Dark matter halos

-- a conclusive test of cold dark matter

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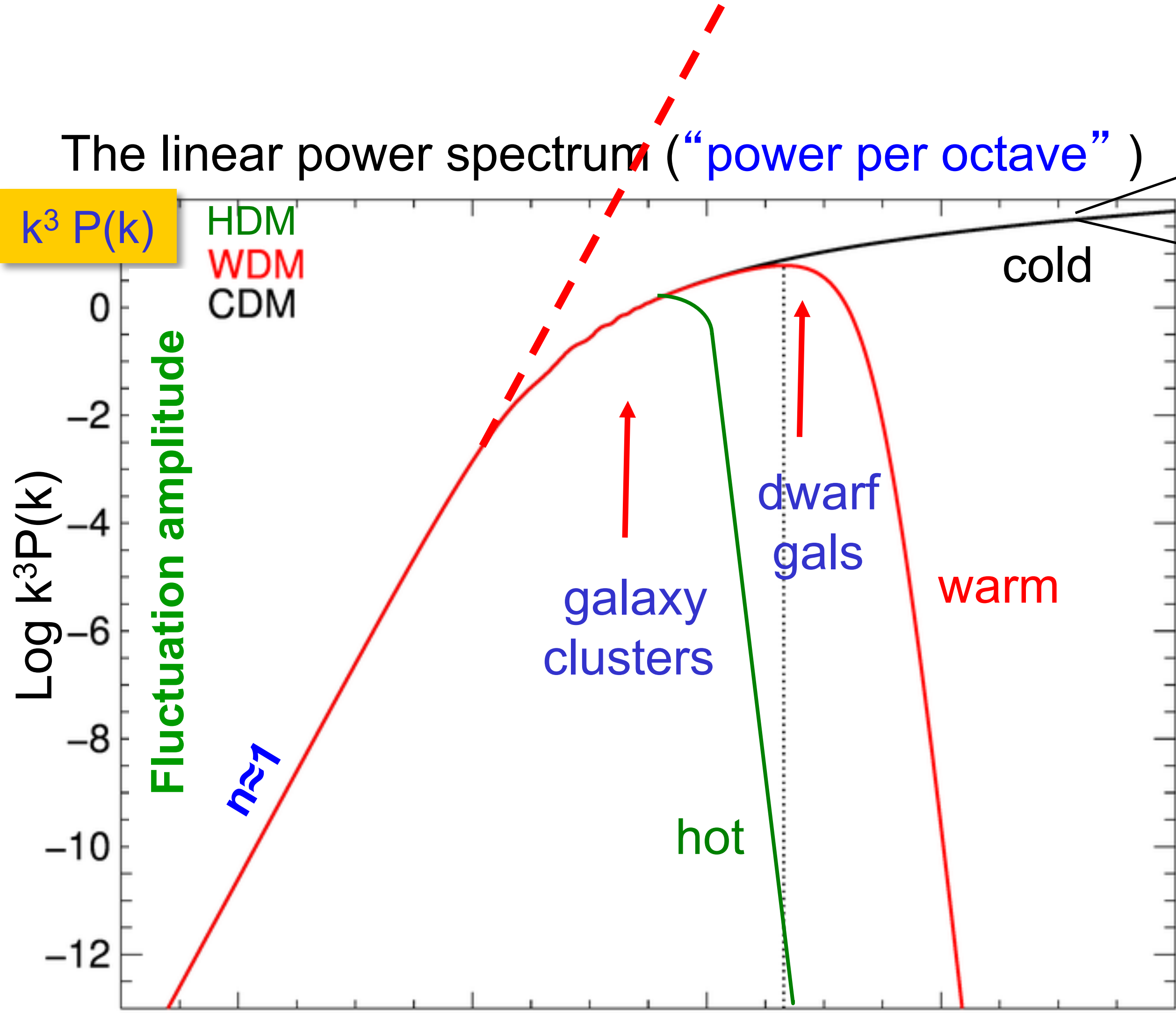
Non-baryonic dark matter candidates

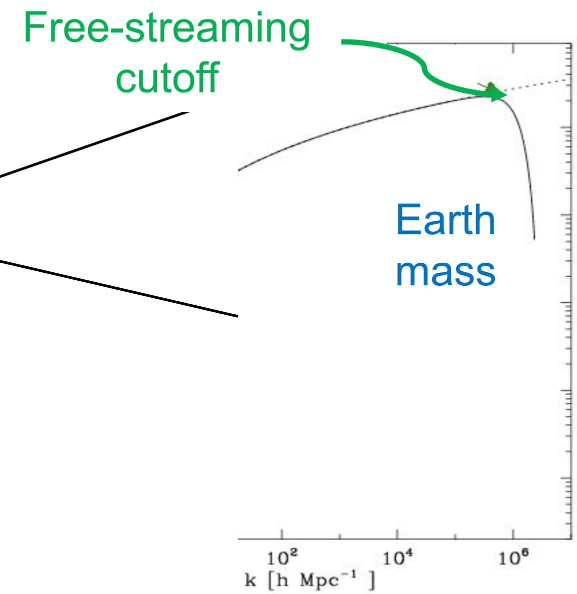
From the early 1980s:

Type	example	mass
hot	neutrino	few tens of eV
warm	sterile ν	keV-MeV
cold	axion neutralino	10^{-5}eV - 100 GeV

The dark matter power spectrum

The linear power spectrum ("power per octave")





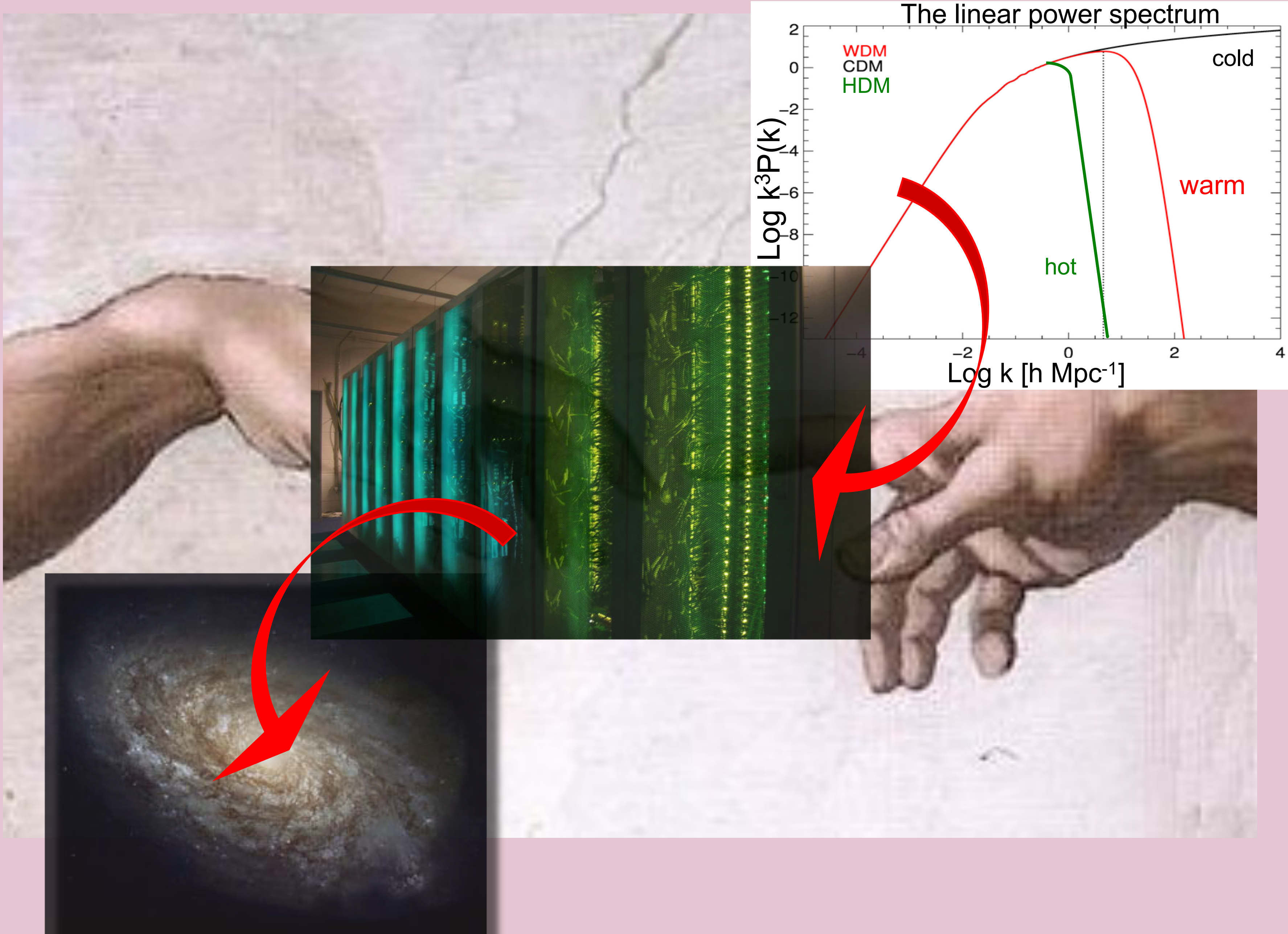
Free streaming →

$\lambda_{cut} \propto m_x^{-1}$

for a thermal relic

These possibilites can be tested with astrophysics

Non-linear evolution



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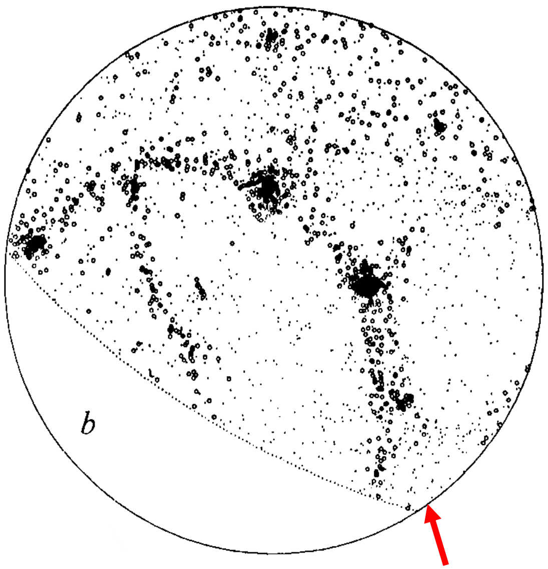
Non-baryonic dark matter cosmologies



Neutrinos
Ω=1

Frenk, White & Davis '83

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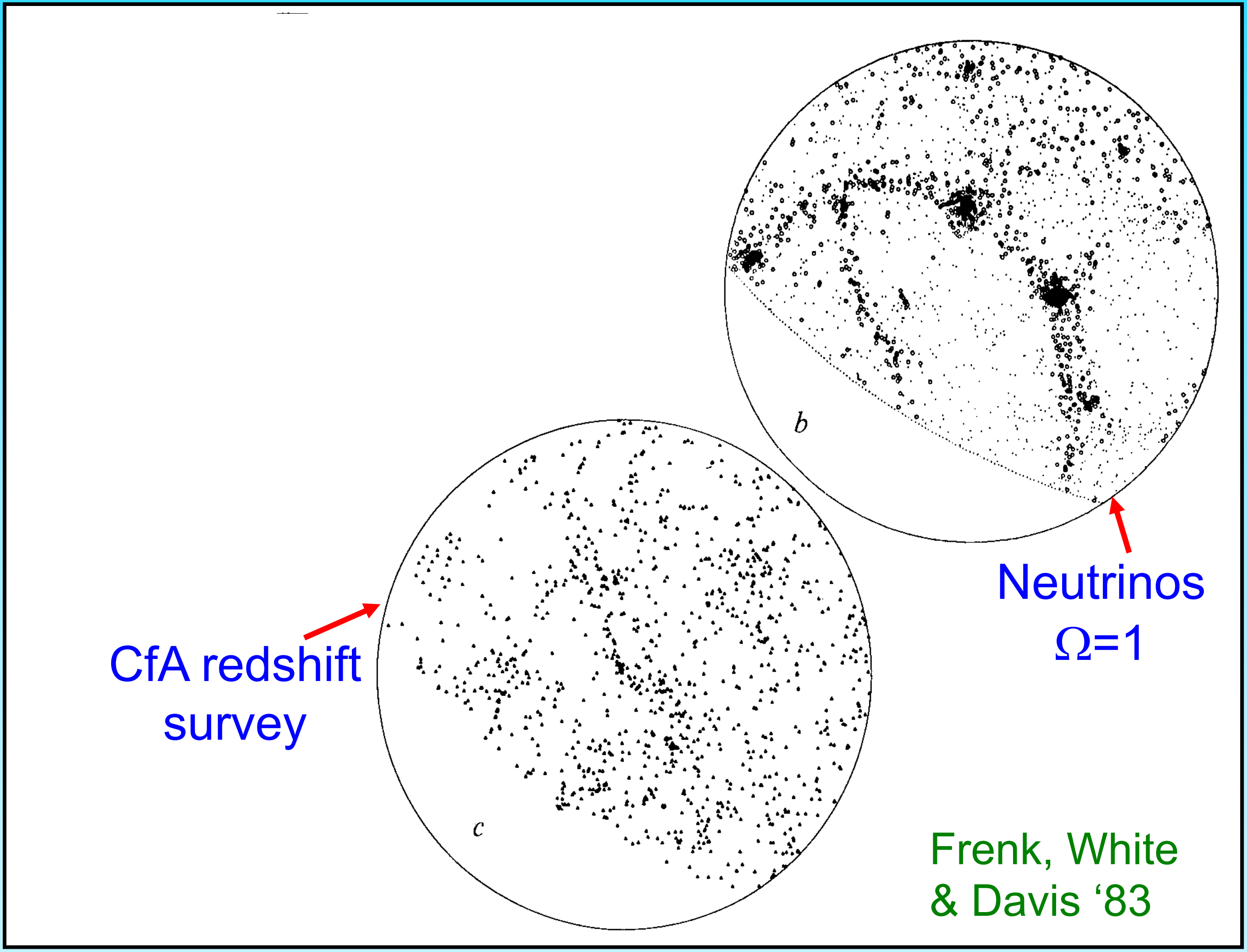
Non-baryonic dark matter cosmologies

Neutrino DM → wrong clustering

Neutrinos cannot make appreciable contribution to Ω

→ $m_\nu << 30$ ev



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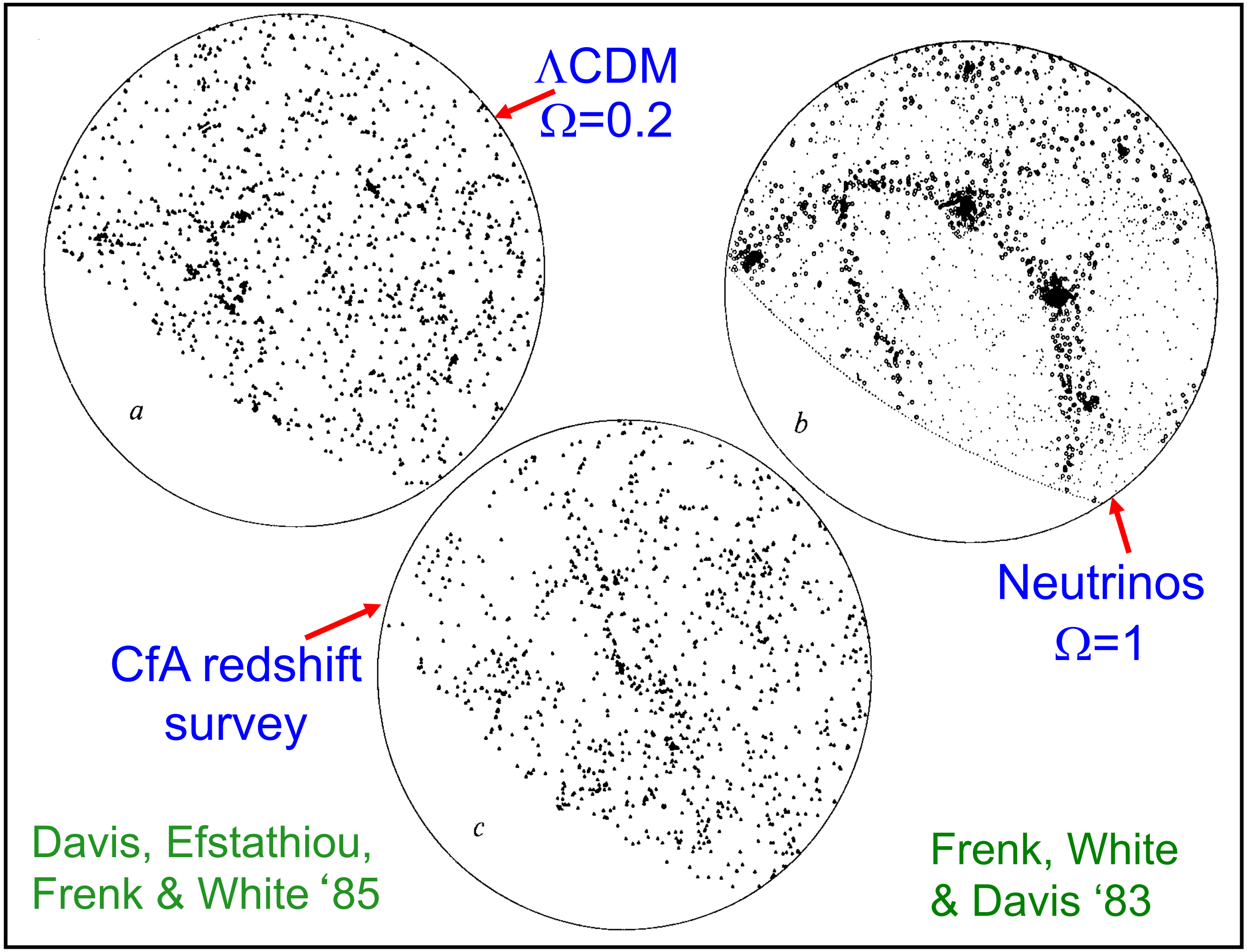
Non-baryonic dark matter cosmologies

