Massive Failures?

ΛCDM subhalos and Milky Way satellites

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Southern California CGE Center for Galaxy Evolution

UCSC Galaxy Formation Workshop
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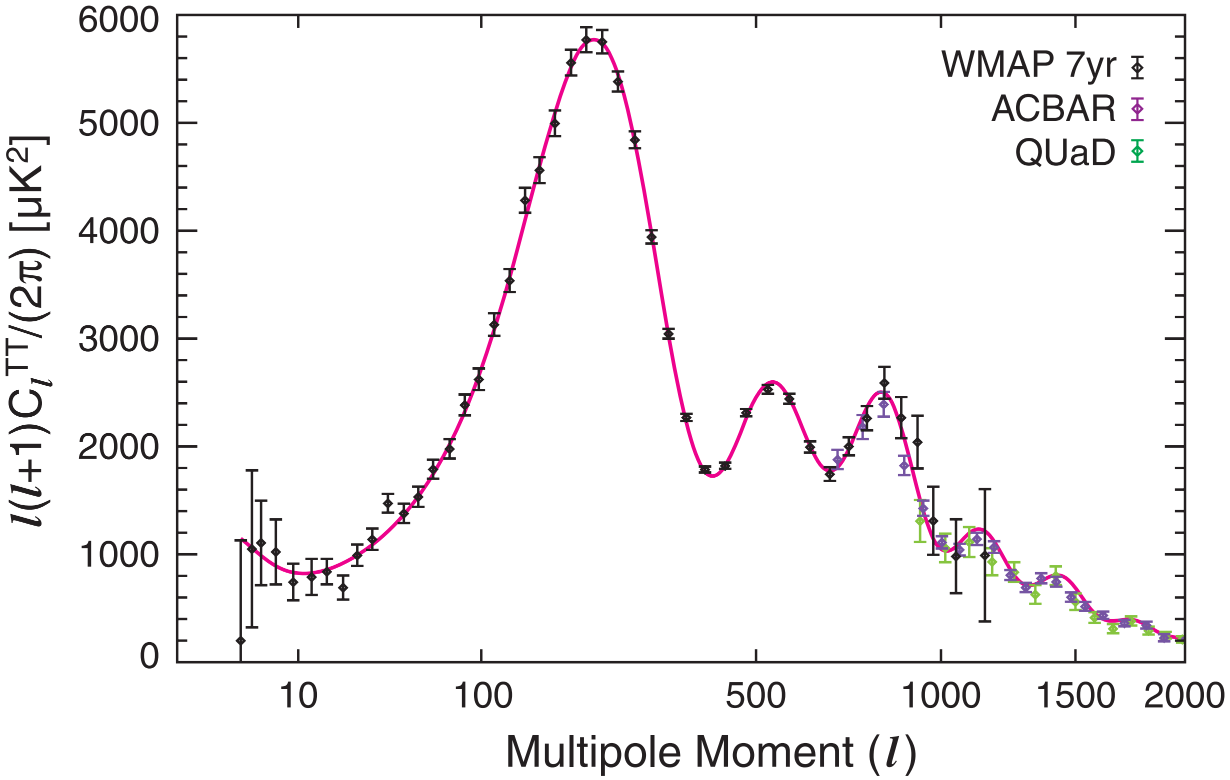
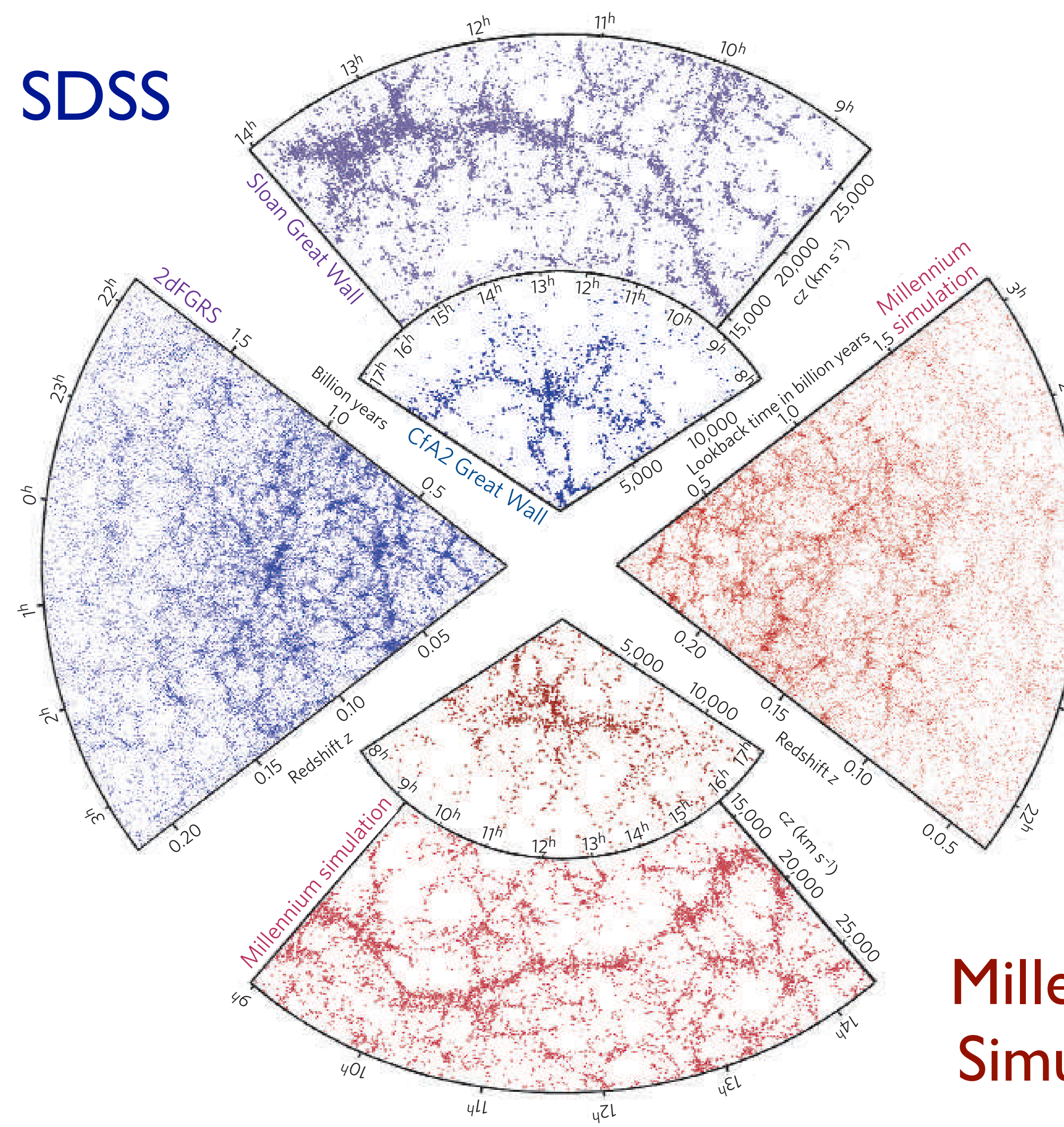
ΛCDM: resounding success on large scales



Komatsu et al. / WMAP (2011)

SDSS



Millennium Simulation

Springel, Frenk, & White 2006

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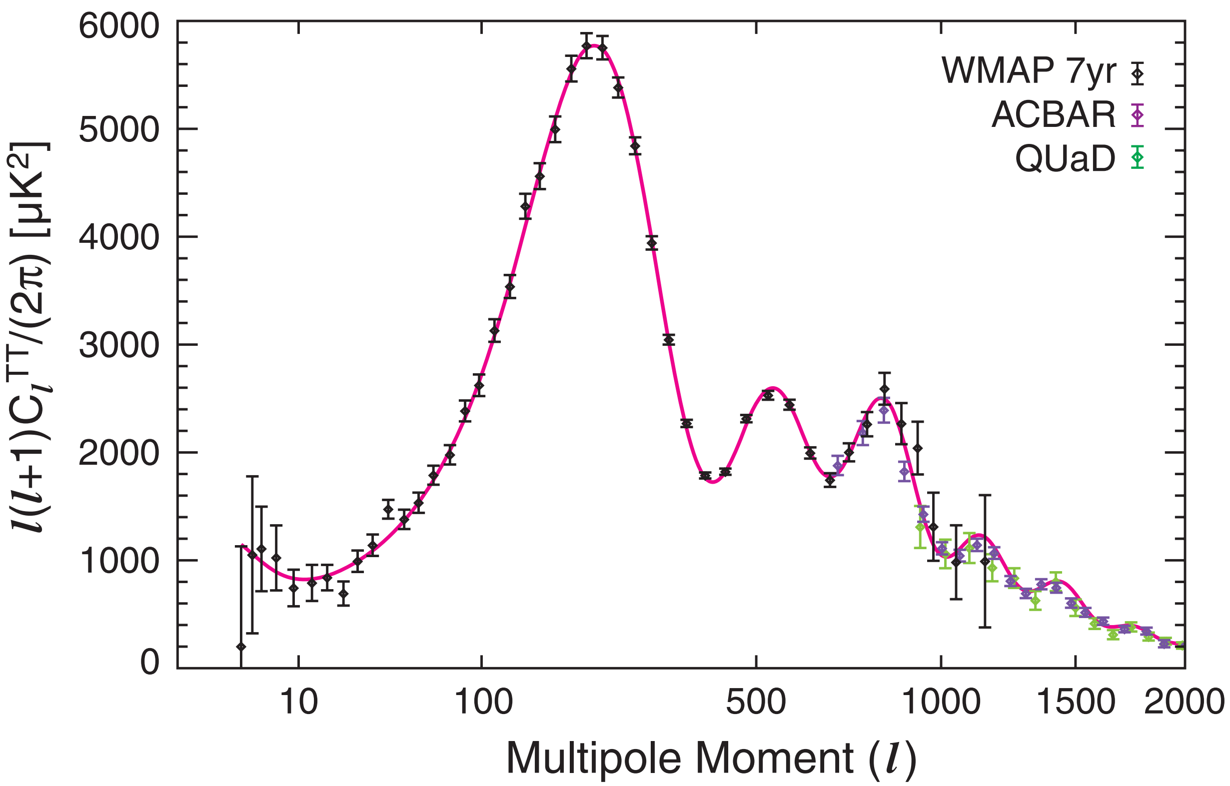

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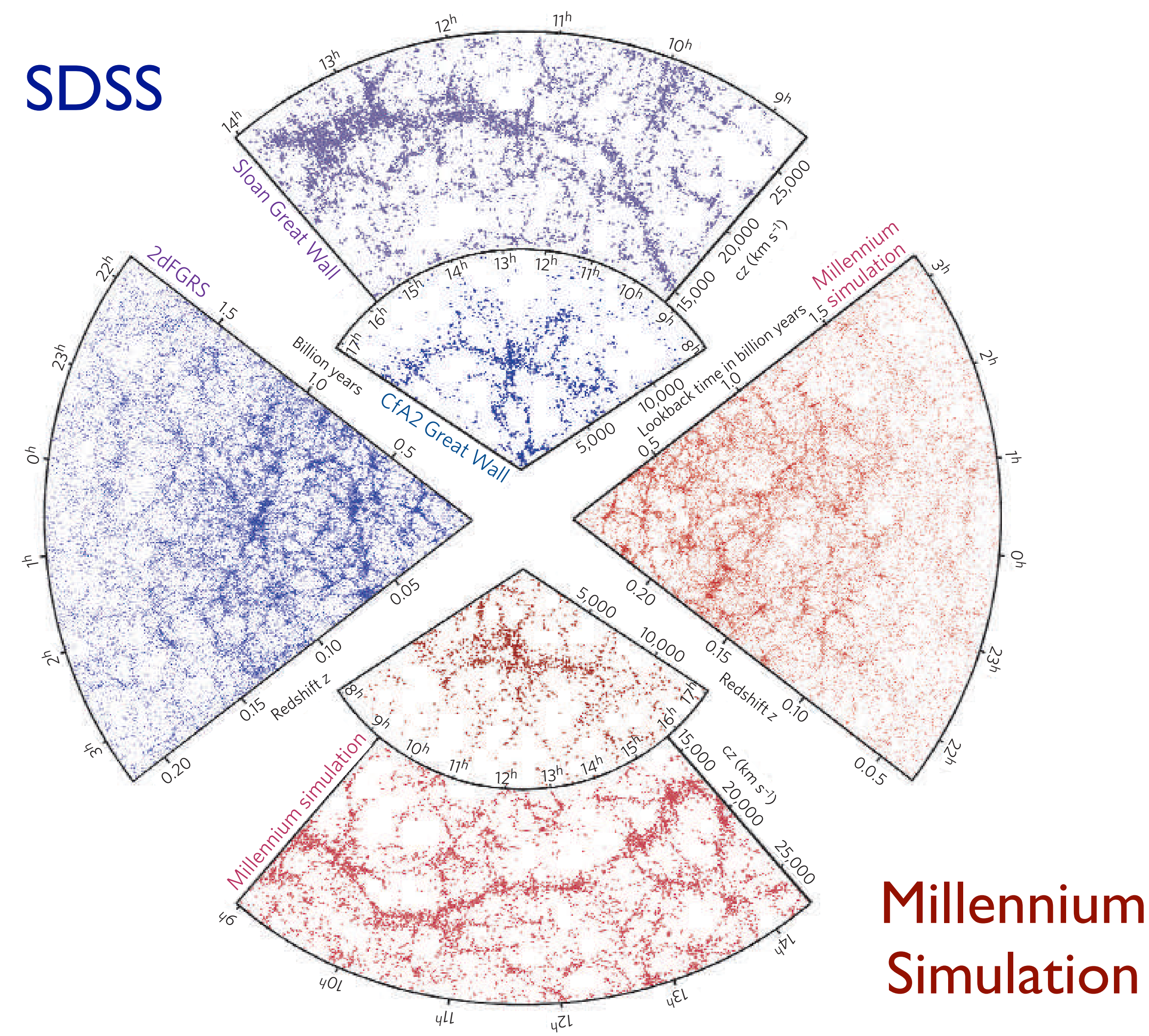
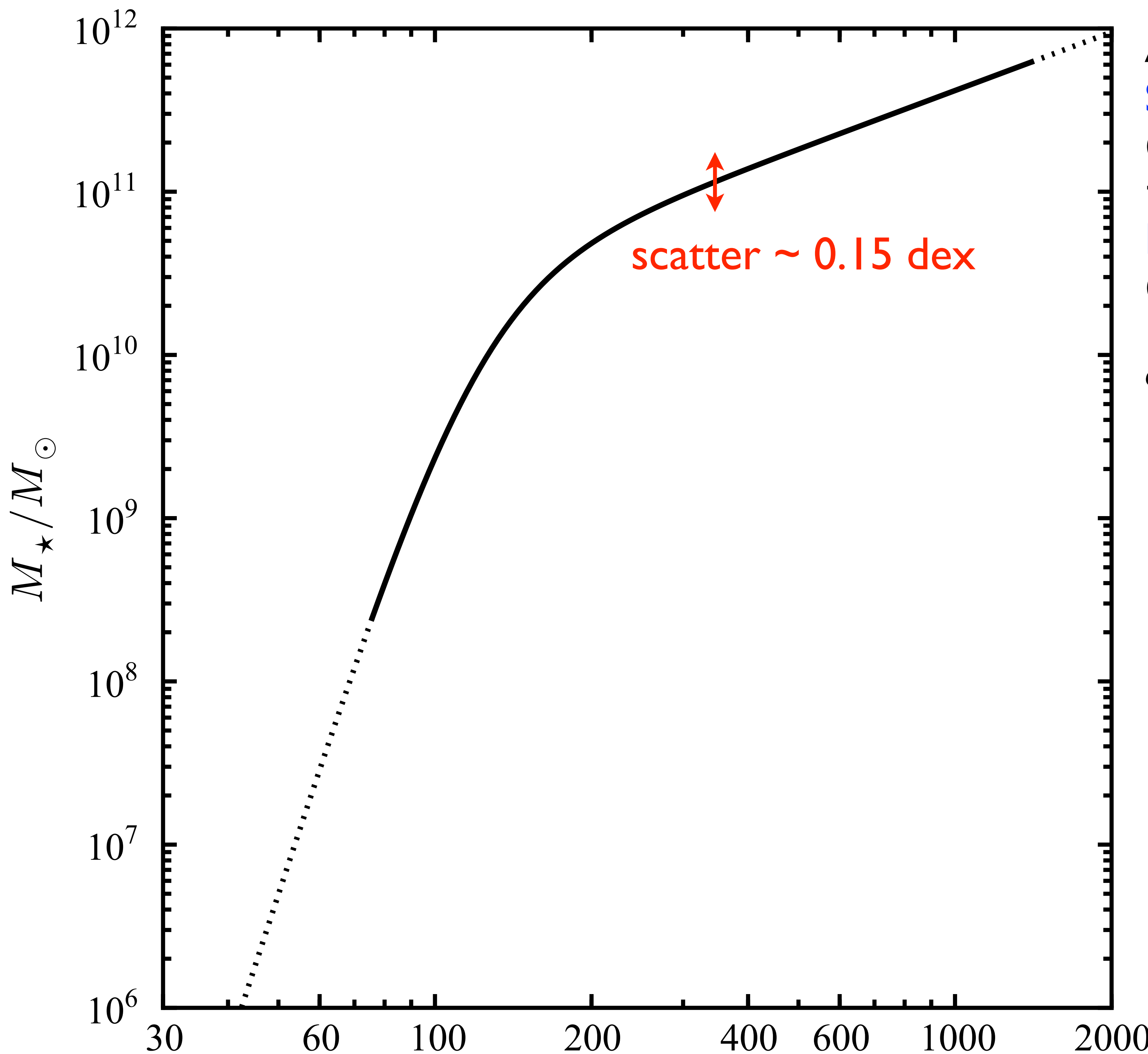


Springel, Frenk, & White 2006

N-body simulations make precise predictions for dark matter distribution over a wide range of scales.

From dark matter halos to galaxies



V_{infall}=maximum V_{max} ever attained,

$$V_{\rm max} = \max\left(\sqrt{\frac{GM_{\rm tot}(<r)}{r}}\right)$$

Abundance matching based on
SDSS stellar mass function
(Li & White)
+
Millennium I and II simulations
(Springel et al. 2005, MBK et al. 2009)

also: Kravtsov et al. 2004, Conroy et al. 2006, ...

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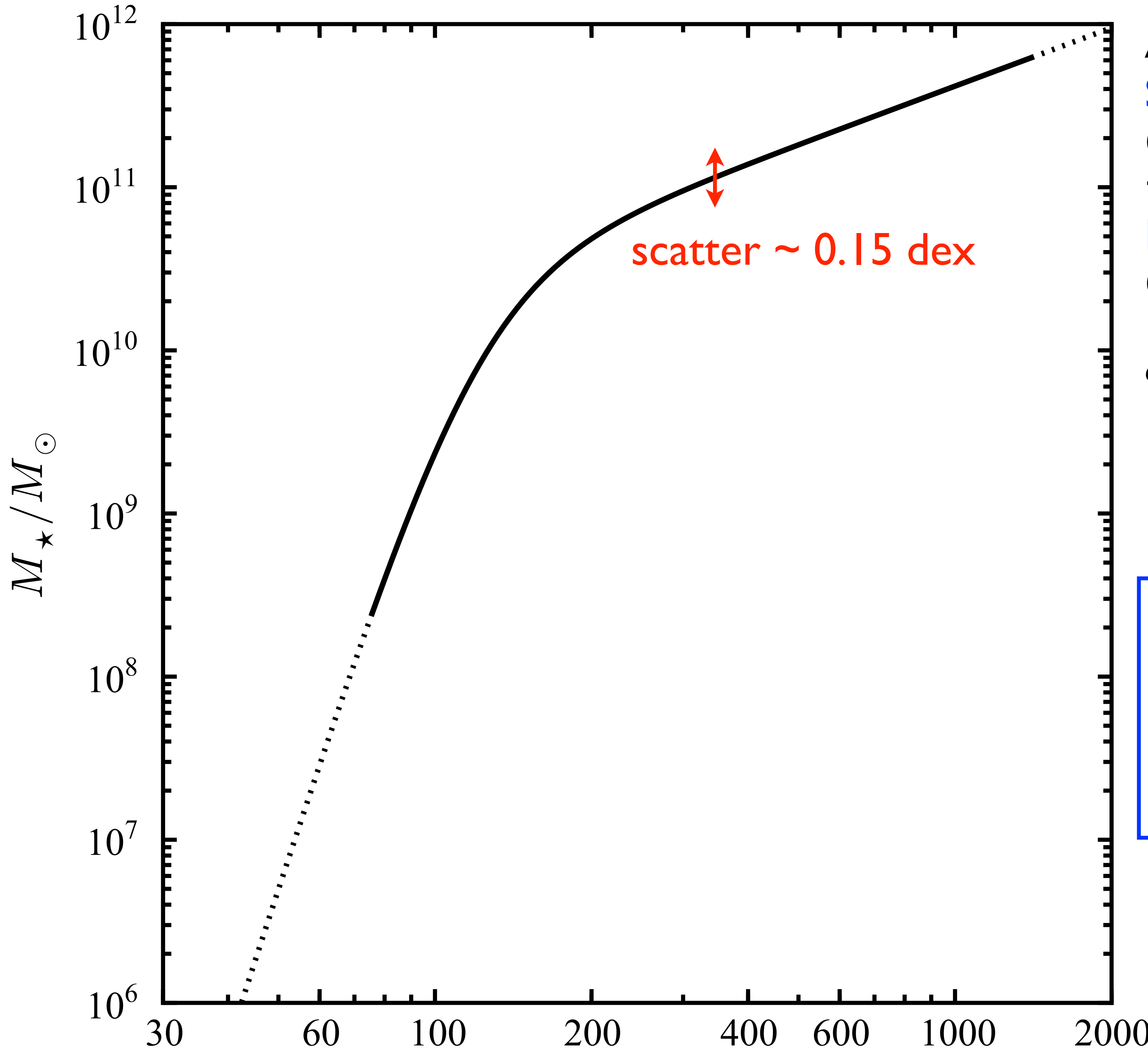

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A galaxy's stellar mass is determined by the maximum mass of its dark matter halo

