Dynamics of disk and elliptical galaxies in Refracted Gravity

Valentina Cesare

Dipartimento di Fisica, Università di Torino

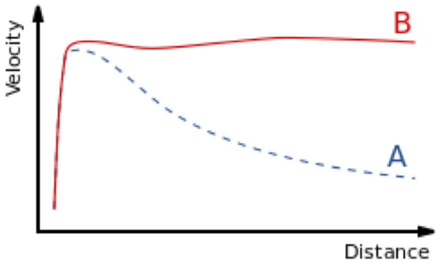
Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Torino

Cosmology from Home 2020

Table of contents

1. Introduction

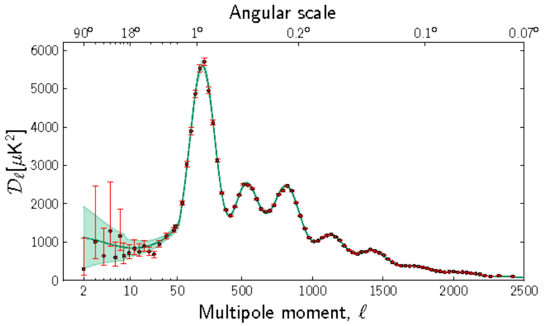
Coma cluster NASA’s Spitzer Space Telescope.



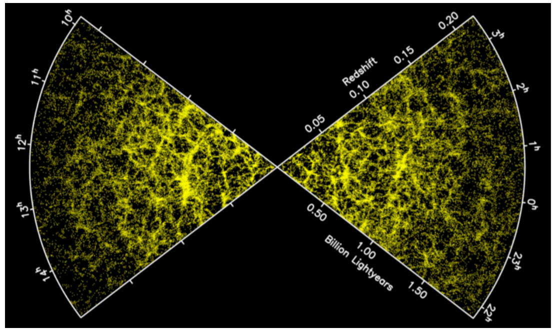
$v(R)$ trend expected (A, keplerian fall) and observed (B) wikipedia.org.

MASS DISCREPANCY PROBLEM

80—90%



CMB power spectrum physics.stackexchange.com.



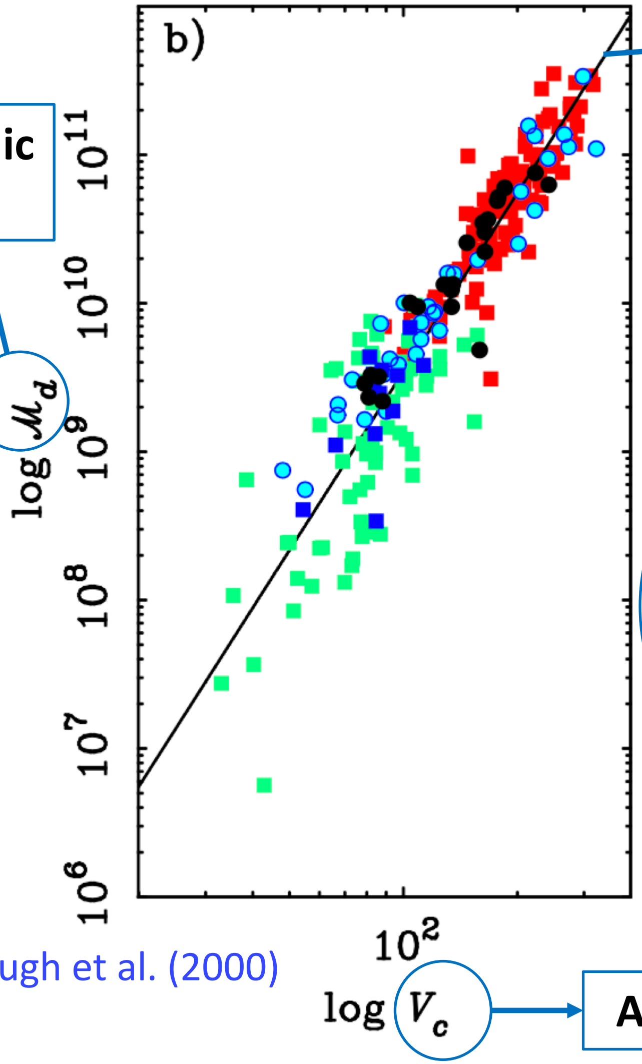
Large scale structure roe.ac.uk.

DARK MATTER

MODIFIED GRAVITY

WHY MODIFIED GRAVITY?

BARYONIC TULLY-FISHER RELATION



Baryonic mass

McGaugh et al. (2000)

