WE-Heraeus Seminar
Astrophysical Windows on Dark Matter
The Royal Society, November 2021

The smallest dark matter halos and their annihilation radiation

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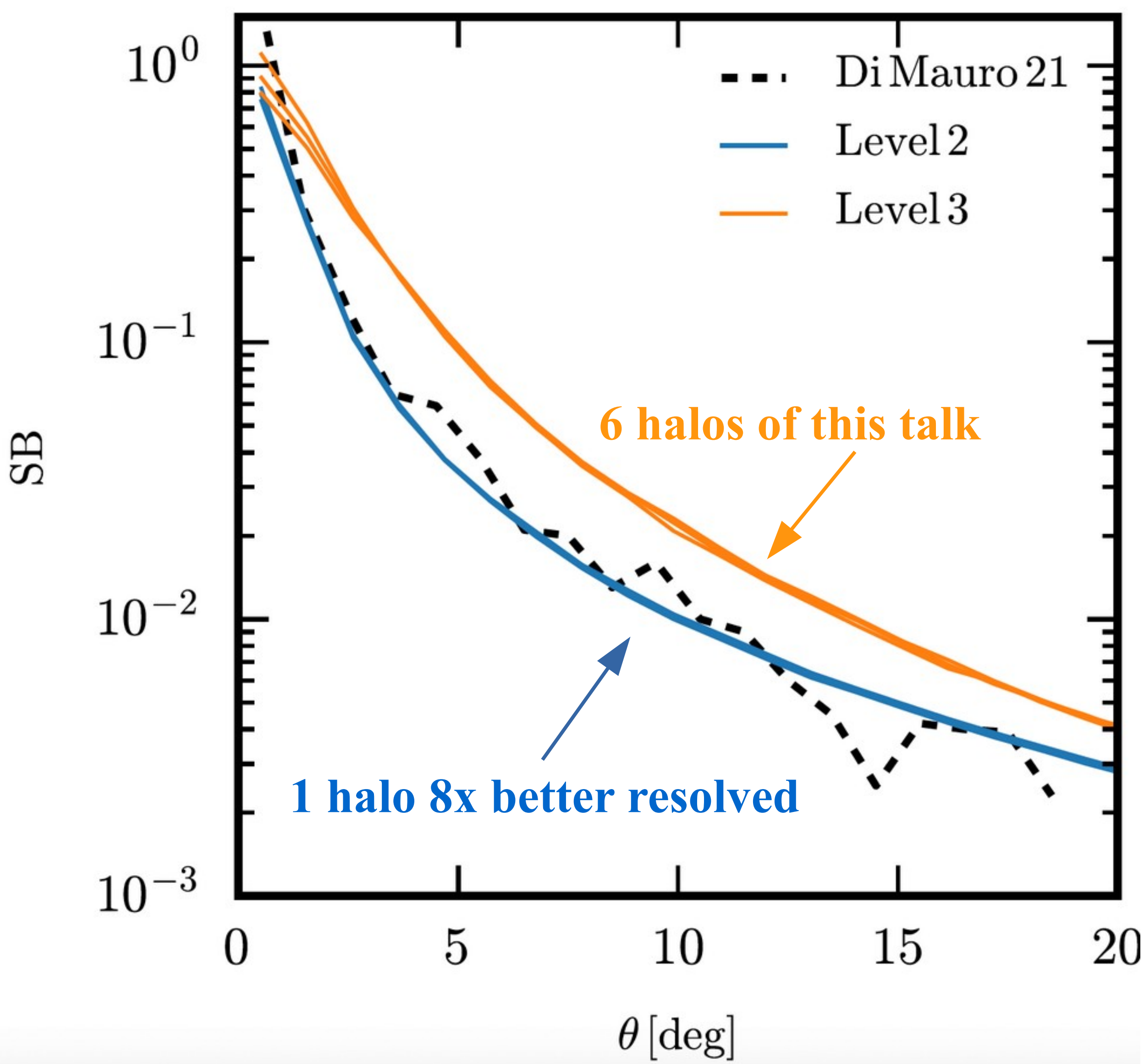
Does the *Fermi* excess "look like" a dark matter halo?

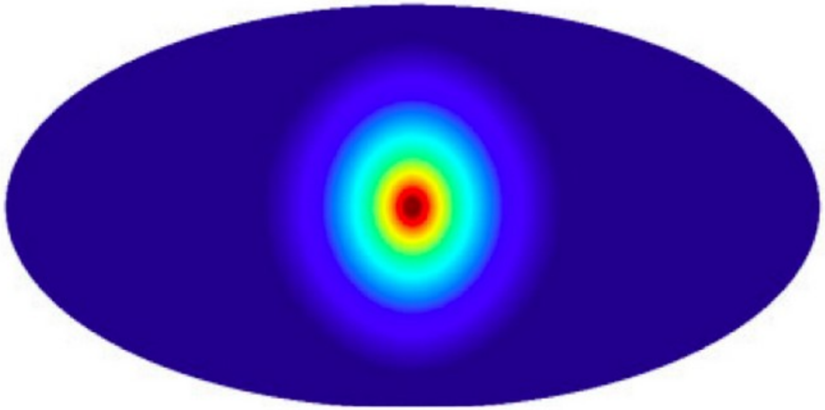


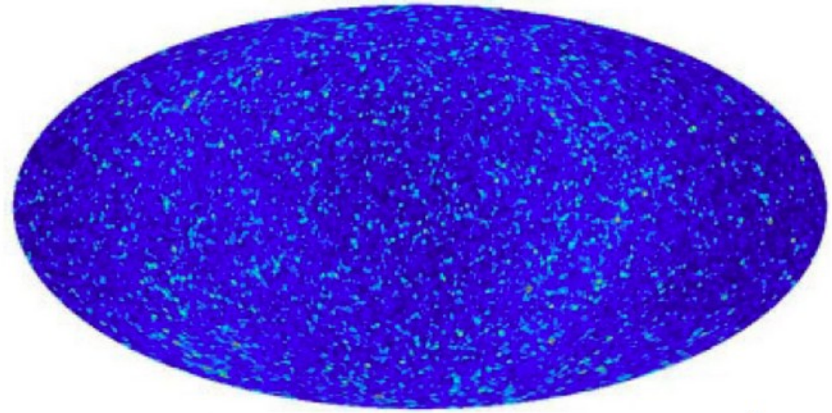
See Tracy Slatyer's talk on Day 1

- The surface brightness profile is similar to that expected
- The shape is also consistent and is inconsistent with a disk
- The spectral shape is consistent with an annihilation origin
- The photon count statistics may prefer a pulsar origin

A detection of DM **or** an upper limit on its γ-ray annihilation X-section

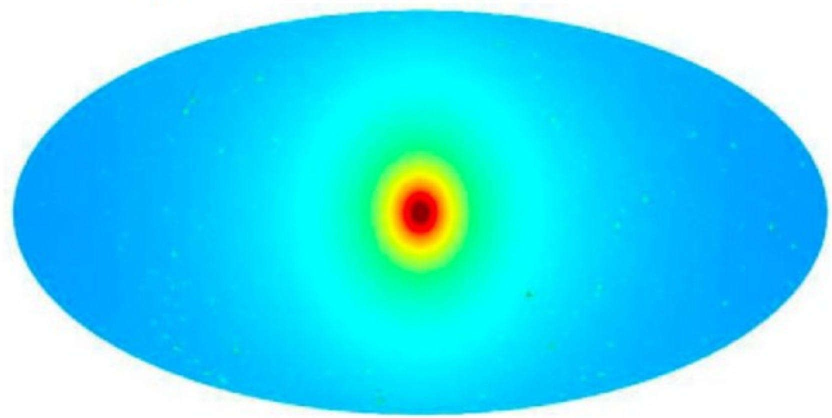
Very small (sub)halos could be seen by annihilation





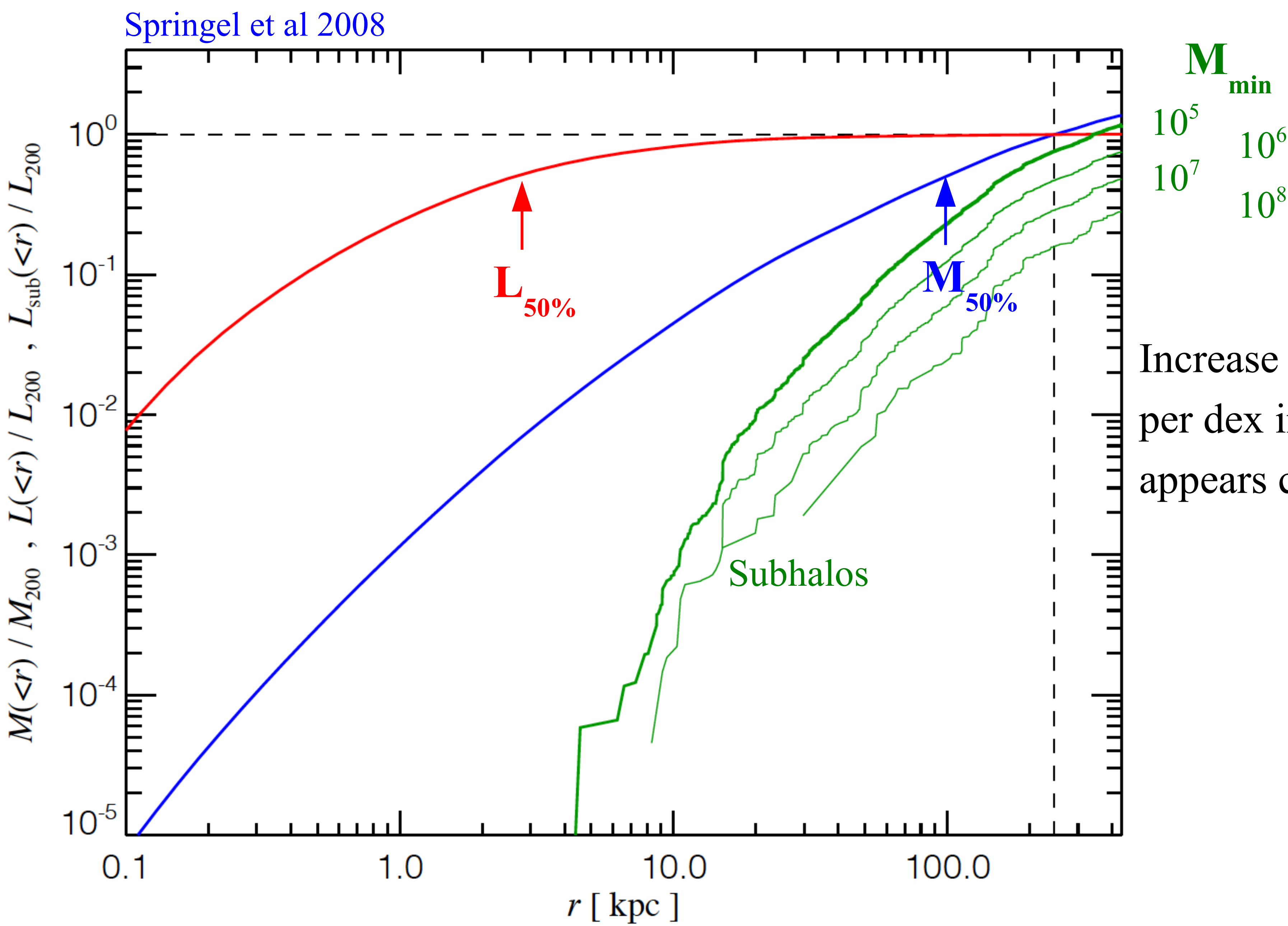
Springel et al 2008

$$L_{ann} = A_{p.p.} \int \rho^2 dV = A_{p.p.} \bar{\rho} M \propto V_{max}^4 / r_{max}$$



- MW's halo annihilation flux may be dominated by that from unresolved small subhalos 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
- The smallest halos may dominate the cosmic annihilation luminosity density

