The astrophysical evidence for dark matter

Parameter	Combined
$\Omega_b h^2$	0.02233 ± 0.00015
$\Omega_c h^2$	0.1198 ± 0.0012
$100\theta_{MC}$	1.04089 ± 0.00031
τ	0.0540 ± 0.0074
$\ln(10^{10} A_s)$	3.043 ± 0.014
n_s	0.9652 ± 0.0042
$\Omega_m h^2$	0.1428 ± 0.0011
H_0 [km s^{-1}Mpc^{-1}]	67.37 ± 0.54
Ω_m	0.3147 ± 0.0074
Age [Gyr]	13.801 ± 0.024
σ_8	0.8101 ± 0.0061
$S_8 \equiv \sigma_8 (\Omega_m/0.3)^{0.5}$	0.830 ± 0.013
z_{re}	7.64 ± 0.74
$100\theta_*$	1.04108 ± 0.00031
r_{drag} [Mpc]	147.18 ± 0.29
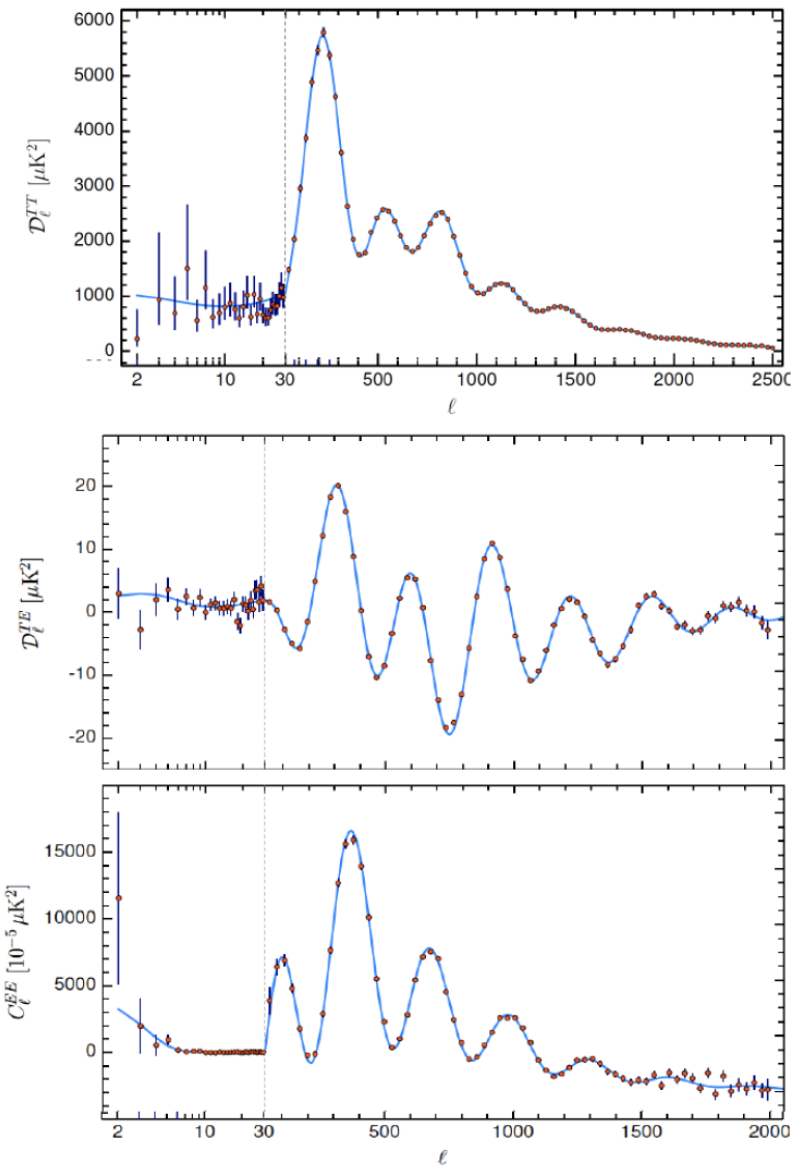
Planck Collaboration 2018

- Results from a single instrument (Planck/HFI)
- <u>No</u> local/low-redshift data are used
- Linear perturbation of a homogeneous medium
- No exotic/HE physics needed to set pattern
- Outside modified gravity regime
- Modelling cosmic structure formation requires extrapolation to smaller scales and later times

Average mass profiles around bright galaxies

Wang et al (2016)

Guo et al 2011 model
Planck13 cosmology

SDSS/DR7

$\log M_*$

•—•	10-10.4
•—•	10.4-10.7
•—•	10.7-11
•—•	11-11.2
•—•	11.2-11.4
•—•	11.4-11.6
•—•	11.6-15

y-axis: $\Delta\Sigma [hM_\odot/pc^2]$

x-axis: $r_p [Mpc/h]$
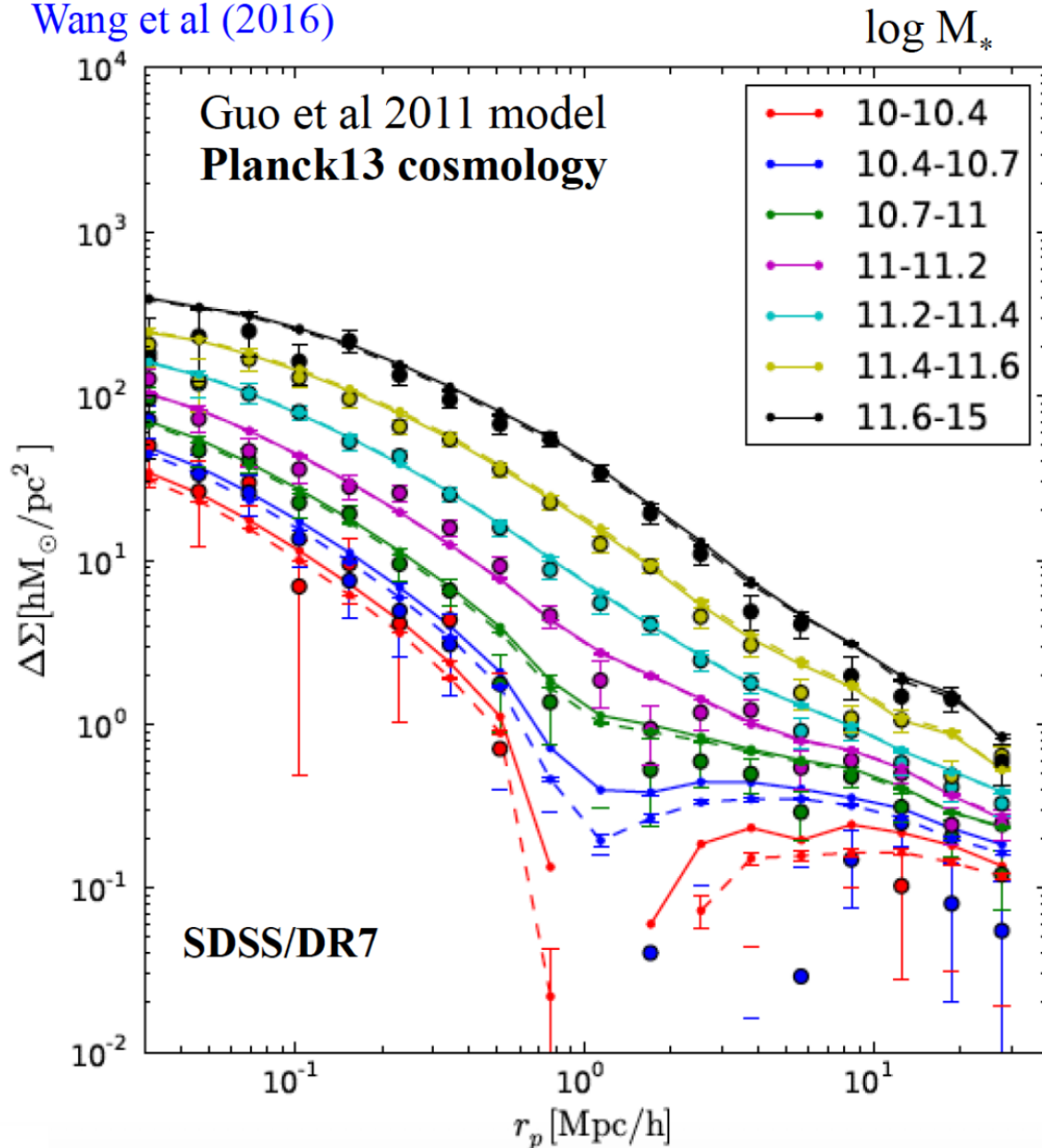
The points are measured mass profiles around the central galaxies of galaxy groups

Top to bottom goes from rich clusters to "Milky Way" groups

The lines are the predicted mass profiles about such groups in the Millennium Simulation

Parameters were fit using galaxy *abundances* only. **No** parameters adjusted to fit clustering

Predicted and observed profiles for abundance-matched halos agree down to ~ MW mass

Where is the dark matter predicted to be today?

$\delta_c = 1.686$

$M_s / M_\odot$

10^{14}

10^{12}

10^9

10^6

1.0

10^{-6}

Diffuse fraction

σ_s
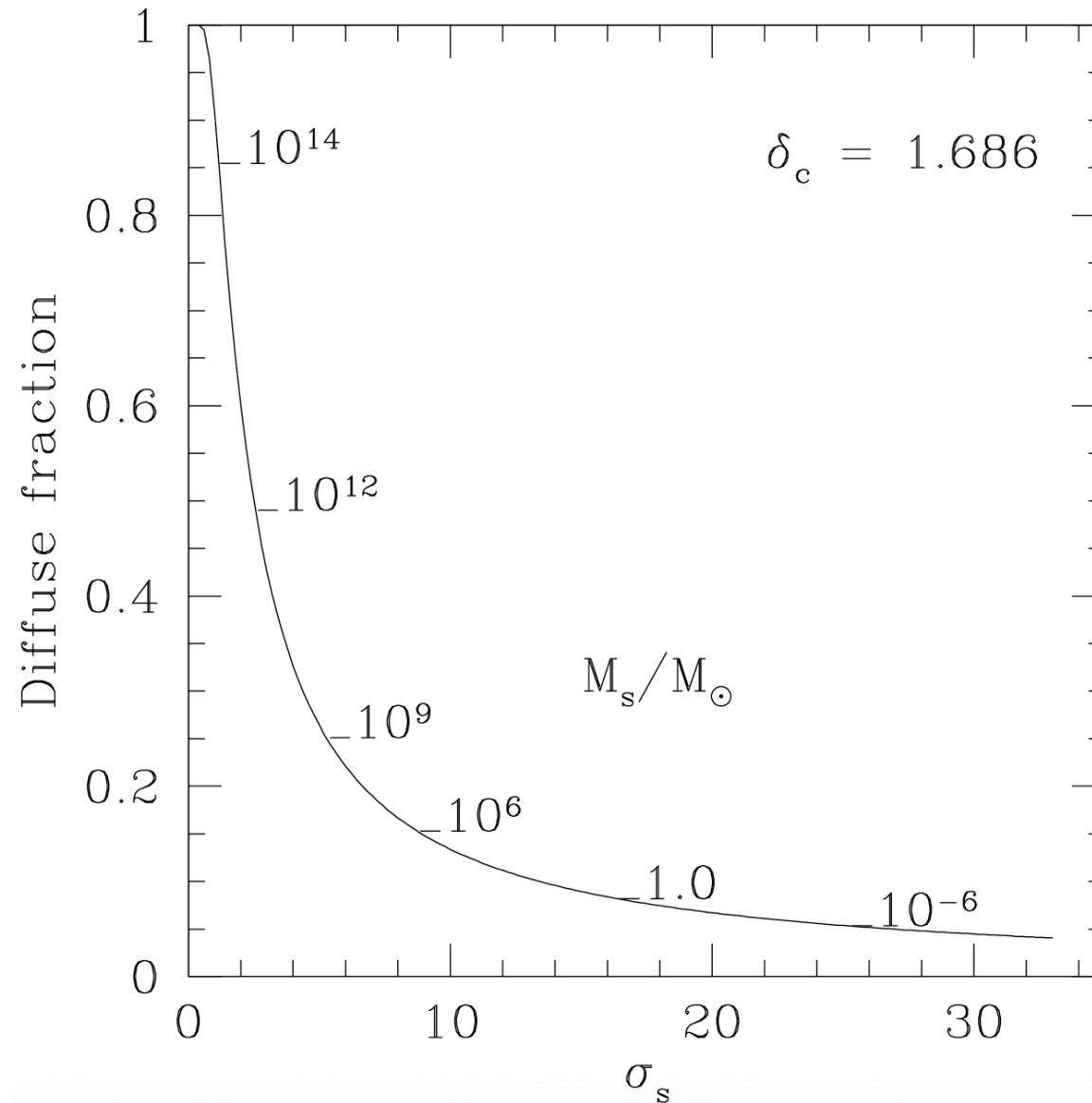
rms (extrapolated) linear overdensity at z=0 equivalent to smoothing scale

In the ΛCDM model, Press-Schechter theory implies

- ~15% of DM is in clusters

- ~50% is in halos more massive than that of the Milky Way

- ~75% is in halos which contain at least some stars

- Almost 95% is in halos above the Earth mass limit

- The rest is still diffuse today, filling the other 99% of space!

