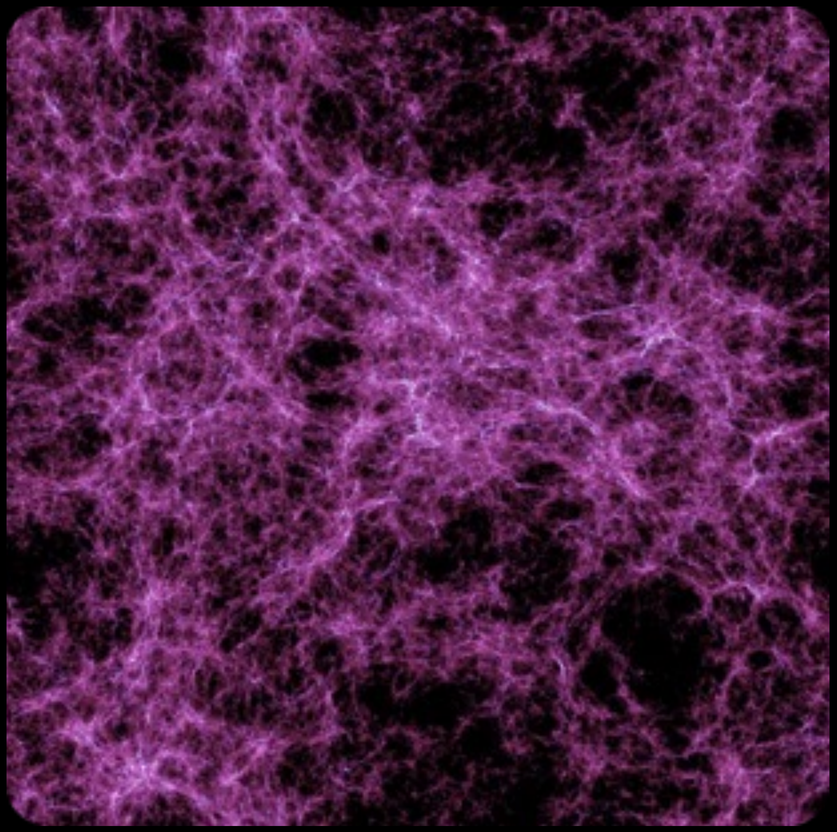
Testing ΛCDM in the Milky Way (and beyond)



Mike Boylan-Kolchin

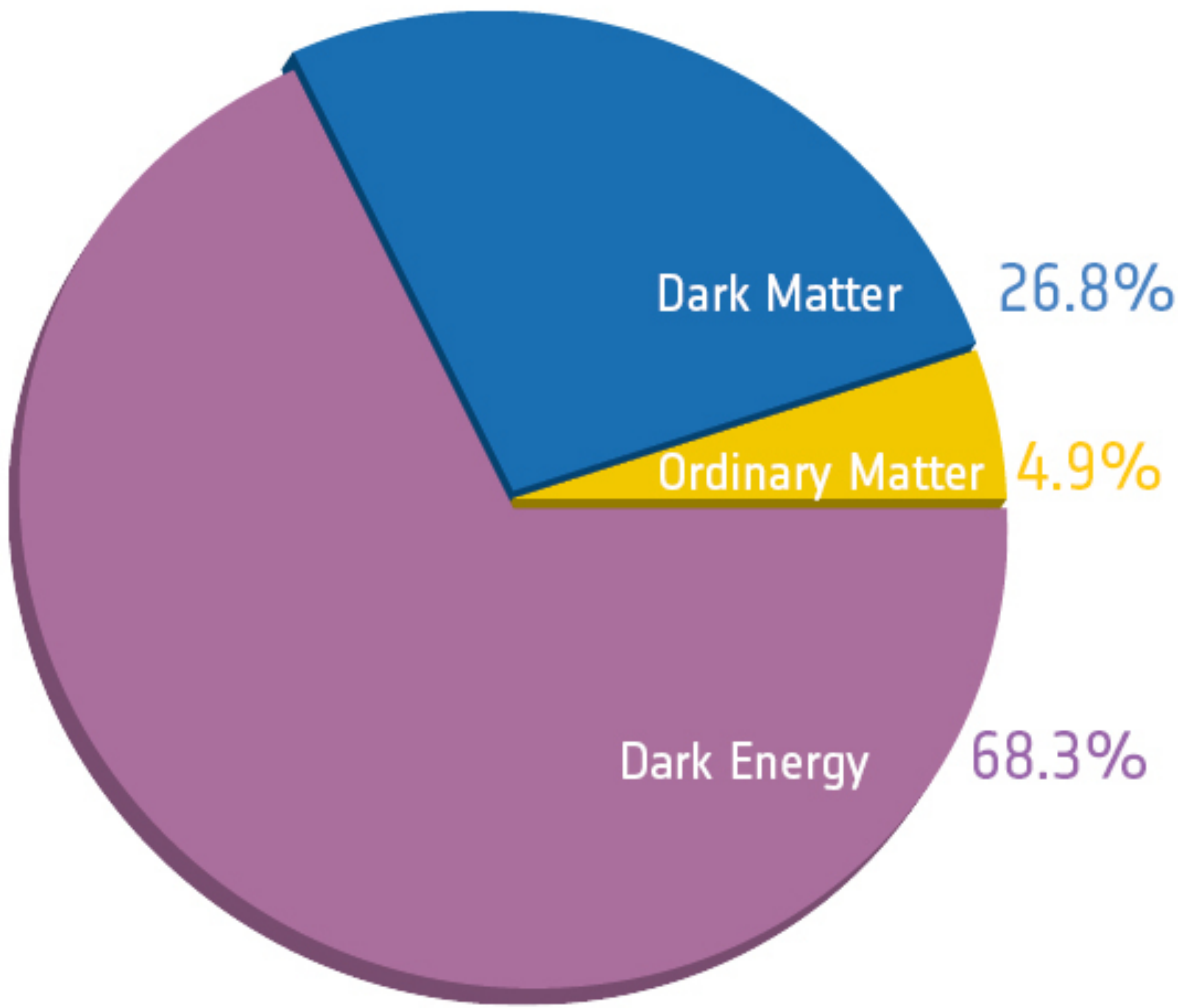
The University of Texas at Austin

Workshop on the Astrophysics of Dark Matter

Kavli IPMU

13 October 2015

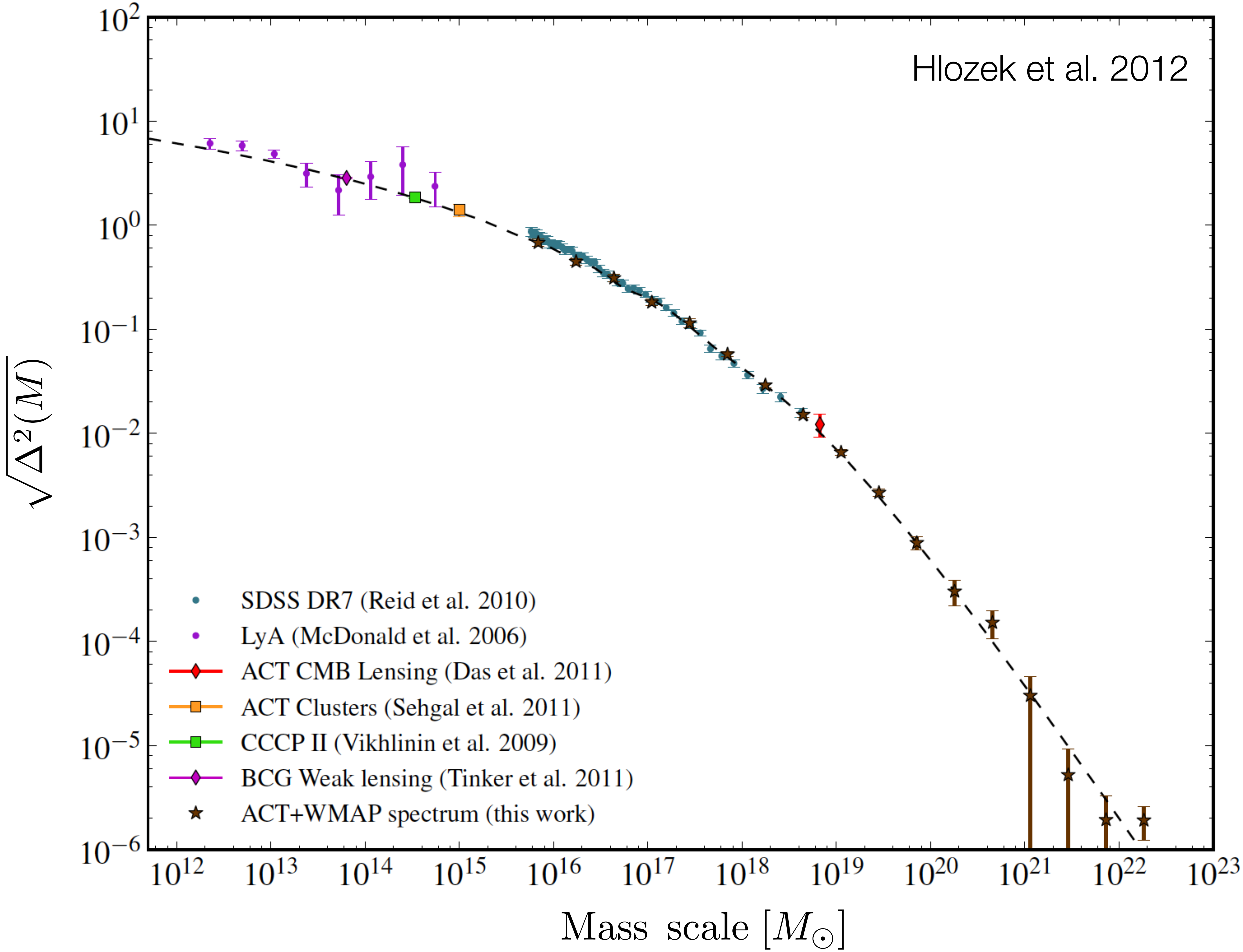
ΛCDM: Our dark Universe



95% of the Universe is “beyond the Standard Model” physics!

Image: Planck / ESA / NASA

ΛCDM: a remarkably successful theory on large scales

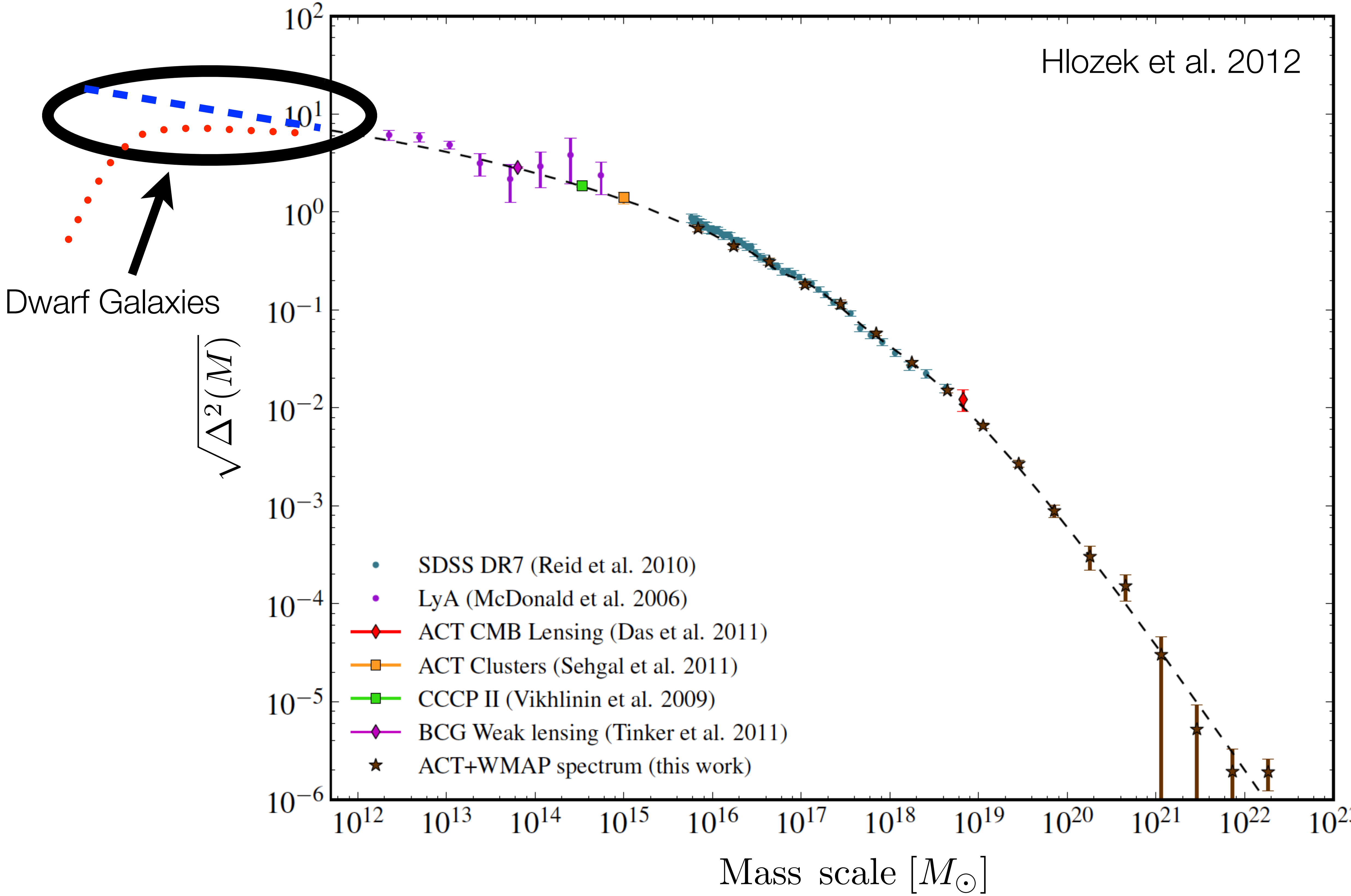


Before we go congratulating ourselves too much....

- CDM is well-tested on large scales; smaller-scale tests are *much* harder
- All data seem to be consistent with dark matter behaving as a cold, collisionless particle (WIMP) .....
- .... however, all attempts to detect these particles non-gravitationally have been unsuccessful
- Dark energy: makes dark matter seem well-understood

Testing the ΛCDM model in the highly non-linear regime is essential for understanding the nature of dark matter

Testing ΛCDM on small(er) scales



Constraining particle physics through astrophysics

- **Early 1980s:** standard model neutrinos ruled out as dominant DM component via observations of galaxy clustering
- **Mid-1980s:** agreement between observed and simulated universes led to support for CDM models, provided early hints for cosmological constant
- **Mid-1990s:** structure in Lyman-alpha forest ruled out then-popular C+HDM models
- **Can history repeat itself?** Looking at the smallest, densest remnants of structure formation is likely to be most fruitful in discriminating between standard CDM and alternative dark matter models.
  - earliest-collapsing, densest DM structures
  - most baryon-deficient DM structures: observed baryons make up 1%-0.001% (or less?) of total mass of system

Large Magellanic Cloud: ~10x fainter than the Milky Way

Image credit: H. Wang

Fornax: 1,000x fainter

Image credit: Celestial Image Co.

Draco: 100,000x fainter

Image credit: J. Moore

Segue I: 100,000,000x fainter than the Milky Way

Image credit: M. Geha

Segue I: 100,000,000x fainter than the Milky Way

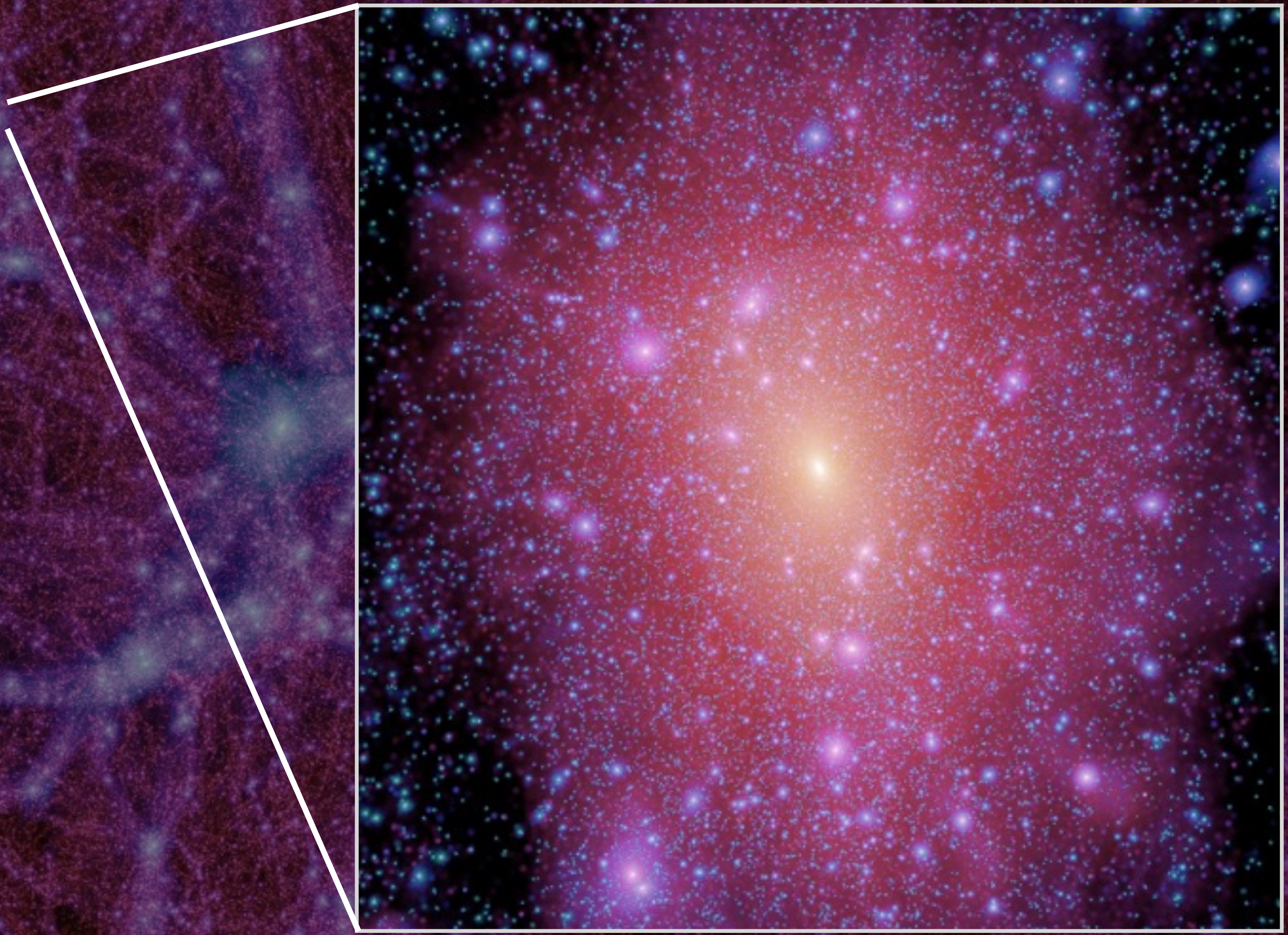
Image credit: M. Geha

ΛCDM predictions for galactic scales:

(1) hierarchical formation
(2) cuspy (sub)halo profiles
(3) vast spectrum of substructure

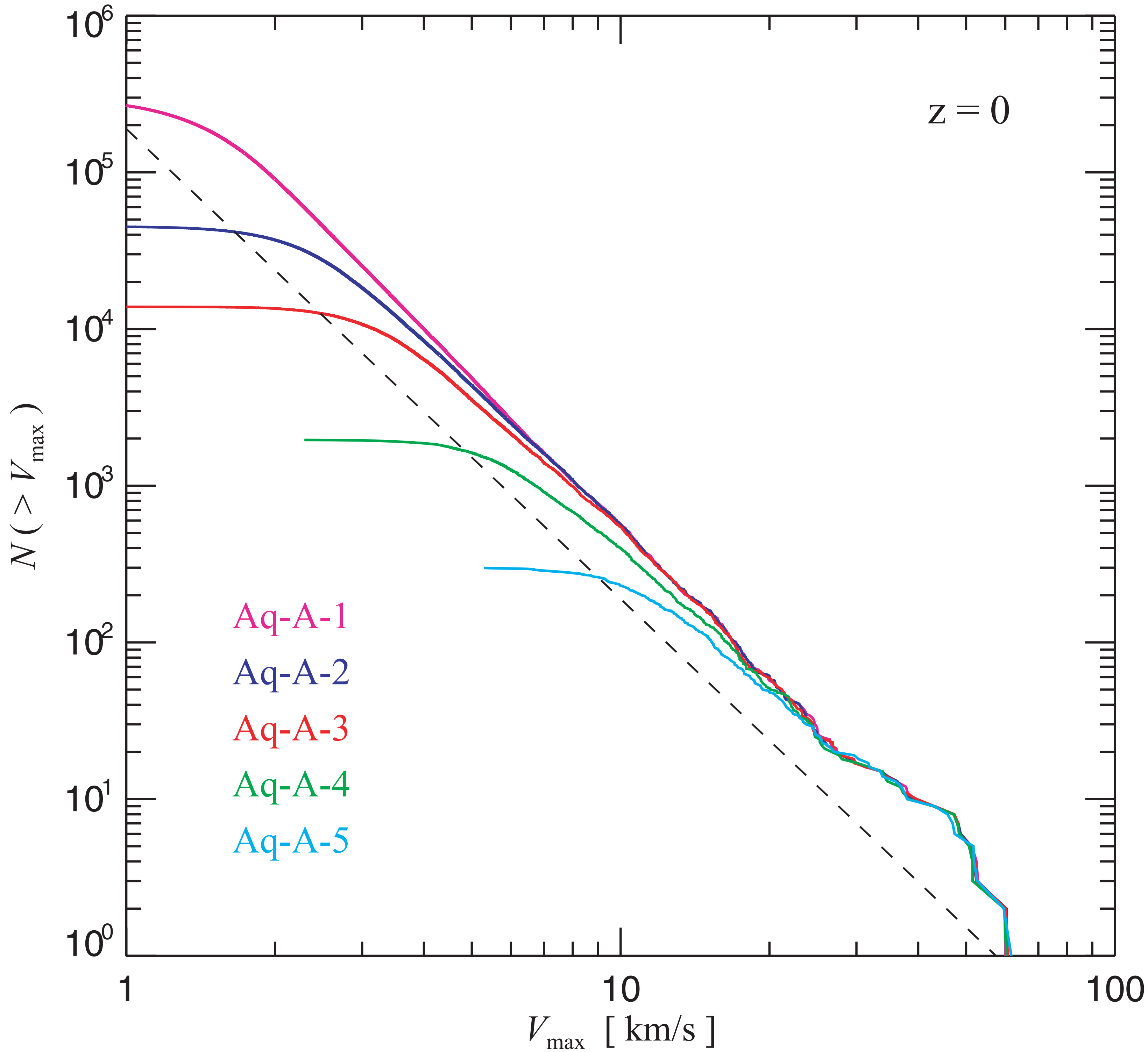
Aquarius project: Springel et al. (2008)
see also Via Lactea II, GHalo simulations (Diemand, Kuhlen, Madau; Stadel et al.)

