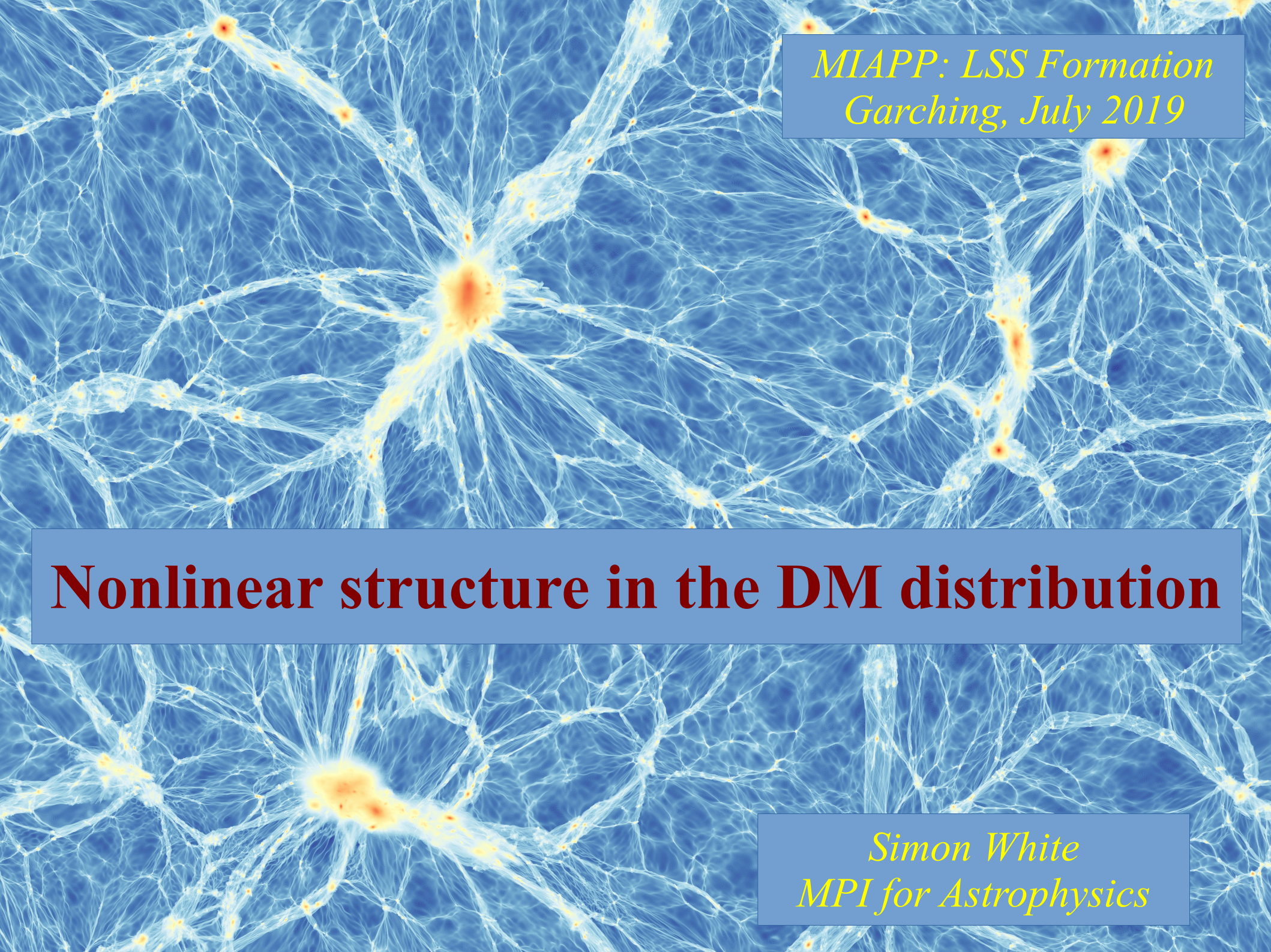


MIAPP: LSS Formation
Garching, July 2019

Nonlinear structure in the DM distribution

Simon White
MPI for Astrophysics

EFT aims to extend structure formation modelling to

$\Delta^2 \sim 1, \quad k \sim 0.4\, h/\mathrm{Mpc}, \quad r_{sm} \sim 2.5\ \mathrm{Mpc}/h, \quad M \sim 10^{13}\, M_\odot/h$

EFT aims to extend structure formation modelling to

$\Delta^2 \sim 1, \quad k \sim 0.4\, h/\mathrm{Mpc}, \quad r_{sm} \sim 2.5\ \mathrm{Mpc}/h, \quad M \sim 10^{13}\, M_\odot/h$

This talk extends structure formation modelling to

$\Delta^2 \sim 650, \quad k \sim 10^6\, h/\mathrm{Mpc}, \quad r_{sm} \sim 1.0\ \mathrm{pc}/h, \quad M \sim 10^{-6}\, M_\odot/h$

EFT aims to extend structure formation modelling to

$\Delta^2 \sim 1, \quad k \sim 0.4\, h/\mathrm{Mpc}, \quad r_{sm} \sim 2.5\ \mathrm{Mpc}/h, \quad M \sim 10^{13}\, M_\odot/h$

This talk extends structure formation modelling to

$\Delta^2 \sim 650, \quad k \sim 10^6\, h/\mathrm{Mpc}, \quad r_{sm} \sim 1.0\ \mathrm{pc}/h, \quad M \sim 10^{-6}\, M_\odot/h$

This poses questions most cosmologists have not thought about

– What is the typical (median) value of the cosmic density ρ?
(We know its mean value, $\langle\rho\rangle = 0.31\, \rho_{crit}$, from e.g. Planck)

EFT aims to extend structure formation modelling to

$\Delta^2 \sim 1, \quad k \sim 0.4\, h/\mathrm{Mpc}, \quad r_{sm} \sim 2.5\ \mathrm{Mpc}/h, \quad M \sim 10^{13}\, M_\odot/h$

This talk extends structure formation modelling to

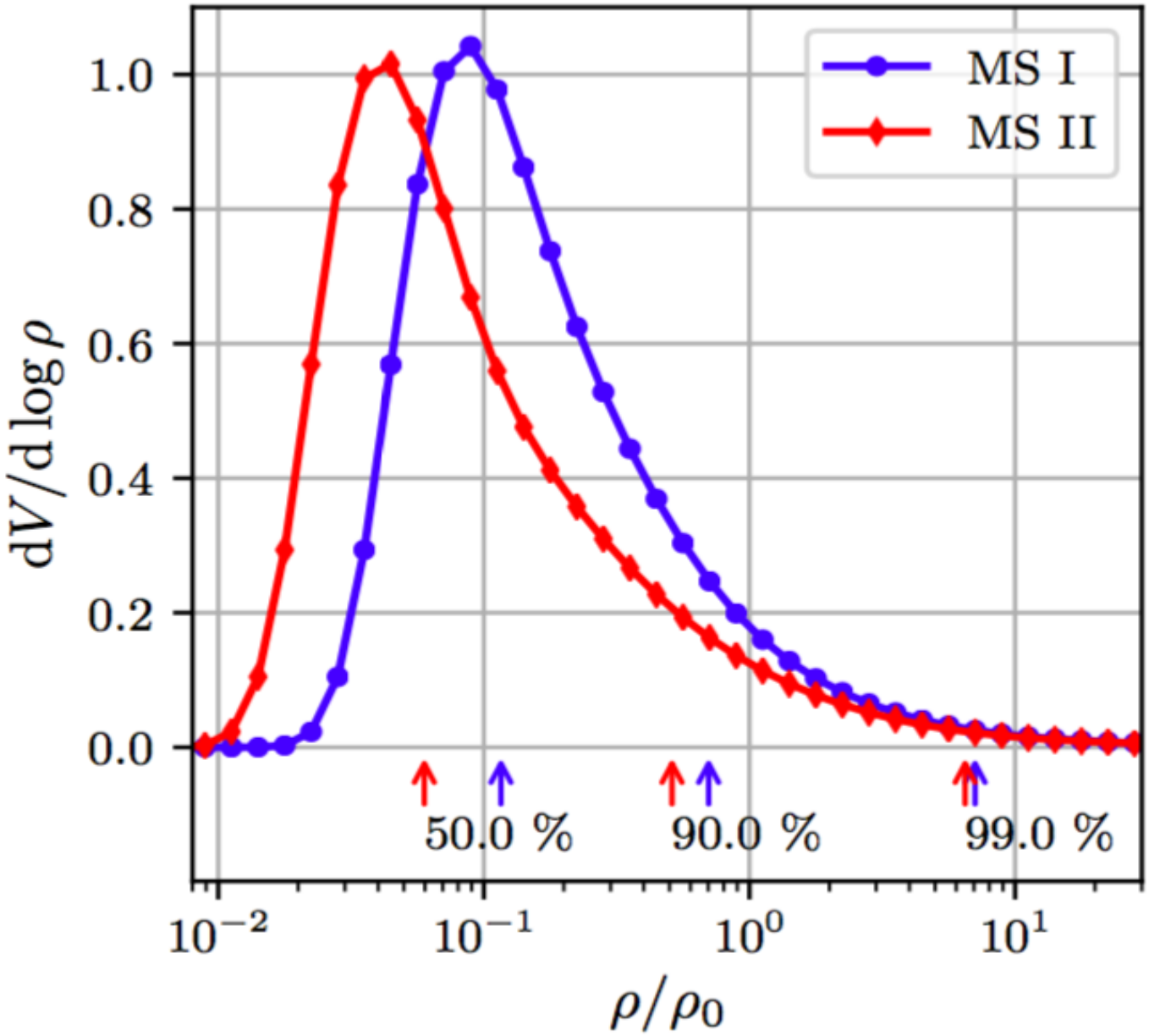
$\Delta^2 \sim 650, \quad k \sim 10^6\, h/\mathrm{Mpc}, \quad r_{sm} \sim 1.0\ \mathrm{pc}/h, \quad M \sim 10^{-6}\, M_\odot/h$

This poses questions most cosmologists have not thought about

- What is the typical (median) value of the cosmic density ρ?
  (We know its mean value, $\langle\rho\rangle = 0.31\, \rho_{crit}$, from e.g. Planck)
- What is the structure and environment of the lowest mass halos?

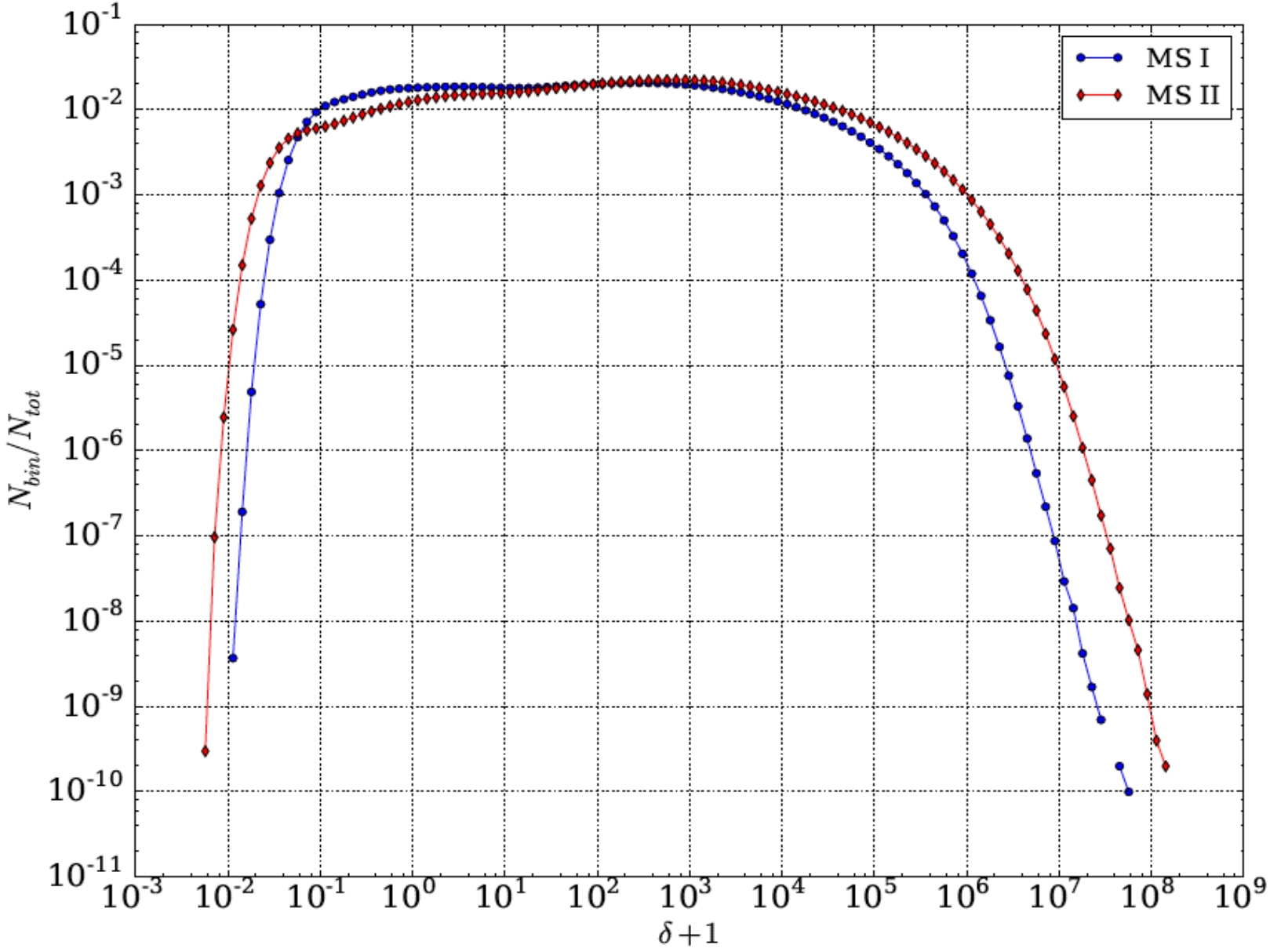
Volume-weighted density distributions in the two MS.