Asymptotic flat rotation velocity

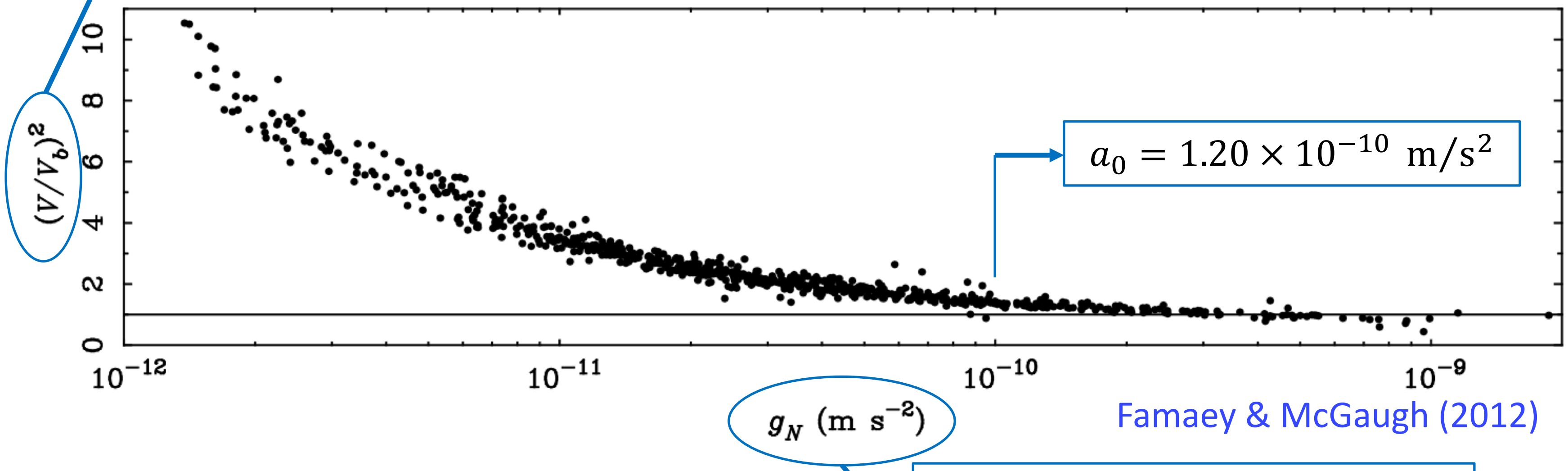
$$M_\mathrm{d} = AV_\mathrm{c}^4$$

$$A = 47 \pm 6\,\frac{M_\odot \mathrm{s}^4}{\mathrm{km}^4} \sim (Ga_0)^{-1}$$

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

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

MASS DISCREPANCY-ACCELERATION RELATION



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

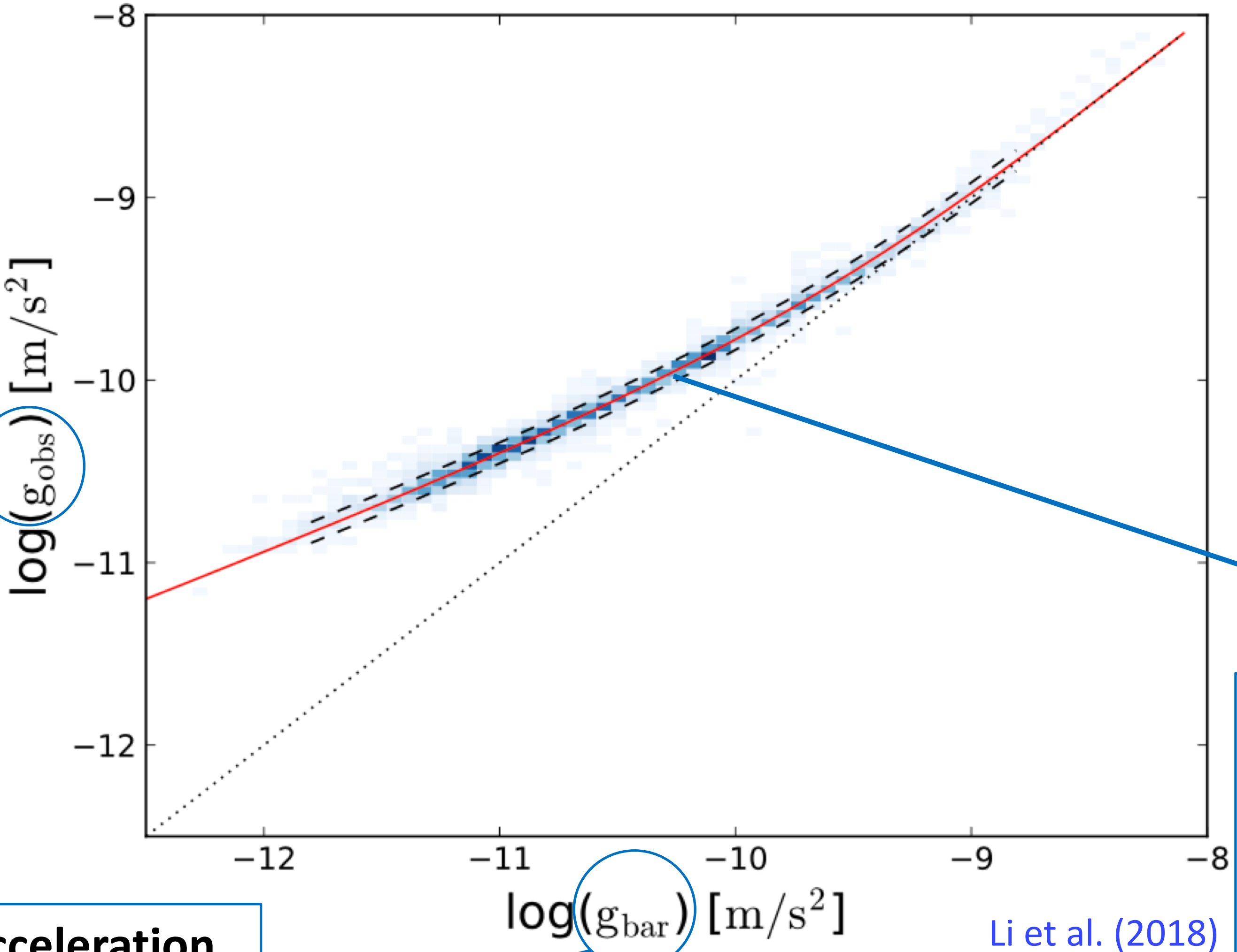
Famaey & McGaugh (2012)

