Small-Scale ΛCDM Problems

Federico Lelli (Arcetri Astrophysical Observatory)

Download Slides at *www.lellifederico.com/students*

Largely based on the following review papers:

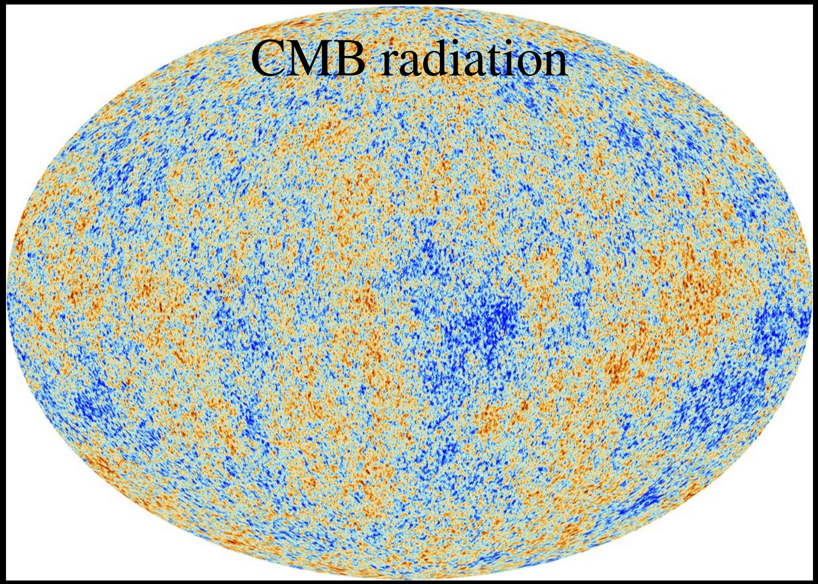
Bullock & Boylan-Kolchin (2017), ARA&A
McGaugh, Lelli, Li, Schombert (2020), IAU Symposium 353
Lelli (2022), Nature Astronomy
Lelli (2023), IAU Symposium 379

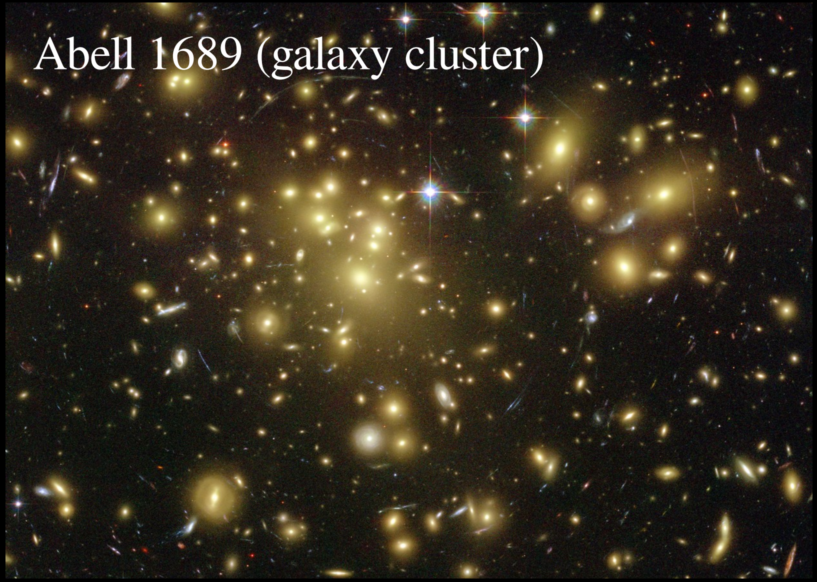
Testing ΛCDM at different astronomical scales

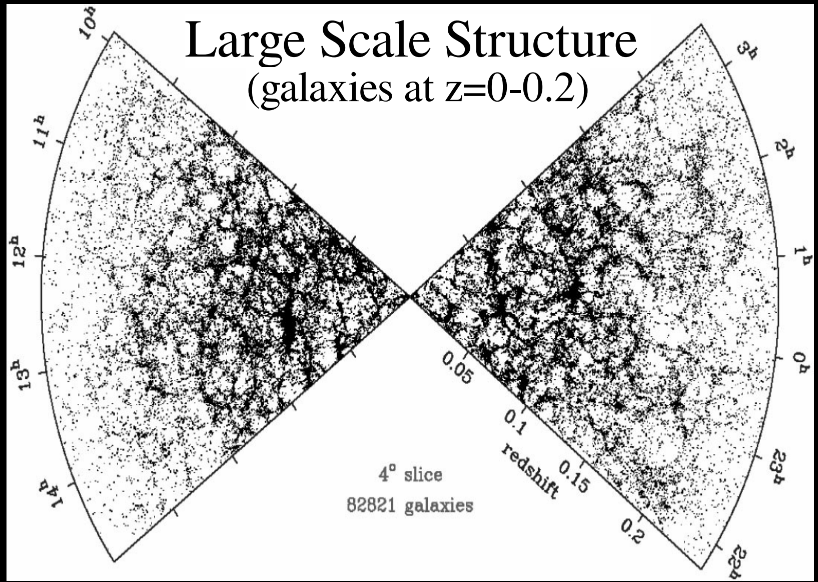
Galaxy Scales (~1-100 kpc)

Group/Cluster Scales (~1-5 Mpc)

Cosmological Scales (>100 Mpc)







Small-Scale ΛCDM Problems

1. Missing Satellites
2. Cusp vs Core
3. Too-Big-To-Fail
4. Planes of Satellites
5. Dynamical Regularities

Small-Scale ΛCDM Problems

1. Missing Satellites
2. Cusp vs Core
3. Too-Big-To-Fail

"Classical" problems (~25 years old)

4. Planes of Satellites
5. Dynamical Regularities

"New" problems (~10 years old)

Why are these problems interesting?

1. Baryonic physics inside CDM halos?

Gas cooling, star formation, stellar feedback, etc.

Why are these problems interesting?

1. Baryonic physics inside CDM halos?
   Gas cooling, star formation, stellar feedback, etc.

2. New physics in the dark sector?
   Self-interacting DM, fuzzy DM, superfluid DM, etc.

Why are these problems interesting?

1. Baryonic physics inside CDM halos?
   Gas cooling, star formation, stellar feedback, etc.

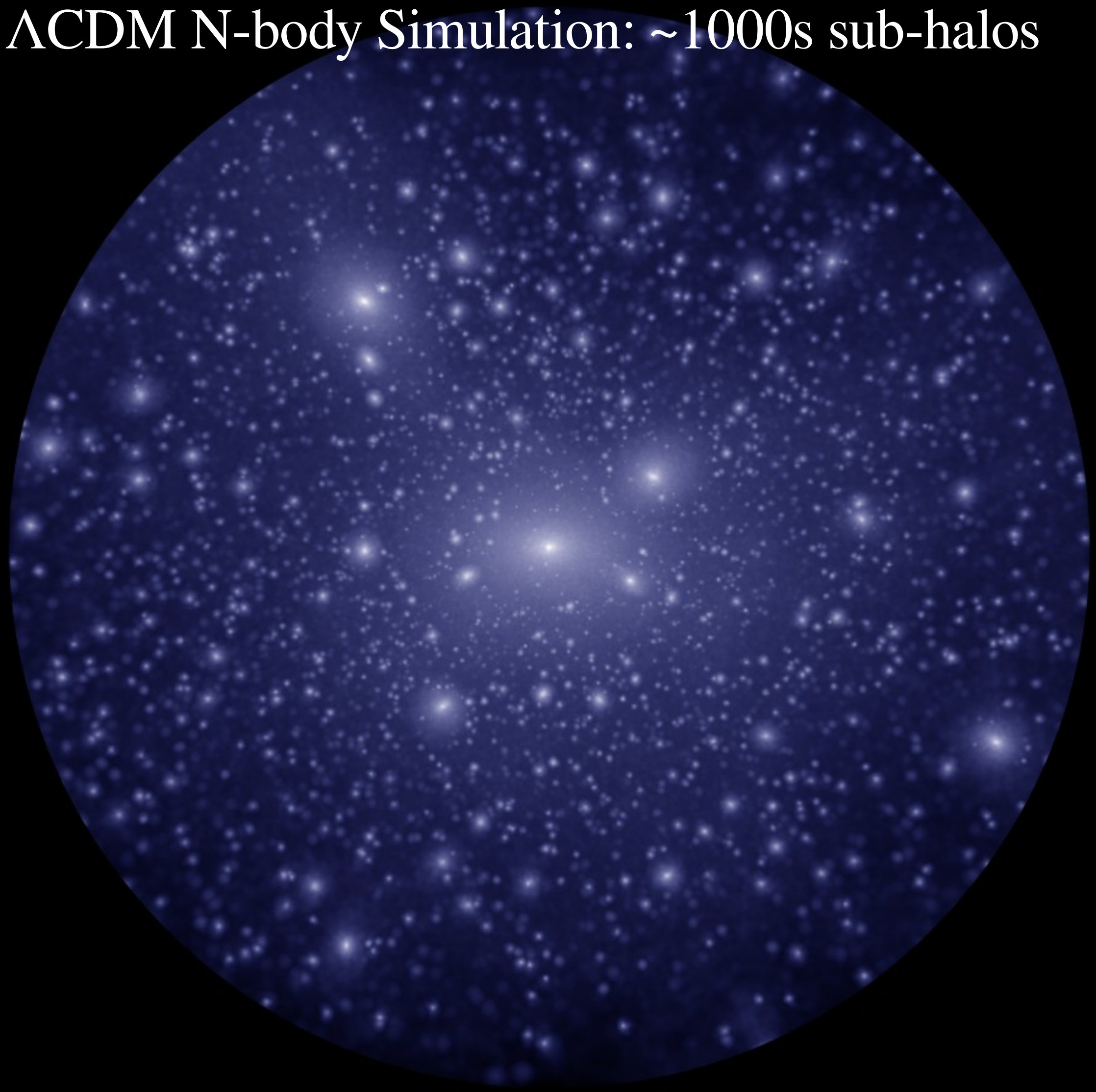
2. New physics in the dark sector?
   Self-interacting DM, fuzzy DM, superfluid DM, etc.

3. New dynamical laws rather than DM?
   Milgromian dynamics (MOND), modified gravity, etc.

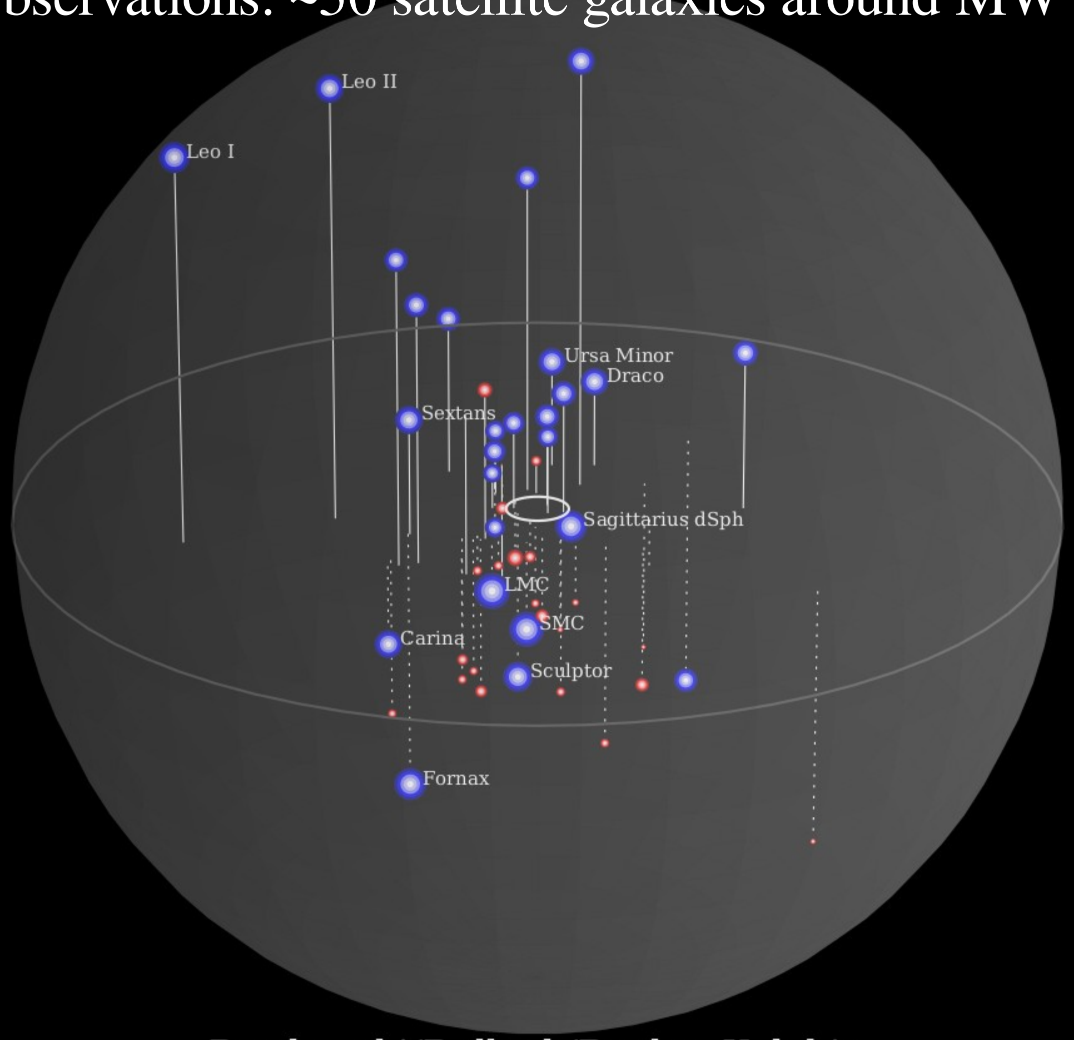
1. Missing Satellites Problem (Mass Function Problem)

The Missing Satellites Problem

ΛCDM N-body Simulation: ~1000s sub-halos

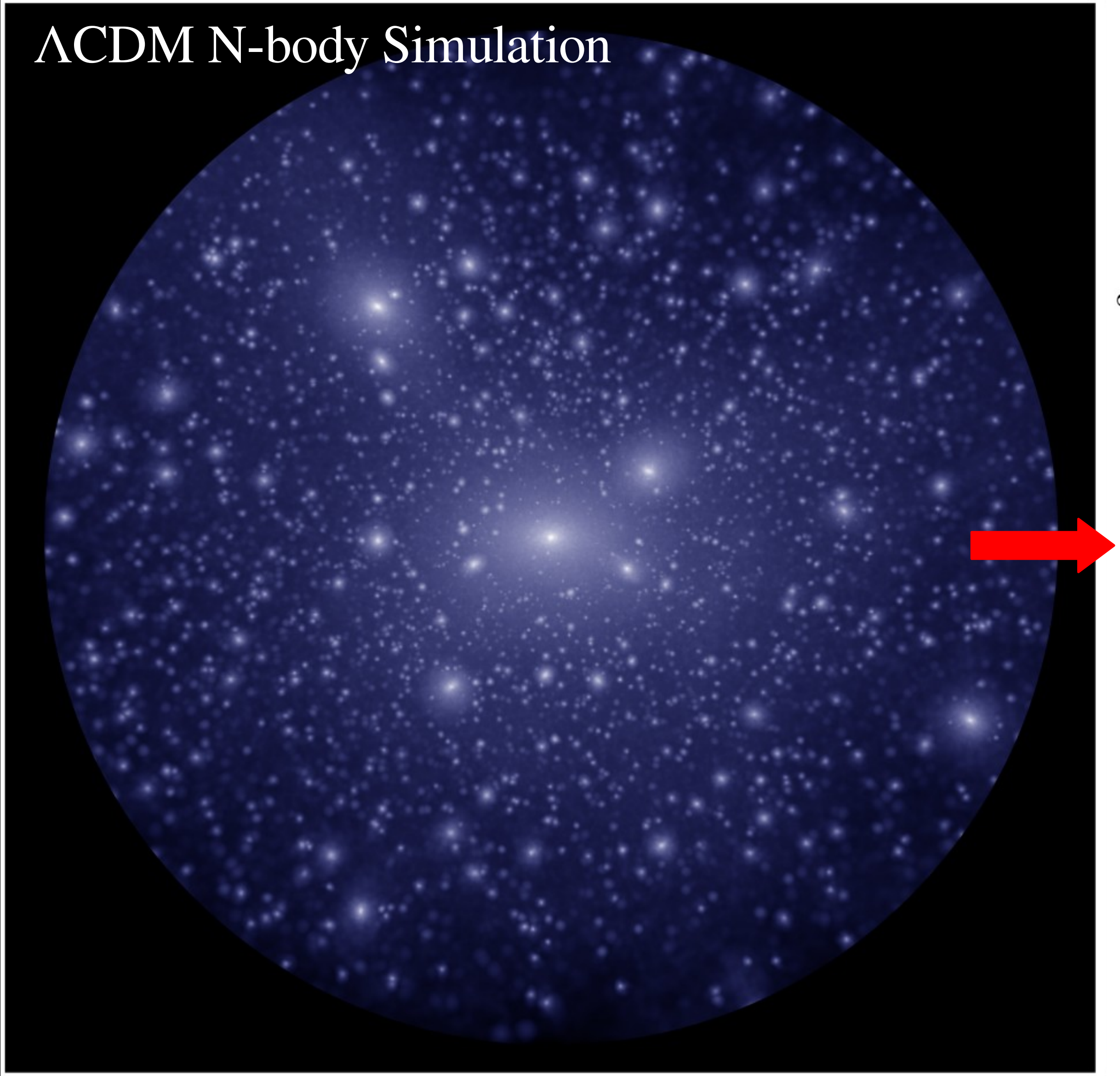


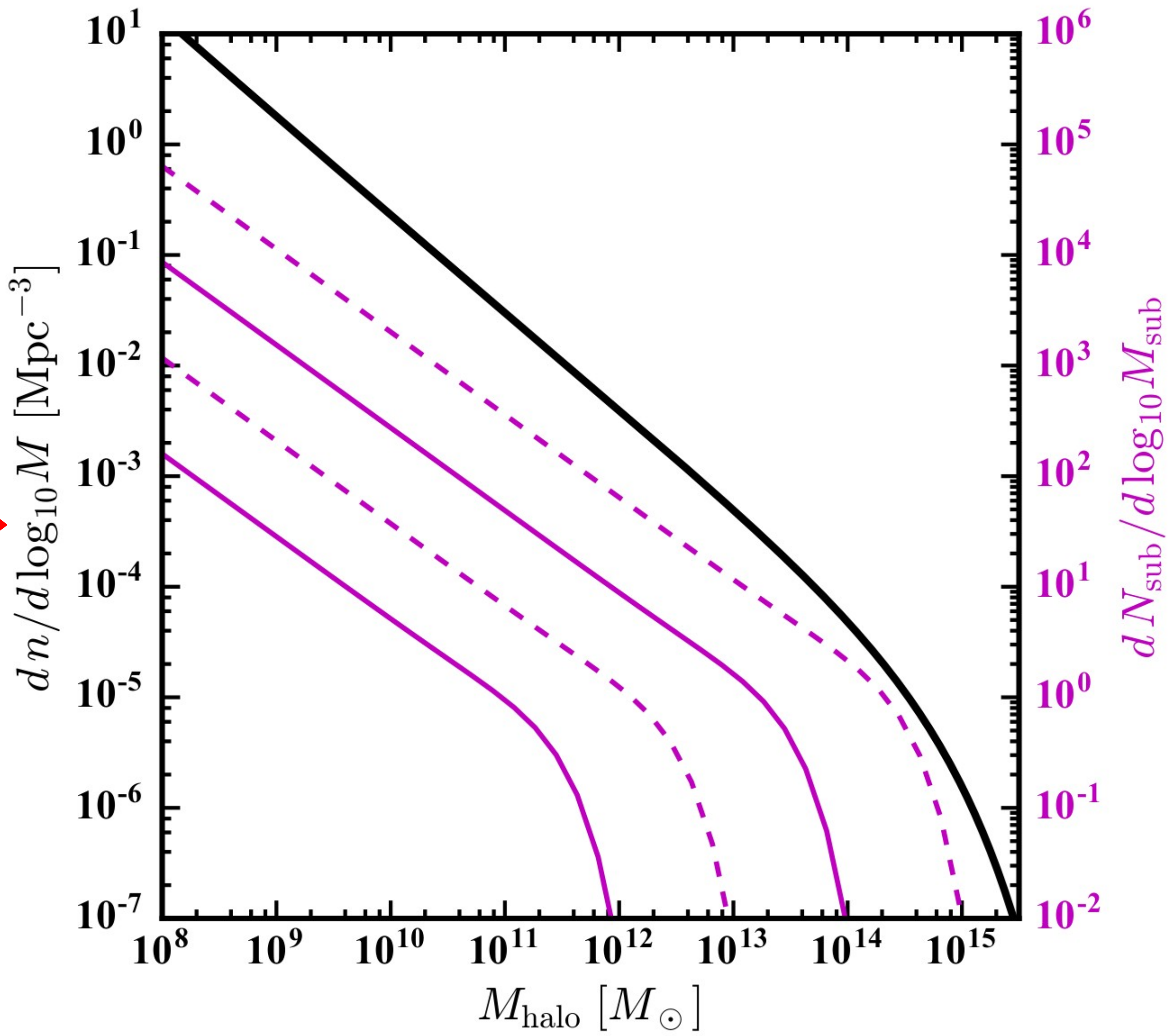
Observations: ~50 satellite galaxies around MW