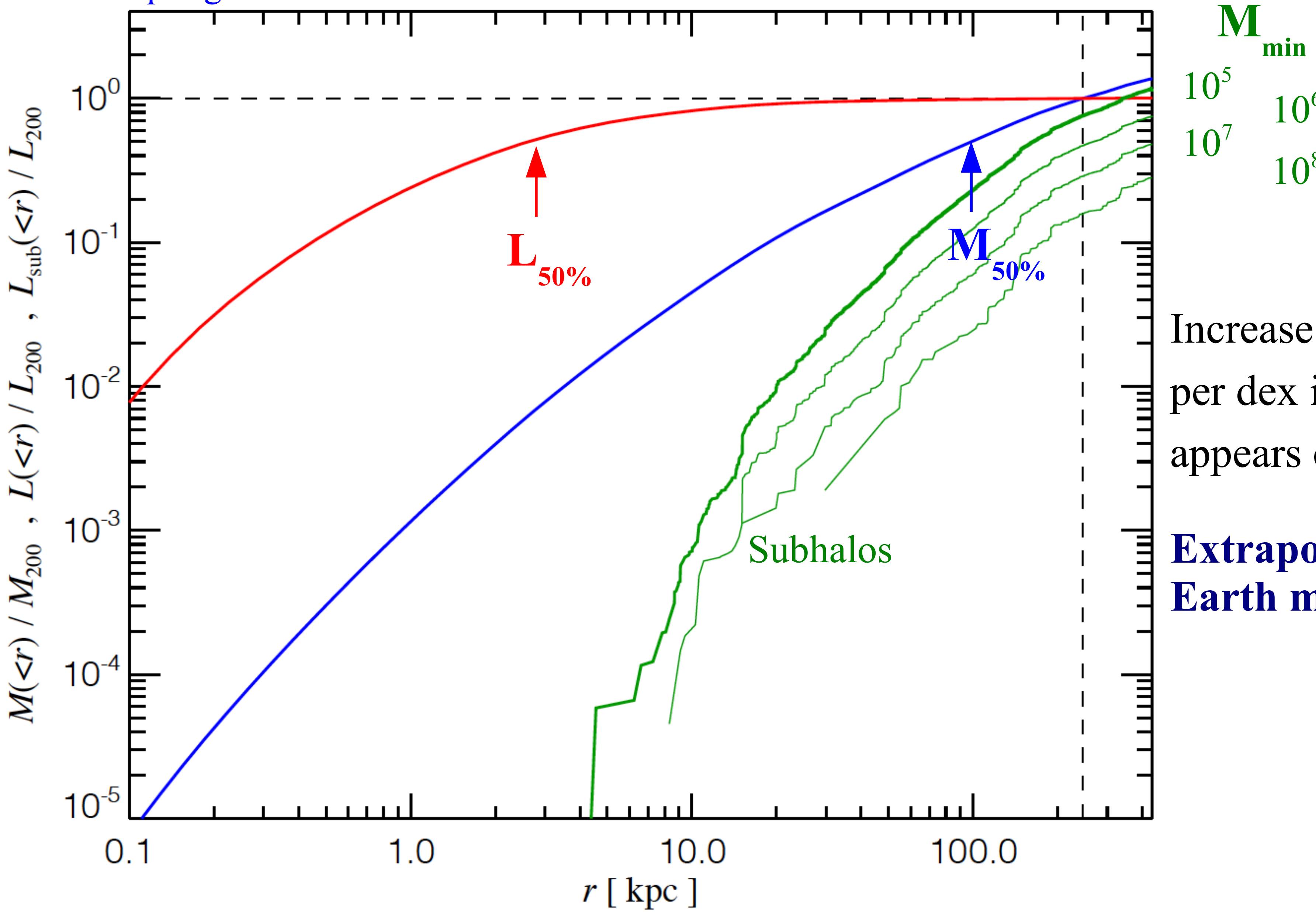
The $N=10^9$ Aquarius model for the MW Halo (DM only)



Increase in L_{sub} per dex in M_{min} appears constant

The N=10^9 Aquarius model for the MW Halo (DM only)

Springel et al 2008



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Extrapolate to Earth mass?

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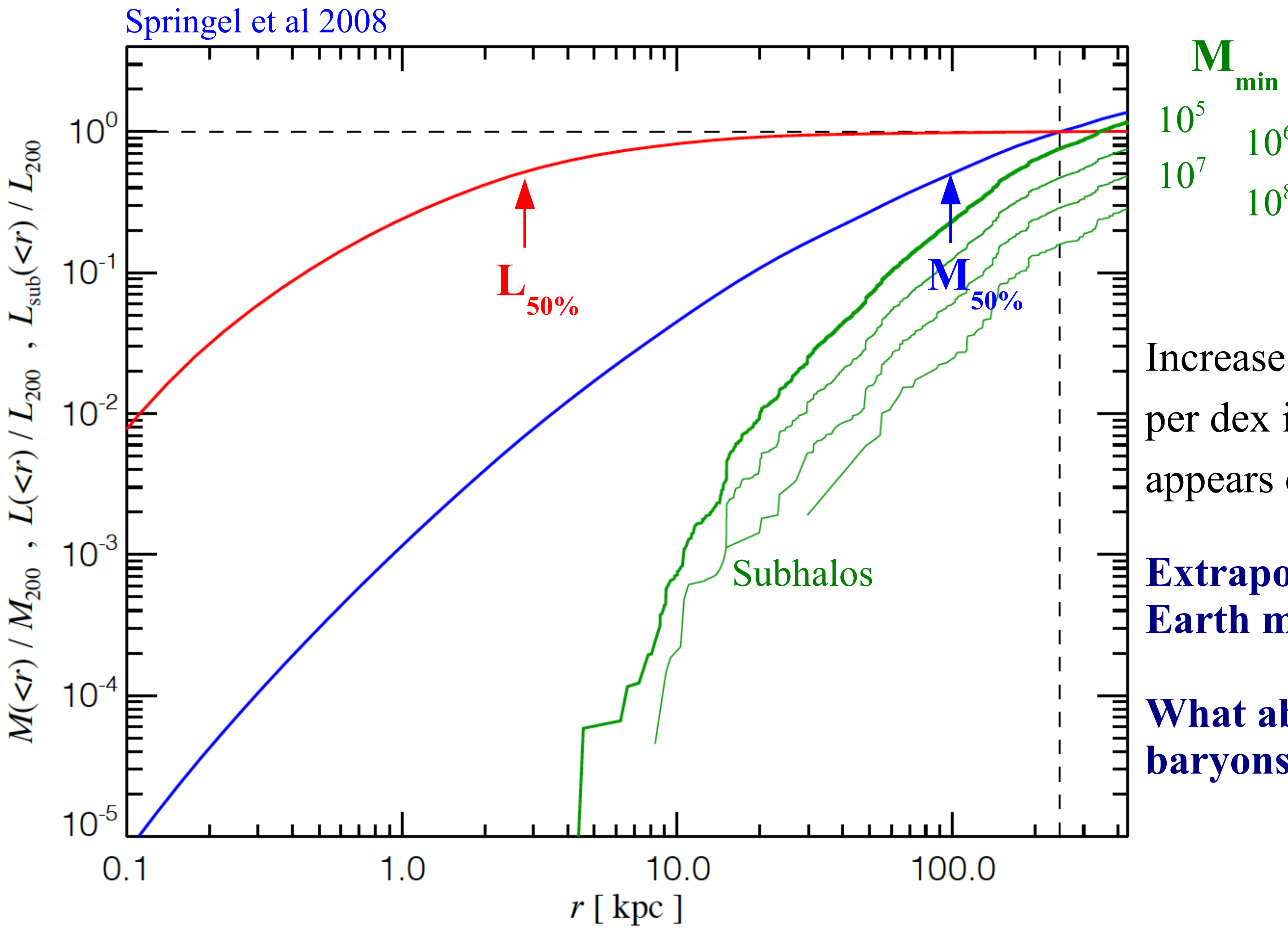
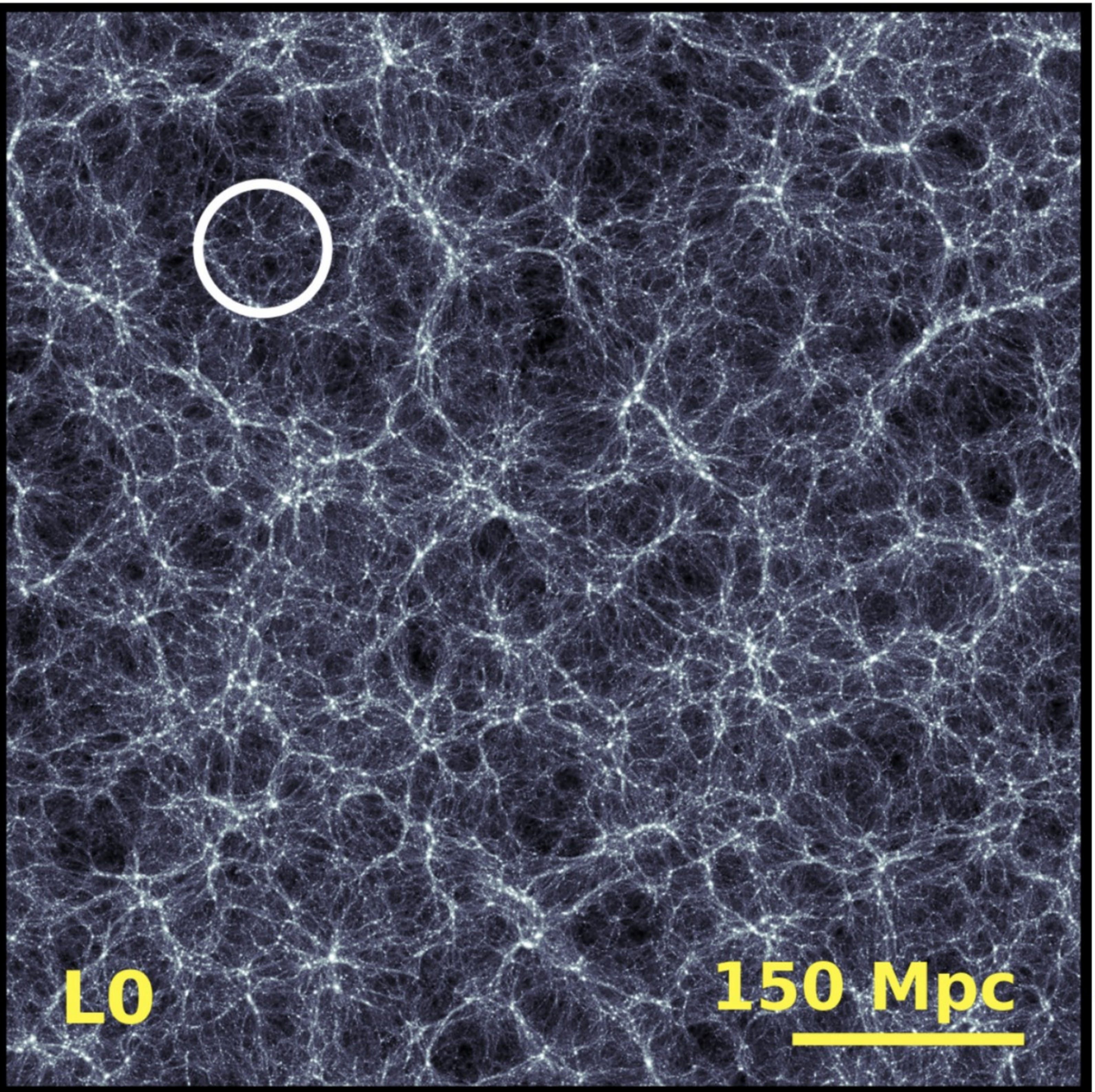


Increase in L_{sub} per dex in M_{min} appears constant

Extrapolate to Earth mass?

What about the baryons?