Stuecker et al 2018

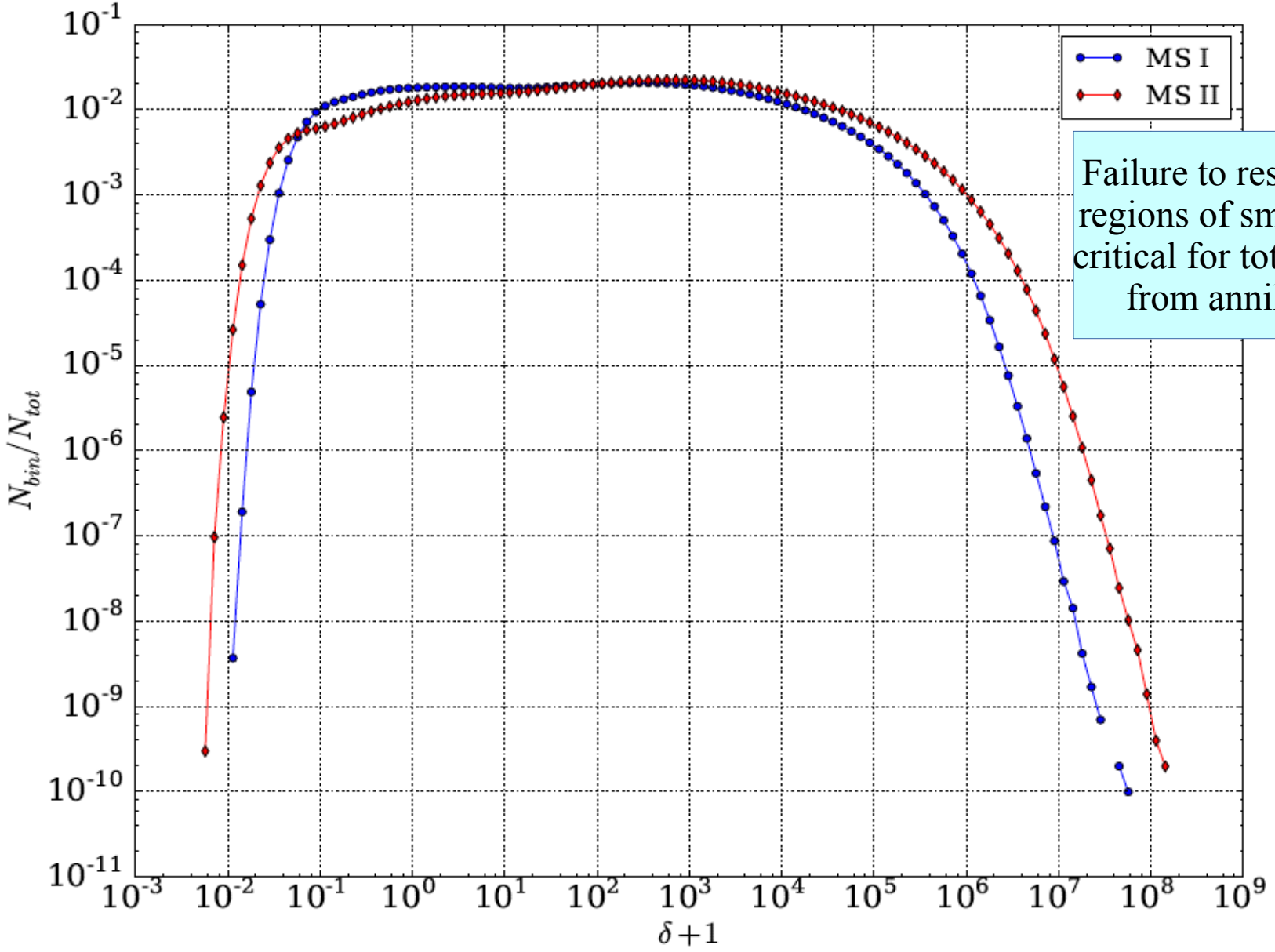


What is the median density of the Universe?

Voronoi-estimated DM densities at the particle positions in the two Millennium Simulations, estimated as: $\rho_i \propto 1 / V_{Vor,i}$



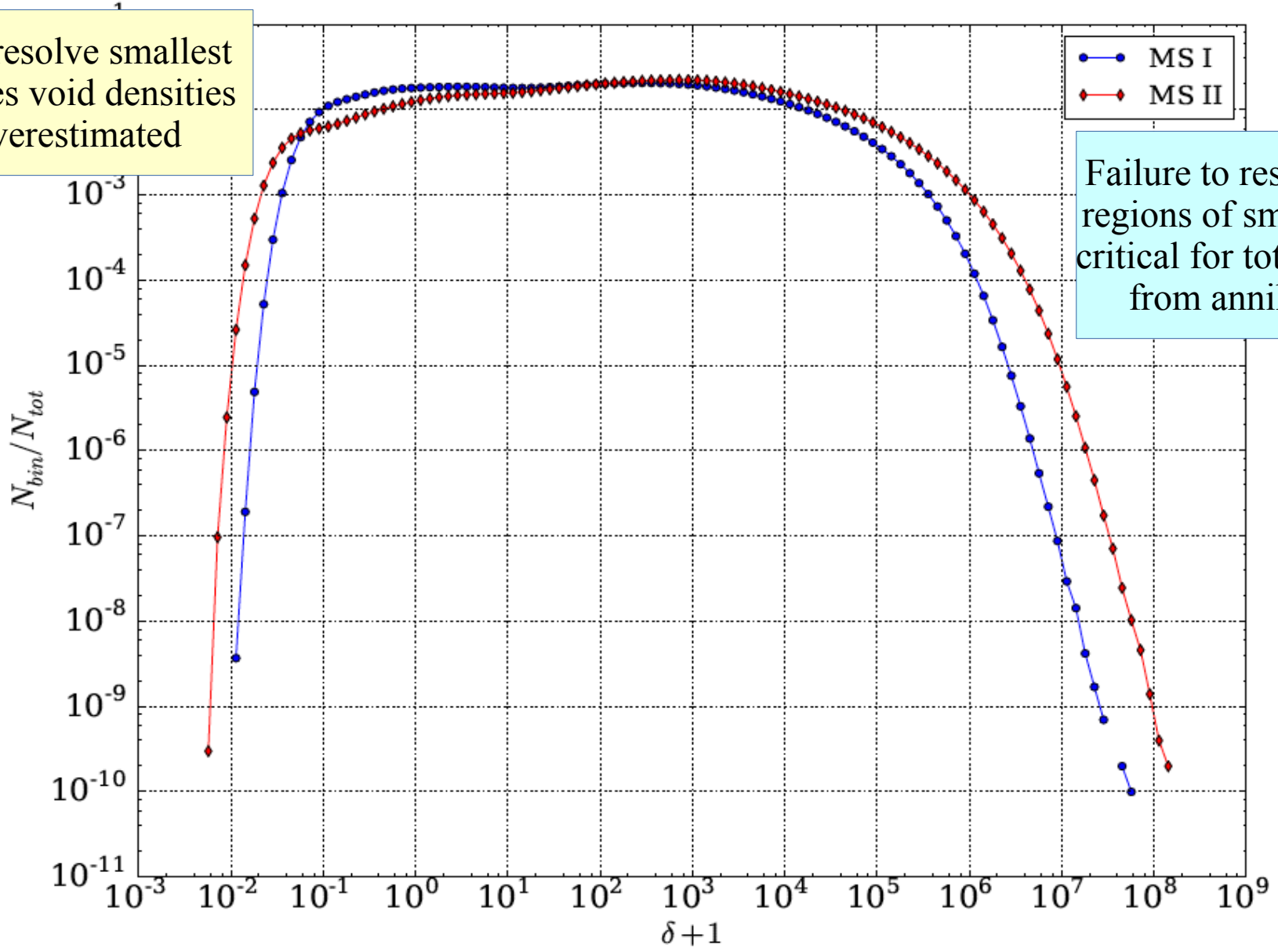
Voronoi-estimated DM densities at the particle positions in the two Millennium Simulations, estimated as: $\rho_i \propto 1 / V_{Vor,i}$



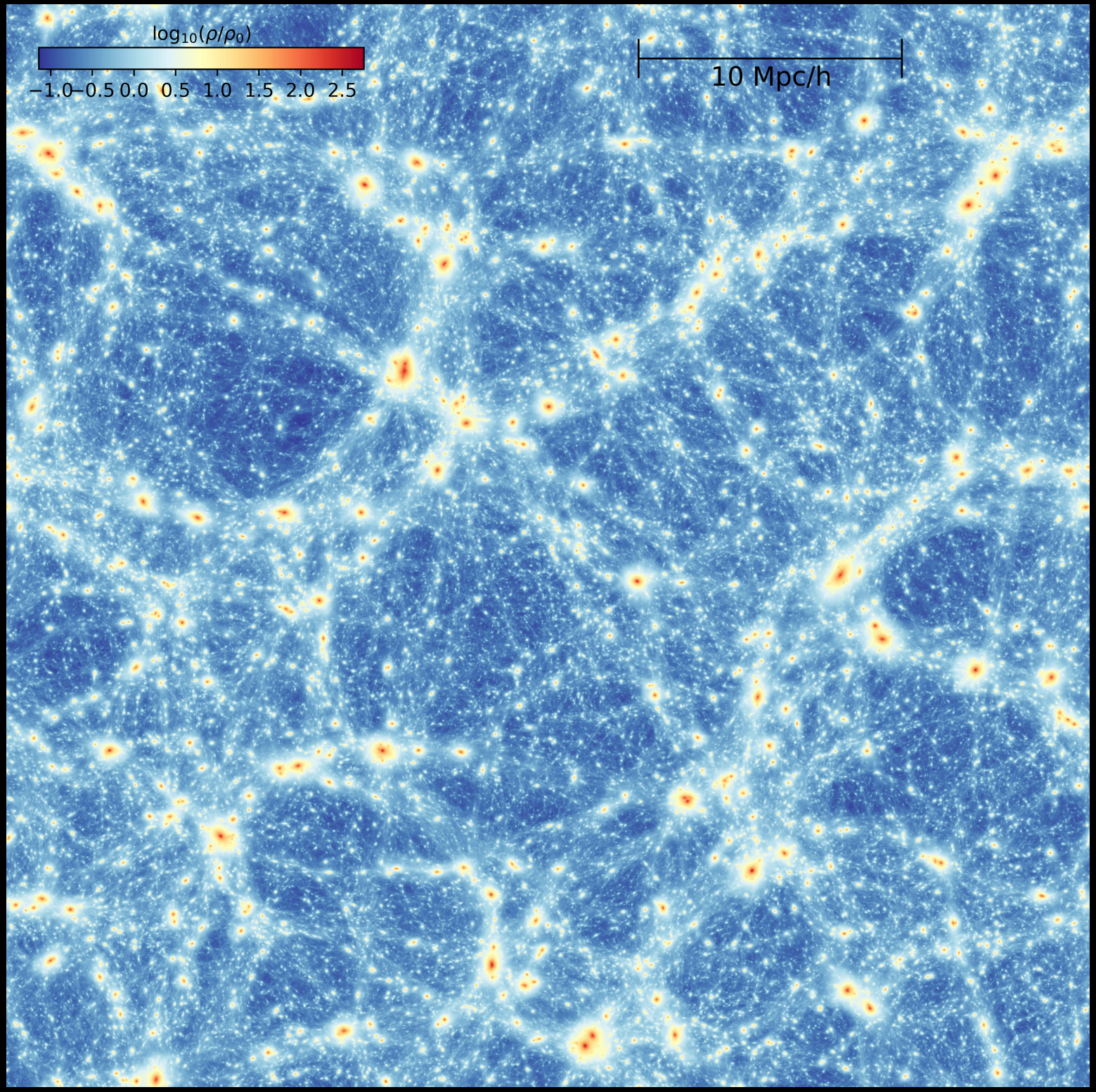
Failure to resolve inner regions of small halos is critical for total emission from annihilation

