GRAVITATIONAL PERMITTIVITY

$$1 \quad \text{for} \quad \rho \gg \rho_c$$

$$\epsilon_0 \quad \text{for} \quad \rho \ll \rho_c$$

$$0 < \epsilon_0 \leq 1$$

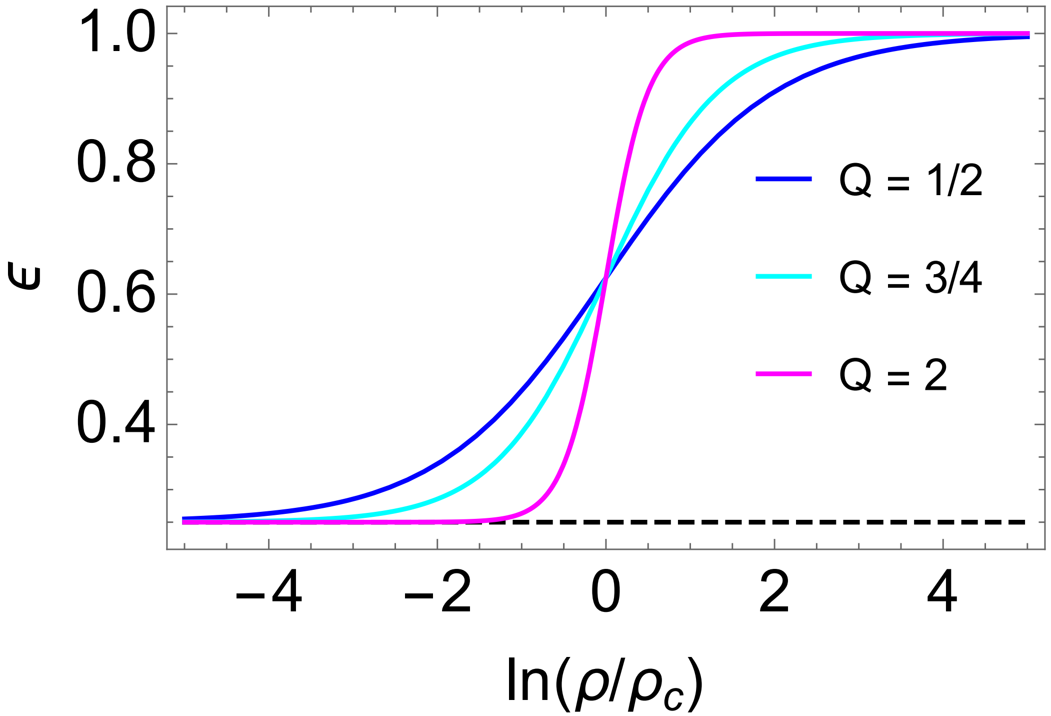
Matsakos & Diaferio (2016)

Arbitrary choice for the gravitational permittivity $\epsilon(\rho)$

$$\epsilon(\rho) = \epsilon_0 + (1 - \epsilon_0)\frac{1}{2}\left\{\tanh\left[\ln\left(\frac{\rho}{\rho_c}\right)^Q\right] + 1\right\}$$

with $\{\epsilon_0, Q, \rho_c\}$ free universal parameters

Matsakos & Diaferio (2016), **Cesare et al. (2020b)**



Cesare et al. (2020b)

3. Disk galaxies: the DiskMass Survey

- Analysis in **Cesare et al. (2020b)**
- 30 disk galaxies from the **DiskMass Survey (DMS)** (Bershady et al. 2010a)
- Density model:
  - a) **Stellar disk**: $\rho_{\rm d}(R,z) = \frac{\Upsilon}{2h_z} I_{\rm d,interp}(R)\exp\left(-\frac{|z|}{h_z}\right)$
  - b) **Spherical stellar bulge**: $\rho_{\rm b}(r) = -\frac{\Upsilon}{\pi}\int_r^{+\infty}\frac{{\rm d}I_{\rm b}(R)}{{\rm d}R}\frac{{\rm d}R}{\sqrt{R^2-r^2}}$, where

$$I_{\rm b}(R) = I_{\rm e}\exp\left\{-7.67\left[\left(\frac{R}{R_{\rm e}}\right)^{1/n_{\rm s}} - 1\right]\right\}$$

  - c) **Atomic and molecular gas**: $\rho_{\rm atom,mol}(R,z) = \Sigma_{\rm atom,mol,interp}(R)\,\delta(z)$

