What's the Matter with Dwarf Galaxies?

Hot gas explodes out of young dwarf galaxies

Simulation by **Andrew Pontzen**, **Fabio Governato** and **Alyson Brooks** on the **Darwin Supercomputer**, Cambridge UK.

Simulation code **Gasoline** by **James Wadsley** and **Tom Quinn** with metal cooling by **Sijing Sheng**.

Visualization by **Andrew Pontzen**.

Alyson Brooks
Rutgers, the State University of New Jersey
Center for Computational Astrophysics, Flatiron Institute

No Small Scale "Crisis" if Consider the Influence of Normal Matter

	CDM+Baryons	
Missing Satellites	✓	Brooks et al. (2013), Wetzel et al. (2016), Buck et al. (2019)
Too Big to Fail	✓	Zolotov et al. (2012), Brooks & Zolotov (2014), Frings (2017), Garrison-Kimmel et al. (2019)
Missing Dwarfs	✓	Maccio et al. (2016), Brooks et al. (2017), Chauhan et al. (2019)
Bulge-less disk galaxies	✓	Governato et al. (2010), Nature, 463, 203 Brook et al. (2011), MNRAS, 415, 1051
The Cusp/Core Problem	✓	Pontzen & Governato (2012), MNRAS, 421, 3464 DiCintio et al. (2014); Chan et al. (2015), Tollet et al. (2016)
Diversity	?	Santos-Santos et al. (2018, 2020), Roper et al. (2022)
Planes of Satellites		Garavito-Camargo et al. (2021)

No MESSY Baryonic Feedback Needed! (Just Gravity)

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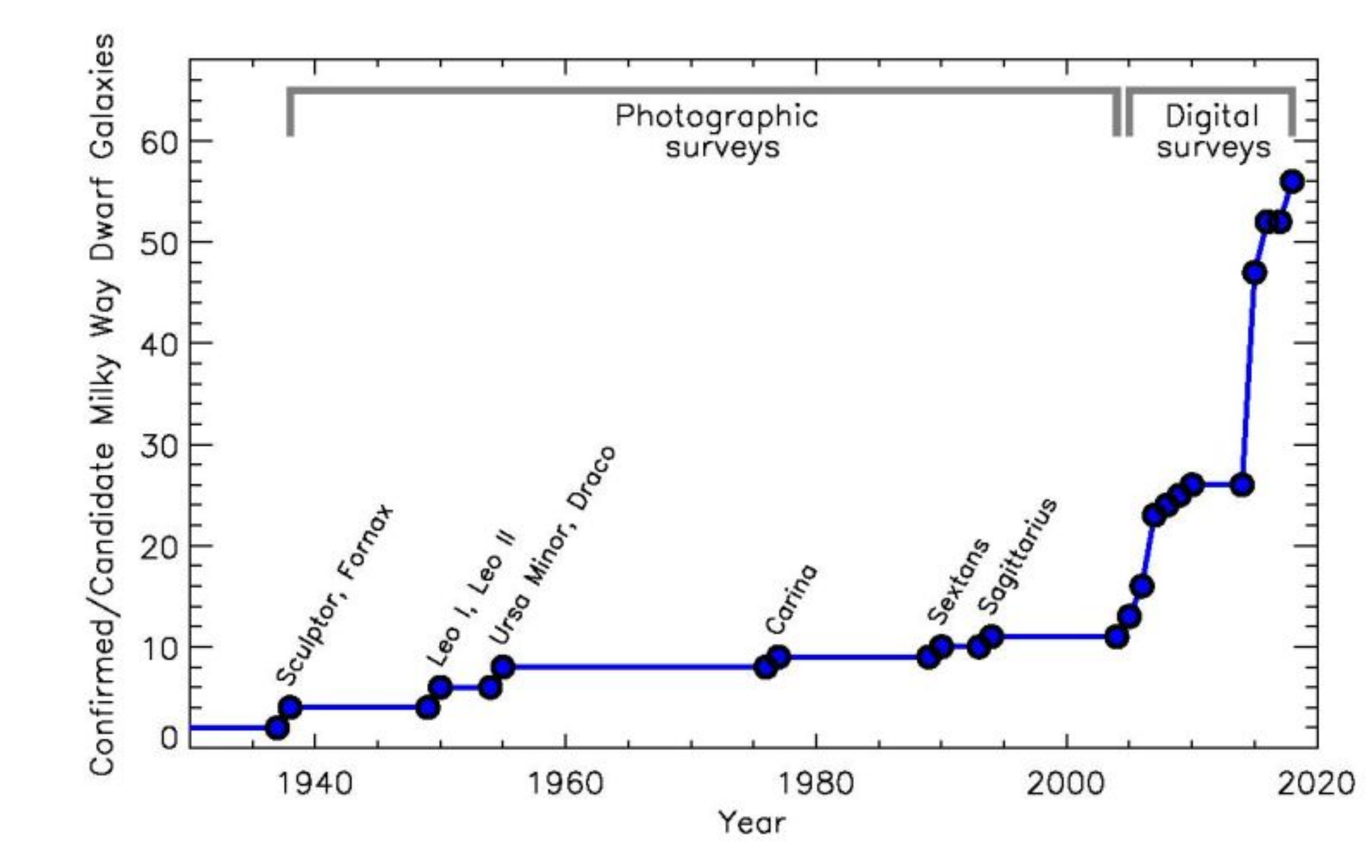
The Rest of the Missing Satellites: Ultra-Faint Dwarfs



J. Simon, ARA&A (2019)

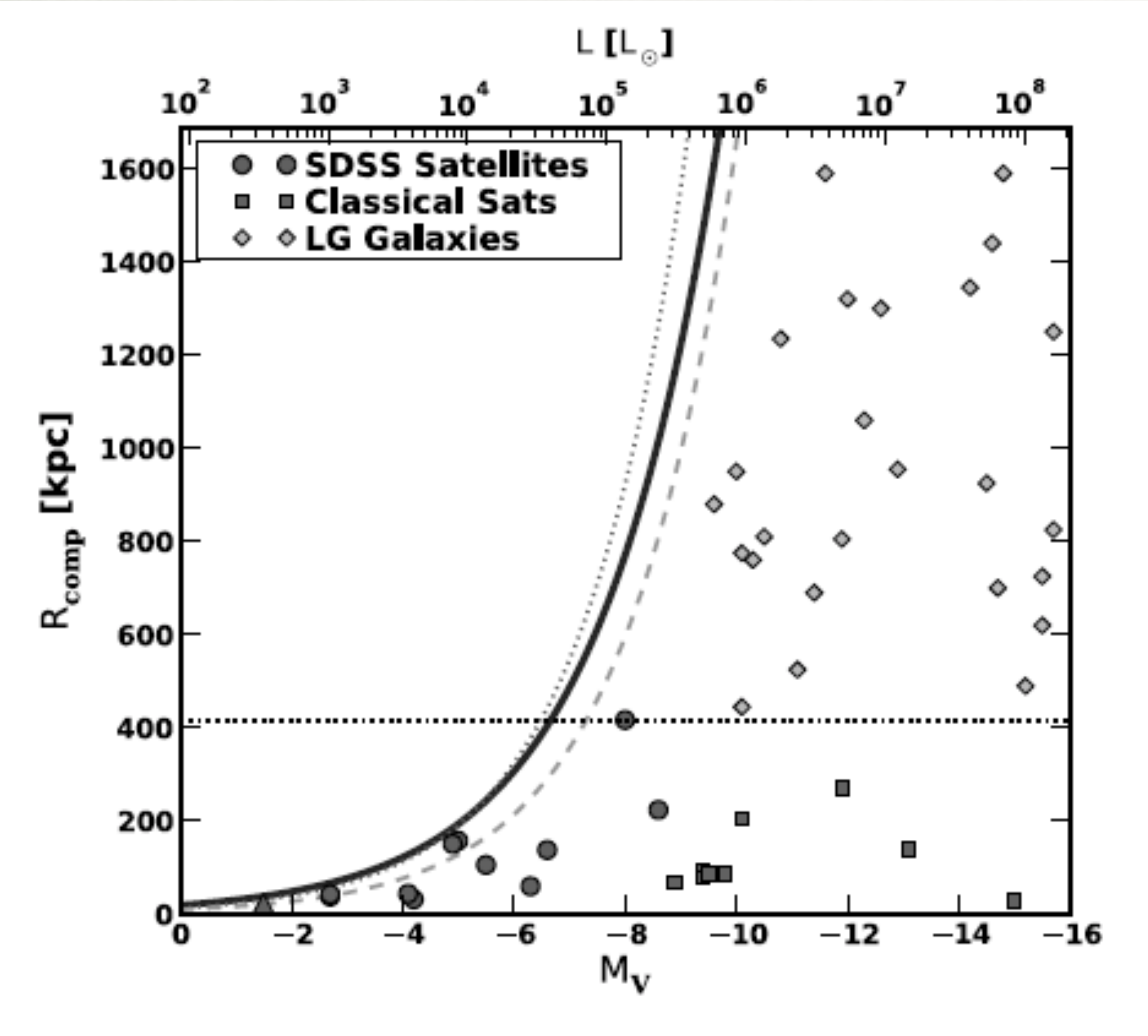
Sculptor Dwarf Galaxy

$M_V \sim -10$

Reticulum II

$M_V \sim -3$

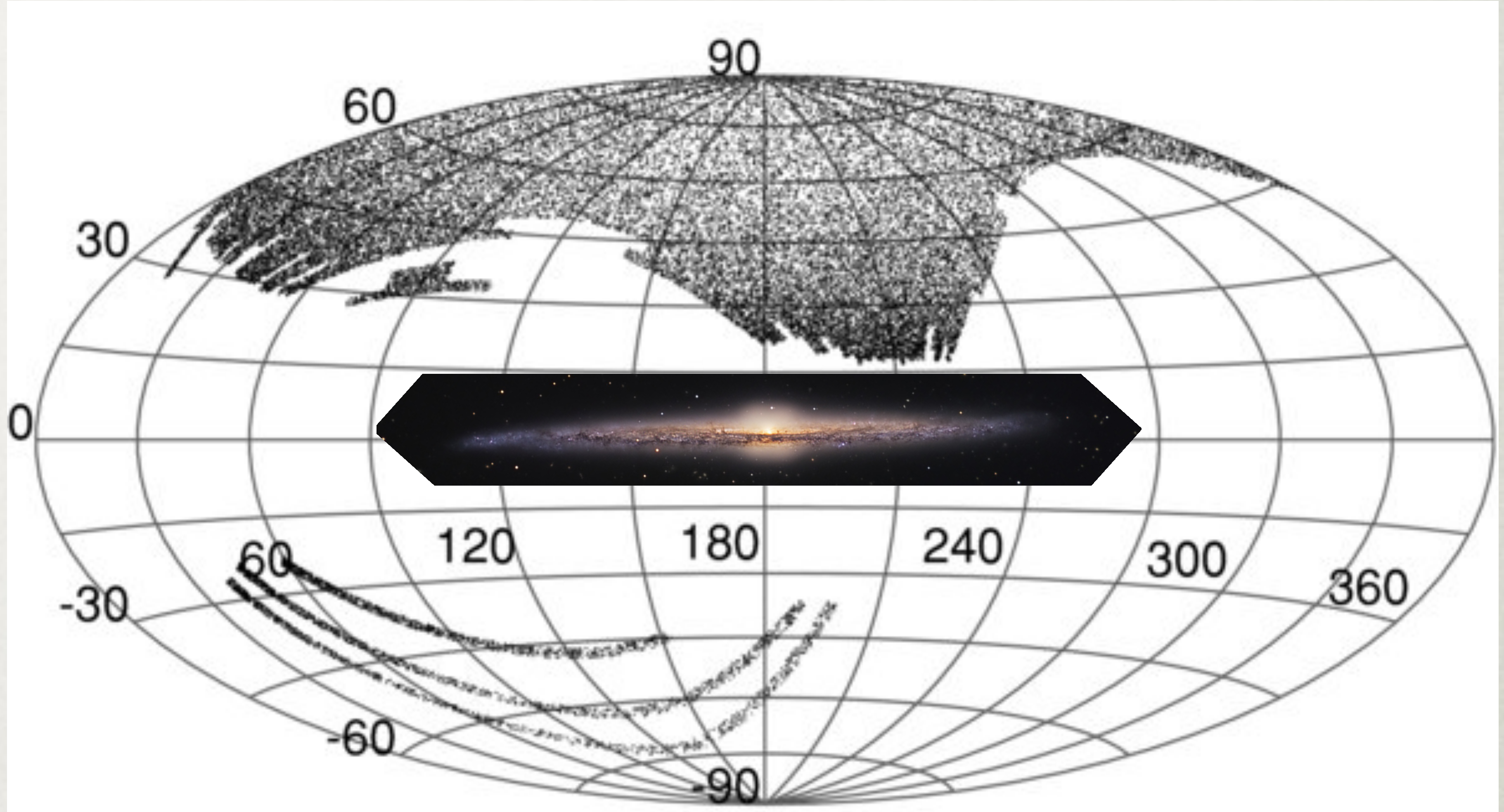
Missing Satellites

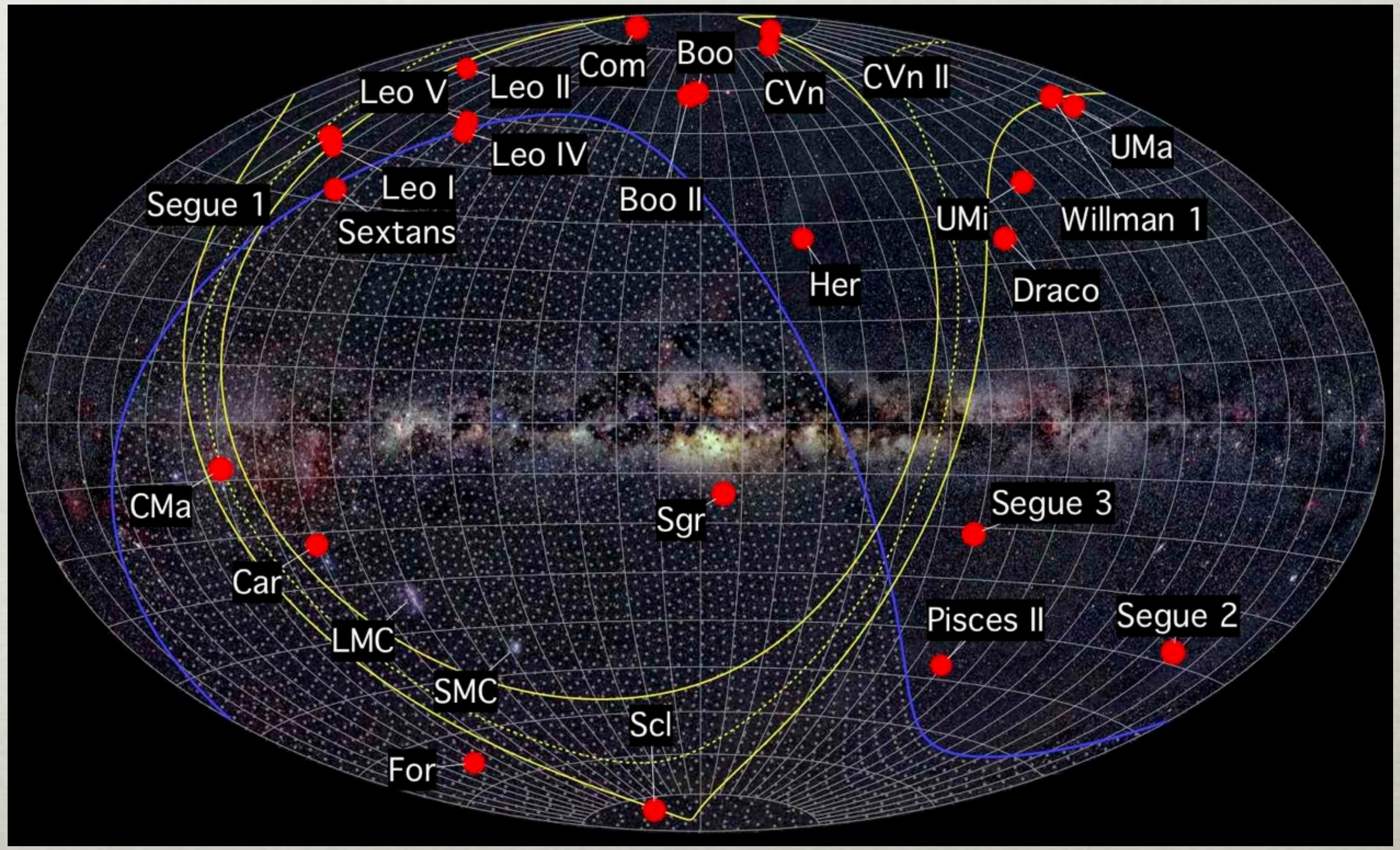


Fainter

Brighter

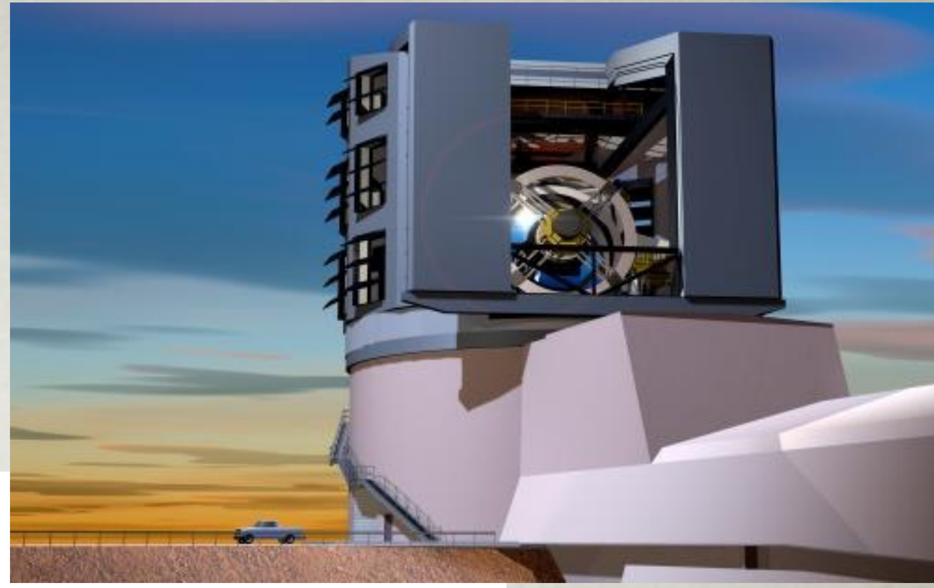
Tollerud et al. (2008)