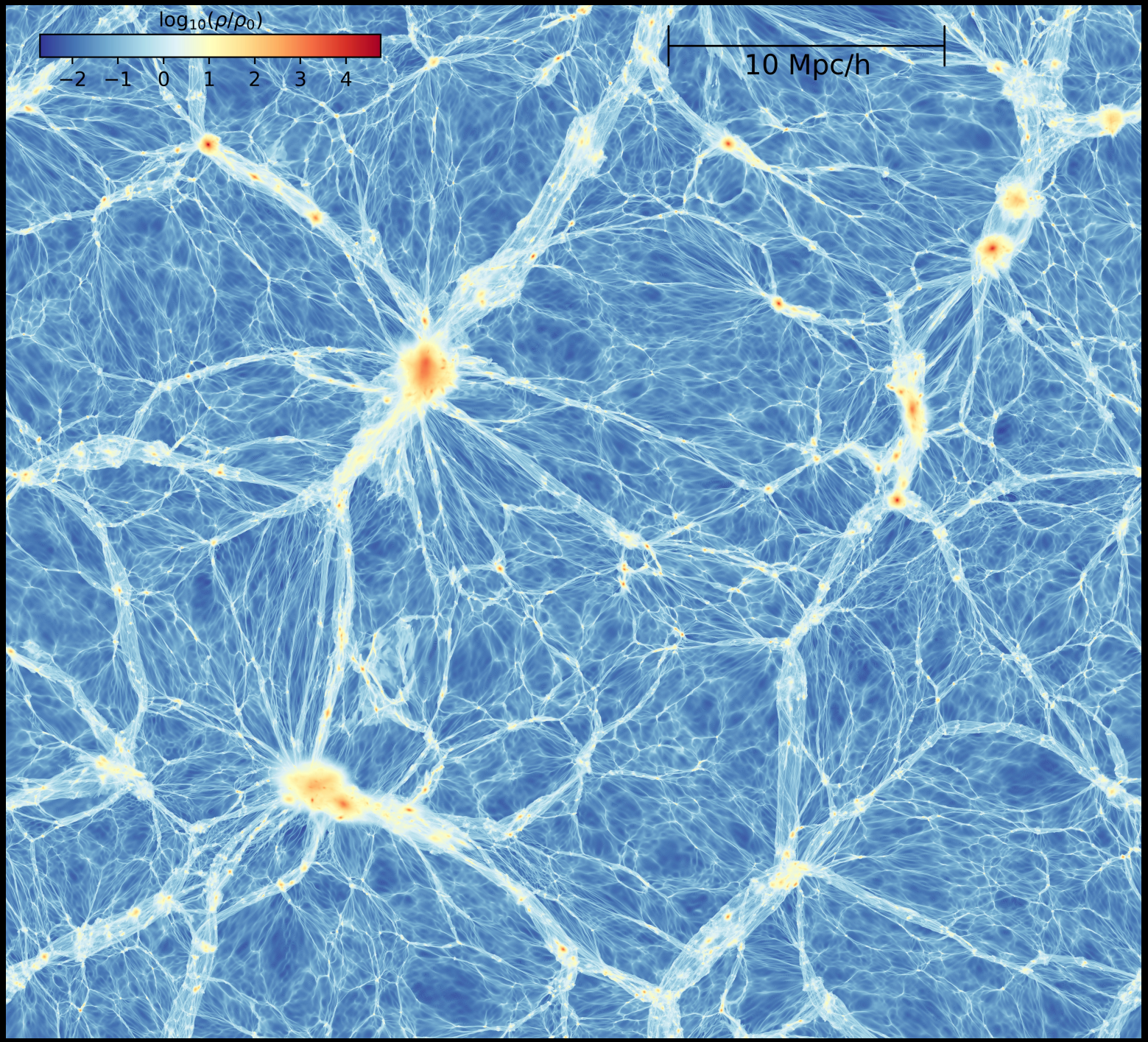
Voronoi-estimated DM densities at the particle positions in the two Millennium Simulations, estimated as: $\rho_i \propto 1 / V_{Vor,i}$

Failure to resolve smallest halos causes void densities to be overestimated

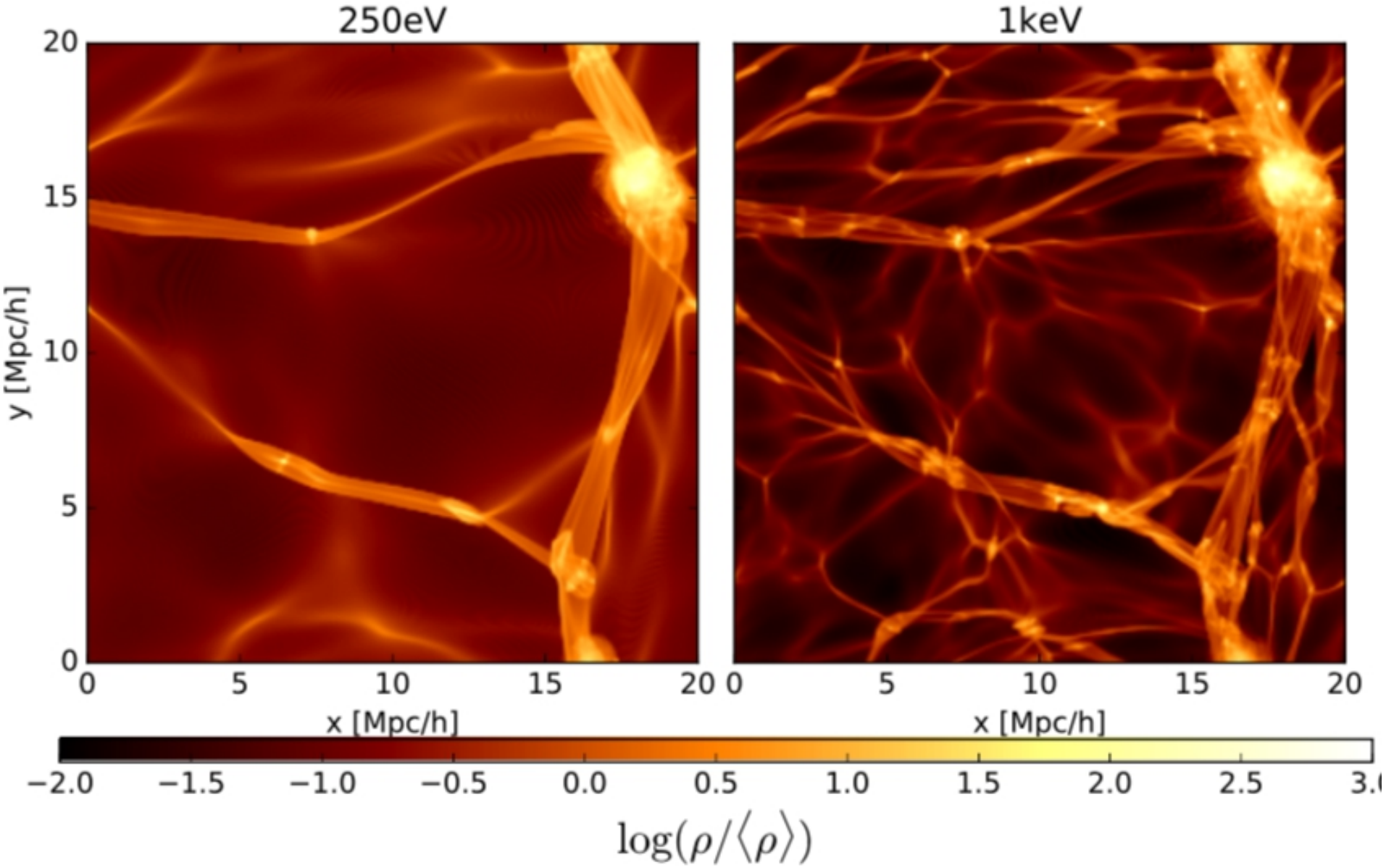


Failure to resolve inner regions of small halos is critical for total emission from annihilation


$\log_{10}(\rho/\rho_0)$
−1.0 −0.5 0.0 0.5 1.0 1.5 2.0 2.5
10 Mpc/h

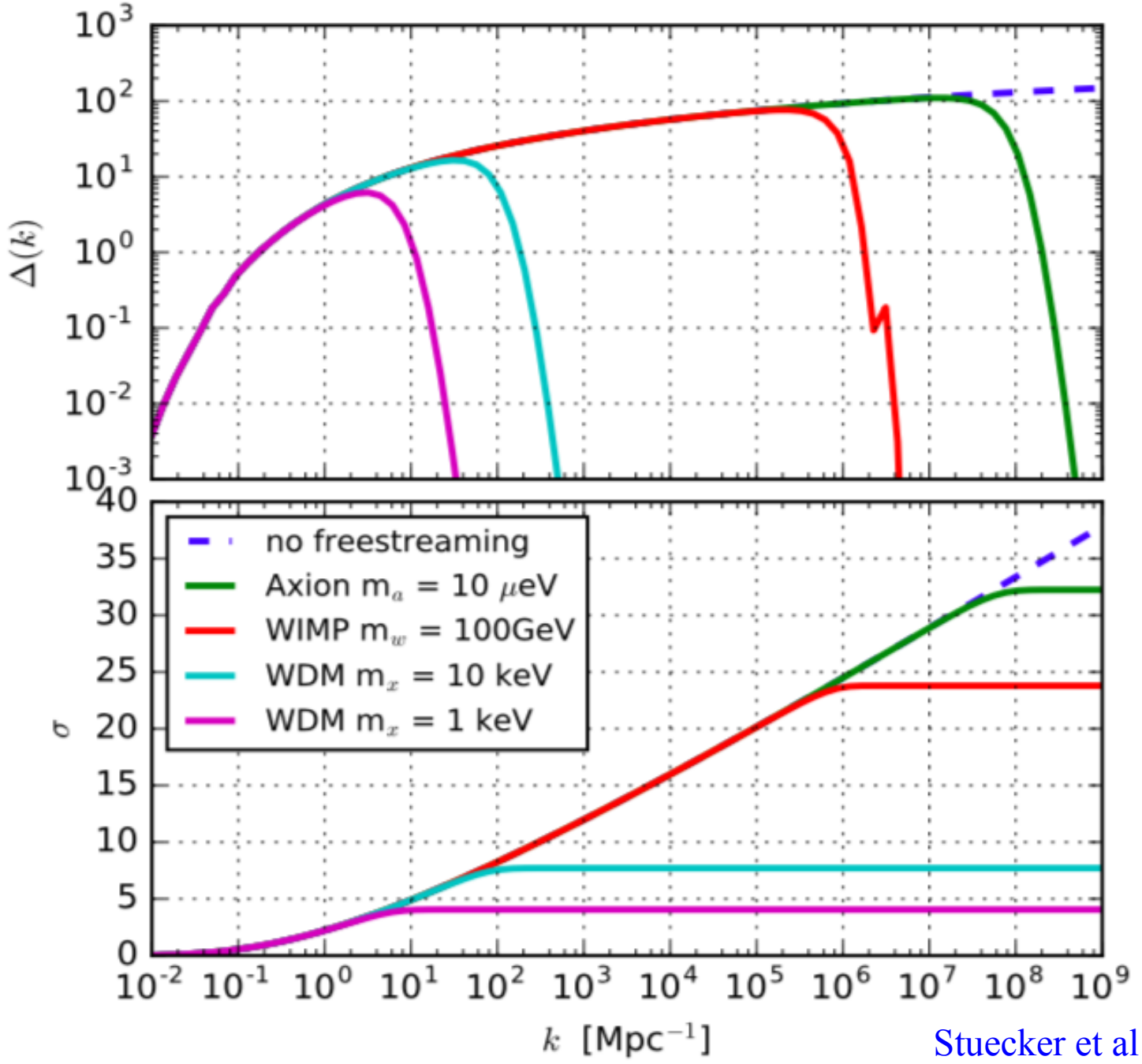

$\log_{10}(\rho/\rho_0)$
−2 −1 0 1 2 3 4
10 Mpc/h

The median density is sensitive to the amount of small-scale structure: voids are emptier with more small-scale structure.



