Too Big To Fail?
The puzzling darkness of massive DM subhalos

James Bullock

Southern California
Center for
Galaxy
Evolution

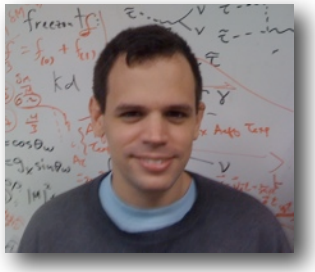
Collaborators

Mike Boylan-Kolchin
(UC Irvine)

Boylan-Kolchin, JSB, Kaplinghat (2011, arXiv:1103.0007)

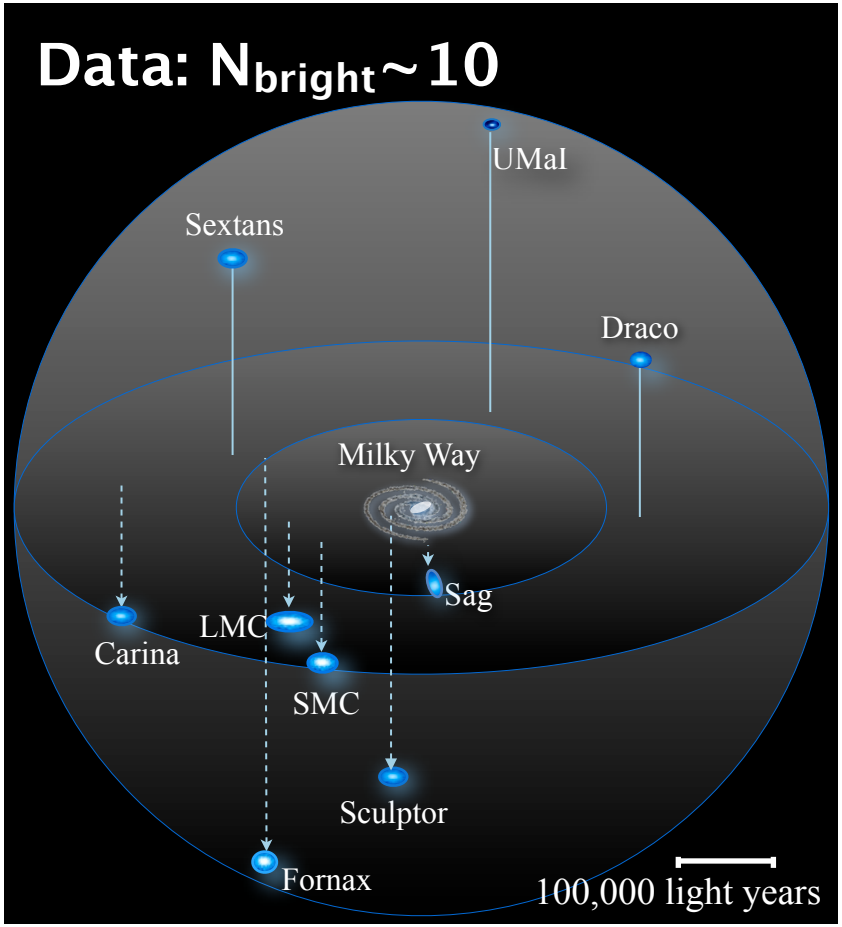
Erik Tollerud
(UC Irvine)

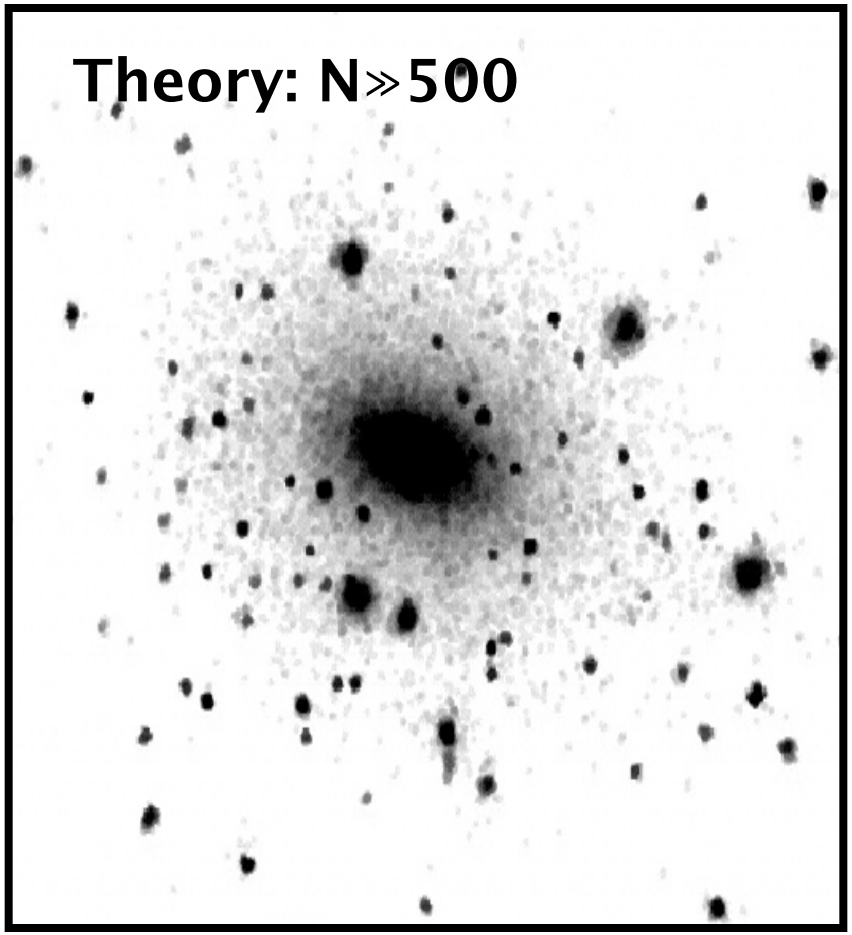
Joseph Wolf
(UC Irvine)



Greg Martinez
(UC Irvine)

Missing Satellites Problem (1999)





Klypin et al. 1999 Moore et al. 1999

Where would you put the classical MW dwarfs?

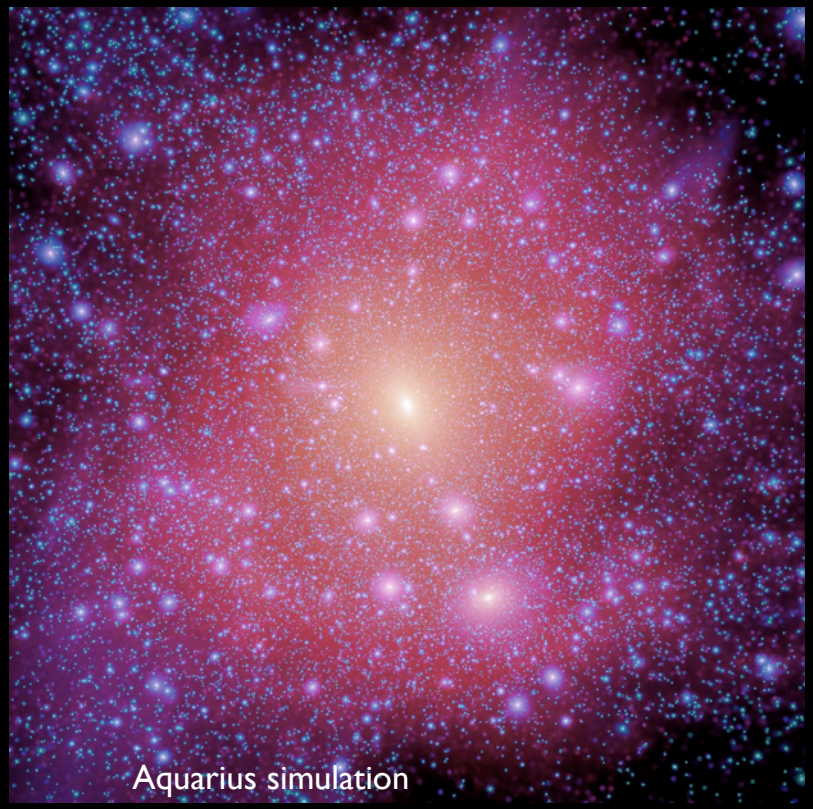


Image credits: V. Springel / Virgo Consortium; A. Riess / HST; W. Wang; AAO; M. Schirmer

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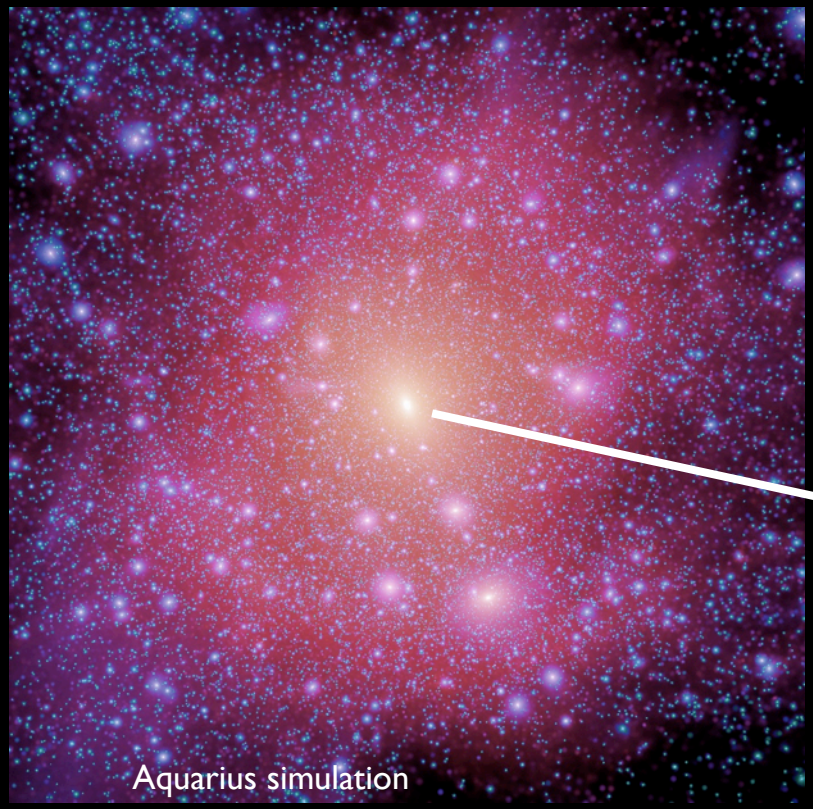

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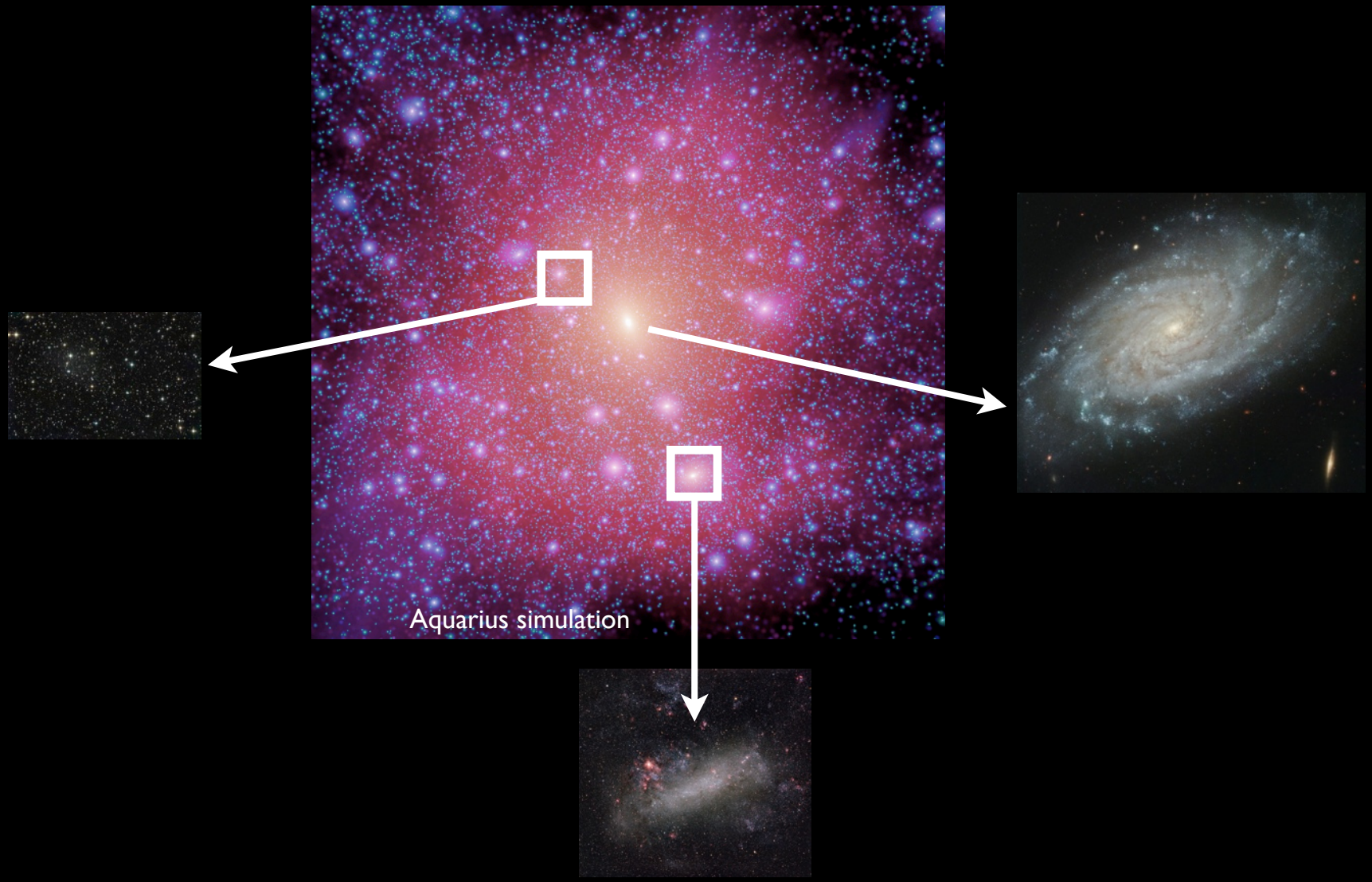

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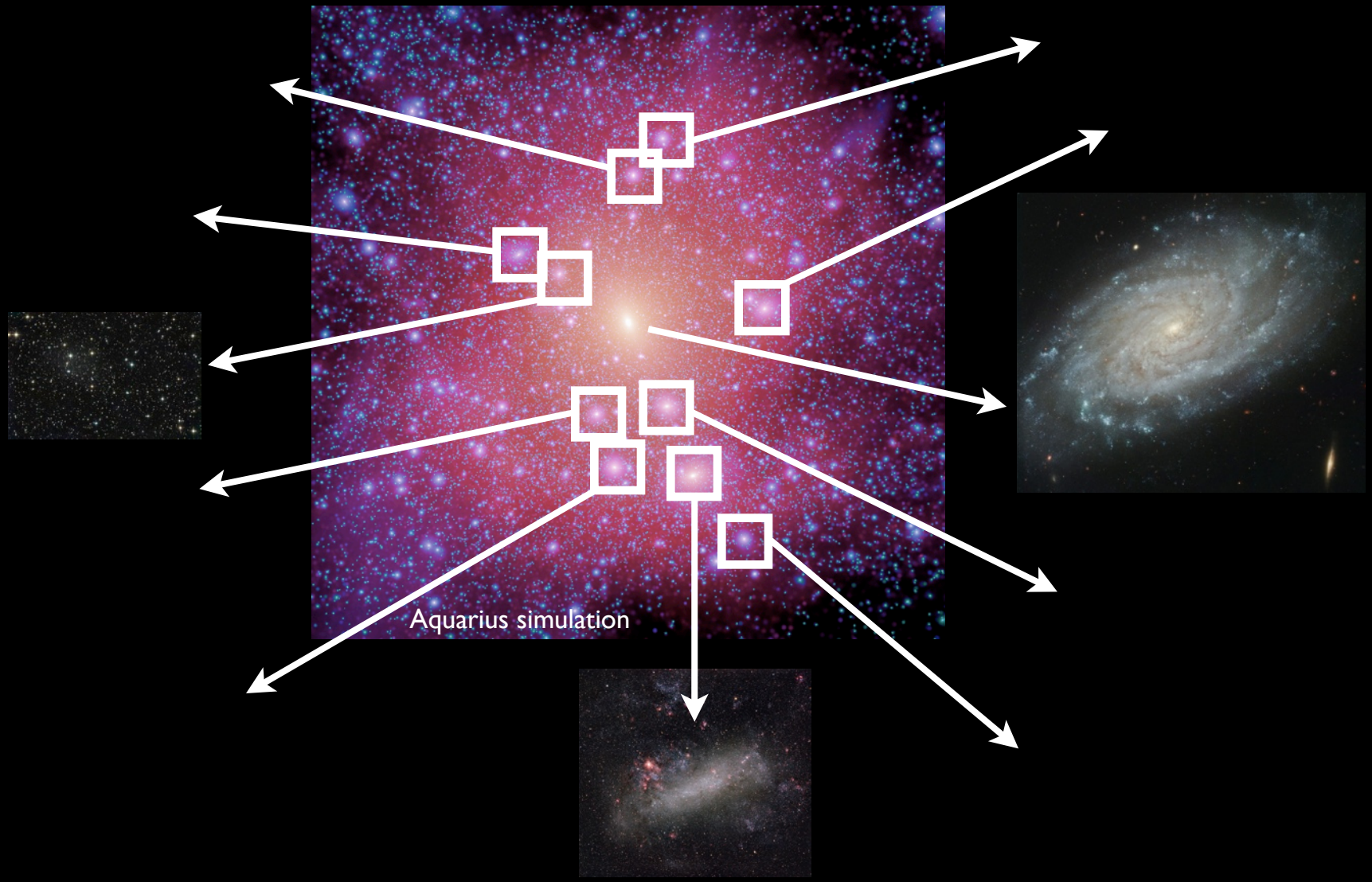

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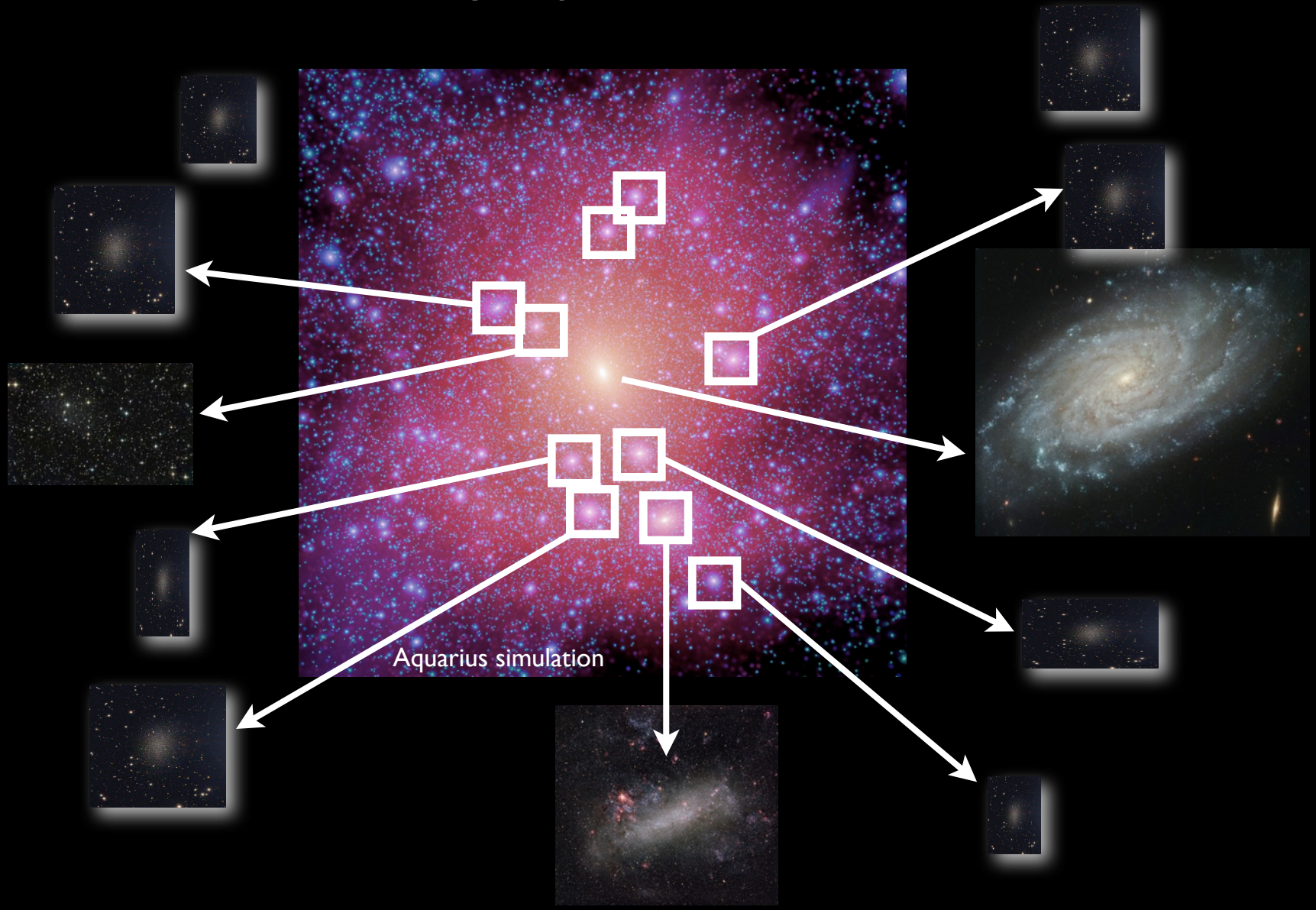

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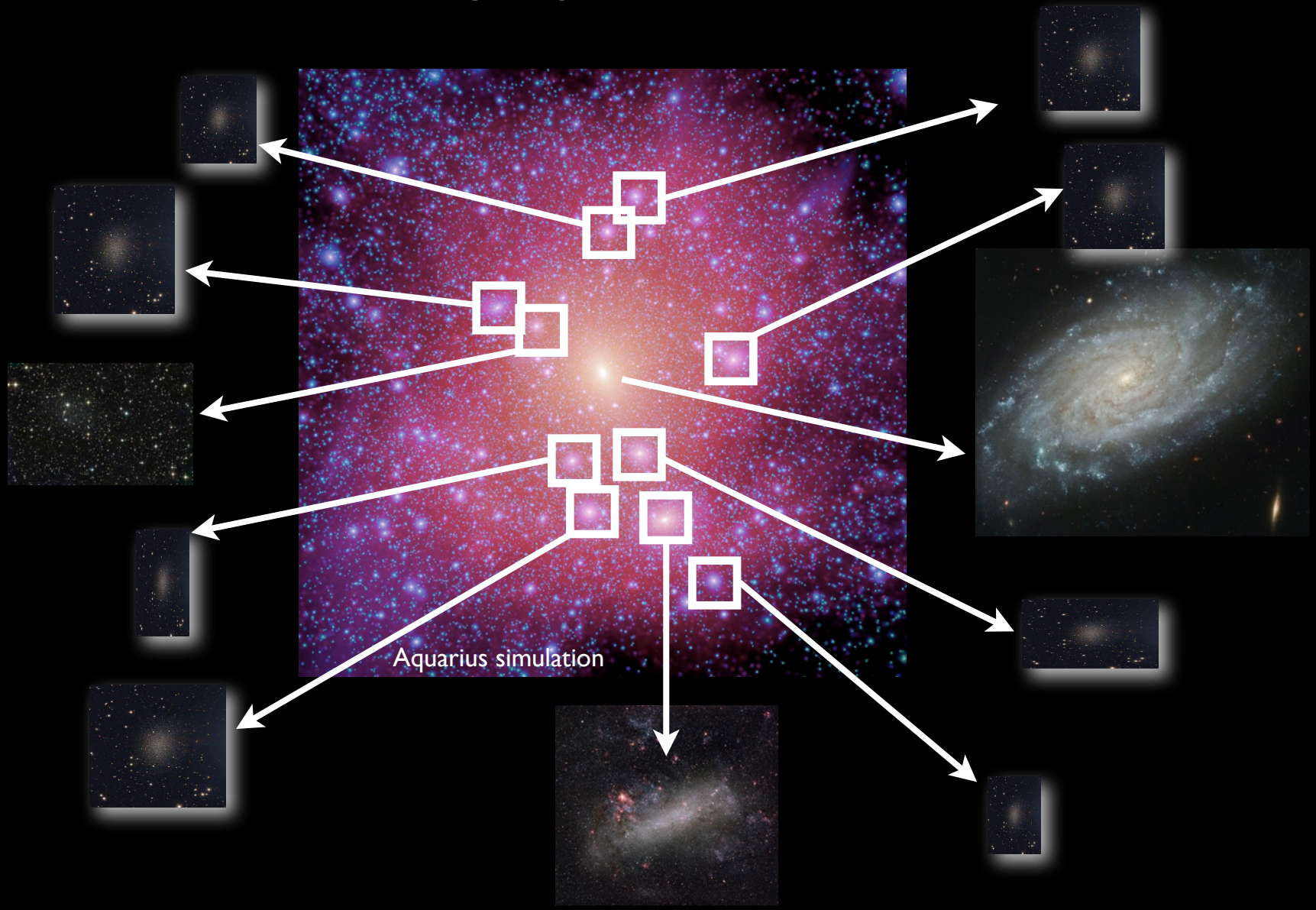

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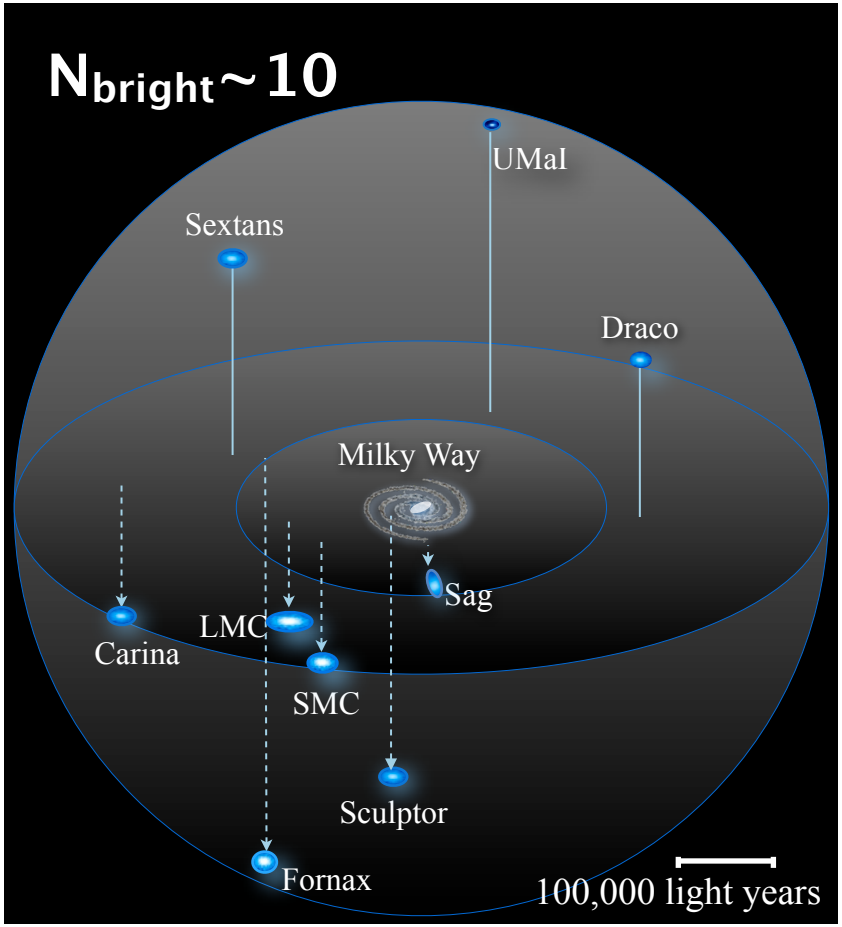
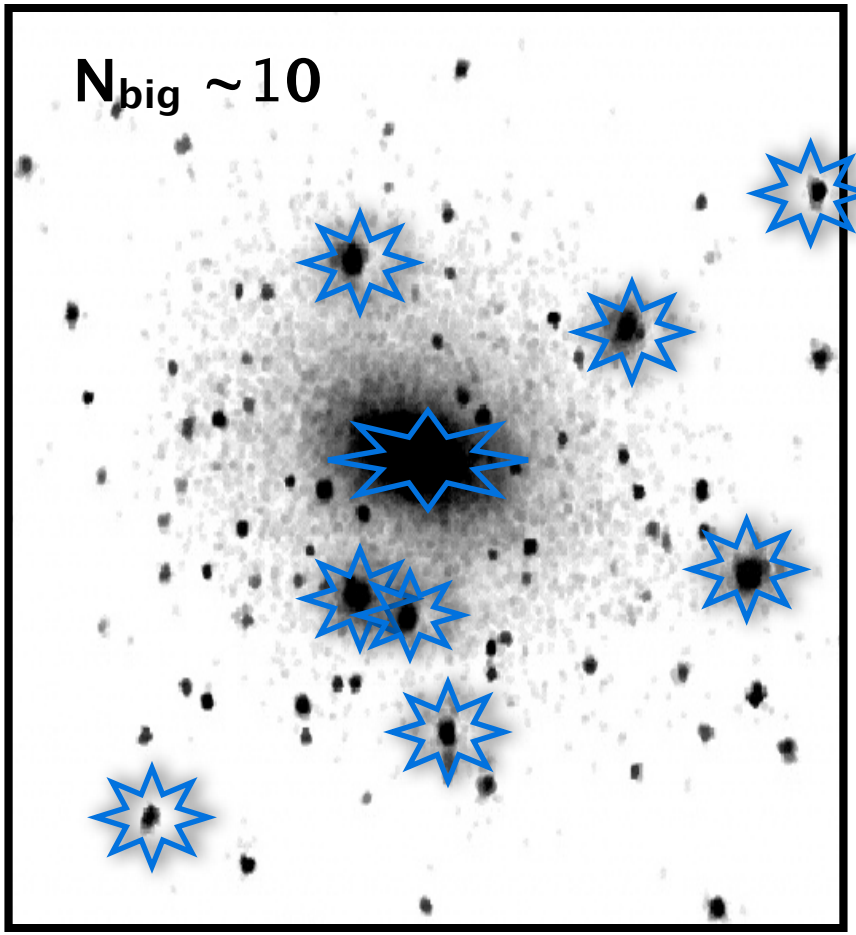
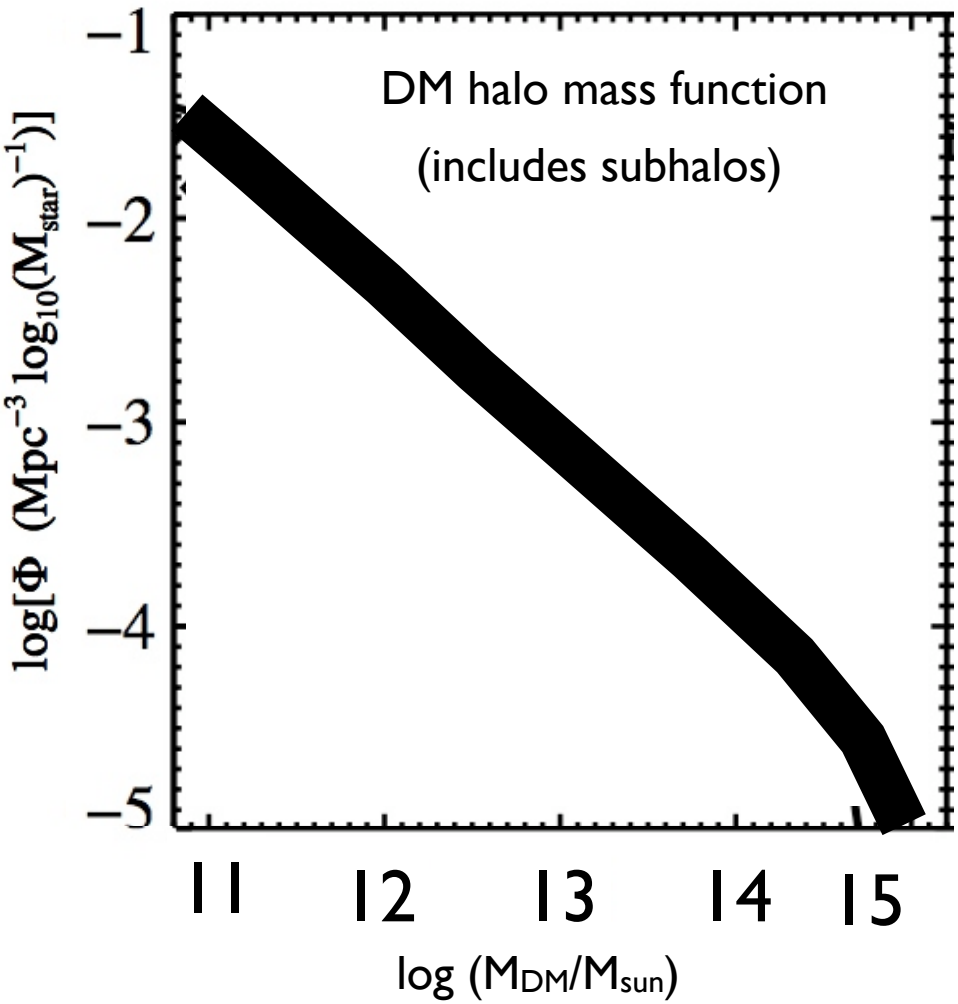
Natural Solution?





Only the big ones have enough stars to see?