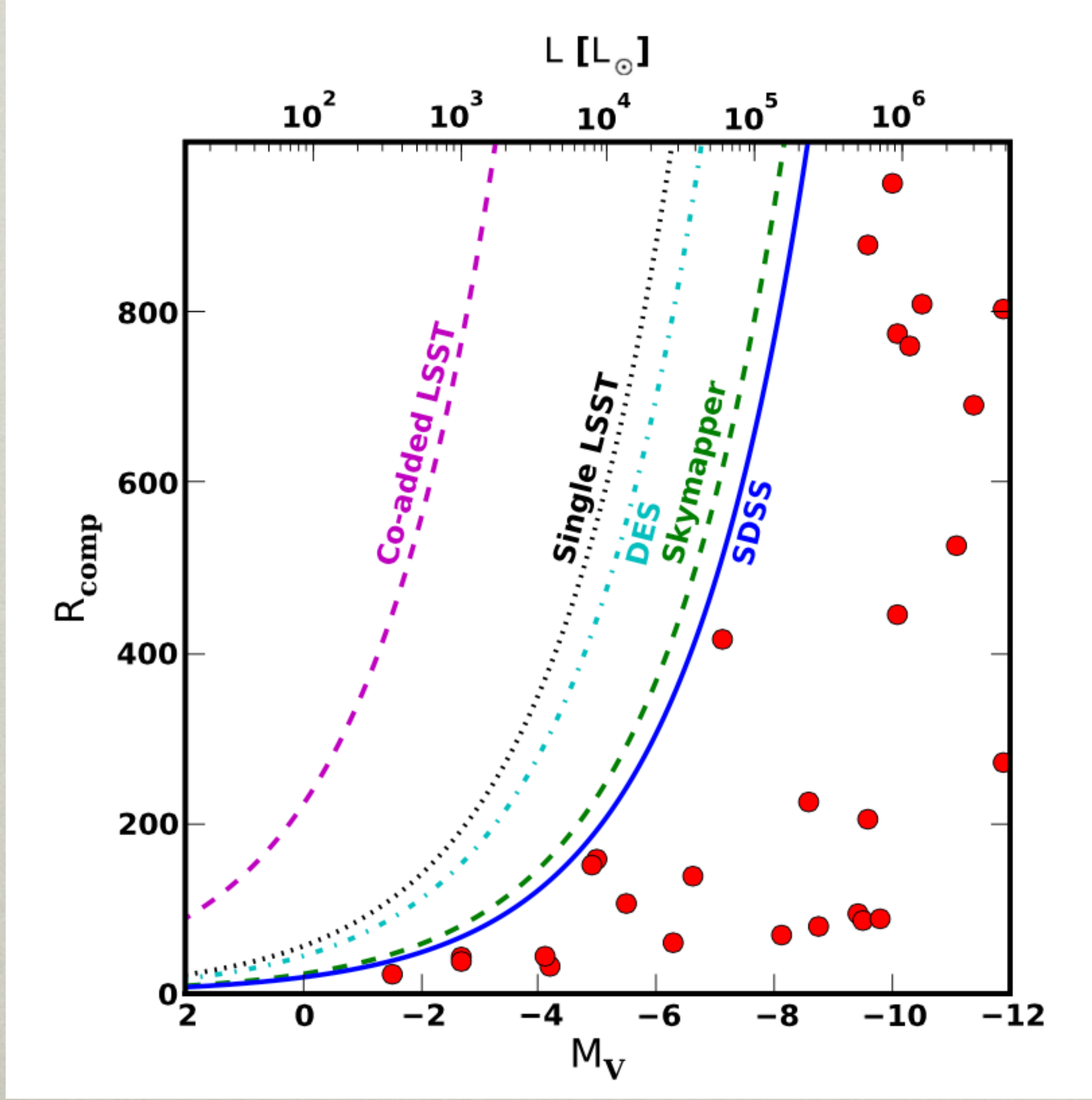


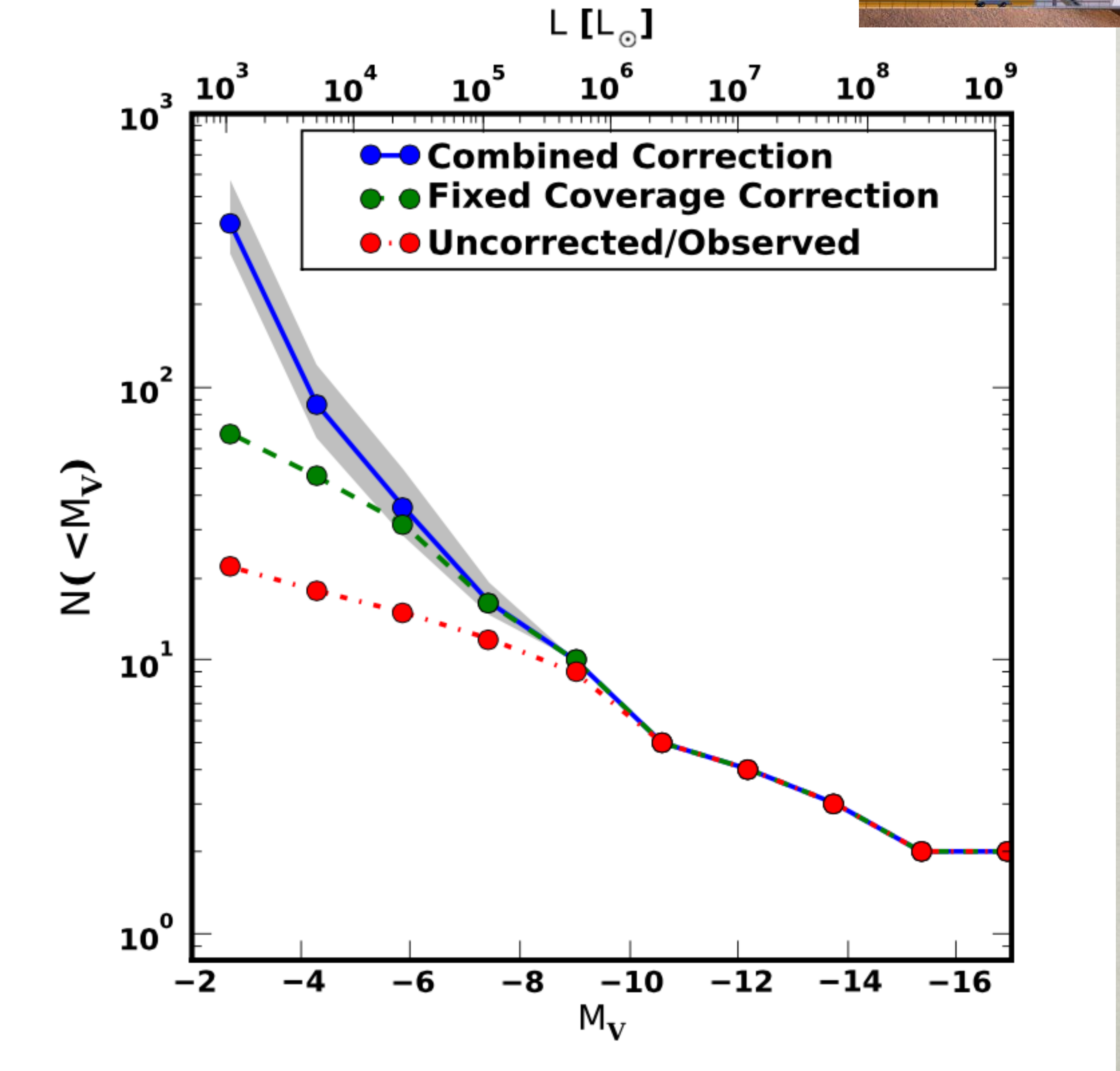


The SDSS "footprint"

The Future is Not Bright!







Fainter

Brighter

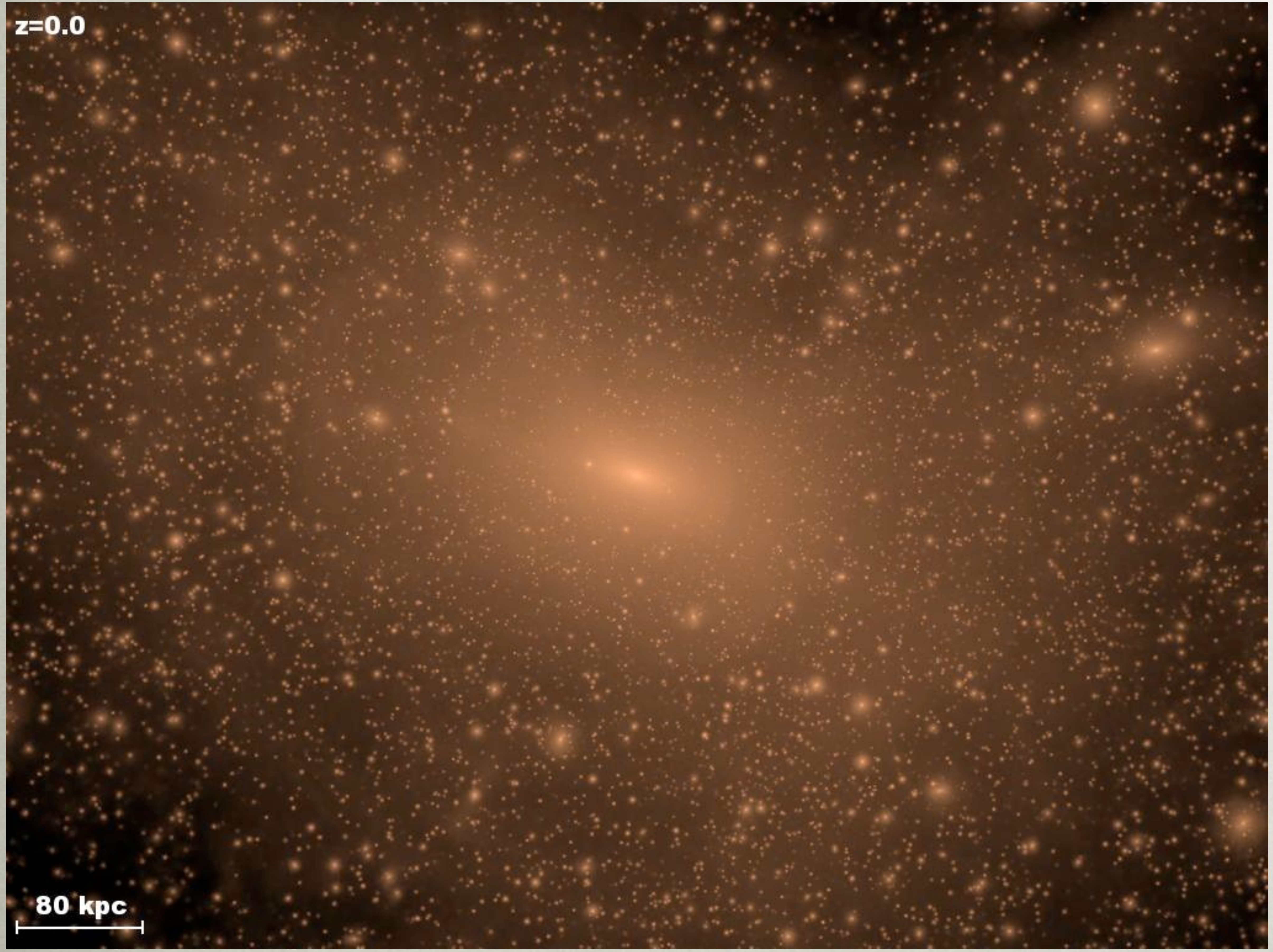
Tollerud et al. (2008)

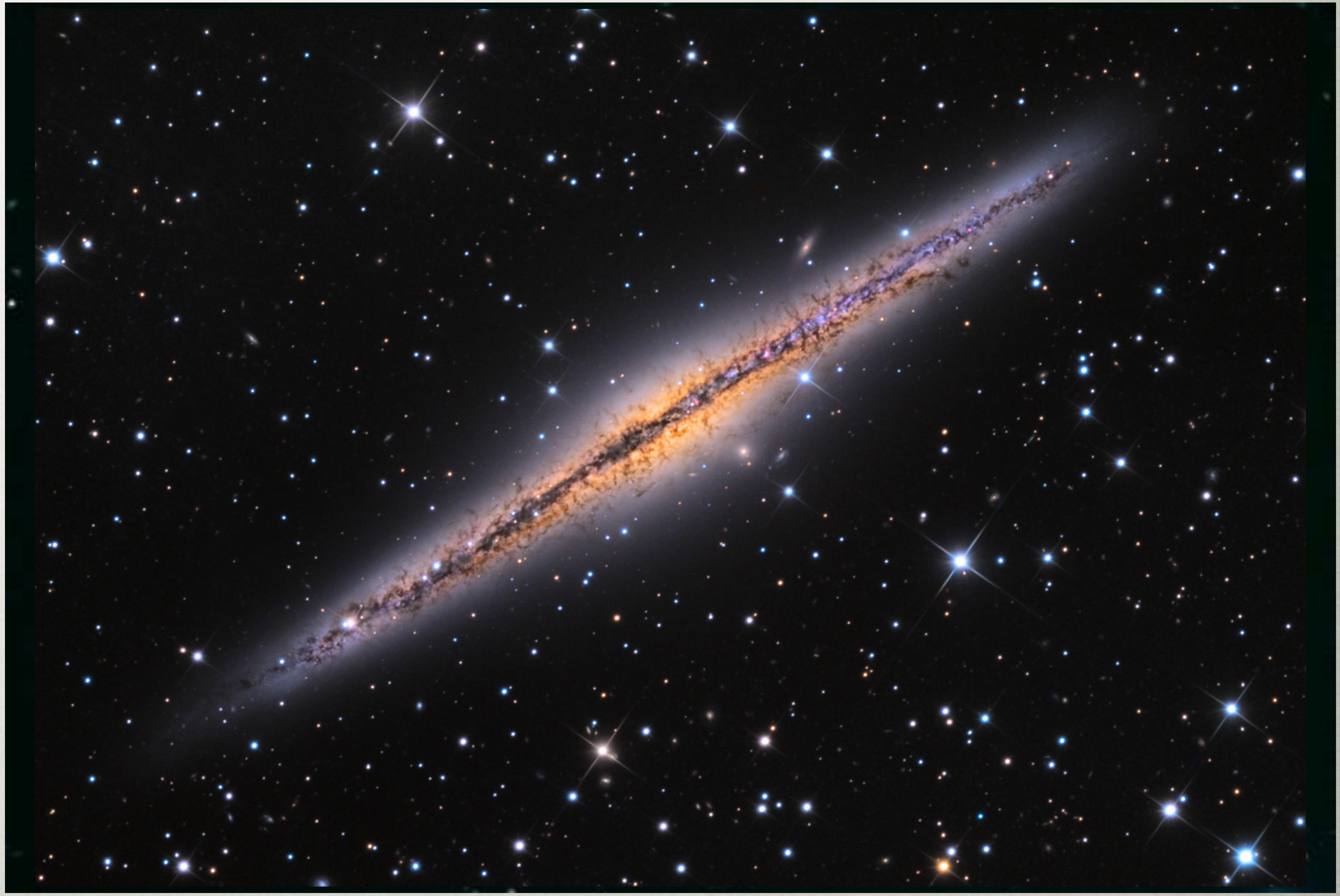
see also Walsh et al. (2009); Newton et al. (2018)

Baryons Make a Disk (Dark Matter Doesn't)

Via Lactea, Image: © Jurg Diemand

NGC 891, Image: © Adam Block, Mt. Lemmon Sky Center, U Arizona



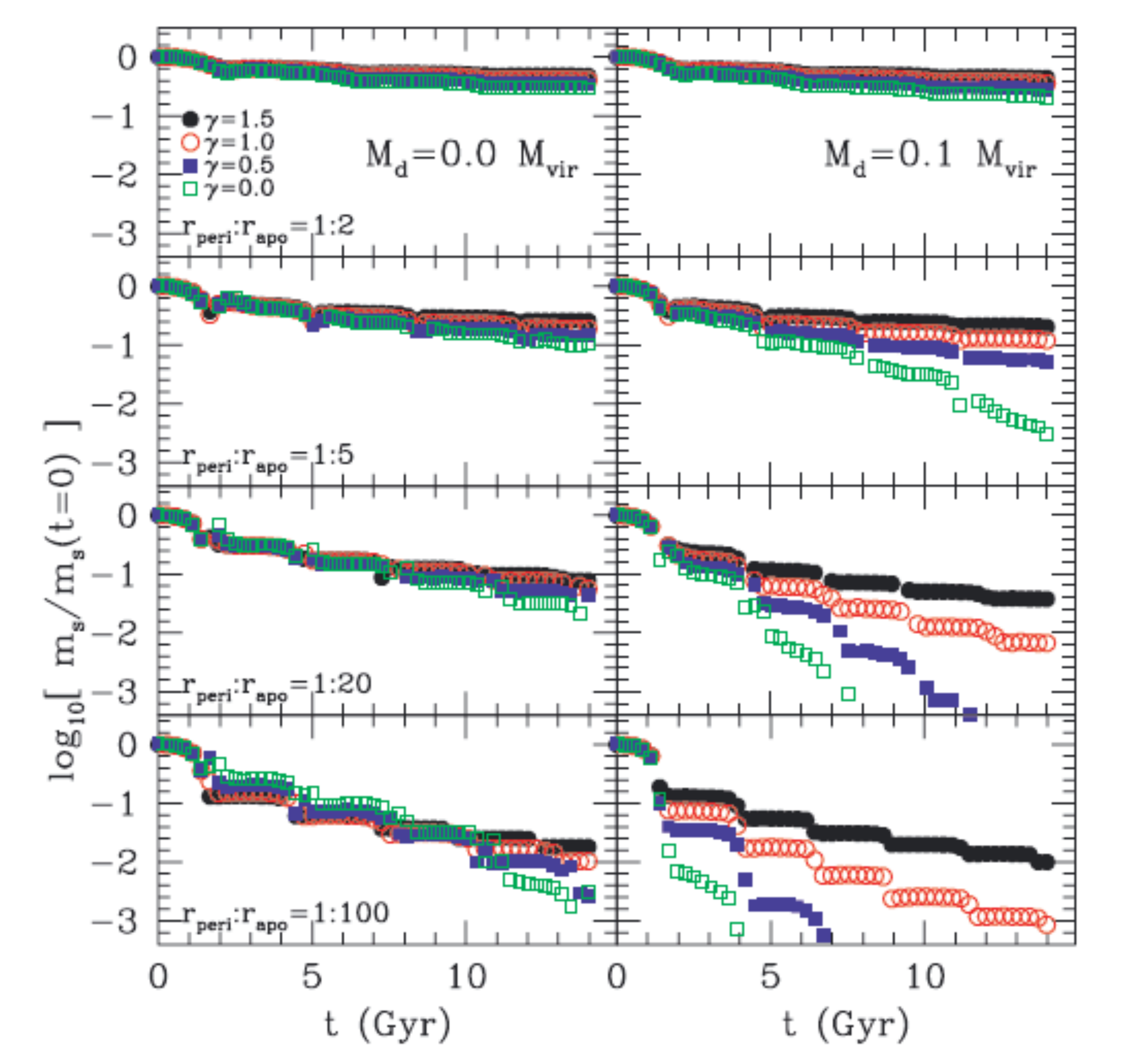


Dark Matter

Baryons

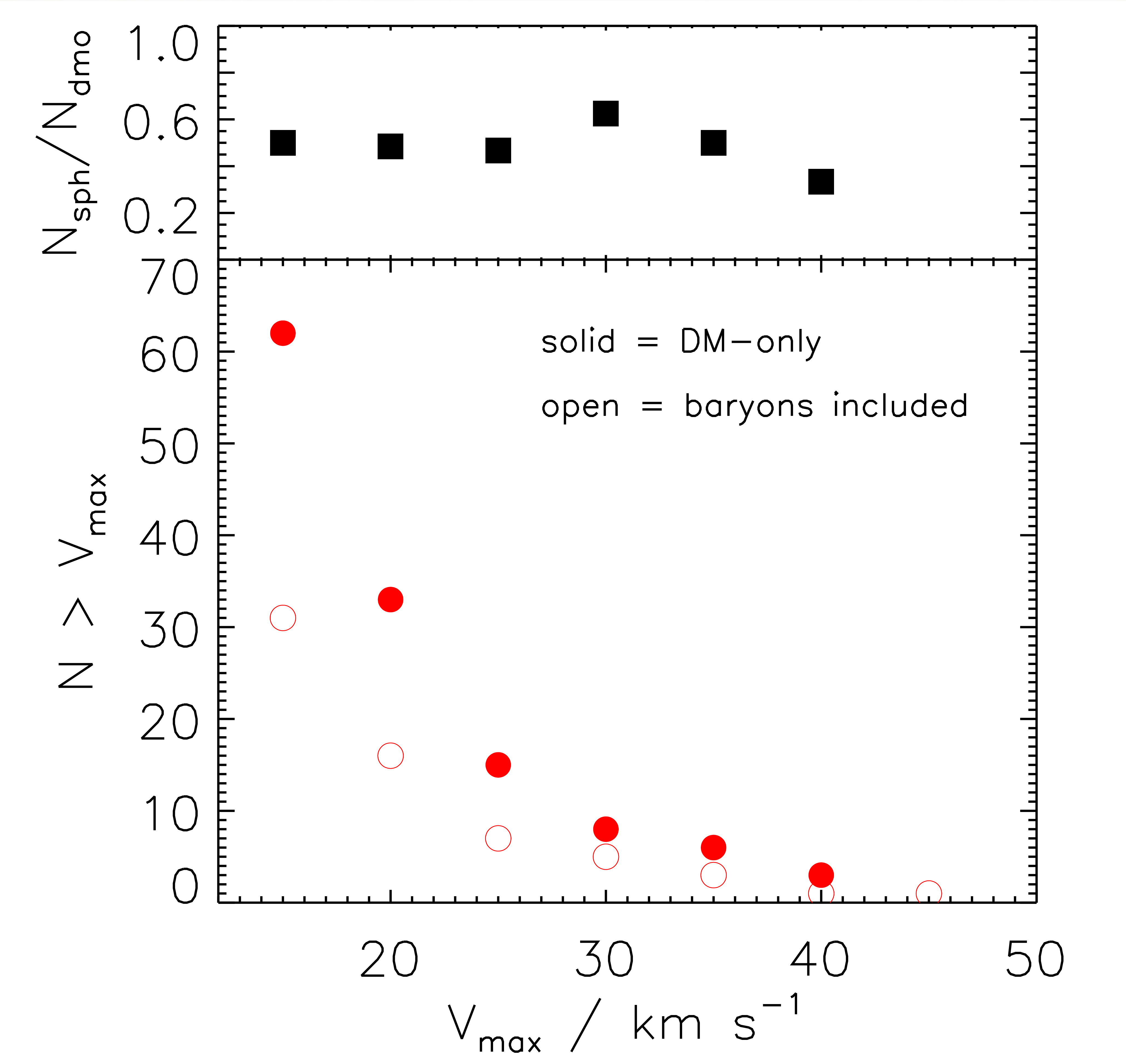
or any central baryonic concentration; Chang et al. (2012)

