A conclusive test of the validity of the cold dark matter model

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CDM

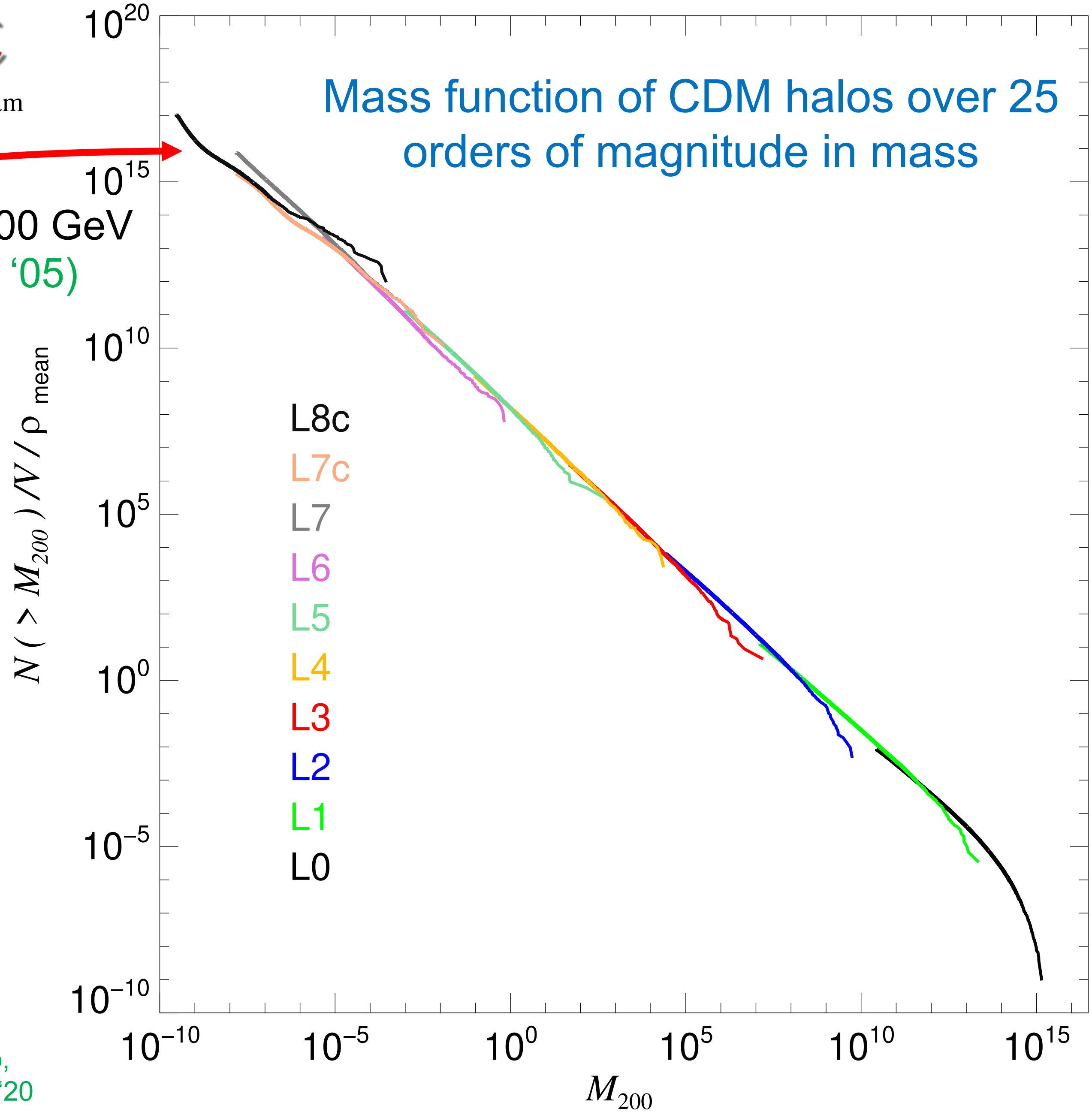
Fundamental prediction of CDM

A very large number of dark matter halos and subhalos

University of Durham

Mass function of CDM halos over 25 orders of magnitude in mass

Earth mass (for 100 GeV WIMP) (Green '05)



Wang, Bose, CSF, Gao, Jenkins, Springel, White '20

Institute for Computational Cosmology

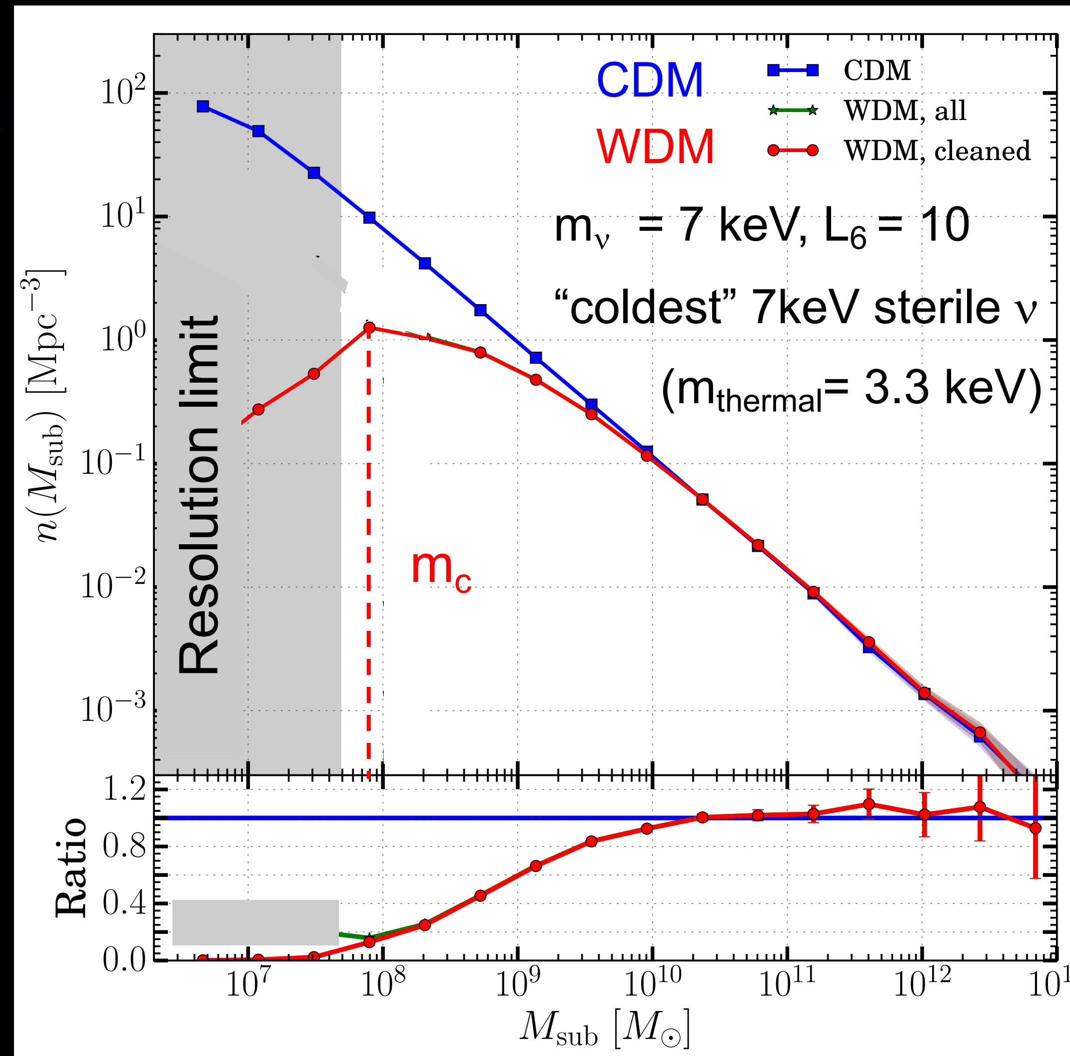
cold dark matter

warm dark matter

Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy ‘12

The subhalo mass function

CDM WDM



3 x fewer WDM subhalos at $3x10^9 M_o$

10 x fewer at $10^8 M_o$

Bose, CSF et al '16

How can we distinguish the two?

Astrophysical tests of dark matter

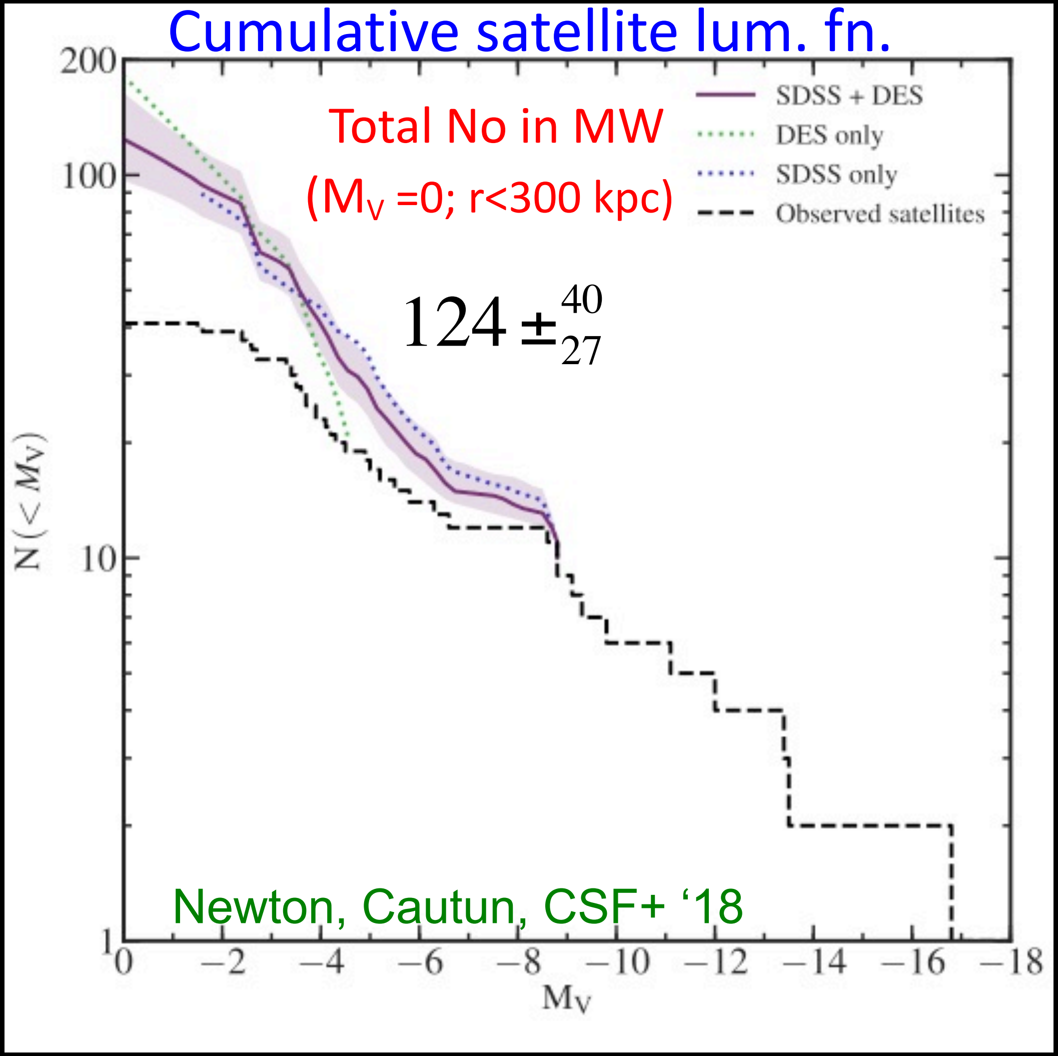
Count the number of small-mass halos

1. Number of dark matter halos: the halos mass fn.
2. Annihilation/decay radiation

Let's begin by counting what we can see

The satellites of the Milky Way

In the MW: ~55 satellites discovered so far



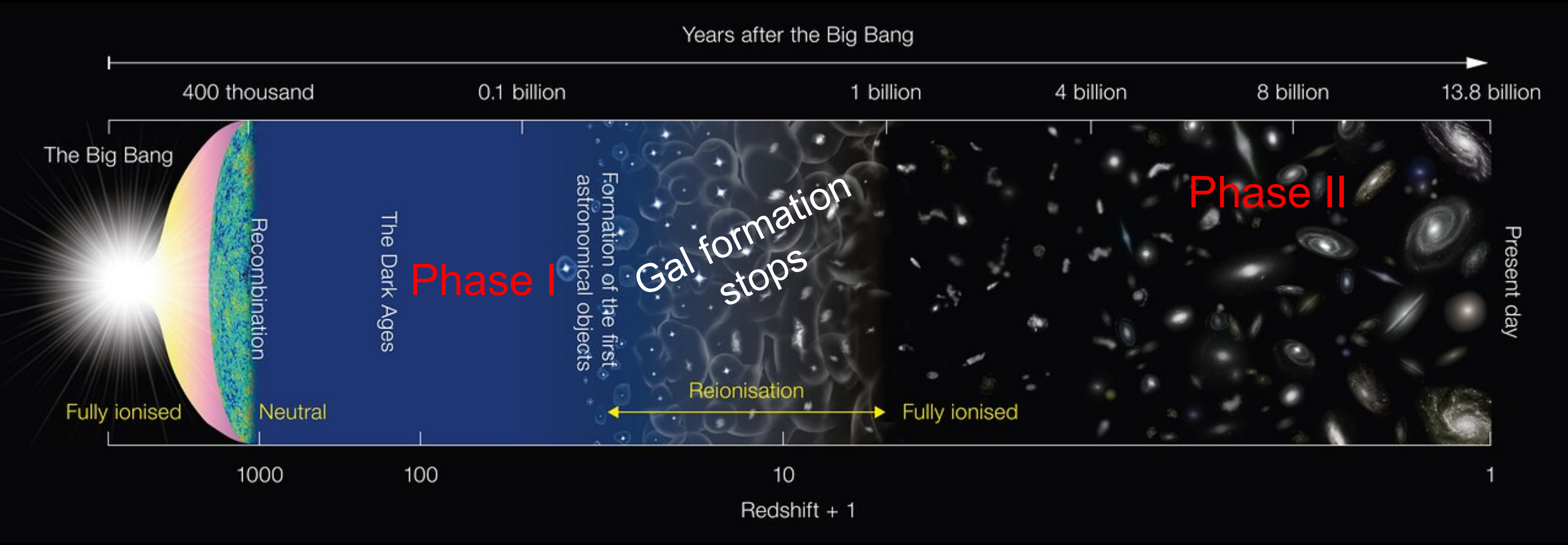
CDM

Most subhalos never make a galaxy!

“Missing satellites” problem:

CDM predicts many more subhalos in the Milky Way than there are observed satellites

The two phases of galaxy formation



Phase I: During the "dark ages" H gas is neutral

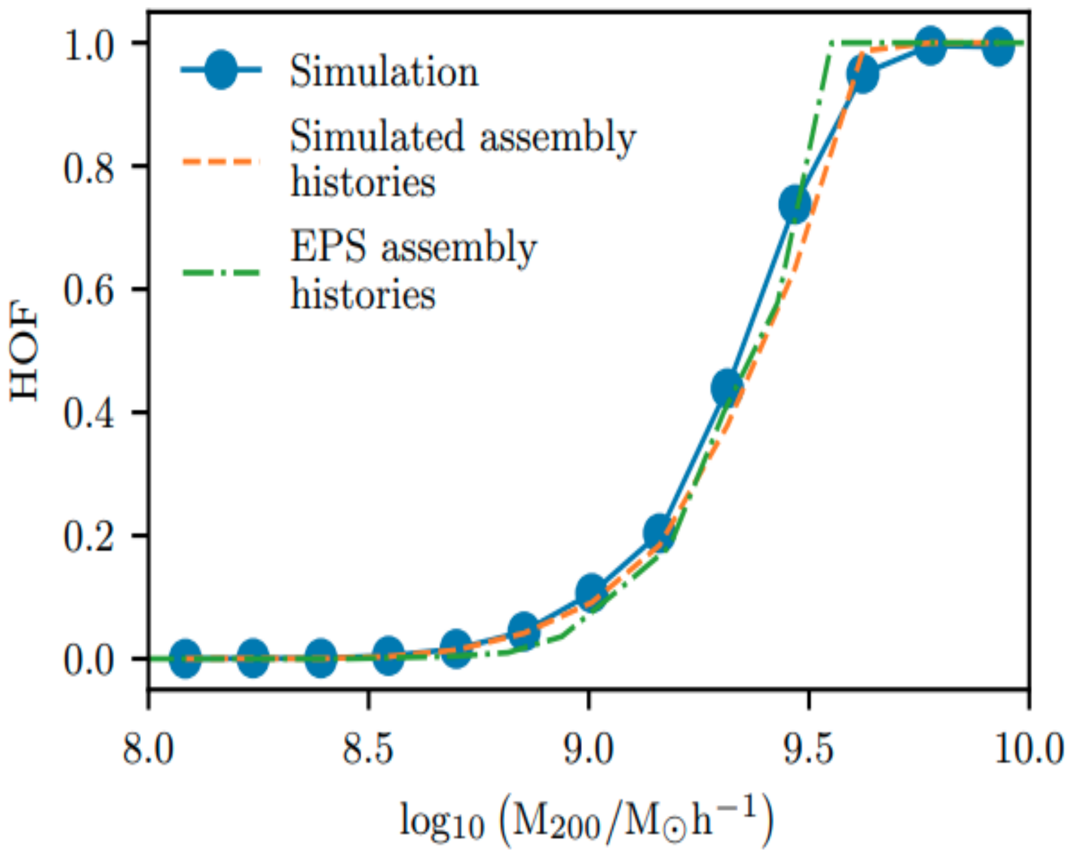
First stars reionize H and heat it up to 10^4K