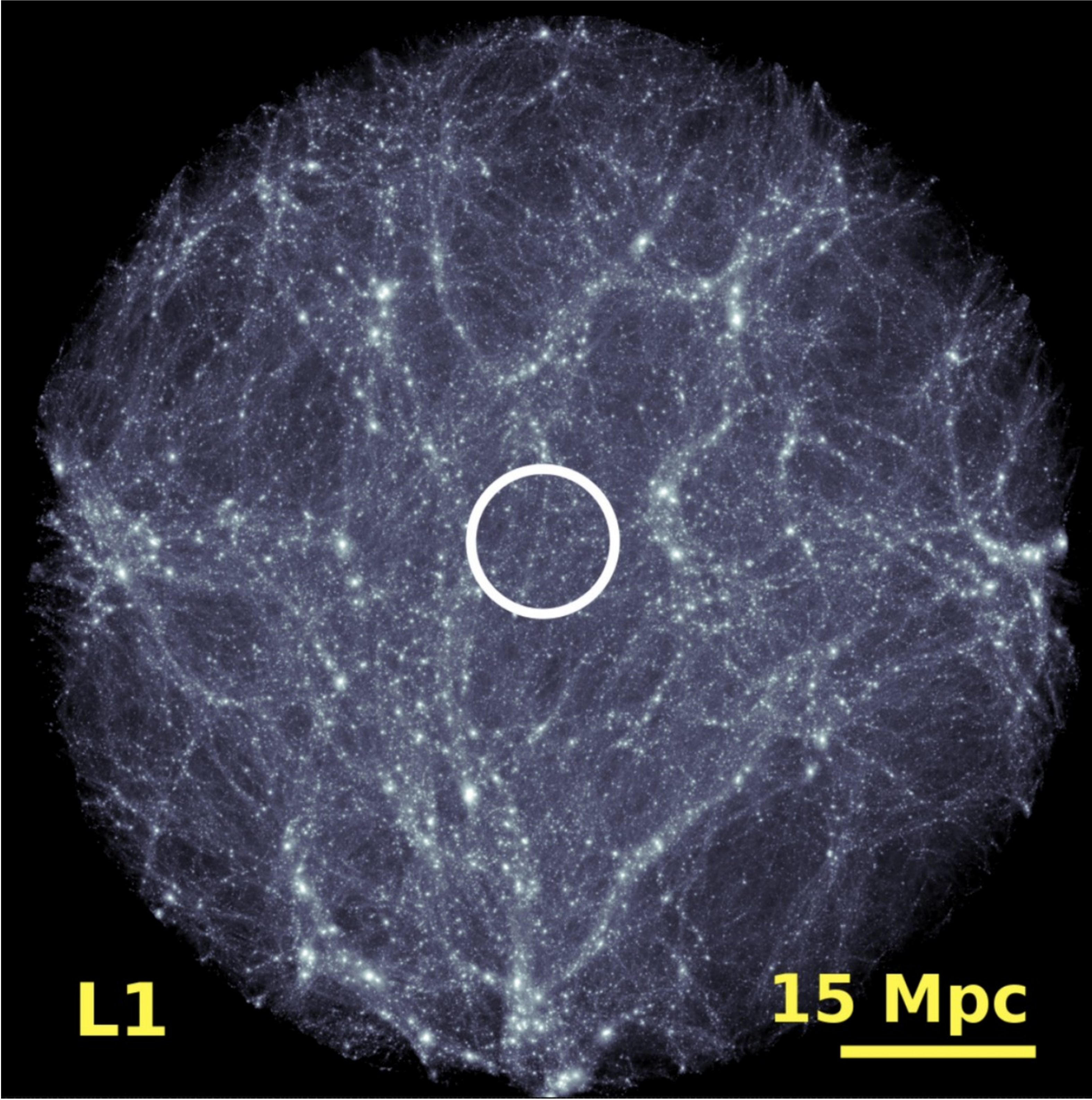
The VVV simulation

Planck cosmology

Dark matter only

Base Level

Wang, Bose et al 2020



The VVV simulation

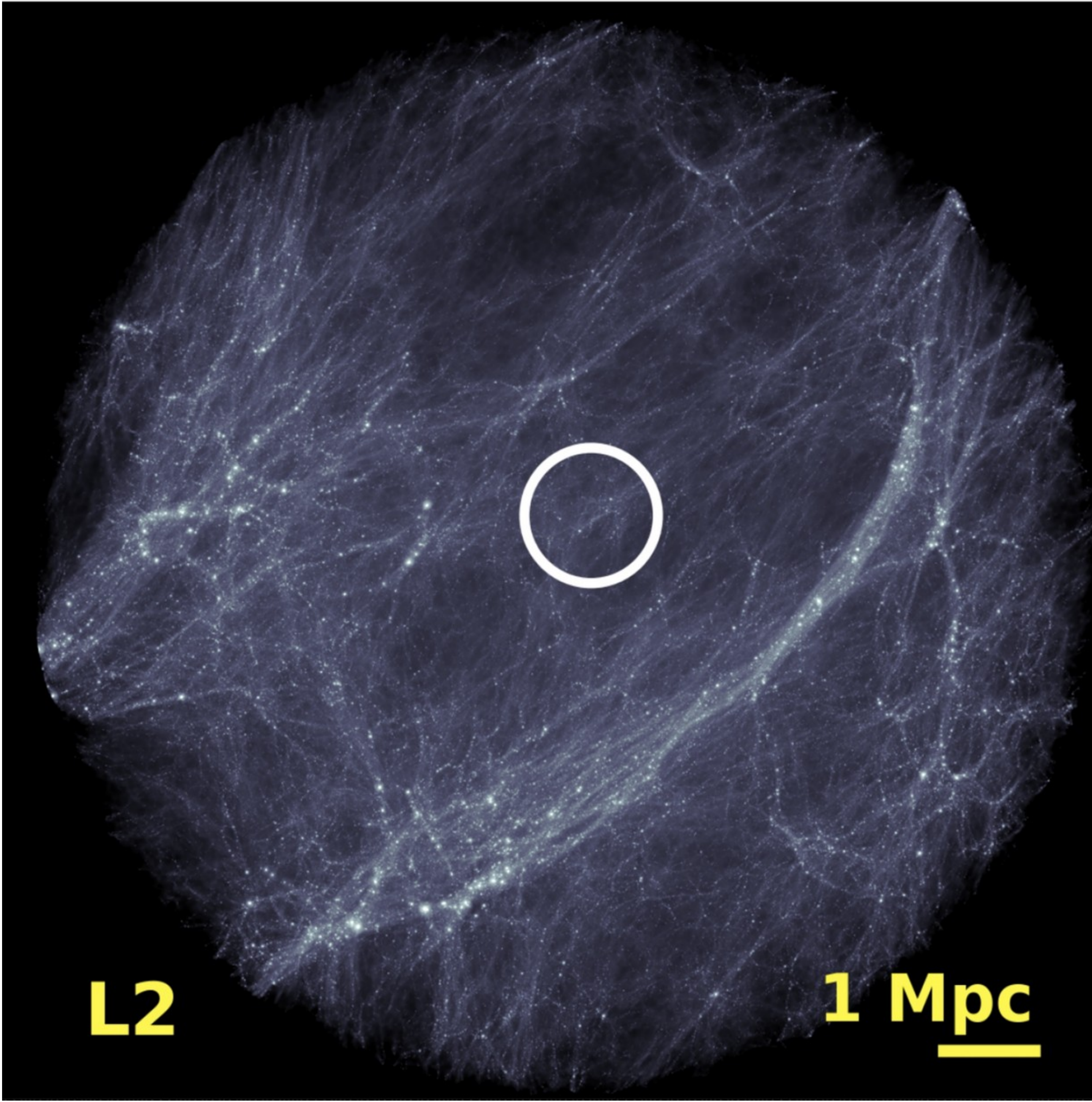
Planck cosmology

Dark matter only

Zoom Level 1

Wang, Bose et al 2020

The VVV simulation

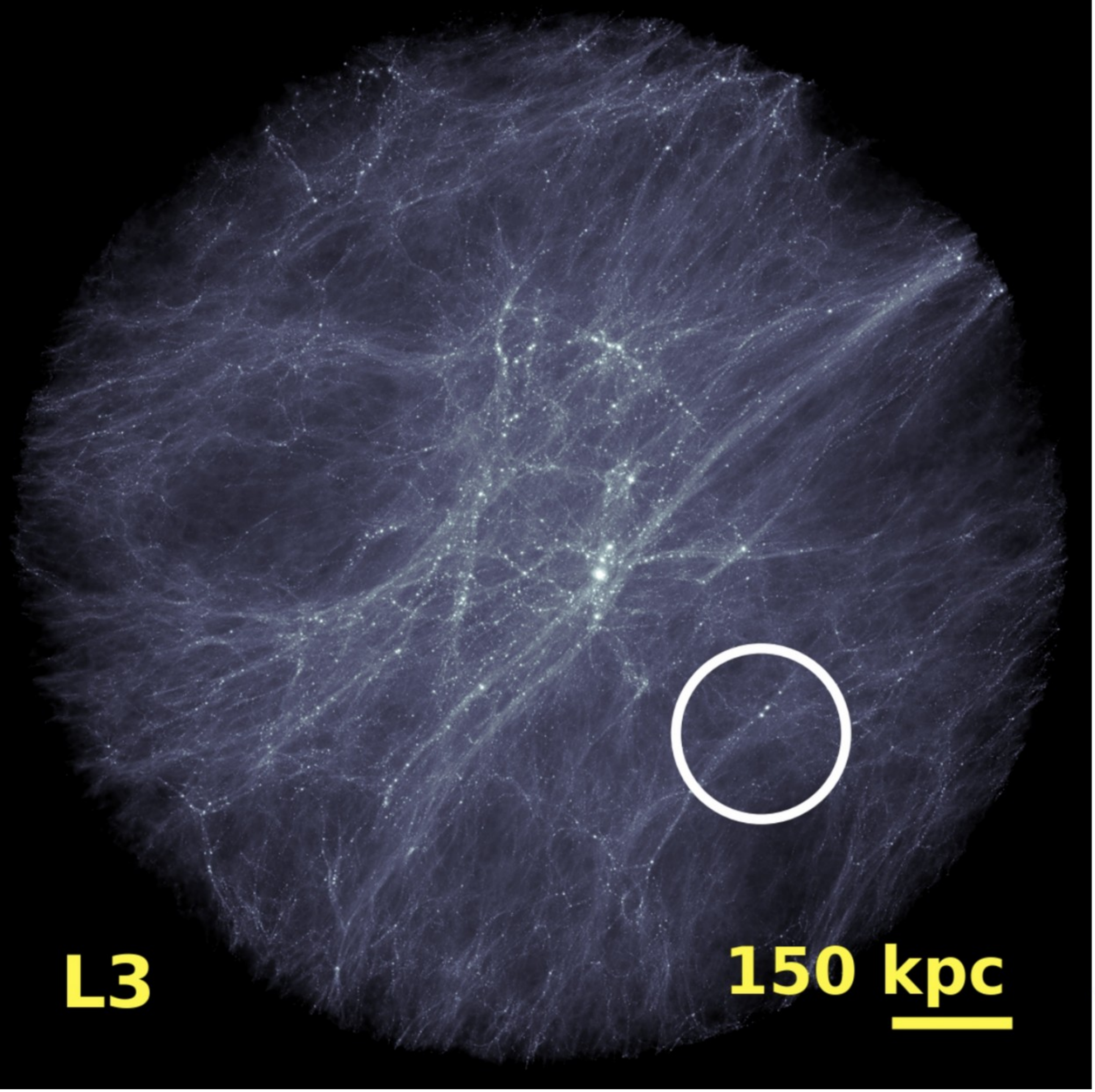


Planck cosmology

Dark matter only

Zoom Level 2

Wang, Bose et al 2020



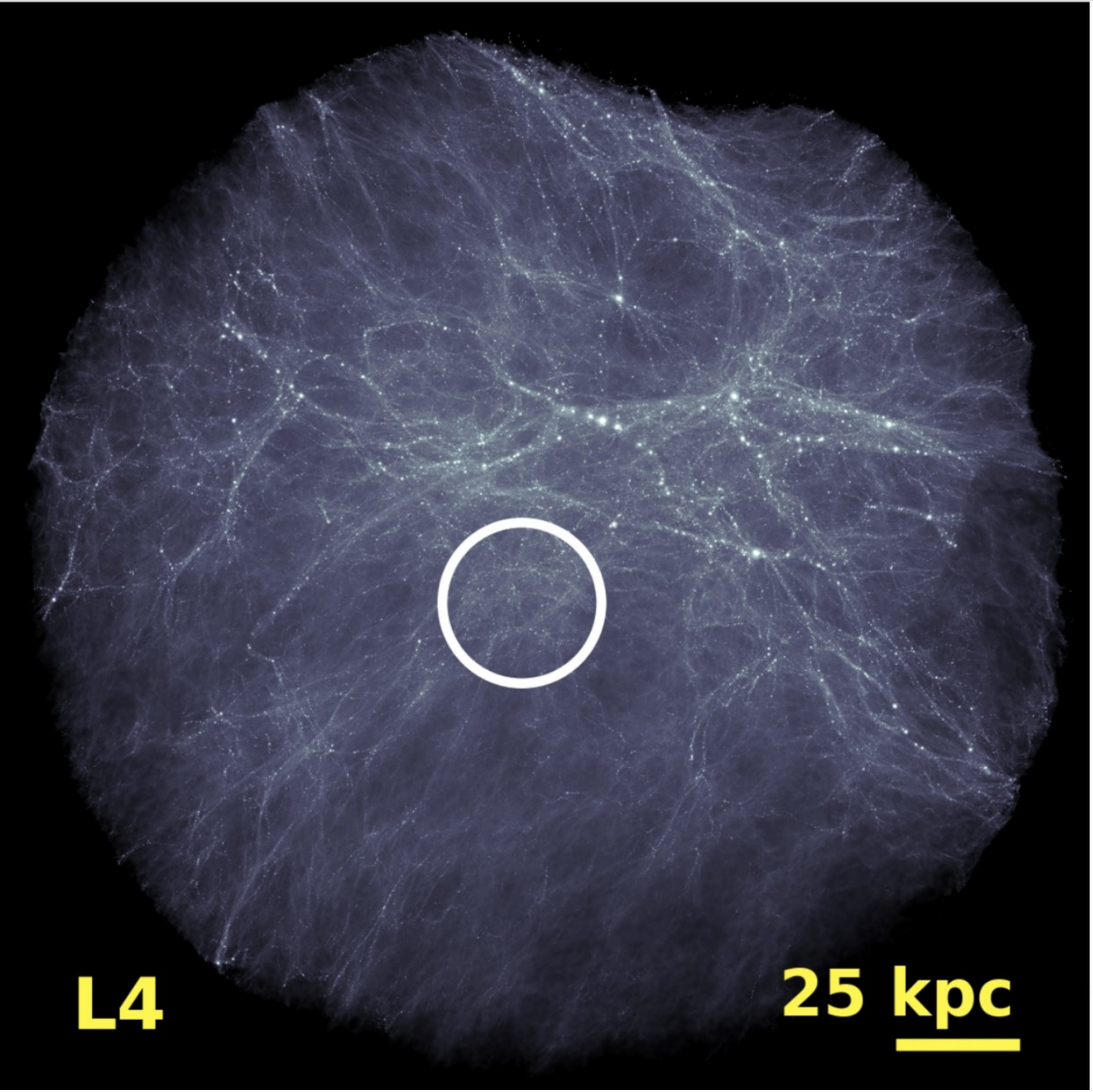
The VVV simulation

Planck cosmology

Dark matter only

Zoom Level 3

Wang, Bose et al 2020



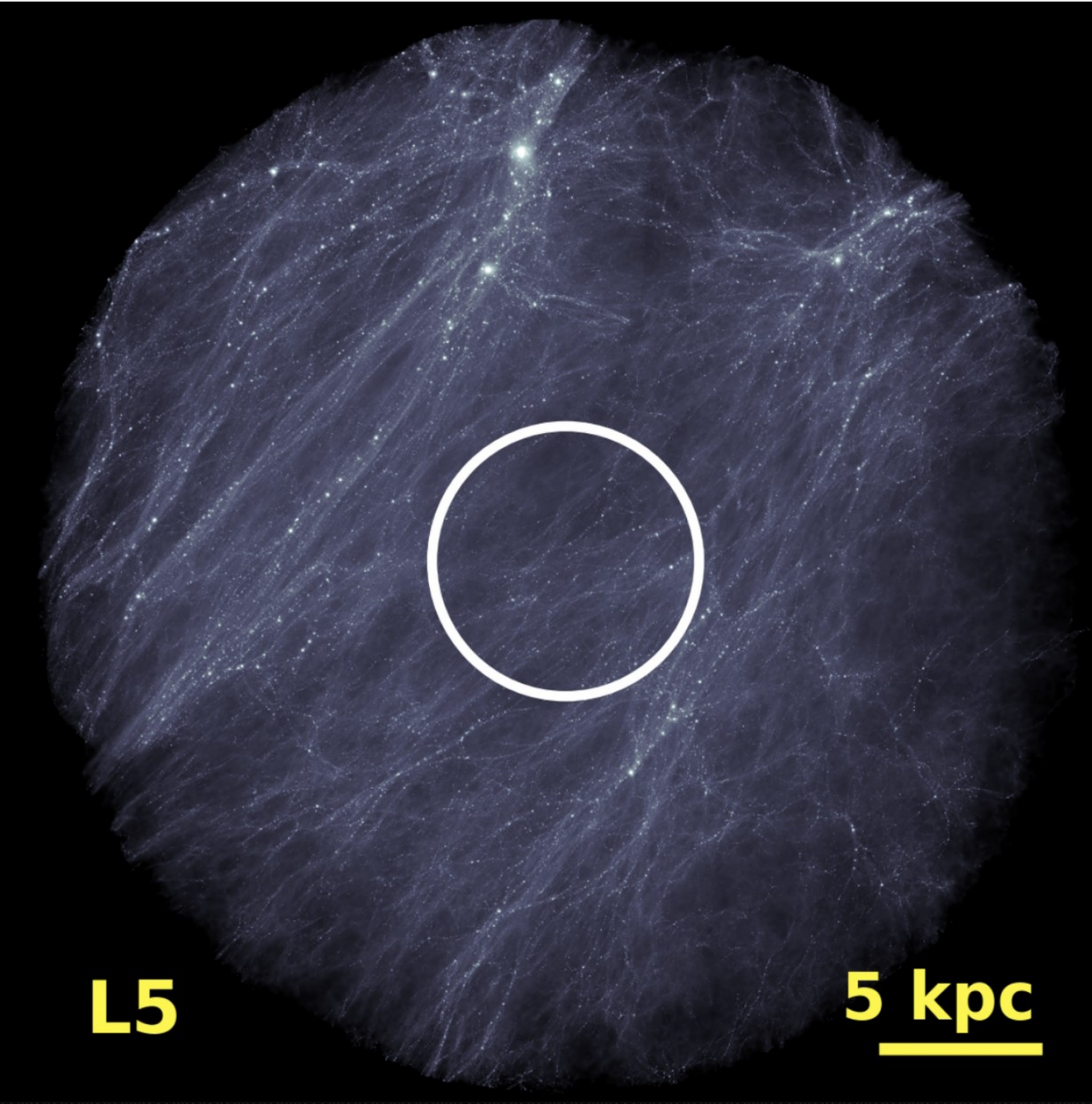
The VVV simulation

Planck cosmology

Dark matter only

Zoom Level 4

Wang, Bose et al 2020



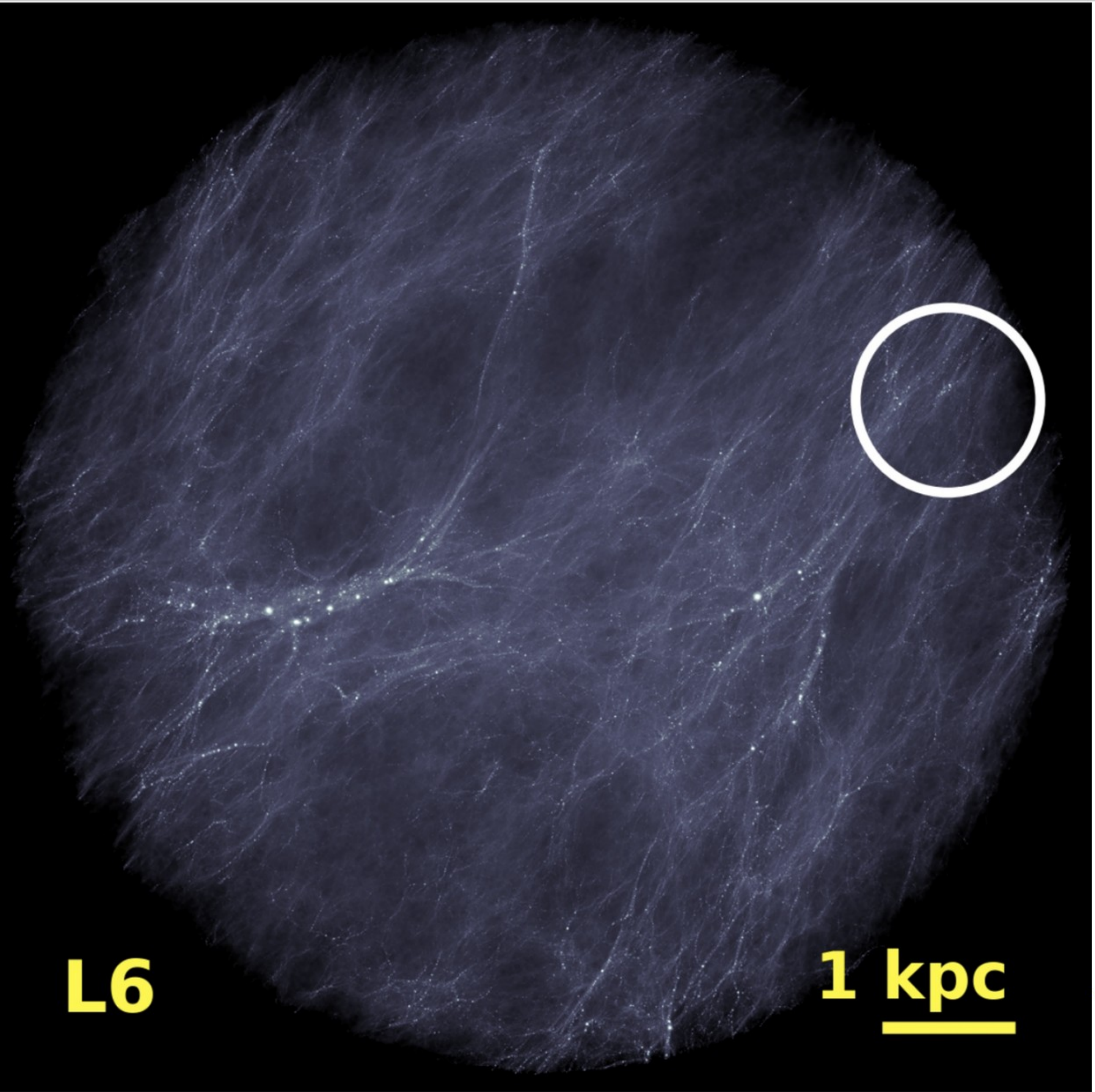
The VVV simulation

Planck cosmology

Dark matter only

Zoom Level 5

Wang, Bose et al 2020



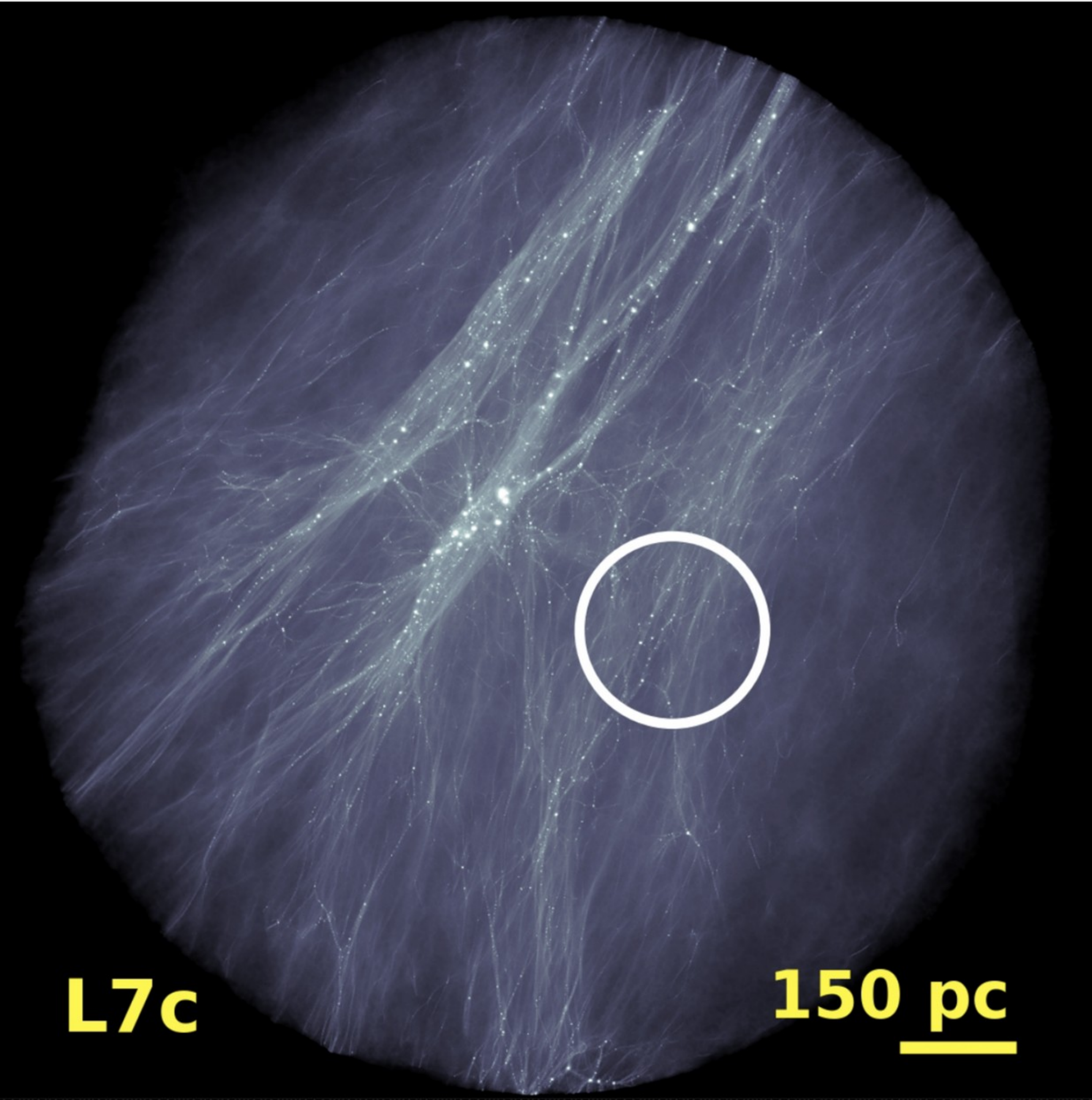
