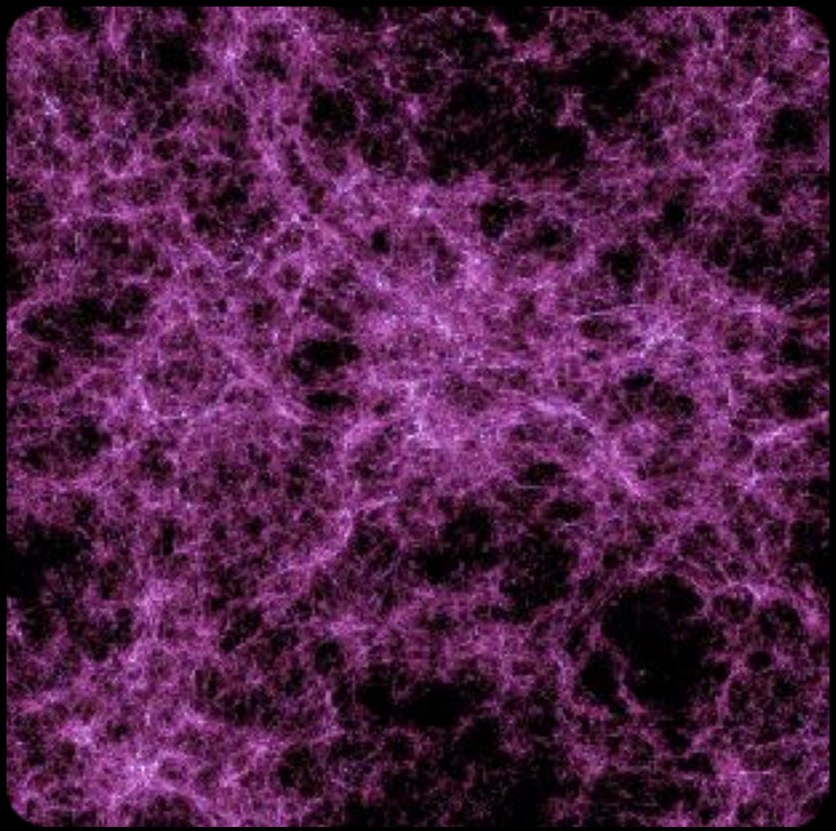
The Edge of Galaxy Formation

Small Scales and the Nature of Dark Matter



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The University of Texas at Austin

Dwarfs on the Shoulders of Giants

Case Western Reserve University

5 June 2017

The Edge of Galaxy Formation: Small Scales and the Nature of Dark Matter

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Bullock & Boylan-Kolchin 2017, *Ann. Rev. Astron. & Astrophys.*

XSEDE Extreme Science and Engineering Discovery Environment

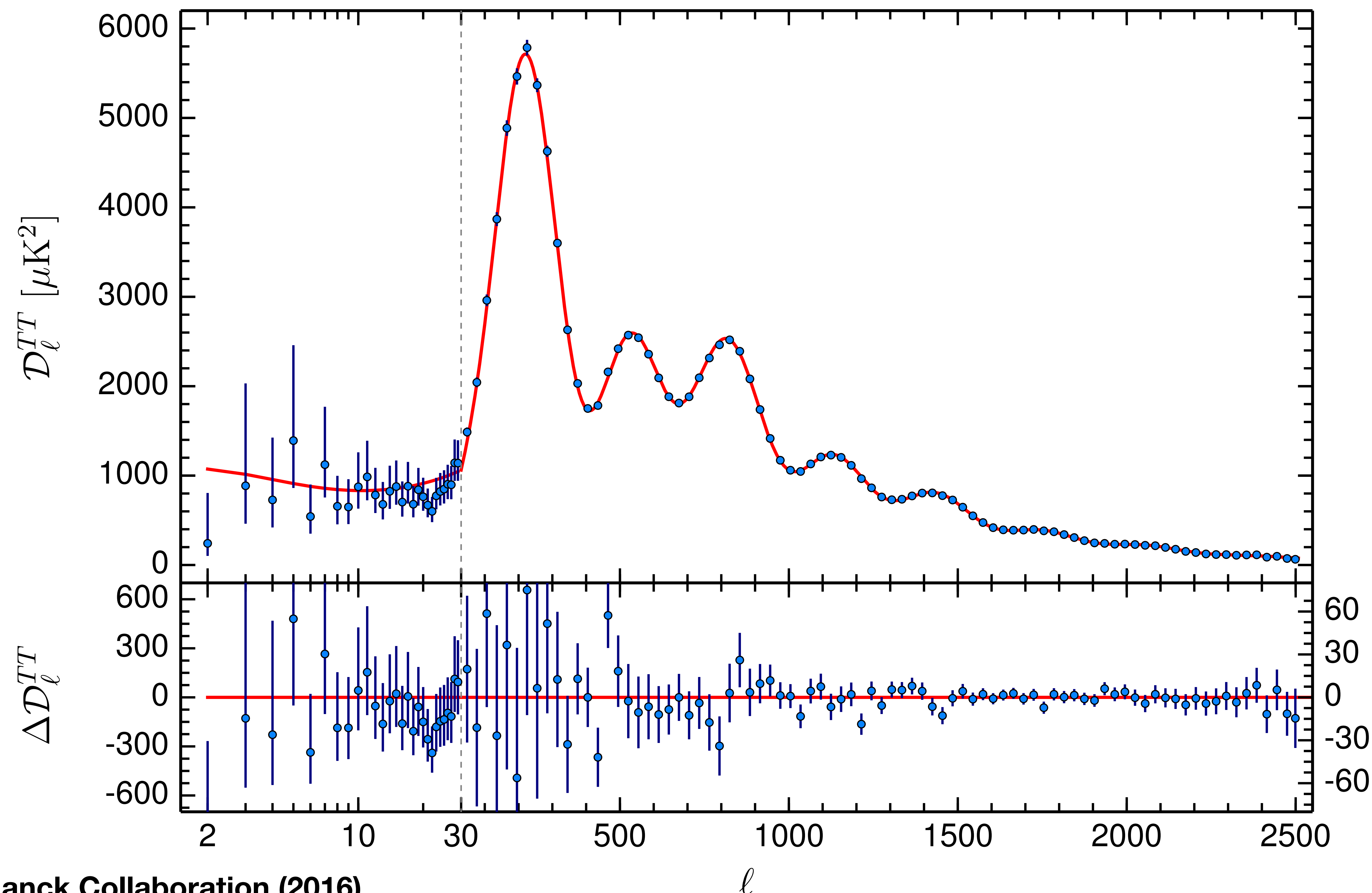
TACC

NSF

STScI SPACE TELESCOPE SCIENCE INSTITUTE

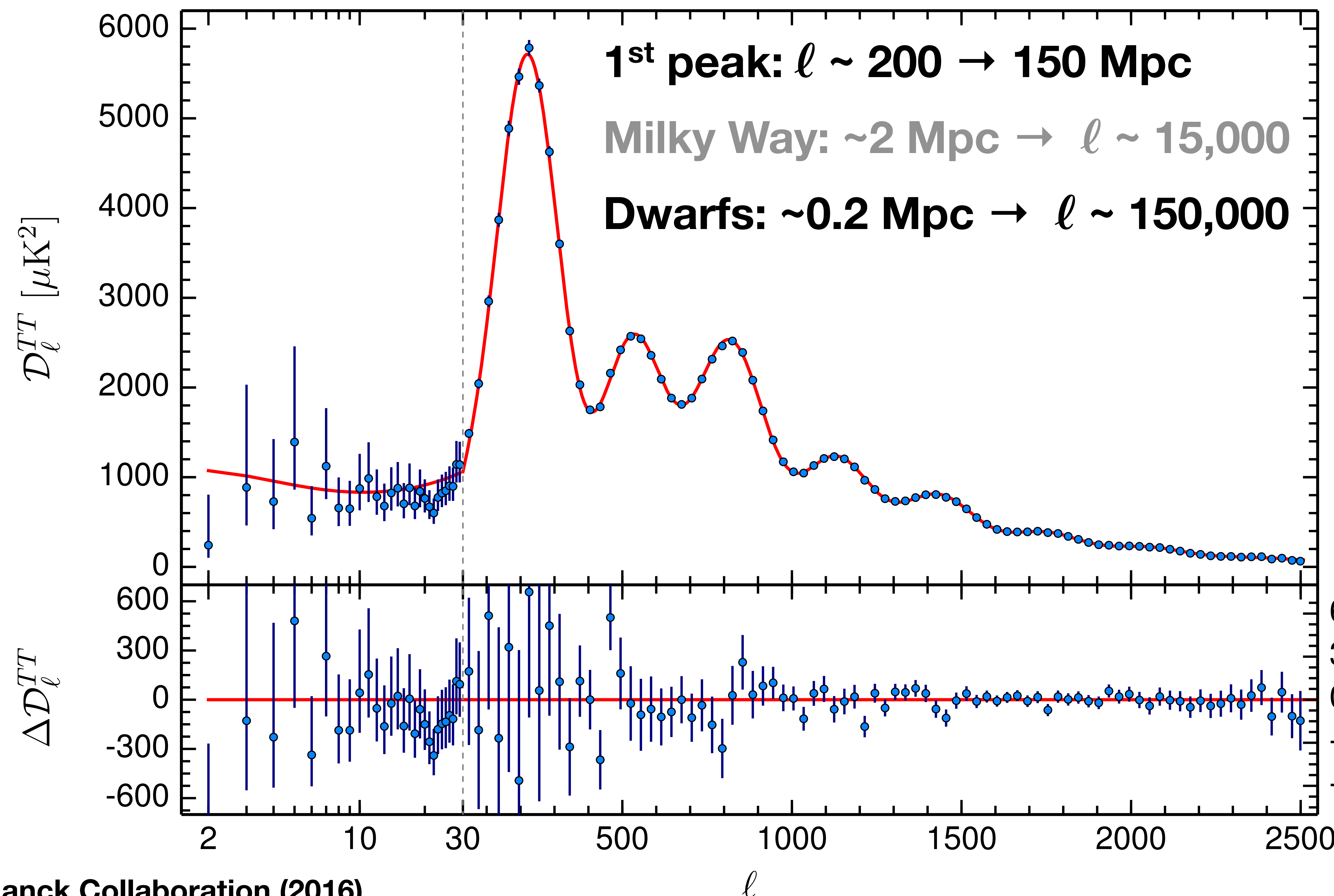
NASA

Large Scales: Concordance ΛCDM



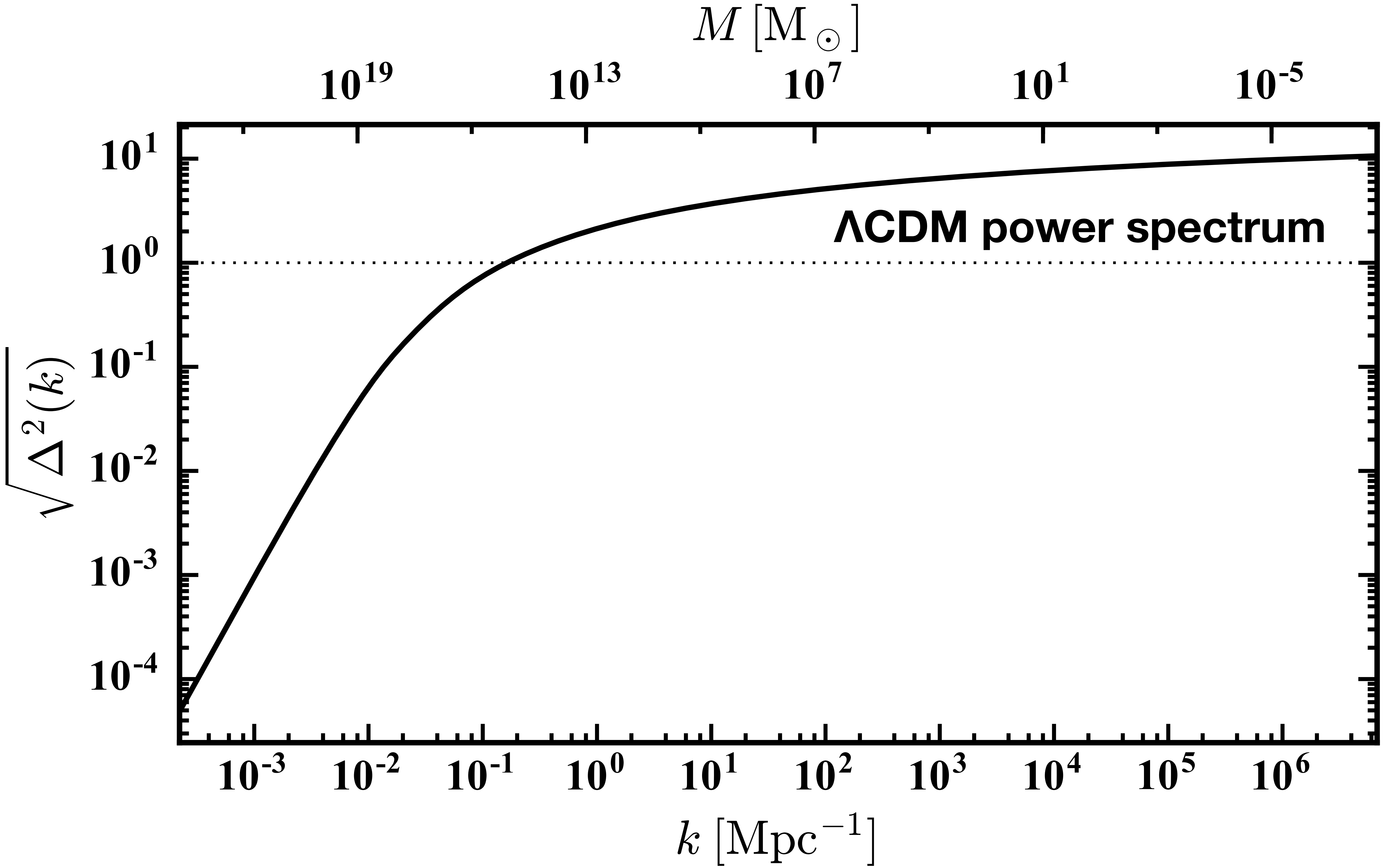
Planck Collaboration (2016)

Large Scales: Concordance ΛCDM



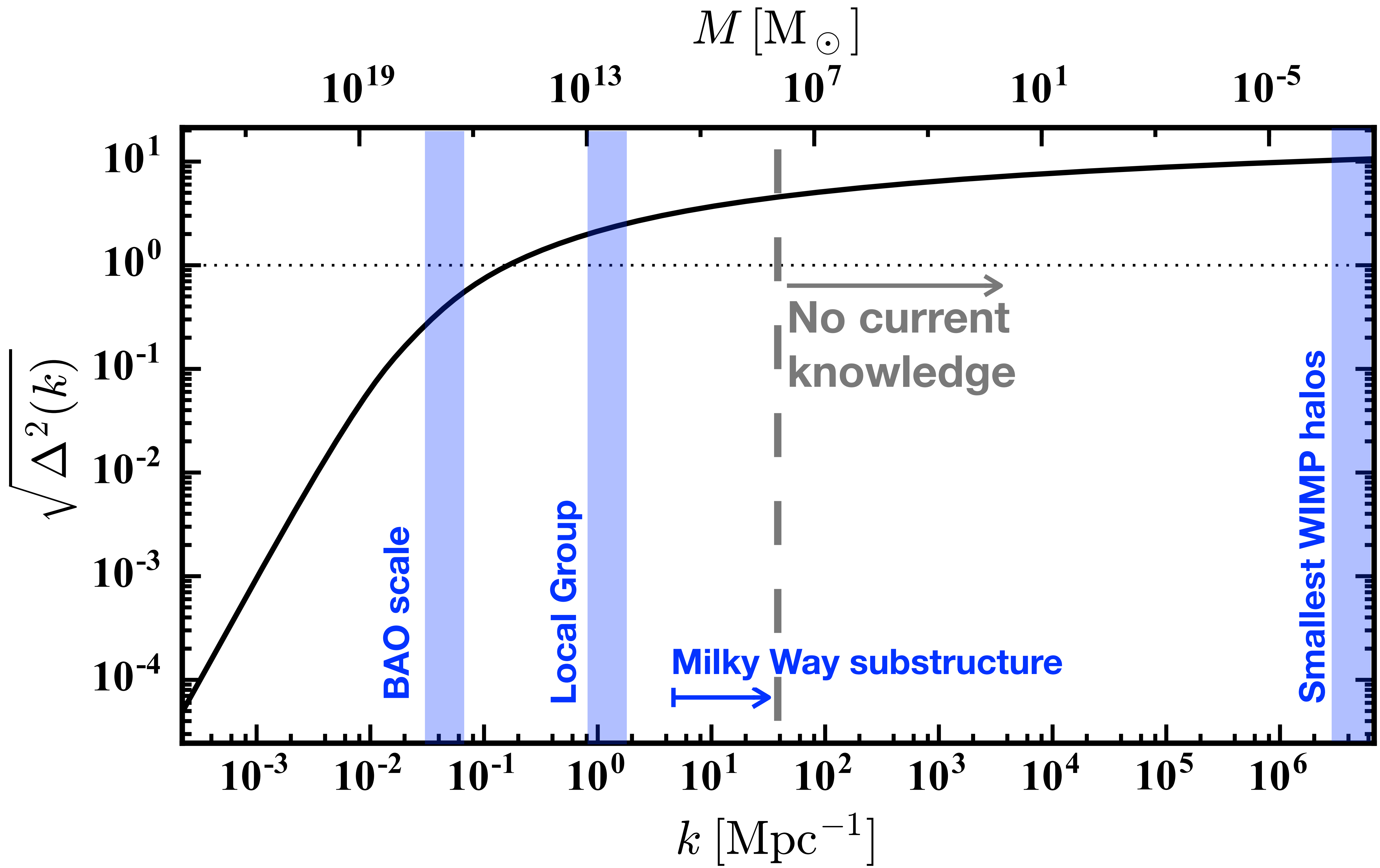
Planck Collaboration (2016)