Phase II: H Gas is ionized but can cool into large enough halos

A galaxy formation primer

Halo Occupation Fraction (HOF): fraction of halos of a given mass that host a galaxy

fraction of halos that host a galaxy

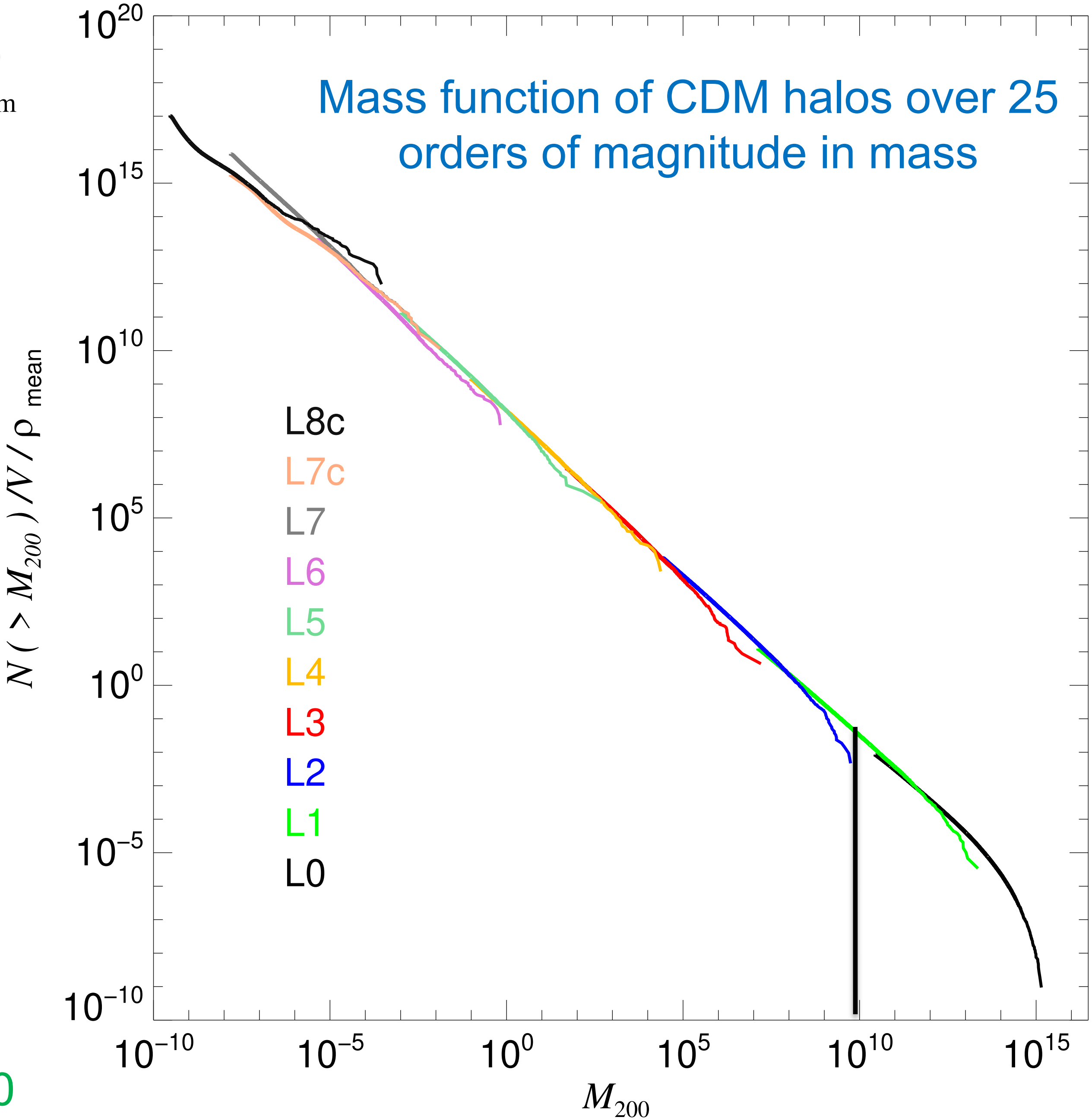


Halos of $M<3x10^8M_o$ have NO galaxy

Halos of $M<5x10^9M_o$ all have a galaxy

Benitez-Llambay & CSF ‘20

ICC
University of Durham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10^{5}
10^{10}
10^{15}

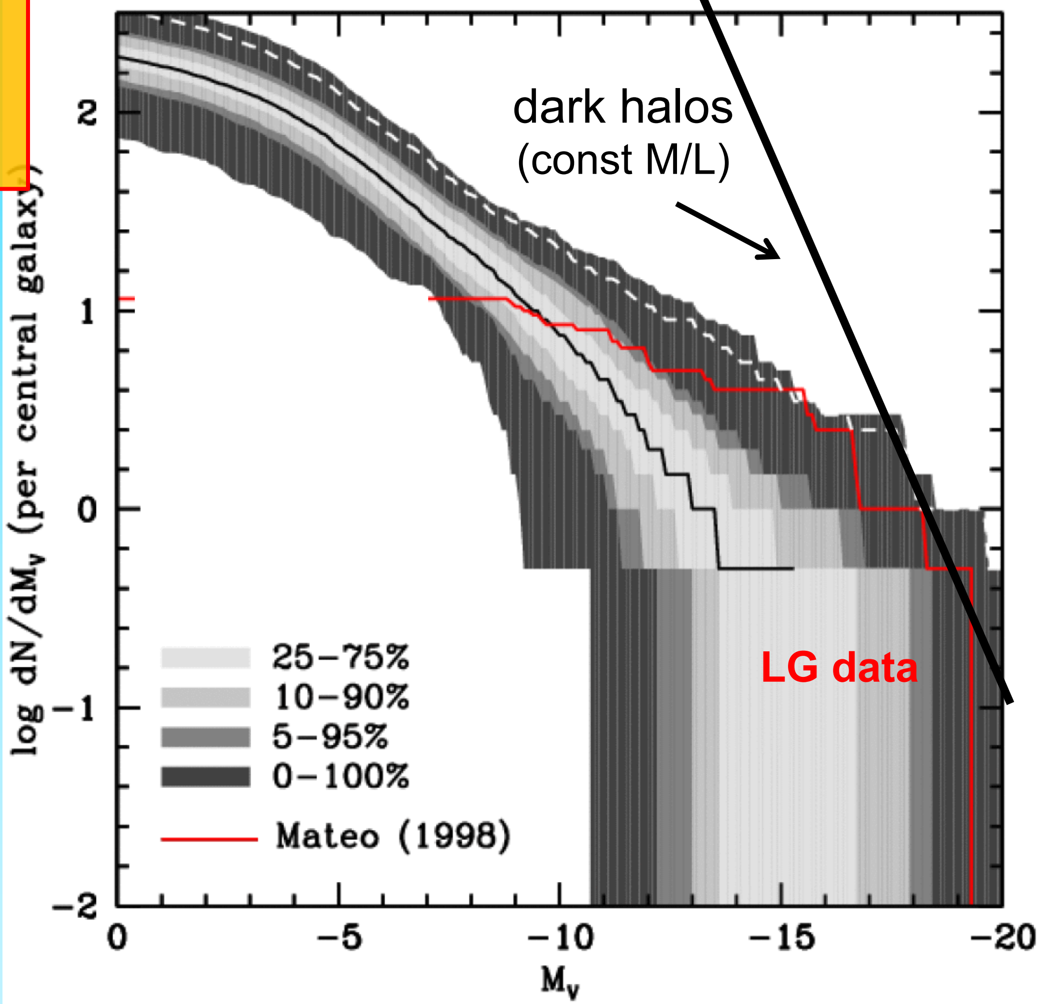
Wang et al '20

Luminosity Function of Local Group Satellites

Semi-analytic model of galaxy formation including effects of reionization and SN feedback

- Median model → correct abundance of sats brighter than M_V=-9 (V_{cir} > 12 km/s)

- Model predicts many, as yet undiscovered, faint satellites



Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman+ '93, Bullock+ '00, Somerville '02)

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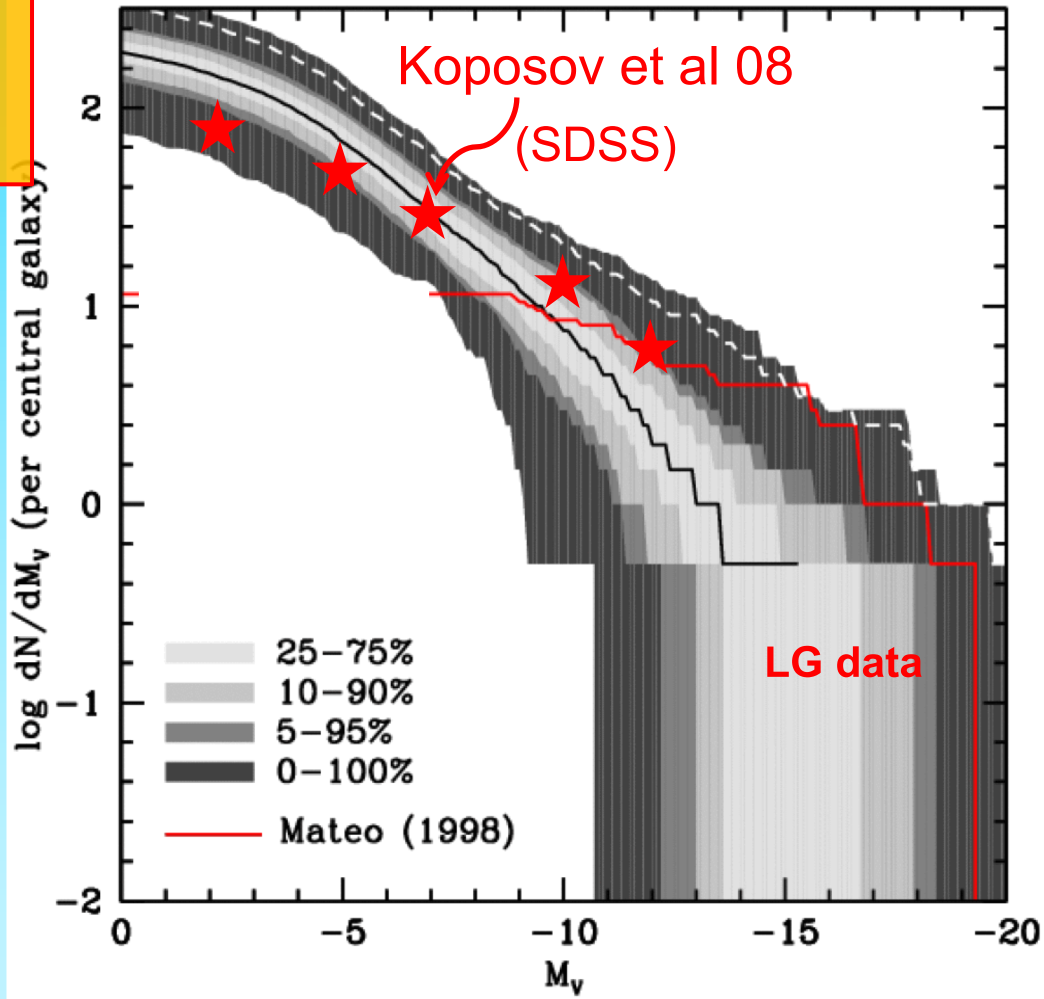

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VIRGO

icc.dur.ac.uk/Eagle

“Evolution and assembly of galaxies and their environment”

THE EAGLE PROJECT

Virgo Consortium

Durham: Richard Bower, Michelle Furlong, Carlos Frenk, Matthieu Schaller, James Trayford, Yelti Rosas-Guevara, Tom Theuns, Yan Qu, John Helly, Adrian Jenkins.

Leiden: Rob Crain, Joop Schaye.

Other: Claudio Dalla Vecchia, Ian McCarthy, Craig Booth…

Durham University VIRGO ICC DiRAC PRACE

The EAGLE simulation is a project by the Virgo Consortium.
Images courtesy of Richard Bower.

