# From the Structure of Milky Way Satellites to the Nature of Dark Matter


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SLAC
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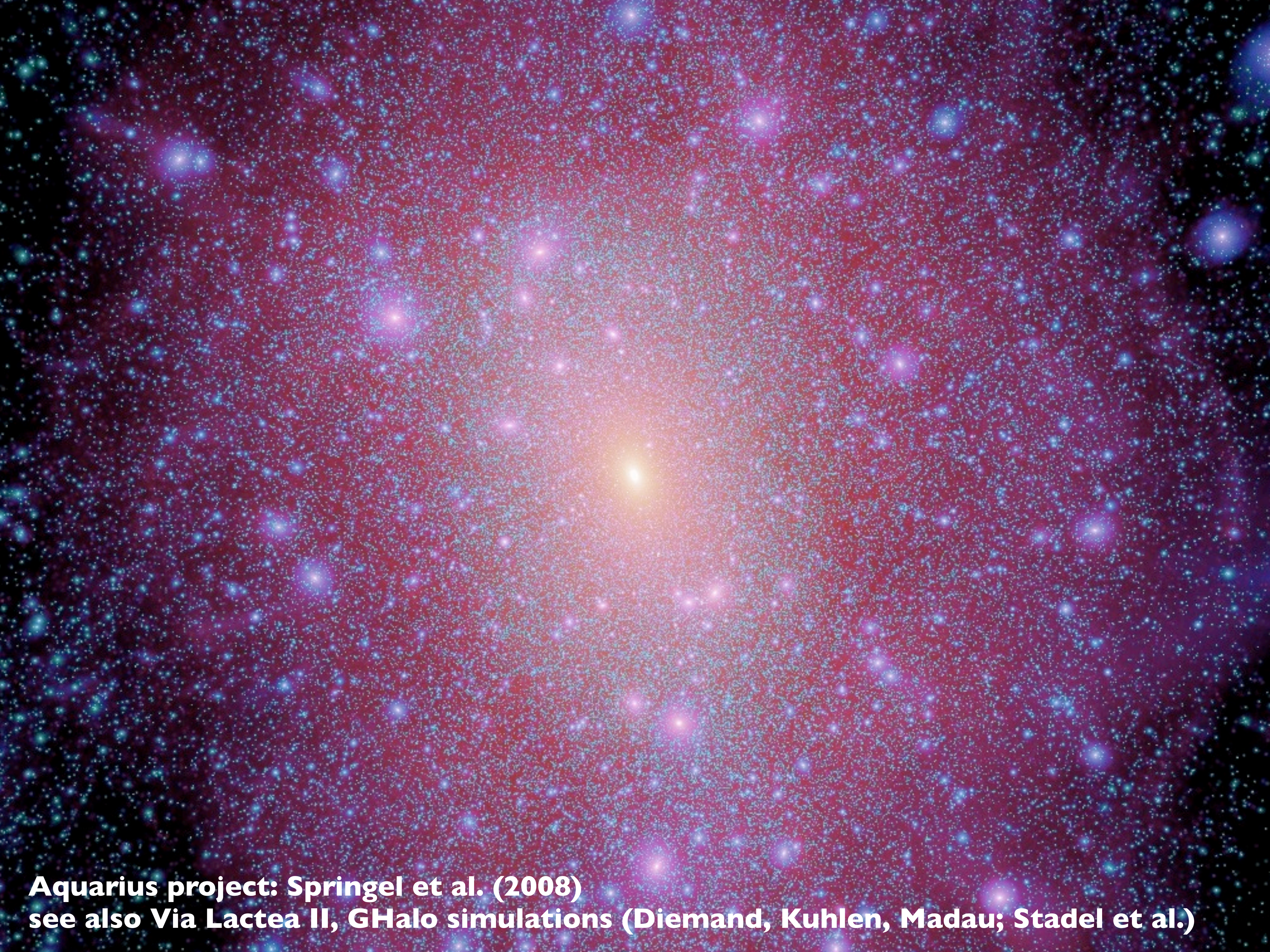
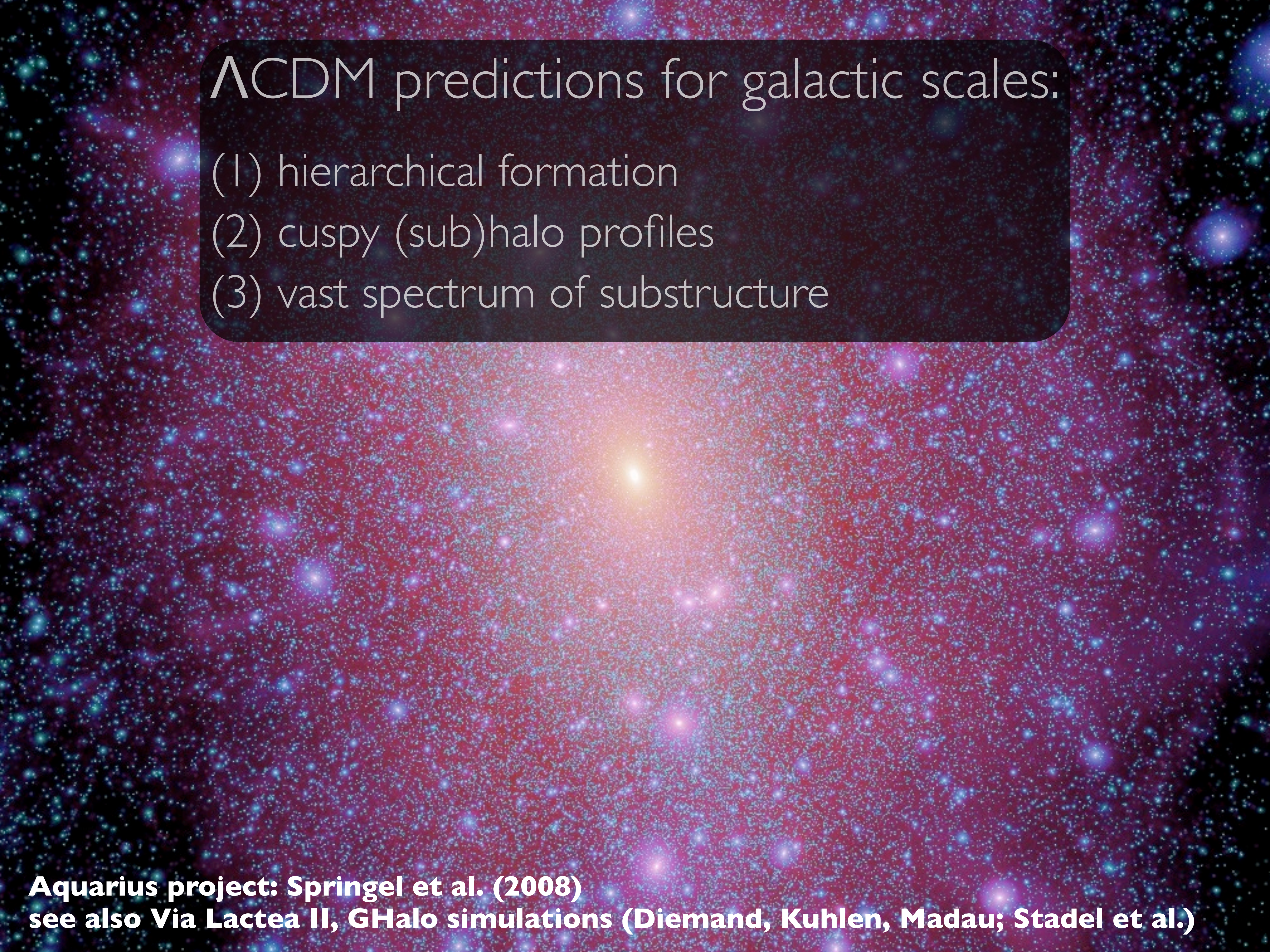
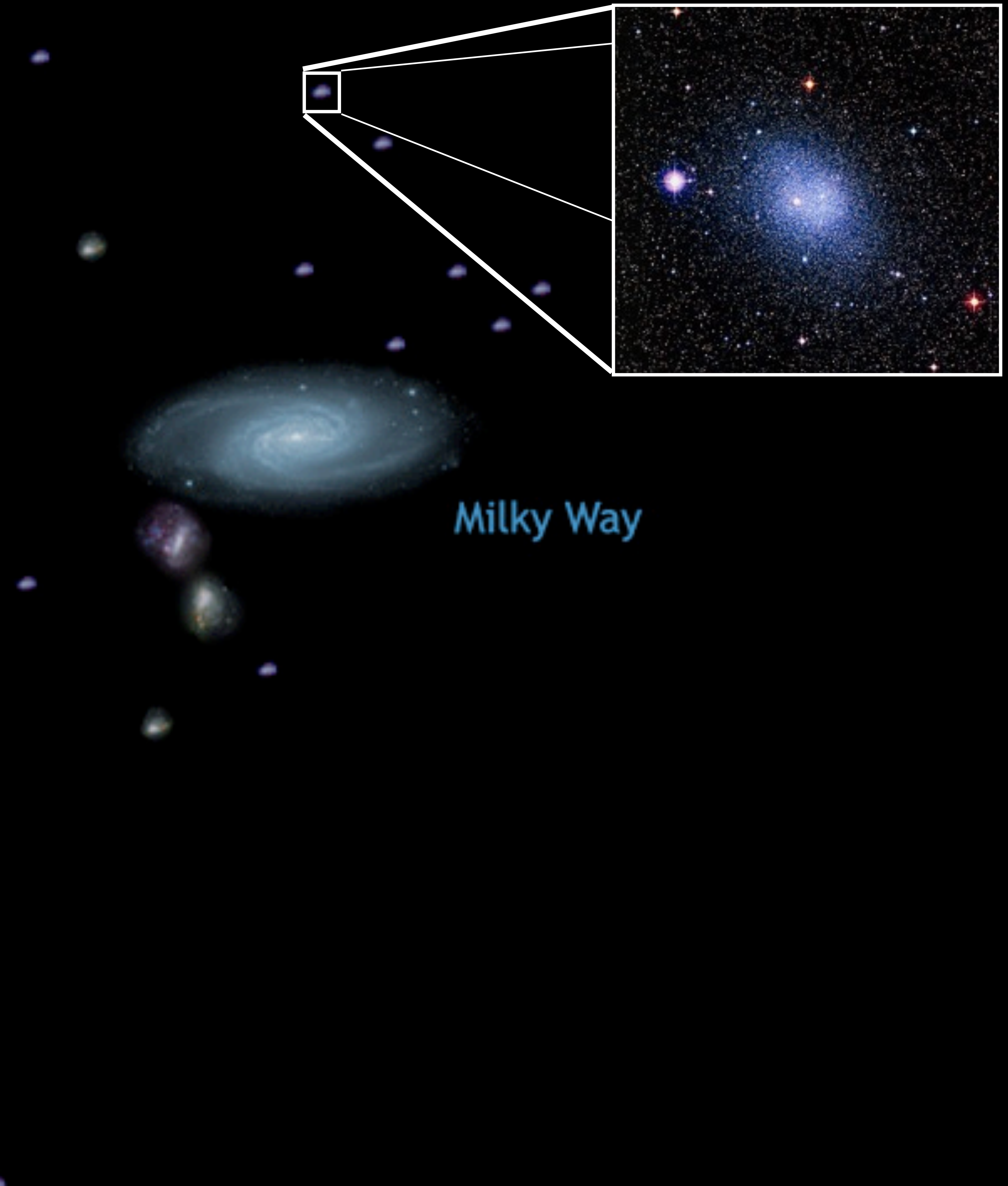


**Aquarius project: Springel et al. (2008)**
**see also Via Lactea II, GHalo simulations (Diemand, Kuhlen, Madau; Stadel et al.)**

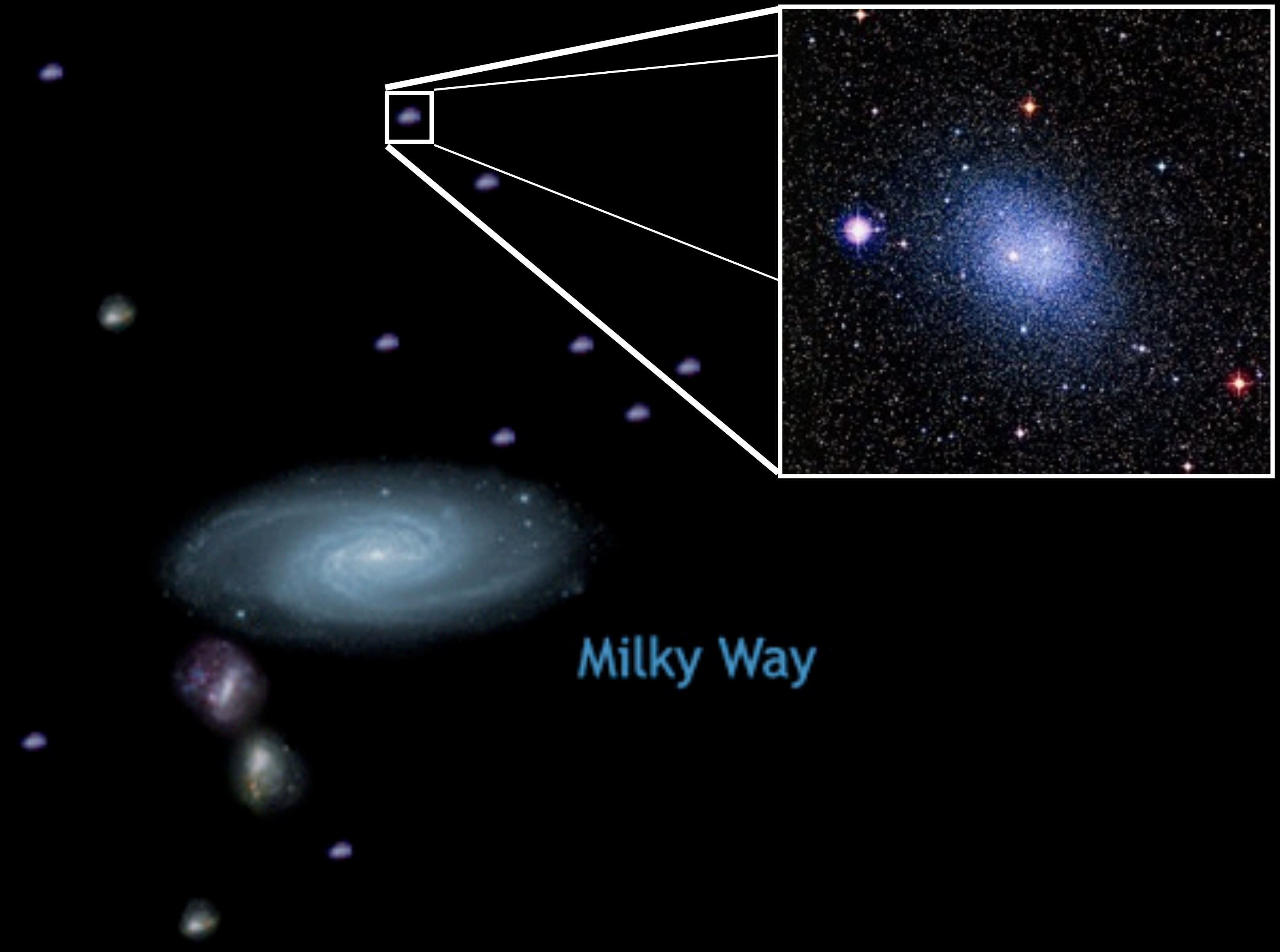

ΛCDM predictions for galactic scales:
(1) hierarchical formation
(2) cuspy (sub)halo profiles
(3) vast spectrum of substructure
Aquarius project: Springel et al. (2008)
see also Via Lactea II, GHalo simulations (Diemand, Kuhlen, Madau; Stadel et al.)




**Dwarf spheroidal galaxies**

Luminosity: $\sim 10^{6}\ L_{sun}$

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




**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.

**These objects are dark matter laboratories**

mass-to-light ratios of ~10-1000 within stellar extent

# Dwarf galaxies around the Milky Way

"Bright" satellites ($L_V > 10^5\ L_\odot$)

| | |
|---|---|
| LMC | pre-1519 |
| SMC | pre-1519 |
| Sculptor | 1937 |
| Fornax | 1938 |
| Leo II | 1950 |
| Leo I | 1950 |
| Ursa Minor | 1954 |
| Draco | 1954 |
| Carina | 1977 |
| Sextans | 1990 |
| Sagittarius | 1994 |

# Dwarf galaxies around the Milky Way

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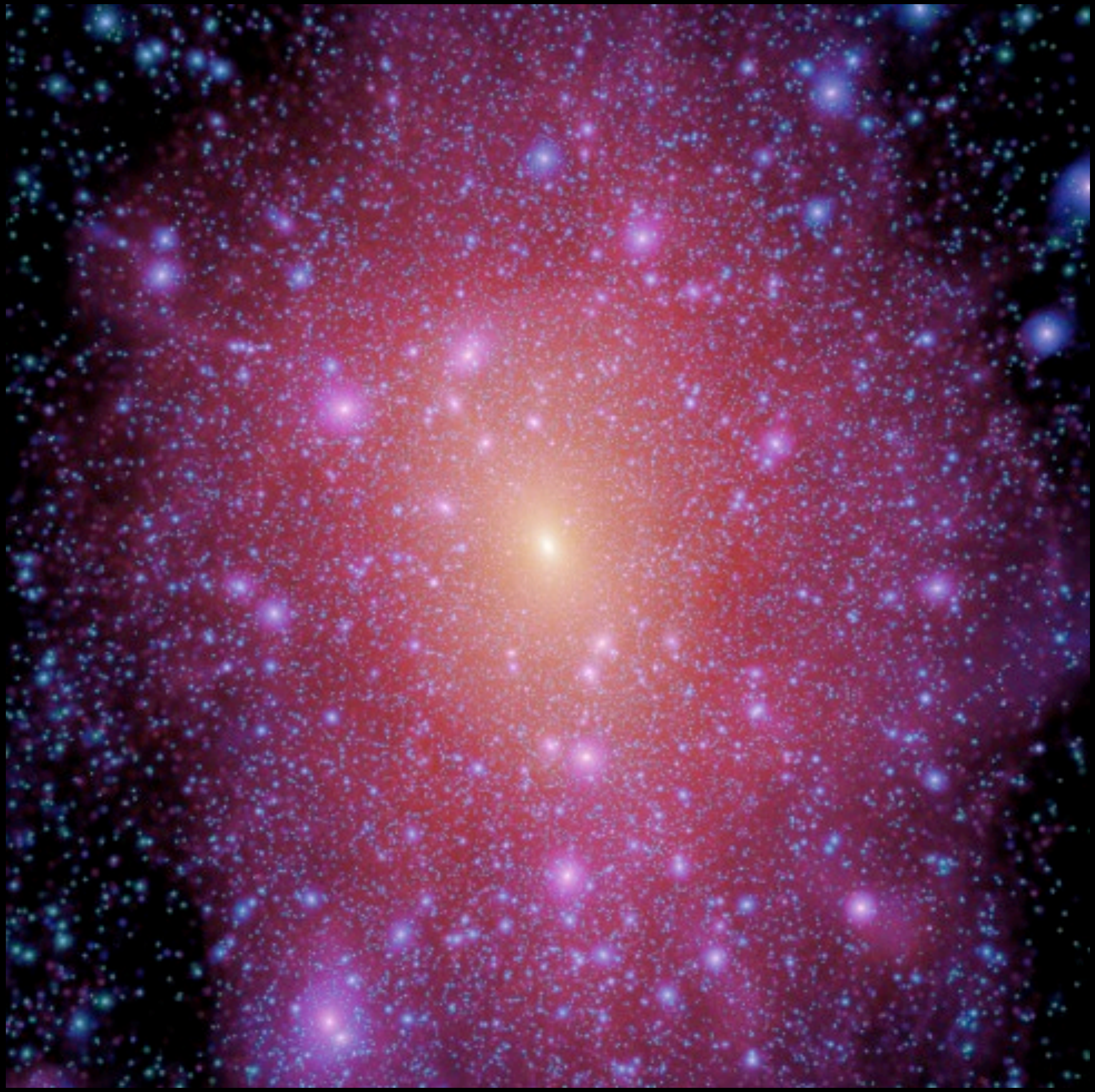
| | |
|---|---|
| Canes Venatici I | 2006 |
| Leo T | 2007 |

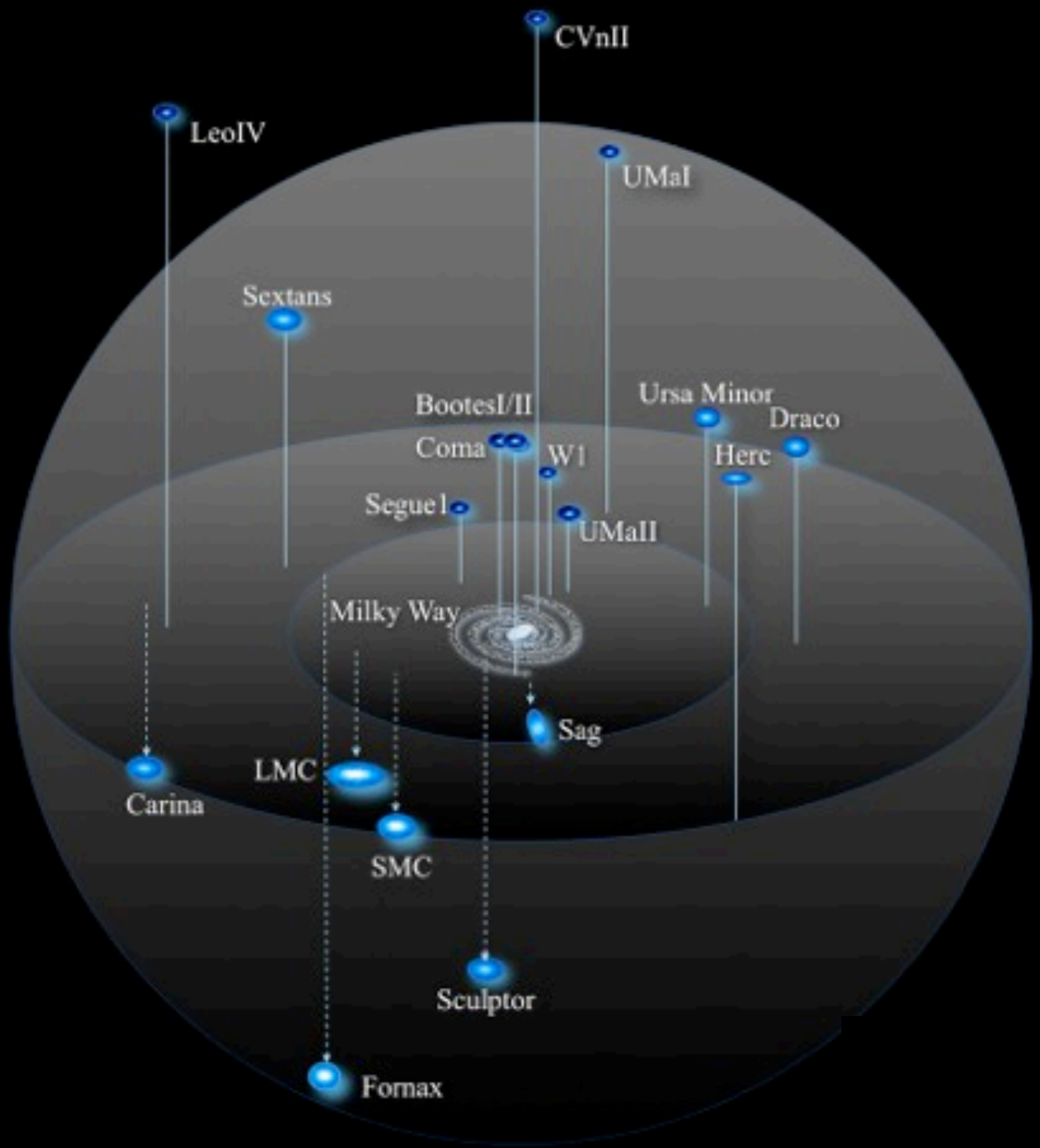
## "Faint" satellites ($L_V < 10^5 L_\odot$)

| | |
|---|---|
| Ursa Major I | 2005 |
| Willman I | 2005 |
| Ursa Major II | 2006 |
| Bootes | 2006 |
| Canes Venatici II | 2006 |
| Coma | 2006 |
| Segue I | 2006 |
| Leo IV | 2006 |
| Hercules | 2006 |
| Bootes II | 2007 |
| Leo V | 2008 |
| Segue II | 2009 |

# $\Lambda$CDM vs. the Milky Way, Round 1: **Missing Satellites**

Klypin et al. 1999, Moore et al. 1999






>$10^5$ identified subhalos

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

*V. Springel / Virgo Consortium*

*J. Bullock*

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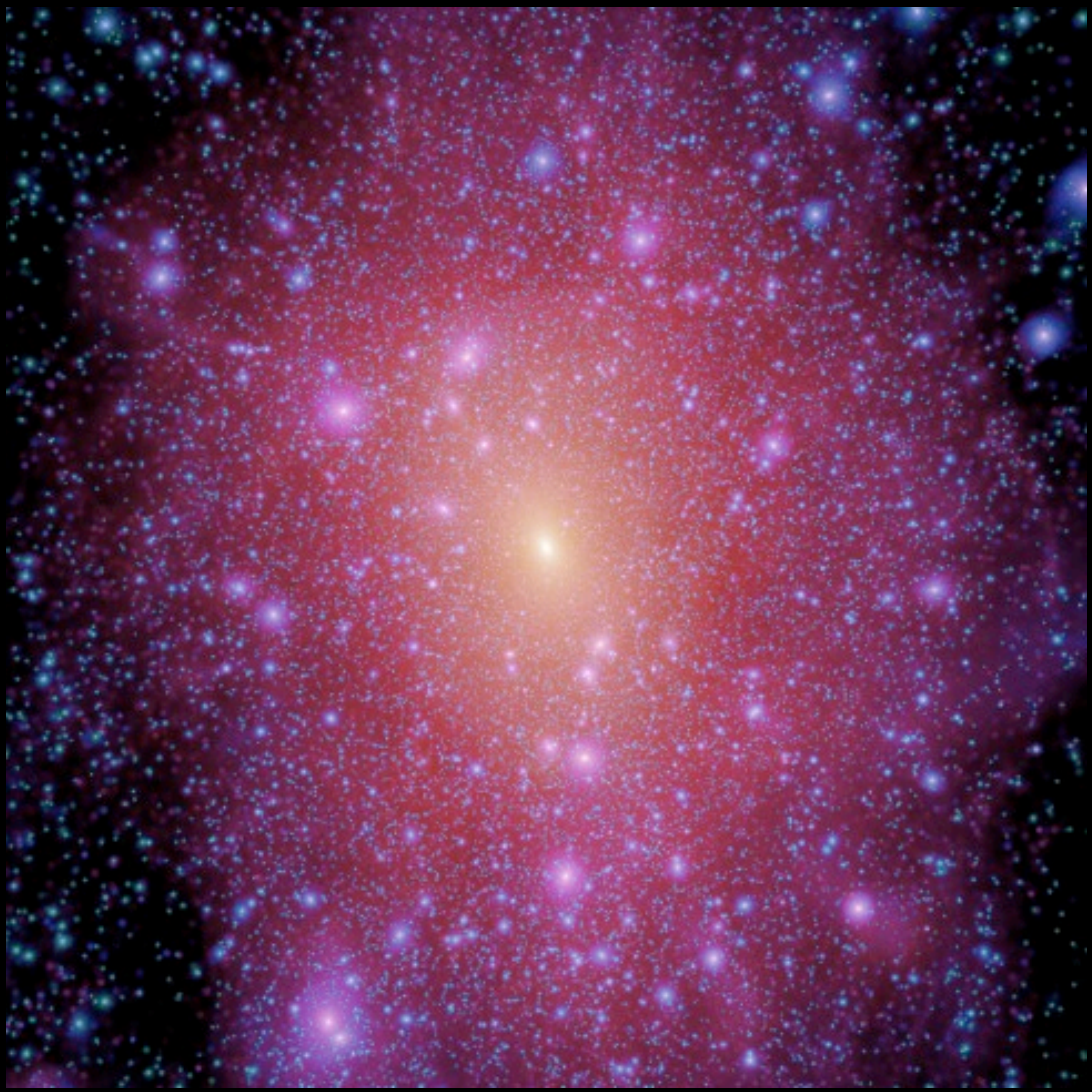