ΛCDM: abundant, self-similar structure to *very* low masses



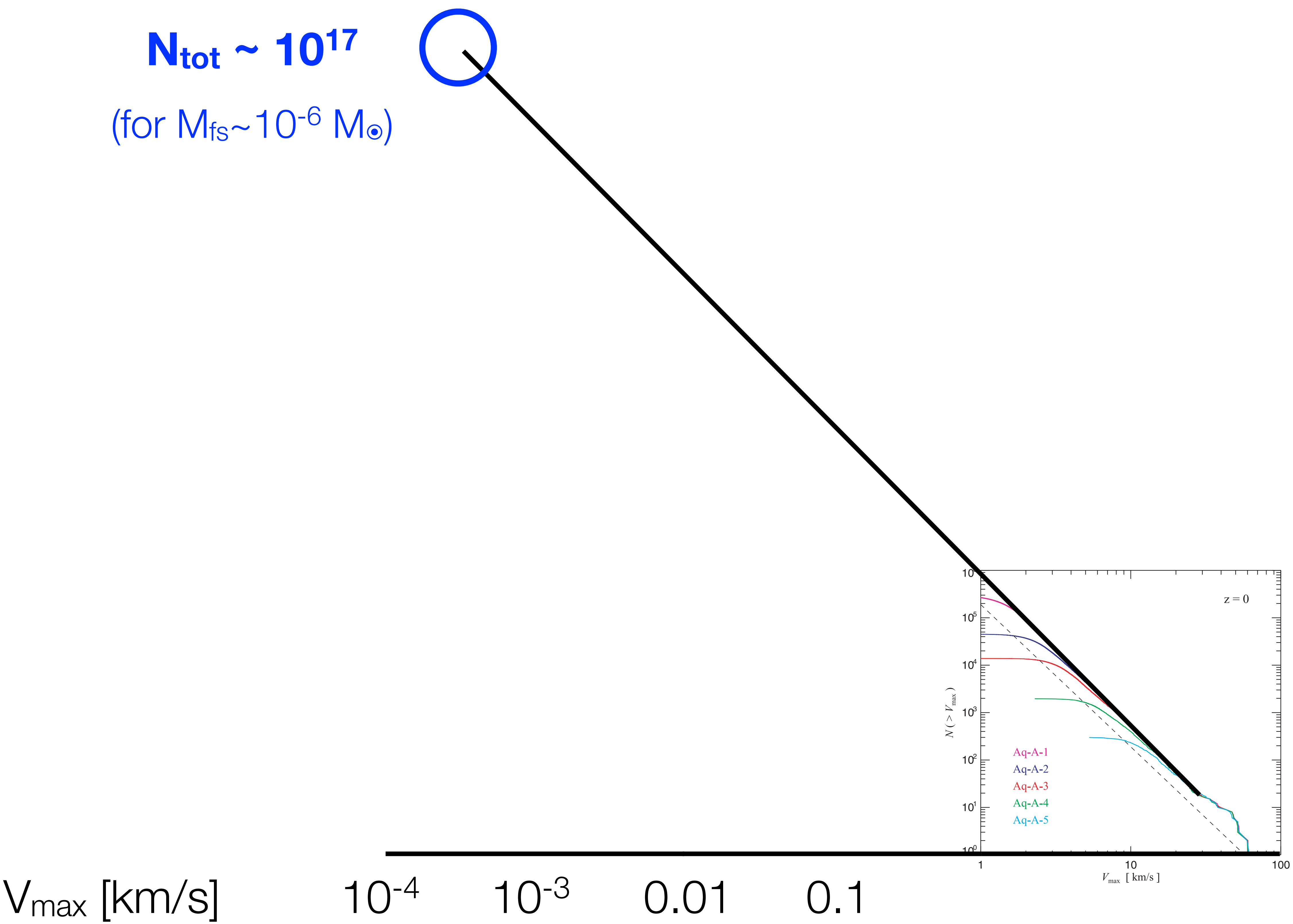
This is a DIRECT consequence of the assumption that dark matter is cold and collisionless

Resolving Galactic Substructure



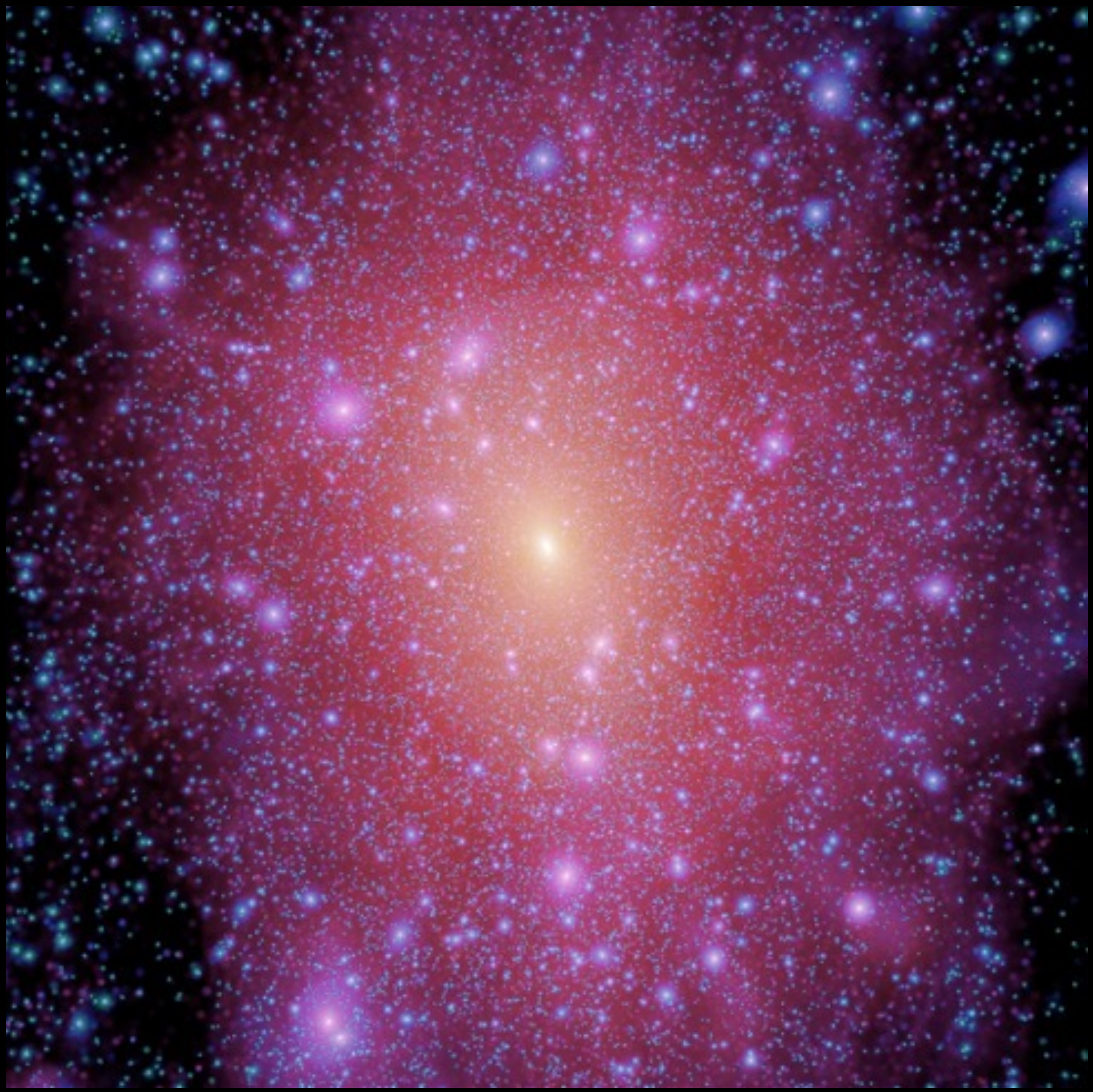
Springel et al. 2008

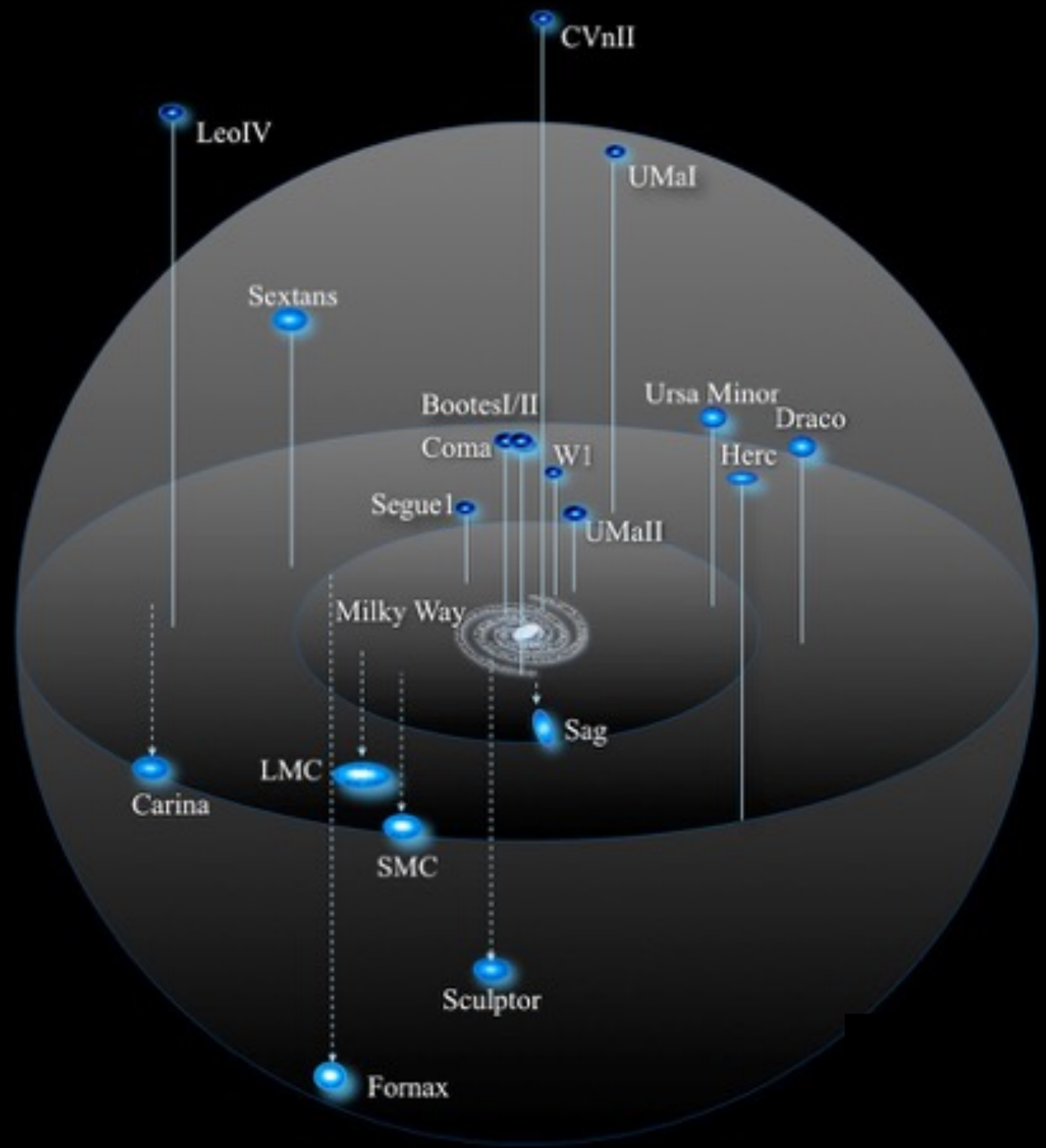
Resolving Galactic Substructure



ΛCDM vs. the Milky Way, Round 1: **Missing Satellites**

Klypin et al. 1999, Moore et al. 1999





>10^5 identified subhalos in simulations

Expect 10^{17} subhalos for WIMP models

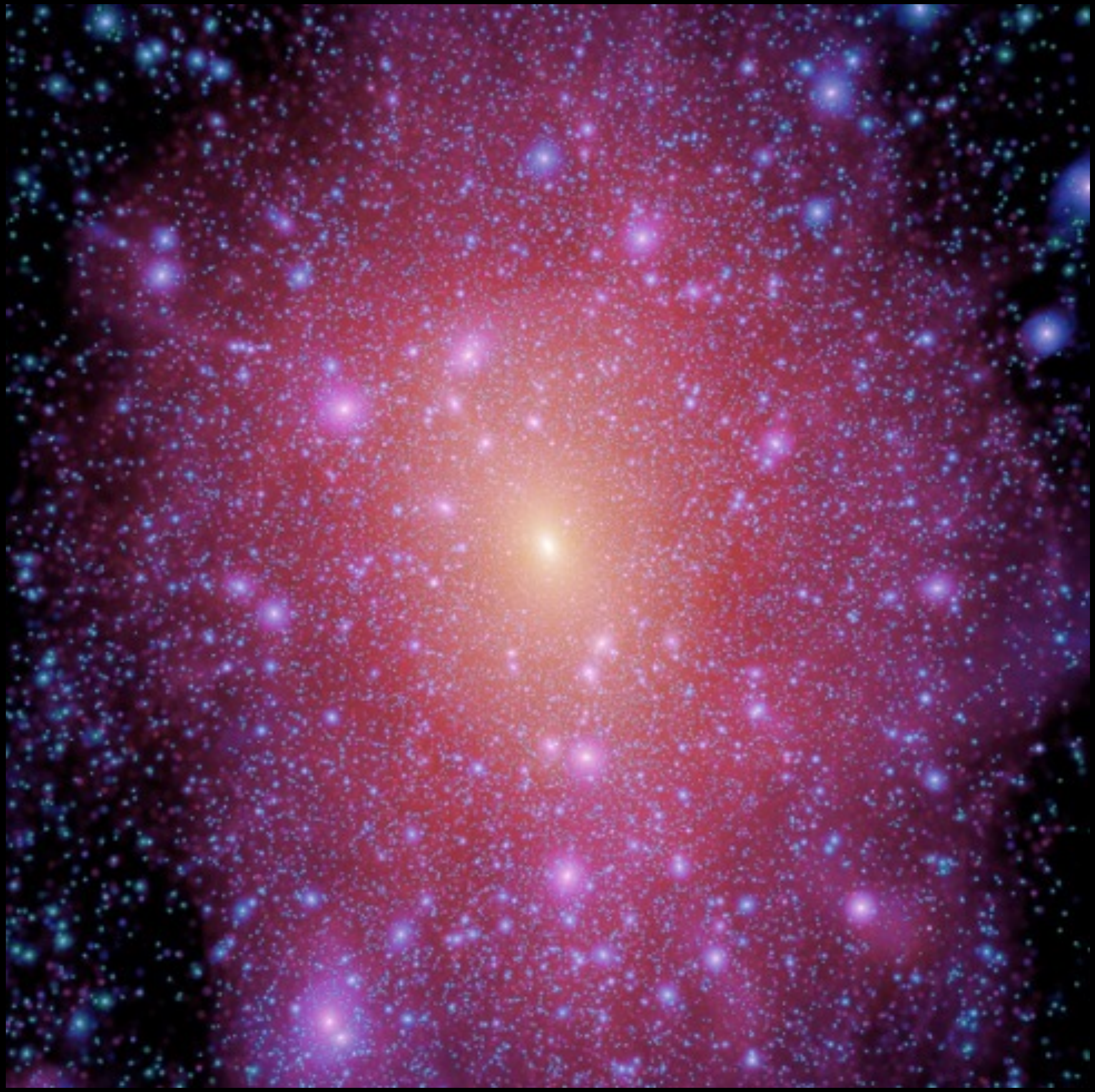
12 bright satellites $(L_V > 10^5 L_\odot)$

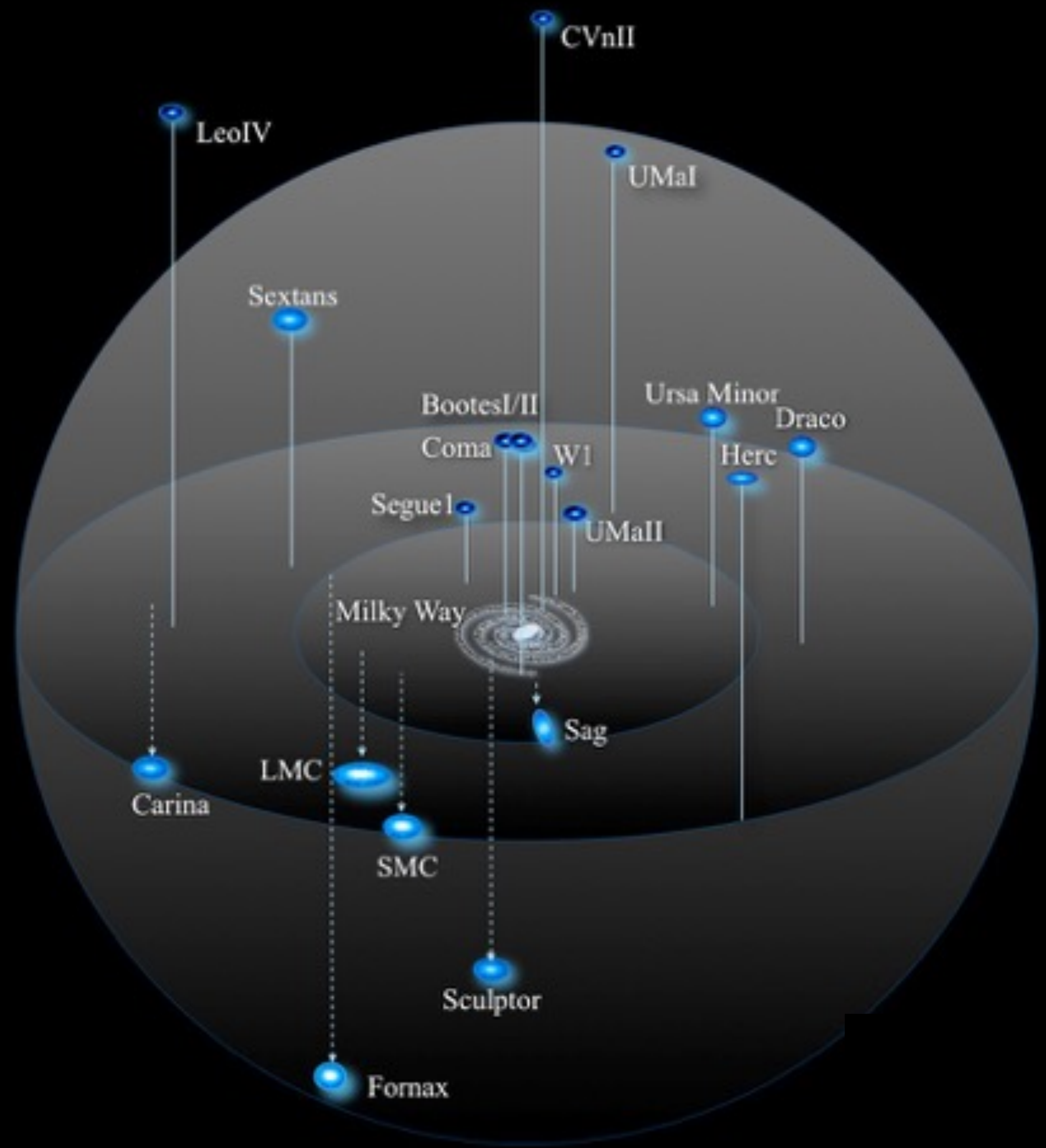
V. Springel / Virgo Consortium

J. Bullock

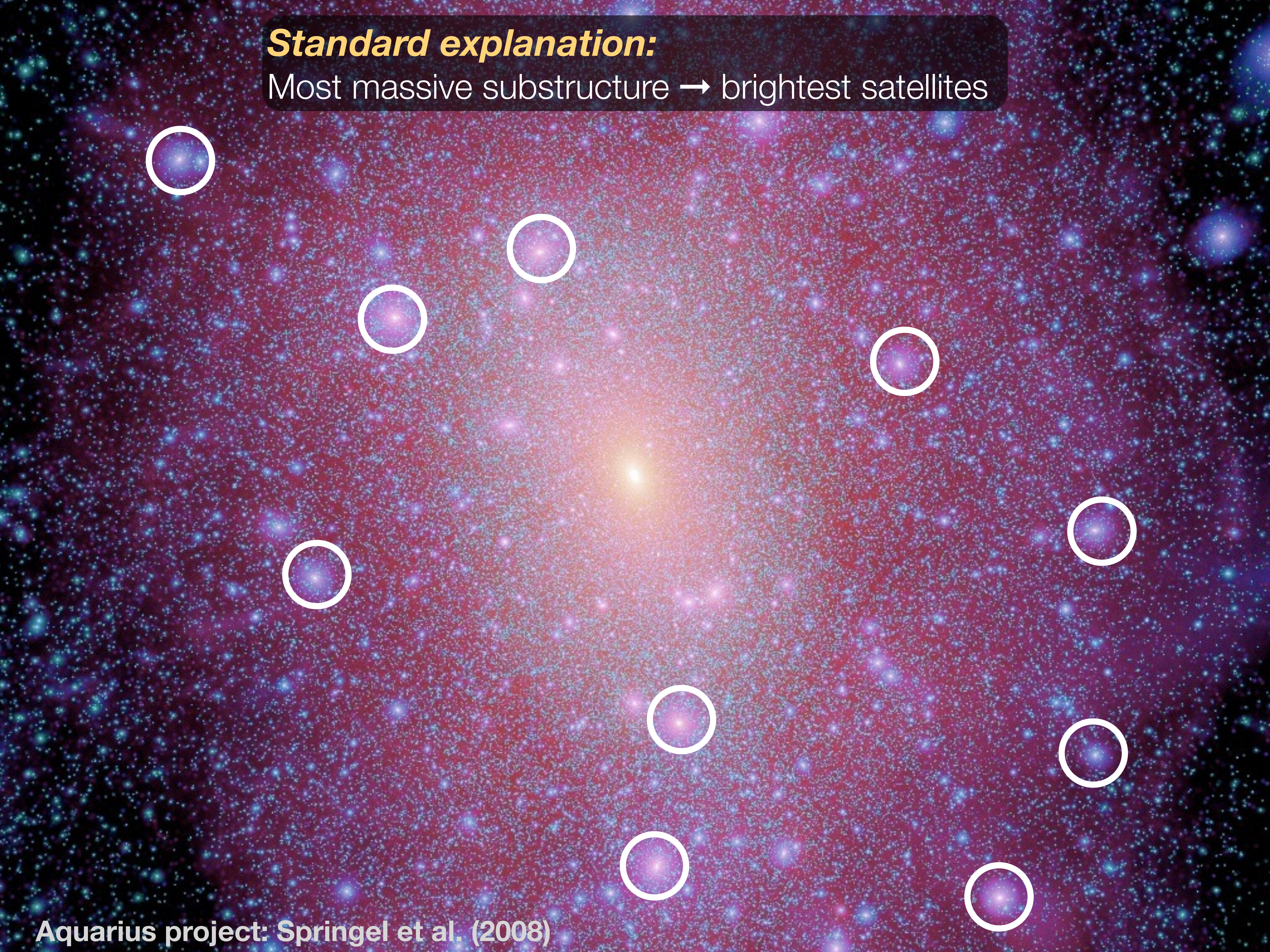
ΛCDM vs. the Milky Way, Round 1: **Missing Satellites**