The scales of ΛCDM



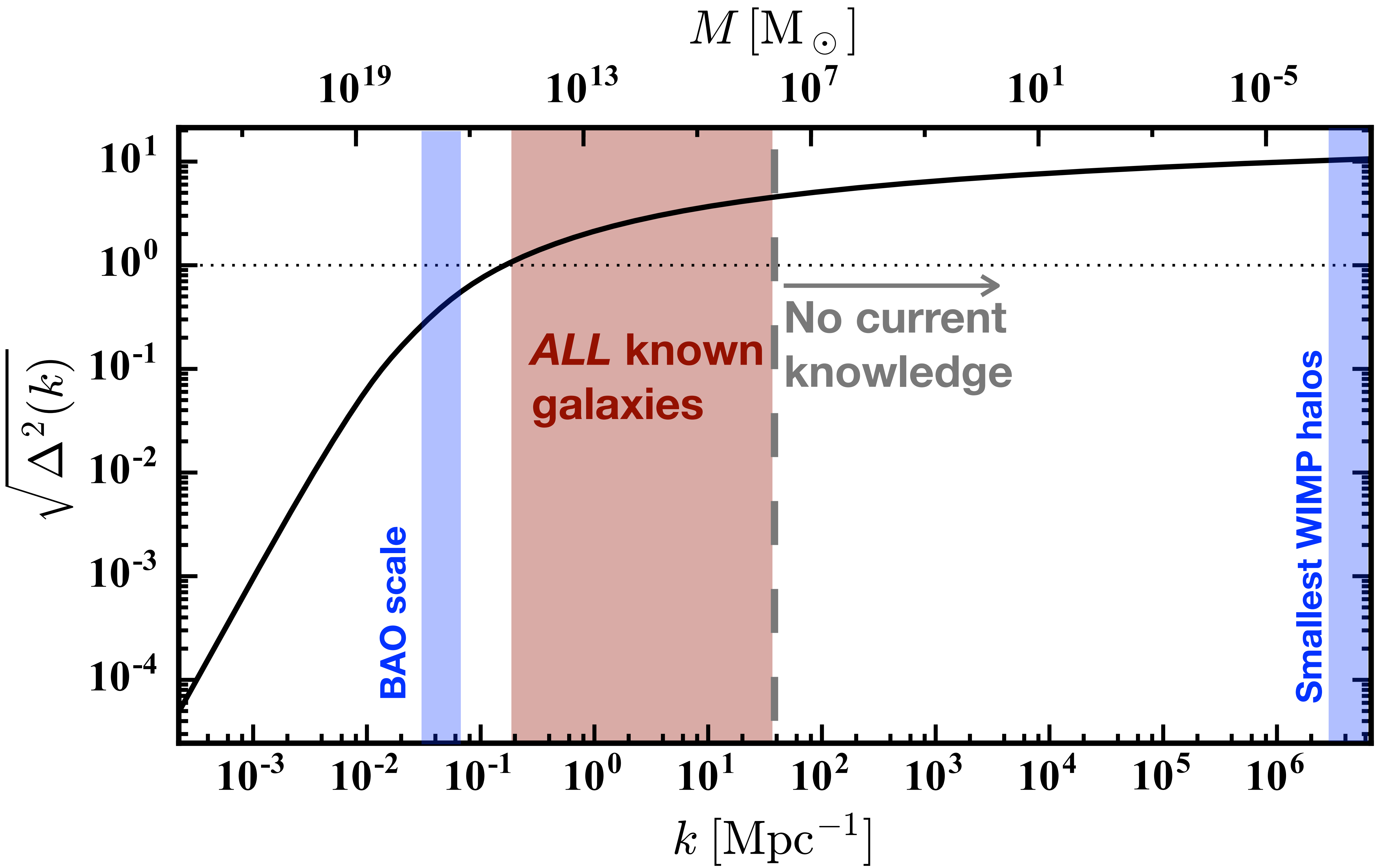
Bullock & Boylan-Kolchin 2017

The scales of ΛCDM



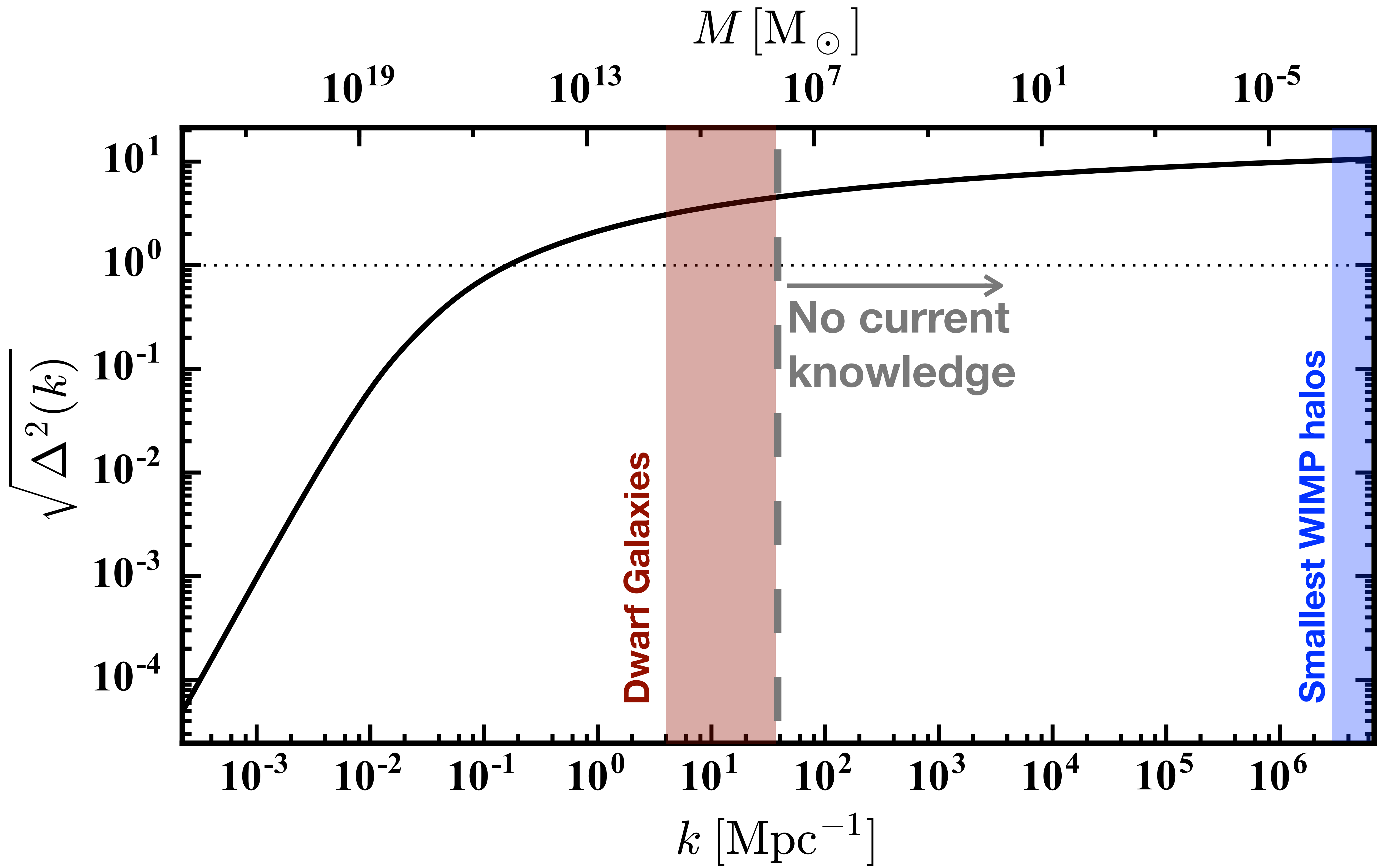
Bullock & Boylan-Kolchin 2017

The scales of ΛCDM

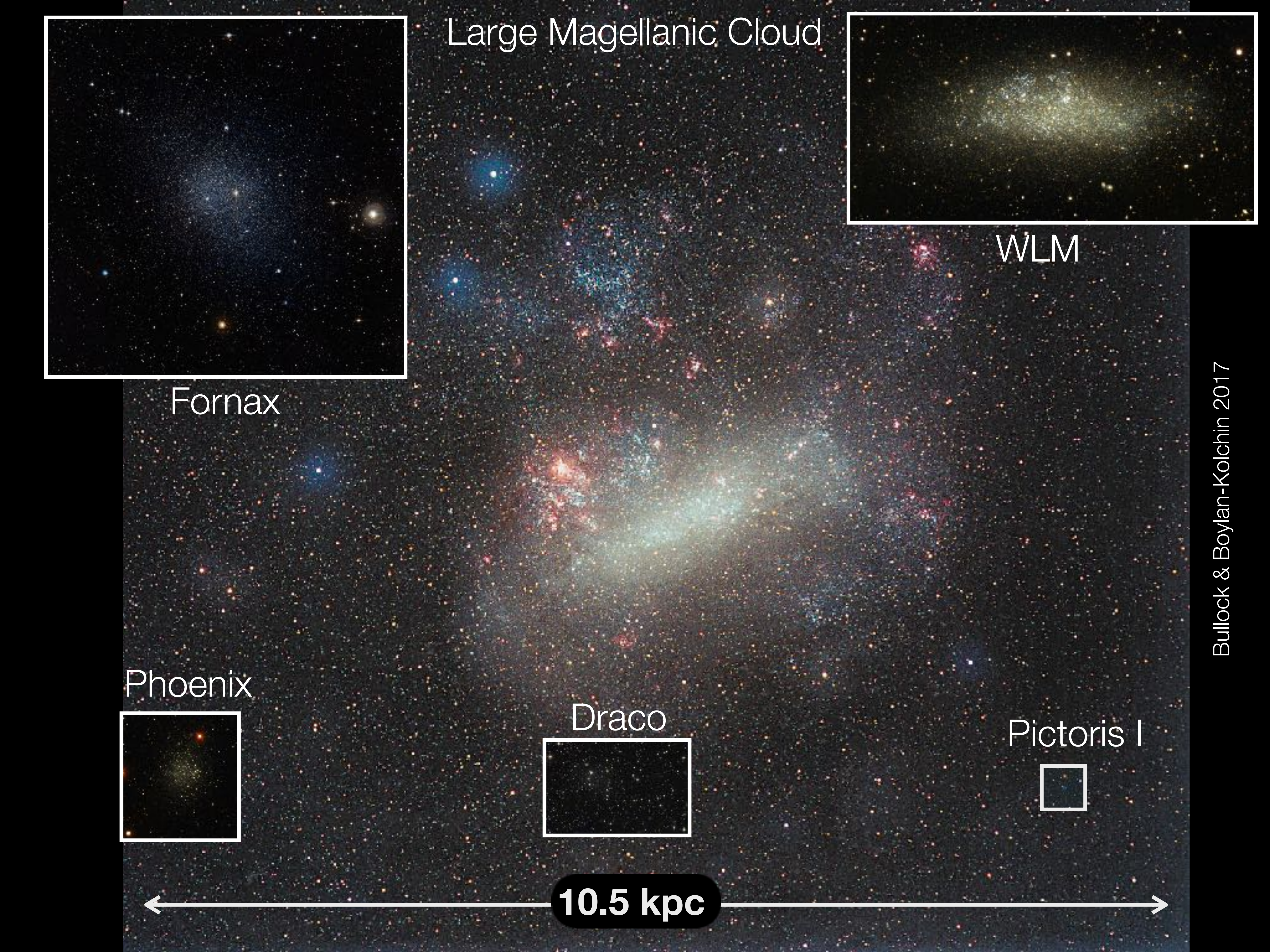


Bullock & Boylan-Kolchin 2017

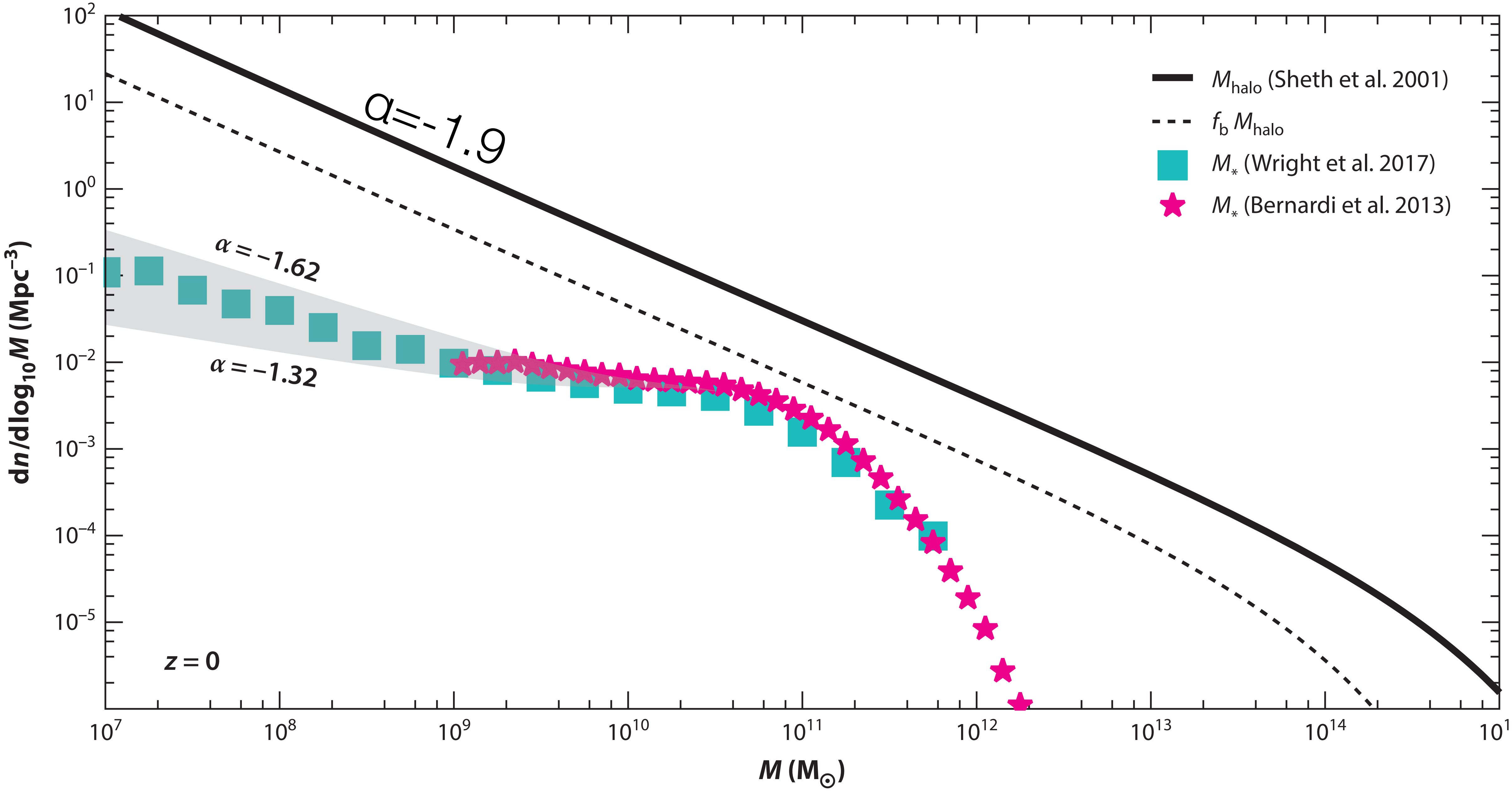
The scales of ΛCDM



Bullock & Boylan-Kolchin 2017

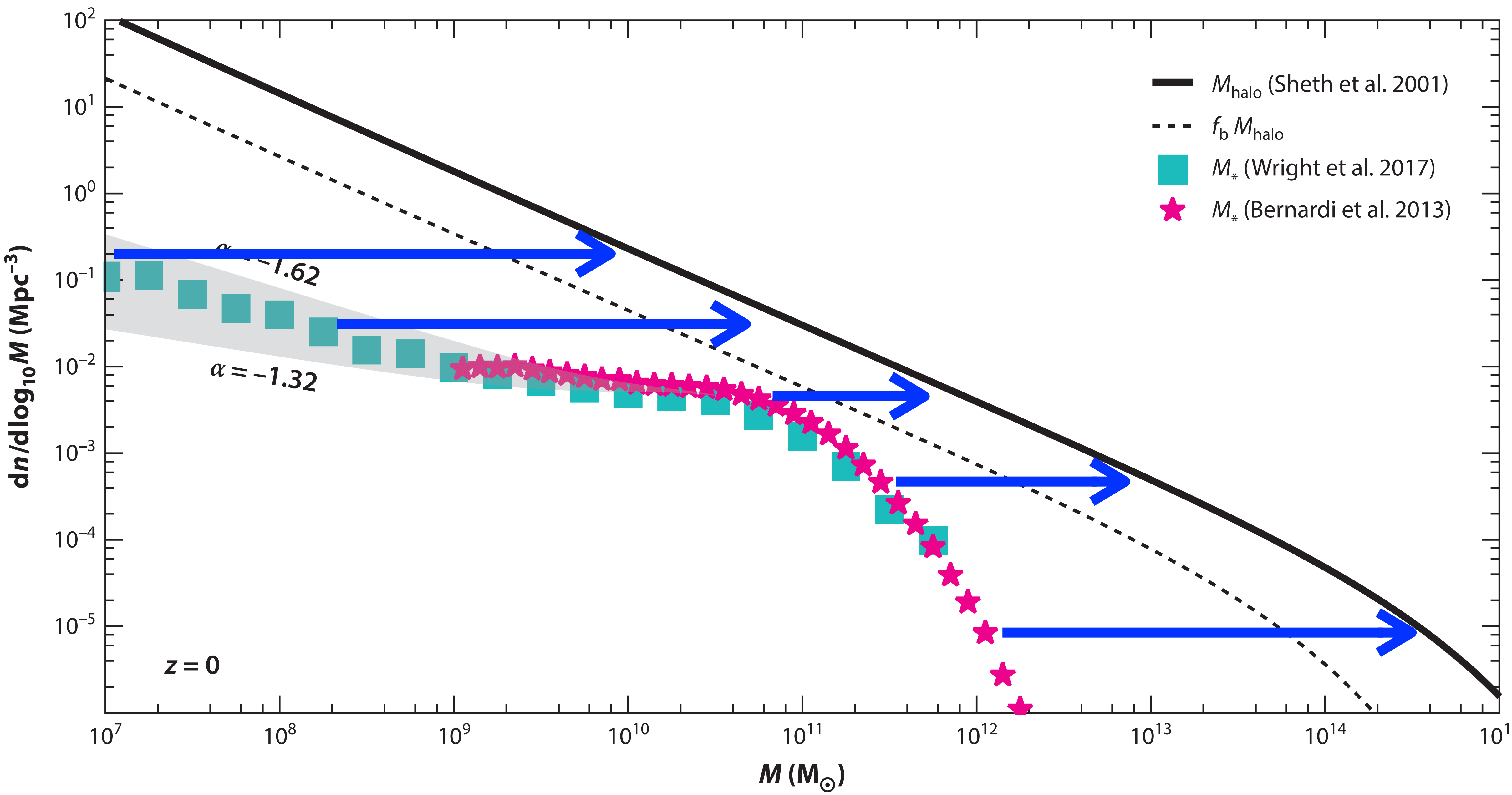

Large Magellanic Cloud
WLM
Fornax
Phoenix
Draco
Pictoris I
10.5 kpc
Bullock & Boylan-Kolchin 2017

