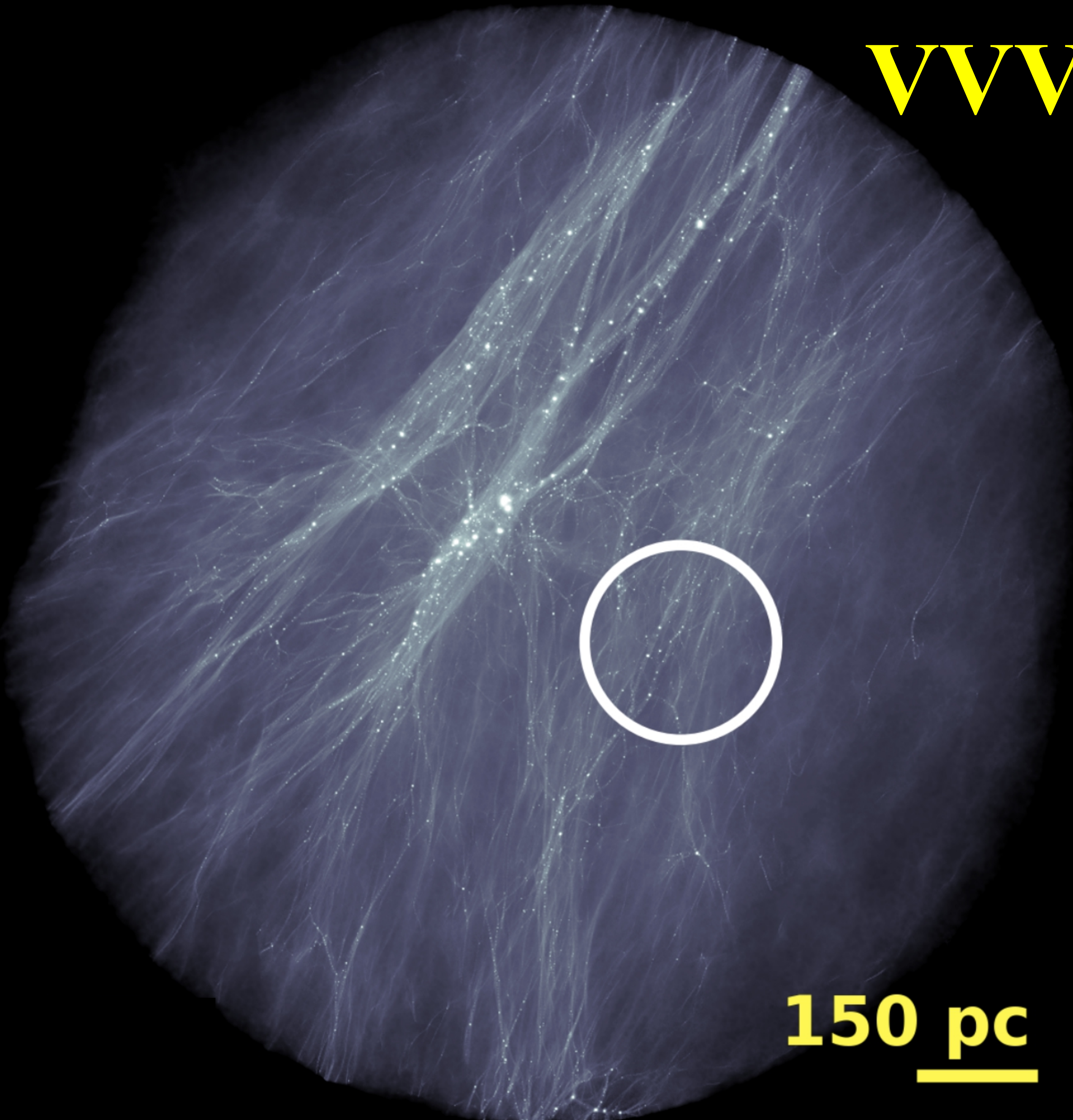
VVV at Virgo



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

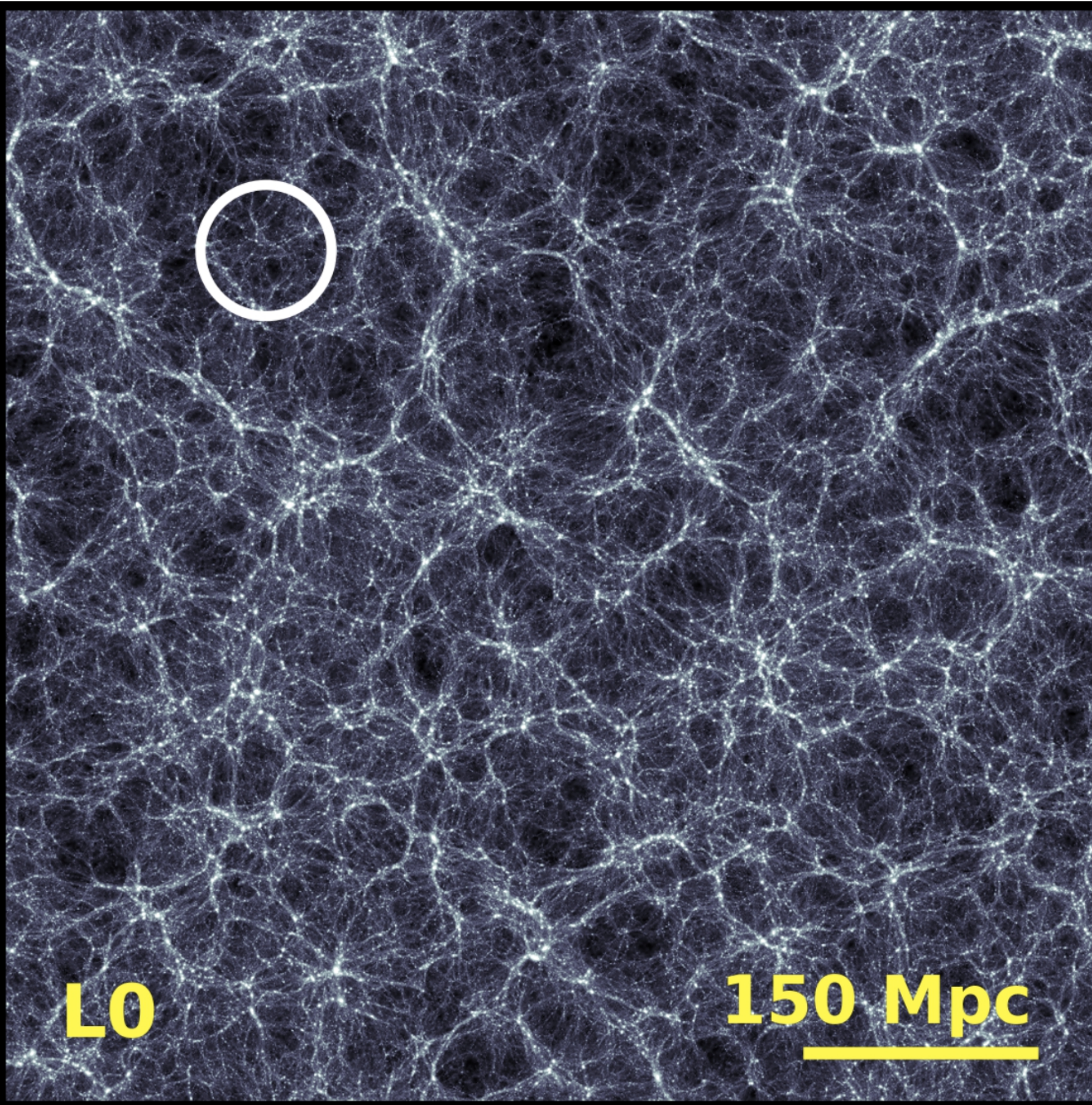
The Voids in Voids in Voids Simulation

Goal: To simulate the structure of a representative set of isolated field halos at $z = 0$ with good resolution over the full halo mass range that should be populated if CDM is a 100 GeV WIMP: $-6 < \log M_{halo} < 15$

Challenges: Dynamic range!
~21 orders of magnitude in halo mass
~7 orders of magnitude in halo radius/velocity disp.

An isolated Earth mass halo at $z = 0$ has internal velocities ~10 cm/s but bulk velocity ~100 km/s
→ Local forces are $\sim 10^{-6}$ of total forces

<1% of initial (Lagrangian) space gives rise to "field" regions containing isolated low-mass halos



