Dark Matter & Dwarf Galaxies

James Bullock
UC Irvine

Southern California Center for Galaxy Evolution

Collaborators

Mike **Boylan-Kolchin**

Manoj **Kaplinghat**

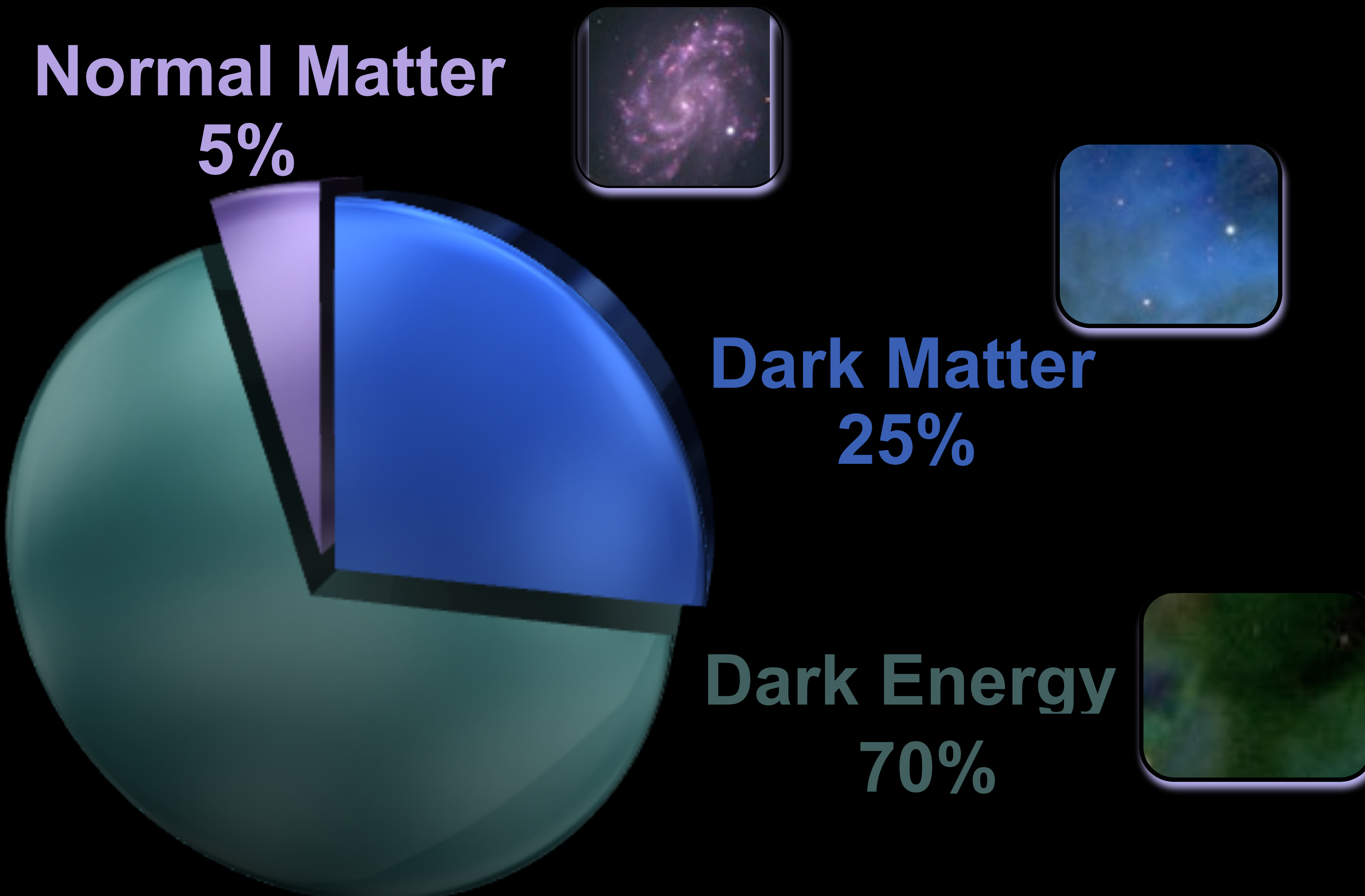
Miguel **Rocha**

Shea **Garrison-Kimmel**

Annika **Peter**

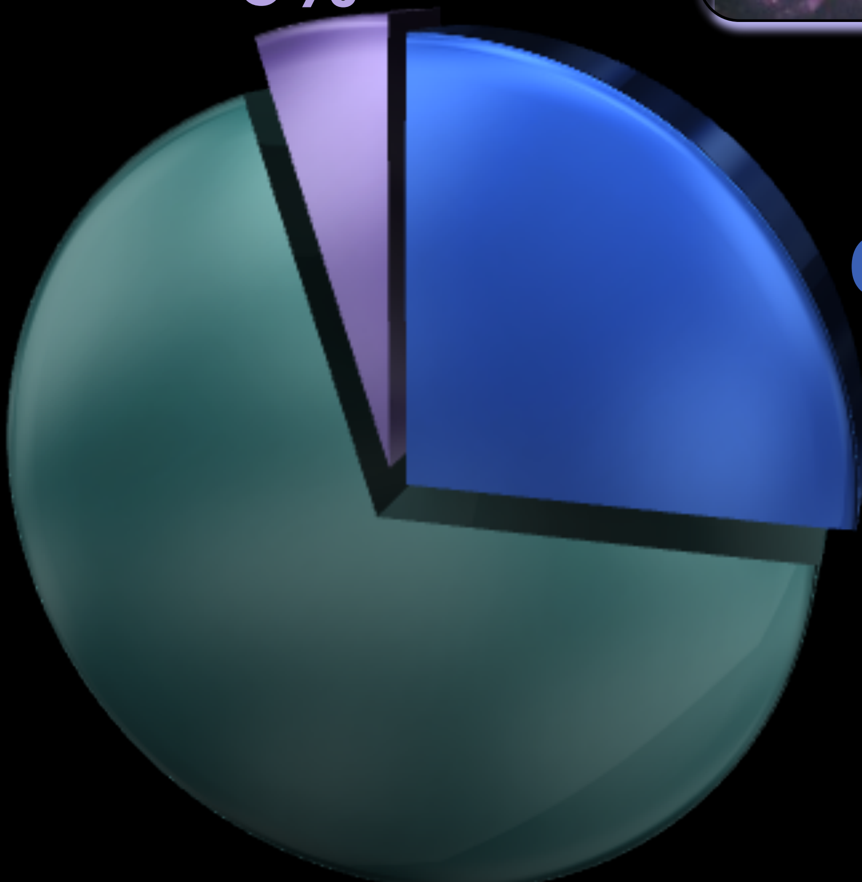
Jose **Oñorbe**

Standard Cosmology



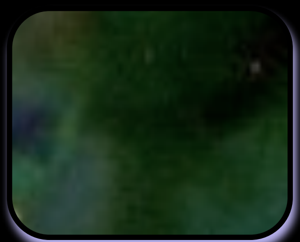
Standard Cosmology

Normal Matter
5%



Cold Dark Matter
25%

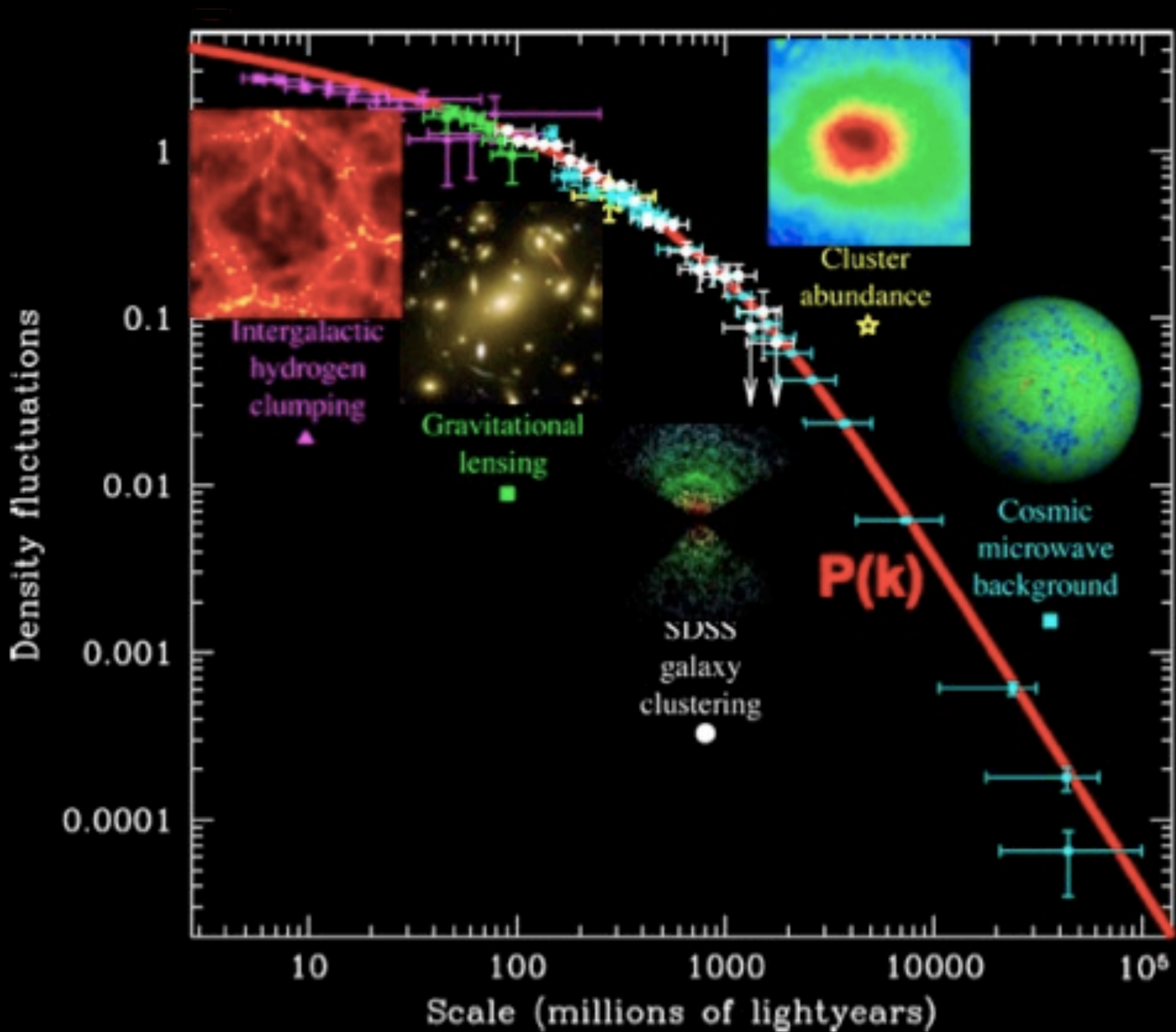
Λ
70%



LCDM

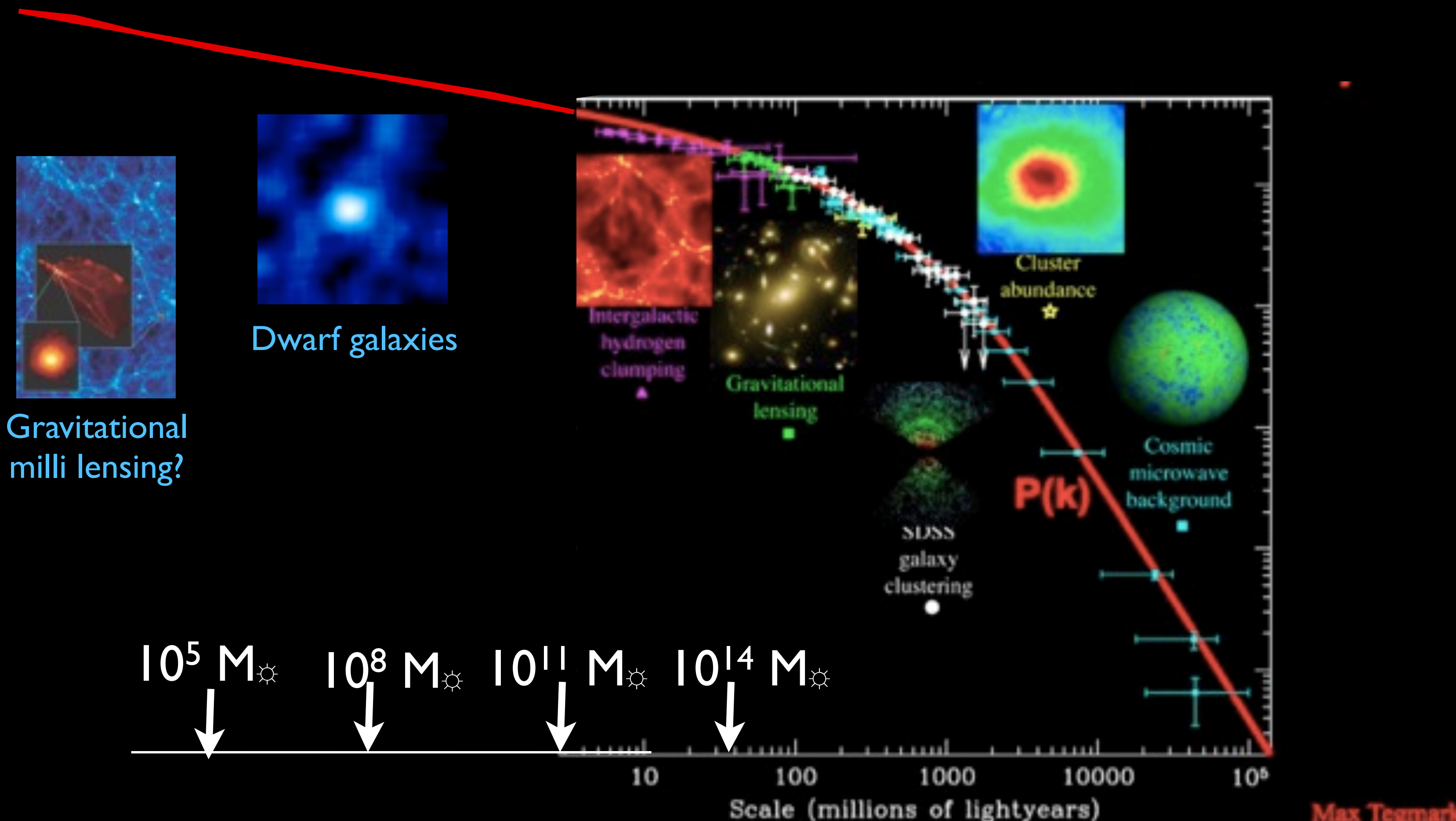
75 Mpc

Large-Scales: looks like CDM + Dark Energy



Max Tegmark

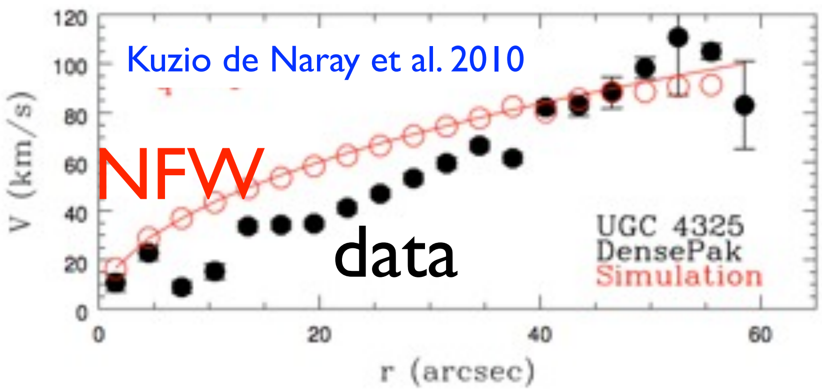
What about smaller scales?



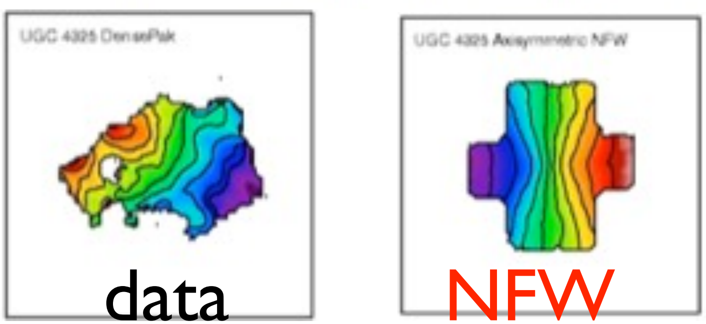
Small scale troubles with LCDM?

LSB galaxies:

- not as dense as predicted
- core density at ~few kpc

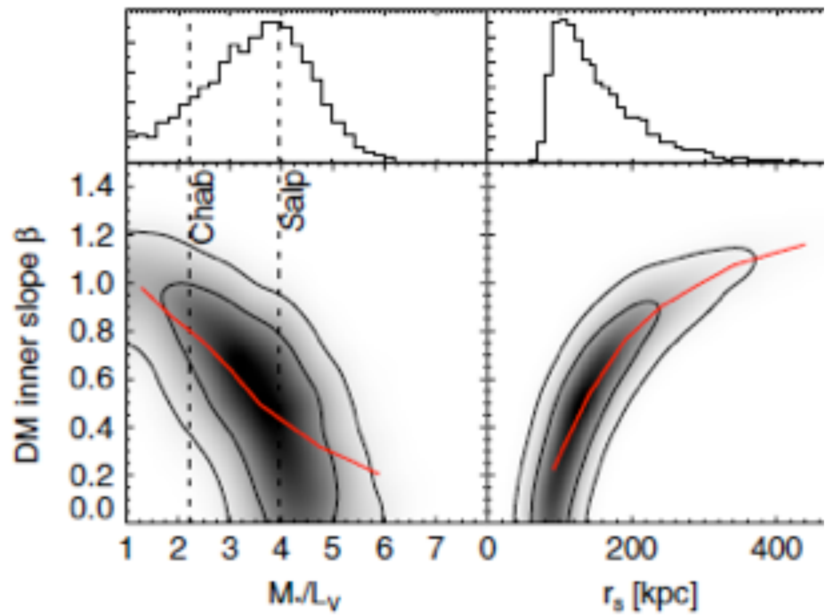


cusps would be easily detected if present



Galaxy Clusters:

- density profiles are too shallow?
- core density at ~100 kpc



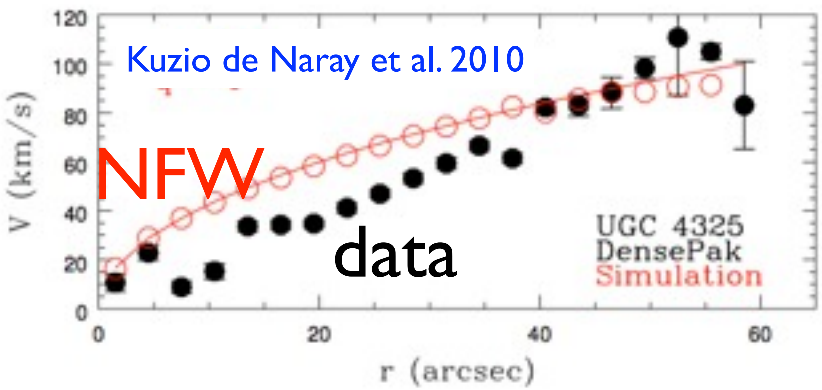
- strong lensing + stellar kinematics -

Tyson et al. 1998; Sand et al. 2008; Newman et al. 2011

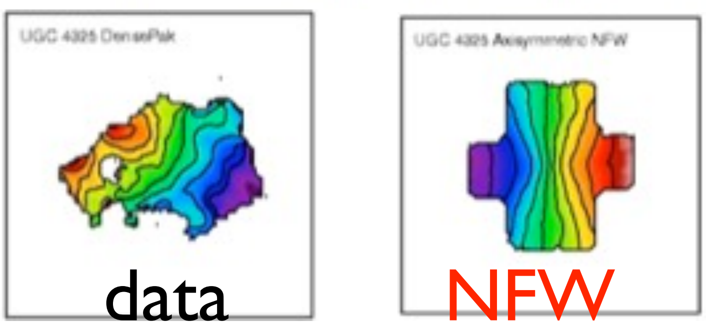
Small scale troubles with LCDM?

<u>LSB galaxies</u>:

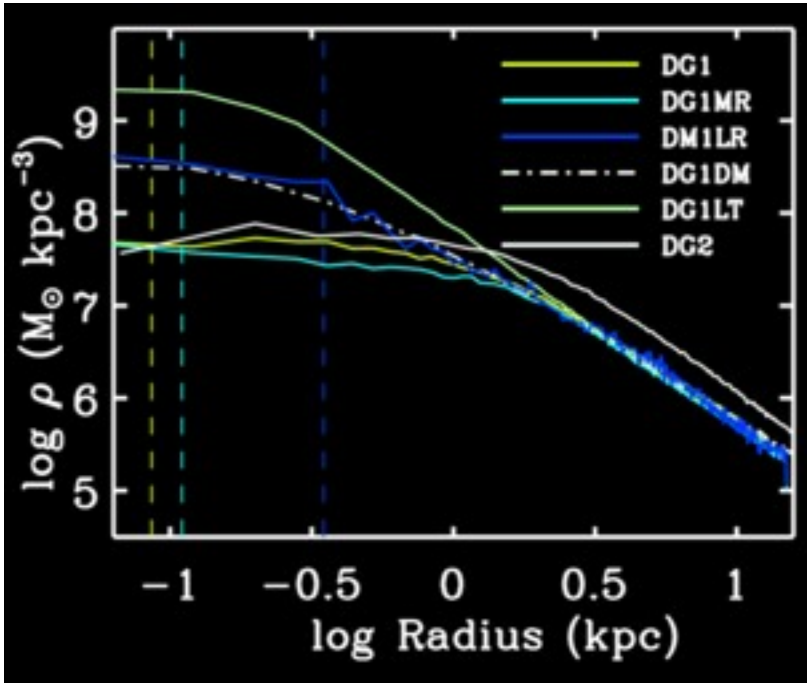
- not as dense as predicted
- core density at ~few kpc



cusps would be easily detected if present



LCDM + baryonic effects create cores?



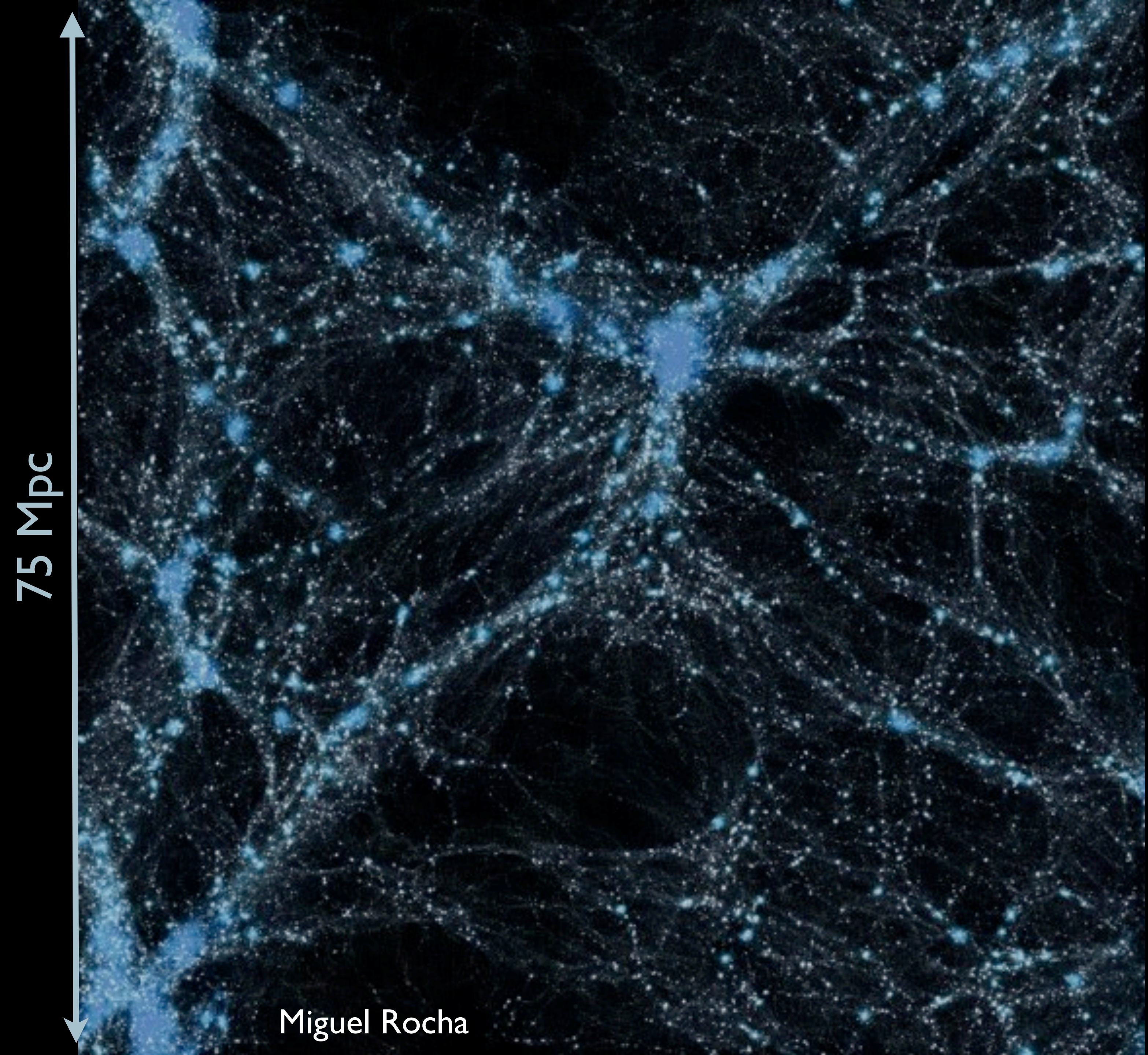
Governato et al. 2010

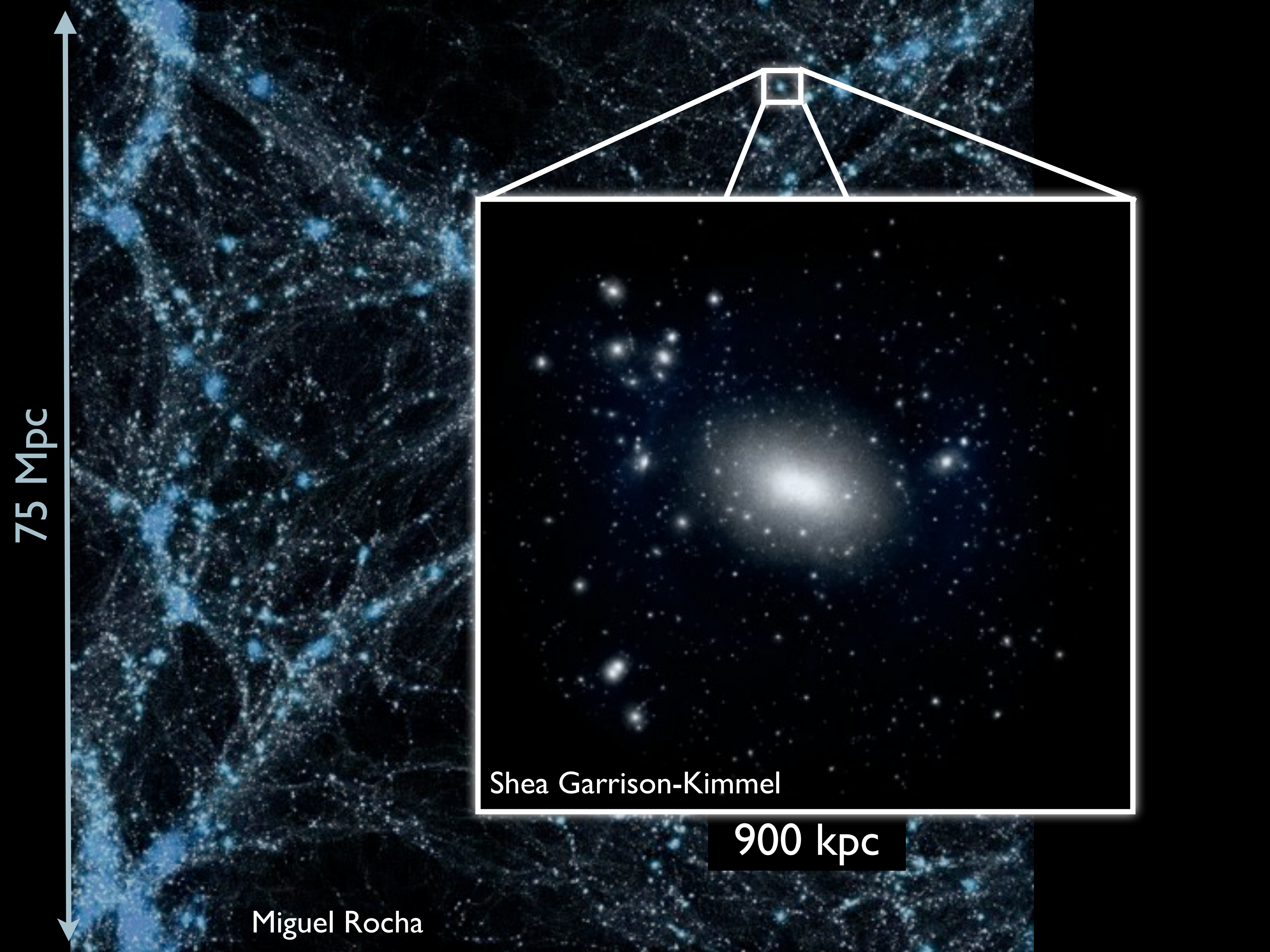
Dwarf Satellite Galaxies

$$L \sim 10^5 - 10^6 L_\odot$$

$$M/L \sim 100$$

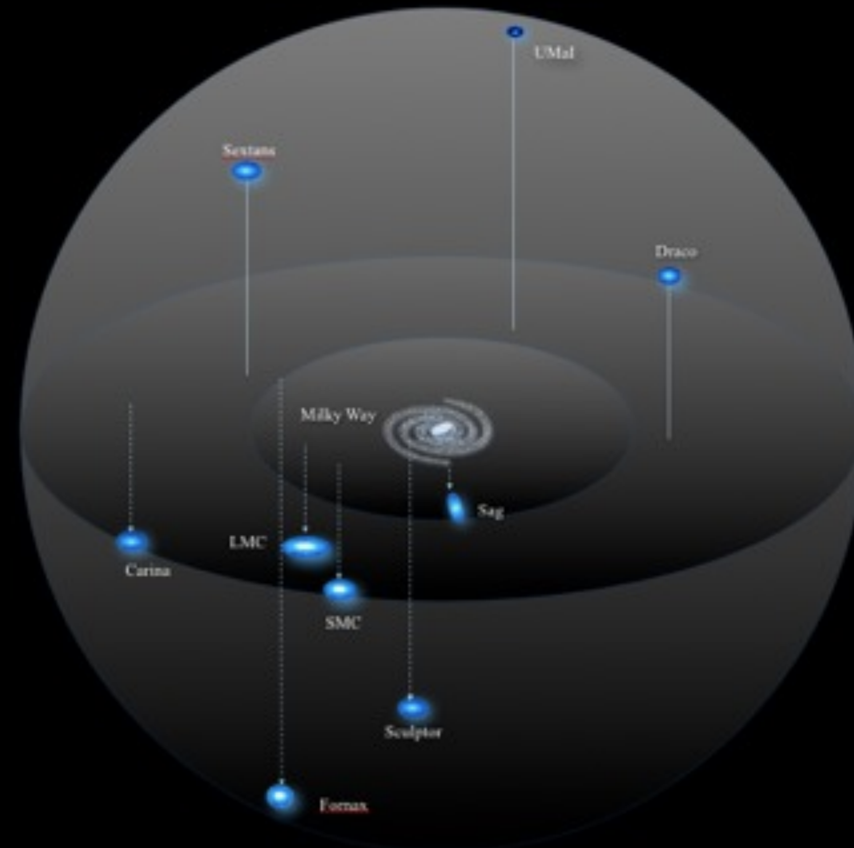
Dark Matter Dominated => Easy to interpret


75 Mpc
Miguel Rocha


75 Mpc
Shea Garrison-Kimmel
900 kpc
Miguel Rocha

Garrison-Kimmel, Oñorbe et Irvine 2012

"Missing Satellites Problem"