Abundance Matching: (sub)halo mass ⇔ galaxy L or M*



Kravtsov et al. 2004; Conroy et al. 2006, Guo et al. 2010;Behroozi et al. 2010

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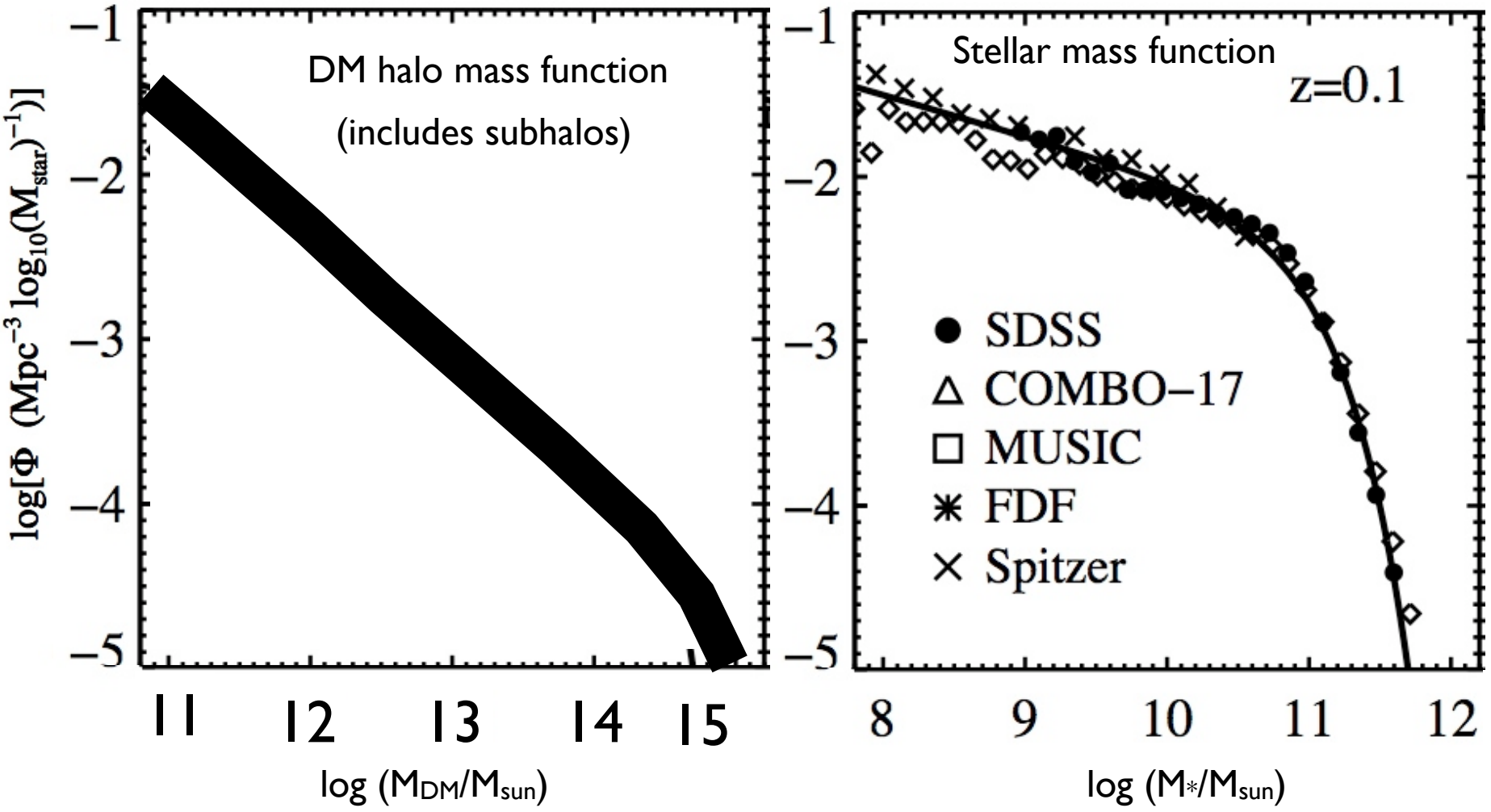

compilation by Conroy & Wechsler 08

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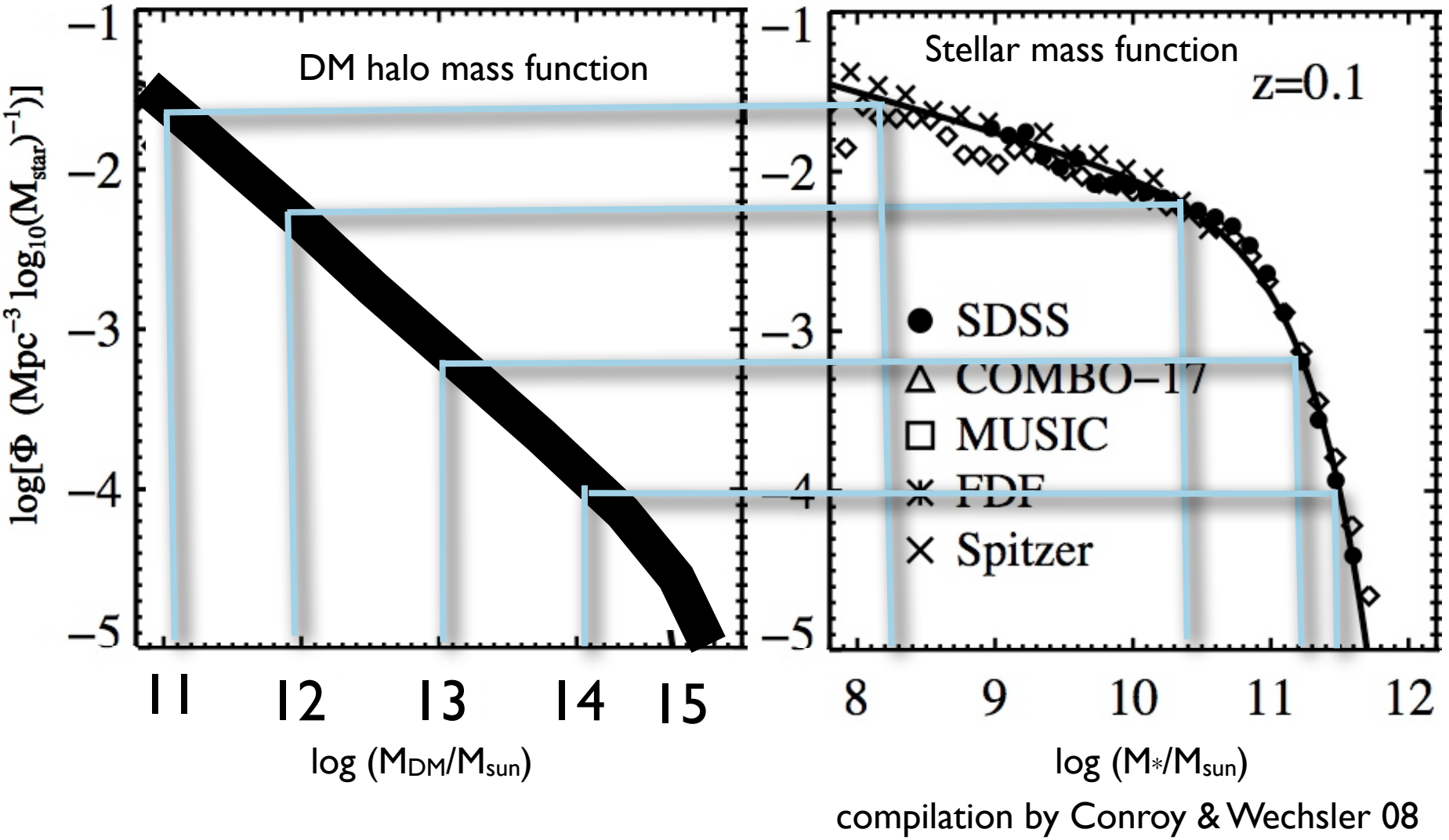

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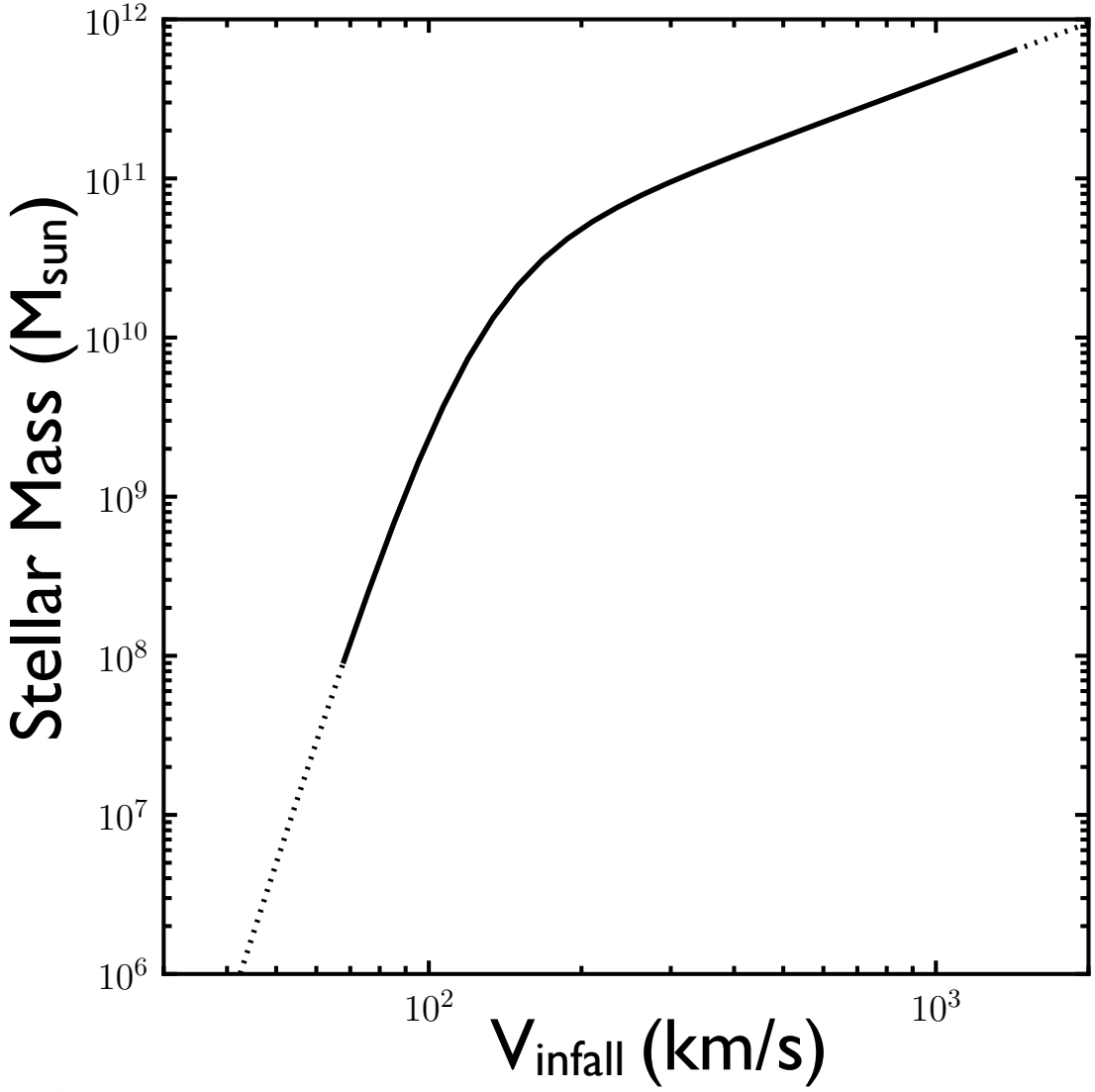
Galaxy luminosities matched with (sub)halo's peak V_{max}



"Abundance Matching"

$$n(> M_\star) = n(> V_{\rm infall})$$

SDSS DR 7
(Abazajian et al. 2009, Li & White 2009)

Millennium-II simulations
Boylan-Kolchin et al. 2009

Boylan-Kolchin et al. 2011

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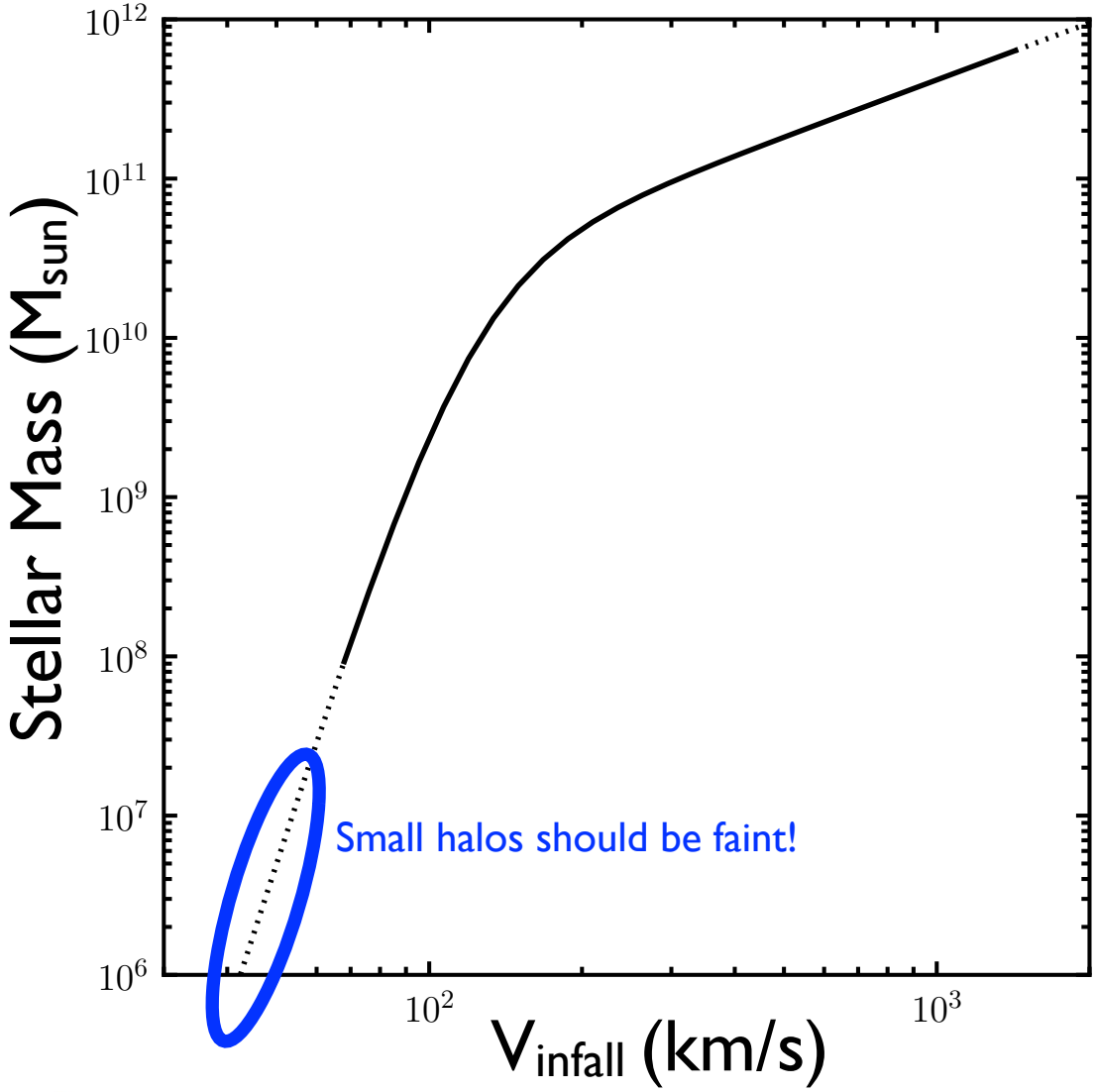

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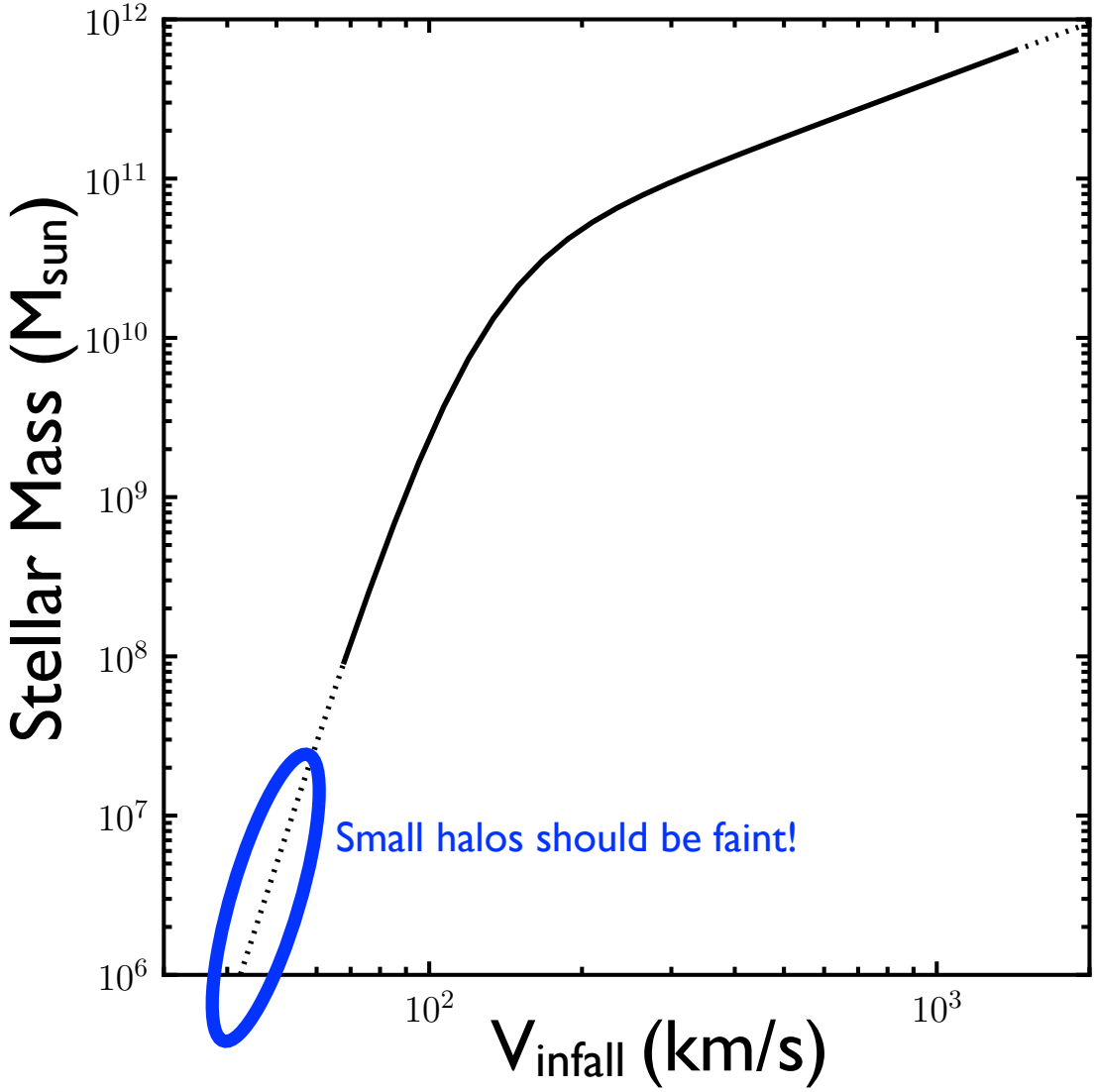

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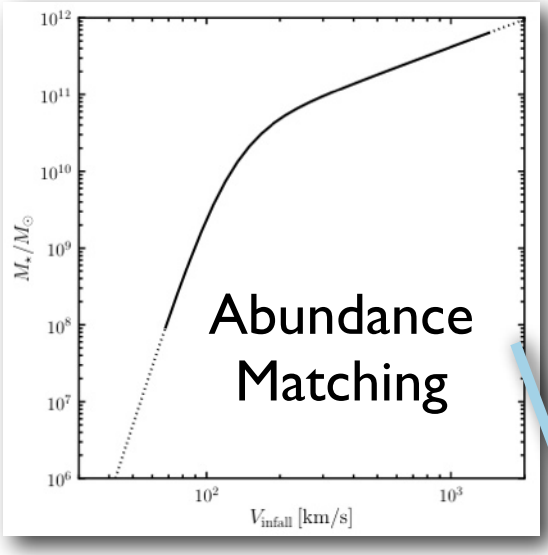
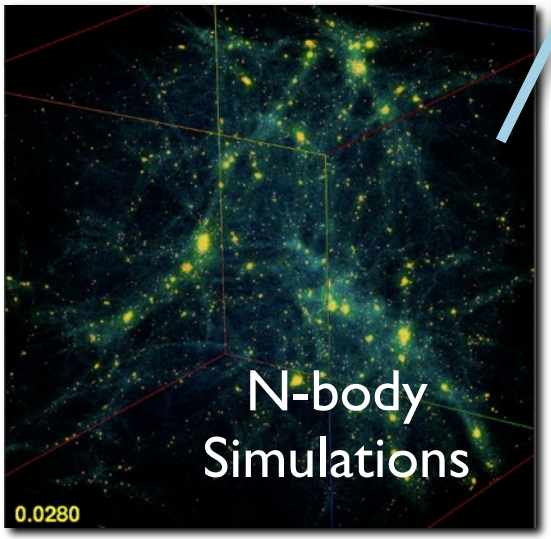
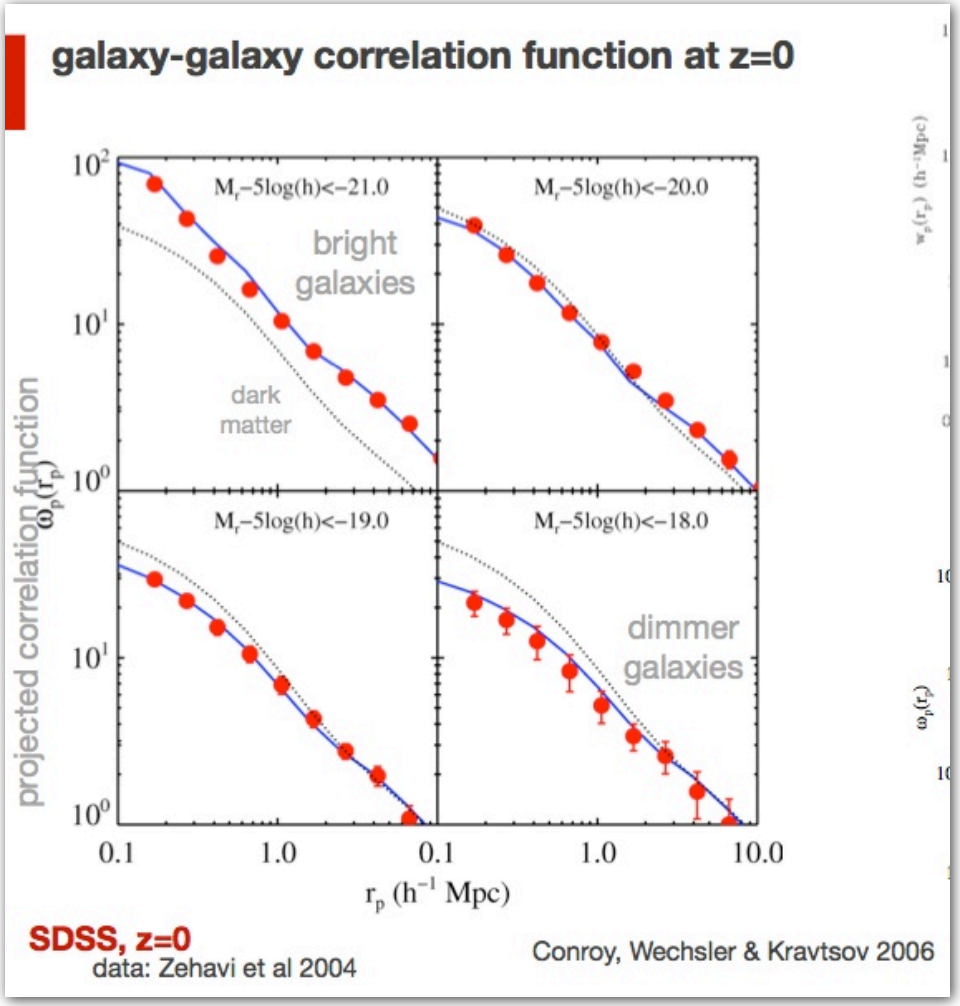
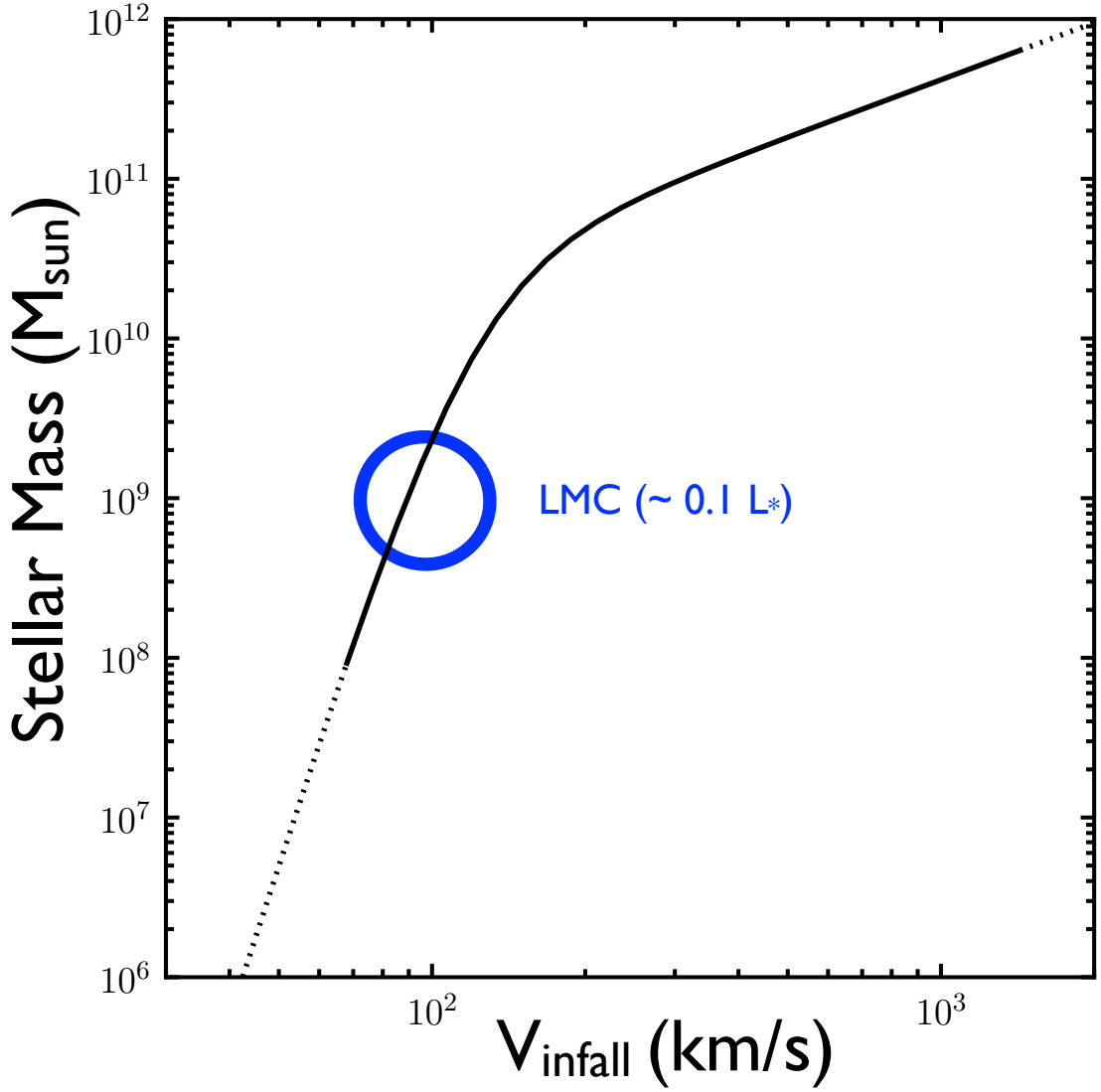
Simple mapping does well matching galaxy clustering



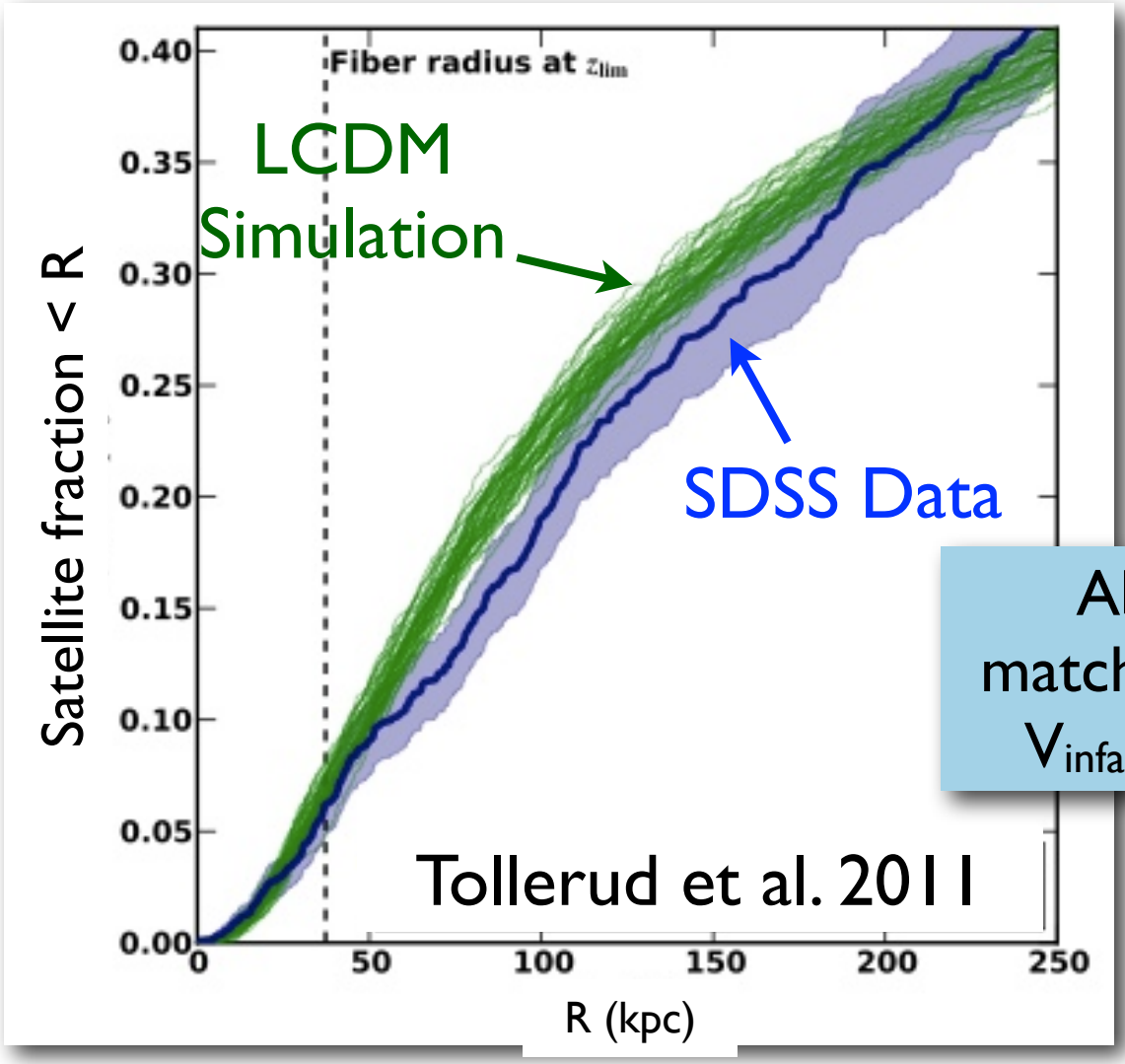




Abundance Matching for Satellite Galaxies?

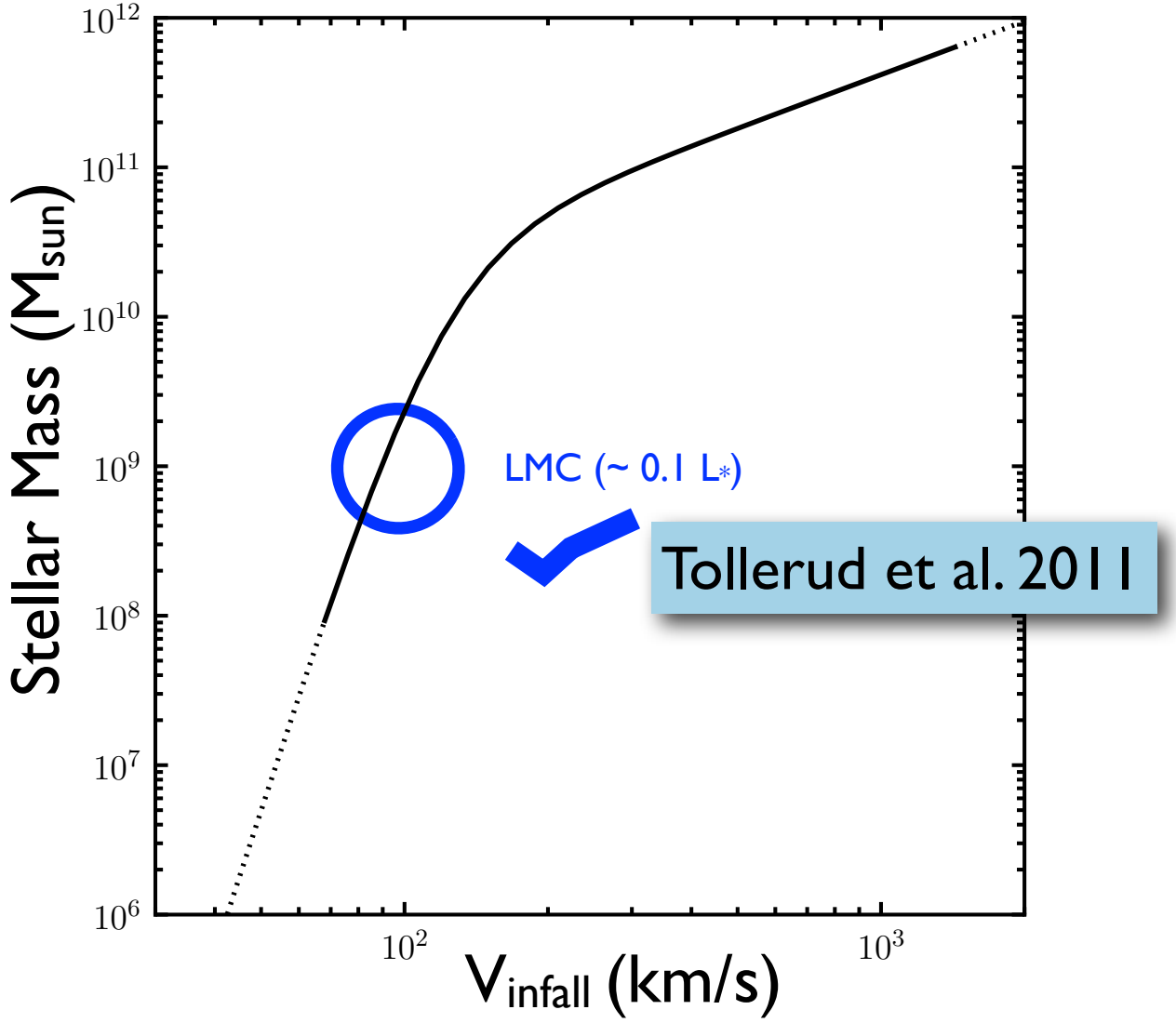


Tollerud et al. 2011



Abundance matching works at V_{infall}~100 km/s

Abundance Matching for Satellite Galaxies?



