Small Scales Problems for ΛCDM Cosmology

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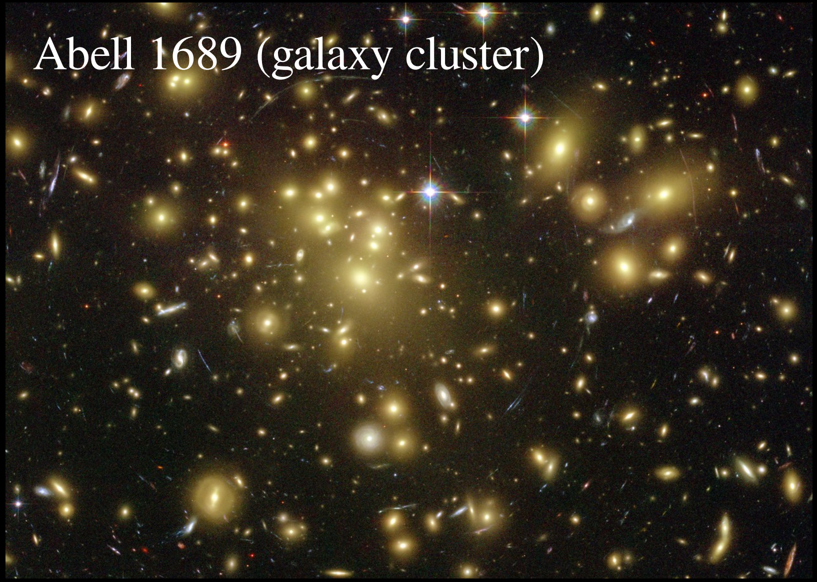
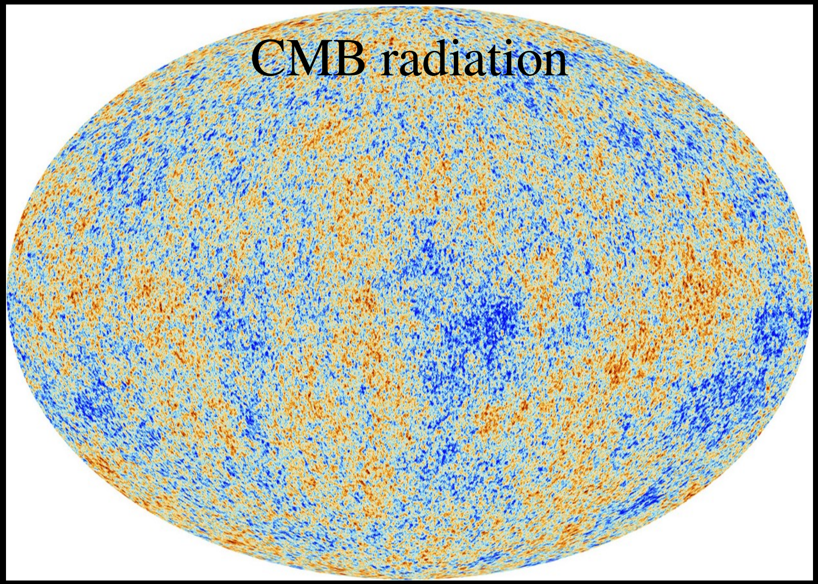
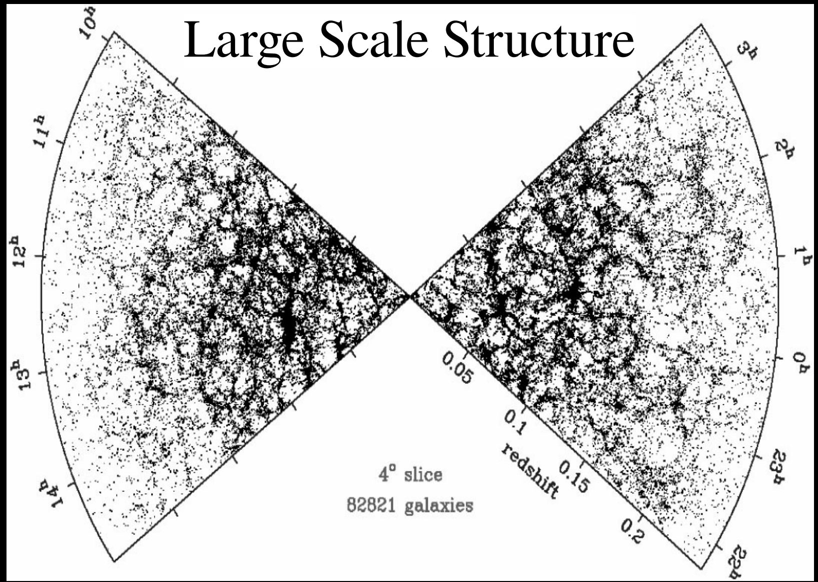
Largely based on:
Bullock & Boylan-Kolchin (2017)
Ann. Rev. Astron. & Astrophys, 55:343

Testing ΛCDM at Different Scales

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







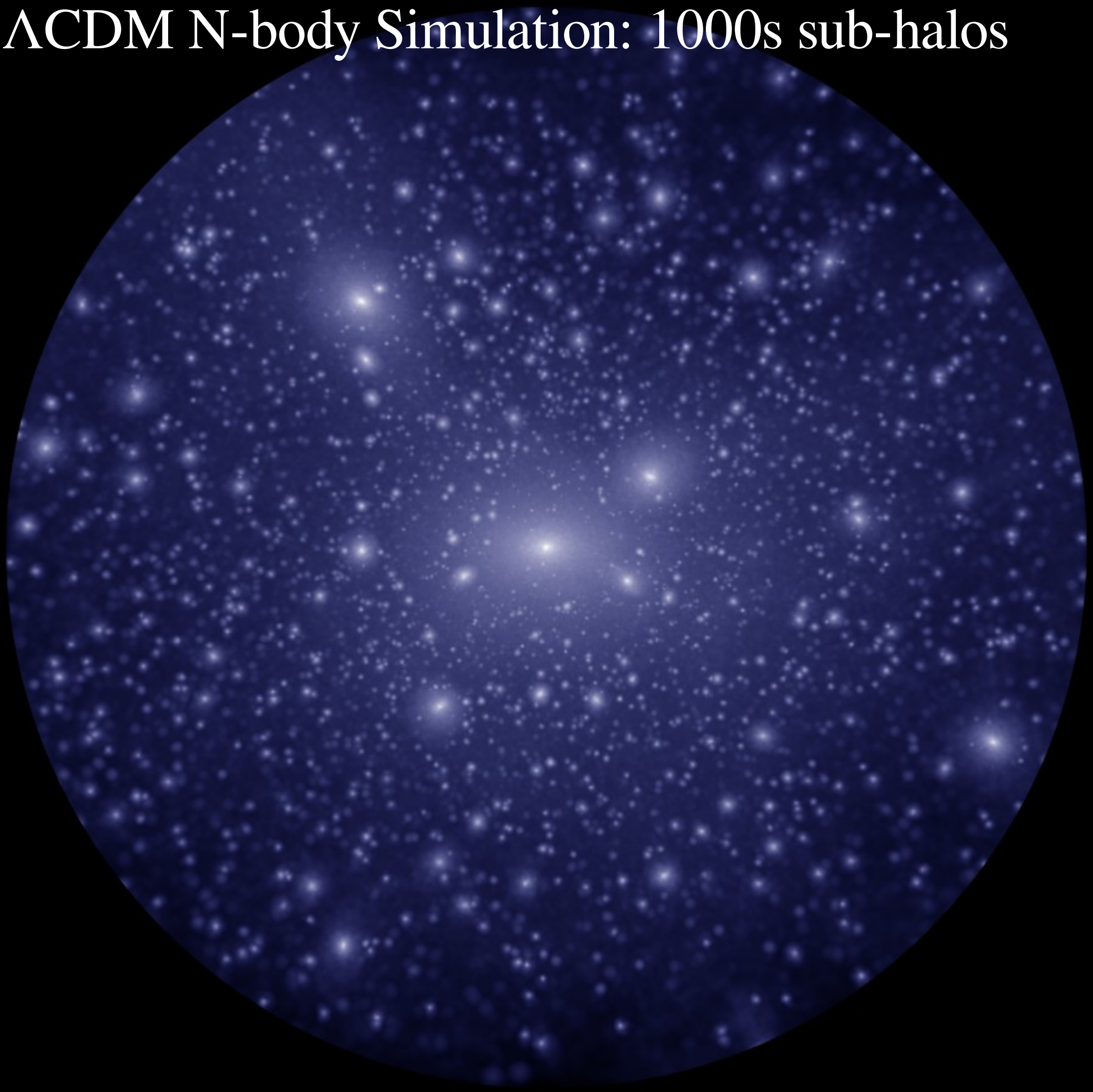
Small Scale ΛCDM Problems:

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

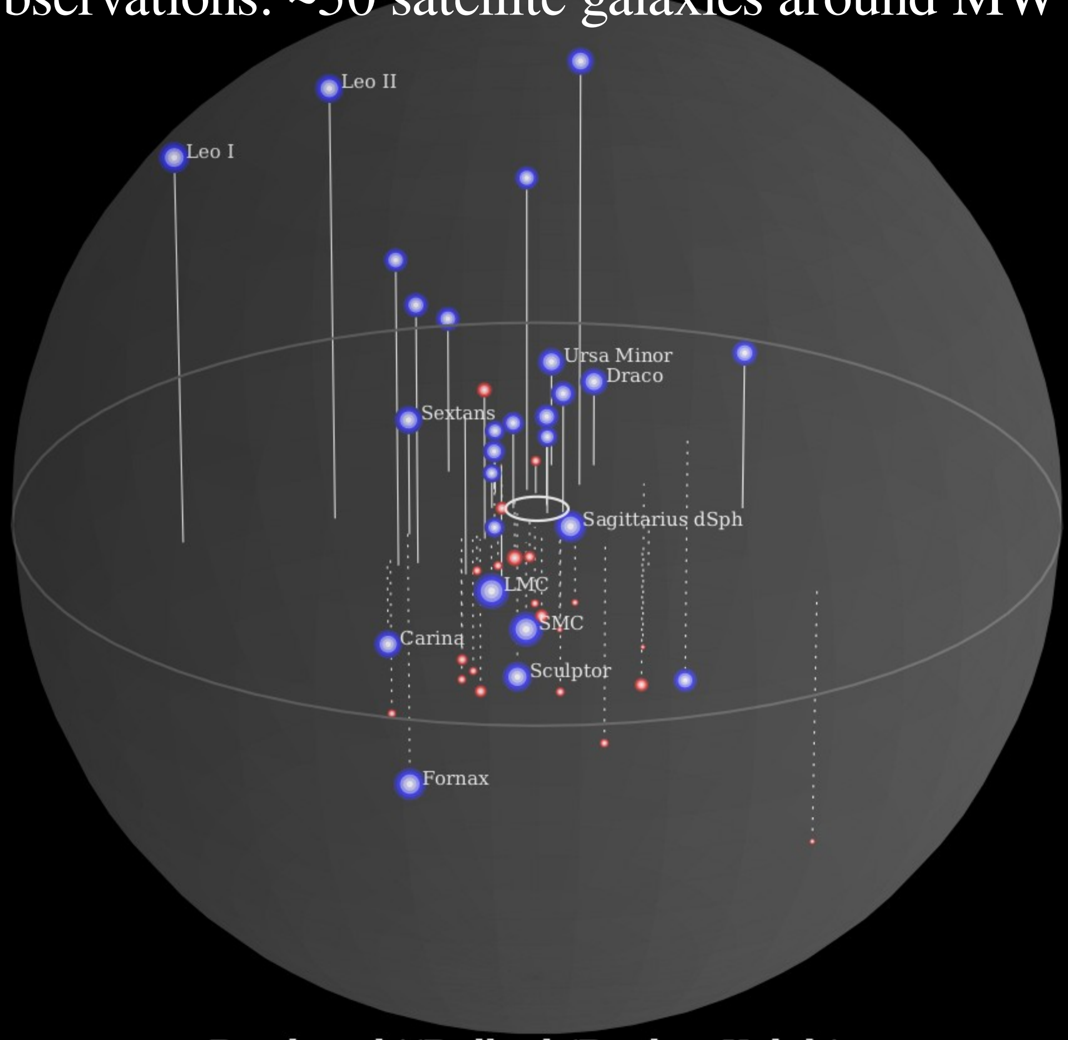
1. Missing Satellites Problem (Mass Function Problem)

