ΛCDM: The End of the Road?
(or)
The End of the Road for ΛCDM?

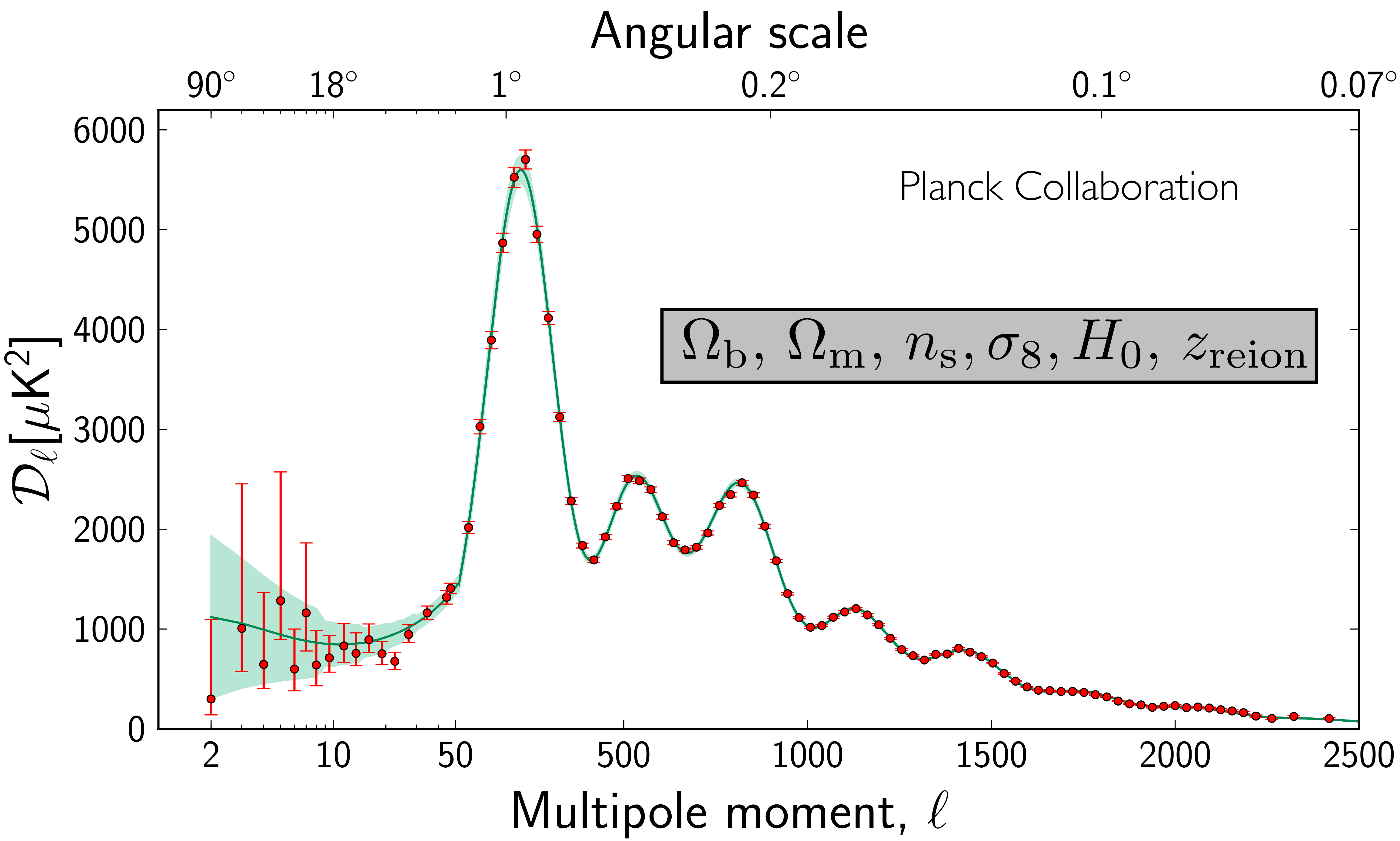
Astrophysical motivations for considering alternatives to collisionless Cold Dark Matter

Mike Boylan-Kolchin

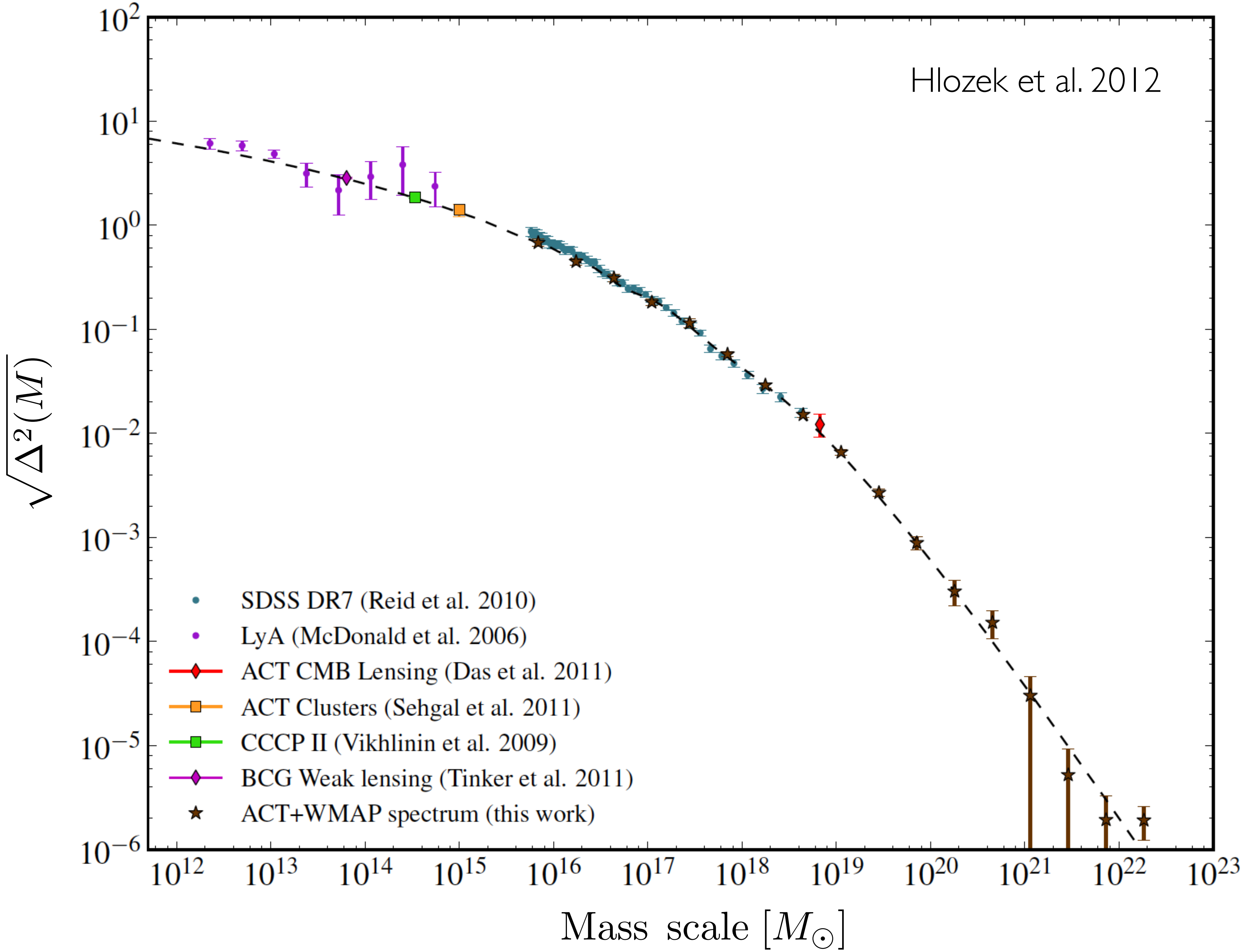
UNIVERSITY OF MARYLAND

Workshop on SIDM
Harvard
7 August 2013

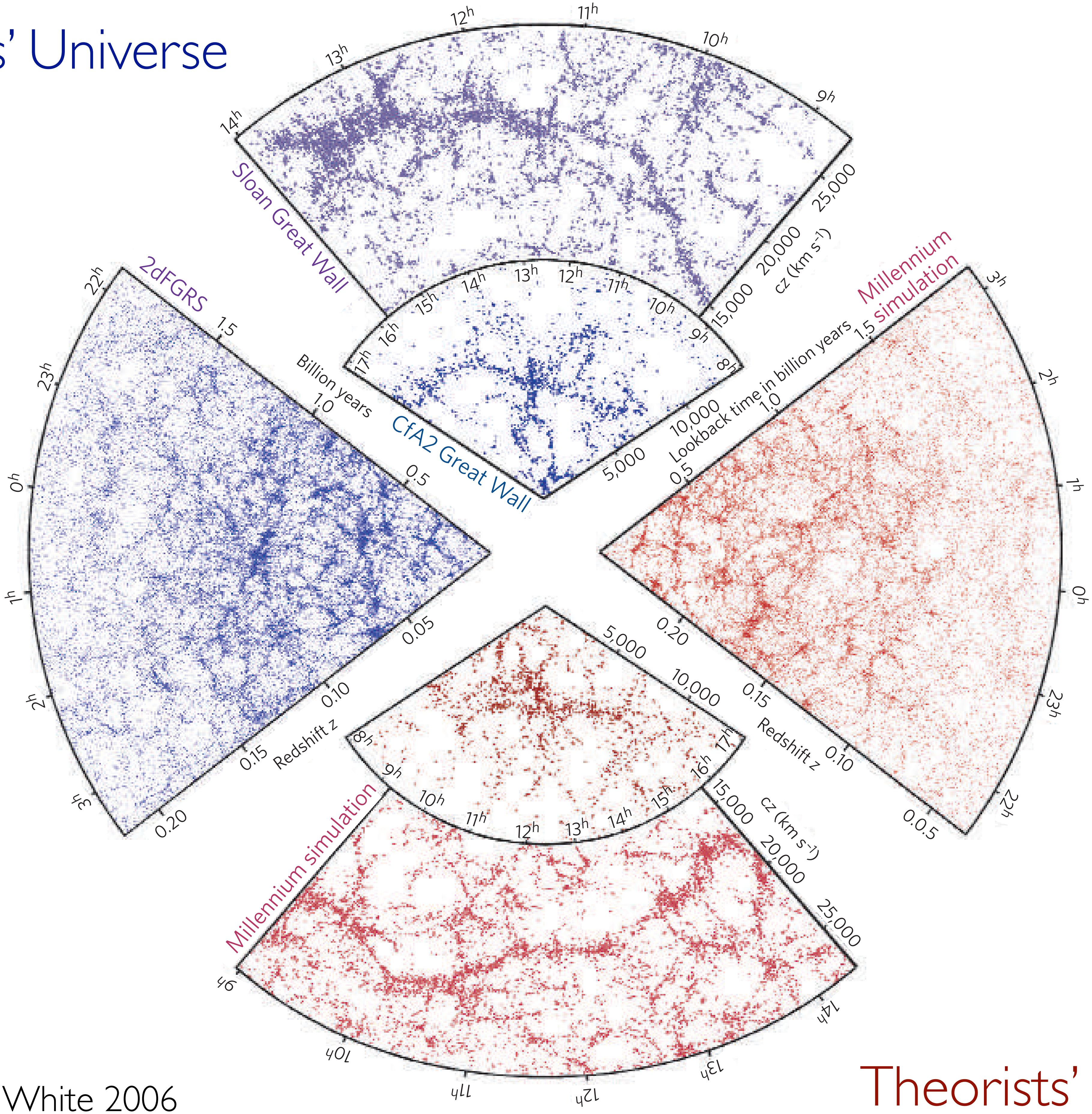
ΛCDM: a remarkably successful theory on large scales



ΛCDM: a remarkably successful theory on large scales



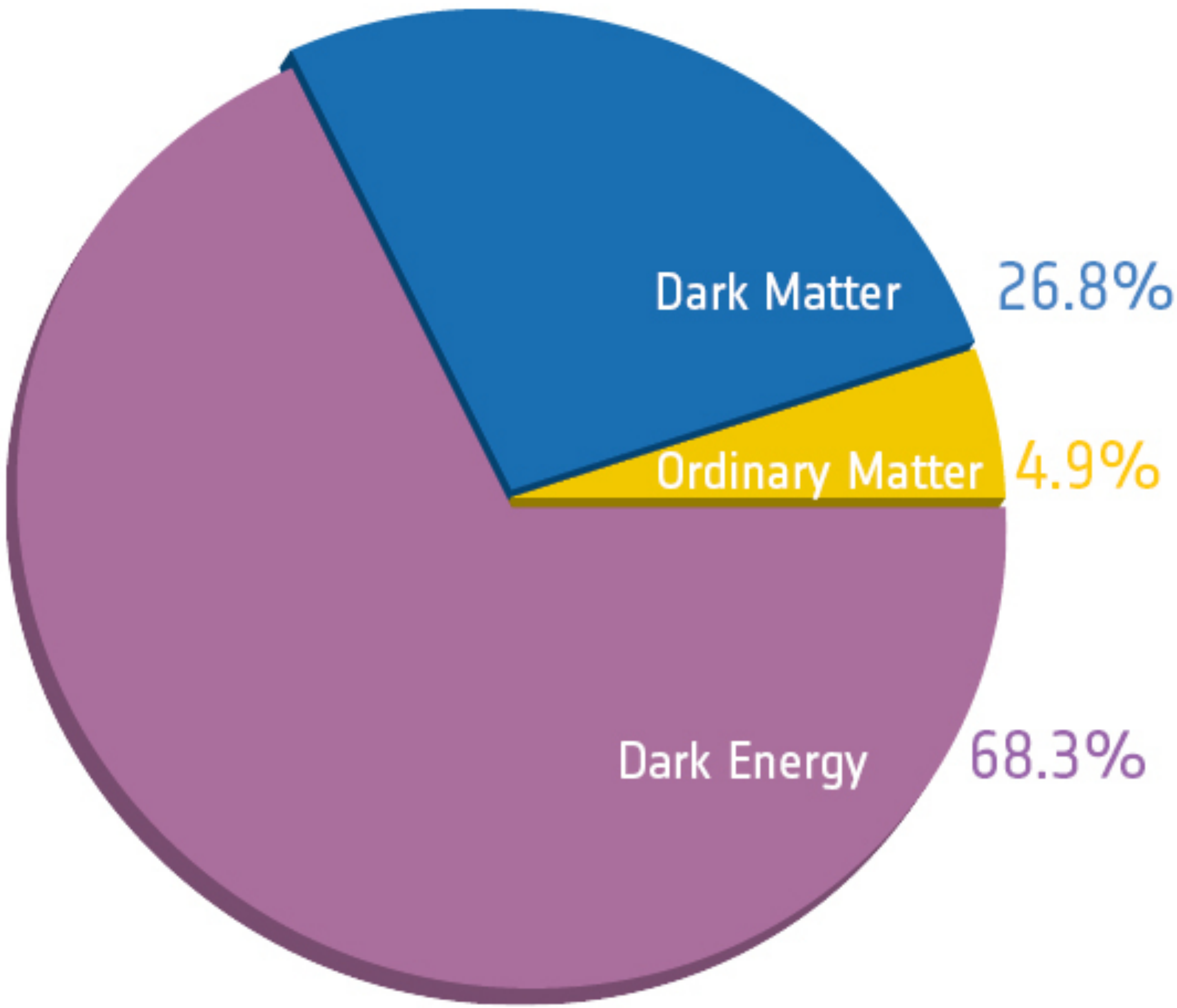
Observers' Universe



Theorists' universe

Springel, Frenk, White 2006

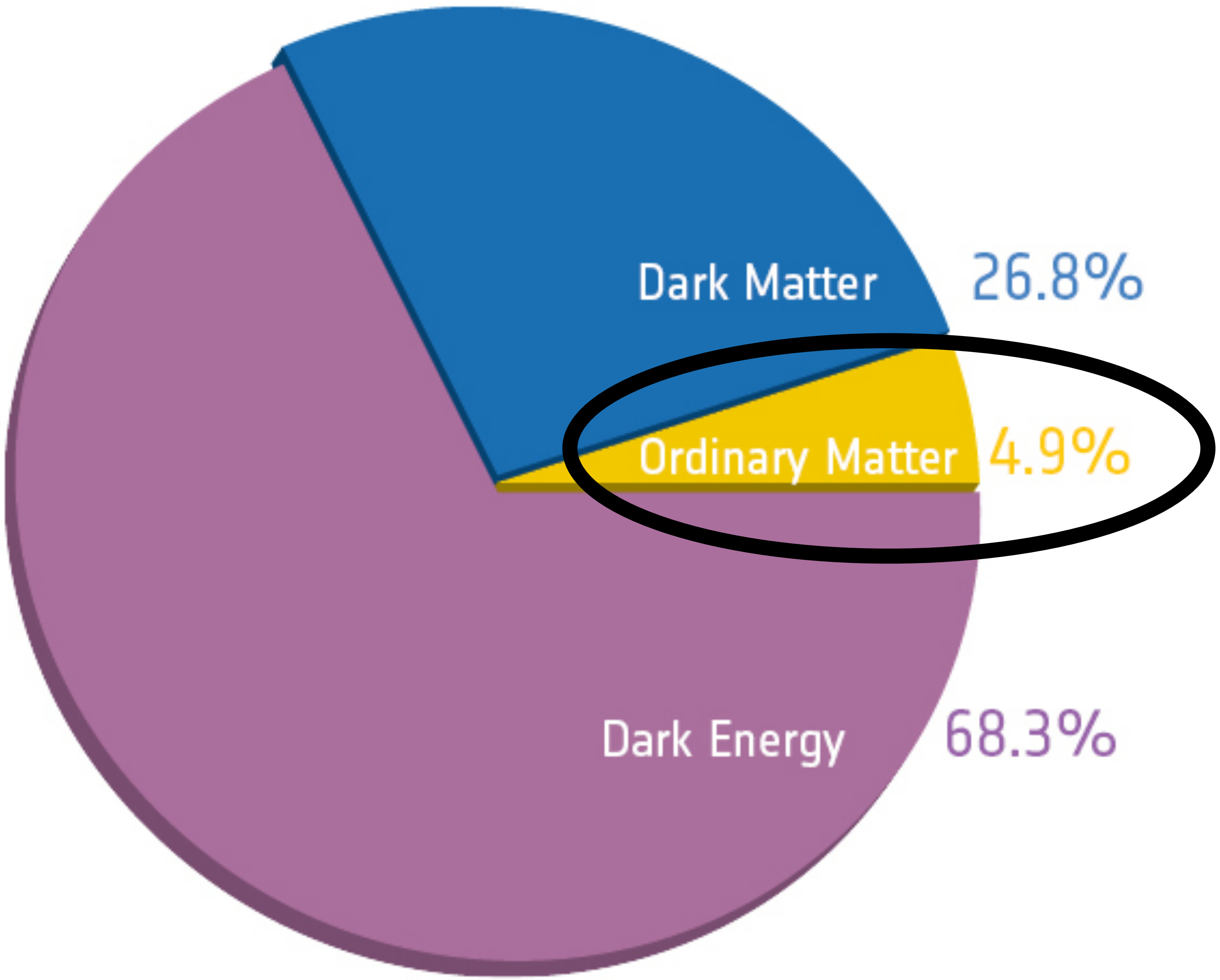
ΛCDM: plenty left to explain



95% of the Universe is "beyond the Standard Model" physics

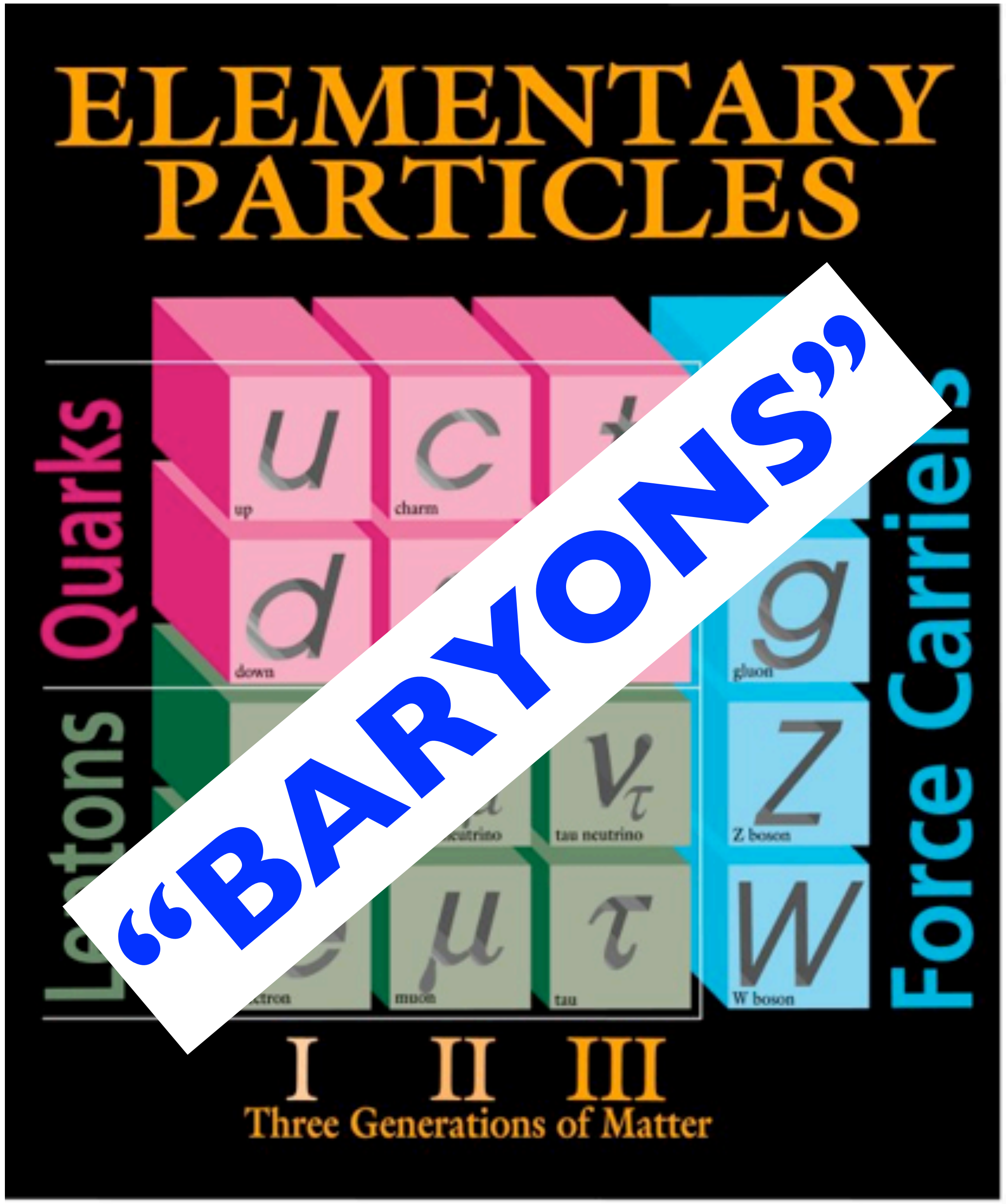
Image: Planck / ESA / NASA

Side note



= "baryons" to Astronomers

Side note



Fermilab 95-759

Side note

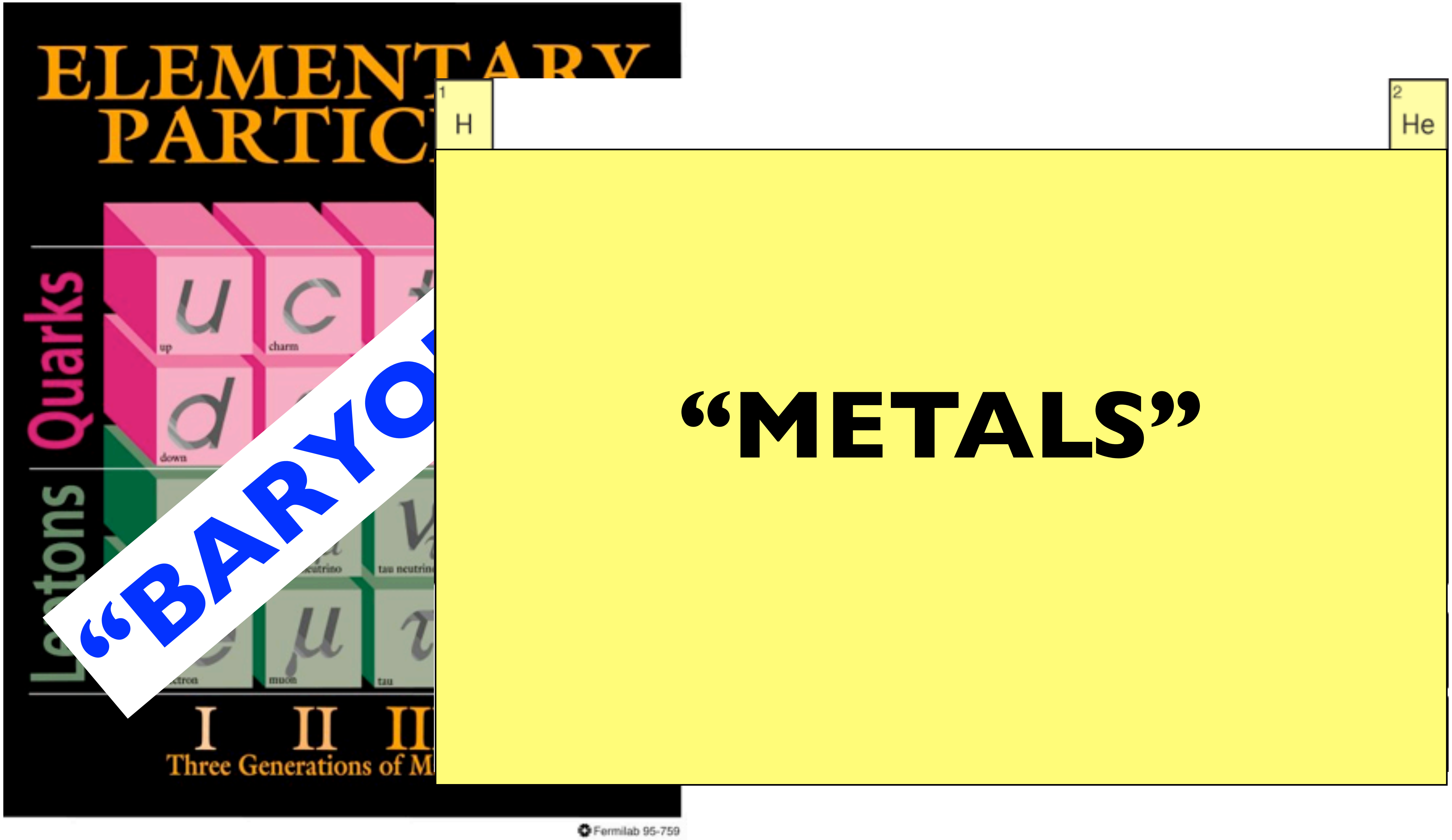
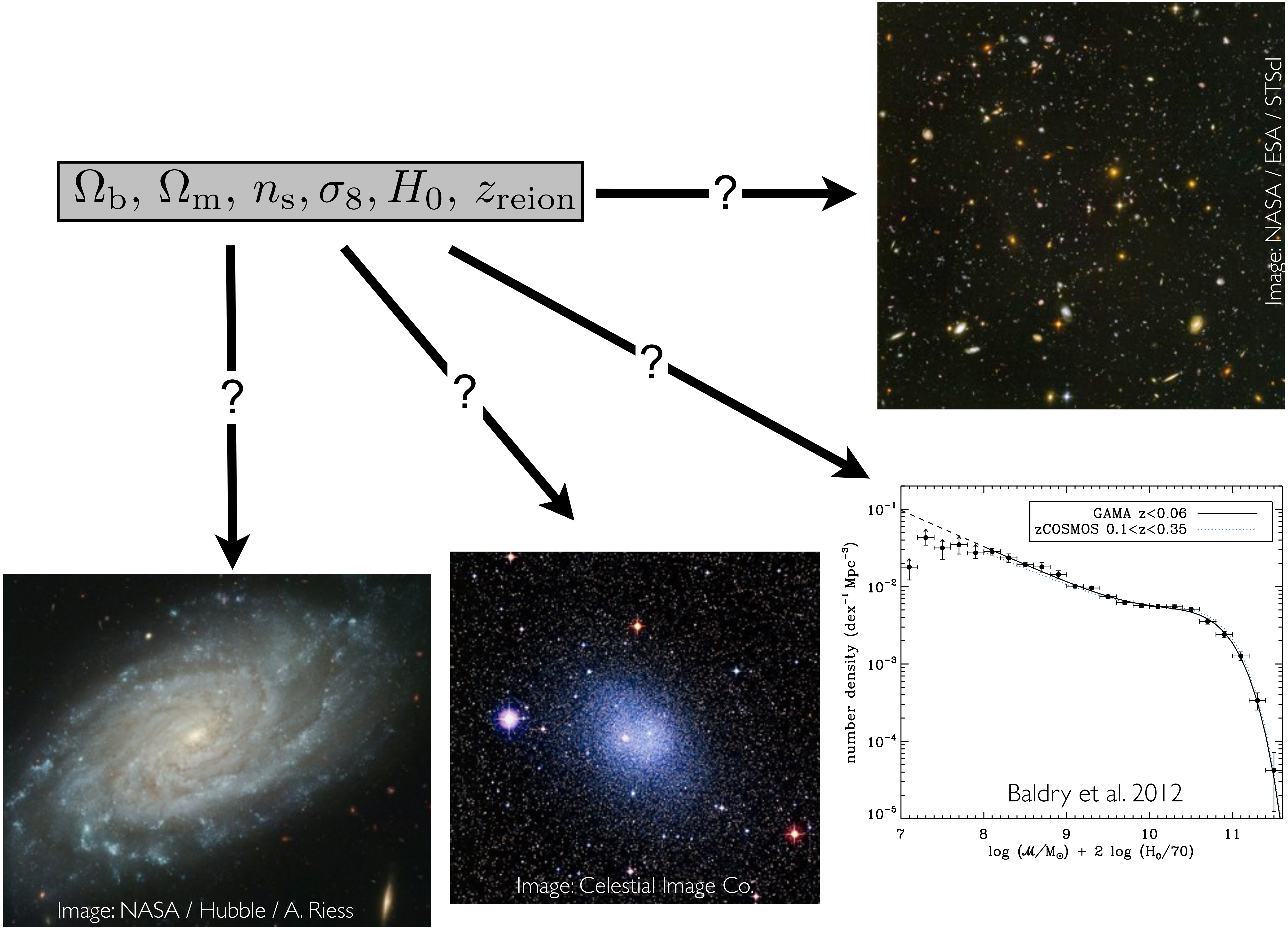