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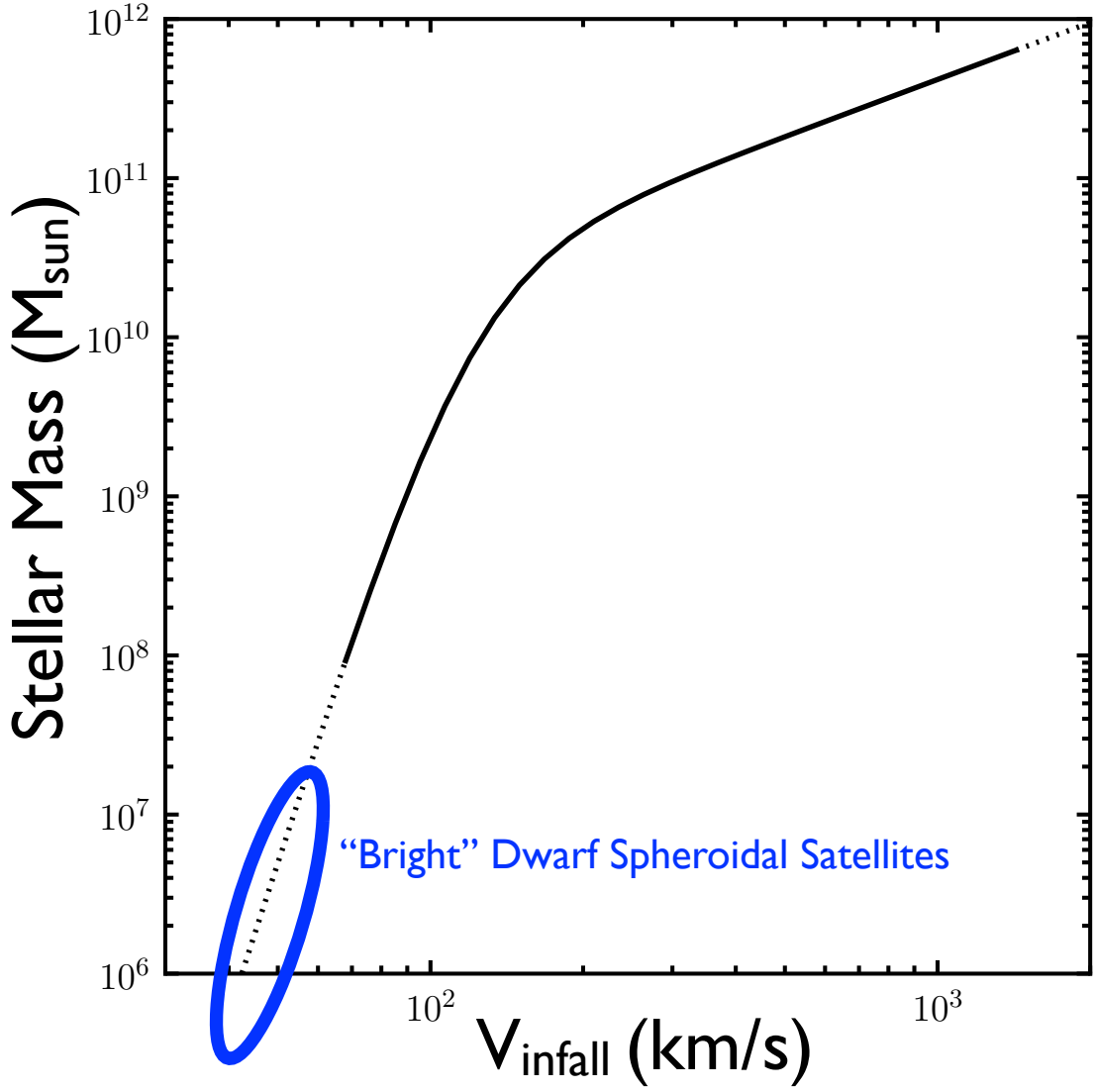
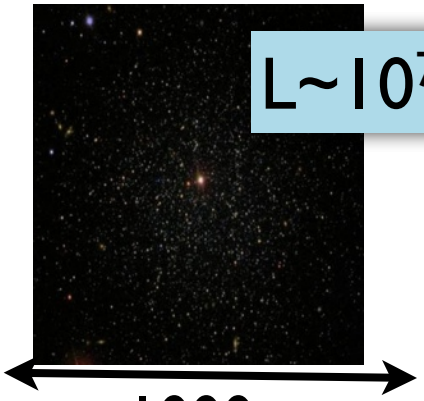


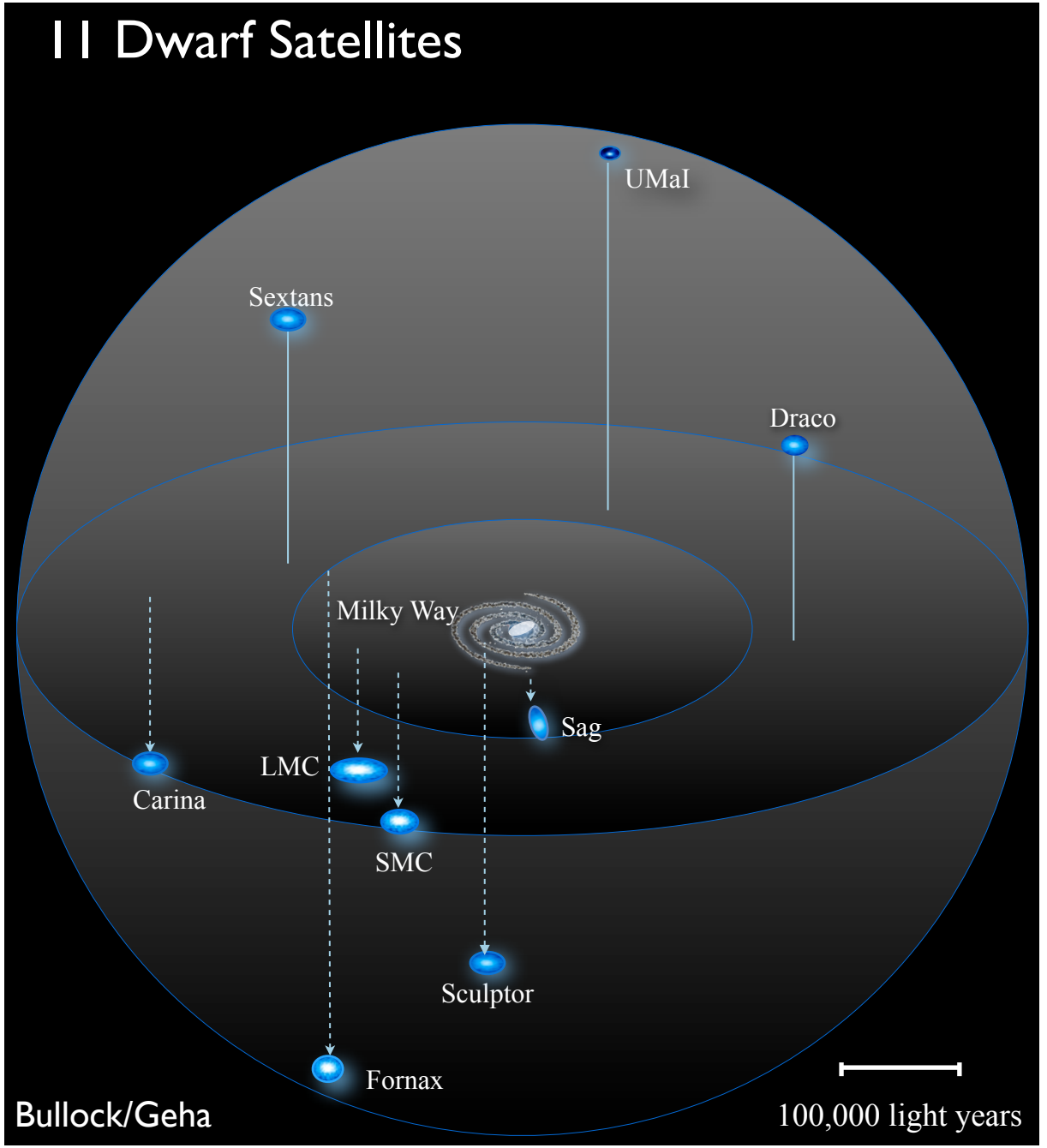
Milky Way 2004

Fornax:



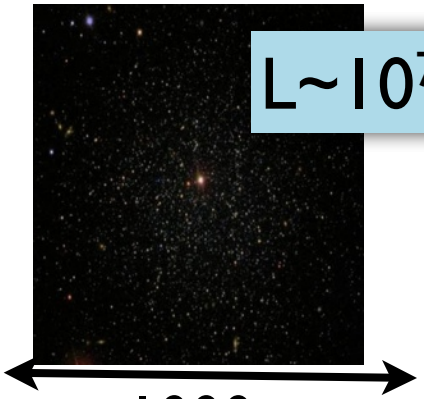
$L \sim 10^7 L_{sun}$

~1000 pc



Milky Way 2011

Fornax (1938):



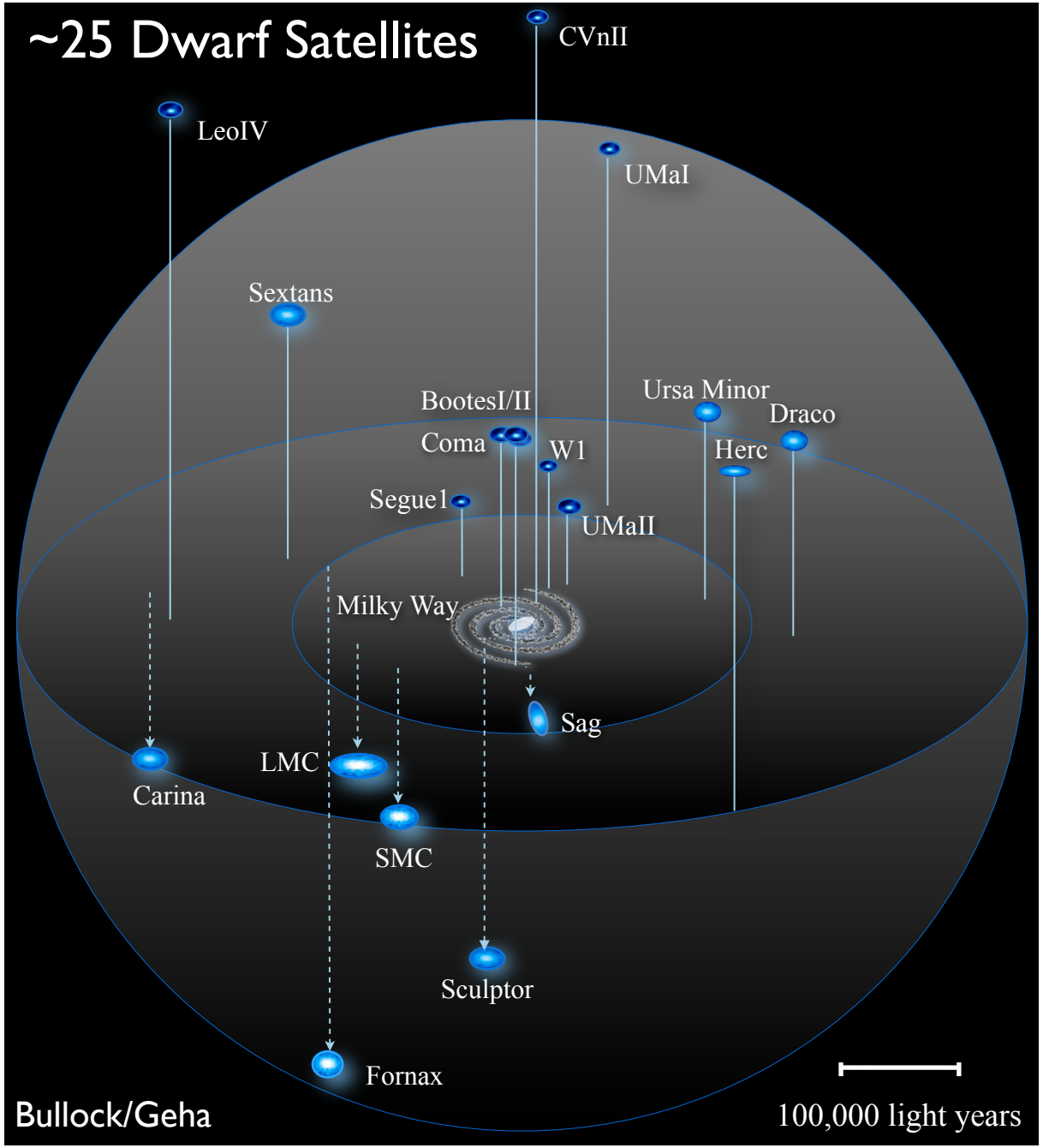
$L \sim 10^7 L_{sun}$

~1000 pc

Segue I (2006):

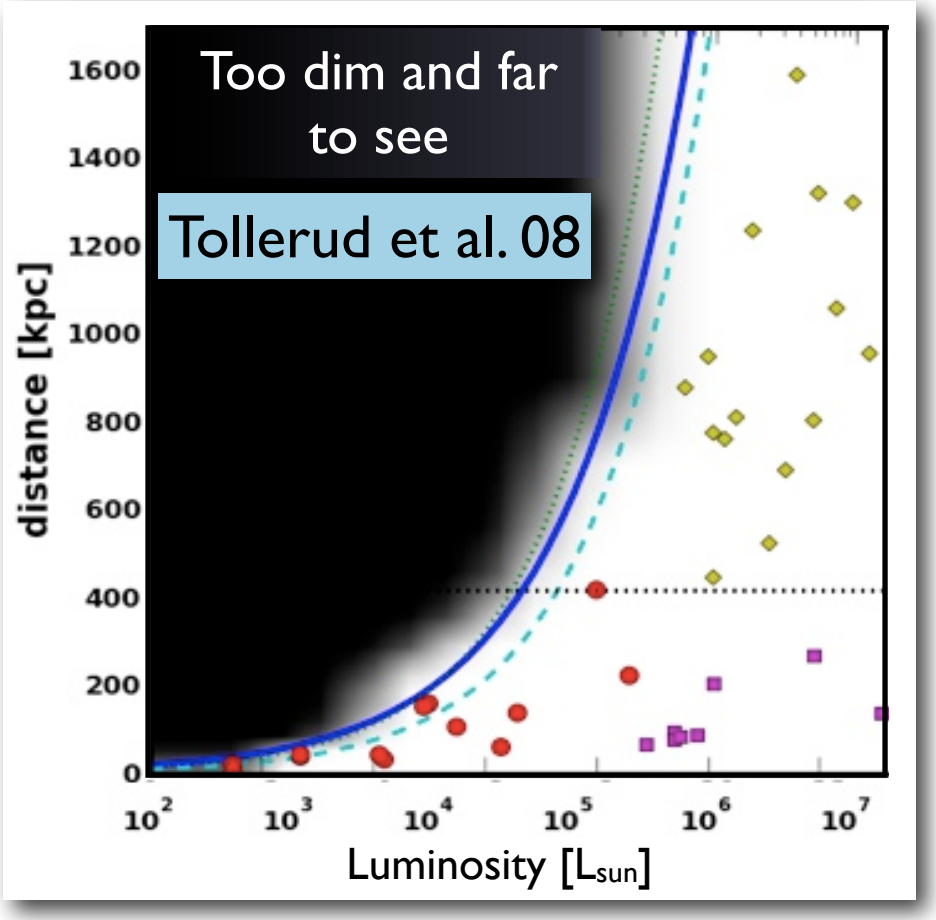
$L \sim 300 L_{sun}$

~100 pc

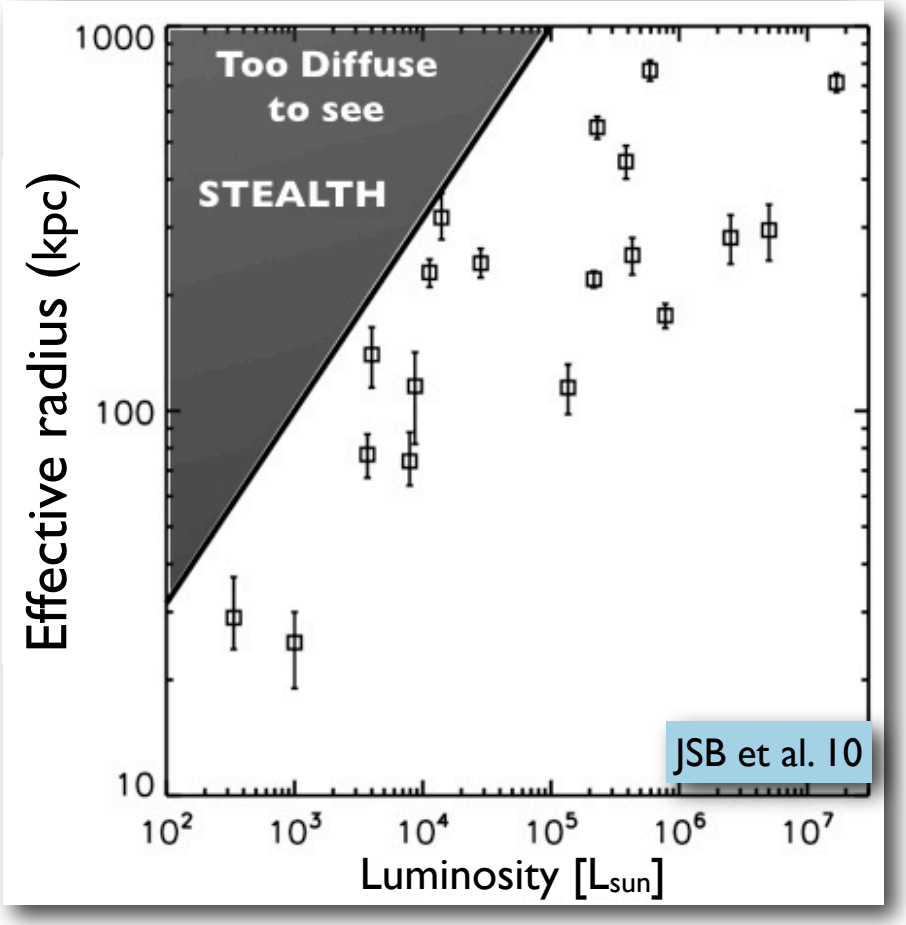


There ARE missing satellites

Luminosity Bias

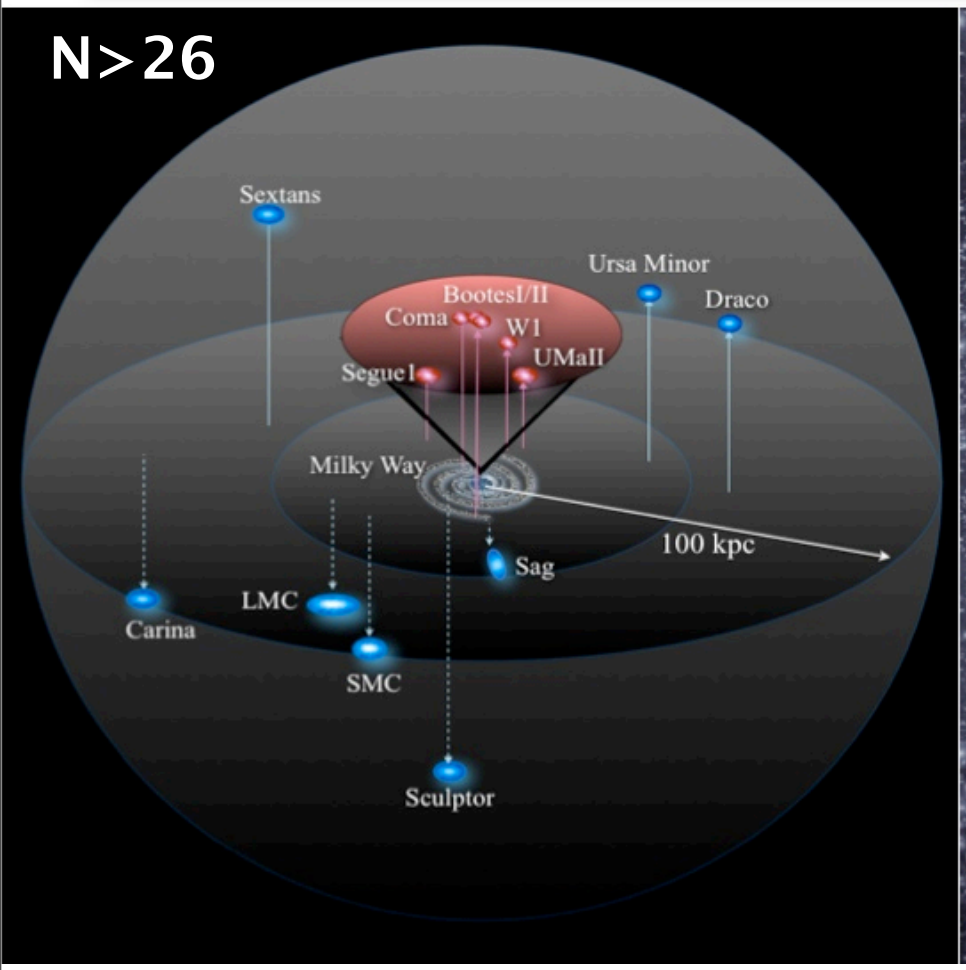


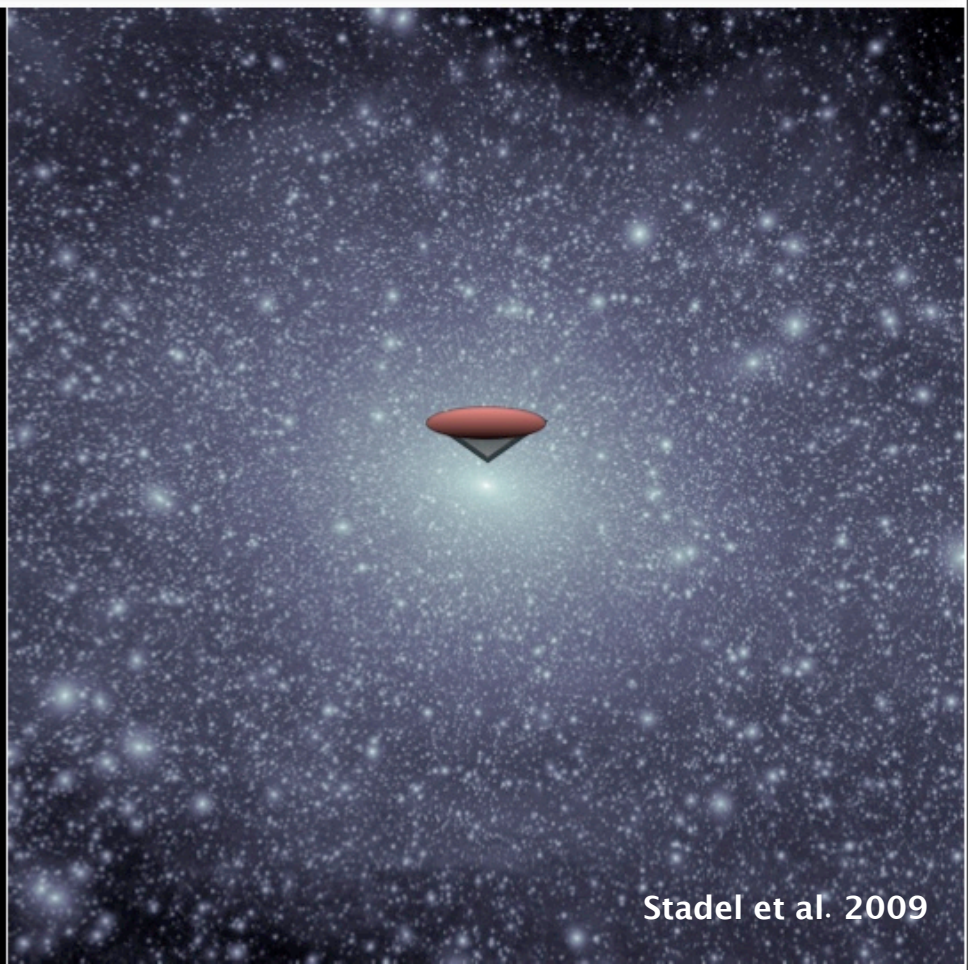
Surface Brightness



Koposov et al. 2007, Walsh et al. 2009

Probably ~100's more faint dwarfs to be discovered





Tollerud et al. 08

See also:
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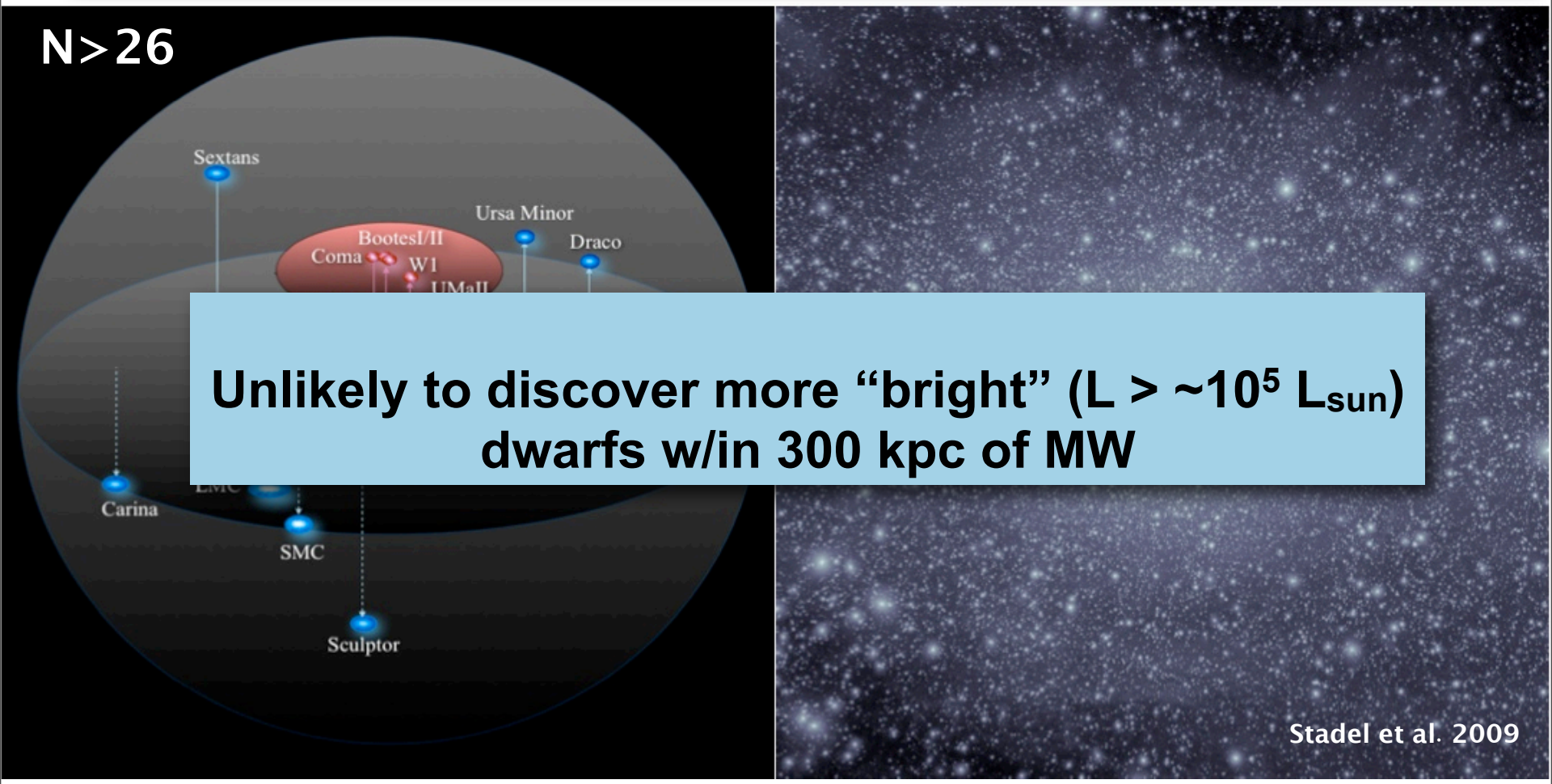

Unlikely to discover more "bright" ($L > \sim 10^5\ L_{sun}$) dwarfs w/in 300 kpc of MW

Tollerud et al. 08

See also:
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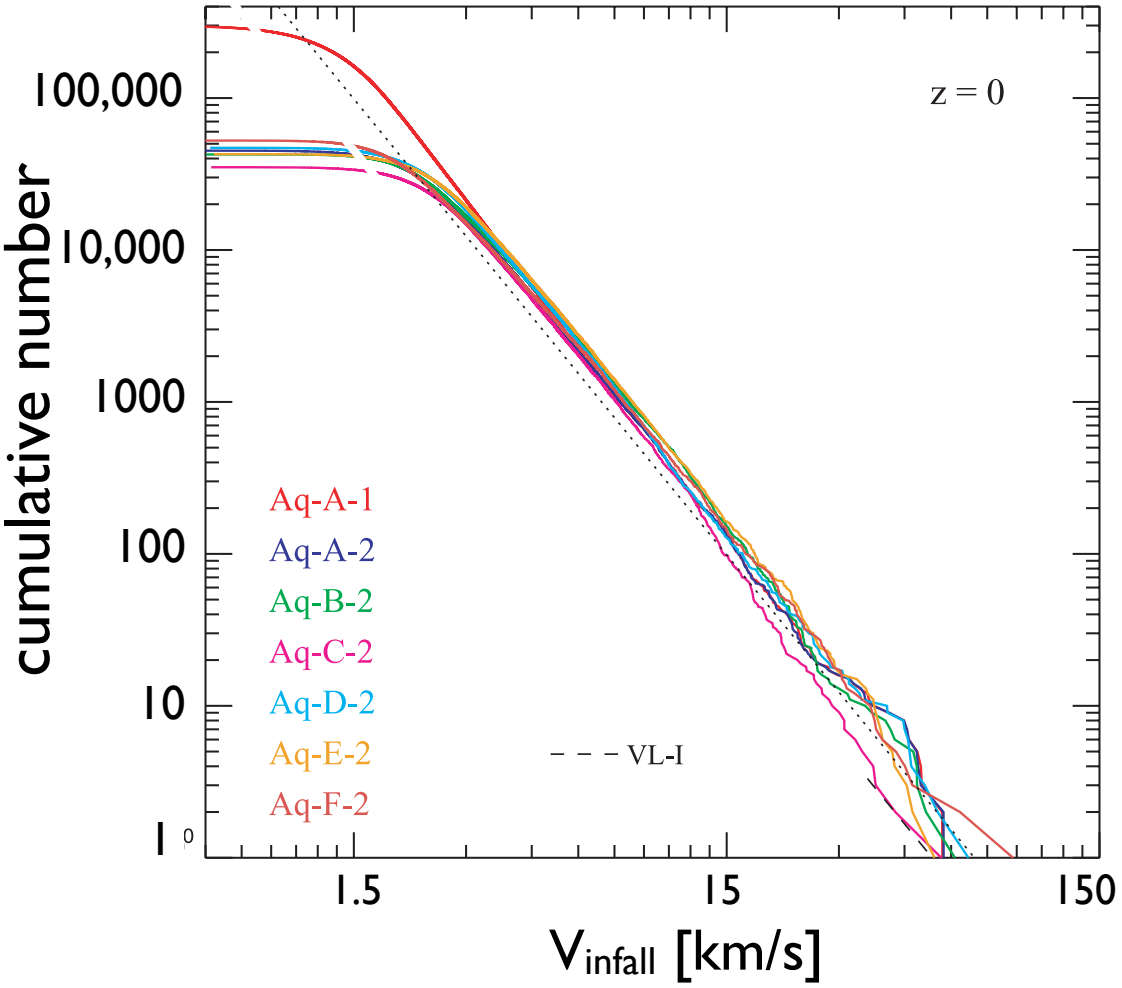
A seductive story...



