Voids-in-Voids-in-Voids(VVV) project:

Dark matter halo profiles over 20 orders of magnitude in halo mass

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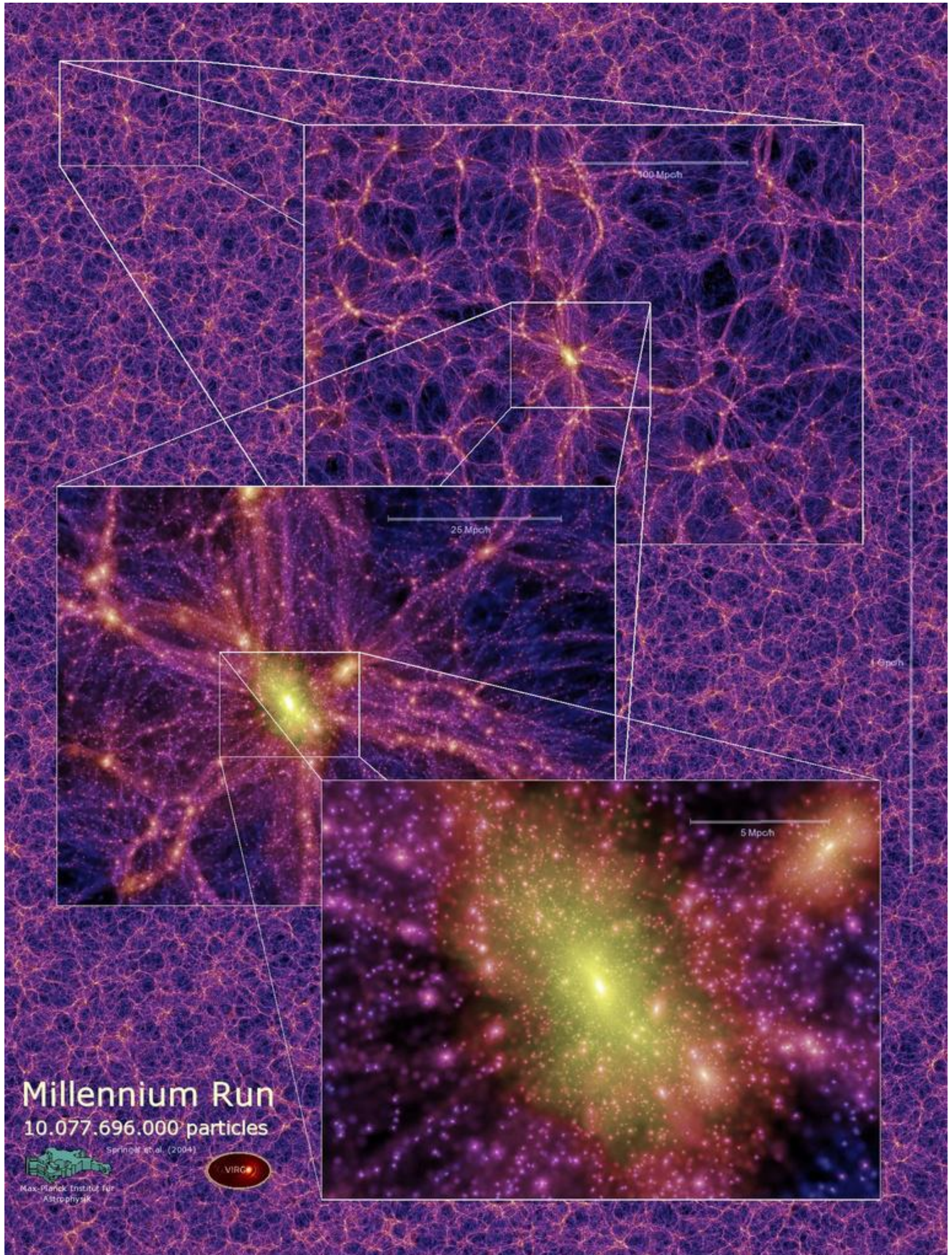
Outline

- ✓A fancy Simulation - A hard job

  The hardest job ever done --- Adrian Jenkins

- ✓ *A universal dark matter density profile over 20 orders of* magnitude in halo mass

- ✓ A useful fitting Function



What we have learn on the dark matter halo from the simulations?

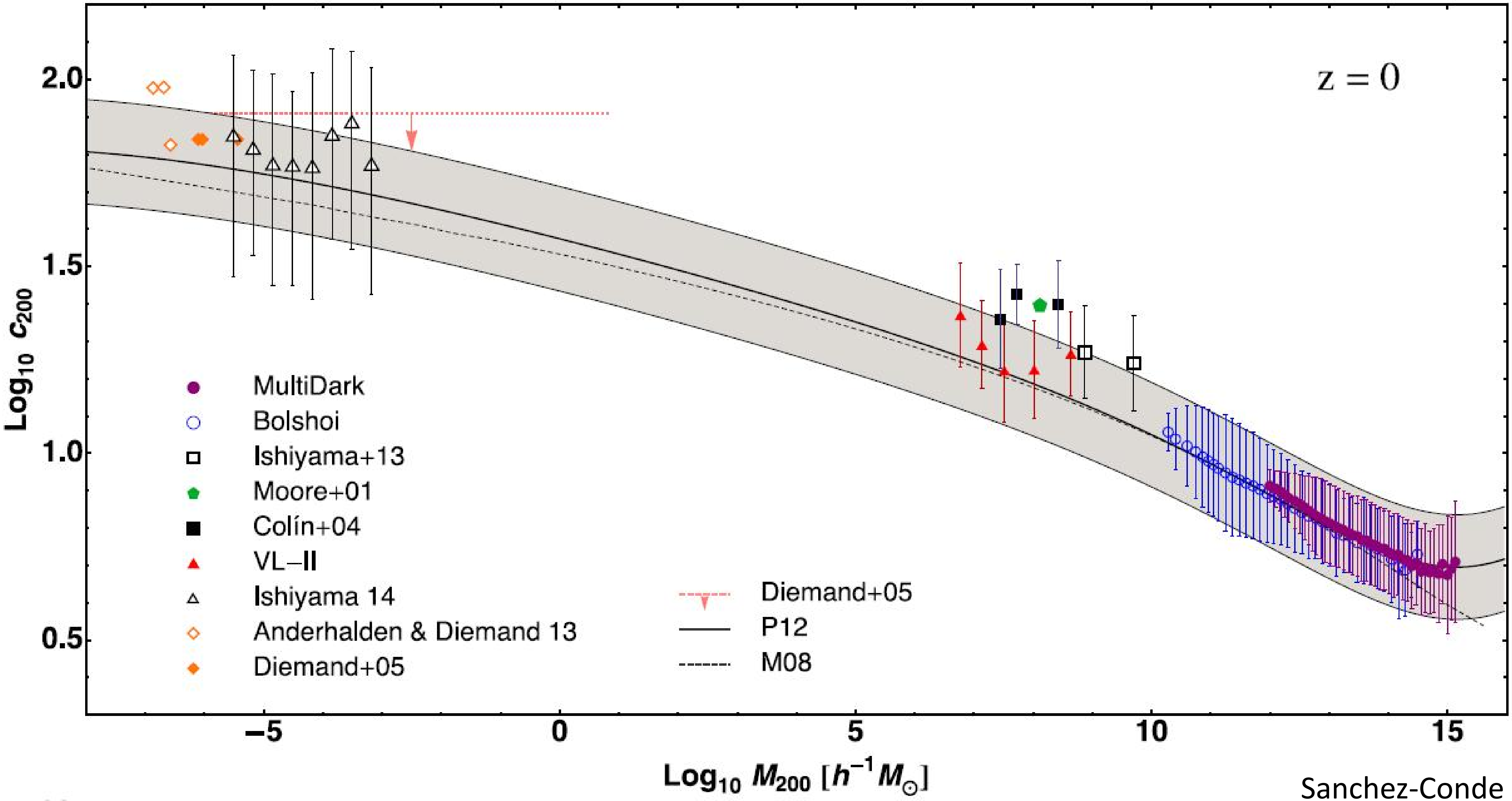
- Halo mass function
  (Jenkins2001, Tinker2018..)

- Assembly history
  (NFW97.....)

