MOND: An alternative to particle dark matter

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INAF
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DI ASTROFISICA

OSSERVATORIO ASTROFISICO DI ARCETRI

MOND = MOdified Newtonian Dynamics

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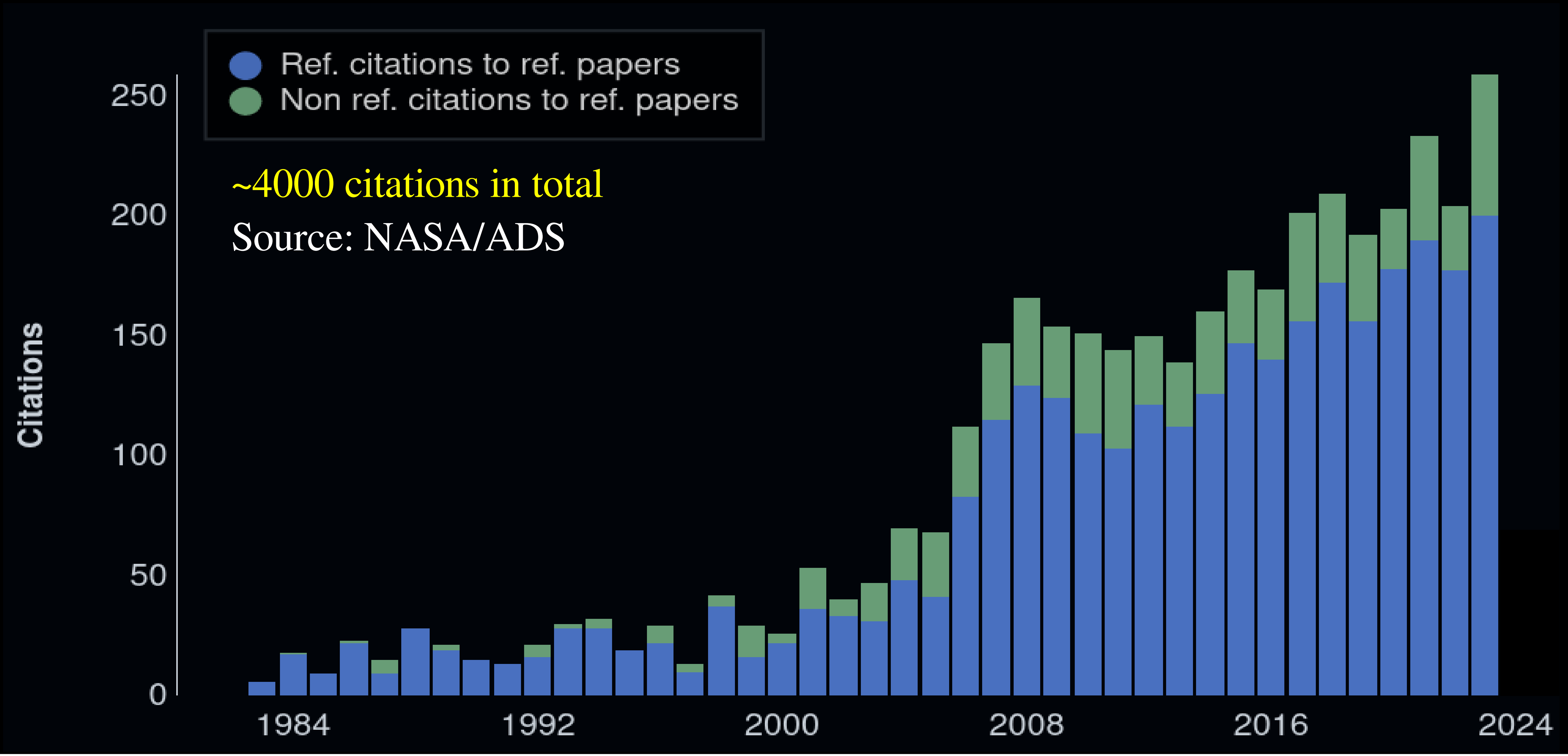
MOND = MilgrOmiaN Dynamics

Proposed by Moti Milgrom (1983a, b, c)

MOND is not a new idea. But it has gained "momentum" over the past 40+ years.

Citations to the original MOND trilogy (Milgrom 1983a, b, c)



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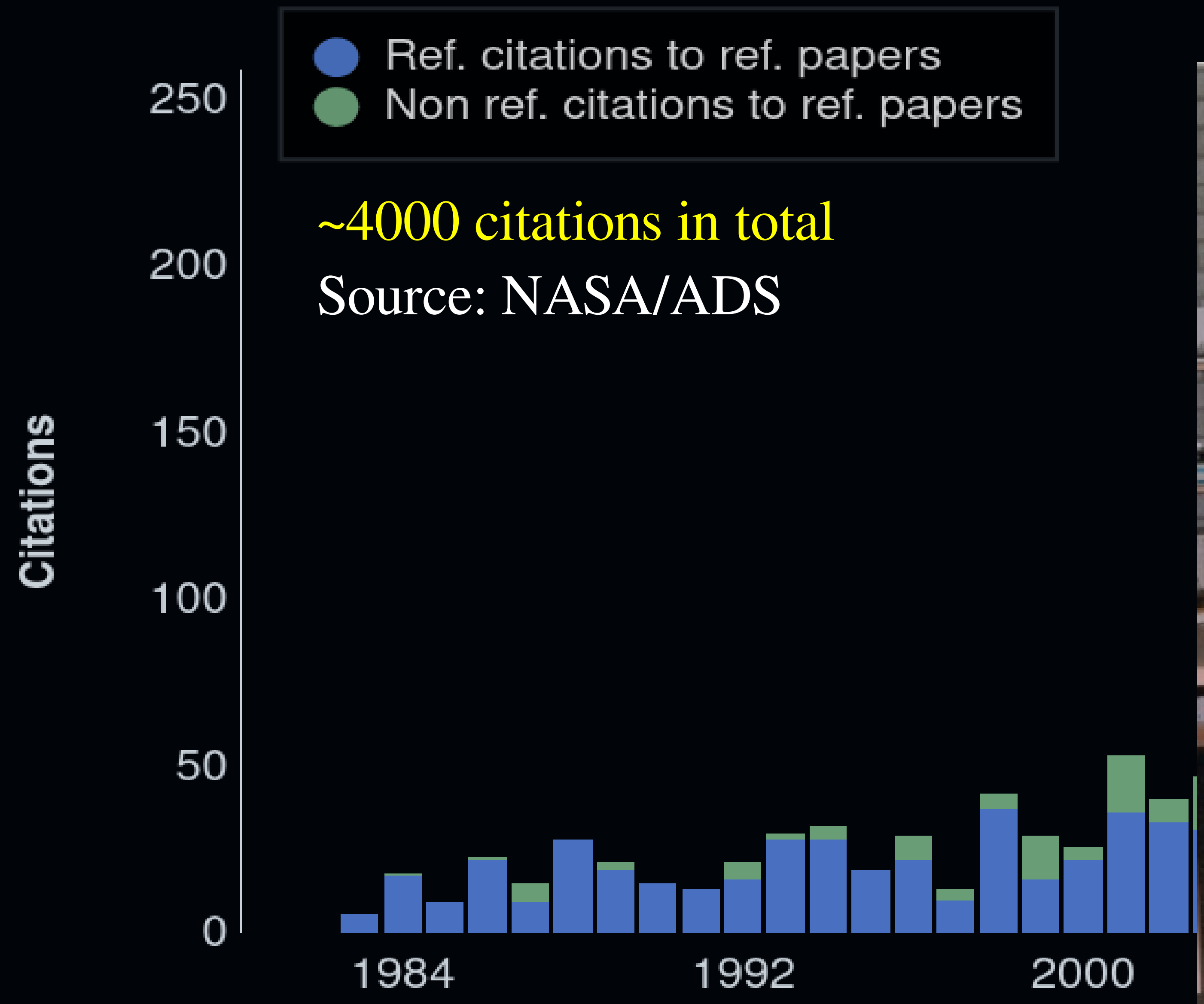

~4000 citations in total

Source: NASA/ADS

People working on MOND in the late 90s

Sanders Milgrom Bekenstein

Citations to the original MOND trilogy (Milgrom 1983a, b, c)

(Fraction of the) people working on MOND today

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Talk Outline

1. General MOND paradigm
2. Tests on galaxy scales
3. Tests on groups/clusters scales
4. MOND theories & cosmology

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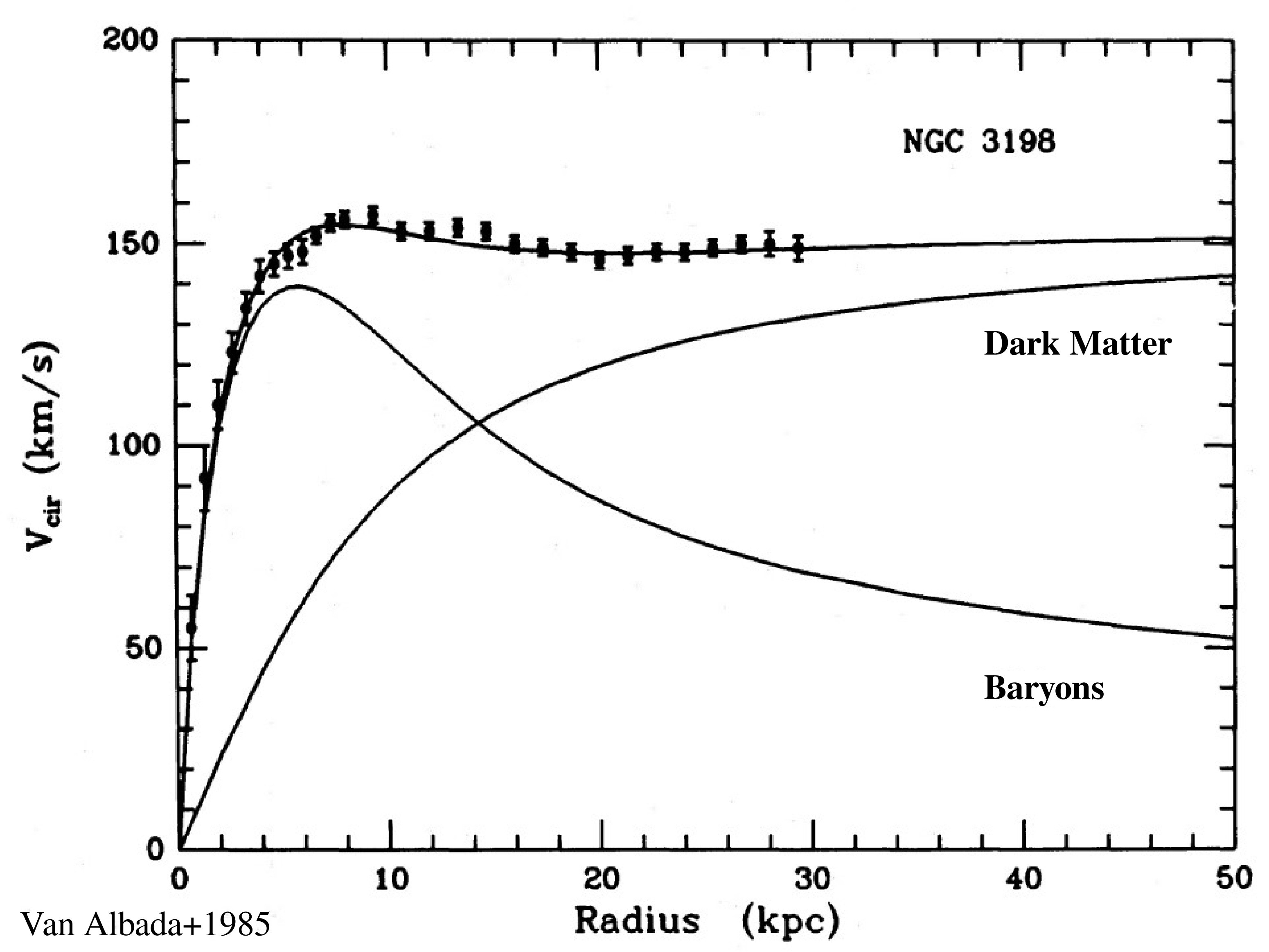
Rotation curves of disk galaxies: baryon-halo conspiracy



$$V_c^2(R) = V_{bary}^2(R) + V_{DM}^2(R) = const$$

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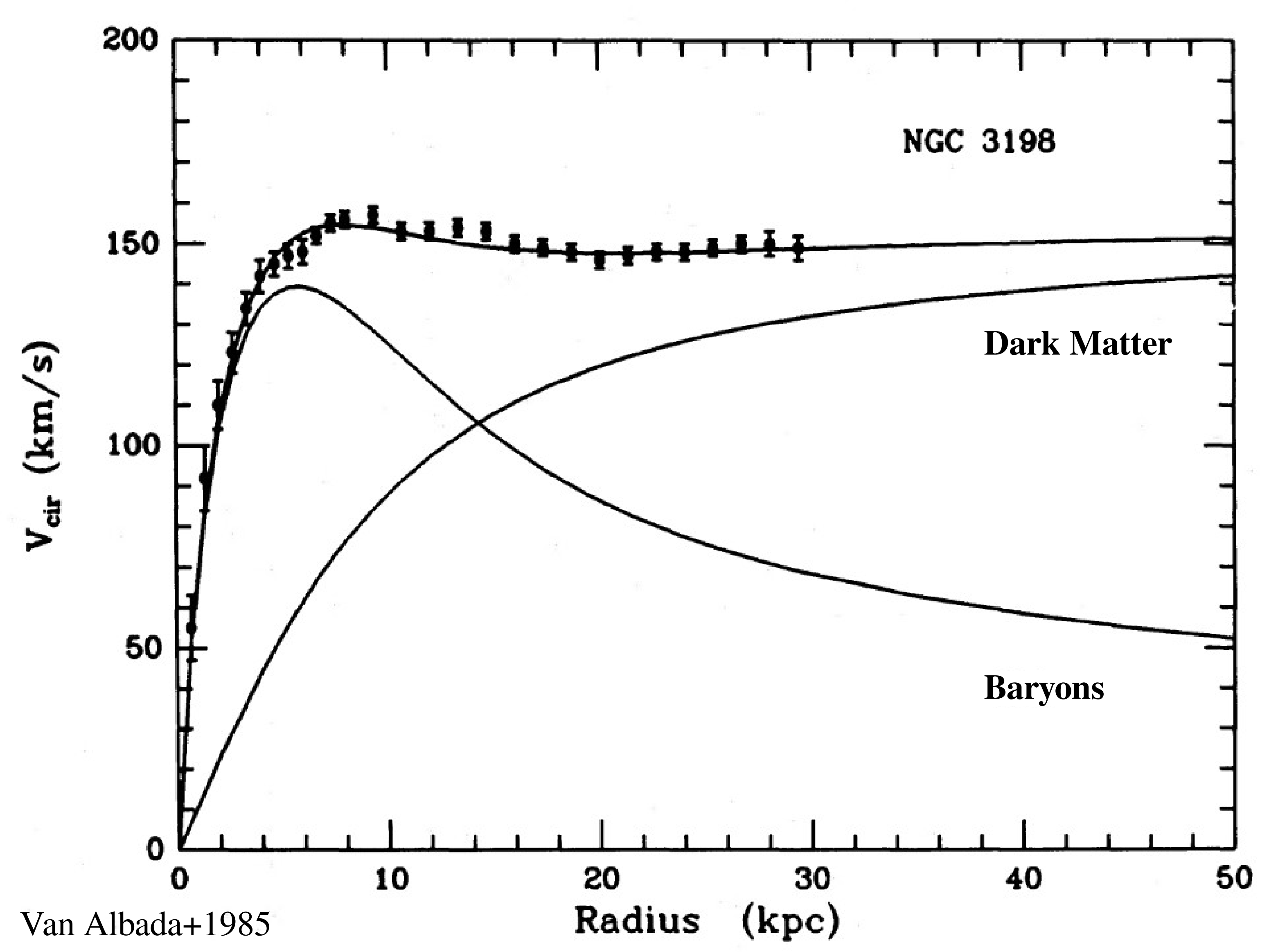

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"Luminous and dark matter seem to conspire to produce the flat observed rotation curves in the outer regions. It seems unlikely that this coupling […] results from the large-scale gravitational interaction between the two components."

Van Albada & Sancisi (1986, RSPTA)

Still a problem for ΛCDM!

See Desmond (2017, MNRAS)

Flat rotation curves = Law of Nature. What would Newton do?

Kinematic acceleration along a circular orbit: $$a = \left| \frac{d^2 \vec{x}}{dt^2} \right| = \frac{V_c^2}{R} \propto \frac{1}{R}$$

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Newtonian gravitational field *<u>at large radii</u>*: $g_{N,b} = -\left| \vec{\nabla} \phi_{N,b} \right| \simeq \frac{G_N M_b}{R^2} \propto \frac{1}{R^2}$

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$\Rightarrow$ $a = \sqrt{a_0 \, g_{N,b}}$ a_0 constant with dimensions of acceleration

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⇒ $a = \sqrt{a_0 g_{N,b}}$ a_0 constant with dimensions of acceleration

⇒ $\frac{V_c^2}{\cancel{R}} = \sqrt{\frac{a_0 G_N M_b}{\cancel{R^2}}}$ Flat rotation curve *at large radii*

MOND postulates at the non-relativistic level (Milgrom 2009, ApJ)

1) New constant of Physics: $a_0 \simeq 10^{-10}$ m/s^2

similar role as c in Relativity and $\hbar$ in Quantum Mechanics

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$$a = \sqrt{a_0 \, g_{N,b}} \qquad V_c = invariant$$

A MODIFICATION OF THE NEWTONIAN DYNAMICS: IMPLICATIONS FOR GALAXIES[1]

M. MILGROM
Department of Physics, Weizmann Institute, Rehovot, Israel; and The Institute for Advanced Study
Received 1982 February 4; accepted 1982 December 28

ABSTRACT

I use a modified form of the Newtonian dynamics (inertia and/or gravity) to describe the motion of bodies in the gravitational fields of galaxies, *assuming that galaxies contain no hidden mass*, with the following main results.

1. The Keplerian, circular velocity around a finite galaxy becomes independent of r at large radii, thus resulting in asymptotically flat velocity curves.

2. The asymptotic circular velocity (V_∞) is determined only by the total mass of the galaxy (M): $V_\infty^4 = a_0 GM$, where a_0 is an acceleration constant appearing in the modified dynamics. This relation is consistent with the observed Tully-Fisher relation if one uses a luminosity parameter which is proportional to the observable mass.

3. The discrepancy between the dynamically determined Oort density in the solar neighborhood and the density of observed matter disappears.

4. The rotation curve of a galaxy can remain flat down to very small radii, as observed, only if the galaxy's average surface density Σ falls in some narrow range of values which agrees with the Fish and Freeman laws. For smaller values of Σ, the velocity rises more slowly to the asymptotic value.

5. The value of the acceleration constant, a_0, determined in a few independent ways is approximately $2 \times 10^{-8}(H_0/50 \text{ km s}^{-1} \text{ Mpc}^{-1})^2 \text{ cm s}^{-2}$, which is of the order of $CH_0 = 5 \times 10^{-8}(H_0/50 \text{ km s}^{-1} \text{ Mpc}^{-1}) \text{ cm s}^{-2}$.

The main predictions are:

1. Rotation curves calculated on the basis of the *observed* mass distribution and the modified dynamics should agree with the observed velocity curves.

2. The $V_\infty^4 = a_0 GM$ relation should hold exactly.

3. An analog of the Oort discrepancy should exist in all galaxies and become more severe with increasing r in a predictable way.

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1. ~~General MOND paradigm~~