Neutrino DM → wrong clustering

Neutrinos cannot make appreciable contribution to Ω → $m_\nu << 30$ ev

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically



Formation of CDM halos

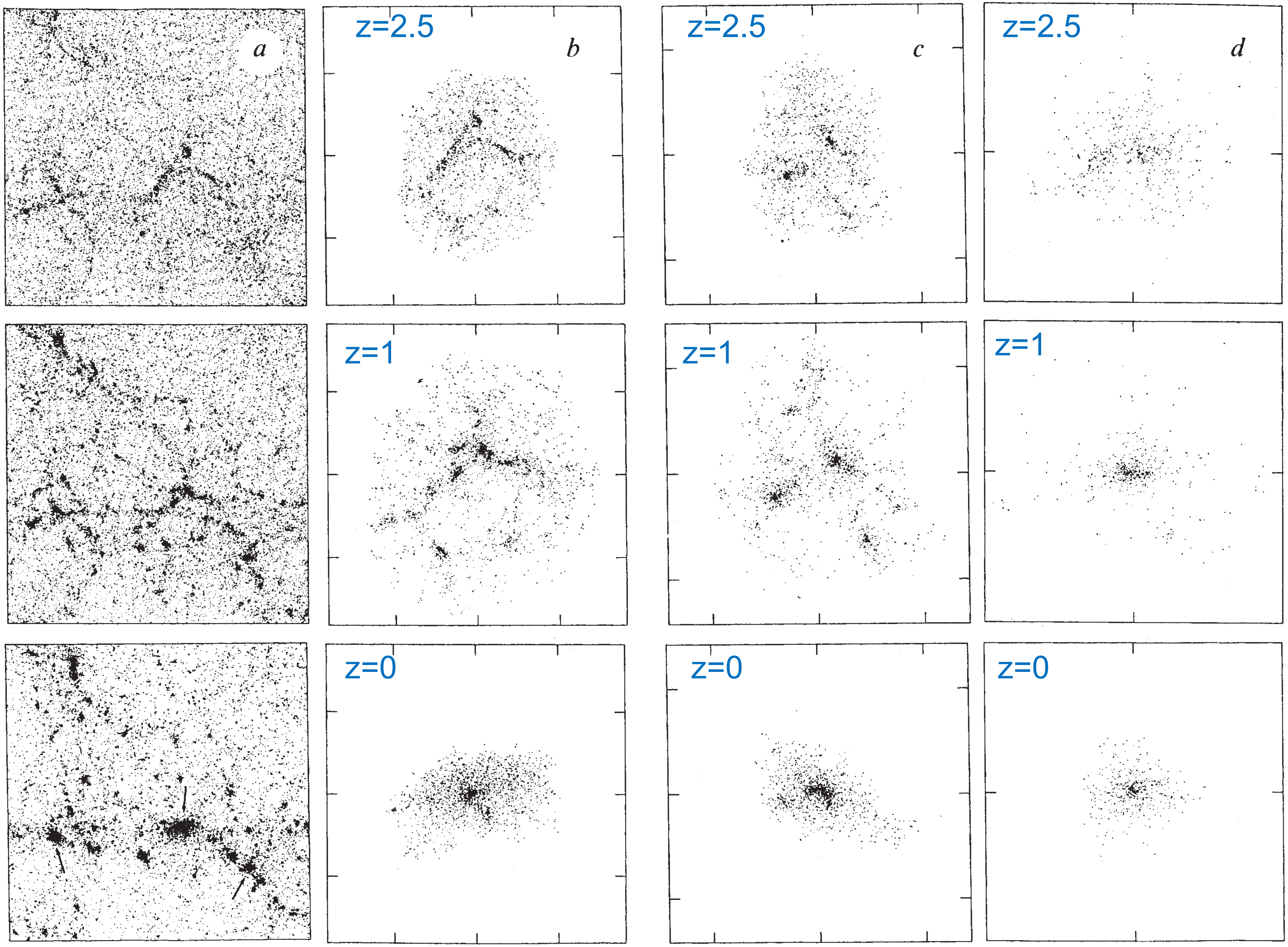
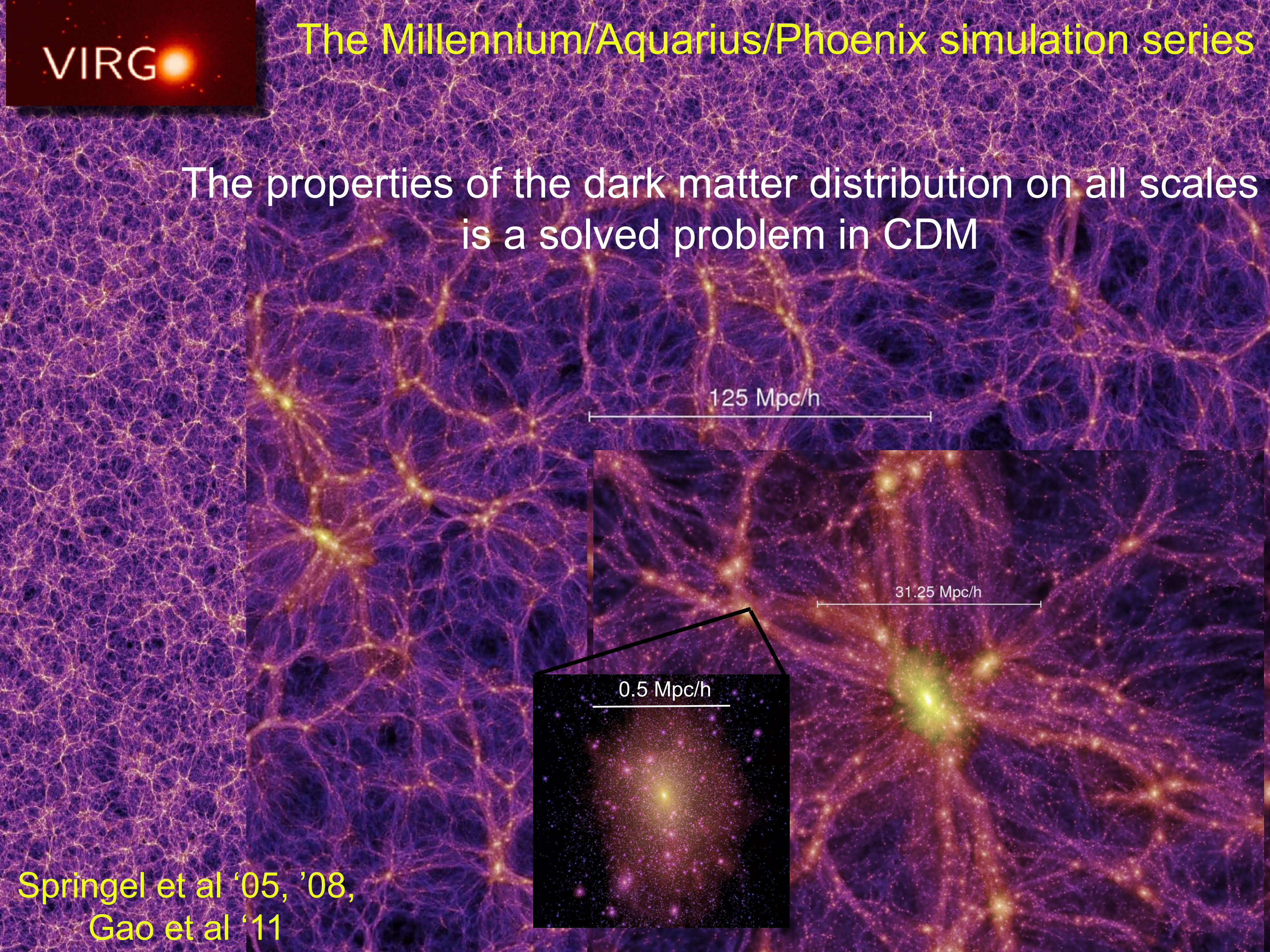
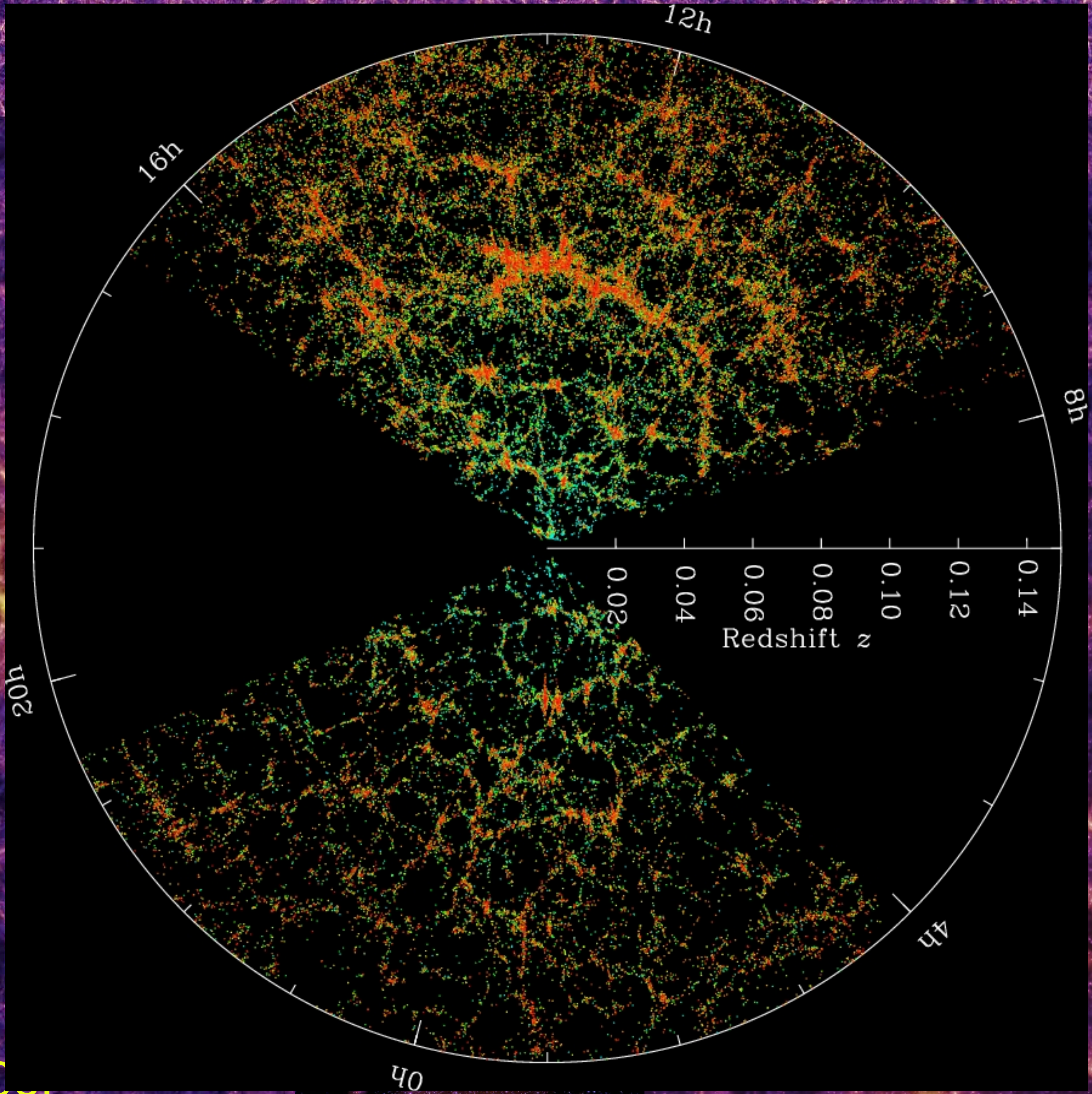


Fig. 1

Frenk et al 1985


VIRGO
The Millennium/Aquarius/Phoenix simulation series
The properties of the dark matter distribution on all scales is a solved problem in CDM
125 Mpc/h
31.25 Mpc/h
0.5 Mpc/h
Springel et al '05, '08, Gao et al '11

The Millennium/Aquarius/Phoenix simulation series



Springel et al '05, '0[illegible];
Gao et al '11

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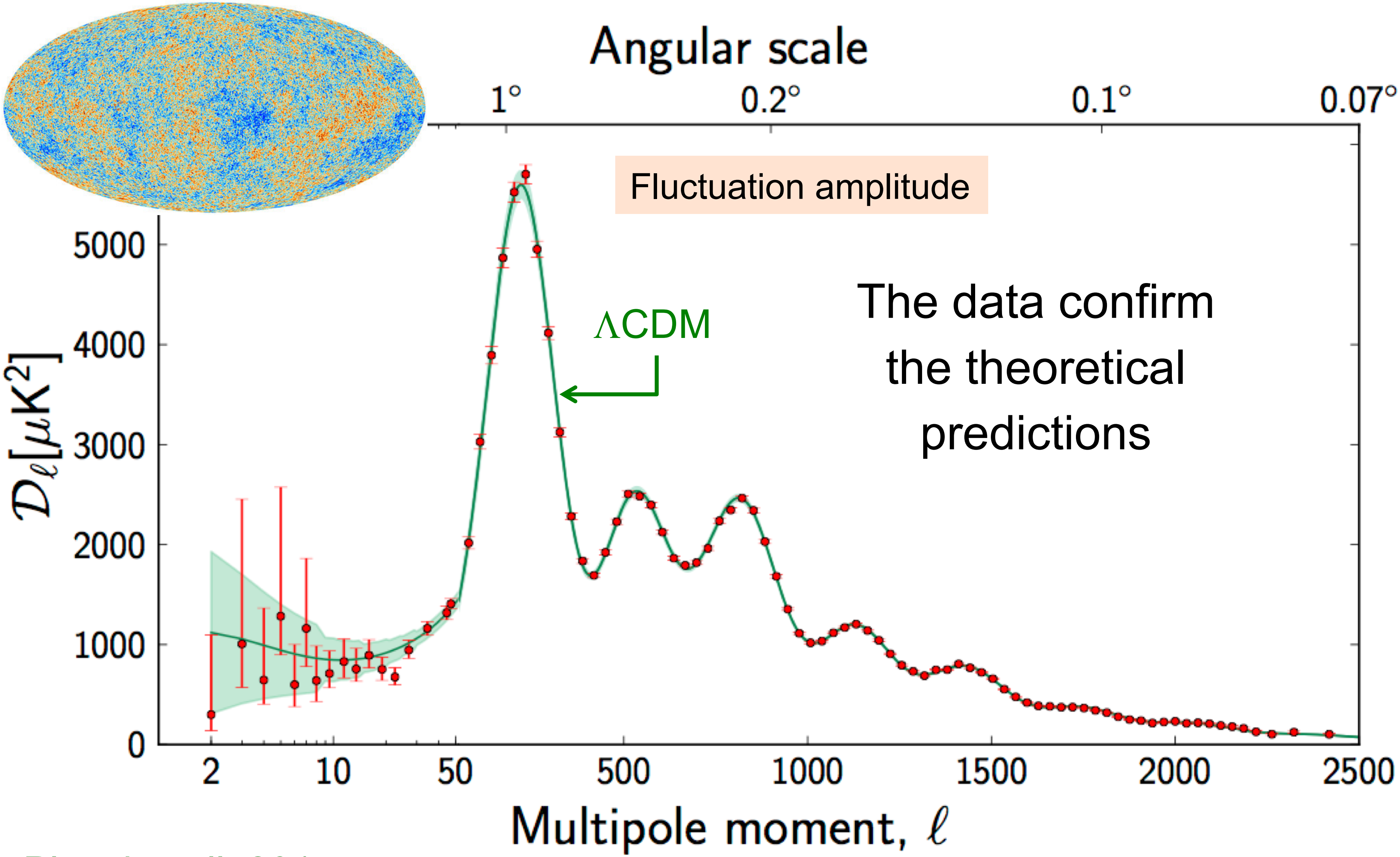
Planck: CMB temperature anisotropies



Planck coll. 2015

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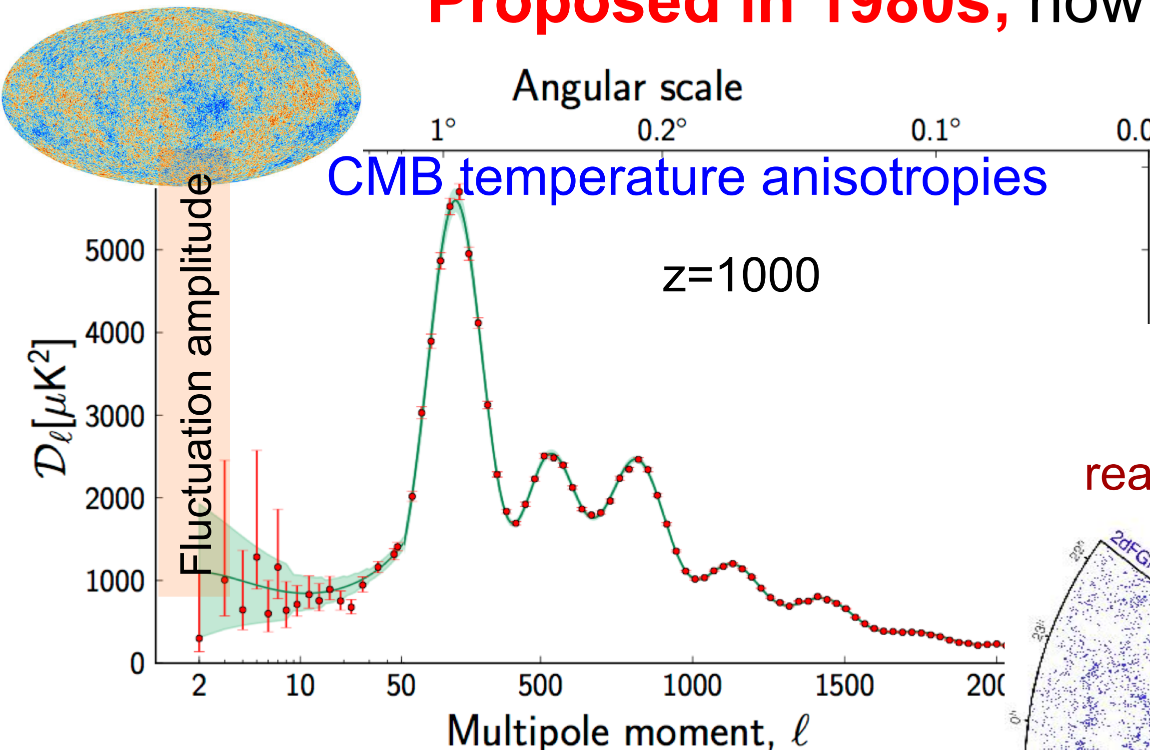
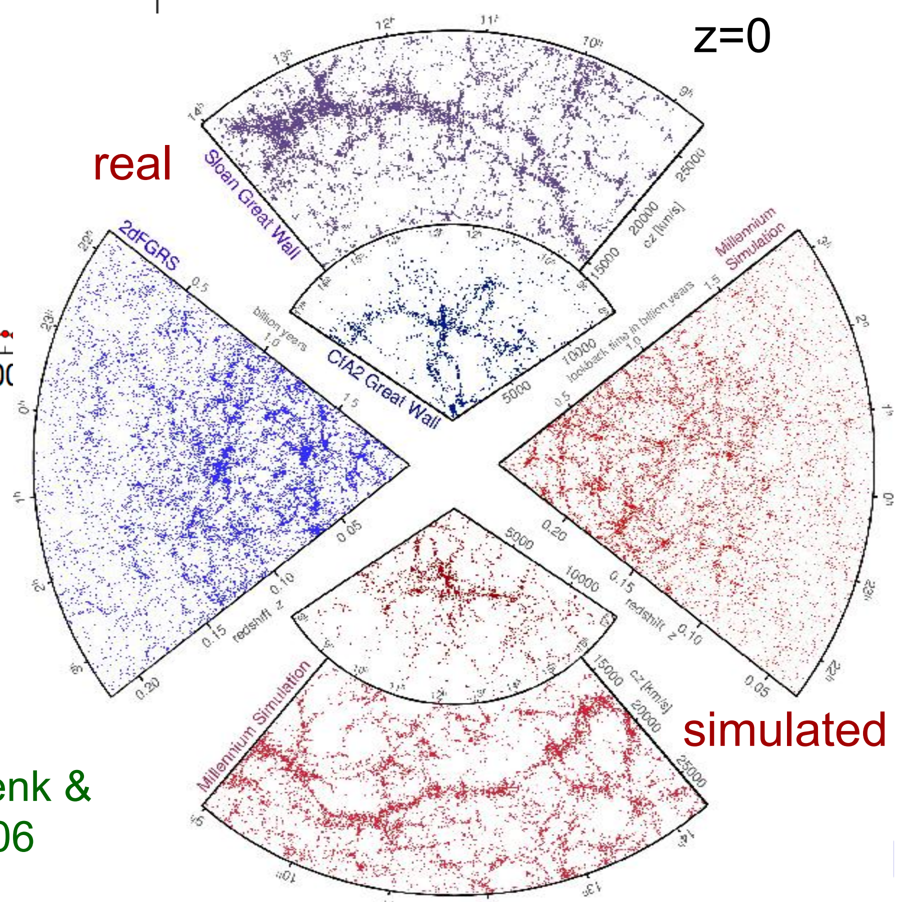
The ΛCDM model of cosmogony

Proposed in 1980s; now empirically supported by:



Planck coll. 2015

Galaxy clustering



Springel, Frenk & White 2006

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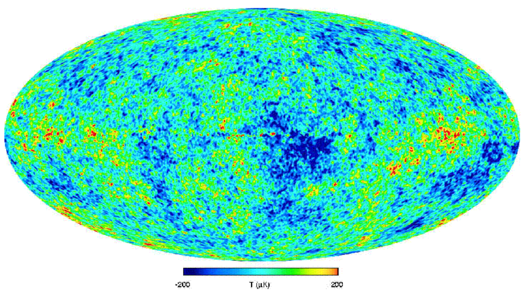
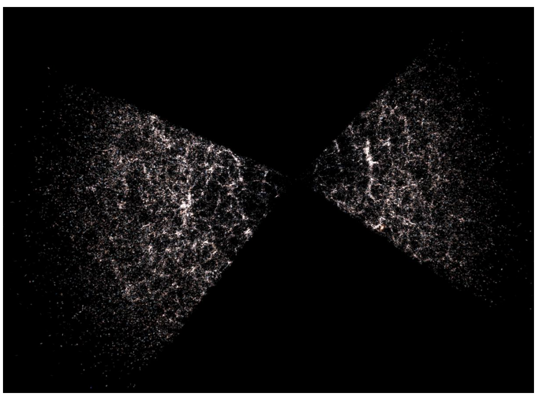
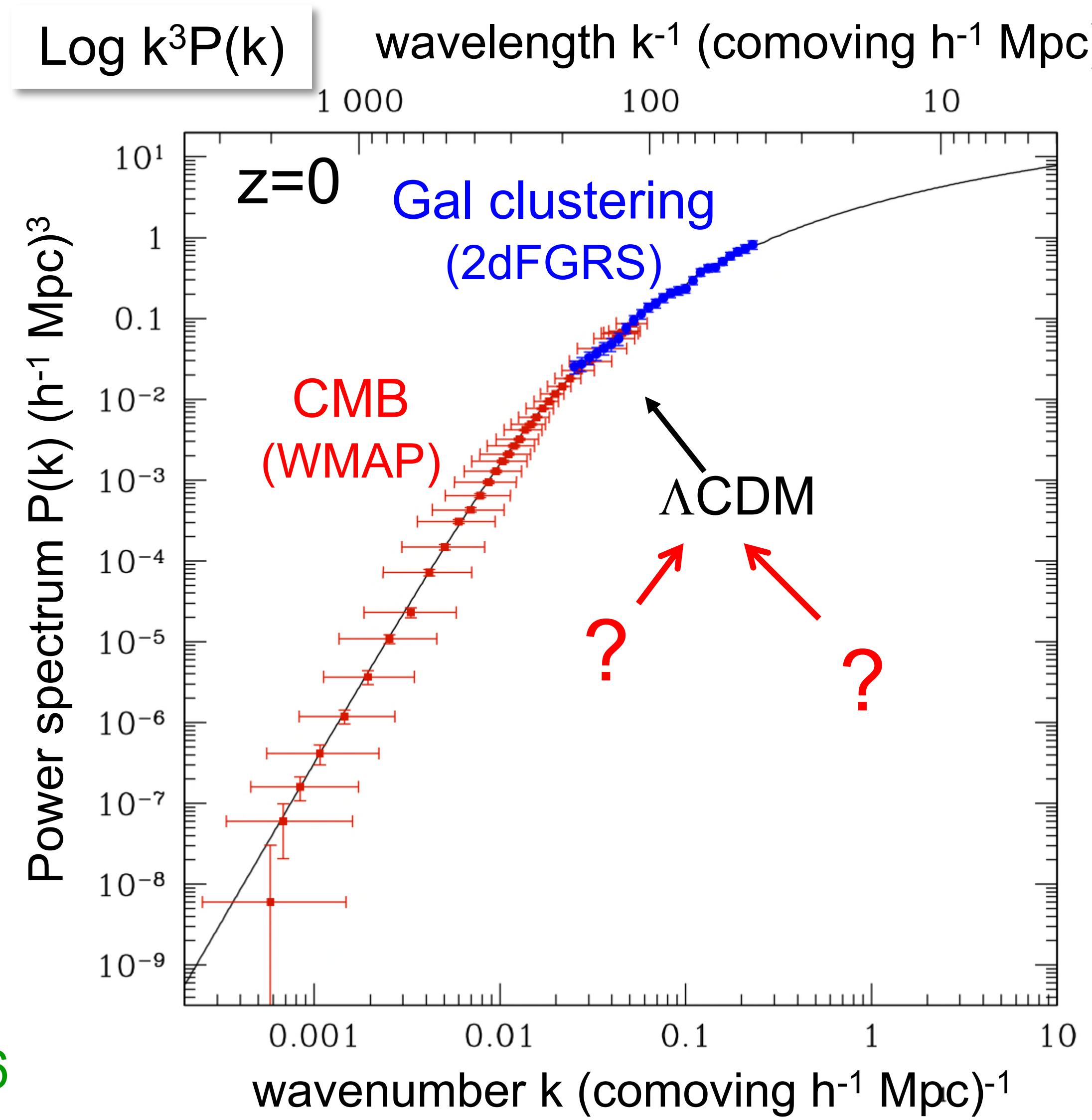
The cosmic power spectrum: from the CMB to the 2dFGRS



