The Puzzling Darkness of Massive Milky Way Subhalos

Mike Boylan-Kolchin

Center for Galaxy Evolution
UC Irvine

with James Bullock and Manoj Kaplinghat

Southern California CGE Center for Galaxy Evolution

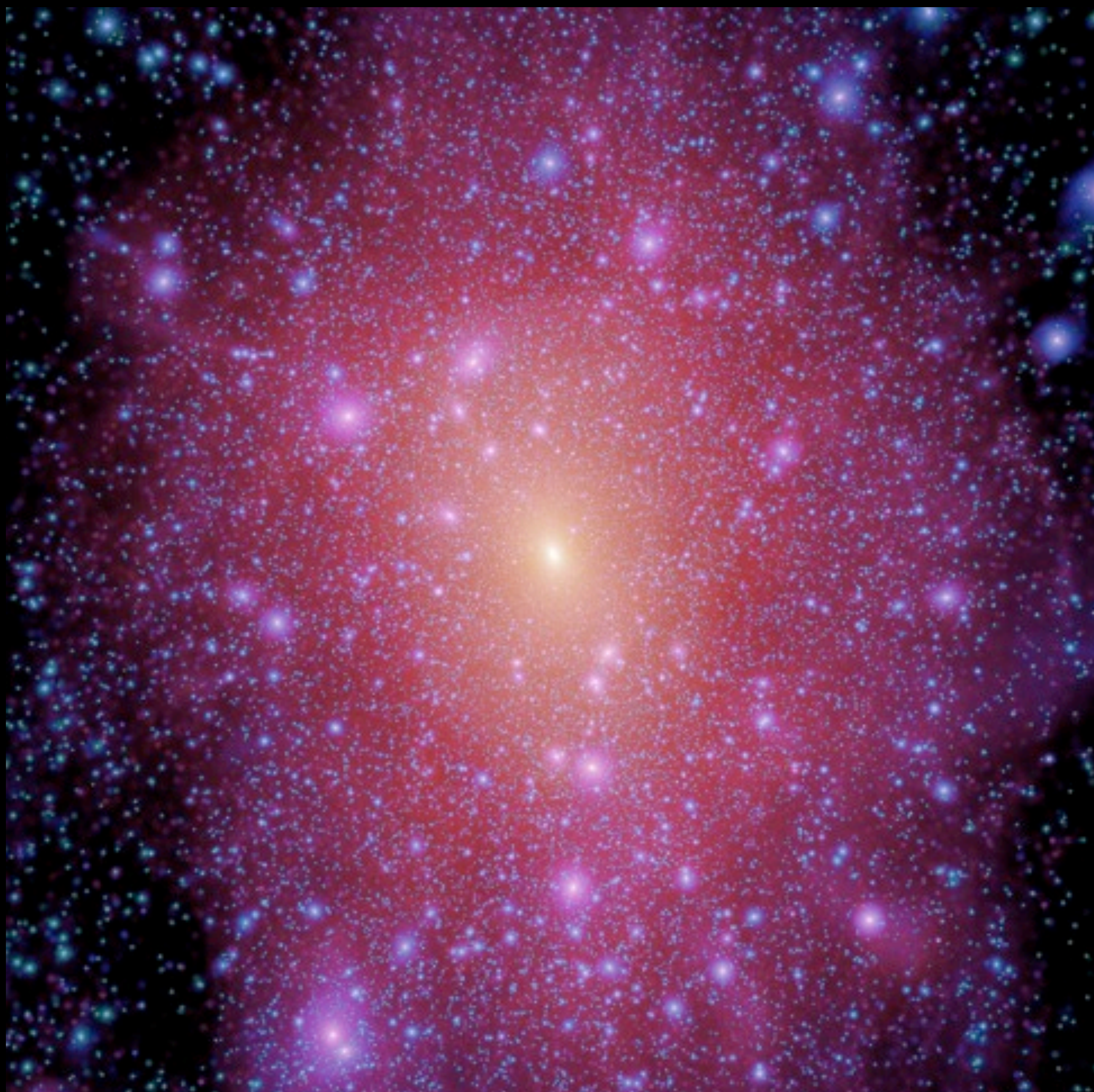
First Light and Faintest Dwarfs (KITP)
16 February 2012

Executive Summary

The most massive subhalos in the current generation of ultra-high-resolution N-body simulations are too dense to host any of the Milky Way's bright dwarf spheroidal galaxies, and are not massive enough to host the Magellanic Clouds.

ΛCDM subhalos vs. Milky Way satellites

"Missing satellites": Klypin et al. 1999, Moore et al. 1999



$>10^5$ identified subhalos

V. Springel / Virgo Consortium

State-of-the-art (ca. 2009): 10^9 particles in a single Milky Way-like halo

Aquarius (Springel et al. / Virgo Consortium)

Via Lactea I, II (Diemand, Kuhlen, Madau)

G-Halo (Stadel et al.)

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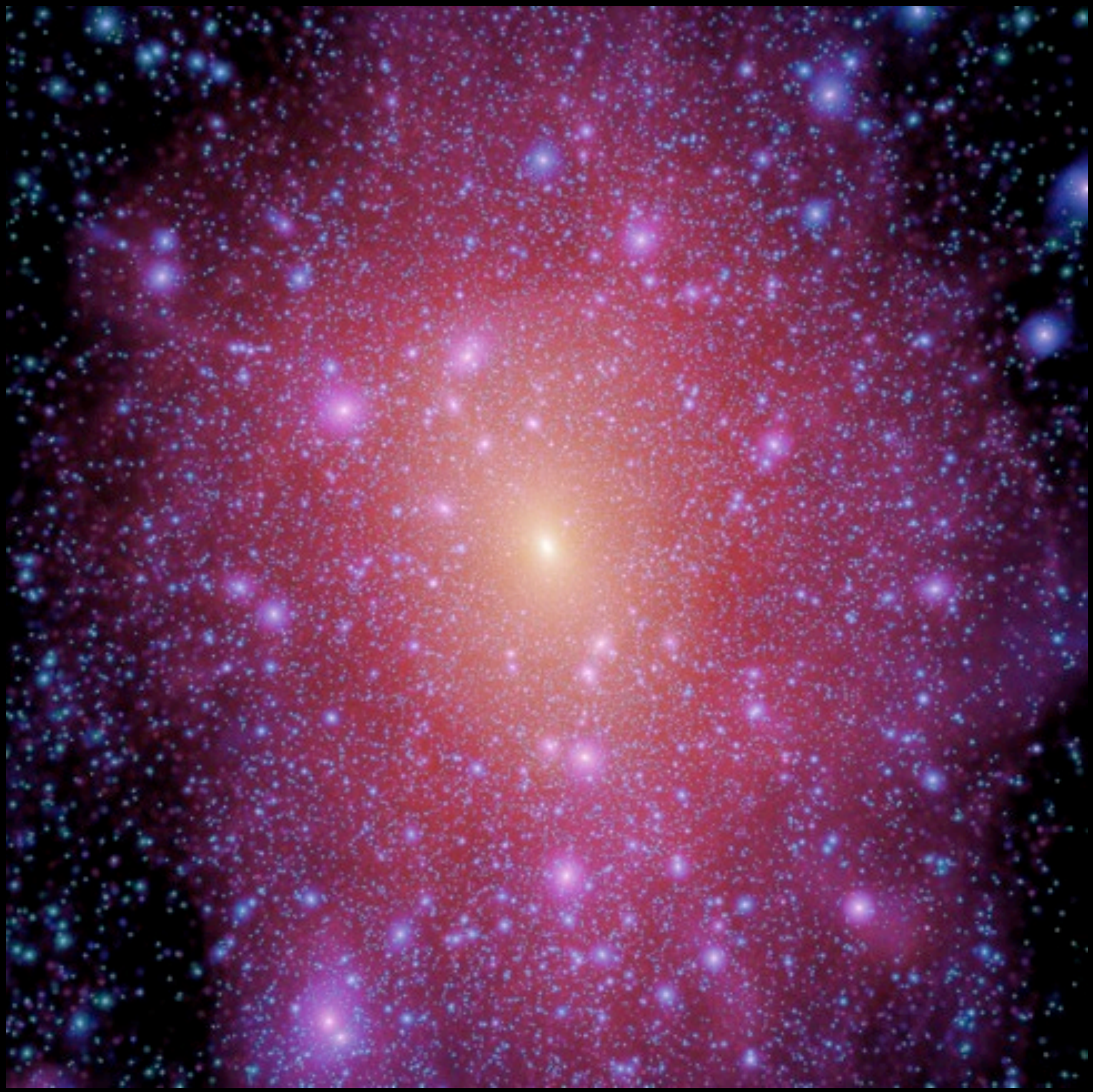

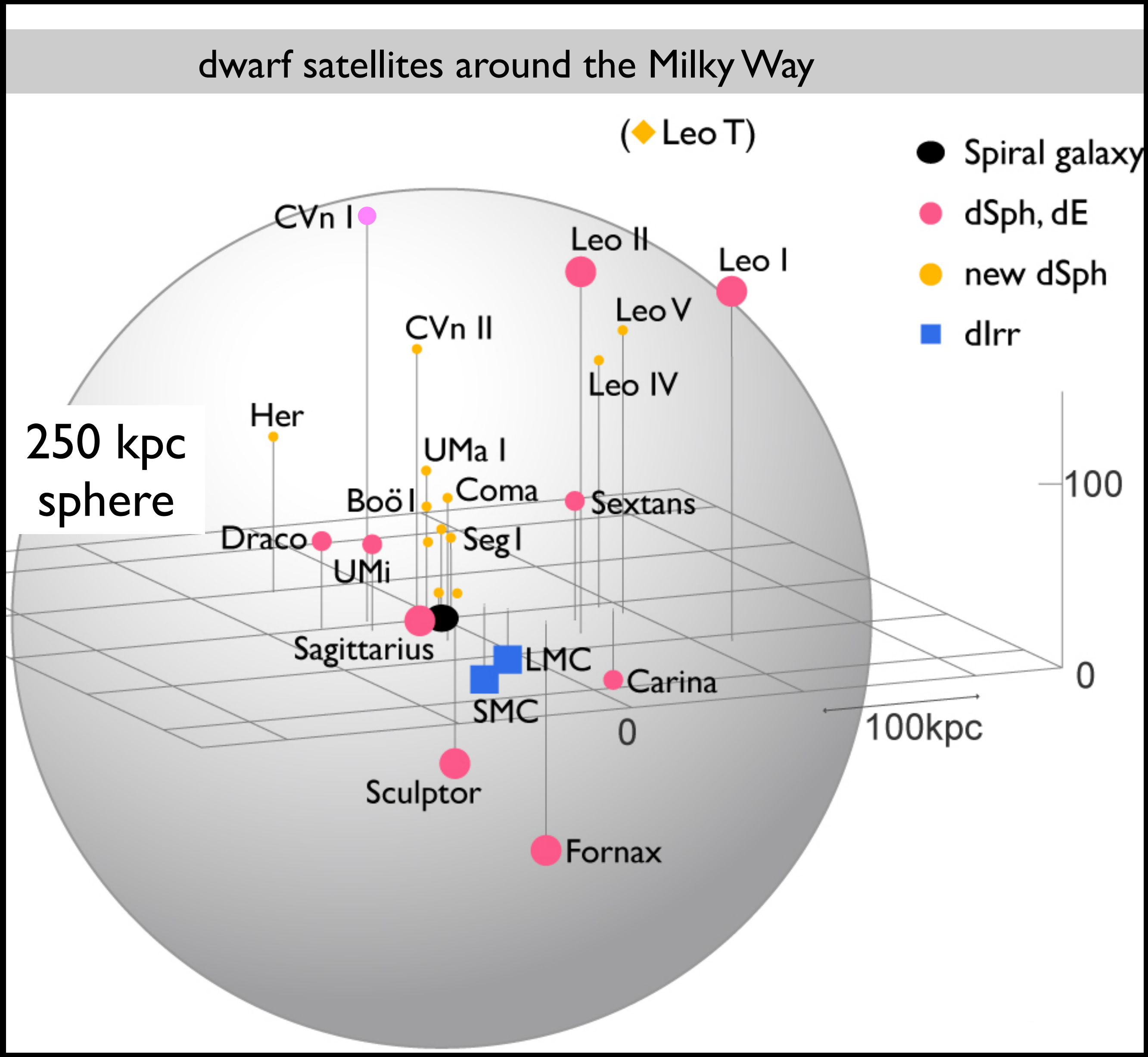

>10^5 identified subhalos

V. Springel / Virgo Consortium

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

S. Okamoto

ΛCDM-based explanations of the Missing Satellites

- **Tidal heating** alters inner structure of galaxies: $V_{\rm circ} \gg \sqrt{3}\,\sigma_\star$ (observed satellites $\Longleftrightarrow$ most massive subhalos at z=0)

Stoehr et al. 2002; Penarrubia et al. 2008; Benson et al. 2000; Bullock et al. 2000; Ricotti & Gnedin 2005; Okamoto & Frenk 2009; Koposov et al. 2009; Bovill & Ricotti 2011; Kravtsov et al. 2004; Conroy et al. 2006

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➡ Discovery of new dwarfs in SDSS + reasonable physics = no problem?

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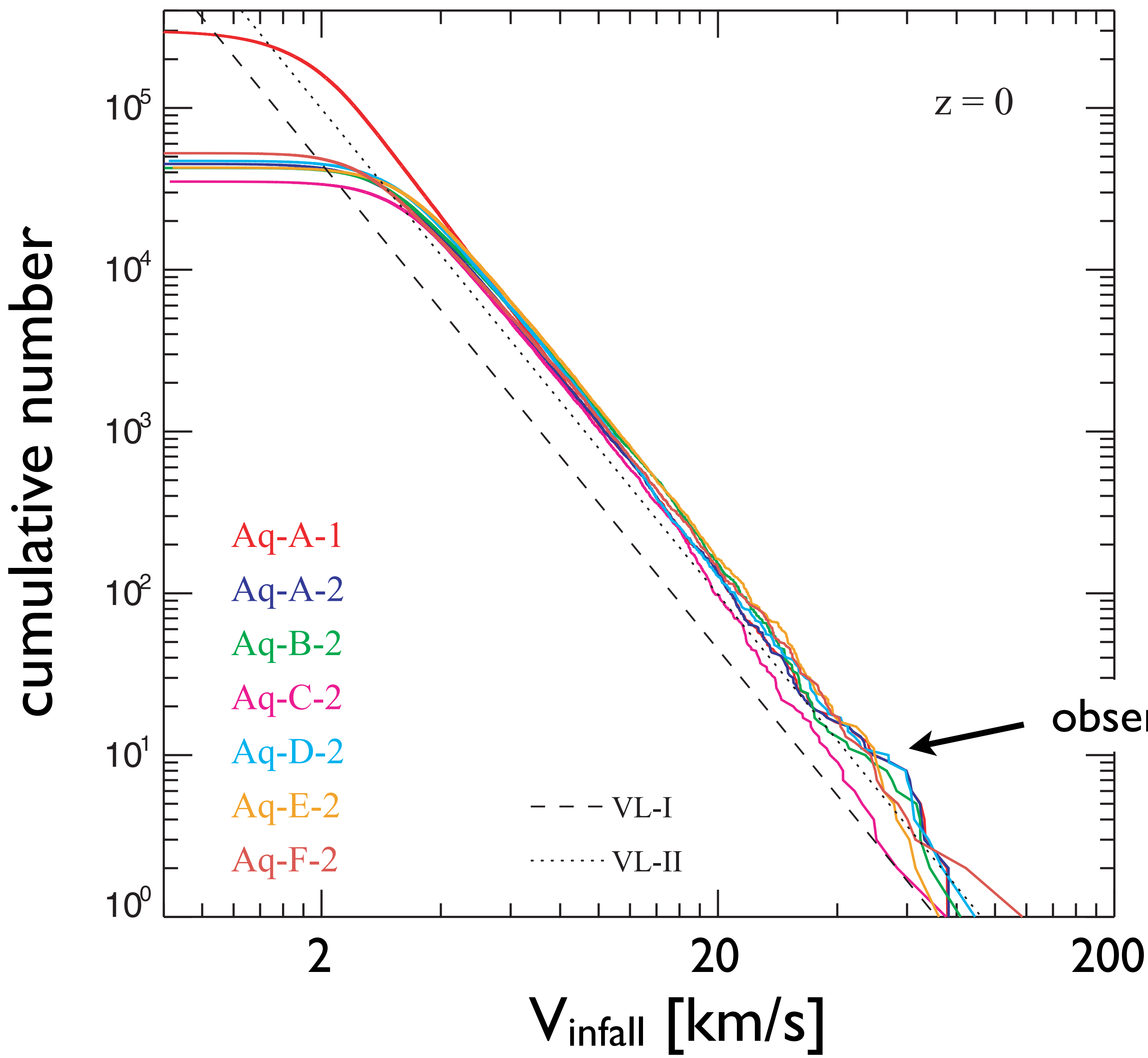
A simple explanation (?)



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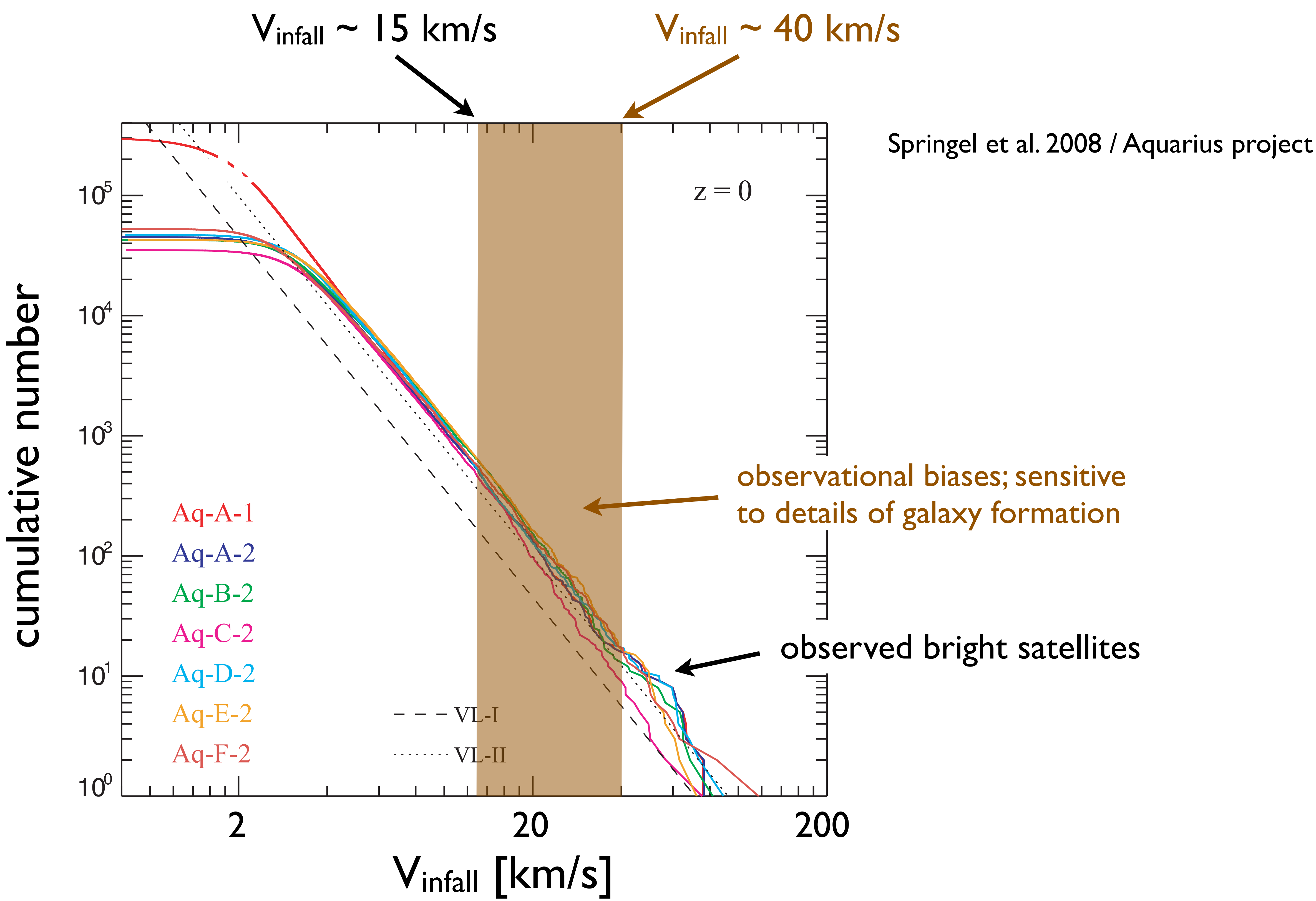