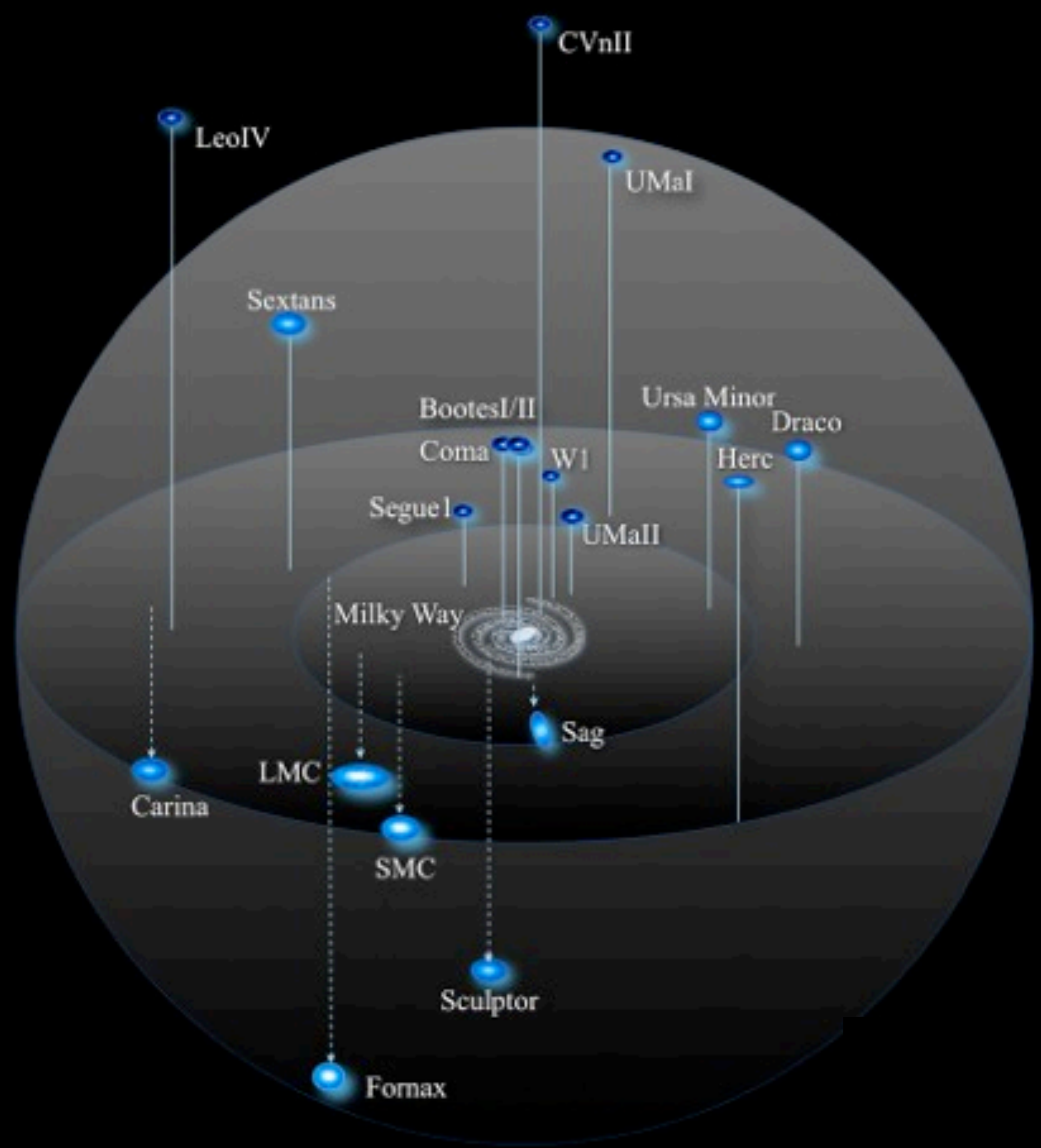

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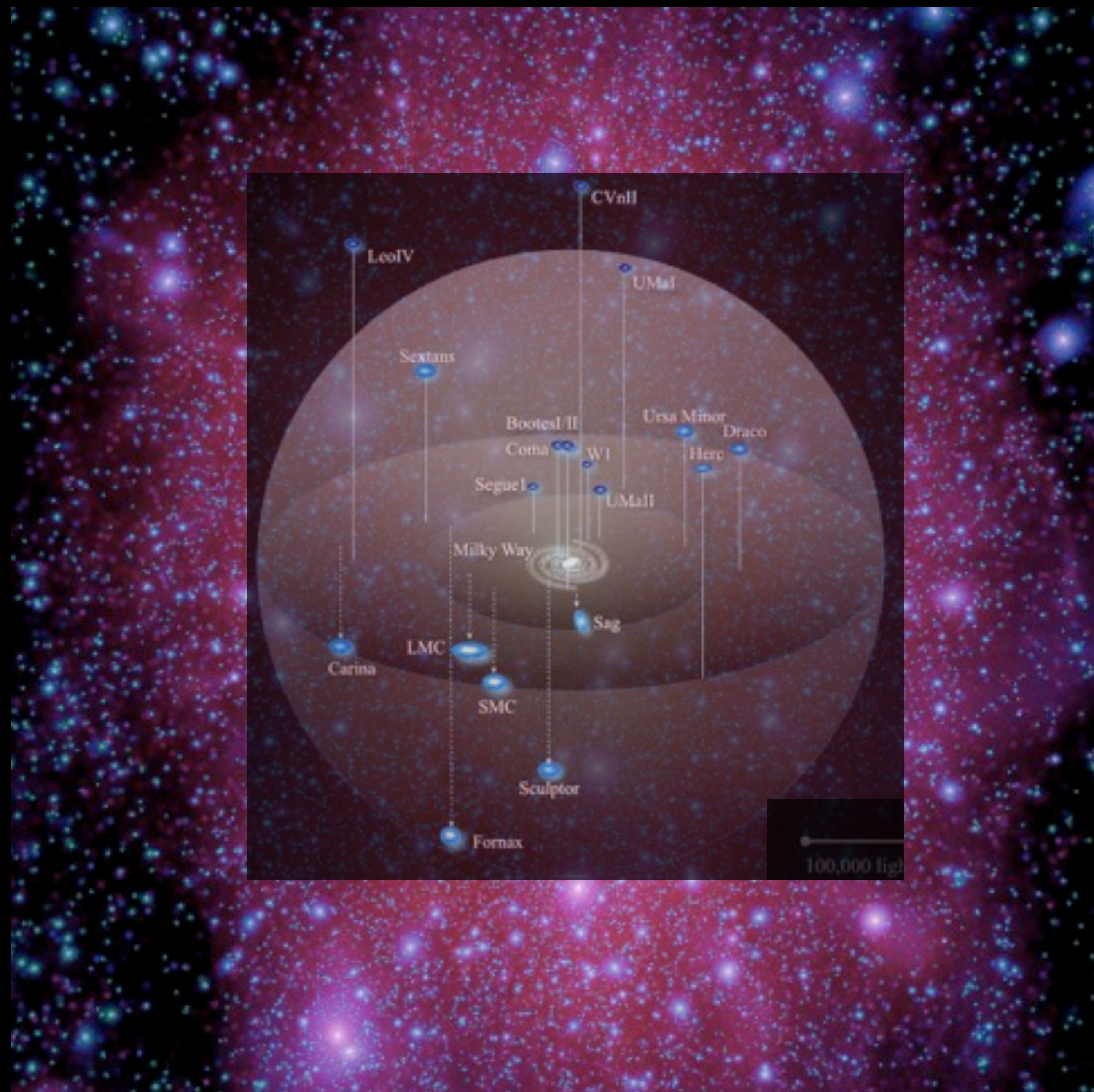
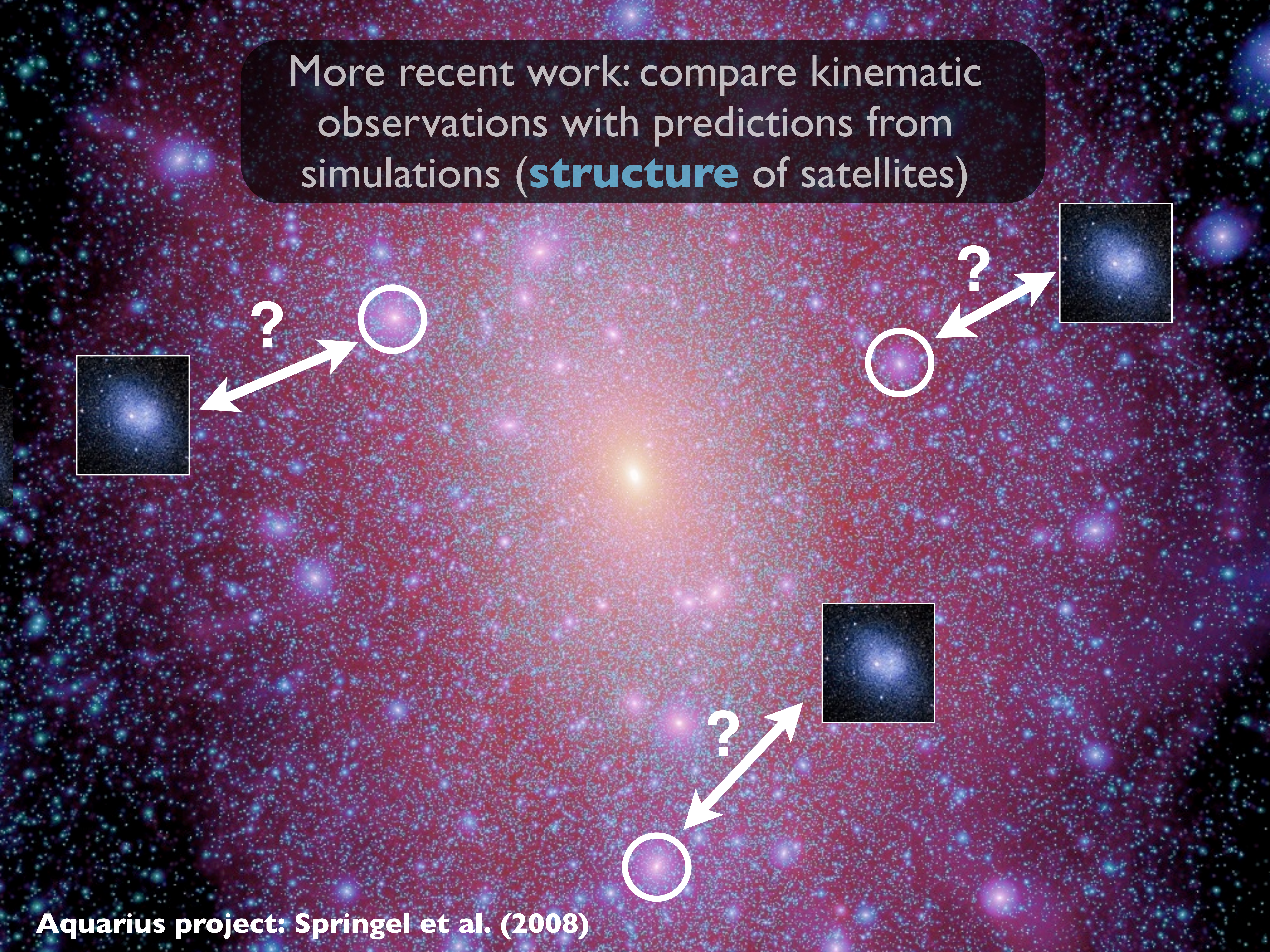
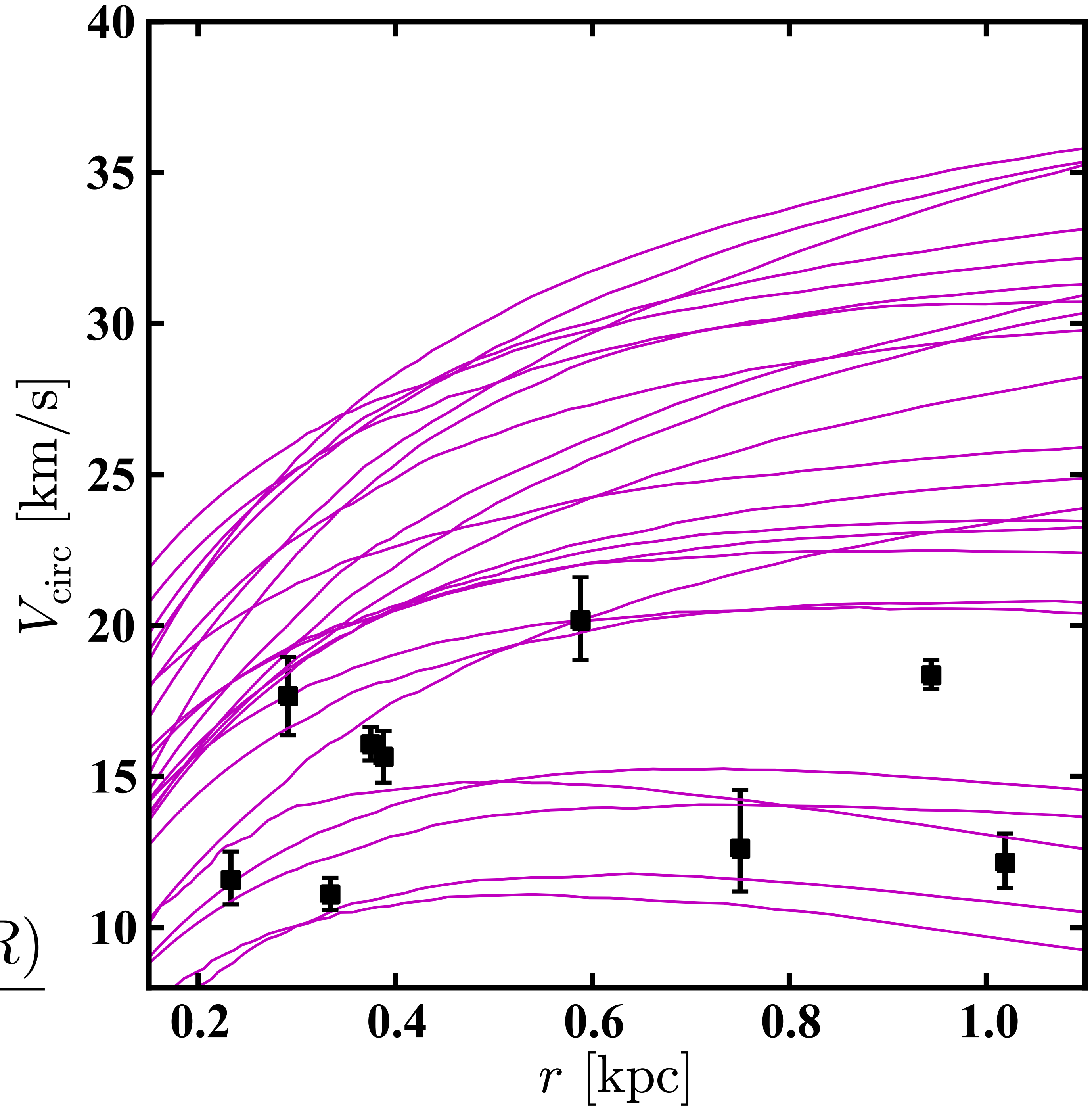



**Number** mismatch: can be explained through (1) additional ultra-faint satellites and (2) galaxy formation processes (supernova feedback, reionization)


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

# Missing the **biggest** substructure?




Use **$\mathbf{V_{circ}}$** & **mass** interchangeably:

$$V_{\rm circ}^2 = \frac{G\,M(<R)}{R}$$

MBK, Bullock, & Kaplinghat 2011, 2012
see also Lovell et al. 2012; Anderhalden et al. 2012, 2013;
Rashkov, Madau, Kuhlen, Diemand 2012 (plus many others)

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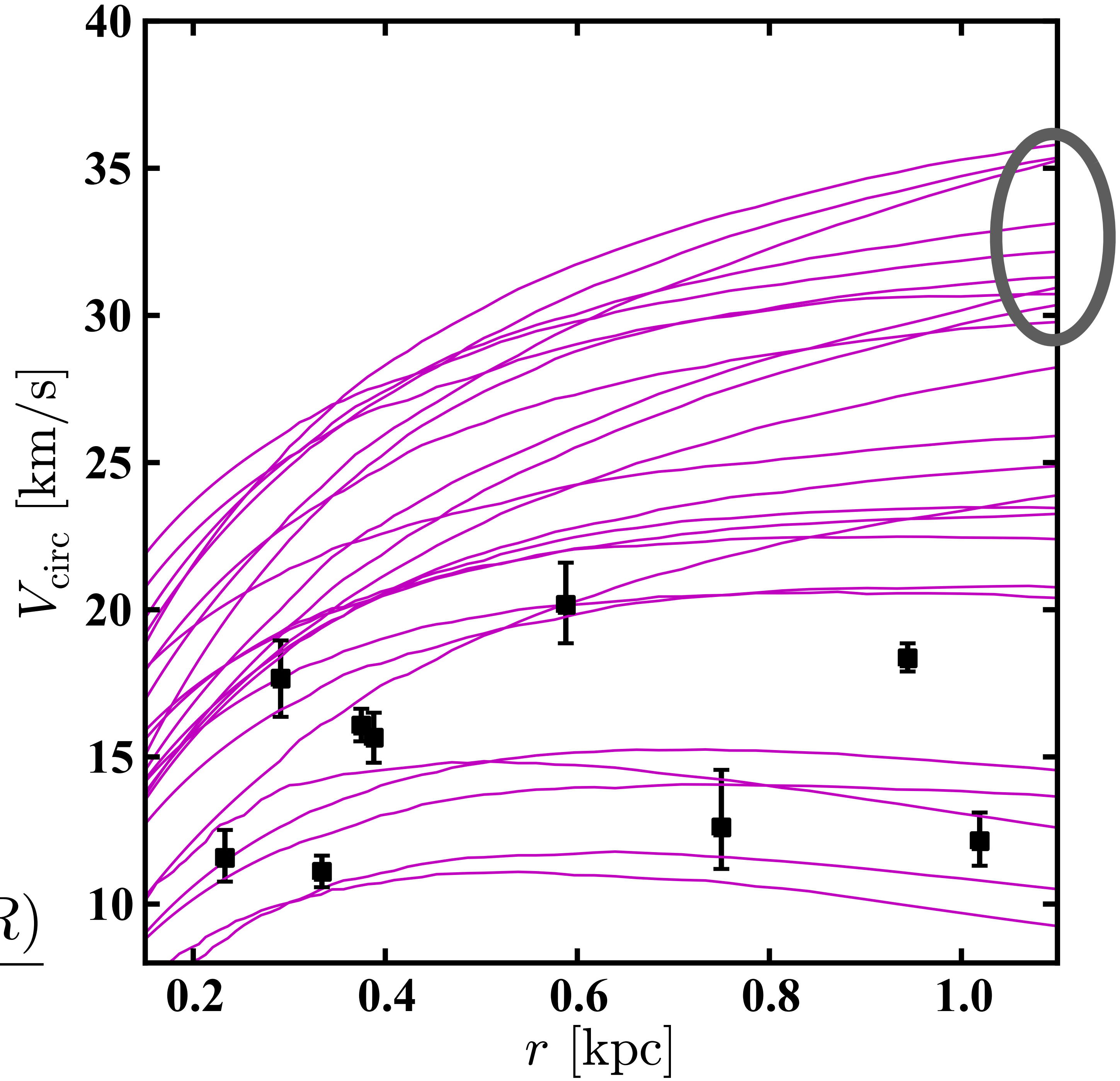


"Too big to fail?"

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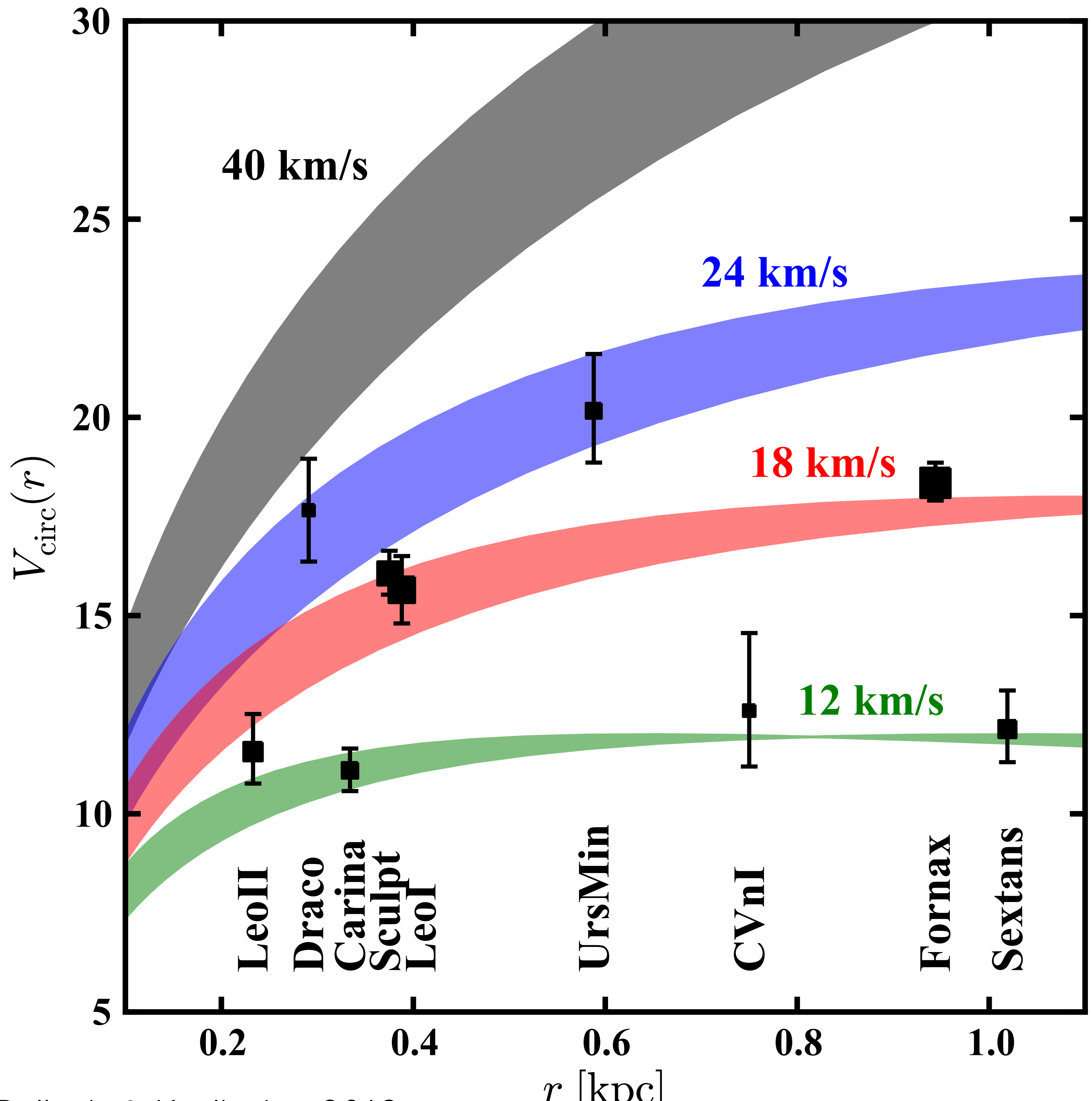
# Brightest Milky Way satellites: why so low mass?