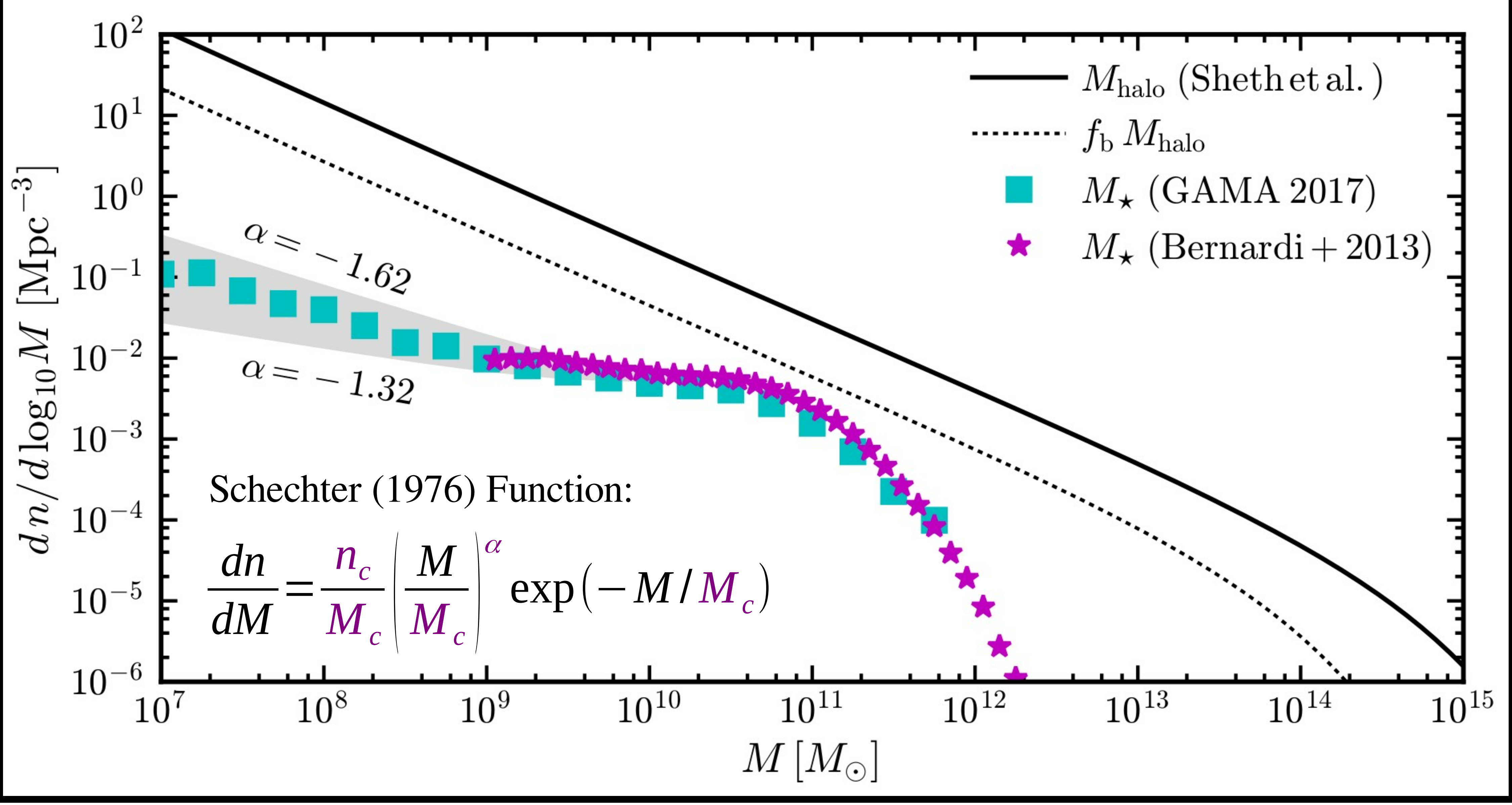
Pawlowski/Bullock/Boylan-Kolchin

The Halo Mass Function

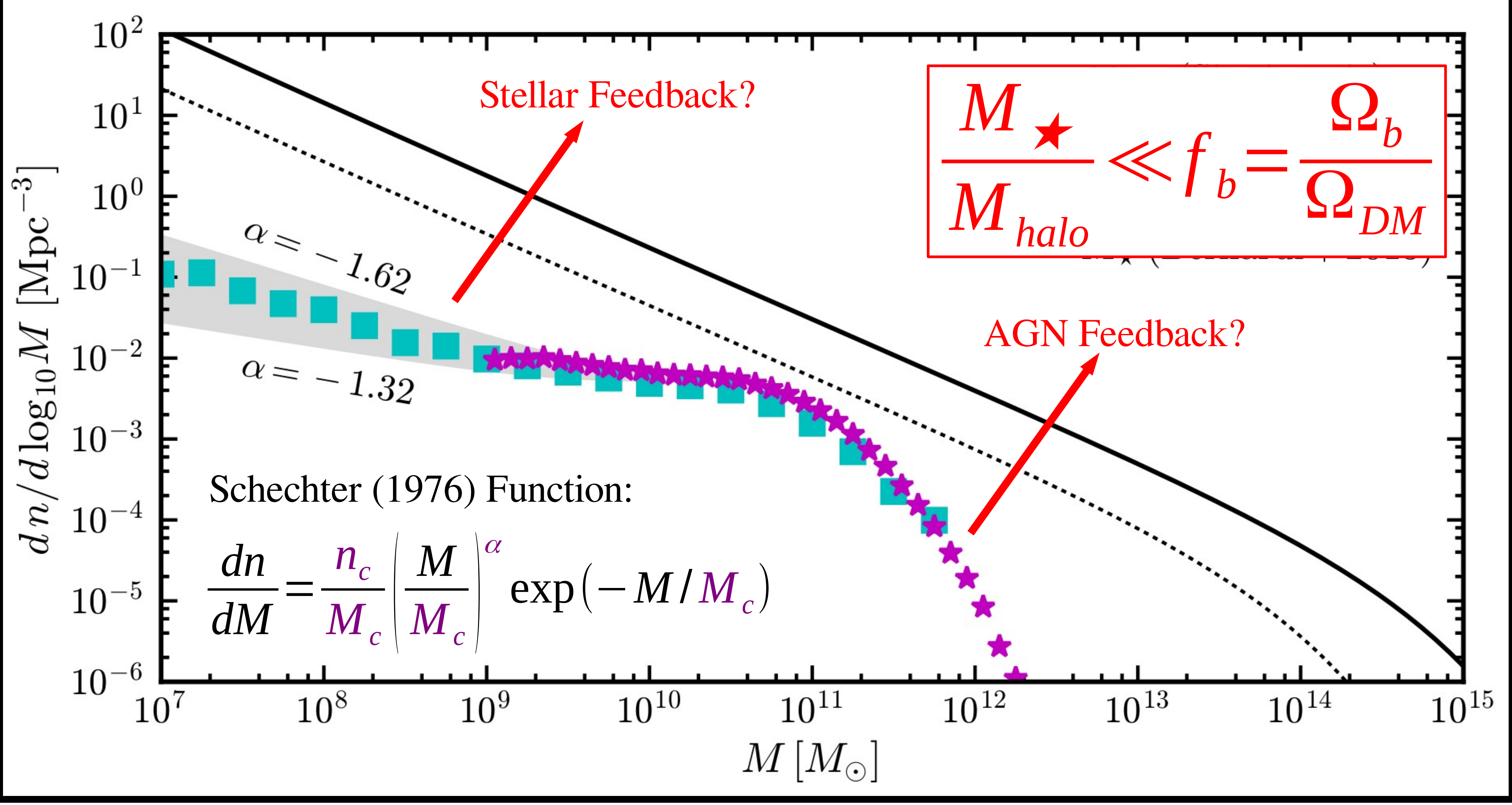




Stellar versus Halo Mass Function

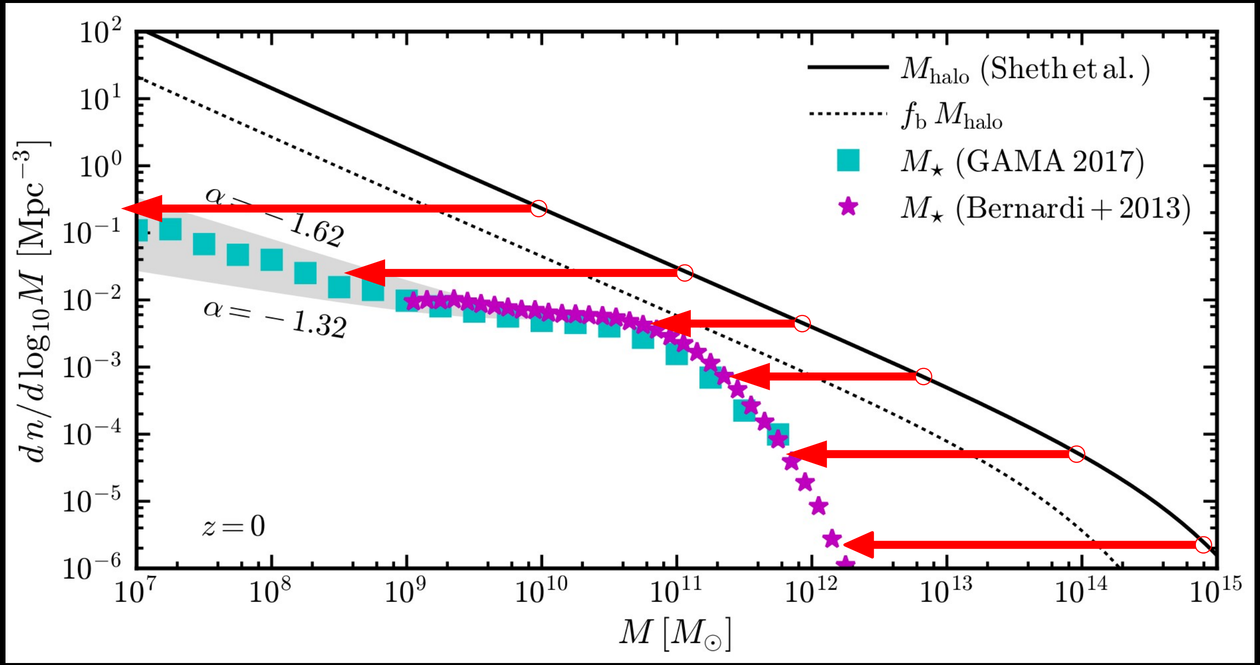


Stellar versus Halo Mass Function



The Stellar Mass – Halo Mass Relation

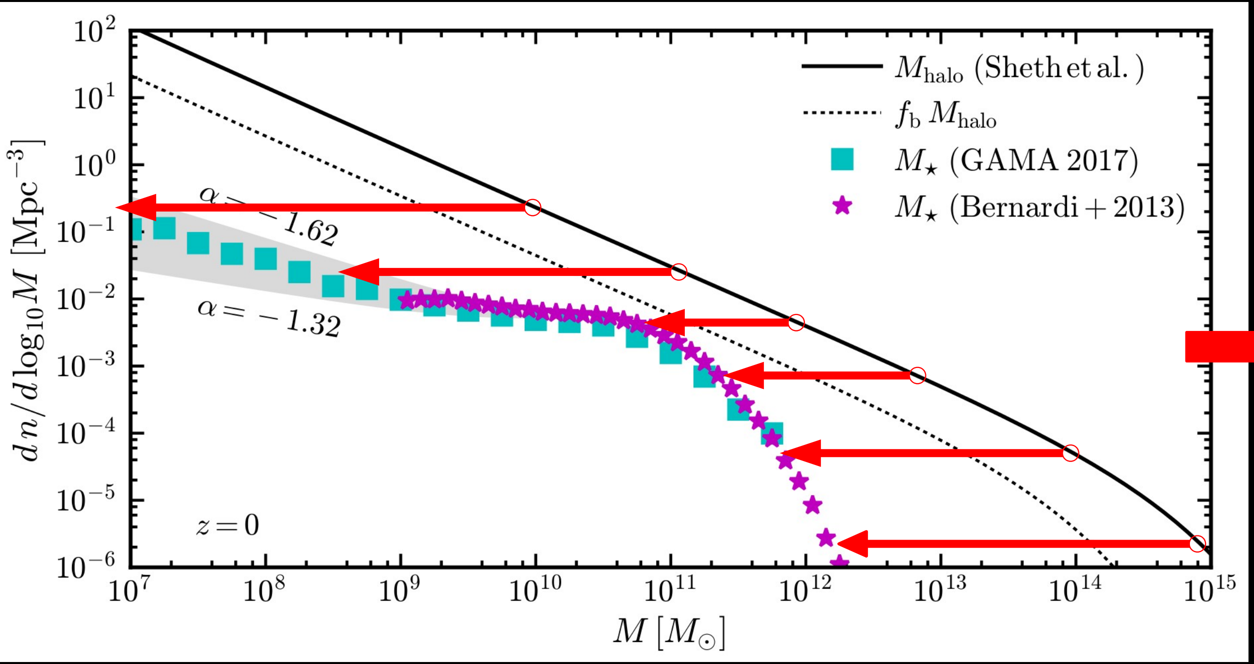
Abundance Matching: “brute-force” method that require no knowledge of baryonic physics

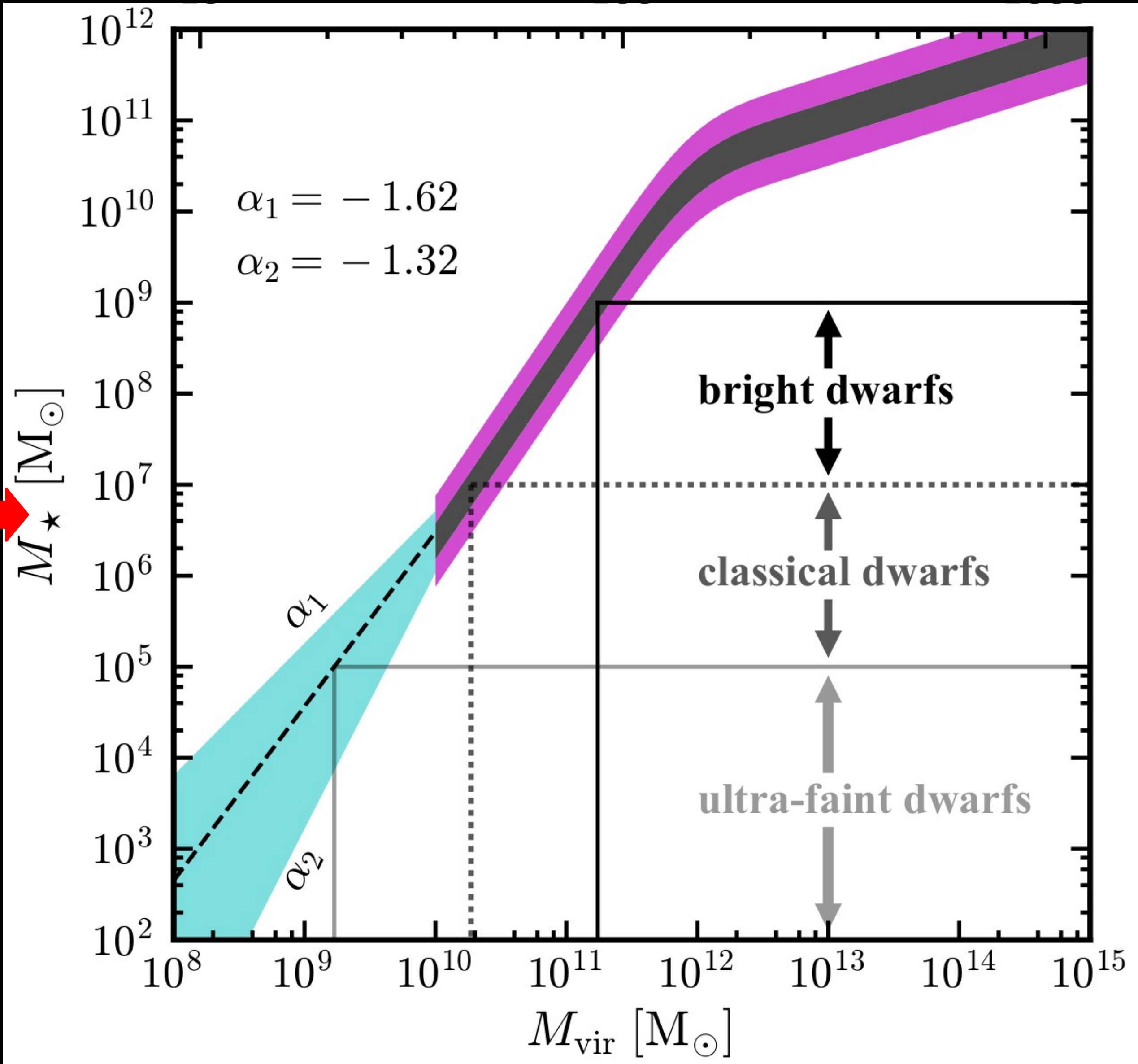


Given a volume of the Universe (say 1 Gpc^3), assign the most massive halo (in a simulation) to the most massive galaxy (in a survey).

The Stellar Mass – Halo Mass Relation

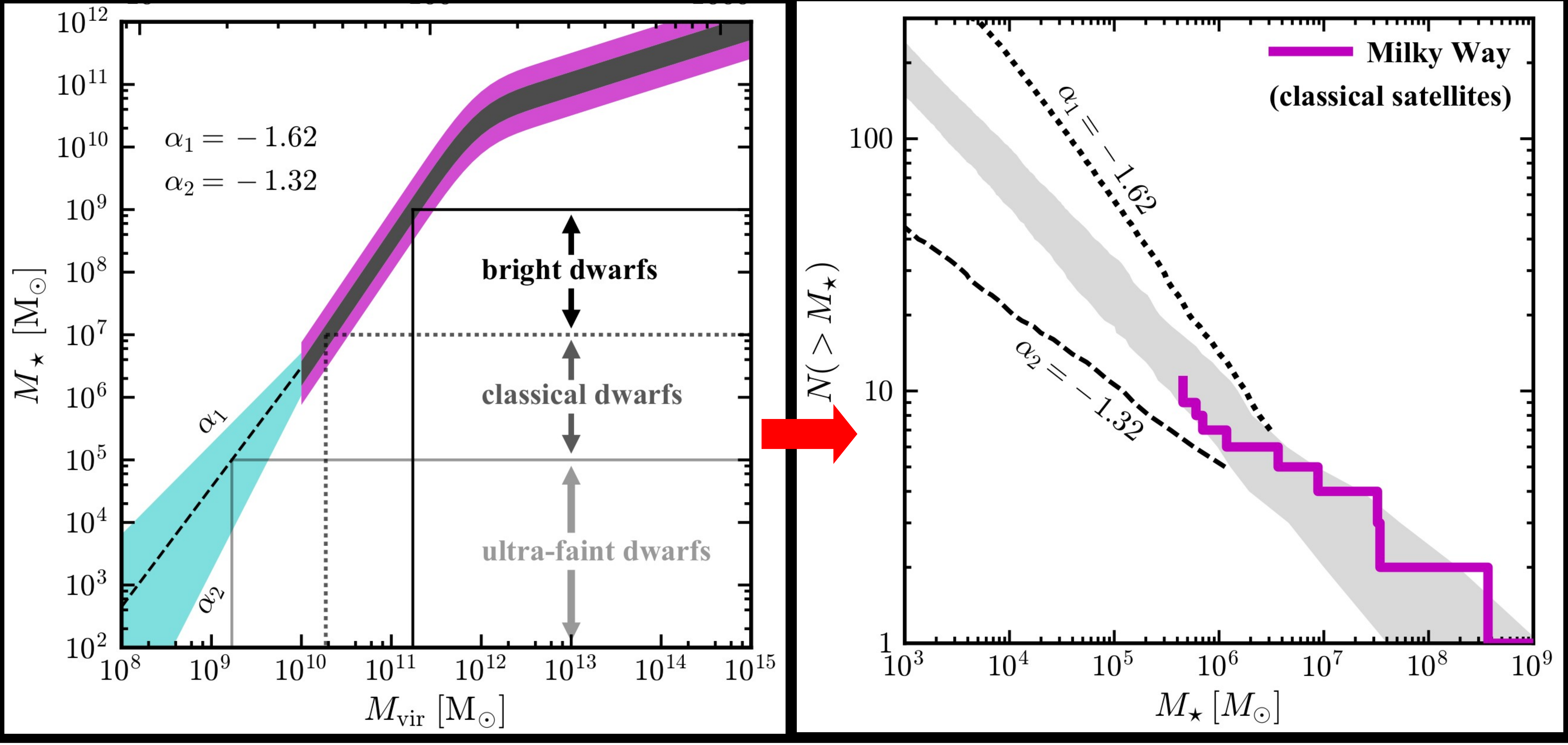
Abundance Matching: “brute-force” method that require no knowledge of baryonic physics





Given a volume of the Universe (say 1 Gpc^3), assign the most massive halo (in a simulation) to the most massive galaxy (in a survey).