Not Just Core Creation: The Tidal Effect of the Disk



Penarrubia et al. (2010)

The Change to the Velocity/Mass Function



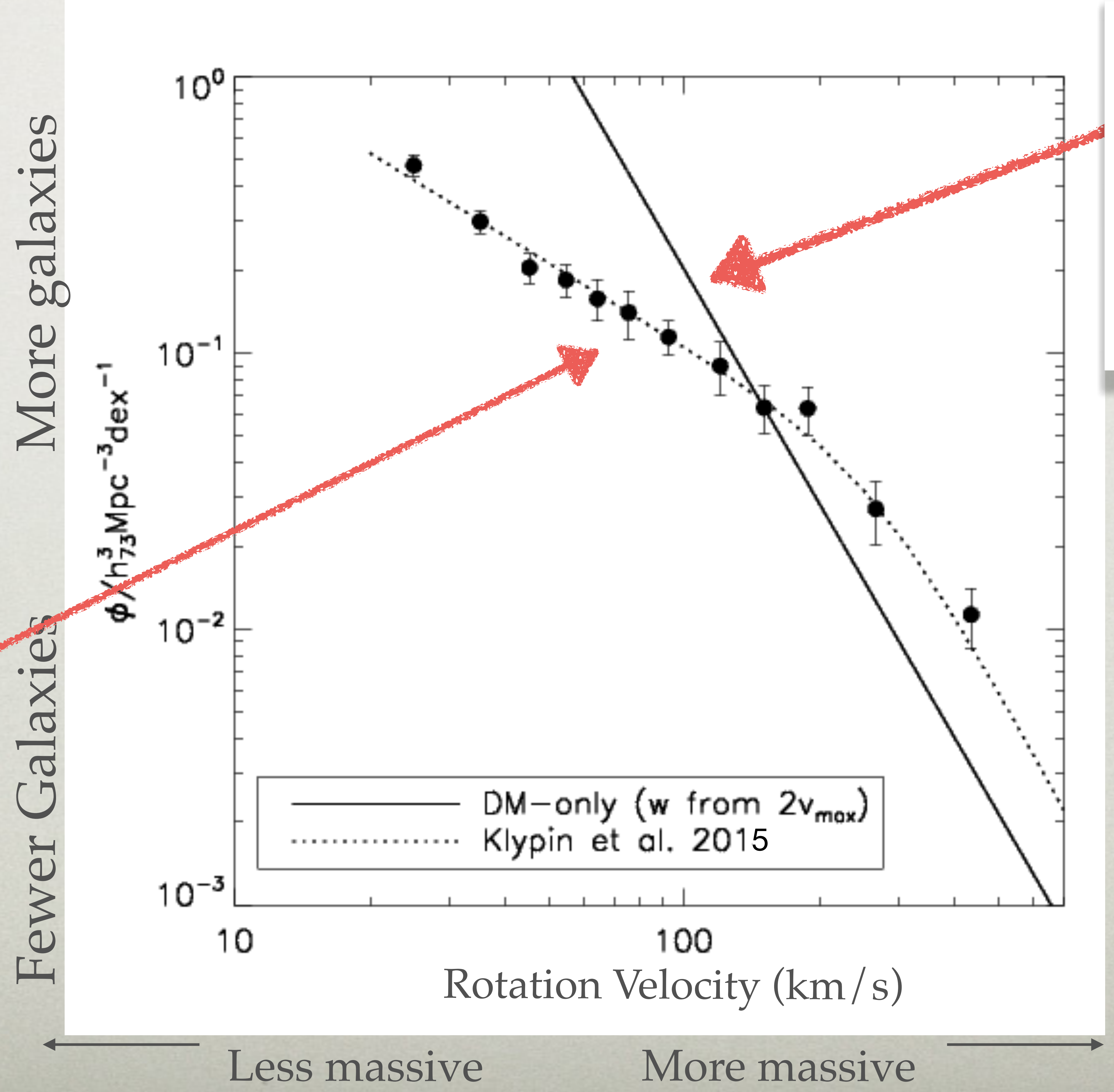
Brooks & Zolotov (2014), ApJ, arXiv:1207.2468

see also Wetzel et al. (2016)

Missing Dwarfs in the Field

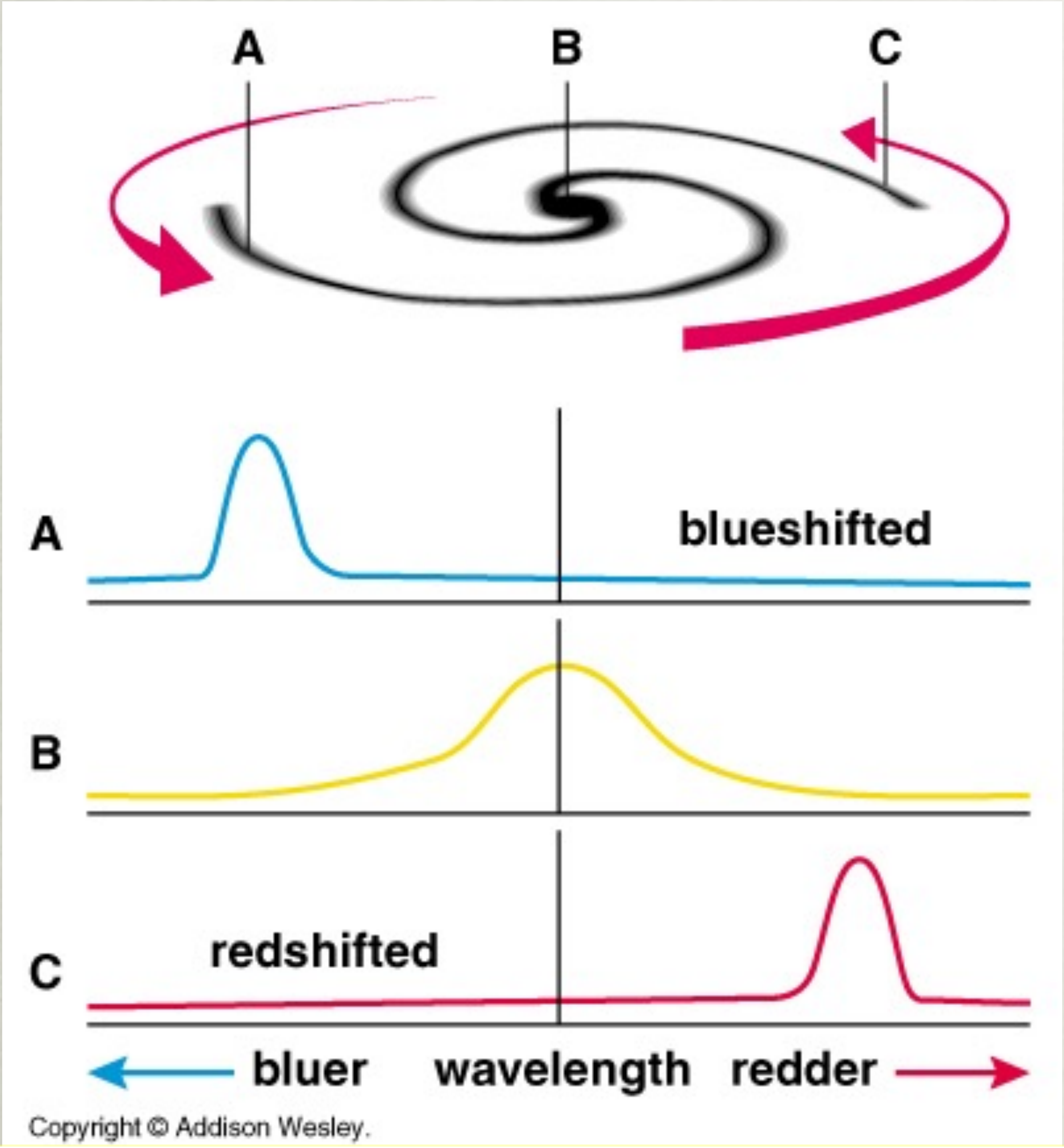
Predicted number of galaxies

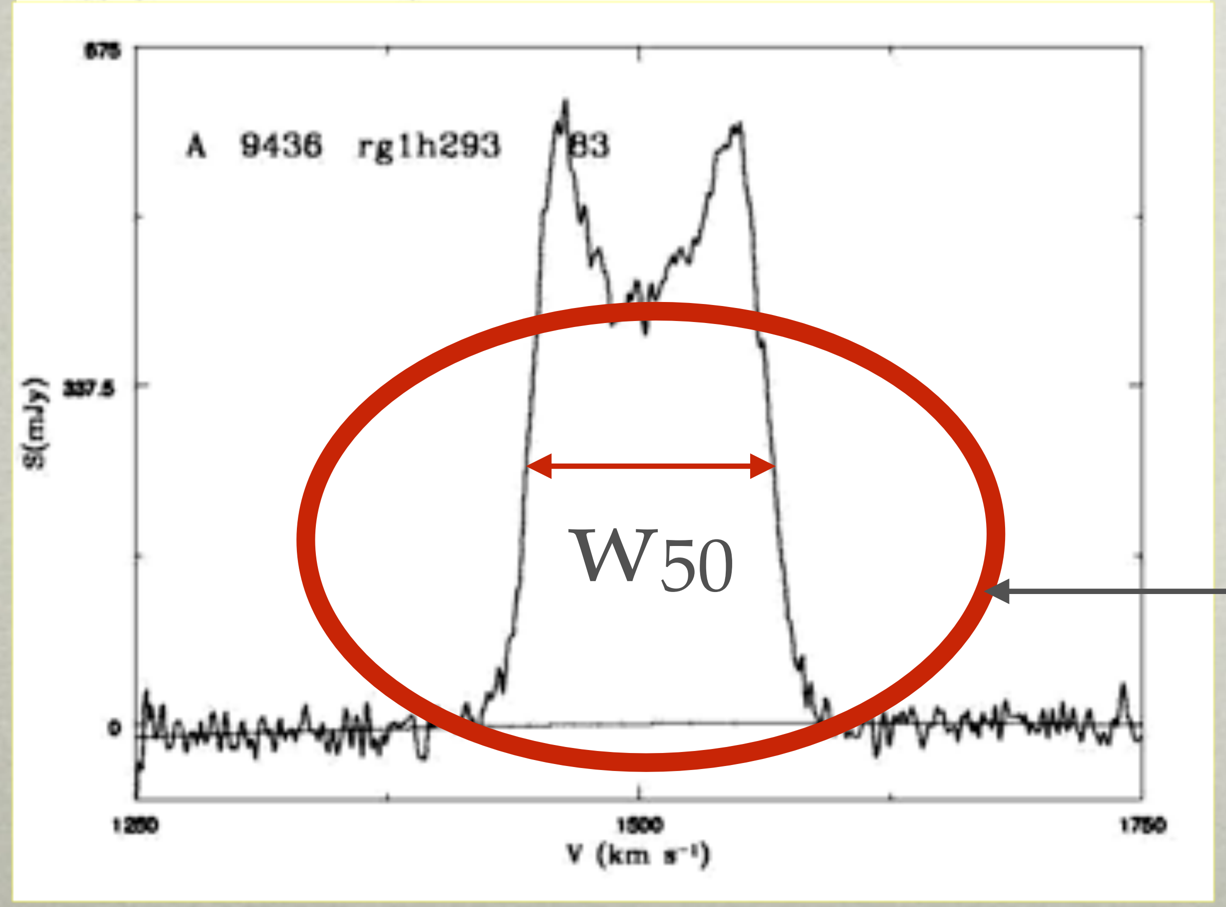
Observed number of galaxies



Klypin et al. (2015)

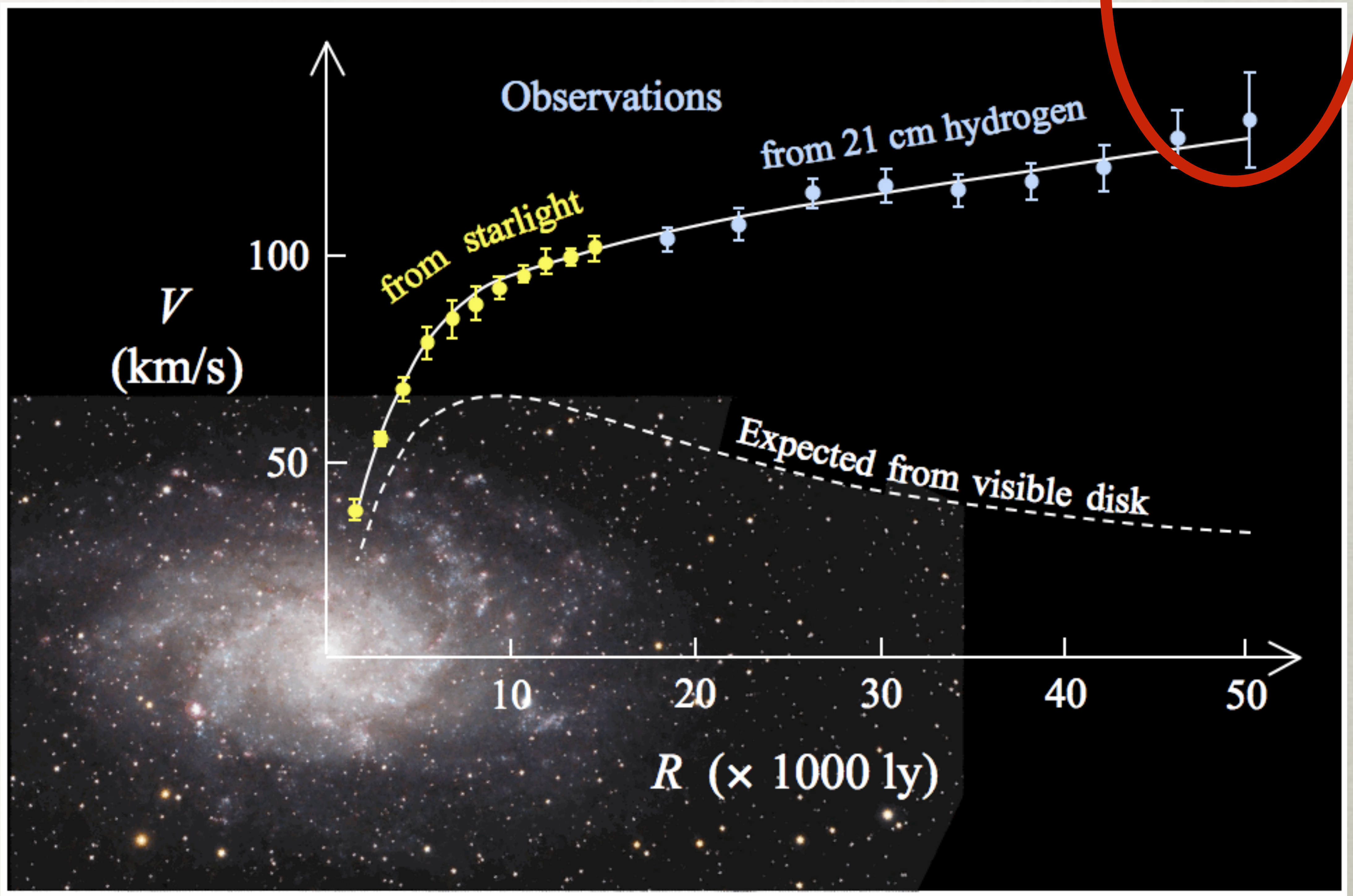
BUT: Two Ways to Measure Rotation (Resolved vs Unresolved)



