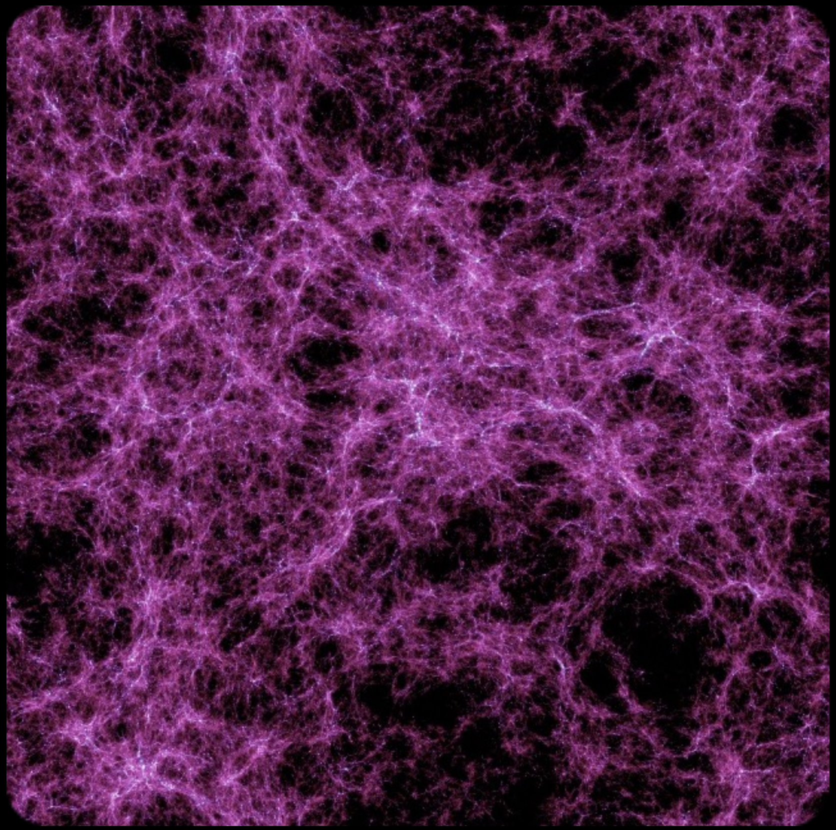
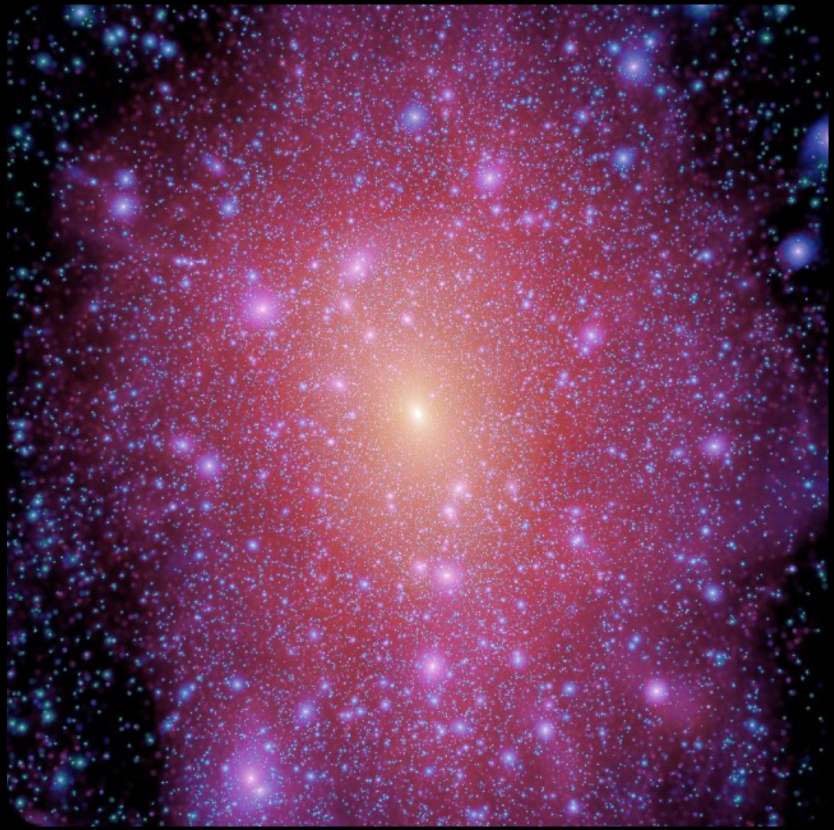
Dwarf Galaxies and the Nature of Dark Matter





Mike Boylan-Kolchin

The University of Texas at Austin

UCLA Dark Matter Workshop

22 February 2018

Dwarf Galaxies and the Nature of Dark Matter

Mike Boylan-Kolchin
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Small-Scale Challenges to the ΛCDM Paradigm
J. Bullock & MBK (2017), *Annual Review of Astronomy & Astrophysics* (55, 343)

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Why study dwarf galaxies?

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Dwarf galaxies are **<adjective>** **<plural noun>** of galaxy formation. They also are the **<adjective>** place to test CDM, as **<adjective>** of the most **<adjective>** challenges to the model are found in the dwarf regime.

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sensitive probes; best; several; serious

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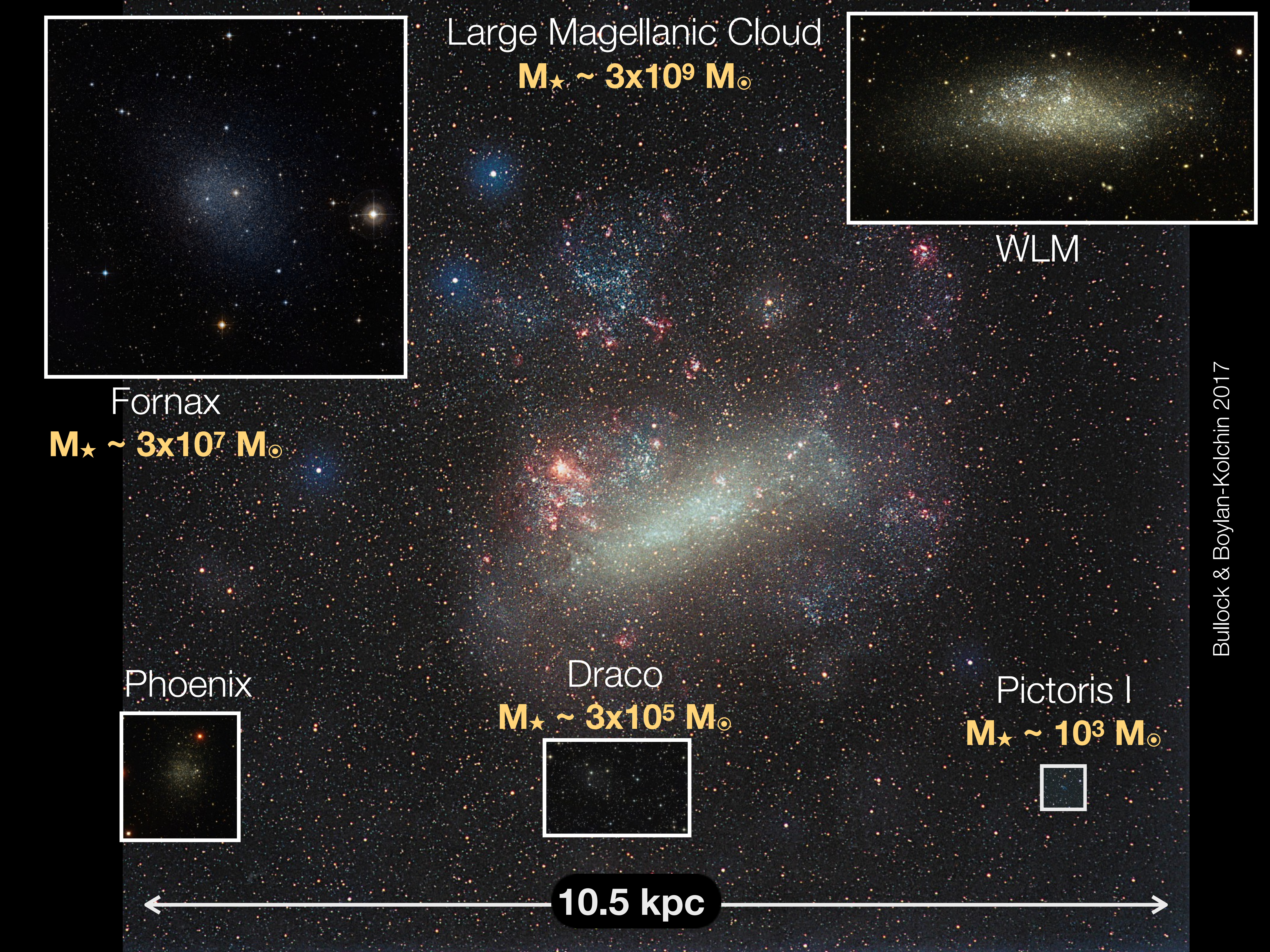
Dwarf galaxies are **<adjective>** **<plural noun>** of galaxy formation. They also are the **<adjective>** place to test CDM, as **<adjective>** of the most **<adjective>** challenges to the model are found in the dwarf regime.

sensitive probes; **best**; **several**; **serious**

annoying leftovers; **worst**; **none**; **interesting**


Large Magellanic Cloud
$M_\star \sim 3x10^9\ M_\odot$
WLM
Fornax
$M_\star \sim 3x10^7\ M_\odot$
Phoenix
Draco
$M_\star \sim 3x10^5\ M_\odot$
Pictoris I
$M_\star \sim 10^3\ M_\odot$
10.5 kpc
Bullock & Boylan-Kolchin 2017

Small-scale issues: ΛCDM vs dwarf galaxies

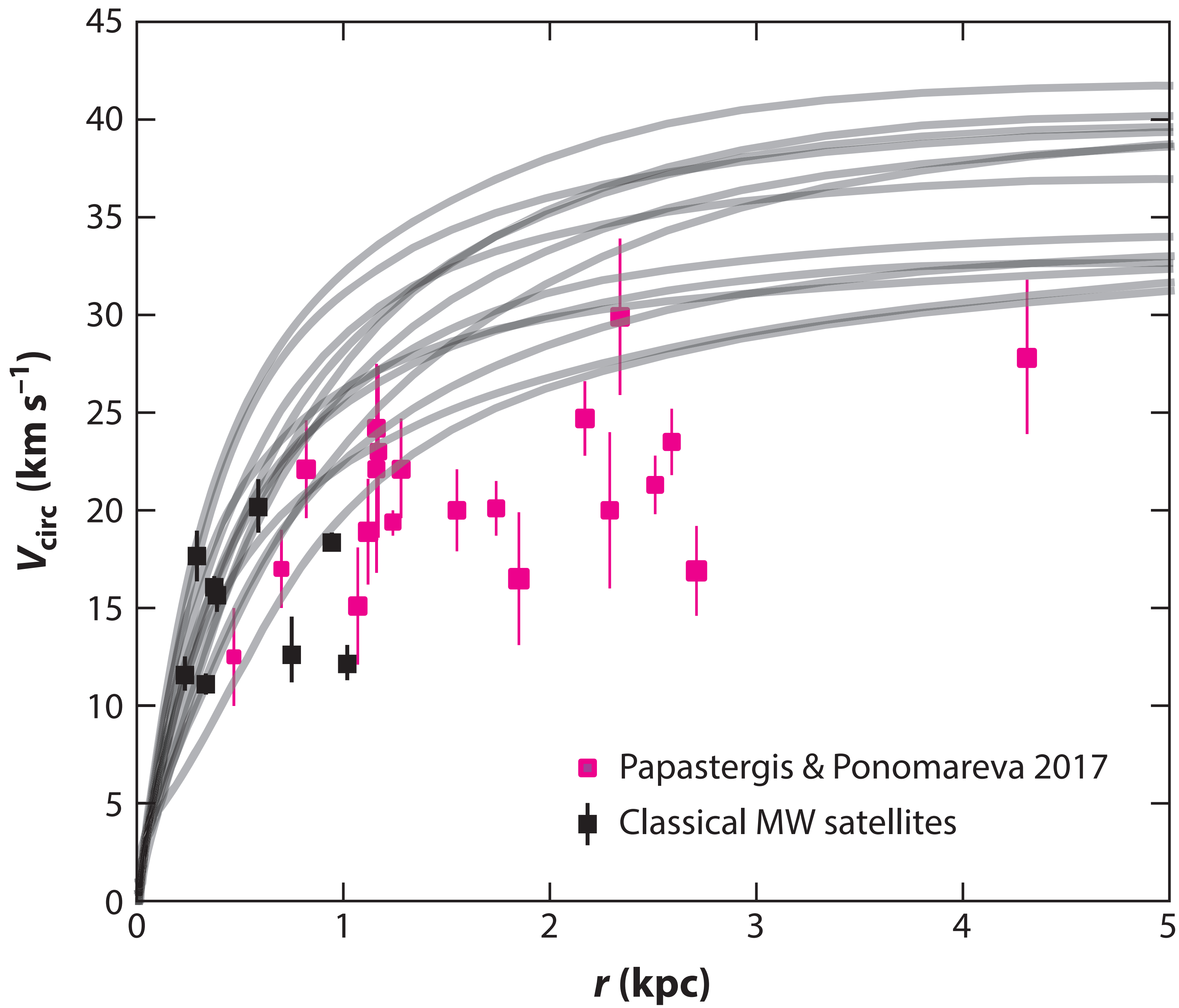
Vast spectrum of substructure, but only a handful of dwarf galaxies (***missing satellites;*** Klypin et al. 1999, Moore et al. 1999)

Cuspy density profiles, but observations indicate cored density profiles (***cusp-core problem***; Moore et al. 1994, Flores & Primack 1994)

Measurable masses of brightest dwarfs: much smaller than expected for biggest dark matter subhalos (***too big to fail***; MBK et al. 2011, 2012)

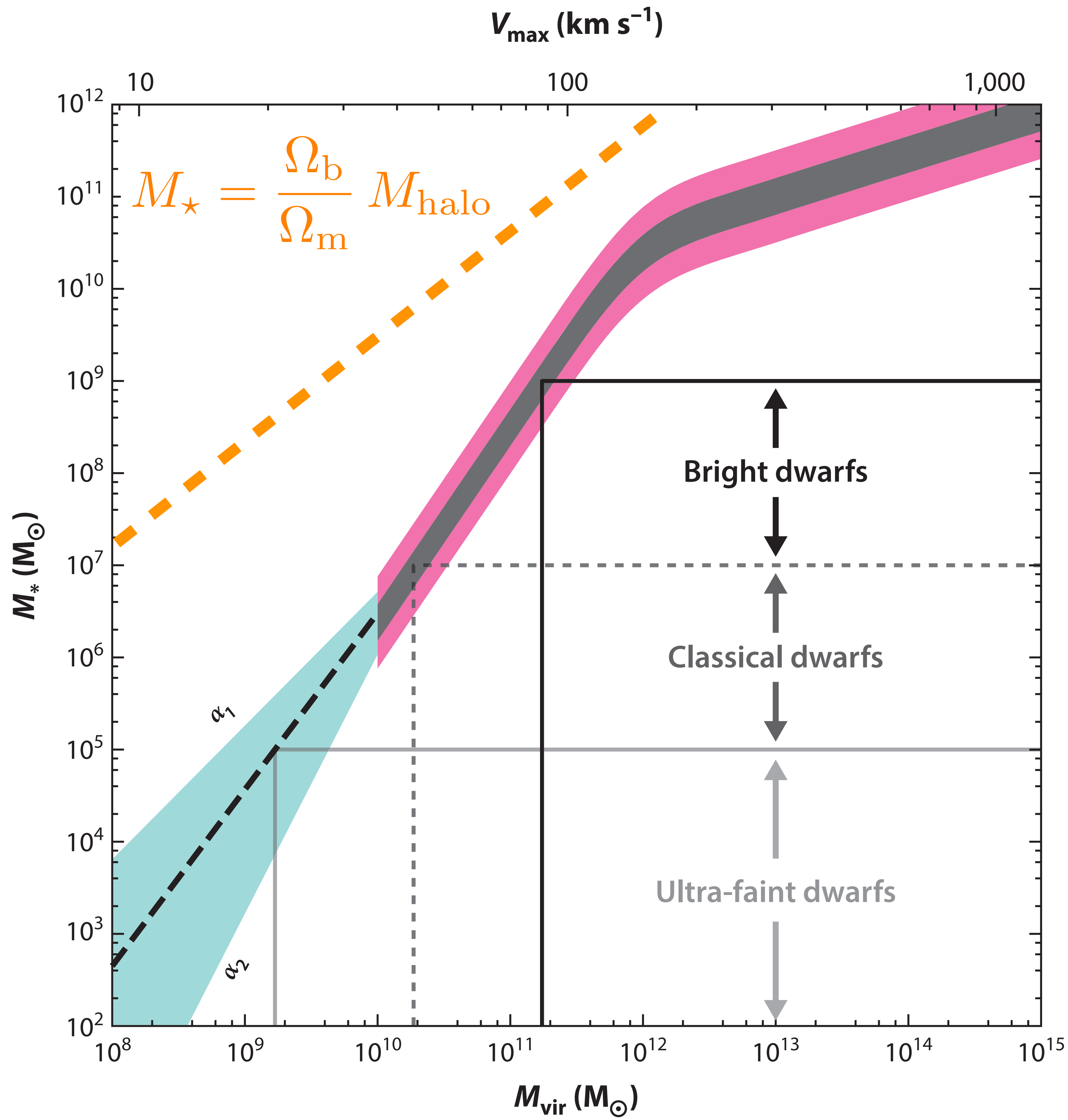
Simulated dark matter halos are generically too abundant and too dense compared to observations of low-mass galaxies

Issues persist independent of environment



Bullock & Boylan-Kolchin 2017

Why study dwarf galaxies?

