MOND: An Alternative to Particle Dark Matter

Federico Lelli

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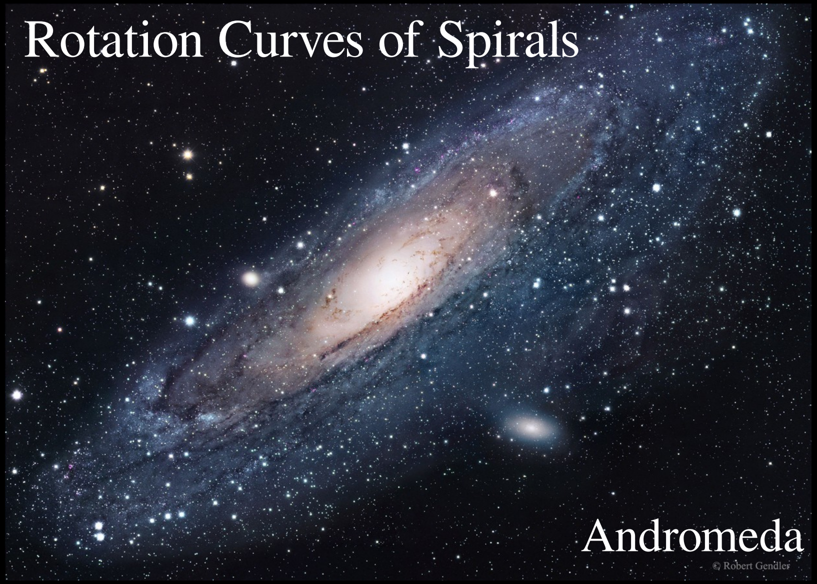
The Dark Matter Effect at Various Scales

Galaxy Scales (~1-100 kpc)



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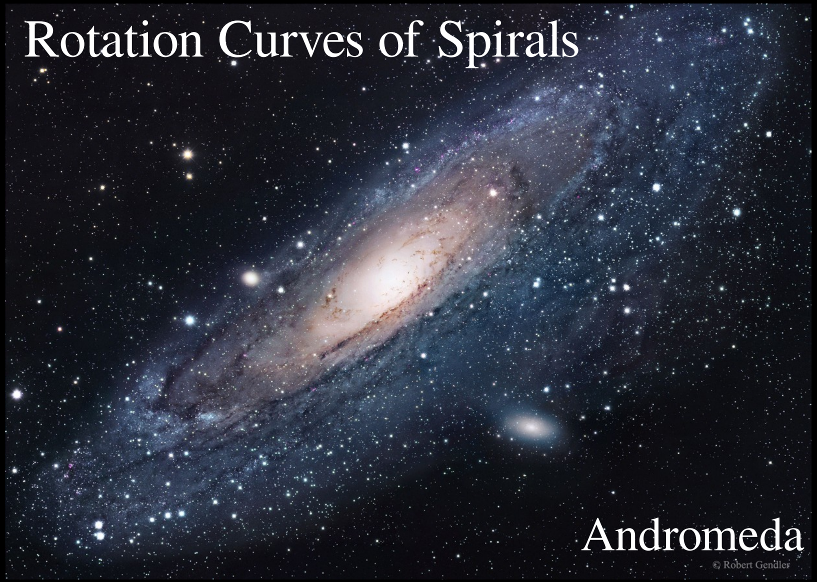

Groups/Clusters Scales (~1-5 Mpc)

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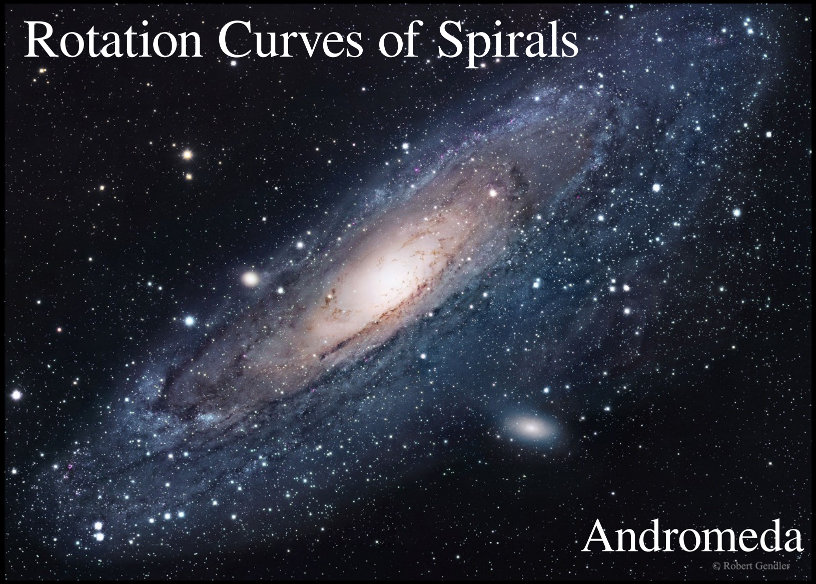
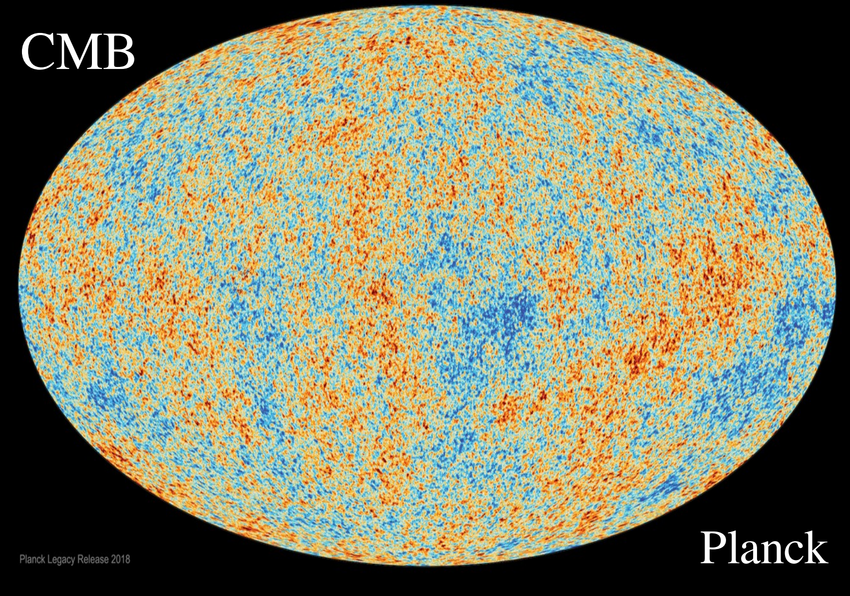
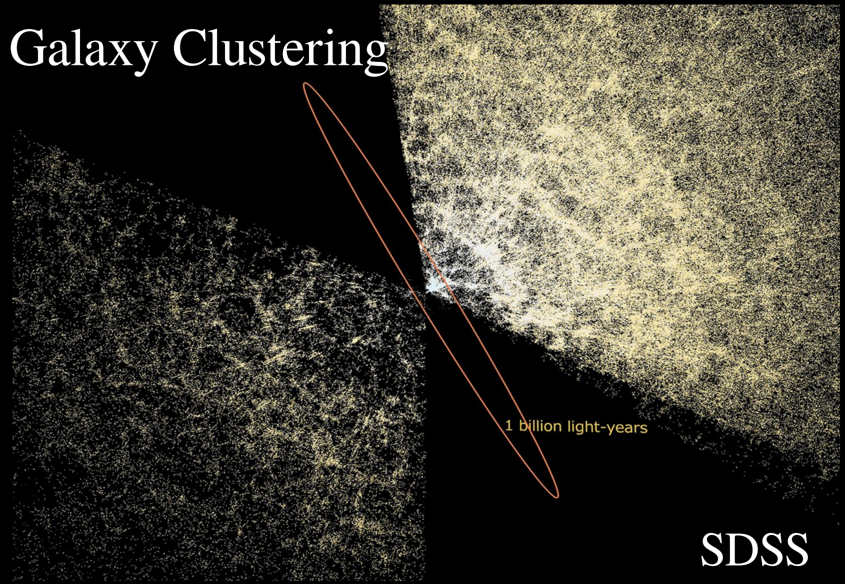
Galaxy Scales (~1-100 kpc) | **Groups/Clusters Scales (~1-5 Mpc)** | **Cosmological Scales (>100 Mpc)**







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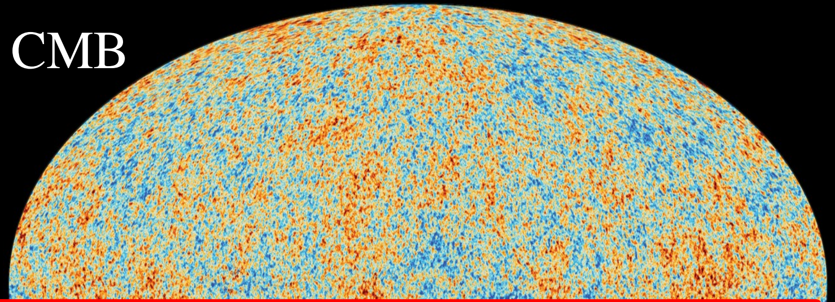
Galaxy Scales (~1-100 kpc) | **Groups/Clusters Scales (~1-5 Mpc)** | **Cosmological Scales (>100 Mpc)**


Rotation Curves of Spirals


Interactions & Mergers in Groups


CMB

This is *not* direct evidence for *particle* dark matter:

Standard Laws of Gravity (Einstein & Newton) +

Standard Model of Particle Physics = Do NOT work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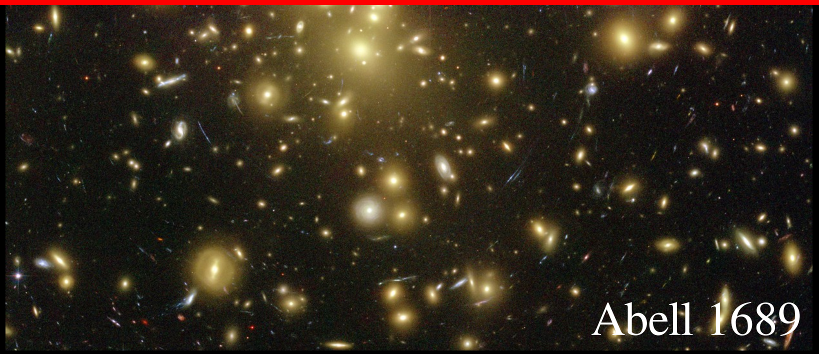
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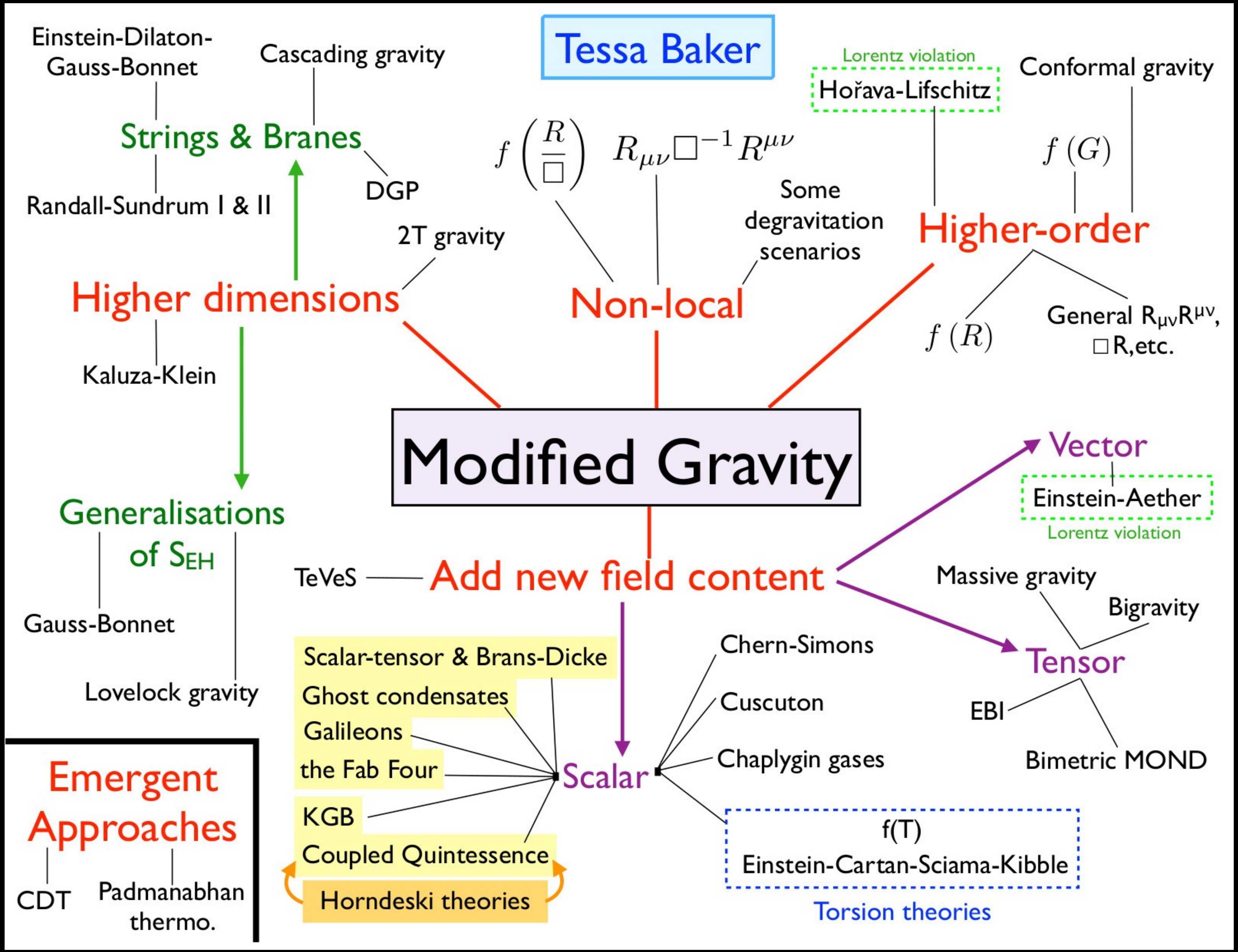
SDSS



Many versions of Modified Gravity to explain DM or DE.

This talk will not cover all this.

I will focus on Milgromian Dynamics (aka MOND). Empirically motivated alternative to CDM.

Talk Outline:

I. General MOND paradigm

→ Theory postulates & general predictions

→ Tests on stationary systems: "isolated" galaxies & clusters

II. Specific MOND theories

→ Tests on non-stationary systems: interacting galaxies & clusters

→ Relativistic theories: cosmology and the CMB

I. The general MOND paradigm

MOND = Modified Newtonian Dynamics

or MilgrOmiaN Dynamics

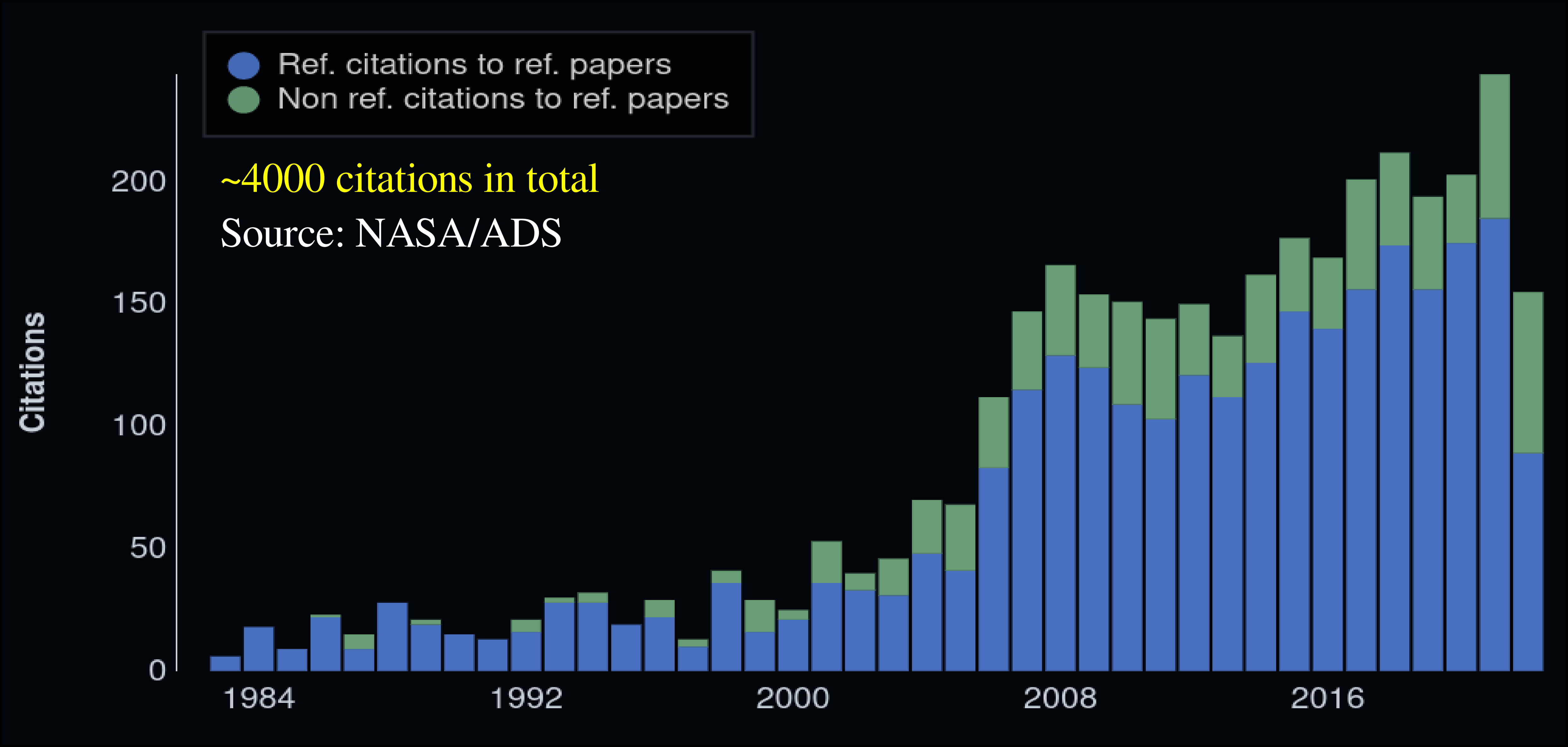
Proposed by Moderhai Milgrom (1983a, b, c; ApJ).

"40 years of MOND" conference

St. Andrews (Scotland), 5-9 June 2023

Registration deadline: 1st of May

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



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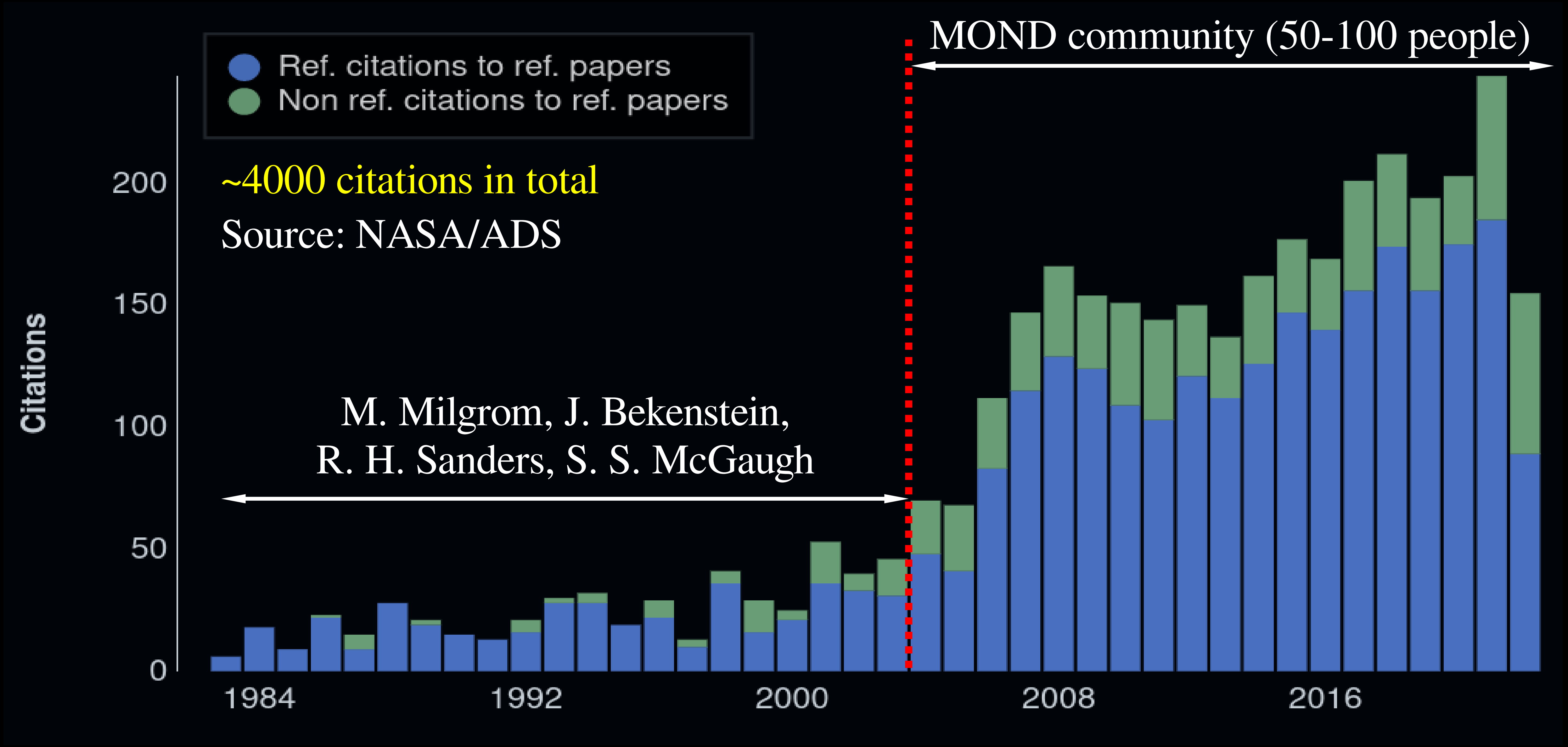

General MOND postulates (at the non-relativistic level)

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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$\vec{a} = \frac{d^2 \vec{x}}{dt^2}$ kinetic (observed) acceleration of a particle

$\vec{g}_N = -\vec{\nabla} \phi_N$ Newtonian gravitational field (from the Poisson's equation)

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Or impose scale invariance (Milgrom 2009, ApJ): $(\vec{x}, t) \rightarrow (\lambda \vec{x}, \lambda t)$ V is 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

40 years ago!

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 $2 \times 10^{-8} (H_0/50 \text{ km s}^{-1} \text{ Mpc}^{-1})^2$ cm s^{-2}, which is of the order of $CH_0 = 5 \times 10^{-8} (H_0/50 \text{ km s}^{-1} \text{ Mpc}^{-1})$ 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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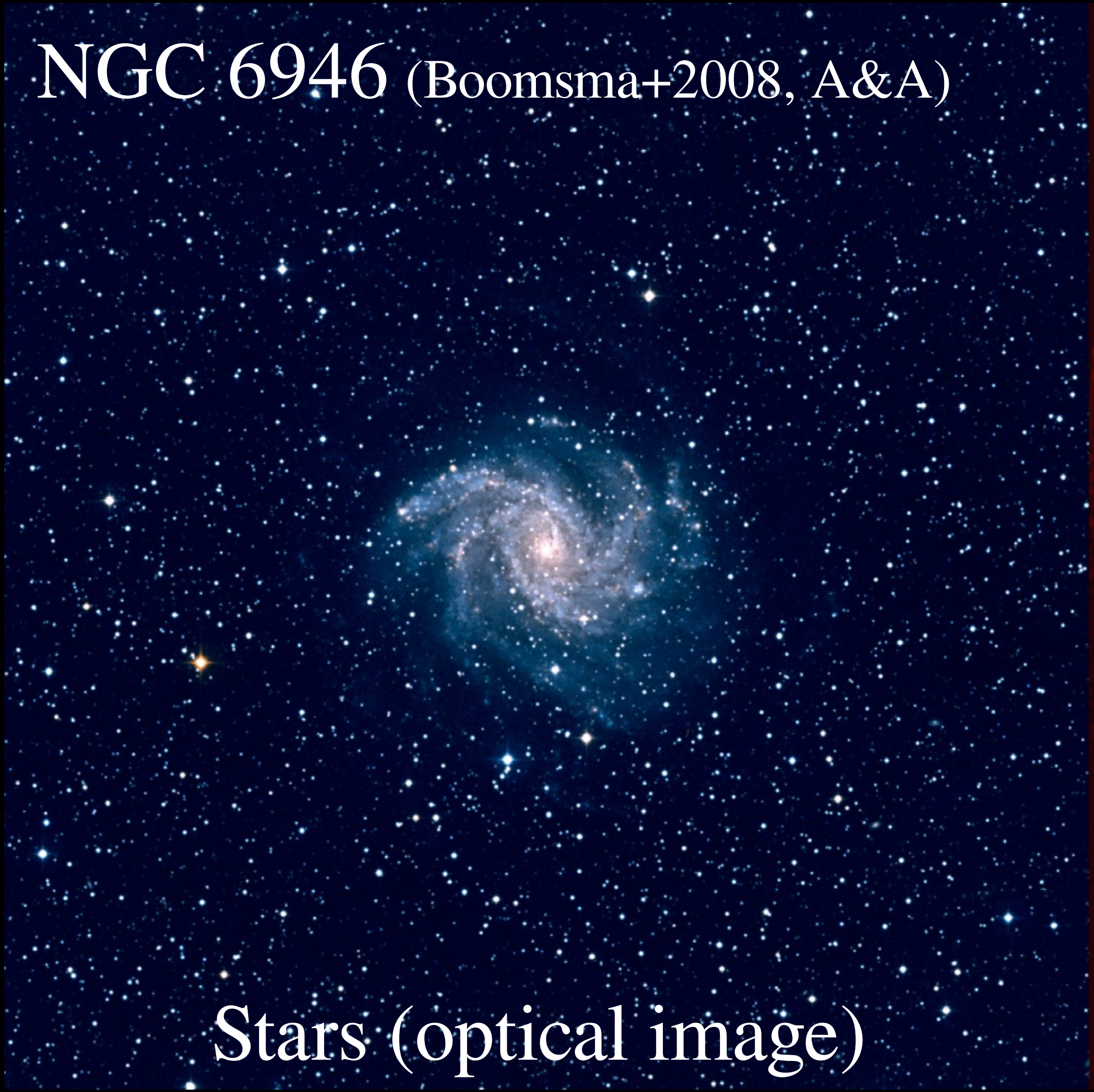