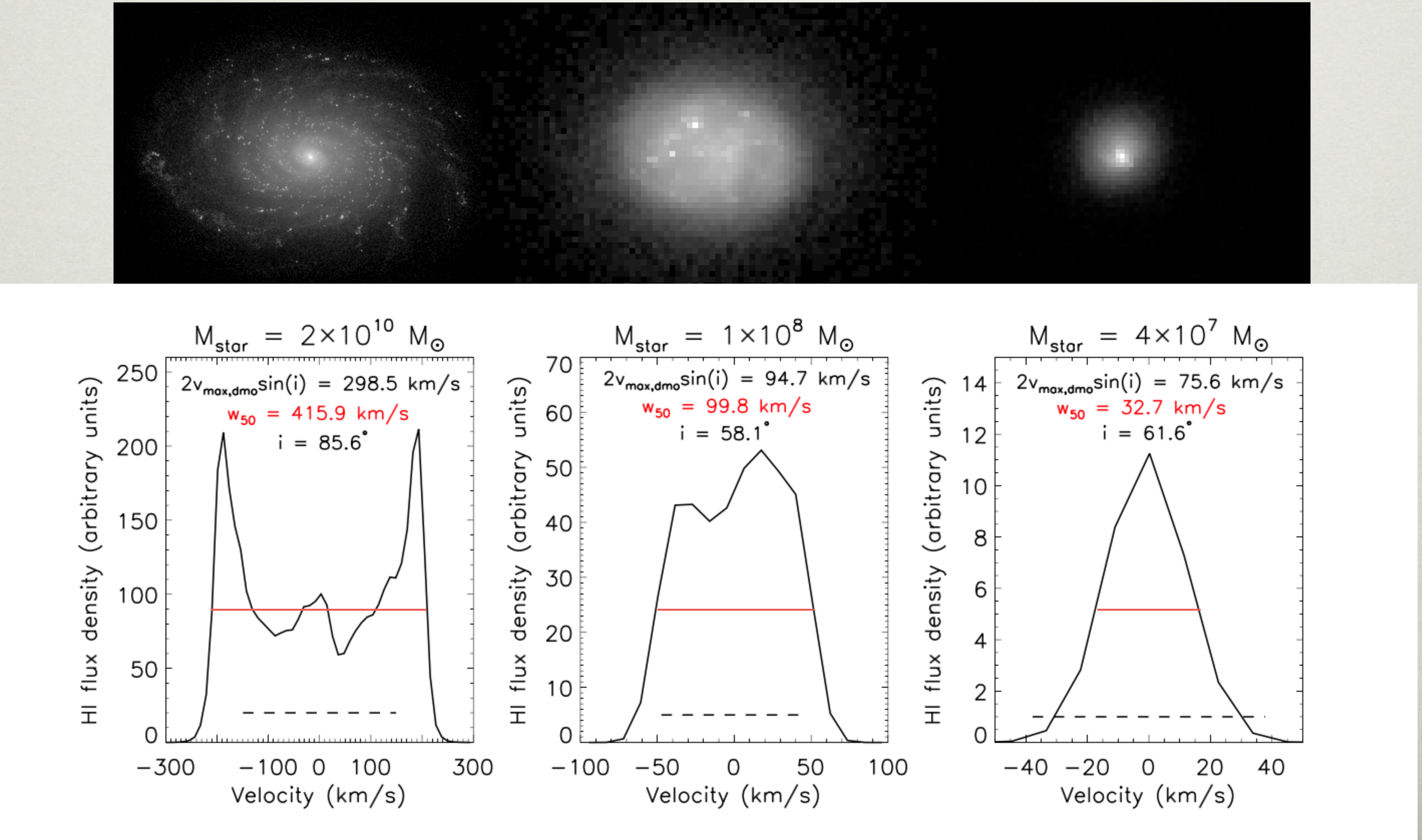


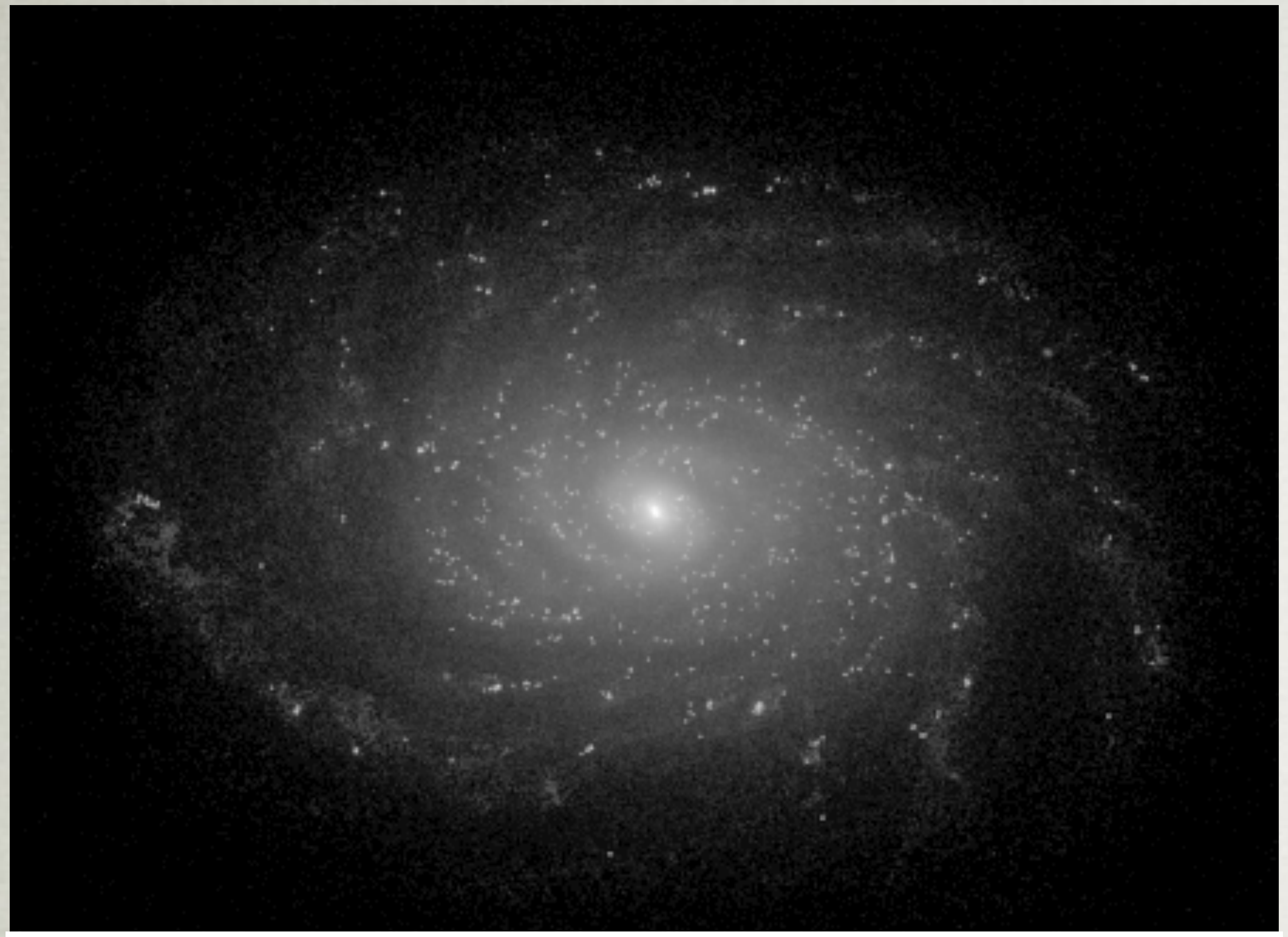
Observations

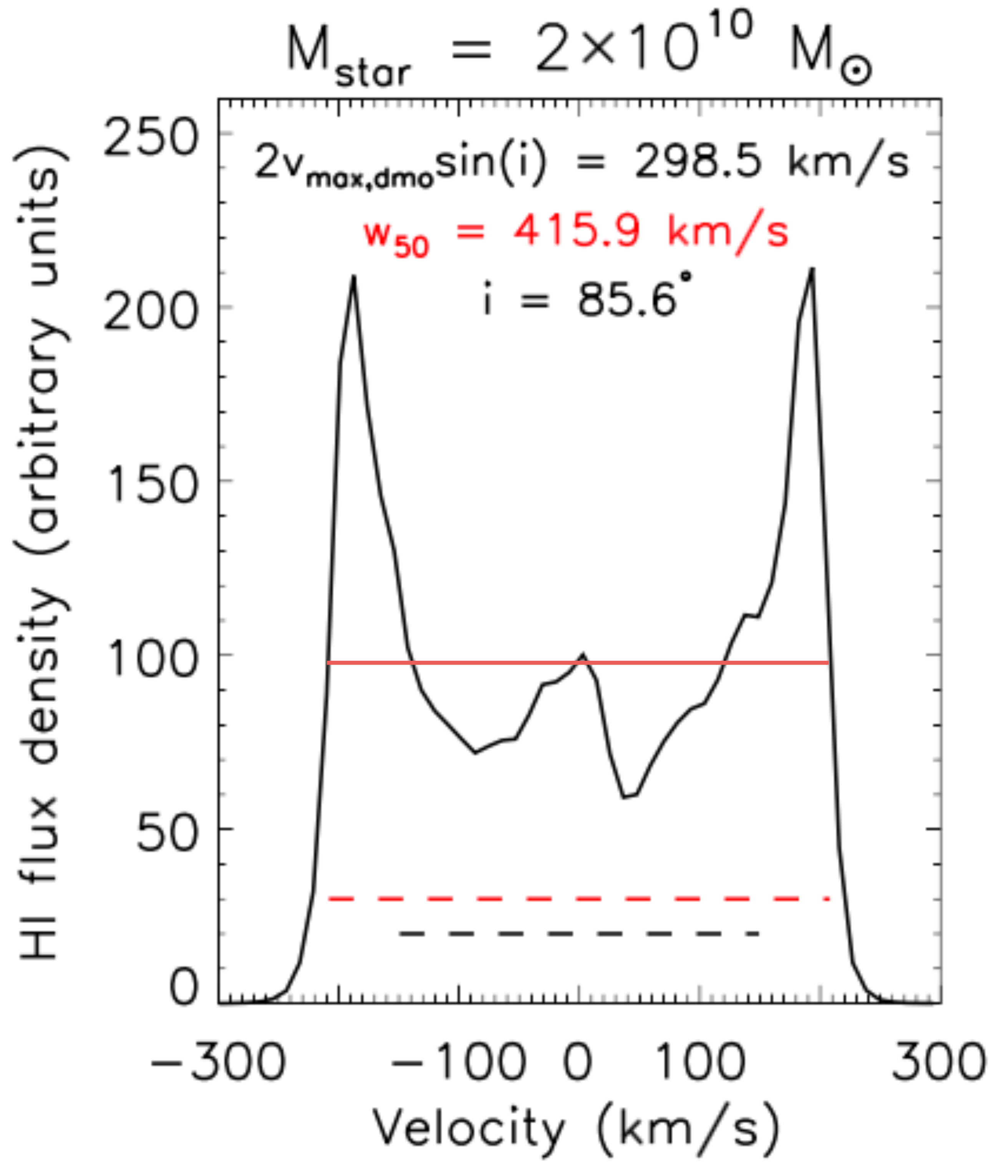
Theory → v_{max}

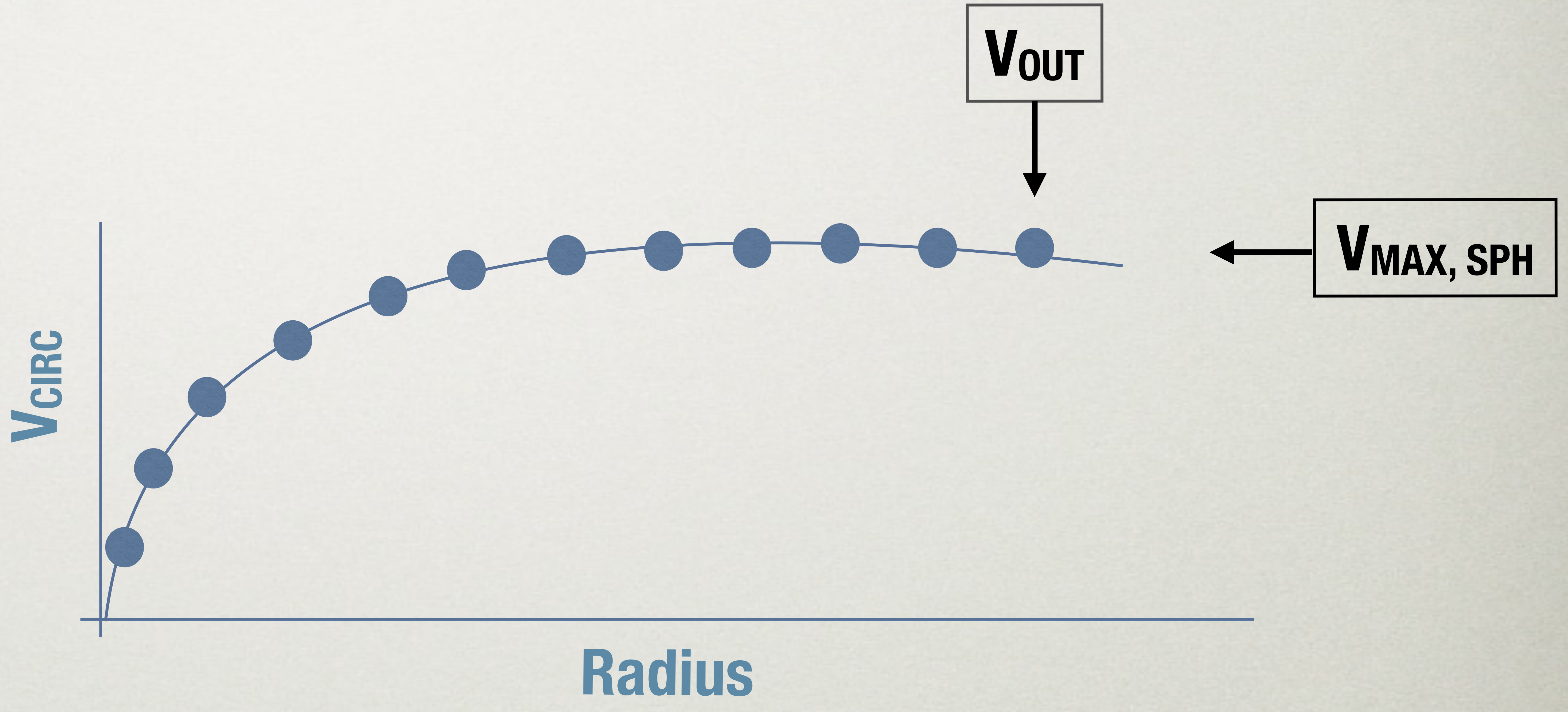


Creating Mock Observations

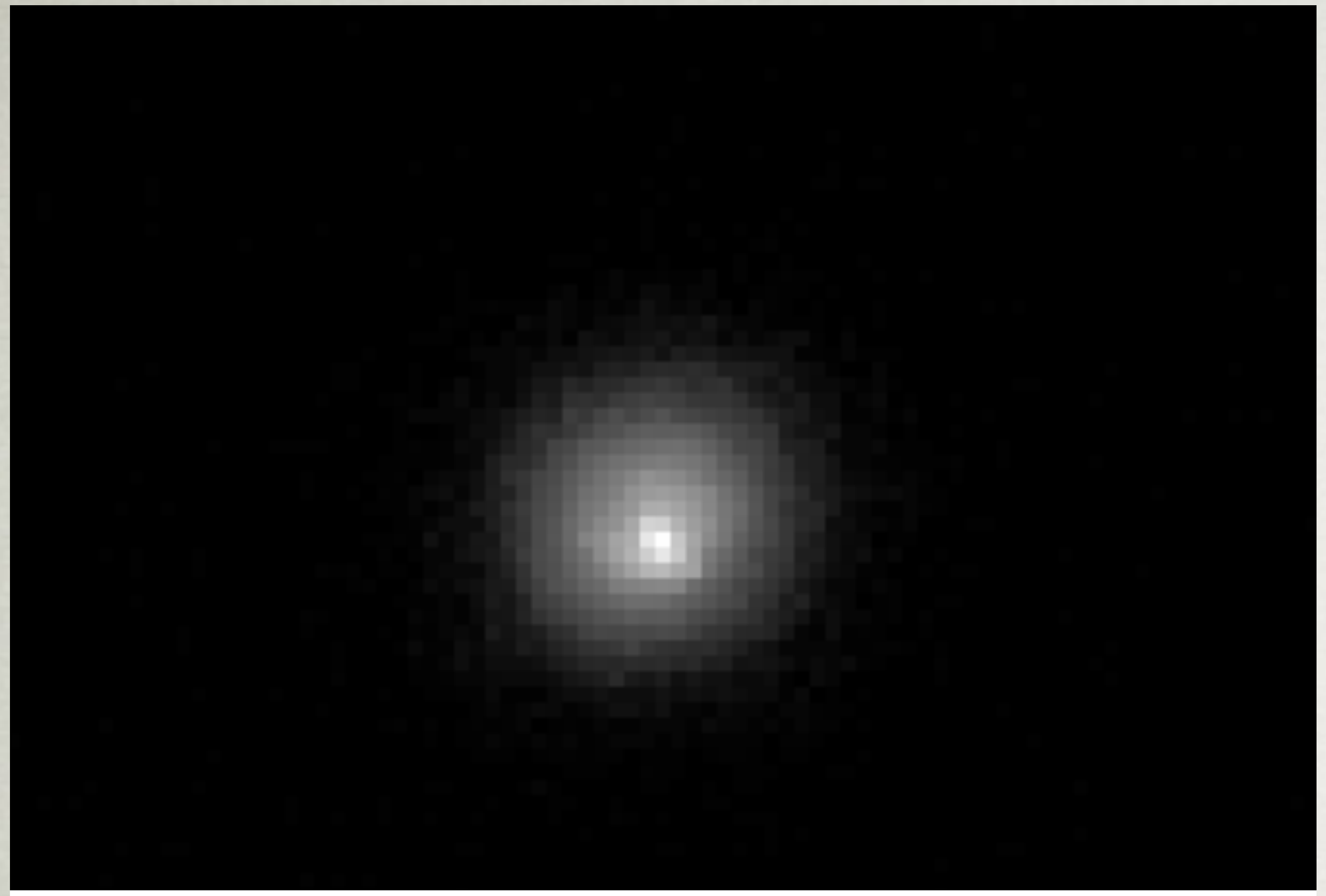


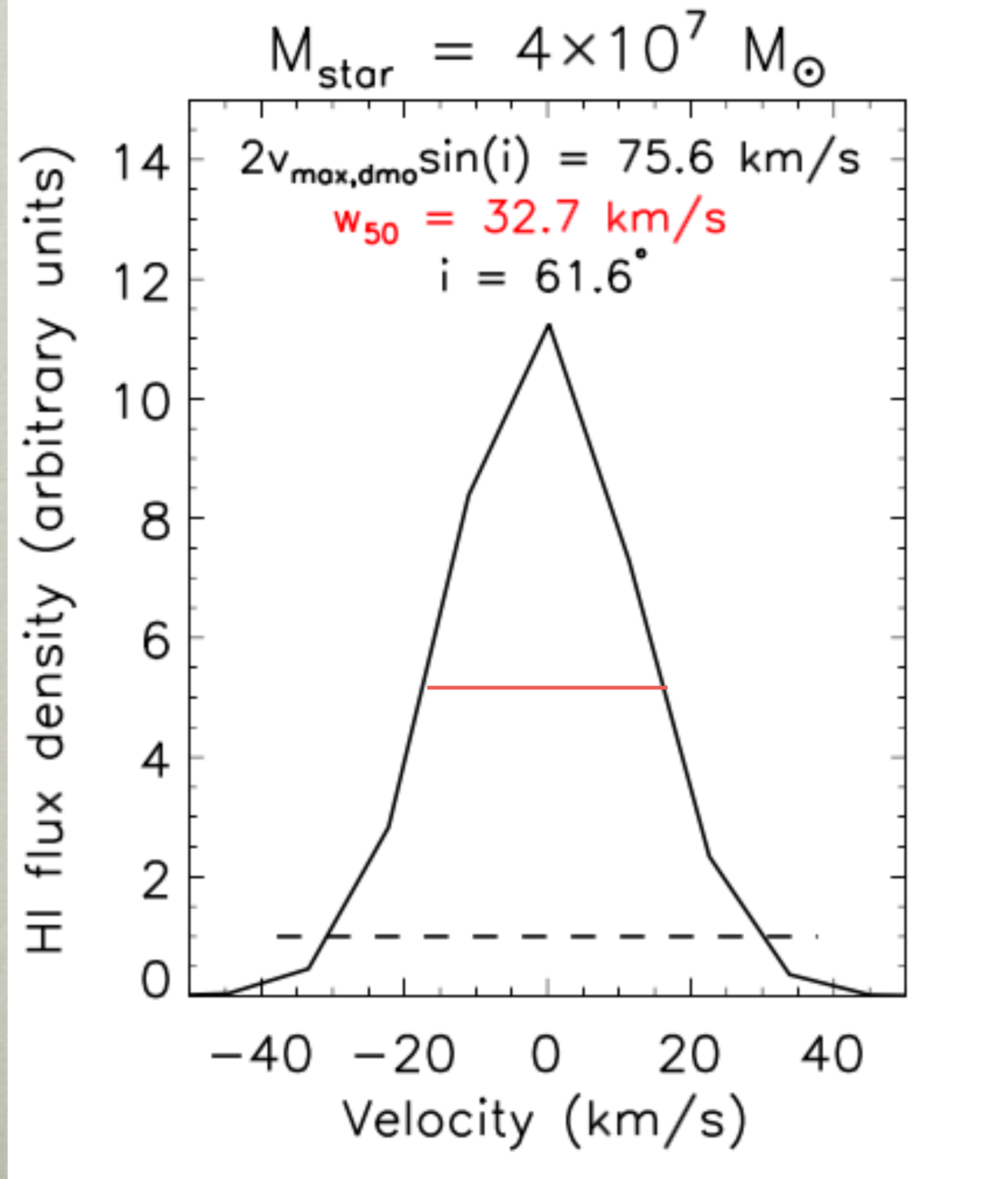


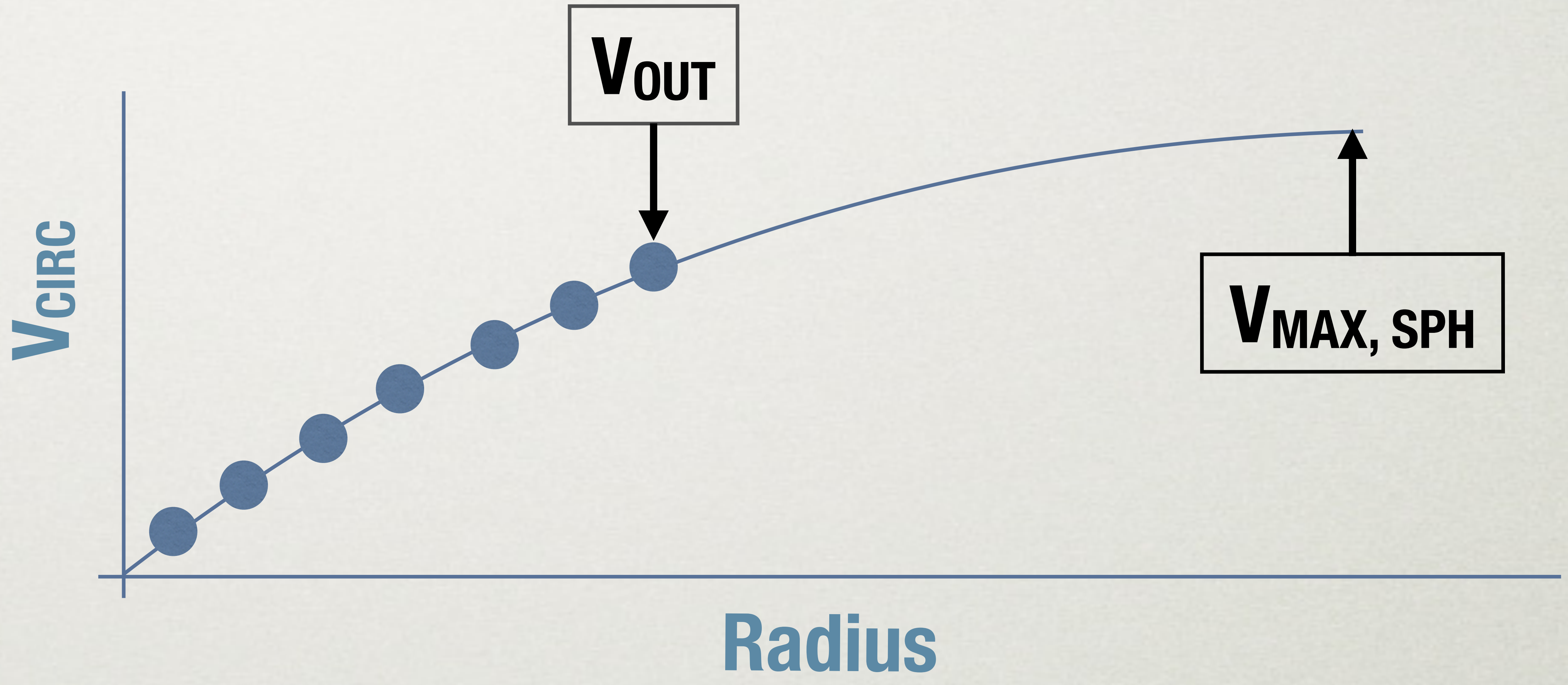




$W_{50} \sim 2*V_{OUT} \sim 2* V_{MAX, SPH}$

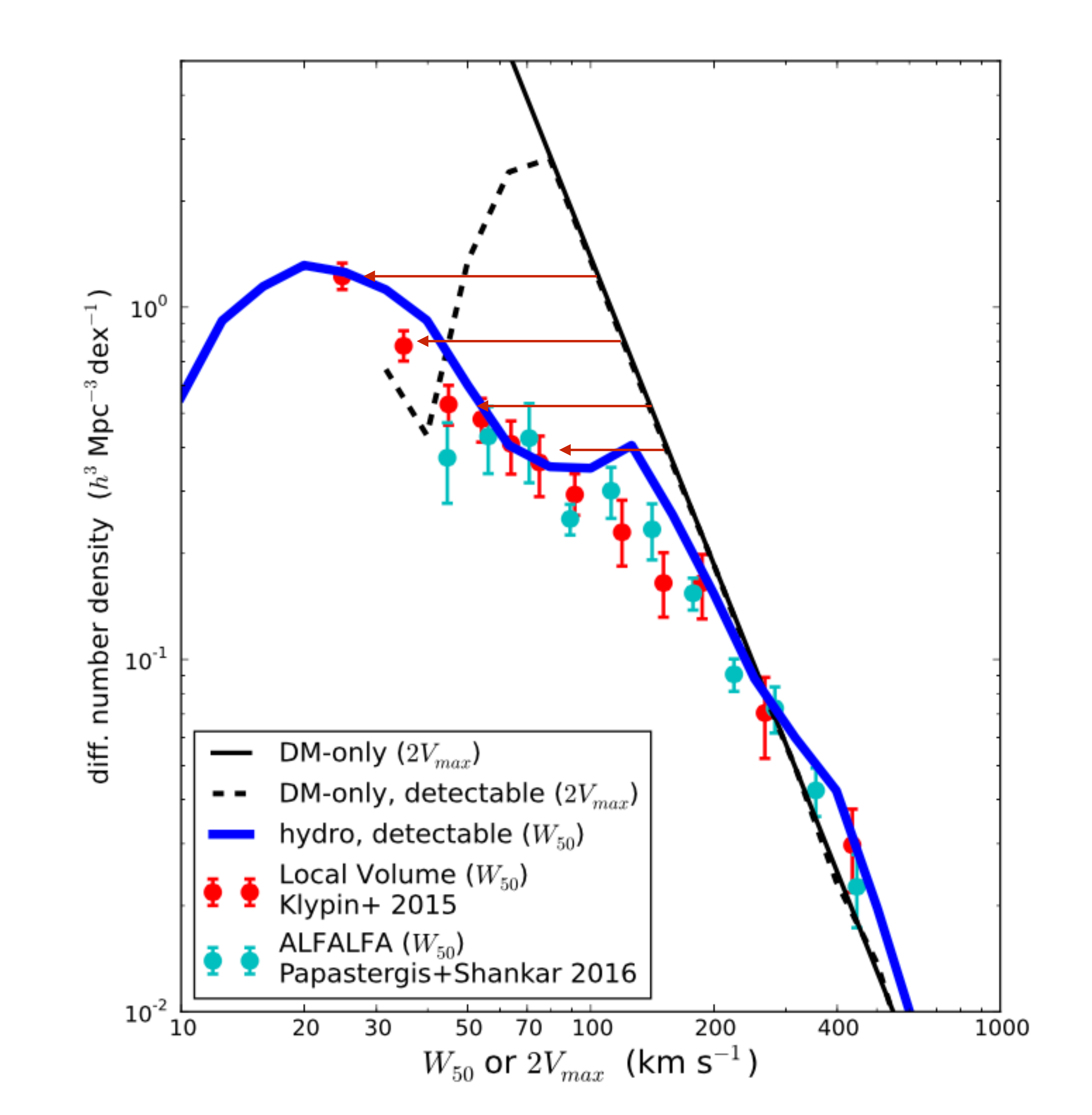






$W_{50} < 2*V_{OUT} < 2*V_{MAX,\ SPH}$

Putting it Together



Brooks et al. (2017), arXiv:1701.07835

Key Points (so far):

- There is no evidence for missing dwarfs!

Quite the opposite! There is now compelling evidence that halos down to at least 10^8 $M_\odot$ are occupied by galaxies (down to ~100 $L_\odot$) , e.g., Nadler et al. (2020)

Rubin Observatory's LSST (and WALLABY) will open up a new era in dwarf galaxy studies that will allow us to directly test this fact