Springel et al. 2008
(Aquarius project)

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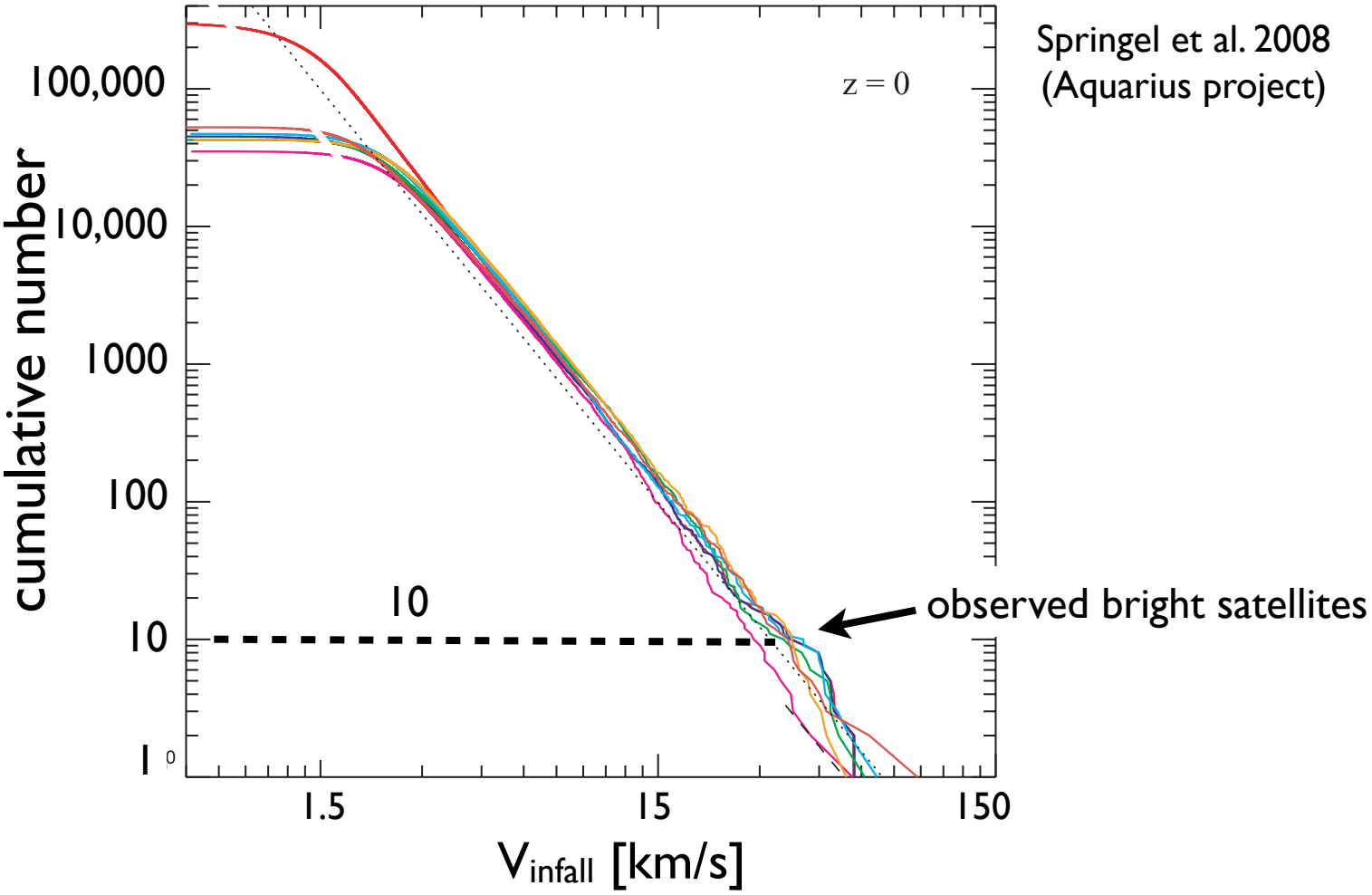

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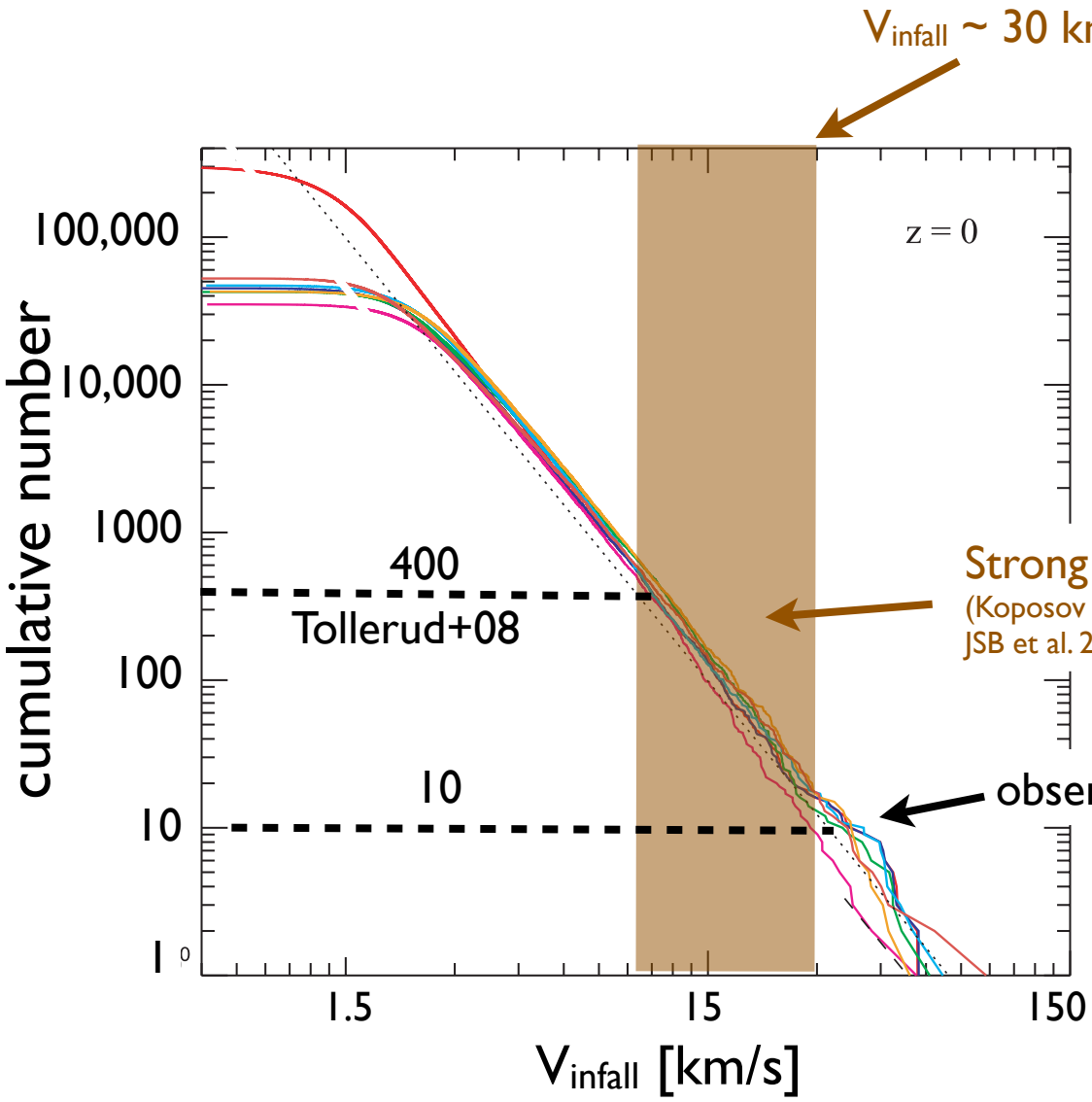

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Strong observational biases
(Koposov et al. 2008; Tollerud et al. 2008, Walsh et al. 2009, JSB et al. 2010)

observed bright satellites

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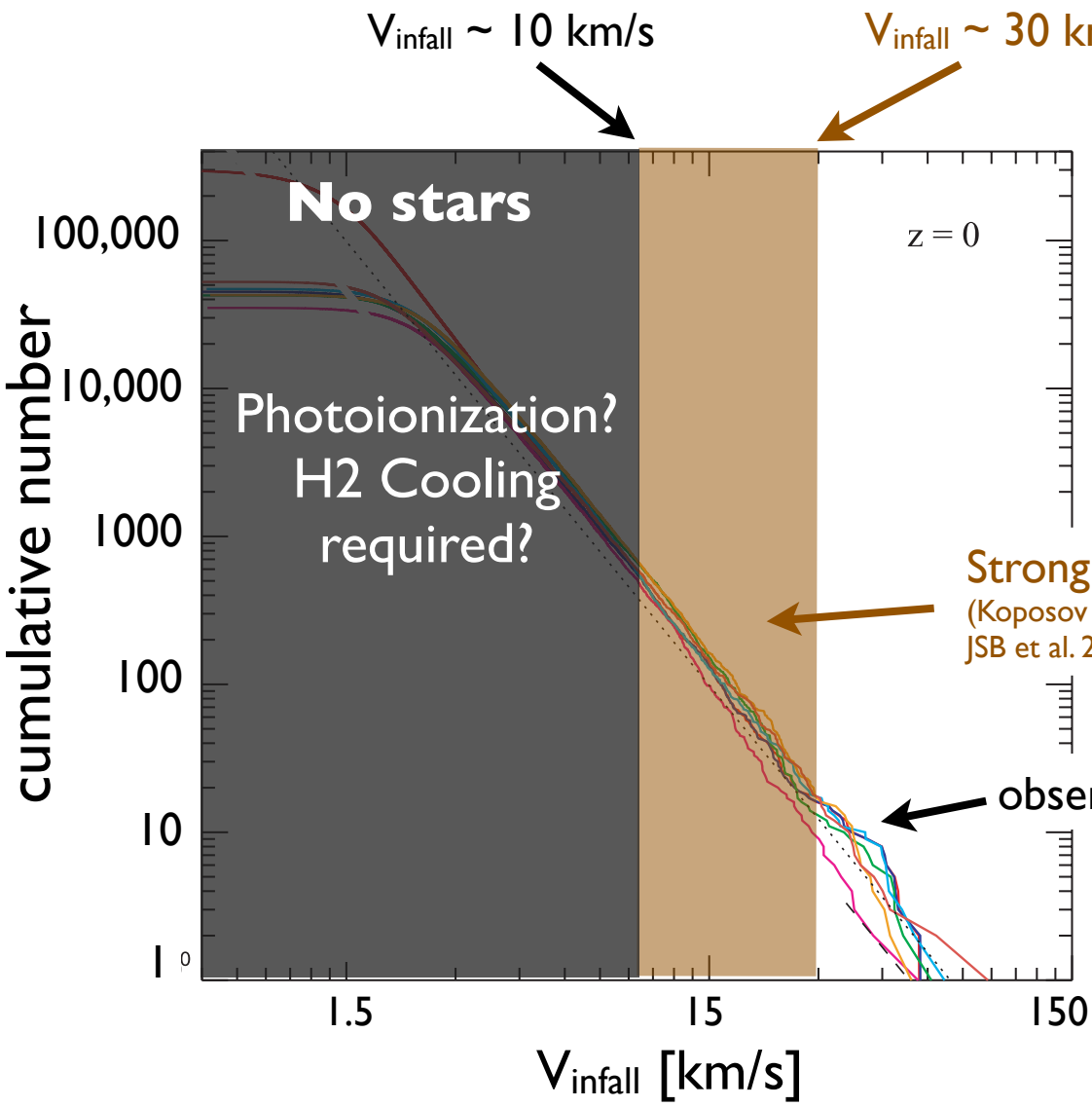

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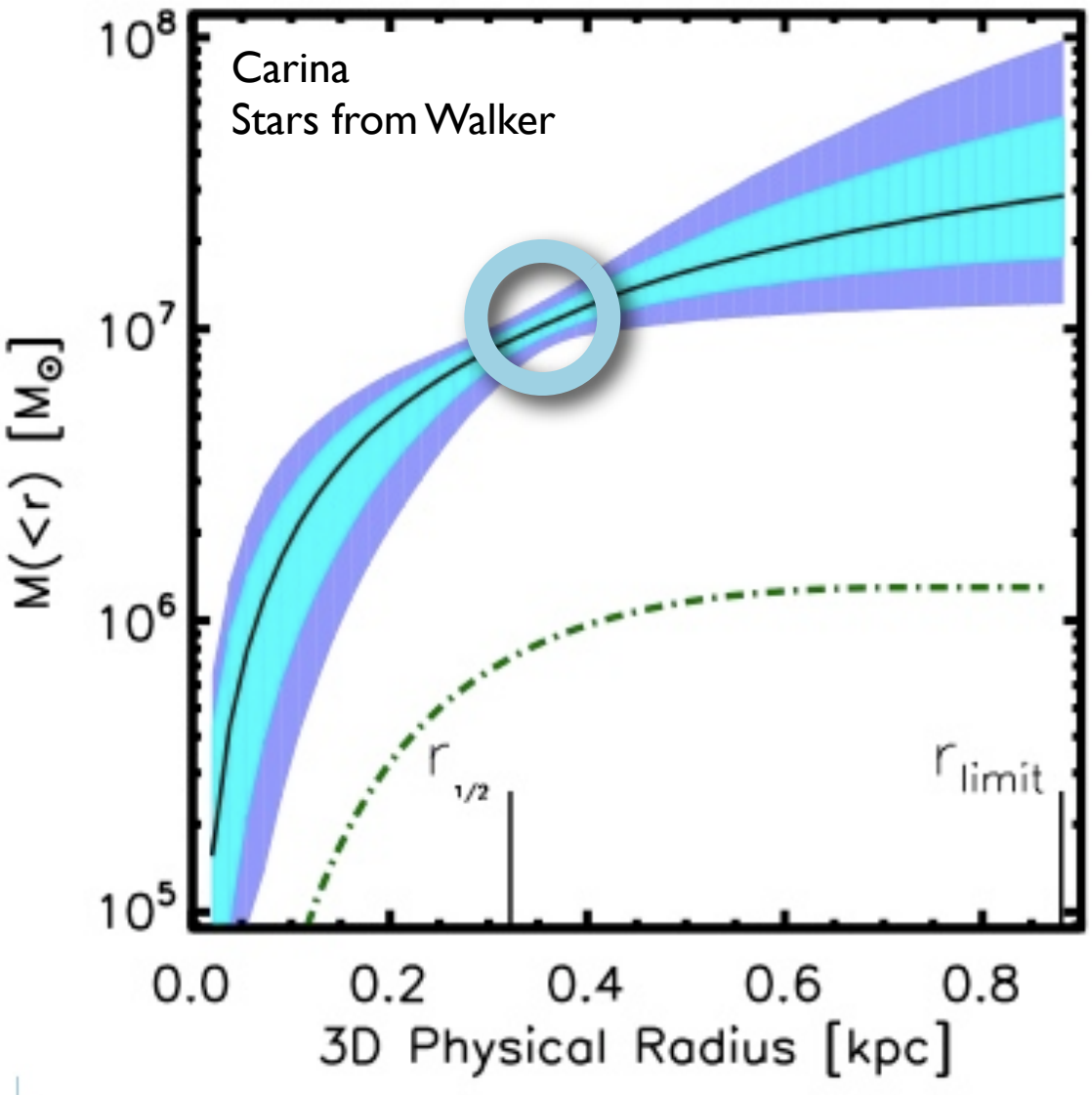
Does this picture actually work?

Compare Masses of Bright $L>10^5$ L_{sun} MW satellites
to
Masses of LCDM subhalos

Dynamical masses at $r_{1/2}$ known to ~20% for bright dwarfs



Mass is best constrained near 3d half-light radius

$$V_c(r_{1/2}) = \sqrt{3}\,\sigma_*$$

Wolf et al. 2010

See also:
Walker et al. 2009
Strigari et al. 2007

W+10 estimator agrees with axisymmetric Schwarzschild modeling by Thomas et al. 2011

Bright Dwarfs vs. Massive Subhalos

- Dynamical mass **at $r_{1/2}$** constrained to ≲20% by observations
  - Wolf et al. 10; ←Walker et al. 09; Koch et al. 07; Munoz et al. 05;
- *N*-body simulations now resolve $r_{1/2}$ (~300 pc)
  - Springel et al. 2008, Diemand et al. 2008

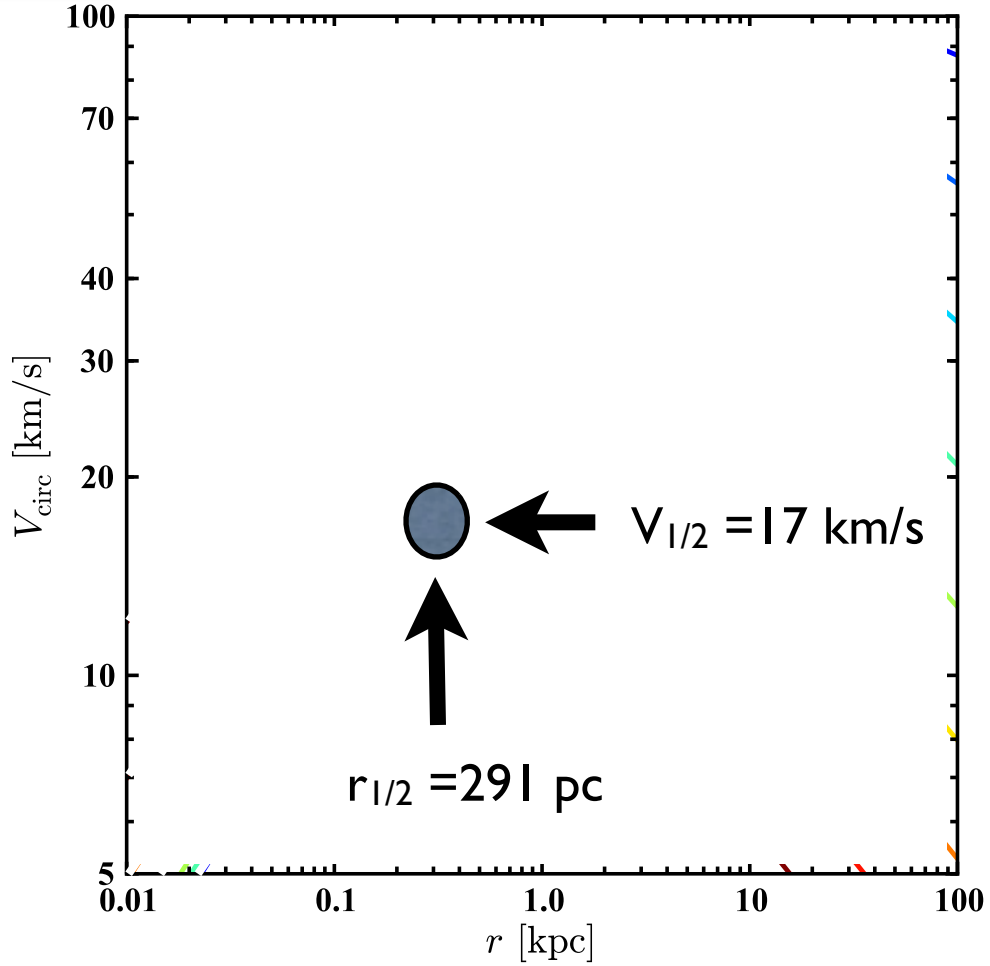
→ Directly compare observed satellites to simulated subhalos at $r_{1/2}$

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

Example of kinematic constraint: Draco

Wolf et al. 2010 →

$$V_c(r_{1/2}) = \sqrt{3}\,\sigma_* \simeq 17\,\mathrm{km\,s^{-1}}$$



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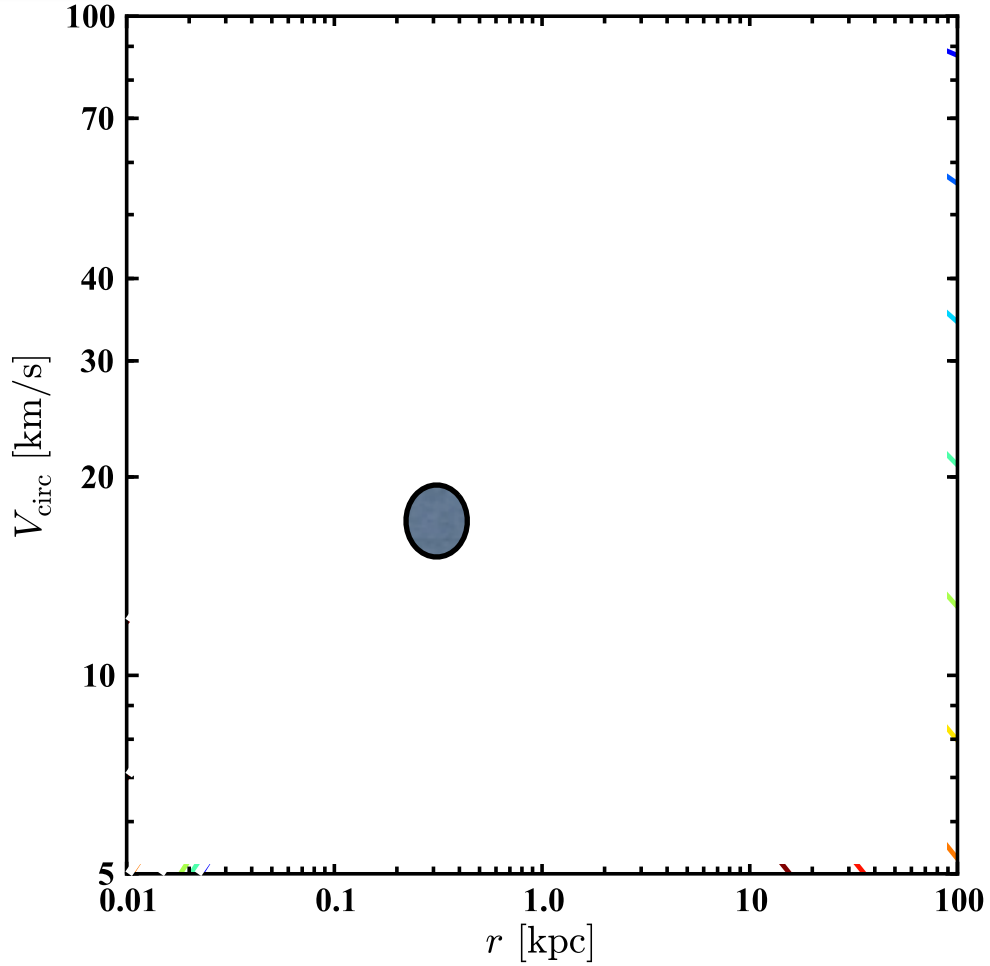
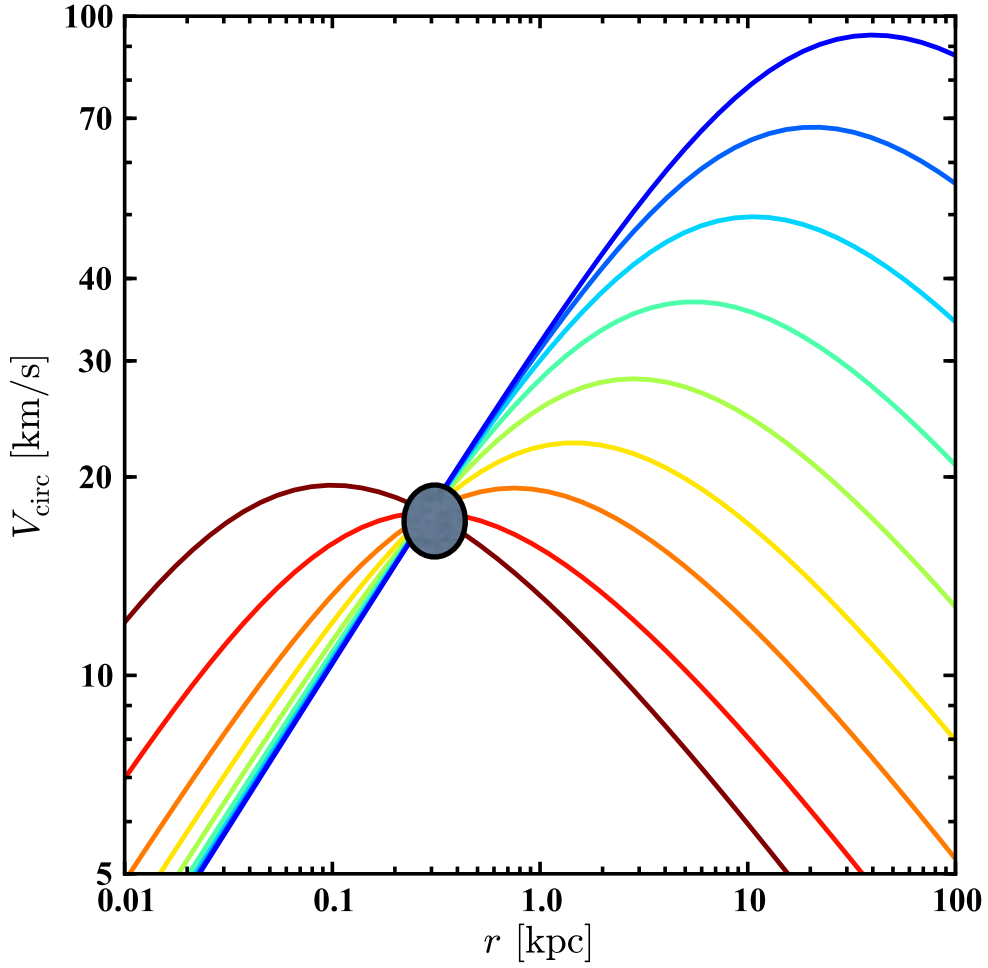


Example of kinematic constraint: Draco

assume NFW mass profiles for subhalos (verified in simulations)



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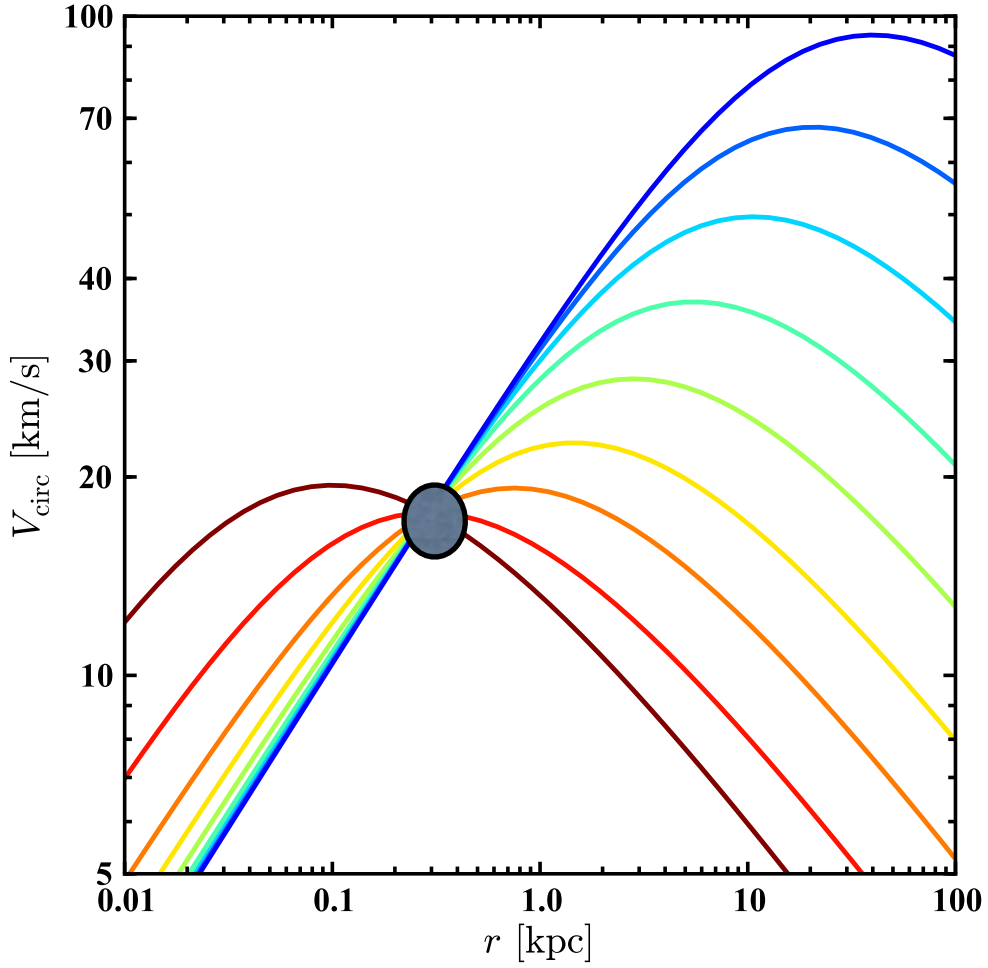

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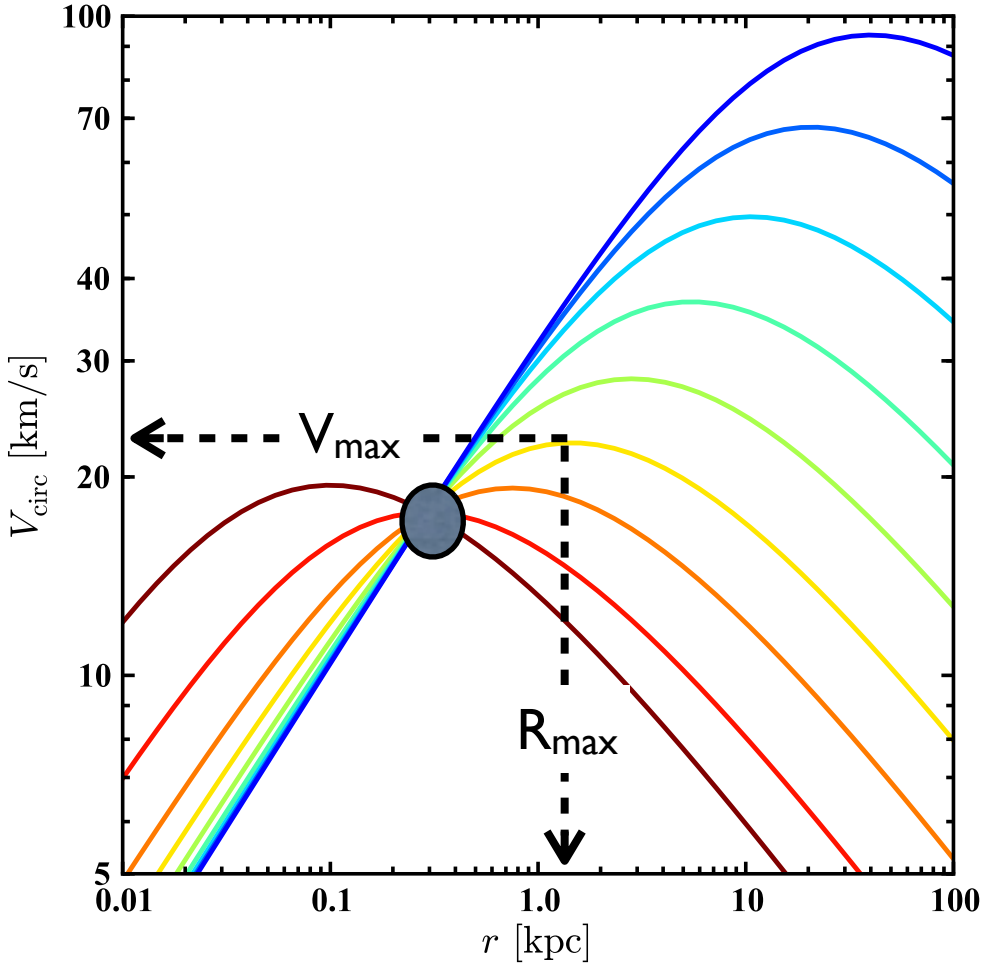

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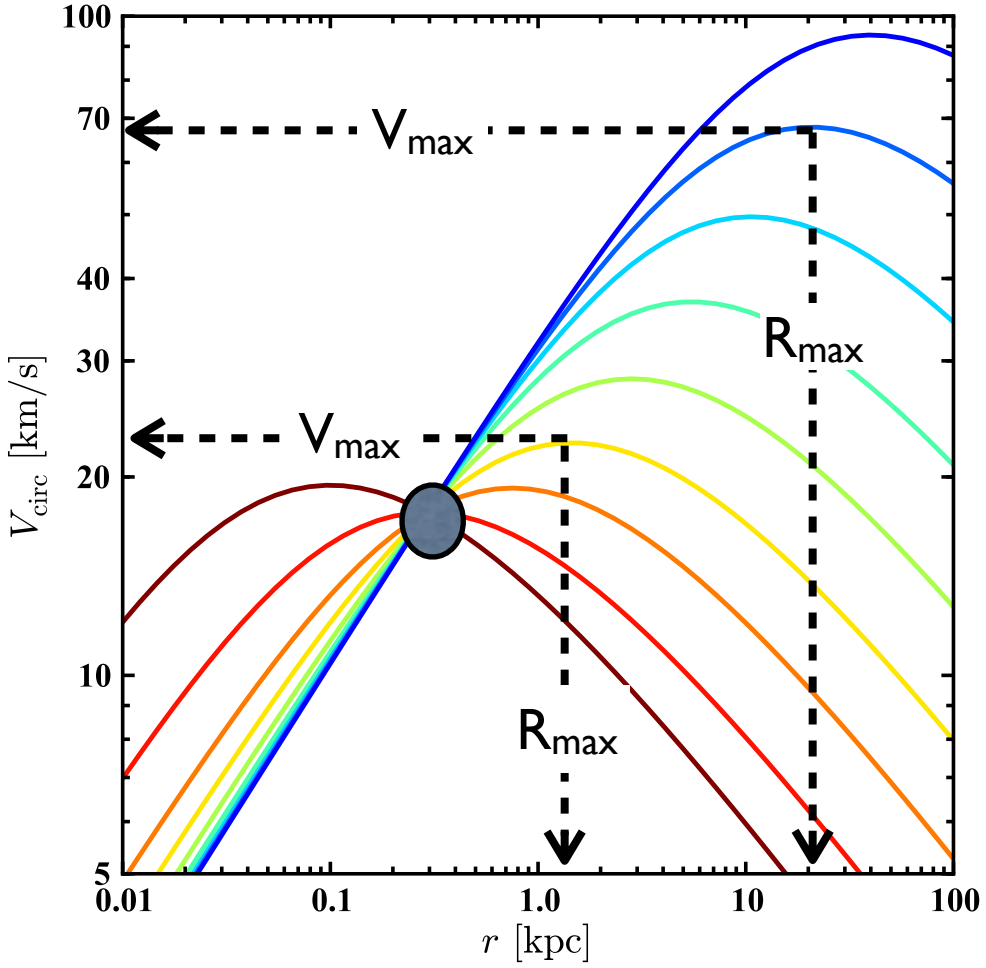