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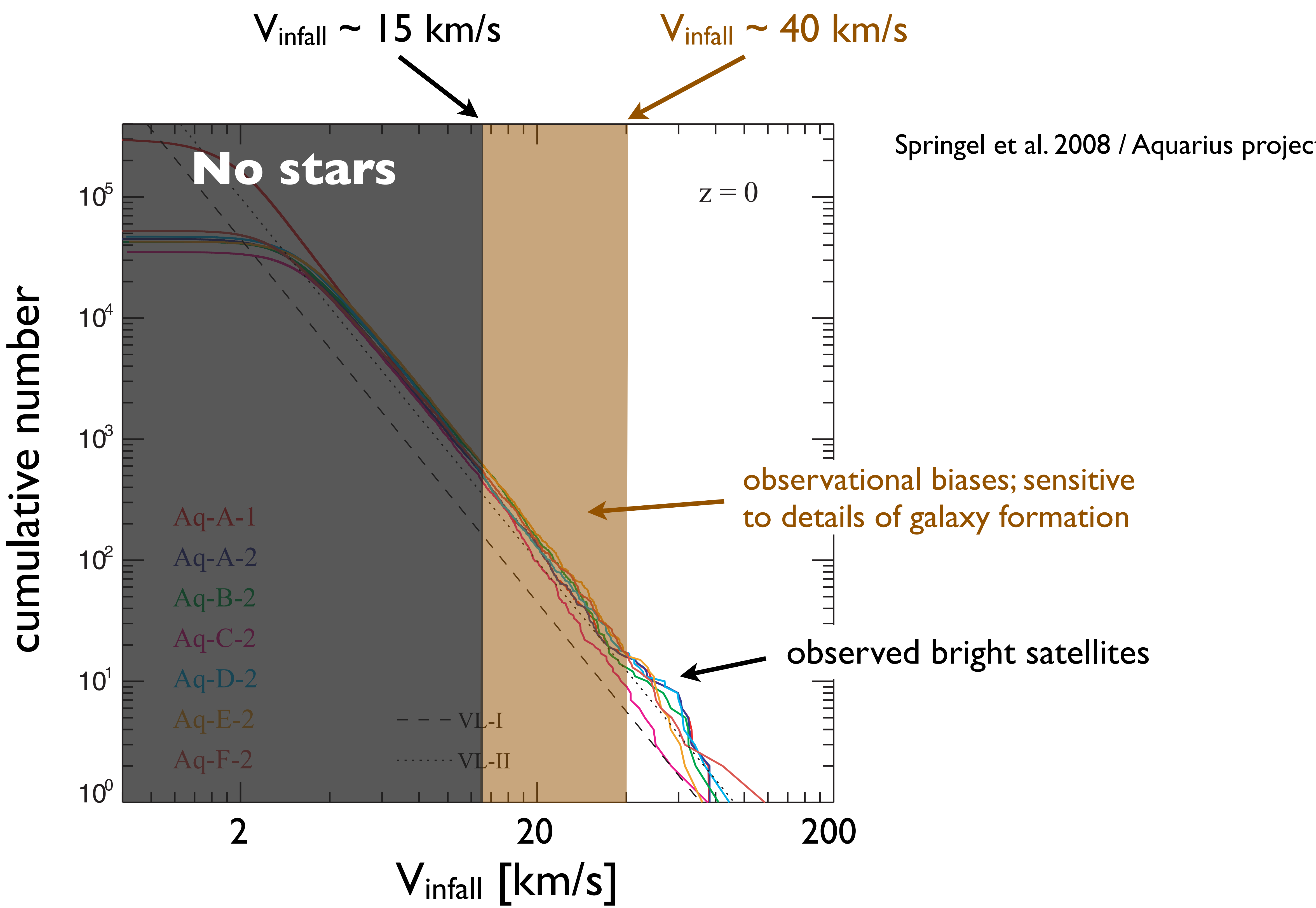
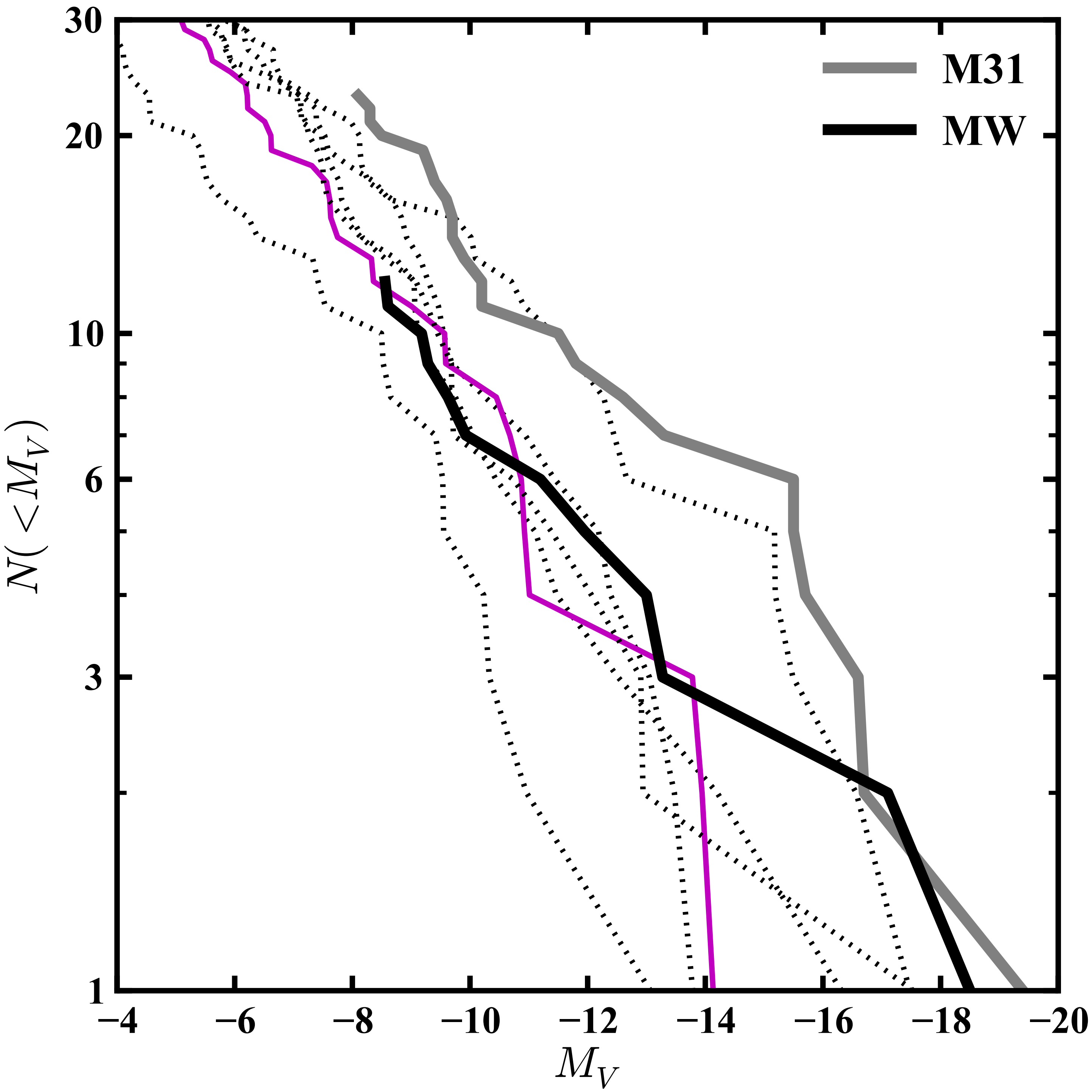


Zero scatter abundance matching reproduces the MW satellite luminosity function nicely (if you think this is good enough, you won't like the rest of my talk)



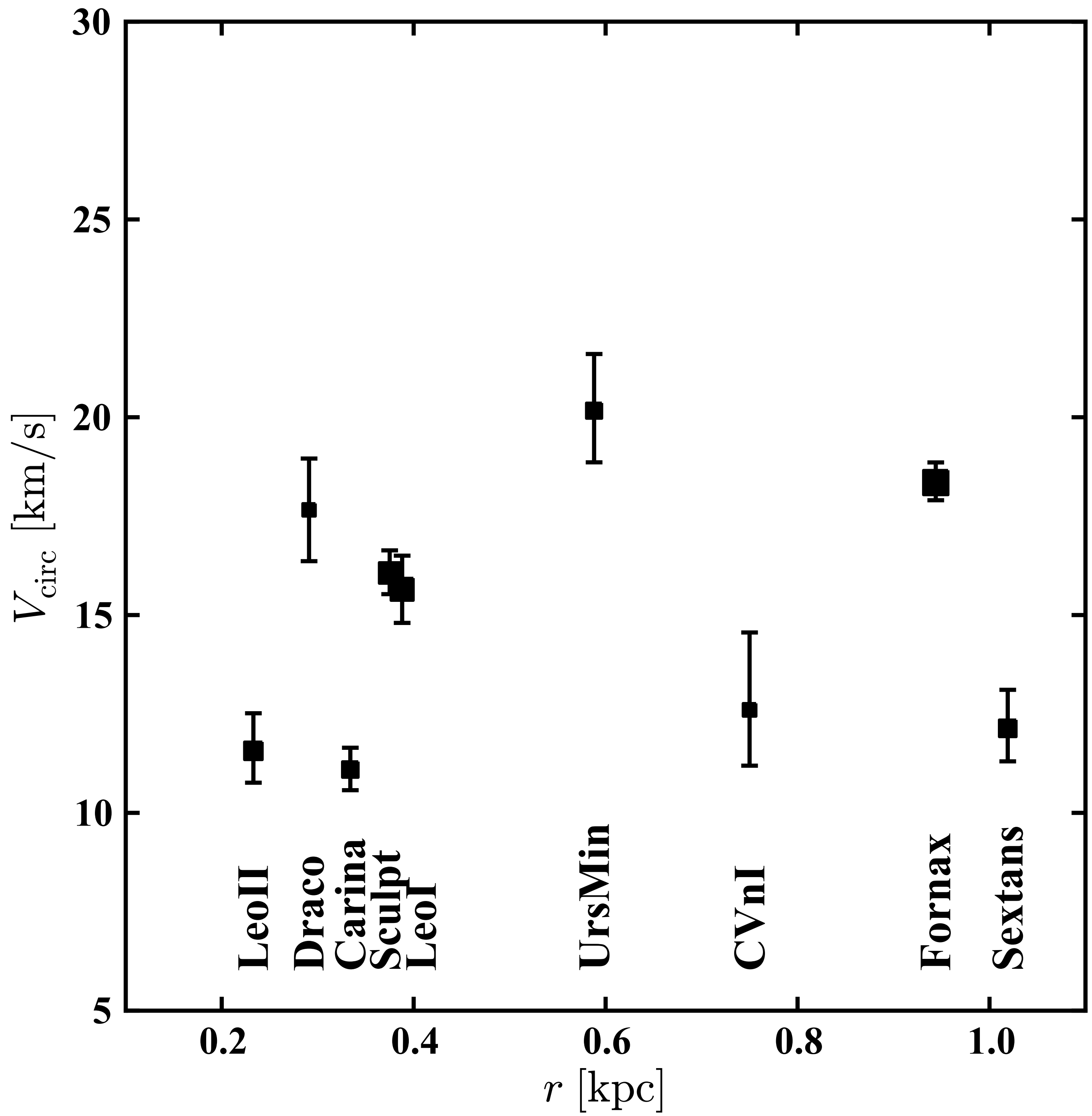
Measured masses for bright MW dwarfs

Masses of MW dwarfs are well-constrained at $R_{1/2}$:
(Walker et al. 2009, Wolf et al. 2010)

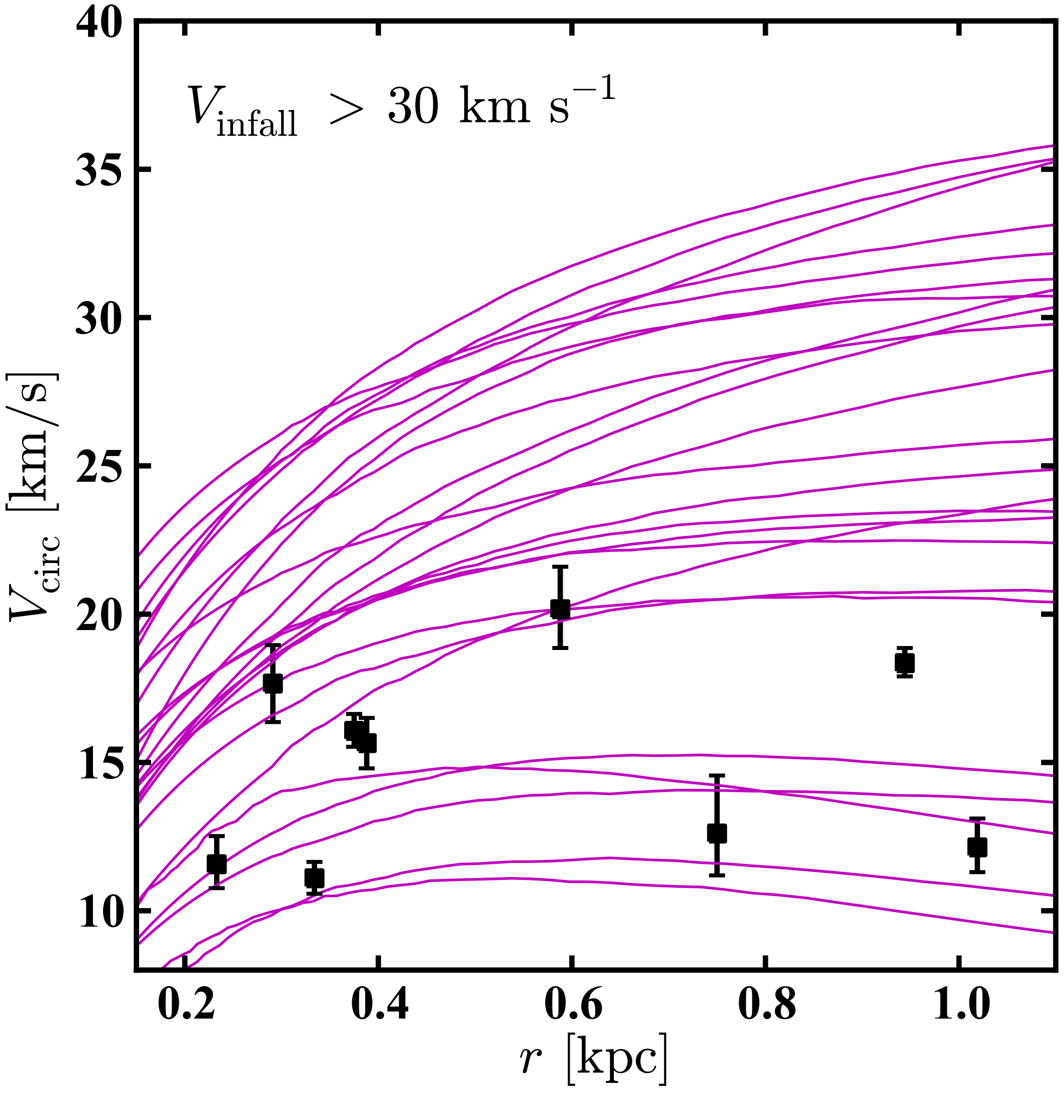
$$V_{\rm circ}(R_{1/2}) = \sqrt{3}\,\sigma_\star$$

***N*-body simulations now resolve $R_{1/2}$ for MW dwarfs**
Requirement: resolve scales of ~100 pc → 10^8 particles in R_{vir}
(Springel et al. 2008; Diemand et al. 2008)

Directly compare observed satellites to simulated subhalos at $R_{1/2}$



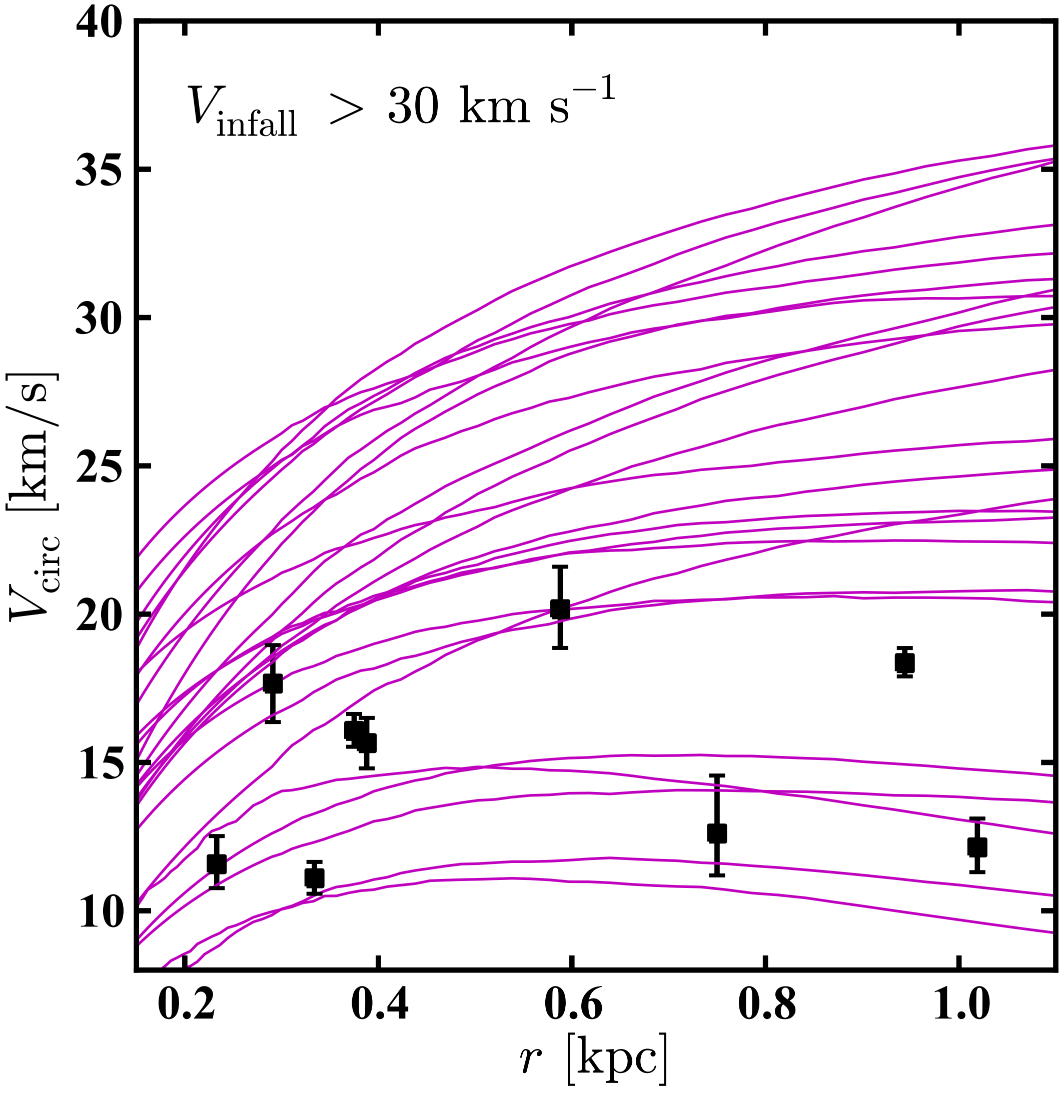
MBK, Bullock, & Kaplinghat 2011, 2012

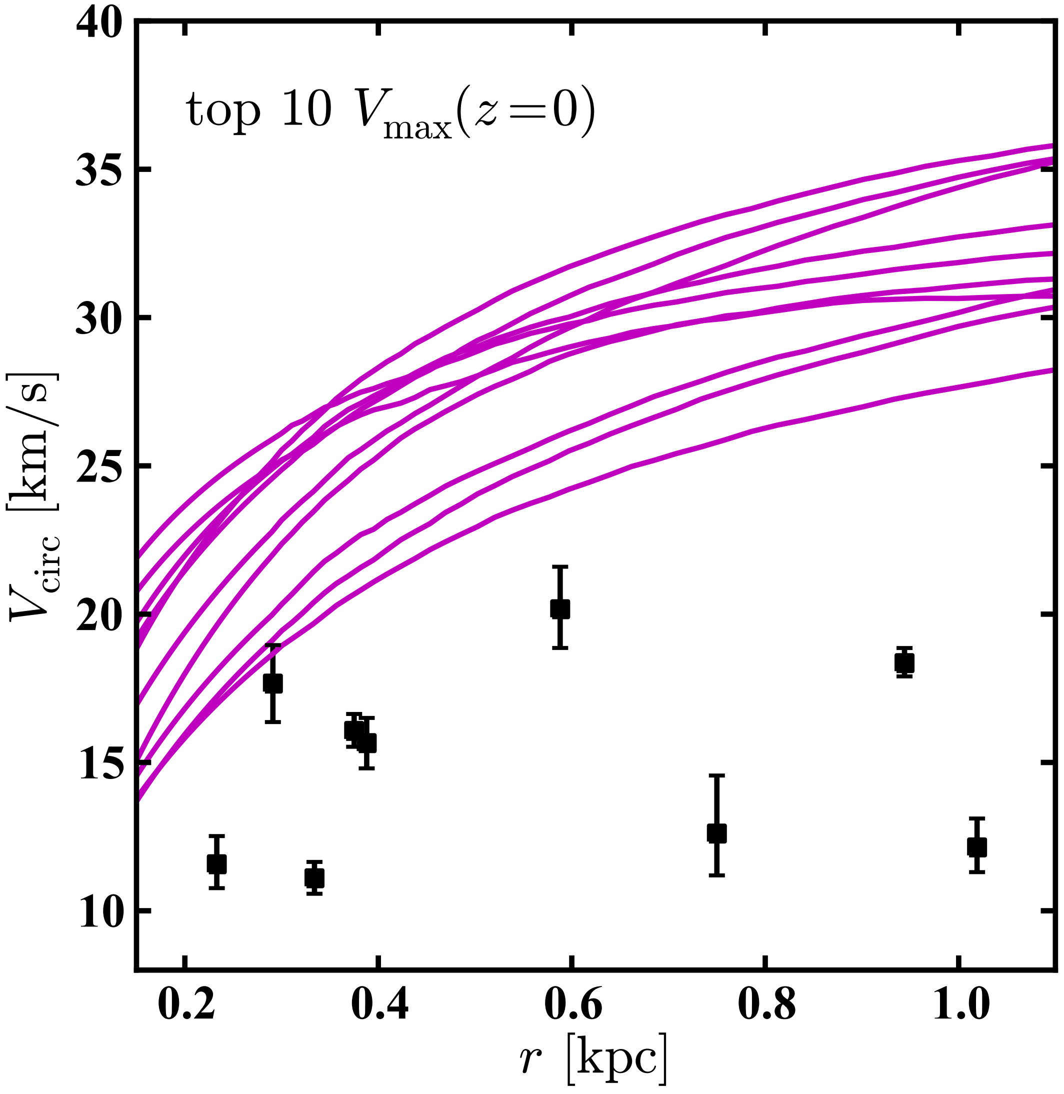


mass profiles of subhalos measured **directly** from Aquarius E simulation ($M_{vir}=1.4 \times 10^{12}\ M_{sun}$)