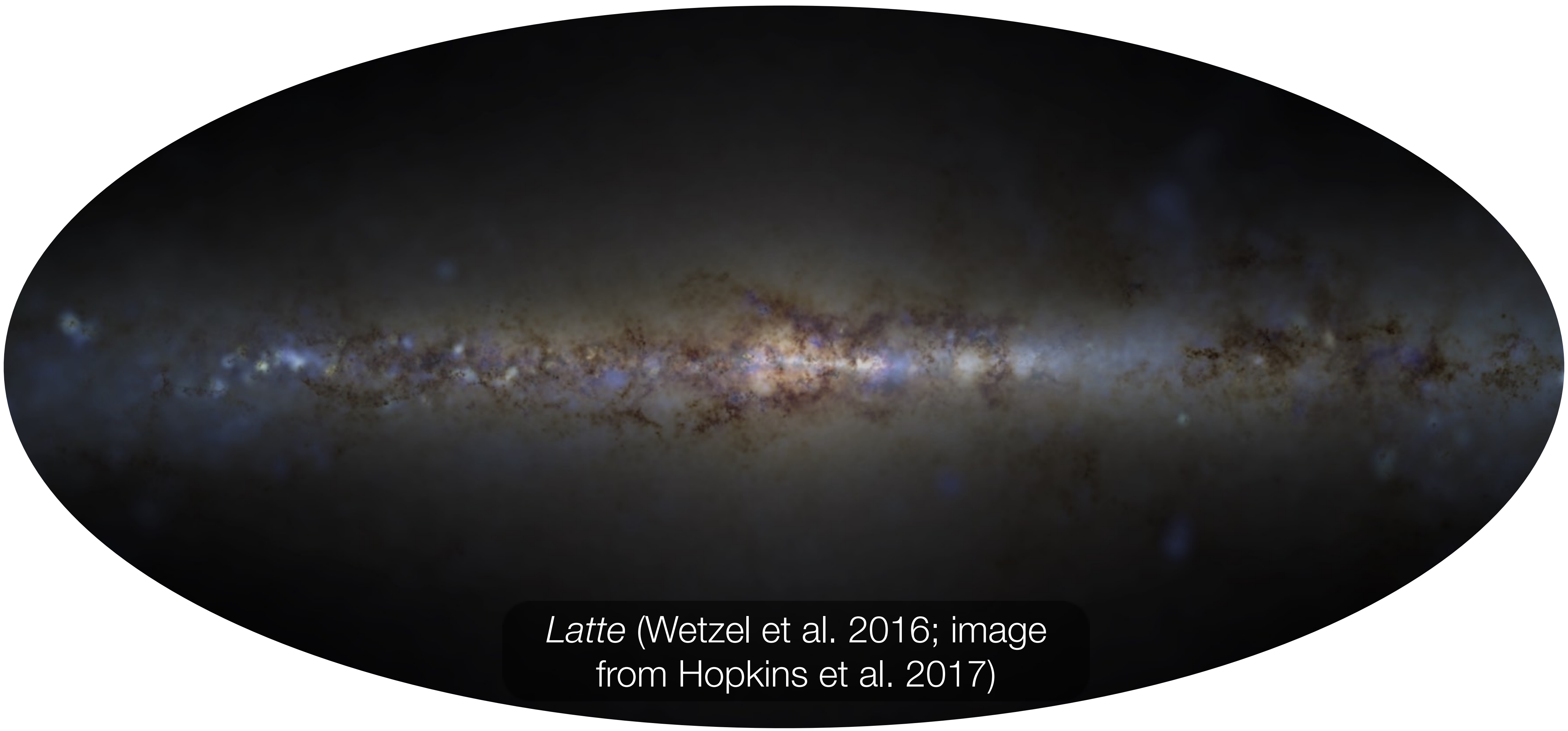


Bullock & Boylan-Kolchin 2017

“Zoom-in” simulations

State of the art for Milky Way simulations:

$$M_{\rm halo} = 10^{12}\, M_\odot$$



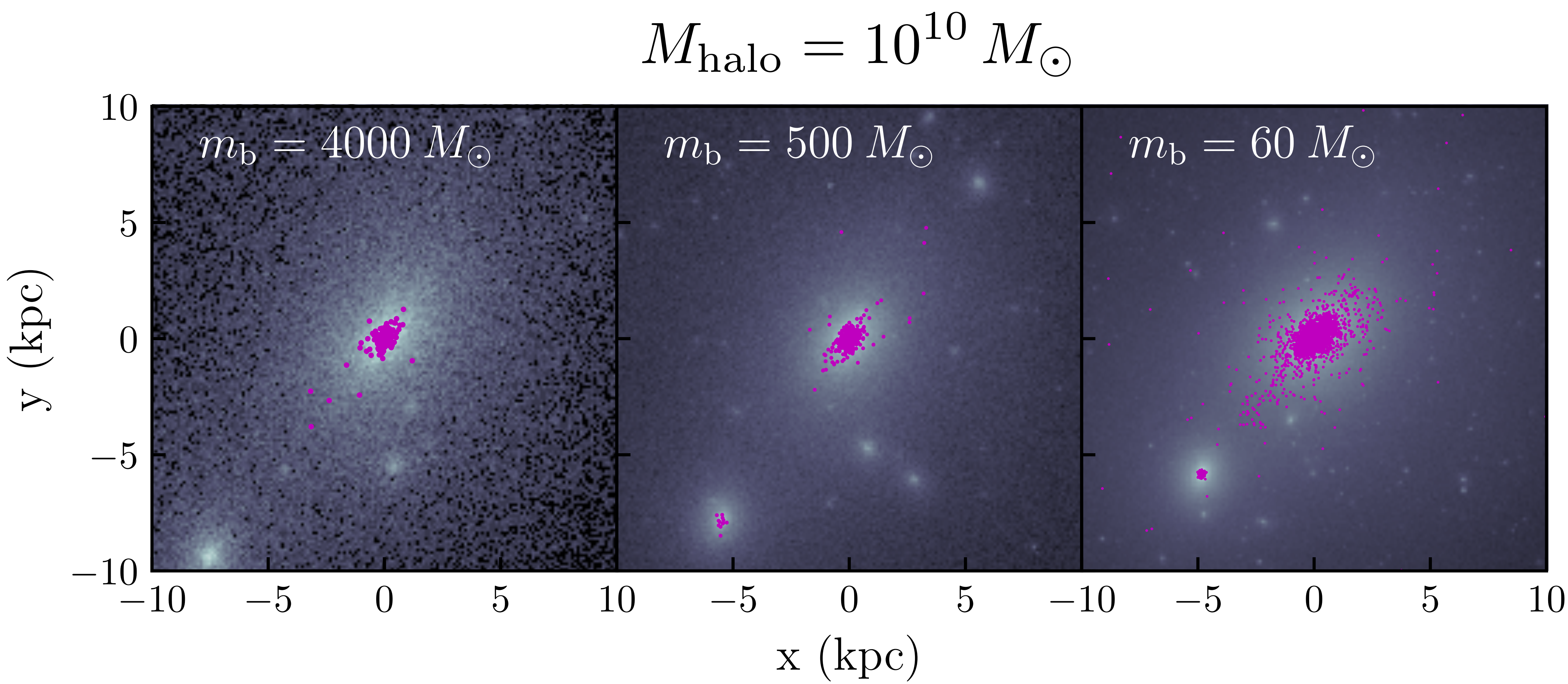
Latte (Wetzel et al. 2016; image from Hopkins et al. 2017)

Current version: m_{gas}~7000 M_{sun}
Forthcoming: m_{gas}~900 M_{sun} (1 billion particles!)

“Zoom-in” simulations

State of the art for (isolated) dwarf galaxy simulations:

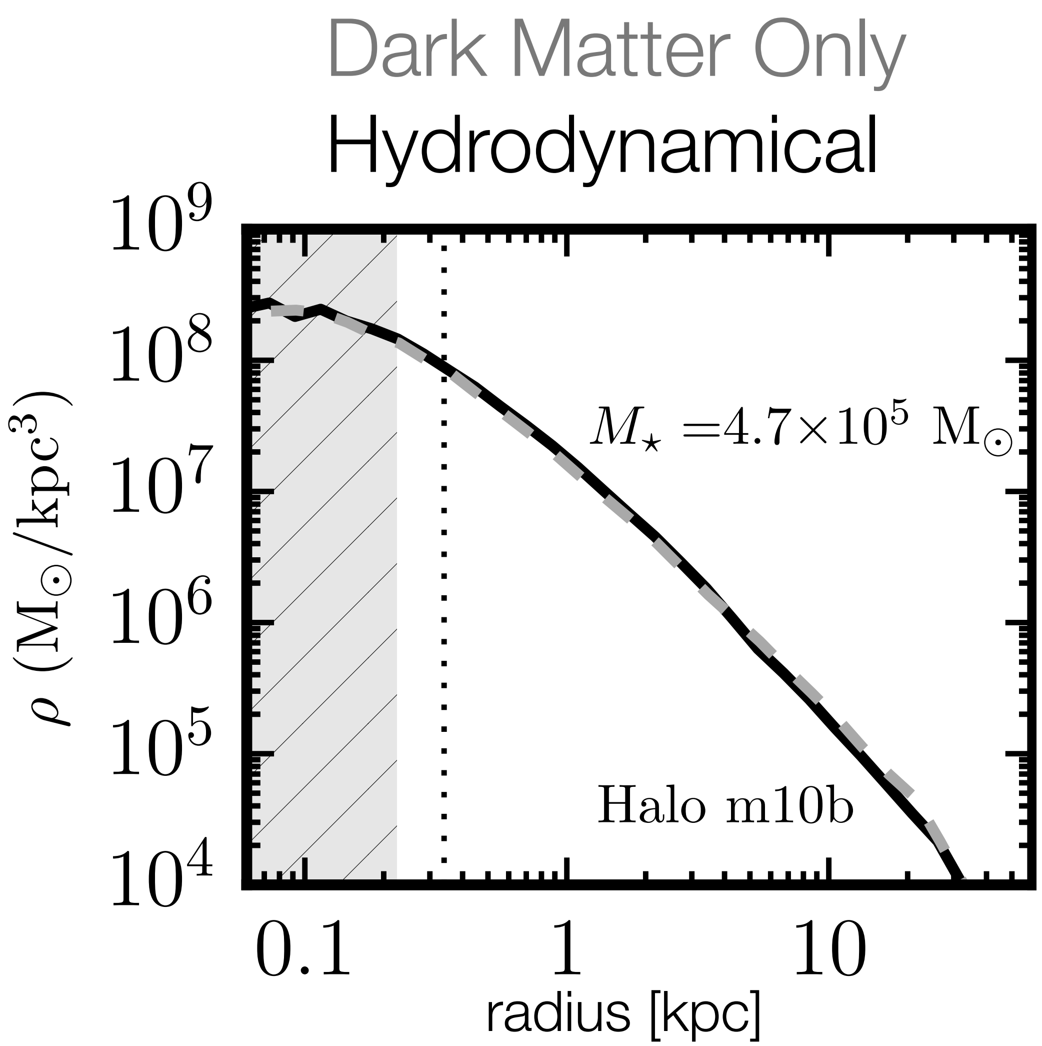
m_{gas}~500 M_{sun} (with 30-60 M_{sun} simulations imminent)



Fitts, MBK et al. 2018

Adding Baryons: zoom-in simulations

$$M_{\rm halo} = 10^{10}\, M_{\odot}$$



Fitts, MBK et al. (2017)

Adding Baryons: zoom-in simulations

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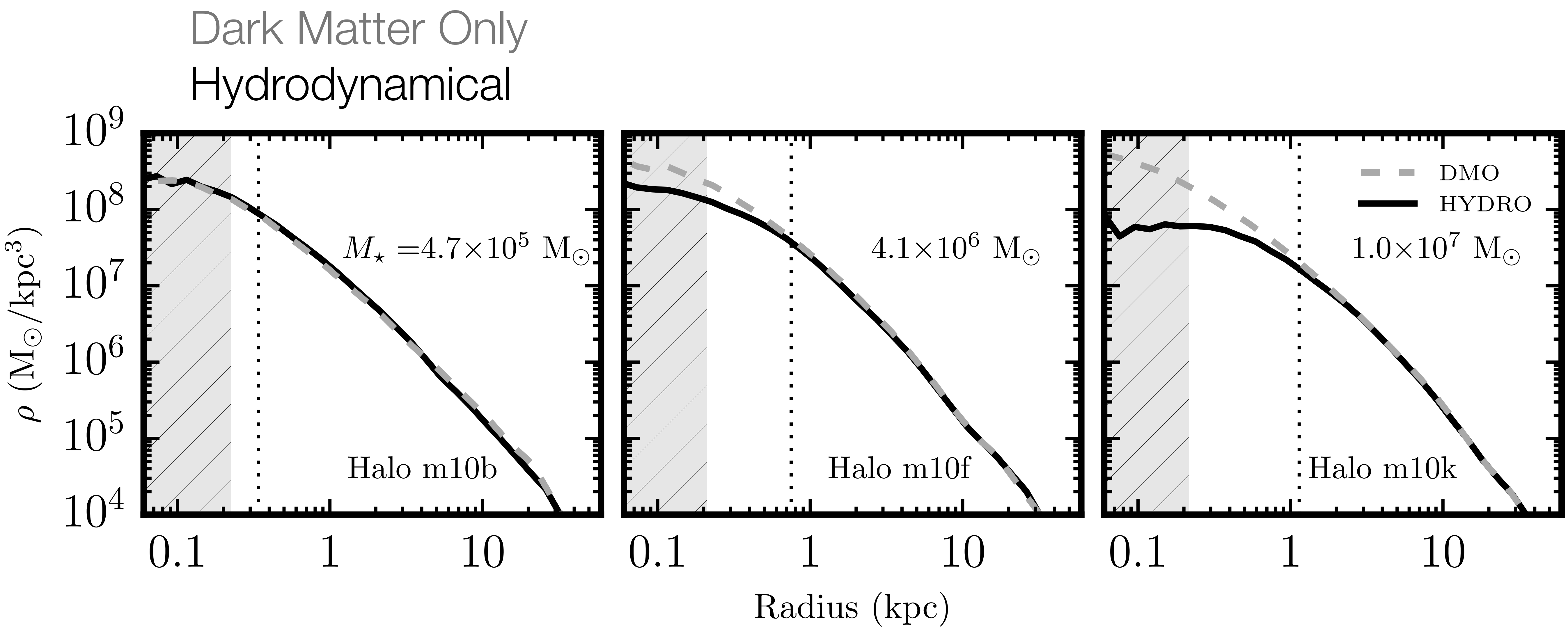
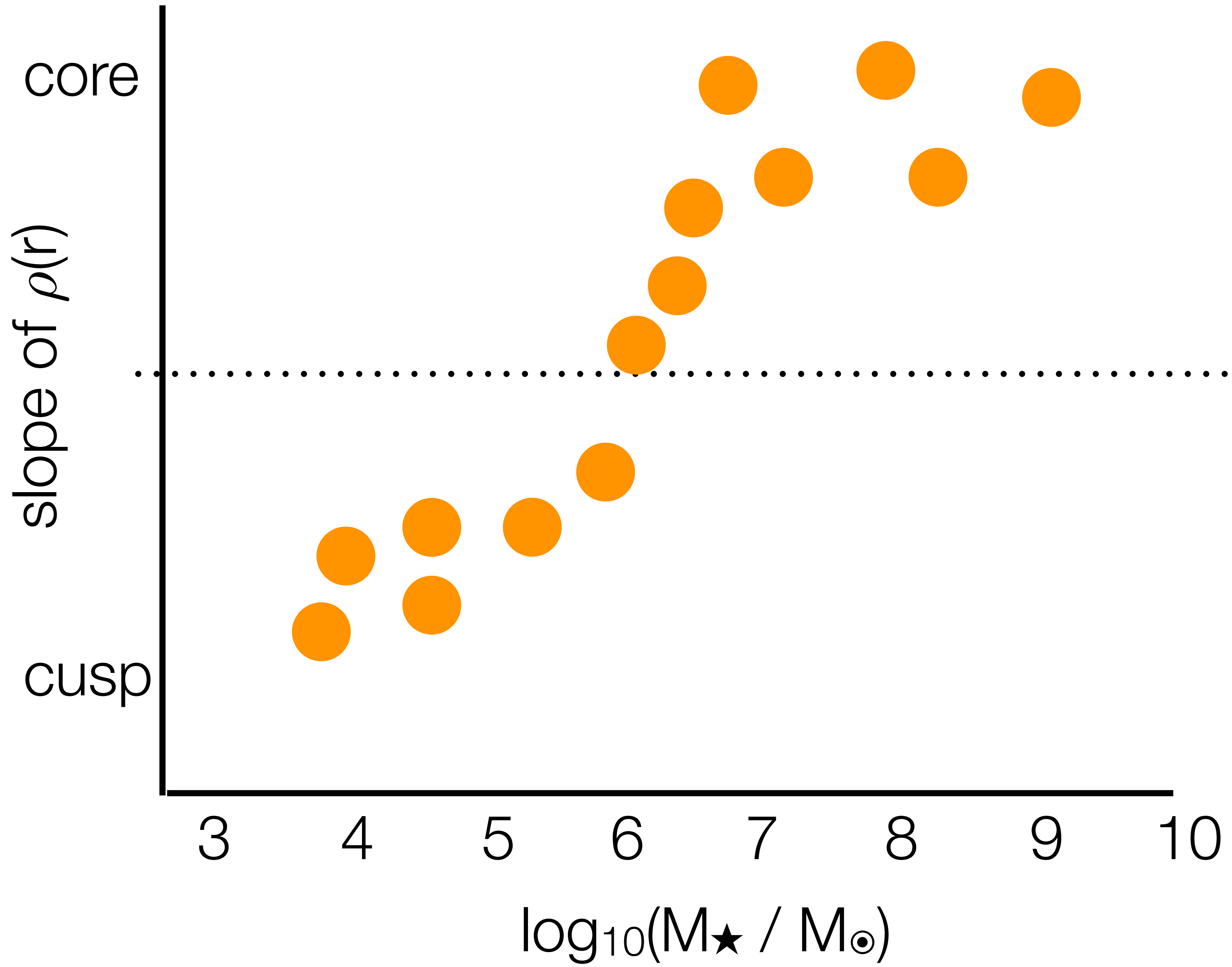