The VVV simulation

Planck cosmology

Dark matter only

Zoom Level 6

Wang, Bose et al 2020



The VVV simulation

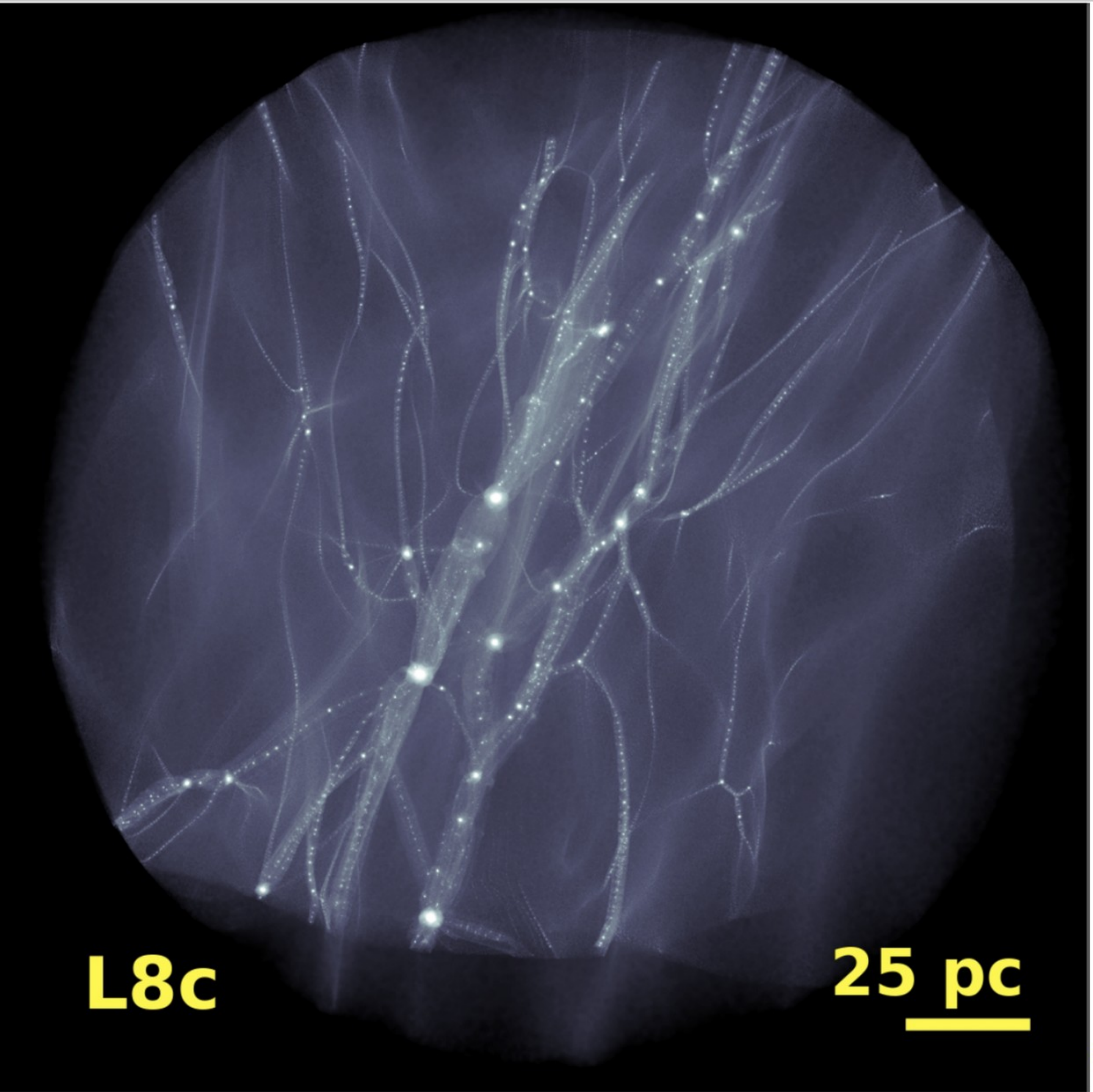
Planck cosmology

Dark matter only

Zoom Level 7

Wang, Bose et al 2020

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 ~3% of the cosmic mean

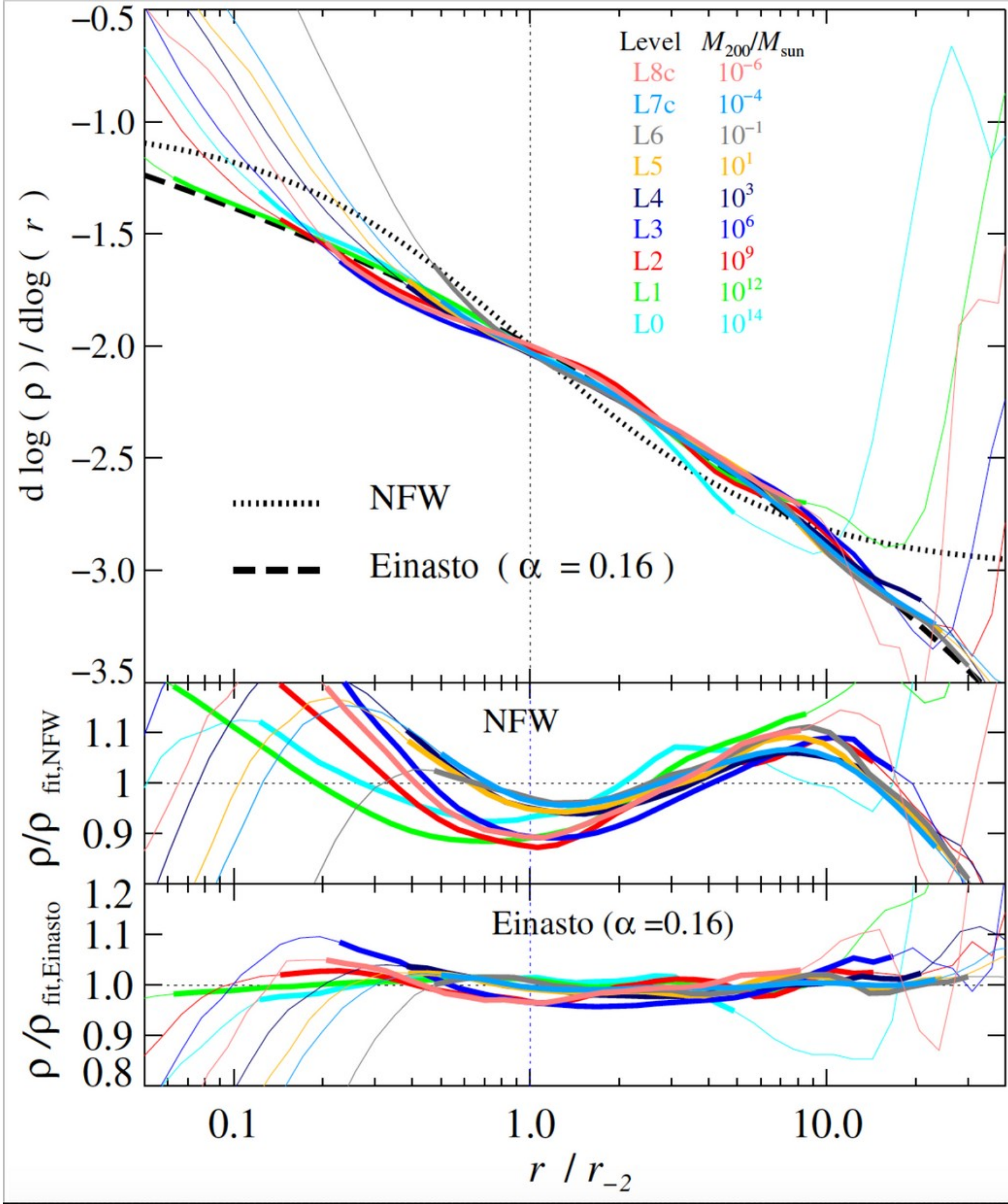
Wang, Bose et al 2020

The various levels of the VVV* simulation

Wang, Bose, Frenk, Gao, Jenkins, Springel & White 2020

level	$R_{\rm high}$ [Mpc]	$n_{\rm p}$	ε [kpc]	$m_{\rm p}$ [$M_\odot$]	$\sigma(M_{\rm tot}, z=0)$	$\langle\rho\rangle/\rho_{\rm mean}$	$M_{\rm char}$ [$M_\odot$]	$N_{\rm char}$	$z_{\rm form}$	$f_{\rm vir}$
L0	738	1.0×10^{10}	7.4	1.5×10^{9}		1.0	10^{14}	127	0.94	0.92
L1	52	1.0×10^{10}	4.4×10^{-1}	7.4×10^{5}	0.34	0.39	10^{12}	59	1.66	0.91
L2	8.8	5.4×10^{9}	5.6×10^{-2}	1.5×10^{3}	1.66	0.082	10^{9}	29	1.91	0.93