MBK, Bullock, & Kaplinghat 2011, 2012

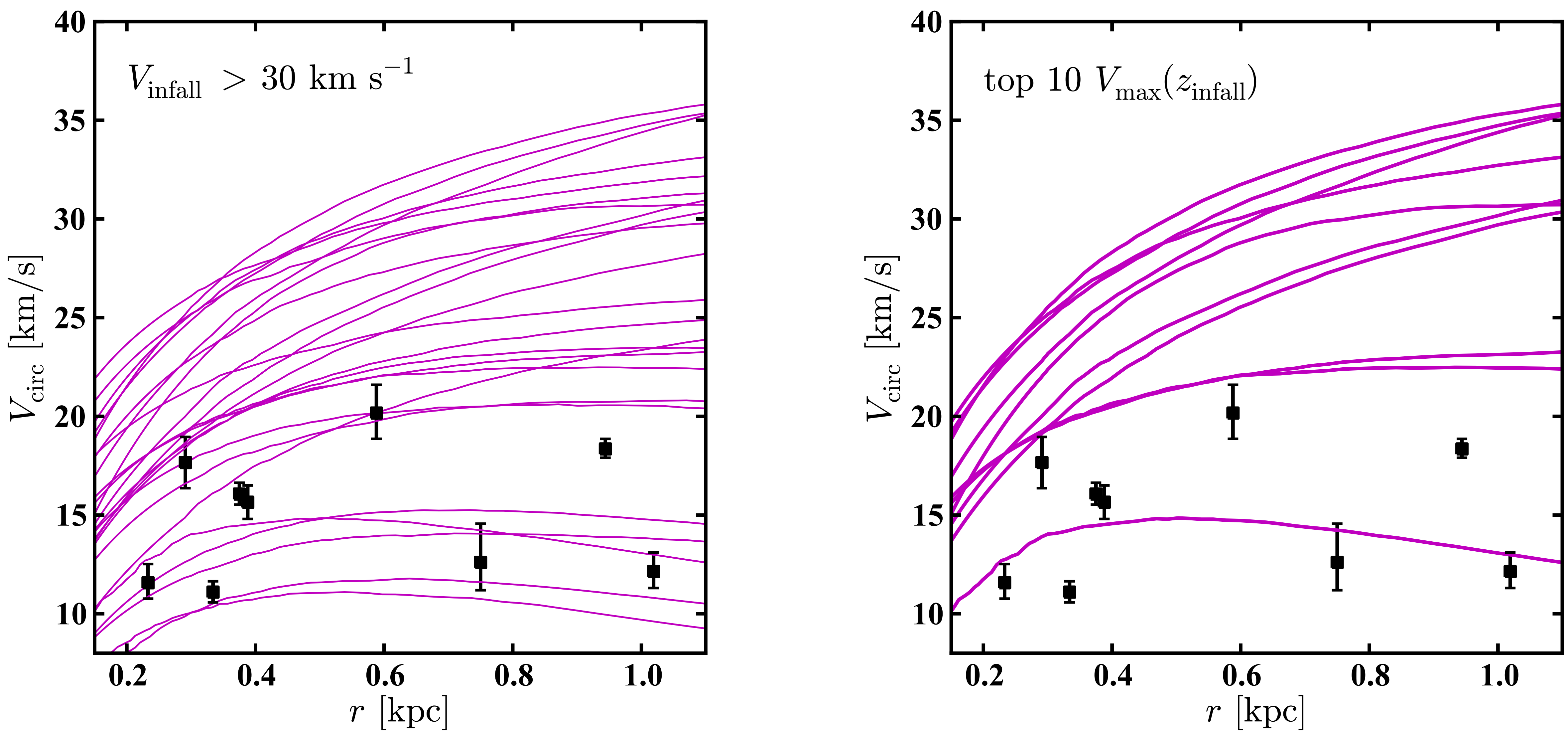
Most massive subhalos at z=0





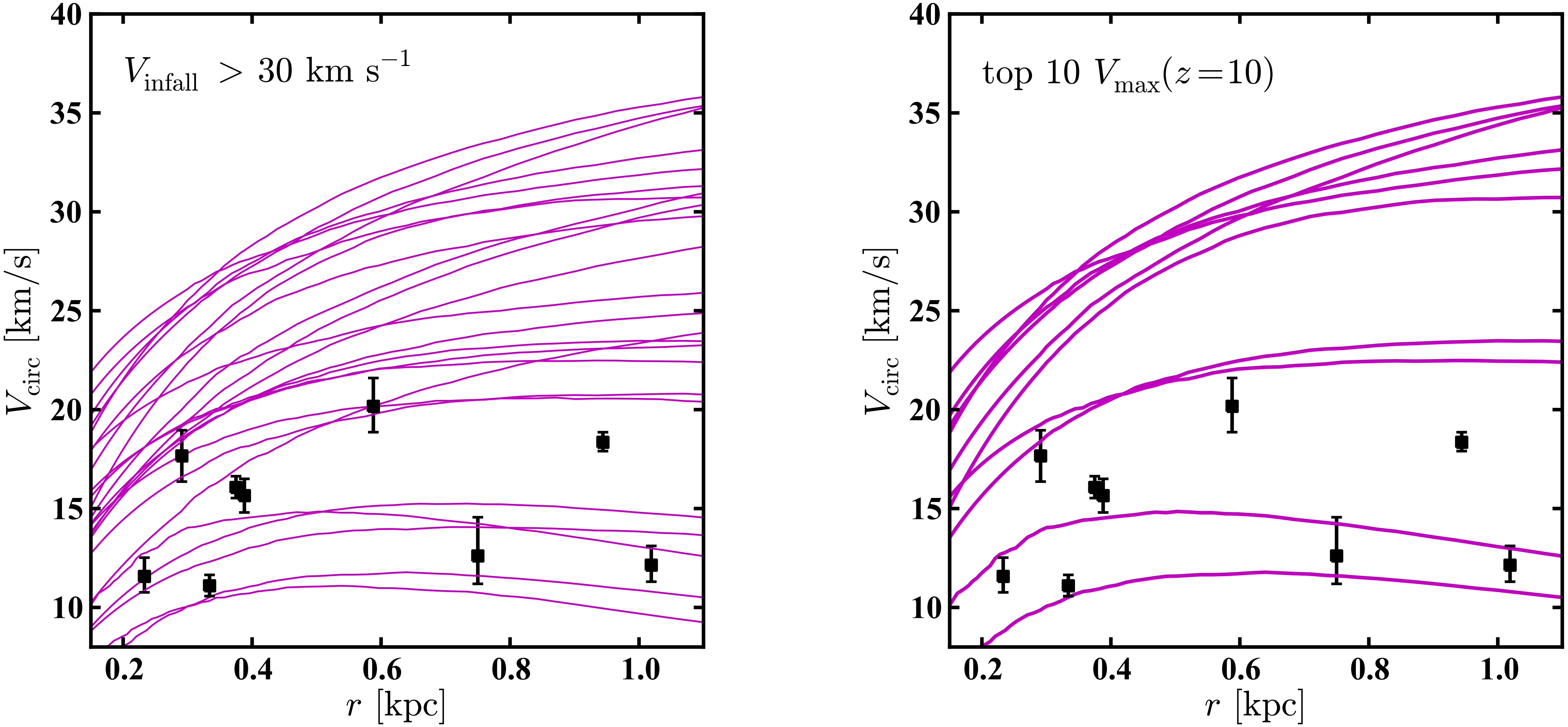
MBK, Bullock, & Kaplinghat 2011, 2012

Abundance matching / internal feedback model



MBK, Bullock, & Kaplinghat 2011, 2012

Reionization model



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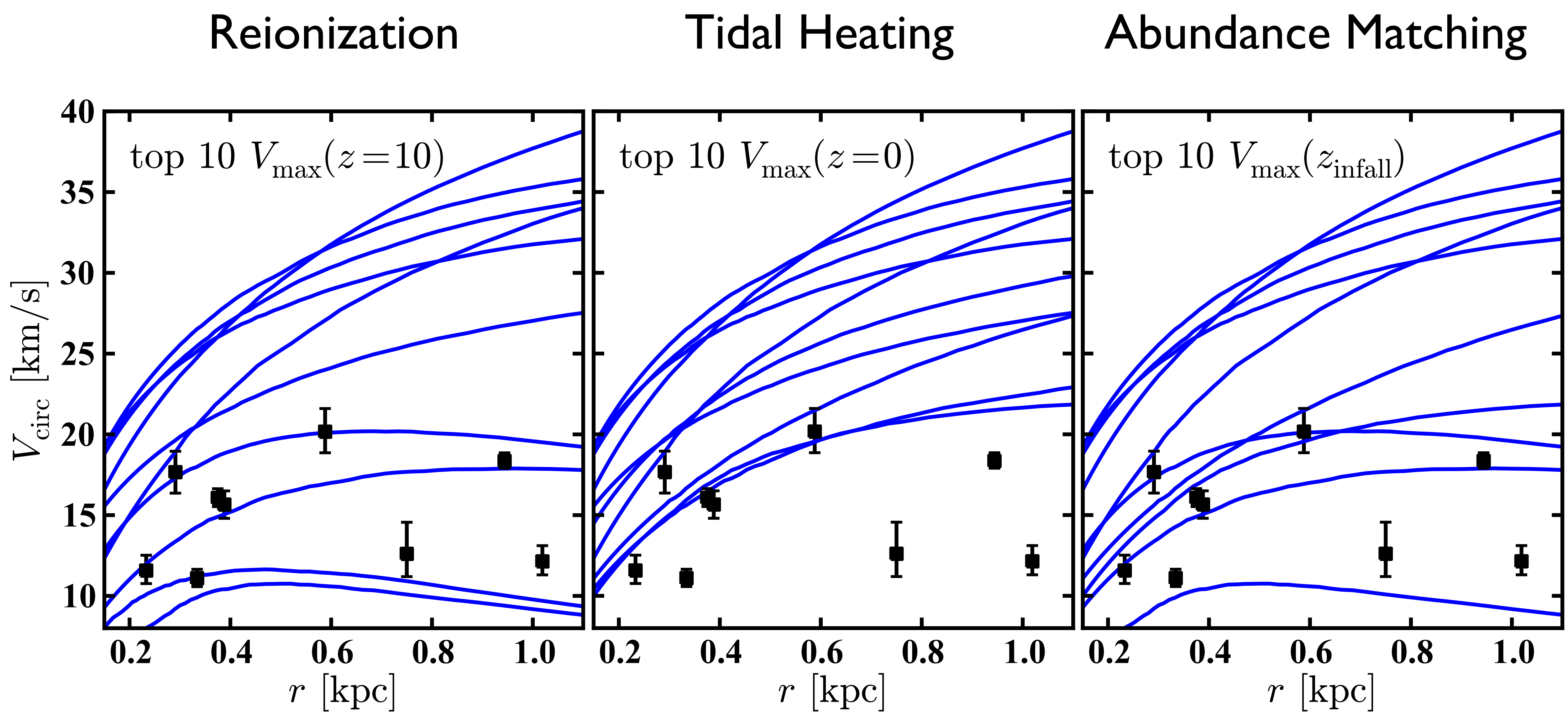
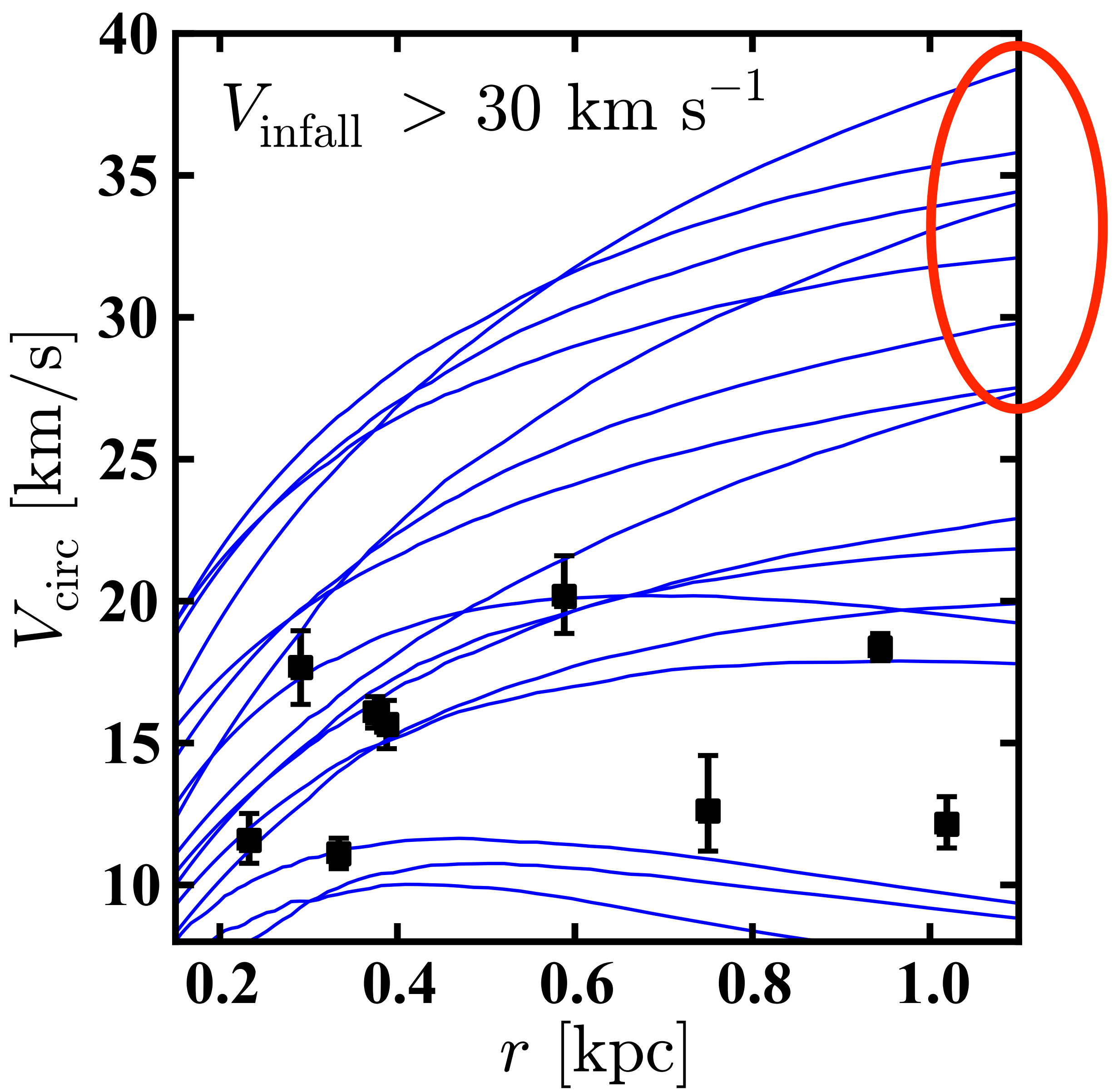


Aquarius B (M_{vir}=9.5x10^{11} M_{sun})



7 subhalos, only 2 dwarfs (Draco + Sagittarius)

Probability of finding 2 Magellanic Clouds in such a halo: ~3% or less
(MBK et al. 2010, Busha et al. 2011)

Aquarius B (M_{vir}=9.5x10^{11} M_{sun})

This problem is much worse in more massive halos

Name	L_V $[L_\odot]$	$V_{\rm max}$ $[{\rm km\,s^{-1}}]$	$V_{\rm infall}$ $[{\rm km\,s^{-1}}]$	$M_{\rm infall}$ $[M_\odot]$
Fornax	$1.7^{+0.5}_{-0.4} \times 10^7$	$17.8^{+0.7}_{-0.7}$	$22.0^{+4.7}_{-3.9}$	$7.4^{+6.1}_{-3.3} \times 10^8$
LeoI	$5.0^{+1.8}_{-1.3} \times 10^6$	$16.4^{+2.3}_{-2.0}$	$20.6^{+5.7}_{-4.5}$	$5.6^{+6.8}_{-3.1} \times 10^8$
Sculpt	$2.5^{+0.9}_{-0.7} \times 10^6$	$17.3^{+2.2}_{-2.0}$	$21.7^{+5.8}_{-4.6}$	$6.6^{+7.8}_{-3.6} \times 10^8$
LeoII	$7.8^{+2.5}_{-1.9} \times 10^5$	$12.8^{+2.2}_{-1.9}$	$16.0^{+4.7}_{-3.6}$	$2.4^{+3.1}_{-1.4} \times 10^8$
Sextans	$5.9^{+2.0}_{-1.4} \times 10^5$	$11.8^{+1.0}_{-0.9}$	$14.2^{+3.7}_{-2.9}$	$1.9^{+1.7}_{-0.9} \times 10^8$
Carina	$4.3^{+1.1}_{-0.9} \times 10^5$	$11.4^{+1.1}_{-1.0}$	$14.4^{+3.7}_{-3.0}$	$1.8^{+1.8}_{-0.9} \times 10^8$
UrsMin	$3.9^{+1.7}_{-1.3} \times 10^5$	$20.0^{+2.4}_{-2.2}$	$25.5^{+7.4}_{-5.8}$	$1.1^{+1.5}_{-0.6} \times 10^9$
CVnI	$2.3^{+0.4}_{-0.3} \times 10^5$	$11.8^{+1.3}_{-1.2}$	$14.5^{+4.0}_{-3.1}$	$1.9^{+2.0}_{-1.0} \times 10^8$
Draco	$2.2^{+0.7}_{-0.6} \times 10^5$	$20.5^{+4.8}_{-3.9}$	$25.9^{+8.8}_{-6.6}$	$1.2^{+2.0}_{-0.7} \times 10^9$

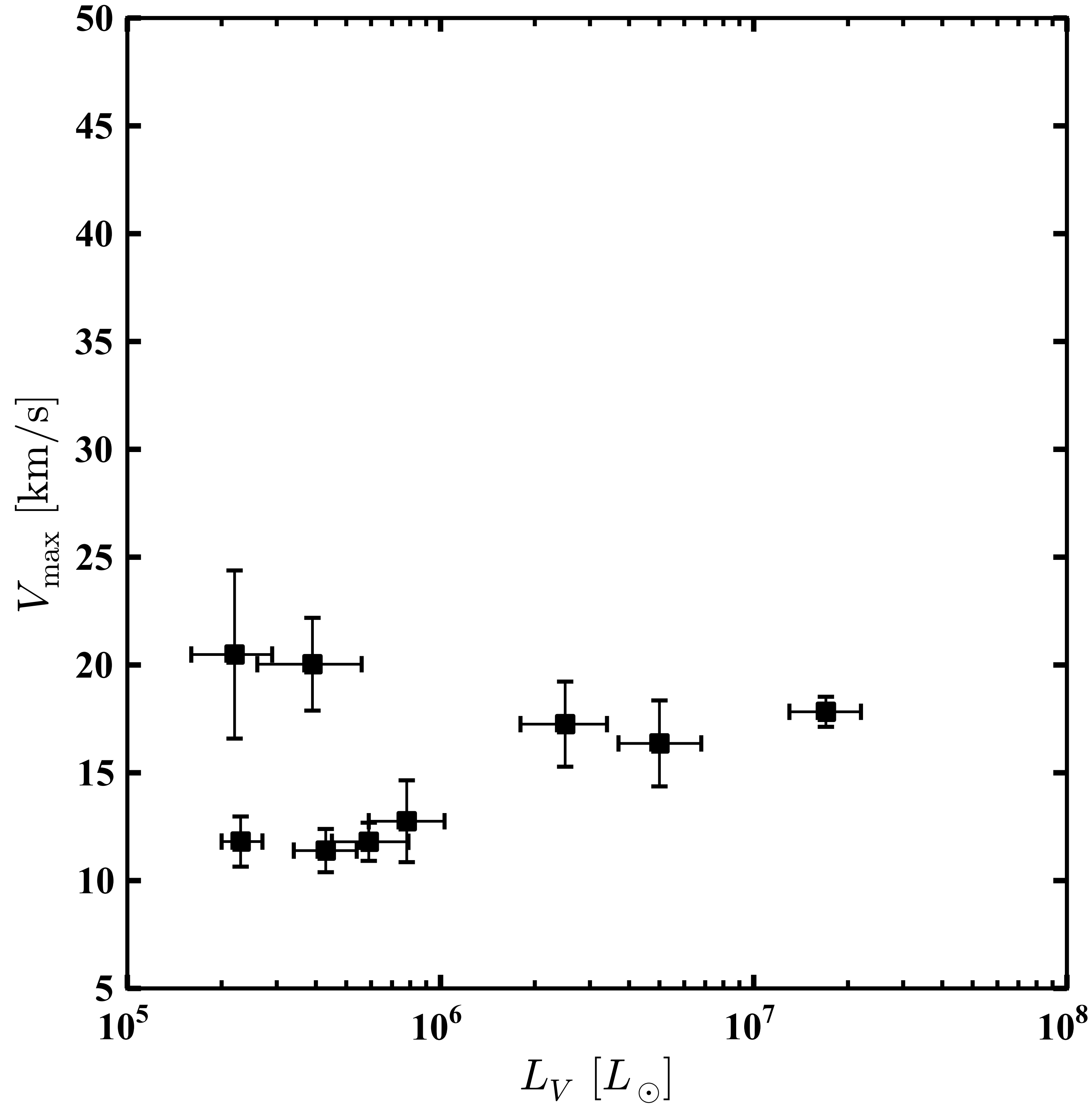
derived values of $V_{\rm infall}$: 14-26 km/s

Name	$M_{\rm vir}$ $[M_\odot]$	N_{20}	N_{30}	N_{40}	N_{50}
Aq-A	2.19×10^{12}	105	33	15	6
Aq-B	9.54×10^{11}	60	16	7	1
Aq-C	1.99×10^{12}	81	28	12	4
Aq-D	2.19×10^{12}	111	31	15	10
Aq-E	1.39×10^{12}	85	25	11	3
Aq-F	1.32×10^{12}	99	29	12	5

7-15 subhalos in each system with $V_{\rm infall}$ > 40 km/s

MBK, Bullock, & Kaplinghat 2012

Observed Milky Way Satellites



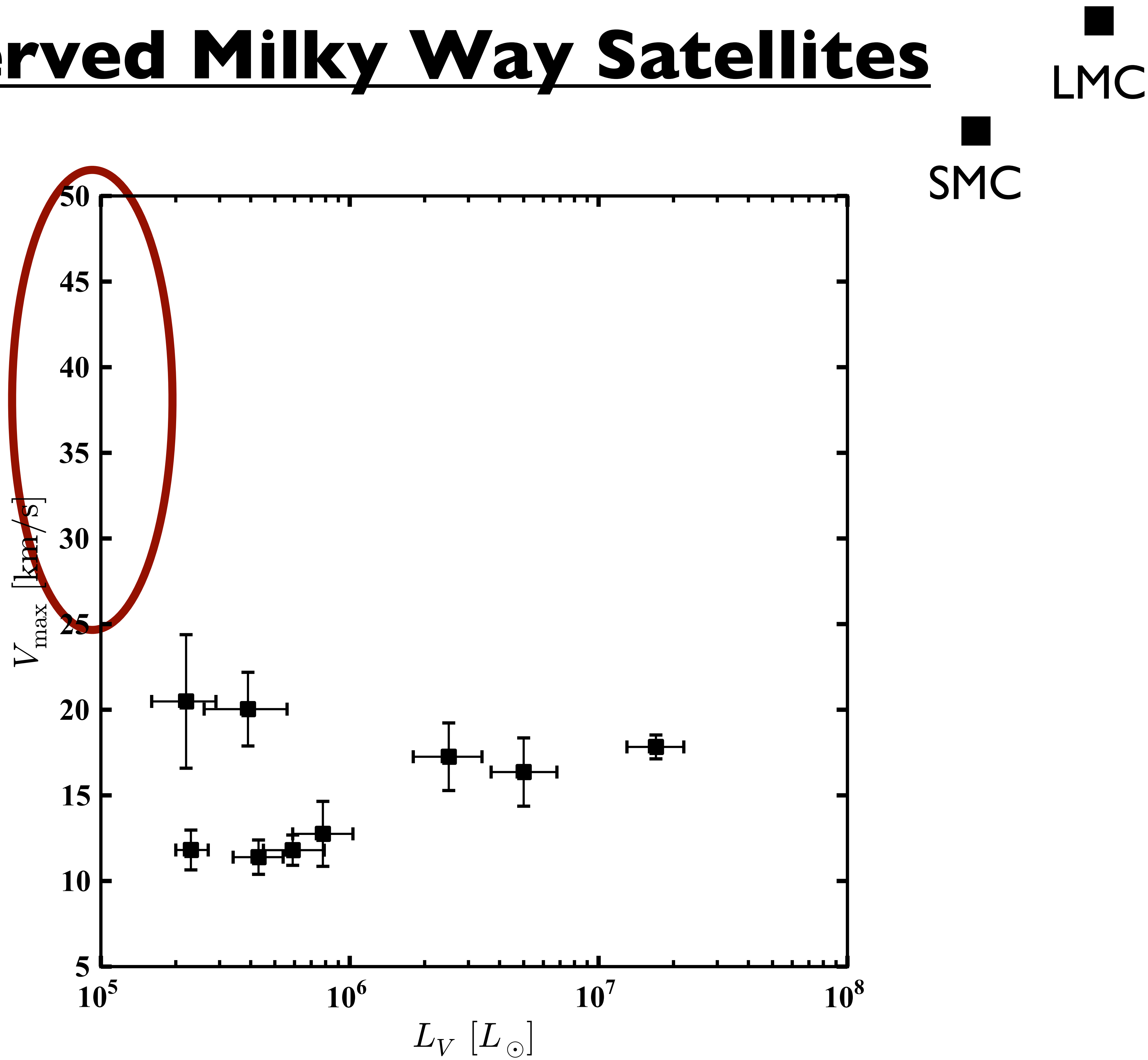
All of the bright MW dSphs are consistent with $V_{\max} \lesssim 25\,\mathrm{km/s}$

(see also Strigari, Frenk, & White 2010)

MBK, Bullock, & Kaplinghat (2012)

Observed Milky Way Satellites

"massive failures": highest resolution LCDM simulations predict ~10 subhalos in this range in the MW, but we don't see ***any*** such galaxies [except Sagittarius (?)]