Minimum mass scale for core formation / density reduction:
$M_\star \sim 3 \times 10^6\, M_\odot$

Fitts, MBK et al. (2017)

Baryonic effects: sensitive to stellar mass



Fitts, MBK et al. 2017; see also Governato++, Brooks++, Oñorbe++, Penarrubia++, Garrison-Kimmel++, Chan ++, Di Cintio ++, Tollet ++… *For opposing opinions, see Read et al. 2016, Sawala et al. 2016*

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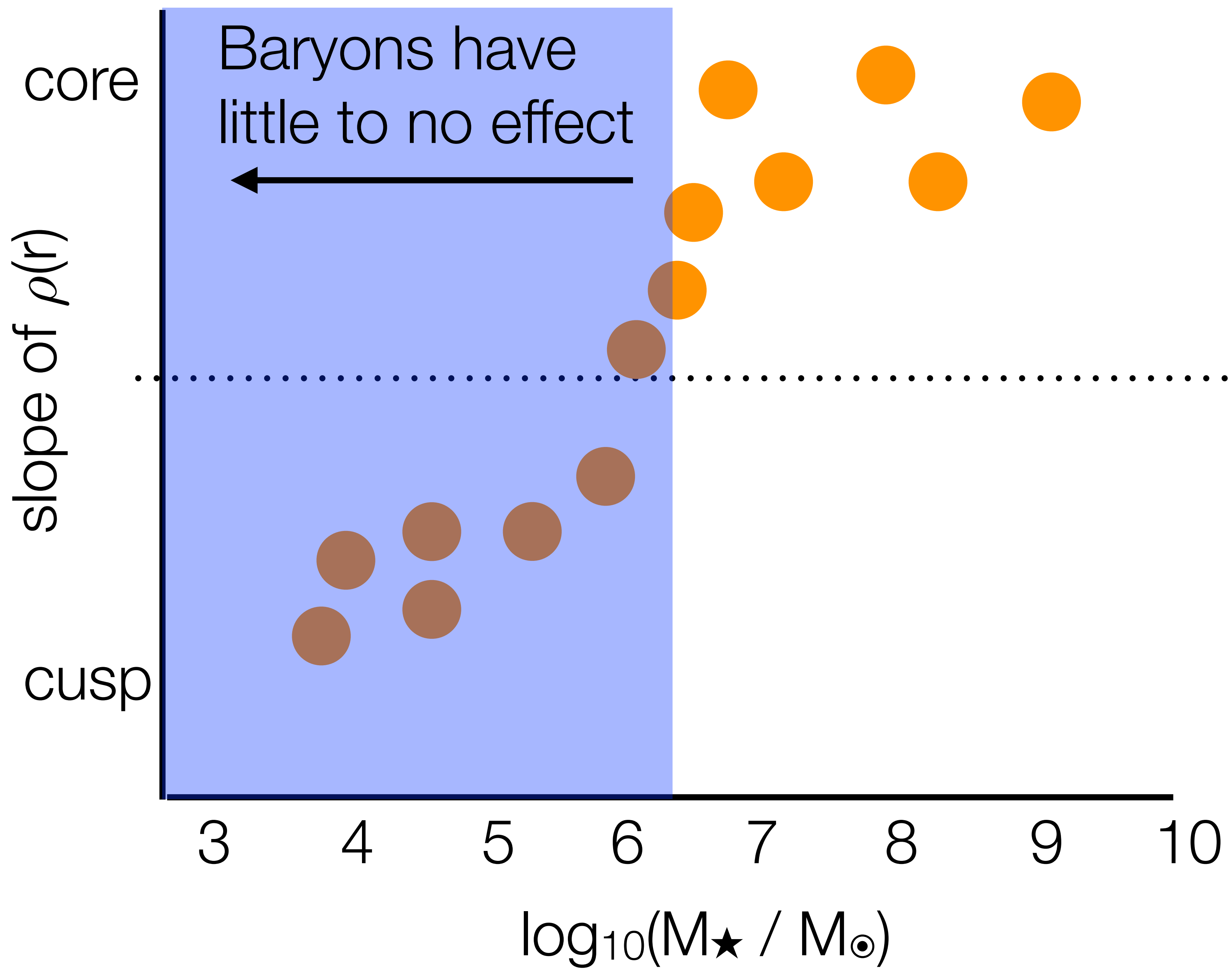

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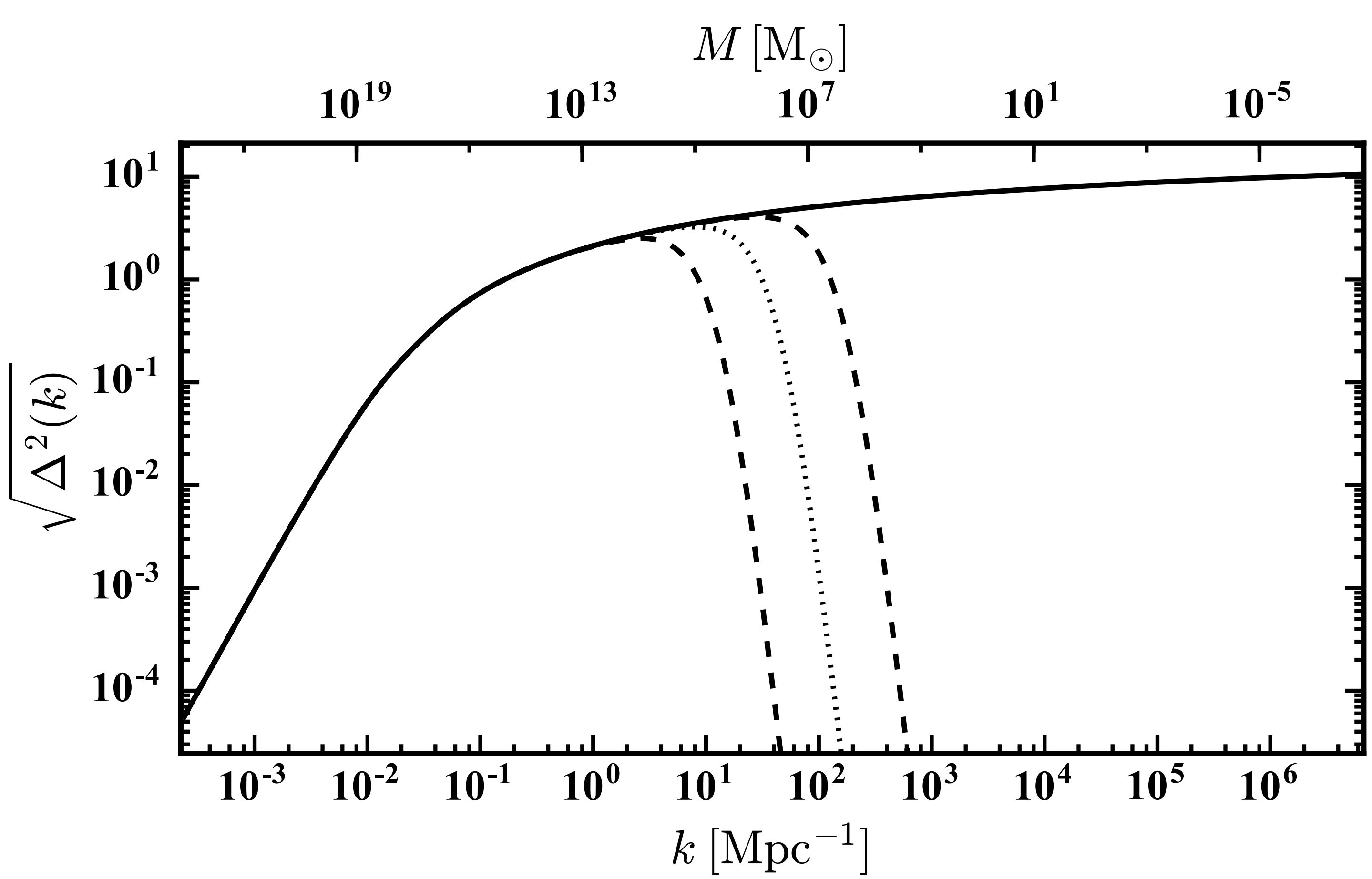
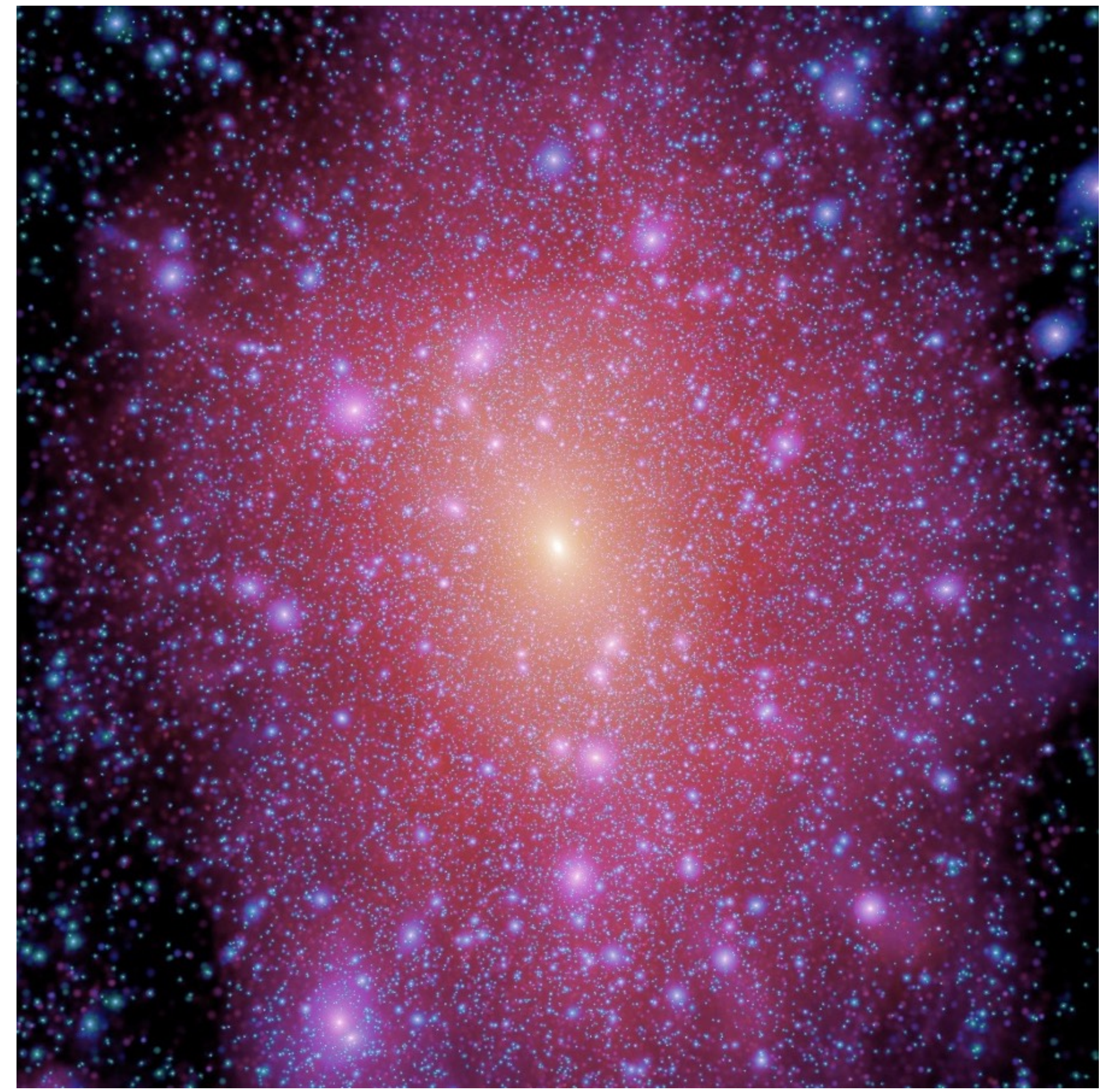
Alternative Dark Matter Models

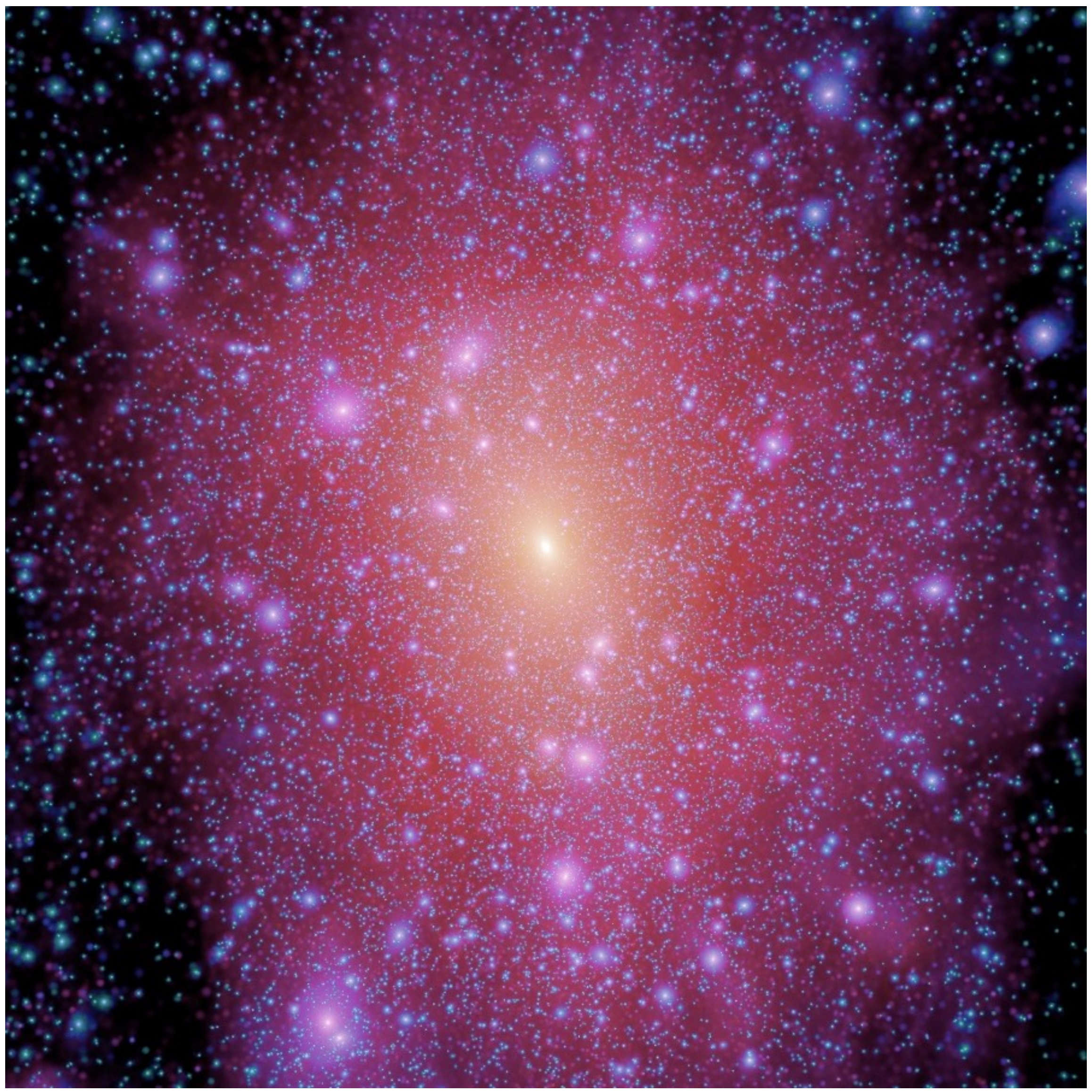
Modify *linear* physics or *non-linear* physics