image: education.jlab.org

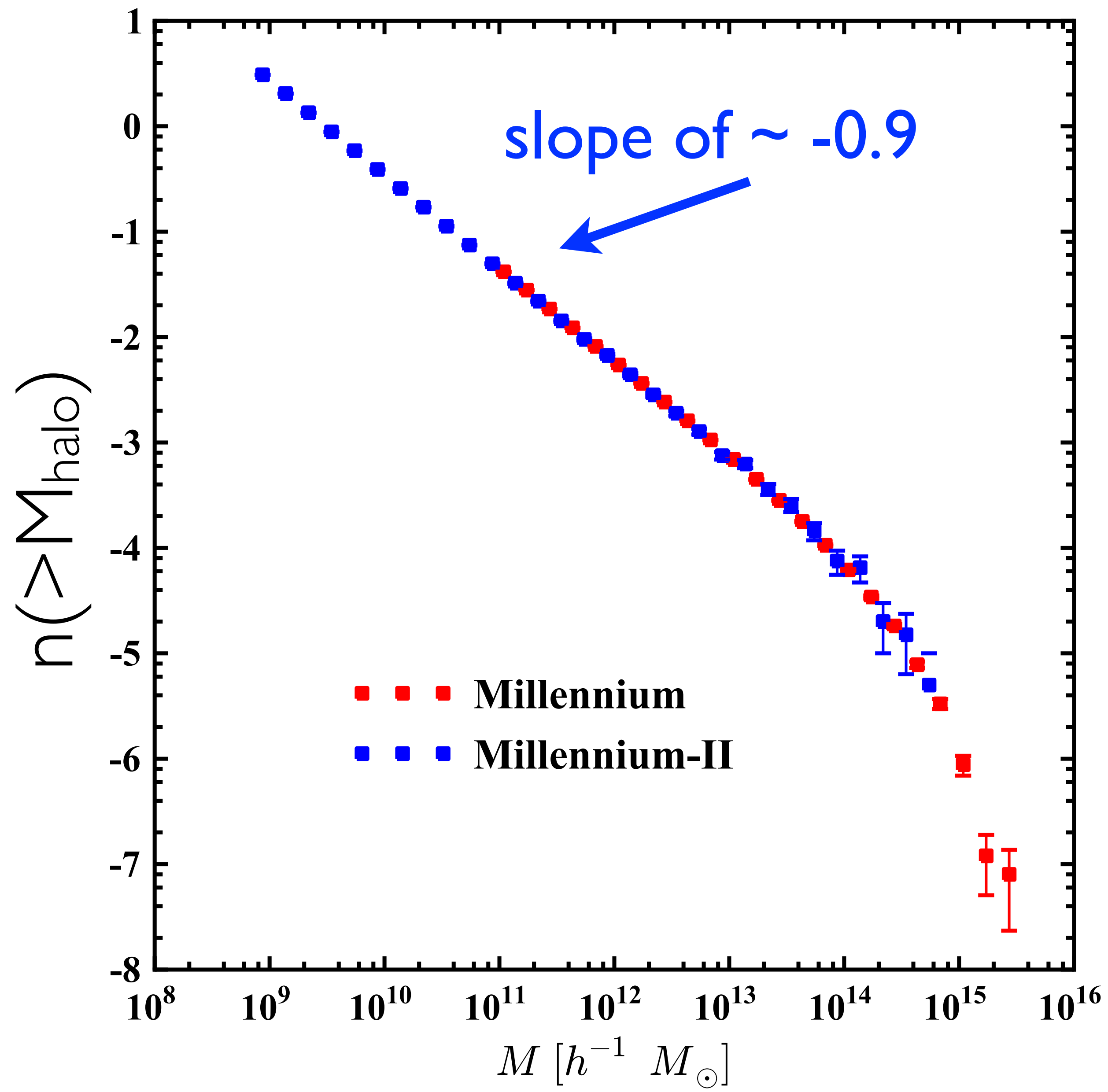

$\Omega_{\rm b}$, $\Omega_{\rm m}$, $n_{\rm s}, \sigma_8, H_0$, $z_{\rm reion}$
?
?
?
?
Image: NASA / ESA / STScI
GAMA z<0.06
zCOSMOS 0.1<z<0.35
number density (dex^{-1} Mpc^{-3})
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Baldry et al. 2012
7
8
9
10
11
log ($\mathcal{M}$/M$_\odot$) + 2 log (H$_0$/70)
Image: NASA / Hubble / A. Riess
Image: Celestial Image Co.

Constraining particle physics through astrophysics

- **Early 1980s:** standard model neutrinos ruled out as dominant DM component via observations of galaxy clustering
- **Mid-1980s:** agreement between observed and simulated universes led to support for CDM models, provided early hints for cosmological constant
- **Mid-1990s:** structure in Lyman-alpha forest ruled out then-popular C+HDM models
- **Can history repeat itself?** Looking at the smallest, densest remnants of structure formation is likely to be most fruitful in discriminating between standard CDM and alternative dark matter models.

ΛCDM predictions

Abundance of dark matter halos



Springel et al. 2005, MBK et al. 2009
(goes as far back as Press & Schechter 1974, and maybe farther)

ΛCDM predictions

"Universal" profile for dark matter halos

[Navarro, Frenk, & White (**NFW**) 1996, 1997; also Dubinski & Carlberg 1991]:

ΛCDM predictions

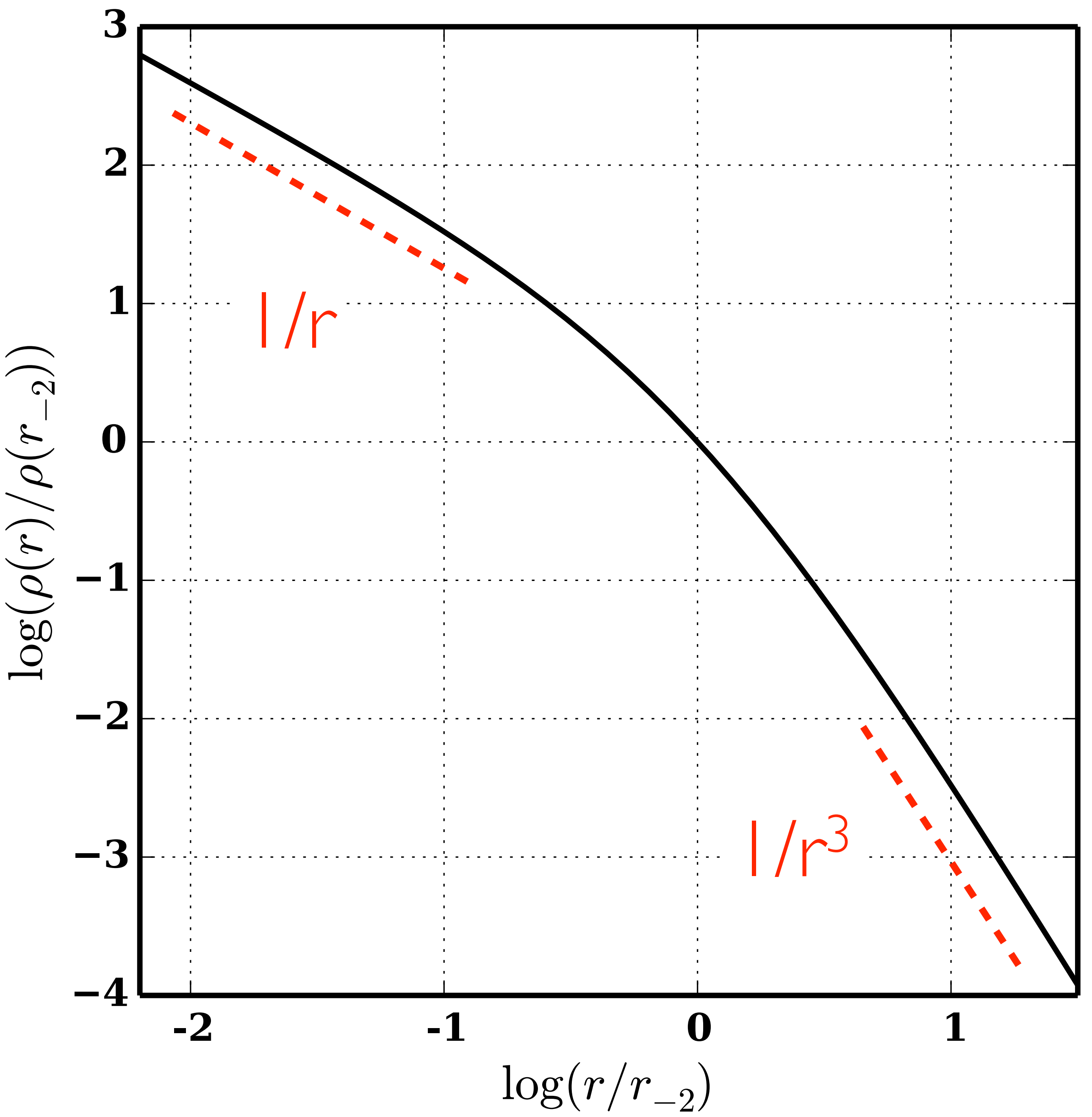
"Universal" profile for dark matter halos

[Navarro, Frenk, & White (**NFW**) 1996, 1997; also Dubinski & Carlberg 1991]:

$$\rho\left(x \equiv \frac{r}{r_{-2}}\right) = \frac{\rho_0}{x\,(1+x)^2}$$

Profile defined by 2 parameters:

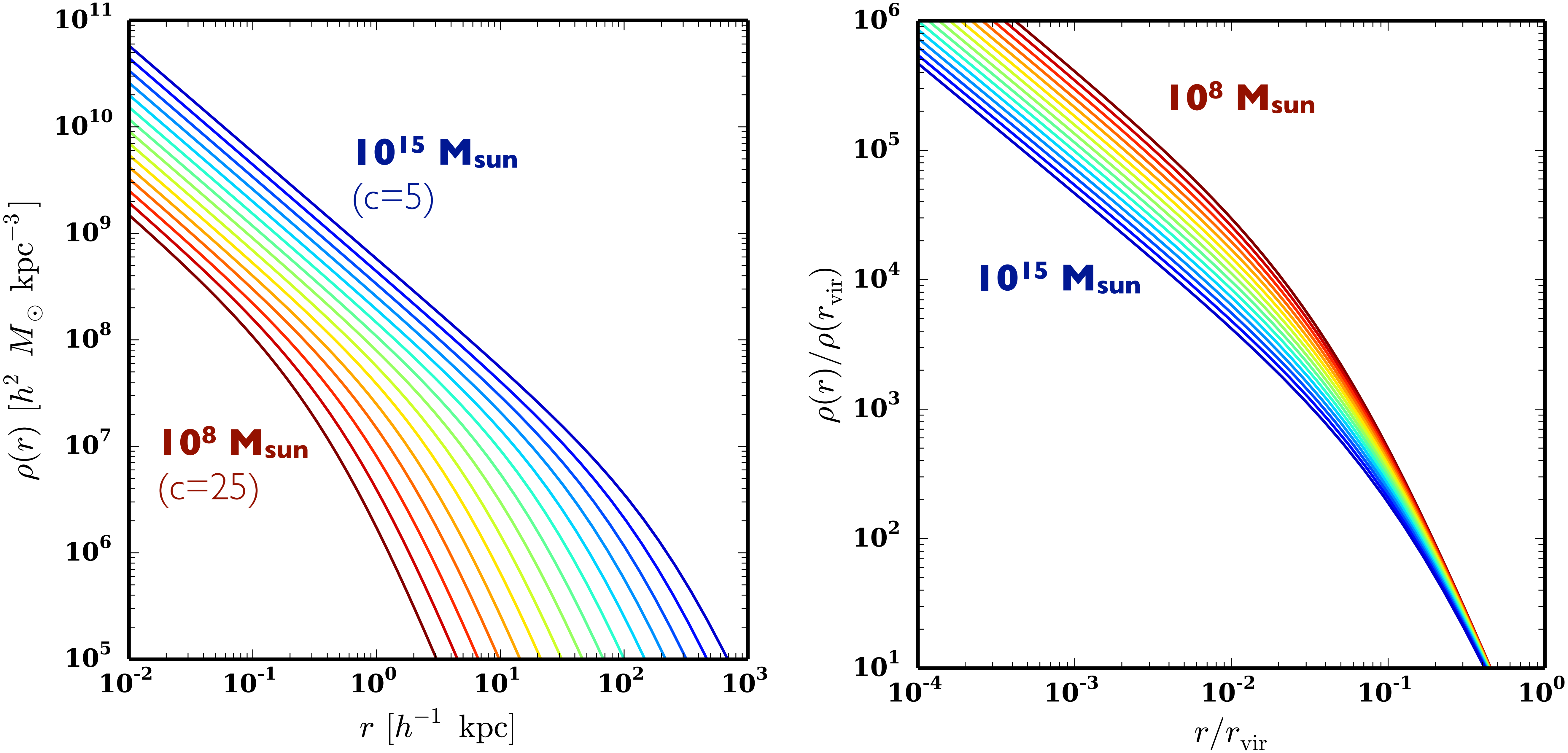
$(\rho_0,\ r_{-2})$ or $(M_{\rm vir}, c_{\rm vir})$



ΛCDM predictions

Correlation between density profile parameters (Bullock et al. 2001):

$$c(M_{\rm vir}) = 10 \left(\frac{M_{\rm vir}}{10^{12}\, M_\odot} \right)^{-0.1}$$

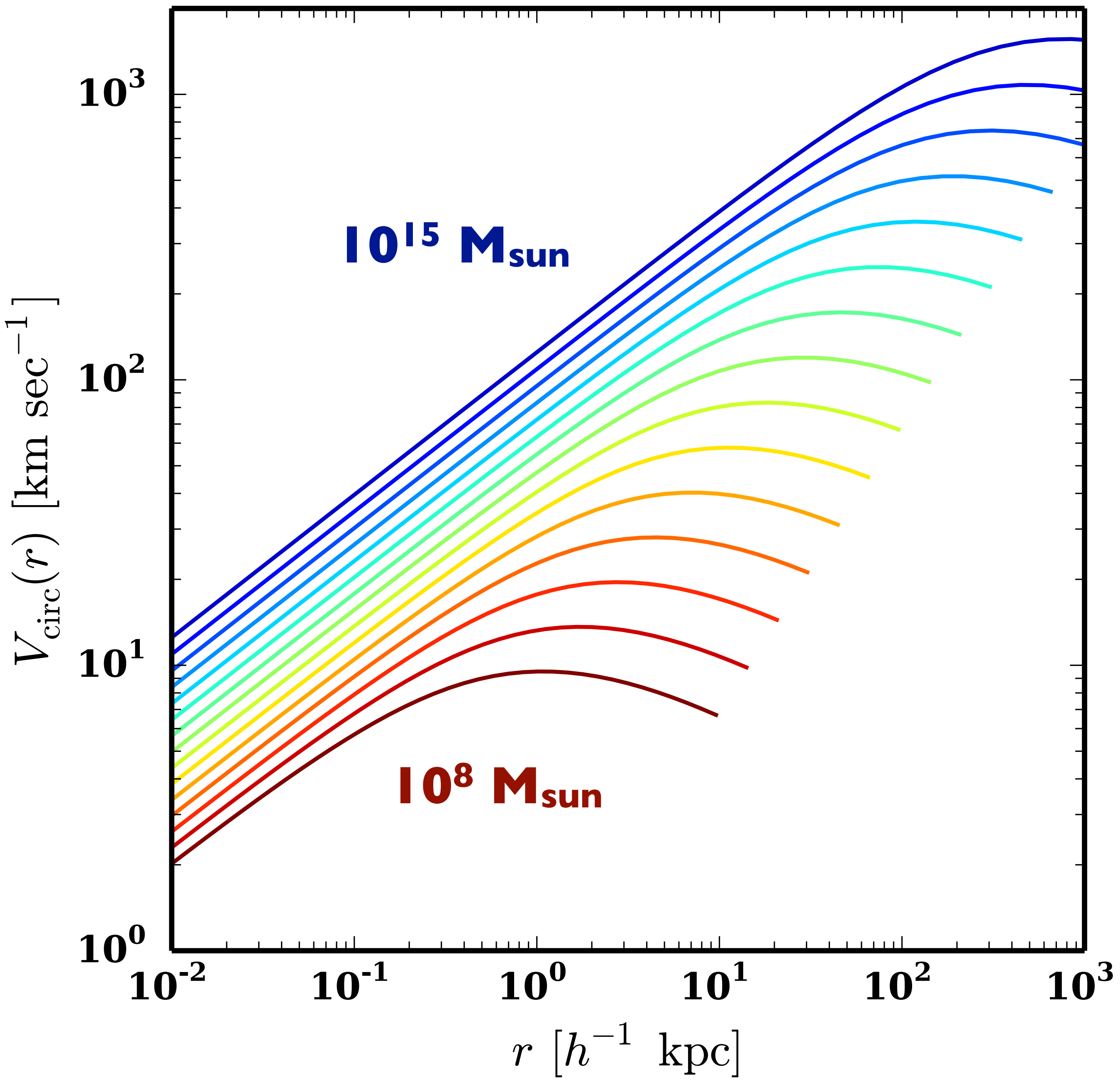


Mass Profiles

- Dark matter **densities** are hard to measure; **enclosed mass** is often the observable quantity
- Astronomers often use **circular velocity** and **enclosed mass** interchangeably:

$$V_{\rm circ}^2 = \frac{GM(<r)}{r}$$

V_{max}: peak value of V_{circ}



What do observations say?

Local Group galaxy M33

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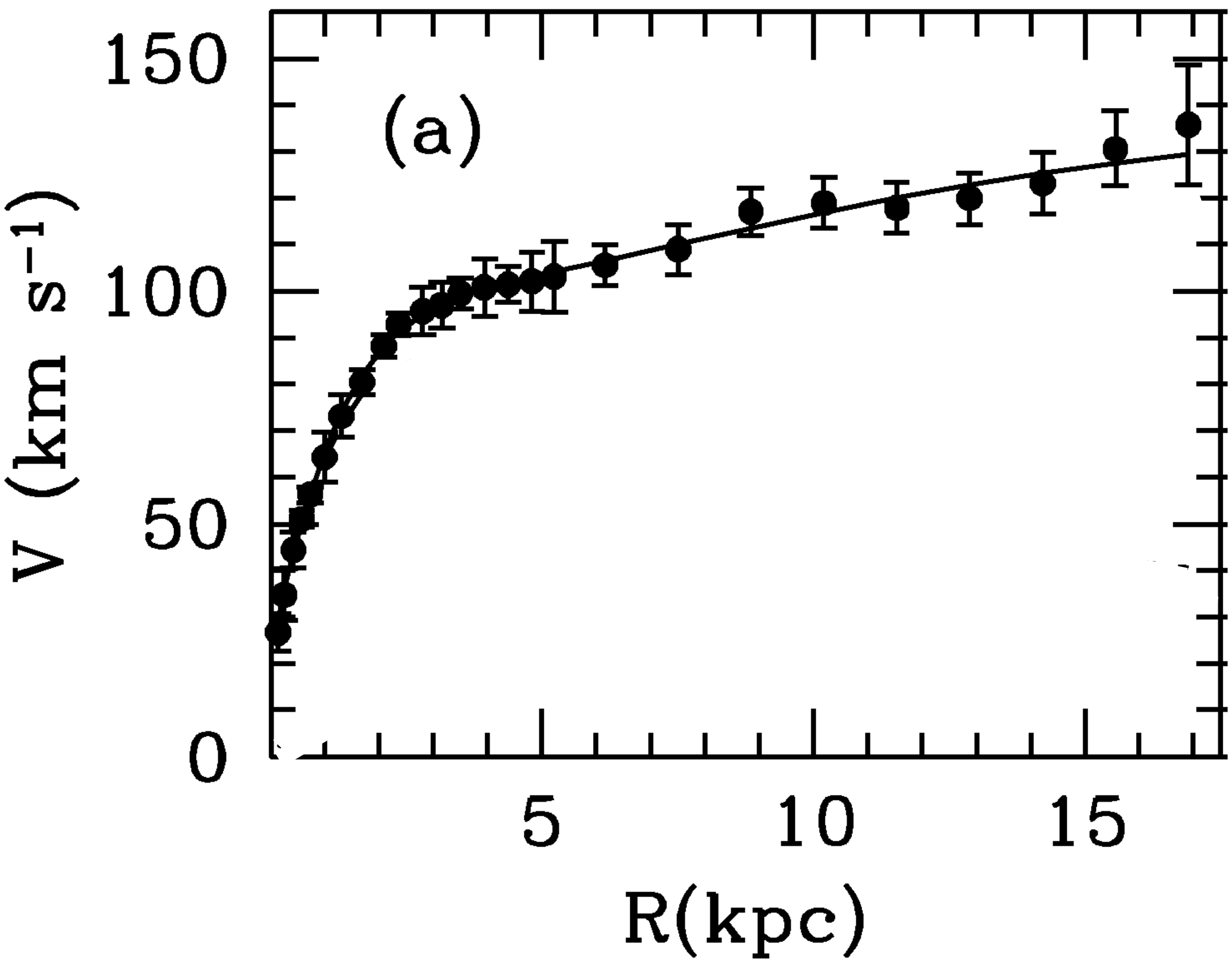
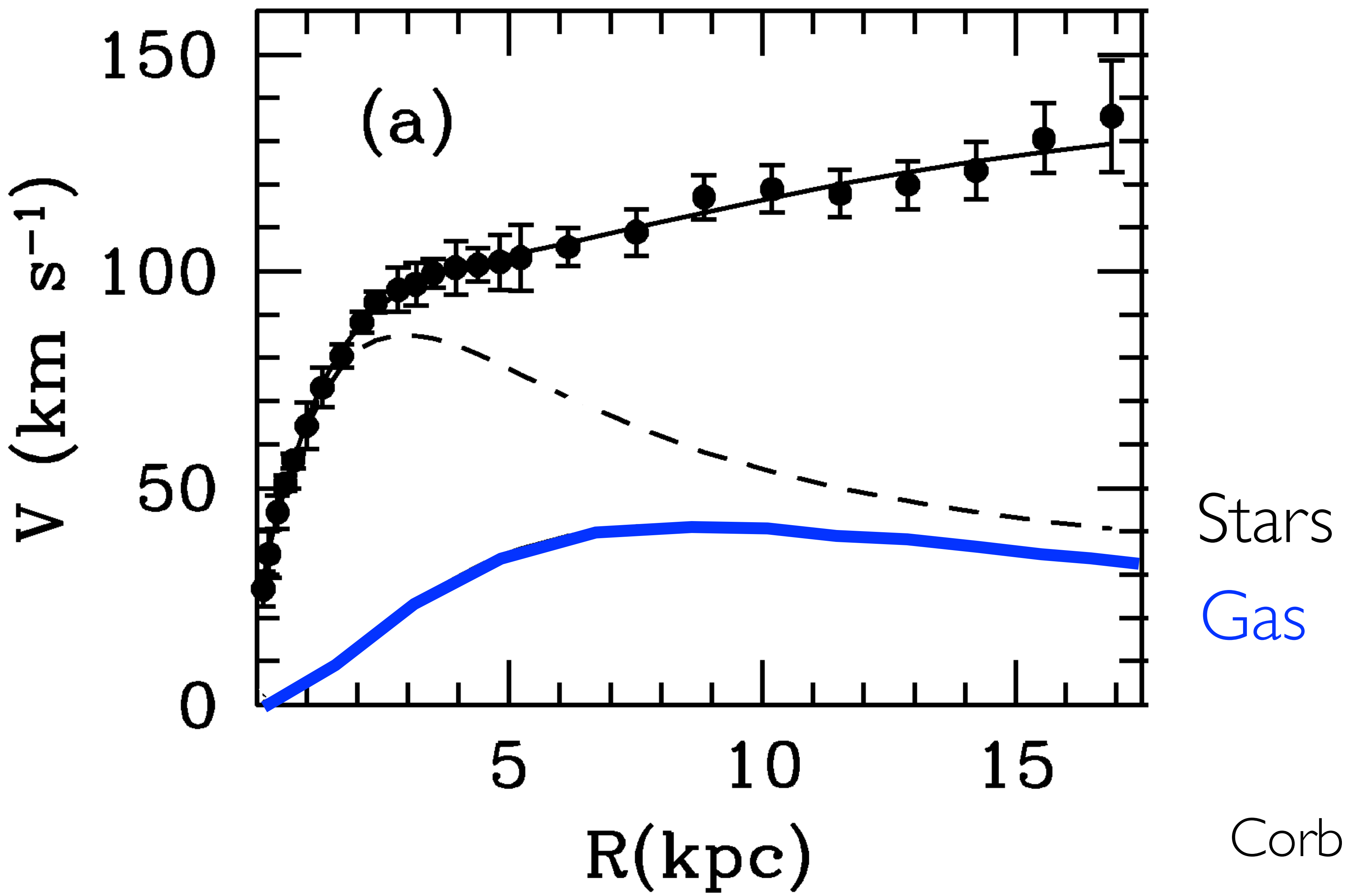


Corbelli 2003

Dark Matter: Definitely Needed*!