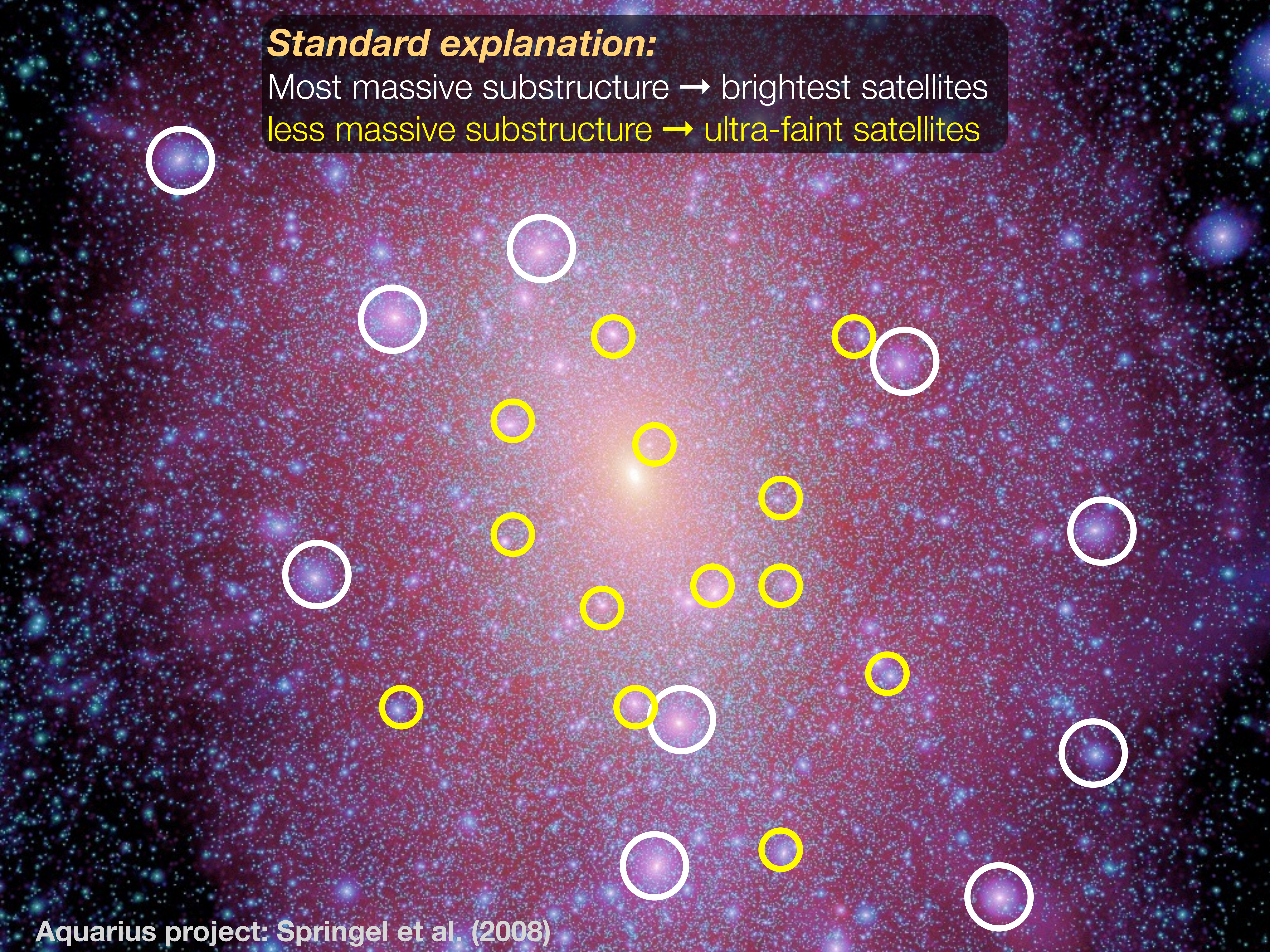
Klypin et al. 1999, Moore et al. 1999





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


Standard explanation:
Most massive substructure → brightest satellites
Aquarius project: Springel et al. (2008)



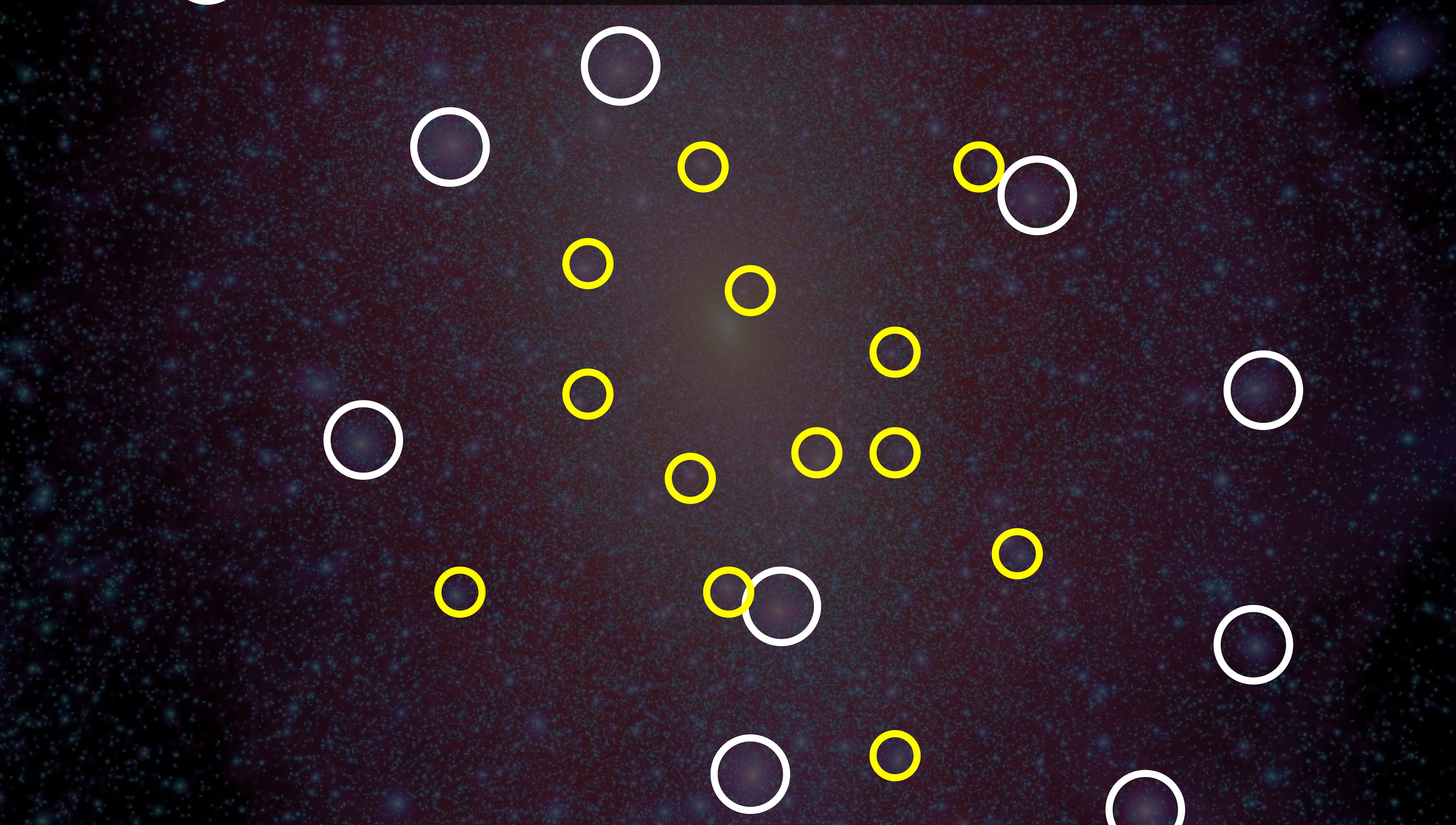
Aquarius project: Springel et al. (2008)

Standard explanation:

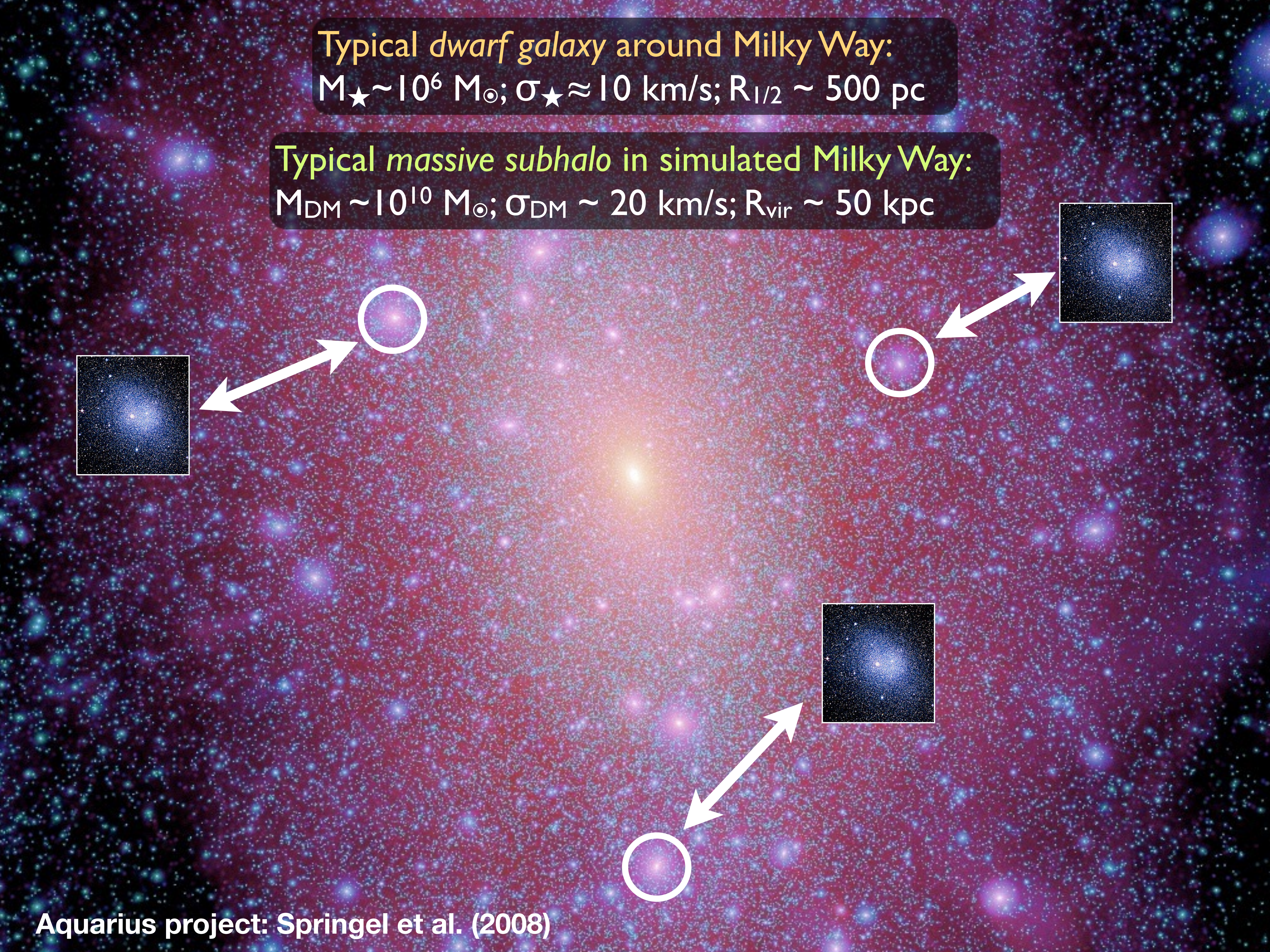
Most massive substructure → brightest satellites

less massive substructure → ultra-faint satellites

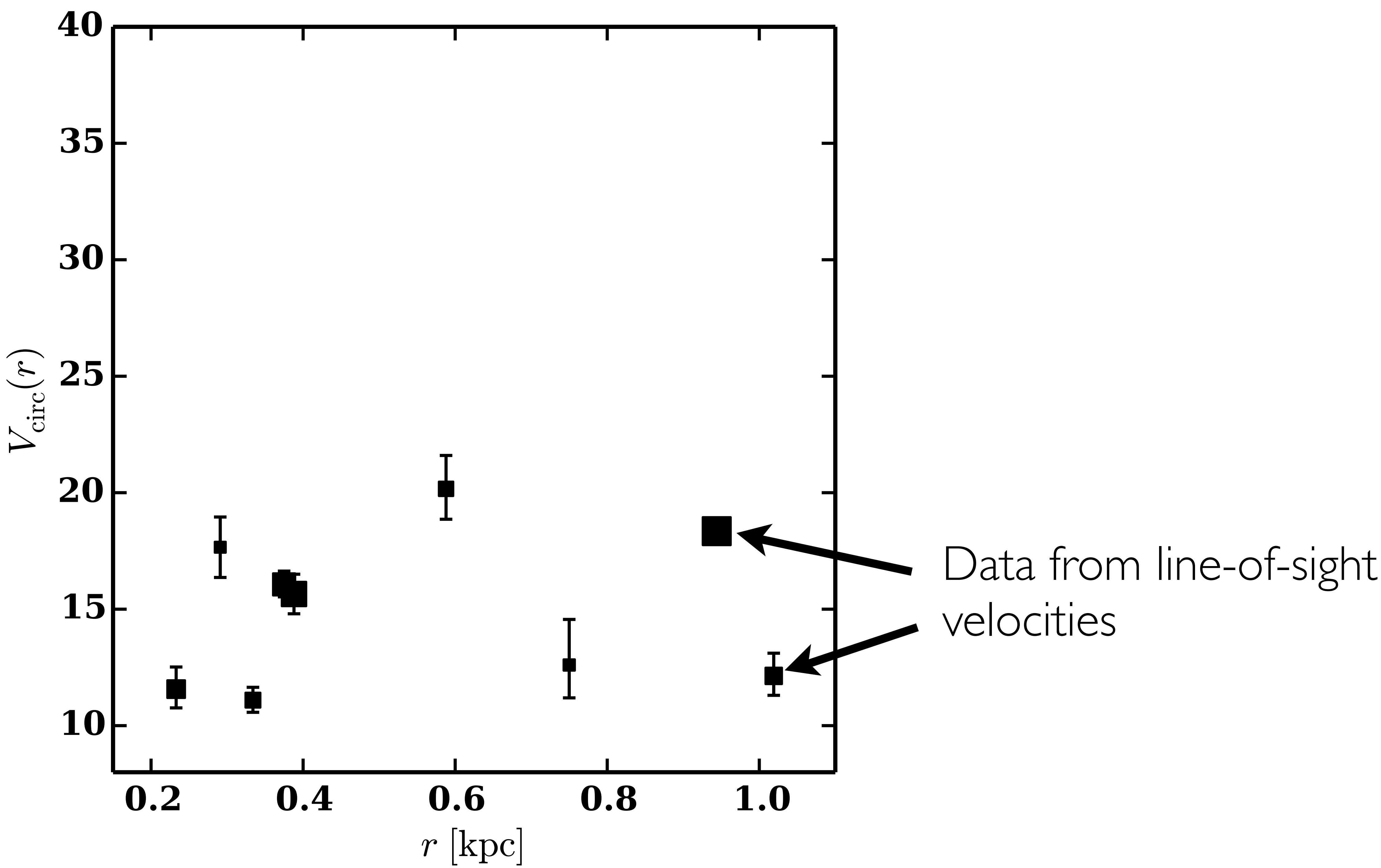
remaining substructure: fully suppressed by reionization



Aquarius project: Springel et al. (2008)

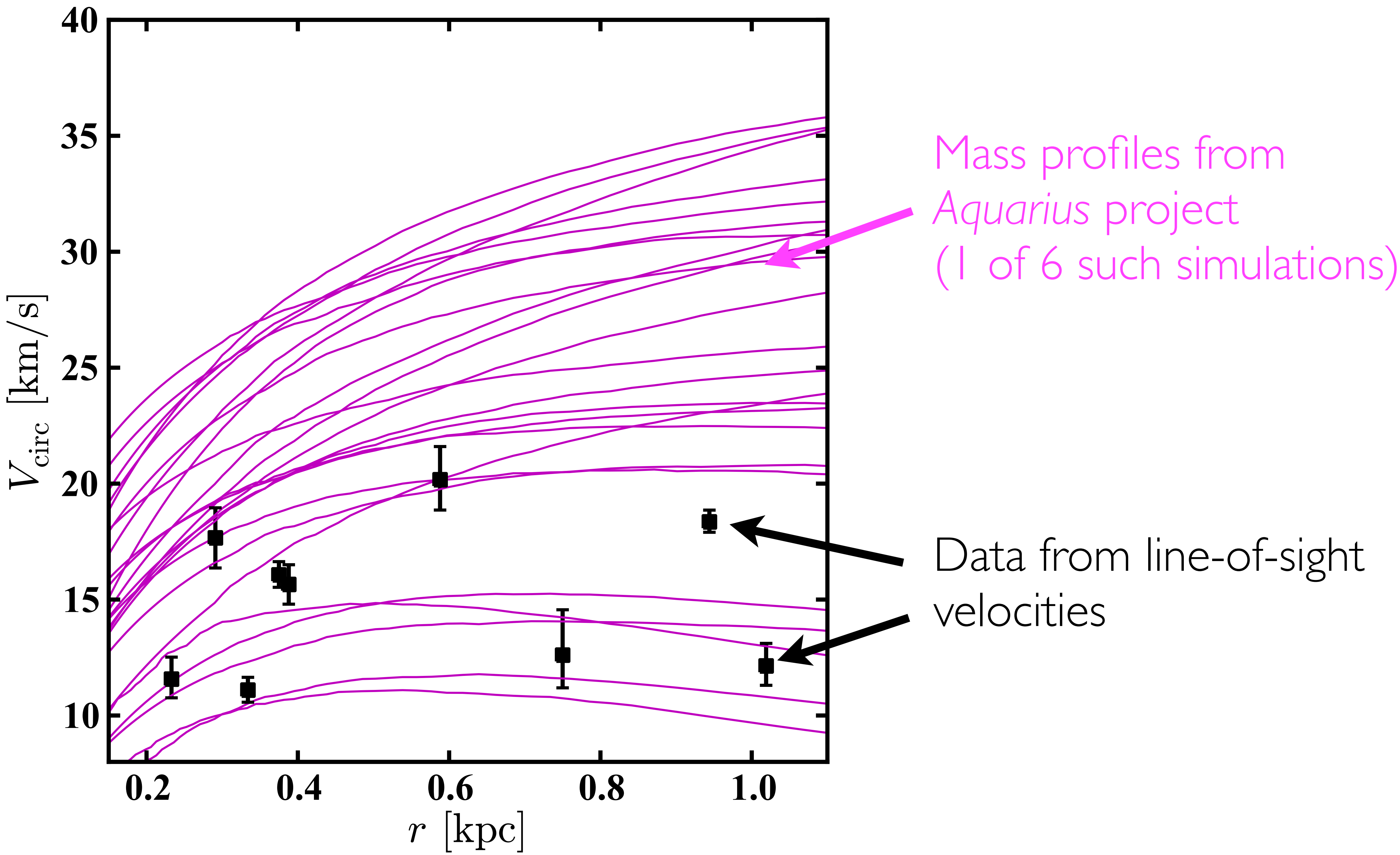

Typical *dwarf galaxy* around Milky Way:
$M_\star \sim 10^6\ M_\odot$; $\sigma_\star \approx 10$ km/s; $R_{1/2} \sim 500$ pc
Typical *massive subhalo* in simulated Milky Way:
$M_{DM} \sim 10^{10}\ M_\odot$; $\sigma_{DM} \sim 20$ km/s; $R_{vir} \sim 50$ kpc
Aquarius project: Springel et al. (2008)