From M_{gal} to M_{halo}



Bullock & Boylan-Kolchin 2017

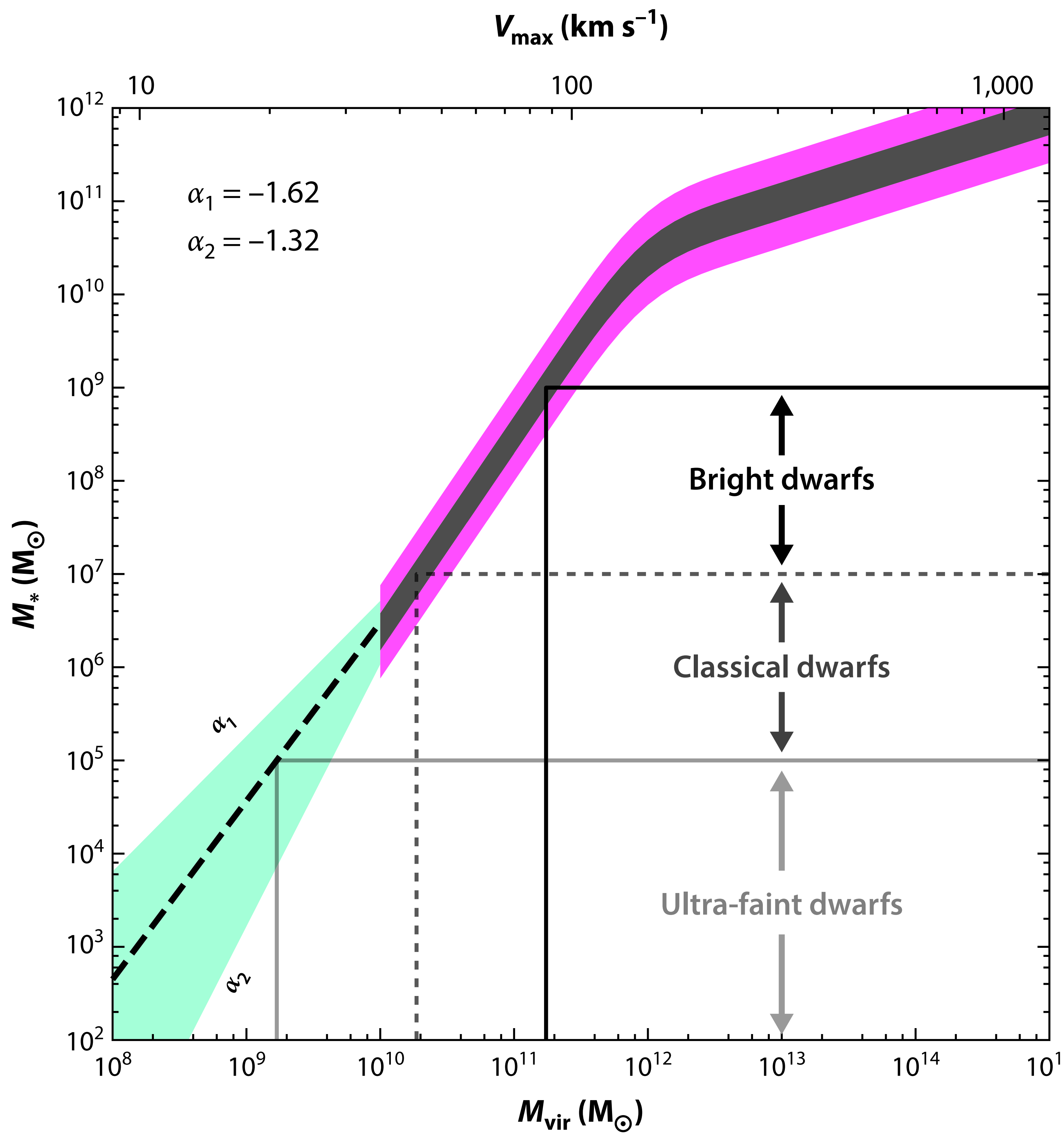
From M_{gal} to M_{halo}



abundance matching: demand that $n(>M_{halo})=n(>M_\star)$

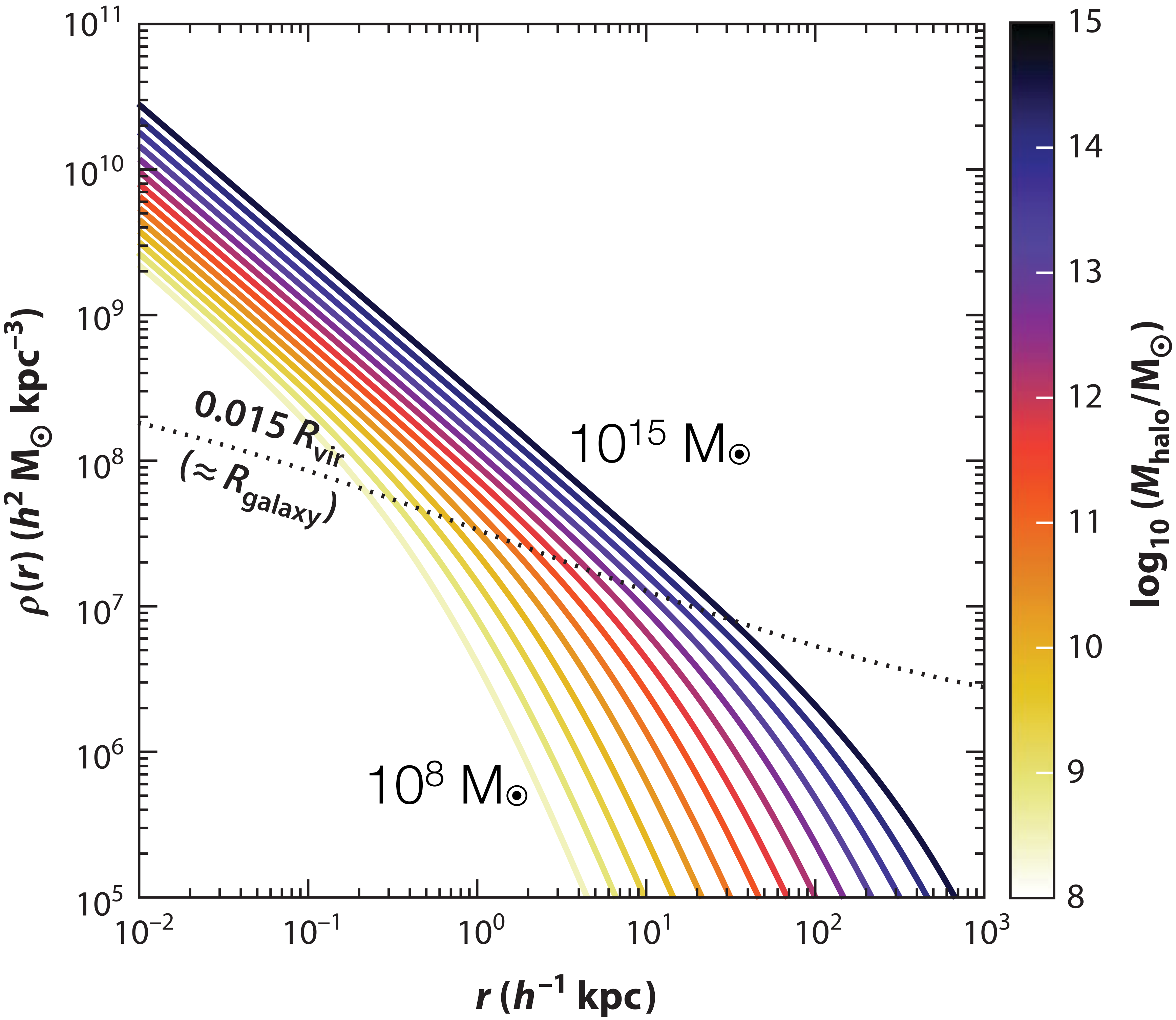
Bullock & Boylan-Kolchin 2017

Relevant mass scales in ΛCDM



Bullock & Boylan-Kolchin 2017

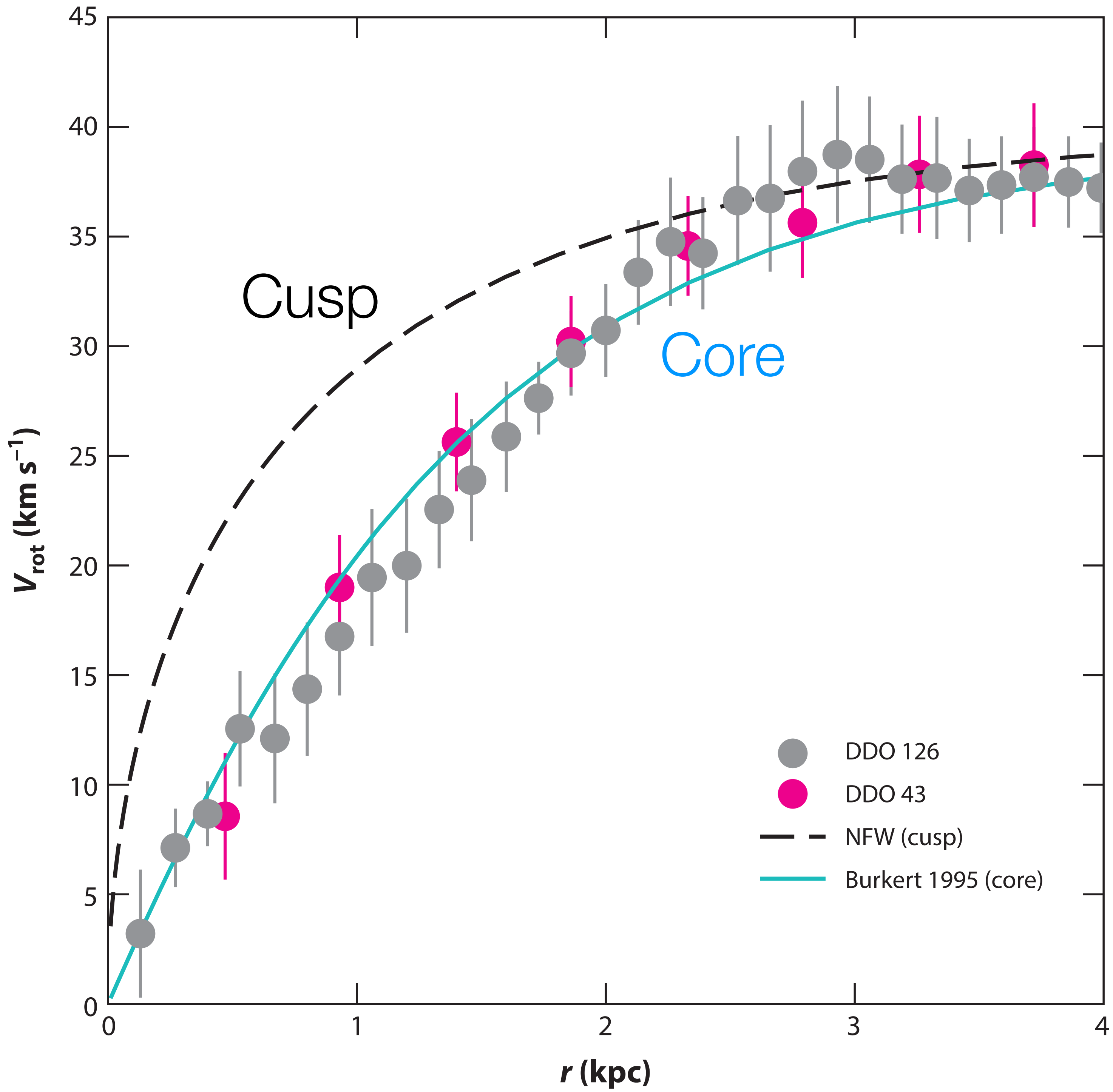
Prediction: steep (sub)halo density profiles



Bullock & Boylan-Kolchin 2017

Dwarf galaxies vs ΛCDM: cores & cusps

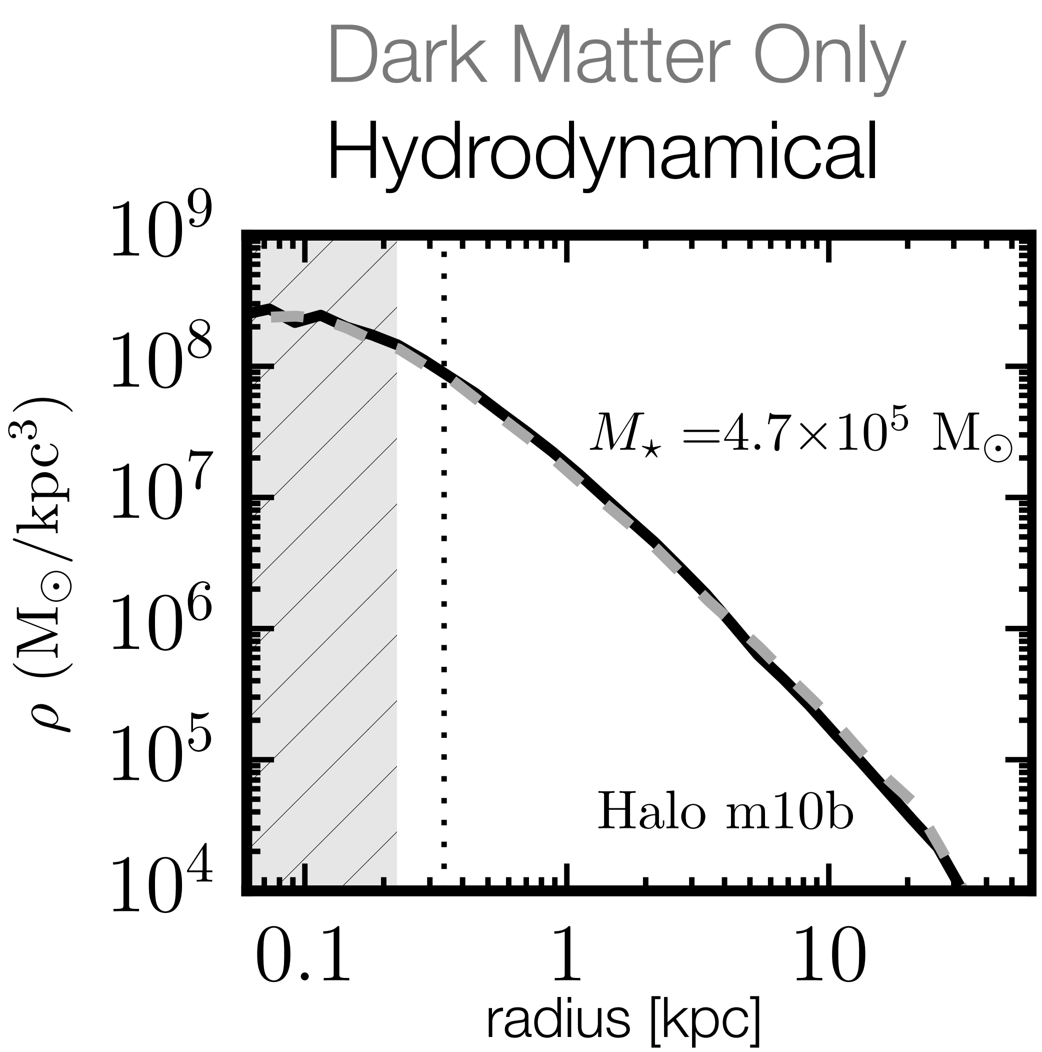
Observations indicate **cored** density profiles, while *N*-body simulations robustly predict density **cusps** (Moore et al. 1994, Flores & Primack 1994)



Bullock & Boylan-Kolchin 2017

Dark matter core formation?