The Missing Satellites Problem

ΛCDM N-body Simulation: 1000s sub-halos

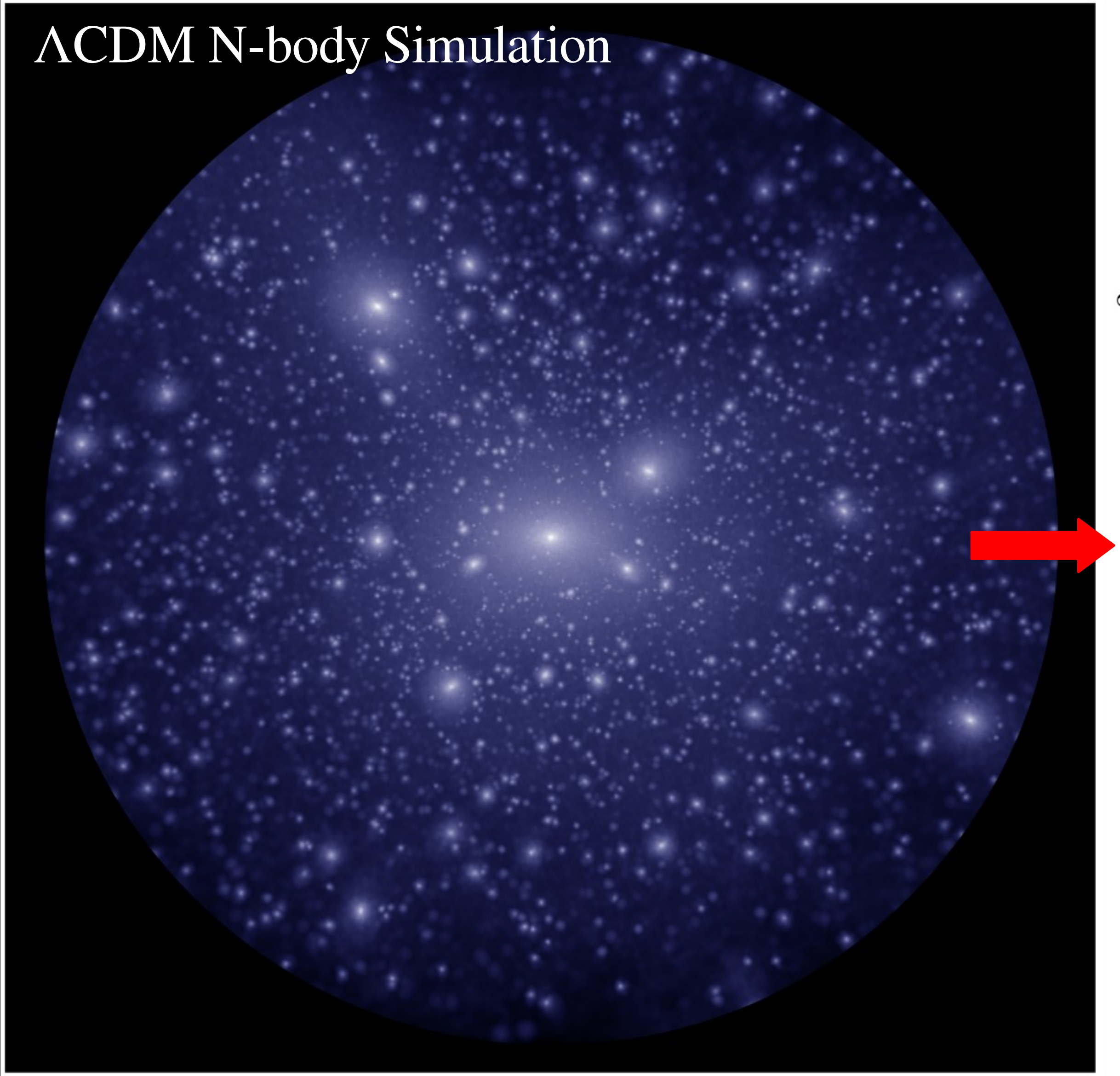


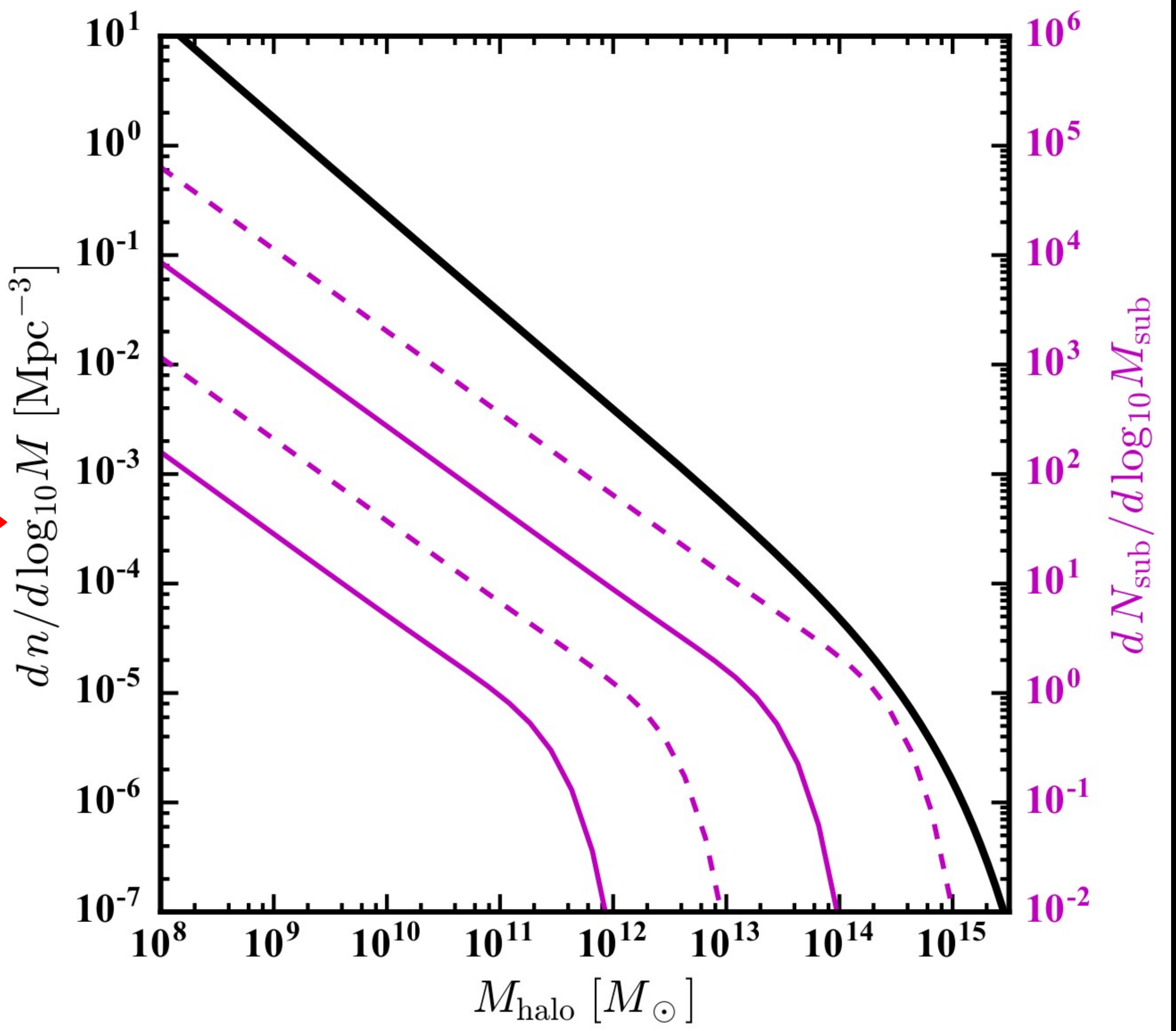
Observations: ~50 satellite galaxies around MW