Abundance Matching ↔ Missing Satellites



Possible Solutions to the Missing Satellite (Mass Function) Problem

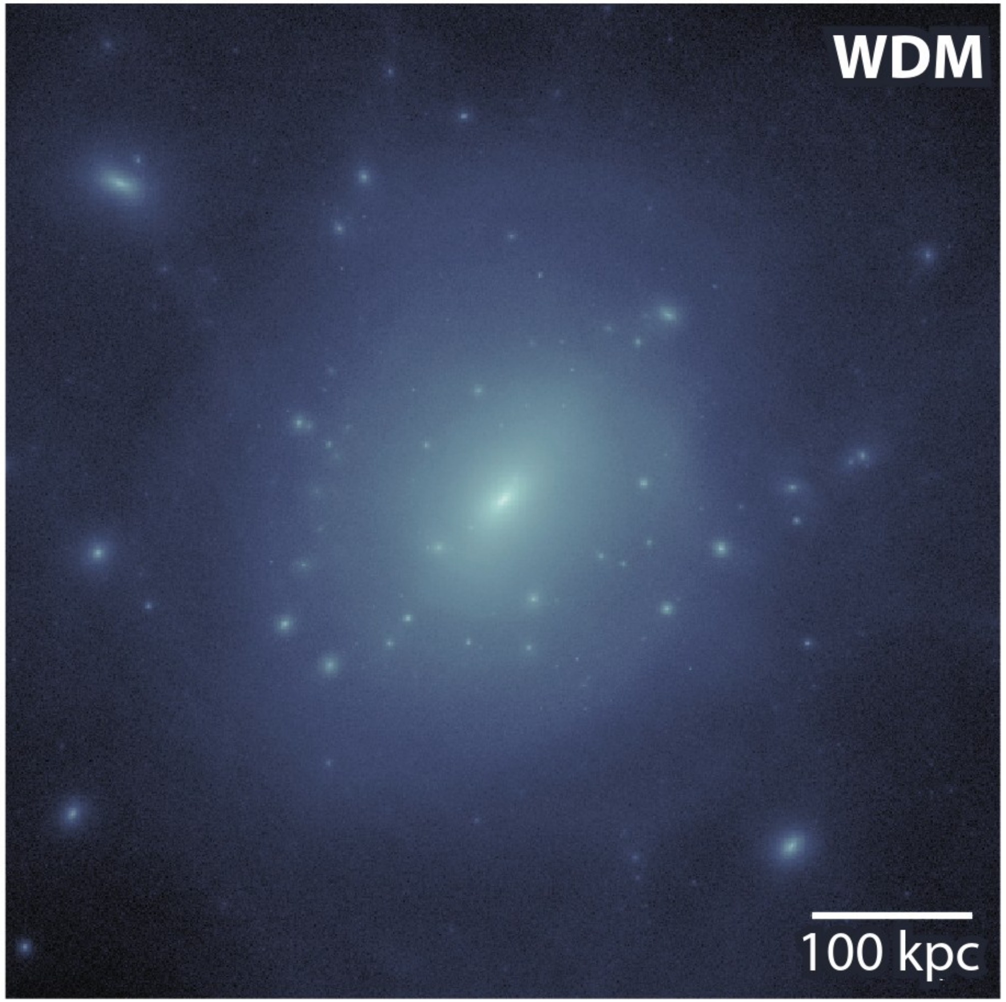
1. Baryonic physics: stellar & AGN feedback somehow reduce the amount of collapsed baryons (stars & cold gas) in galaxies → most baryons are in a hot "invisible" form (missing baryons)

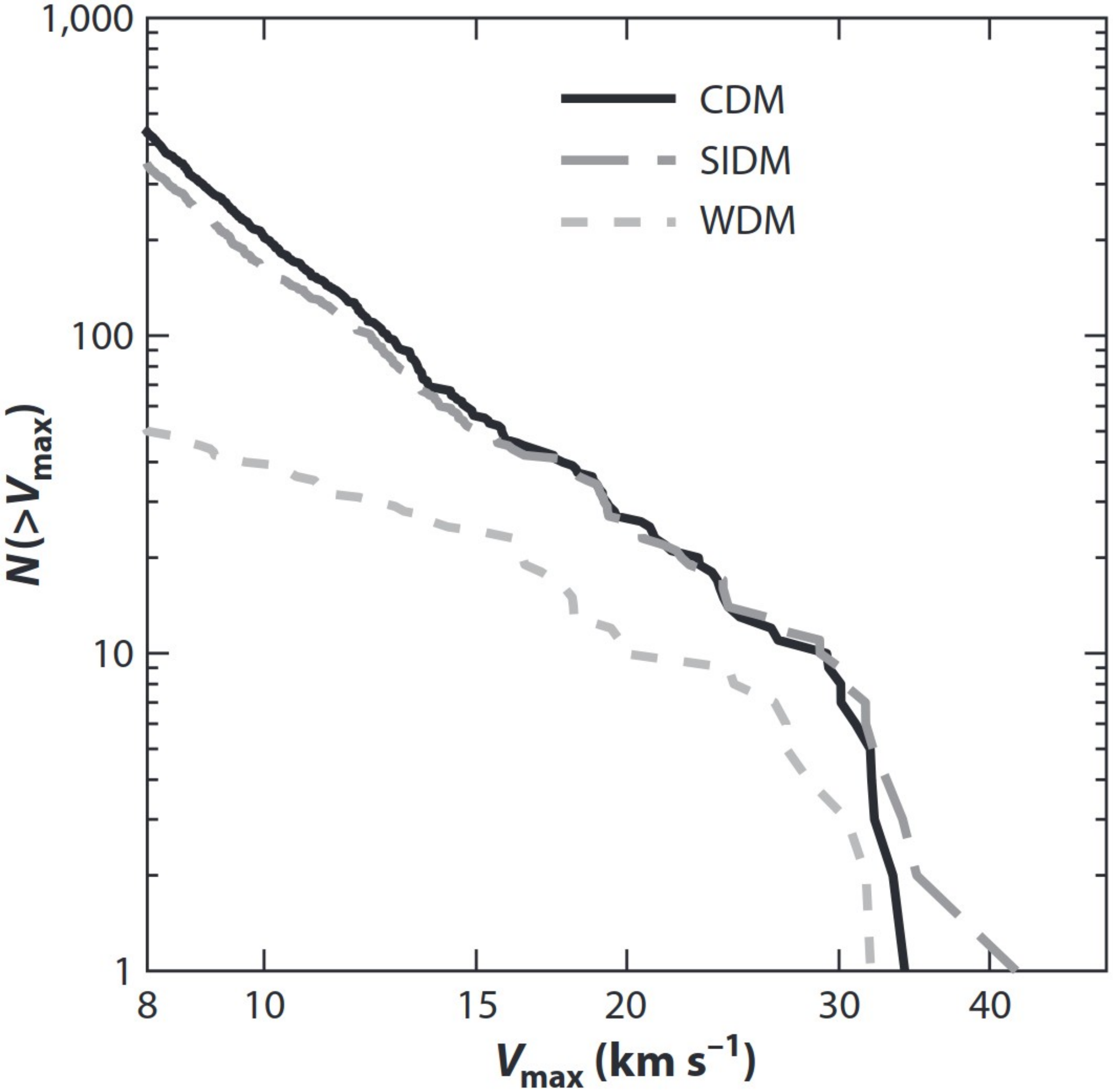
Possible Solutions to the Missing Satellite (Mass Function) Problem

1. Baryonic physics: stellar & AGN feedback somehow reduce the amount of collapsed baryons (stars & cold gas) in galaxies → most baryons are in a hot "invisible" form (missing baryons)

2. Warm Dark Matter (WDM): reduce power on small scales → reduce number of predicted low-mass DM halos

Smaller number of sub-halos in WDM





From Bullock & Boylan-Kolchin (2017)

Possible Solutions to the Missing Satellite (Mass Function) Problem

1. Baryonic physics: stellar & AGN feedback somehow reduce the amount of collapsed baryons (stars & cold gas) in galaxies → most baryons are in a hot "invisible" form (missing baryons)

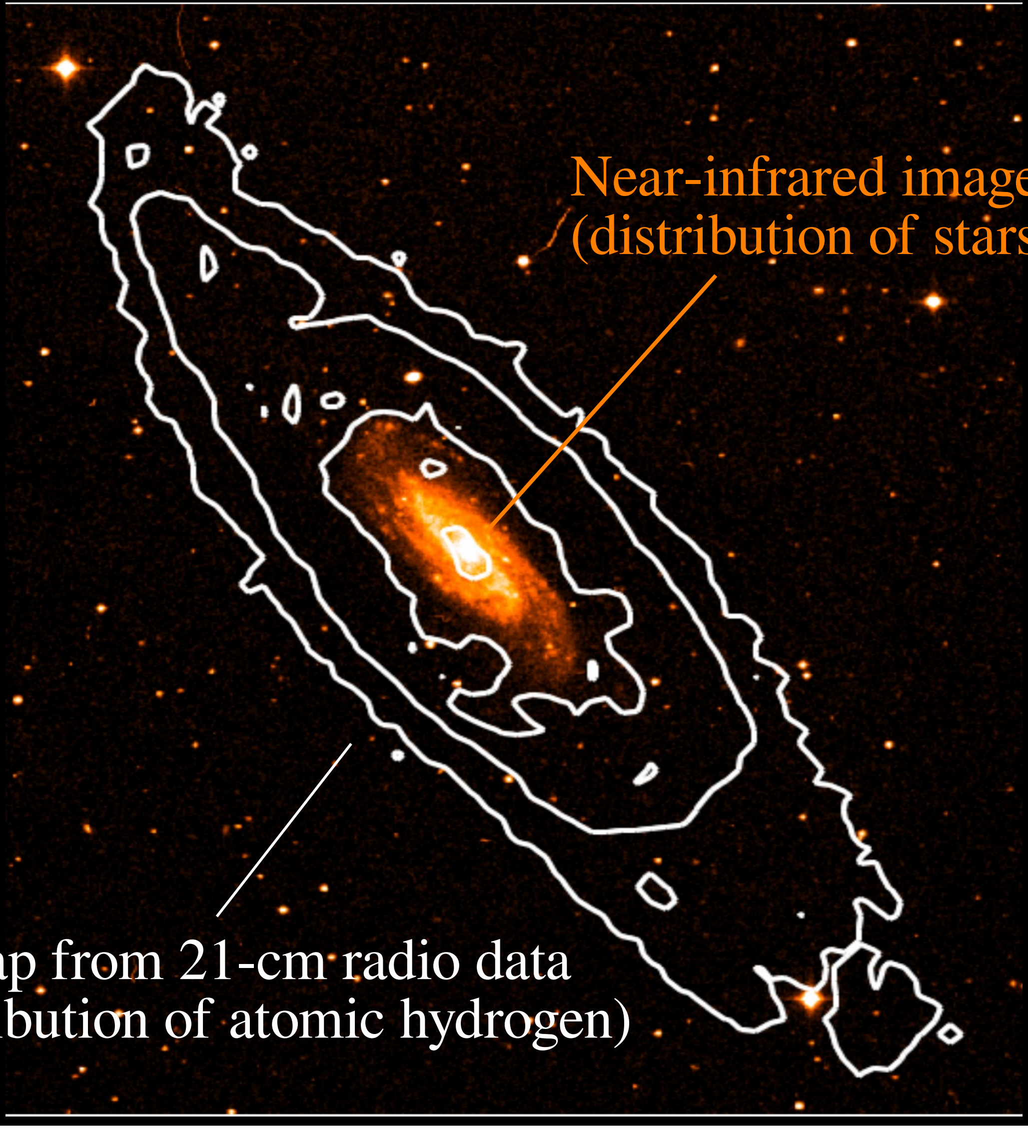
2. Warm Dark Matter (WDM): reduce power on small scales → reduce number of predicted low-mass DM halos

3. Modified gravity: need to re-assess the whole problem of galaxy formation and derive the stellar mass function (not done yet!)

2. Cusp vs Core Problem (Rotation Curves Problem)

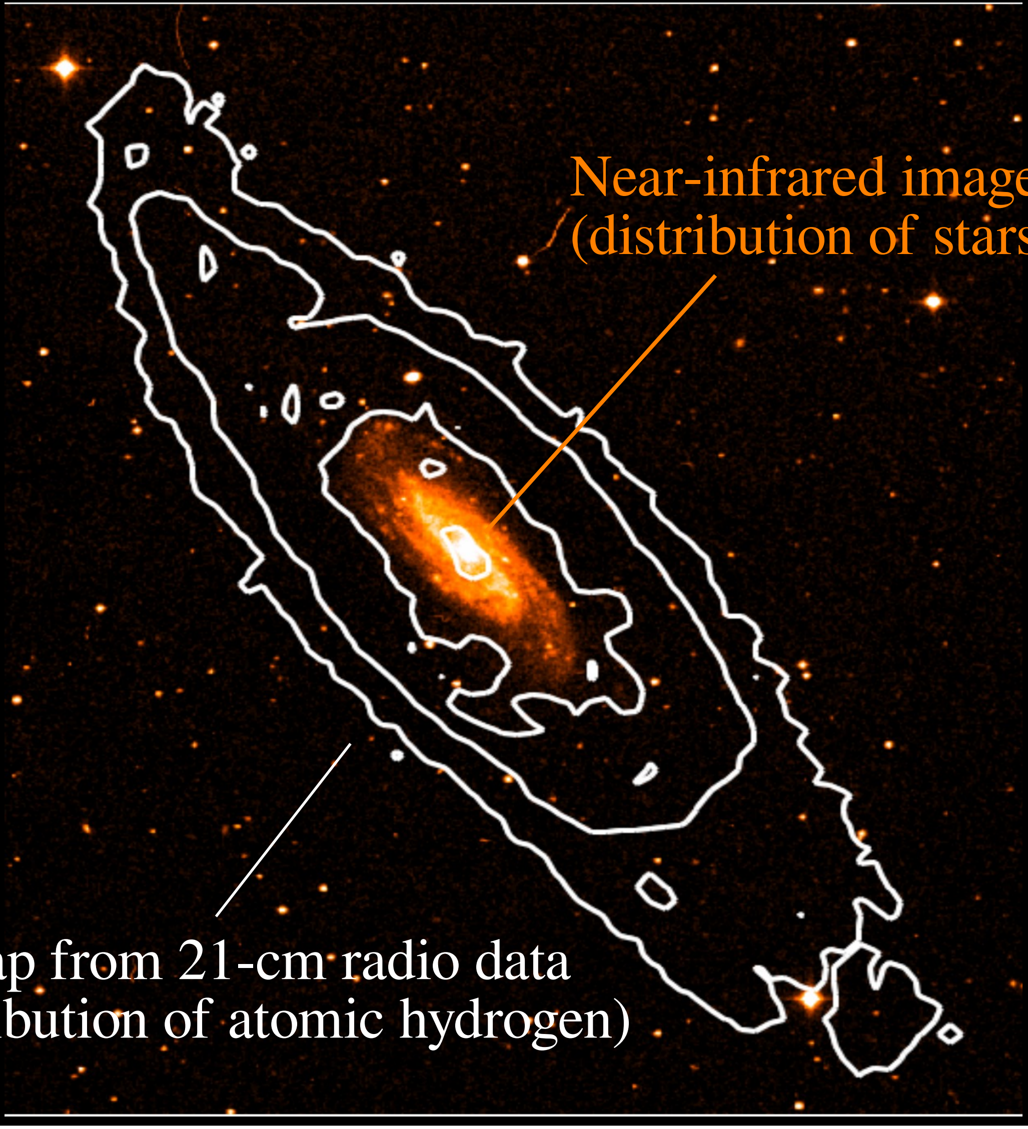
Rotation Curves of Disk Galaxies

Distribution of baryons (gas & stars)

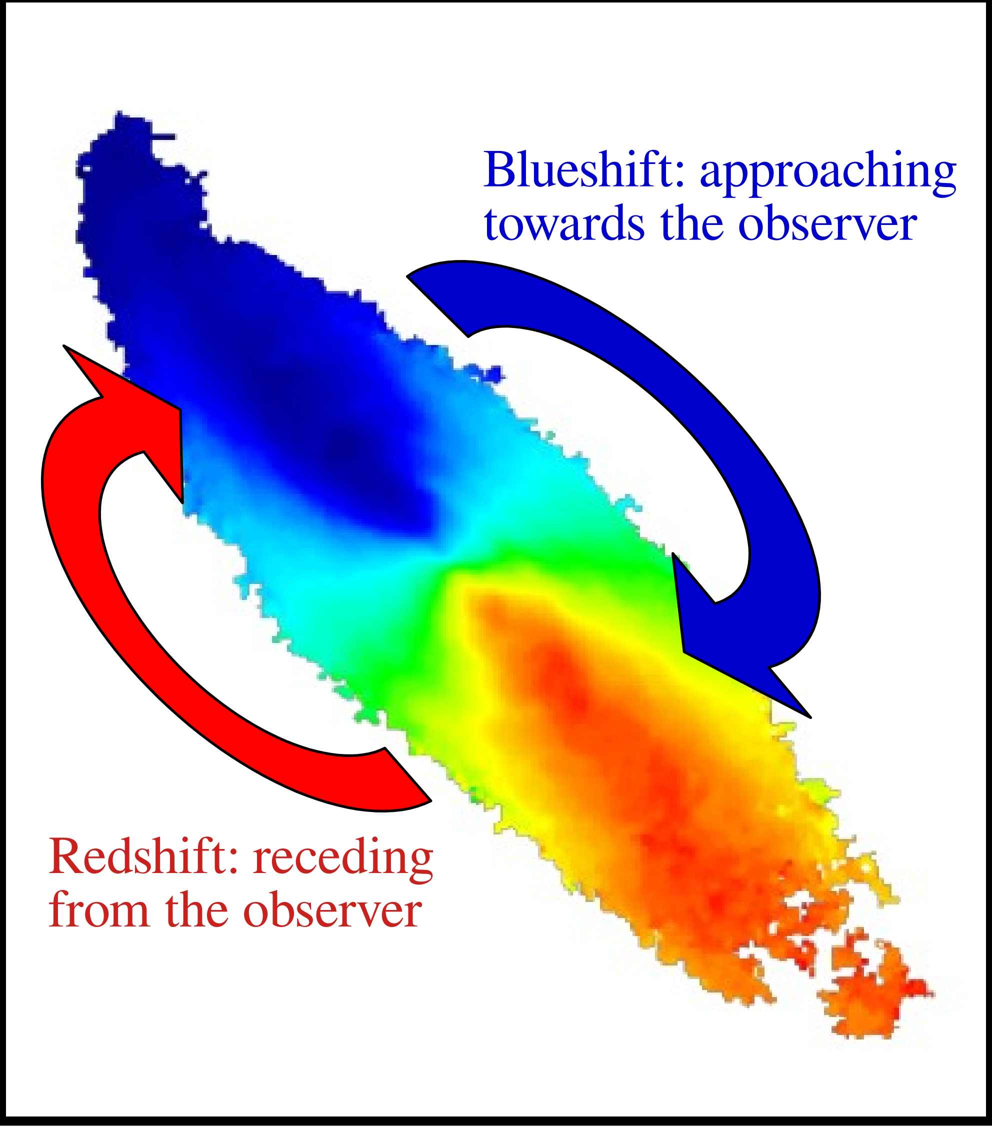


Rotation Curves of Disk Galaxies

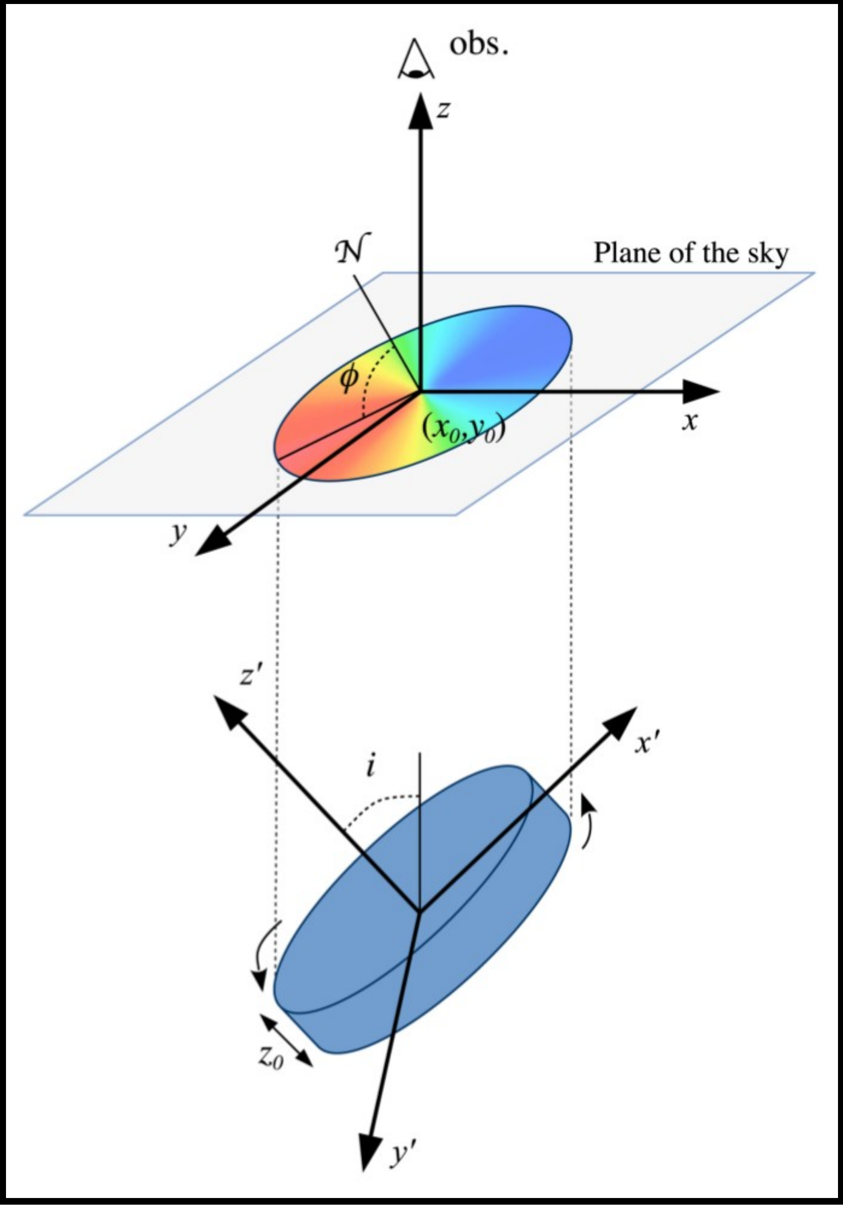
Distribution of baryons (gas & stars)



Velocity along the Line of Sight (LoS)