Mass profiles of subhalos from *N*-body simulations



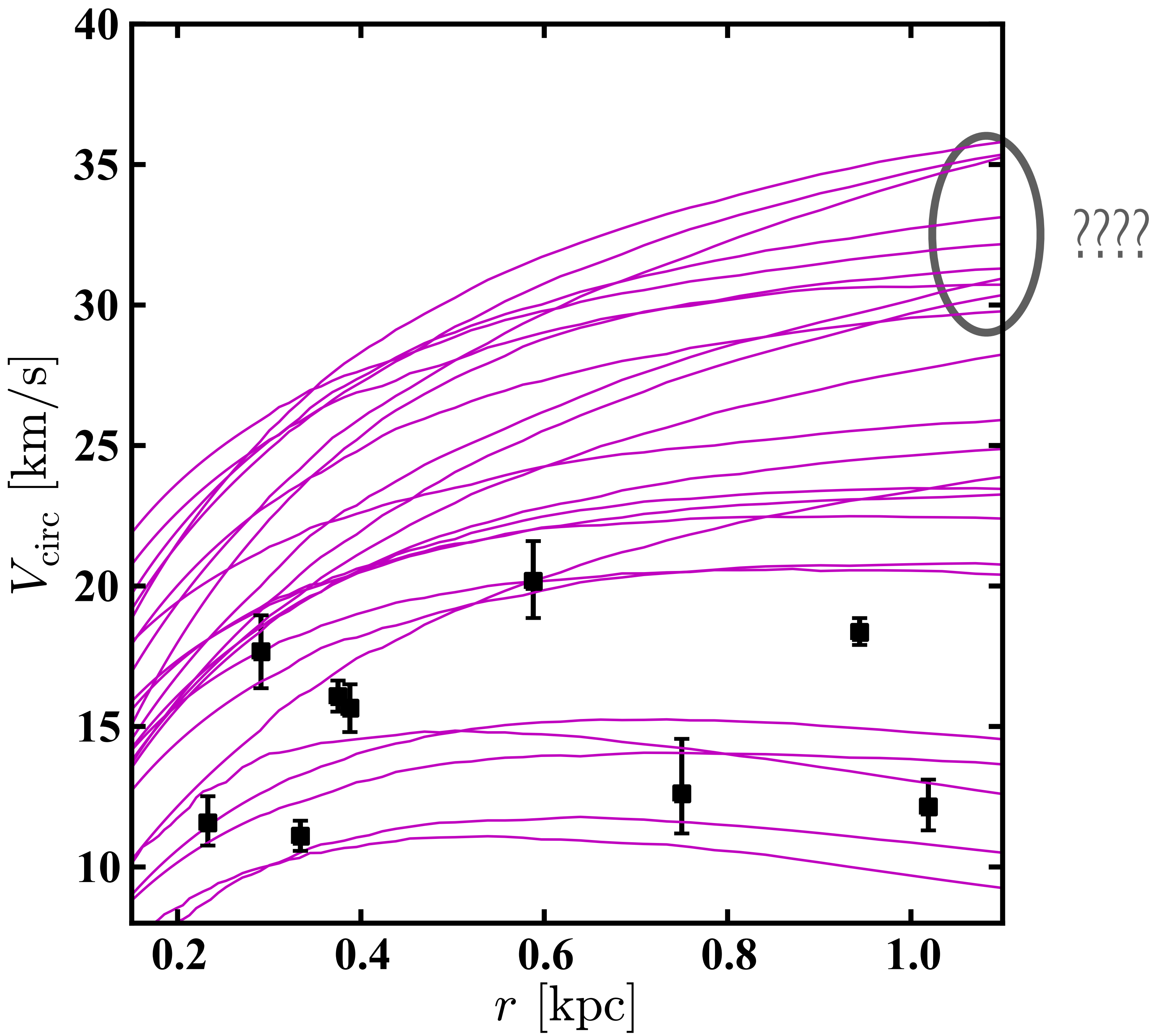
MBK, Bullock, & Kaplinghat 2011, 2012

Mass profiles of subhalos from *N*-body simulations



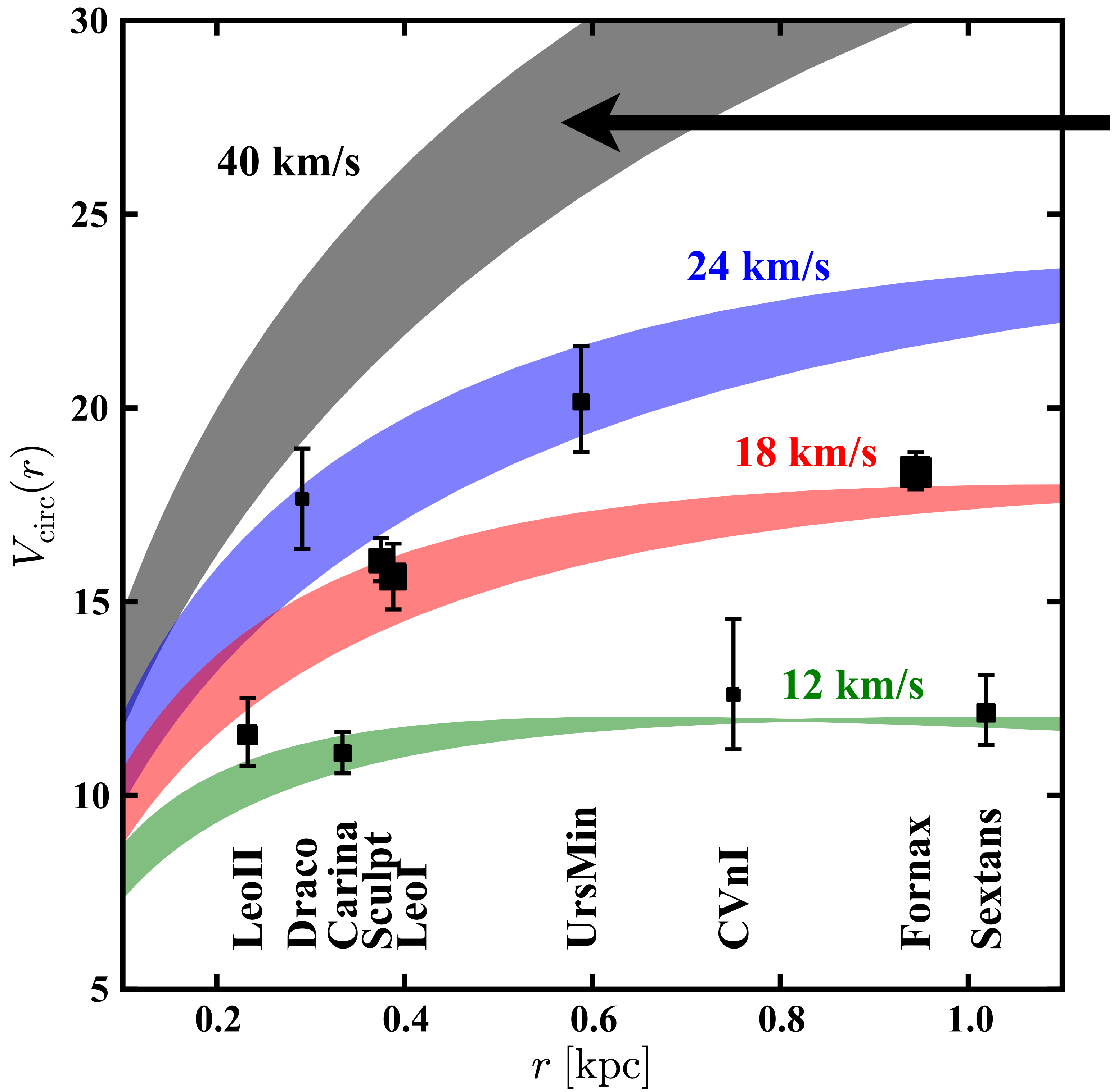
MBK, Bullock, & Kaplinghat 2011, 2012

Missing the **biggest** substructure?



MBK, Bullock, & Kaplinghat 2011, 2012

Brightest Milky Way satellites: why so low mass?



MBK, Bullock, & Kaplinghat 2011, 2012

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

Bright dSphs around MW:
$M_{halo} = 10^8 - 10^9\ M_{sun}$

Same behavior in M31, Local Group, and low-z Universe more broadly

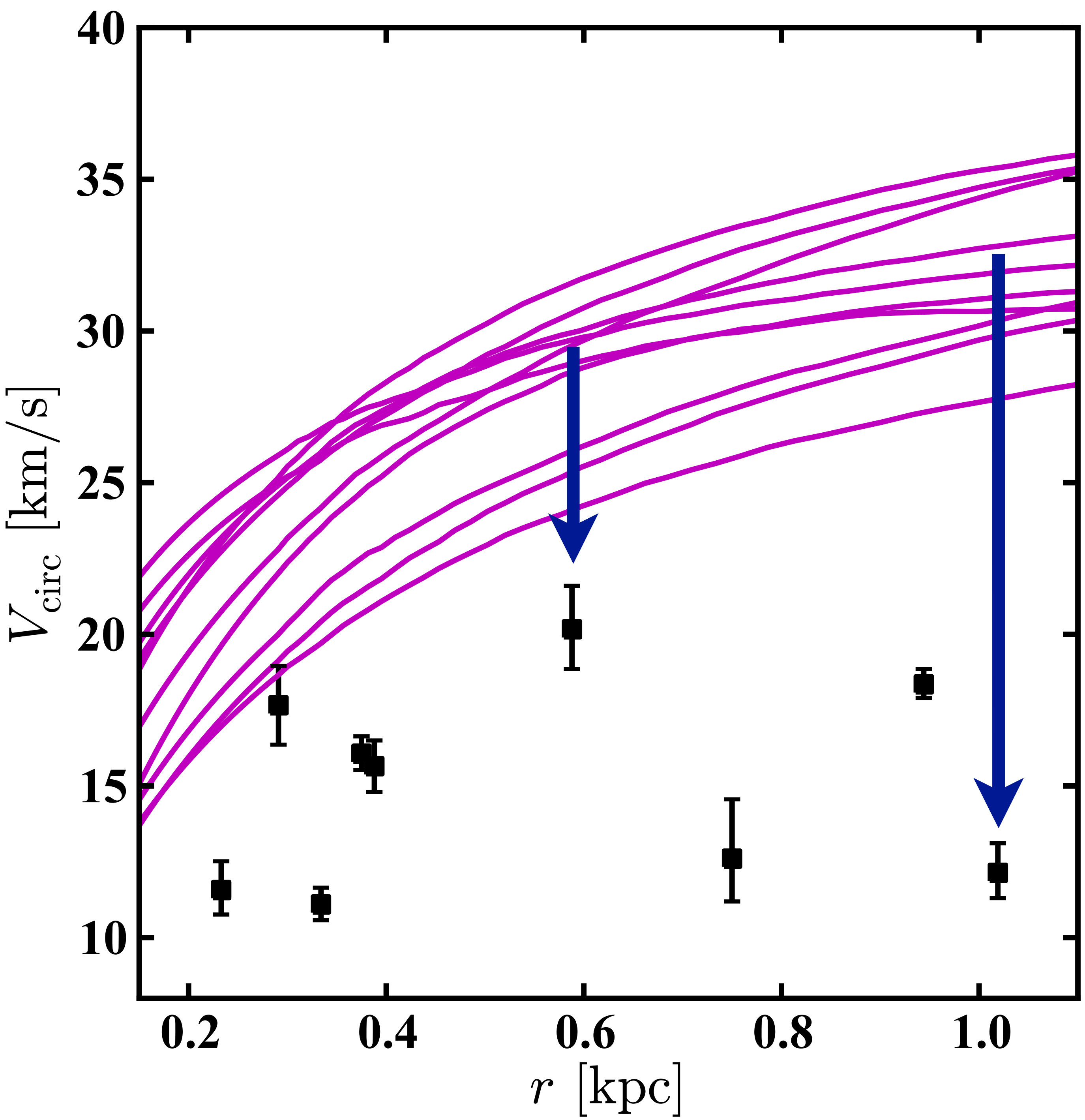
(Tollerud, MBK, Bullock 2014; Garrison-Kimmel, MBK et al. 2014; Papastergis et al. 2014)

The “too big to fail” problem

- It is easy to make models that reproduce the luminosity function of Milky Way satellite galaxies
- It is easy to find dark matter subhalos that match the observed kinematics of the Milky Way satellites
- **It does not seem possible to match both the luminosity function and structure (kinematics) at the same time**
    - Models that match the luminosity function: V_{circ} ~ 30-60 km/s
    - Models that match the kinematics: V_{circ} ~ 12-25 km/s
- There is a basic problem with our understanding of galaxy formation or cosmology / dark matter physics on small scales

MBK, Bullock, & Kaplinghat 2011, 2012

From CDM to observations

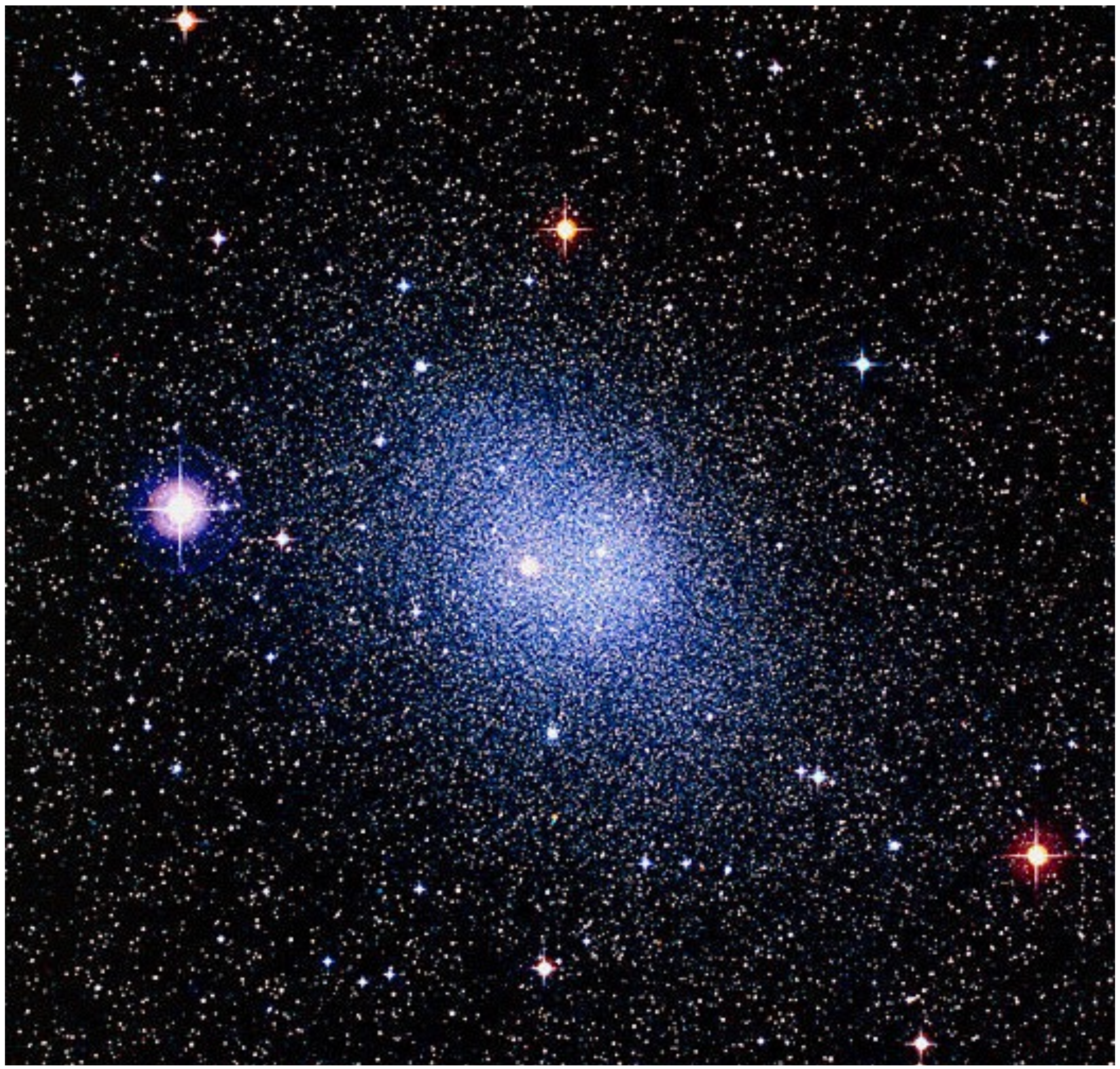


Observations of MW satellites:
Pointing to a problem with CDM-only predictions for densities on small scales (0.1-1 kpc)

need ~50% less dark matter mass in the inner 500 pc — *reduce amplitude* or *change shape* of density profile

Related issue (?): density profile of MW dwarf galaxies

Cusps or cores in MW satellites? Disagreement among different groups using different methods on same data sets



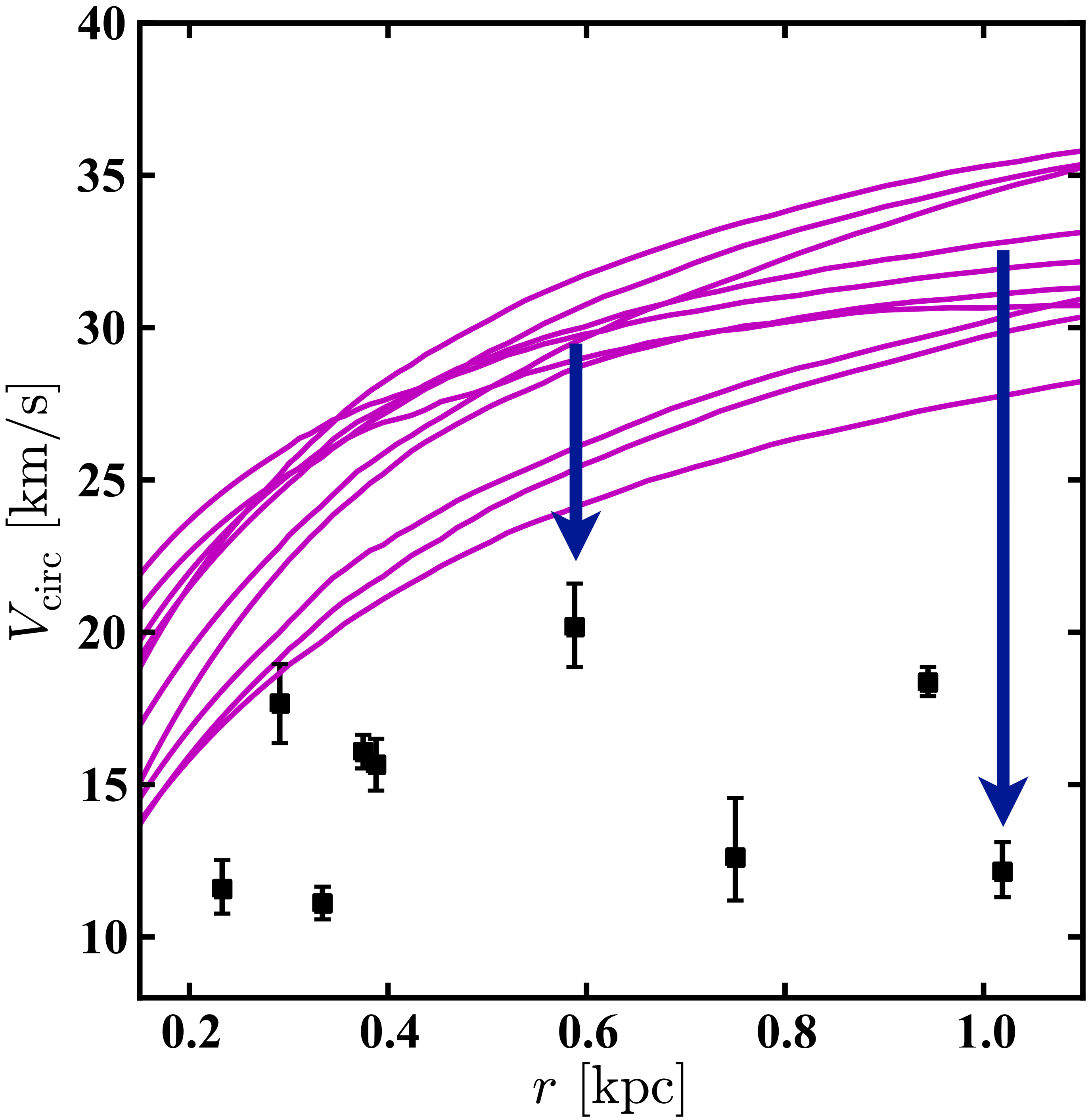
$$\rho(r) \propto \left(\frac{r}{r_0}\right)^{-\alpha} \quad (r \ll r_0)$$

$$\alpha = 0 \text{ or } \alpha = 1???$$

Note: "Too Big to Fail" issue is independent of density profiles of dwarfs, but cores in MW dwarfs would likely solve Too Big to Fail

Battaglia et al. 2008, Strigari et al. 2010, Walker et al. 2011, Breddels & Helmi 2012, Jardel & Gebhart 2012, …

From CDM to observations



Observations of MW satellites: Pointing to a problem with CDM-only predictions for densities on small scales (0.1-1 kpc)

need ~50% less dark matter mass in the inner 500 pc — *reduce amplitude* or *change shape* of density profile

Possible culprits: baryonic feedback, dark matter physics

Adding Baryons

Simple picture: baryons are only 20% of matter budget; stars are <<1% of DM mass in smallest galaxies, so baryons are unimportant

But: (1) baryons can cool radiatively, collect at center of DM halos, amplifying effects, and (2) energy and momentum input from stars may be important even in the lowest mass systems.

Examples:
(i) get 1 type II supernova for every 100 M_{sun} of stars formed; dumps 10^{51} ergs of energy into surrounding ISM
(ii) first stars and galaxies produce background of energetic photons, raising temperature of intergalactic gas throughout the Universe

Adding baryons — why is this still under debate?