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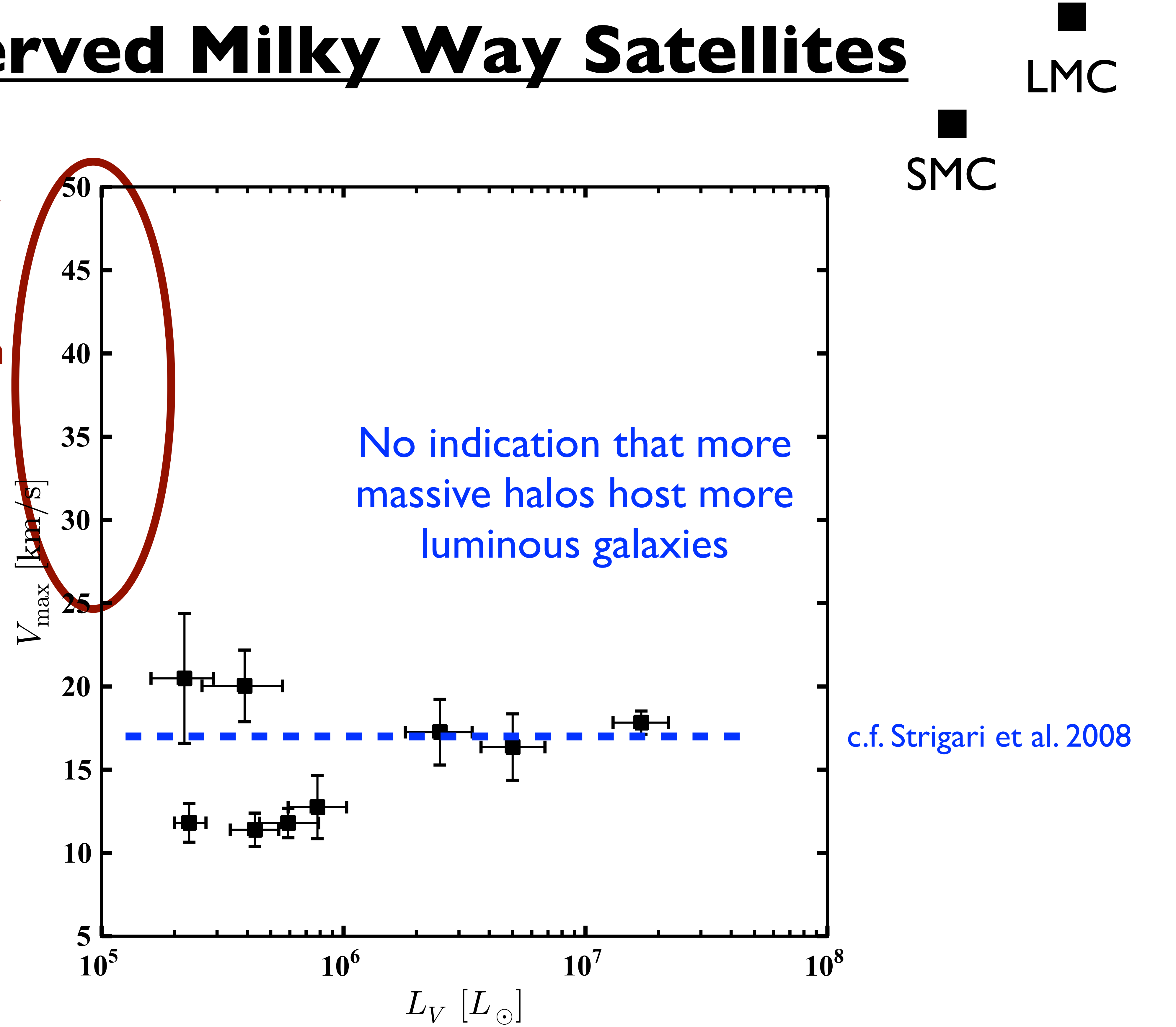
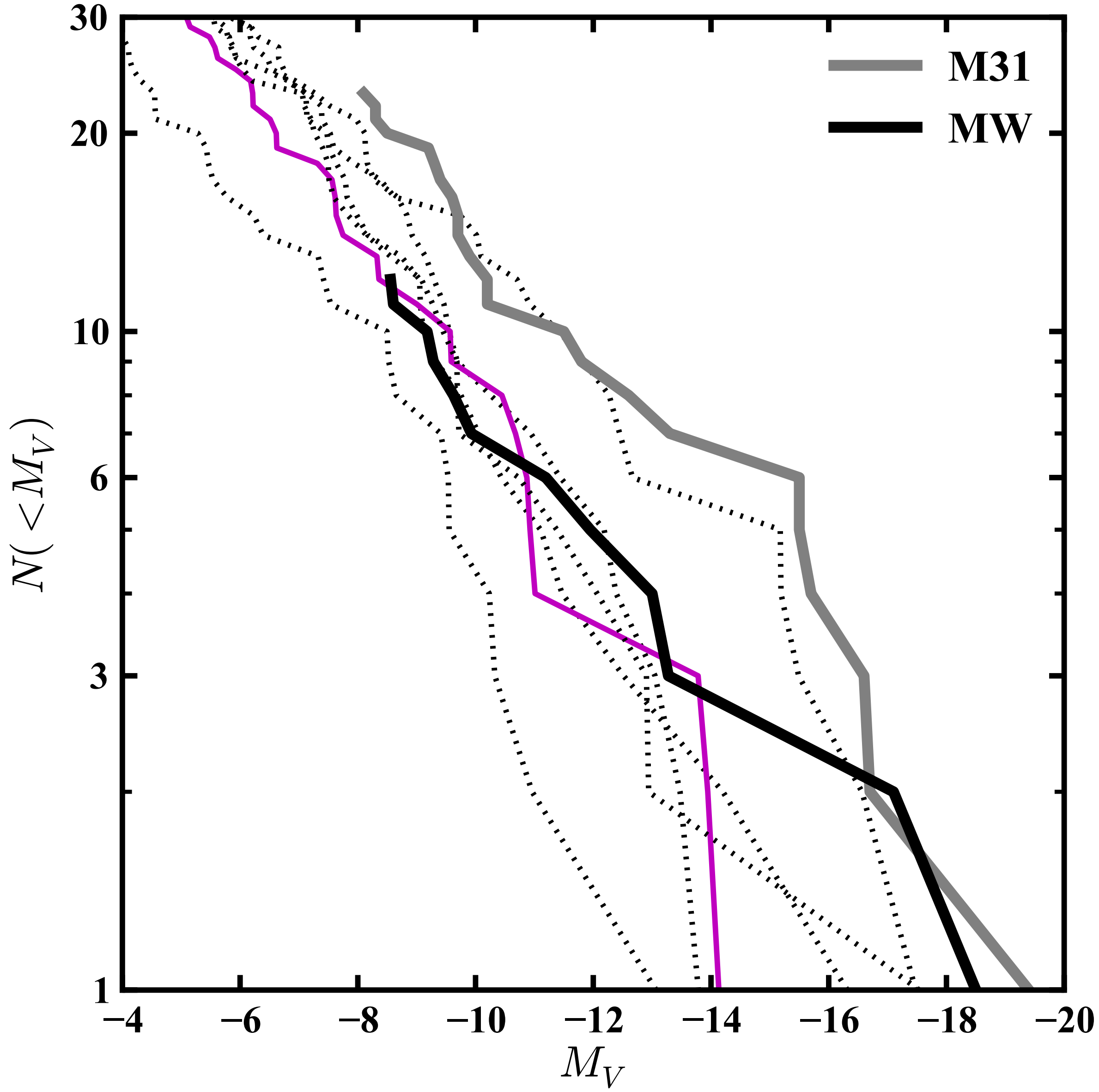
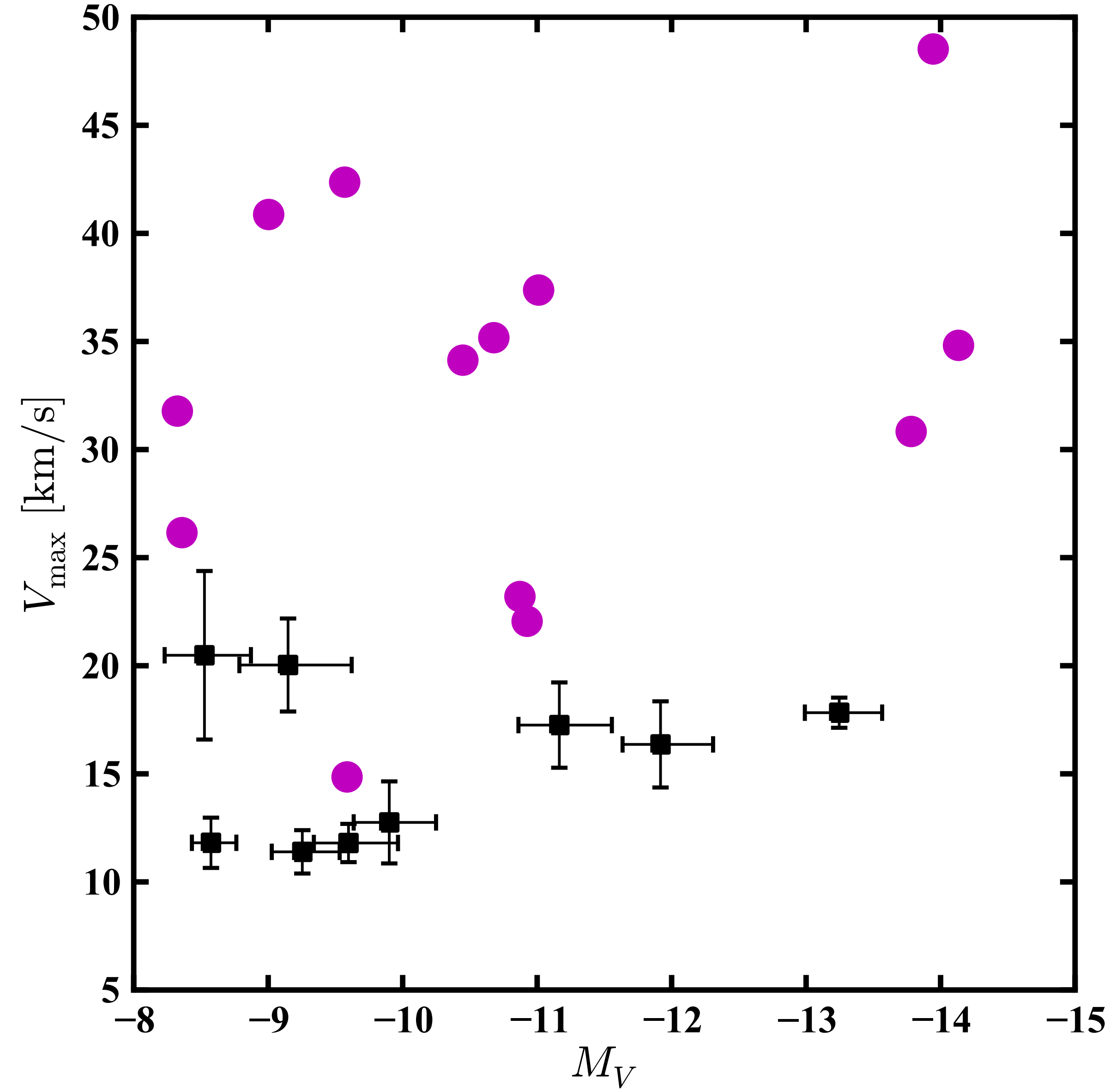


MBK, Bullock, & Kaplinghat (2012)

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





Extrapolation of M_{halo}-M_{star} relation to MW dwarf masses matches the MW satellite luminosity function...

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

MBK, Bullock, & Kaplinghat 2012

Of the ~10 biggest subhalos, ~8 cannot host *any* known bright MW satellite

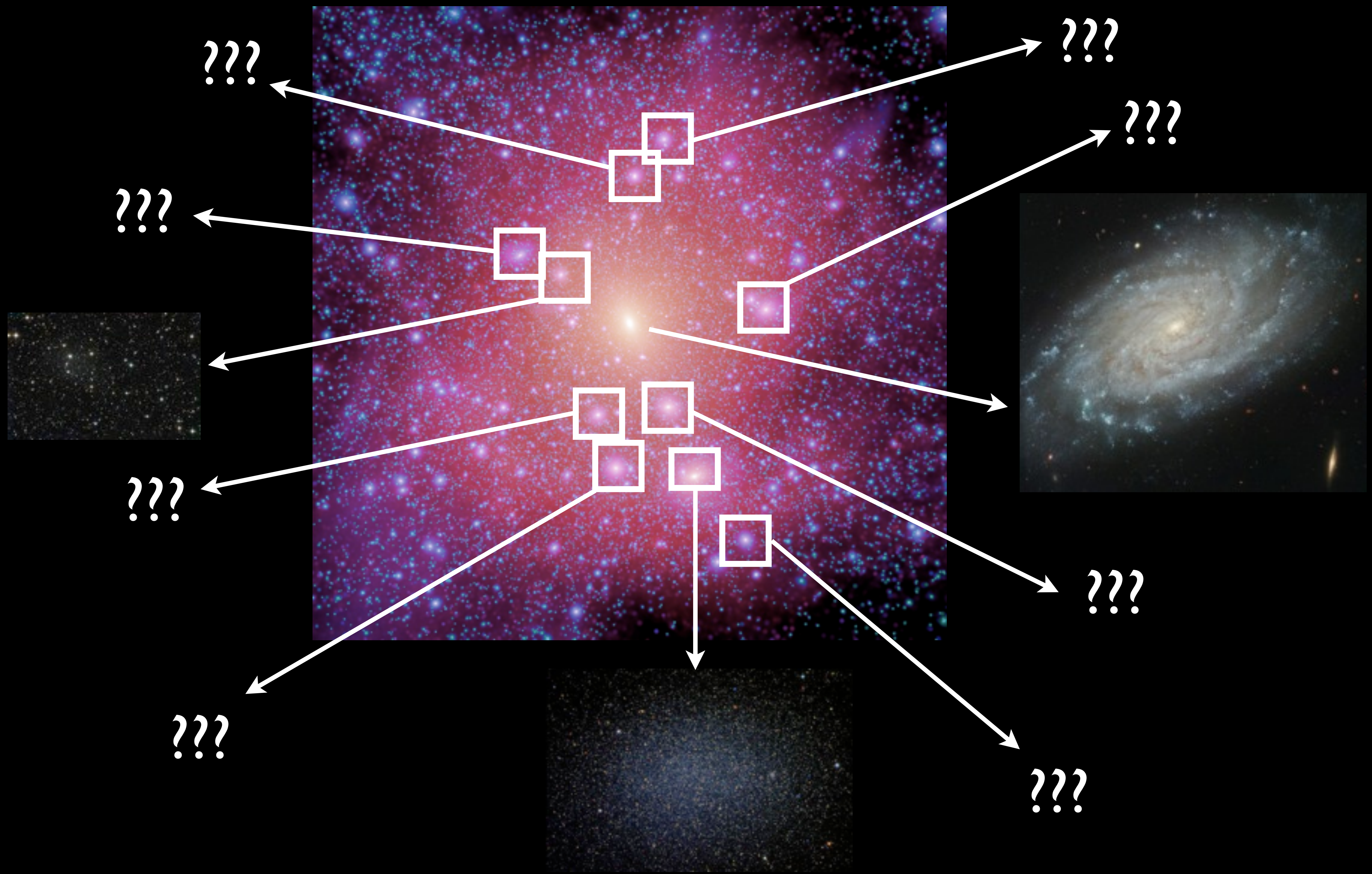


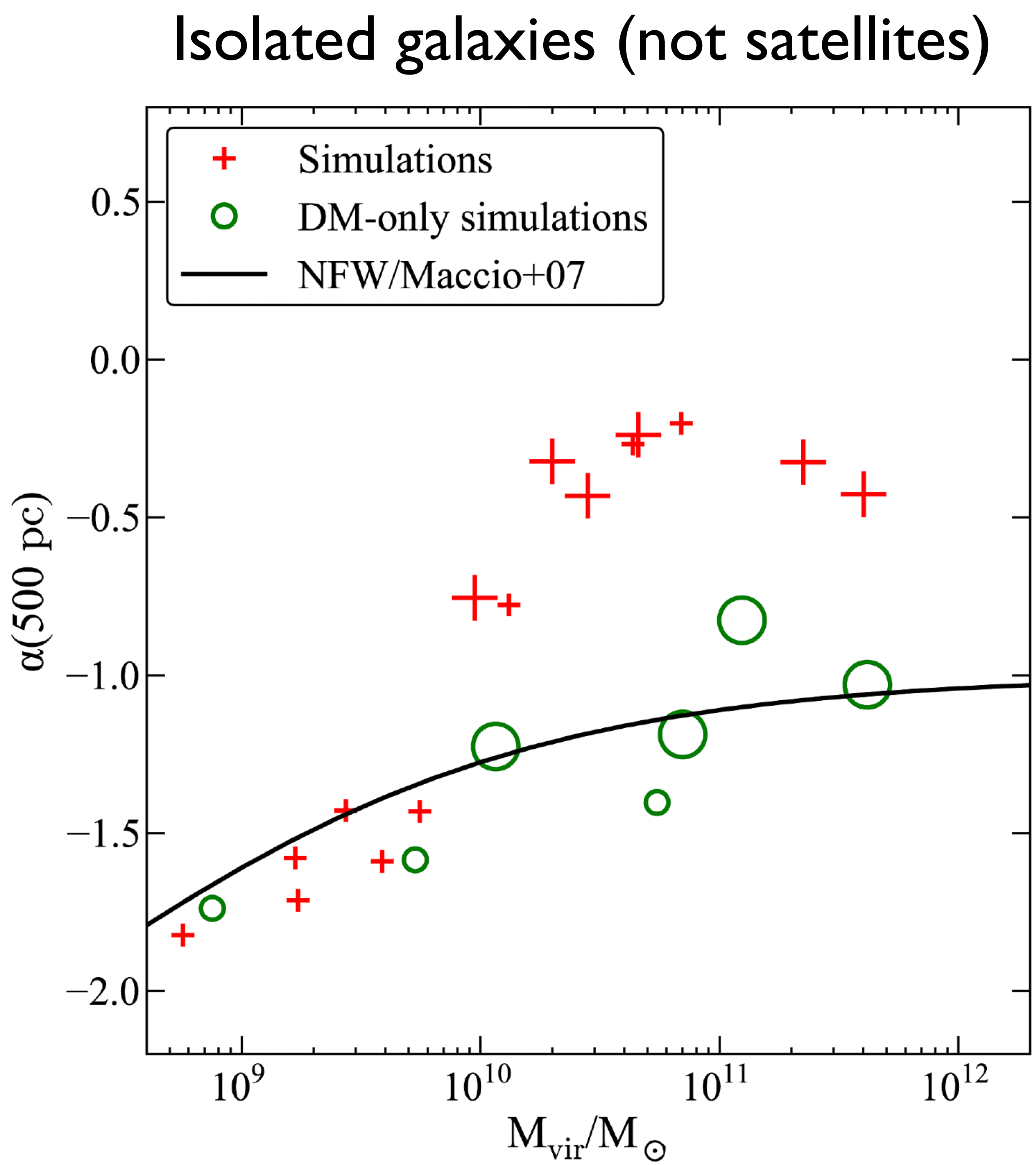
Image credits: V. Springel / Virgo Consortium; A. Riess / HST; SDSS; M. Schirmer

Possible solutions

Baryons strongly modify the structure of subhalos

Reduction in dark matter density from supernova feedback?

(e.g., Navarro et al. 1996; Read & Gilmore 2005; Governato et al. 2010; Pontzen & Governato 2012)



Governato et al. 2012

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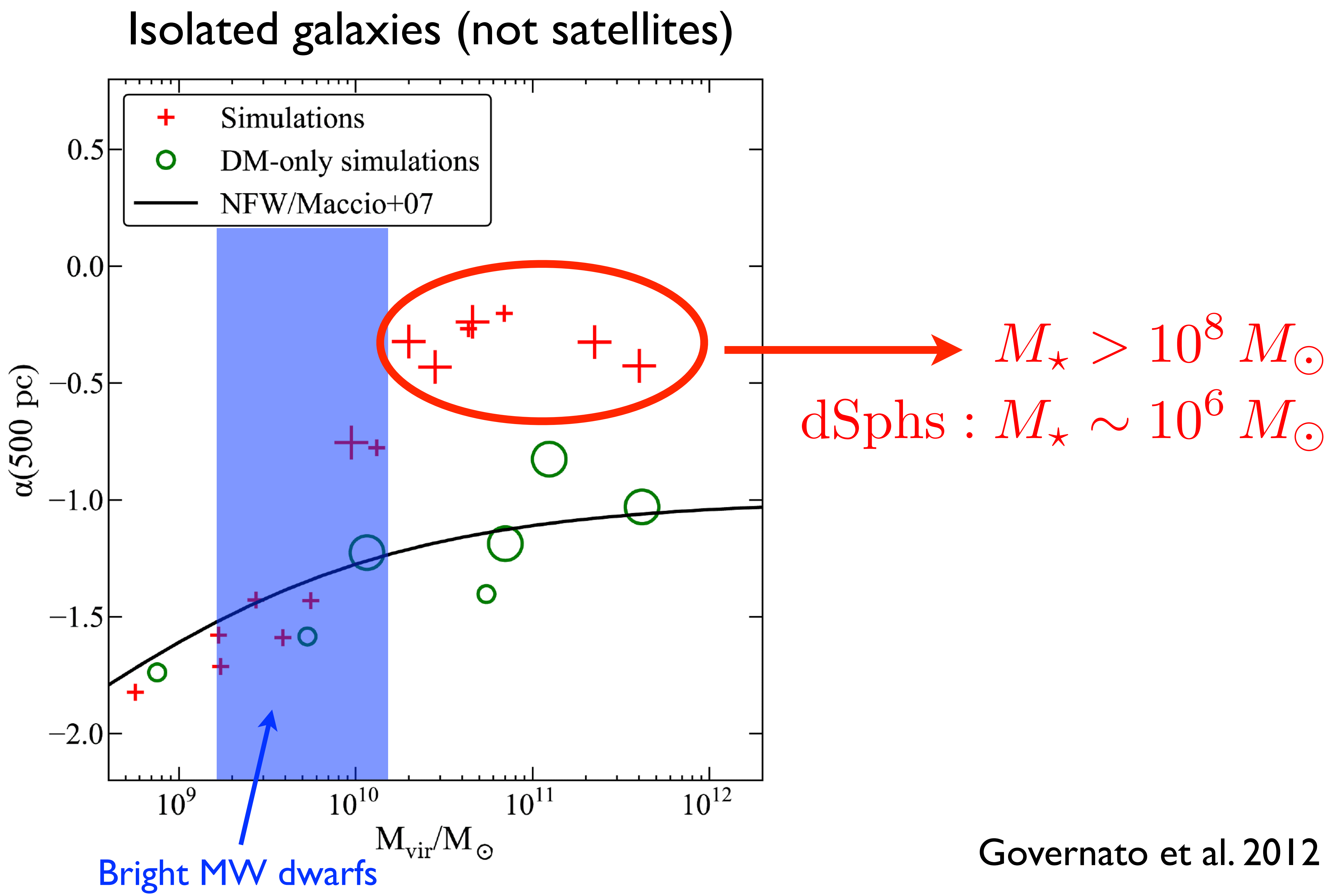
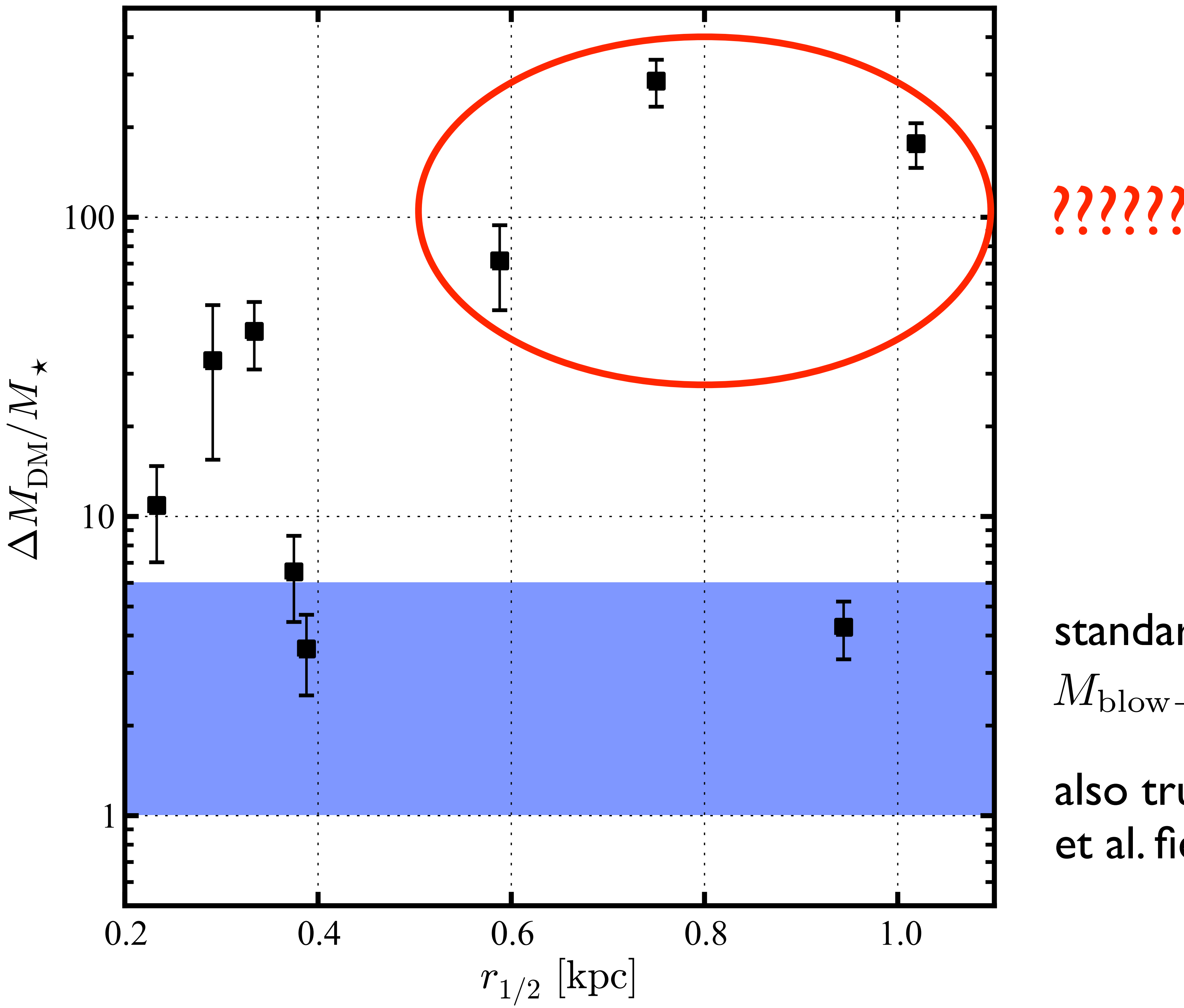