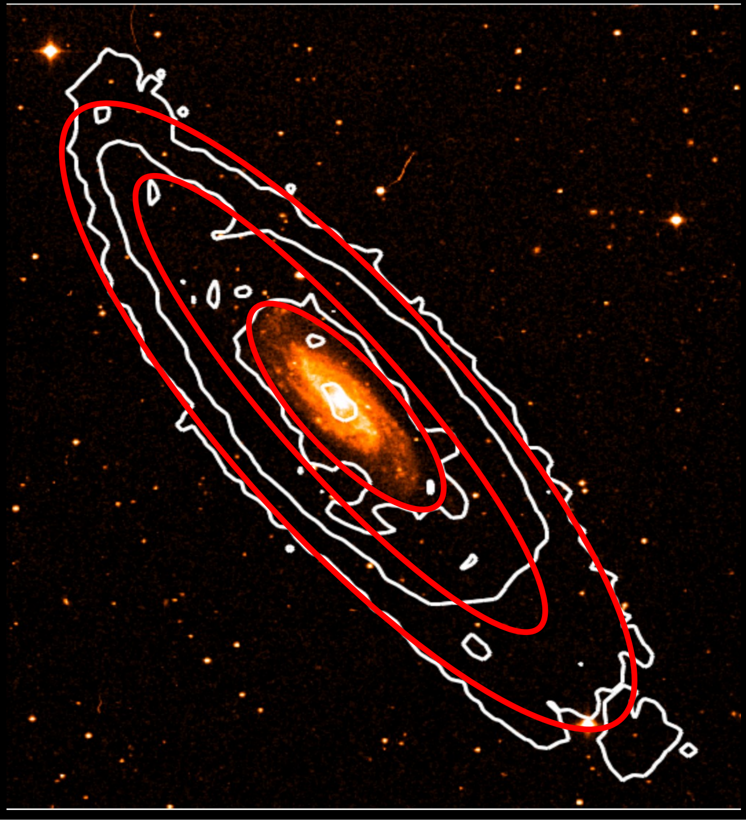
Deprojection from sky-plane to galaxy-plane

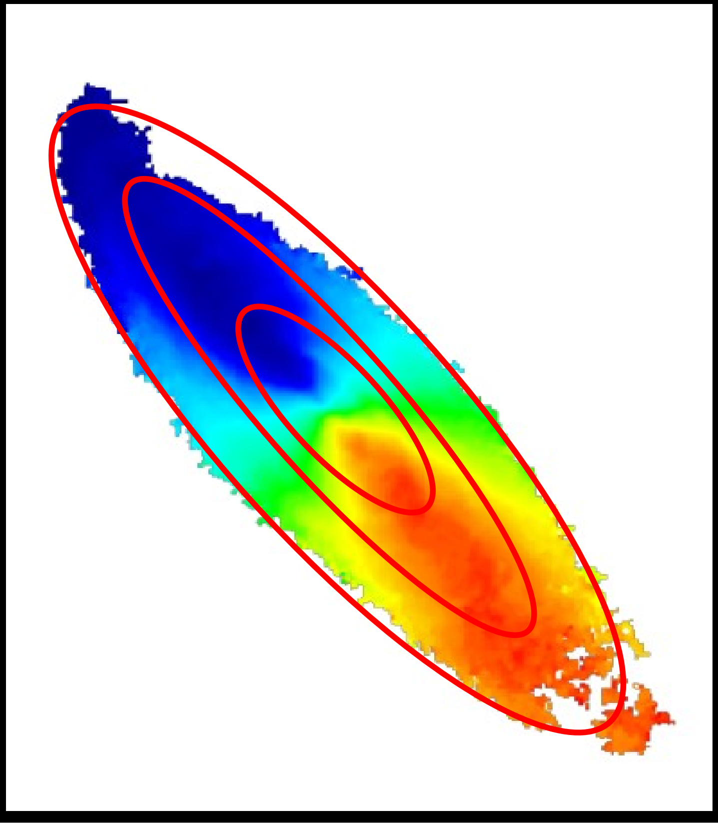


For a thin disk ($V_{rot} \gg \sigma_V$) projected on the sky:

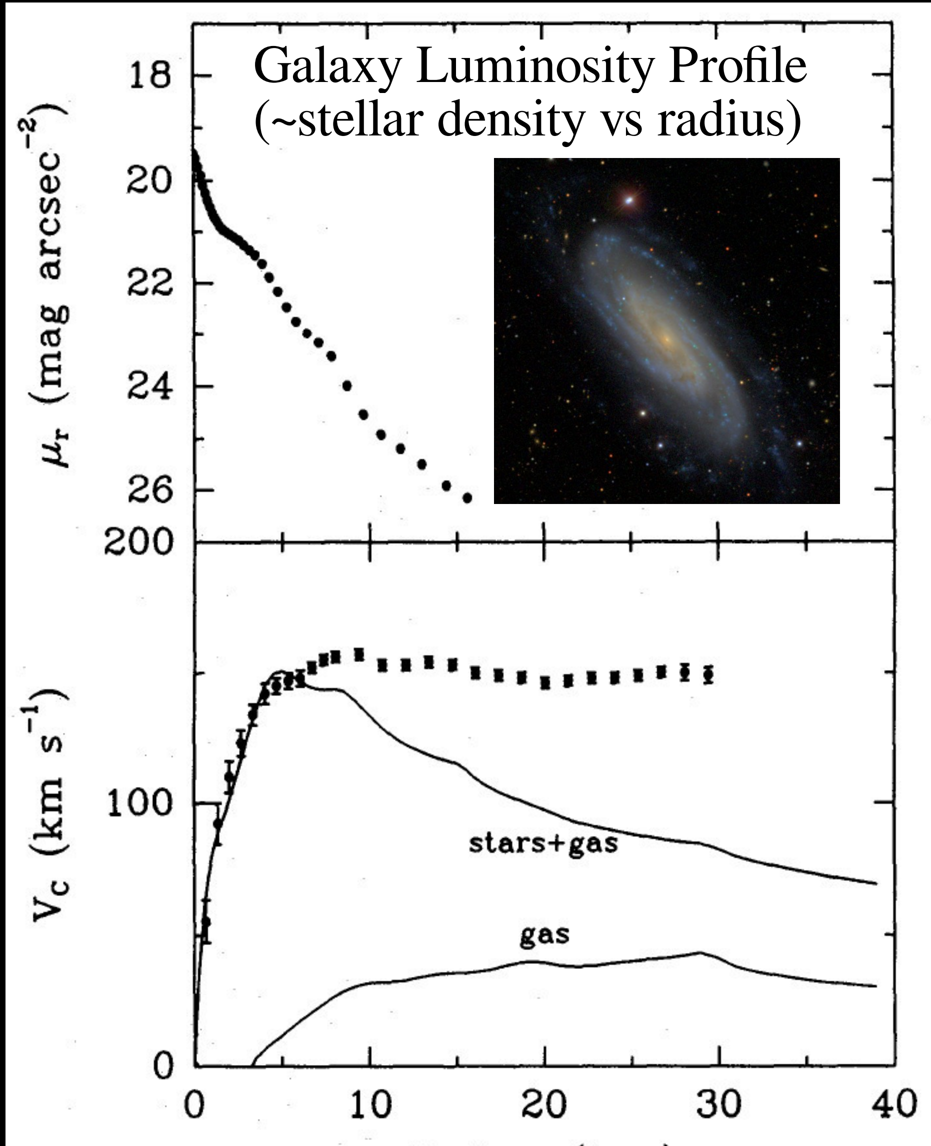
$$V_{LoS}(x,y) = V_{sys} + V_{rot}(R)\sin(i)\cos(\theta)$$

$$\cos(\theta) = f(x_0, y_0, PA) \rightarrow \text{Disk Geometric Parameters}$$





Mass Models of Disk Galaxies

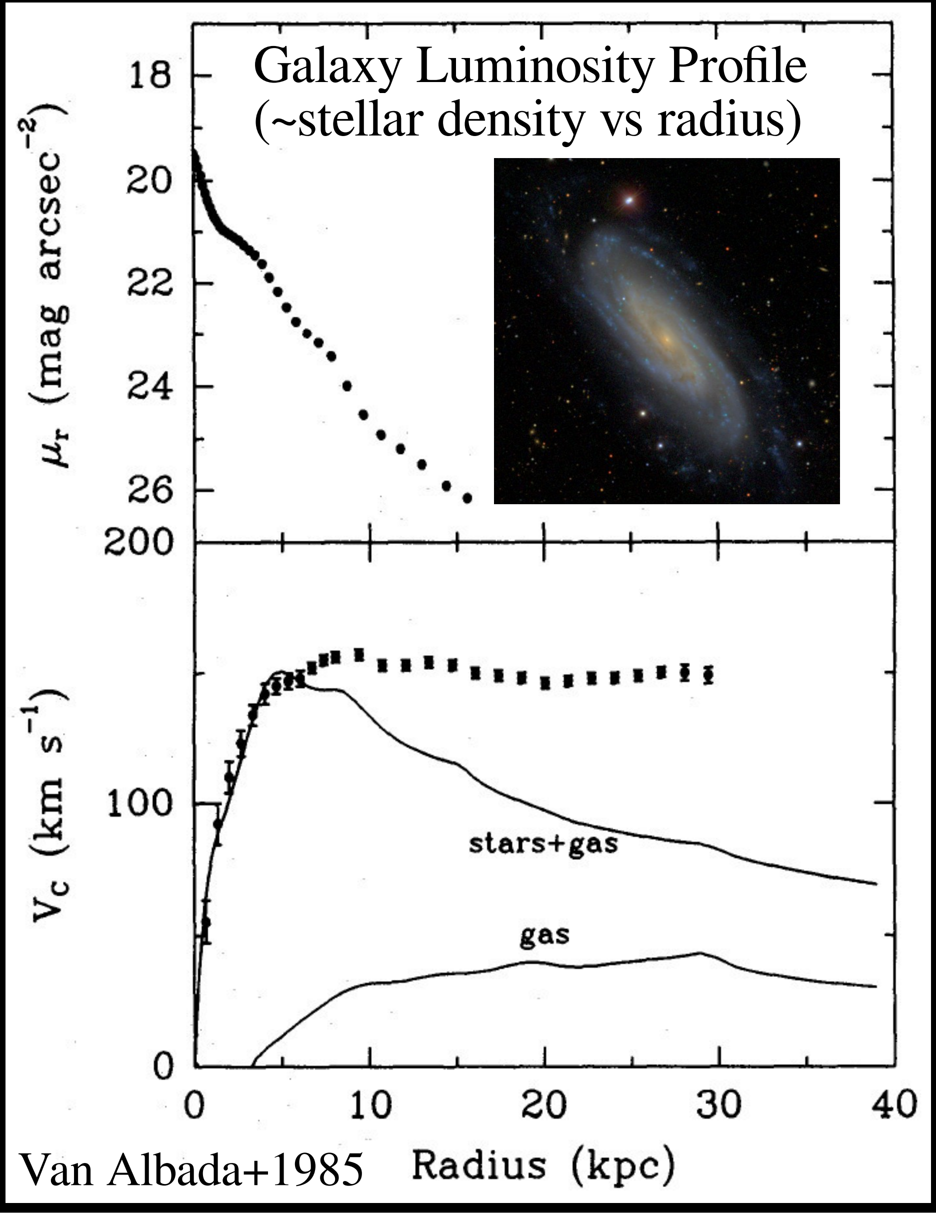


Van Albada+1985

- Solve (numerically) Poisson's equation in cylindrical coordinates for each component (i = stars or gas):

$$\nabla^2 \Phi_i(R, z) = 4\pi G \rho_i(R, z)$$

Mass Models of Disk Galaxies



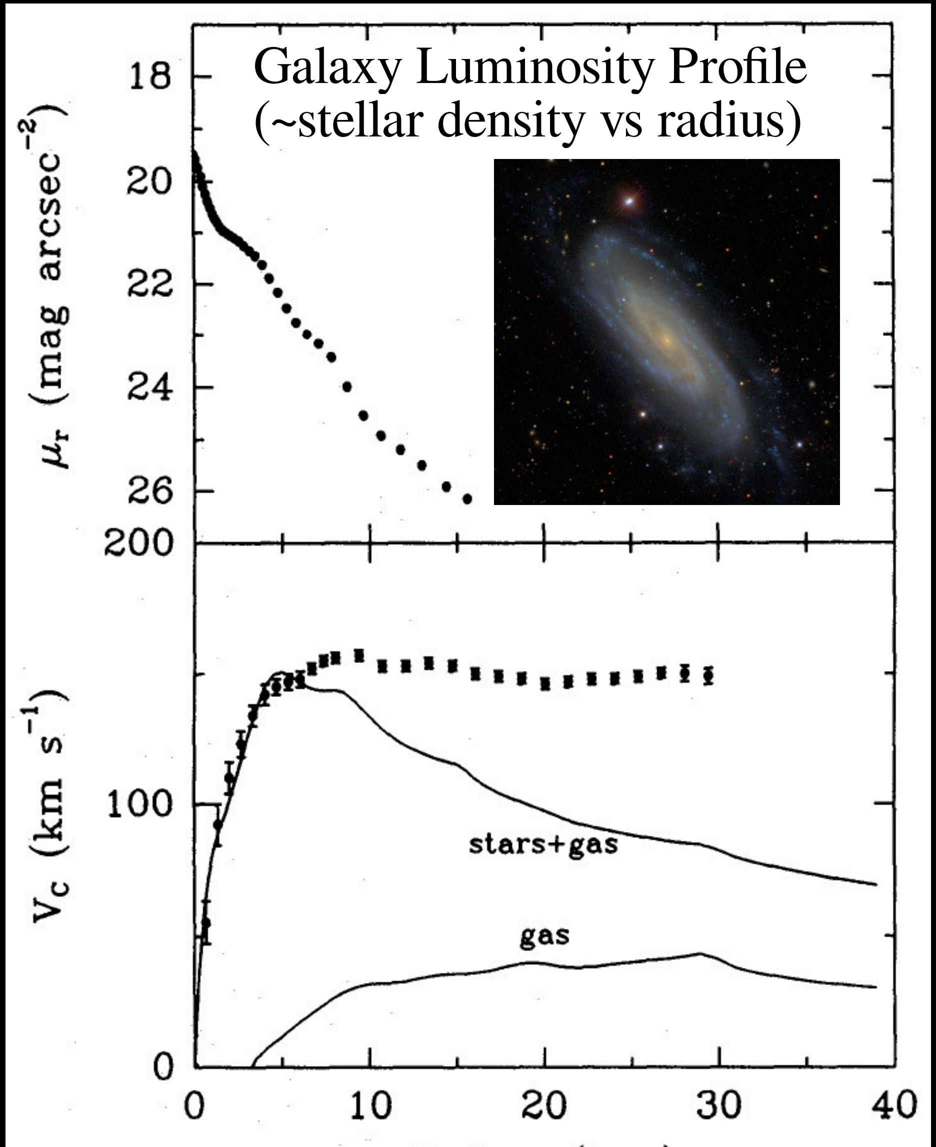
- Solve (numerically) Poisson's equation in cylindrical coordinates for each component (i = stars or gas):

$$\nabla^2 \Phi_i(R,z) = 4\pi G \rho_i(R,z)$$

- Find expected circular velocity in disk mid-plane:

$$\frac{V_i^2(R,z=0)}{R} = -\frac{\partial \Phi_i(R,z=0)}{\partial R}$$

Mass Models of Disk Galaxies



Van Albada+1985

- Solve (numerically) Poisson's equation in cylindrical coordinates for each component (i = stars or gas):

$$\nabla^2 \Phi_i(R,z) = 4\pi G \rho_i(R,z)$$

- Find expected circular velocity in disk mid-plane:

$$\frac{V_i^2(R,z=0)}{R} = -\frac{\partial \Phi_i(R,z=0)}{\partial R}$$

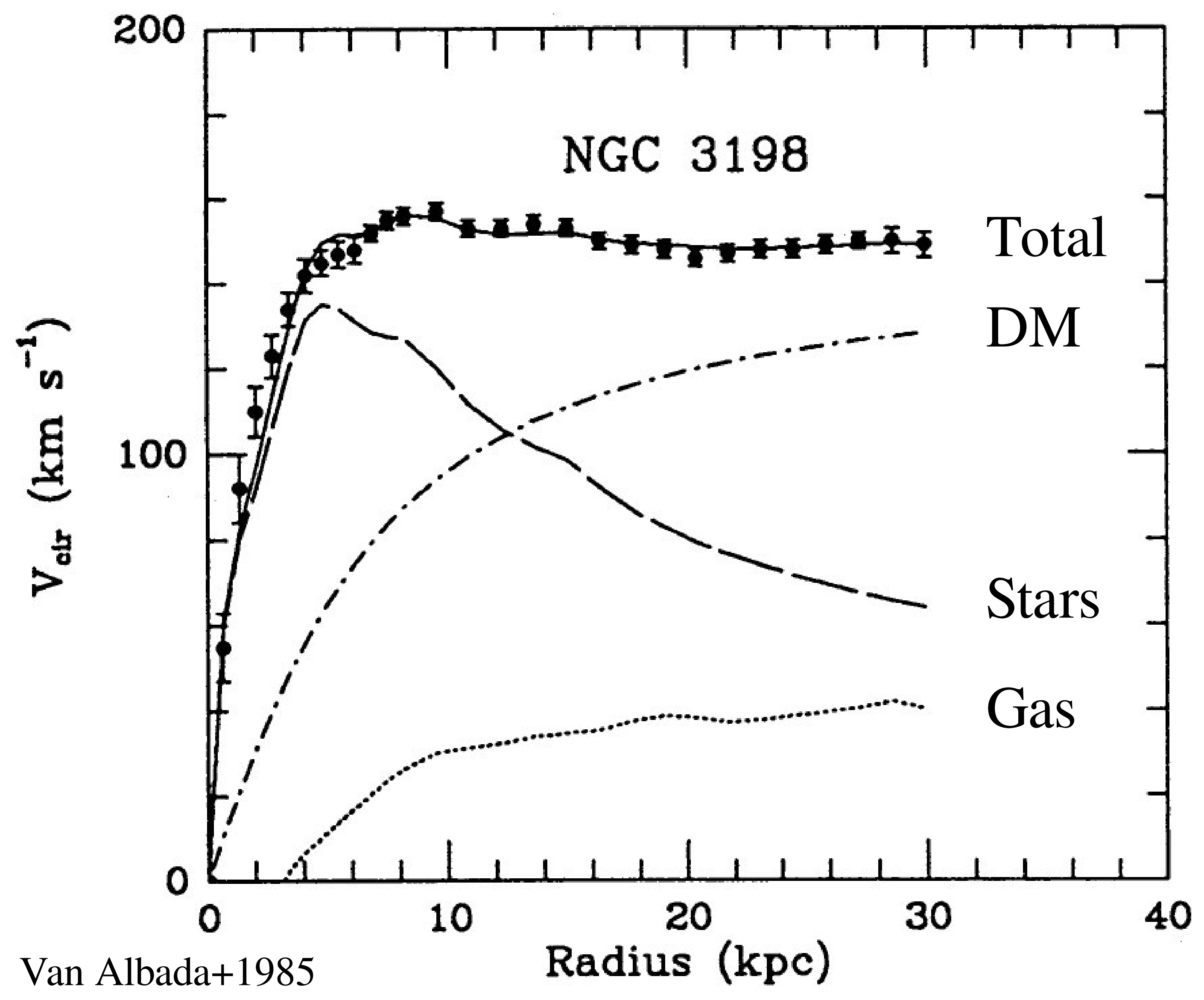
- Sum over gravitational fields ($g_i = V_i^2/R$):

$$V_b^2(R) = \Upsilon_\star V_\star^2(R) + \Upsilon_g V_g^2(R)$$

Υ_s = M_s/L estimated from stellar population models

Υ_g = known for HI from atomic physics (spin-flip) + small corrections for H_2, He, heavier elements