Collisionless simulations: exact solution to an approximate problem

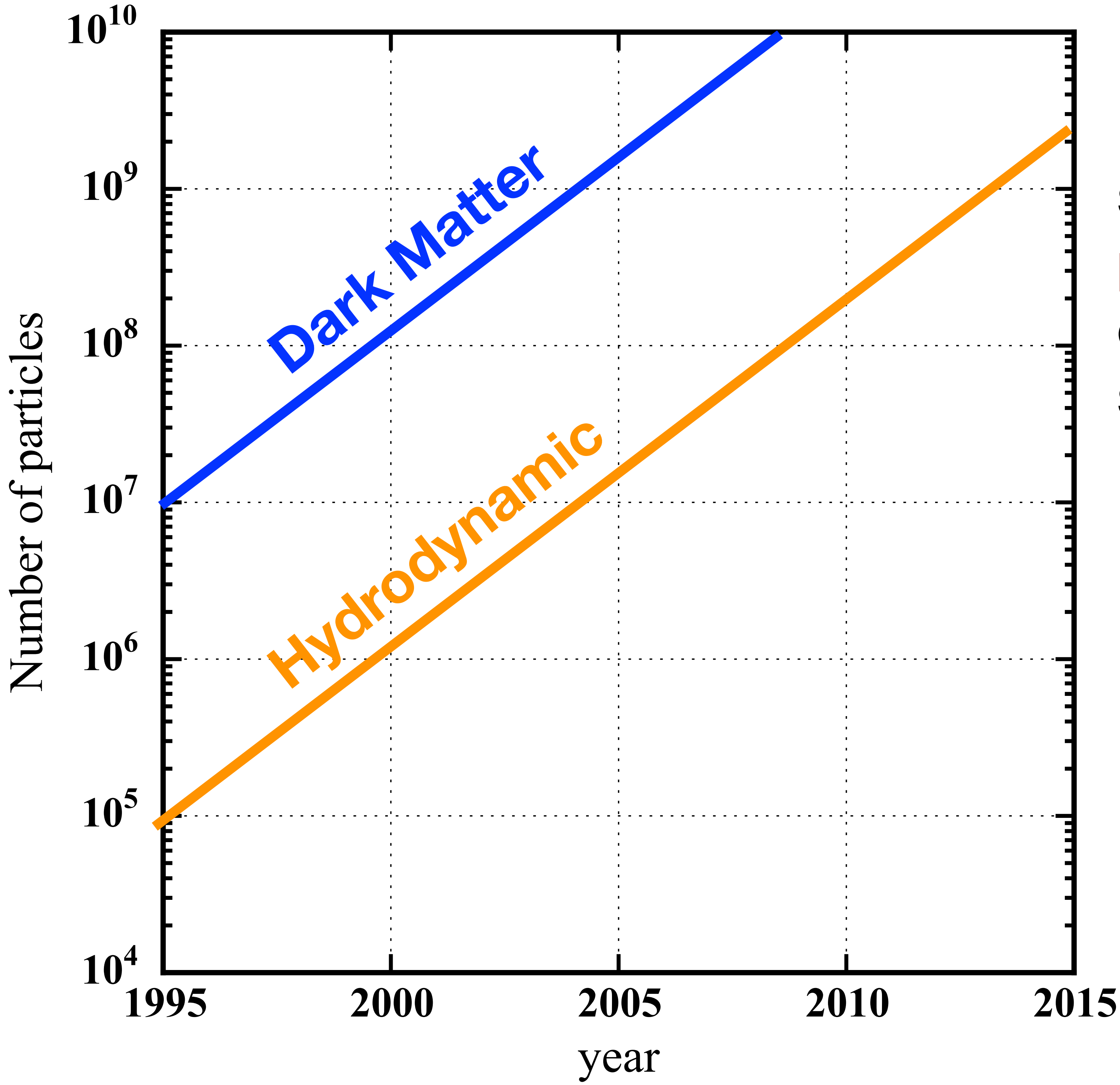
Hydrodynamical simulations: approximate solutions to full problem

- How much energy from a single supernova explosion couples to gas in galaxy? All simulations must make a choice for this (not unique)
- How important is radiation pressure versus thermal or kinetic energy?
- What physics is important? Cosmic rays? Magnetic fields?
- Inherently limited by spatial and temporal resolution — how do we treat processes on smaller length and time scales than we resolve?

- ***All*** simulations require parameter choices and approximations

Adding Baryons

Large-Scale Simulations: hydrodynamic simulations are **10 years behind** dark-matter-only simulations at fixed particle number.

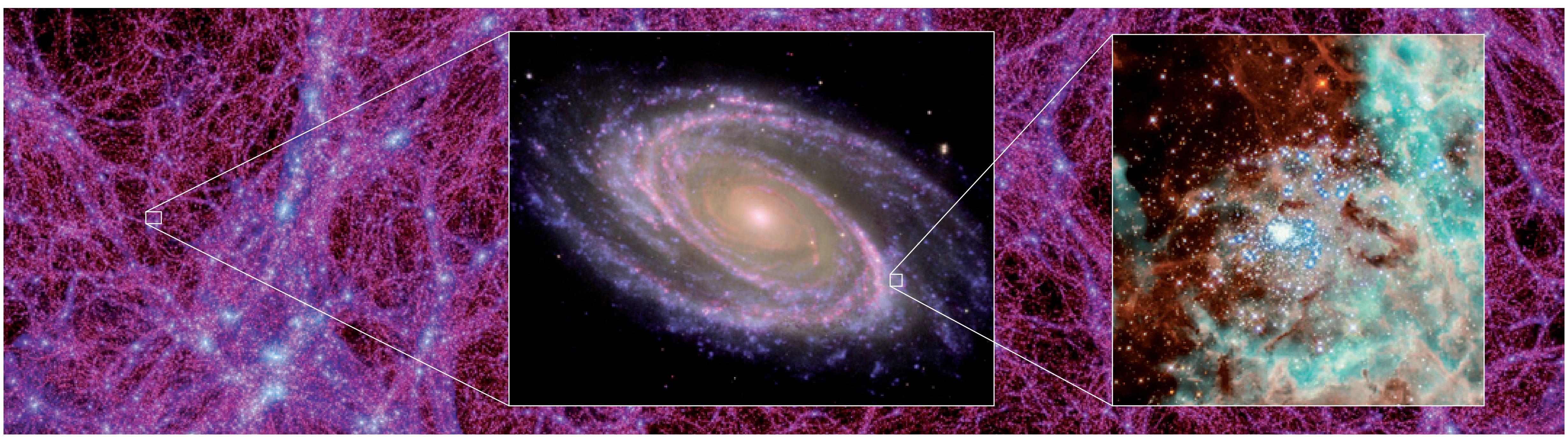


Equivalently, hydrodynamic simulations use **100x fewer particles** than dark-matter-only simulations for identical system at a given time.

Adding Baryons

Zoom-in Simulations: State-of-the-art simulations of the Milky Way represent gas with particles of 10^4-10^5 M_{sun}, spatial scales of ~40 pc. *Galaxy formation physics is still largely phenomenological at this level*.

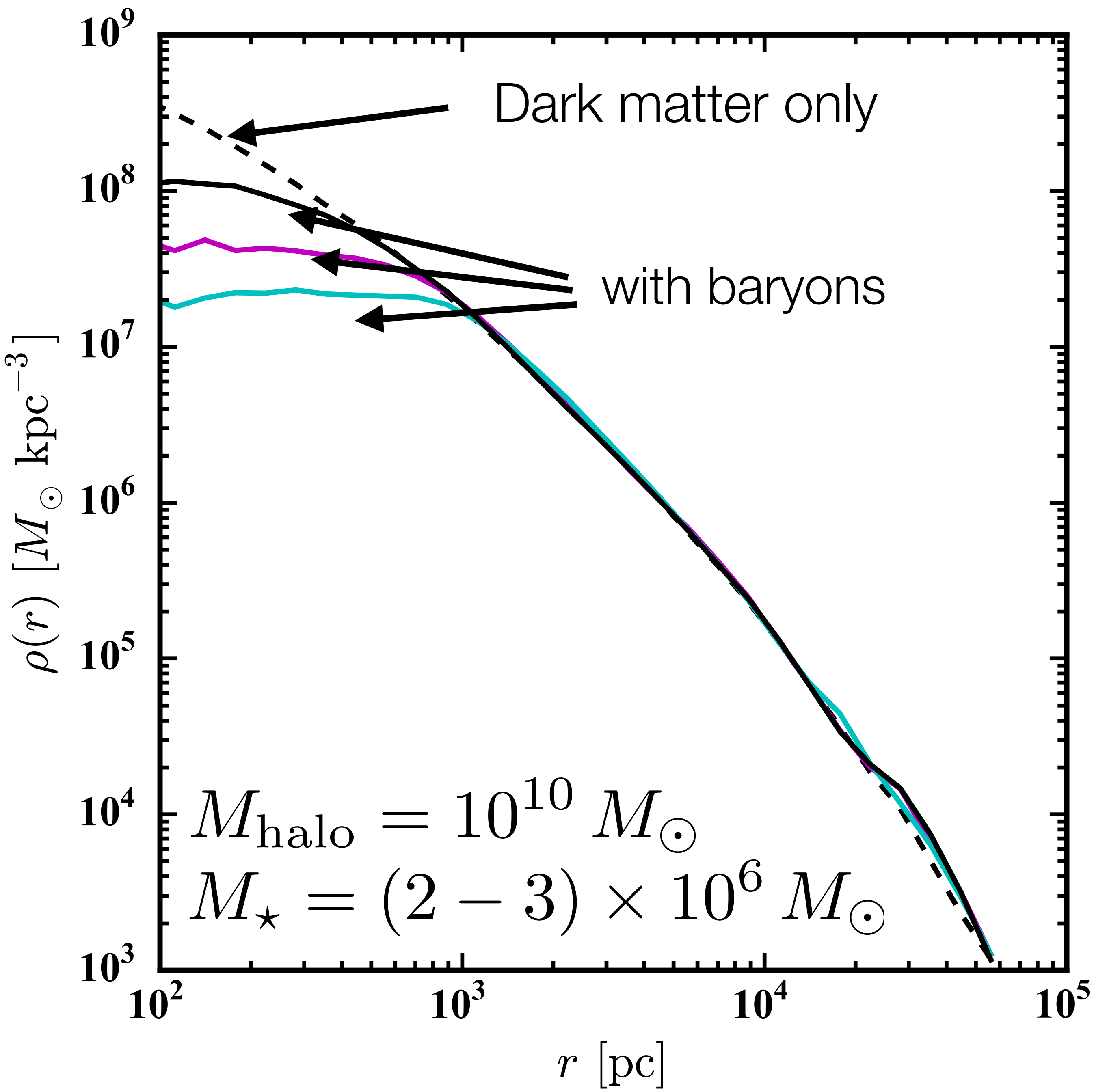
For dwarf galaxies, gas particles represent ~100 M_{sun} at present, resolve spatial scales of ~1 pc. *Getting more realistic, but still far from ideal.*



MBK 2014

Adding Baryons

Dwarf galaxies + baryons: easing tensions?



Onorbe, MBK et al. 2015

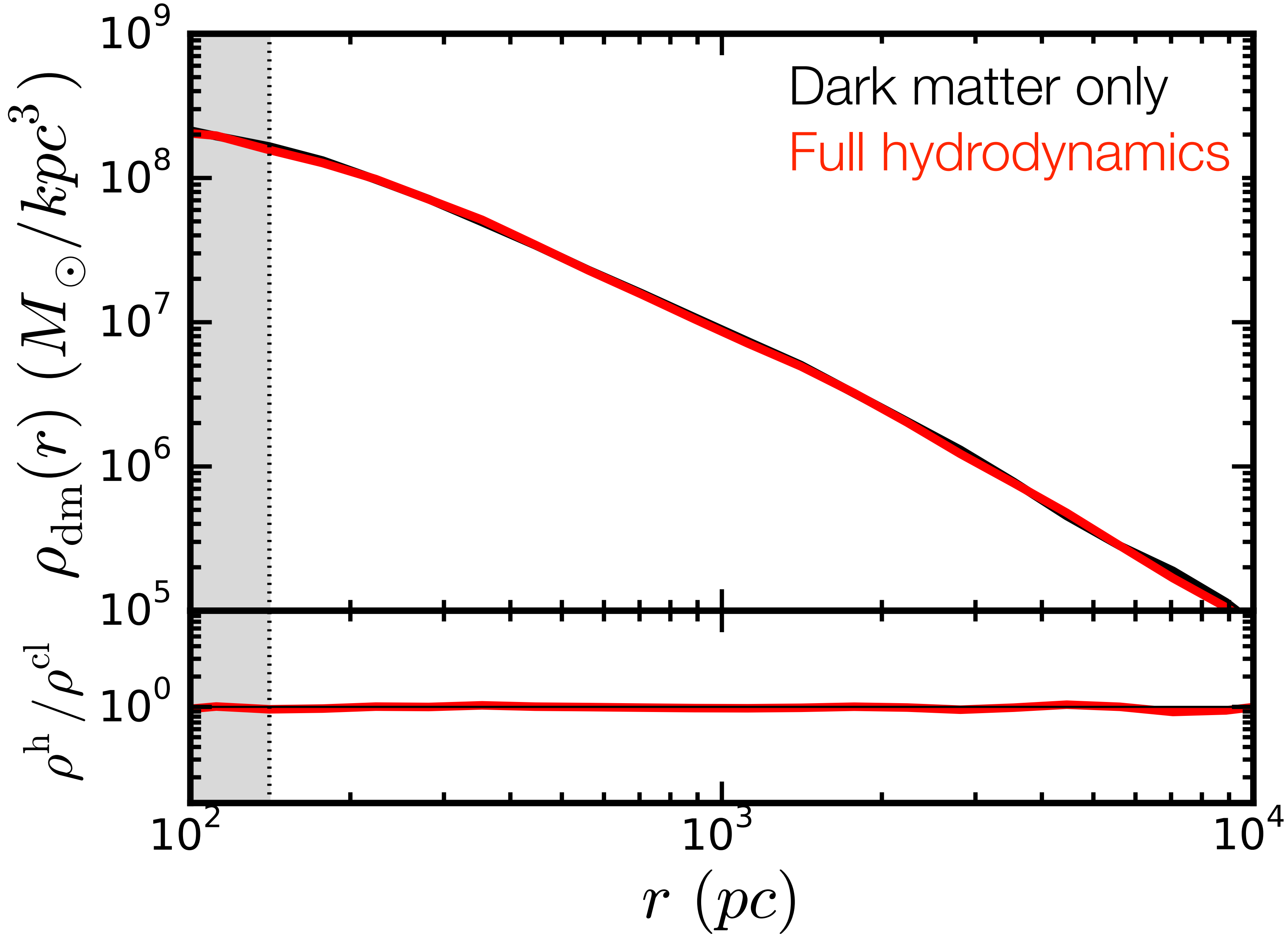
Find cores with R~0.5 kpc formed by galaxy formation feedback (Pontzen & Governato)

Caution: results may not be converged even in best simulations today

Adding Baryons

Slightly lower mass halo (3x smaller):

much lower stellar mass (100x), **no core**



$$M_\star = 2\times10^4\,M_\odot$$
$$M_{\rm halo} = 3\times10^9\,M_\odot$$

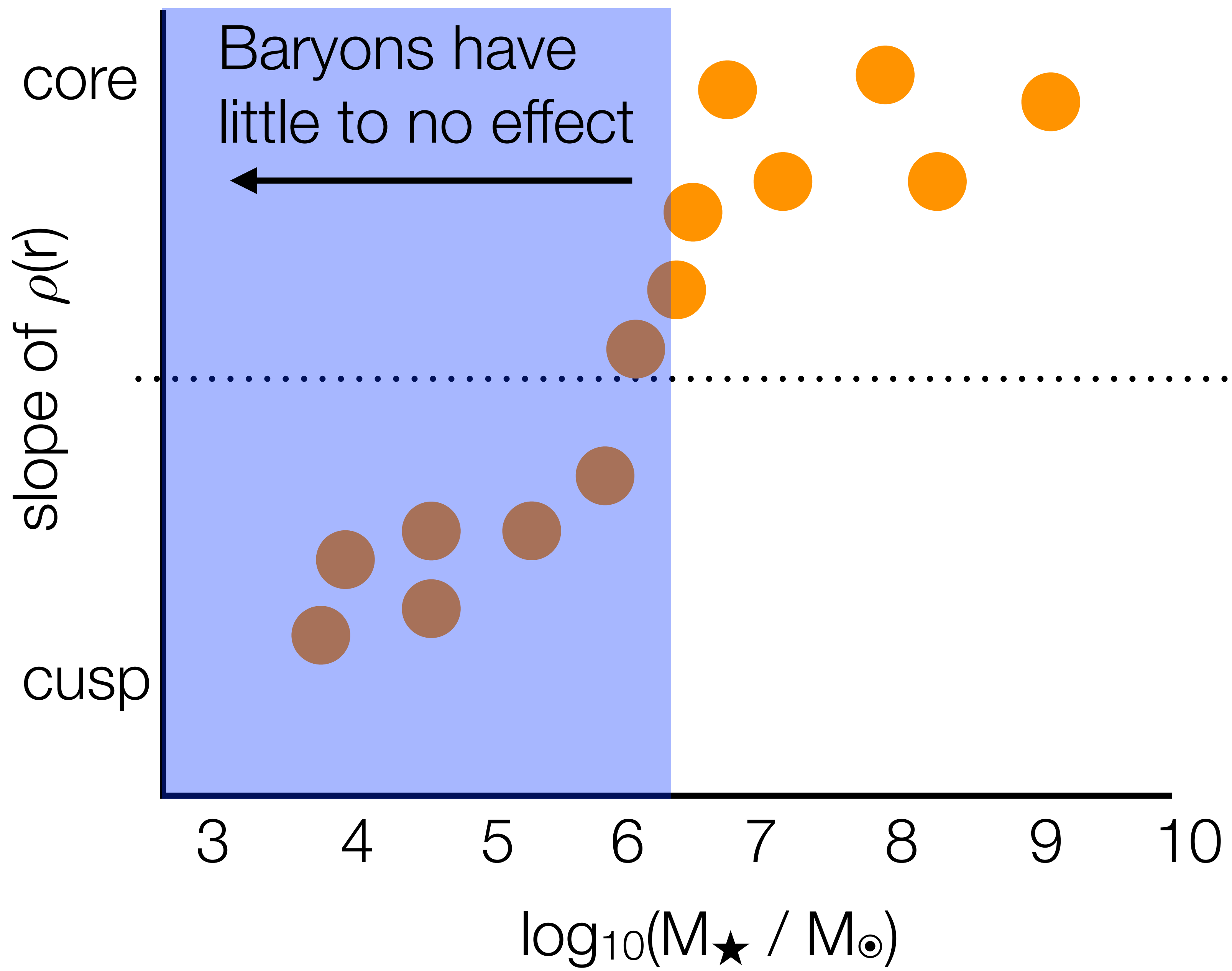
Oñorbe, MBK et al. (2015)

Minimum mass scale for core formation: $M_{\rm vir}\sim10^{10}\,M_\odot$ ($M_\star \sim 3\times10^6\,M_\odot$)

Governato++, Oñorbe++, Penarrubia++, Garrison-Kimmel++, Di Cintio ++, Brooks & Zolotov, …

Baryonic effects: sensitive to stellar mass

Argues we should look at low-mass systems ($M_\star \lesssim 10^6$ $M_\odot$) that are isolated from environmental effects



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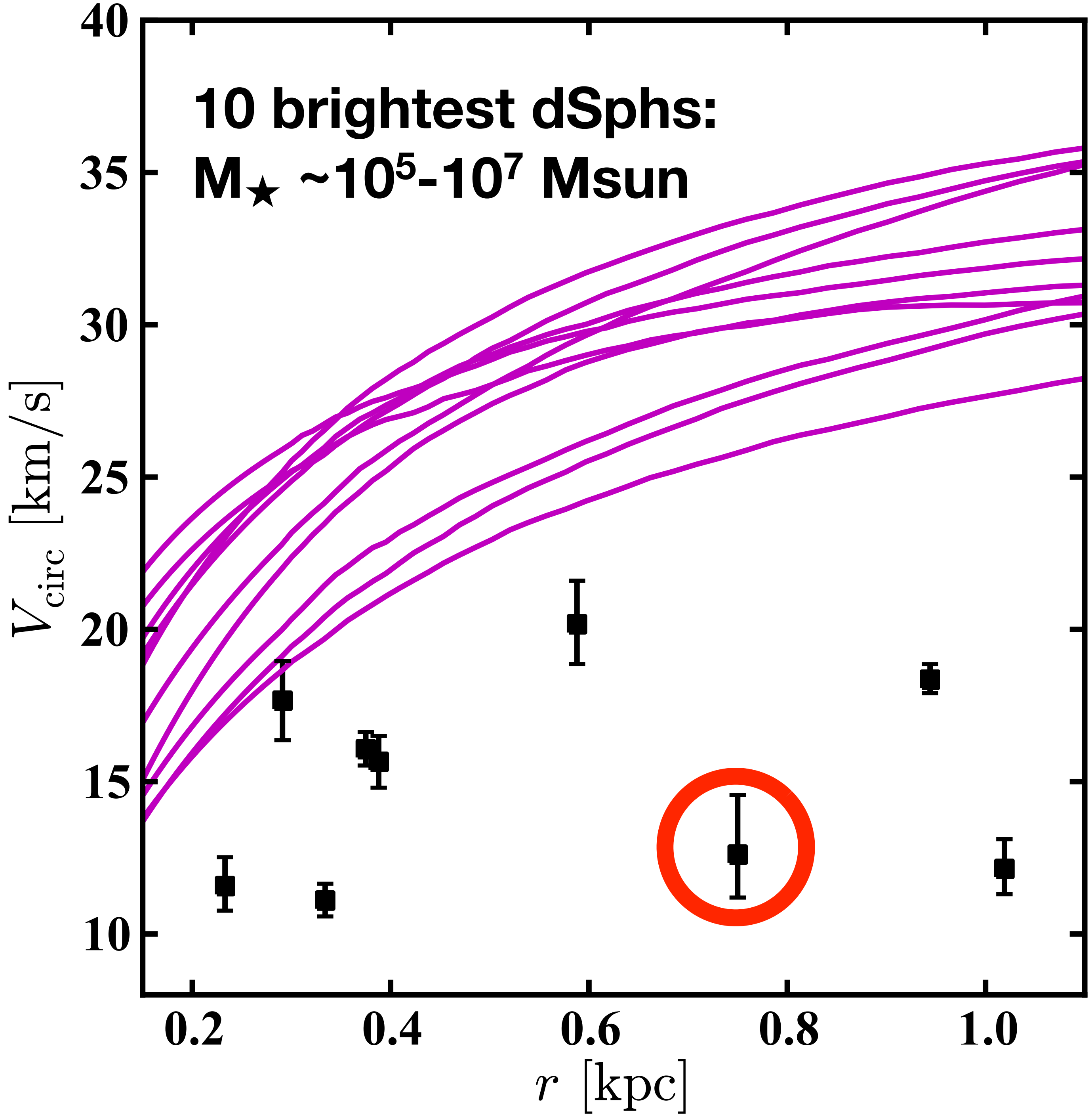
Governato++, Oñorbe++, Penarrubia++, Garrison-Kimmel++, Di Cintio ++, Brooks & Zolotov, …

A test of the baryonic feedback model?