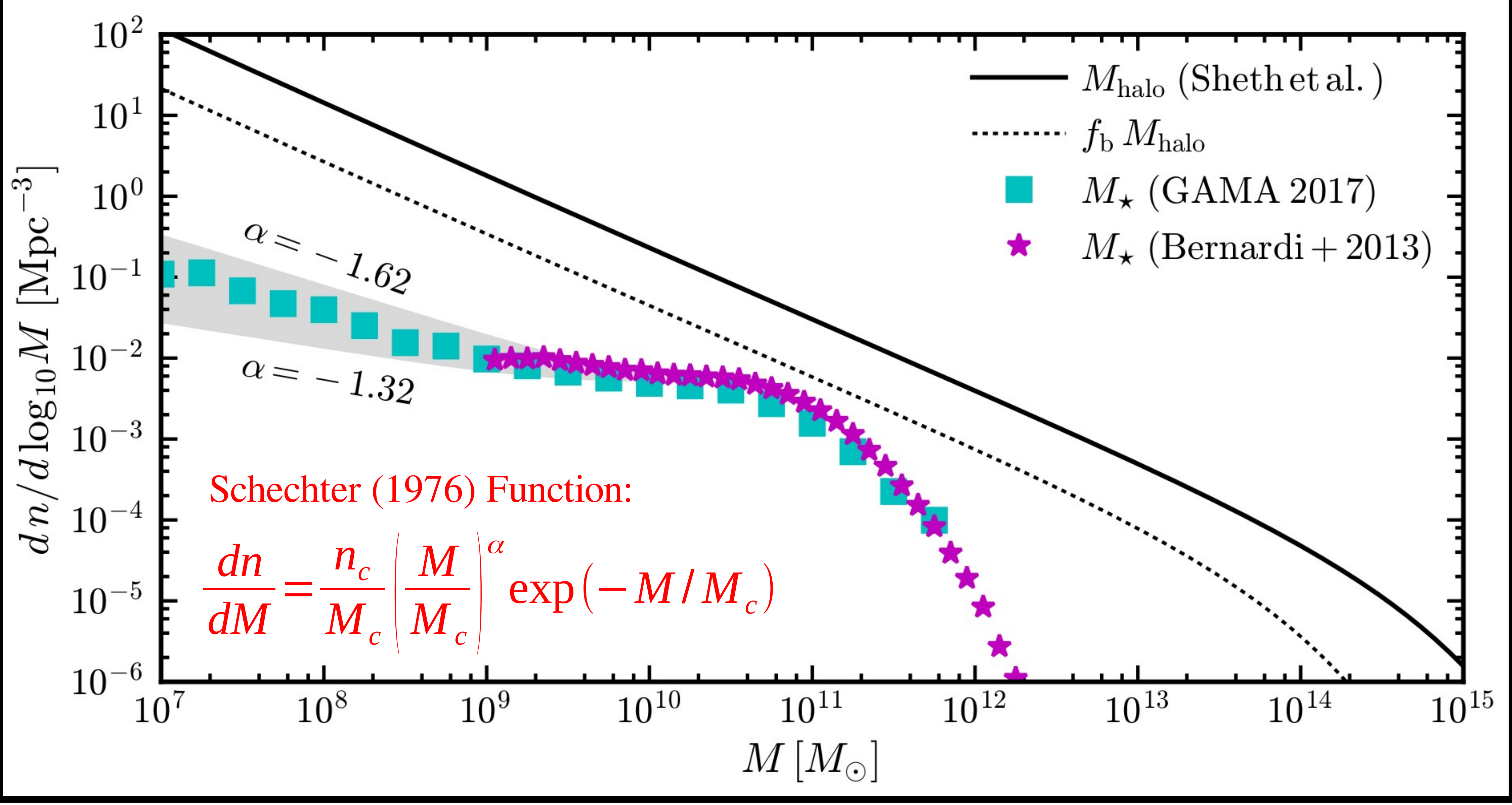
Pawlowski/Bullock/Boylan-Kolchin

The Mass Function Problem

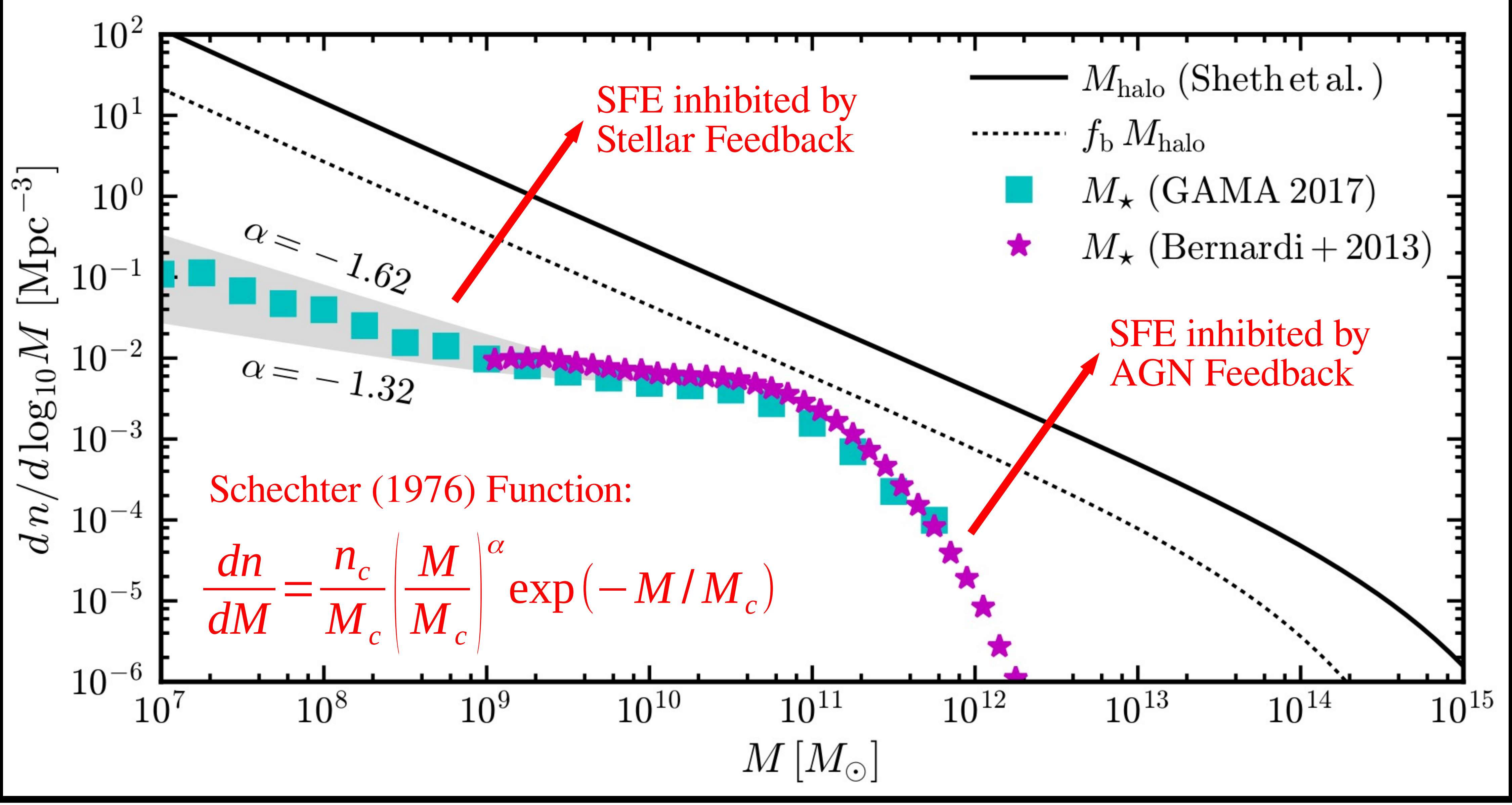




Stellar vs Halo Mass Function



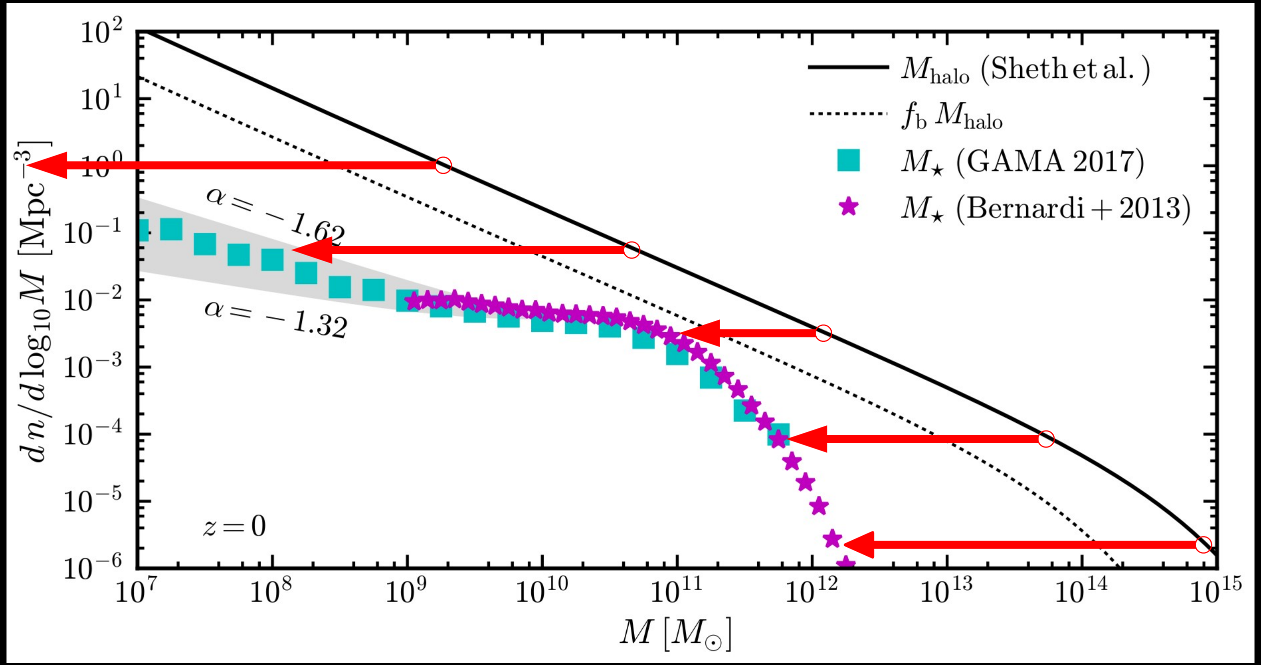
Stellar vs Halo Mass Function

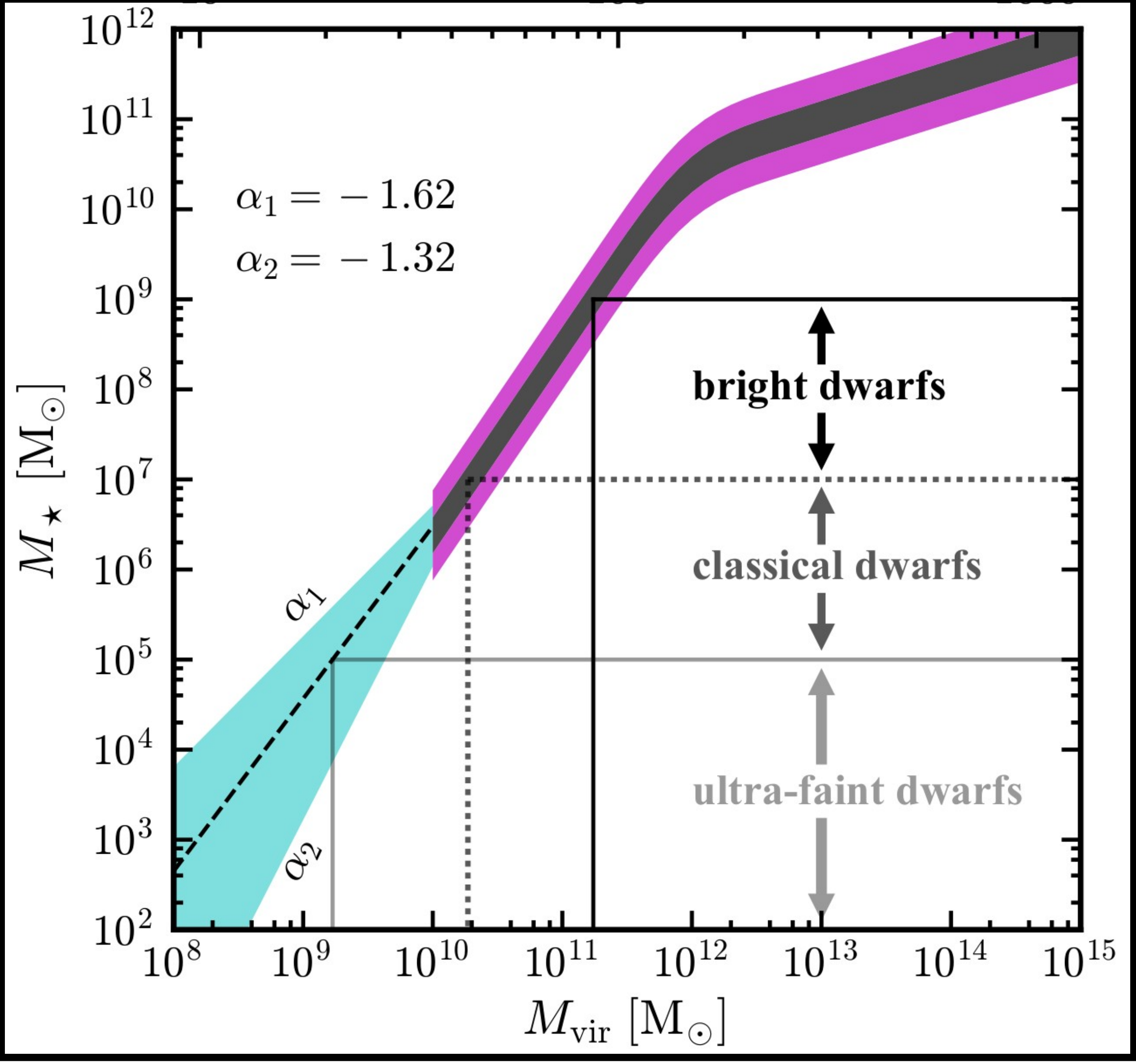


Stellar Mass – Halo Mass Relation

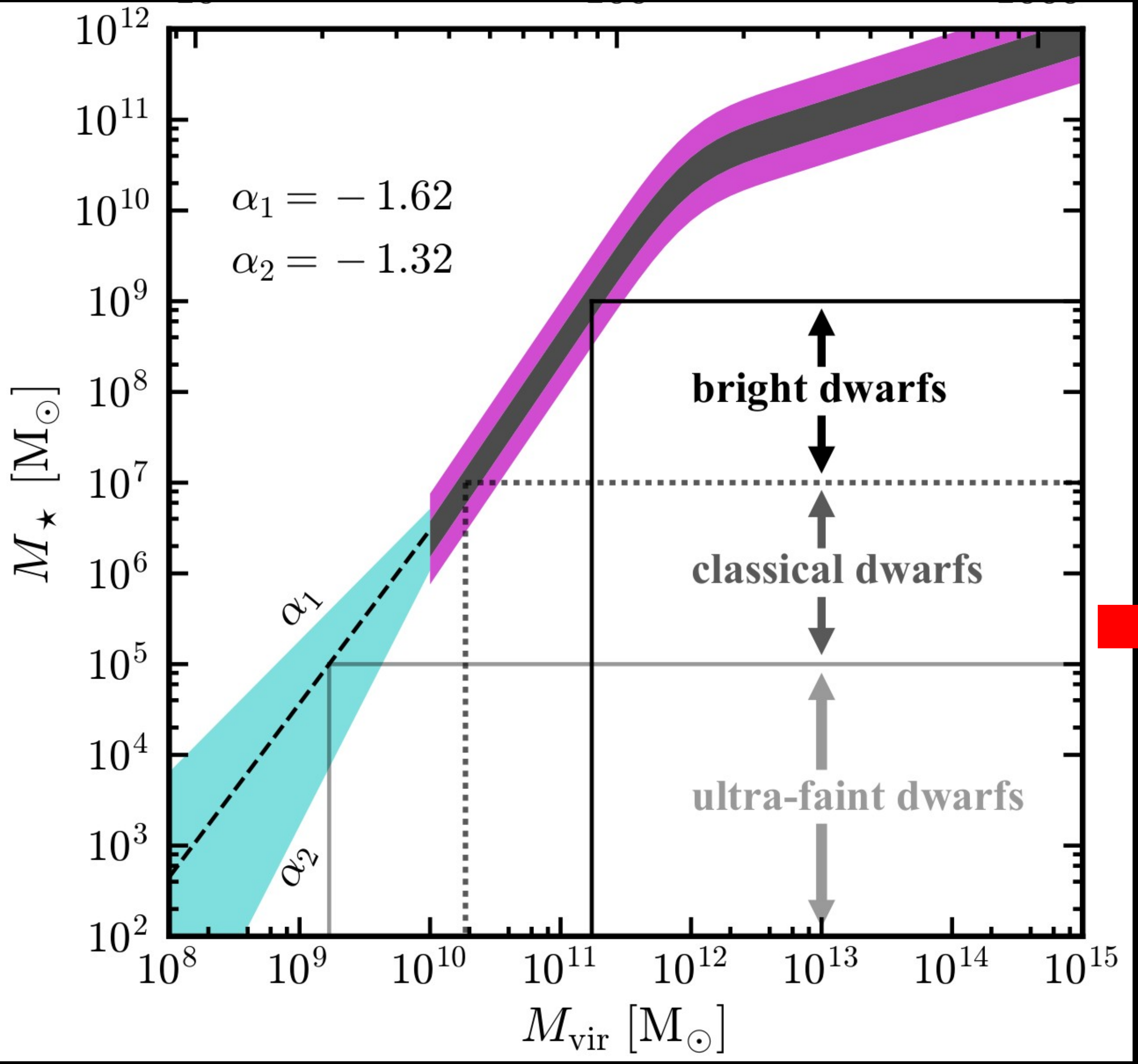
Abundance Matching:

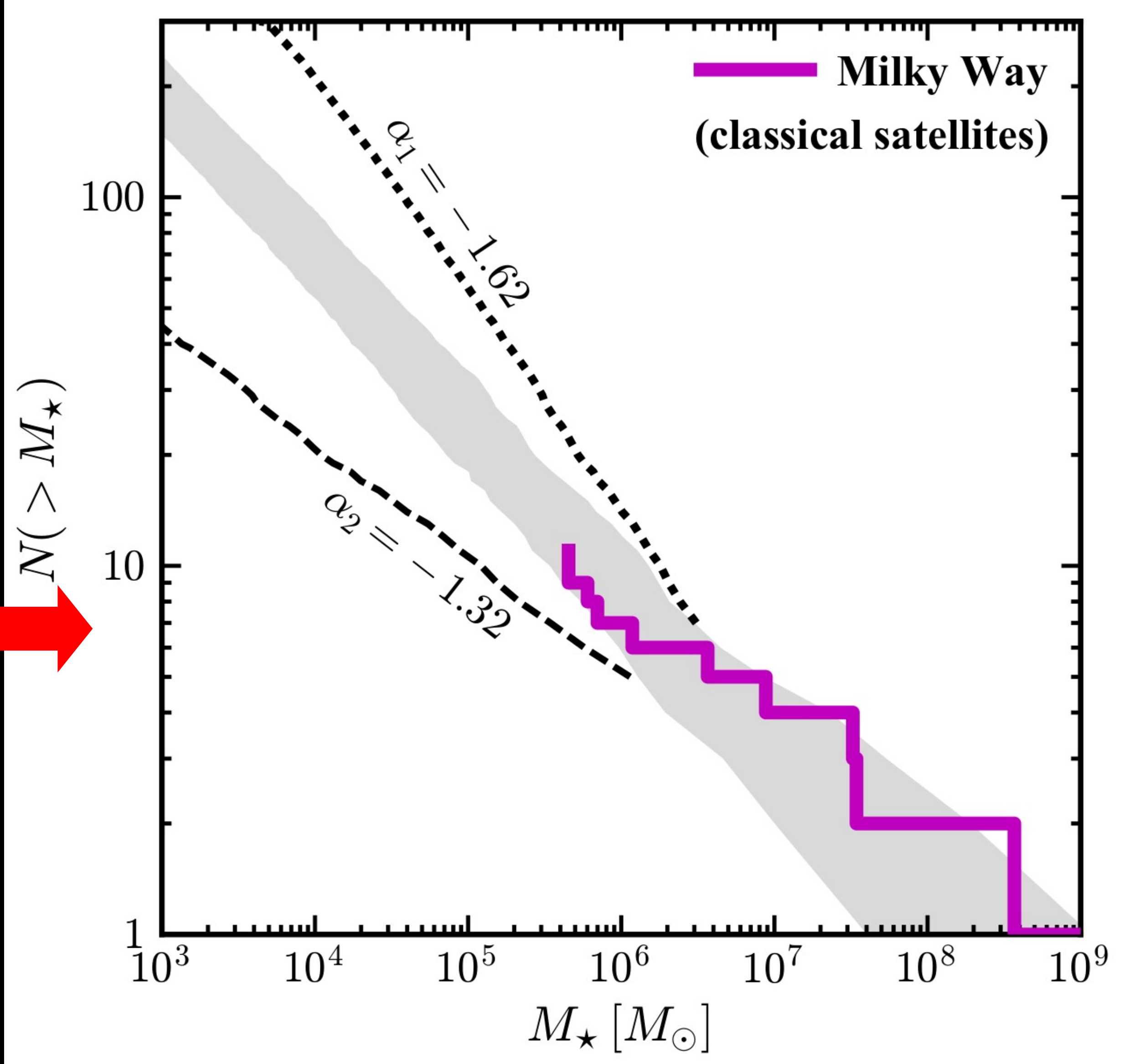
Most massive galaxy → most massive halo





Abundance Matching ↔ Missing Satellites

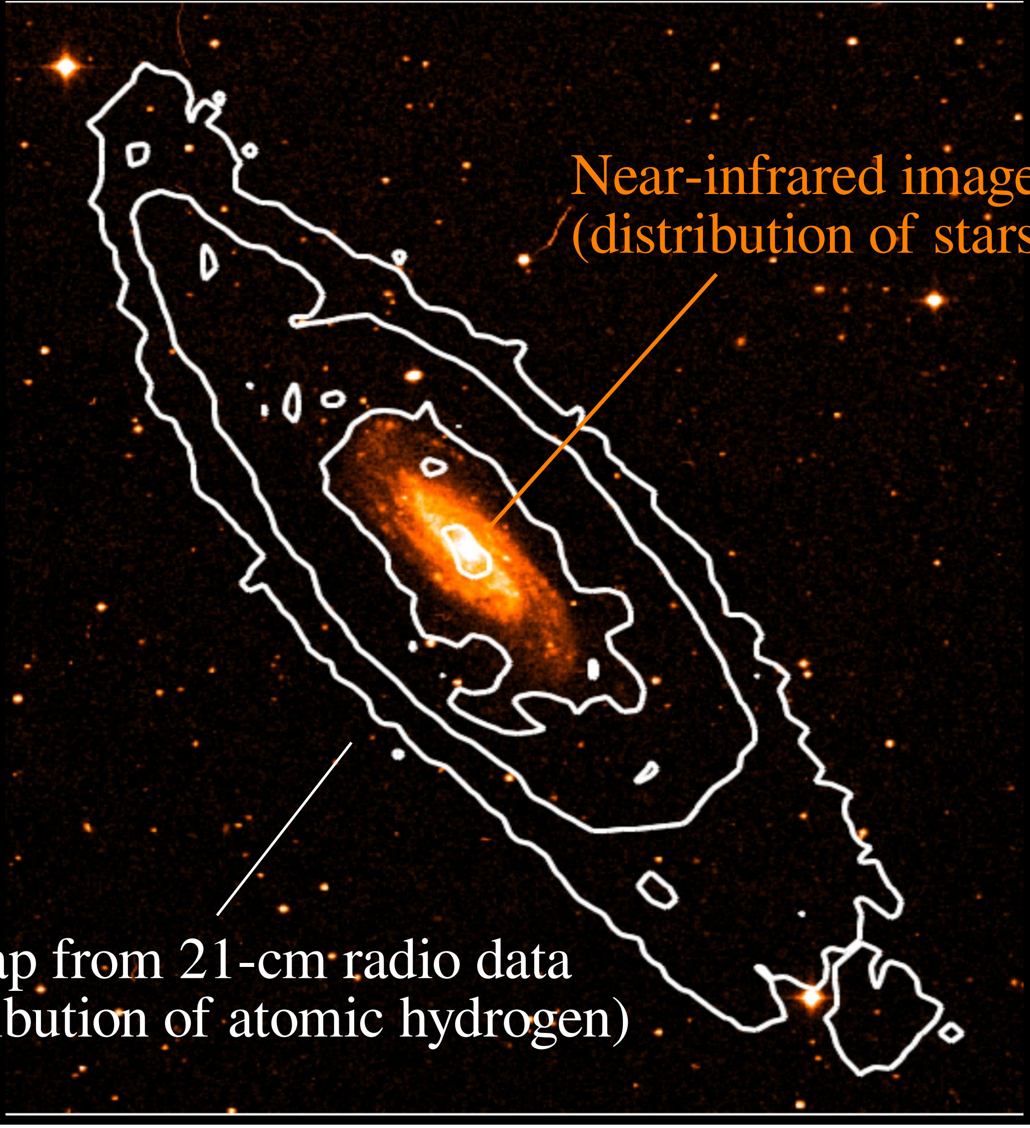




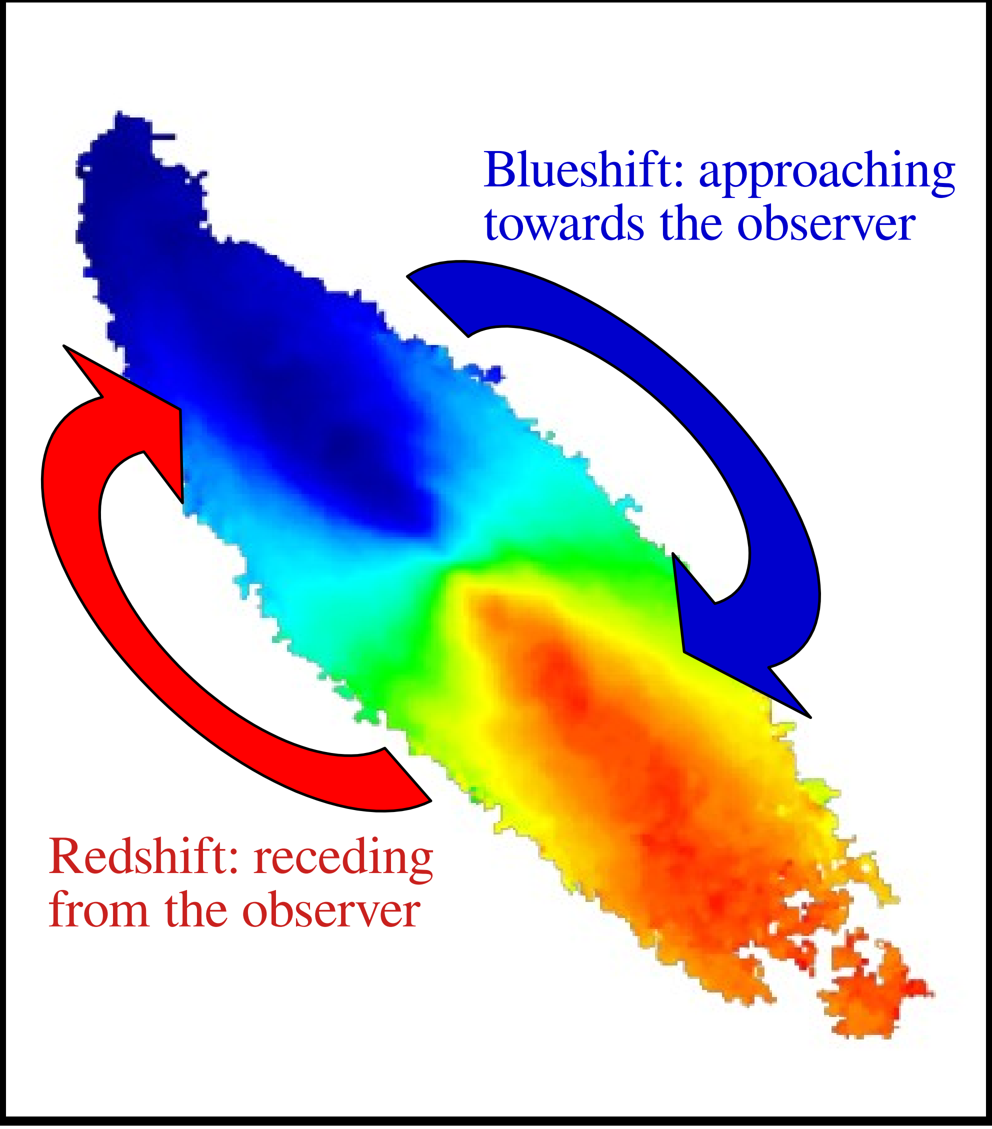
2. Cusp vs Core Problem
(Rotation Curves Problem)