Local Group galaxy M33

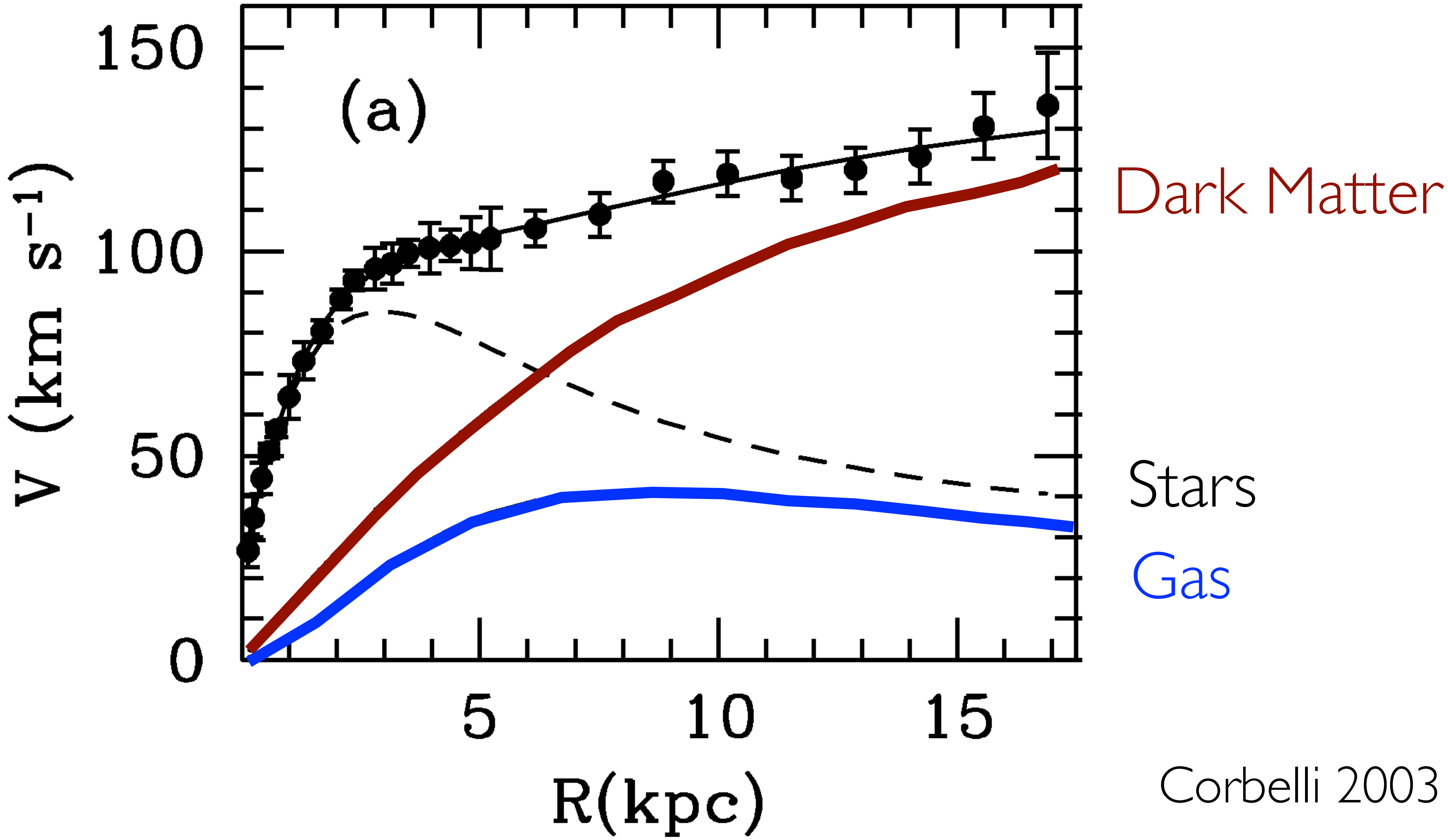


Corbelli 2003

*in context of Newtonian dynamics

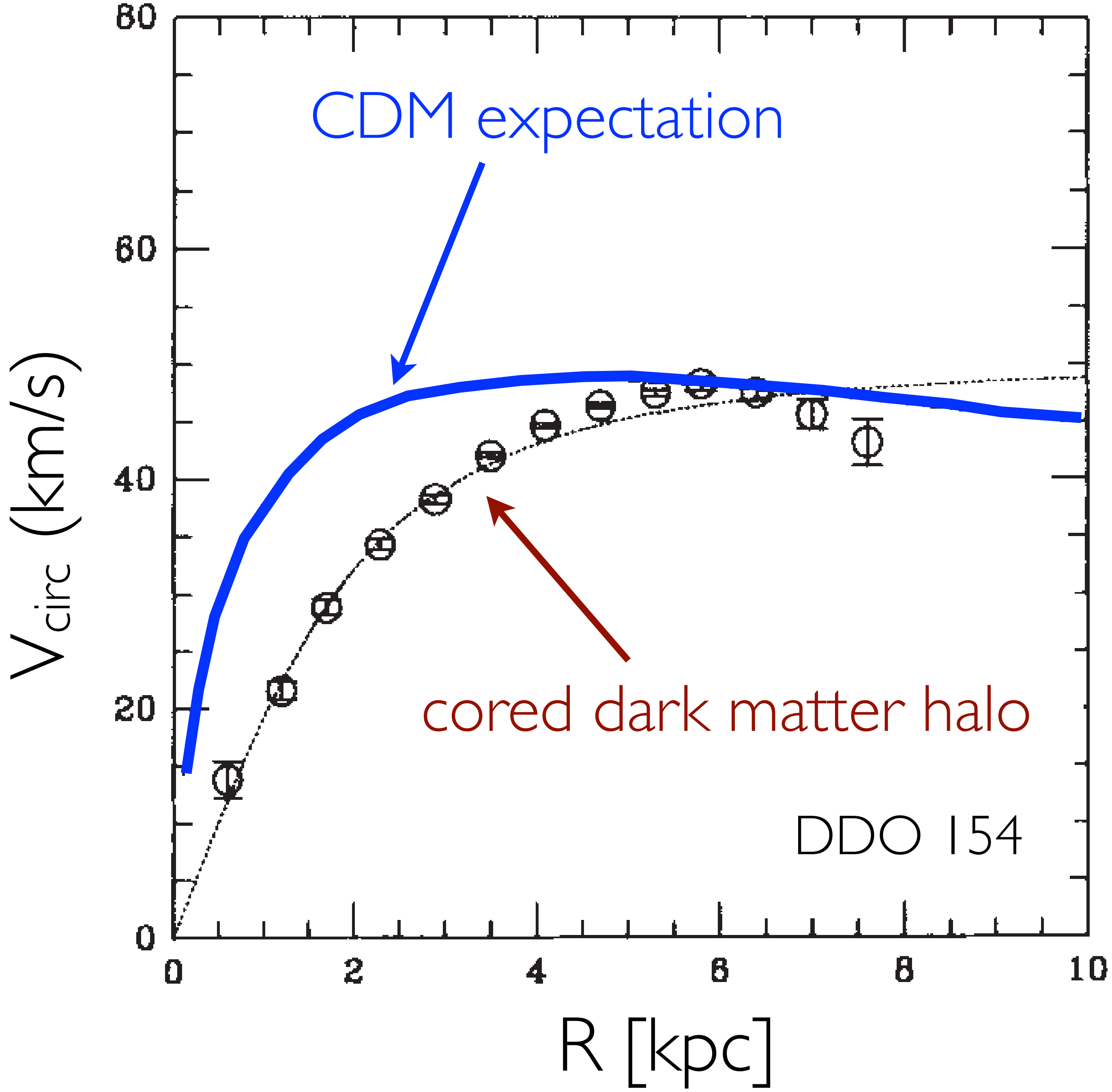
Dark Matter: Definitely Needed!

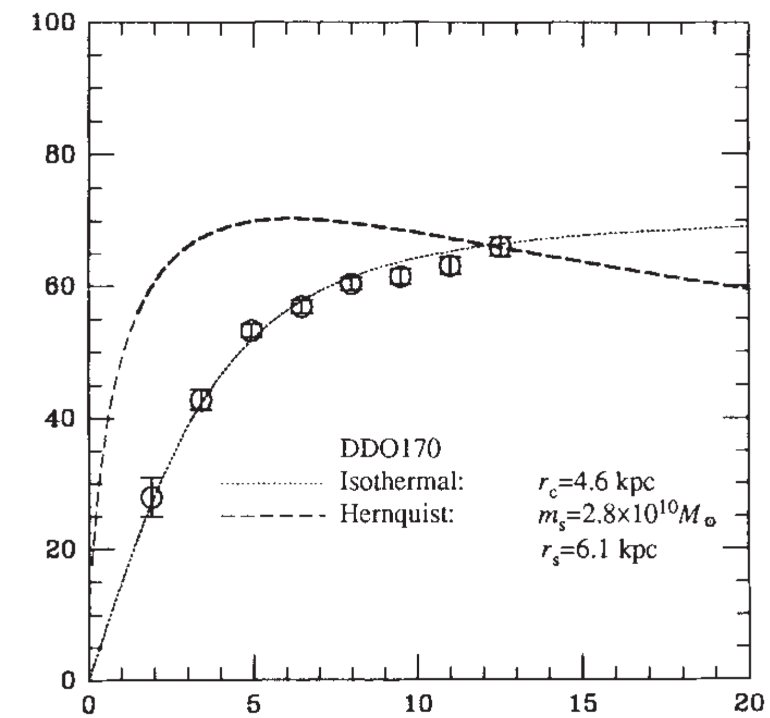
Local Group galaxy M33

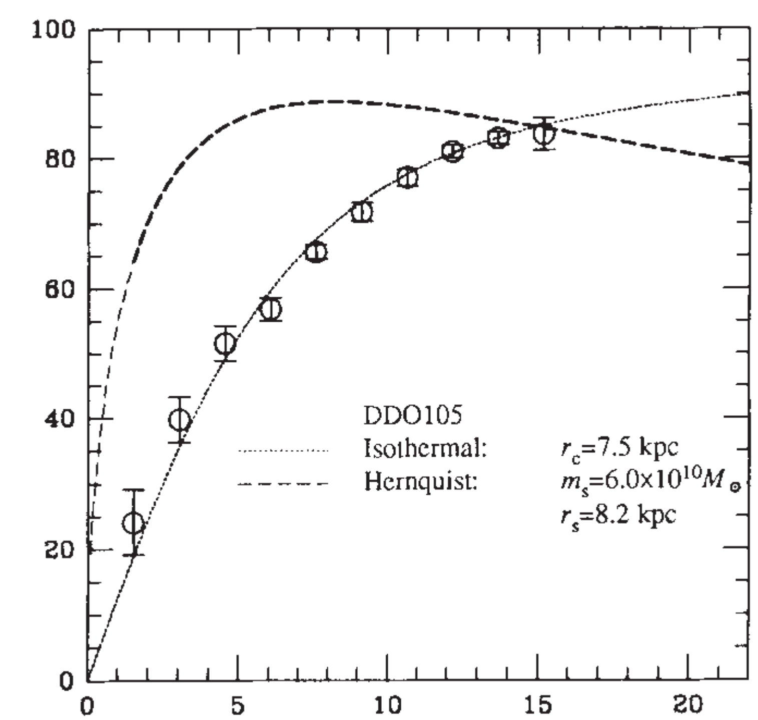


Corbelli 2003

Core-Cusp Problem (crisis / catastrophe)

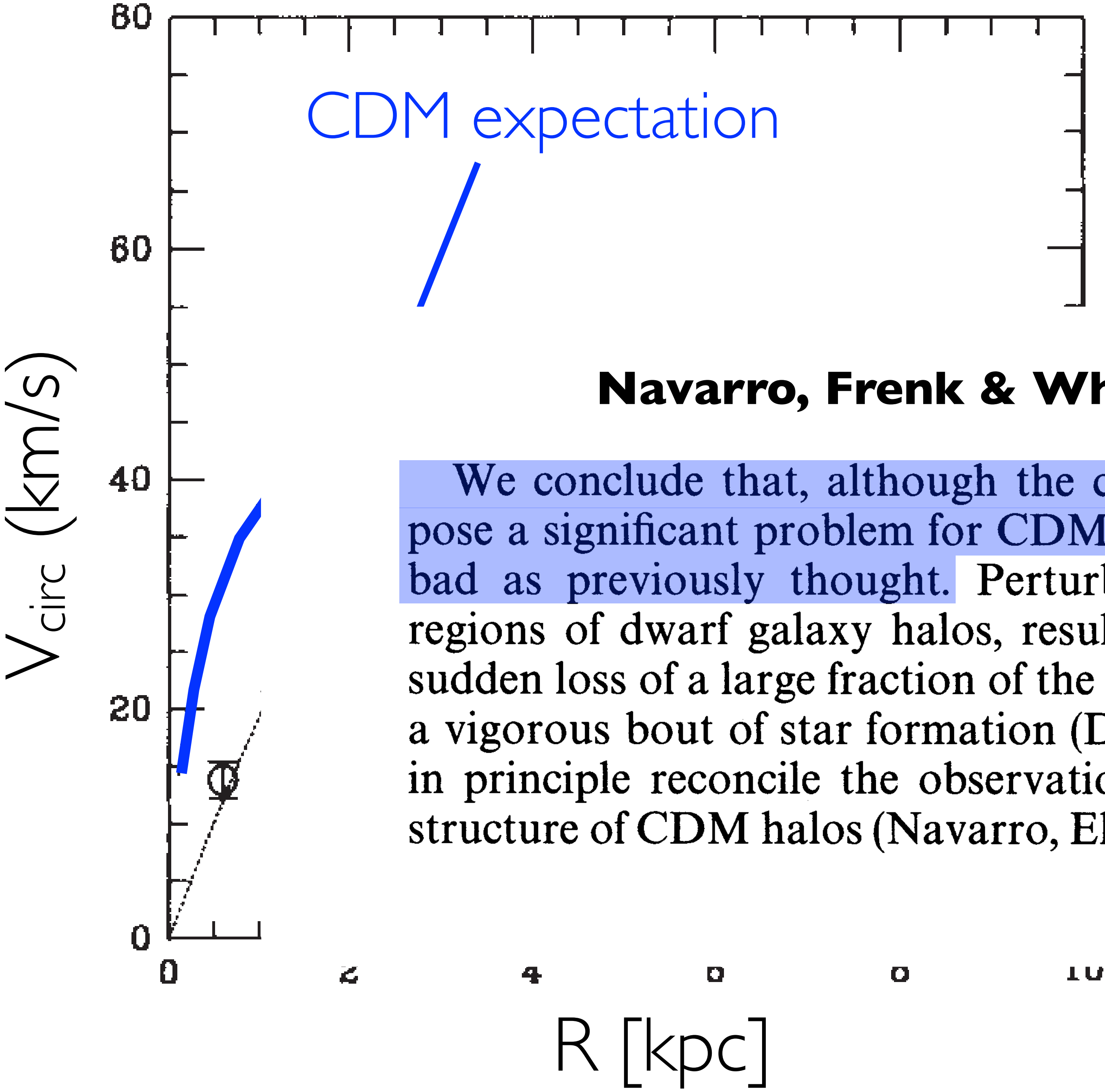


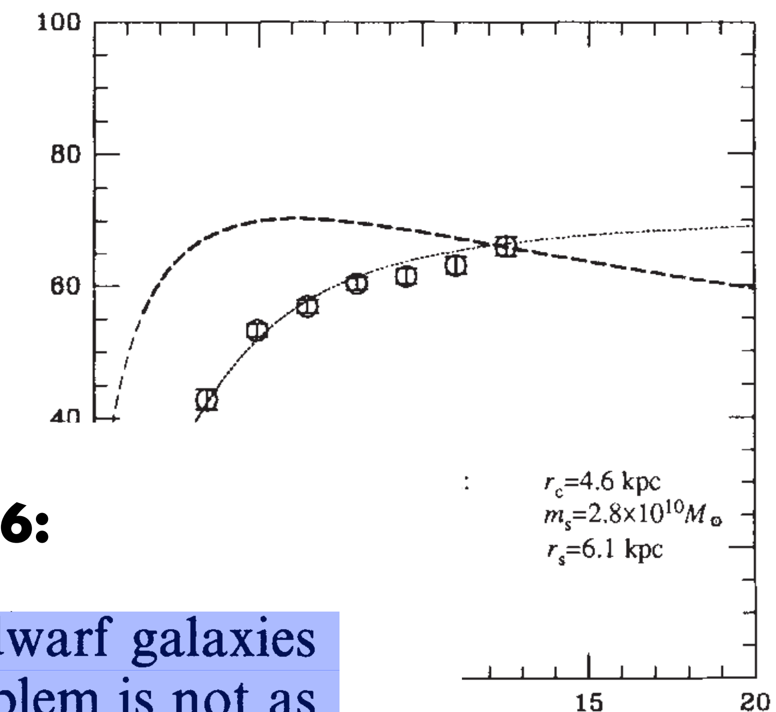


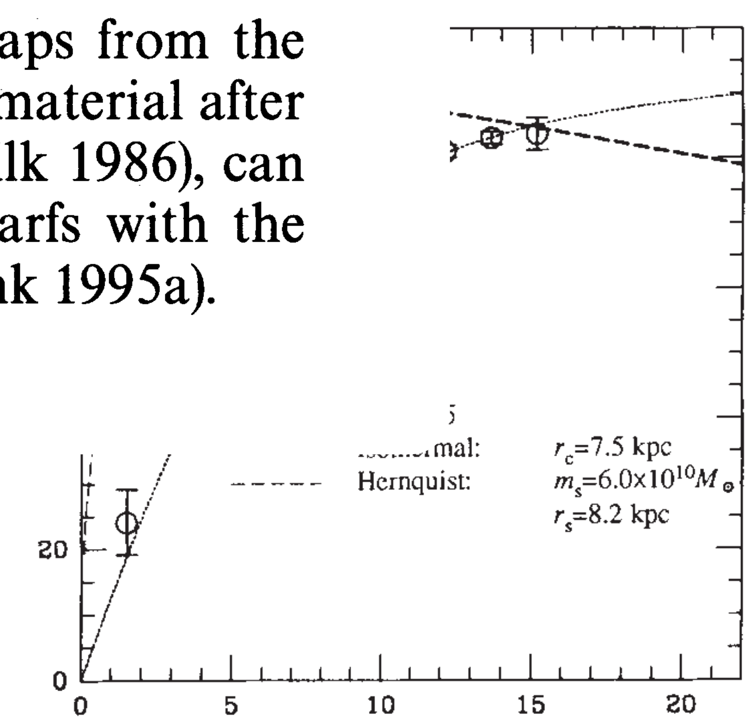


Moore (1994); also Flores & Primack (1994)

Core-Cusp Problem (crisis / catastrophe)







Navarro, Frenk & White 1996:

We conclude that, although the cores of dwarf galaxies pose a significant problem for CDM, the problem is not as bad as previously thought. Perturbations to the central regions of dwarf galaxy halos, resulting perhaps from the sudden loss of a large fraction of the baryonic material after a vigorous bout of star formation (Dekel & Silk 1986), can in principle reconcile the observations of dwarfs with the structure of CDM halos (Navarro, Eke, & Frenk 1995a).

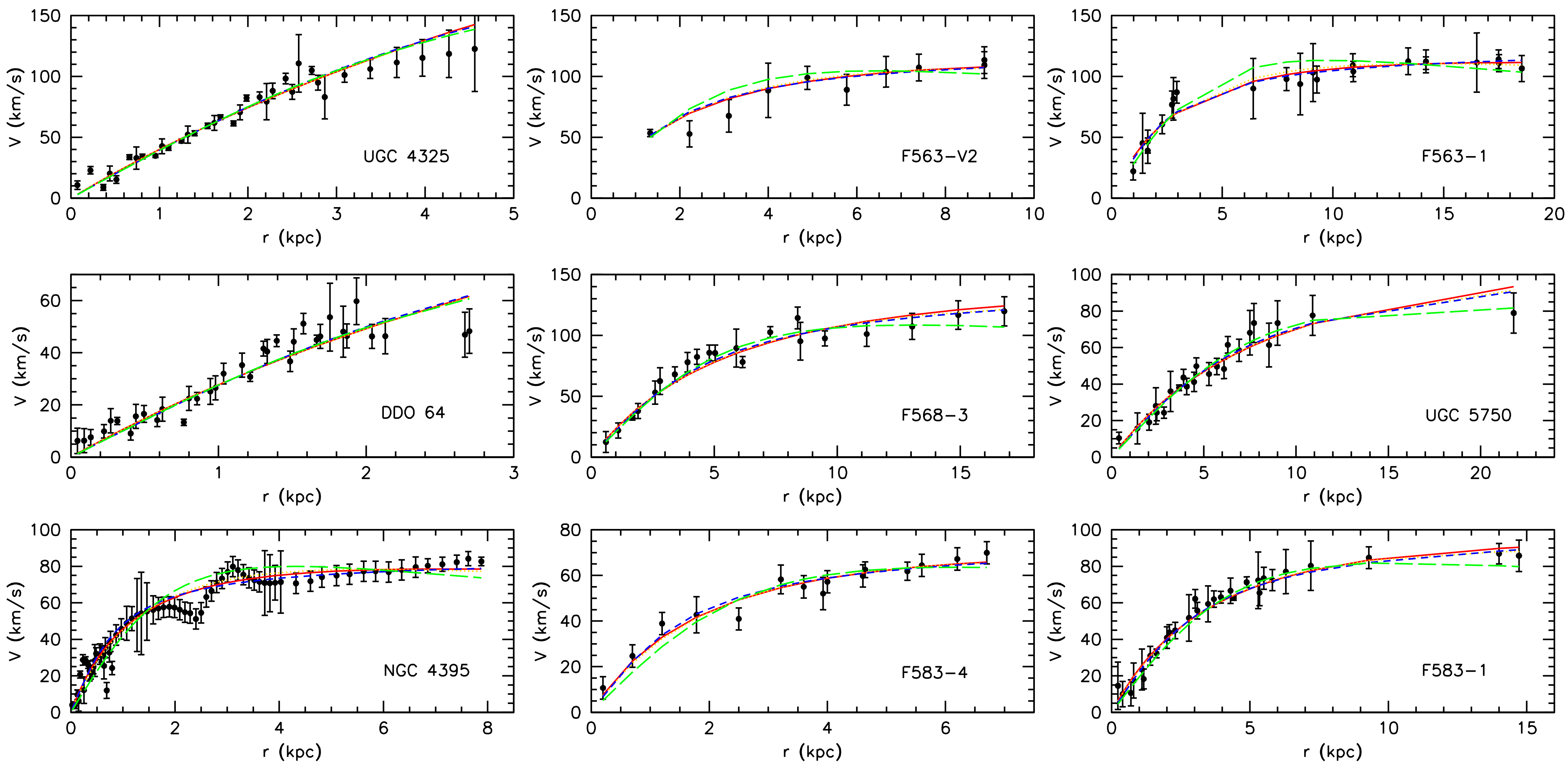
Moore (1994); also Flores & Primack (1994)

Problem: slowly-rising rotation curves

$$\rho \propto r^{-\alpha} \rightarrow V_{\rm circ} \propto r^{1-\alpha/2}$$

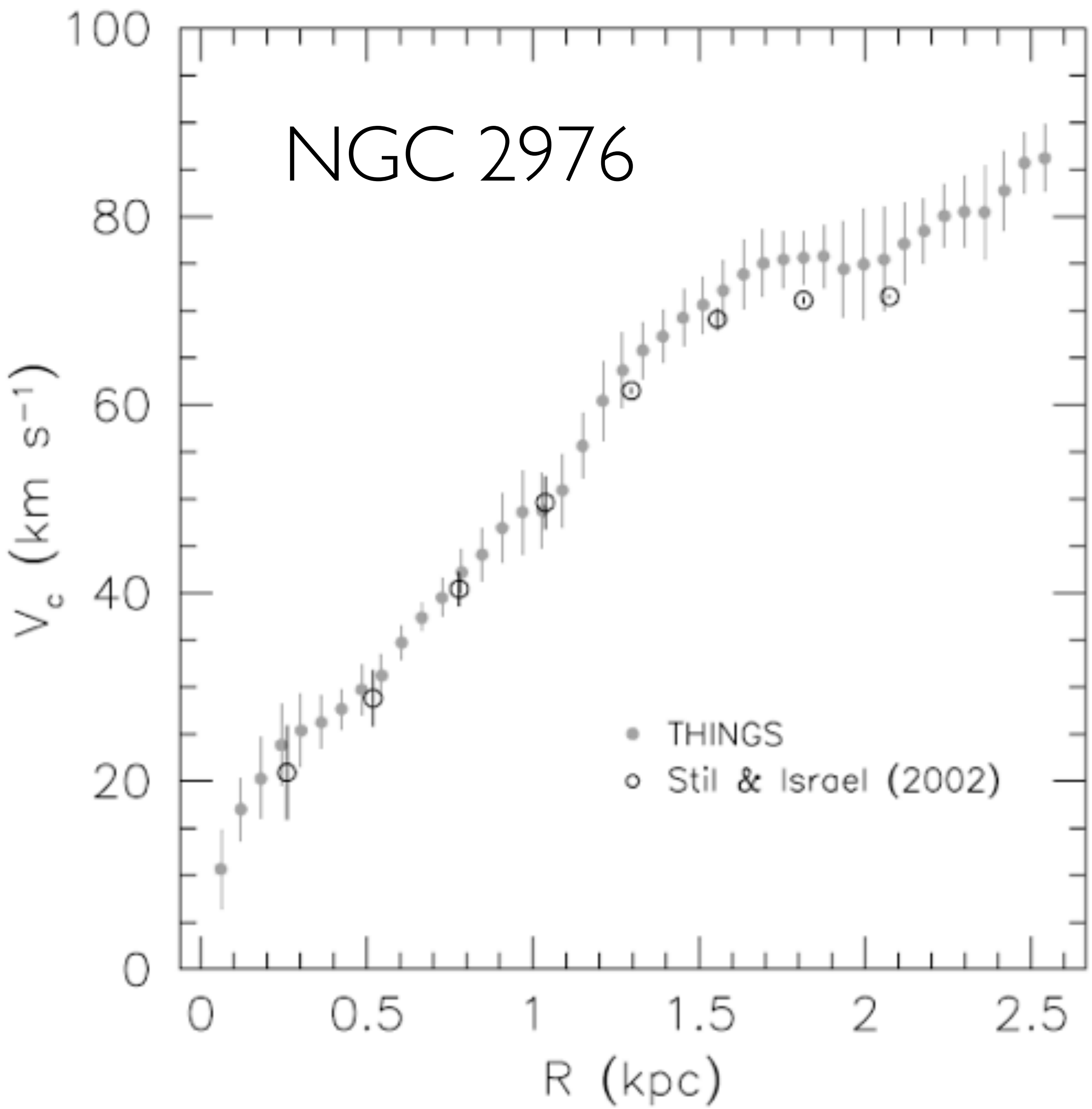
$$\alpha = 0 : \; V_{\rm circ} \propto r$$

$$\alpha = 1 : \; V_{\rm circ} \propto r^{0.5}$$



Kuzio de Naray et al. (2010)