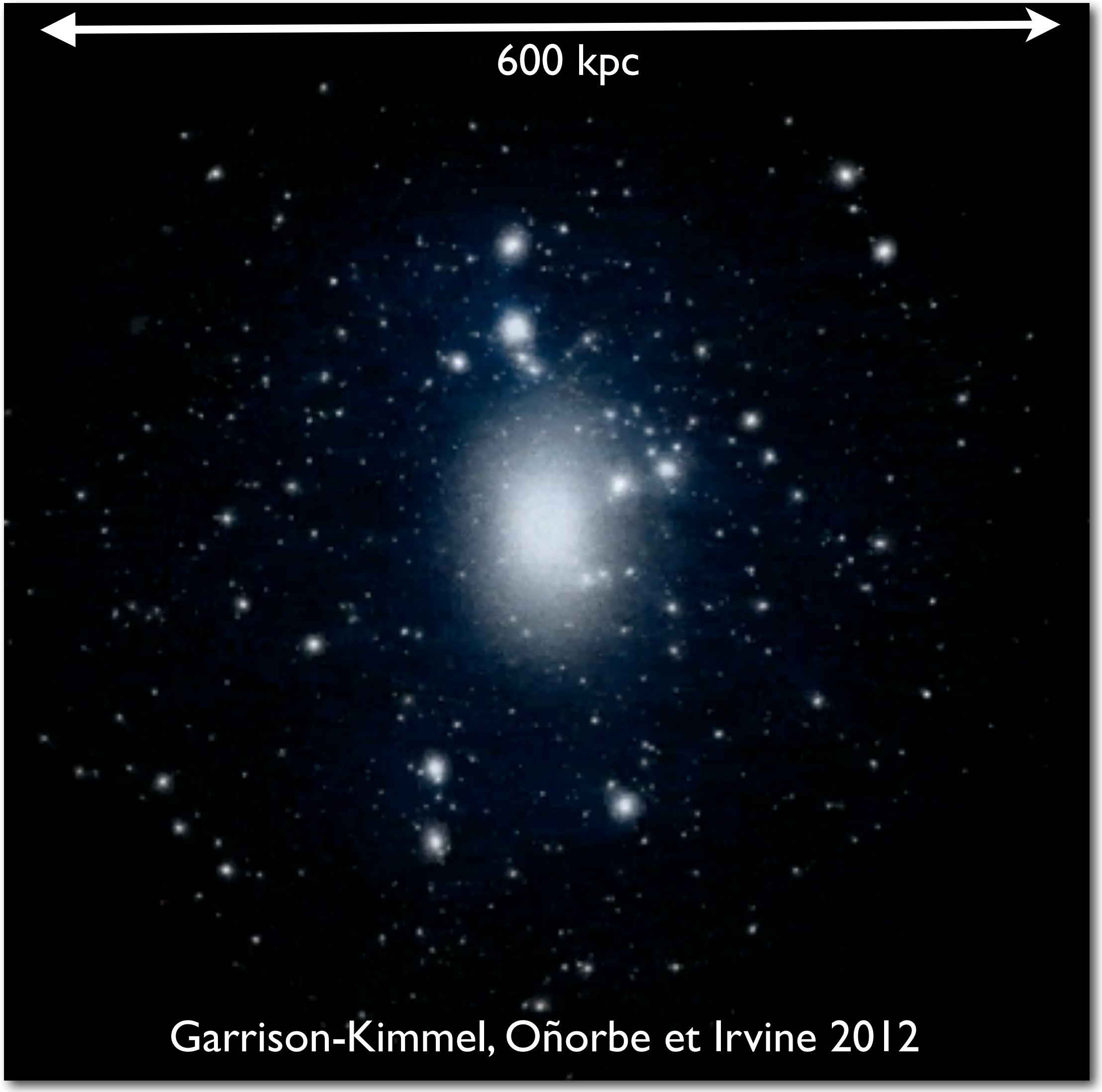


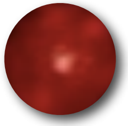
Theory: N>>1000

Observation: N_{bright}~10

Klypin et al. 1999; Moore et al. 1999; Kauffmann et al. 1993

Quantifying Substructure: Subhalos





Subhalo

V_{max} = peak circular velocity

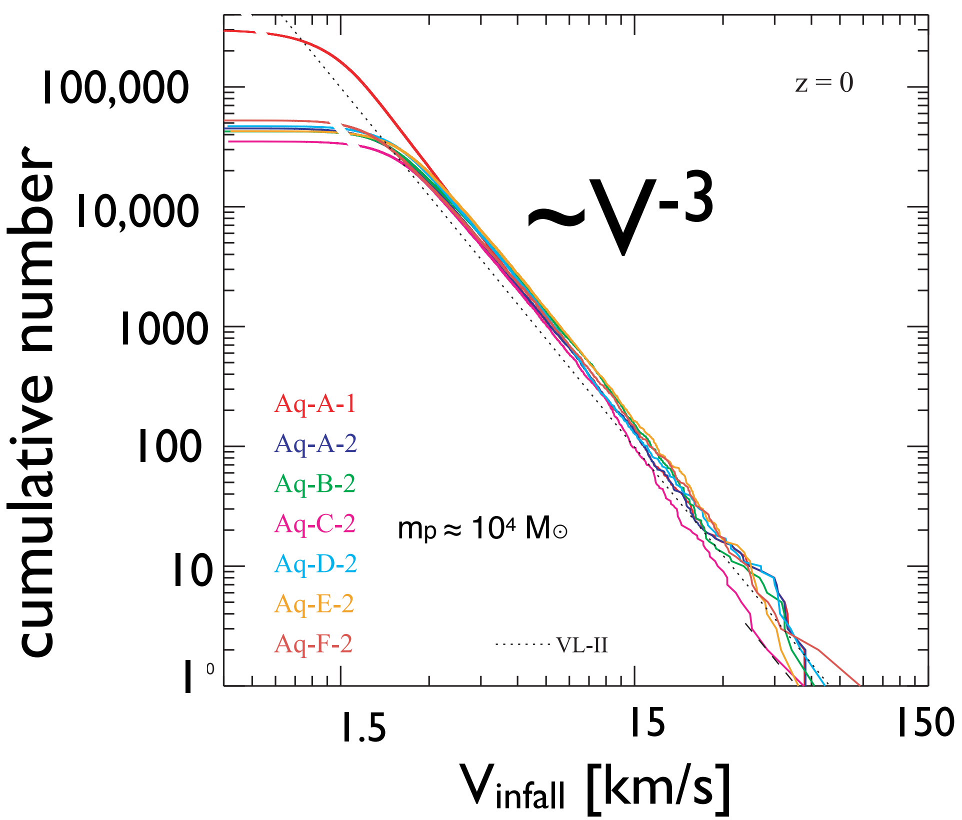
V_{infall} = V_{max} before fell in

M_{infall} = Virial mass before fell in

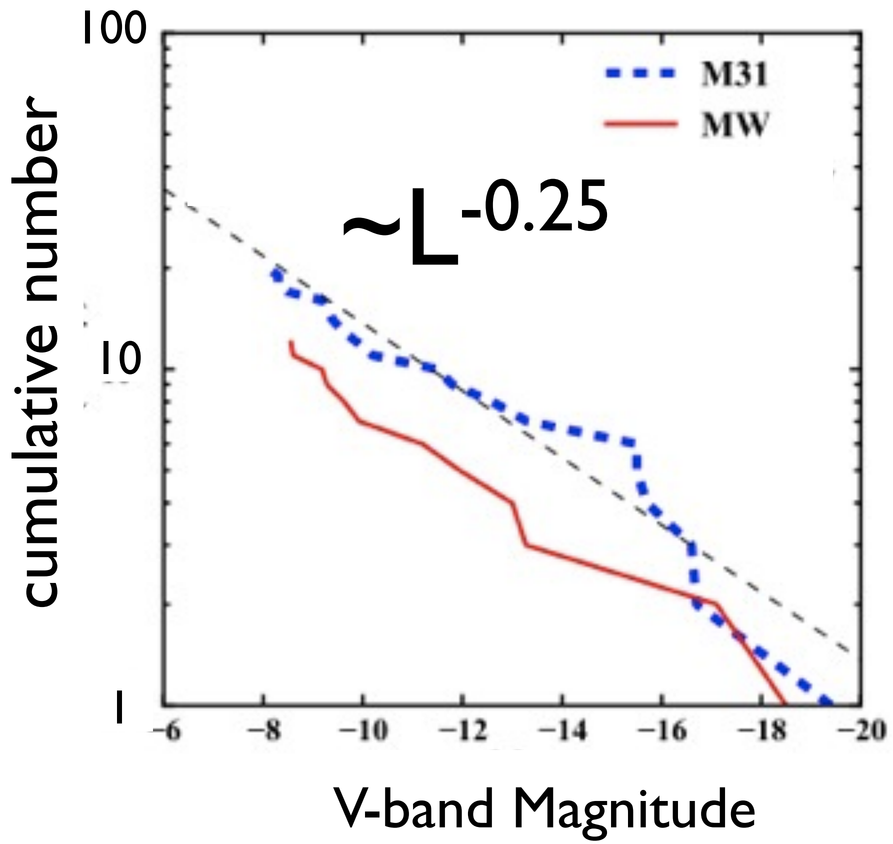
Record:
Mass & V_{max} at all times prior to infall.

Missing Satellites Problem

Simulated mass/velocity functions: Steep

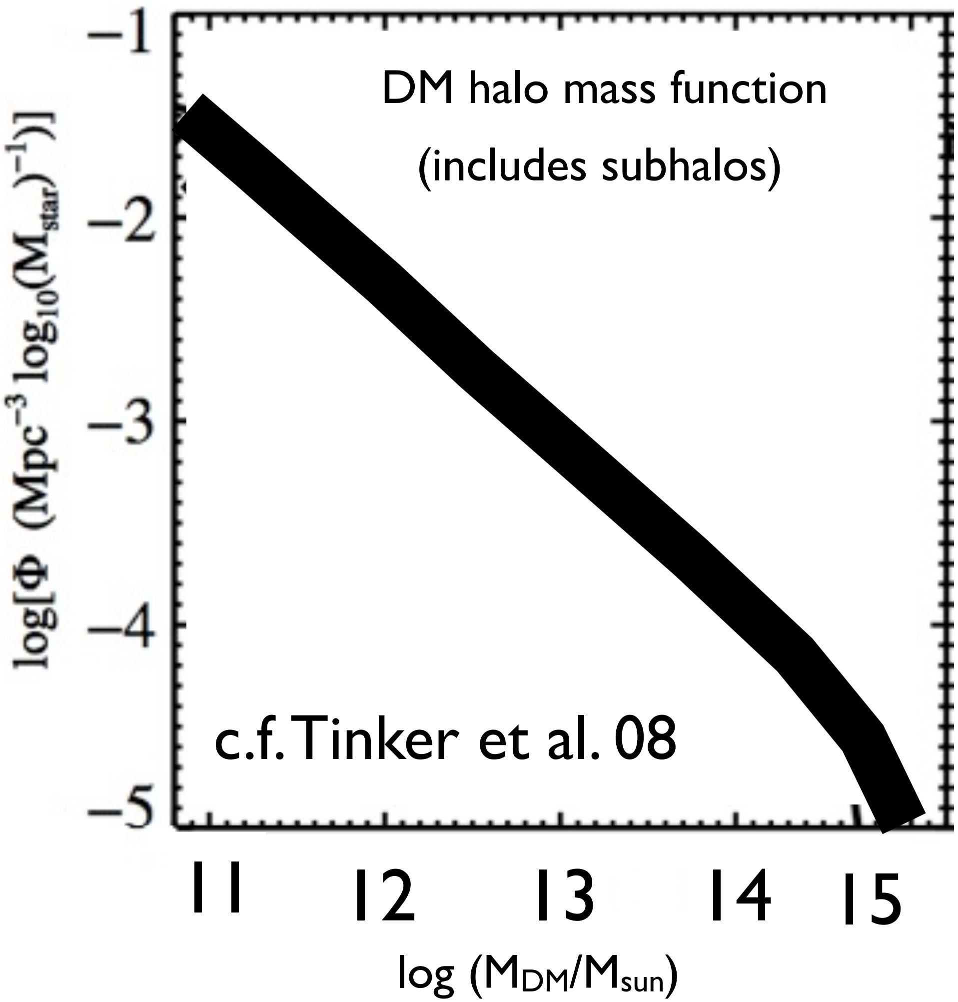


Observed Luminosity Functions: Flat



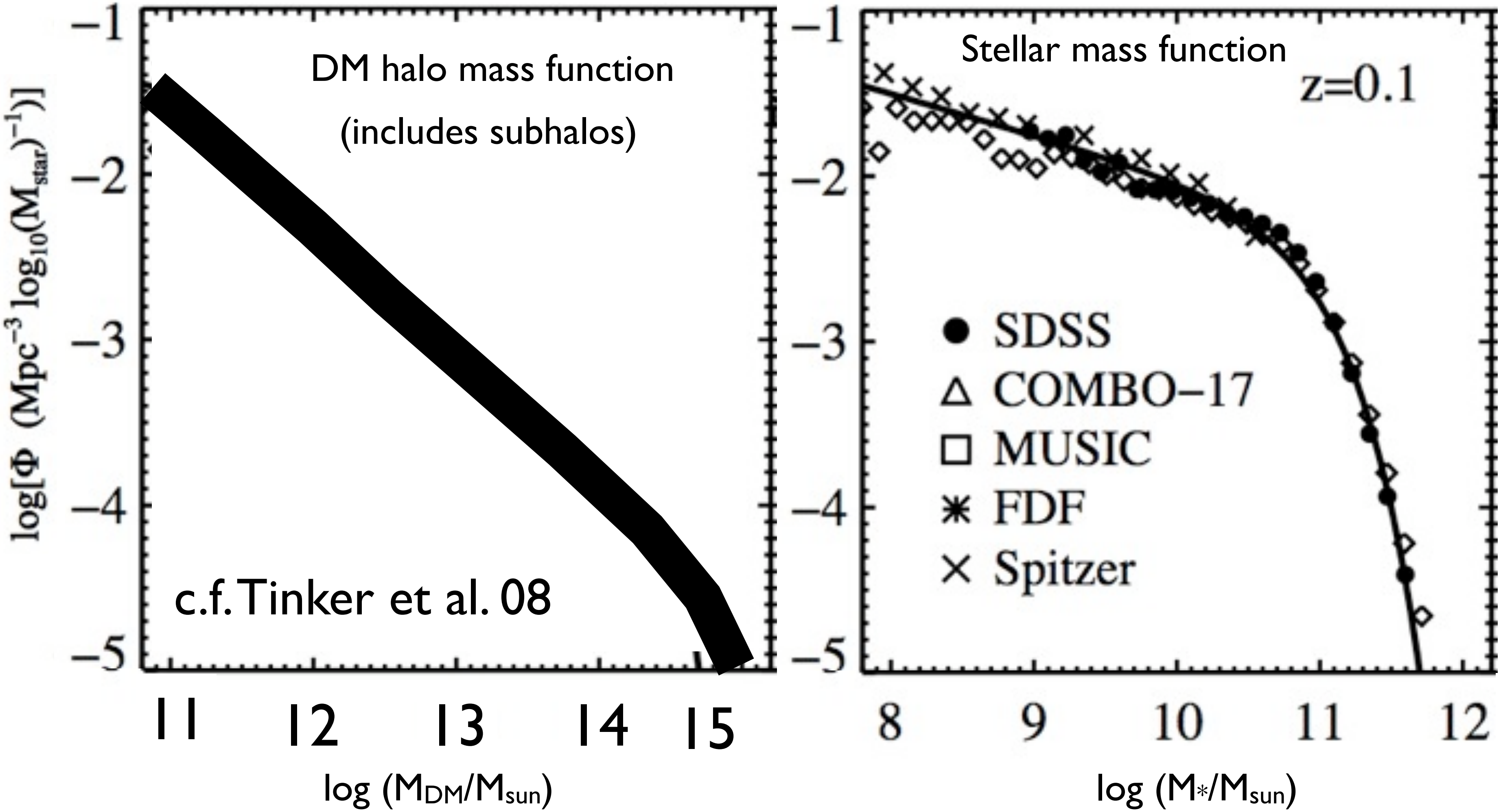
Springel et al. 2008 ; Diemand et al. 2008

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

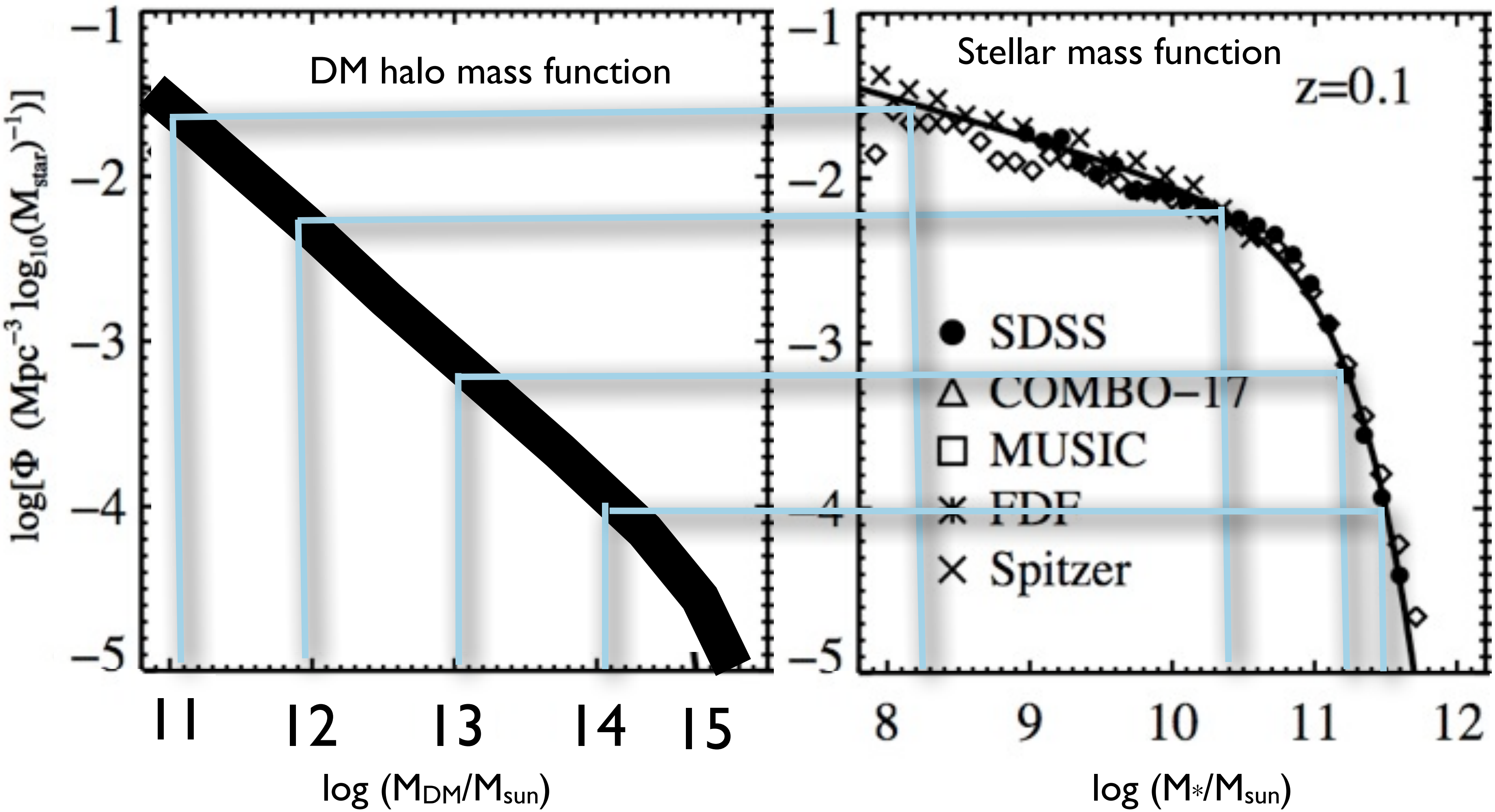
Abundance Matching: (sub)halo mass ⇔ galaxy L or M*



compilation by Conroy & Wechsler 08

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

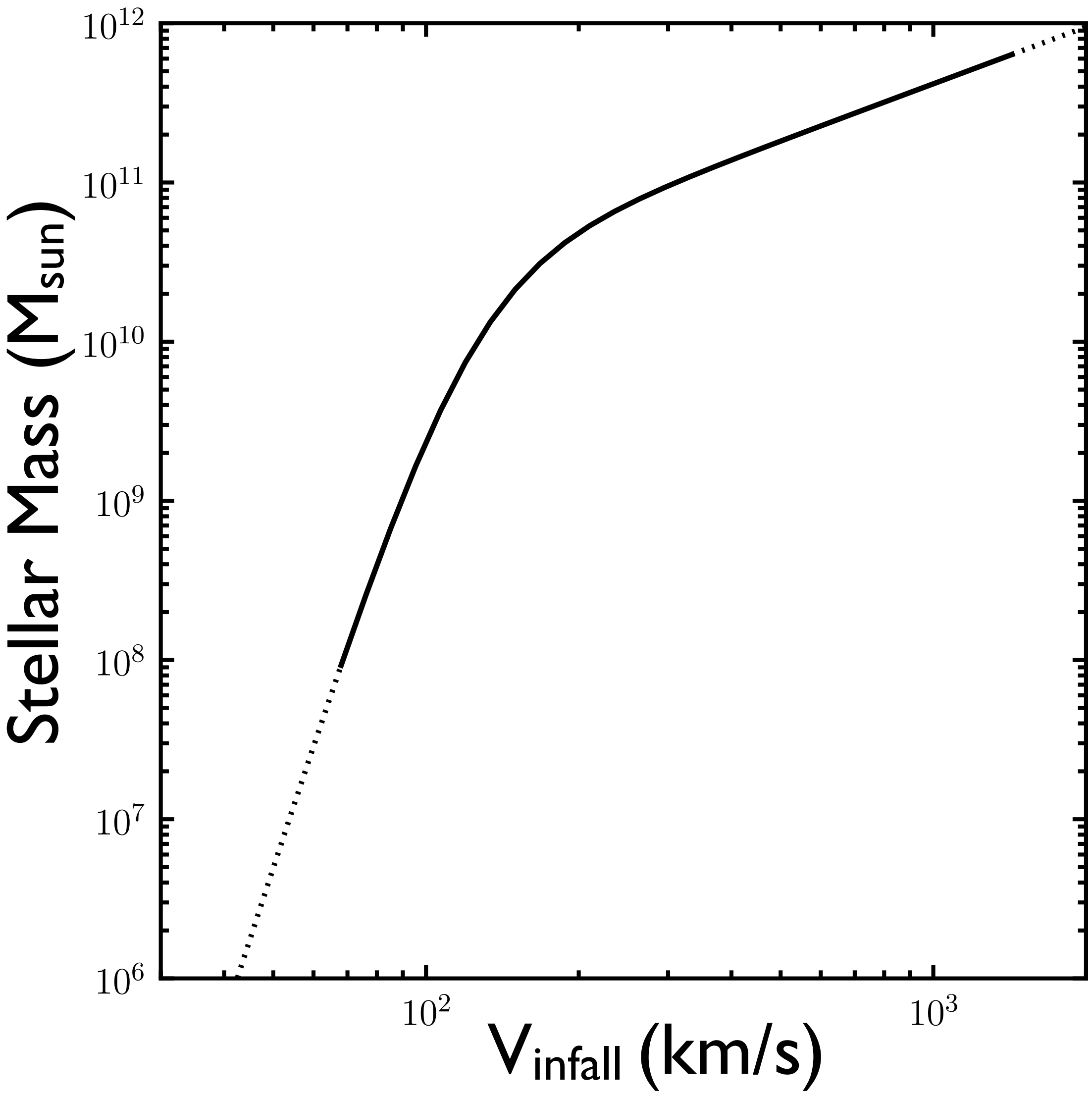
Abundance Matching: (sub)halo mass ⇔ galaxy L or M*



compilation by Conroy & Wechsler 08

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

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



"Abundance Matching"

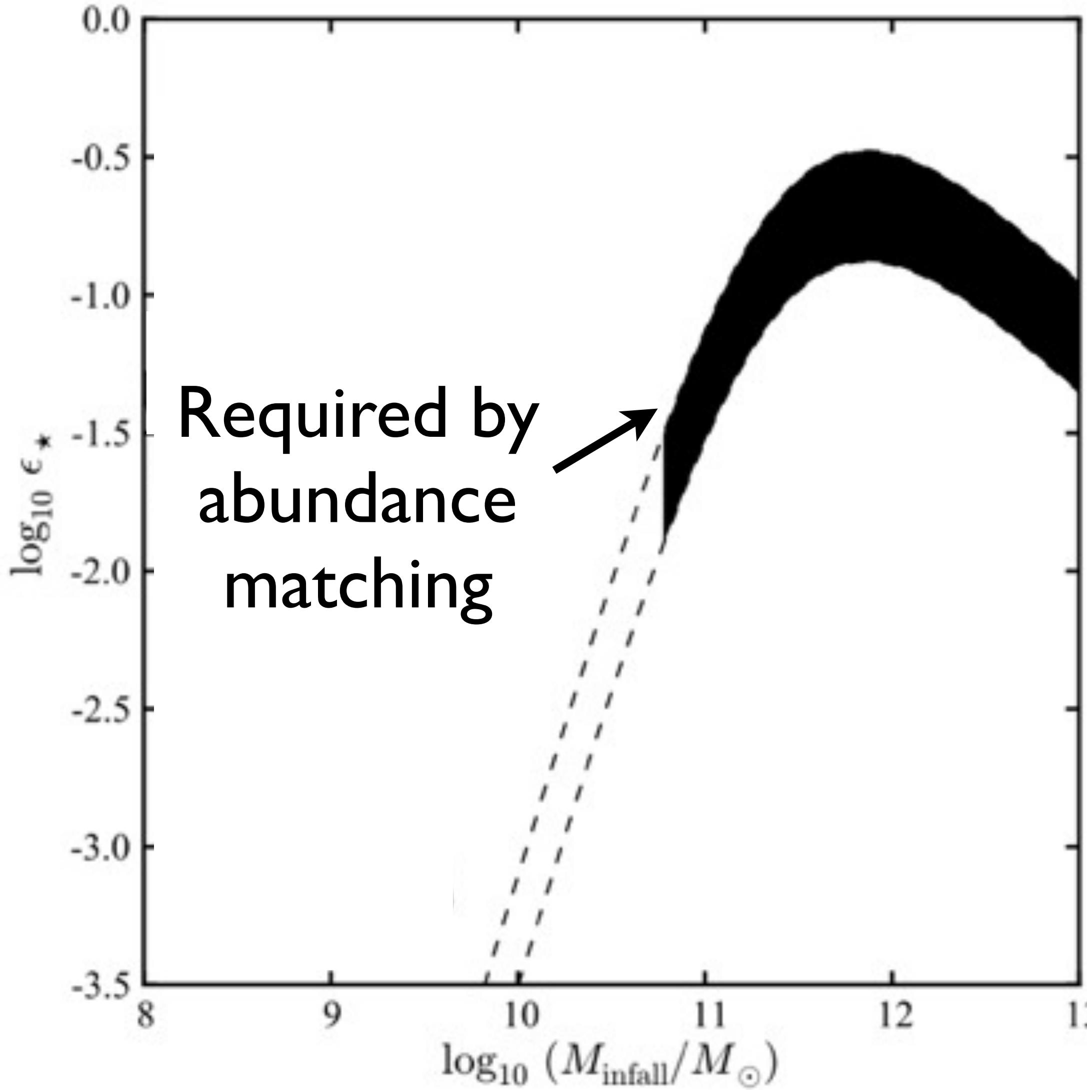
$$n(> M_\star) = n(> V_{\mathrm{infall}})$$

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

Millennium-II simulations
Boylan-Kolchin et al. 2009

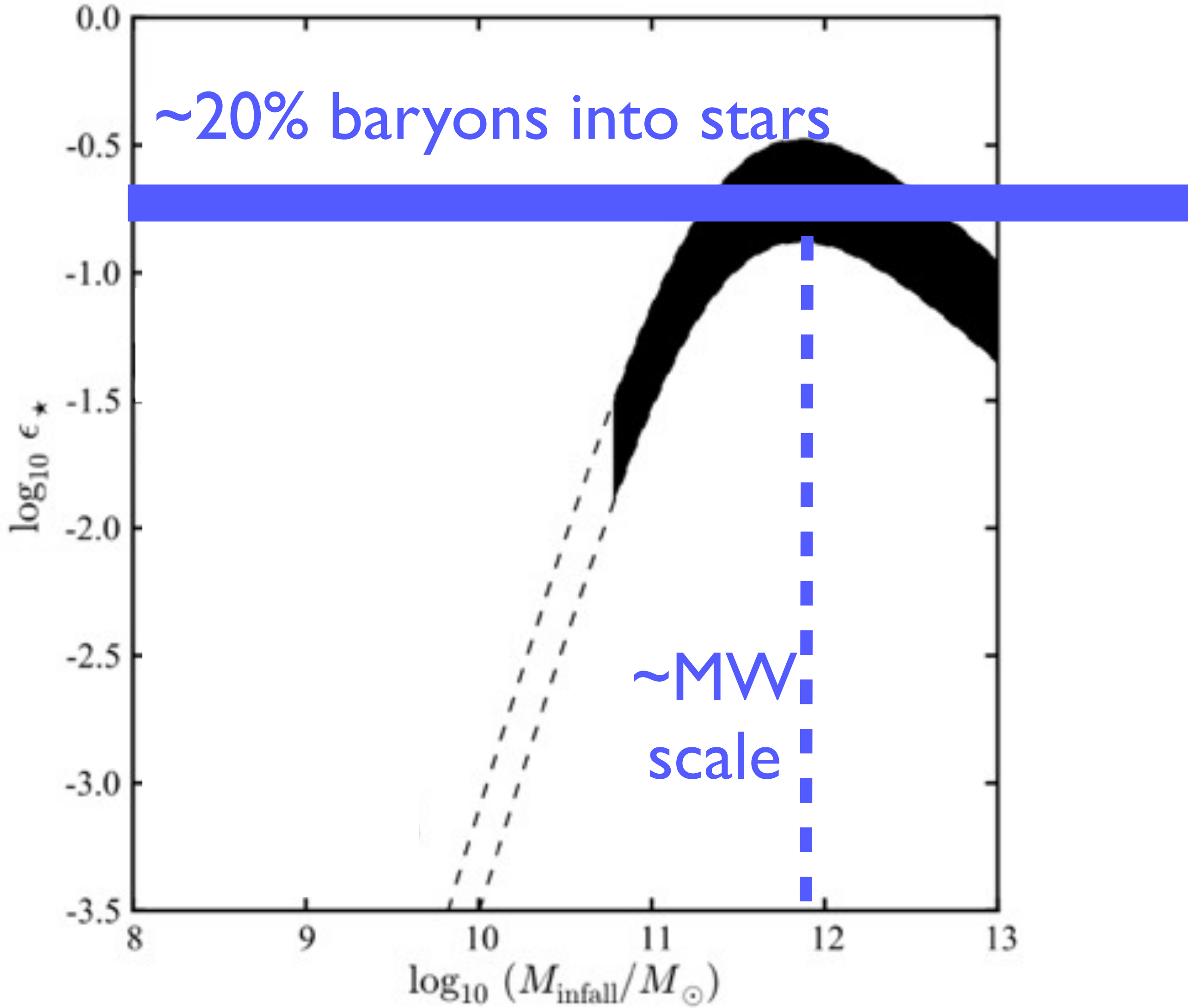
Boylan-Kolchin et al. 2011

Galaxy formation efficiency



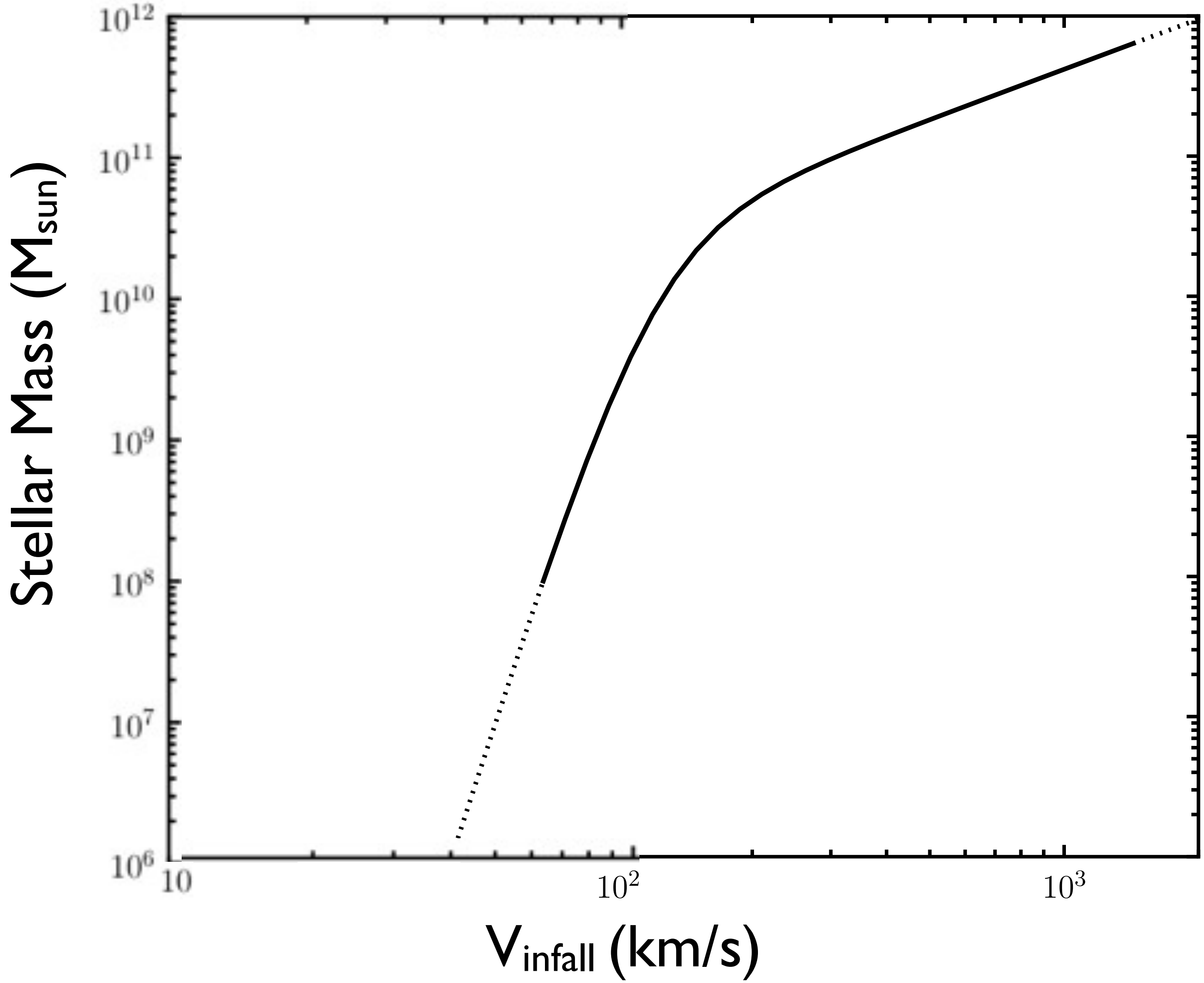
Boylan-Kolchin et al. 2011b

Galaxy formation efficiency

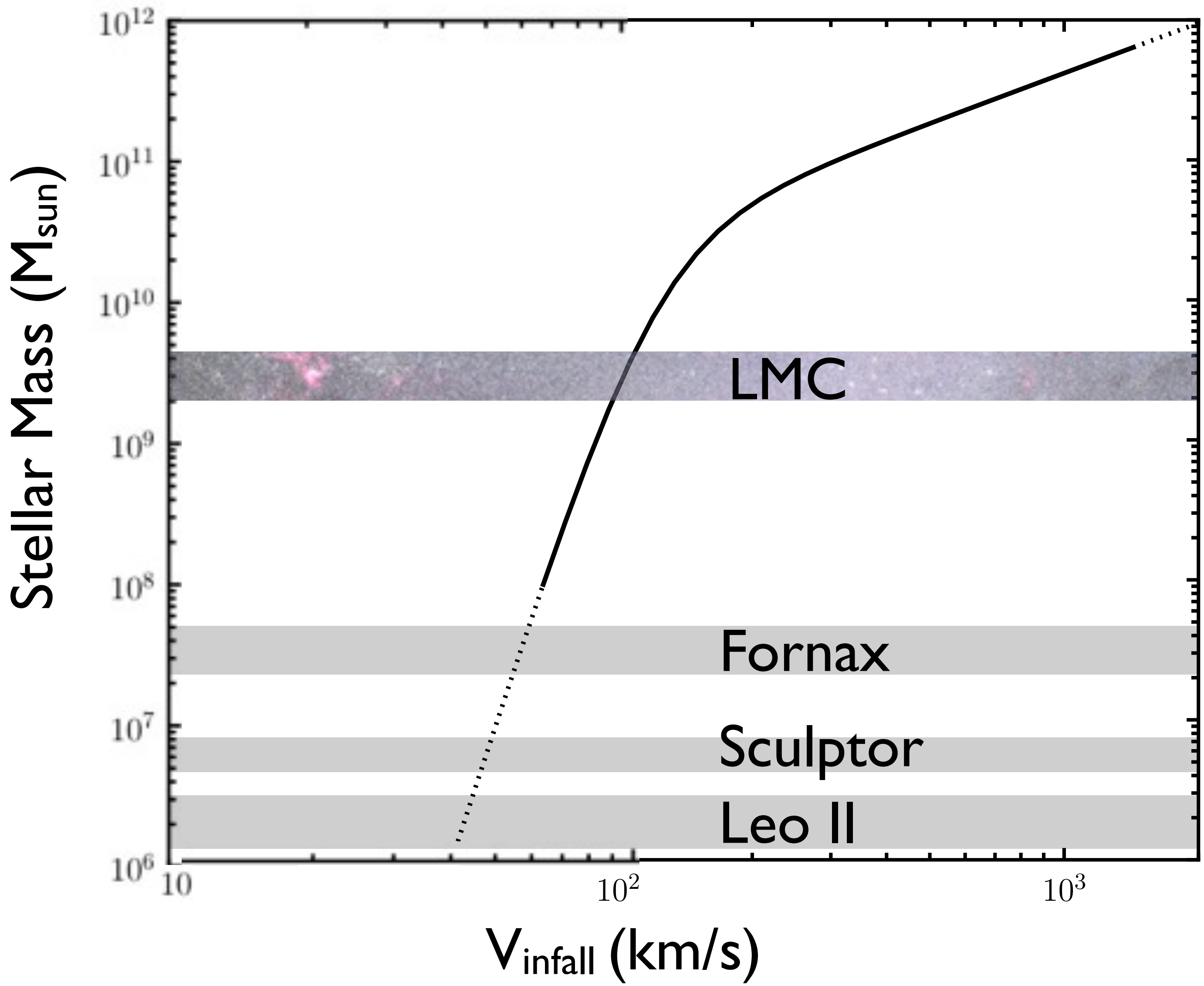


Boylan-Kolchin et al. 2011b

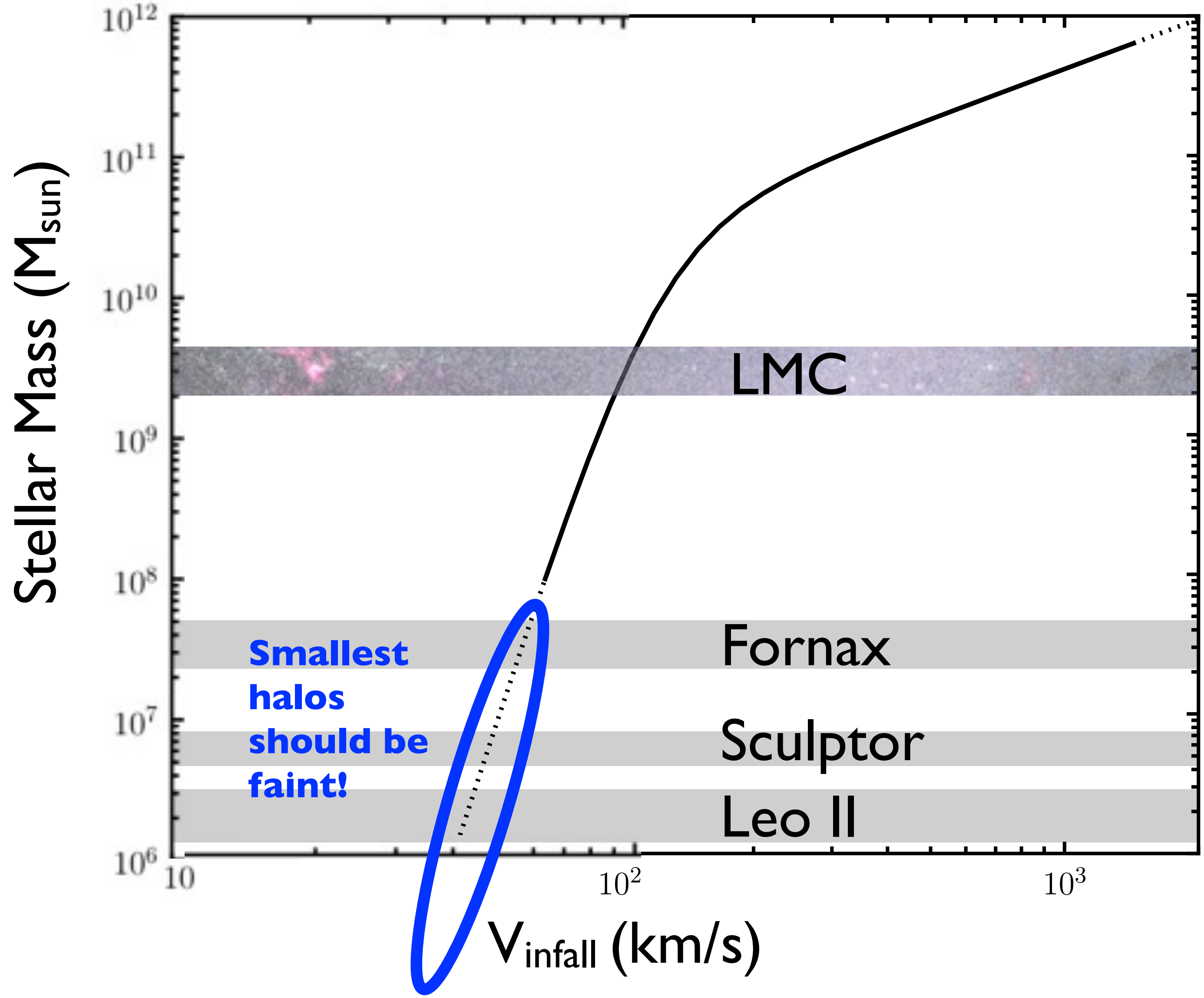
Abundance Matching for Satellite Galaxies?