2. Tests on galaxy scales

3. Tests on groups/clusters scales

4. MOND theories & cosmology

(1) $V_c(R) = \text{const}$ at large R for isolated objects

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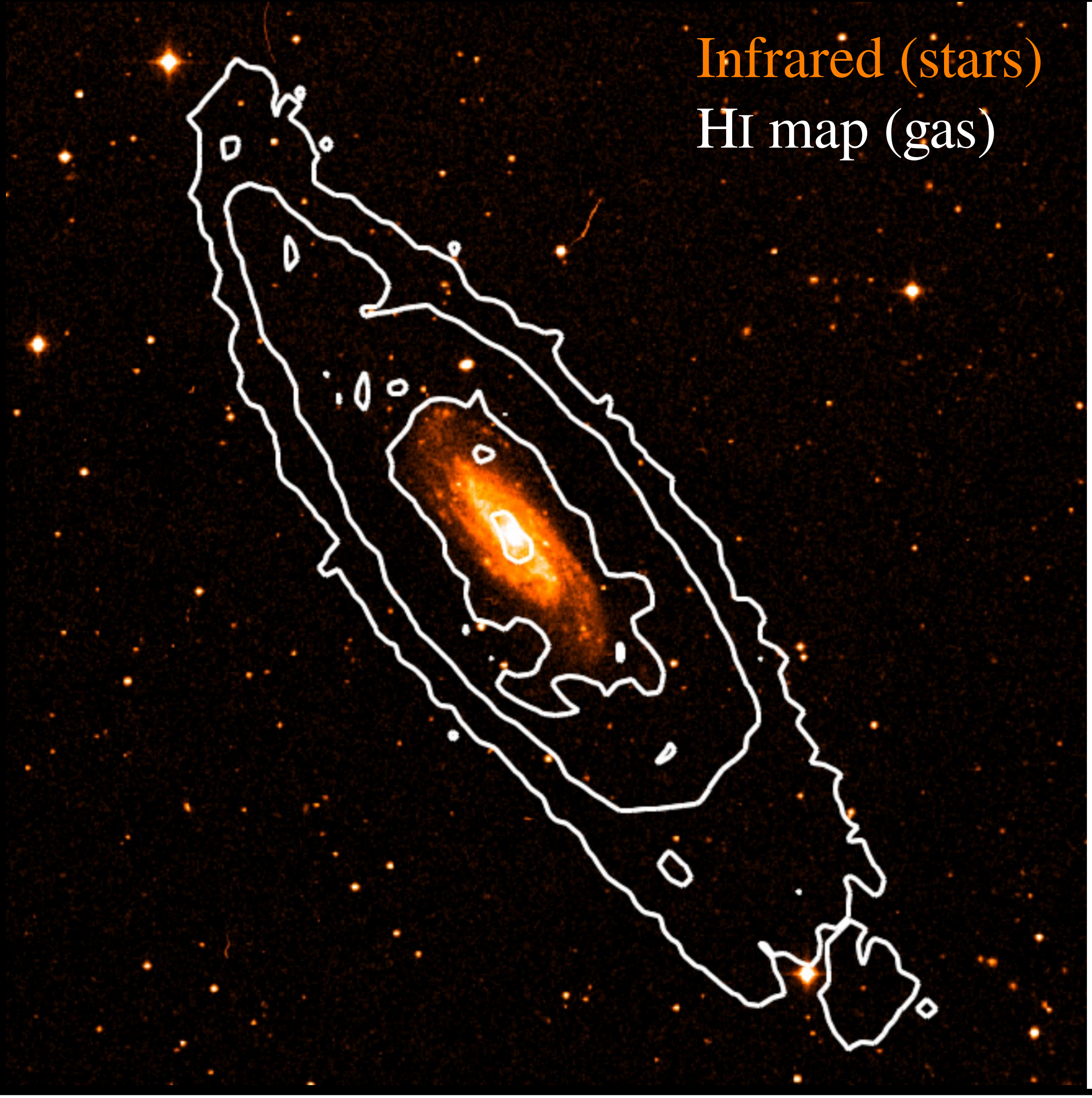
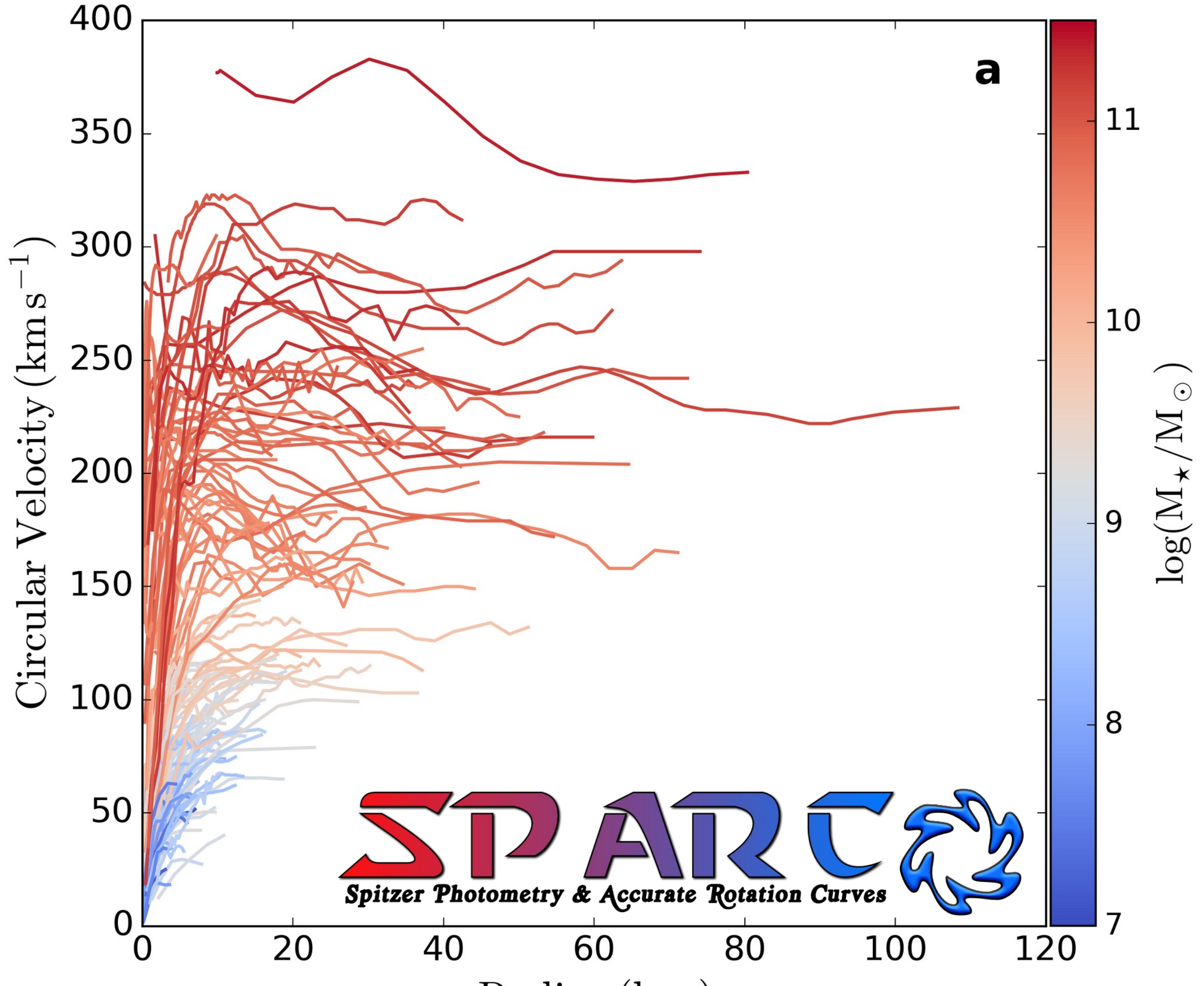
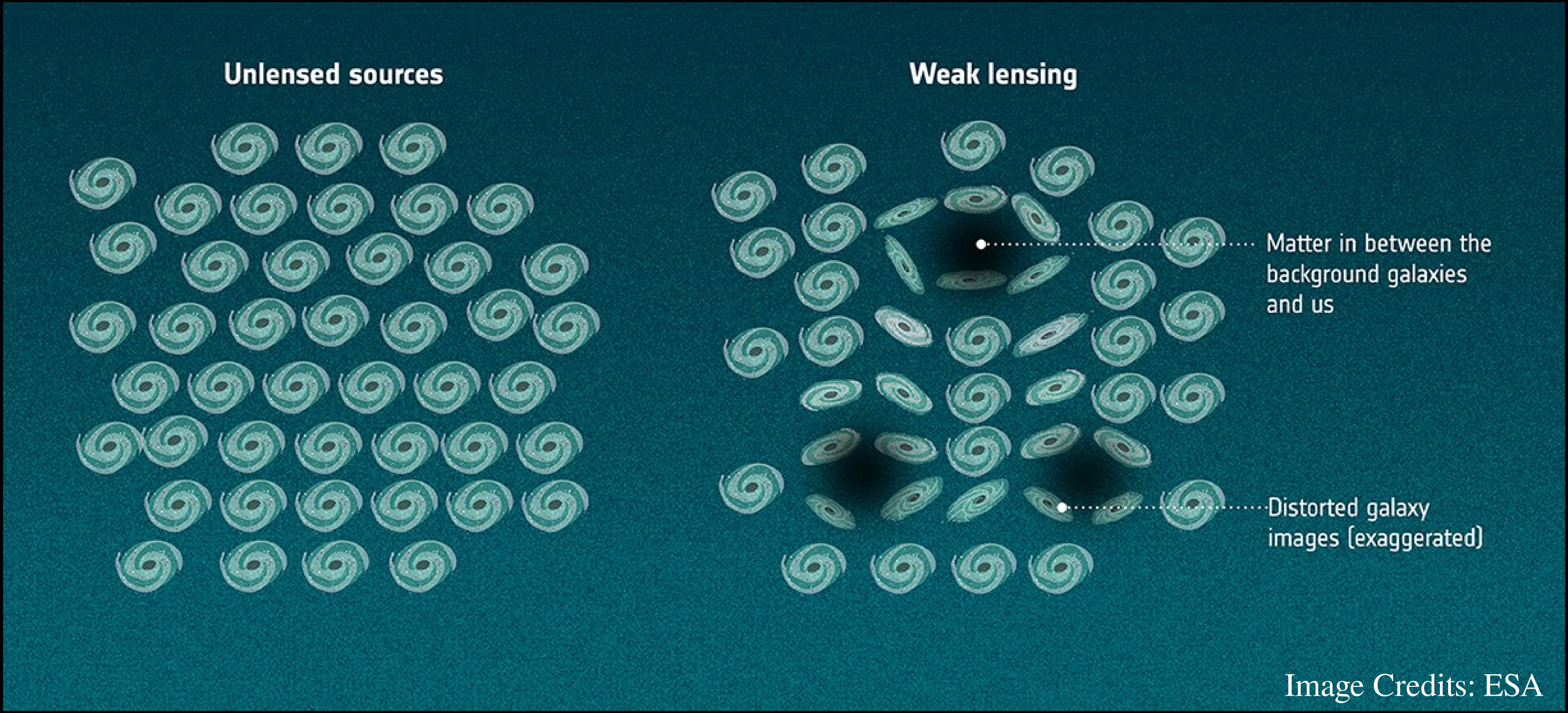




Lelli+(2016, 2022)

(1) $V_c(R)$ = const at large R for isolated objects → Weak Lensing



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$$\frac{V_c^2}{r} = 4 G_N \int_0^{\pi/2} \Delta\Sigma\left(\frac{r}{\sin(\theta)}\right) d\theta$$

From weak lensing data ($\Delta\Sigma$) to gravitational acceleration ($g = V_c^2/r$) in spherical symmetry

→ Isolated galaxies from KiDS (Mistele+2024a, b)

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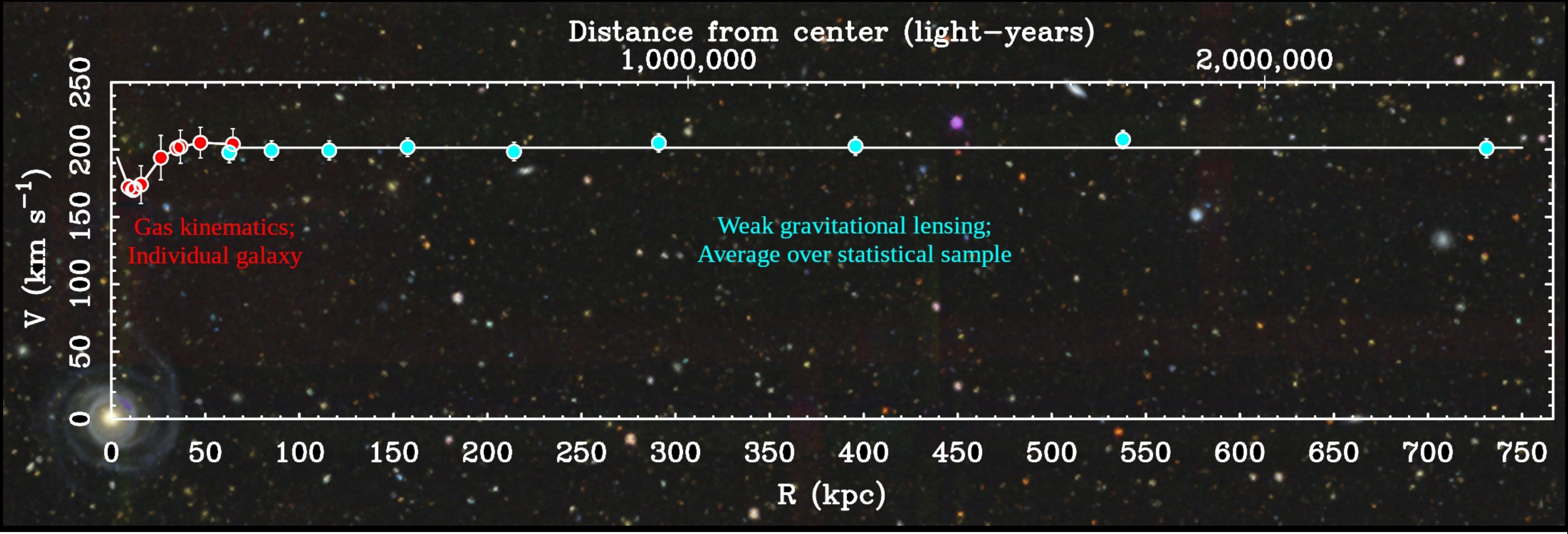

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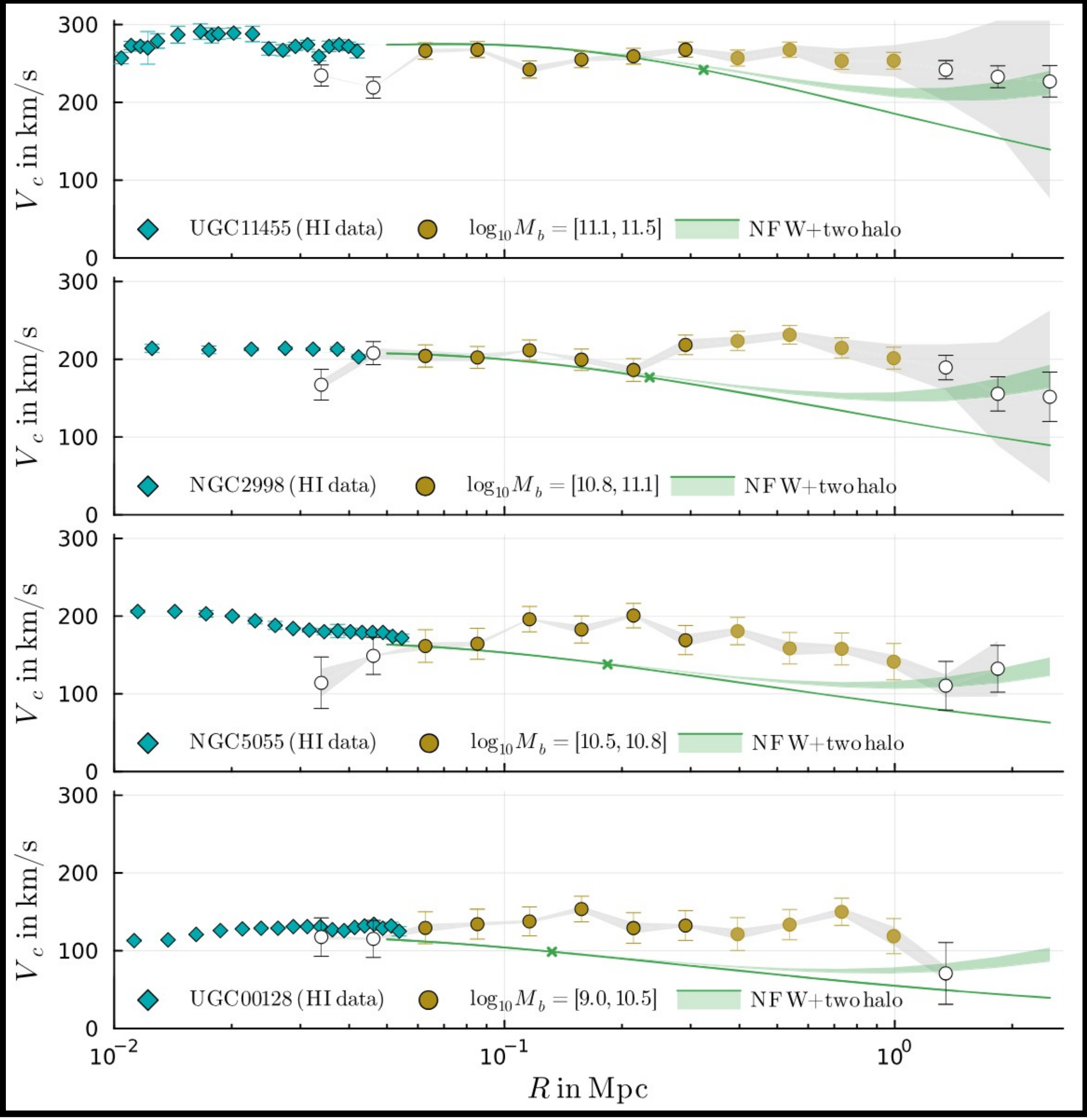

Binning by baryonic mass:

Circular-velocity curve stays flat beyond the “virial radius” of the DM halo:

→ In contradiction with ΛCDM predictions

→ In agreement with MOND predictions

Mistele+(2024b, ApJ)

(2) $V_{flat}^{4} = a_0 \, G_N \, M_b$ for isolated objects

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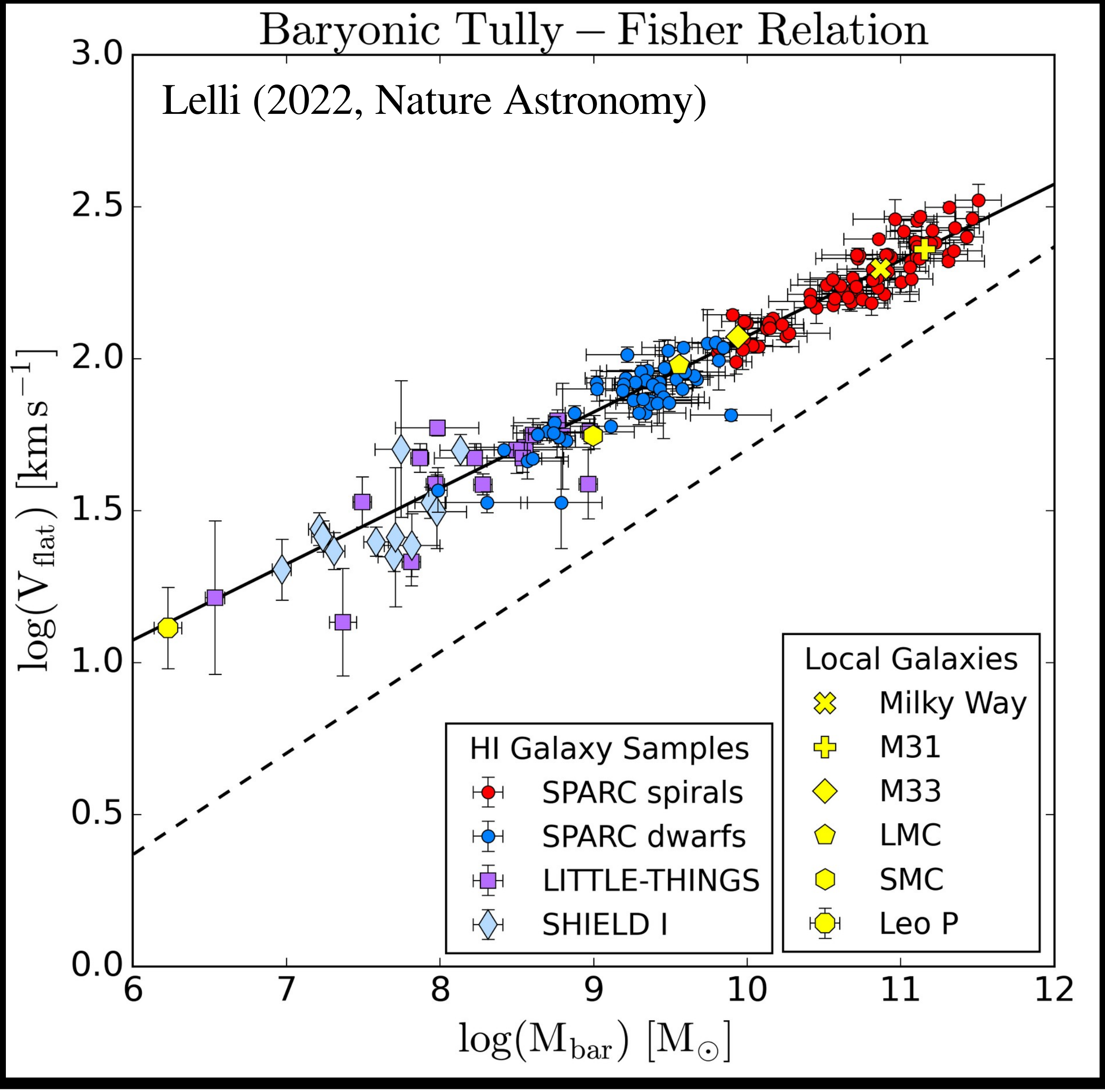

Four predictions in one equation:

✔ Key quantities are V_{flat} and M_b (stars+gas)

Some References: McGaugh+(2000, 2005, 2010); Verheijen (2001); Noordermeer & Verheijen (2005); Lelli+(2016, 2019, 2022, 2024); Ponomareva+(2018); Schombert+(2020), Di Teodoro+(2021, 2022).

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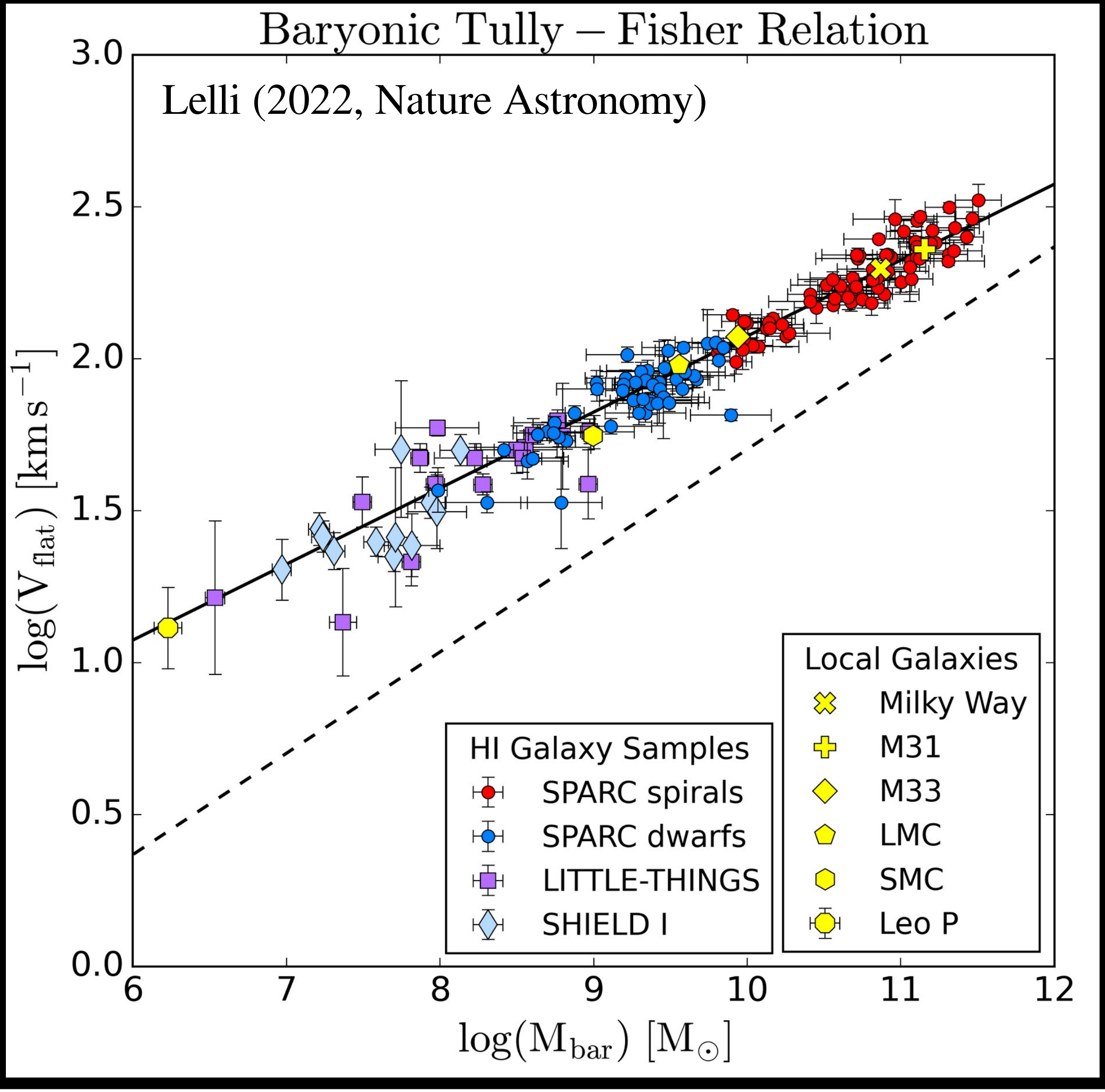