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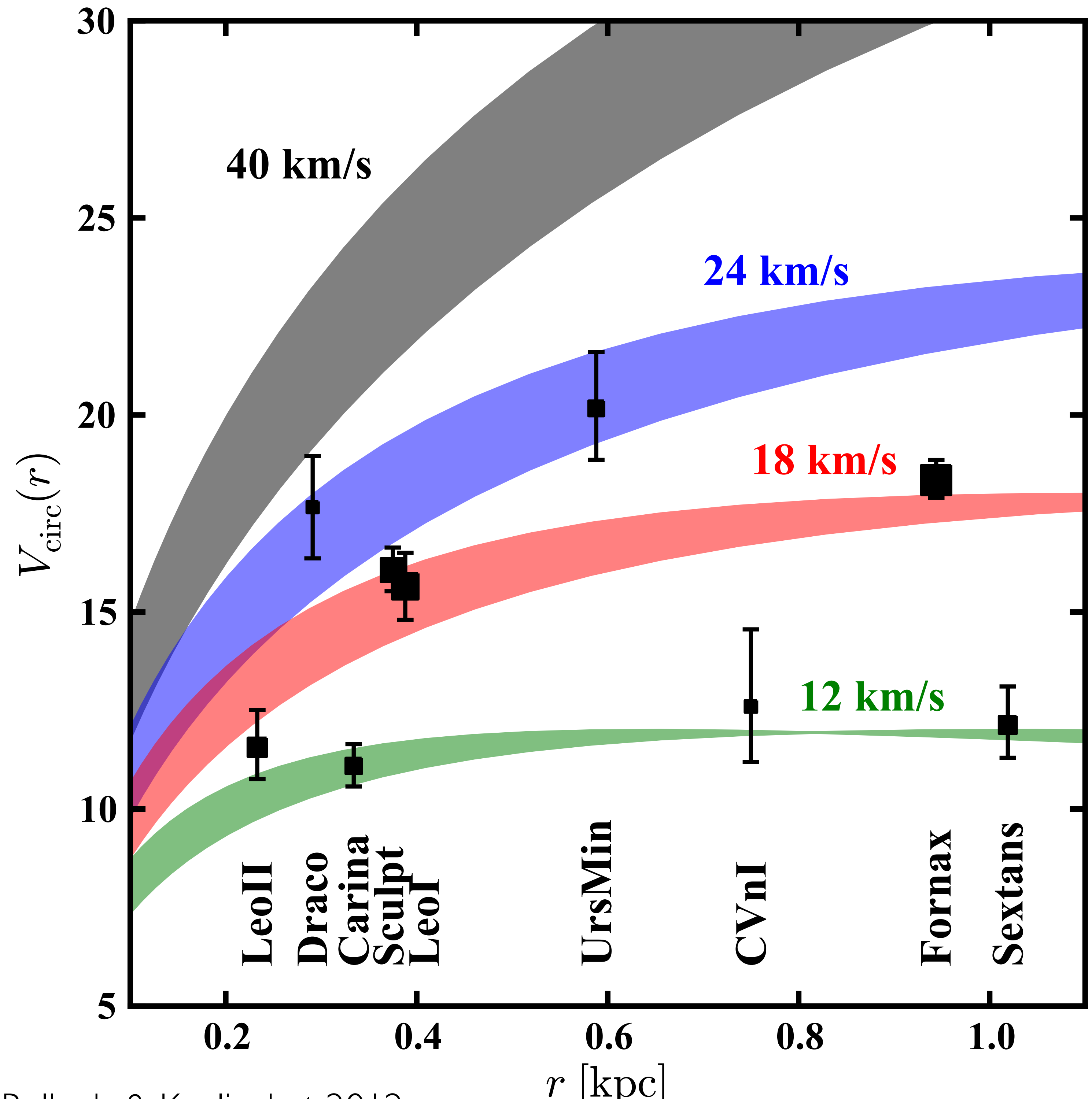


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Bright spheroidal satellites:
$M_{halo} = 10^8 - 10^9 M_{sun}$

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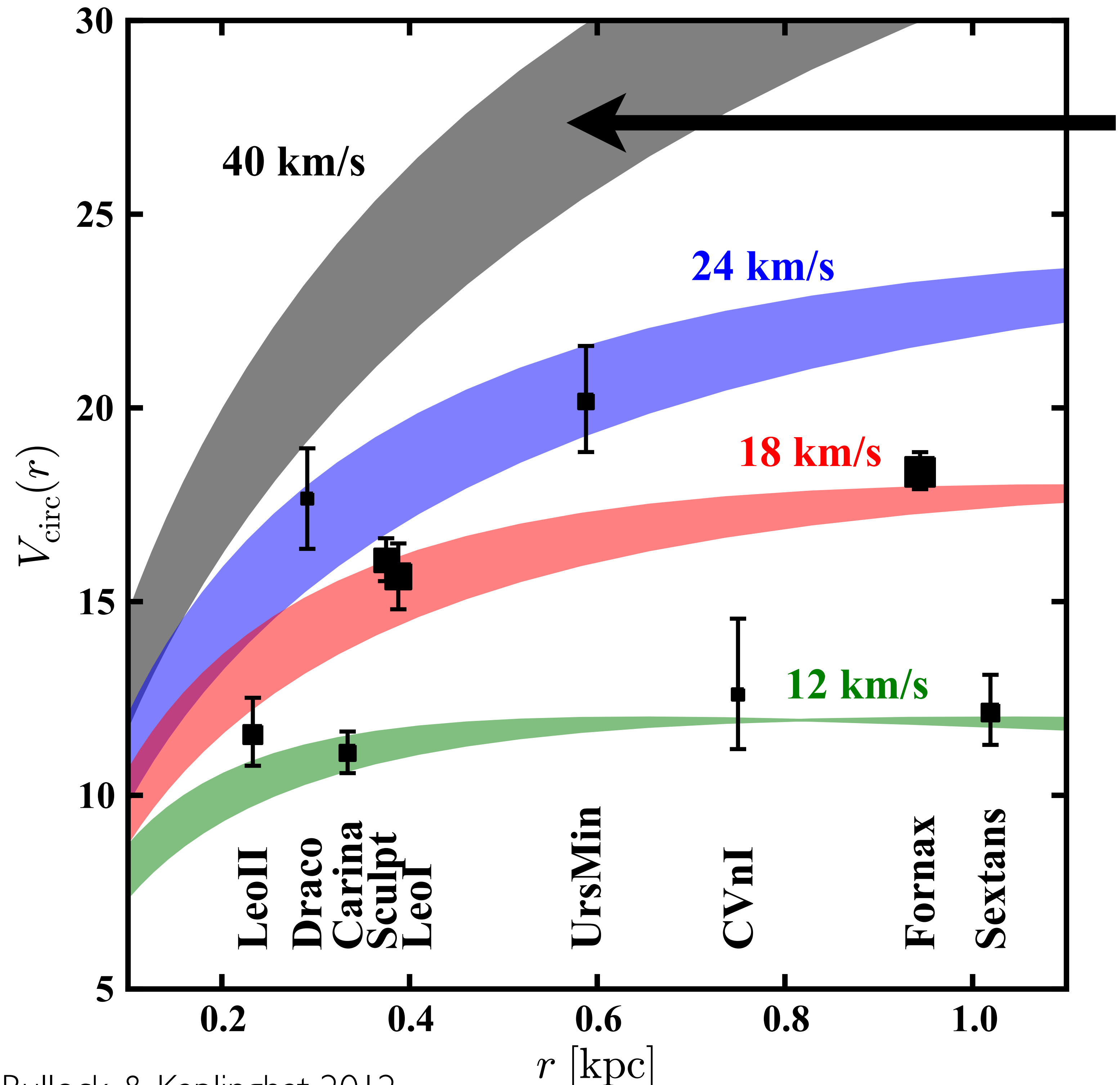


Biggest predicted satellites:
$M_{halo} \sim 10^{10}\ M_{sun}$

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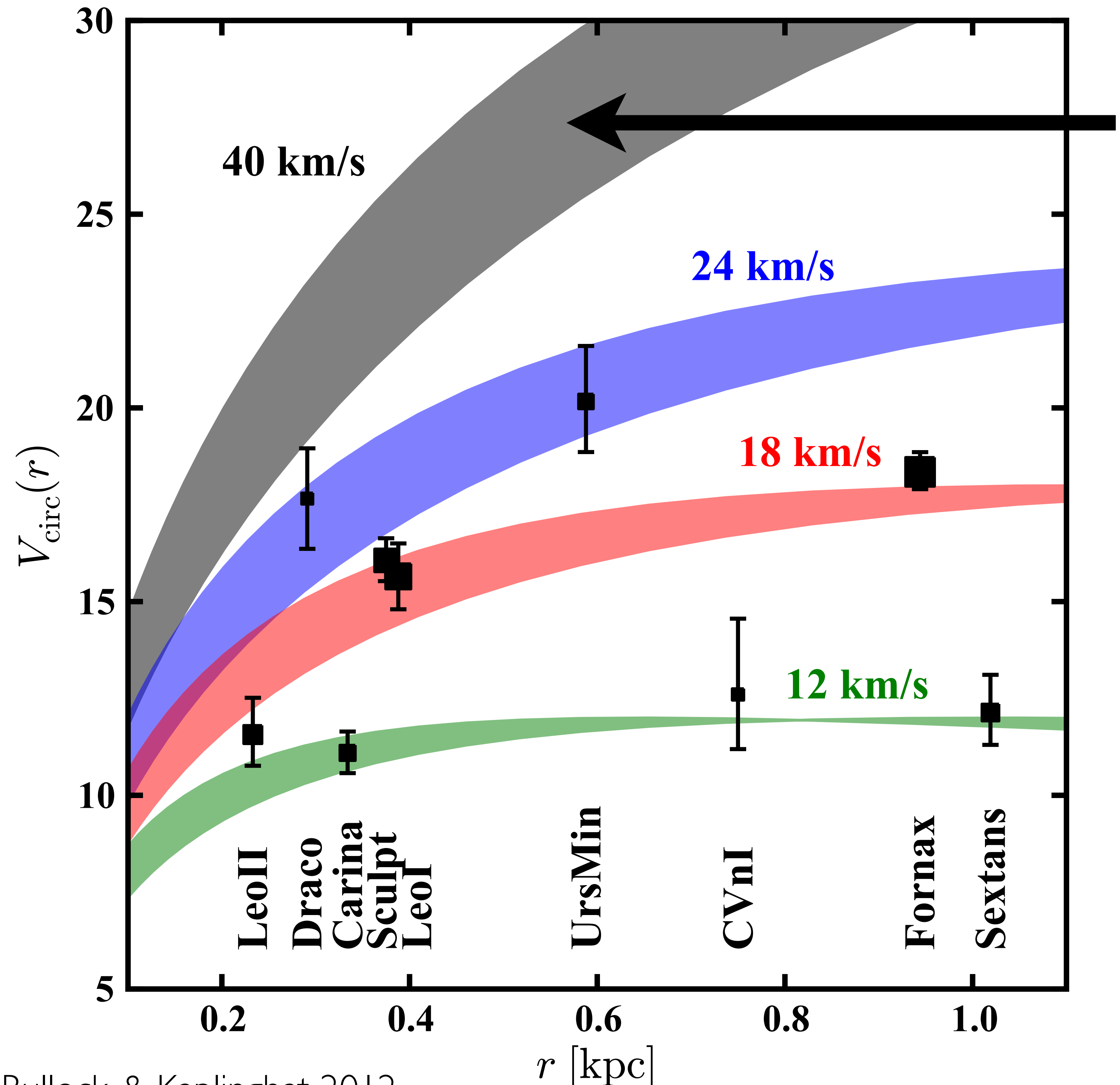


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Biggest predicted satellites: $M_{halo} \sim 10^{10}\ M_{sun}$

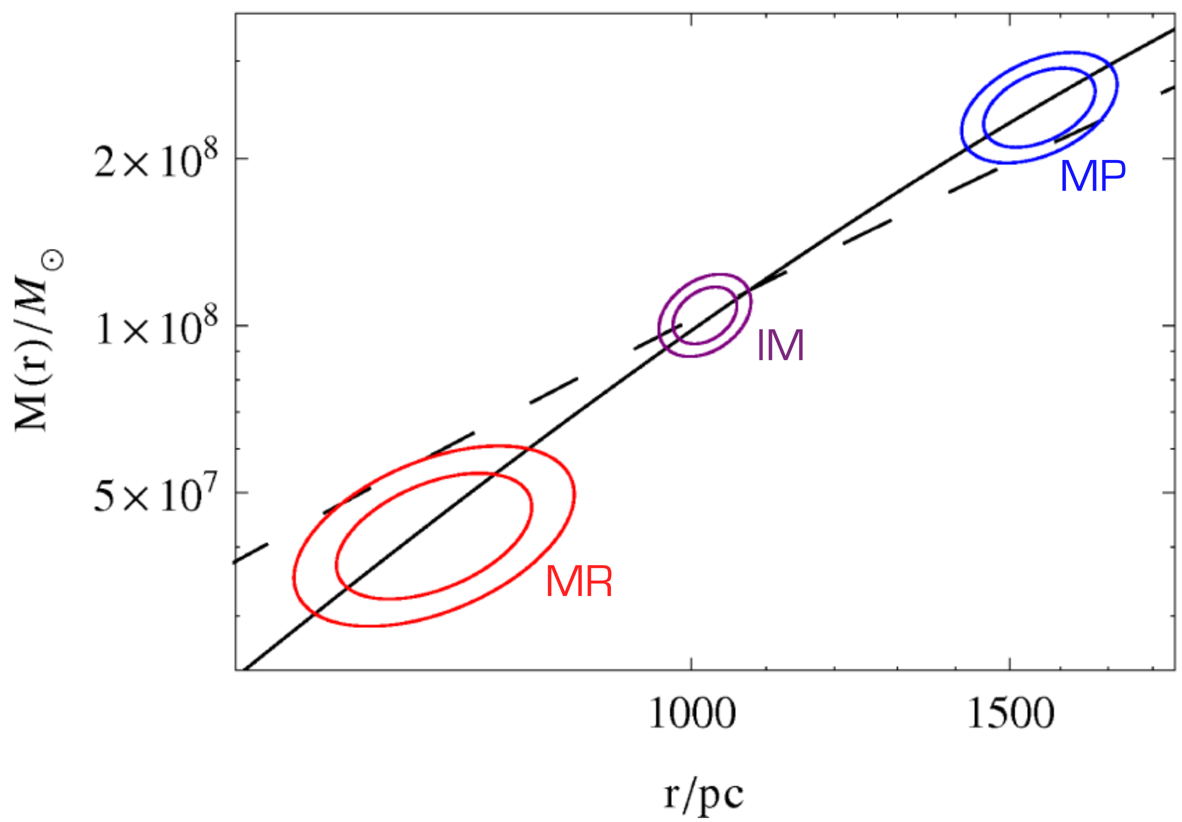
Bright spheroidal satellites: $M_{halo} = 10^{8}$ -$10^{9}\ M_{sun}$

Similar results found for isolated, low-mass galaxies

(Ferrero, Abadi, Navarro + 2012)

# Dark matter densities through stellar chemistry

Initial work: Battaglia et al. 2008




Amorisco & Evans 2012

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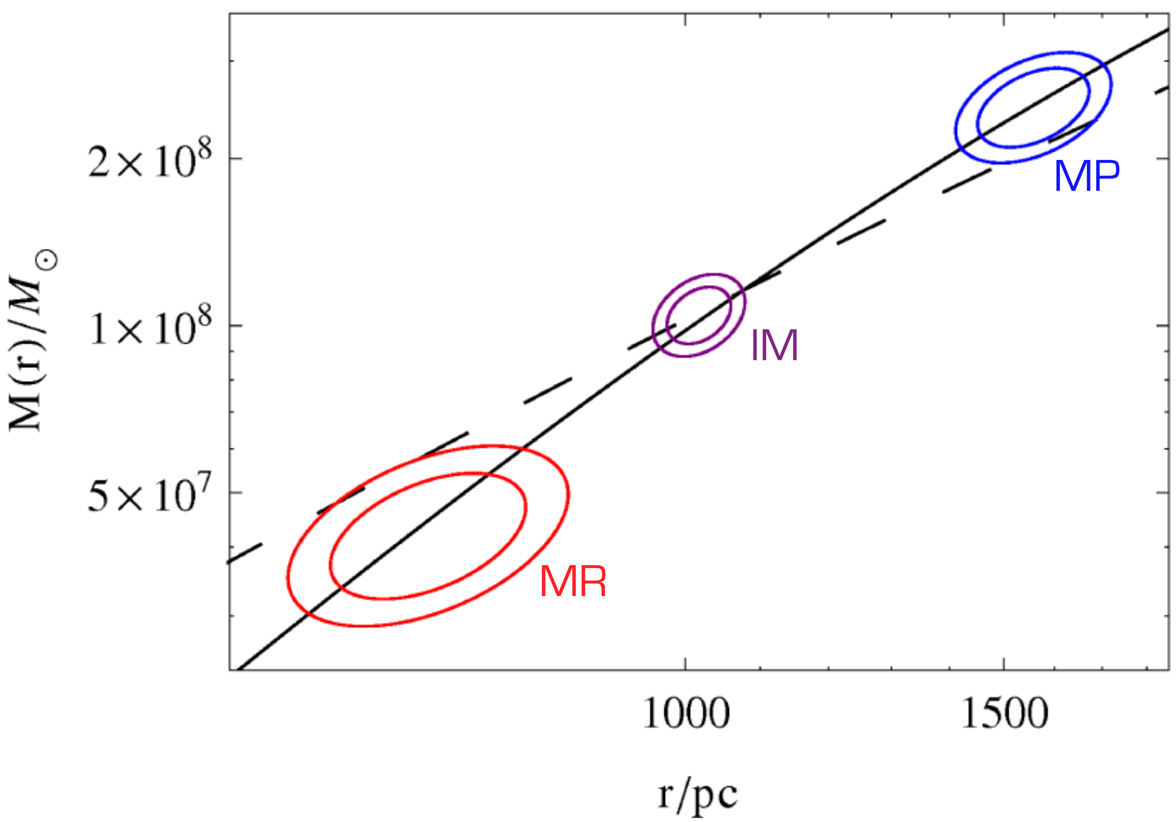


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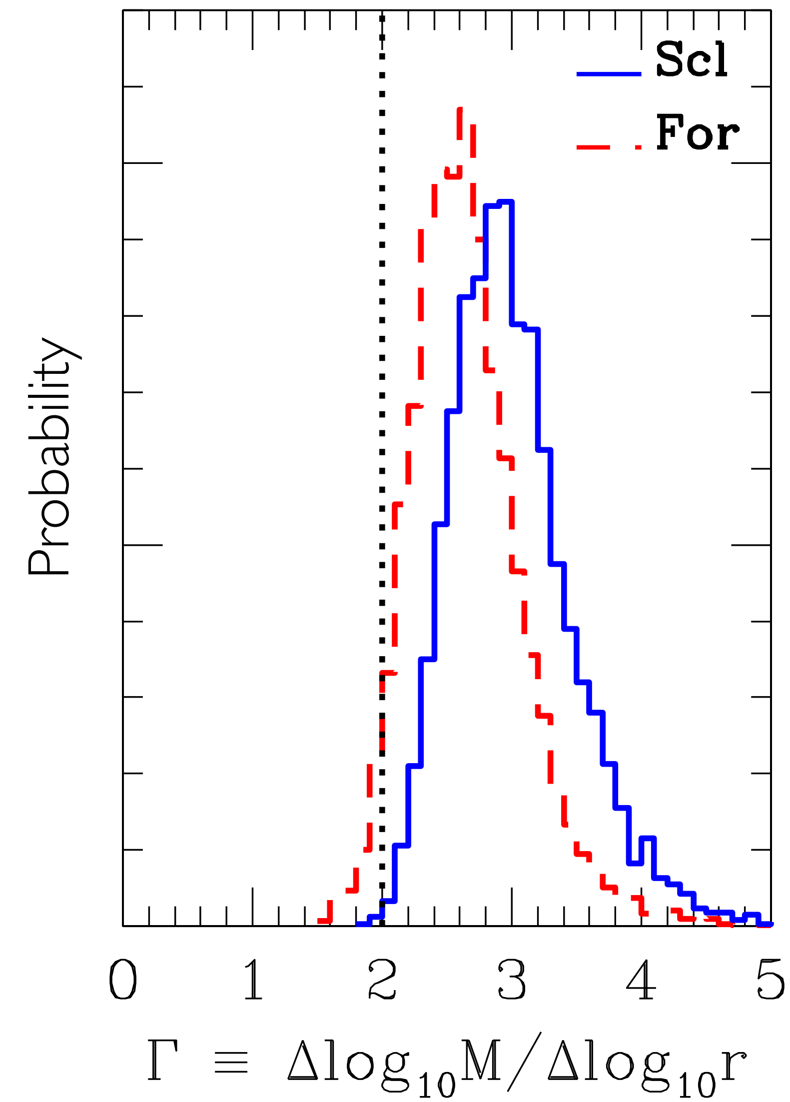


Walker & Peñarrubia 2011

# Dark matter densities through stellar chemistry

$$\rho \propto r^{-\alpha} \quad (r \ll r_s)$$

**CDM / NFW**
**α = -1**

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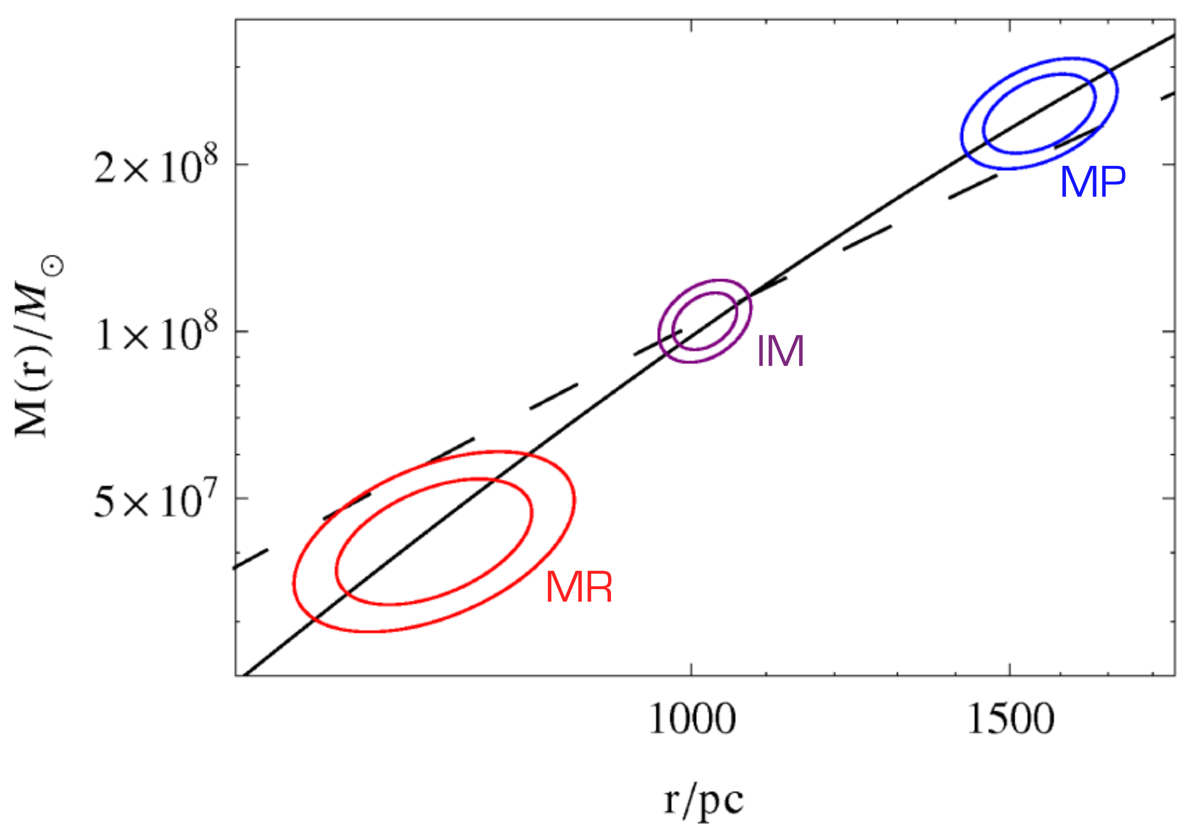


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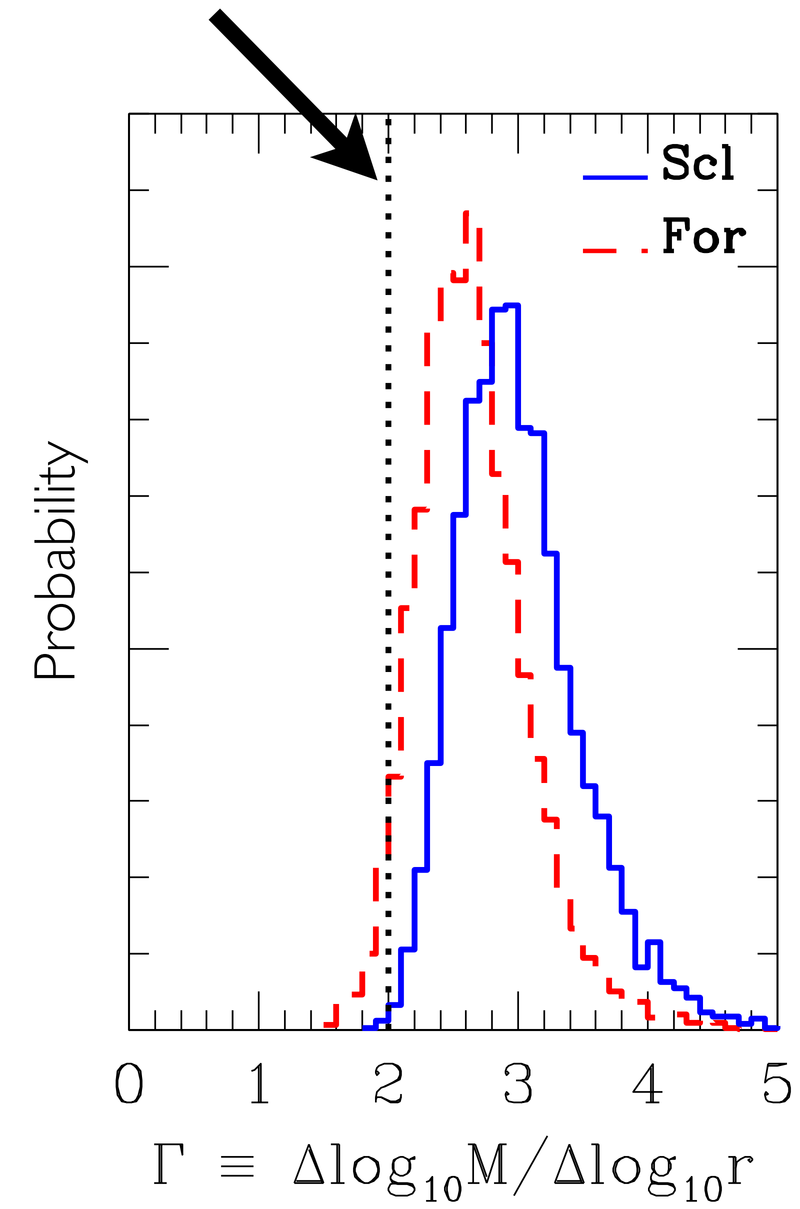