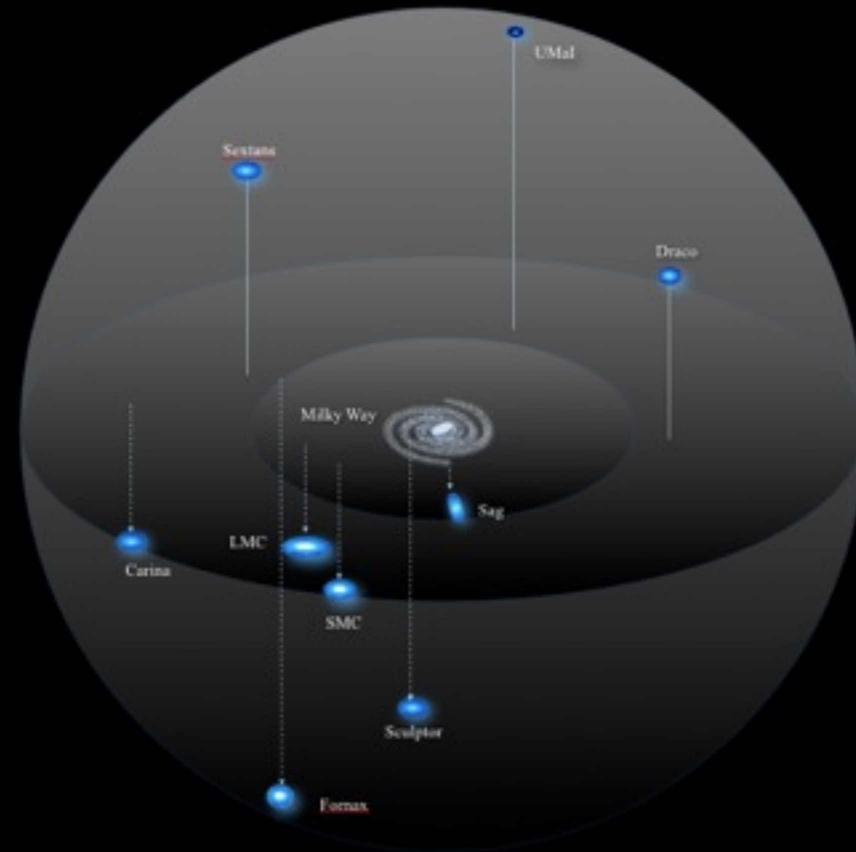
Abundance Matching for Satellite Galaxies?



Abundance Matching for Satellite Galaxies?



“Missing Satellites Problem”

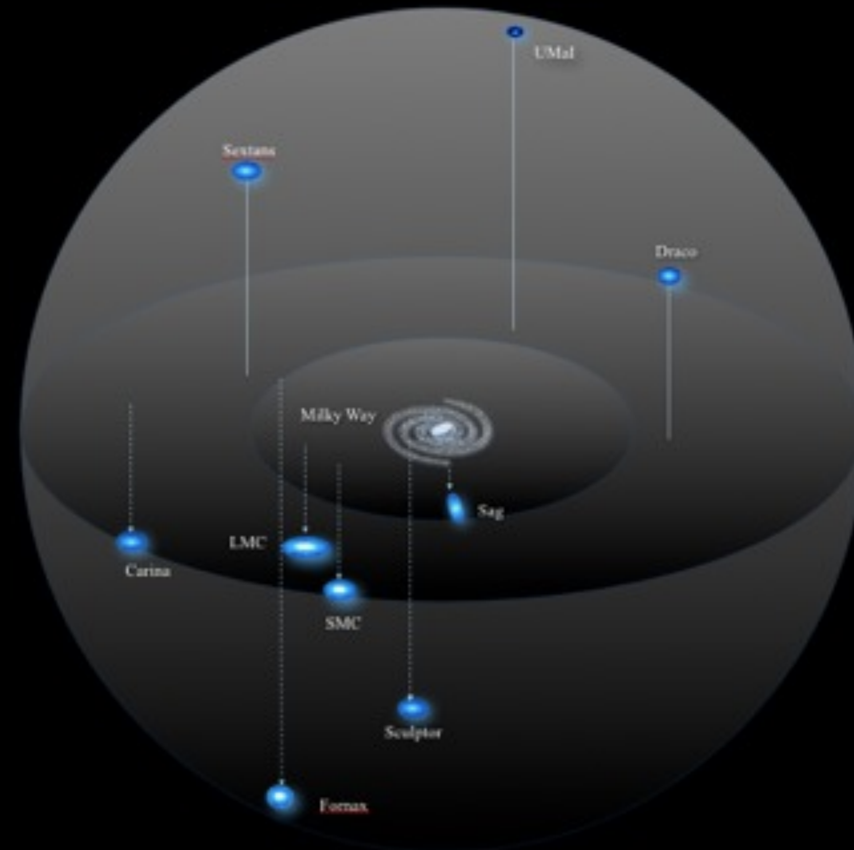


Theory: N>>1000

Observation: N_{bright}~10

Klypin et al. 1999

“Easy” answer: only the biggest clumps have stars?

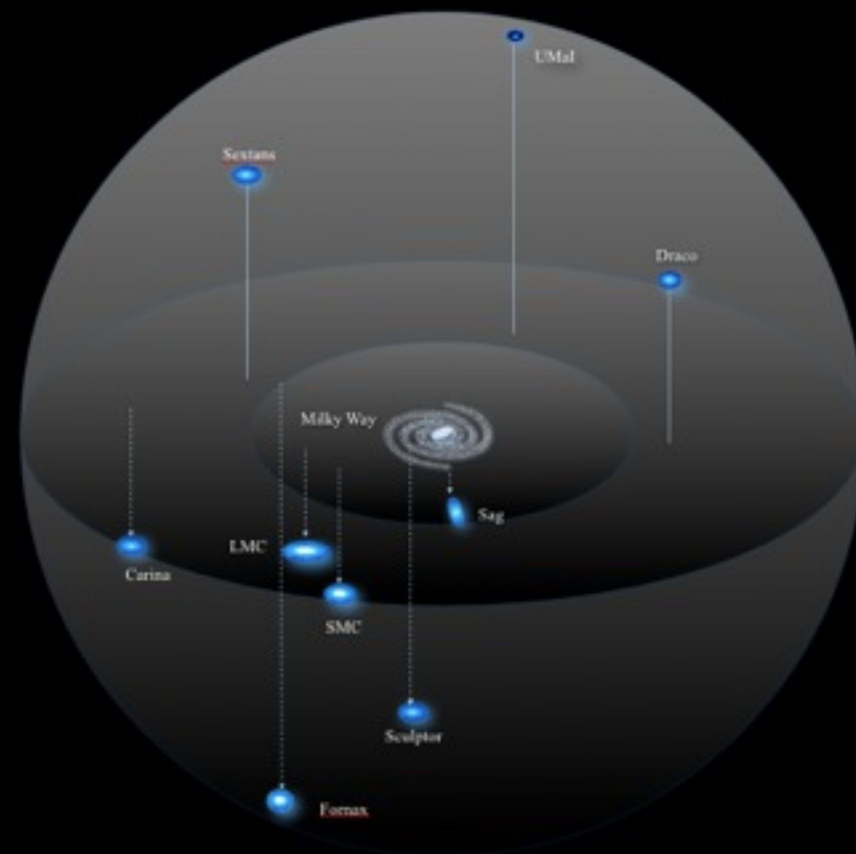


Theory: N>>1000

Observation: N_{bright}~10

Klypin et al. 1999

"Easy" answer: only the biggest clumps have stars?

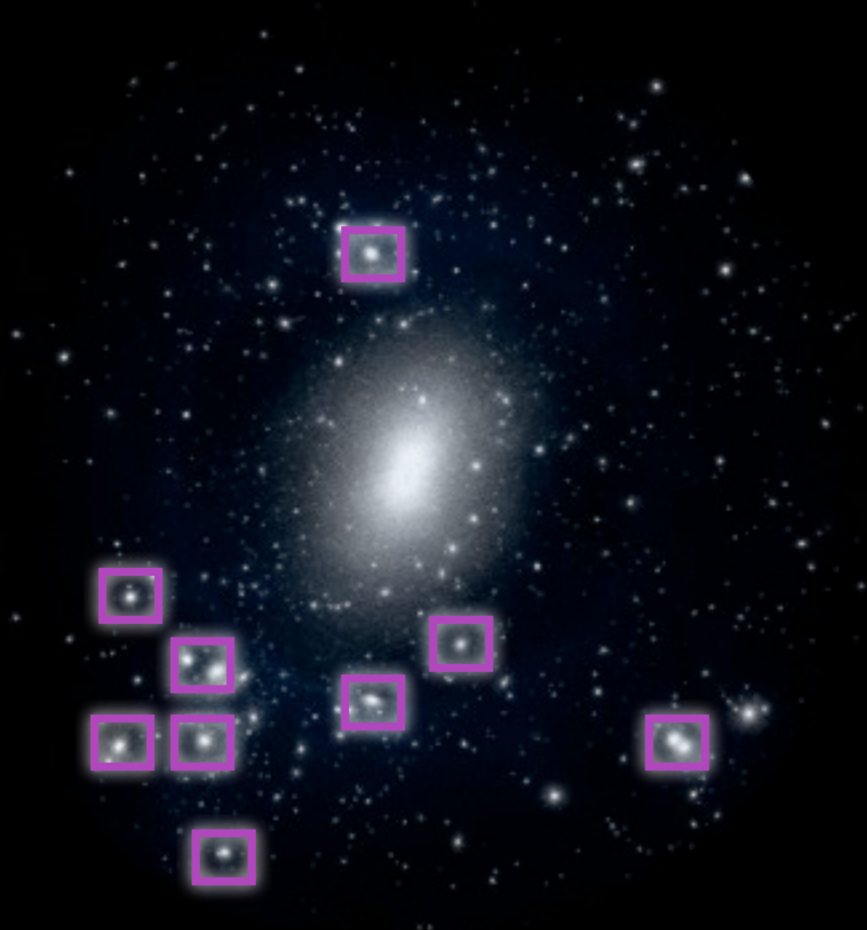


Theory: N>>1000

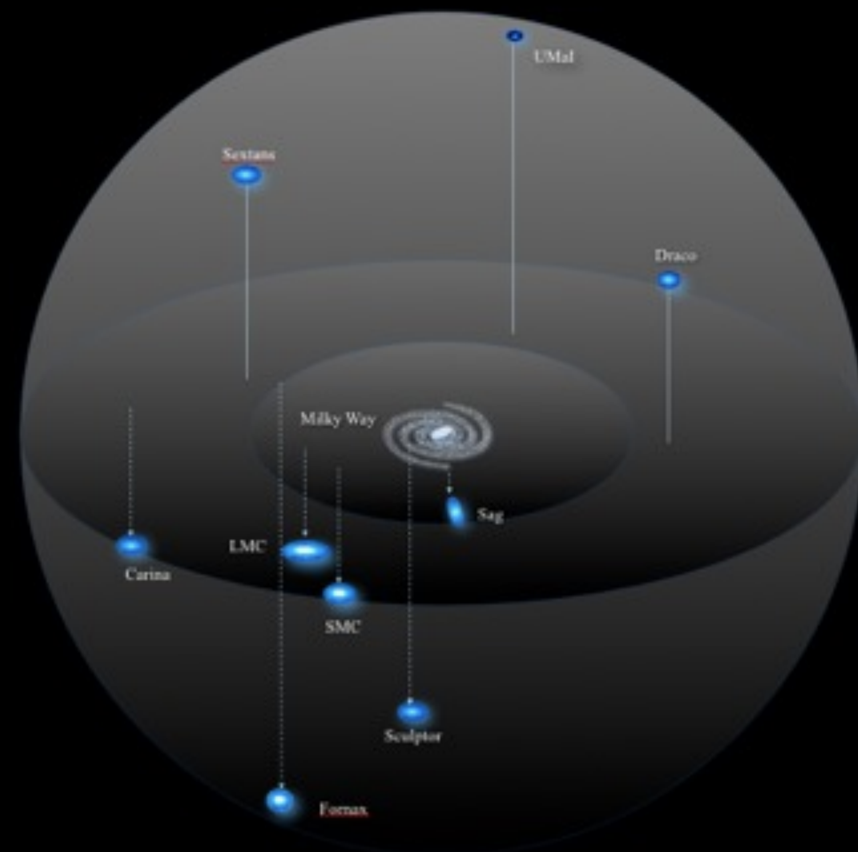
Observation: N_{bright}~10

Klypin et al. 1999

“Easy” answer: only the biggest clumps have stars?



Theory: N>>1000

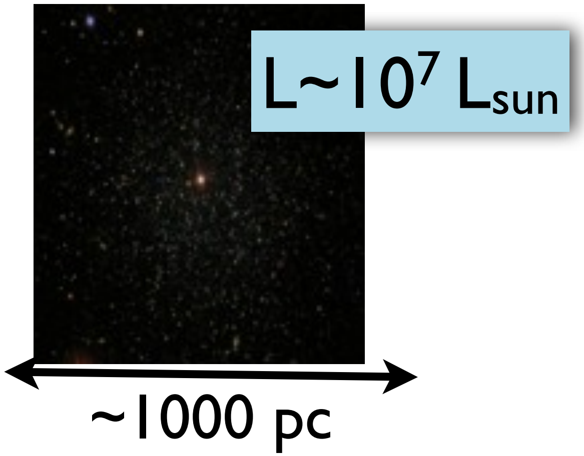


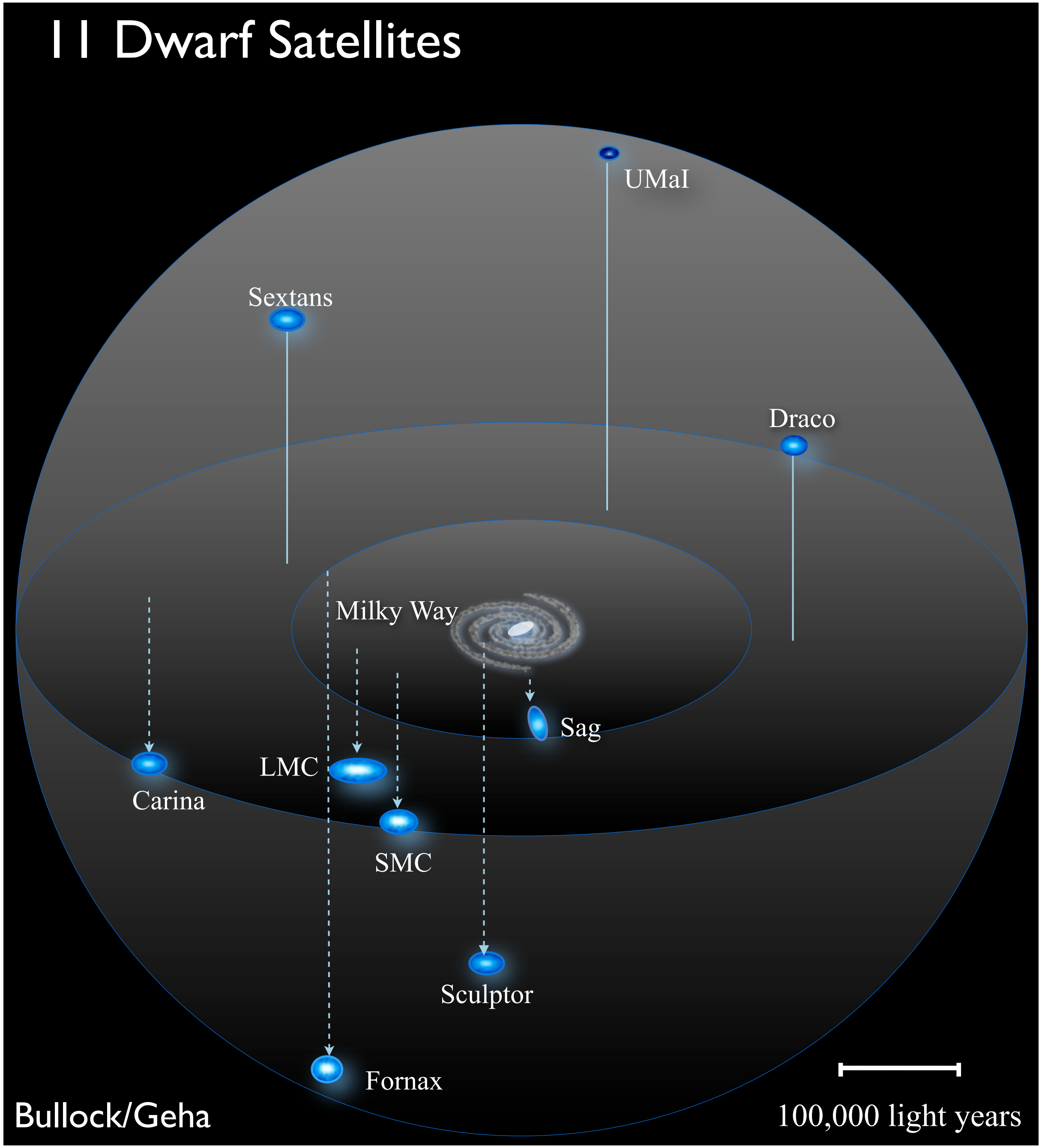
Observation: N_{bright}~10

Klypin et al. 1999

Milky Way 2004

Fornax:





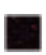
Milky Way 2012

Fornax (1938):

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

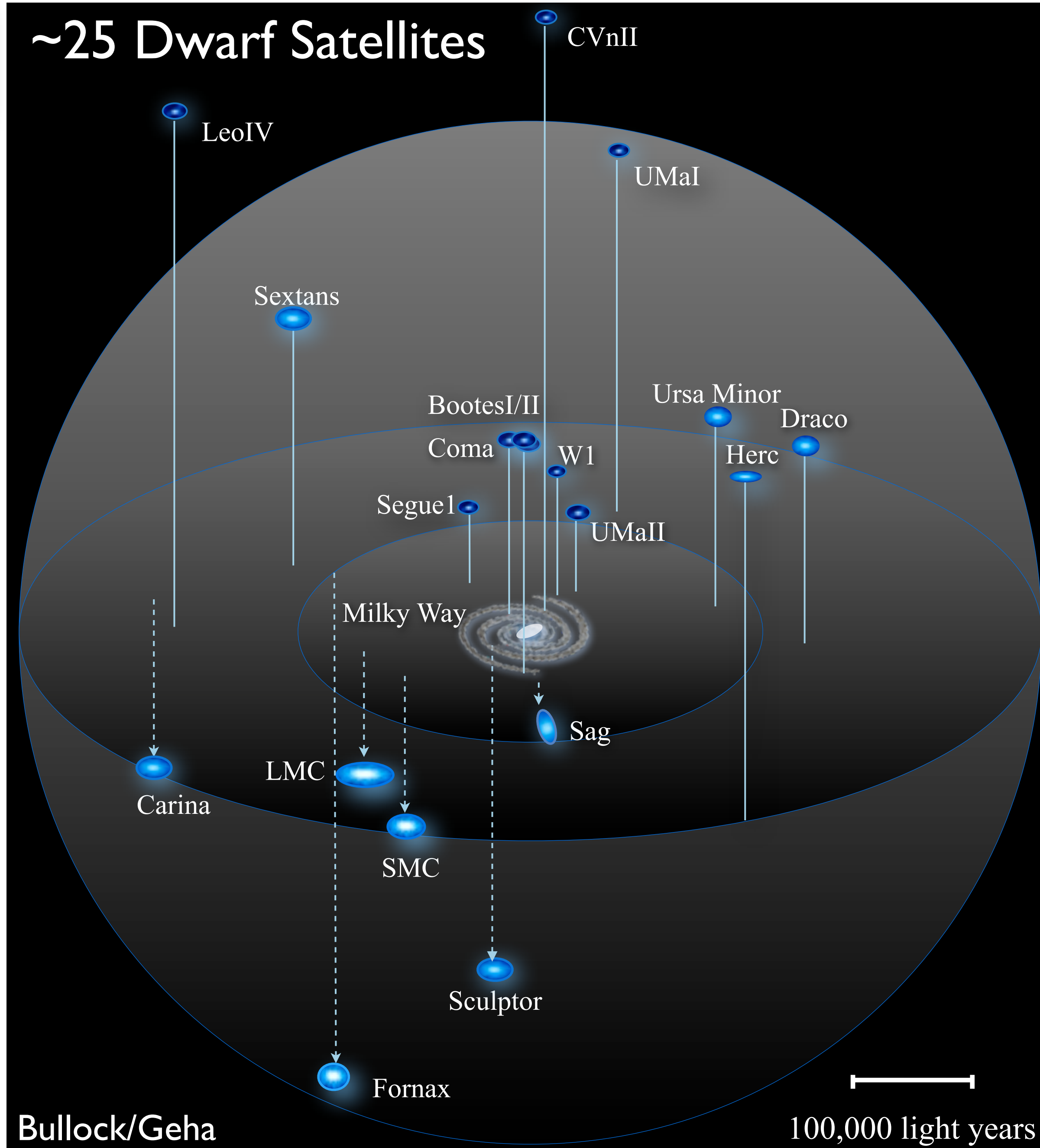
~1000 pc

Segue 1 (2006):

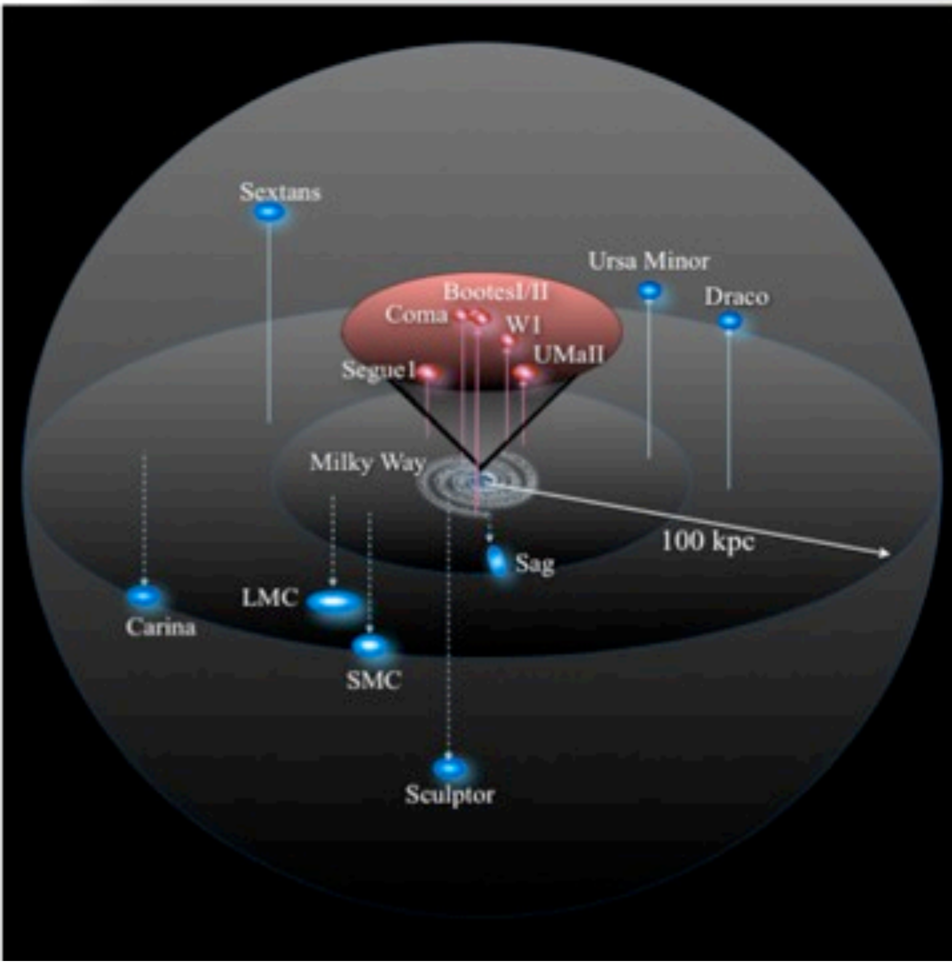


$L \sim 300 \, L_{sun}$

~100 pc



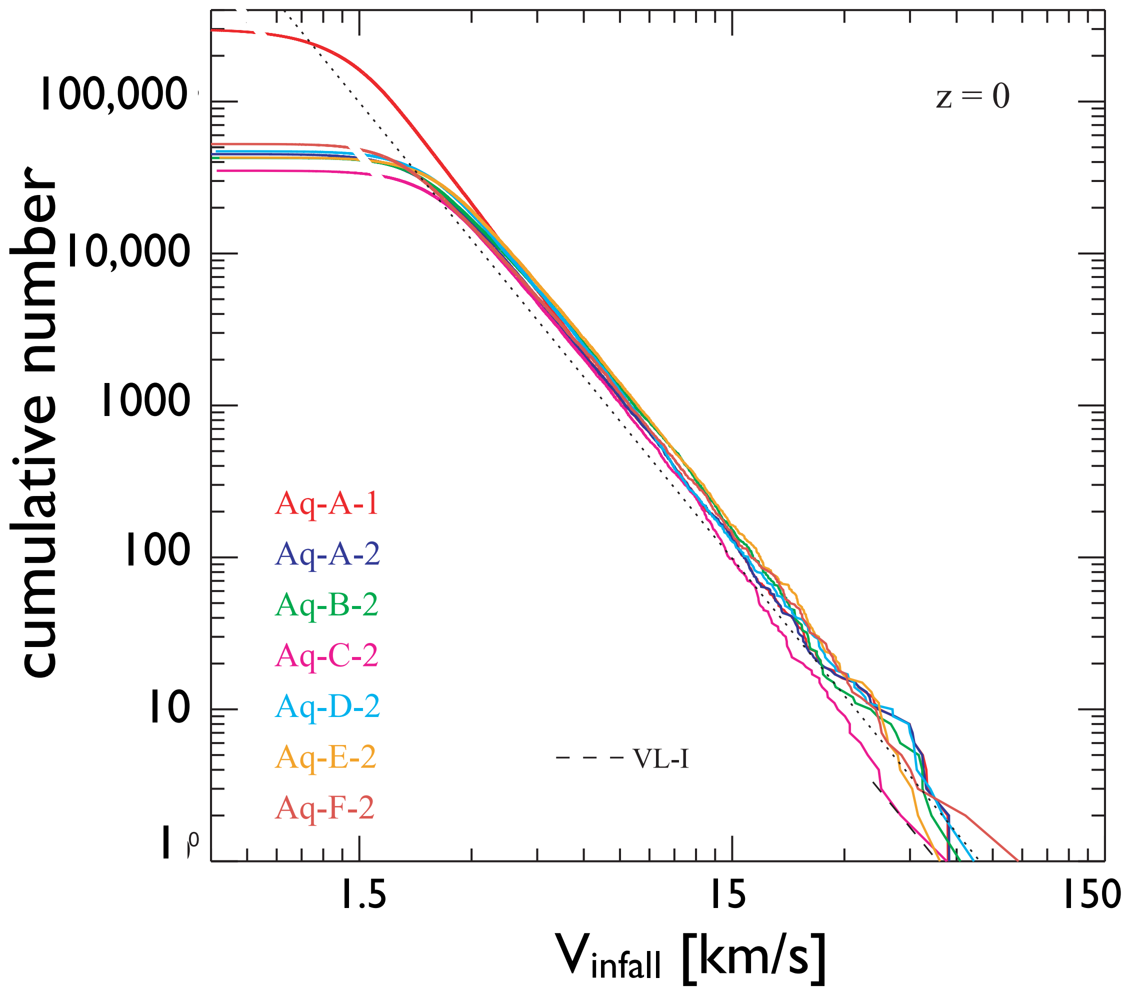
Probably ~100's more faint dwarfs to be discovered



Tollerud et al. 08

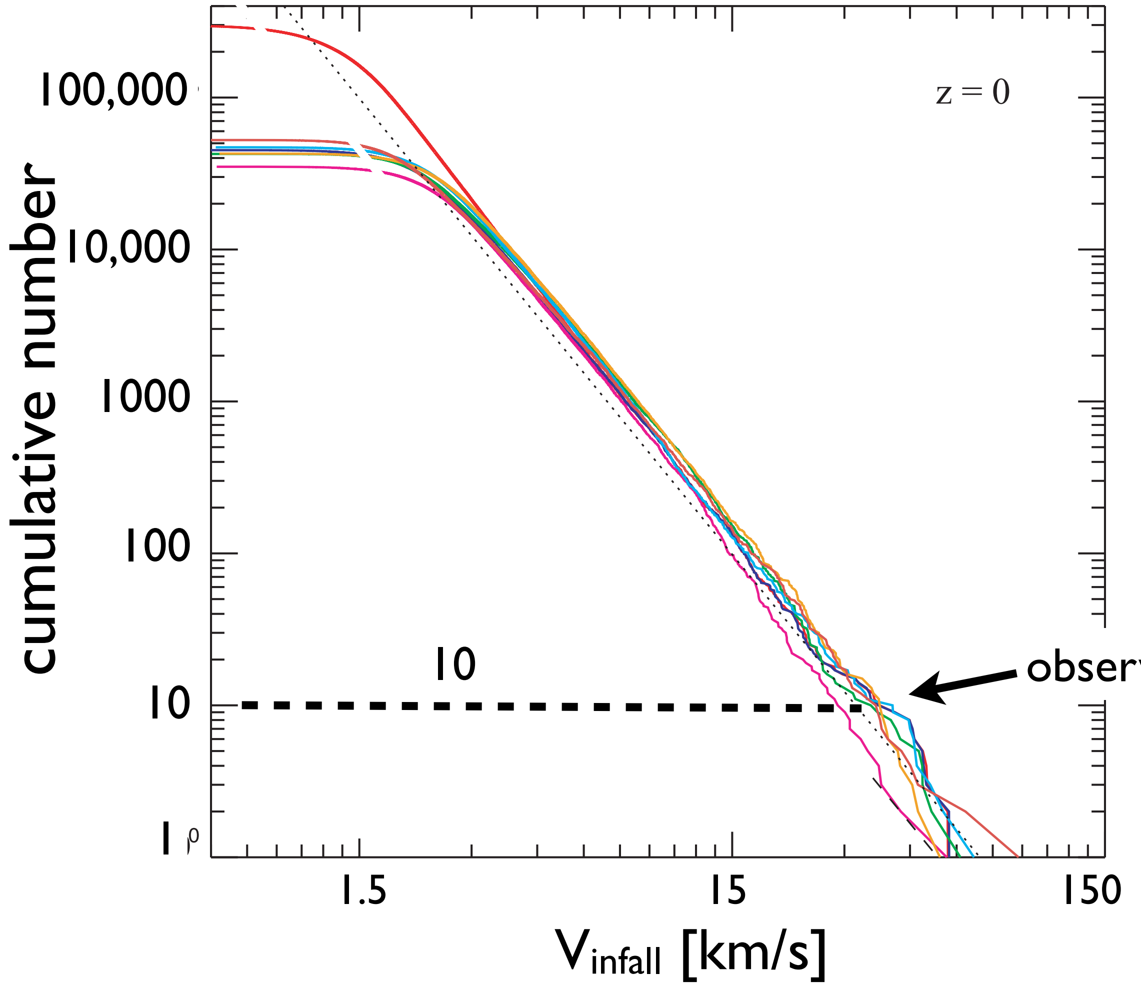
See also:
Koposov et al. 2007, Walsh et al. 2009, JSB et al. 2010

A seductive story...