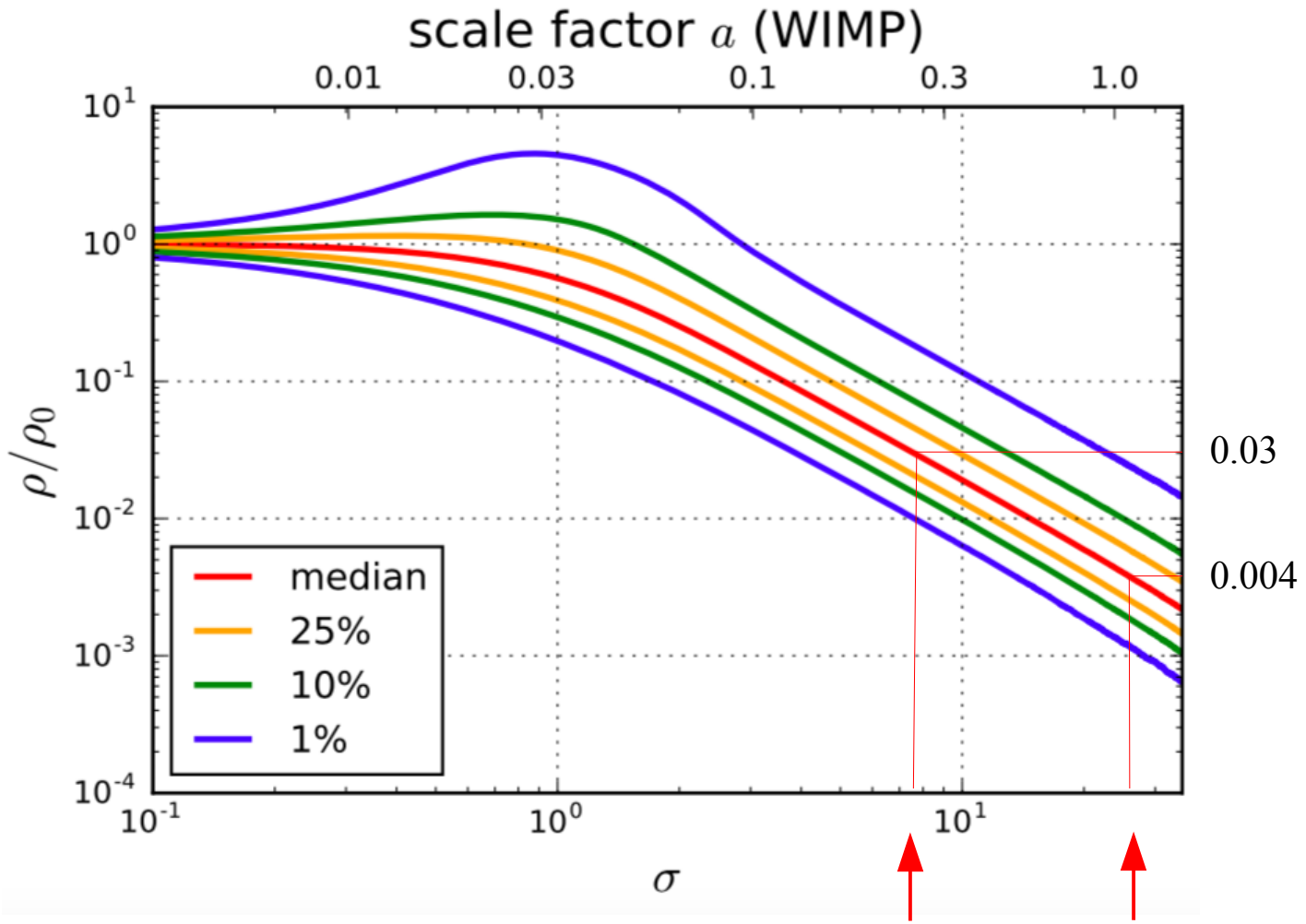
Stuecker et al 2018

The amount of small-scale structure depends on the nature of the dark matter.

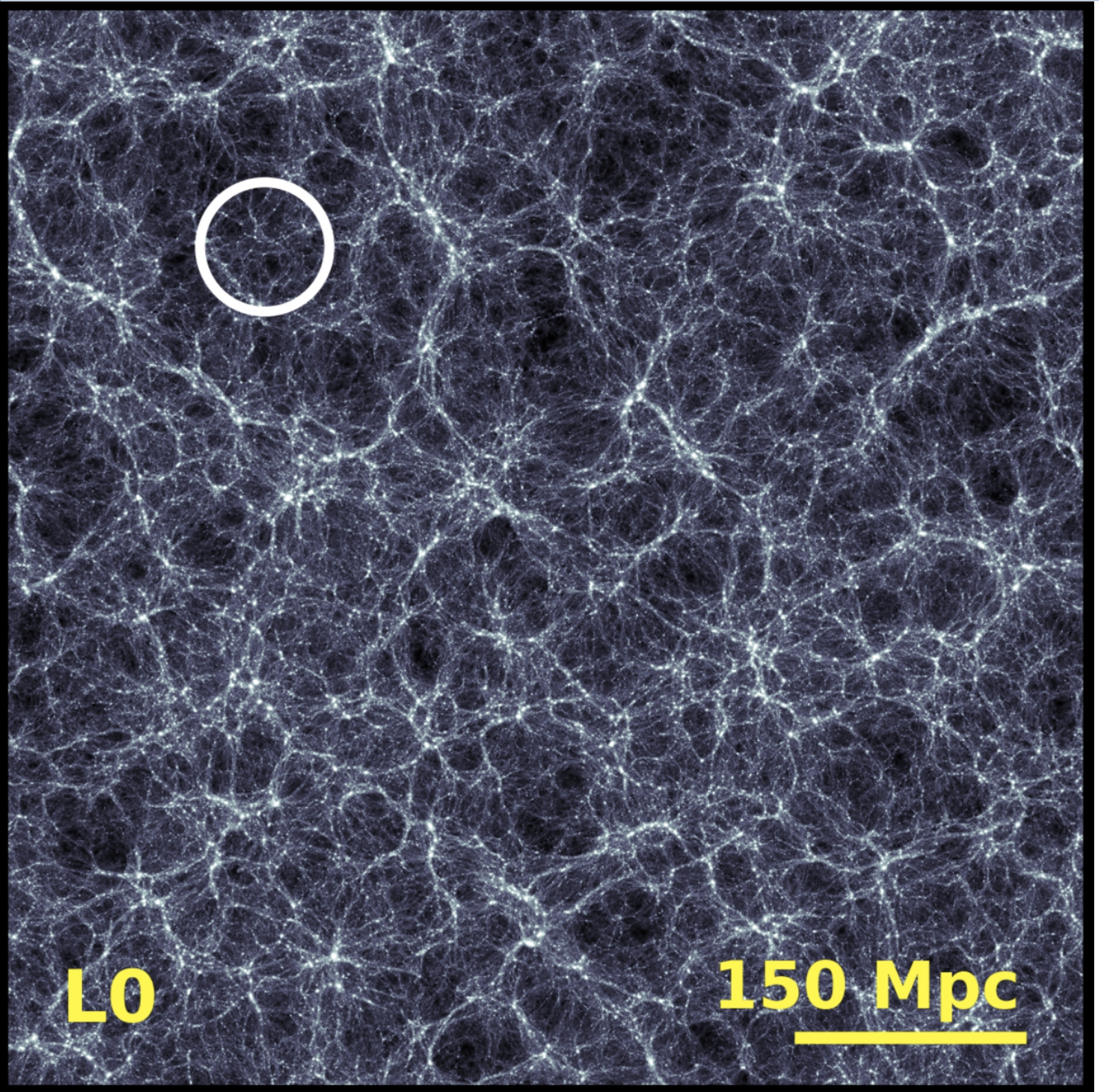


Stuecker et al 2018

In an excursion set model, the density distribution in single stream regions depends only on σ, hence on the nature of DM