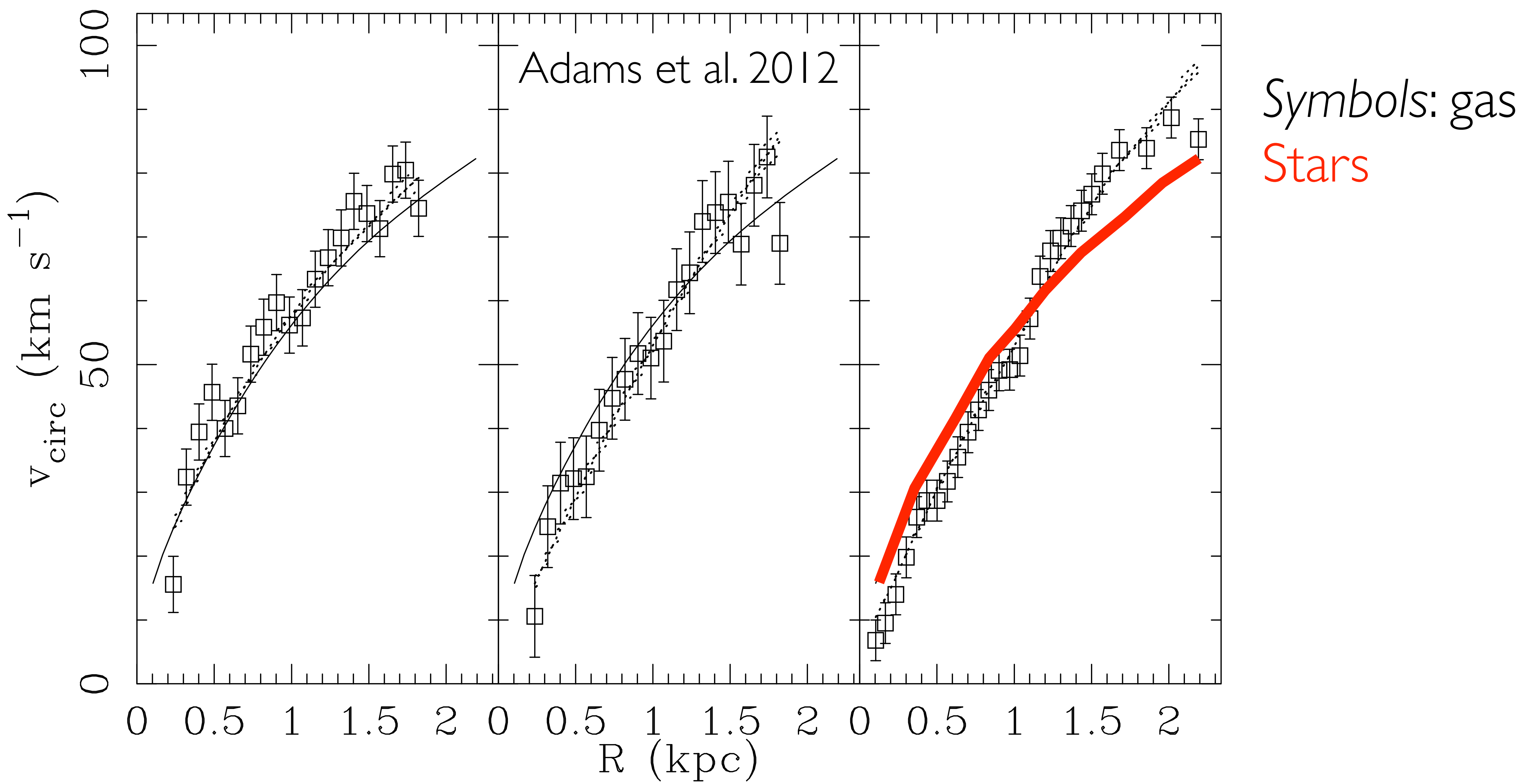
The Debate Persists....



de Blok et al. 2008

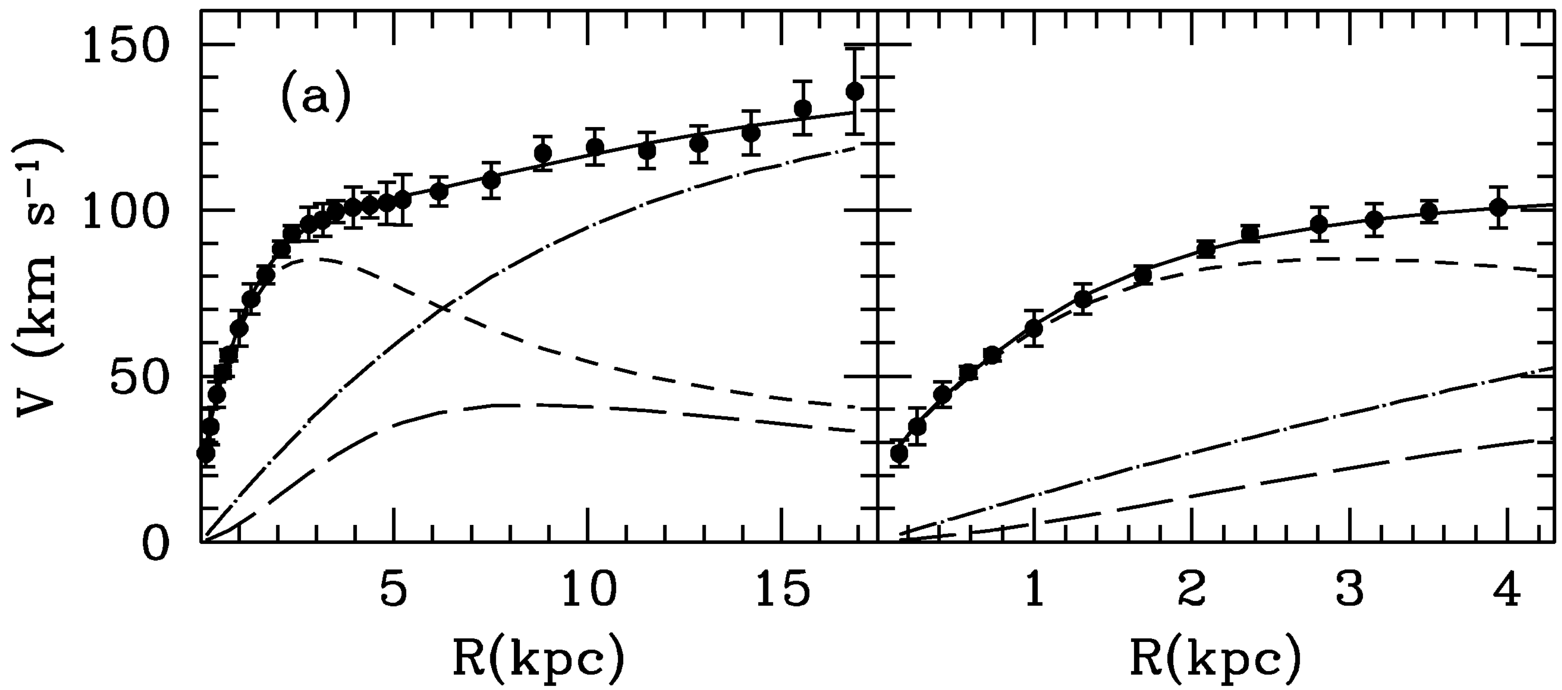
HI gas profile from THINGS survey: strongly indicates **cored** distribution of dark matter

The Debate Persists….



Stars in same galaxy indicate dark matter cusp

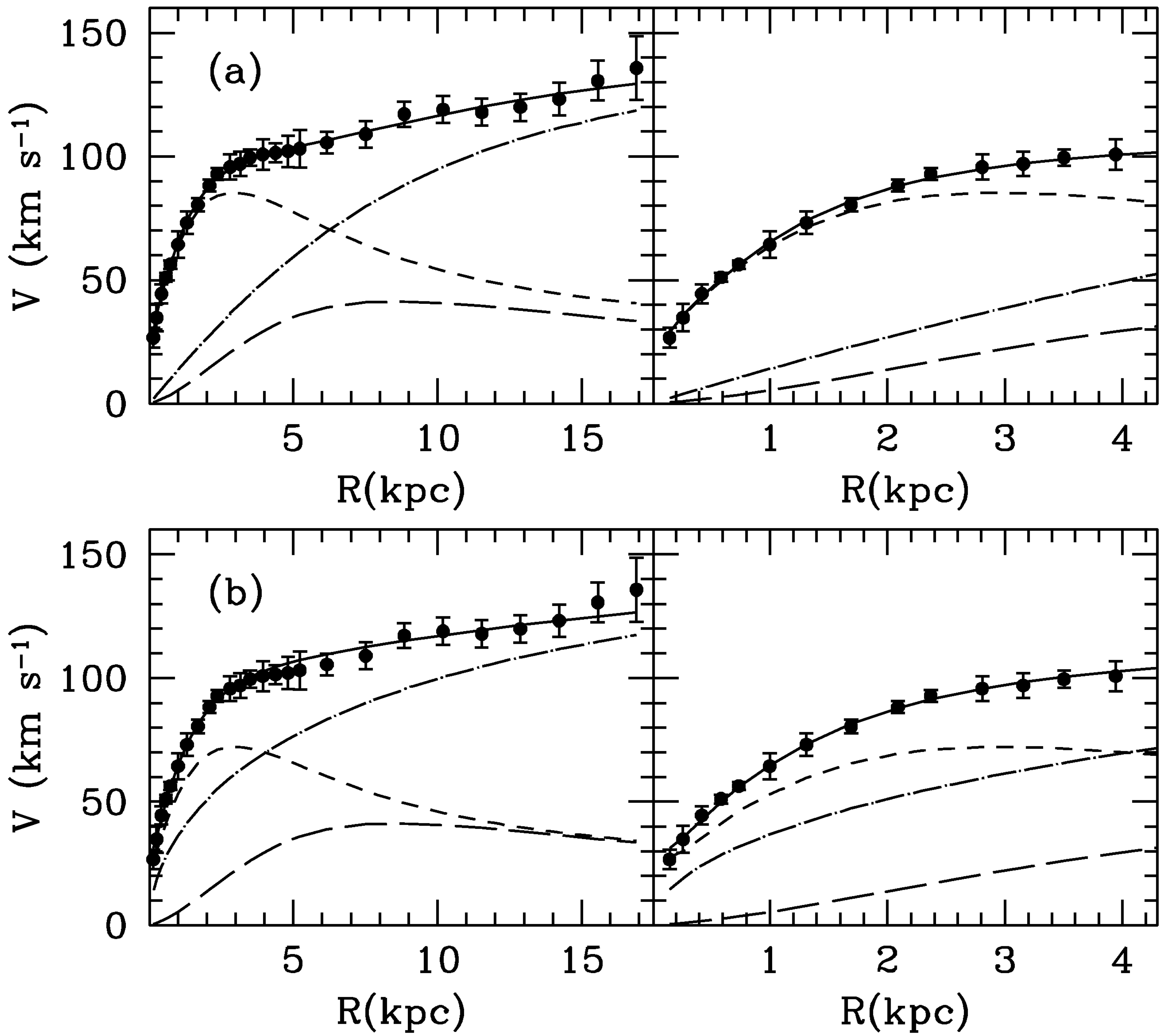
Additional complications



Cored dark matter halo

Corbelli 2003

Additional complications

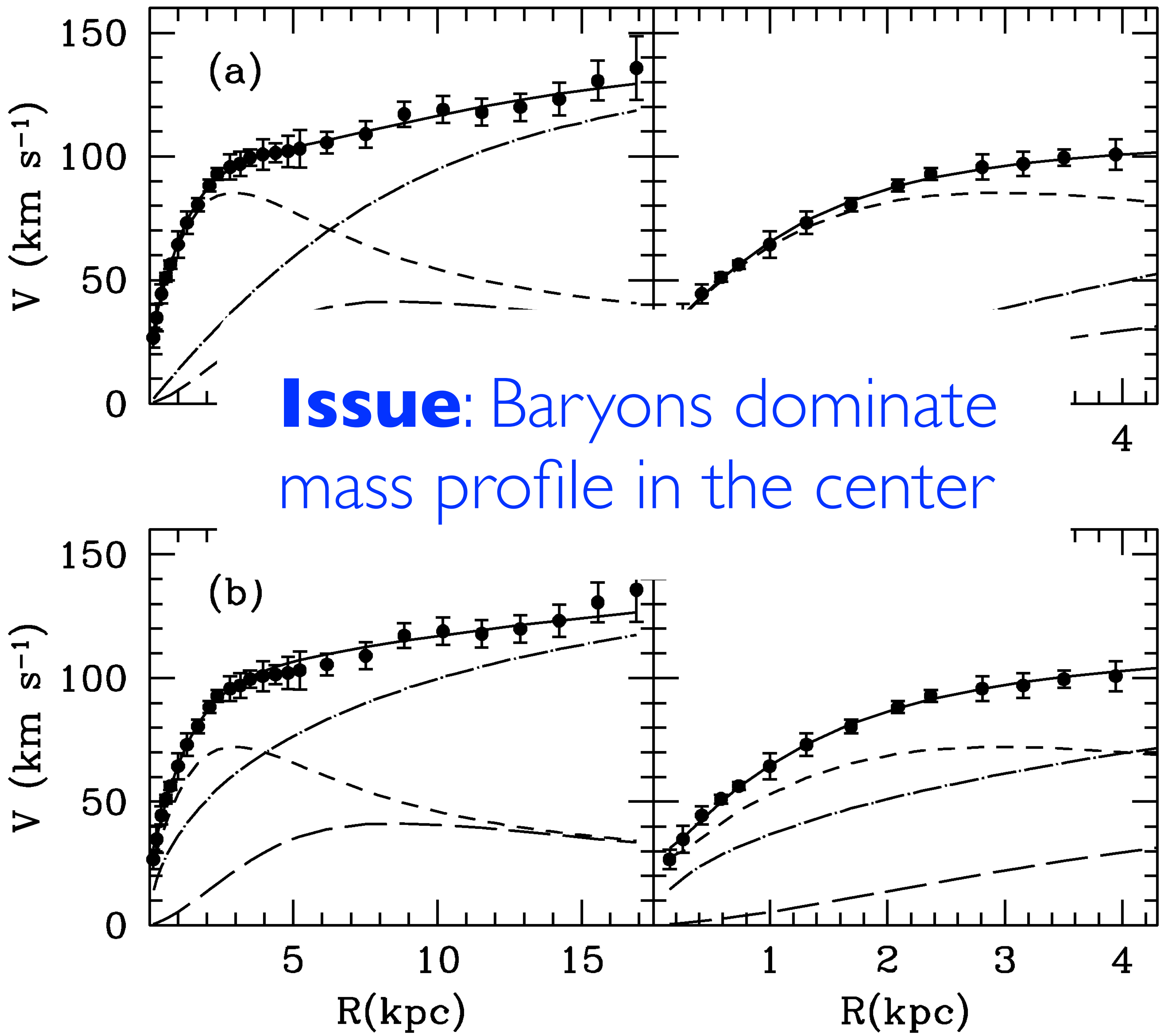


Cored dark matter halo

NFW dark matter halo (requires ~30% less stellar mass)

Corbelli 2003

Additional complications



Issue: Baryons dominate mass profile in the center

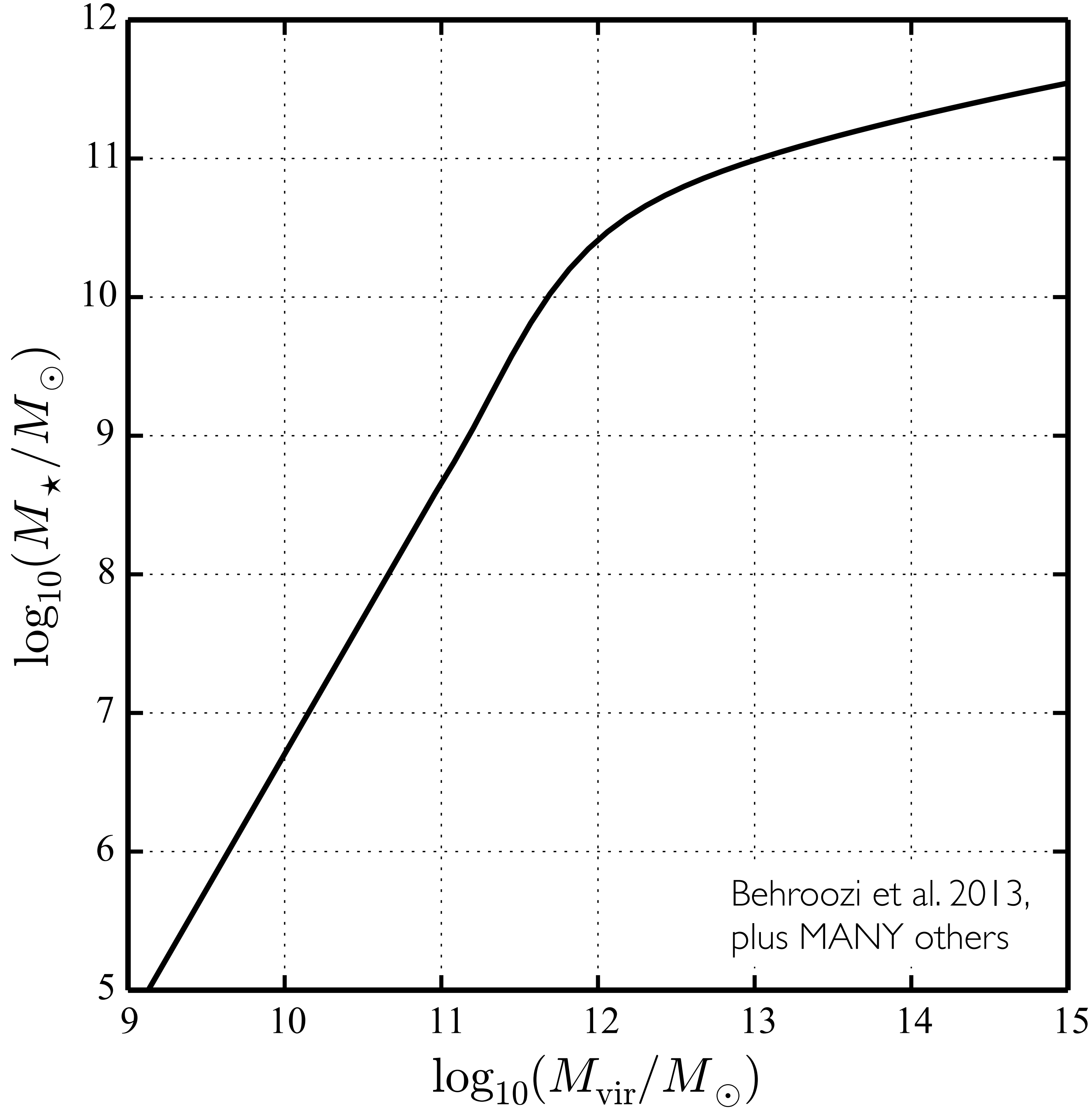
Cored dark matter halo

NFW dark matter halo (requires ~30% less stellar mass)

Corbelli 2003

The Halo-Galaxy Connection

$M_\star$ - $M_{\text{dark matter}}$ relation



The Halo-Galaxy Connection

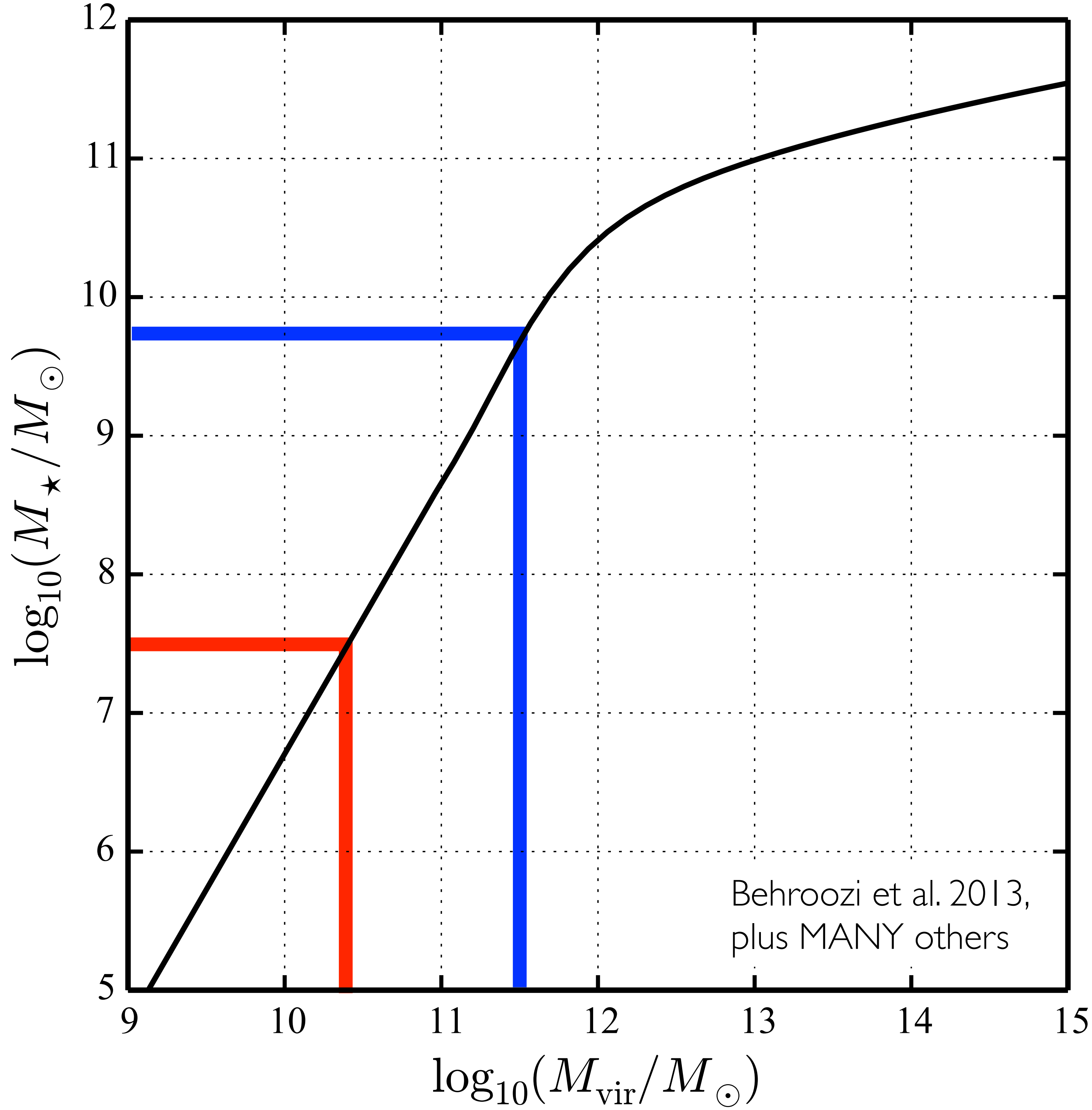
$M_\star$ - $M_{\text{dark matter}}$ relation

M33:

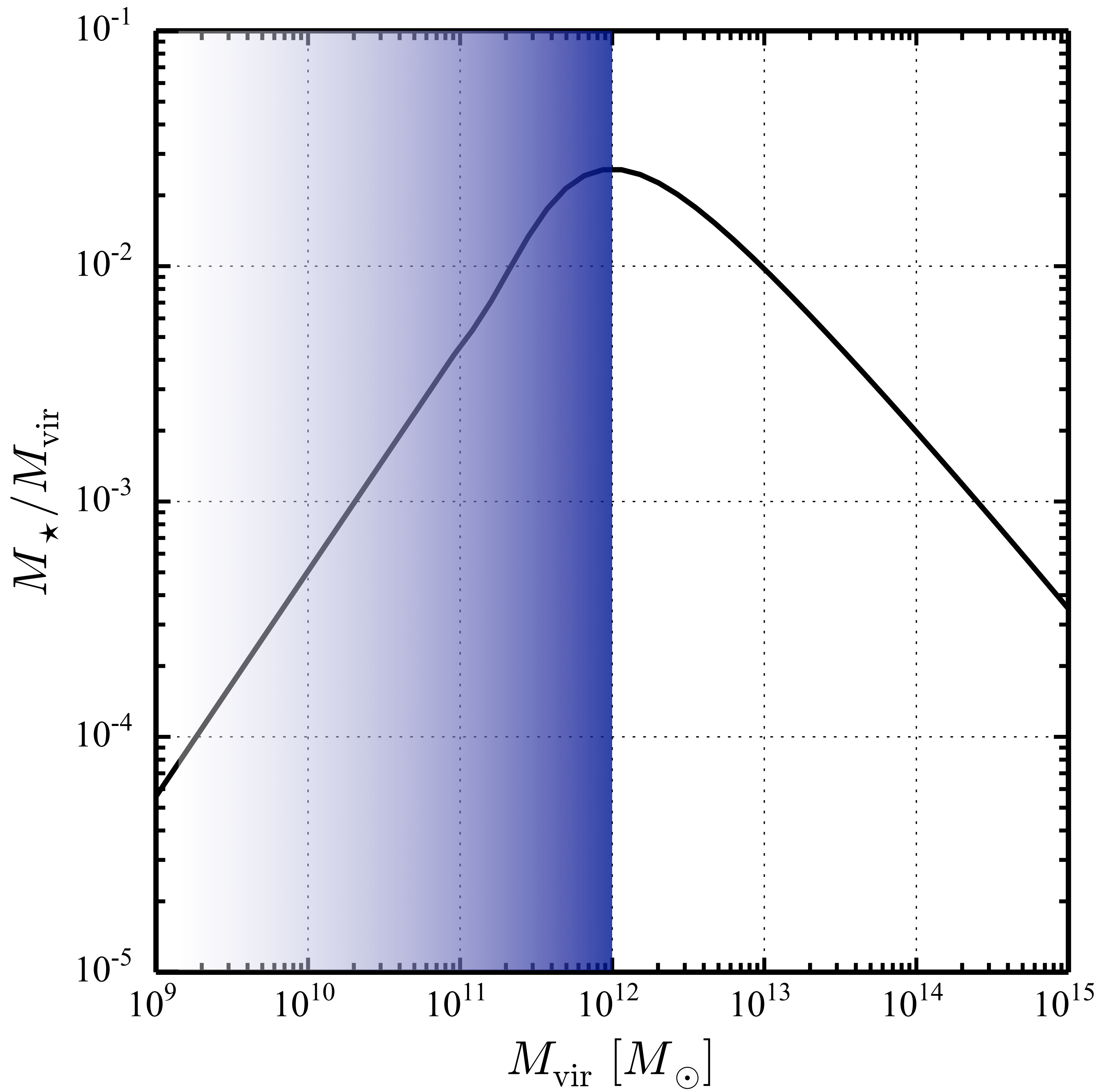
$M_\star \sim 0.02\ M_{\text{halo}}$

DDO 154:

$M_\star \sim 0.001\ M_{\text{halo}}$

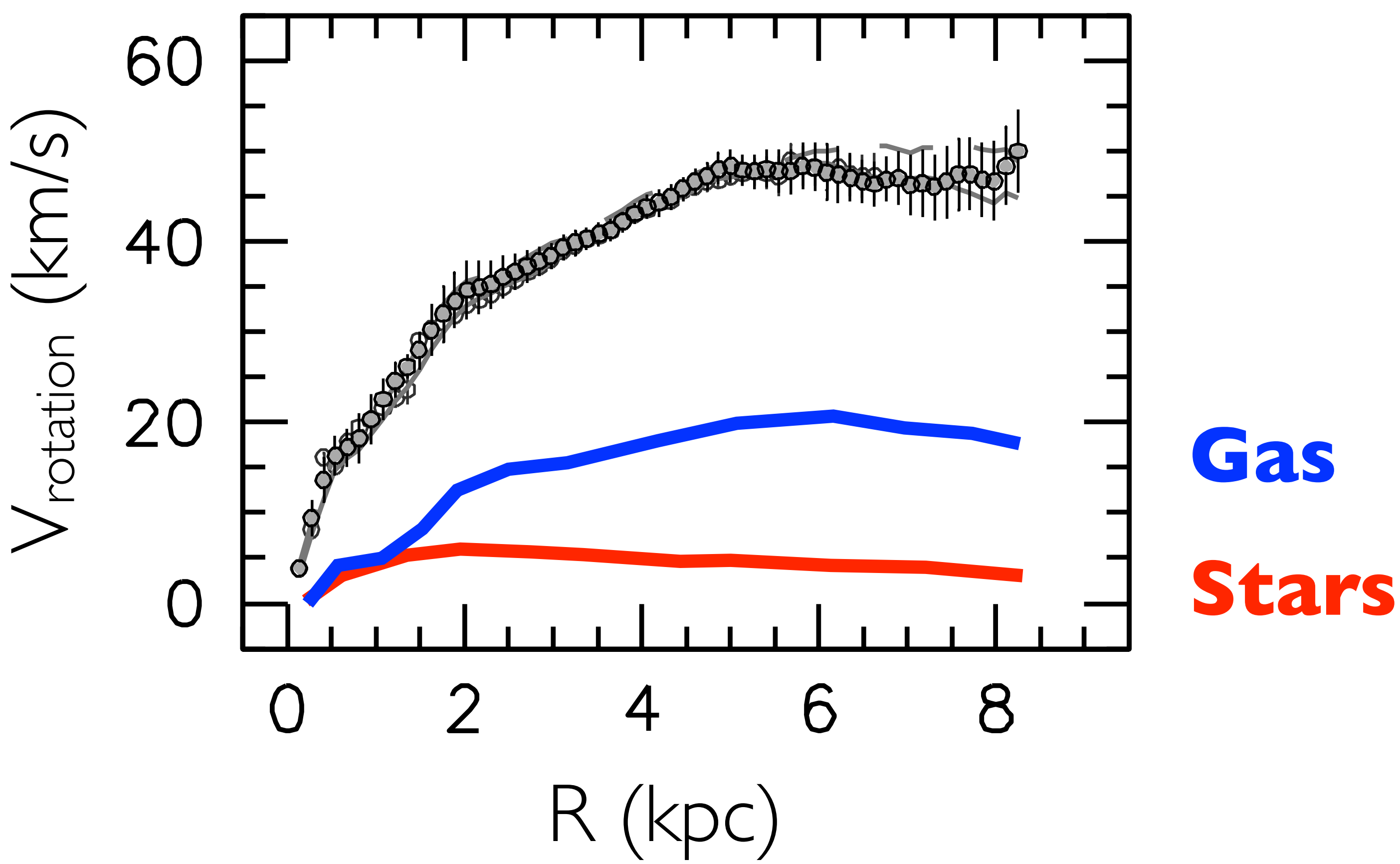


The Halo-Galaxy Connection



Going Fainter

DDO 154: $M_\star = 3\times10^7\ M_\odot$, $M_{gas} = 4\times10^8\ M_\odot$



best-fitting dark matter profile: $\rho \propto r^{-0.3}\ (r \ll 8\,\mathrm{kpc})$

best-fitting NFW profile: requires concentration of 4-5 (expected for galaxy clusters, not dwarf galaxies)

Oh et al. (2011)

Status of the Core-Cusp Issue for Central Galaxies

Observations of Low Surface Brightness galaxies and nearby dwarf galaxies typically show that there is **less dark matter** in the central regions than dark-matter-only CDM simulations predict

The precise distribution of dark matter in these galaxies is more controversial: often inconsistent with NFW profiles, sometimes consistent with NFW profiles but with parameters inconsistent with expectations; perhaps fully consistent with predictions from ΛCDM simulations in some cases.