Springel et al. 2008
(Aquarius project)

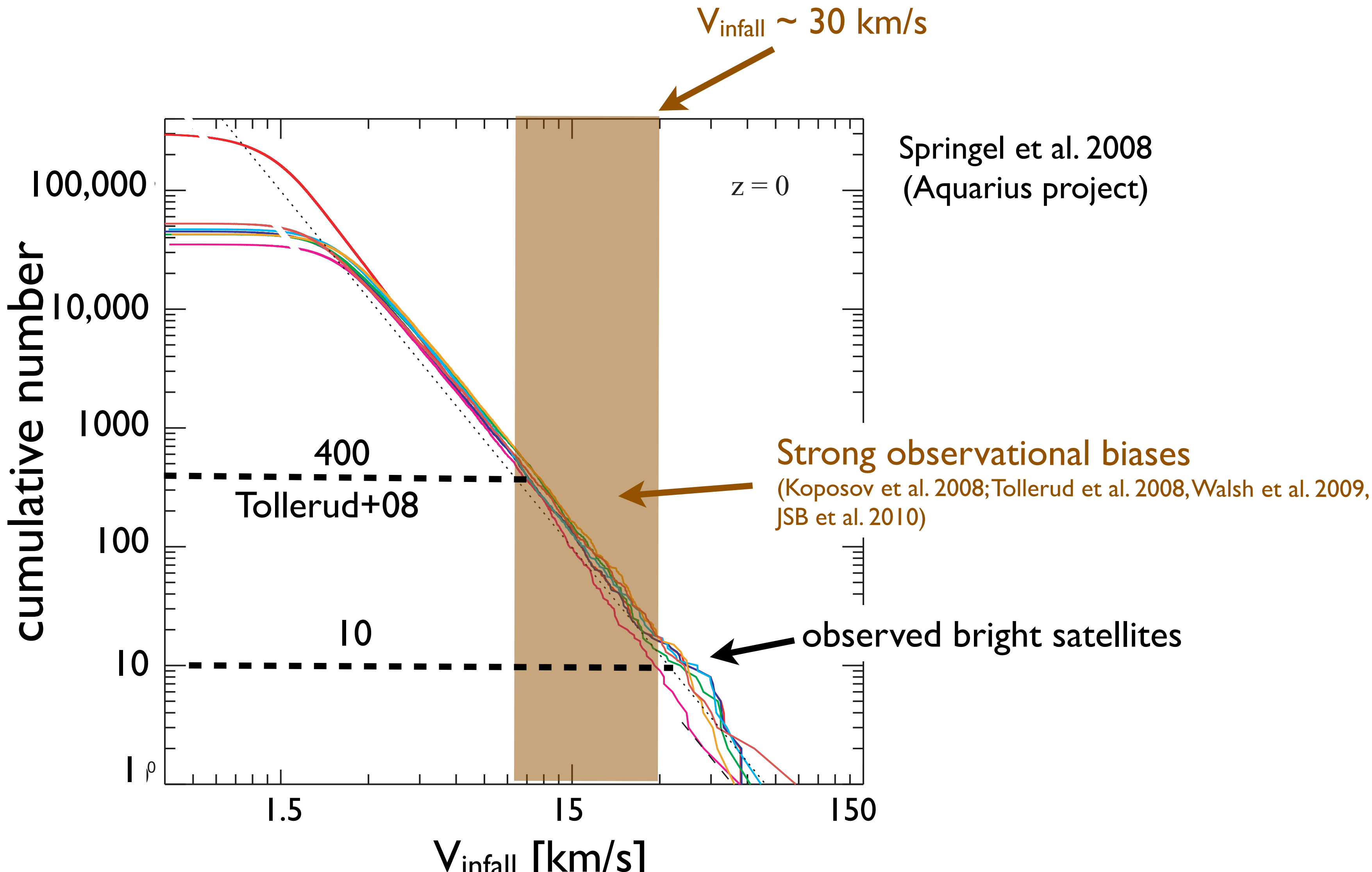
A seductive story...



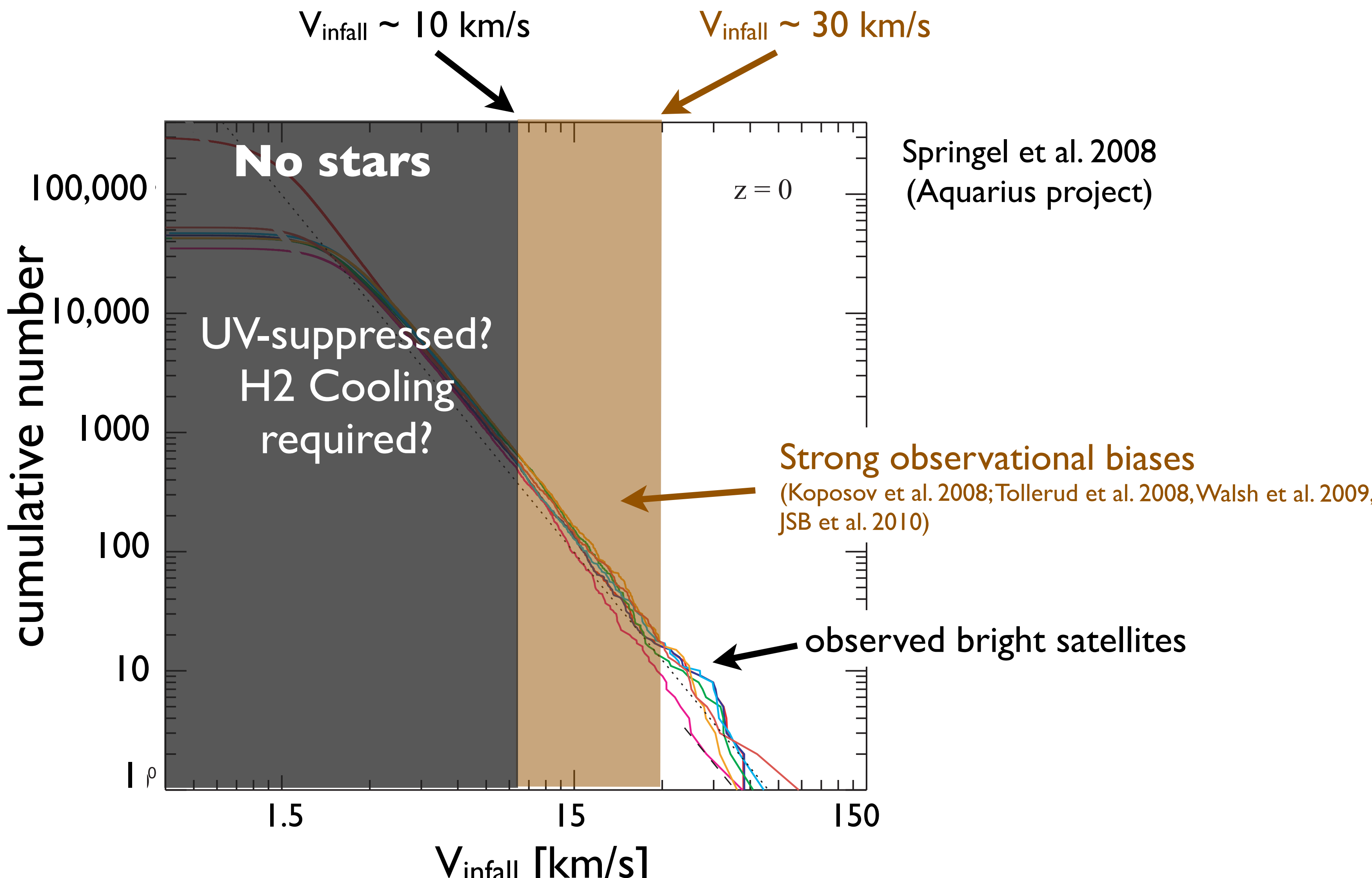
Springel et al. 2008
(Aquarius project)

observed bright satellites

A seductive story...



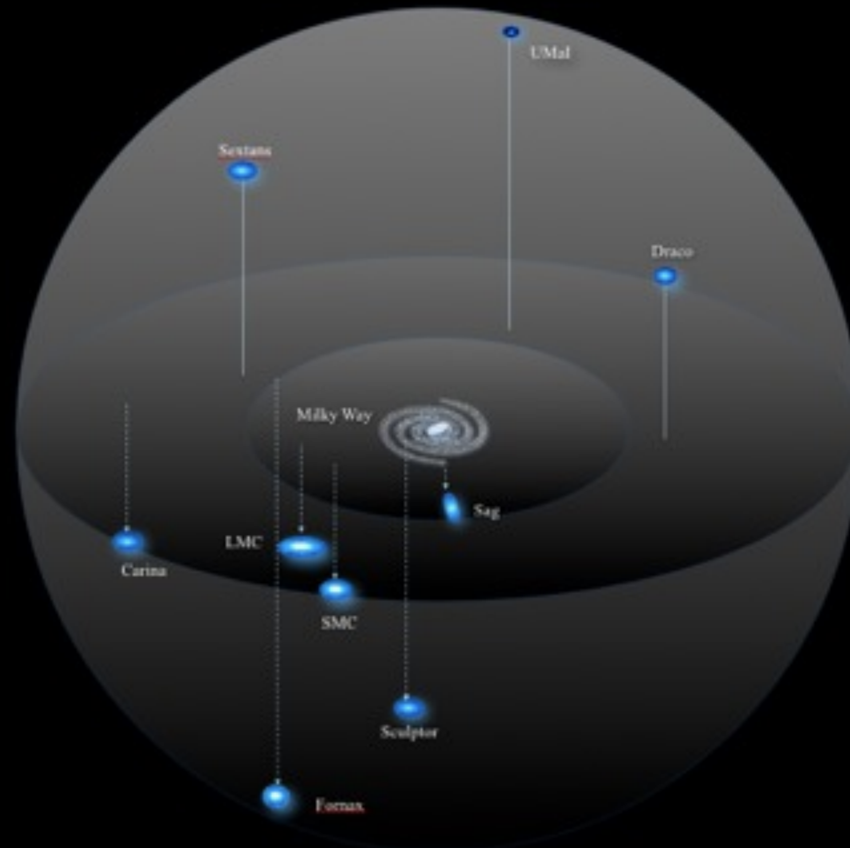
A seductive story...



Springel et al. 2008
(Aquarius project)

Does this actually work?

Theory: N>>1000

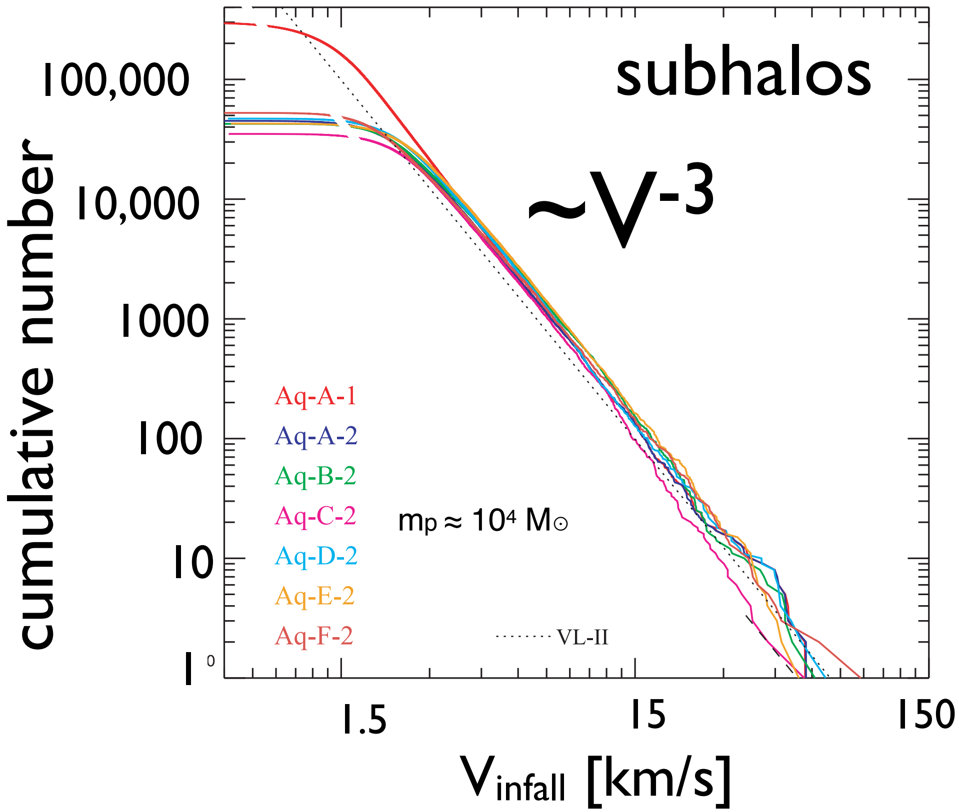


Observation: N_{bright}~10

Klypin et al. 1999

Abundance matching for satellite galaxies

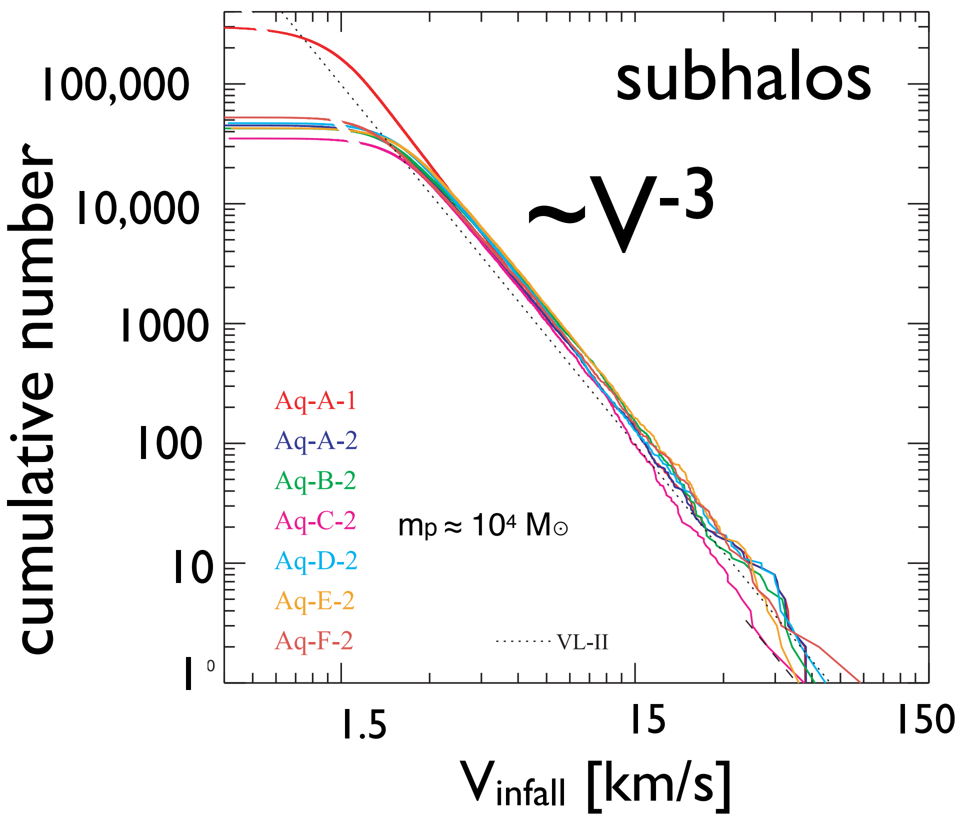
V_{max} function



Springel et al. 2008; Aquarius project

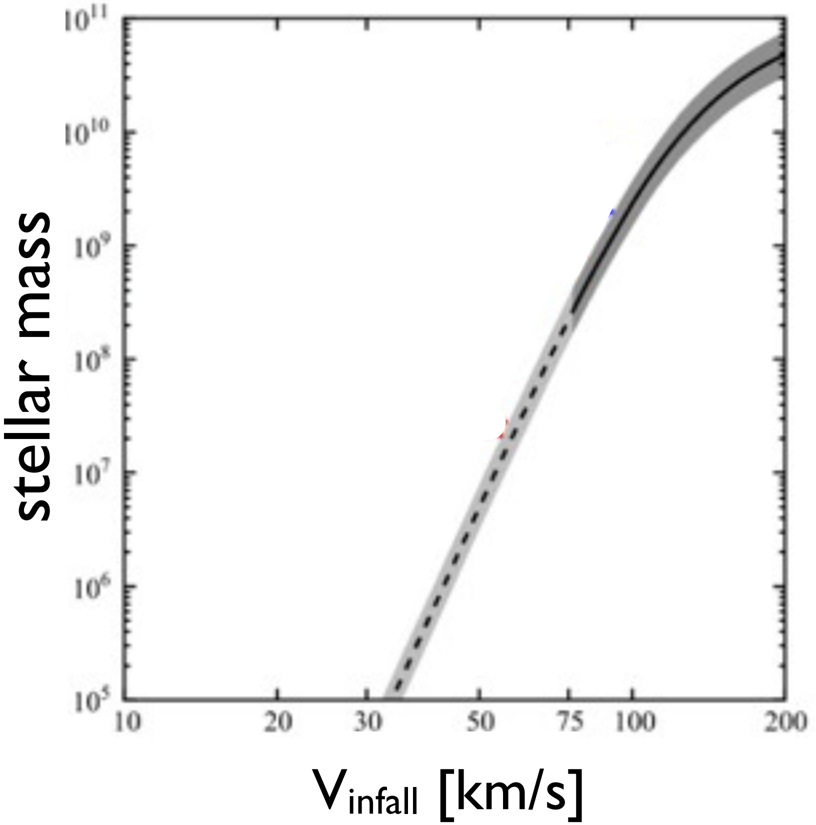
Abundance matching for satellite galaxies

V_{max} function



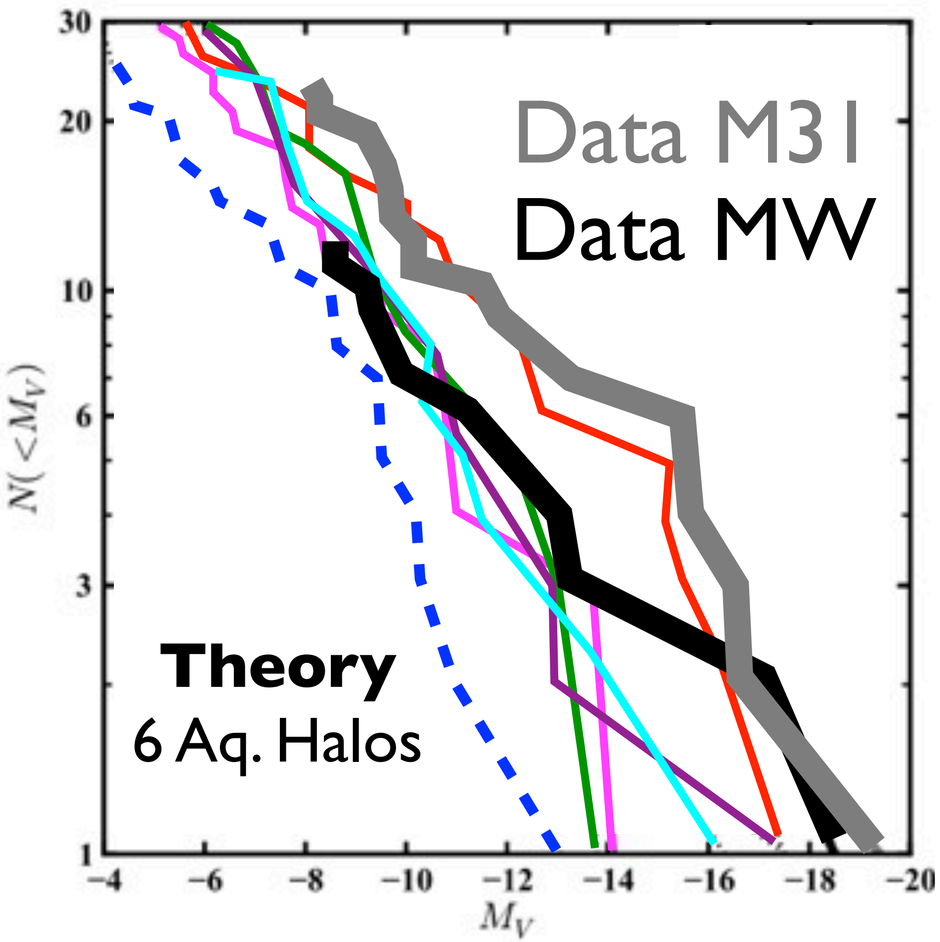
Springel et al. 2008; Aquarius project

Stellar mass mapping



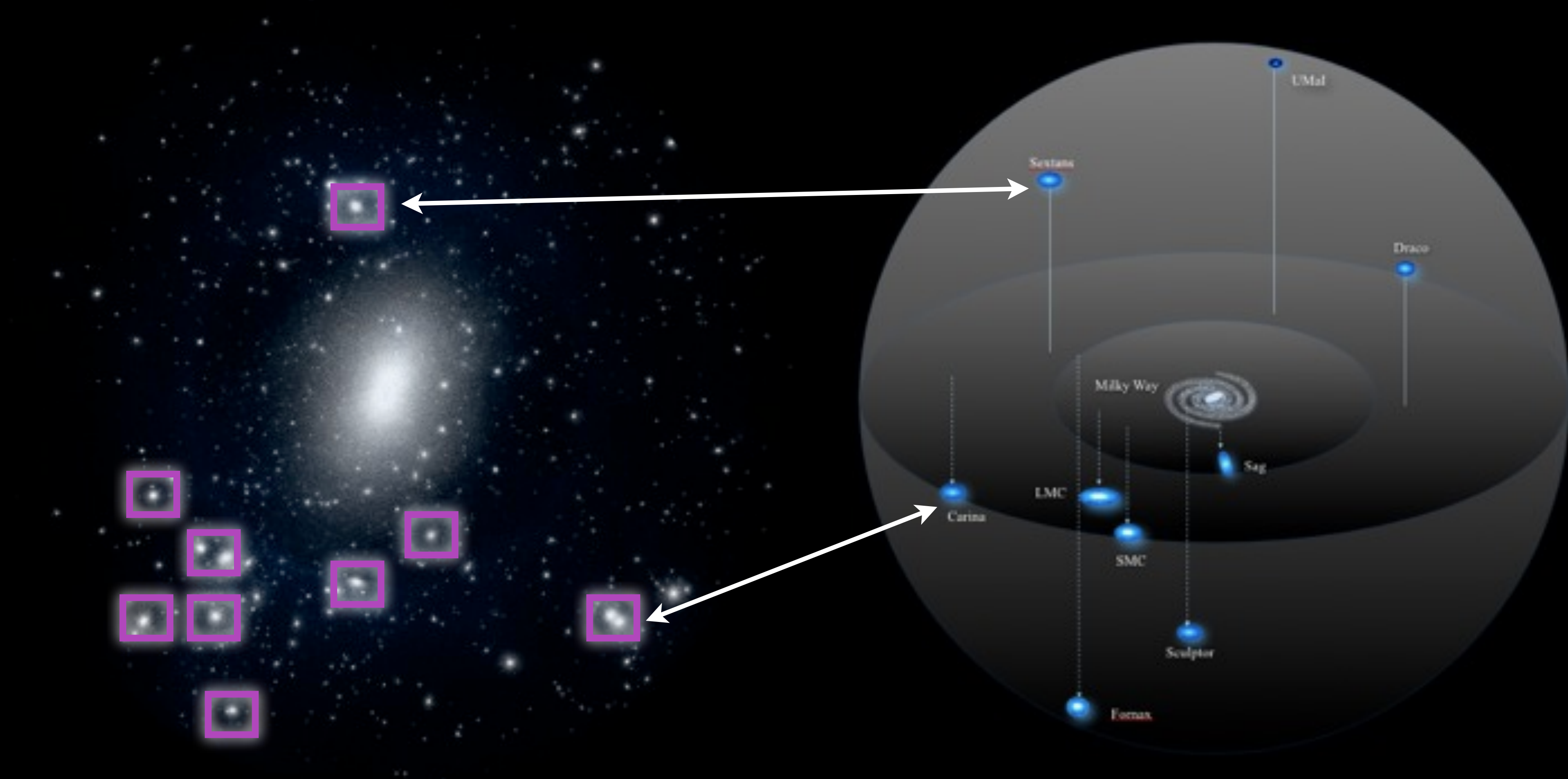
Boylan-Kolchin et al. 2012

Abundance Matching: can reproduce obs. LF



Boylan-Kolchin et al. 2011b

How do the masses compare?