Stuecker et al 2018



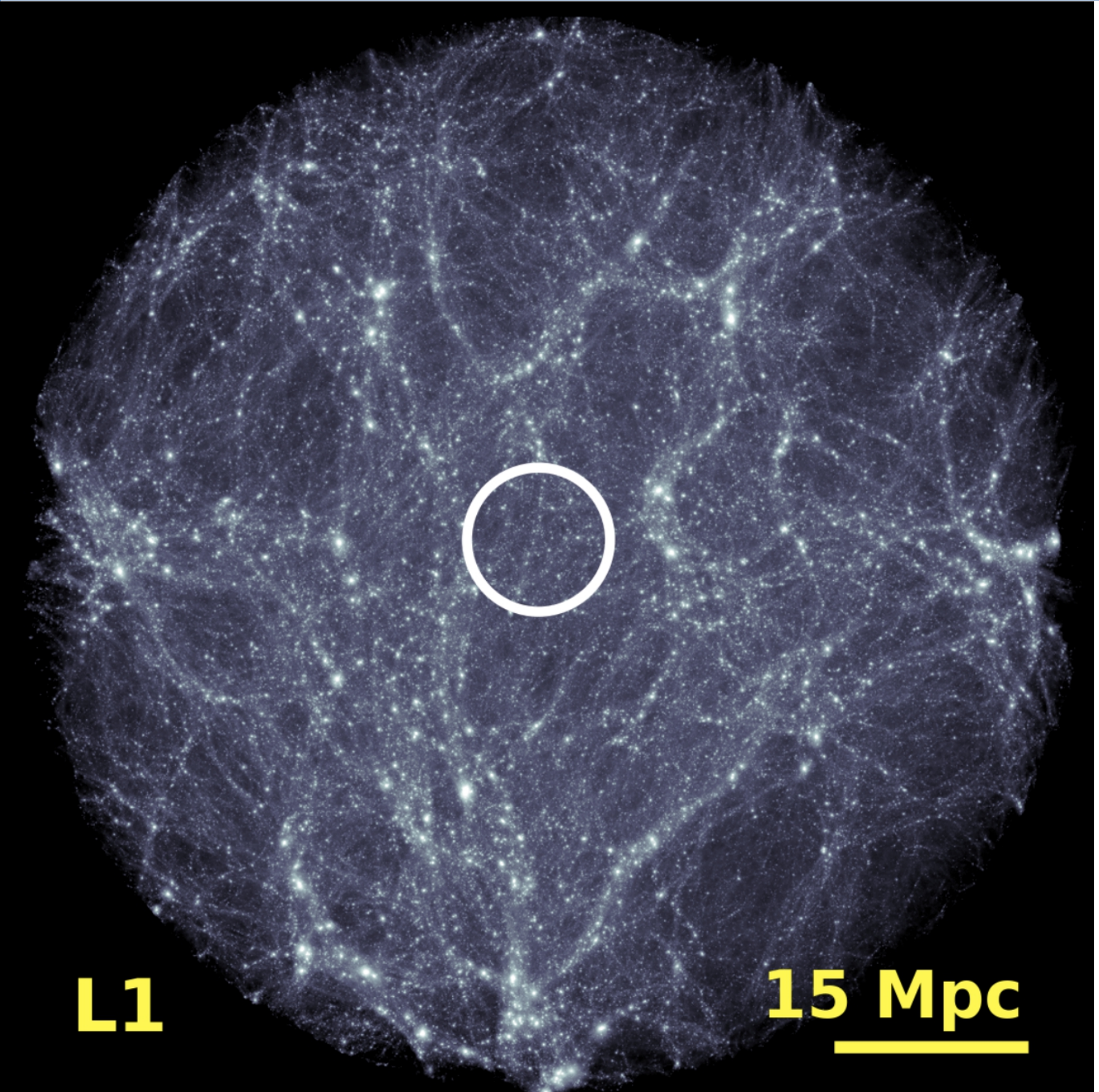
The VVV simulation

Planck cosmology

Dark matter only

Dynamic range of 30 orders of magnitude in mass

Base Level



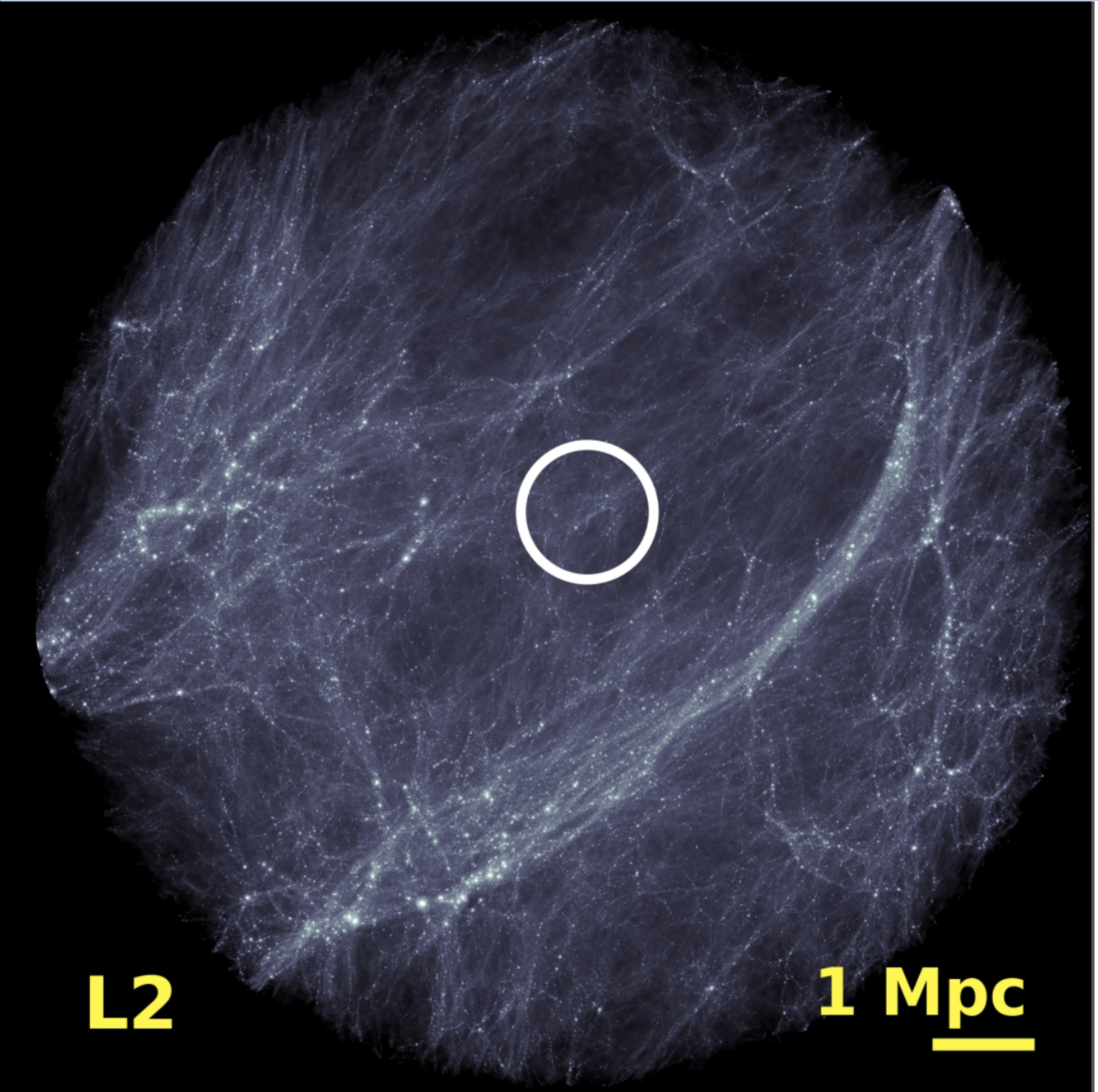
The VVV simulation

Planck cosmology

Dark matter only

Dynamic range of 30 orders of magnitude in mass

Zoom Level 1



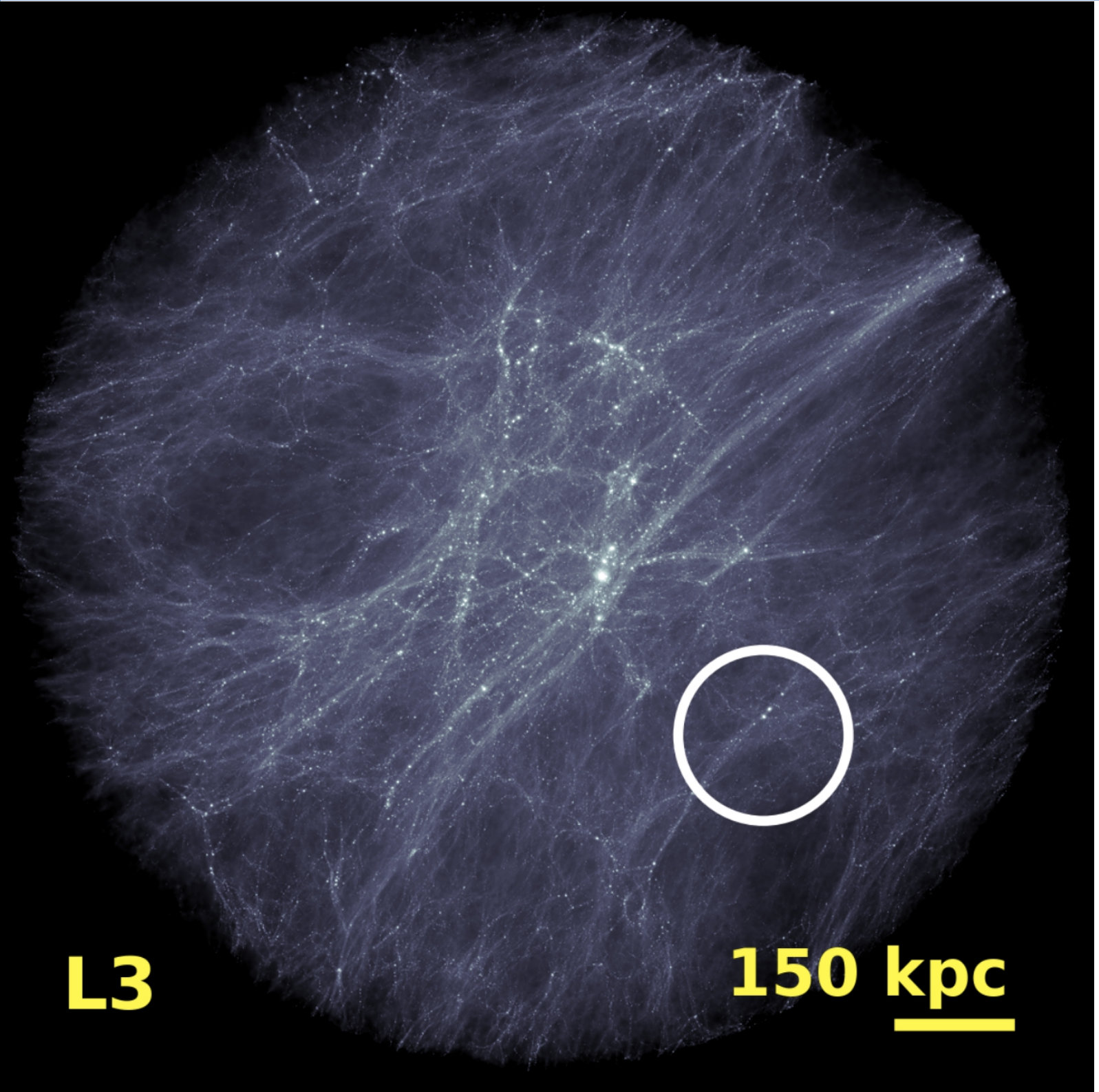
The VVV simulation

Planck cosmology

Dark matter only

Dynamic range of 30 orders of magnitude in mass

Zoom Level 2



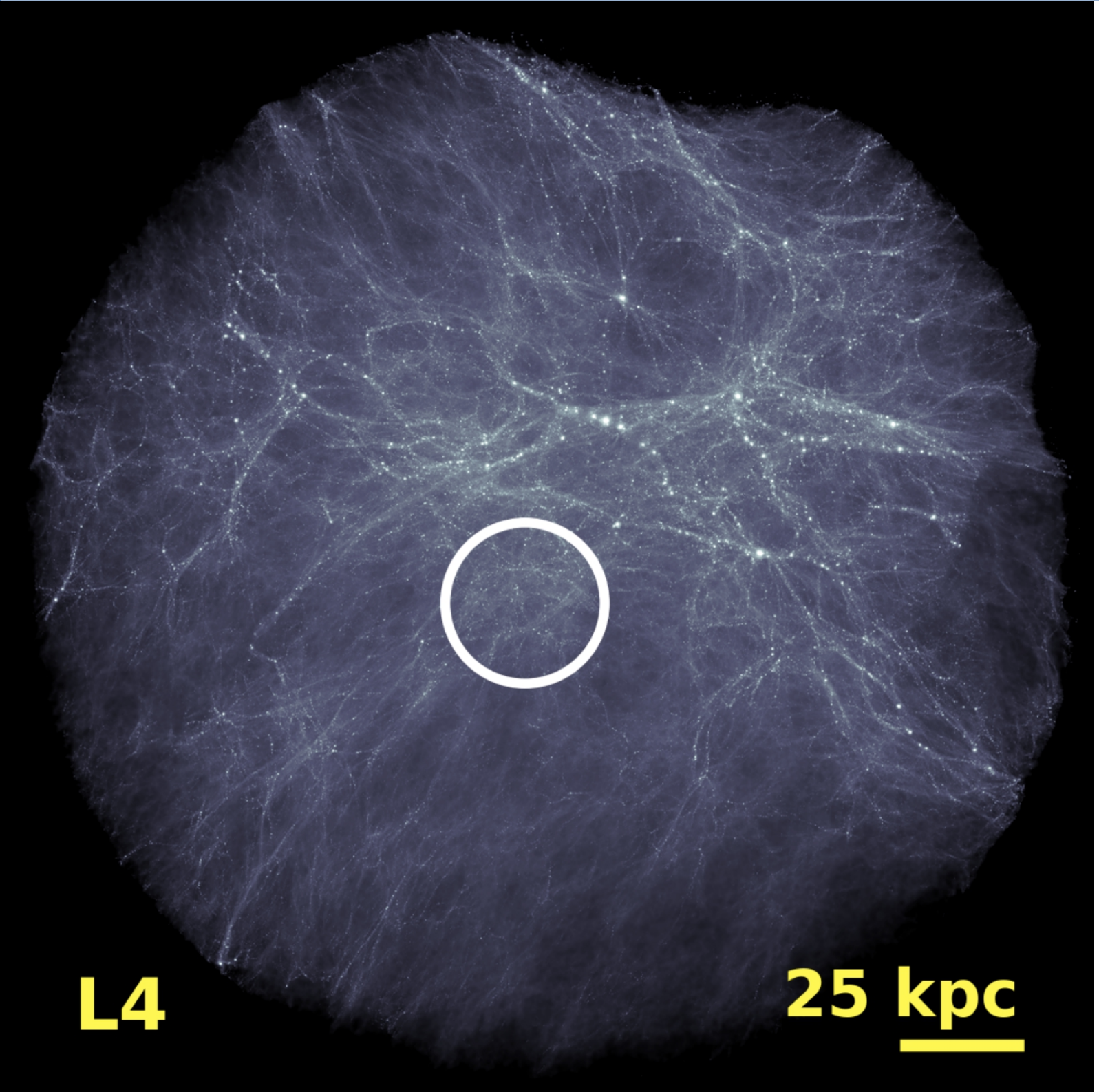
The VVV simulation

Planck cosmology

Dark matter only

Dynamic range of 30 orders of magnitude in mass

Zoom Level 3



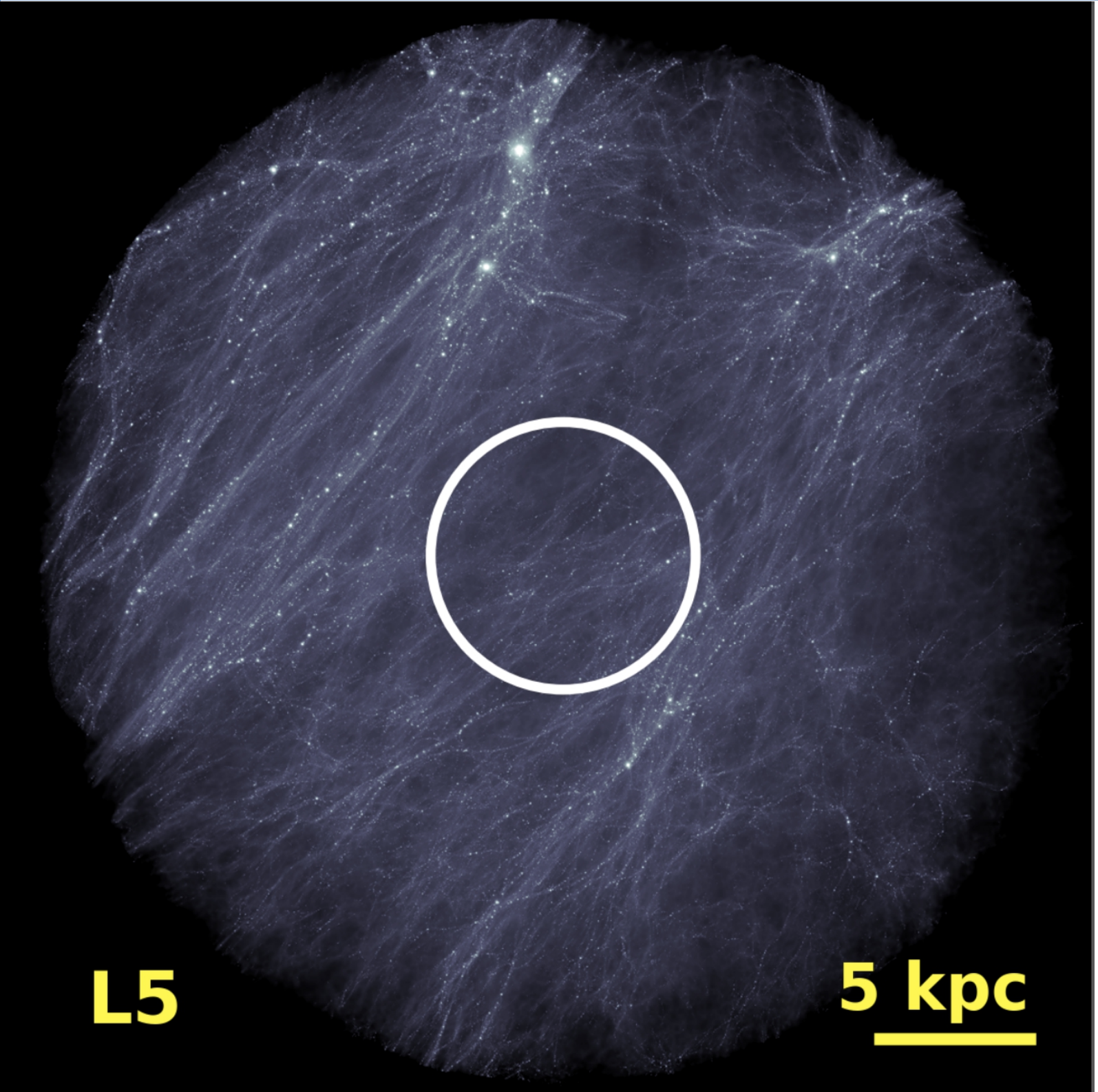
The VVV simulation

Planck cosmology

Dark matter only

Dynamic range of 30 orders of magnitude in mass