Obvious next step: go to even fainter galaxies, where baryons are even less dynamically relevant

The Local Group of galaxies

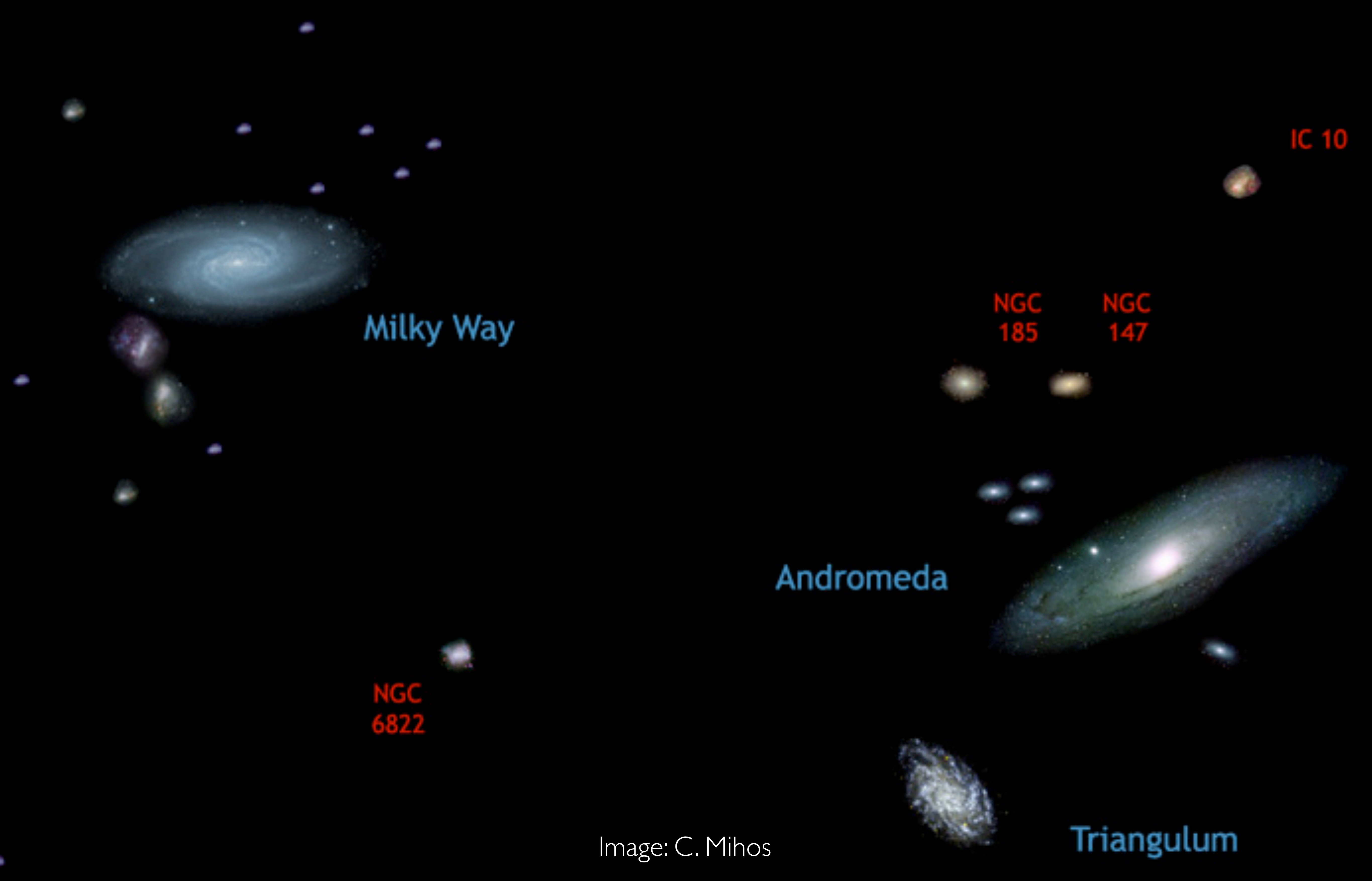
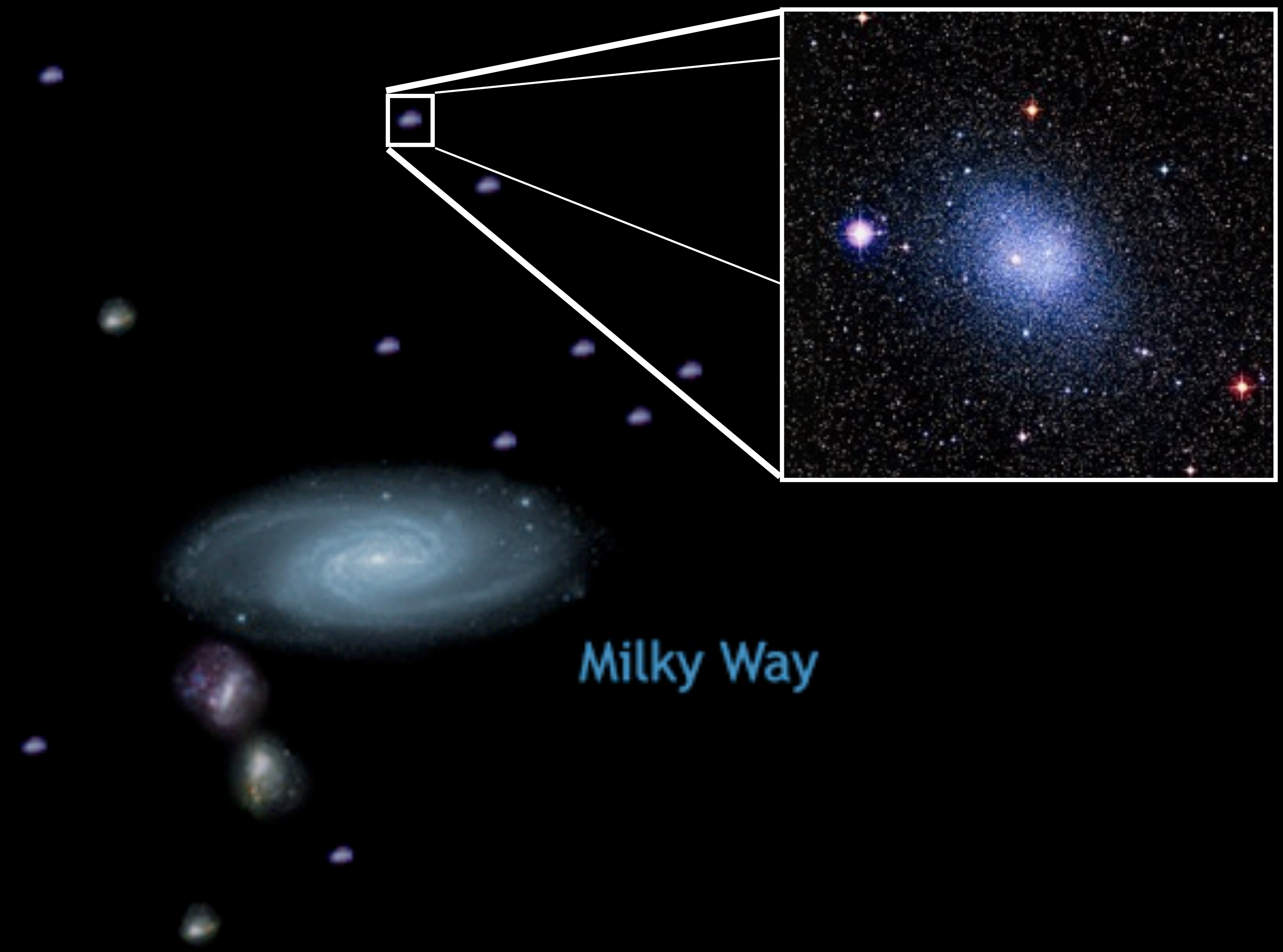


Image: C. Mihos



Dwarf spheroidal galaxies

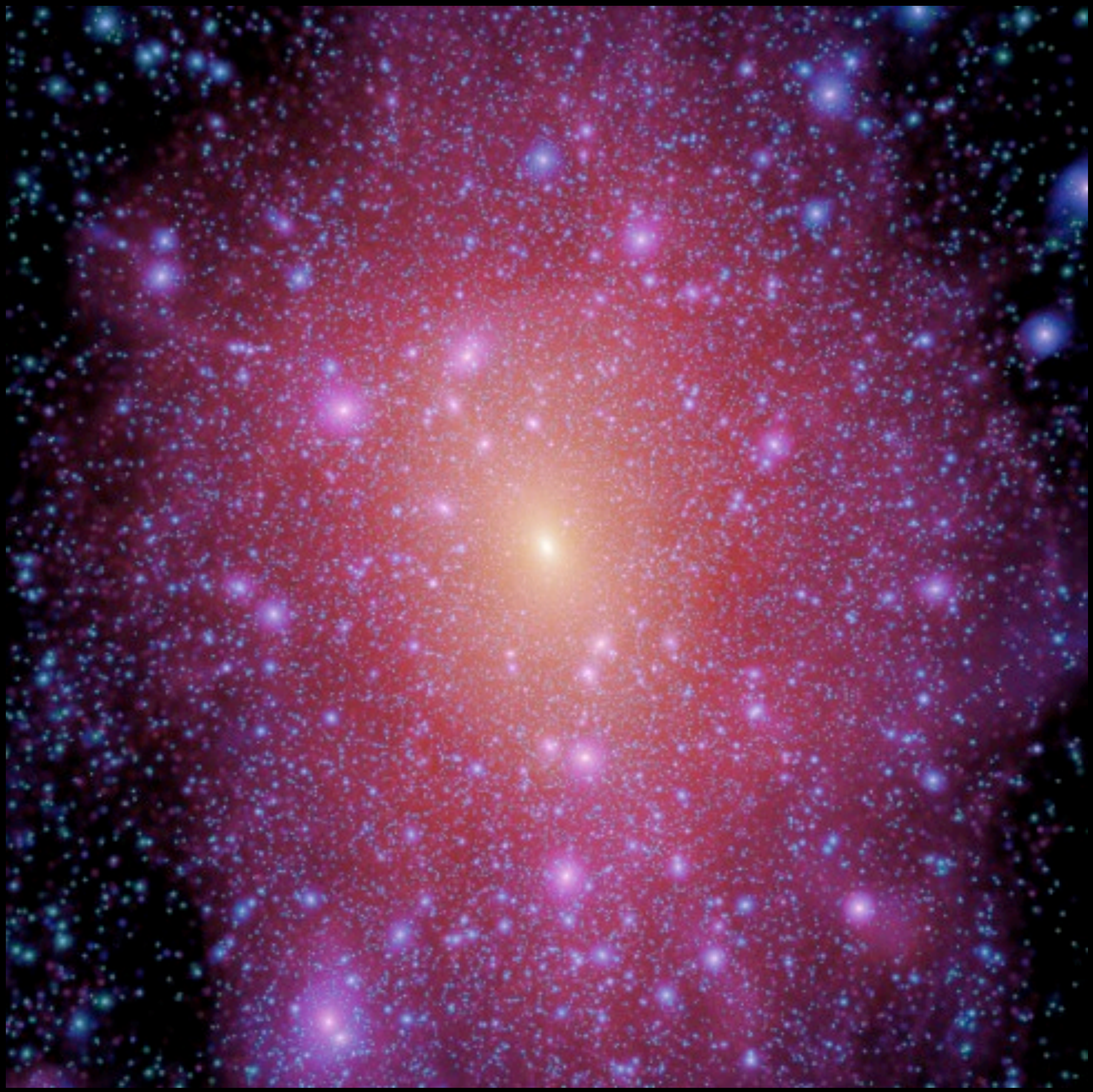
Luminosity: ~10^6 L_{sun}

Mass: ~$10^{8\text{-}9}$ M_{sun}

~25 known satellite galaxies around the Milky Way, spanning a factor of 10^7 in luminosity.

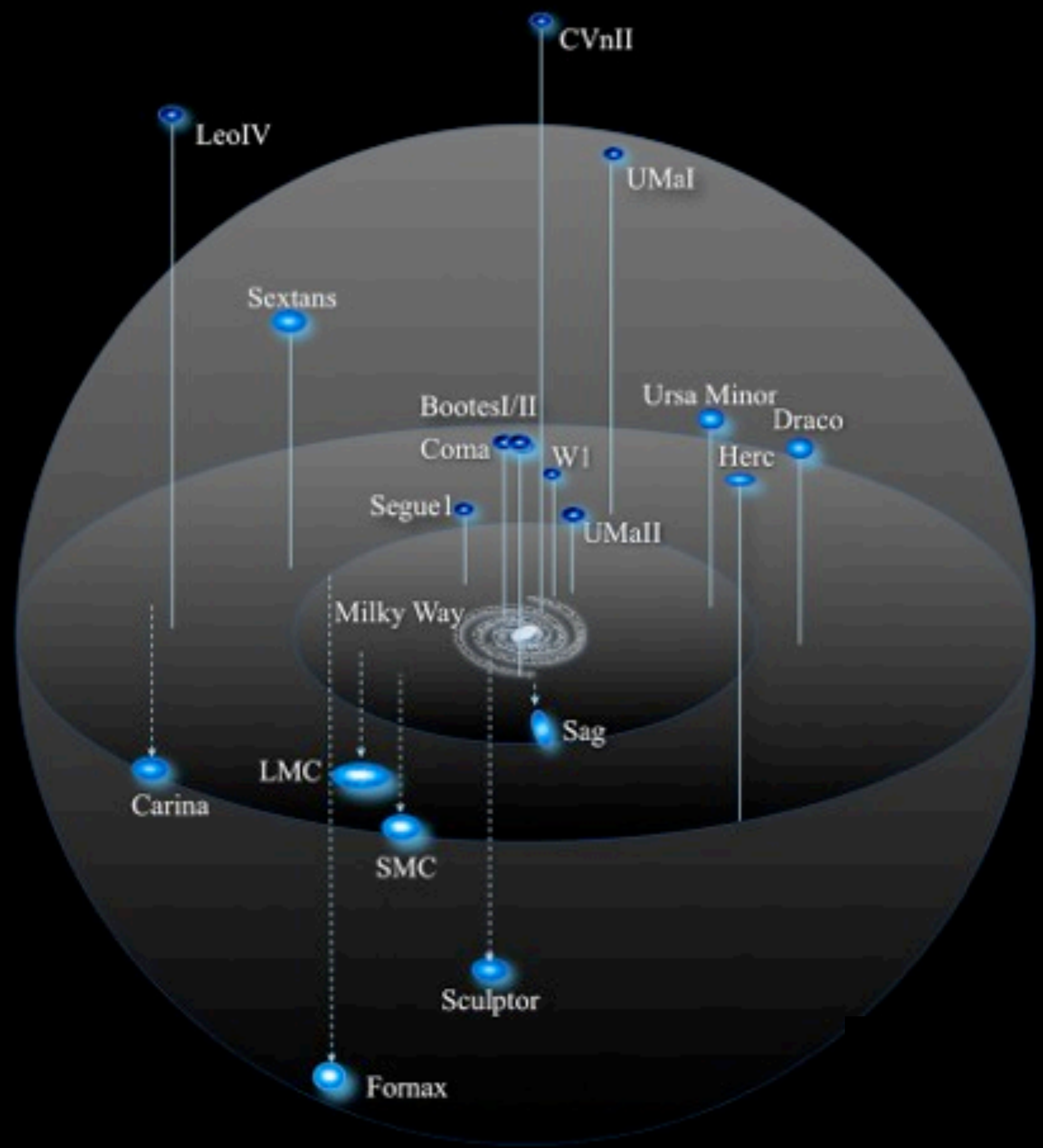
ΛCDM vs. the Milky Way, Round 1: **Missing Satellites**

Klypin et al. 1999, Moore et al. 1999



>10^5 identified subhalos

V. Springel / Virgo Consortium

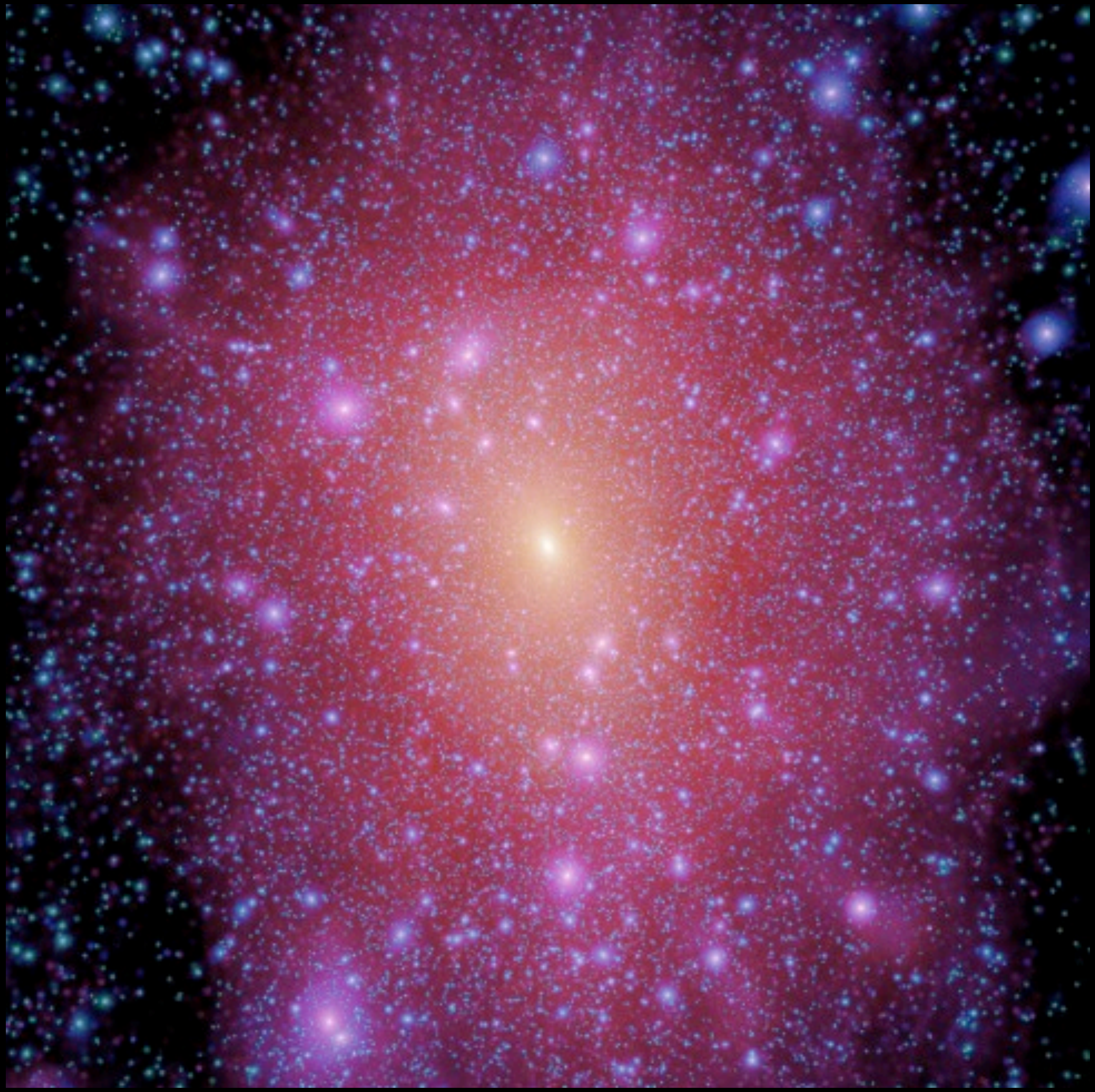


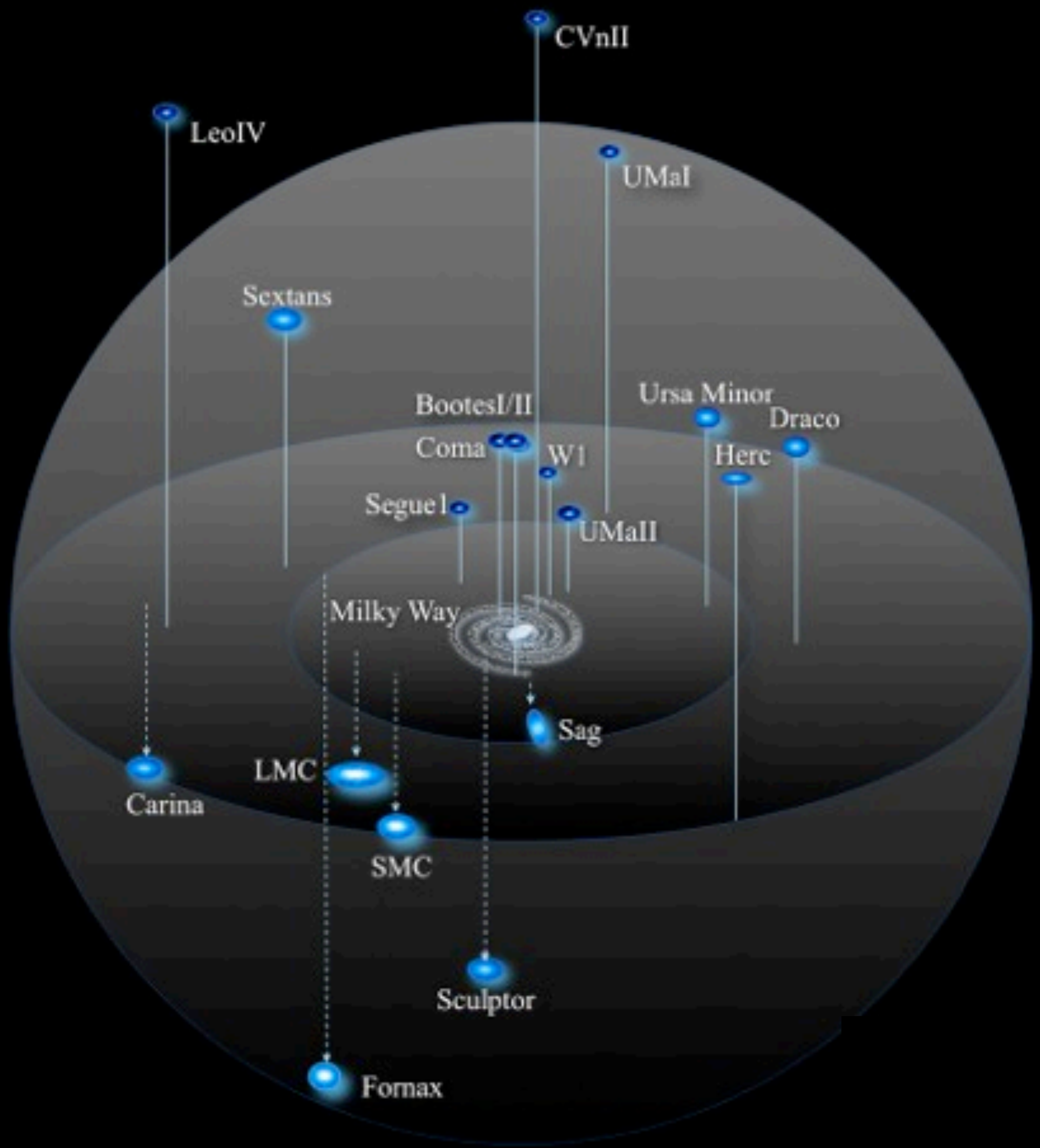
12 bright satellites $(L_V > 10^5 L_\odot)$

J. Bullock

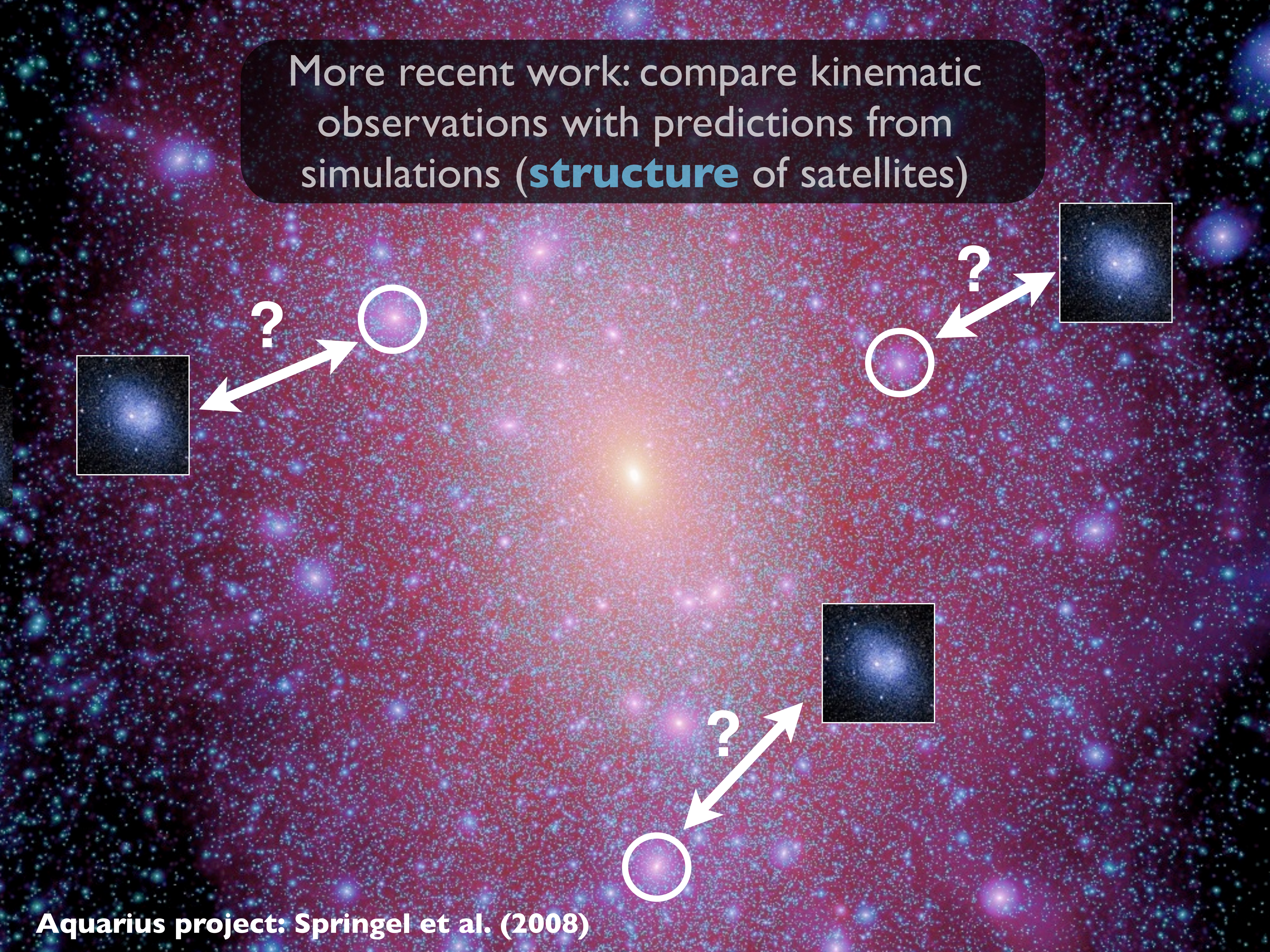
ΛCDM vs. the Milky Way, Round 1: **Missing Satellites**