Mass Model with a Dark Matter Halo



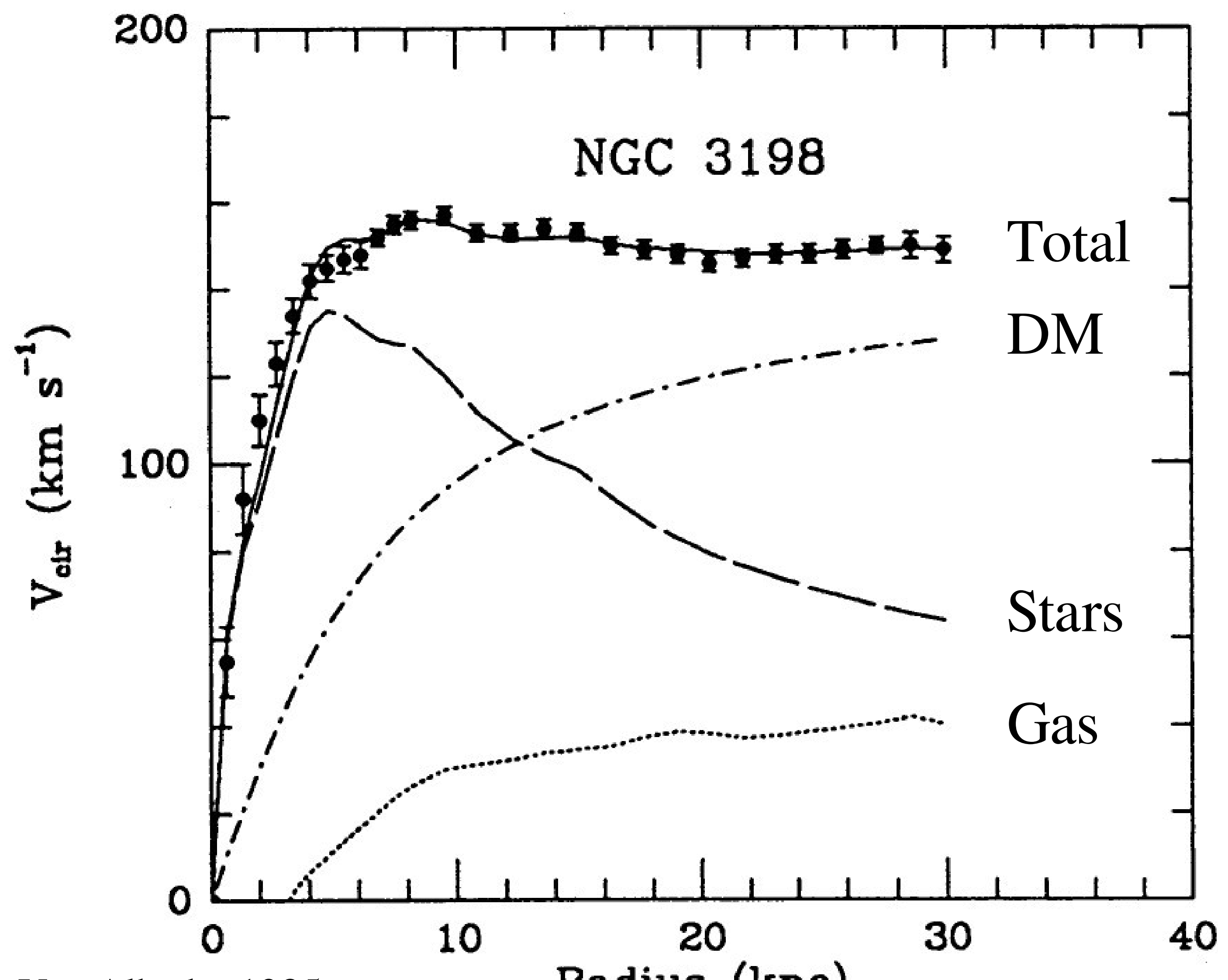
- Assume spherical DM halo profile:

$$\rho_{DM} = \rho(r; \rho_c, r_c)$$

- Add it together with the baryons:

$$V_c^2 = \Upsilon_\star V_\star^2 + \Upsilon_g V_g^2 + V_{DM}^2(\rho_c, r_c)$$

Mass Model with a Dark Matter Halo



Van Albada+1985

- Assume spherical DM halo profile:

$$\rho_{DM} = \rho(r; \rho_c, r_c)$$

- Add it together with the baryons:

$$V_c^2 = \Upsilon_\star V_\star^2 + \Upsilon_g V_g^2 + V_{DM}^2(\rho_c, r_c)$$

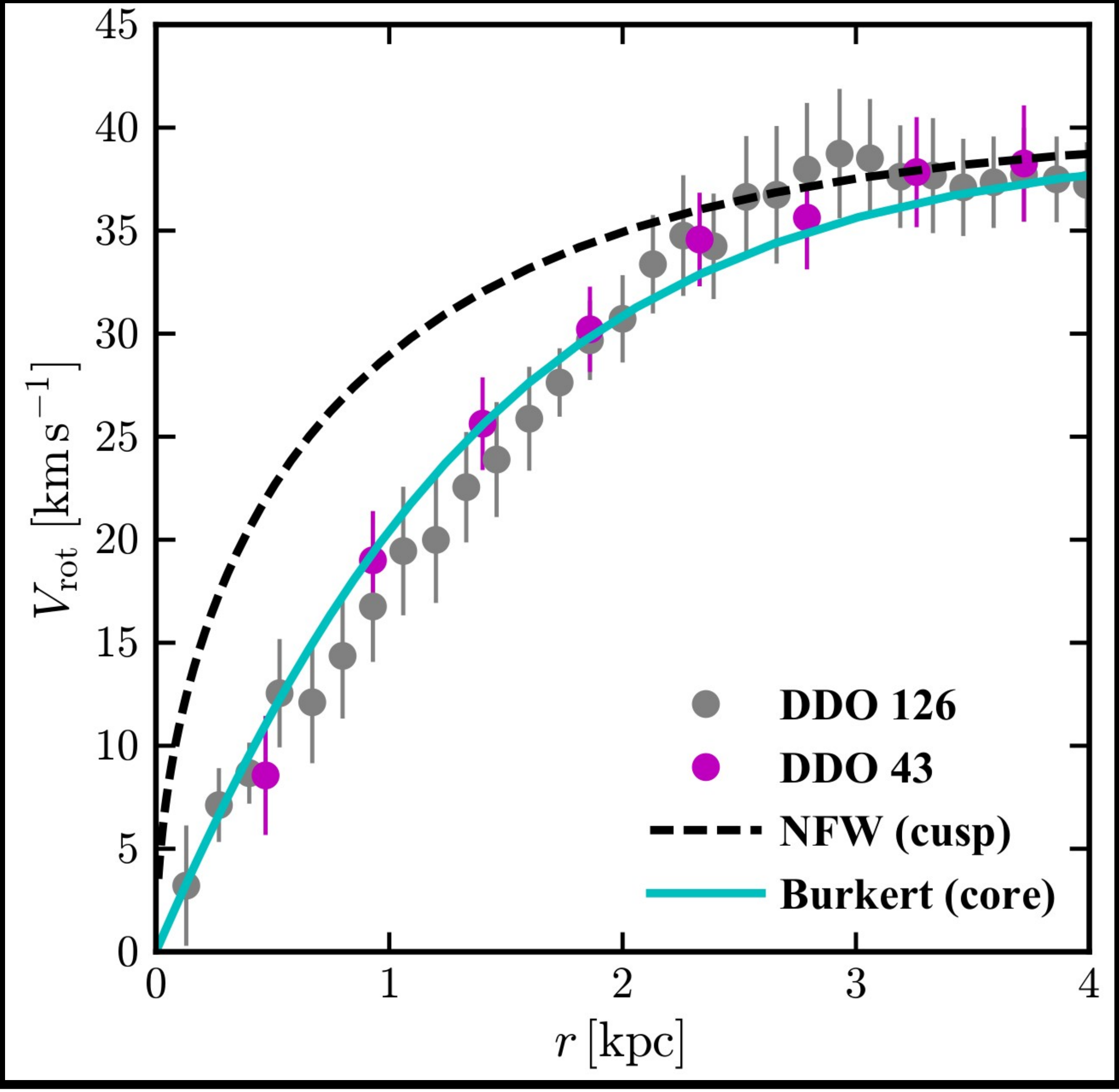
For spiral galaxies like the Milky Way, baryons dominate in the inner parts while DM is needed in the outer regions

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

Why are rotation curves flat? Unclear!

Fine-tuning issue: “Disk-halo conspiracy” (van Albada & Sancisi 1986)

Cusp-Core Problem in Dwarf Galaxies



NFW profile (from N-body sims):

$$\rho_{DM}(r) = \frac{4\rho_c}{(r/r_c)(1+r/r_c)^2}$$

Burkert profile (empirical):

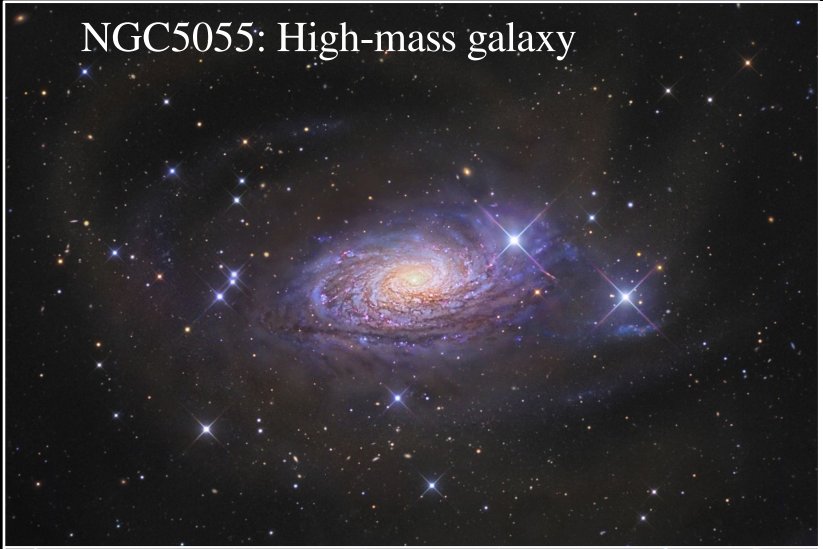
$$\rho_{DM}(r) = \frac{\rho_c}{(1+r/r_c)[1+(r/r_c)^2]}$$

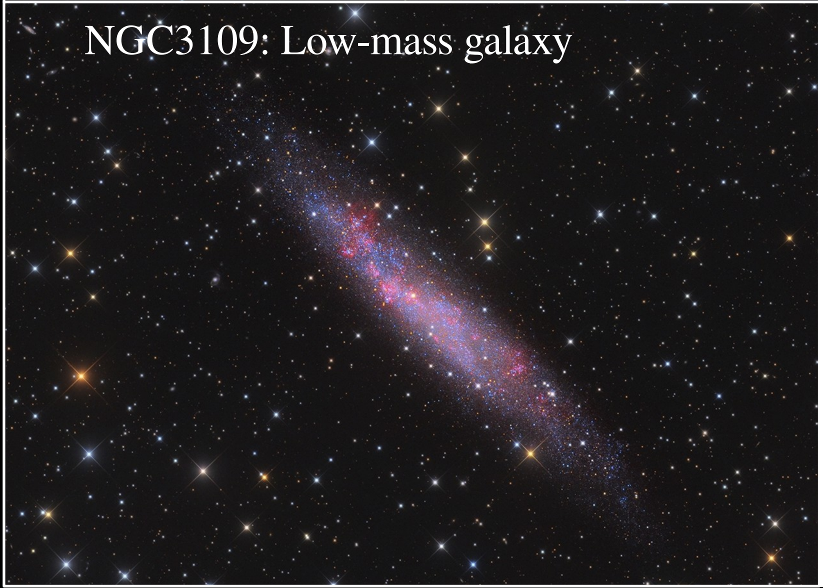
Possible Solutions to the Cusp-Core (Rotation Curve) Problem

1. Baryonic physics: repeated, massive, and fast gas outflows due to stellar feedback produce non-adiabatic oscillations in the gravitational potential → transform DM cusp into a DM core

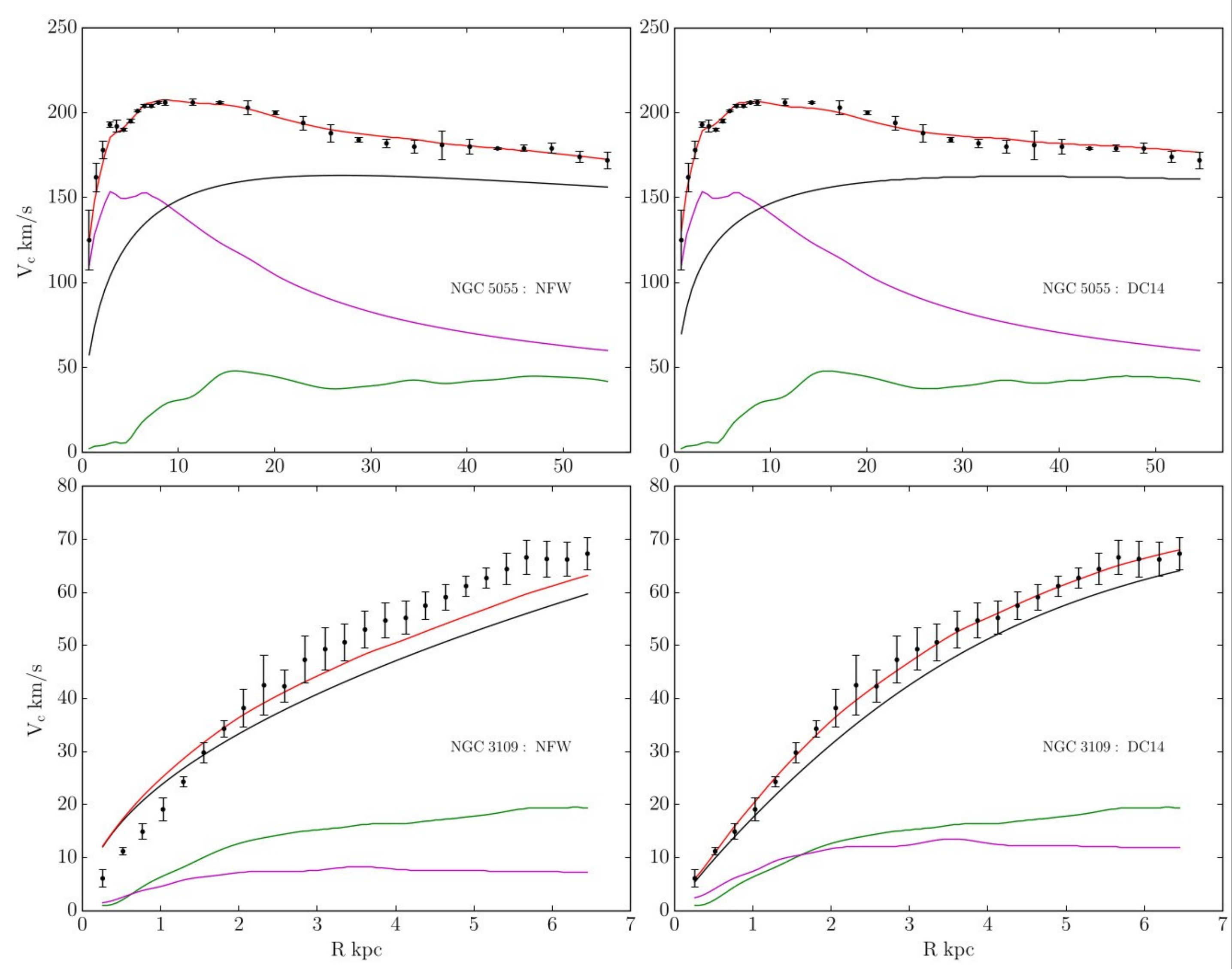
Baryon-modified DM halos

From Katz, Lelli et al. (2017)





Cuspy Halo (NFW) | Baryonic-feedback-altered Halo

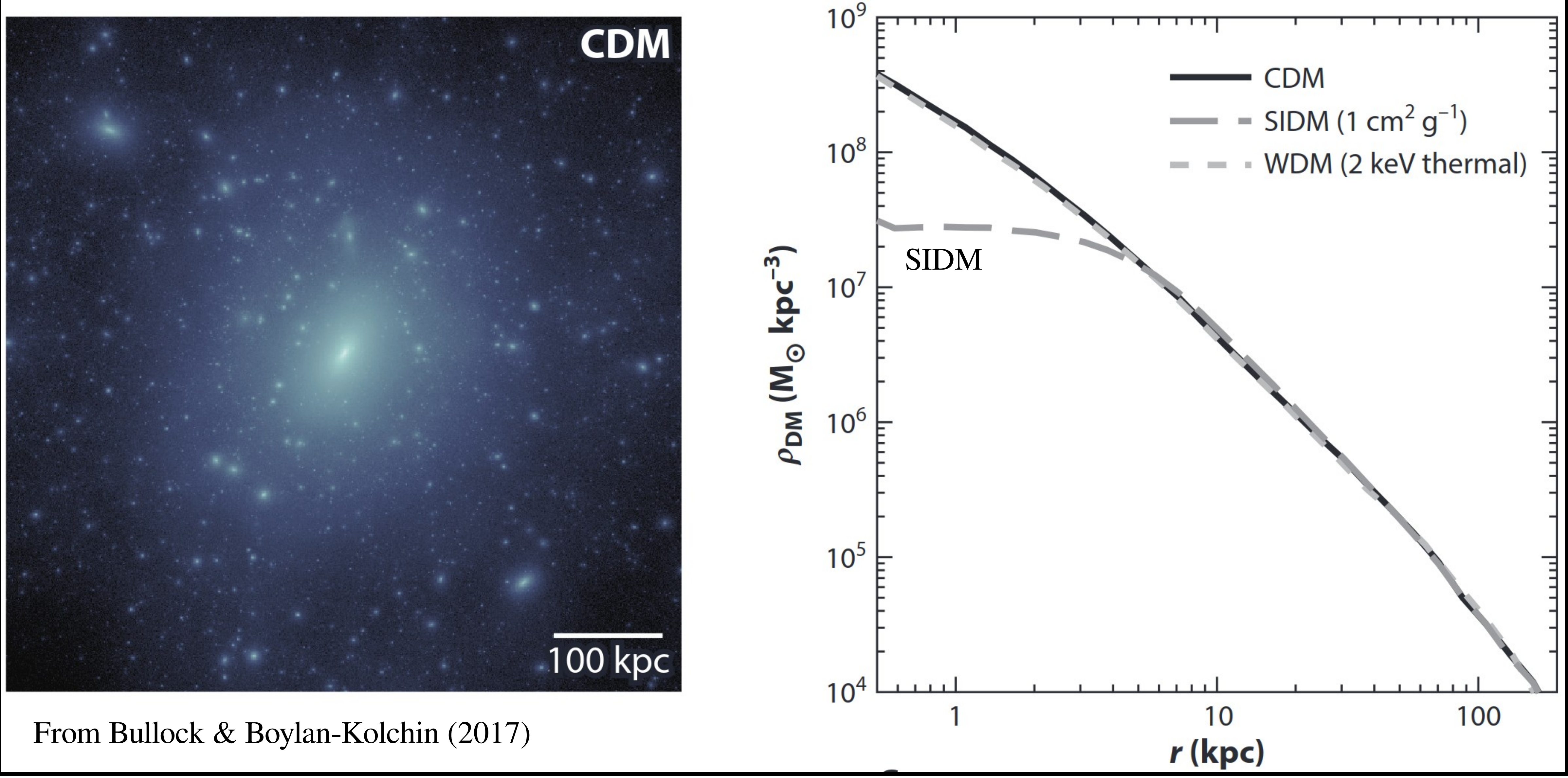


Possible Solutions to the Cusp-Core (Rotation Curve) Problem

1. Baryonic physics: repeated, massive, and fast gas outflows due to stellar feedback produce non-adiabatic oscillations in the gravitational potential → transform DM cusp into a DM core

2. Self-interacting DM (SIDM): cores are created because of the "pressure" from DM self-interactions (WDM don't work!)

Constant-density cores in SIDM



From Bullock & Boylan-Kolchin (2017)

Possible Solutions to the Cusp-Core (Rotation Curve) Problem

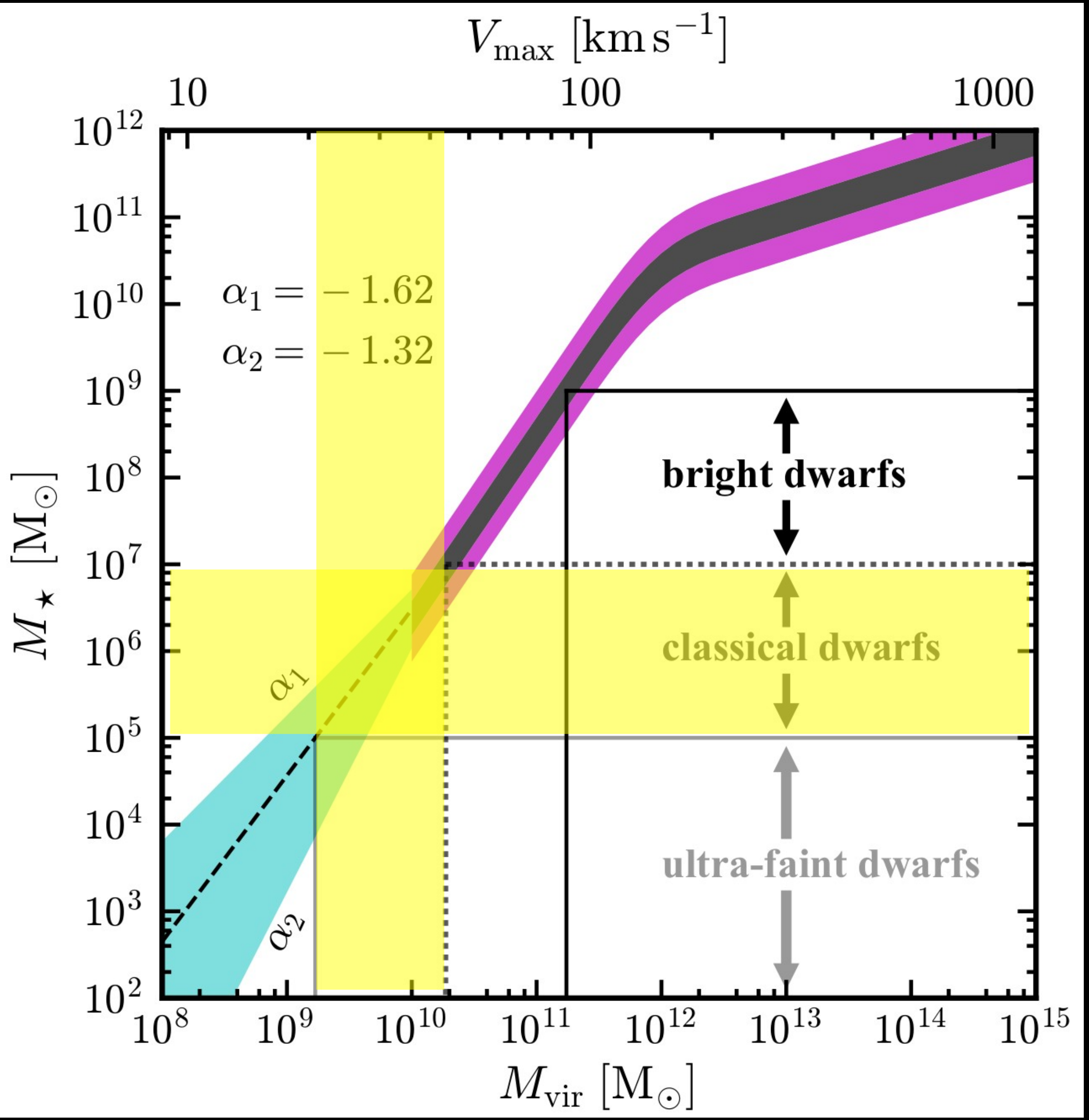
1. Baryonic physics: repeated, massive, and fast gas outflows due to stellar feedback produce non-adiabatic oscillations in the gravitational potential → transform DM cusp into a DM core