Rotation Curves of Disk Galaxies

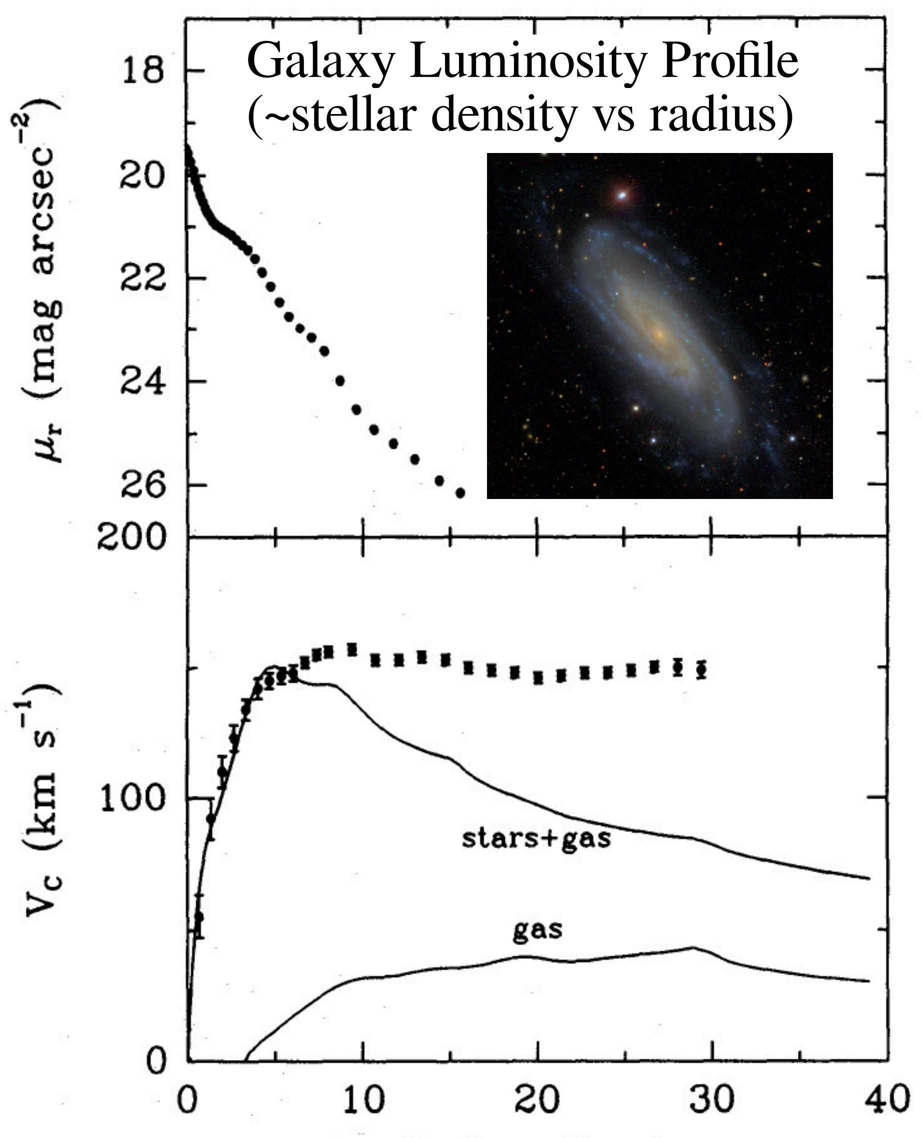
Distribution of baryons (gas & stars)



Gas Velocity along the Line of Sight



Building a Newtonian Mass Model



Van Albada+1985

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

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

- Find expected circular velocity in disk mid-plane:

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

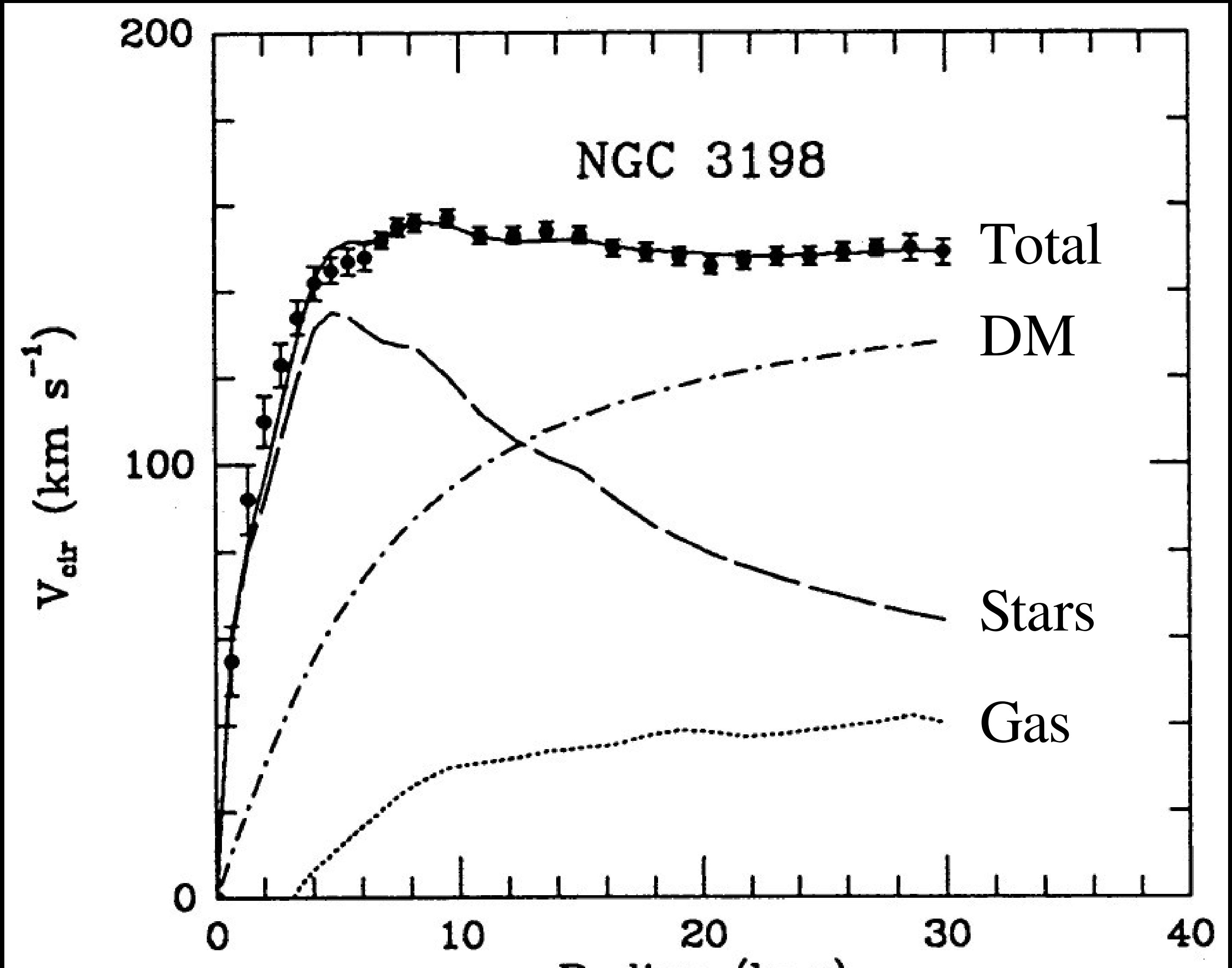
- Sum over gravitational fields ($g_i = V_i^2/R$):

$$V_b^2(R) = \Upsilon_s V_s^2(R) + \Upsilon_g V_g^2(R)$$

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



Van Albada+1985

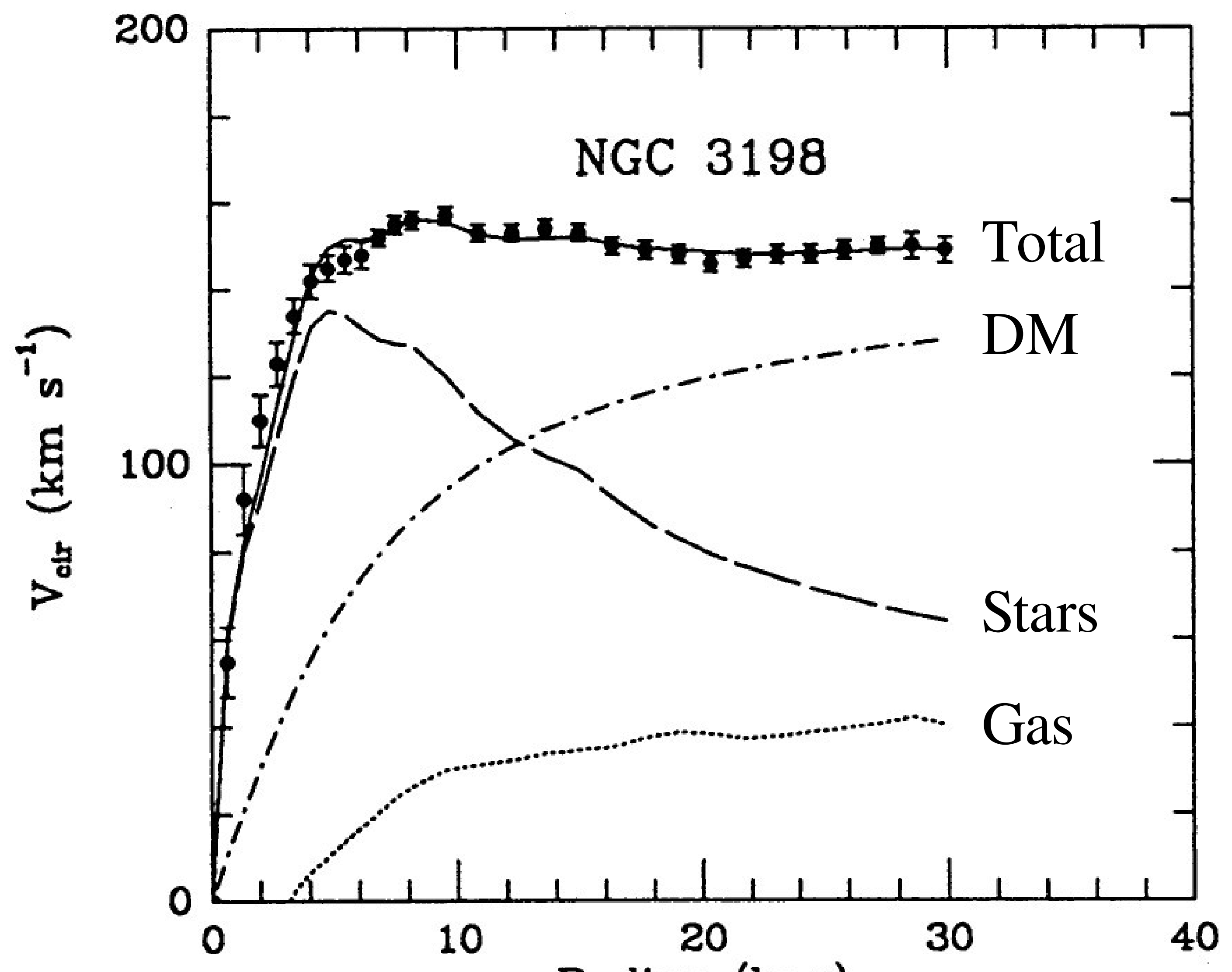
- Assume spherical DM halo profile:

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

- Add it together with the baryons:

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

Mass Model with a Dark Matter Halo



Van Albada+1985

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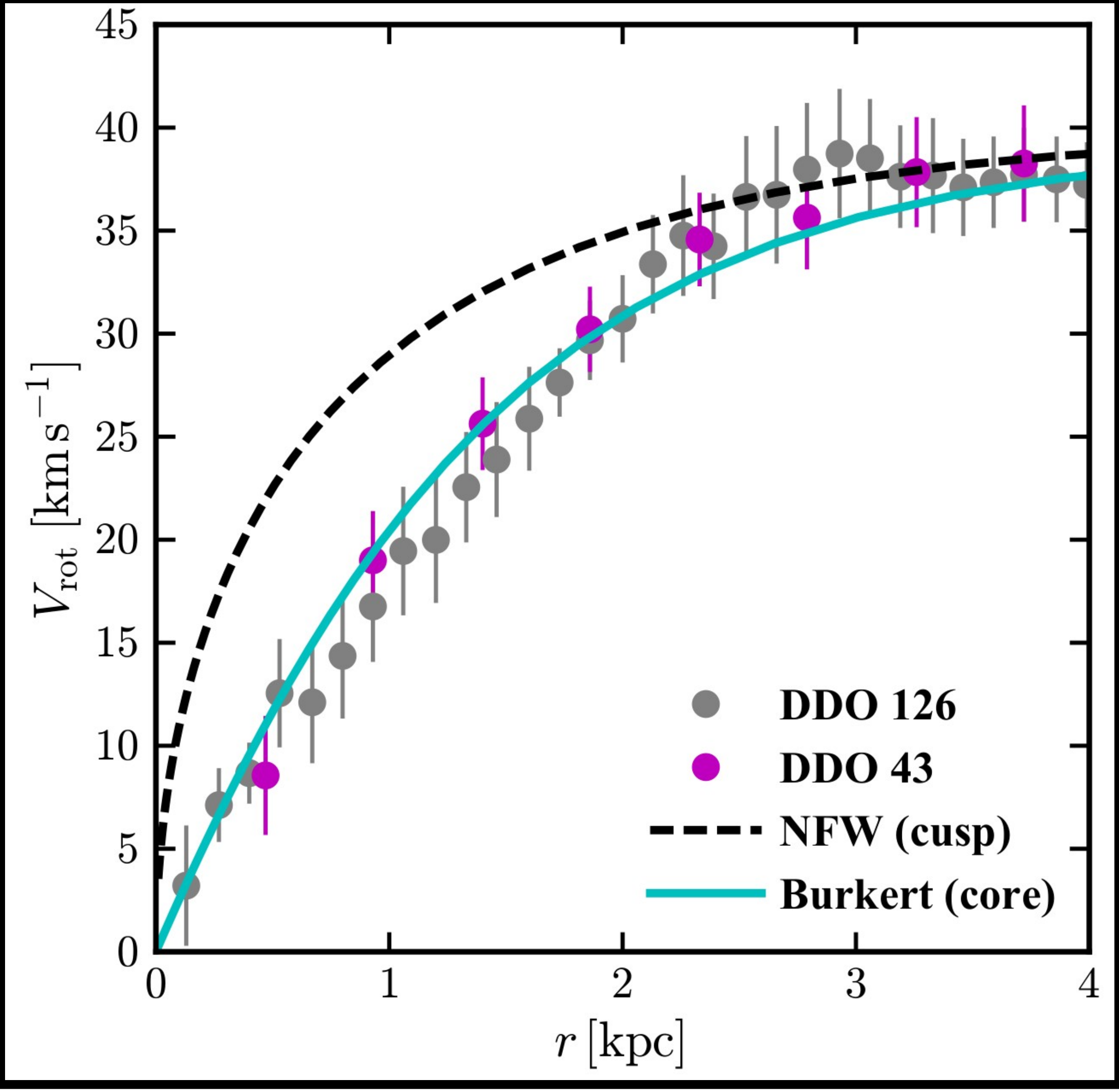
For spiral galaxies like the Milky Way, baryons dominate in the inner parts while DM is needed in the outer regions → the sum of the two gives the flat part!