Fluctuations in gravitational potential from episodic star formation can heat dark matter
(Pontzen & Governato 2012)

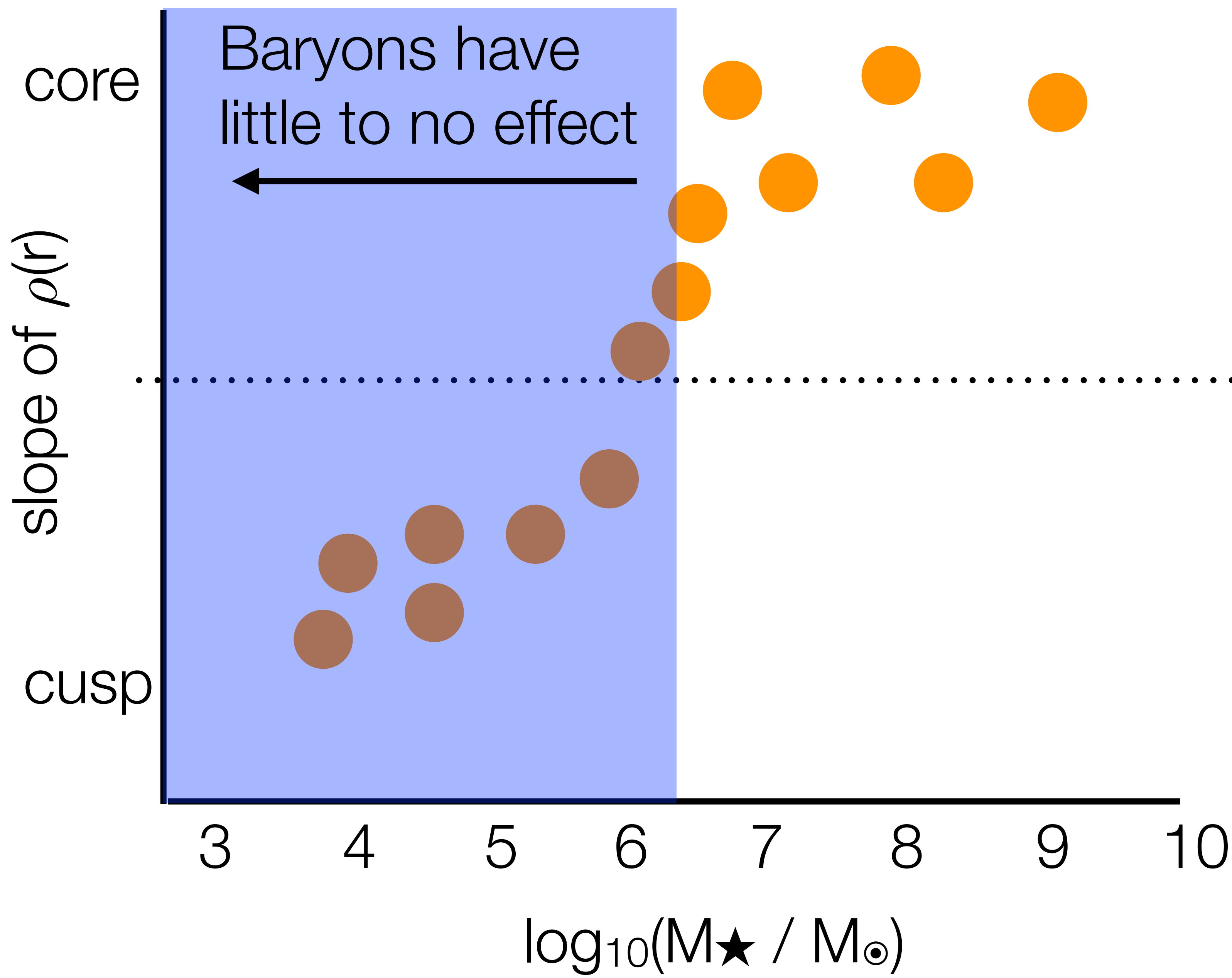


Minimum mass scale for core formation / density reduction:
M★ ~ 3x10^6 M⊙

Fitts, MBK et al. (2016)

Baryonic effects: sensitive to stellar mass

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

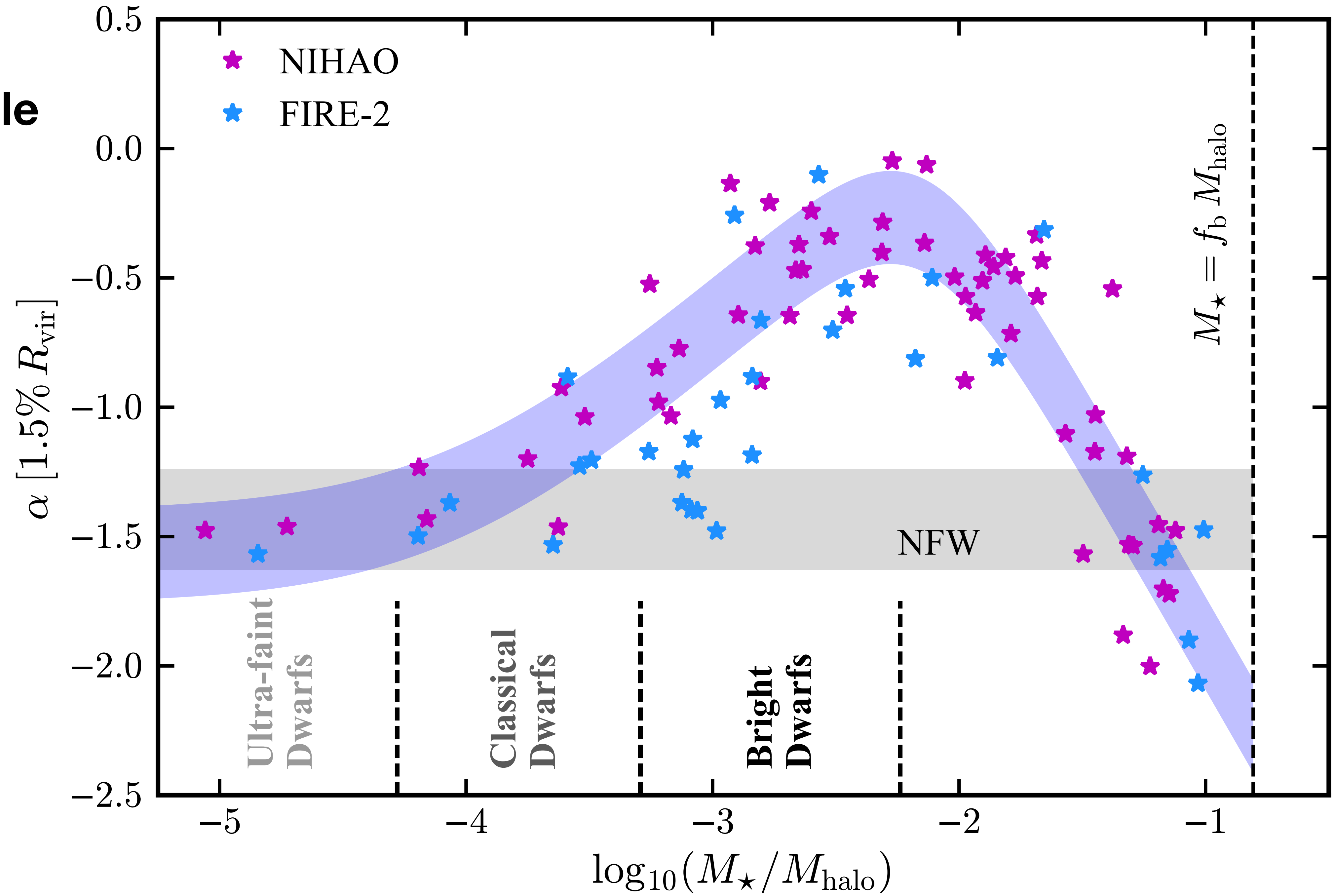


Fitts, MBK et al. 2016; see also Governato++, Brooks++, Oñorbe++, Penarrubia++, Garrison-Kimmel++, Chan ++, Di Cintio ++, Tollet ++… *For opposing opinions, see Read et al. 2016, Sawala et al. 2016*

Baryonic effects: sensitive to stellar mass

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

density profile slope on galaxy scale



Bullock & Boylan-Kolchin 2017, based on Tollet et al. 2016

Are we there yet?

- **There is no definitive need to move beyond CDM**.
- However, in ΛCDM, need at least two large baryonic effects:
    - density cores induced by star formation feedback (cusp/core, too-big-to-fail)
    - suppressed galaxy formation from reionization feedback (missing satellites)
- Furthermore, these effects must maintain observed regularity in various galaxy properties (unclear as to why)

➡ **Star formation, feedback, and cosmic reionization are central to understanding small-scale cosmological structure in all ΛCDM-based galaxy formation models**

Clues to the nature of dark matter

- Multiple cosmological simulations run by different groups, codes: galaxies w/ $M_\star \lesssim 3 \times 10^6\ M_\odot$ should **not** have appreciable density cores

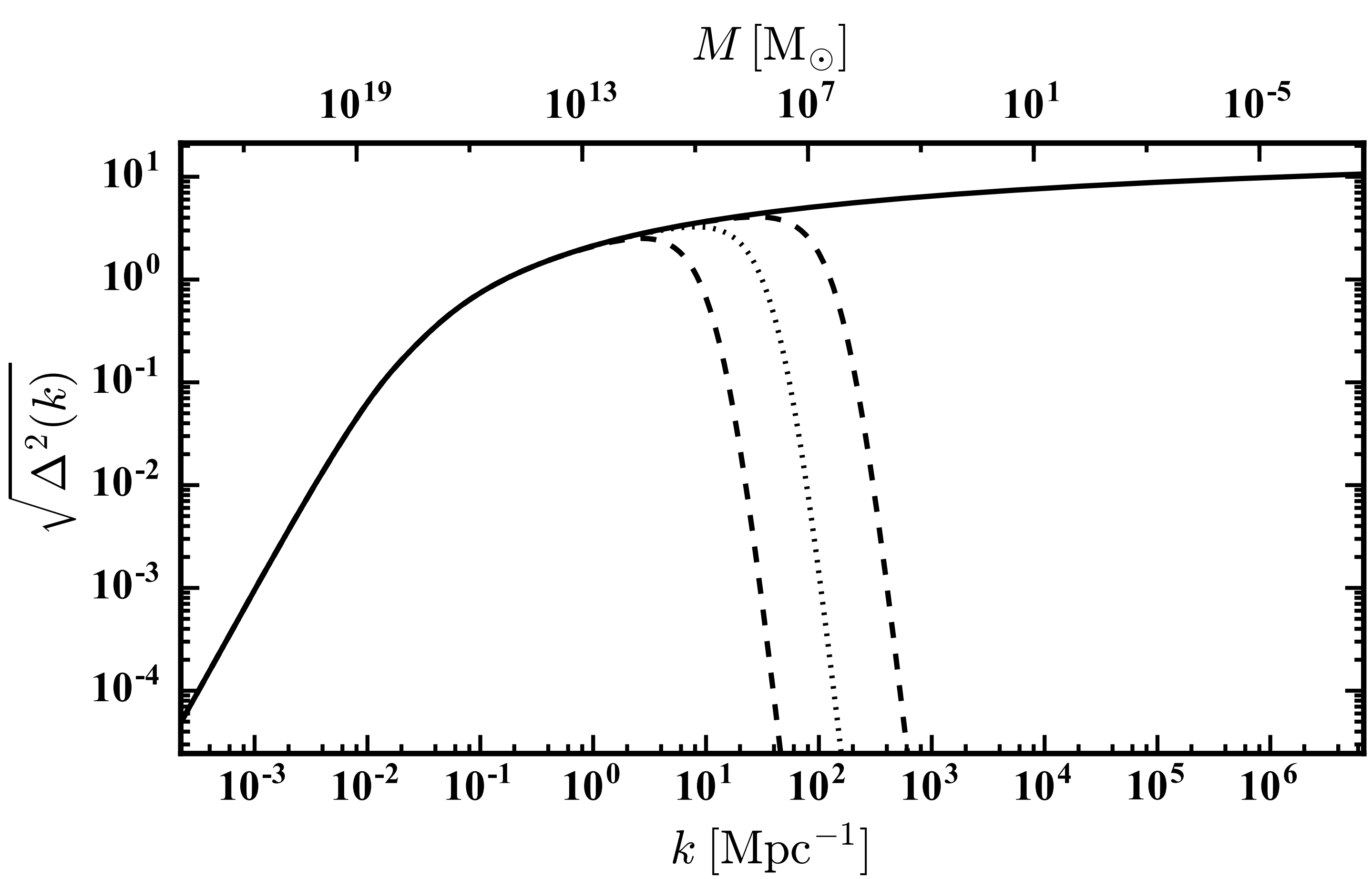
- Density profiles of low-mass galaxies ***outside of the Milky Way*** will provide sensitive tests of the CDM (+ baryon) model

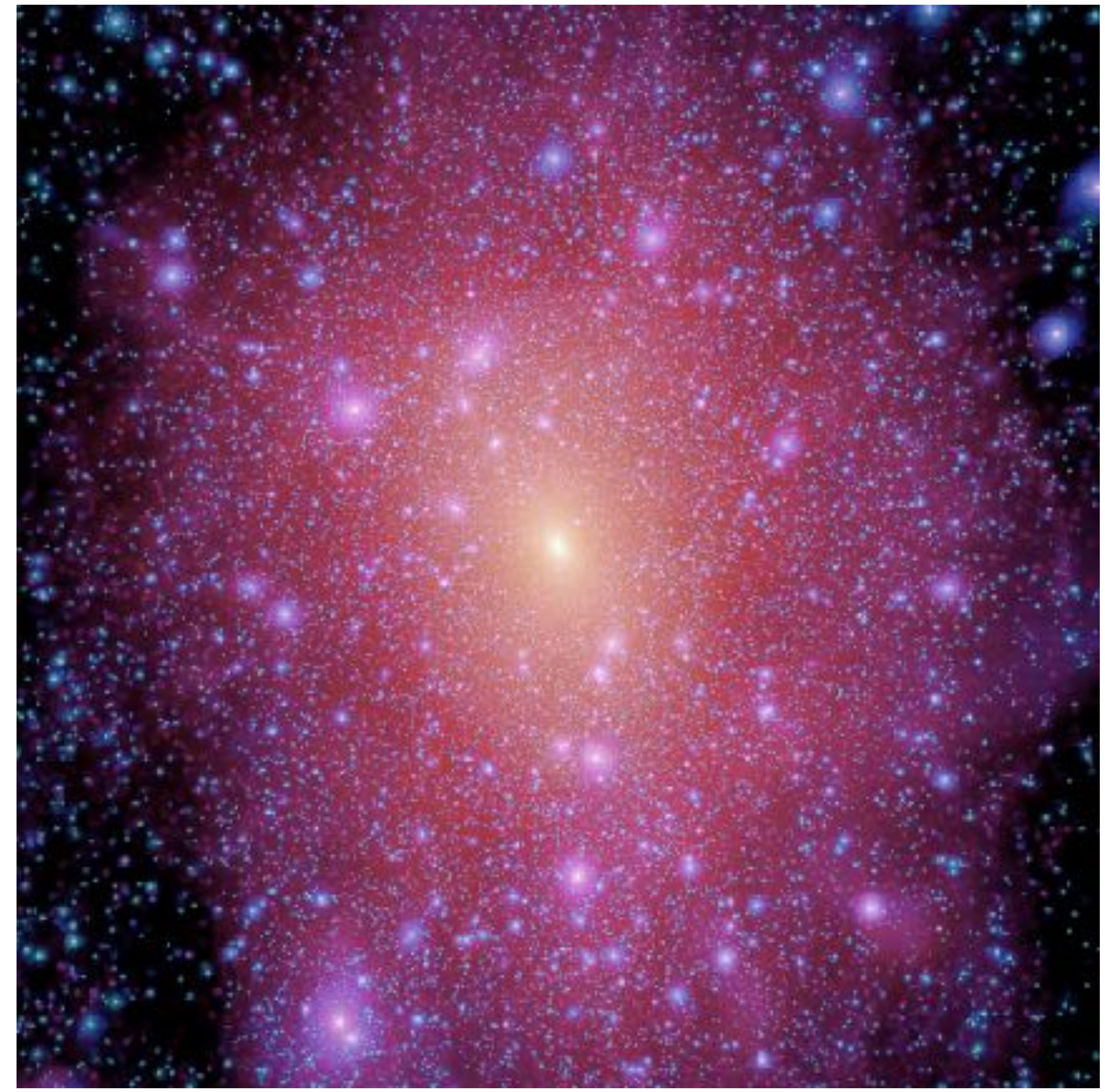
- If galaxies below this mass tend to have cores, then we may have to consider alternatives

  - **Self-Interacting Dark Matter (SIDM)**: allow for dark matter self-scattering
  - **Warm Dark Matter (WDM)**: non-negligible primordial thermal velocities
  - **Ultra-light Axions**: quantum effects on galaxy scales
  - **Modified Gravity (MOND / TeVeS, etc.)**: modify gravity
  - **Superfluid Dark Matter**: phonons give MOND-like phenomenology