- Successive Over Relaxation **Poisson solver** to obtain RG potential
- **MCMC** to estimate the M/L, Υ, the disk-scale height, h_z, and the three RG parameters, ϵ_0, Q and ρ_c
  - ➢ From rotation curves
  - ➢ From rotation curves and vertical velocity dispersions

UGC 7917

Bershady et al. (2010a)

3.1 Rotation curves and vertical velocity dispersions

$$\nabla \cdot [\epsilon(\rho)\nabla\phi] = 4\pi G\rho$$

$$\phi$$

ROTATION CURVE

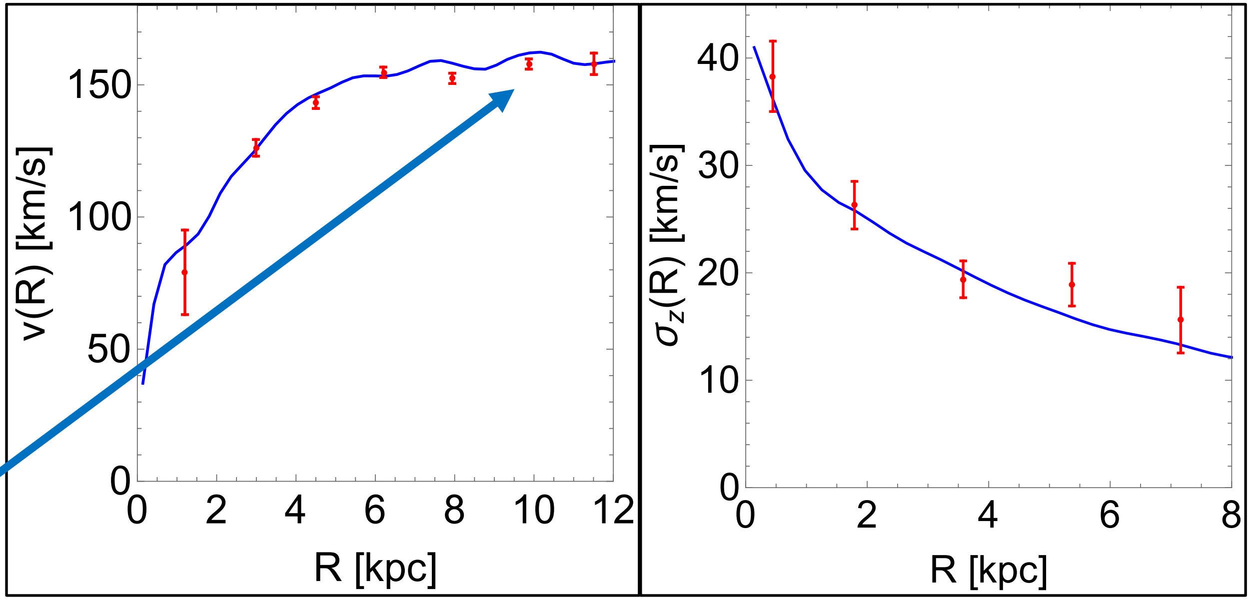
$$v(R, z=0) = \sqrt{R\frac{\partial\phi(R,z)}{\partial R}}$$

VERTICAL VELOCITY DISPERSION PROFILE

$$\sigma_z^2(R) = \frac{1}{h_z}\int_0^{+\infty}\left[\int_z^{+\infty}\exp\left(-\frac{|z'|}{h_z}\right)\frac{\partial\phi(R,z')}{\partial z'}\mathrm{d}z'\right]\mathrm{d}z$$

From Jeans analysis
(Nagai & Miyamoto 1976; Nipoti et al. 2007)