Klypin et al. 1999, Moore et al. 1999



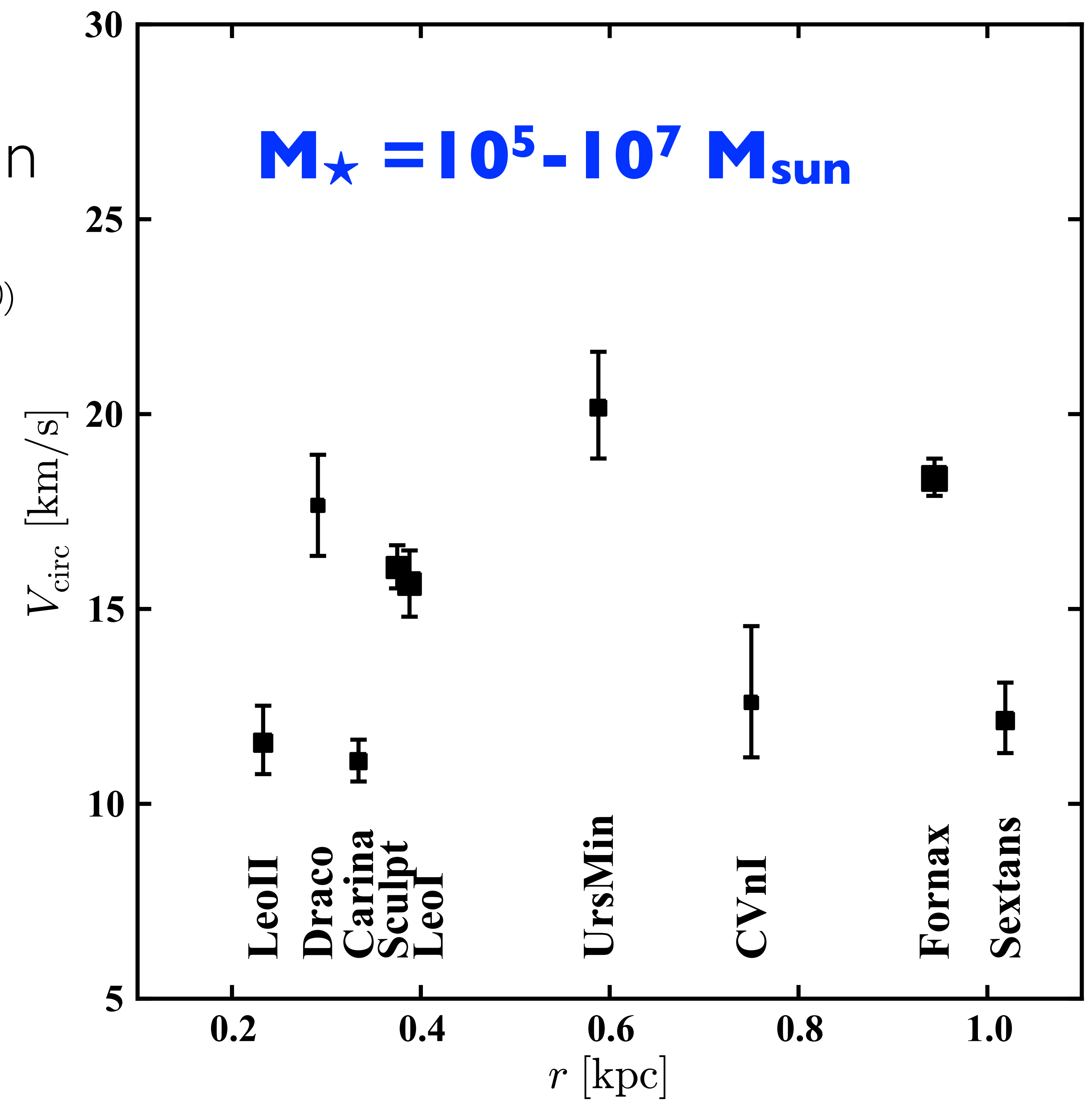


Number mismatch: maybe explained through (1) additional ultra-faint satellites and (2) galaxy formation processes (supernova feedback, reionization)?


More recent work: compare kinematic observations with predictions from simulations (**structure** of satellites)
?
?
?
Aquarius project: Springel et al. (2008)

Kinematic data for "bright" dwarfs

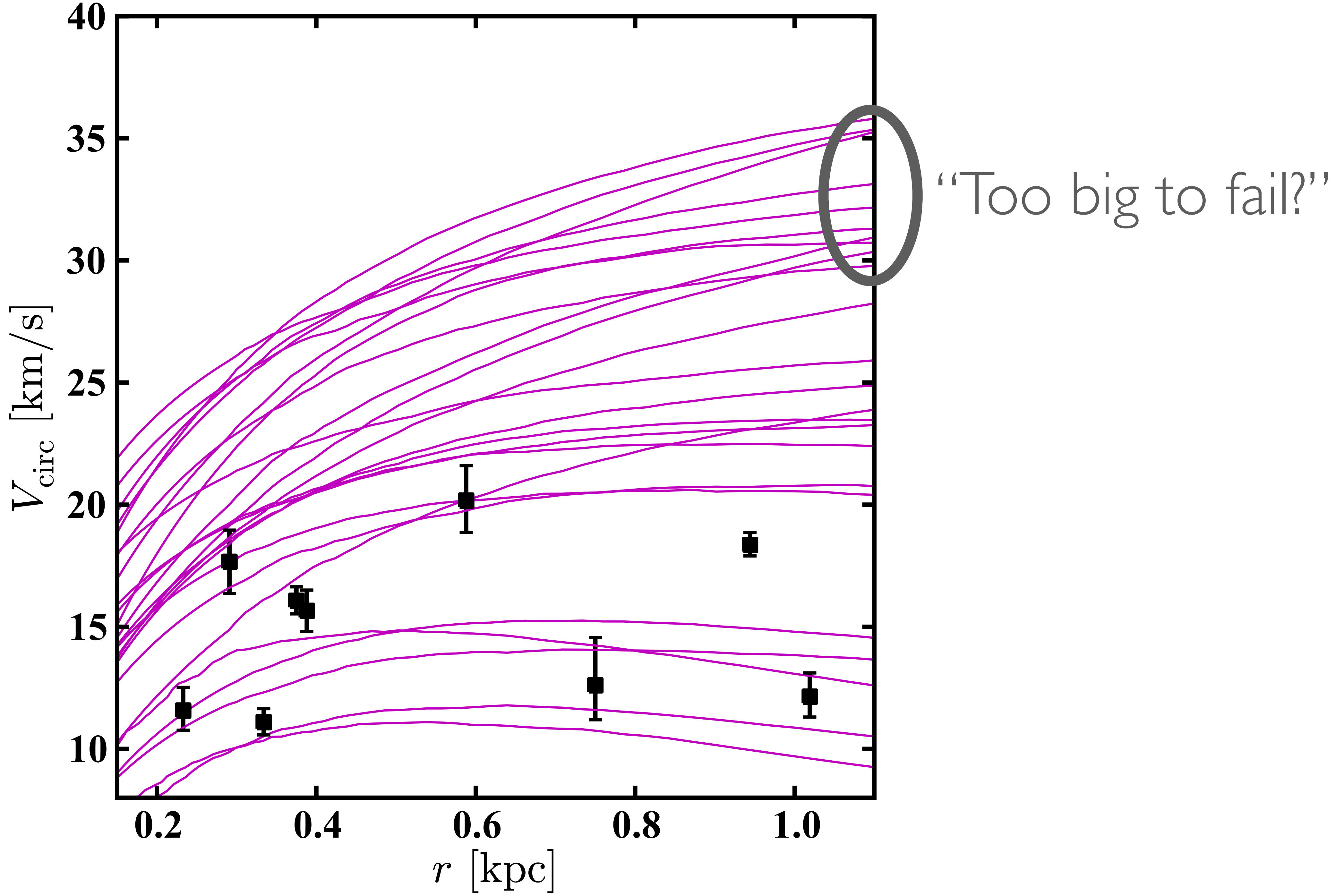
Strong constraint on total mass within half-light radius
(Walker et al. 2009, Wolf et al. 2010)



Data from Walker et al., Munoz et al., Koch et al., Simon & Geha, Mateo et al.

MBK, Bullock, & Kaplinghat 2011, 2012

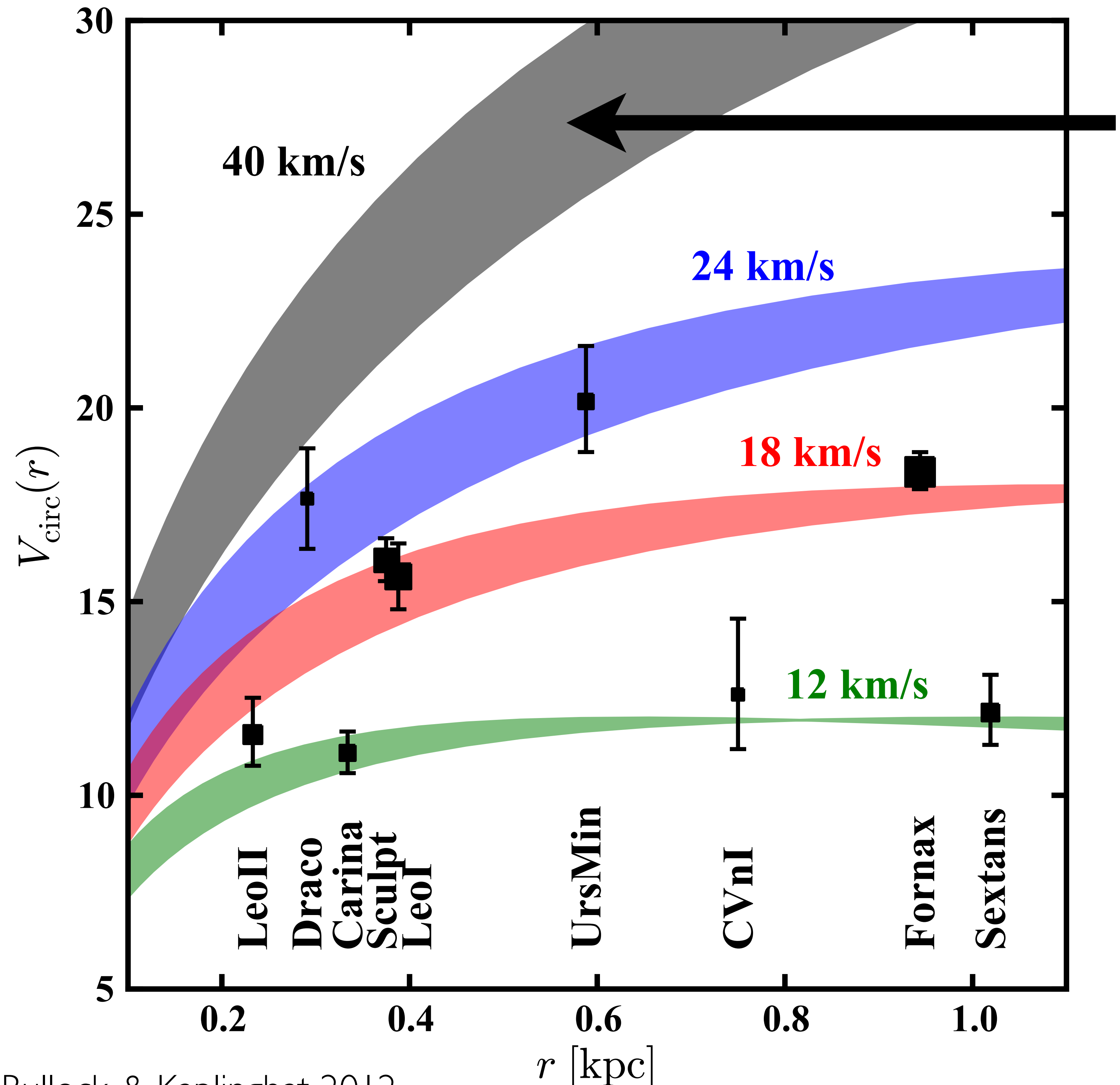
Missing the **biggest** substructure?



MBK, Bullock, & Kaplinghat 2011, 2012

2 LEGIT
2 QUIT.

Brightest Milky Way satellites: why so low mass?



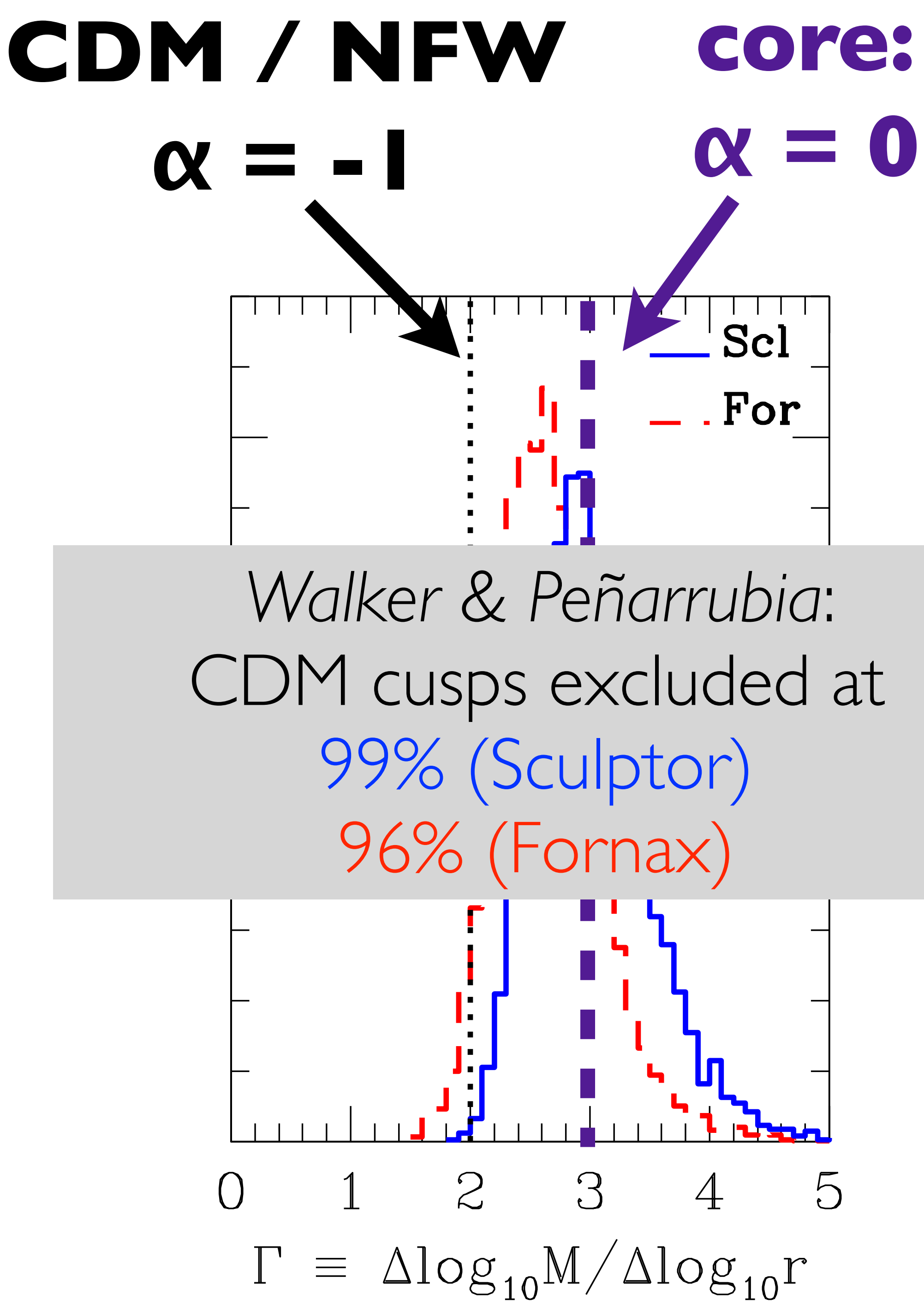
Biggest predicted satellites: $M_{halo} \sim 10^{10}\ M_{sun}$

Bright spheroidal satellites: $M_{halo} = 10^{8}$ -$10^{9}\ M_{sun}$

Similar results found for isolated, low-mass galaxies
(Ferrero, Abadi, Navarro + 2012)

MBK, Bullock, & Kaplinghat 2012

Possibly related: dark matter cores in MW satellites



Walker & Peñarrubia:
CDM cusps excluded at
99% (Sculptor)
96% (Fornax)

Walker & Peñarrubia 2011

also: Battaglia et al. 2008, Amorisco & Evans 2012, ...

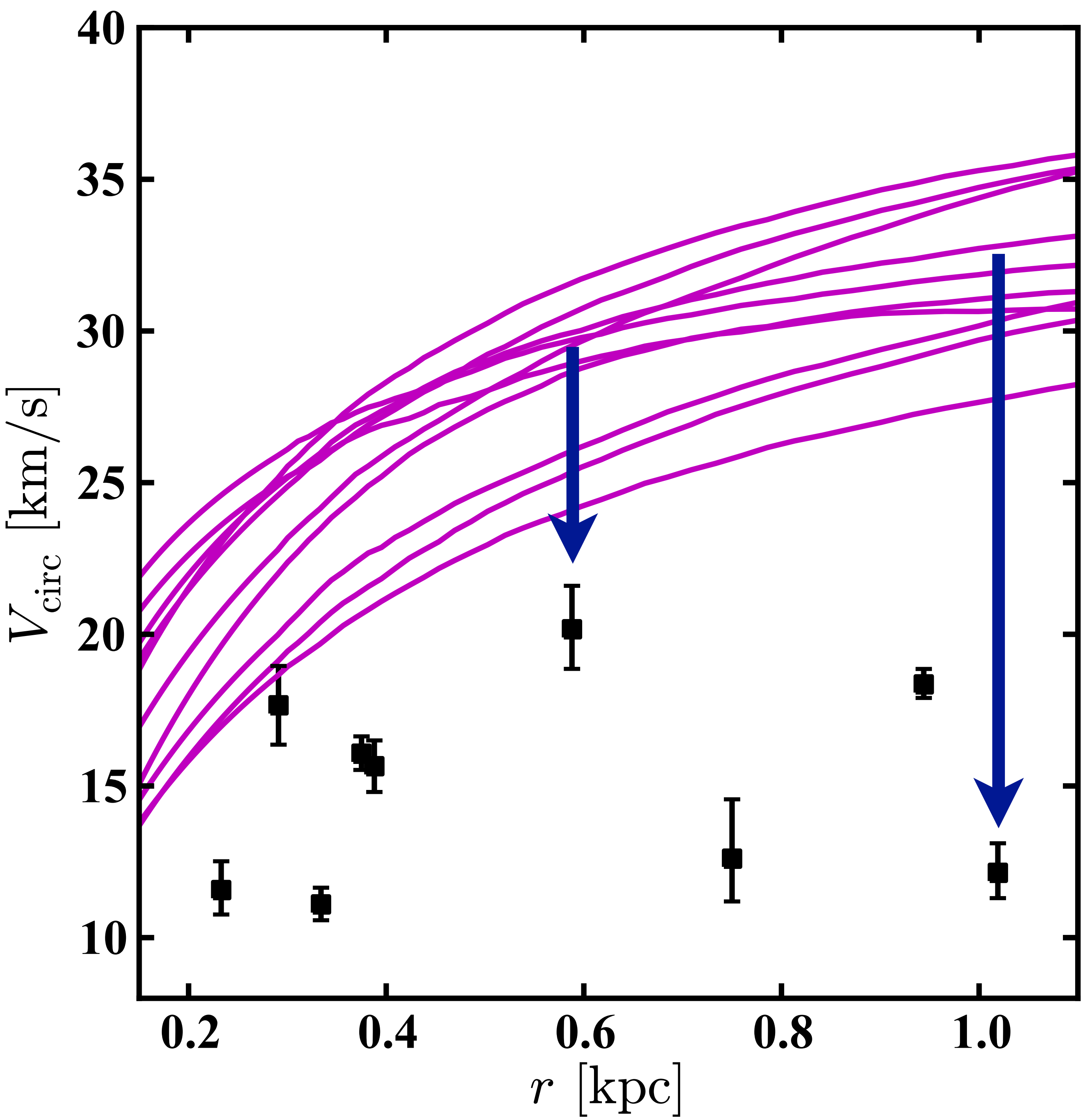
Why "possibly" related?

- **TBTF**: only indicates that the **total mass** within ~500 pc of observed dSph galaxies is substantially lower than simple LCDM predictions.
- Can have cores in dSphs without solving TBTF or explain TBTF without cores
- This distinction is **important** in the context of non-CDM particle physics models

Cores in MW satellites?

- **Fundamental issue**: Limited by degeneracy between mass profile and velocity anisotropy of stars. Internal proper motions may help.
- DM distribution in Fornax:
  - Jeans models: strongly prefer cores (Walker & Peñarrubia), or maybe not (Strigari et al.)?
  - Orbit modeling: evidence for core (Jardel & Gebhardt) or neutral as to cusp / core (Breddels & Helmi).
- Additional hints at cores in some MW satellites?
  - Globular clusters in Fornax (Goerdt, Moore, Read, Stadel, & Zemp 2006; Cole, Dehnen, Read, & Wilkinson 2012): should have merged in a cuspy DM halo
  - Cold clump in Ursa Minor: a subhalo within a subhalo? (Pace et al. 2013) Should be short-lived phenomenon in a cuspy DM distribution (Lora et al. 2013)

From CDM to observations



Too big to fail, cores in MW satellites: Pointing to a problem with CDM-only predictions for densities on small scales (0.1-1 kpc)

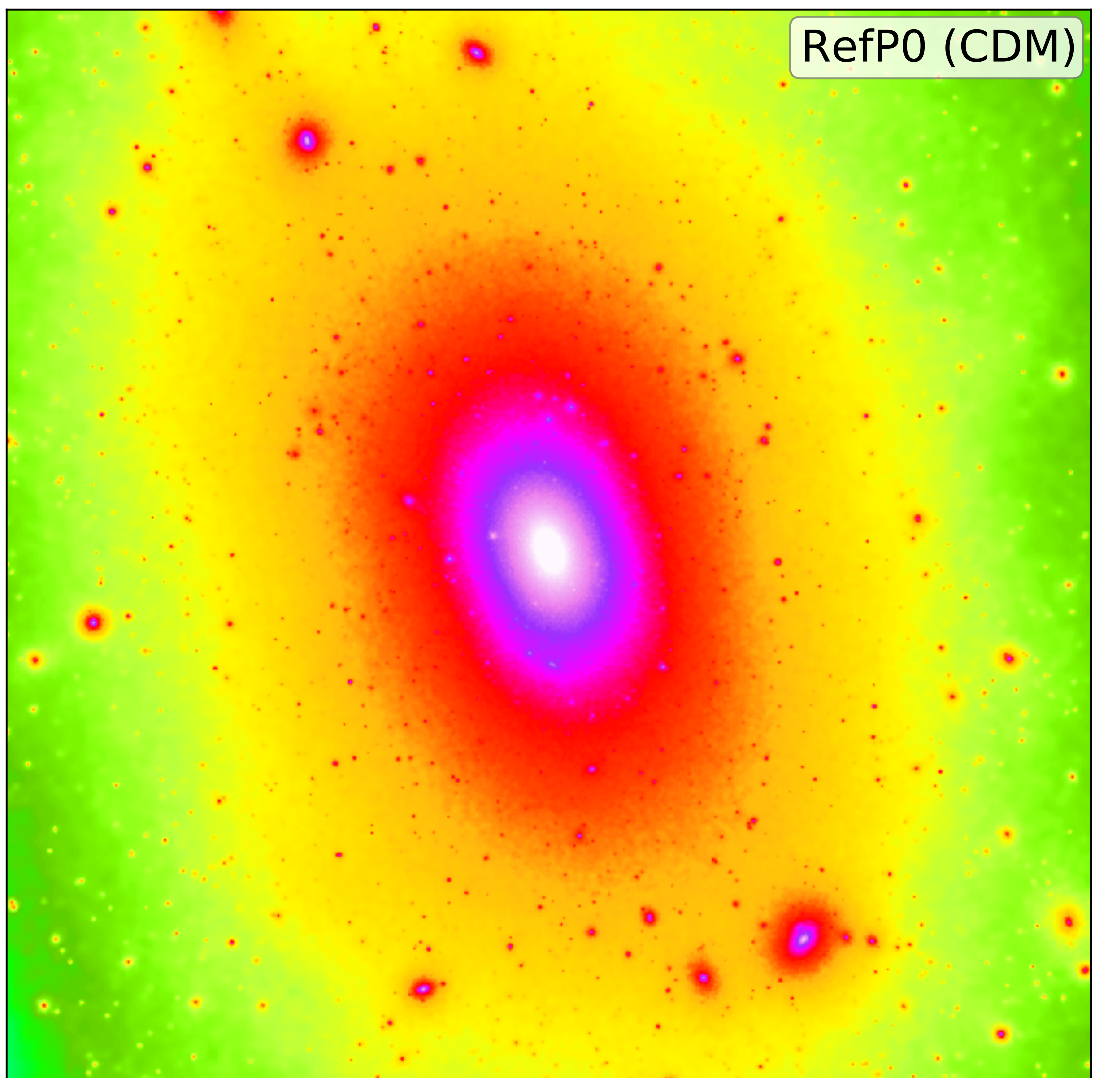
need ~50% less dark matter mass in the inner 500 pc