z~1000



z~0



⇒ ΛCDM provides an excellent description of mass power spectrum from 10-1000 Mpc

Sanchez et al 06

The cosmic power spectrum: from the CMB to the 2dFGRS

Free streaming →

$\lambda_{cut} \propto m_x^{-1}$

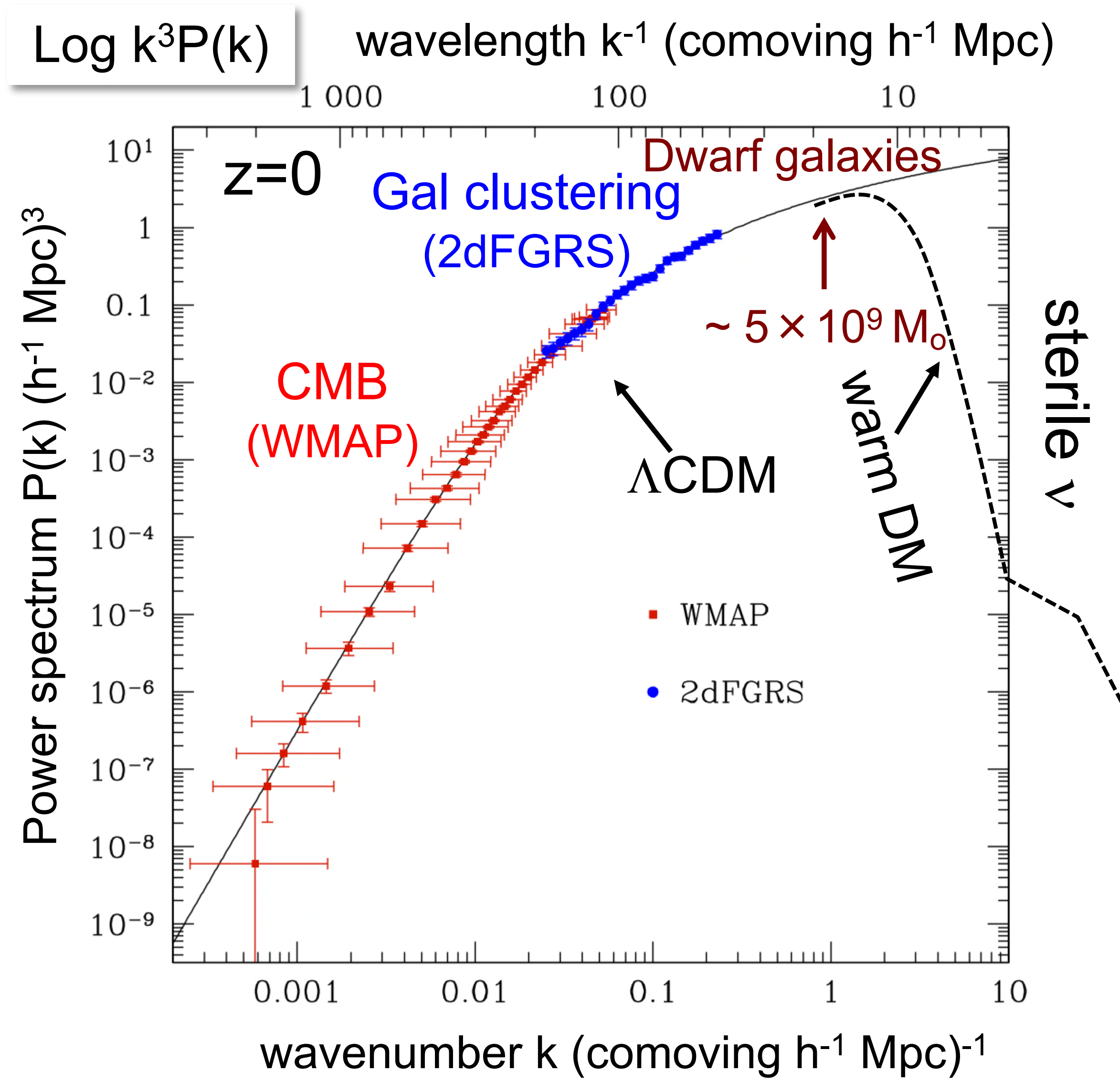
for thermal relic

$m_{CDM} \sim 100GeV$

susy; $M_{cut} \sim 10^{-6}\ M_o$

$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^{9}\ M_o$



Sterile neutrinos

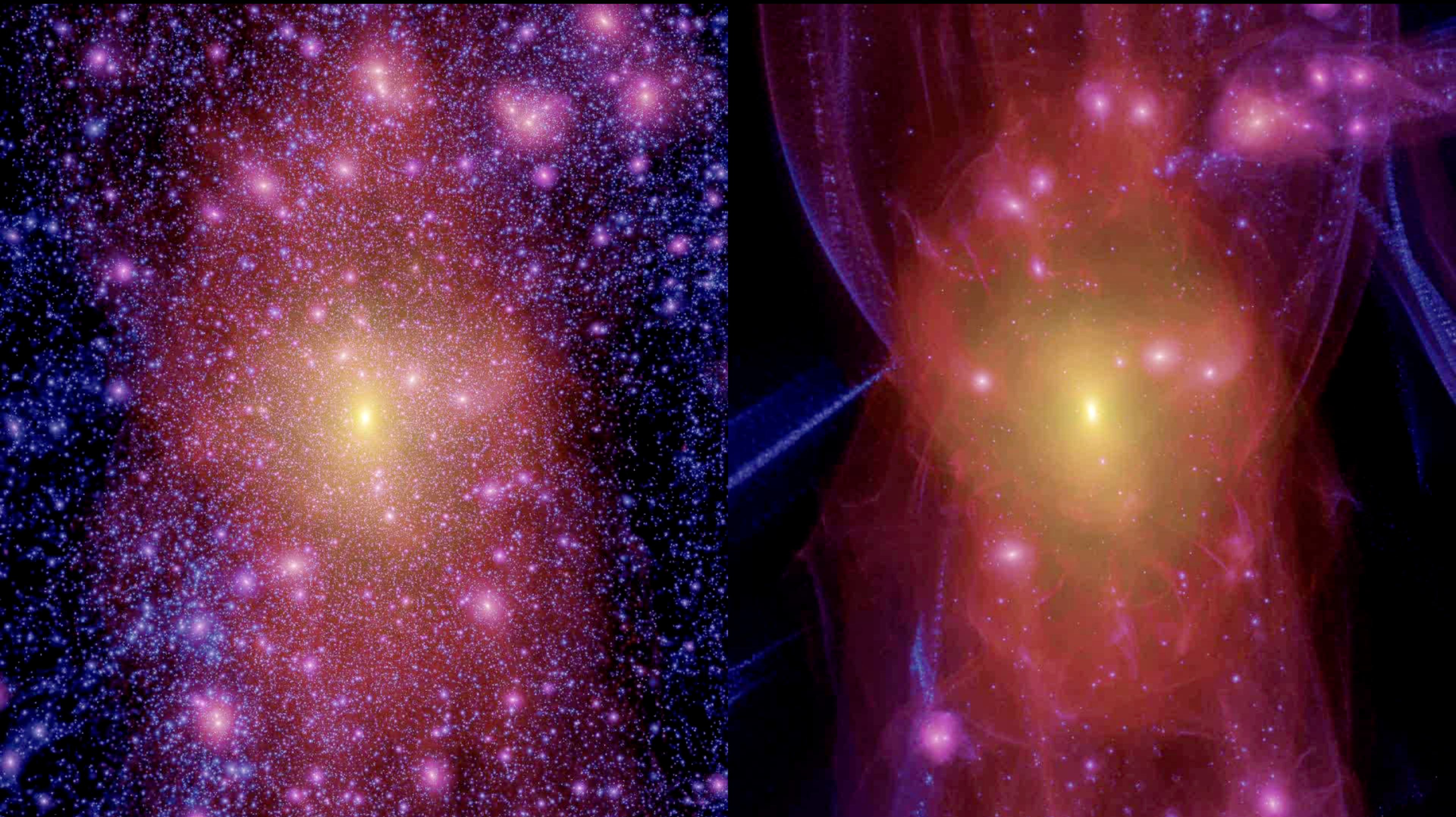
Explain:

- Neutrino oscillations and masses
- Baryogenesis
- Absence of right-handed neutrinos in standard model
- Dark matter

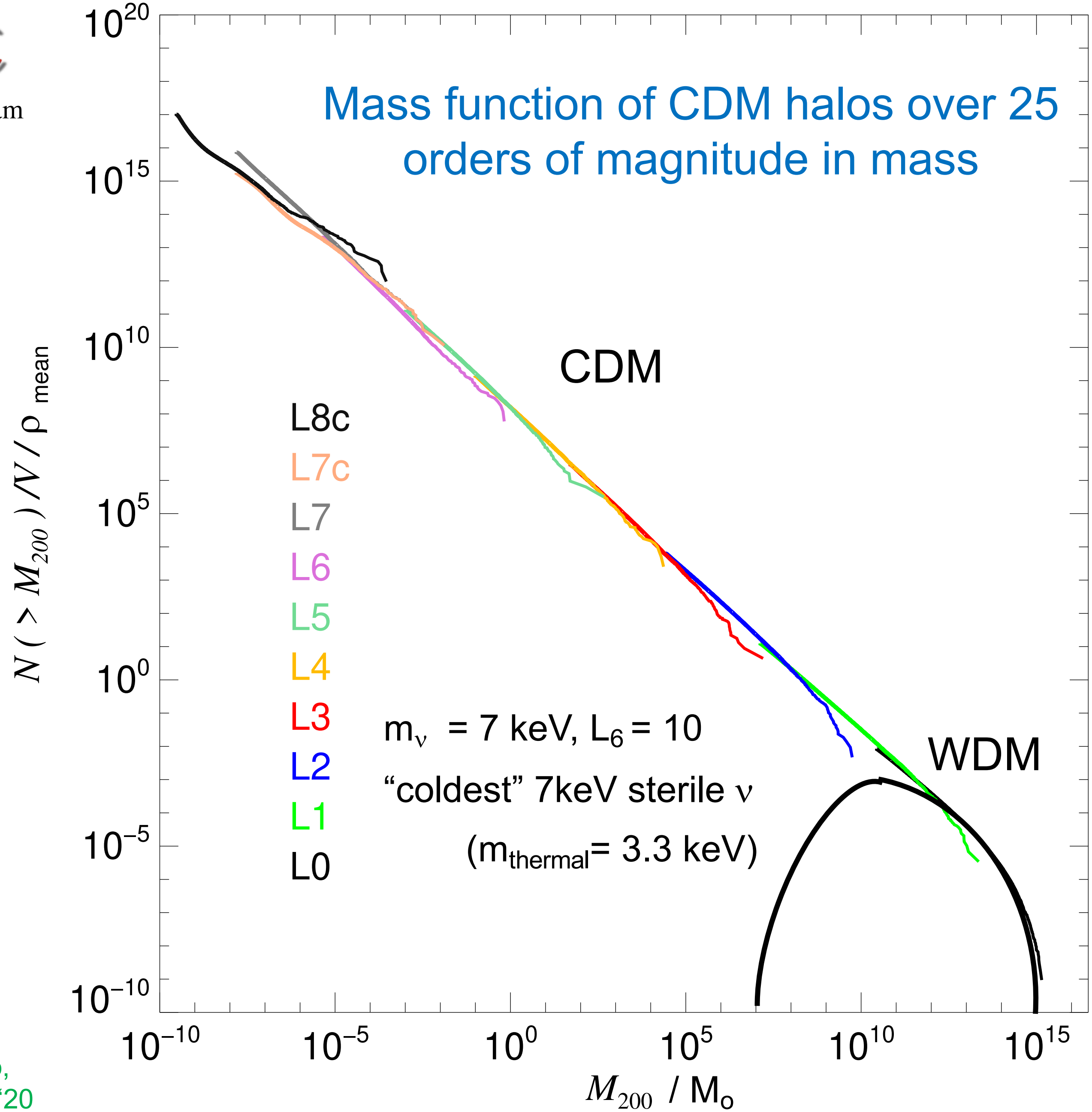
Sterile neutrino minimal standard model (νMSM; Boyarski+ 09):

- Extension of SM w. 3 sterile neutrinos: 2 of GeV; 1 of keV mass
- If $\Omega_N=\Omega_{DM}$, 2 parameters: mass, lepton asymmetry/mixing angle
- GeV particles may be detected at CERN (SHiP)
- Dark matter candidate can be detected by X-ray decay

cold dark matter warm dark matter



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



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

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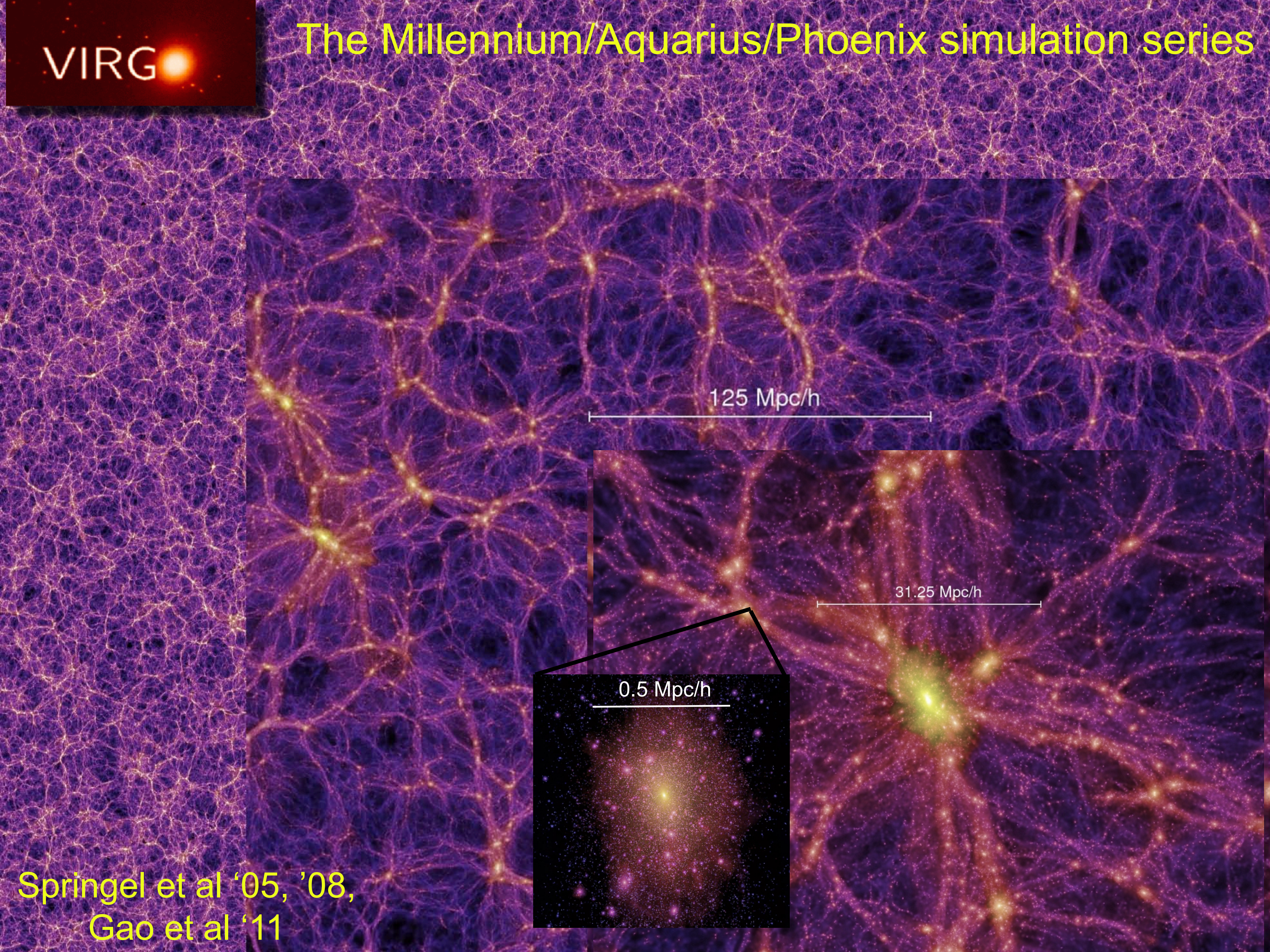
The abundance of dark matter halos of all masses in CDM

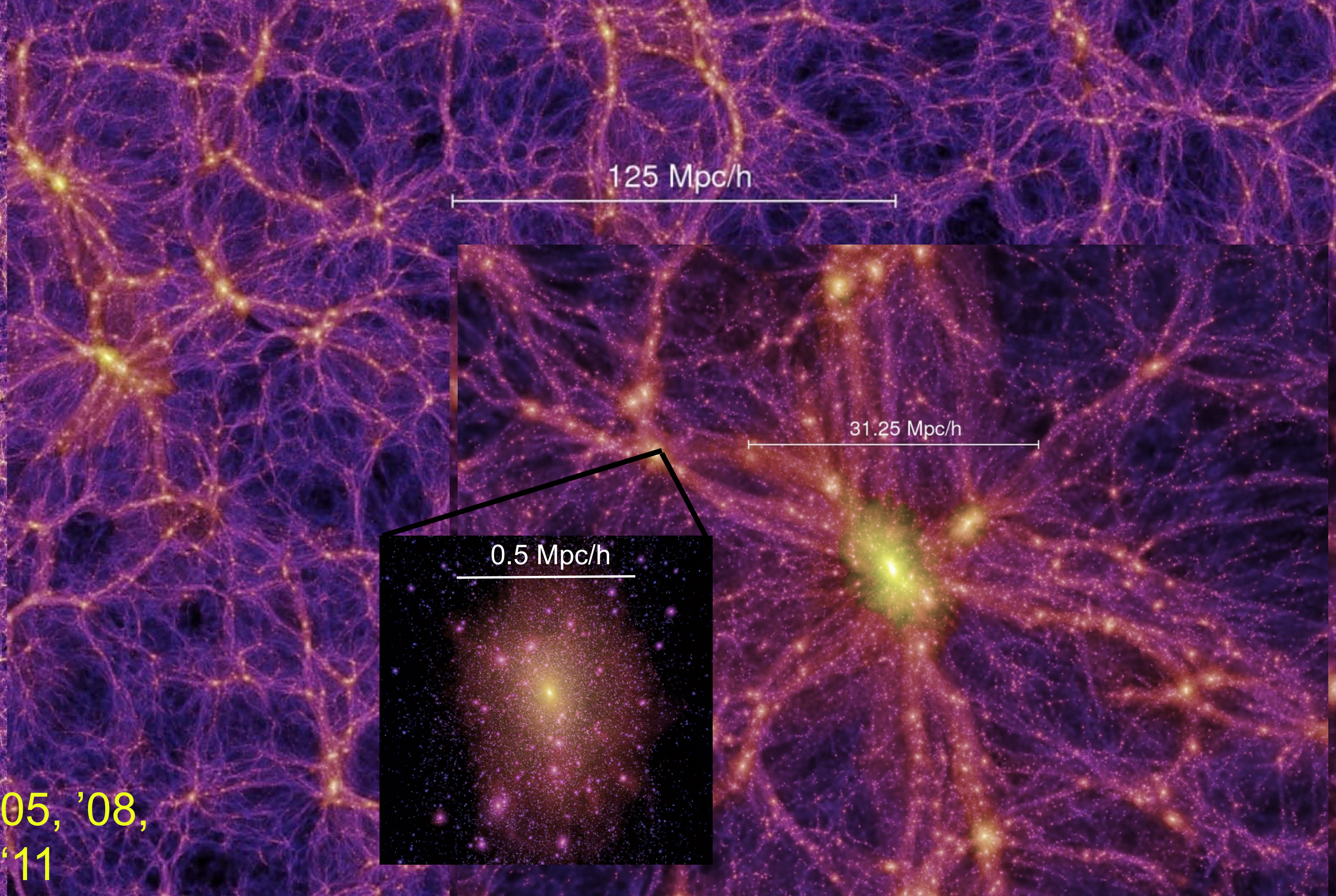
The Millennium/Aquarius/Phoenix simulation series