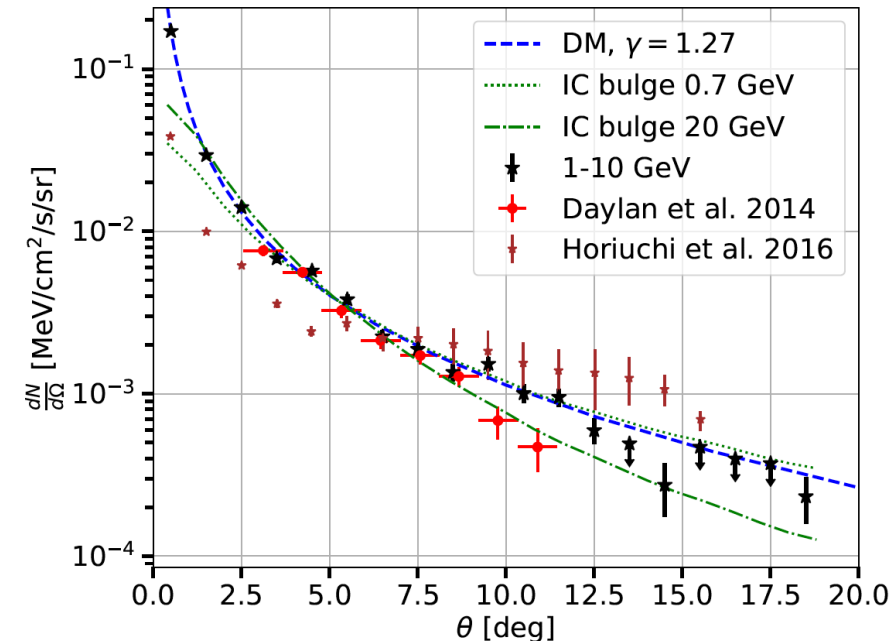# Could the dark matter produce detectable radiation?

Dessert et al 2021
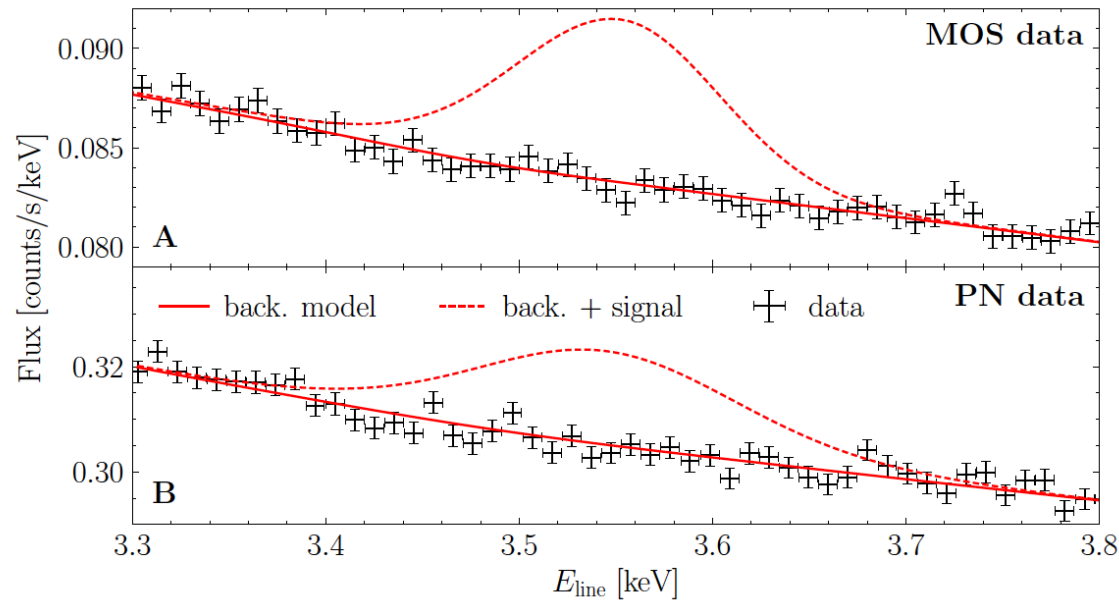
Dark matter decay can produce continuum or line emission.

An X-ray line was claimed to be detected at 3.5 keV in galaxy clusters. ⟶ Decay of a sterile neutrino of mass 7 keV?

Strongly excluded by non-detection from the MW halo.
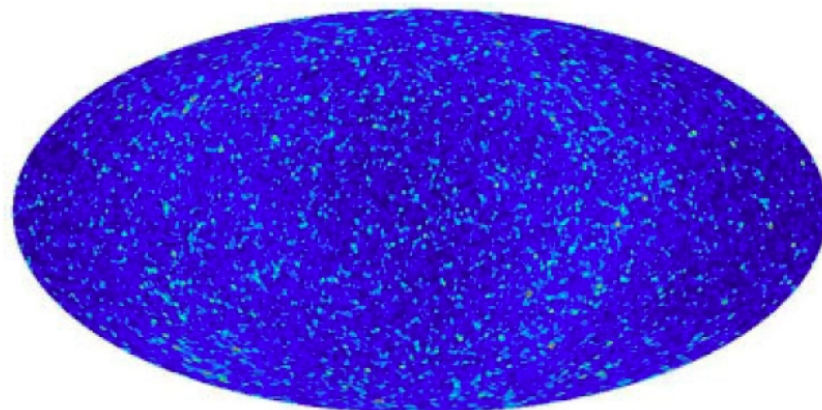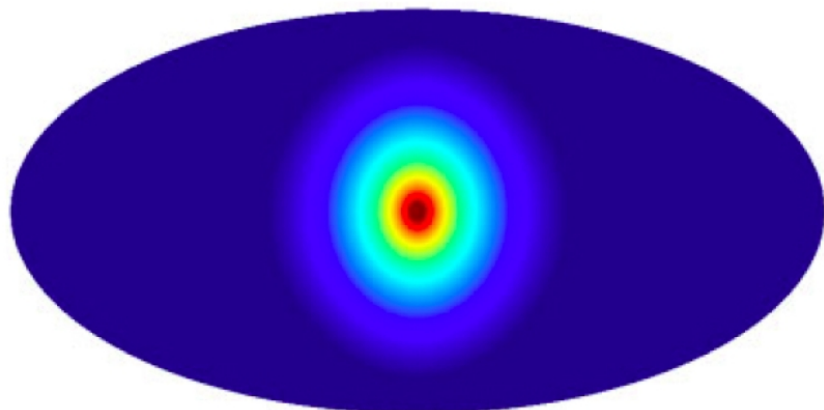
$$L_{halo} \propto M_{halo}$$

Di Mauro 2021

Dark matter annihilation, for example of SUSY WIMPS, could produce continuum or line radiation in the γ-ray range.

Possibly detection as an excess at $1-10$ GeV towards the Galactic bulge.
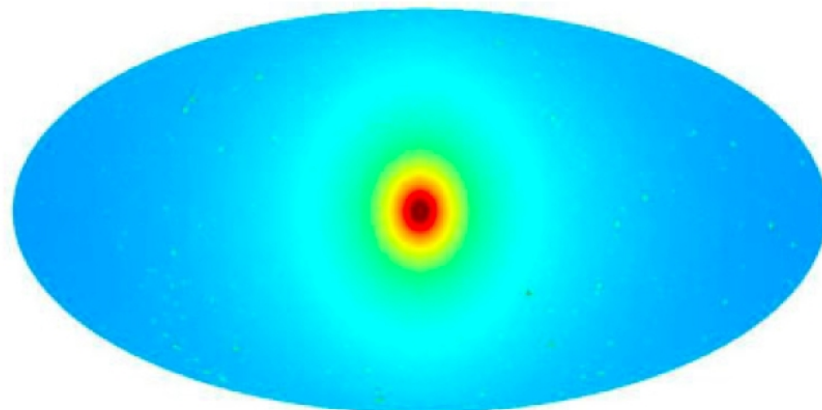
$$L_{halo} \propto \overline{\rho}_{halo} \, M_{halo}$$

Luminosity biased to high-density (i.e. low-mass?) halos/subhalos

# 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 <u>dominate</u> the cosmic annihilation luminosity density

The N=10⁹ Aquarius model for the MW Halo (DM only)

Springel et al 2008

M_{min}
10^5 10^6
10^7 10^8

$L_{50\%}$

$M_{50\%}$

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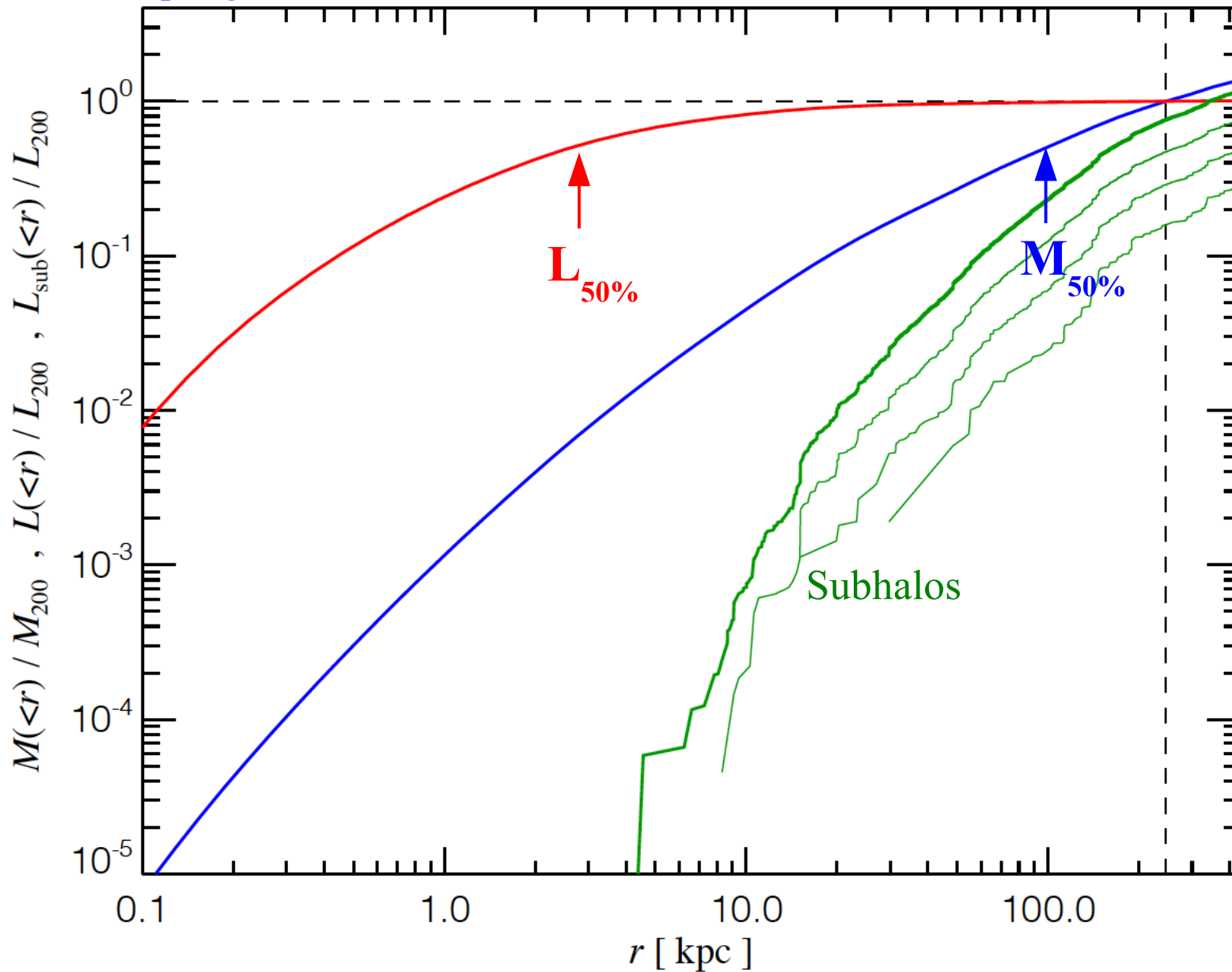
Increase in L_{sub}
per dex in M_{min}
appears constant

Extrapolate down
to Earth mass?

What about the
baryons?