L3	1.0	1.8×10^{9}	8.3×10^{-3}	2.8	4.22	0.036	10^{6}	27	2.61	0.94
L4	0.27	2.0×10^{9}	1.0×10^{-3}	5.5×10^{-3}	6.96	0.026	10^{3}	59	4.44	0.94
L5	0.035	1.5×10^{9}	2.2×10^{-4}	5.8×10^{-5}	9.36	0.024	10	30	4.68	0.94
L6	0.0066	1.7×10^{9}	3.8×10^{-5}	2.6×10^{-7}	12.12	0.014	10^{-1}	35	4.84	0.94
L7	0.0011	2.5×10^{9}	5.3×10^{-6}	8.6×10^{-10}	15.06	0.016	10^{-4}	201	5.21	0.96
L7c	0.0011	2.5×10^{9}	5.3×10^{-6}	8.6×10^{-10}	15.06	0.016	10^{-4}	202	4.83	0.97
L8c	0.00024	1.5×10^{9}	1.4×10^{-6}	1.6×10^{-11}	17.60	0.028	10^{-6}	24	1.96	0.94

* VVV = “voids-in-voids-in-voids”



Density profile shapes

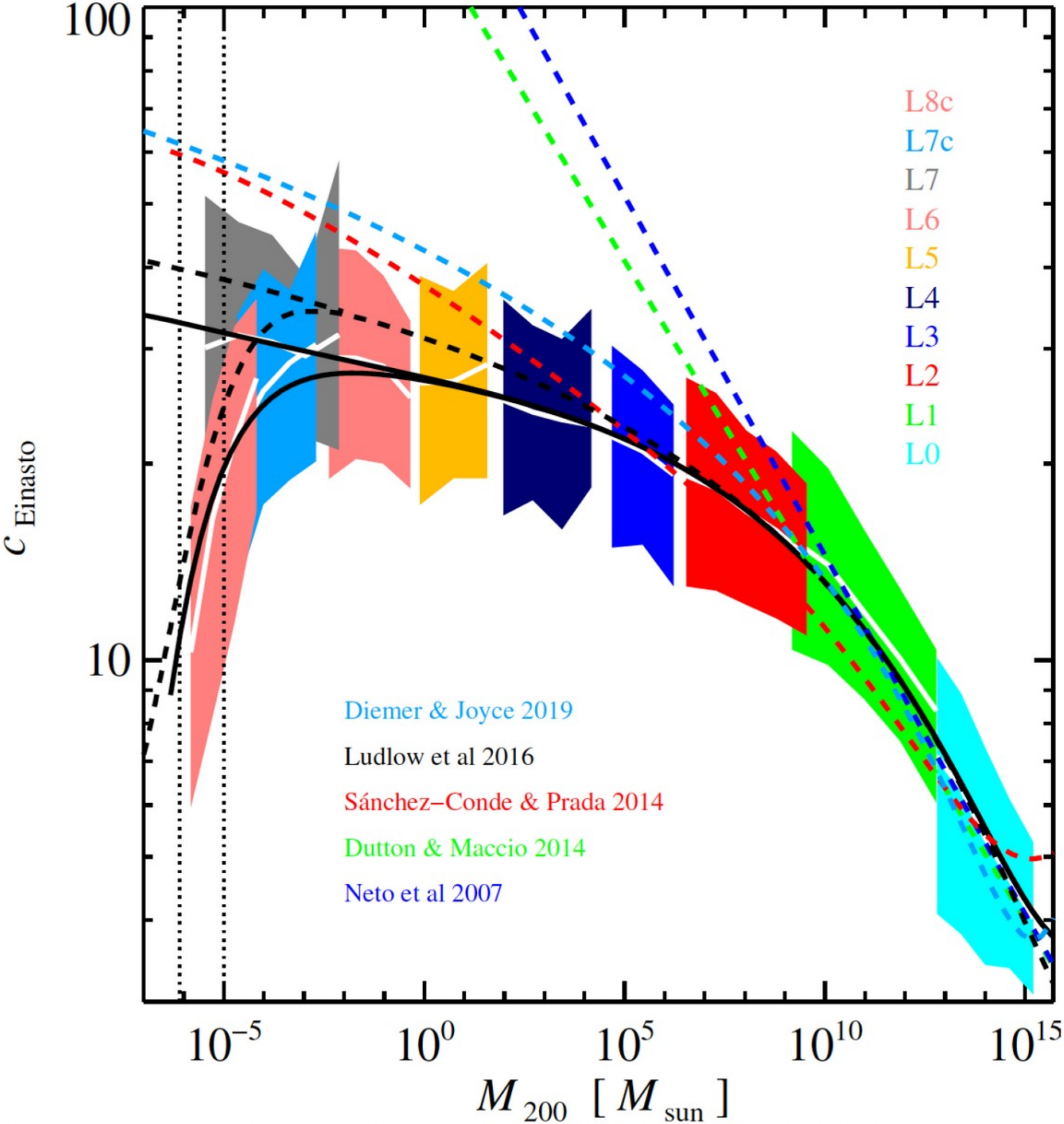
Over 19 orders of magnitude in halo mass and 4 orders of magnitude in density, the mean density profiles of halos are fit by NFW to within 20% and by Einasto (with α = 0.16) to within 7%