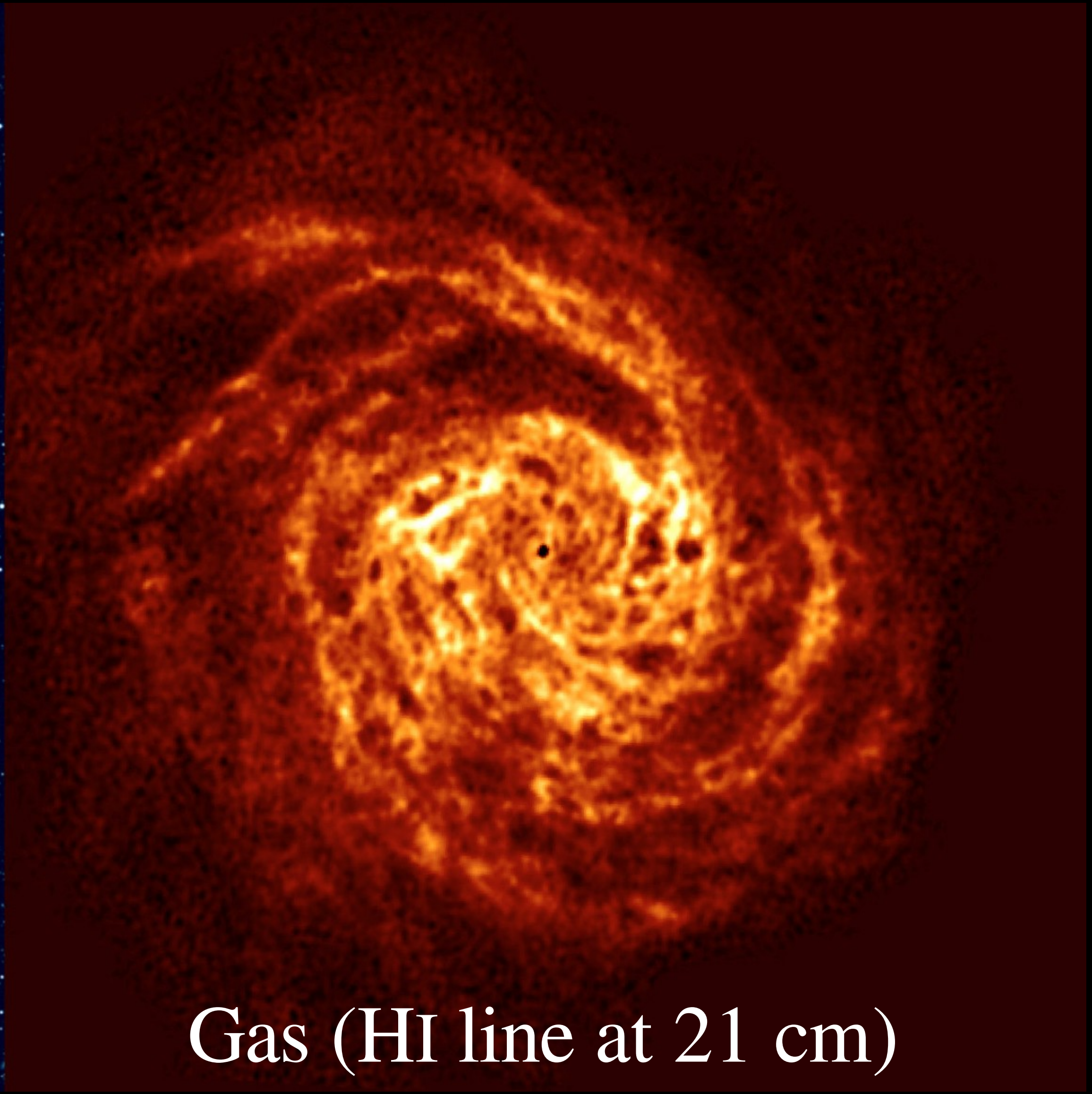

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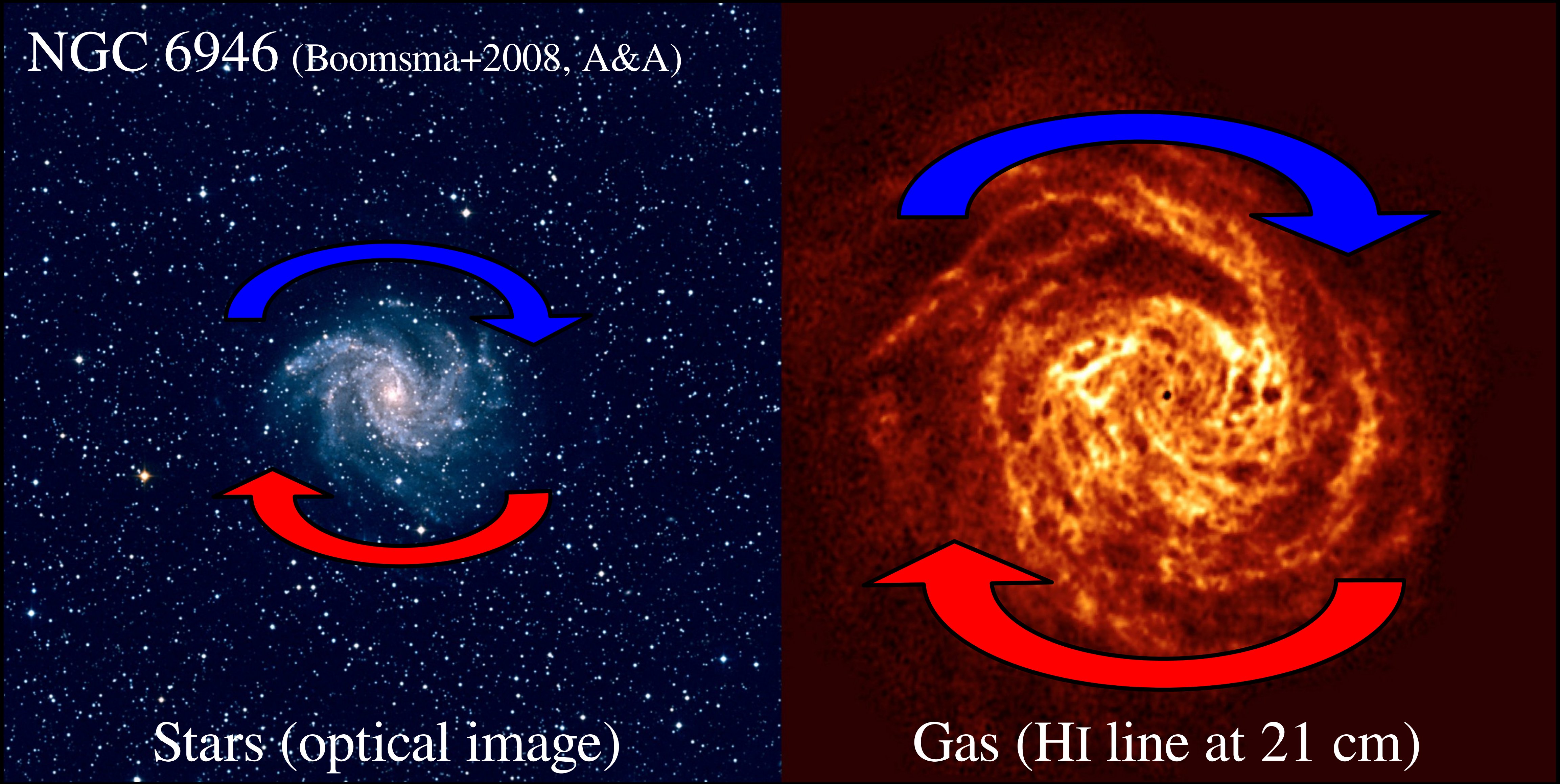

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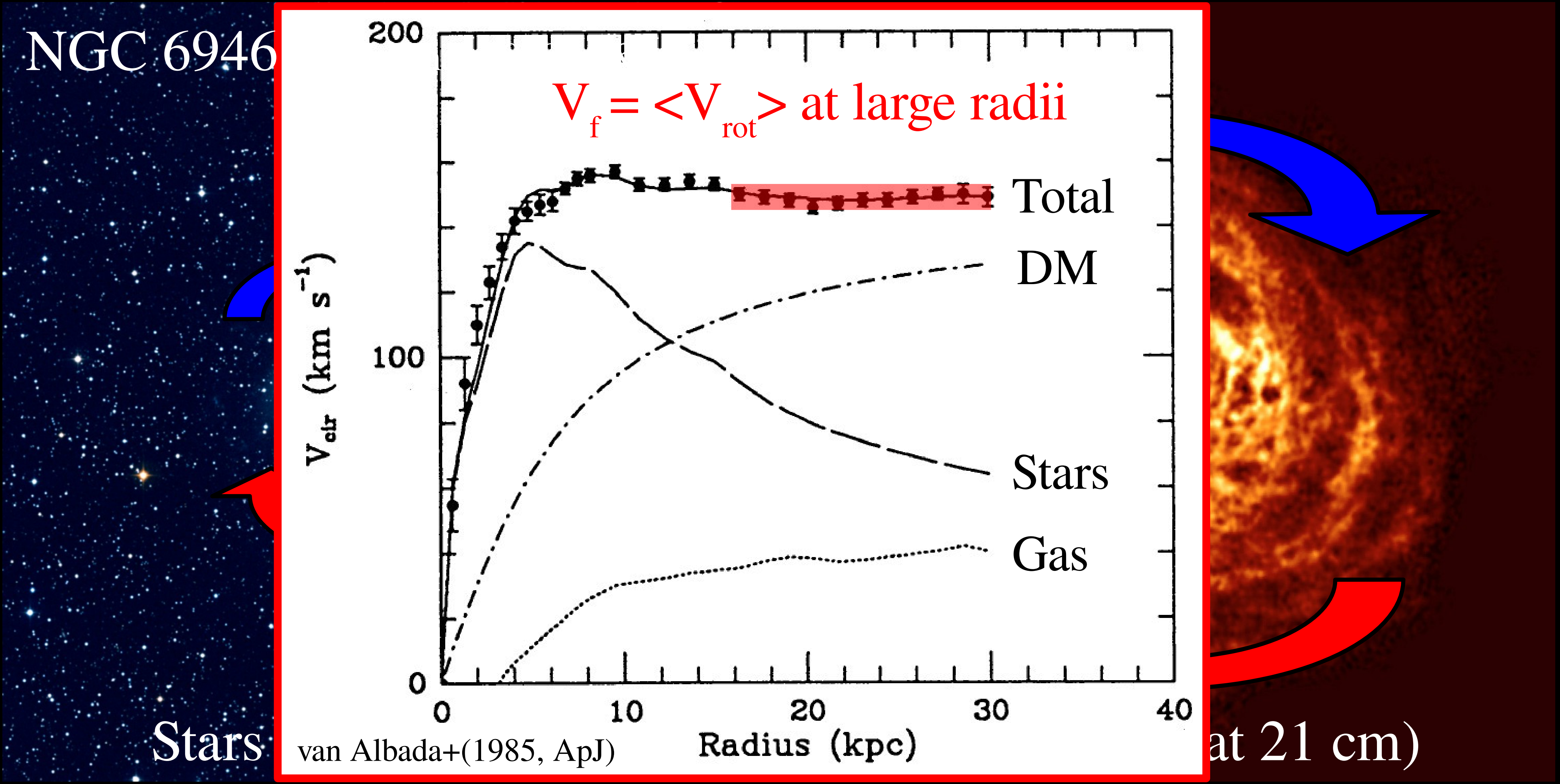

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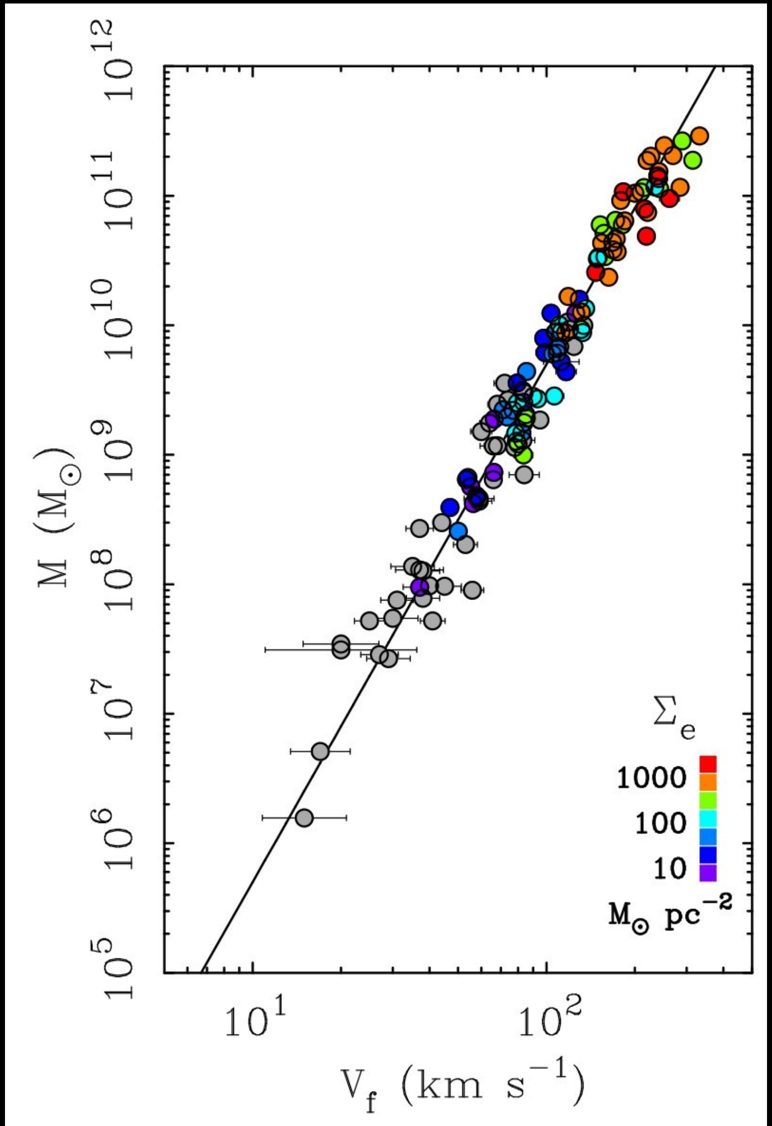

Tully-Fisher relation (1977, A&A): L_B *vs* HI linewidth

McGaugh+(2000, 2005, 2010), Verheijen+2001, Lelli+(2016, 2019, 2022), Di Teodoro (2021, 2022)

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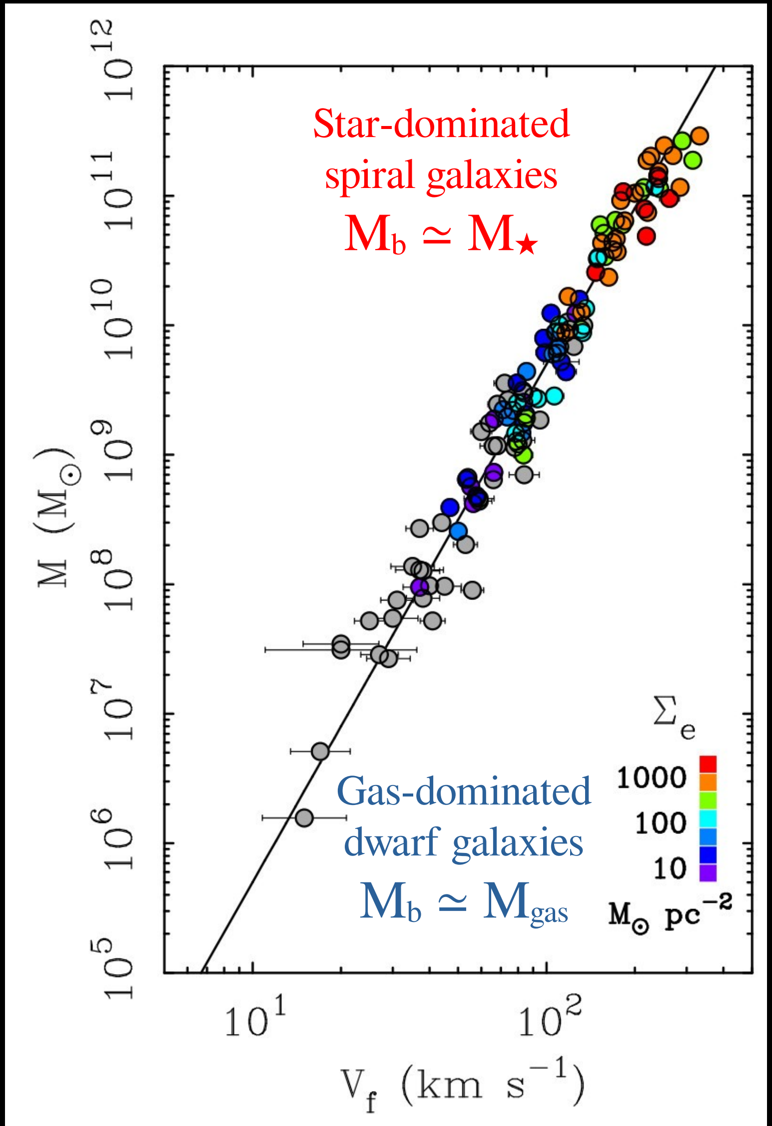

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Four a-priori independent predictions in one equation:

(i) The relevant quantities are M_b (stars+gas) and V_f → OK

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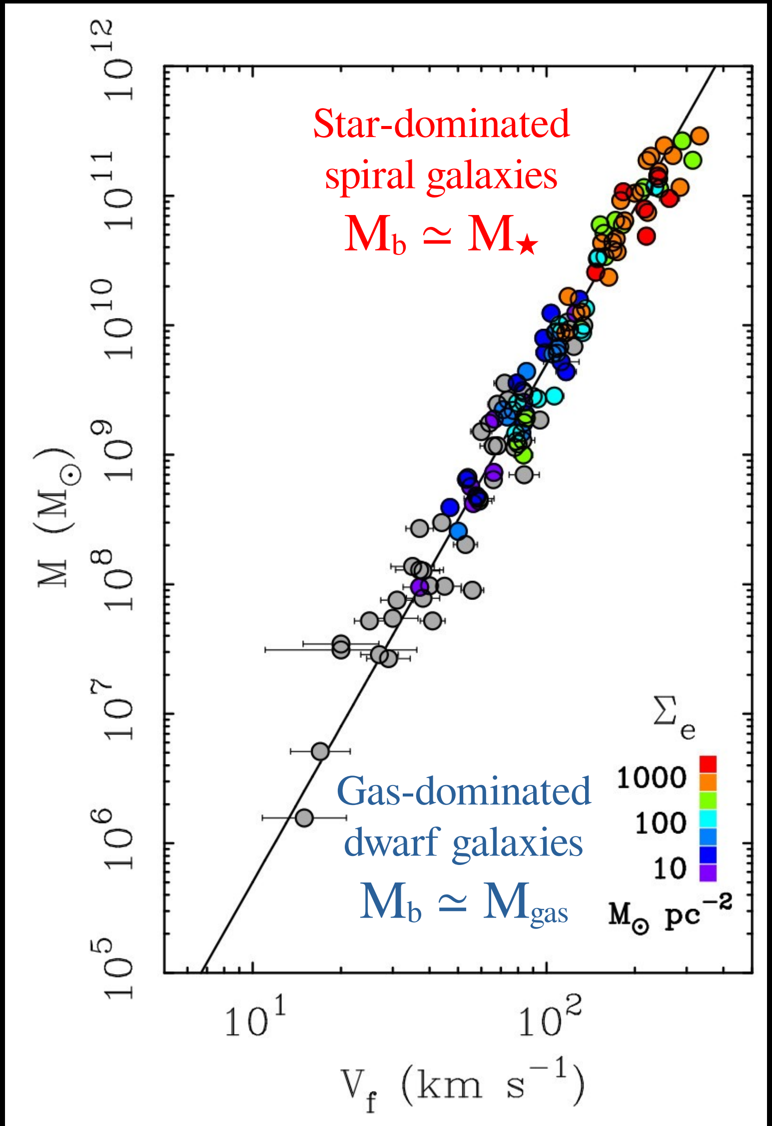

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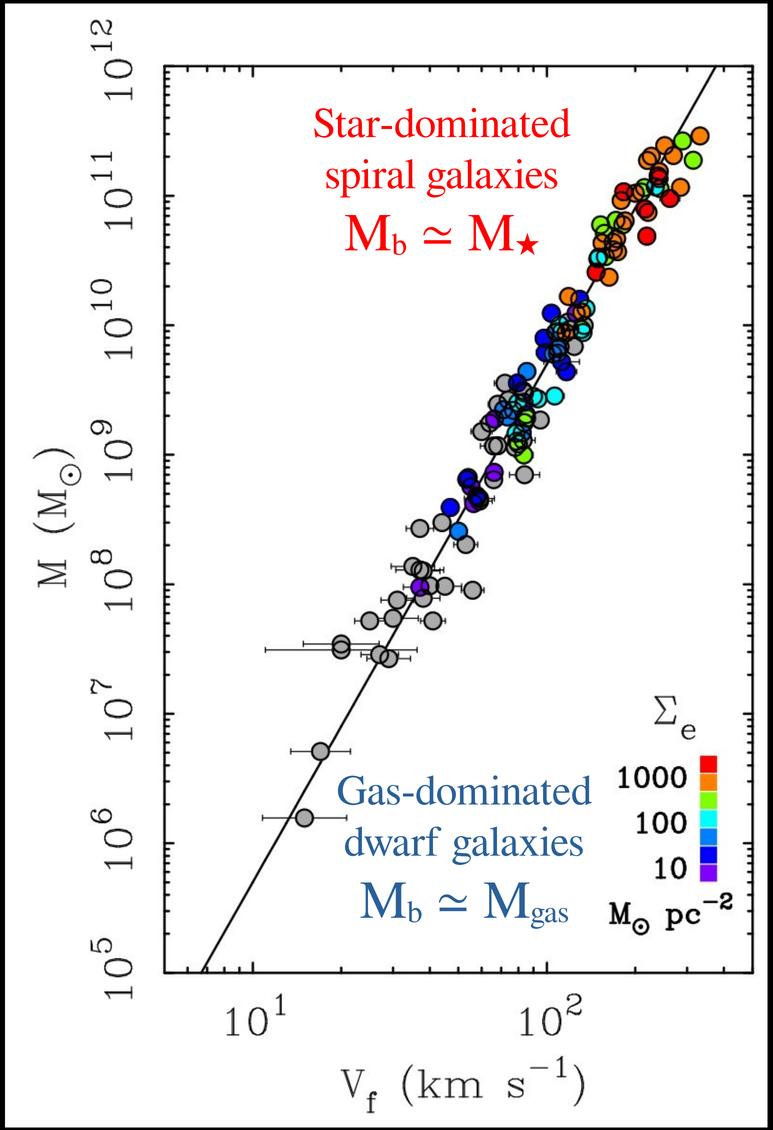

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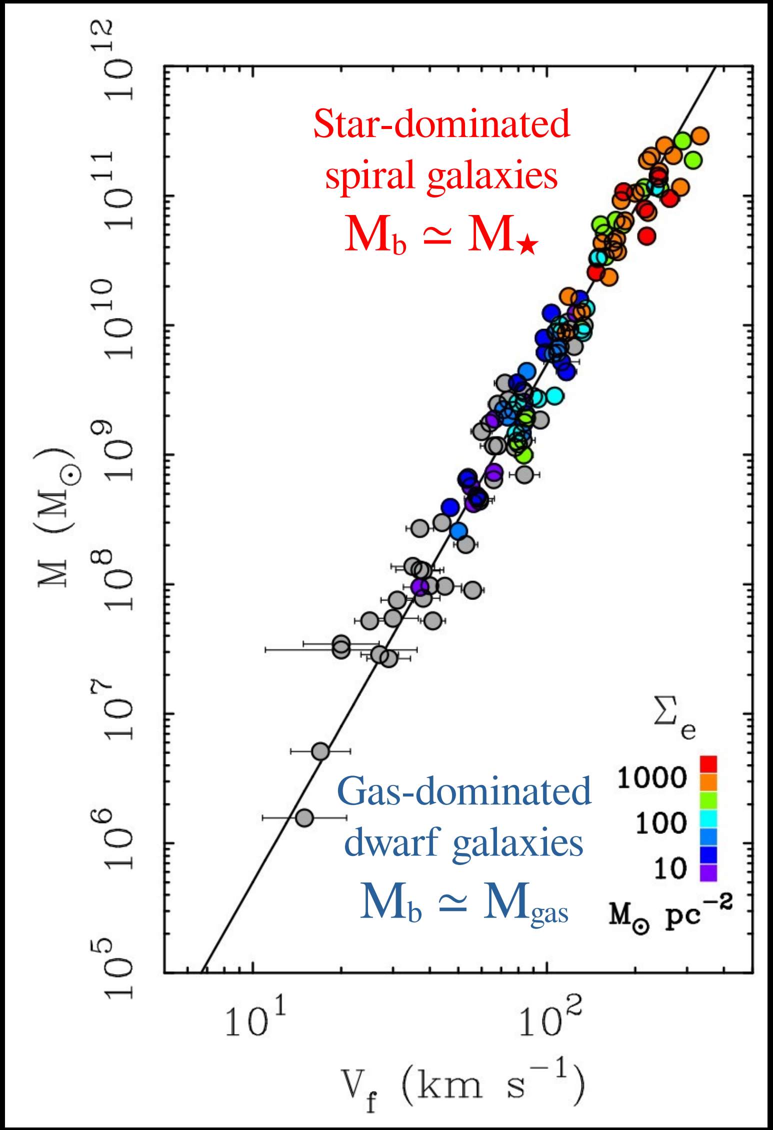

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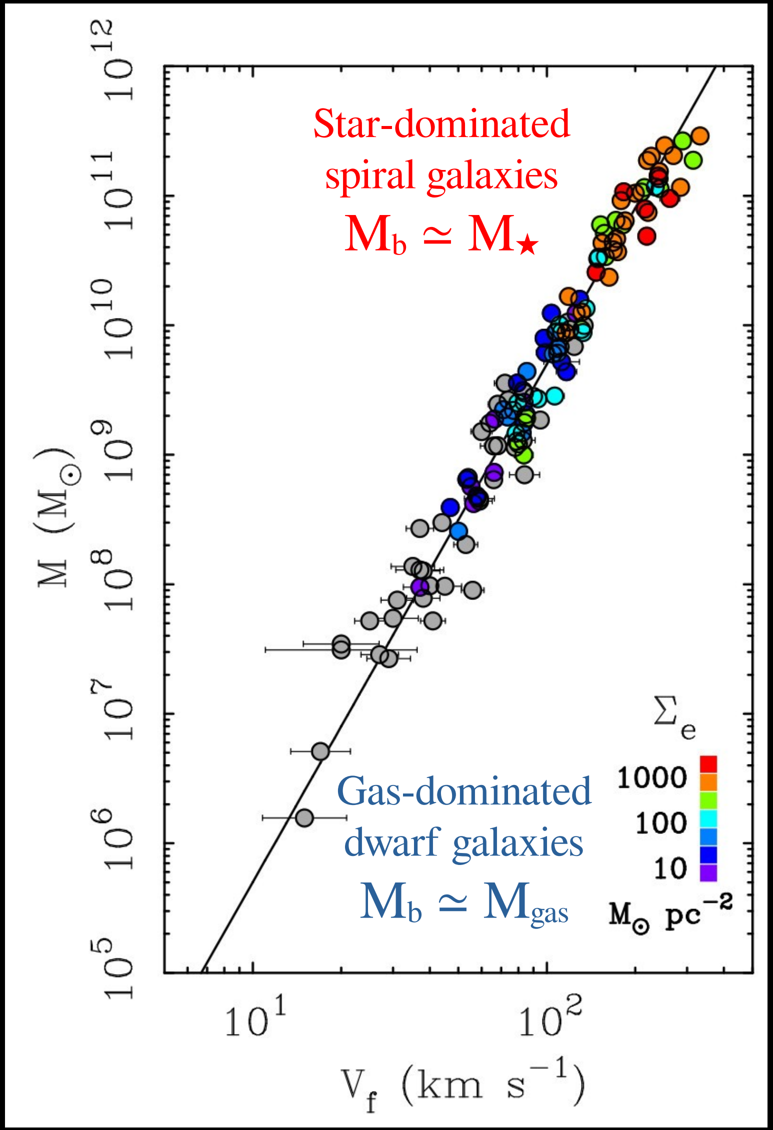