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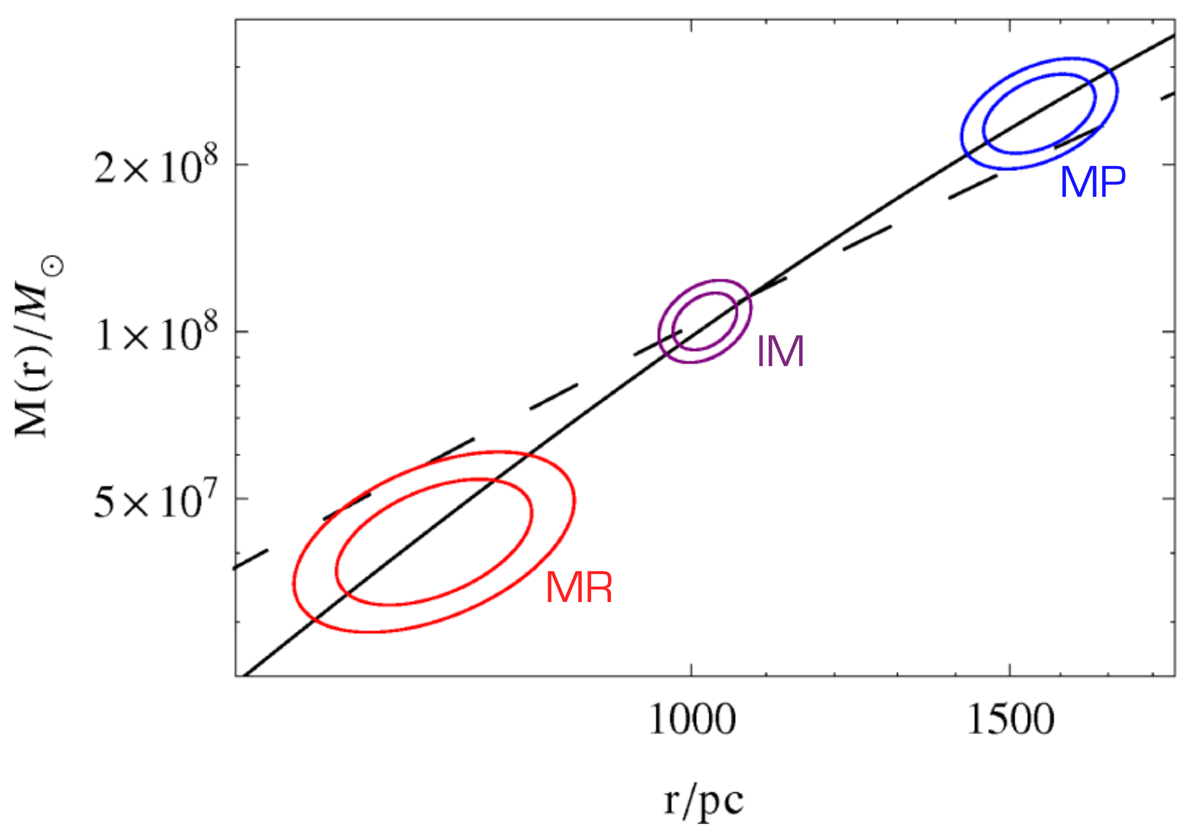
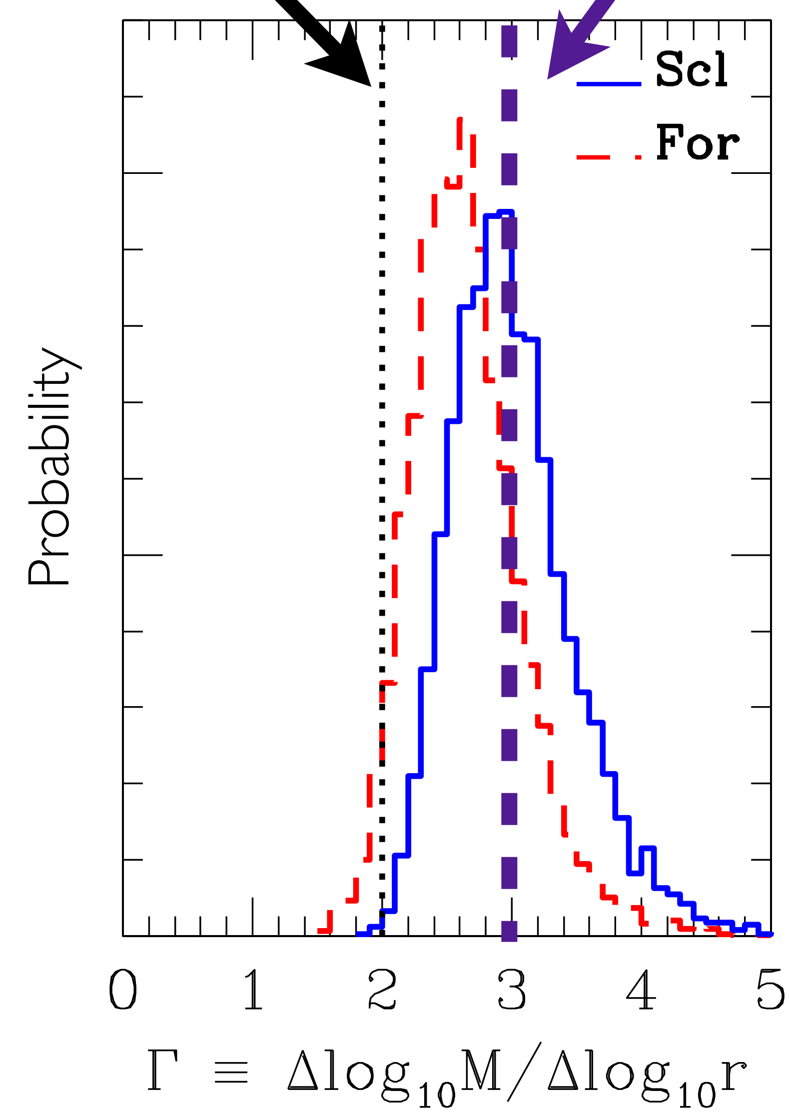



Amorisco & Evans 2012

**CDM / NFW**
**α = -1**

**core:**
**α = 0**

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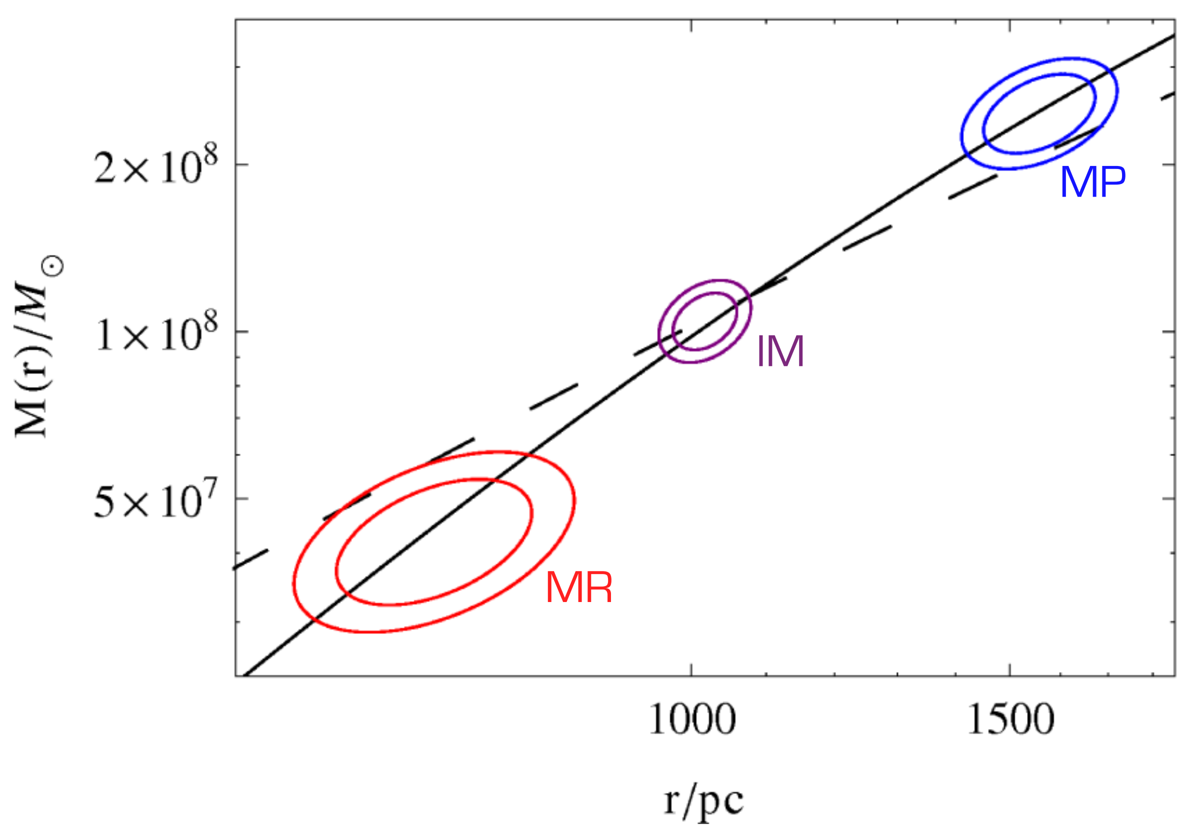


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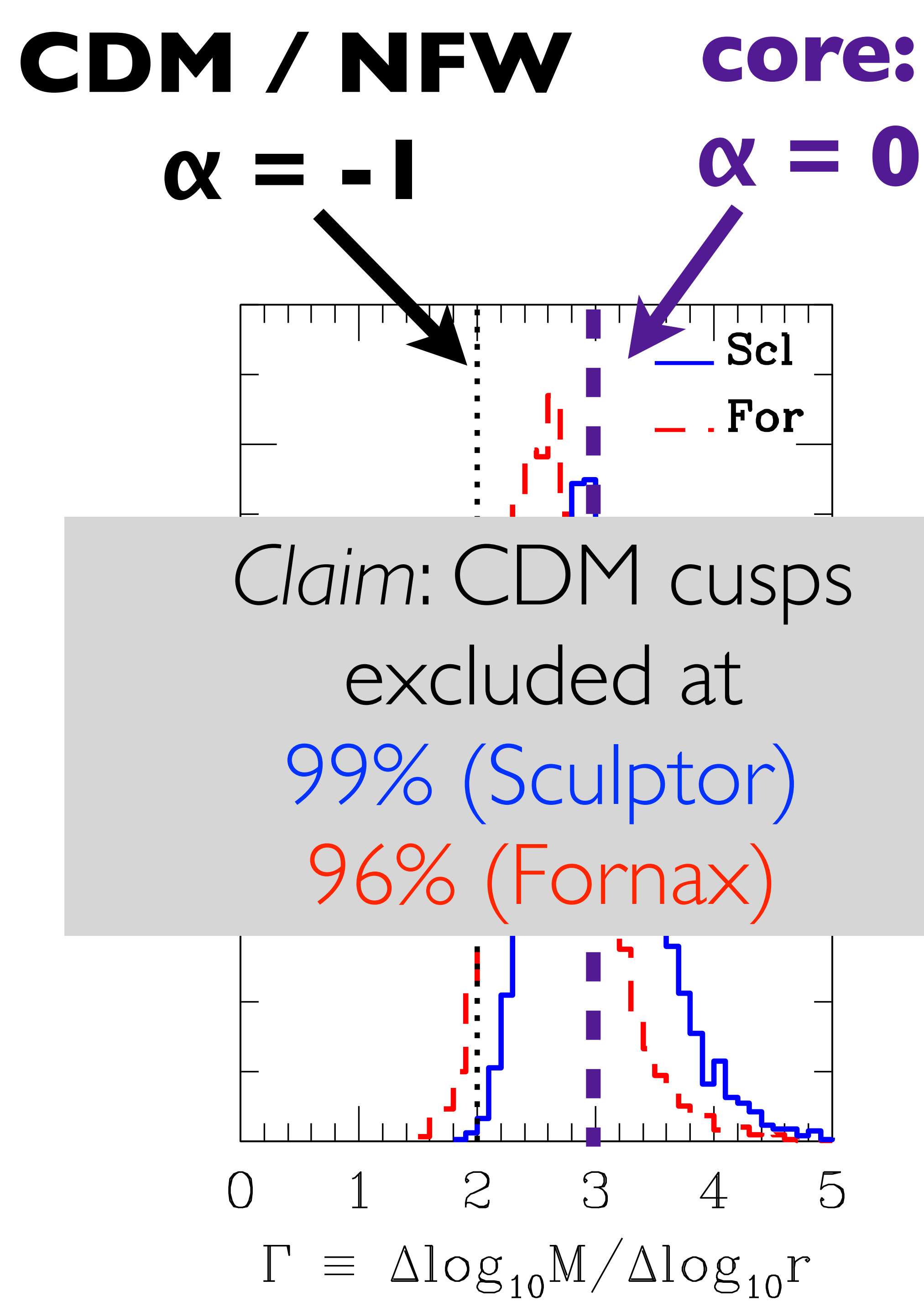
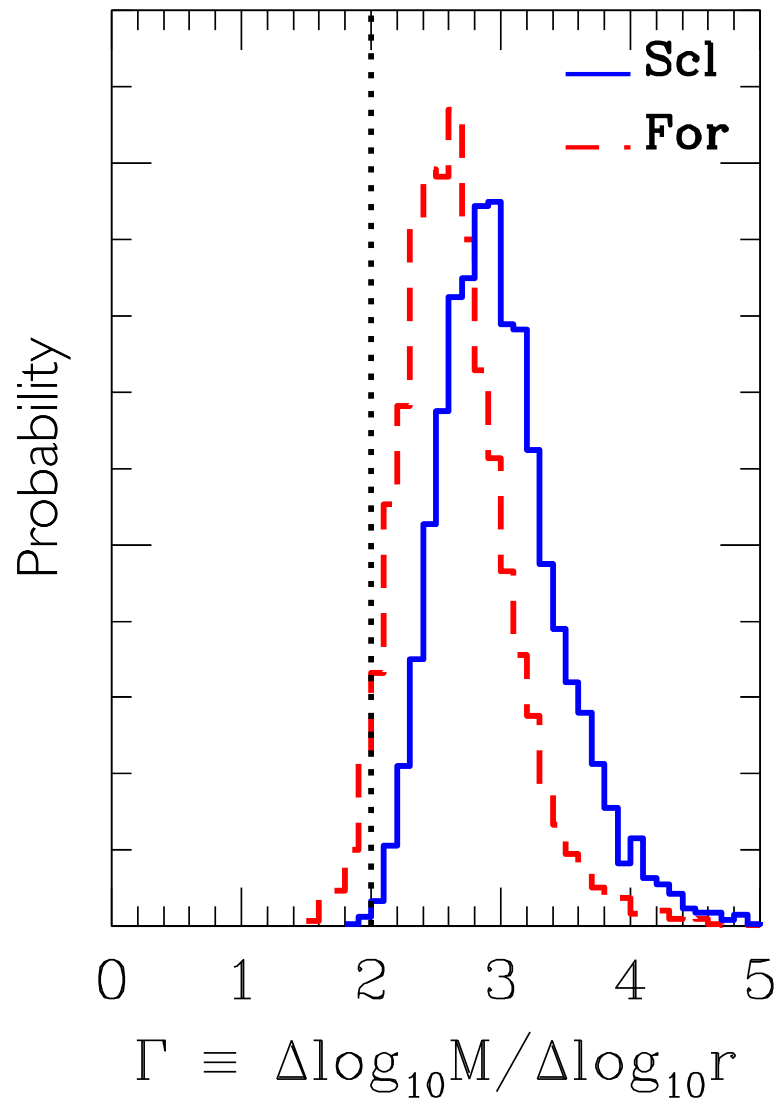



*Claim*: CDM cusps excluded at
99% (Sculptor)
96% (Fornax)

Walker & Peñarrubia 2011

# Additional evidence for cores in dwarf spheroidals




Walker & Peñarrubia 2011

- Globular clusters in Fornax
  (Goerdt, Moore, Read, Stadel, & Zemp 2006; Cole, Dehnen, Read, & Wilkinson 2012)

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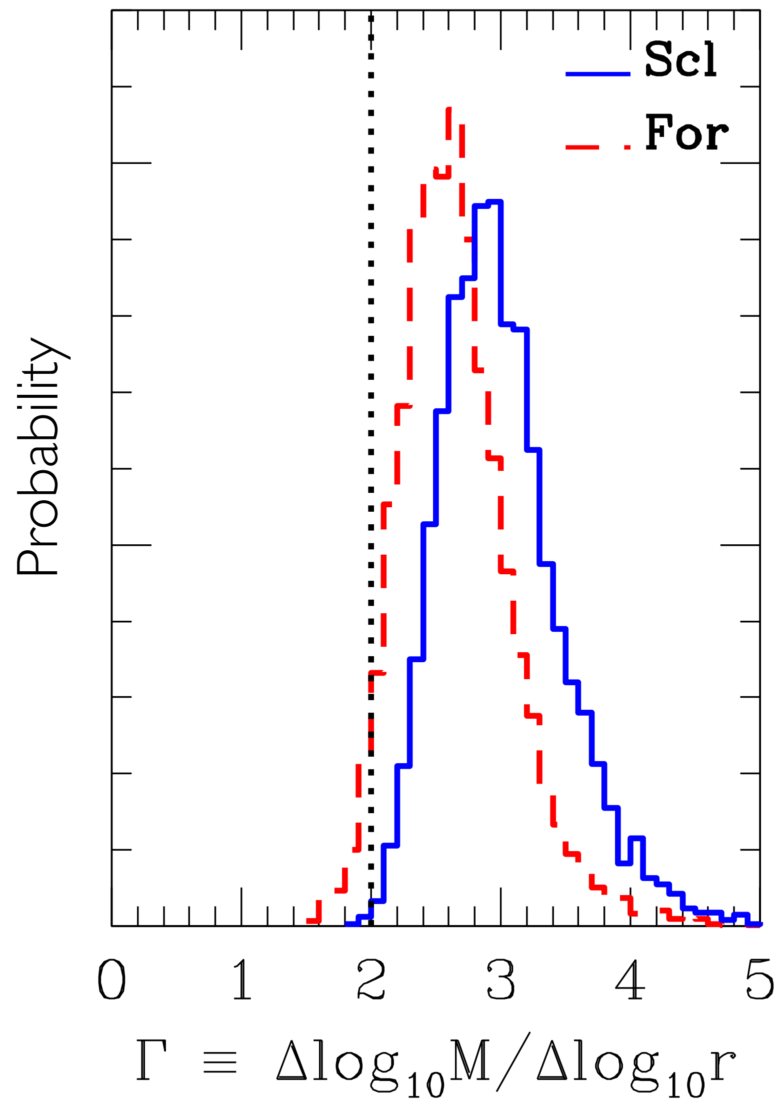
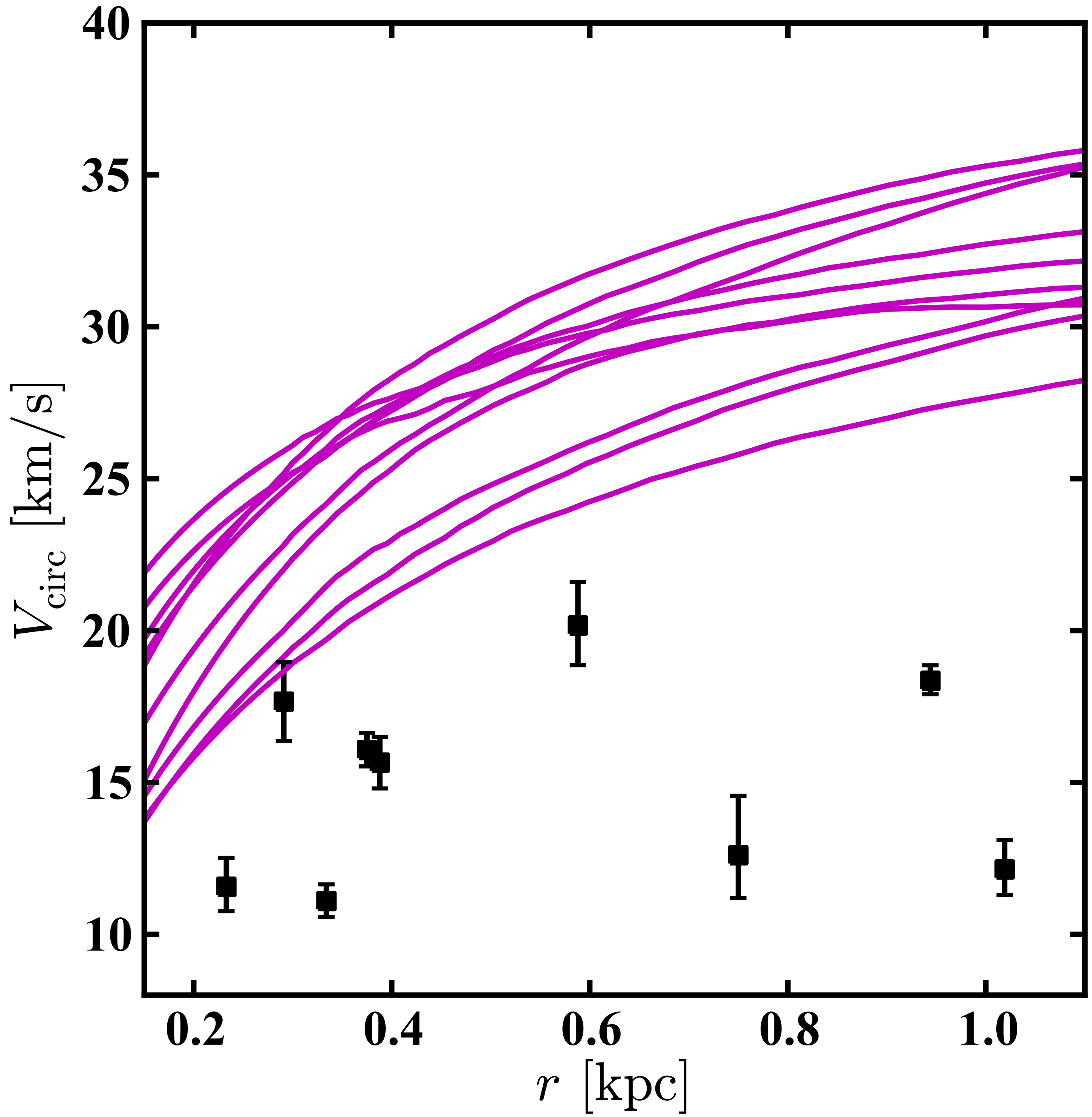



Walker & Peñarrubia 2011

- Globular clusters in Fornax (Goerdt, Moore, Read, Stadel, & Zemp 2006; Cole, Dehnen, Read, & Wilkinson 2012)
- 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)

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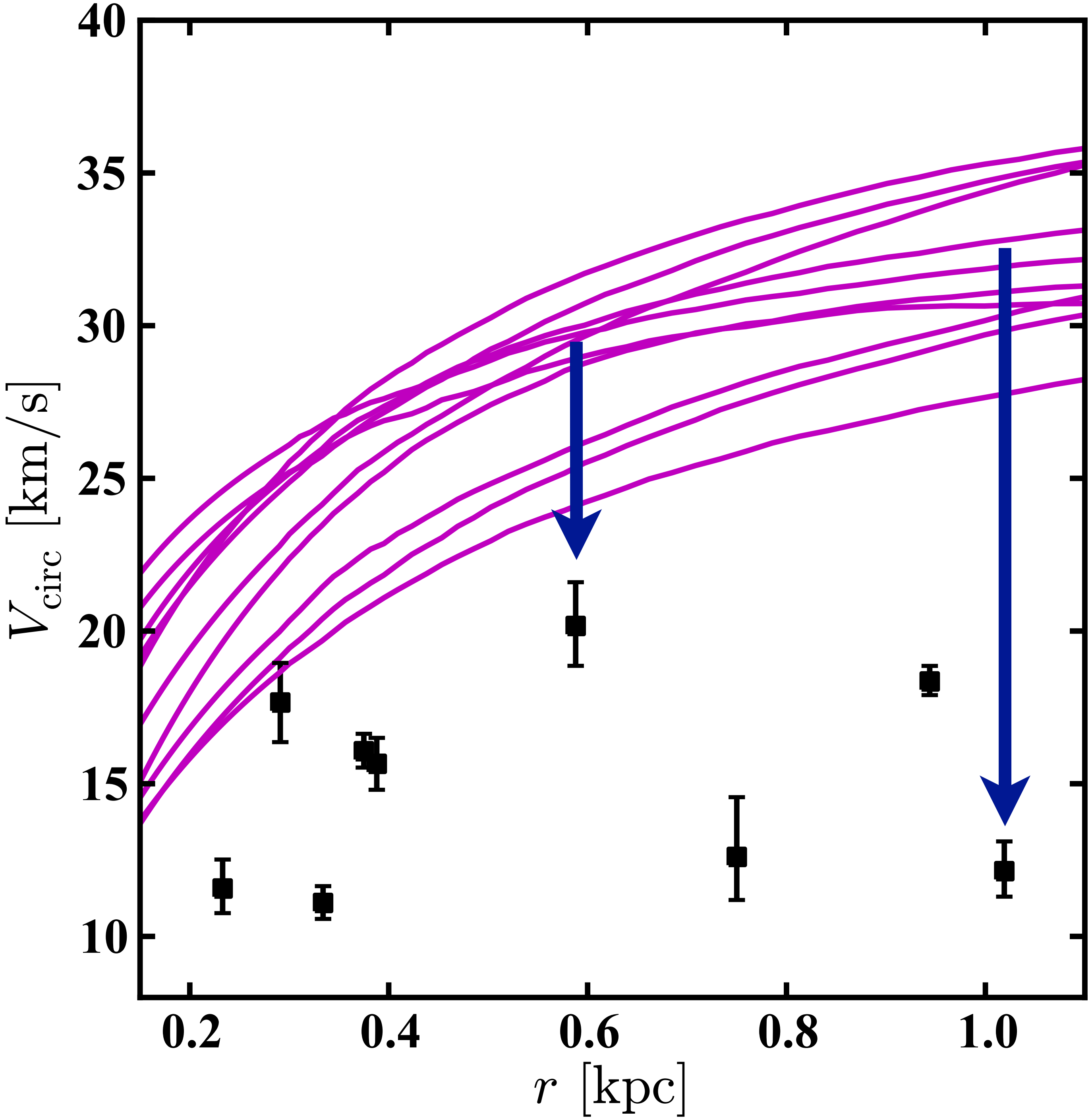


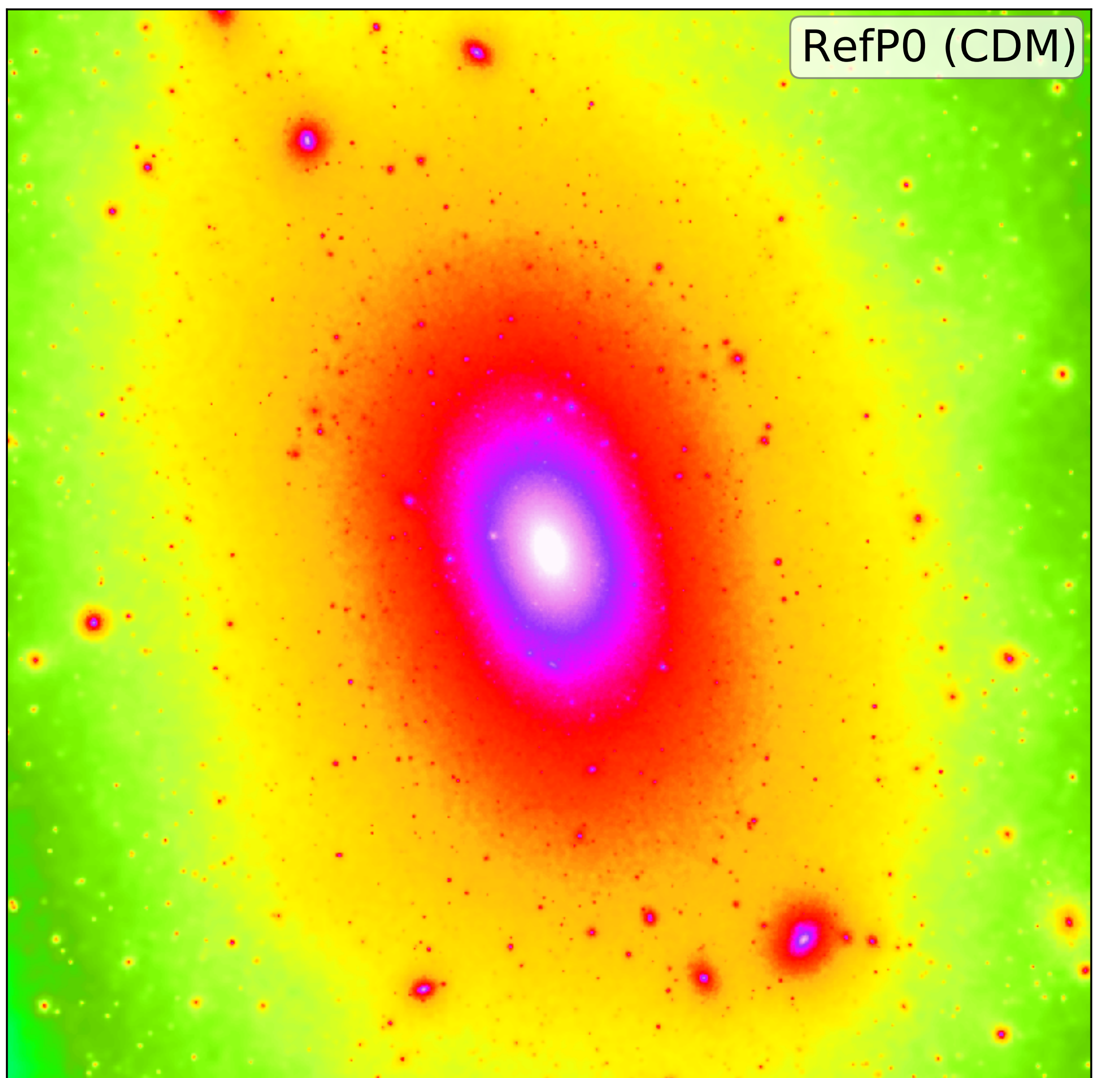

*Too big to fail, cores in MW satellites:*
Pointing to a problem with CDM-only predictions for densities on small scales (0.1-1 kpc)