Governato et al. 2012

Removing enough dark matter with SN-driven outflows requires **very** efficient feedback



standard outflow physics:
$M_{\rm blow-out} \approx M_\star$

also true for Governato et al. field dwarf galaxies

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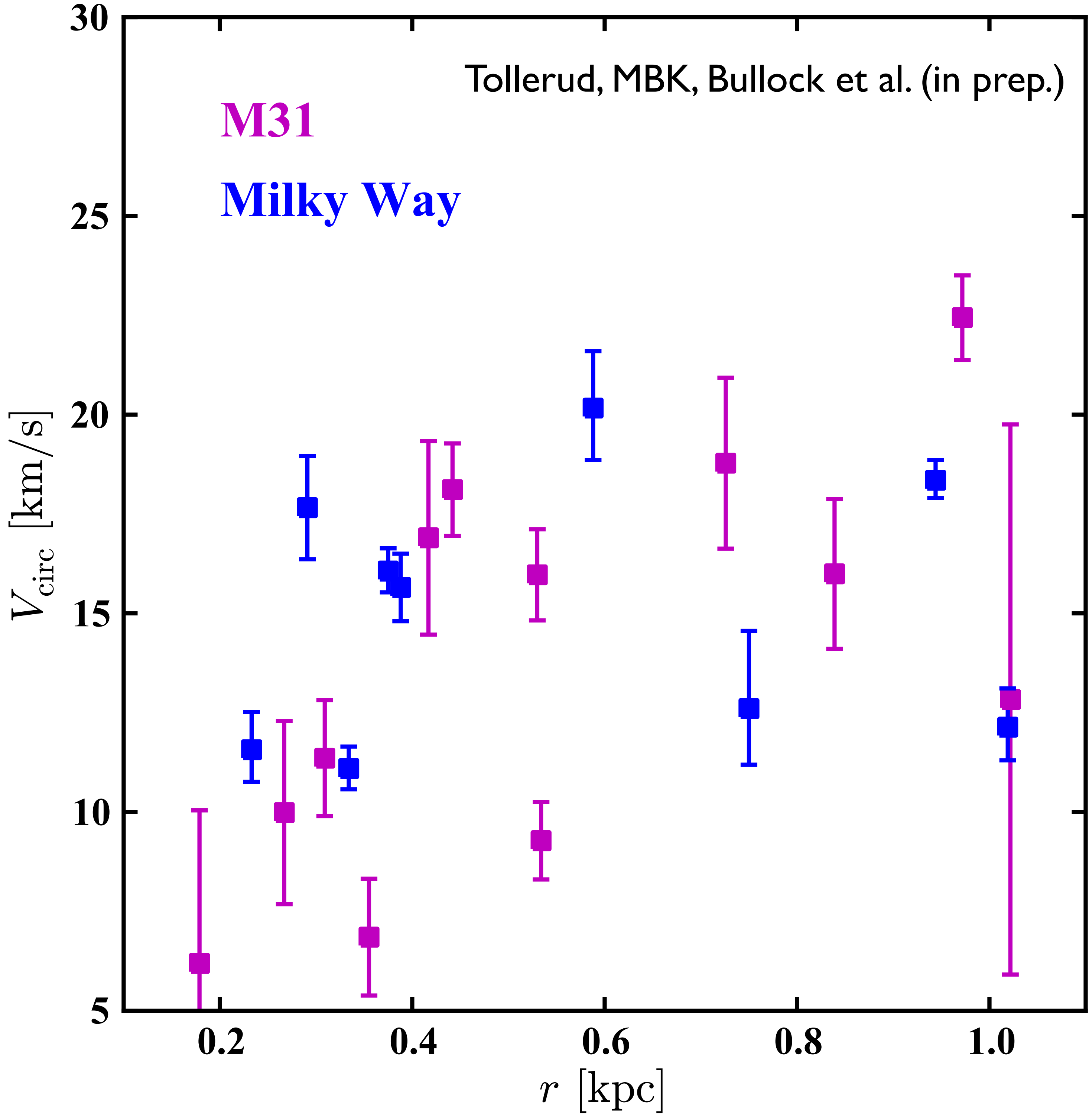
The Milky Way is anomalous



M31 dwarf spheroidals

MW dwarf spheroidals

Abundance of satellites as bright as Fornax consistent between MW and SDSS averages
(Strigari & Wechsler 2012)

Preliminary; based on data on M31 from the SPLASH collaboration
(see also Collins et al. / PAndAS)

Possible solutions

Baryons strongly modify the structure of subhalos

The Milky Way is anomalous

The Milky Way has a low mass dark matter halo

Recent estimates of the Milky Way's dark matter halo mass

Aquarius simulations: M_{vir}=(0.95-2.2) x 10^{12} M_{sun}

- Escape velocity from solar circle (Smith et al. 2007, from RAVE):
  - No adiabatic contraction: $\mathbf{M_{vir}=0.85^{+0.55}_{-0.29} \times 10^{12}}$
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- Timing argument (Li & White 2008):
  - Median value: $\mathbf{M_{vir}=2.7 \times 10^{12}}$
  - $\mathbf{M_{vir} > 0.95 \times 10^{12}}$ (95% confidence)

Pick your poison

Aquarius simulations: M_{vir}=(0.95-2.2) x 10^{12} M_{sun}

Recent observational estimates: (0.85-2.7) x 10^{12} M_{sun}

- If true value is $\gtrsim 1.3 \times 10^{12}\, M_\odot$

  ✓ easier to get the Magellanic Clouds, match dynamics of satellite population

  \- "Too big to fail" / massive failure problem is **severe**

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- If true value is $\gtrsim 1.3 \times 10^{12}\, M_\odot$
  - ✓ easier to get the Magellanic Clouds, match dynamics of satellite population
  - "Too big to fail" / massive failure problem is **severe**
- If true value is ~1.0 x 10^{12} or less:
  - ✓ Number of massive failures is substantially lowered
  - Magellanic Clouds are very rare (~3% or less; MBK et al. 2010, Busha et al. 2011)
  - Milky Way has an unusually high fraction of baryons locked up in stars
  - Still don't understand gap between dSphs and Magellanic Clouds
  - Dynamics of satellite population disagrees strongly with observations
- M_{MW} is the biggest uncertainty in interpreting the MW cosmologically

Satellites like Leo I not found in a low-mass MW

Leo I data from Mateo, Olszewski, & Walker 2008:
D=255 kpc, V_r=174.9 km/s

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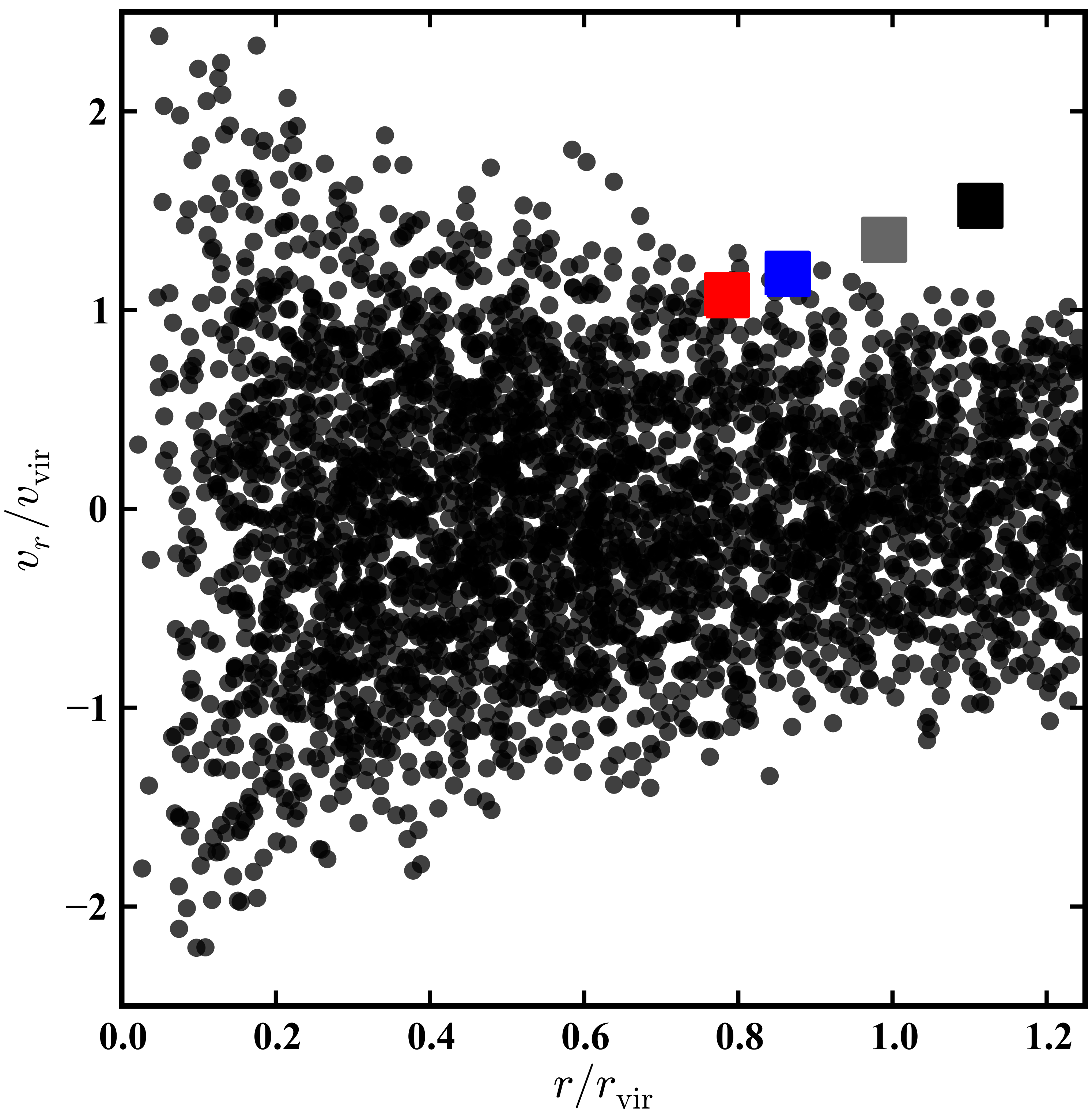

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$M_{\rm vir}\ [10^{12}\ M_\odot]$

0.7 x 10^{12}
1.0 x 10^{12}
1.5 x 10^{12}
2.0 x 10^{12}

MBK, Besla, Bullock, Sohn, van der Marel, Majewski (in prep.)

Possible solutions

Baryons strongly modify the structure of subhalos

The Milky Way is anomalous

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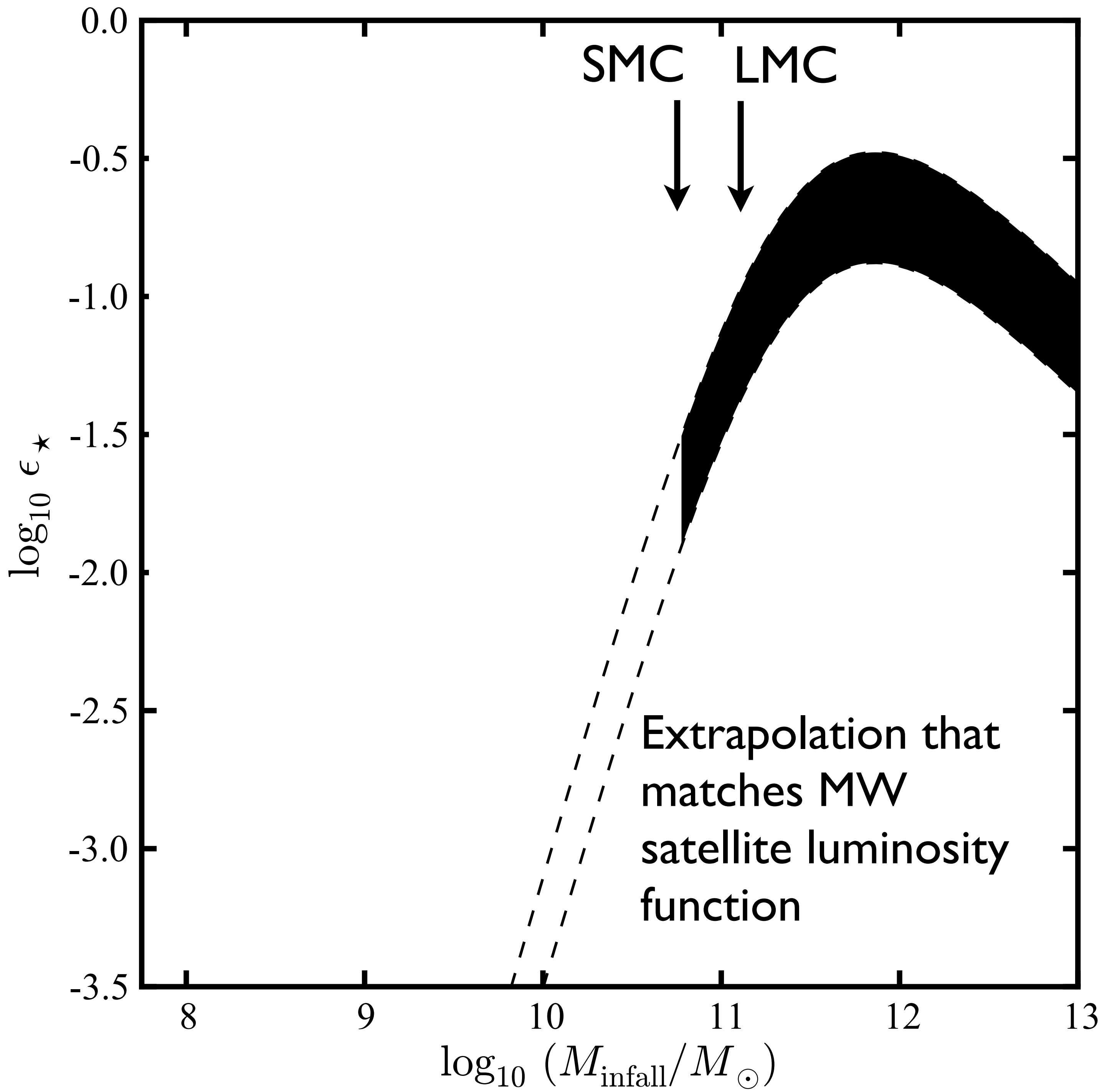
Galaxy formation is effectively stochastic at low masses

Stochastic galaxy formation

star formation efficiency



Tight relation between **L** and $\mathbf{M_{infall}}$ on scale of Magellanic Clouds and larger

MBK, Bullock, & Kaplinghat (2012)

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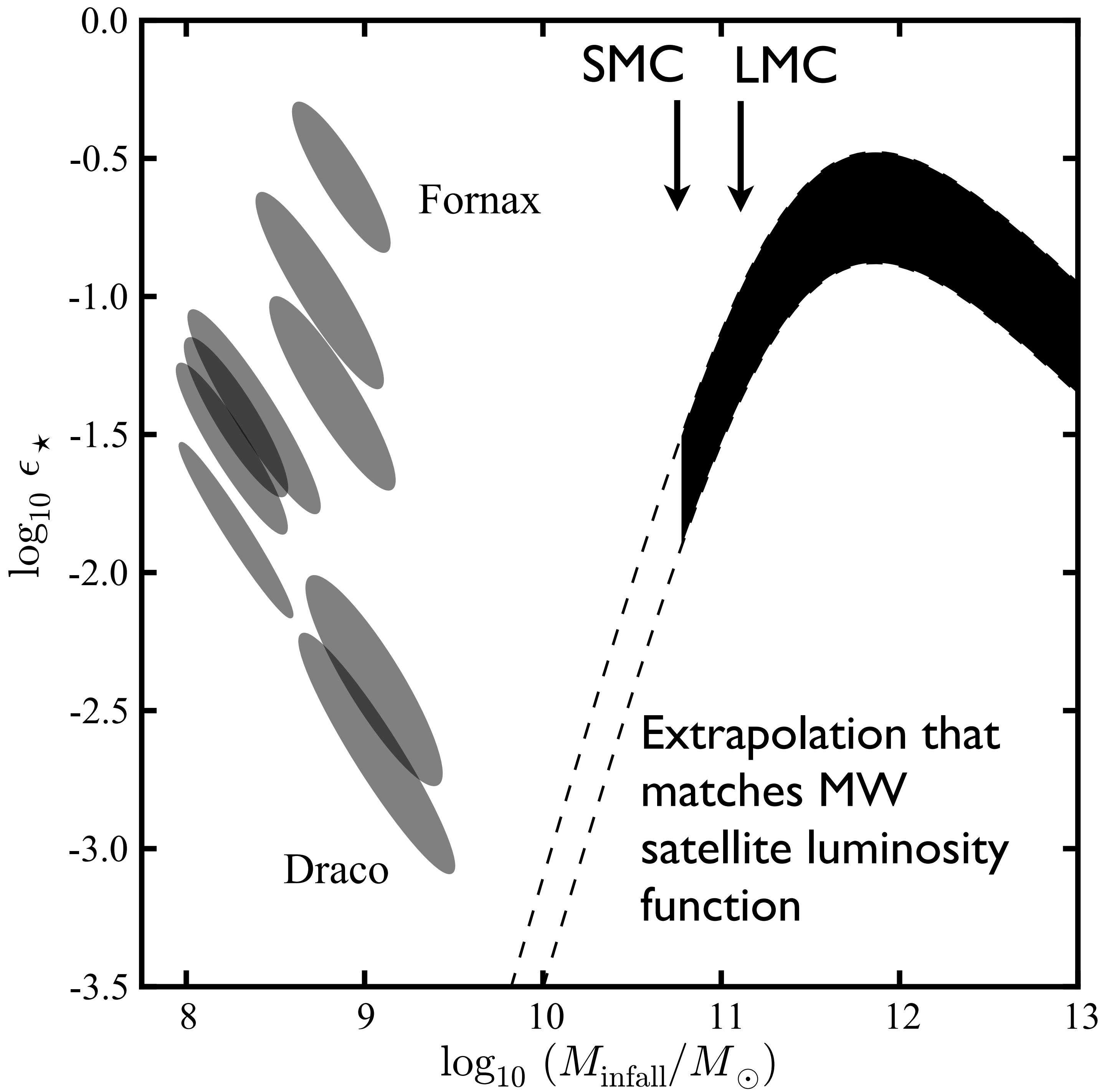

Tight relation between **L** and **M_{infall}** on scale of Magellanic Clouds and larger

No relation between **L** and **M_{infall}** on scale of MW dwarf spheroidals

Requires presence of massive subhalos with very high M/L (ultra-faints?)

Source of stochasticity: H_2 regulated star formation? (Gnedin, Kravtsov, Kuhlen et al.)