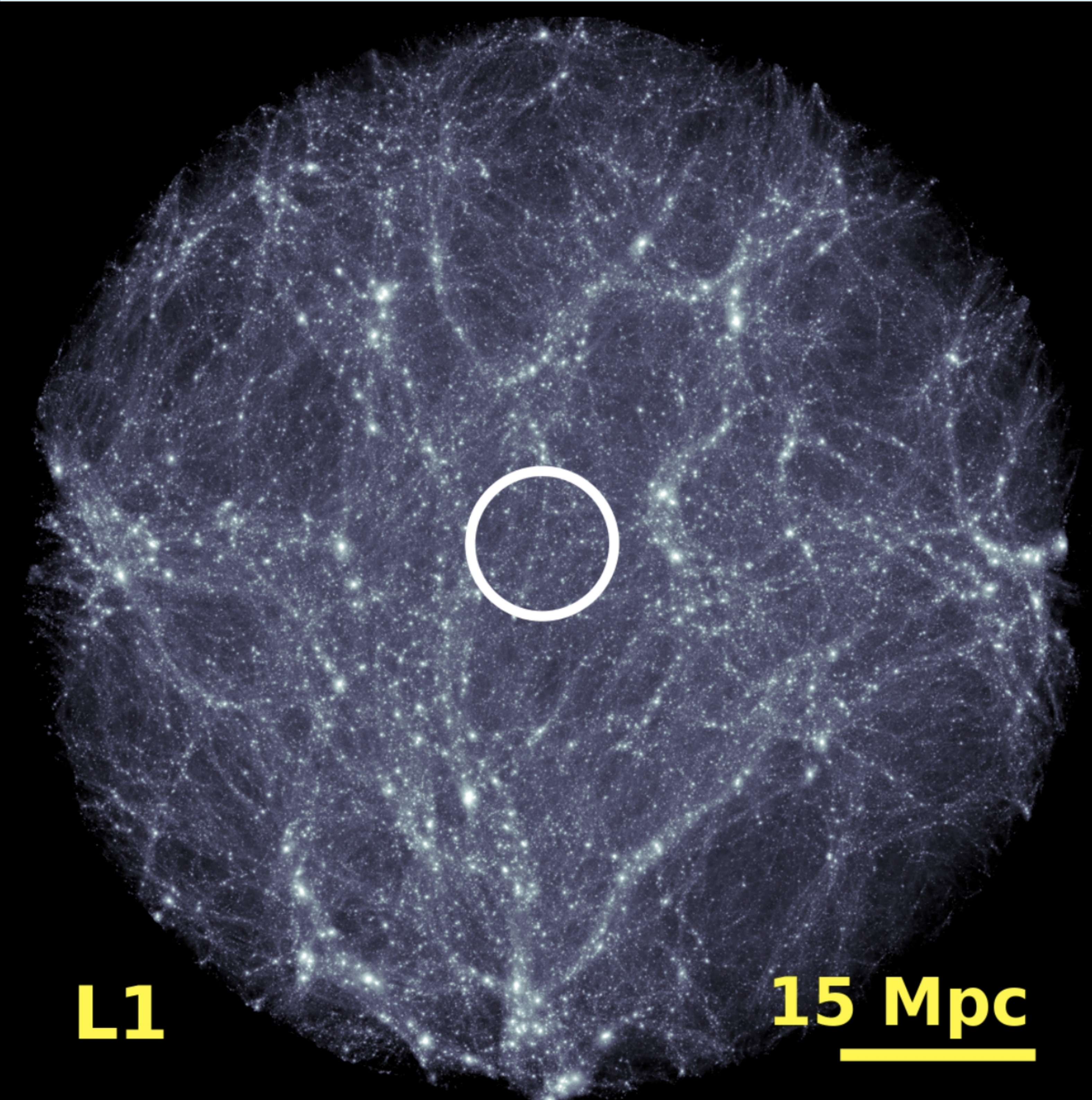
The VVV simulation

Planck cosmology

Dark matter only

Dynamic range of 30 orders of magnitude in mass

Base Level



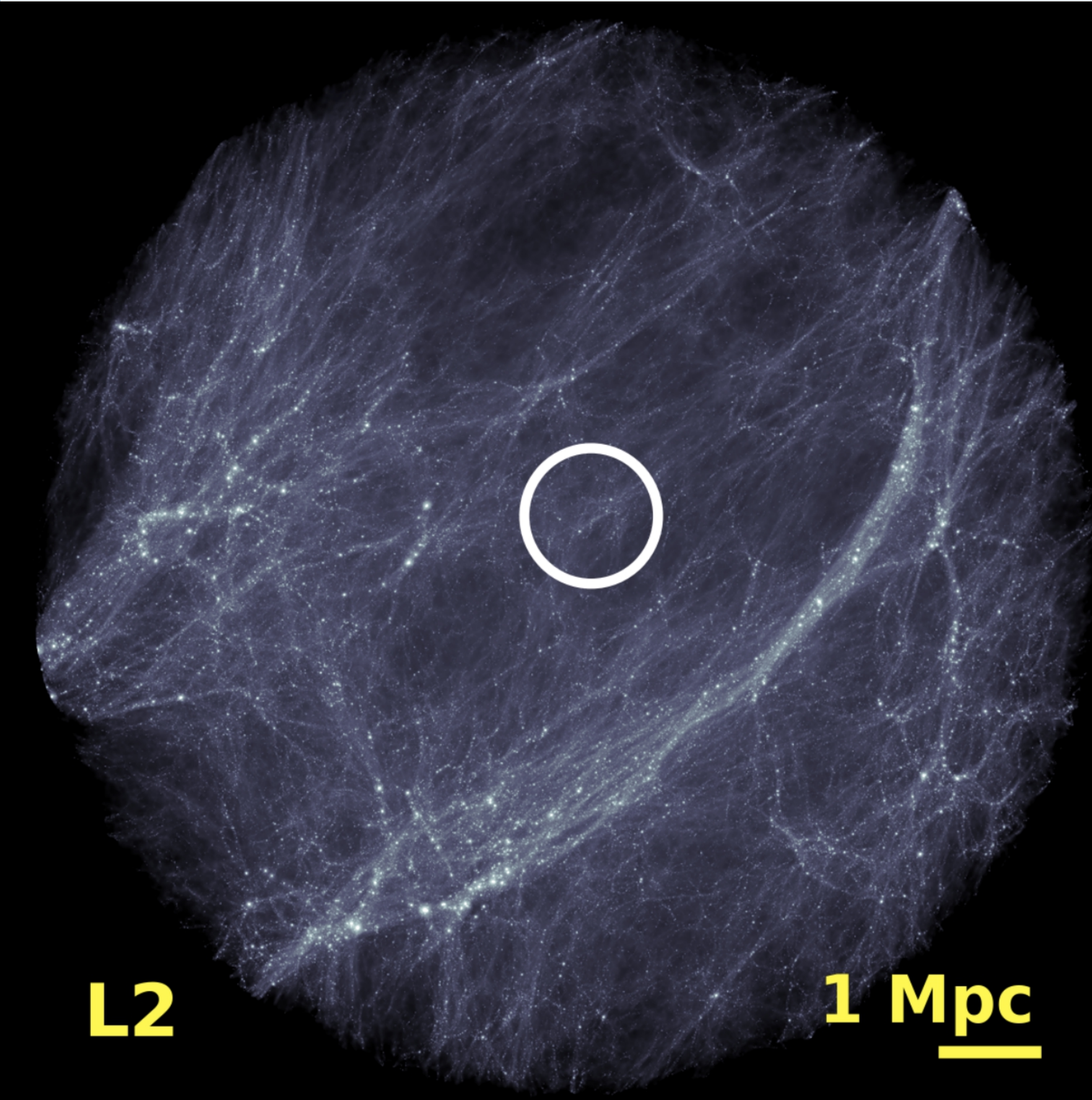
The VVV simulation

Planck cosmology

Dark matter only

Dynamic range of 30 orders of magnitude in mass

Zoom Level 1



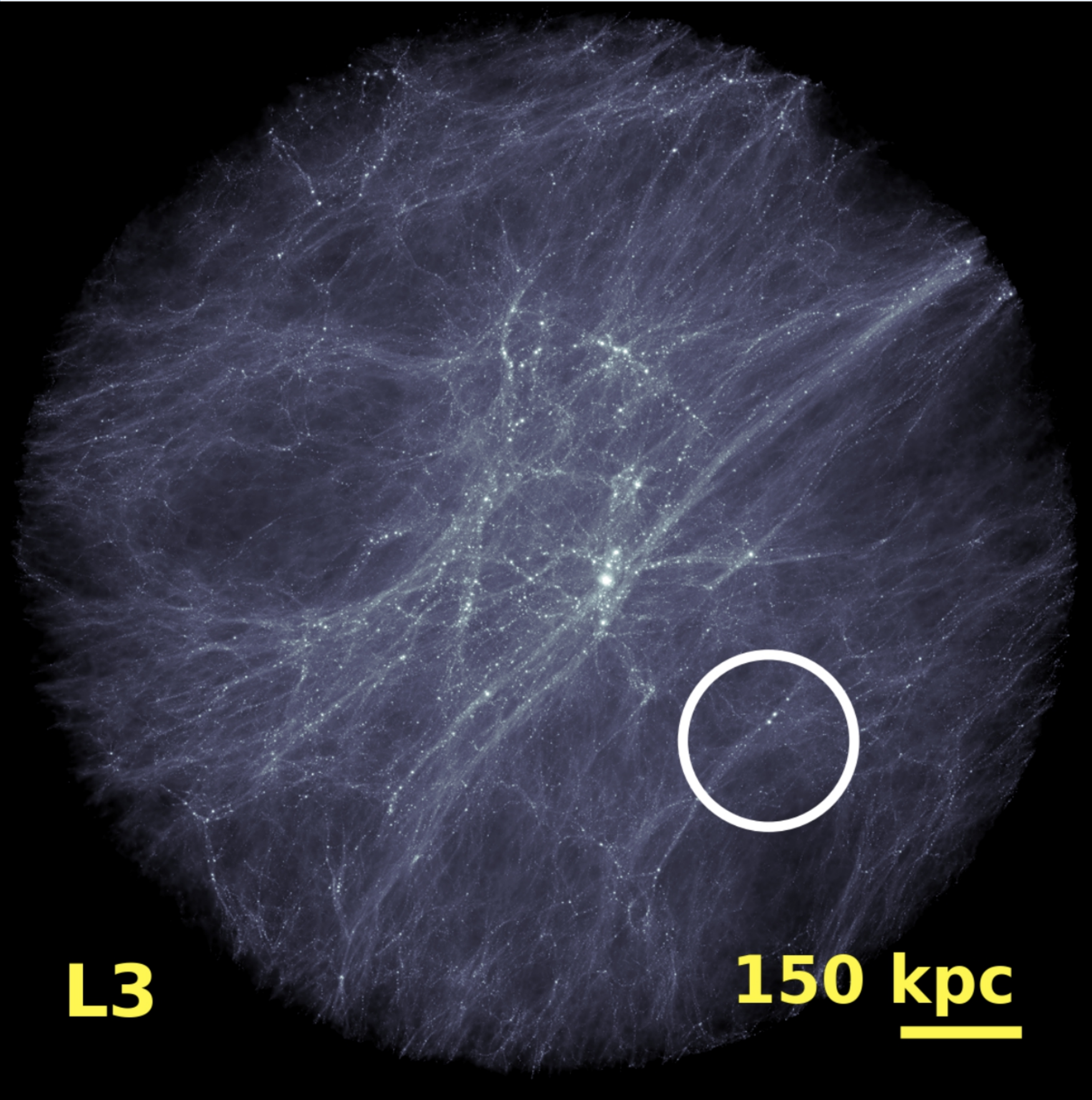
The VVV simulation

Planck cosmology

Dark matter only

Dynamic range of 30 orders of magnitude in mass