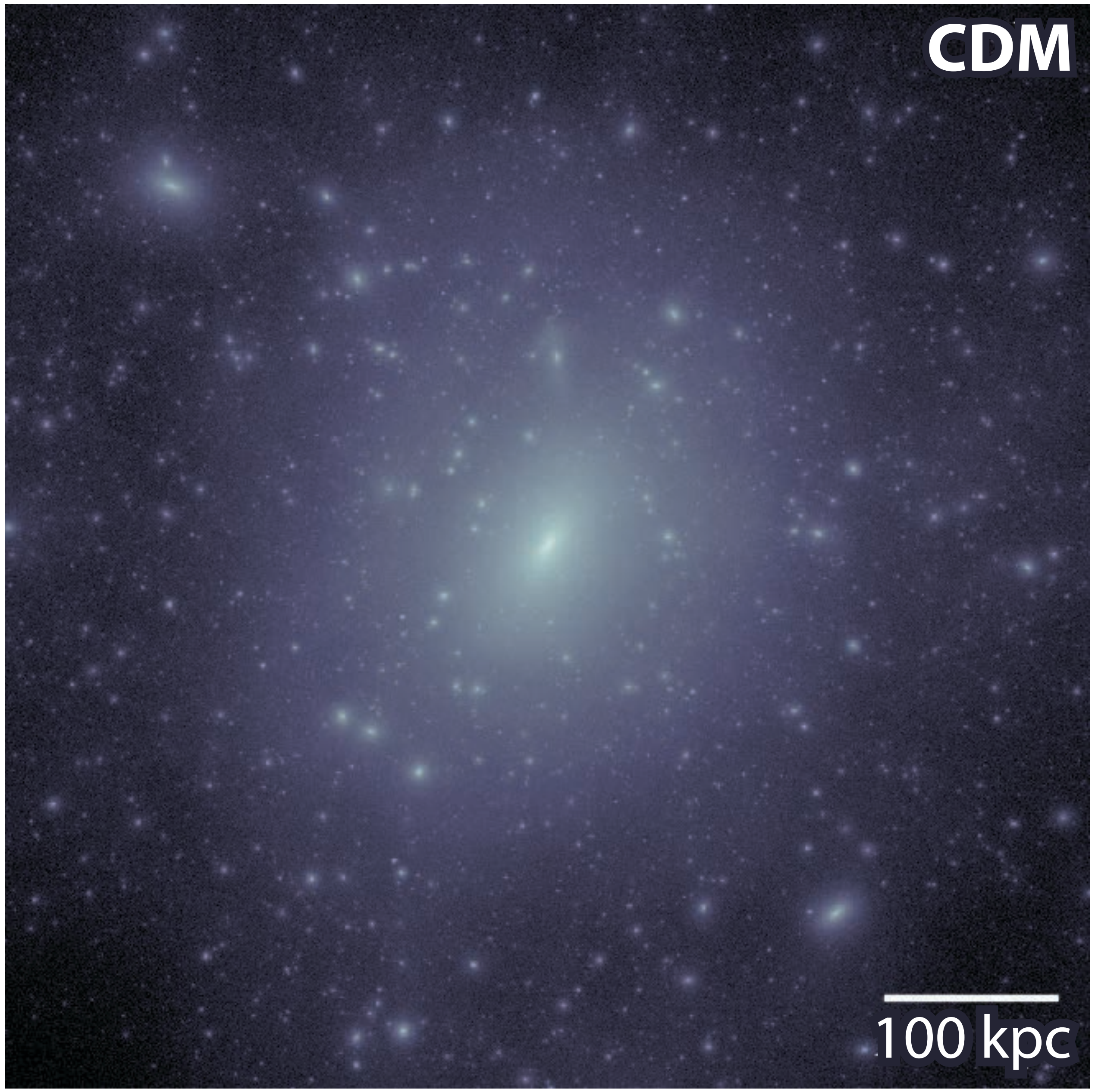
Dark Matter Models Beyond CDM

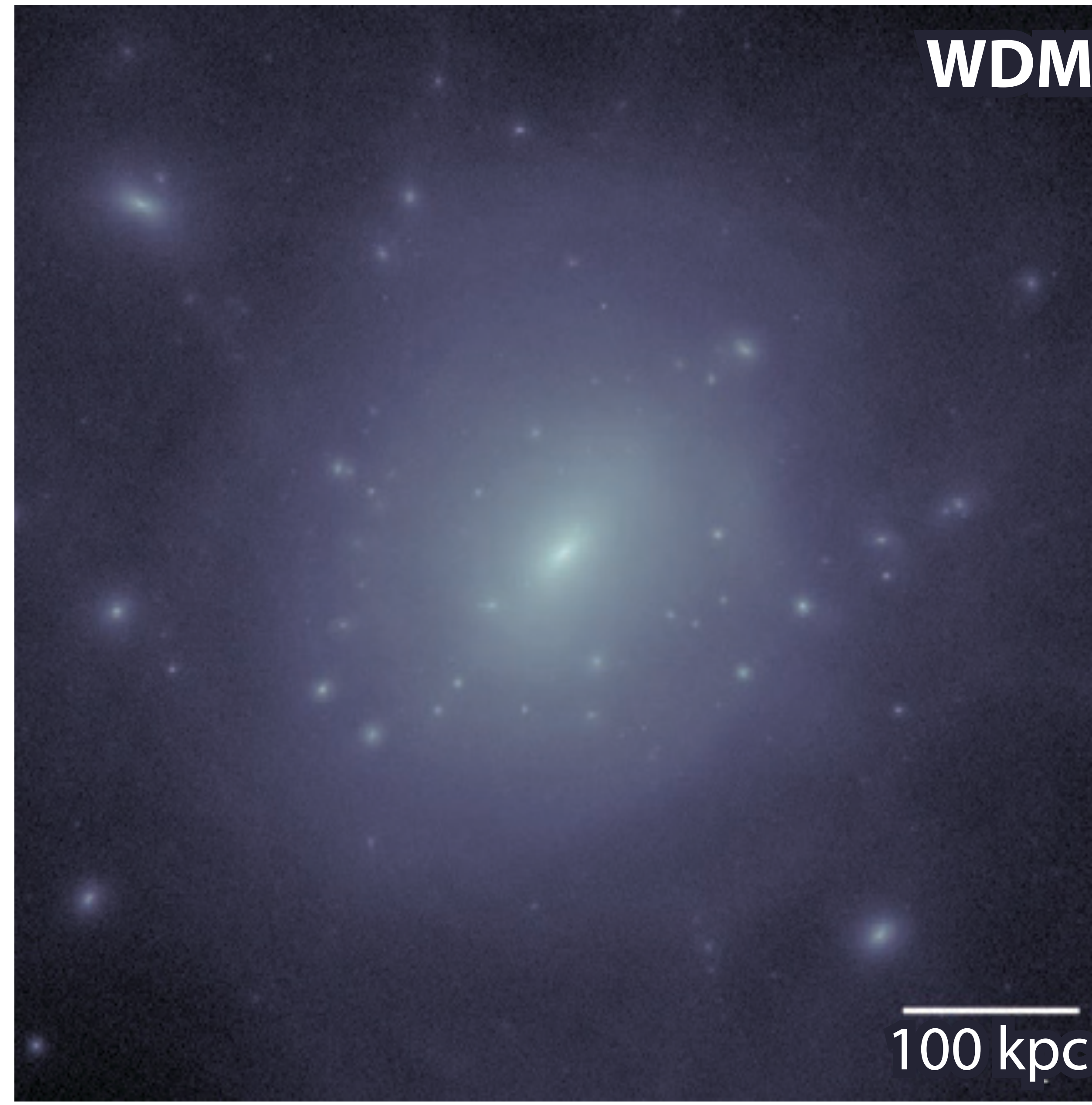
Modify *linear* physics or *non-linear* physics



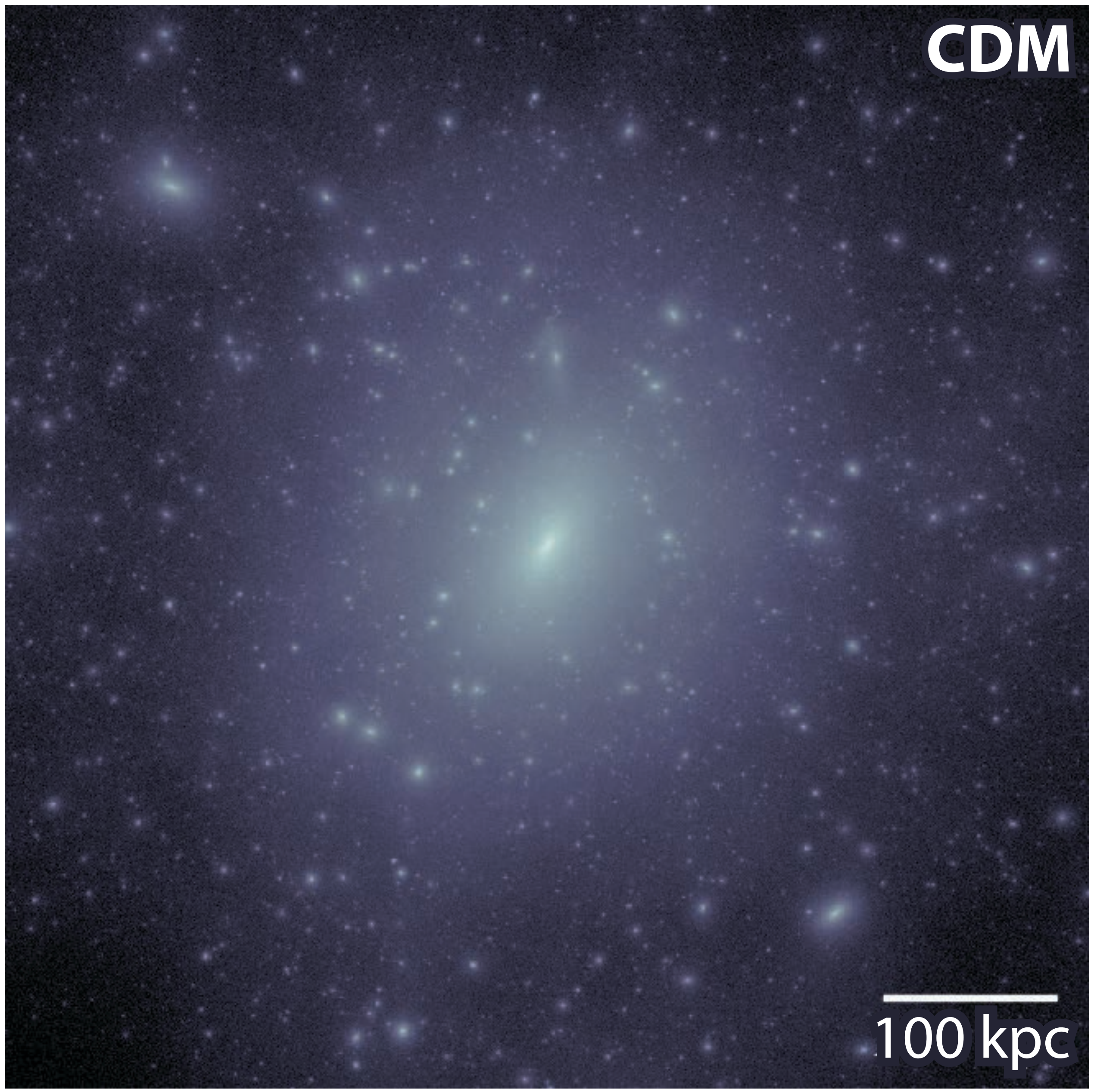


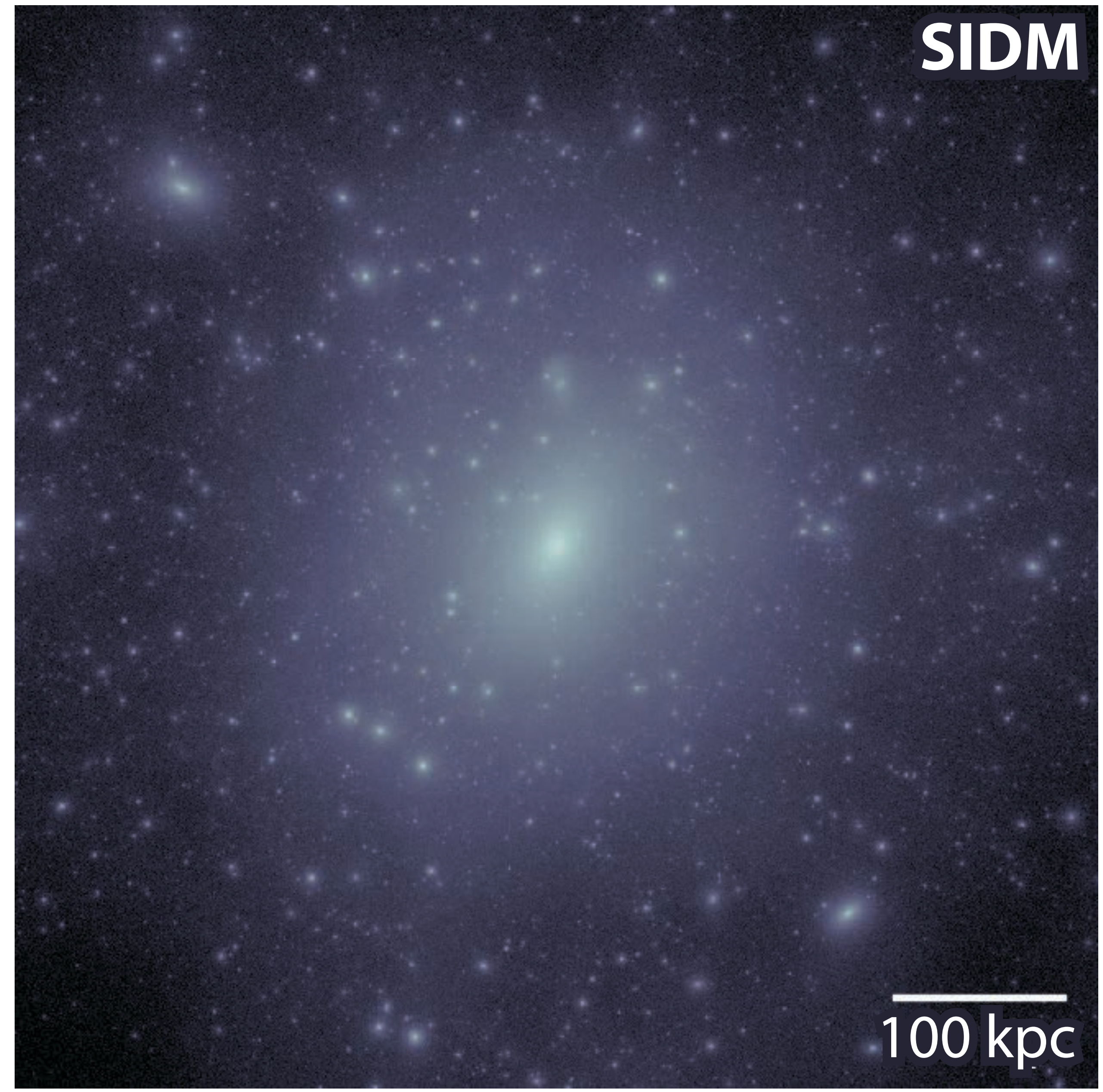
Power Spectrum Modifications (CDM vs WDM)



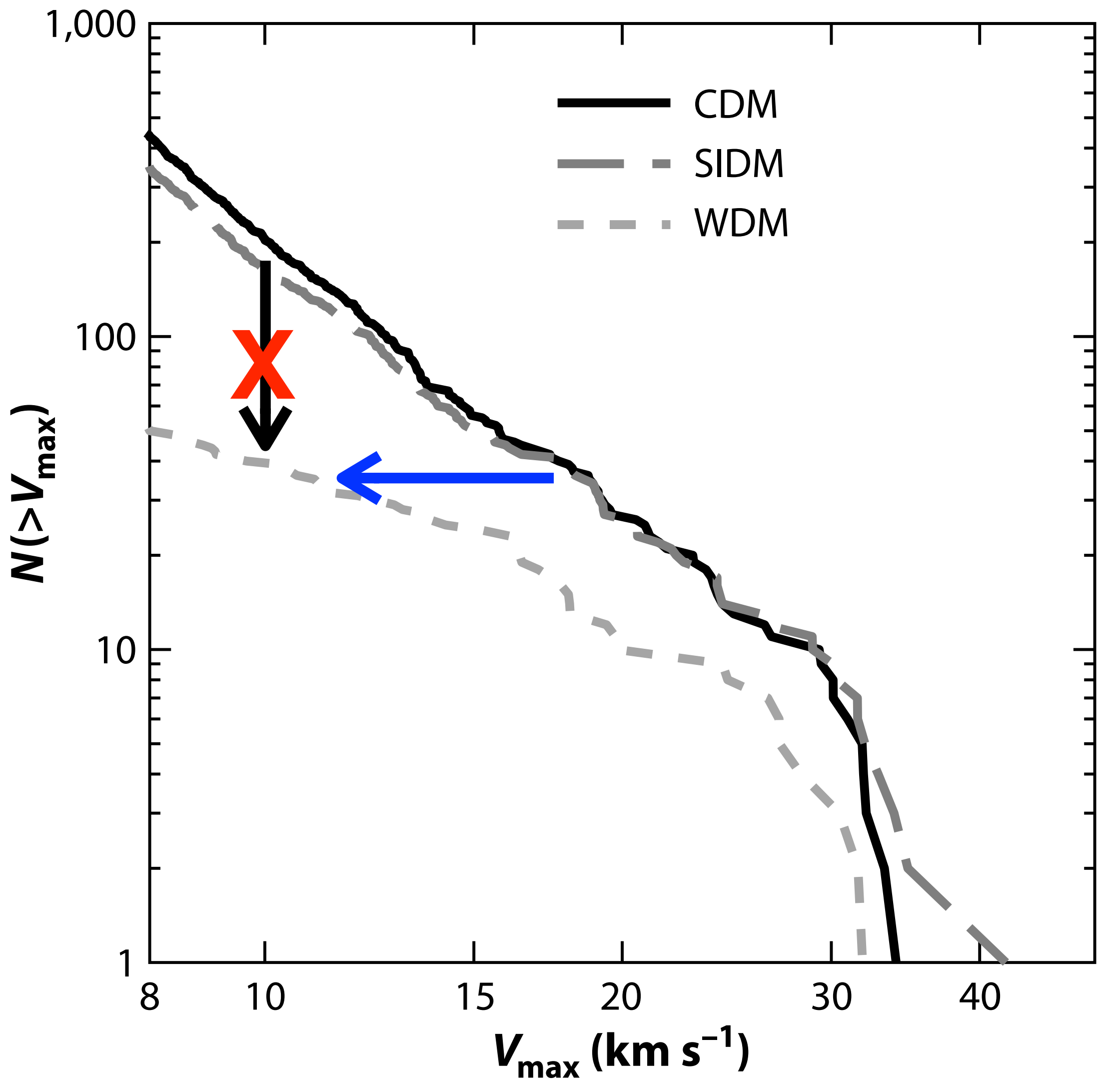


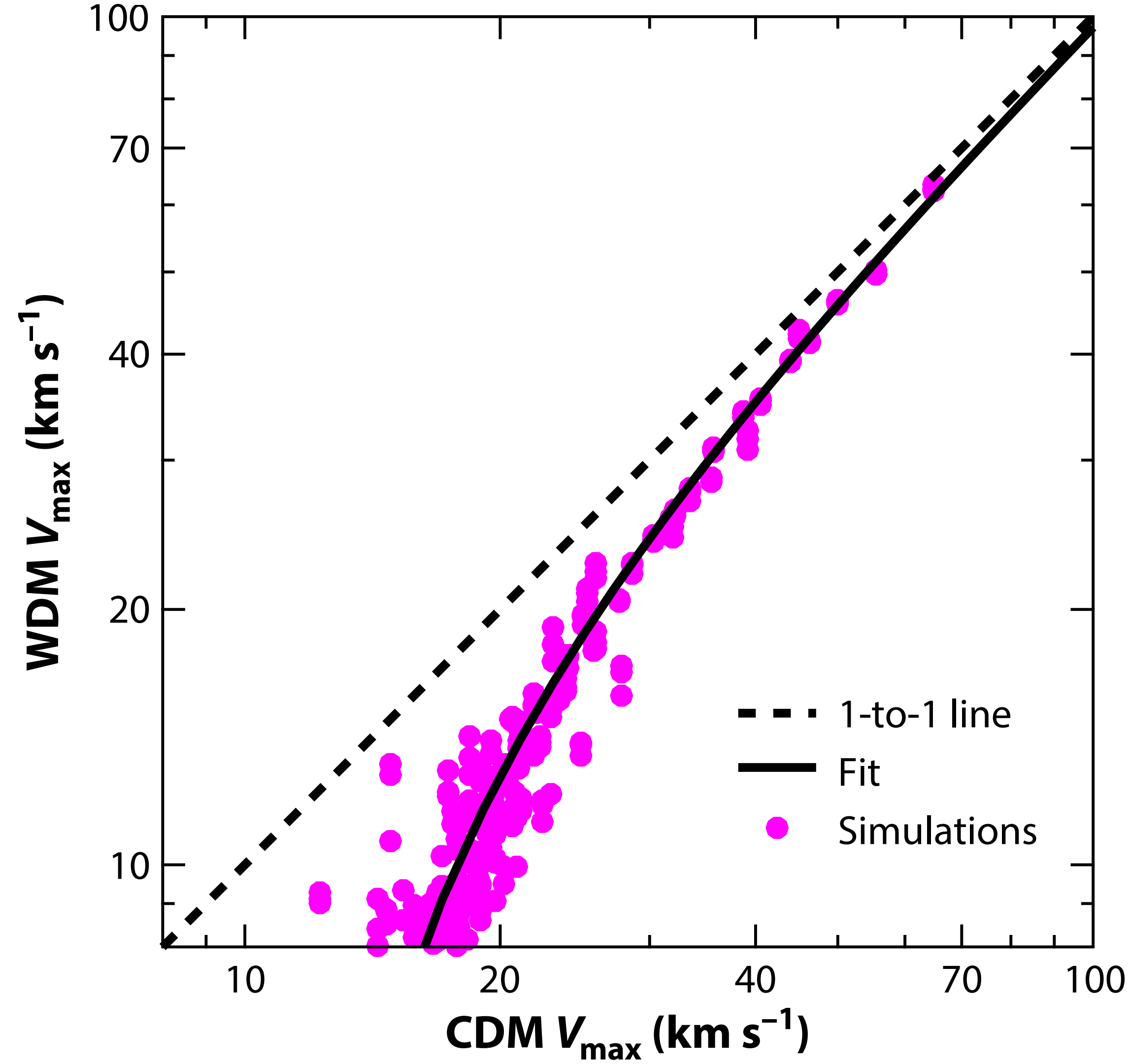
Dark Matter Self-Interactions (CDM vs SIDM)