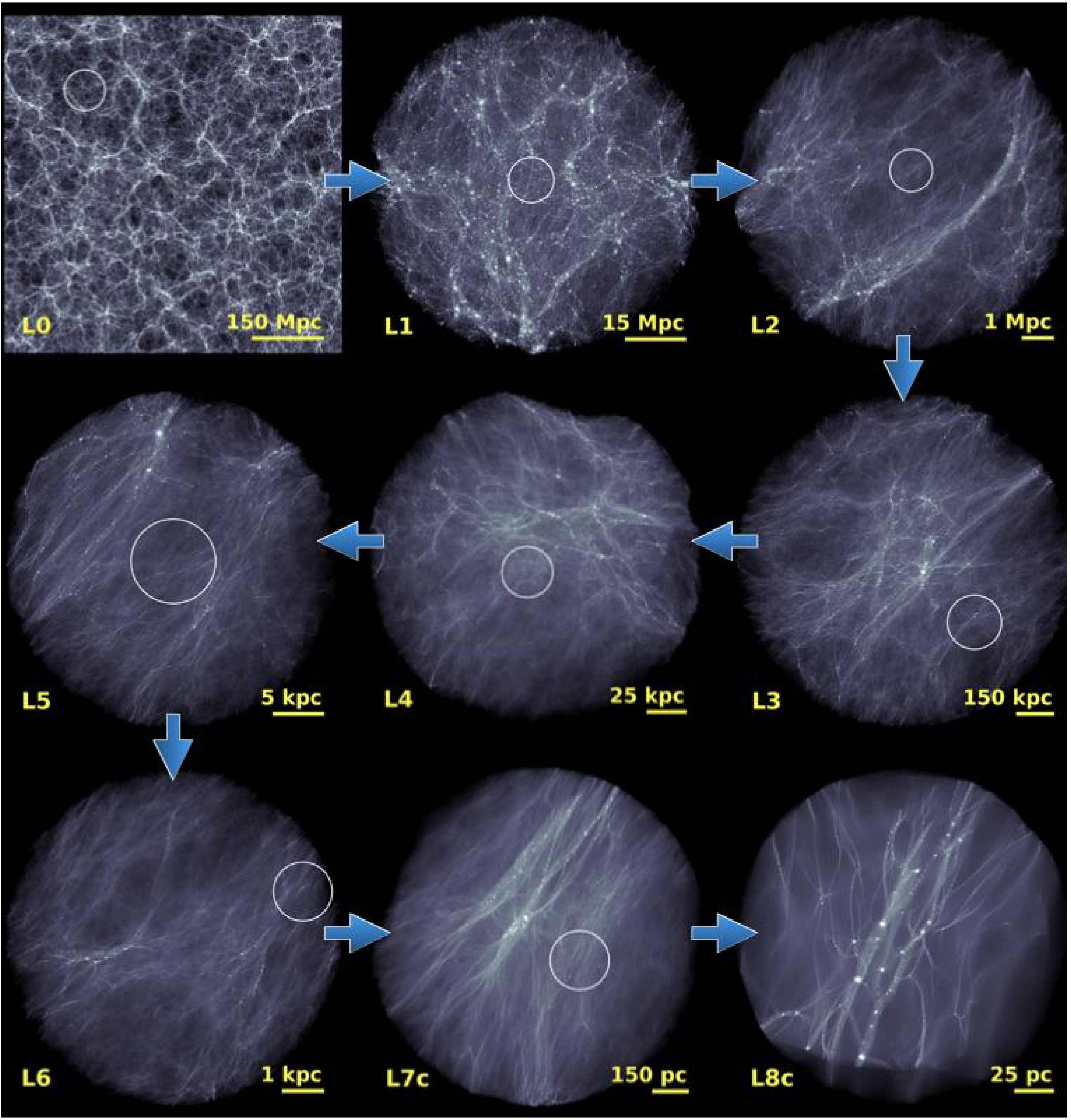
- Internal structure
  Density profile (NFW96 ....)
  Sub-structures (Klypin99,Moore99...)

  。。。。

Resolved haloes up to now



Sanchez-Conde & Prada 2014



Planck Cosmology

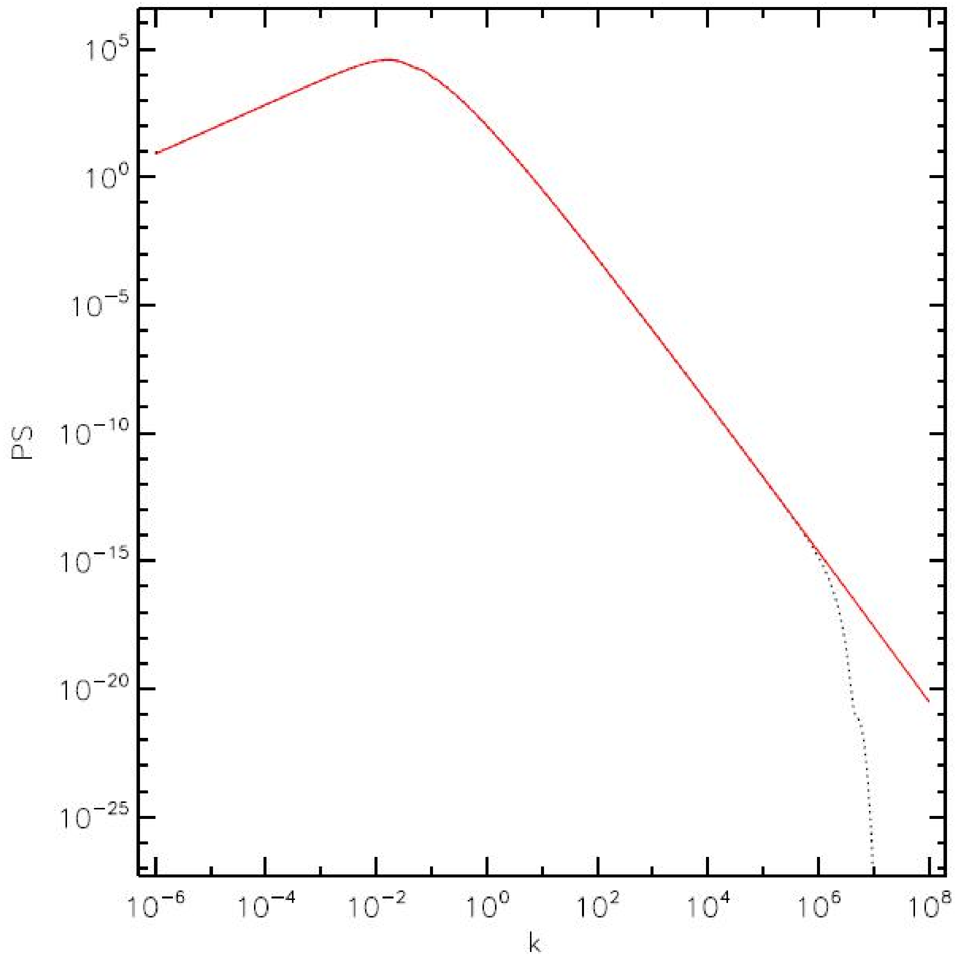
Planck Collaboration et al 2014

Ω_{matter}	0.307
Ω_{Λ}	0.693
H_0 / kms^{-1} Mpc^{-1}	67.77

σ_8	0.8288
n_s	0.9611
Ω_{baryon}	0.04825
Y_{He}	0.24

run	R_{high} [Mpc]	n_p	ε [kpc]	m_p [$M_\odot$]	$\langle\rho\rangle/\rho_{\mathrm{mean}}$	M_{char} [$M_\odot$]	N_{char}	f_{vir}
L0	738	1.0×10^{10}	7.4	1.4×10^{9}	1.0	10^{14}	127	0.91
L1	52	1.0×10^{10}	4.4×10^{-1}	7.4×10^{5}	0.39	10^{12}	59	0.75
L2	8.8	5.4×10^{9}	5.6×10^{-2}	1.5×10^{3}	0.082	10^{9}	29	0.81
L3	1.0	1.8×10^{9}	8.3×10^{-3}	2.8	0.036	10^{6}	27	0.88
L4	0.27	2.0×10^{9}	1.0×10^{-3}	5.5×10^{-3}	0.026	10^{3}	59	0.87
L5	0.035	1.5×10^{9}	2.2×10^{-4}	5.8×10^{-5}	0.024	10	30	0.88
L6	0.0066	1.7×10^{9}	3.8×10^{-5}	2.6×10^{-7}	0.014	10^{-2}	35	0.69
L7	0.0011	2.5×10^{9}	5.3×10^{-6}	8.6×10^{-10}	0.016	10^{-4}	201	0.95
L7c	0.0011	2.5×10^{9}	5.3×10^{-6}	8.6×10^{-10}	0.016	10^{-4}	202	0.96
L8c	0.00024	1.5×10^{9}	1.4×10^{-6}	1.6×10^{-11}	0.028	10^{-6}	24	0.95