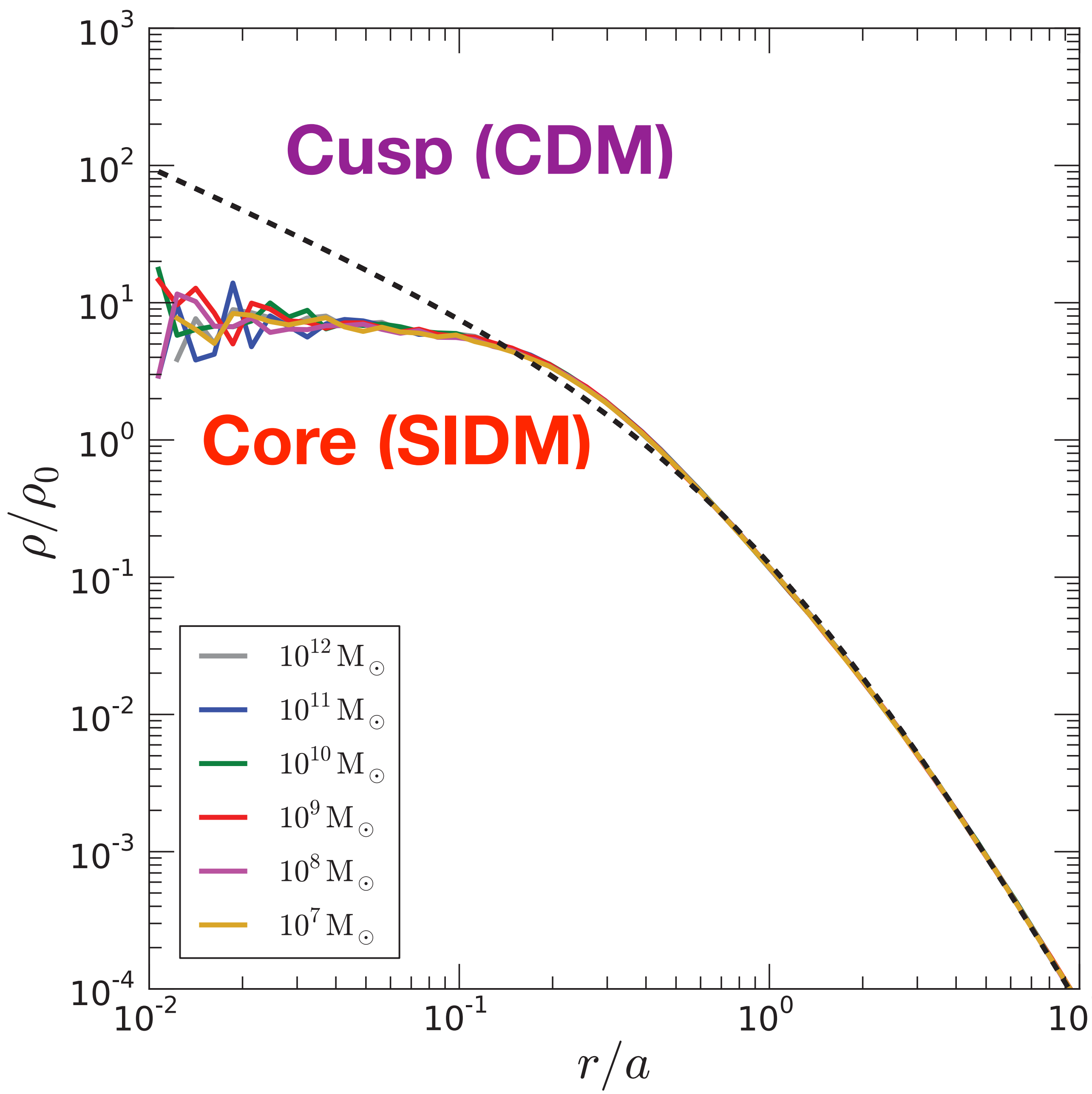




Beyond CDM: dark matter self-interactions

Modifies dark matter physics in the *non-linear* regime. SIDM exchanges energy among DM particles in center of DM halo, reduces central density:

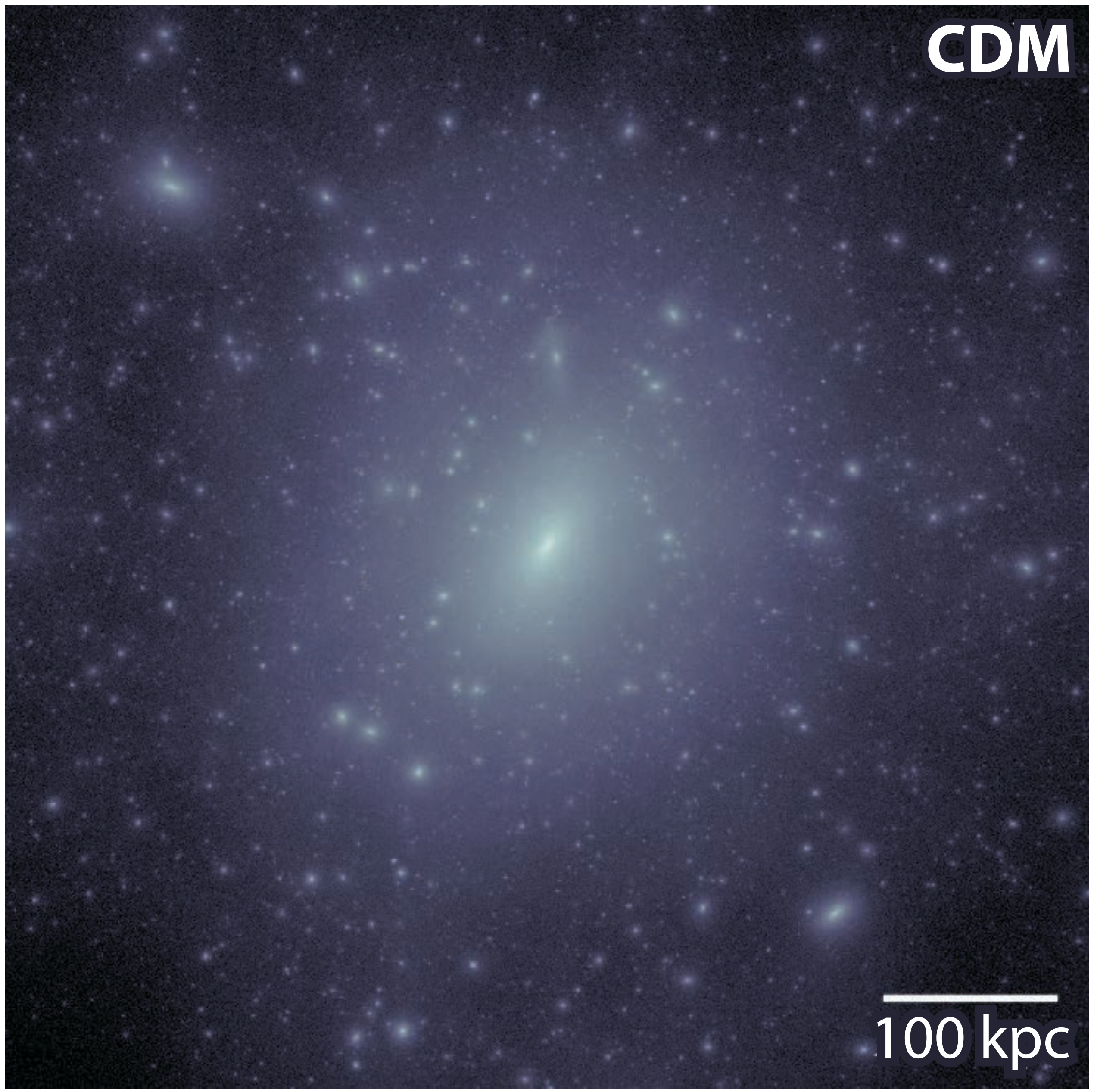




$$\frac{\sigma}{m} \lesssim 10\,\mathrm{cm}^2/\mathrm{g} \;\; (\mathrm{v} \sim 10\,\mathrm{km\,s}^{-1})$$

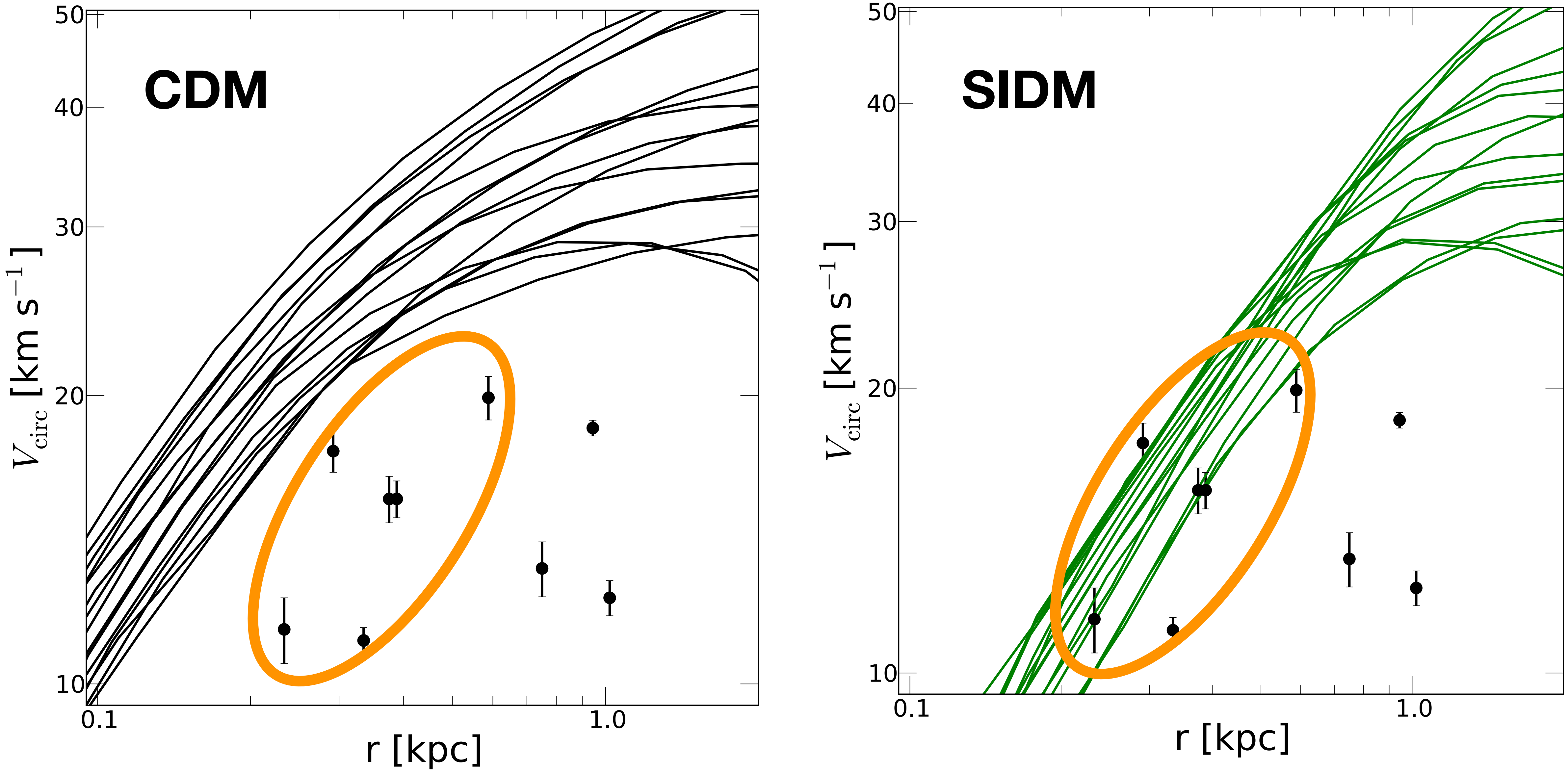
Vogelsberger et al. 2012

On large scales: ΛSIDM = ΛCDM



Simulating SIDM Models

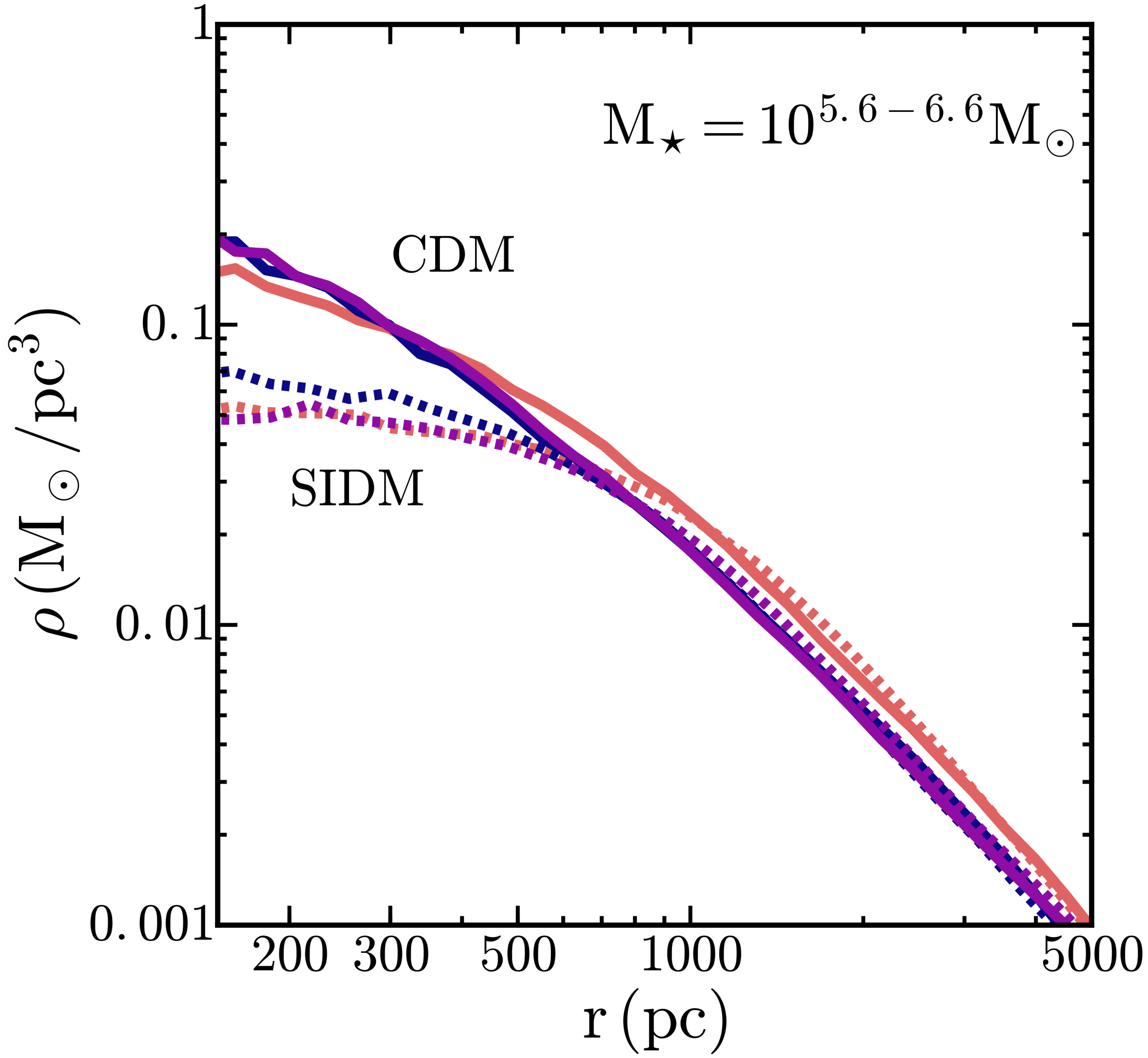
σ/m~(0.1-5) cm^2/g: creates cores in low-mass dwarfs, potentially solving multiple small-scale problems.



Vogelsberger et al. 2013

Simulations of dwarf galaxies with SIDM + baryons

low-mass dwarfs:
density **cusps** in CDM,
density **cores** in SIDM



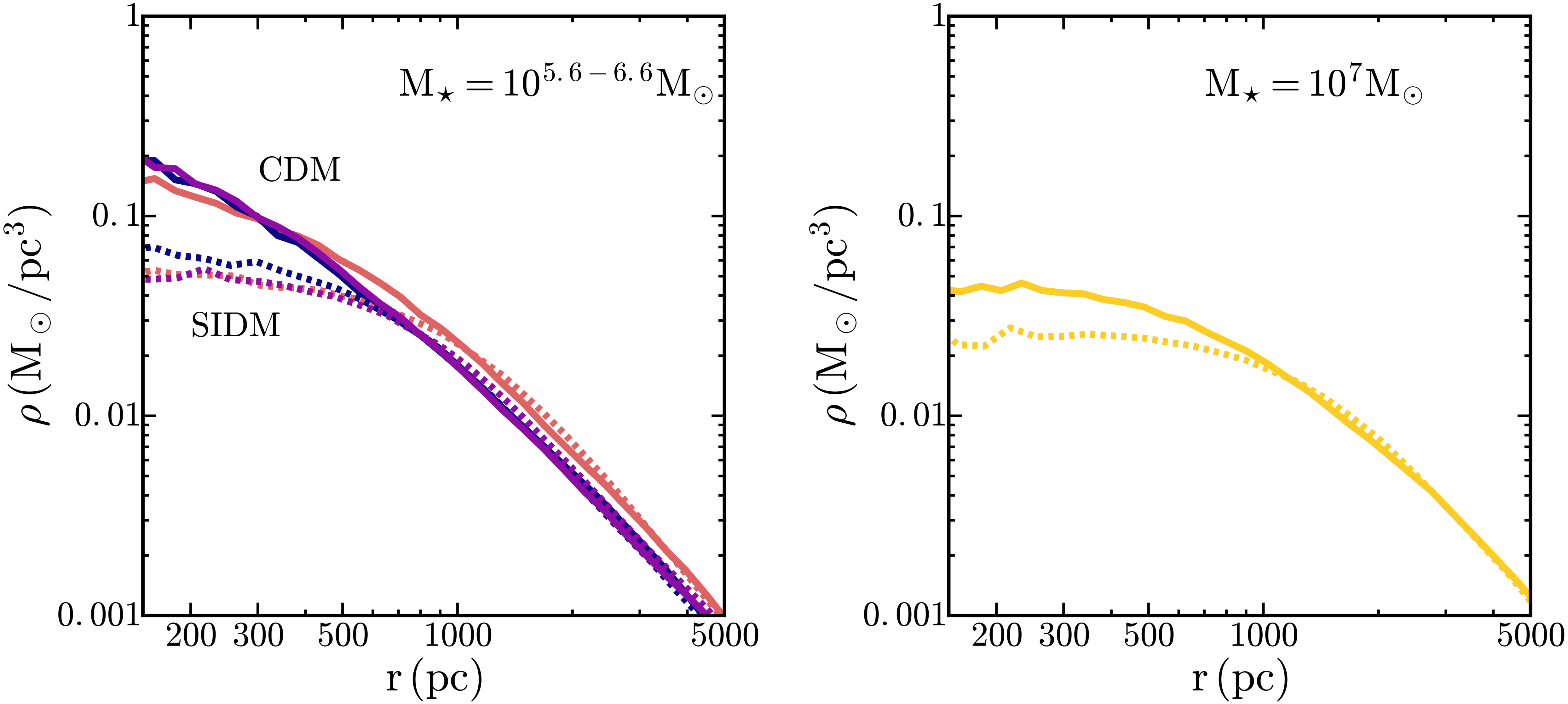
$$\frac{\sigma}{m} = 1\,\mathrm{cm}^2/\mathrm{g}$$