Zoom Level 2



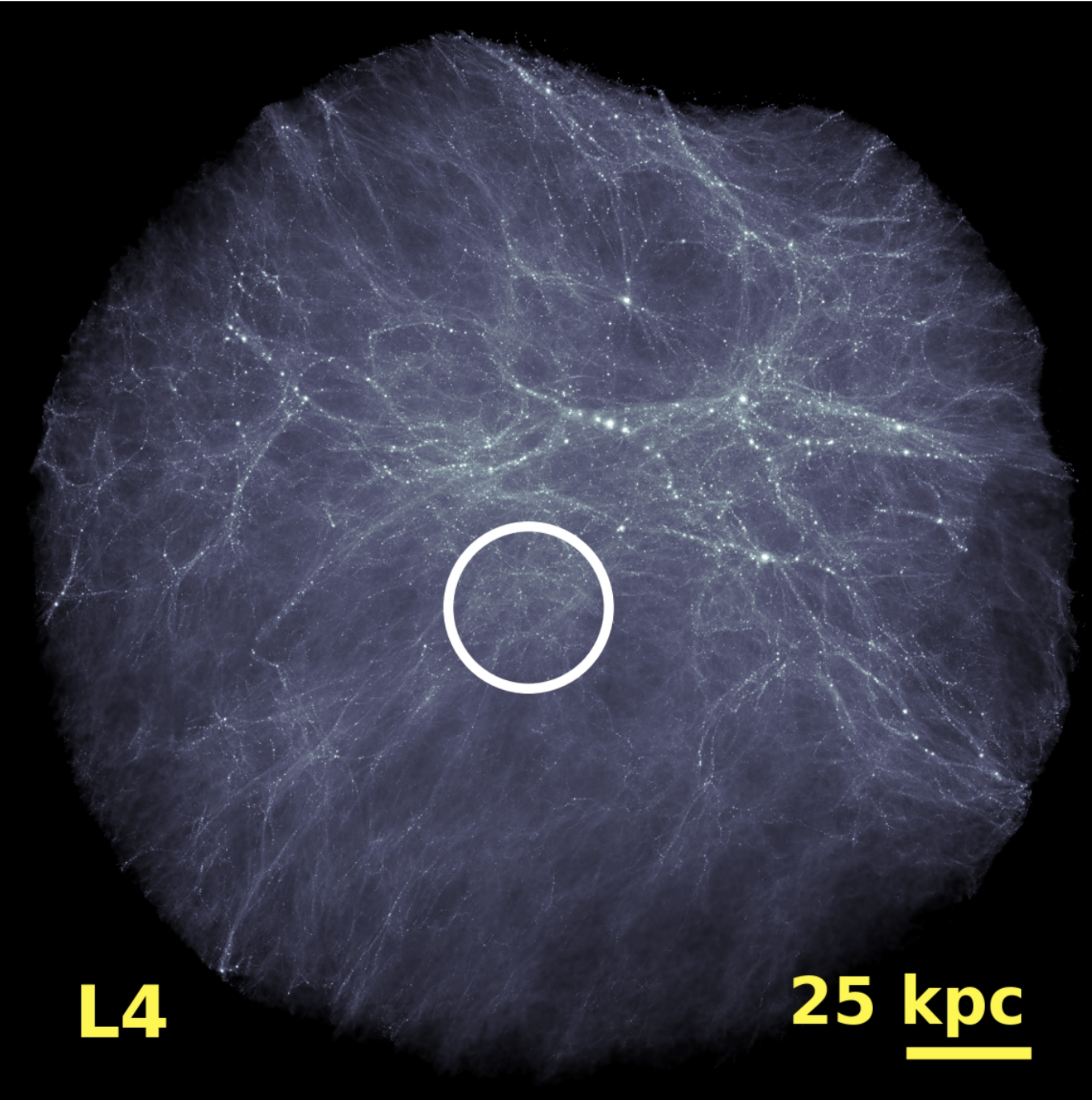
The VVV simulation

Planck cosmology

Dark matter only

Dynamic range of 30 orders of magnitude in mass

Zoom Level 3



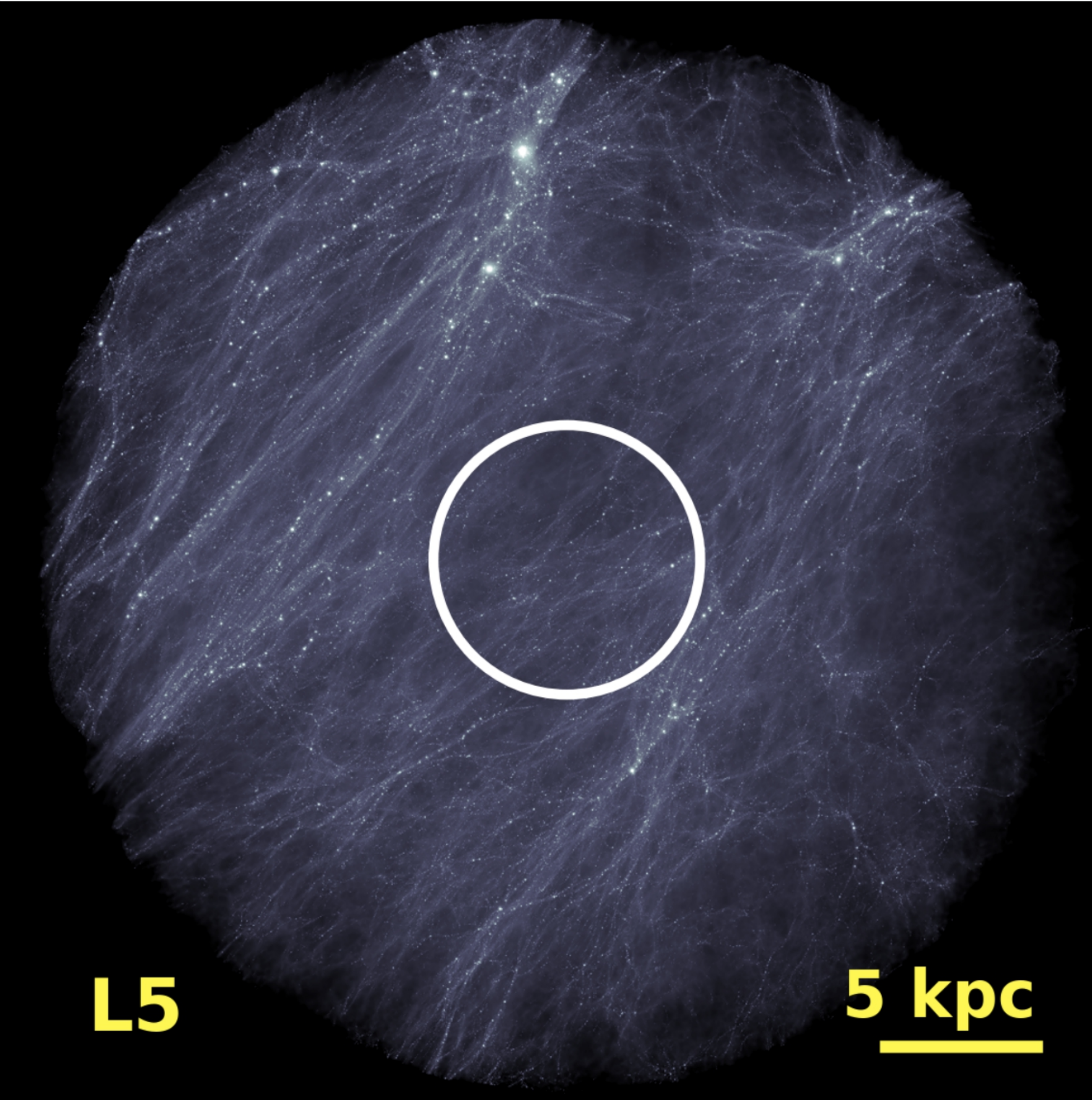
The VVV simulation

Planck cosmology

Dark matter only

Dynamic range of 30 orders of magnitude in mass

Zoom Level 4



The VVV simulation

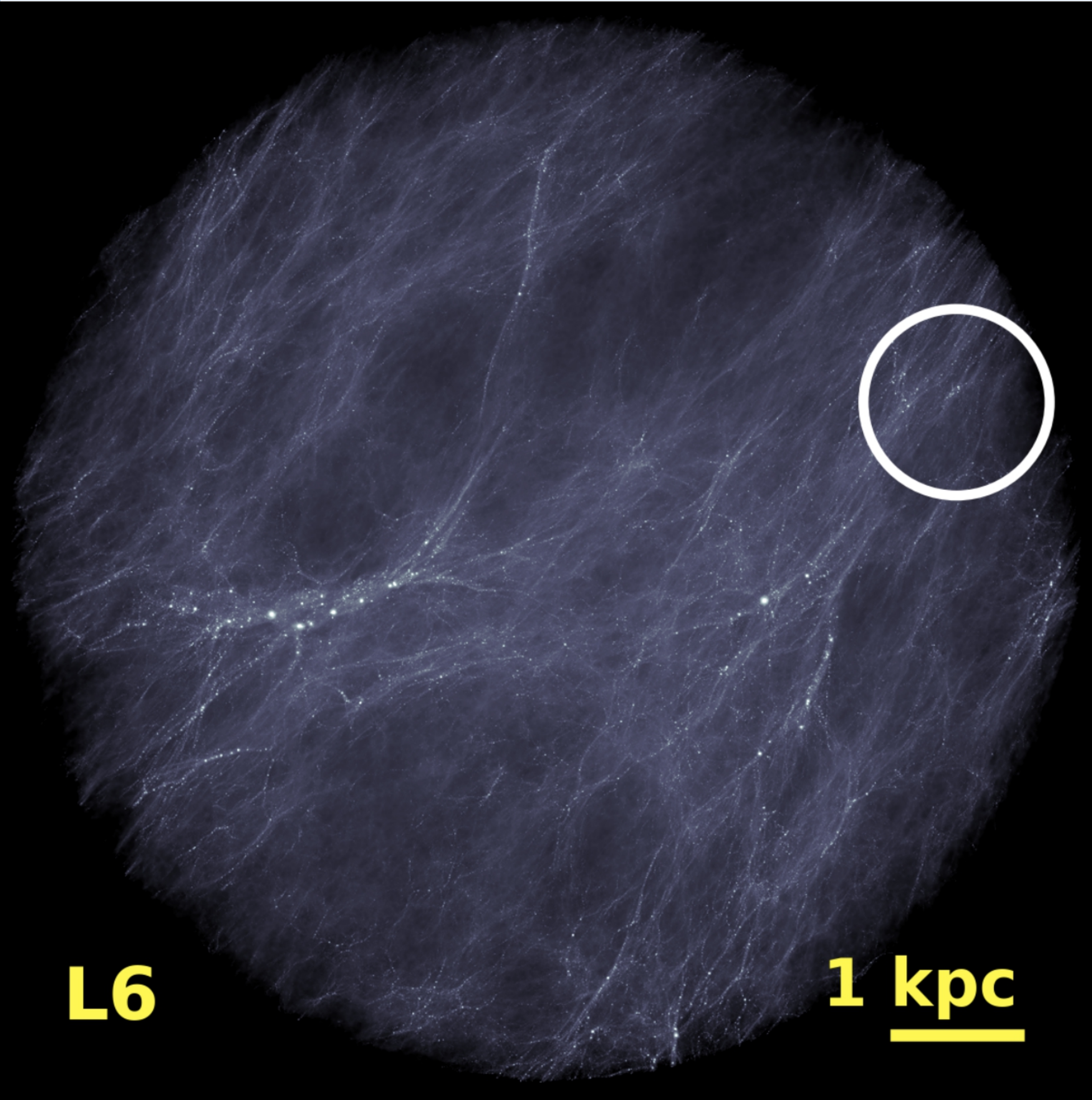
Planck cosmology

Dark matter only