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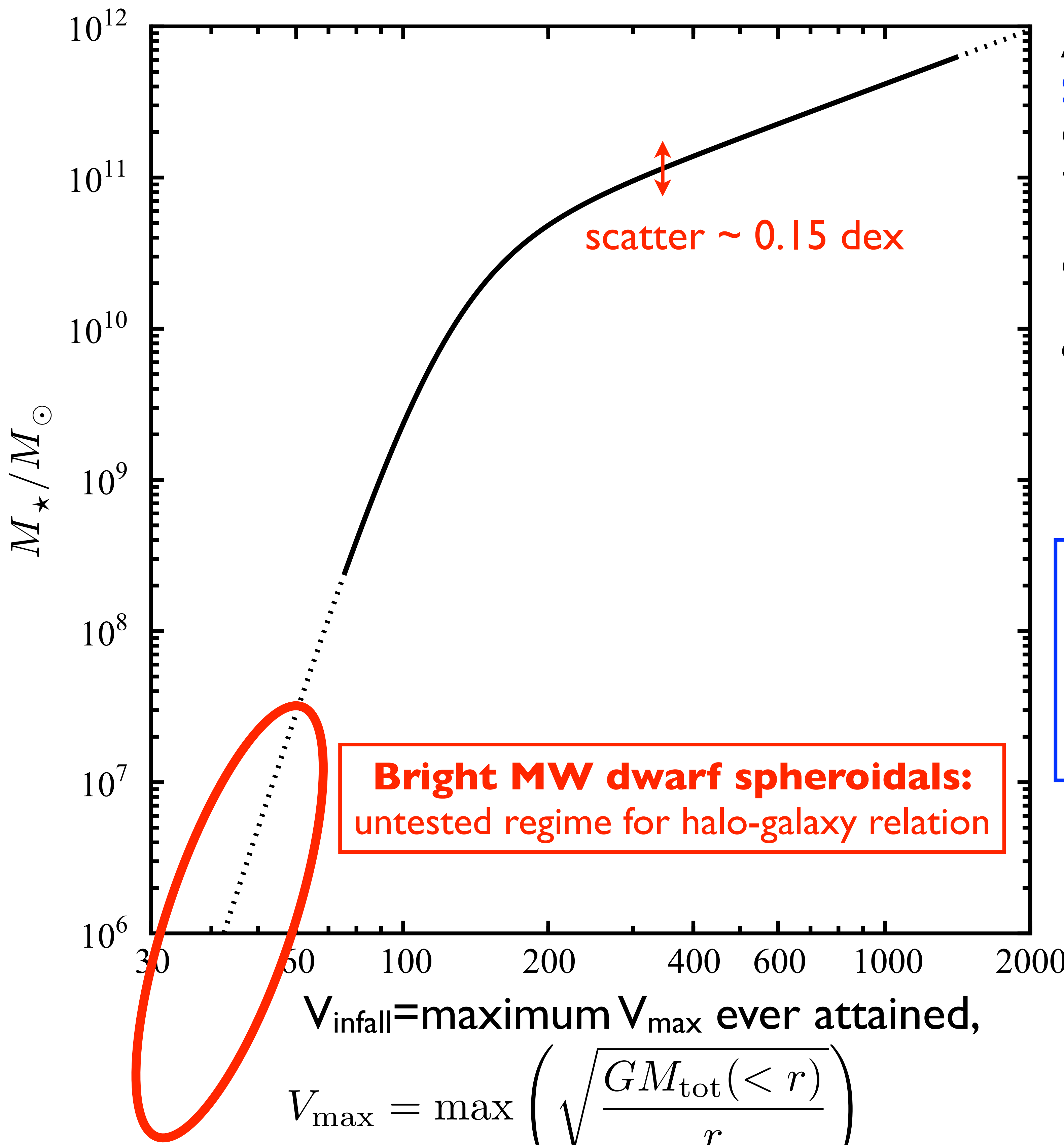

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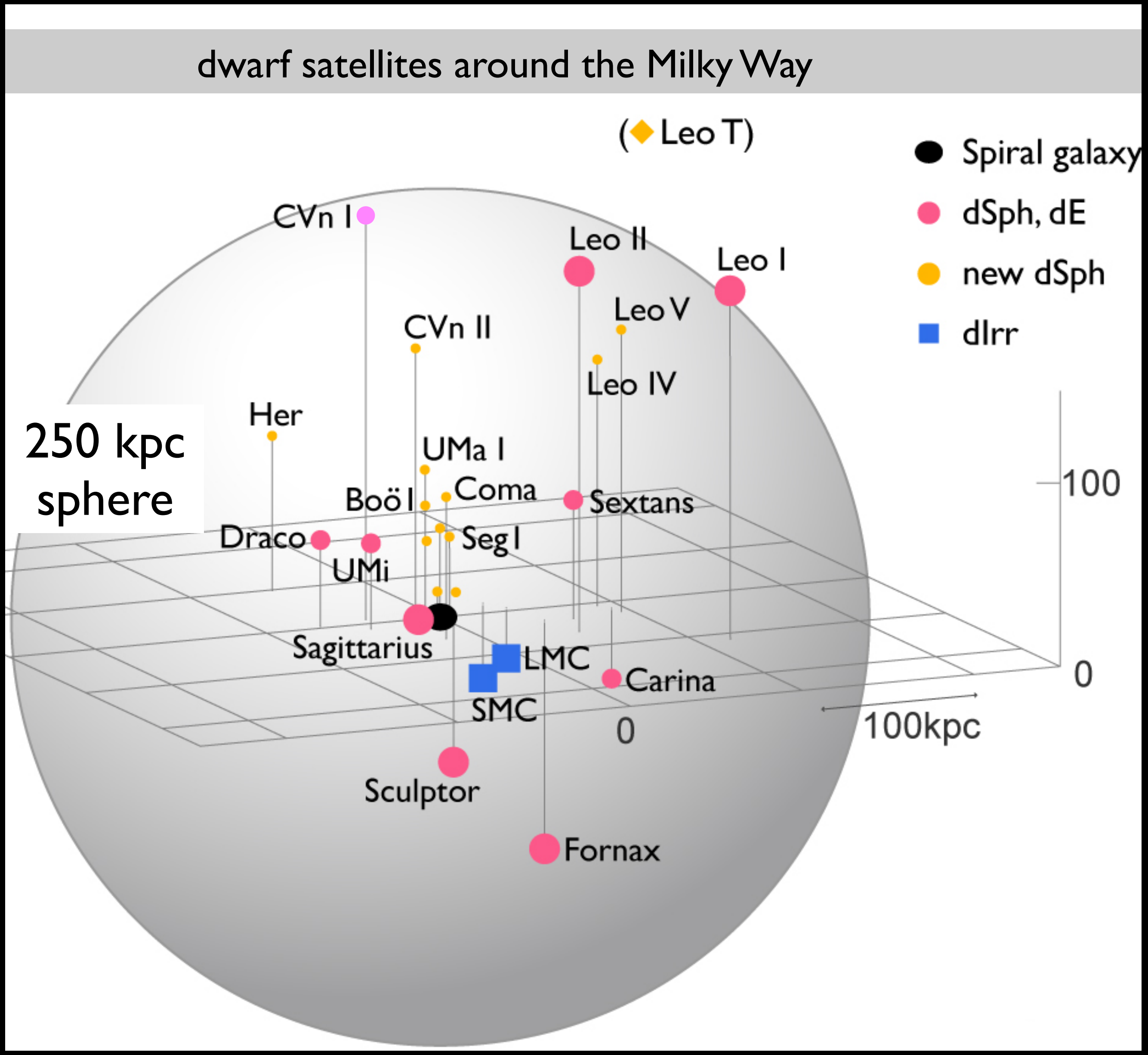
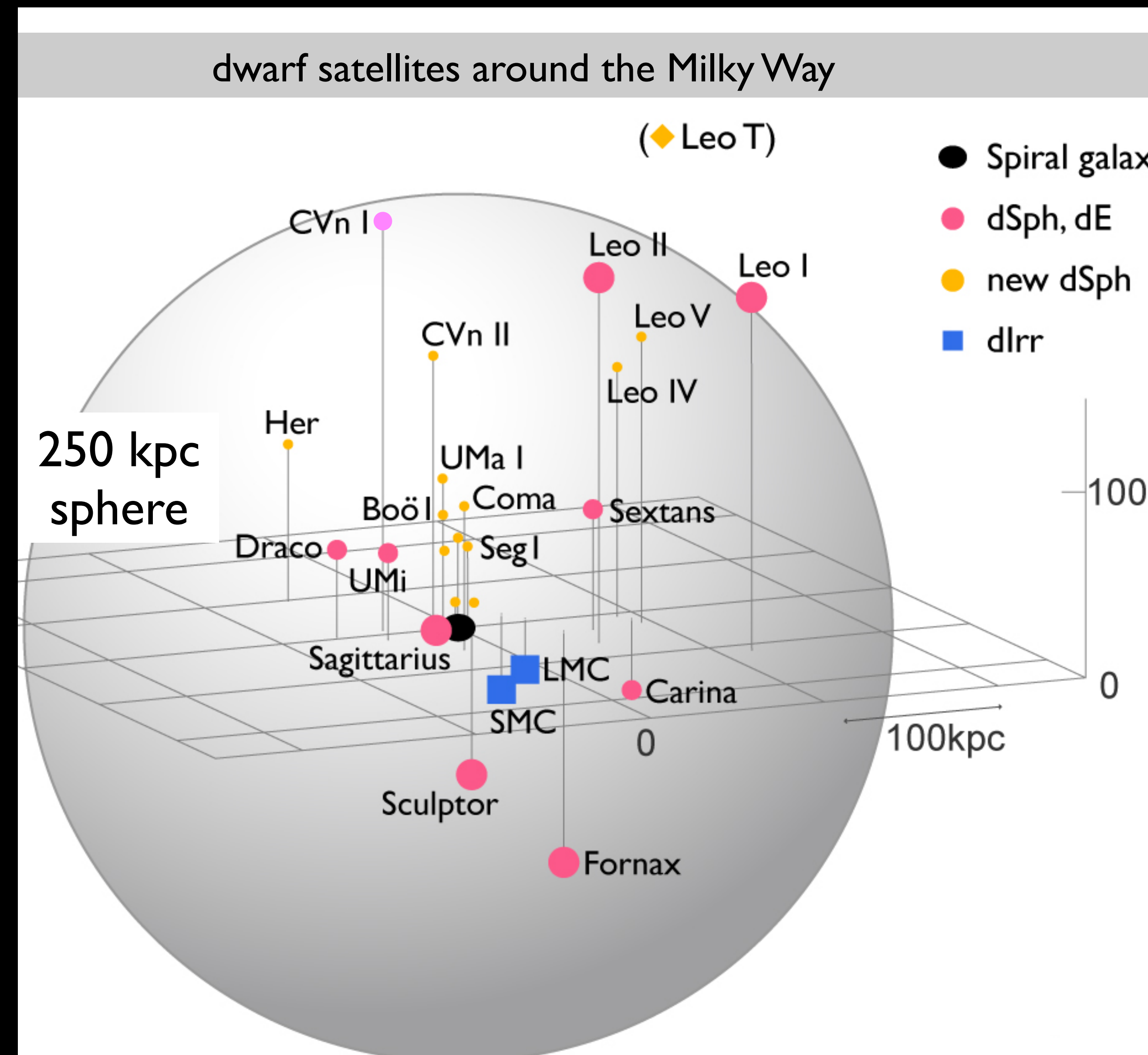
ΛCDM subhalos versus Milky Way satellites



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

S. Okamoto

ΛCDM subhalos versus Milky Way satellites



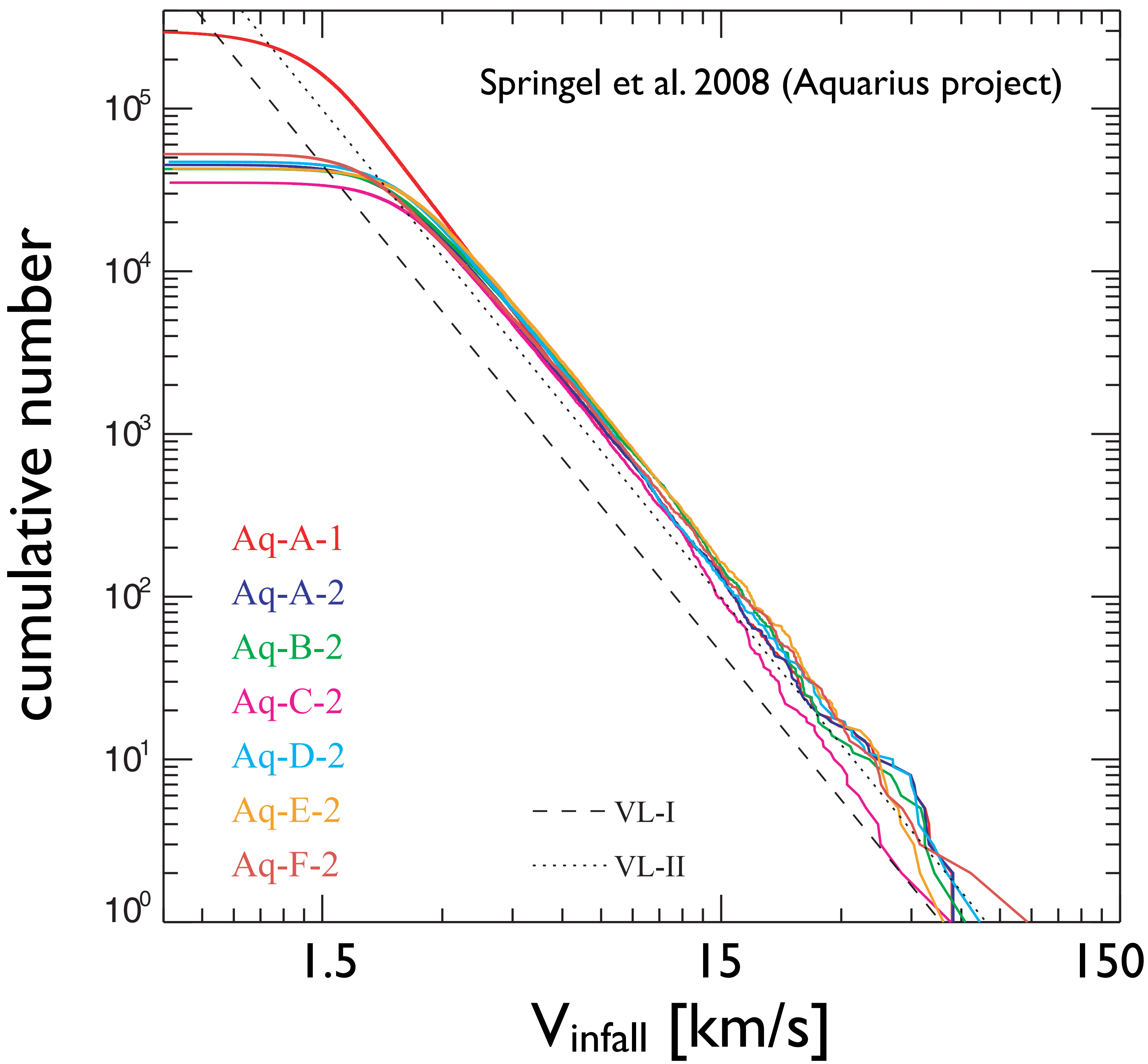
$>10^5$ identified subhalos

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

V. Springel / Virgo Consortium

S. Okamoto

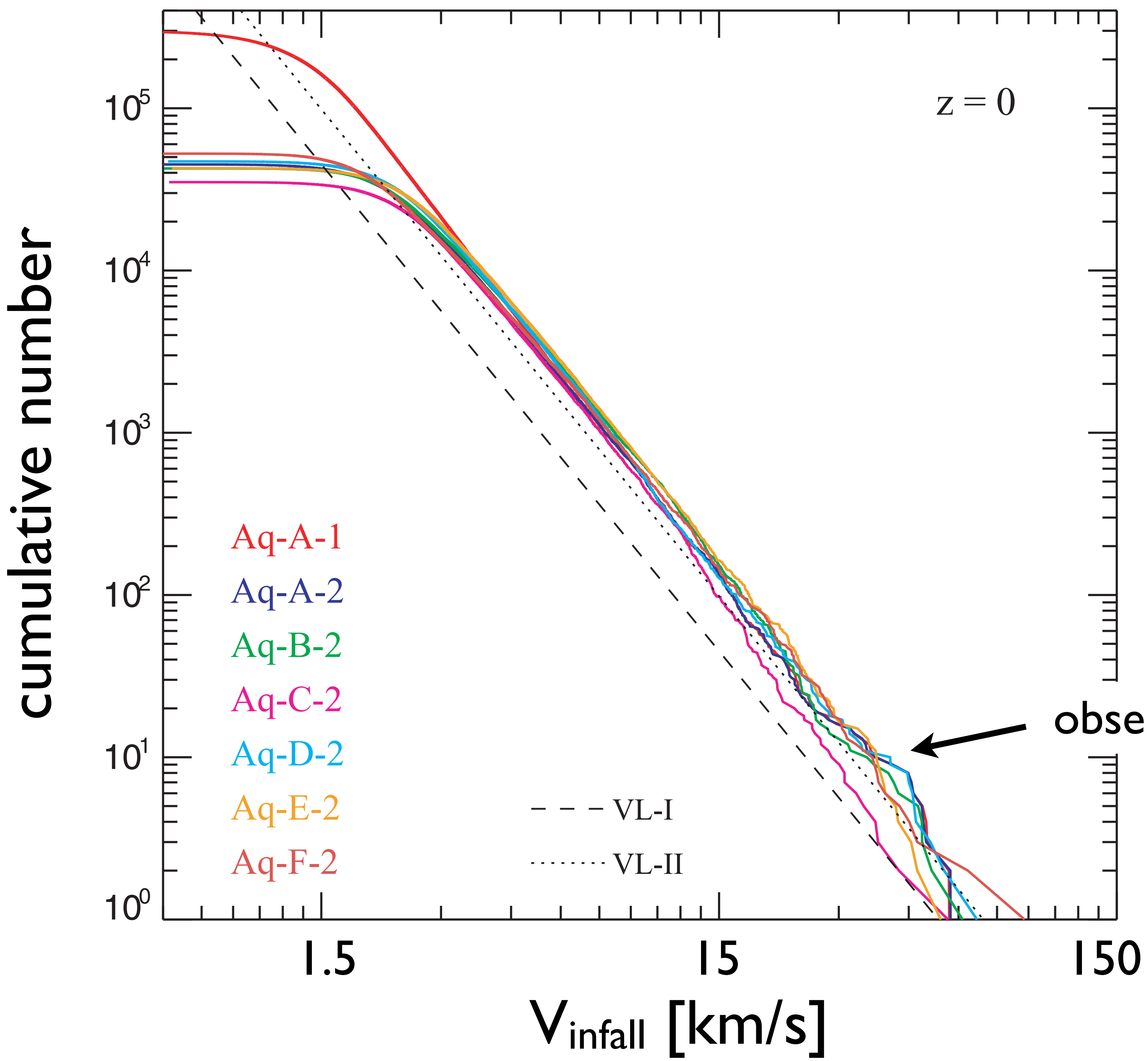
CDM subhalos and MW satellites



Missing Satellites
(Klypin et al. 1999, Moore et al. 1999):

Mismatch between number of observed MW satellites and predicted subhalos

A simple explanation (?)