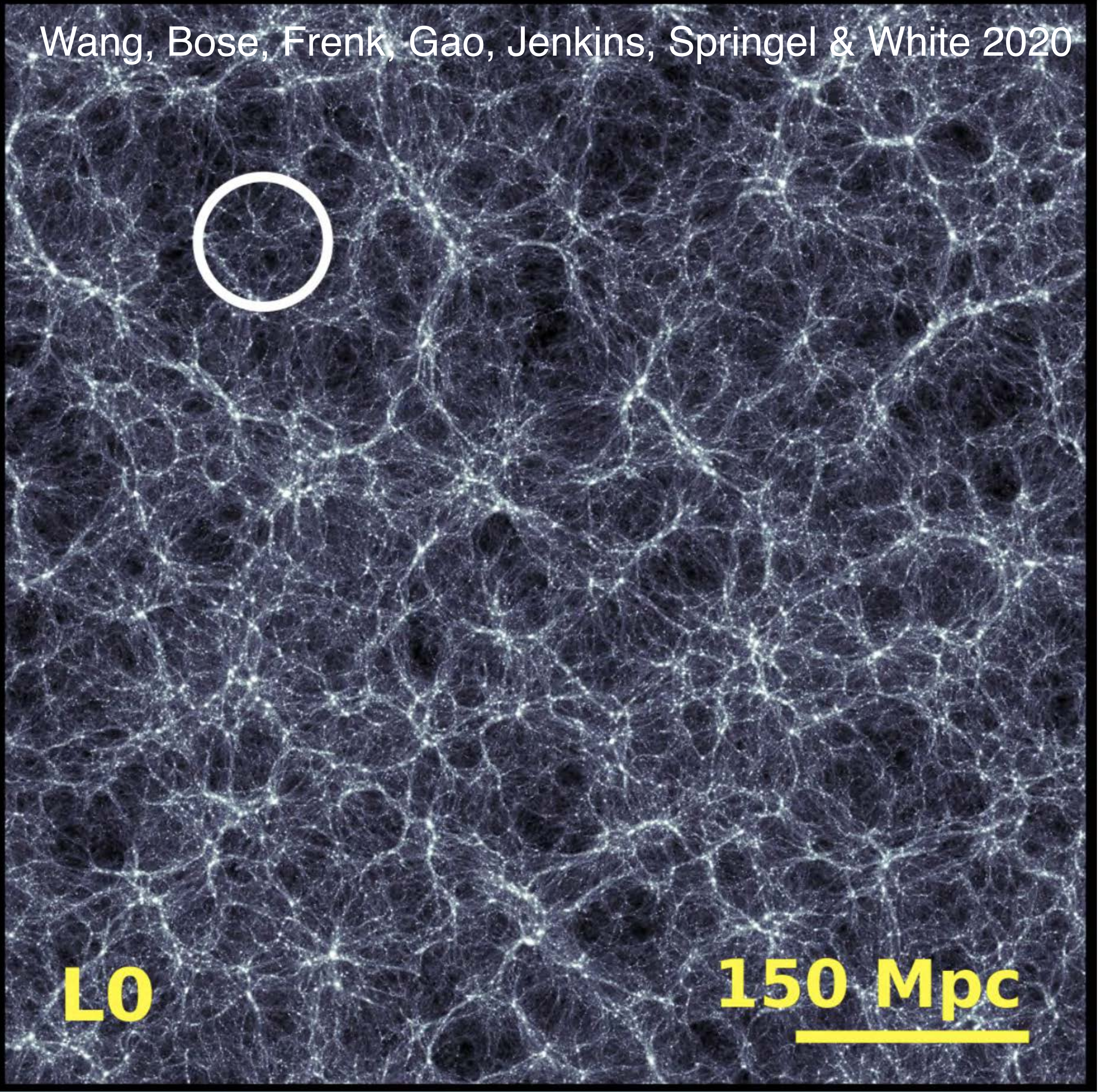
Springel et al ‘05, ’08,
Gao et al ‘11

The Millennium/Aquarius/Phoenix simulation series

To resolve Earth-mass halos in a cosmological simulation would require 10^{27} particles → impossible



Springel et al '05, '08,
Gao et al '11



The VVV simulation

Planck cosmology

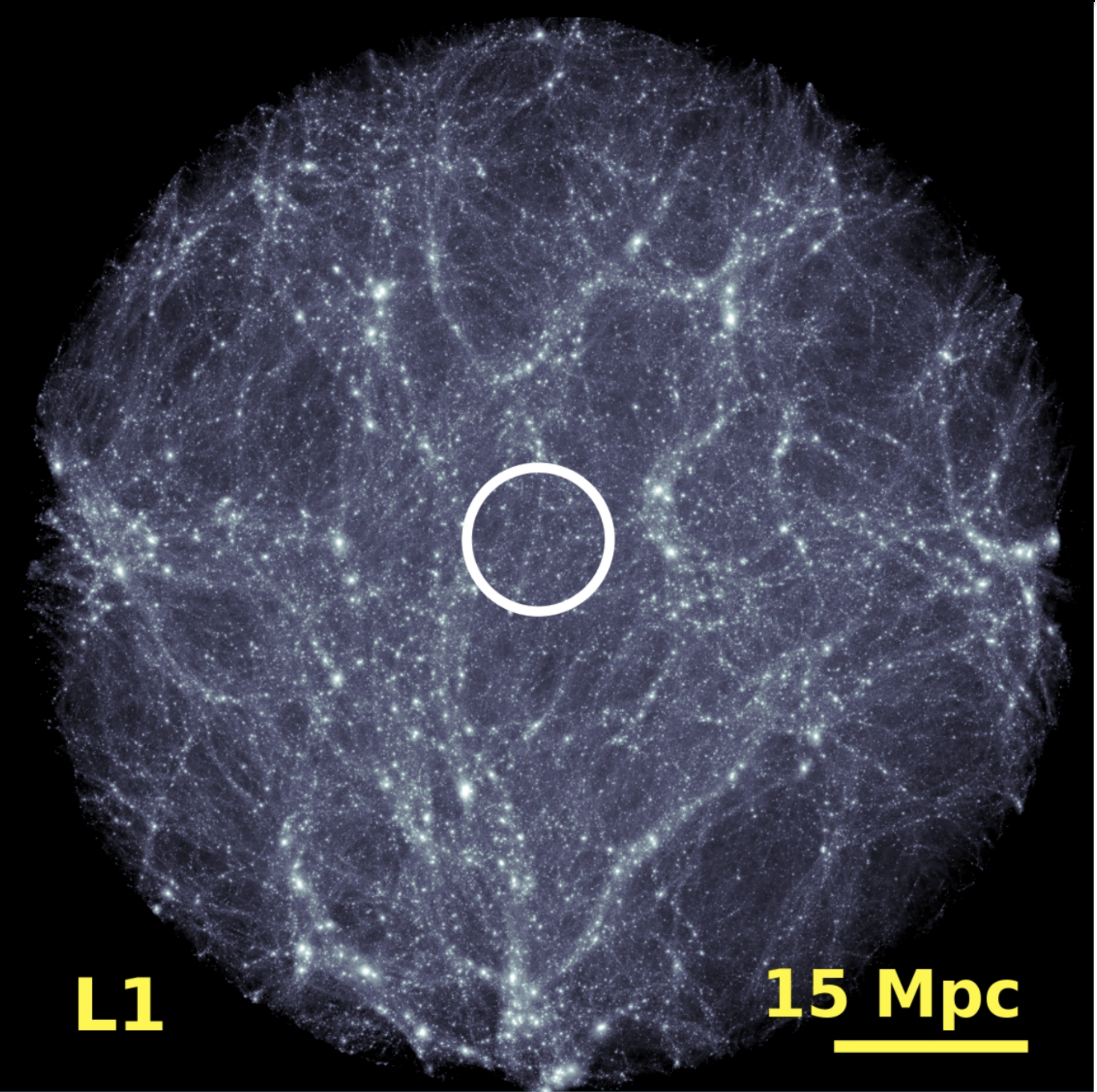
Dark matter only

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

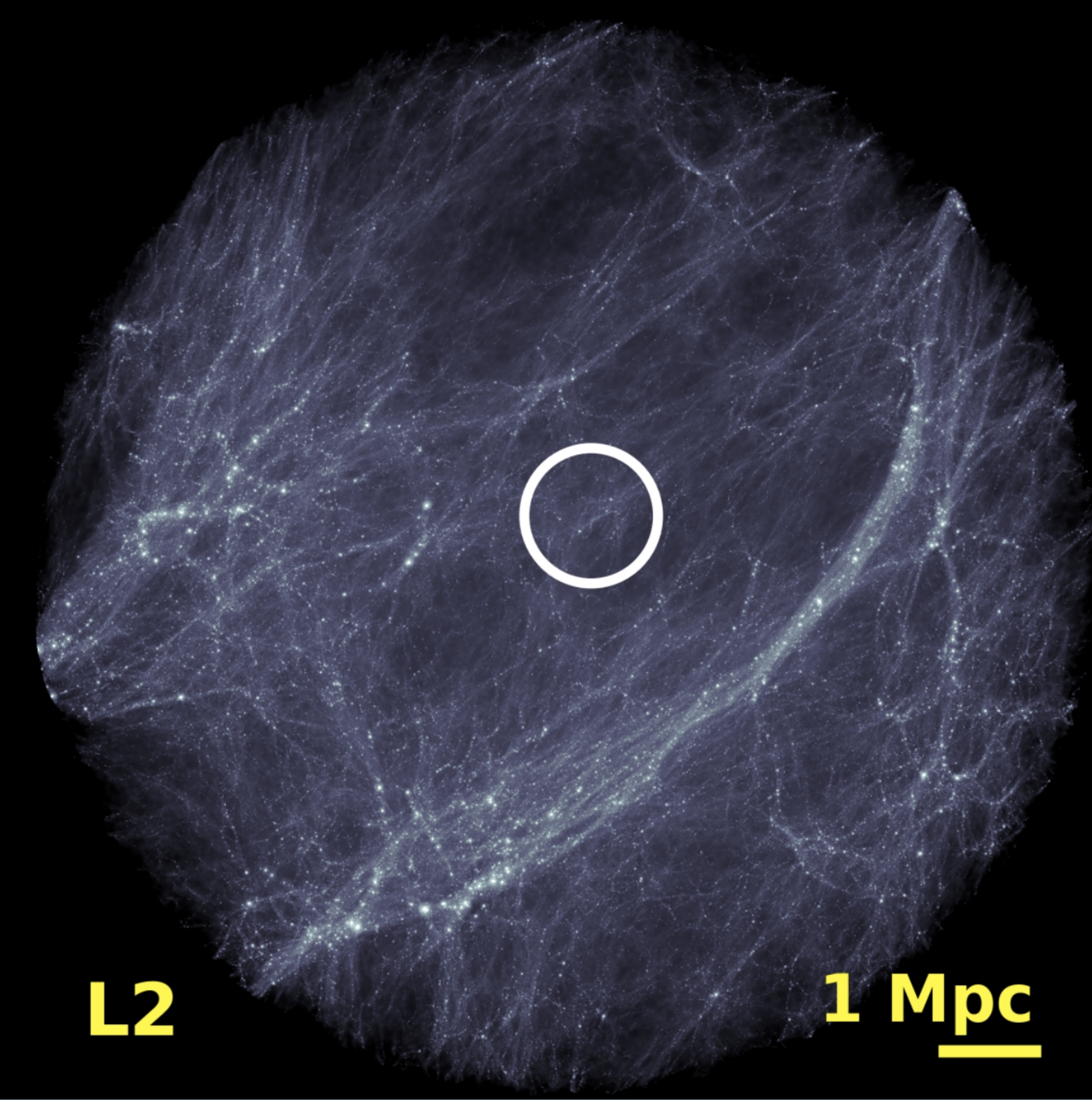
Dynamic range of 30 orders of magnitude in mass