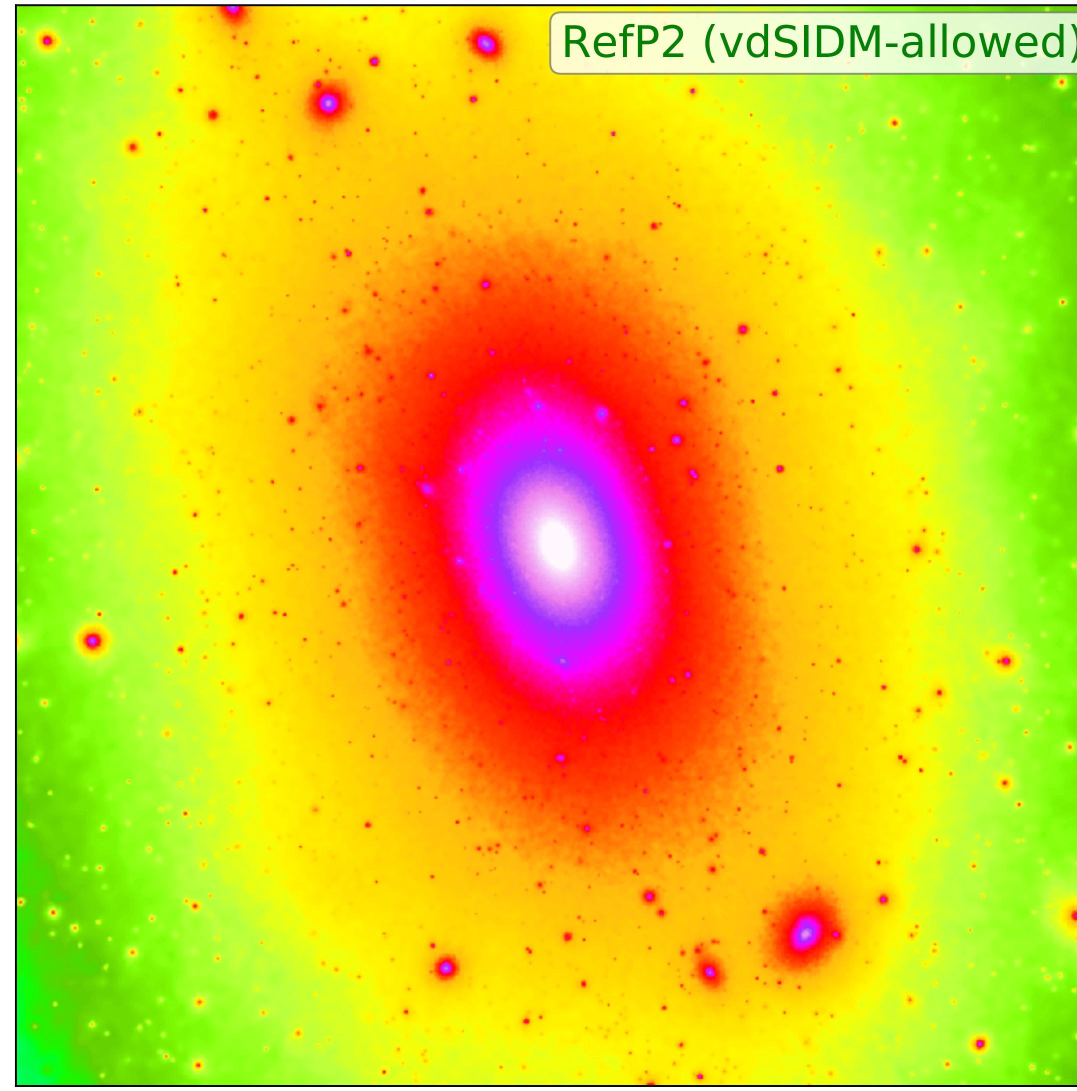
need at least 50% less dark matter mass in the inner 500 pc, 70% less at 1 kpc
(MBK et al. 2012)

# Self-interacting dark matter

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

CDM



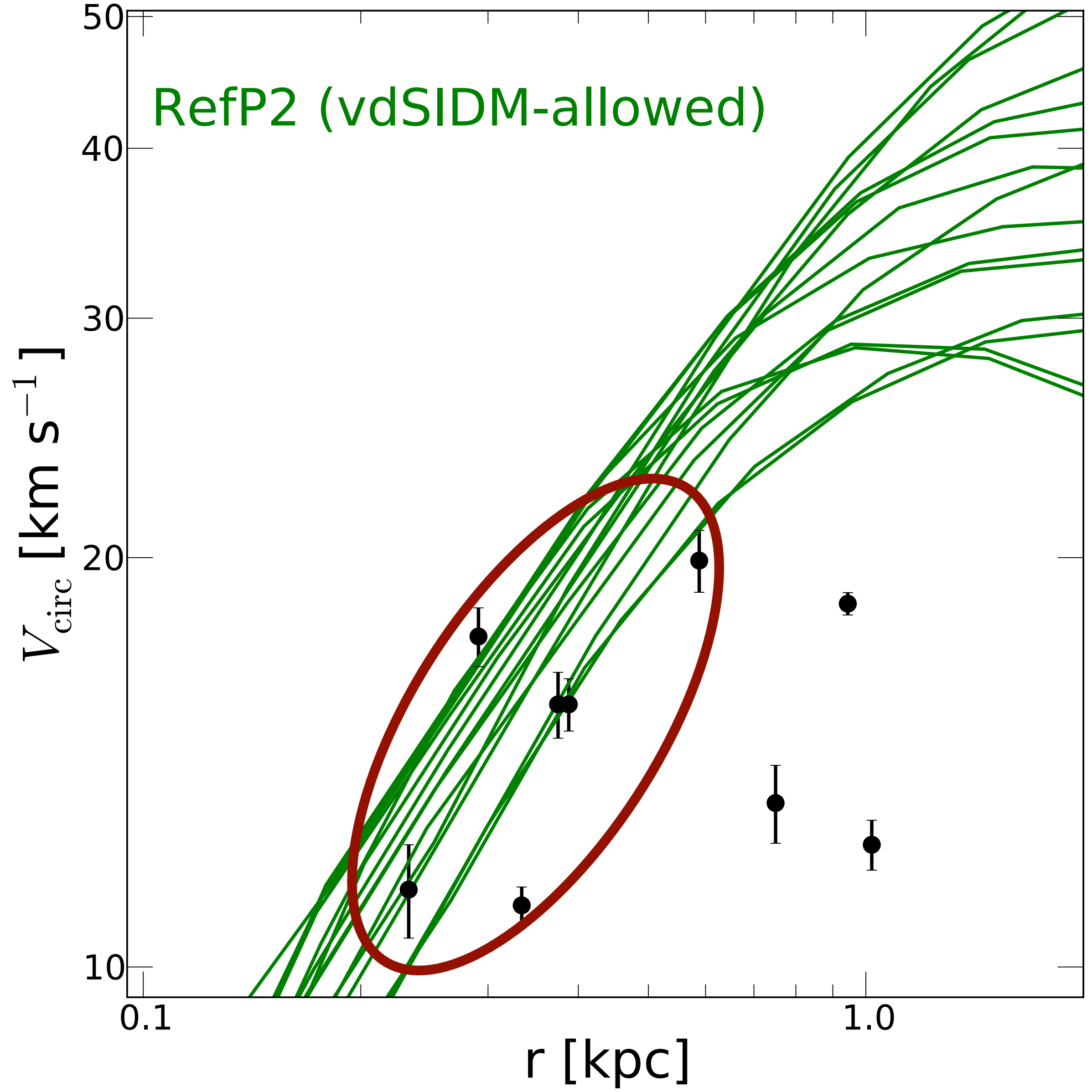



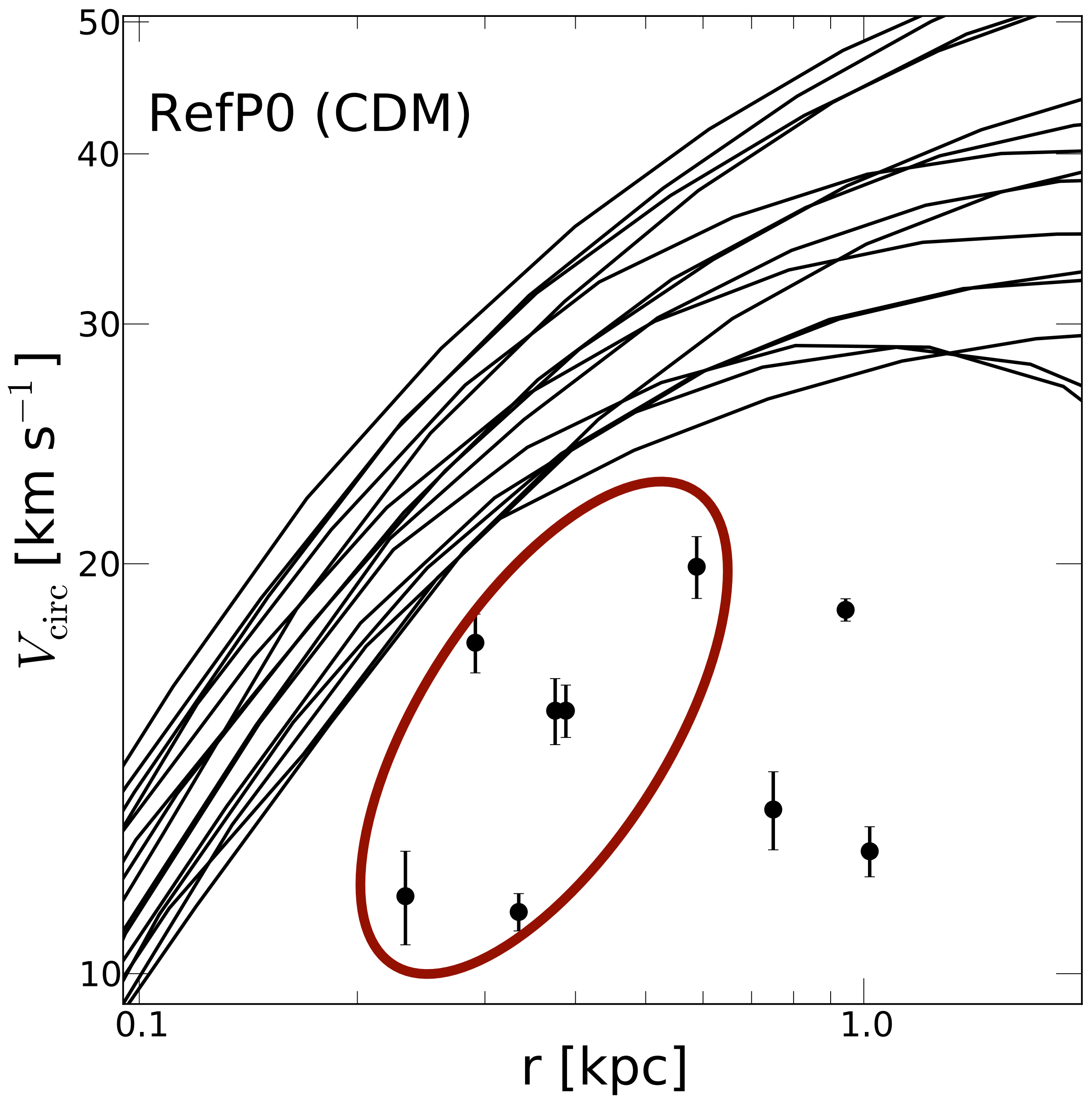

Self-Interacting Dark Matter

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

# Self-interacting dark matter

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



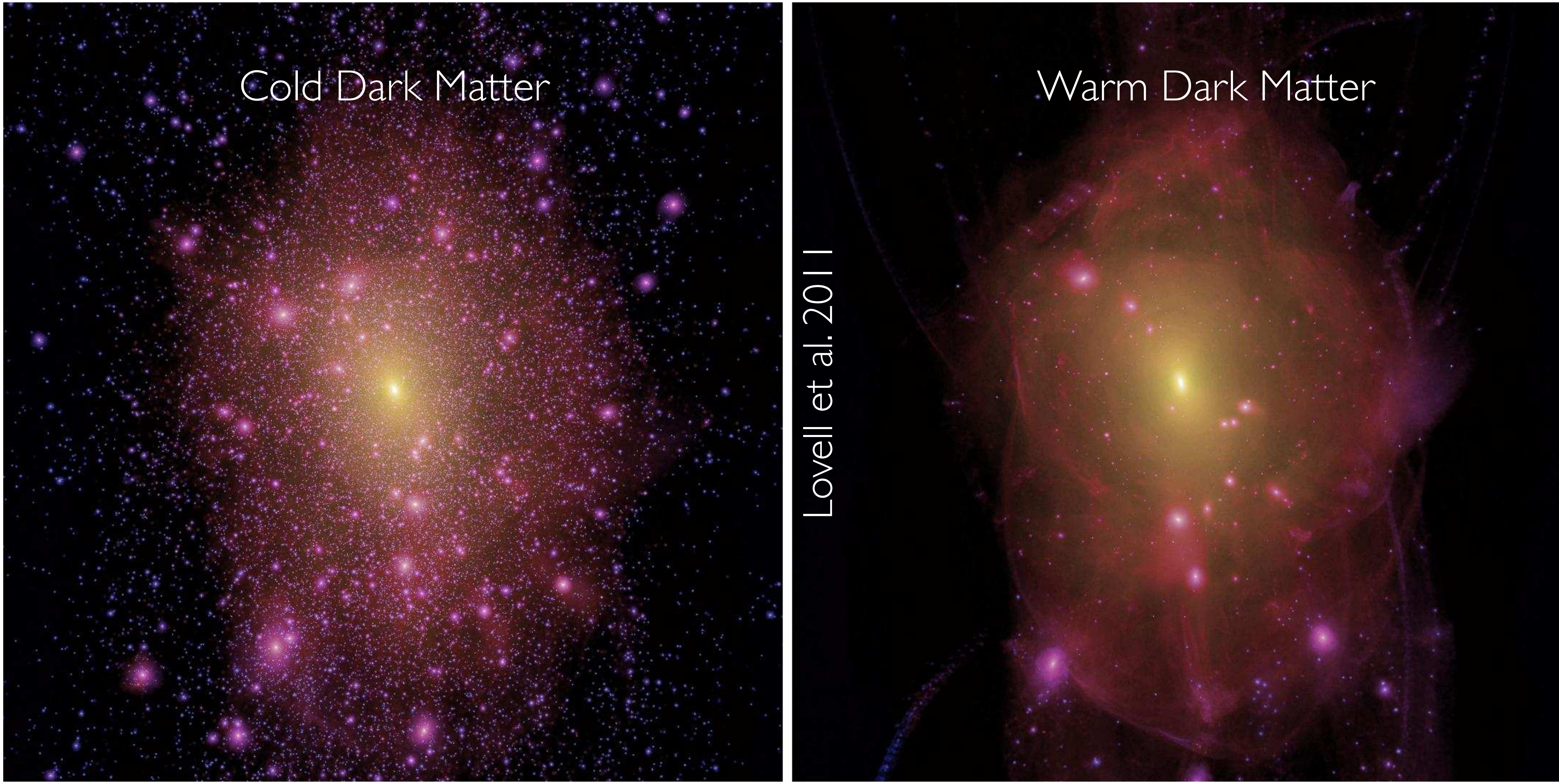

Above: velocity-dependent σ

Velocity-independent σ should work for

σ ~0.3 cm$^2$/g

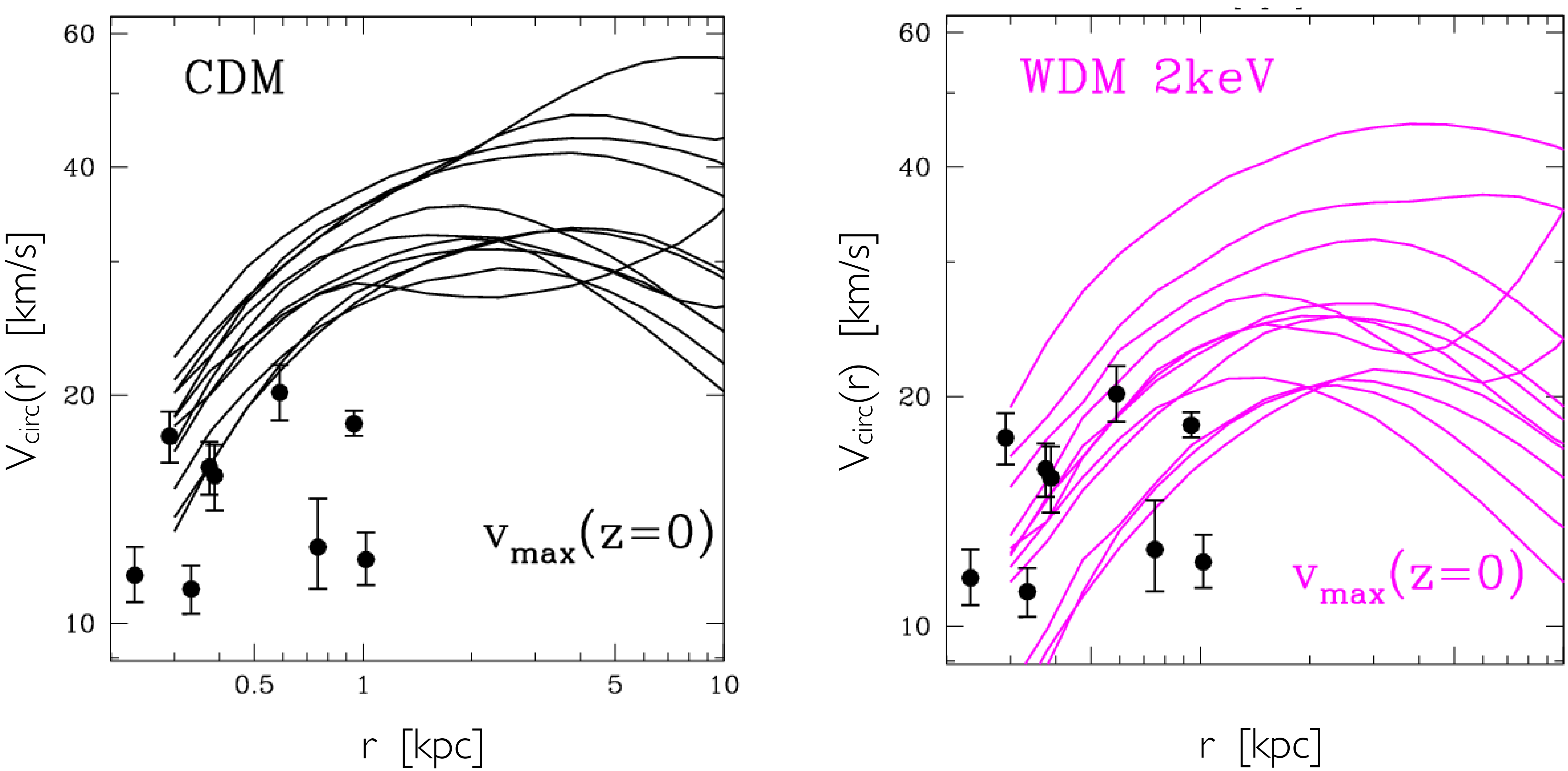
(Vogelsberger et al. 2013, Rocha et al. 2013, Peter et al. 2013)

# Or Warm Dark Matter?



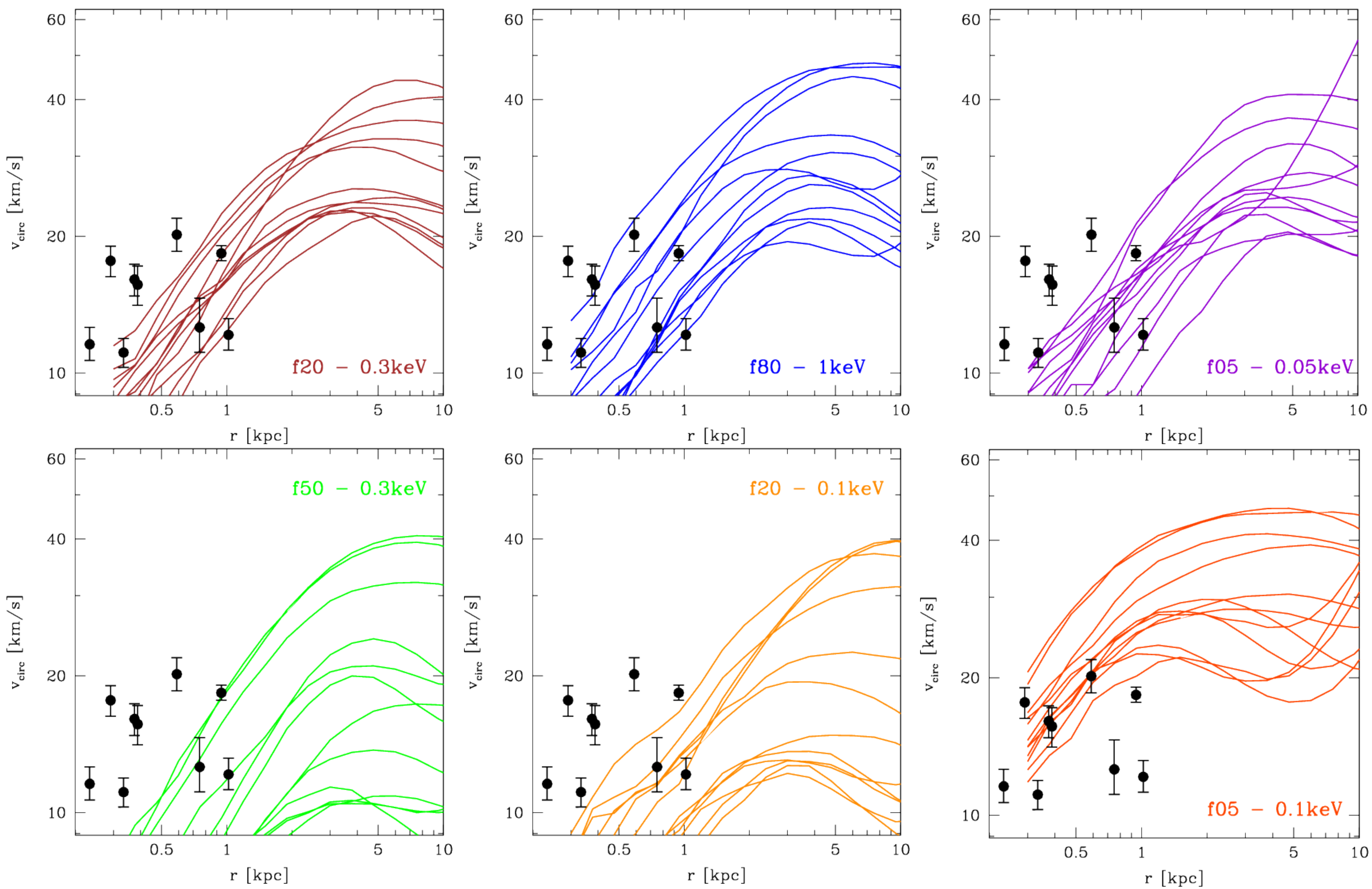

WDM: modifies **density** of subhalos, not the underlying dark matter profile **shape** for models not excluded by complementary astrophysical data (m~2 keV or more).
Also affects **number** of subhalos (relevant for ultra-faint satellites; Maccio et al. 2010, Polisensky & Ricotti 2011)

# “Too big to fail” (or not) in WDM




Anderhalden, Schneider, Maccio, Diemand, & Bertone 2013

# Or, C+WDM?




Anderhalden, Schneider, Maccio, Diemand, & Bertone 2013

# Small scales: proof of non-standard dark matter physics?


image: BThomas64 / bthomas64.deviantart.com

# 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, ....

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All from the past ~1 year!