Springel et al. 2008 (Aquarius project)

observed bright satellites

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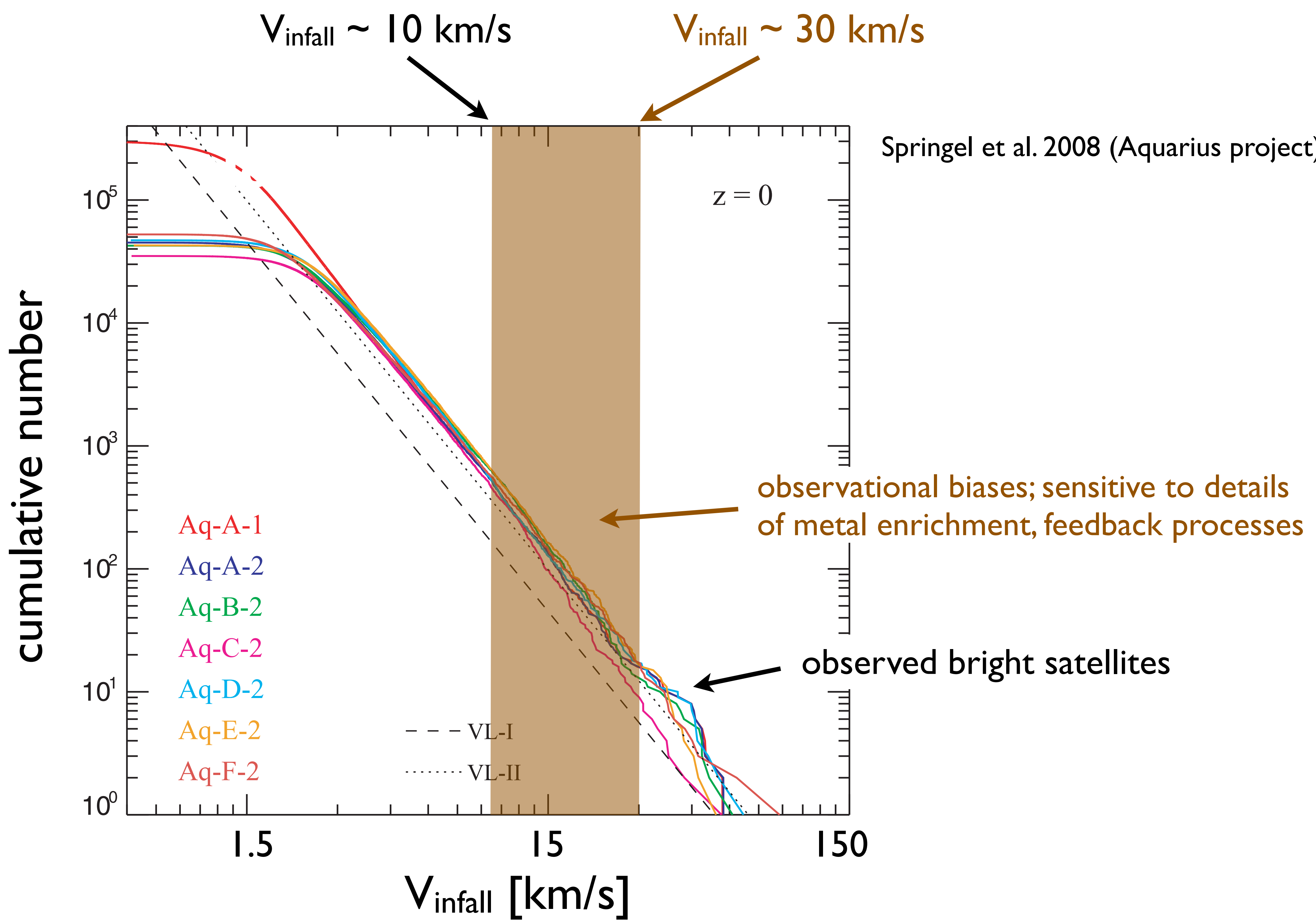

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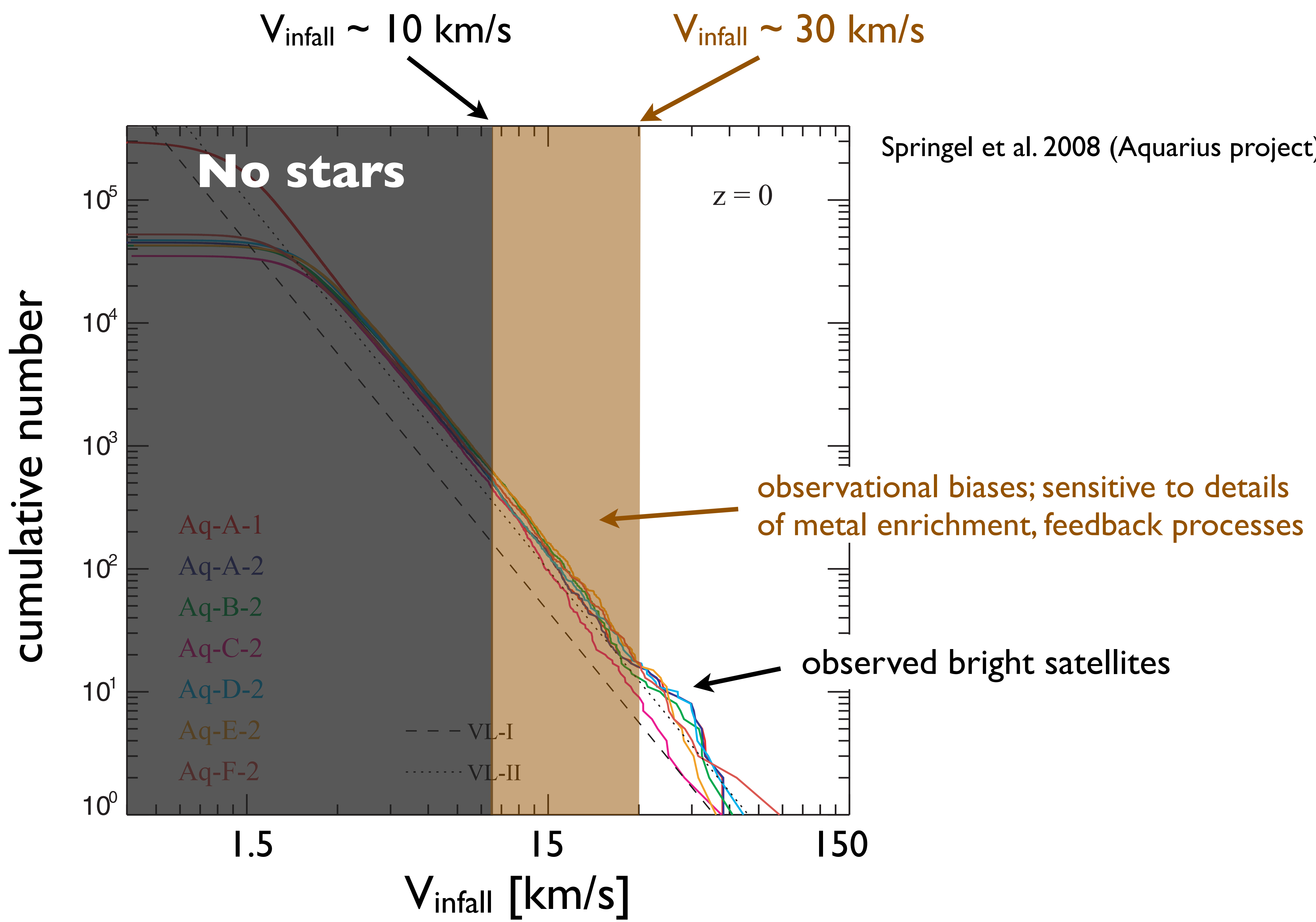
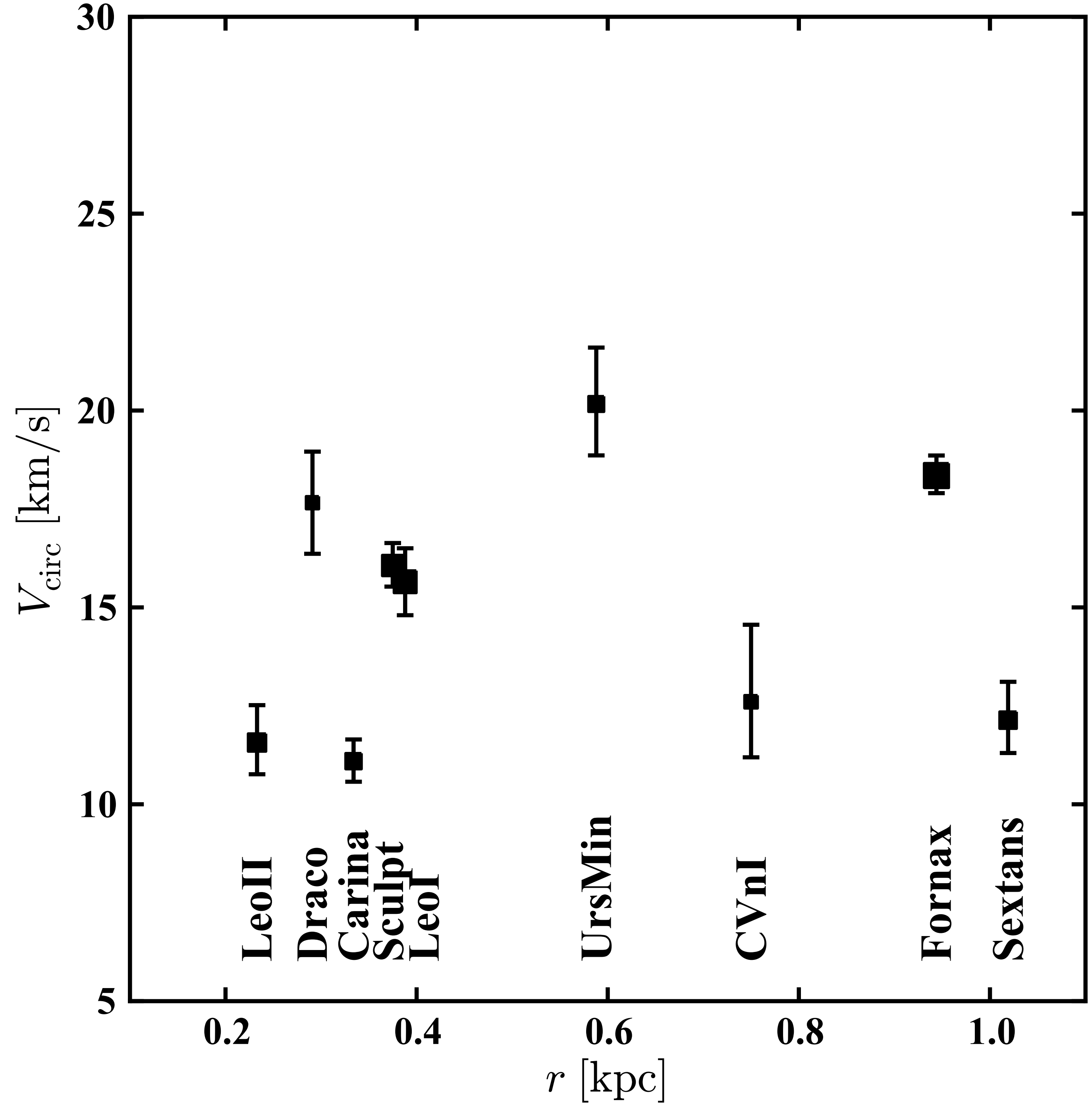


Measured values of V_{circ} for MW dwarfs

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



MBK, Bullock, & Kaplinghat 2011b (in prep.)

Observational constraints on dwarfs' dark matter hosts

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

- if mass agrees: the subhalo may be able to host the satellite;
- if mass disagrees: no way for the subhalo to host the satellite.

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assume NFW mass profiles for subhalos (verified in simulations)

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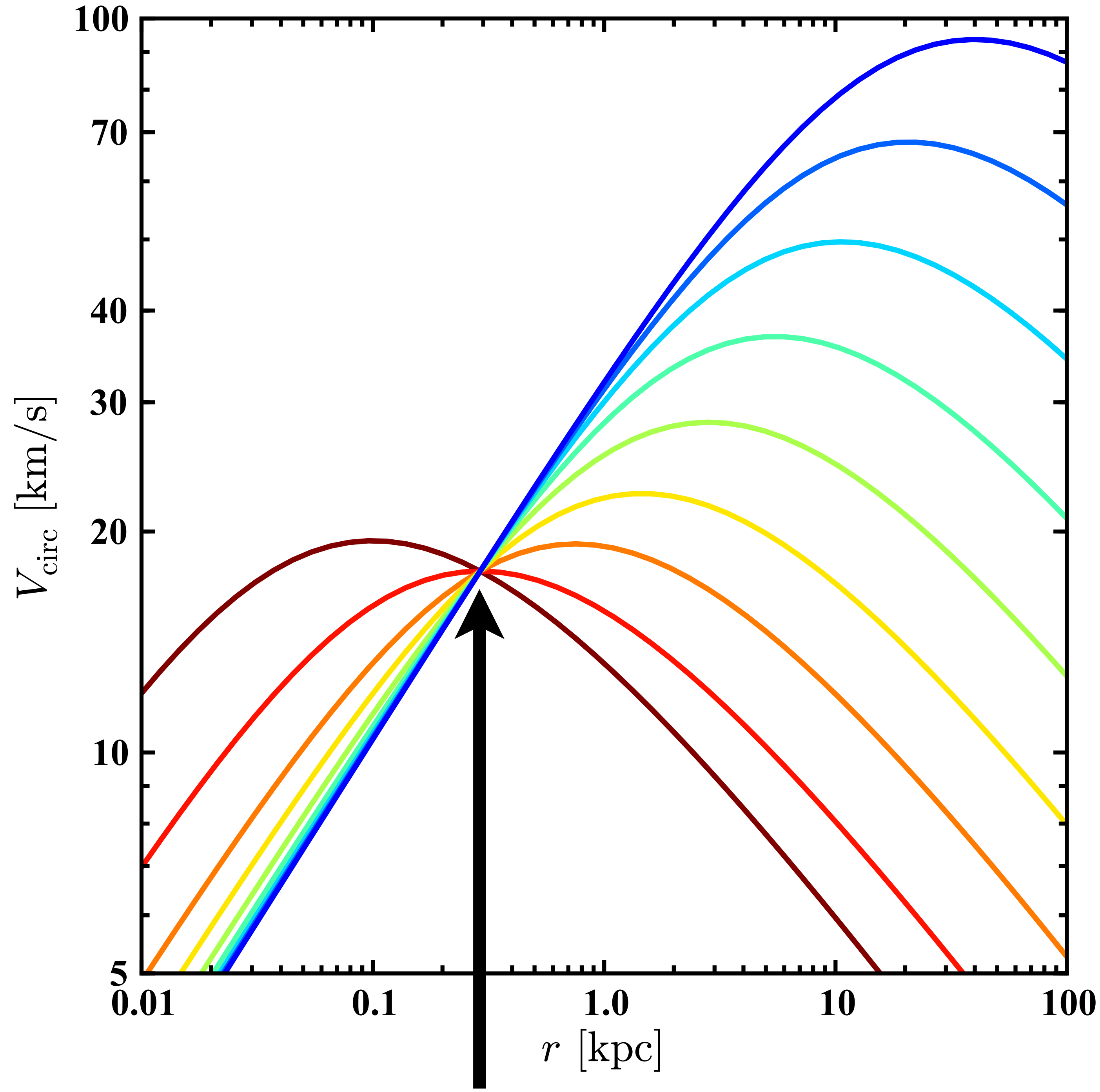

Mass well-determined at $R_{1/2}$ (291 pc for Draco)

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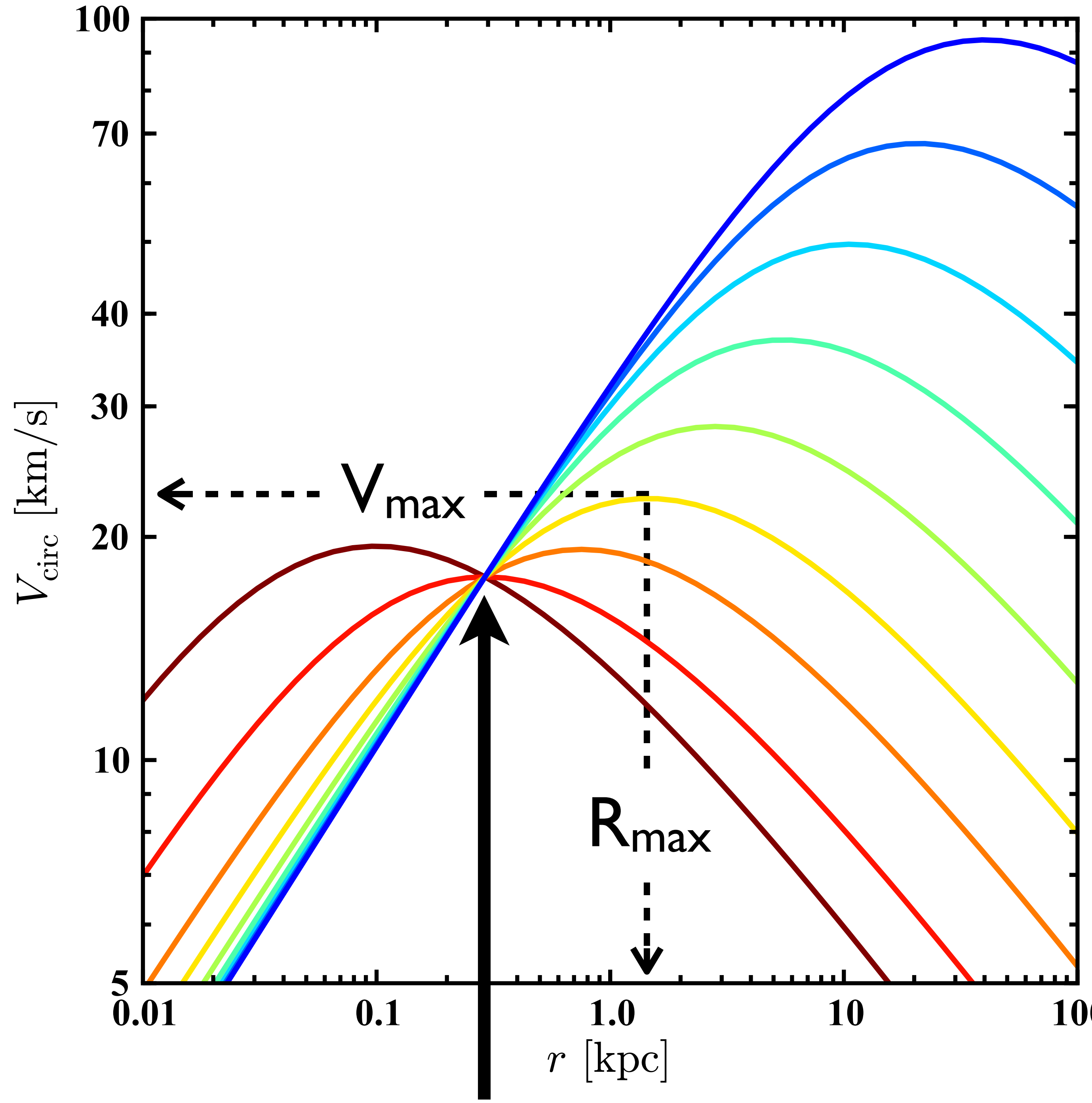

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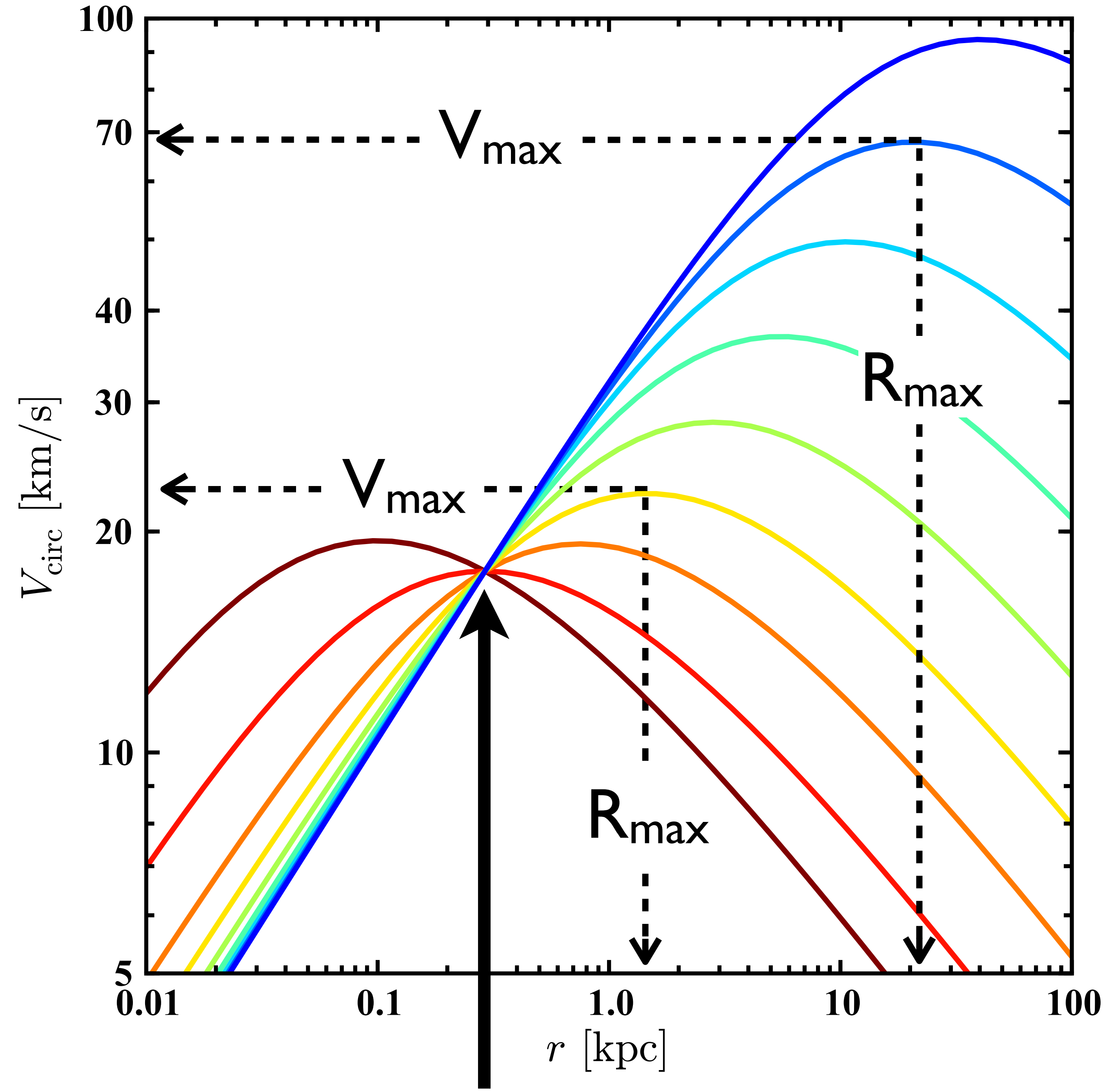

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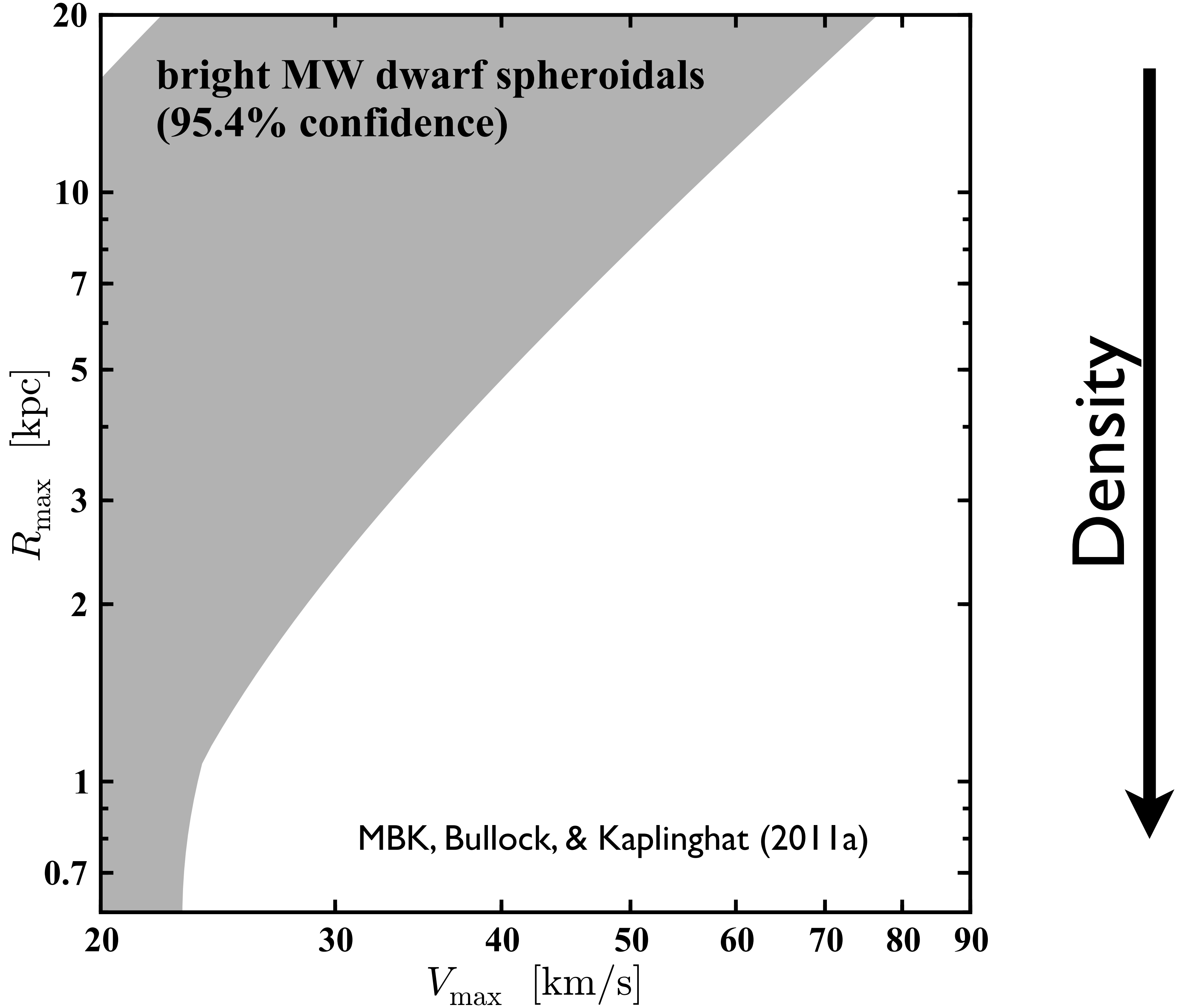
Combined dark matter profile constraints for MW dwarfs