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)

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

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

McGaugh et al. (2016)

Newtonian acceleration due to baryons

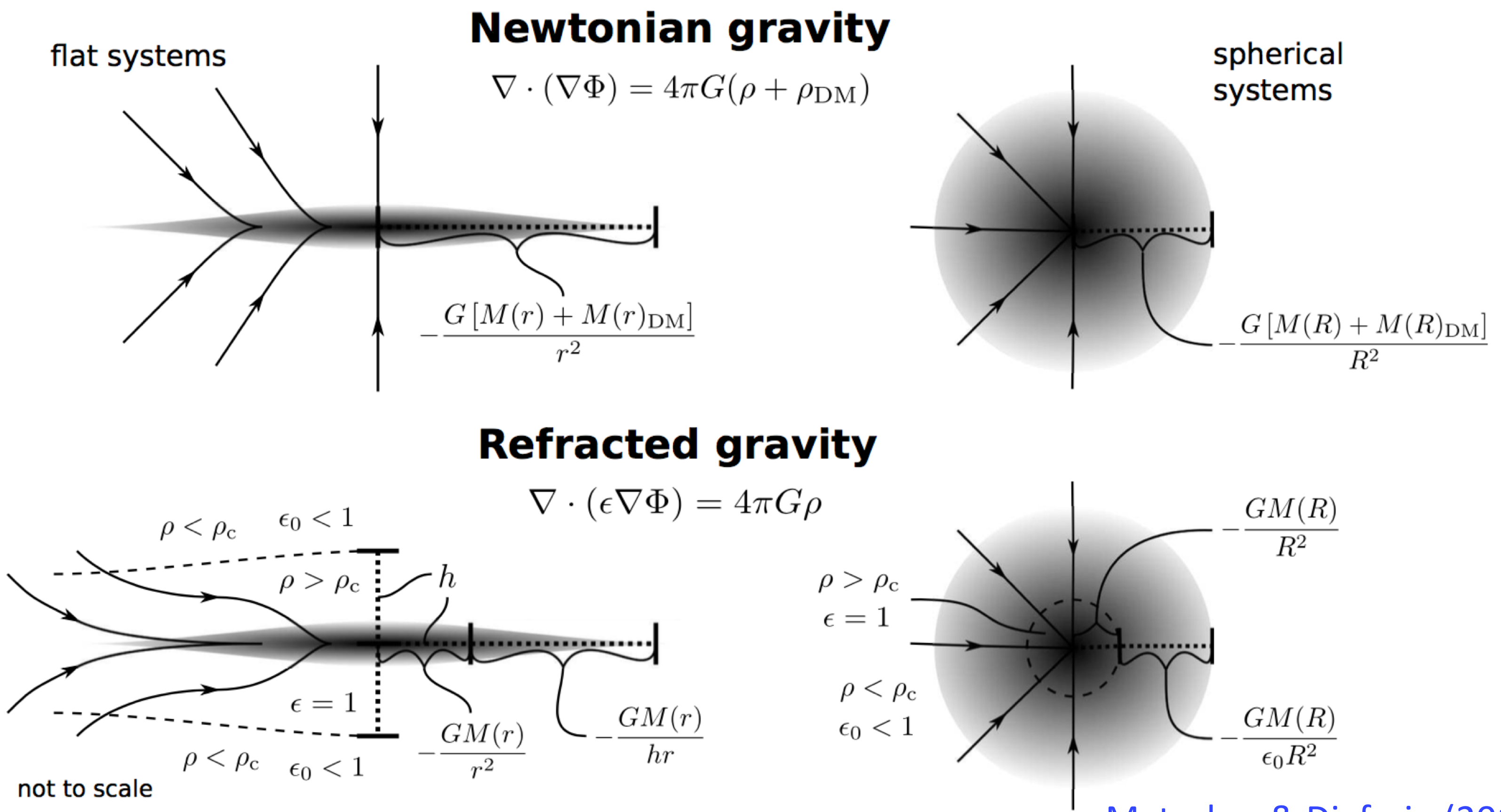
$$\frac{\partial \phi_{\rm N}}{\partial R} \leftarrow \nabla^2\phi_{\rm N} = 4\pi G\rho$$