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

Zoom Level 1

Wang, Bose et al 2020

The VVV simulation



Planck cosmology

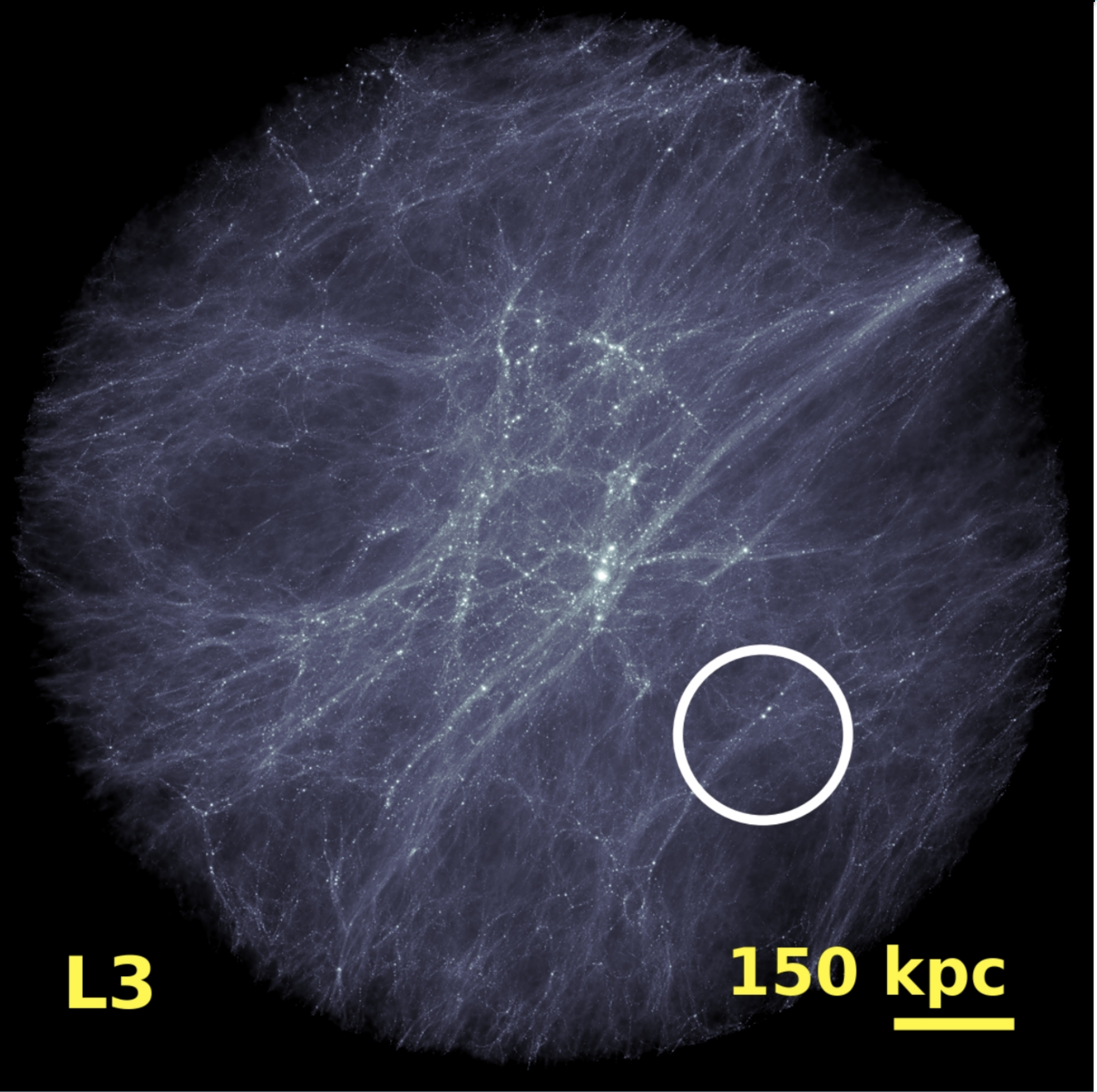
Dark matter only

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

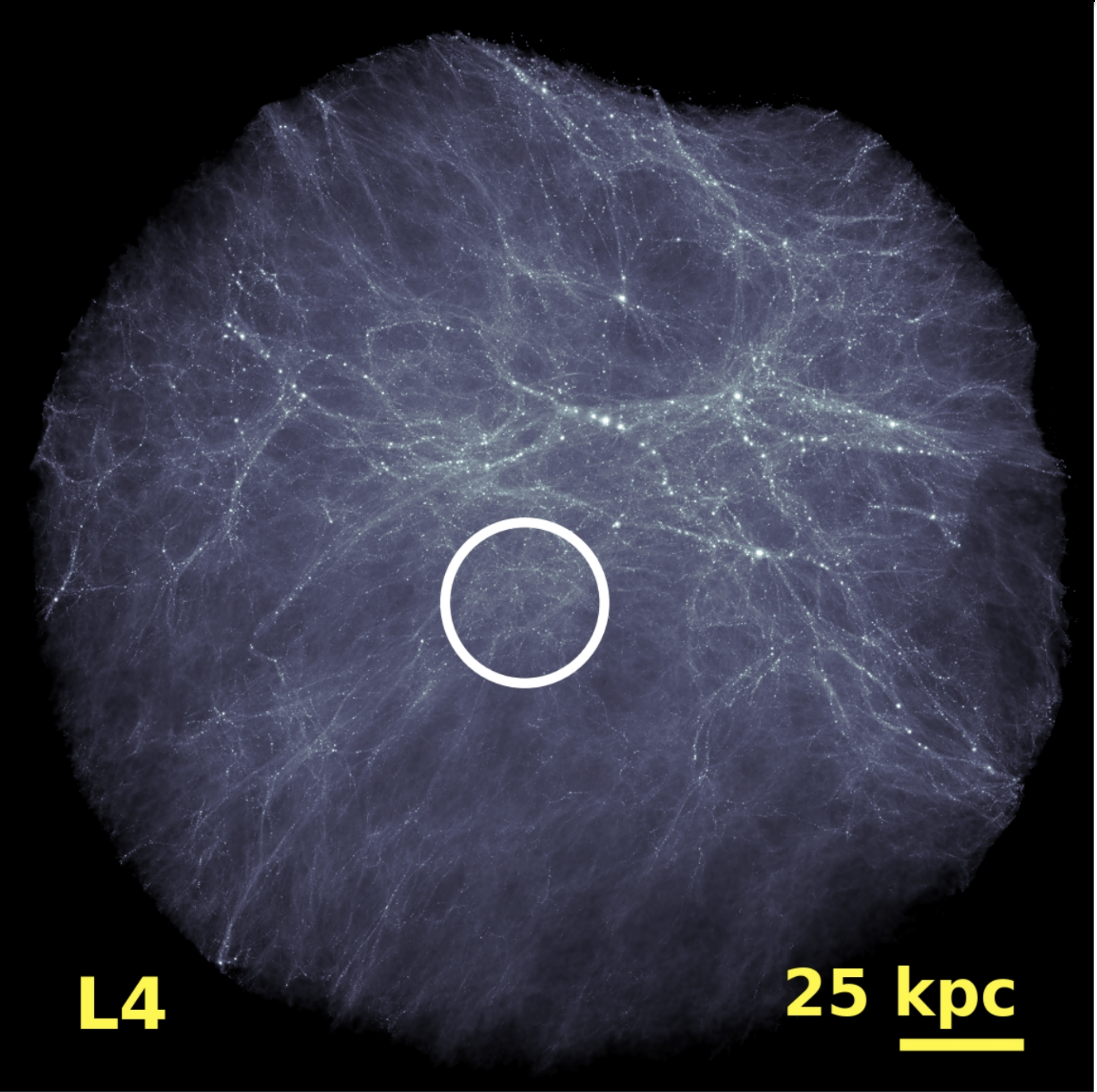
Dark matter only

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

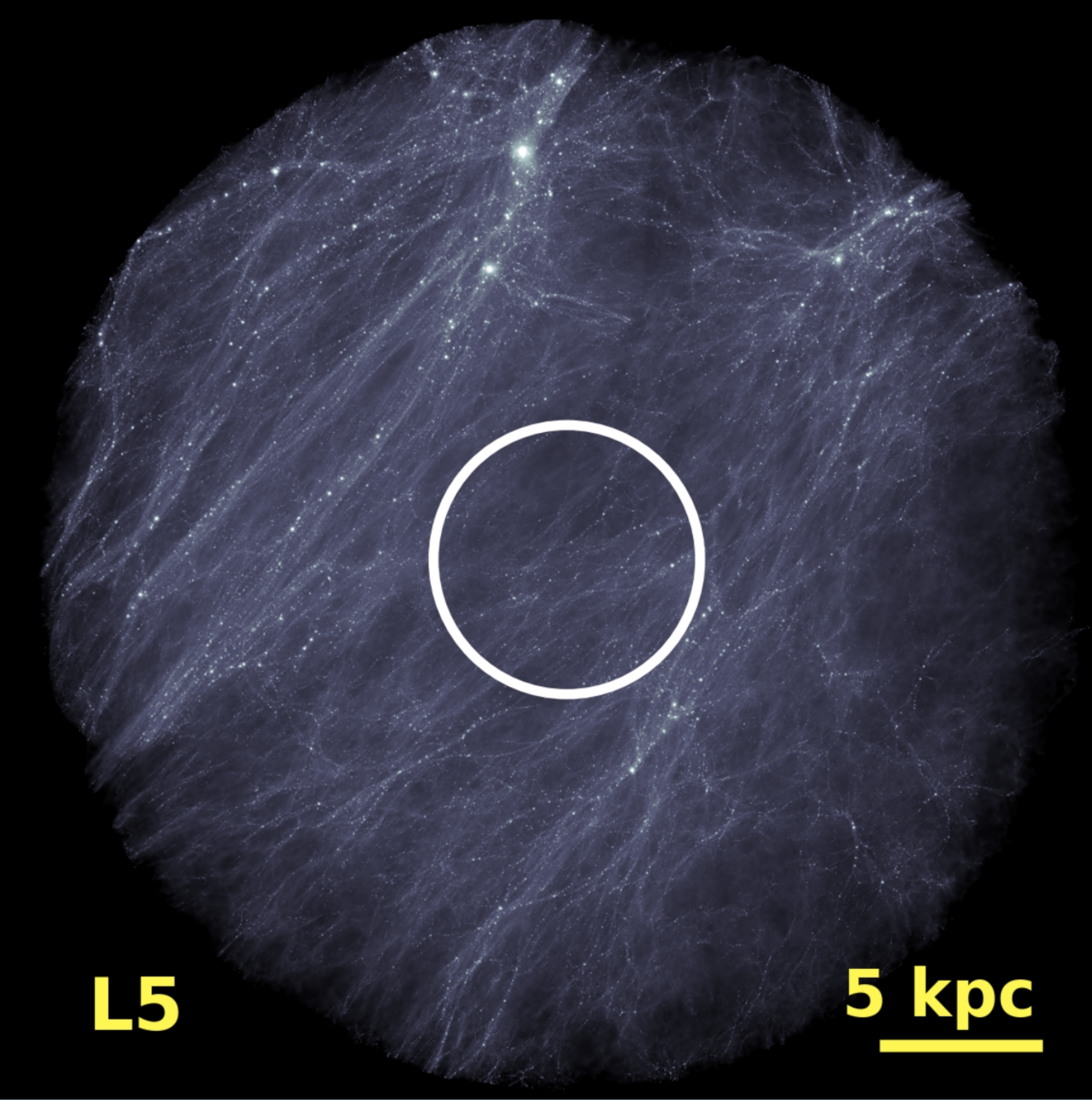
Dark matter only

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

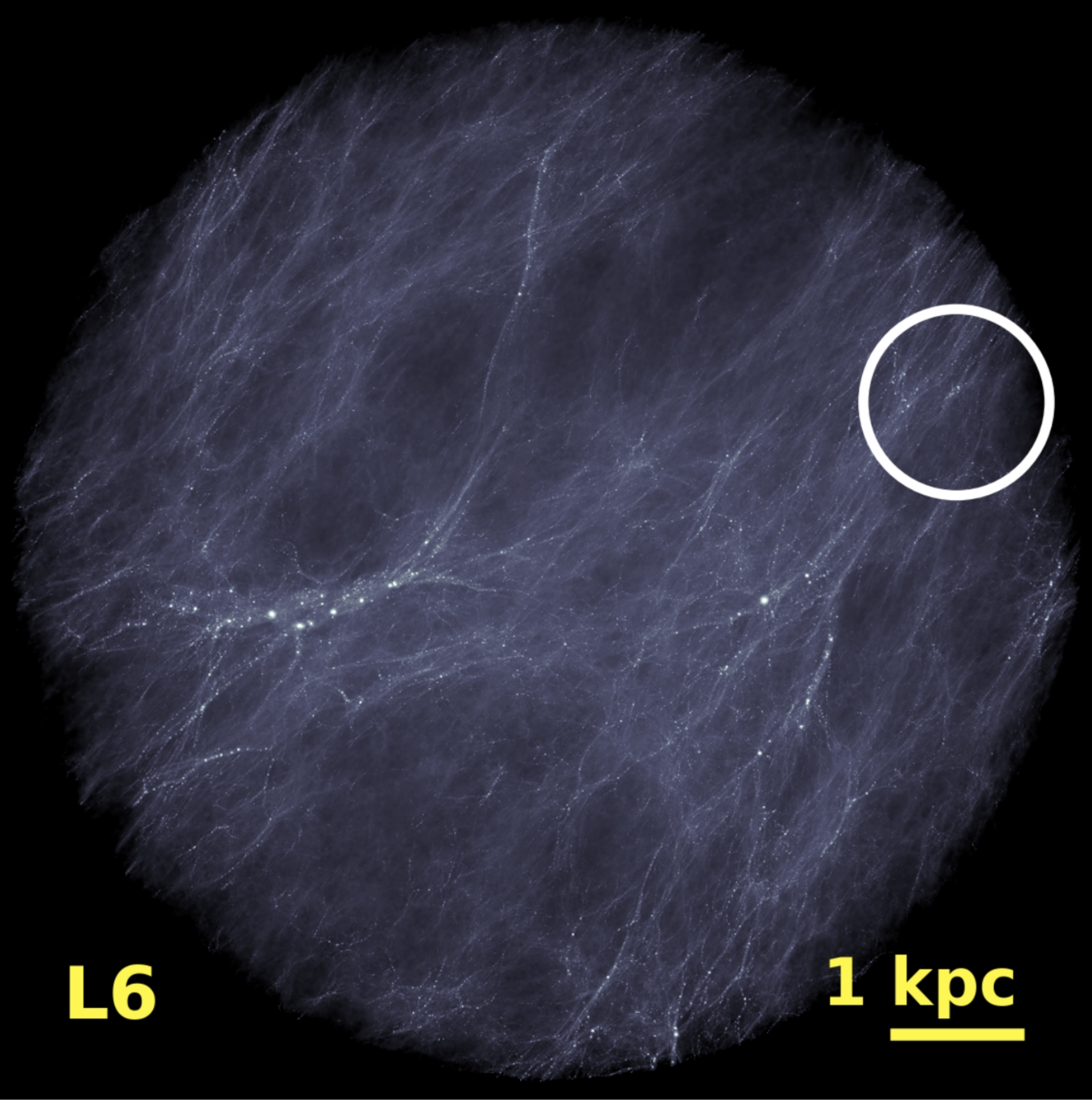
Dark matter only

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

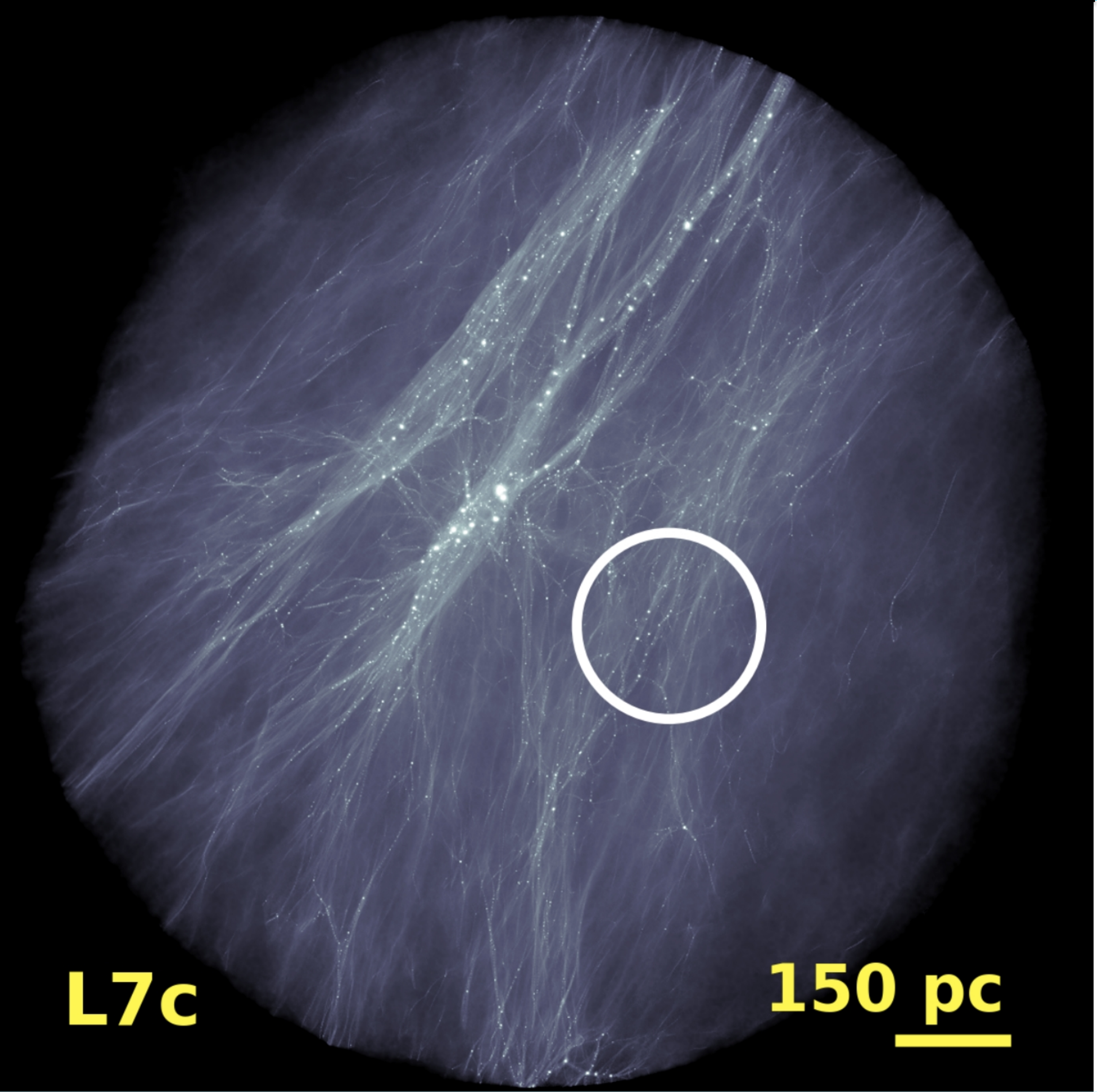
Dark matter only

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

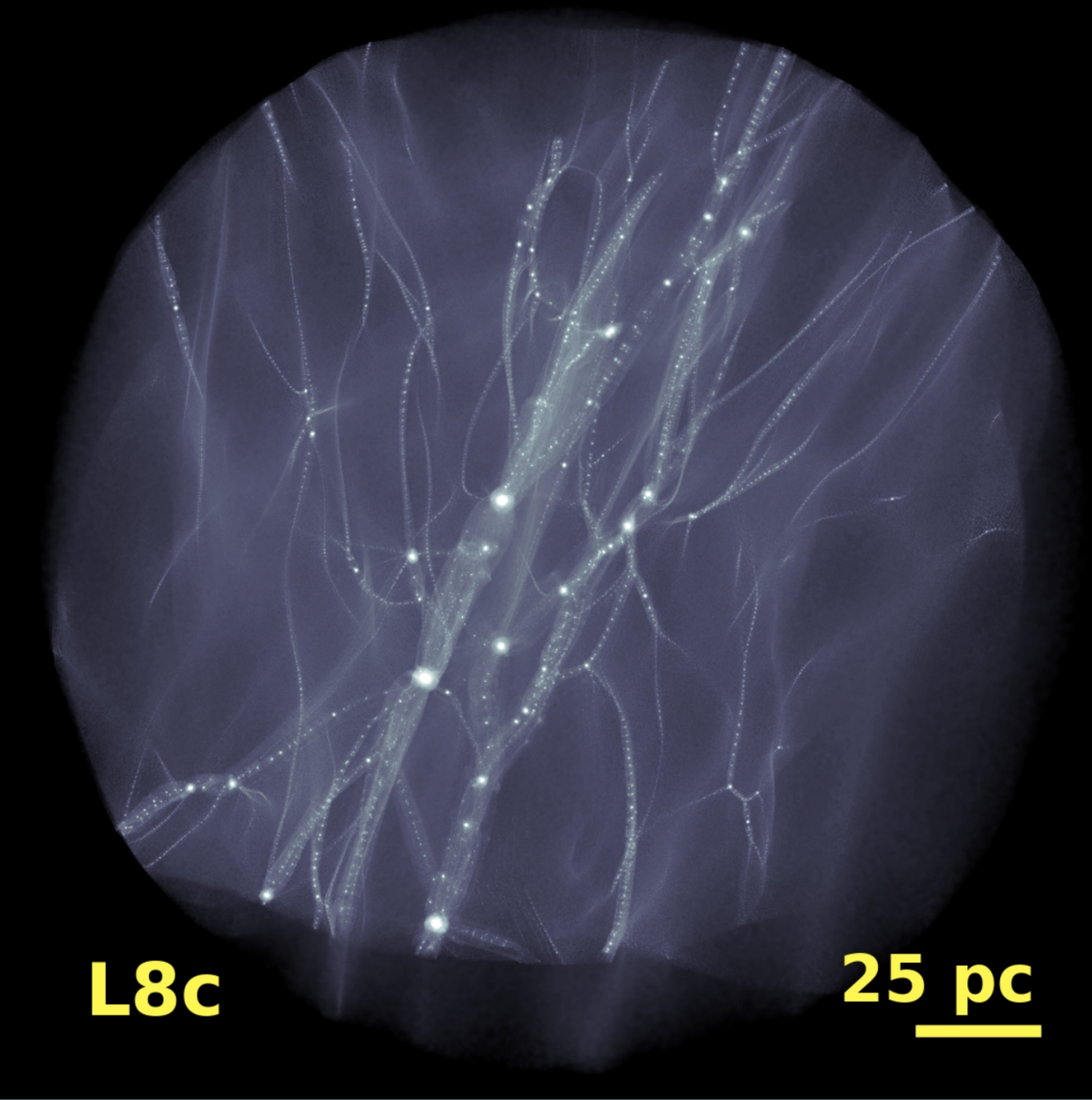
Dark matter only

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

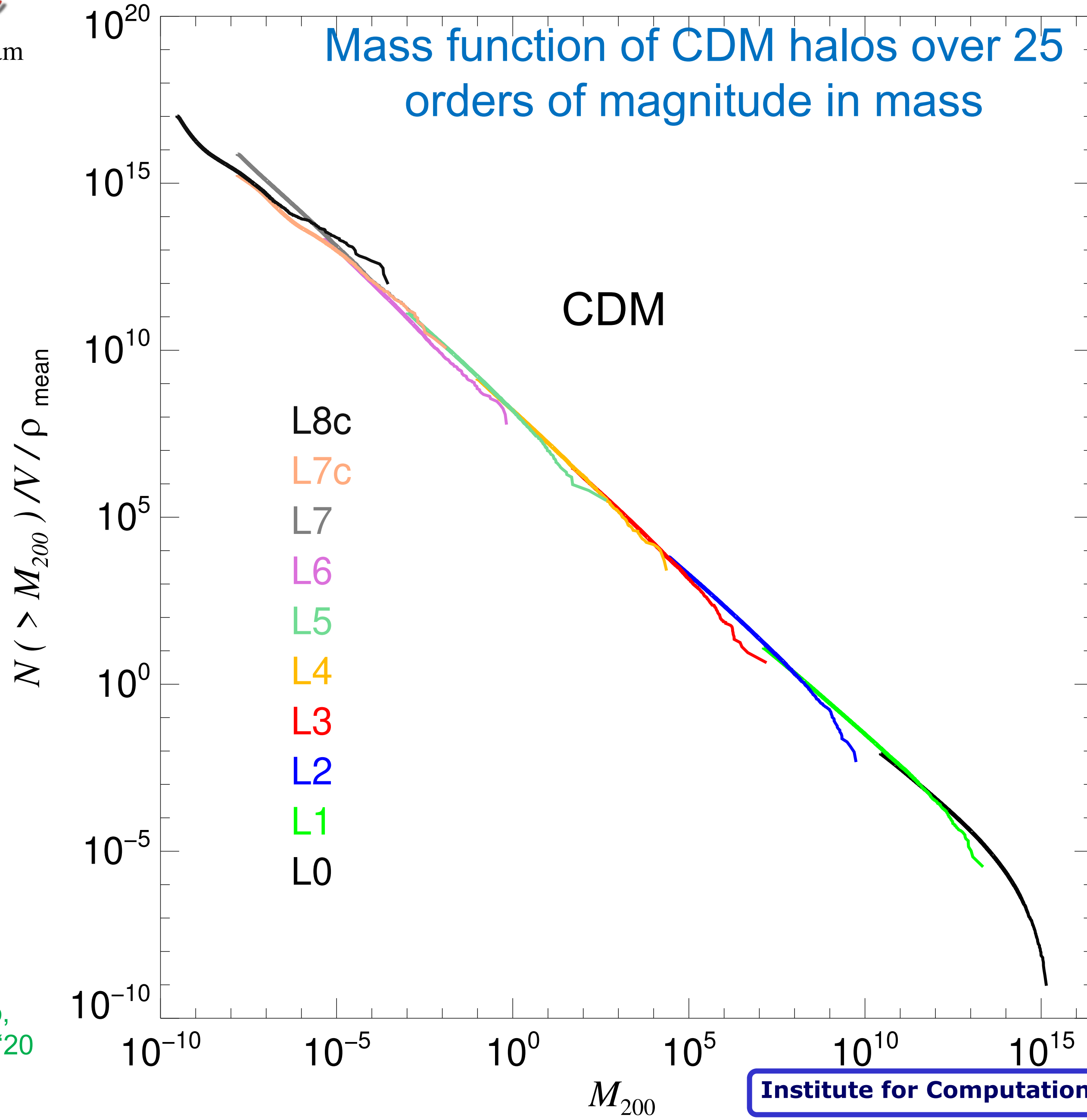
Dynamic range of 30 orders of magnitude in mass

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

Zoom Level 8

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

Wang, Bose et al 2020



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

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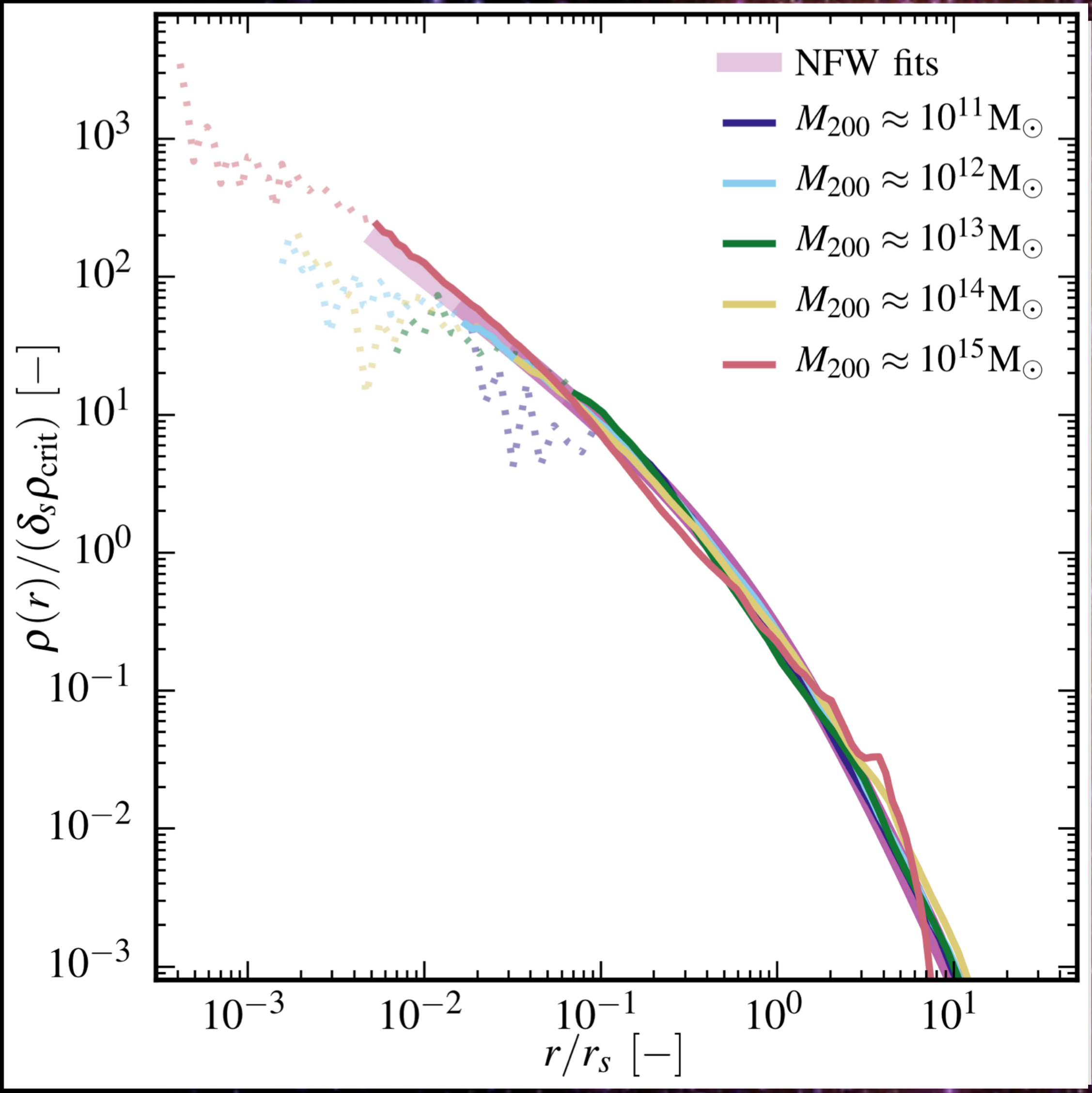
The structure of dark matter halos of all masses

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)

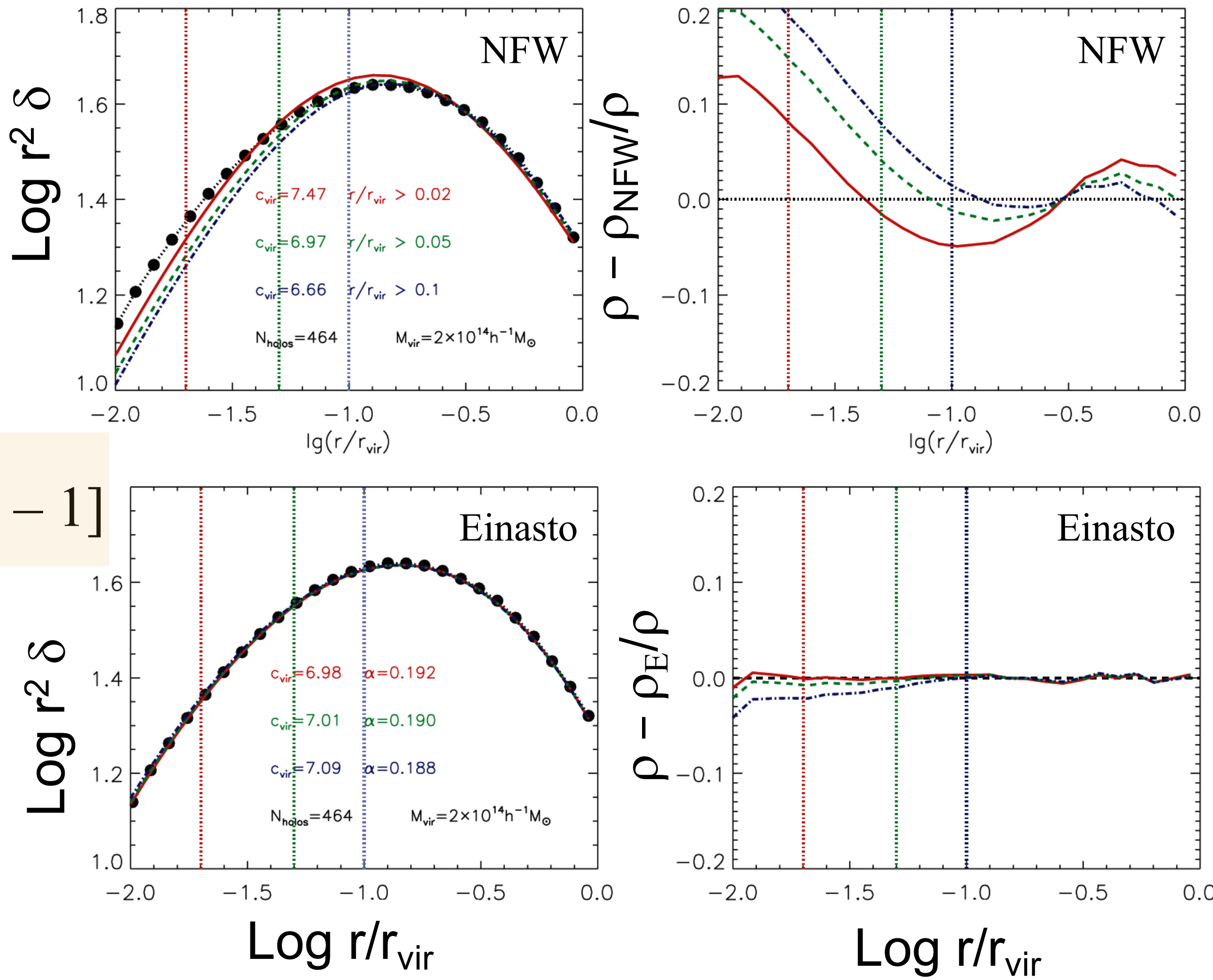
More massive halos and halos that form earlier have higher densities (bigger δ)