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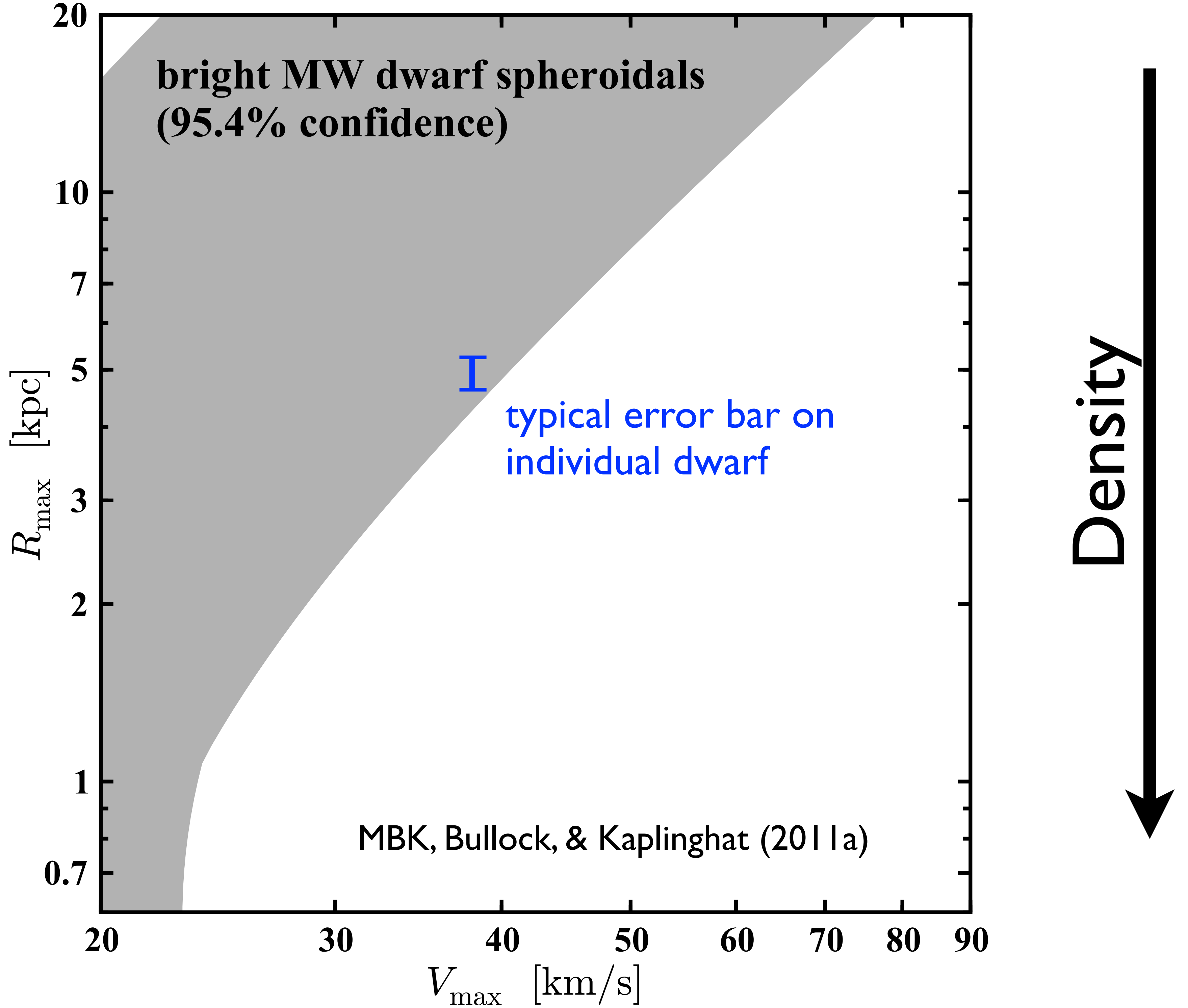
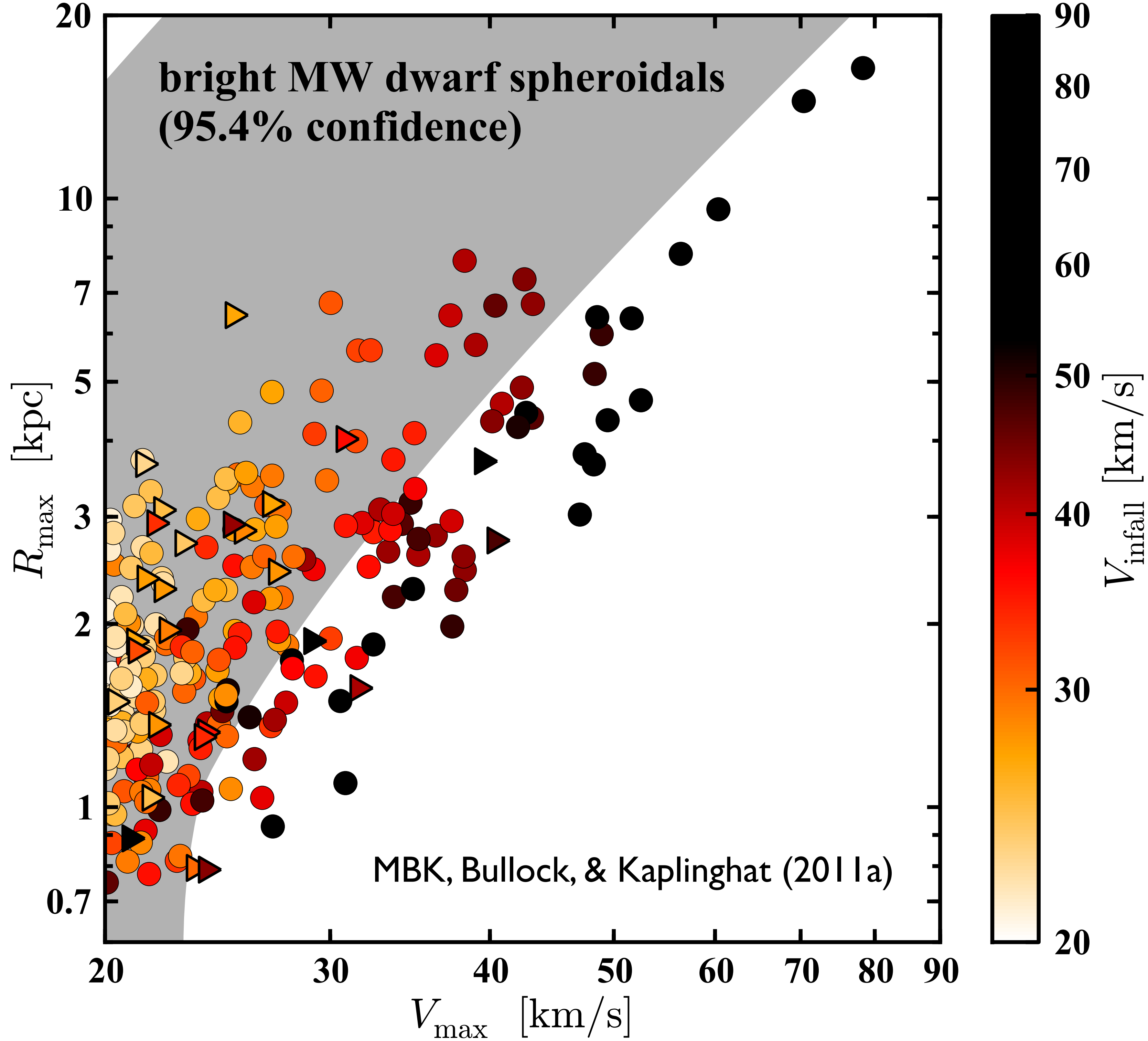


Adding in subhalos from simulations

seven simulations: six Aquarius + Via Lactea II



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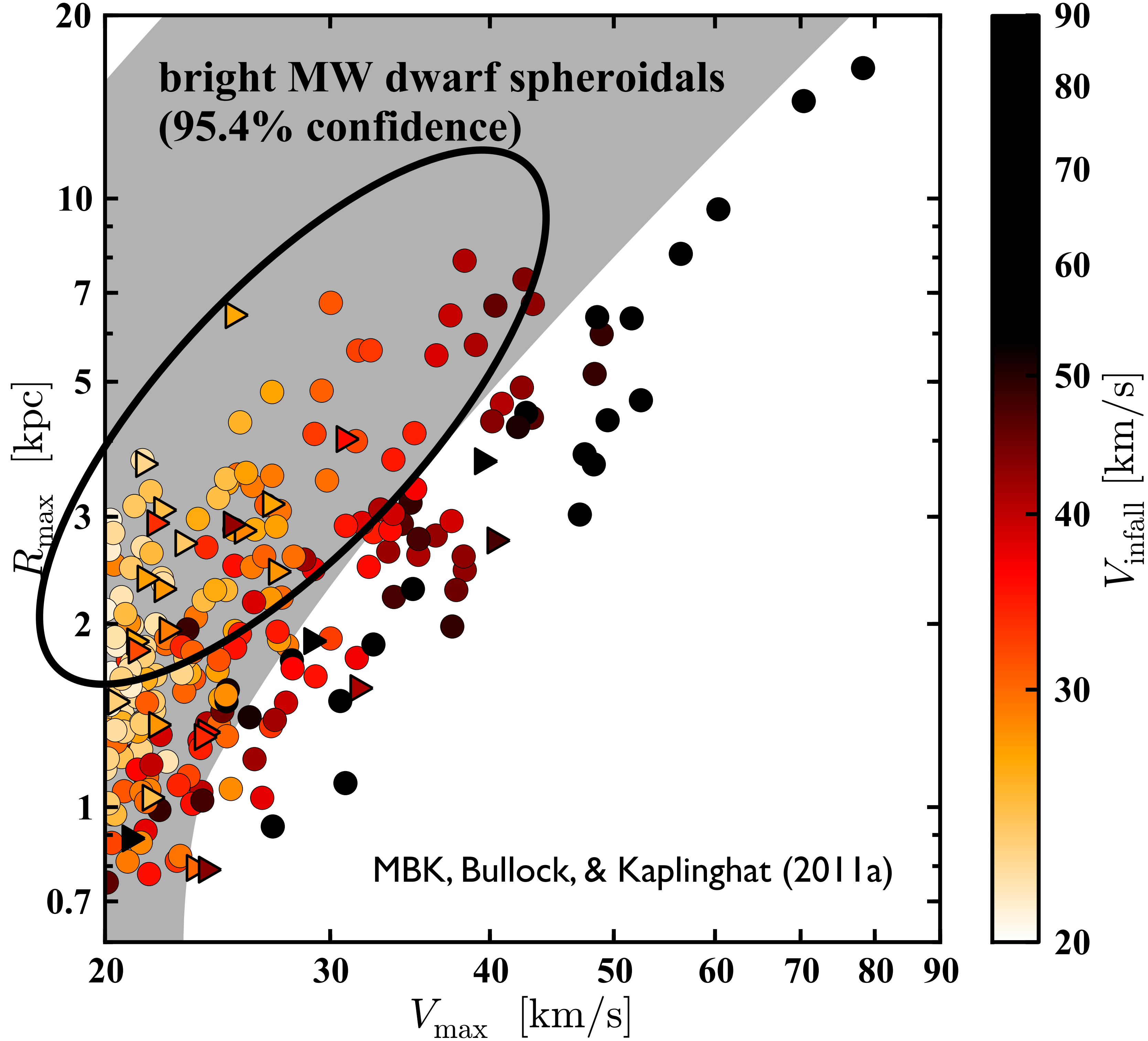

MANY subhalos consistent with dynamics of dSphs

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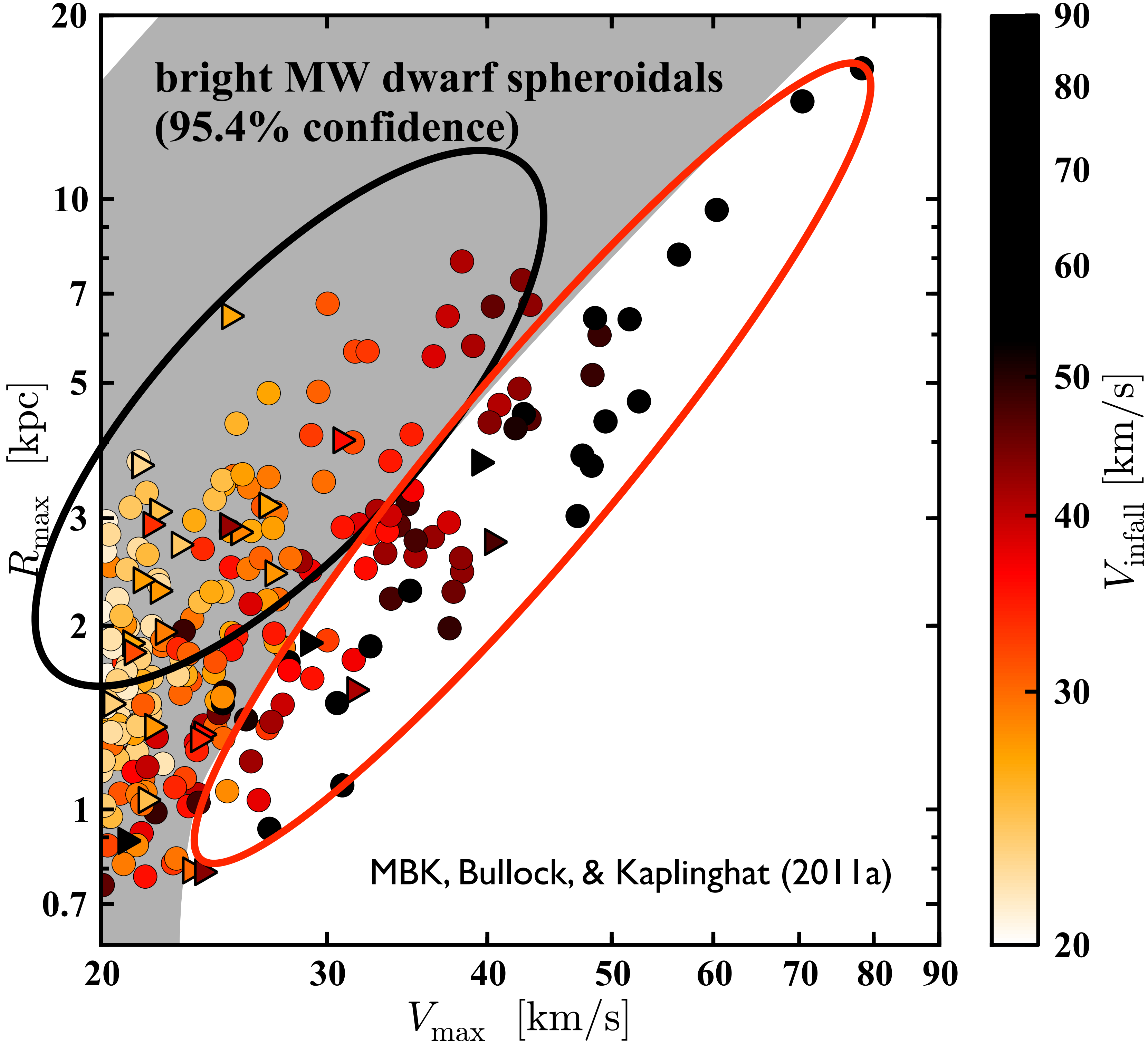

MANY subhalos consistent with dynamics of dSphs

significant population of subhalos ***not*** consistent with dynamics of dSphs

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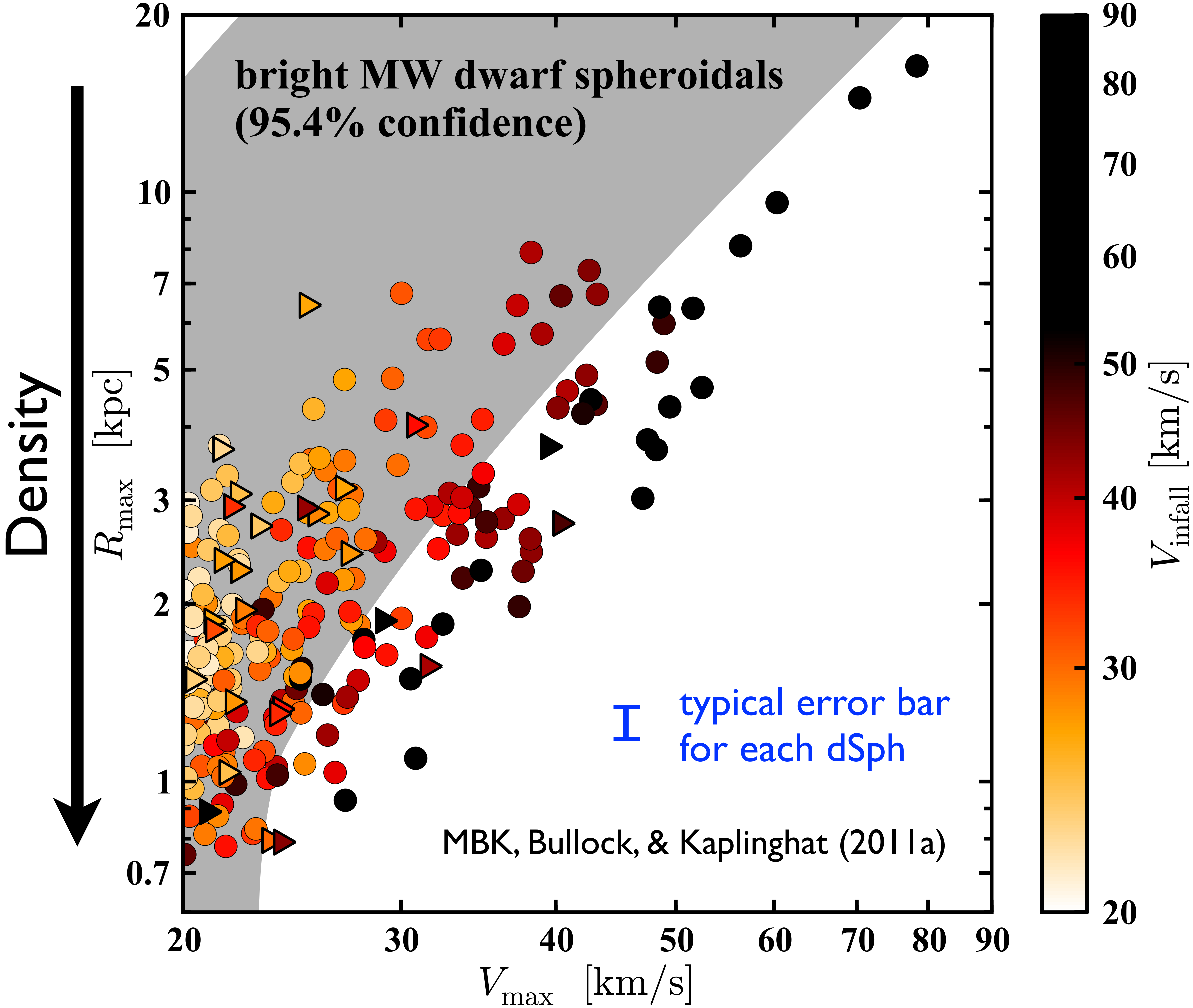
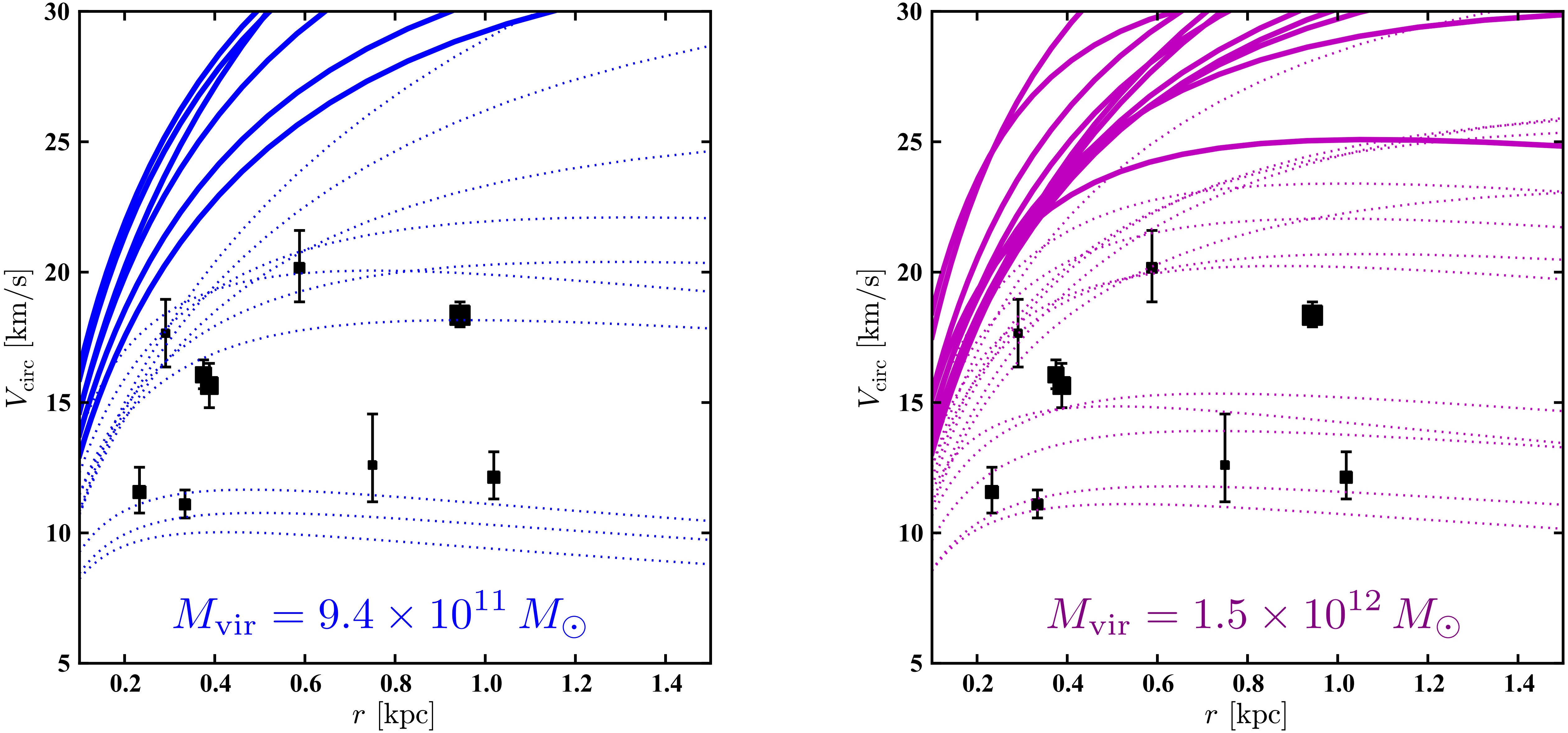