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 for $\rho \gg \rho_c$

ϵ_0 for $\rho \ll \rho_c$

$0 \leq \epsilon_0 \leq 1$

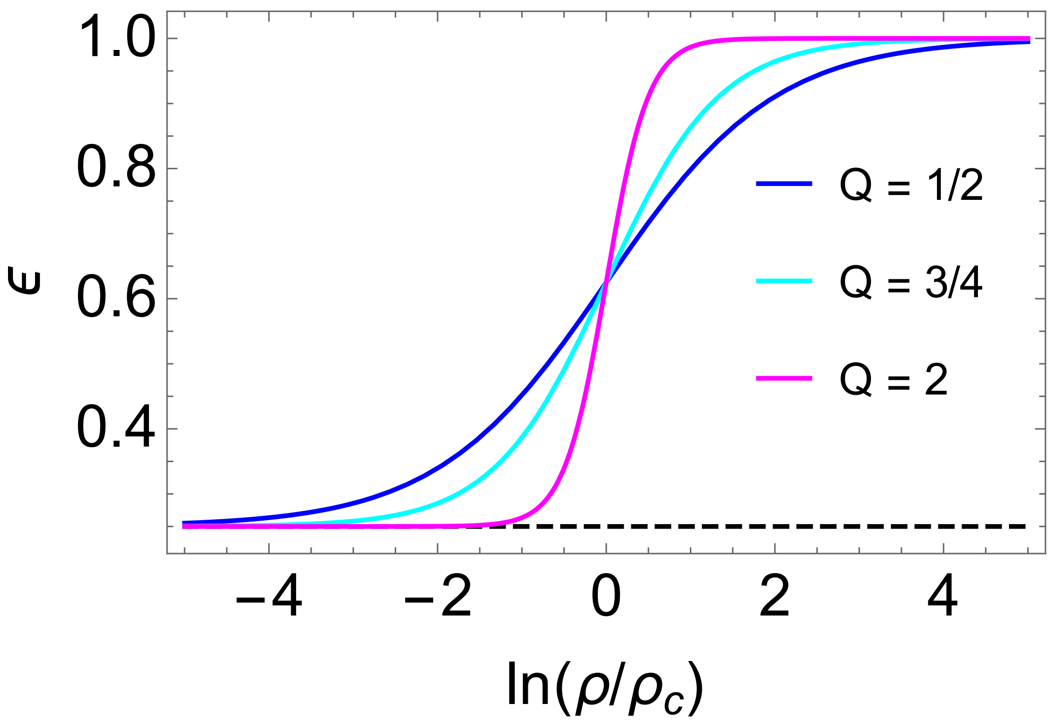
Matsakos & Diaferio (2016)

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. (2020)**



Cesare et al. (2020)

3. Disk galaxies: the DiskMass Survey

- Analysis in **Cesare et al. (2020)**
- 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