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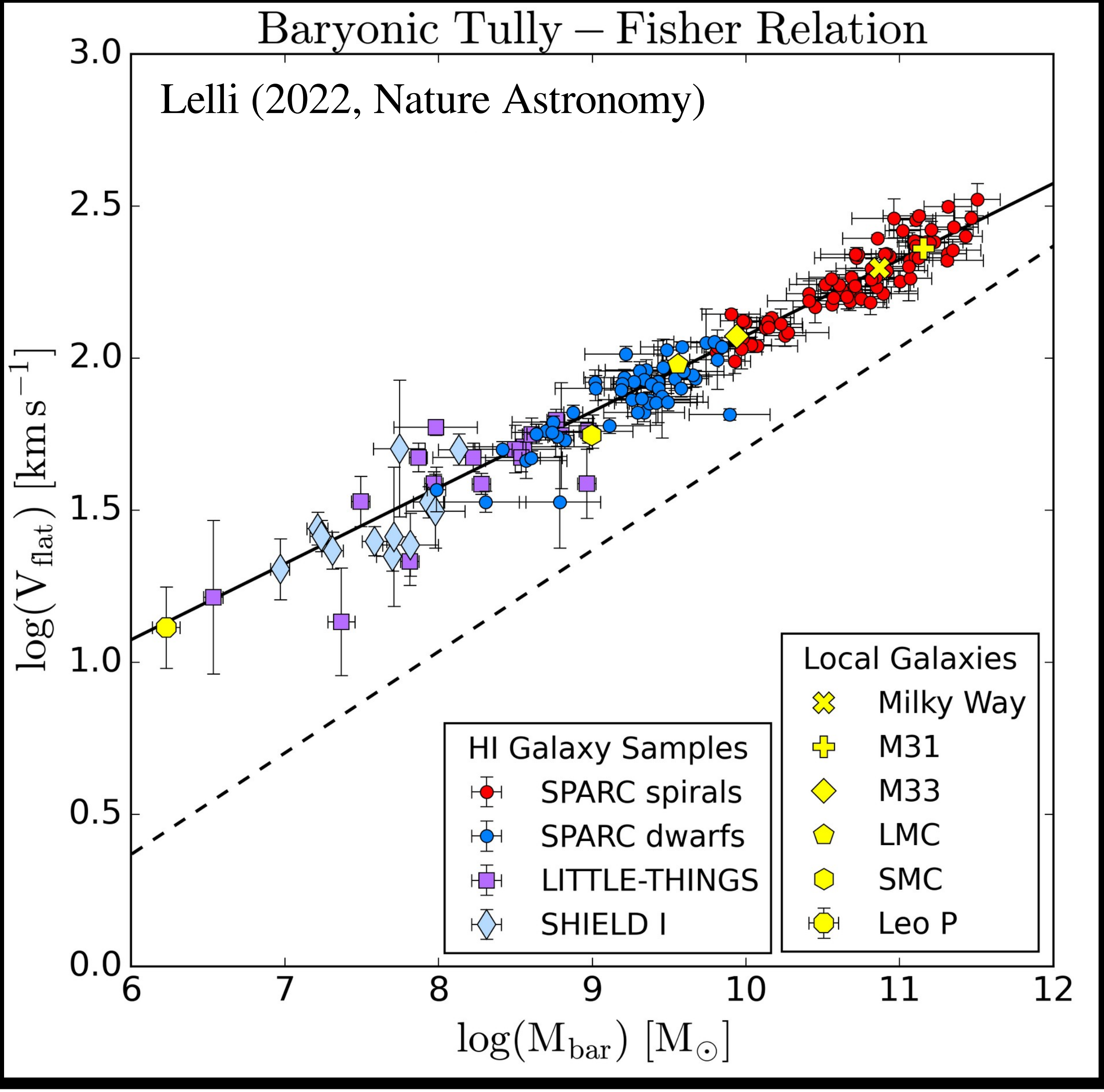

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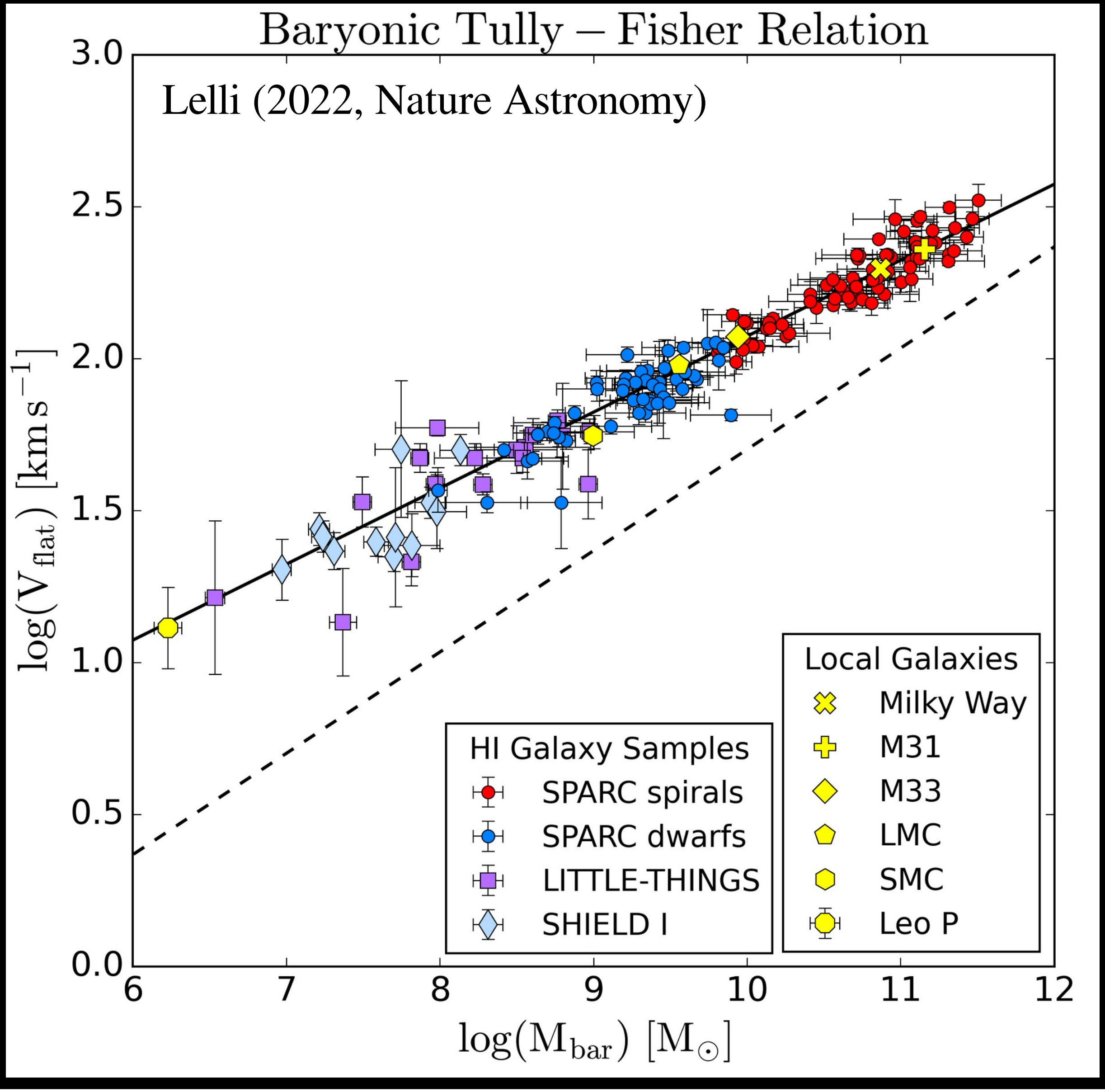

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- ✔ Key quantities are V_{flat} and M_b (stars+gas)
- ✔ Slope should be exactly 4
- ✔ Normalization is $a_0 G_N$

  → OK with independent estimates
- ✔ No dependence on other galaxy properties

  (e.g., size, gas fraction, morphology)

  → NO intrinsic scatter along the relation

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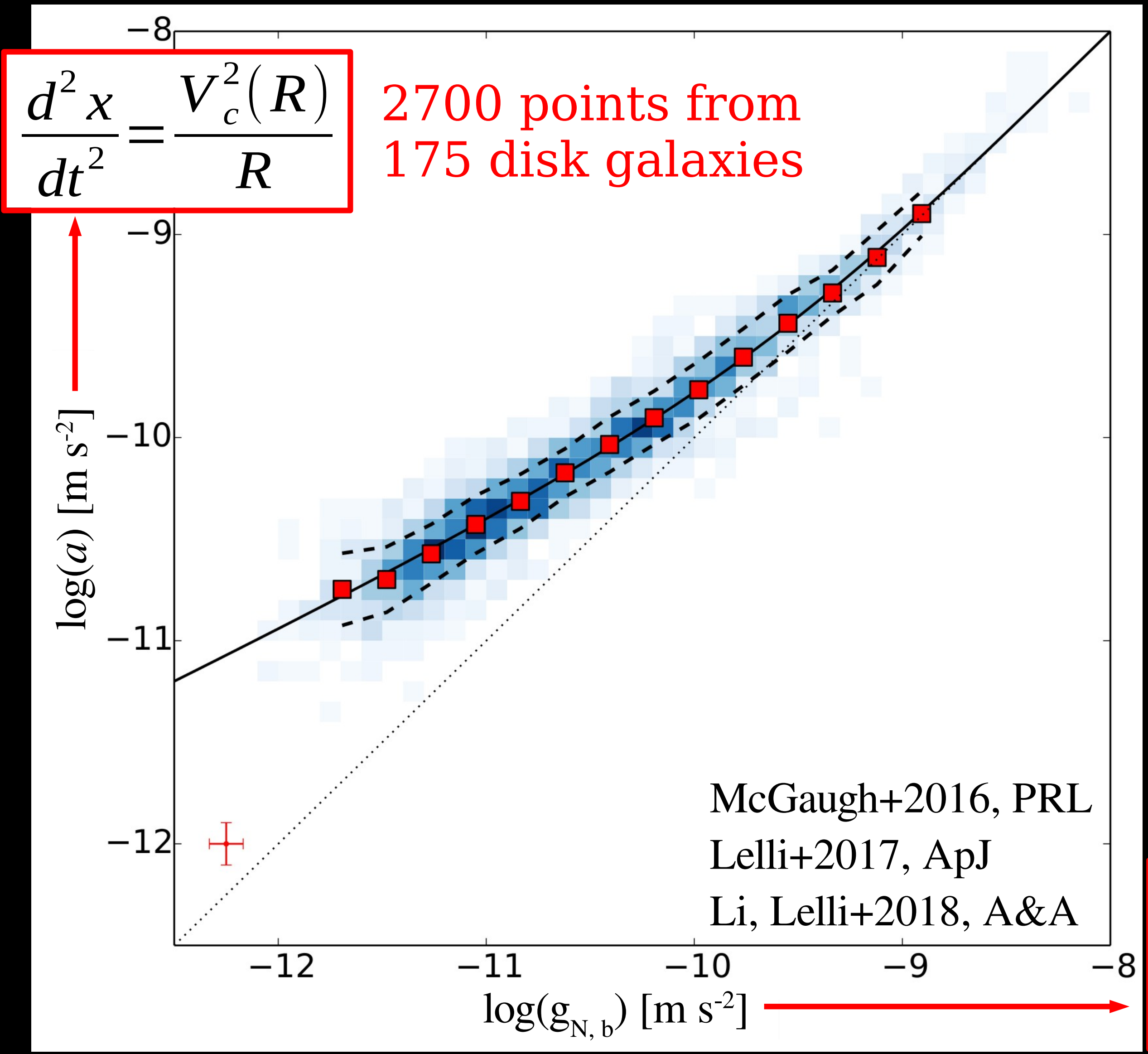

Radial Acceleration Relation (RAR)

(i) Fully empirical, independent of MOND

$$\nabla^2 \Phi_{N,b}(R,z) = 4\pi G \rho_b(R,z)$$
$$g_{N,b}(R,z=0) = -\nabla \Phi_{N,b}(R,z=0)$$

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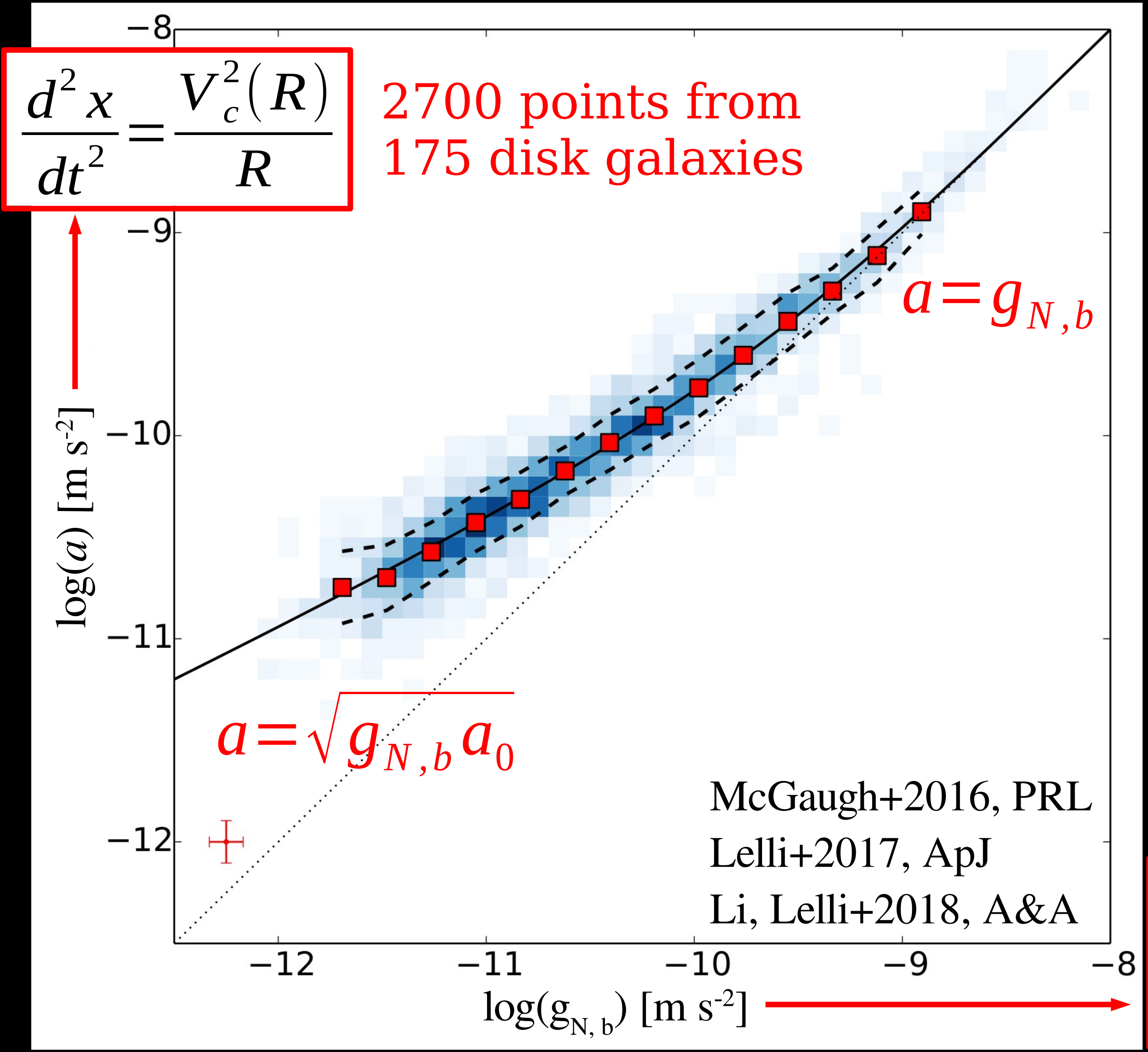

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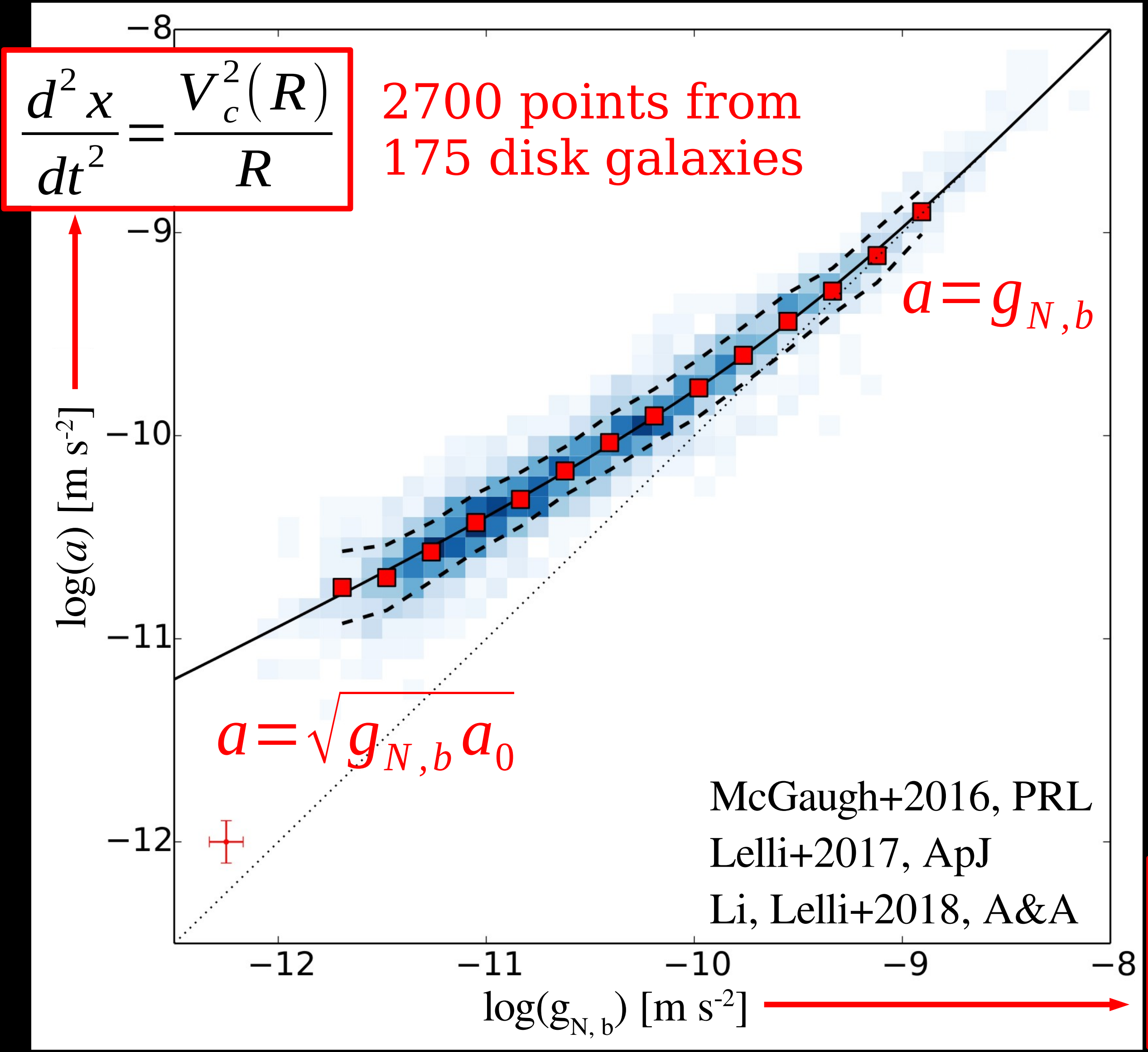

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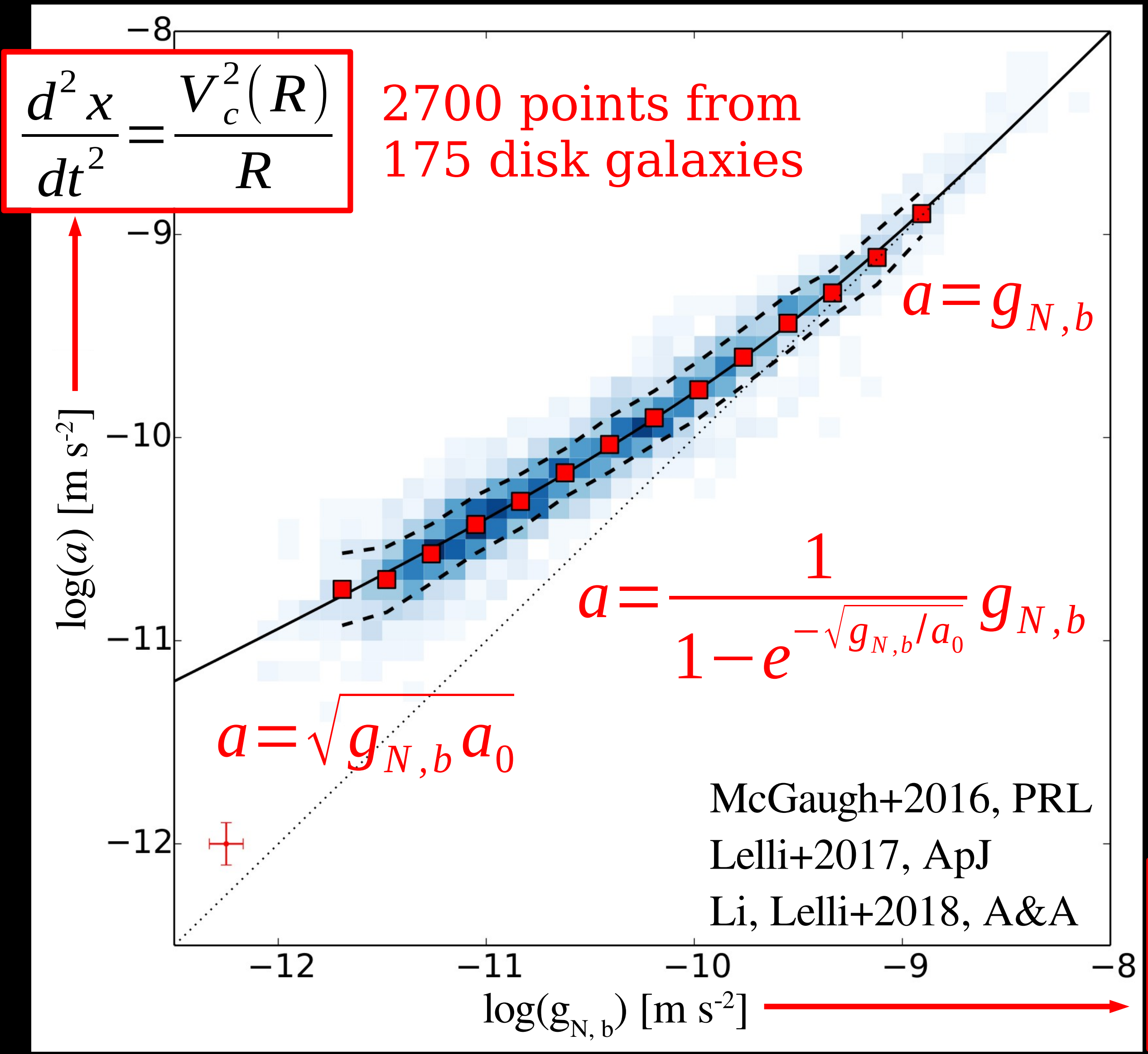

Radial Acceleration Relation (RAR)

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(iv) MOND interpolation function ν or μ

$$a = \nu\left(\frac{g_{N,b}}{a_0}\right) g_{N,b} \iff a\,\mu\left(\frac{a}{a_0}\right) = g_{N,b}$$