MBK, Bullock, & Kaplinghat (2012)

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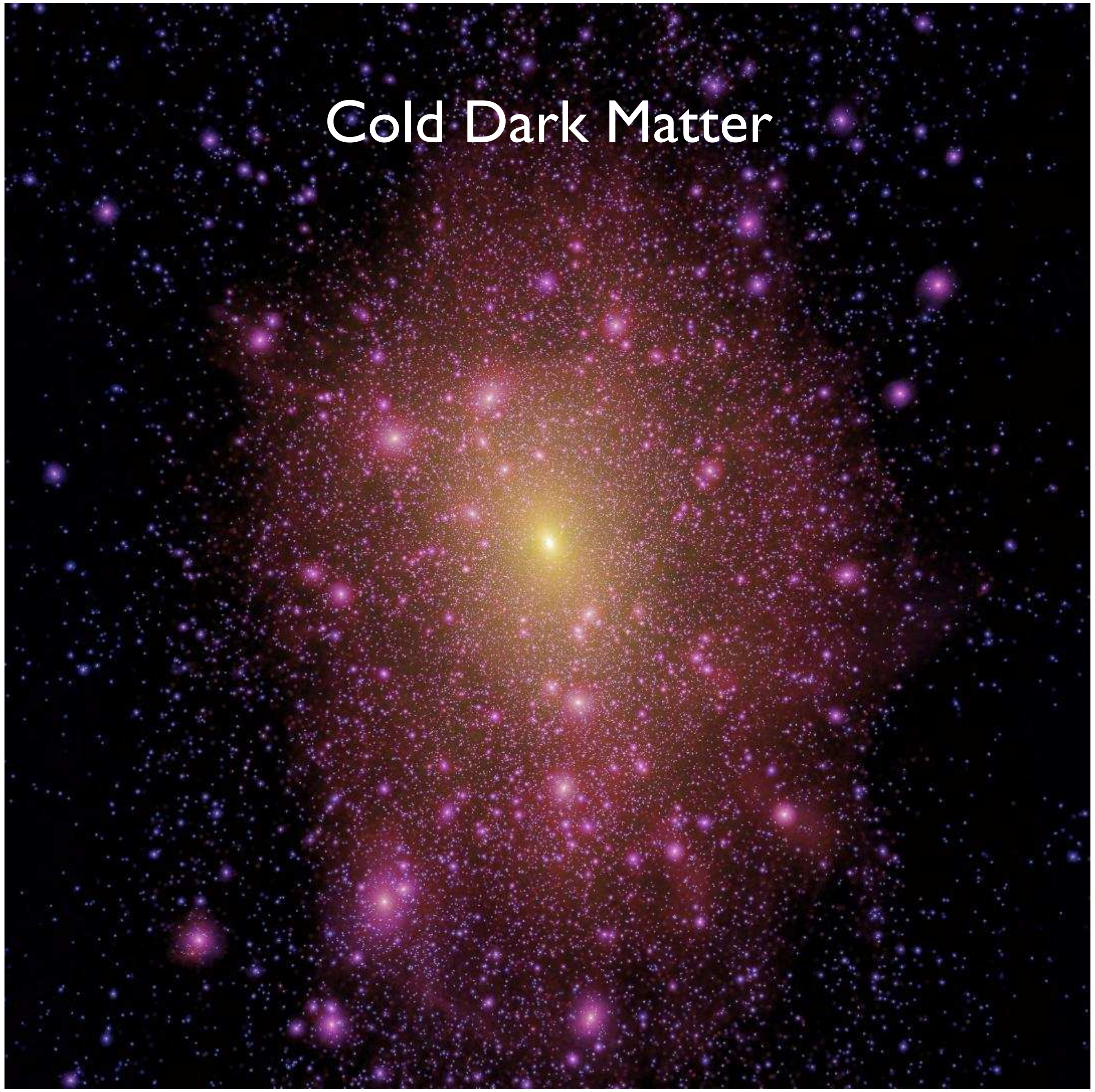
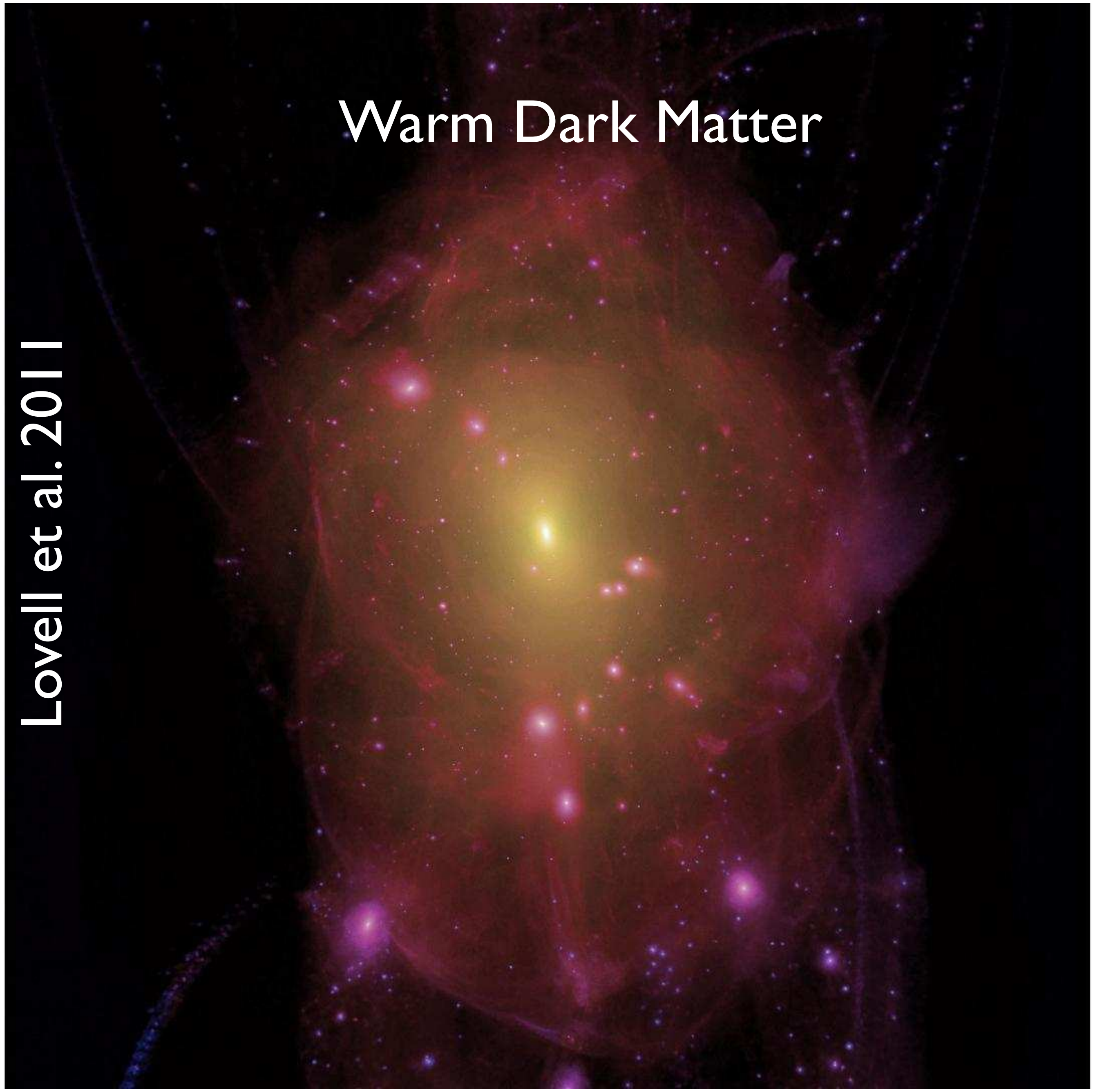
Dark matter has physics beyond simplest WIMP models

Properties of dark matter particle may be reflected in substructure abundance



Lovell et al. 2011

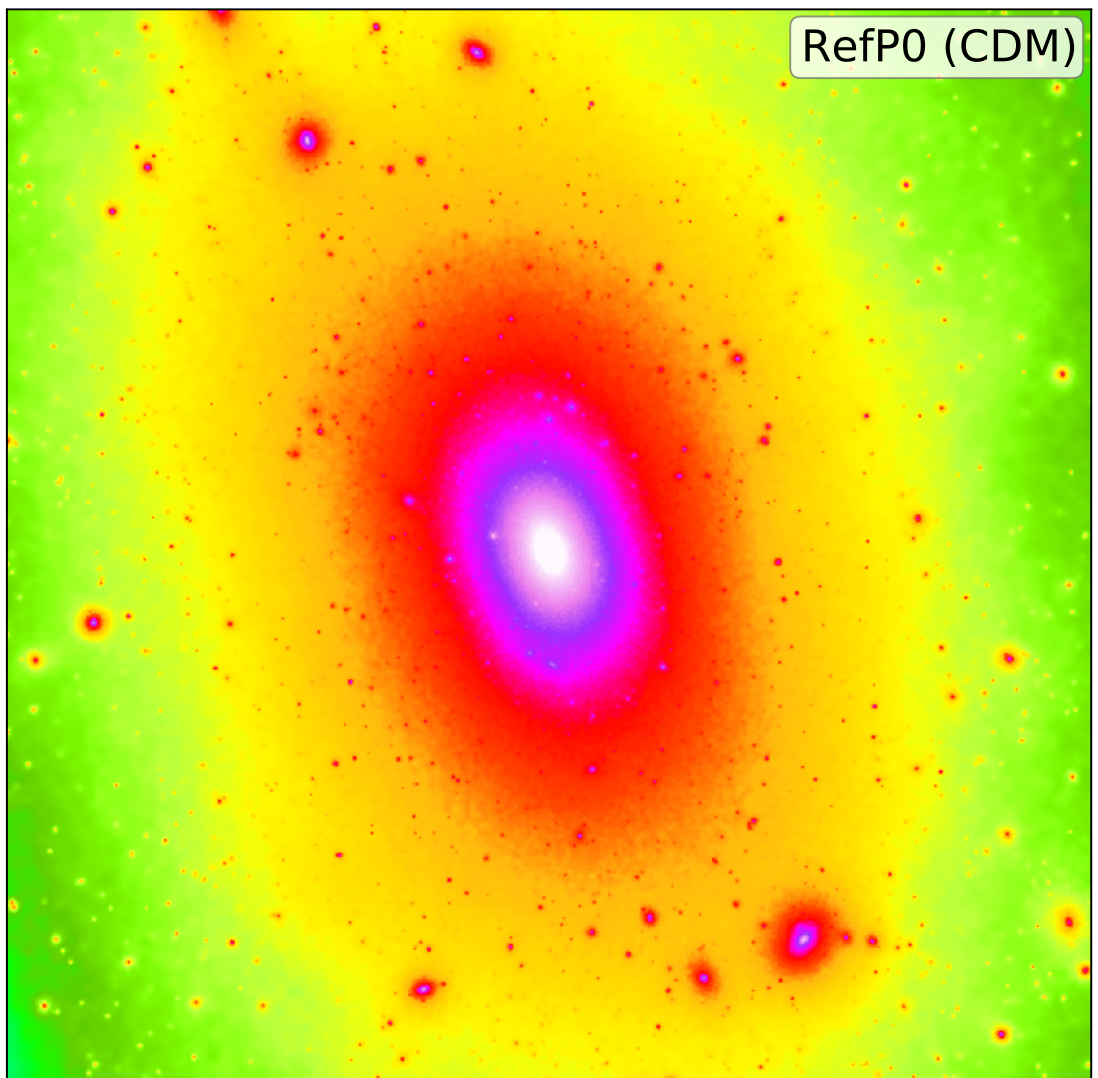


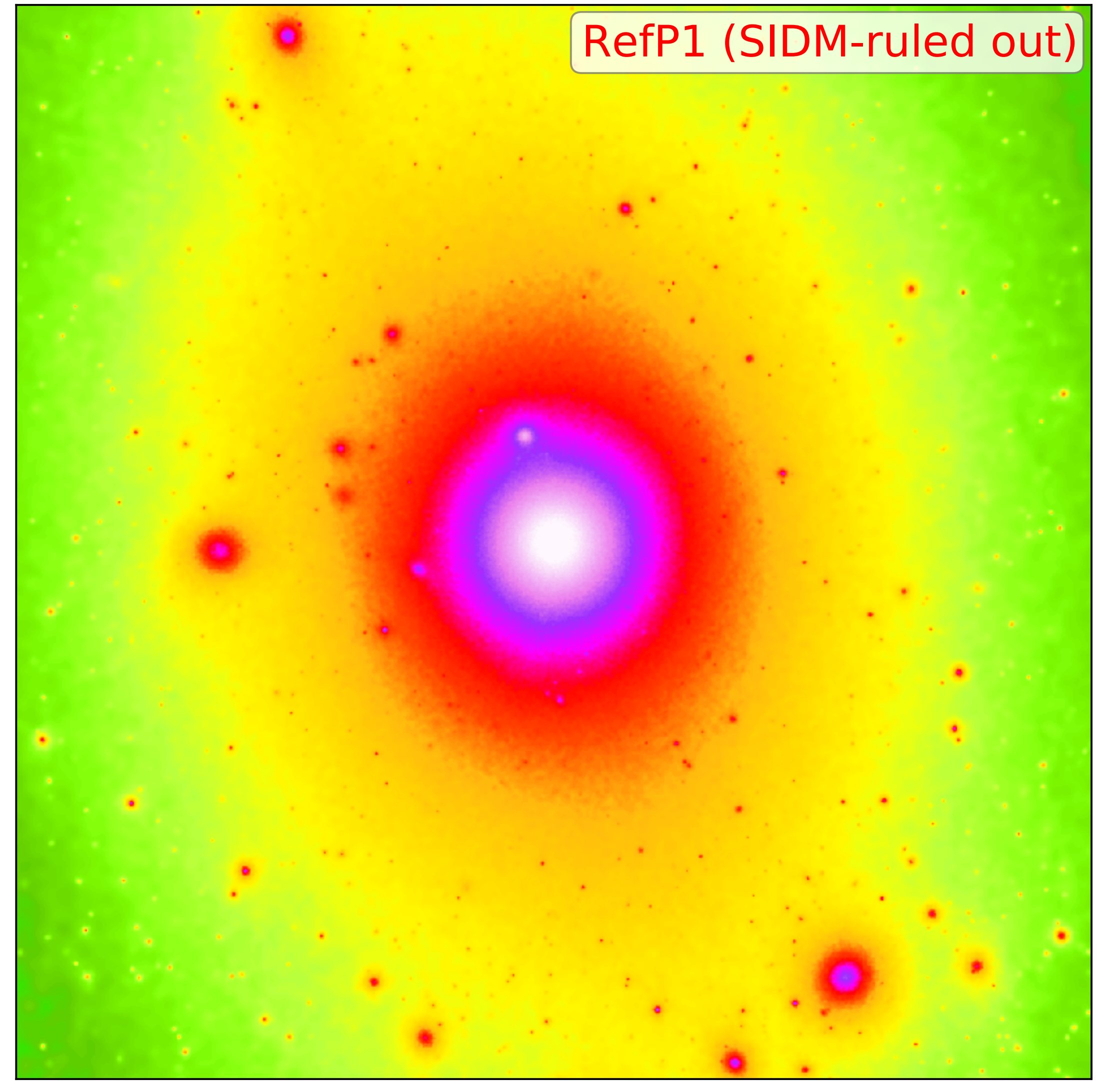
future counts of ultra-faints dwarfs will strongly constrain mass of WDM particle
(e.g., Maccio et al. 2010; Polisensky & Ricotti 2011)

Self-interacting dark matter

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

CDM





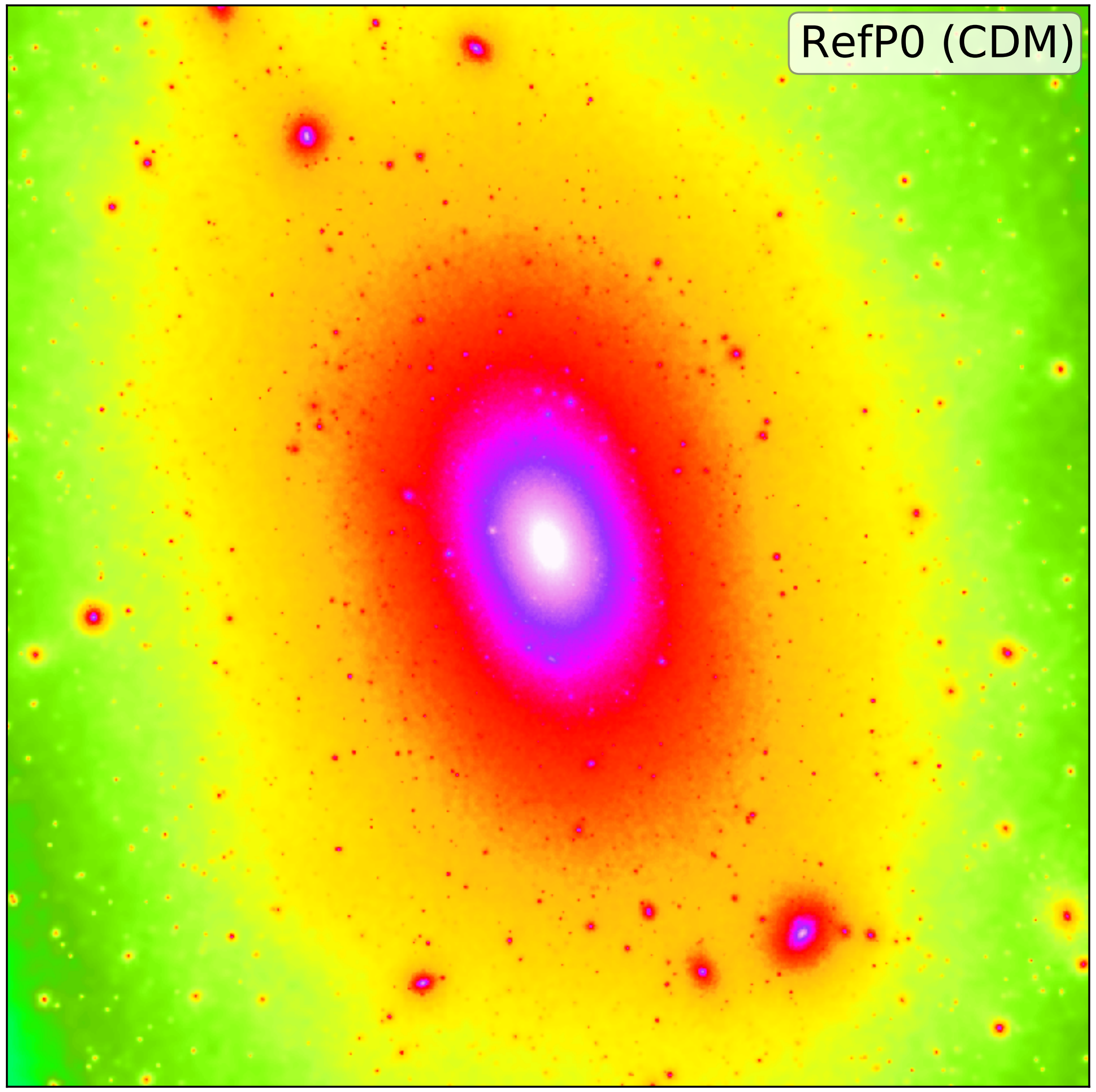
$\mathrm{SIDM} : \sigma = 10\,\mathrm{cm}^2\,\mathrm{g}^{-1}$

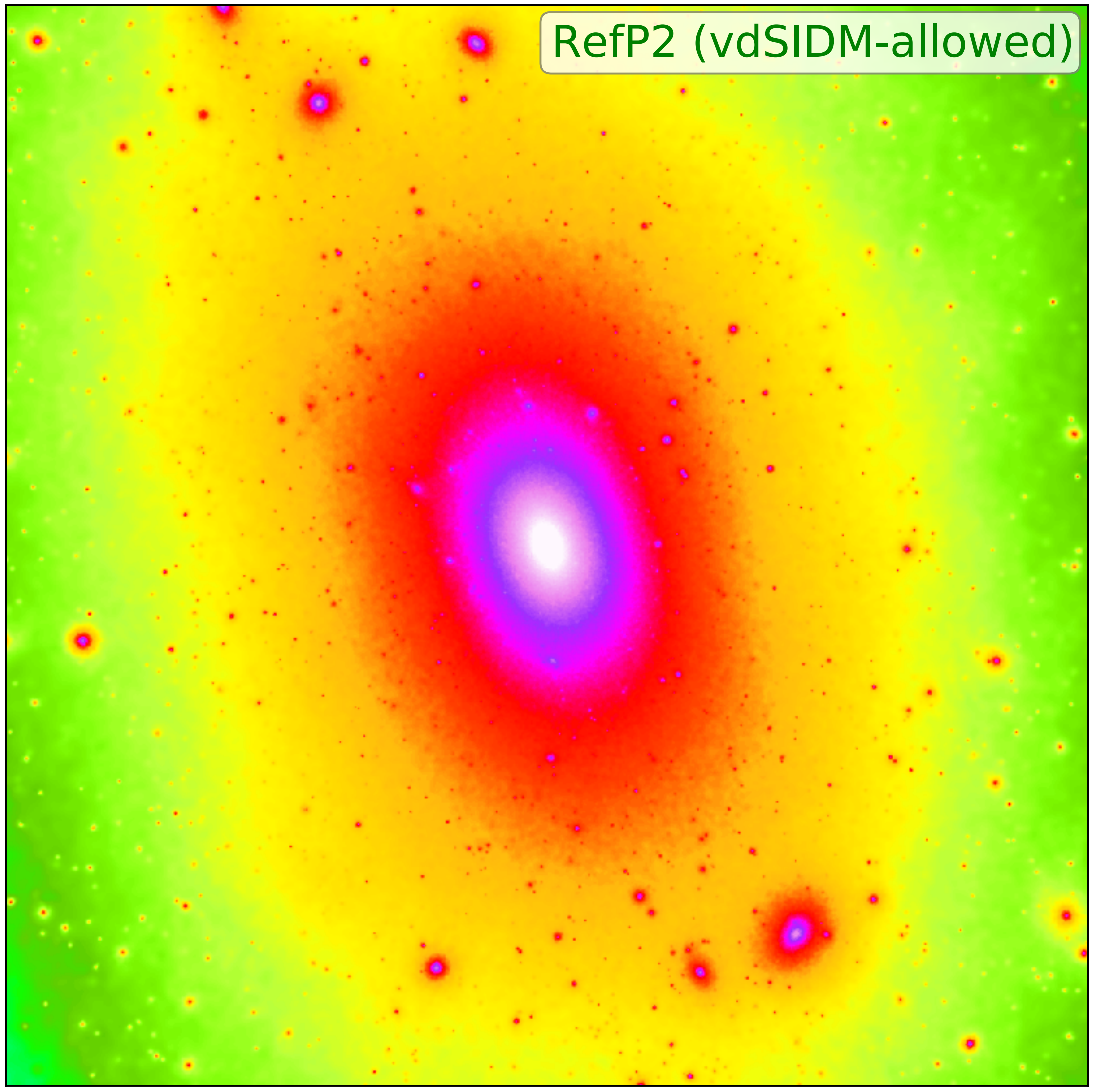
(Vogelsberger et al. 2012; *also Rocha, Peter, Kaplinghat, & Bullock 2012*)