Initial Condition



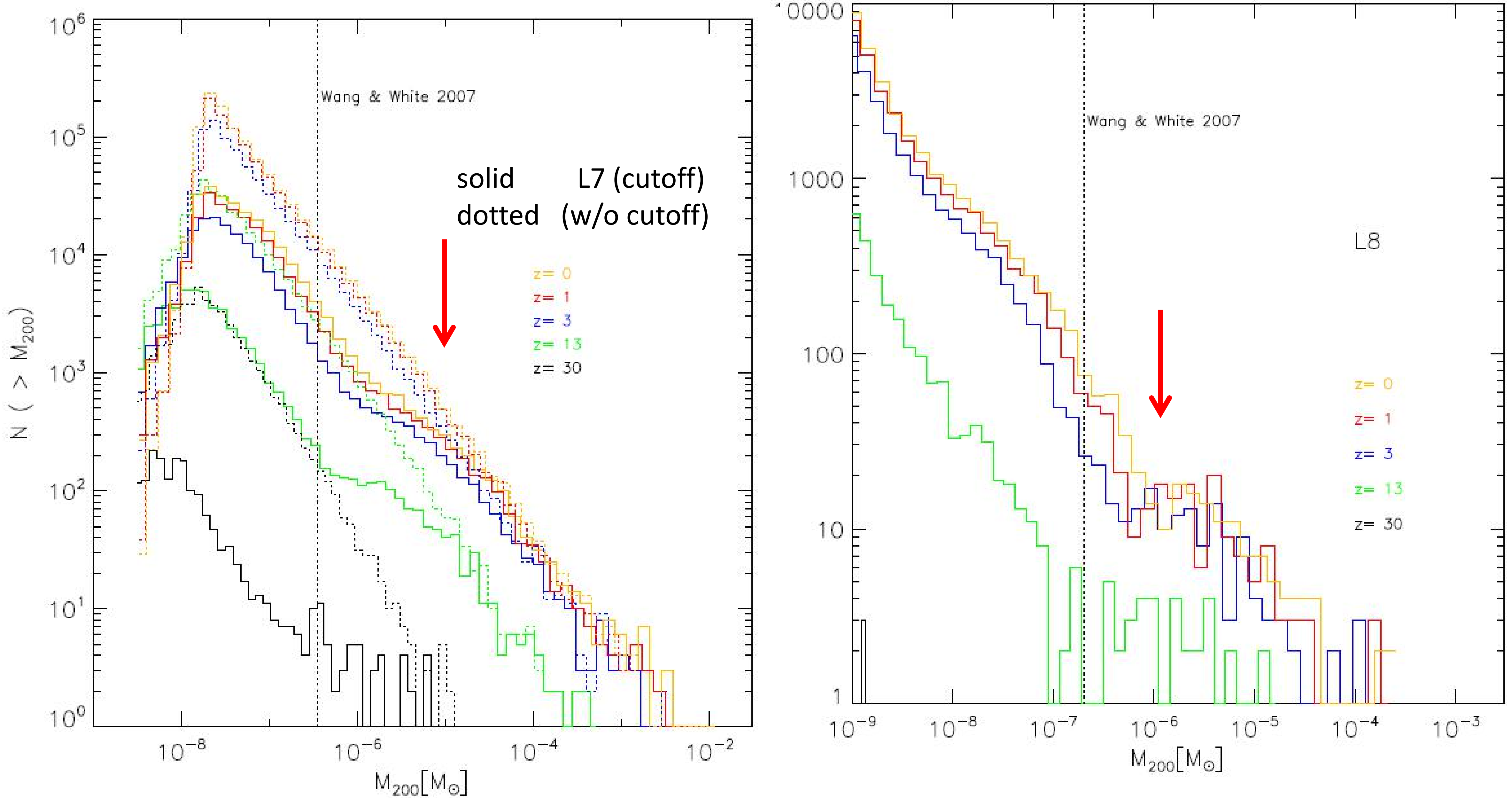
$$\Delta^2_{\rm lin}(k) = \begin{cases} \Delta^2_{\rm CAMB}(k) & \text{if } \left(\log_{10}(\frac{kh}{\rm Mpc}) \le 1\right) \\ (1-w)\Delta^2_{\rm CAMB}(k) + w\Delta^2_{\rm BBKS}(k) & \text{if } \left(1 < \log_{10}(\frac{kh}{\rm Mpc}) < 2\right) \\ \Delta^2_{\rm BBKS}(k) & \text{if } \left(\log_{10}(\frac{kh}{\rm Mpc}) > 2\right), \end{cases}$$

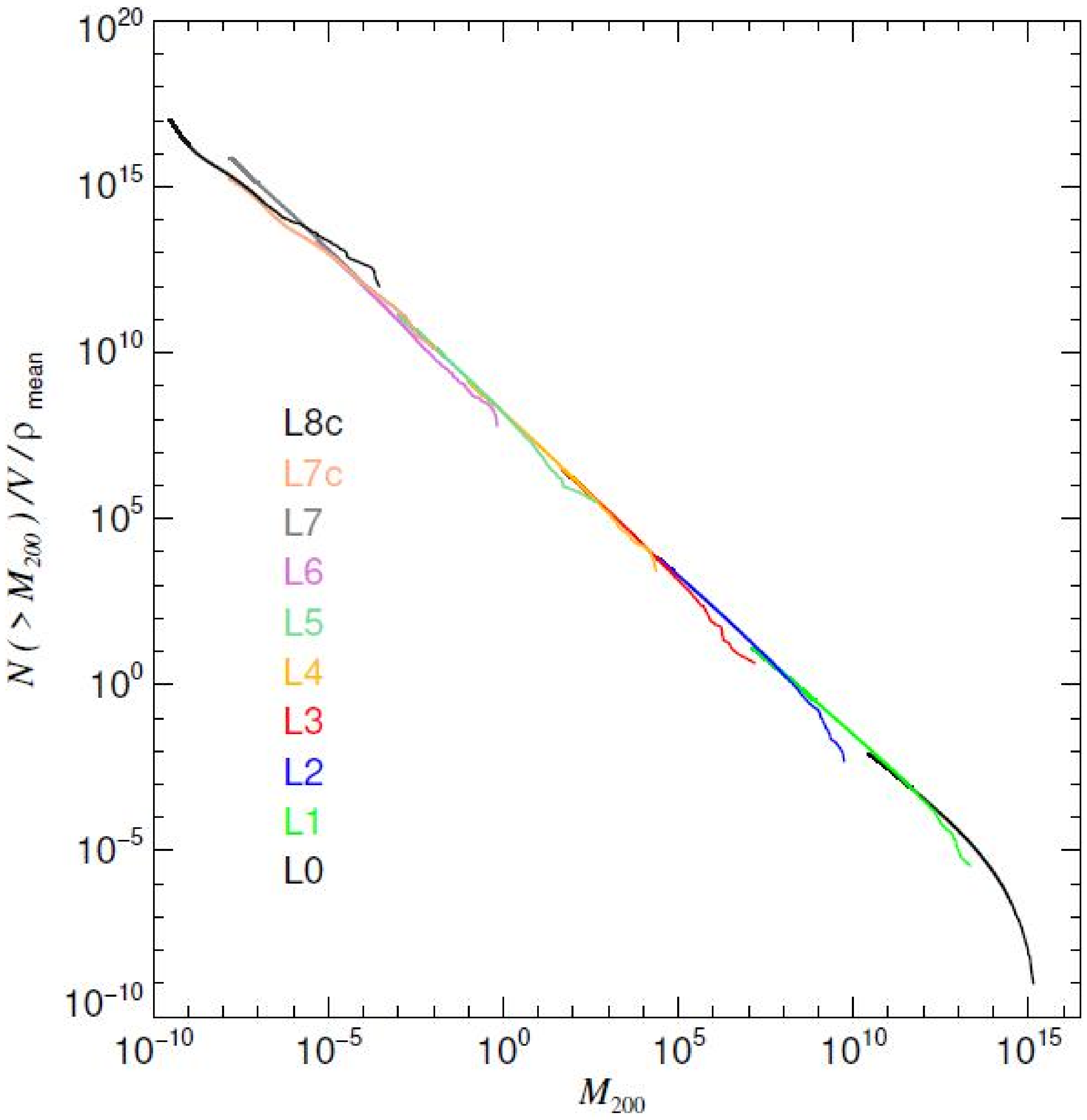
$$\Delta^2_{\rm ICs}(k) = \Delta^2_{\rm lin}\left[1 - \frac{2}{3}\left(\frac{k}{k_{\rm fs}}\right)^2\right]^2 \exp\left[-2\left(\frac{k}{k_{\rm fs}}\right)^2 - 2\left(\frac{k}{k_{\rm d}}\right)^2\right]$$