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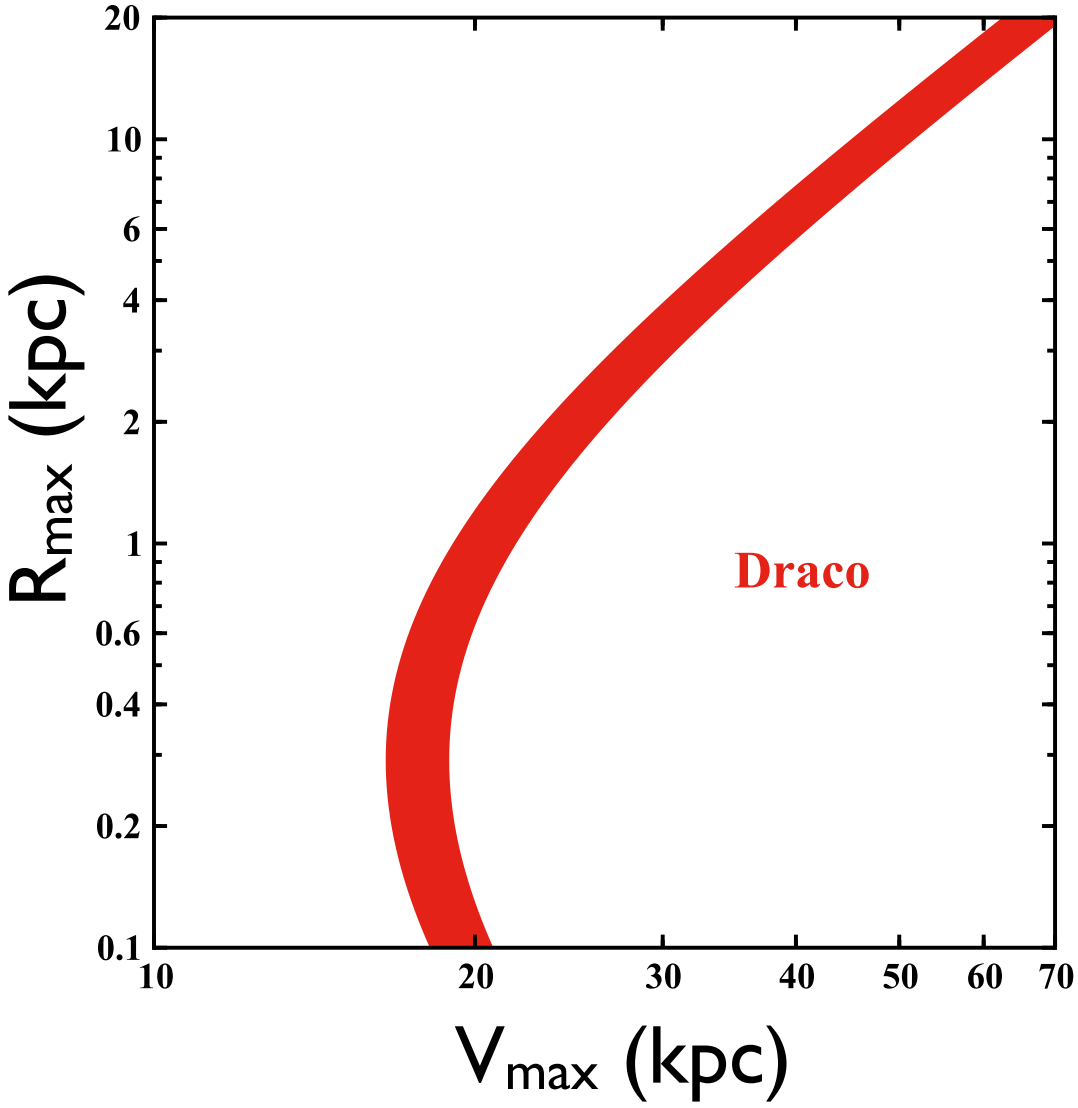
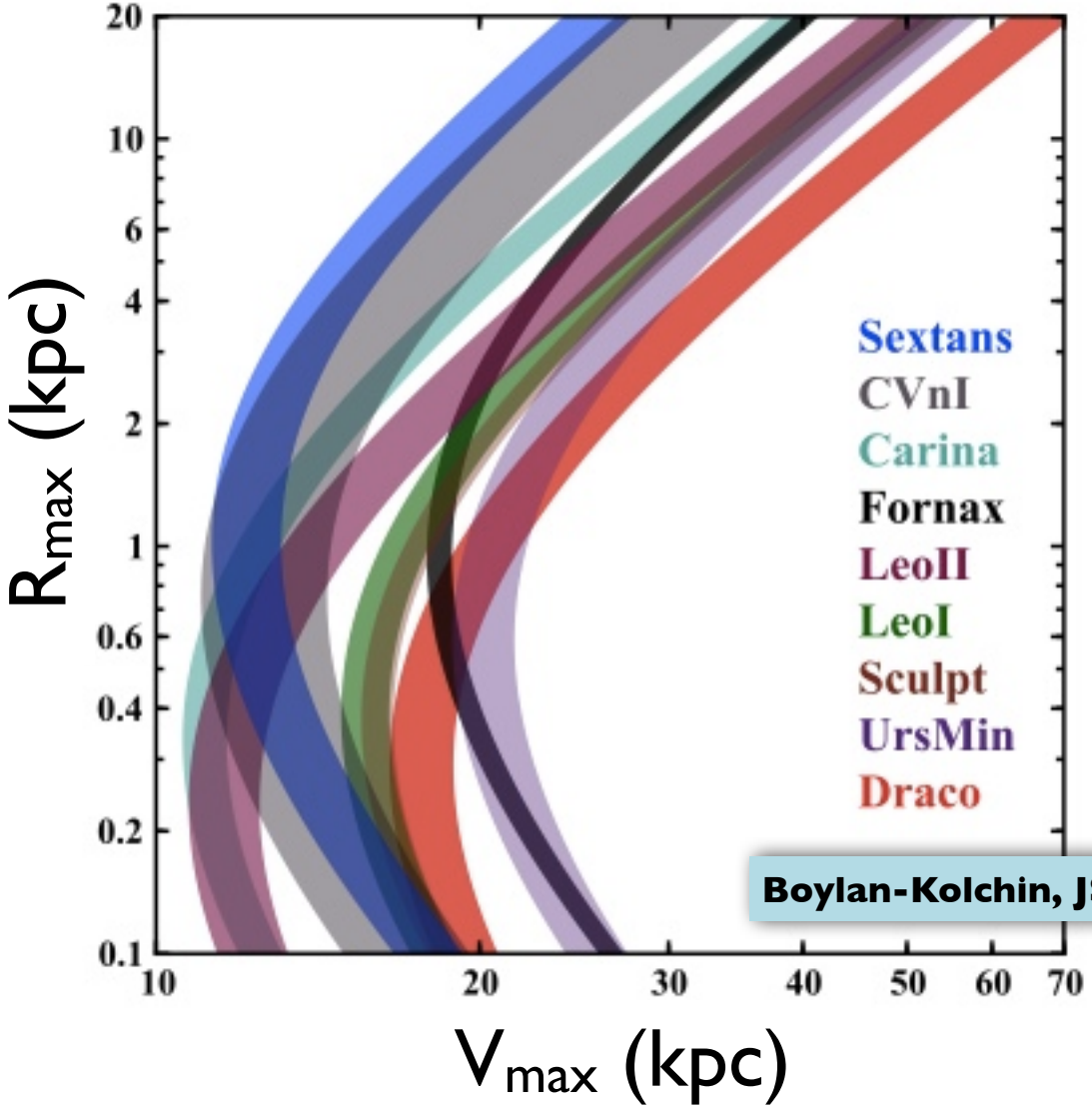


c.f. Zentner & JSB 03
Penarrubia et al. 07

Kinematic Constraints for all $L>10^5 L_{sun}$ MW dSphs



Boylan-Kolchin, JSB, Kaplinghat 2011

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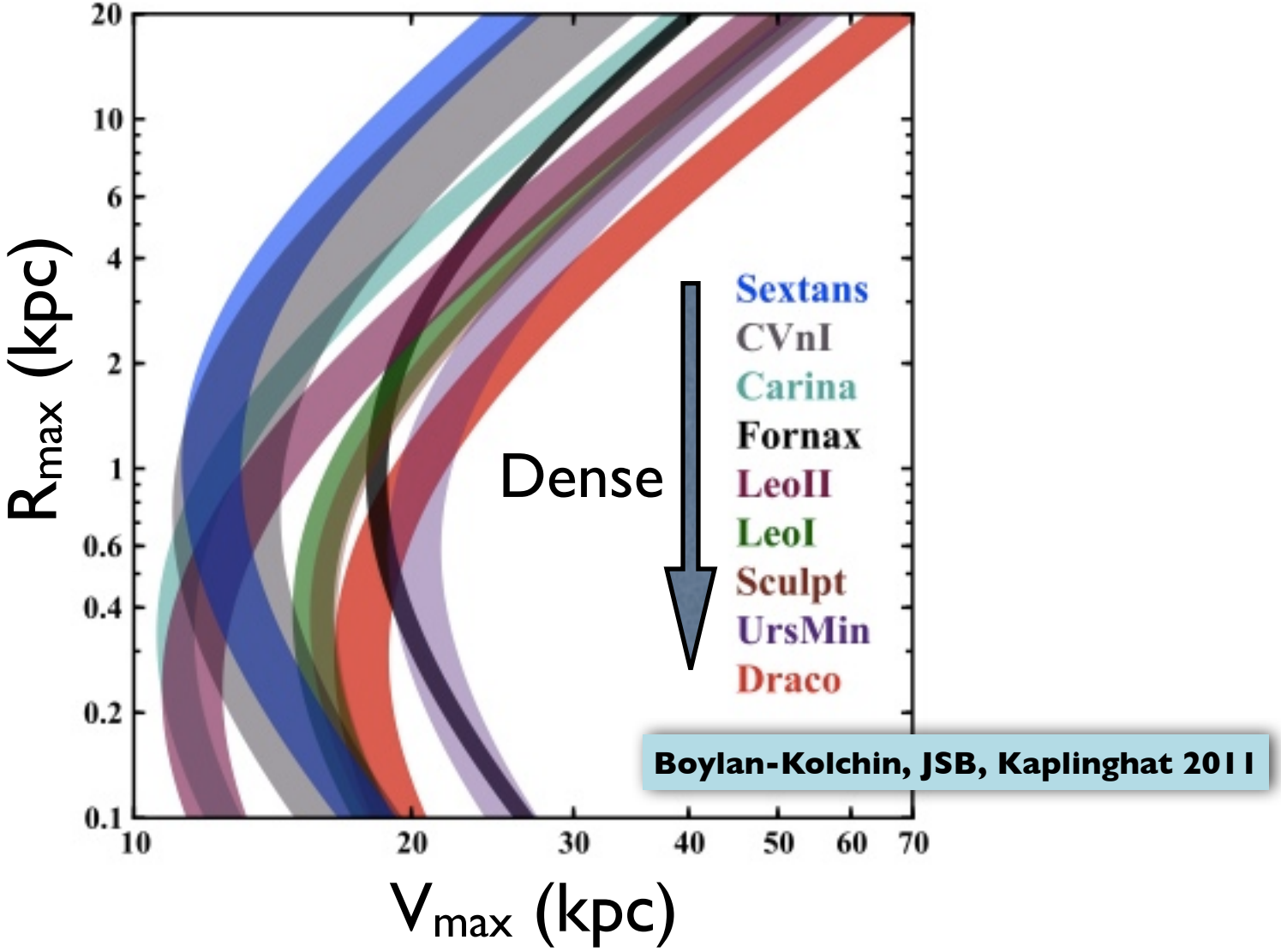
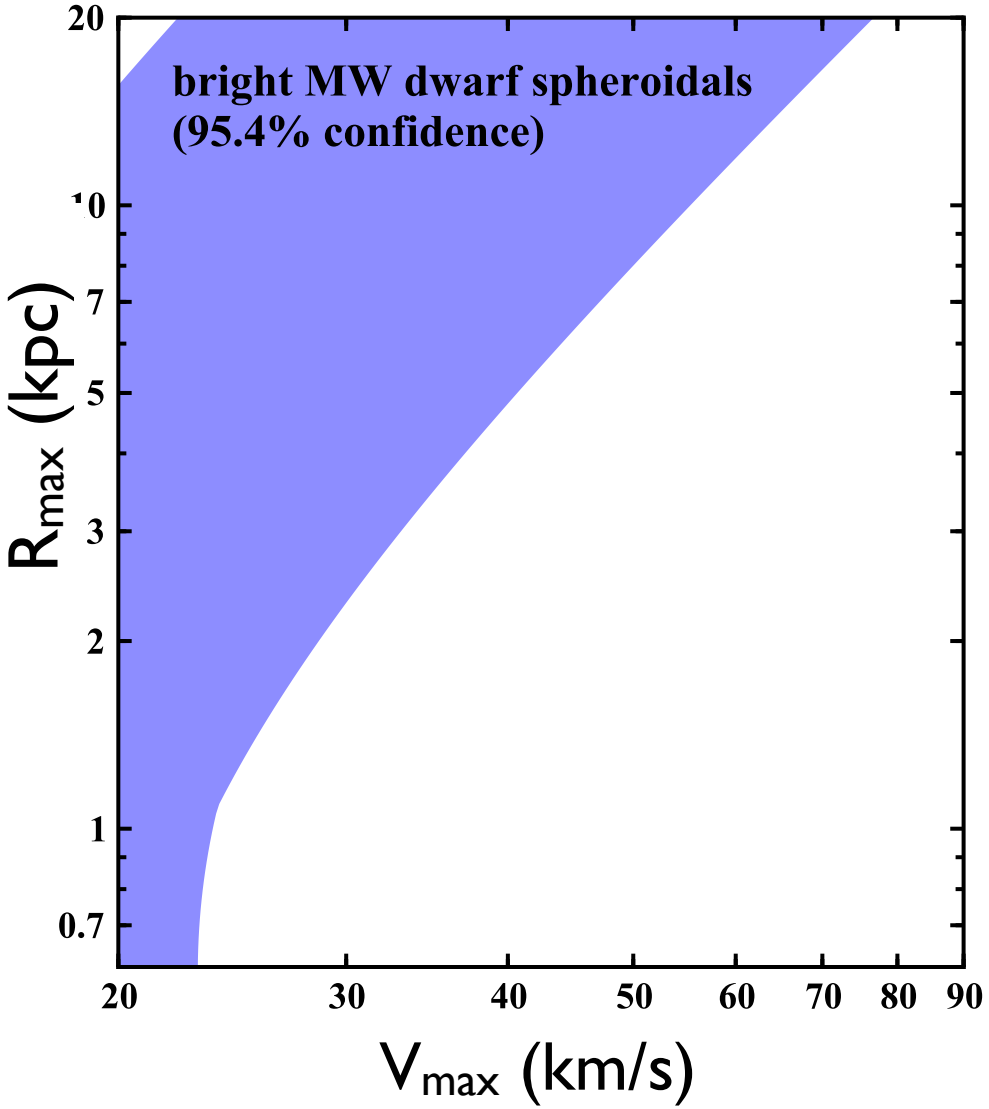


Masses of Bright dSphs vs. Subhalos



Boylan-Kolchin et al. 2011

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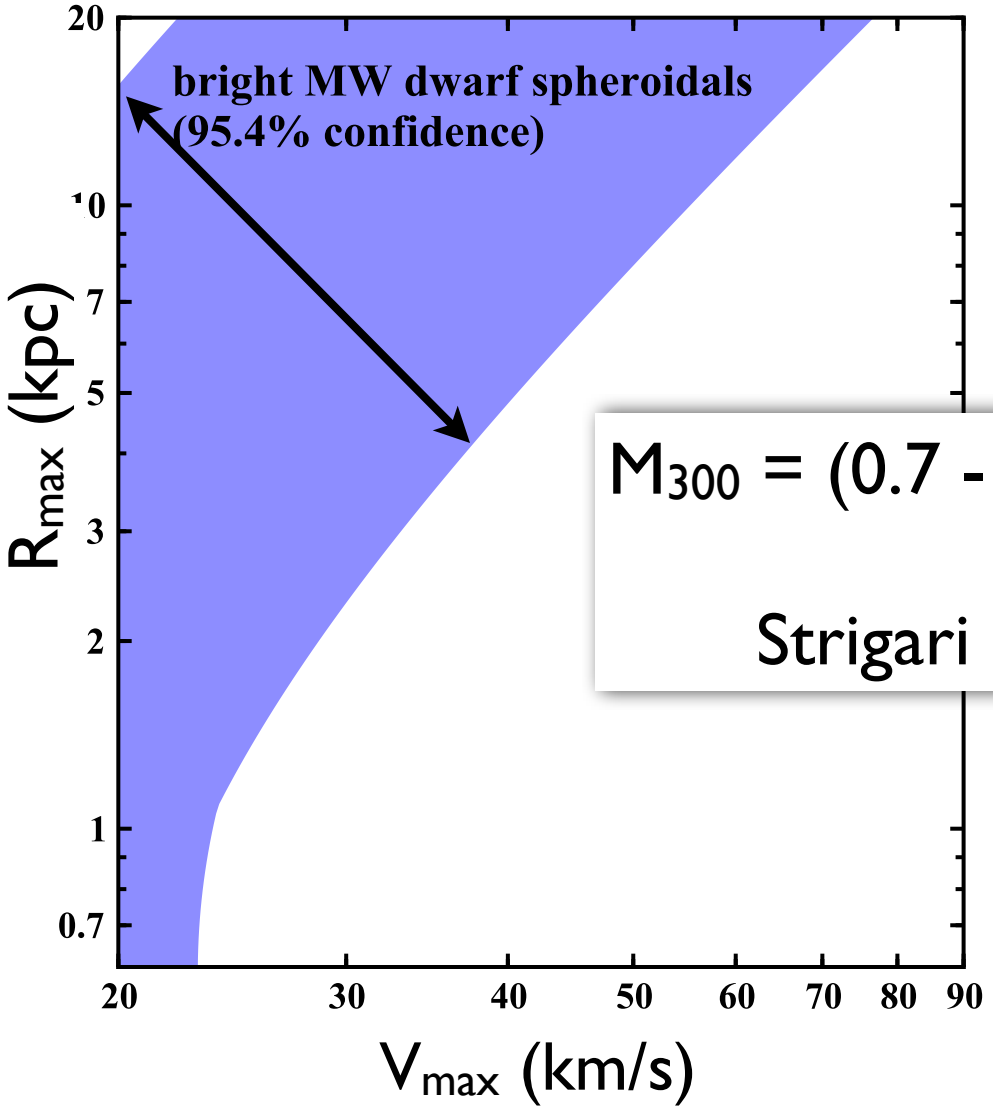
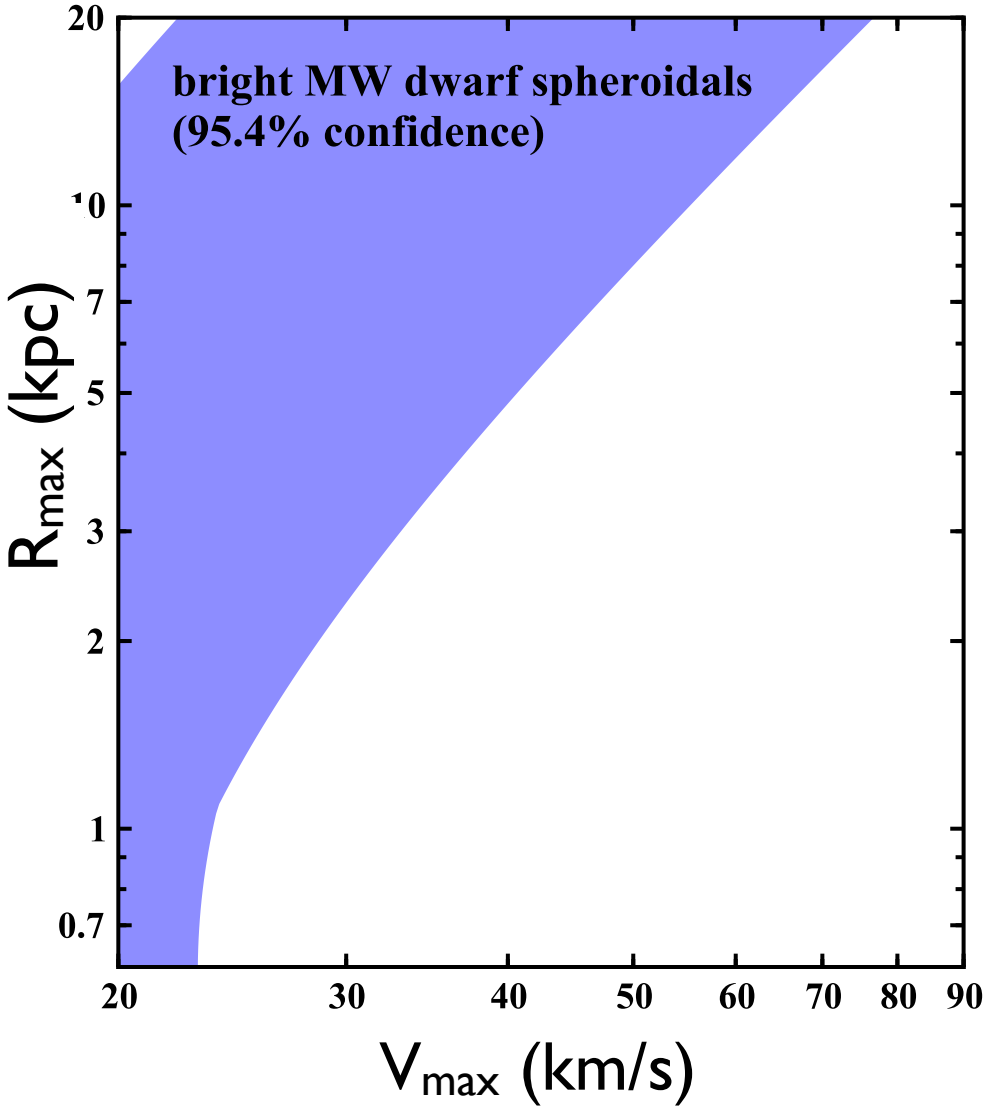


$M_{300} = (0.7 - 3.0) \times 10^7 M_{sun}$

Strigari et al. 2008

Boylan-Kolchin et al. 2011

Masses of Bright dSphs vs. Subhalos



Boylan-Kolchin et al. 2011

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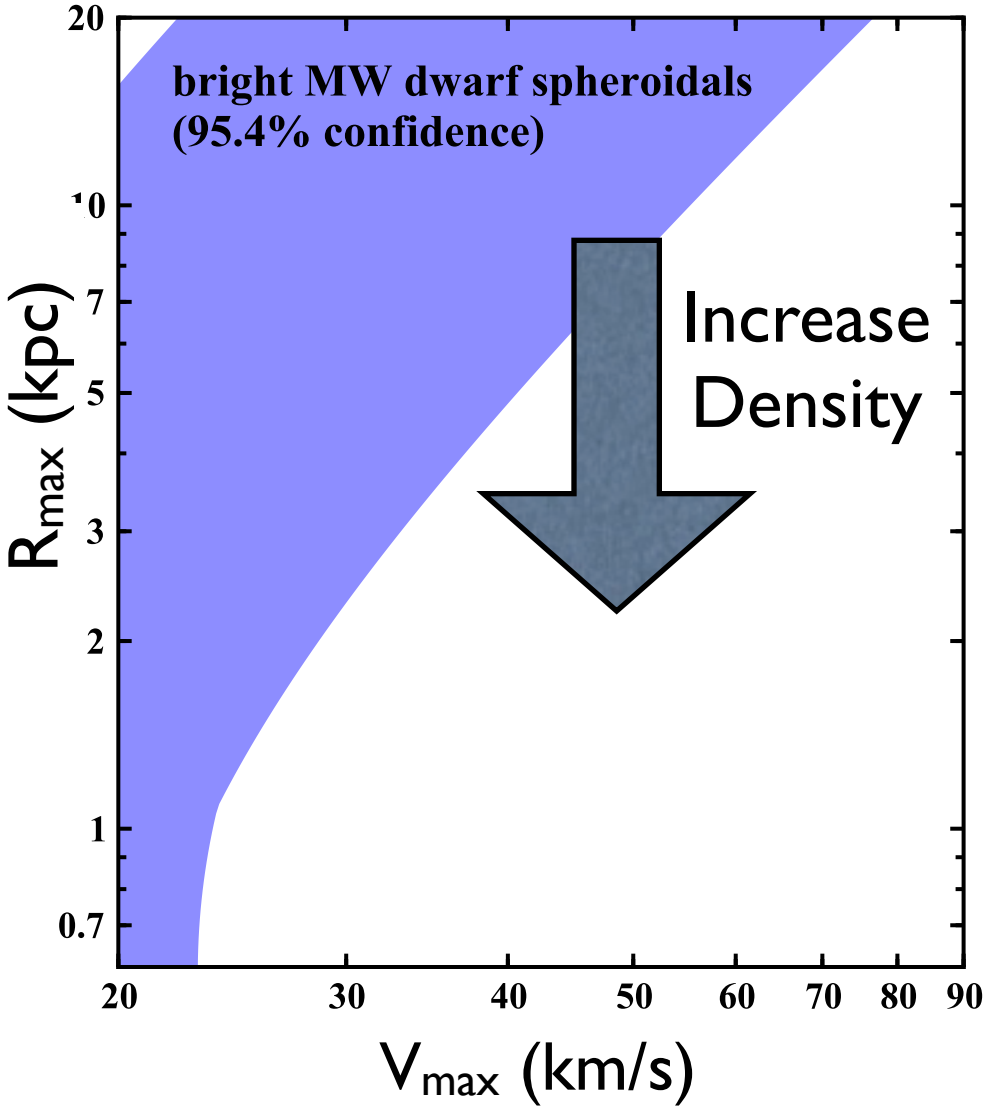
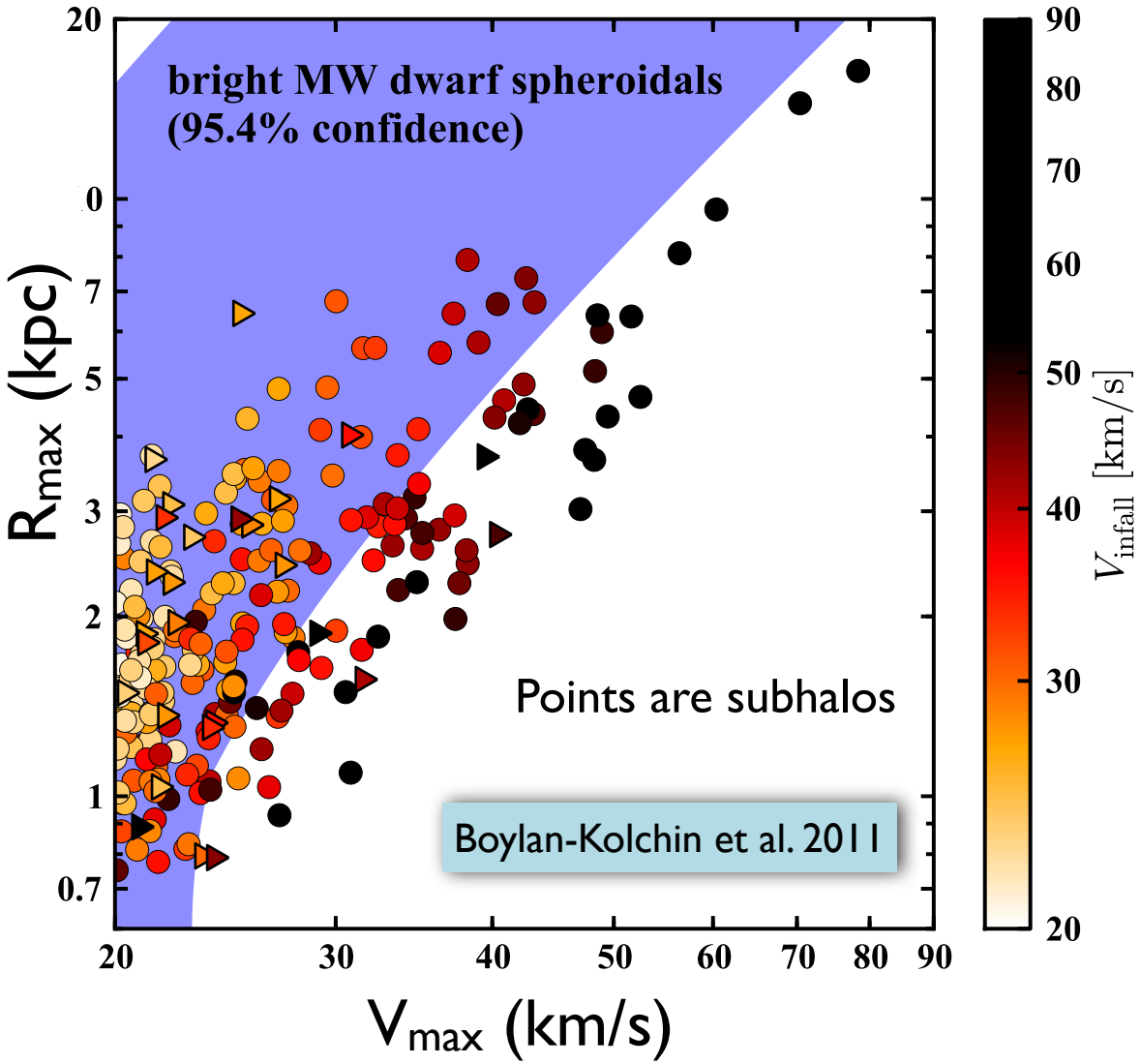


Boylan-Kolchin et al. 2011

Masses of Bright dSphs vs. Subhalos

seven simulations: six Aquarius + Via Lactea II



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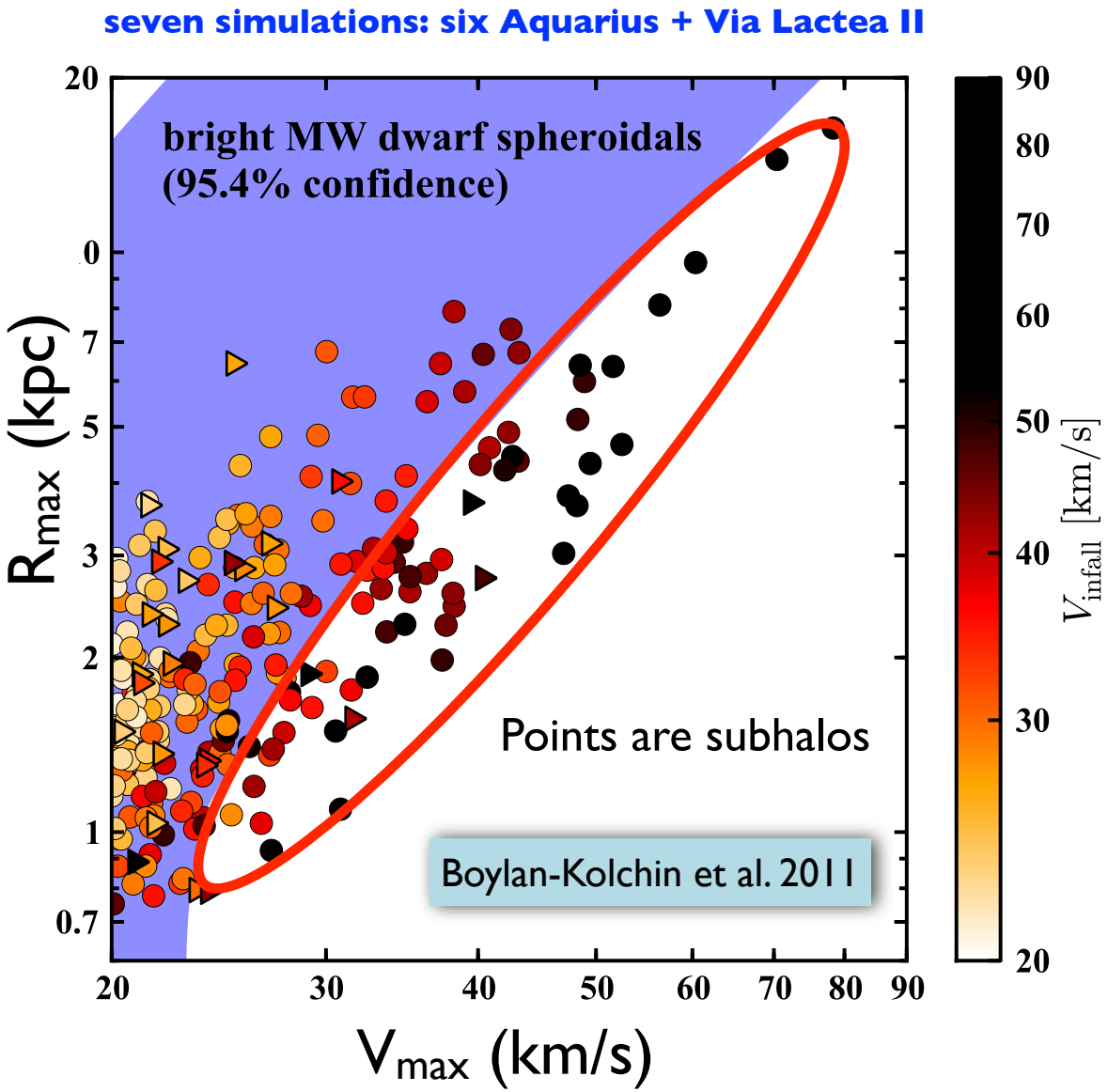

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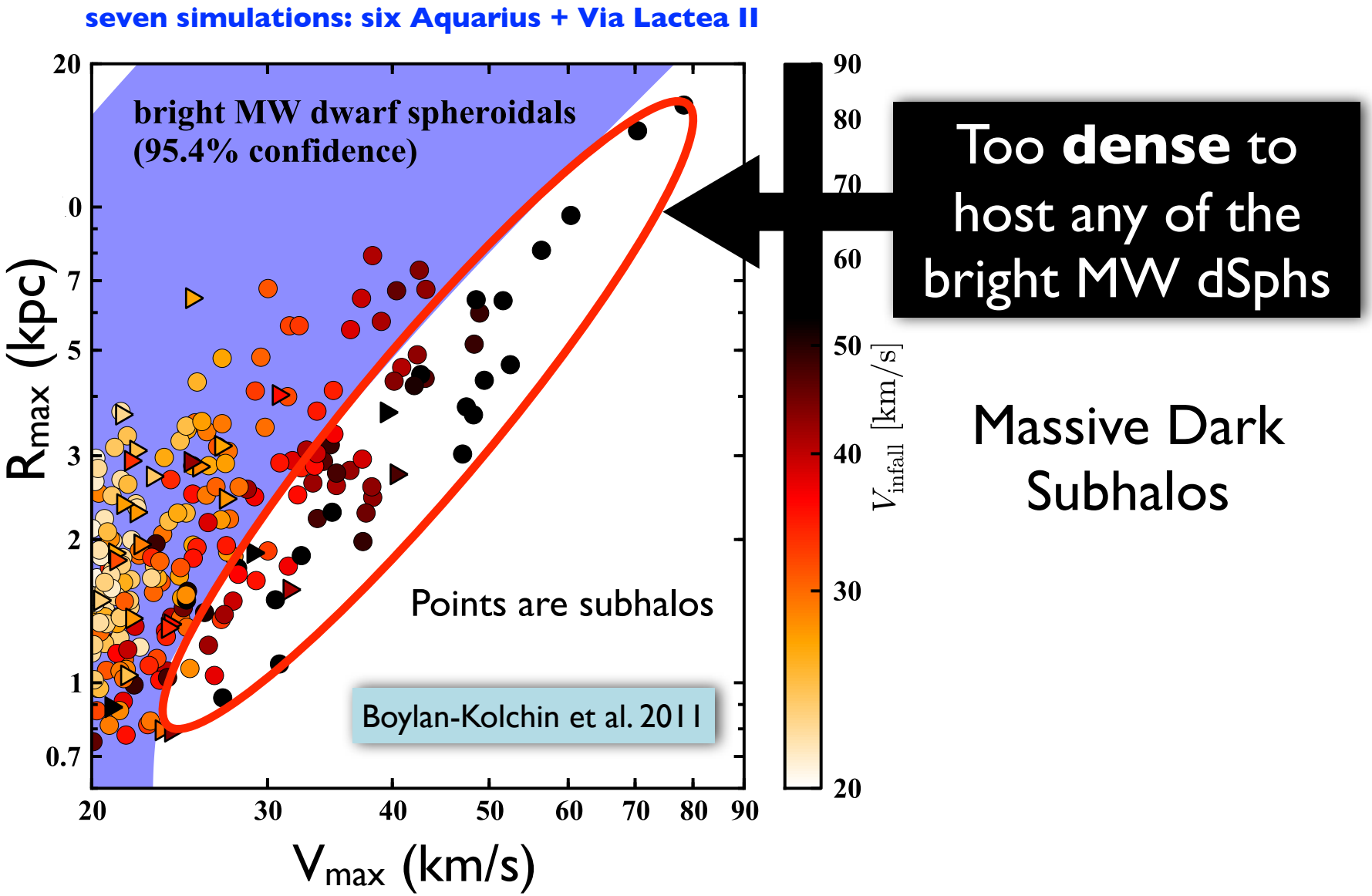