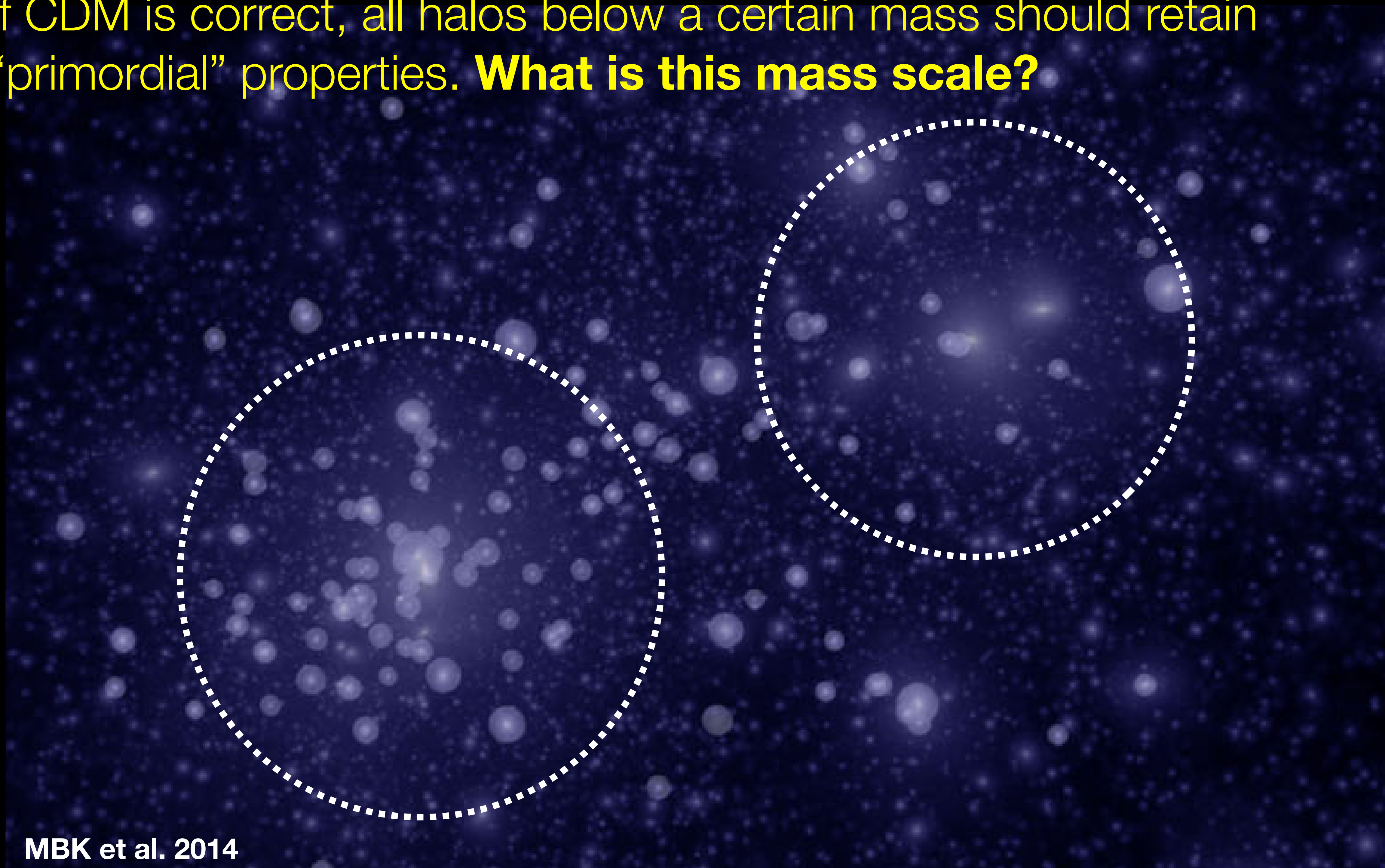
Possible test of the baryon feedback model:
Does CVnI ($M_\star$ ~10^5) have a ~1 kpc core? If not, can tidal effects explain its extremely low density?

Gaia proper motions should help with the 2nd question

The future: LSST + JWST + 30m telescopes

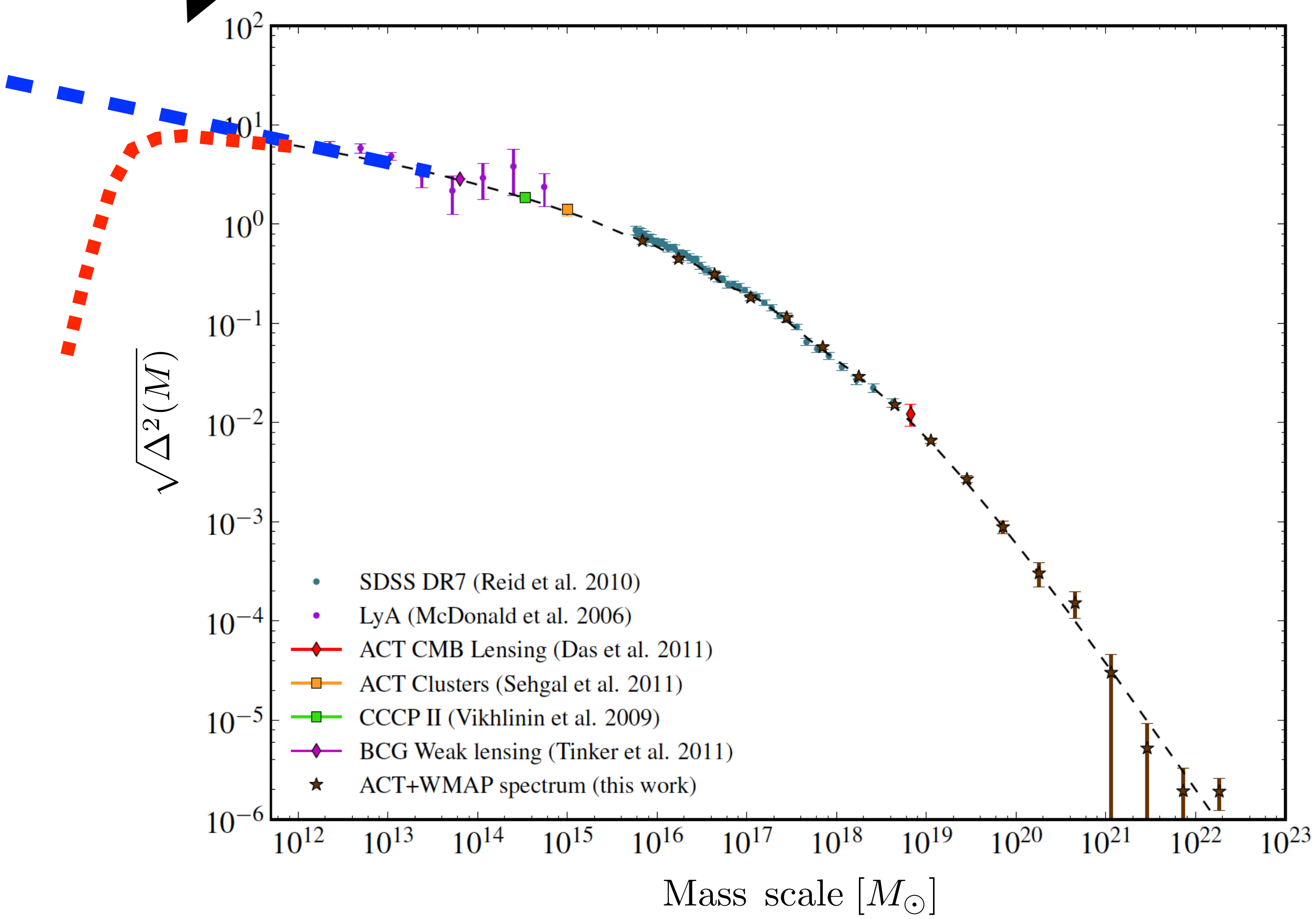
These observatories will find and characterize isolated, low-mass galaxies throughout the nearby Universe

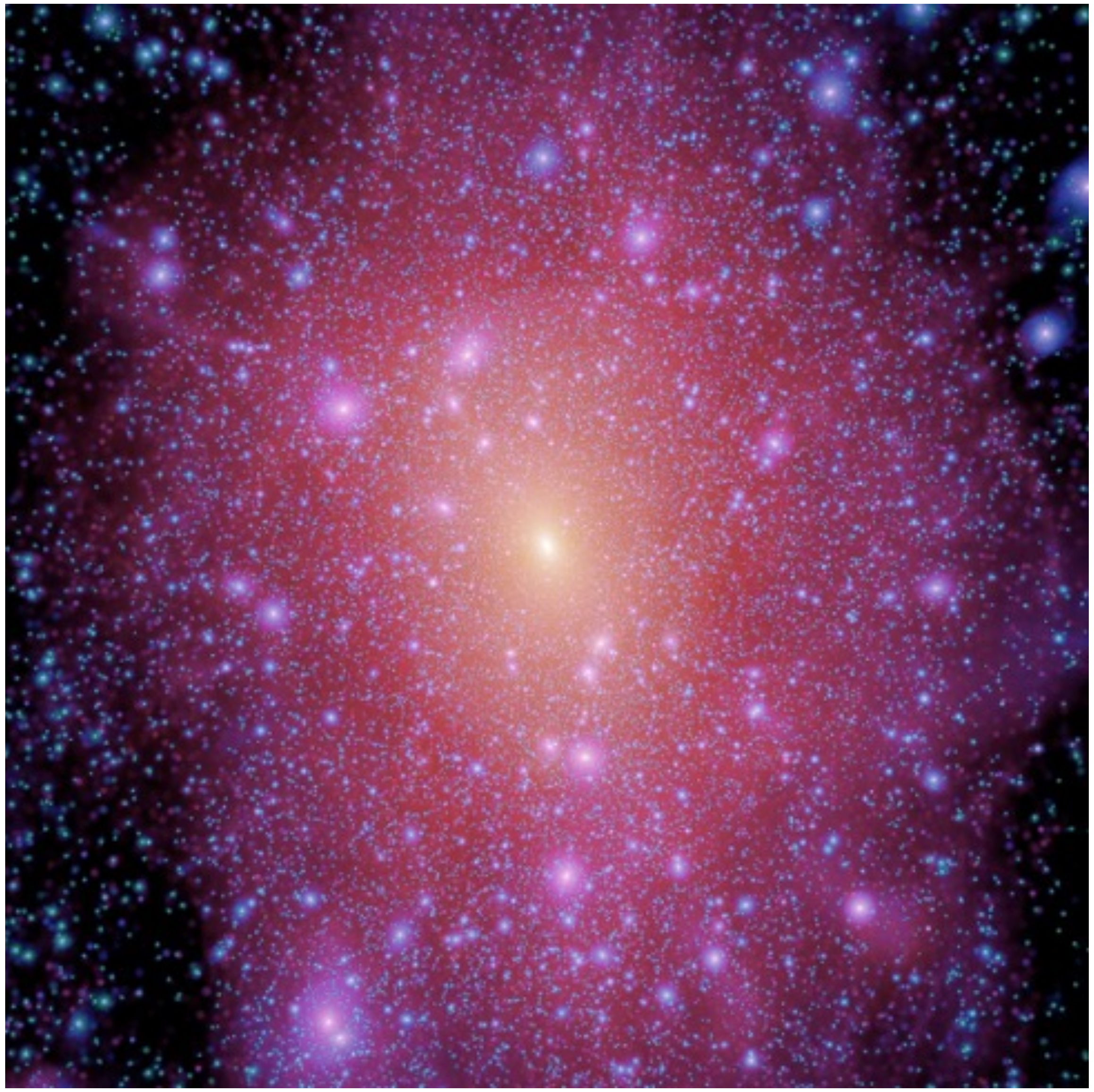
If CDM is correct, all halos below a certain mass should retain "primordial" properties. **What is this mass scale?**



Alternative Dark Matter Models

Modify *linear* physics or *non-linear* physics

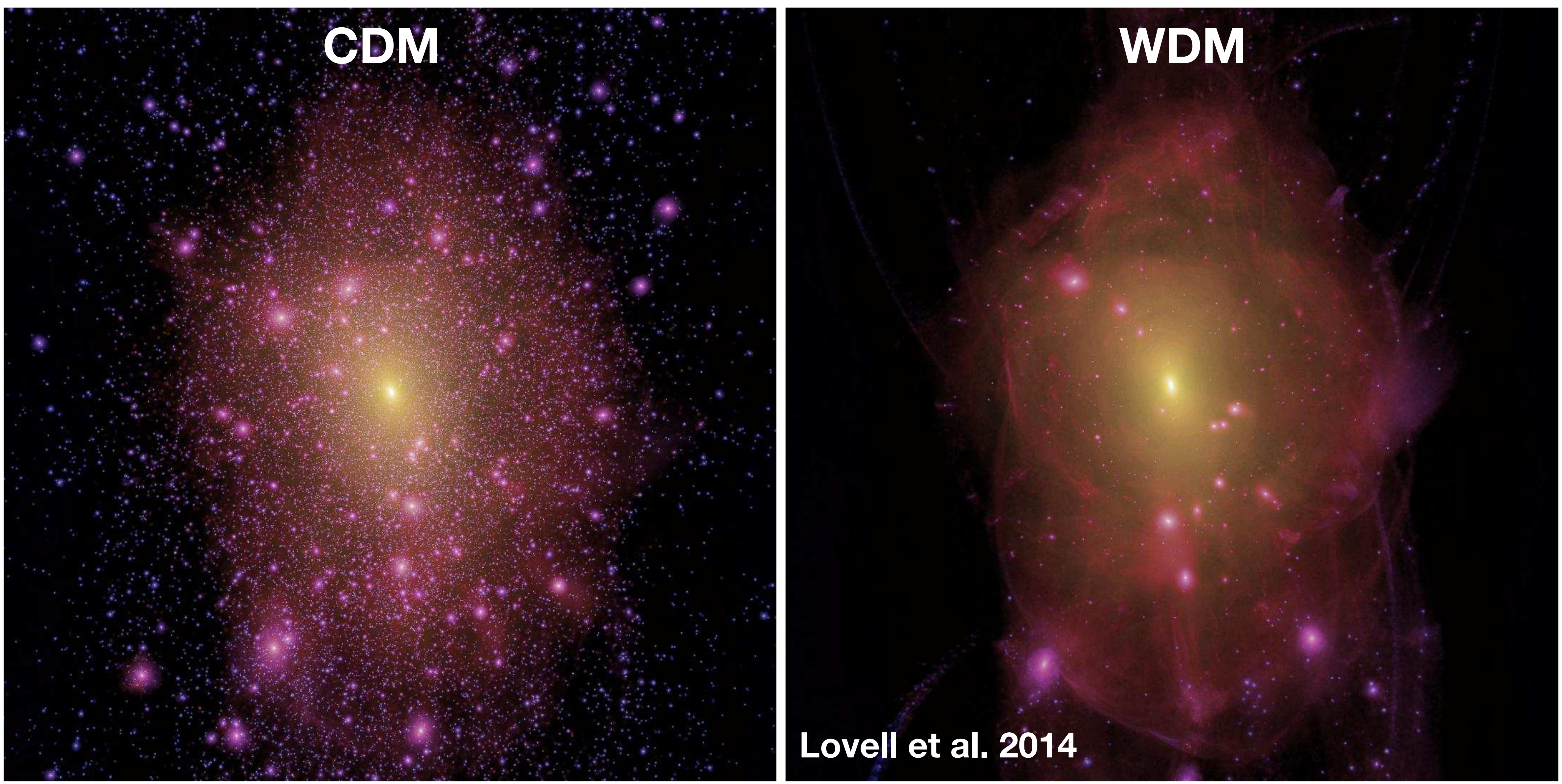




Alternative Dark Matter Models

Modify *linear* physics or *non-linear* physics

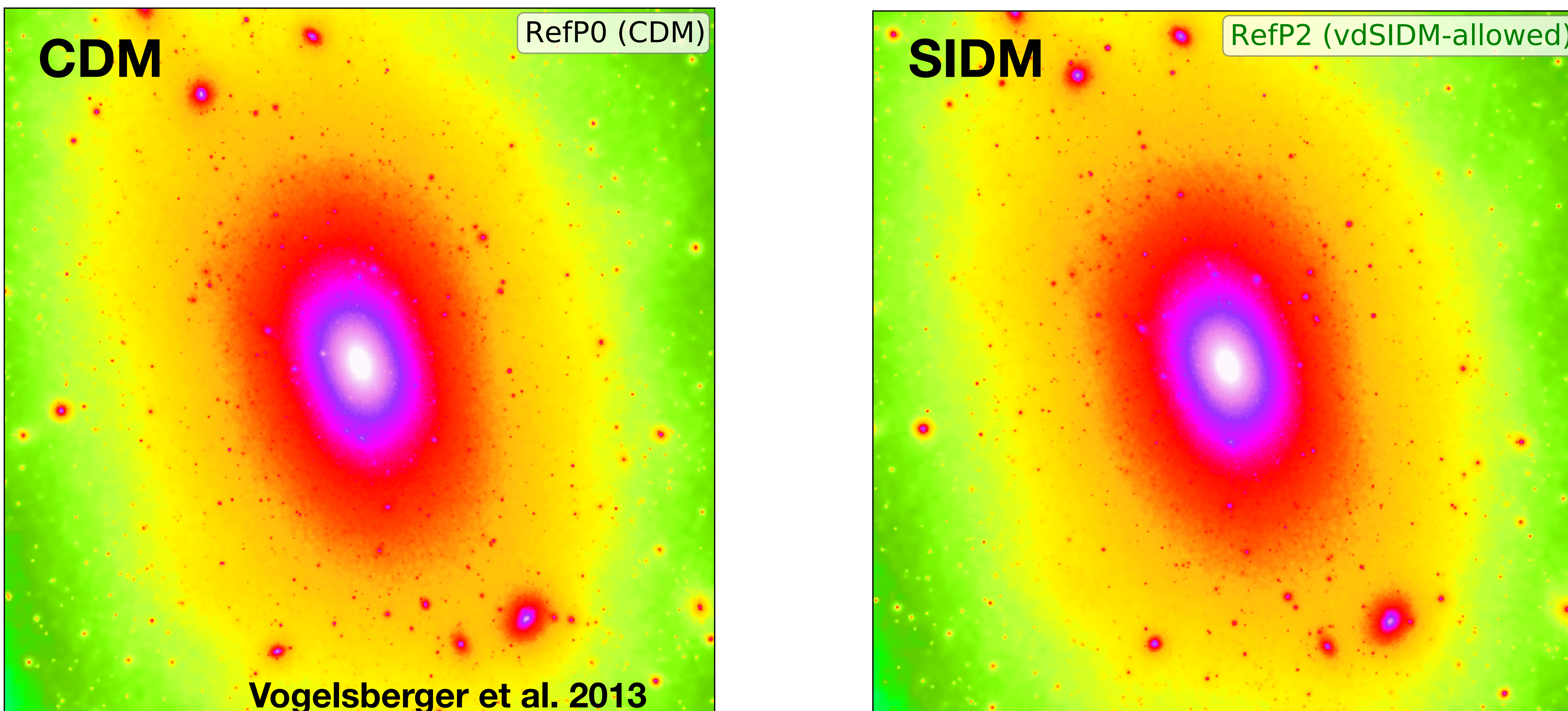
Modifying linear physics: allow non-zero thermal velocity in early Universe. *Example*: Warm Dark Matter (WDM). Erases gravitational perturbations before they form.



Alternative Dark Matter Models

Modify *linear* physics or *non-linear* physics

Modifying non-linear physics: introduce interactions in dark sector (e.g., self-scattering). Interactions become important for $\Gamma > H(z)$, so only affects dense centers of collapsed dark matter structures. *Canonical example: Self-Interacting Dark Matter (SIDM)*



Alternative Dark Matter Models

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Modifying linear physics: allow non-zero thermal velocity in early Universe (Warm Dark Matter). Erases gravitational perturbations before they form.

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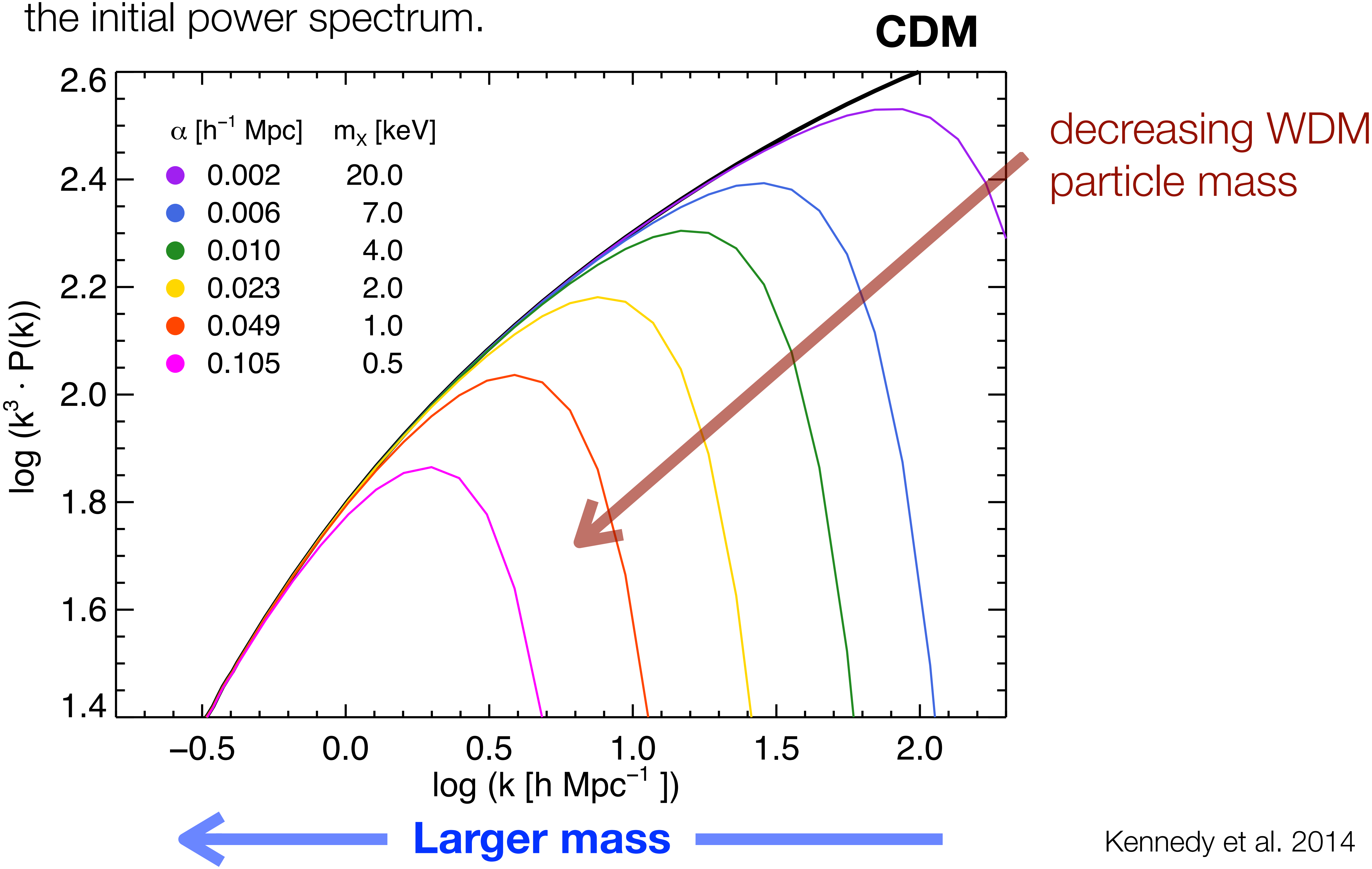
Note: some specific models modify both (see, e.g., Cyr-Racine et al.)