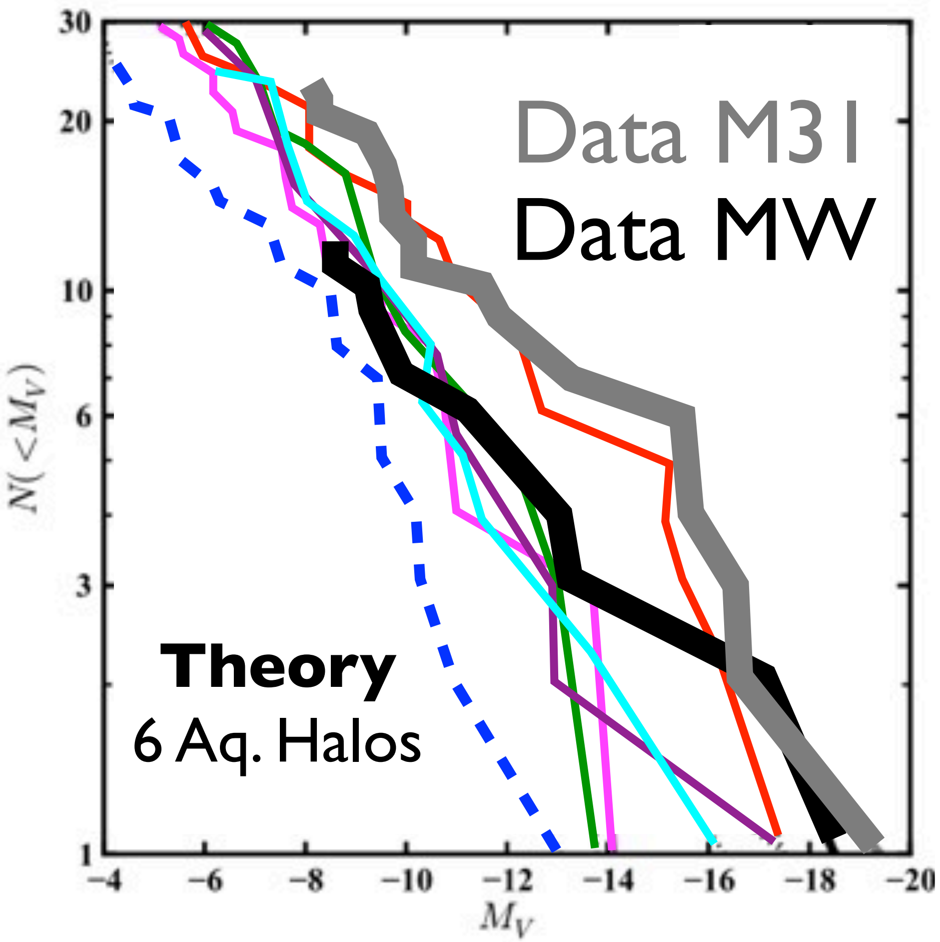


Theory: N>>1000

Observation: N_{bright}~10

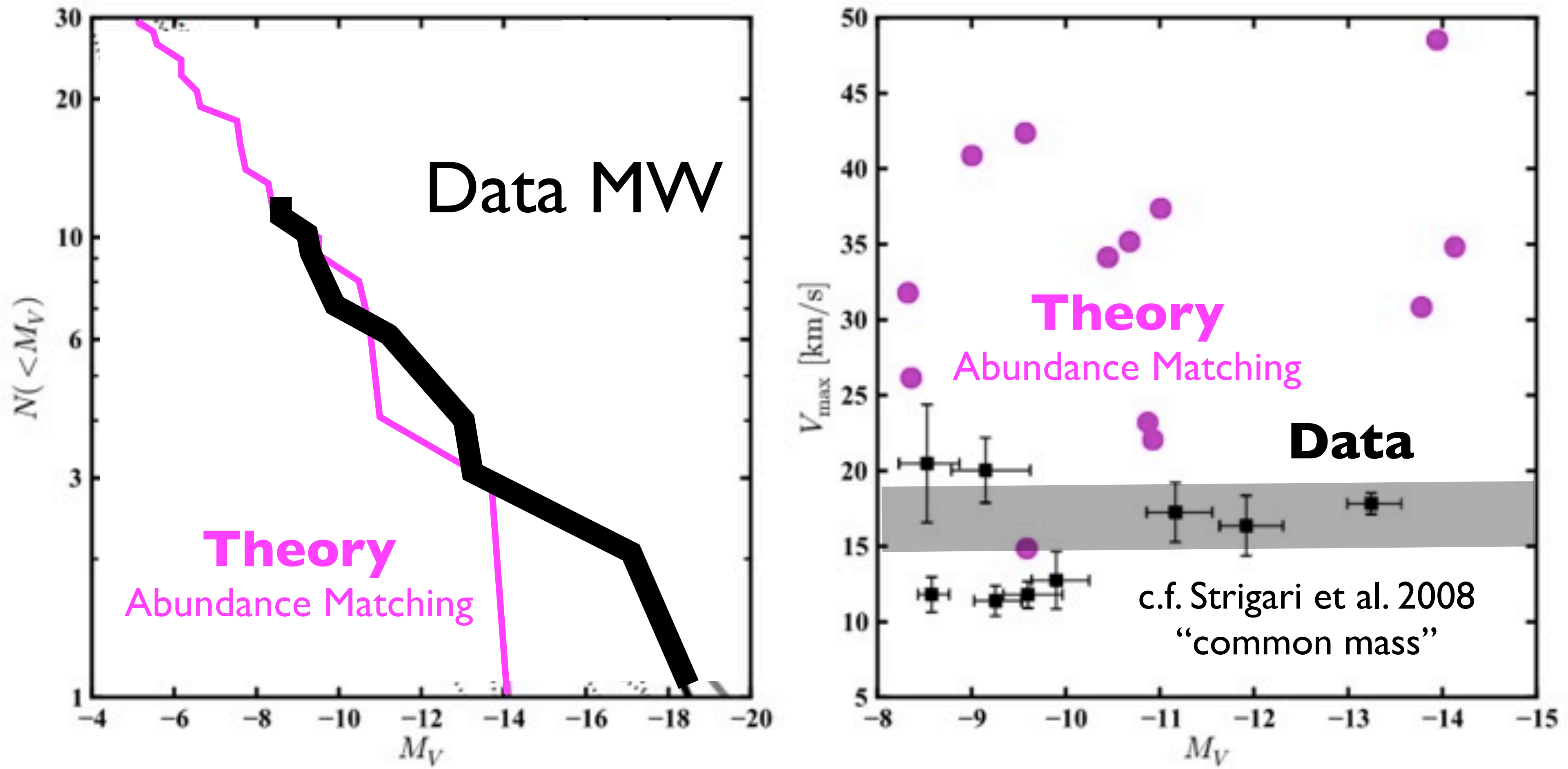
Klypin et al. 1999

Abundance Matching: can reproduce obs. LF



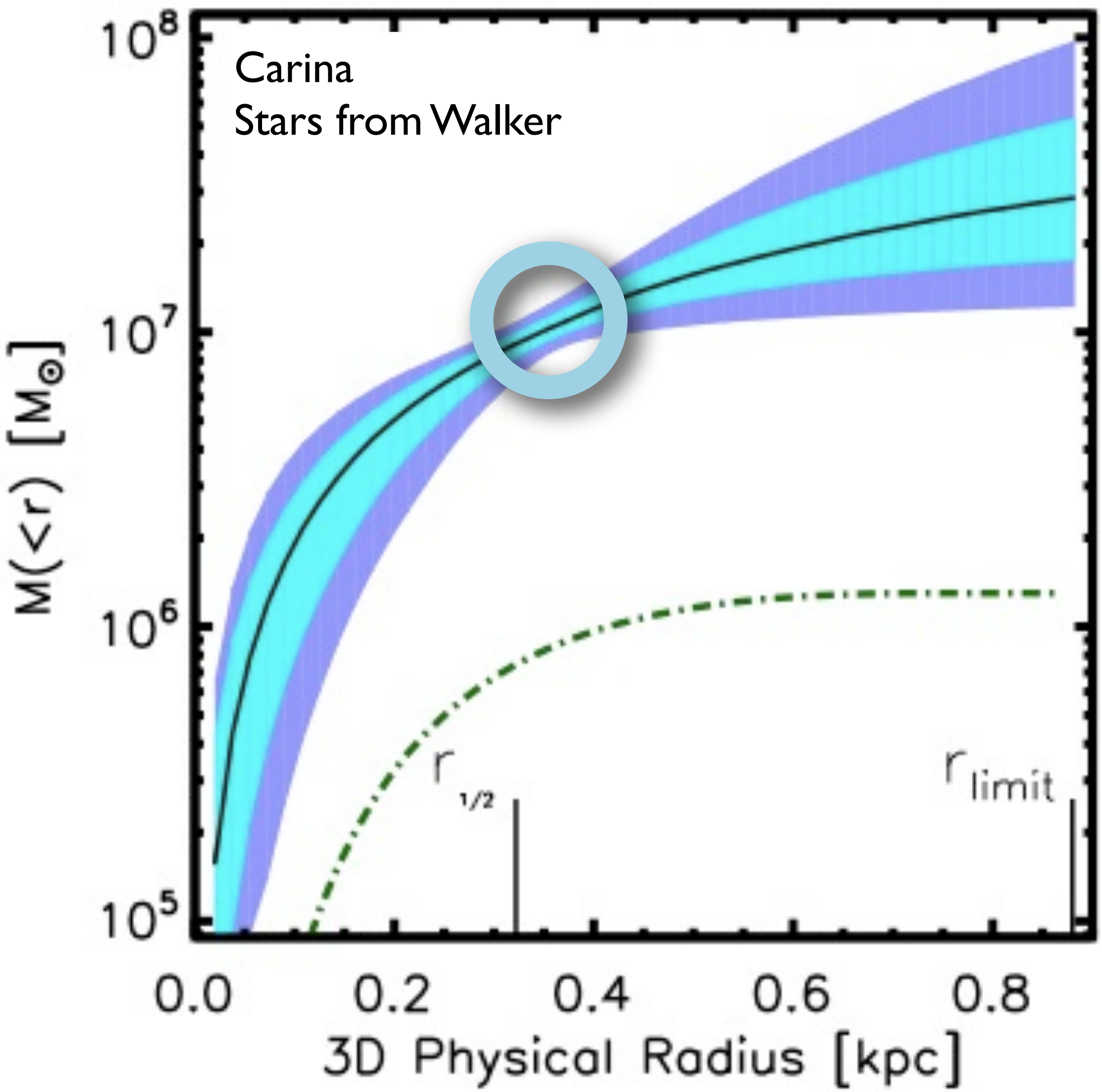
Boylan-Kolchin et al. 2011b

Abundance Matching: can reproduce obs. LF



Boylan-Kolchin et al. 2011b

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



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

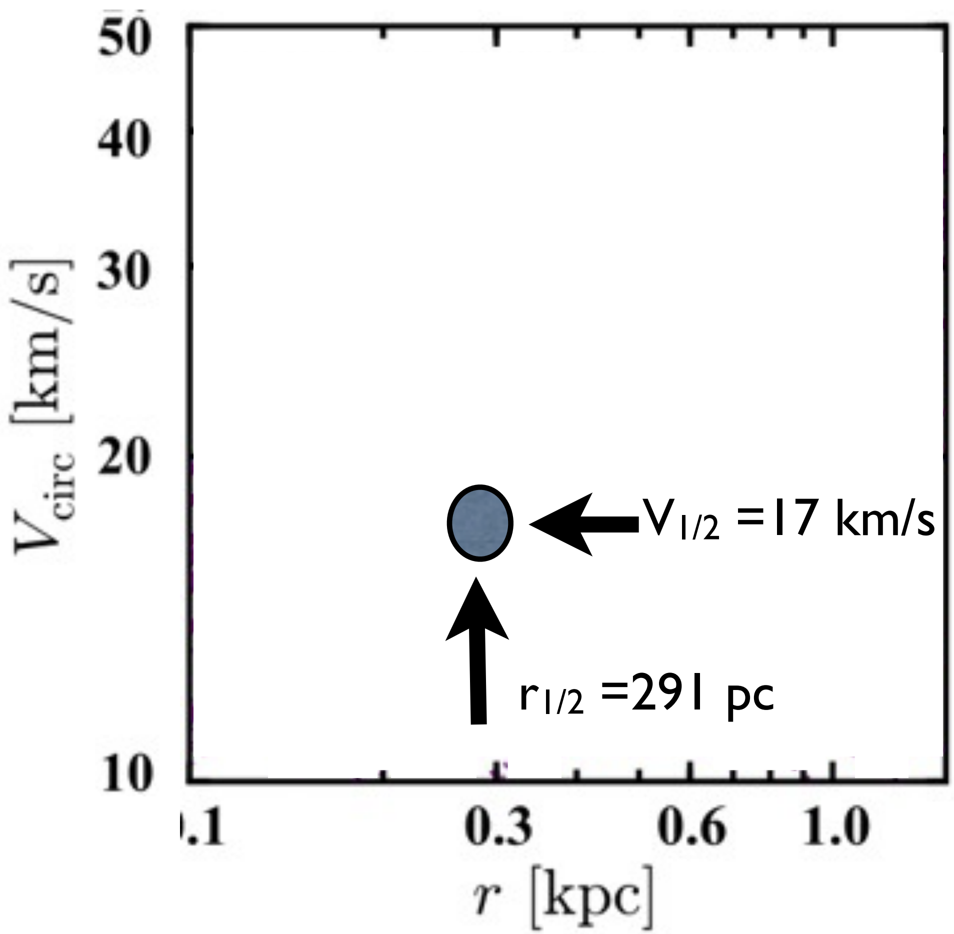
Wolf et al. 2010

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

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

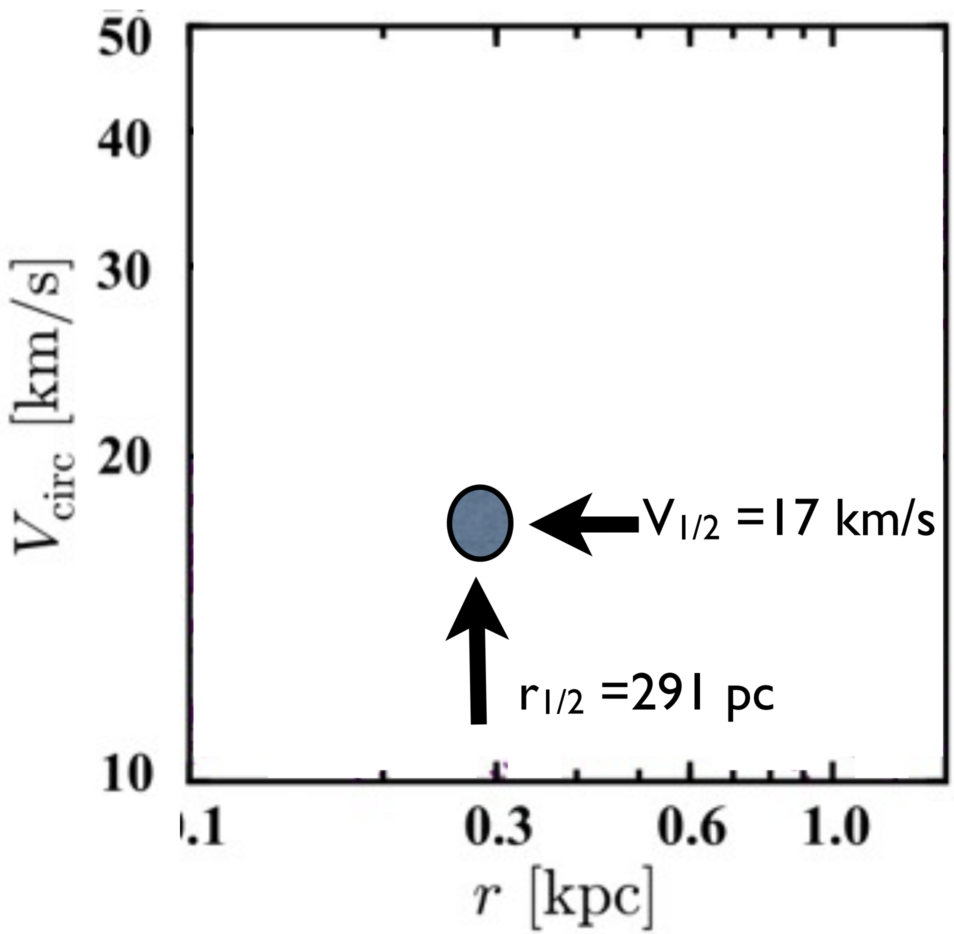
Example of kinematic constraint: Draco

Wolf et al. 2010 → $V_c(r_{1/2}) = \sqrt{3}\,\sigma_* \simeq 17\,\mathrm{km\,s^{-1}}$



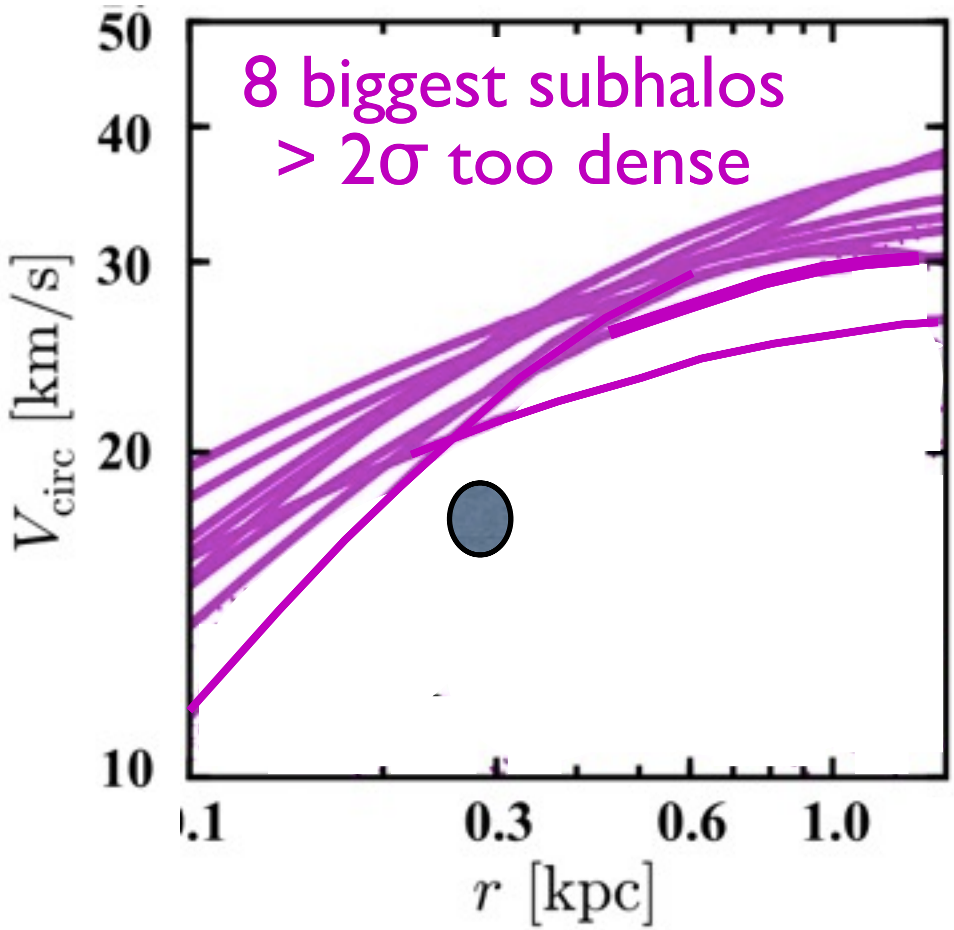
Example of kinematic constraint: Draco

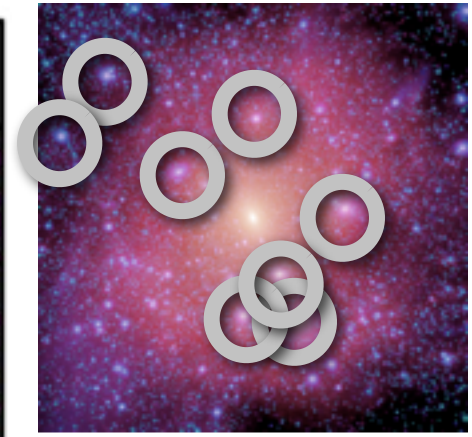
Wolf et al. 2010 → $V_c(r_{1/2}) = \sqrt{3}\,\sigma_* \simeq 17\,\mathrm{km\,s^{-1}}$



Example of kinematic constraint: Draco

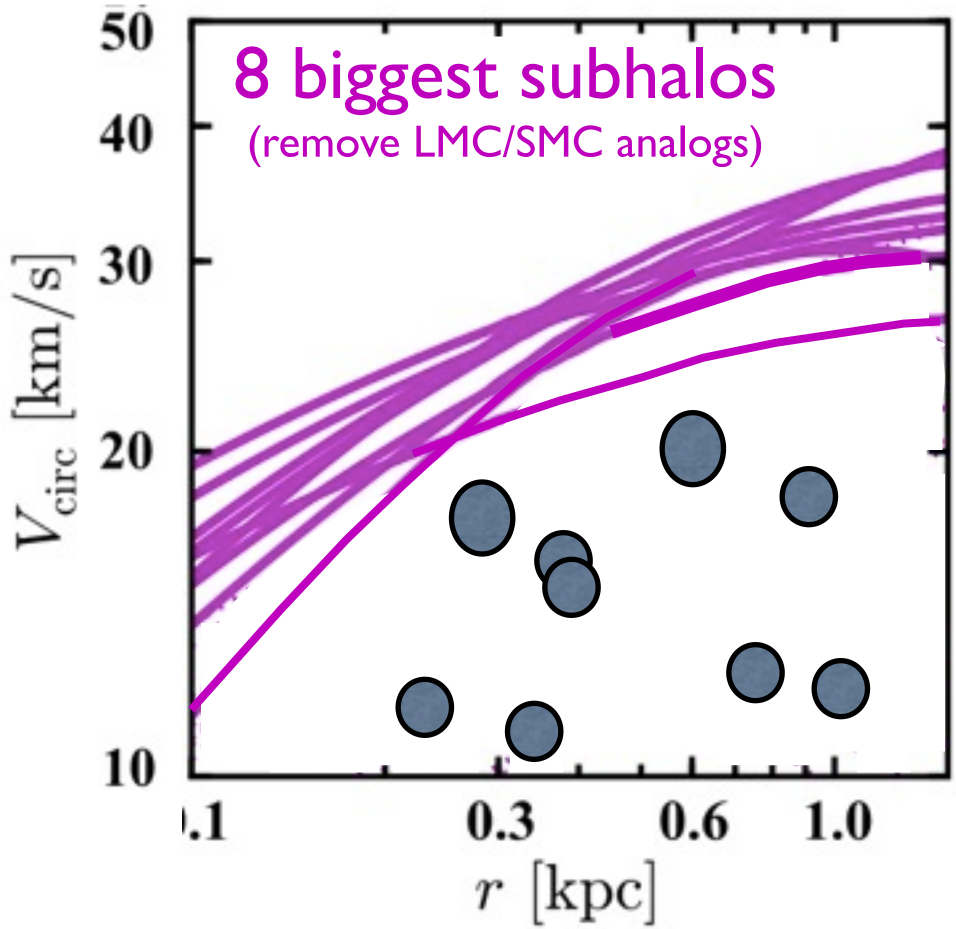
Wolf et al. 2010 → $V_c(r_{1/2}) = \sqrt{3}\,\sigma_* \simeq 17\,\mathrm{km\,s^{-1}}$

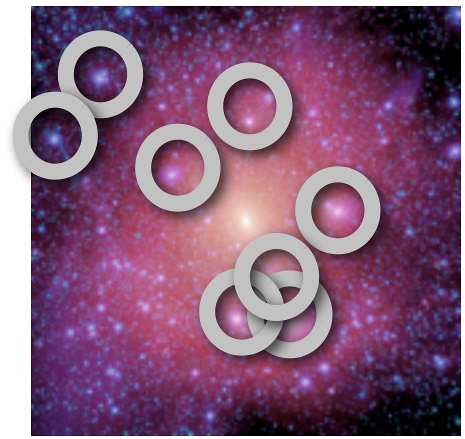




Springel et al. 2008
(Aquarius project)

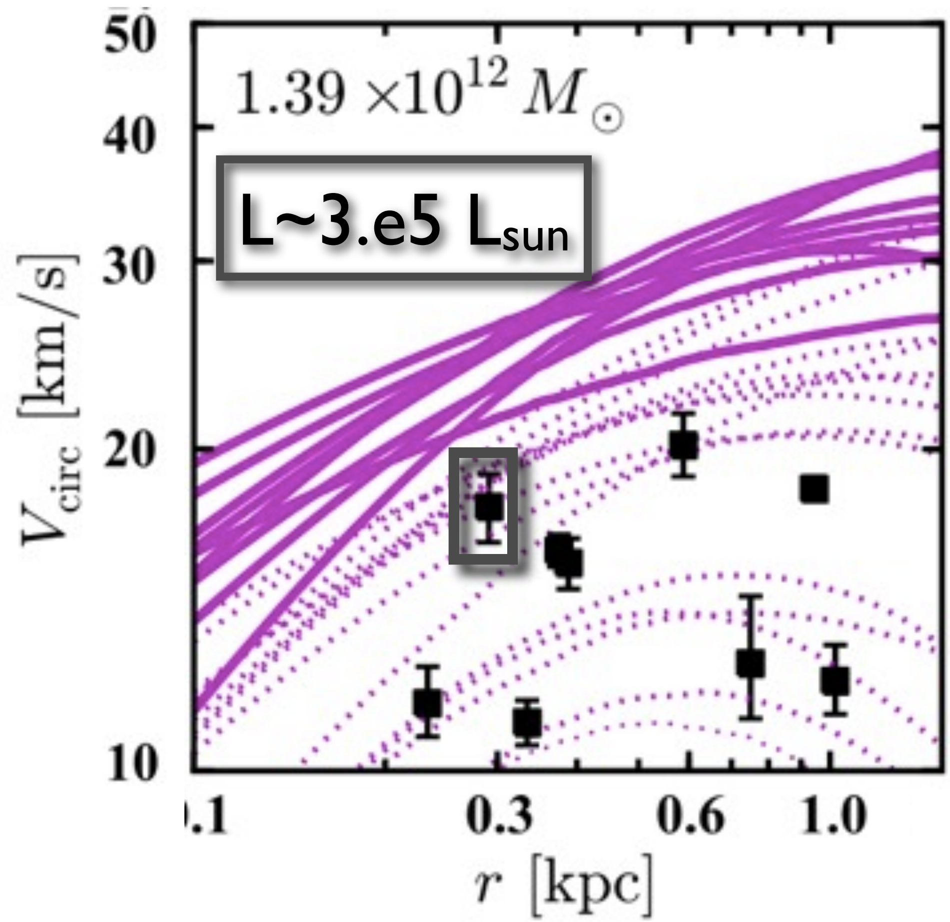
All bright MW dSphs (L>10^5 L$_{sun}$)





8 biggest subhalos are too dense to host ANY of MW dSph satellites

All bright MW dSphs (L>10^5 L_{sun})

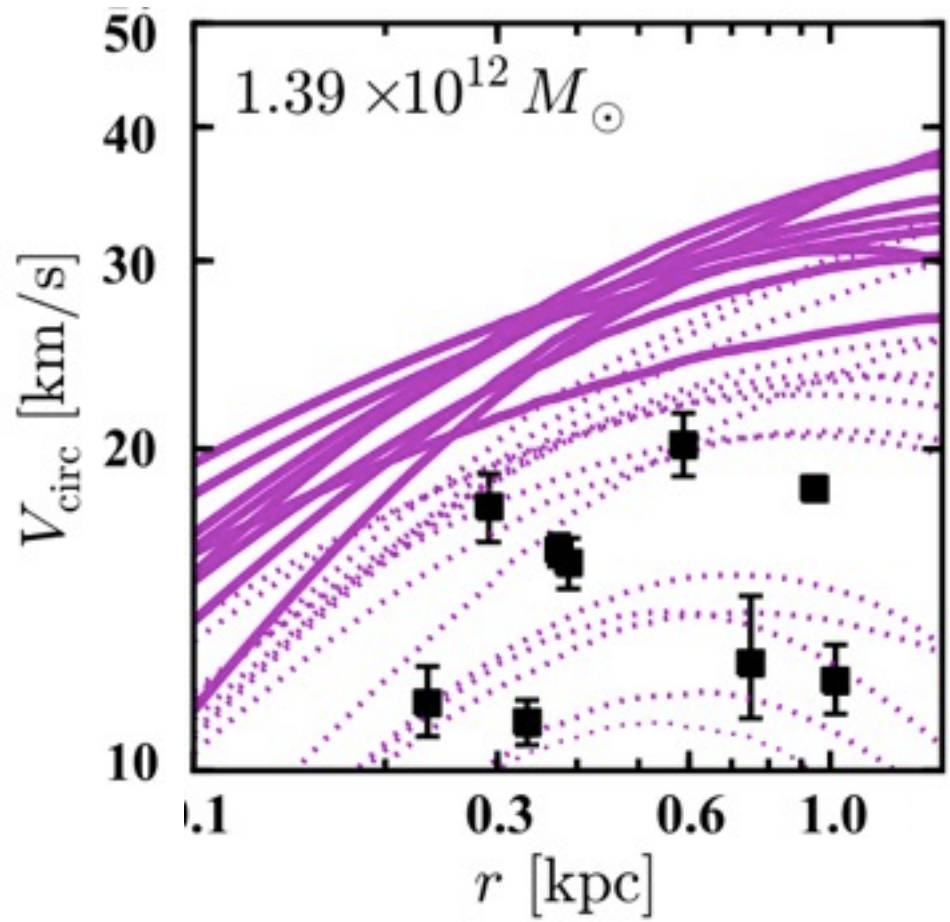


Plotted: all halos with V_{infall} > 30km/s

~15 are unaccounted for

Boylan-Kolchin et al. 2011, 2012

All bright MW dSphs (L>10^5 L_{sun})



Massive Failures:

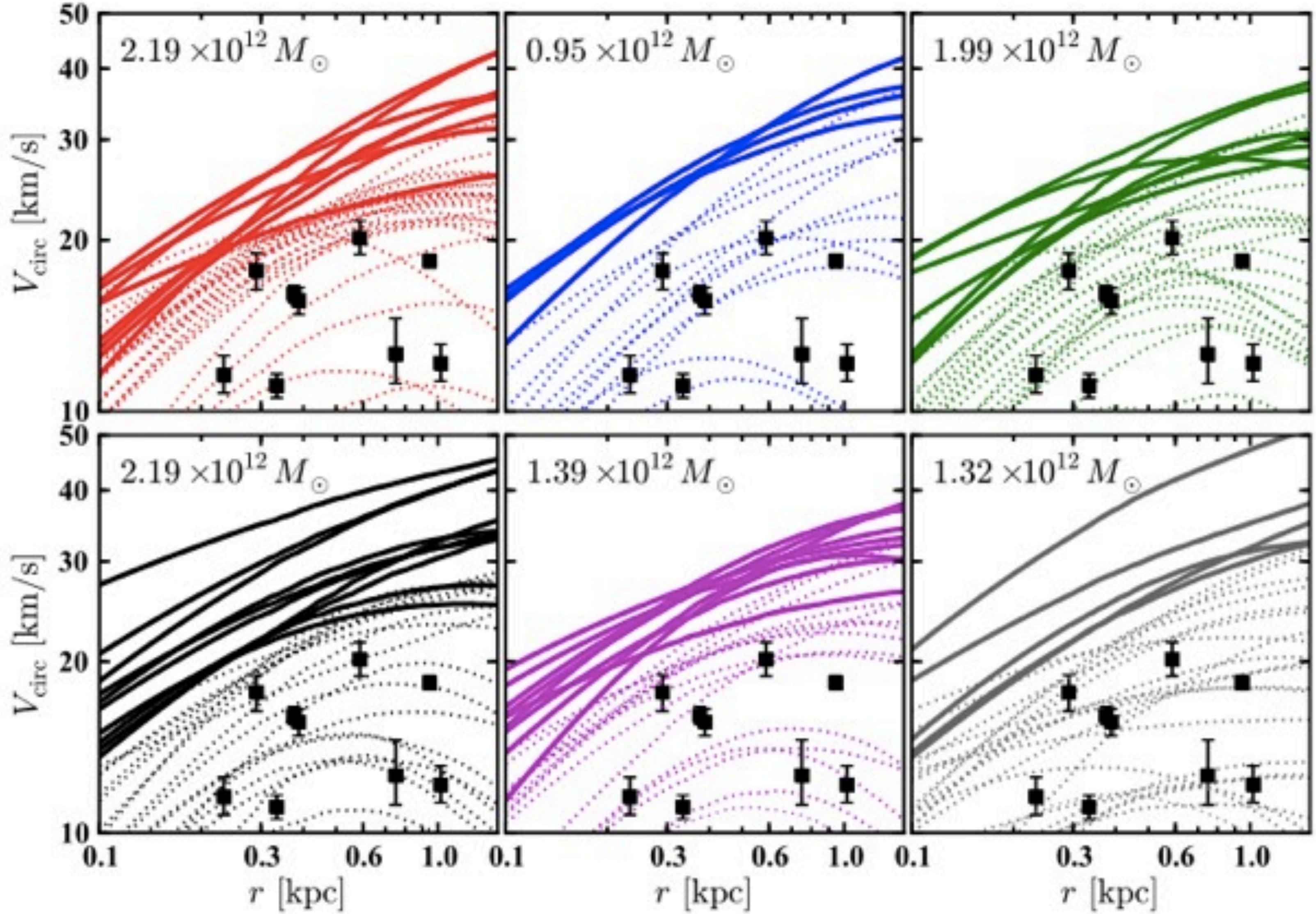
V_{infall} = 30-70 km/s

Plotted: all halos with V_{infall} > 30km/s

~15 are unaccounted for

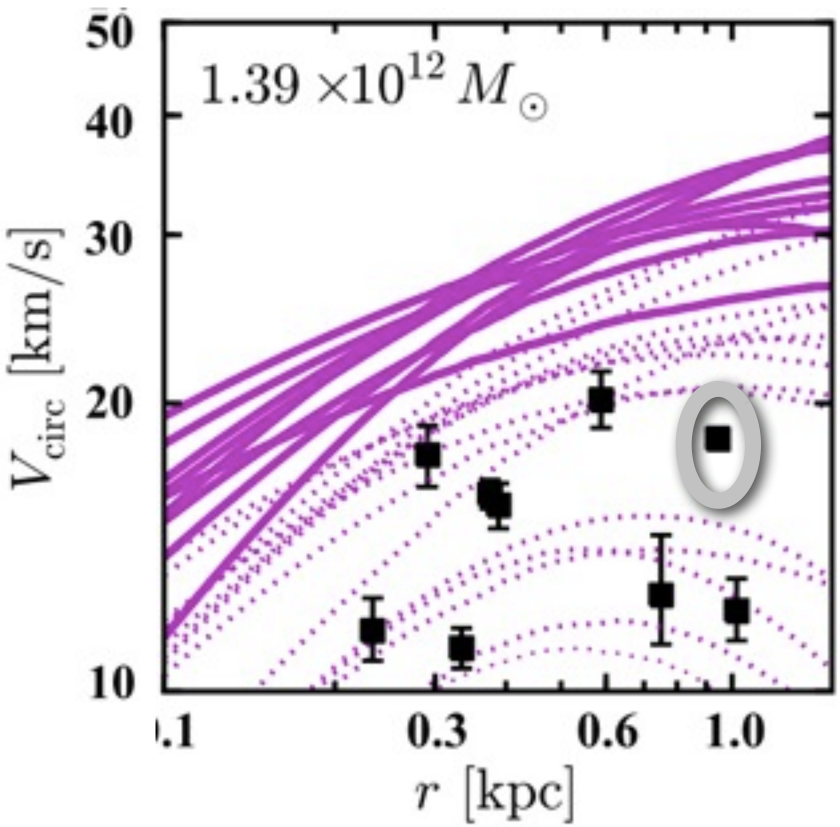
Boylan-Kolchin et al. 2011, 2012

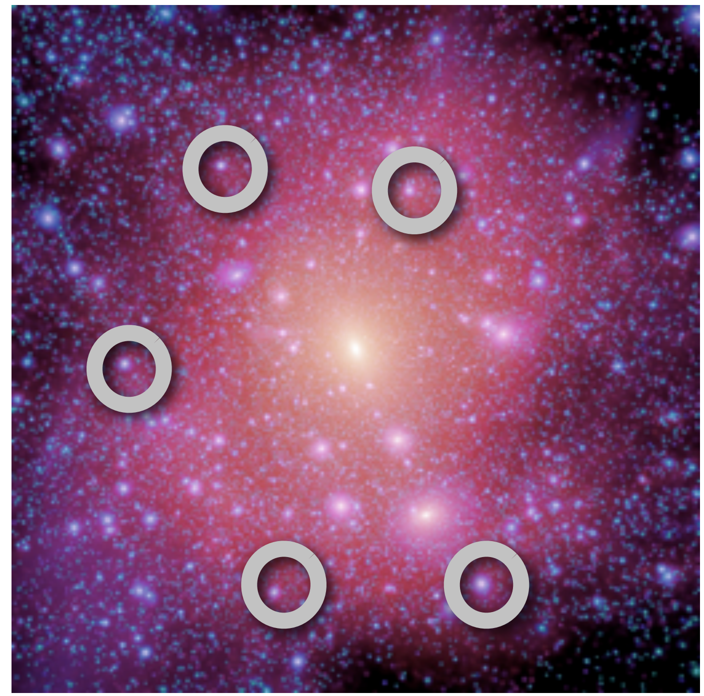
Six Aquarius Halos: ~10-20 massive failures each



Boylan-Kolchin et al. 2011a,b

For subhalos that can match dSphs: how big at infall?