Why are rotation curves flat? Unclear!
This is called "disk-halo conspiracy"
(van Albada & Sancisi 1986)

The Cusp vs Core Problem



NFW profile (from N-body sims):

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

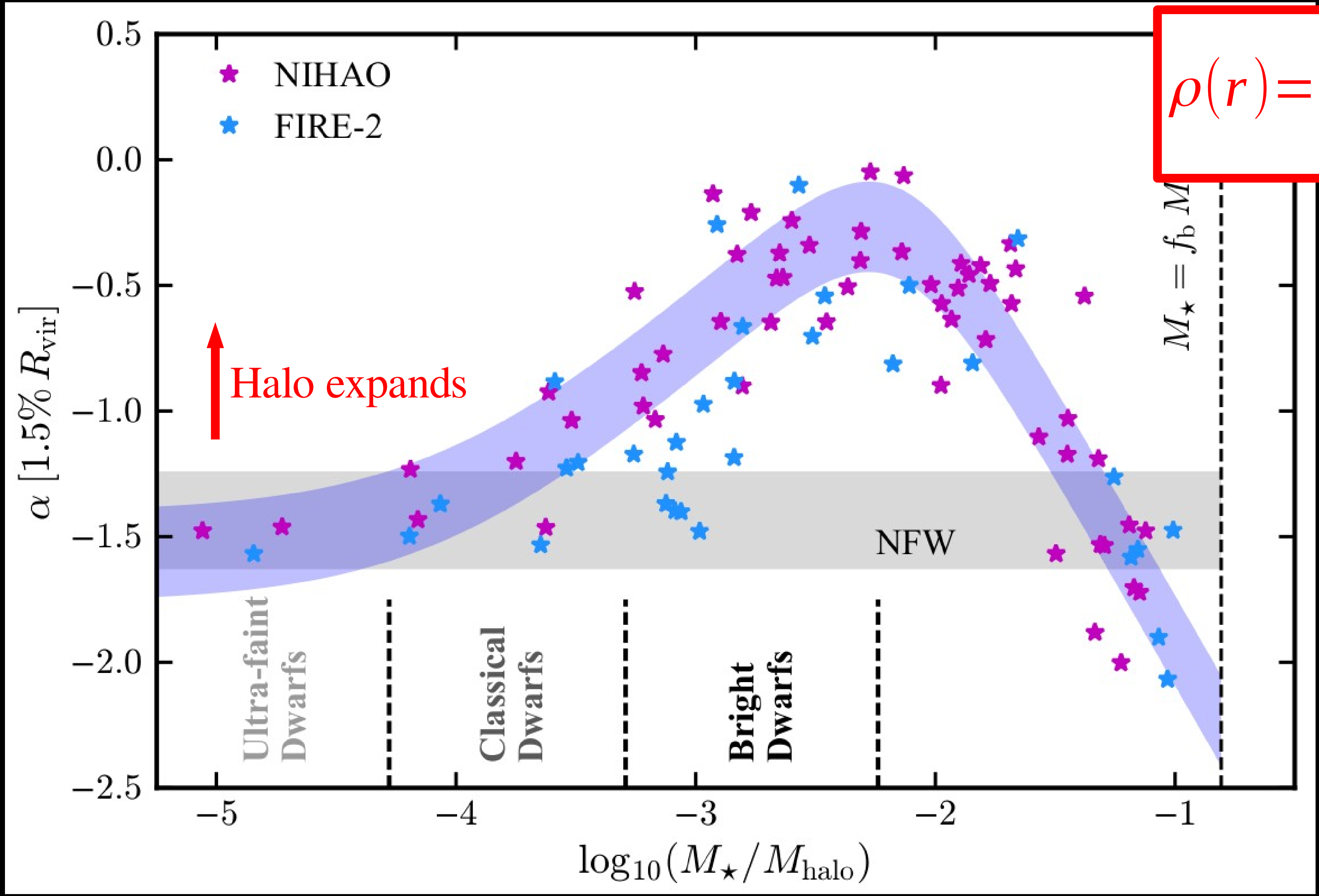
Burkert profile (empirical):

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

Pseudo-isothermal profile (empirical):

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

Core Formation from Stellar Feedback



$$\rho(r) = \frac{4\rho_c}{(r/r_c)^{\alpha}\left(1+(r/r_c)^{\gamma}\right)^{(\beta-\alpha)/\gamma}}$$

αβγ profile fitted to DM halos from hydro sims of galaxy formation with stellar feedback