Simulating WDM Models

Standard operating procedure: only difference from CDM simulations is the initial power spectrum.



Kennedy et al. 2014

Simulating WDM Models

Standard operating procedure: only difference from CDM simulations is the initial power spectrum. Assume thermal (Fermi-Dirac) distribution function, with overall suppression factor.

In this case, effects on structure formation of, e.g., sterile neutrino (s) can always be mapped into effects of an equivalent thermal relic (t):

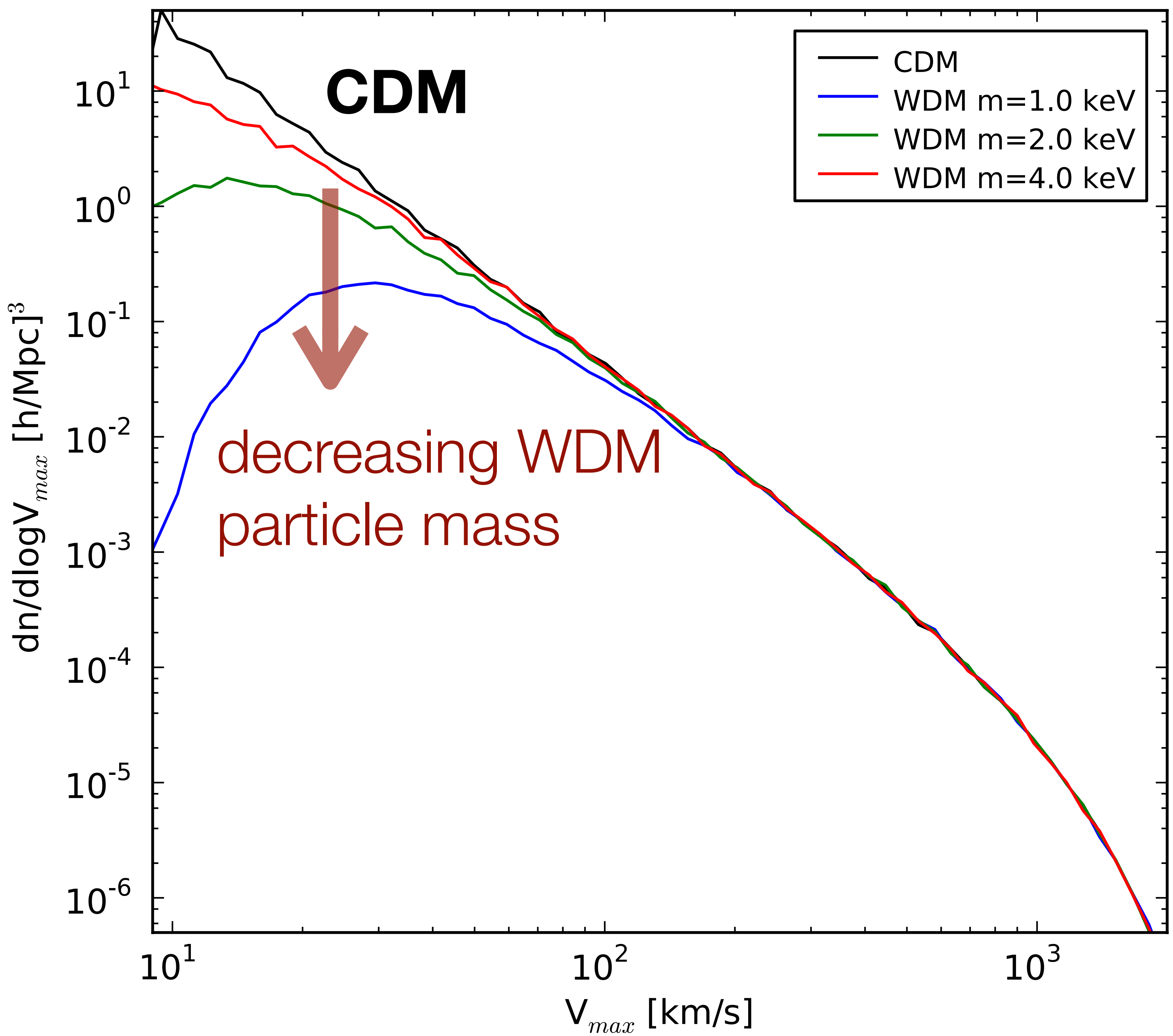
$$\begin{aligned} \Omega_{\rm s} &= \Omega_{\rm t} \\ \frac{m_{\rm s}}{T_{\rm s}} &= \frac{m_{\rm t}}{T_{\rm t}} \end{aligned} \quad \longrightarrow \quad m_{\rm s} = 4.423\,{\rm keV}\left(\frac{m_{\rm t}}{1\,{\rm keV}}\right)^{4/3}$$

For example: excluding $m_t < 2$ keV ↔ excluding $m_s < 11.1$ keV.

Requires that DM has distribution function that looks like Fermi-Dirac.

Simulating WDM Models

Strongest effect: decreased abundance of dark matter halos below free-streaming scale

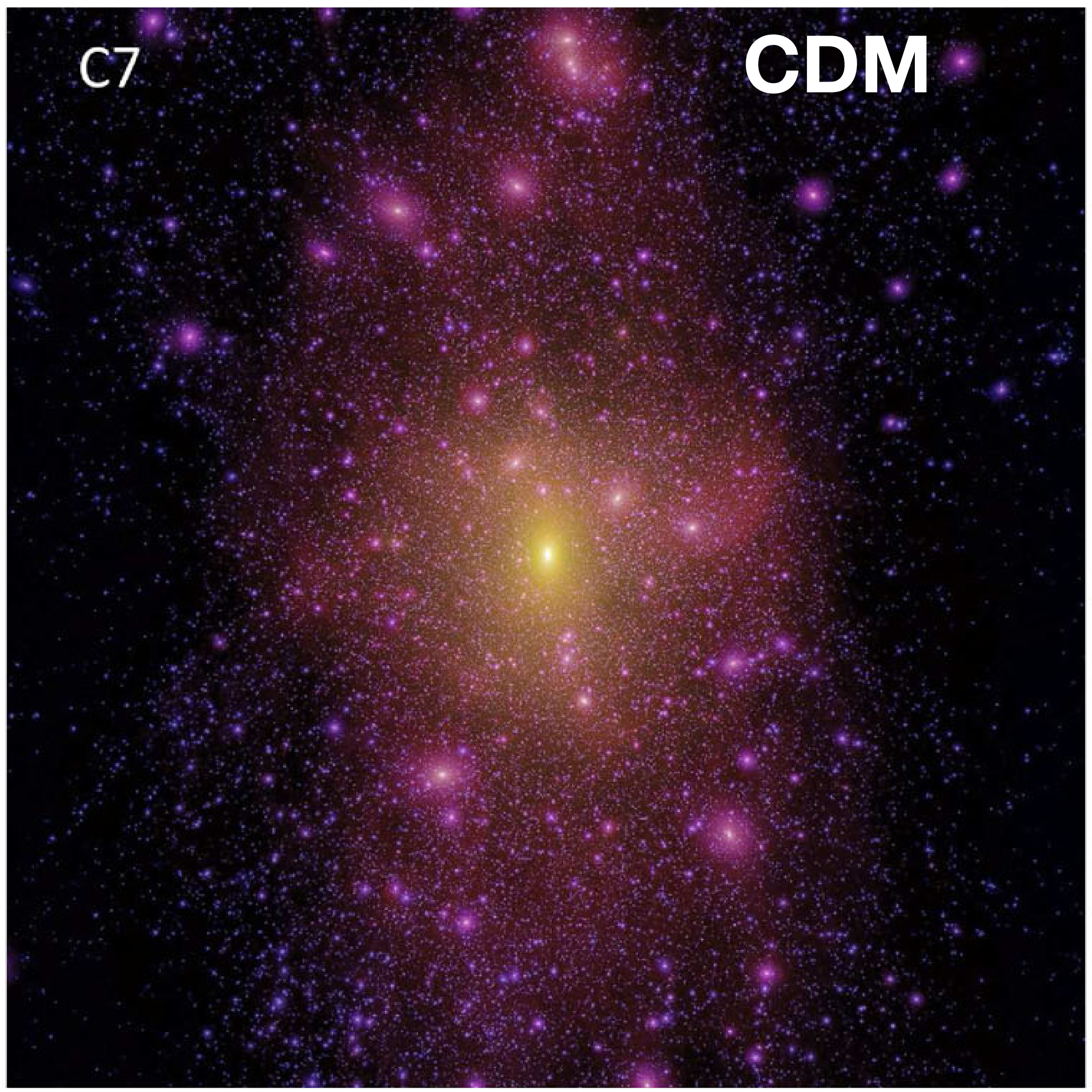


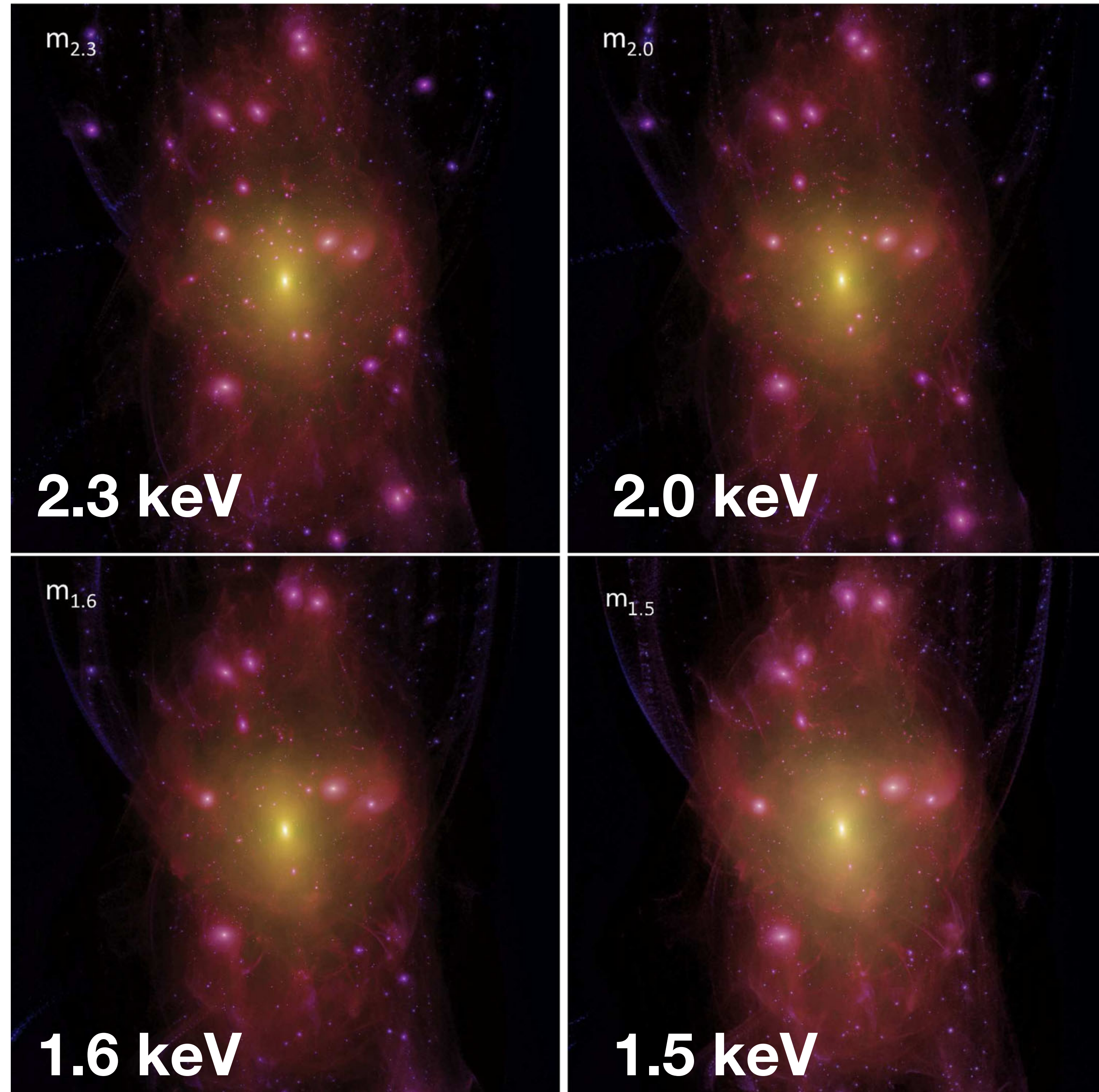
Mass

Schneider et al. 2014

Simulating WDM Models

Counts of satellites around Milky Way, M31 are strong constraints on thermal WDM models



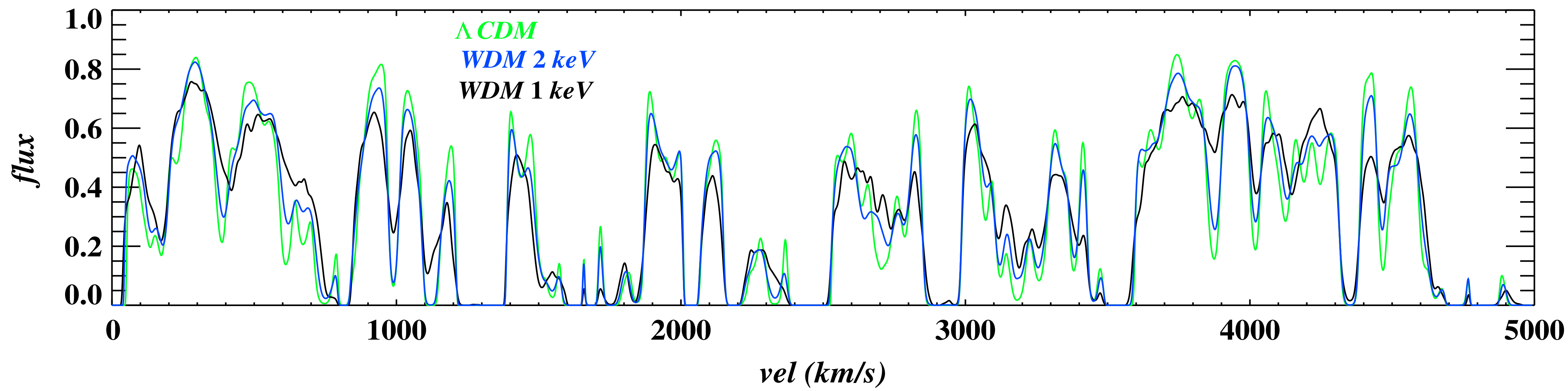


Lovell et al. 2014

Simulating WDM Models

Structure of Lyman-alpha forest provides strong constraints on thermal WDM models

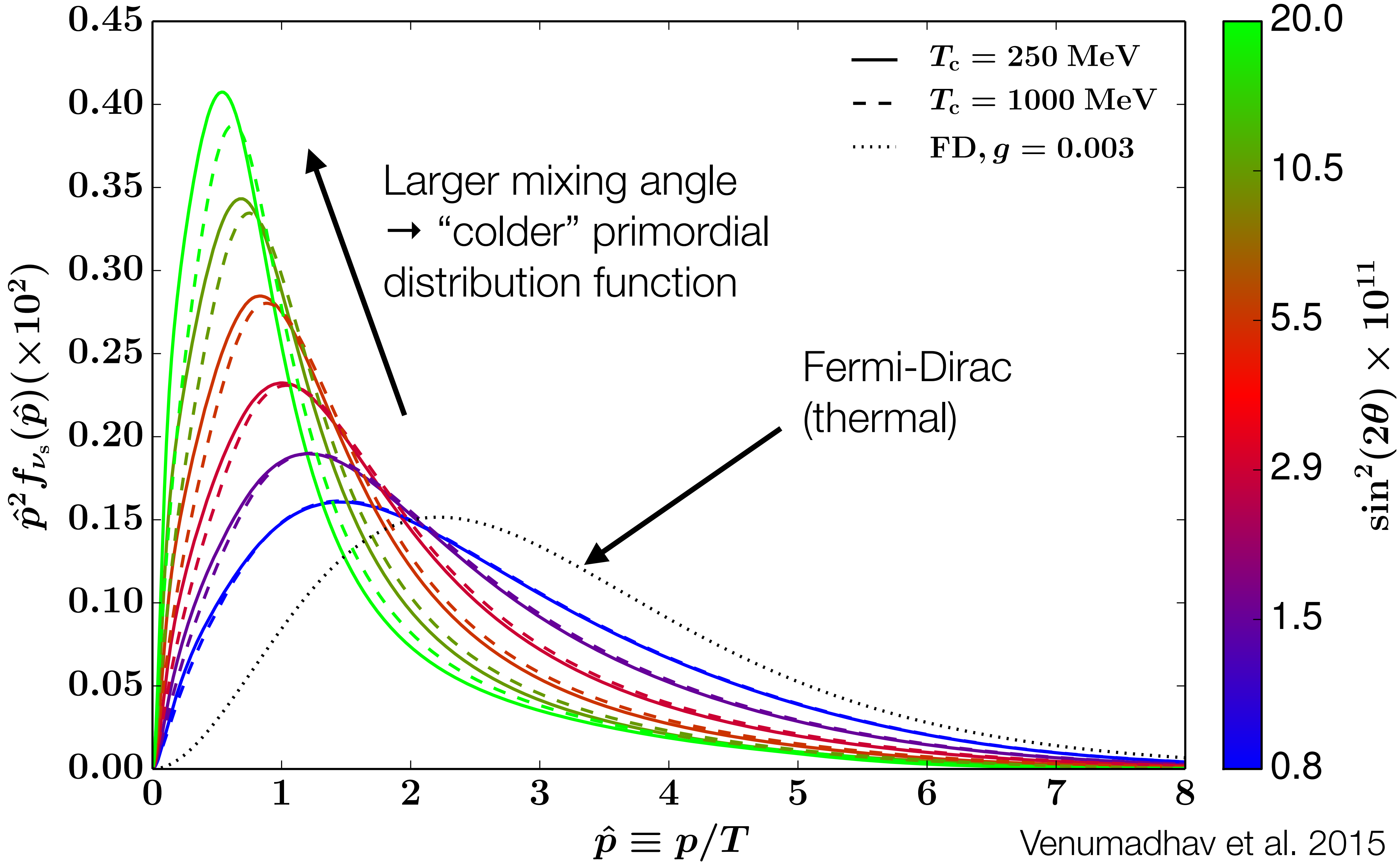
Viel et al. 2013



Limit: m_{WDM} > 3.3 keV (2σ) for thermal WDM. 2 keV (thermal) excluded at 4σ.