$$L_{ann} = A_{p.p}\int\rho^2 dV$$
$$= A_{p.p.} \, . \, 1.87\, V^4_{max}/G^2R_{max}$$

across the <u>full</u> mass range

Wang, Bose et al 2020

Concentration-mass relation



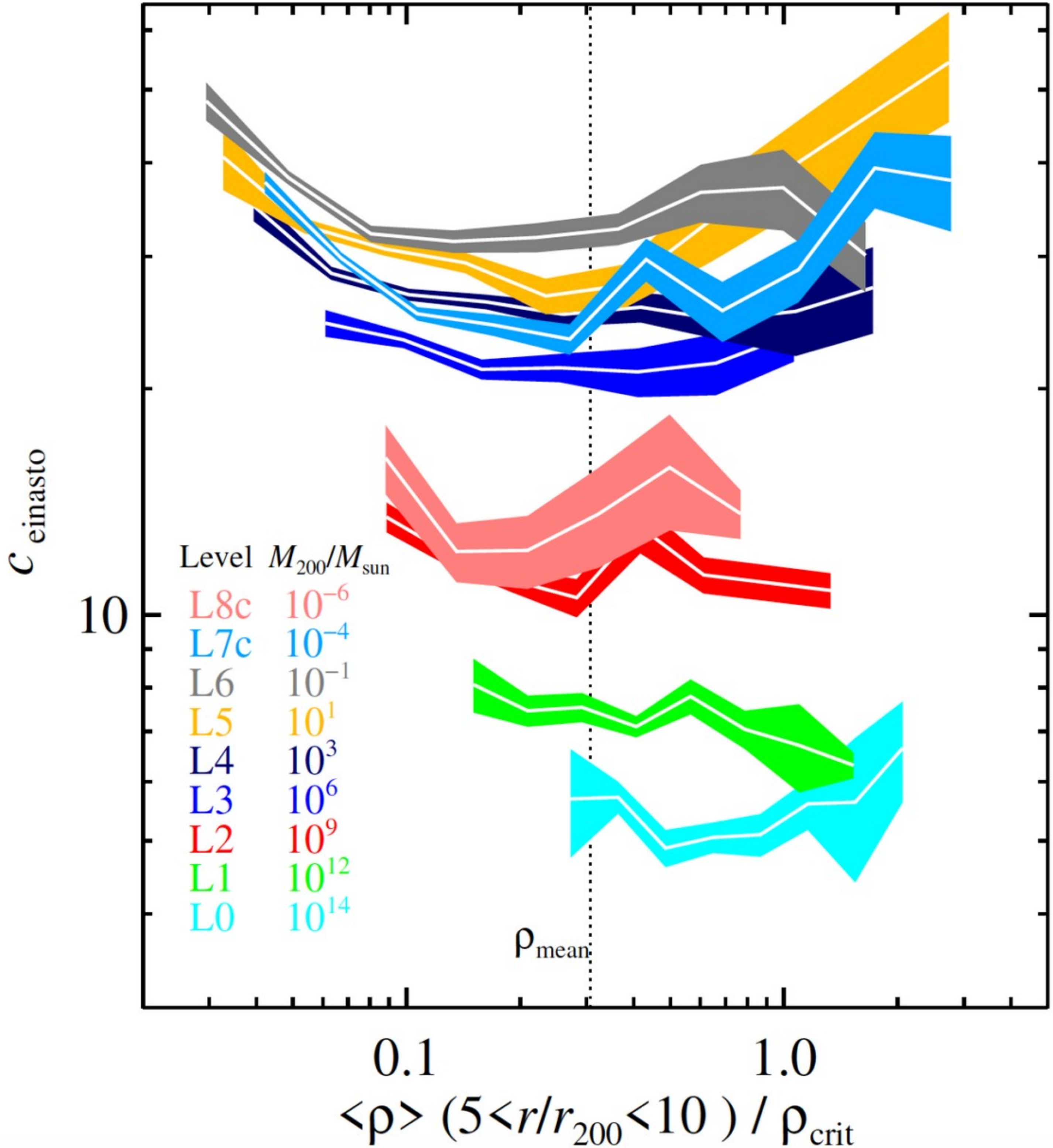
Concentrations at small mass are lower than all previous extrapolations by up to factors of tens

A turndown at 10^3 Earth masses is due to the free-streaming limit.

The scatter depends only weakly on halo mass.

Sets the $V_{max} - R_{max}$ and so the $L_{ann} - M$ relation for all halos

Wang, Bose et al 2020



Concentration-density relation

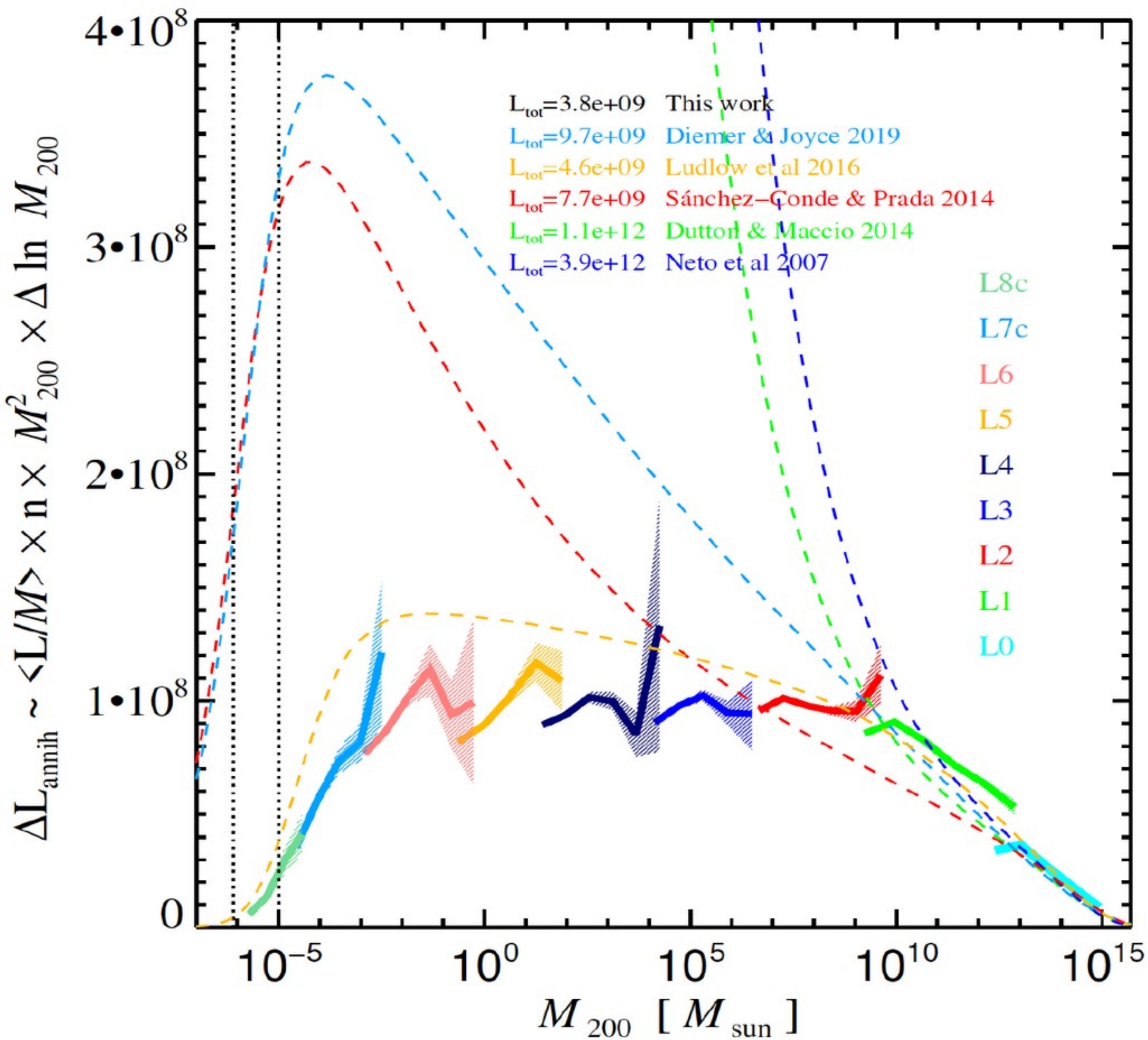
At given halo mass, concentration does not depend on *local* environment density.

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

Wang, Bose et al 2020

Annihilation luminosity per unit cosmological volume as a function of halo mass

Halo abundance n(M) from Angulo et al (2012)



The contribution of halos to the mean z = 0 luminosity density of the Universe is almost independent of their mass over the mass range