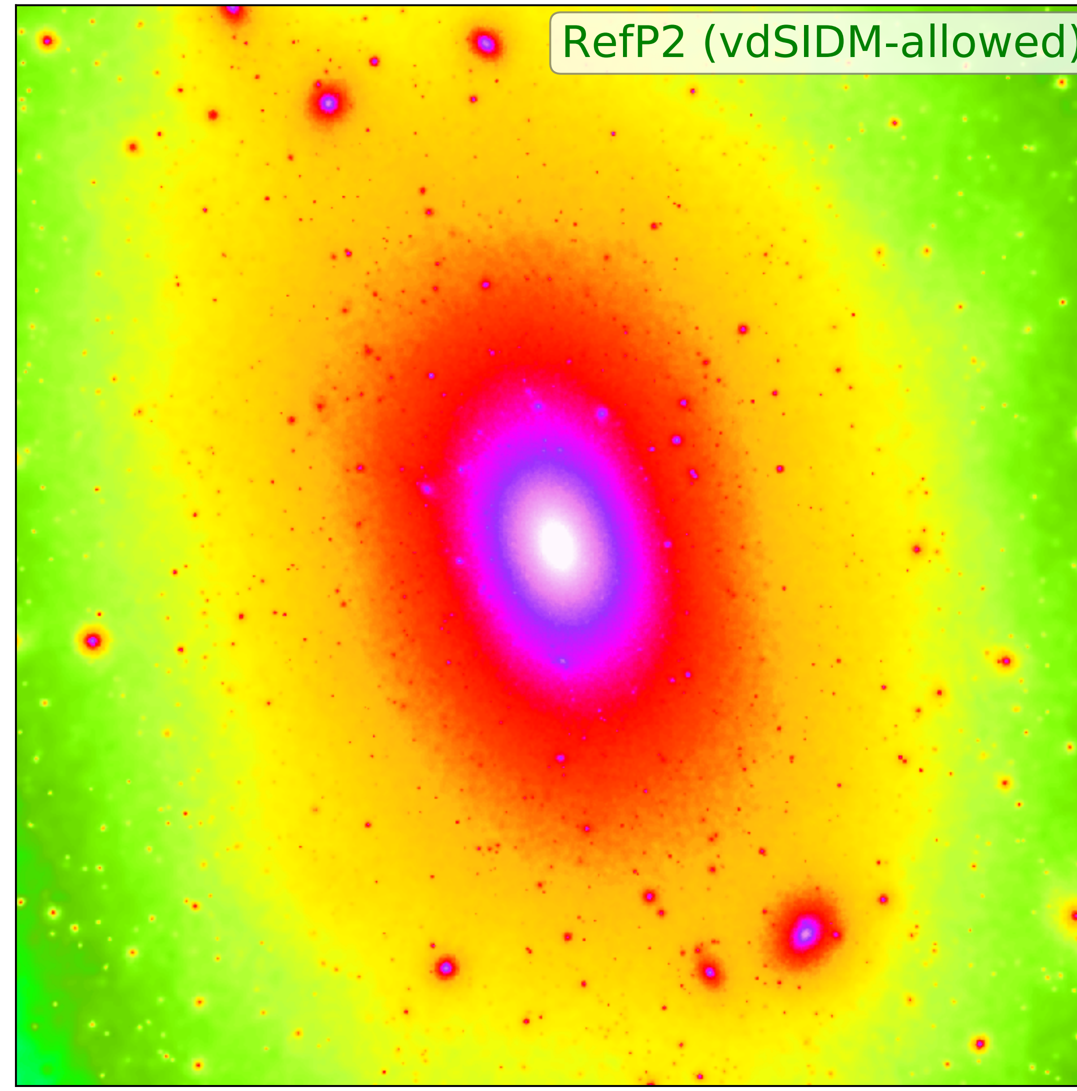
Recent work argues this can be achieved with WDM, SIDM, or baryonic feedback

Self-interacting dark matter

(e.g., Spergel & Steinhardt 2000; Feng et al. 2009; Loeb & Weiner 2011)

CDM



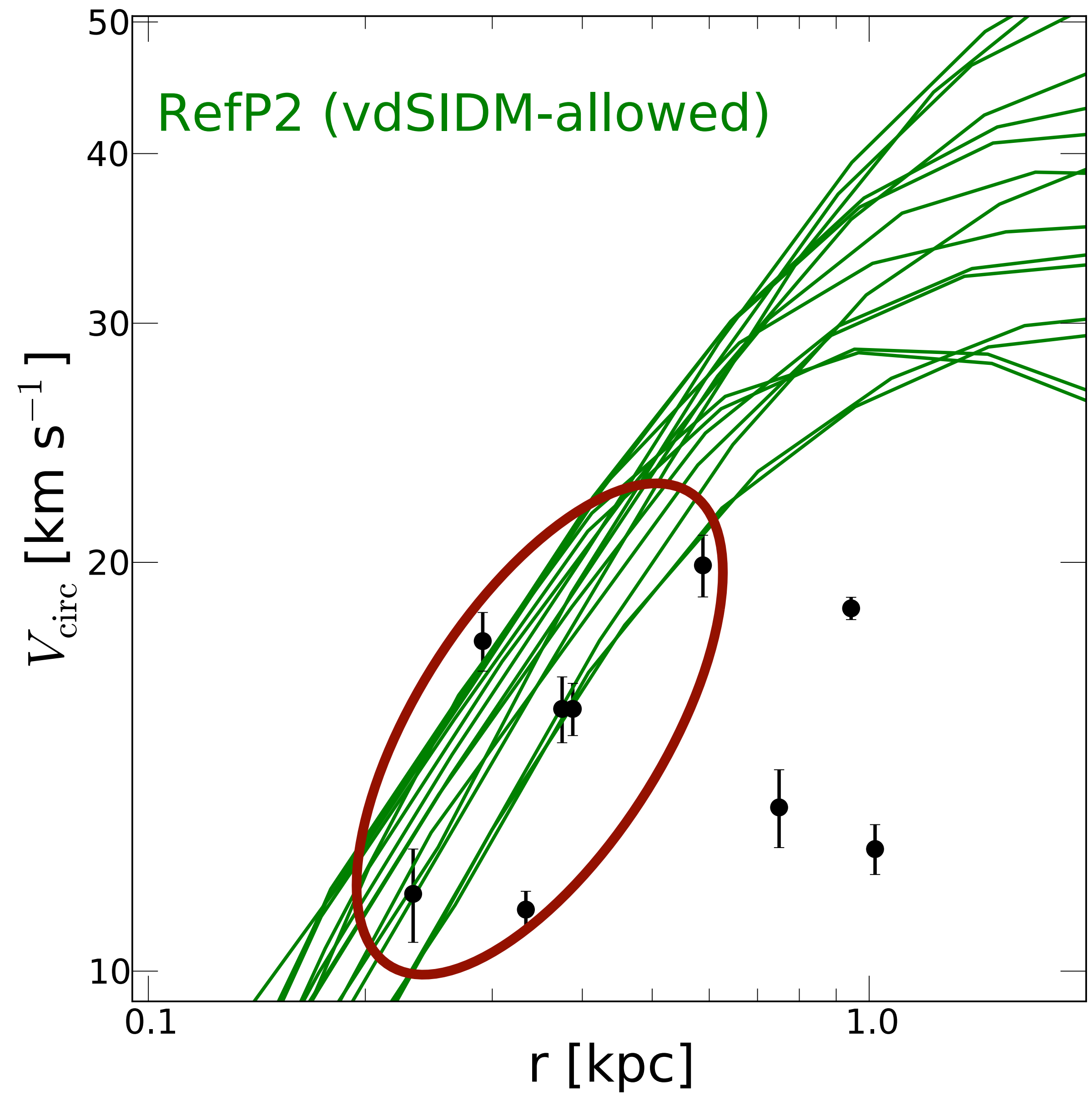


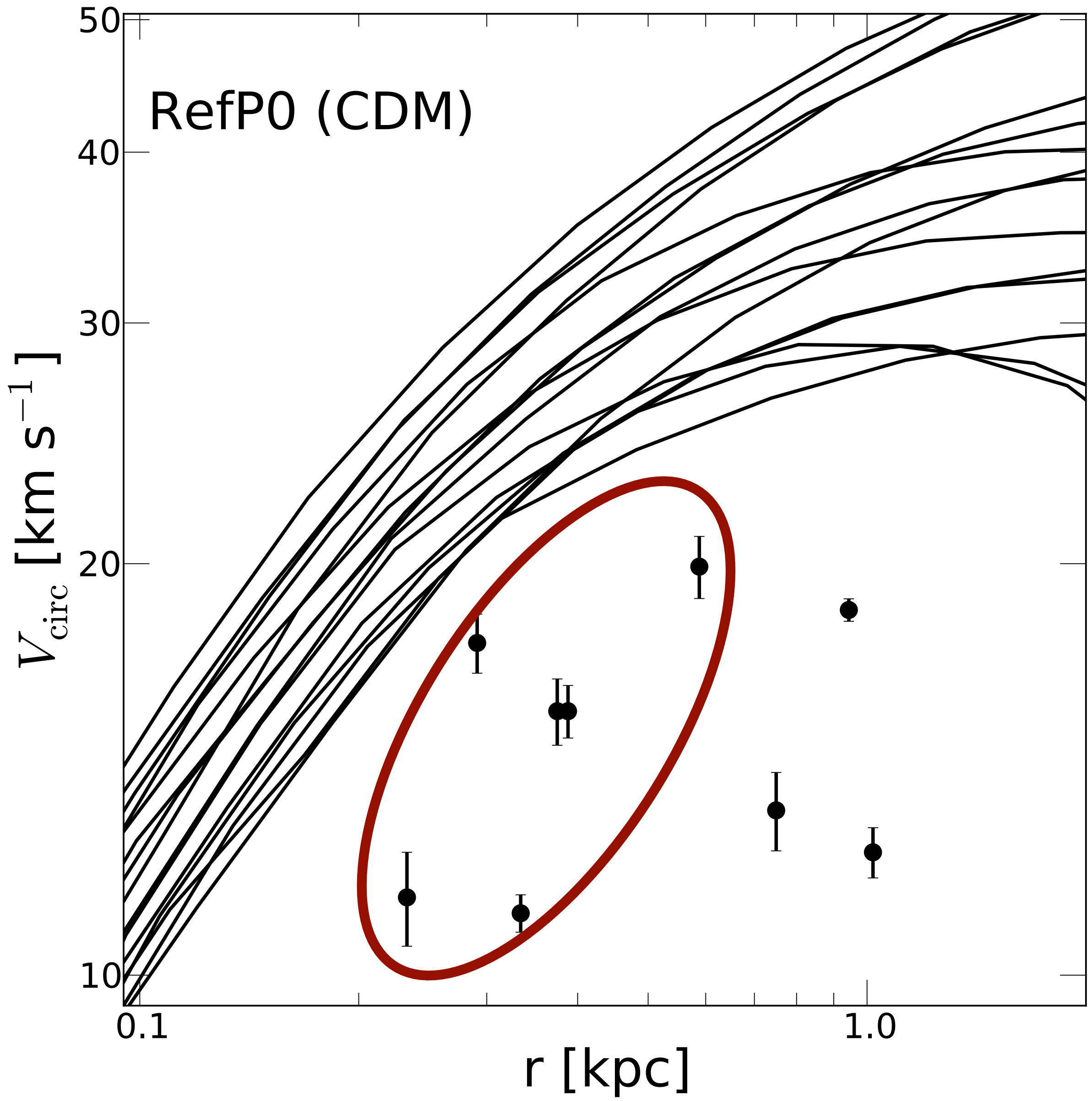
Self-Interacting Dark Matter

(Vogelsberger et al. 2012; *also Rocha, Peter, Kaplinghat, & Bullock 2013*)

Self-interacting dark matter

(Vogelsberger, Zavala, Loeb, Walker 2012, 2013)





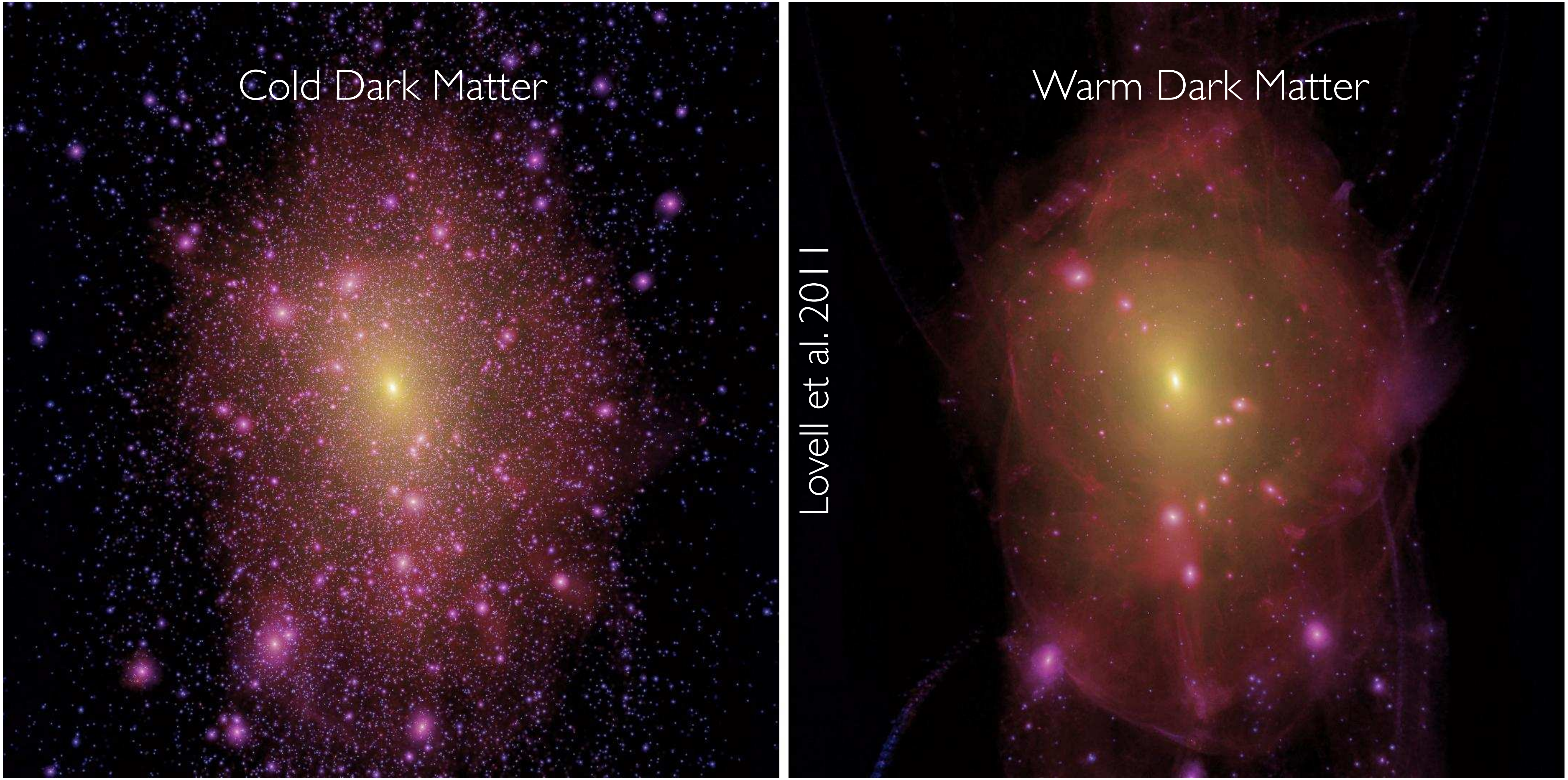
Above: velocity-dependent σ

Velocity-independent σ should work for

σ ~0.3 cm^2/g

(Vogelsberger et al. 2013, Rocha et al. 2013, Peter et al. 2013)

Warm Dark Matter?



WDM: modifies **density** of subhalos, not the underlying dark matter profile **shape** for models not excluded by complementary astrophysical data (m~2 keV or more).

Allowed WDM particle masses **cannot produce ~0.5 kpc cores** through free streaming / phase-space considerations (such cores would be 50 x smaller).

Reduction in dark matter density through supernova feedback?

How supernova feedback turns dark matter cusps into cores

Andrew Pontzen[1,2,3★] and Fabio Governato[4]

BARYONS MATTER: WHY LUMINOUS SATELLITE GALAXIES HAVE REDUCED CENTRAL MASSES

ADI ZOLOTOV[1], ALYSON M. BROOKS[2], BETH WILLMAN[3], FABIO GOVERNATO[4], ANDREW PONTZEN[5], CHARLOTTE CHRISTENSEN[6], AVISHAI DEKEL[1], TOM QUINN[4], SIJING SHEN[7], AND JAMES WADSLEY[8]

The baryons in the Milky Way satellites

O. H. Parry,[1★] V. R. Eke,[1] C. S. Frenk[1] and T. Okamoto[1,2]

Cusp-core transformations in dwarf galaxies: observational predictions

Romain Teyssier[1,4⋆], Andrew Pontzen[2], Yohan Dubois[3] and Justin I. Read[5,6]

EXPLAINING THE OBSERVED VELOCITY DISPERSION OF DWARF GALAXIES BY BARYONIC MASS LOSS DURING THE FIRST COLLAPSE

MATTHIAS GRITSCHNEDER[1,2], DOUGLAS N.C. LIN[1,2]

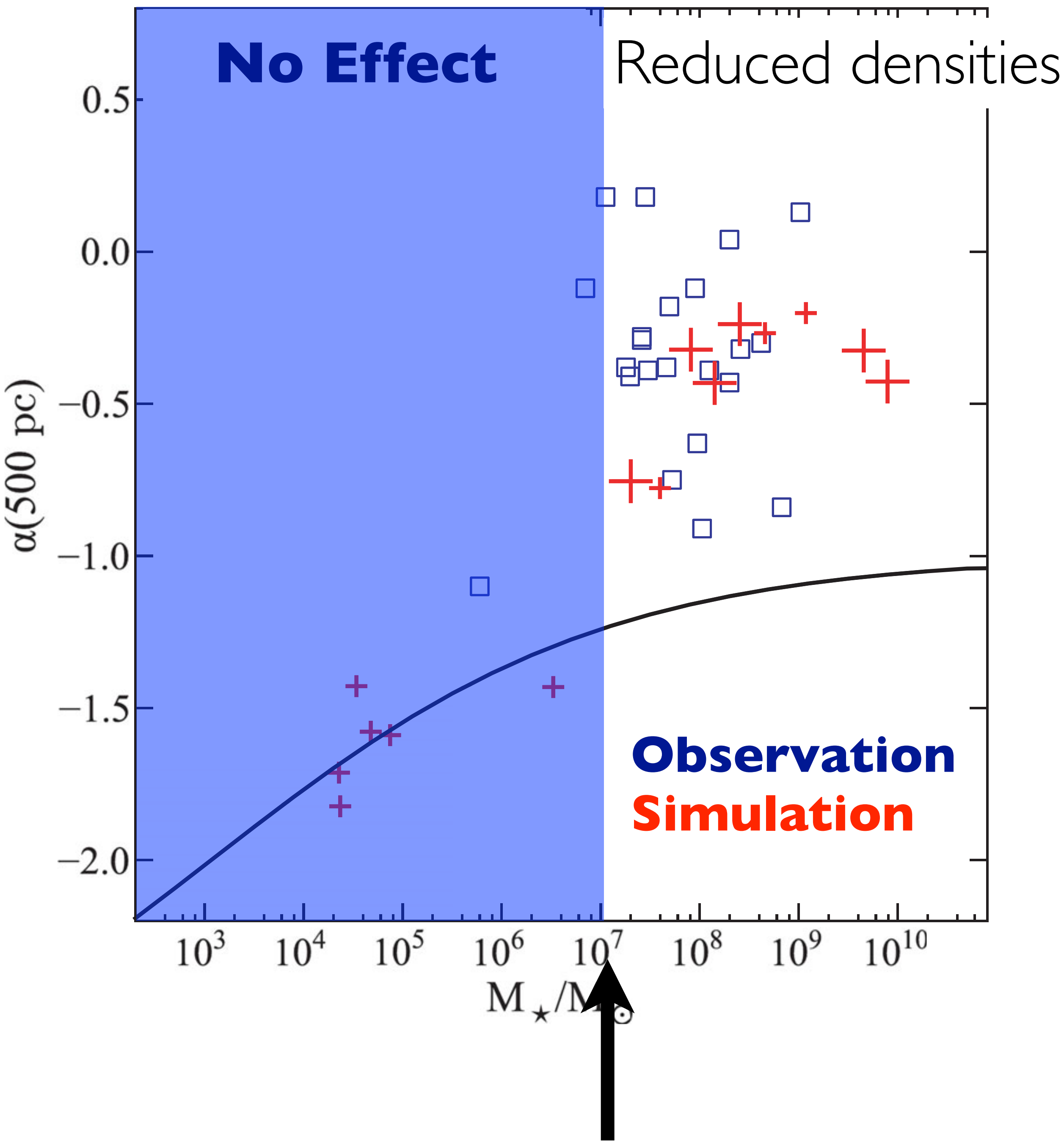
Effects of baryon removal on the structure of dwarf spheroidal galaxies

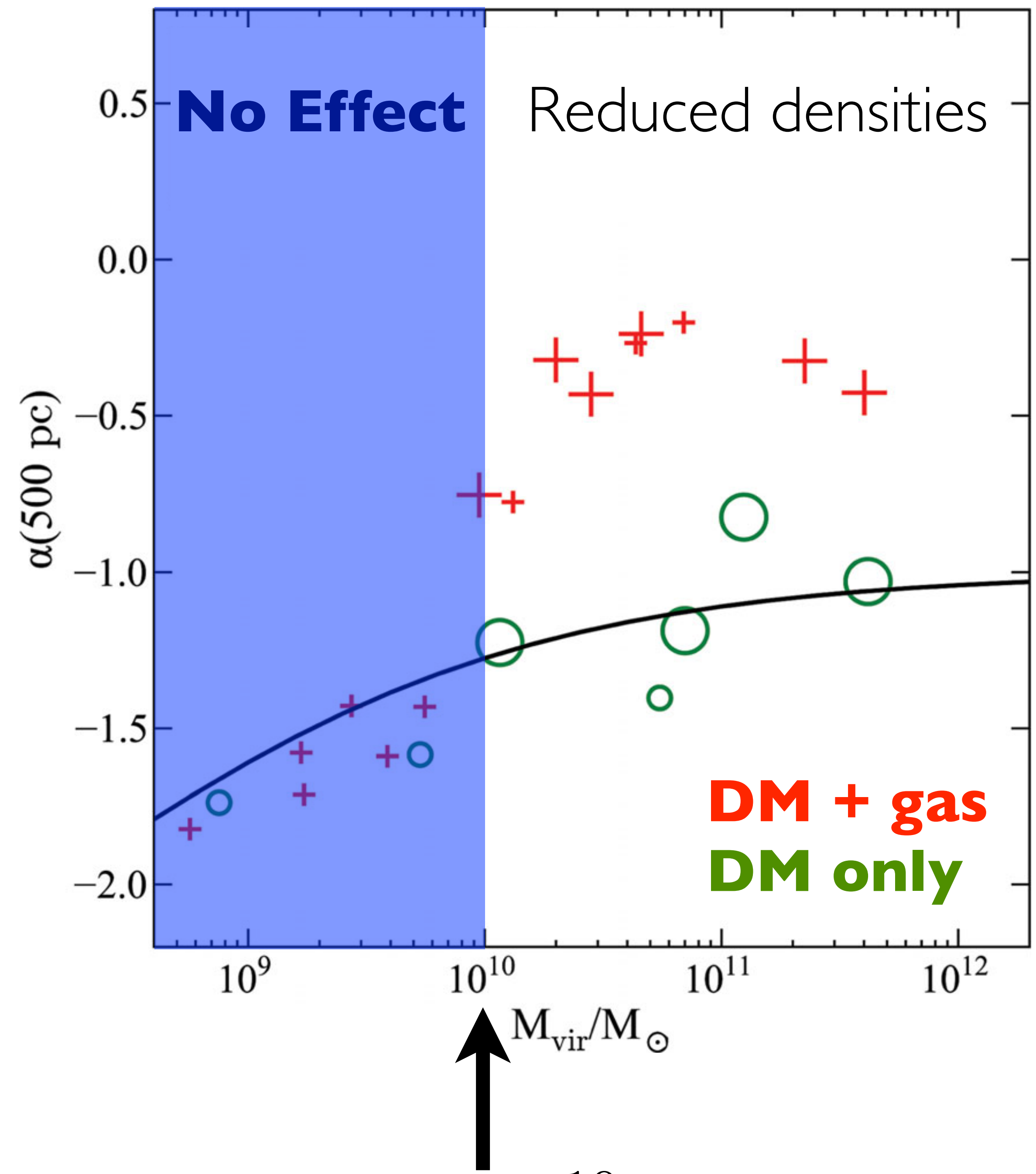
Kenza S. Arraki[1 ∗ †], Anatoly Klypin[1], Surhud More[2,3] and Sebastian Trujillo-Gomez[1]

Rooted in earlier work by Larson 1974, White & Rees 1978, Dekel & Silk 1986, Navarro et al. 1996, ...

Galaxy formation imprints scale on DM distribution

Governato et al. 2012





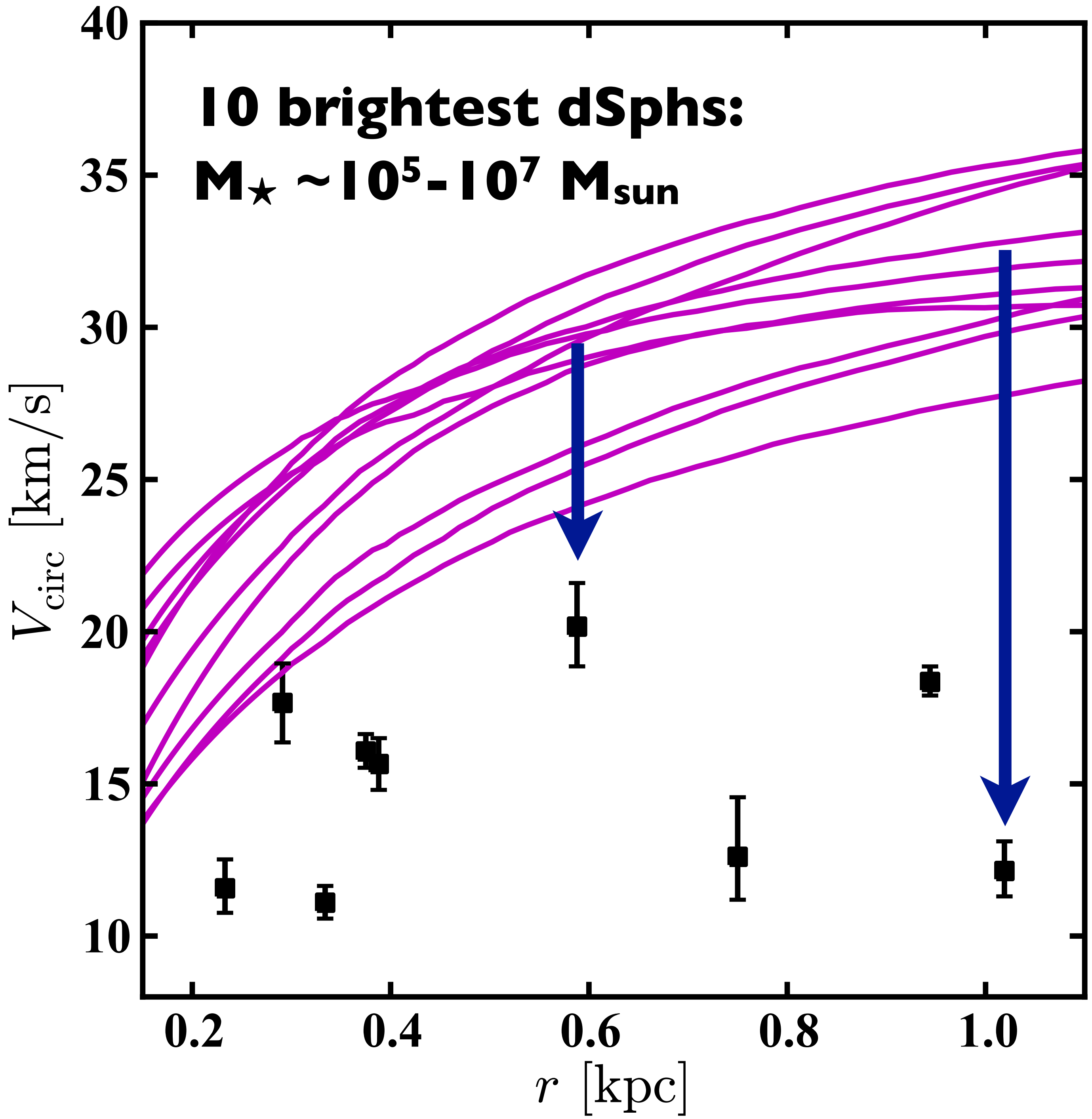
$$M_\star = 10^7 \, M_\odot$$

Same scale as for MW satellites

$$M_{\rm halo} = 10^{10} \, M_\odot$$

$$V_{\rm halo} = 40 \, {\rm km/s}$$

Supernova feedback: limited by number of stars



Low stellar mass of dSphs ⟹ (probably) *impossible* to reduce density with SN feedback alone

(Garrison-Kimmel et al. 2013; see also Peñarrubia et al. 2012)

Combine with tidal effects?

(Zolotov et al. 2012, Brooks et al. 2013, Arraki et al. 2013)

Why is this still under debate?