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$$\frac{V^2}{R} = \frac{G\,M_{tot}}{R^2} \quad f_b = \frac{M_b}{M_{tot}} \quad \Sigma_b = \frac{M_b}{\pi R^2}$$

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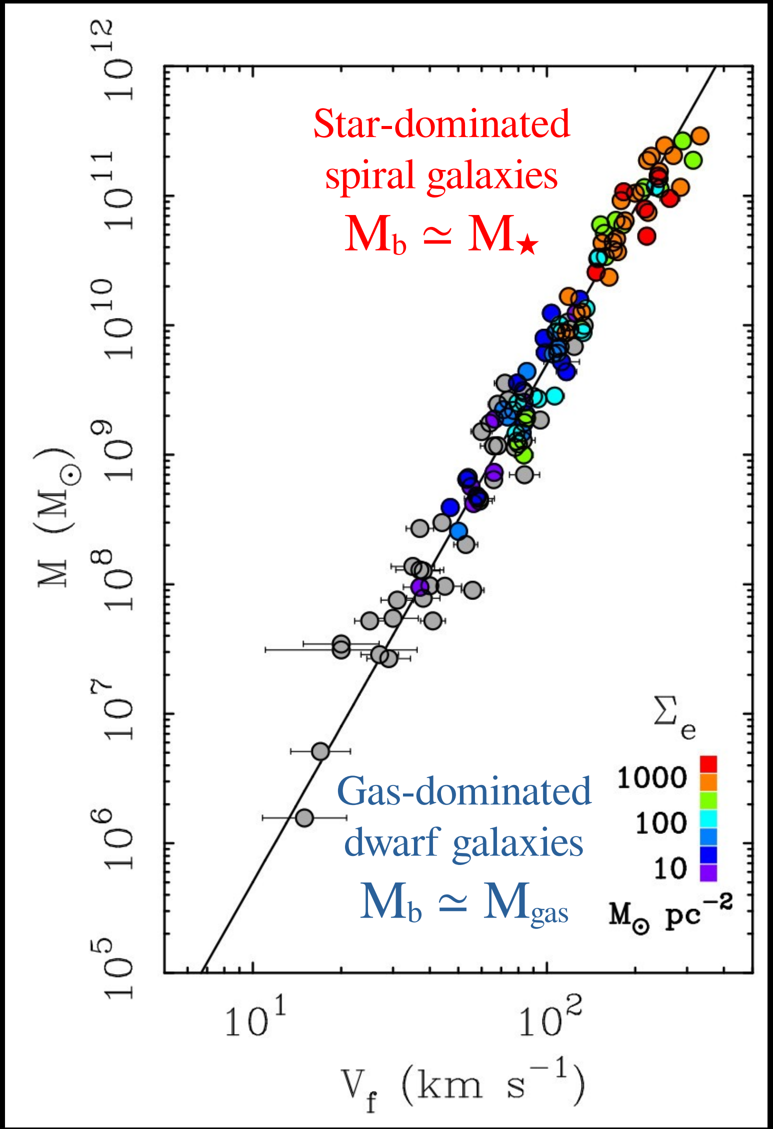

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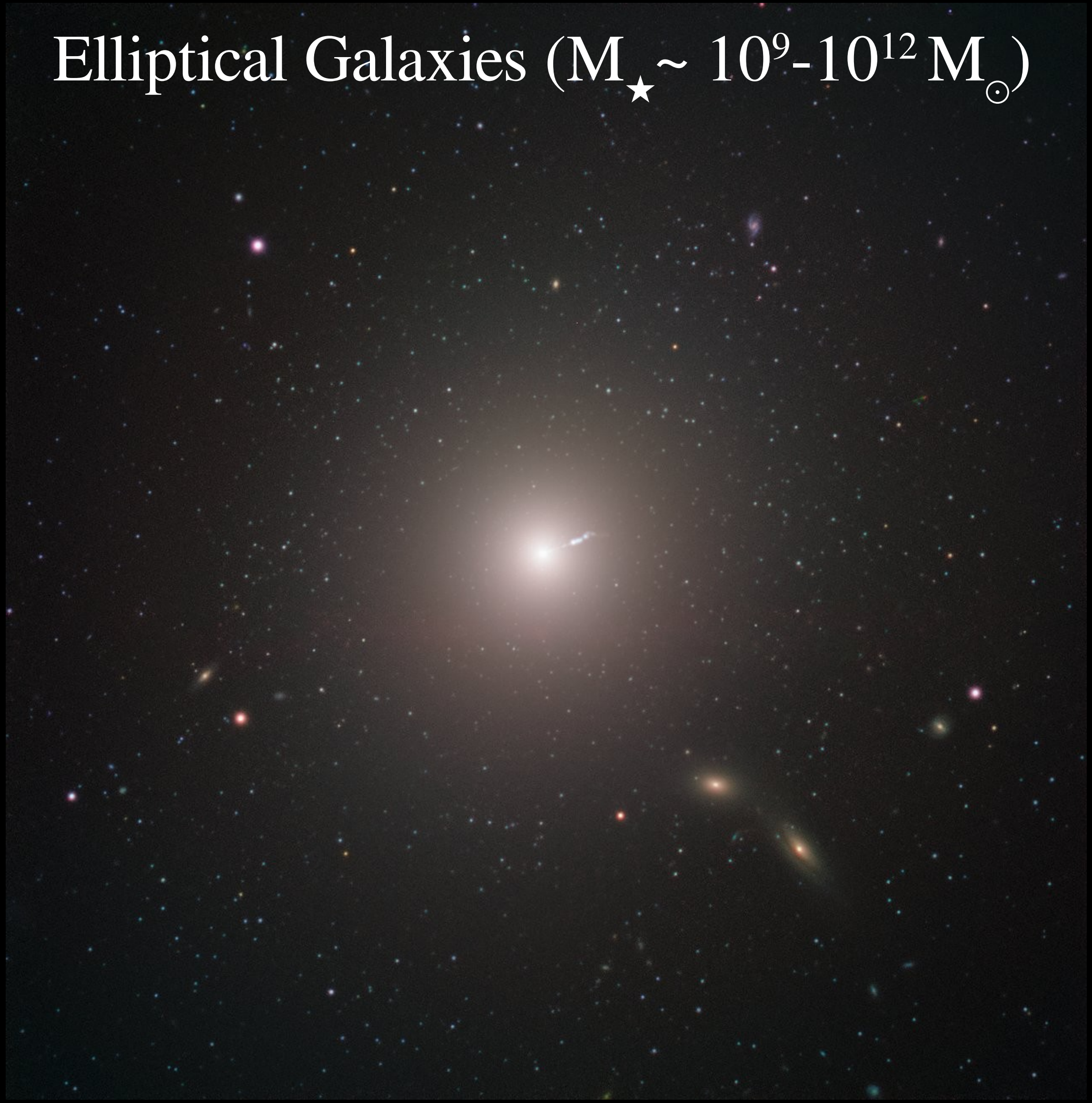

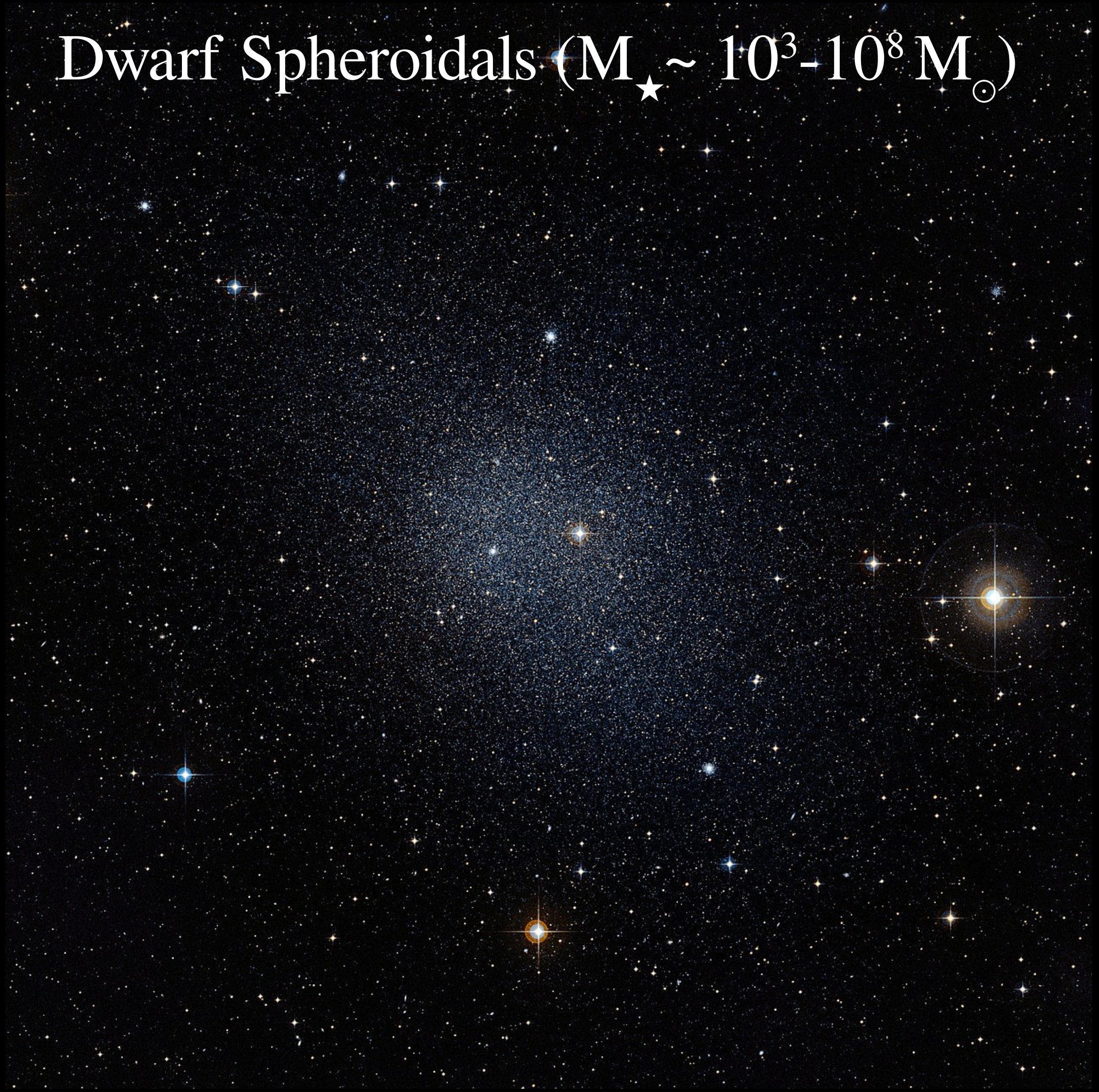

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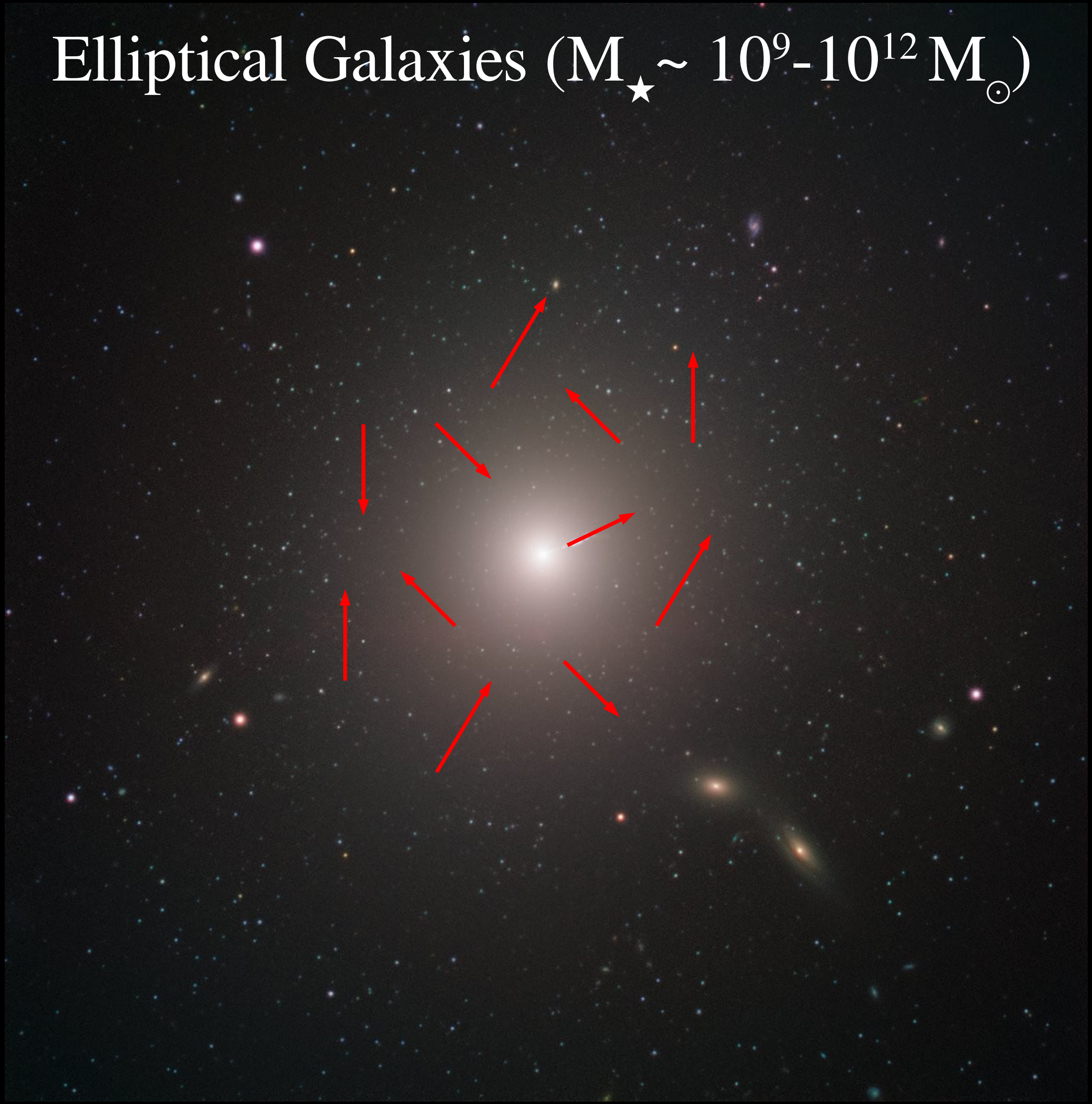

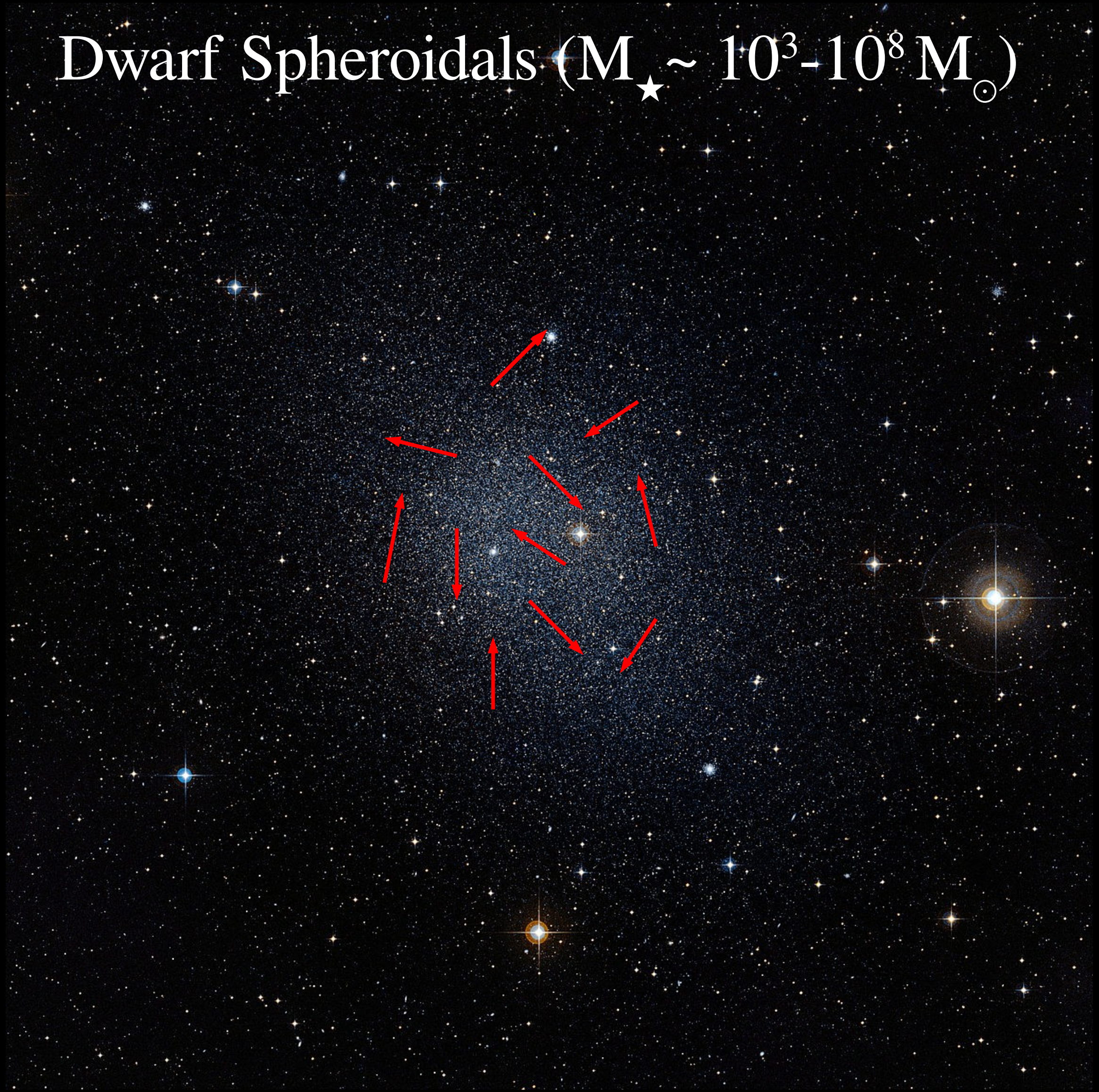

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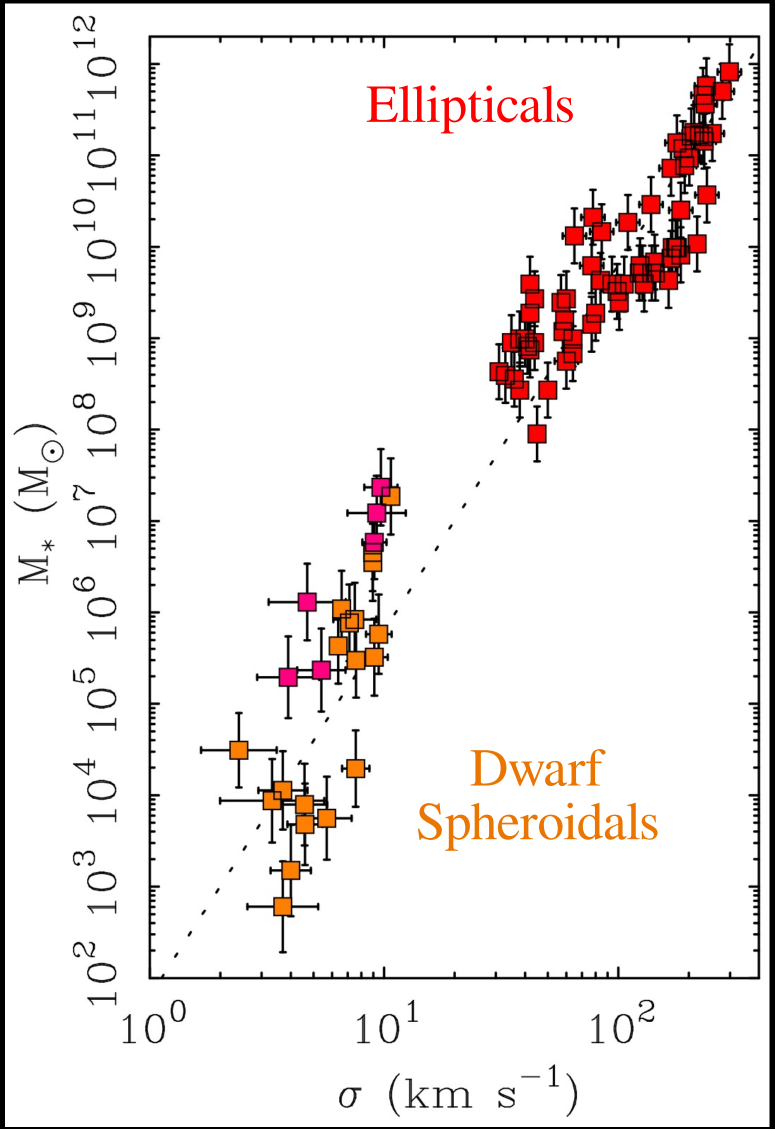

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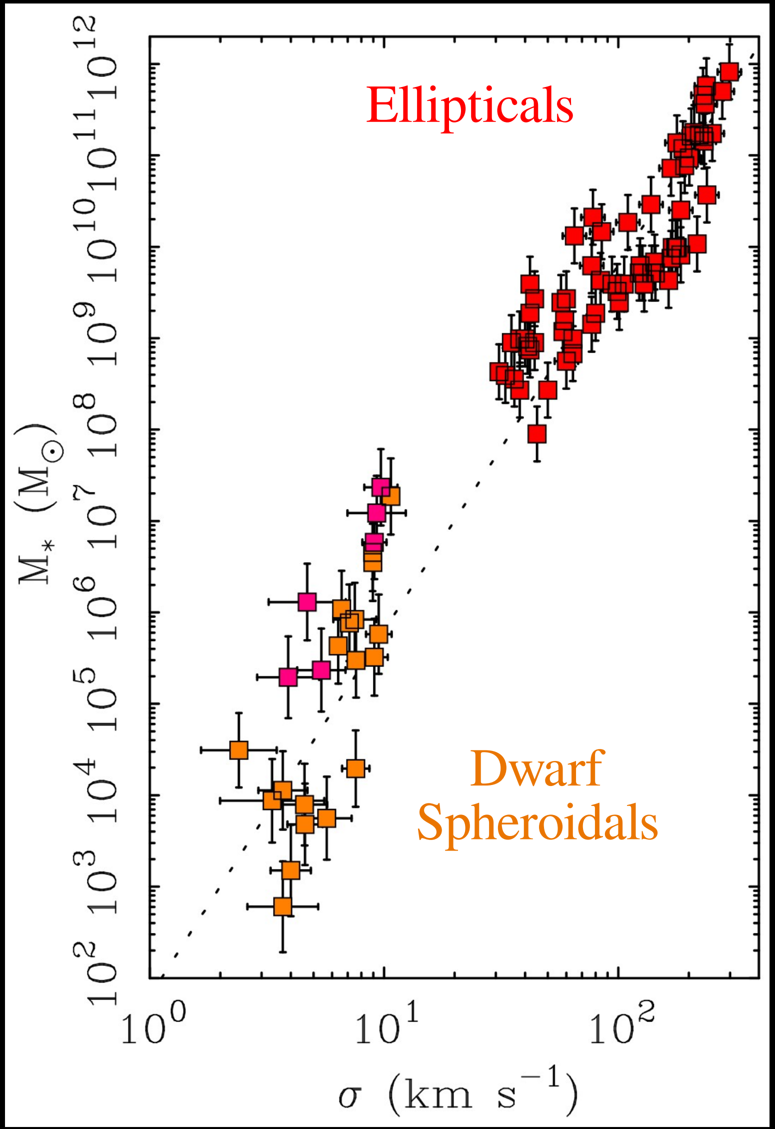

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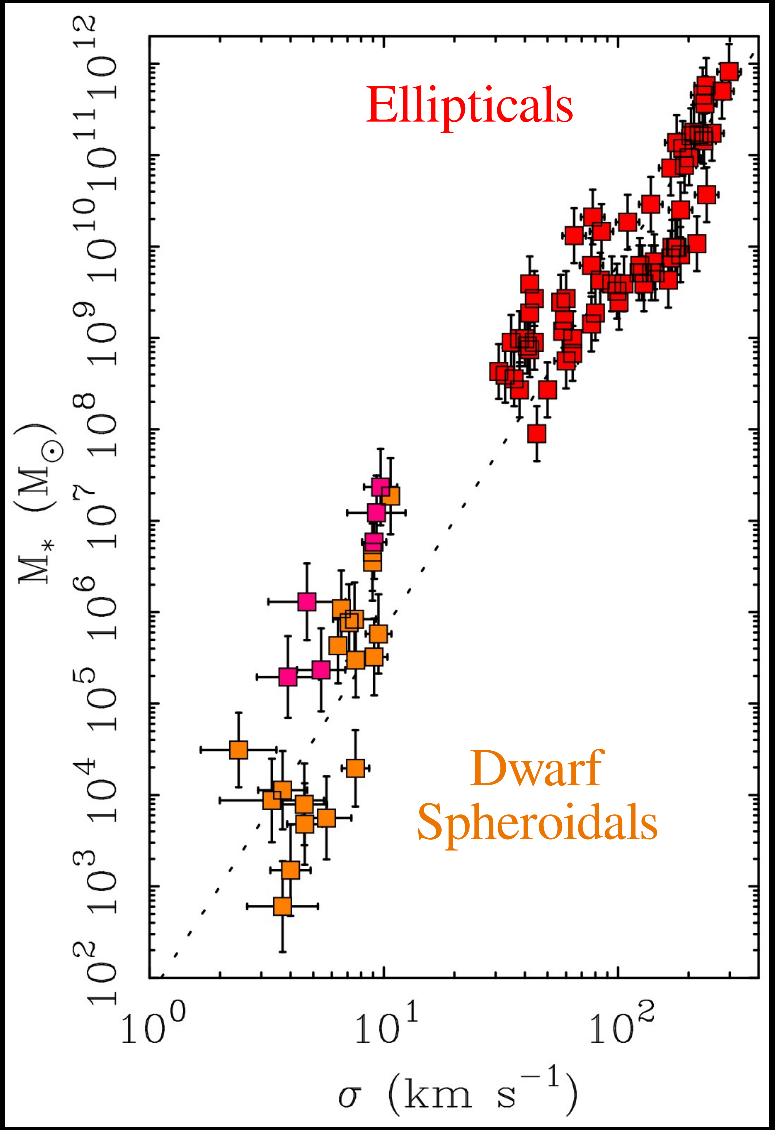