Axis labels: $M(<r) / M_{200}$, $L(<r) / L_{200}$, $L_{sub}(<r) / L_{200}$

r [kpc]

The VVV simulation
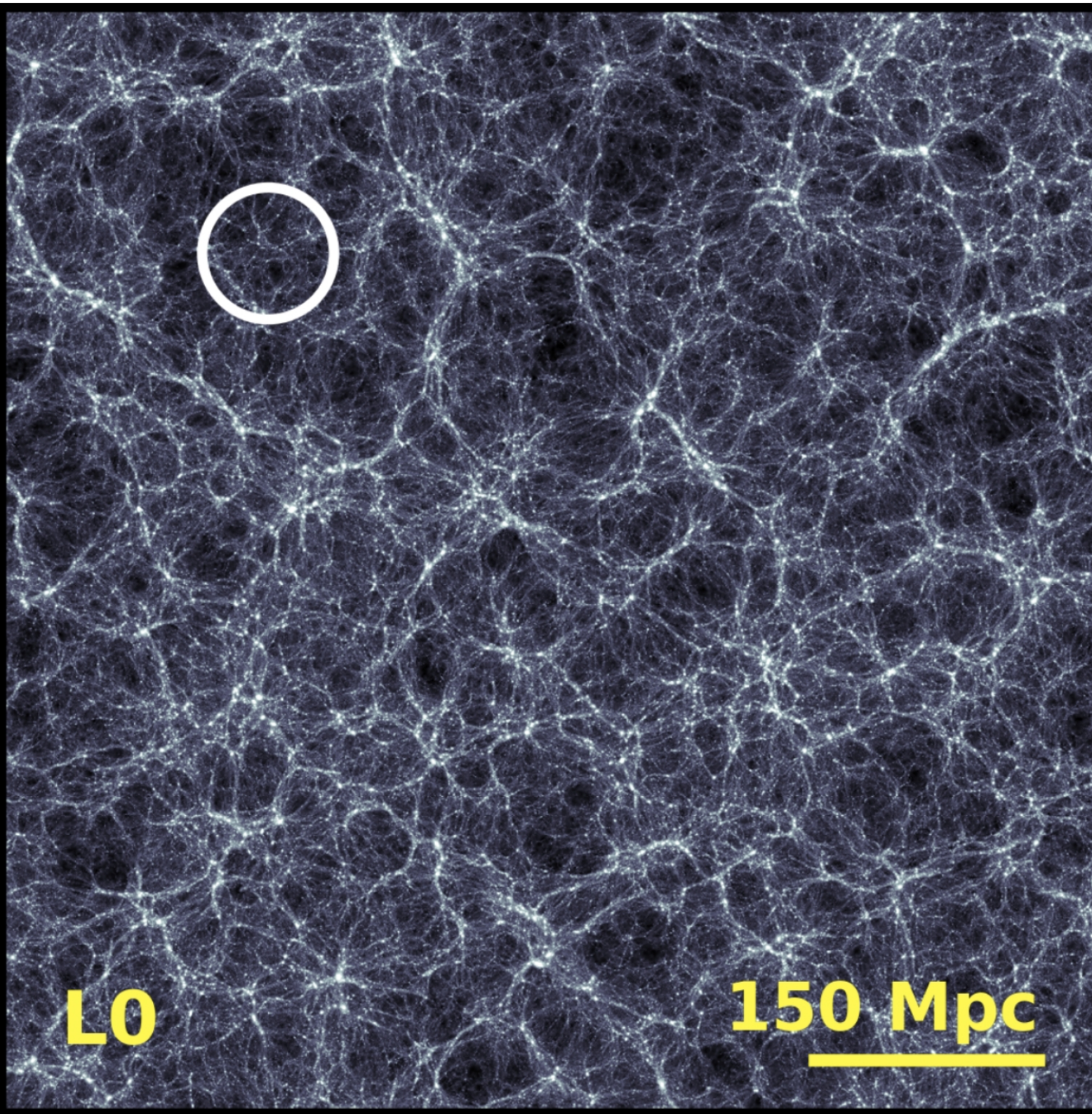
Planck cosmology

Dark matter only

Base Level

L0

150 Mpc

Wang, Bose et al 2020

The VVV simulation

Planck cosmology

Dark matter only

Zoom Level 1

L1

15 Mpc

Wang, Bose et al 2020
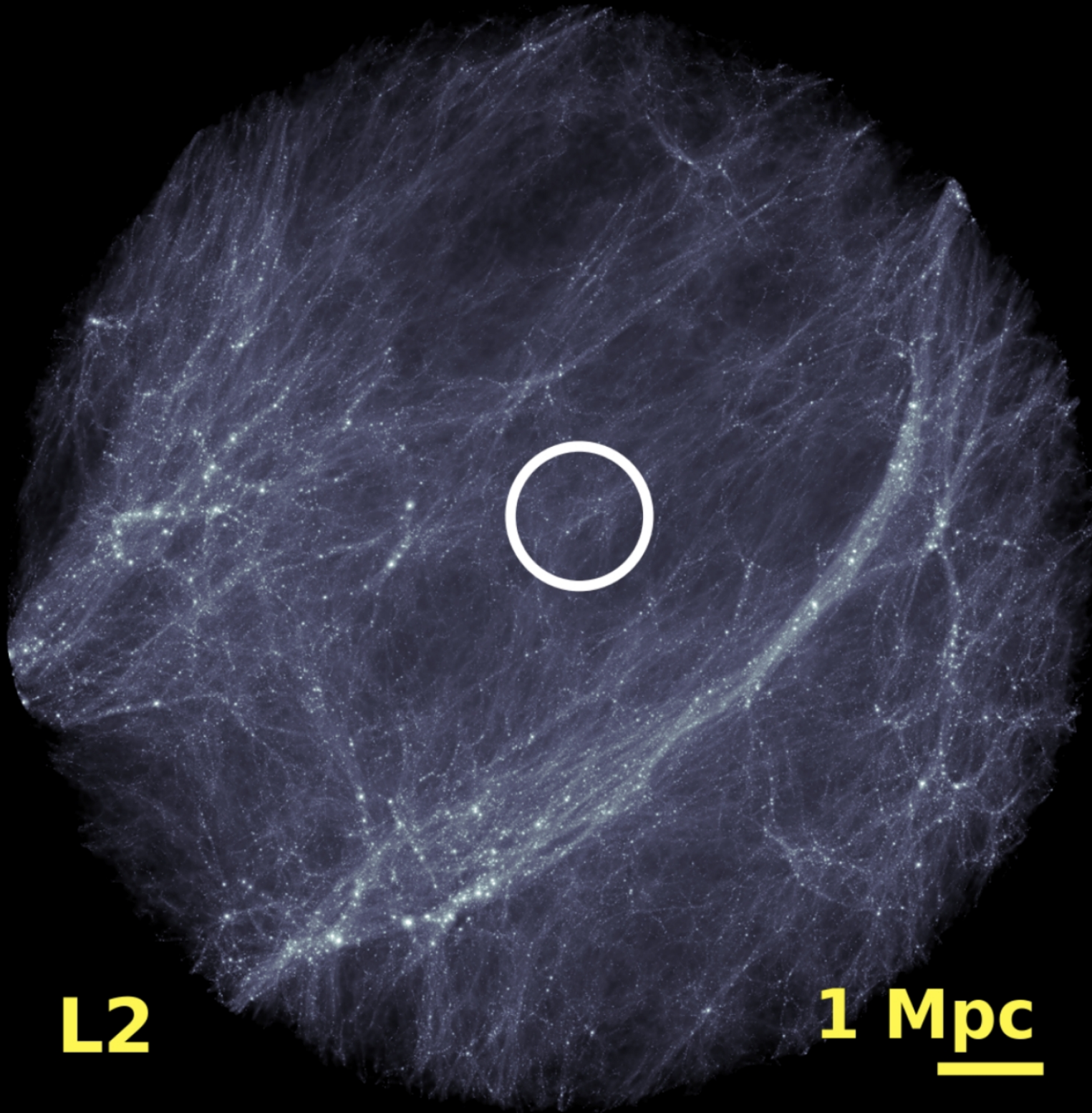
The VVV simulation