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

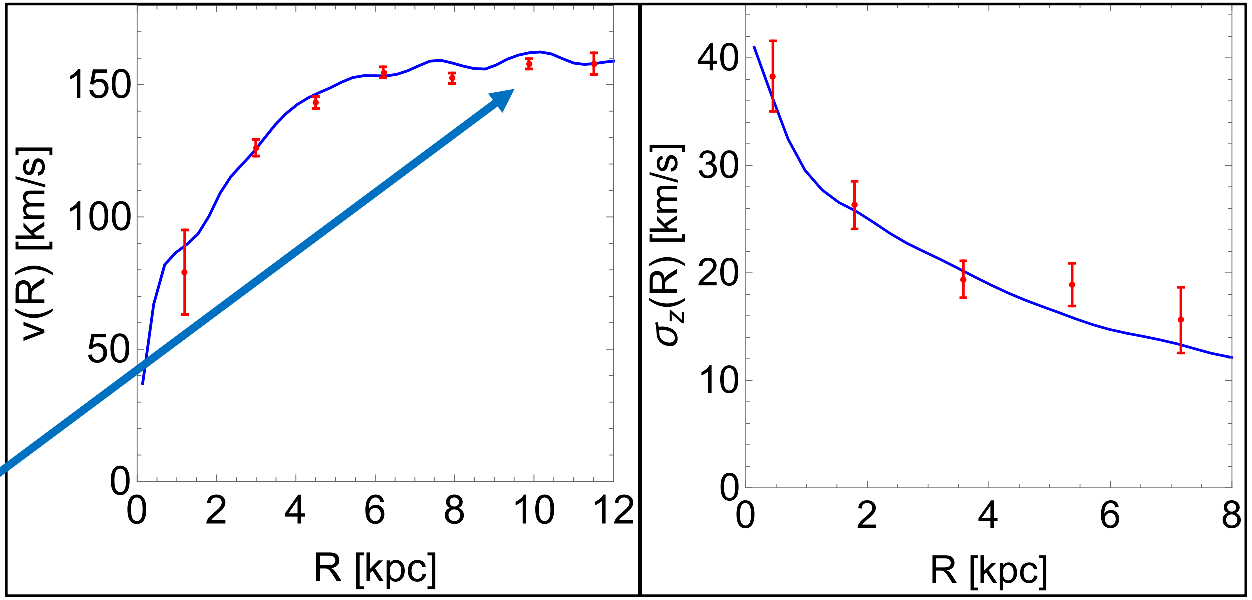
VERTICAL VELOCITY DISPERSION PROFILE

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

From Jeans analysis

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

UGC 3091

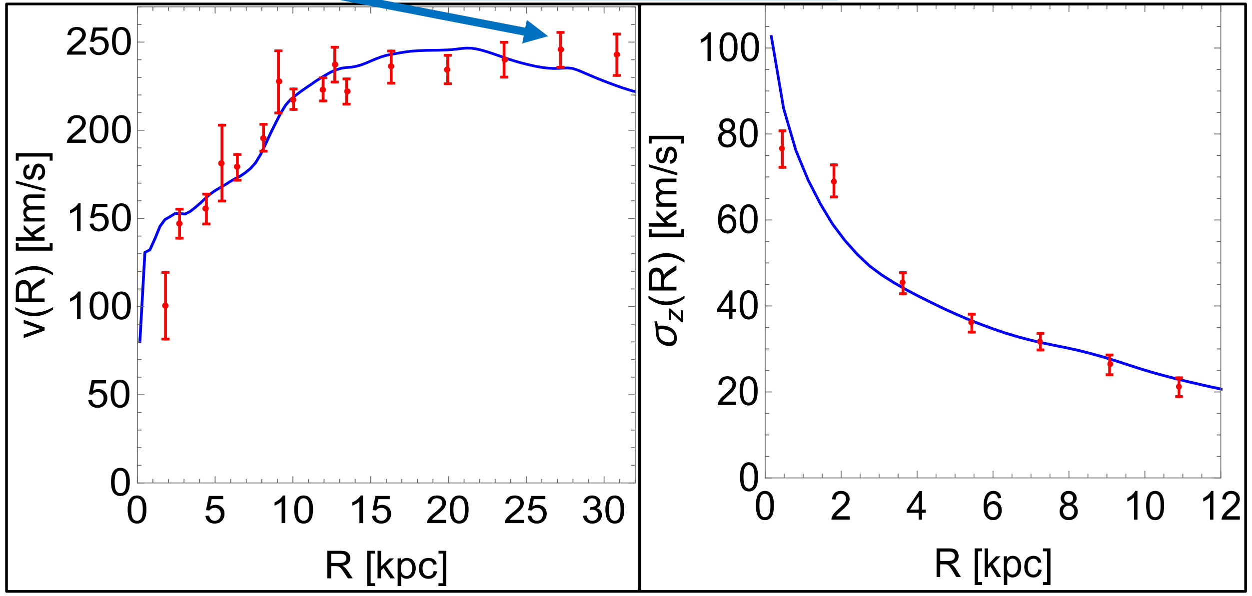


Flat trend recovered

Renzo's rule

Good description of kinematic profiles

UGC 4256

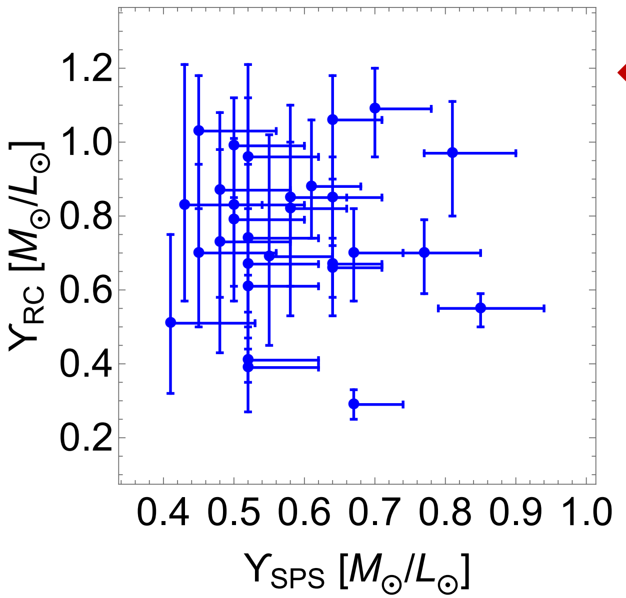


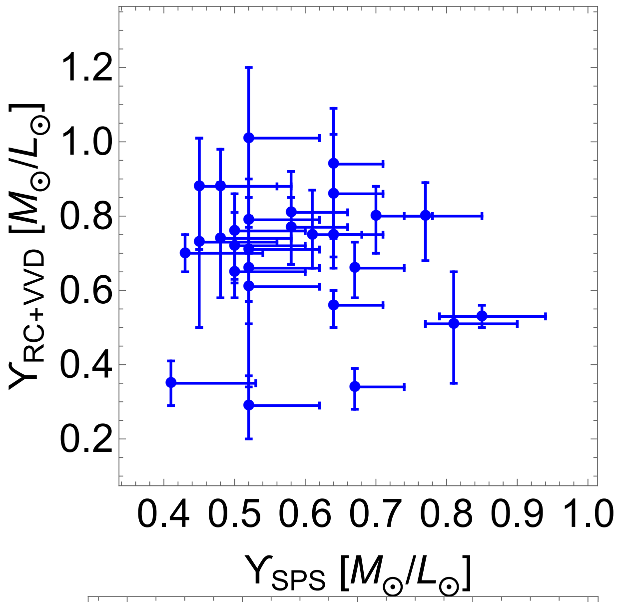
Cesare et al. (2020)

ROTATION CURVES ALONE

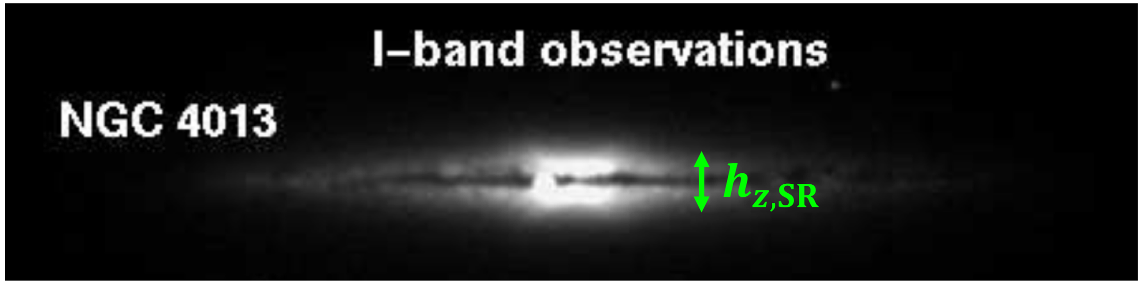
Cesare et al. (2020)