Dynamic range of 30 orders of magnitude in mass

Zoom Level 5

The VVV simulation

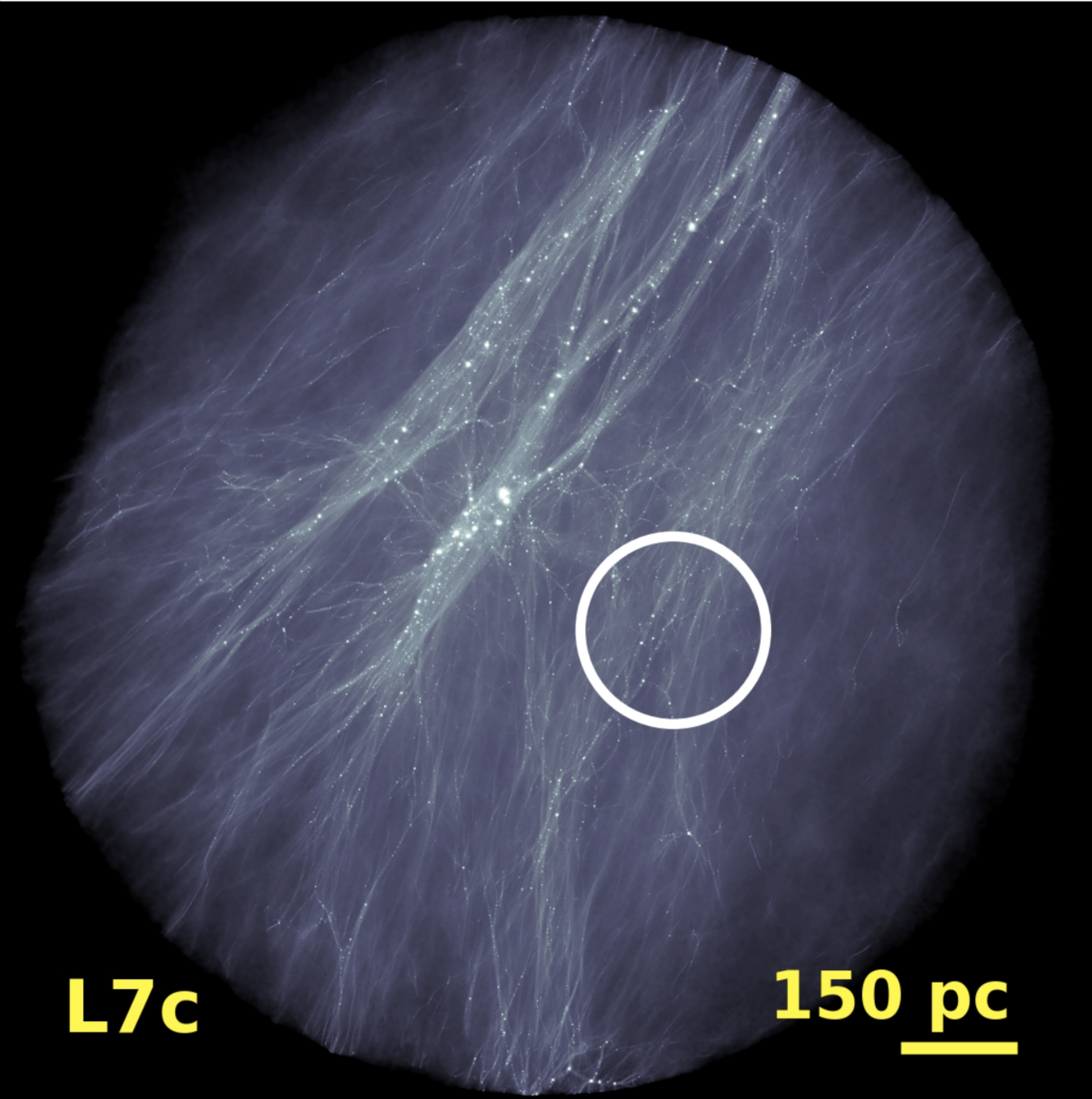


Planck cosmology

Dark matter only

Dynamic range of 30 orders of magnitude in mass

Zoom Level 6



The VVV simulation

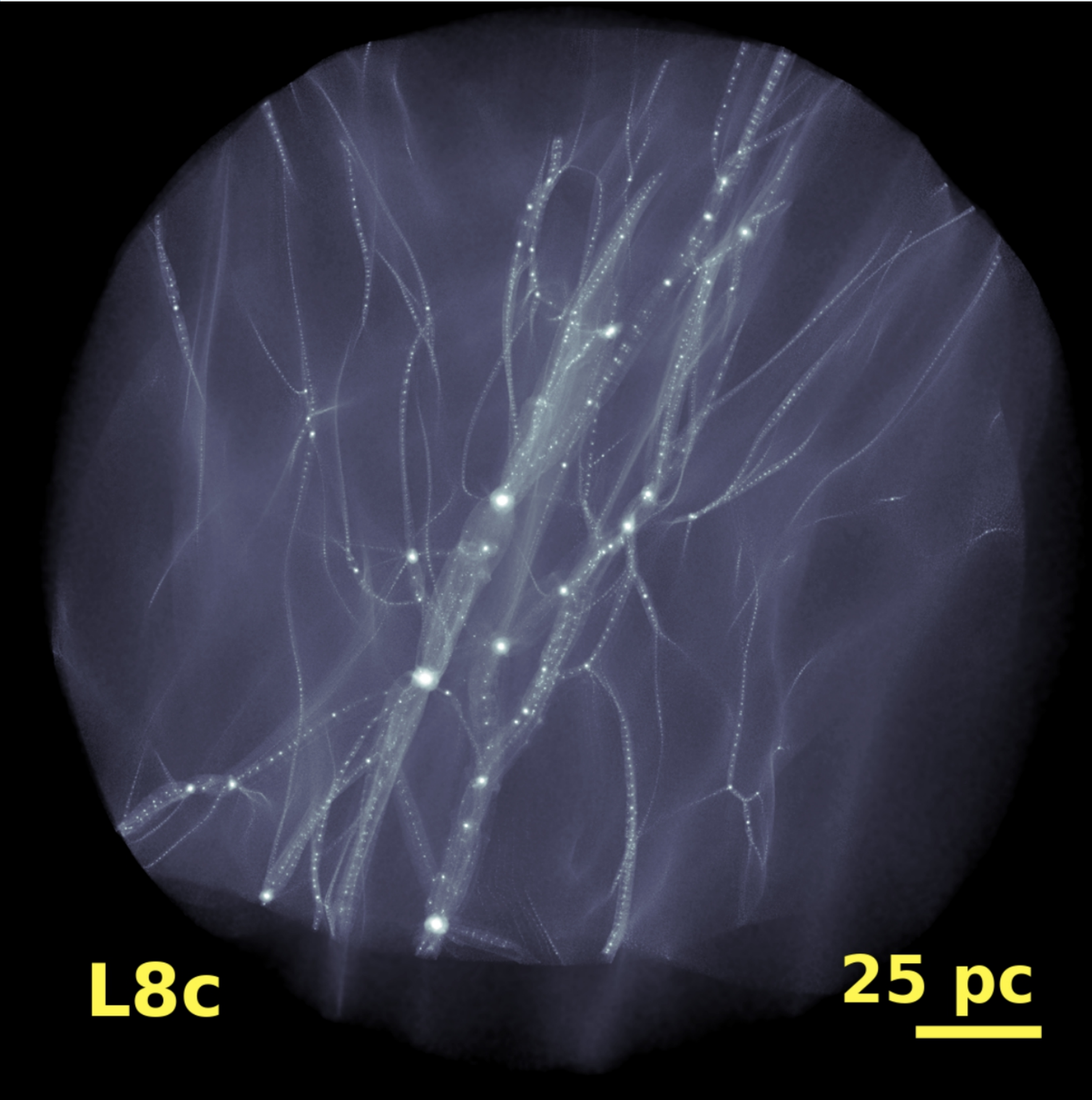
Planck cosmology

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

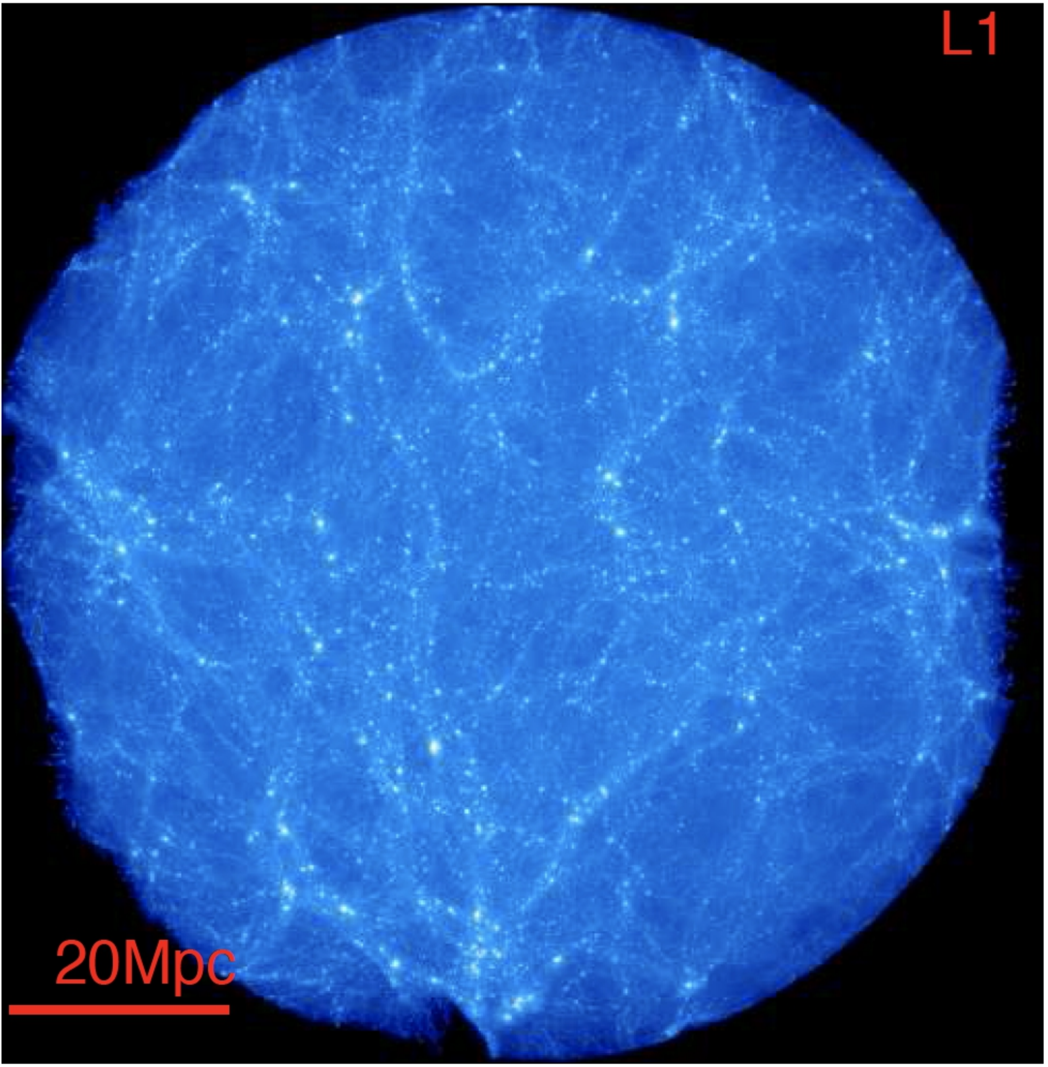
The various levels of the VVV simulation