Planck cosmology

Dark matter only

Zoom Level 2

L2

1 Mpc

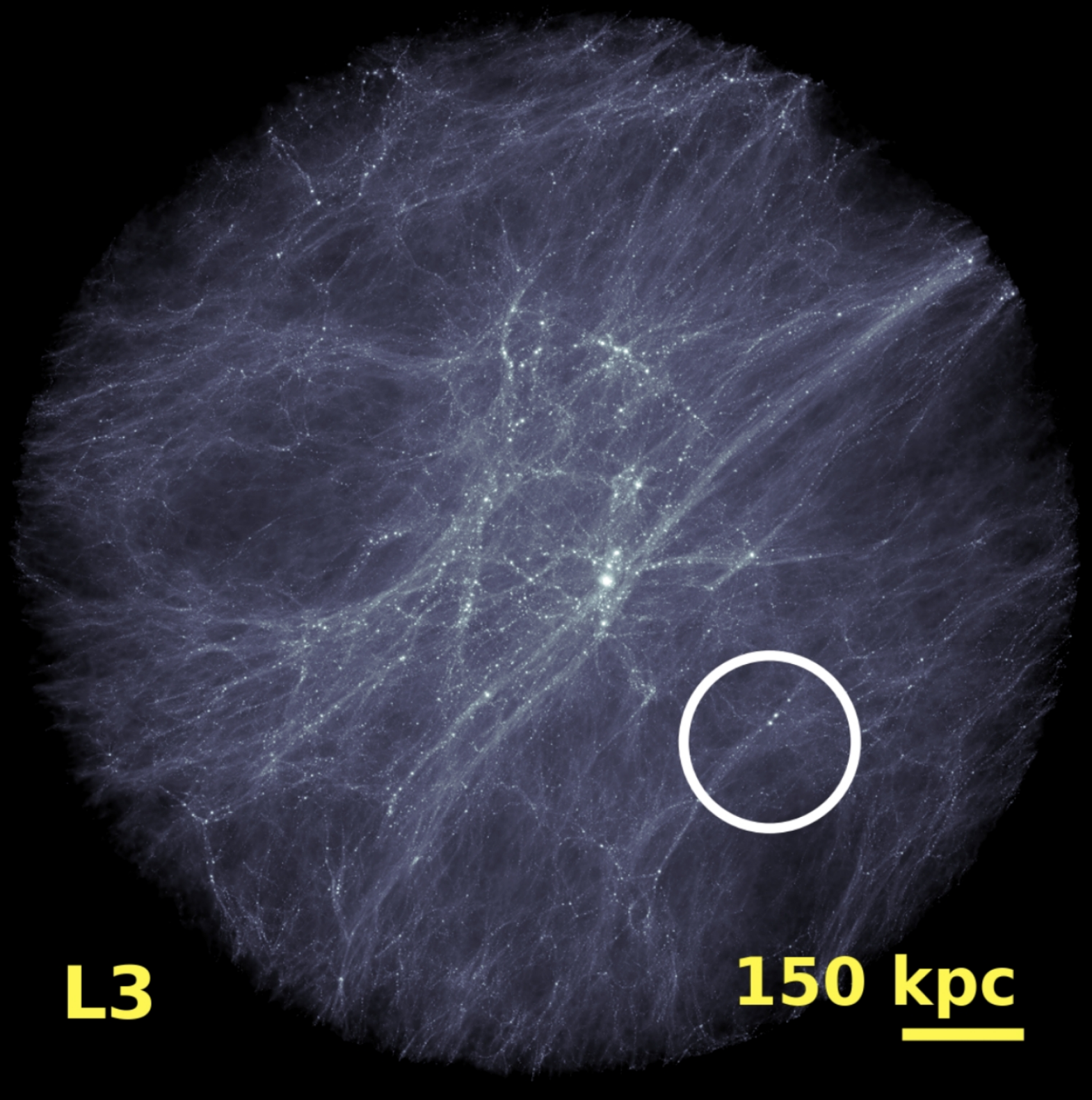Wang, Bose et al 2020

The VVV simulation

Planck cosmology

Dark matter only

Zoom Level 3

L3

150 kpc

Wang, Bose et al 2020
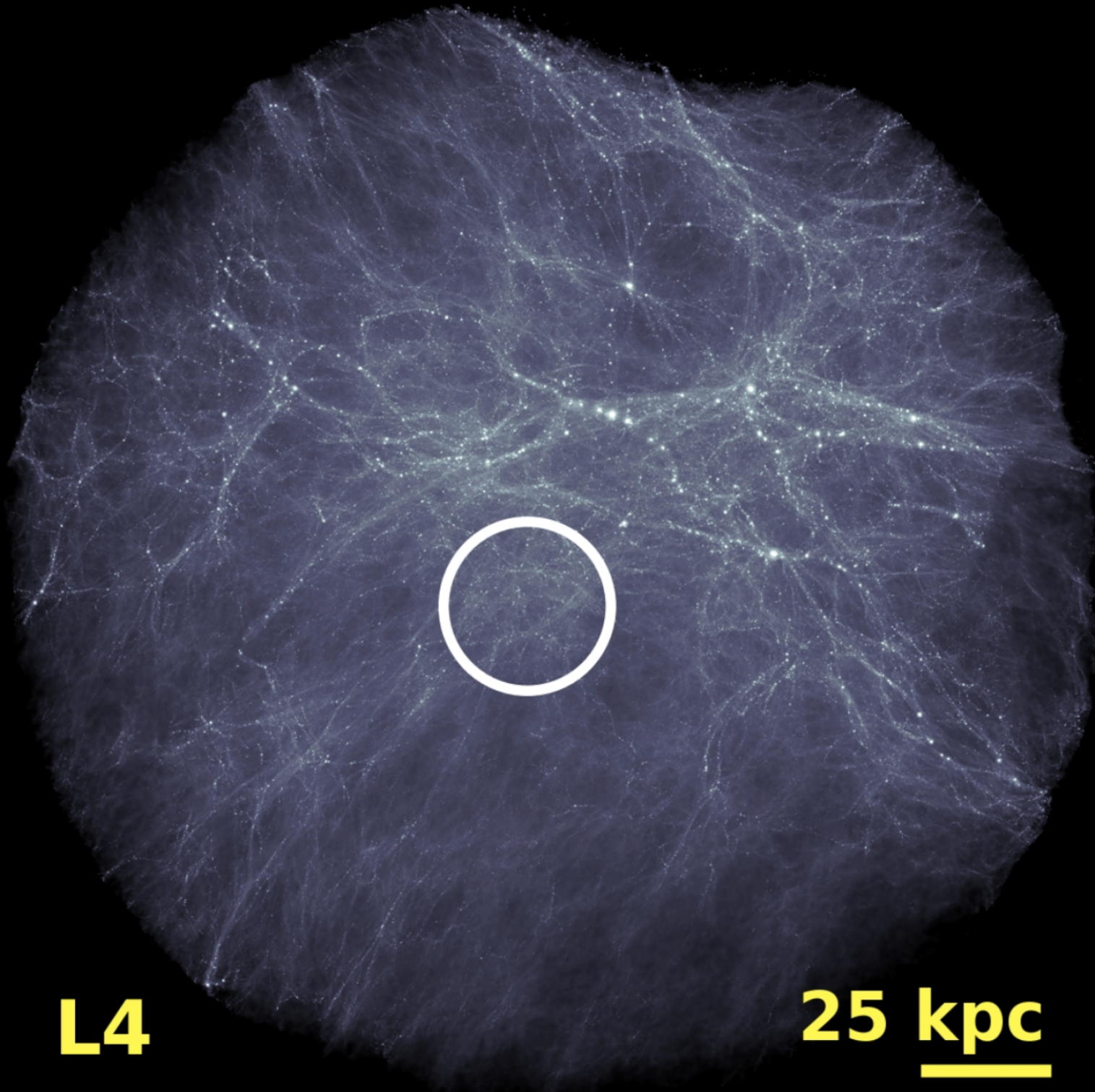
The VVV simulation