We can now assume $\nu(g_{N,b}/a_0)$ and predict rotation curves given ρ_b (within the errors)

$$\nabla^2 \Phi_{N,b}(R,z) = 4\pi G \rho_b(R,z)$$
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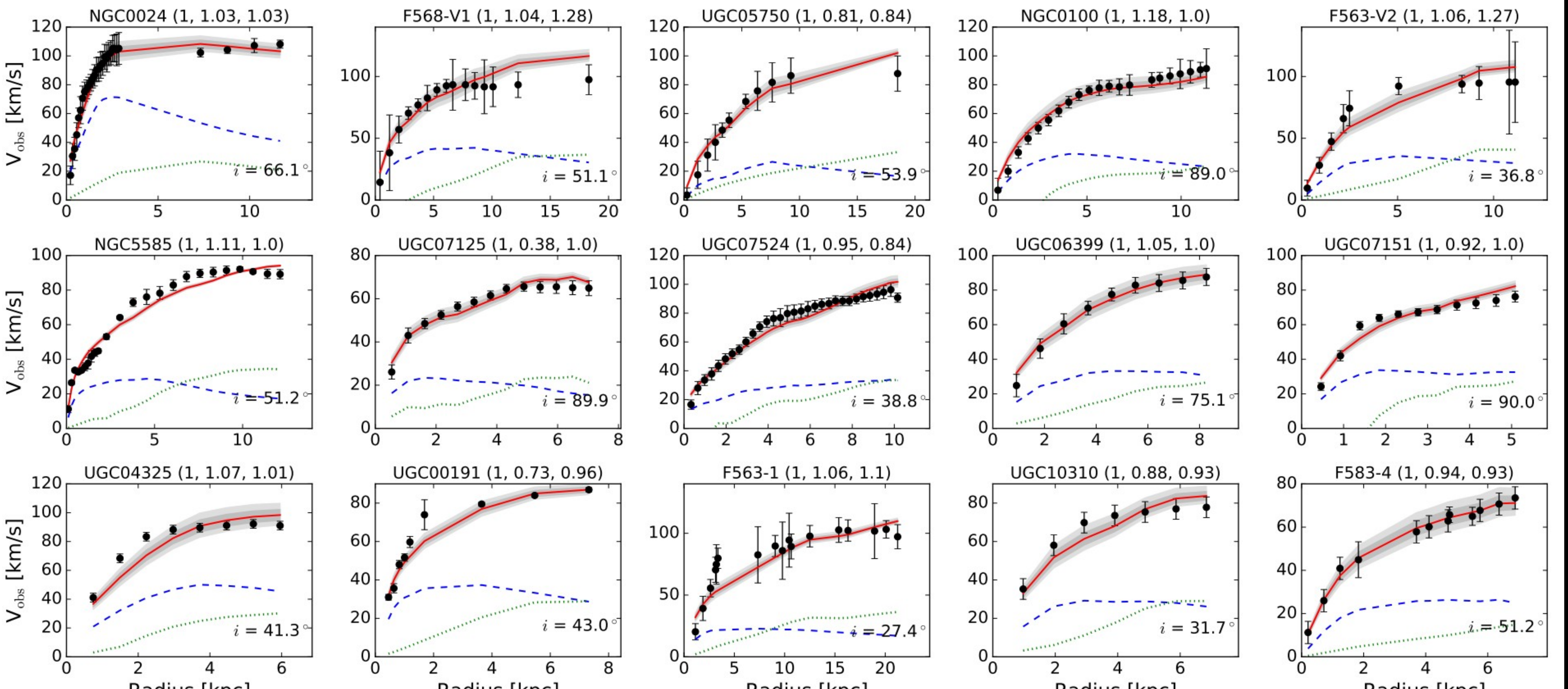

Li+2018

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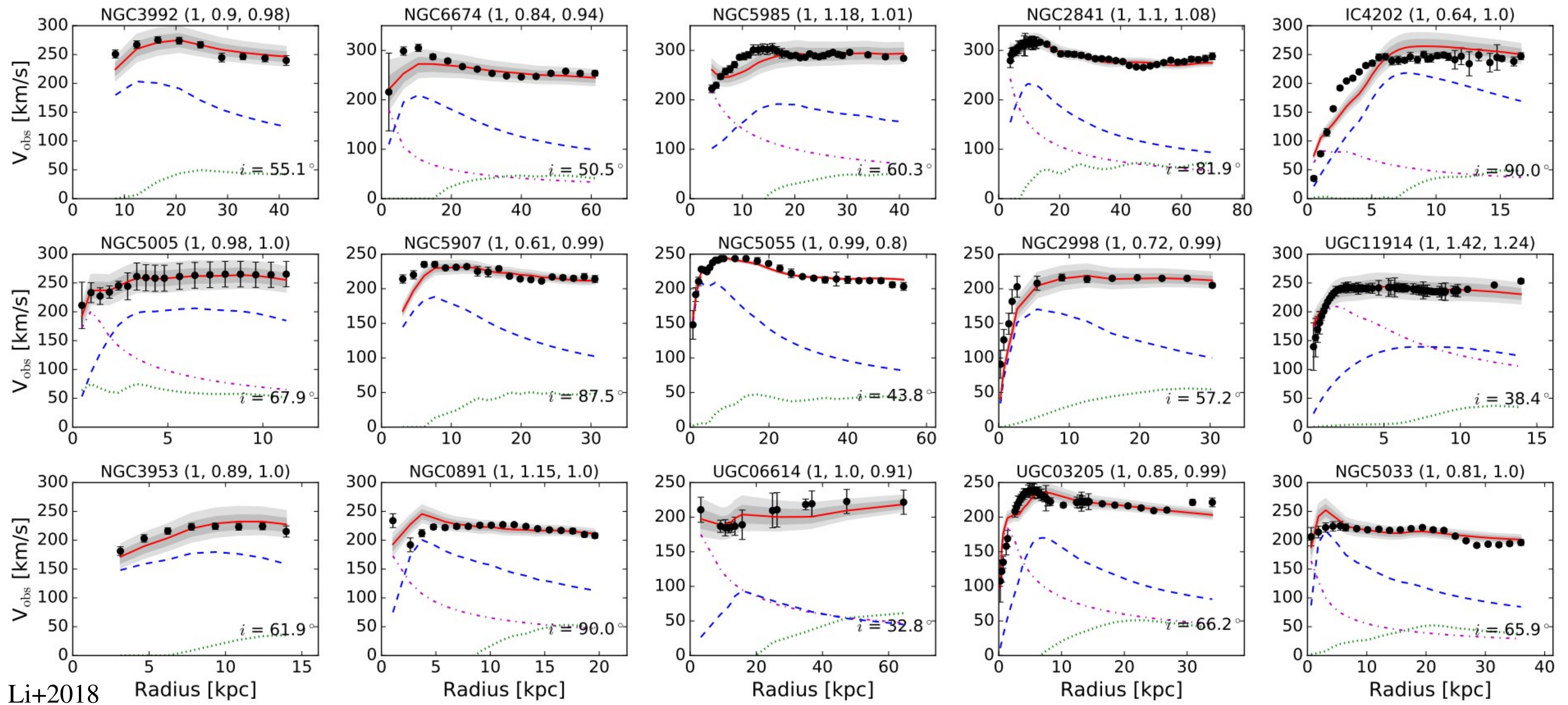

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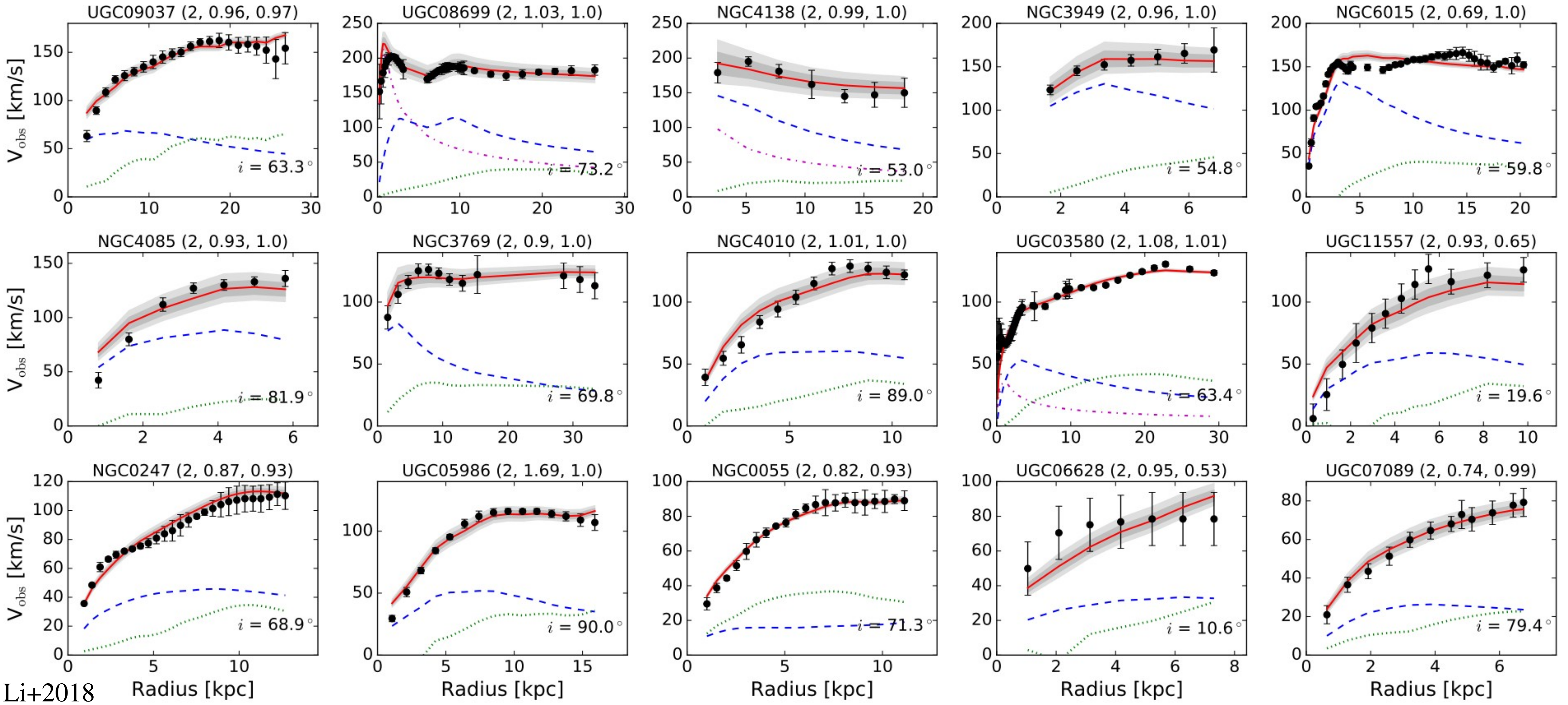

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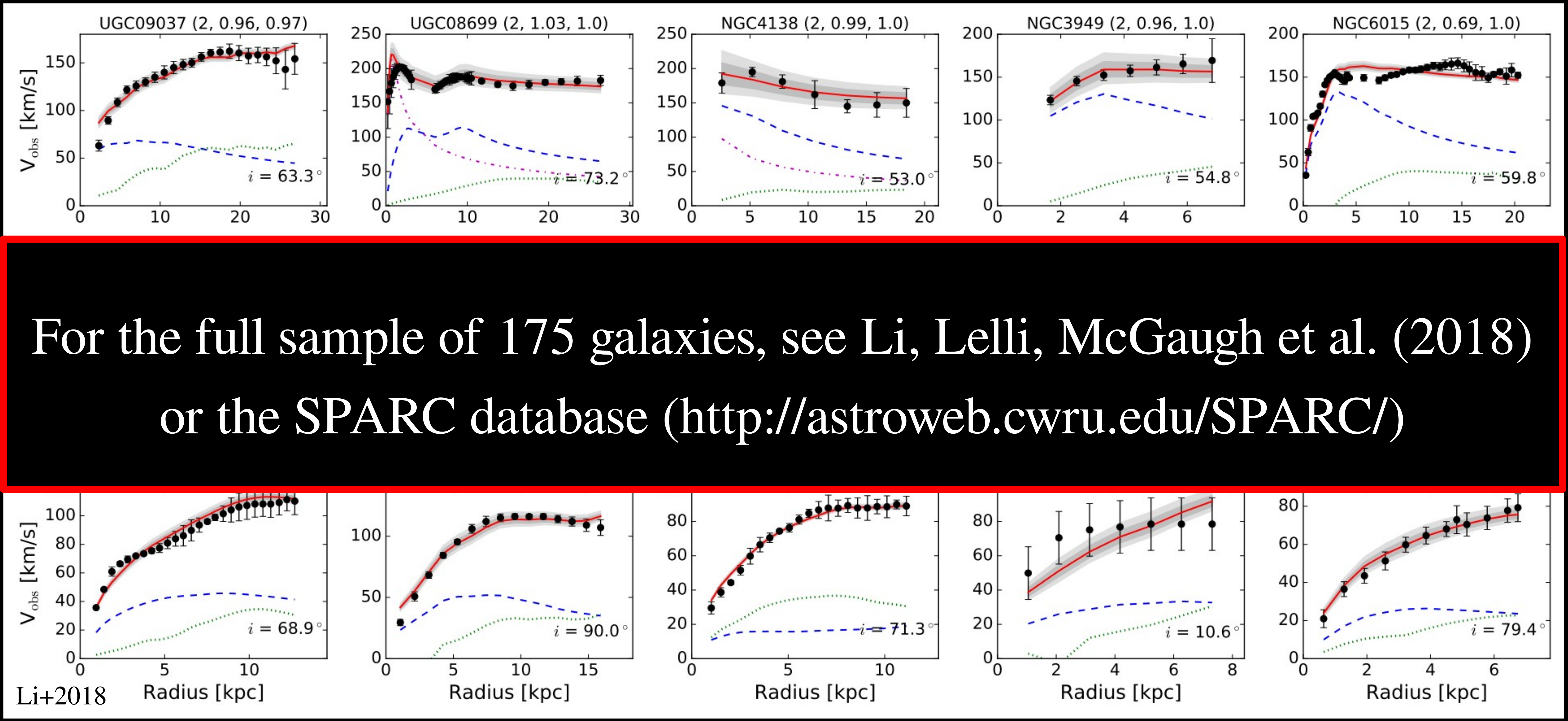

For the full sample of 175 galaxies, see Li, Lelli, McGaugh et al. (2018) or the SPARC database (http://astroweb.cwru.edu/SPARC/)

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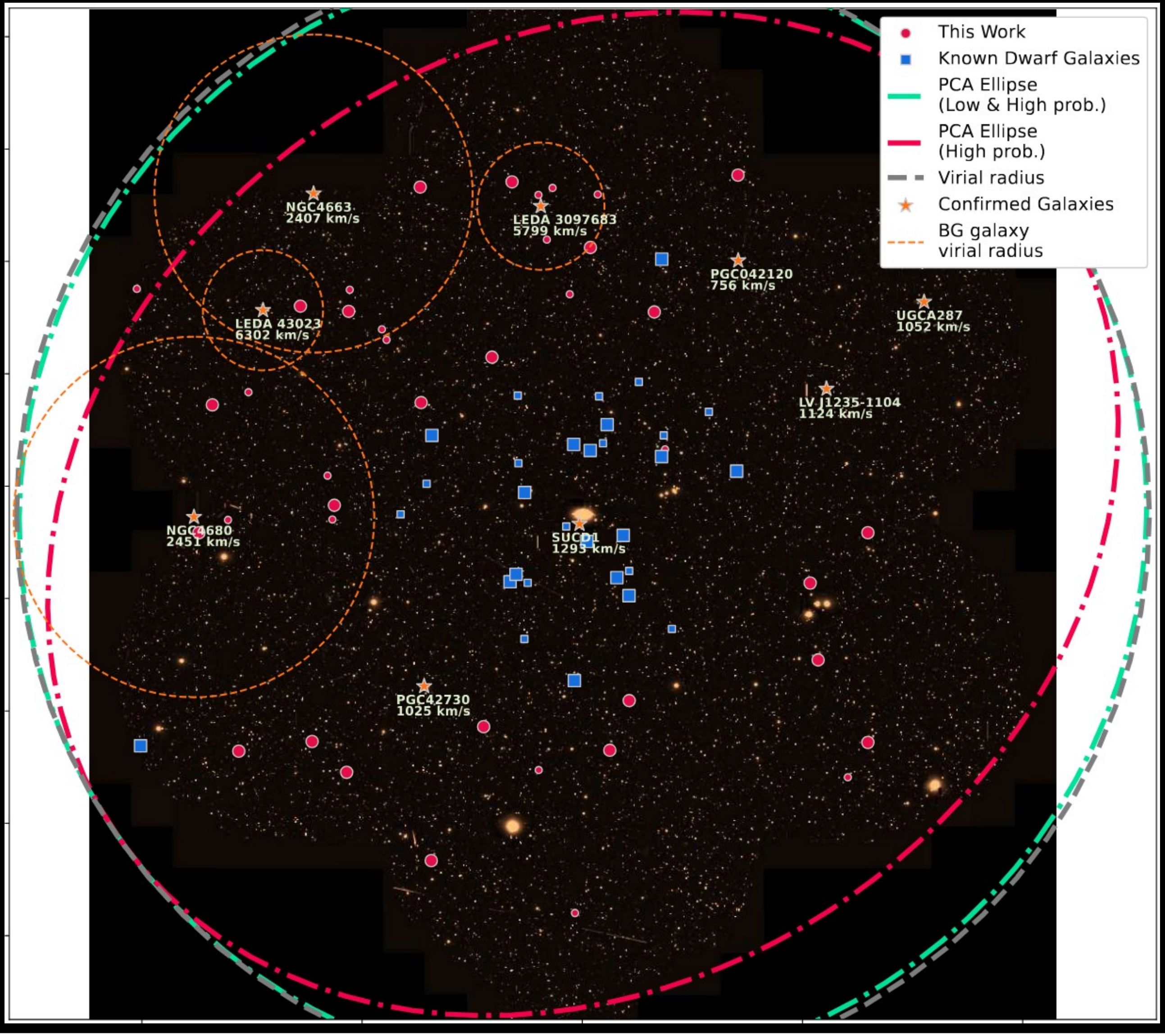
Galaxy Groups: bound systems with ~10-100 galaxies

Sombrero (M104) galaxy group (Crosby et al. 2022)



Velocity dispersion ("temperature"):

$$\sigma_V^2 = \frac{1}{M_b} \sum_i m_i V_i^2$$

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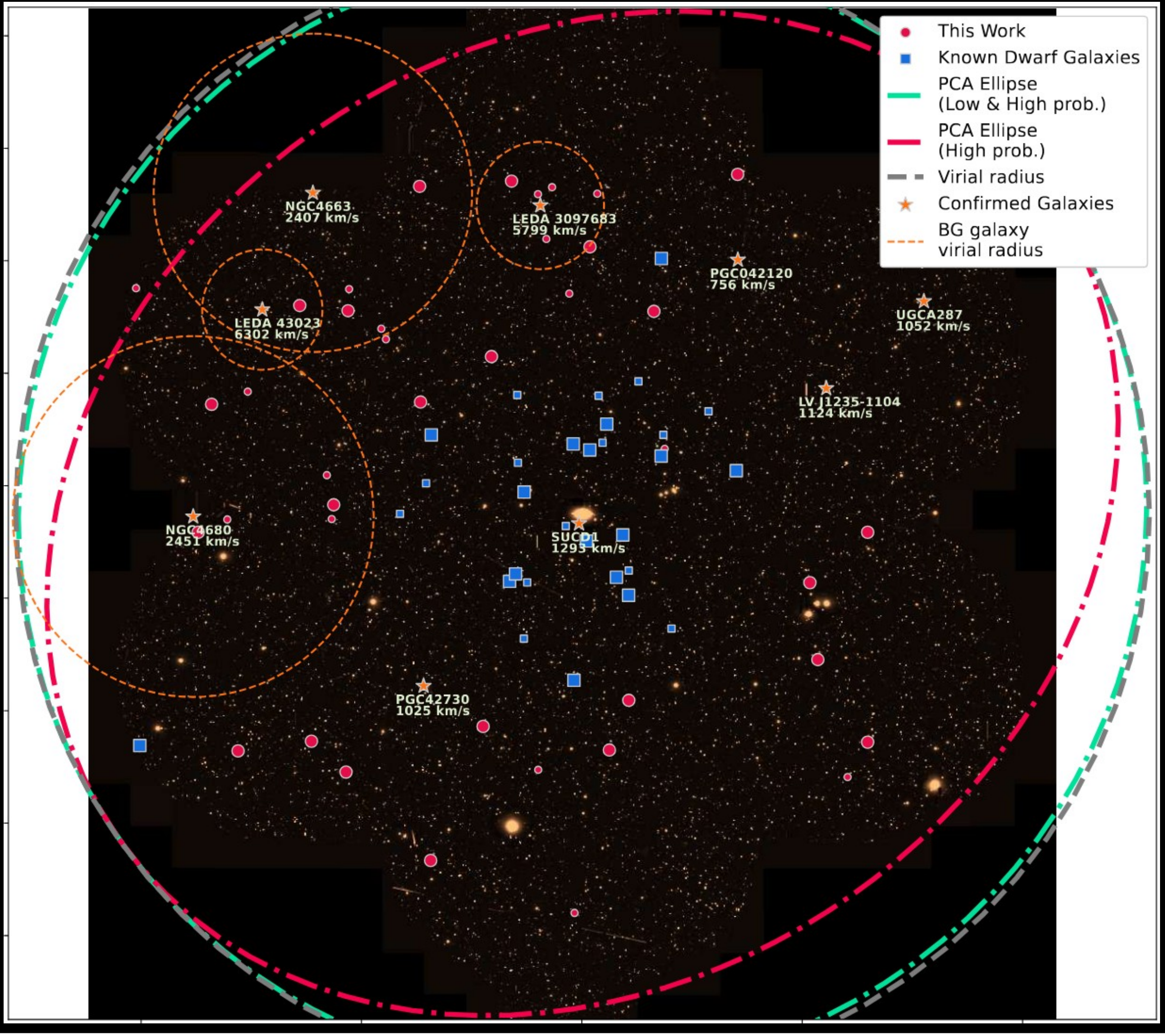

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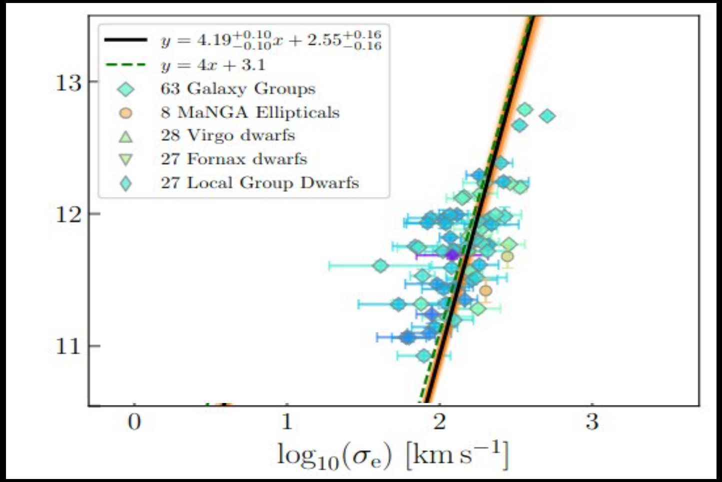
MOND virial theorem (Milgrom 2014):

$$\sigma_V^4 = \frac{a_0 G_N}{c} M_b$$

- It applies only to objects for which $a \ll a_0$ everywhere (fully in the deep MOND limit)
- c is theory-dependent but is expected ~O(1)
- $c = 9/4$ for a broad class of MOND theories

Galaxy Groups: bound systems with ~10-100 galaxies



$$\sigma_V^4 = \frac{a_0 G_N}{c} M_b \rightarrow$$ confirmed in galaxy groups!