V. Robles et al. (incl. MBK), 2017

Simulations of dwarf galaxies with SIDM + baryons

low-mass dwarfs:
density **cusps** in CDM,
density **cores** in SIDM

higher-mass dwarfs:
density **cores** in both
CDM and SIDM



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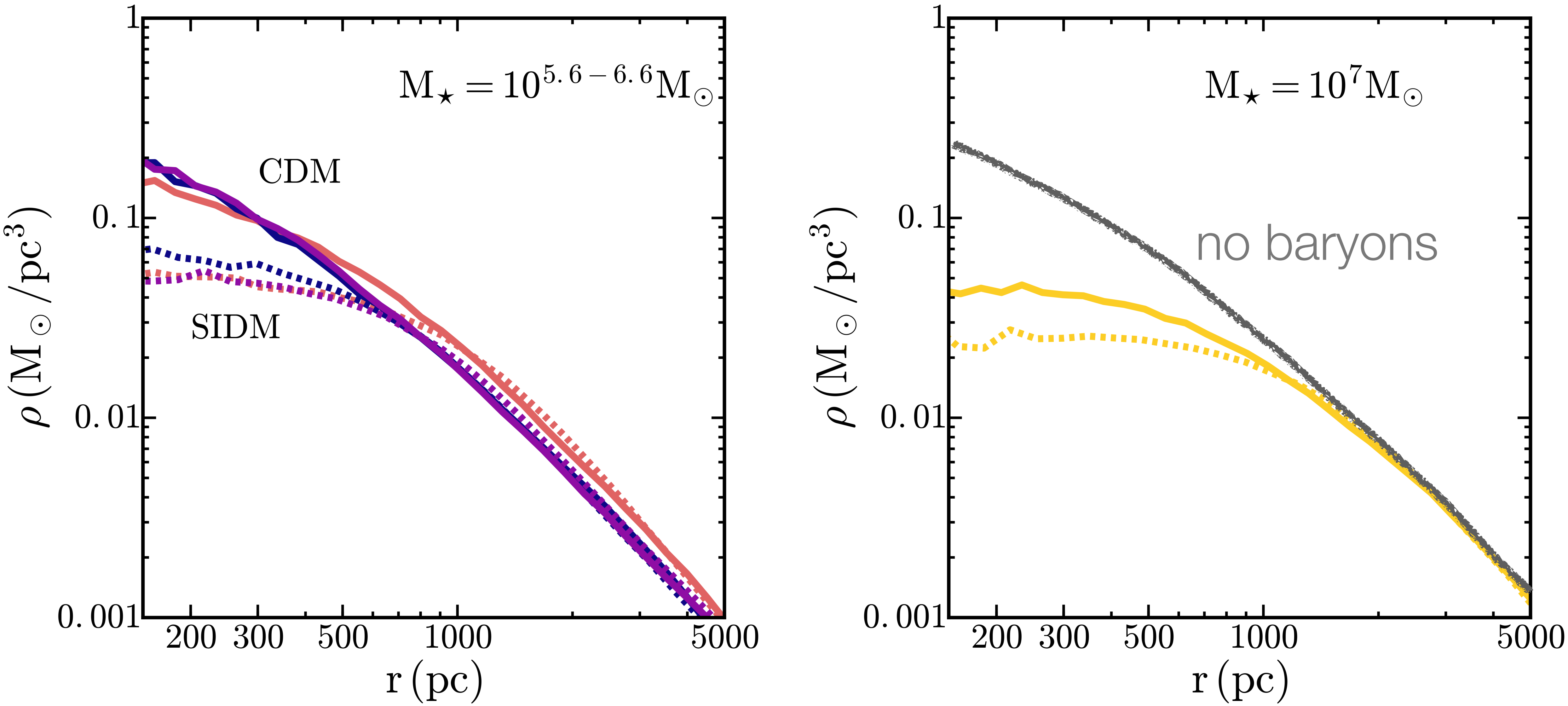
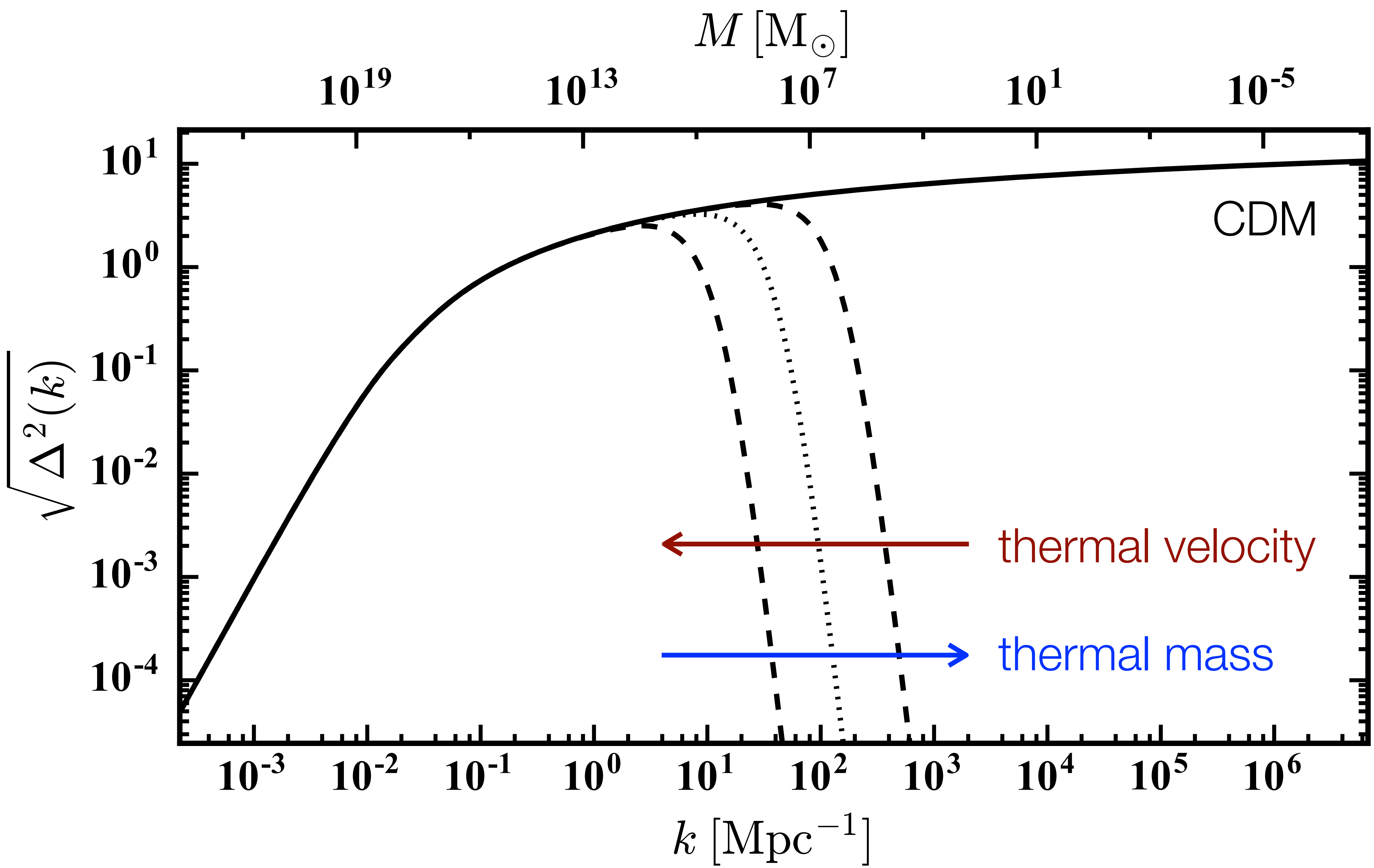


$$\frac{\sigma}{m} = 1\,\mathrm{cm}^2/\mathrm{g}$$

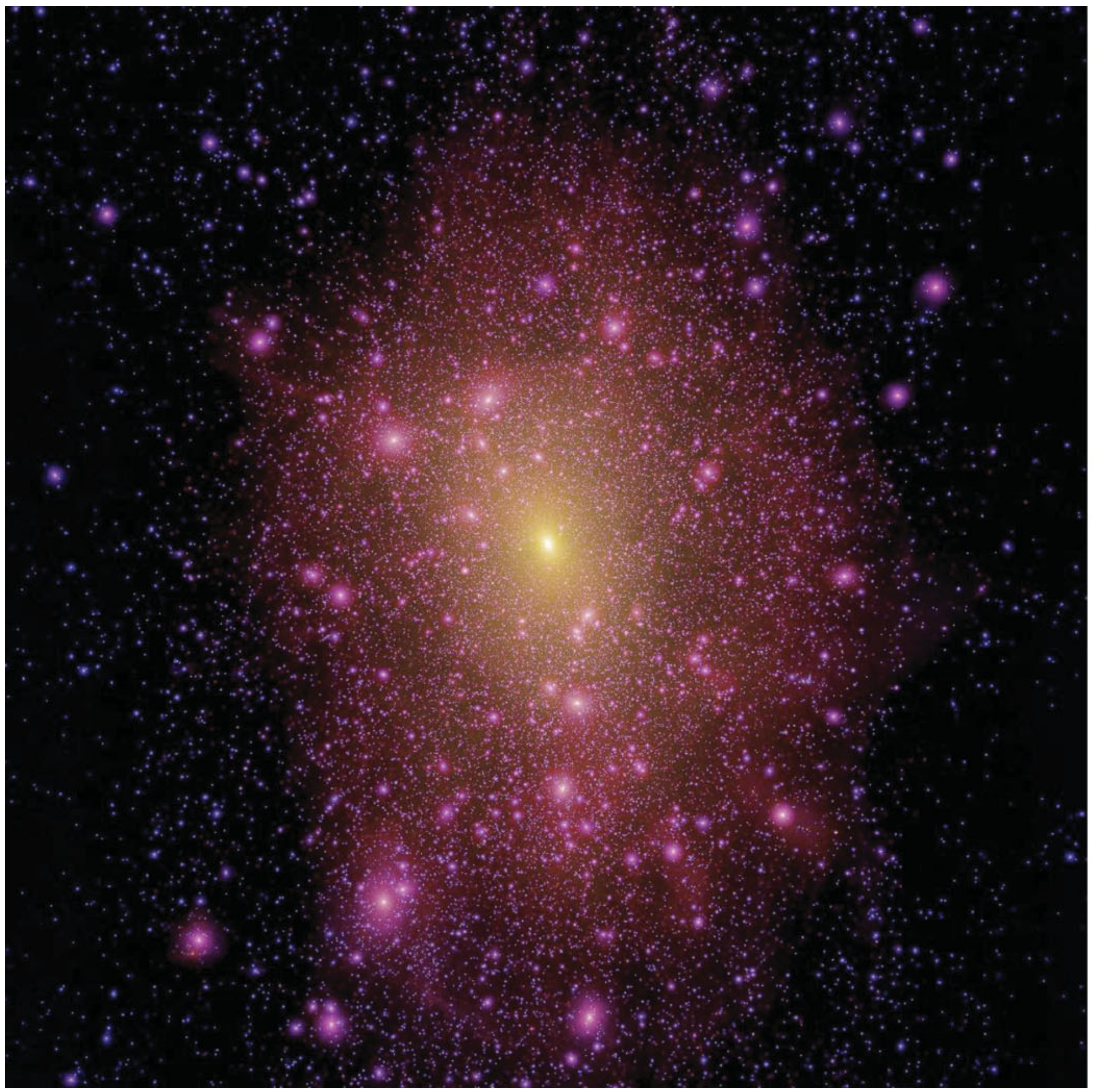
V. Robles et al. (incl. MBK), 2017

What if we modify linear physics?

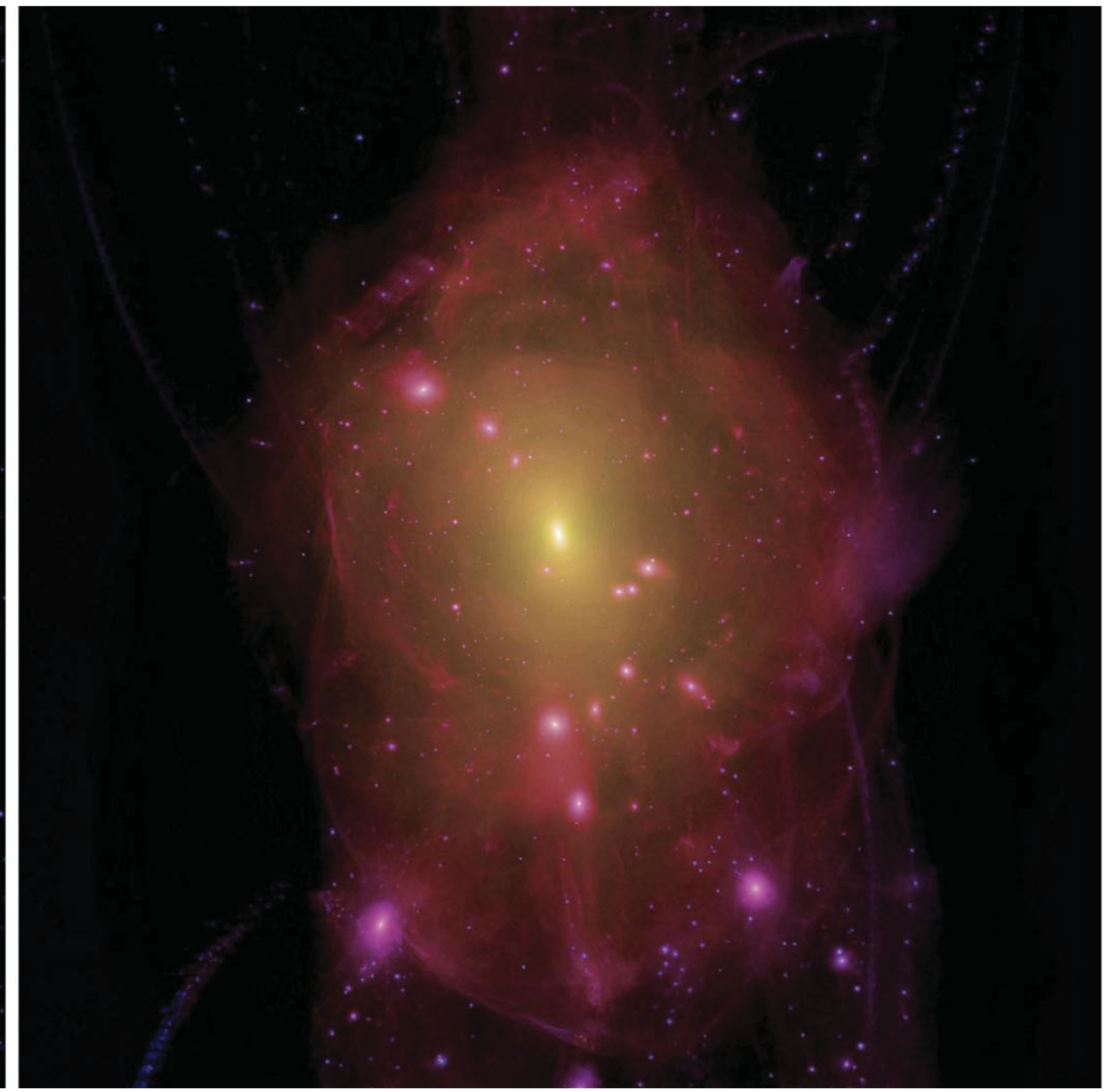


Simulating Warm Dark Matter

CDM

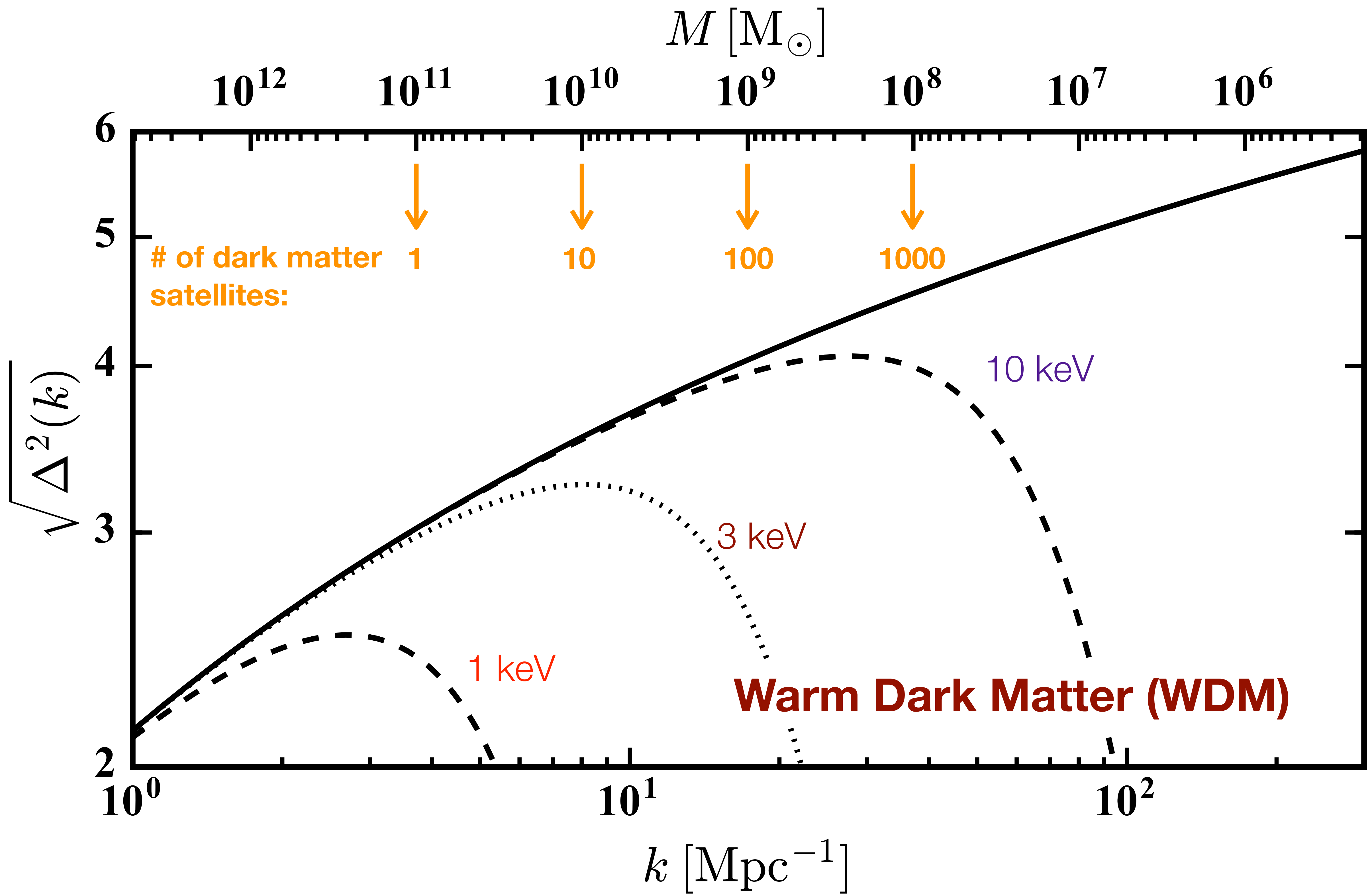


WDM (~2 keV)