Zoom Level 4



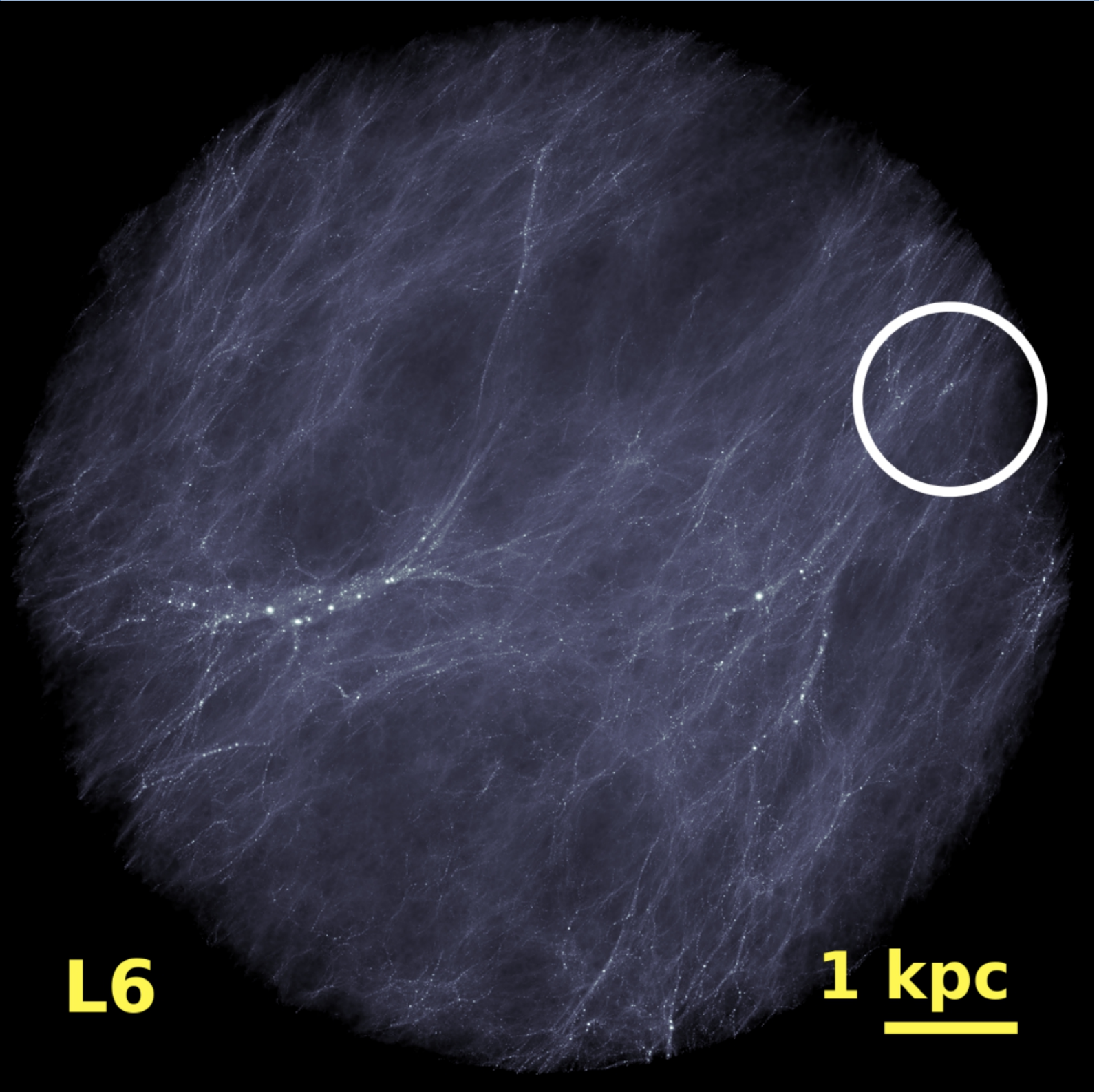
The VVV simulation

Planck cosmology

Dark matter only

Dynamic range of 30 orders of magnitude in mass

Zoom Level 5



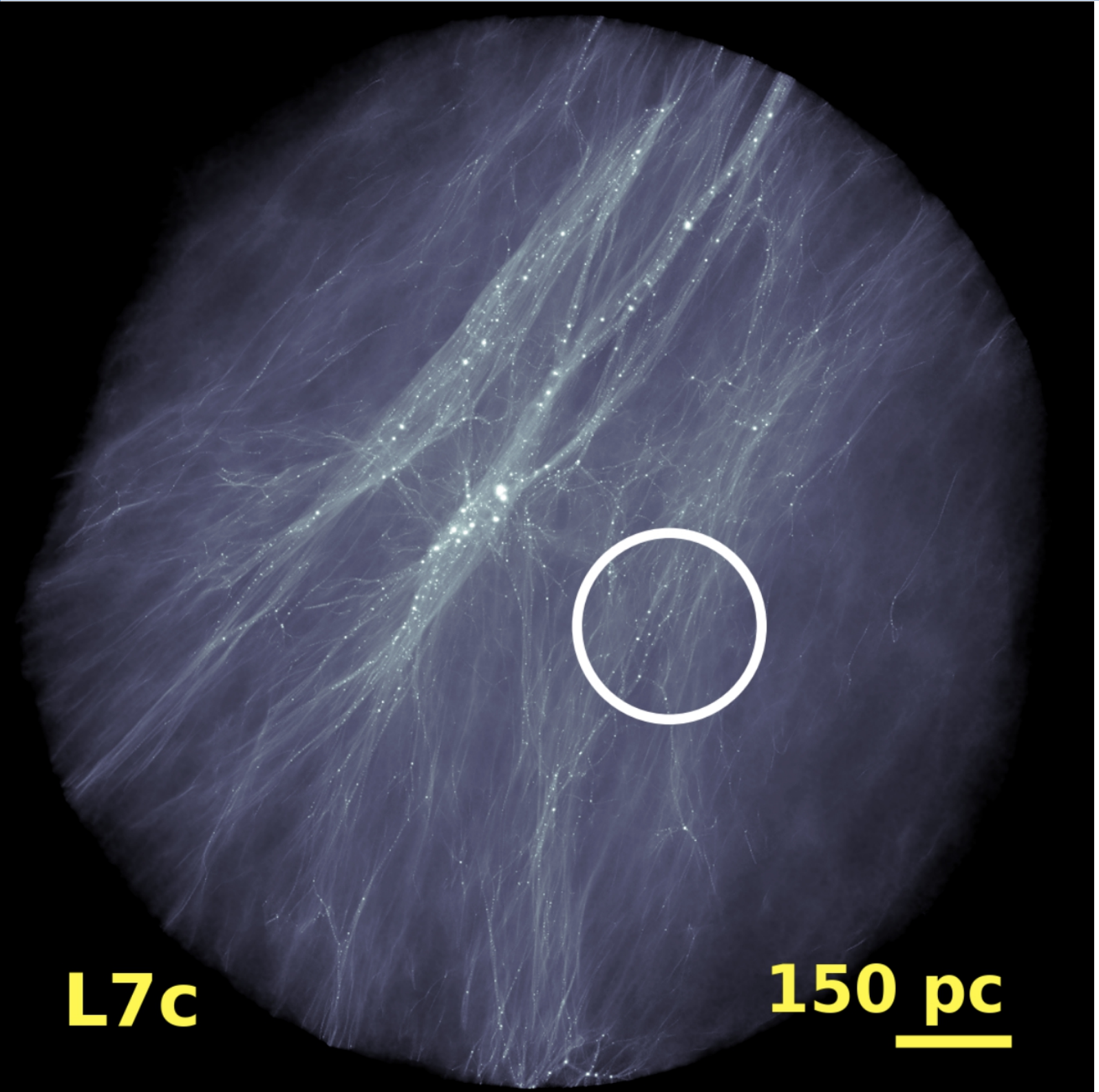
The VVV simulation

Planck cosmology

Dark matter only

Dynamic range of 30 orders of magnitude in mass

Zoom Level 6



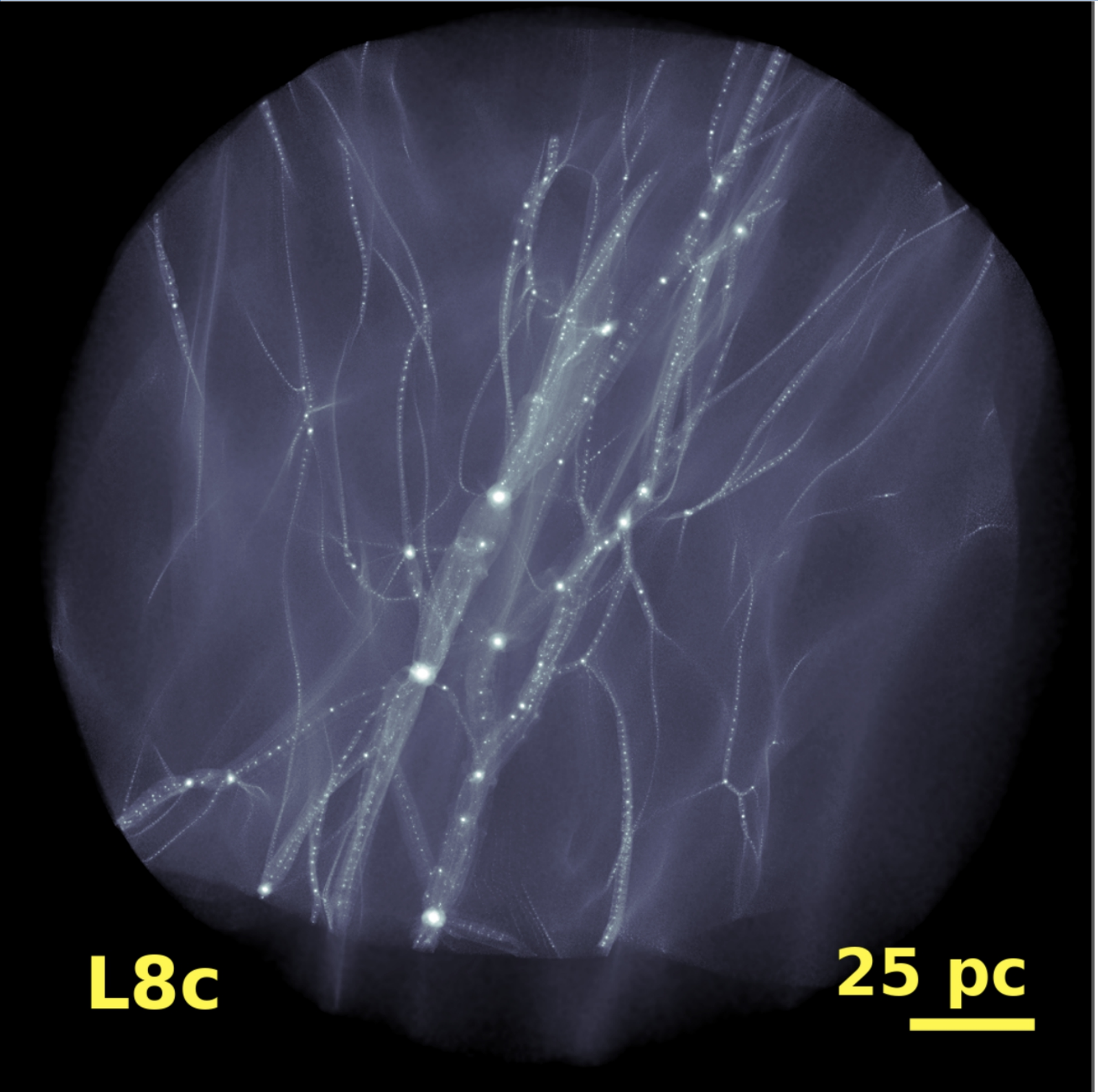
The VVV simulation

Planck cosmology

Dark matter only

Dynamic range of 30 orders of magnitude in mass

Zoom Level 7



The VVV simulation

Planck cosmology

Dark matter only

Dynamic range of 30 orders of magnitude in mass

Zoom Level 8

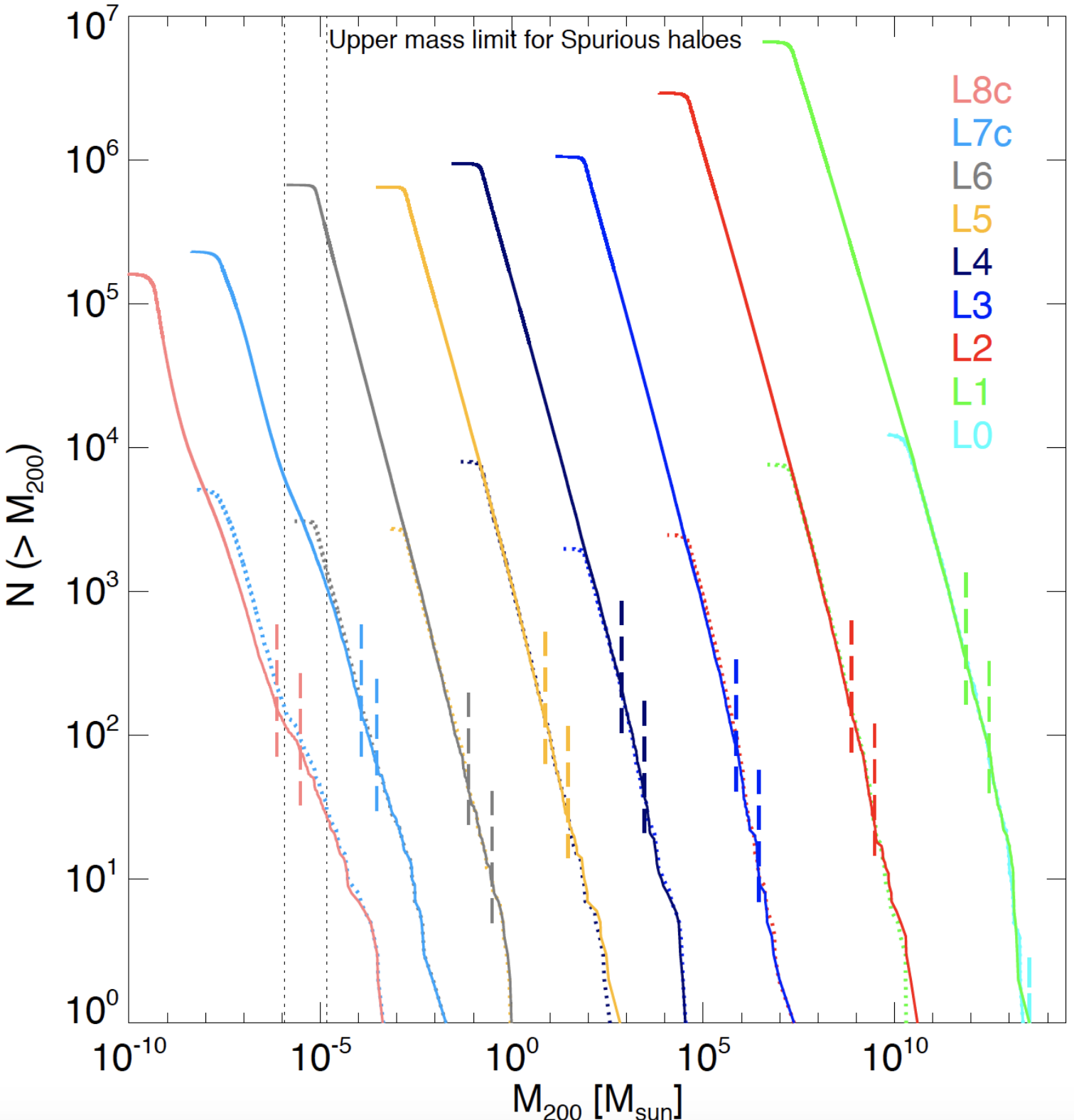
The density of this region is only 0.4% of the cosmic mean

The various levels of the VVV simulation