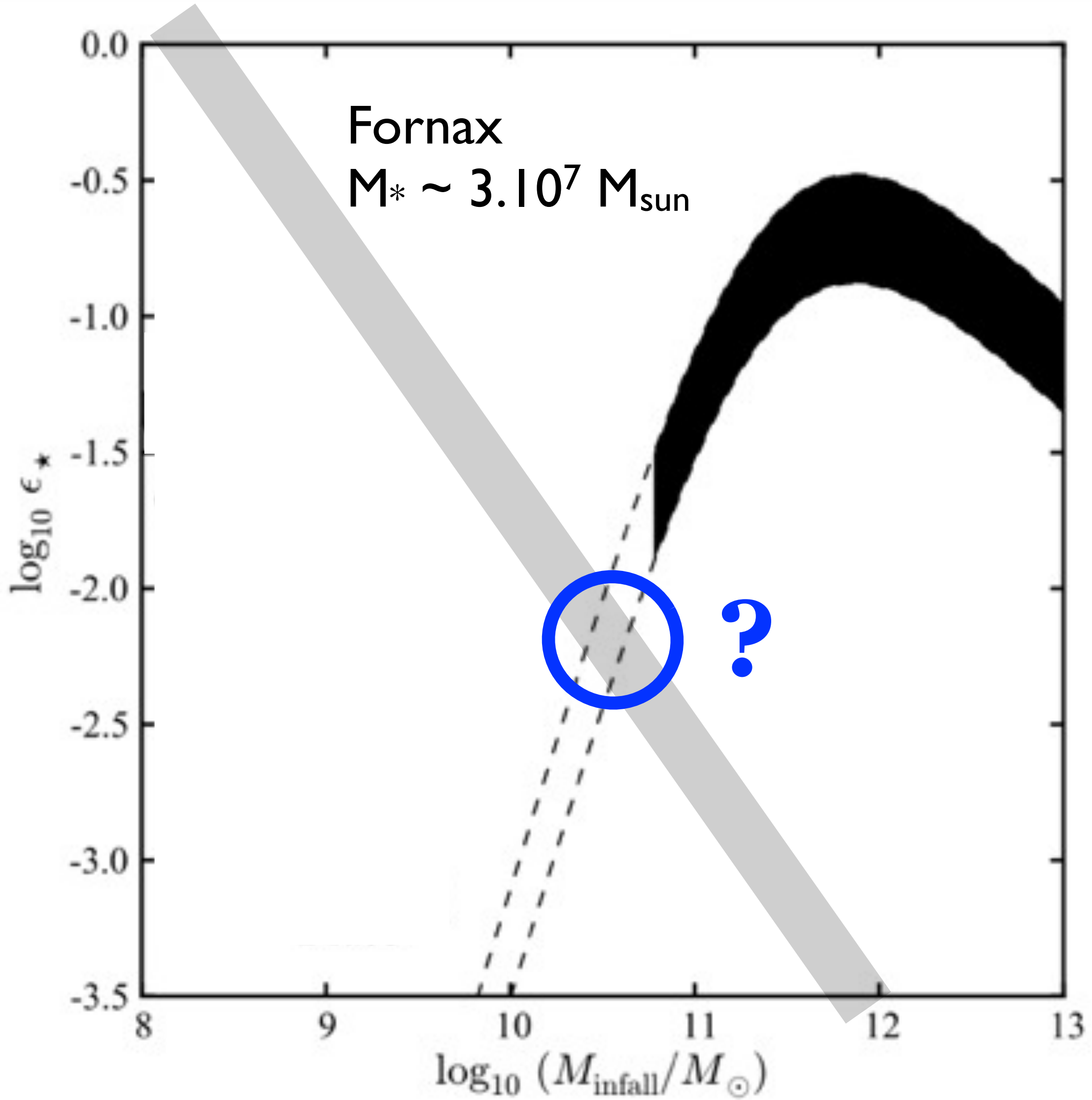




V_{infall} = 15-25 km/s
for all MW dSphs

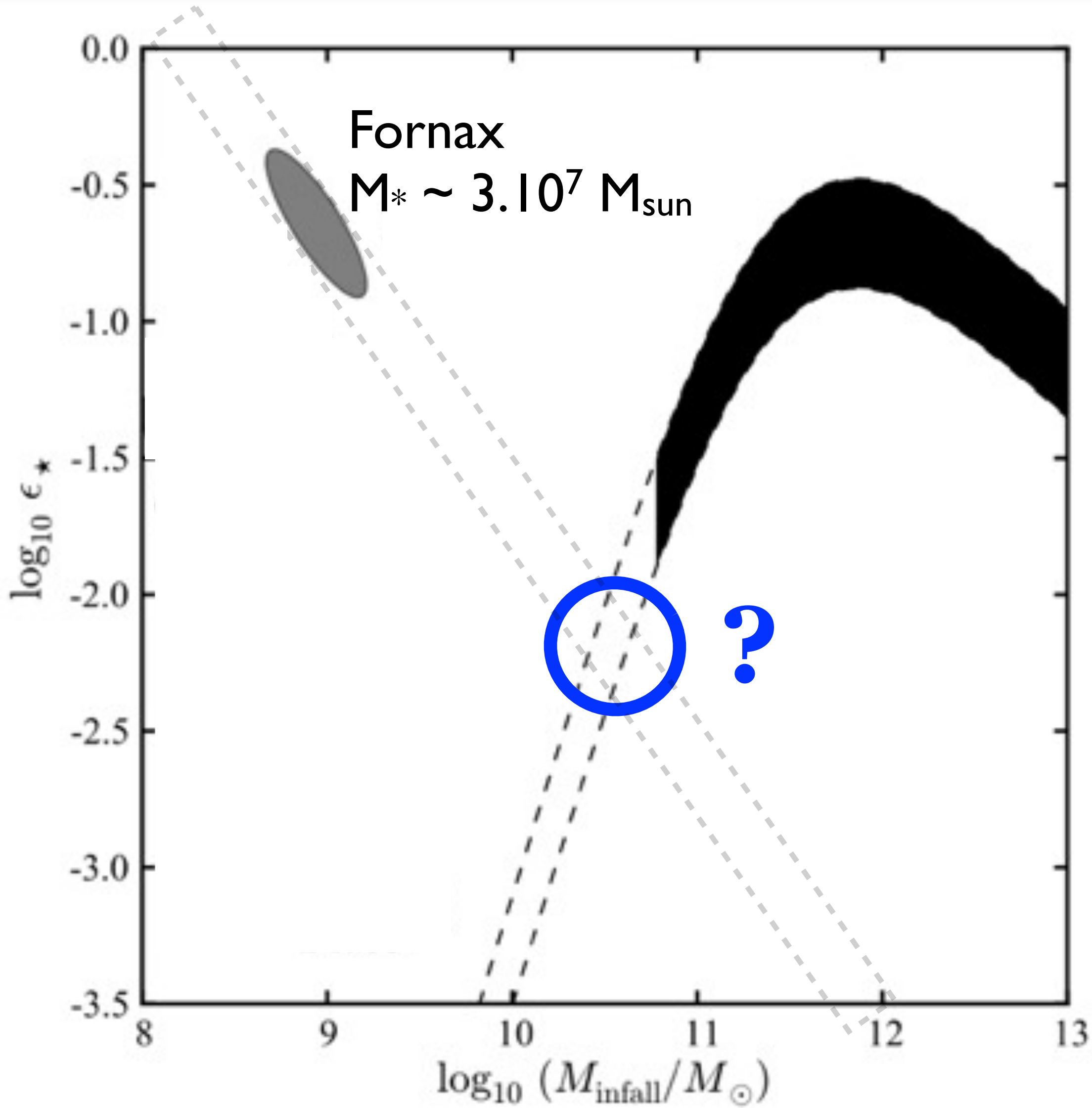
Galaxy formation efficiency

$$\frac{\text{Stellar Mass}}{f_{baryon}{}^{*}M_{dm}}$$



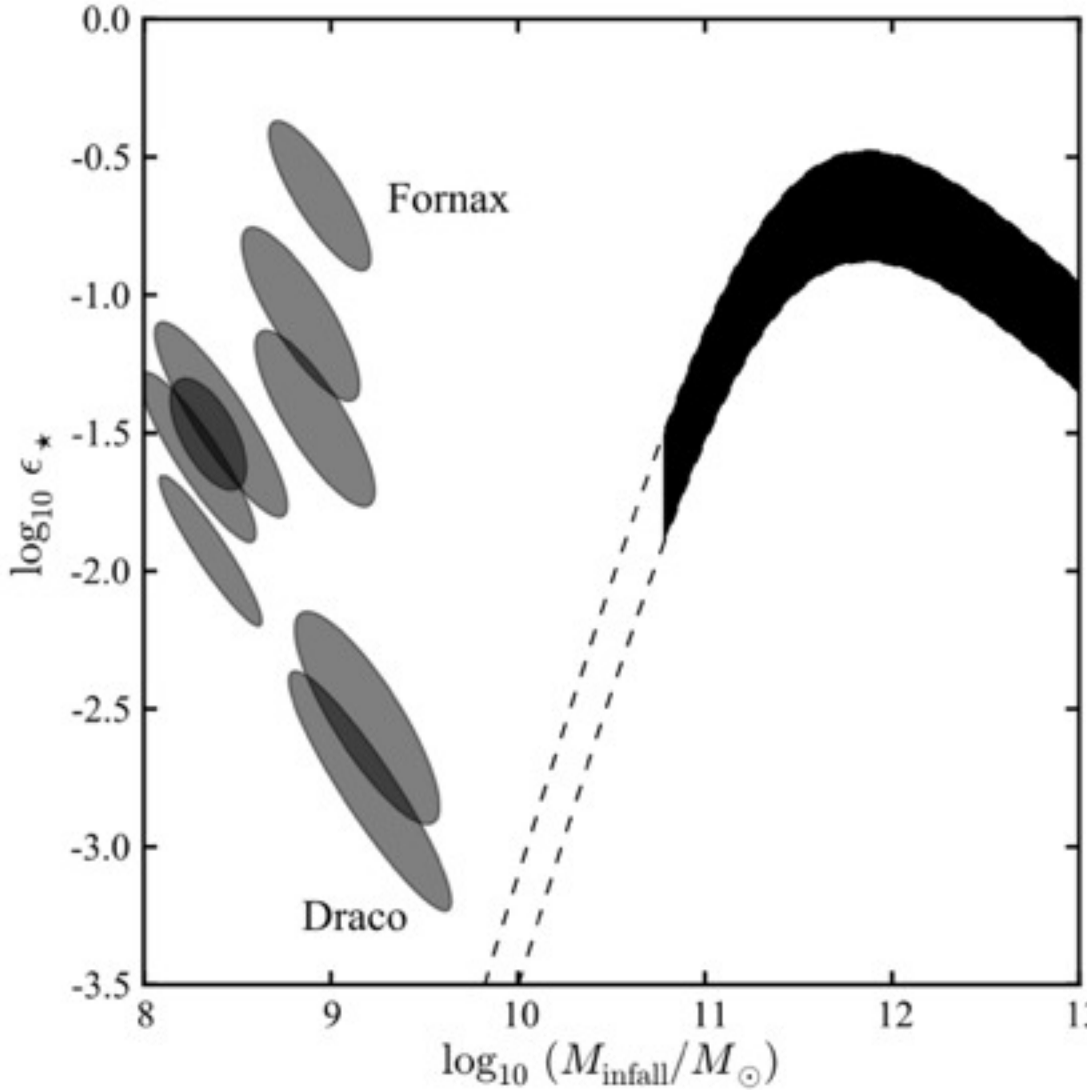
Galaxy formation efficiency

$$\frac{\text{Stellar Mass}}{f_{baryon} * M_{dm}}$$



Galaxy formation efficiency

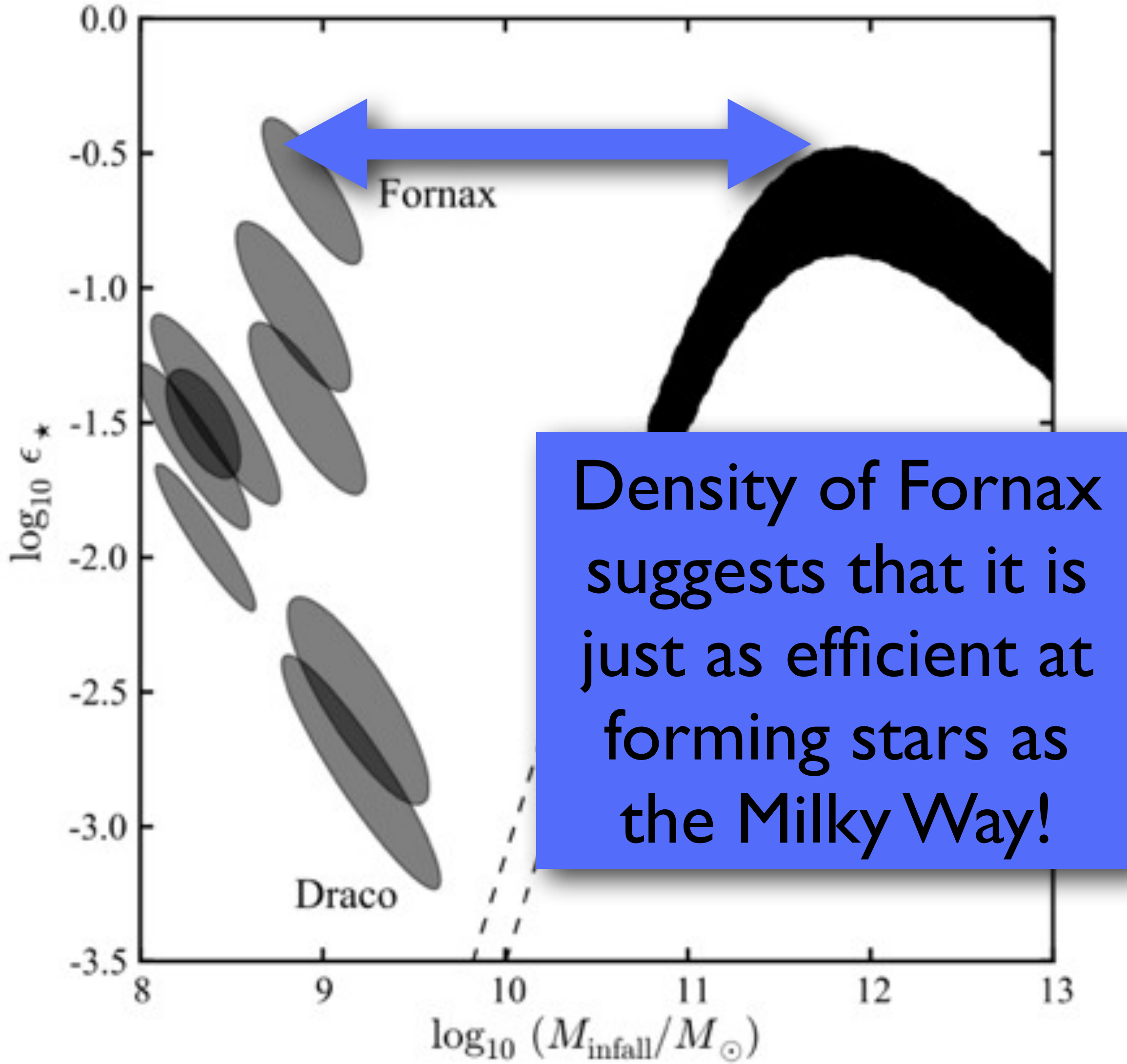
$$\frac{\text{Stellar Mass}}{f_{baryon} * M_{dm}}$$



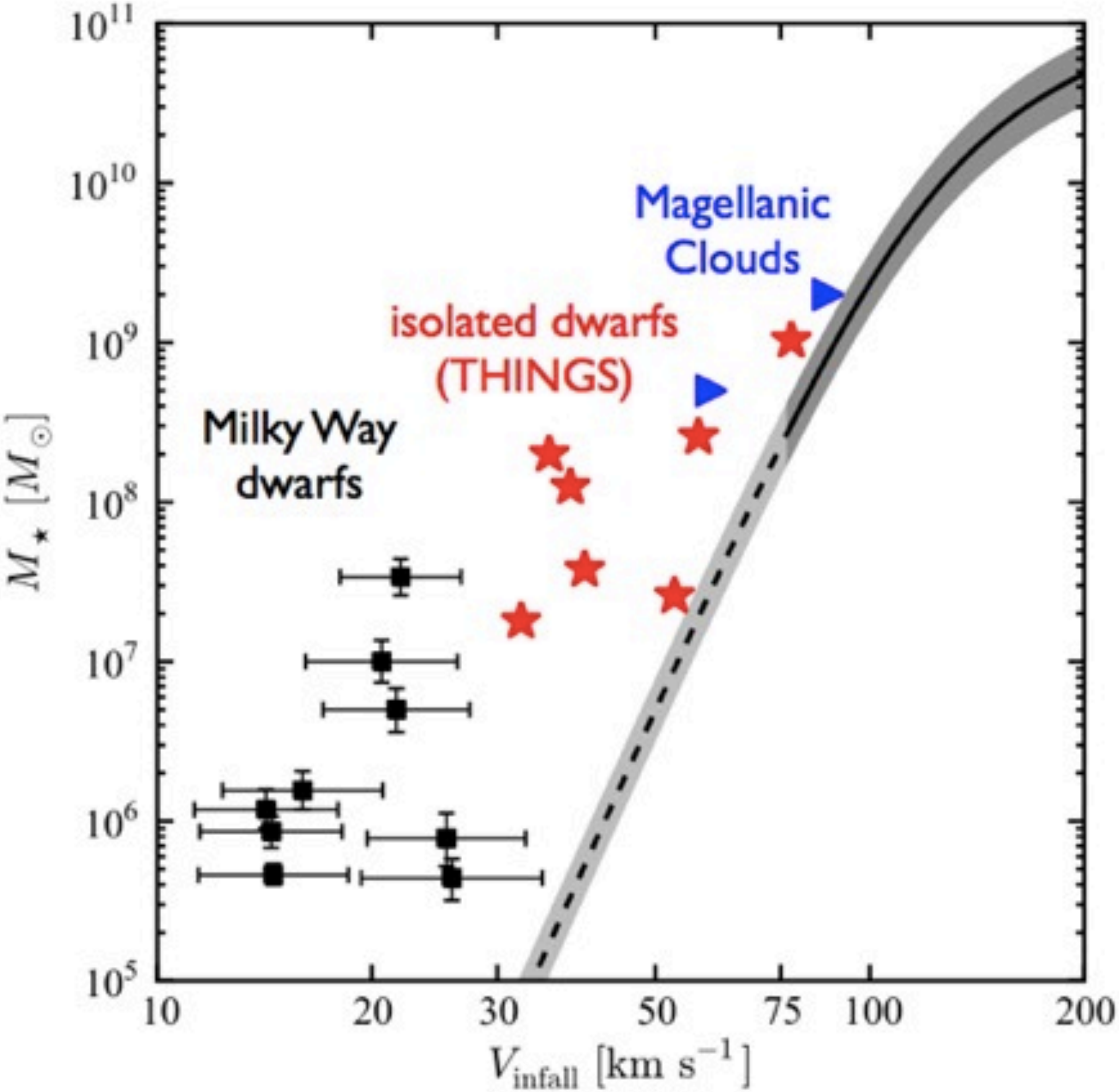
Boylan-Kolchin et al. 2011, 2012

Galaxy formation efficiency

$$\frac{\text{Stellar Mass}}{f_{baryon} * M_{dm}}$$

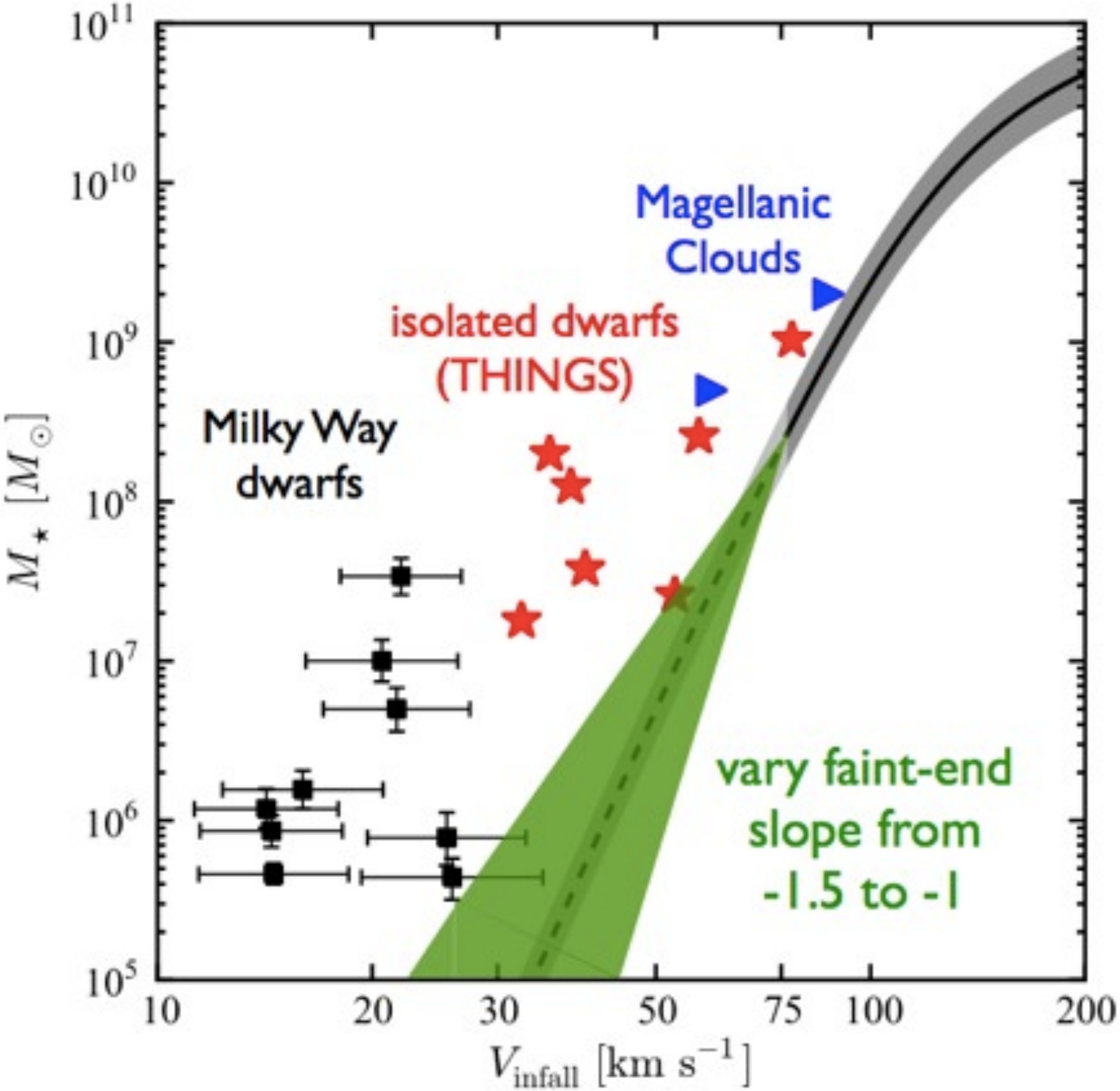


Boylan-Kolchin et al. 2011a,b



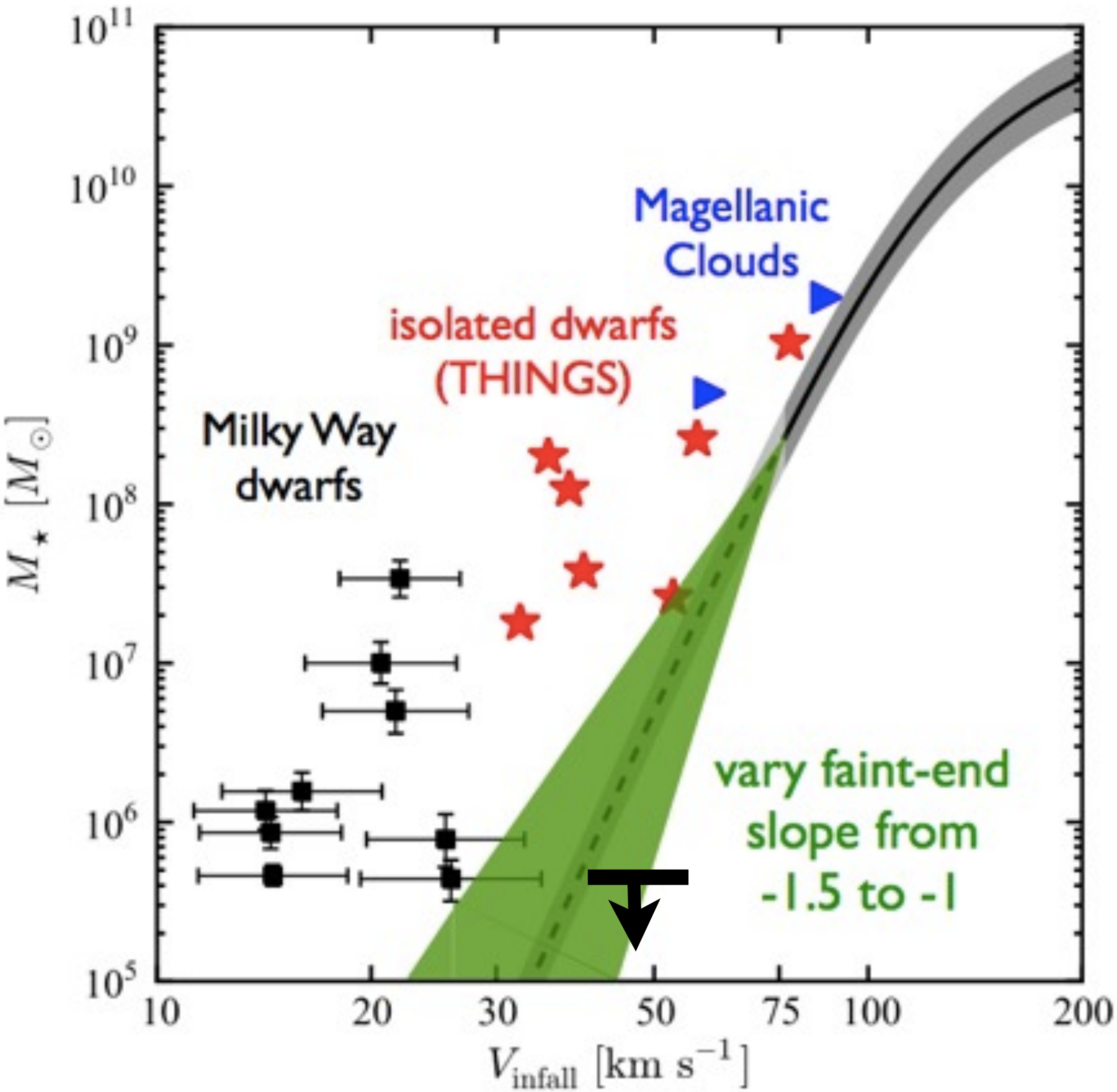
THINGS dwarfs:
Oh et al. 2011

Boylan-Kolchin et al. 2012



THINGS dwarfs: Oh et al. 2011

Boylan-Kolchin et al. 2012



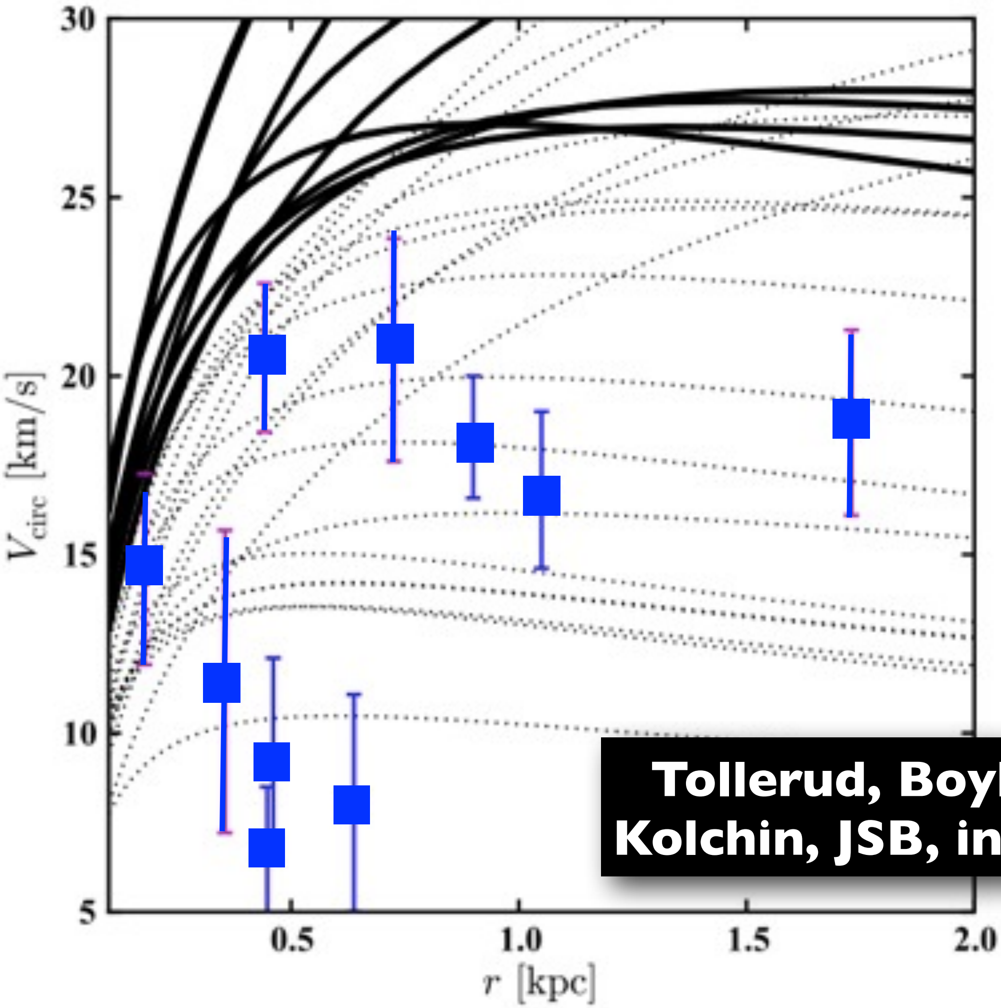
THINGS dwarfs: Oh et al. 2011

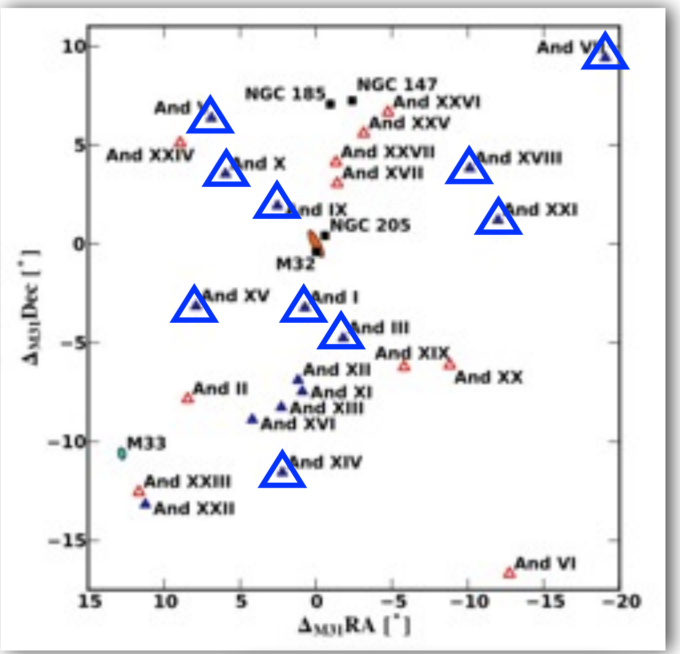
Boylan-Kolchin et al. 2012

Options

Option 0 The Milky Way is weird.

New Data: M31 dSph population





Tollerud, Boylan-Kolchin, JSB, in prep

Erik **Tollerud**

Options

Option 0

~~The Milky Way is weird.~~
M31 would have to be weird too.

Options

Option 1

Galaxy formation is effectively stochastic in small(ish) dark matter halos ($V_{max} \lesssim 50$ km/s).

Option 2

Baryonic effects lower densities in the centers of $L \sim 10^6$ L_{sun} galaxies.

Option 3

Dark matter is not so simple. Self-interacting? Something changes small-scale behavior.

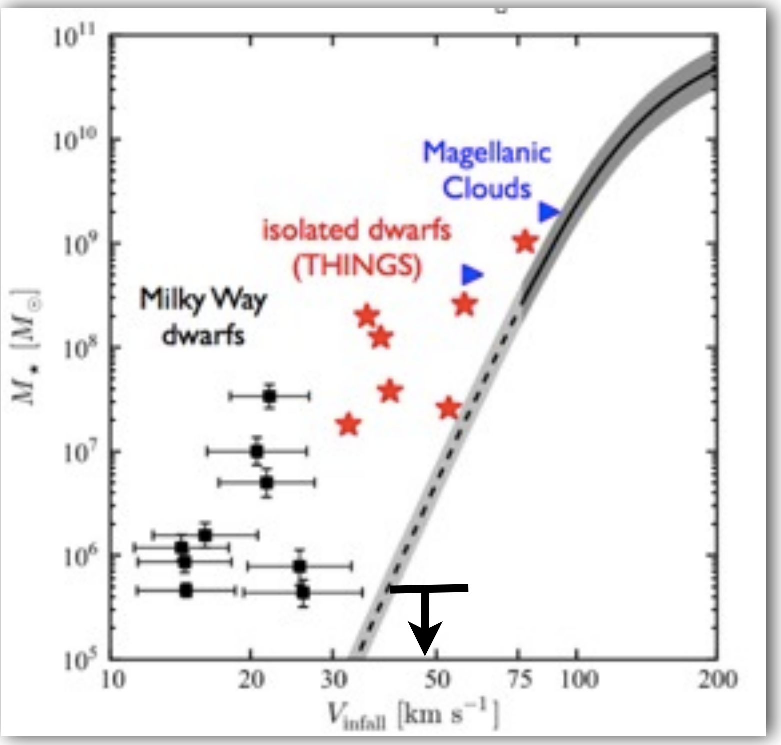
Options

Option 1

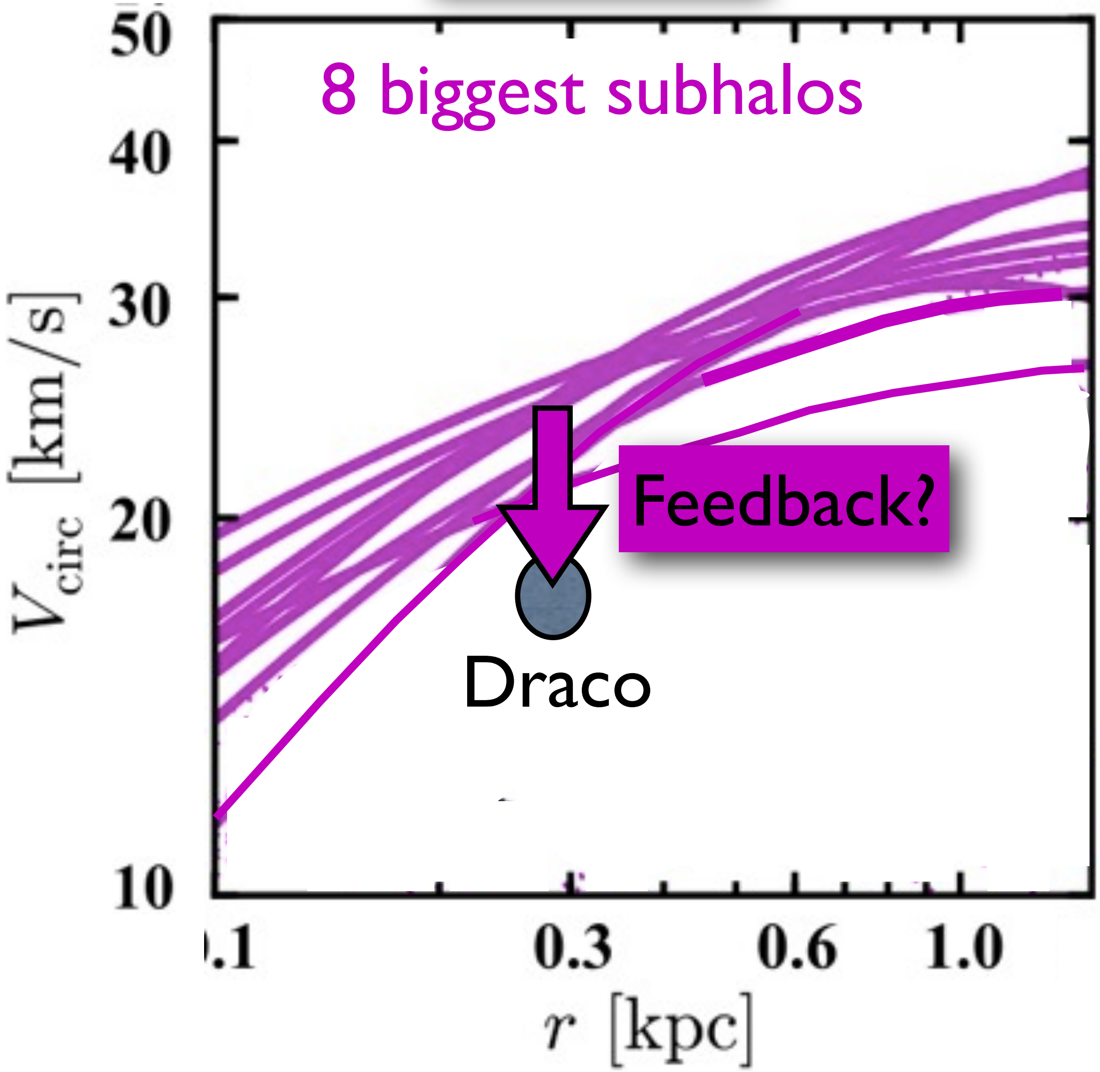
Galaxy formation is effectively stochastic in small(ish) dark matter halos ($V_{max} \lesssim 50$ km/s).

Problem with option 1

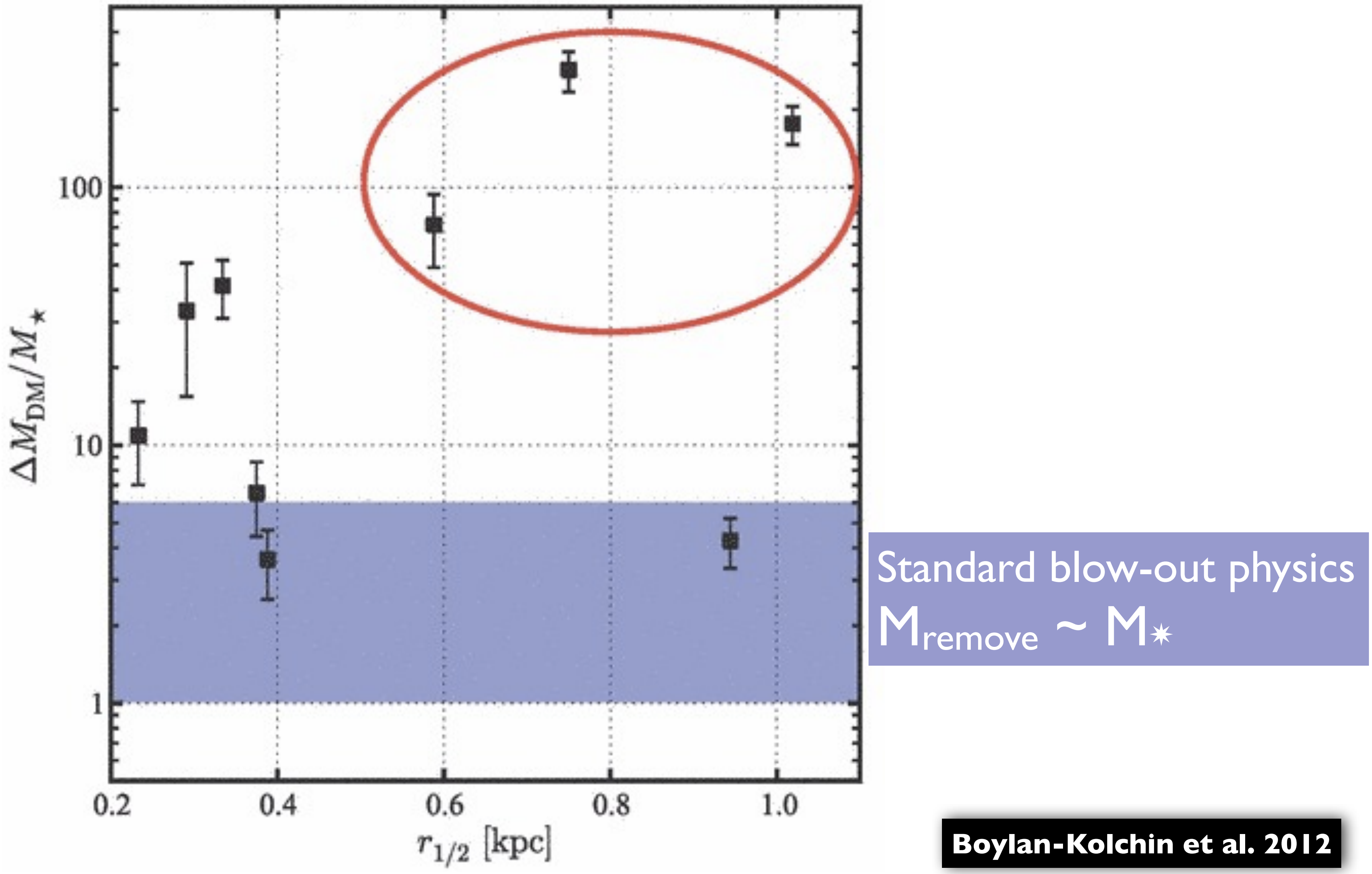
➔ Huge scatter in luminosity-mass relationship.
➔ factor of ~1000 variation in luminosity at fixed halo mass...