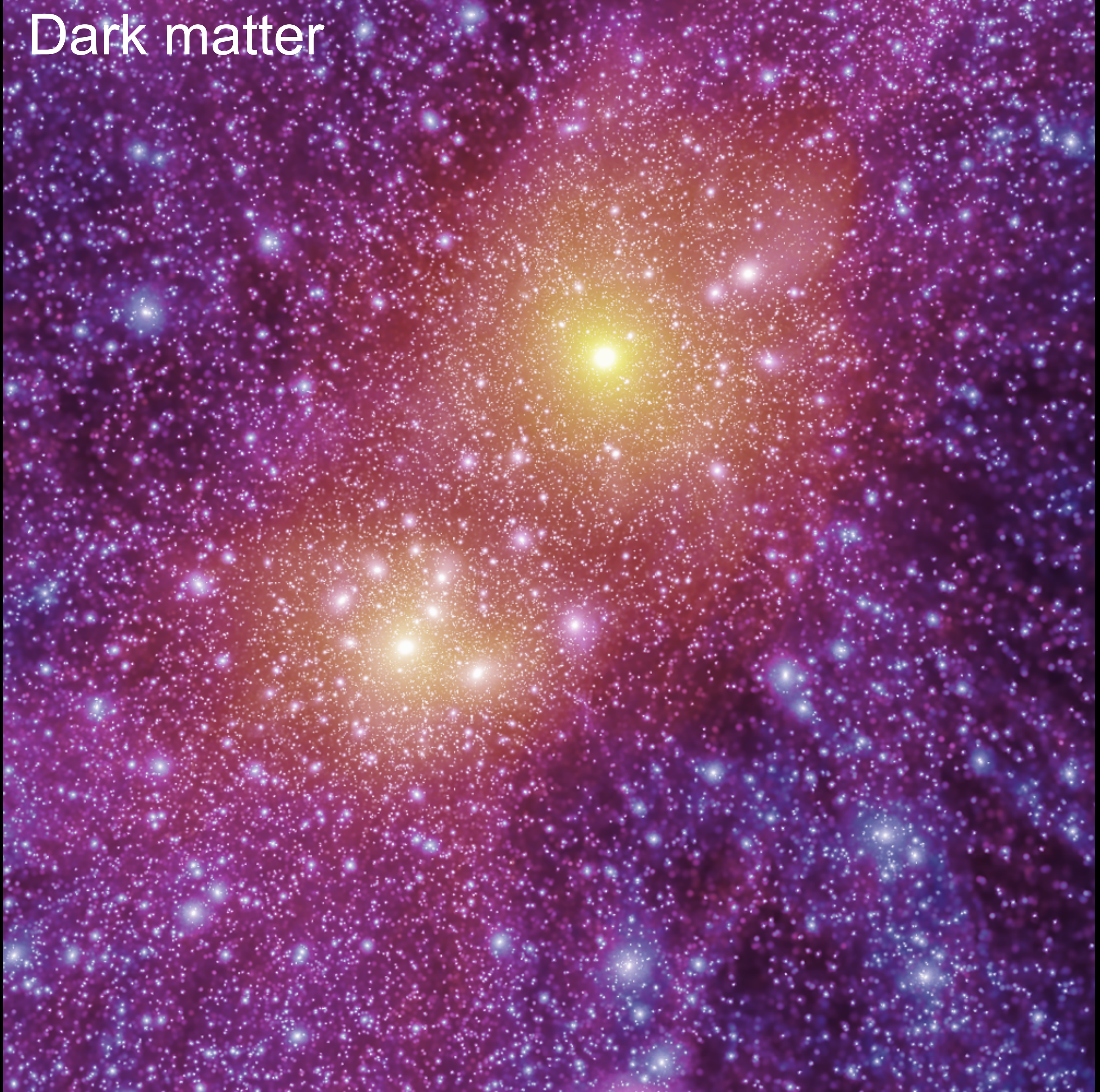
VIRGO

APOSTLE EAGLE full hydro simulations

Local Group

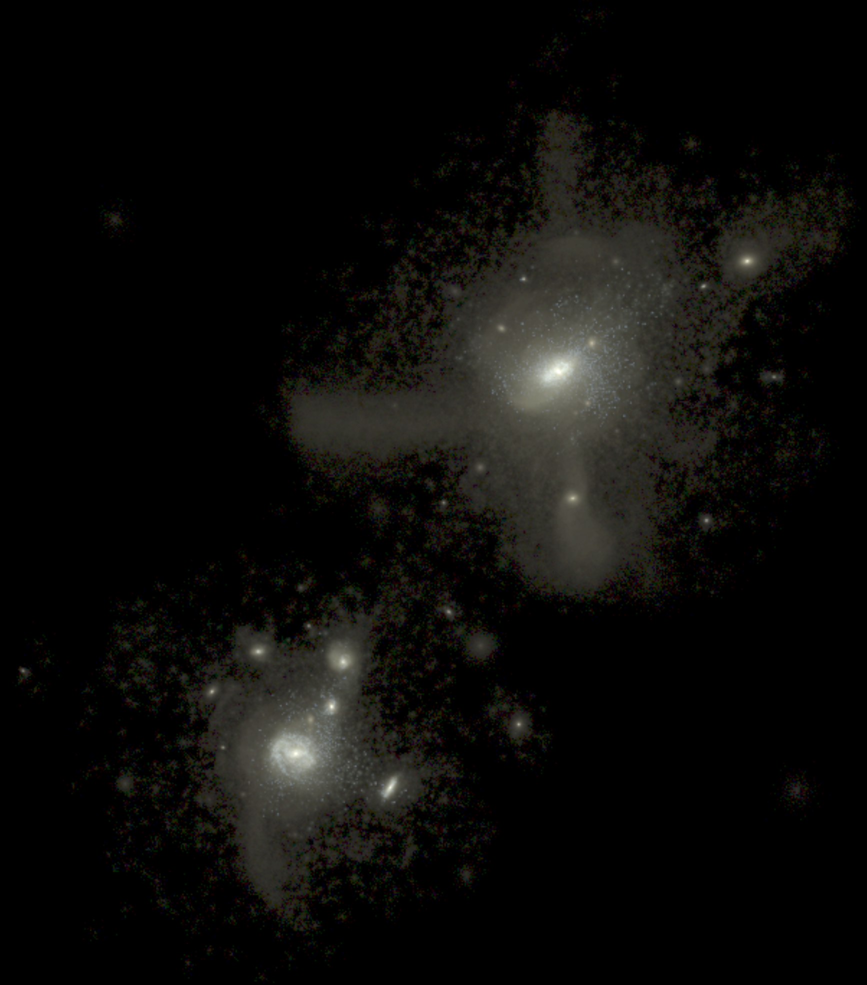
CDM

Sawala, CSF et al ‘16



VIRGO

Stars



APOSTLE EAGLE full hydro simulations

Local Group

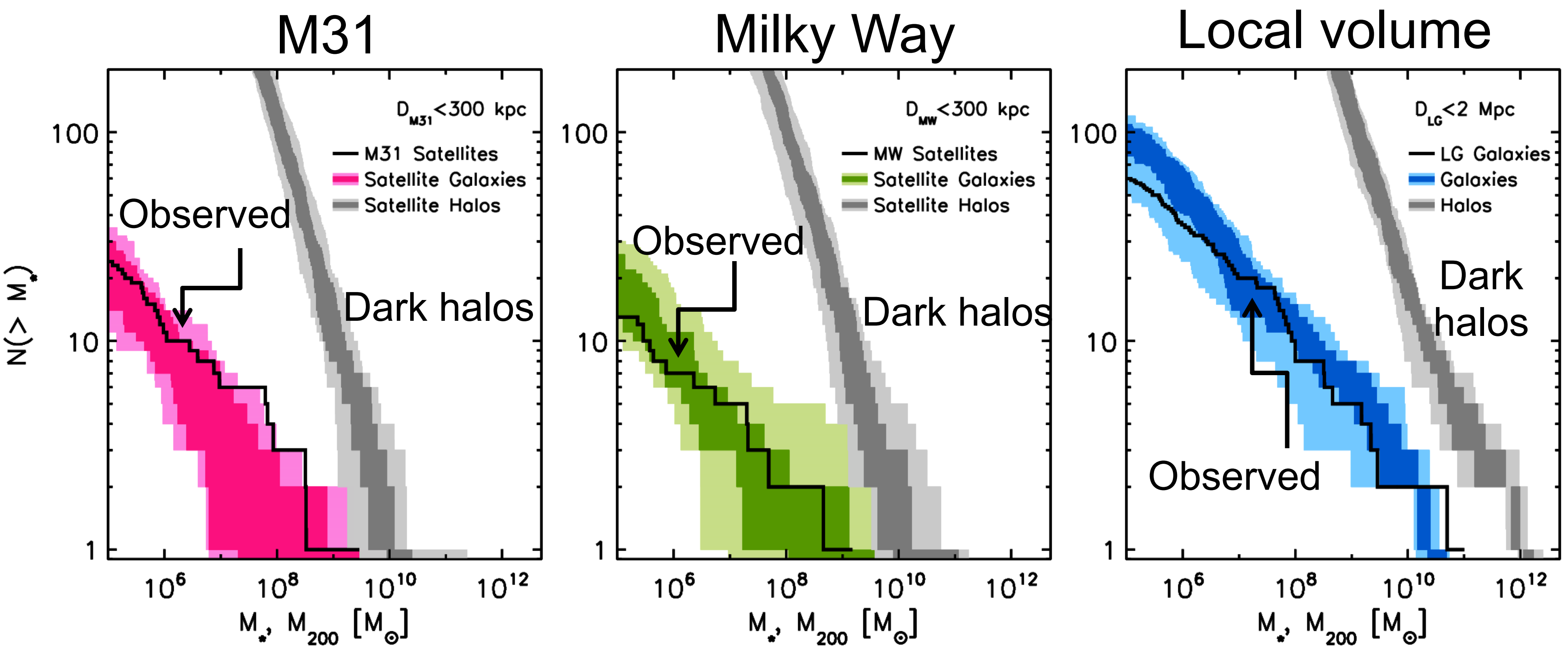
Stars

Far fewer satellite galaxies than CDM halos

Sawala, CSF et al ‘16

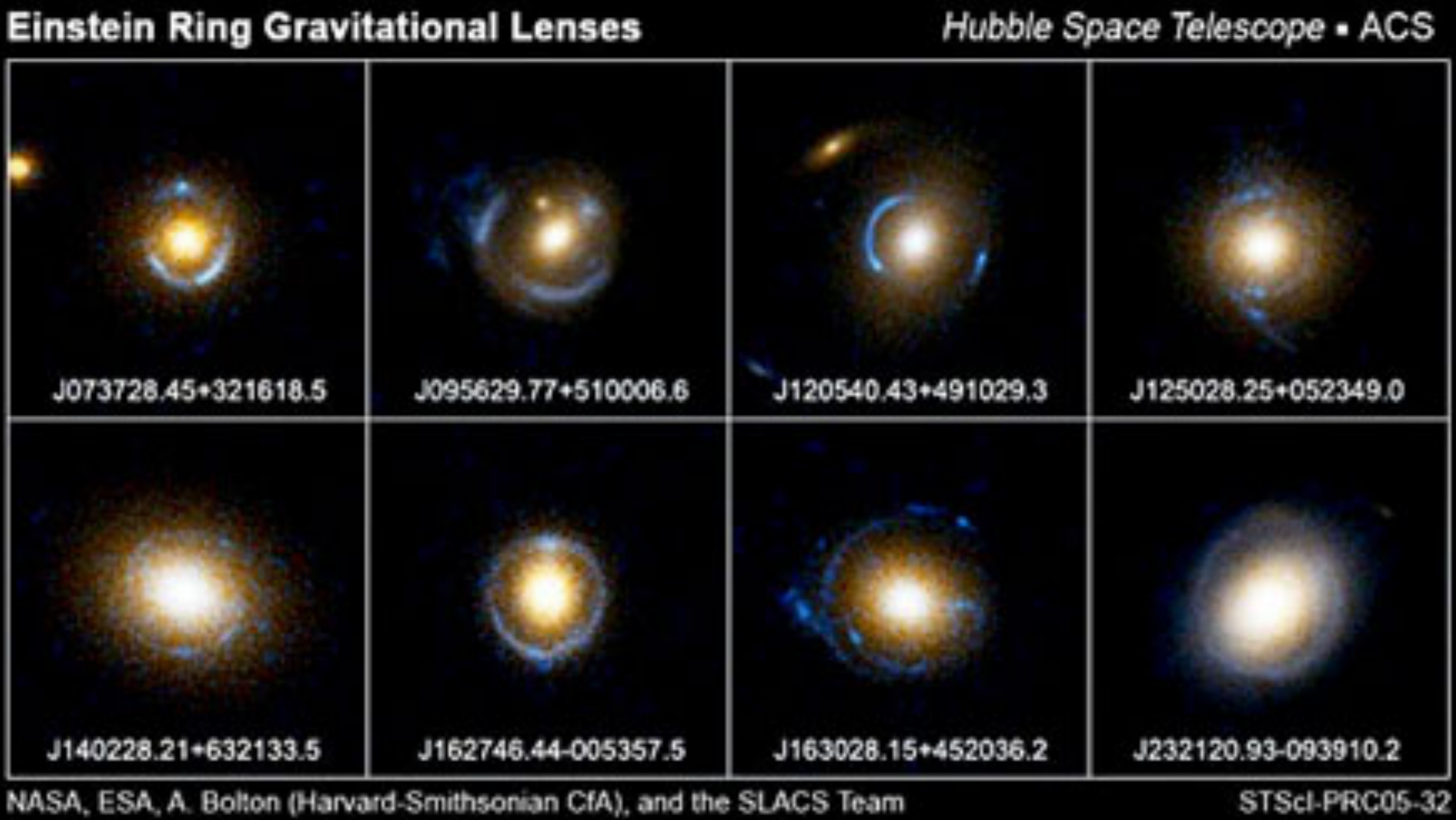
EAGLE Local Group simulation

University of Durham

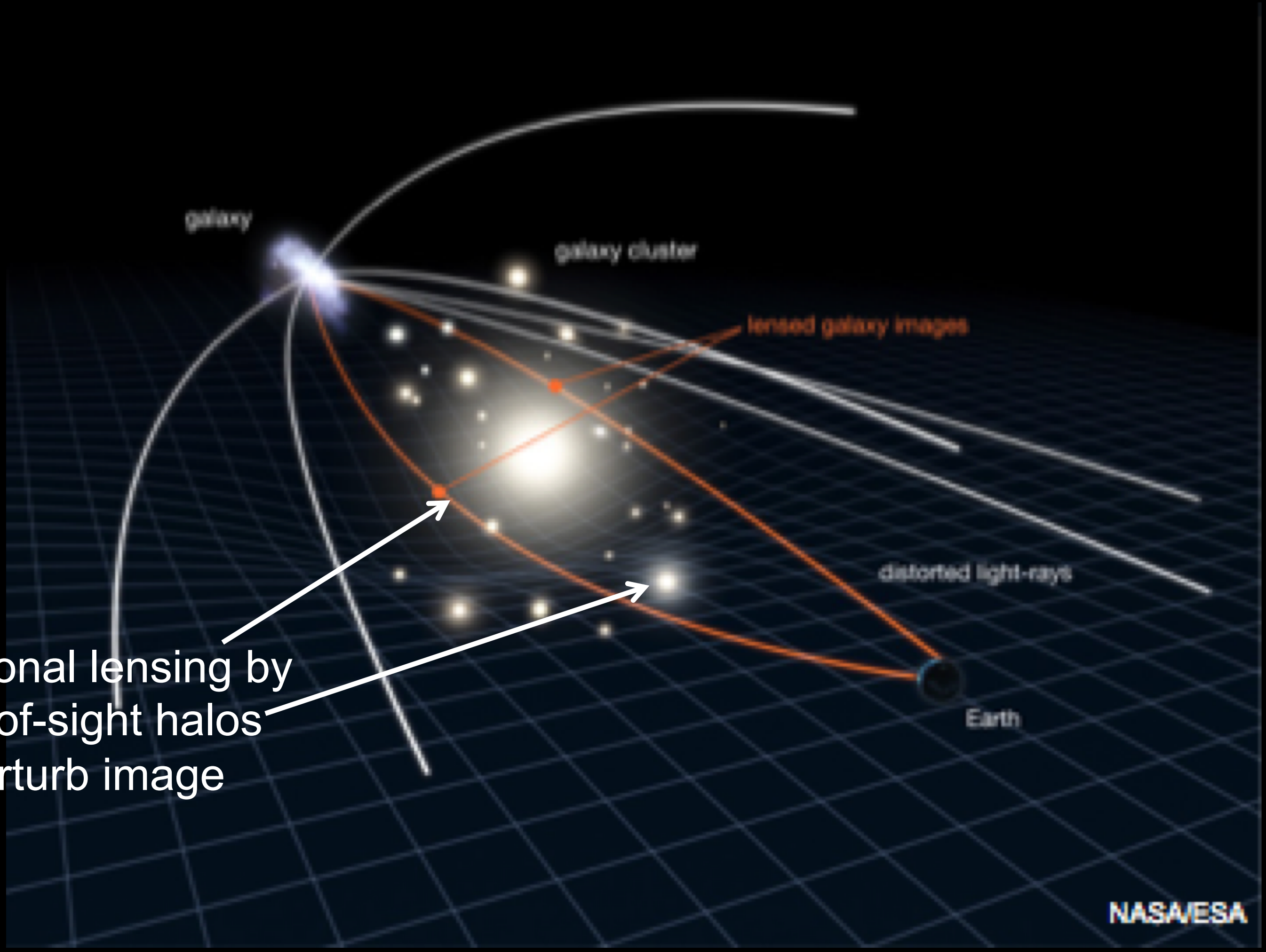


Sawala, CSF et al ‘16

SLAC sample of strong lenses



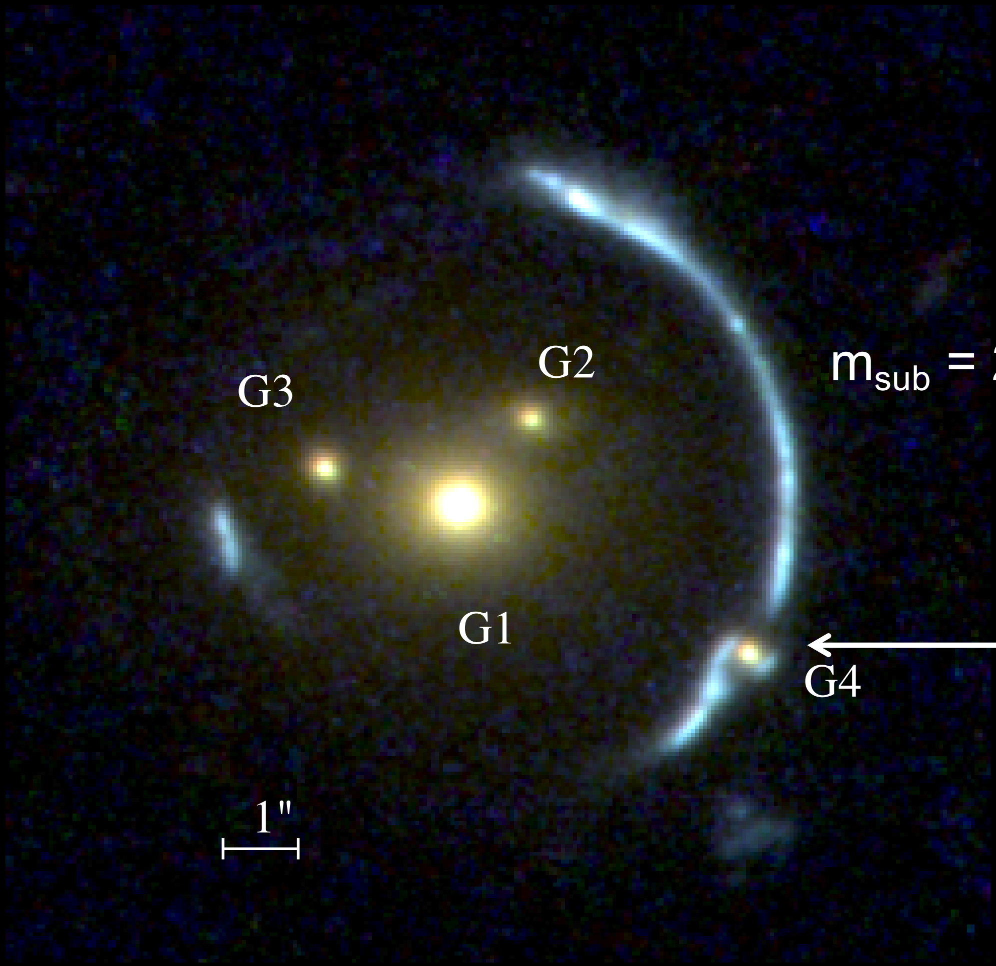
Gravitational lensing: Einstein rings



When the source and the lens are well aligned → strong arc or an Einstein ring

Gravitational lensing: Einstein rings

Halos projected onto an Einstein ring distort the image



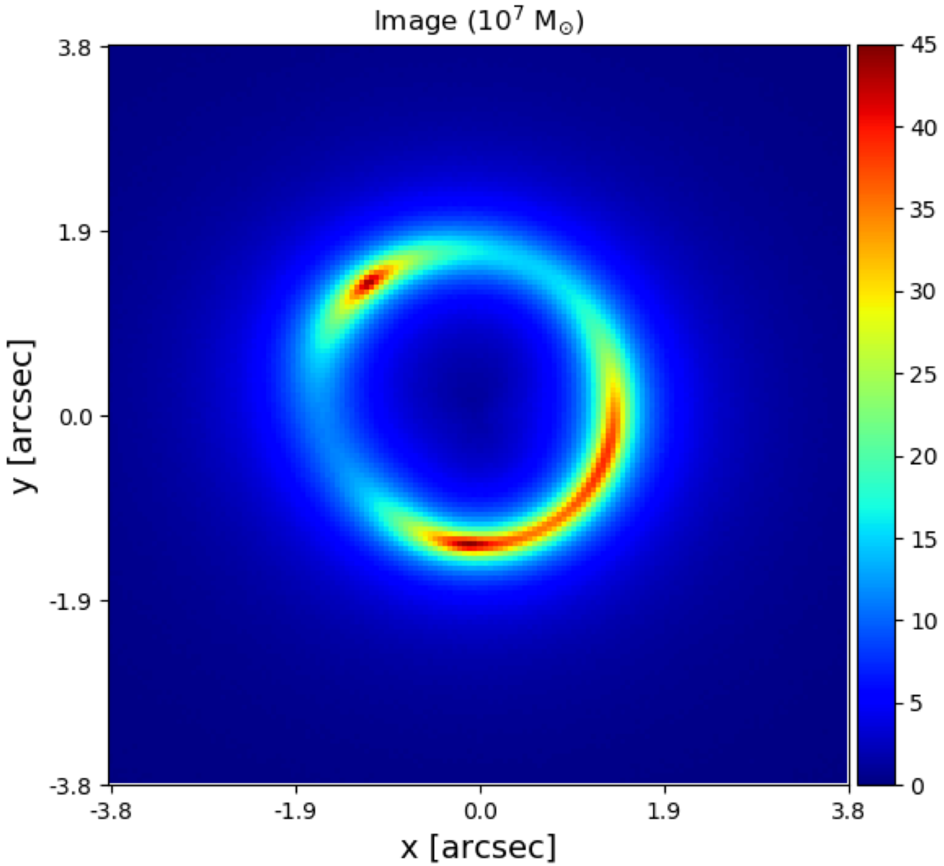
$m_{sub} = 2.8 \times 10^{10} M_o$

Vegetti et al '10

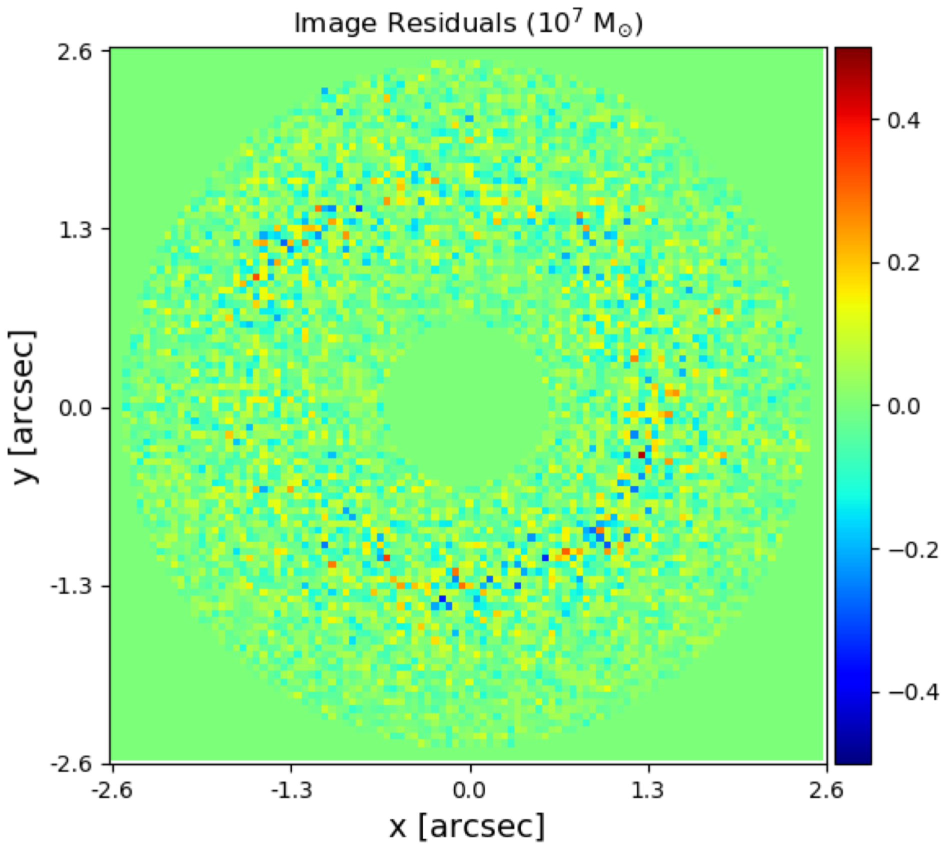
Strong lensing: detecting small halos

HST "data": z_{source}=1; z_{lens}=0.2 10^7 M_o halo – NOT so easy to spot

Image



Residuals



He, Li, CSF et al '19

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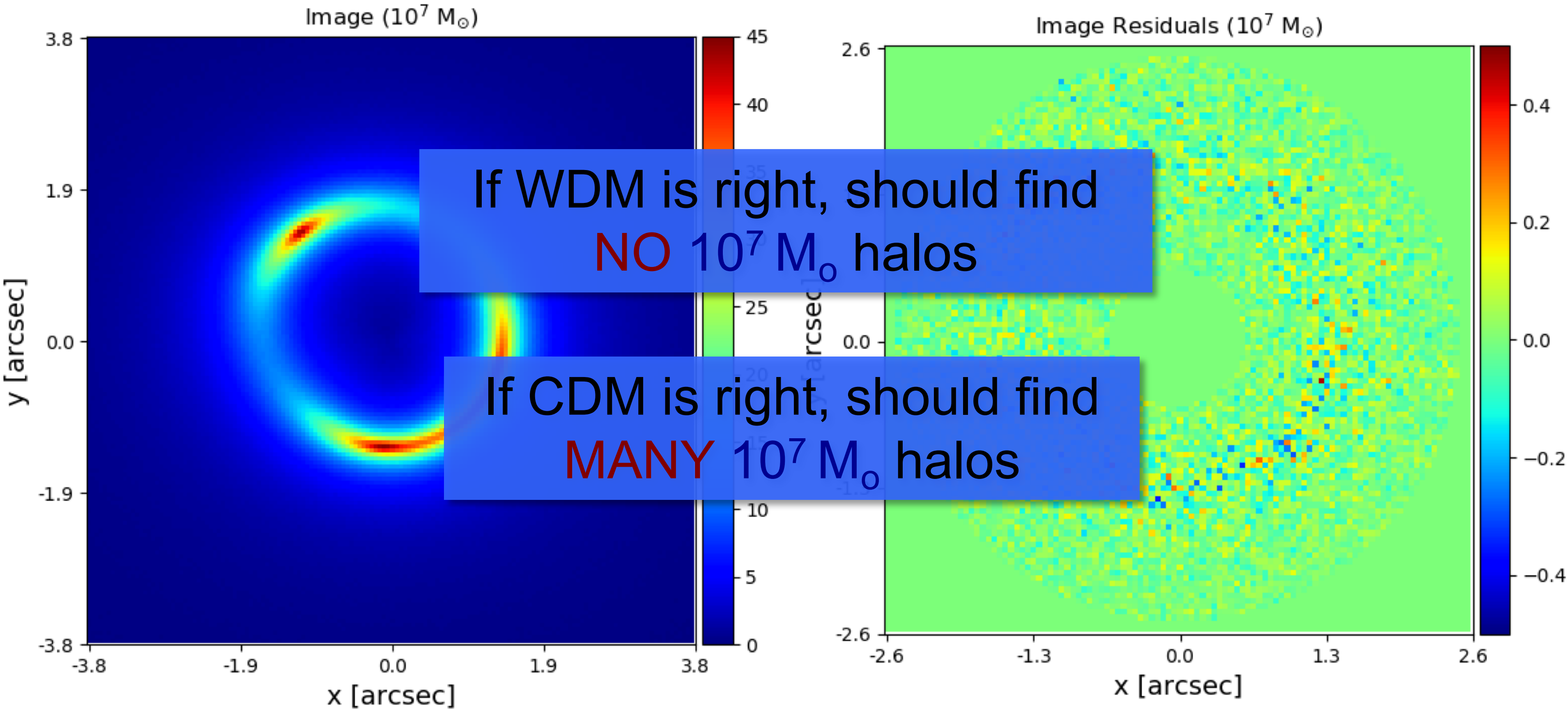
Detecting halos w. strong lensing

Can detect halos as small as $10^7 - 10^8\ M_o$



If WDM is right, should find NO $10^7\ M_o$ halos

If CDM is right, should find MANY $10^7\ M_o$ halos

He, Li, CSF et al '19