Universal halo density profiles

University of Durham

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

Averaged cluster mass halos fit with NFW and Einasto



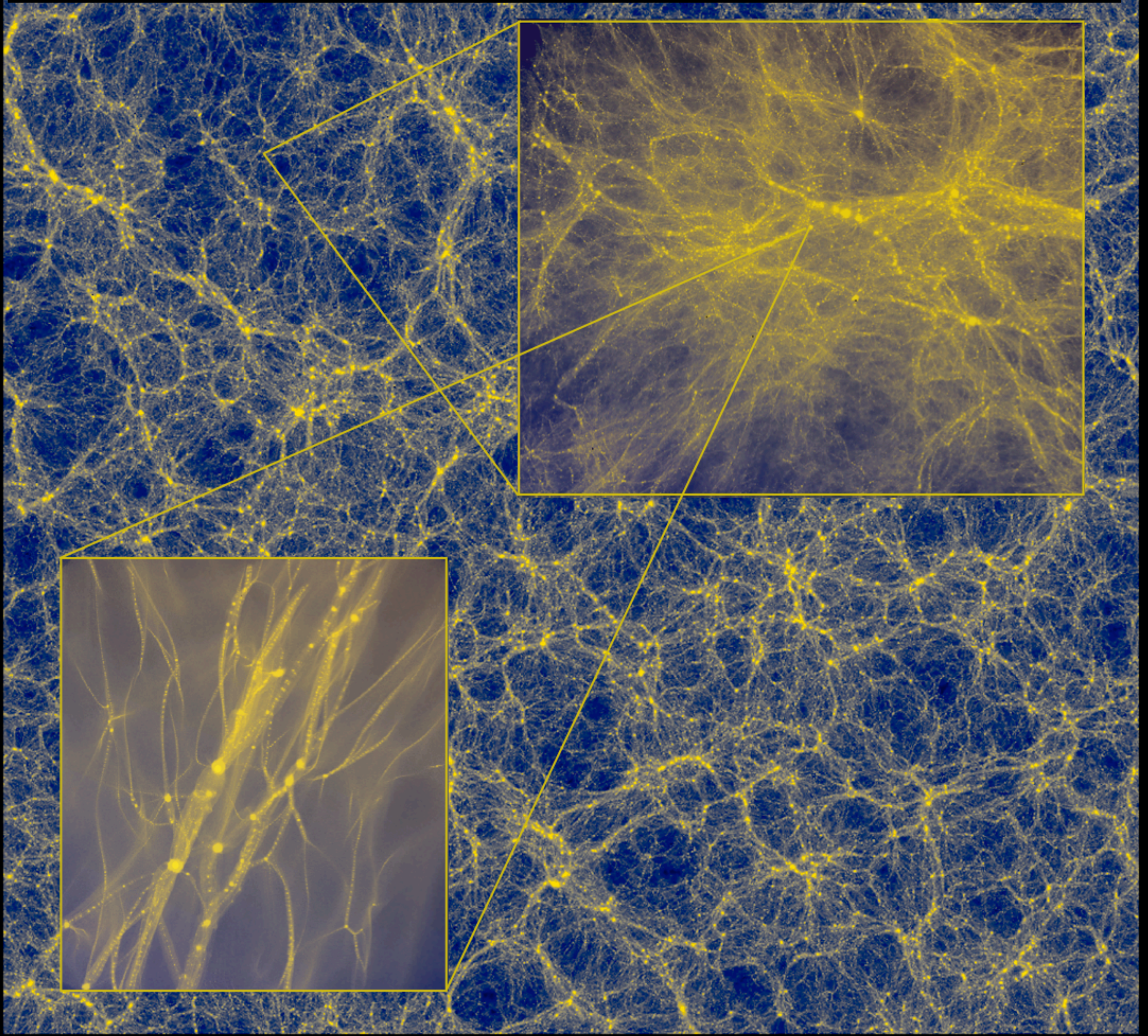
The "Einasto" formula

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

Fits mean profiles even better

Gao, N, F, W + 2008

Halo density profiles down to Earth mass



Wang et al '20

Density profile shapes

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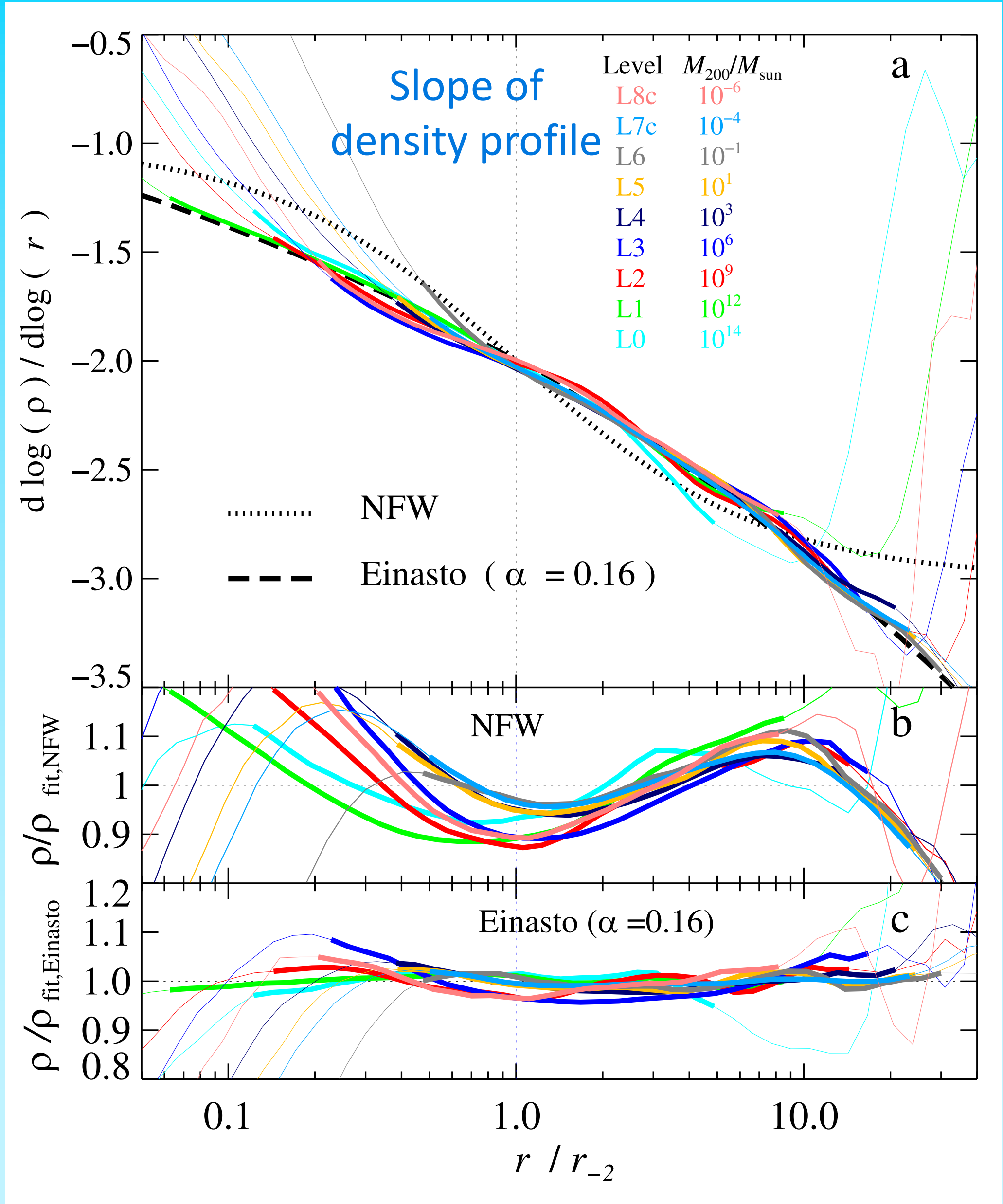
Over 20 orders of magnitude in halo mass and 4 orders of magnitude in density, the mean density profiles of halos are fit by NFW to within 20% and by Einasto (α =0.16) to within 7%



Wang, Bose, CSF + '20

Concentration-mass relation

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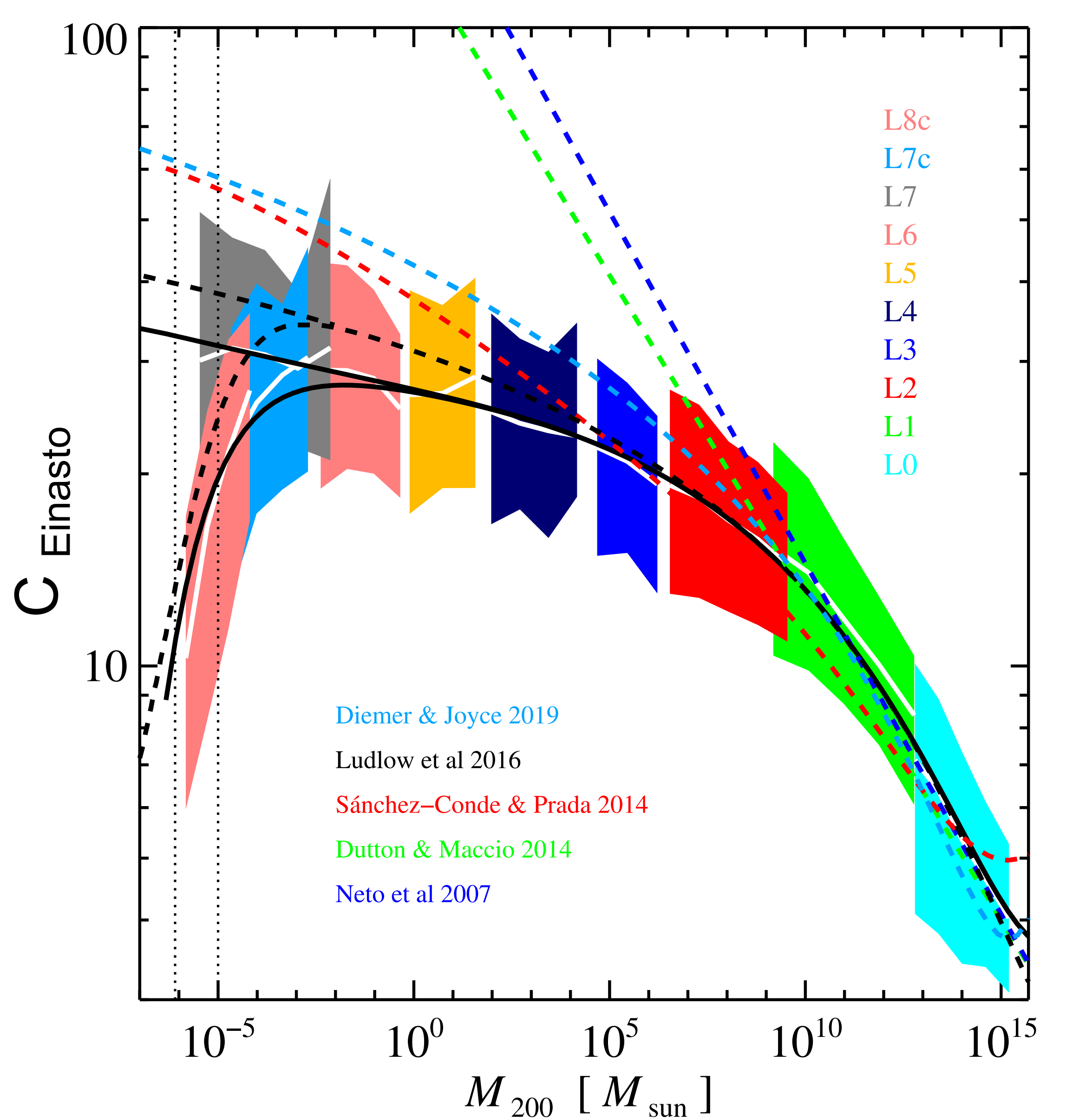
Concentrations at small mass are lower than all previous extrapolations by up to factors of tens.

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

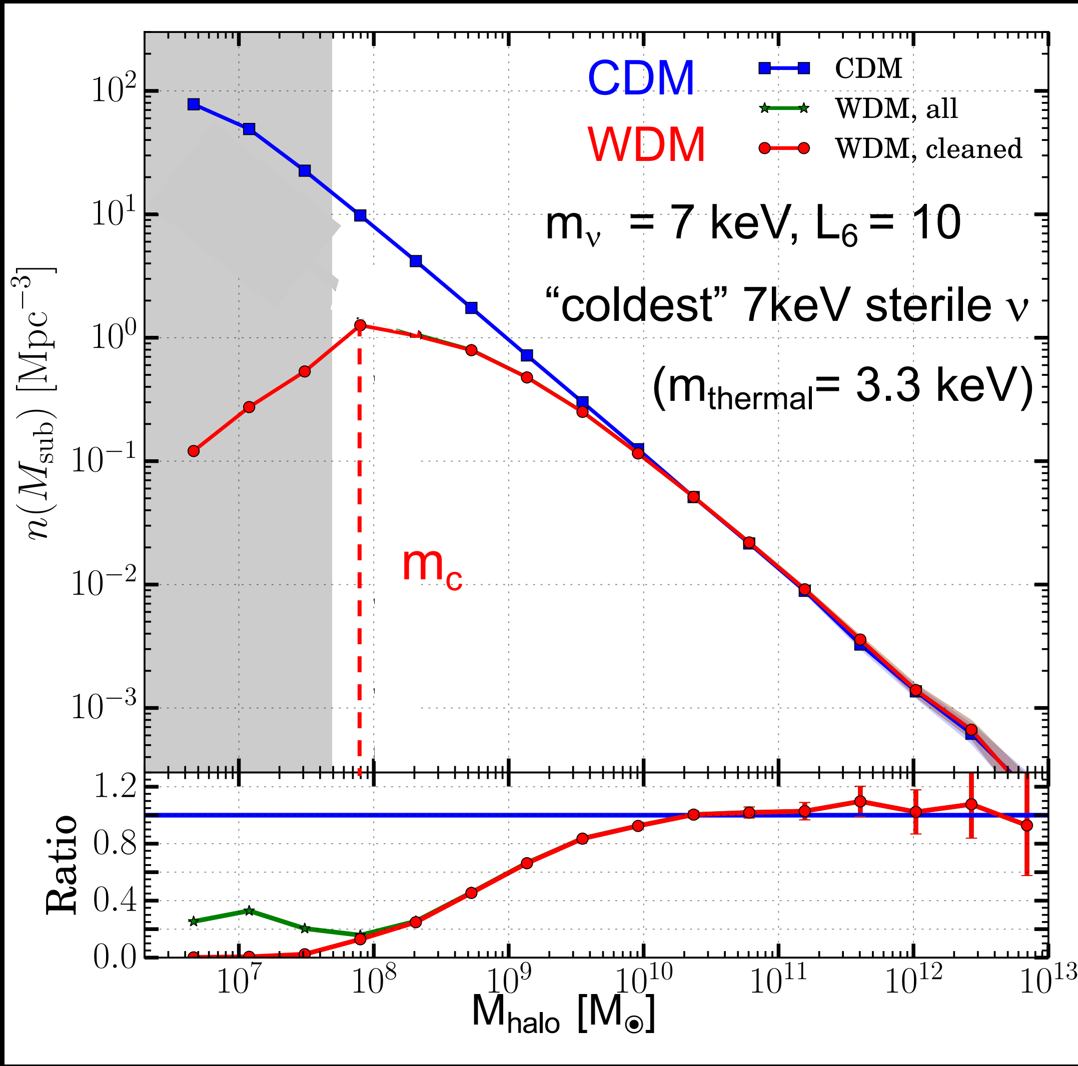
The scatter depends only weakly on halo mass



Wang, Bose, CSF + '20

The subhalo mass function

CDM WDM



3 x fewer WDM subhalos at 3×10^9 M_o

10 x fewer at 10^8 M_o

Bose, CSF et al '16

In both CDM and WDM abundance and structure of dark matter halos of all masses is known!

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How can we distinguish the two?

Astrophysical tests of dark matter

Count the number of small-mass halos!

- Counting visible galaxies (Milky Way satellites)
- Counting dark halos using gravitational lensing
- Annihilation radiation for CDM

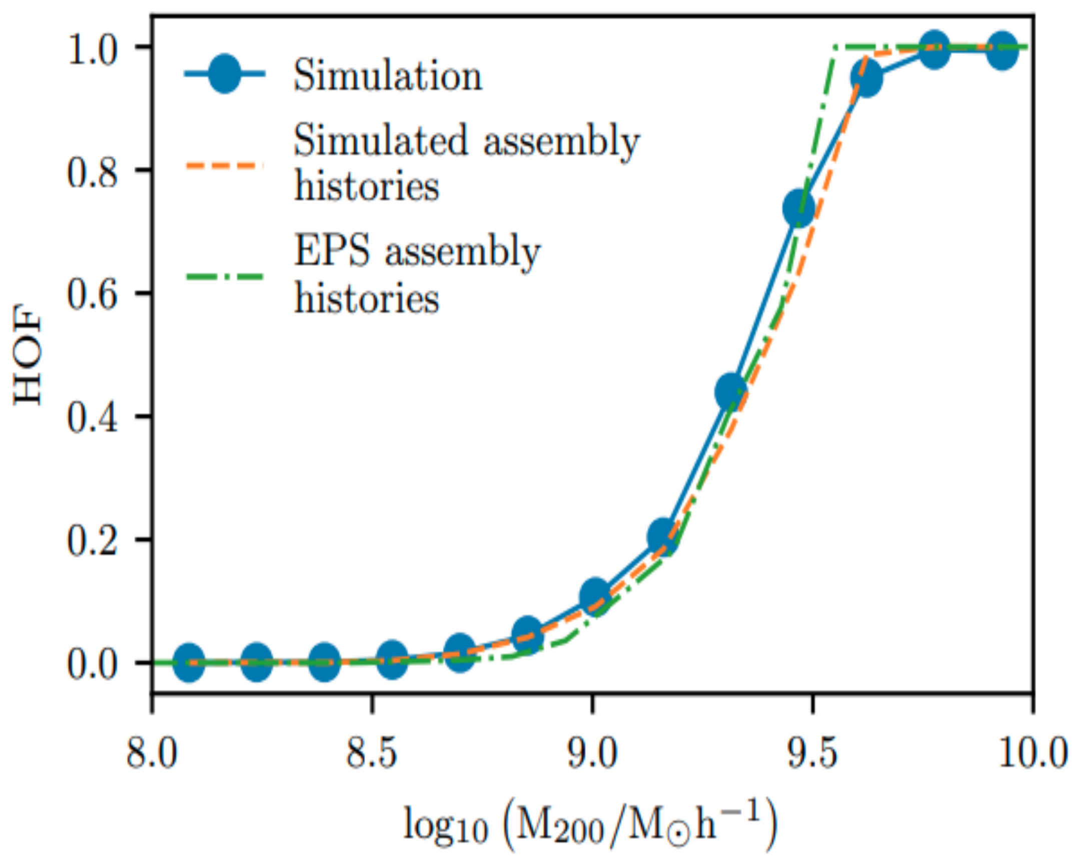
Let's begin by counting what we can see: number of dwarf galaxies orbiting the Milky Way


CDM
Most subhalos never make a galaxy!