$10^{-4}\,M_\odot < M_{halo} < 10^{12}\,M_\odot$

It is lower than previously estimated by factors between 3 and 1000

This still neglects the substructure contribution to halo luminosity

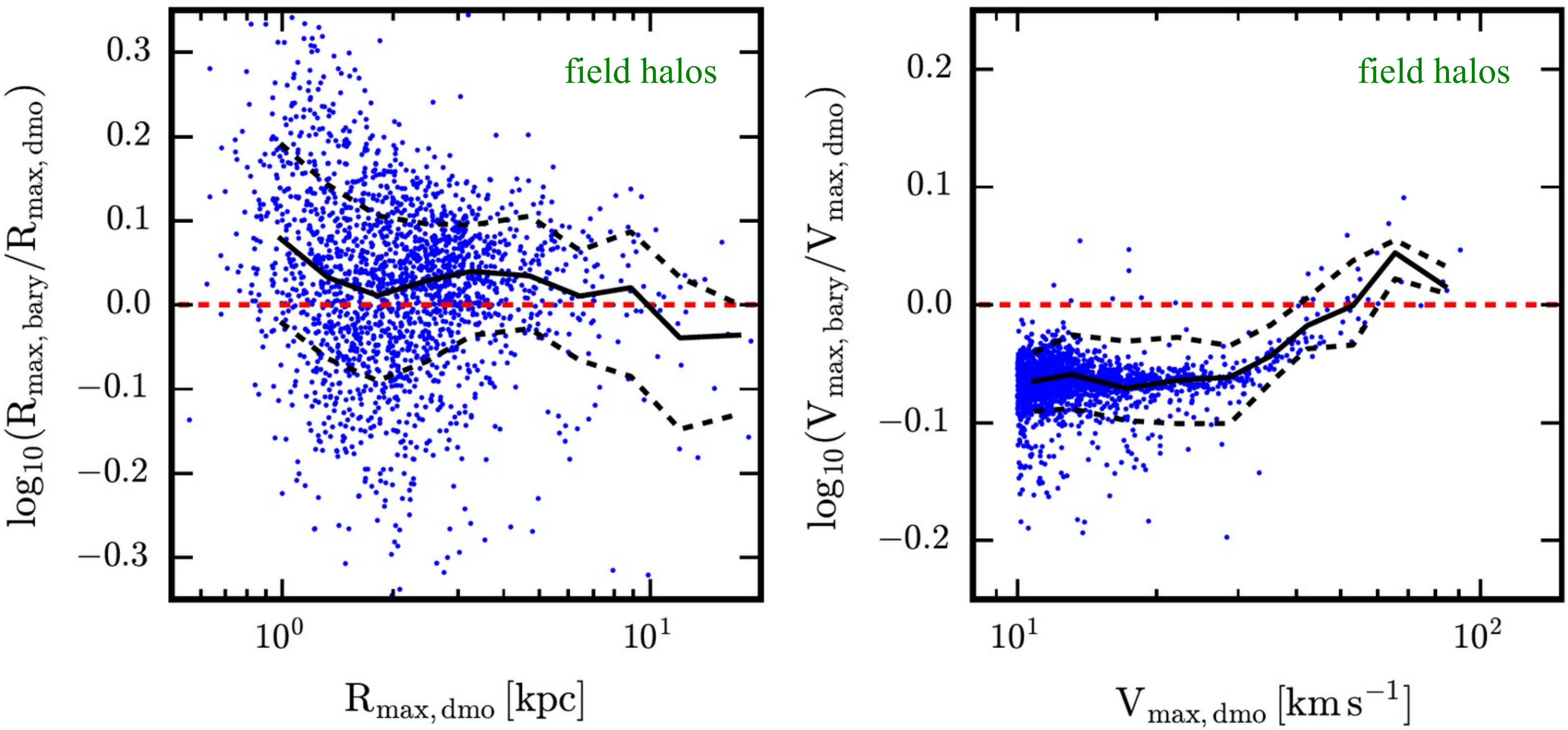
Wang, Bose et al 2020

High-resolution Auriga simulations

Grand & White 2021

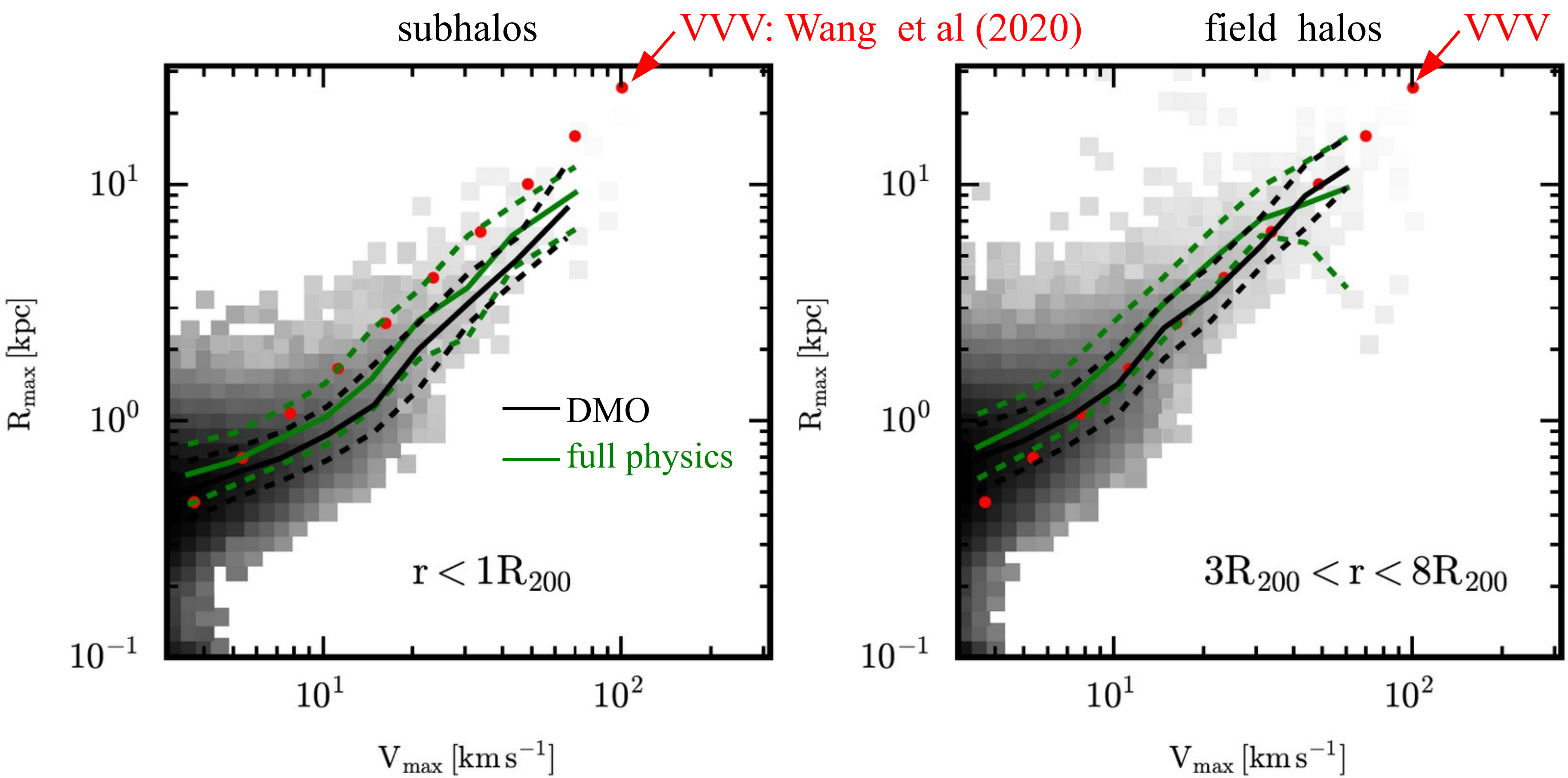
- Six simulations of "Milky Way" formation in ΛCDM
  $m_{DM} \sim 5 \times 10^4 M_\odot$, $m_{bar} \sim 6 \times 10^3 M_\odot$
- Each is simulated twice – "full physics" and dark matter only
- Each also includes the nearby "field" environment
- For large objects, $L_{ann} = \int \rho^2 dV$ is estimated by Voronoi tesselation
- For small objects, $L_{ann} = 1.87\, V^4_{max}/G^2 R_{max}$ from Einasto fits to $V_c(r)$

How do baryons affect the DM structure of small halos?



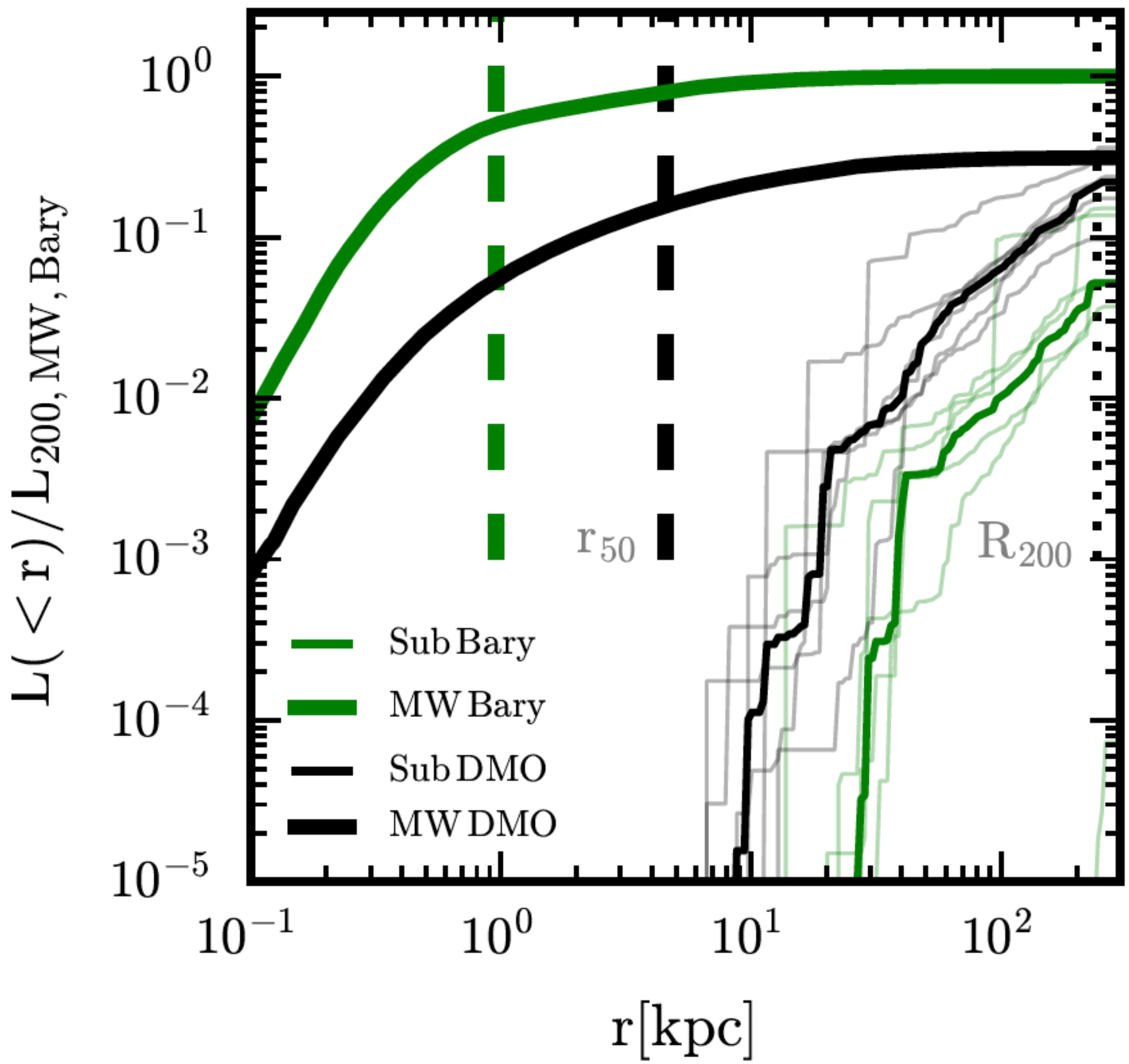
- Individual small field halos have slightly larger R_{max} and slightly smaller V_{max} in the full physics simulation → L_{ann} drops by almost a factor of 2

How do they affect the $V_{max} - R_{max}$ relations of (sub)halos?

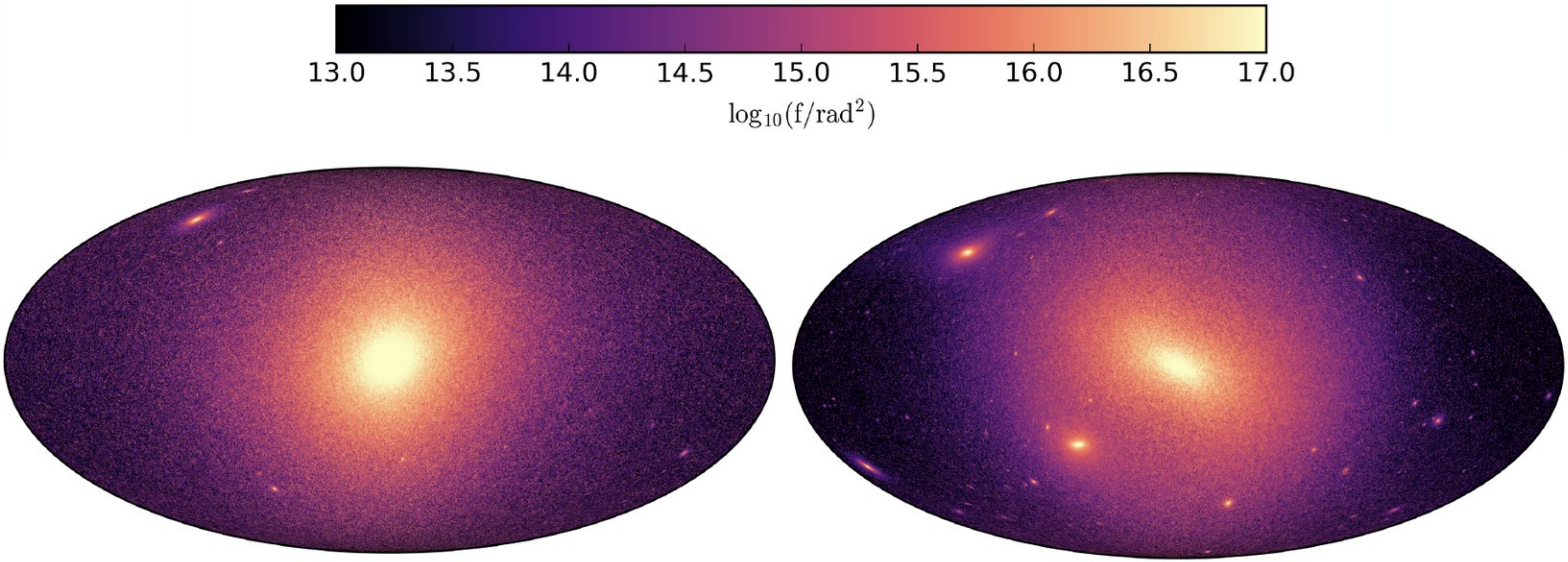


- The DMO field halo relation matches Wang et al (2020) down to the resolution limit
- The full physics field halo relation is parallel but higher by a factor of 1.4
- Both relations are shifted down by a factor of about 2 for subhalos
- Resolution affects the subhalo relation below V_{max} ~ 10 km/s

How do baryons affect MW annihilation luminosities?