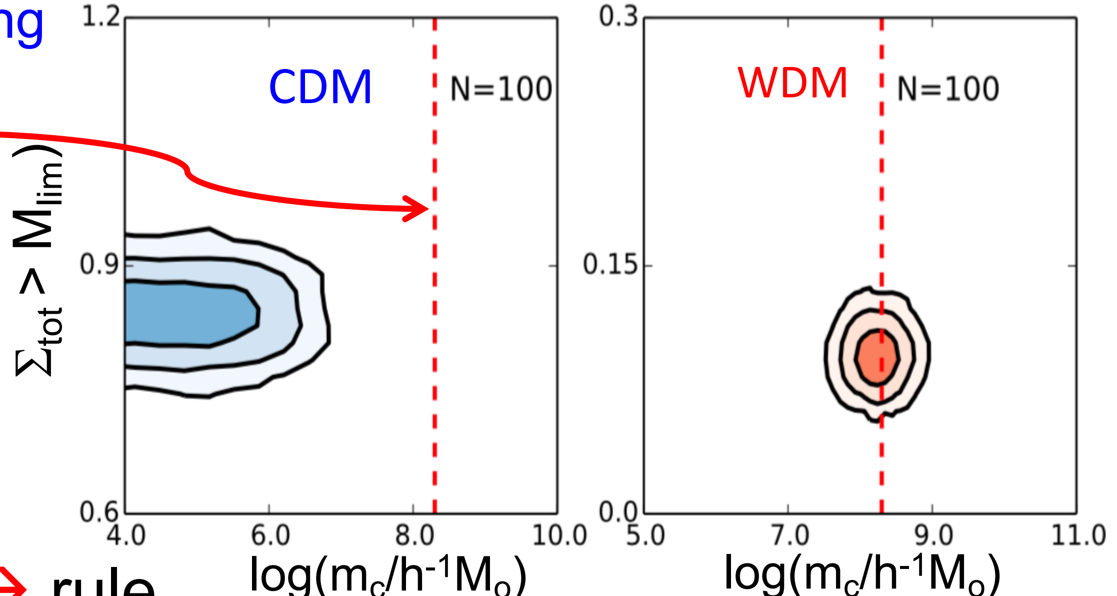
Detecting substructures with strong lensing

Σ_{tot}= projected halo number density within Einstein ring

Detection limit = $10^7\ h^{-1}M_o$

m_c= 1.3 × $10^8\ h^{-1}M_o$ for coldest 7 keV sterile neutrino

100 Einstein ring systems and detection limit: $m_{low} = 10^7\ h^{-1}M_o$



m_c= halo cutoff mass

- If DM is 7 keV sterile ν → rule out CDM at >3σ!
- If DM is CDM → rule out 7 keV sterile ν at many σ

Li, CSF et al '16

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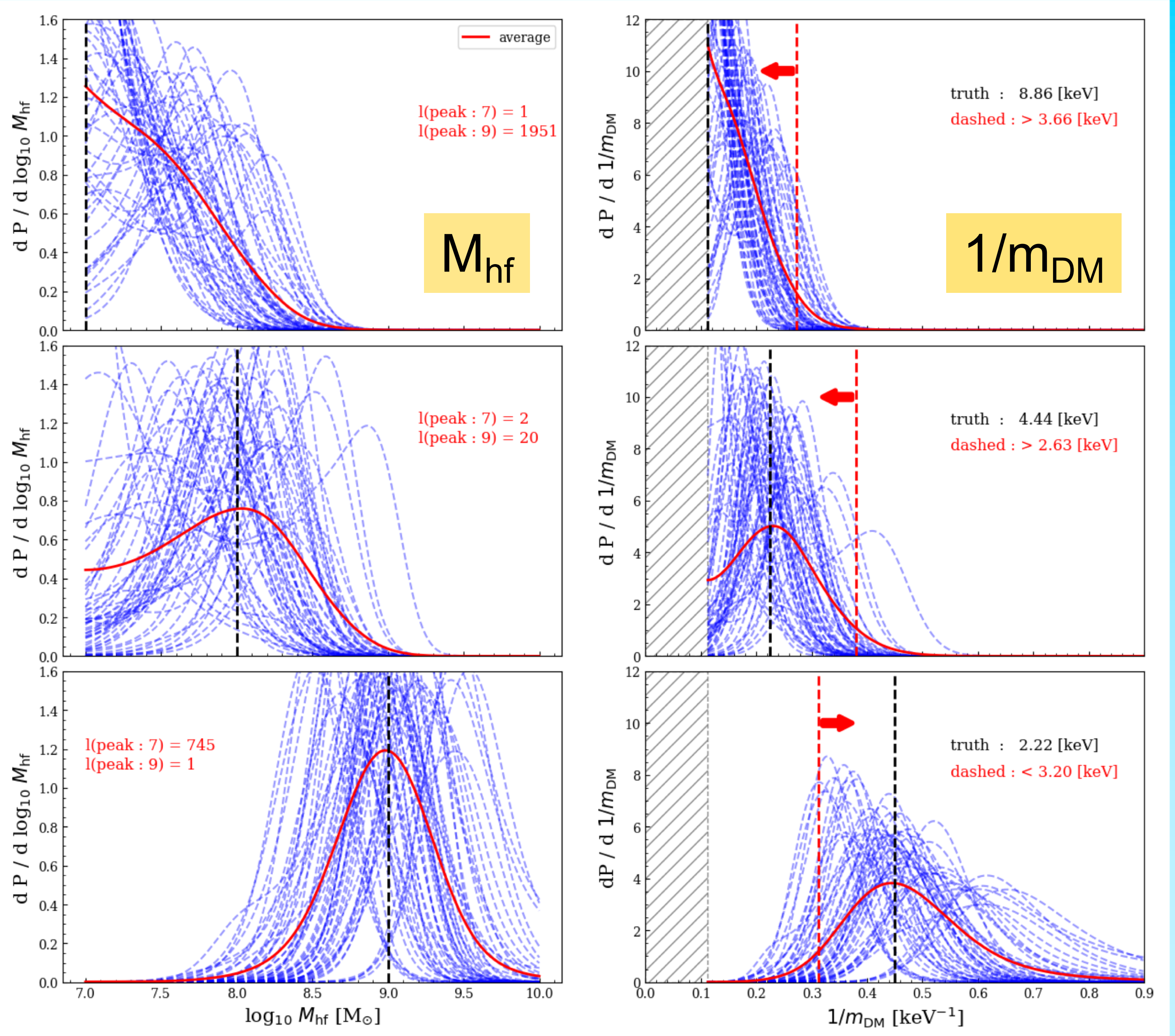
Strong lensing: detecting small halos

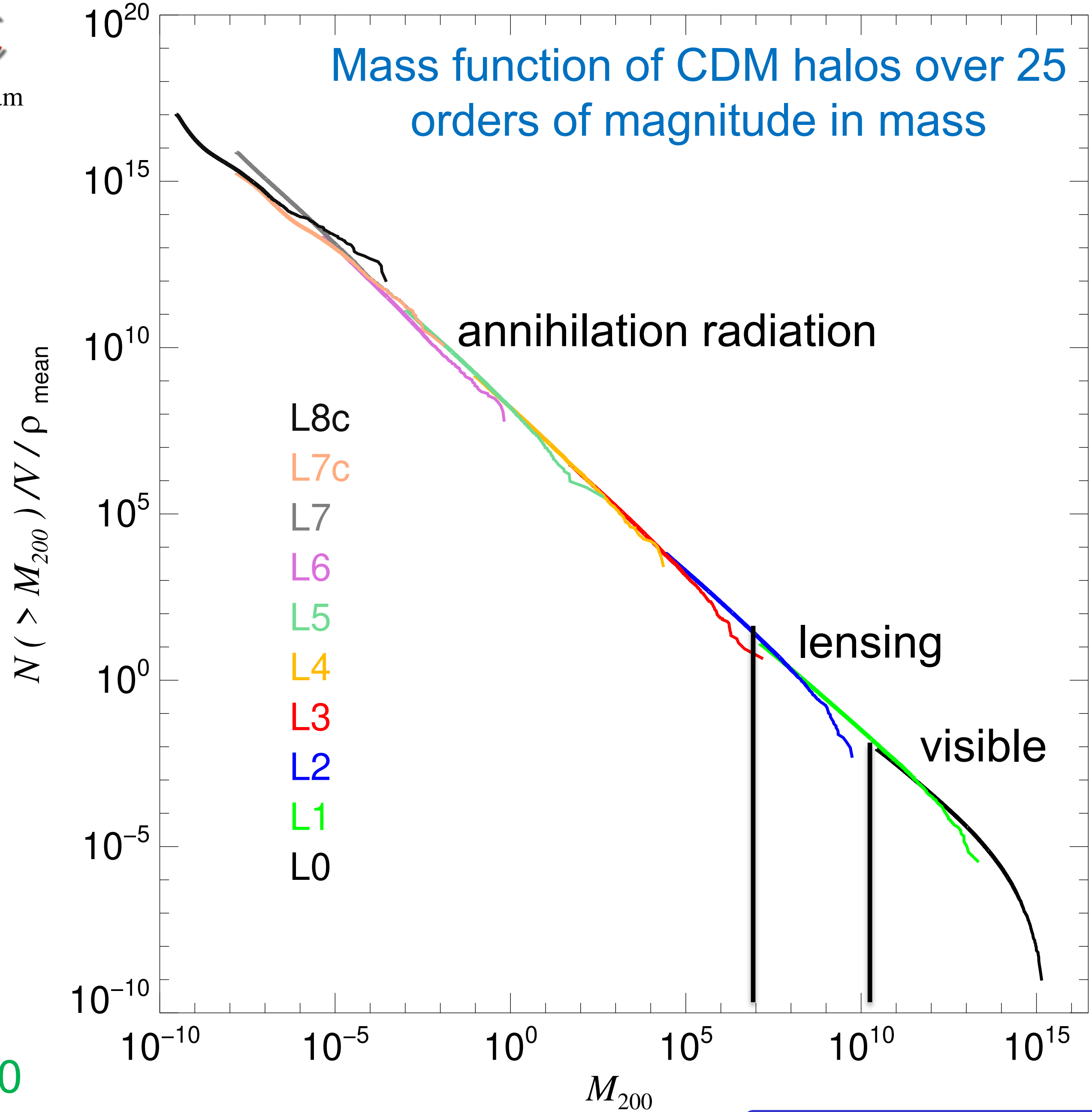
University of Durham

Posterior distributions (mock observations) for power spectrum of residuals

Constraints from forward modelling of 50 systems

He et al. '20





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Wang et al '20

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Indirect CDM detection through annihilation radiation

Supersymmetric particles are Majorana particles → annihilate into Standard Model particles (including γ-rays)

Intensity of annihilation radiation at *x* is:

halo density at ***x*** (astrophysics)

$$I(x) = \frac{1}{8\pi} \sum_f \frac{dN_f}{dE} \langle \sigma_f v \rangle \int_{los} \left(\frac{\rho_\chi}{M_\chi} \right)^2 ldl$$

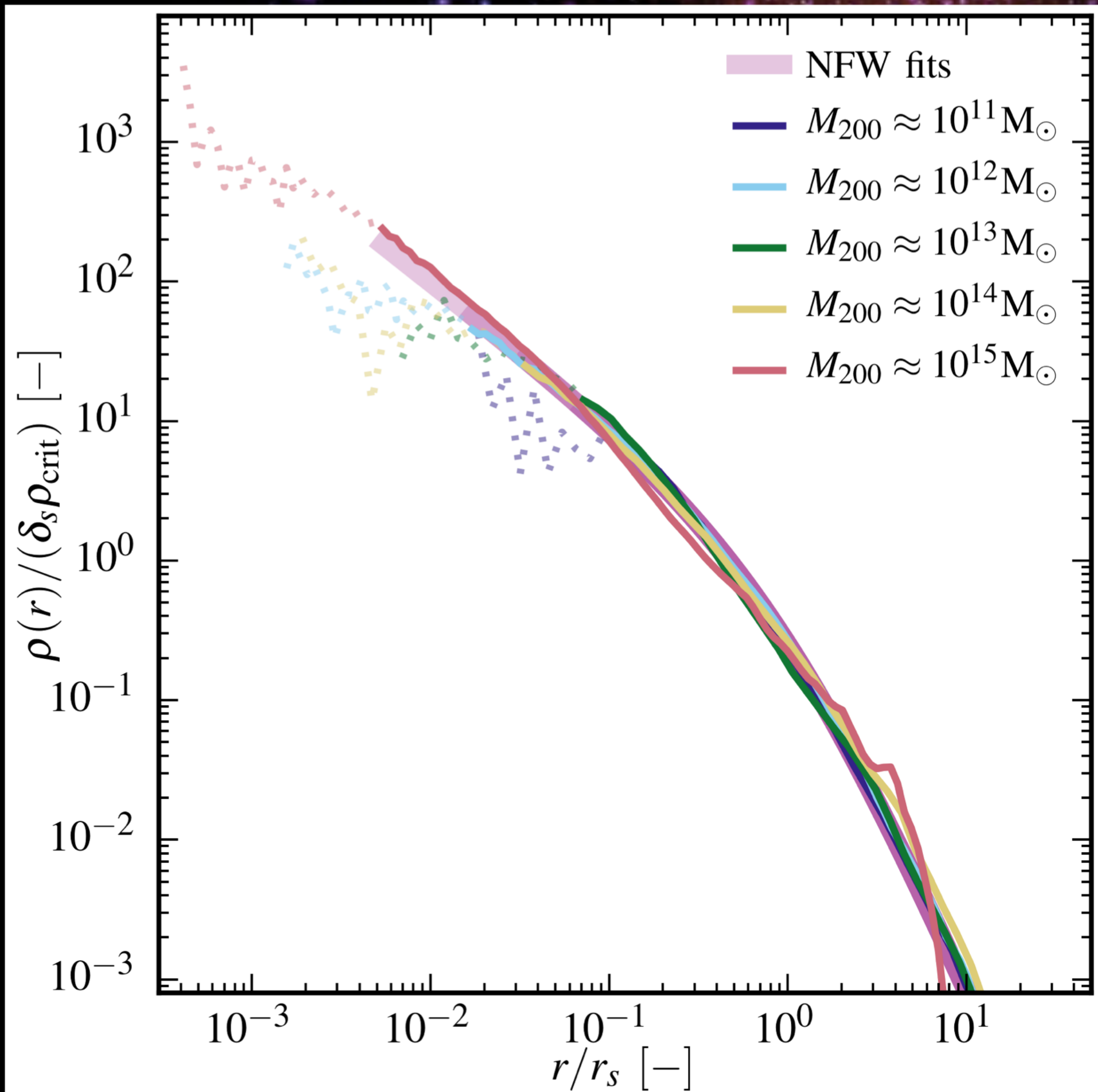
cross-section (particle physics)