Sownak Bose, Carlos Frenk, Liang Gao, **Adrian Jenkins**, **Volker Springel**, **Jie Wang**, Simon White

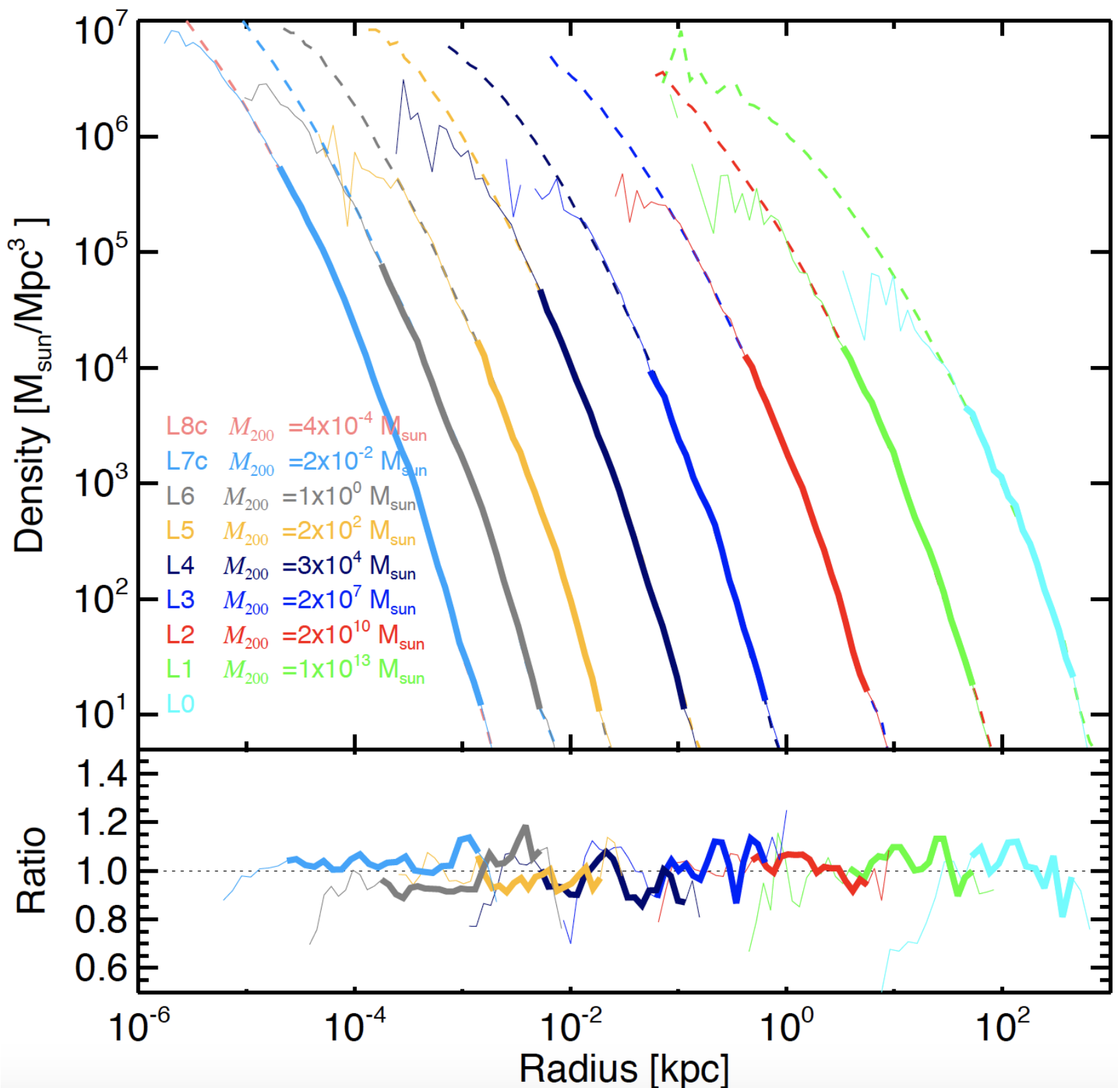
Dark matter only – IC's assume a 100 GeV thermal WIMP

run	$D_{\rm high}$[Mpc/h]	$n_{\rm p}$	ϵ[kpc/h]	$m_{\rm p}[M_\odot/h]$	ρ/ρ_{mean}
L0	500	1.0e10	5	9.3e8	1.
L1	35	1.0e10	3.e-1	5.0e5	0.2
L2	6	5.4e9	3.8e-2	9.8e2	0.07
L3	1.4	1.8e9	5.6e-3	1.9	0.04
L4	0.18	2.0e9	7.1e-4	3.7e-3	0.03
L5	0.03	1.5e9	1.5e-4	3.9e-5	0.02
L6	0.008	1.7e9	2.6e-5	1.8e-7	0.01
L7	0.0015	2.5e9	3.6e-6	5.8e-10	0.01
L7c	0.0015	2.5e9	3.6e-6	5.8e-10	0.01
L8c	0.00025	1.5e9	9.4e-7	1.1e-11	0.005



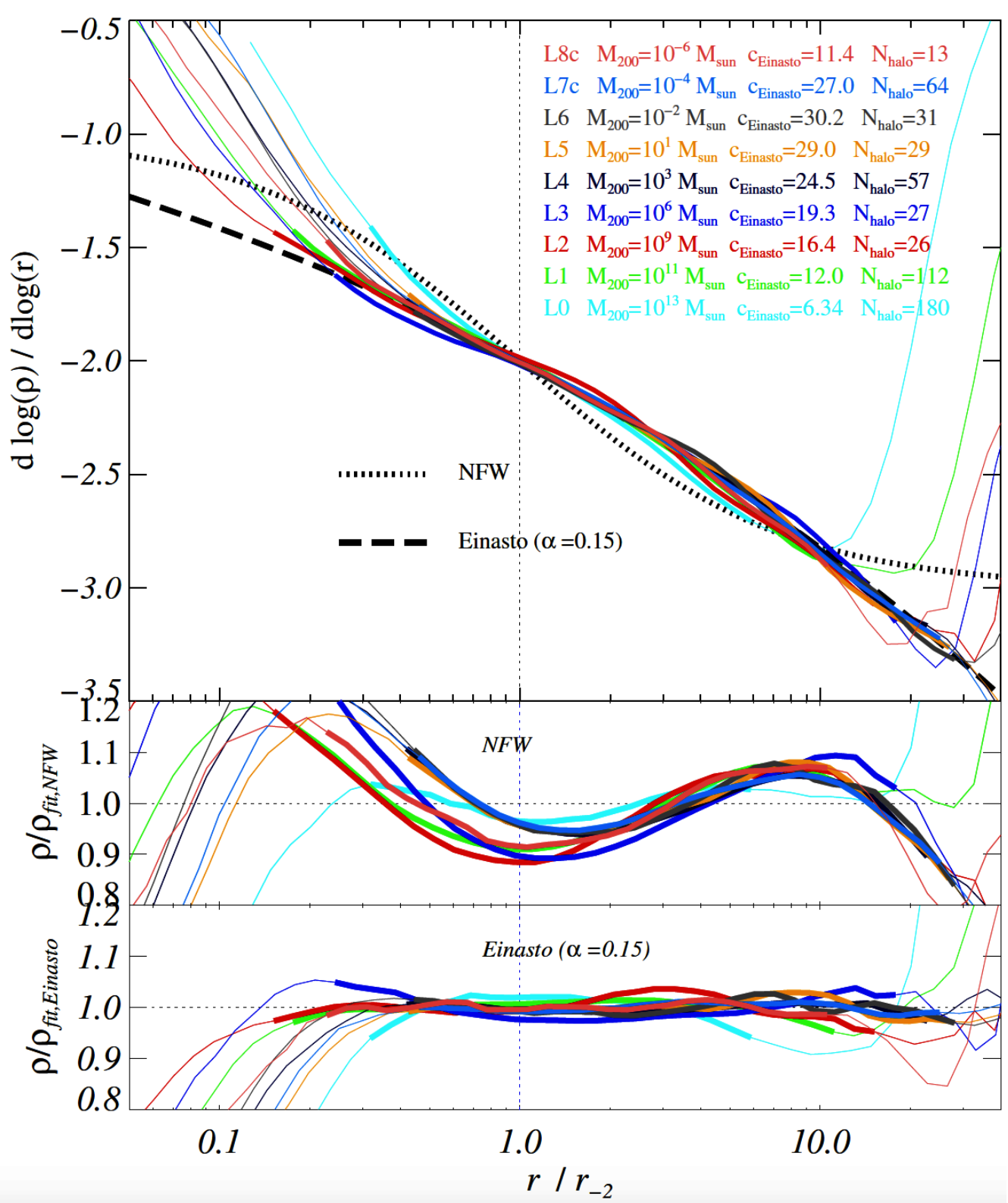
Convergence in halo abundance

The number of halos in the maximal spherical subregion of each simulation compared to that in the same region of its parent