...ATTER: WHY LUMINOUS SATELLITE GALAXIES HAVE REDUCED CENTRAL MASSES

..., Alyson M. Brooks[2], Beth Willman[3], Fabio Governato[4], Andrew Pontzen[5],
...ensen[6], Avishai Dekel[1], Tom Quinn[4], Sijing Shen[7], and James Wadsley[8]

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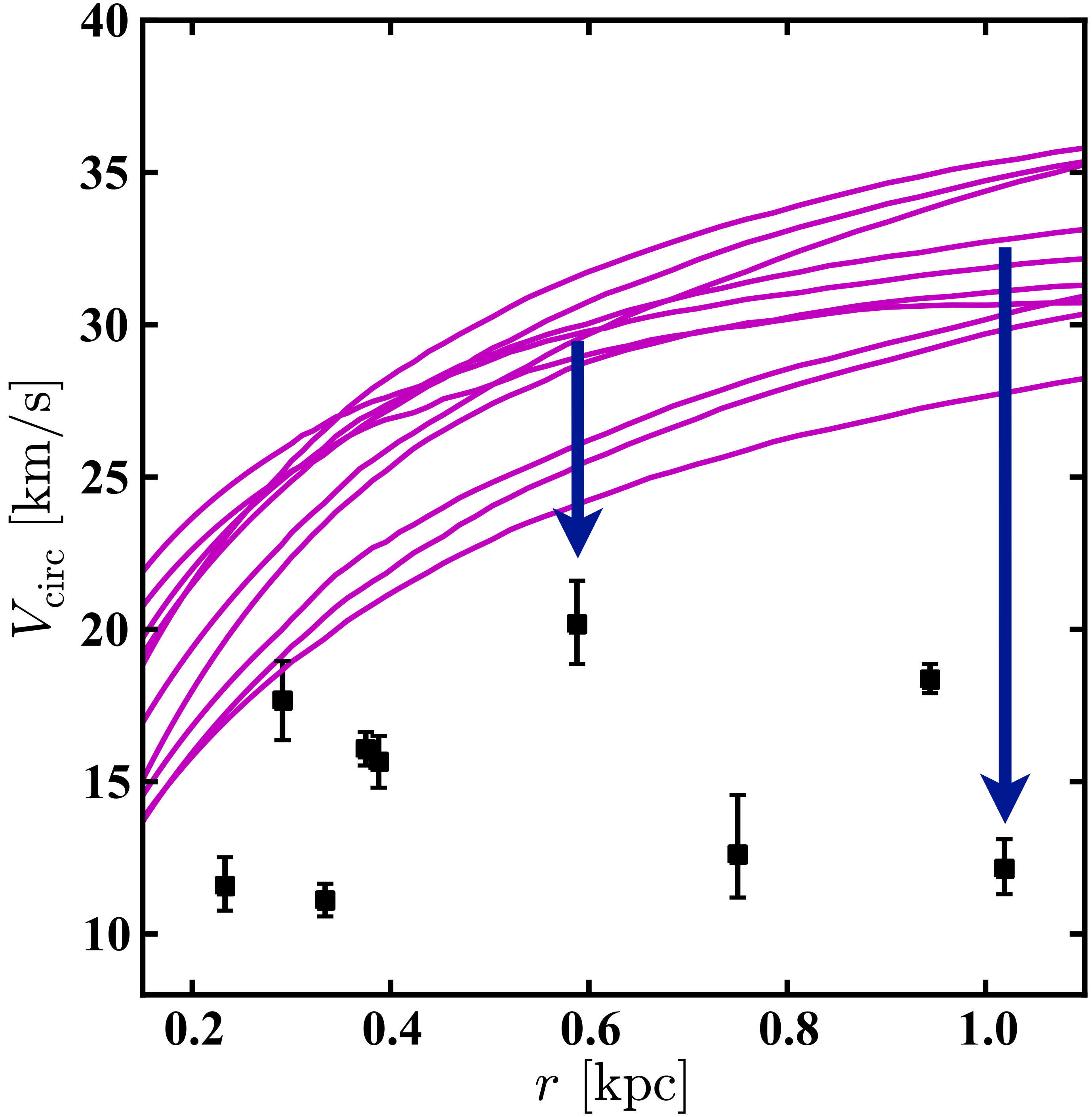
# Supernova feedback: limited by number of stars




need to remove ~5x10$^7$ $M_{sun}$ of dark matter from inner 500 pc

Requires 100% of energy from $M_\star = 10^6\, M_\odot$ coupled directly to dark matter

(Garrison-Kimmel, Rocha, MBK et al. 2013)

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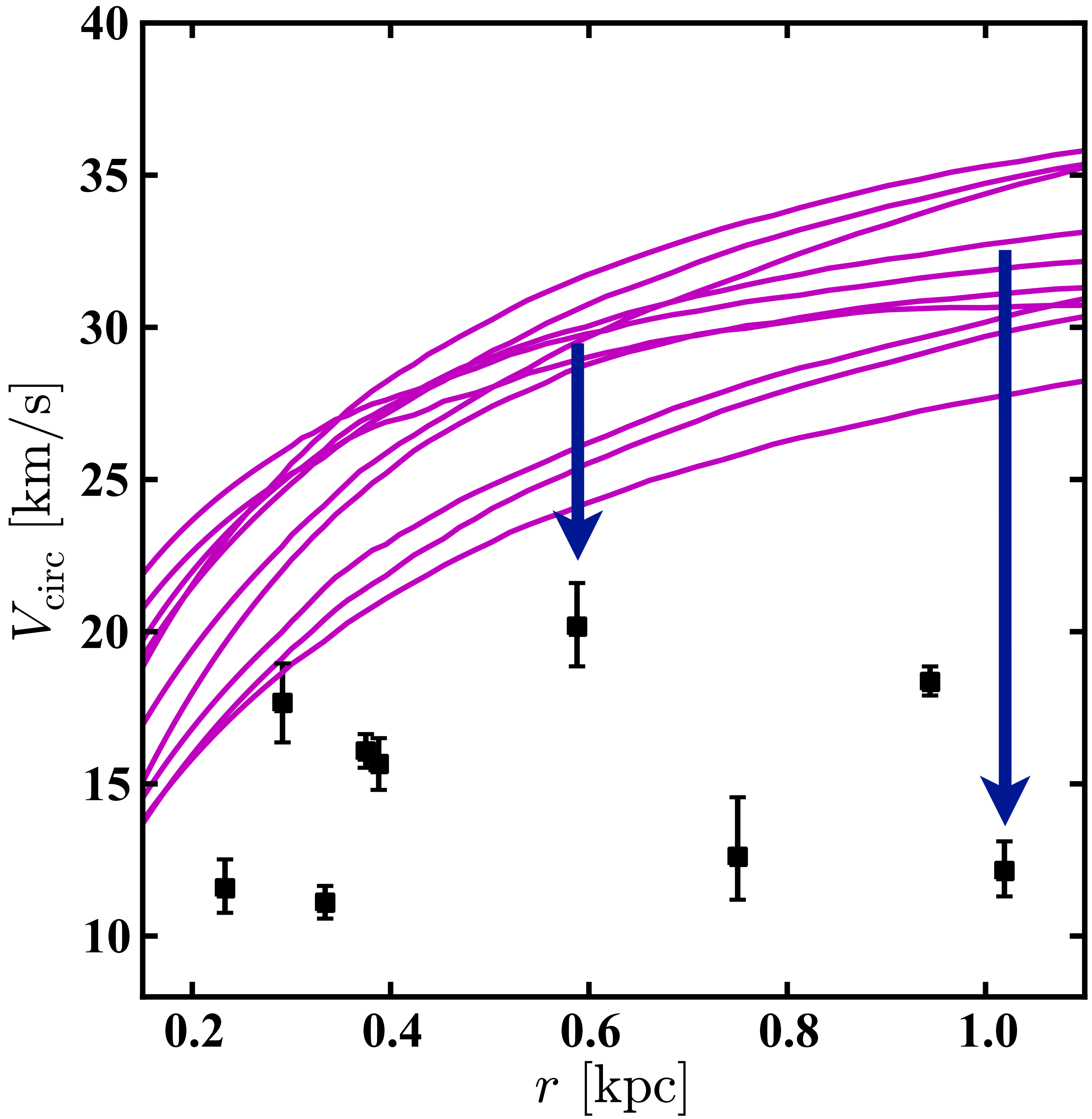


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Low stellar mass of dSphs $\Rightarrow$ (probably) *impossible* to reduce density with SN feedback
(see also Peñarrubia et al. 2012)

Combine with tidal effects?
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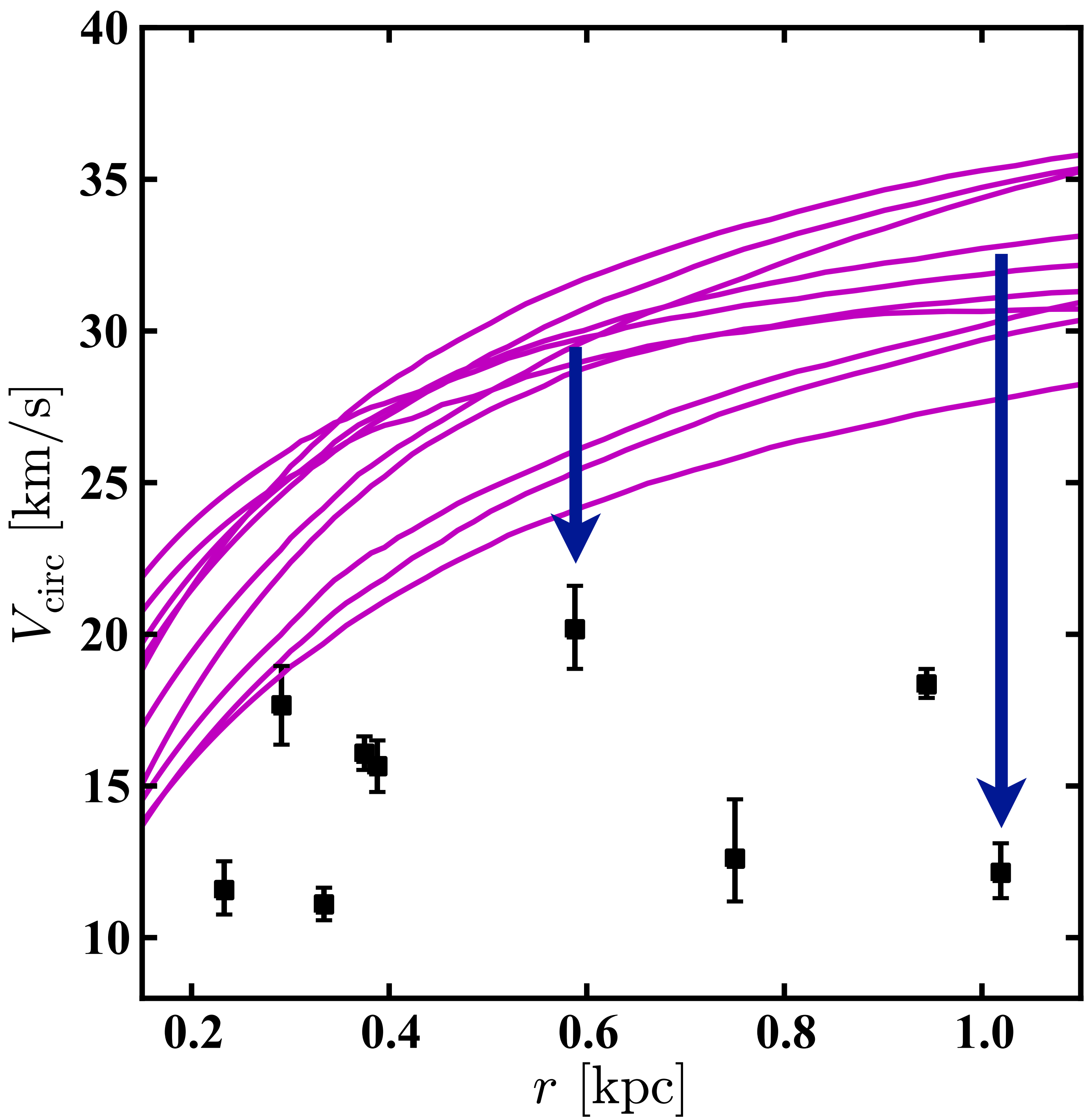


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# Why the uncertainty?

Simulating MW and its satellites with full gas physics is a daunting computational challenge

- Length scales: ~1 pc (sites of star formation) to > 1 Mpc
- Mass scales: ~10 $M_{sun}$ (SN progenitor) to > $10^{12}$ $M_{sun}$
- Time scales: ~10,000 years (shock wave deceleration) to 13.7 Gyr

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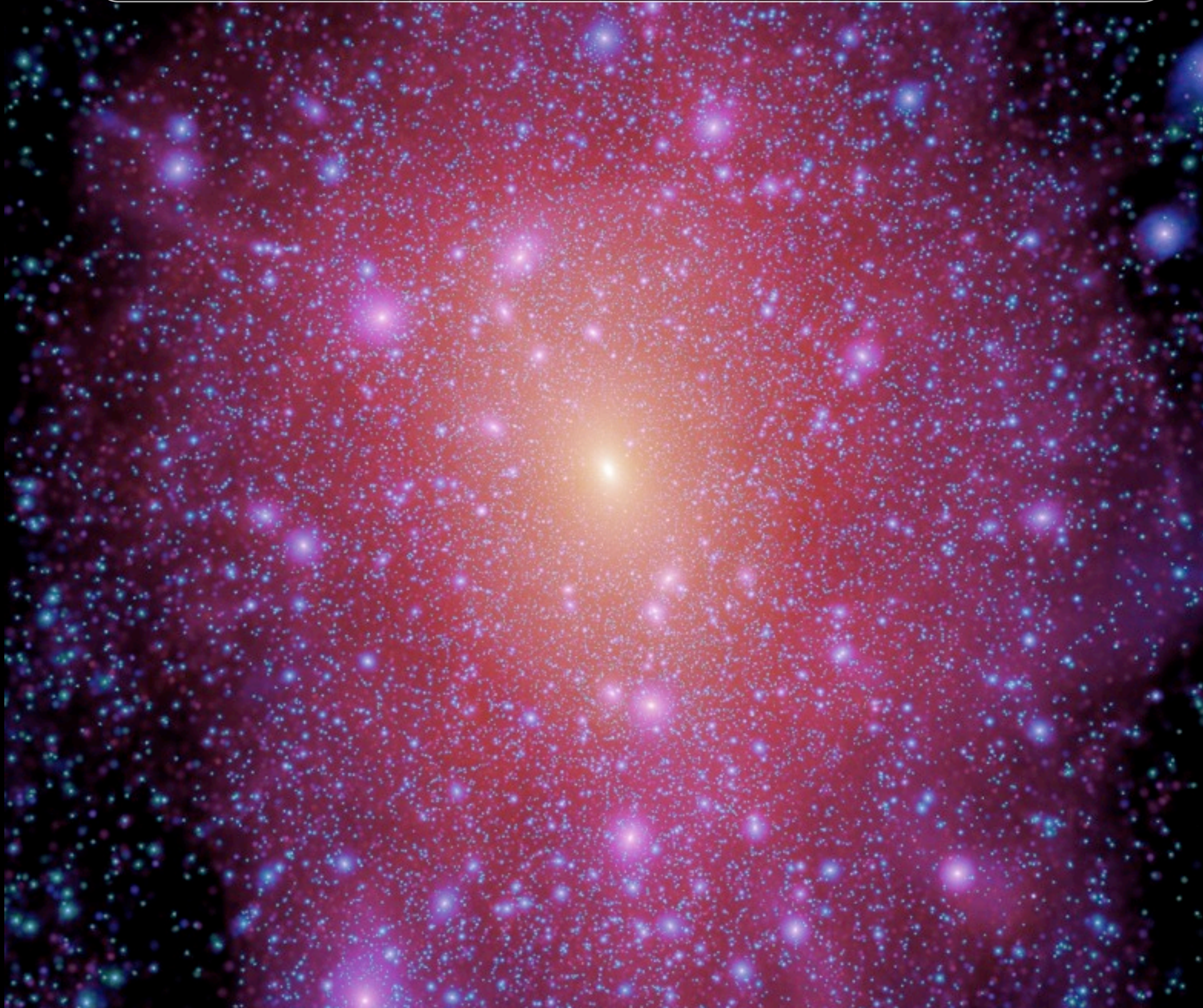
State-of-the-art in CDM dark-matter-only simulations:
particle masses of ~1000 $M_{sun}$, minimum length scales of ~20 pc;
~10 million CPU hours, 0.1-1 Petabyte of data

# How can we make progress in understanding constraining DM physics with satellites?



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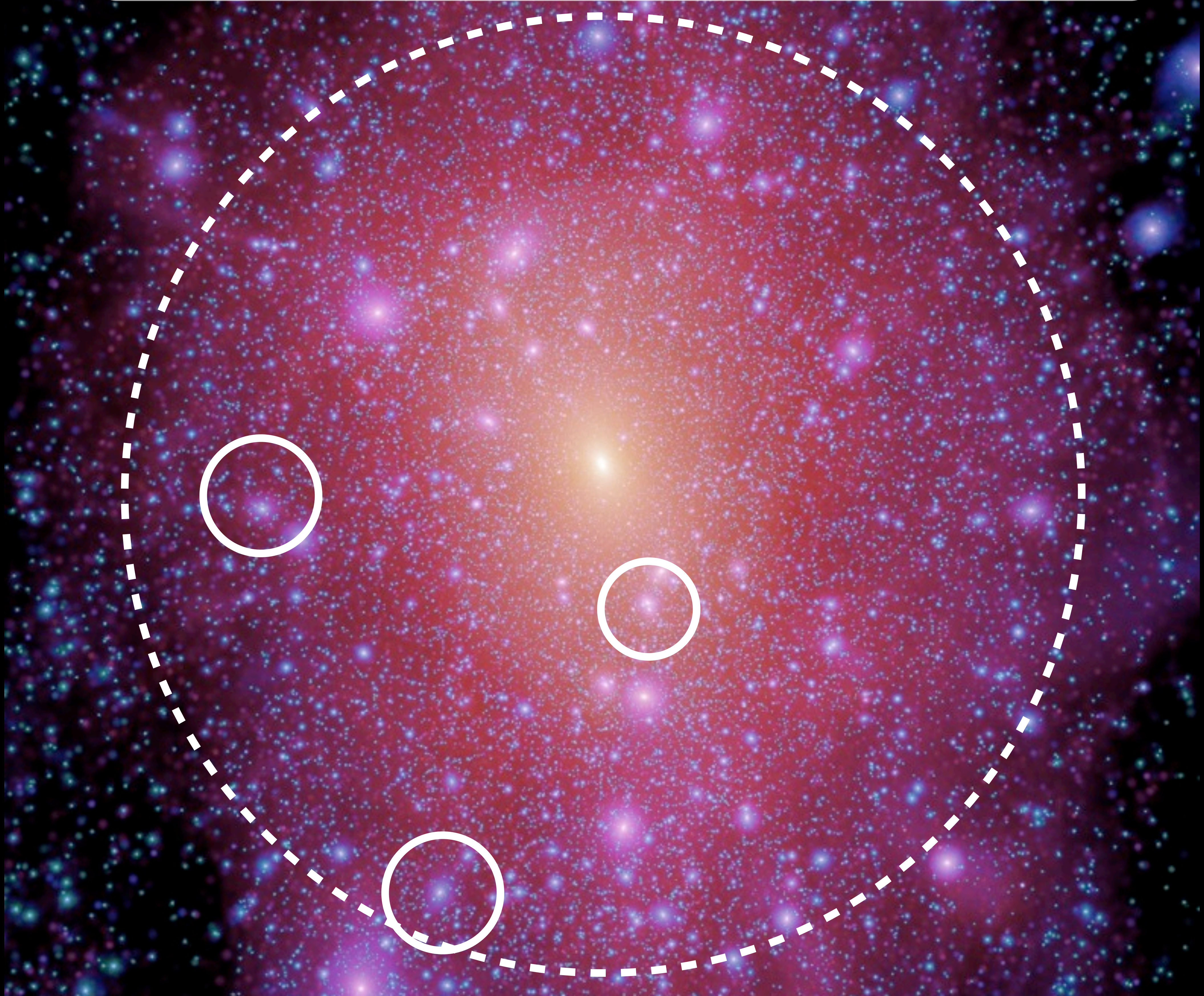
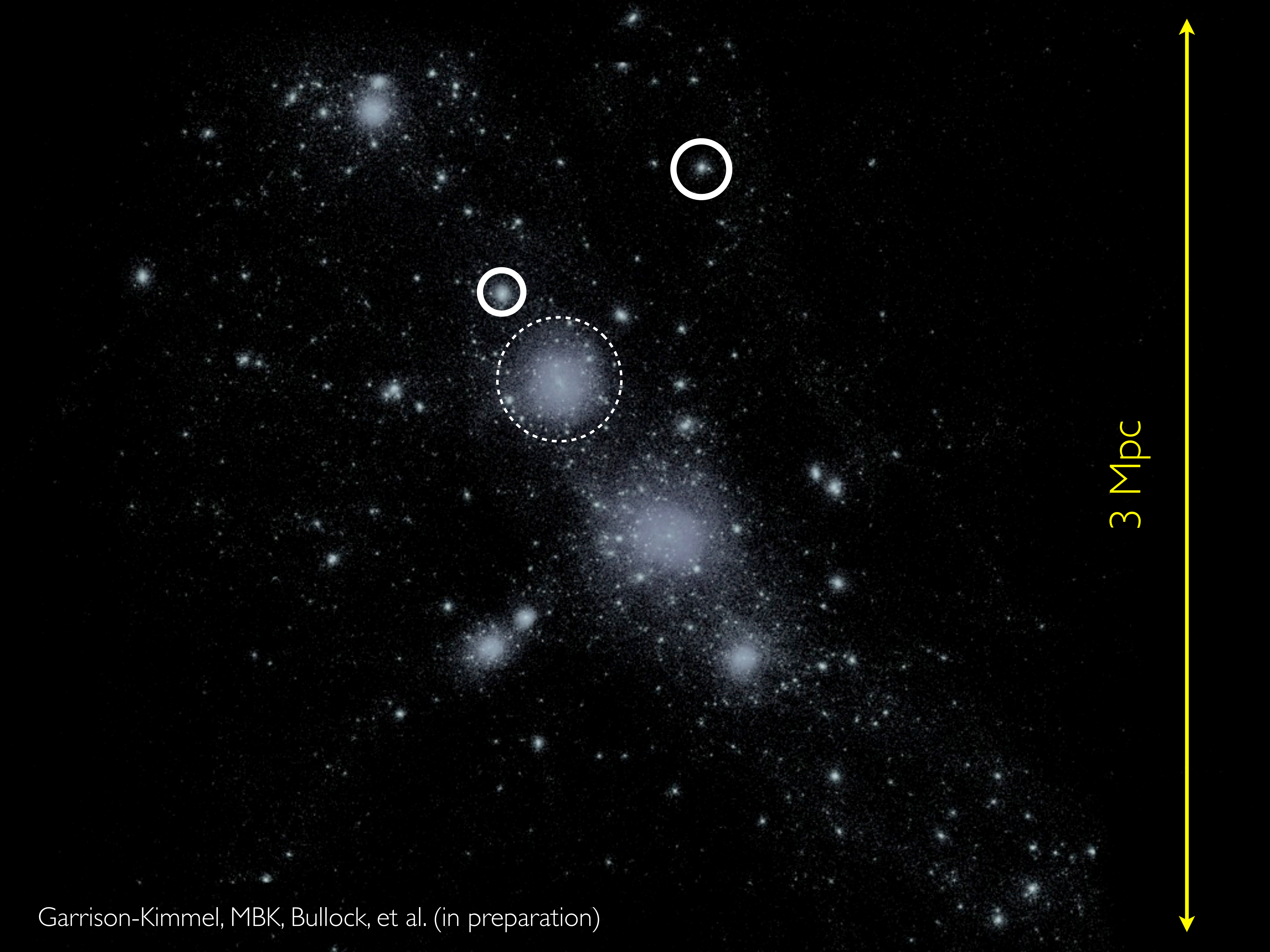
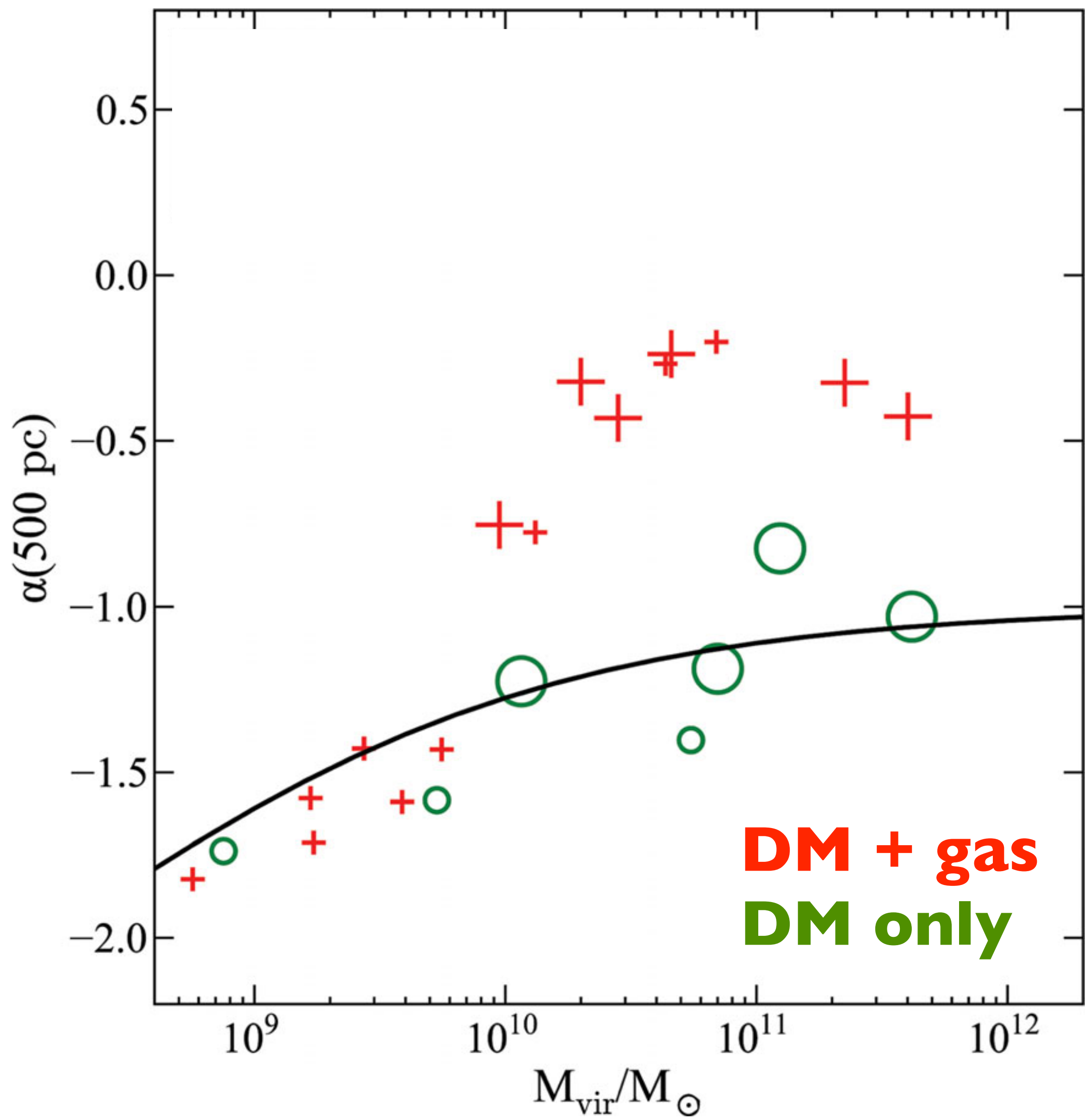





Garrison-Kimmel, MBK, Bullock, et al. (in preparation)