- Note that these solutions to the small scale crisis do NOT (so far) require stellar feedback!

MESSY BARYONIC FEEDBACK NEEDED...

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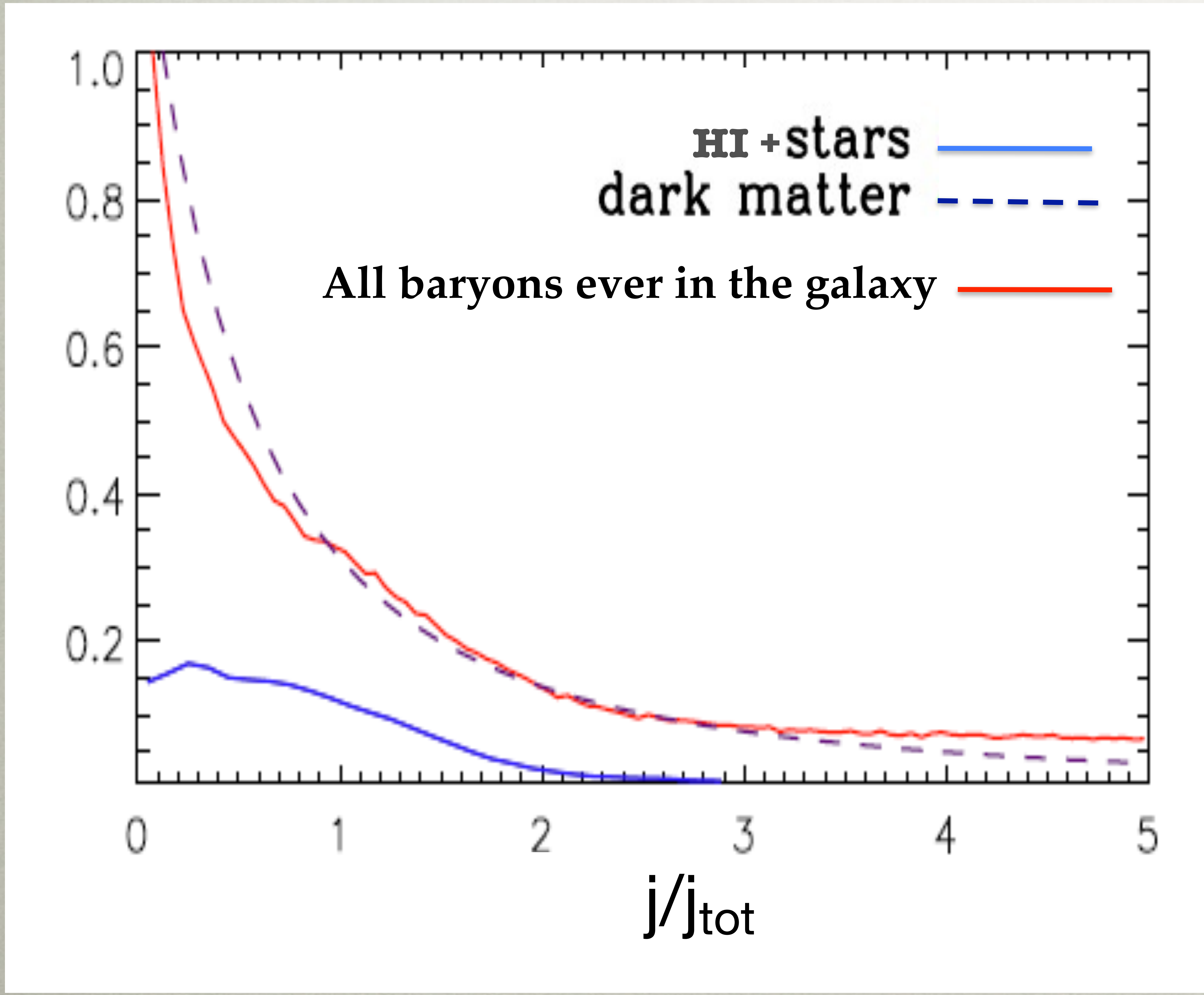
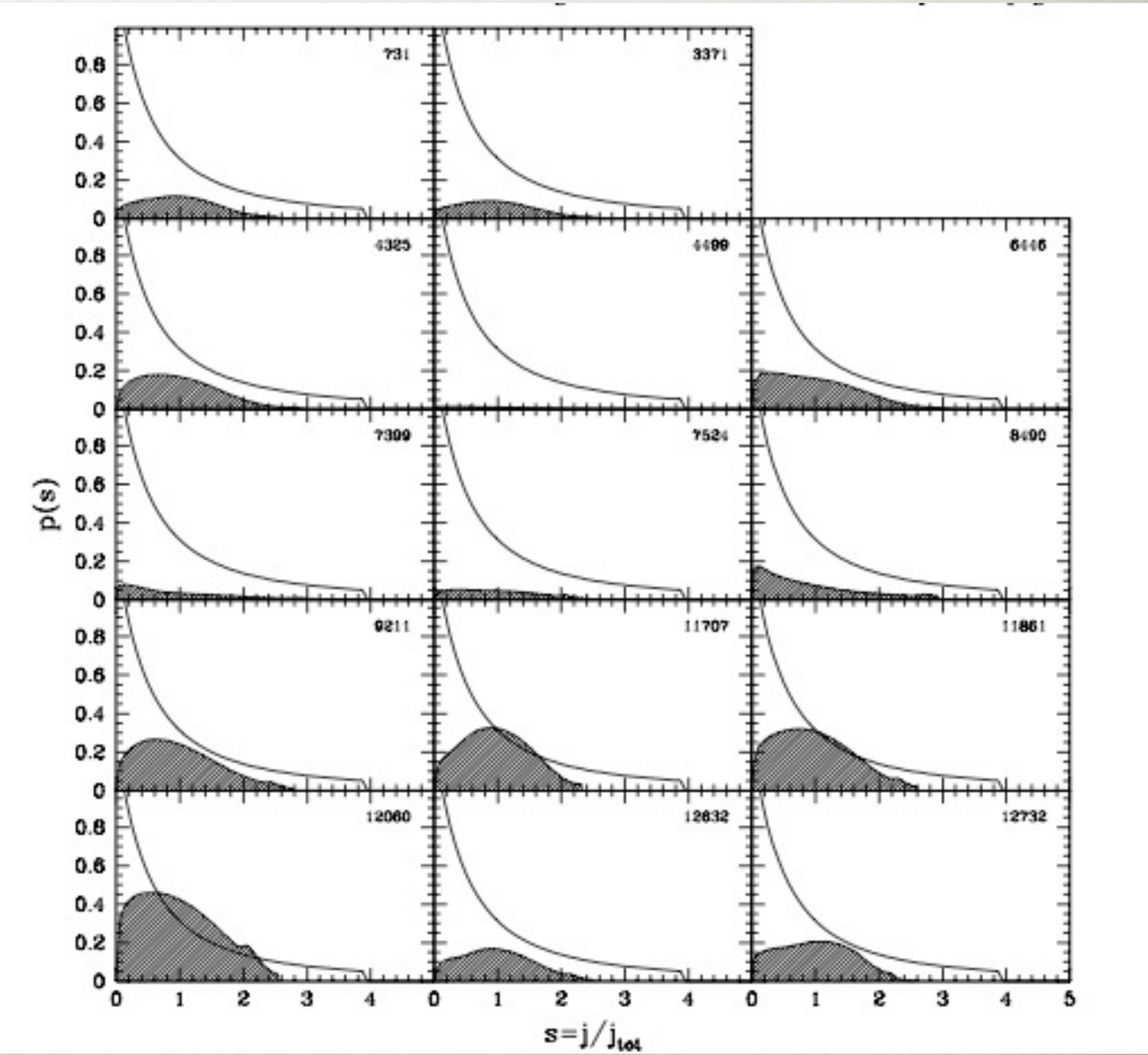
Diversity	?	Santos-Santos et al. (2018, 2020), Roper et al. (2022)
Planes of Satellites		Garavito-Camargo et al. (2021)

Bulgeless disk galaxies are a really good argument in favor of messy baryonic physics

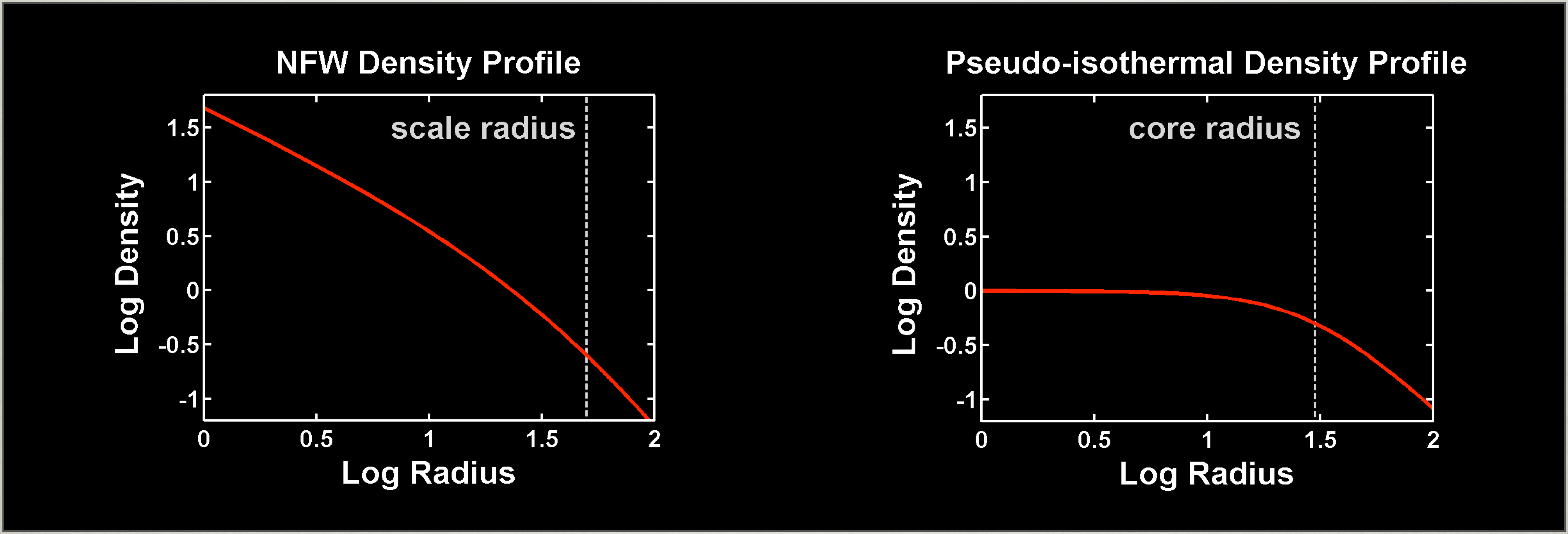




Brook et al., 2011, MNRAS, 415, 1051

van den Bosch et al. (2001)

The Cusp/Core Problem

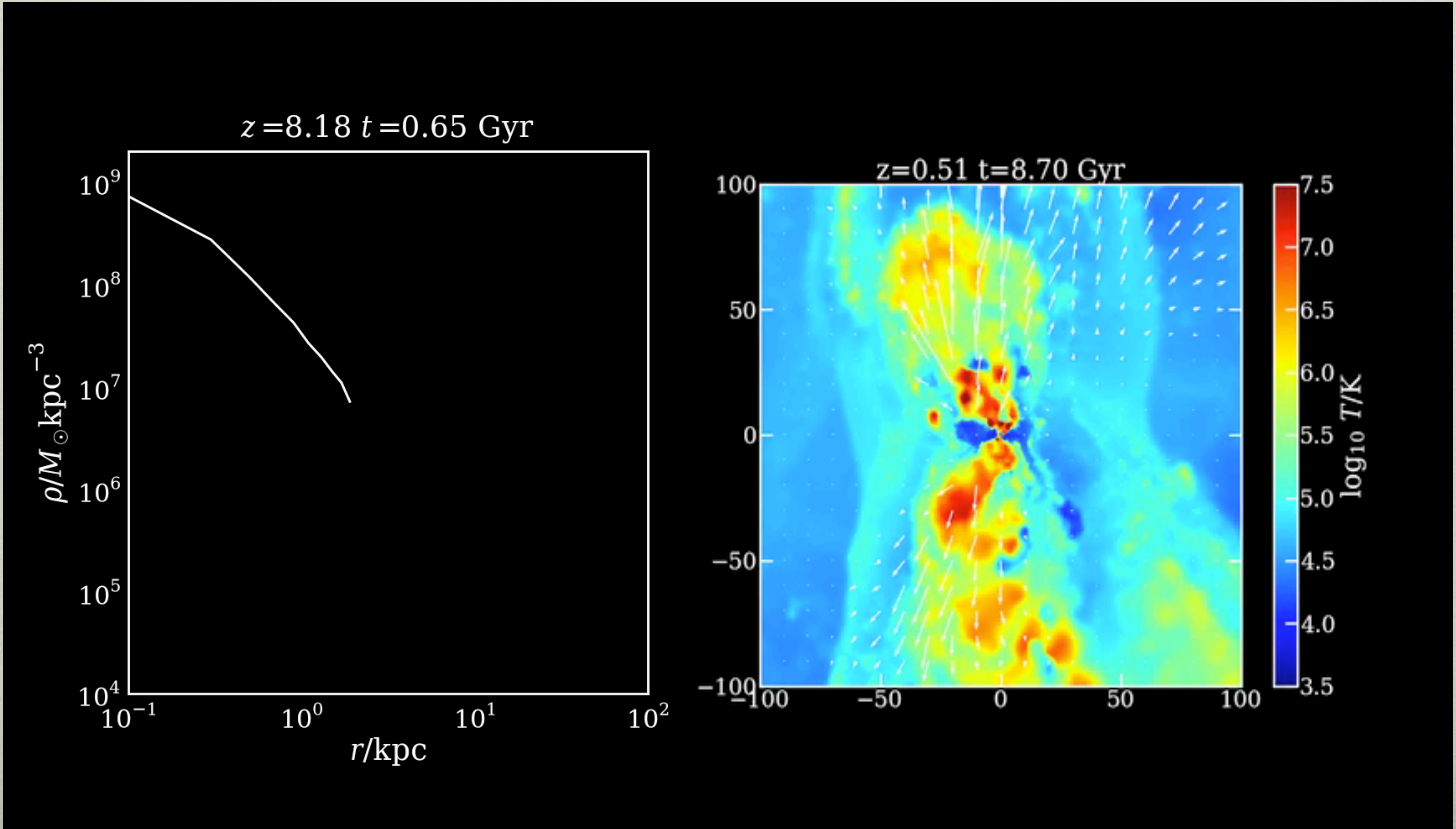


Parameterize density profile as $\varrho(r) \propto r^{-\alpha}$

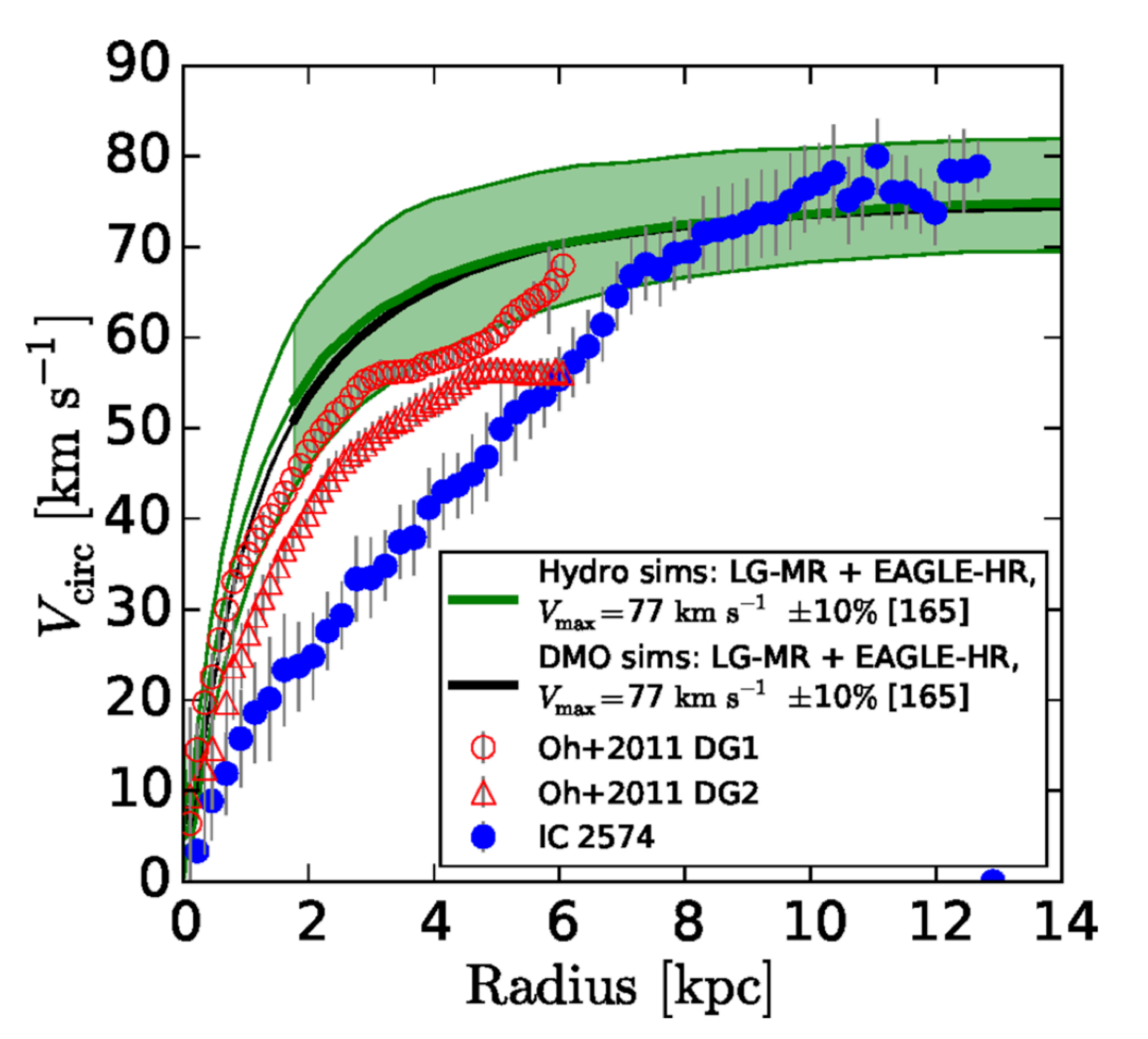
Simulations predict $\alpha \sim 1$ (a steeply rising central cusp)