Planck cosmology

Dark matter only

Zoom Level 4

L4

25 kpc

Wang, Bose et al 2020

The VVV
simulation

Planck cosmology

Dark matter only

Zoom Level 5

L5

5 kpc

Wang, Bose et al 2020

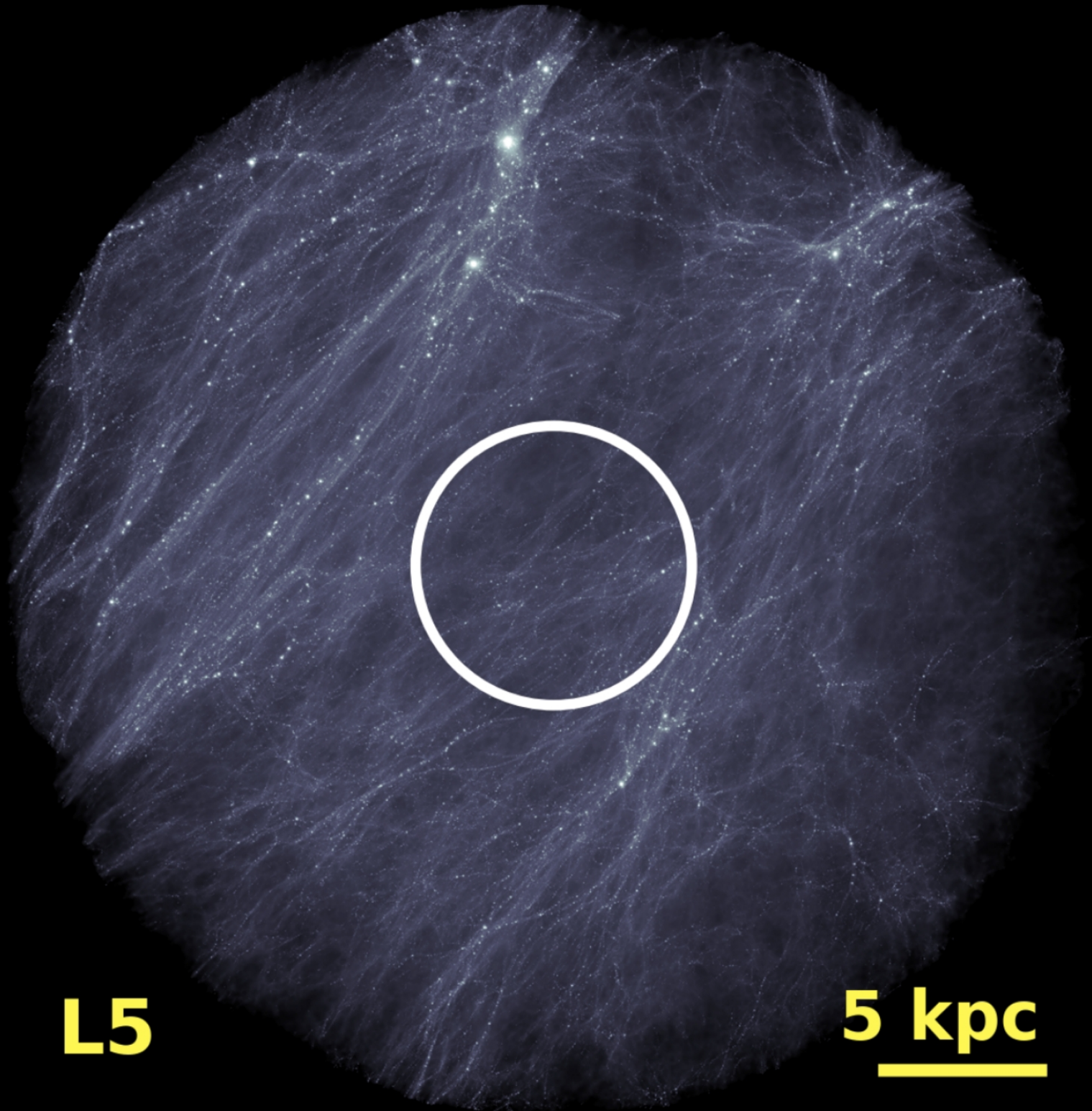**The VVV simulation**

Planck cosmology

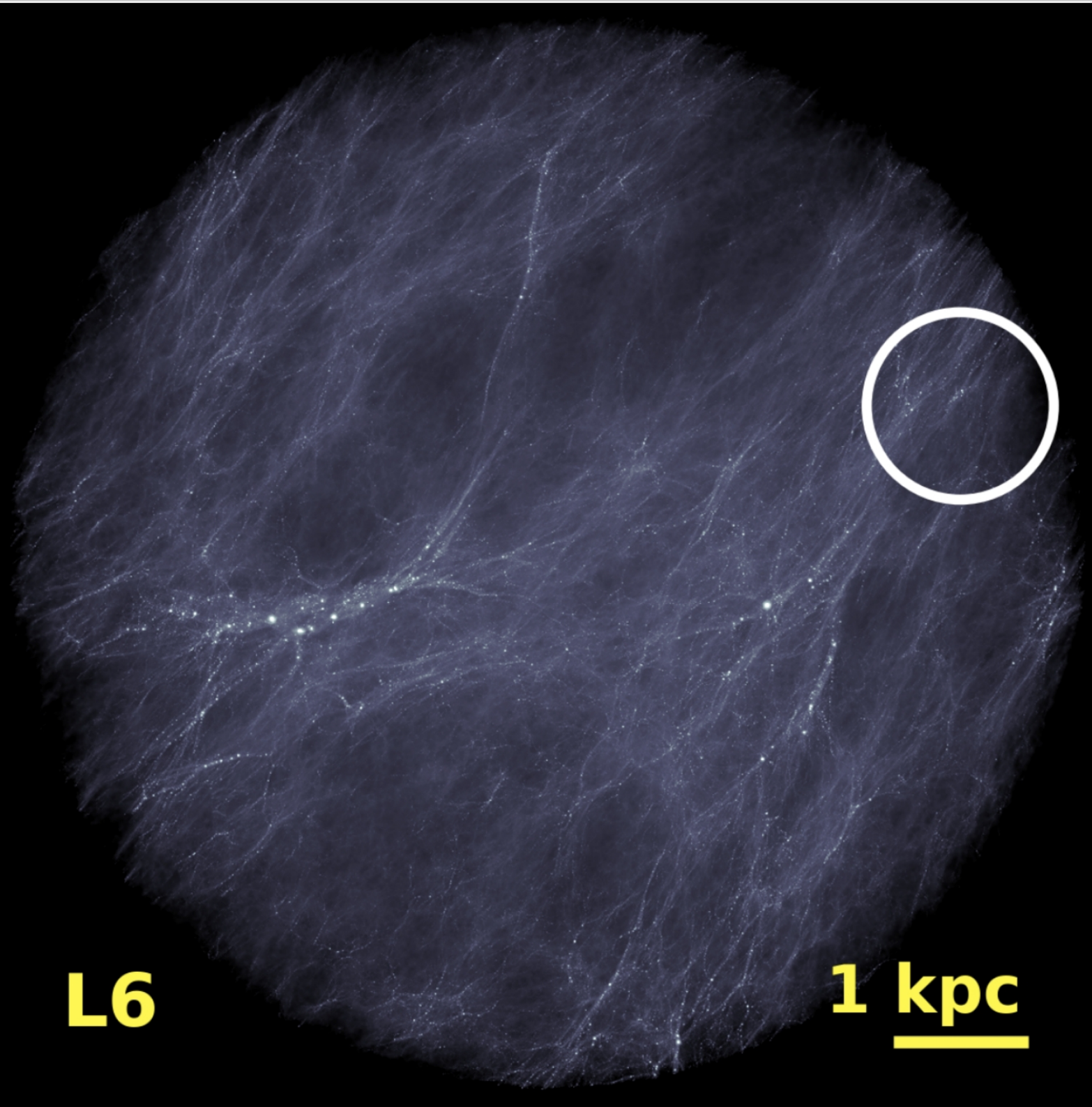Dark matter only

Zoom Level 6

L6

1 kpc

Wang, Bose et al 2020
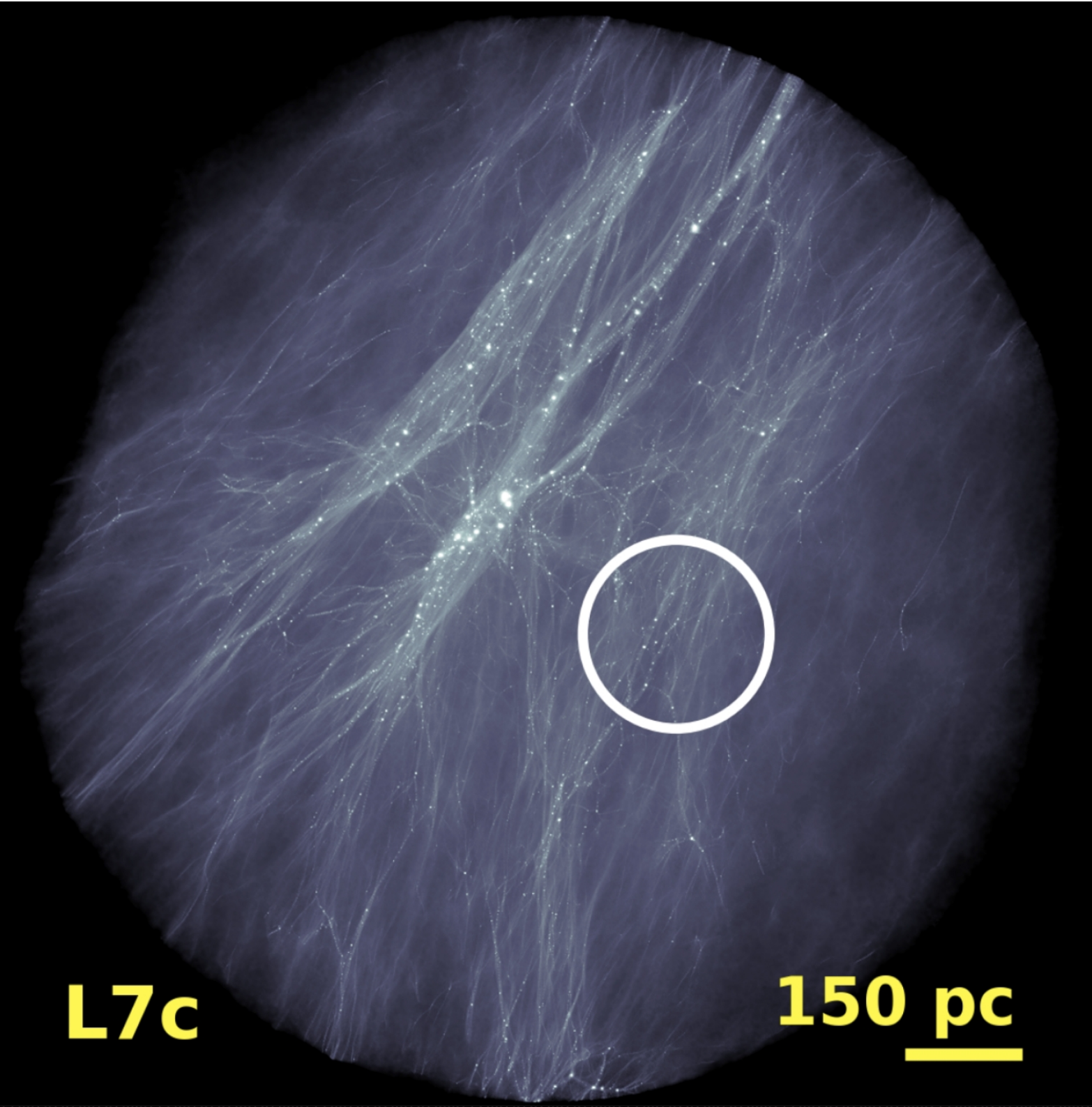
The VVV simulation

Planck cosmology

Dark matter only

Zoom Level 7

L7c

150 pc

Wang, Bose et al 2020

The VVV simulation

Planck cosmology

Dark matter only

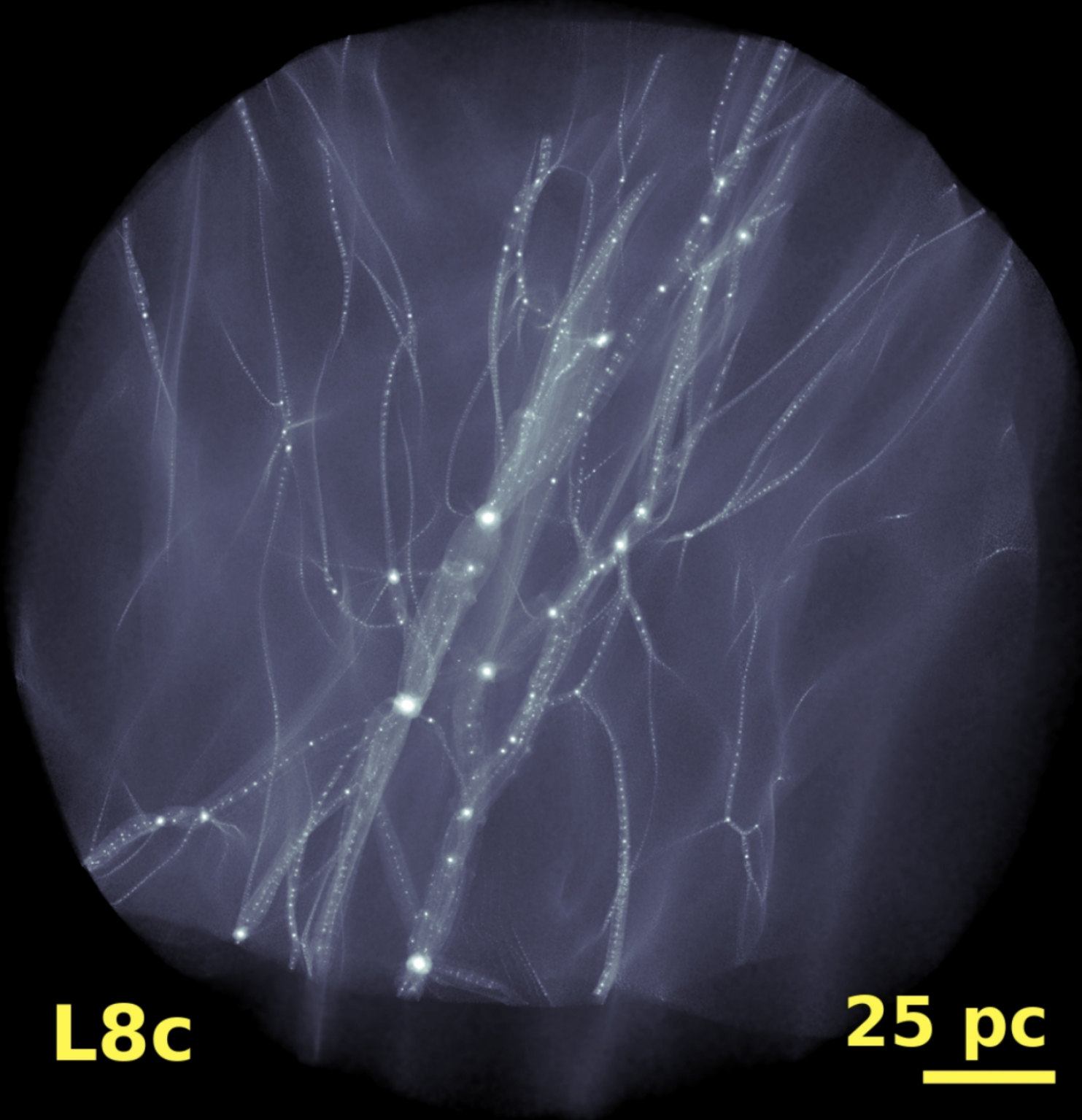Dynamic range of 30 orders of magnitude in mass

Zoom Level 8

The density of this region is only ~3% of the cosmic mean

Wang, Bose et al 2020

L8c

25 pc

The various levels of the VVV* simulation

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

level	R_{high} [Mpc]	n_{p}	ε [kpc]	m_{p} [$M_\odot$]	$\sigma(M_{\text{tot}}, z=0)$	$\langle\rho\rangle/\rho_{\text{mean}}$	M_{char} [$M_\odot$]	N_{char}	z_{form}	f_{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"
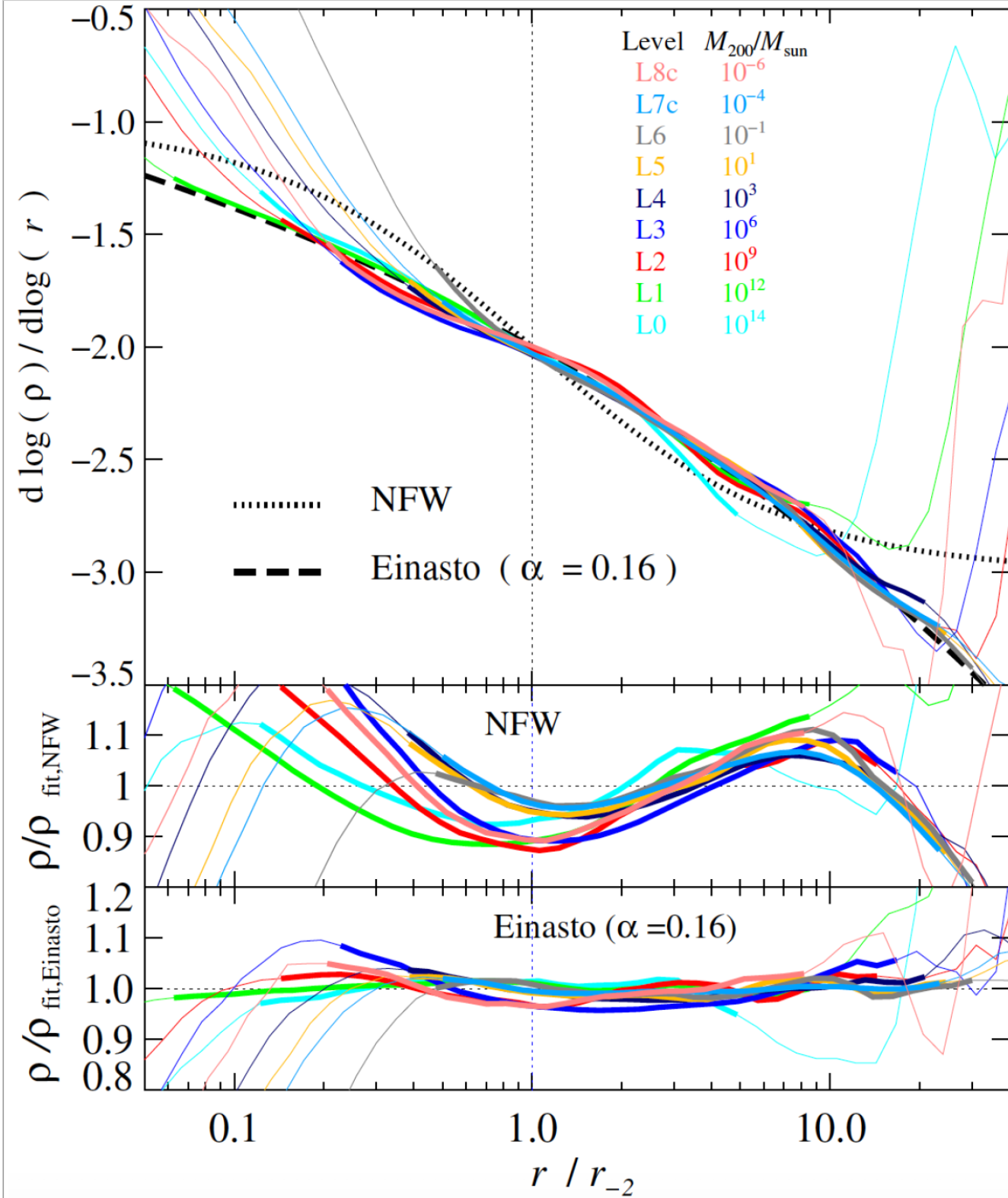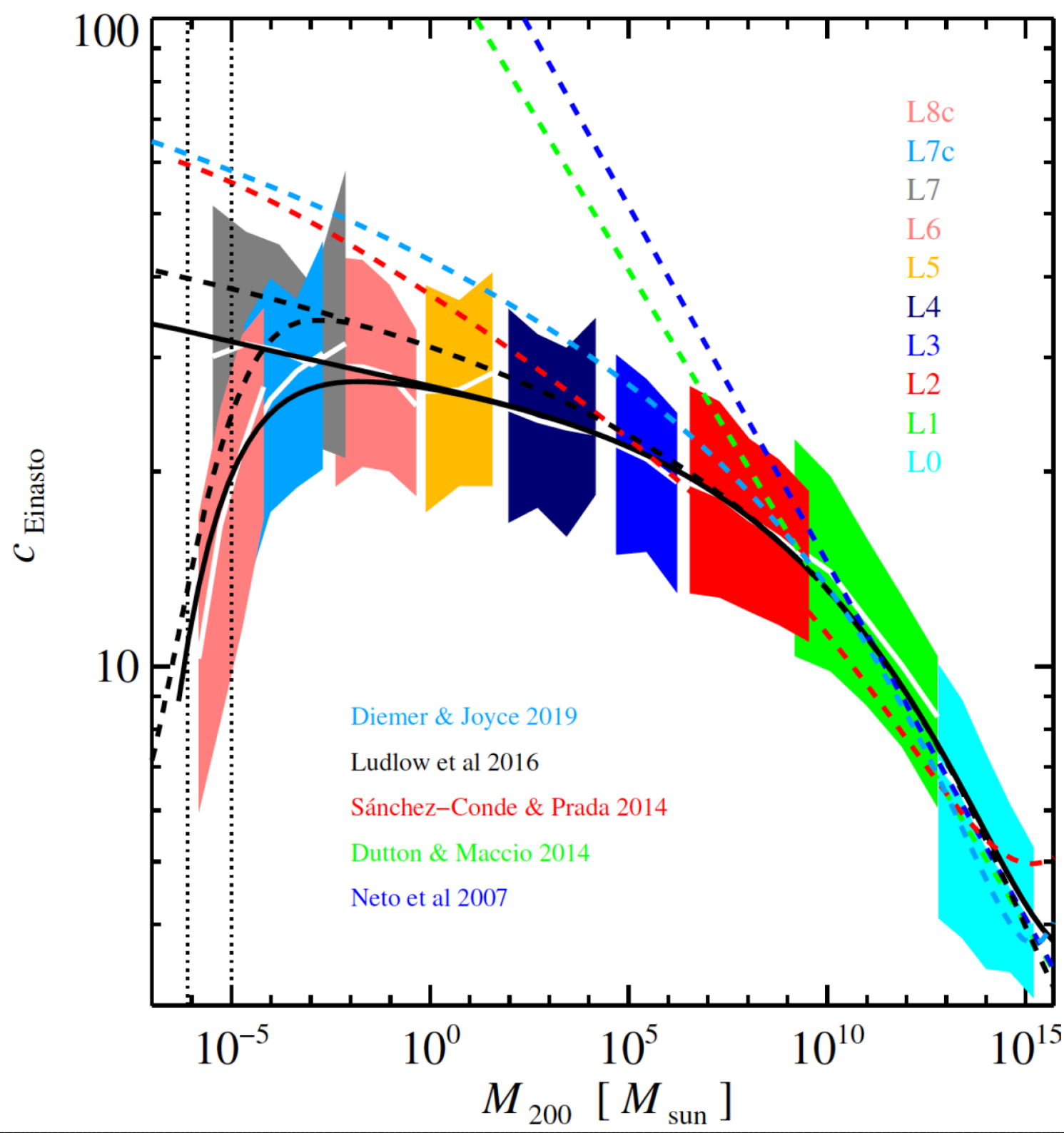
Density profile shapes