MANY subhalos consistent with dynamics of dSphs

significant population of subhalos ***not*** consistent with dynamics of dSphs

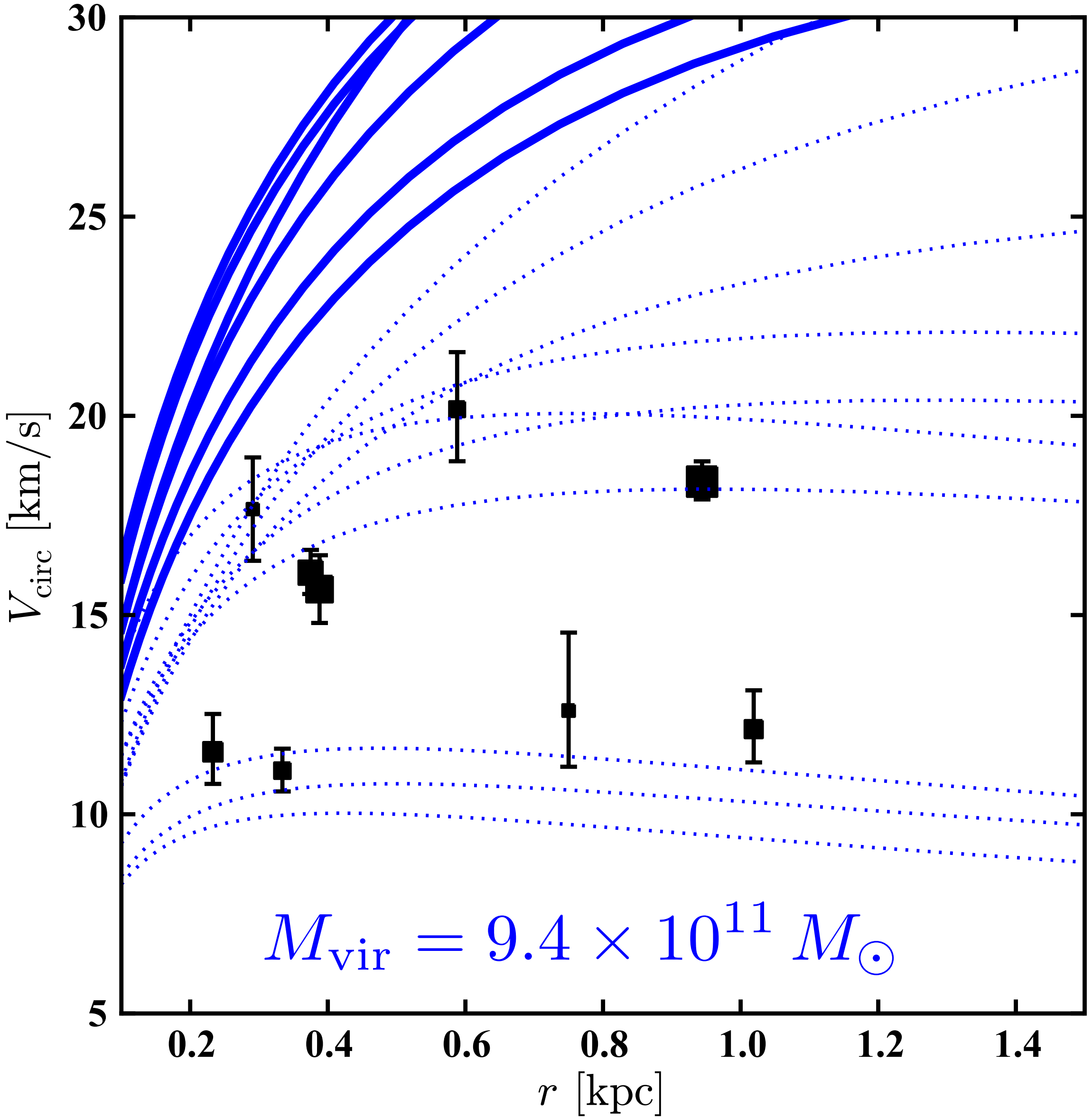
Each simulated MW halo has at least 6 **massive** subhalos that are too dense to host ***any*** dSph (*after* excluding potential Magellanic Cloud hosts)

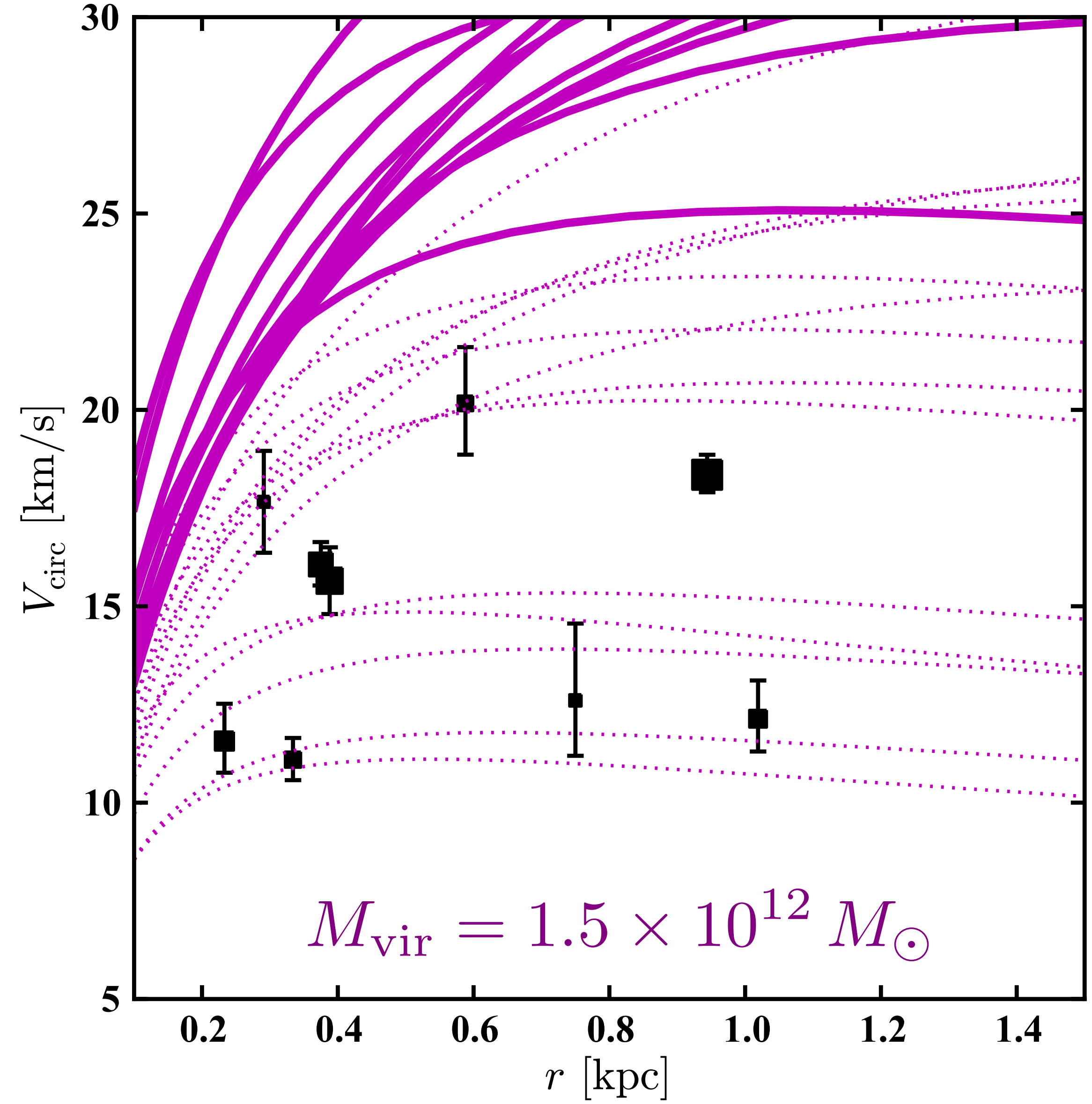


6 subhalos denser than all satellites

11 subhalos denser than all satellites

MBK, Bullock, & Kaplinghat 2011b (in prep.)





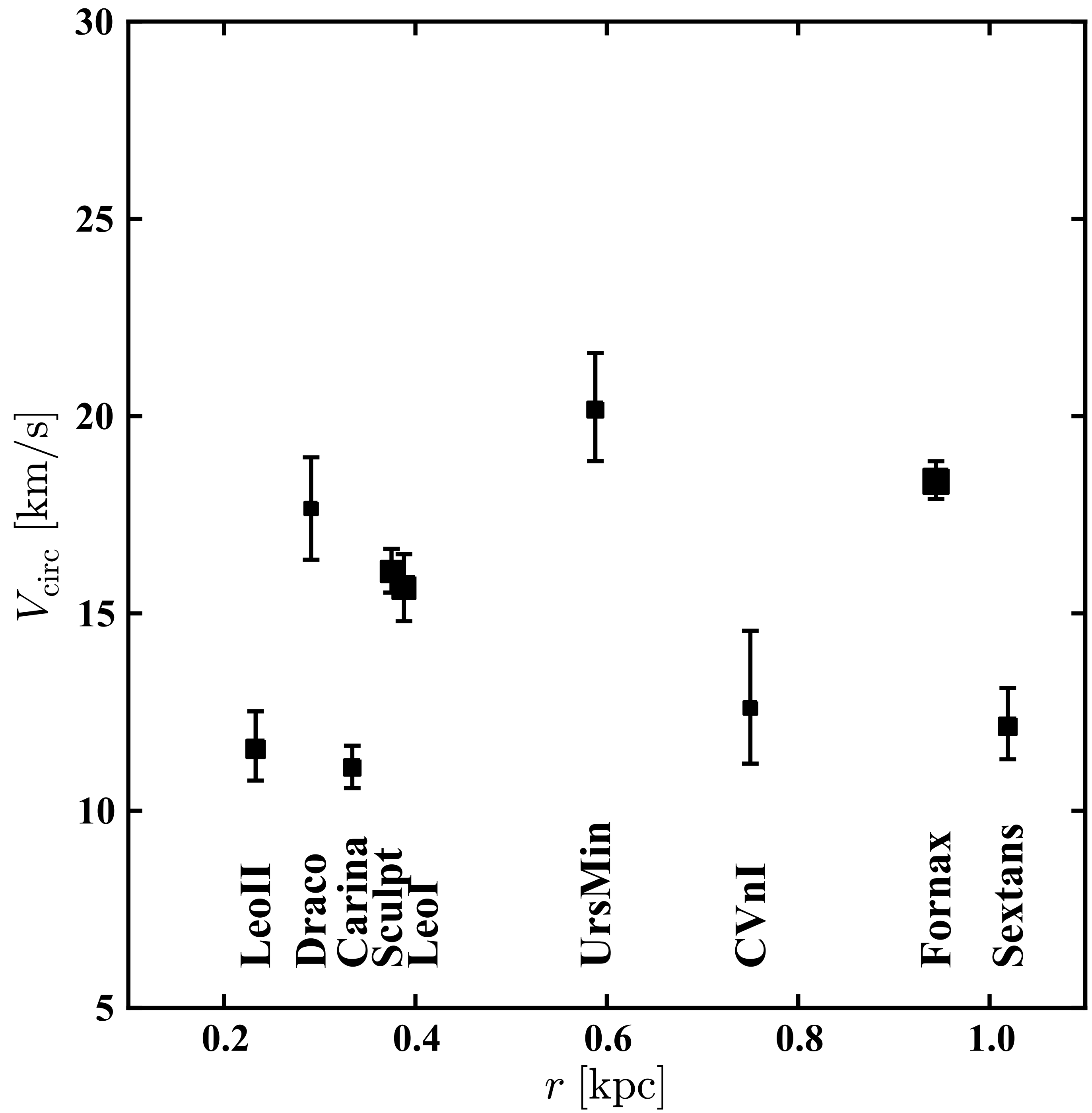
6 subhalos denser than all satellites

11 subhalos denser than all satellites

several additional subhalos with $V_{\rm infall}$ > 30 km/s that have no bright counterpart

MBK, Bullock, & Kaplinghat 2011b (in prep.)

Measured values of V_{circ} for MW dwarfs



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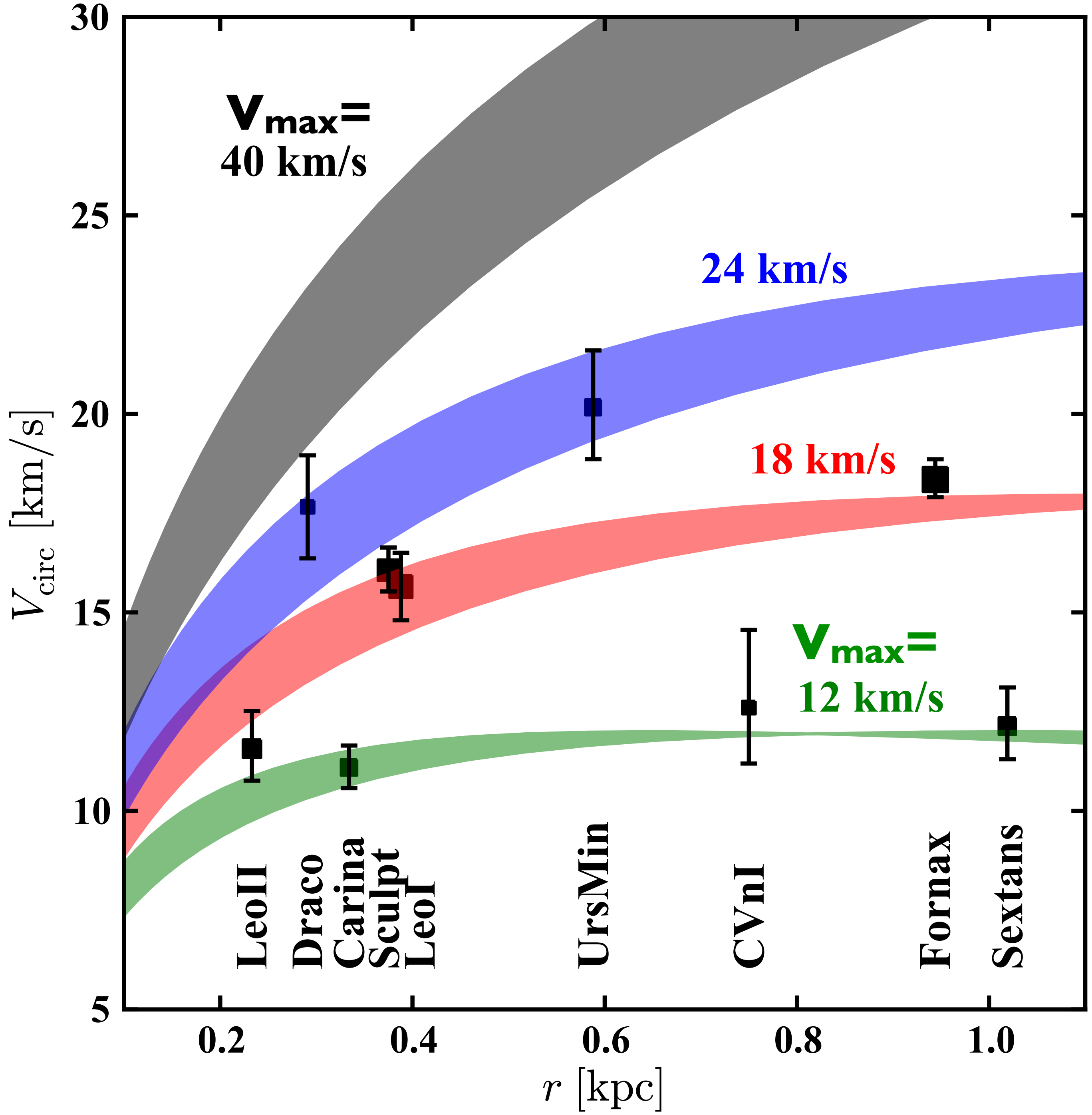

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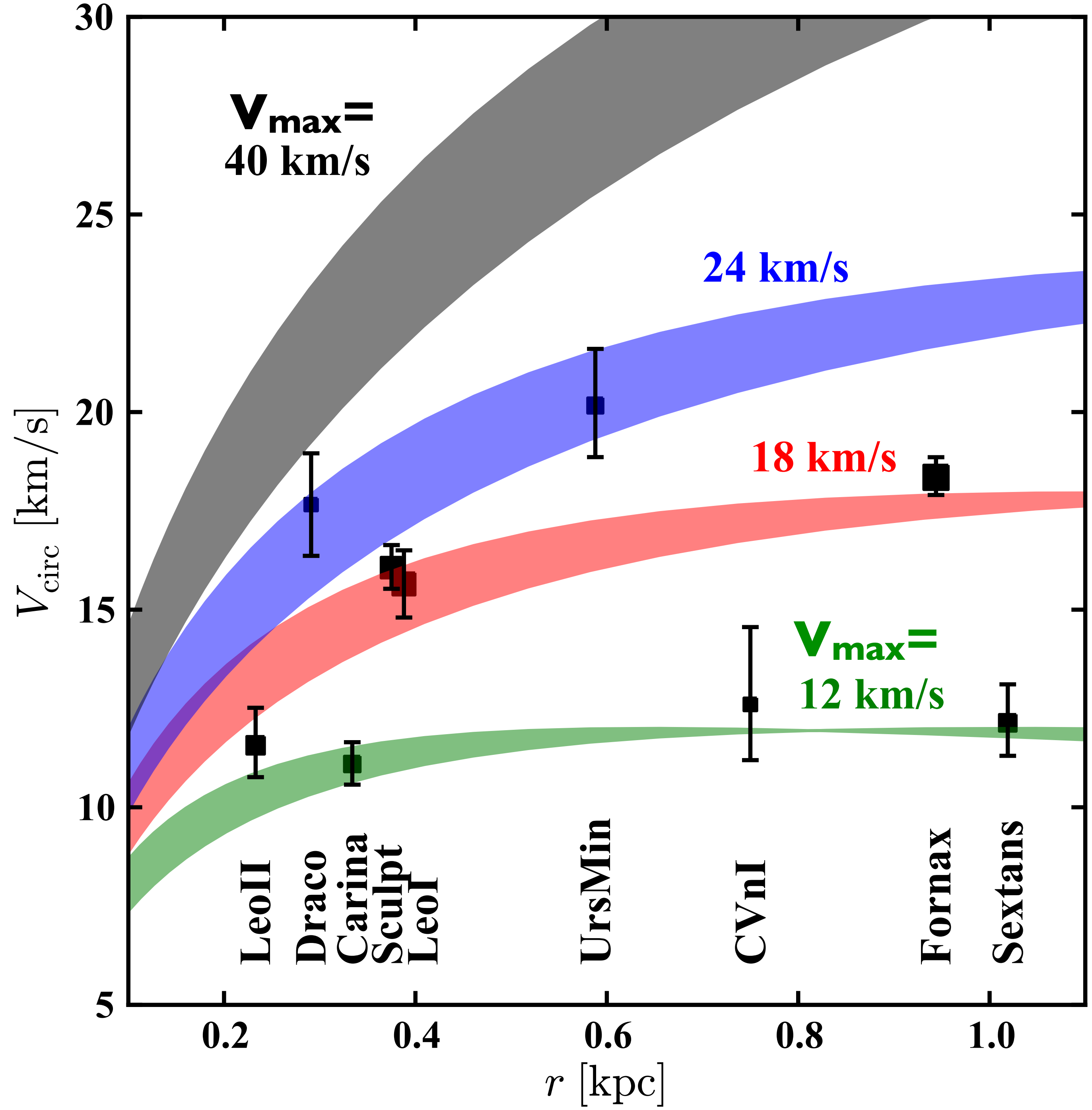
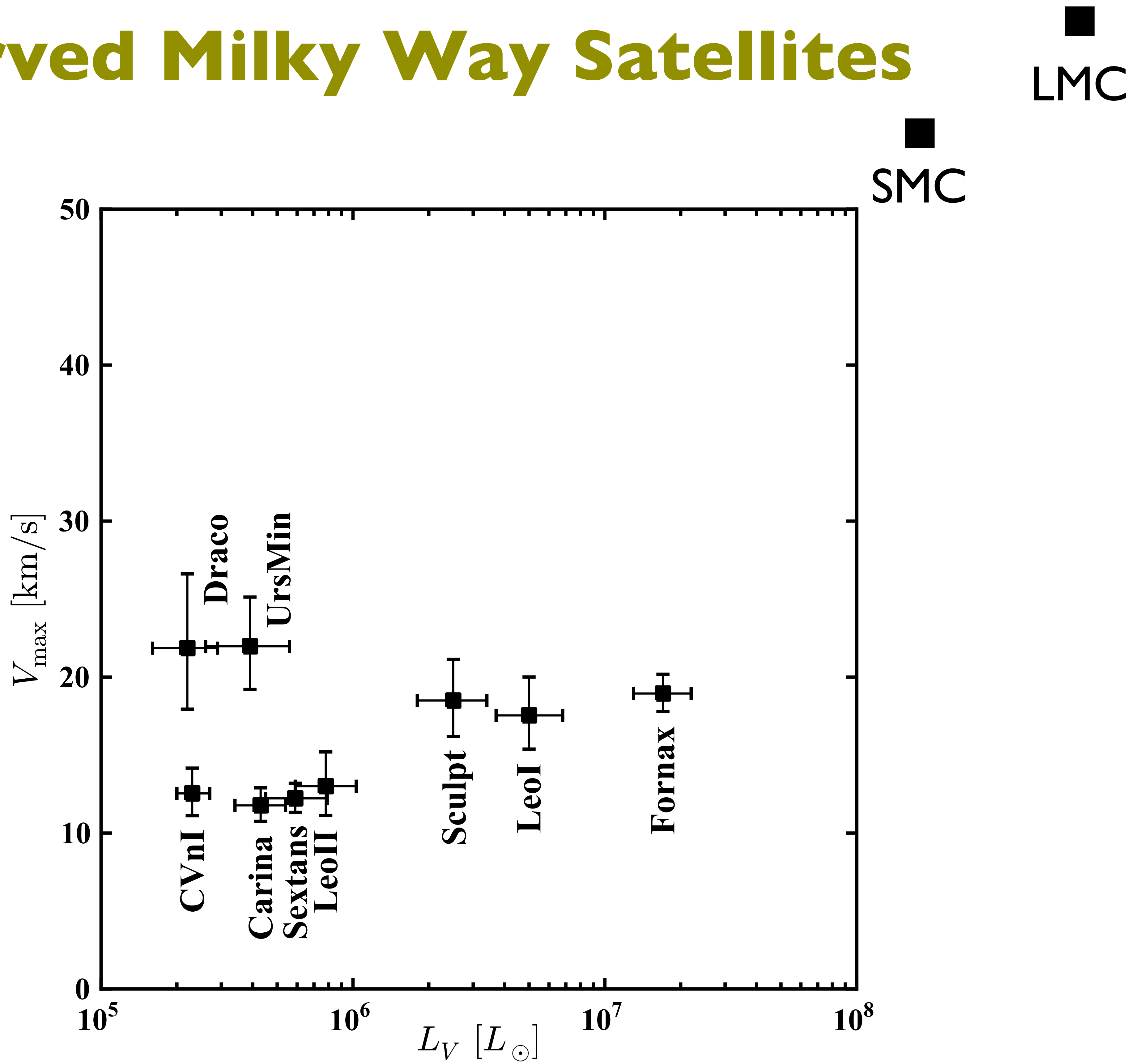