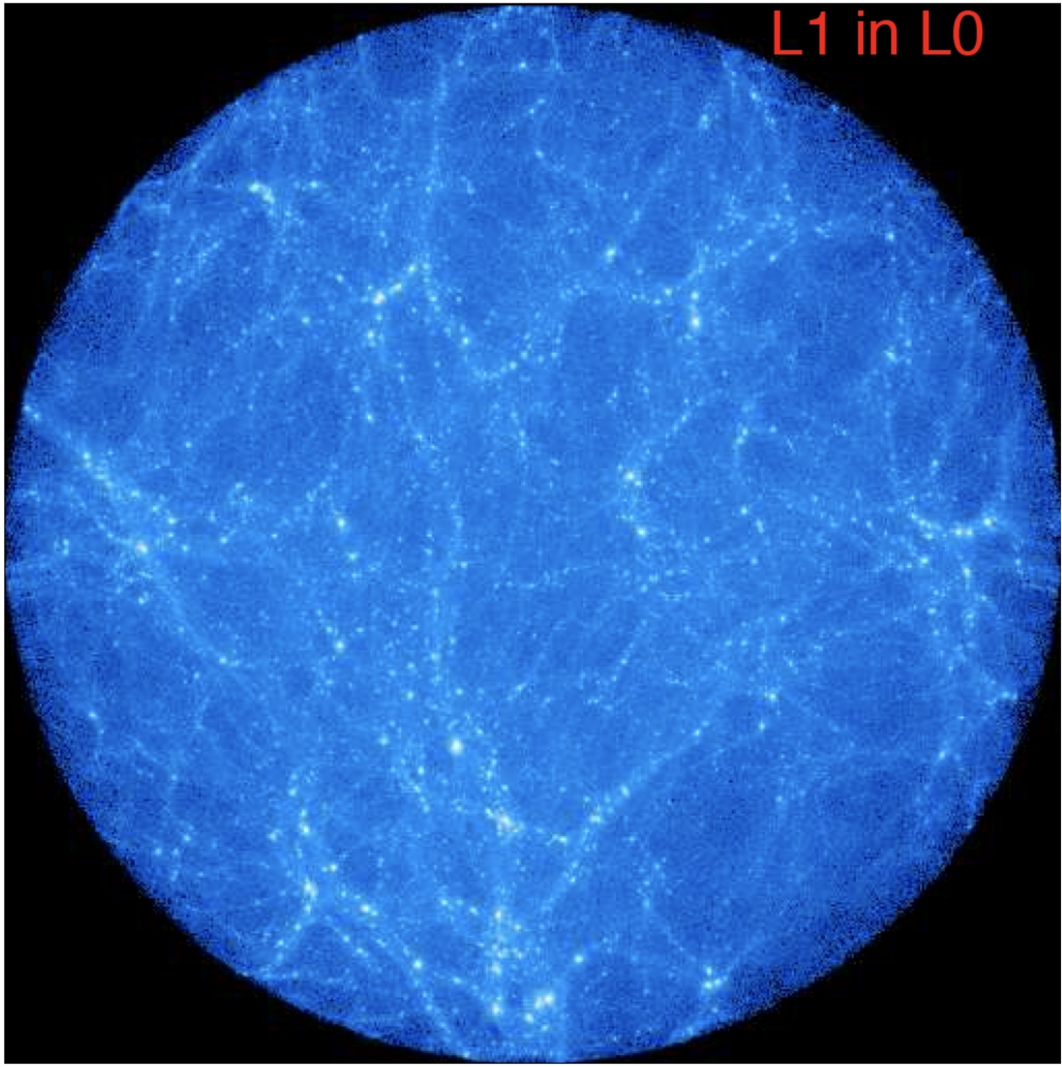
level	R_{high} [Mpc]	n_p	ε [kpc]	m_p [$M_\odot$]	$\langle\rho\rangle/\rho_{mean}$	M_{char} [$M_\odot$]	N_{char}	f_{vir}
L0	738	1.0×10^{10}	7.4	1.5×10^{9}	1.0	10^{14}	127	0.92
L1	52	1.0×10^{10}	4.4×10^{-1}	7.4×10^{5}	0.39	10^{12}	59	0.91
L2	8.8	5.4×10^{9}	5.6×10^{-2}	1.5×10^{3}	0.082	10^{9}	29	0.93
L3	1.0	1.8×10^{9}	8.3×10^{-3}	2.8	0.036	10^{6}	27	0.94
L4	0.27	2.0×10^{9}	1.0×10^{-3}	5.5×10^{-3}	0.026	10^{3}	59	0.94
L5	0.035	1.5×10^{9}	2.2×10^{-4}	5.8×10^{-5}	0.024	10	30	0.94
L6	0.0066	1.7×10^{9}	3.8×10^{-5}	2.6×10^{-7}	0.014	10^{-1}	35	0.94
L7	0.0011	2.5×10^{9}	5.3×10^{-6}	8.6×10^{-10}	0.016	10^{-4}	201	0.96
L7c	0.0011	2.5×10^{9}	5.3×10^{-6}	8.6×10^{-10}	0.016	10^{-4}	202	0.97
L8c	0.00024	1.5×10^{9}	1.4×10^{-6}	1.6×10^{-11}	0.028	10^{-6}	24	0.94