UGC 3091

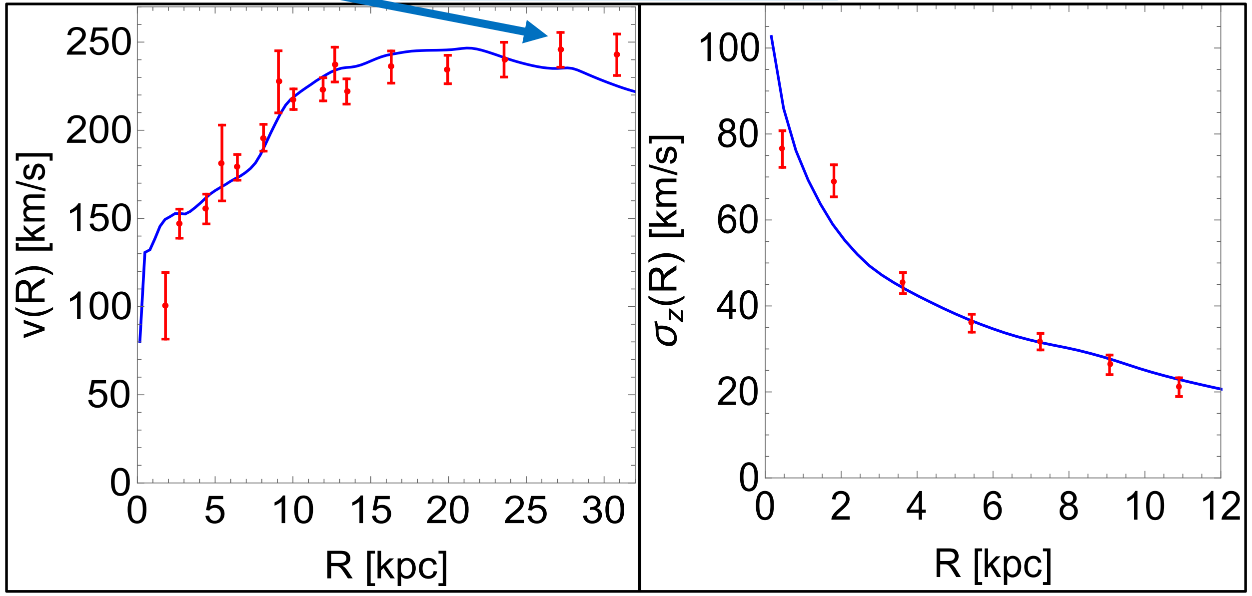


Flat trend recovered

Renzo's rule

Good description of kinematic profiles

UGC 4256

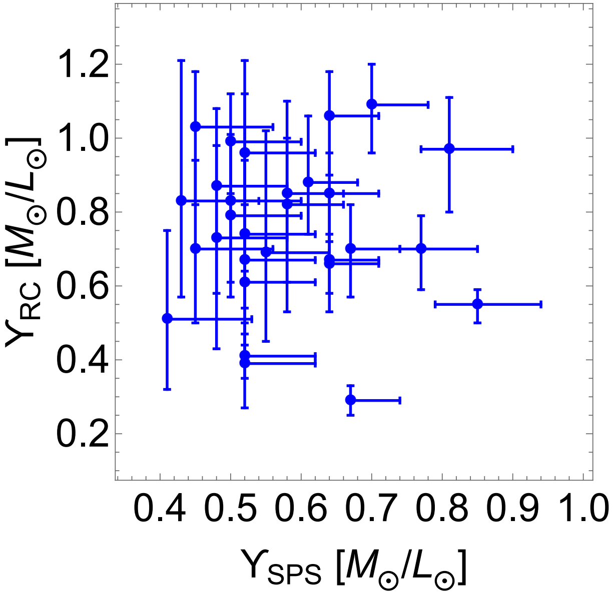


Cesare et al. (2020b)