k_fs = 2.6176e6 h/Mpc
k_d = 5.5e6 h/Mpc

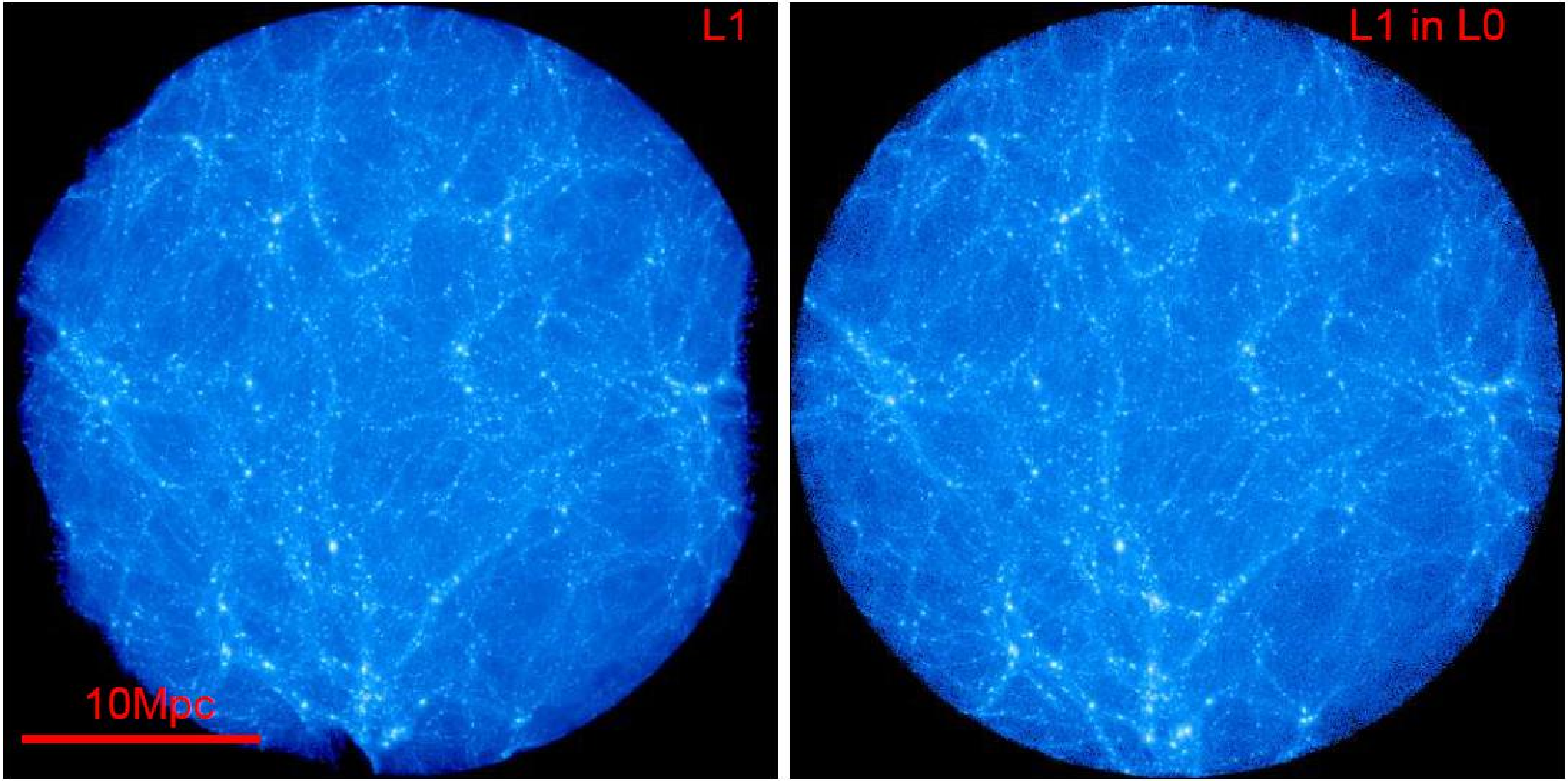
Green et al 2004

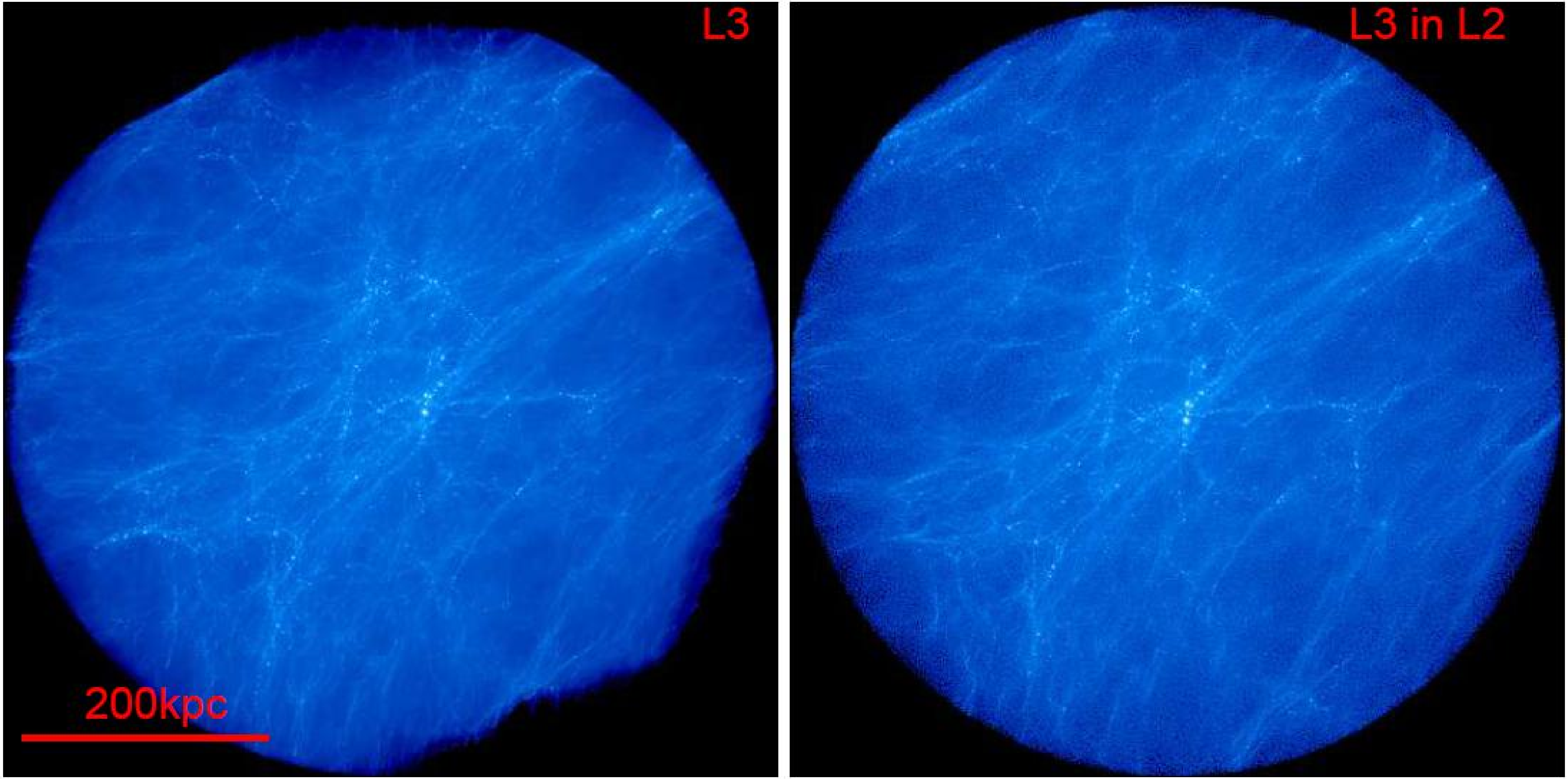
up mass limit for artificial haloes

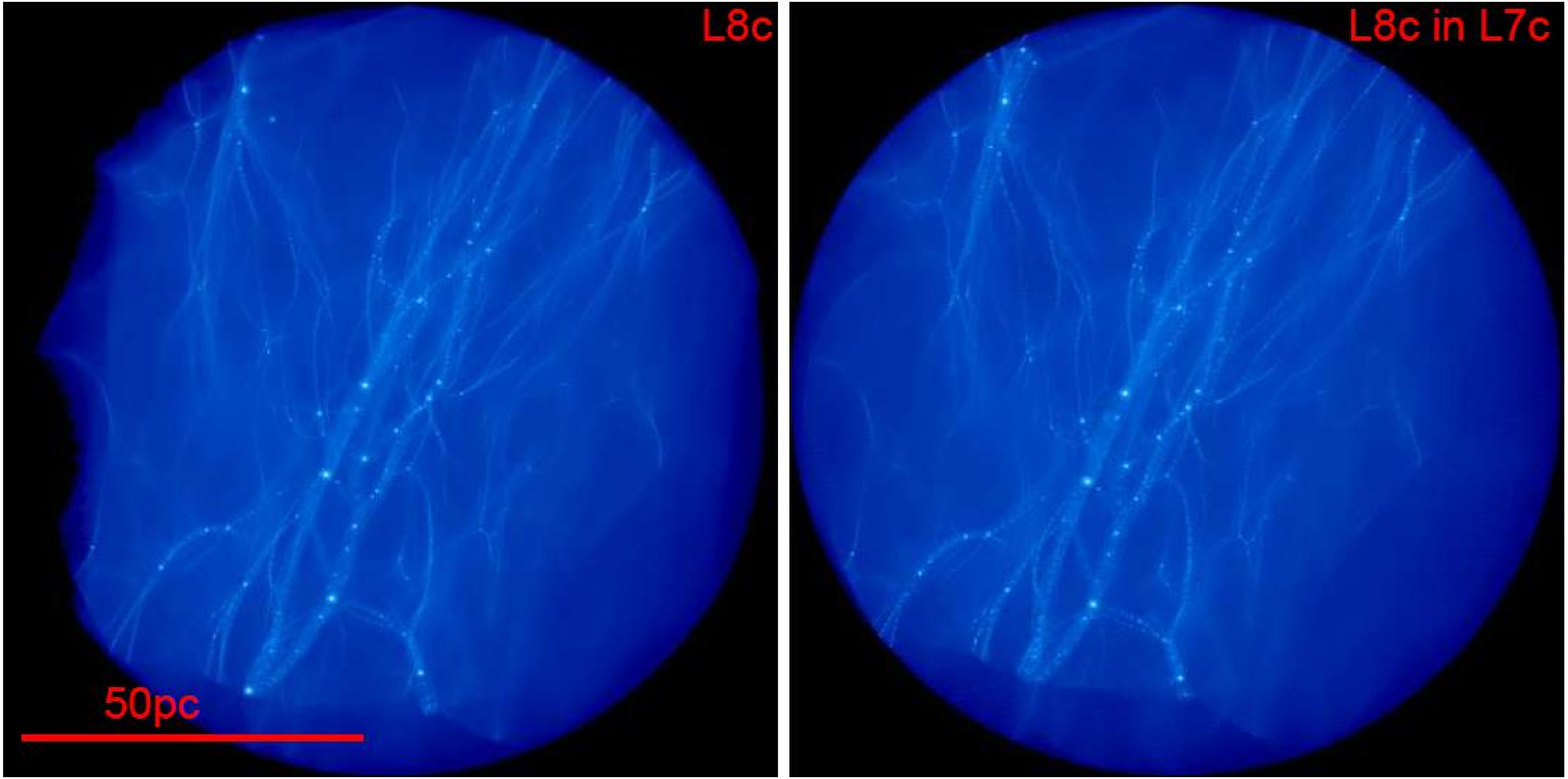


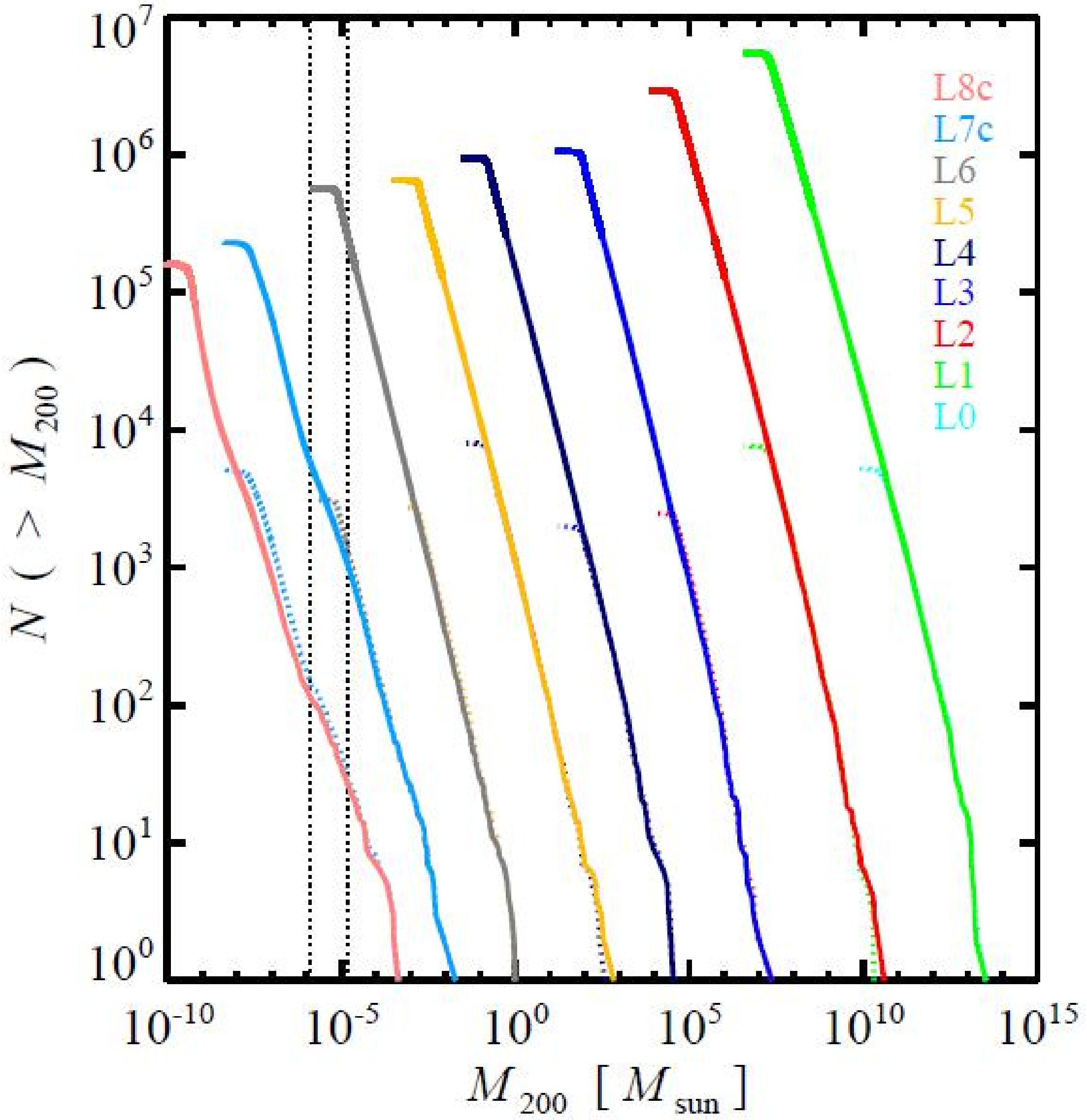


Halo mass function per mass unit over more than 20 orders on halo mass