$\langle \sigma v \rangle = 3 \times 10^{-26} cm^3 s^{-1}$ → relic abundance in simple SUSY models

⟹ Theoretical expectation requires knowing ρ(***x***)

⟹ Accurate high resolution N-body simulations of halo formation from CDM initial conditions

The Density Profile of Cold Dark Matter Halos



Shape of halo profiles ~independent of halo mass & cosmological parameters

Density profiles are “cuspy” - no `core' near the centre

Fitted by simple formula:

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

(Navarro, Frenk & White ’97)

More massive halos and halos that form earlier have higher densities (bigger δ)

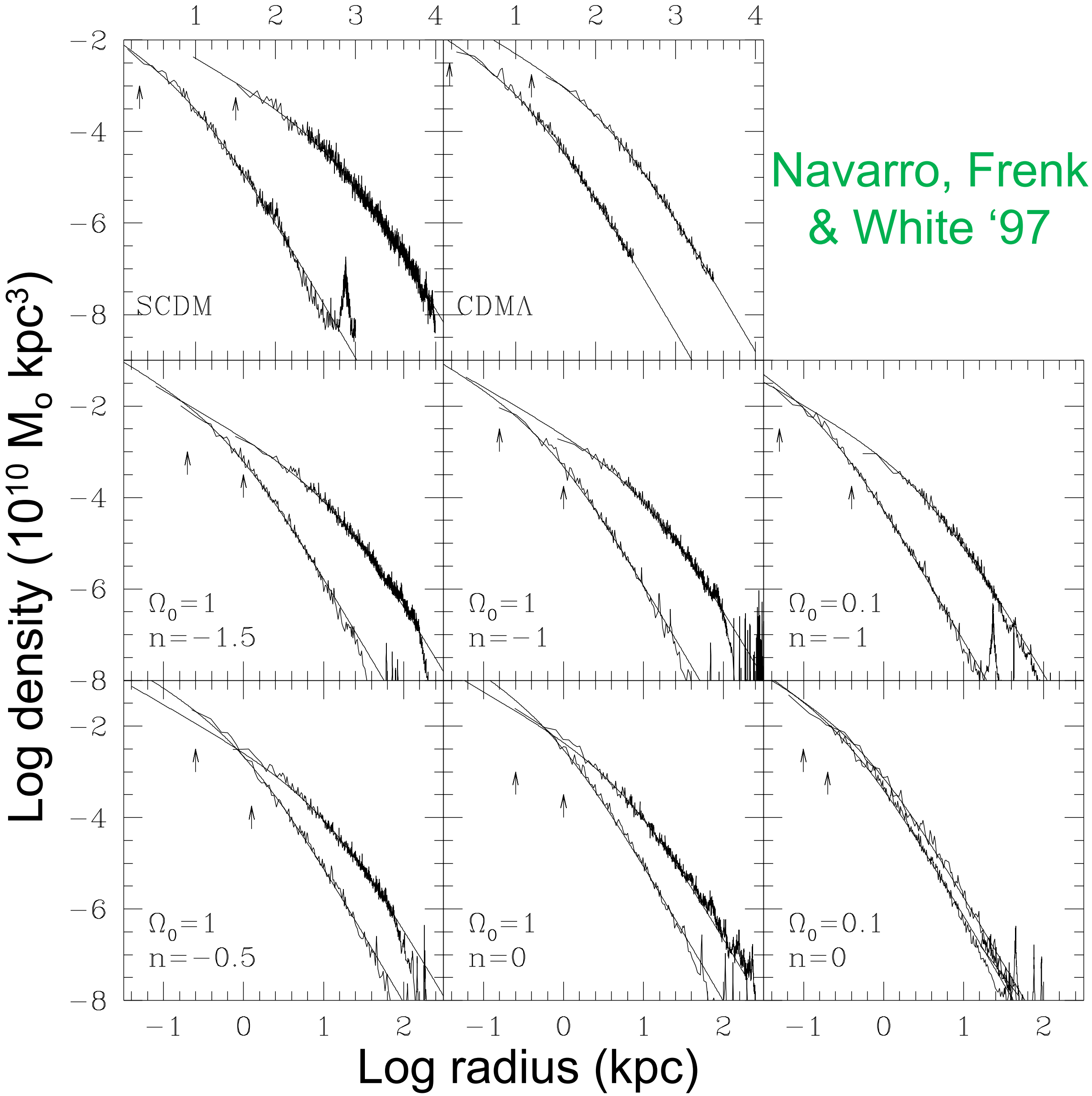
Universal halo density profiles

University of Durham

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

Fits the spherically averaged density profiles of halos over a wide mass range.

2 parameters:
Characteristic density δ_C
radius: r_s



Navarro, Frenk & White '97

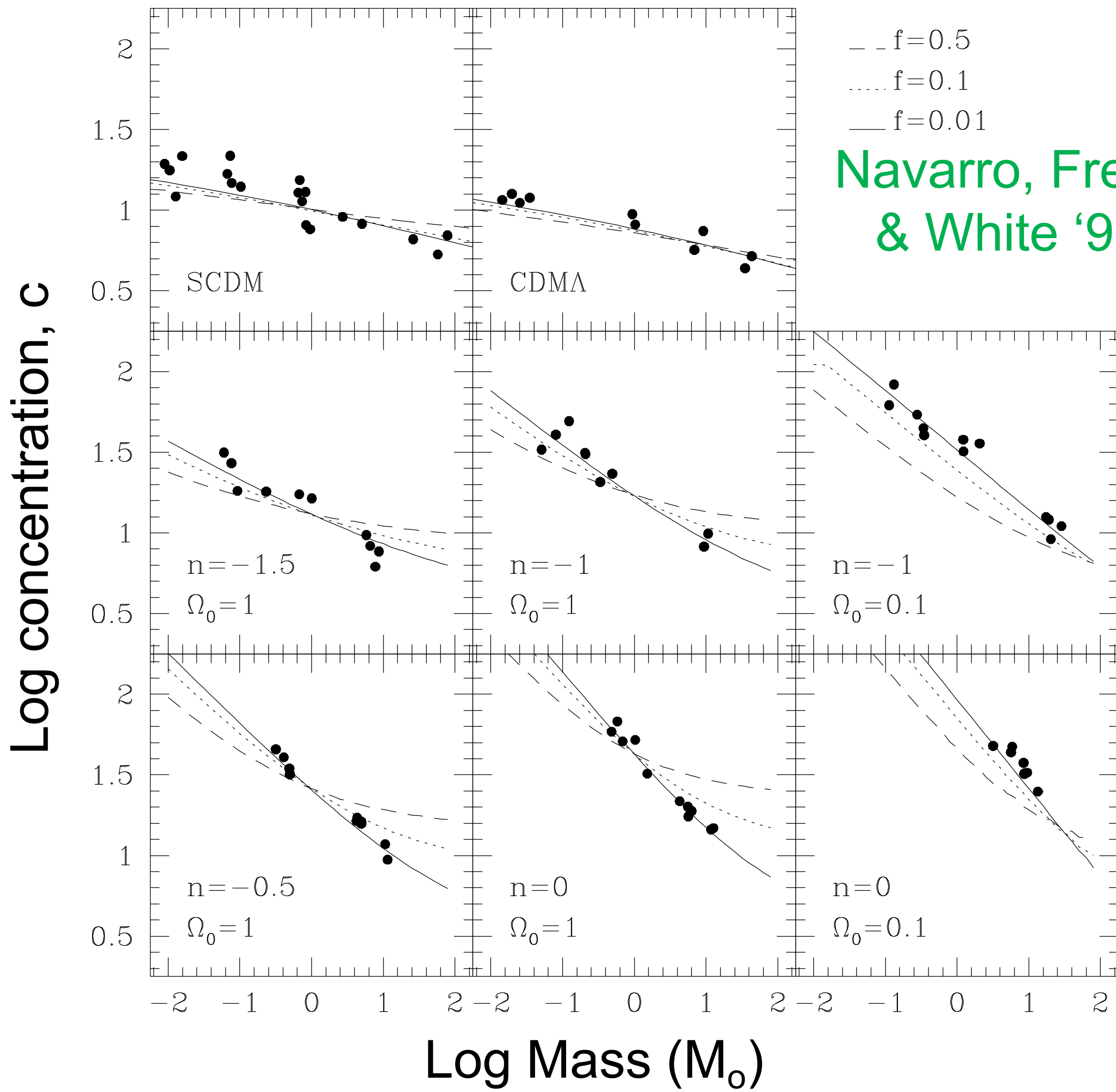
Universal halo density profiles

University of Durham

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

2 parameters:
Characteristic density, δ_C
radius, r_s

The two parameters are related to halo mass in a way that is cosmology dependent:
c ↘ as M ↗



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$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

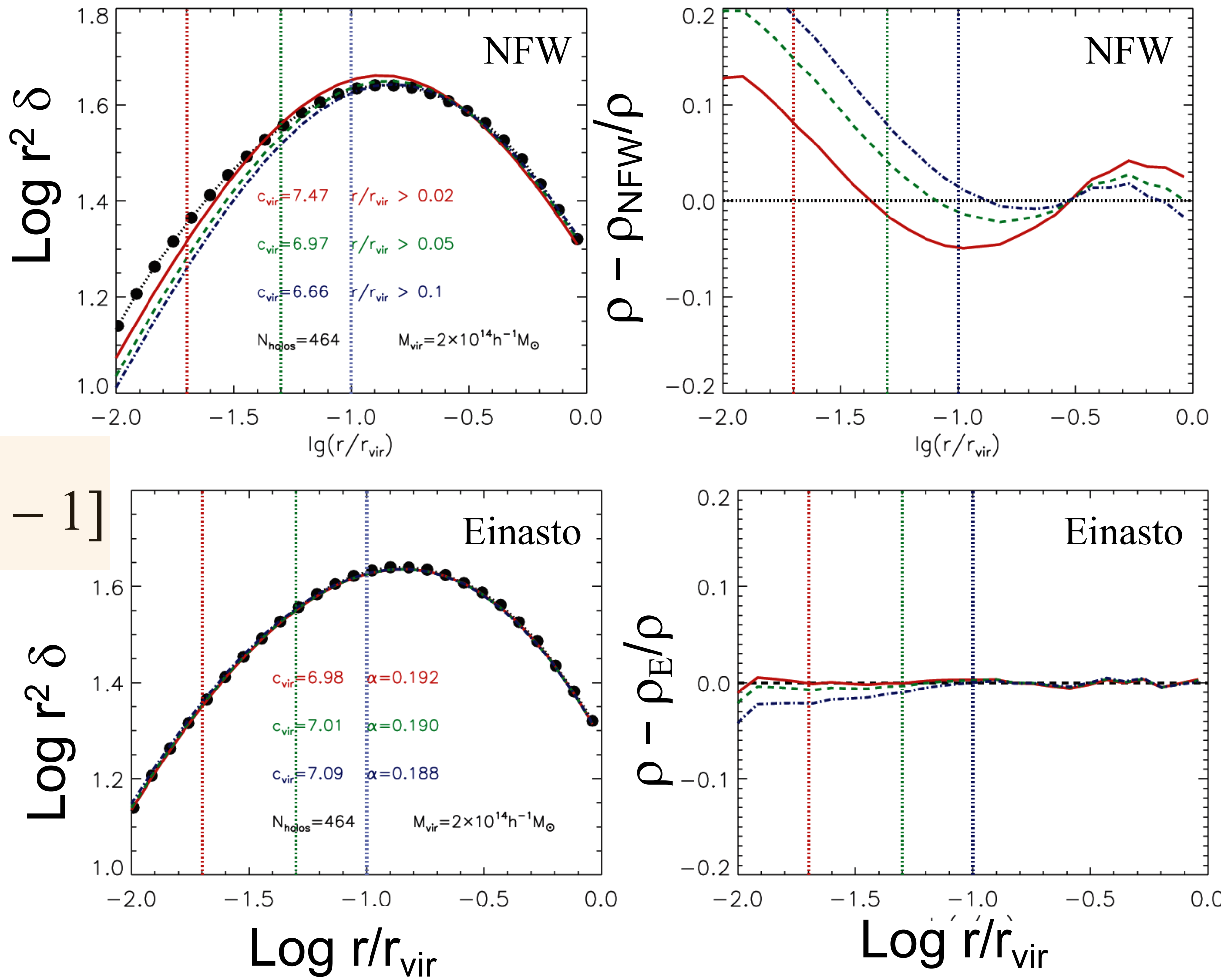
The "Einasto" formula

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

Fits mean profiles even better

Gao et al 2008

Averaged cluster mass halos fit with NFW and Einasto



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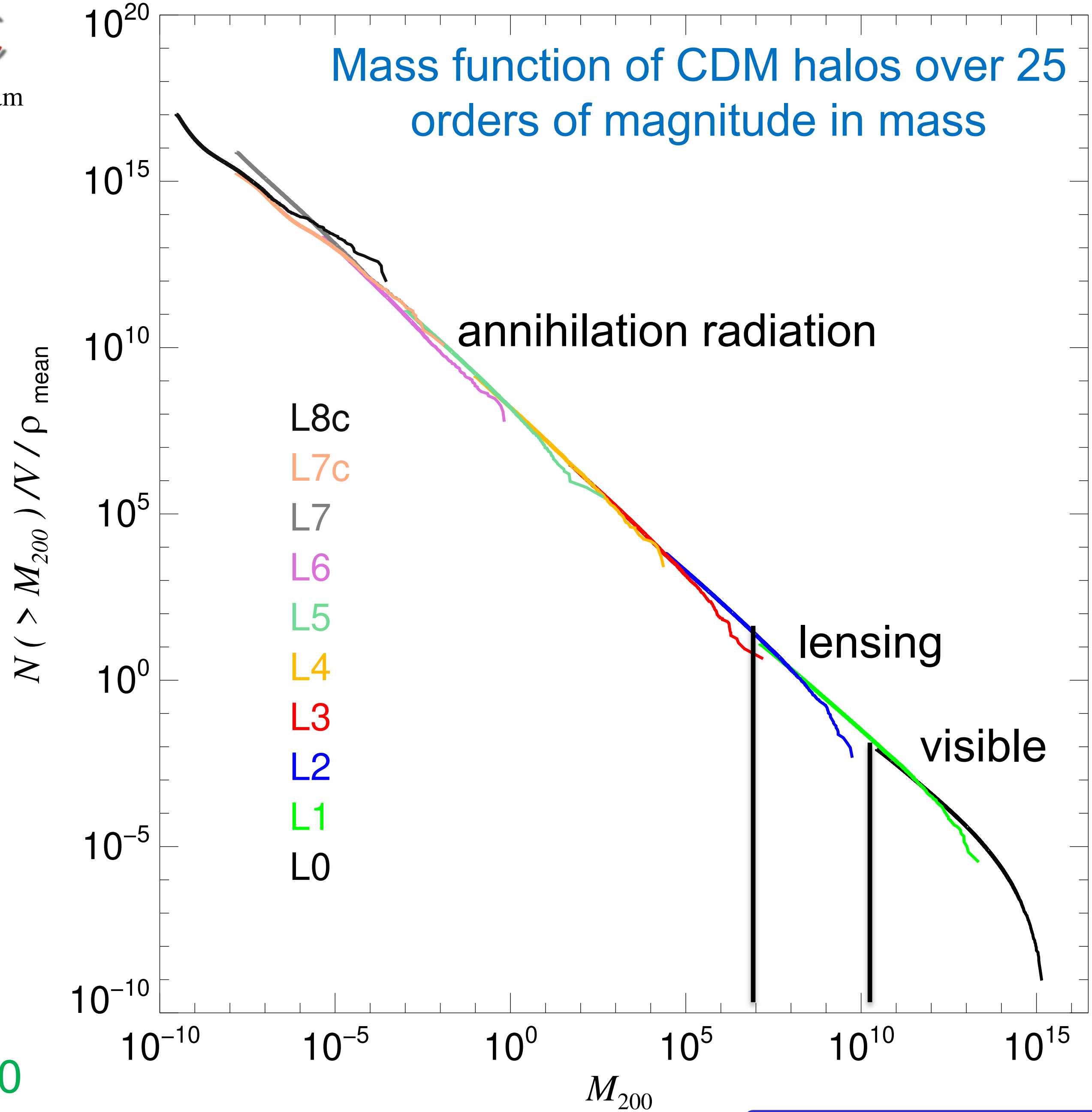
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annihilation radiation
lensing
visible
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L7c
L7
L6
L5
L4
L3
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10^{-10}
10^{-5}
10^{0}
10^{5}
10^{10}
10^{15}
M_{200}