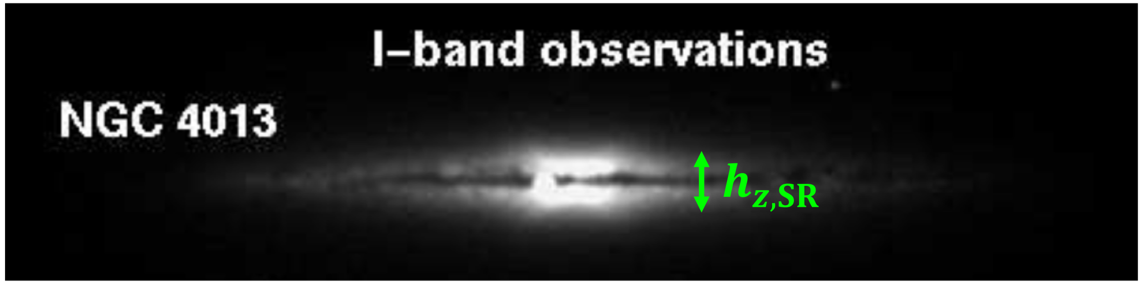
ROTATION CURVES ALONE

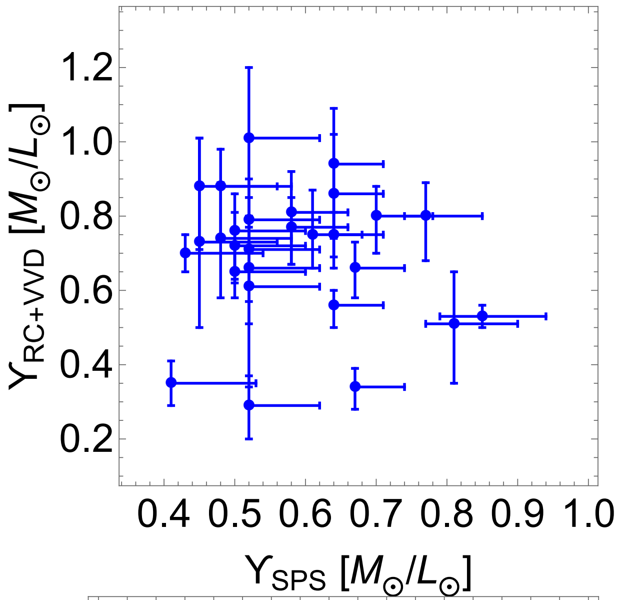
Cesare et al. (2020b)

ROTATION CURVES AND VERTICAL VELOCITY DISPERSIONS

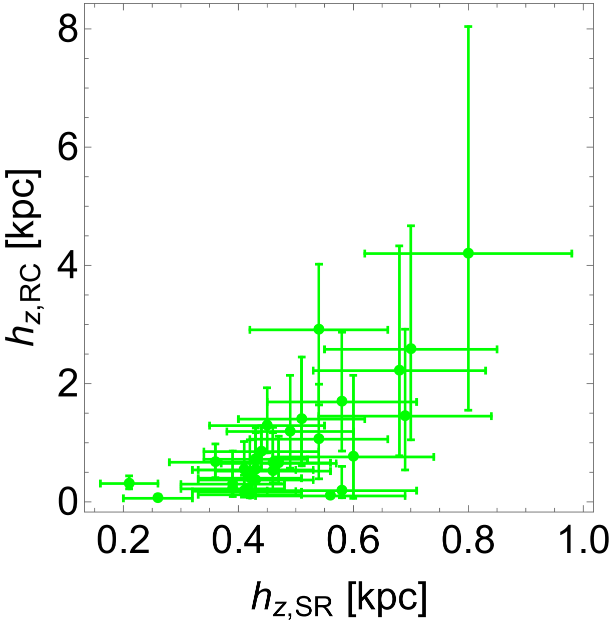


Good agreement with SPS models in both cases





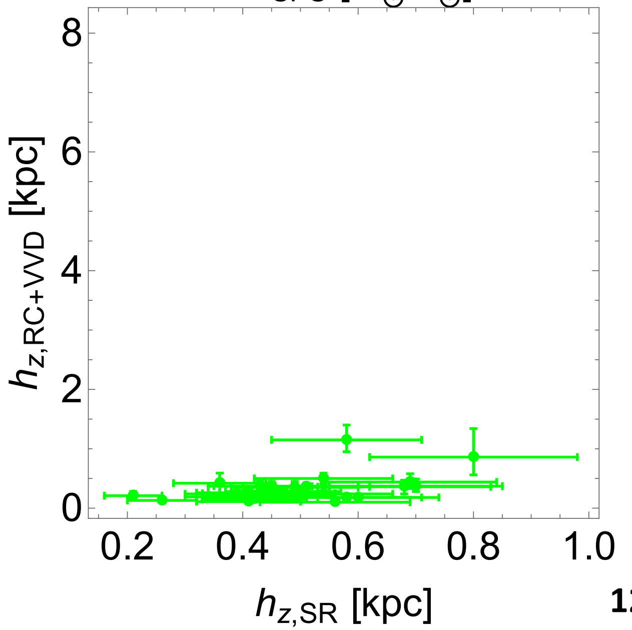
Xilouris et al. (1999)



h_z decreases

Same result in Angus et al. (2015) with QUMOND

Observational bias
(Milgrom 2015, Aniyan et al. 2016)