ROTATION CURVES AND VERTICAL VELOCITY DISPERSIONS

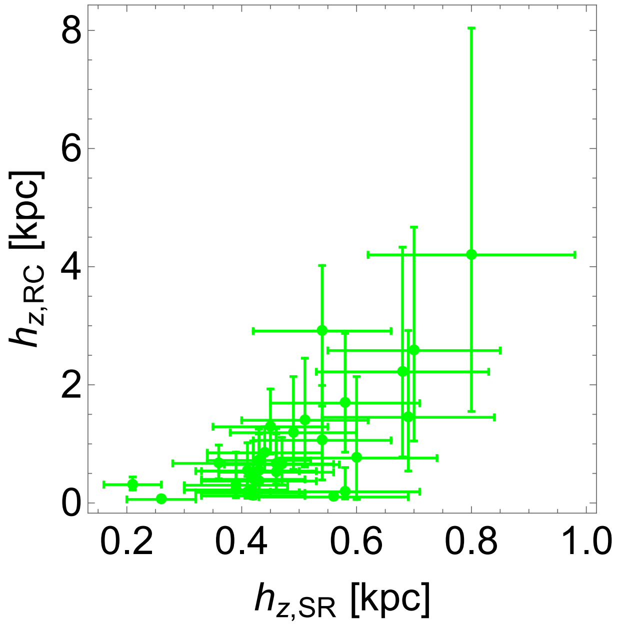


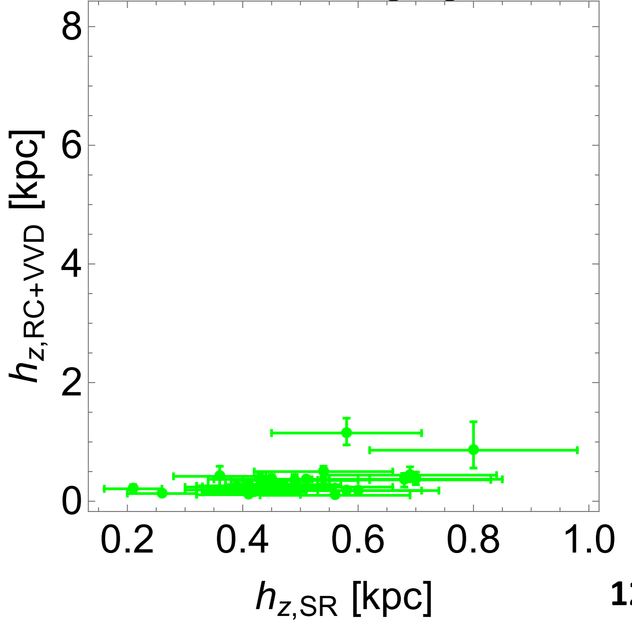


Good agreement with SPS models in both cases



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**

Mean RG parameter from previous analysis

IDEAL APPROACH

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

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

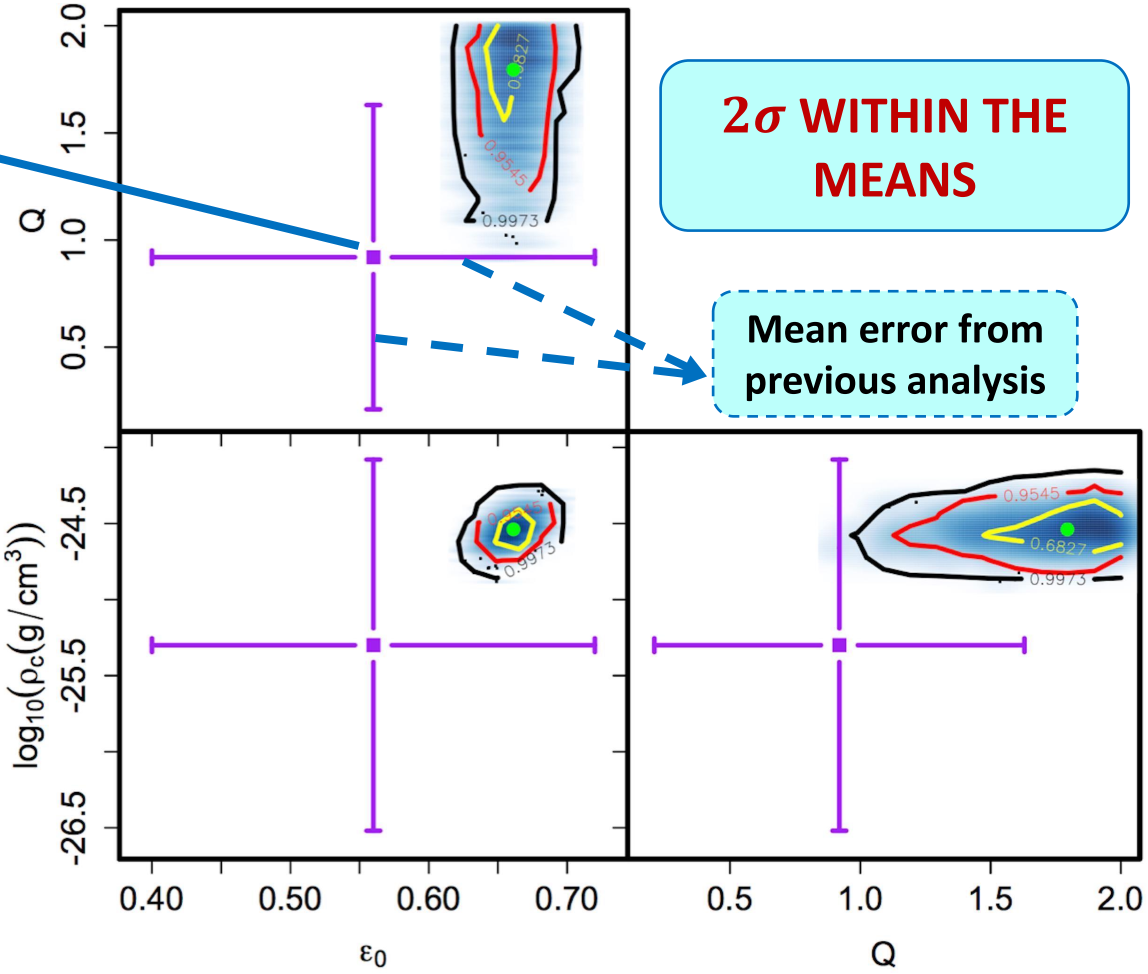
ADOPTED APPROACH

- 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 (2020)** and on GitHub **(https://github.com/alpha-unito/astroMP)**.