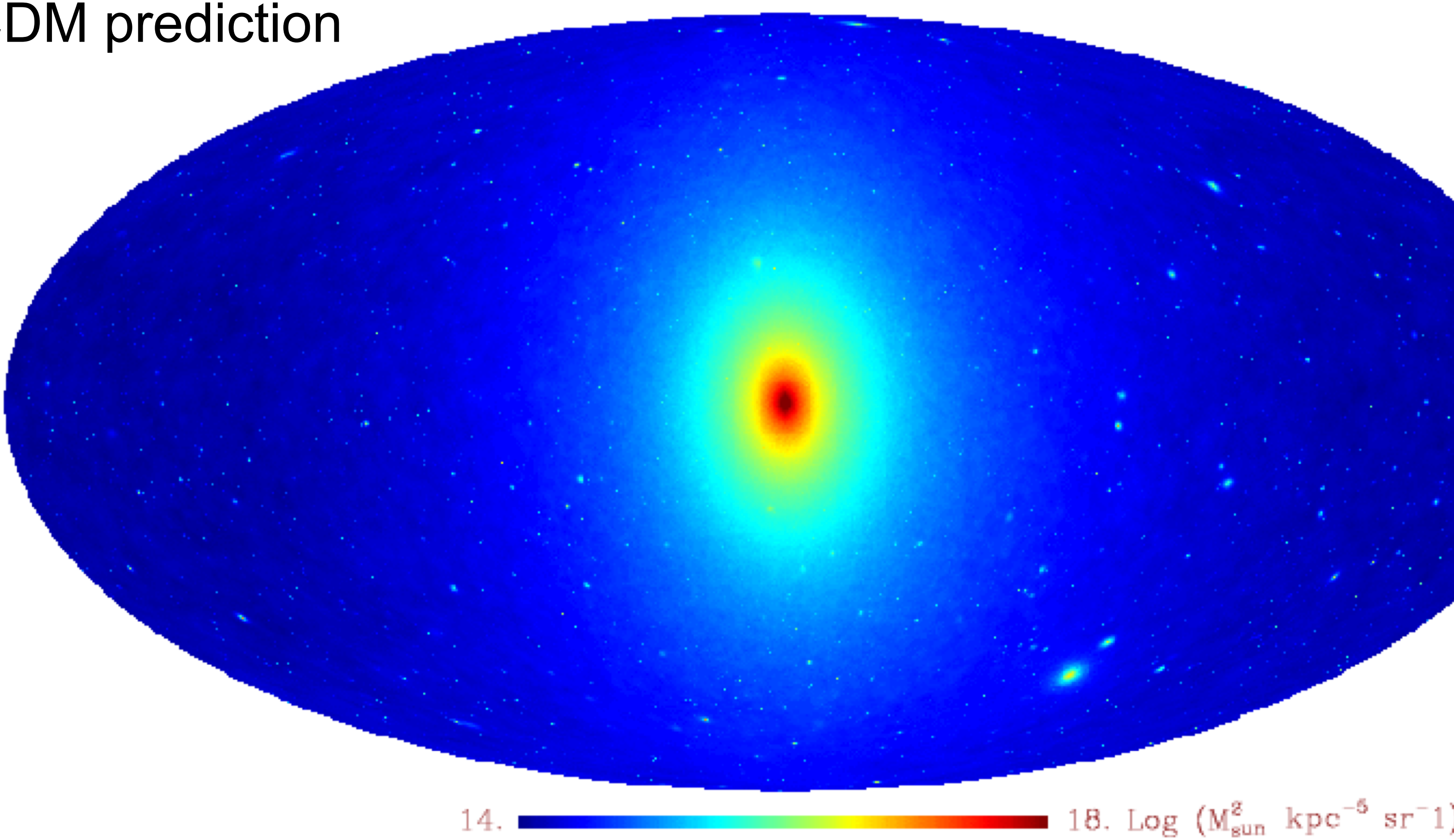
Wang et al '20

University of Durham

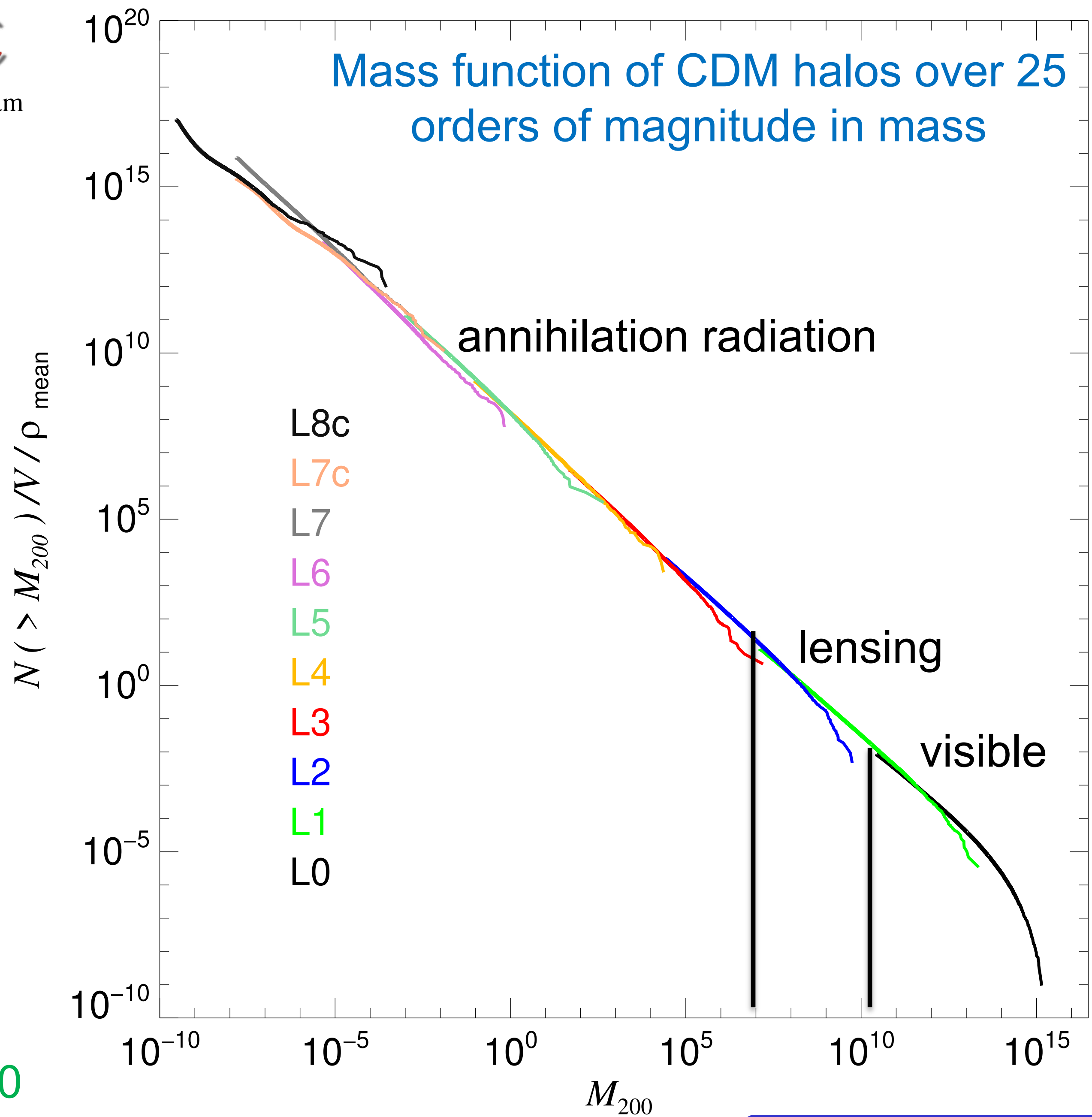
The Milky Way seen in annihilation radiation

Aquarius simulation: $N_{200} = 1.1 \times 10^9$

CDM prediction



Springel et al. ‘08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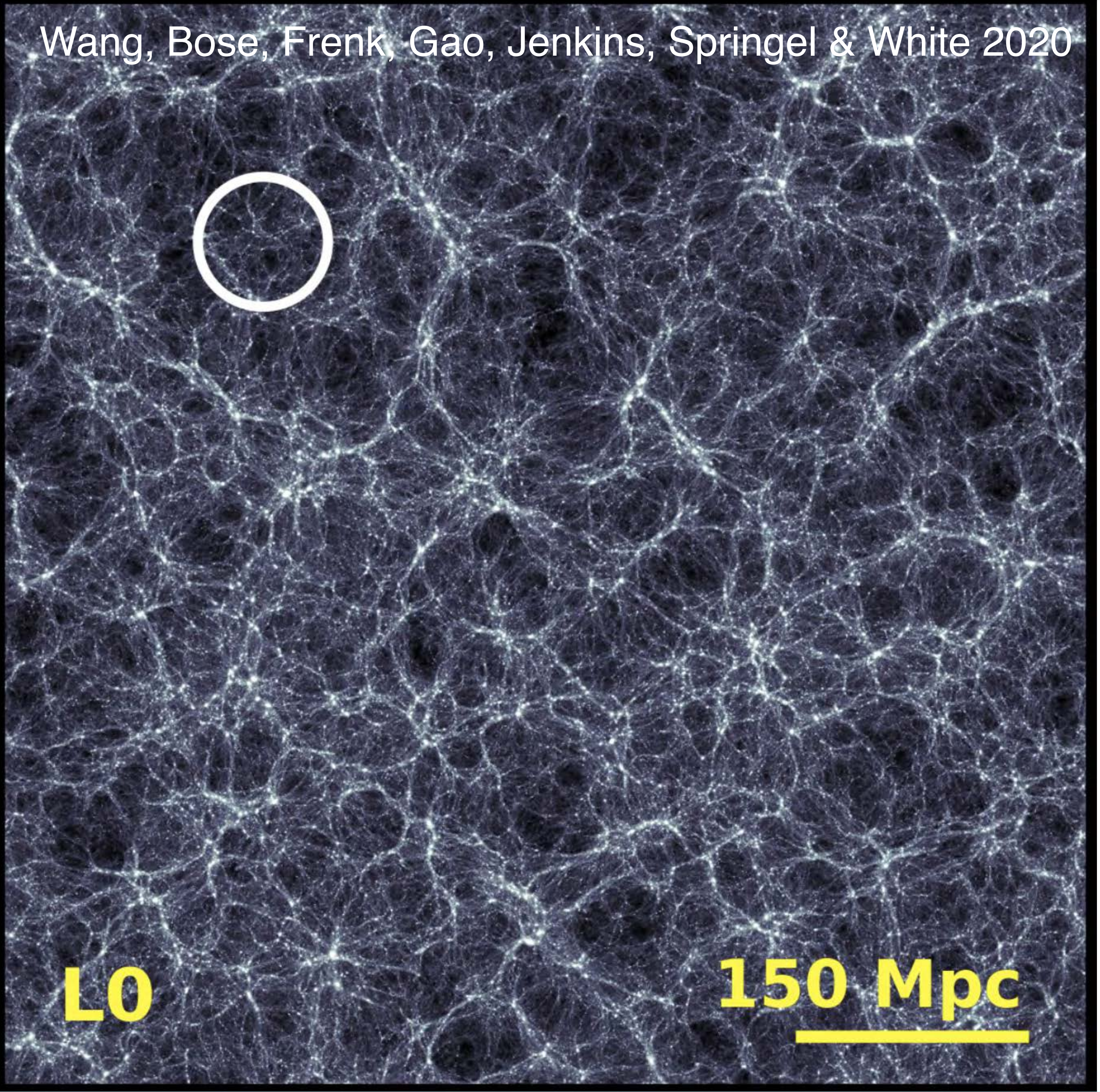
Wang et al '20



The VVV simulation

Planck cosmology

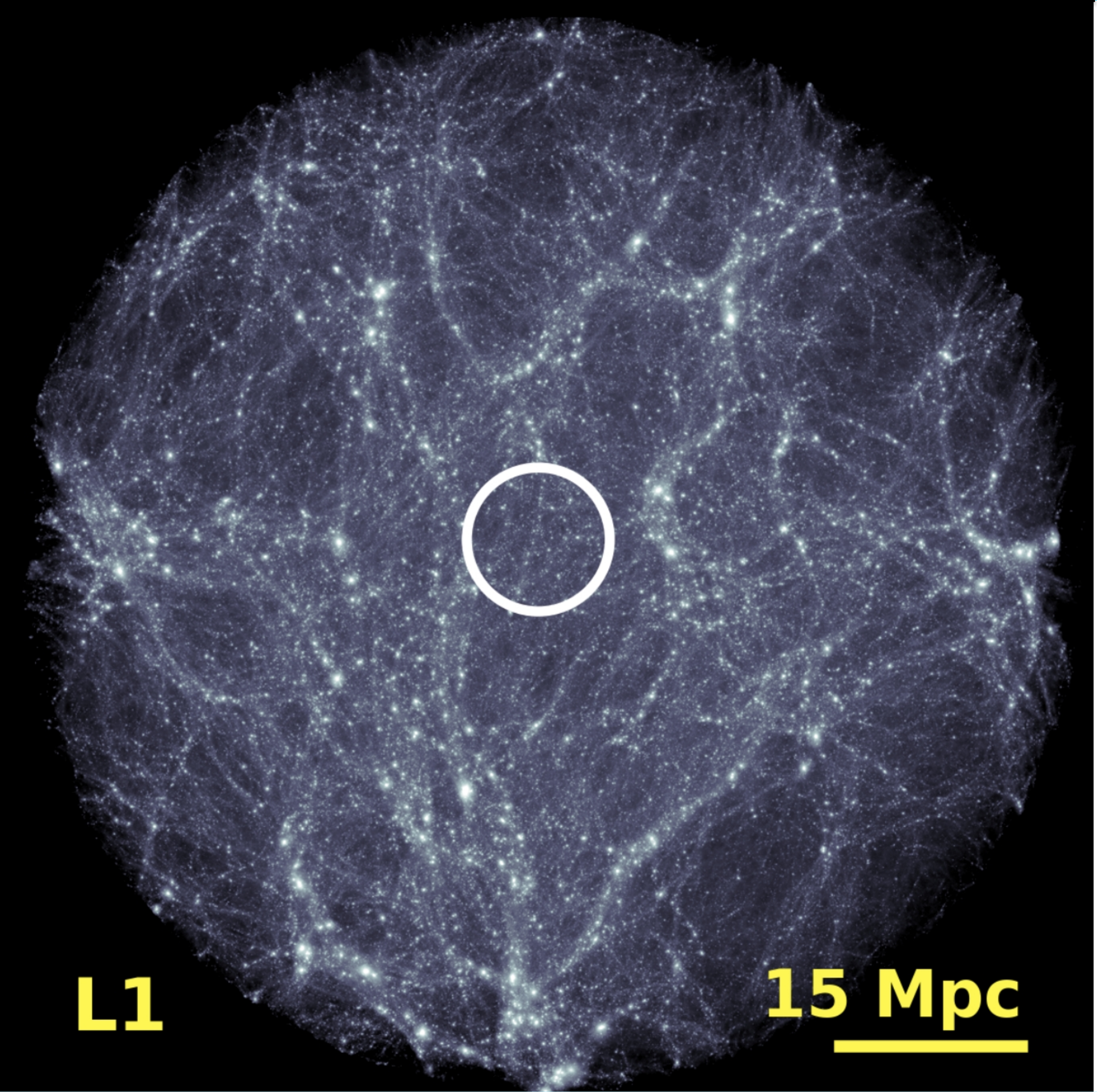
Dark matter only

Dynamic range of 30 orders of magnitude in mass

$M_{char} = 10^{14}\ M_{\odot}$

Base Level

Wang, Bose et al 2020



The VVV simulation

Planck cosmology

Dark matter only

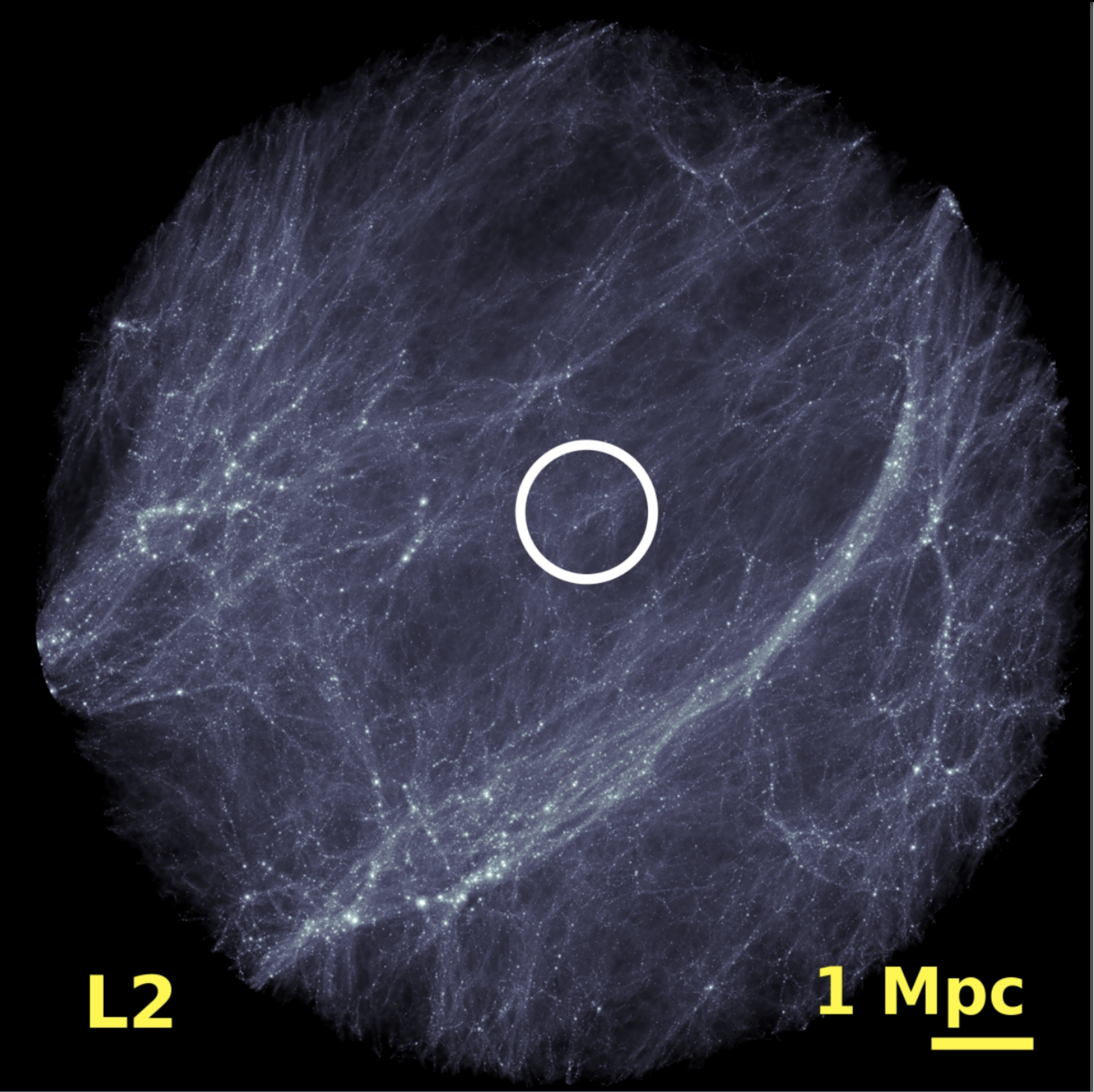
Dynamic range of 30 orders of magnitude in mass