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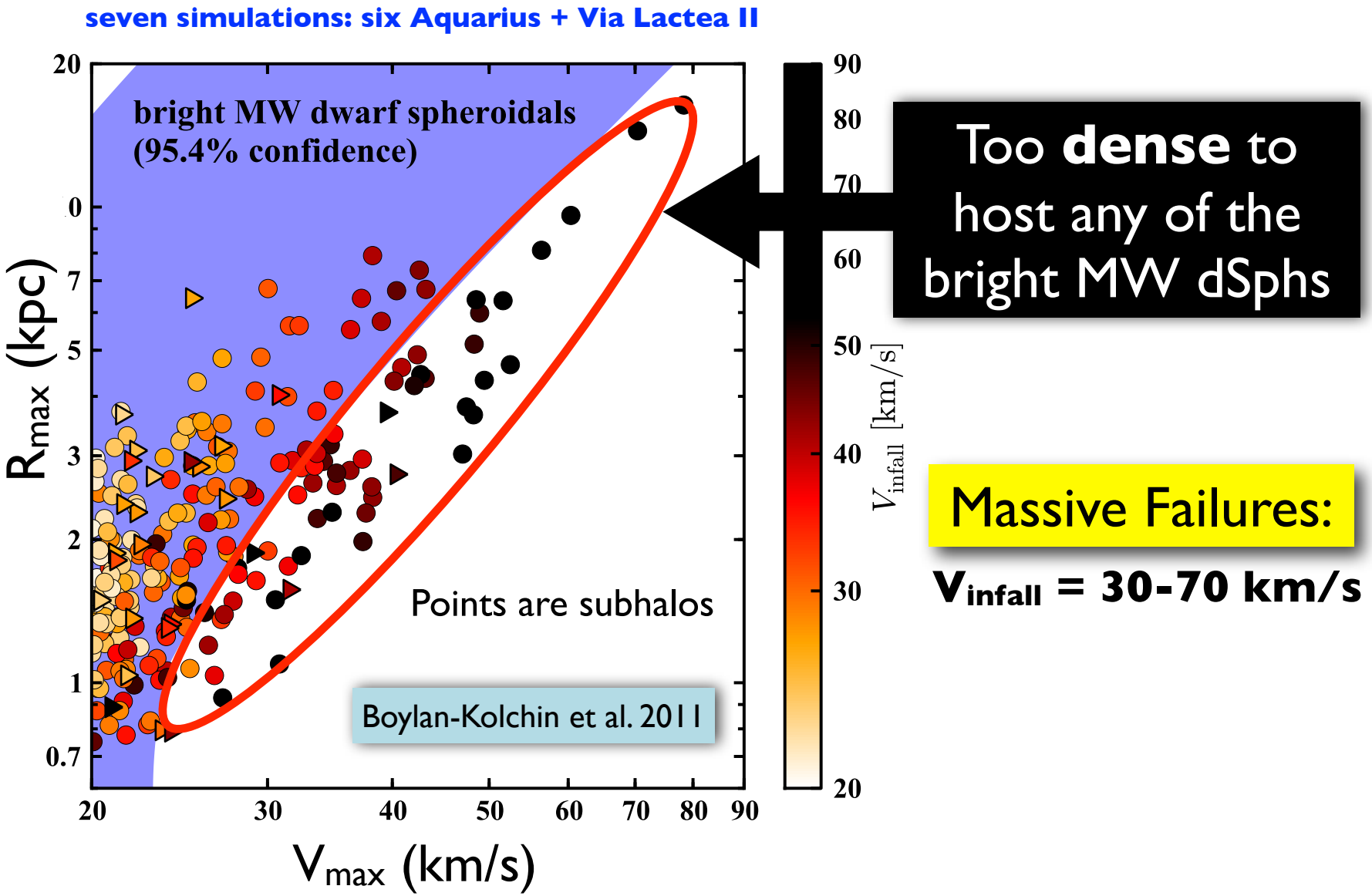
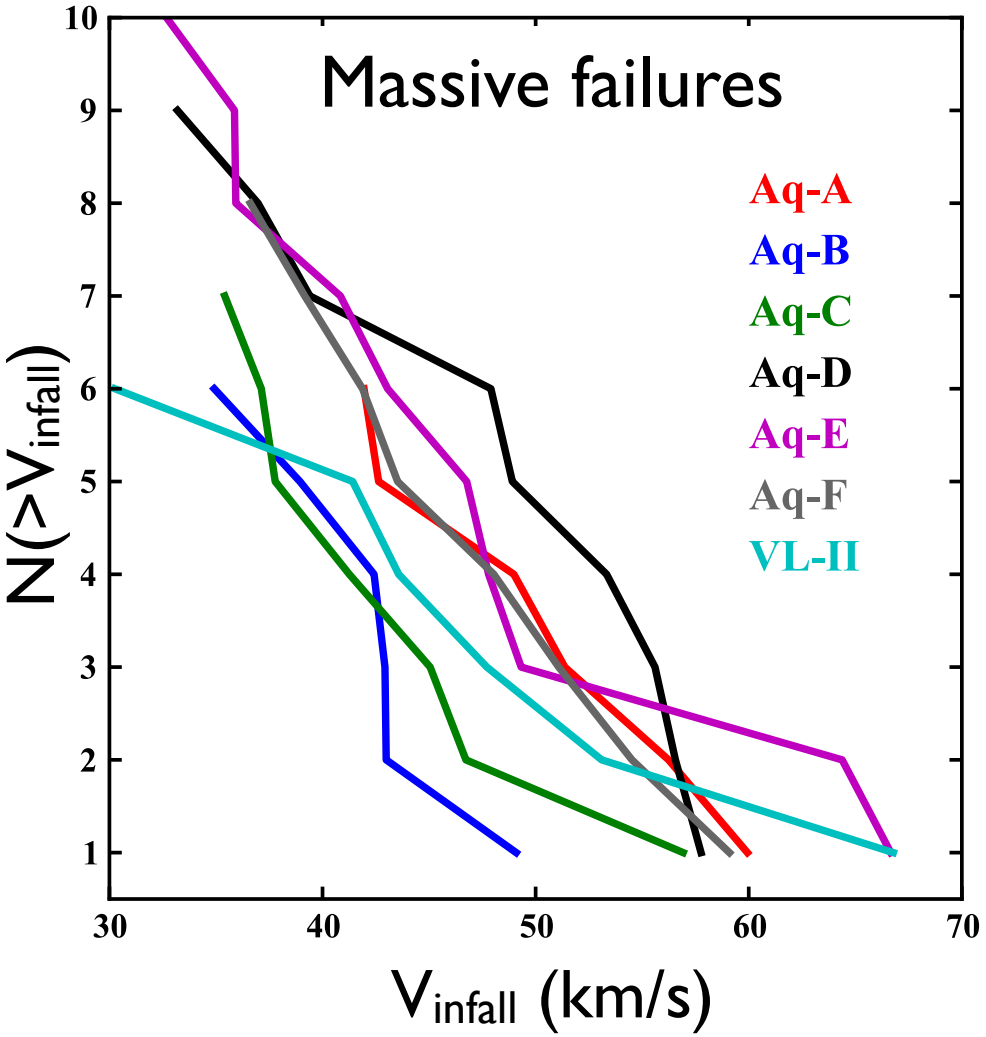


How Many Massive Failures?



Boylan-Kolchin et al. 2011

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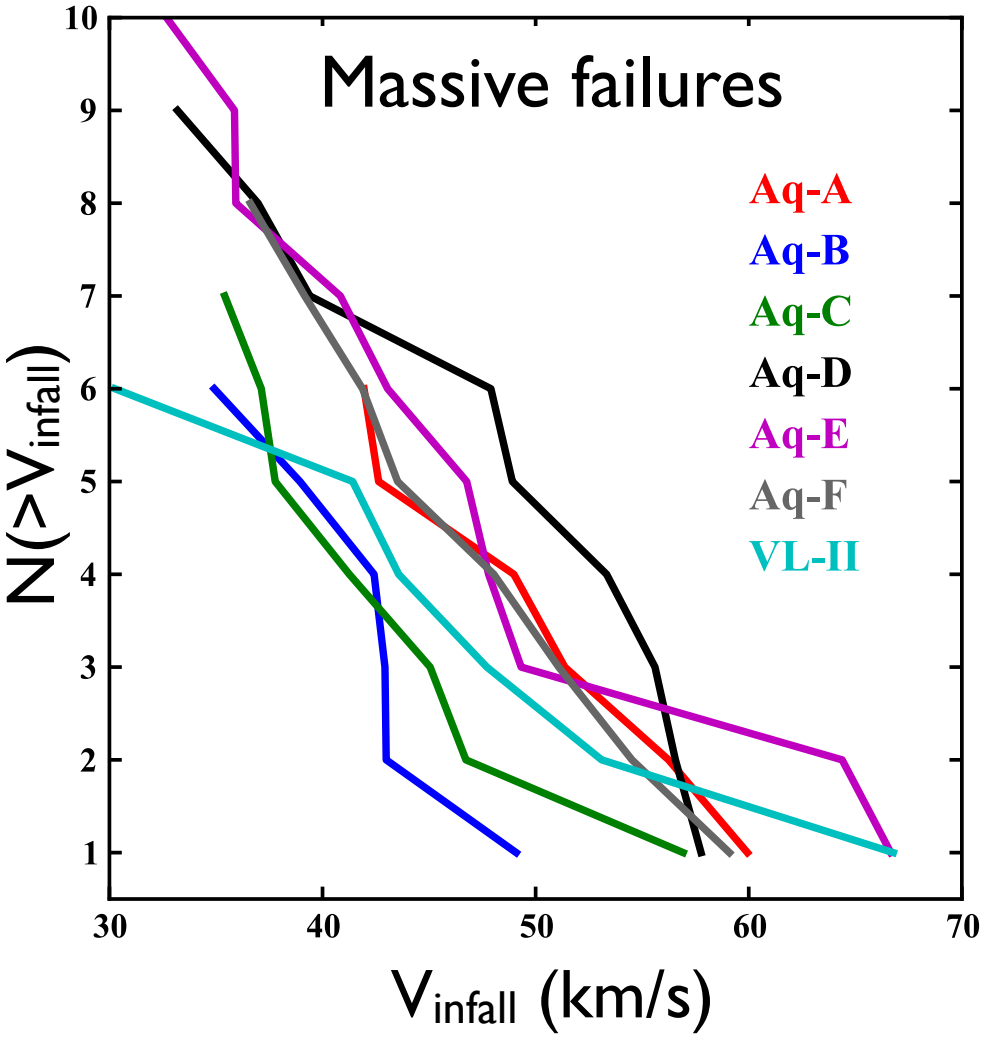


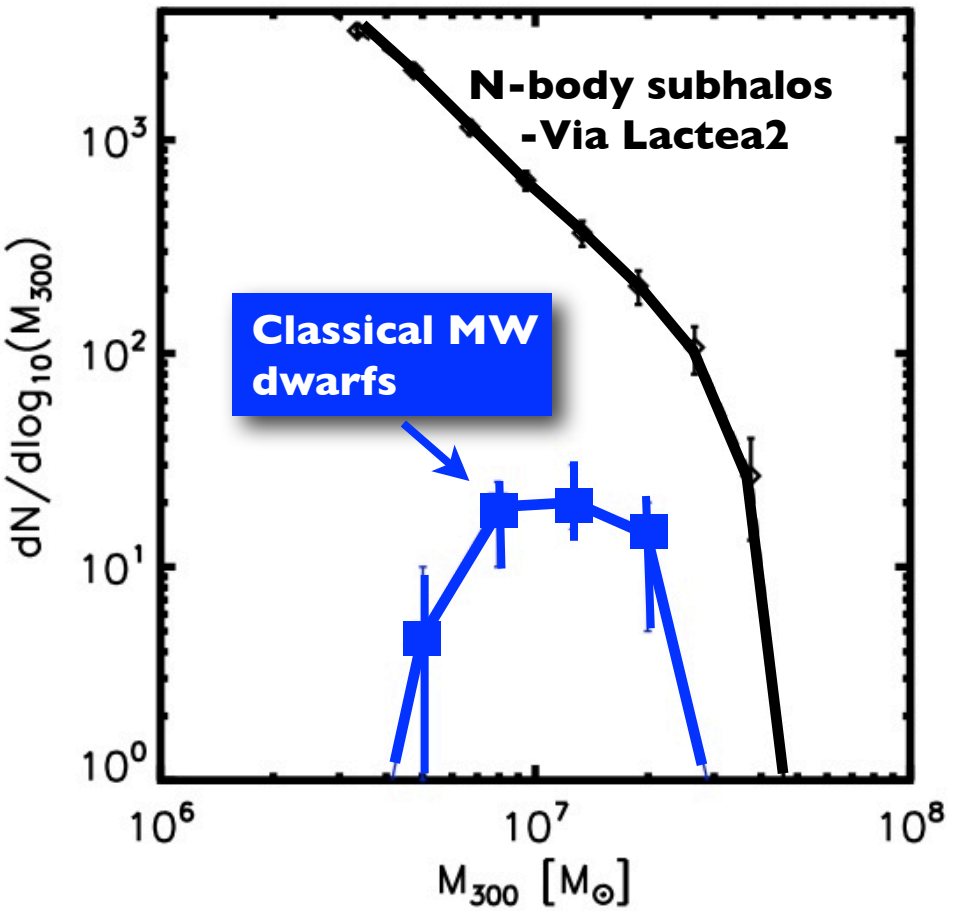
All 7 hosts have:
at least 6 dark subhalos with V_{infall}>30 km/s
at least 4 dark subhalos with V_{infall}>40 km/s

Note: Magellanic Cloud analogs already removed from this sample (Remove those with Vin>60 and Vnow>40)

Boylan-Kolchin et al. 2011

Mass within 300pc

Wolf et al. 2011



c.f. Strigari et al. 2008

Mass within 300pc

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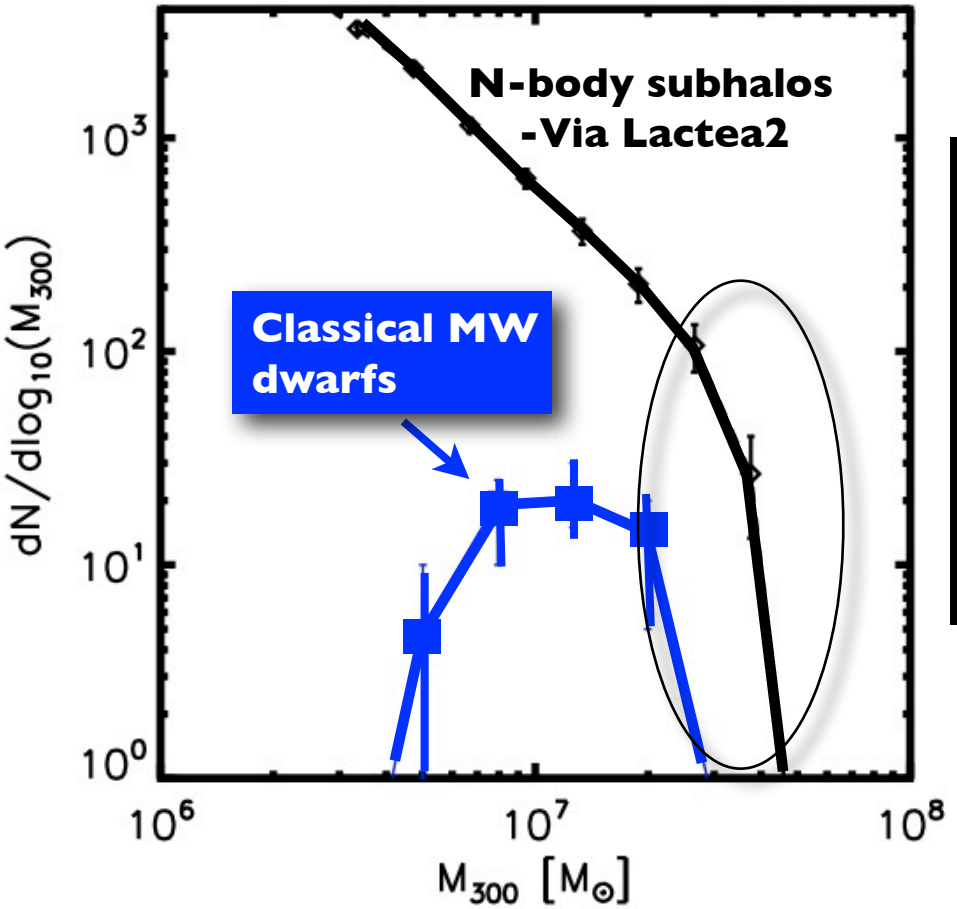

~8 massive subhalos unaccounted for among bright satellites.

c.f. Strigari et al. 2008

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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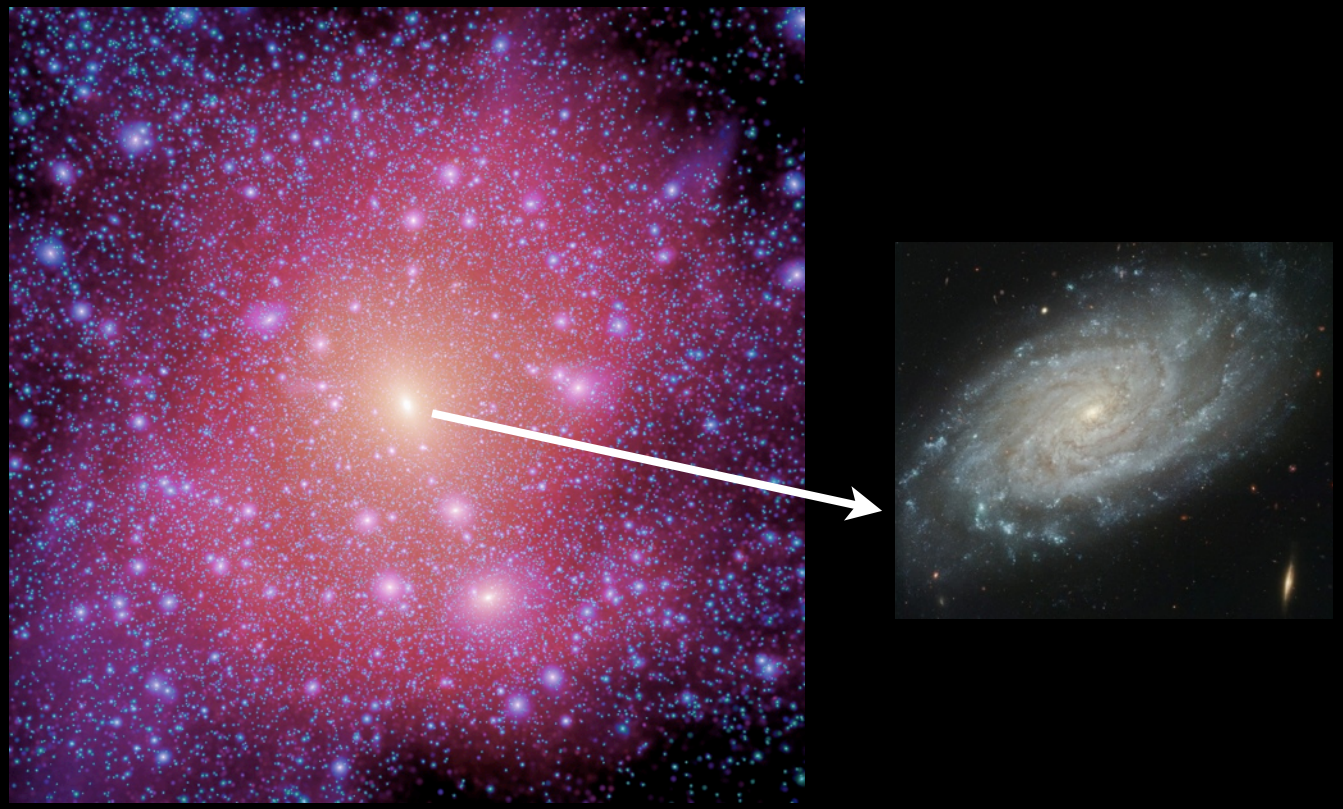

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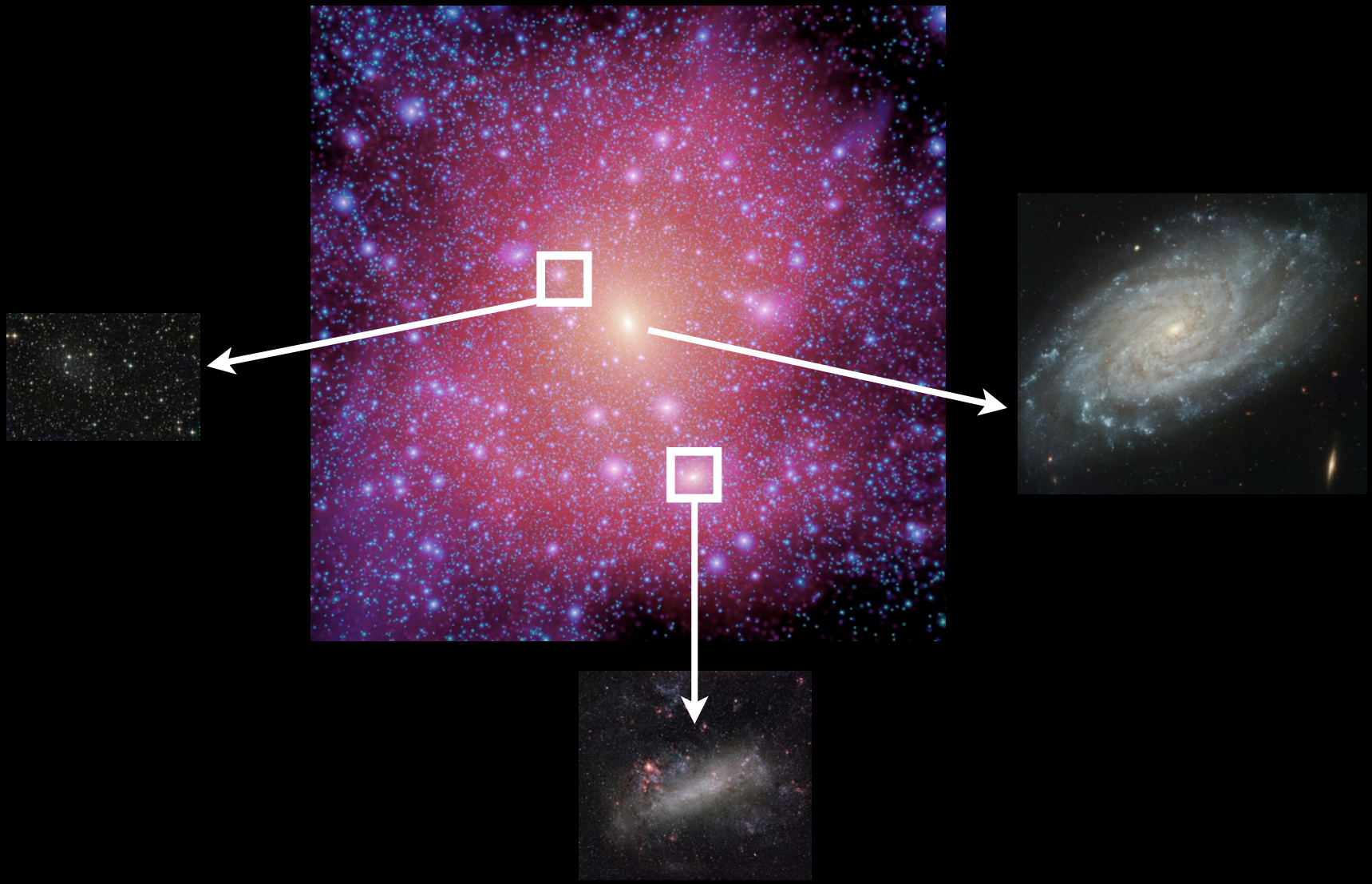

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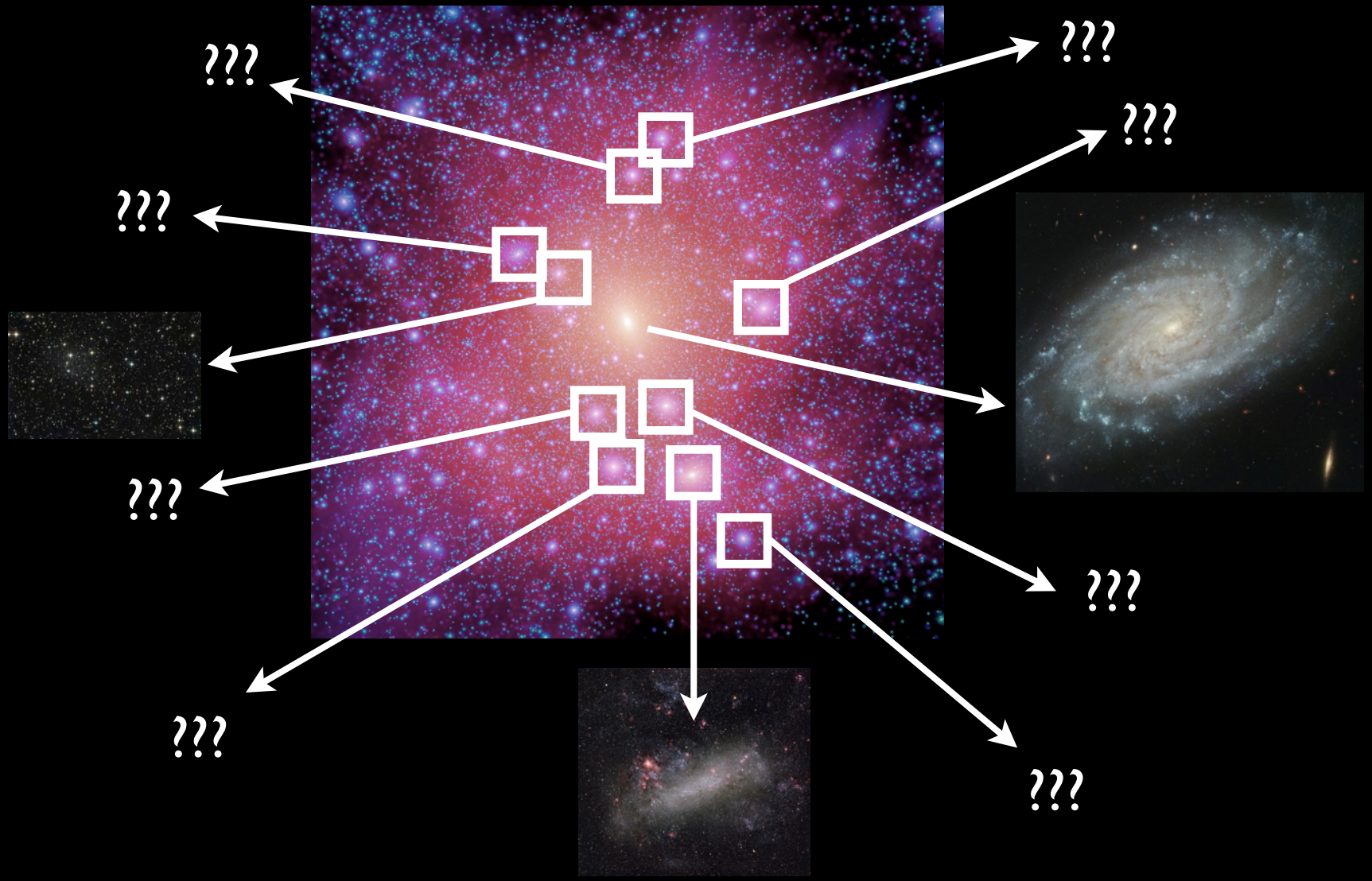
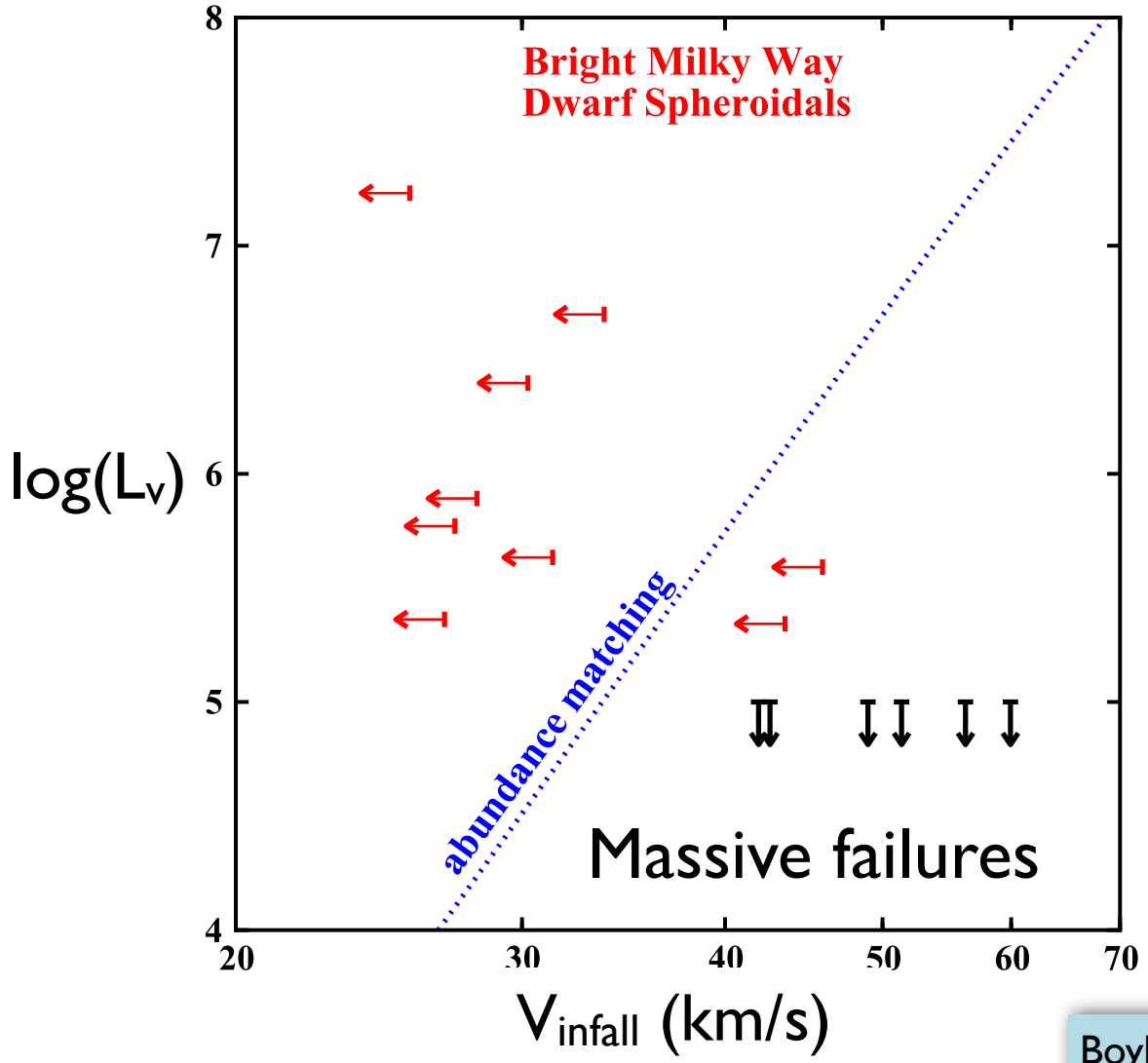


Image credits: V. Springel / Virgo Consortium; A. Riess / HST; W. Wang; AAO; M. Schirmer

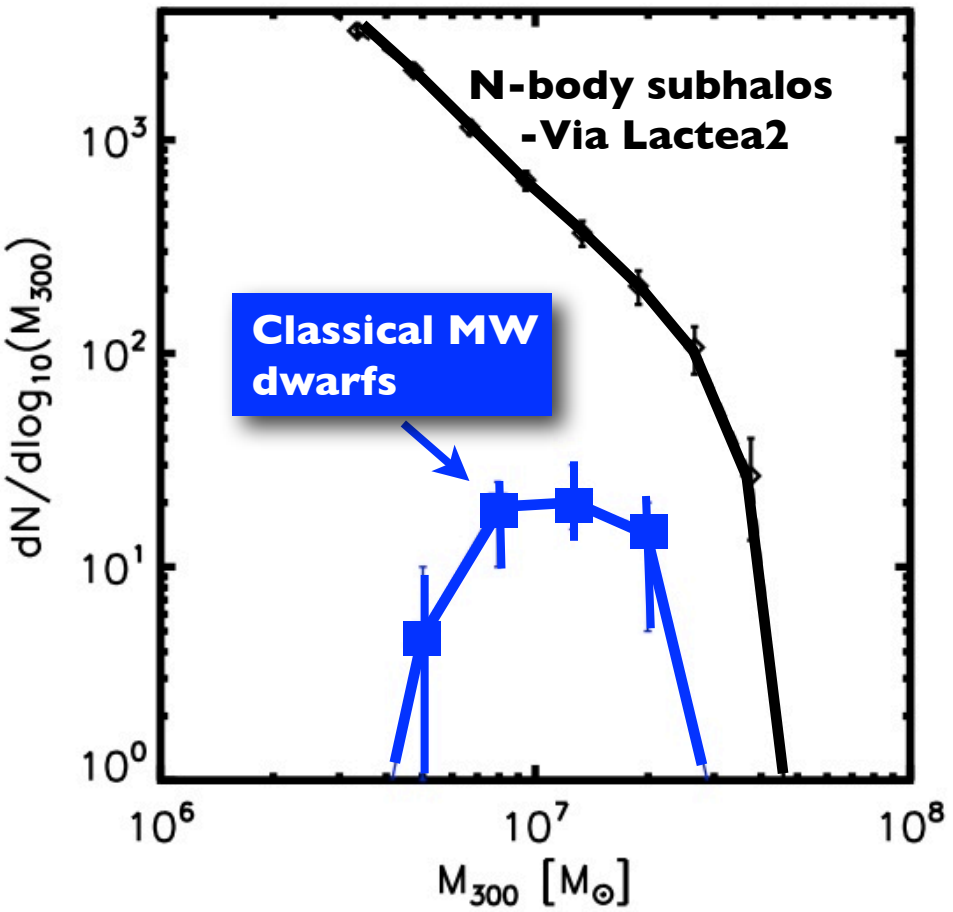
Stochastic Galaxy formation for V < 50km/s?