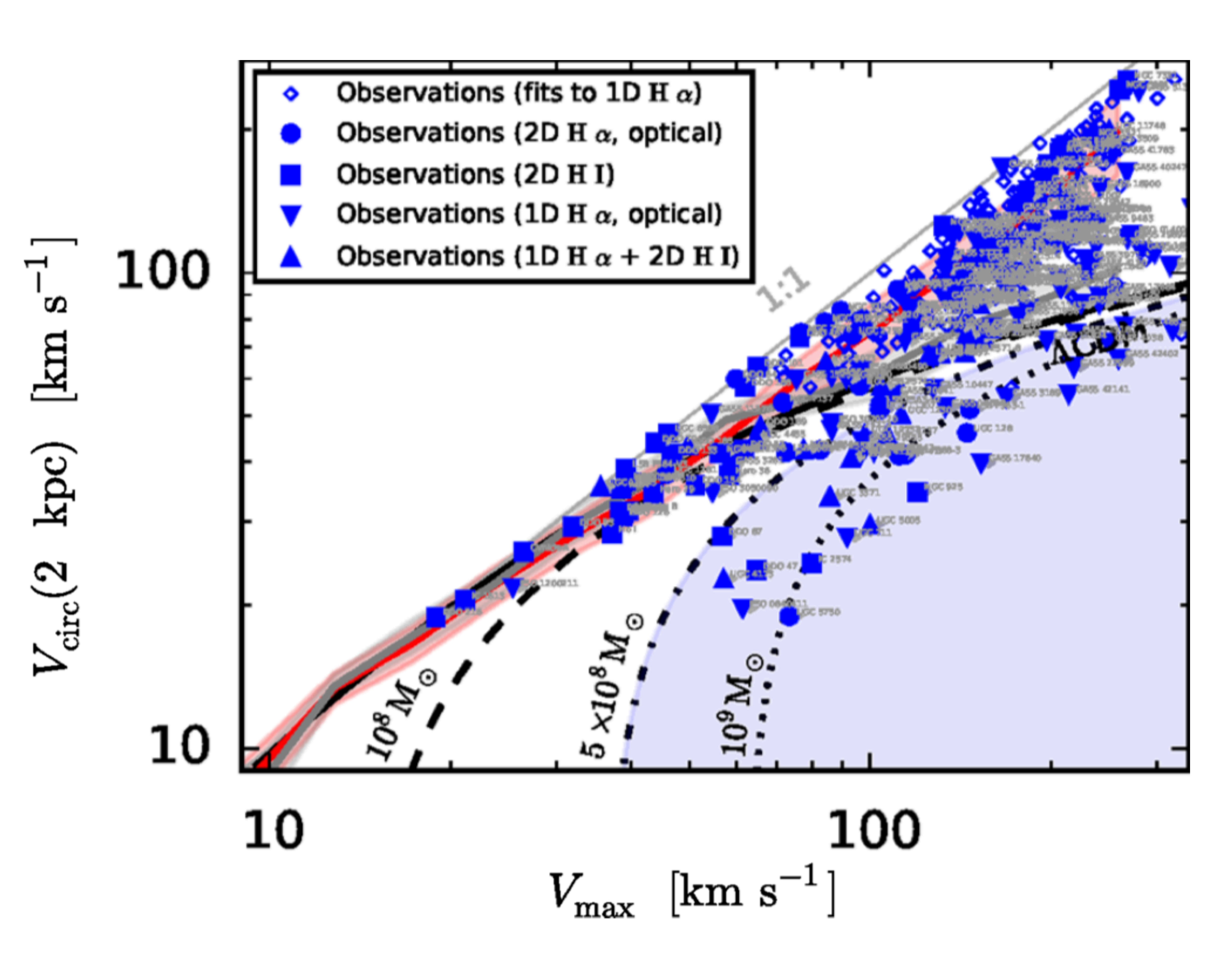
Observations show $\alpha \sim 0$ (constant-density core)

Creation of a Dark Matter Core



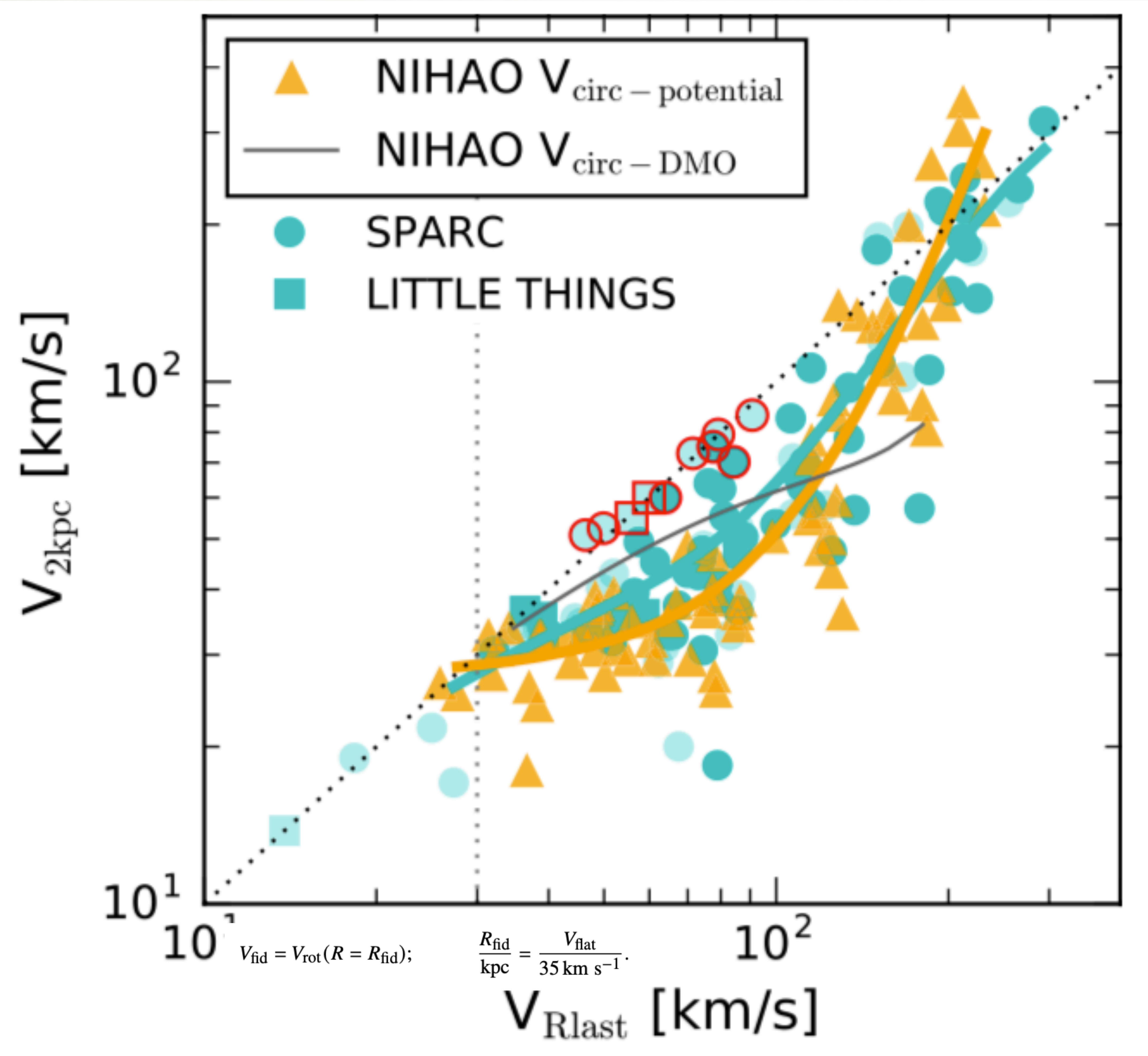
Diversity Problem



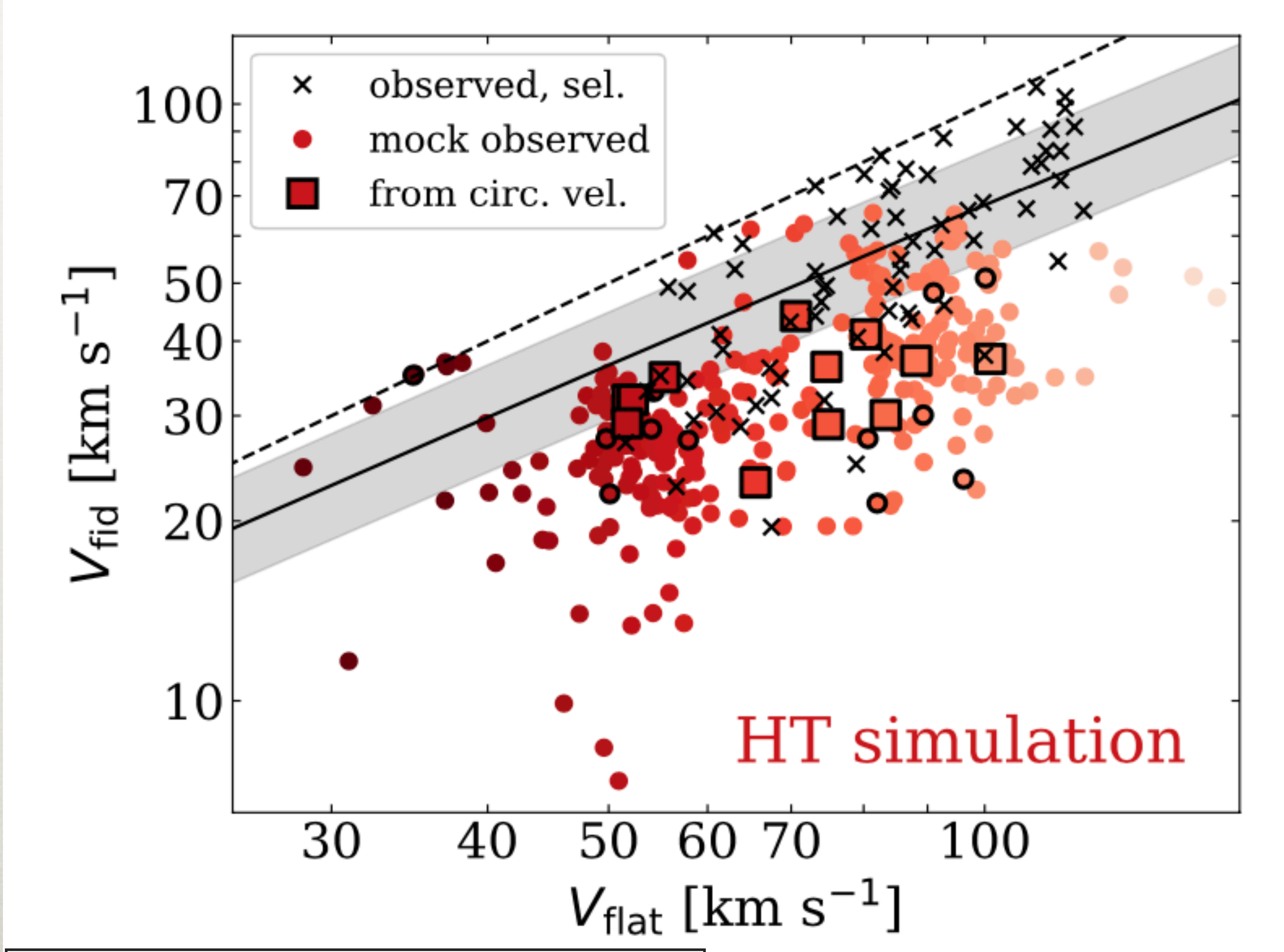


Oman et al. (2015)

Diversity Problem



Santos-Santos et al. (2018)



$$V_{fid} = V_{rot}(R = R_{fid}); \quad \frac{R_{fid}}{kpc} = \frac{V_{flat}}{35\,km\,s^{-1}}.$$

Roper et al. (2022)

Diversity Problem

$$V_{fid} = V_{rot}(R = R_{fid}); \qquad \frac{R_{fid}}{\mathrm{kpc}} = \frac{V_{flat}}{35\,\mathrm{km\,s^{-1}}}.$$

Roper et al. (2022)

Diversity of Rotation Curves in SIDM

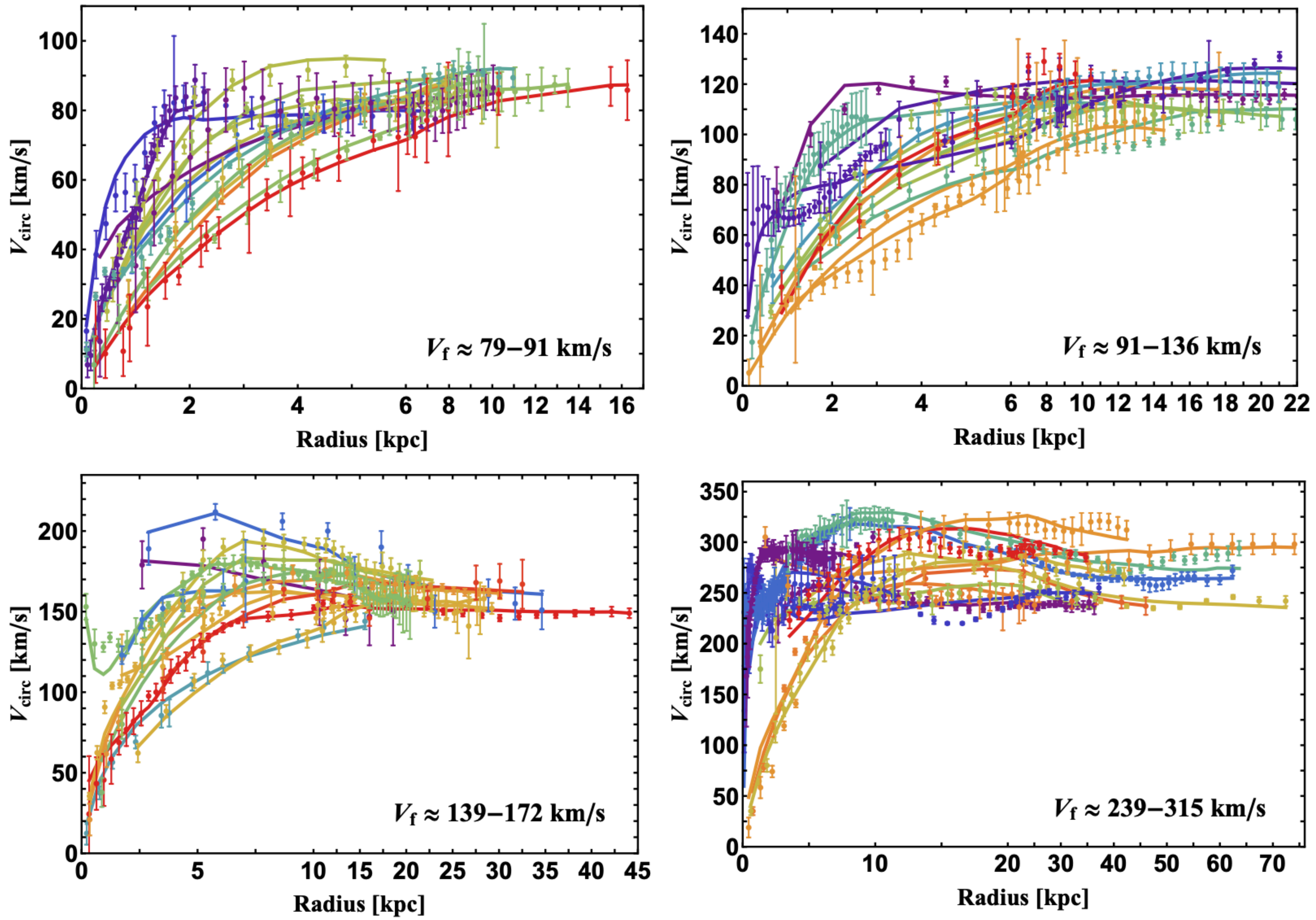
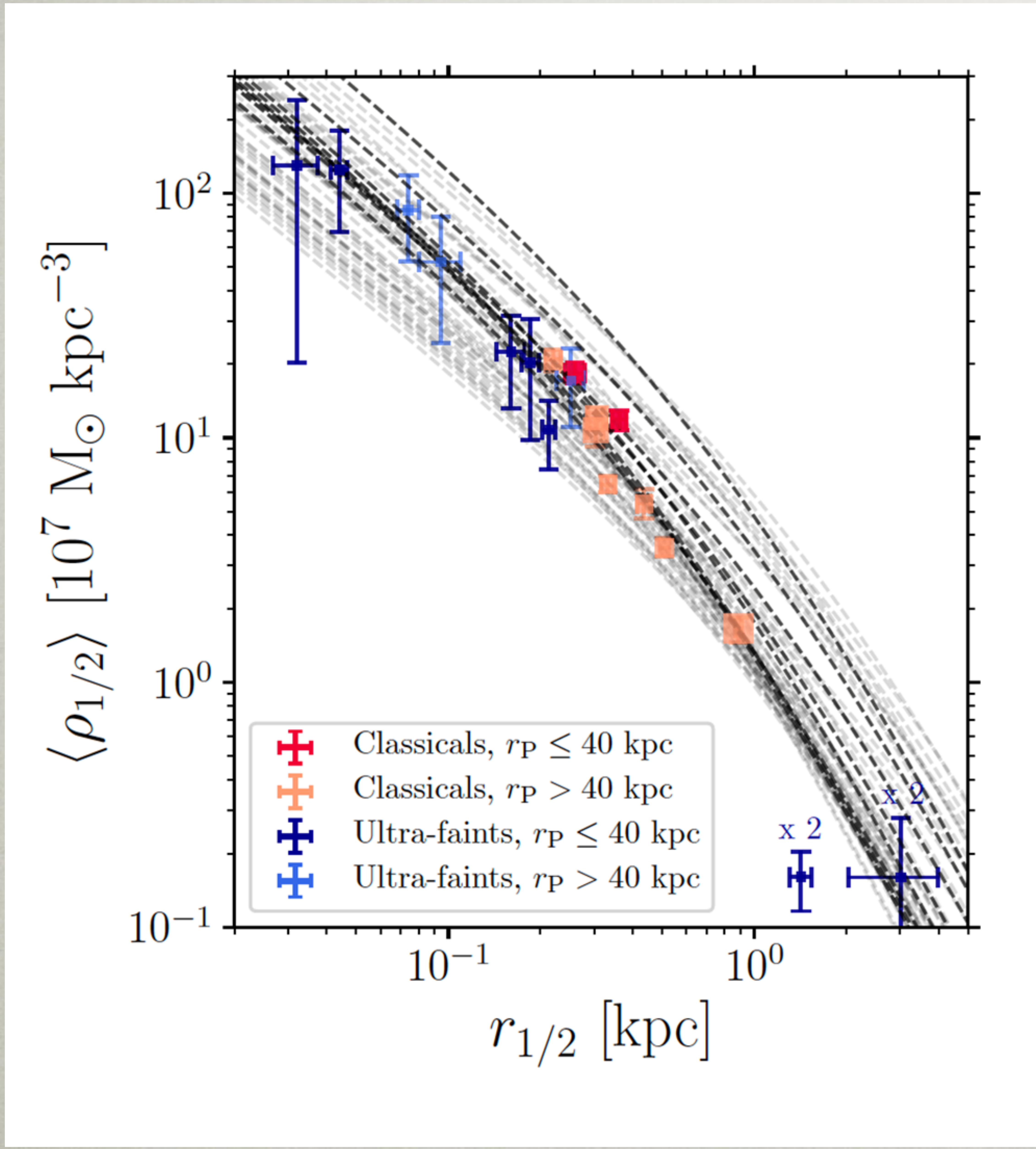


FIG. 1: SIDM fits (solid) to the diverse rotation curves across a range of spiral galaxy masses, where we take $\sigma/\mathrm{m} = 3\ \mathrm{cm}^2/\mathrm{g}$.