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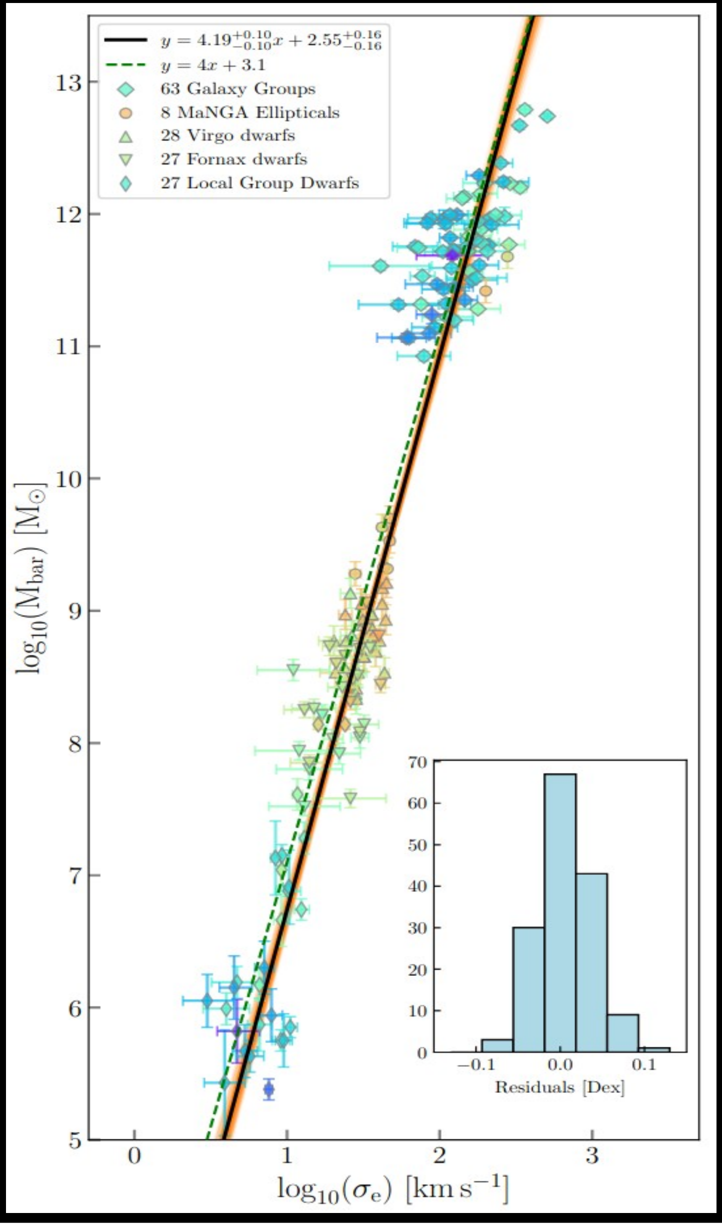

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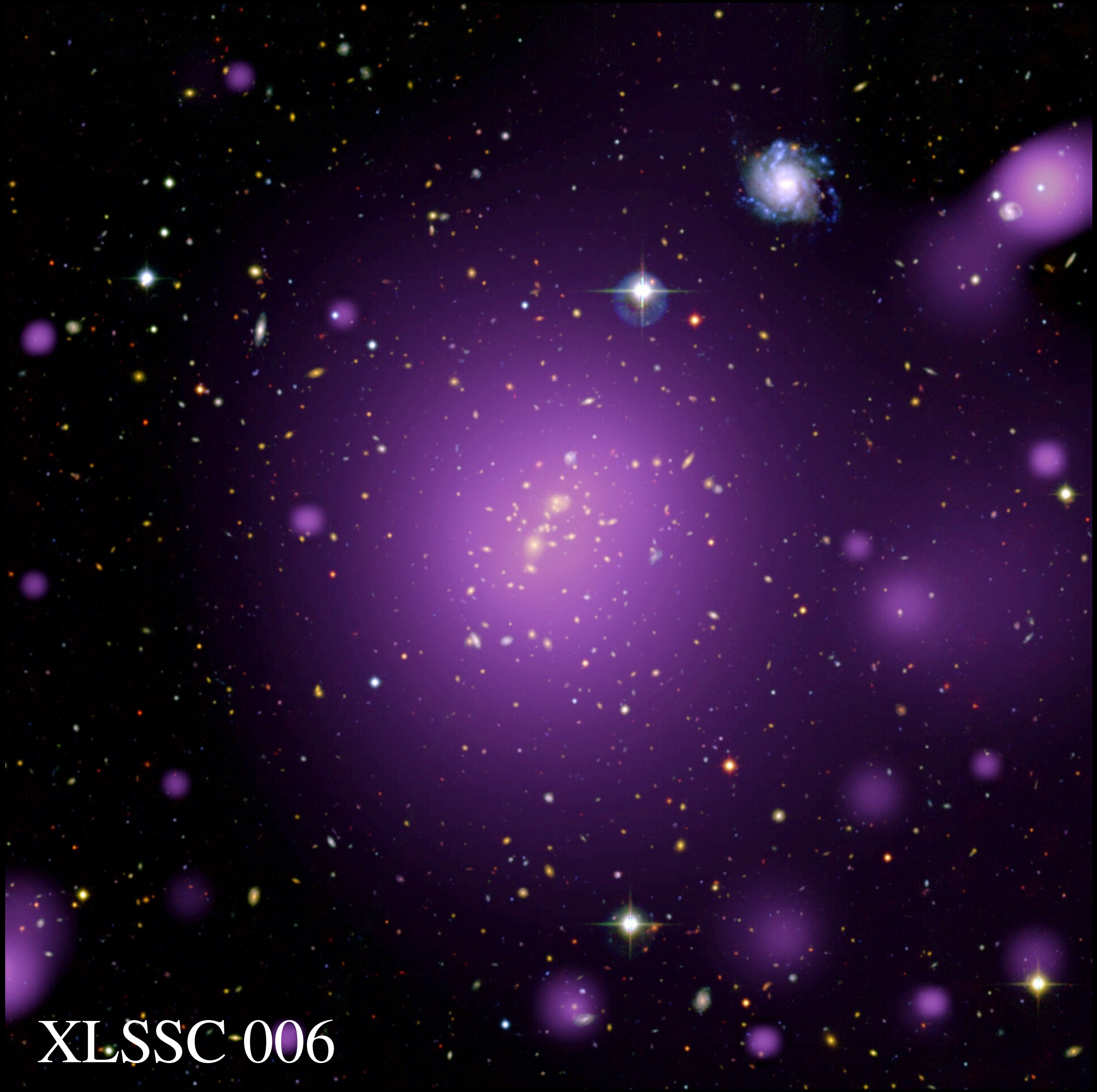
The same relation is followed by pressure-supported galaxies in the deep-MOND limit (Tian et al. in prep.):

- Dwarf ellipticals in galaxy clusters
- Dwarf spheroidals in the Local Group

MOND virial theorem confirmed over ~8 dex in M_b!

Same value of a_0 from BTFR, RAR, and this relation!

Galaxy Clusters: bound systems with ~100-1000 galaxies



Observed baryon budget:

~10% galaxies (optical & NIR)

~90% hot ionized gas (X rays)

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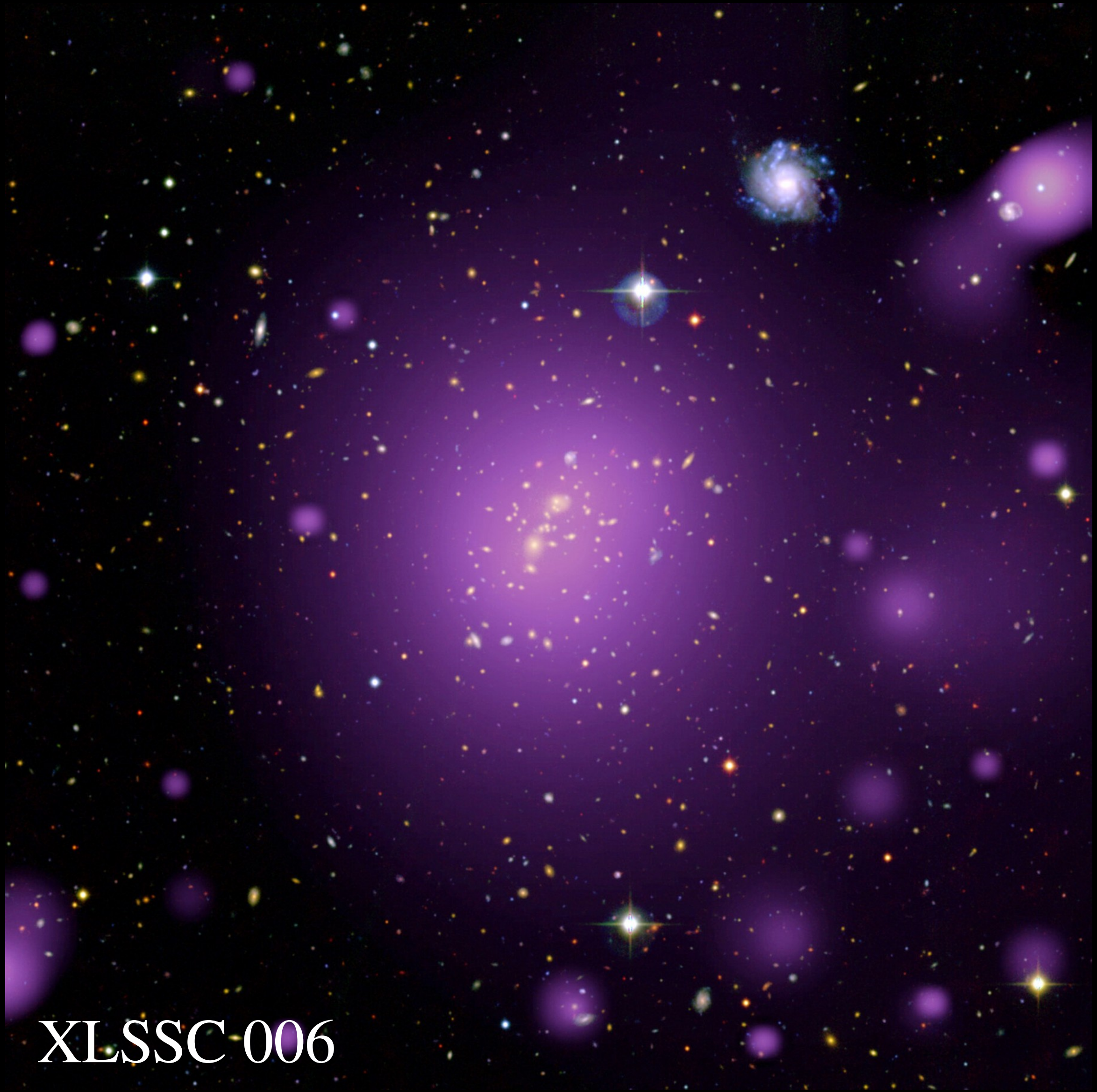

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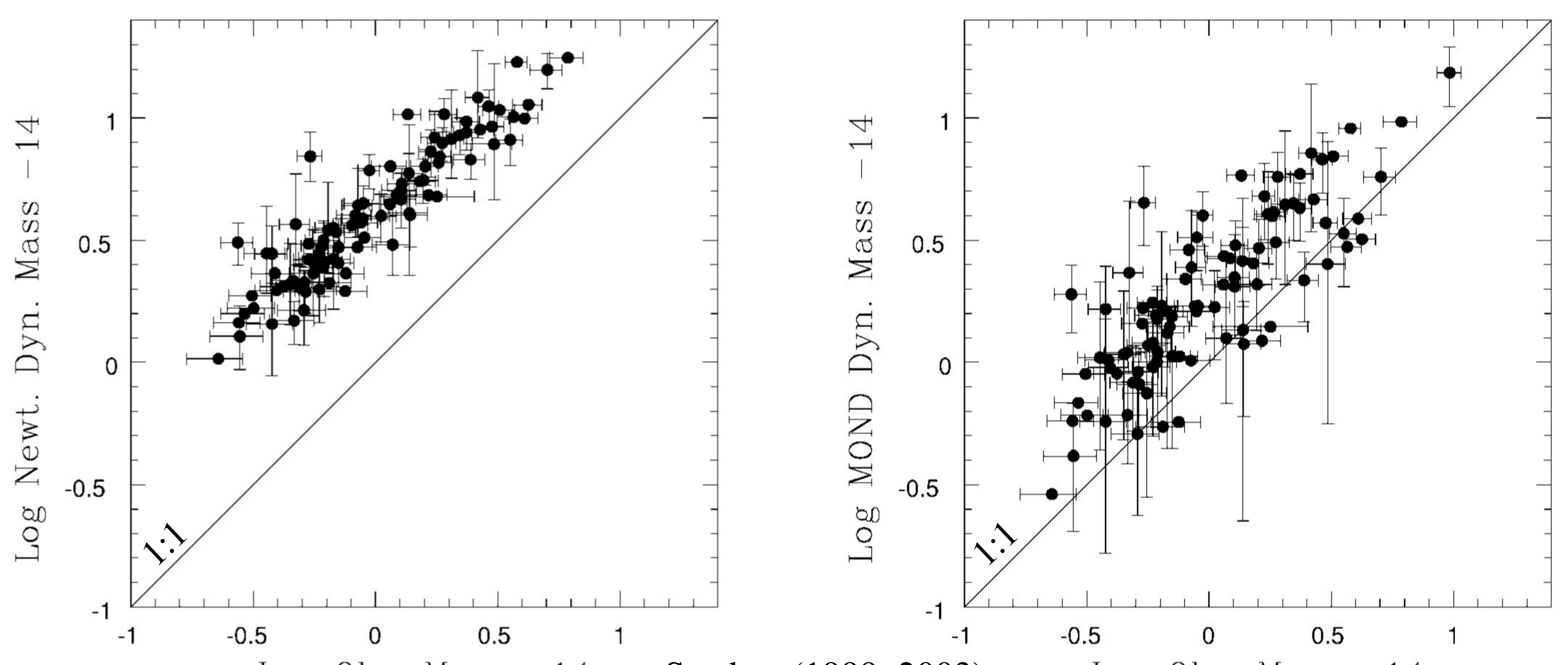
Sphere in Hydrostatic Equilibrium

$$\frac{\partial P_{gas}}{\partial r} = \rho_{gas} \frac{\partial \Phi}{\partial r} \qquad P_{gas} = \frac{k_B T_{gas}}{w\, m_p}$$

$$\Rightarrow \quad \frac{\partial \Phi}{\partial r} = \frac{k_B}{w\, m_p} \frac{1}{\rho_{gas}} \frac{\partial}{\partial r} \left(\rho_{gas} T_{gas} \right)$$

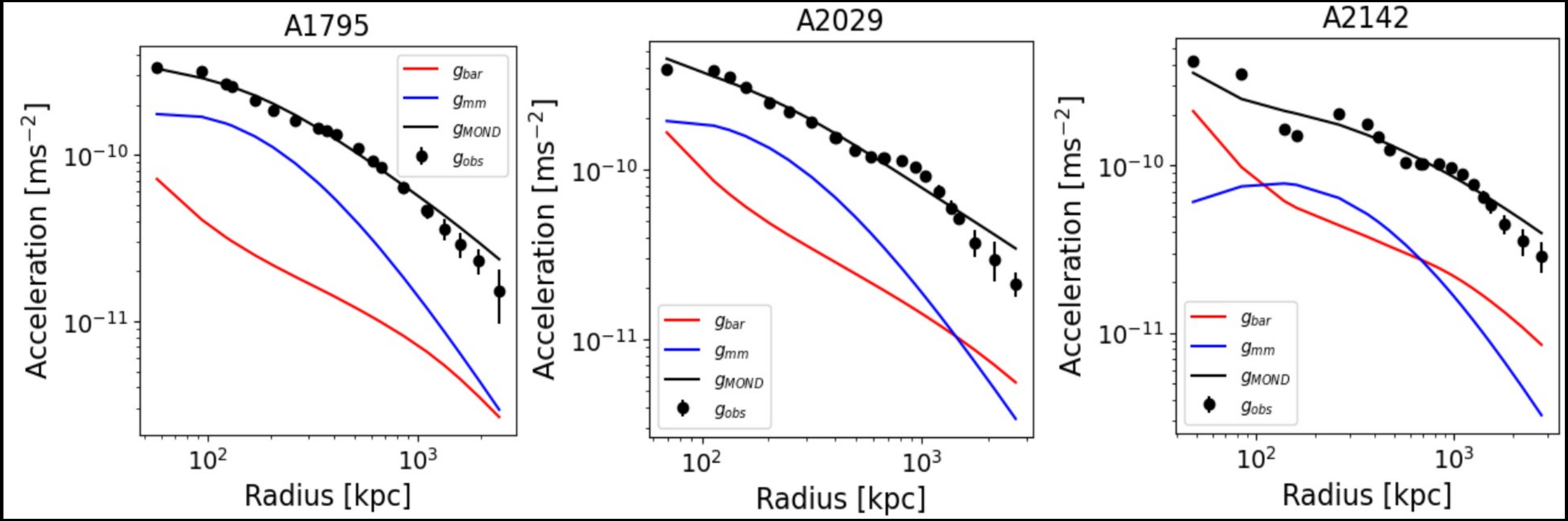
Galaxy Clusters: Long-standing challenge for MOND

Newtonian analysis: $M_{dyn}/M_{bar} \simeq 5$ MOND analysis: $M_{dyn}/M_{bar} \simeq 2$



Sanders (1999, 2003)

MOND fits with a missing mass component (Kelleher & Lelli 2024)



Density profile of missing mass:

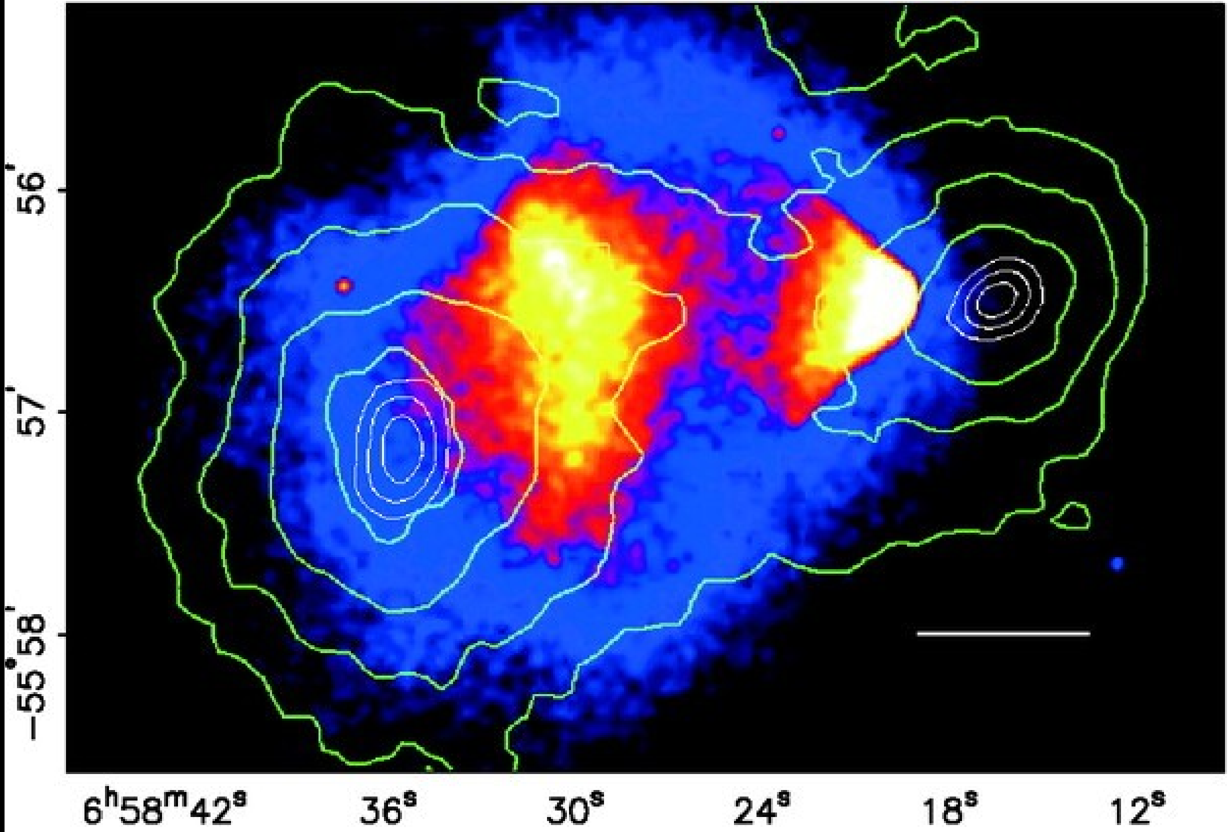
$$\rho_{mm}(r) = \frac{\rho_0}{(1 + r/r_s)^4}$$

Converged (physical) total mass:

$$\Rightarrow \quad M_{mm,tot} = \int_0^\infty \rho(r) 4\pi_{mm} r^2 dr = \frac{4\pi}{3} \rho_0 r_s^3$$

The bullet cluster in MOND: missing mass must be collisionless

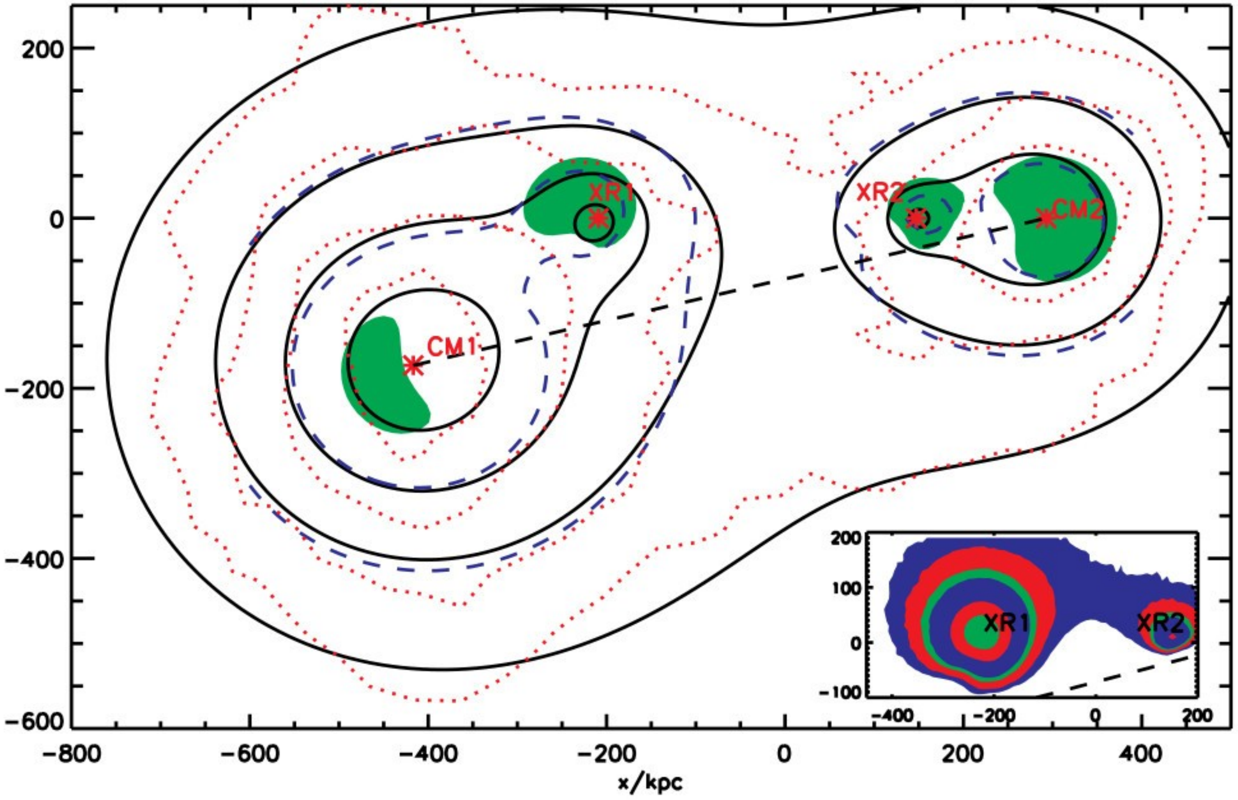
OBSERVATIONS (Clowe+2004, ApJ)