Boylan-Kolchin et al. 2011

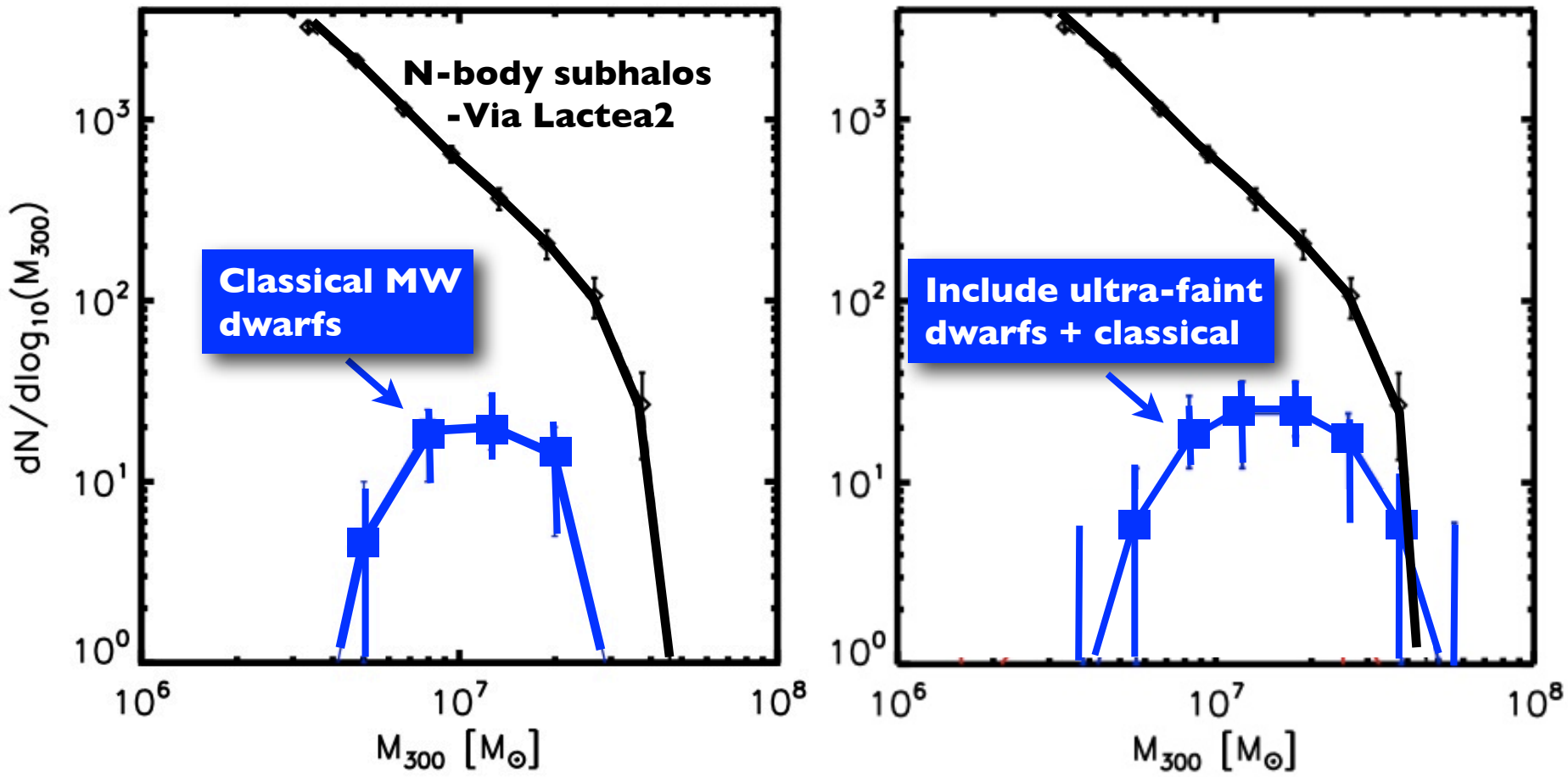
Mass within 300pc

Wolf et al. 2011



Mass within 300pc

Wolf et al. 2011

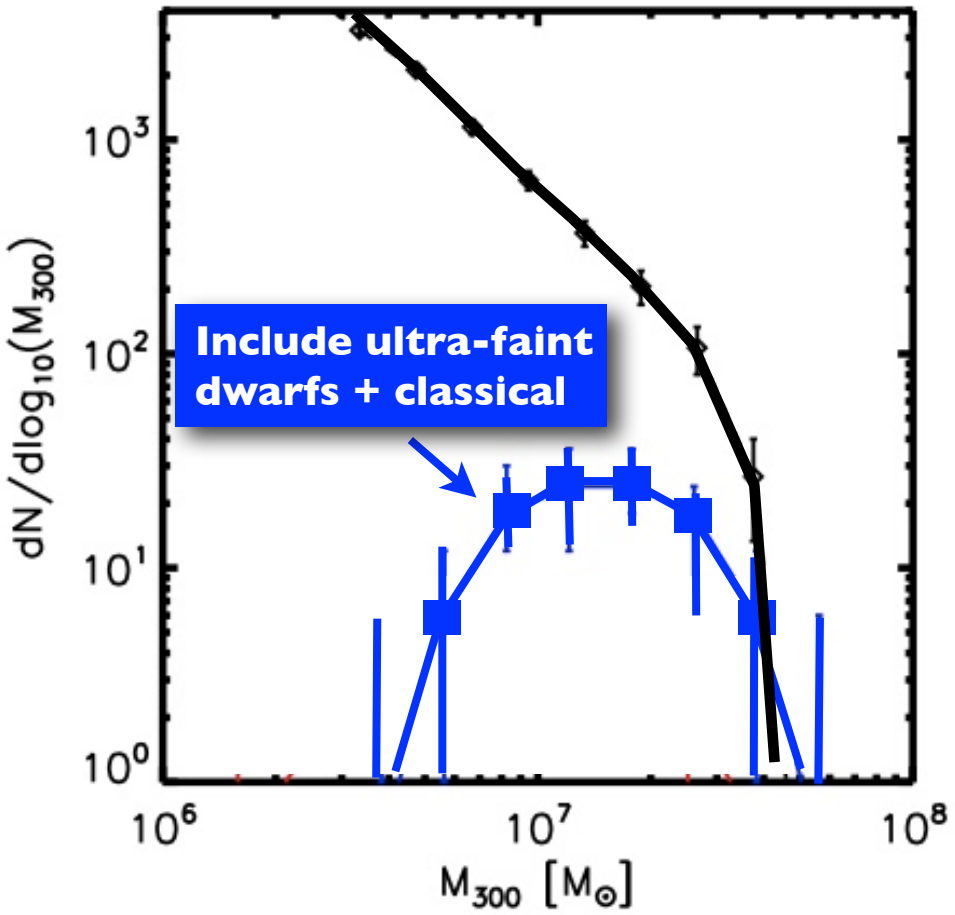


Mass within 300pc

Wolf et al. 2011

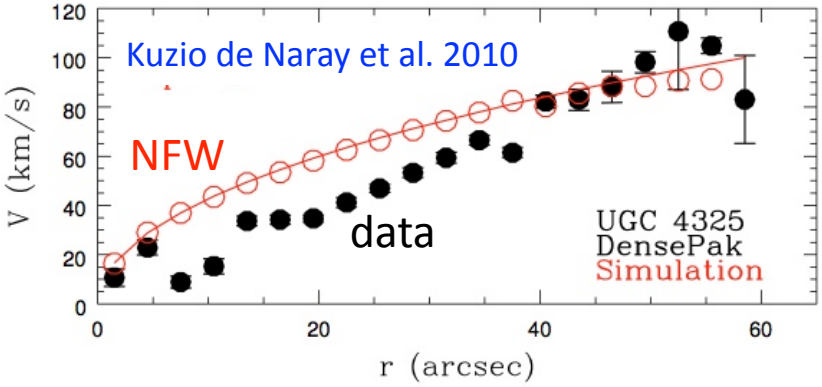
Given large mass uncertainties, ultrafaint dwarfs could sit within most MASSIVE subhalos.

Crazy?

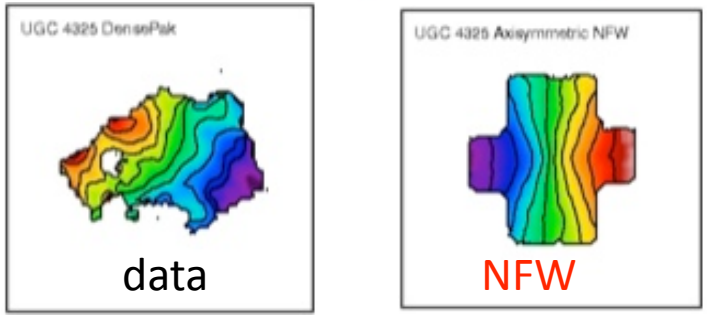


Connection with cusp/core problem in LCDM?

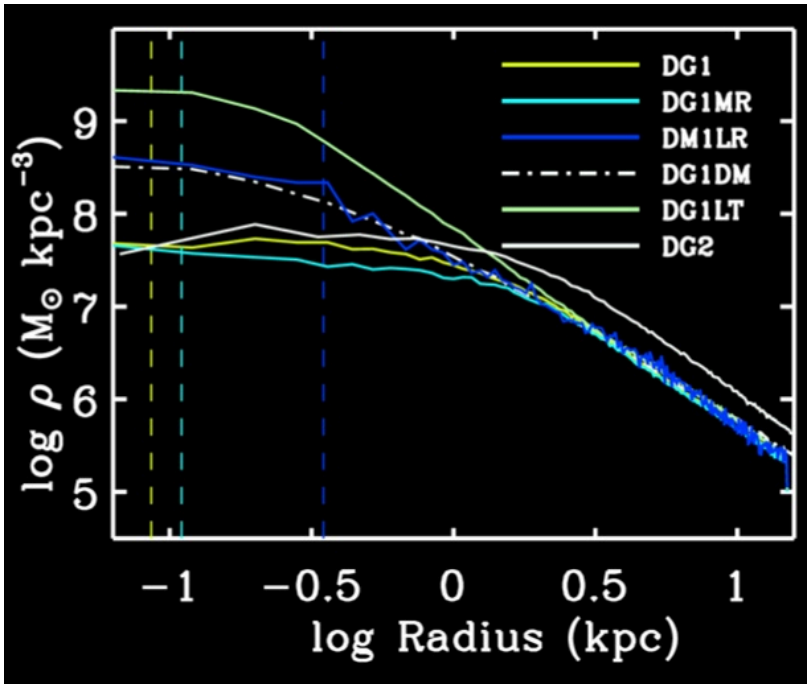
If massive subhalos had low-density cores, they could still host bright dwarfs.
- modify dark matter (self-interactions?)
- baryonic effects make cores?



cusps would be easily detected if present



LCDM + baryonic effects create cores?



Governato et al. 2010

See poster by Megan Jackson - NGC 1569

Conclusions & Discussion

- **Option 1**: massive dark subhalos **do** exist in the MW as predicted
  - Galaxy formation is stochastic for V < 50 km/s
  - Already found? Some ultra-faint galaxies could lie in these subhalos

Conclusions & Discussion

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  - the subhalo content of the Milky Way is anomalous compared to expectations
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  - MW disk has important effects on subhalo populations

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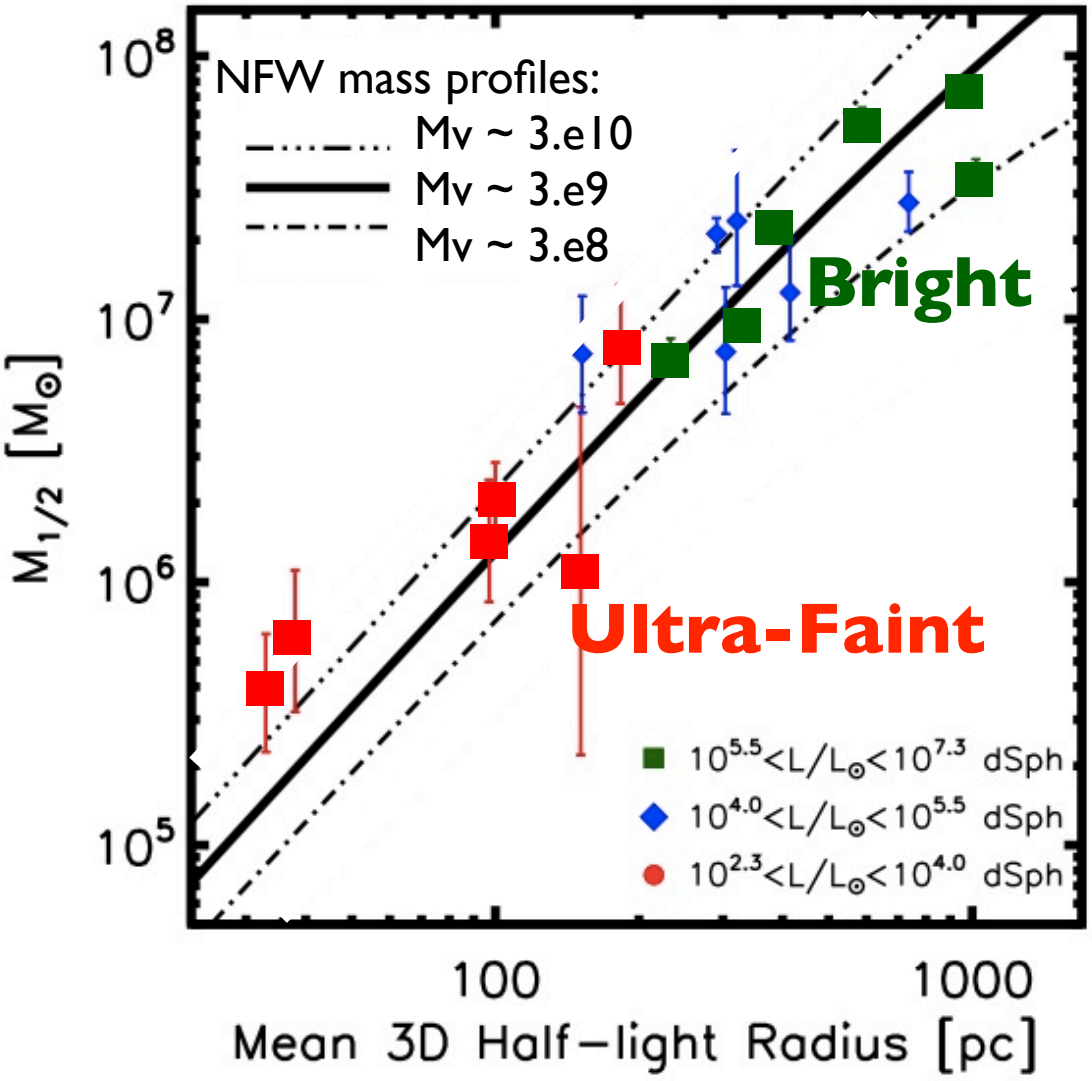
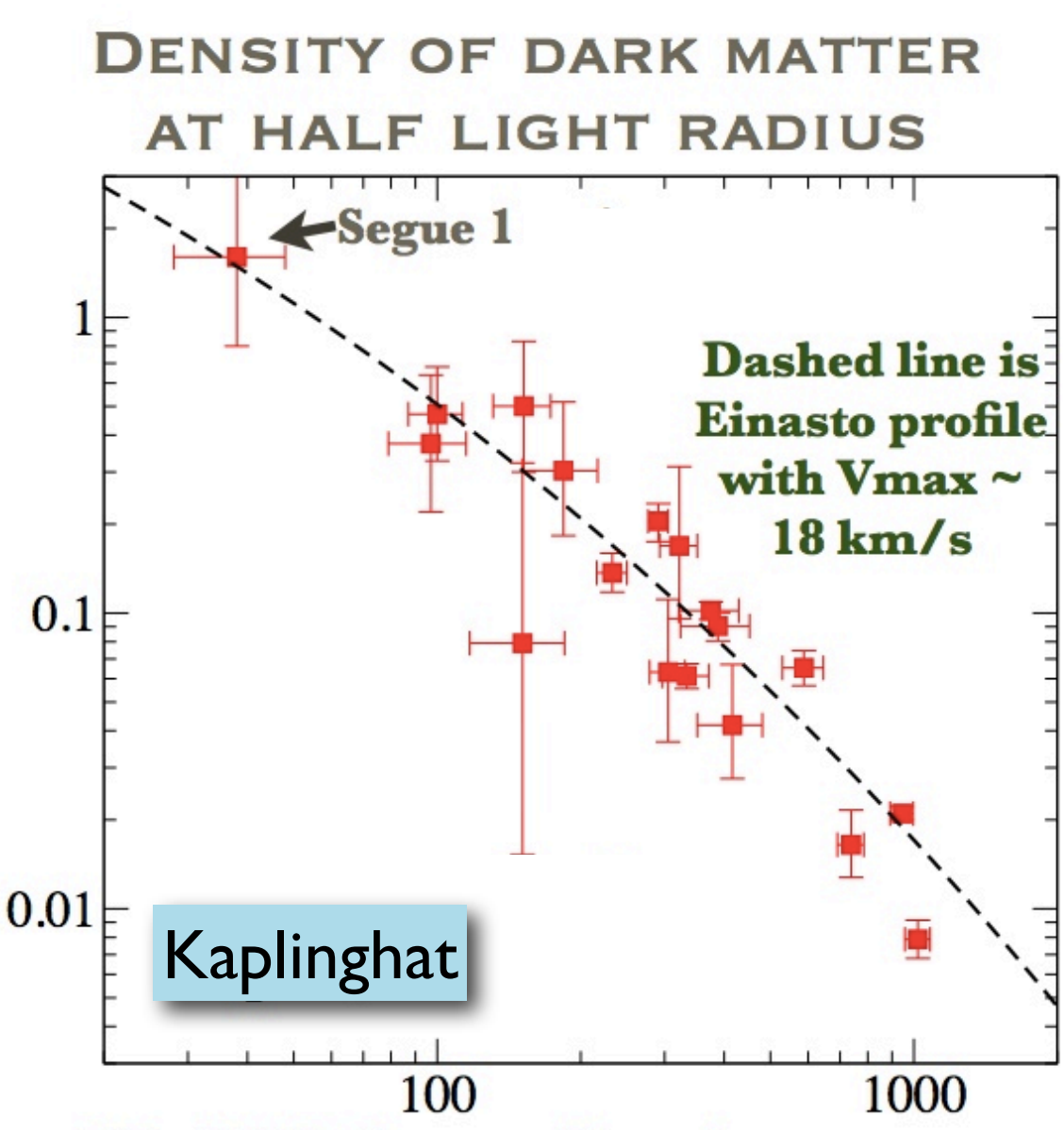
- **Option 3: No** massive dark subhalos in MW (modifications to ΛCDM)
  - dark matter is somewhat warm, characteristic suppression scale of ~40-50 km/s
  - dark matter has self-interactions
  - something else??

End

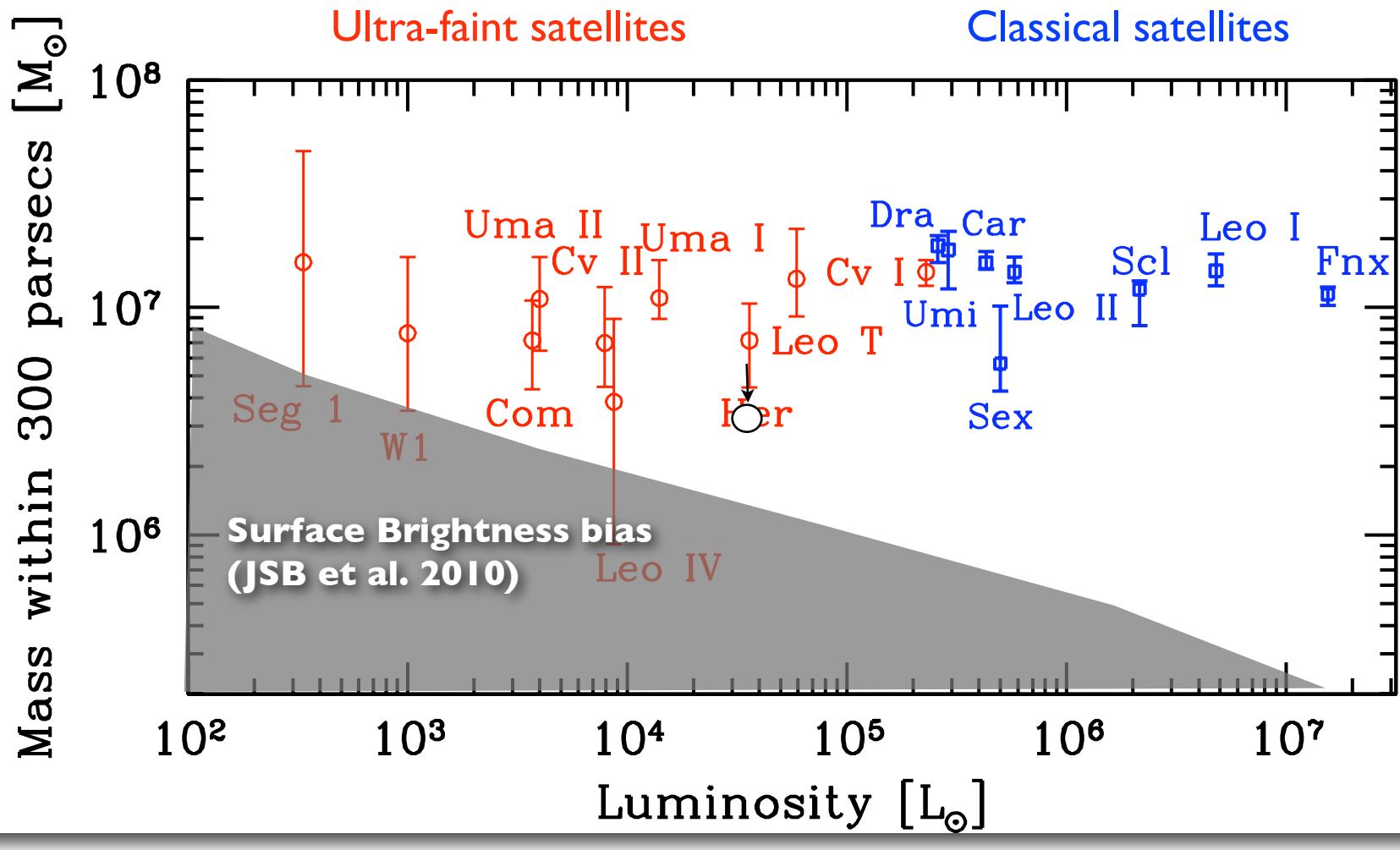
Bright and Faint Dwarfs Together



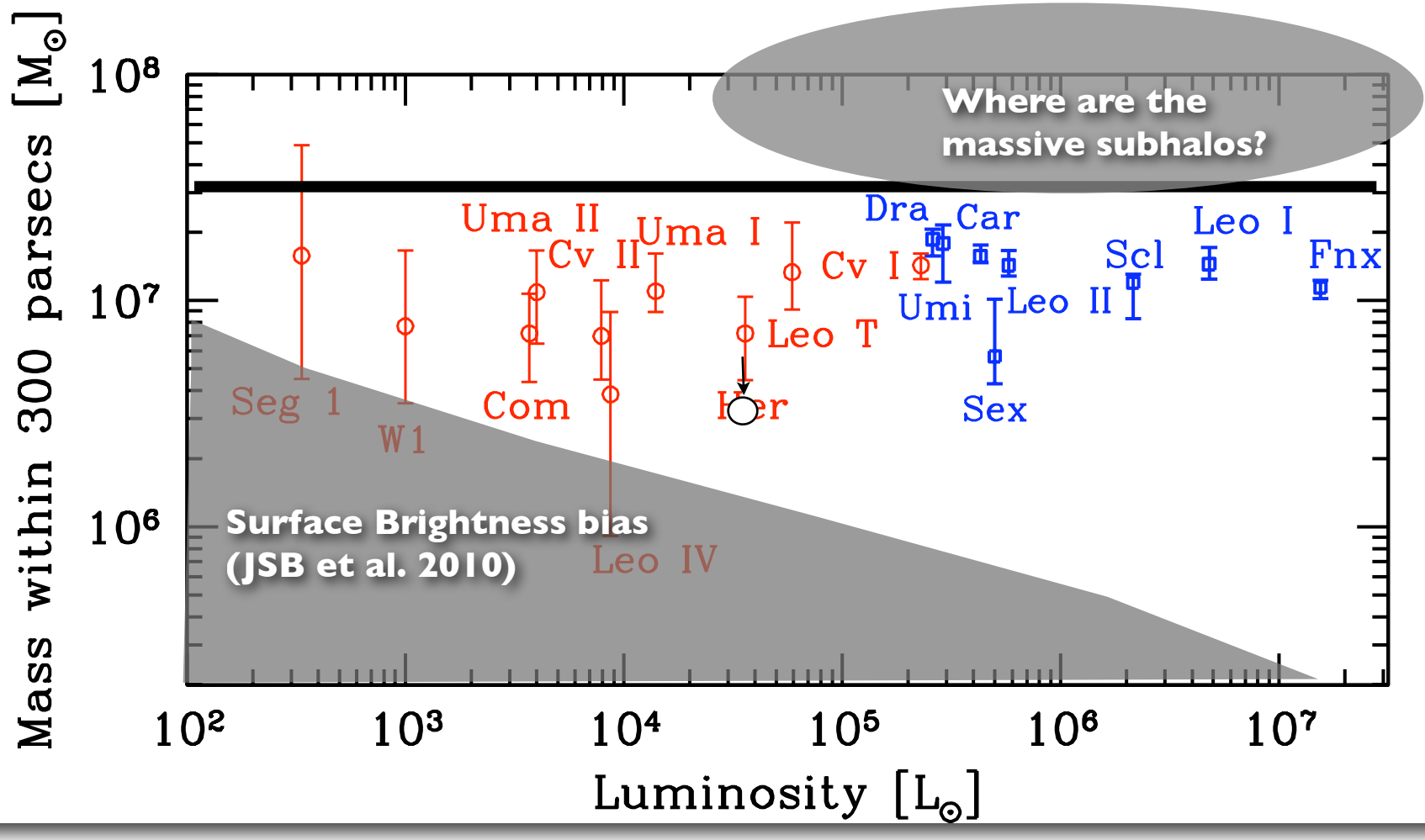
Wolf et al. 2010

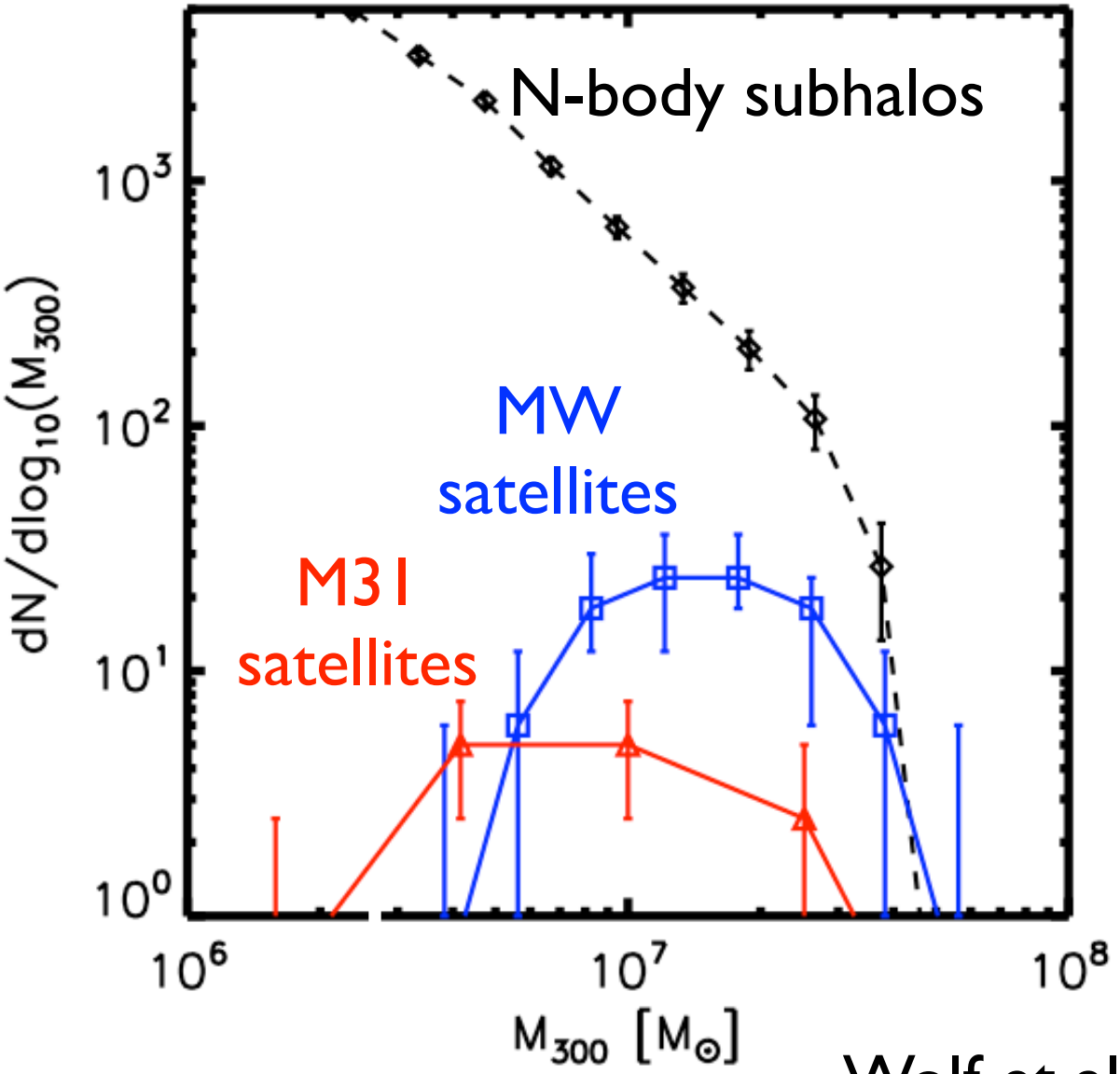

DENSITY OF DARK MATTER
AT HALF LIGHT RADIUS
Segue 1
Dashed line is
Einasto profile
with Vmax ~
18 km/s
Kaplinghat
1
0.1
0.01
100
1000
Ave.
Density
M_{sun}/pc^3
Half light radius (pc)

Strigari et al. 2008



Strigari et al. 2008



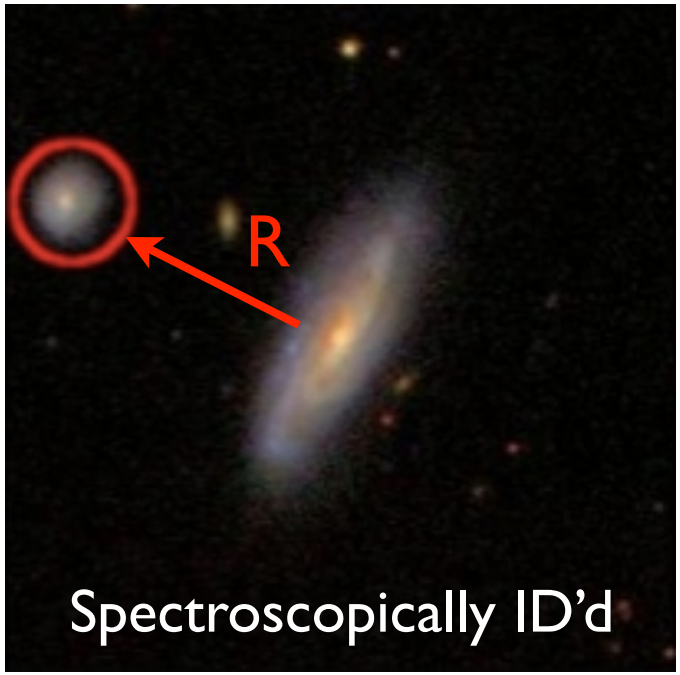


Wolf et al., in prep.