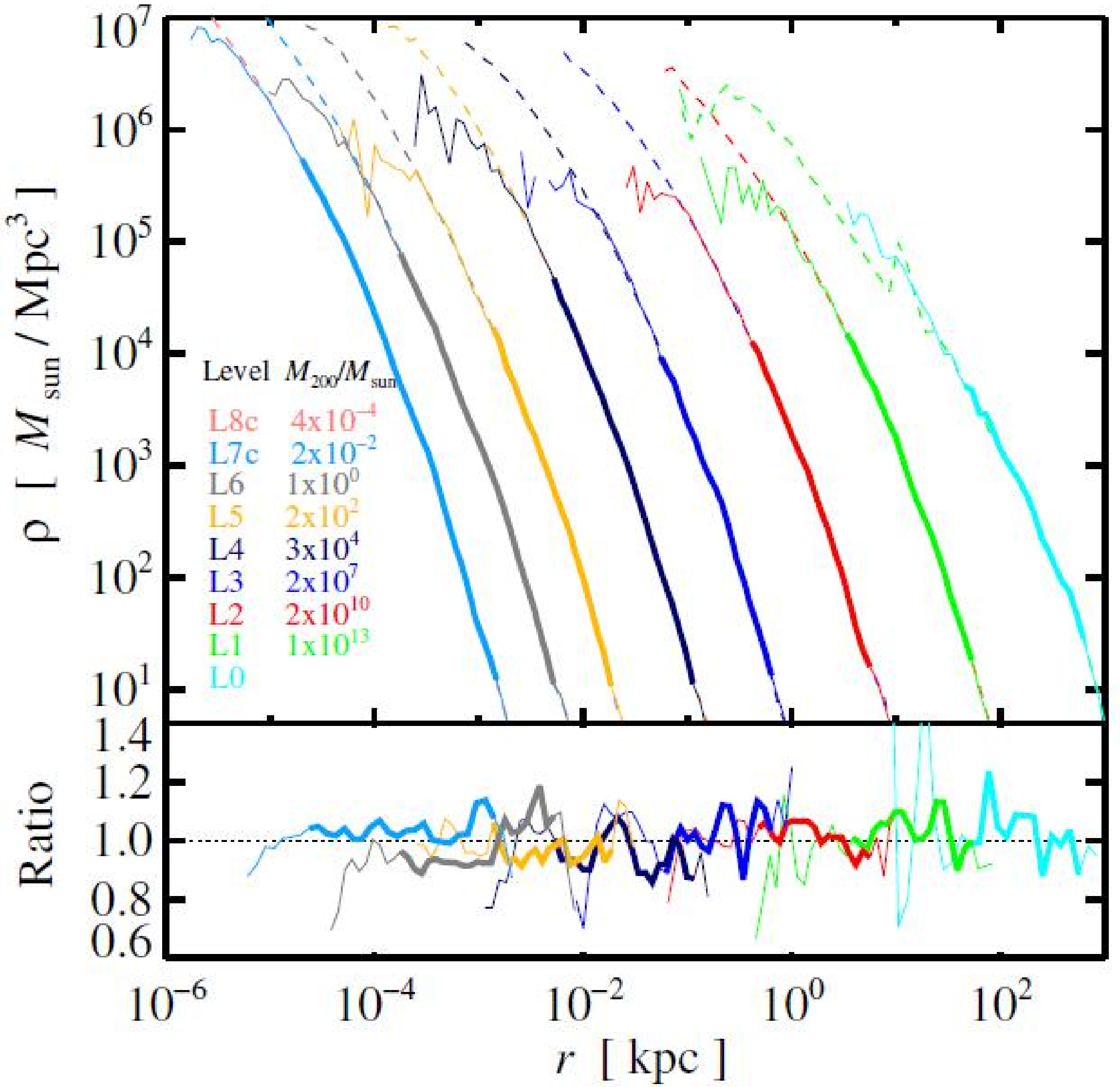

L1
10Mpc
L1 in L0


L3
200kpc
L3 in L2

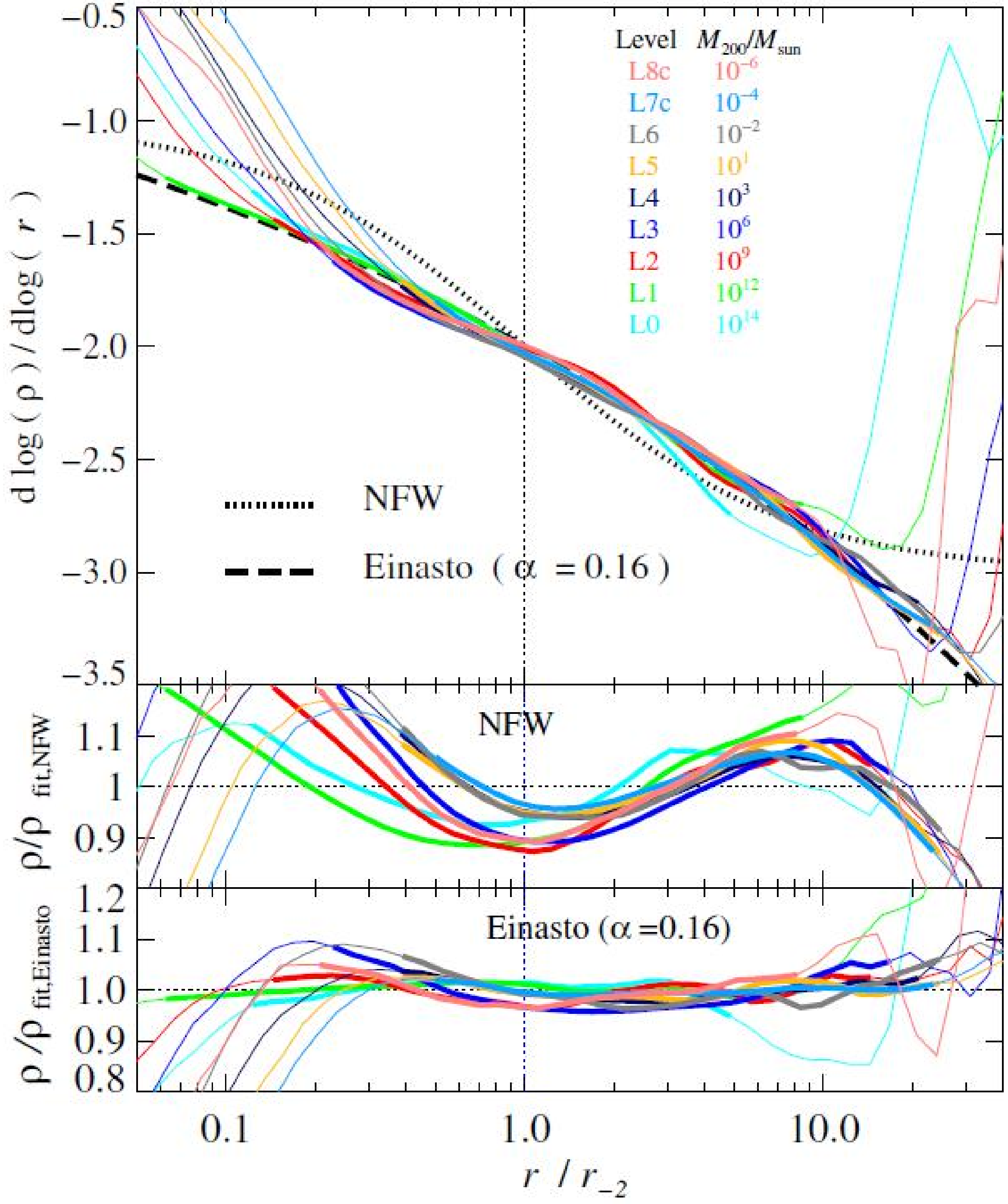

L8c
50pc
L8c in L7c



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



The density profile of one of the mostmassive halos in each level compared to that of the same halo in the parent level