Green: Observed lensing map (total mass)

Blue/**Red**/**Yellow**: X-ray emission (hot gas)

MOND (Angus+2006, MNRAS; Angus+2007, ApJ)

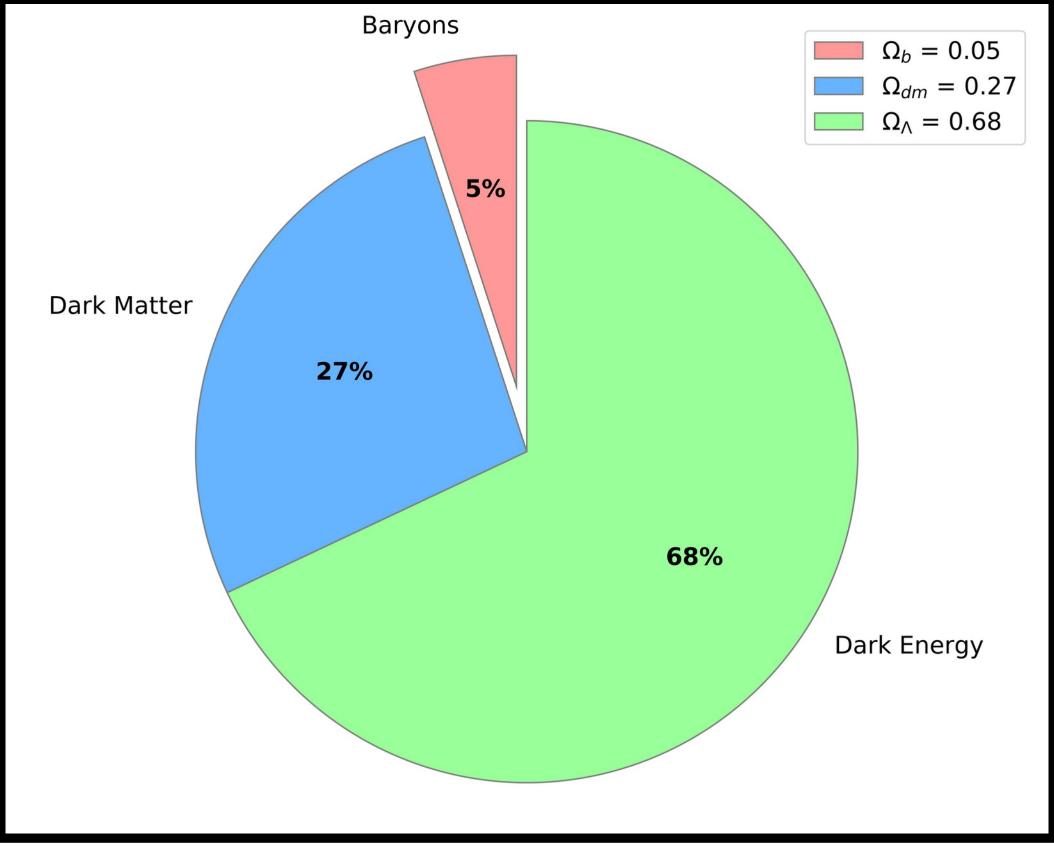


Red: Observed lensing convergence map

Black: TeVeS model with 2eV neutrinos

Blue: total surface densities (baryons+υ)

The missing baryons problem in Cosmology



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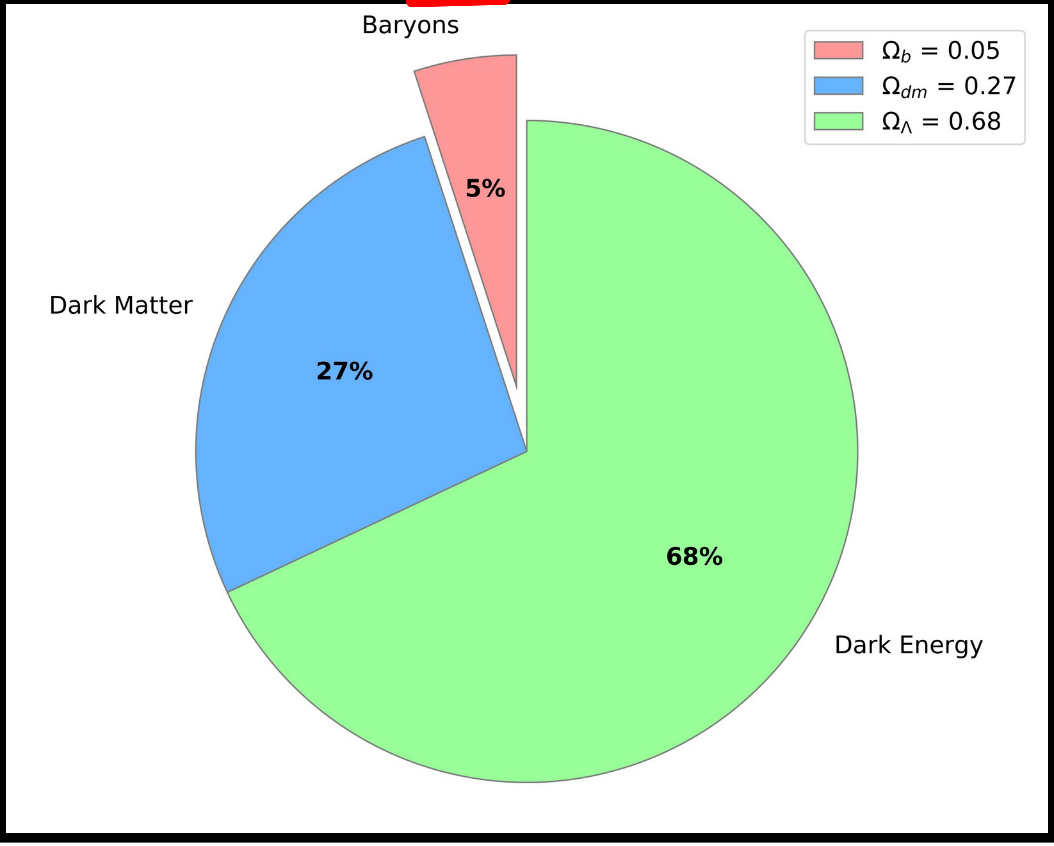

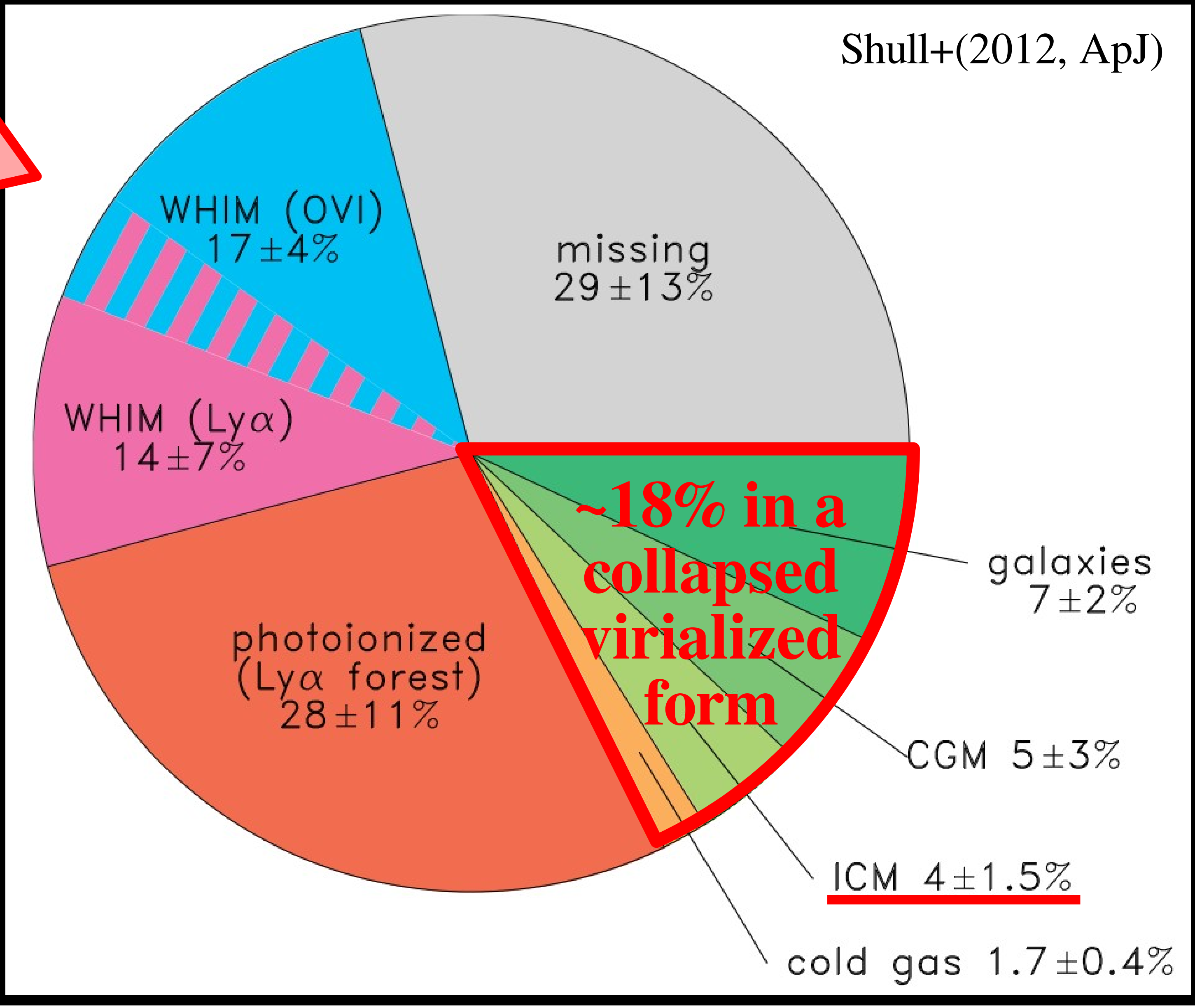

Talk Outline

1. General MOND paradigm

2. Tests on galaxy scales

3. ~~Tests on groups/clusters scales~~

4. MOND theories & cosmology

MOND paradigm

Modified Gravity ($\rightarrow \nabla^2\Phi = 4\pi G\rho$)

Modified Inertia ($\rightarrow F = ma$)

MOND paradigm

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Mach's principle for inertia ?

$a_0 \simeq c\,\Lambda^{1/2} \rightarrow$ quantum vacuum? (Milgrom 1999)

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Superfluid DM (Berezhiani & Khoury 2015)

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Let's start from the Newtonian non-relativistic Action

$$S=\int dt\,L=\int dt\left(L_{matter}+L_{gravity}+L_{coupling}\right)=\int dt\,d^3x\left(\rho\frac{V^2}{2}-\frac{\left|\vec{\nabla}\Phi\right|^2}{8\pi G}-\rho\Phi\right)$$

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Principle of Least Action:

$$\frac{\delta S}{\delta \Phi} = 0 \rightarrow \nabla^2 \Phi = 4\pi G \rho$$ Poisson's equation

$$\frac{\delta S}{\delta \vec{x}} = 0 \rightarrow \vec{a} = -\vec{\nabla}\Phi$$ Newton's 2nd Law

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Change this for modified inertia

Change this for modified gravity

Changing this modify both

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AQUAL = Aquadratic Lagrangian (Bekenstein & Milgrom 1984)

$$S_N = \int dt\, L_N = \int dt\, d^3x \left(\rho \frac{V^2}{2} - \frac{|\vec{\nabla}\Phi|^2}{8\pi G} - \rho\Phi \right)$$

Lagrangian is quadratic in $\nabla\Phi$

$$\downarrow$$

$$-\frac{a_0^2}{8\pi G} F\left(\frac{|\vec{\nabla}\Phi|^2}{a_0^2} \right)$$

$F(y) \rightarrow y$ for $y = |\nabla\Phi|^2/a_0{}^2 \gg 1$

$F(y) \rightarrow y^{3/2}$ for $y = |\nabla\Phi|^2/a_0{}^2 \ll 1$

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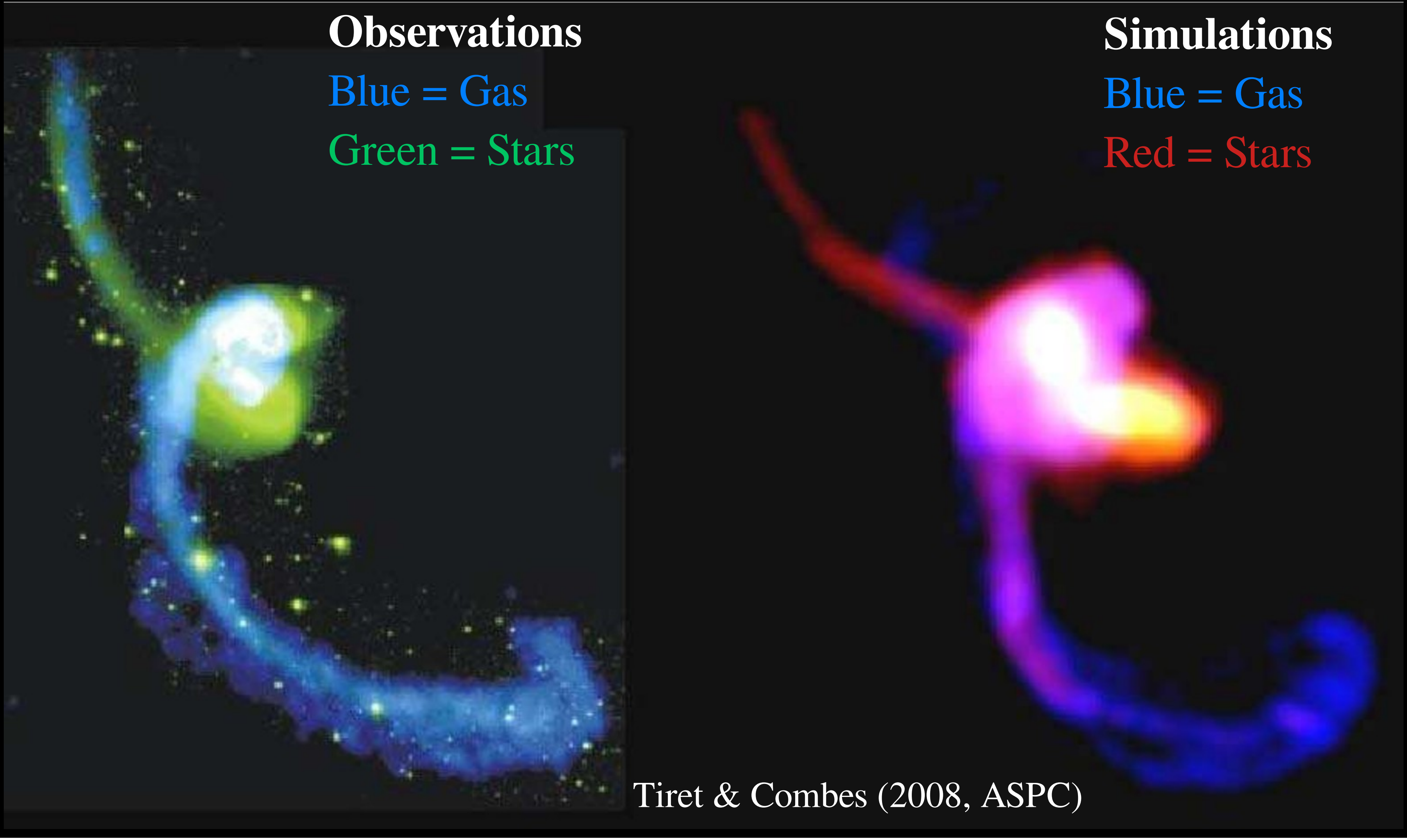
$$\frac{\delta S}{\delta\Phi} = 0 \rightarrow \nabla \cdot \left[\mu\left(\frac{|\vec{\nabla}\Phi|}{a_0}\right) \vec{\nabla}\Phi \right] = 4\pi G\rho$$

Modified Poisson's Equation

$$\mu(x) = \frac{dF(y)}{dy} \qquad y = x^2$$

$F(y)$ provides the interpolation function $\mu = \upsilon^{-1}$, whose full shape is set empirically by the RAR

Application of AQUAL: simulations of interacting galaxies



Tiret & Combes (2008, ASPC)

Lovelock-Grigore Theorem

GR (+Λ) is the only theory that satisfy these assumptions:

1) Geometry is Reimannian

2) Action depends only on $g_{\mu\upsilon}$

3) It is diffeomorphism invariant

4) It is local

5) It leads to 2nd order field equations

Lovelock-Grigore Theorem

GR (+Λ) is the only theory that satisfy these assumptions:

1) Geometry is Reimannian

~~2) Action depends only on $g_{\mu\upsilon}$~~ → add new dynamical fields

3) It is diffeomorphism invariant

4) It is local

5) It leads to 2^{nd} order field equations

Khronon = Tensor – Scalar Theory (Blanchet & Skordis 2024)

Tensor $g_{\mu\nu}$ → Einstein's metric (universally coupled to matter fields Ψ)

Scalar τ → Khronon field (units of time; drive a foliation in 3D space-like hypersurfaces)

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$$n_\mu = -\frac{c}{Q}\nabla_\mu \tau \qquad Q = c\sqrt{-g^{\mu\nu}\nabla_\mu\tau\nabla_\nu\tau}$$

Dimensionless unit timelike ($n^\mu n_\mu = -1$) vector, pointing in the future ($n^0 > 0$).

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Covariant spacelike acceleration

$$Y = \frac{A_\mu A^\mu}{c^4}$$

Squared "acceleration" with units of $1/L^2$

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$$S = \frac{c^3}{16\pi G} \int d^4x \sqrt{-g} \left[R - 2I(Y) + 2K(Q) \right] + S_m[\Psi, g]$$

Ricci Scalar (as in GR)

Free function to get MOND

Free function to get cosmology

Matter Action

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It gives dust-like behaviour: $\rho_K \propto a(t)^{-3}$ like CDM

μ_Q = constant with dimension of inverse length

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⟹ AQUAL + $\mu_Q^2\Phi$ $\mu_Q^{-1} \gg 1$ Mpc

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$y=|\nabla\Phi|/a_0$

for $y\ll 1 \quad \mu(y)=y \quad \Rightarrow \quad I(Y)=\Lambda-Y+\frac{2c^2}{3a_0}Y^{3/2}+O\left(\frac{Y^4}{a_0^2}\right)$

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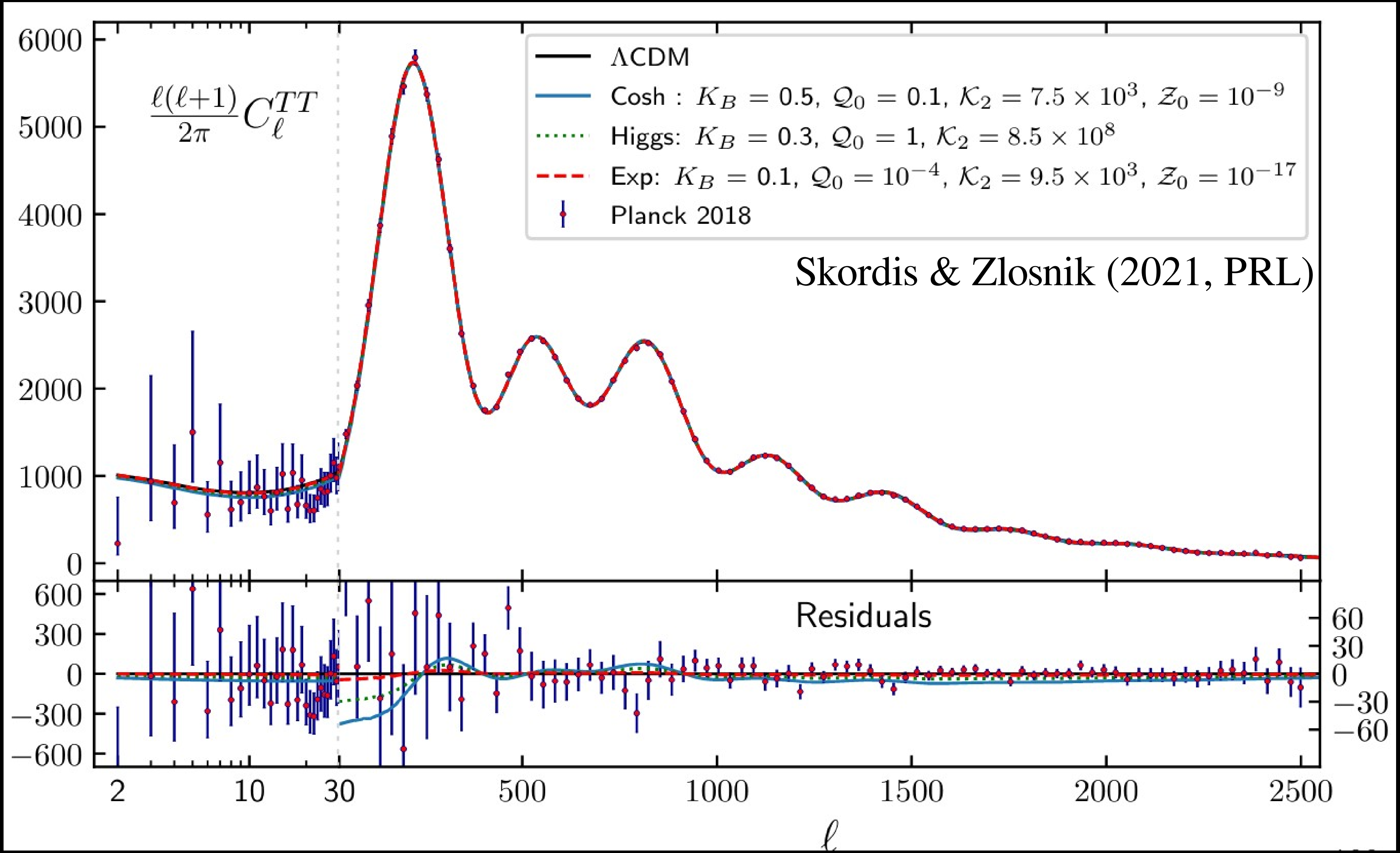
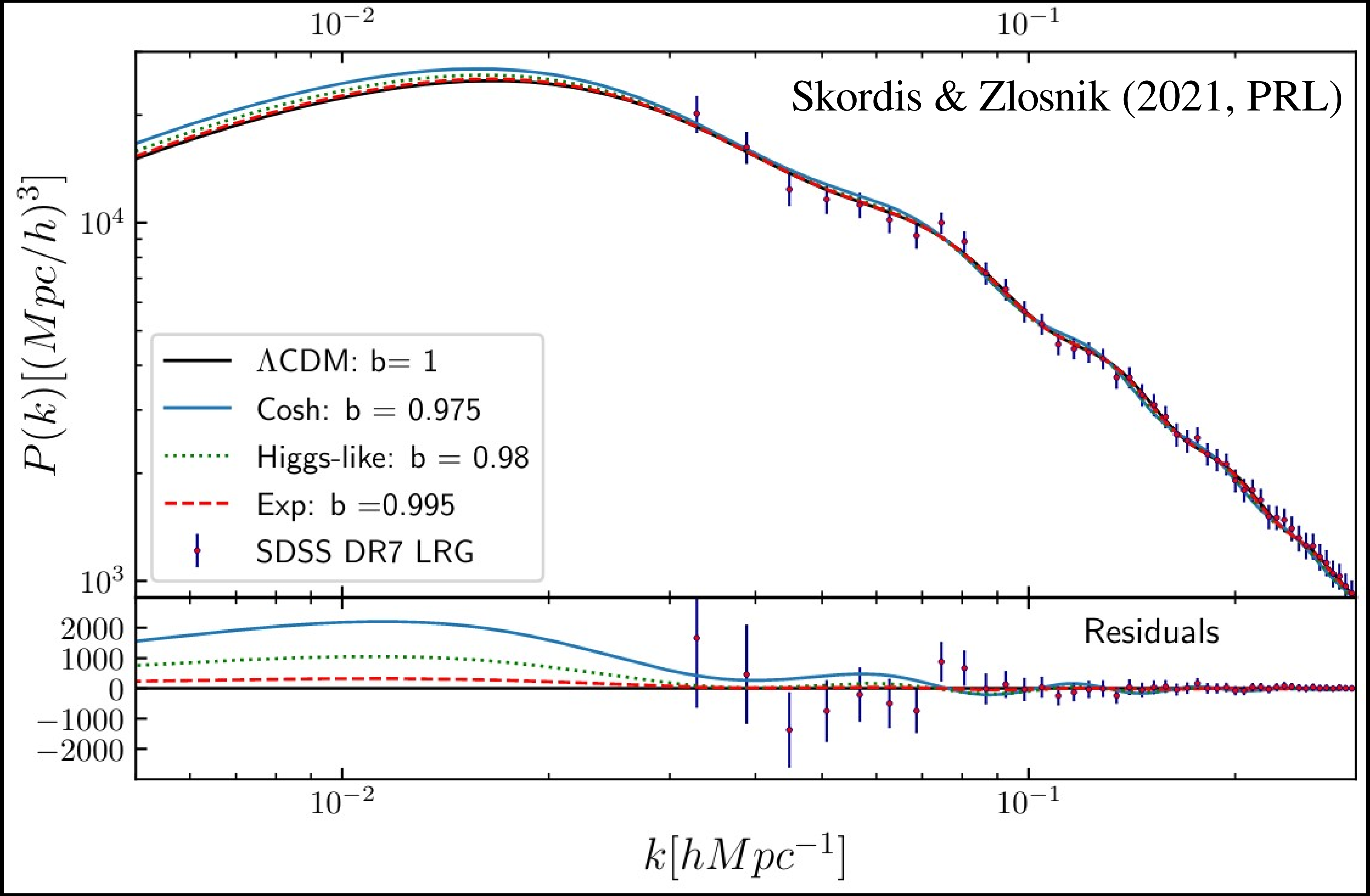
$$\text{for } y\gg 1 \quad \mu(y)=1 \quad \Rightarrow \quad I(Y)=\Lambda_\infty+O(a_0/y)$$