Abundances in CDM vs WDM vs SIDM

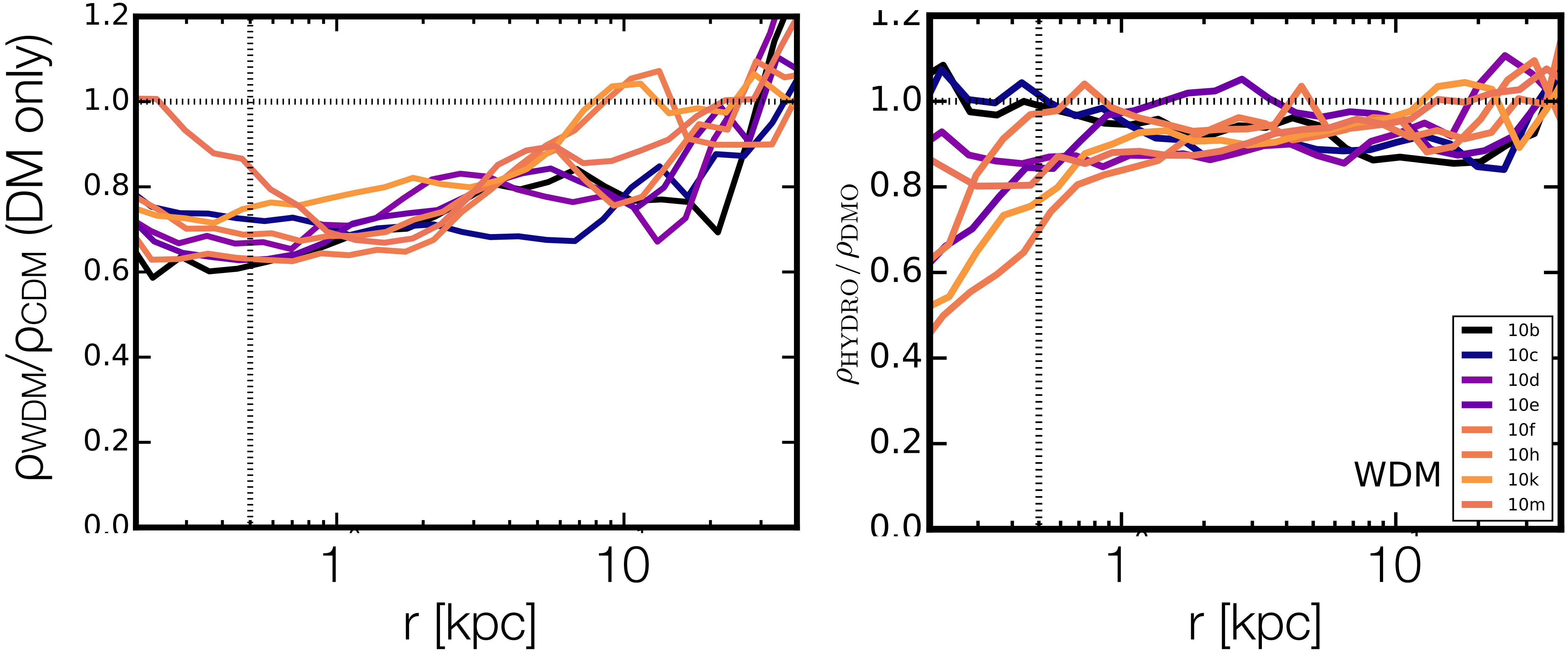




Relevant for dwarf galaxy “abundance” problem (see Alyson Brooks’ talk)

Bullock & Boylan-Kolchin 2017;
Bozek, Boylan-Kolchin, ++ 2016

WDM simulations



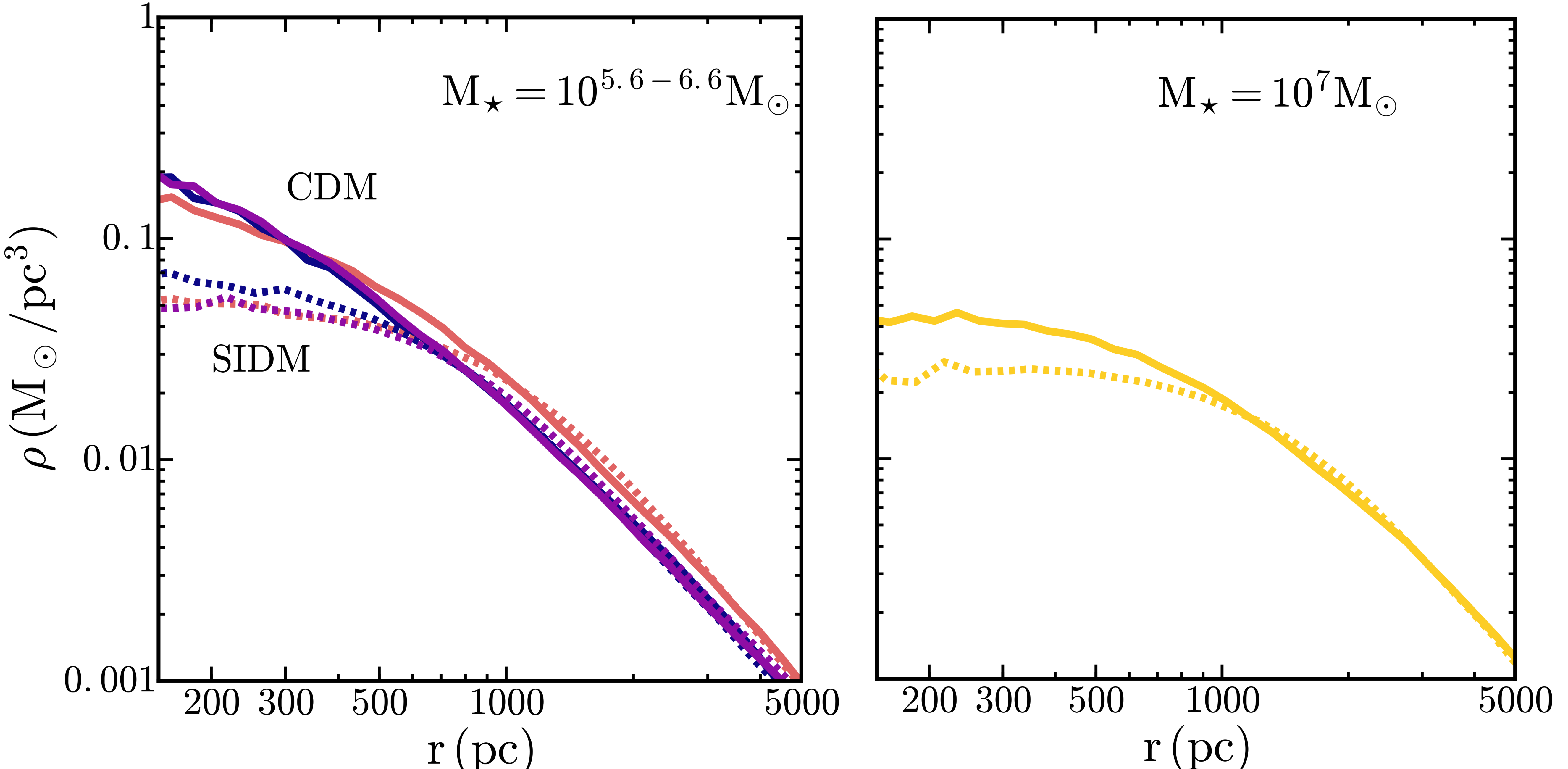
30% suppression in central density in WDM (dark matter only)

Additional suppression from star formation feedback

Bozek, Fitts, MBK ++ (in preparation)

Simulations of dwarf galaxies with SIDM + baryons

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



V. Robles et al., in preparation

Bottom Line

There are a lot of ways to accommodate observations within ΛCDM, with varying degrees of "naturalness". Can also get agreement using relatively minor modifications to DM (warm, self-interacting) with baryons.

Fundamental question: (how) can we definitively test the ΛCDM model?

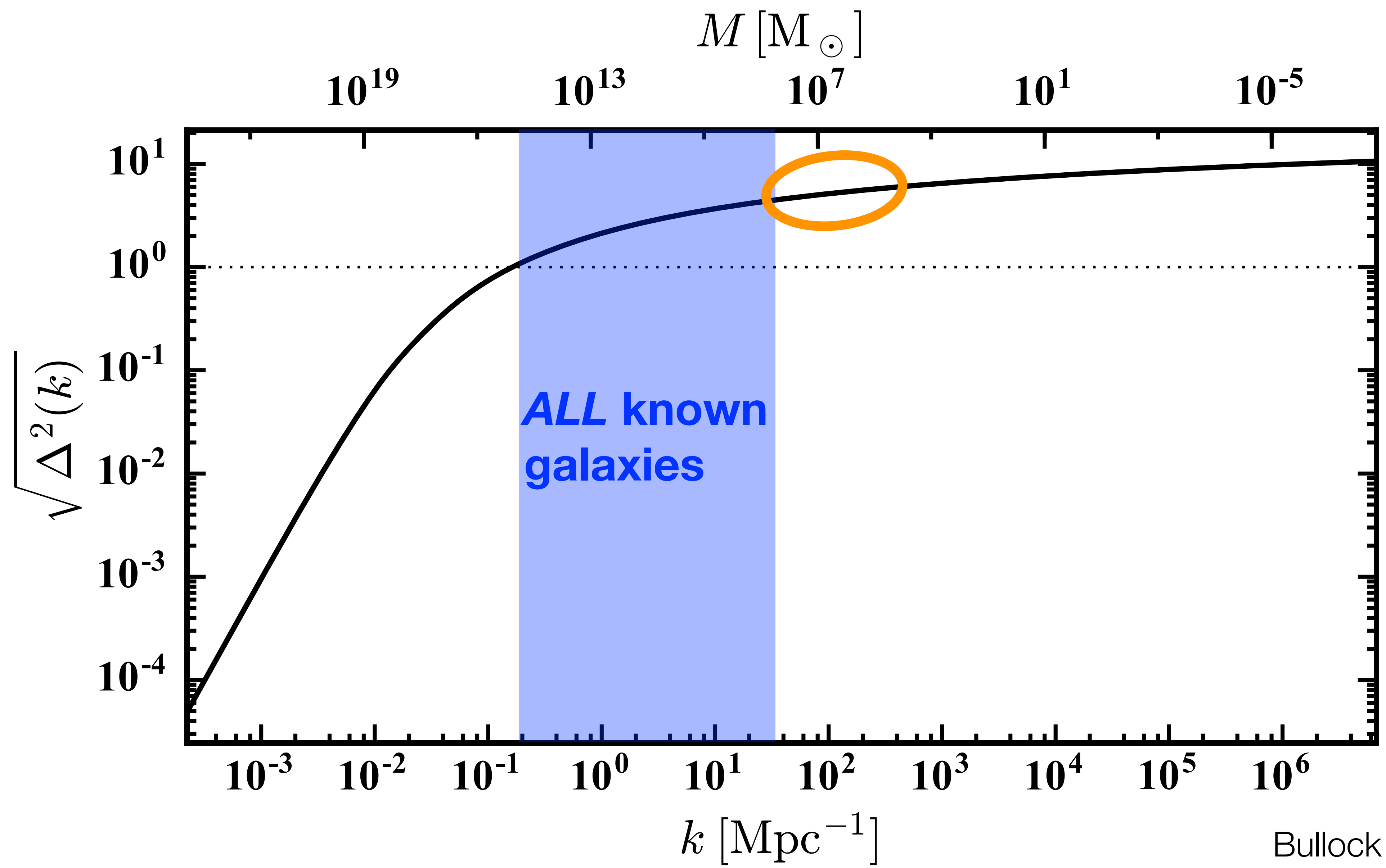
My feeling: yes! …. but it's hard.

Simplest option: directly detect dark matter in the laboratory. However: "we have made excellent progress on not detecting WIMPs" (P. Sorensen)

Bottom Line

Simplest option: directly detect dark matter in the laboratory. However: "we have made excellent progress on not detecting WIMPs" (P. Sorensen)

Next best option: look for fundamental prediction of ΛCDM model — dark matter structure below the mass scale of galaxies