Convergence in halo profile

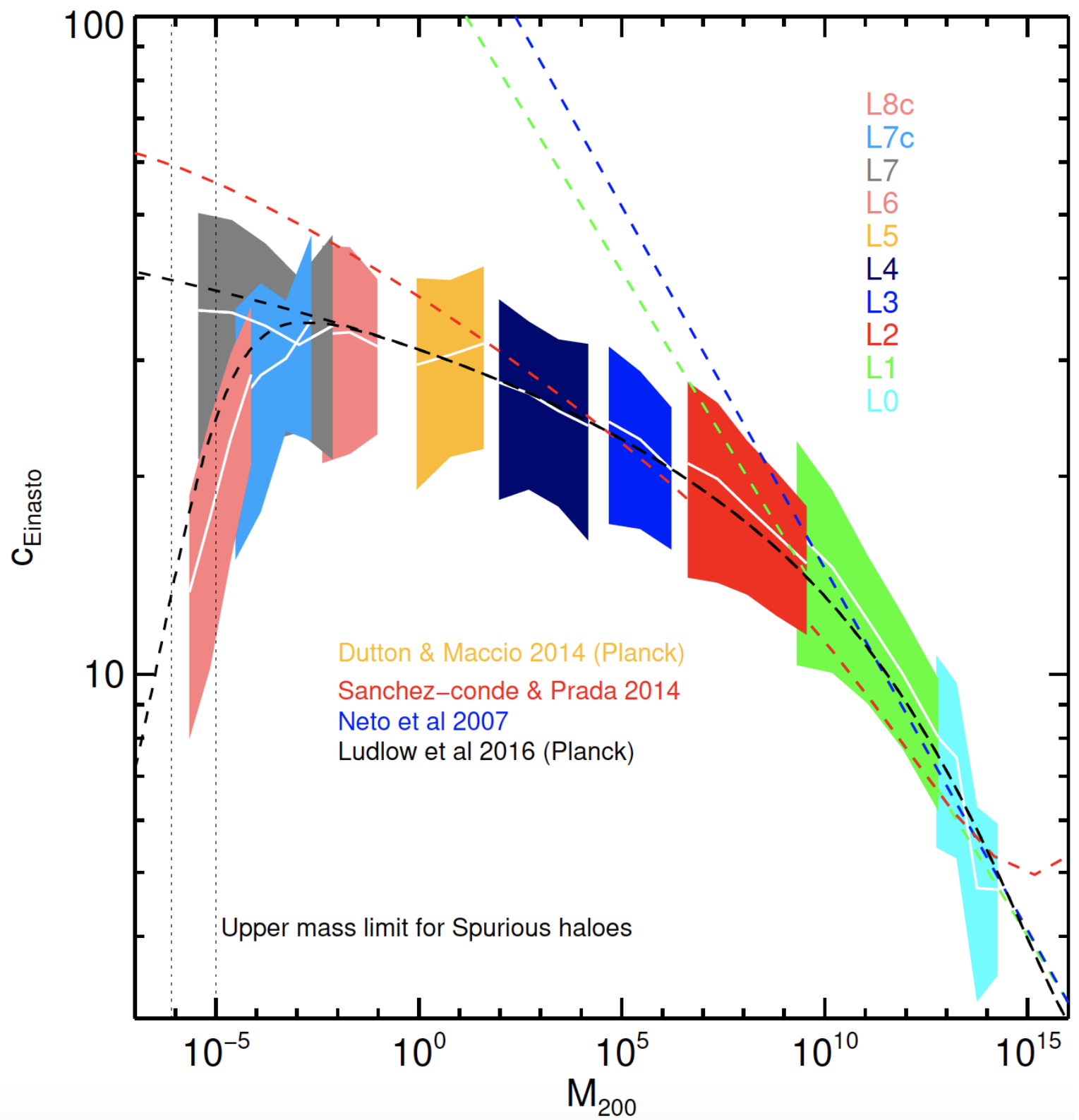
The density profile of one of the most massive halos in each simulation compared to that of the same halo in the parent simulation



Density profile shapes

Over 19 orders of magnitude in halo mass and 4 orders of magnitude in halo density, the mean density profiles of halos are fit by NFW to within 20% and by Einasto with $\alpha = 0.15$ to within 7%

Wang, Bose et al 2019



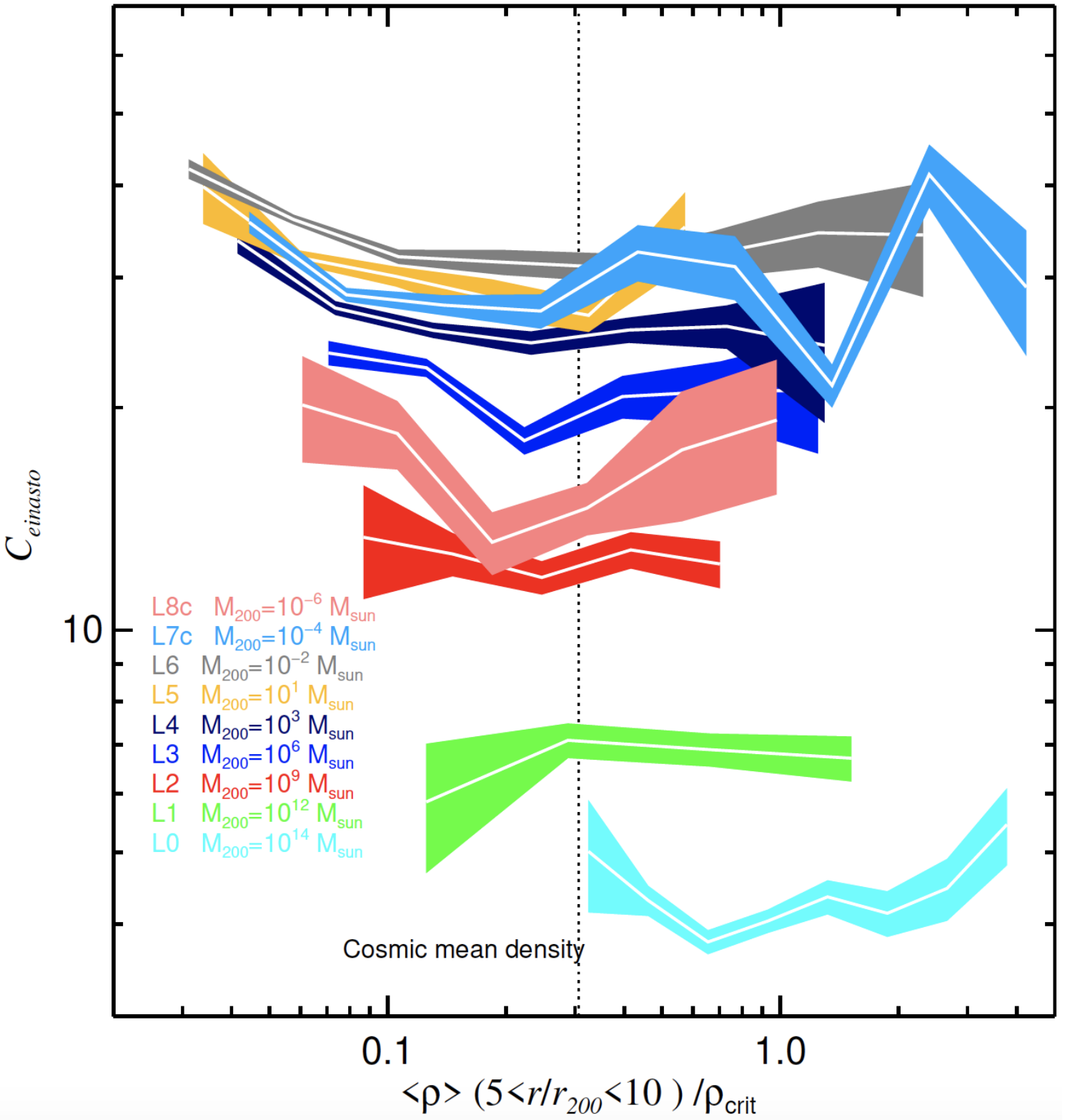
Concentration-mass relation

Over the full 20 orders of magnitude probed, the relation of Ludlow et al (2016) is followed quite closely.

There is a turndown at 1000 Earth masses due to the free-streaming limit.

The scatter does not depend strongly on halo mass.

Wang, Bose et al 2019

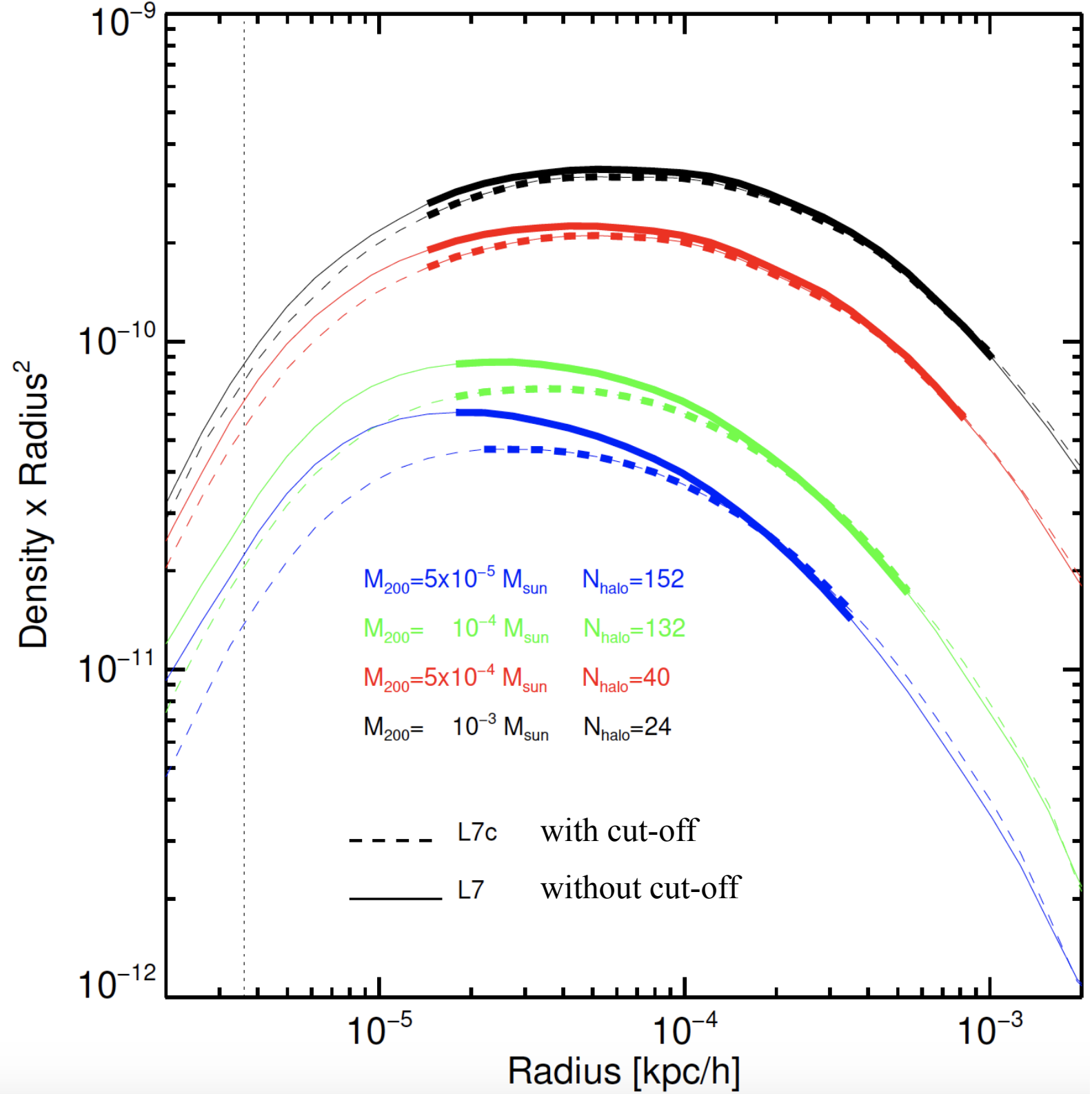


Concentration-density relation

At given halo mass, concentration does not depend on *local* environment density.

The *range* of local environment density does not depend strongly on halo mass

Wang, Bose et al 2019



Free-streaming effects on halo density profiles

The concentration of halos near the cut-off mass is reduced by free-streaming

Wang, Bose et al 2019

To conclude...

- The *typical* DM density in the Universe (also that in the environment of low-mass halos) is *much* less than the mean and depends on the nature of the DM, $\sim 0.004 \langle \rho \rangle$ for a 100 GeV WIMP

- Halos of all masses have NFW-like profiles at $z = 0$ with a mass-concentration relation much shallower than most of those published

- At high resolution, low-density regions of the universe form topologically *isolated* single-stream regions bounded by sheet-like caustics.