# Galaxy formation imprints scale on DM distribution

Governato et al. 2012



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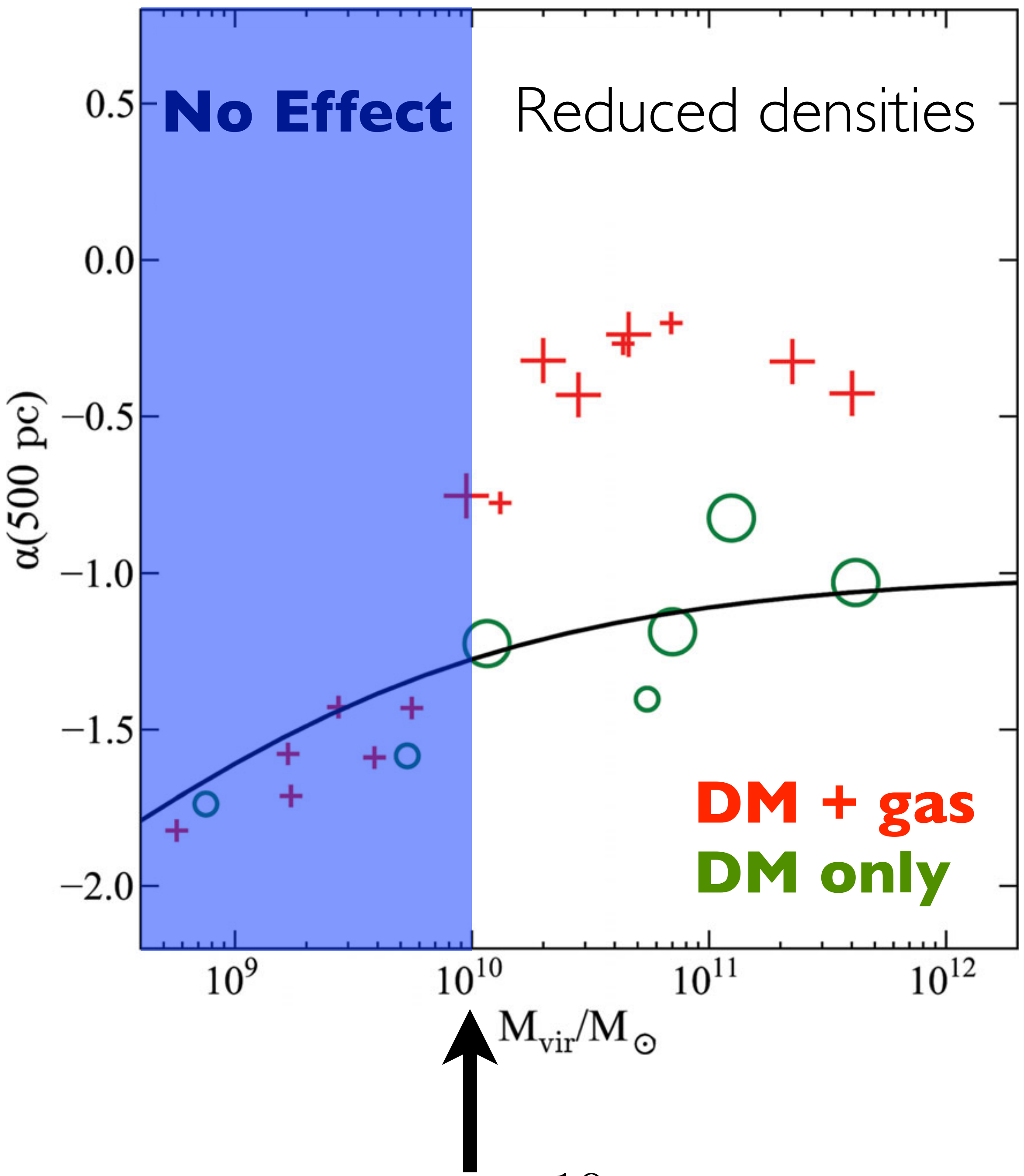


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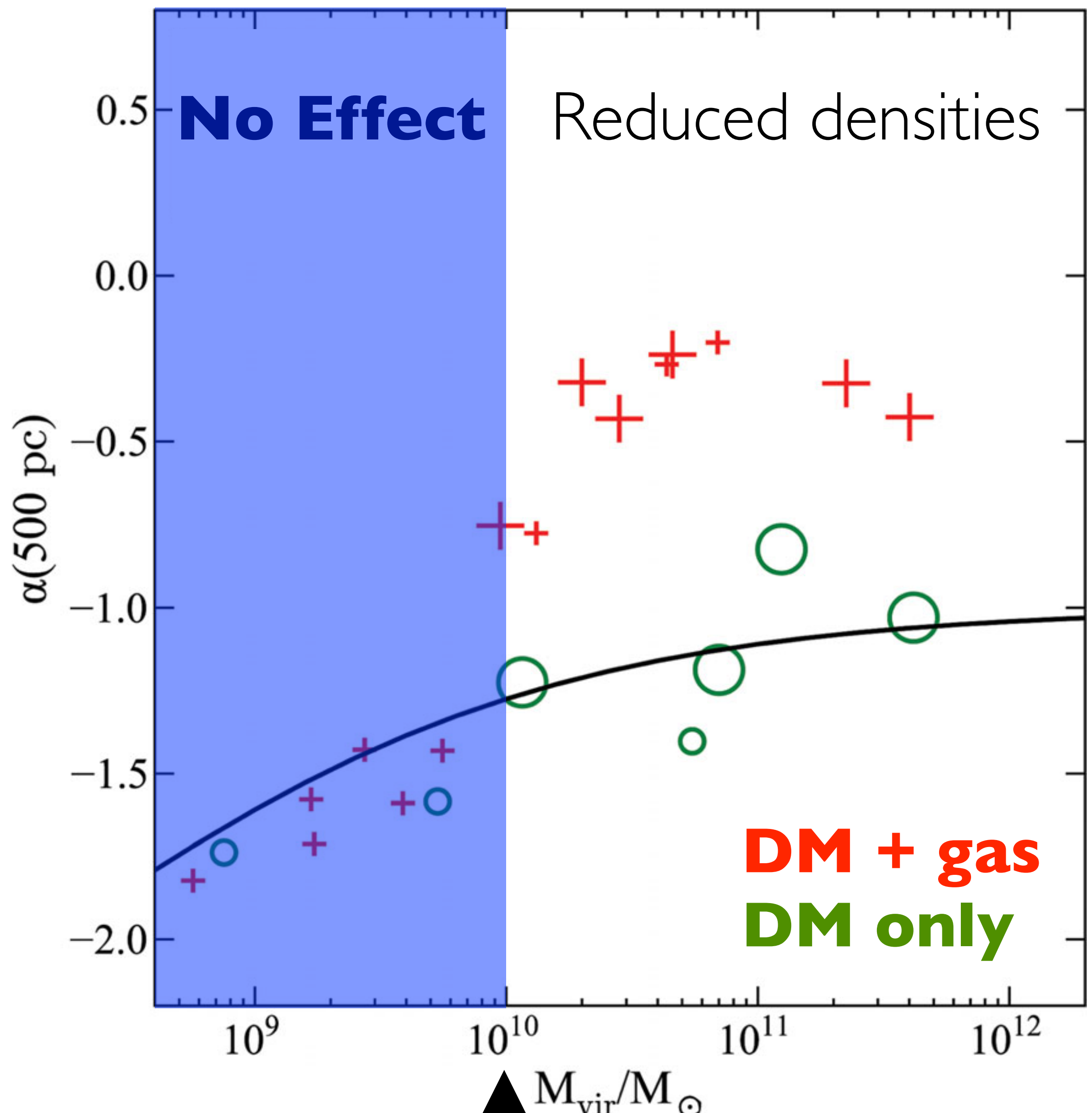


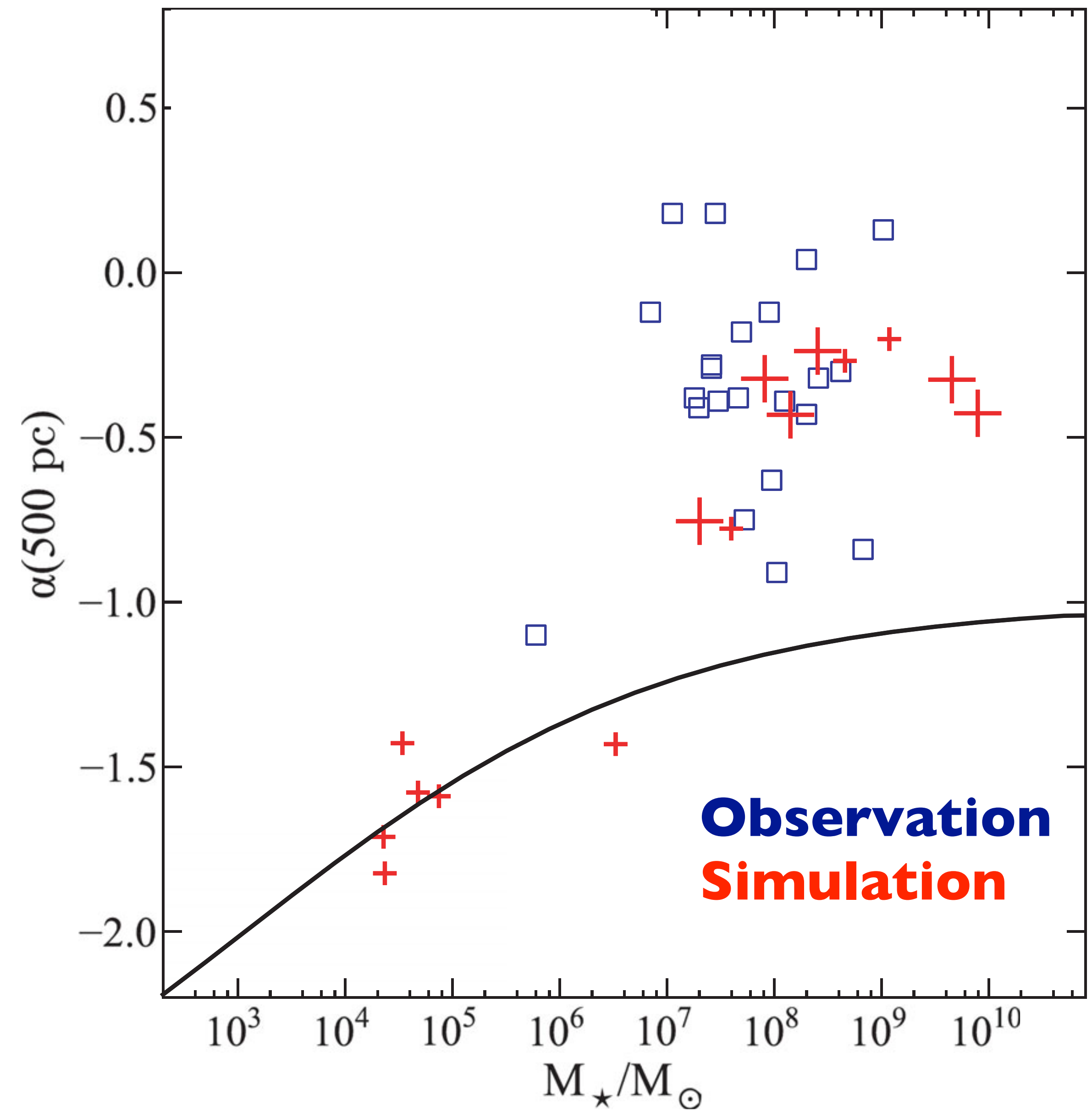


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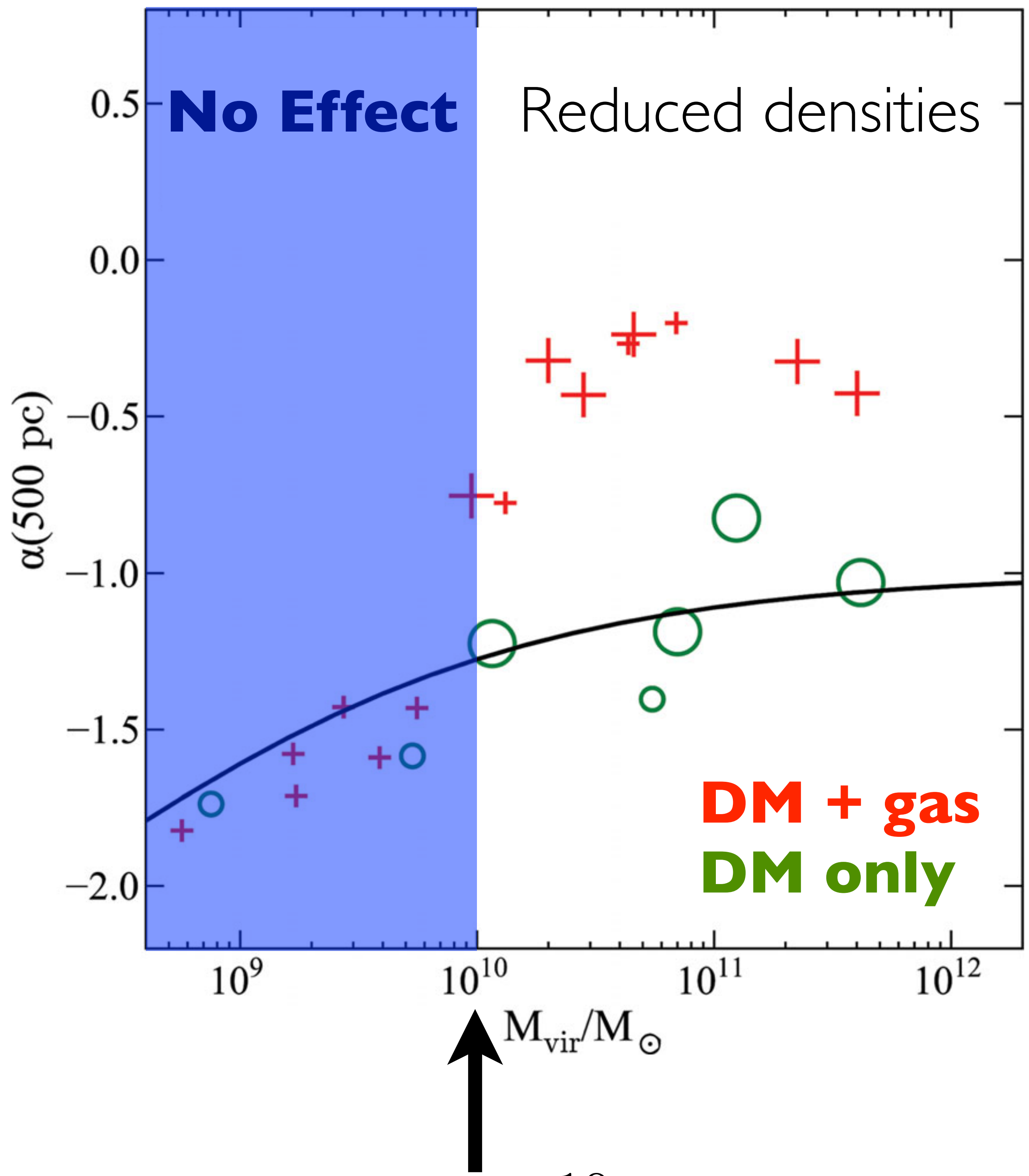


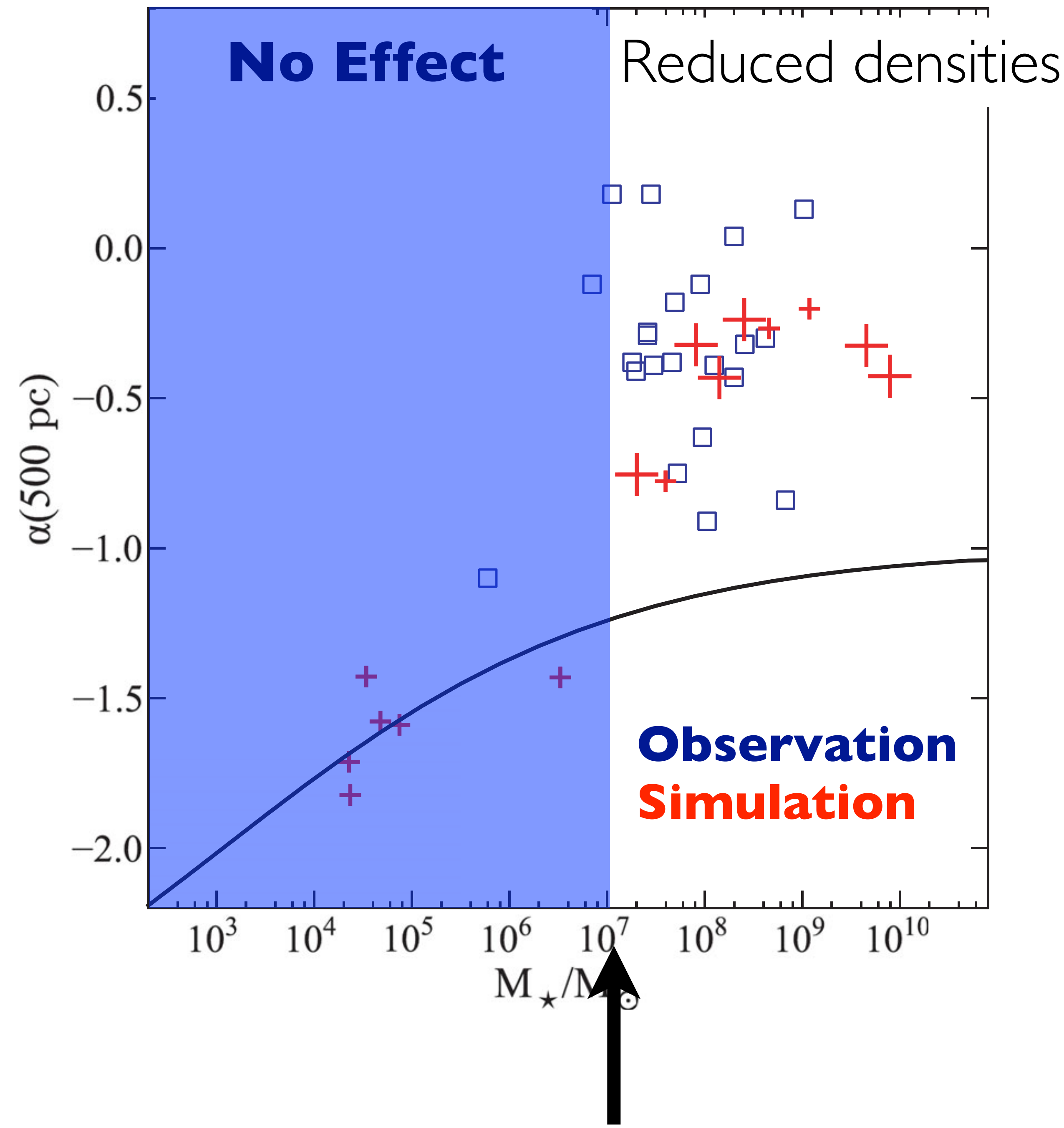


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Same scale as for MW satellites

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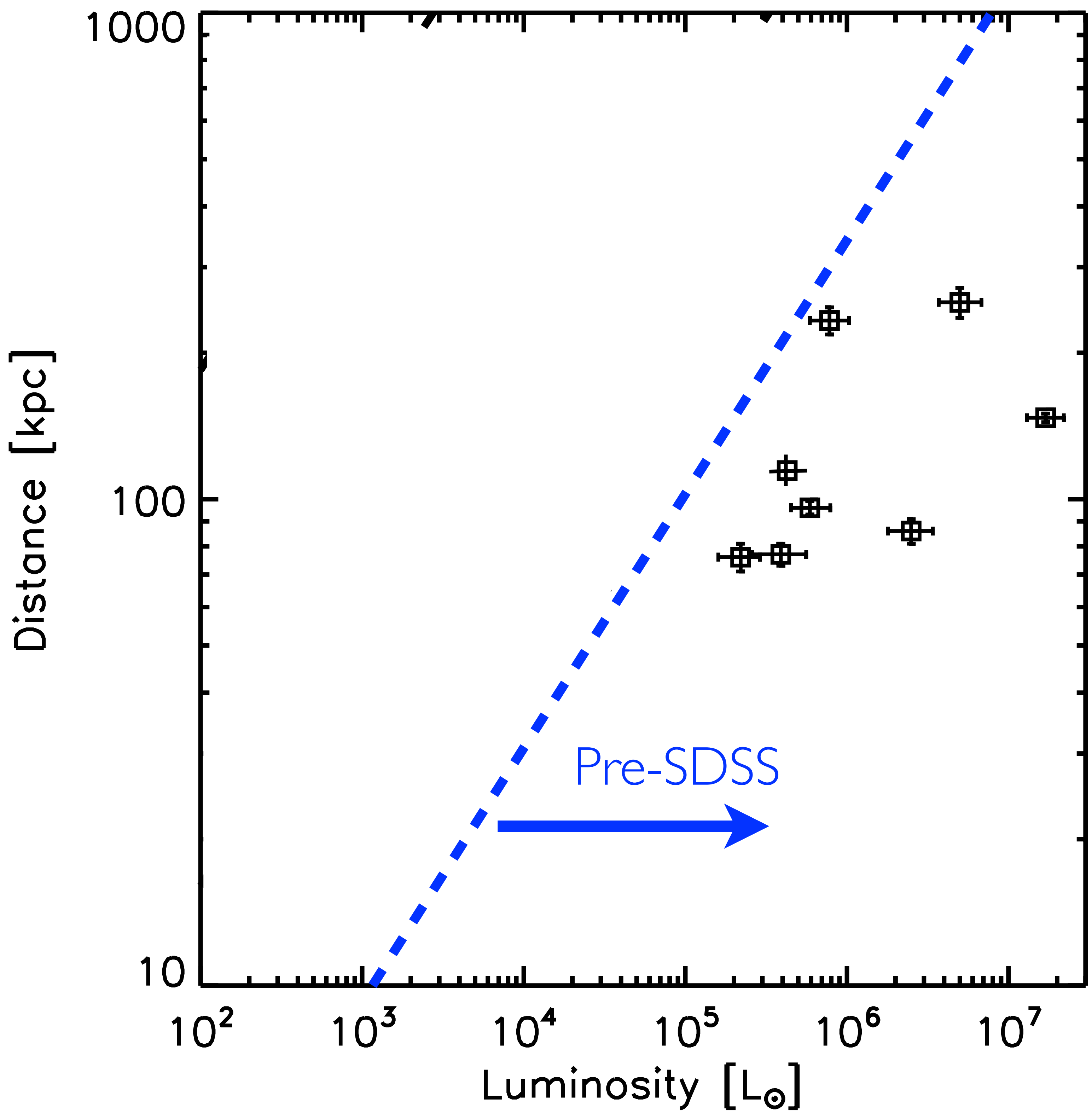
- Both SIDM and WDM can alleviate or eliminate this problem, but for different reasons
- Gas physics may change the picture, but almost everyone now agrees there is a scale ($M_{halo} \sim 10^{10}$ $M_{sun} \Rightarrow M_{star} \sim 10^{7}$ $M_{sun}$) below which number of supernovae is insufficient to affect dark matter structure

# DM distribution in MW satellites: what next?

- **As usual**: try to separate astrophysics from dark matter physics
- Move beyond the edge of the Milky Way
  - Supernova feedback scale is a robust prediction. Evidence of transition from cores in more luminous galaxies to cusps in less luminous ones?