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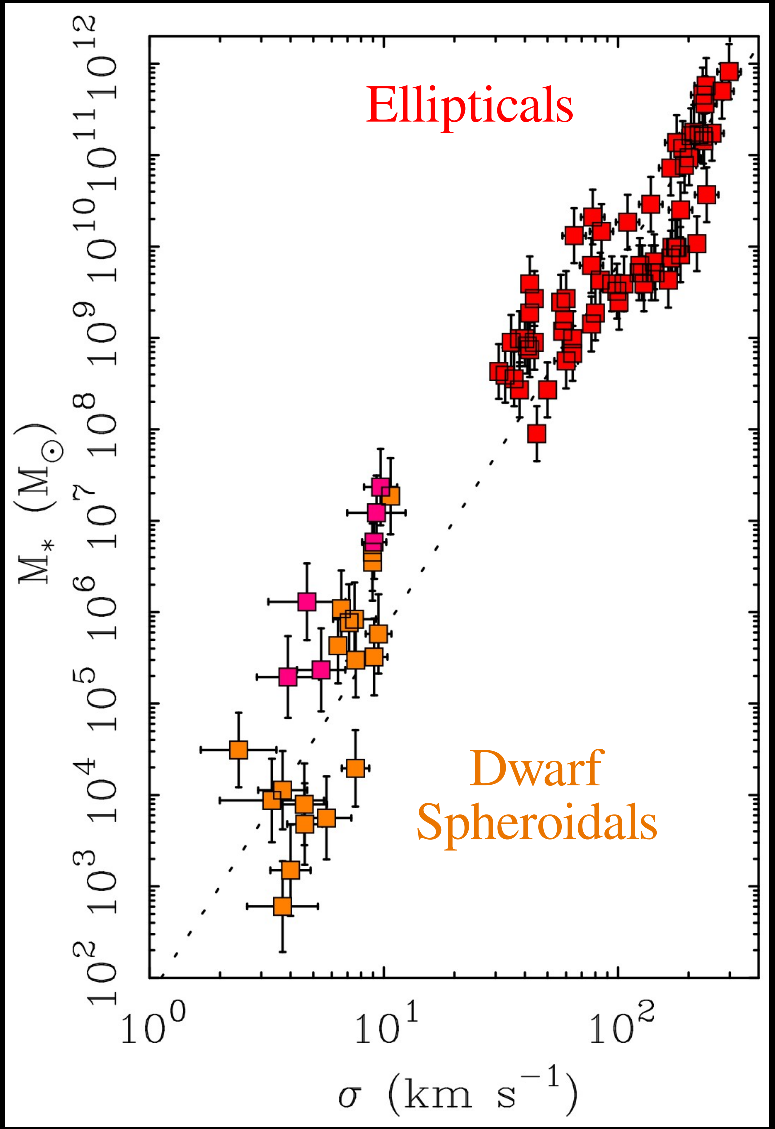

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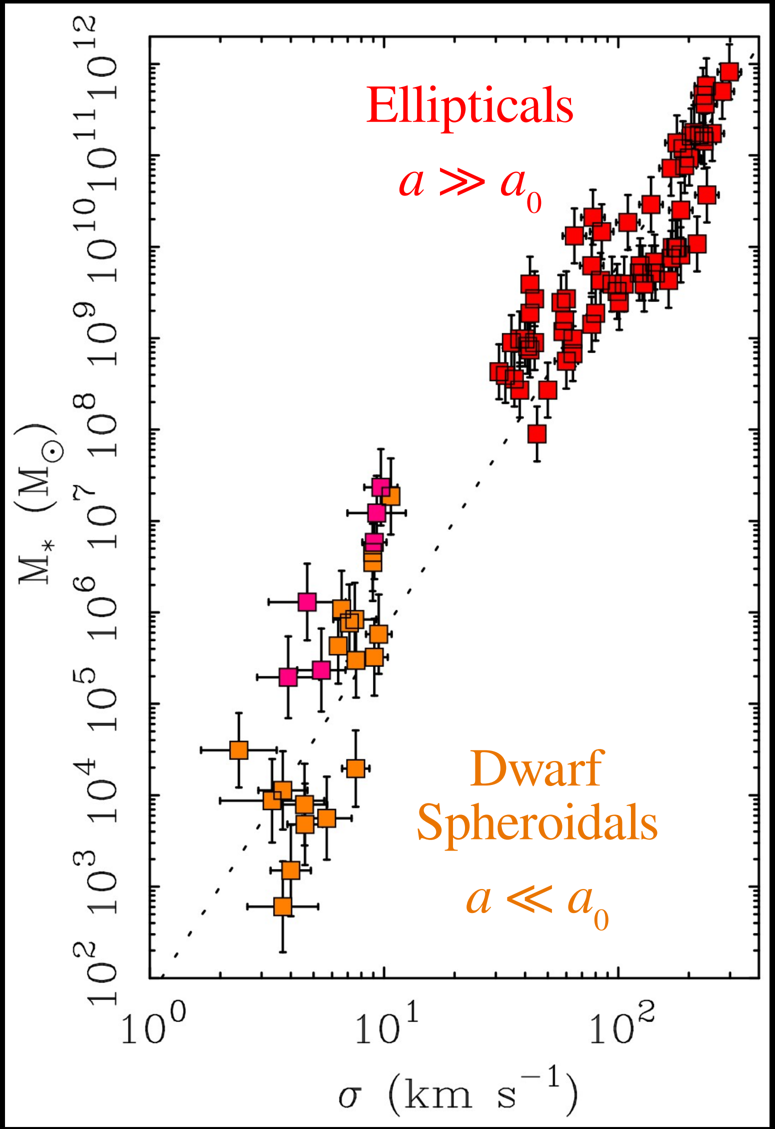

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σ_V is measured at R < R_e (containing half luminosity):

For dwarf spheroidals: $a \ll a_0$ at R<R_e → MOND regime

For giant ellipticals: $a \gg a_0$ at R<R_e → Newtonian regime

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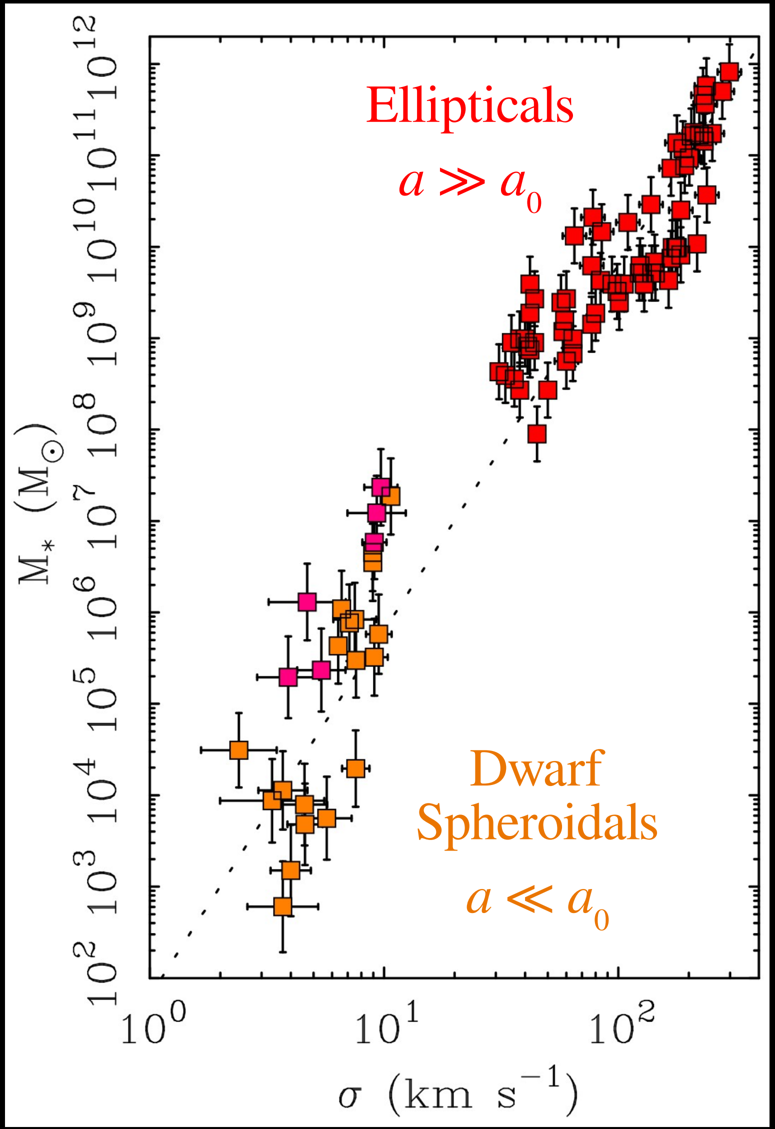

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$$\frac{\sigma_V^2}{R} \simeq \frac{G\,M}{R^2} \Rightarrow M \simeq \sigma_V^2 R_e$$

Fundamental plane of ellipticals
(Djorgovski & Davis 1987; Dressler 1987)

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Interpolation functions are *common* in Physics. Examples:

- Lorentz factor γ (via c): Newton's second law ↔ special relativity
- Planck's law for the blackbody radiation (via $\hbar$): Rayleigh-Jeans ↔ Wein regimes
- Probability for quantum tunnelling (via $\hbar$): classical mechanics ↔ quantum theory

MOND postulates specify only asymptotic limits of μ. Which function to choose?

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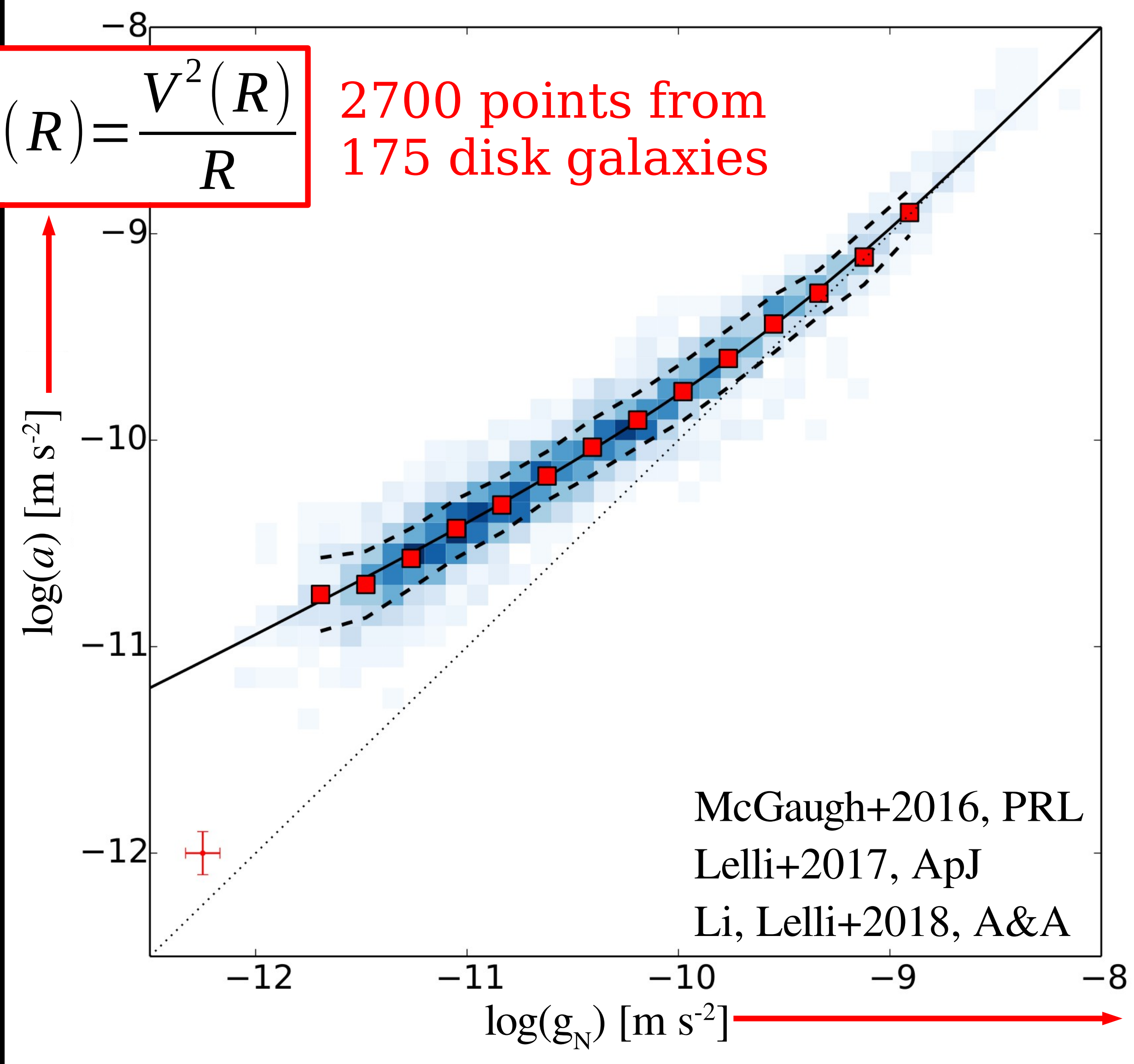


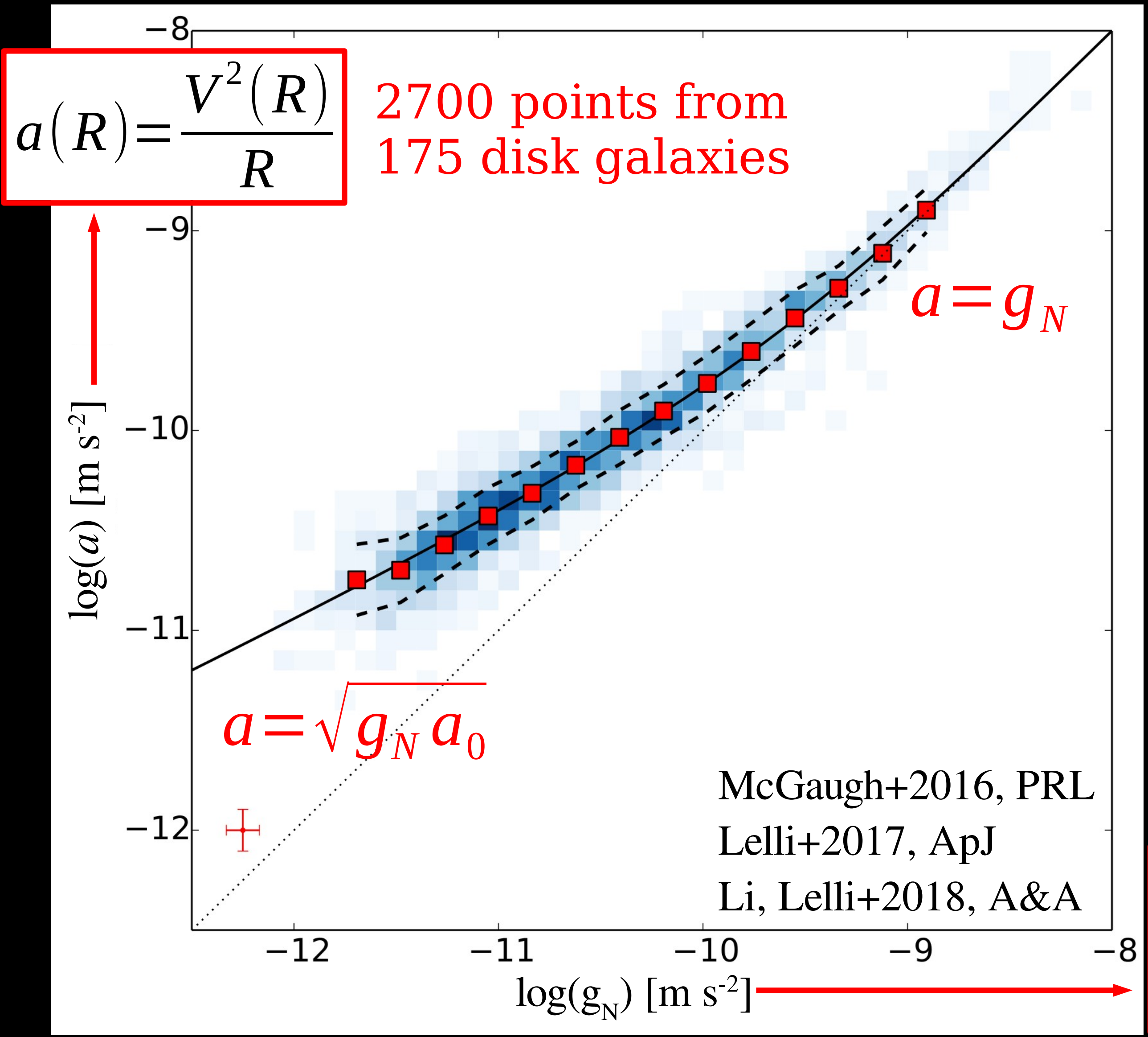
$$a(R) = \frac{V^2(R)}{R}$$

Radial Acceleration Relation (RAR)

- Fully empirical - independent of MOND

$$\nabla^2 \Phi_N(R,z) = 4\pi G \rho_b(R,z)$$
$$g_N(R,z=0) = -\nabla \Phi_N(R,z=0)$$

(3) Rotation curves can be predicted from the baryon distribution



Radial Acceleration Relation (RAR)

- Fully empirical - independent of MOND
- Asymptotic limits consistent with MOND

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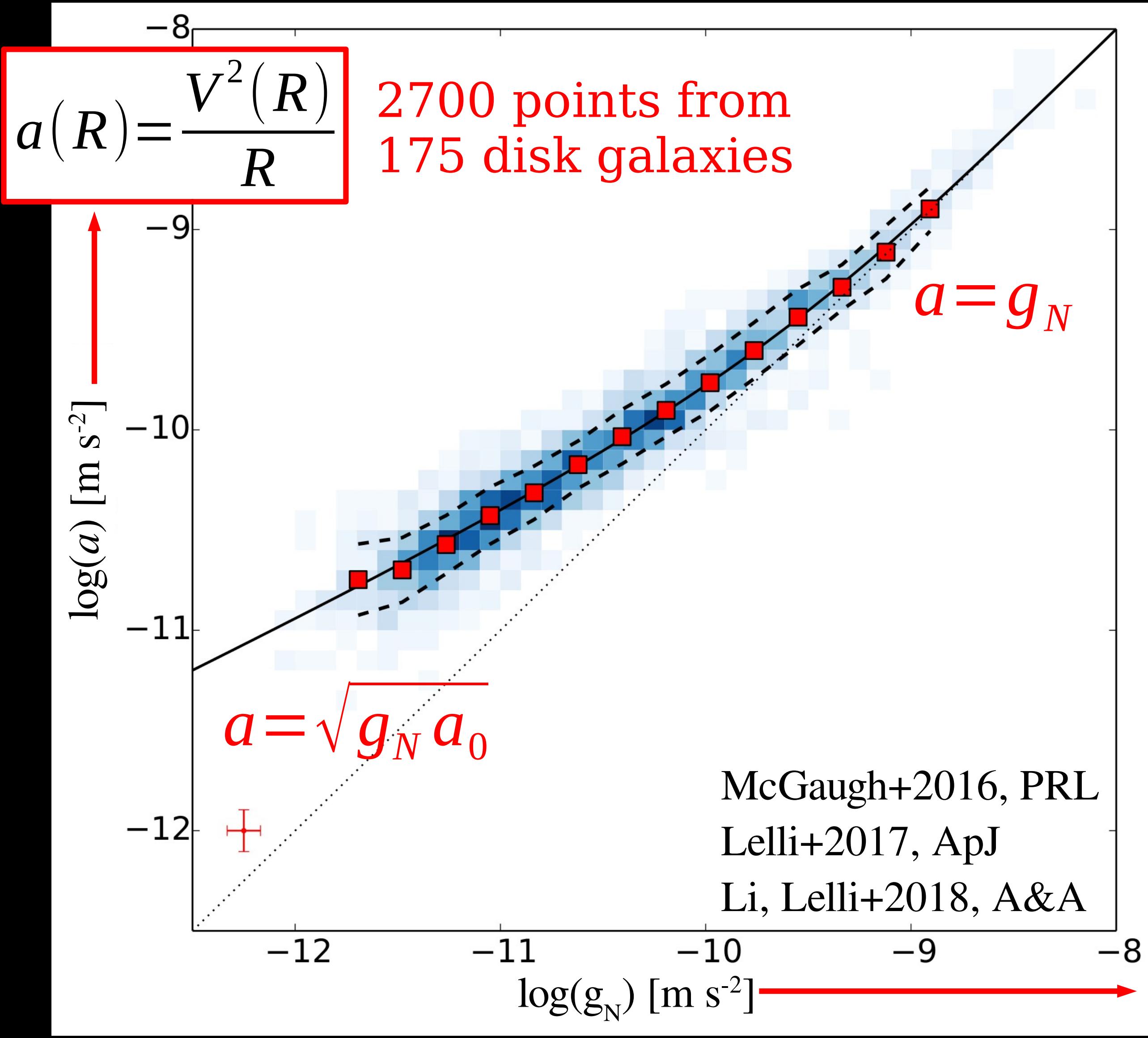

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- RAR shape specifies the form of $\mu(x)$

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

$$\nu = \mu^{-1}$$

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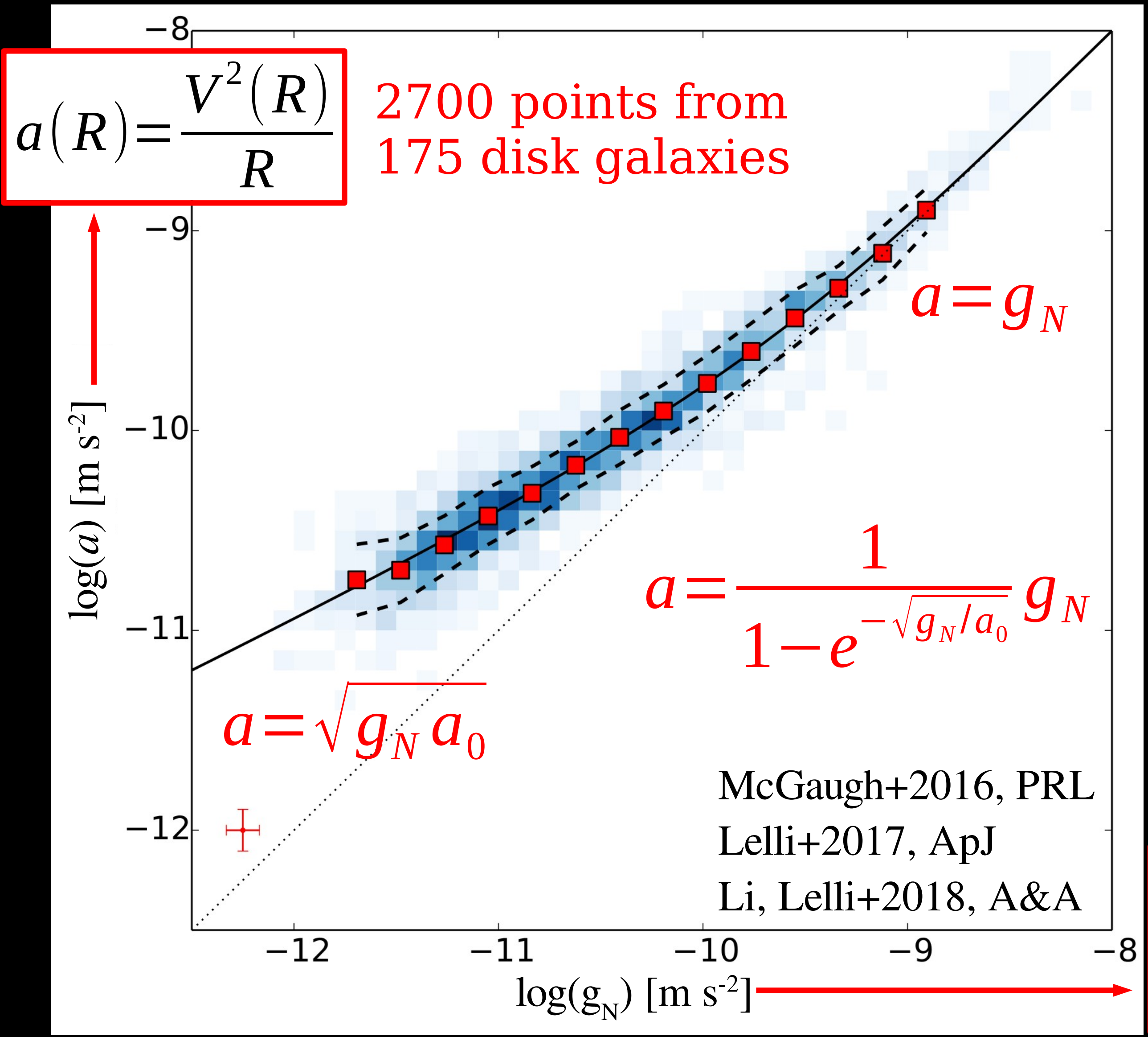