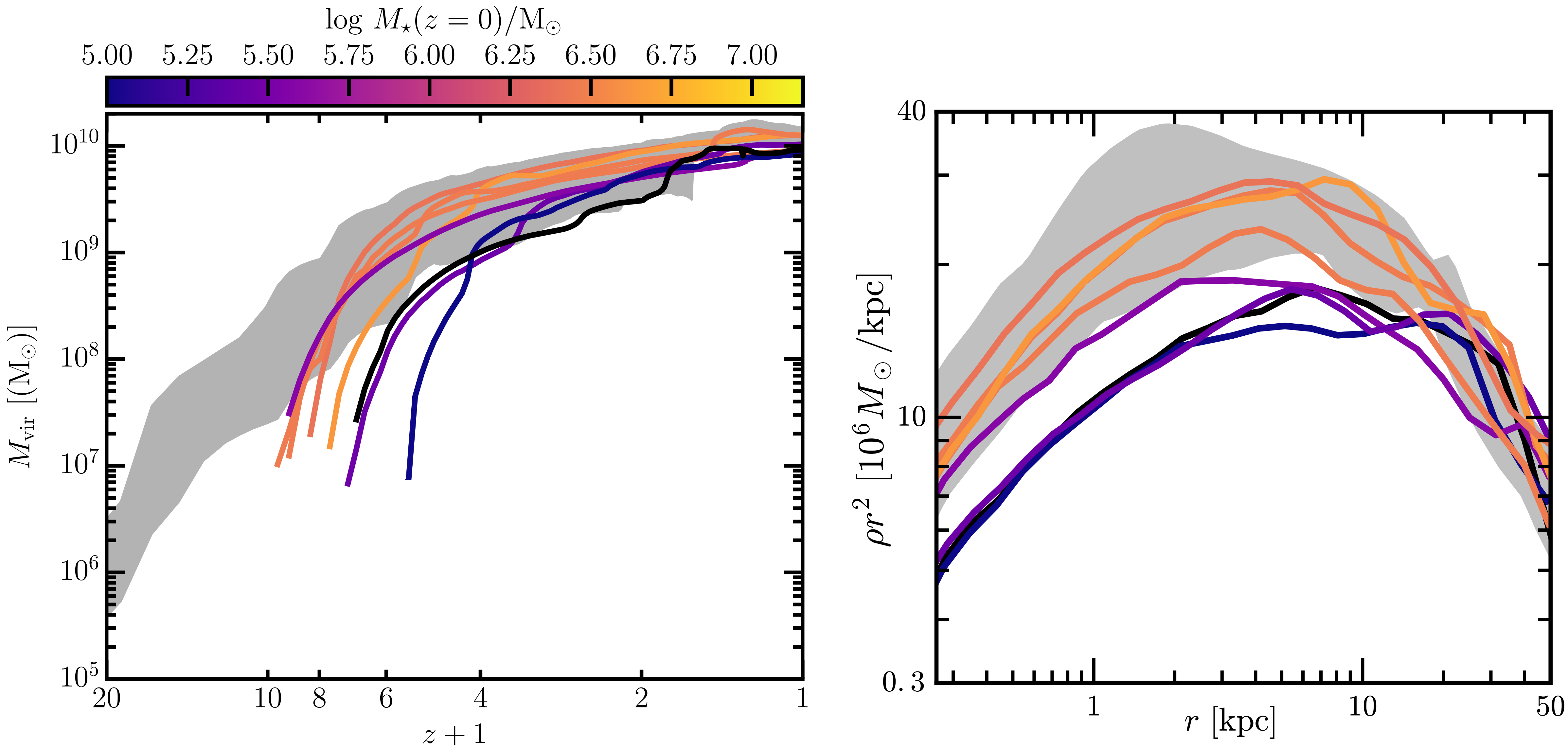
Lovell et al. 2012

Galaxy counts: strong constraints on WDM



Bullock & Boylan-Kolchin 2017

Dwarf galaxy formation in WDM

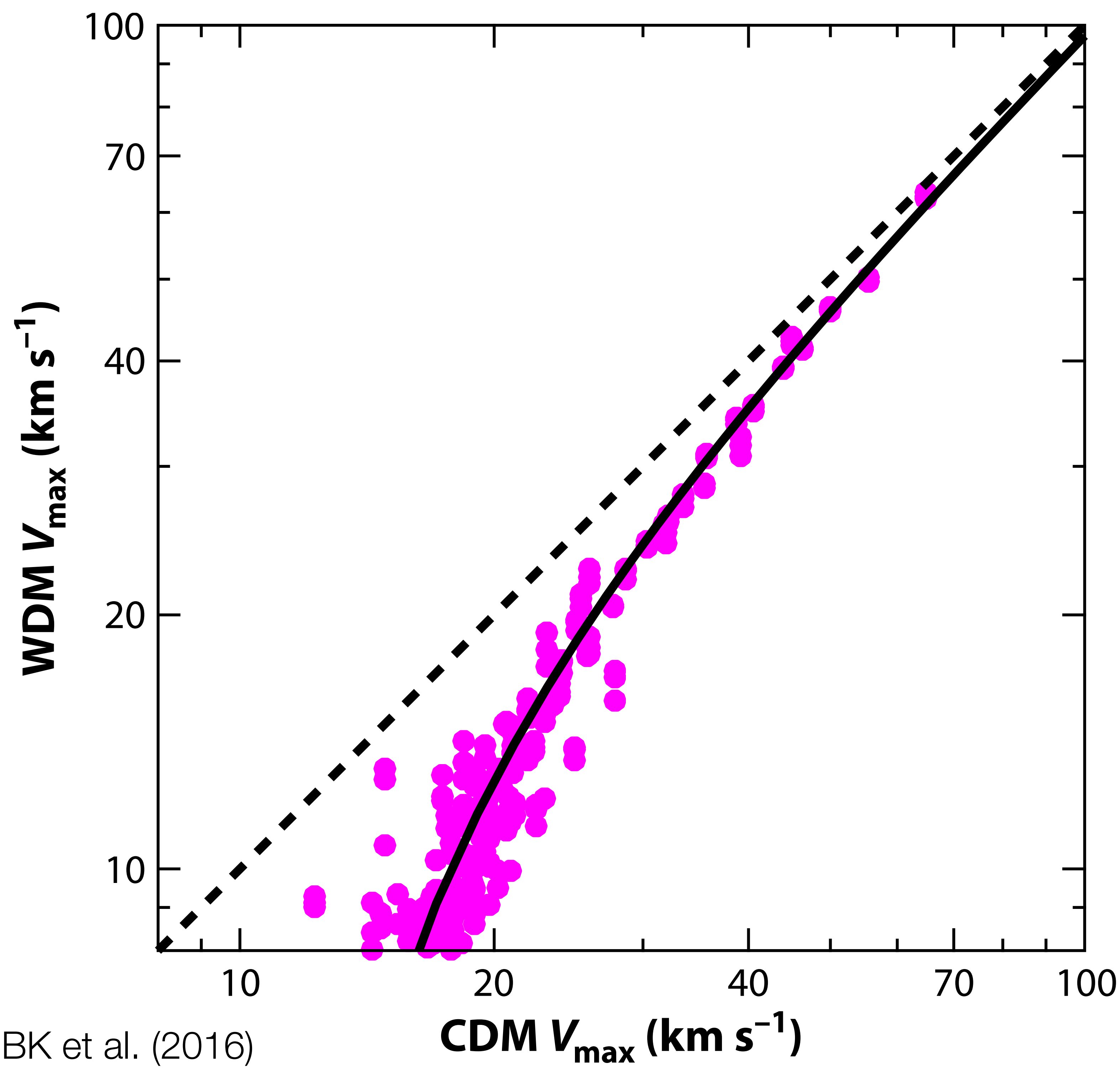


WDM halo form **later** (left) and are therefore **less dense** (right)

Bozek, Fitts, MBK et al. (in prep)

WDM halos: less centrally concentrated

Lower central concentration = reduced M(r) & lower V_{max}

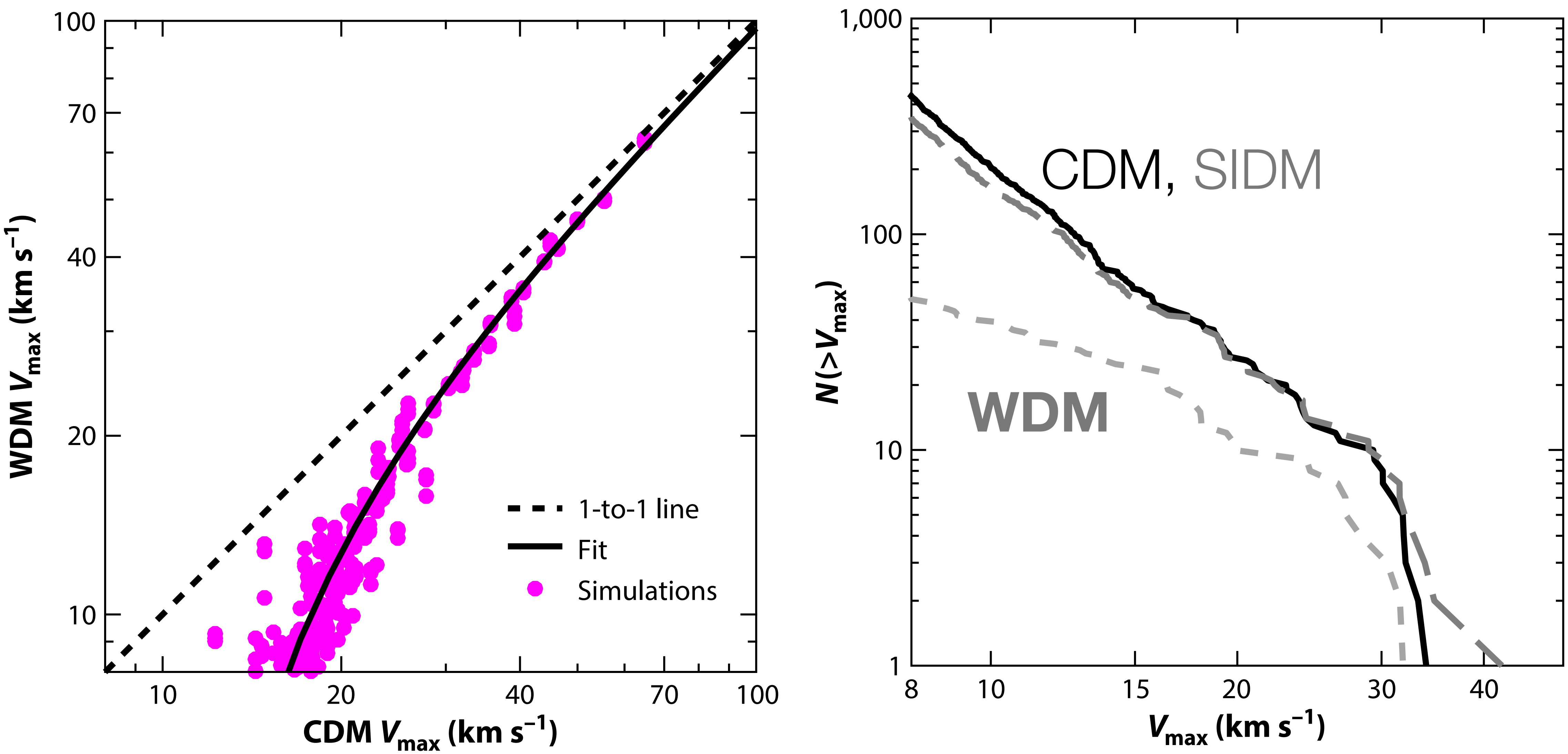


High-mass halos: unmodified

Low-mass halos: reduced central mass (or V_{max})

B. Bozek, MBK et al. (2016)

Abundances in CDM vs WDM vs SIDM



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

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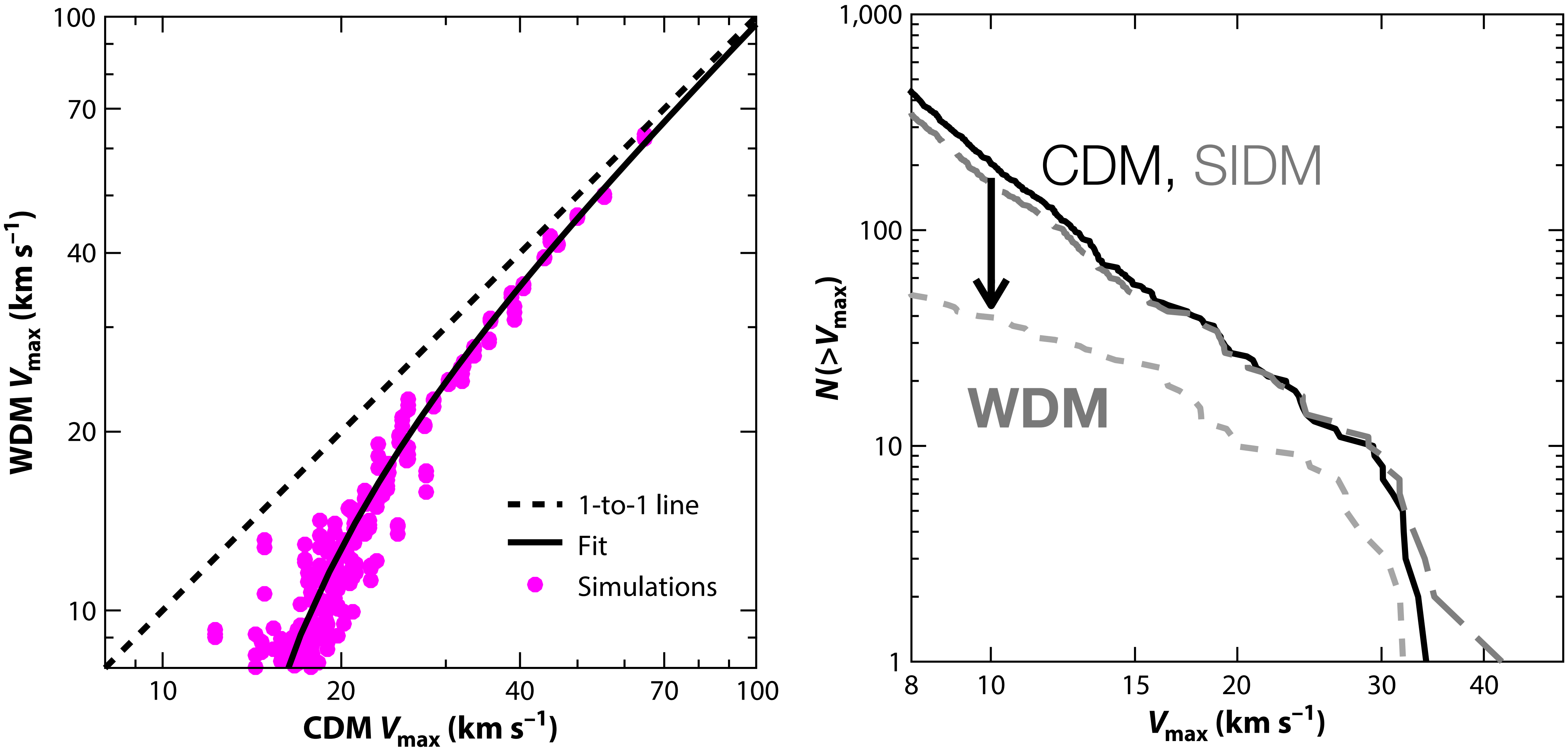