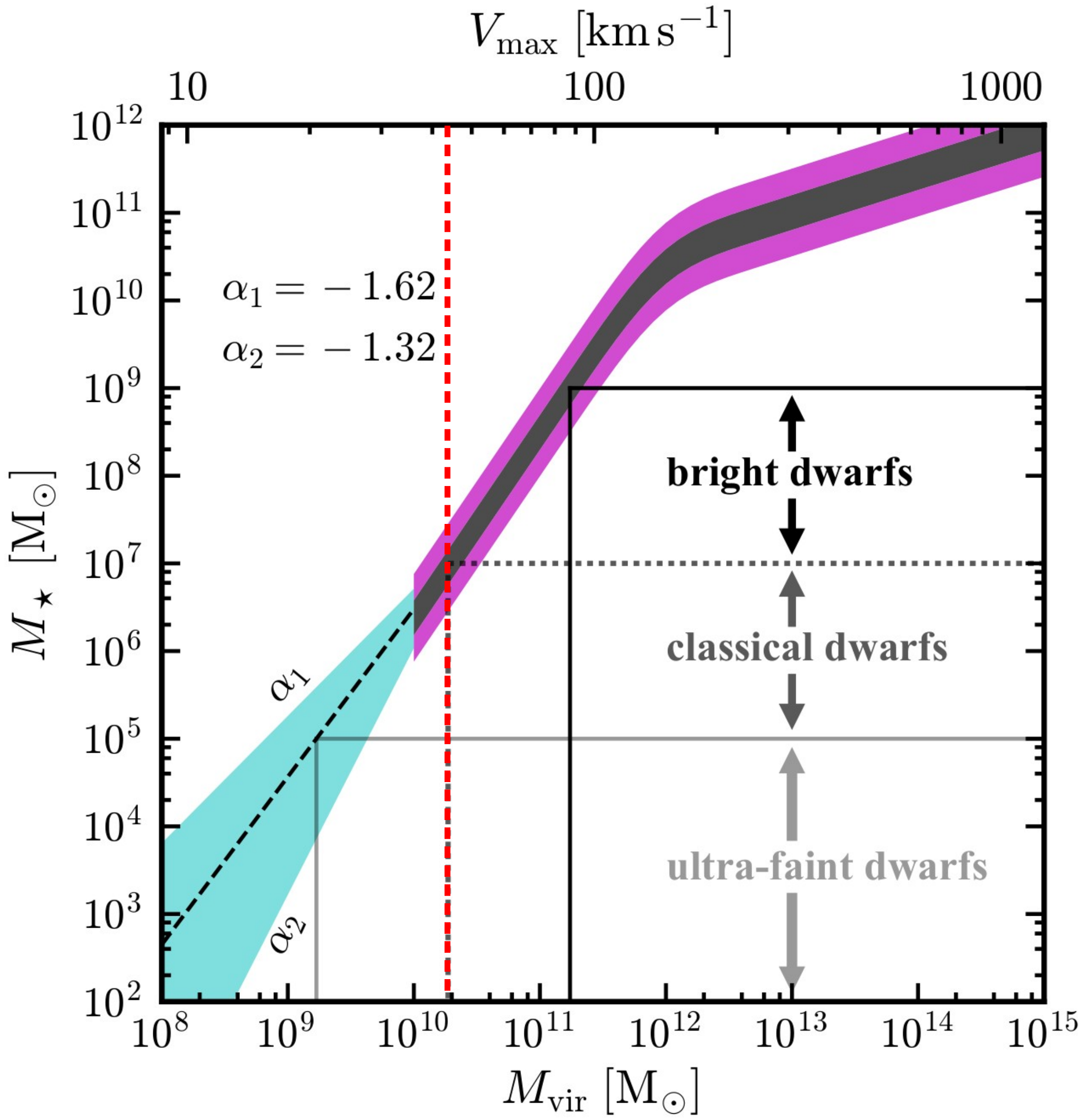
$\alpha = f_1(M_\star/M_{halo})$

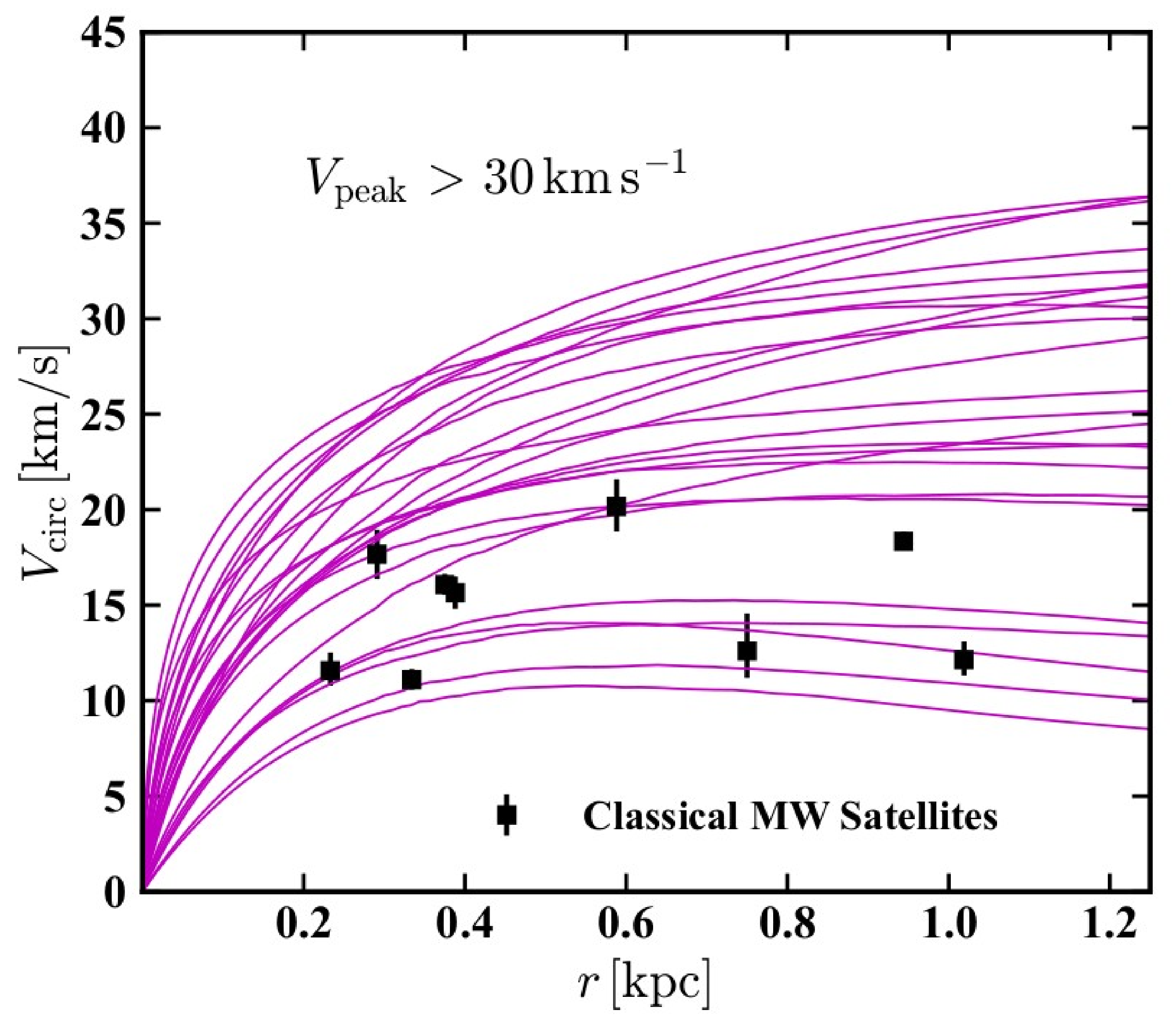
$\beta = f_2(M_\star/M_{halo})$

$\gamma = f_3(M_\star/M_{halo})$

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

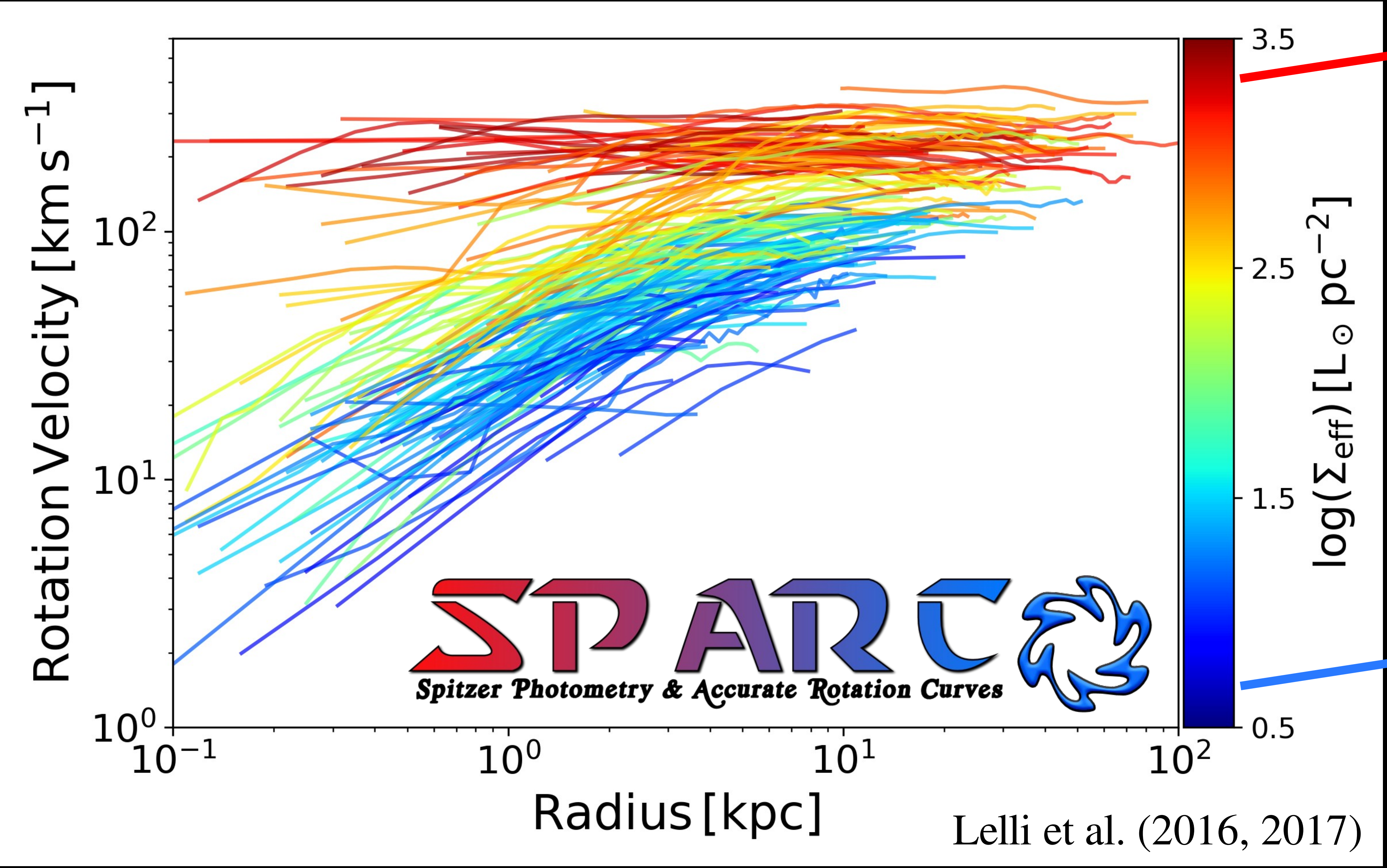
Too-Big-To-Fail Problem





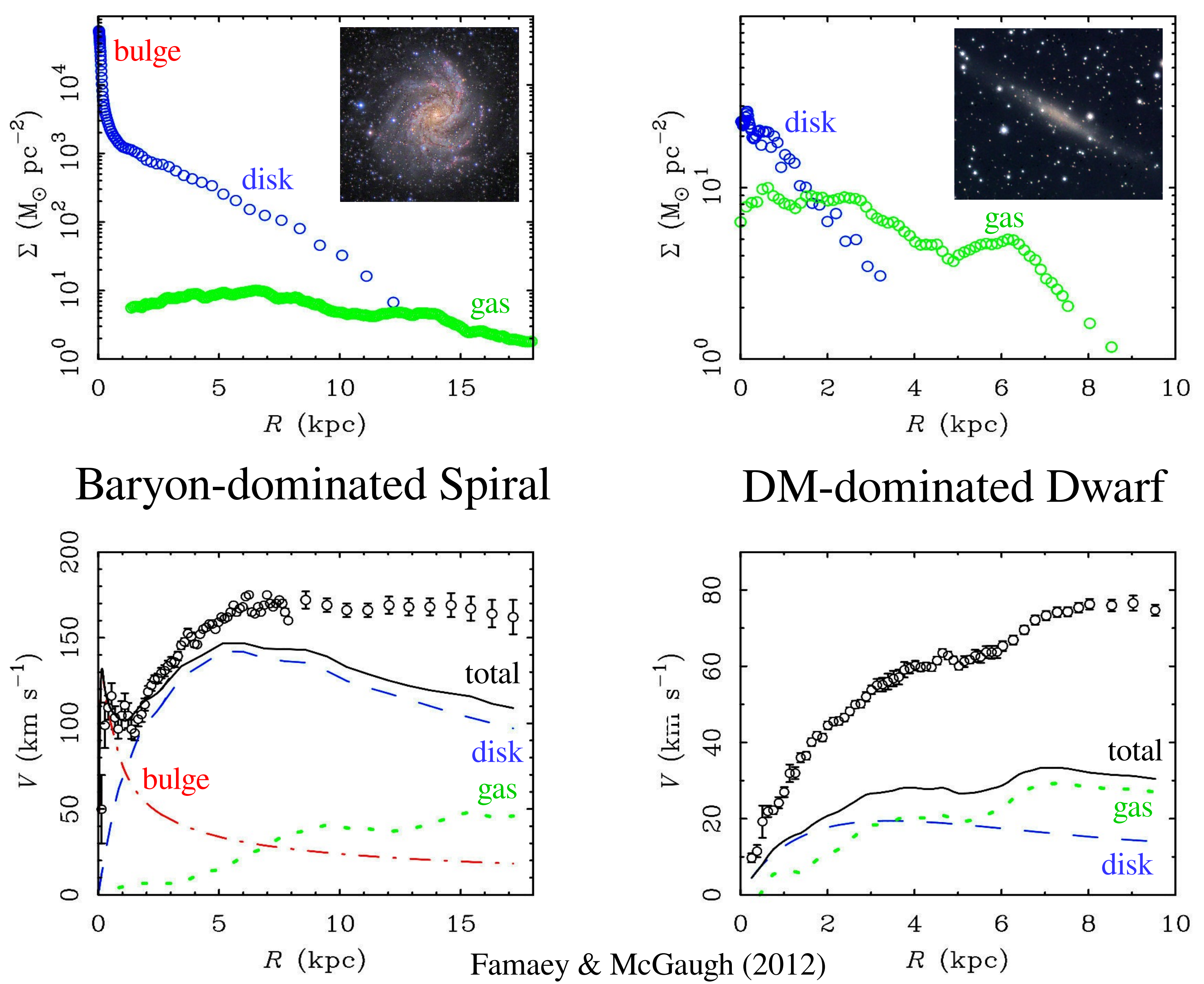
4. Regularity vs Diversity (Baryon-DM Coupling)

Rotation Curves ↔ Baryon Distribution



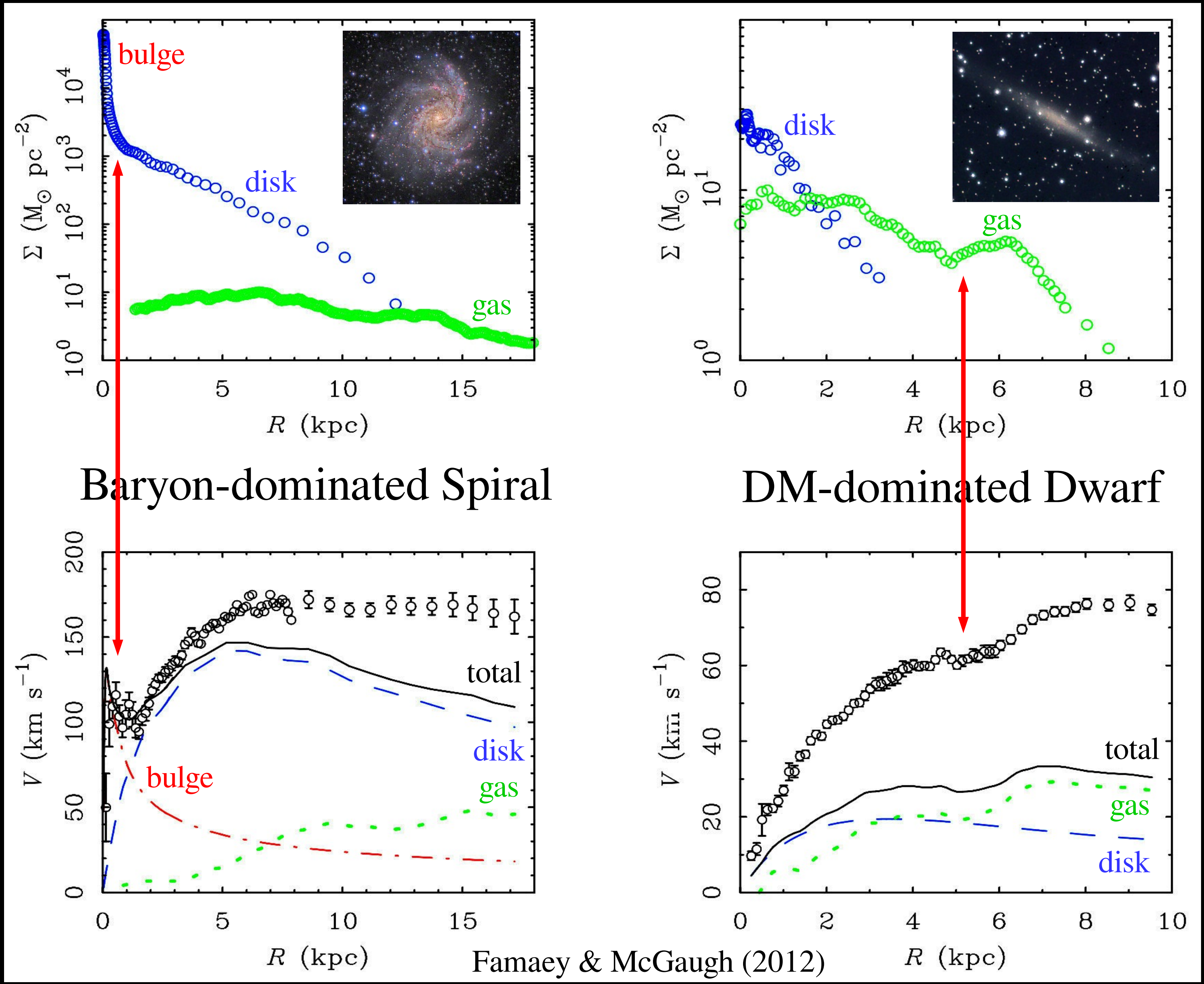
High surface brightness (very dense) galaxies
→ Steeply Rising RCs
→ Baryon dominated in the inner regions

Low surface brightness (very diffuse) galaxies
→ Slowly Rising Rcs
→ DM dominated down to the inner regions



Baryons ↔ Dynamics

Rotation curves are flat at very large radii, but can display structures/features in the inner regions.



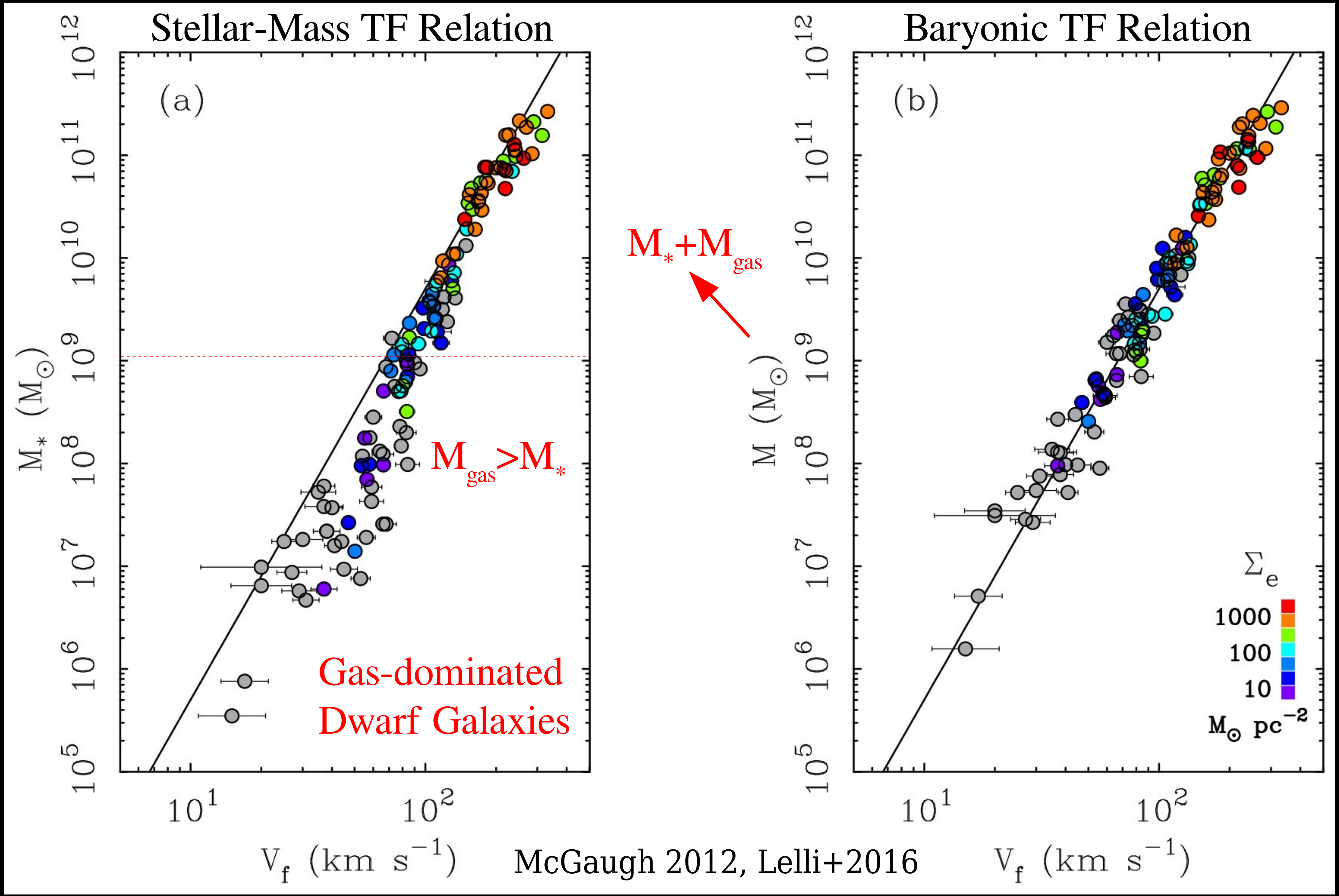
Baryons ↔ Dynamics

Rotation curves are flat at very large radii, but can display structures/features in the inner regions.

Renzo's Rule (Sancisi 2004):

"For any feature in the luminosity profile of a galaxy, there is a corresponding feature in the rotation curve, and vice versa"

Tully Fisher Relation: Mass vs Velocity



Newton's Law gives:

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

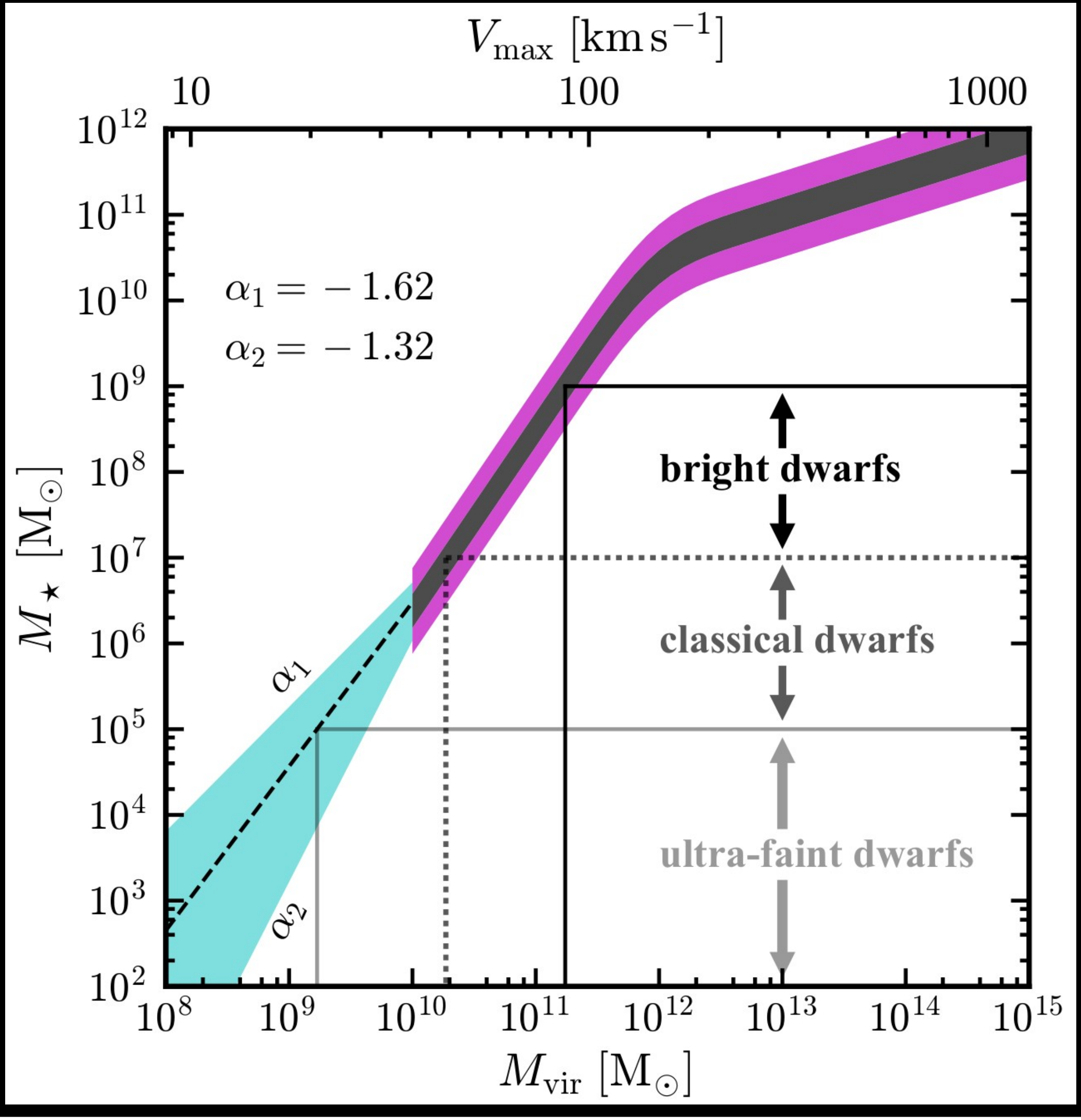
$$f_b = M_b / M_{tot}$$

But no dependence on Σ_b is observed.