CMB Power Spectrum (from AeST or Khronon)

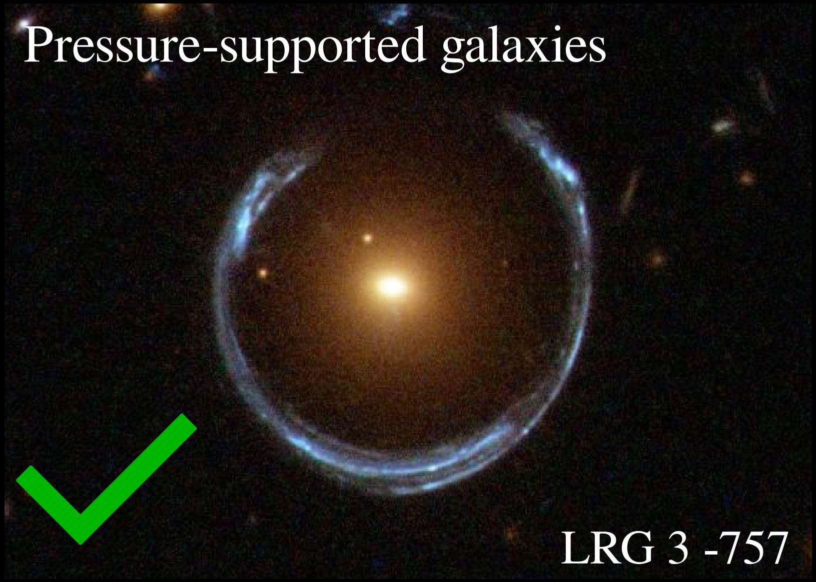


Linear Matter Power Spectrum (from AeST or Khronon)

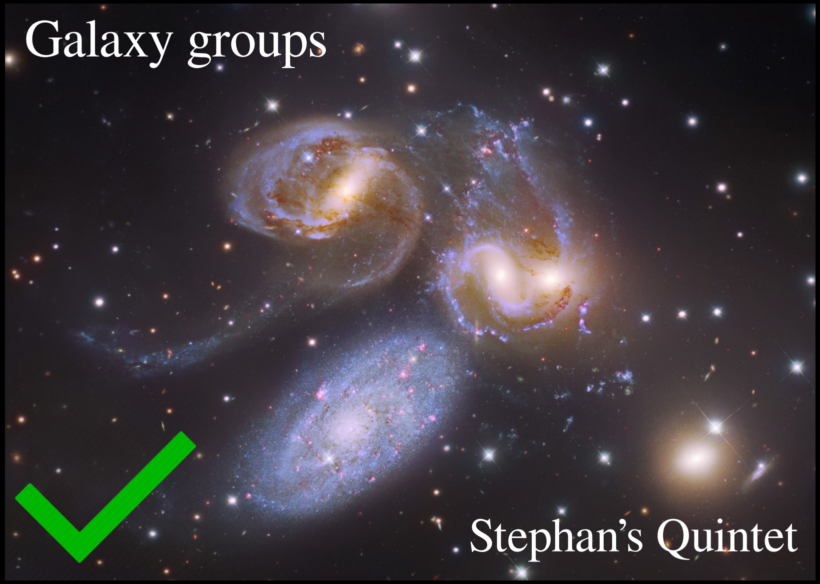


Summary: Status of MOND at Various Scales

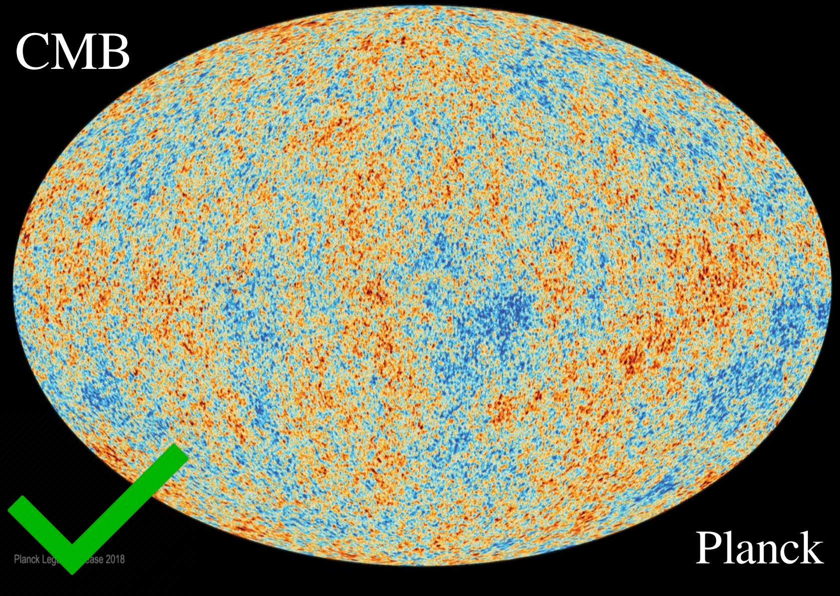
Galaxy Scales (~1-100 kpc)

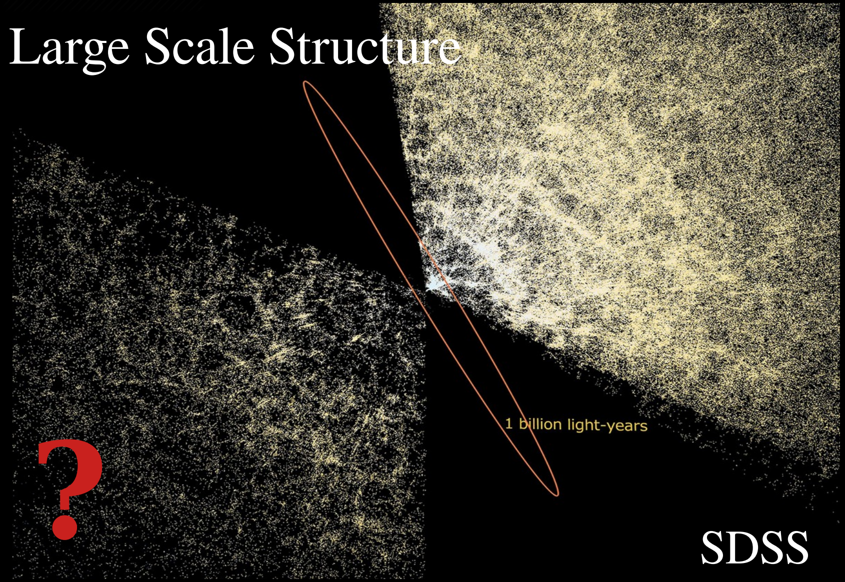


Groups/Clusters Scales (~1-5 Mpc)

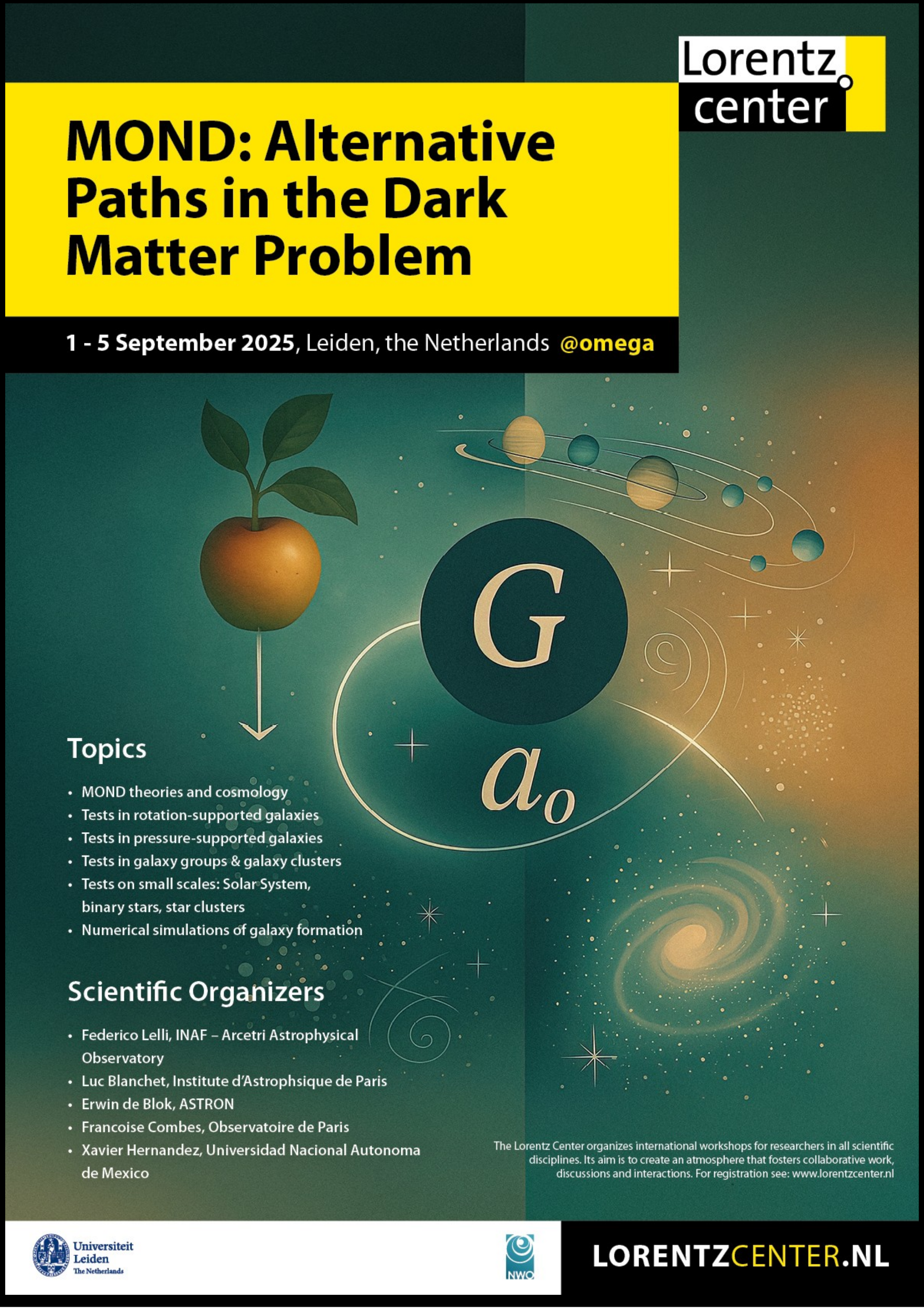


Cosmological Scales (>100 Mpc)





The MOND white paper: coming soon!



More Slides

Khronon Field Equations (Blanchet & Skordis 2024)

$$G^{\mu\nu}+(I-K)g^{\mu\nu}-\frac{2}{c^4}\frac{dI}{dY}A^{\mu}A^{\nu}+\left[\frac{2}{c^4}\nabla_{\rho}\left(\frac{dI}{dY}A^{\rho}\right)-Q\frac{dK}{dQ}\right]n^{\mu}n^{\nu}=\frac{8\pi G}{c^4}T^{\mu\nu}$$

$$T_{\tau}^{\mu\nu}\stackrel{\text{def}}{=}\frac{c^4}{8\pi G}\left(-(I-K)g^{\mu\nu}+\frac{2}{c^4}\frac{dI}{dY}A^{\mu}A^{\nu}-\left[\frac{2}{c^4}\nabla_{\rho}\left(\frac{dI}{dY}A^{\rho}\right)-Q\frac{dK}{dQ}\right]n^{\mu}n^{\nu}\right)$$

The Khronon stress-energy tensor contains $g_{\mu\nu}$ explicitly and implicitly in Y and Q.

This is very different from adding DM to GR!

AeST = Aether - Scalar - Tensor (Skordis & Zlosnik 2021)

Vector A^{μ} → timelike, first introduced by Sanders (1997) to get gravitational lensing

Scalar φ → first introduced by Bekenstein & Milgrom (1984) to get NR AQUAL

Tensor $g_{\mu\nu}$ → Einstein's metric (as usual)

AeST = Aether - Scalar - Tensor (Skordis & Zlosnik 2021)

$Q \equiv A^{\mu} \nabla_{\mu} \varphi$ Kinetic term of φ along the A^{μ} direction ("time")

$Y \equiv \left(g^{\mu\nu} + A^{\mu} A^{\nu}\right) \nabla_{\mu} \varphi \nabla_{\nu} \varphi$ Kinetic term of φ perpendicular to A^{μ} ("space")

$J^{\mu} \equiv A^{\alpha} \left(\nabla_{\alpha} A^{\mu}\right)$ Gradient of A^{μ} projected on A^{μ}

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$$\mathscr{L}_{grav} = \frac{\sqrt{-g}}{16\pi\widetilde{G}} \left[R - \frac{K_B}{2} F^{\mu\nu} F_{\mu\nu} - \lambda (A^{\mu} A_{\mu} + 1) + (2 - K_B) 2 J^{\mu} \nabla_{\mu} \varphi - (2 - K_B) F(Y, Q) \right]$$

Ricci scalar EM-like A^{μ} is unit time-like Coupling constant Free function

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- Cosmology (homogeneous & isotropic spacetime):

$F(Y=0, Q) = F_Q = 4\Lambda - 2K_2 (Q - Q_0)^2 + \ldots$ → gives CDM-like behaviour: $\rho_Q \propto a(t)^{-3}$

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- Weak-field quasi-static limit (no time dependence):

$F(Y, Q=Q_0) = F_Y$

→ $(2 - K_B)\lambda_s Y + \ldots$ → gives Newton for $Y \to \infty$

→ $\frac{(2-K_B) 2\lambda_s}{3(1+\lambda_s)} \frac{Y^{3/2}}{a_0} + O(Y^2)$ → gives MOND for $Y \to 0$

QUMOND = Quasi-Linear MOND (Milgrom 2010, MNRAS)

$$S_N = \int dt\, L_N = \int dt\, d^3x \left(\rho \frac{V^2}{2} - \frac{|\vec{\nabla}\Phi|^2}{8\pi G} - \rho \Phi \right)$$

Single gravitational potential Φ

$$\downarrow$$

$$\frac{-1}{8\pi G} \left[2\vec{\nabla}\Phi \cdot \vec{\nabla}\Phi_N - a_0^2 Q\left(\frac{|\vec{\nabla}\Phi_N|^2}{a_0^2} \right) \right]$$

Two potentials: Φ and Φ_N!

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Two potentials: Φ and Φ_N!

Principle of least Action varying Φ, Φ_N and $\bar{x}$ → set of 3 equations

$\nabla^2 \Phi_N = 4\pi G \rho$ ⟶ Standard, linear Poisson's equation for Φ_N

$\nabla^2 \Phi = \vec{\nabla} \cdot \left[\nu\left(|\vec{\nabla}\Phi_N| / a_0 \right) \vec{\nabla}\Phi_N \right]$ ⟶ Non-linear step: get Φ from Φ_N $\quad \nu(\sqrt{x}) = \frac{dQ(x)}{x}$

$\vec{a} = -\vec{\nabla}\Phi$ ⟶ Acceleration/force set by second potential Φ

MOND as Modified Inertia (Milgrom 1994, 1999, 2022)

$$\vec{A}[\vec{x}(t);a_0]=-\vec{\nabla}\Phi_N$$

$\bar{A}$ is a functional of the full trajectory $\bar{x}(t)$

For $a \gg a_0$, $A \rightarrow a = \mathrm{d}^2x/\mathrm{d}t^2$ (Newton's 2nd law)

No full theory yet, but two general results:

(1) Imposing Newtonian and MOND limits + Galilei Invariance $\vec{x}(t)\rightarrow\vec{x}(t)+\vec{v}_0 t$

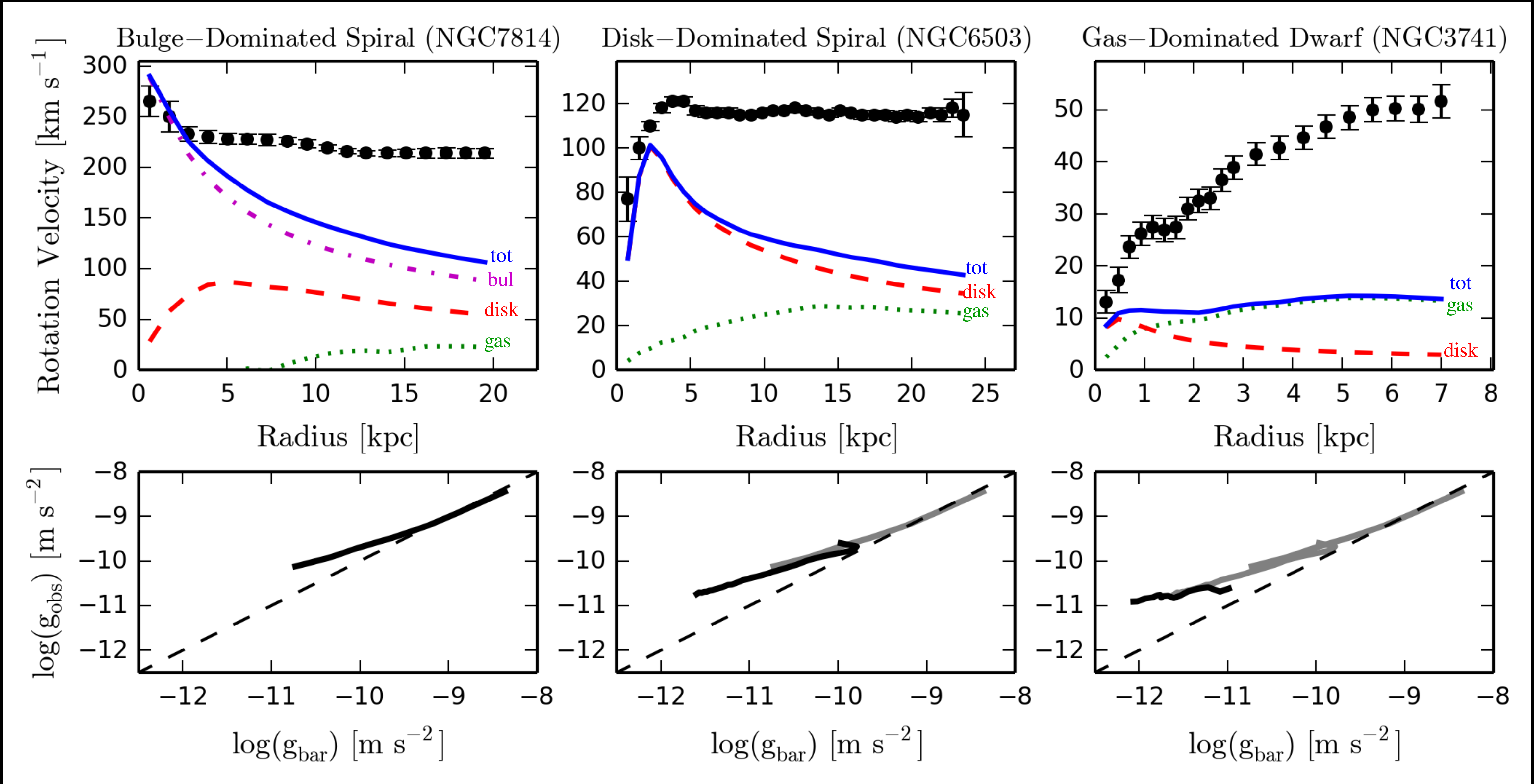
Theory is time non-local: $\vec{A}[\vec{x}(t),a_0]\neq F\left(\frac{d^i\vec{x}}{dt^i};i=1,2,\ldots N\right)$

Accelerations at ($\bar{x}$, t) depend on the full orbital history!