Ren, Kwa, Kaplinghat, Yu (2019)



Ultra-Faint Dwarfs: large densities consistent with CDM, or core collapse in SIDM

Kaplinghat et al. (2019)
See also Silverman et al. (2023)

SIDM: Walking a Fine Line

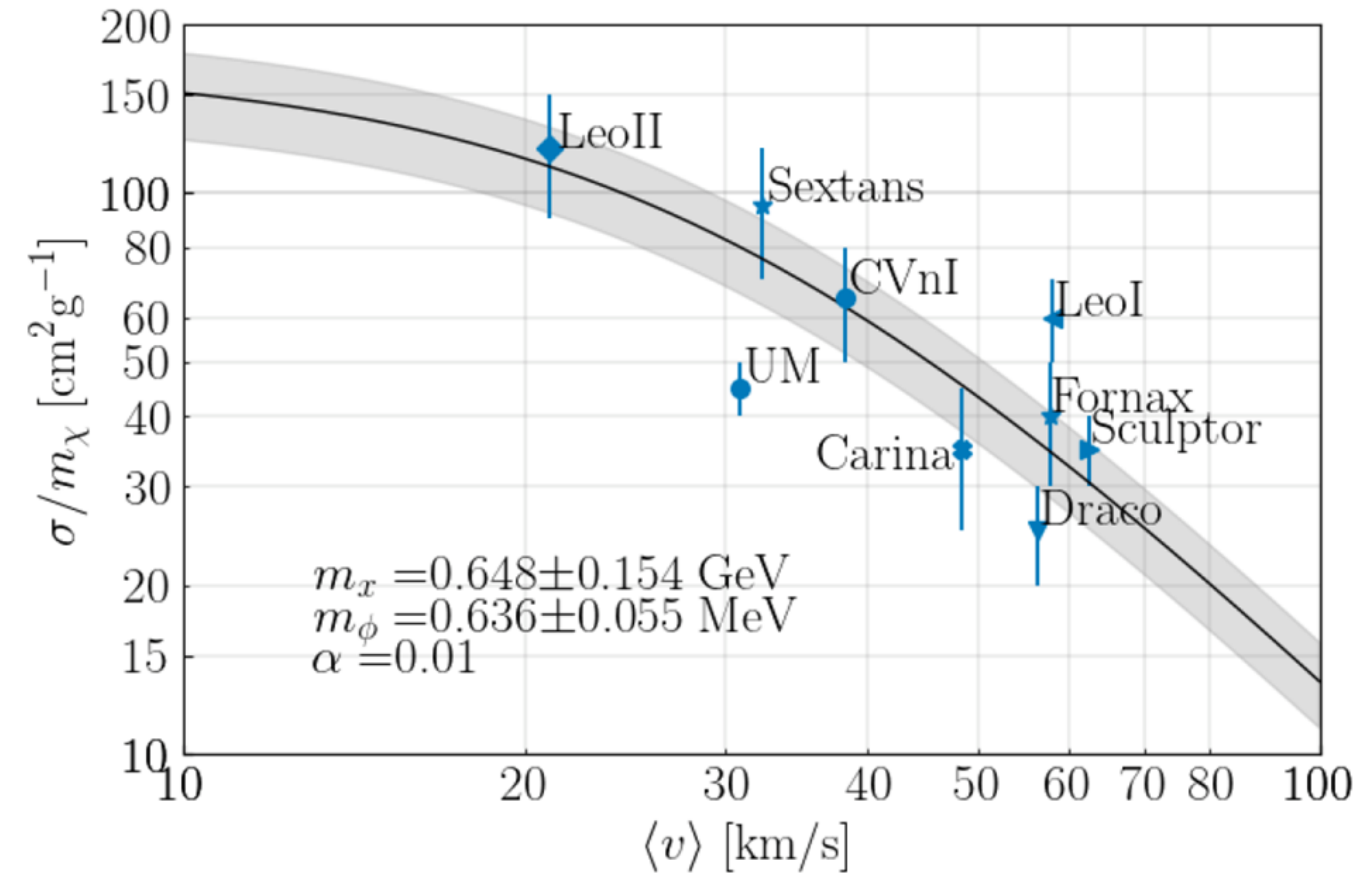


Figure 6. Cross section per unit mass, σ/m_χ, as a function of the average collision velocity, $\langle v \rangle$, of DM particles within each subhalo's core. Symbols show the range of σ/m_χ needed for the SIDM model to reproduce the central DM densities reported by Kaplinghat et al. (2019). The solid line corresponds to the best-fit relation given by eq. (15) to the MW dSph data.

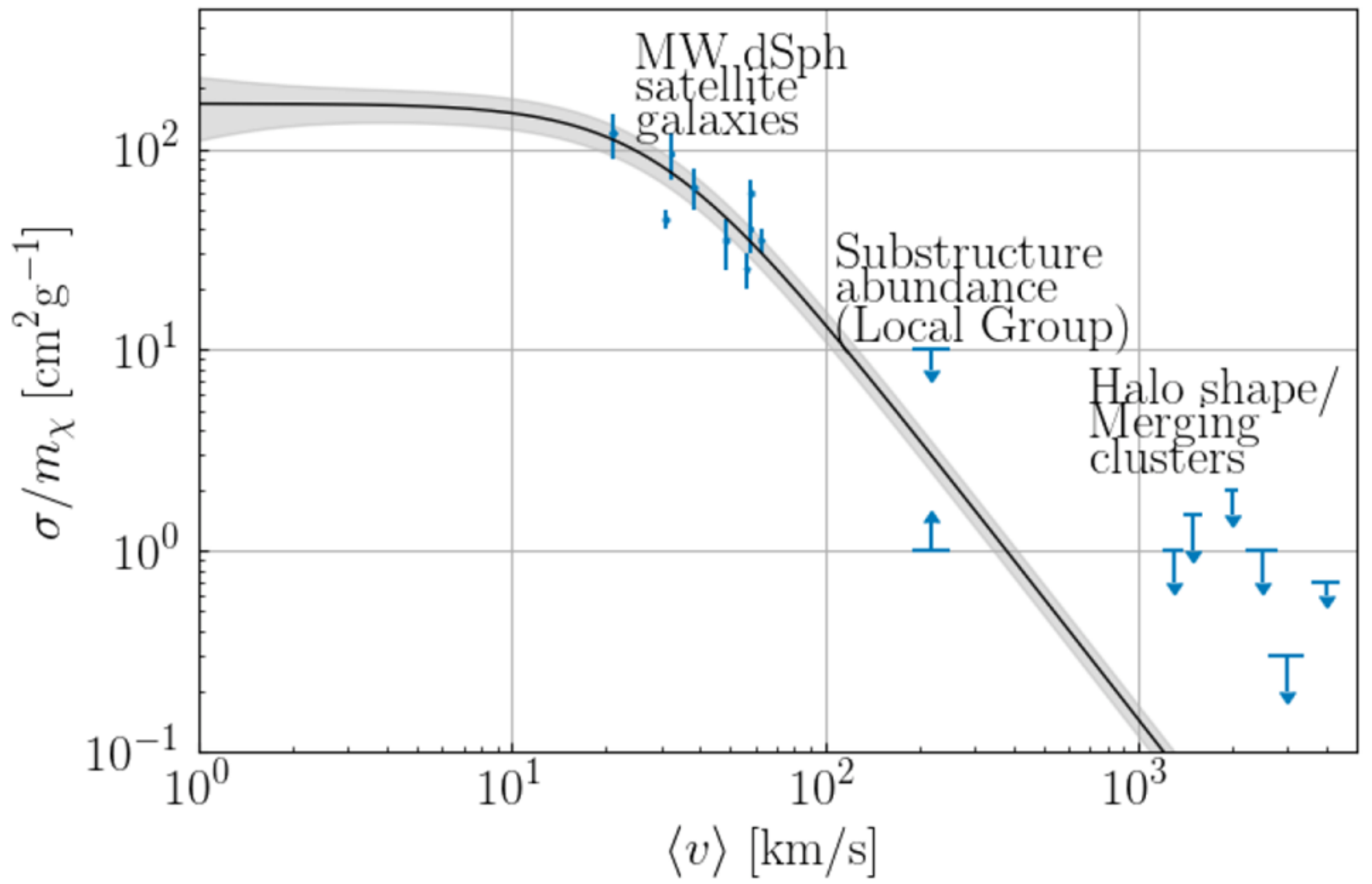
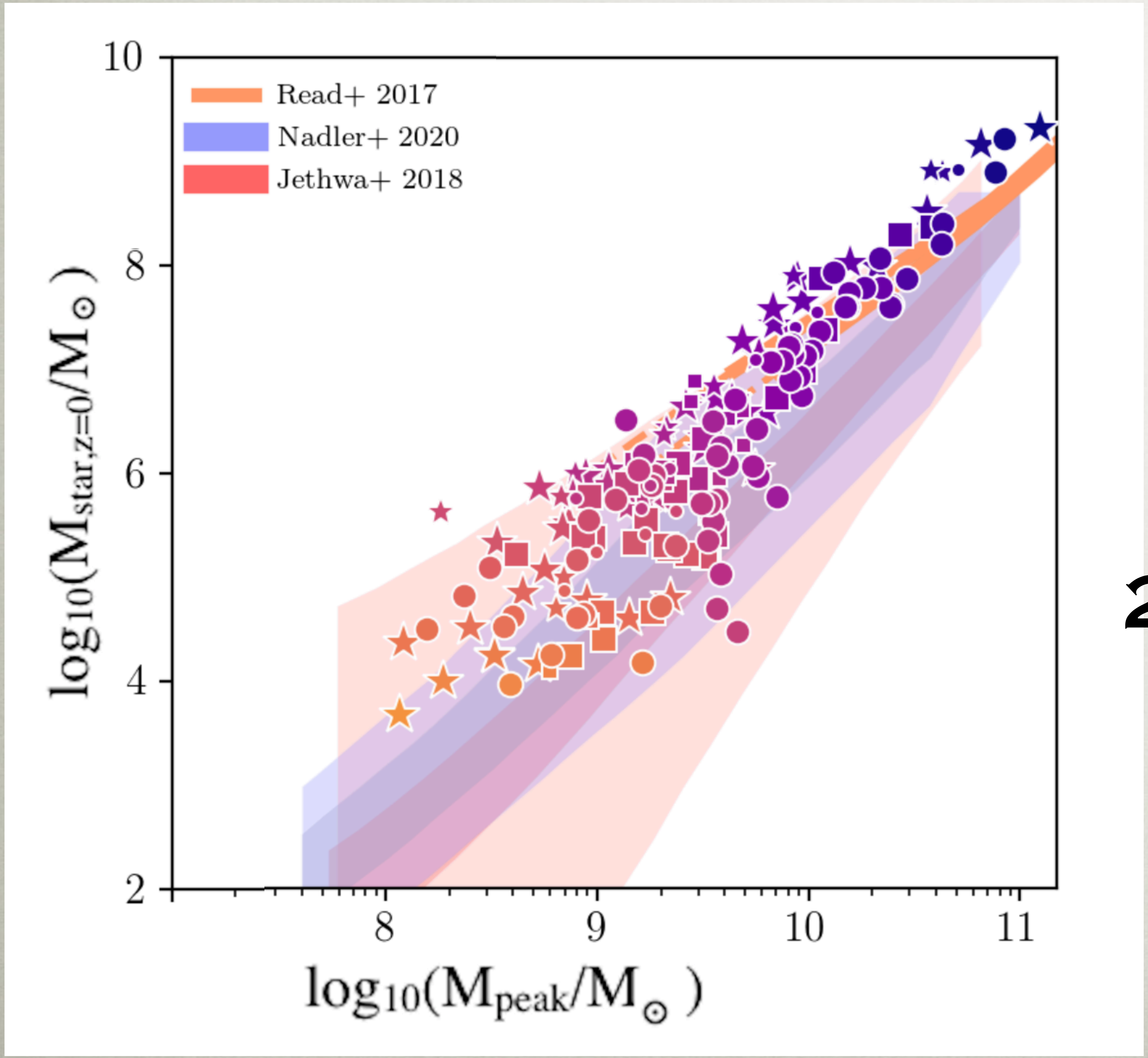
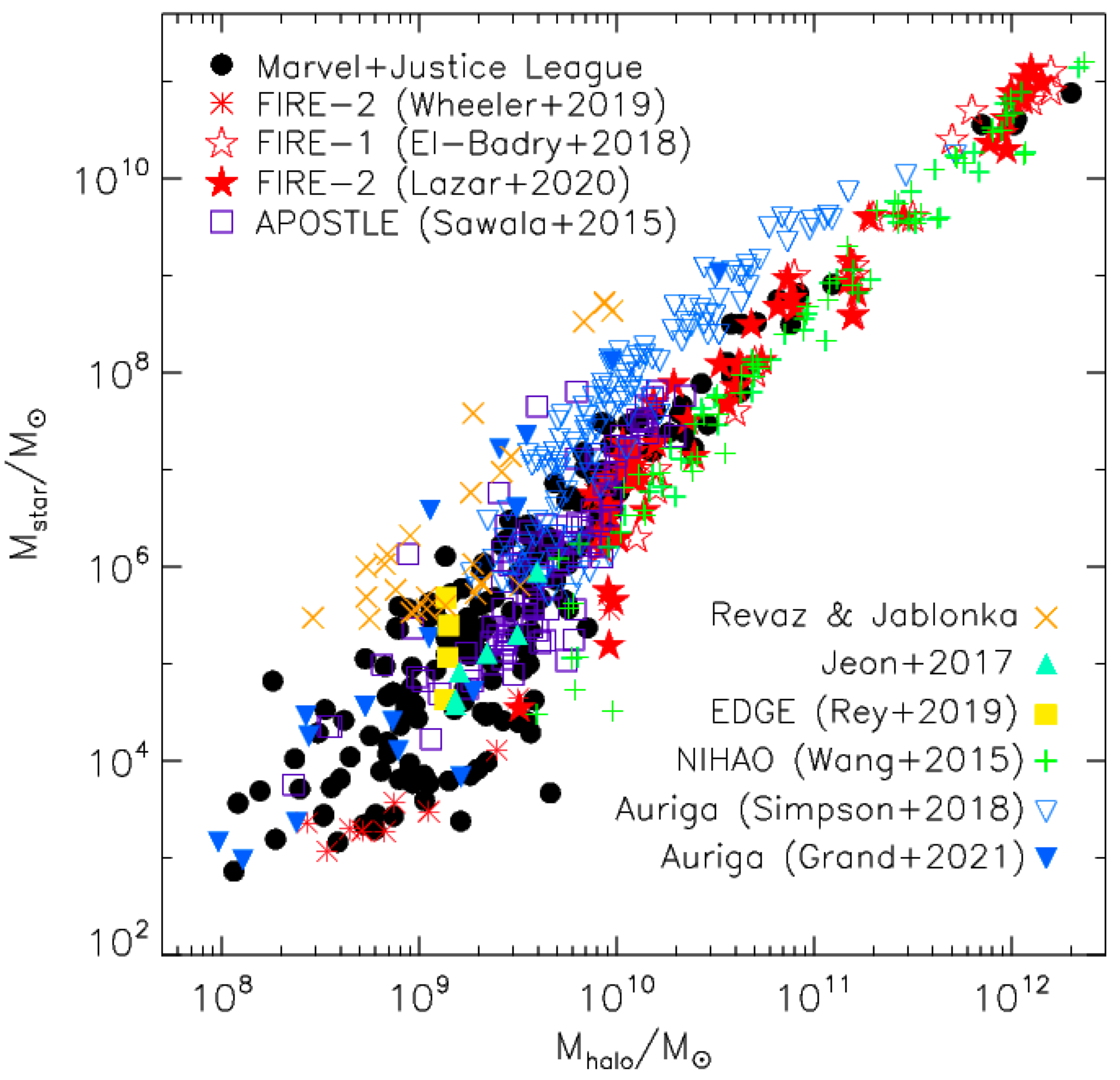


Figure 7. Same as Fig. 6, but extended to cover the range of MW- (~200 km/s) and cluster-size (~1000 – 5000 km/s) haloes' velocities. The figure shows upper and lower limits for σ/m_χ taken for substructure abundance studies (e.g. Volgelsberger et al. 2012 and Zavala et al. 2013), as well as based on halo shape/ellipticity studies and cluster lensing surveys (see text).