2. Self-interacting DM (SIDM): cores are created because of the "pressure" from DM self-interactions (WDM don't work!)

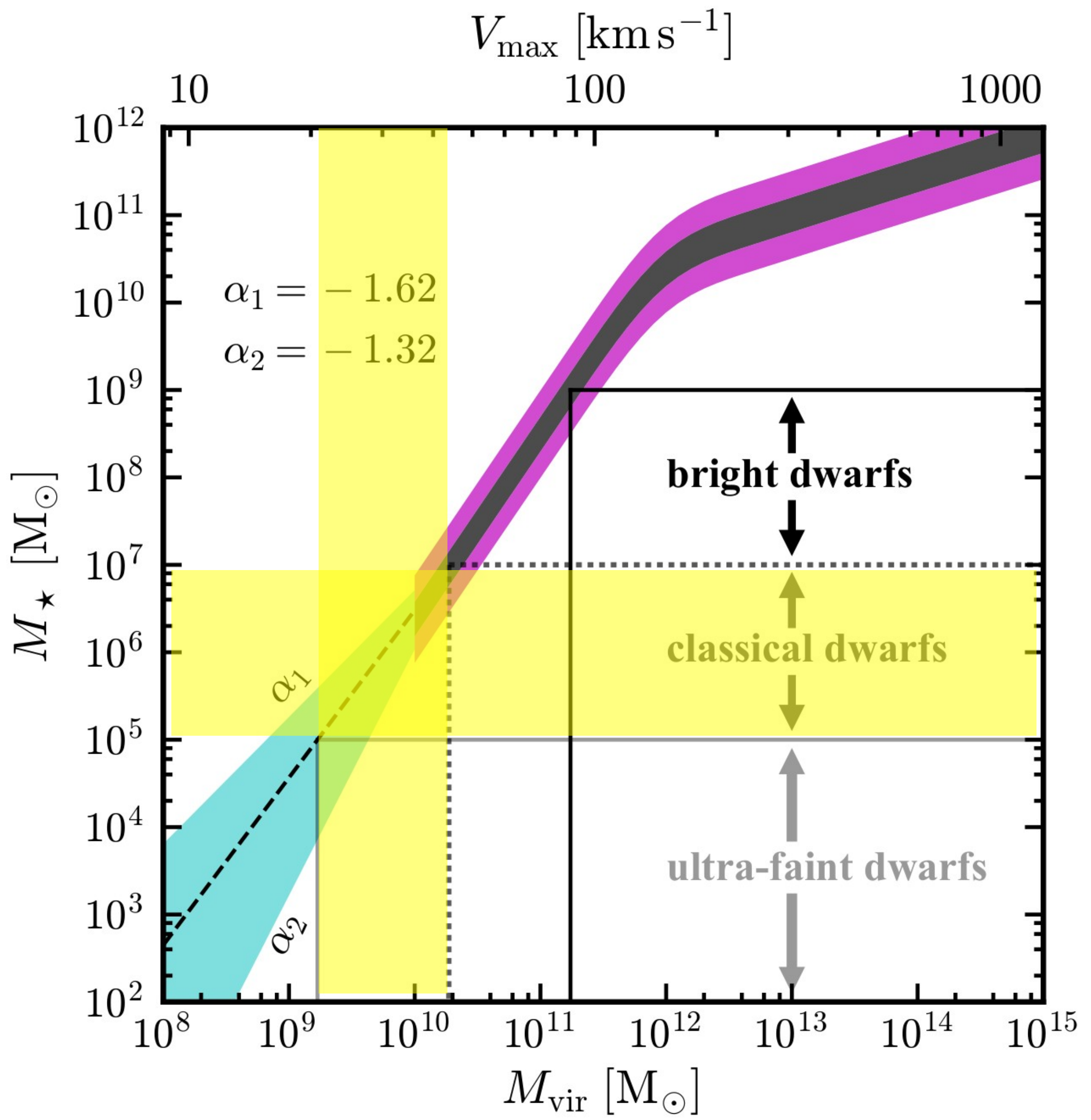
3. Modified gravity (especially MOND): problem does NOT exist! → rotation curves are predicted from the baryonic distribution

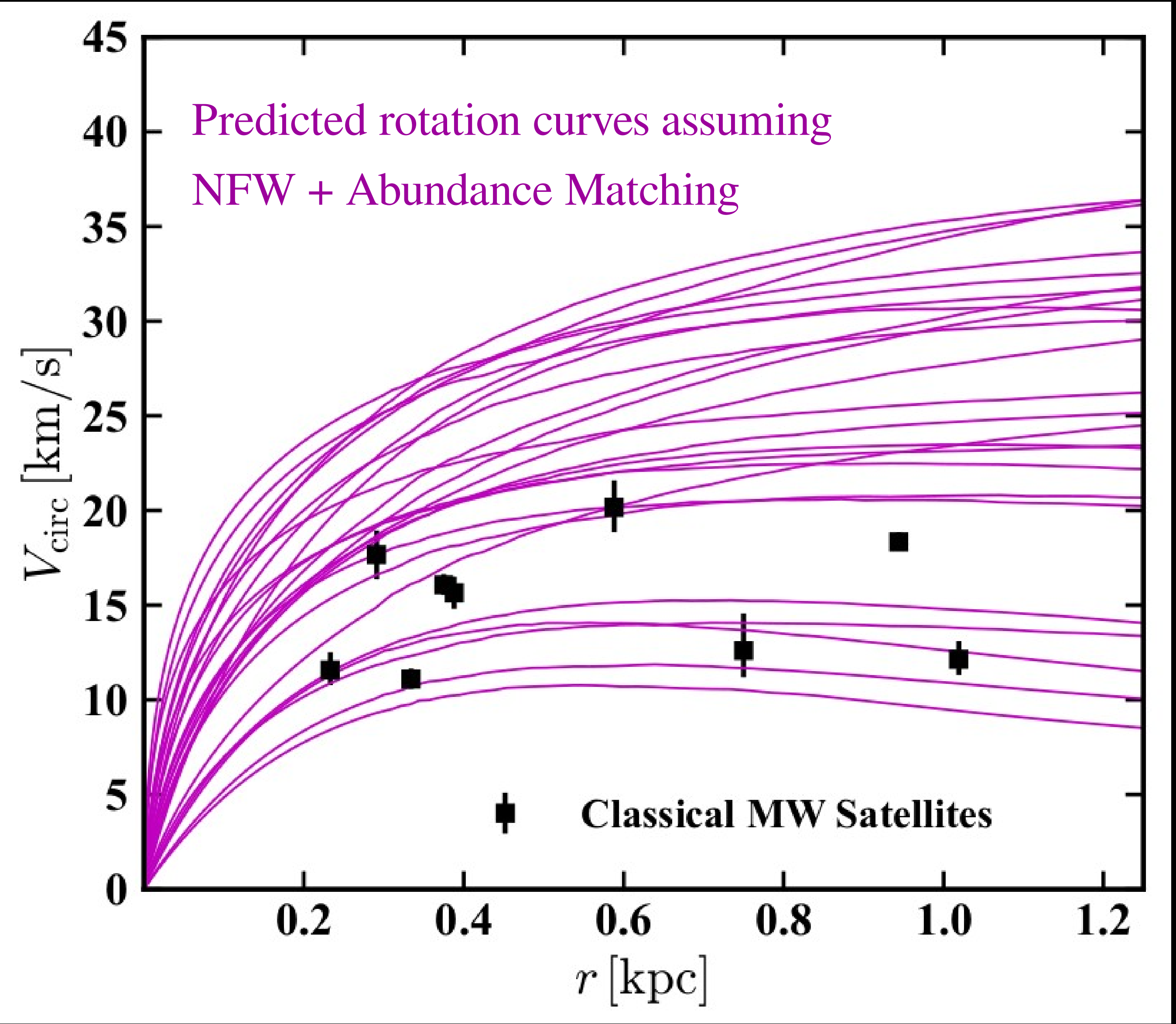
3. Too-Big-To-Fail Problem (Problems 1+2 Reloaded)

Too-Big-To-Fail Problem



Too-Big-To-Fail Problem





Possible Solutions to the TBTF Problem (pushing down to very low-mass galaxies)

1. Baryonic physics: unclear whether it will work; stellar feedback should be inefficient in low-mass galaxies with $M_{\star} < 10^6\ M_{\odot}$ because they produced very few supernovae!

Possible Solutions to the TBTF Problem (pushing down to very low-mass galaxies)

1. Baryonic physics: unclear whether it will work; stellar feedback should be inefficient in low-mass galaxies with $M_\star < 10^6\, M_\odot$ because they produced very few supernovae!

2. Self-interacting DM: cores are "naturally" created because of the "pressure" from DM self-interactions

Possible Solutions to the TBTF Problem (pushing down to very low-mass galaxies)

1. Baryonic physics: unclear whether it will work; stellar feedback should be inefficient in low-mass galaxies with $M_\star < 10^6\,M_\odot$ because they produced very few supernovae!

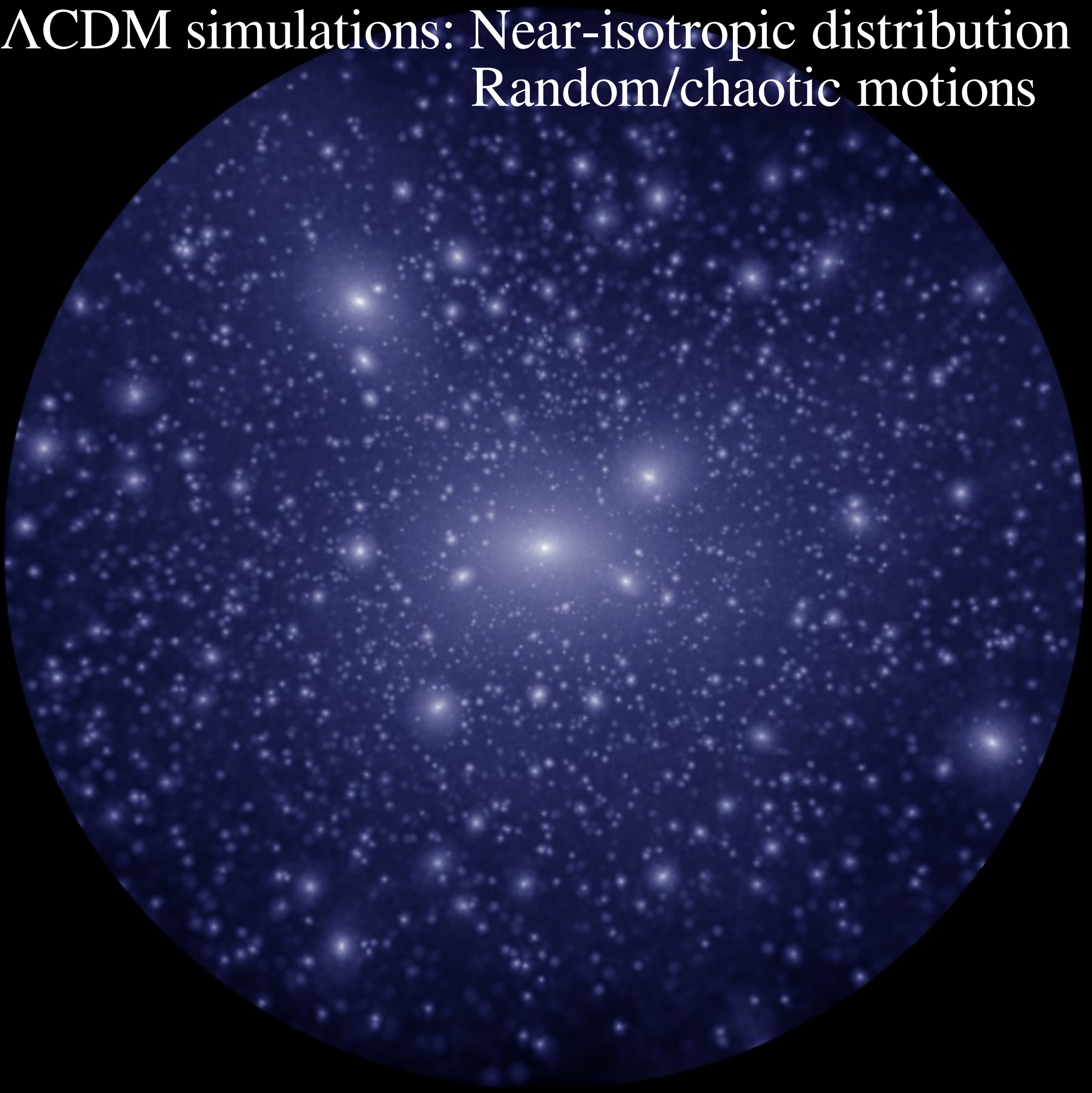
2. Self-interacting DM: cores are "naturally" created because of the "pressure" from DM self-interactions

3. Modified gravity (especially MOND): problem does NOT exist! → circular velocity predicted from the baryonic content

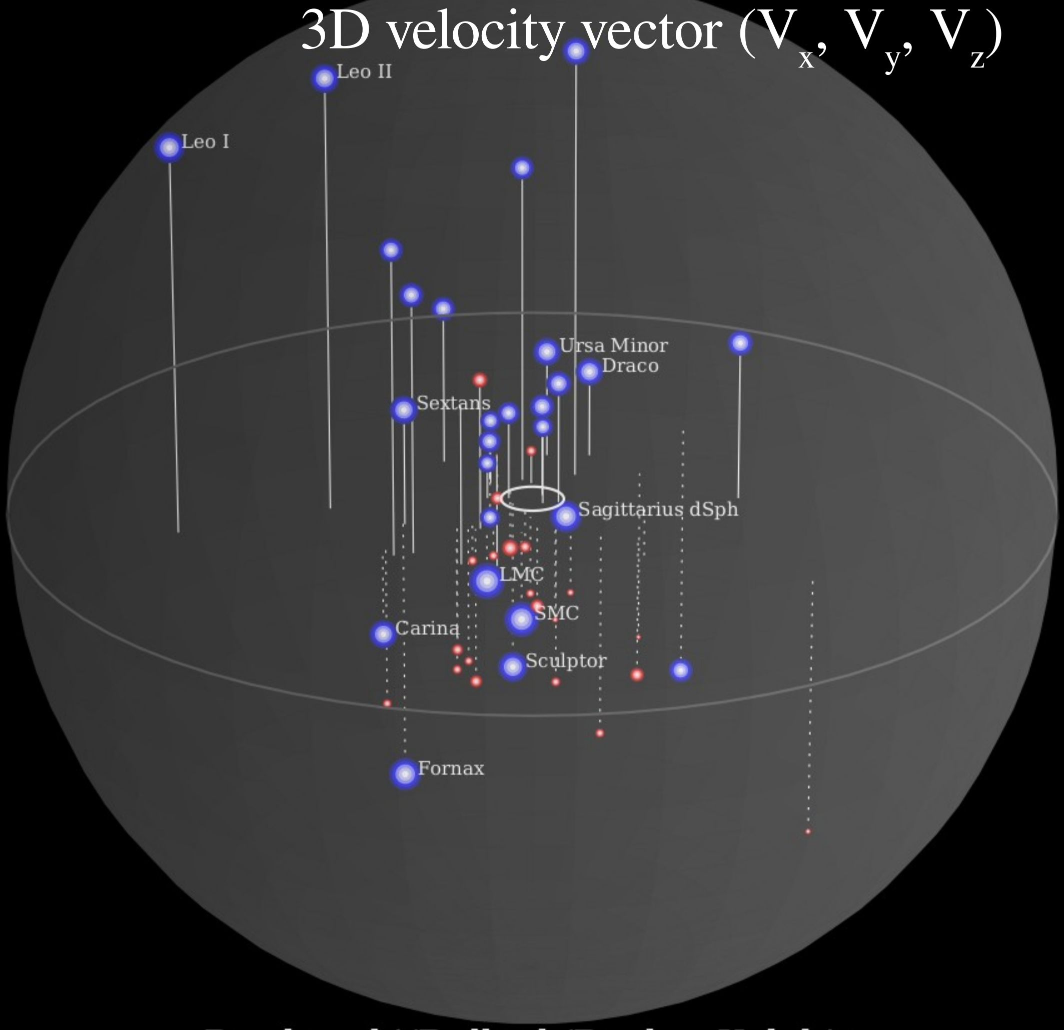
4. Planes of Satellites Problem (Satellites Phase-Space)

Distribution & Kinematics of Satellites

ΛCDM simulations: Near-isotropic distribution
Random/chaotic motions

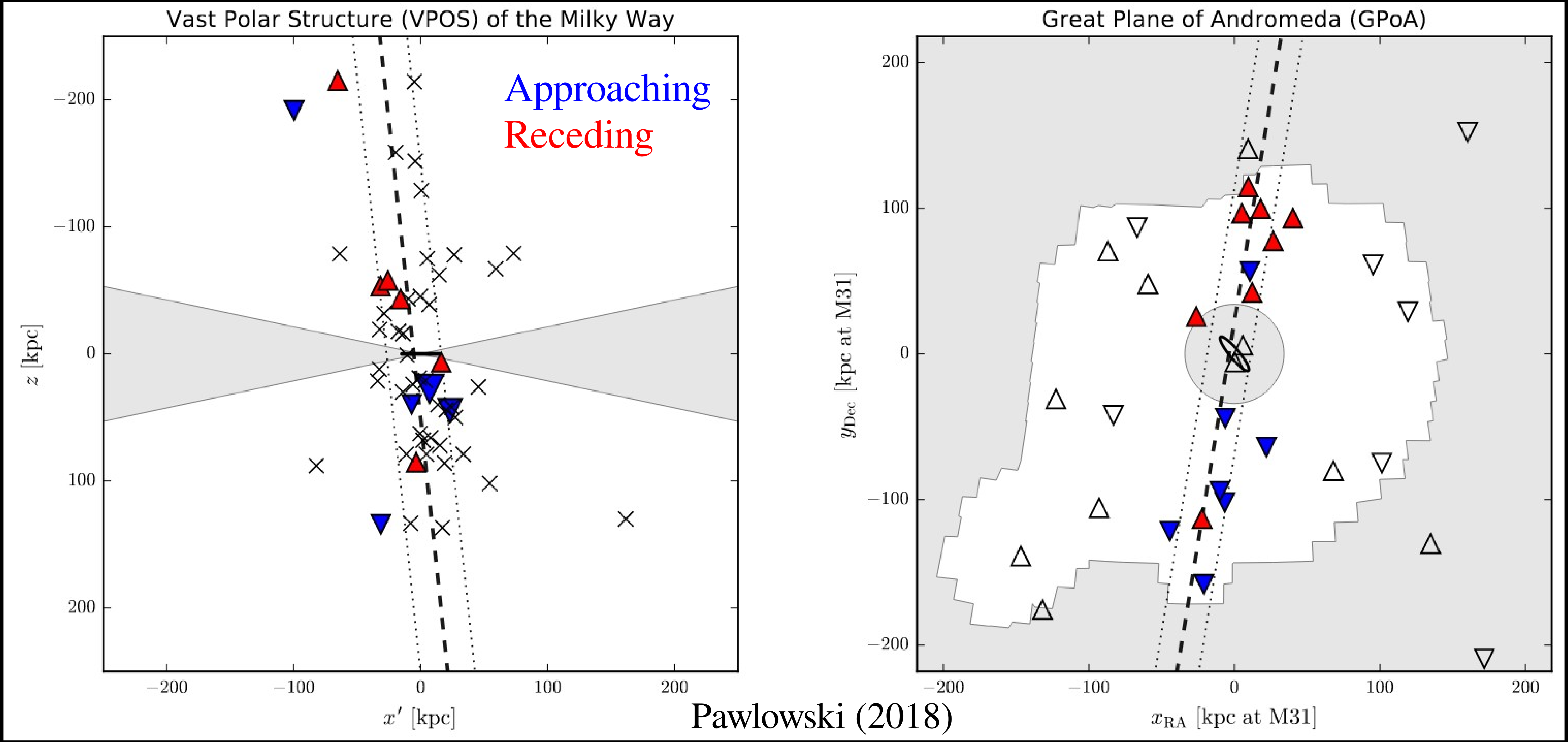


Observations: Need accurate distances +
3D velocity vector (V_x, V_y, V_z)