All of the bright MW dSphs are consistent with $V_{\rm max} \lesssim 25\,{\rm km/s}$

c.f. direct kinematic modeling of dSphs (Strigari, Frenk, & White)

MBK, Bullock, & Kaplinghat 2011b (in prep.)

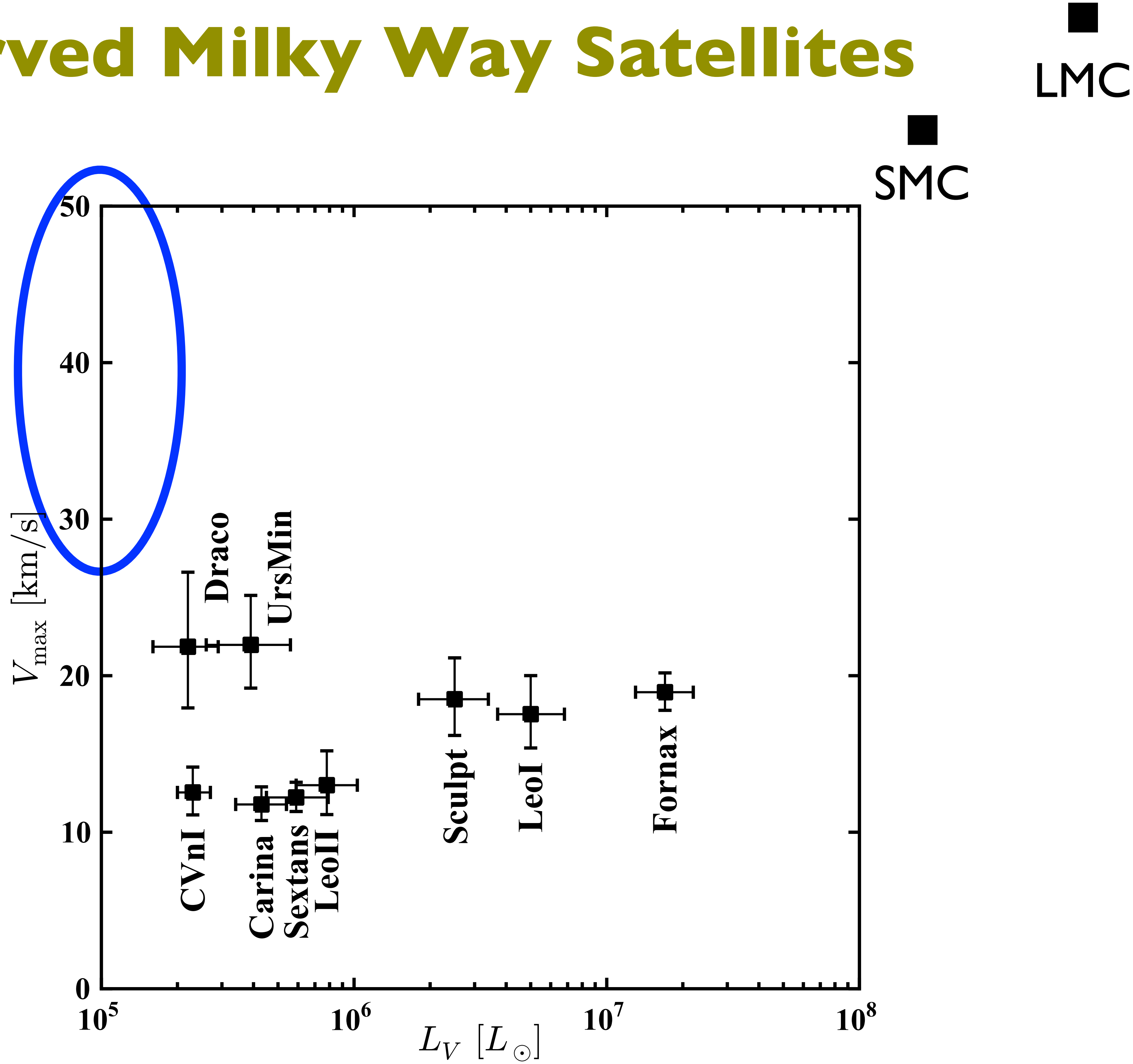
Observed Milky Way Satellites



MBK, Bullock, & Kaplinghat (2011b)

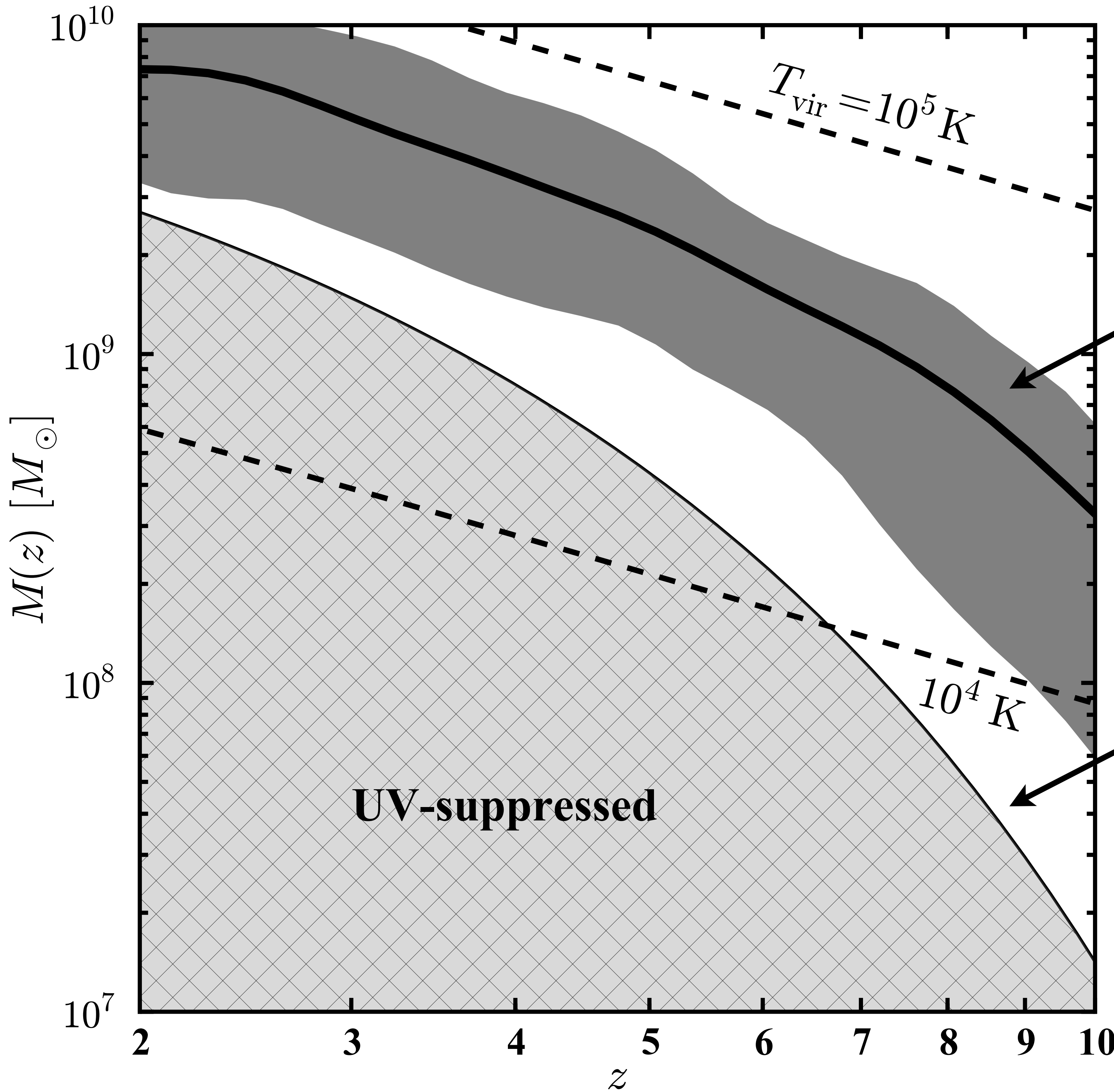
Observed Milky Way Satellites

"massive failures":
LCDM predicts ~10 subhalos in this range in the MW, but we don't see ***any*** such galaxies



MBK, Bullock, & Kaplinghat (2011b)

Reionization is not the answer



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

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

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

Image credits: V. Springel / Virgo Consortium; A. Riess / HST; W. Wang; AAO; M. Schirmer

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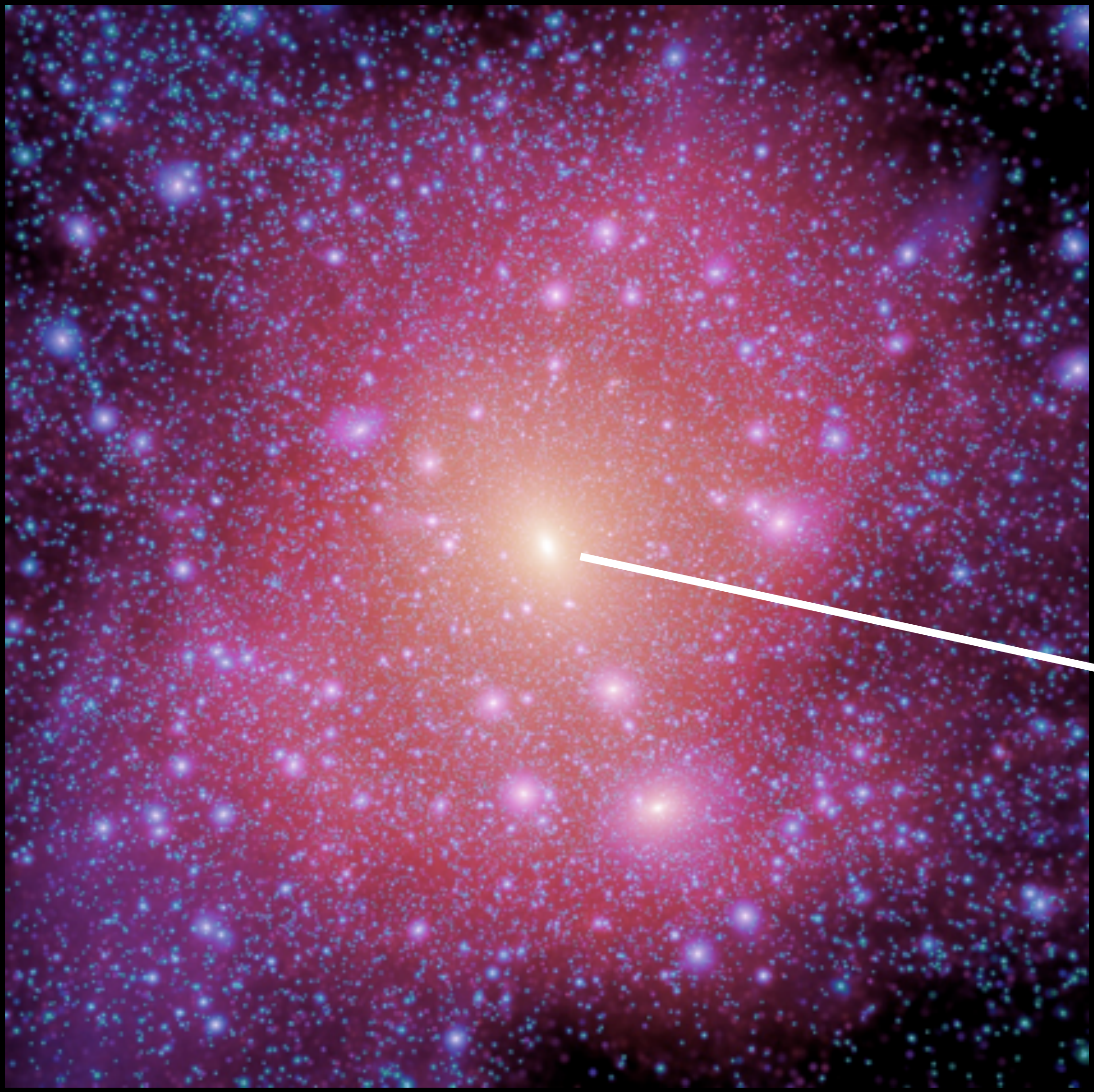

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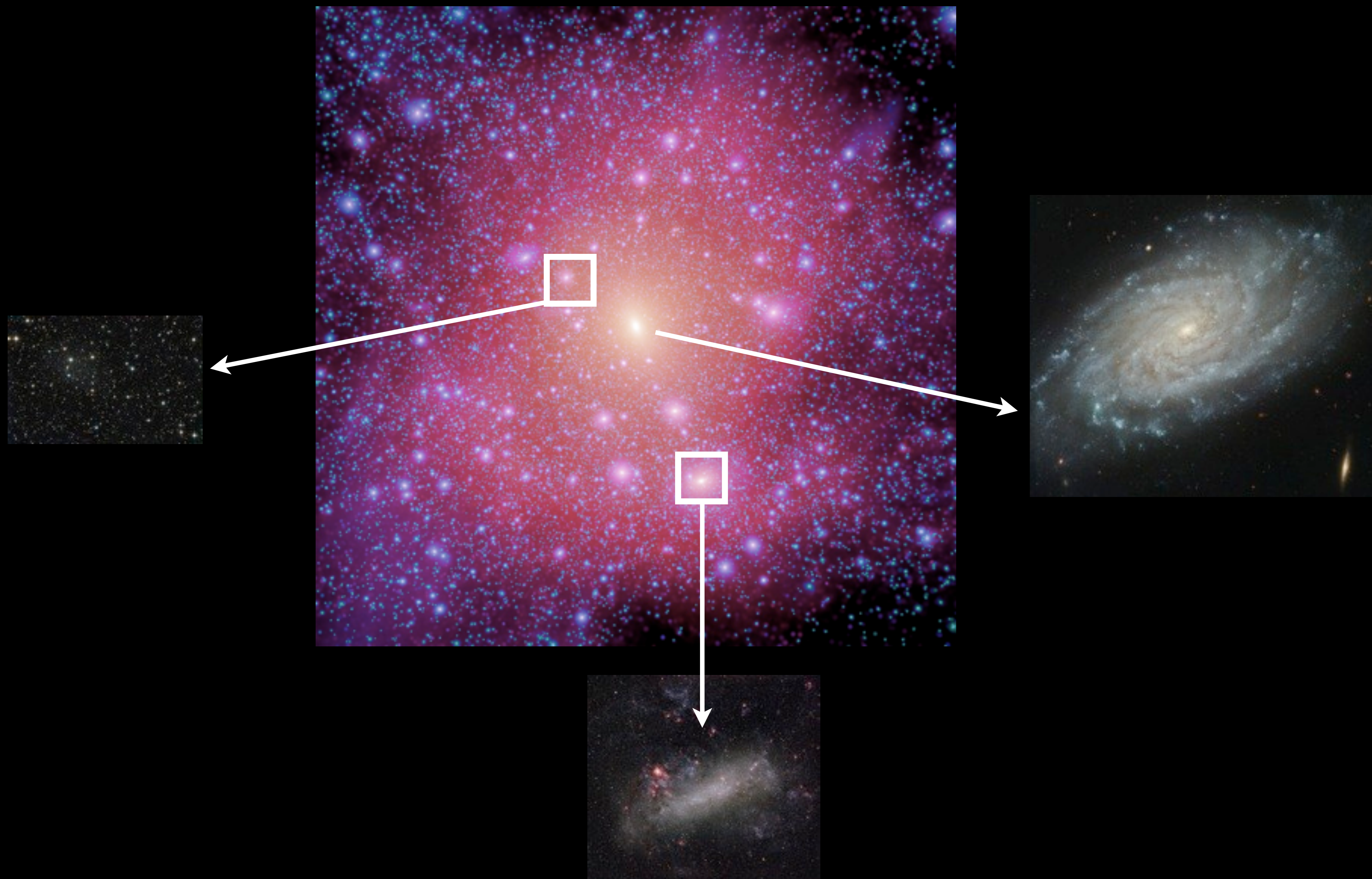

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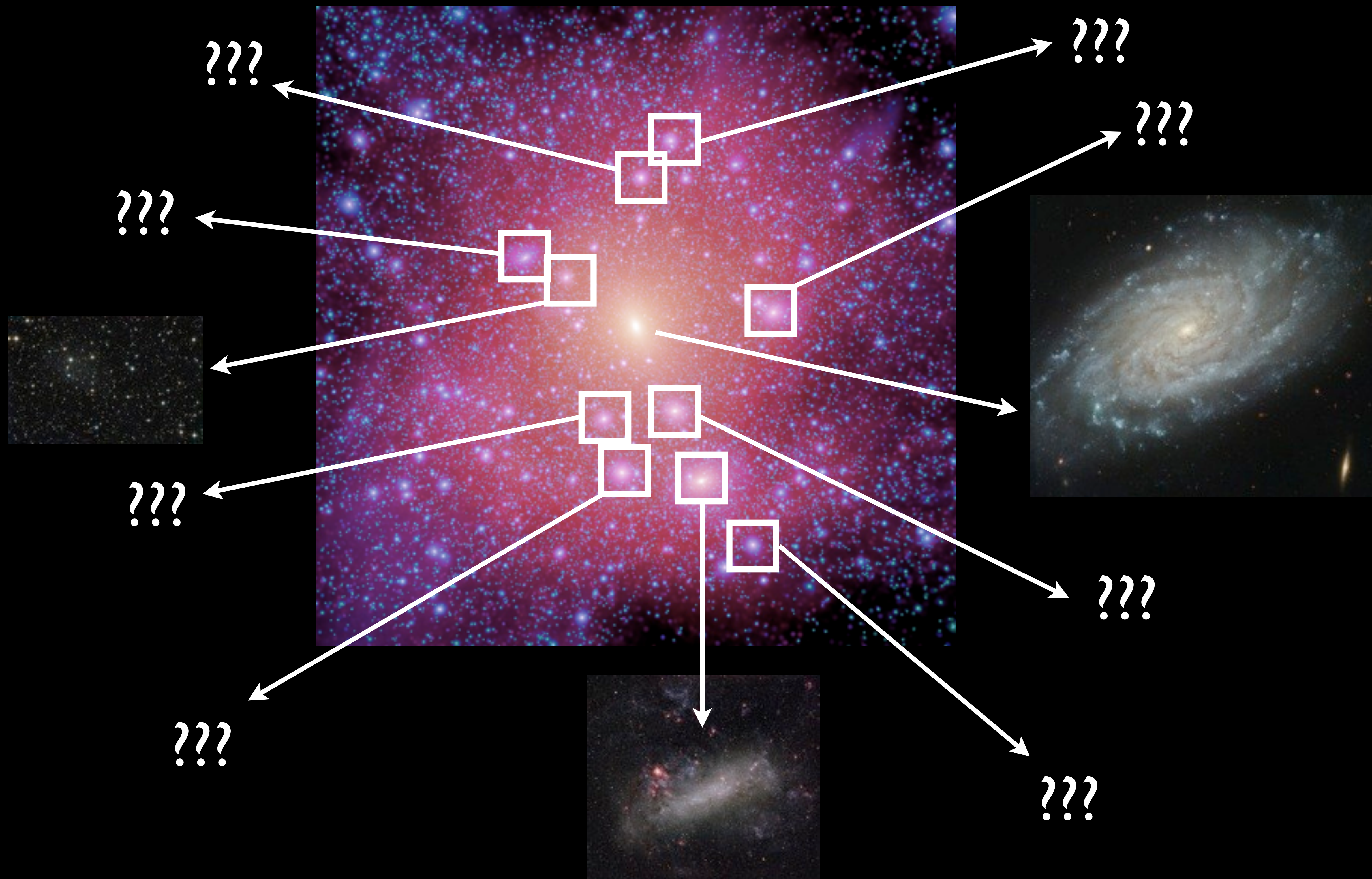