Correa 2021

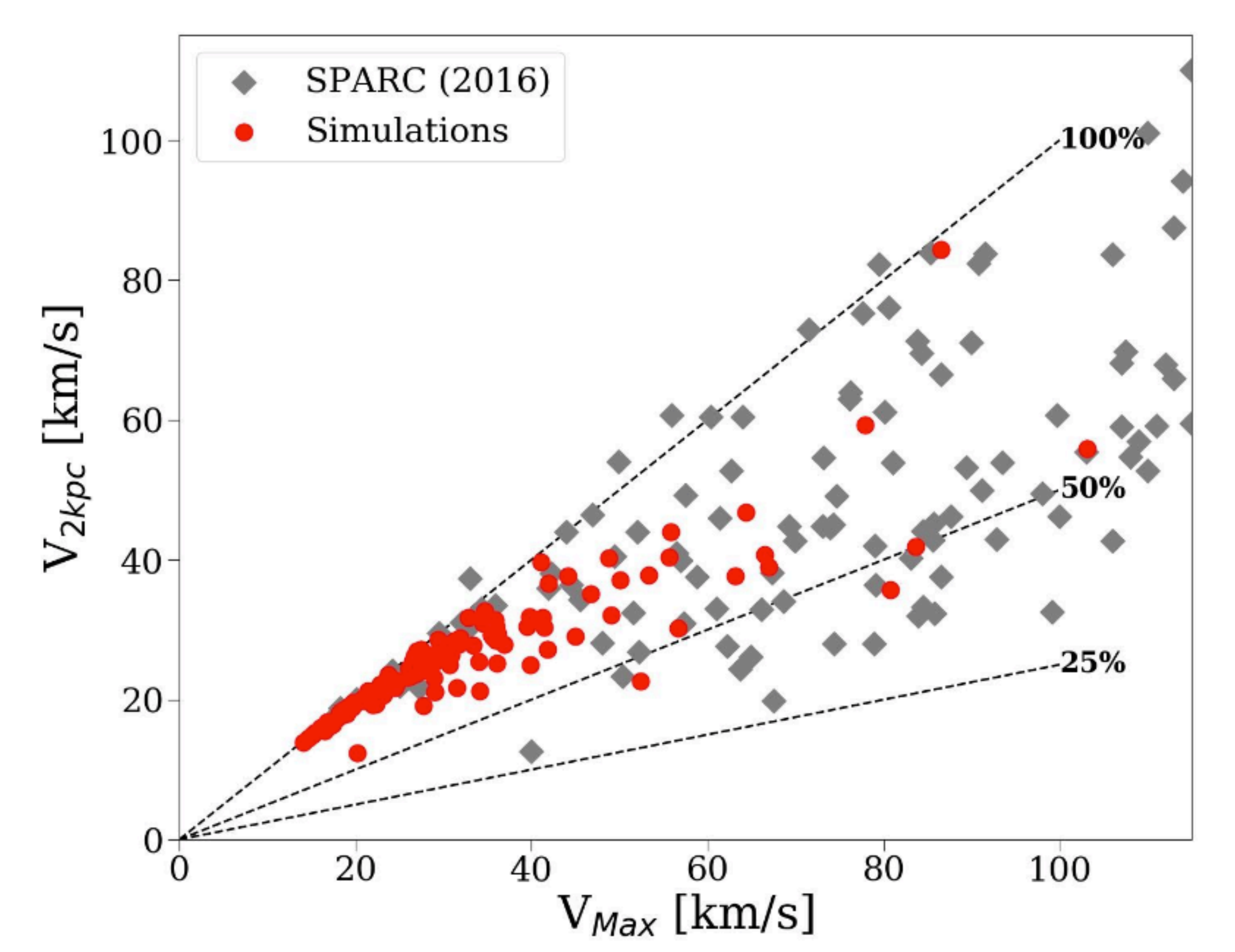


The Marvel + DC Justice League Sample: 200 dwarf galaxies

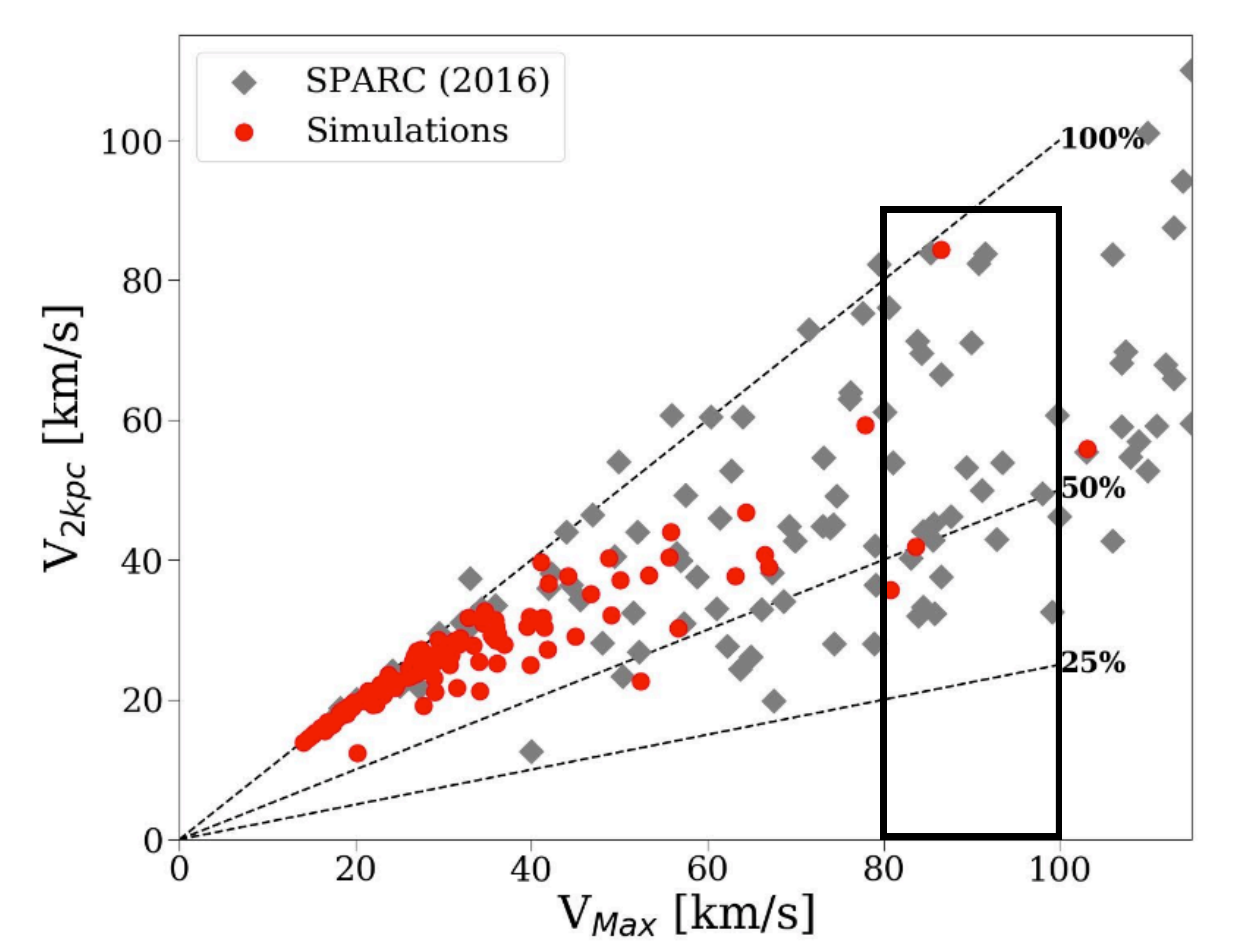


The Landscape of Cosmological Zooms

The Diversity of Rotation Curve Shapes

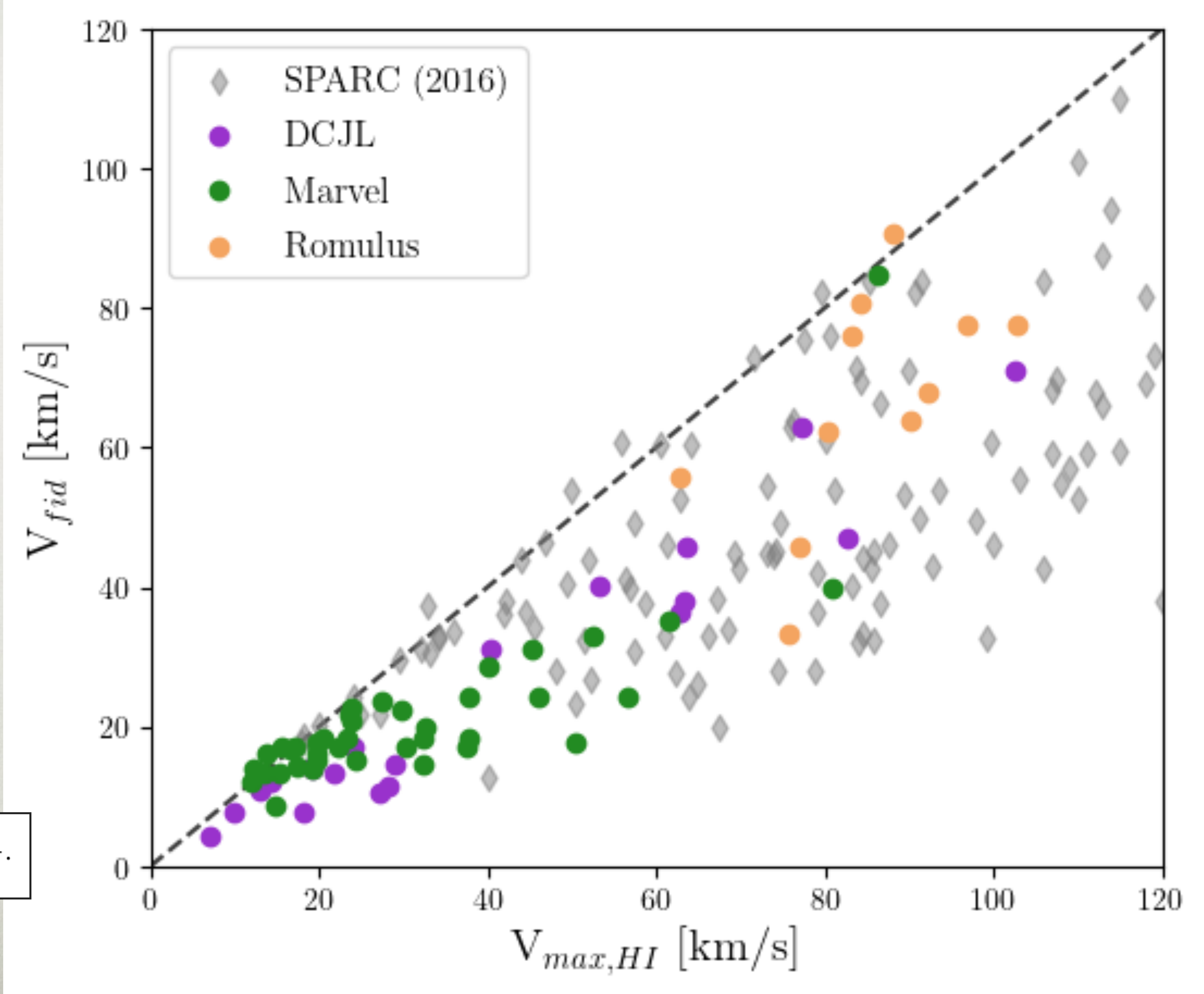


The Diversity of Rotation Curve Shapes



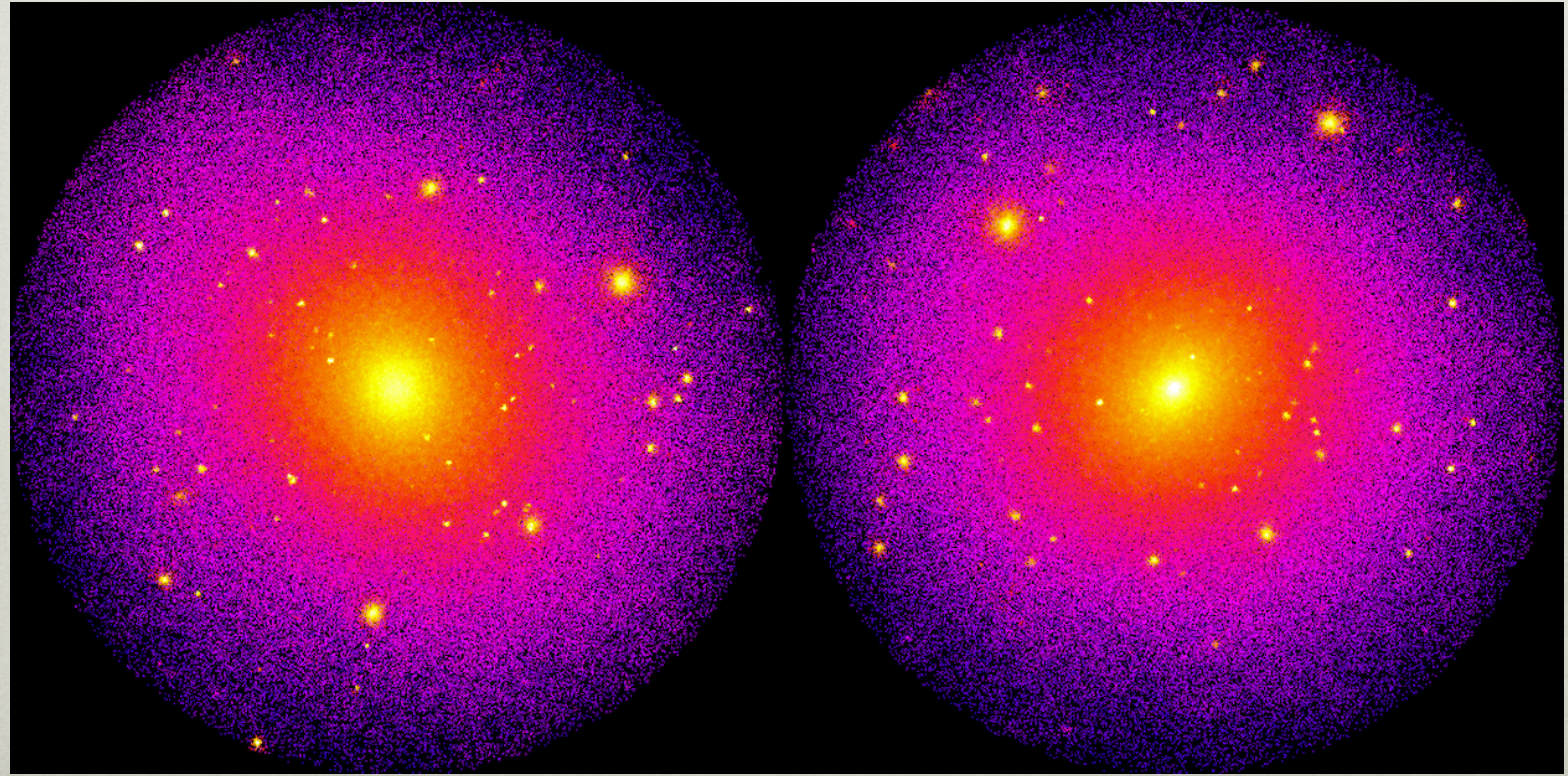
~20 new dwarfs

Diversity Problem?



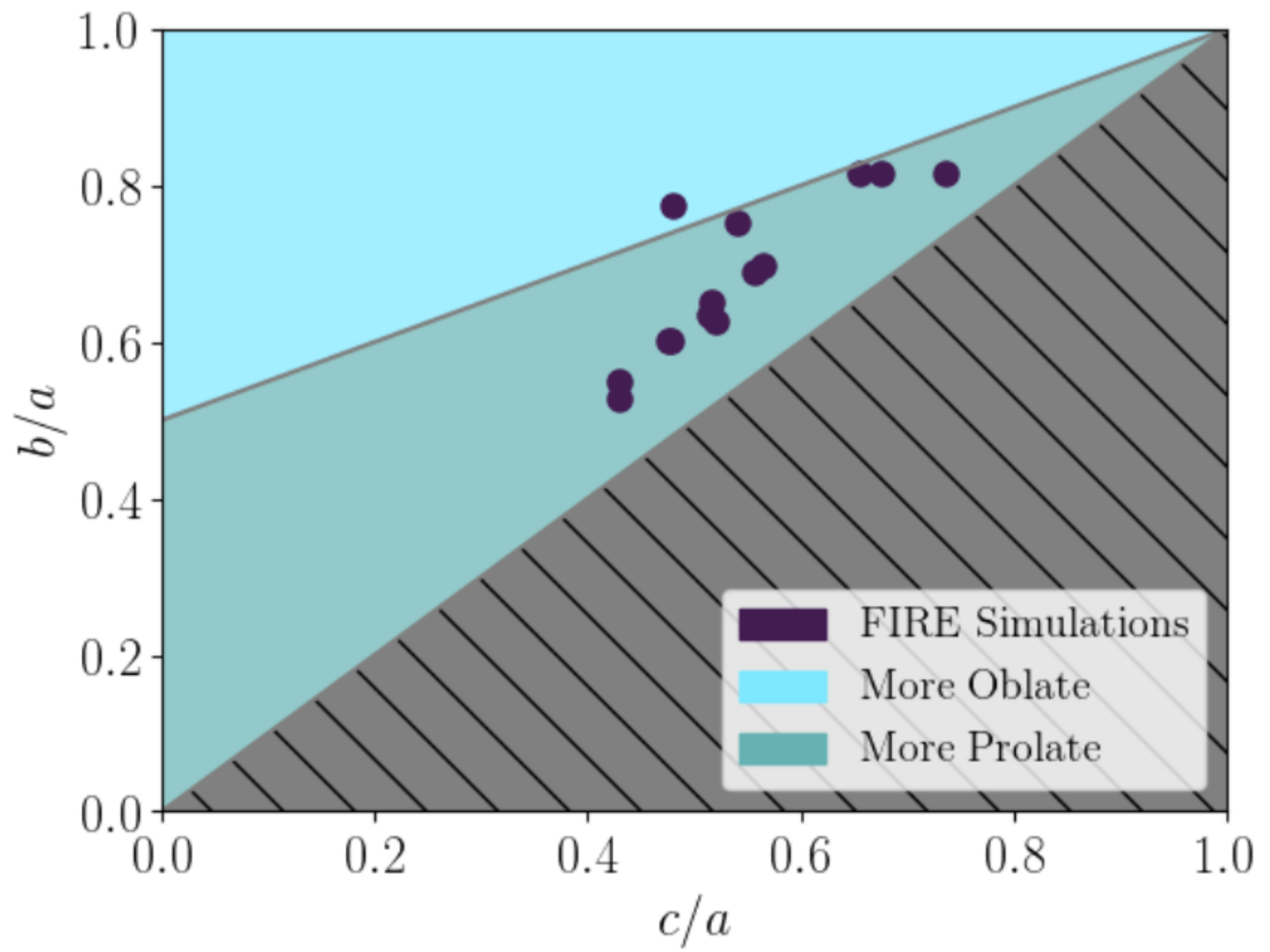
$$V_{\rm fid} = V_{\rm rot}(R = R_{\rm fid}); \qquad \frac{R_{\rm fid}}{\rm kpc} = \frac{V_{\rm flat}}{35\,{\rm km\ s^{-1}}}.$$

Galaxy Shapes as a Tracer?



from review in arXiv:1407.7544

Galaxy Shapes as a Tracer?

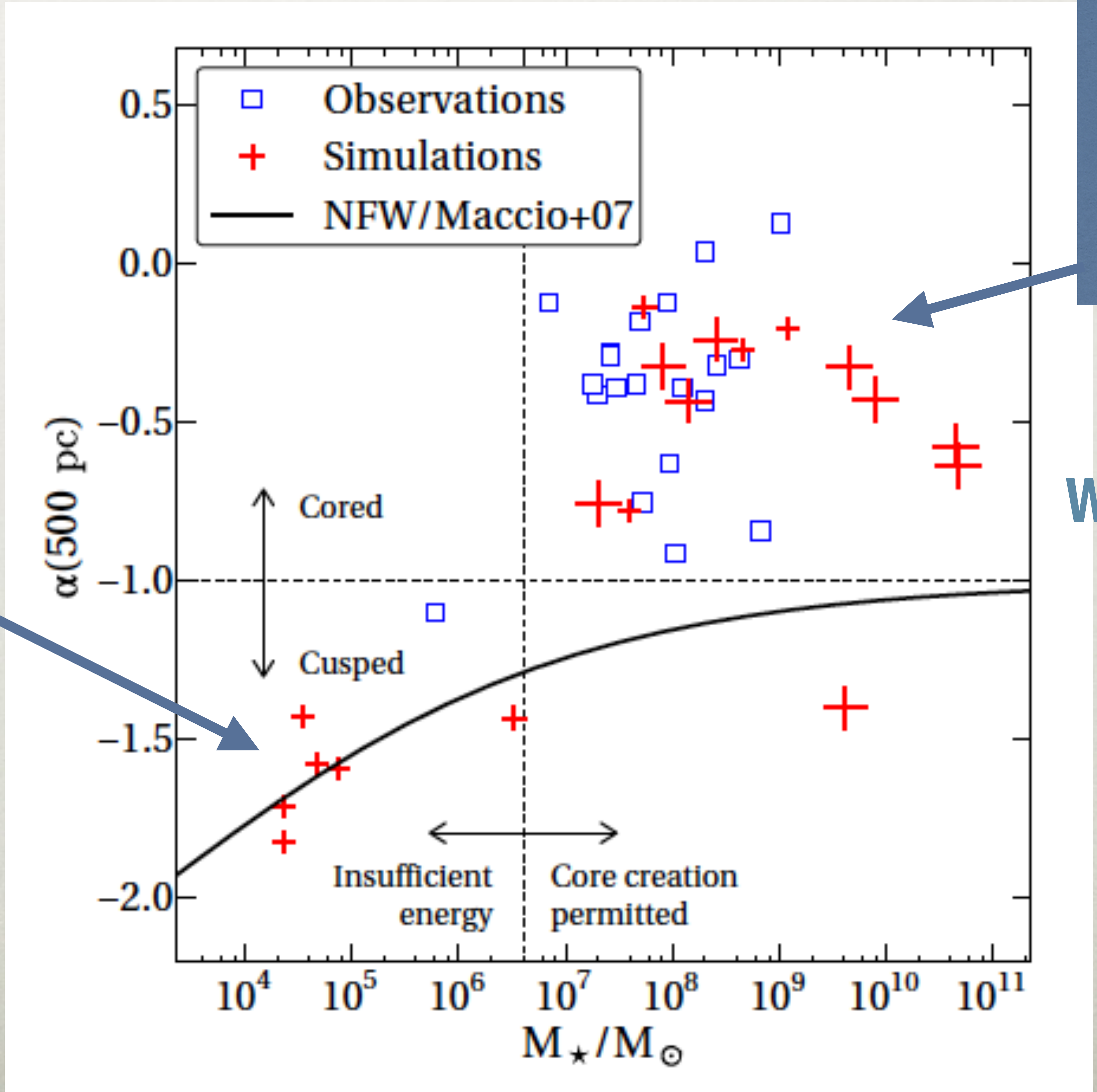


(a) Distribution of stellar axis ratios $b/a, c/a$ evaluated at half-light. As shown, the FIRE galaxies are largely prolate in stellar distribution

Core creation should affect the shapes of dwarf galaxies?

Xu & Randall, arXiv:1904.08949

Astrophysical Constraints on Dark Matter: The Importance of Ultra-Faint Dwarfs



If galaxies in this mass range are observed to have large cores, or deviate from triaxial halos, then something beyond CDM is necessary

Galaxies in this mass range have cores, but triaxial vs spherical halos may isolate the DM model

WLM: a cored galaxy with a prolate halo!
see Leung et al. (2020)

Pontzen & Governato (2014)

Conclusions

To constrain the Dark Matter model, we must understand the impact of baryonic physics on galaxy formation!

Baryonic physics alleviates the current problems with CDM, but that doesn't mean CDM is the correct model! Very little work has been done to discover whether galaxy formation can be reproduced in models outside of CDM

Diversity of rotation curves is the current outstanding problem: not clear if CDM+baryonic physics can reproduce diversity

Halos shapes as a discriminator?