Total simulation mass and size, 1.5×10^{19} $M_\odot$ and 7.4×10^{8} pc

Smallest particle mass and softening, 1.6×10^{-11} $M_\odot$ and 1.4×10^{-6} pc

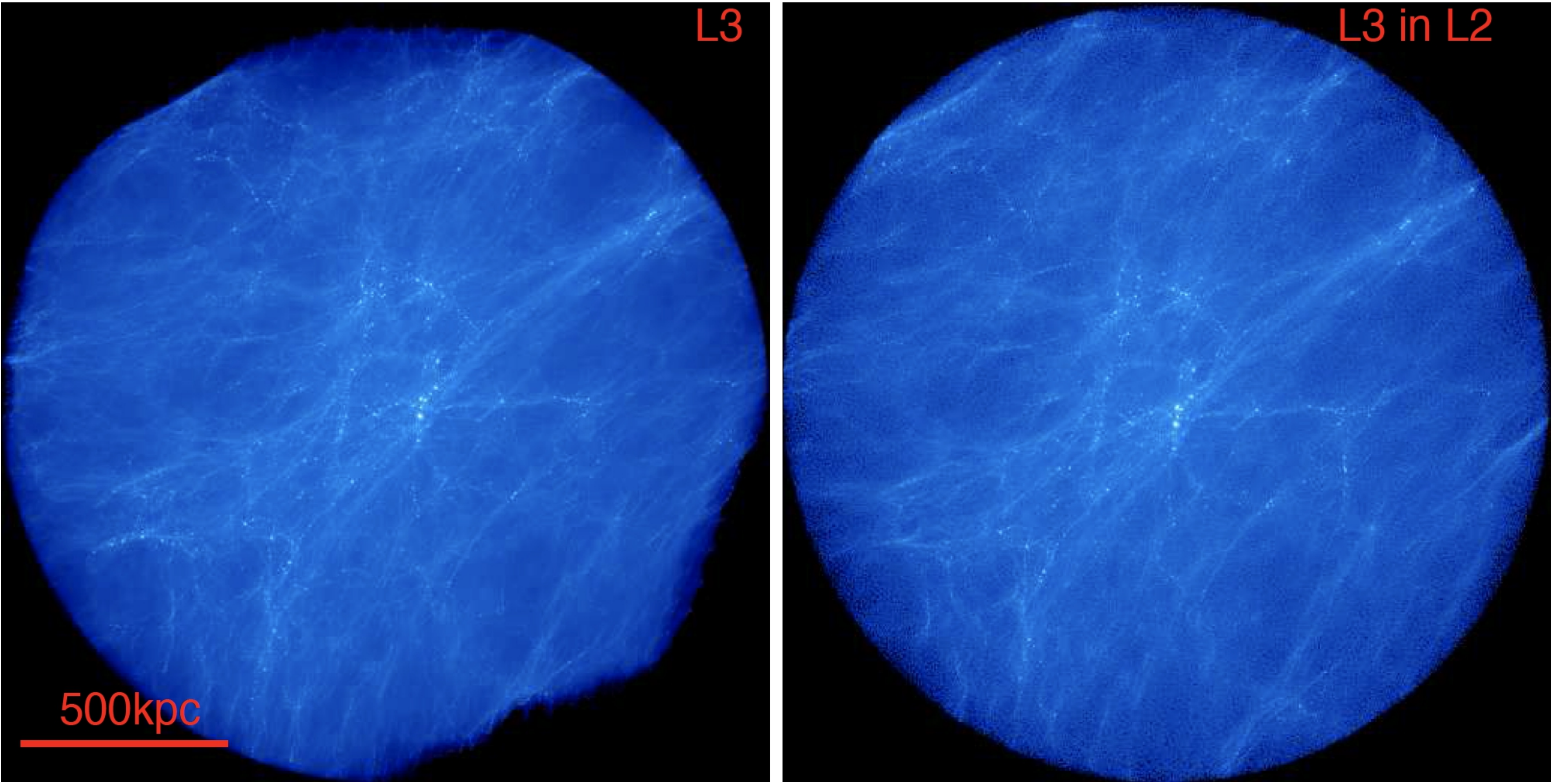
Convergence in halo distribution





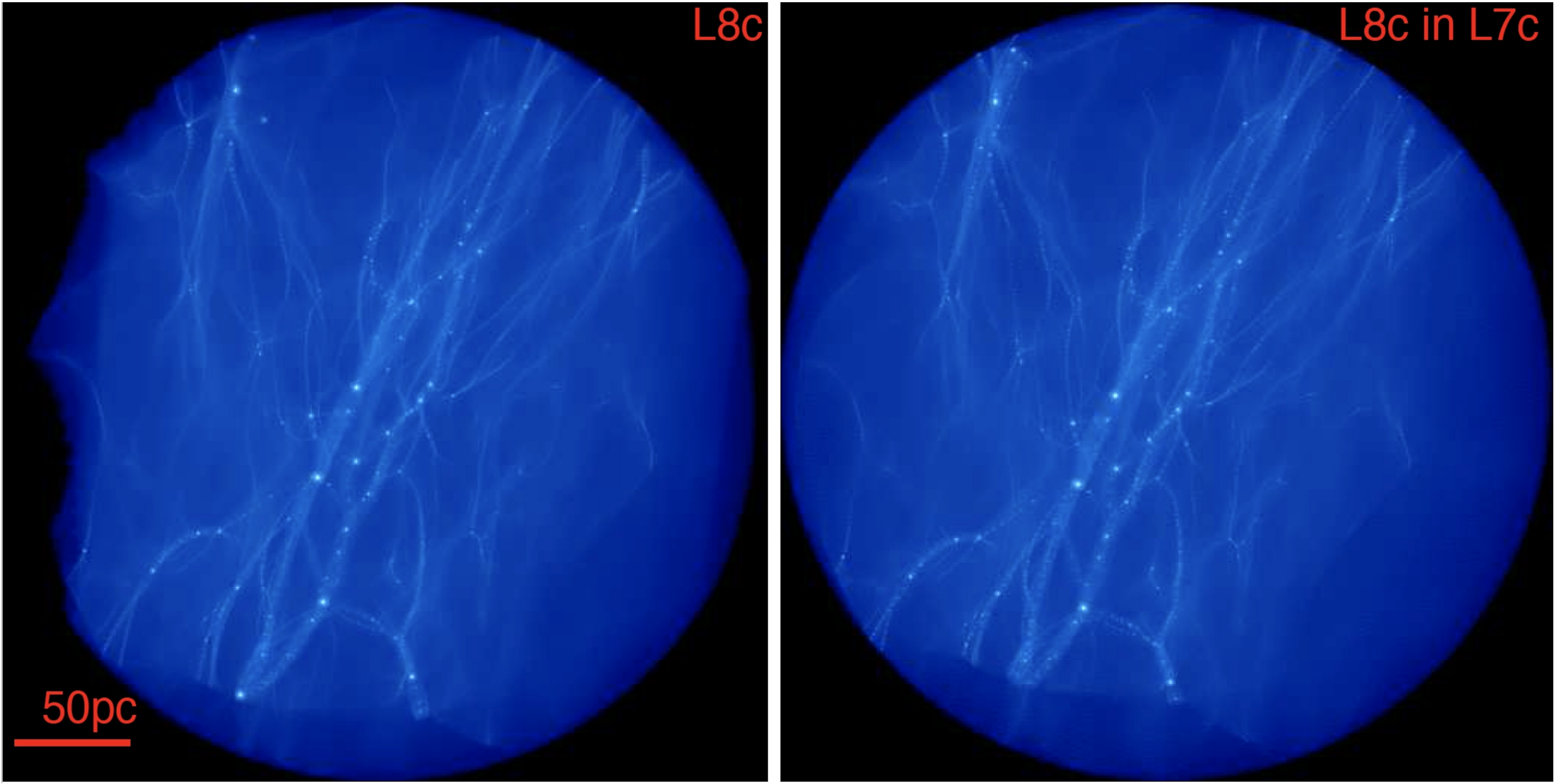
Wang, Bose et al 2019

Convergence in halo distribution



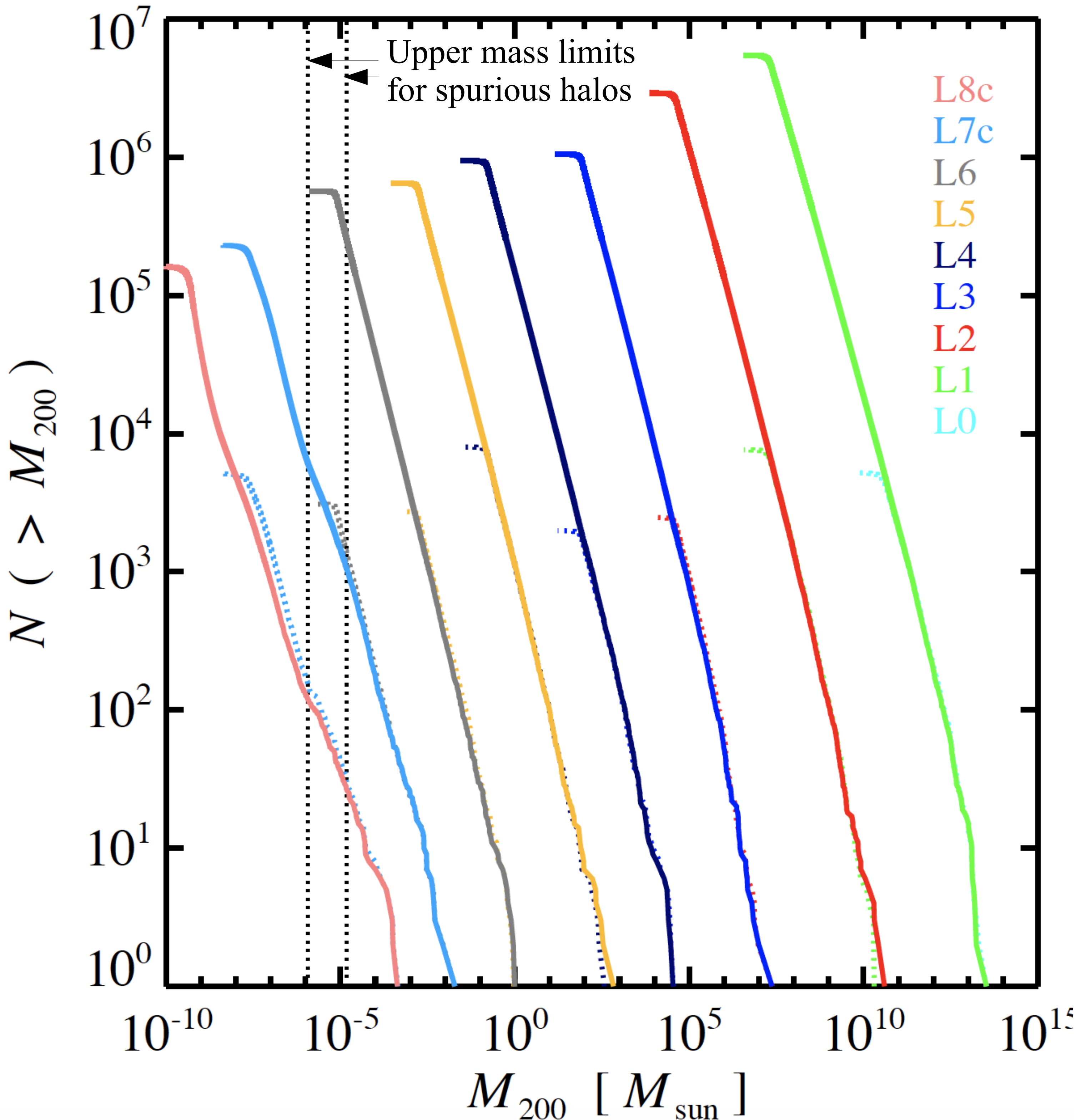
Wang, Bose et al 2019

Convergence in halo distribution



Wang, Bose et al 2019

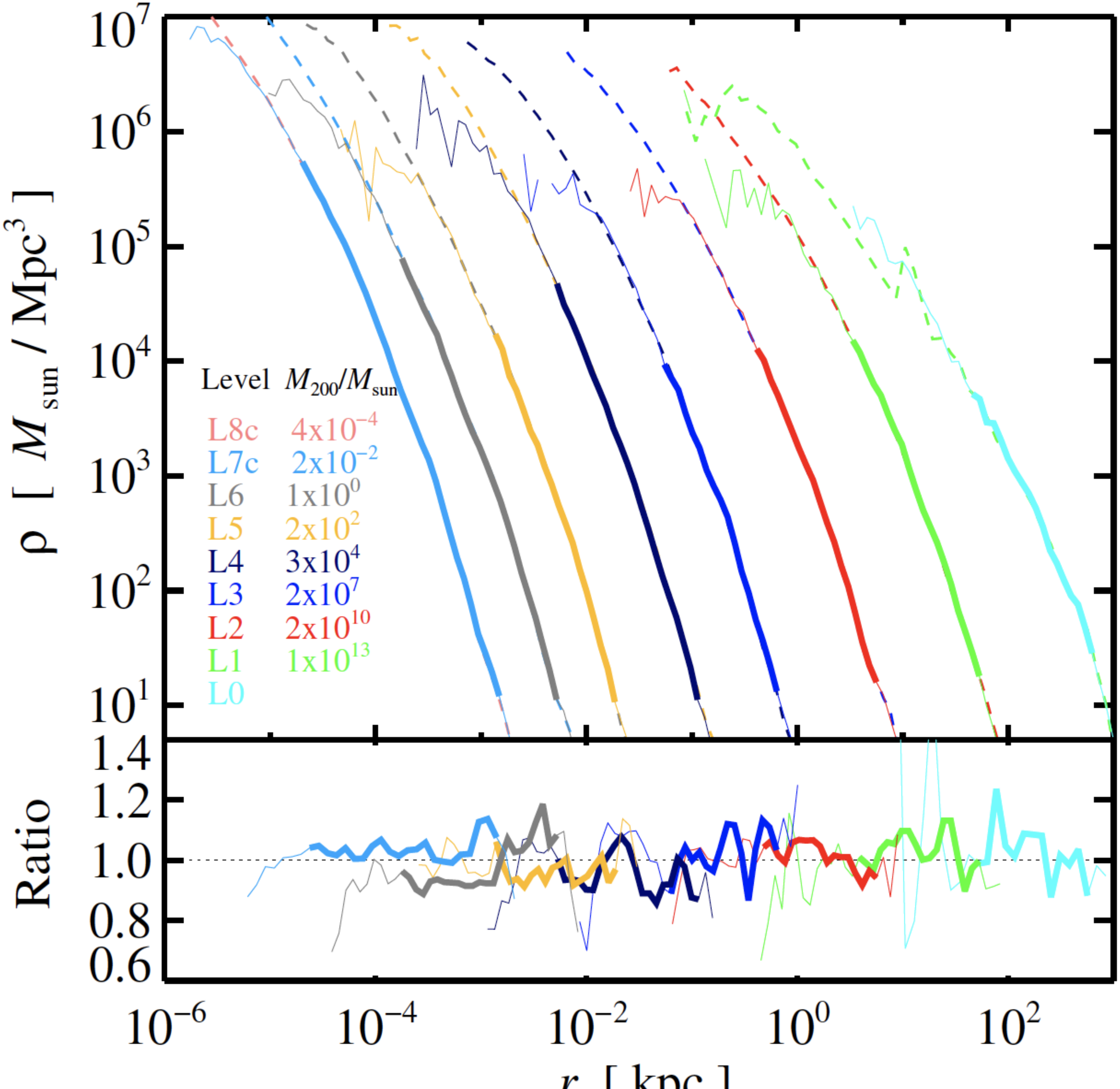
Convergence in halo abundance



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

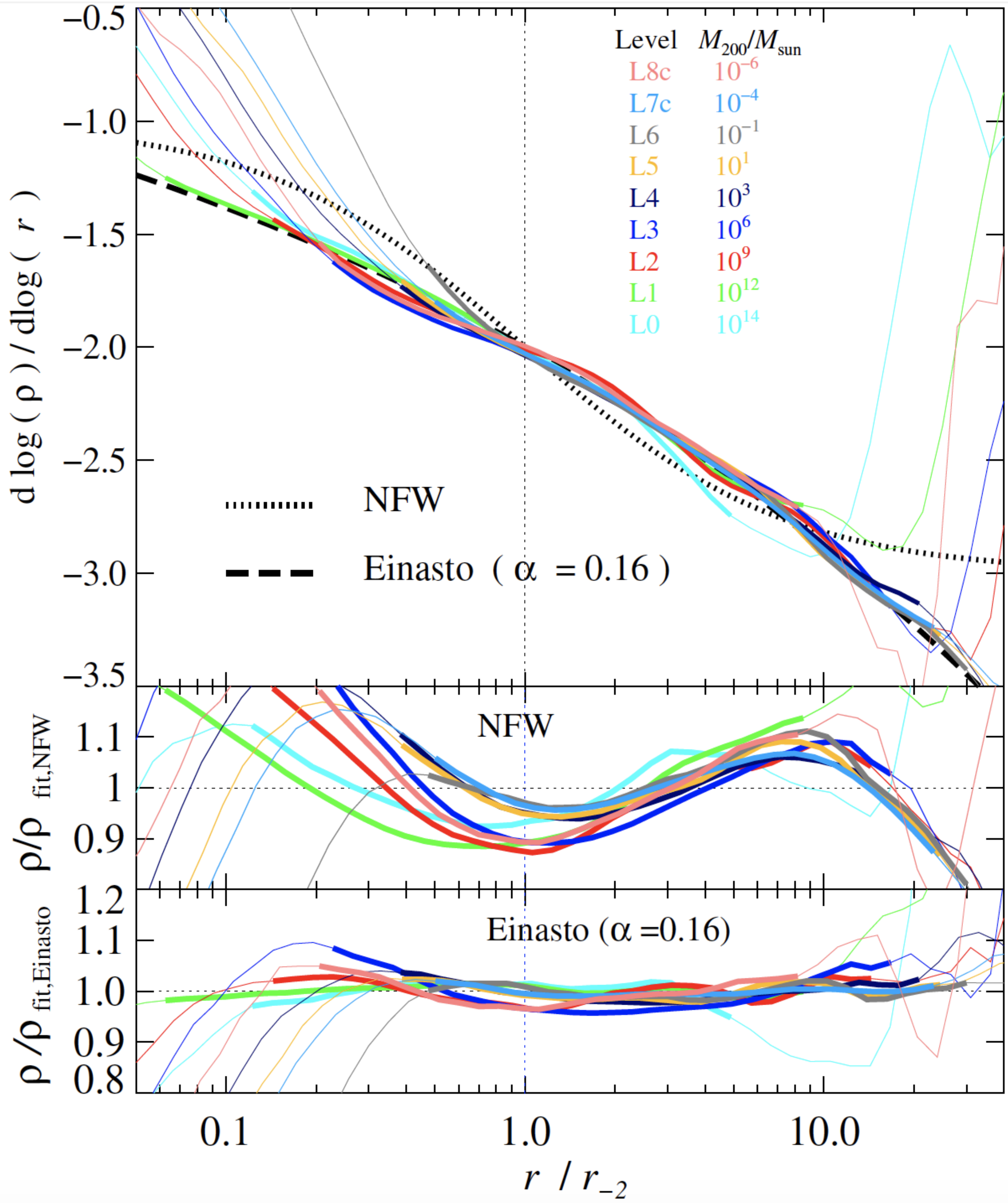
Wang, Bose et al 2019

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

Wang, Bose et al 2019

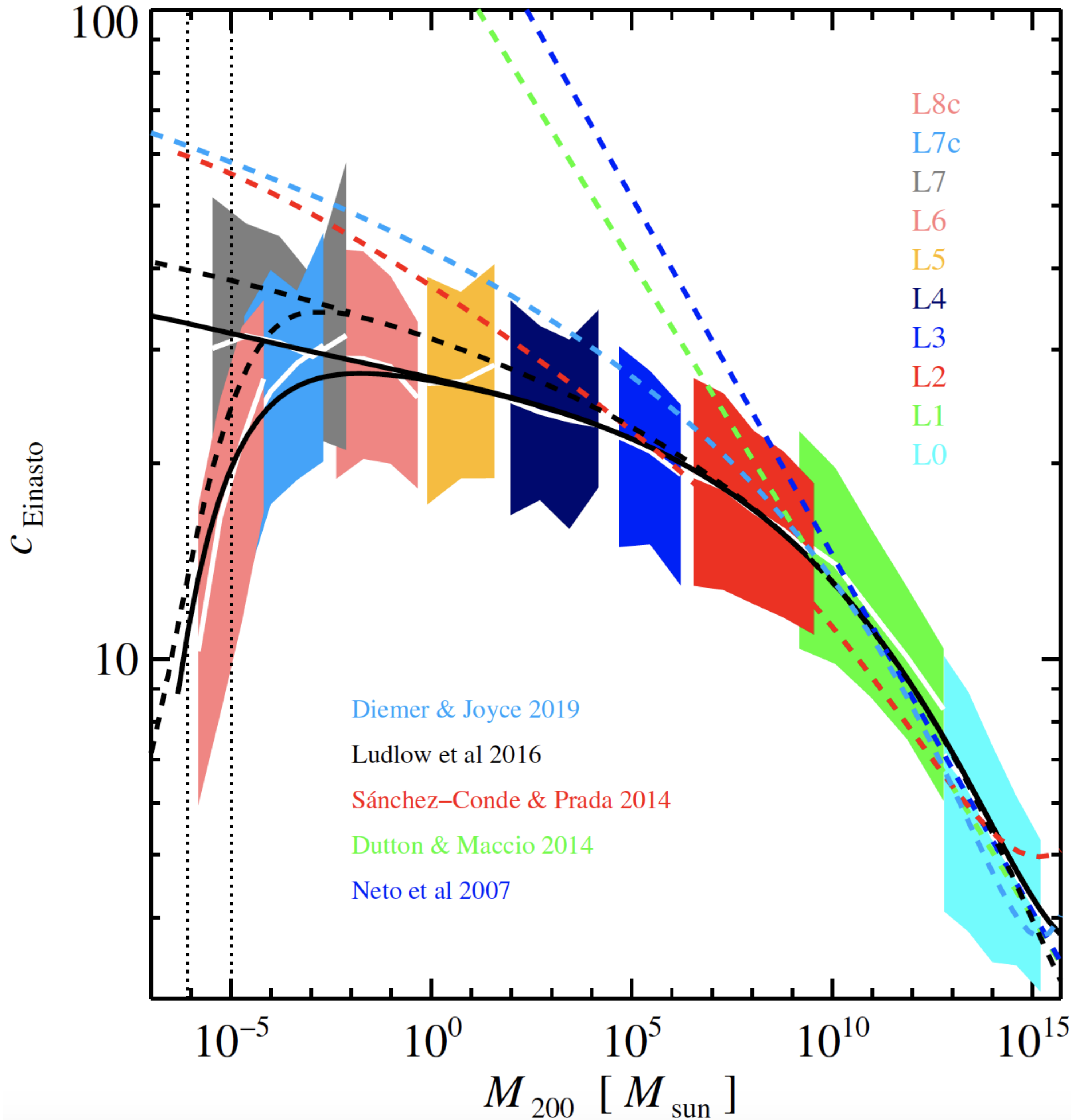