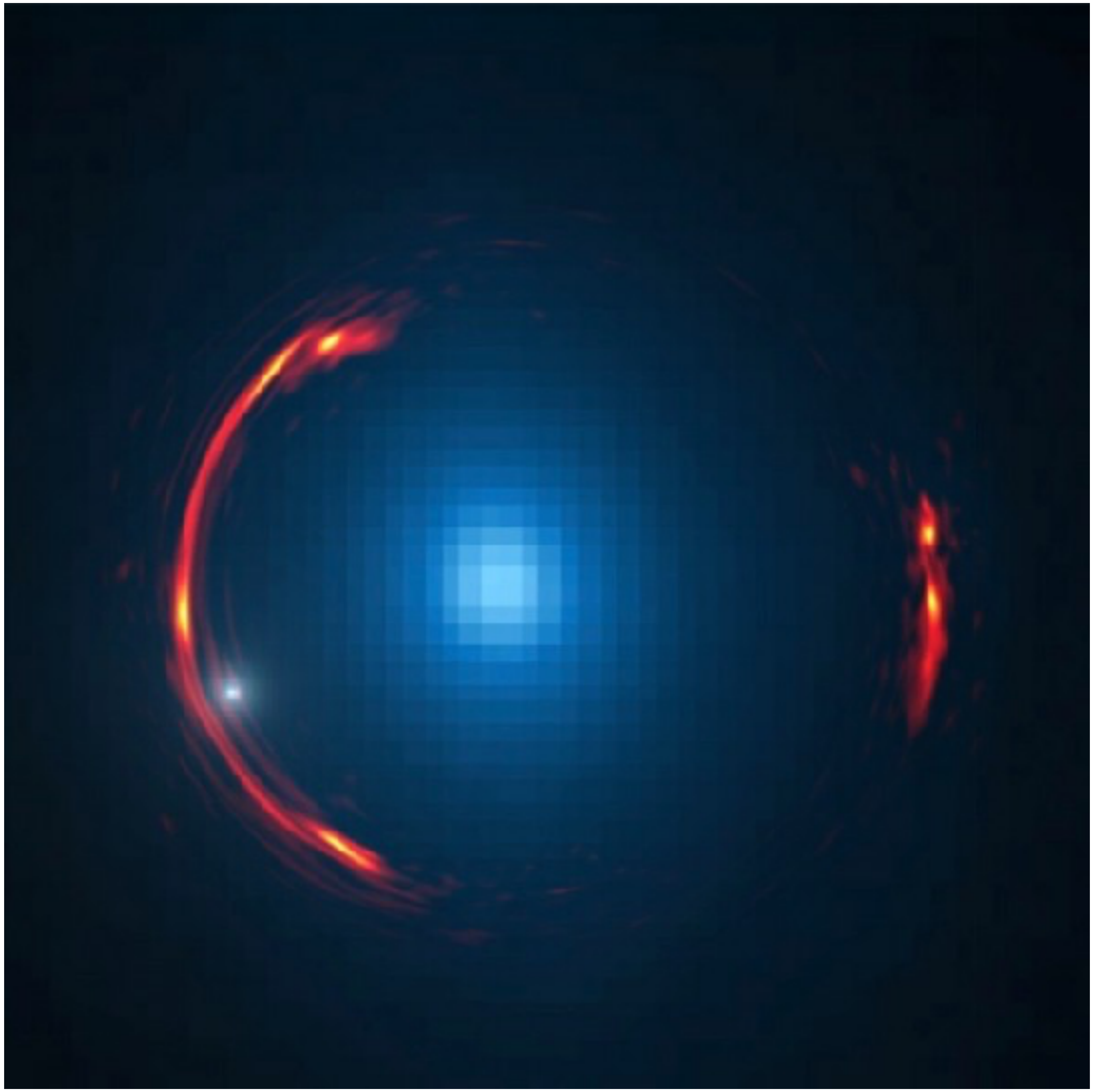


Bullock & Boylan-Kolchin 2017

The future (?): gravitational detection of “dark” (sub)halos

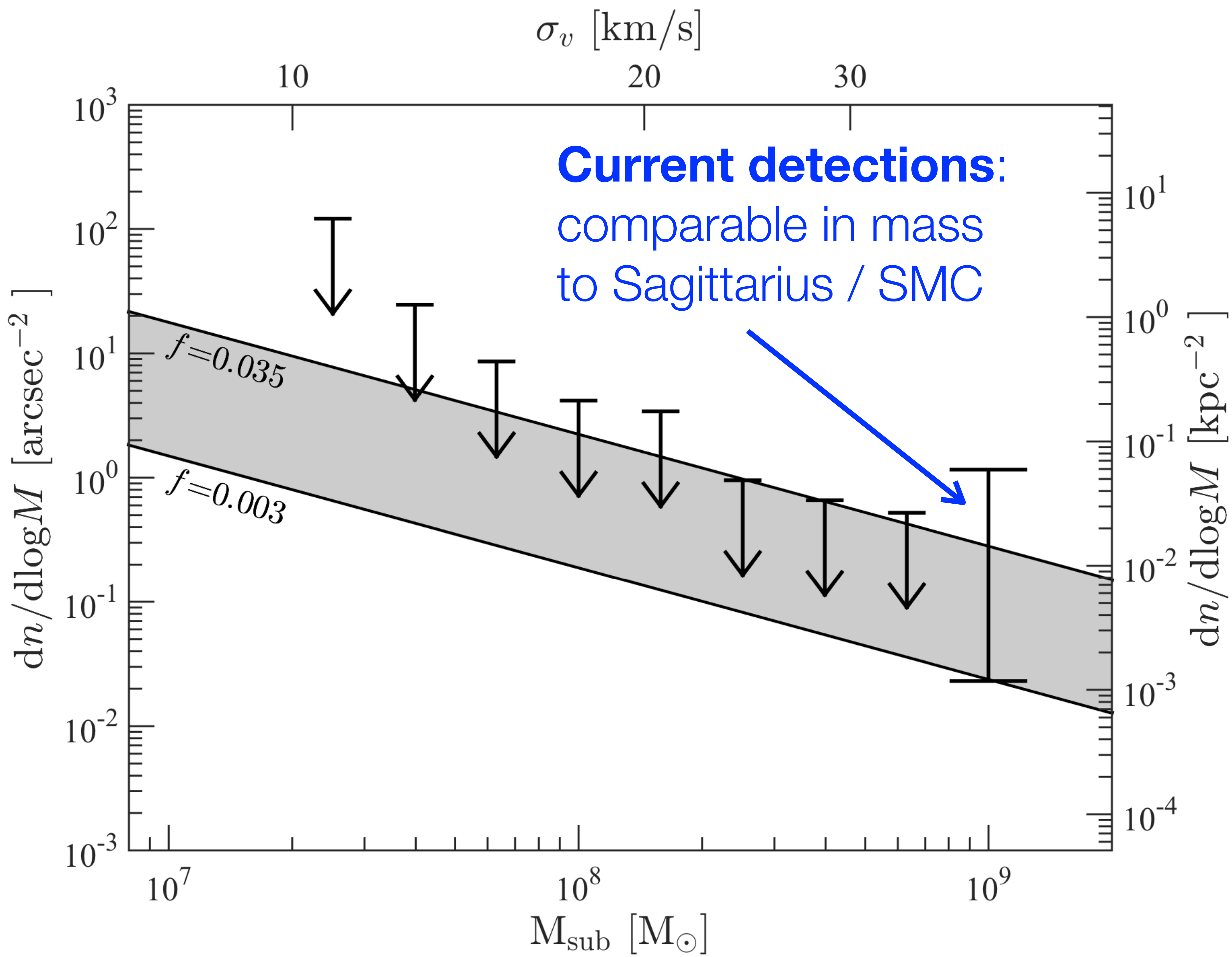
Absent a detection of dark matter particles, discovery of dark substructure is **crucial** for verifying the entire ΛCDM paradigm

This is *extremely* difficult



Y. Hezaveh / ALMA / HST

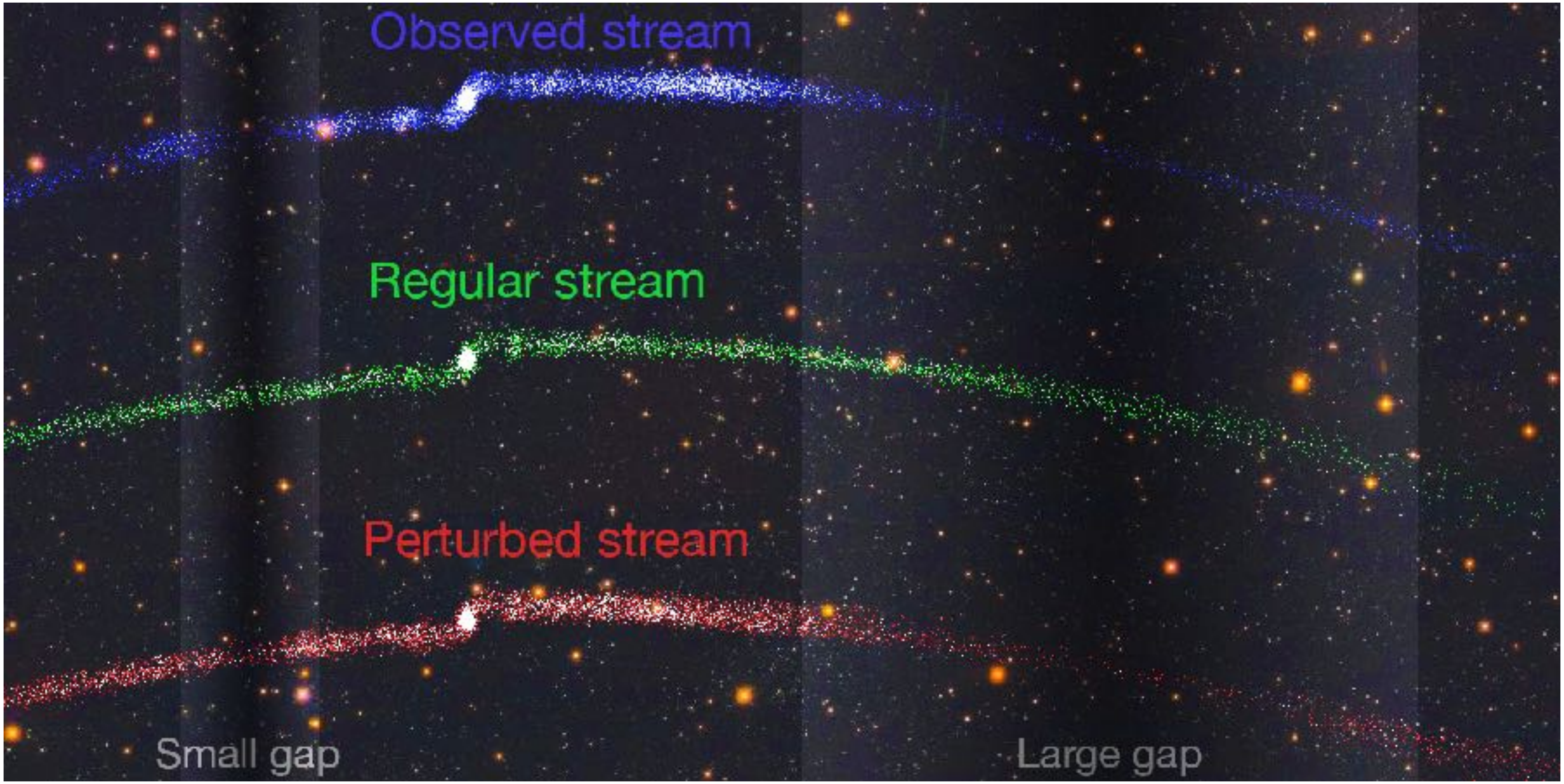
The future (?): gravitational detection of “dark” (sub)halos



Hezaveh et al. 2016

The future (?): star count detection of "dark" (sub)halos

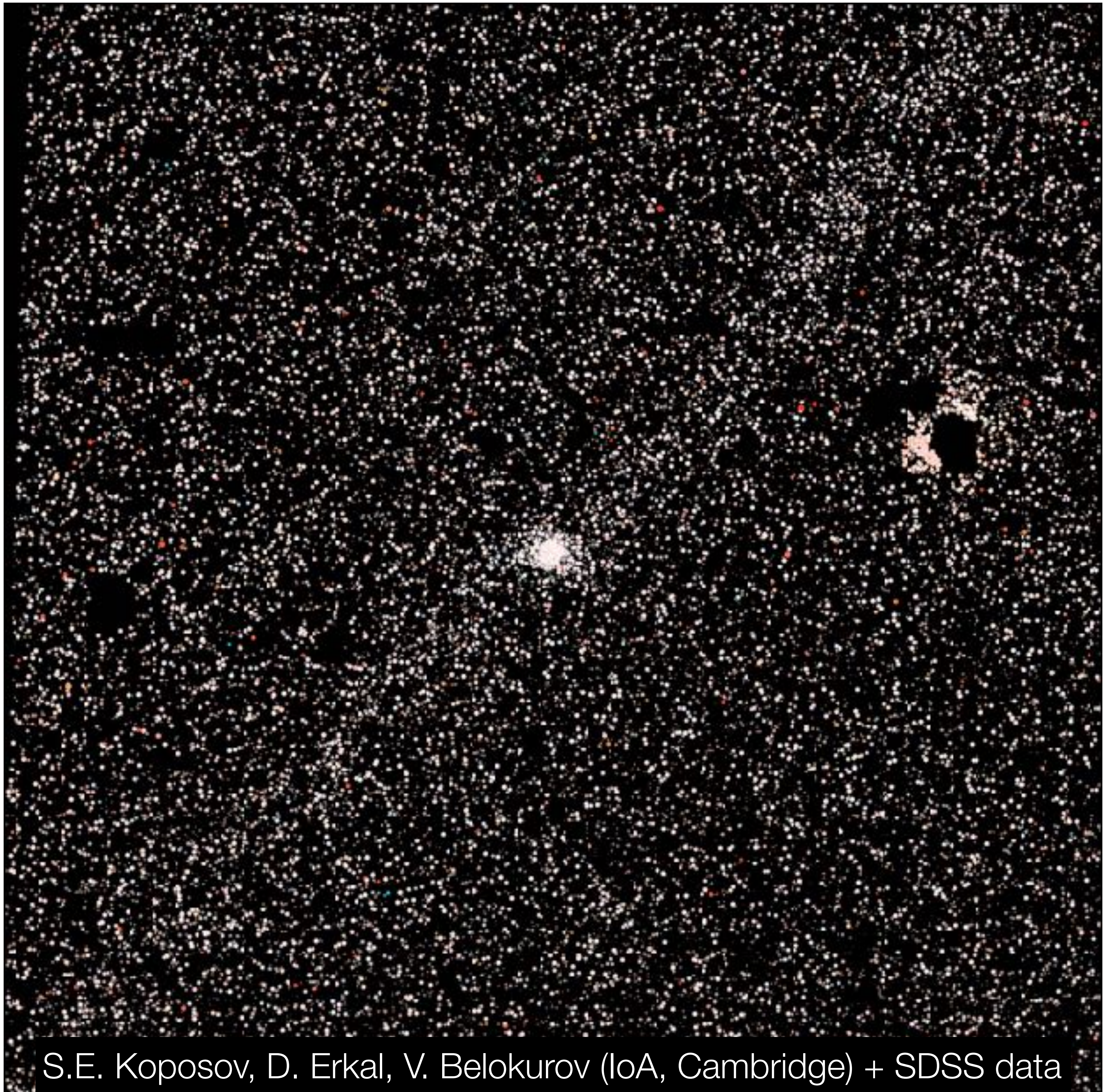
Gaps in stellar streams: already indicate existence of dark substructure?



10^6 M⊙ subhalo $10^{7.7}$ M⊙ subhalo

V. Belokurov, D. Erkal, S.E. Koposov (IoA, Cambridge)

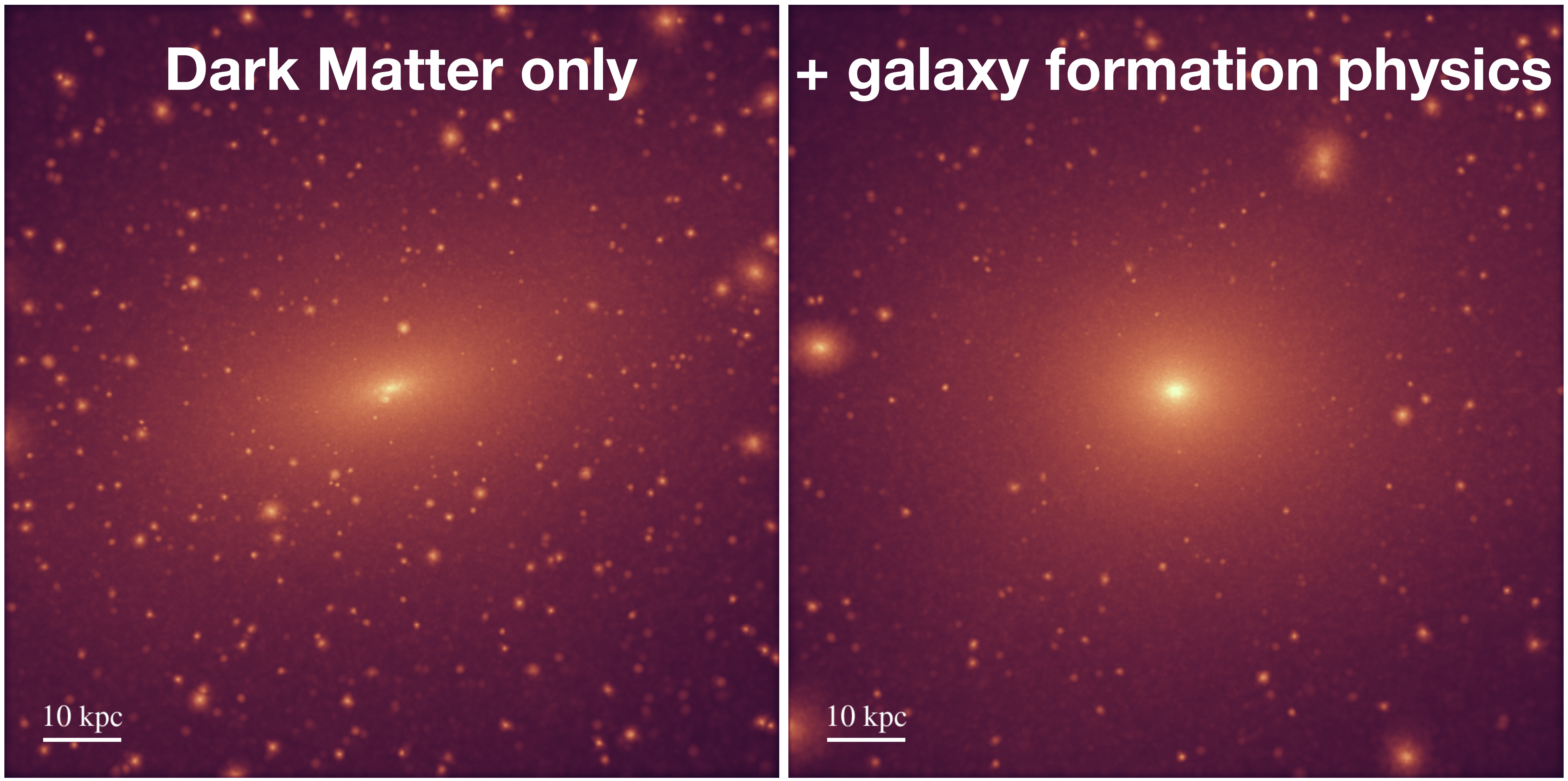
The future (?): star count detection of “dark” (sub)halos



This is *extremely* difficult

“The number of background stars from the Milky Way has been reduced to make the stream more prominent.”

The future (?): star count detection of “dark” (sub)halos



Garrison-Kimmel et al. 2017

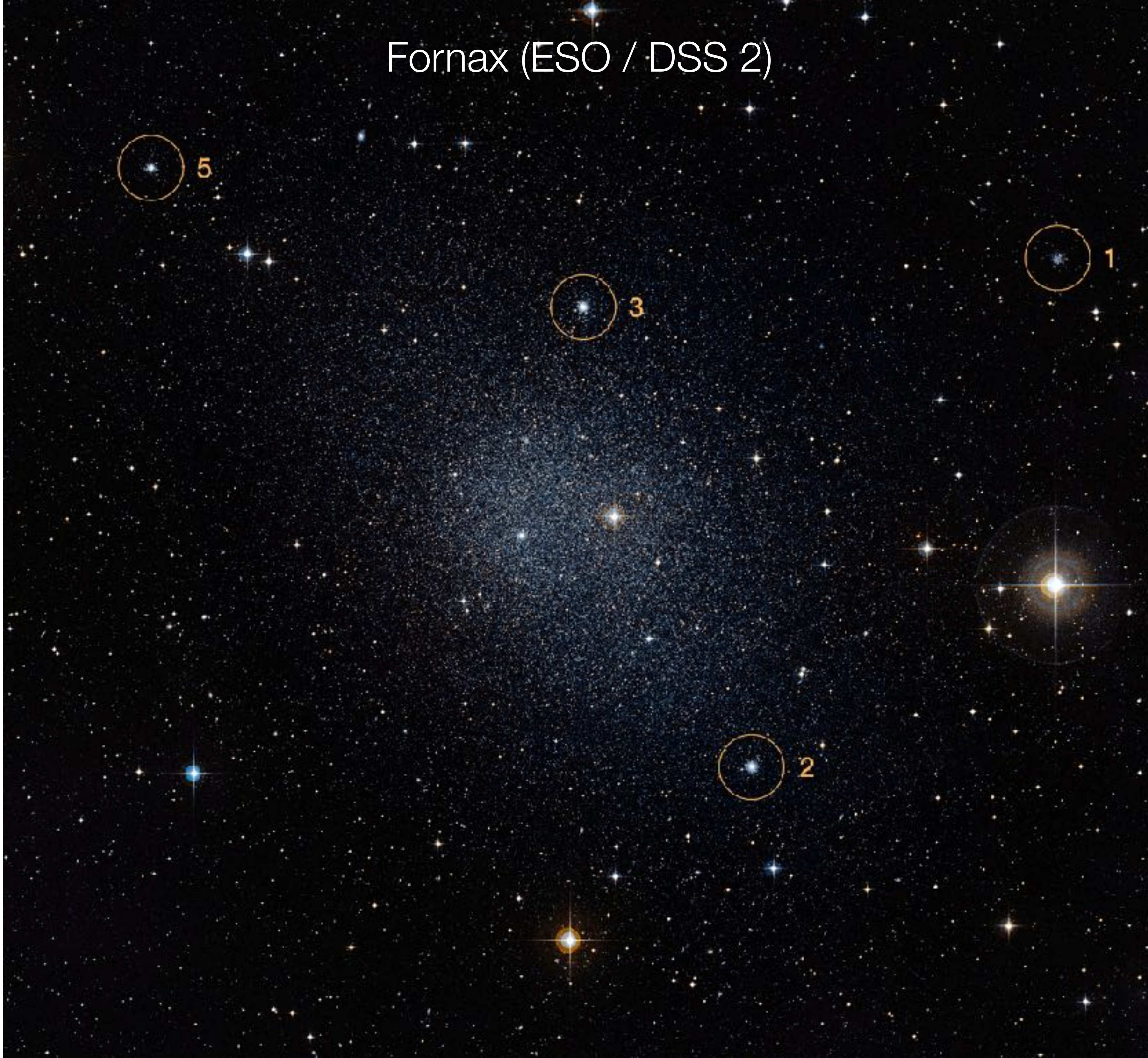
Potential complication: inner halo globular cluster streams are produced by disk shocking; same process destroys dark matter substructure.