→ $\Sigma_b / f_b^{\,2} \sim$ const

Fine-tuning problem

Abundance Matching → Curvated BTFR



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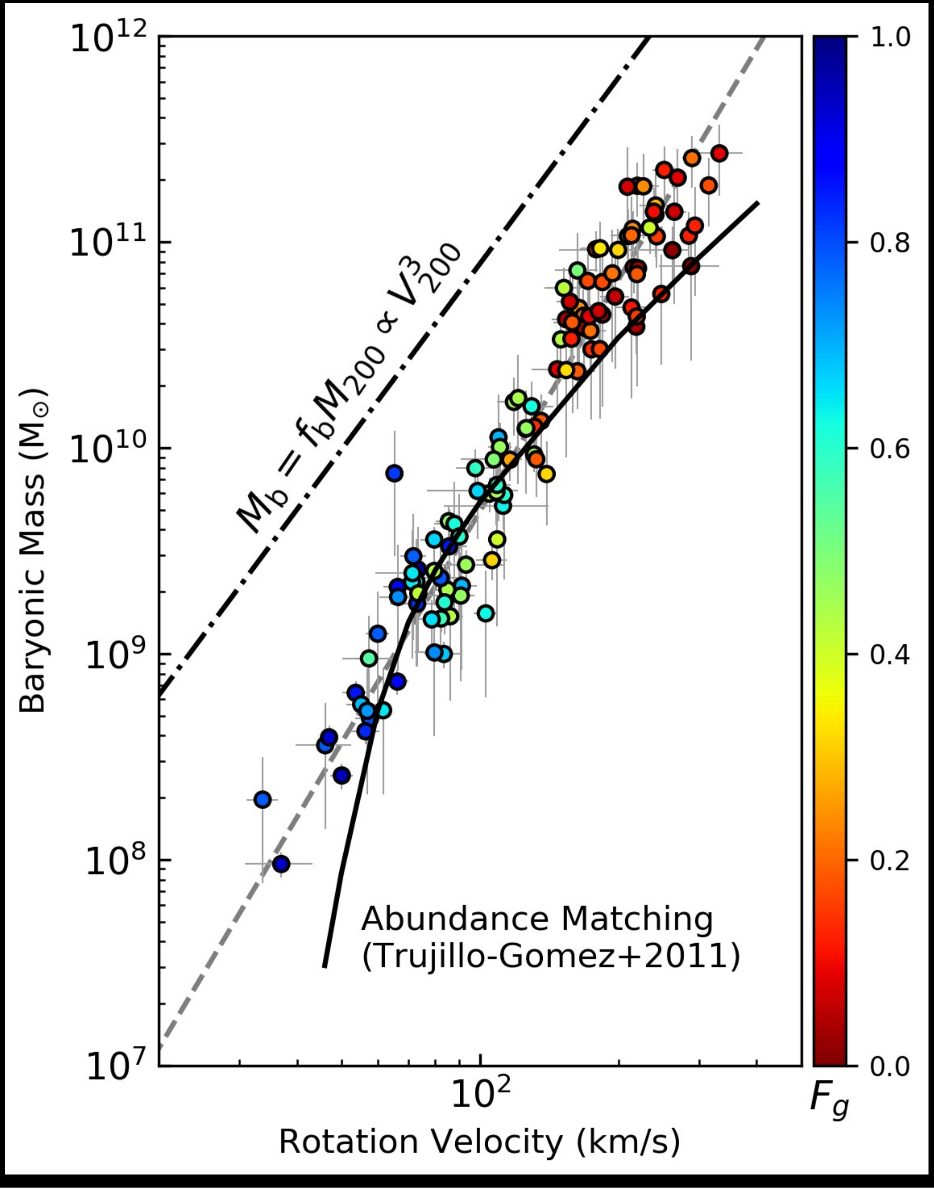
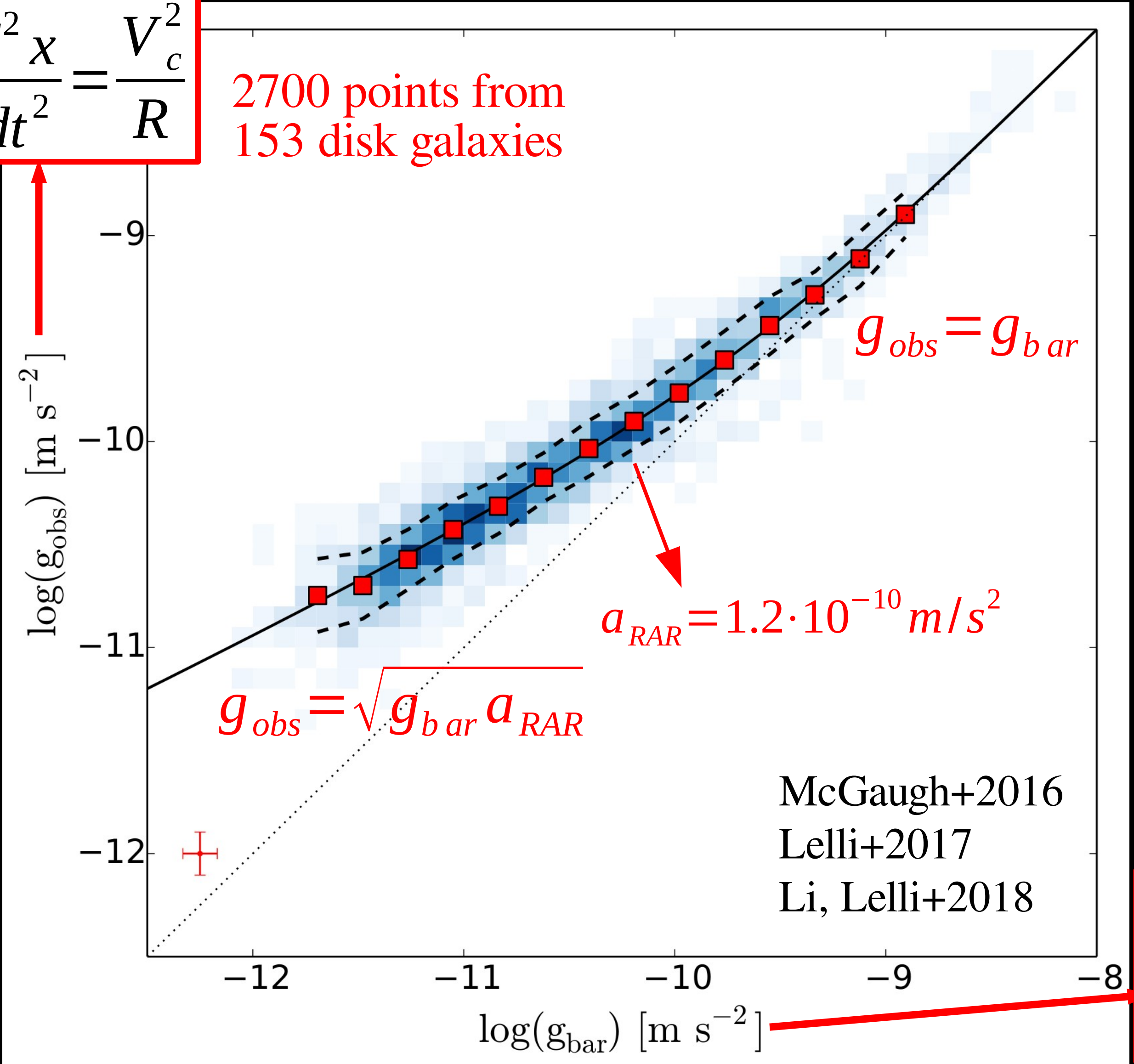


Radial Acceleration Relation (RAR)

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



Observables:

g_{obs} → centripetal acceleration from RCs

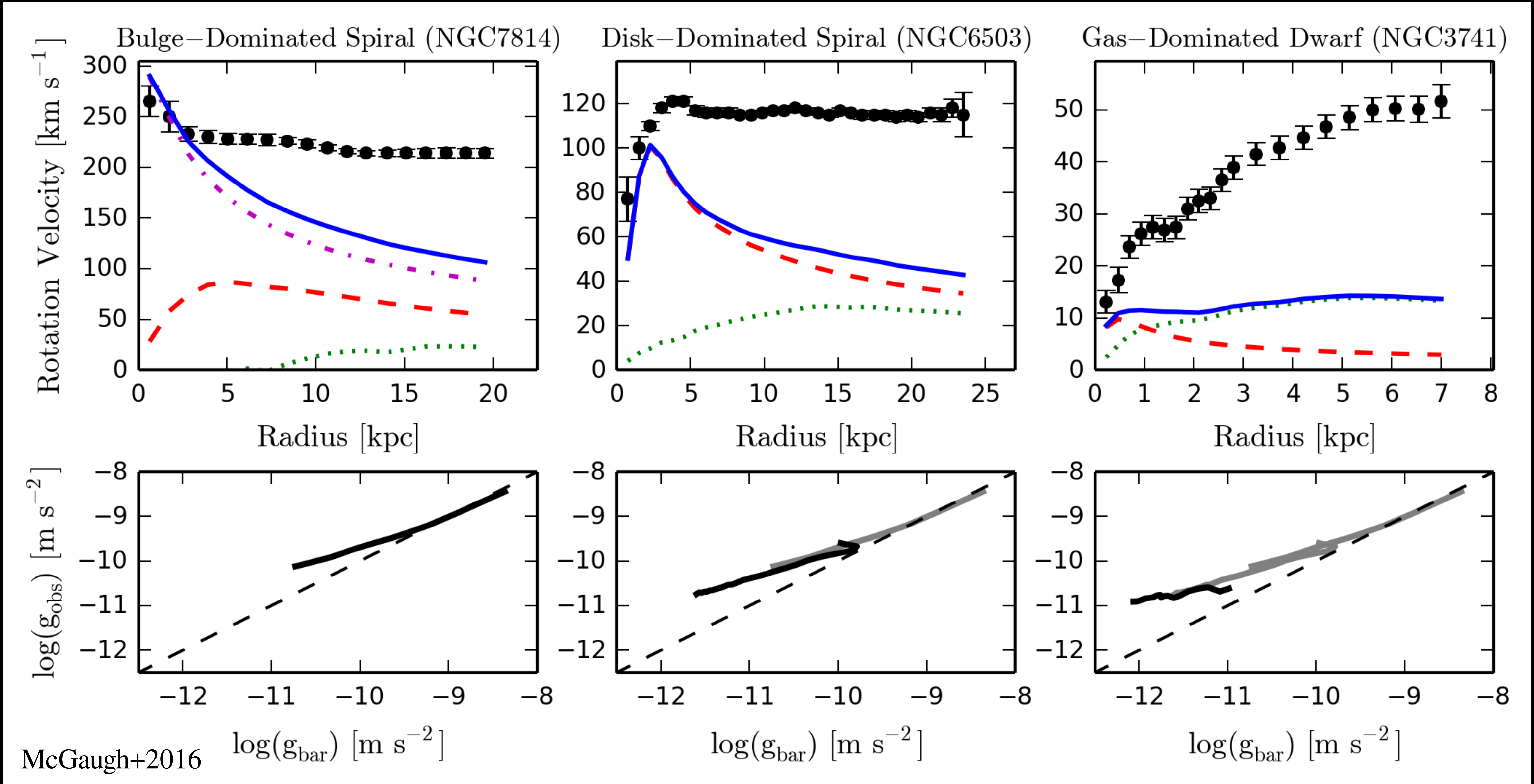
g_{bar} → gravitational field from baryons

Key Properties:

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

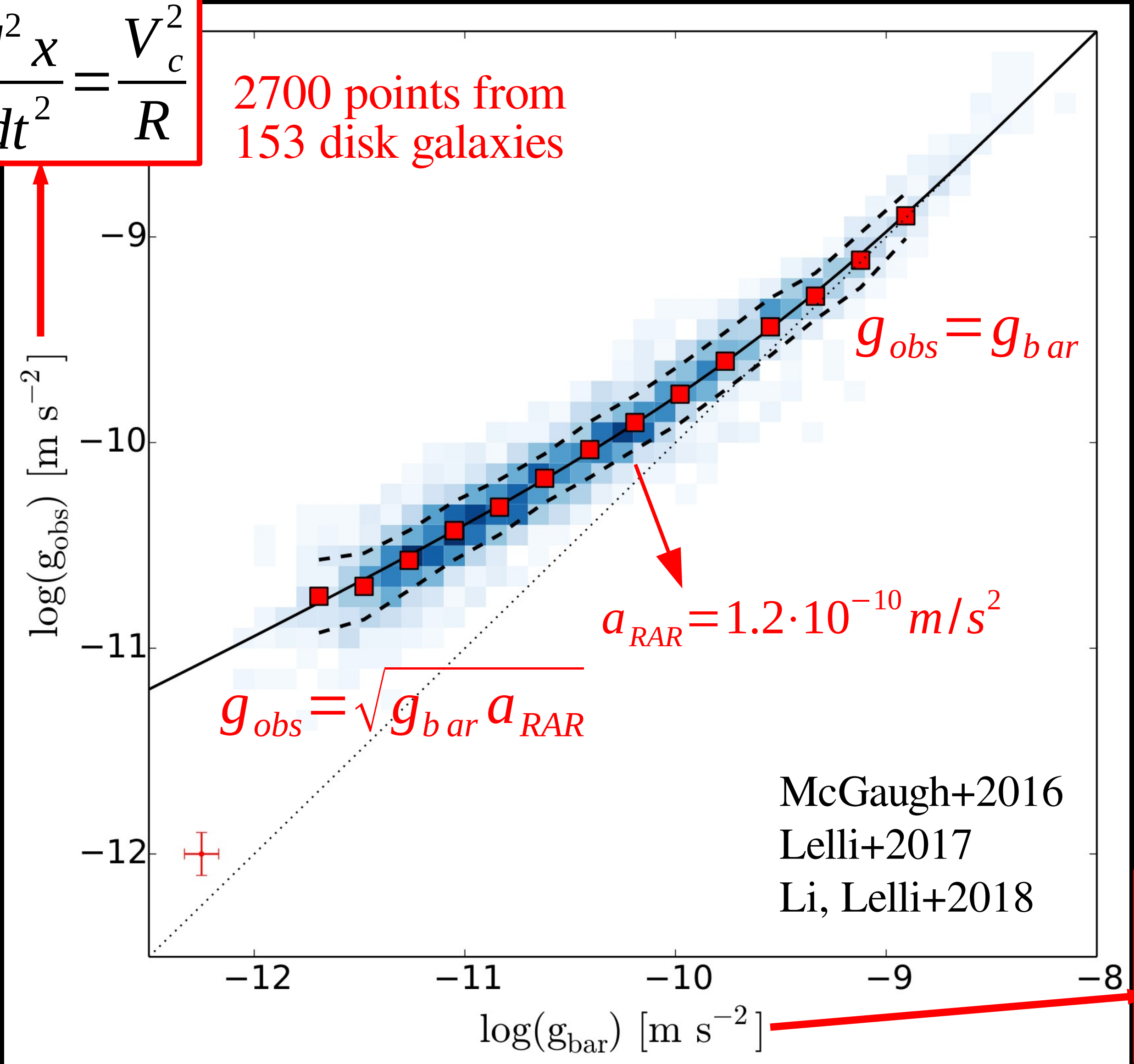
$$g_b = -\nabla \Phi_b$$
$$\nabla^2 \Phi_b = 4\pi G \rho_b$$

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 vsCore" is a symptom of a more serious general illness:

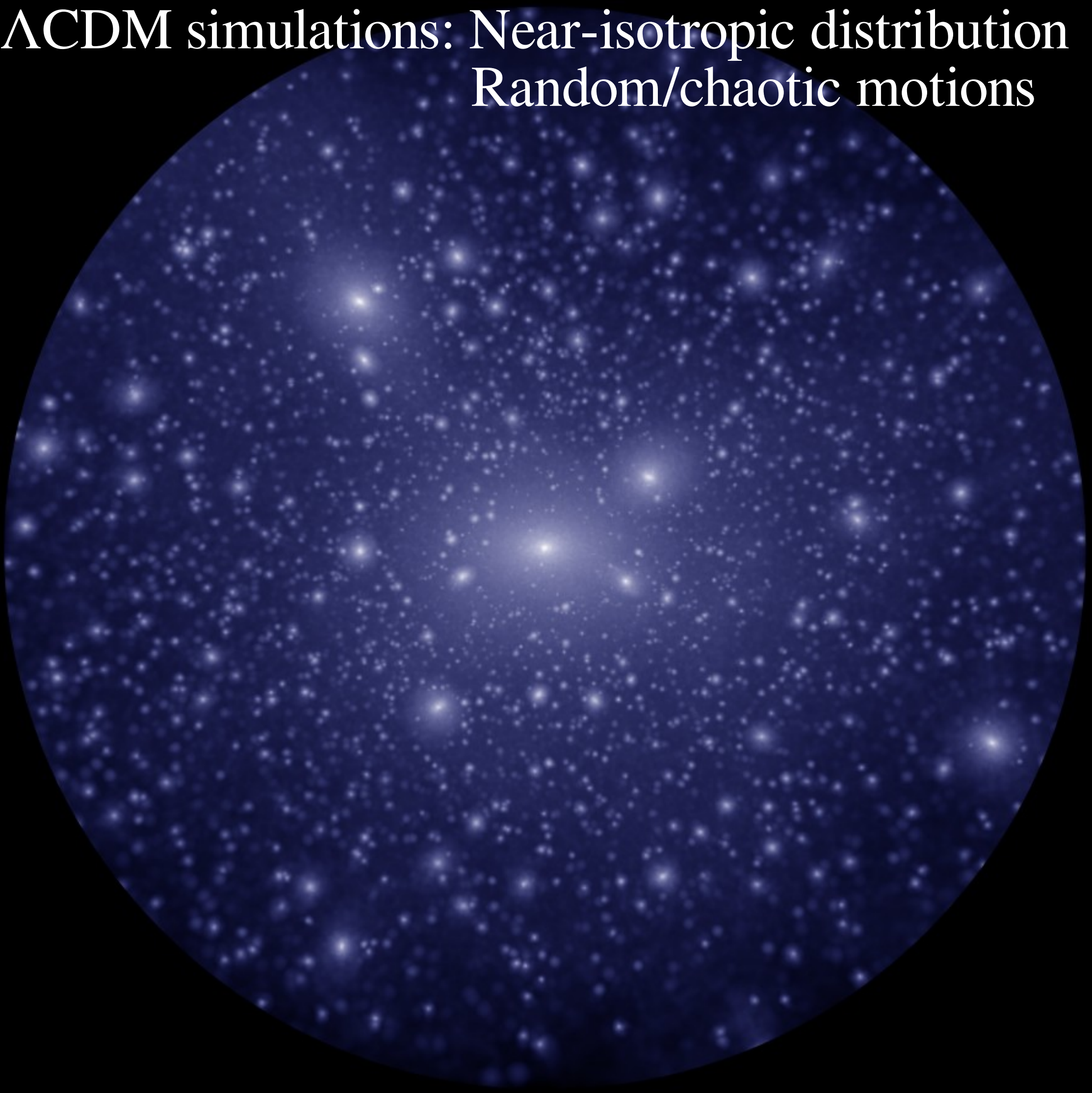
Baryon-DM coupling at any radii!