$$\rho(r) = \rho_s r_s^3 / r(r + r_s)^2,$$

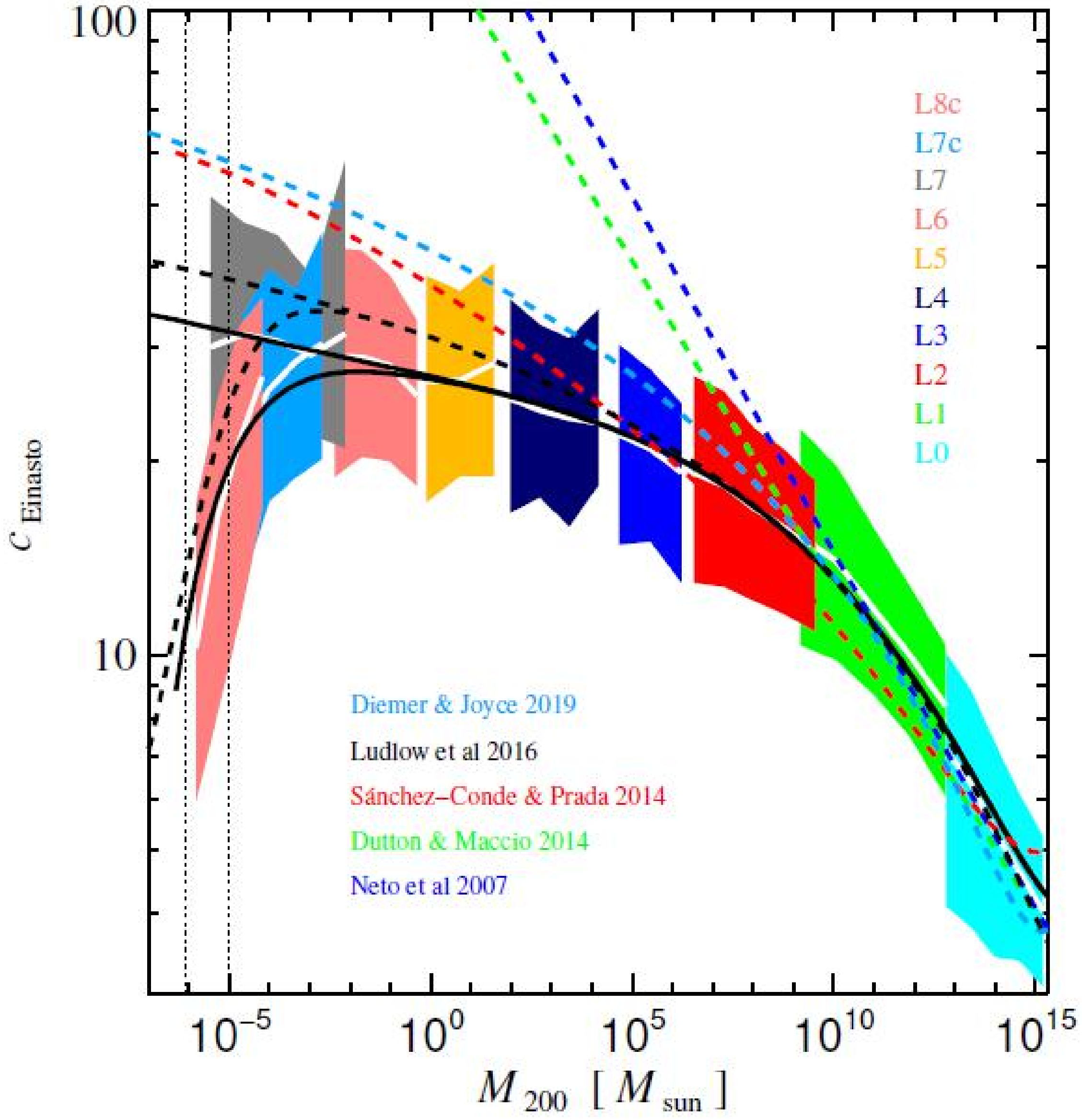
NFW

Einasto

$$\rho(r) = \rho_{-2} \exp[-2\alpha^{-1}((r/r_{-2})^{\alpha} - 1)],$$

Over 20 orders of magnitude in halo mass:
The mean density profiles of halos are fit by NFW to within 20% and by Einasto with α = 0.16 to within 7%