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$$\nu=\mu^{-1}$$

We can now assume $\nu(g_N/a_0)$ and predict rotation curves given ρ_b (within the errors)

$$\nabla^2\Phi_N(R,z)=4\pi G\rho_b(R,z)$$
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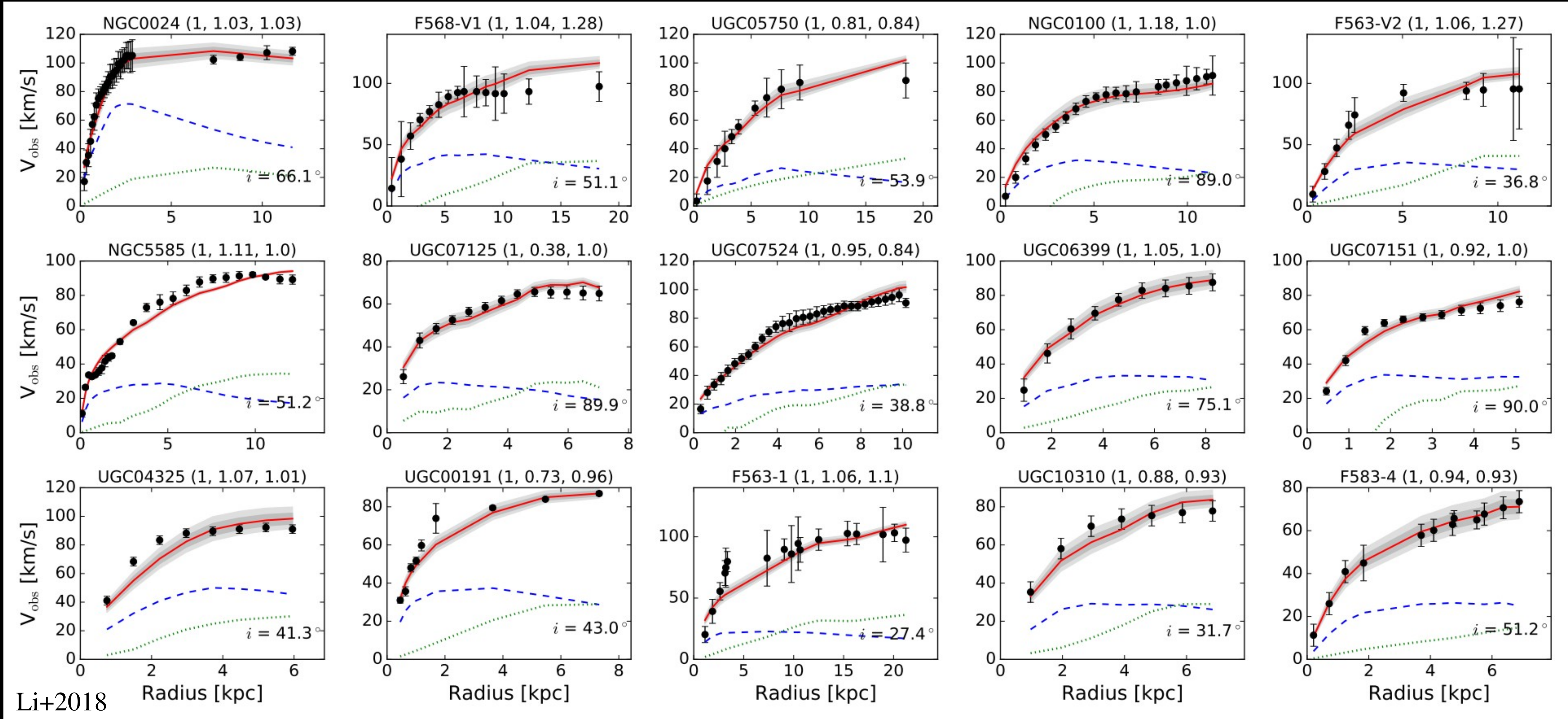

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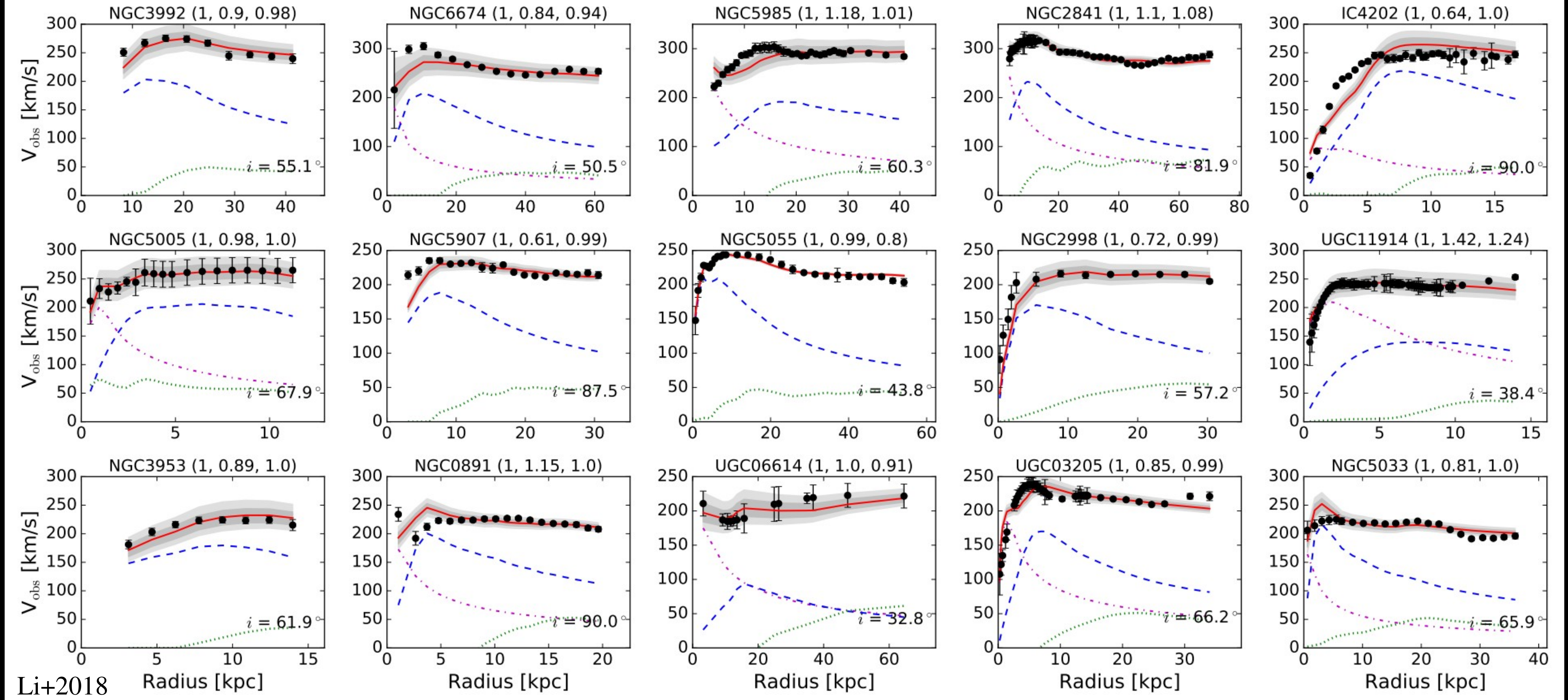

Li+2018

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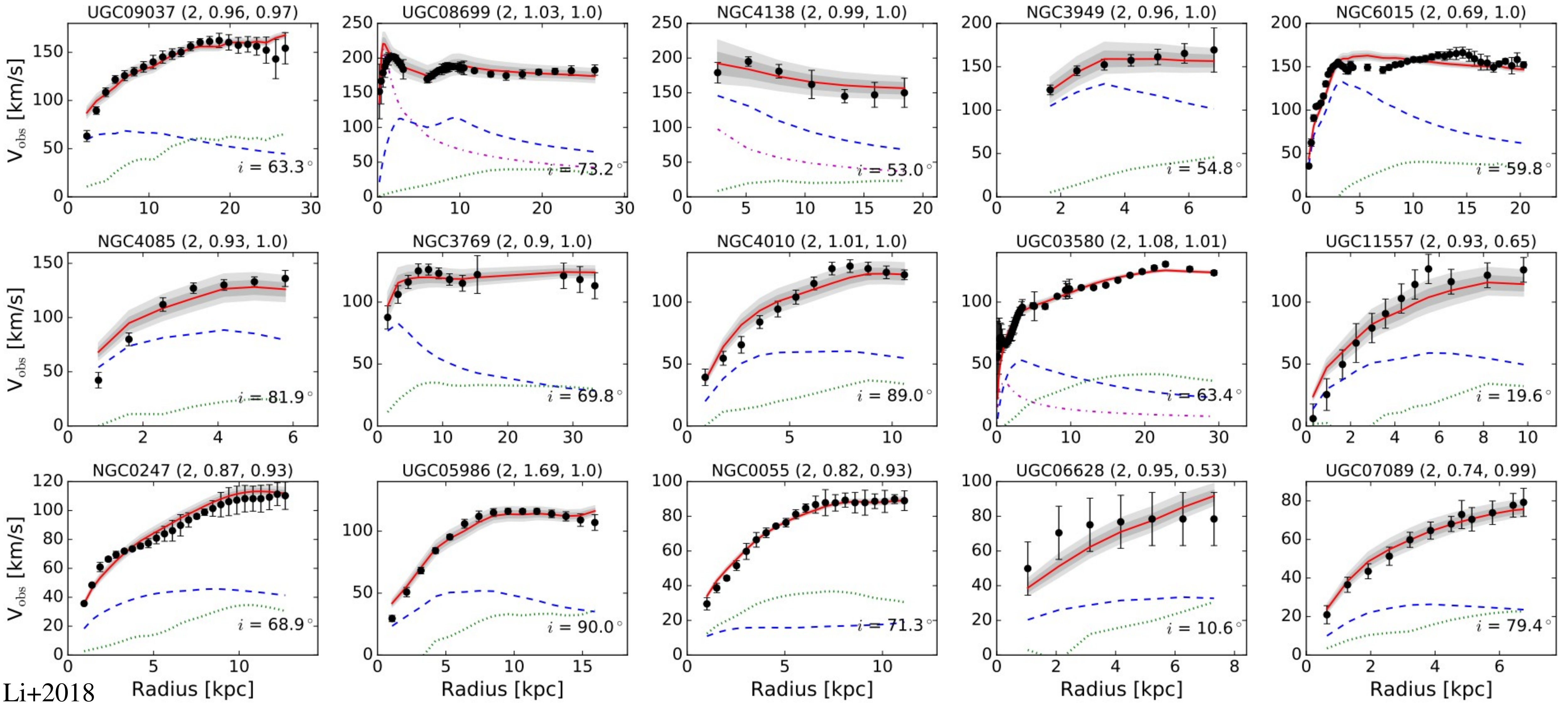
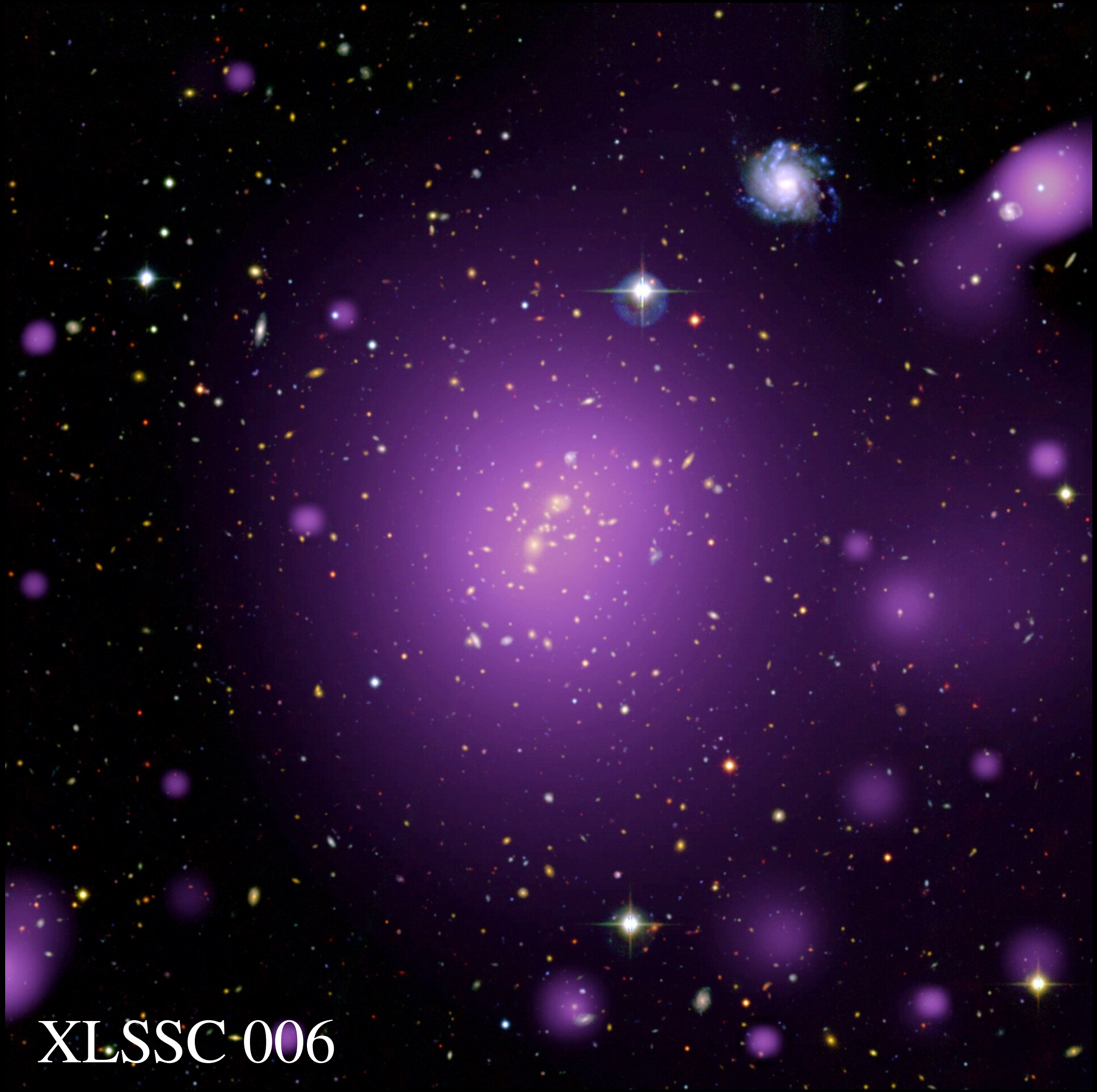


Li+2018

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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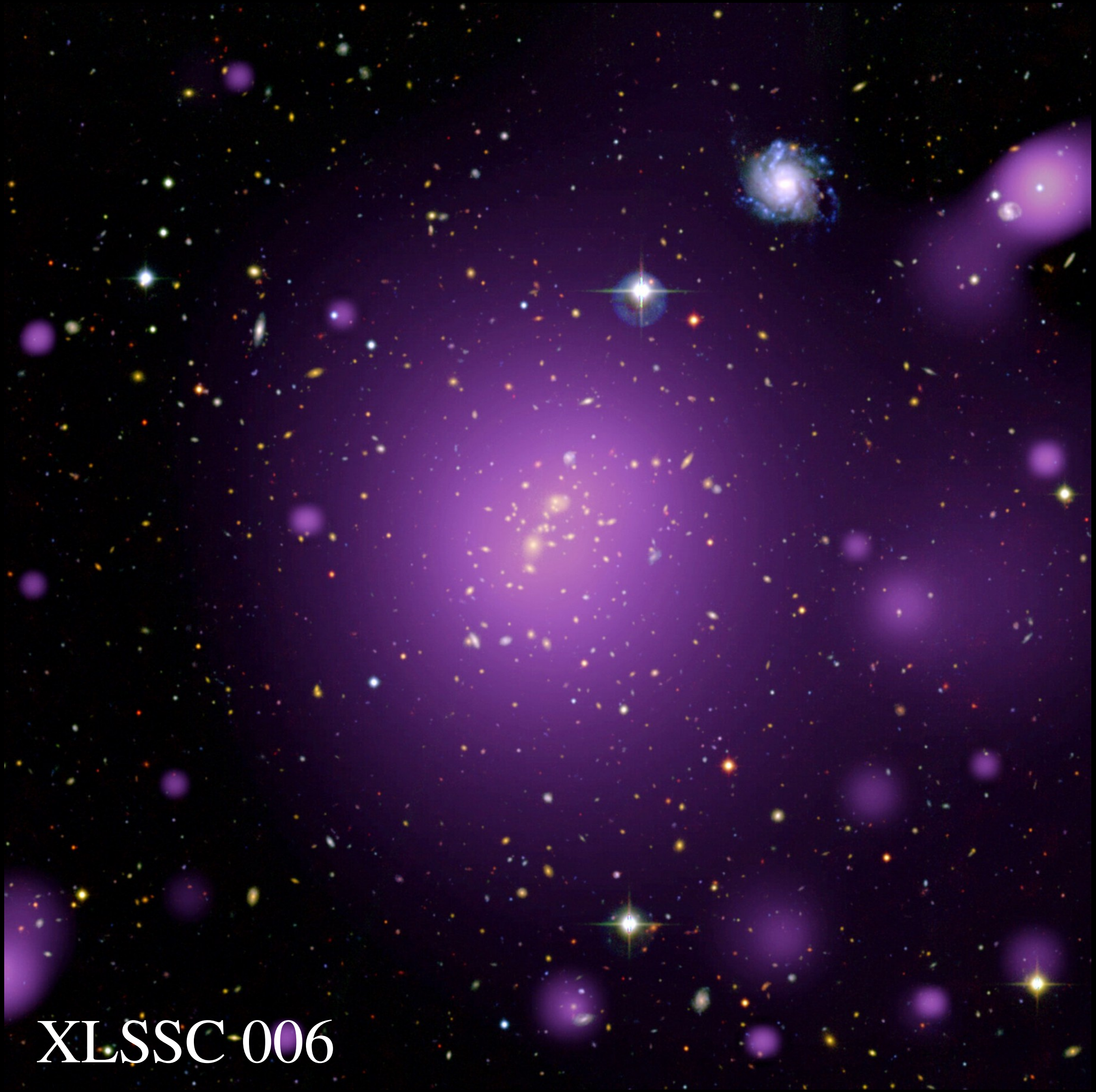

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Sphere in Hydrostatic Equilibrium

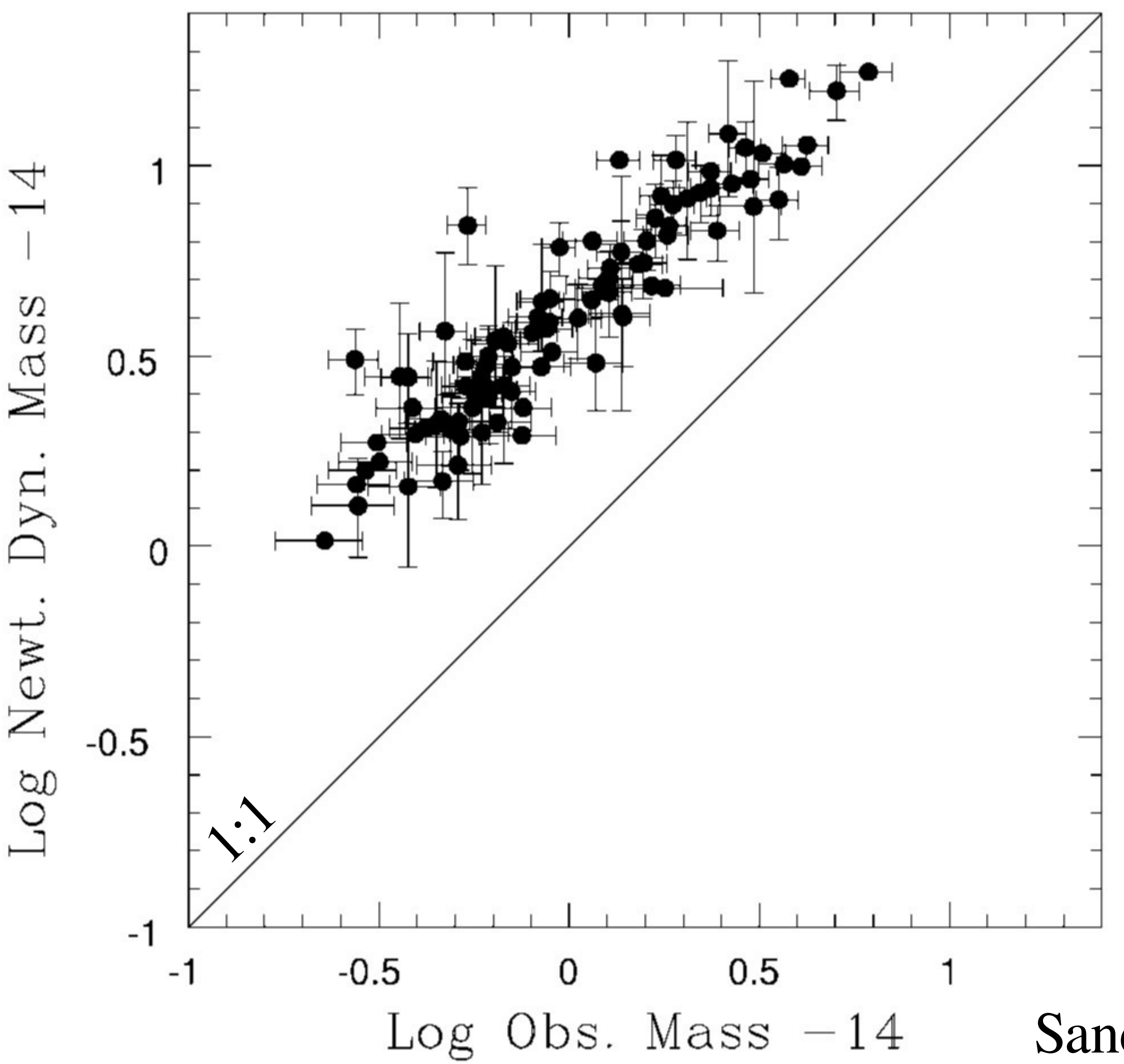
$$\frac{\partial P_{gas}}{\partial r} = \rho_{gas} \frac{\partial \Phi}{\partial r} \qquad P_{gas} = \frac{k_B T_{gas}}{w m_p}$$

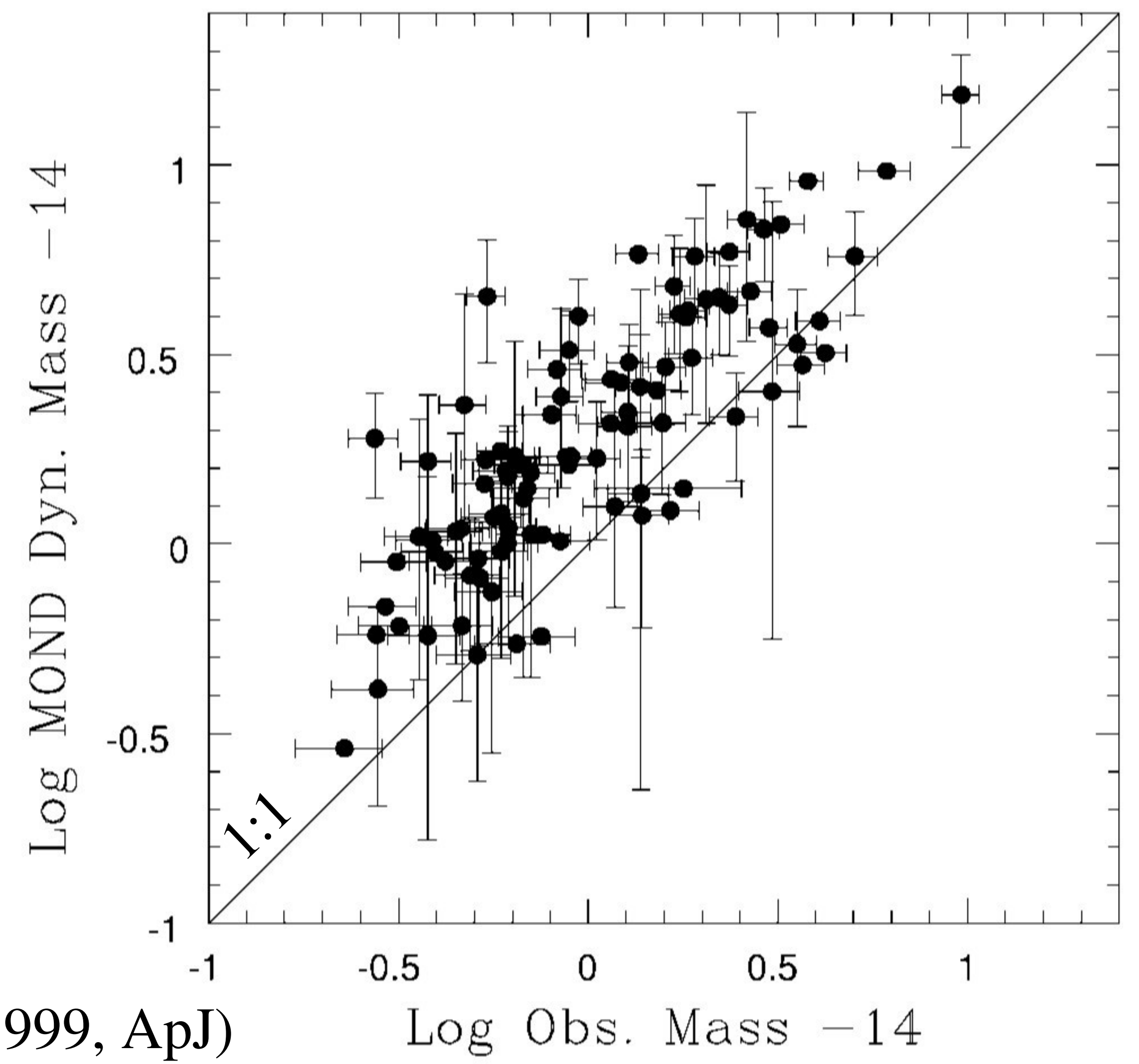
$$\Rightarrow \frac{\partial \Phi}{\partial r} = \frac{k_B}{w m_p} \frac{1}{\rho_{gas}} \frac{\partial}{\partial r} \left(\rho_{gas} T_{gas} \right)$$

Galaxy Clusters: Long-standing problem for MOND

Newtonian analysis: $M_{dyn}/M_{bar} \simeq 4\text{-}5$

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





Sanders (1999, ApJ)

Galaxy Clusters: Long-standing problem for MOND

Proposed Solutions:

- Undetected, missing baryons ?