Density profile shapes

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 α = 0.16 to within 7%

Wang, Bose et al 2019

Concentration-mass relation

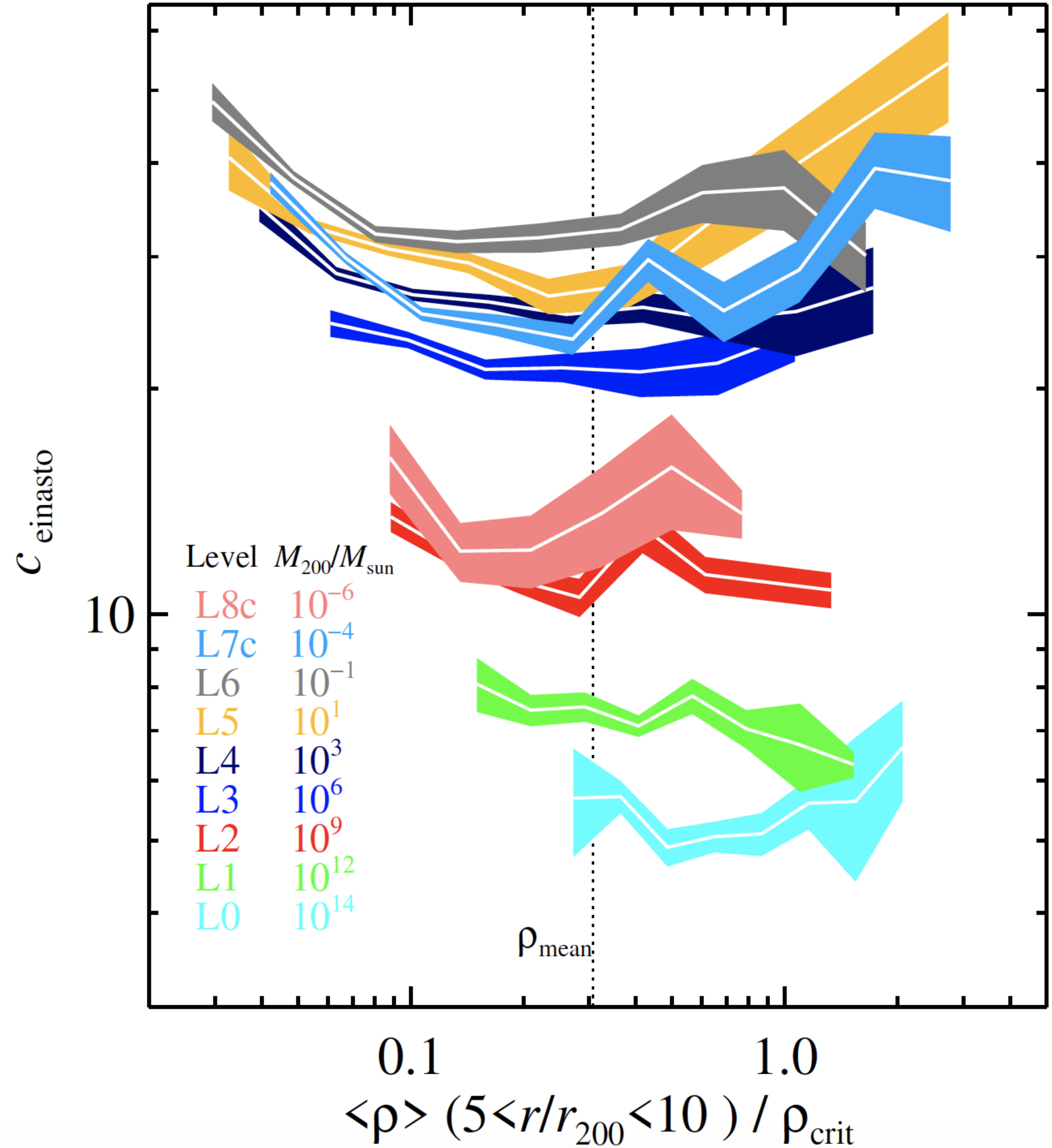


Over the full 20 orders of magnitude probed, the relation of Ludlow et al (2016) is followed quite closely.

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



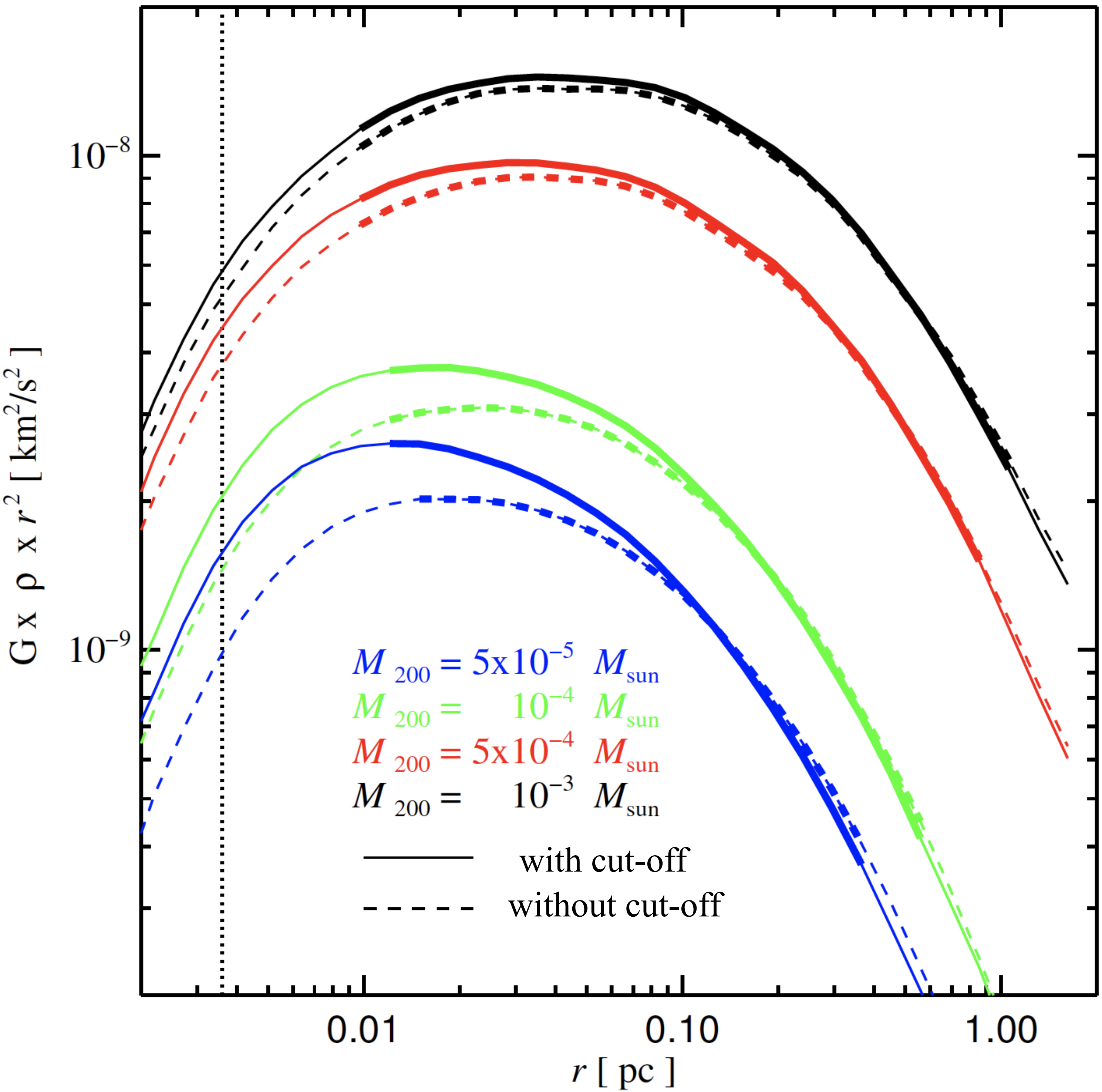
Concentration-density relation

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

The story so far...

- 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

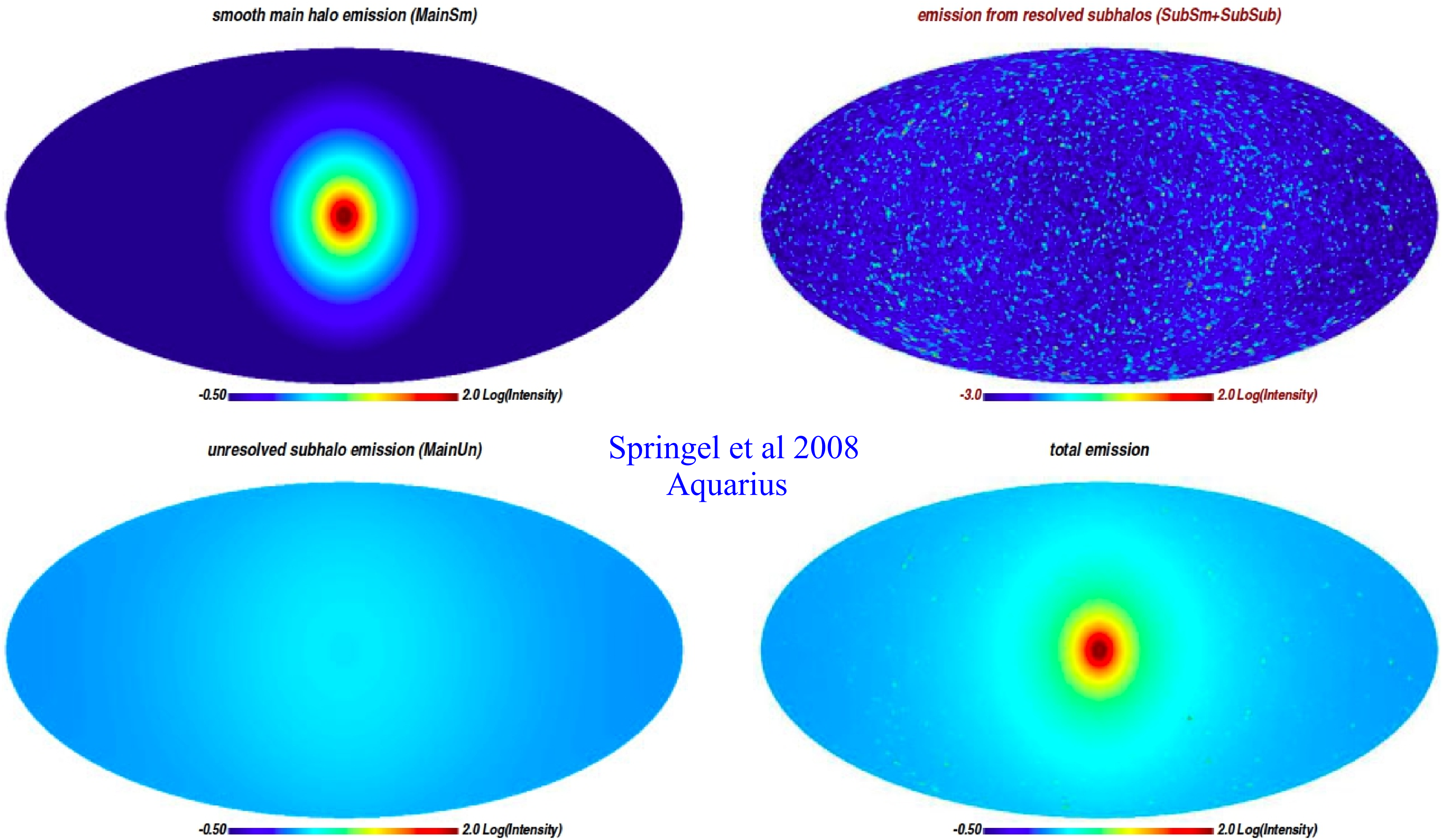
- Halos of all masses have NFW-like profiles at $z = 0$ with a mass-concentration relation much shallower than most of those published

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

The next steps...

- More detailed studies of the central structure of low-mass halos
  - The smallest dark matter halos – cores or cusps? (WDM?)
  - Zoom simulations of individual objects (Bose et al)
  - New numerical methods (Stücker et al)

- Reassessment of expected structure of galaxies in annihilation radiation
  - Effects of baryons on substructures
  - Improved treatment of unresolved substructures
  - Applications both to the Milky Way and M31 (and their dwarfs)



Springel et al 2008
Aquarius

- Halo annihilation flux dominated by that from unresolved small halos but this is nearly uniform over the sky
- Flux from the Galactic centre dominates that from resolved subhalos by a large factor, but relative detectability depends critically on noise sources