Concentration-mass relation over 20 orders



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

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

The scatter does not depend strongly on halo mass

exponential *polynomial*

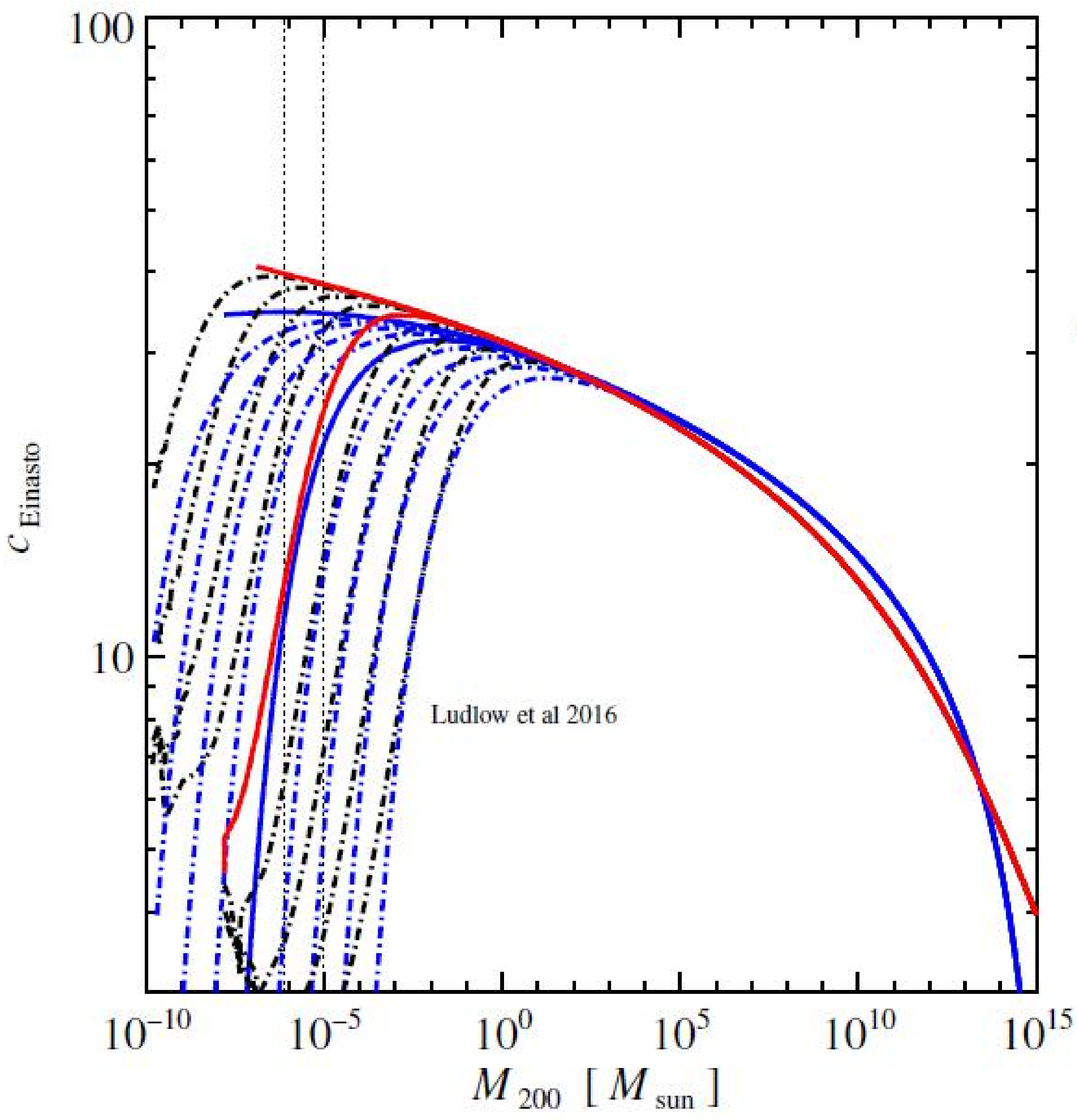
$$c_{\rm Einasto}(M_{200}) = \exp\left[c_6 \times \left(\frac{M_{\rm fs}}{M_{200}}\right)^{\frac{1}{3}}\right] \times \sum_{i=0}^{5} c_i \left[\ln \frac{M_{200}}{h^{-1}M_\odot}\right]^i$$

c0=27.108 ***c1=0.381***

c2=1.815e-3 ***c3=4.089 e-4***

c4=4.282e-06 ***c5=3.188e-07***

c6=-0.602



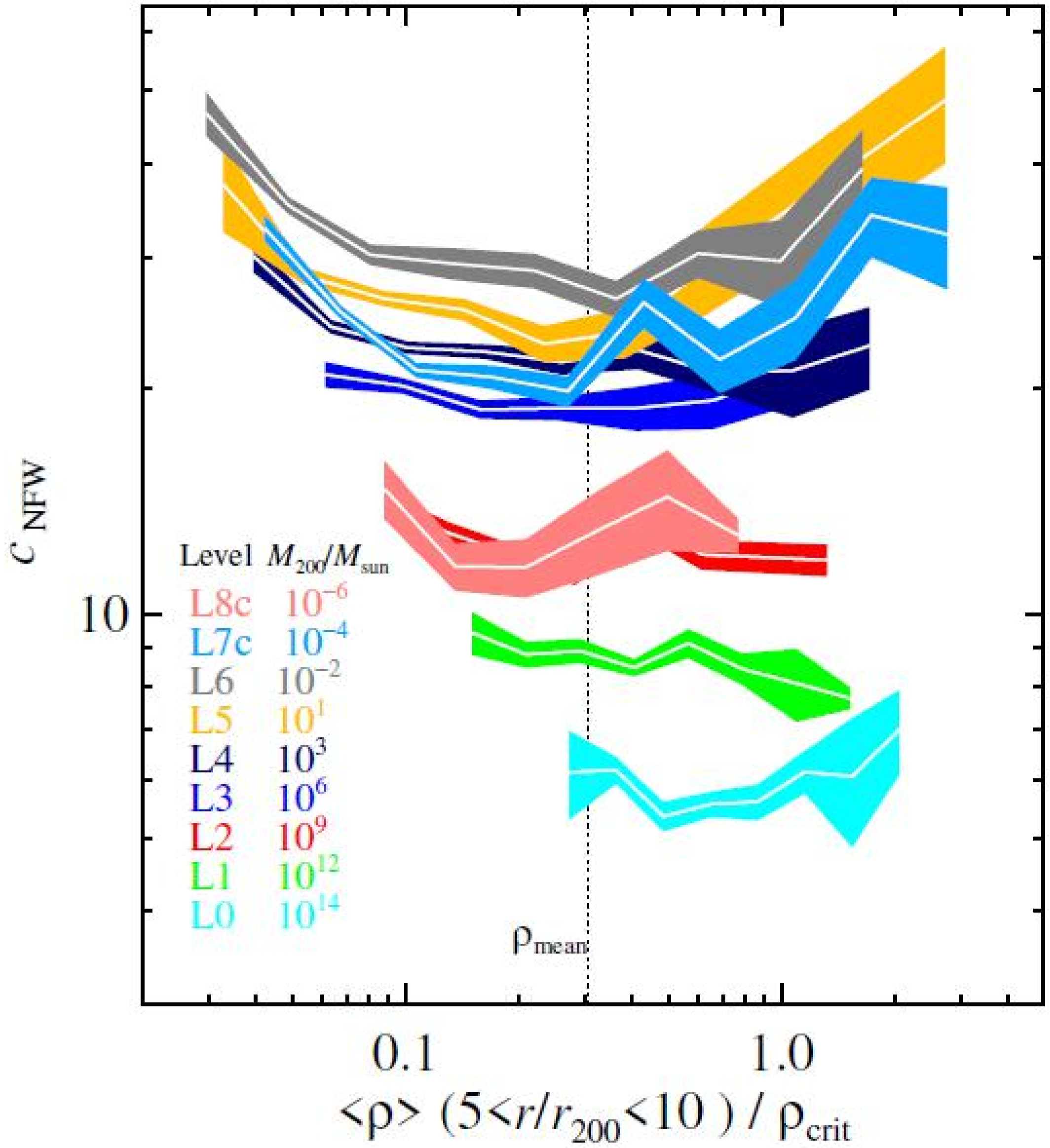
if free-streaming considered

$$c_{\rm Einasto}(M_{200}) = \exp\left[c_6 \times \left(\frac{M_{\rm fs}}{M_{200}}\right)^{\frac{1}{3}}\right] \times \sum_{i=0}^{5} c_{\rm i}\left[\ln \frac{M_{200}}{h^{-1}M_\odot}\right]^i$$

$$M_{\rm fs} = \frac{4\pi}{3} \times \left(\frac{2\pi}{k_{\rm S}}\right)^3 \times \rho_{\rm mean}$$

for a WIMP mass of 100 GeV, is $4.9 \times 10^{-6} M_\odot$.