  Expected from BBN: $\Omega_{bar} > \Omega_{gals} + \Omega_{clusters}$

  Compact clouds of cold gas? (Milgrom 2008)

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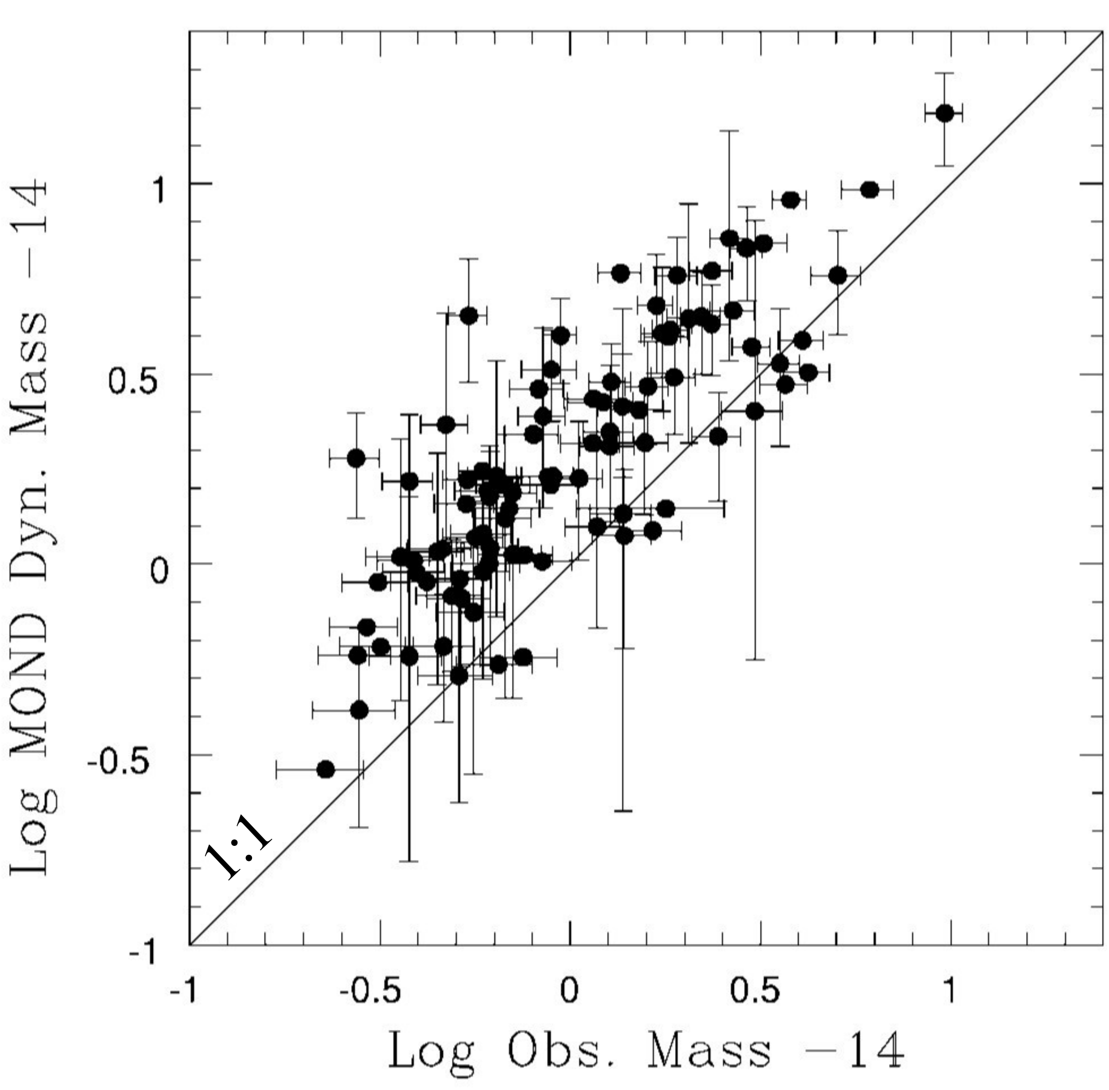

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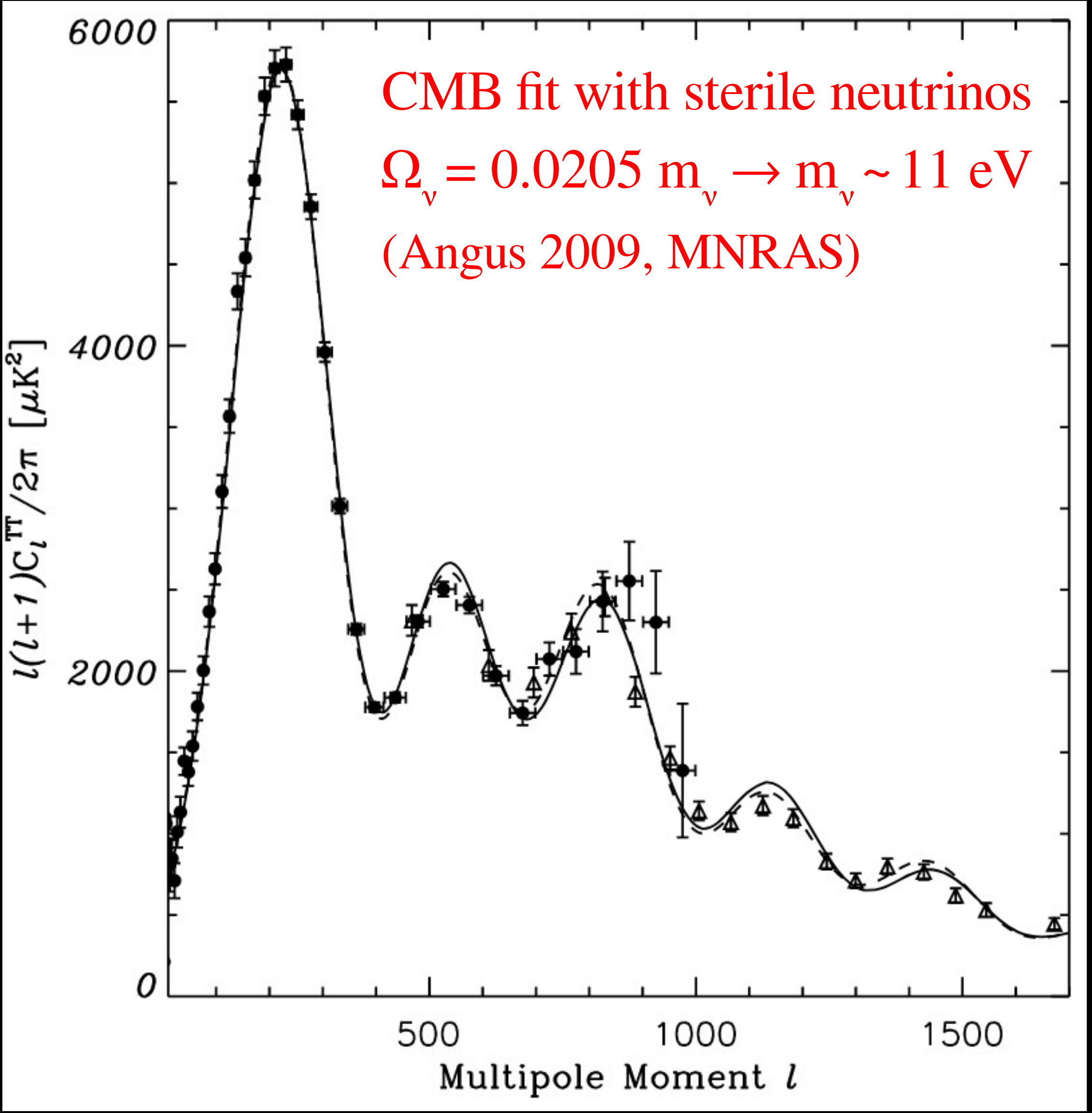

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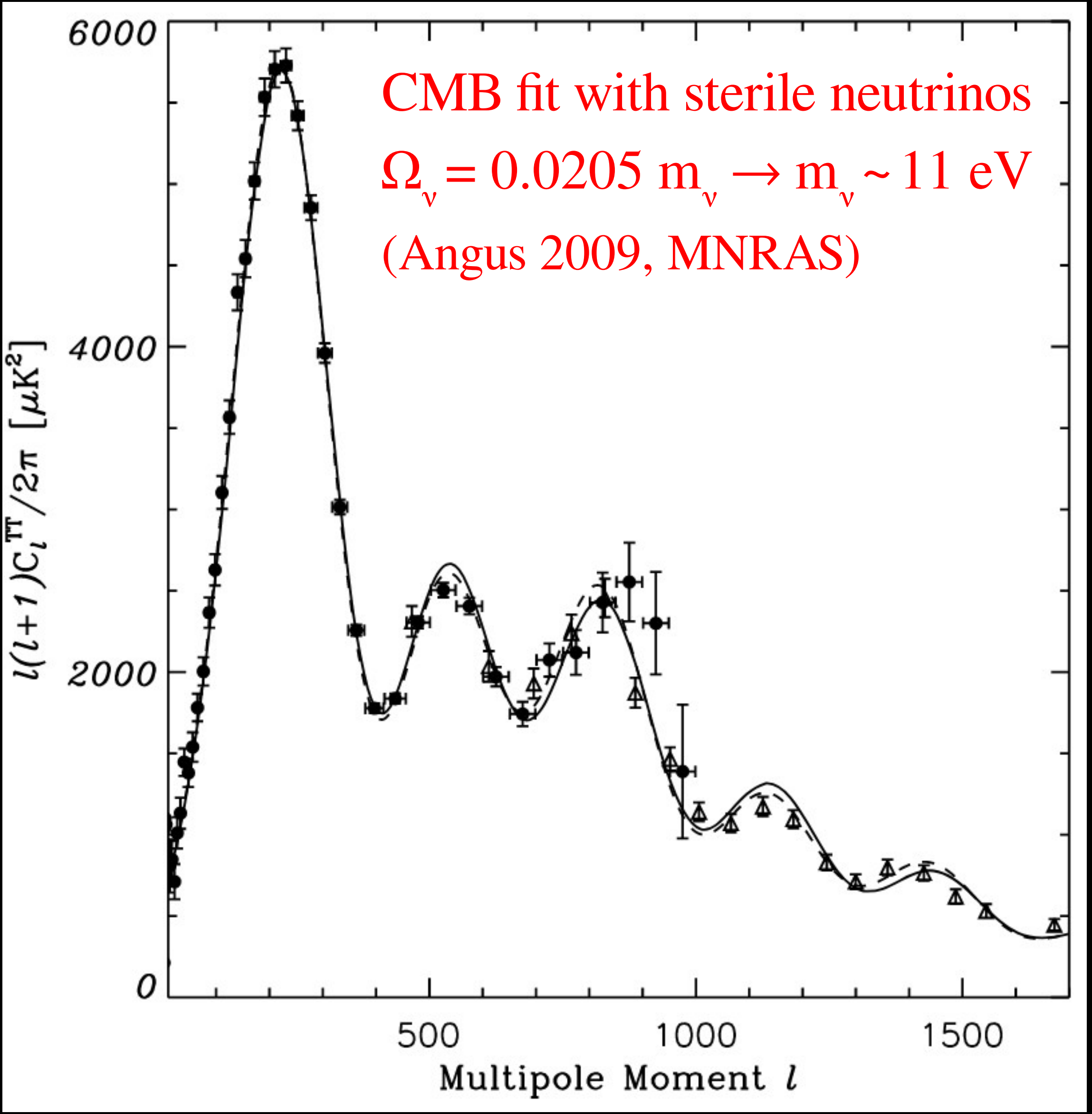
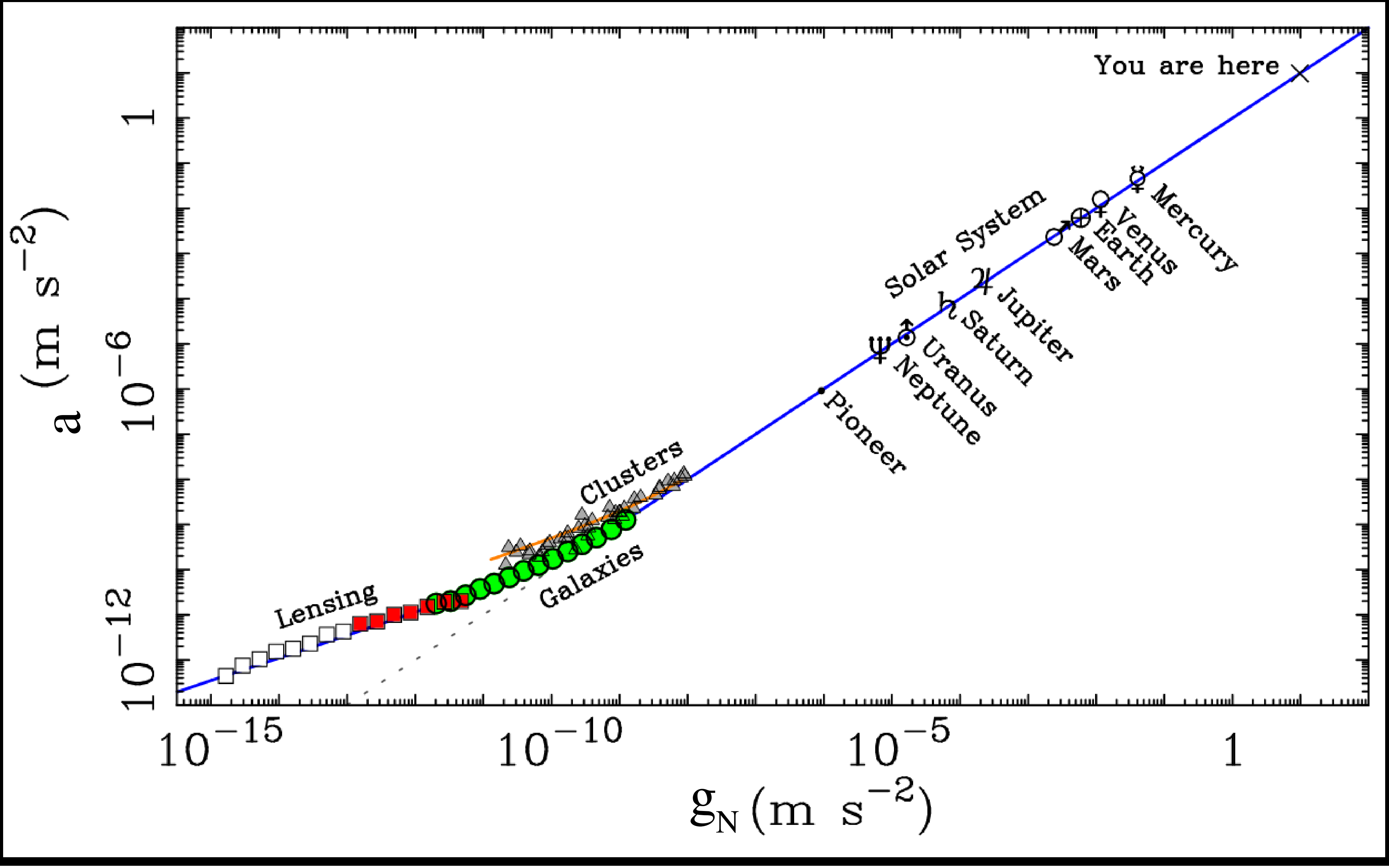
- Extended MOND: $a_0 \propto \Phi$?

  Deeper theory? But more freedom!

  (Zhao & Famaey 2012, PRD)



Galaxy Clusters on the Radial Acceleration Relation



II. Specific MOND theories

MOND paradigm

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

Modified Inertia ($\rightarrow F = ma$)

MOND paradigm

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Modified Inertia ($\rightarrow F = ma$)

Non-relativistic theories:

AQUAL (Bekenstein & Milgrom 1984)

QUMOND (Milgrom 2010)

Relativistic theories:

Stratified Scalar-Tensor theory (Sanders 1997, 2011)

TeVeS: Tensor-Vector-Scalar (Bekenstein 2004)

BIMOND: bimetric theory (Milgrom 2009, 2022)

Non-local metric theories (Deffayet+2011)

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

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Time non-local theories:

$a = \nu(g_N/a_0)g_N$ holds for circular orbits

(Milgrom 1994, 1999, 2022)

Heuristic ideas:

Mach's principle for inertia ?

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

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Hybrid MOND/DM models:

Bipolar DM (Blanchet+2008, 2009, 2015, 2017)

Superfluid DM (Berezhiani & Khoury 2015)

Baryon-interacting DM (Famaey+2018, 2020)

AQUAL = Aquadratic Lagrangian (Bekenstein & Milgrom 1984, ApJ)

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

Lagrangian is quadratic in $\nabla\Phi$

$$\downarrow$$

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

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

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

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Lagrangian is quadratic in ∇Φ

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F(z) → *z* for $z = |\nabla\Phi|^2/a_0^2 \gg 1$

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

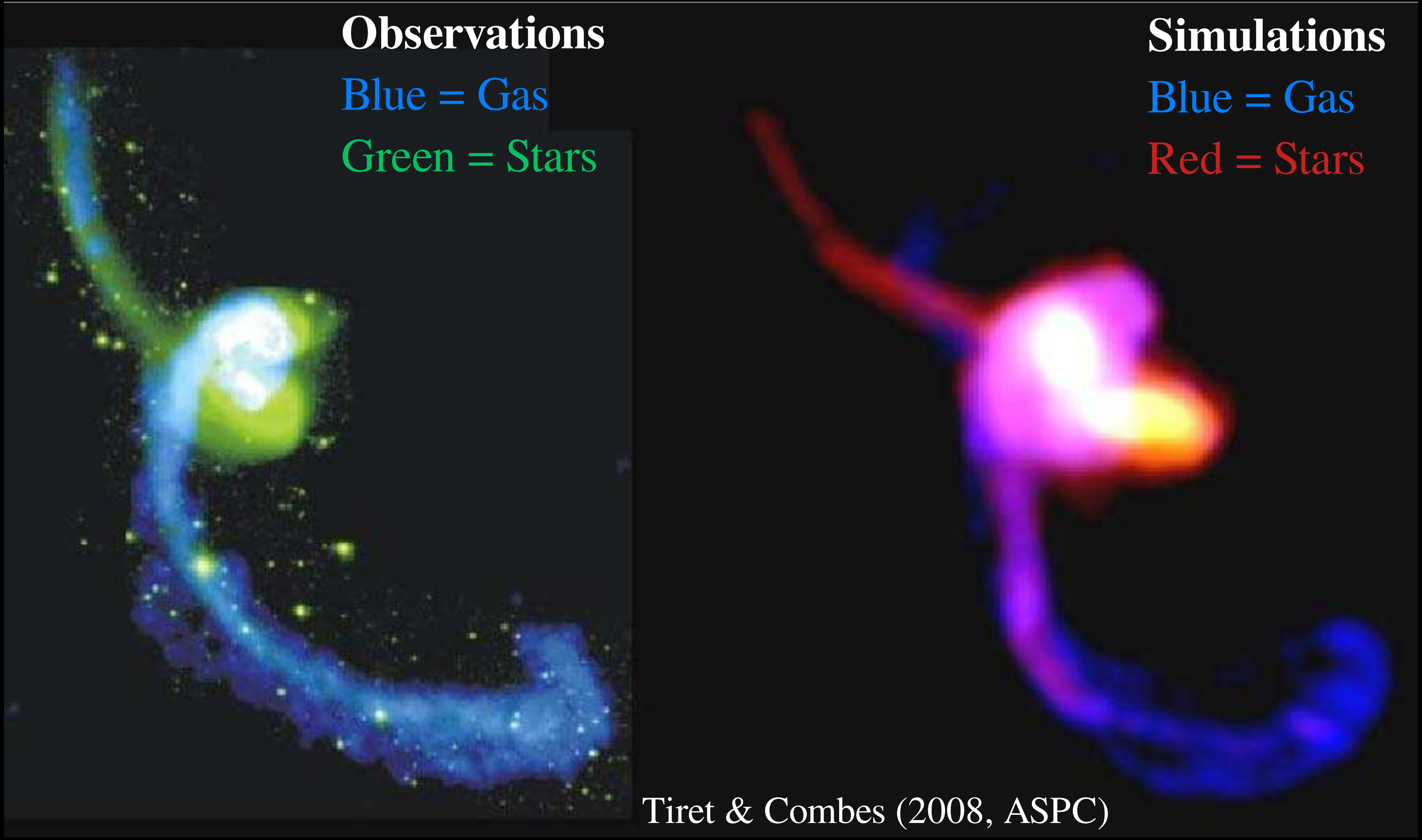
$$\frac{\delta S}{\delta \Phi} = 0 \rightarrow \nabla \cdot \left[\mu\left(\frac{|\vec{\nabla}\Phi|}{a_0} \right) \vec{\nabla}\Phi \right] = 4\pi G \rho$$

Modified Poisson's Equation

$$\mu(x) = \frac{dF(z)}{dz} \qquad z = x^2$$

F(z) provides the interpolation function $\mu = \upsilon^{-1}$

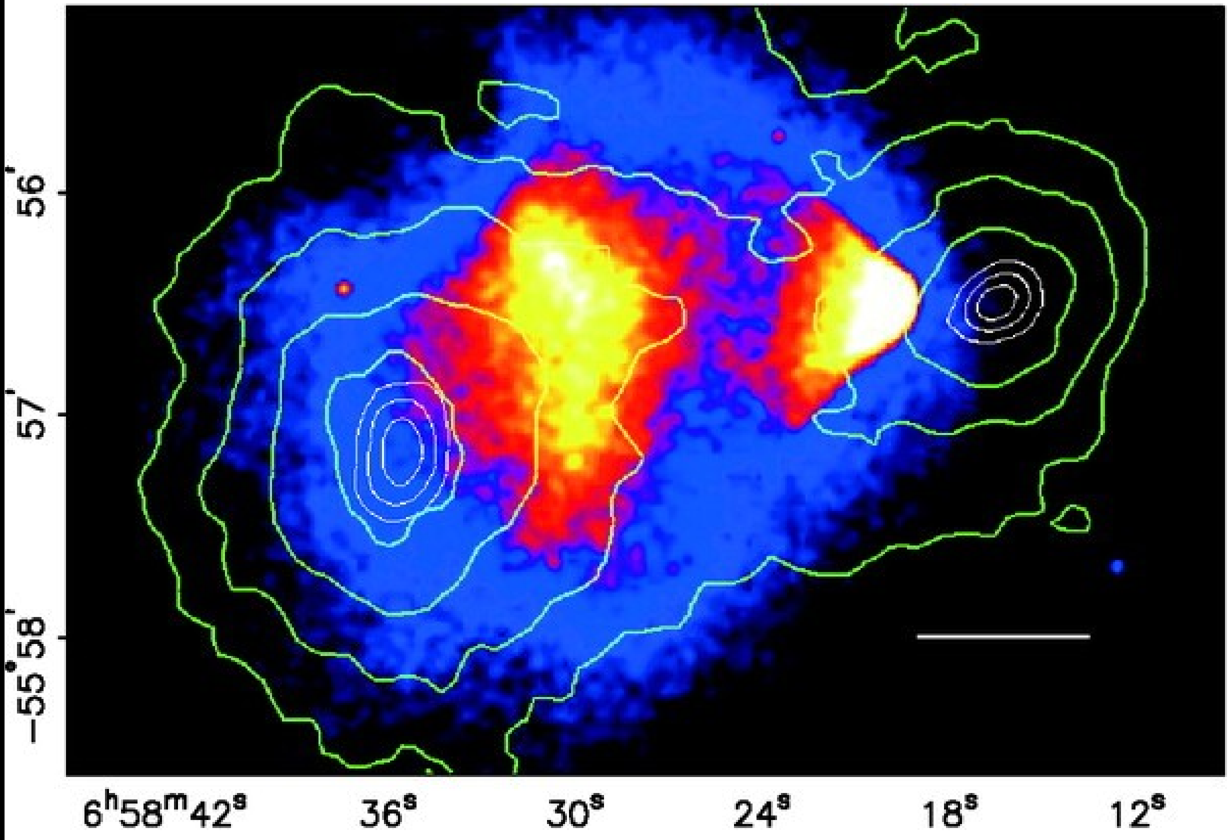
Interacting & Merging Galaxies: The Antennae



Tiret & Combes (2008, ASPC)

Interacting & Merging Clusters: The Bullet Cluster

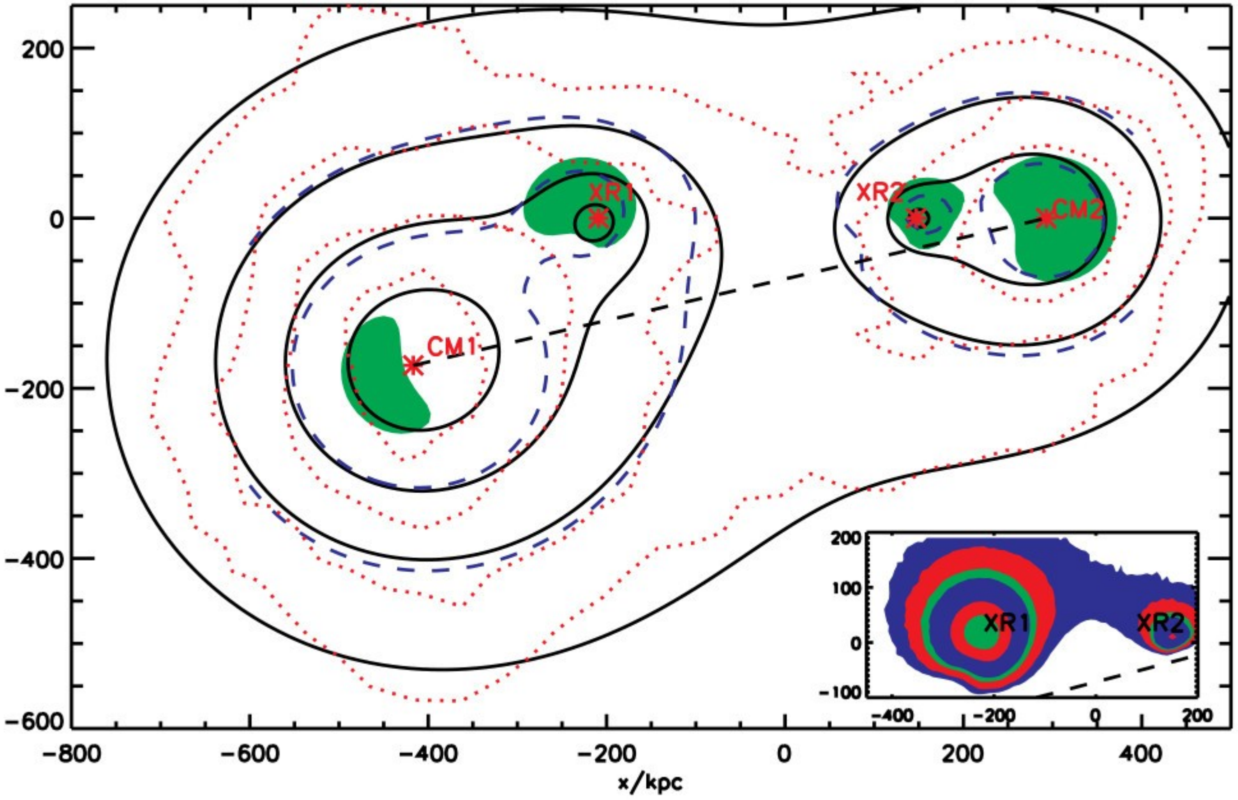
OBSERVATIONS (Clowe+2004, ApJ)



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: MOND model with 2eV neutrinos

Blue: total surface densities (baryons+υ)

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!