$M_{char} = 10^{12} M_{\odot}$

Zoom Level 1

Wang, Bose et al 2020

The VVV simulation



Planck cosmology

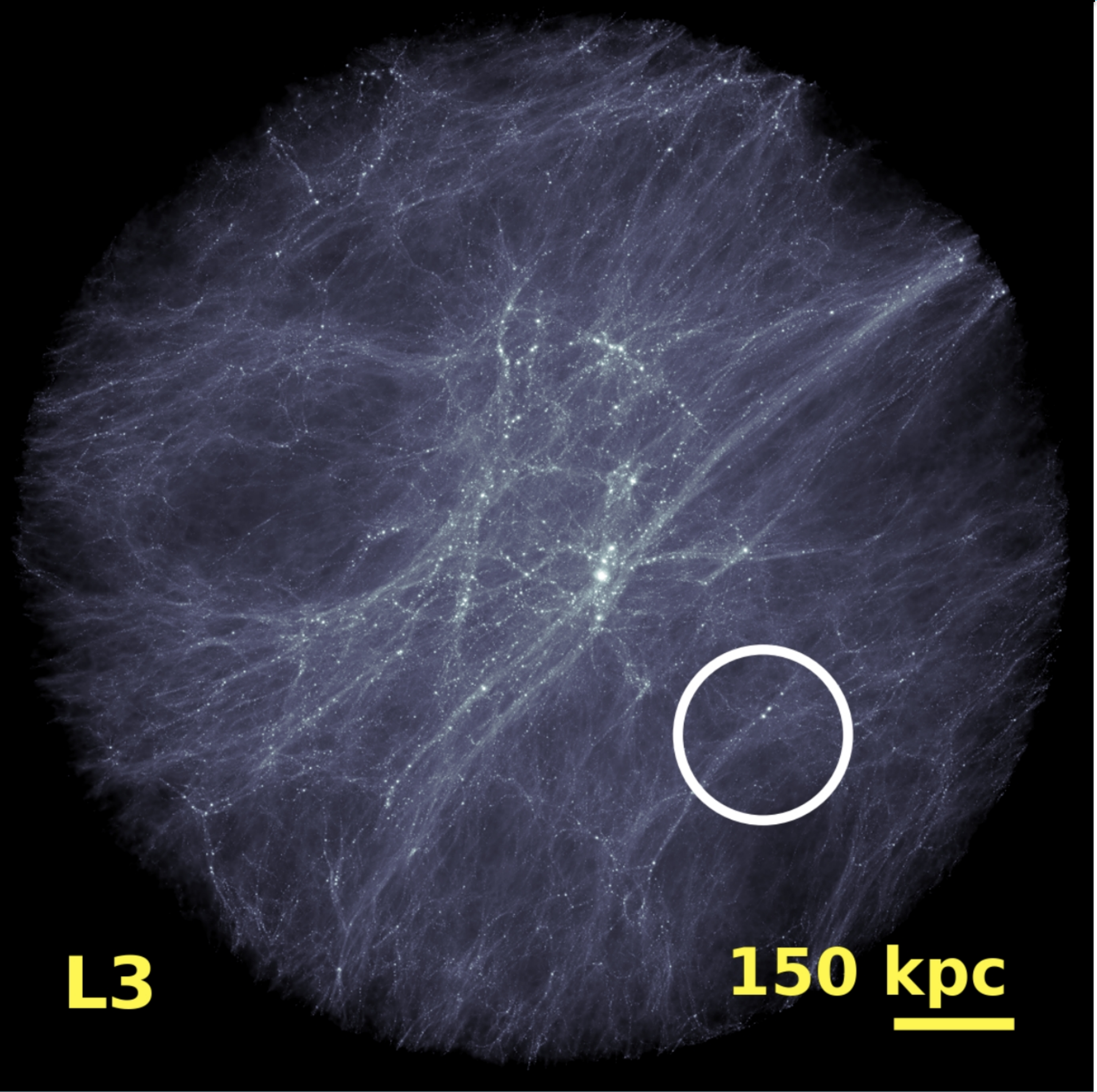
Dark matter only

Dynamic range of 30 orders of magnitude in mass

$M_{char} = 10^9\ M_{\odot}$

Zoom Level 2

Wang, Bose et al 2020



The VVV simulation

Planck cosmology

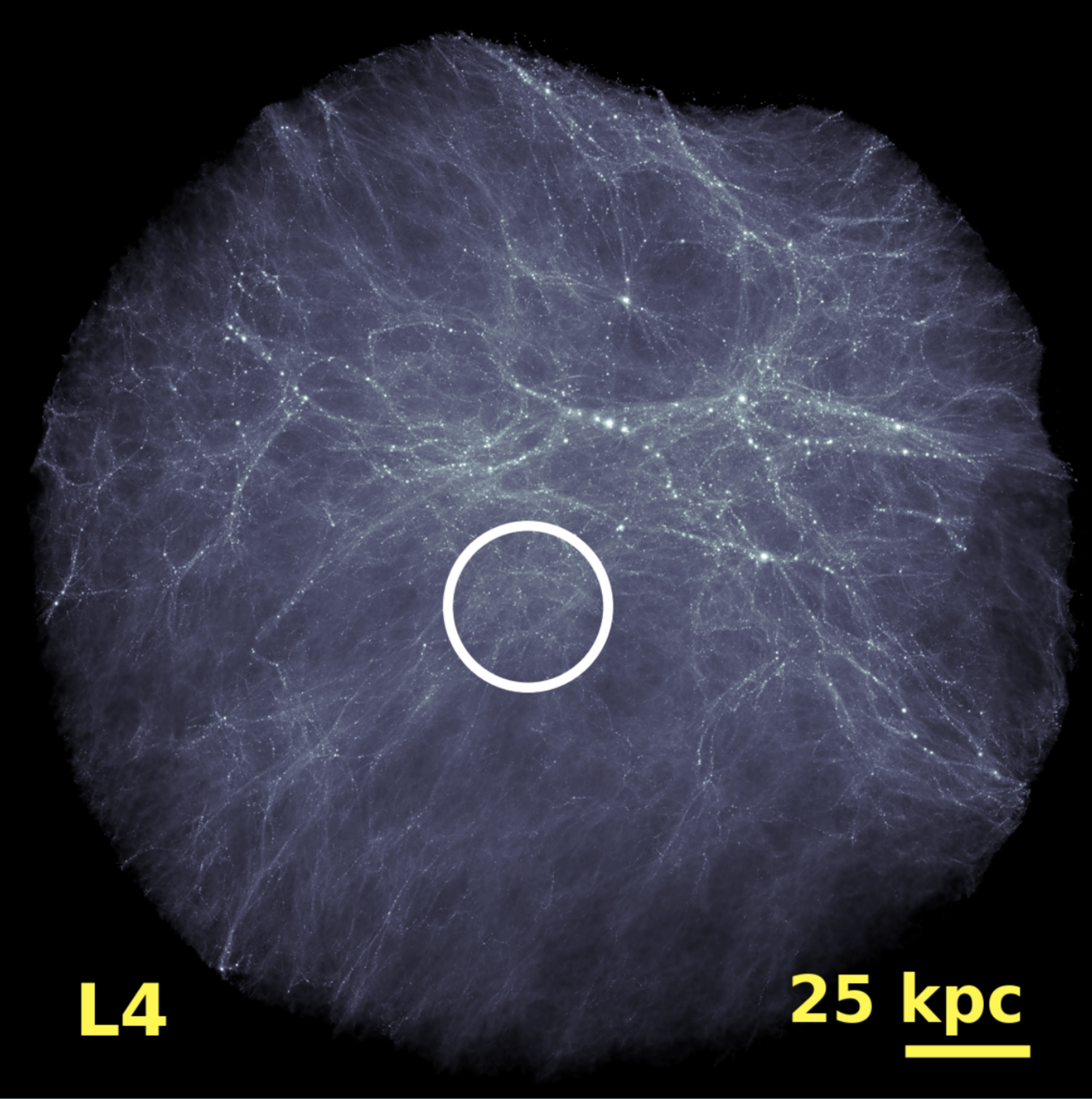
Dark matter only

Dynamic range of 30 orders of magnitude in mass

$M_{char} = 10^6 M_\odot$

Zoom Level 3

Wang, Bose et al 2020



The VVV simulation

Planck cosmology

Dark matter only

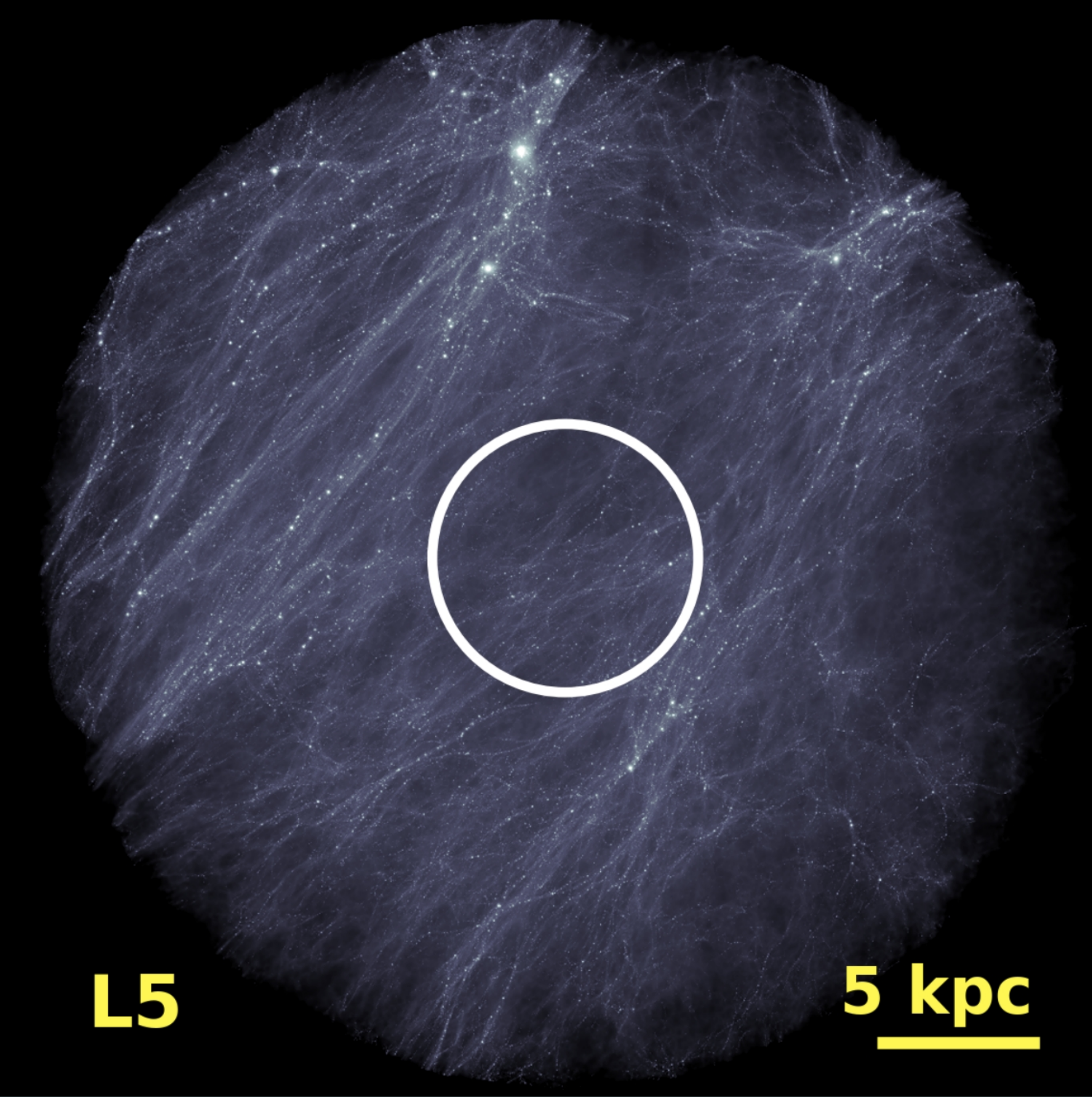
Dynamic range of 30 orders of magnitude in mass

$M_{char} = 10^3\ M_\odot$

Zoom Level 4

Wang, Bose et al 2020

The VVV simulation



Planck cosmology

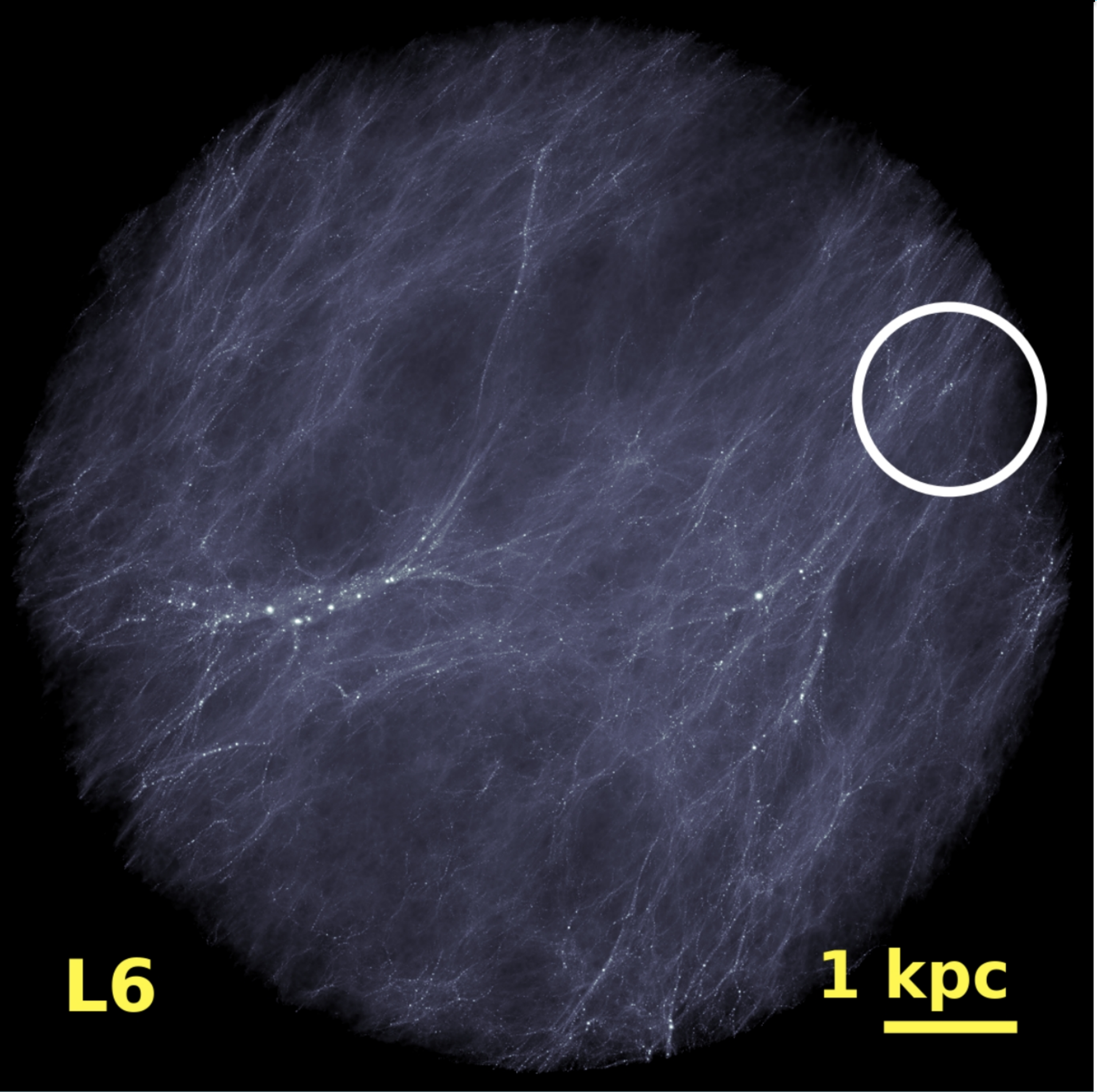
Dark matter only

Dynamic range of 30 orders of magnitude in mass

$M_{char} = 10\ M_{\odot}$

Zoom Level 5

Wang, Bose et al 2020



The VVV simulation

Planck cosmology

Dark matter only

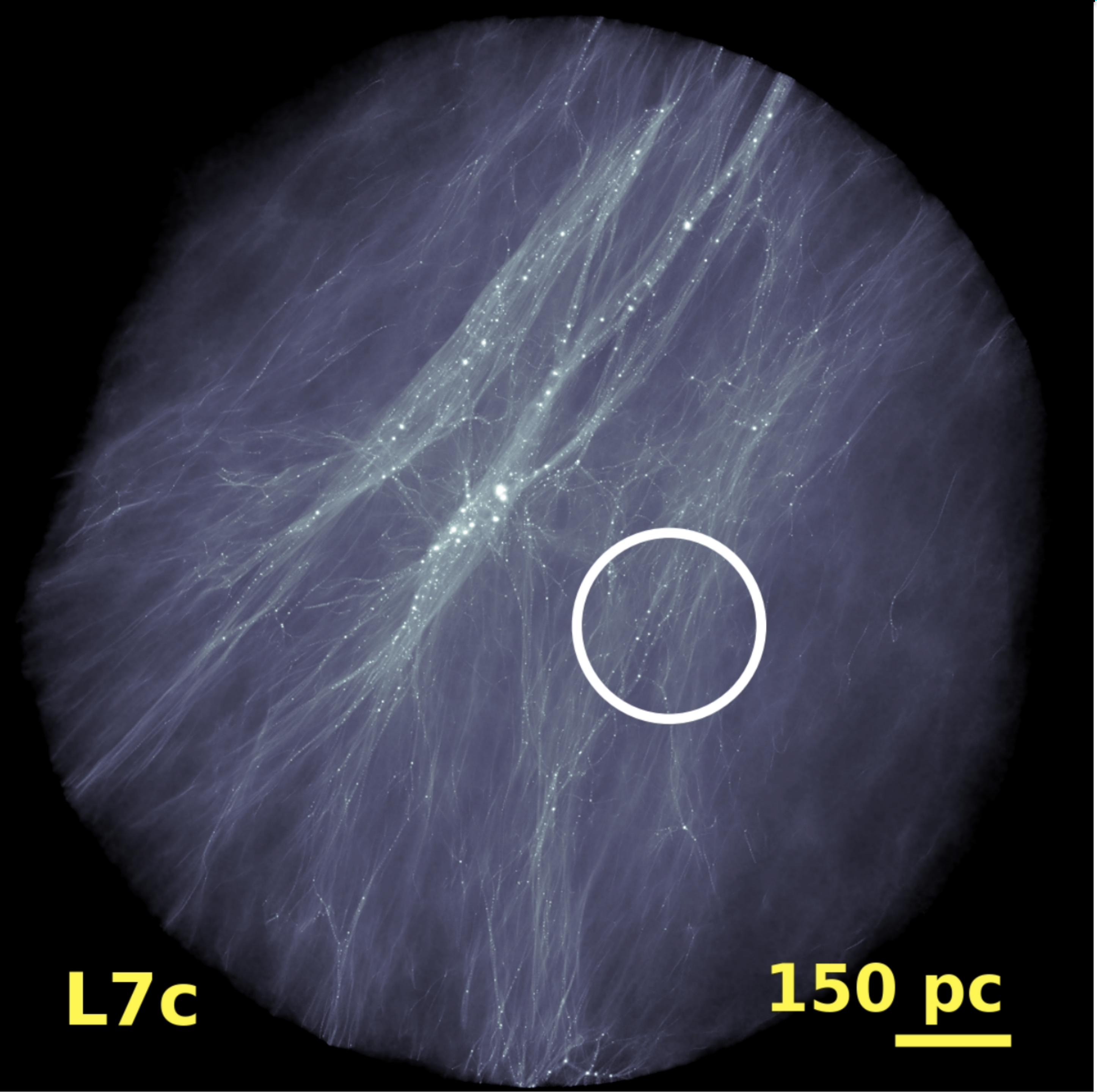
Dynamic range of 30 orders of magnitude in mass