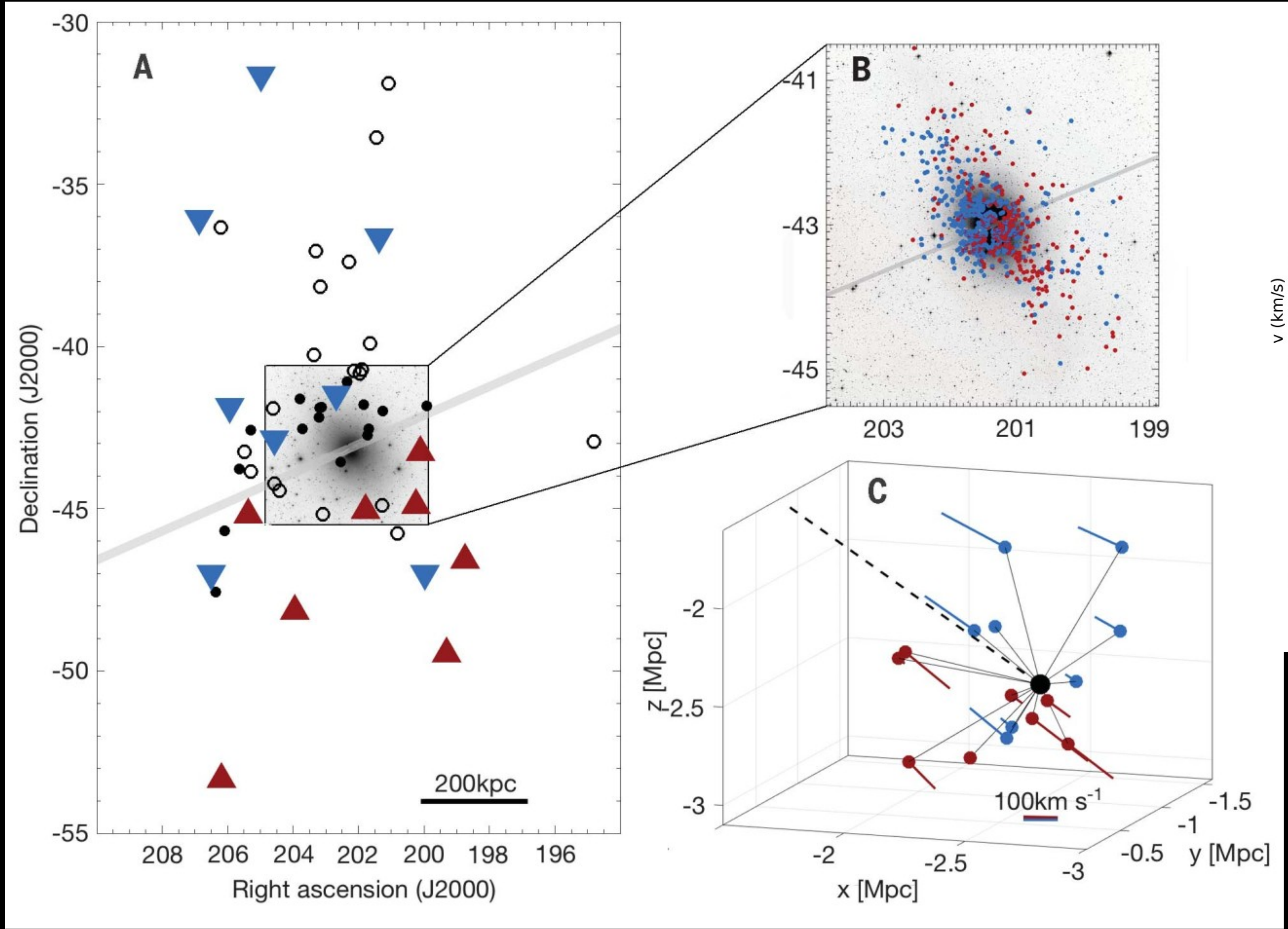
Pawlowski/Bullock/Boylan-Kolchin

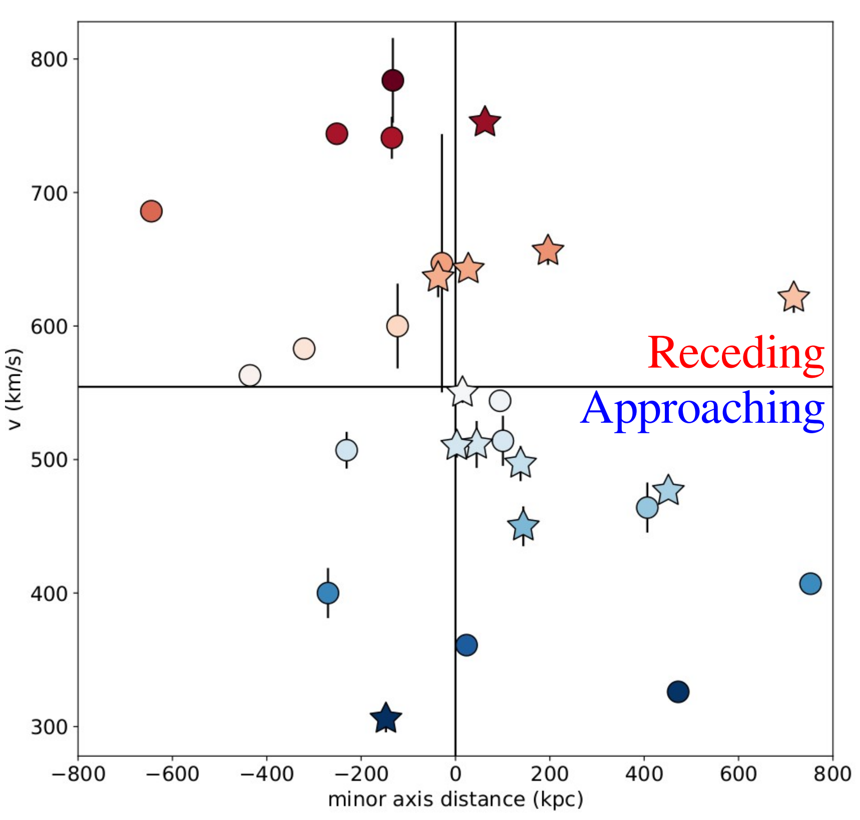
Planes of Satellites in the Local Group



Pawlowski (2018)

Plane of Satellites in the Cen-A Group





Muller et al. (2021, A&A)

Muller, Pawlowski, Jerjen, Lelli (2018, Science)

Possible Solutions to the TBTF Problem (pushing down to very low-mass galaxies)

1. Baryonic physics: it should play NO role because the baryons should not affect the orbital properties of DM sub-halos (confirmed by comparing DM-only with hydro simulations)

Possible Solutions to the TBTF Problem (pushing down to very low-mass galaxies)

1. Baryonic physics: it should play NO role because the baryons should not affect the orbital properties of DM sub-halos (confirmed by comparing DM-only with hydro simulations)

2. Self-interacting DM: it cannot solve the problem because self-interaction affects only the inner parts of DM (sub)-halos

Possible Solutions to the TBTF Problem (pushing down to very low-mass galaxies)

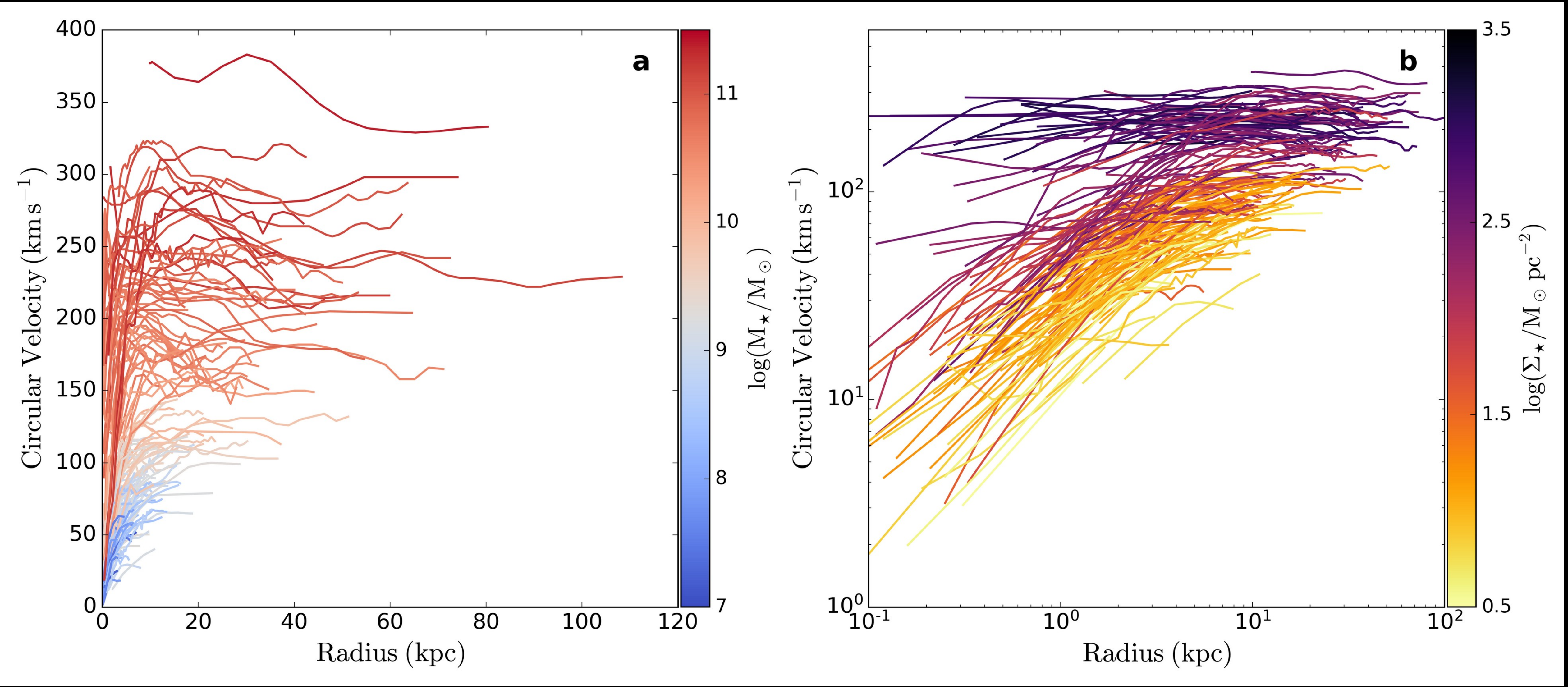
1. Baryonic physics: it should play NO role because the baryons should not affect the orbital properties of DM sub-halos (confirmed by comparing DM-only with hydro simulations)

2. Self-interacting DM: it cannot solve the problem because self-interaction affects only the inner parts of DM (sub)-halos

3. Modified gravity: need to re-assess the whole problem of galaxy formation to study phase-space distr. of satellites (not done yet!)

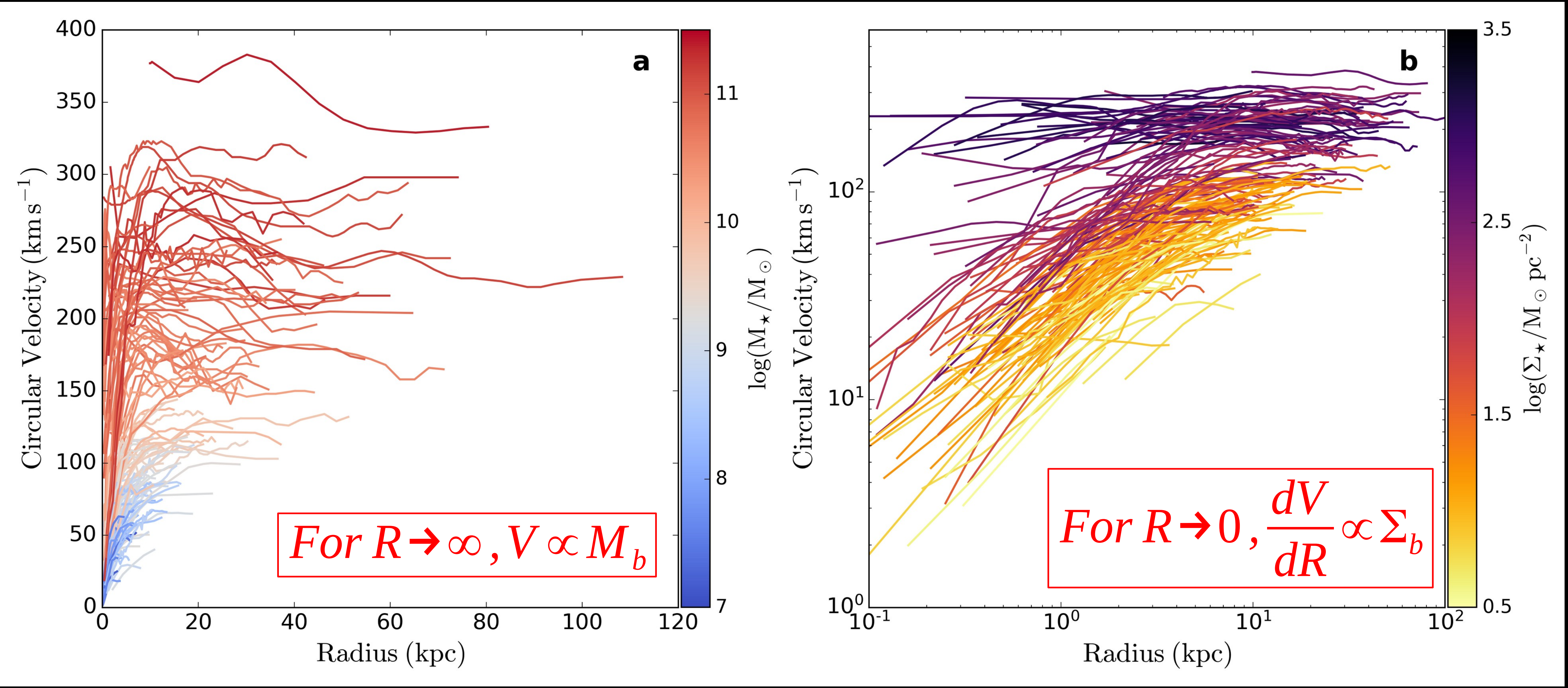
5. Dynamical Regularities (Baryon-DM Coupling)

Rotation Curves Shapes ↔ Baryonic Distribution



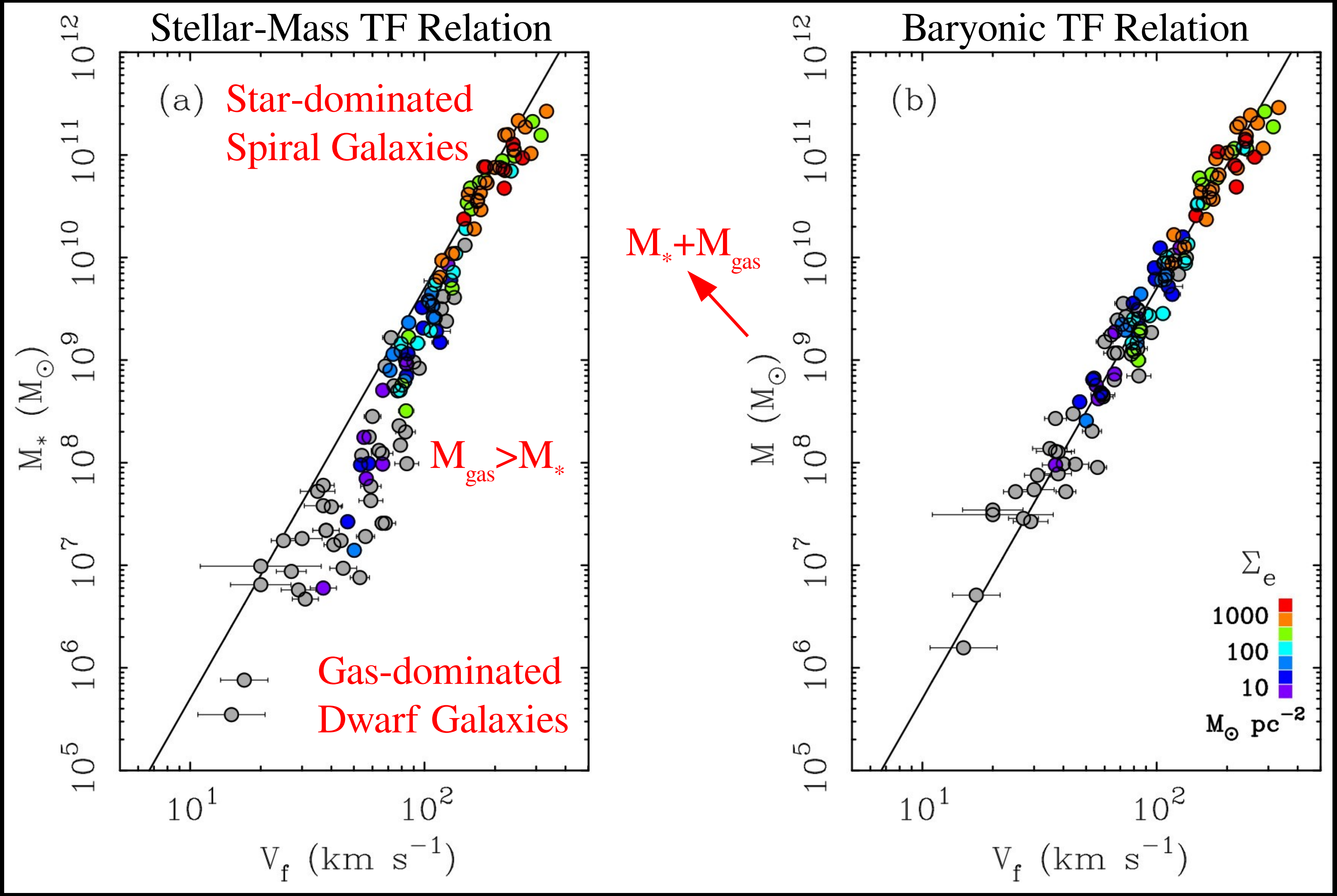
Lelli+(2022, Nature Astronomy)

Rotation Curves Shapes ↔ Baryonic Distribution

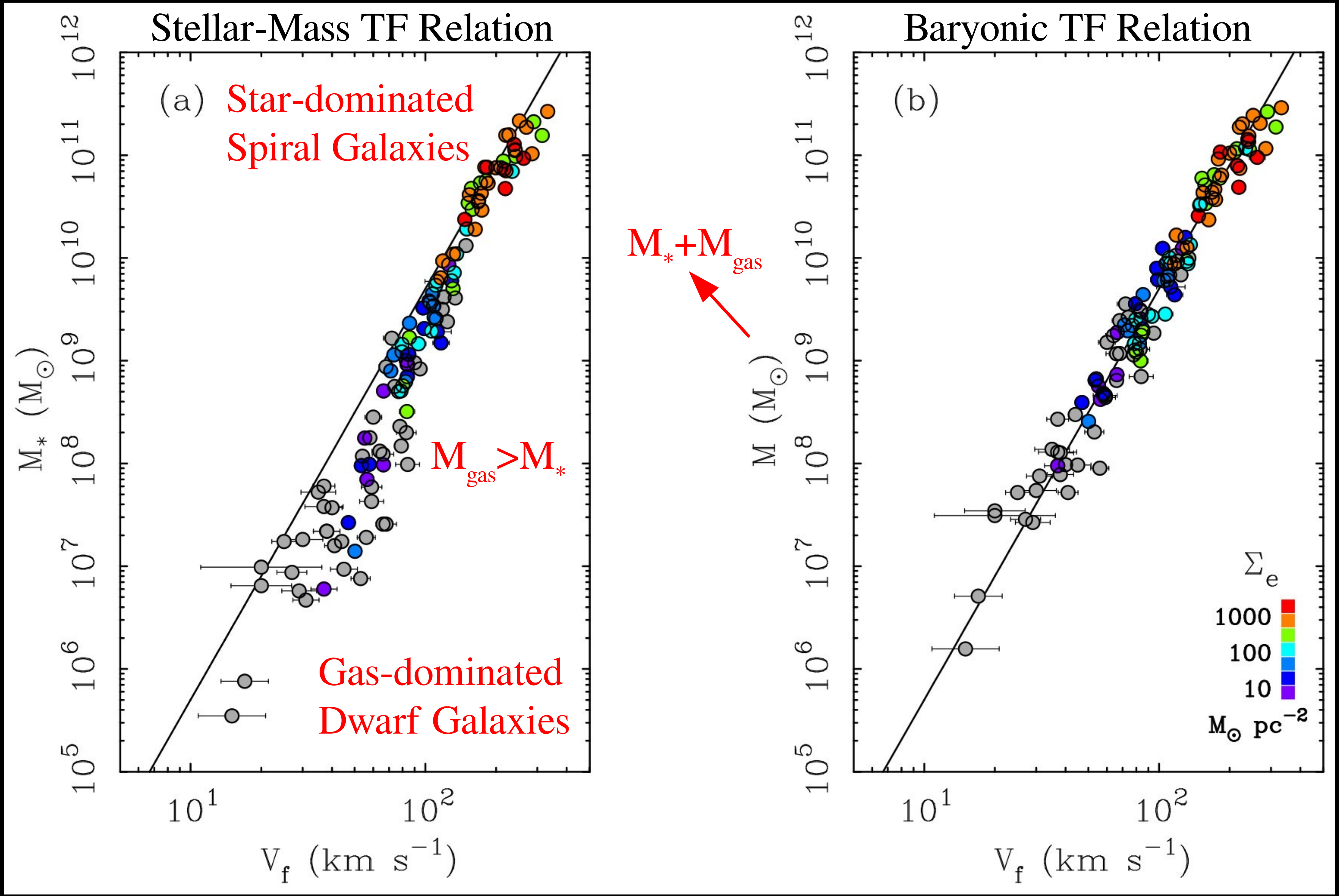


Lelli+(2022, Nature Astronomy)

Tully Fisher Relation: Mass versus Velocity



Tully Fisher Relation: Mass versus Velocity



Newton's Law gives:

$$V^4 = \frac{\pi^2 G^2}{f_b^2} \Sigma_b M_b$$

$$f_b = M_b / M_{tot}$$

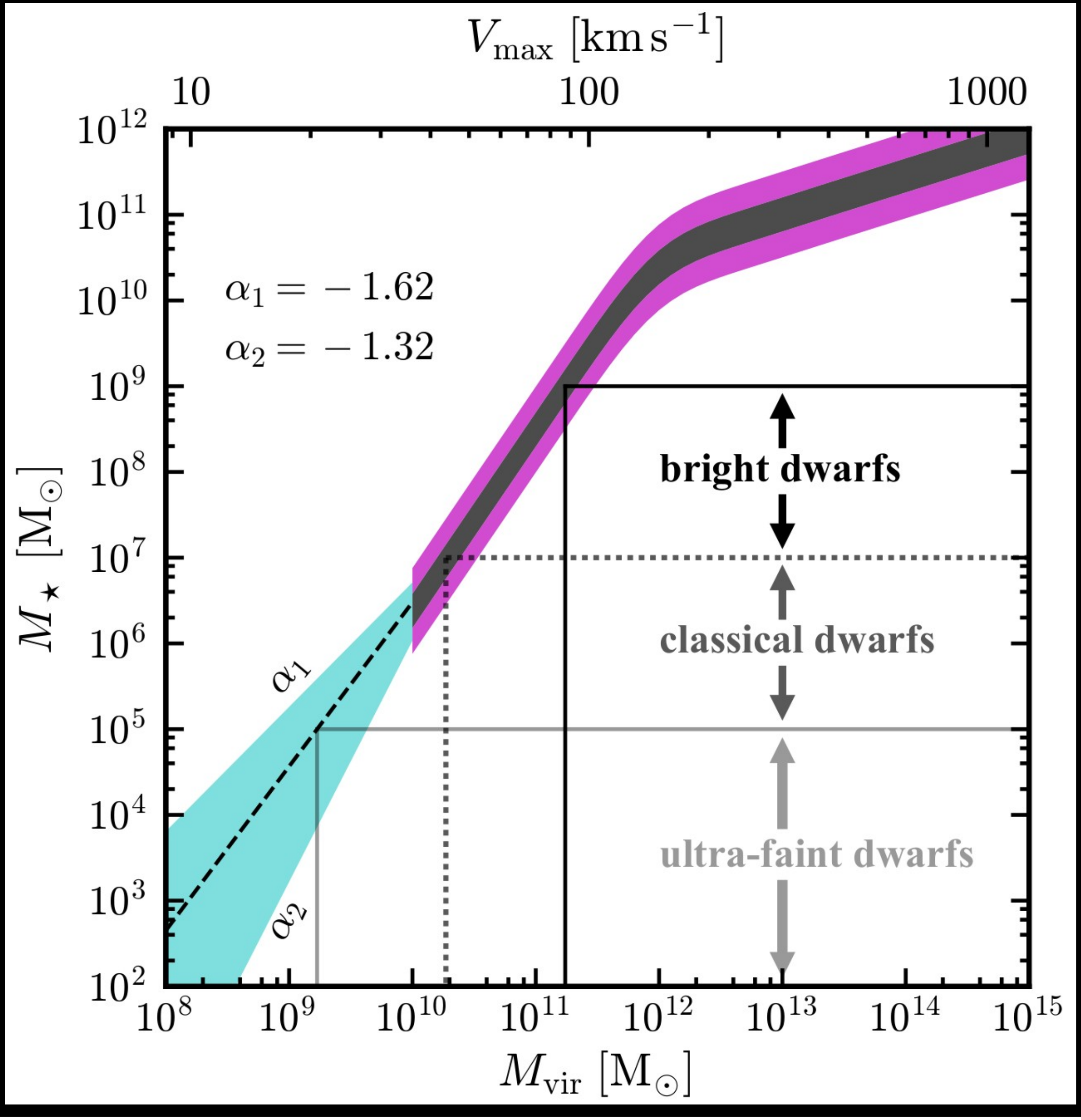
$$\Sigma_b = M_b / \pi R^2$$

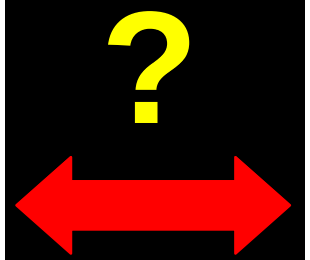
But no dependence on Σ_b is observed.