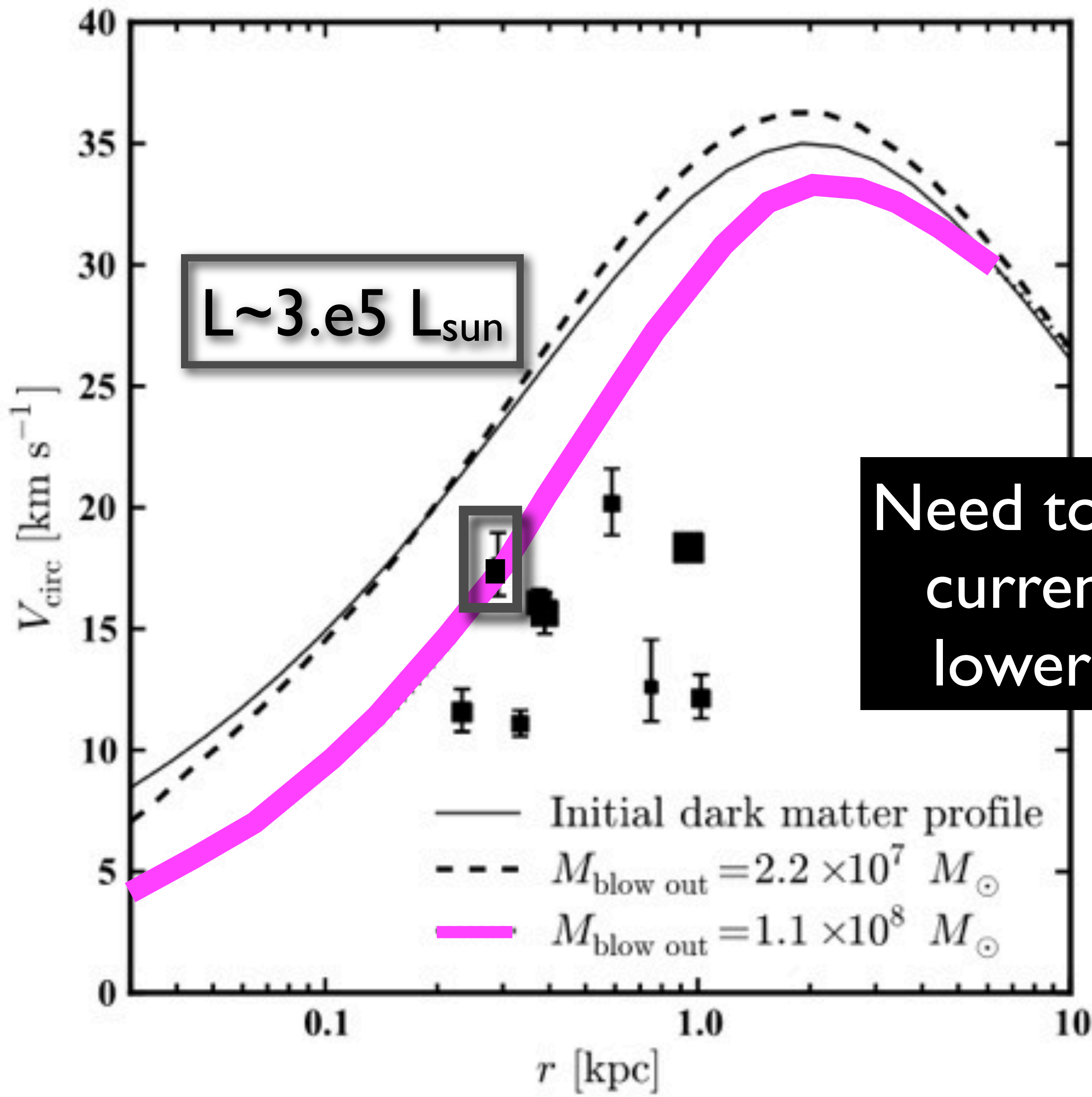
Option 2


8 biggest subhalos
Feedback?
Draco
50
40
30
20
10
.1
0.3
0.6
1.0
V_{circ} [km/s]
r [kpc]

DM blow-out needed to fix the problem



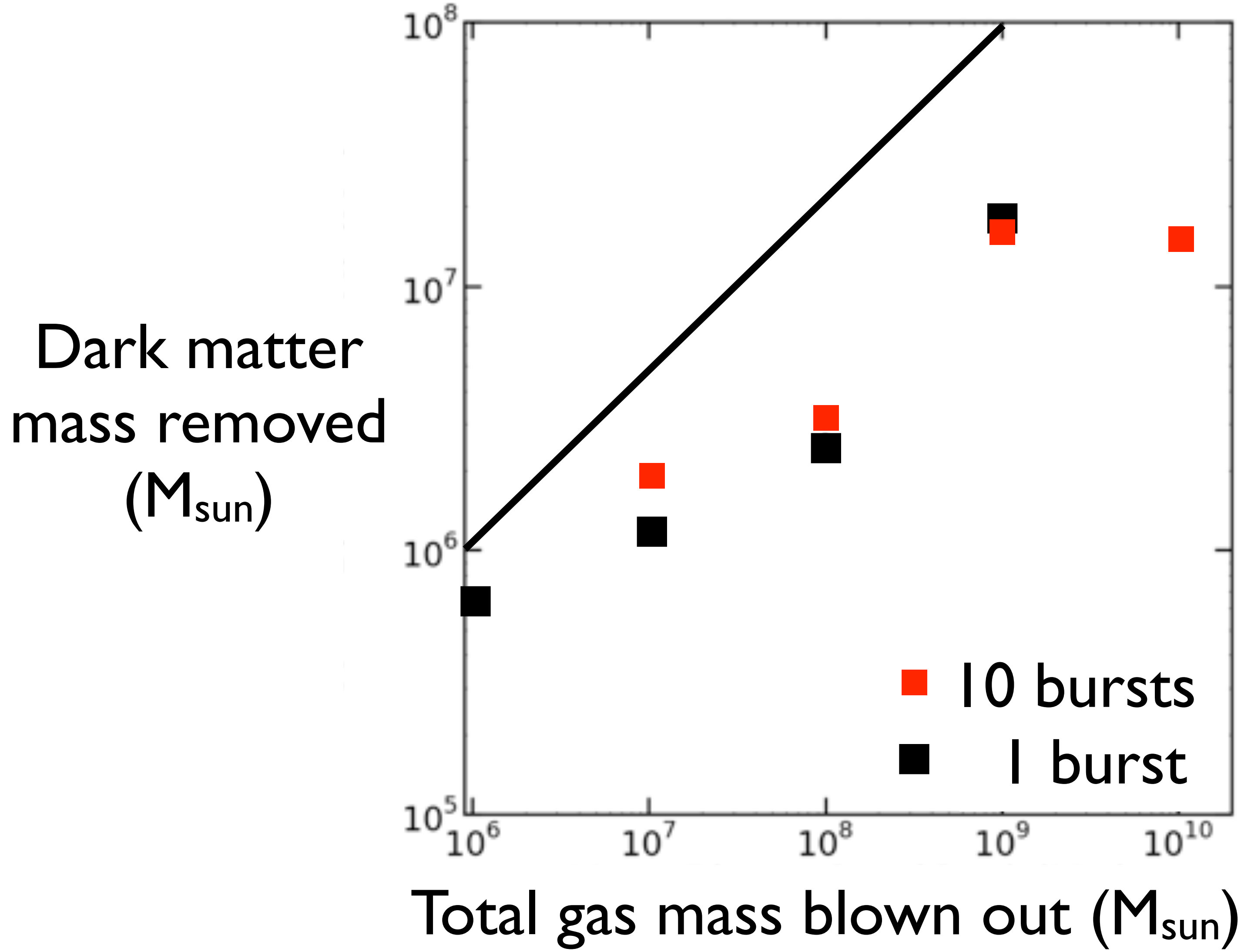
Boylan-Kolchin et al. 2012



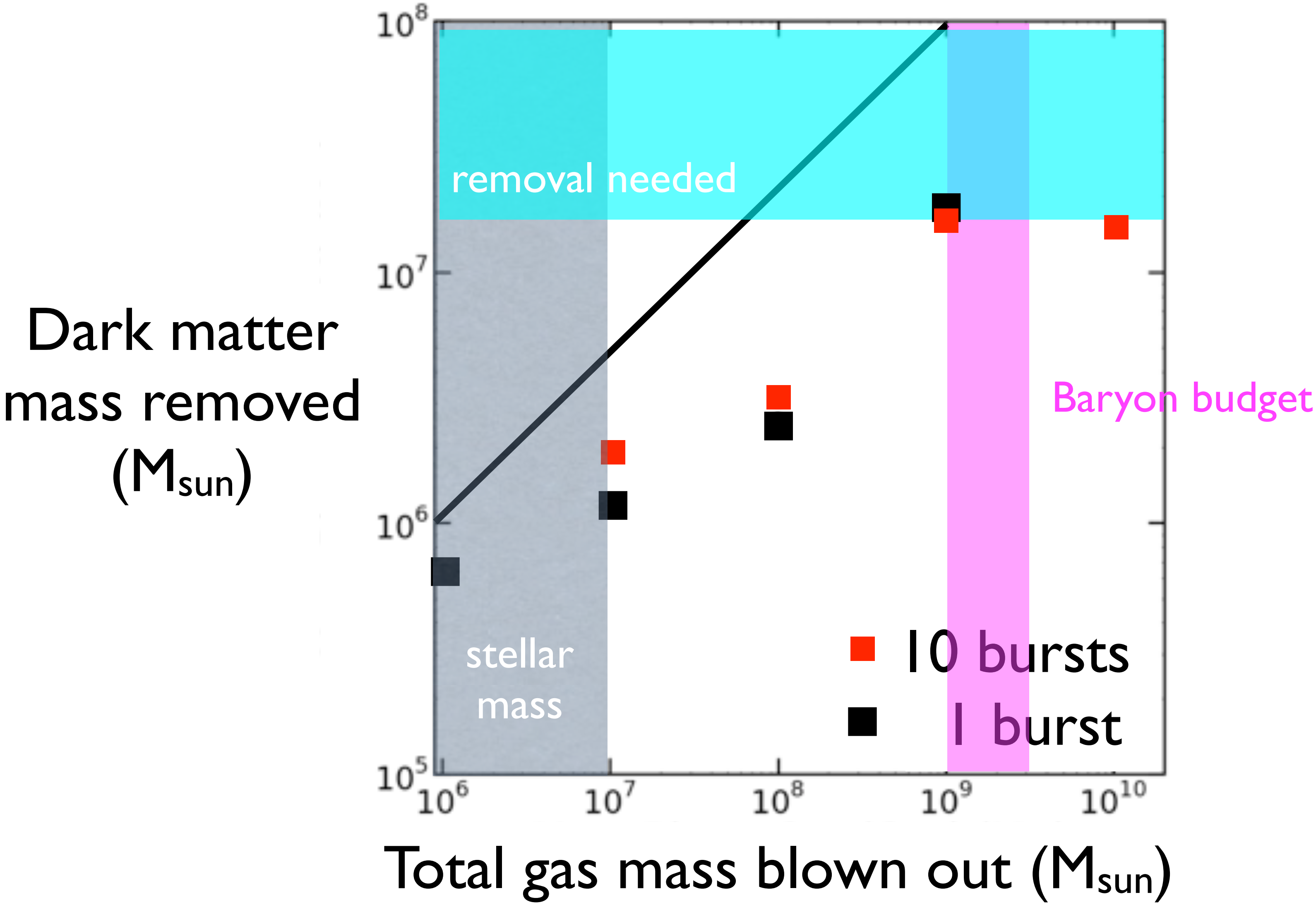
Need to expel >100 times current stellar mass to lower density enough.

Boylan-Kolchin et al. 2012

Garrison-Kimmel, Jally, et al., in prep.



Garrison-Kimmel, Jally, et al., in prep.



Options

Option 2

Baryonic effects lower densities in the centers of $L\sim10^6$ L_{sun} galaxies.

Problem with option 2

Galaxies with $L\sim5.10^5 L_{sun}$ need to have removed $\sim10^7 M_{sun}$ of dark matter.

Standard blow-out physics: $M_{remove} \sim M_*$ formed (true, e.g., for Pontzen & Governato 2012)

Options

Option 3 Dark matter is not so simple.

Options

Option 3 Dark matter is not so simple.

Particle mass is not so big? CDM: $m_{\rm dm} \to \infty$

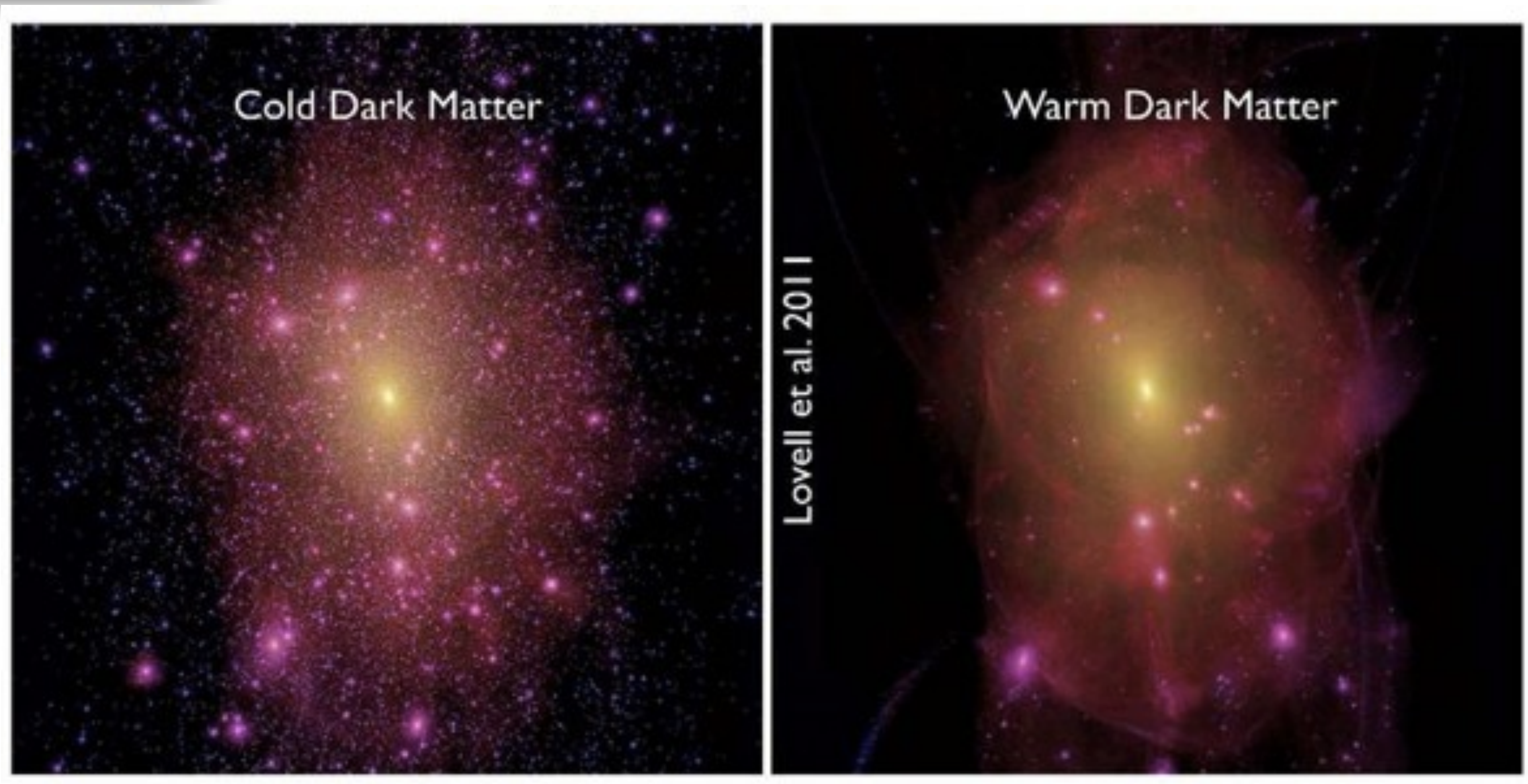
WDM: $m_{\rm dm} \sim \rm keV$

Self-interaction not so small? CDM: $\sigma/m_{\rm dm} \to 0$

SIDM: $\sigma/m_{\rm dm} \sim 1\,{\rm cm}^2/g$

Options

Option 3 Warm Dark Matter?



Just consistent with Ly-alpha forest --> Barely solves problem (Lovell et al. 2011)
+ Possibly NOT ENOUGH substructure.
+ How reionize the universe @ z~10?

Options

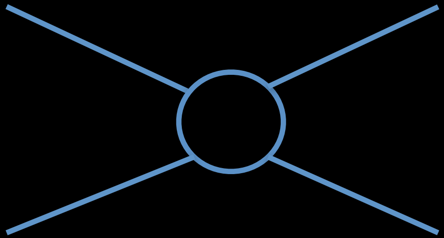
Option 3 Self-interacting dark matter

Simulating Self-interacting CDM


Miguel Rocha


Annika Peter


Manoj Kaplinghat



Scattering rate: $$\Gamma = \rho_{\rm dm} \left(\frac{\sigma}{m}\right) v_{\rm rms}$$

Interesting things happen when $\Gamma \sim H_0$

Long mean-free paths: monte-carlo method

$$P_{ij} = \left(\frac{\sigma}{m}\right) M_p \Delta v_{ij}\, g_{ij}\, \delta t$$

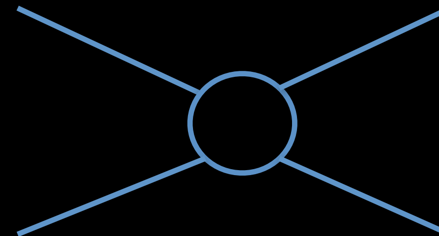
Carlson et al. (1992); Spergel & Steinhardt (2000); Kochanek & White (2000); Feng et al. (2009); Loeb & Weiner (2011); Vogelsberger et al. (2012)

Simulating Self-interacting CDM


Miguel Rocha


Annika Peter


Manoj Kaplinghat



Scattering rate: $\Gamma = \rho_{\rm dm} \left(\frac{\sigma}{m}\right) v_{\rm rms}$

$$\boxed{\frac{\sigma}{m} \sim 1\,{\rm cm}^2/g} \Longleftrightarrow \boxed{\text{lower density cores in DM halos}}$$

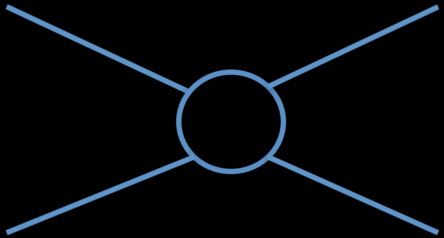
Carlson et al. (1992); Spergel & Steinhardt (2000); Kochanek & White (2000); Feng et al. (2009); Loeb & Weiner (2011); Vogelsberger et al. (2012)