3.2 A universal combination of RG parameters

- $\{\epsilon_0, Q, \rho_c\}$ **FREE UNIVERSAL PARAMETERS**

IDEAL APPROACH

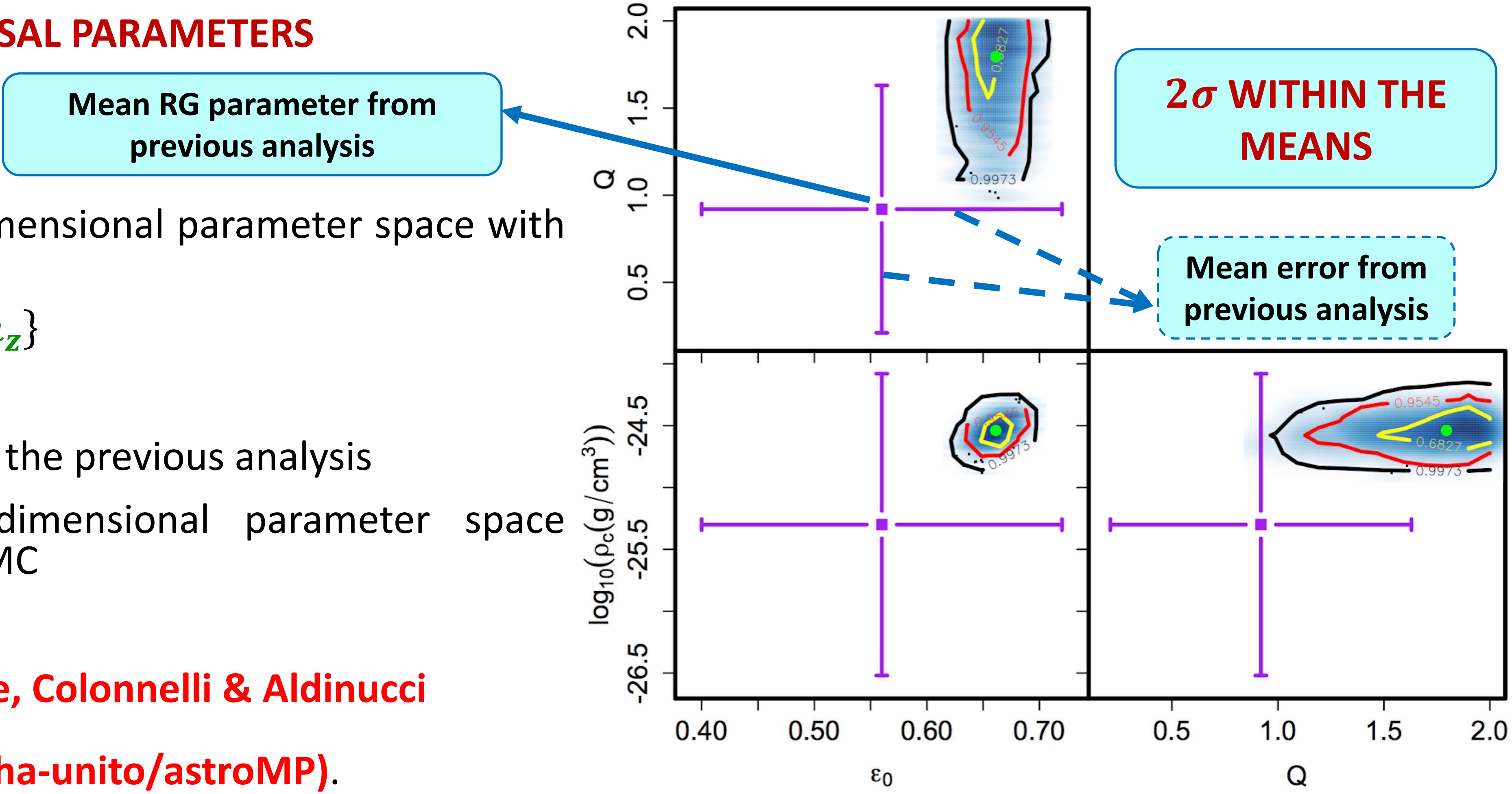
- Exploration of the 63-dimensional parameter space with the MCMC:

  $\{\epsilon_0, Q, \rho_c\} + 2\times 30\,\{\Upsilon, h_z\}$

ADOPTED APPROACH

- Υ and h_z estimated with the previous analysis
- Exploration of the 3-dimensional parameter space $\{\epsilon_0, Q, \rho_c\}$ with the MCMC

- Parallel code from **Cesare, Colonnelli & Aldinucci (2020a)** and on GitHub **(https://github.com/alpha-unito/astroMP)**.