Simulating WDM Models

Many models of ~keV scale particles *do not* require thermal production; resulting collapsed structure may be different. ***Example:*** Shi-Fuller (1999) resonant production



Venumadhav et al. 2015
(also Abazajian 2014)

Simulating Shi-Fuller WDM Models

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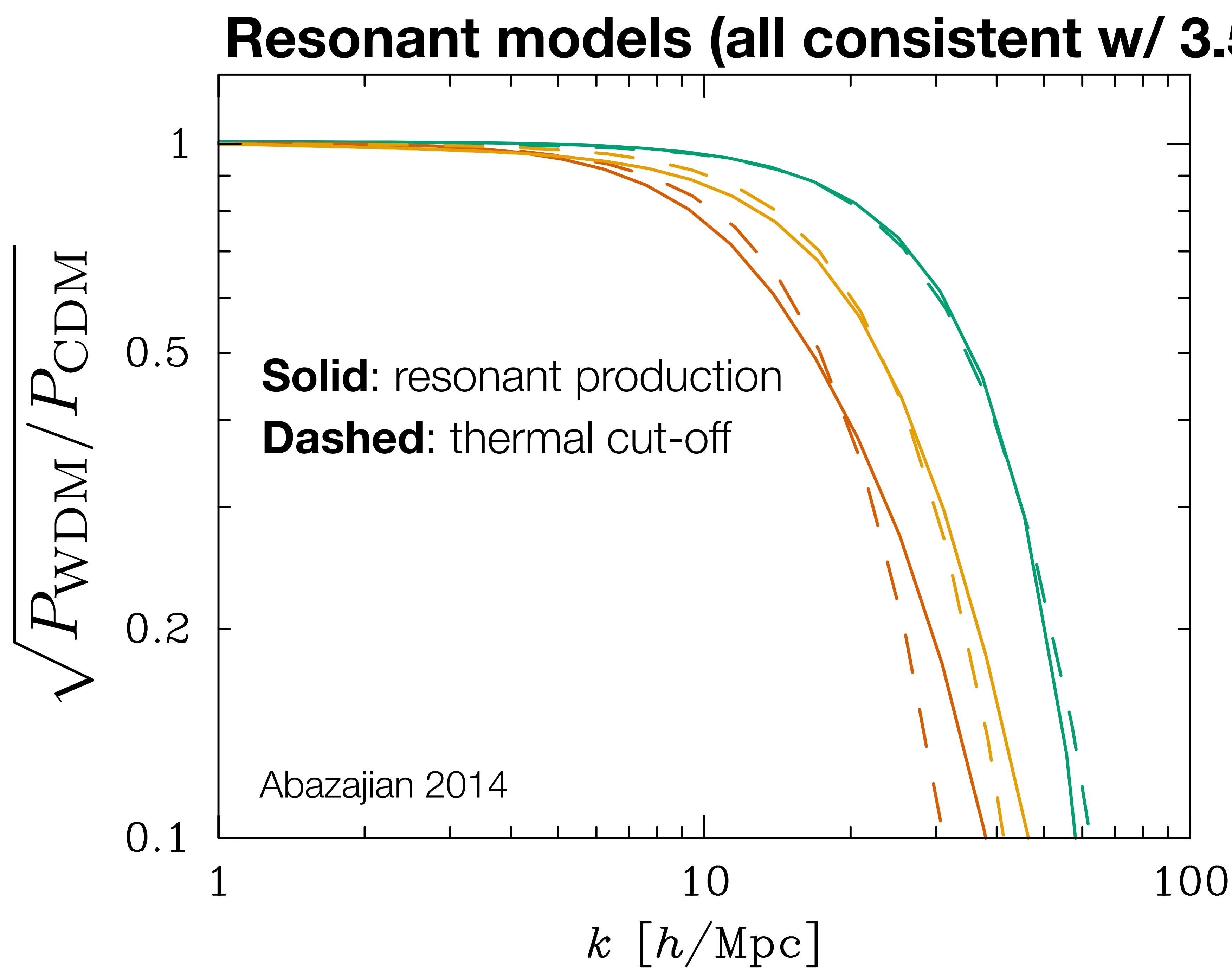
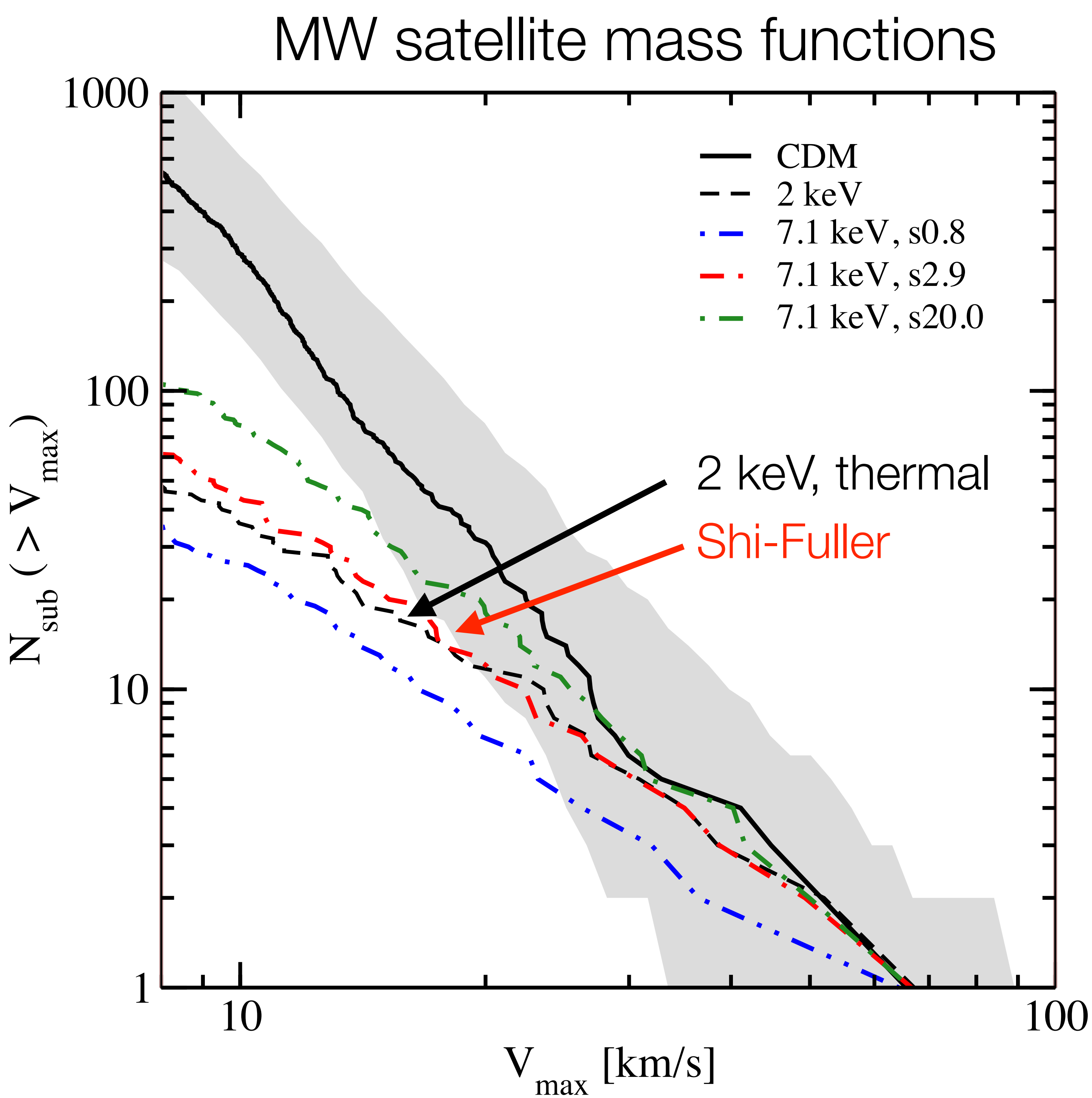


Simulating Shi-Fuller WDM Models

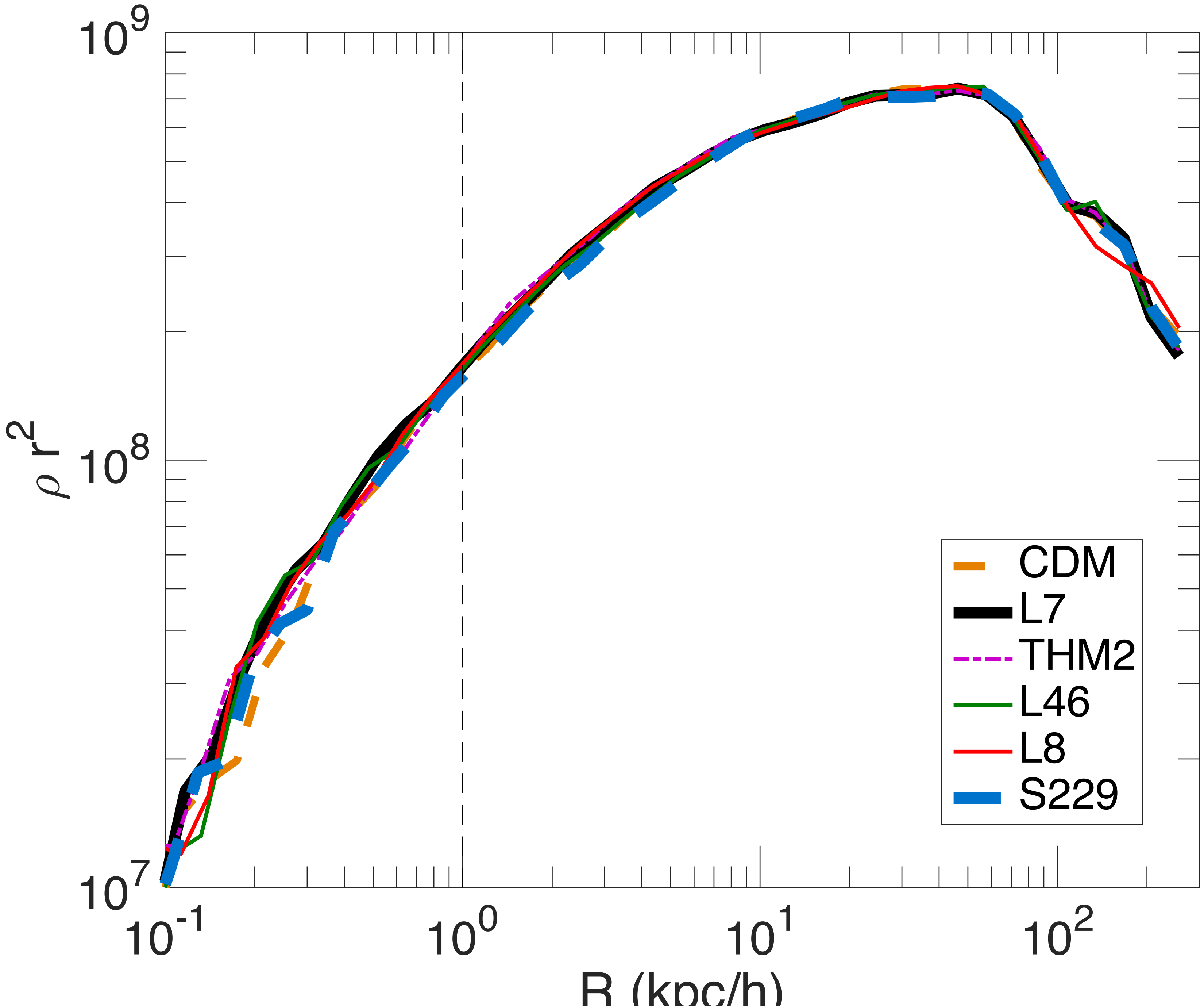
First of a series of simulations comparing Shi-Fuller and thermal WDM:



Horiuchi et al. (in prep)

Simulating Shi-Fuller WDM Models

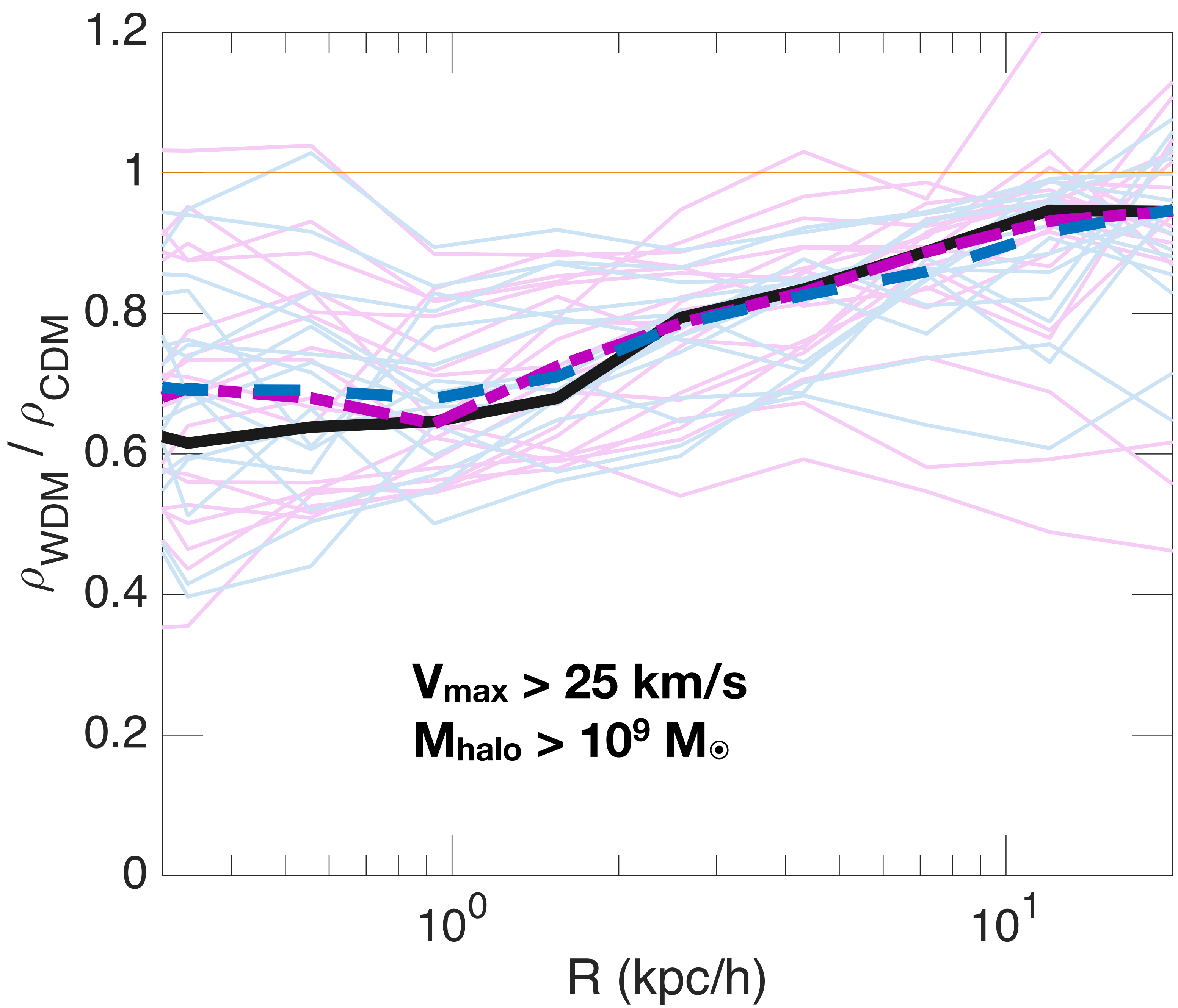
No difference in **density profile** of host relative to thermal WDM, CDM



Bozek, MBK et al. (in prep)

Simulating Shi-Fuller WDM Models

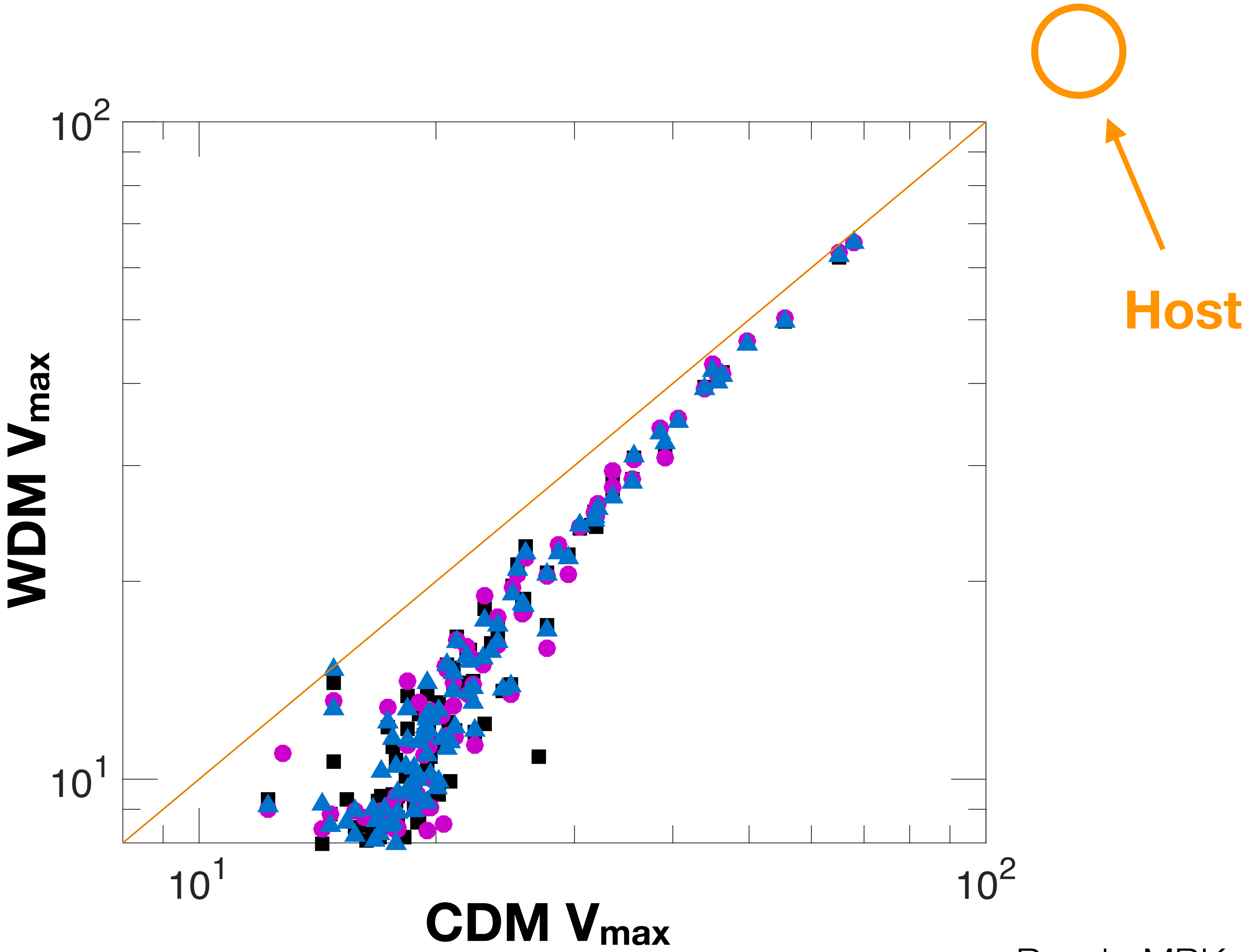
Substantial difference in **central density profile** of satellites vs. CDM



Bozek, MBK et al. (in prep)

Simulating Shi-Fuller WDM Models

Substantial difference in **central density profile** of satellites vs. CDM



Bozek, MBK et al. (in prep)

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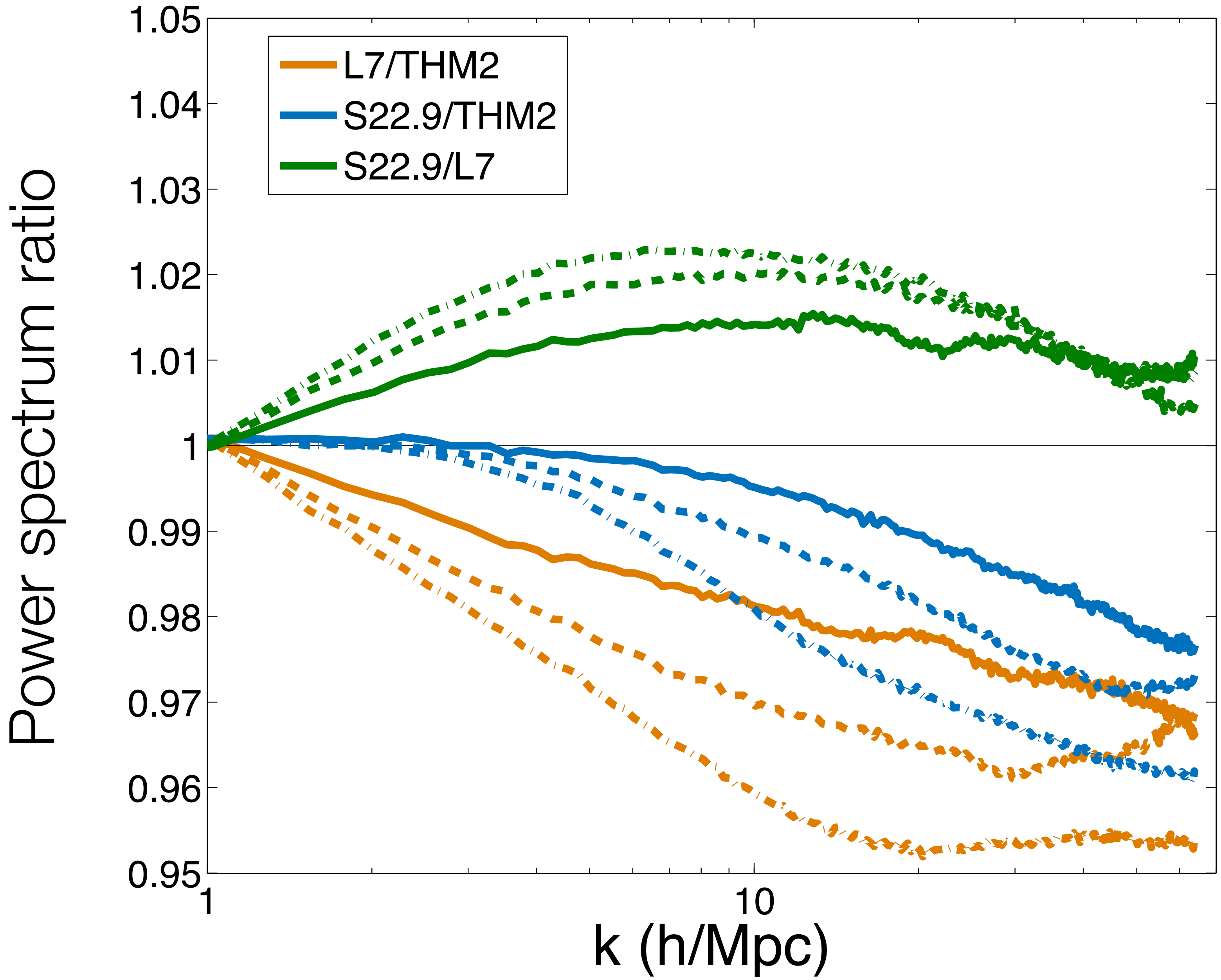
Noticeable difference in **Lyman-alpha power spectrum**



2015 vs 2014 calculation

2015 vs thermal 2 keV

2014 vs thermal 2 keV

Bozek, MBK et al. (in prep)

What is the way forward?

- Fundamental prediction of CDM: scale-free spectrum of substructure down to ~Earth mass halos. **Can we prove they exist?** (Or prove that they don't exist?)
  - Lensing?
  - Gaps in cold stellar streams?
  - Disruption of wide binary systems?

What is the way forward?

- Is there a scale below which baryons do not alter DM profiles? What is this scale, and is it large enough that some galaxies fall in this regime?
  - If classical or ultra-faint dSphs are such systems, there is hope for using stellar spectroscopy with GMT/TMT/E-ELT to prove/disprove existence of cores. This would be a “game-changer”

What is the way forward?

- Can we use high-redshift observations to constrain particle physics?
  - **Reionization:** large free streaming scale delays structure formation; less of a problem with lower value of τ from Planck?
  - **Lyman-alpha forest:** 30-m class telescopes will be able to measure flux power spectrum to smaller physical scales. Fundamental limitation: observations, or IGM modeling?
  - **Galaxy / satellite counts:** Similar to using satellite counts in Milky Way

Conclusion

- Absent a non-gravitational detection of dark matter, astrophysics is the only way to test its properties.
- Generic prediction of CDM models: vast spectrum of dark matter halos within the Milky Way containing no stars. Can we test if this is true?
- Models that modify non-linear DM physics (e.g., SIDM) are much harder to rule out than models that modify linear DM physics (e.g., WDM). What are the best astrophysical tests for distinguishing between CDM and SIDM?
- **Good news:**
  - **SIDM** (constant cross section): likely ruled out for $\sigma > 1$ cm^2/g; unable to produce relevant cores for $\sigma < 0.1$ cm^2/g $\Rightarrow$ narrow range to explore
  - **WDM**: likely ruled out by Ly-alpha forest and MW satellite countsfor $m < 2$ keV; no astrophysical signatures if $m > 4$-5 keV $\Rightarrow$ narrow range to explore