(2) For purely circular orbits: $\vec{a}\,\mu\left(\frac{a}{a_0}\right)=\vec{g}_N$ holds exactly (RAR for disk galaxies)

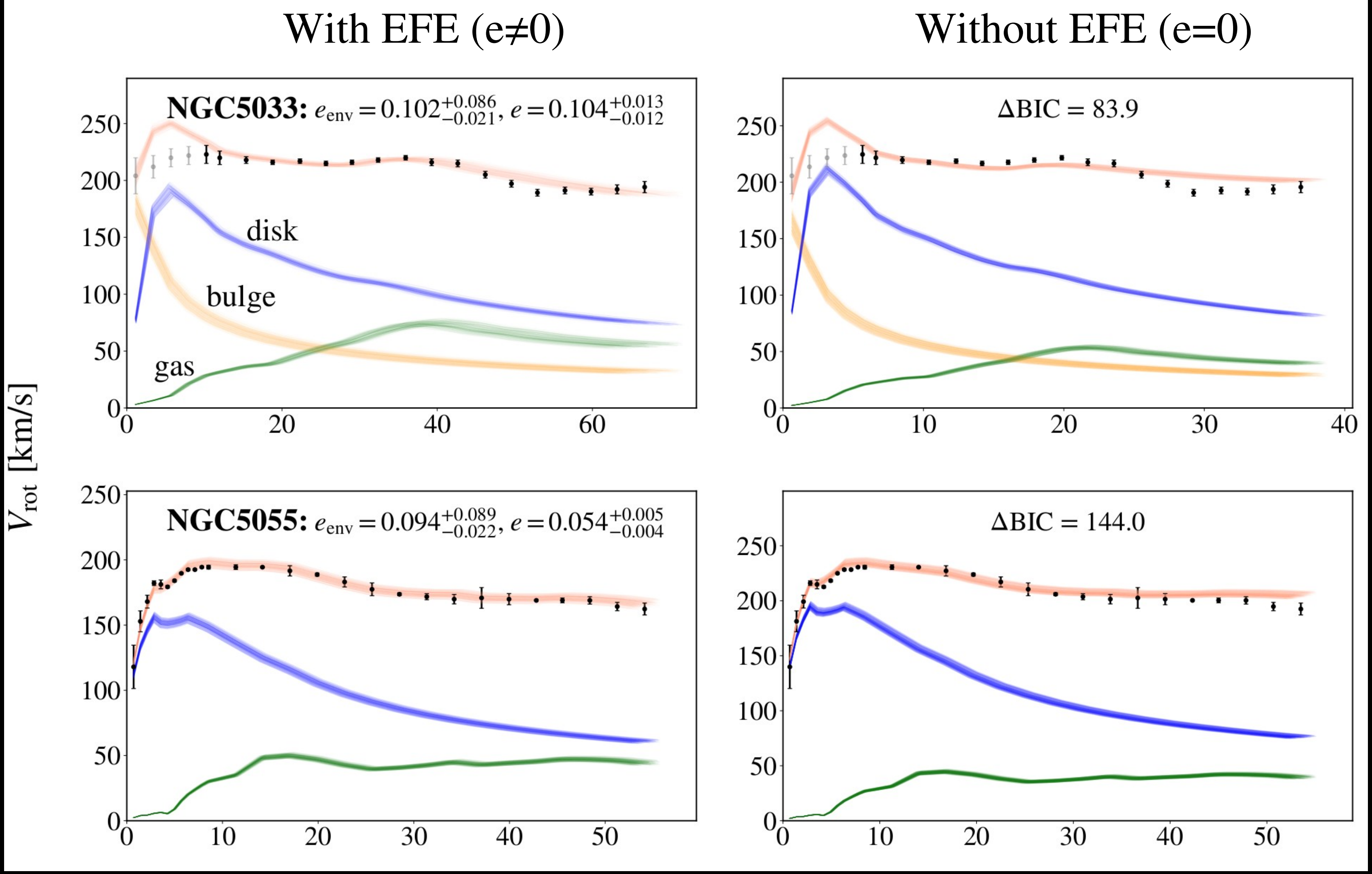
The interpolation function is a derived concept valid for circular orbits!

Galaxies lie on the same RAR *despite* their diversity



EFE is weak: individual detections only in extreme cases

NGC 5055

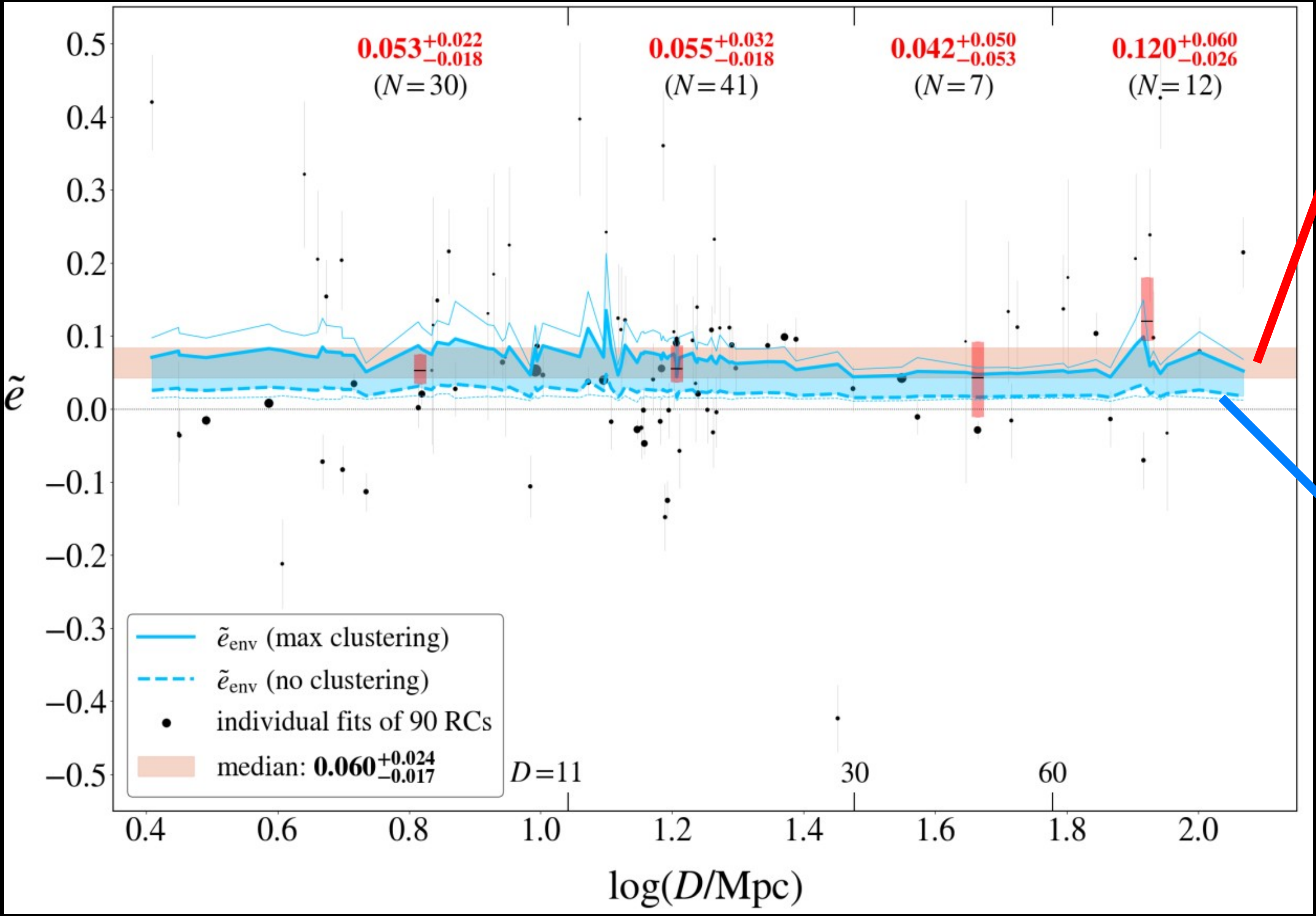


NGC 5033

Chae+2020, 2021

Statistical approach: EFE>0 at >4σ and agrees with LSS

$$\frac{g_{ext}}{a_0}$$

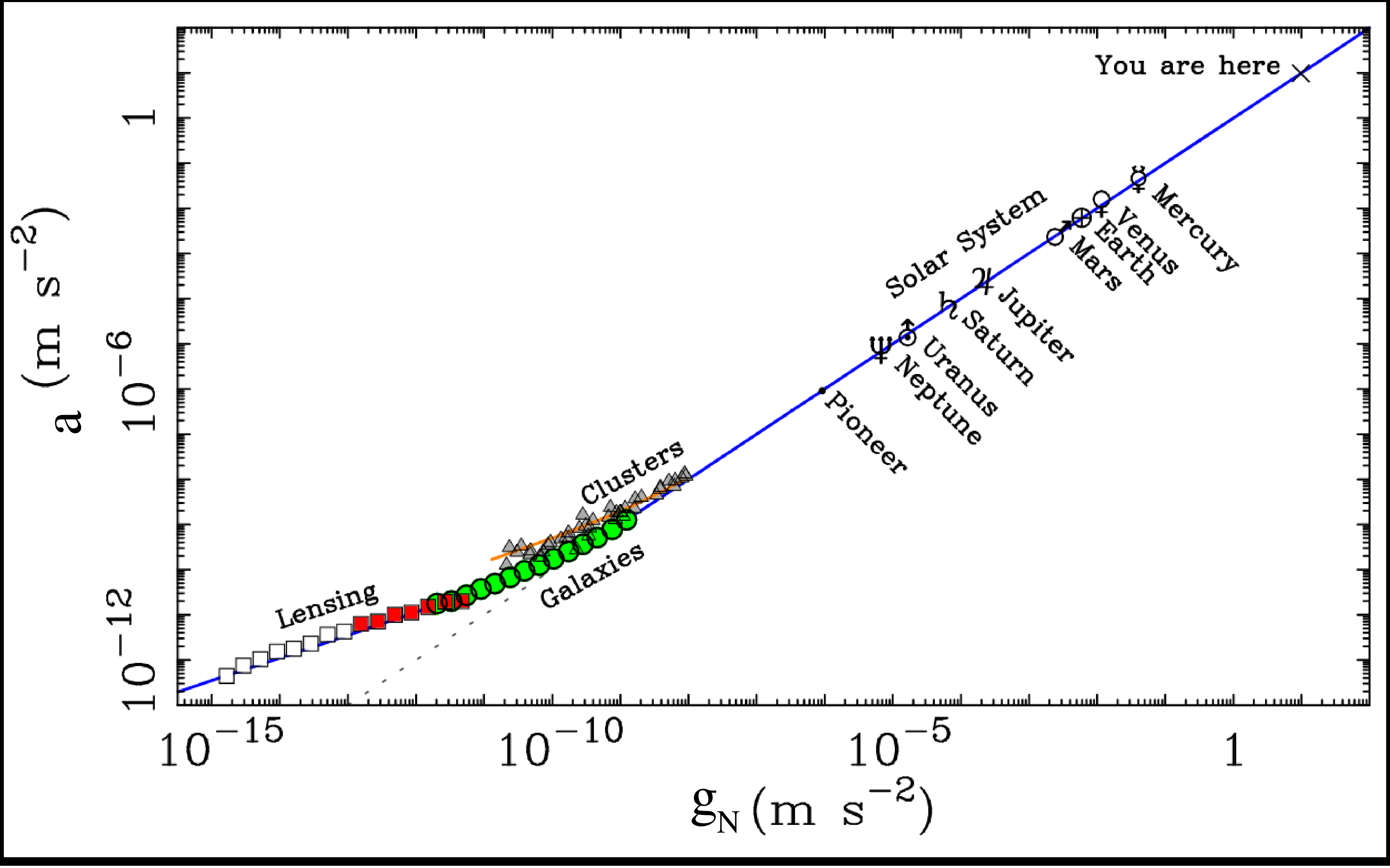


From Rotation Curve Fits

From Baryon Large Scale Structure

Chae+2020, 2021

Galaxy Clusters on the Radial Acceleration Relation



Nature of the missing mass in galaxy clusters?

- Dark baryons such as compact clouds of cold gas (Milgrom 2008)

  For HI clouds ($T \sim 10^4$ K) → $M_{cl} < 10^5\ M_\odot$ and $R_{cl} < 50$ pc

  (Kelleher & Lelli 2024)

  Below current HI detection limits; SKA may detect them.

- Sterile neutrinos of ~10 eV (Angus 2008, 2009) but CMB power spectrum may be problematic (Thomas+2016, Kopp+2018, Ilic+2021)

MOND – Cosmology Connection?

Two numerical coincidences (Milgrom 1983a, ApJ; Milgrom 1999, PhLA):

$$a_0 \simeq \frac{H_0 \cdot c}{2\pi}$$

H_0 = Hubble constant → maybe $a_0(\mathrm{t}) \sim H(\mathrm{t})$?

$$a_0 \simeq \frac{c^2 \sqrt{\Lambda/3}}{2\pi}$$

Λ = Cosmological constant → relation to Dark Energy?

IF this numerology has some deeper, fundamental meaning:

Either the state of the Universe at large enters in local dynamics, or

the same parameters enters both Cosmology (Λ) and local dynamics (a_0).

Cosmology with modified Newtonian dynamics (MOND)

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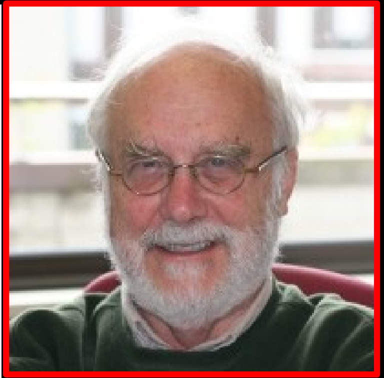
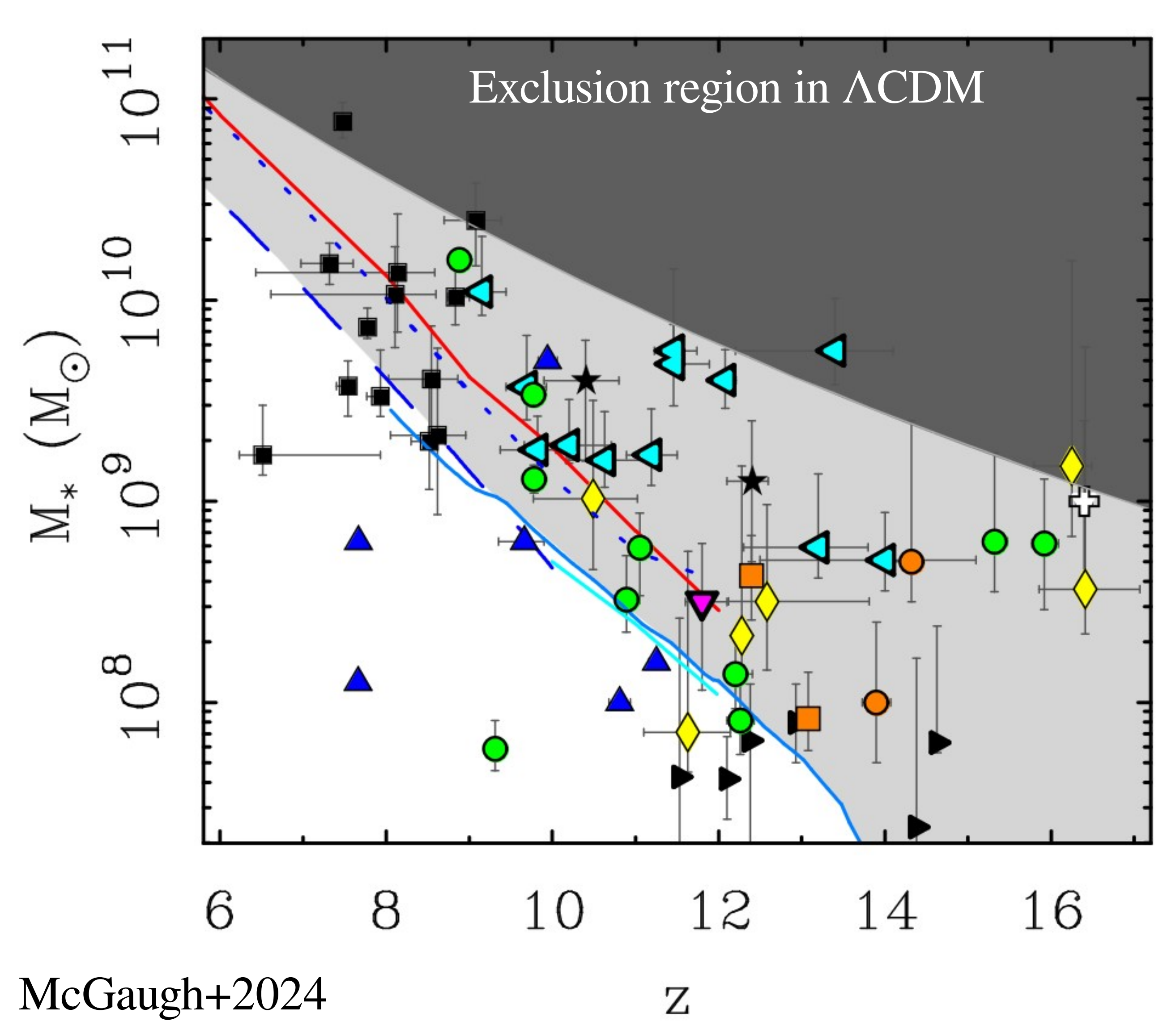


ABSTRACT

It is well known that the application of Newtonian dynamics to an expanding spherical region leads to the correct relativistic expression (the Friedmann equation) for the evolution of the cosmic scalefactor. Here, the cosmological implications of Milgrom's modified Newtonian dynamics (MOND) are considered by means of a similar procedure. Earlier work by Felten demonstrated that in a region dominated by modified dynamics the expansion cannot be uniform (separations cannot be expressed in terms of a scalefactor) and that any such region will eventually recollapse regardless of the initial expansion velocity and mean density. Here I show that, because of the acceleration threshold for the MOND phenomenology, a region dominated by MOND will have a finite size which, in the earlier Universe ($z > 3$), is smaller than the horizon scale. Therefore, uniform expansion and homogeneity on the horizon scale are consistent with MOND-dominated non-uniform expansion and the development of inhomogeneities on smaller scales. In the radiation-dominated era, the amplitude of MOND-induced inhomogeneities is much smaller than that implied by observations of the cosmic background radiation, and the thermal and dynamical history of the Universe is identical to that of the standard big bang model. In particular, the standard results for primordial nucleosynthesis are retained. When matter first dominates the energy density of the Universe, the cosmology diverges from that of the standard model. Objects of galaxy mass are the first virialized objects to form (by $z = 10$), and larger structure develops rapidly. At present, the Universe would be inhomogeneous out to a substantial fraction of the Hubble radius.

Massive galaxies at z >10 is the new normal!

Compilation of JWST observations

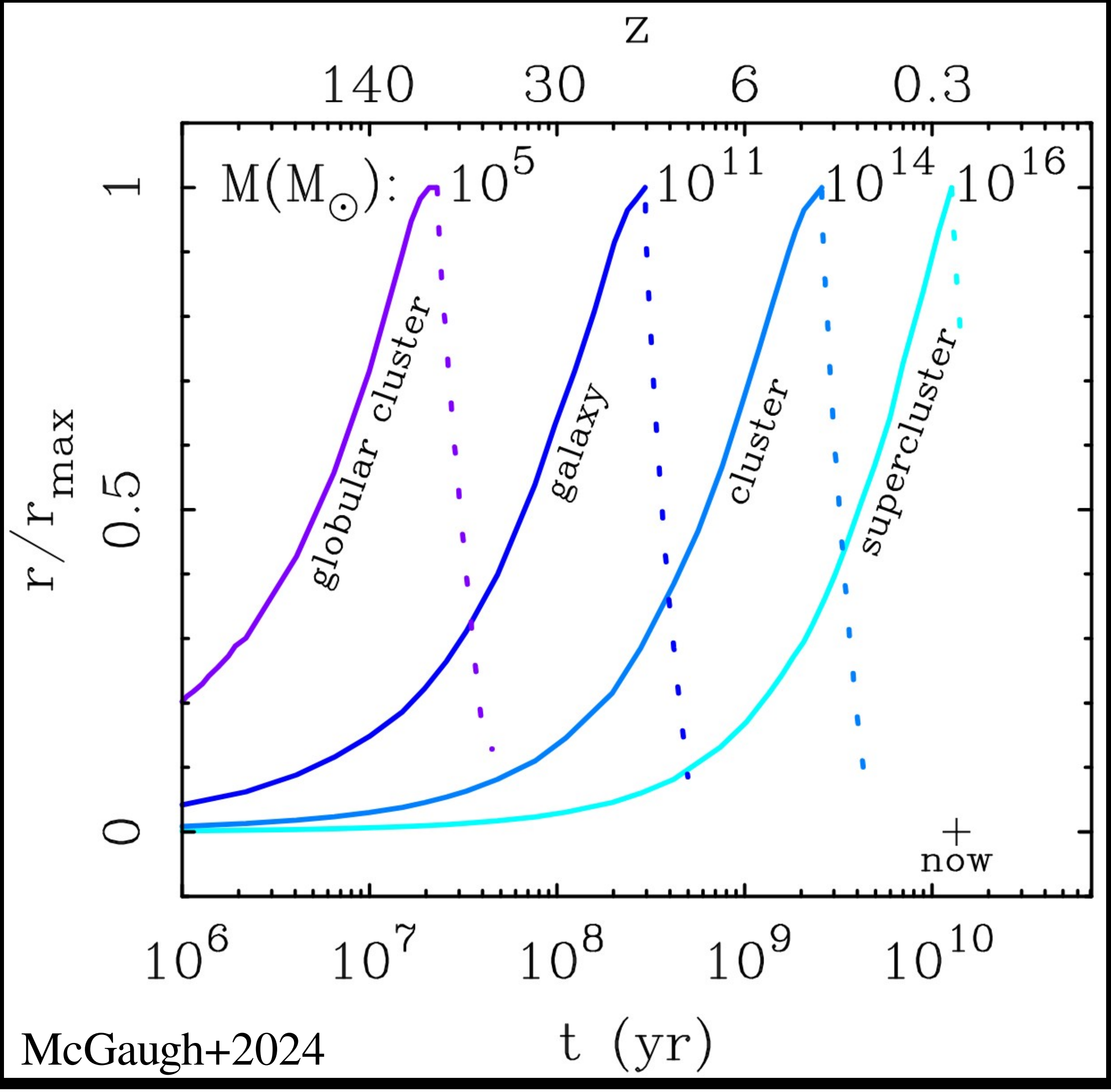


Galaxy formation & evolution happens earlier and faster than anticipated in ΛCDM

- Bright, massive galaxies at $z \gtrsim 10$
- Passive galaxies (without star formation) at $z \gtrsim 4$ and inferred formation at $z \gtrsim 10$
- Regularly rotating galaxy disks at $z \gtrsim 5$
- Disk structures (bars, spiral arms) at $z \gtrsim 3$
- Massive galaxy clusters at $z \gtrsim 3$ and protocluster candidates at $z \gtrsim 6$
- Lα emission at $z \gtrsim 10$ (early reionization)

See, e.g., McGaugh+2024 for a summary

MOND prediction, following Sanders (1998)



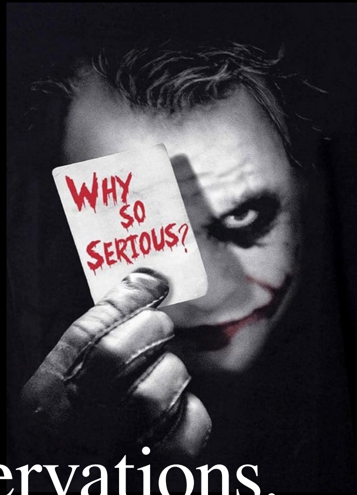
Evolution of a MOND spherical region in an expanding Universe (Felten 1984):

$$V^2(t) = V_i^2 - \sqrt{\frac{16\pi}{3} a_0 G \rho_b r_0^3} \ln\left(\frac{r(t)}{r_i}\right)$$

Any spherical region will initially expand, then unavoidably recollape due to gravity:

- Structures form faster than in ΛCDM
- Late-time Universe is anisotropic (or homogeneity scale is very large)

Why taking MOND seriously?



- MOND made multiple *a-priori* predictions, later confirmed by observations. A-priori predictions are the core of the scientific method.

- Even if MOND is wrong (or DM is detected), there must be a baryon – DM coupling in galaxies acting in a MOND way. It tells us on the nature of DM.

- Over the past ~10 years, substantial progress in MOND research in both observations and theory (new tests, new ideas, new relativistic theories).