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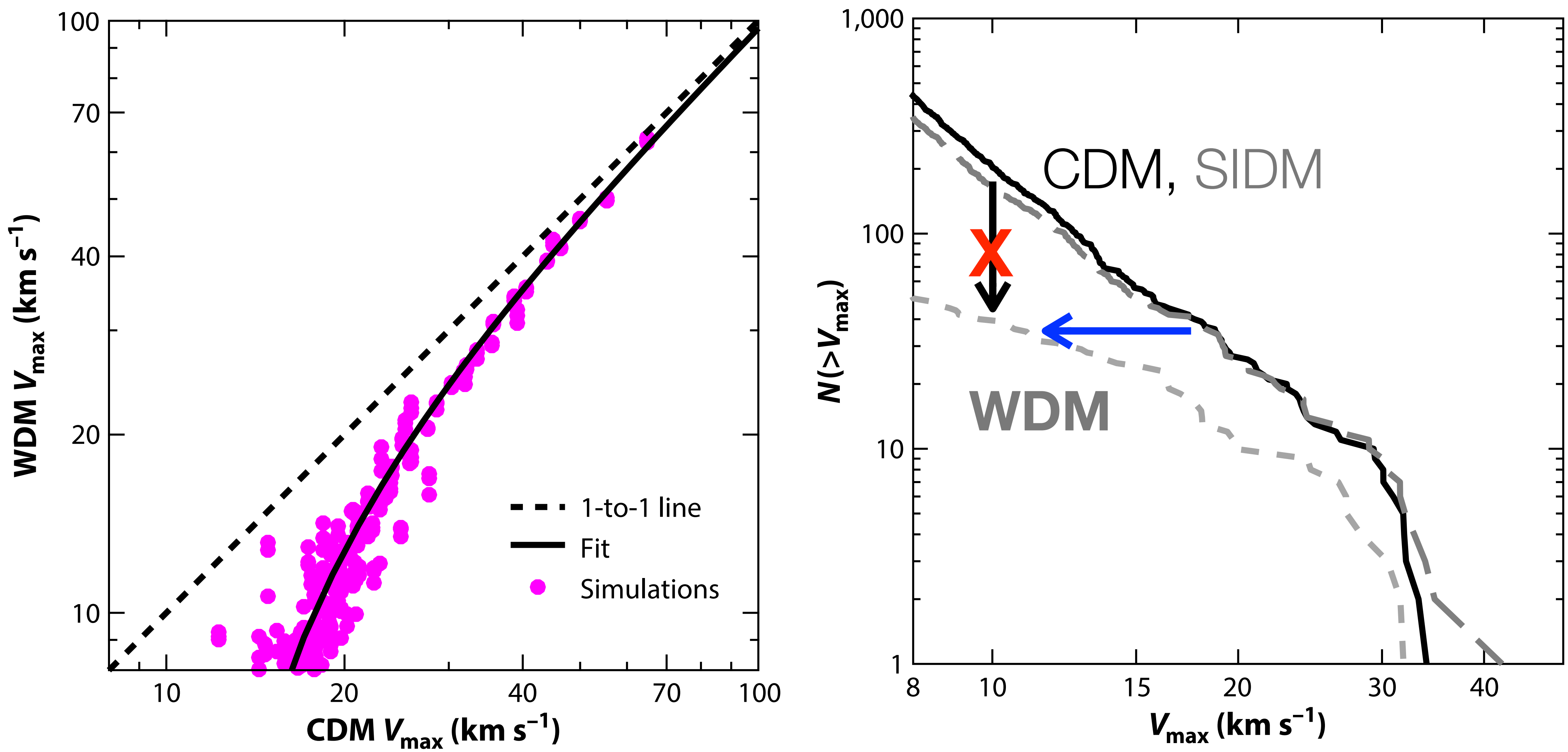
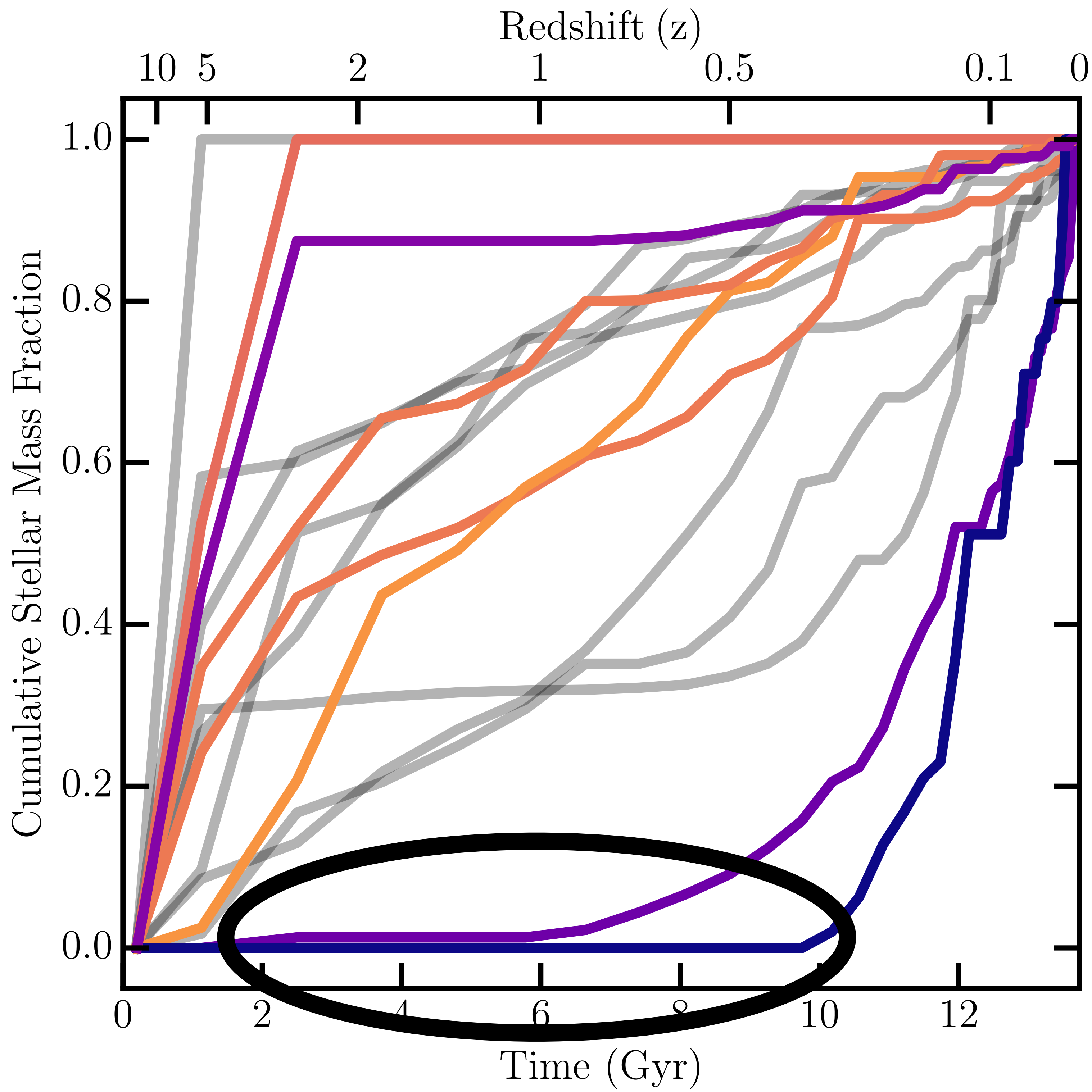


Bullock & Boylan-Kolchin 2017;
Bozek, Boylan-Kolchin, ++ 2016

Simulated star formation histories of dwarf galaxies



CDM galaxies

WDM galaxies

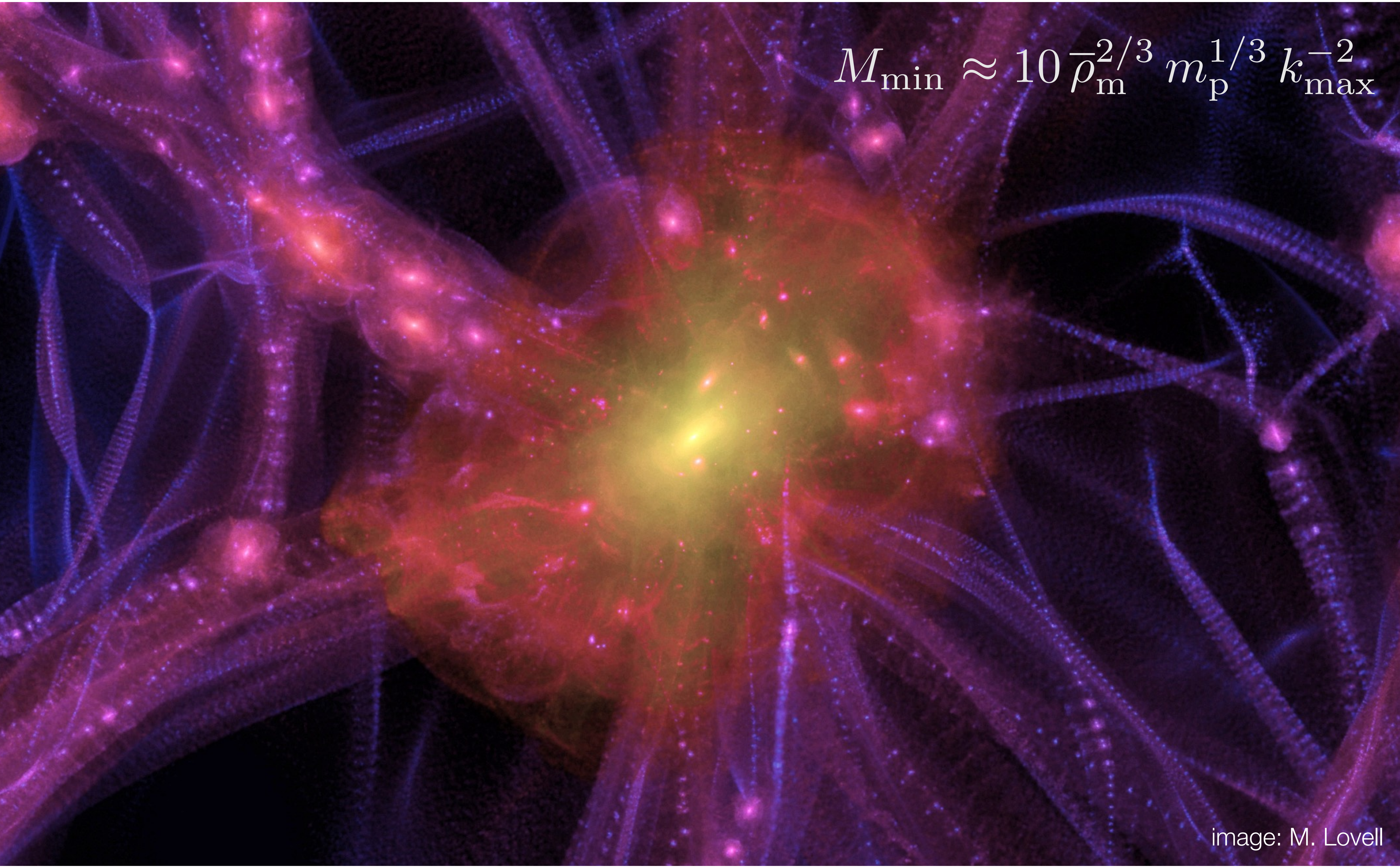
Unique to WDM;
testable via LSST + *JWST*

Bozek, Fitts, MBK et al. 2018 (in prep.)

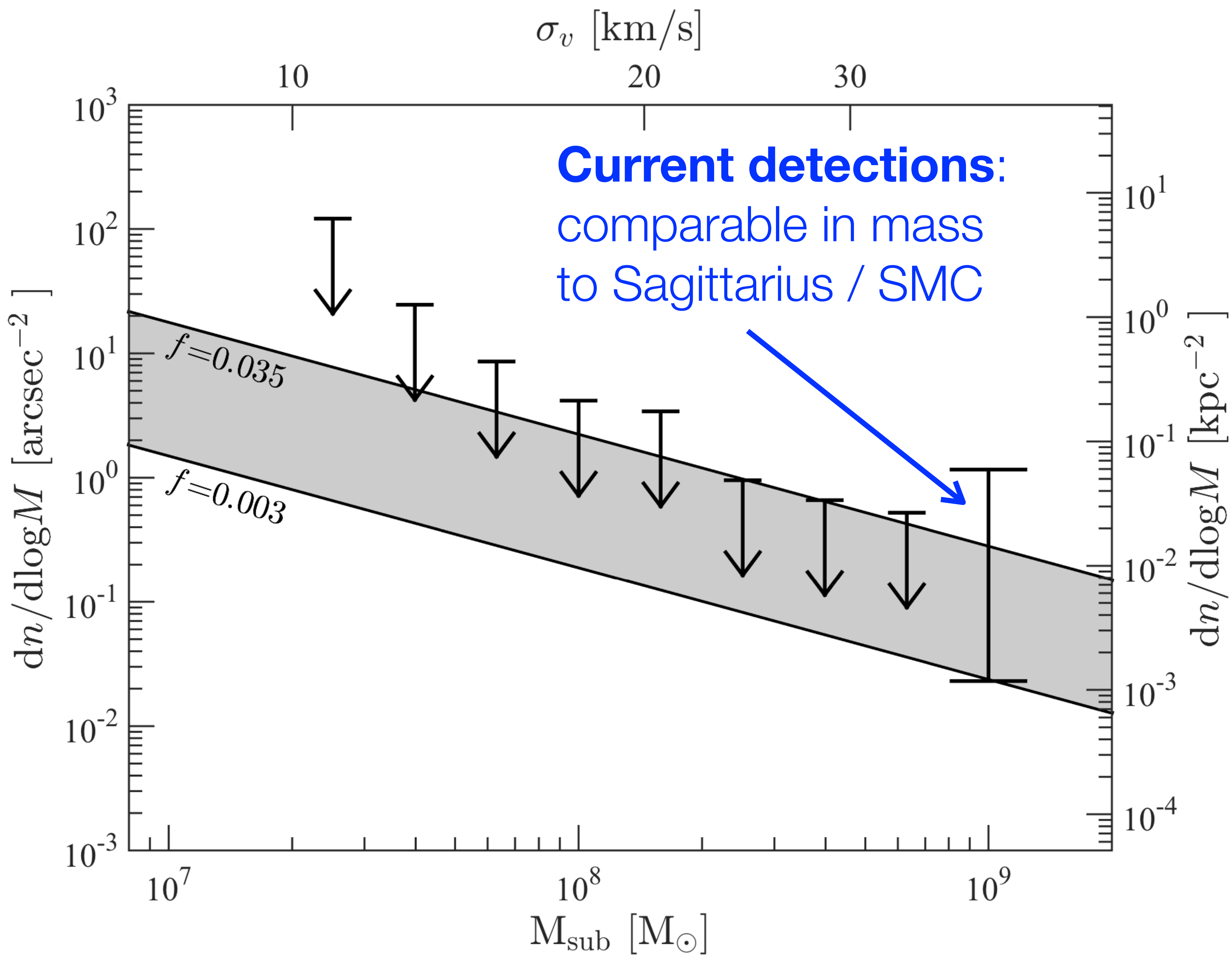
Summary

- 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*.
- As a result: resurgence of interest in Warm, Self-Interacting Dark Matter. **Allowed parameter space for both WDM and SIDM models is relatively narrow, providing encouraging targets.** Understanding baryonic physics is crucially important
- $M_{vir}=10^{10}\ M_{\odot}$ ($M_{\star} \sim 3\times10^{6}\ M_{\odot}$) is a crucial scale for galaxy formation and testing ΛCDM
- If ***cores*** are robust in generic for low-mass galaxies — or if gravitational lensing shows there are **no** low-mass dark subhalos — we will need to move beyond ΛCDM