A galaxy formation primer

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

fraction of halos that host a galaxy



Benitez-Llambay & CSF '20

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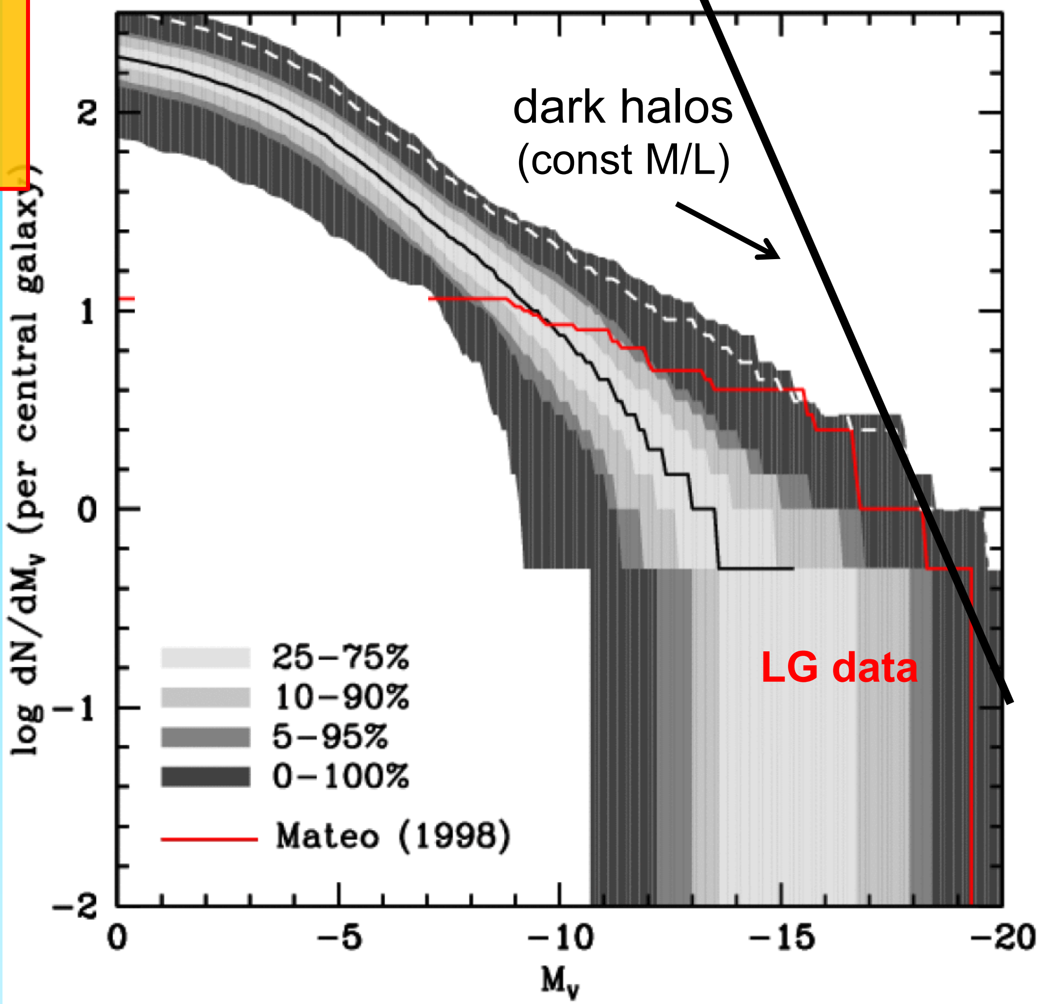
Luminosity Function of Local Group Satellites

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)

Luminosity Function of Local Group Satellites

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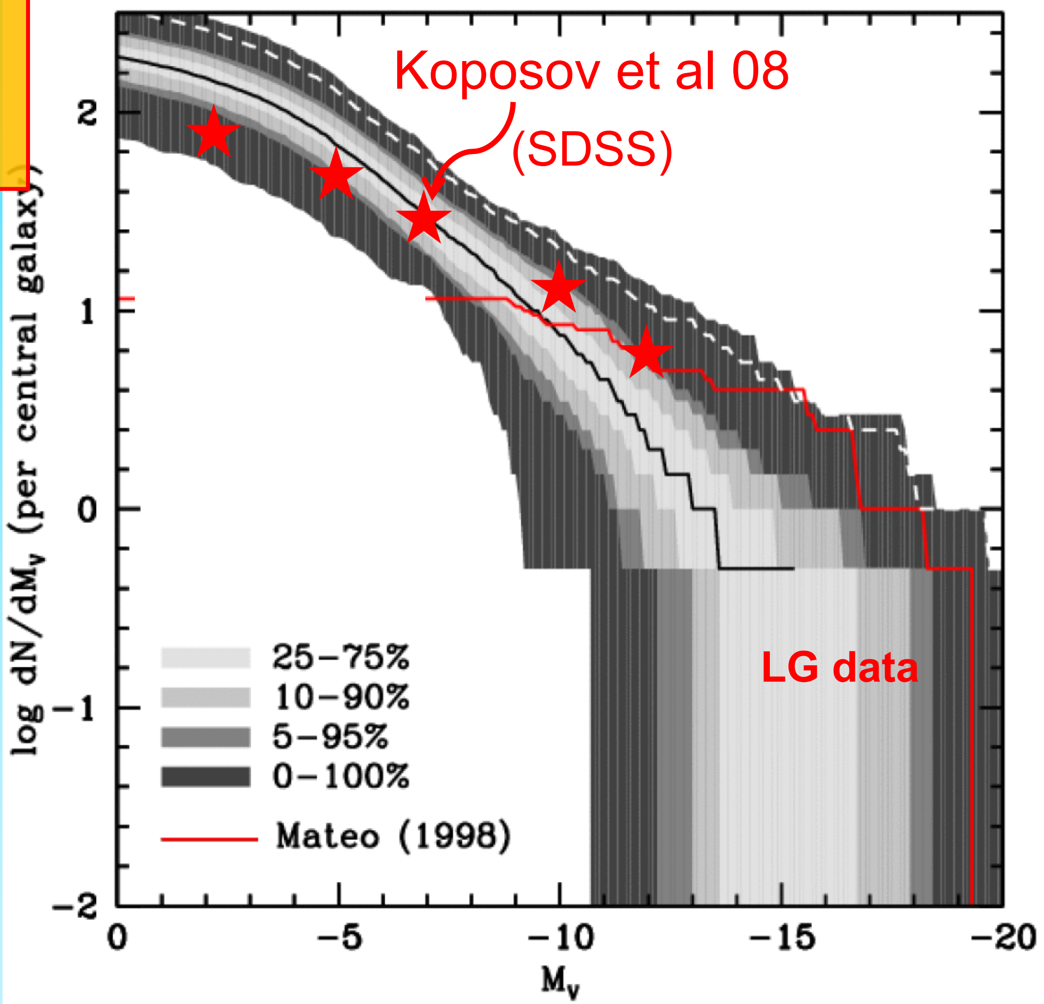

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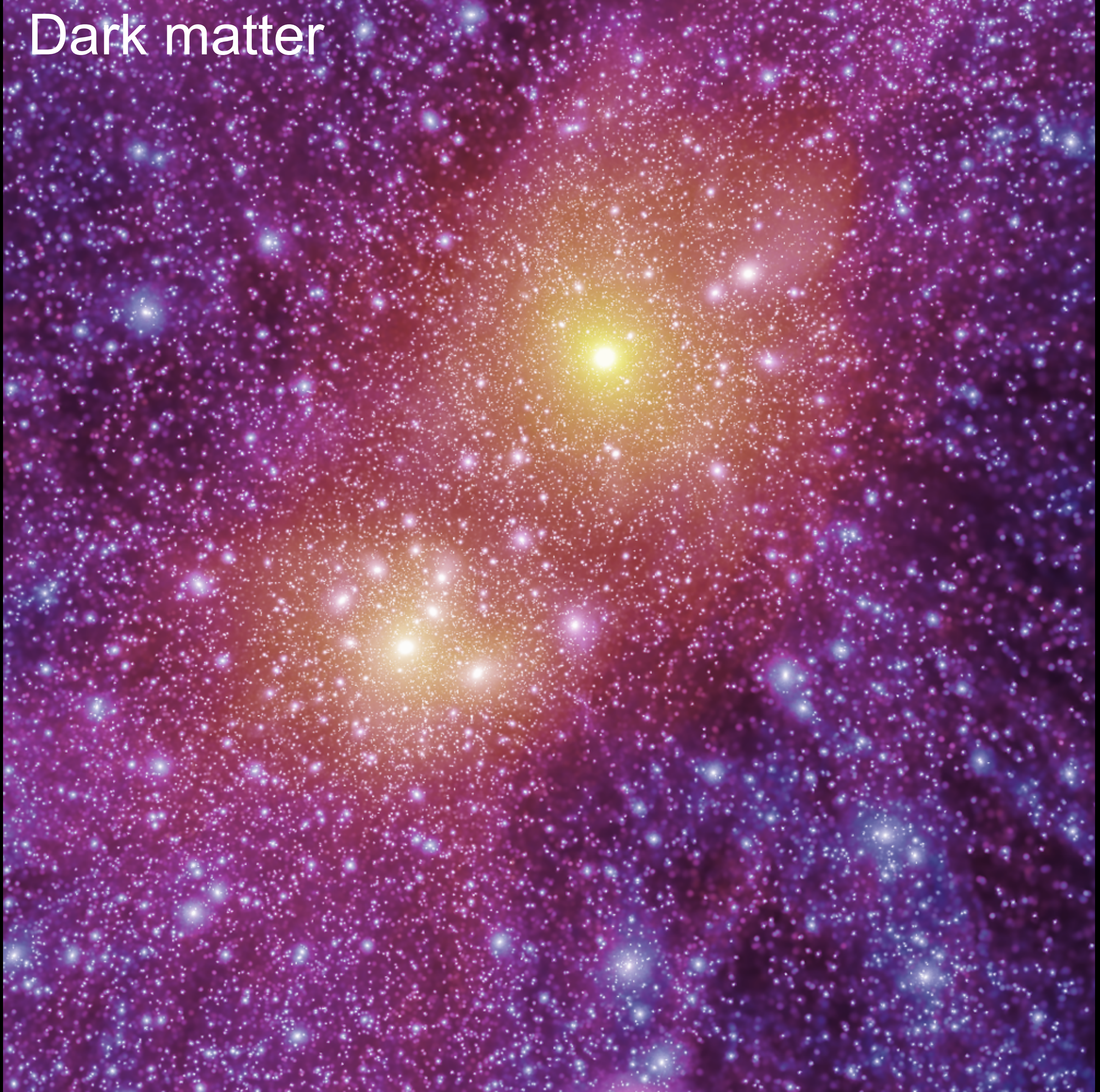
VIRGO

APOSTLE
EAGLE full
hydro
simulations

Local Group

CDM

Sawala, CSF et al '16



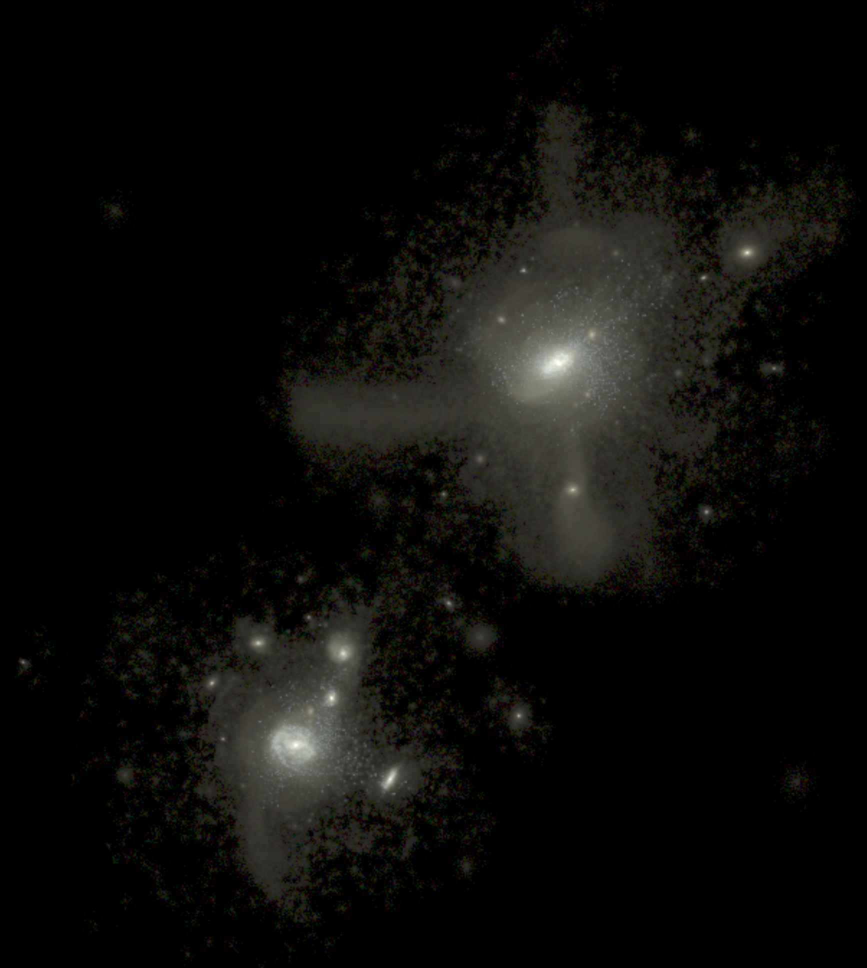
VIRGO

Stars

APOSTLE EAGLE full hydro simulations

Local Group

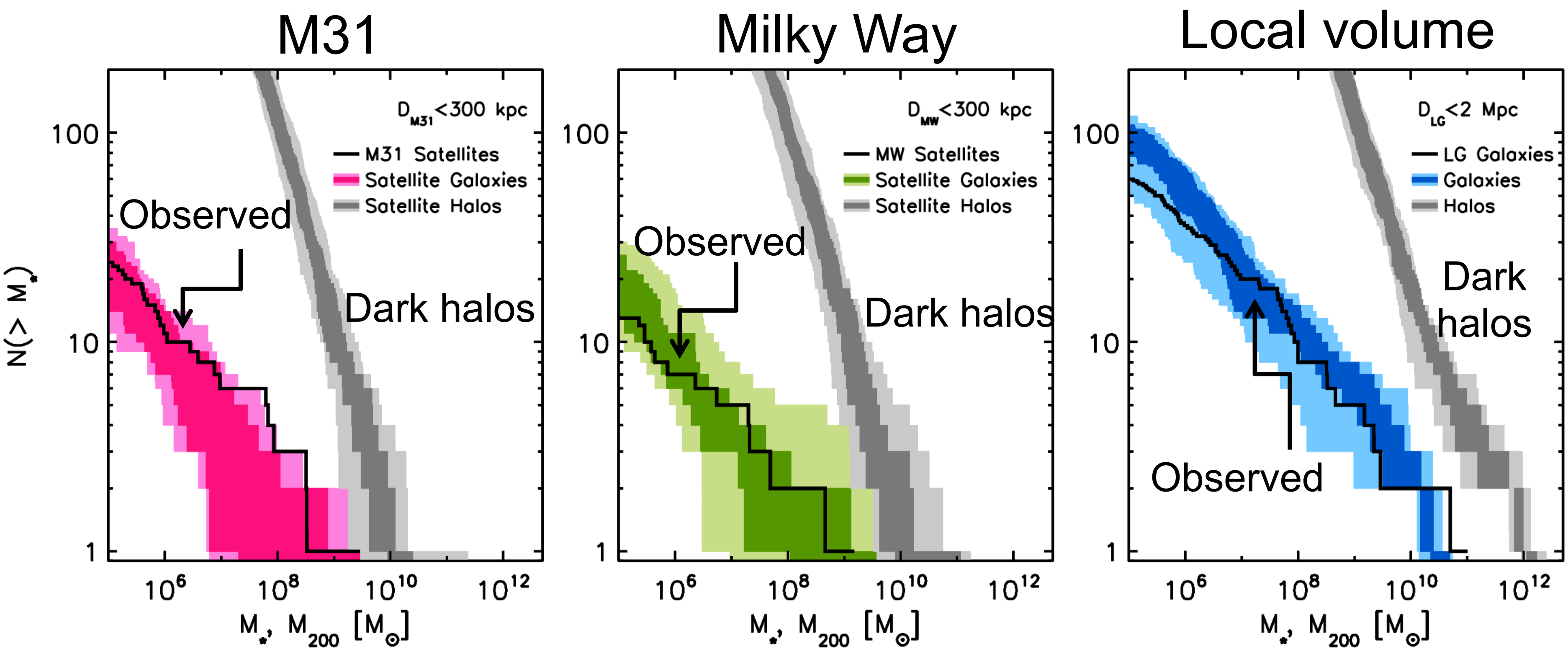
Stars



Far fewer satellite galaxies than CDM halos

Sawala, CSF et al ‘16

EAGLE Local Group simulation



Sawala, CSF et al '16

When galaxy formation is taken into account

→

CDM predicts the observed abundance of satellites

→

There is no such thing as a "missing satellite problem" in CDM!

When galaxy formation is taken into account

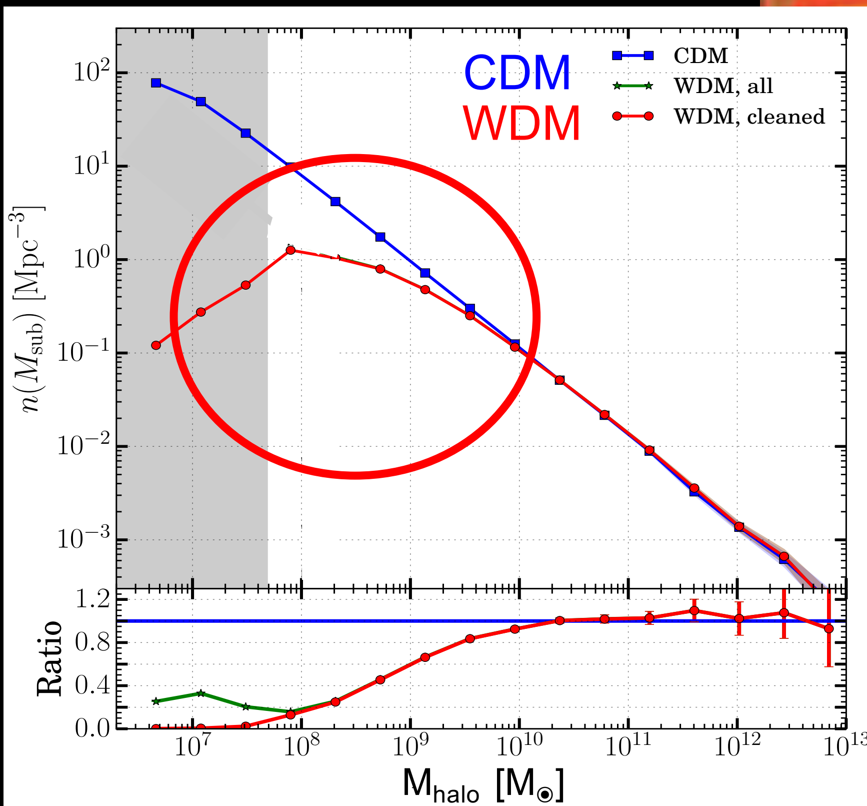
→

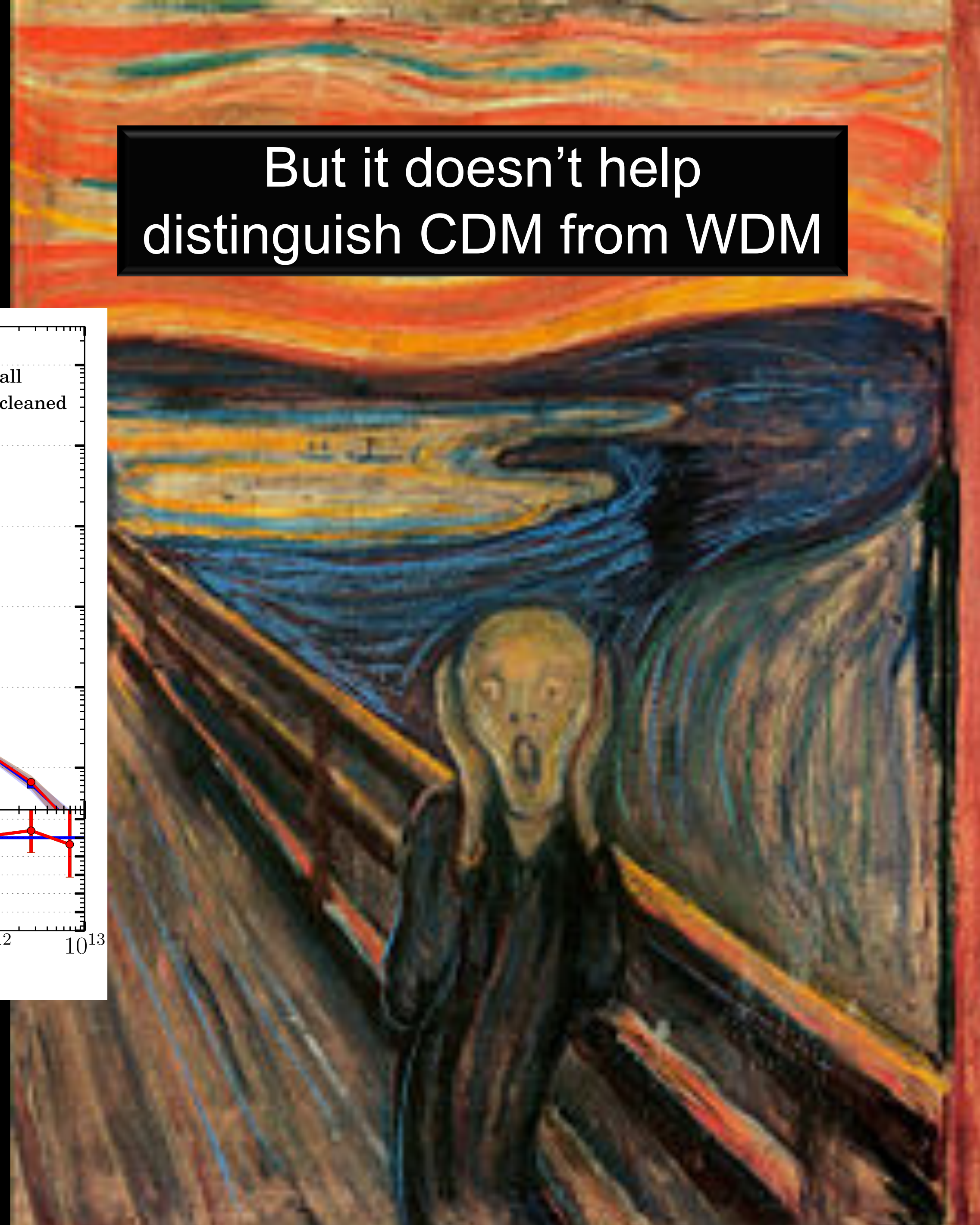
CDM predicts the observed abundance of satellites

→

And WDM as well

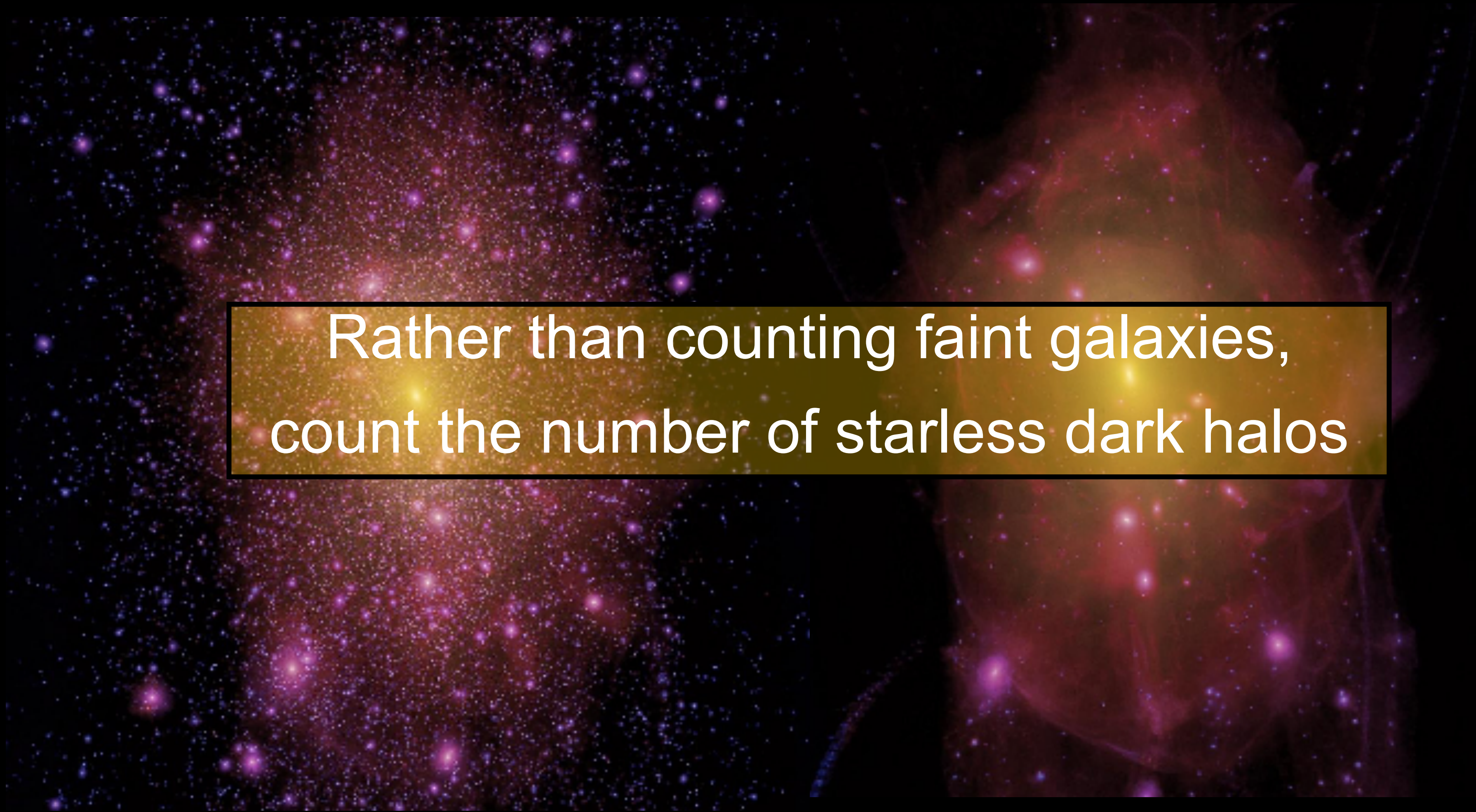
But it doesn’t help distinguish CDM from WDM





Can we distinguish CDM/WDM?