Self-interacting dark matter

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

CDM



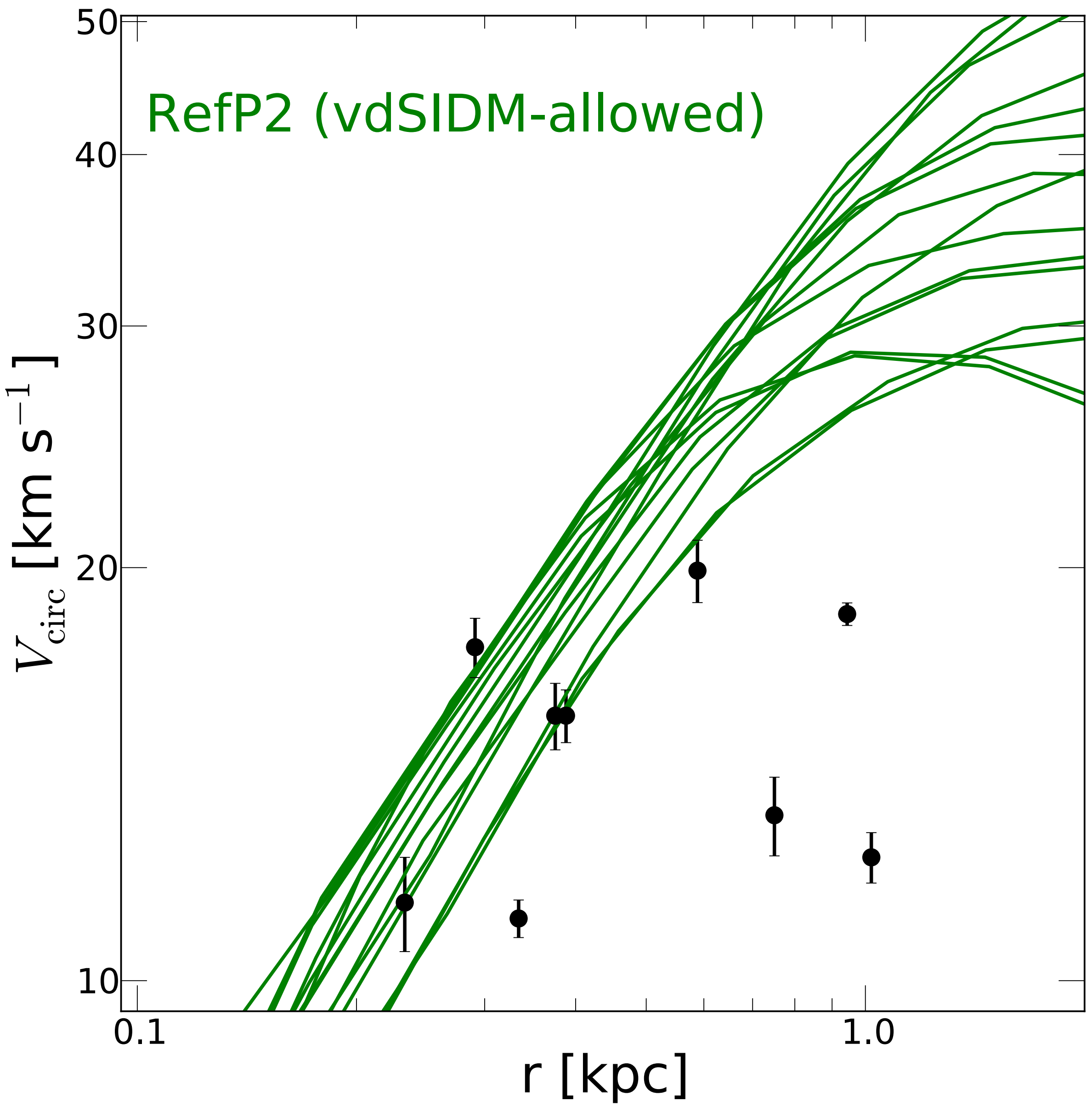


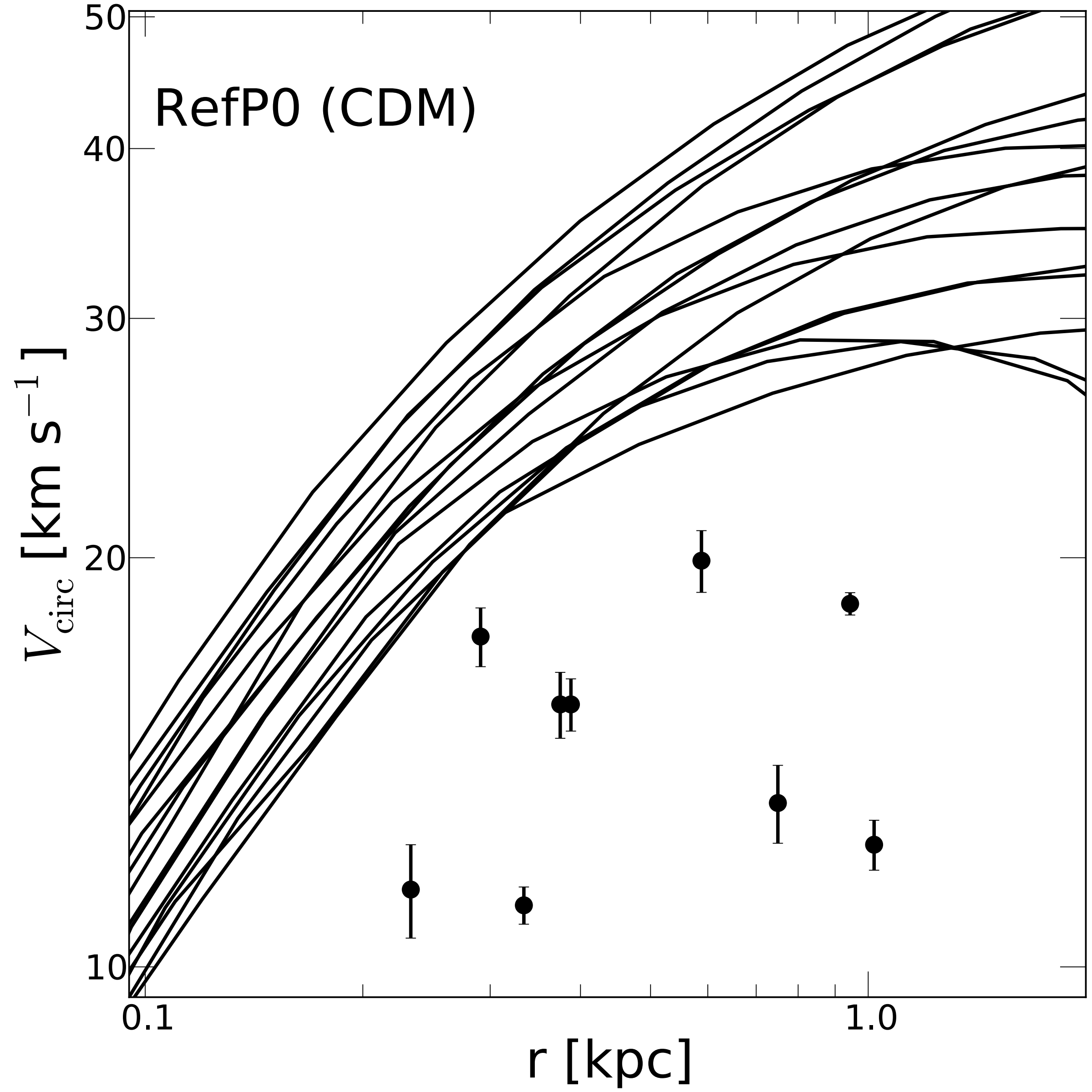
SIDM: velocity-dependent cross section

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

Self-interacting dark matter

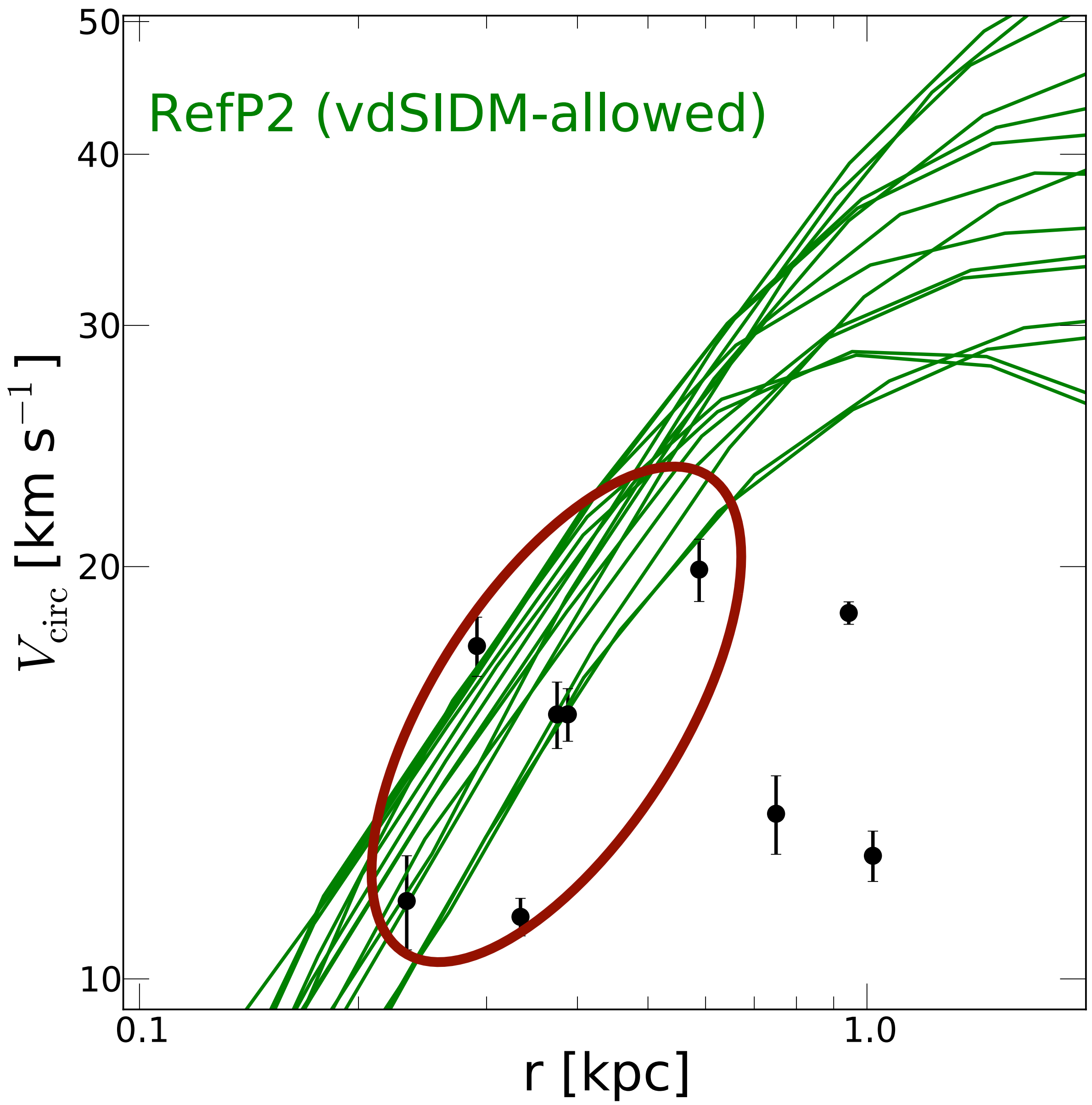
(Vogelsberger et al. 2012)

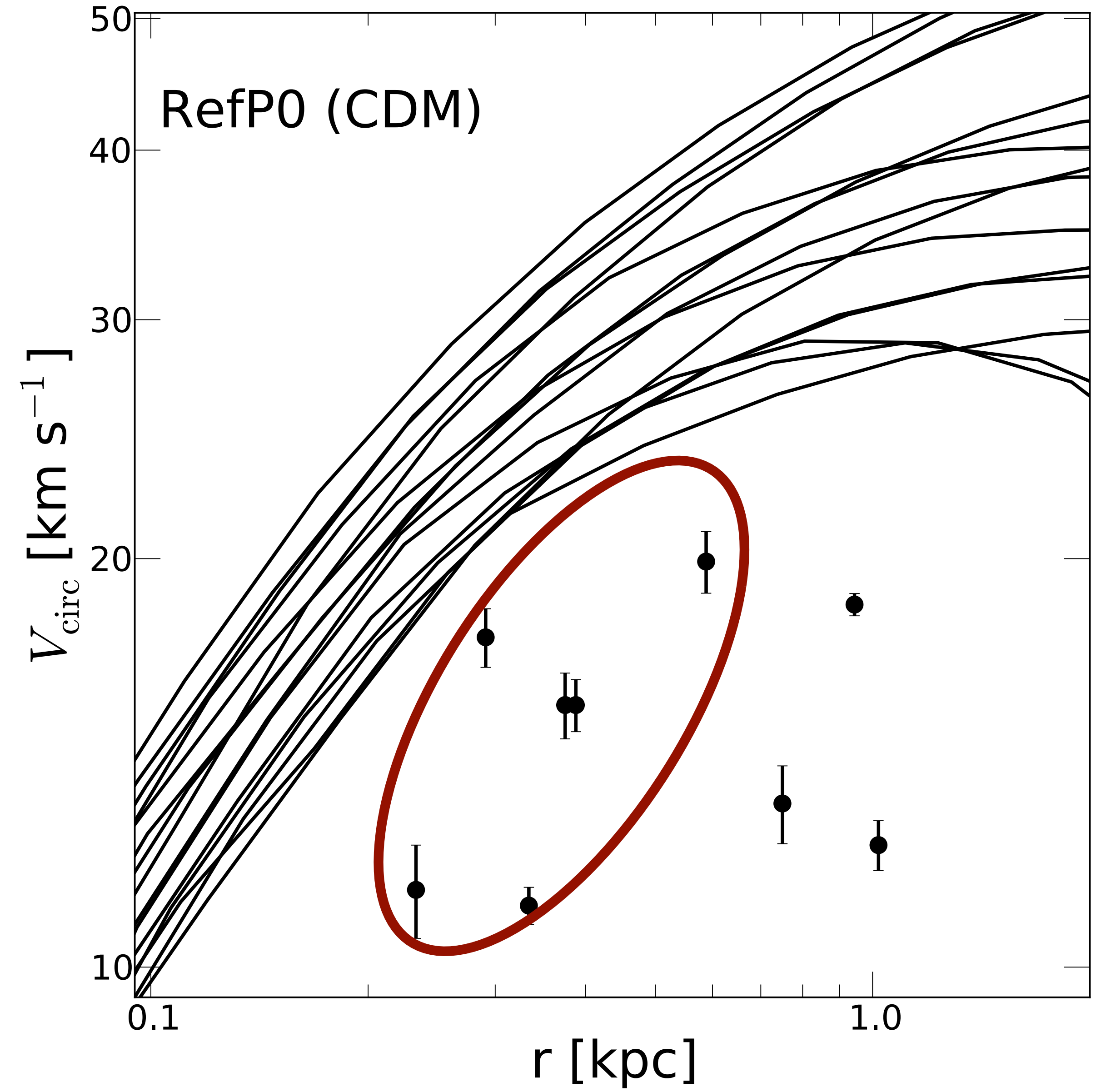




Self-interacting dark matter

(Vogelsberger et al. 2012)





Summary

- Dwarf galaxies test ΛCDM on smallest scales yet; simple ΛCDM-based abundance matching works very well for bright satellites of ~L* galaxies in the local Universe (c.f. talk by E. Tollerud)

- Milky Way: can **directly** probe halo - galaxy connection for dwarf spheroidals because we know *structure* as well as *abundance*

- **Not possible** to put bright MW satellites in most massive MW subhalos from current ΛCDM simulations ⇒ challenge for galaxy formation models or ΛCDM

  - the most massive subhalos in all simulations are substantially more dense than the MW's bright ($L_V > 10^5\ L_{sun}$) satellites.

  - either these subhalos are effectively dark (global $M/L > 10^4$); the MW is a statistical anomaly or has very low mass; baryonic physics strongly modifies structure of DM subhalos; or ΛCDM needs modification on scale of 40-50 km/s

  - observationally: need more complete census of ultra-faint satellites, observations of additional MW-like systems; look for halo-galaxy connection in isolated dwarf galaxies (c.f. Laura Sales' talk, Ferrero et al. 2012); indirect detection of expected CDM structure via lensing, gamma rays, gaps in stellar streams?

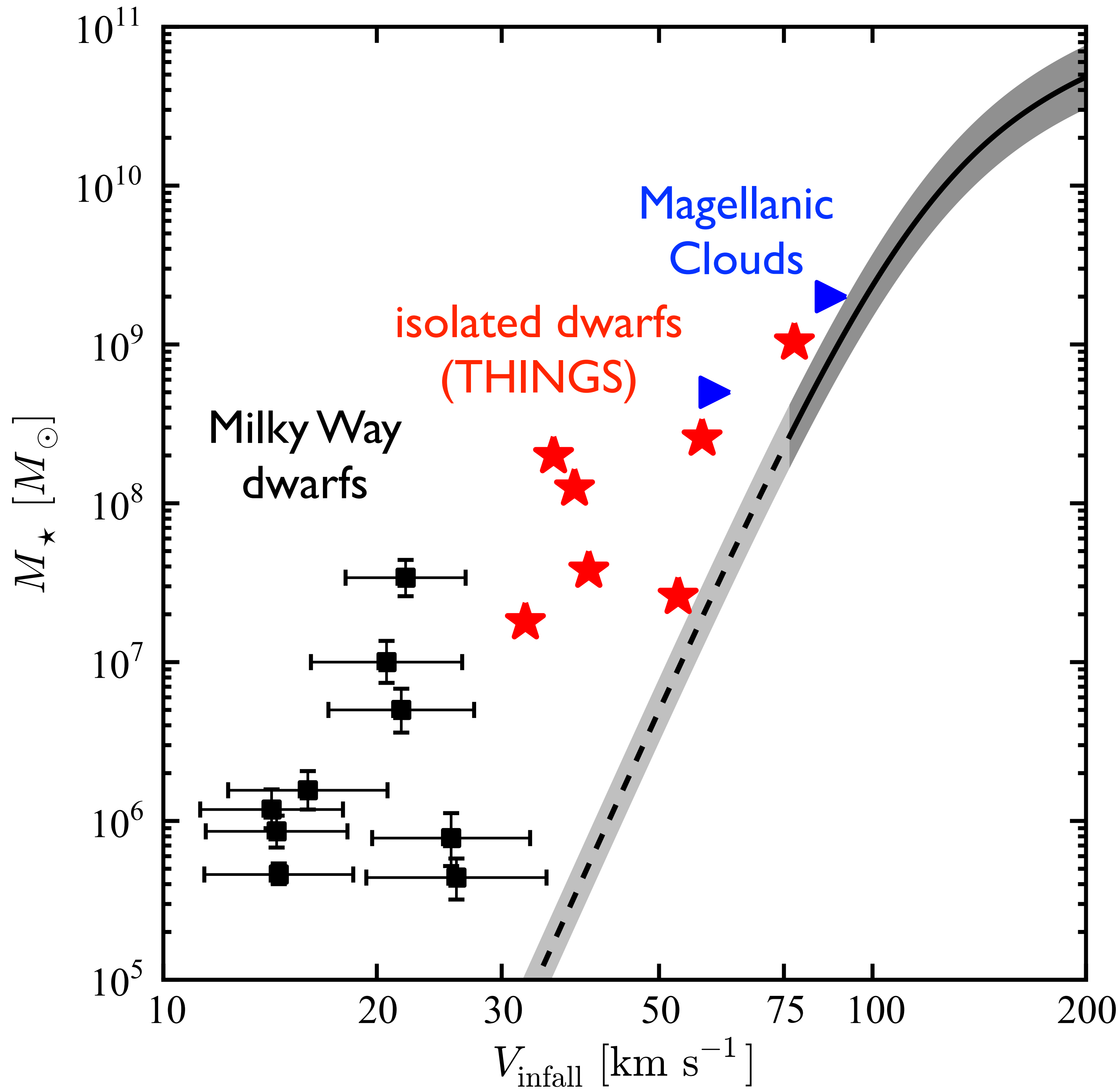
Some advice from the highest levels of government

"You analyze the simulations you have, not the simulations you might want or wish to have at a later time"

Executive Summary

The most massive subhalos in the current generation of ultra-high-resolution N-body simulations are too dense to host any of the Milky Way's bright dwarf spheroidal galaxies (and not massive enough to host the Magellanic Clouds).

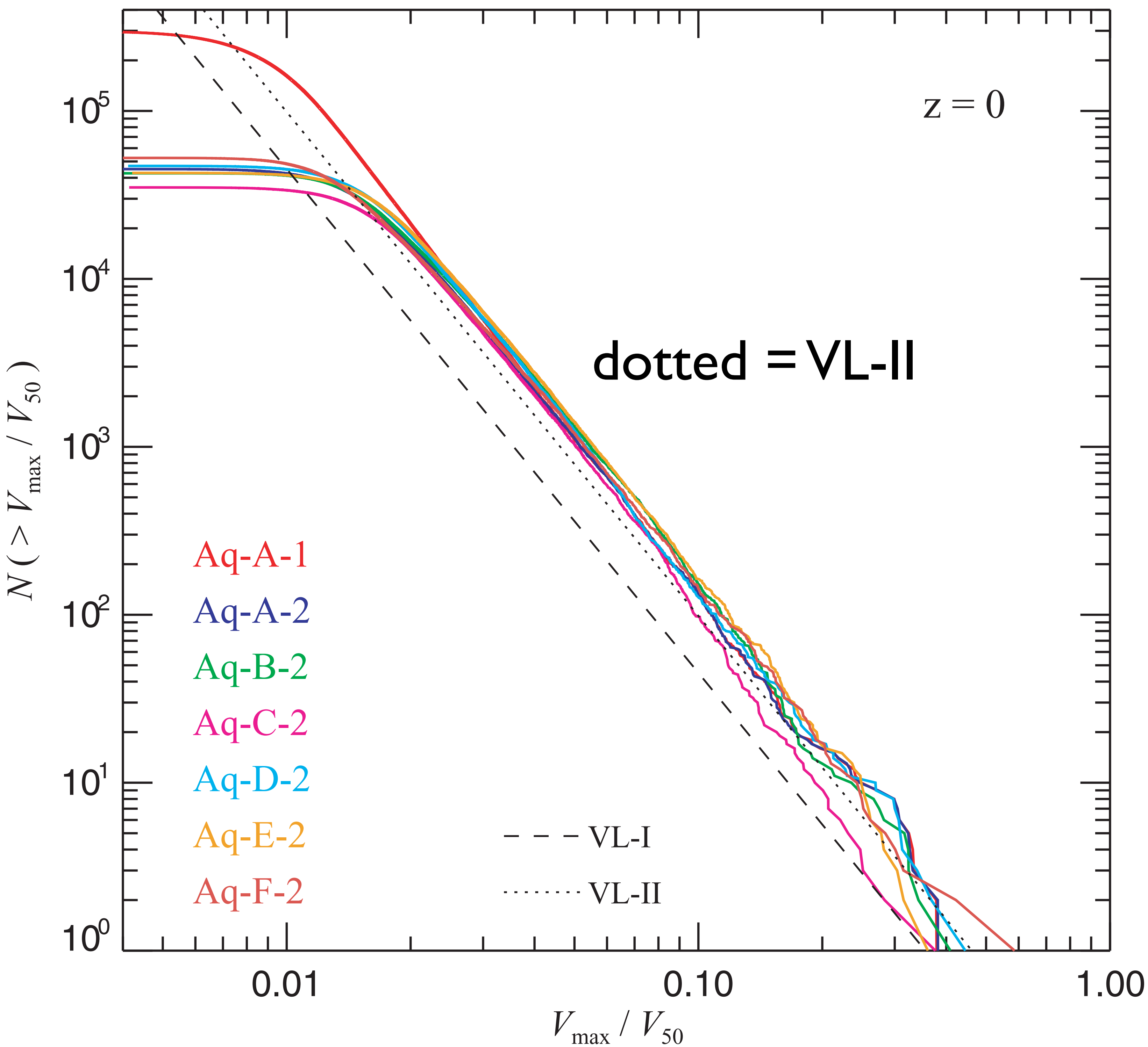
Halo-galaxy relation at low masses



THINGS dwarfs: Oh et al. 2011

MBK, Bullock, & Kaplinghat 2012

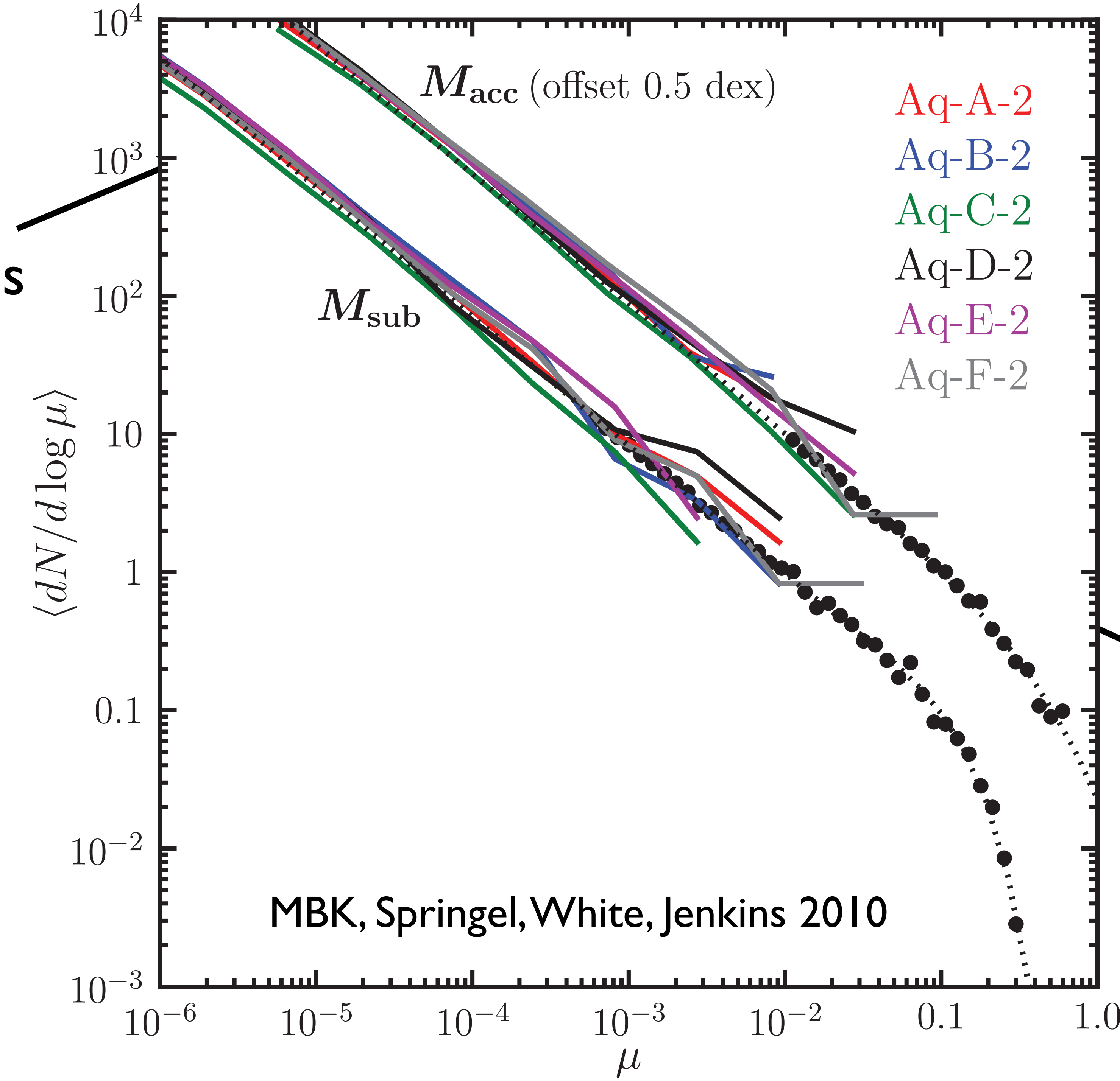
Aquarius, VL-II subhalo abundances agree to ~20%.