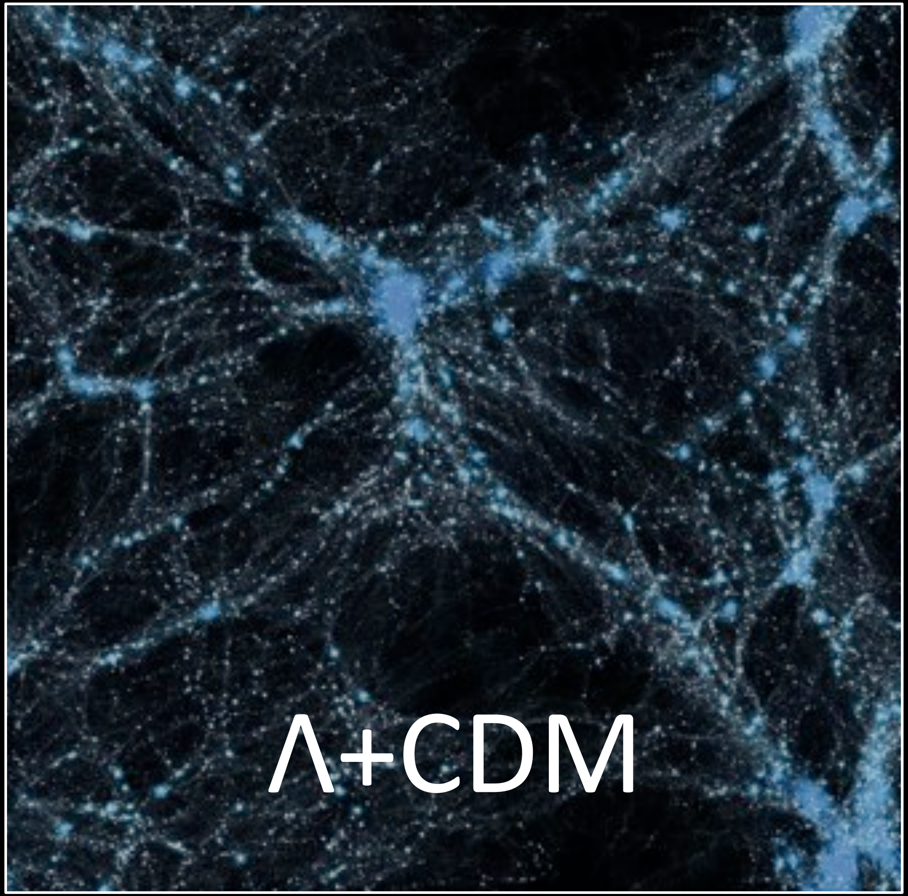
Simulating Self-interacting CDM

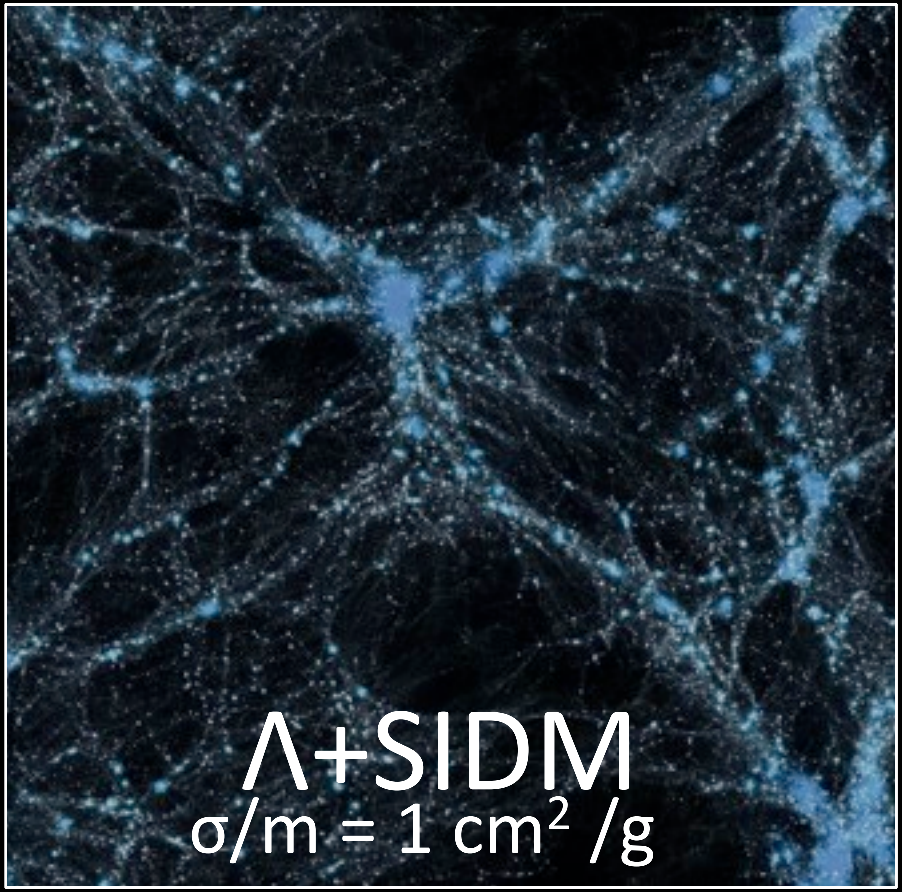
Miguel Rocha

Annika Peter

Manoj Kaplinghat





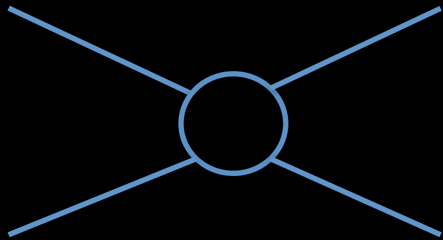


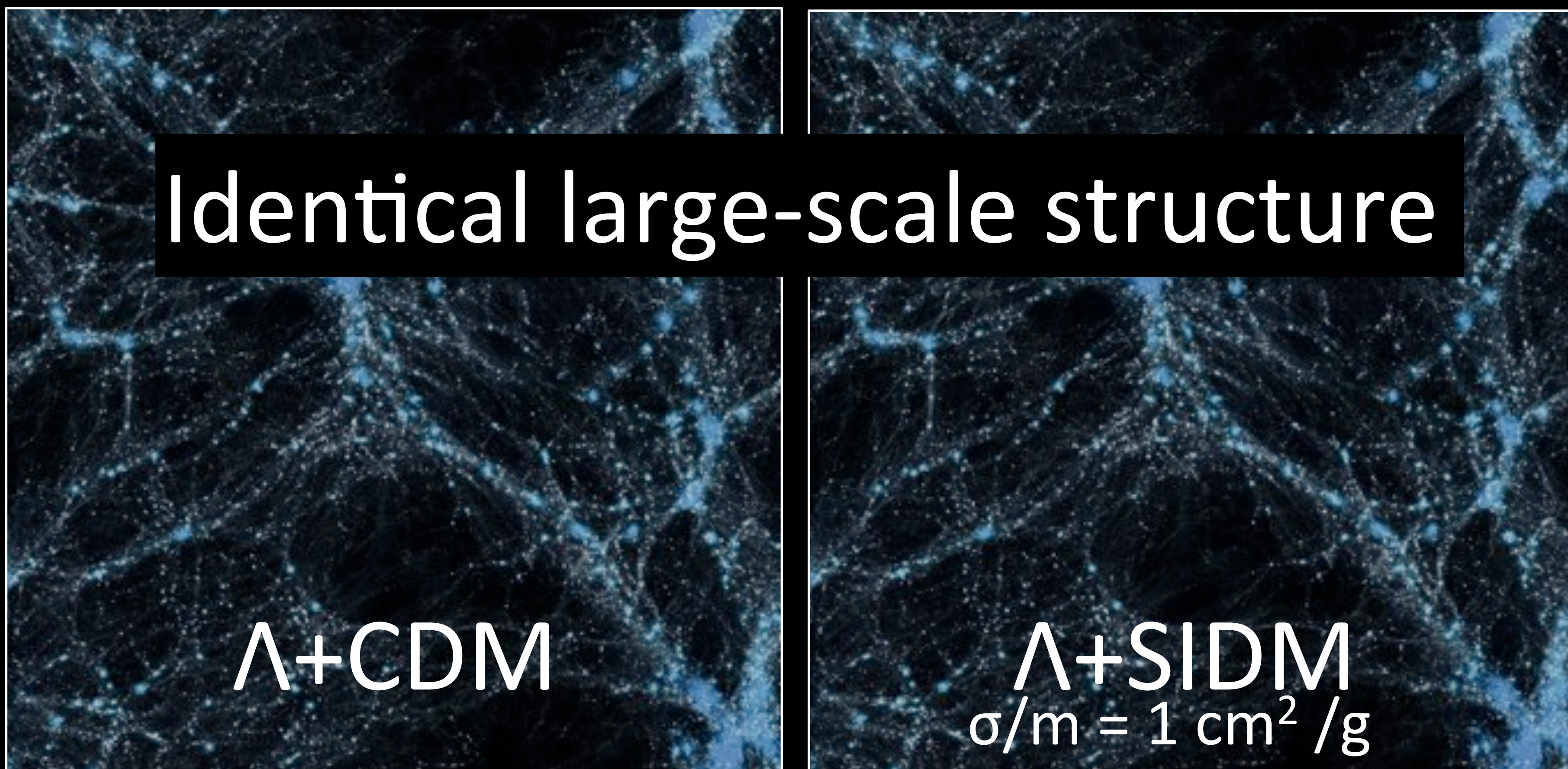
Simulating Self-interacting CDM

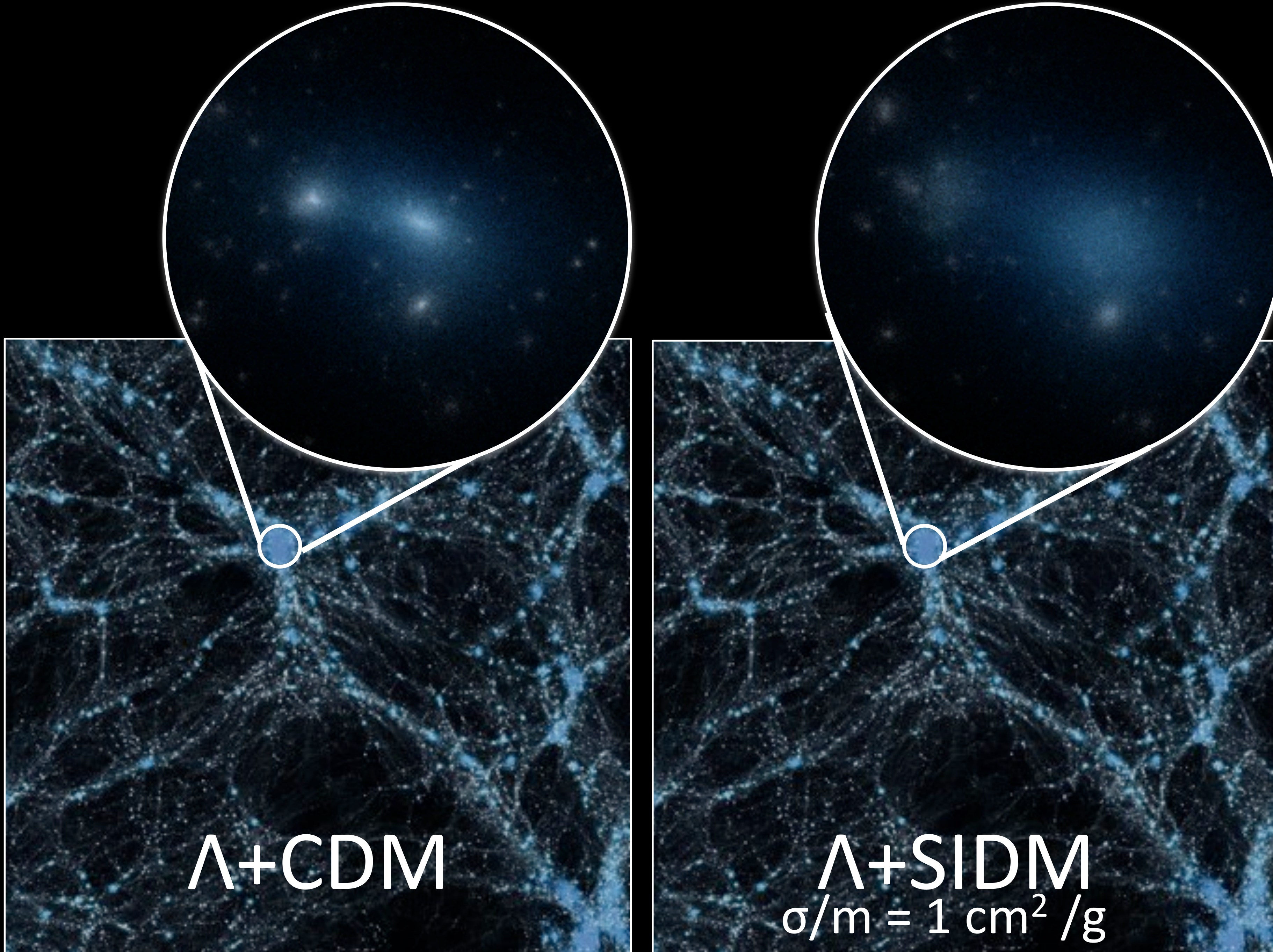
Miguel Rocha

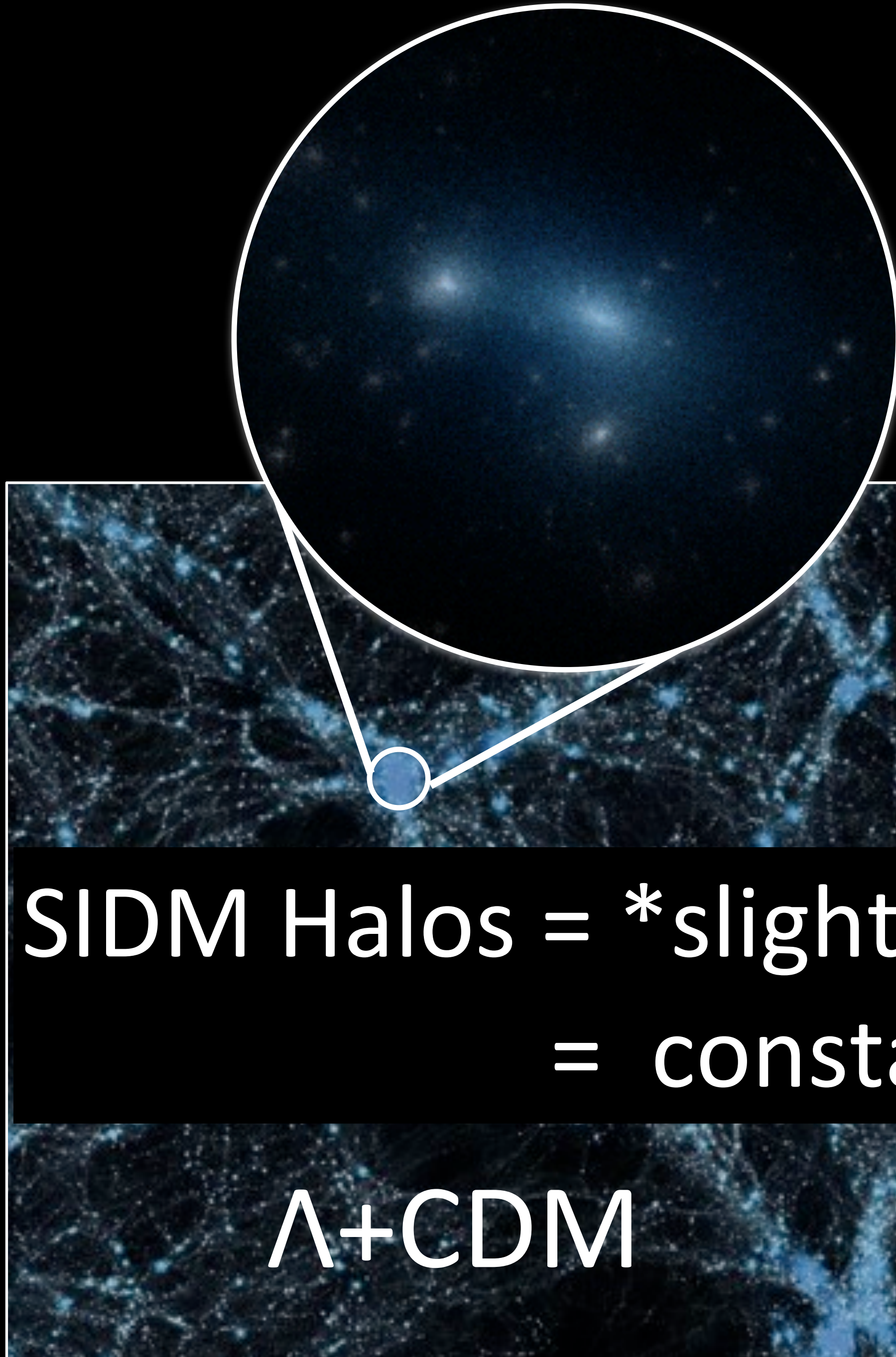
Annika Peter

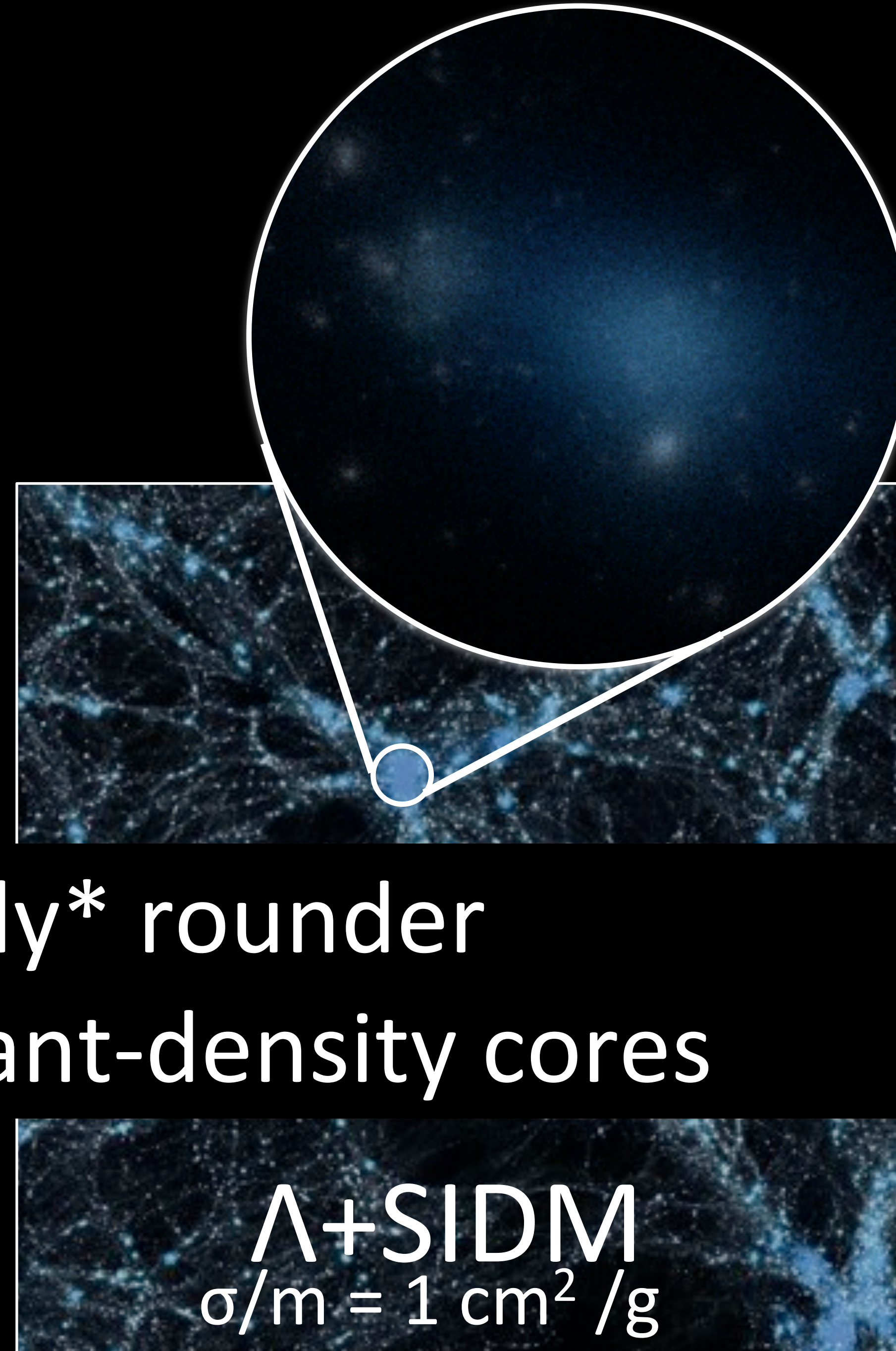
Manoj Kaplinghat






Λ+CDM
Λ+SIDM
σ/m = 1 cm² /g

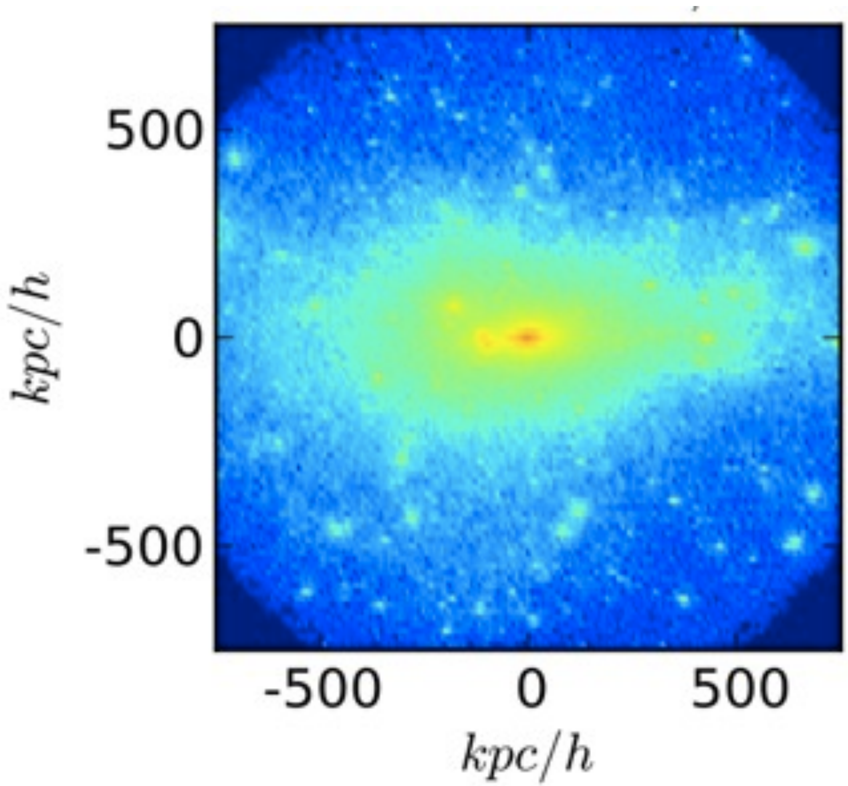




SIDM Halos = *slightly* rounder

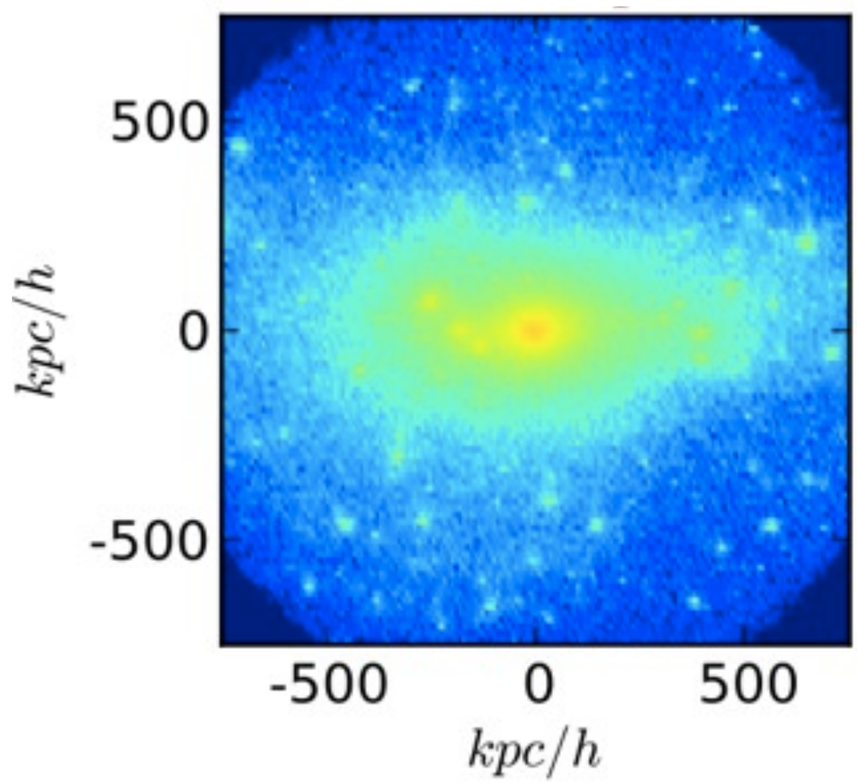
= constant-density cores

CDM



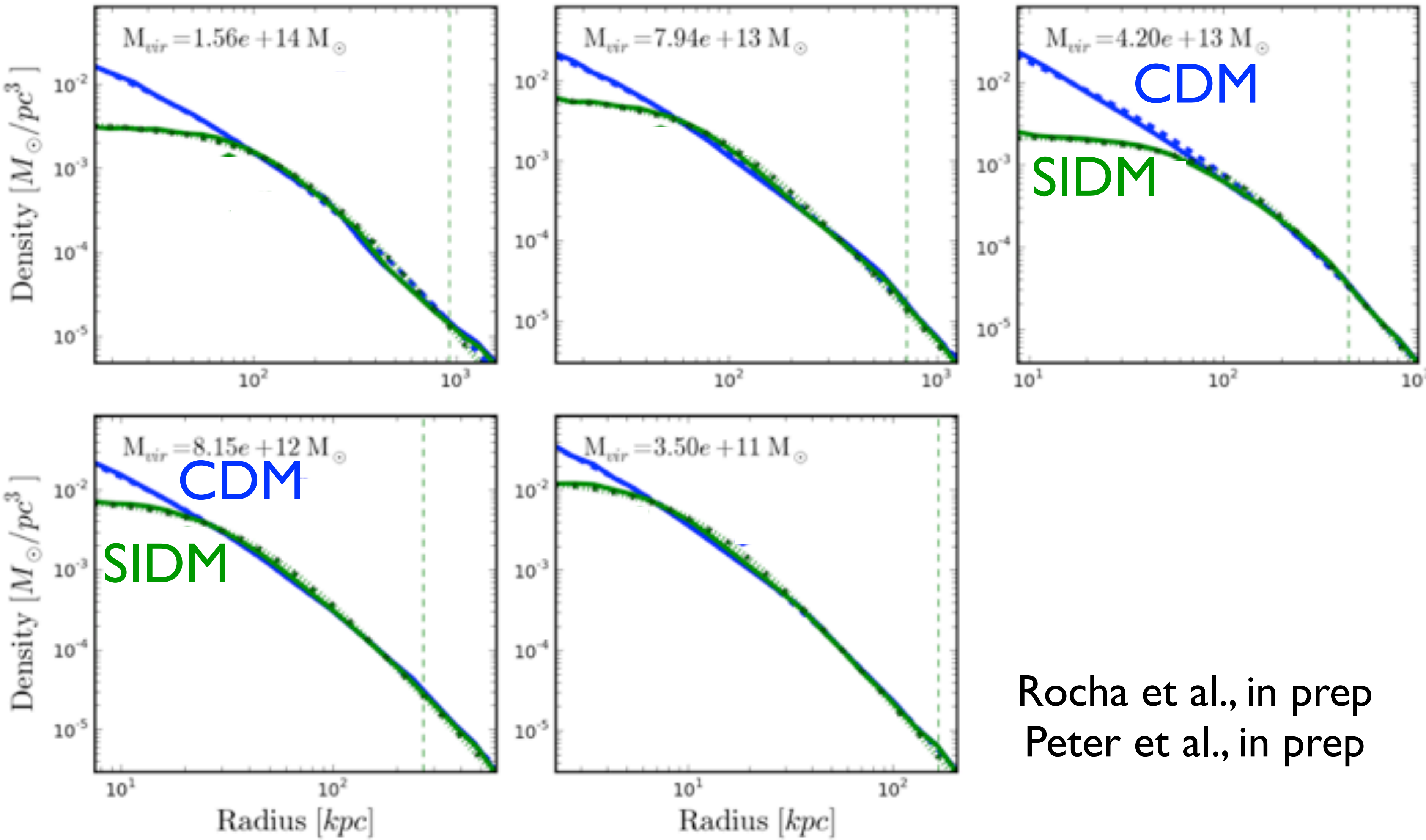
SIDM

$\sigma/m = 1\ \mathrm{cm}^2/\mathrm{g}$

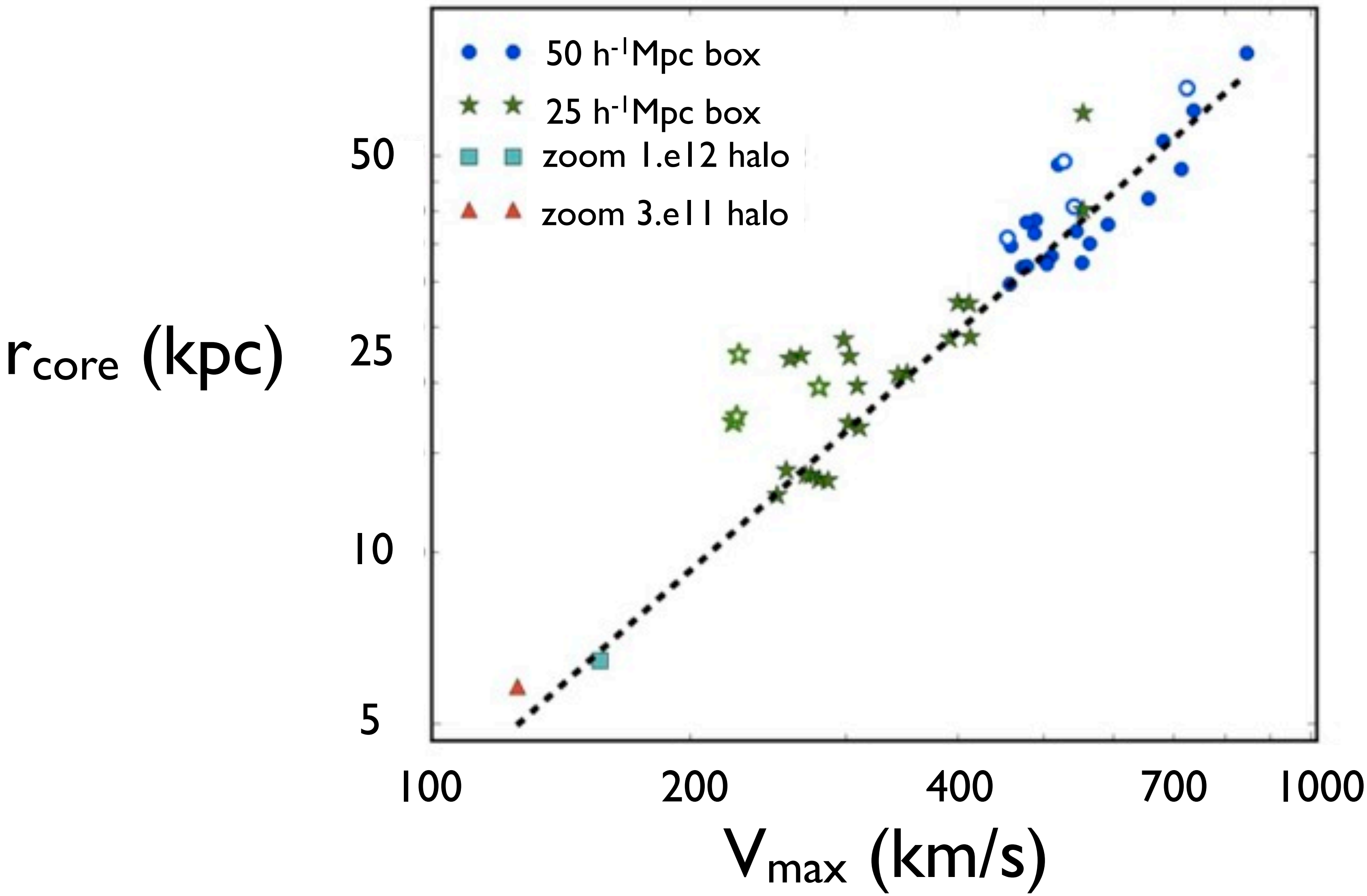


Rocha et al.; Peter et al.

SIDM Density Profiles: Cored Halos



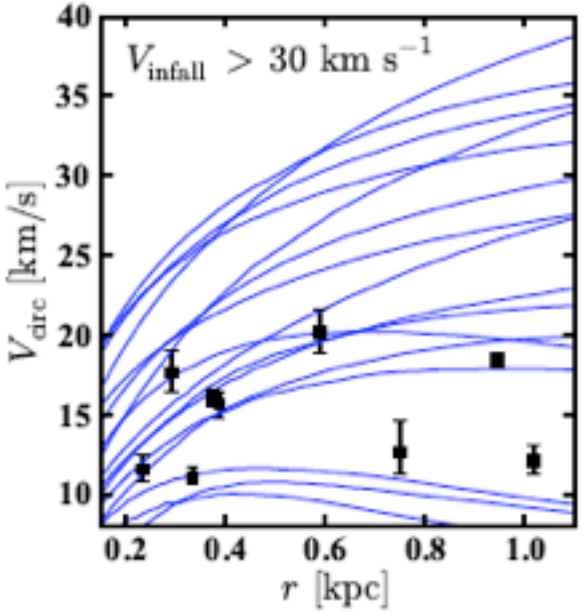
Rocha et al., in prep
Peter et al., in prep



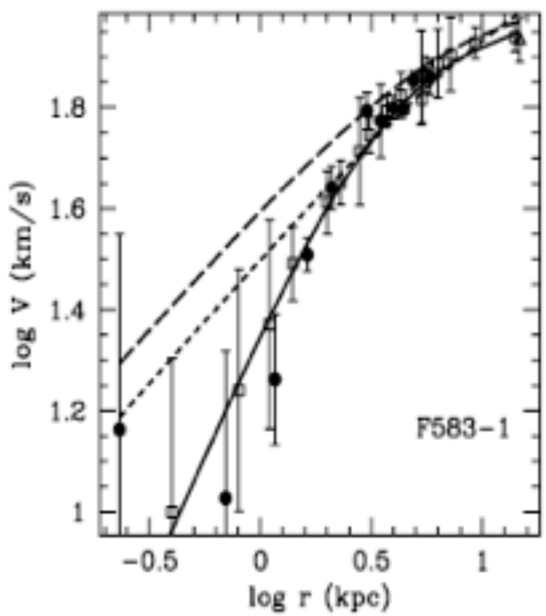
Rocha et al., in prep

Problems with CDM

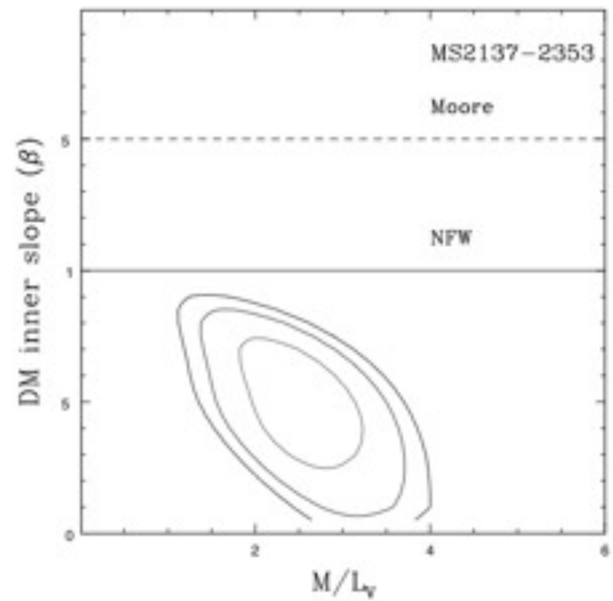
~1 kpc cores	~5 kpc cores	~100 kpc cores
dSph densities	LSB rotation	Cluster lensing



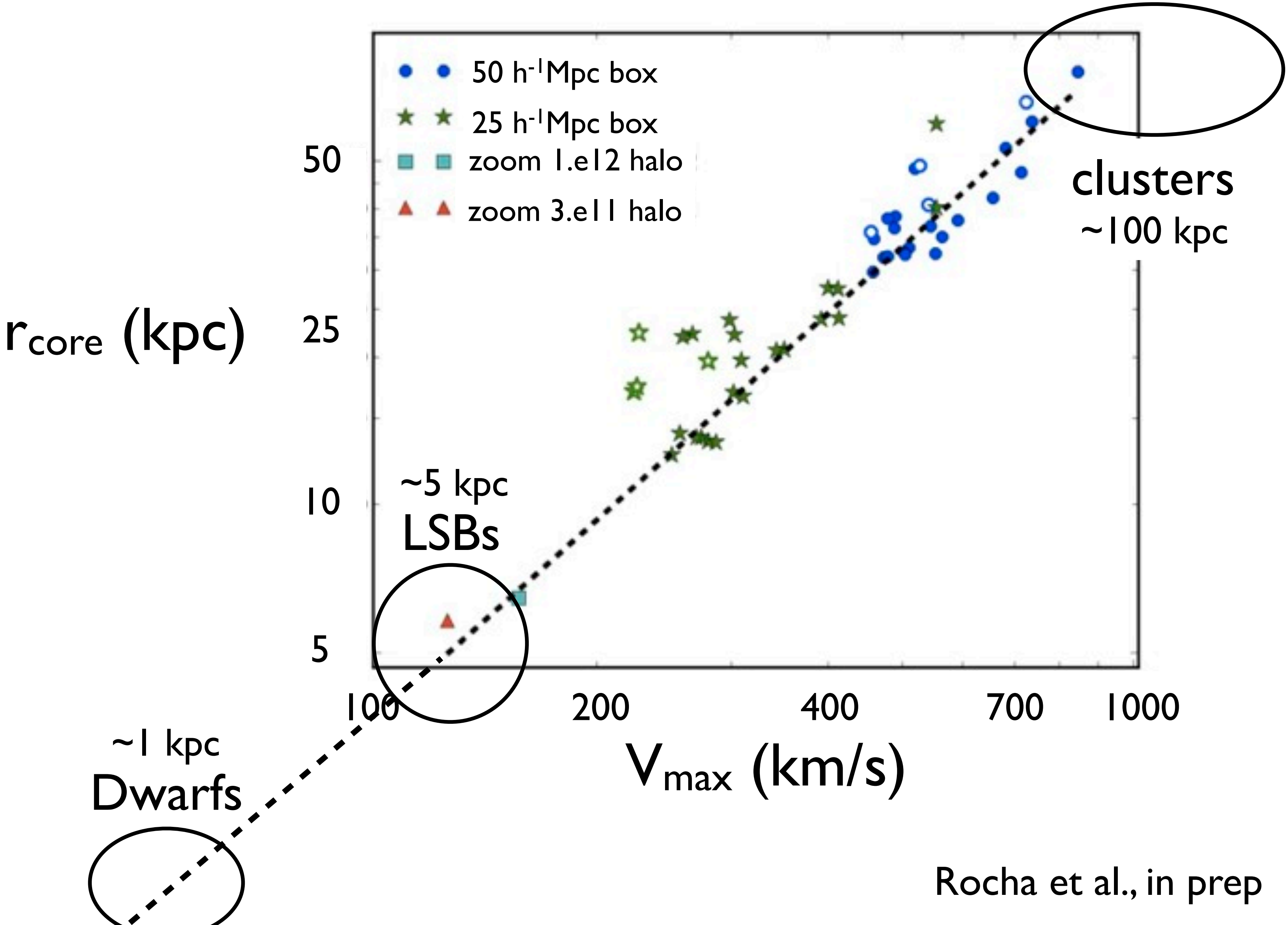
Boylan-Kolchin et al. 2011



Kuzio de Naray et al. 2008

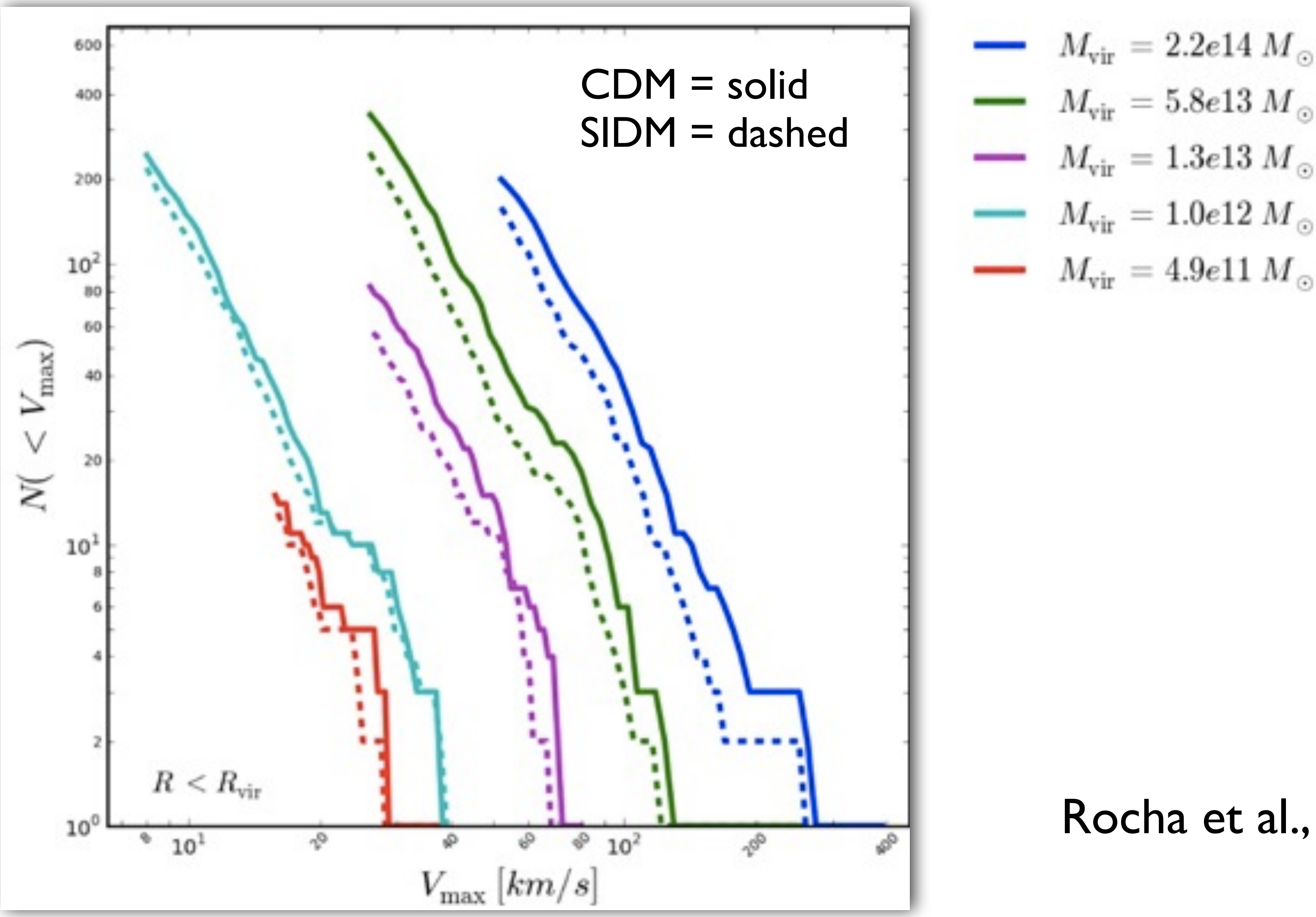


Sand et al. 2008

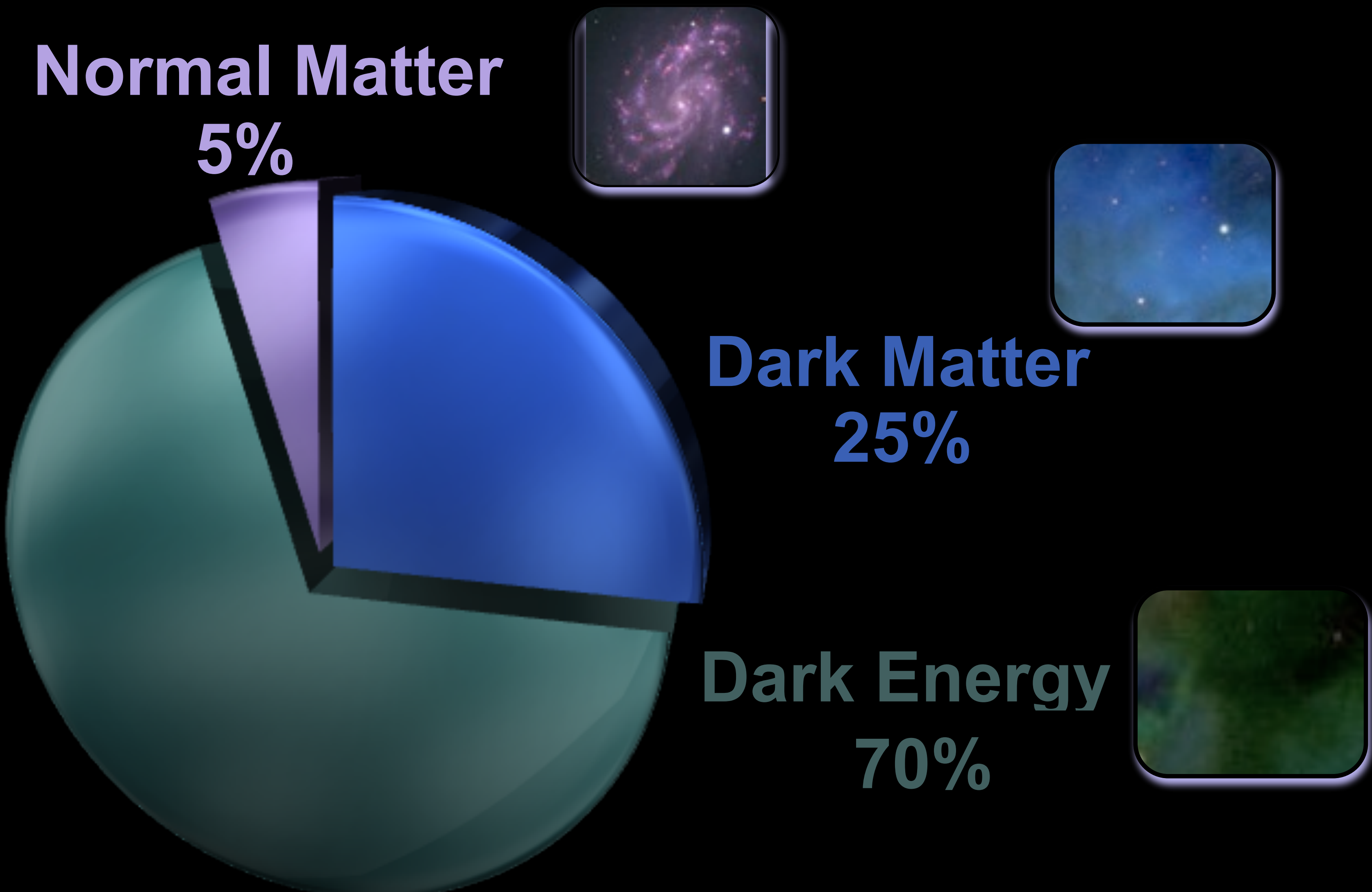


Rocha et al., in prep

SIDM: Substructure survives

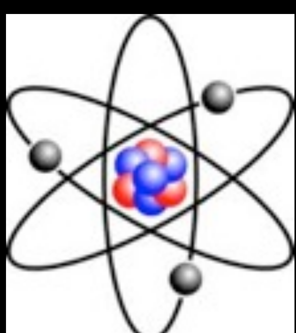


Rocha et al., in prep

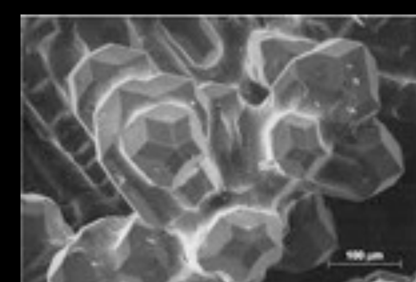

Normal Matter
5%
Dark Matter
25%
Dark Energy
70%

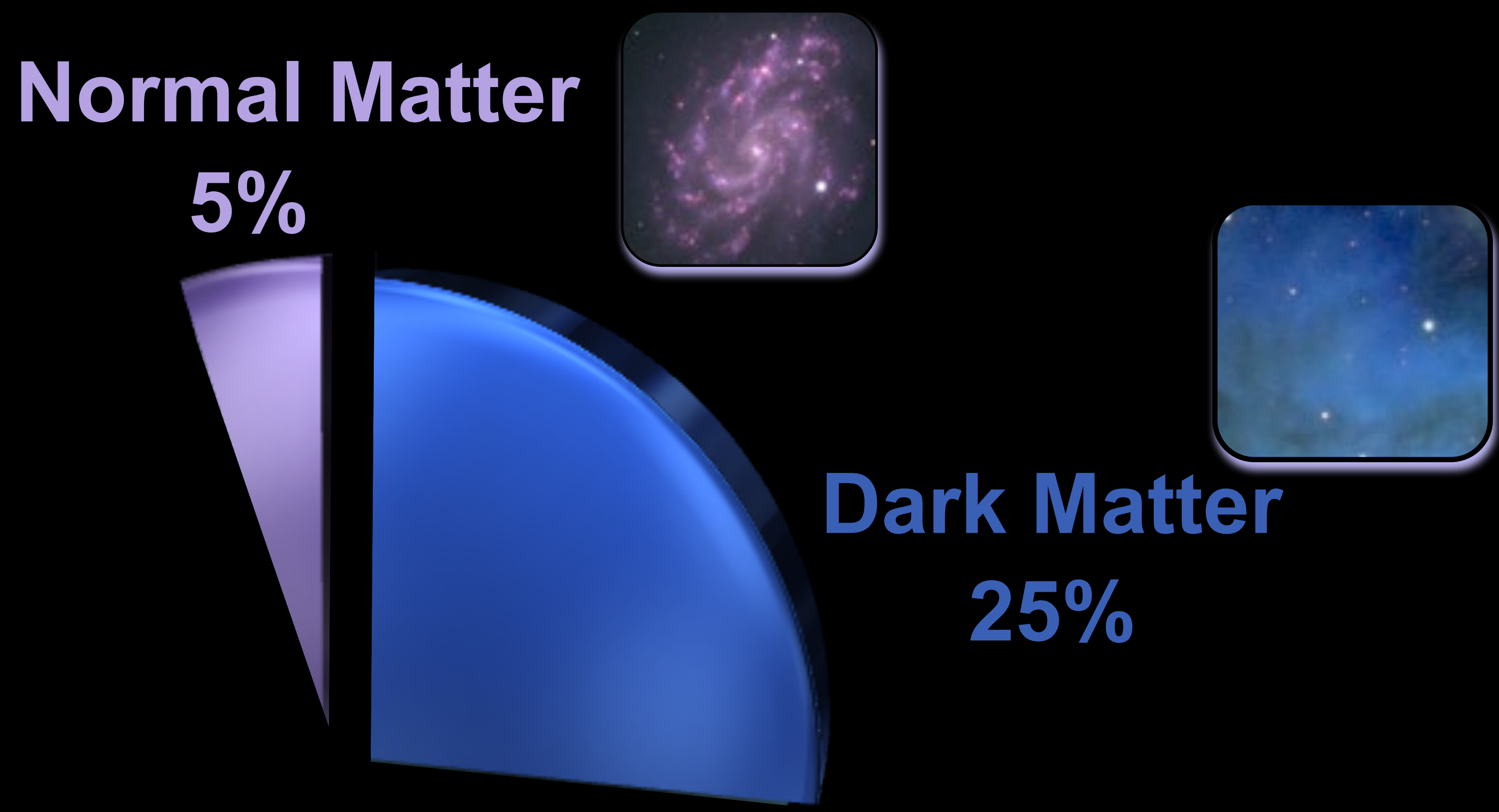
Normal Matter
5%

This piece of the pie is very interesting...



DRIVE-BY TRUCKERS





Maybe this one is too...

Thanks