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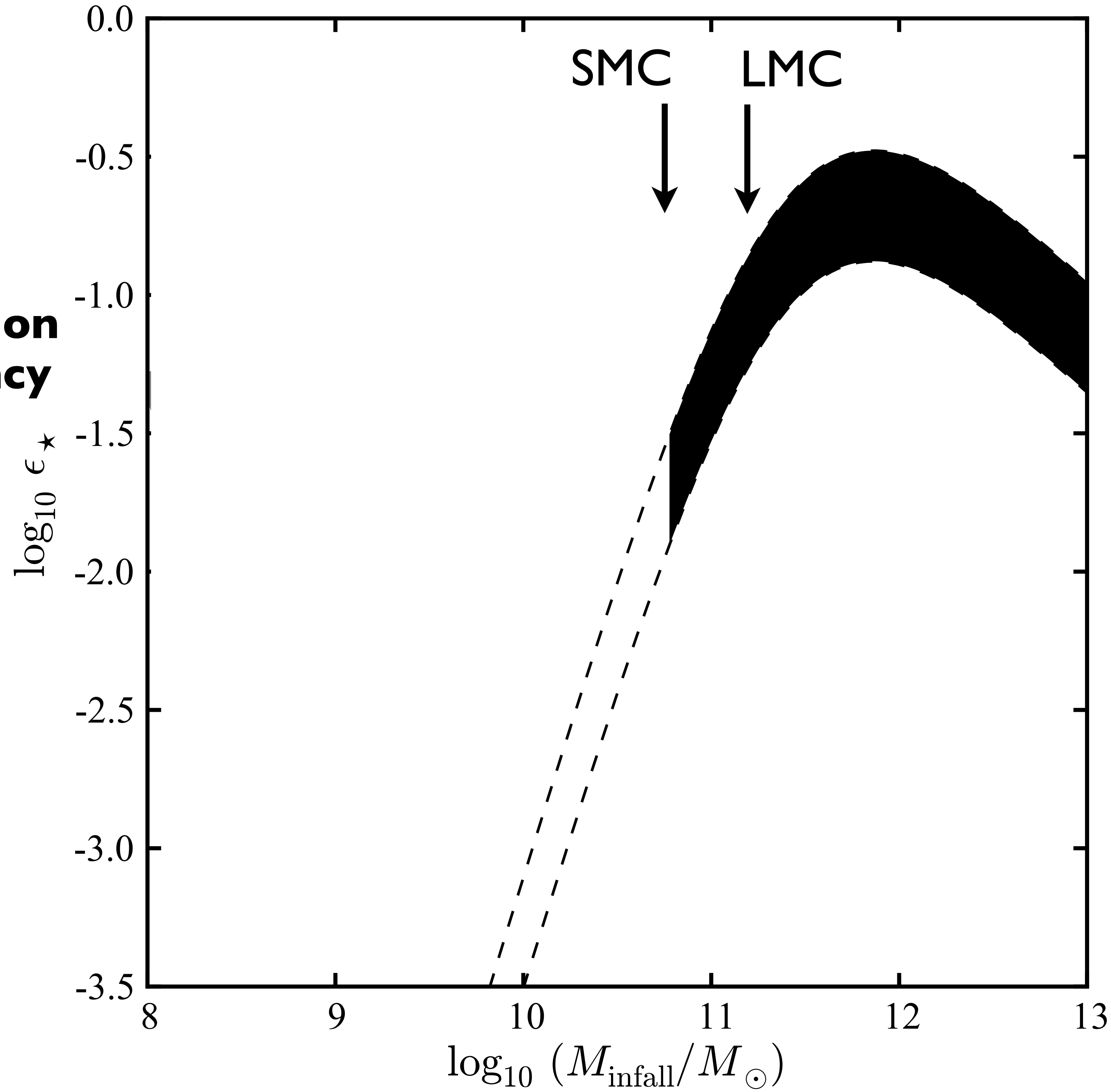
Implications

- **<u>Option 1</u>**: massive dark subhalos **do** exist in the MW as predicted
  - Galaxy formation is stochastic for V < 50 km/s

Stochastic galaxy formation

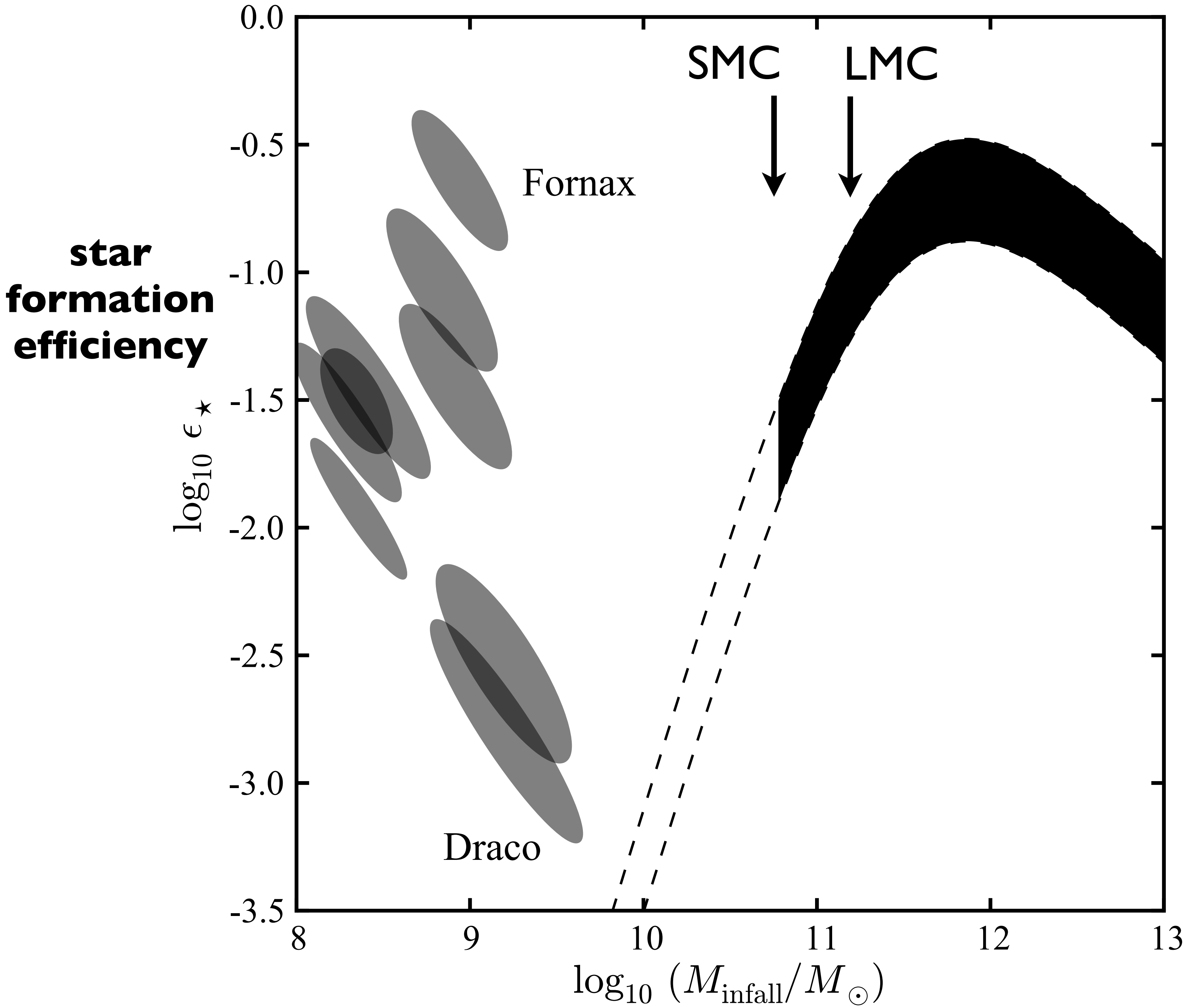
star formation efficiency



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

MBK, Bullock, & Kaplinghat (2011b)

Stochastic galaxy formation



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

<u>No</u> relation between **L** and **$\mathbf{M_{infall}}$** on scale of MW dwarf spheroidals

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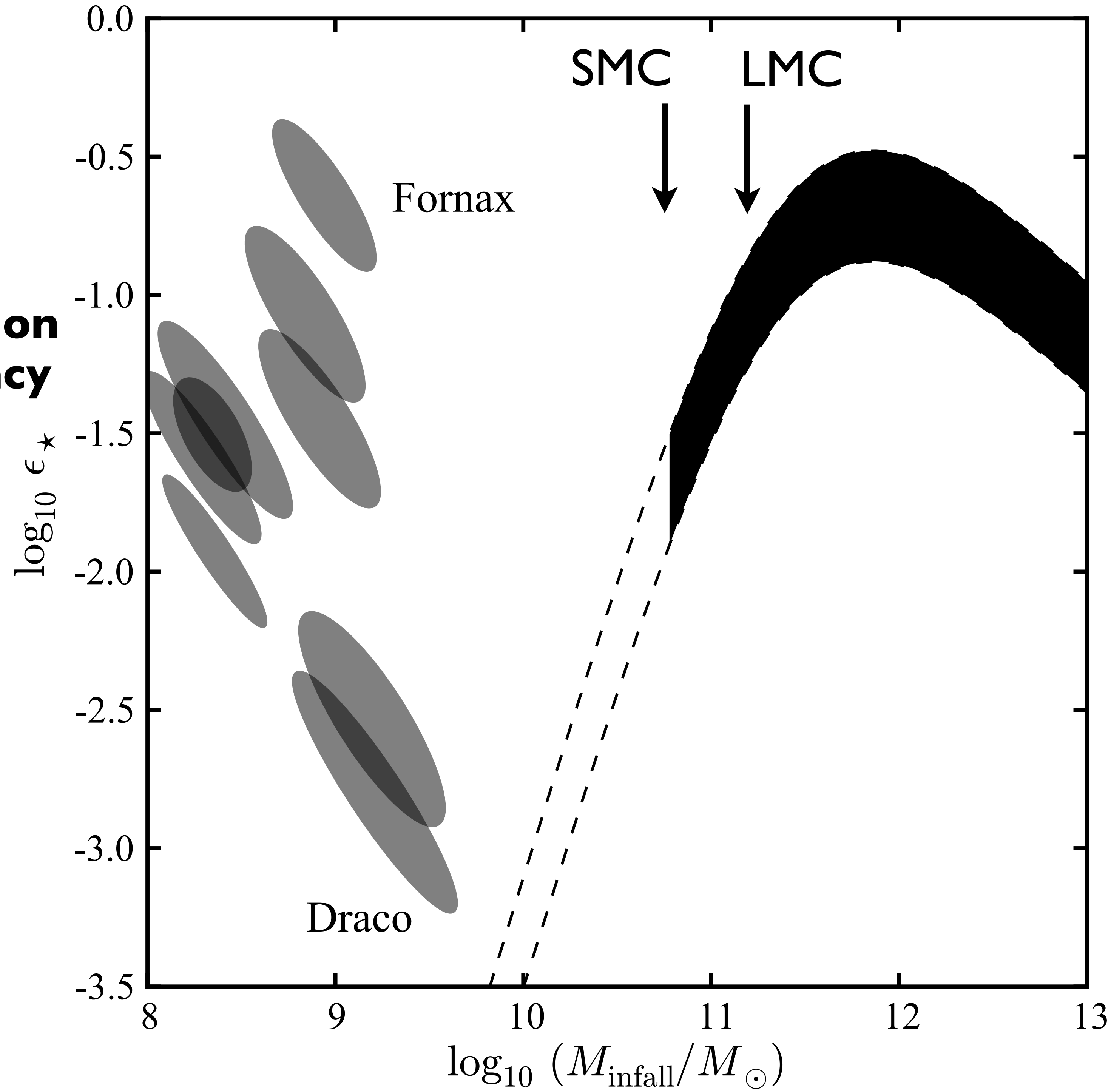

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Tight relation between **L** and **M**$_{\mathbf{infall}}$ on scale of Magellanic Clouds and larger

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Q: what is the source of stochasticity? Metallicity dependence of H_2 formation?

(Gnedin & Kravtsov; Kuhlen et al.)

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- **Option 1**: massive dark subhalos **do** exist in the MW as predicted
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  - Already found? Some ultra-faint galaxies could lie in these subhalos

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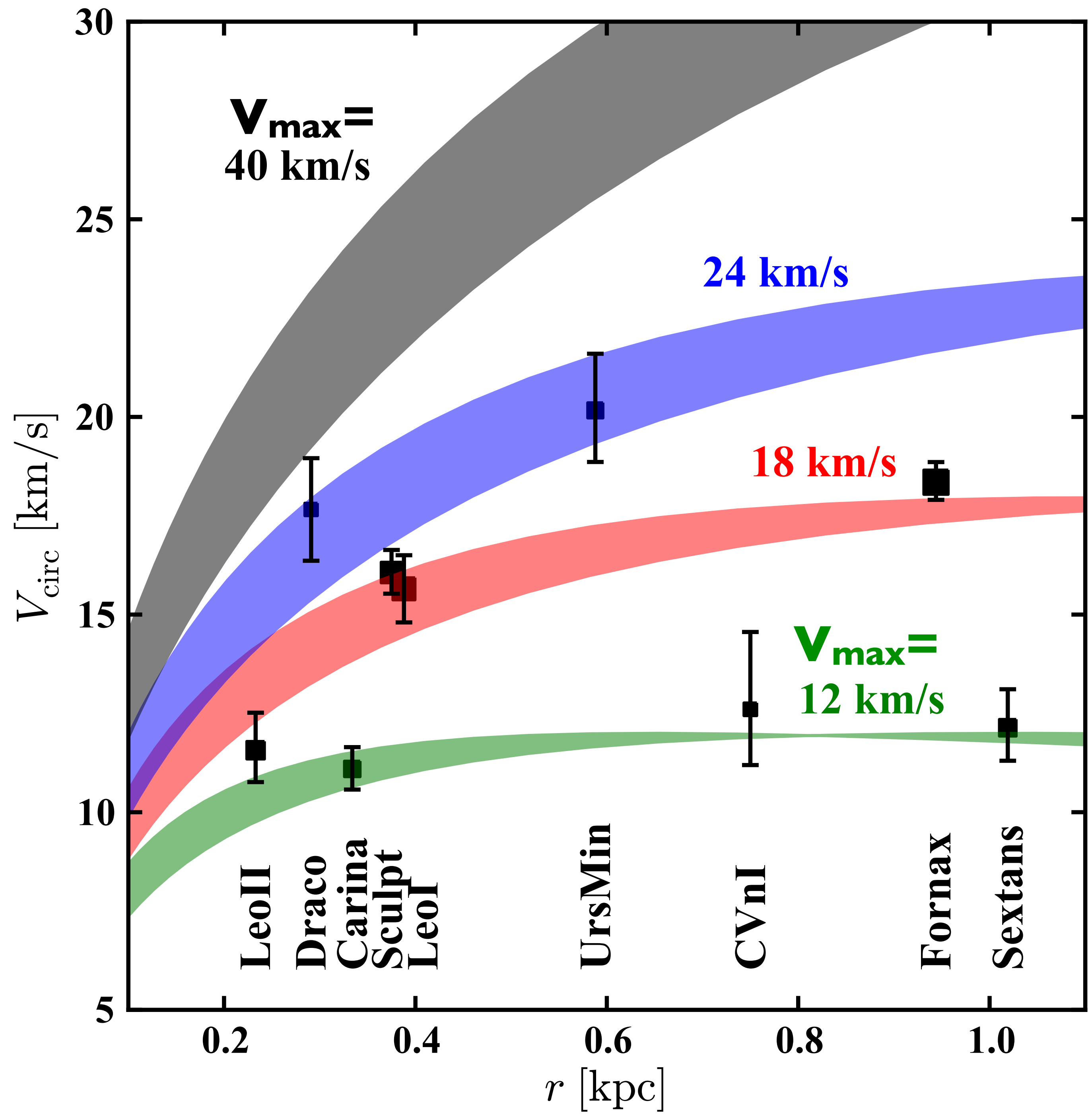
- **Option 2: No** massive dark subhalos in MW (ΛCDM interpretation)
  - the subhalo content of the Milky Way is anomalous compared to expectations
  - MW's dark matter halo mass is $\lesssim$ 7e11 M_{sun} (but this creates other problems)
  - baryonic feedback **strongly** alters structure of subhalos (c.f. Governato)

MW dwarf structure



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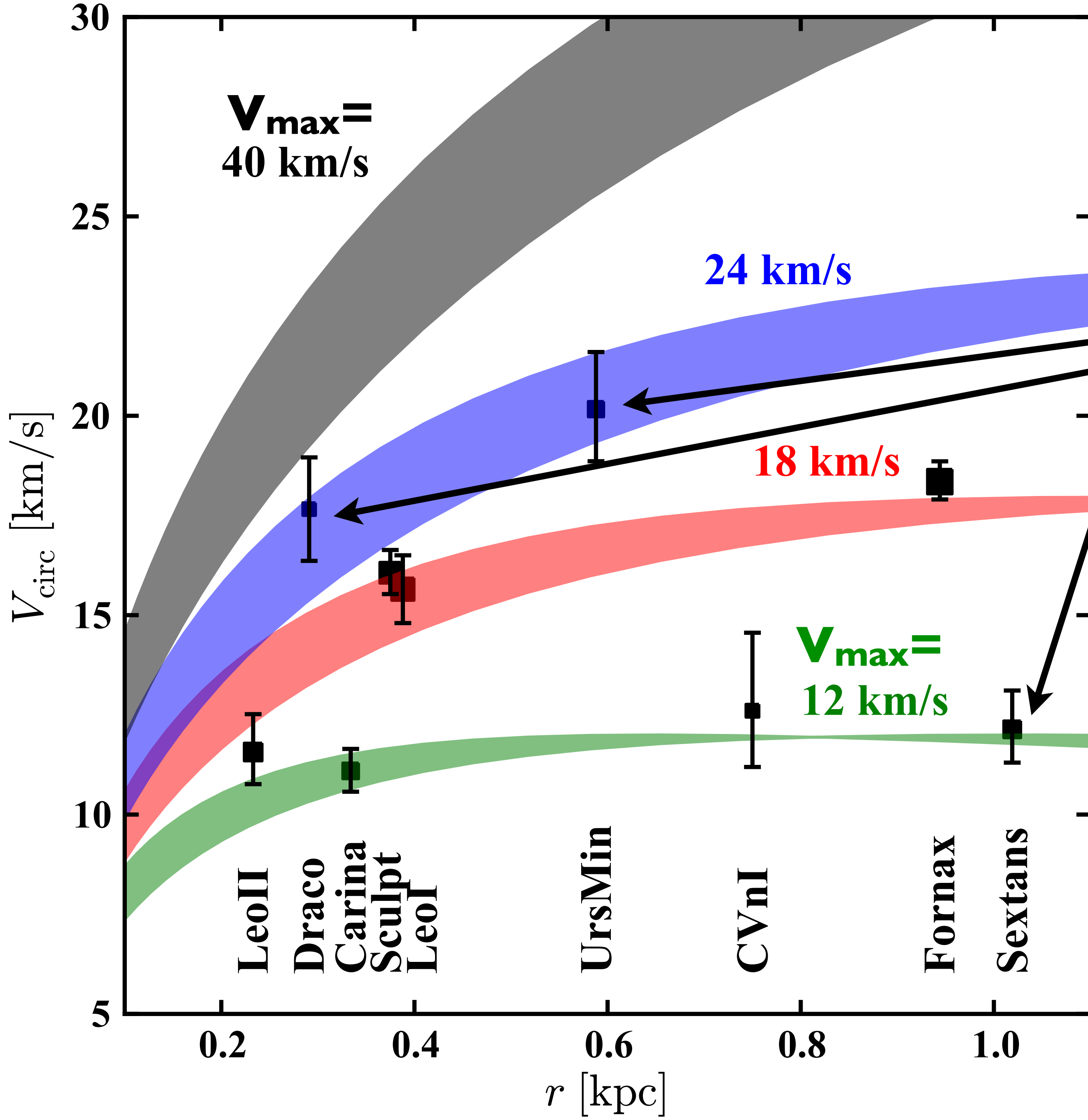
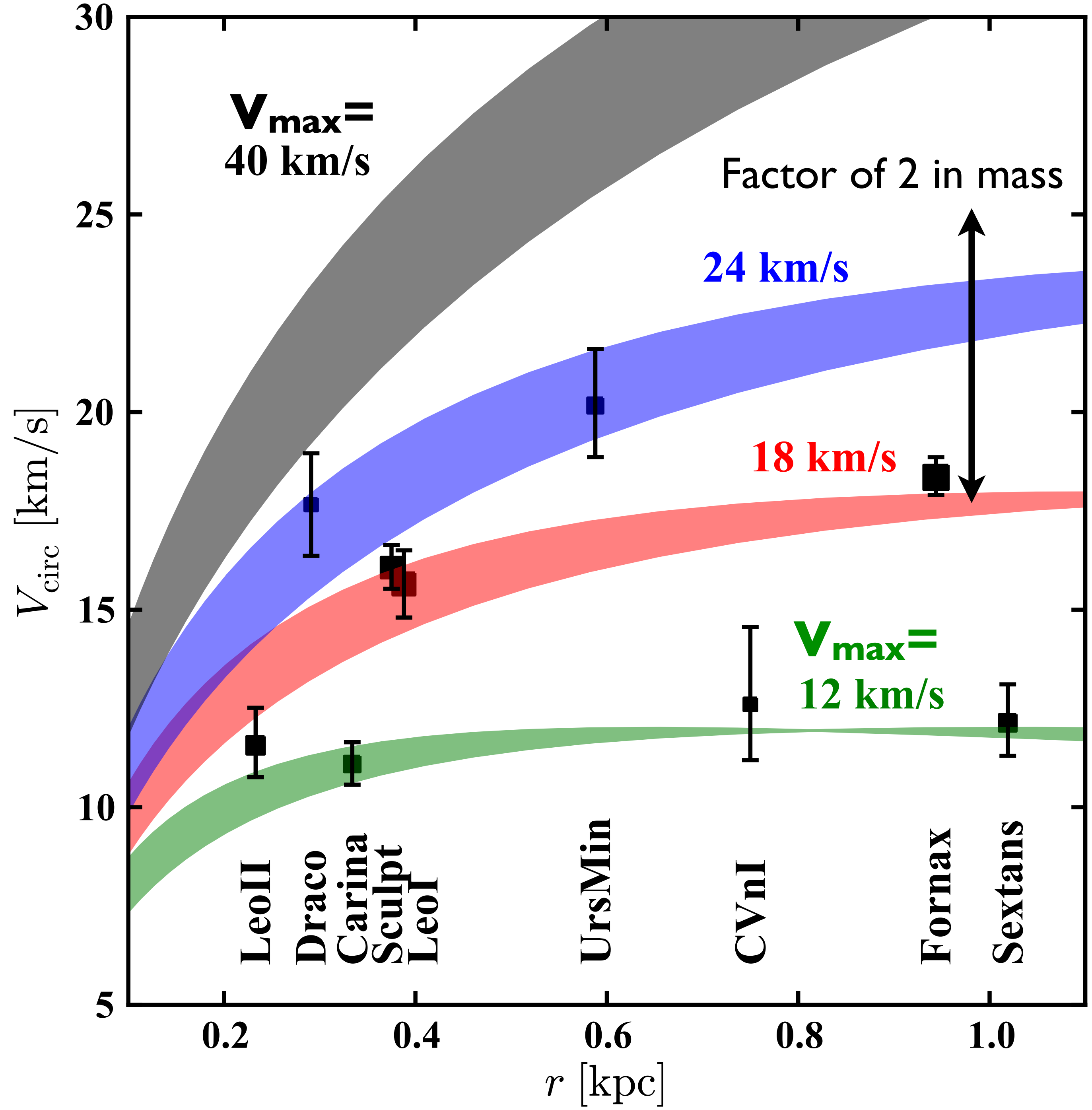


can feedback explain
Draco, Ursa Minor, Sextans?
similar luminosities, stellar populations; drastically different sizes and inferred halo masses

MBK, Bullock, & Kaplinghat 2011b (in prep.)