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 $\alpha = 0.16$) to within 7%

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

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

Wang, Bose et al 2020

Figure legend:

Level	M_{200}/M_{sun}
L8c	10^{-6}
L7c	10^{-4}
L6	10^{-1}
L5	10^{1}
L4	10^{3}
L3	10^{6}
L2	10^{9}
L1	10^{12}
L0	10^{14}

Concentration-mass relation

L8c
L7c
L7
L6
L5
L4
L3
L2
L1
L0

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

$c_{Einasto}$

M_{200} [M_{sun}]

Diemer & Joyce 2019

Ludlow et al 2016

Sánchez−Conde & Prada 2014

Dutton & Maccio 2014

Neto et al 2007

Wang, Bose et al 2020

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

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

The contribution of halos to the mean z = 0 luminosity density of the Universe is almost independent of their mass over the mass range
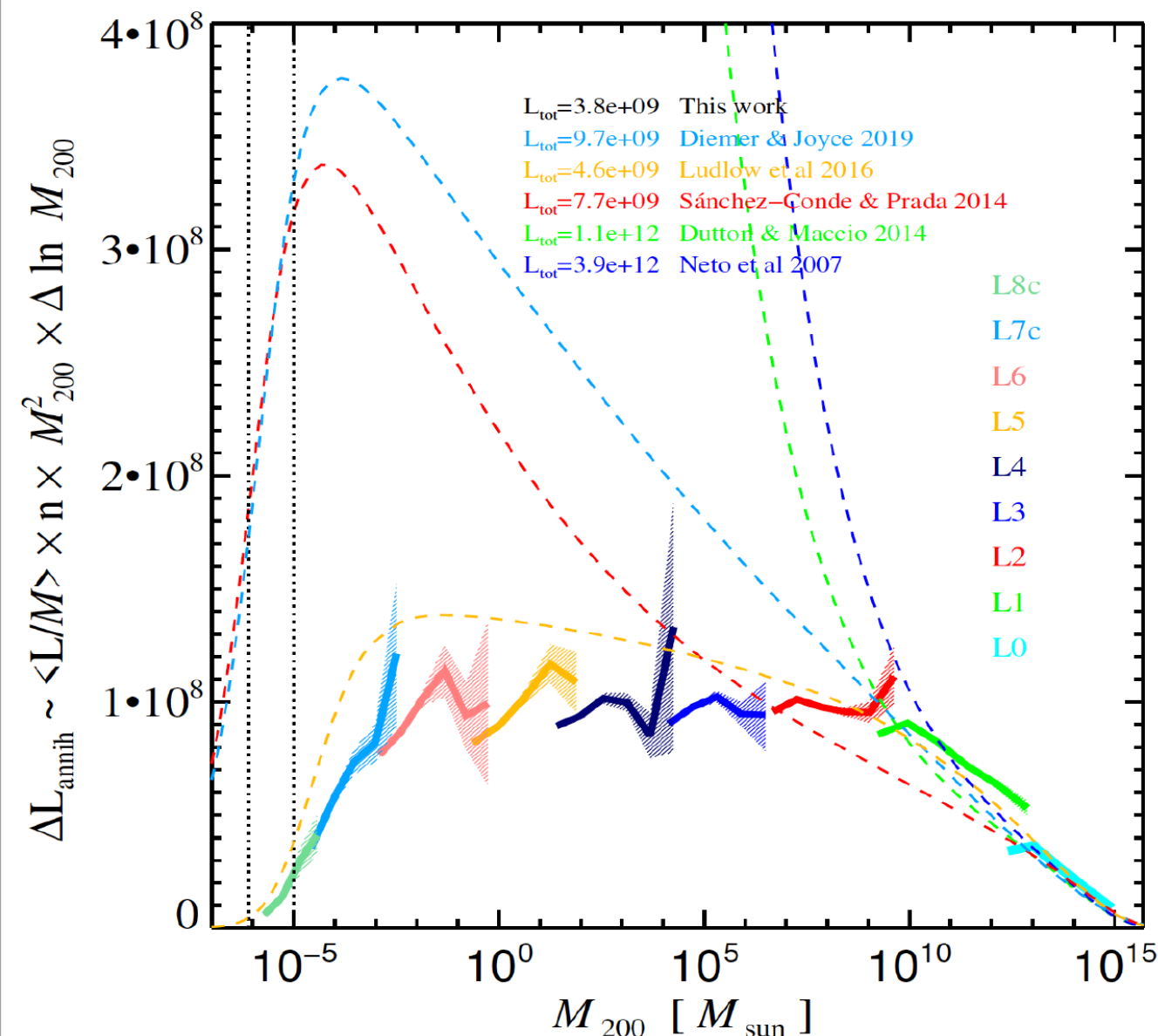
$$10^{-4} \, M_\odot < M_{halo} < 10^{12} \, M_\odot$$

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

Rob Grand

- Six simulations of "Milky Way" formation in ΛCDM
  $$m_{DM} \sim 5 \times 10^4\,M_\odot, \quad m_{bar} \sim 6 \times 10^3\,M_\odot$$

- 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, $L_{ann} = 1.87\,V_{max}^4/G^2 R_{max}$ from Einasto fits to $V_c(r)$

How do baryons affect the DM structure of small halos?
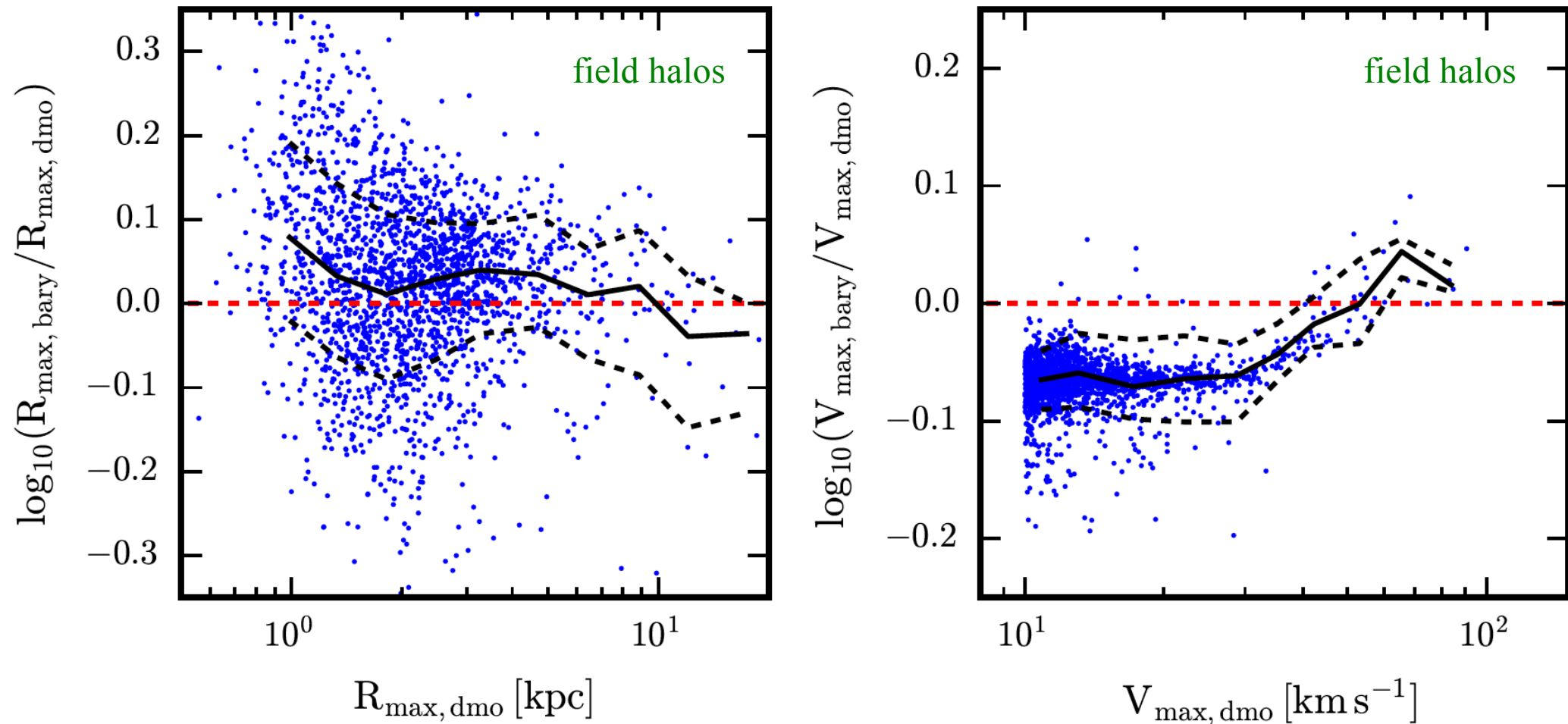
- Individual small field halos have slightly larger R_{max} and slightly smaller V_{max} in the full physics simulation ⟶ L_{ann} drops by almost a factor of 2

# How do they affect the $V_{max} - R_{max}$ relations of (sub)halos?
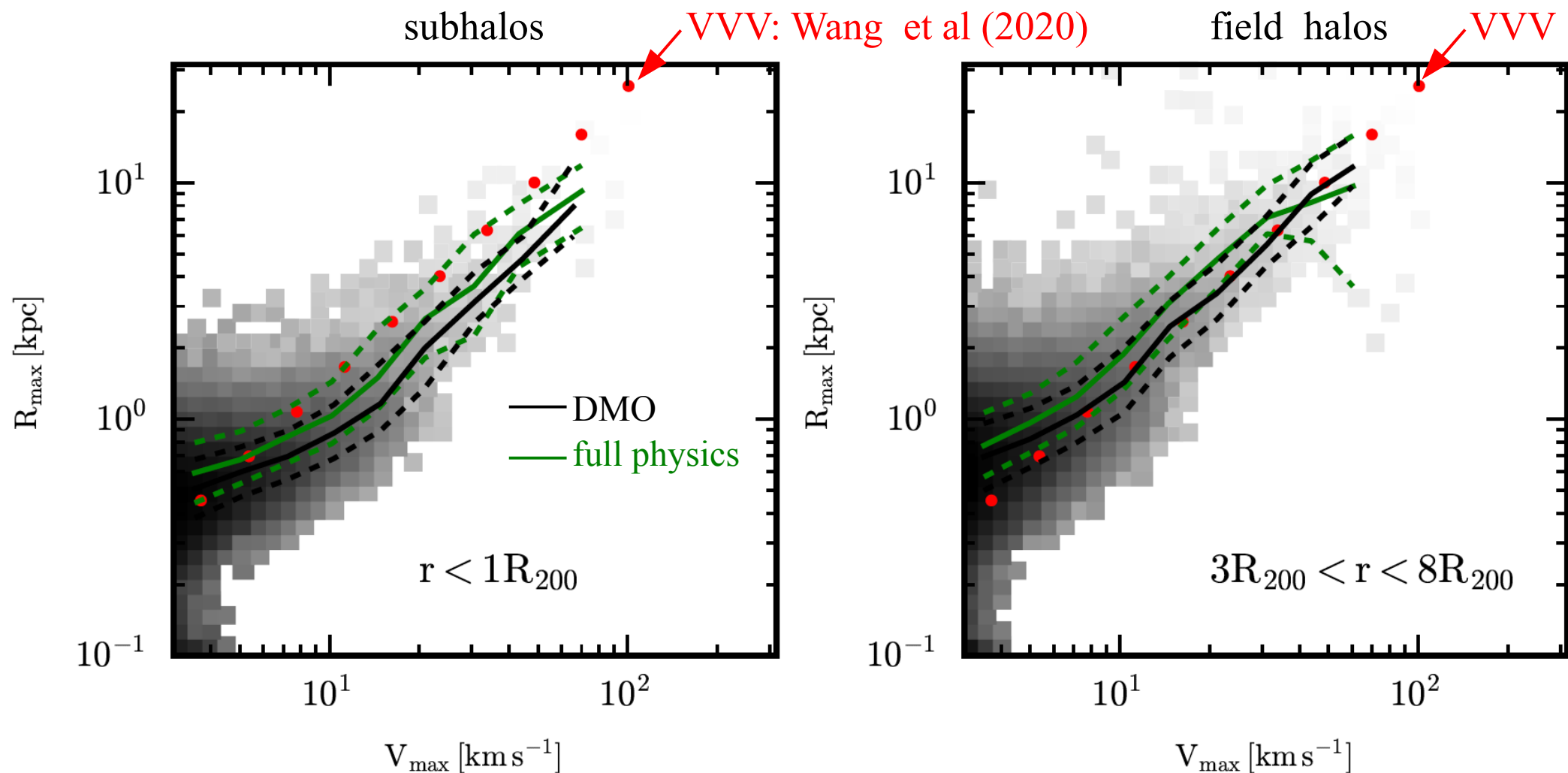
- The DMO field halo relation matches Wang et al (2020) down to the resolution limit
- The full physics field halo relation is parallel but higher by a factor of 1.4
- Both relations are shifted down by a factor of about 2 for subhalos
- Resolution affects the subhalo relation below $V_{max} \sim 10$ km/s