$M_{char} = 10^{-1}\ M_\odot$

Zoom Level 6

Wang, Bose et al 2020

The VVV simulation



Planck cosmology

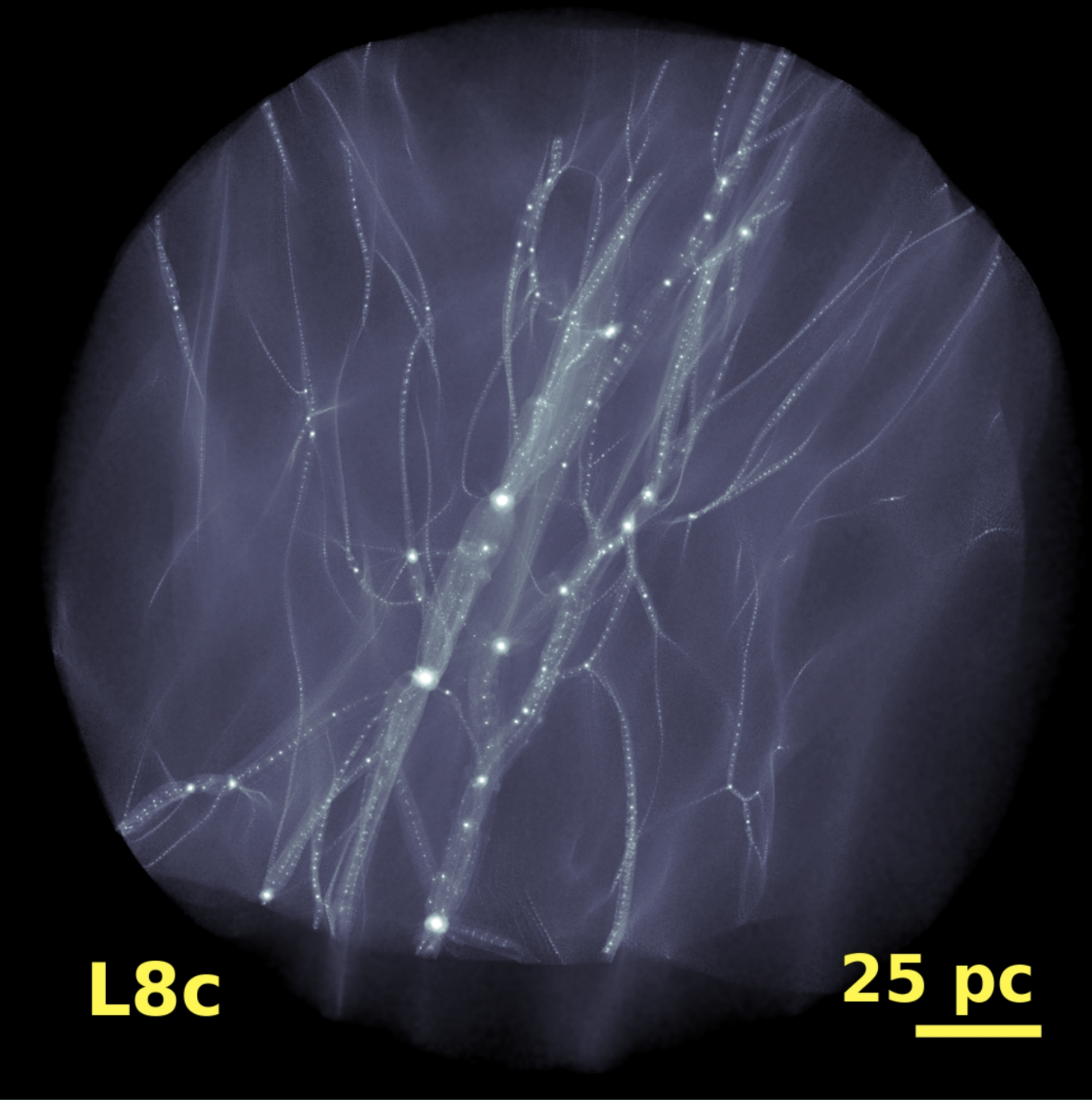
Dark matter only

Dynamic range of 30 orders of magnitude in mass

$M_{char} = 10^{-4}\ M_{\odot}$

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

$M_{char} = 10^{-6}\ M_{\odot}$

Zoom Level 8

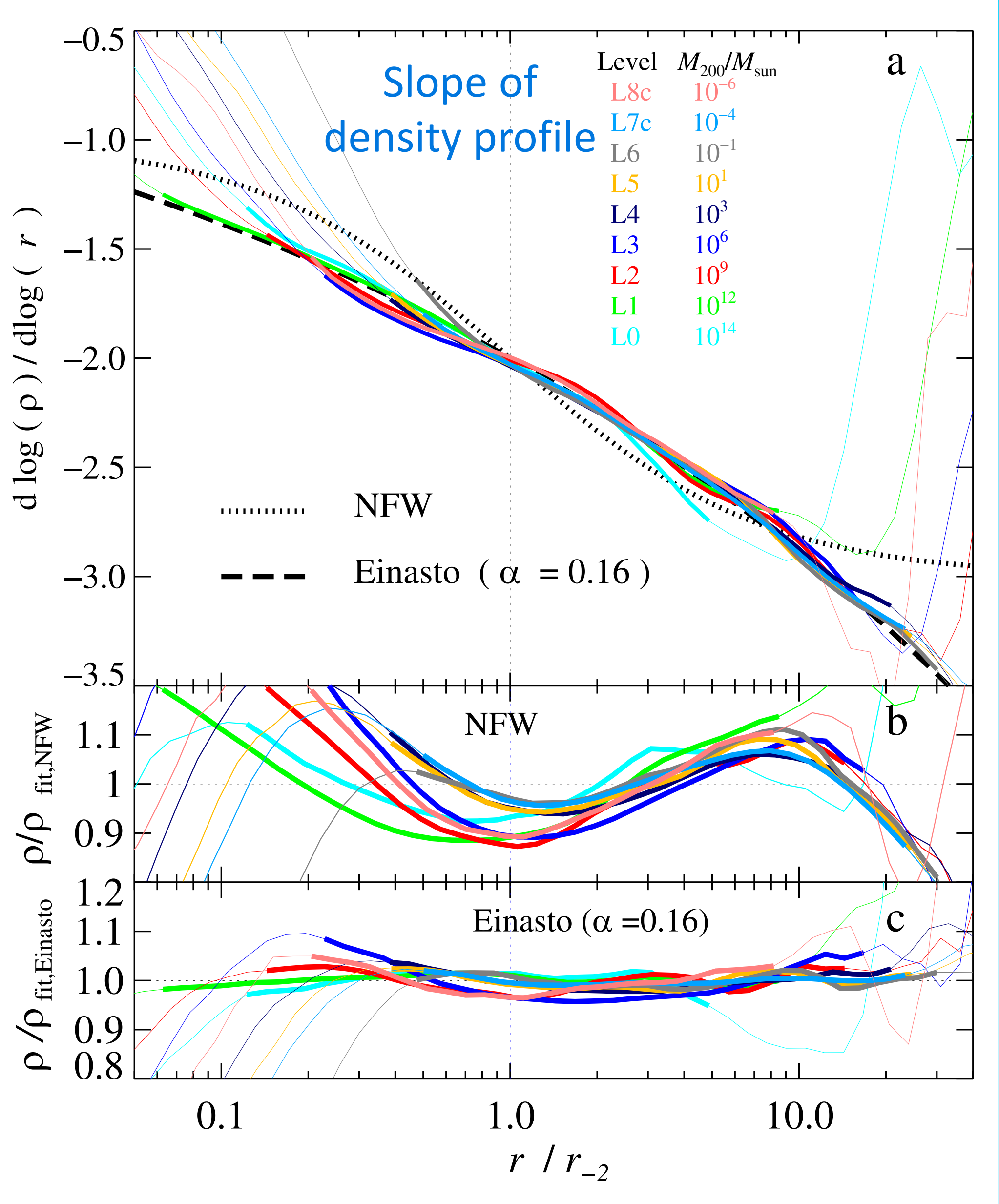
The density of this region is only ~3% of the cosmic mean

Wang, Bose et al 2020

Density profile shapes

University of Durham

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 (α =0.16) to within 7%



Wang, Bose, CSF + ‘20

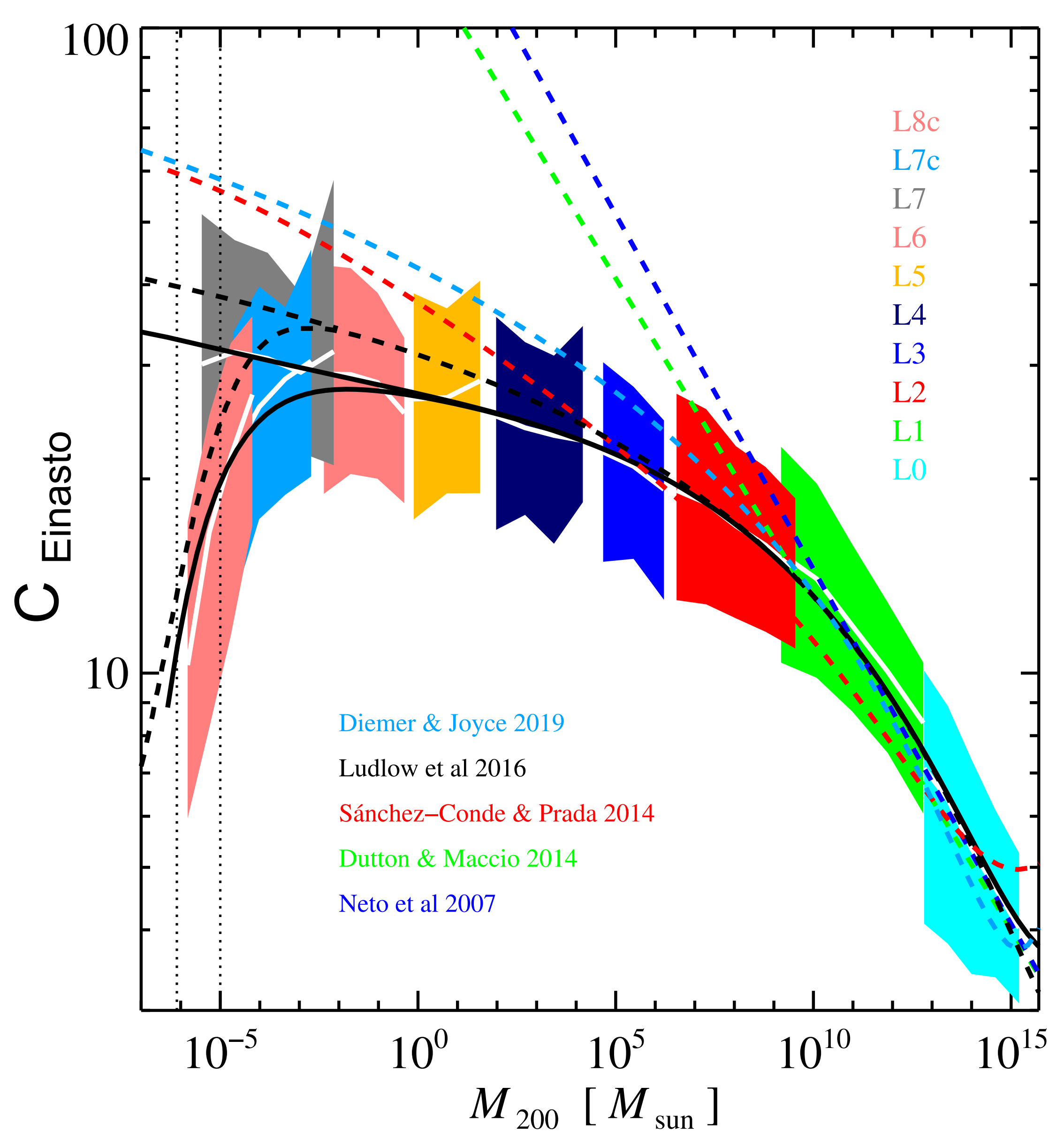
University of Durham

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



Wang, Bose, CSF + ‘20

Annihilation luminosity

University of Durham

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

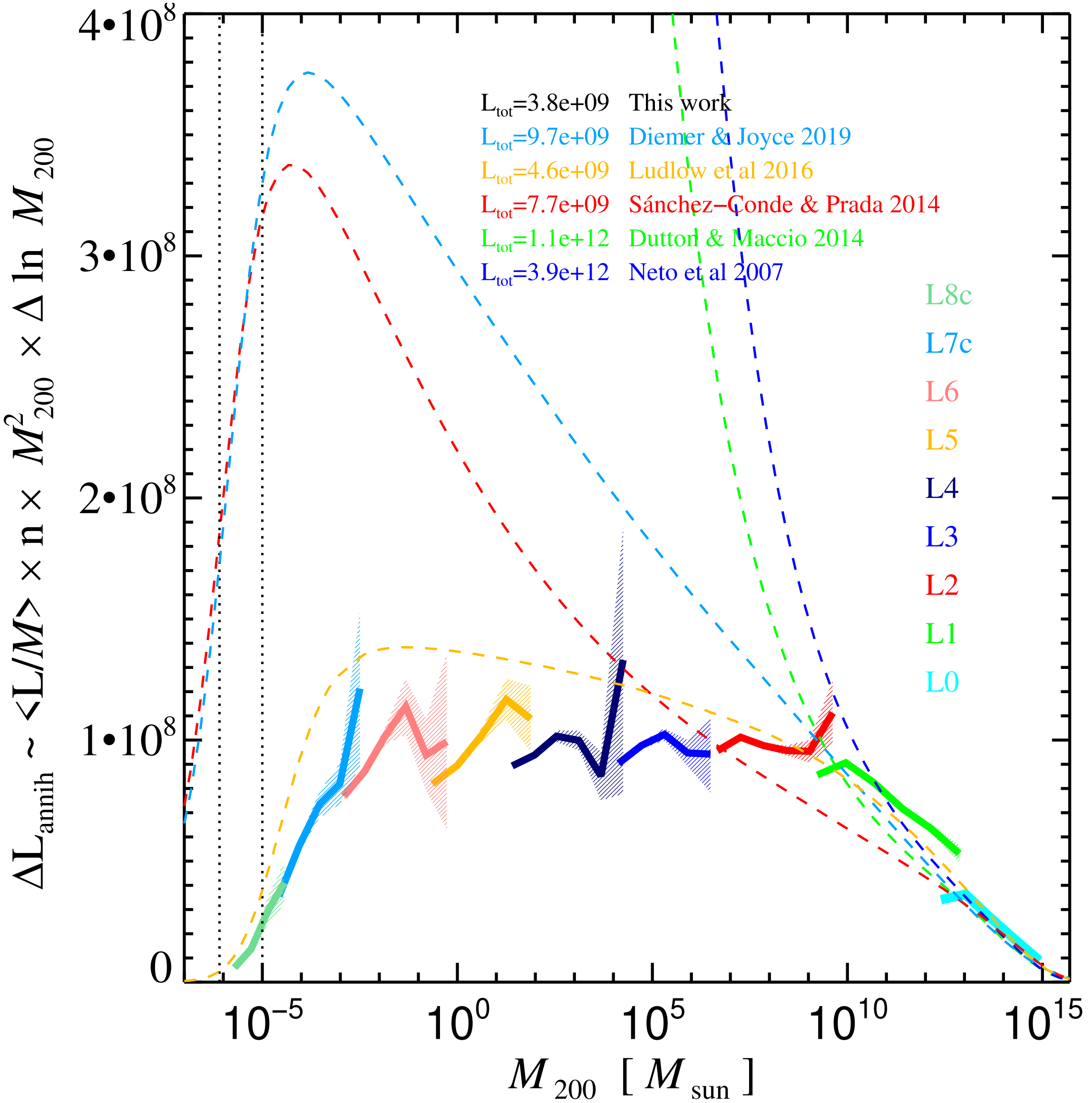
$10^{-4}\ M_\odot < M_{halo} < 10^{12}\ M_\odot$

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

This still neglects the substructure contribution to halo luminosity

Wang, Bose, CSF + '20

Annihilation luminosity per unit cosmological volume



Conclusions

- A dark matter halo mass function extending to ~Earth mass is a fundamental prediction of CDM.

1. CDM makes many small subhalos but most ($<3.10^8 M_0$) are dark → No satellite problem in CDM or WDM
2. Distortions of strong gravitational lenses are clean test of CDM *vs* WDM → and can potentially rule out CDM
3. CDM halos of all masses have NFW profiles
4. Very small halos can dominate annihilation luminosity