MW dwarf structure



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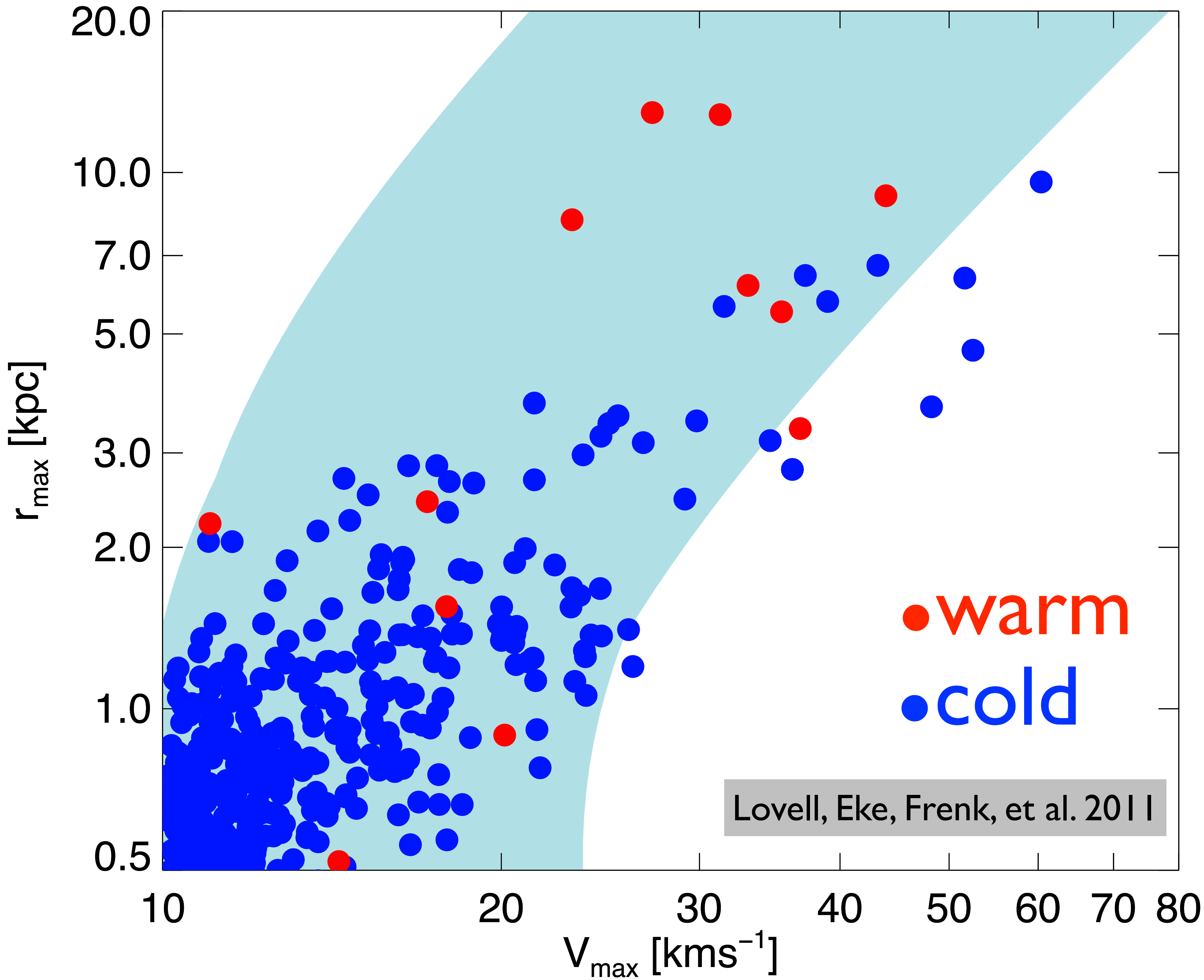
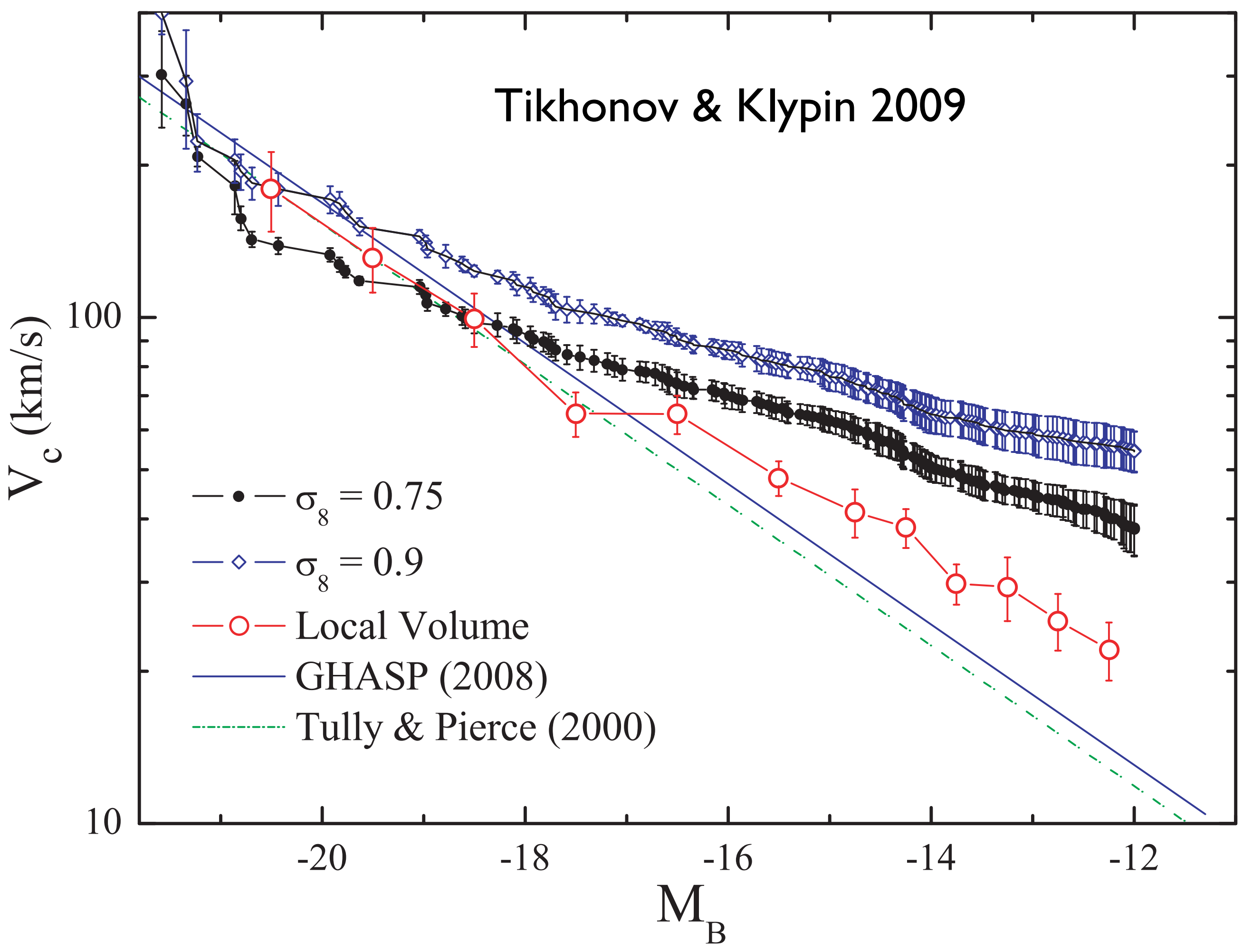
- **<u>Option 3</u>: No** massive dark subhalos in MW (modifications to ΛCDM)
  - warm(ish) dark matter, suppression scale of ~40-50 km/s
  - more complicated dark matter physics

Warm versus cold dark matter



WDM simulations have smaller number of subhalos; surviving subhalos are also less concentrated

galaxy formation: are we missing physics at <50 km/s ?



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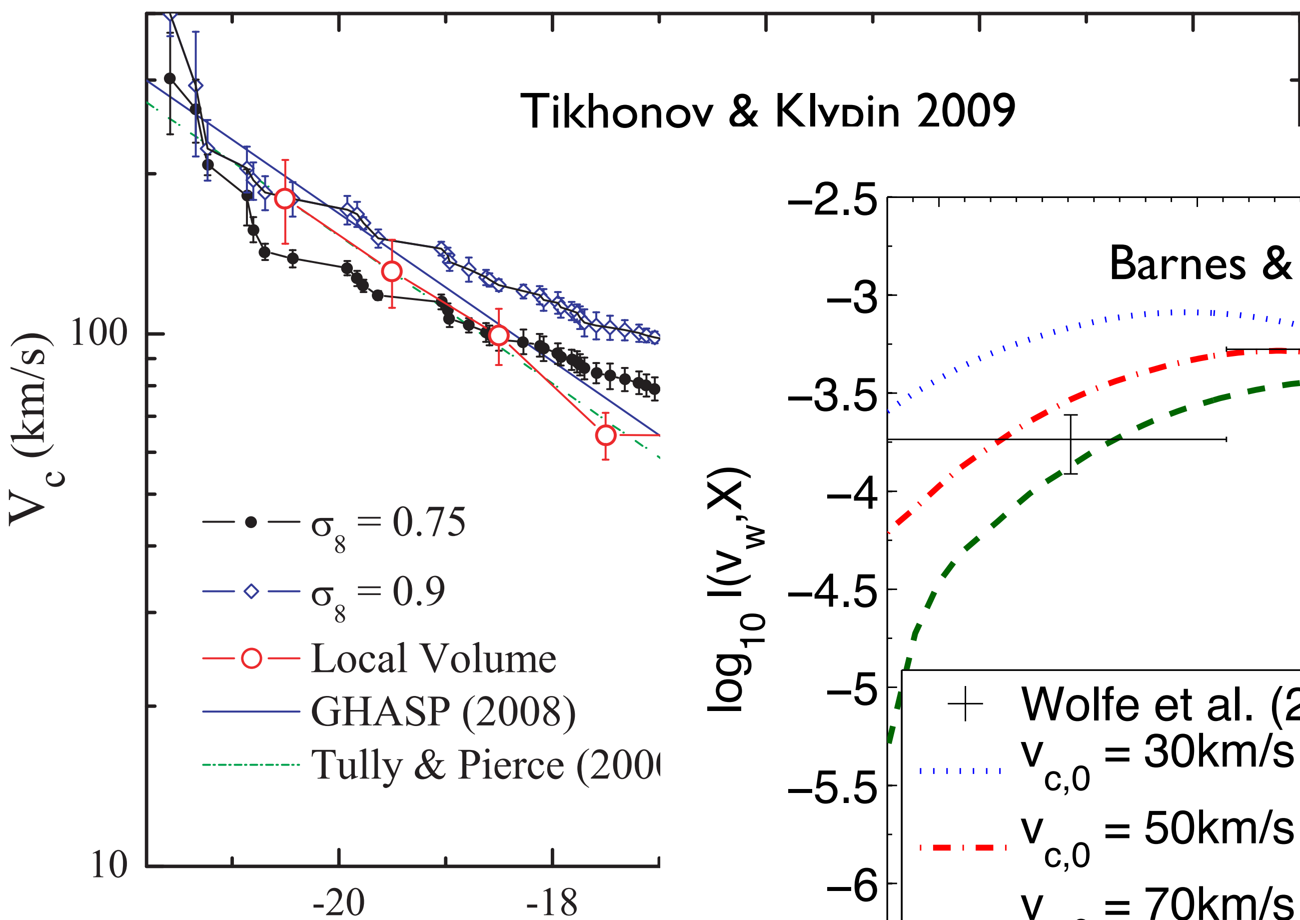

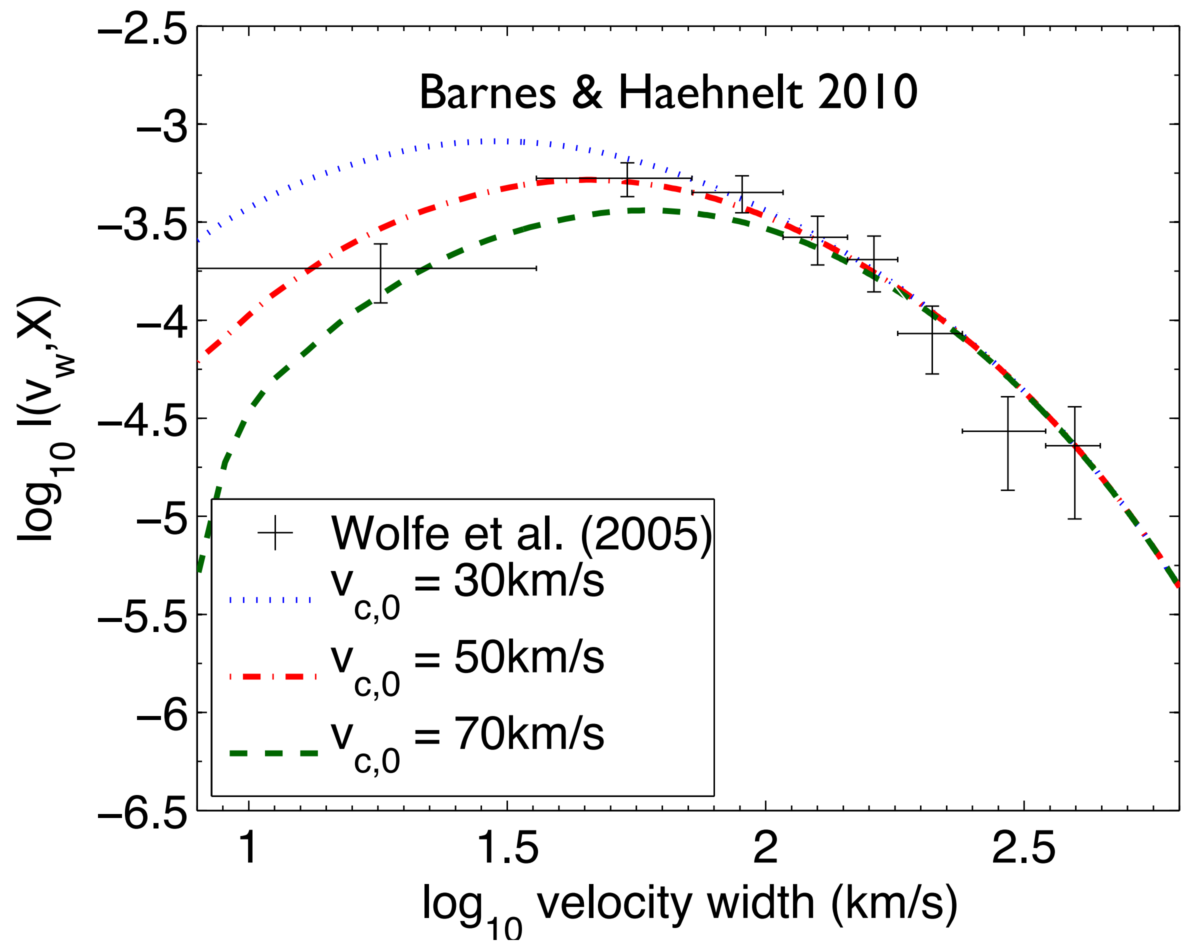

Figure 8. The velocity width distribution $l(v_{\rm w}, X)$ of the associated low-ionization metal absorption of DLAs. The black crosses show the observational data compiled in Figure 10 of Wolfe, Gawiser, & Prochaska (2005). The legend shows the parameter $v_{\rm c,0}$, below which the baryonic fraction is assumed to be suppressed due to the effect of photo-heating and/or galactic winds.

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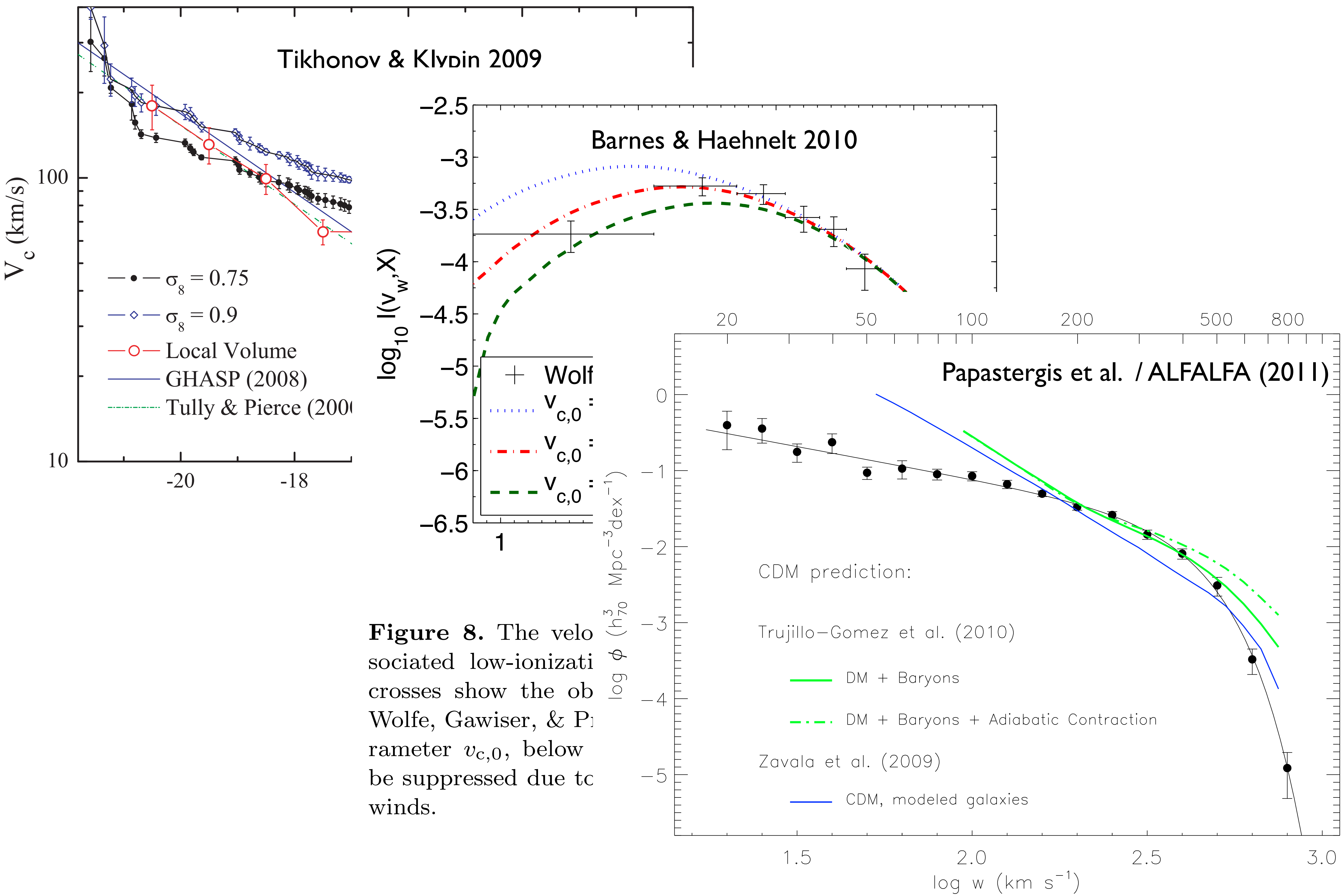

Summary

- 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 (now or at infall) from current ΛCDM simulations $\Rightarrow$ challenge for galaxy formation models

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★ *details in "Too big to fail? The puzzling darkness of massive Milky Way subhalos"*
M. Boylan-Kolchin, J. S. Bullock, M. Kaplinghat (2011), MNRAS 415, L40 (arXiv:1103.0007)