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

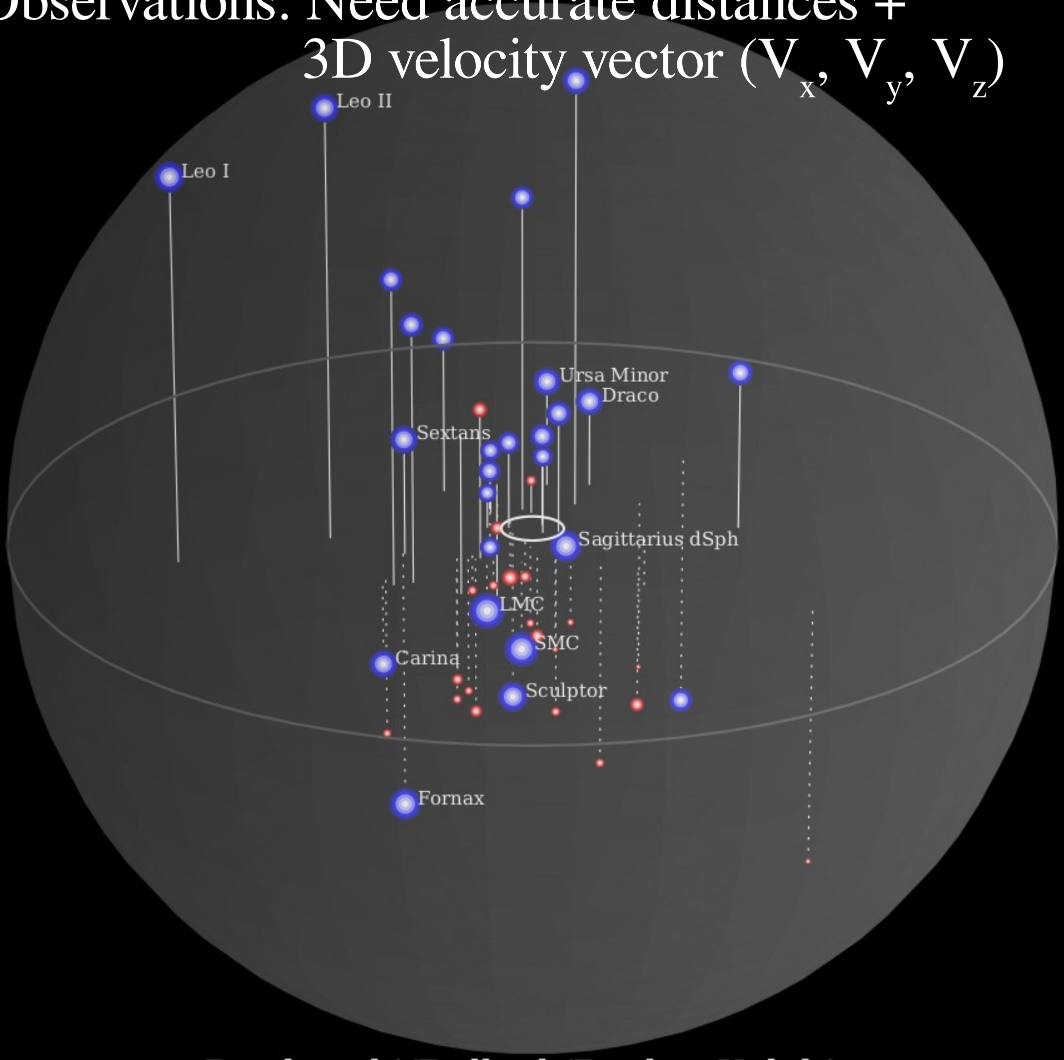
5. Planes of Satellites Problem (Satellites Phase-Space)

Distribution & Kinematics of Satellites

ΛCDM simulations: Near-isotropic distribution
Random/chaotic motions

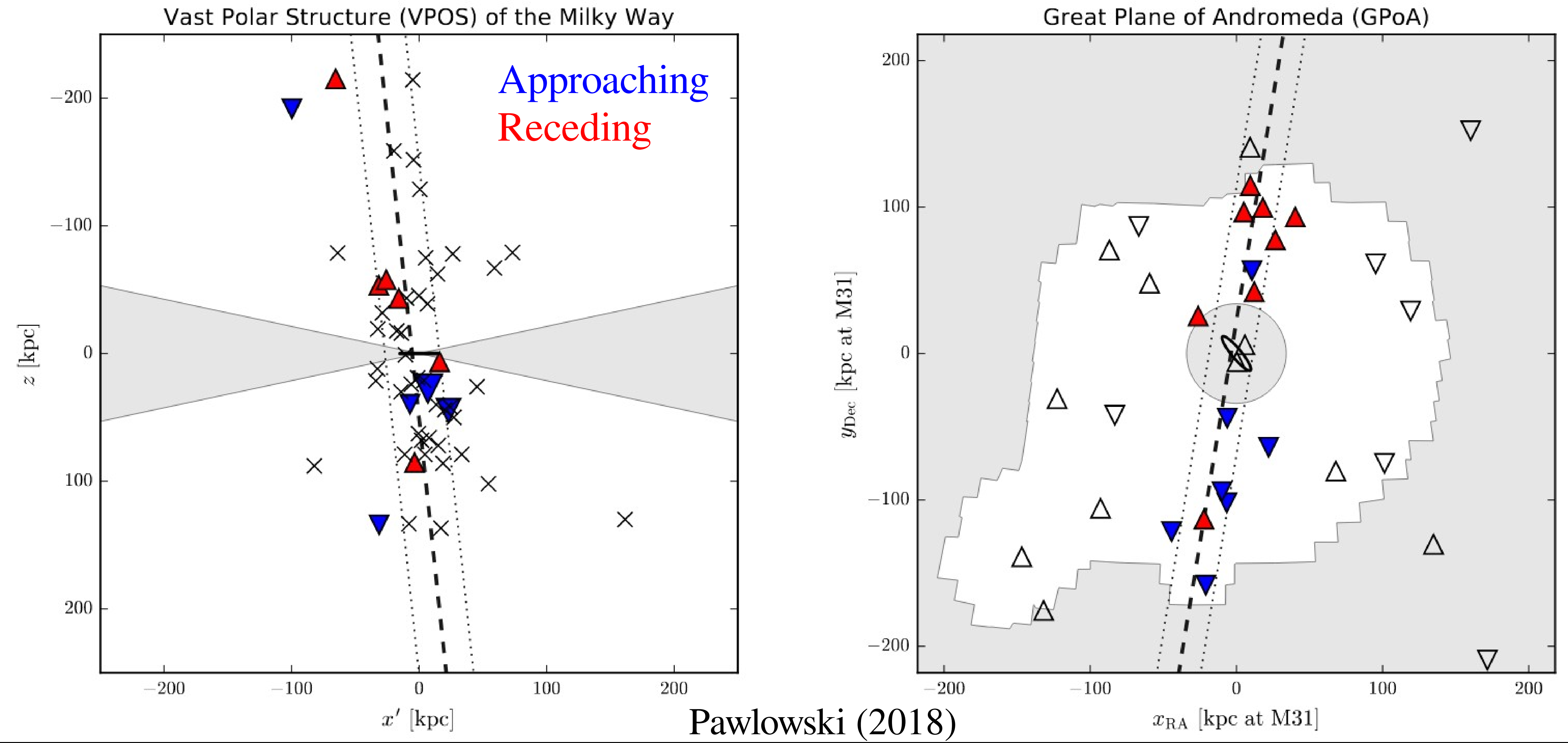


Observations: Need accurate distances +
3D velocity vector (V_x, V_y, V_z)



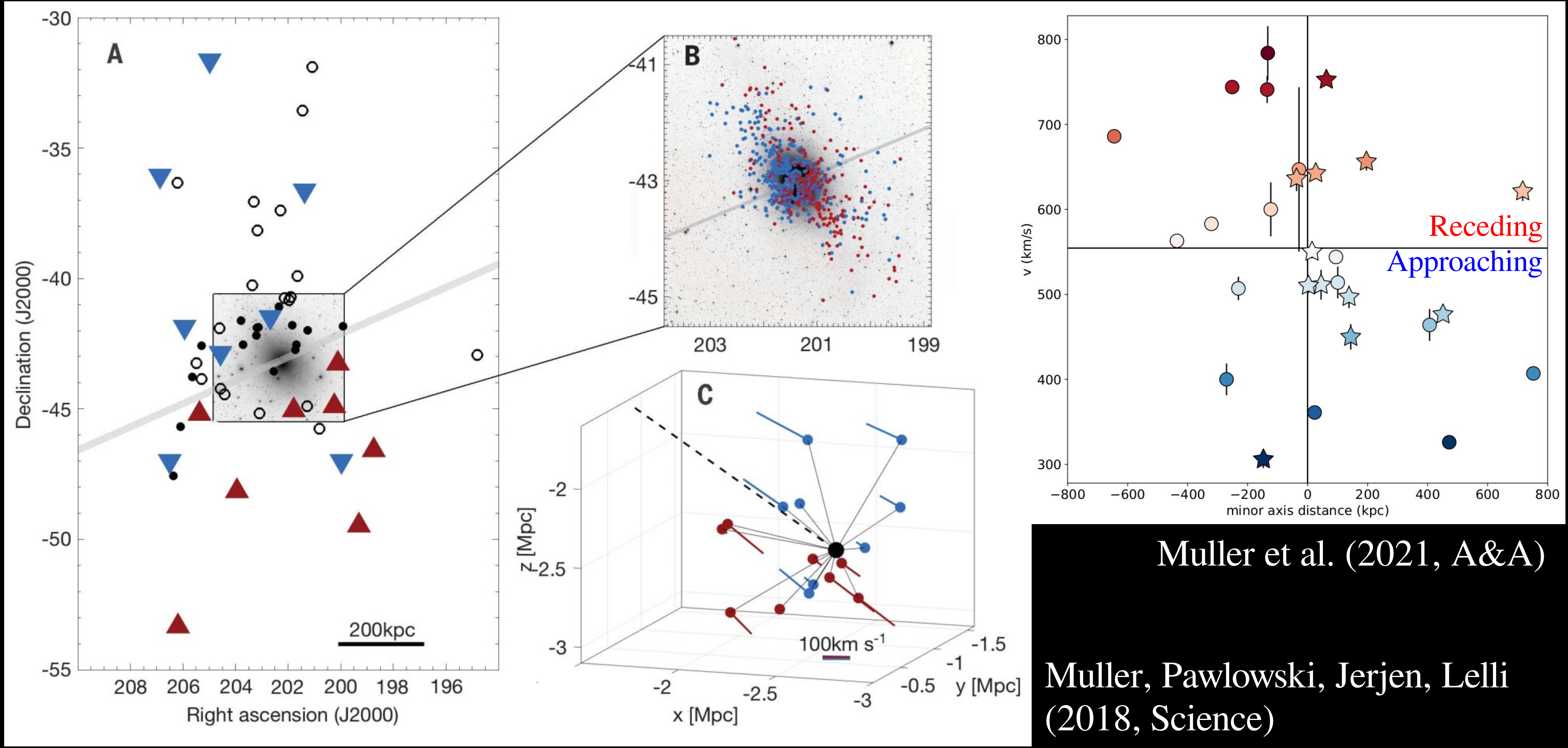
Pawlowski/Bullock/Boylan-Kolchin

Planes of Satellites in the Local Group



Pawlowski (2018)

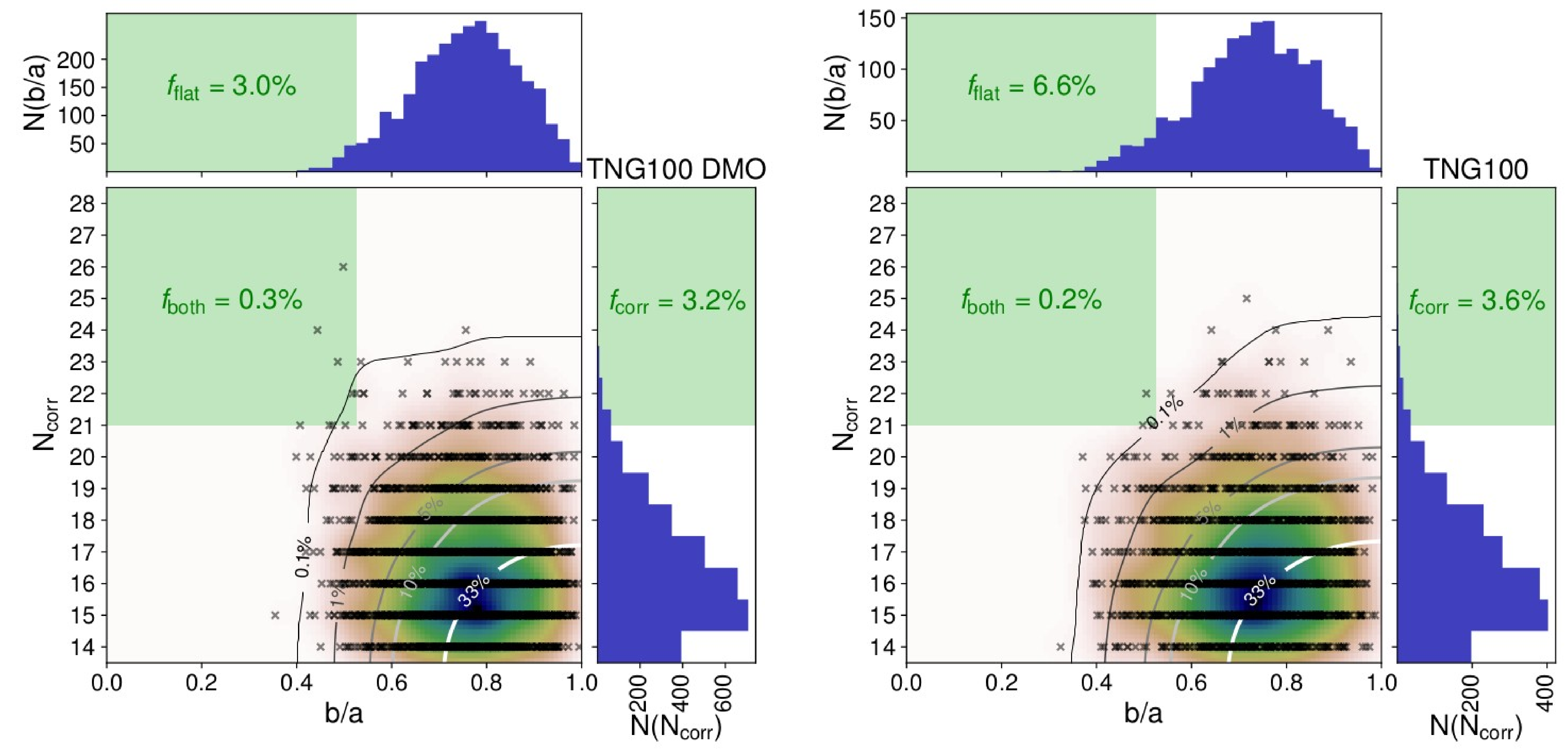
Planes of Satellites in Centaurus A



Muller et al. (2021, A&A)

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

Baryon Physics play NO role here



Small Scale ΛCDM Problems:

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

} Baryon Physics (stellar feedback)?

4. Regularity vs Diversity Problem → Baryon-DM interaction?
5. Planes of Satellites Problem → ?

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http://astro.fisica.unifi.it/tesi/