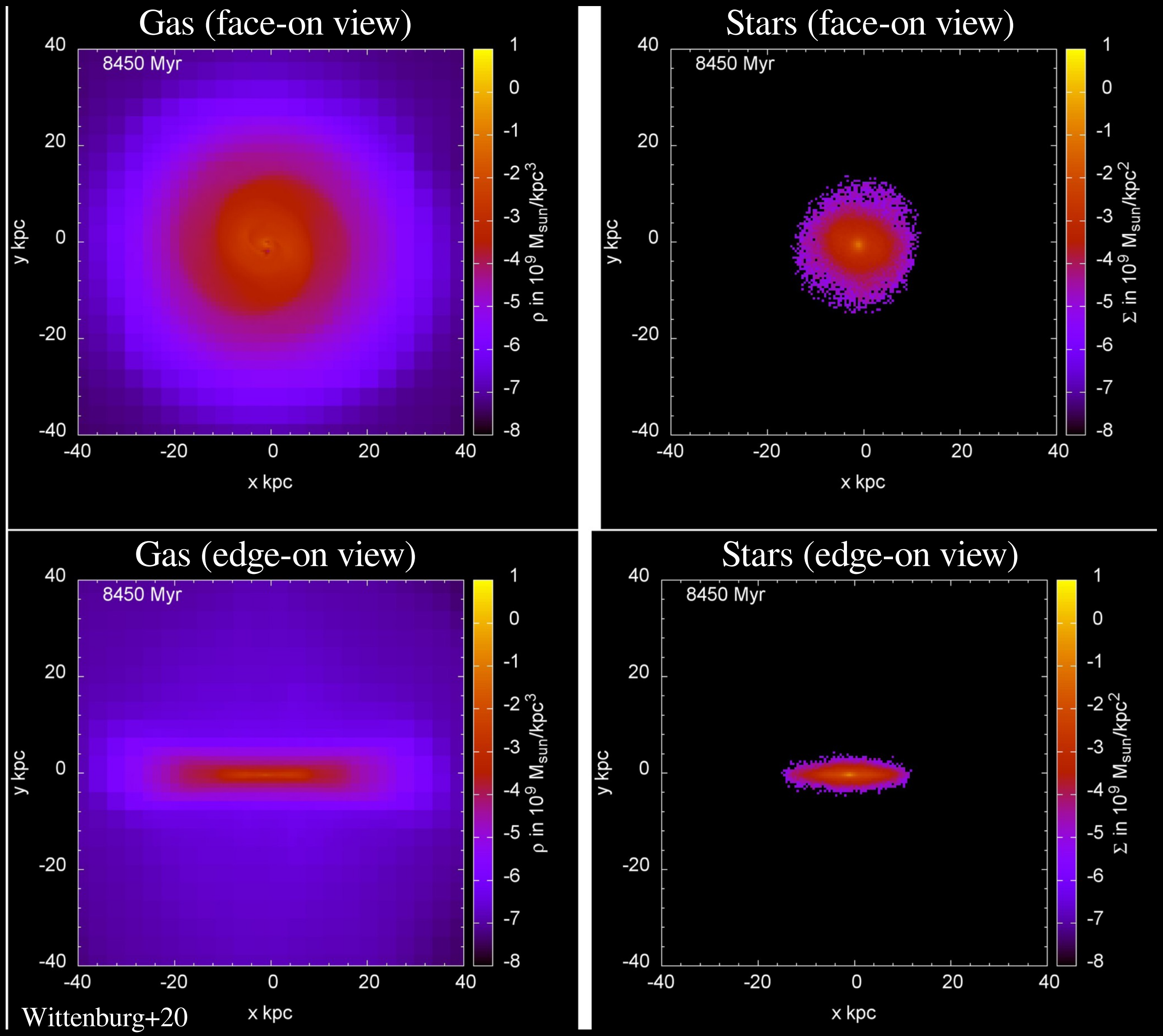
Principle of least Action varying Φ, Φ_N and $\bar{x}$ → set of 3 equations

$\nabla^2\Phi_N = 4\pi G\rho$ ⟶ 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 $\quad \nu(\sqrt{x}) = \frac{dQ(x)}{x}$

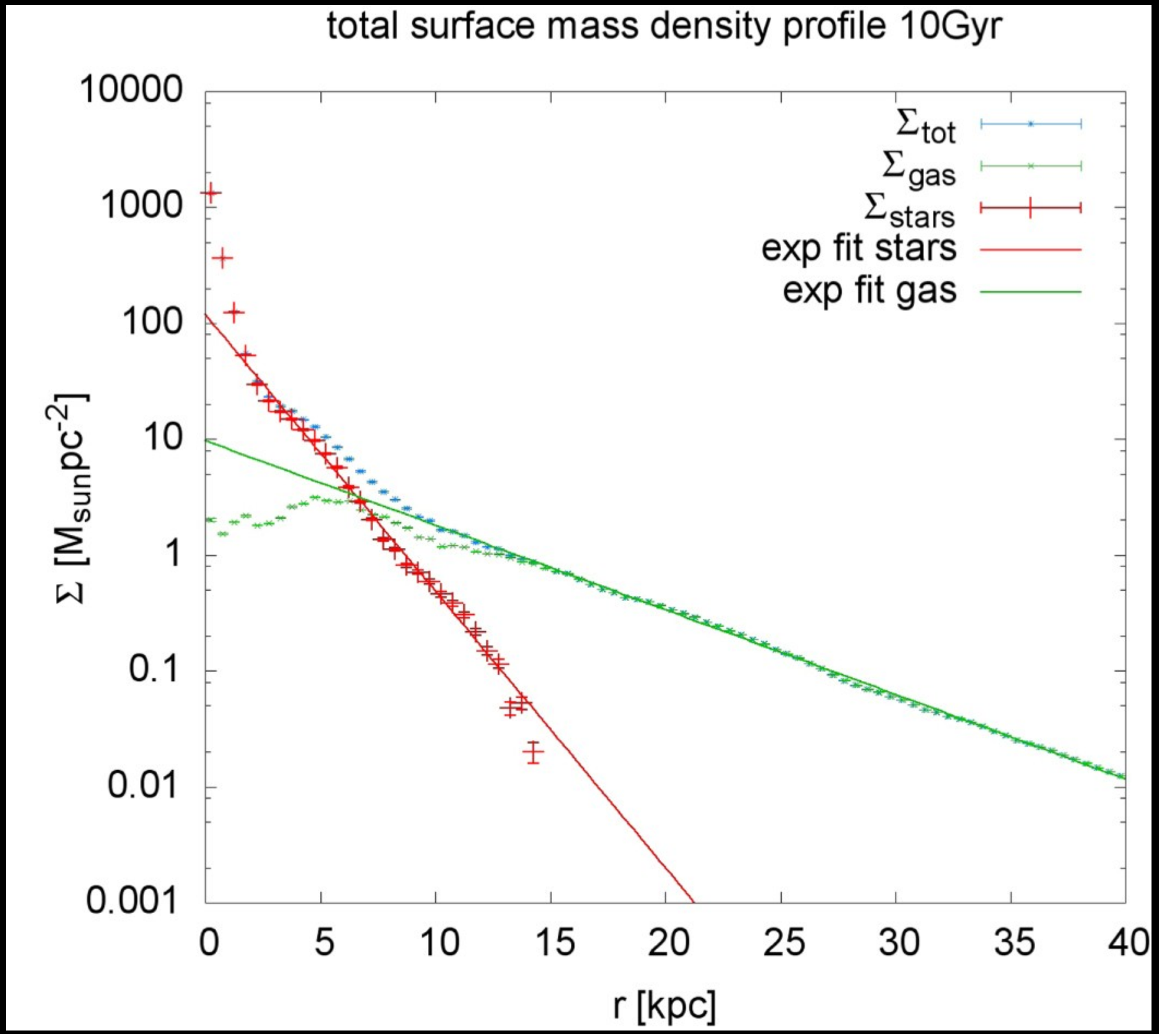
$\vec{a} = -\vec{\nabla}\Phi$ ⟶ Acceleration/force set by second potential Φ

Hydrodynamic Simulations of Galaxy Formation in QUMOND



Wittenburg+20

Monolithic collapse → realistic galaxy



Wittenburg+20, Nagesh+21, Roshan+21, Eappen+22, Banik+22, Srikanth+23

Relativistic MOND → add degrees of fredoom (new fields) to GR

- Tensor $g_{\mu\nu}$ → Einstein's metric
- Scalar ϕ → for the DM effect in the NR limit (Bekenstein & Milgrom 1984, ApJ)
- Vector A^{μ} → for gravitational lensing (Sanders 1997, ApJ; Bekenstein 2004, PRD)
- Free function(s) → interpolation function(s) (non-fundamental effective theories?)

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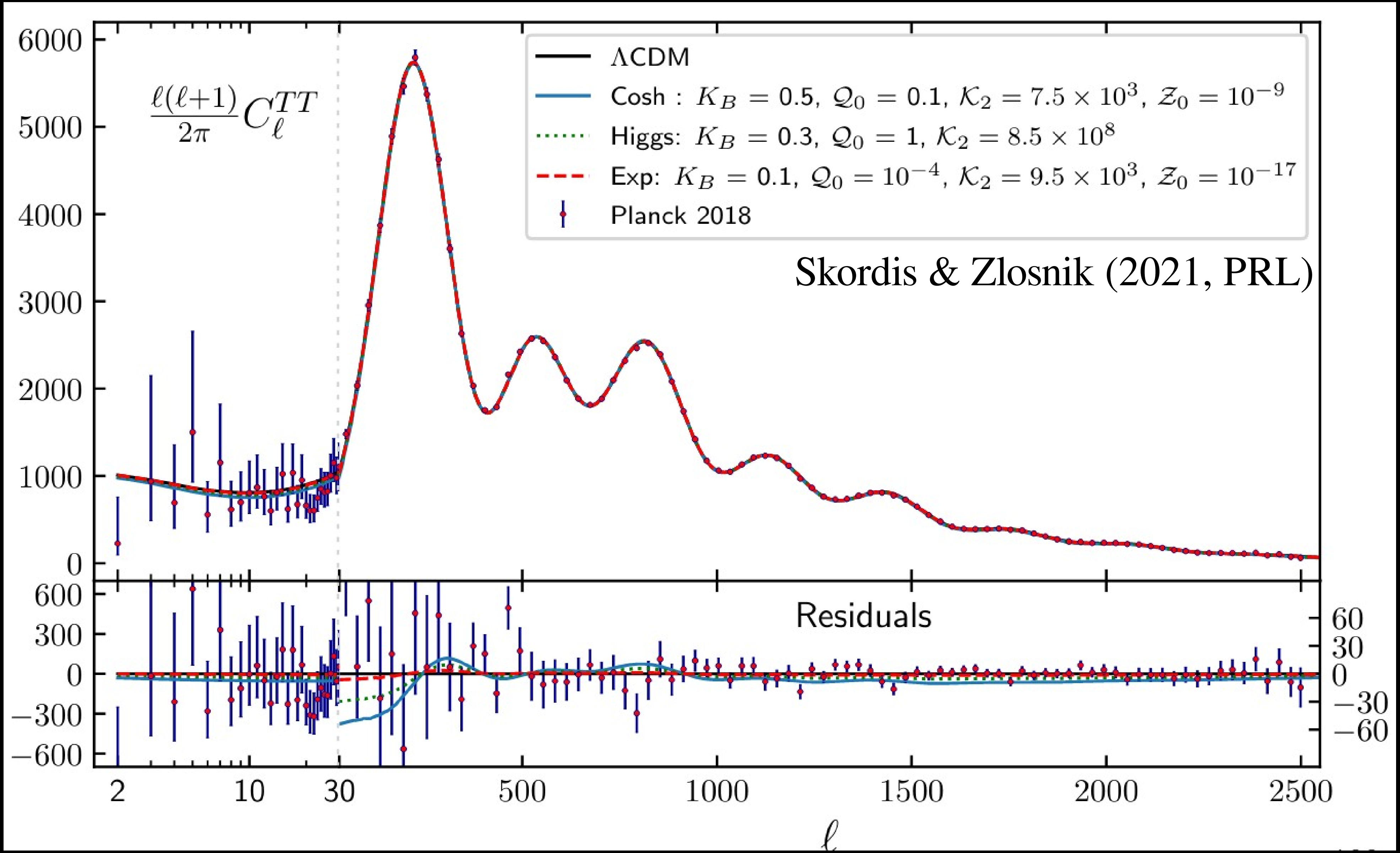
AeST: Aether Scalar-Tensor theory (Skordis & Zlosnik 2019, PRD; 2021, PRL; 2022, PRD)

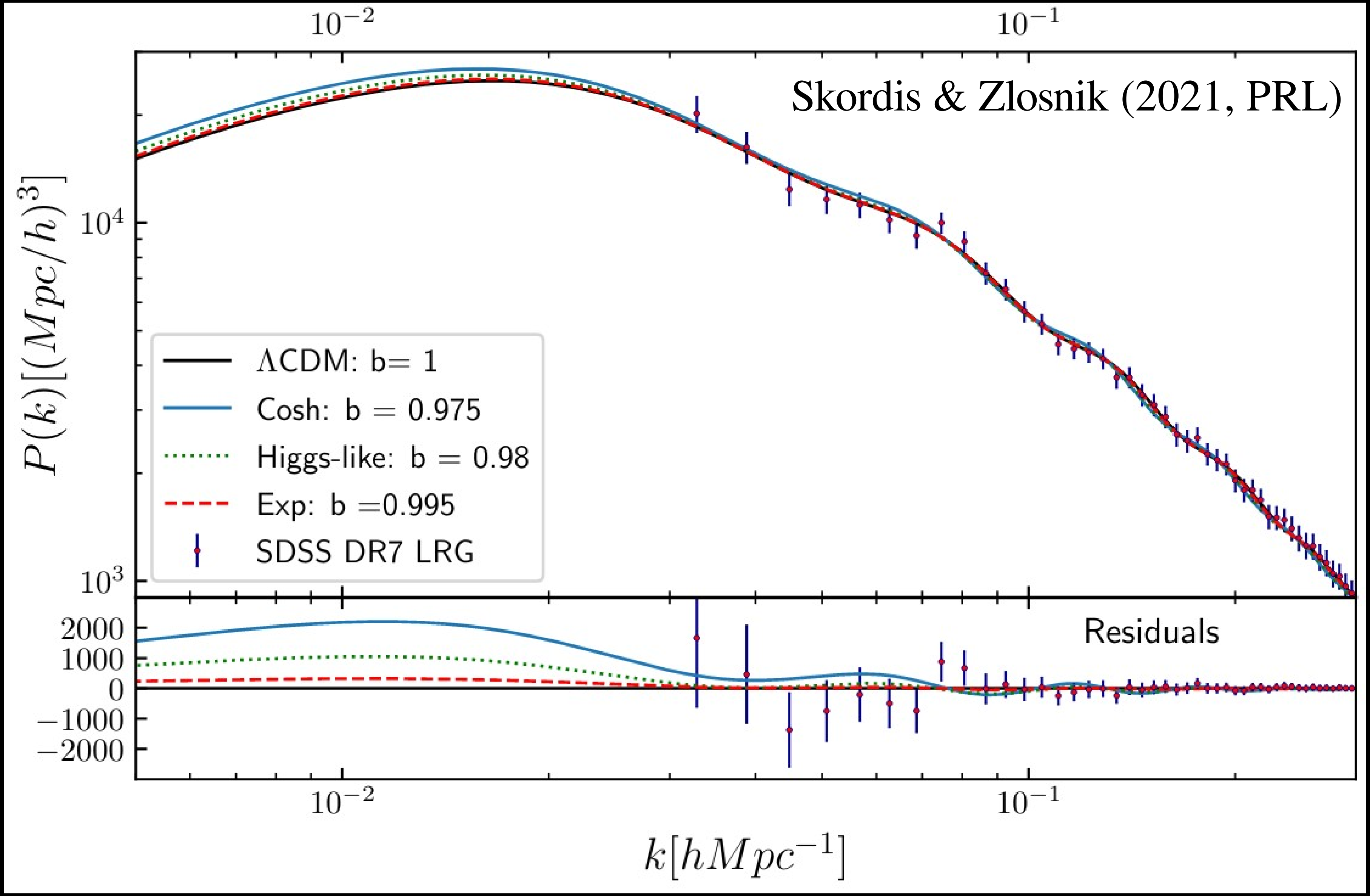
(1) Grav. Waves: $B^{\mu} = e^{-2\phi} A^{\mu}$ (timelike) → theories $\{B_{\mu}, g_{\mu\nu}\}$ → $c_{GW} = c_{EM}$

(2) Cosmology: *k*-essence term for ϕ → $\rho_{\phi} \propto a(t)^{-3}$ (like dust or CDM)

AeST theory: Fit to the CMB Power Spectrum

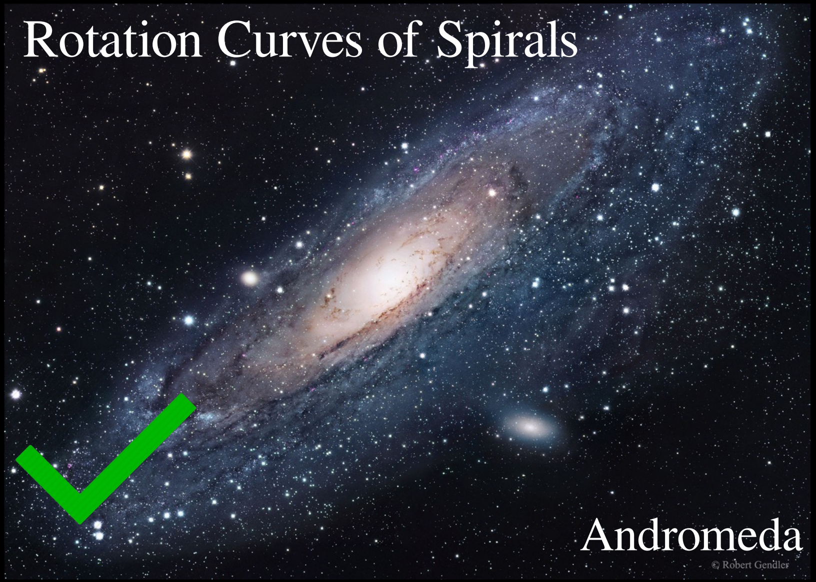


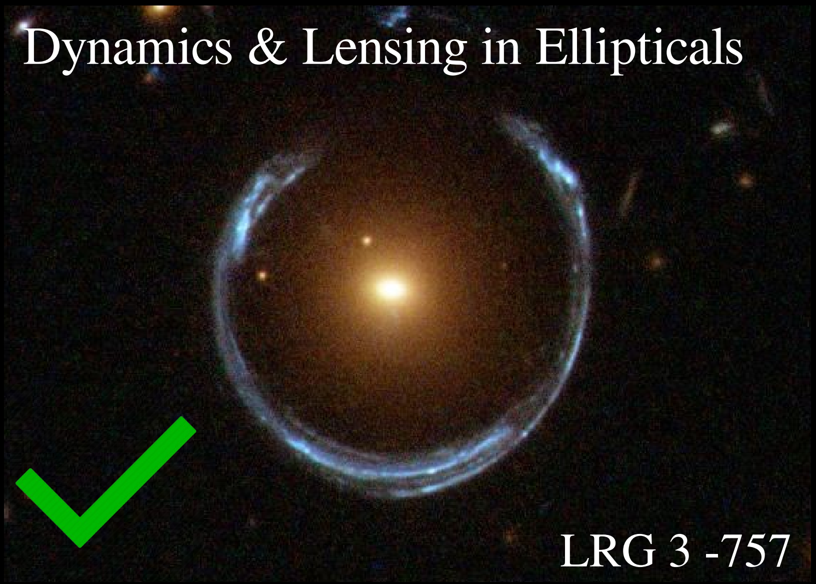
AeST theory: Fit to the Matter Power Spectrum at z=0



Conclusions: Status of MOND at Various Scales

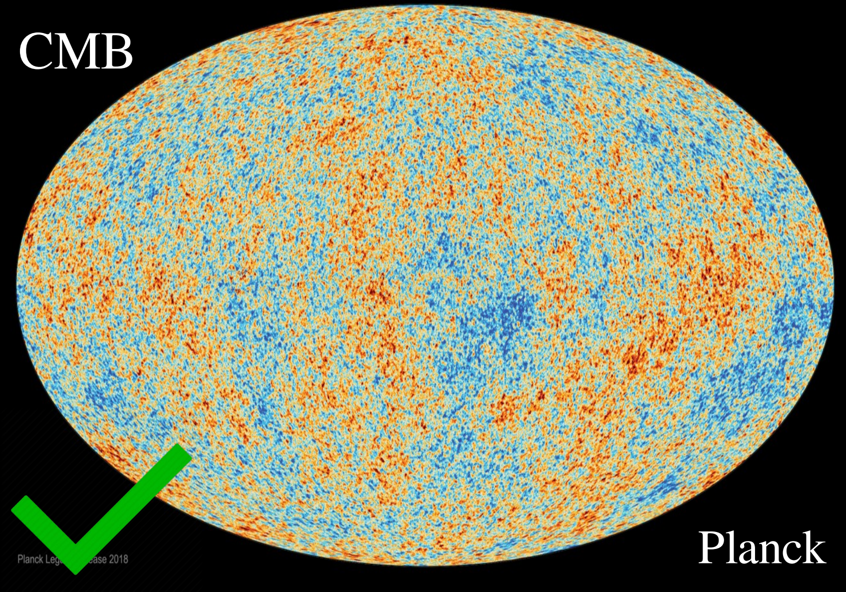
Galaxy Scales (~1-100 kpc)

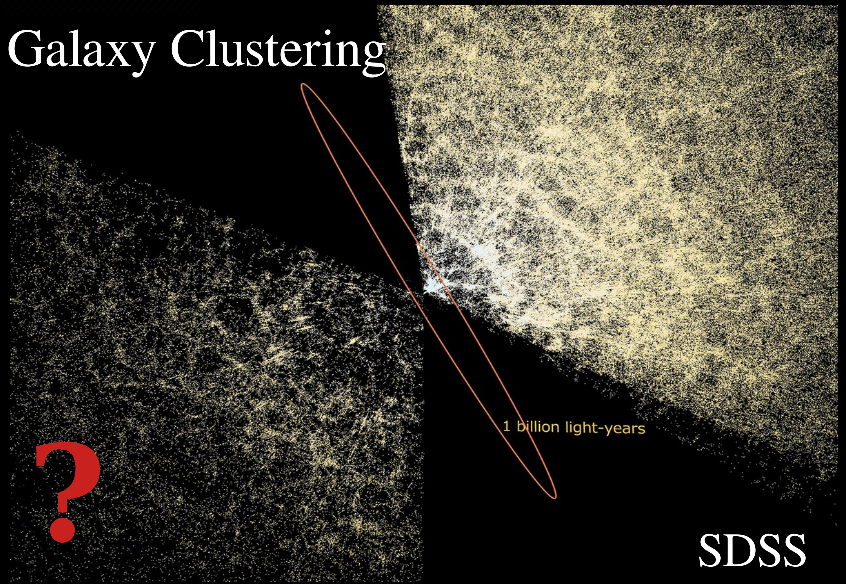




Groups/Clusters Scales (~1-5 Mpc)

Cosmological Scales (>100 Mpc)





More Slides

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 $a_0(t) \sim H(t)$?

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

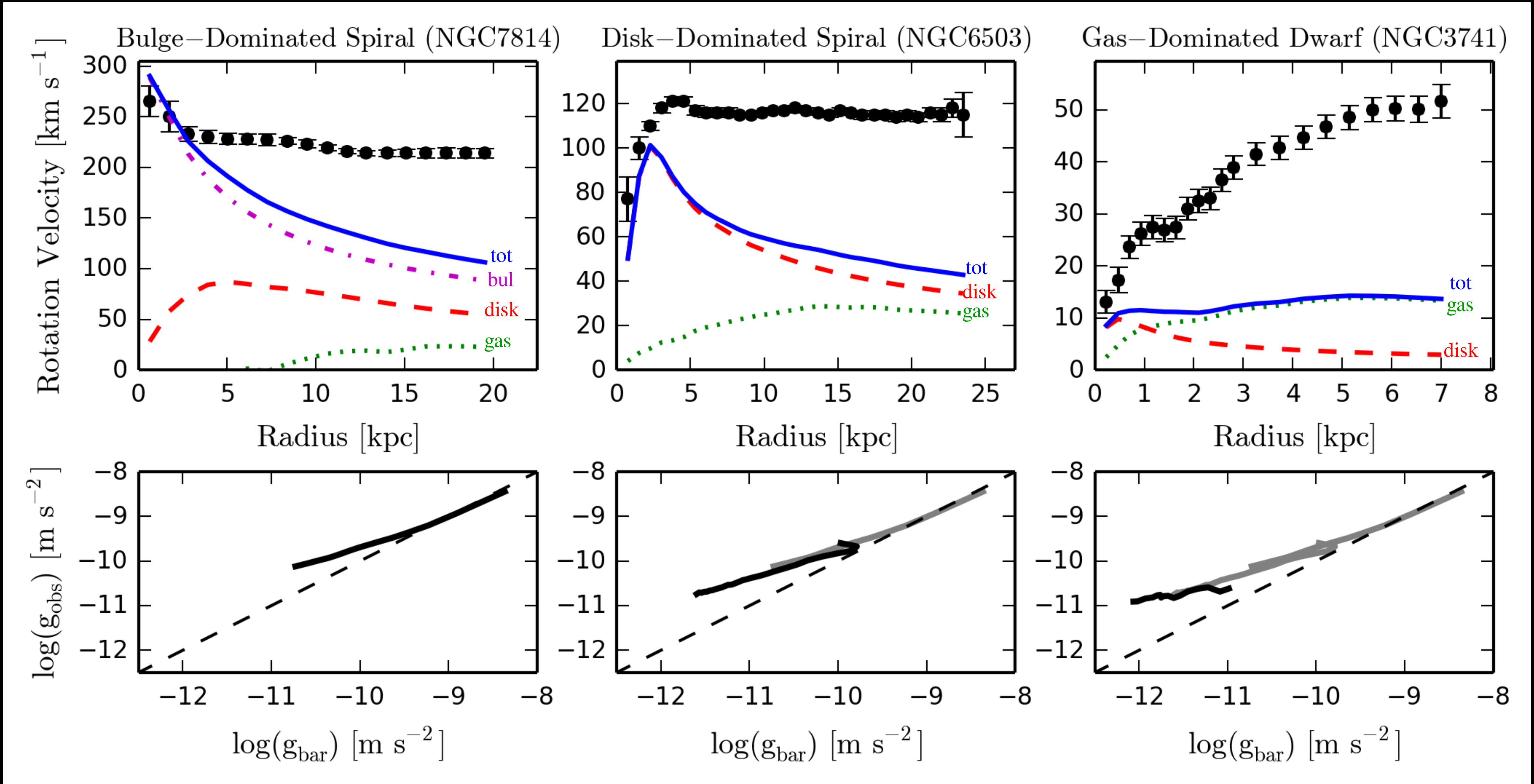
Λ = Cosmological constant → relation to Dark Energy?