Cesare et al. (2020b)

3.3 The Radial Acceleration Relation

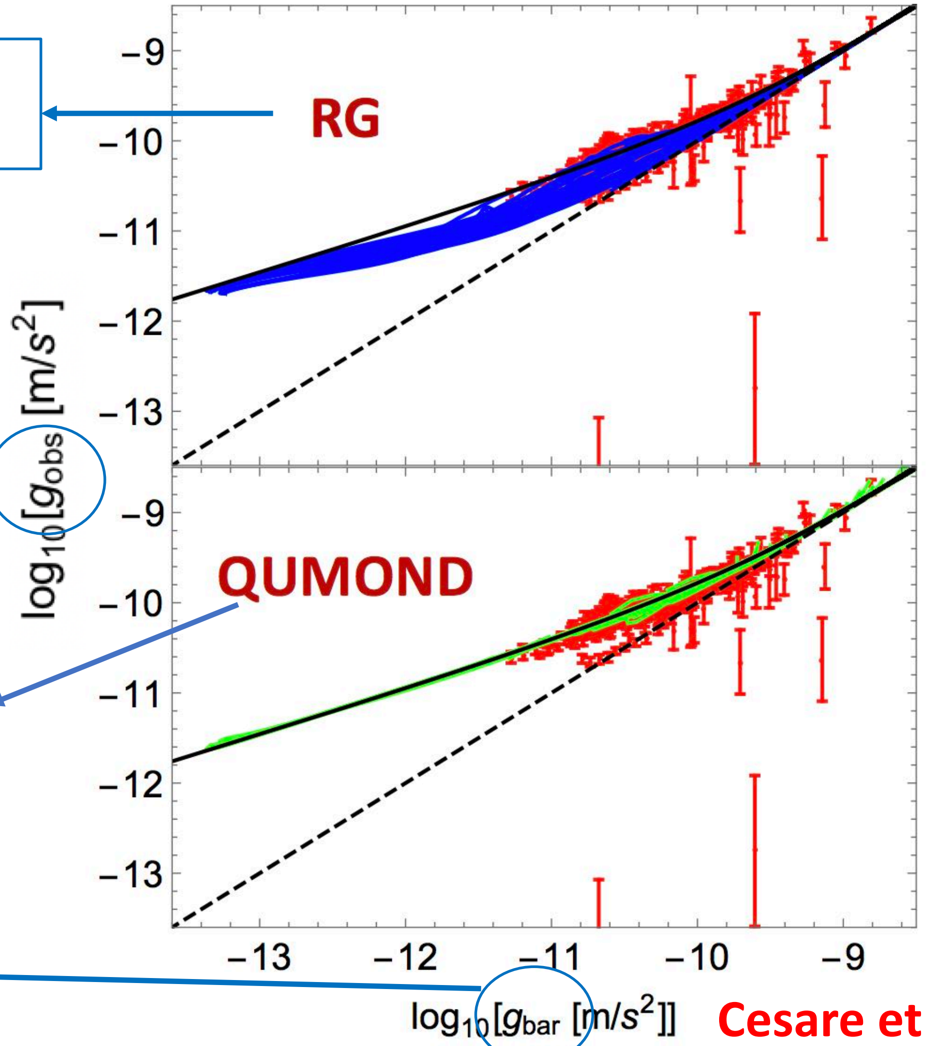
$$\frac{\partial \phi_{\mathrm{RG}}}{\partial R} \leftarrow \nabla \cdot [\epsilon(\rho)\nabla\phi] = 4\pi G\rho$$

$$\frac{v_{\mathrm{obs}}(R)^2}{R}$$

$$\frac{\partial \phi_{\mathrm{QUMOND}}}{\partial R} \leftarrow \nabla^2 \phi_{\mathrm{QUMOND}} = \nabla \cdot \left[\nu\left(\frac{|\nabla\phi_{\mathrm{N}}|}{a_0}\right)\nabla\phi_{\mathrm{N}}\right]$$

$$\nu\left(\frac{|\nabla\phi_{\mathrm{N}}|}{a_0}\right) = \frac{1}{2}\left(1 + \sqrt{1 + \frac{4}{|\nabla\phi_{\mathrm{N}}|/a_0}}\right)$$

$$\frac{\partial \phi_{\mathrm{N}}}{\partial R} \leftarrow \nabla^2\phi_{\mathrm{N}} = 4\pi G\rho$$



Cesare et al. (2020b)