How do baryons affect MW annihilation luminosities?
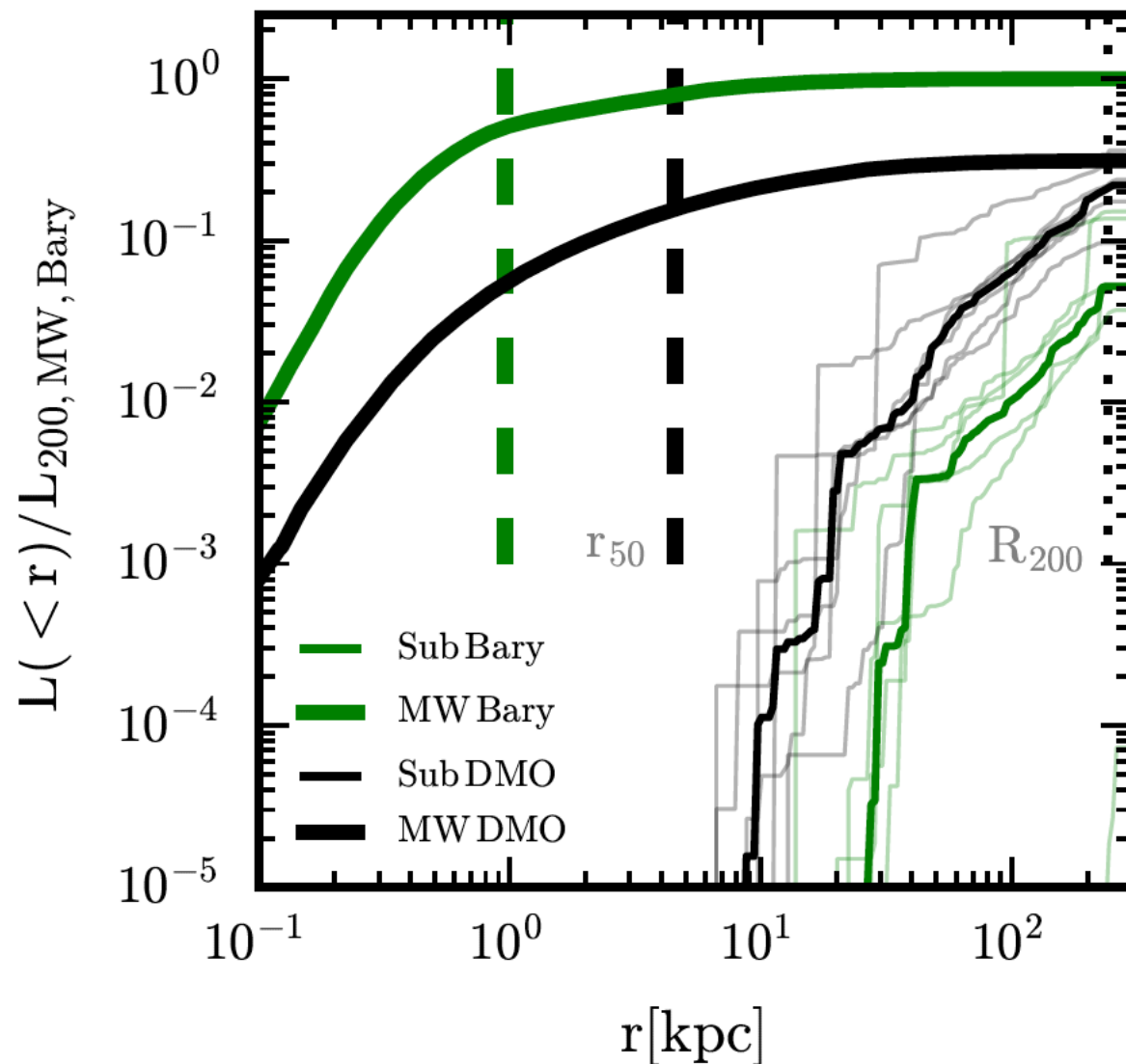
- The luminosity of the main halo goes up by a factor of 3

- 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
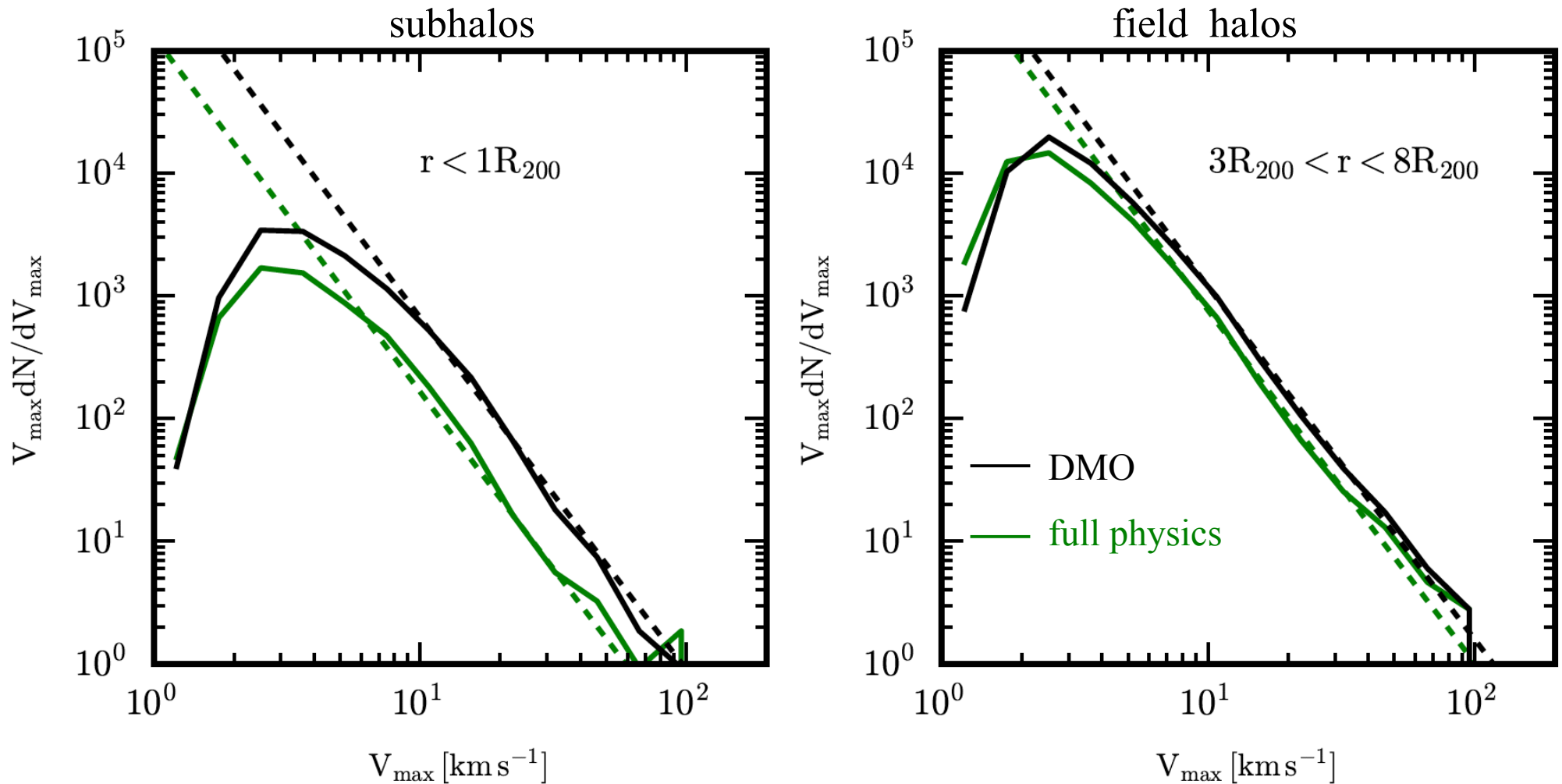
The colorbar reads $\log_{10}(\mathrm{f/rad}^2)$ with values 13.0, 13.5, 14.0, 14.5, 15.0, 15.5, 16.0, 16.5, 17.0.
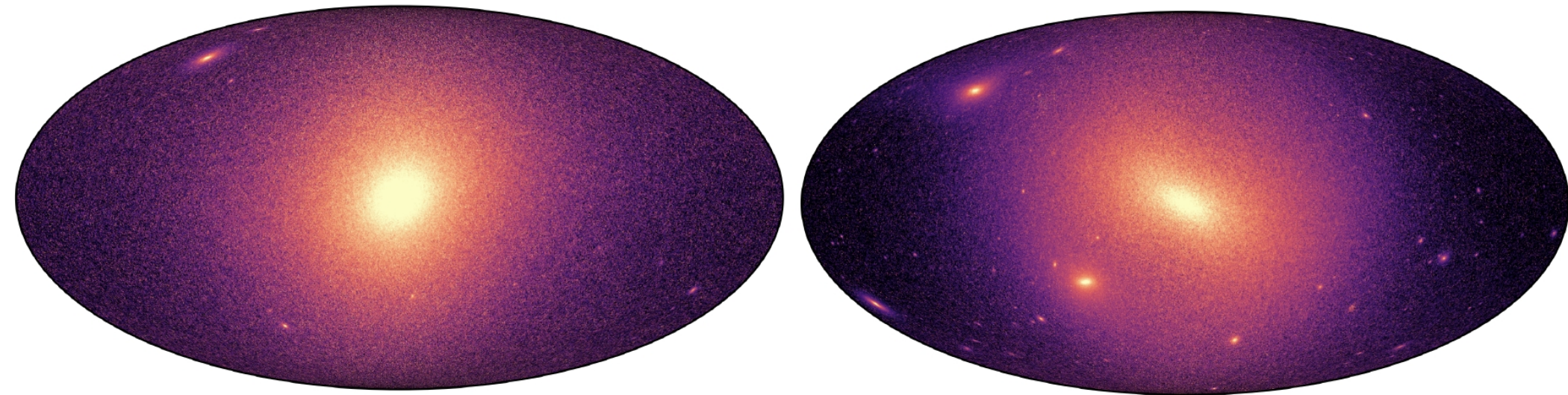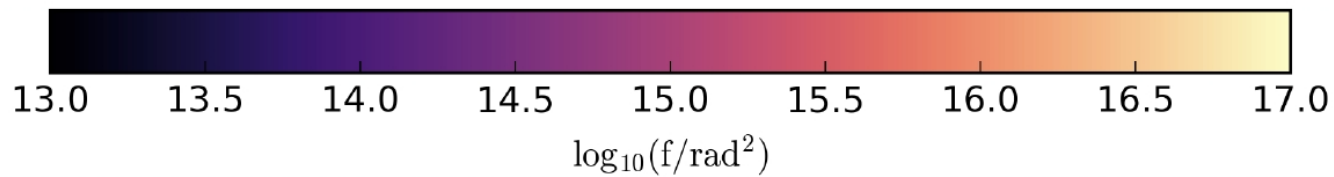
"Full physics"   Dark matter only