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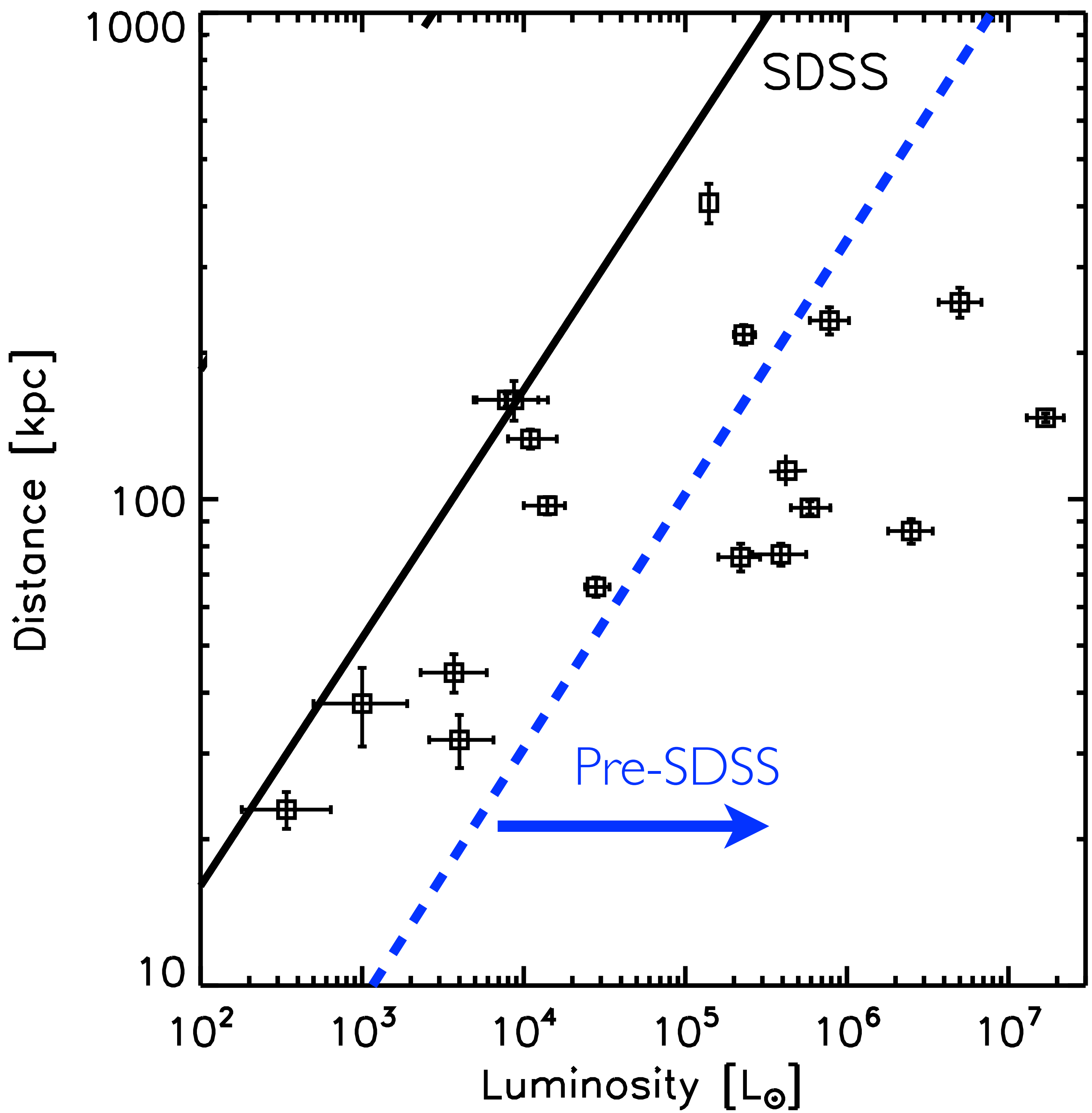


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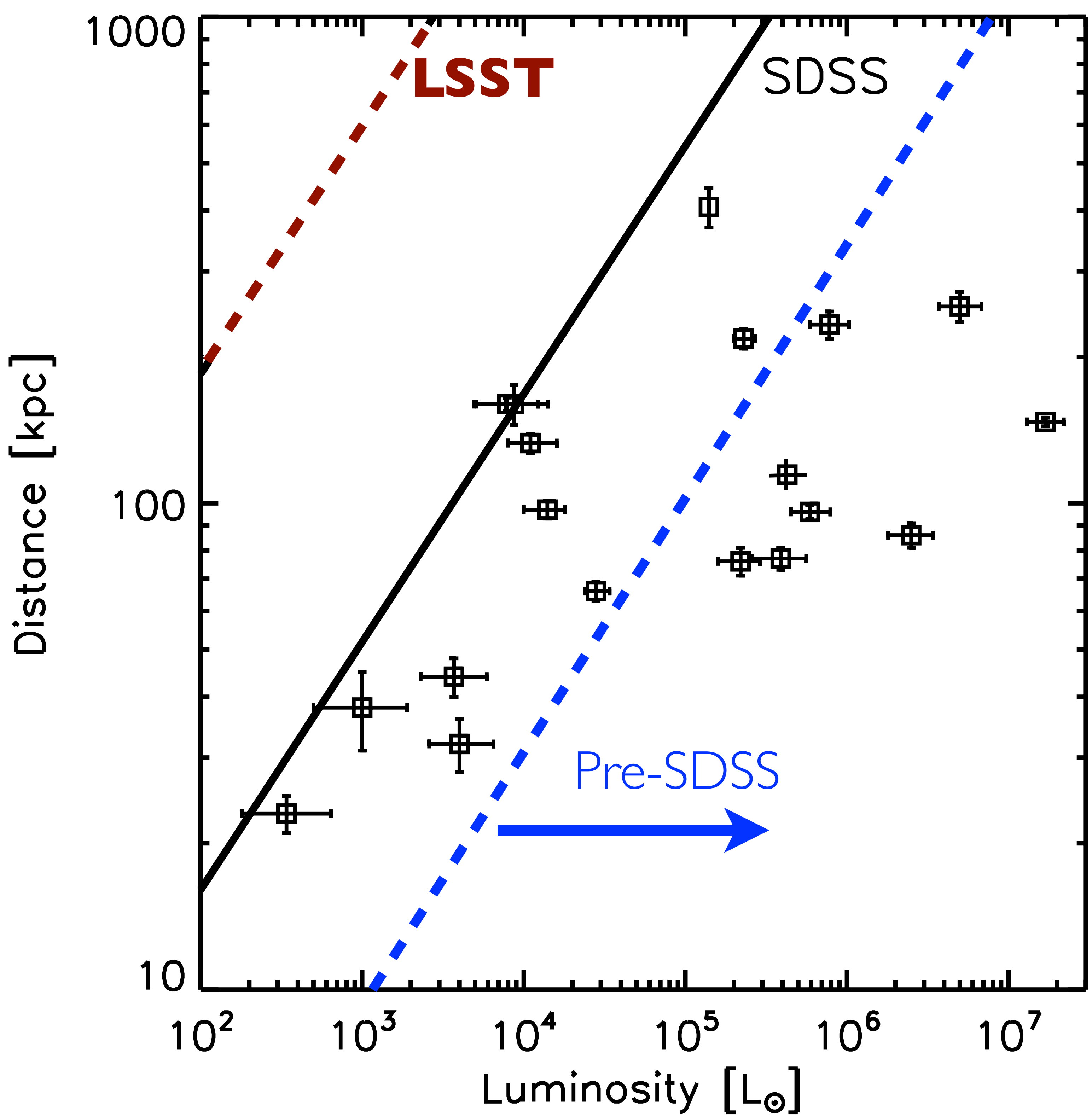


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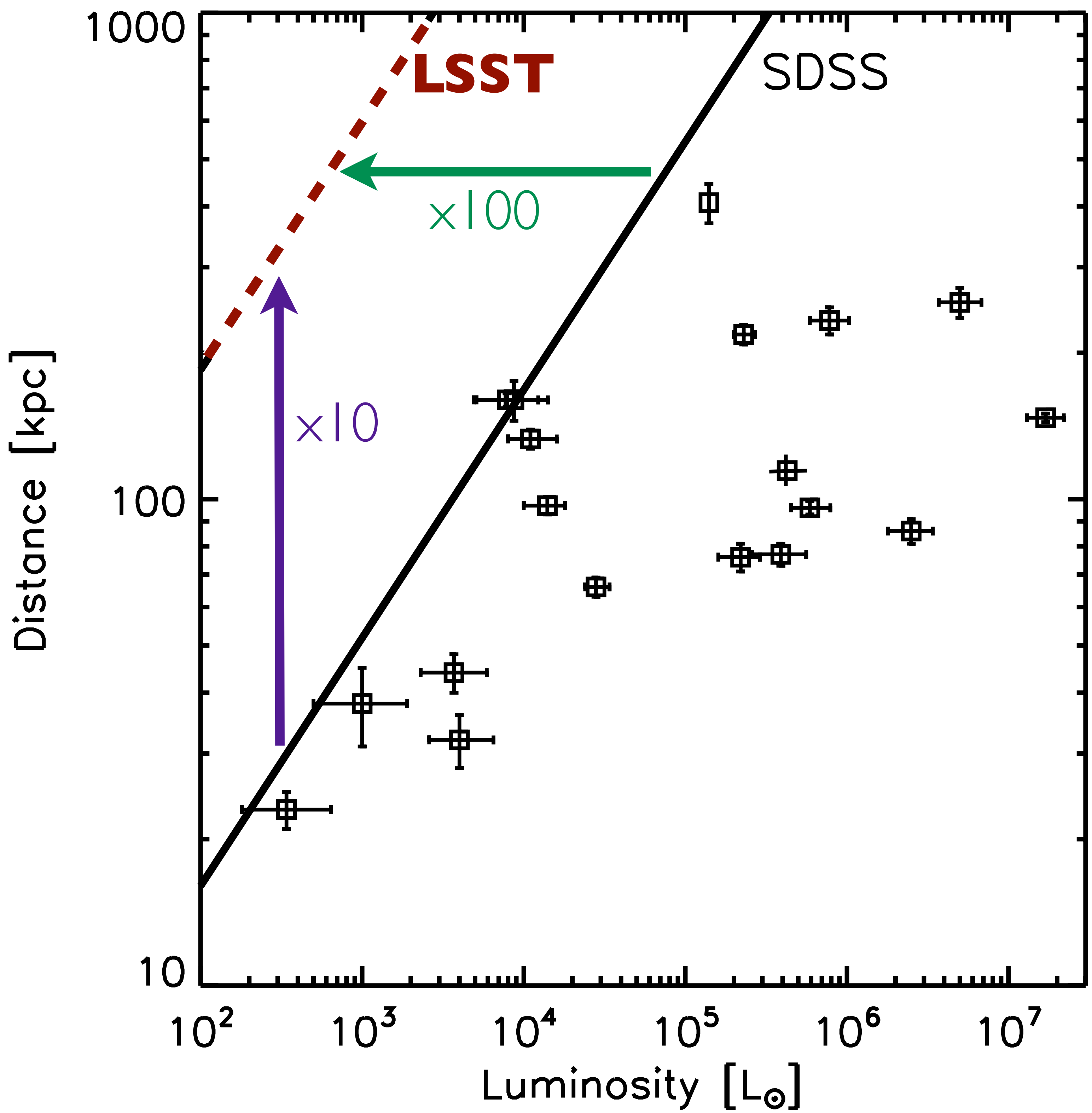


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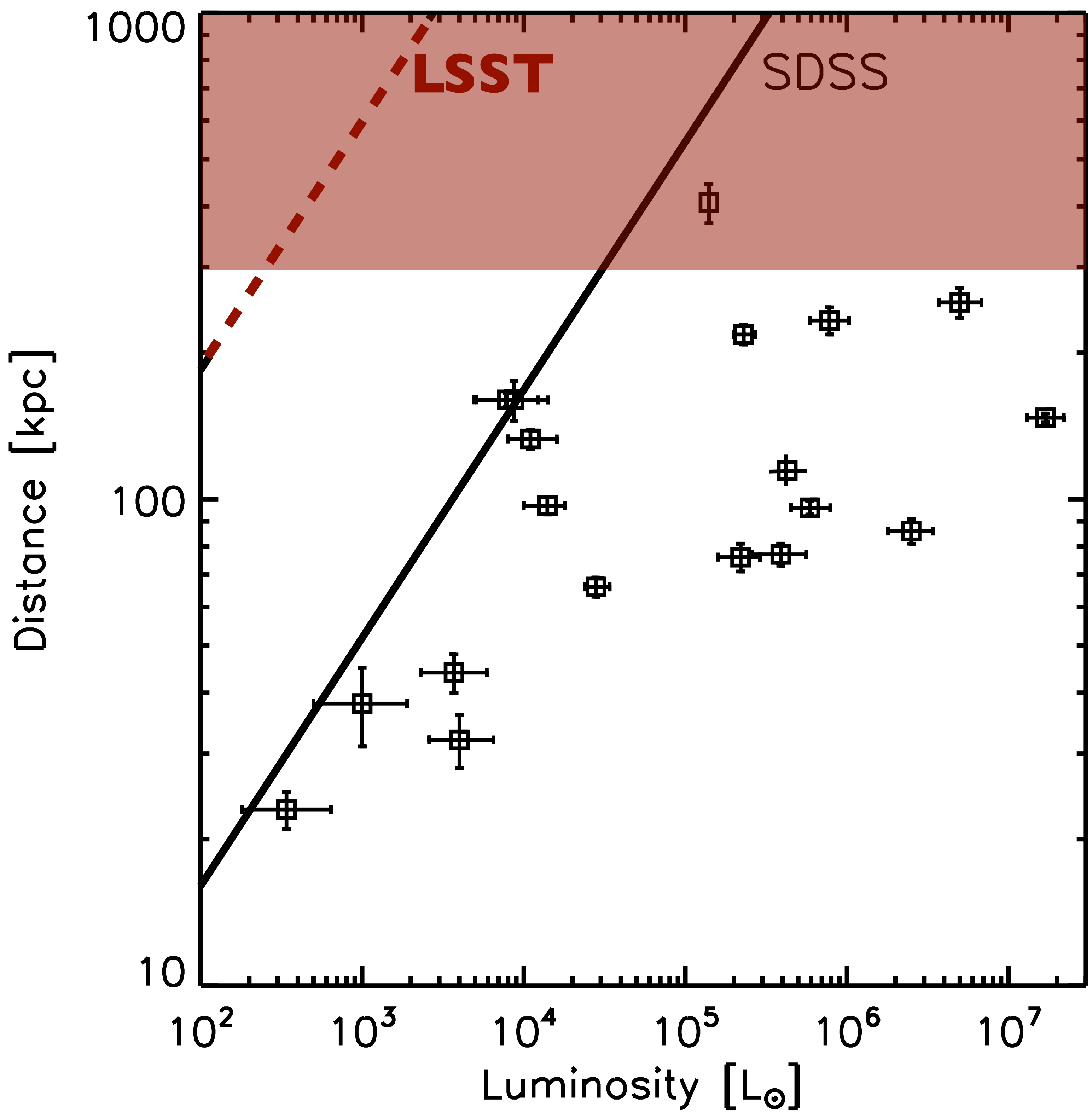


Virial radius of Milky Way

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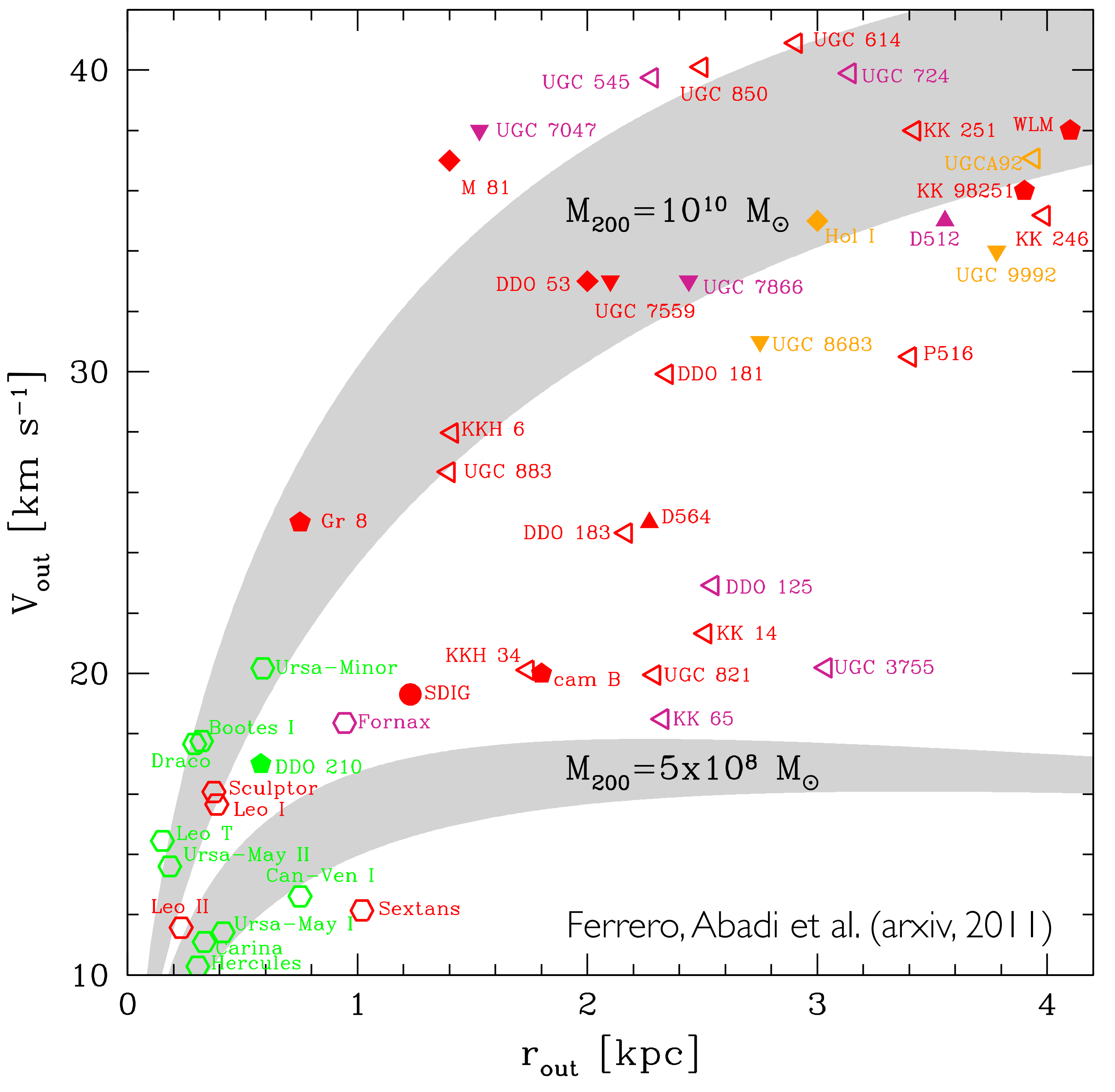
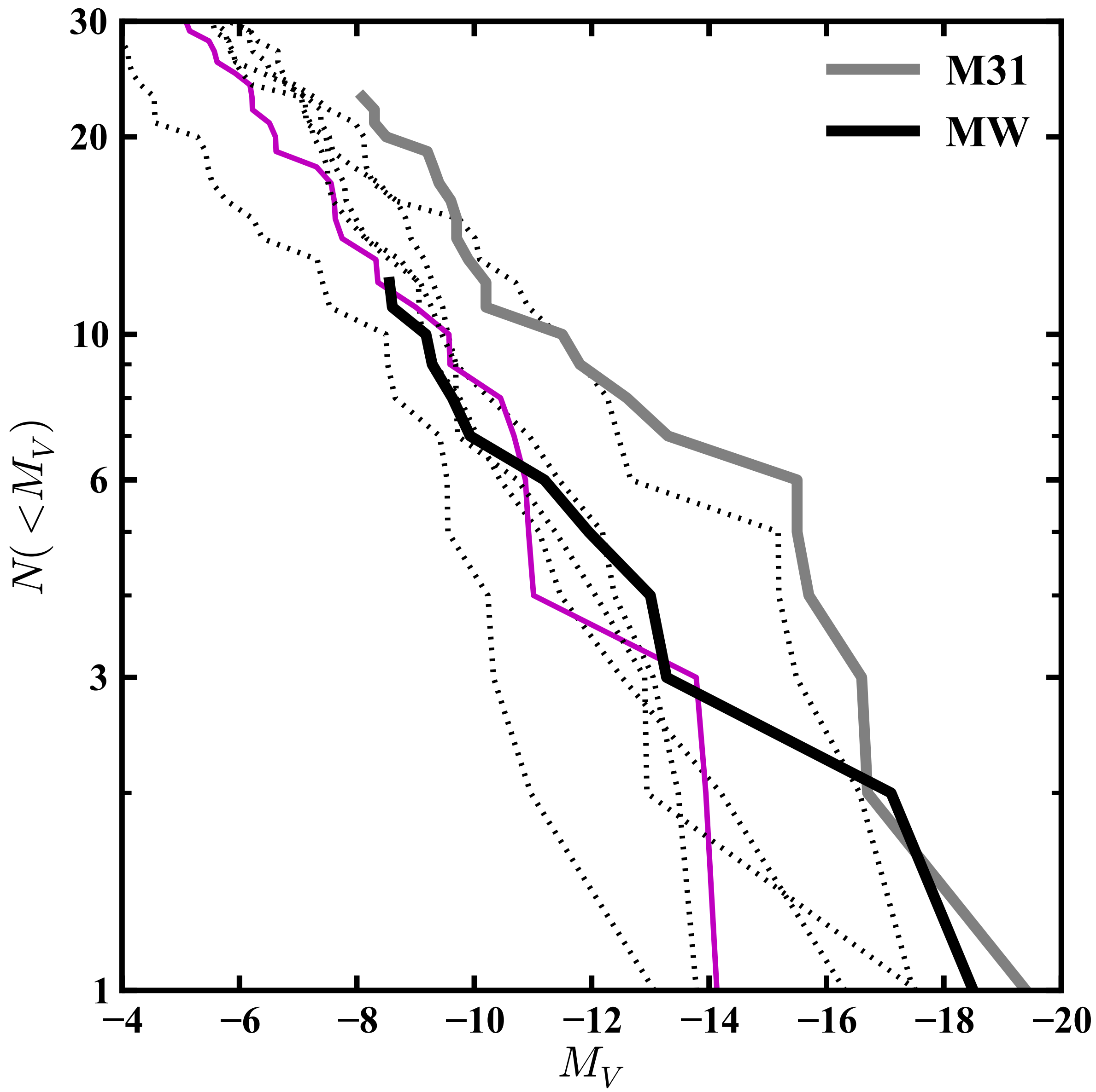
- **Simulations**: more dark-matter-only (current level of resolution OK); more, more realistic, higher resolution with full hydrodynamics

# Extra Slides

# Similar issues in isolated field galaxies



# Not possible to match the abundance and structure of the MW dSphs simultaneously

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MBK, Bullock, & Kaplinghat 2012

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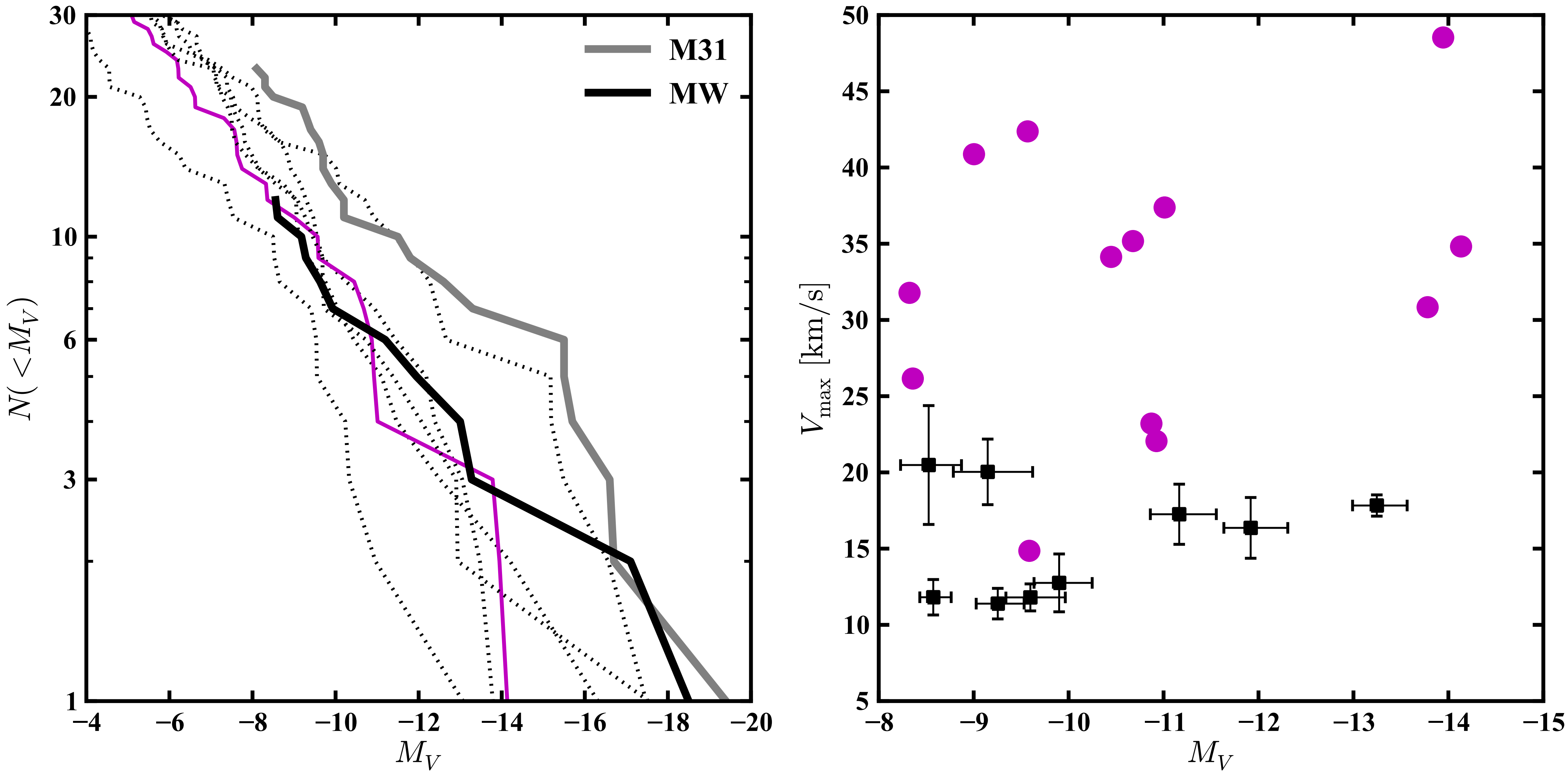


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... but puts the MW satellites in halos that are 2-5 times more massive than is observed

MBK, Bullock, & Kaplinghat 2012

# Power Spectra for C+WDM

Anderhalden, Schneider, Maccio, Diemand, & Bertone 2013

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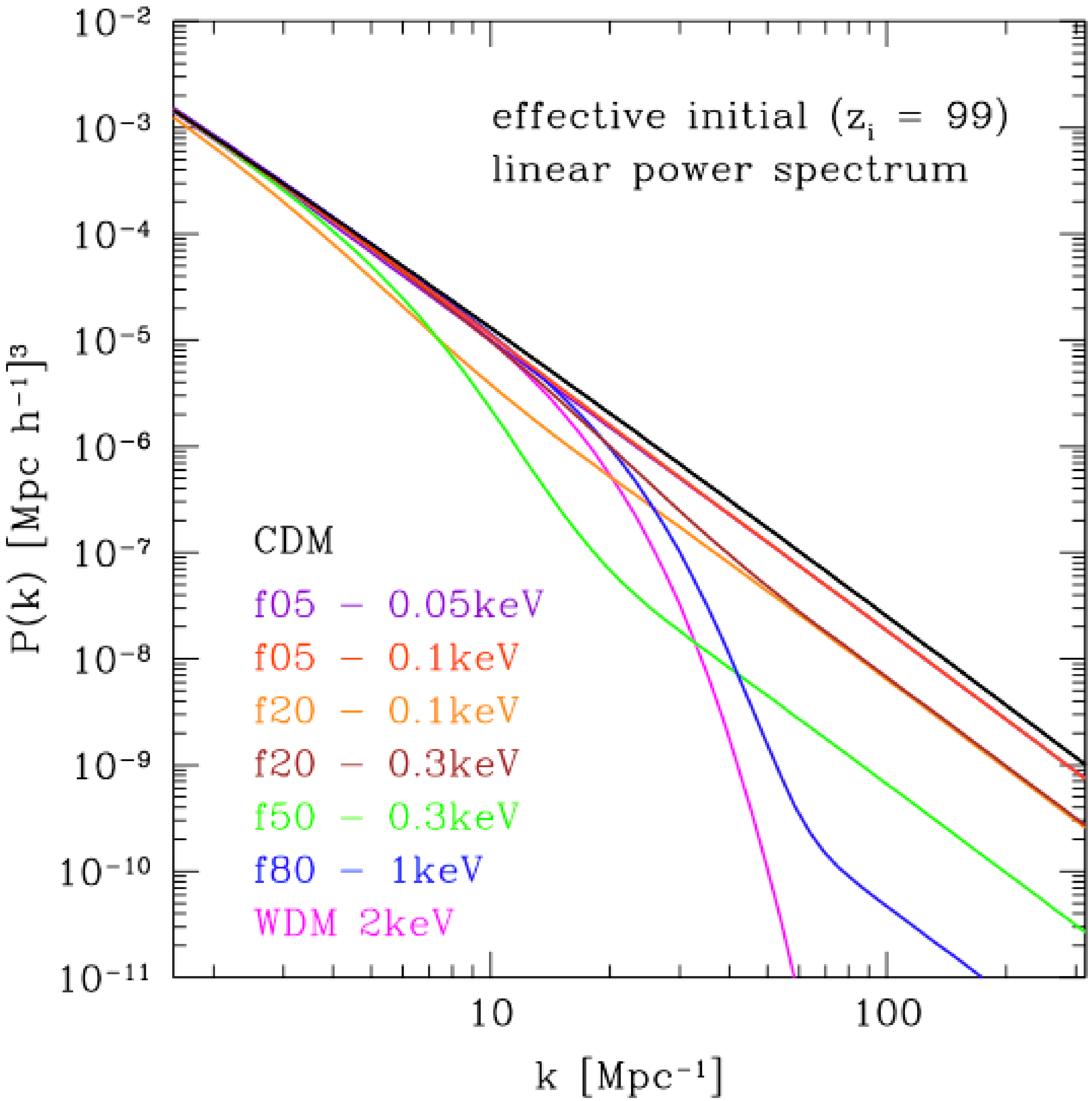


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