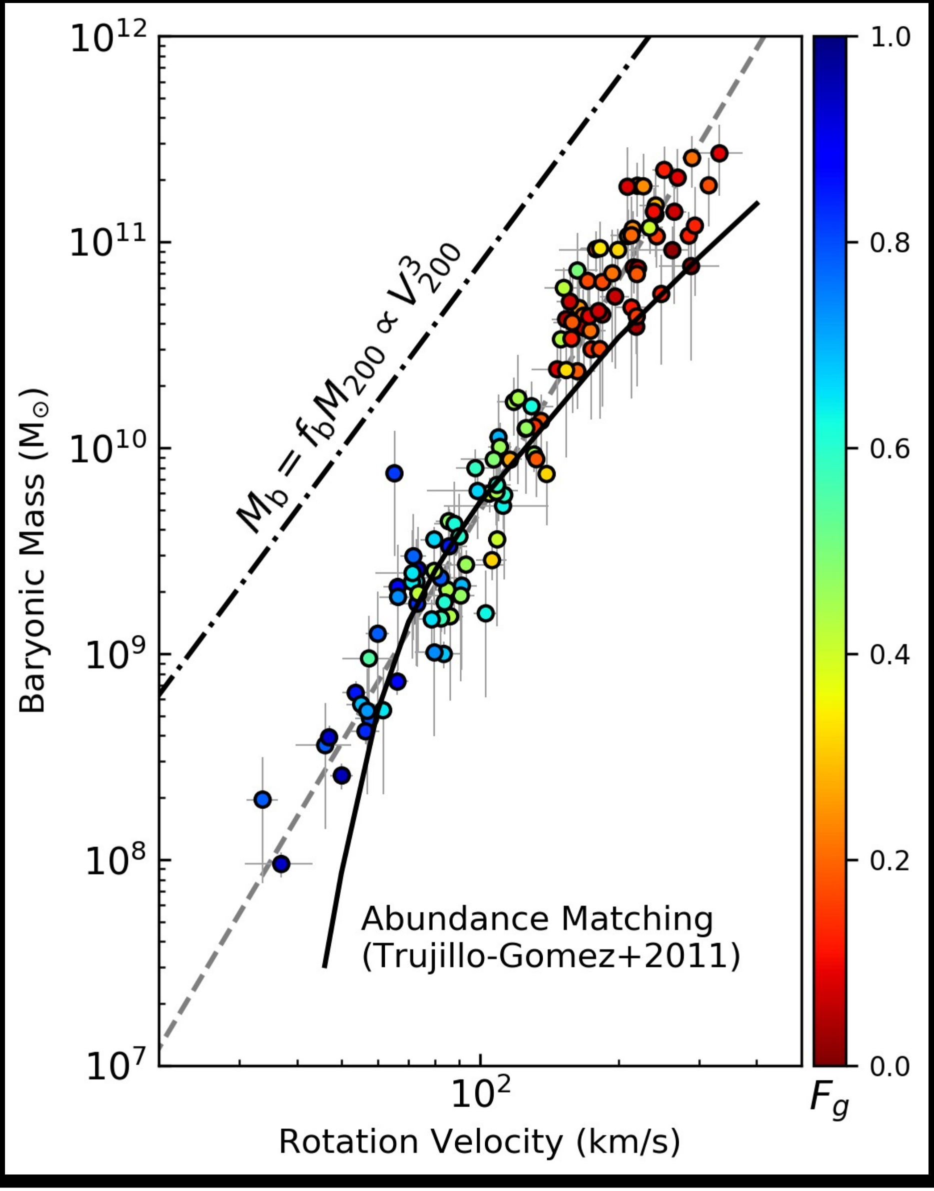
$\rightarrow \Sigma_b / f_b^2 \sim$ const

Fine-tuning problem

Abundance Matching → Curved BTFR?

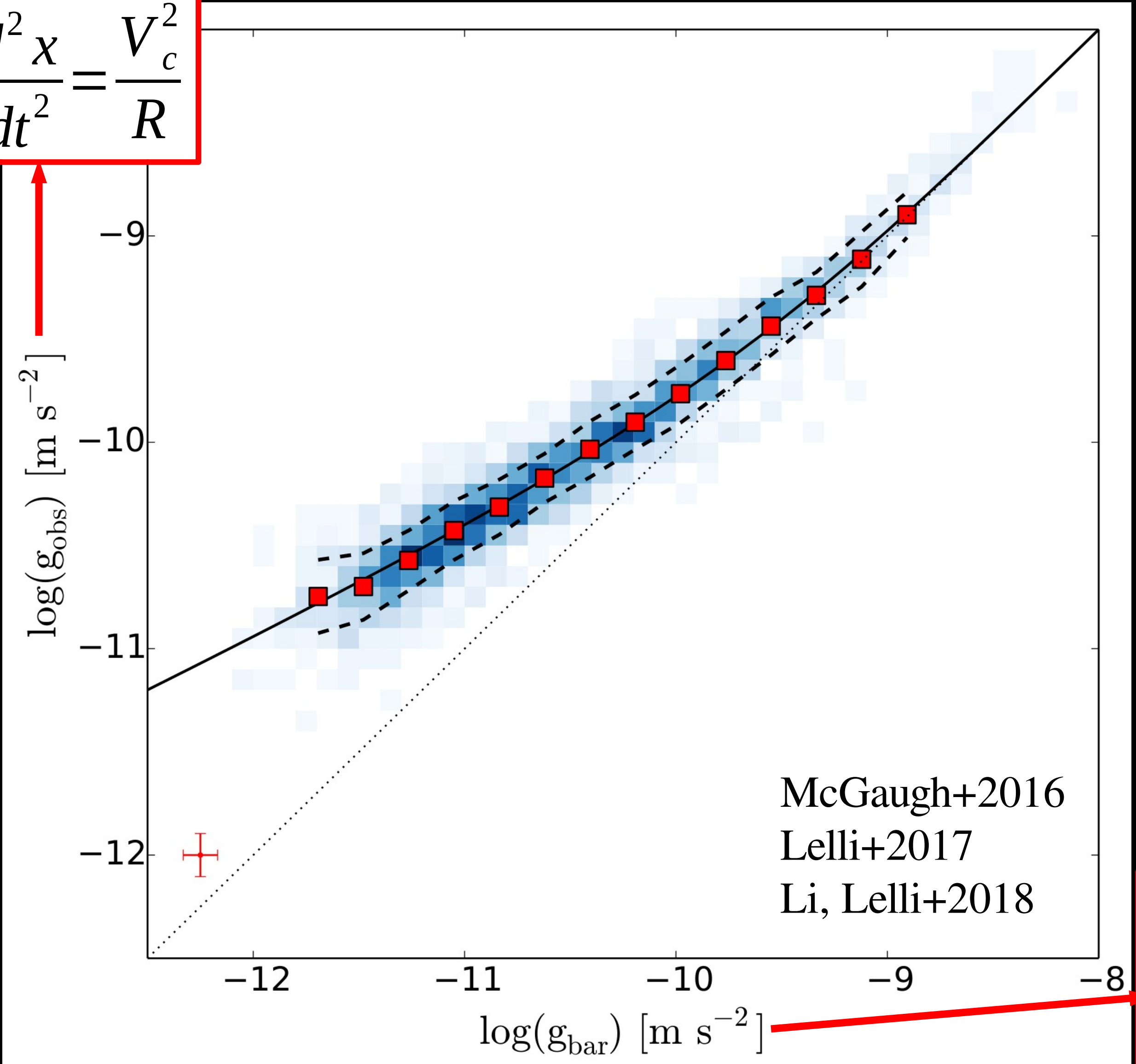






Radial Acceleration Relation (RAR)

$$\frac{d^2x}{dt^2} = \frac{V_c^2}{R}$$



Observables:

g_{obs} → centripetal acceleration from RCs

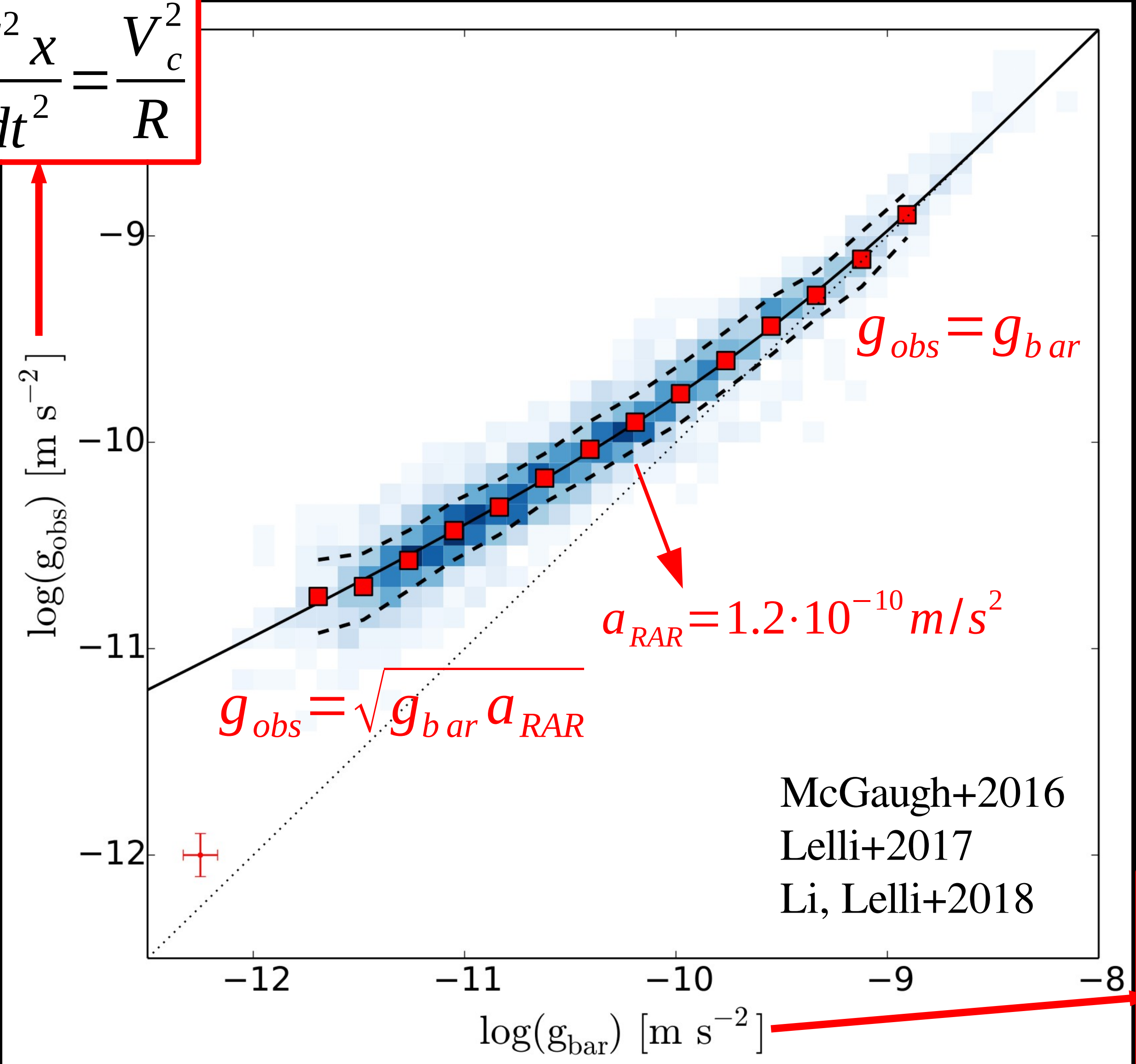
g_{bar} → gravitational field from baryons

$$g_b = -\nabla\Phi_b$$

$$\nabla^2\Phi_b = 4\pi G\rho_b$$

Radial Acceleration Relation (RAR)

$$\frac{d^2x}{dt^2} = \frac{V_c^2}{R}$$



Observables:

g_{obs} → centripetal acceleration from RCs

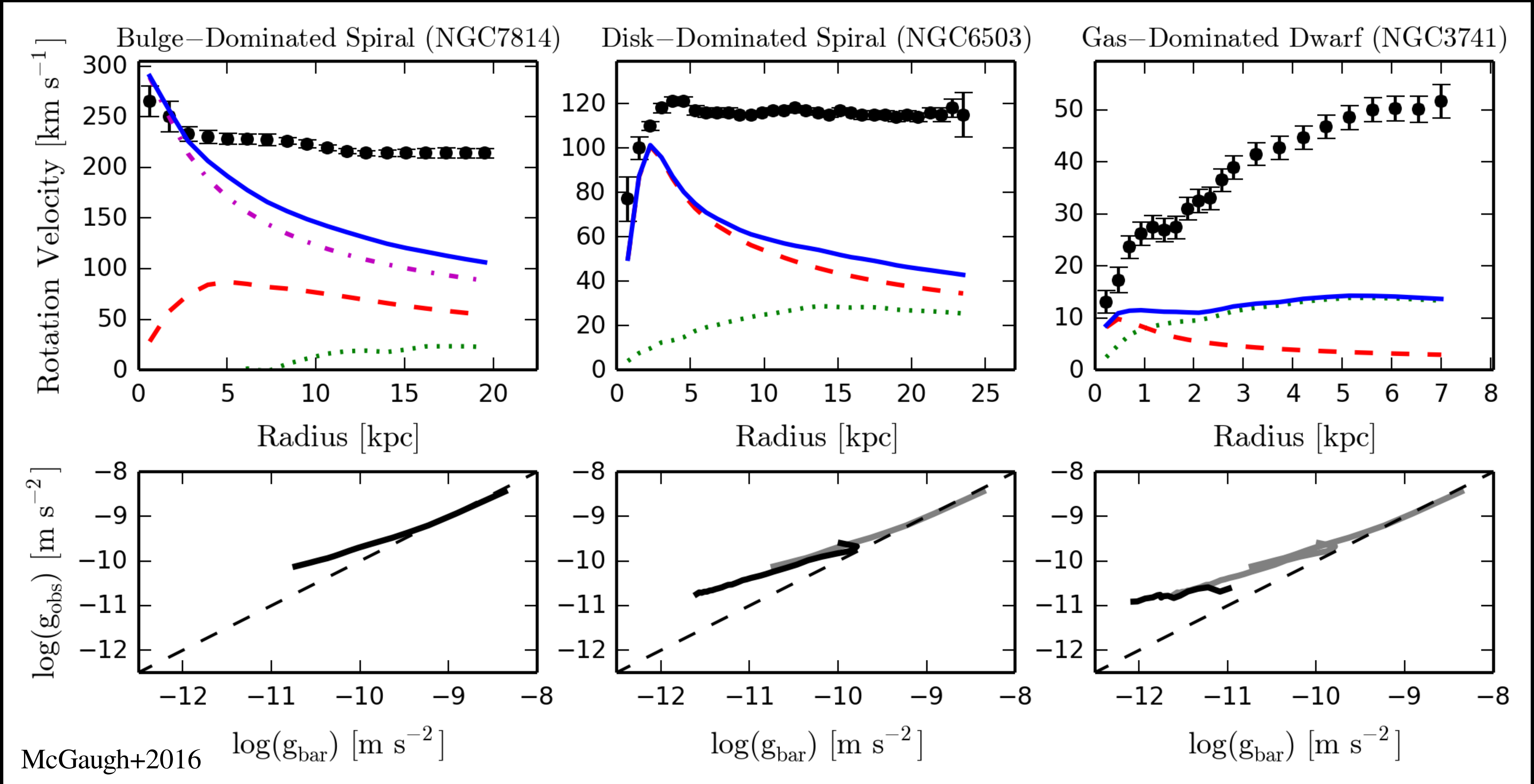
g_{bar} → gravitational field from baryons

Key Properties:

- Acceleration scale a_{RAR}~10^{-10} m/s^2
- Small scatter (consistent with obs. errors)
- No residual dependencies (radius, etc.)
- Baryon distribution ↔ Rotation Curve

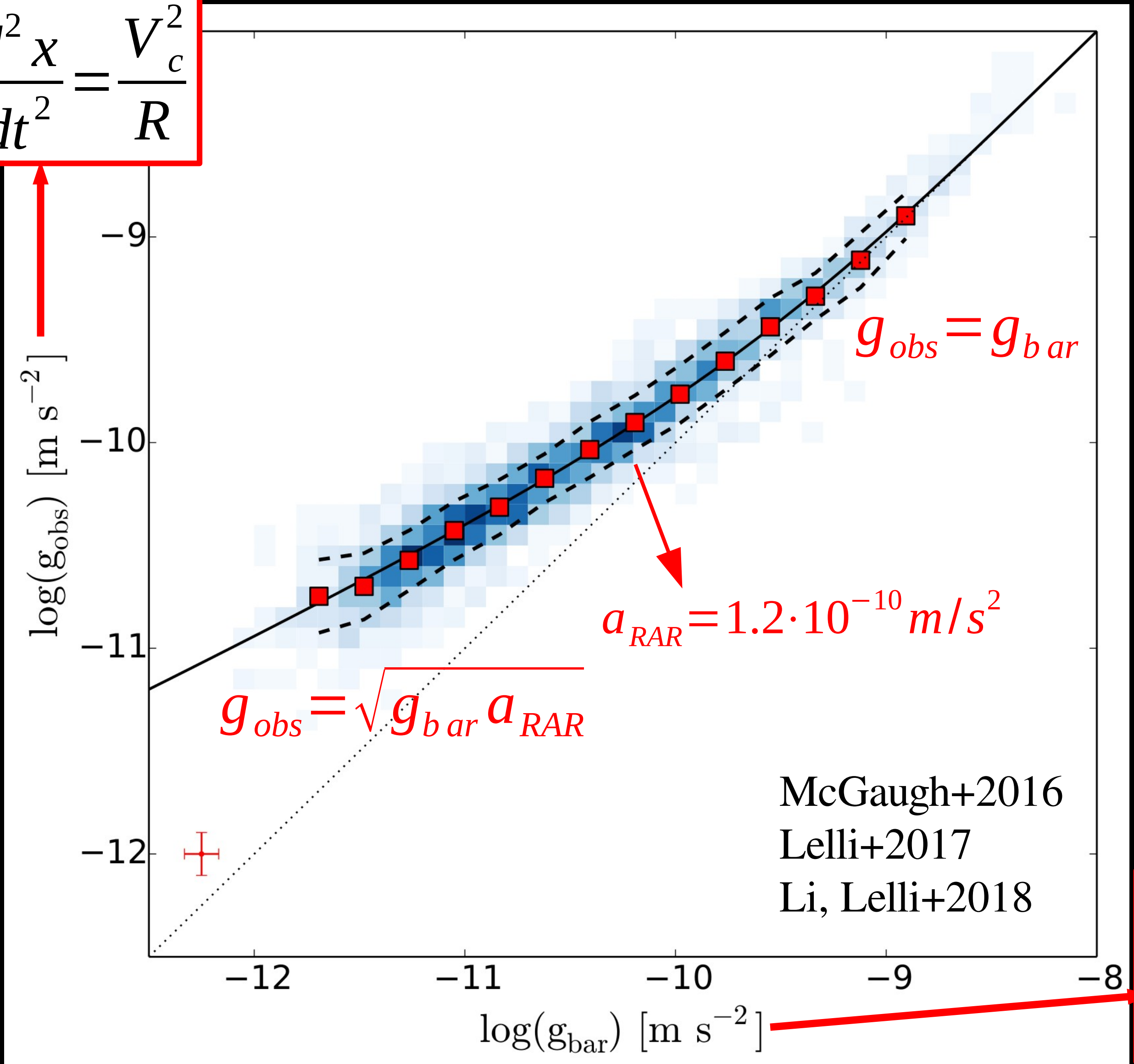
$$g_b = -\nabla \Phi_b$$
$$\nabla^2 \Phi_b = 4\pi G \rho_b$$

Very different galaxies on the same RAR



RAR sets the DM halo profiles

$$\frac{d^2 x}{dt^2} = \frac{V_c^2}{R}$$



$$g_{DM} = g_{obs} - g_{bar} = F(g_{bar})$$

$$M_{DM}(R) = \frac{R^2}{G} F(g_{bar})$$

No freedom to fit arbitrary DM halos!

"Cusp vs Core" is a symptom of a more serious general illness:

Baryon-DM coupling at any radii!

$$g_b = -\nabla \Phi_b$$
$$\nabla^2 \Phi_b = 4\pi G \rho_b$$

Small Scale ΛCDM Problems

1. Missing Satellites Problem
2. Cusp vs Core Problem
3. Too-Big-Too-Fail Problem

} Baryonic physics in ΛCDM?
WDM+SIDM ?
Modified gravity (MOND)?

4. Planes of Satellites Problem → ?

5. Dynamical Regularities → Baryon-DM interaction? MOND?