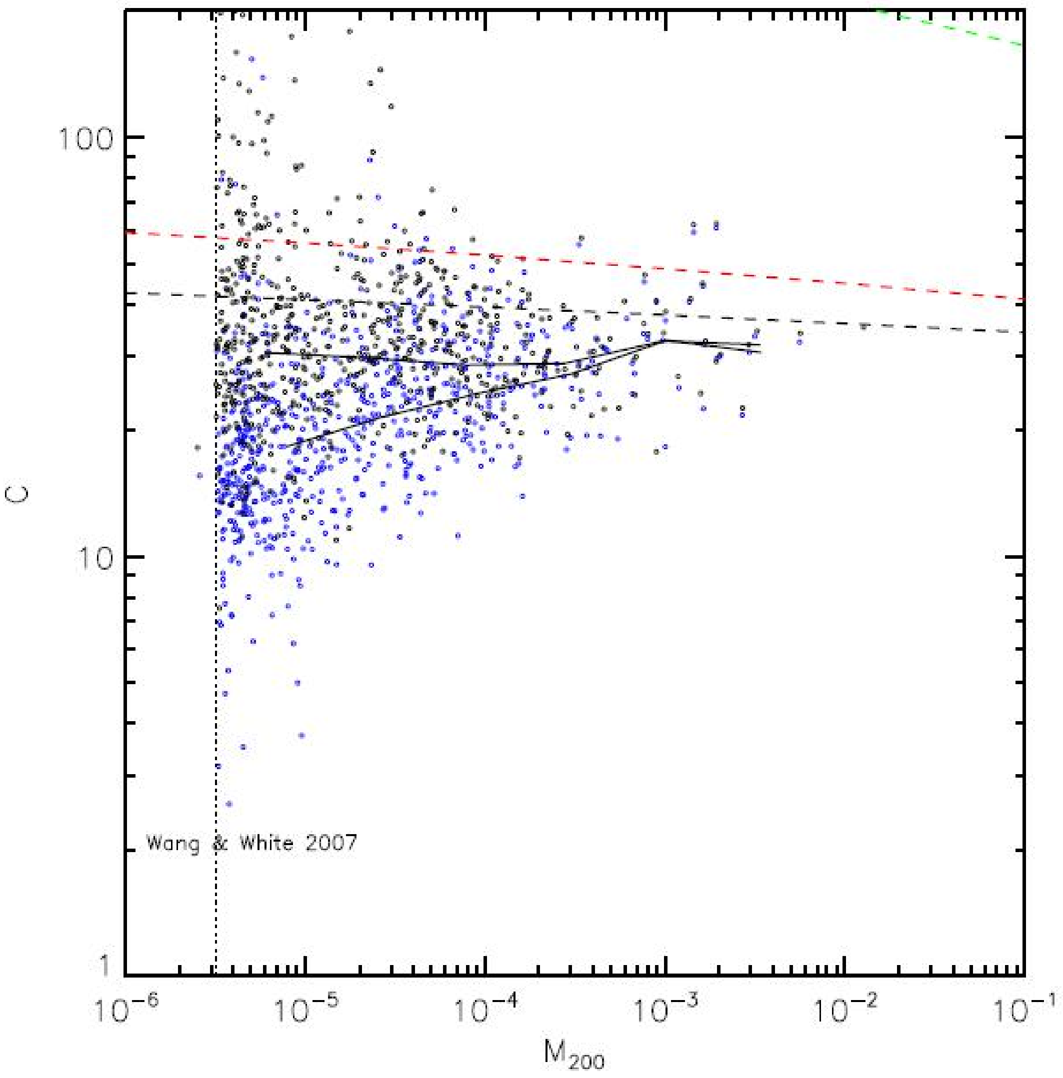
Environmental dependence of concentration

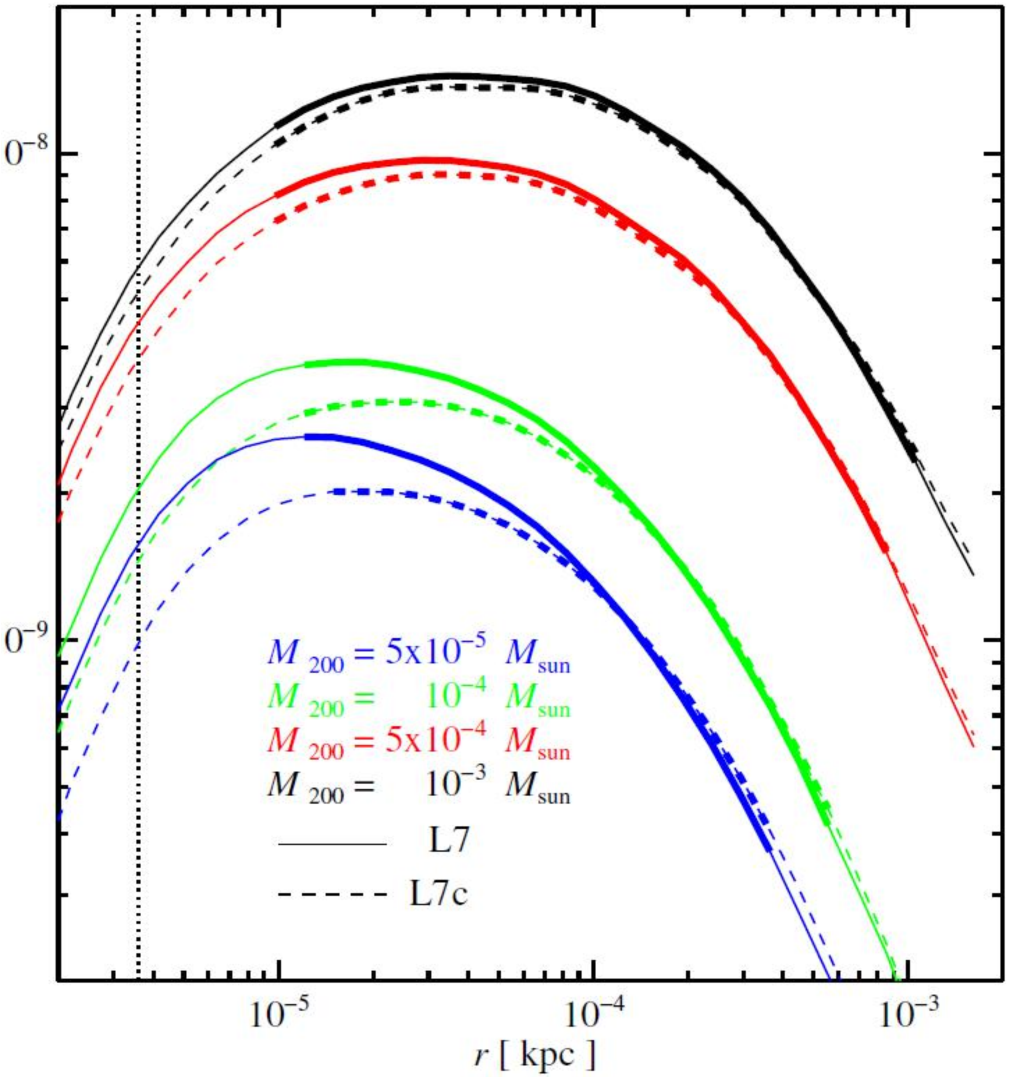


At given halo mass, concentration does not depend on local environment density.

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

Free-streaming effects on halo density profiles





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

Bringing back message

A Universal density profile over 20 order of magnitudes on halo mass

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Planck cosmology

Thanks!