IF this numerology has some deeper, fundamental meaning:

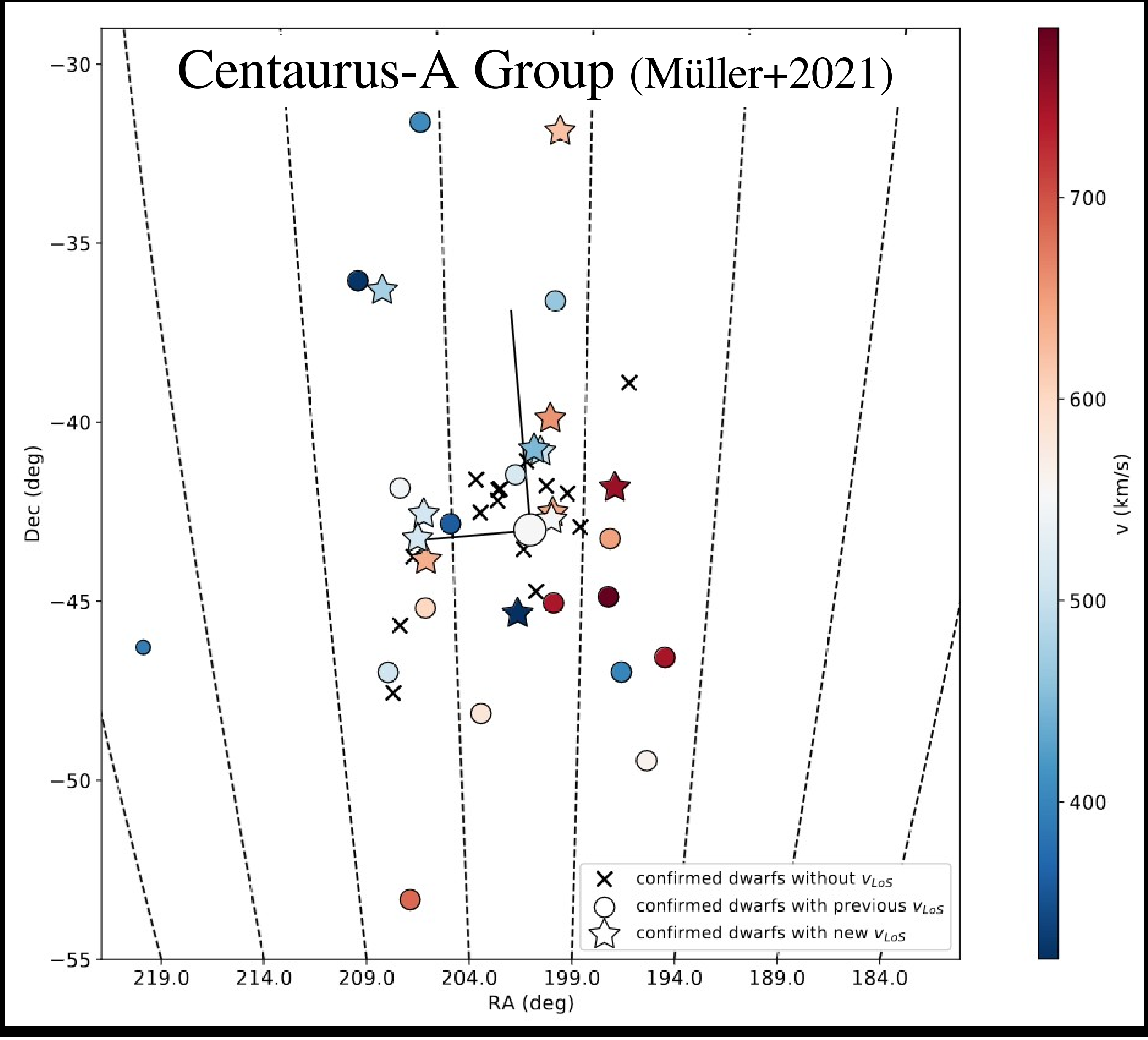
either the state of the Universe at large enters in local dynamics, or

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

Galaxies lie on the same RAR *despite* their diversity



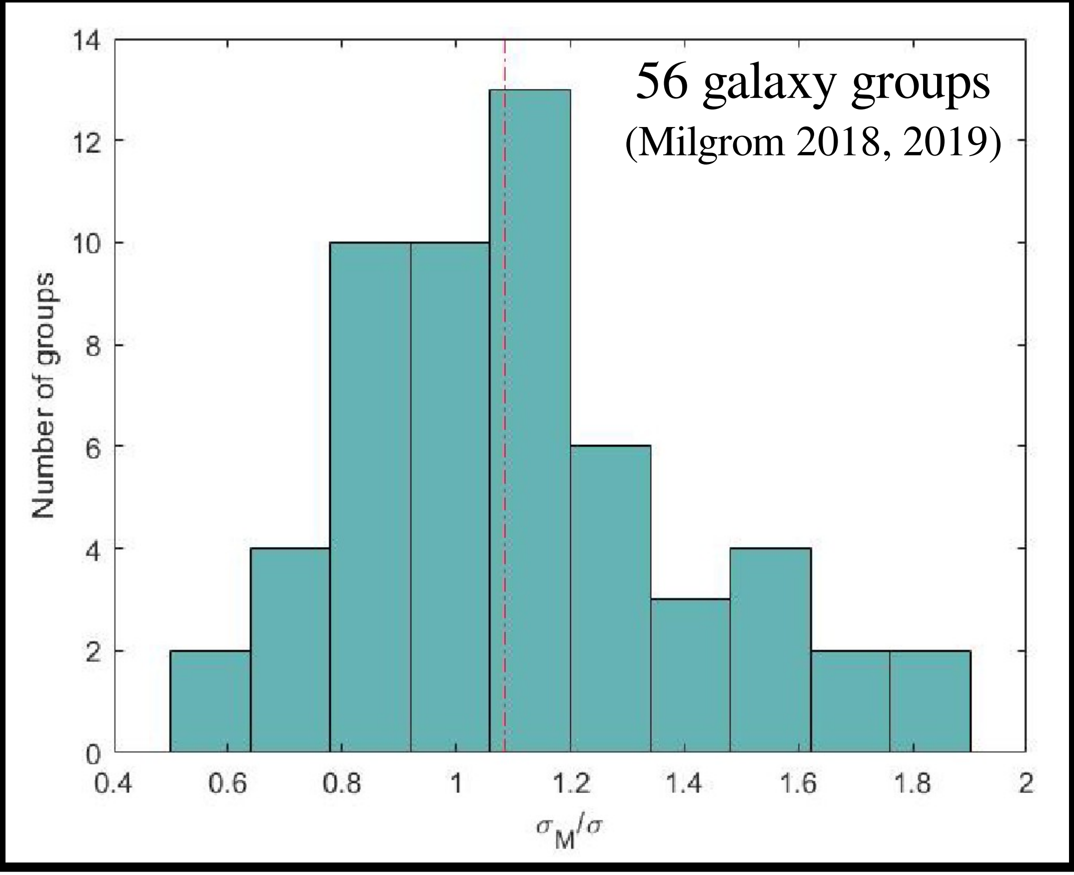
Galaxy Groups: bound systems with ~10-100 galaxies



σ_{obs} → group velocity dispersion

$M_b = (M/L)\sum_i L_i \rightarrow \sigma_M^4 \simeq a_0 G M_b$

→ $\sigma_{obs}/\sigma_M \simeq 1$ (within uncertainties)



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 $a \gg a_0$, $A \rightarrow a = d^2x/dt^2$ (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: $\vec{A}[\vec{x}(t), a_0] \neq F\left(\frac{d^i \vec{x}}{dt^i}; i = 1, 2, \dots N\right)$

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!

Weak Equivalence Principle (WEP):

→ Universality of free fall (center-of-mass motion)

Einstein Equivalence Principle (EEP):

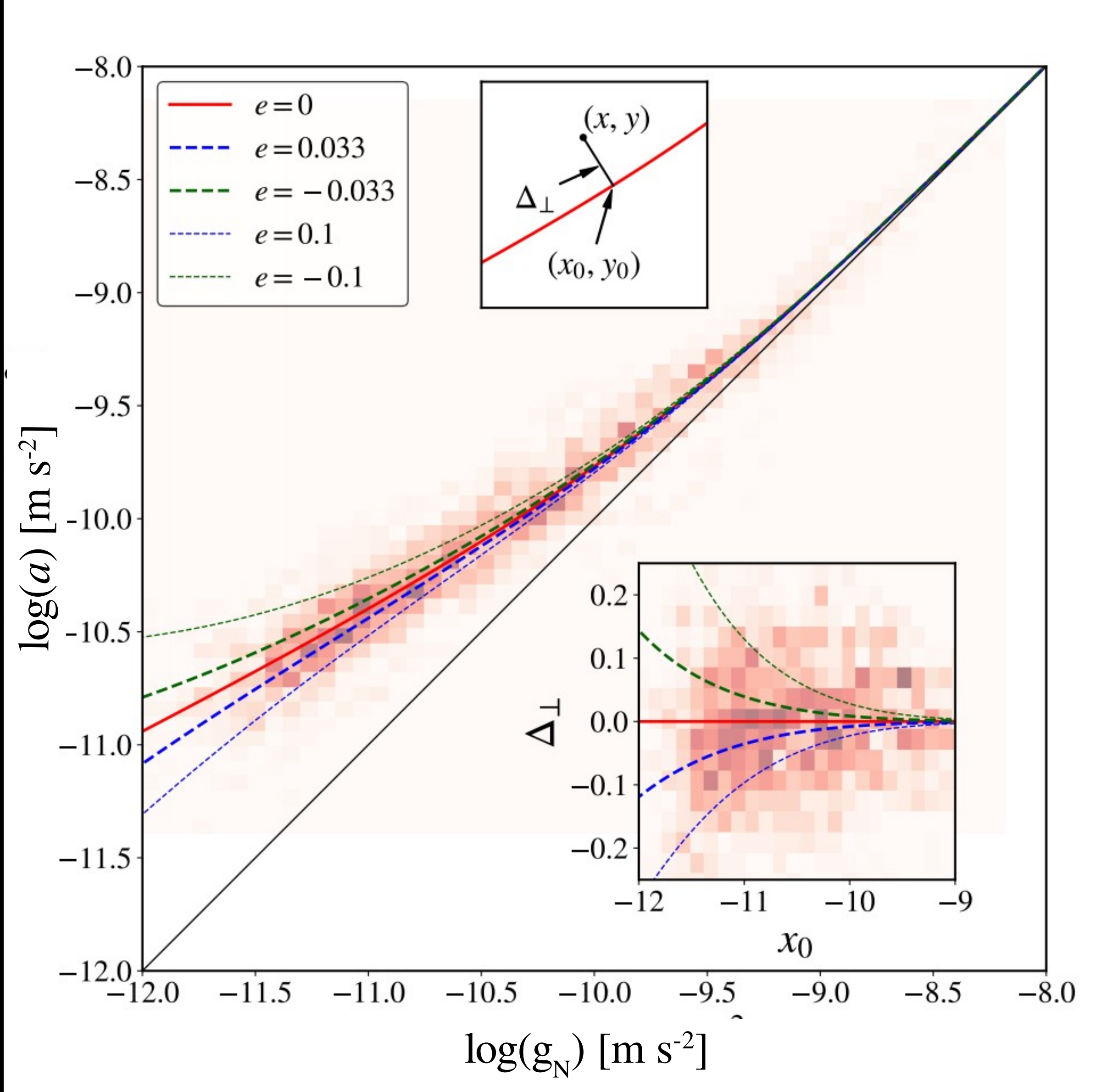
→ WEP + Lorentz invariance (spacetime rotations)
+ Local Position Invariance (LPI) for non-gravitational experiments:
the results of experiments do not depend on where/when they are done

Strong Equivalence Principle (SEP):

→ EEP ~~+ LPI for gravitational experiments too~~

Broken by MOND:
External Field Effect
(Bekenstein & Milgrom 1984, ApJ)

External field effect (EFE): implications for the RAR



- For truly ***isolated*** galaxies:

  $a = \nu_0(g_{N,int}/a_0)g_{N,int}$

- For galaxies subjected to $e = g_{N,ext}/a_0$:

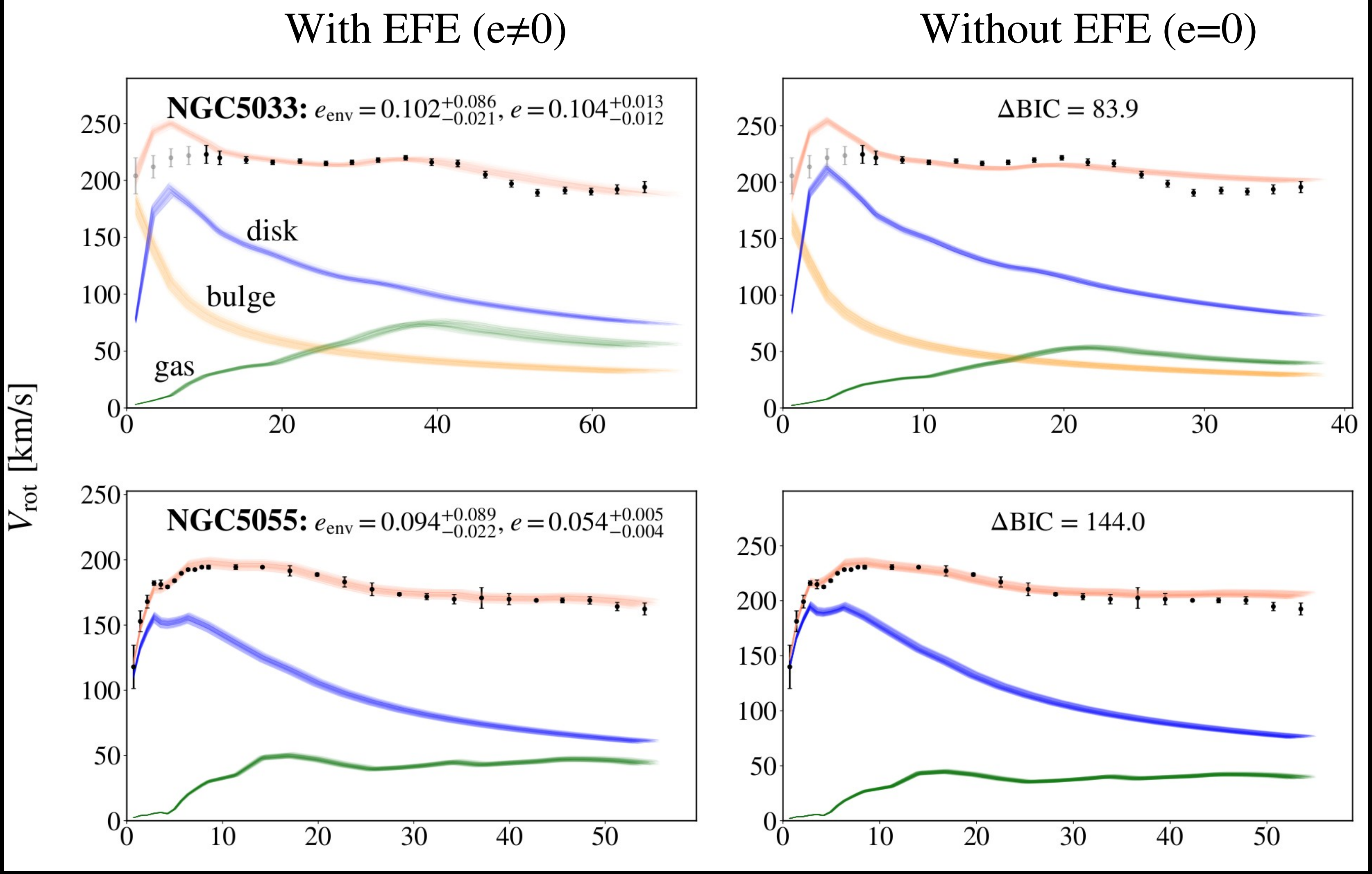
  $a = \nu_e(g_{N,int}/a_0; e)g_{N,int}$

- RAR should be a ***family of curves*** depending on the galaxy environment
- We can fit RCs to infer the value of e and independently estimate e_{env} from the galaxy large-scale environment.

Chae, Lelli, Desmond et al. (2020)

EFE is weak: individual detections only in extreme cases

NGC 5055

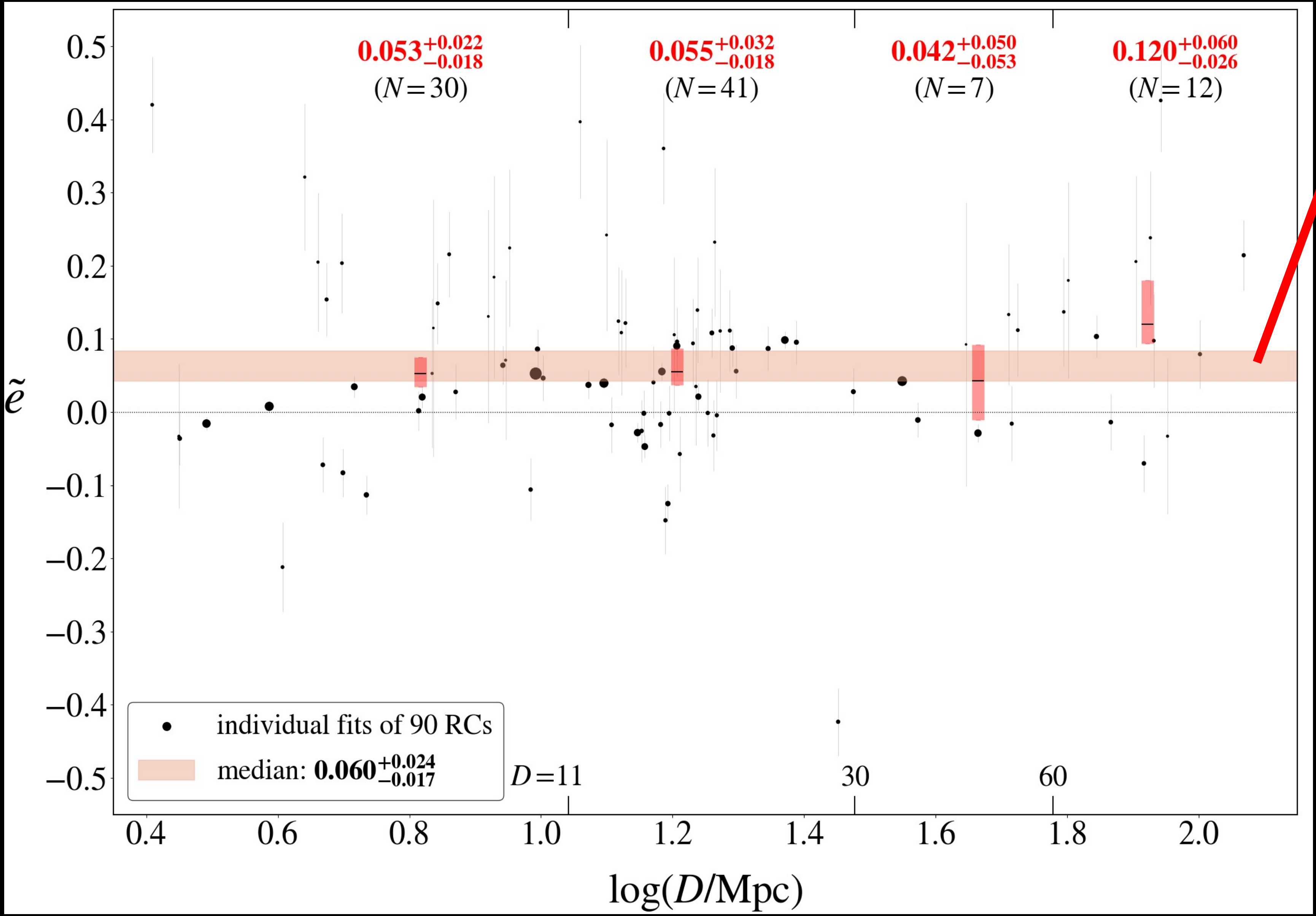


NGC 5033

Chae+2020, 2021

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

$$\frac{g_{ext}}{a_0} \leftarrow \tilde{e}$$

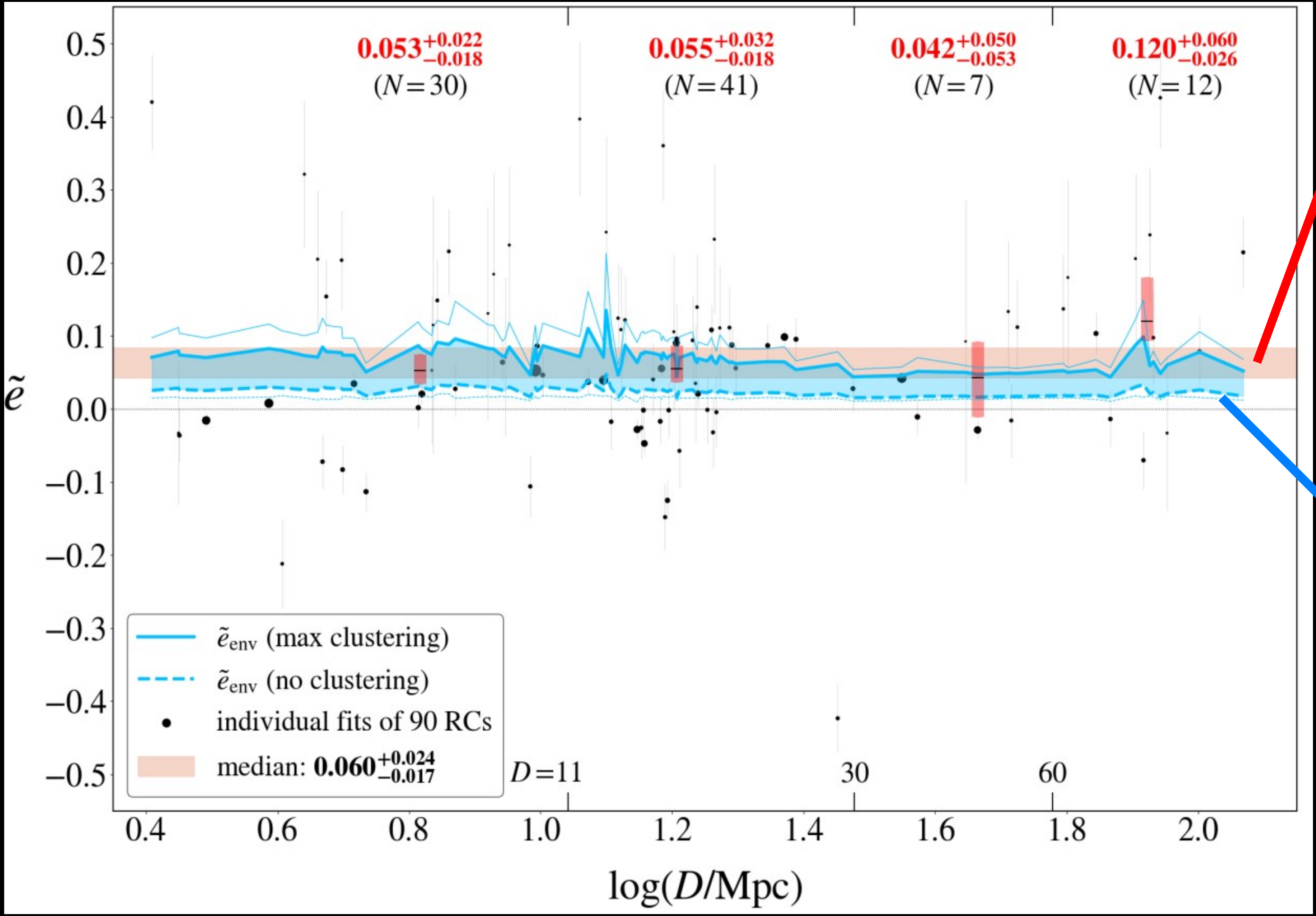


From Rotation Curve Fits

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

MOND External Field effect (EFE)

MOND is non-linear → both internal ($g_{N,int}$) and external ($g_{N,ext}$) fields

For non-isolated systems, three possibilities:

(1) $g_{N,ext} \ll g_{N,int} \ll a_0$

→ MOND regime (e.g. nearly isolated galaxies)

(2) $g_{N,int} \ll a_0 \ll g_{N,ext}$

→ Newtonian regime (e.g. star clusters in the inner MW)

(3) $g_{N,int} \ll g_{N,ext} \ll a_0$

→ Newton with $G_{eff} \sim G\, a_0/g_{N,ext}$ (e.g. some satellites of MW)

EFE is a general MOND prediction but details depend on the specific theory

Relativistic Theories: Lovelock-Grigore Theorem

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

1- Geometry is Reimannian

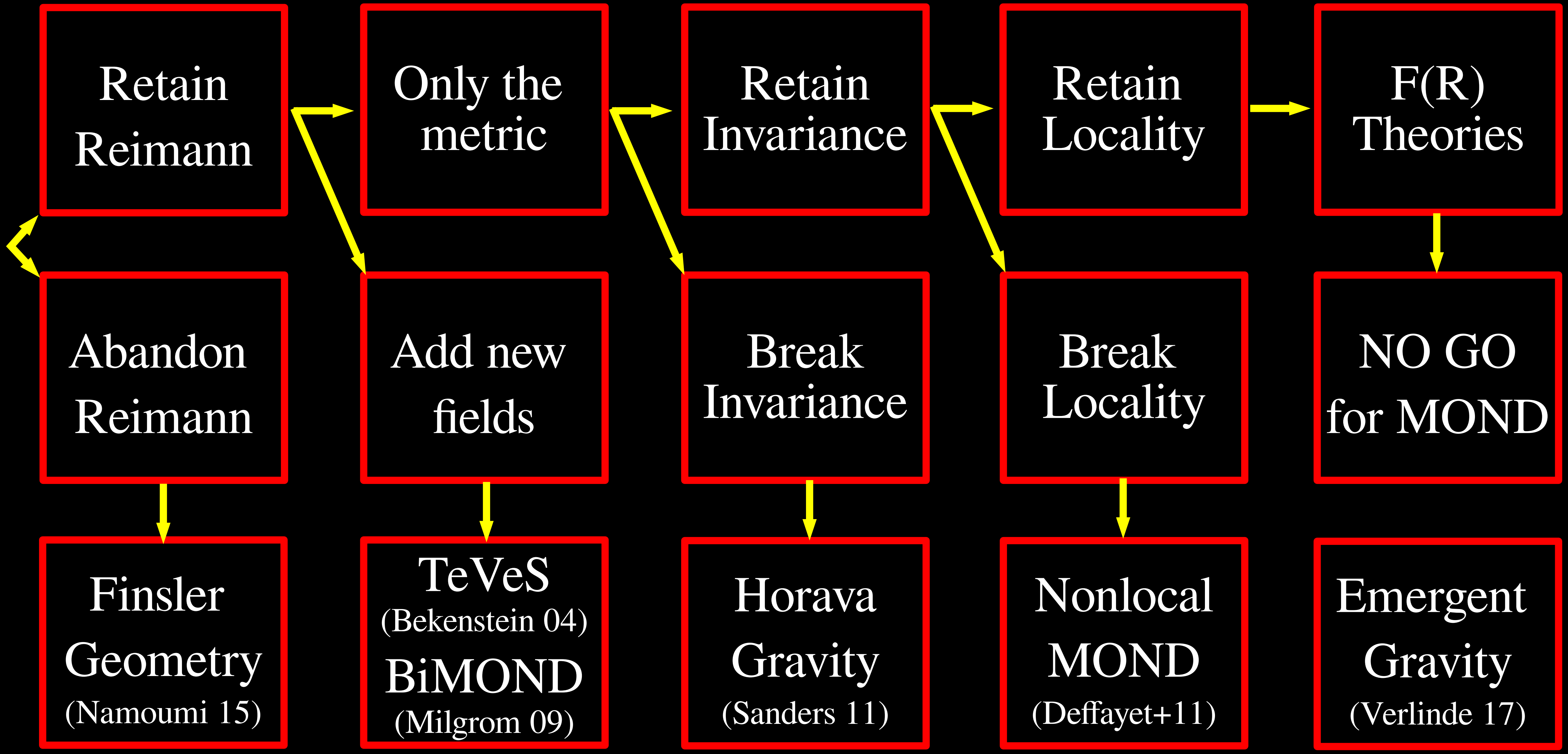
2- The Action depends only on $g_{\mu\upsilon}$

3- It is diffeomorphism invariant

4- It is local

5- It leads to 2nd order field equations

Paths towards a relativistic version of MOND



Intuitive Cartoon: Scale Invariance = Flat Rotation Curves