Tollerud et al. 2011

~0.1 L_* satellites within ~L_* galaxy halos

Abazajian et al. 2009

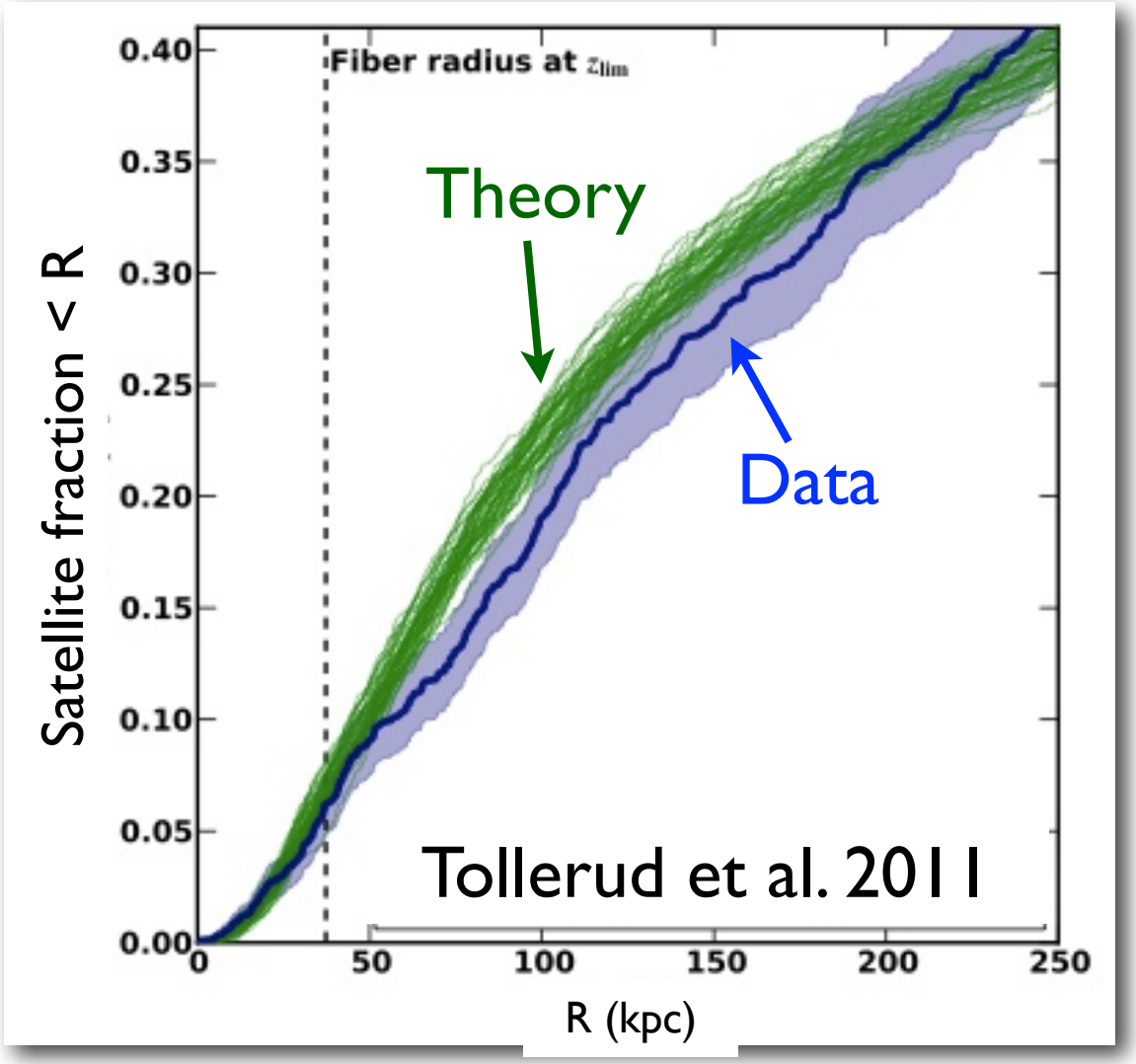


Boylan-Kolchin et al. 2010

Volume-Lim. SDSS for ~0.1 L* satellites (z<.034)
Around isolated L* galaxies (not in clusters)

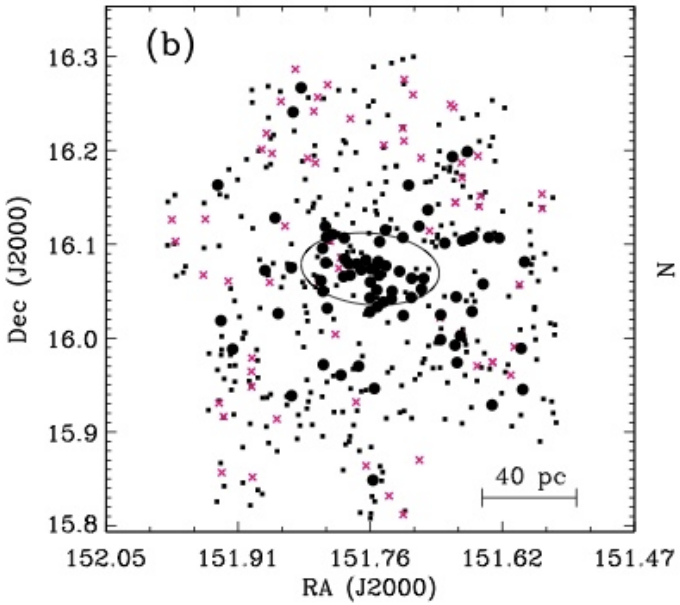
Mill II simulation "observed" like SDSS sample

40% of ~L* galaxies have a ~0.1L* satellite within 250 kpc



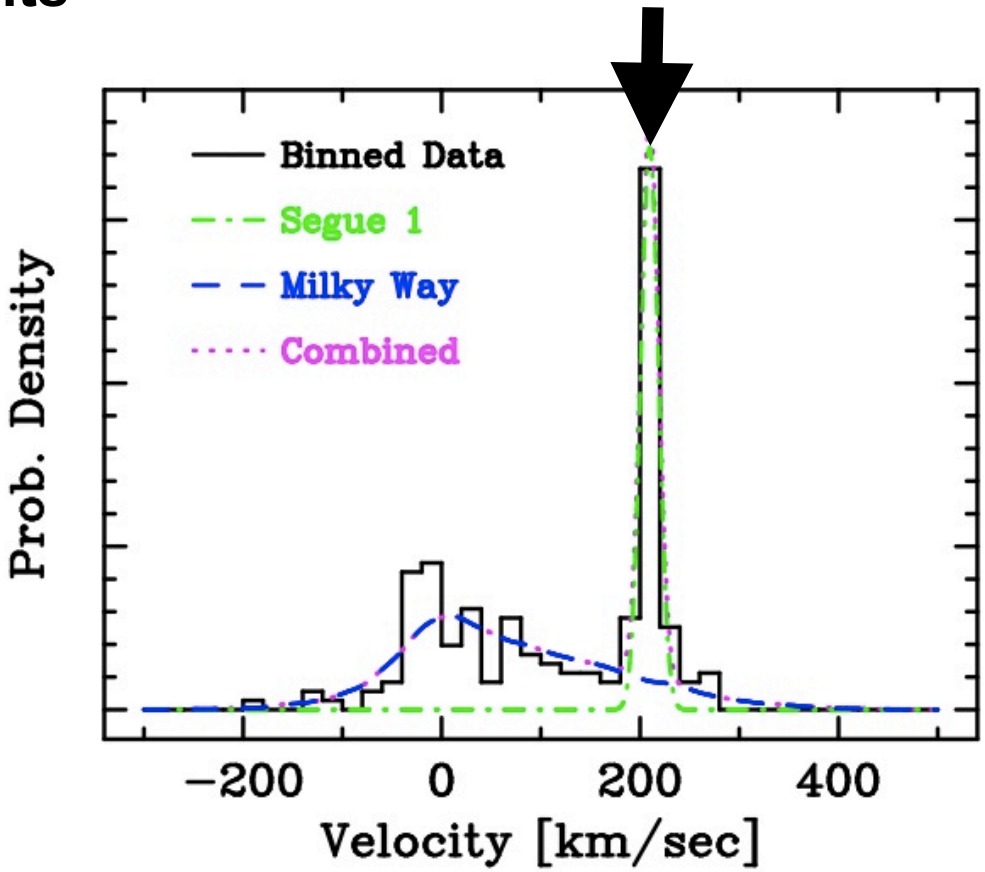
Kinematic Sample: Segue 1

181 candidate member stars
67 have repeat measurements



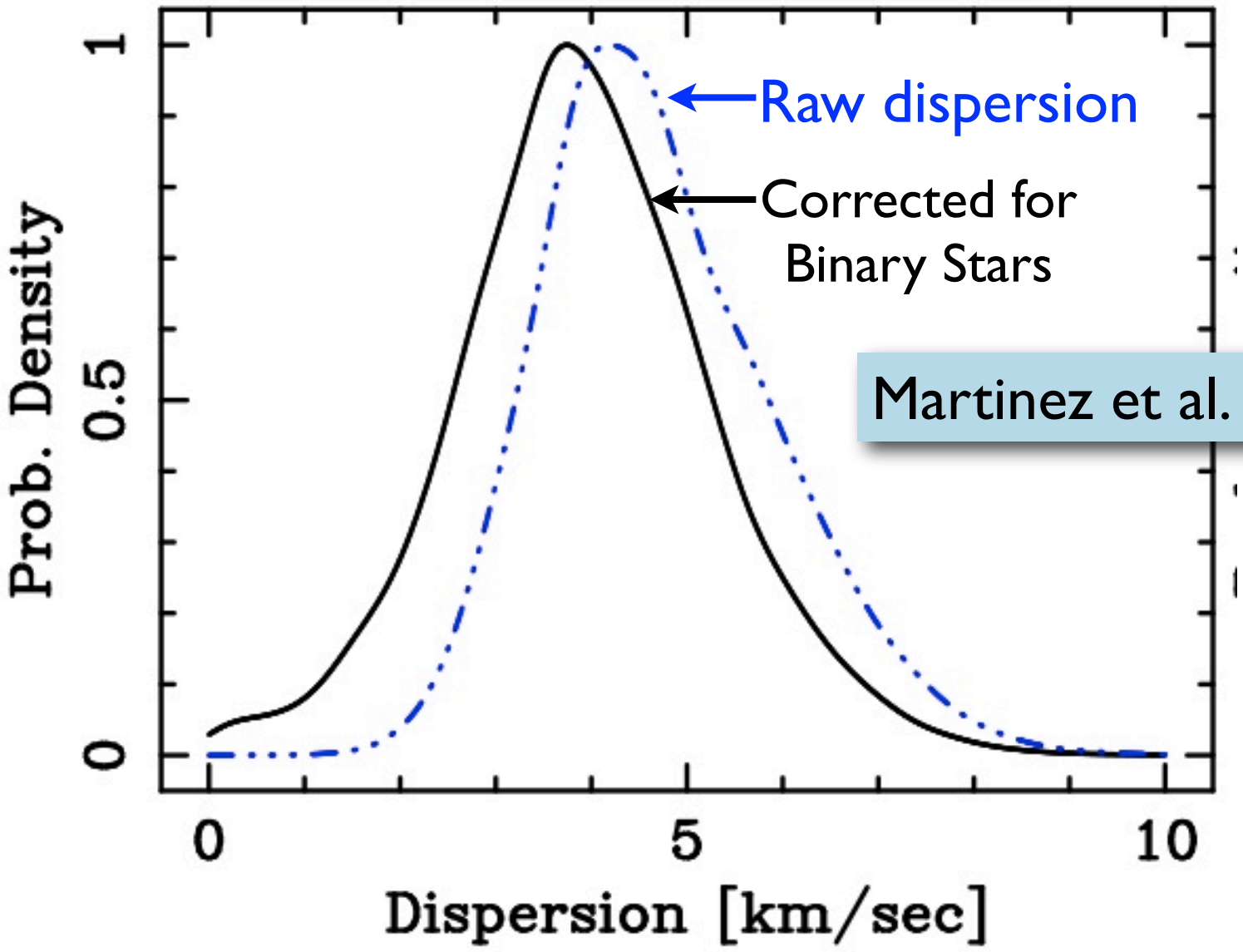
Simon et al. 2010

$\sigma_* \simeq 5\mathrm{km/s}$



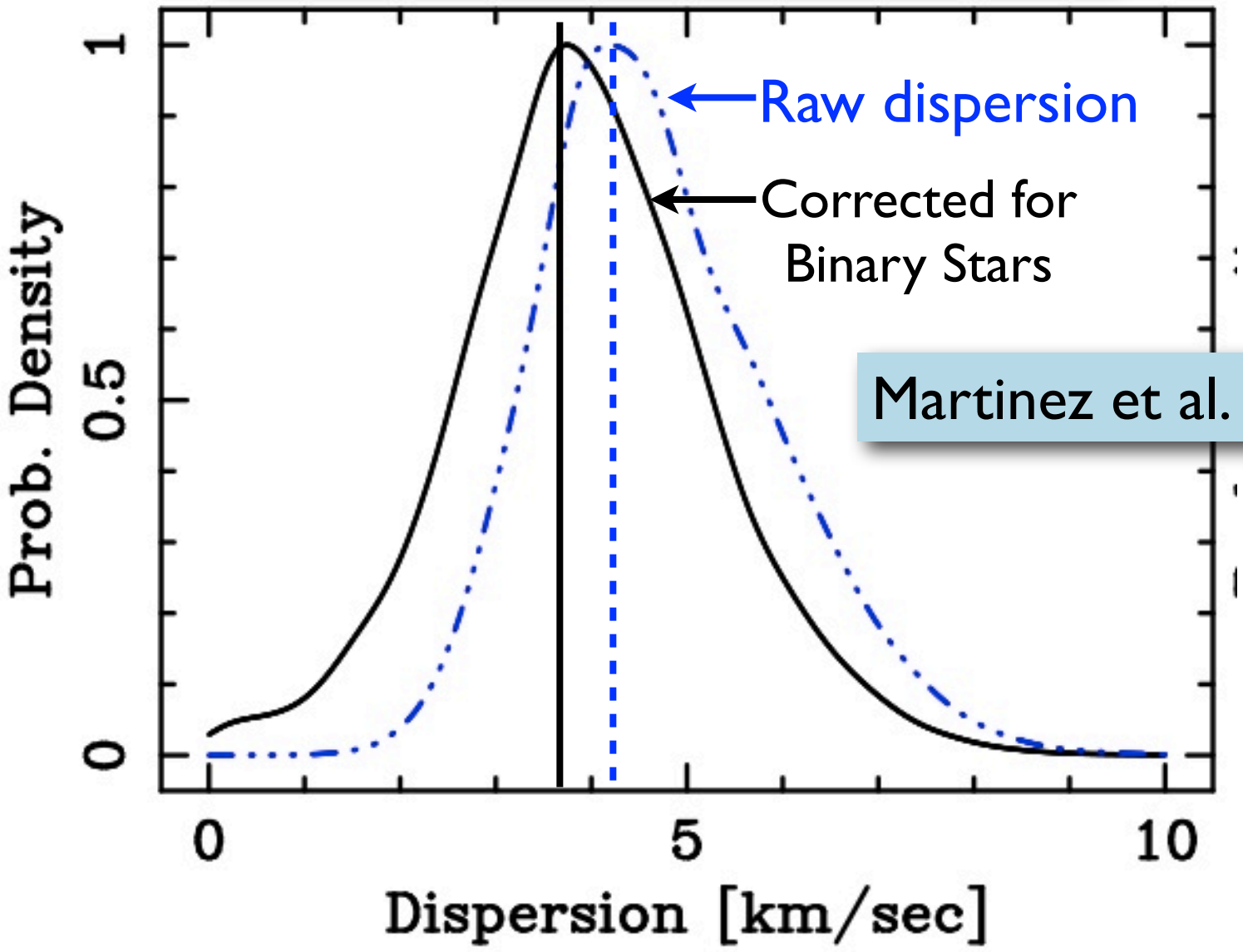
Martinez et al. 2010

14 Parameter Bayesian Analysis



Martinez et al. 2010

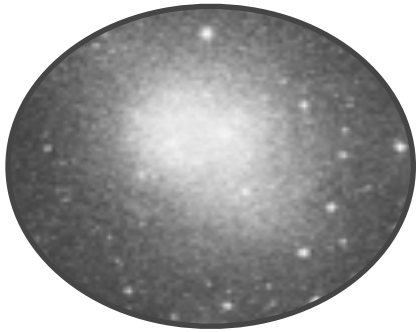
Binary Stars of Minimal Importance



Martinez et al. 2010

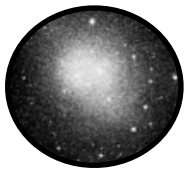
Stealth Galaxies? Surface Brightness & Mass Bias

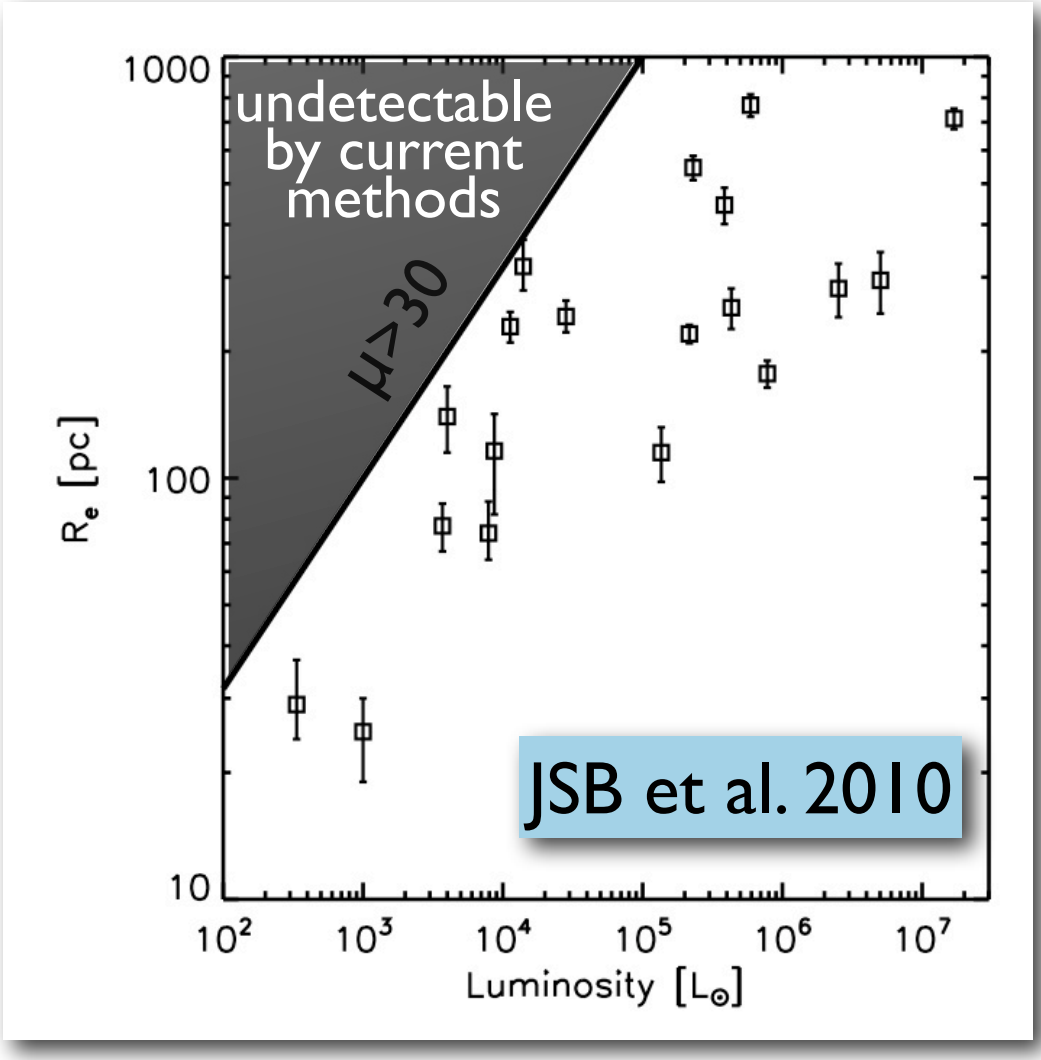
Less Massive Halo



For a fixed velocity dispersion and luminosity

Massive Halo

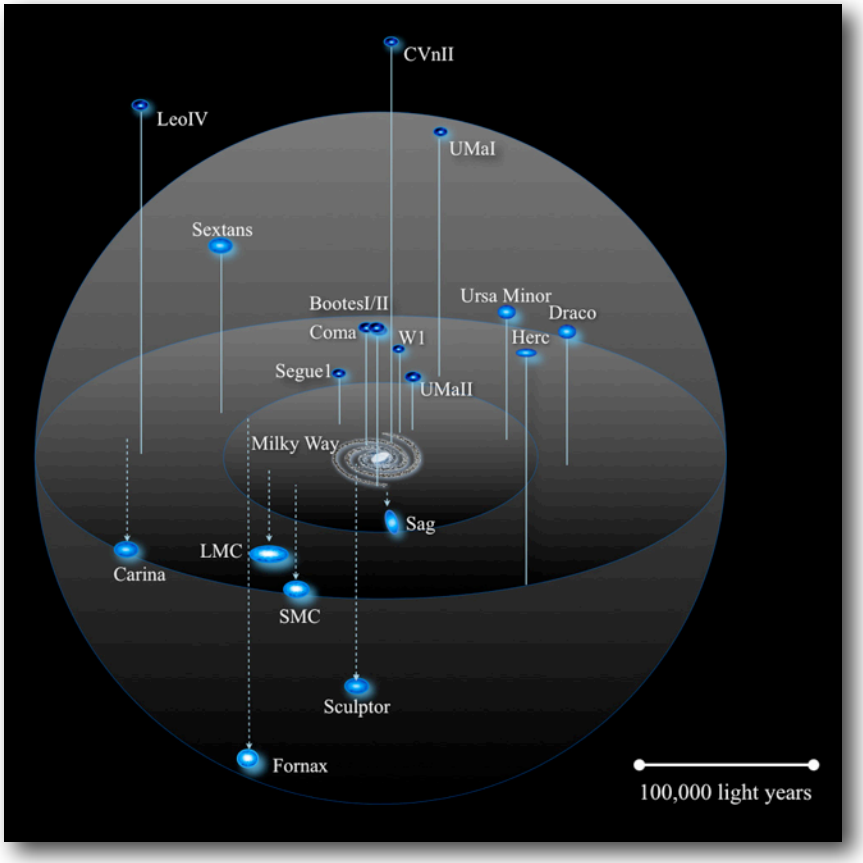




"Missing Satellites Problem" circa 2010

Theory: N~10^{16}

Observation: N~25

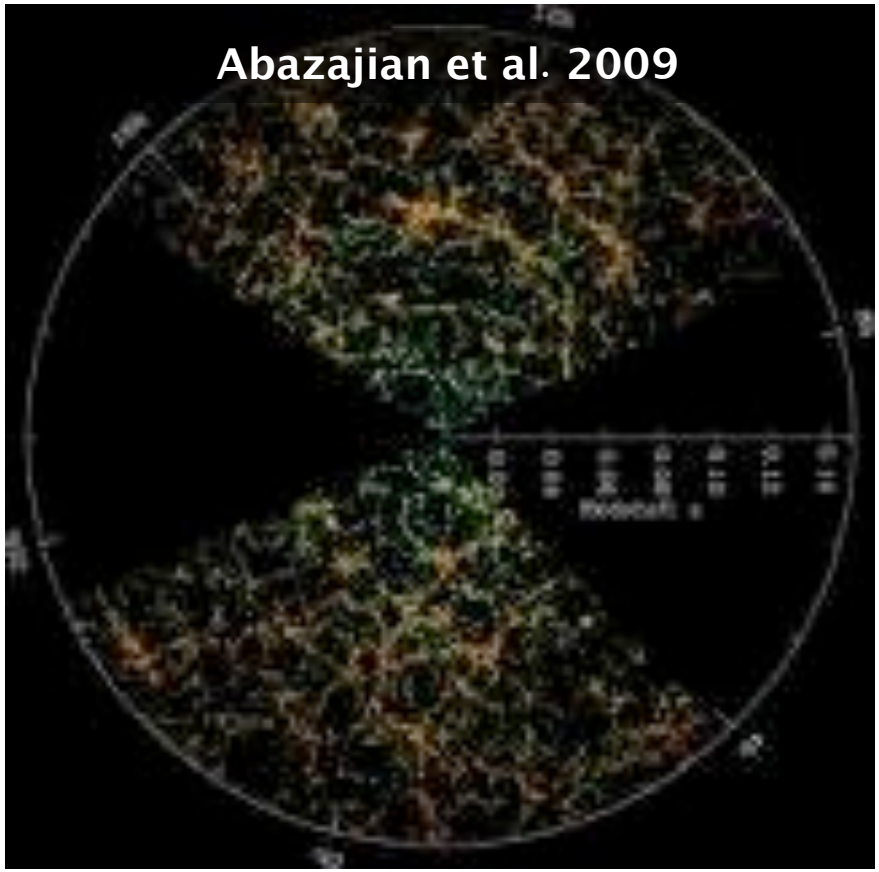


(down to ~Earth mass subhalos)

(maybe ~500 will be found)

Tollerud, Boylan-Kolchin et al. 2011

Spectroscopic ~0.1 L_* satellites within ~L_* galaxy halos



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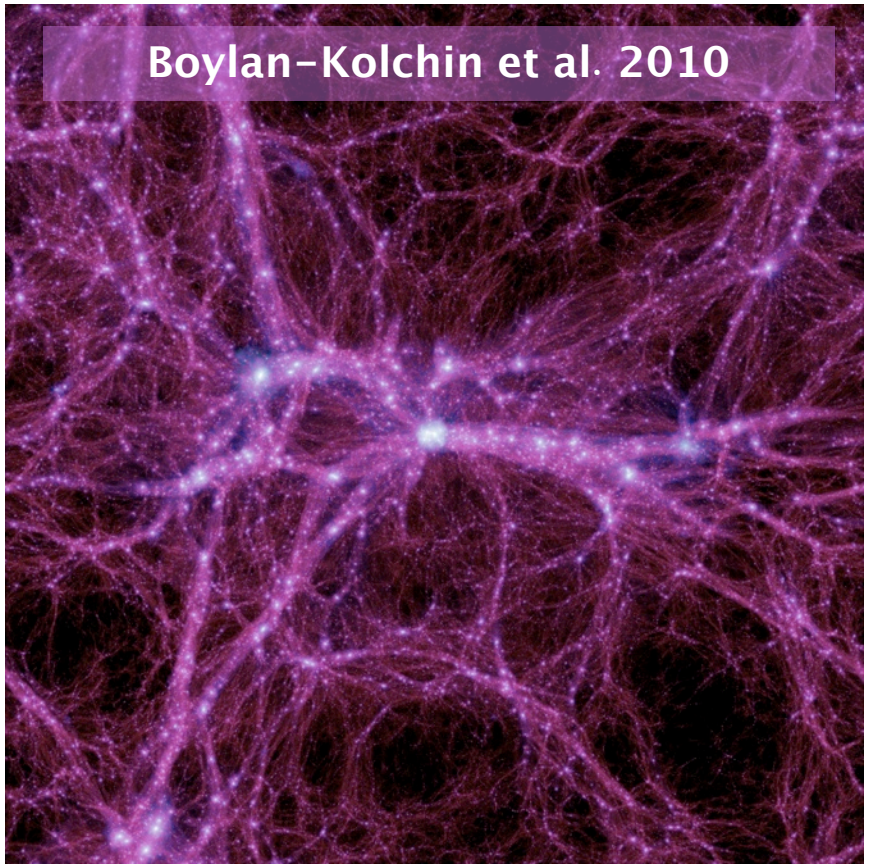
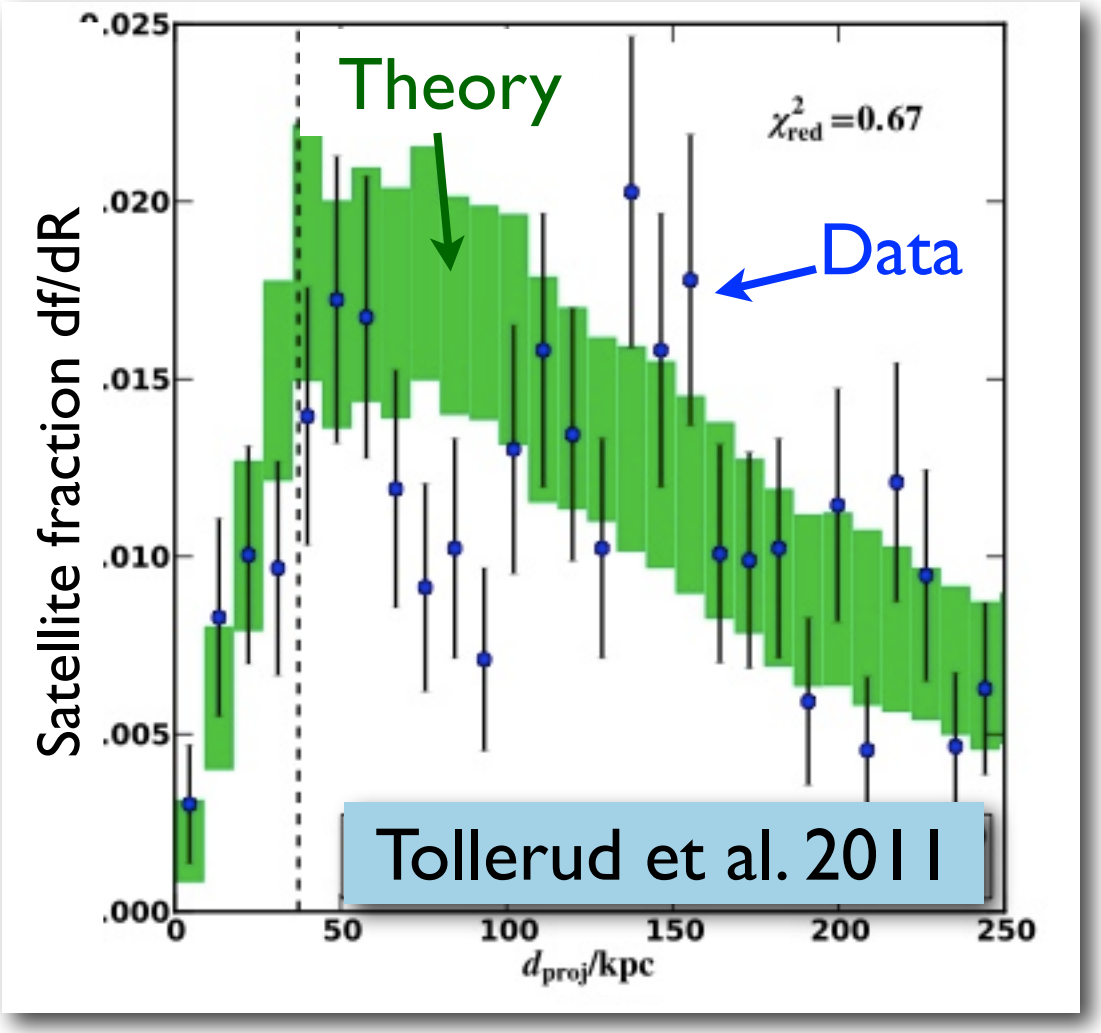
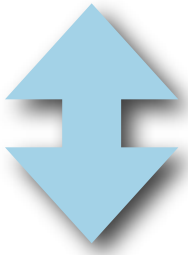


Mill II simulation “observed” like SDSS sample

Abundance matching works at V_{infall}~100 km/s



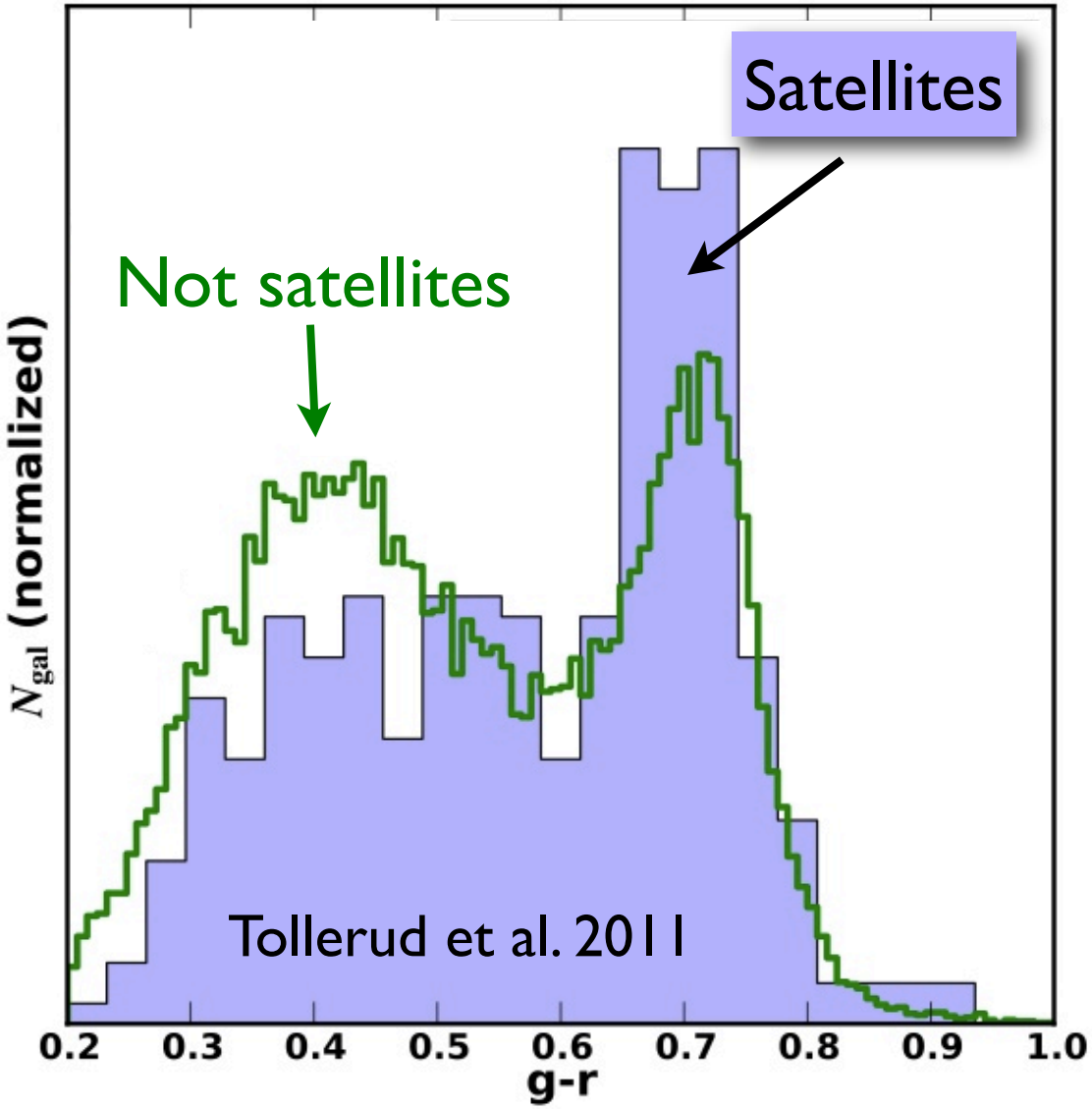
~100 km/s subhalos



~0.1 L* satellites

Bright satellites of isolated L* galaxies are RED

~0.1 L_* satellites w/in ~L_* galaxy halos are **RED**



The LMC is unusually blue for a satellite

~0.1 L_* satellites w/in ~L_* galaxy halos are **RED**