- The luminosity of the main halo goes up by a factor of 3
- Its half-light radius goes down by a factor of 5
- The luminosity in resolved satellites drops by a factor of 6
- Satellites are particularly suppressed in the inner regions
- The contrast between the main component and the brightest subhalos increases by 1.5 dex

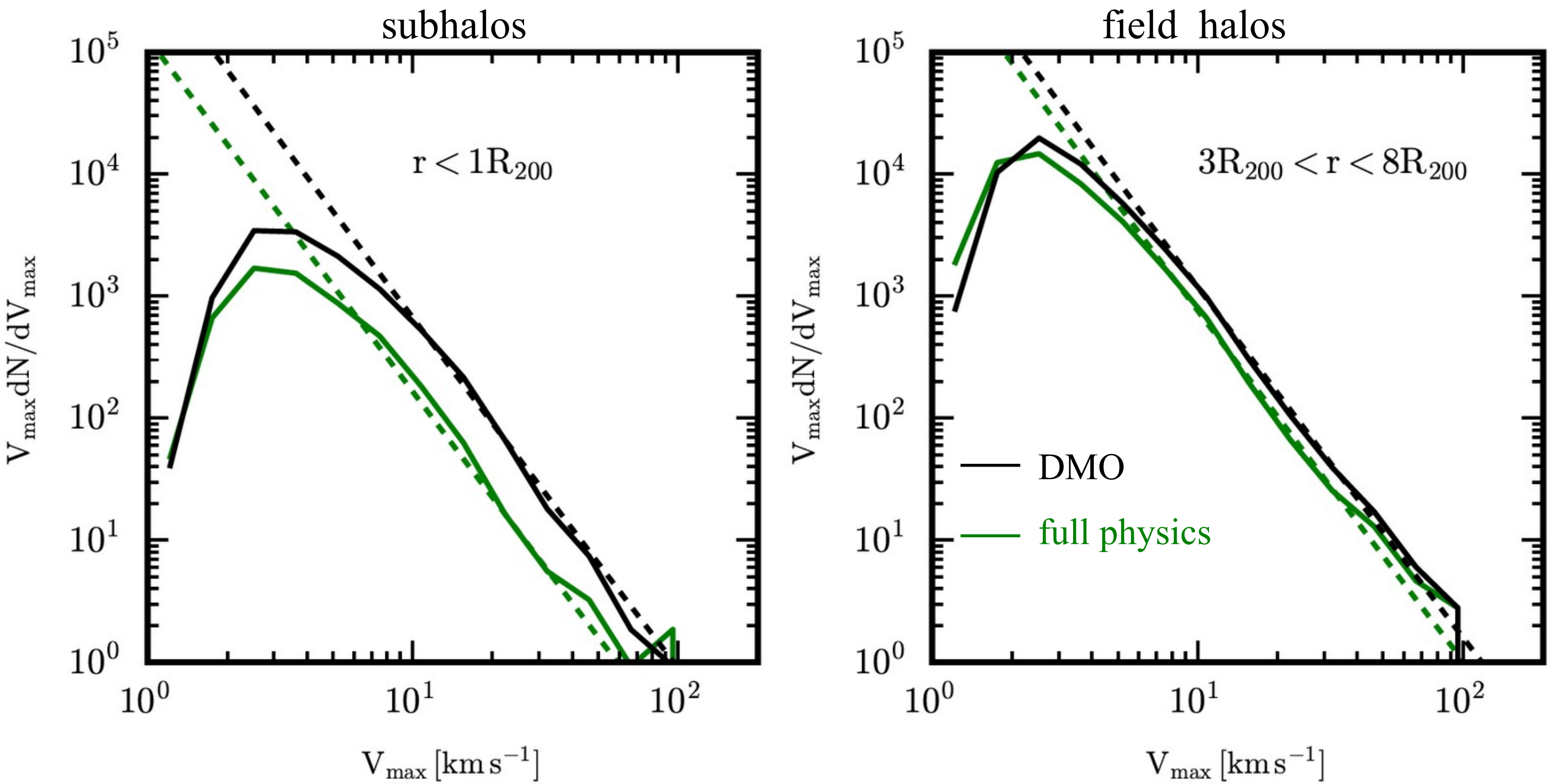


“Full physics” Dark matter only

The cooling and condensation of gas into galaxies makes the main halo emission brighter, more concentrated and rounder.

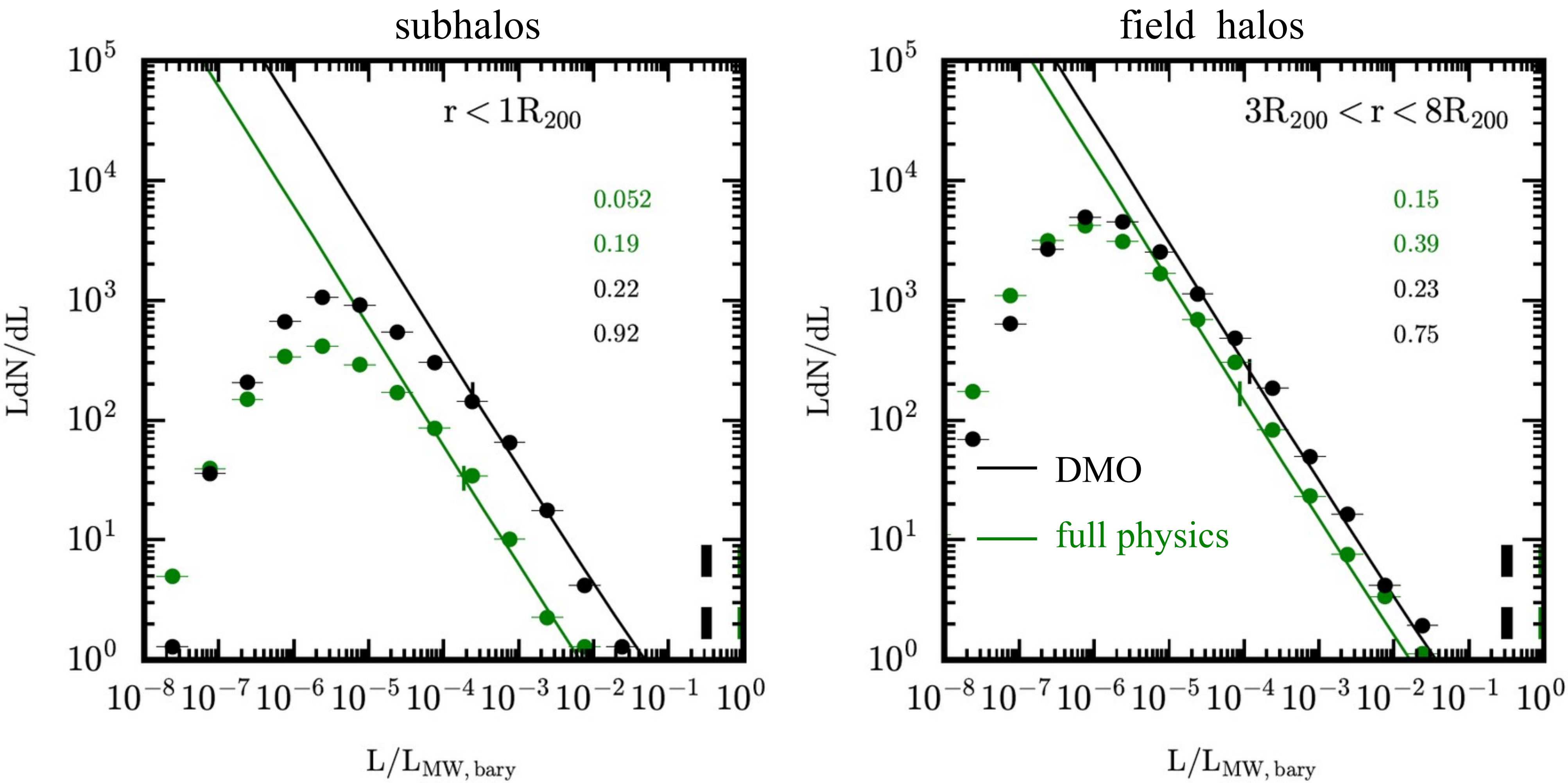
The subhalos become fainter

Extrapolating to the lowest masses – the n(V_{max}) function



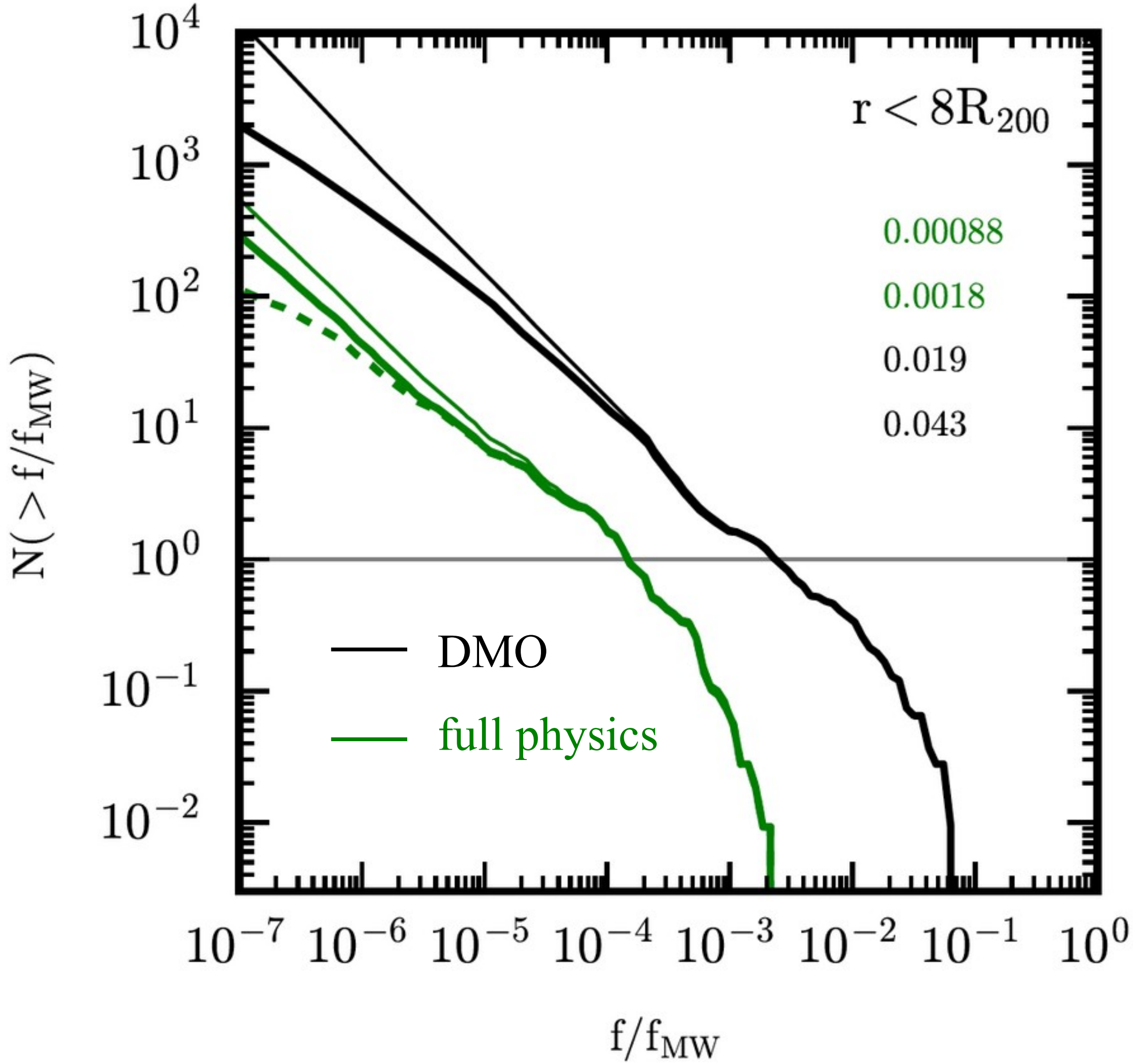
- DMO → full phys. drop is larger for subhalos due to enhanced tidal effects
- Abundances converge down to $V_{max} \sim 8$ km/s
- Shape of the dashed extrapolations taken from the VVV $V_{max} - R_{max} - M$ relations of Wang et al (2020) together with n(M) from Angulo et al (2012)

Extrapolating to the lowest masses – the n(L_{ann}) function



- Upper number in each pair is $L_{tot}/L_{MW,bar}$ for the resolved subhalos
- The lower number extrapolates all the way down to Earth mass
- Unresolved (sub)halos increase the luminosities by factors of just 2.5 – 4.5

Extrapolating to the lowest masses – subhalo fluxes



- Fluxes are as observed from a “Solar” position in units of the main halo flux
- The brightest subhalo has expected $f/f_{MW} \sim 0.0002$ (f.p) or 0.003 (DMO)
- The total subhalo flux is expected to be < 0.2% of the main halo flux (f.p.)
- About half the subhalo flux is in numerically resolved subhalos

Conclusions

- Baryonic effects substantially enhance and concentrate the predicted luminosity of the main MilkyWay halo in annihilation radiation

- They reduce the luminosity predicted for small halos, $V_{max} < 50$ km/s

- The enhanced mass concentration of the MW due to baryons leads to enhanced tidal disruption of satellites, especially in the inner halo

- The expected ratio of the flux of the brightest subhalo to that of the main halo is reduced by about 1.5 dex, to ~ 0.0002.
  $\longrightarrow$ no subhalo will be detected before the main halo is confirmed?

- Previous work greatly overestimated the contribution from very small subhalos (i.e. *boost factors*) by overestimating their concentrations.

- The *Fermi* excess could well be annihilation radiation