Simulating Warm Dark Matter

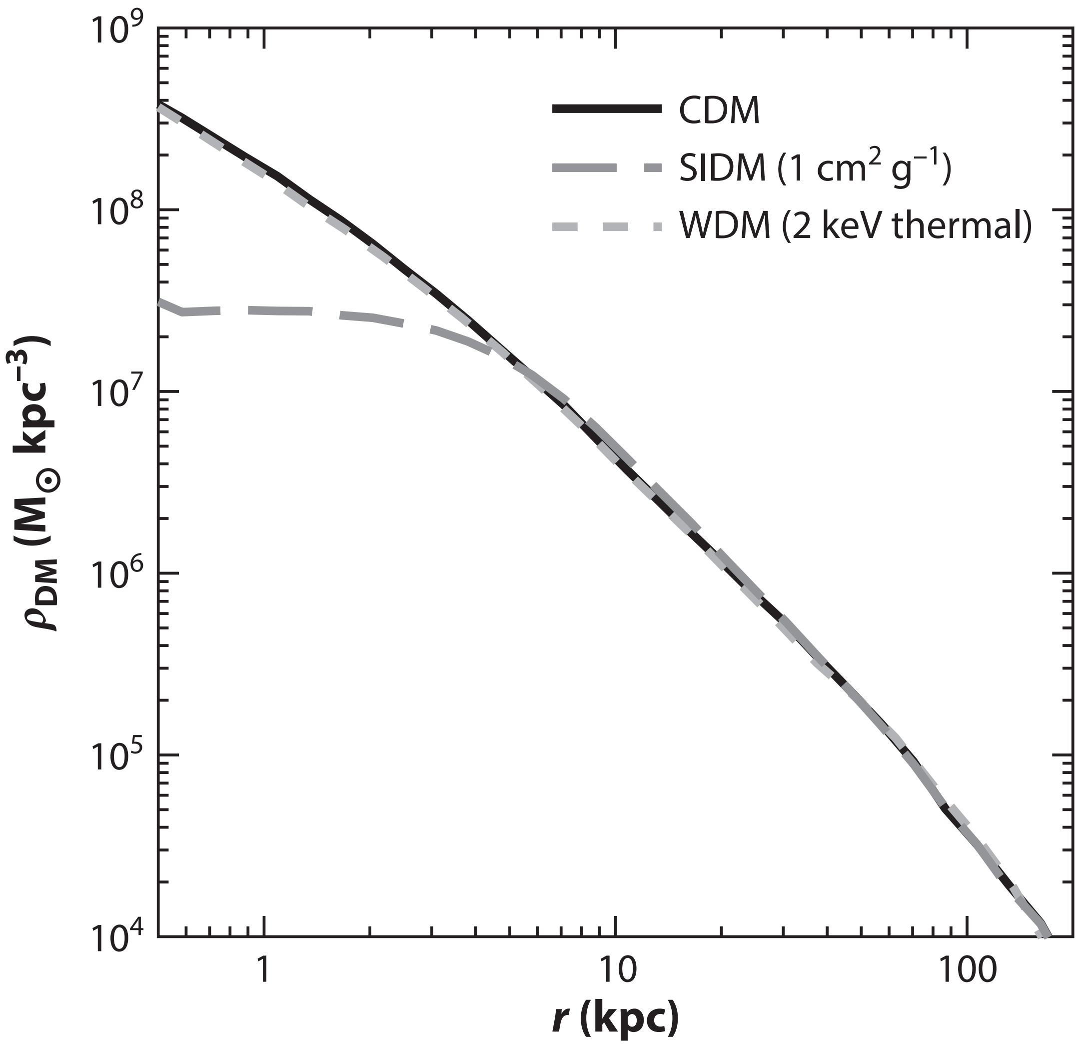


The future (?): gravitational detection of “dark” (sub)halos



Hezaveh et al. 2016

CDM vs WDM vs SIDM at Milky Way scale



Density profiles:

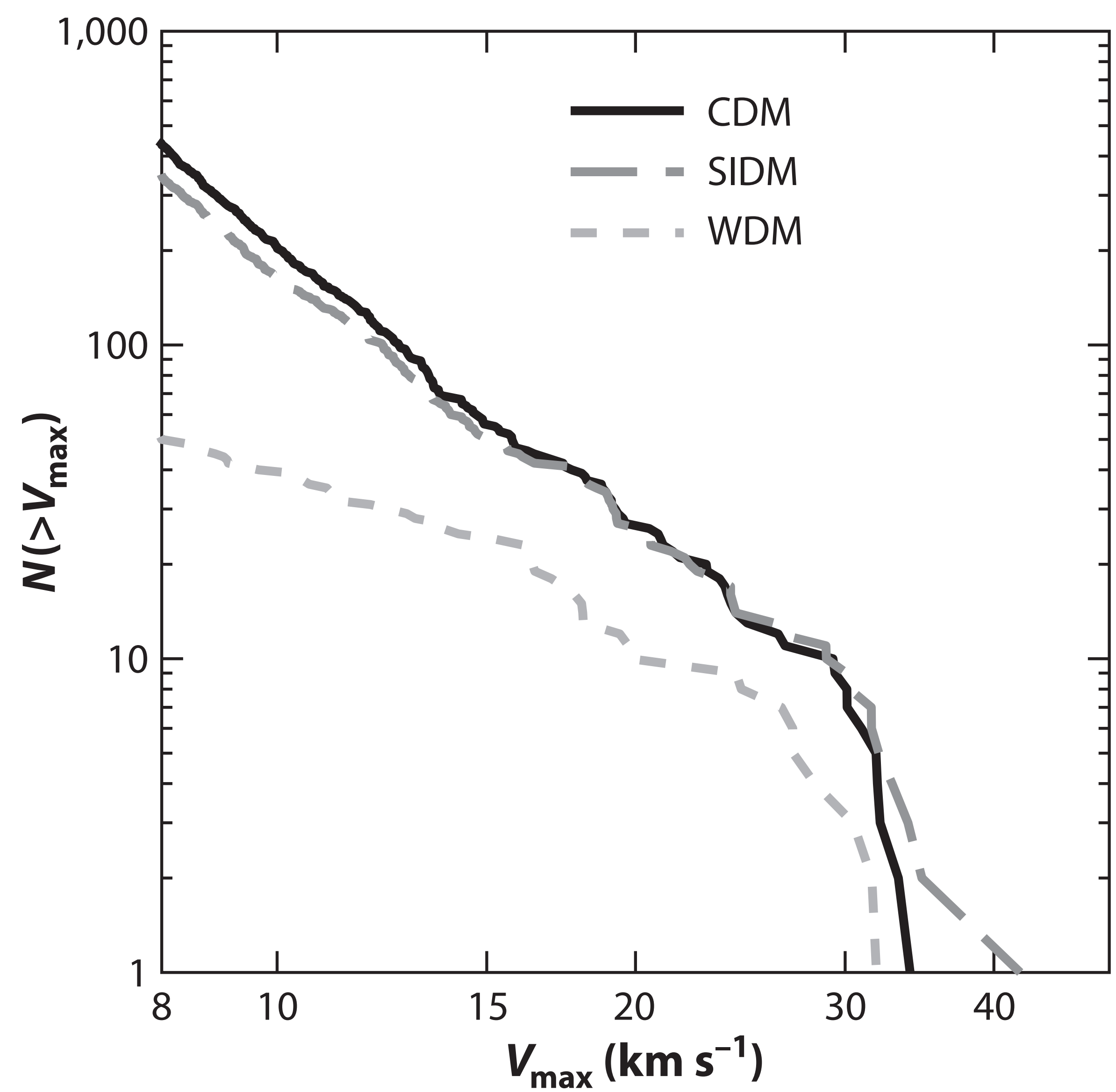
WDM: very little difference

SIDM: large core

Subhalo counts:

WDM: significant suppression

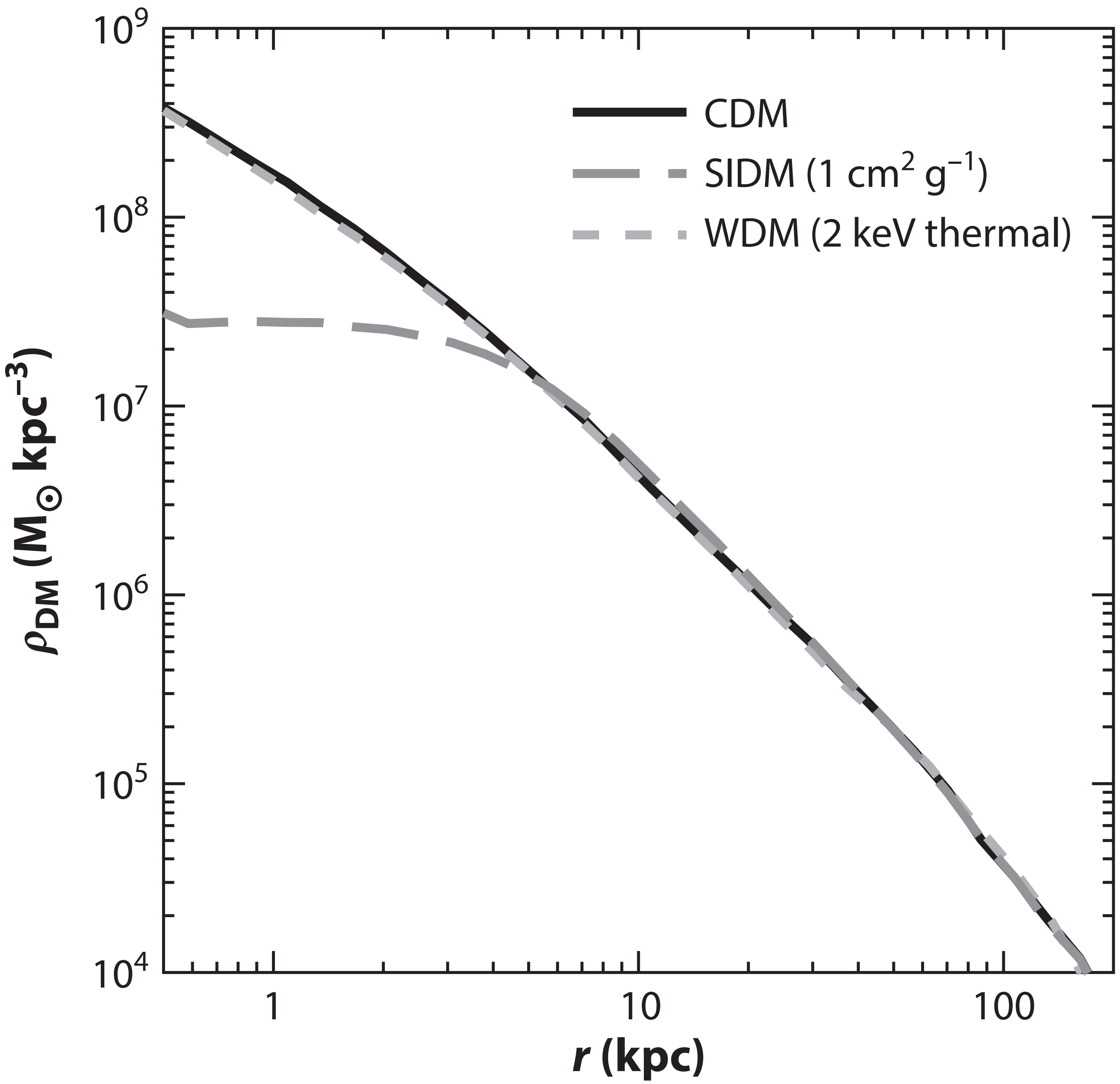
SIDM: very little difference



Bullock & Boylan-Kolchin 2017

WDM halos: less centrally concentrated

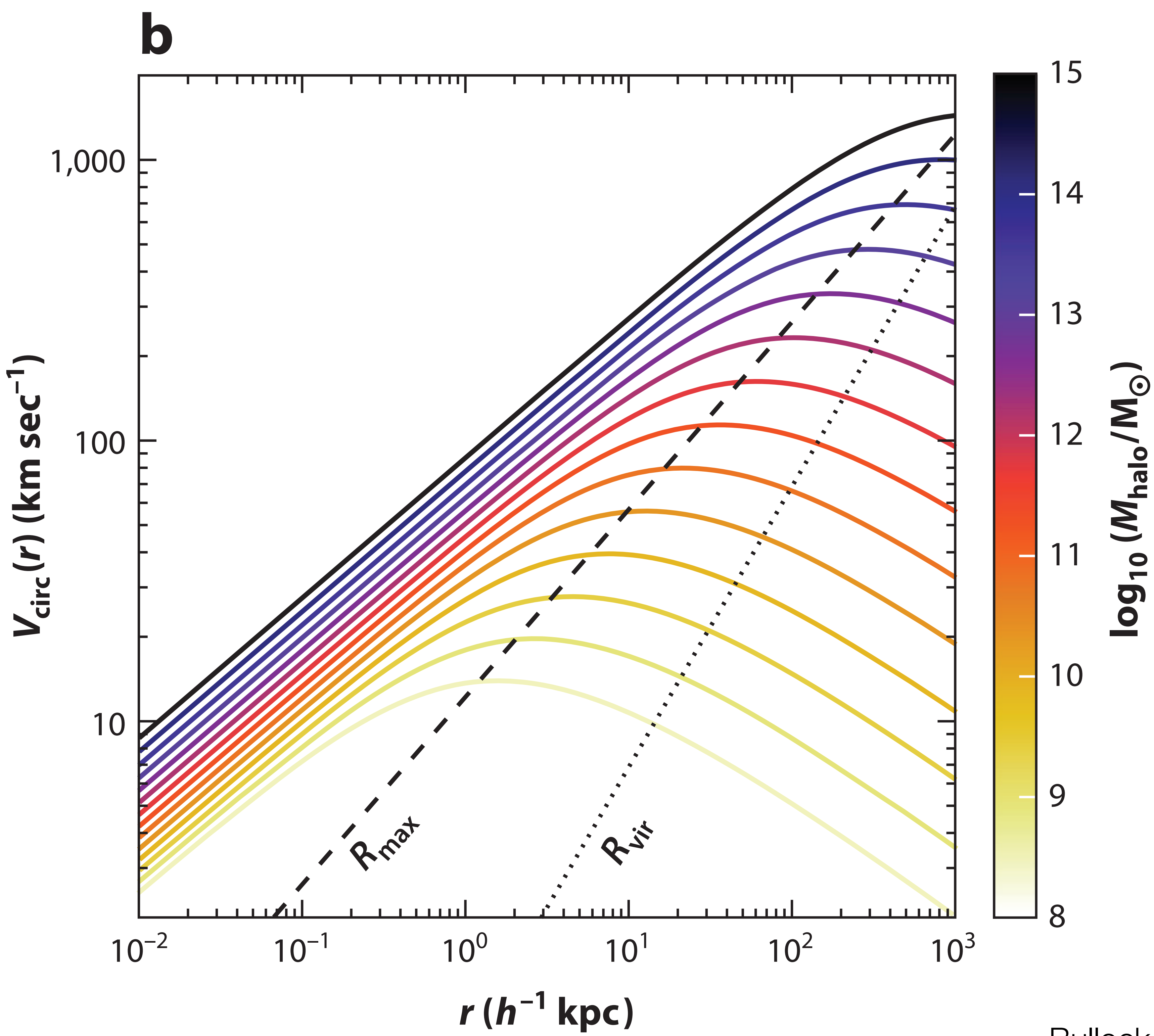
But: still have ***cuspy*** dark matter centers (cores on scales of 10s of pc)



Simulation of **Milky Way** mass halo

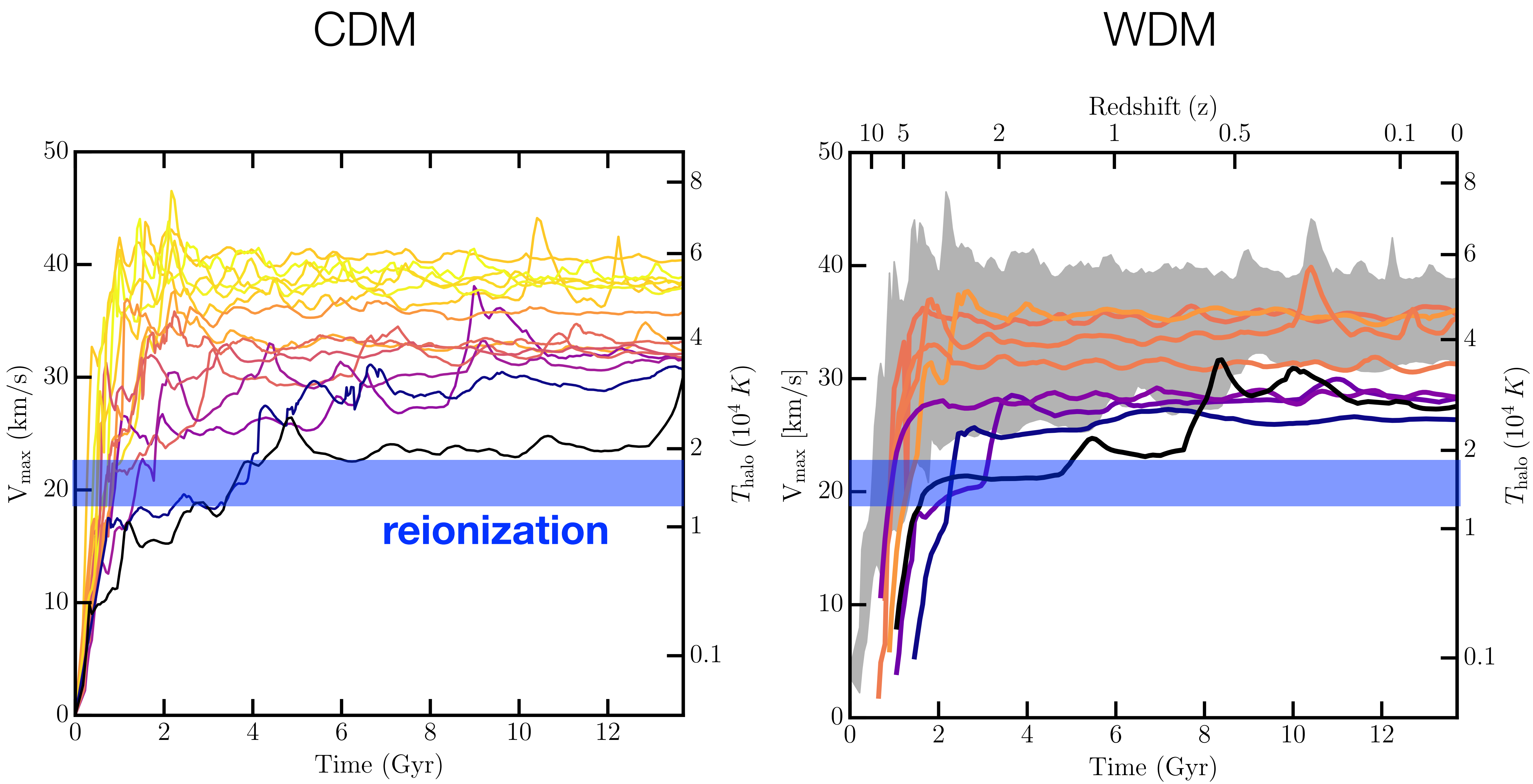
Bullock & Boylan-Kolchin 2017

Predicted circular velocities



Bullock & Boylan-Kolchin 2017

V_{max} determines stellar mass



L: Fitts, MBK, et al. *R*: Bozek, Fitts, MBK et al.