Springel et al. 2008

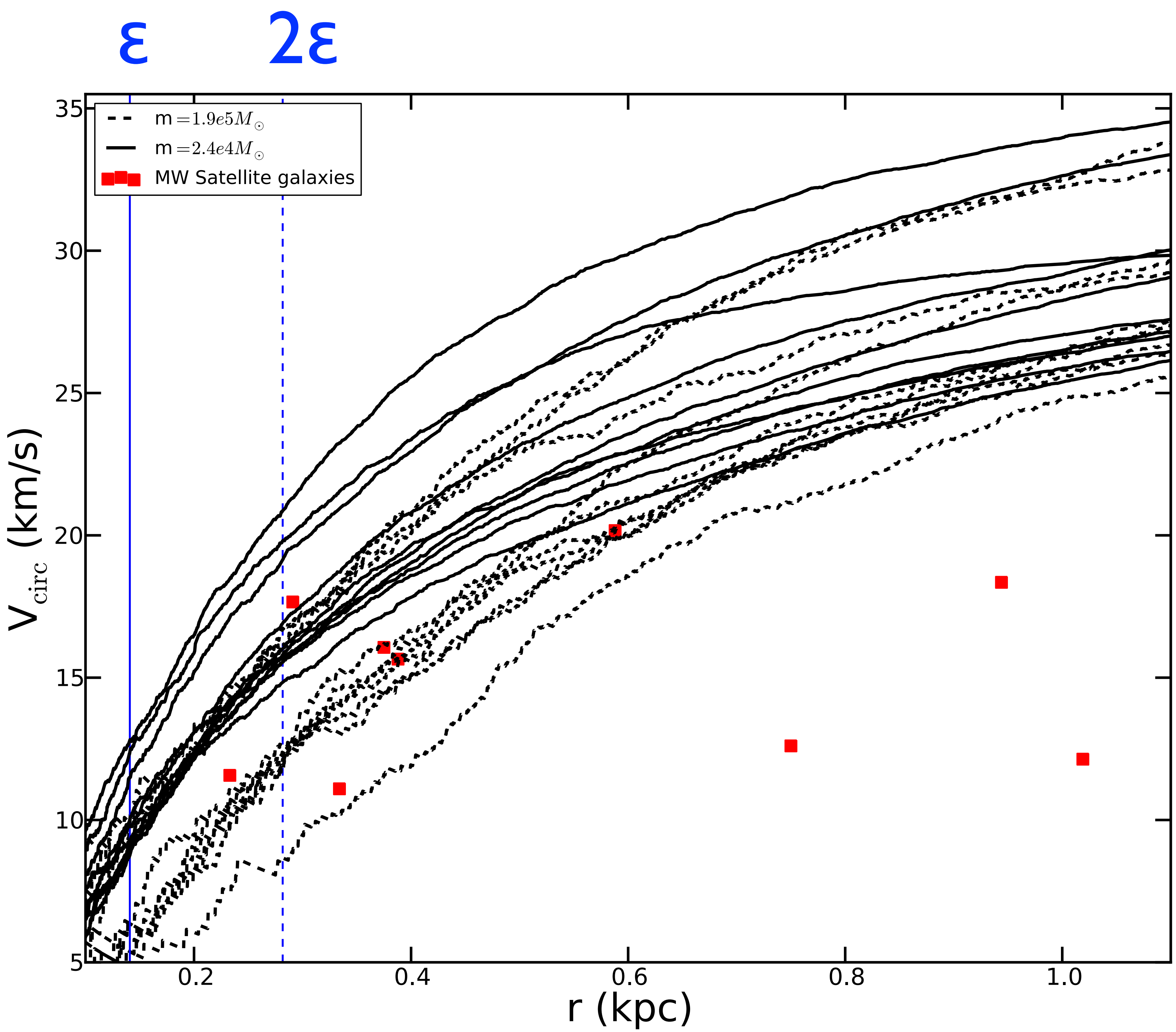
The abundance of substructure and its scatter is **very** well known from simulations

6 Aquarius halos



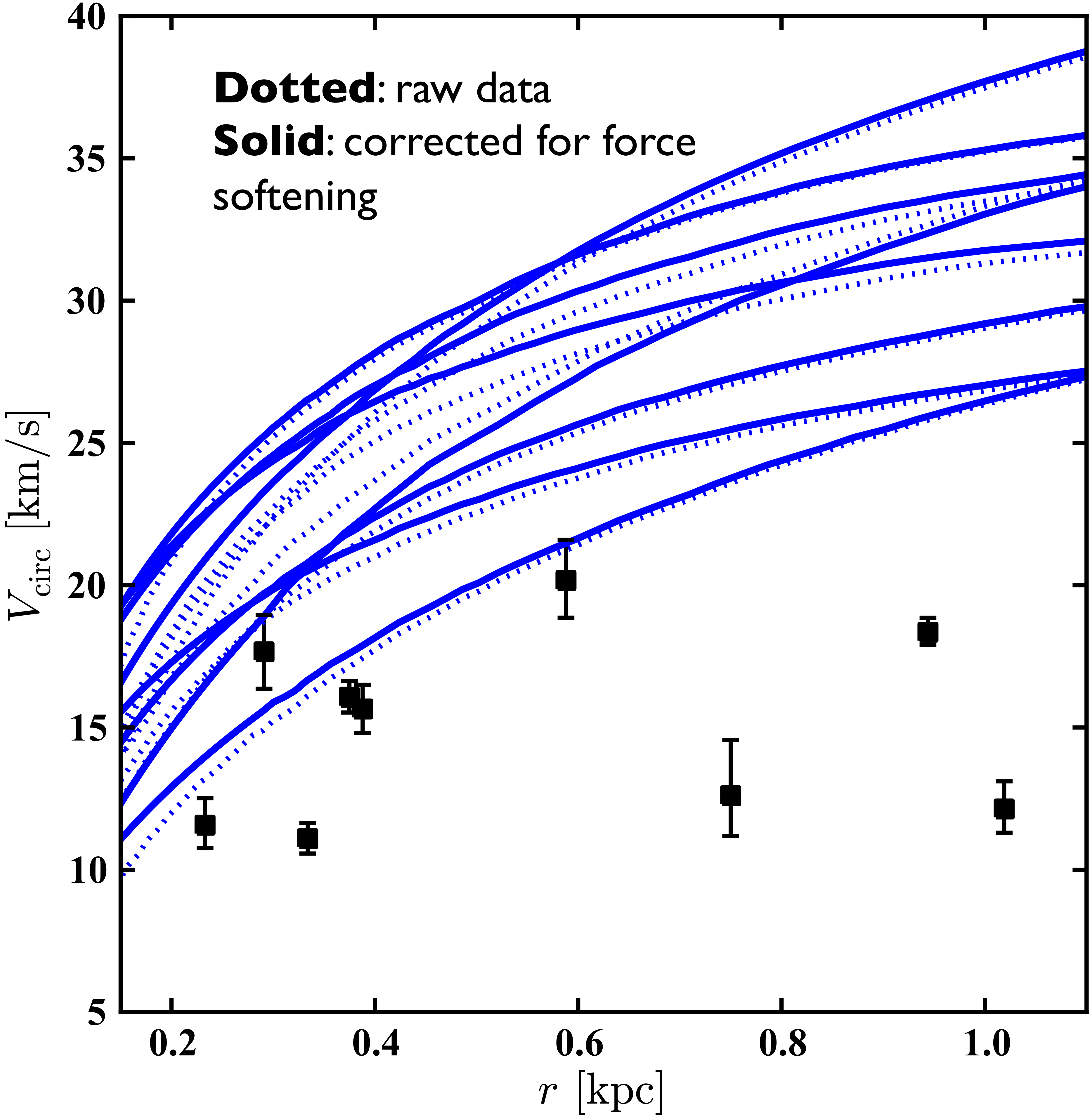
2000 MW-mass halos from Millennium-II

Scatter: Poisson for massive subhalos, ~20% intrinsic scatter for low mass subhalos. Excellent agreement between Millennium-II (MBK et al. 2010) & Bolshoi (Busha et al 2011)



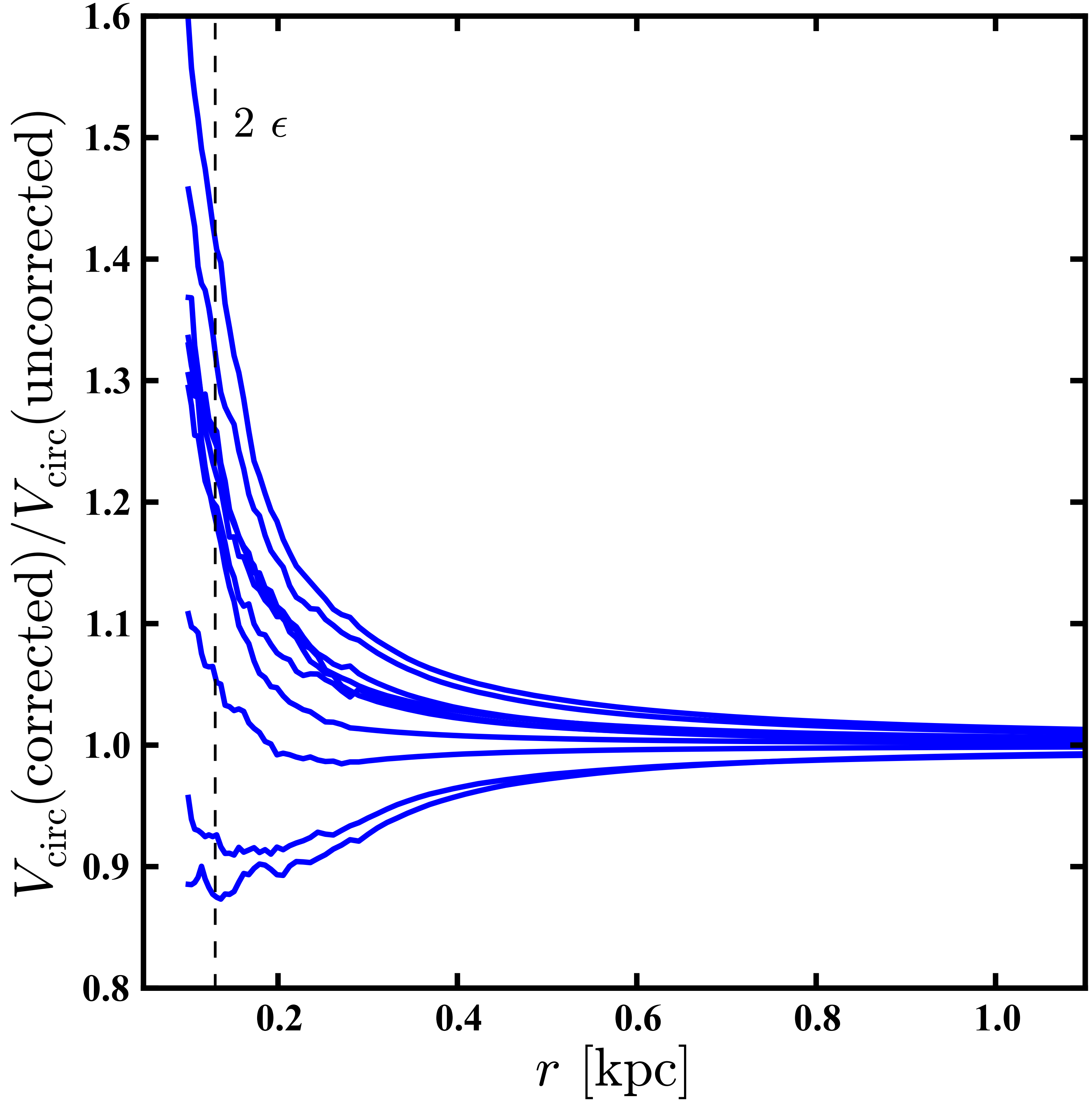
Systematic offset between high resolution (solid) and lower resolution (dotted) rotation curves.
Offset persists to several softening lengths.

from S. Garrison-Kimmel, MBK, Bullock et al. (in prep)

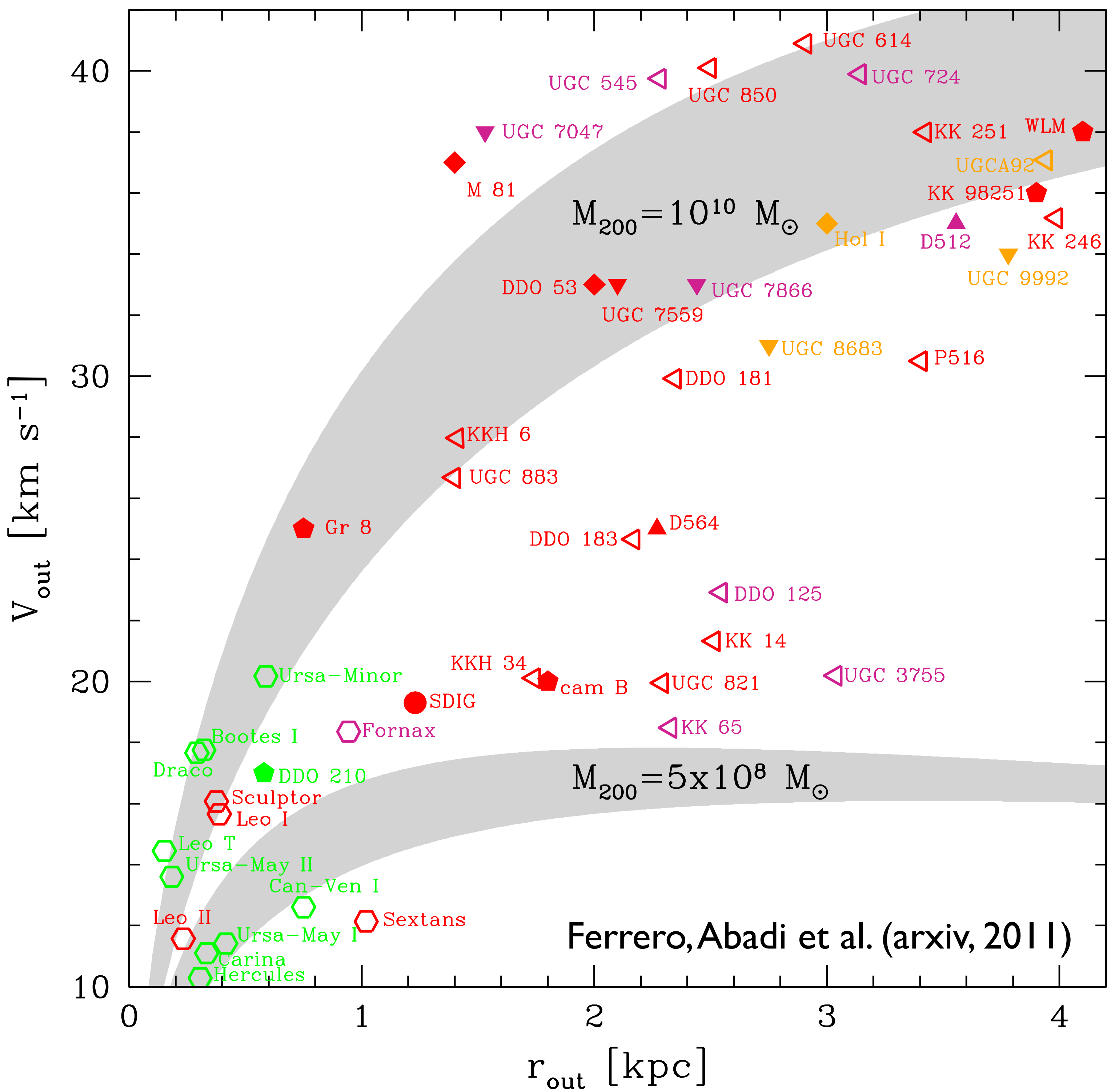


Dotted: raw data
Solid: corrected for force softening
40
35
30
25
20
15
10
5
0.2
0.4
0.6
0.8
1.0
$V_{\rm circ}$ [km/s]
r [kpc]

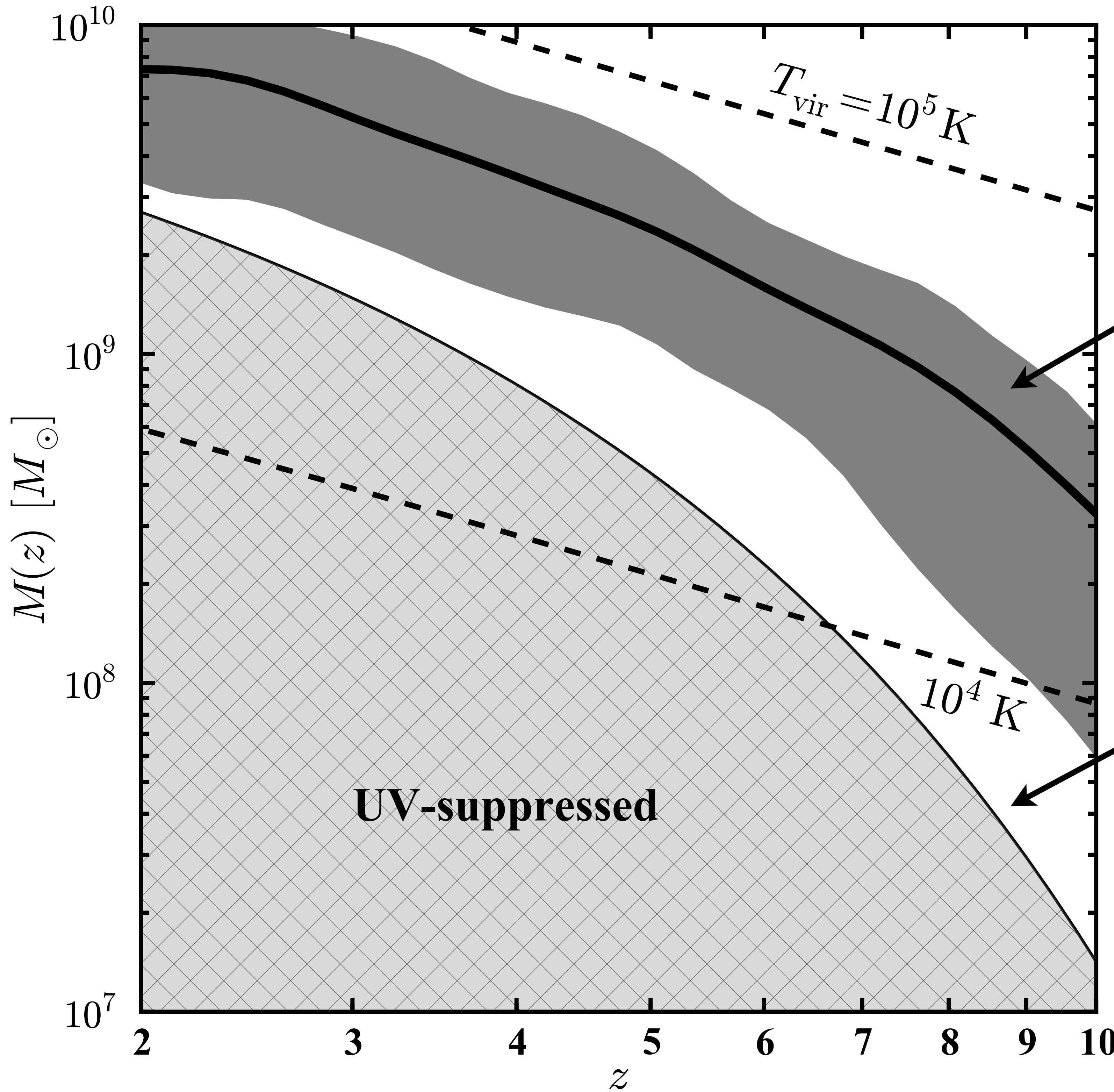
Even at Aquarius level 2 resolution, V_{circ} is underestimated by 25% -- Mass underestimated by 50% -- at 2 x Plummer-equivalent softening length



Similar issues in isolated field galaxies



Reionization does not solve the "massive failures" problem



Median mass for subhalos with V_{infall} > 30 km/s

Characteristic mass where UV background removes 50% of baryons
(Okamoto et al.; also Gnedin 2000)

MBK, Bullock, & Kaplinghat 2012