Correlation between RAR residuals and galaxy properties

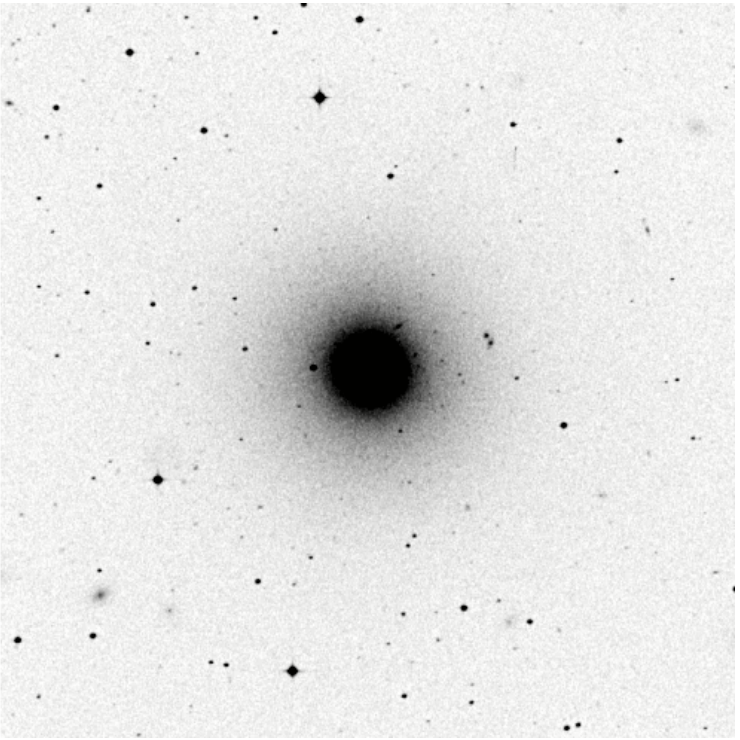
Sample dependence or RG issue?

SCATTER OF THE RAR

4. Elliptical galaxies: three E0 galaxies in the SLUGGS survey

- Analysis in **Cesare et al., in prep.**
- 3 E0 galaxies from the SLUGGS survey: NGC 1407, NGC 4486 (M87), and NGC 5846
- Spherical systems: $\varepsilon \in [0,0.15] \Leftrightarrow q = 1 - \varepsilon \in [0.85,1]$
- Kinematics probed up to $\sim 10\ R_{\rm e}$ thanks to the detection of GCs
- Two populations of GCs (blue and red) $\Rightarrow$ stronger constraint for RG

NGC 1407



https://ned.ipac.caltech.edu/uri/NED::Image/gif/1994DSS...1...0000:/Bd/NGC_1407:I:IIIaJ:dss1

4.1 The mass model

Model, at the same time, of the root-mean-square velocity dispersion of the stars, the blue GCs, and the red GCs in each E0 galaxy from spherical Jeans analysis:

$$V_{\mathrm{rms,t}}^2(R) = \frac{2}{I_{\mathrm{t}}(R)} \int_R^{+\infty} K\left(\beta_{\mathrm{t}}, \frac{r}{R}\right) \nu_{\mathrm{t}}(r) \frac{\mathrm{d}\phi}{\mathrm{d}r} r \, \mathrm{d}r$$

$\mathrm{t} =$ **tracer** (stars, blue GCs and red GCs)

Surface brightness of stars/number density of GCs

3D luminosity (number) density of stars (GCs)

Gravitational field

$$\frac{\partial \phi}{\partial r} = \frac{1}{\epsilon(\rho)} \frac{GM(<r)}{r^2}$$

3D mass/mass density (stars + gas + SMBH)

Orbital anisotropy:

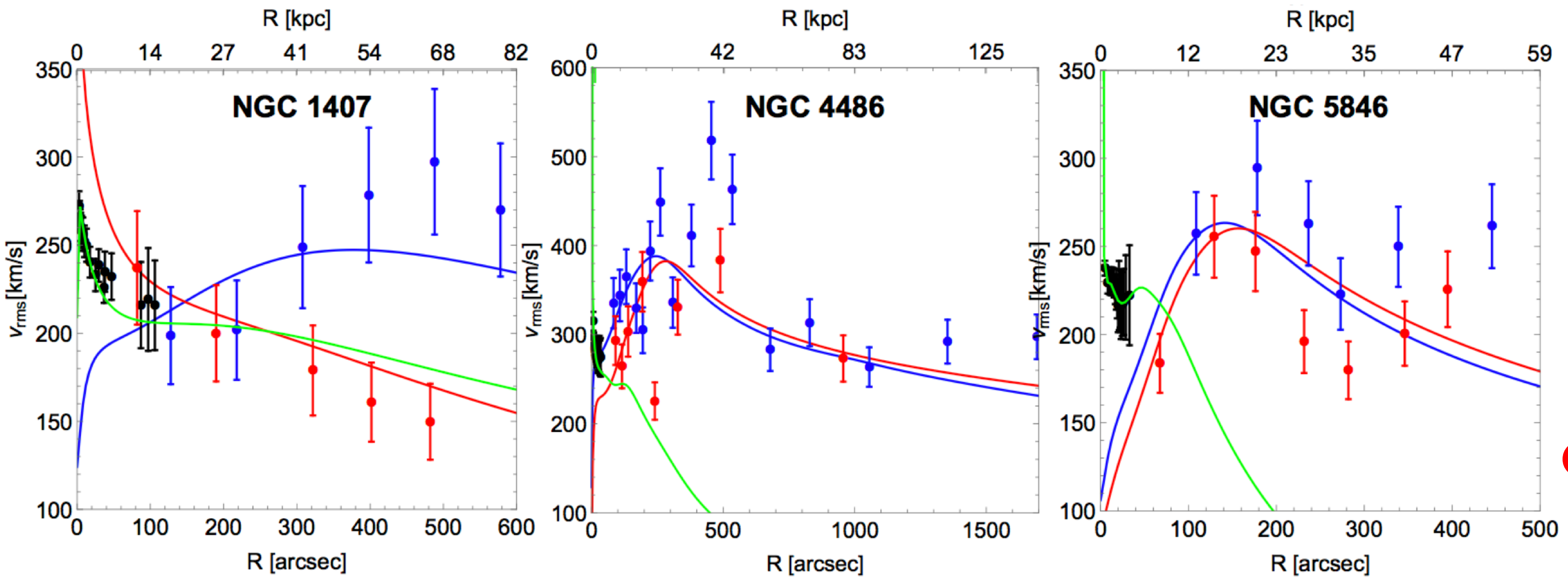
$$\beta = 1 - \frac{\sigma_\theta^2}{\sigma_r^2}$$

7 free parameters:

- Stellar M/L: Υ
- Three RG parameters: ϵ_0, Q, $\mathcal{P}_{\mathrm{c}} = \log_{10}\rho_{\mathrm{c}}$
- Three anisotropy parameters: $\mathcal{B}_{\mathrm{t}} = -\log_{10}(1 - \beta_{\mathrm{t}})$

4.2 Results

- Global good description of the kinematic profiles of the three tracers with mass-to-ratios consistent with SPS models and anisotropy parameters consistent with the literature (Pota et al. 2015)
- Some points of the kinematic profiles of blue GCs in NGC 4486 and NGC 5846 not interpolated: systems treated as isolated and not embedded in larger systems
- RG parameters consistent between the individual galaxies (1σ) and with the DMS ($\boldsymbol{Q}$, $\boldsymbol{\mathcal{P}_c}$; 3σ)
- 10σ tension between the $\boldsymbol{\epsilon_0}$ from the three E0 galaxies and the DMS



Cesare et al., in prep.

5. Future projects

- Extension of the current analysis to elliptical galaxies with different ellipticities belonging to SLUGGS and ePN.S surveys
- Dwarf galaxies and GCs
- Galaxy clusters (two encouraging results in Matsakos & Diaferio (2016))
- Covariant formulation of the theory (Sanna et al. in preparation)
- Linear perturbation theory for the density field
- Power spectrum of the CMB anisotropies
- Formation and evolution of cosmic structures (N-body simulations)

6. Conclusions

- RG properly reproduces the kinematics of DMS galaxies
- Introducing the vertical velocity dispersions we obtain disk scale heights smaller than observations → **observational bias, not issue of the theory**
- A unique combination of $\{\epsilon_0, Q, \rho_c\}$ is likely to be found to properly describe DMS kinematic profiles
- RG predicts a RAR with the correct asymptotic limits, with too large intrinsic scatter and with correlations between residuals and galaxy properties → further investigation with **SPARC** (Lelli et al. 2016)
- RG can model the kinematics of both flattened and spherical systems
- RG can compete with other theories of gravity to describe the dynamics on galactic scale, deserving further investigation

THANK YOU FOR THE ATTENTION! ☺