2σ WITHIN THE MEANS

Mean error from previous analysis



Cesare et al. (2020)

3.3 The Radial Acceleration Relation

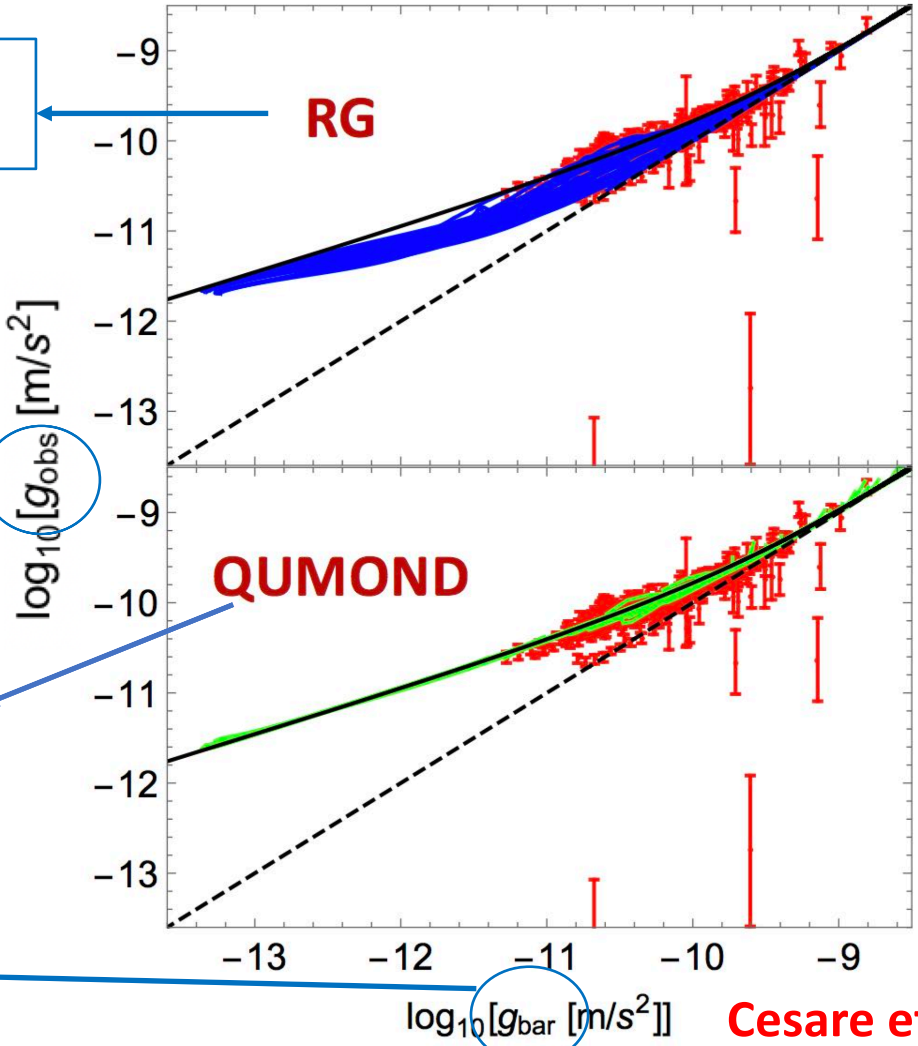
$$\frac{\partial \phi_{\mathrm{RG}}}{\partial R} \leftarrow \nabla \cdot [\epsilon(\rho)\nabla\phi] = 4\pi G\rho$$

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

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

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

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



Cesare et al. (2020)

Correlation between RAR residuals and galaxy properties

Sample dependence or RG issue?