Collisionless simulations: exact solution to an approximate problem

Hydrodynamical simulations: approximate solutions to full problem

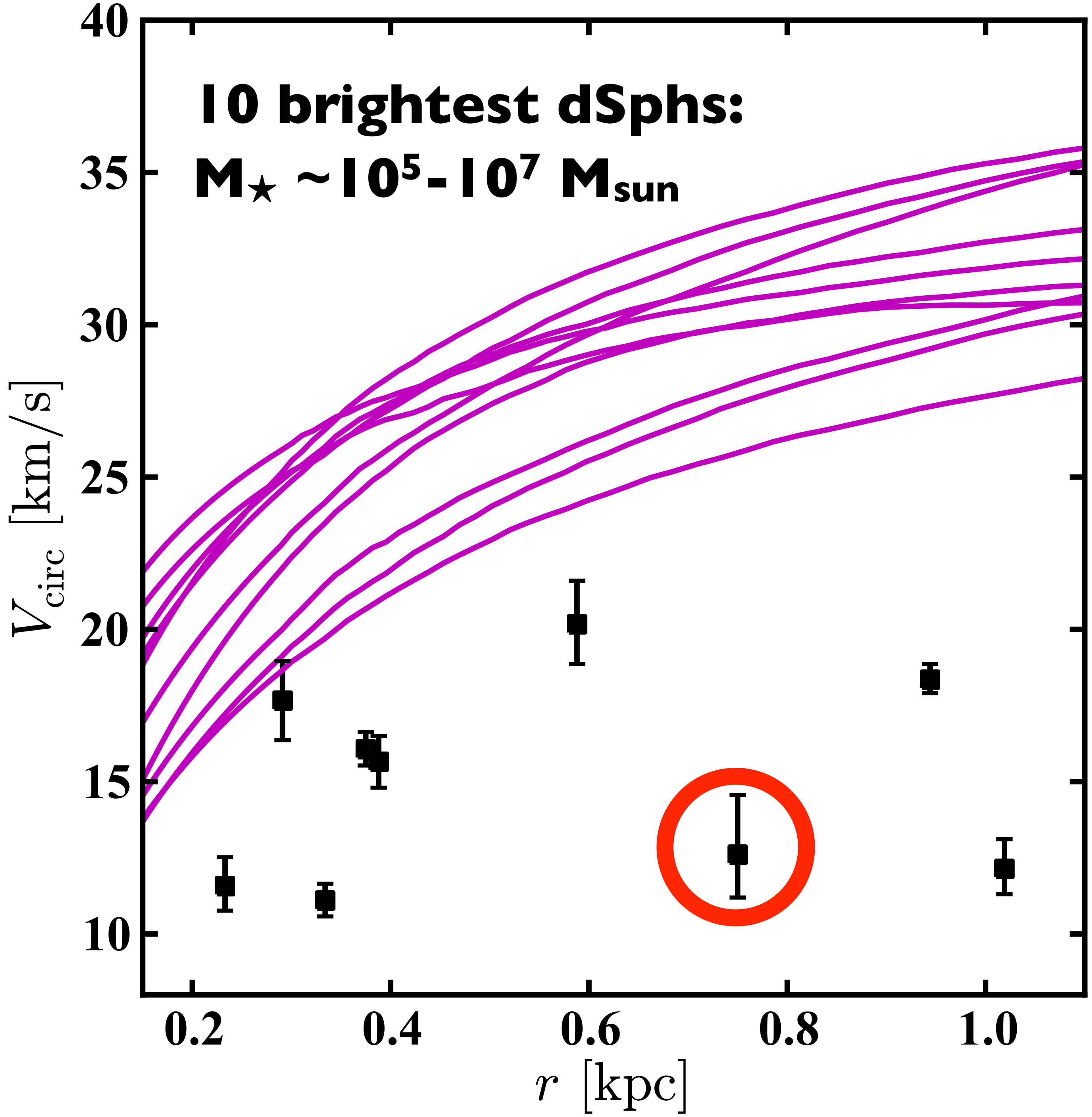
- How much energy from a single supernova explosion couples to gas in galaxy? All simulations must make a choice for this (not unique)
- How important is radiation pressure versus thermal or kinetic energy?
- What physics is important? Cosmic rays? Magnetic fields?
- Inherently limited by spatial and temporal resolution -- how do we treat processes on smaller length and time scales than we resolve?

- All simulations require parameter choices and approximations

Why is this still under debate?

- Only in past ~1-2 years have simulations produced fairly realistic-looking "Milky Way" galaxies. **Simulating the MW satellites and the Galaxy together is a very demanding problem and will be for the foreseeable future.**
  - **Mass profiles are typically resolved at ~10 resolution elements**
  - **2008: DM-only simulations of MW with 10^9 particles, each of mass 10^3 M_{sun}, and force resolution of 20 pc.**
  - **2011: Hydro simulations of MW with 10^7 (DM) particles, each of mass 10^5 M_{sun}, and force resolution of 90 pc.**

A test of the baryonic feedback model?



Possible test of the baryon feedback model: Does **CVnI** ($M_\star \sim 10^5$) have a ~1 kpc core? If not, can tidal effects explain its extremely low density?

Gaia proper motions should help with the 2nd question

How can we differentiate between effects of astrophysics and fundamental physics in low-mass galaxies?

(1) Look at recently-accreted satellites

Leo T:

- 420 kpc from galactic center
- stellar mass of $\sim 10^5$ M_{sun} - not affected by SN feedback
- HI content ($\sim 2.5 \times 10^5$ M_{sun})
- ongoing star formation
- falling into MW for first time

➡ Prototype for discriminating between baryonic and dark matter physics in a "satellite"

(1) Look at recently-accreted satellites

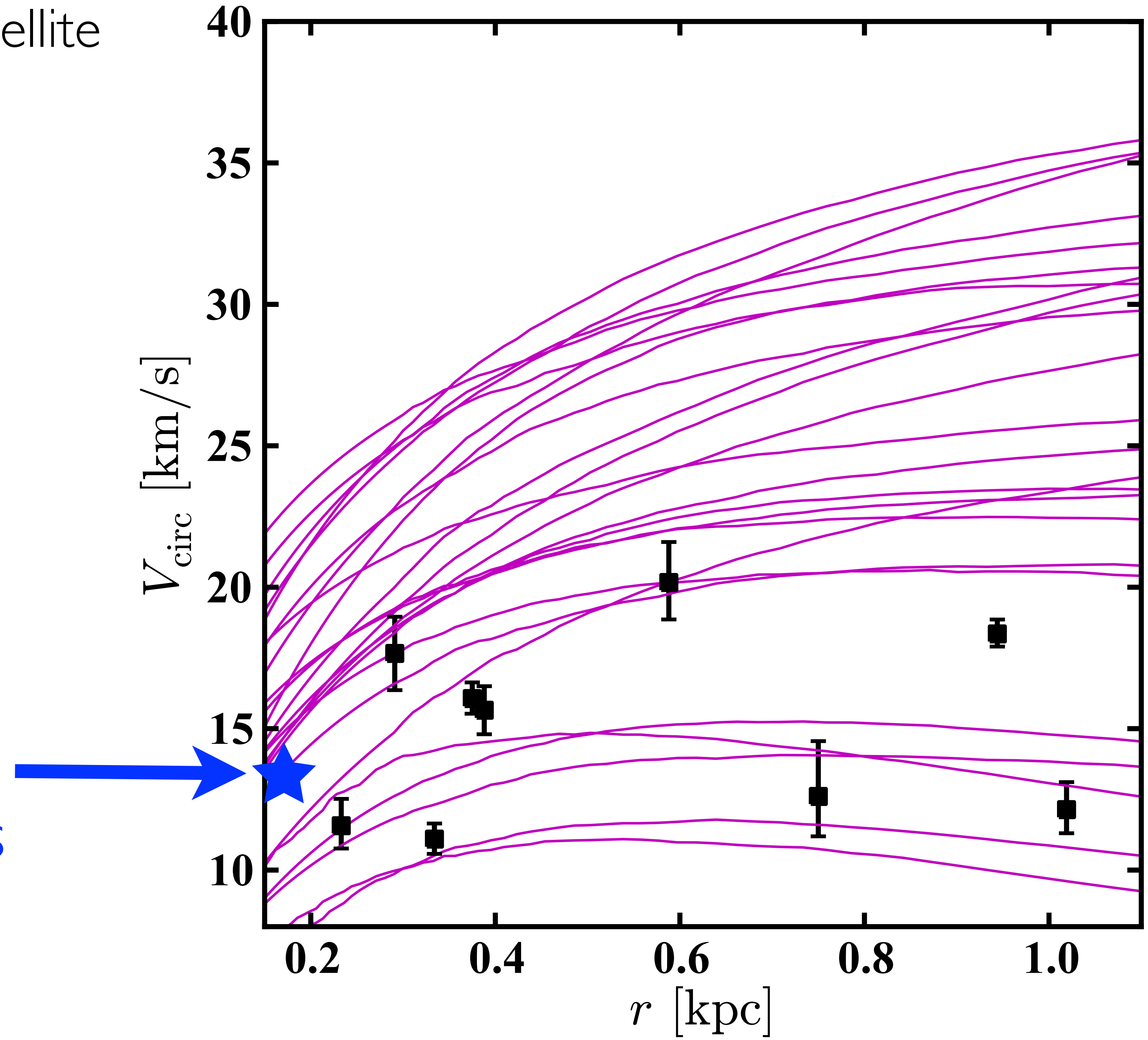
Leo T:

➡ Prototype for discriminating between baryonic and dark matter physics in a satellite

$M_\star \sim 10^5$

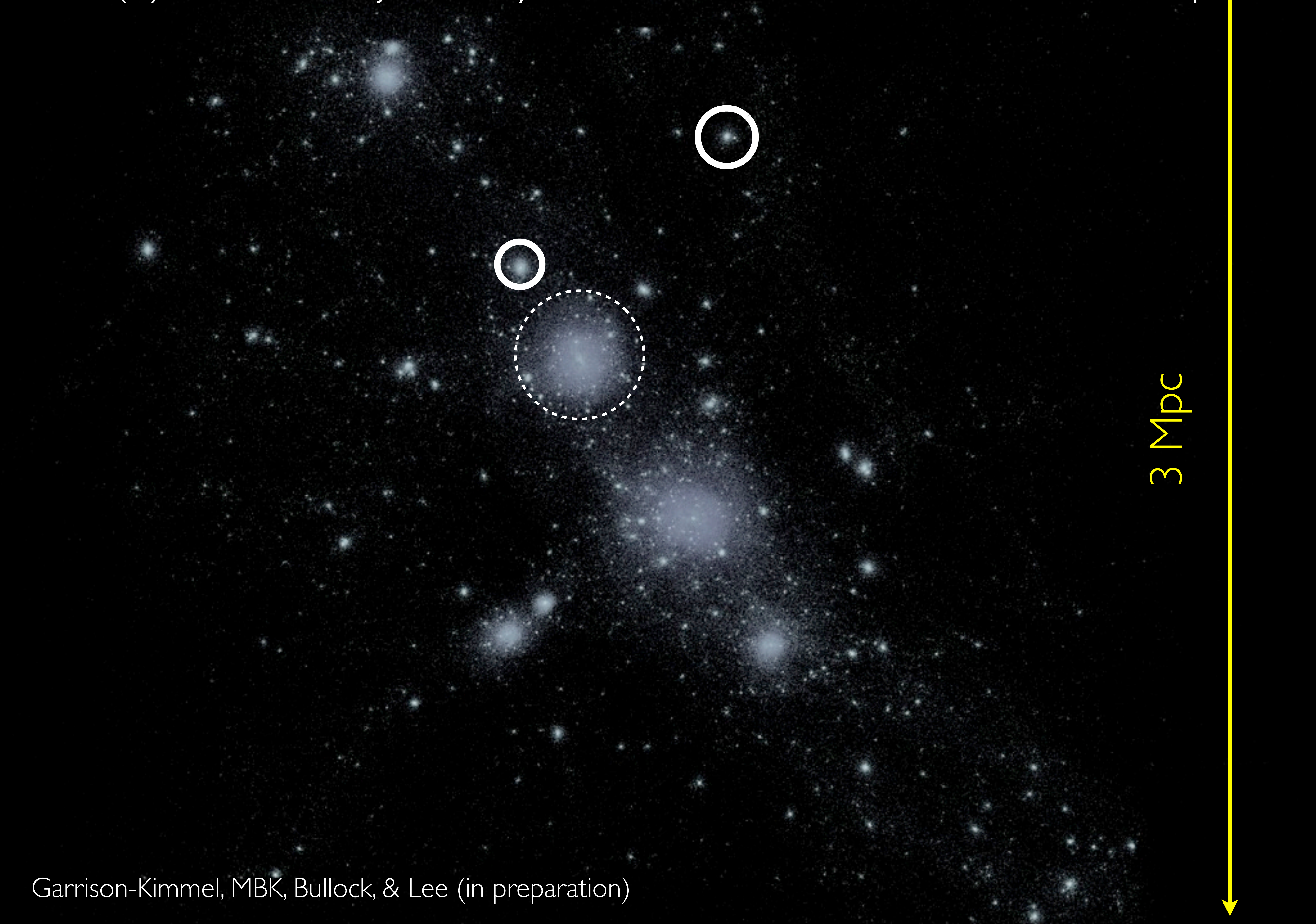
$r_{1/2} = 160$ pc

$\sigma = 7.5$ km/s



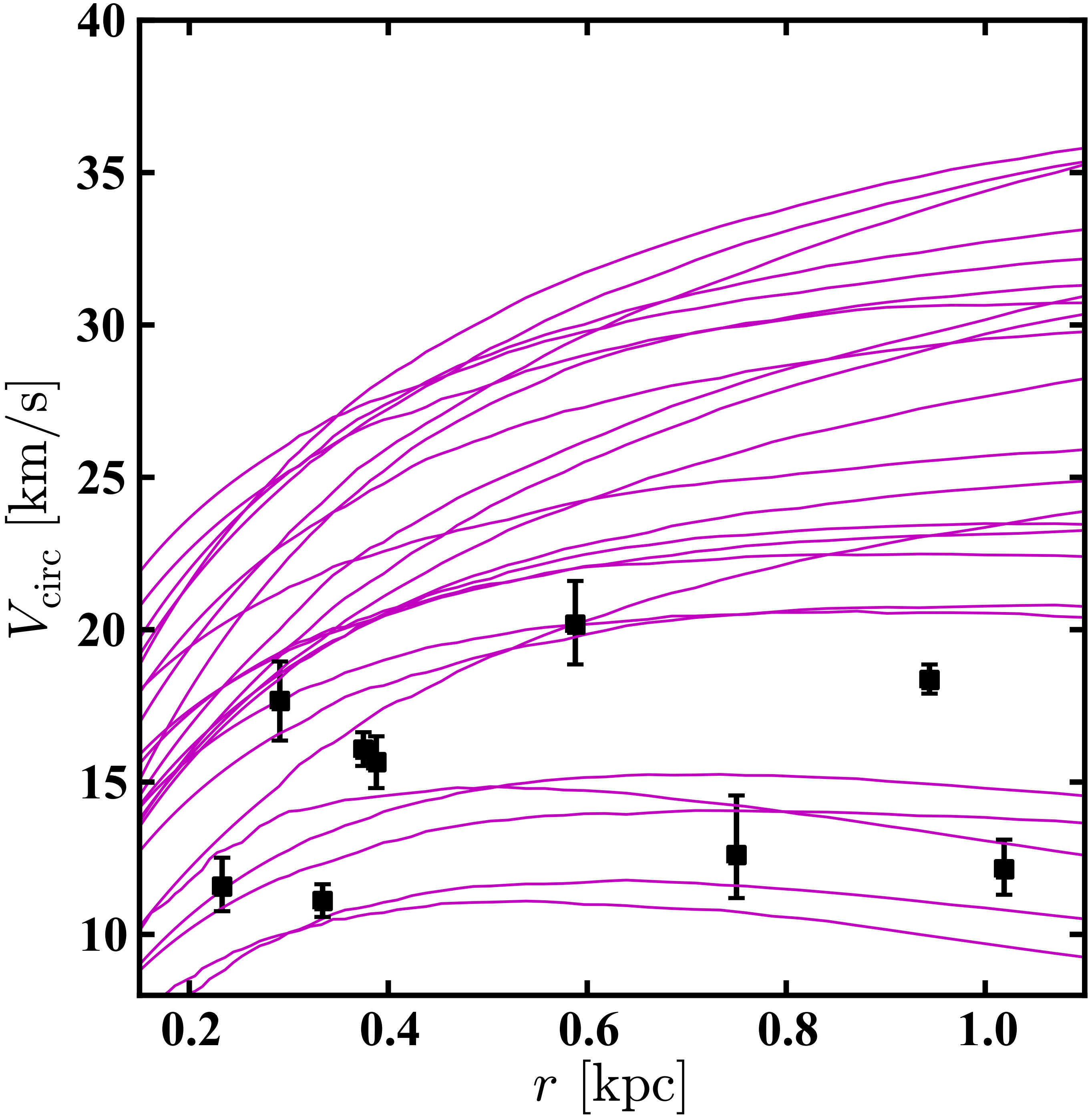
De Jong et al. (2008), Simon & Geha (2007)

(2) Look at objects beyond the influence of the Local Group

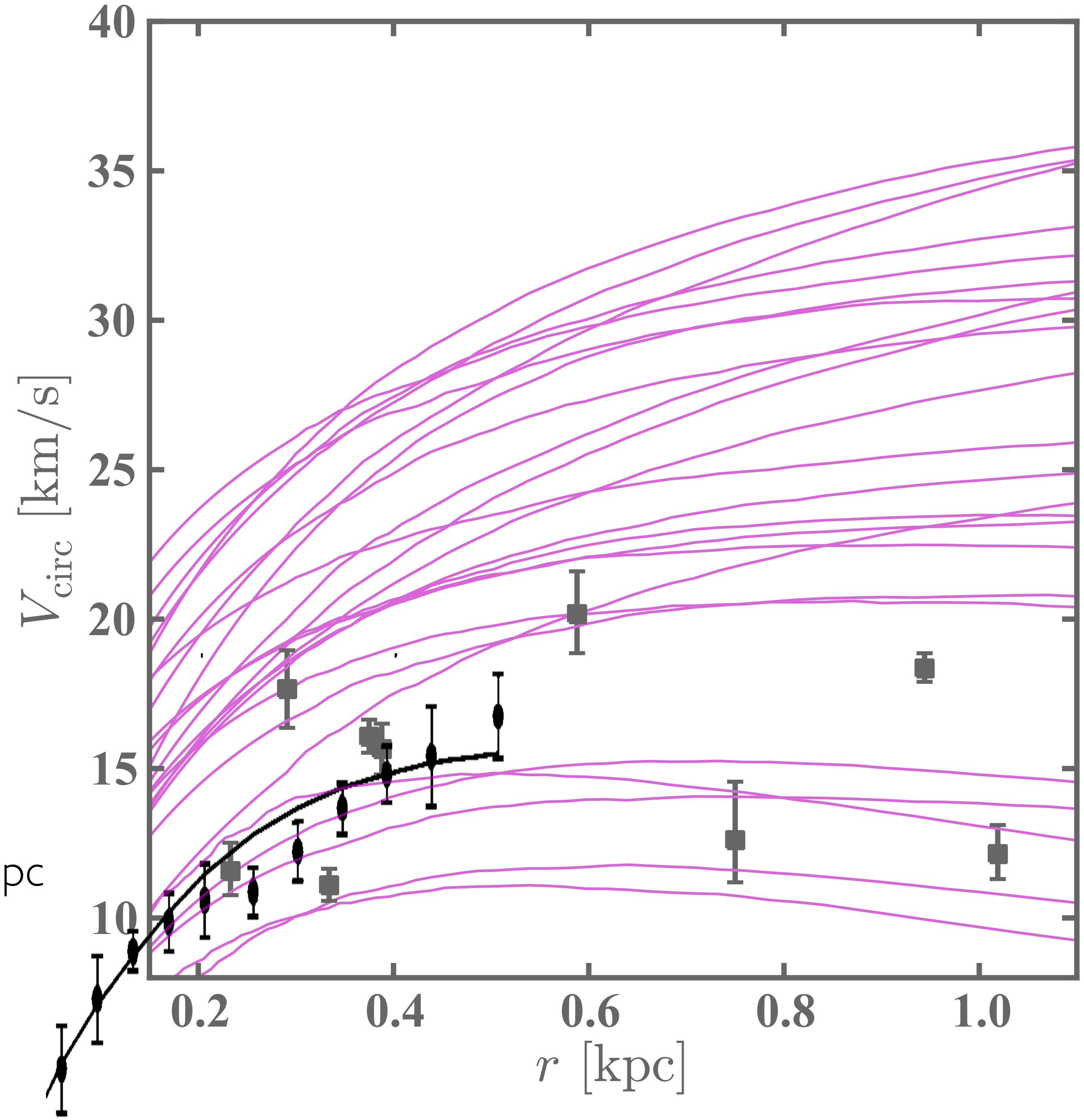


Garrison-Kimmel, MBK, Bullock, & Lee (in preparation)

Low densities in isolated Local Group dwarfs



Low densities in isolated Local Group dwarfs



DDO 210

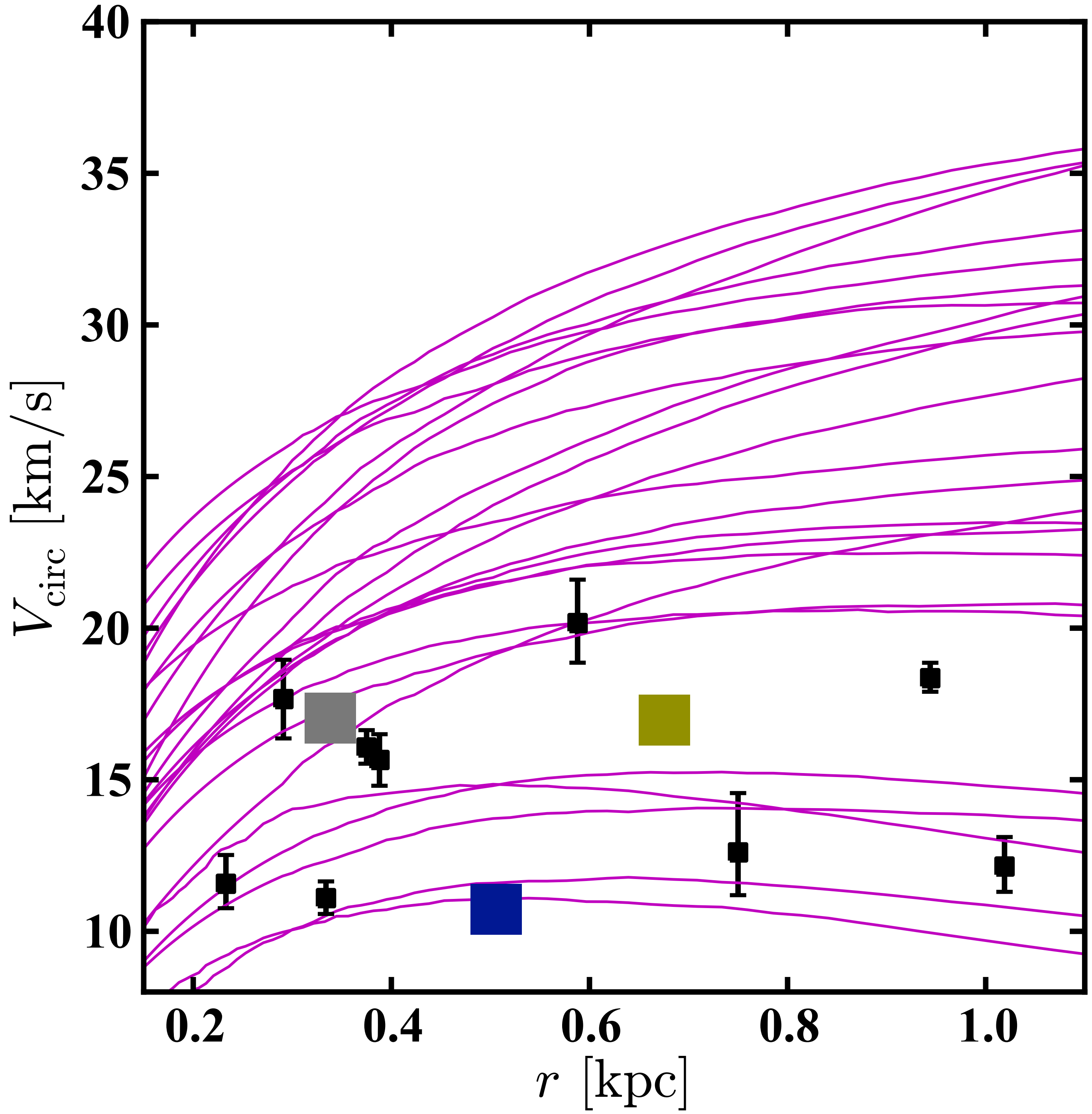
$D_{MW}=D_{M31}=1.1$ Mpc

$M_\star=10^6$

$M_{HI}=4\times10^6$

(Begum et al.)

Low densities in isolated Local Group dwarfs



Leo A:
D_{MW}: 0.800 Mpc
$M_\star = 8 \times 10^6$
$\sigma = 9.3$ km/s
$r_{1/2} = 670$ pc

Leo P:
$D_{MW} = 1.5$ Mpc
$M_\star \sim 6 \times 10^5$
$V_{rot} = 10$ km/s (maybe??)
2D $R_{gas} = 500$ pc

VV 124:
$D_{MW} = 1.4$ Mpc
$M_\star = 9.5 \times 10^6$
$\sigma = 9.4$ km/s
$r_{1/2} = 350$ pc

No difference between MW satellites and isolated galaxies of the same mass ⇒ preliminary evidence that reduced densities aren't from interaction with MW

Summary of Controversies

- **Cusp-core problem**: persists in isolated galaxies. Supernova feedback may explain this in LCDM; SIDM can also explain this.
- **Cores in MW satellites**: controversial at this point; imperative to get additional data. LCDM *may* explain this for the most massive satellites; need to understand SIDM predictions for core sizes.
- **Too big to fail**: evident in dSphs of MW and M31 (makes "unlucky" Milky Way less likely explanation). May be explained in LCDM if SN feedback is very efficient *and* most dwarfs have been orbiting for a long time *and* MW mass is low. Can be explained in SIDM for specific values of interaction cross-section.
- **Missing satellites**: persists to today, at some level. May be explained by reionization suppression + inefficient galaxy formation; is this too finely-tuned, or is it natural? SIDM likely faces similar issue.
- Additional issue(s)? Planes of satellites? Unlikely to be solved through modification of DM properties

Conclusions and outstanding questions

- There are good motivations from astrophysics to consider scenarios beyond vanilla WIMPs. At this point, there is **not** incontrovertible evidence that LCDM is lacking.
  - Core-cusp, missing satellites, too big to fail: could point to failings of LCDM model on small scales ... or could be telling us about physics of galaxy formation.
- Understanding effects of galaxy formation in *both* CDM and SIDM is crucial ... but *extremely* difficult. Numerical simulations including baryons are not (yet?) fully predictive.
- Comparison of low-mass galaxies in the MW with isolated galaxies of the same mass will be very revealing in testing the galaxy formation physics hypothesis. Preliminary evidence argues against environmental effects as cause of low dark matter densities.

Conclusions and outstanding questions

- **Good news:**
  - **SIDM** (constant cross section): likely ruled out for $\boldsymbol{\sigma} > 1 cm^2/g$; unable to produce relevant cores for $\boldsymbol{\sigma} < 0.1\ cm^2/g \Rightarrow$ narrow range to explore
  - **WDM**: likely ruled out by Ly-alpha forest for $m < 2$ keV; no astrophysical signatures if $m > 10$-15 keV $\Rightarrow$ narrow range to explore
- Generic prediction of CDM models: vast spectrum of dark matter halos within the Milky Way containing no stars. **How can we test if this is true?** (Thin-ness of stellar streams? Gravitational lensing in external galaxies?)
- What are the generic, testable predictions of SIDM models?
- Do we still need to consider WDM as a viable alternative?