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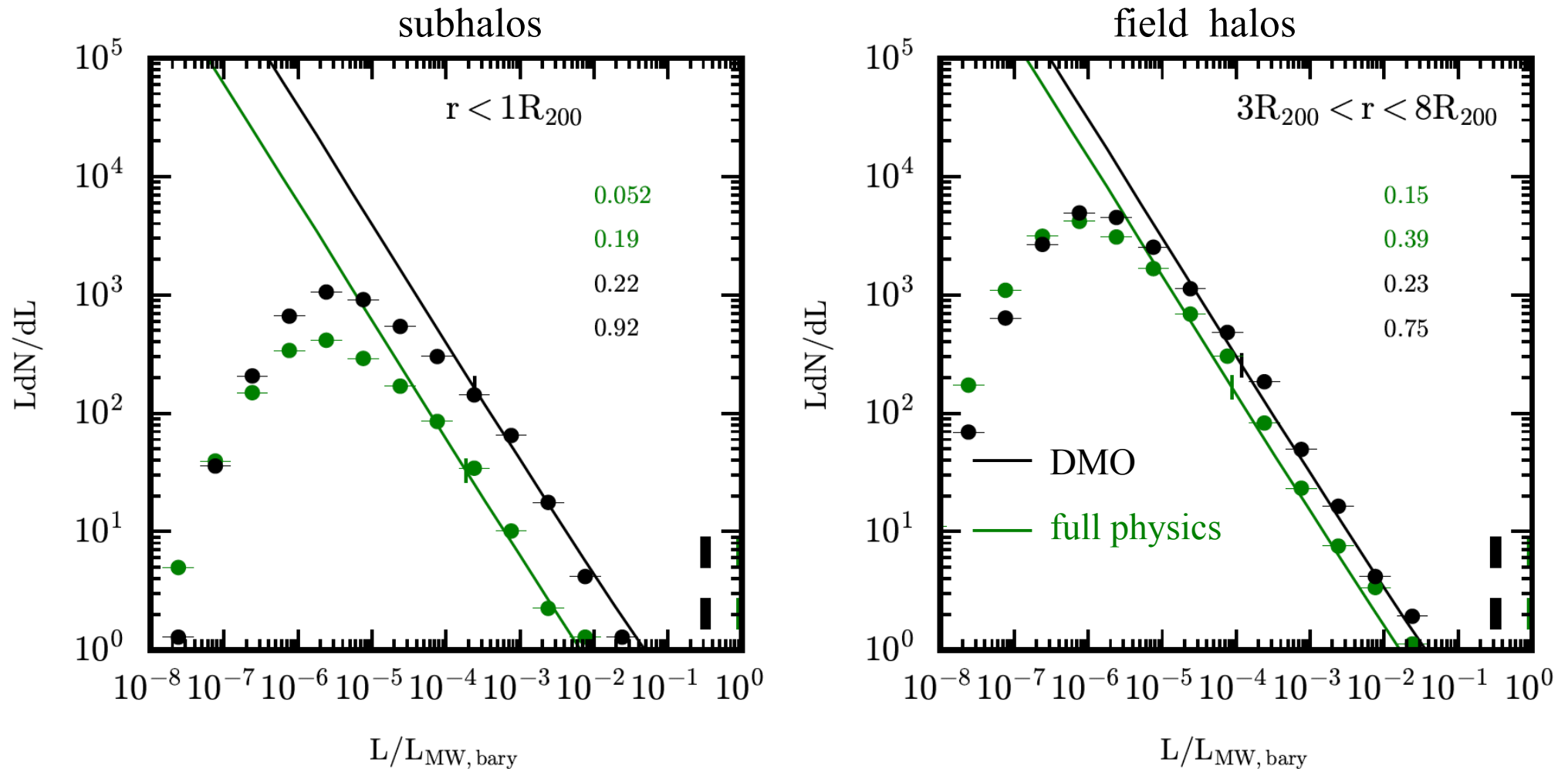
The subhalos become fainter

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

subhalos

field halos

$r < 1R_{200}$

$3R_{200} < r < 8R_{200}$

DMO

full physics

$V_{max}\,dN/dV_{max}$

$V_{max}\,[\mathrm{km\,s^{-1}}]$

- 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

subhalos

$r < 1R_{200}$

0.052
0.19
0.22
0.92

field halos

$3R_{200} < r < 8R_{200}$

0.15
0.39
0.23
0.75

DMO
full physics

LdN/dL

$L/L_{MW,bary}$

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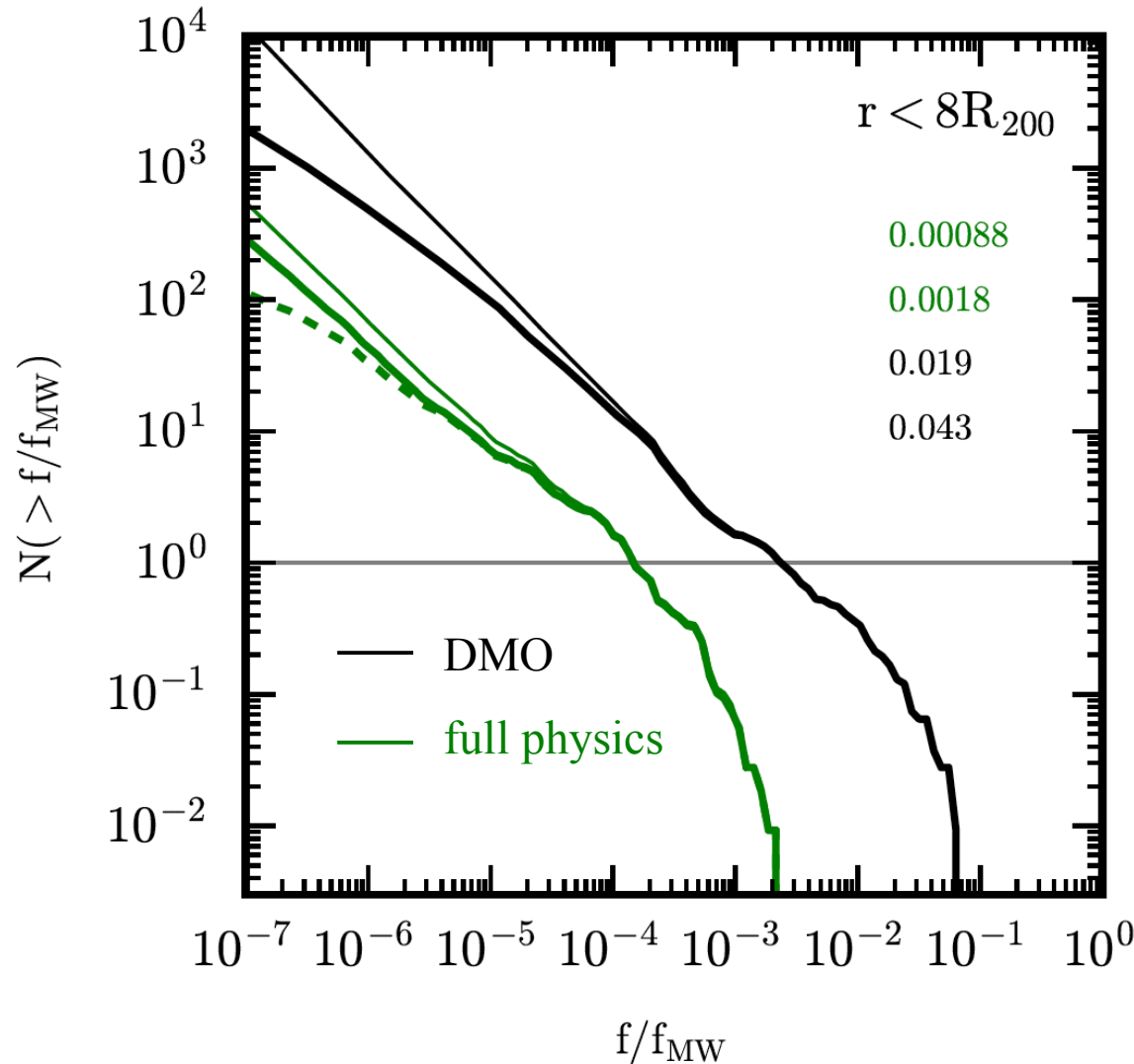
- Fluxes are as observed from a "Solar" position in units of the main halo flux
- The brightest subhalo has expected f/f$_{MW}$ ~ 0.0002 (f.p) or 0.003 (DMO)
- The total subhalo flux is expected to be < 0.2% of the main halo flux (f.p.)
- About half the subhalo flux is in numerically resolved subhalos

Does the main halo profile look like the *Fermi* excess?
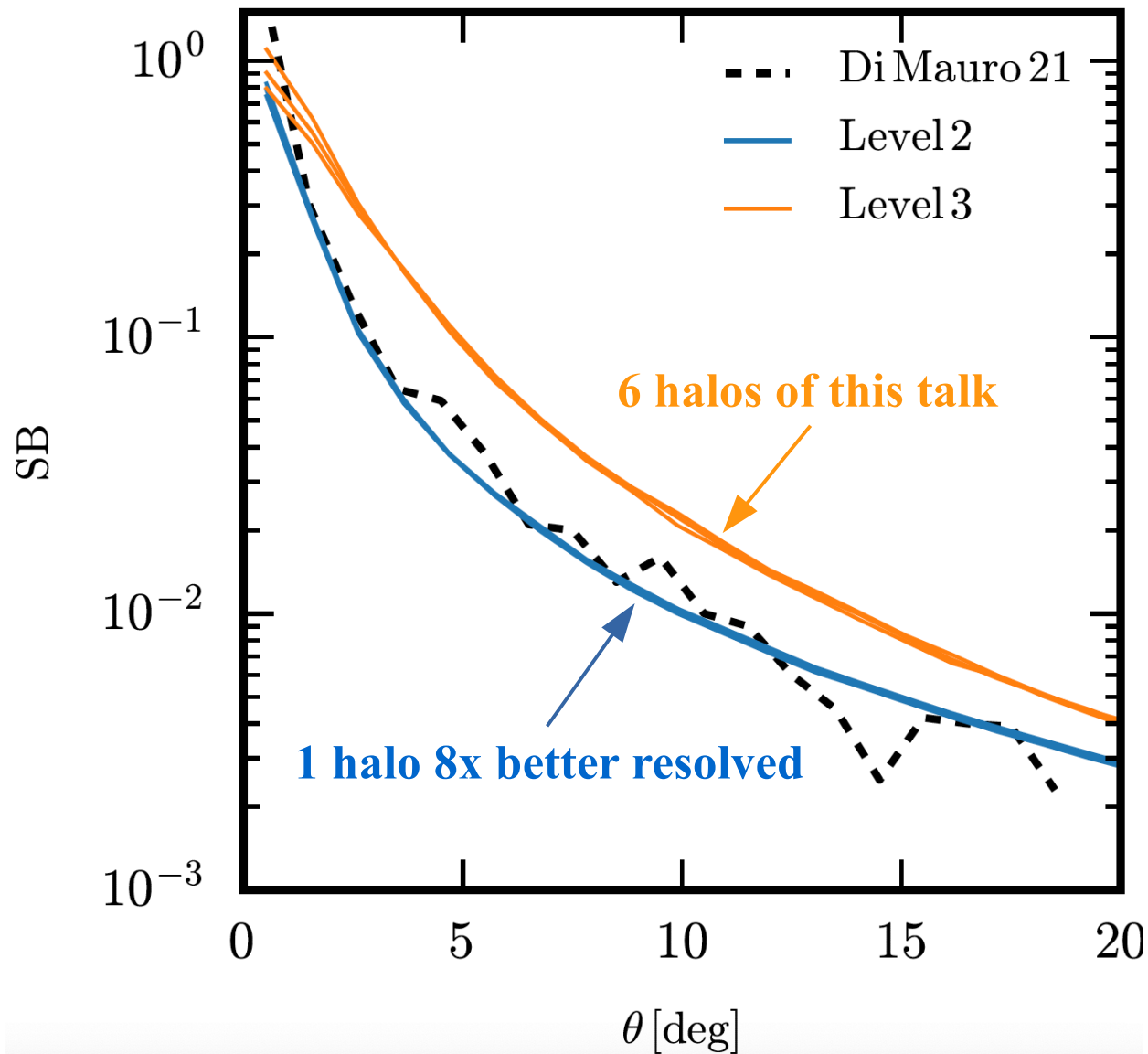
Has dark matter been observed directly?

Conclusions

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

- They <u>reduce</u> 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.
  → no subhalo is likely to be detected before the main halo.

- Previous work greatly overestimated the relative contribution from very small subhalos, because it overestimated their concentrations.

- The *Fermi* excess could well be annihilation radiation