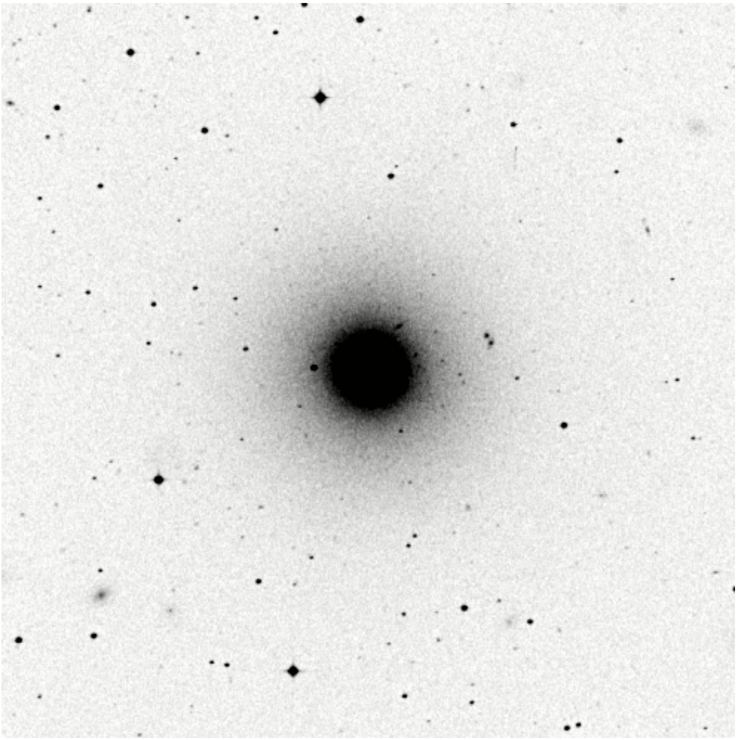
SCATTER OF THE RAR

4. Elliptical galaxies

- Monotonically increasing relation between elliptical galaxies ellipticities and mass-to-light ratios (Deur 2014) → naturally predicted by the RG framework

- SLUGGS survey probes the kinematics of galaxies up to $\sim 10\, R_\mathrm{e}$ thanks to the detection of globular clusters (GCs): suitable sample to test this prediction

NGC 1407



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

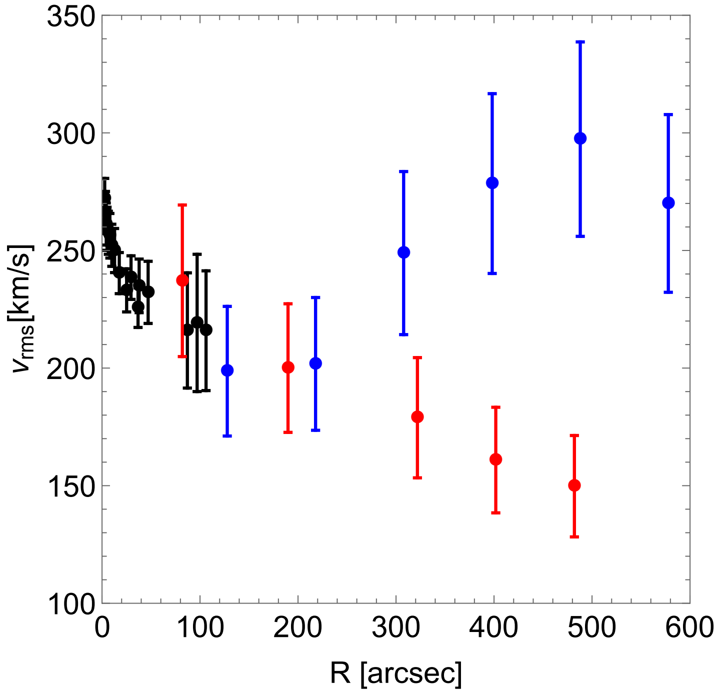
4.1 The test case of NGC 1407: ongoing analysis

- Elliptical E0 galaxy (minor-to-major axis ratio $q = 0.95$)
- Three kinematic tracers: stars, blue GCs and red GCs

VELOCITY DISPERSION MODEL (from Jeans analysis)

$$V^2_{\mathrm{rms,t}}(R') = \frac{2}{I_{\mathrm{t}}(R')} \int_{R'}^{+\infty} K\left(\beta_{\mathrm{t}}, \frac{r}{R'}\right) \nu_{\mathrm{t}}(r) \frac{\mathrm{d}\phi}{\mathrm{d}r} r \, \mathrm{d}r$$

- $\mathrm{t} =$ **tracer** (stars, blue GCs and red GCs)
- **Surface brightness/ number density** → Sérsic profile
- **Orbital anisotropy:** $\beta = 1 - \frac{\sigma_\theta^2}{\sigma_r^2}$
- **3D luminosity/ number density**
- **Gravitational potential** ← $\nabla \cdot [\epsilon(\rho) \nabla \phi] = 4\pi G \rho$ ← **3D mass density** (stars only)



Adjusted from Pota et al. (2015)

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 $\{\boldsymbol{\epsilon_0}, \boldsymbol{Q}, \boldsymbol{\rho_c}\}$ 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 could potentially describe systems with different degrees of flatness
- RG can compete with other theories of gravity to describe the dynamics on galactic scale, deserving further investigation

THANK YOU FOR THE ATTENTION! ☺