Donald J. Trump @realDonaldTrump · 22h

Ever notice that galactic disks destroy substructure of all kinds? Very sad and unfair. Ridiculous that this isn’t getting more ApJ covfefe. #dwdm17

58K 46K 149K

Fornax (ESO / DSS 2)


Fornax (ESO / DSS 2)
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1
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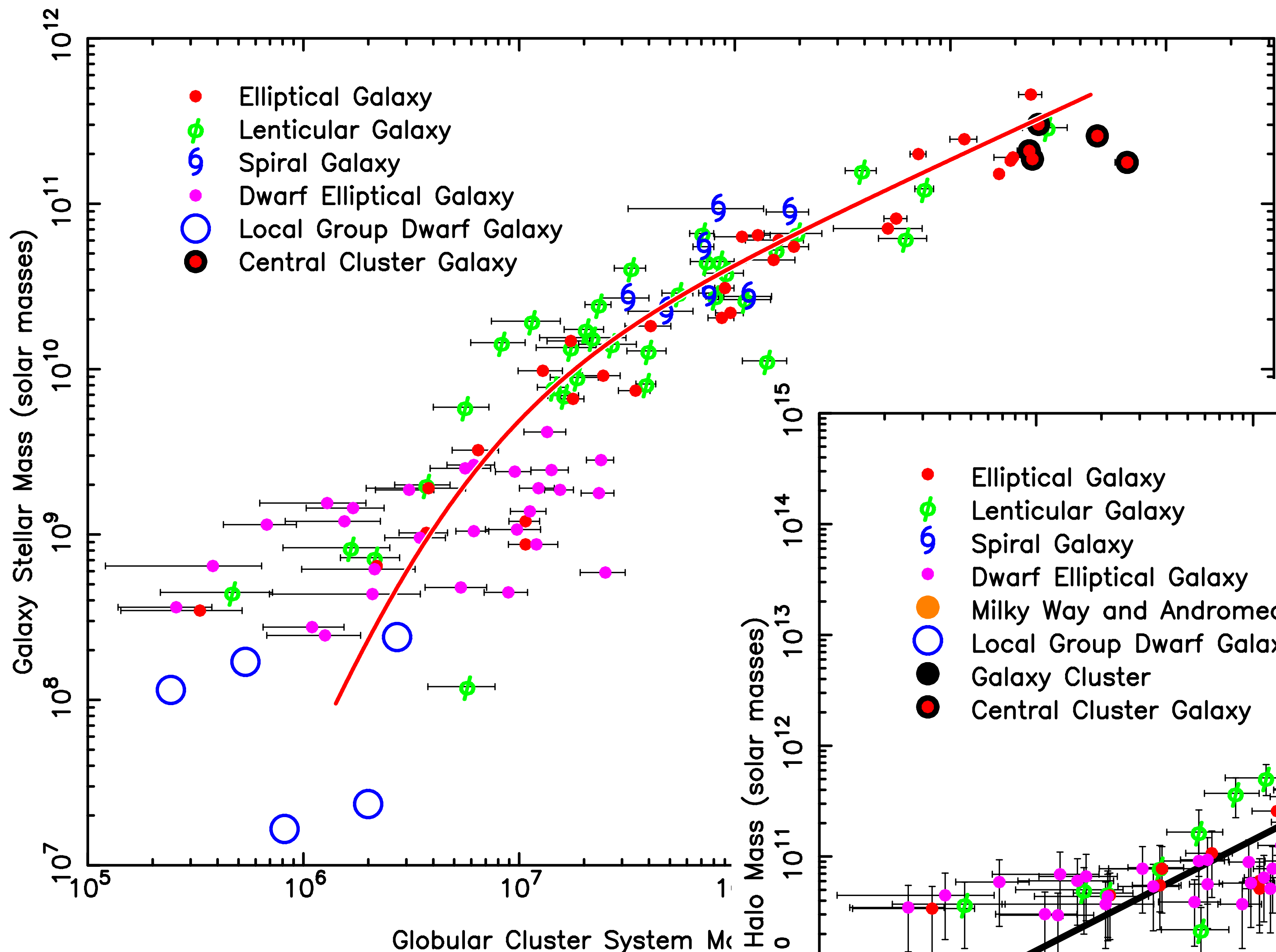
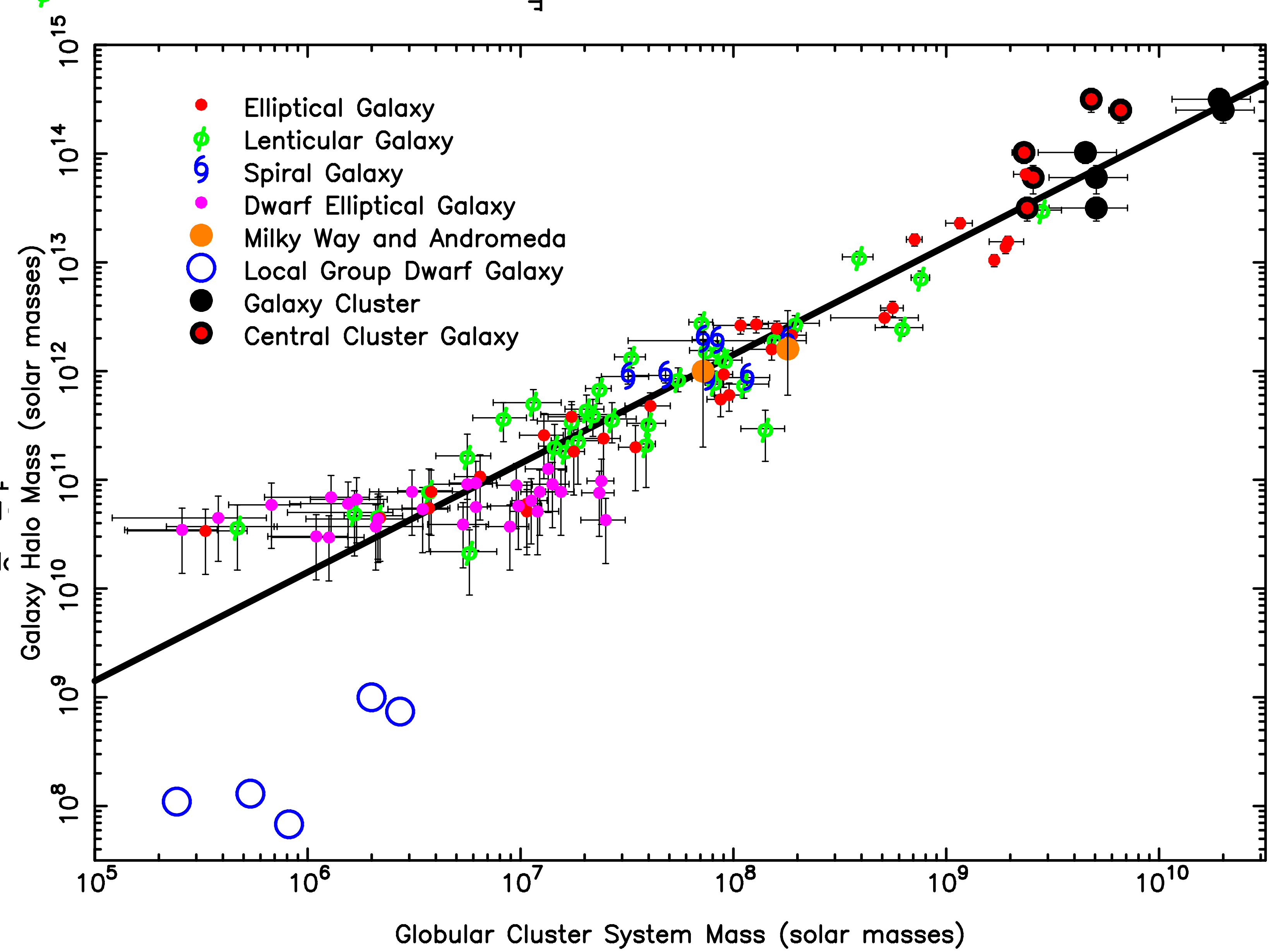
2

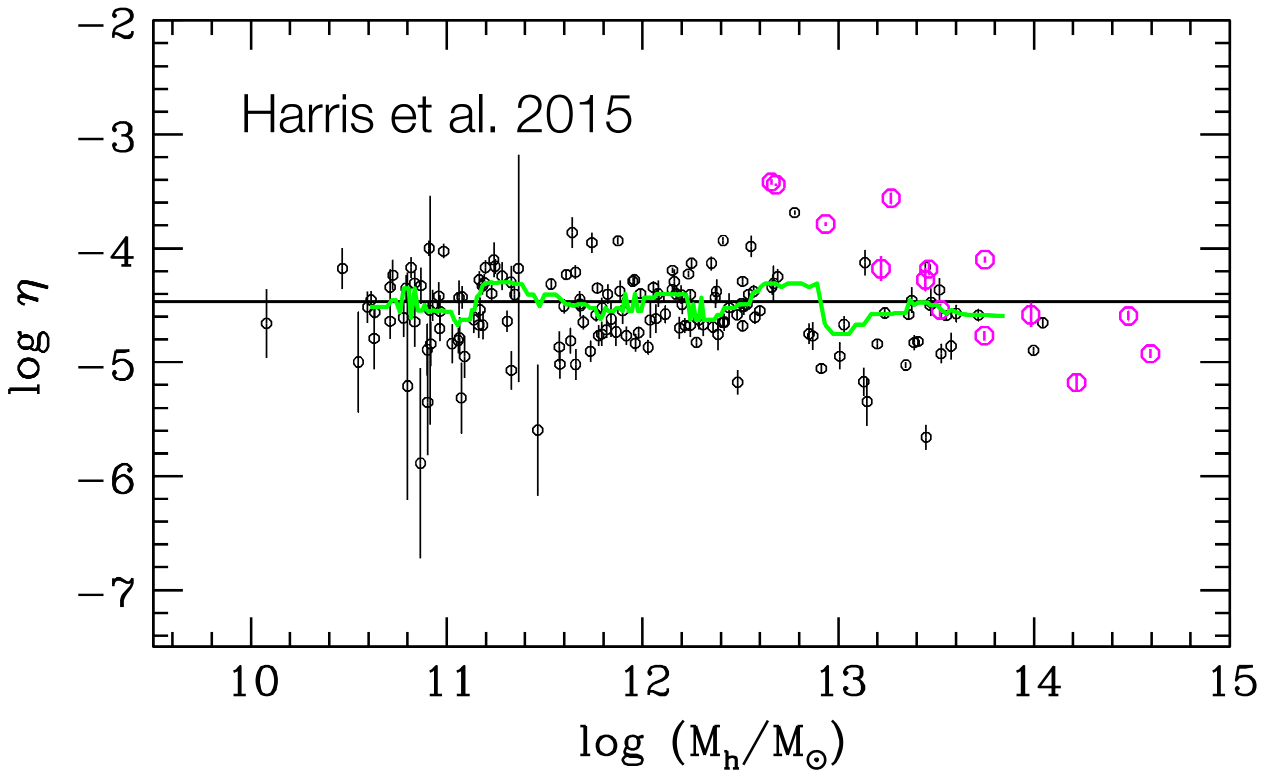
Globular Clusters as cosmological probes

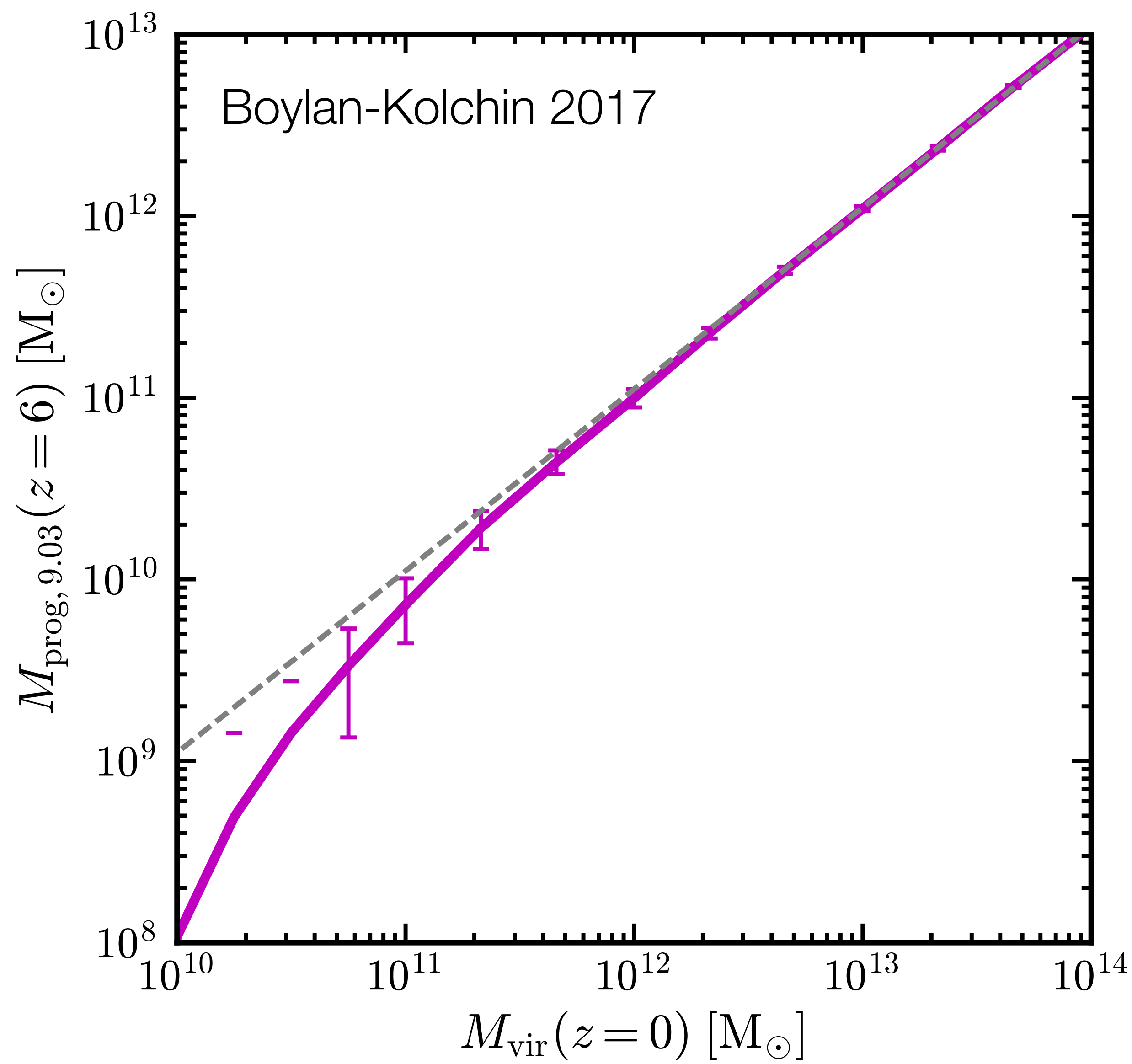




Spitler & Forbes 2009

Globular Clusters as cosmological probes





Can we use globular clusters to map out the low-mass edge of galaxy formation in statistical samples of galaxies?

Summary

- On large scales, the Universe is well-described by ΛCDM. Several issues exist on smaller (sub-galactic scales): *nearby galaxies are generically less abundant & less dense than naive predictions of ΛCDM*.

- $M_{vir}=10^{10}\ M_\odot$ ($M_\star \sim 3\times10^6\ M_\odot$) is a crucial scale for galaxy formation and testing ΛCDM

- If cores are robust in generic for low-mass galaxies, we may need to move beyond ΛCDM: WDM, SIDM, something else?

- ***Searching for star-less dark matter halos should be the highest priority for astrophysical dark matter investigations.*** Gravitational lensing, star stream gaps are potential ways forward; worth considering new approaches, given the stakes.

ARA&A review on small-scale problems for ΛCDM (with J. Bullock, 2017); KITP program on small-scale structure of Cold (?) Dark Matter, Spring 2018 (lead organizer: J. Navarro)

Questions for discussion

- What is the low-mass threshold for galaxy formation, in terms of M_{halo}?
- Is there any evidence for star formation below the atomic cooling limit?
- Can we come up with consistent definitions for halo mass?
- How seriously should we be taking the results of any individual numerical simulation?
- How sensitive are dwarfs' properties to, e.g., T and z of reionization?
- What are new ways of searching for the low-mass (star-less) halos that must be present if ΛCDM is correct?
- What can globular clusters teach us about cosmology?
- How the *%$# can we understand objects like Crater 2 in ΛCDM?
- Is dark matter related to the hierarchy problem of the Standard Model?