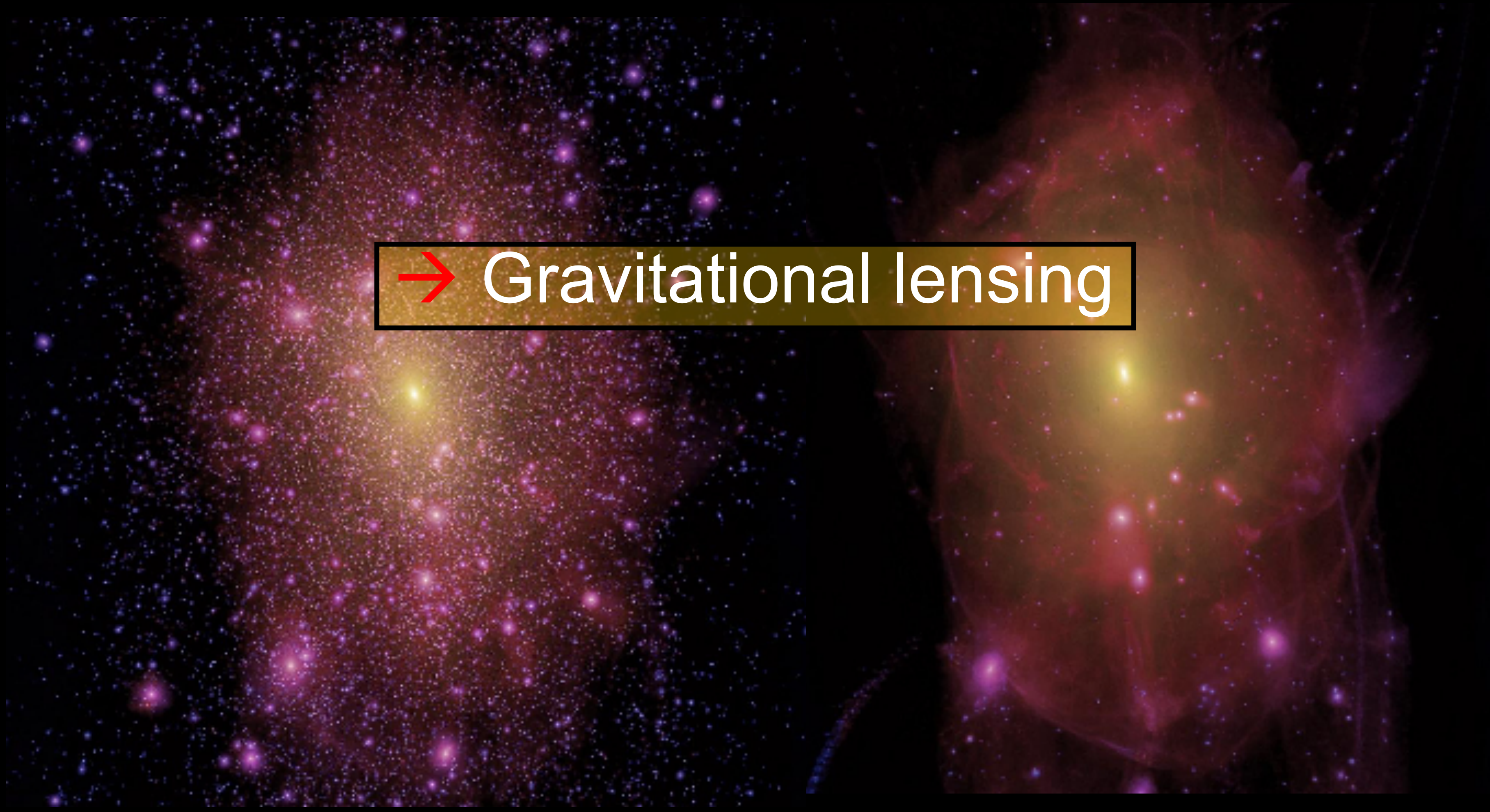
cold dark matter | warm dark matter



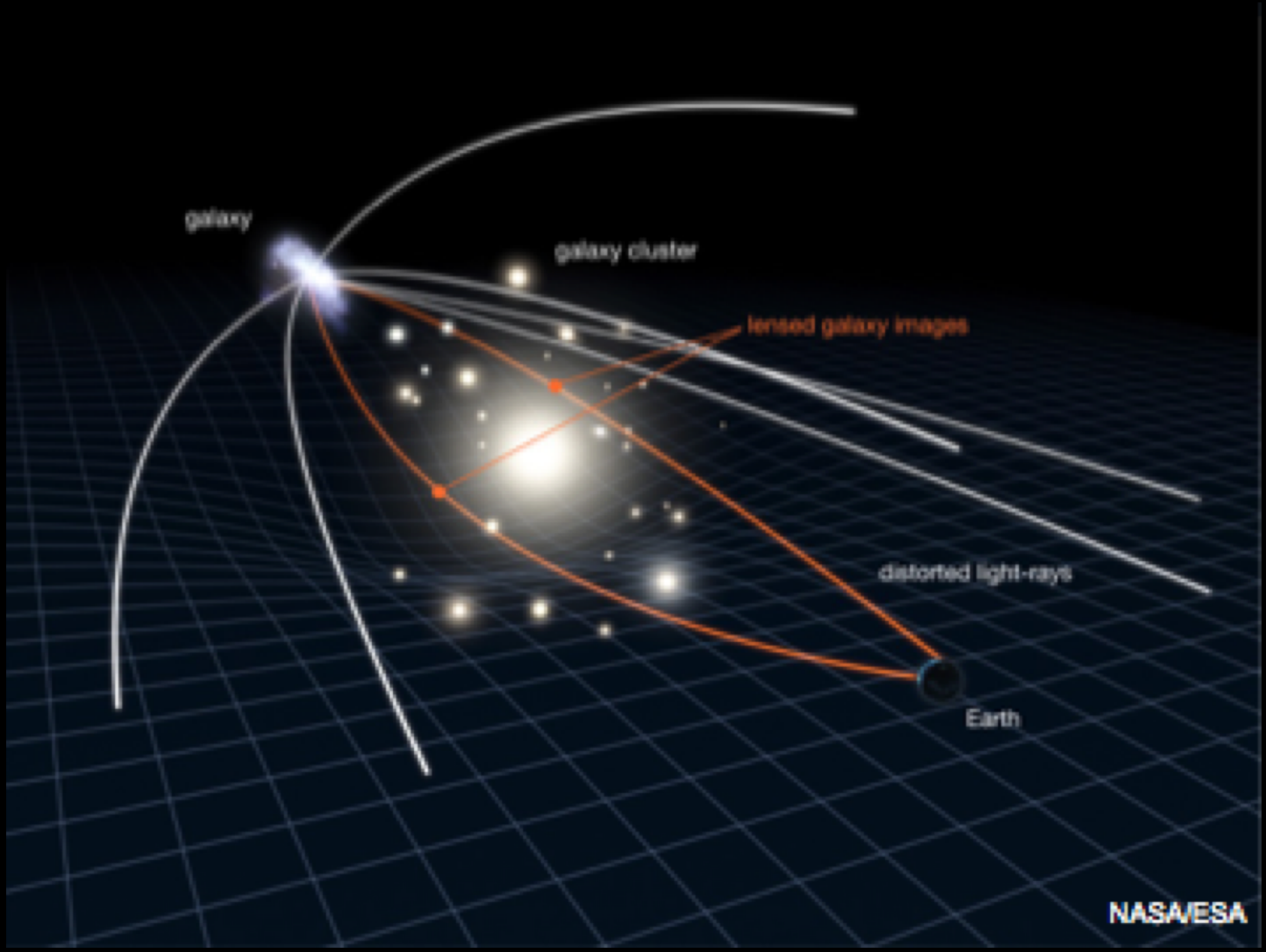
Rather than counting faint galaxies,
count the number of starless dark halos

Can we count dark haloes?

cold dark matter　　　　warm dark matter

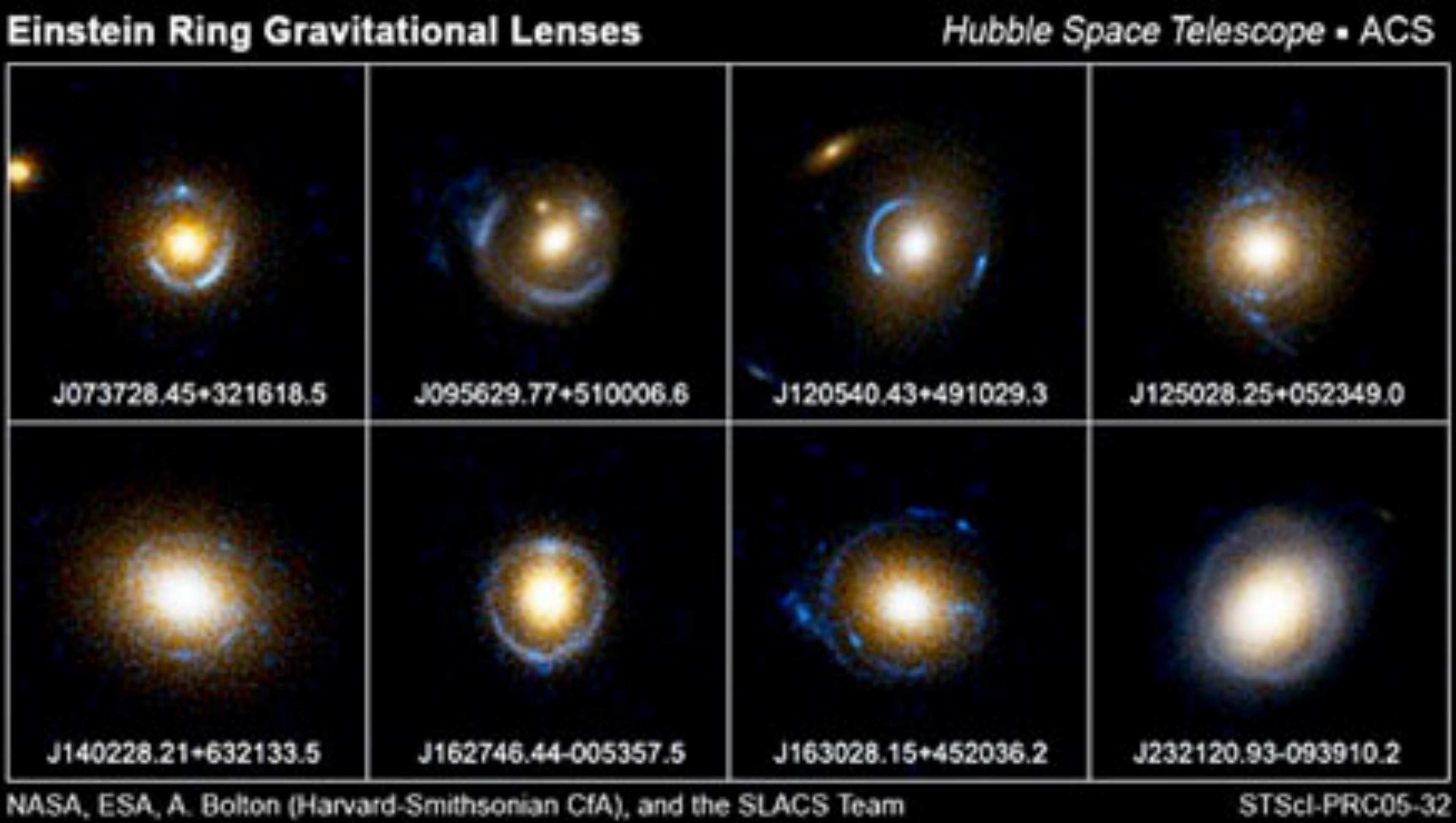


Gravitational lensing: Einstein rings

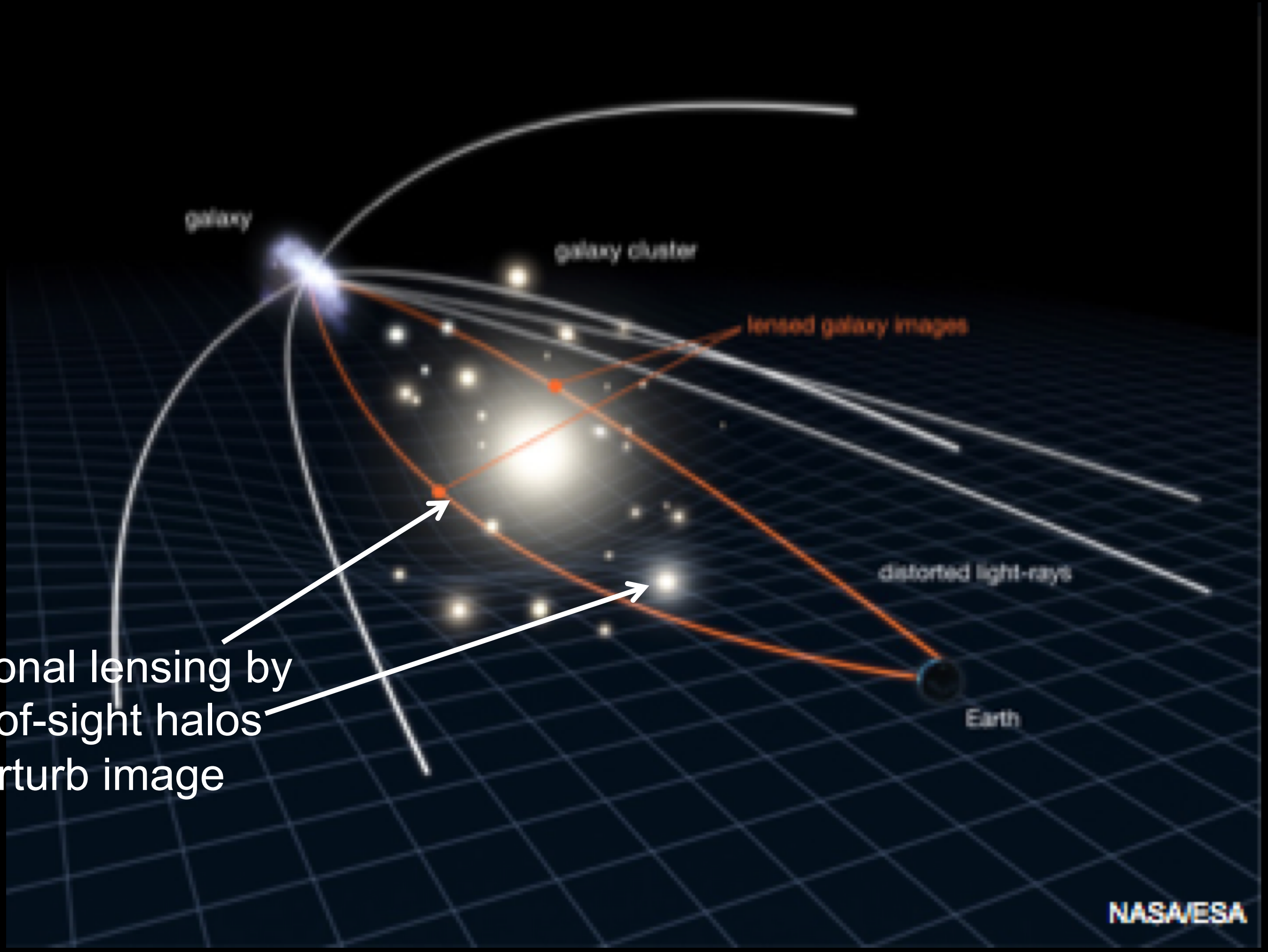


When the source and the lens are well aligned → strong arc or an Einstein ring

SLAC sample of strong lenses



Gravitational lensing: Einstein rings

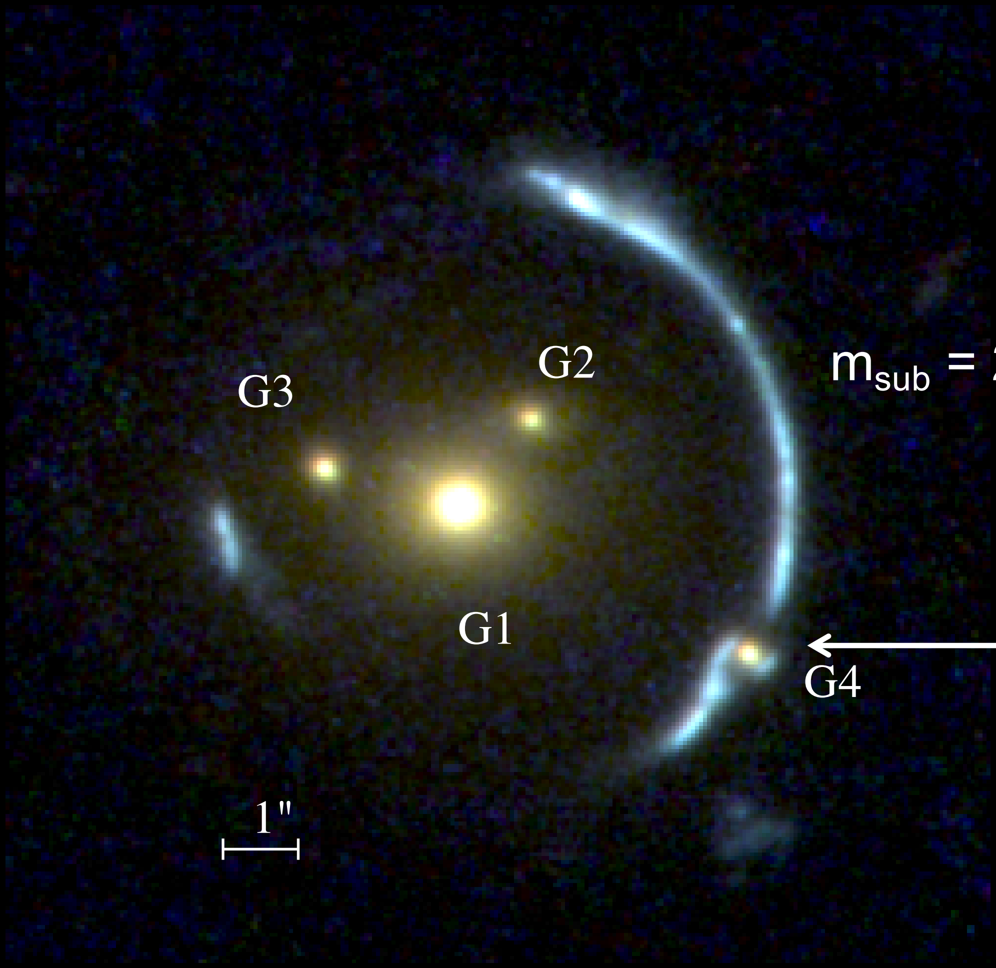


Additional lensing by line-of-sight halos perturb image

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



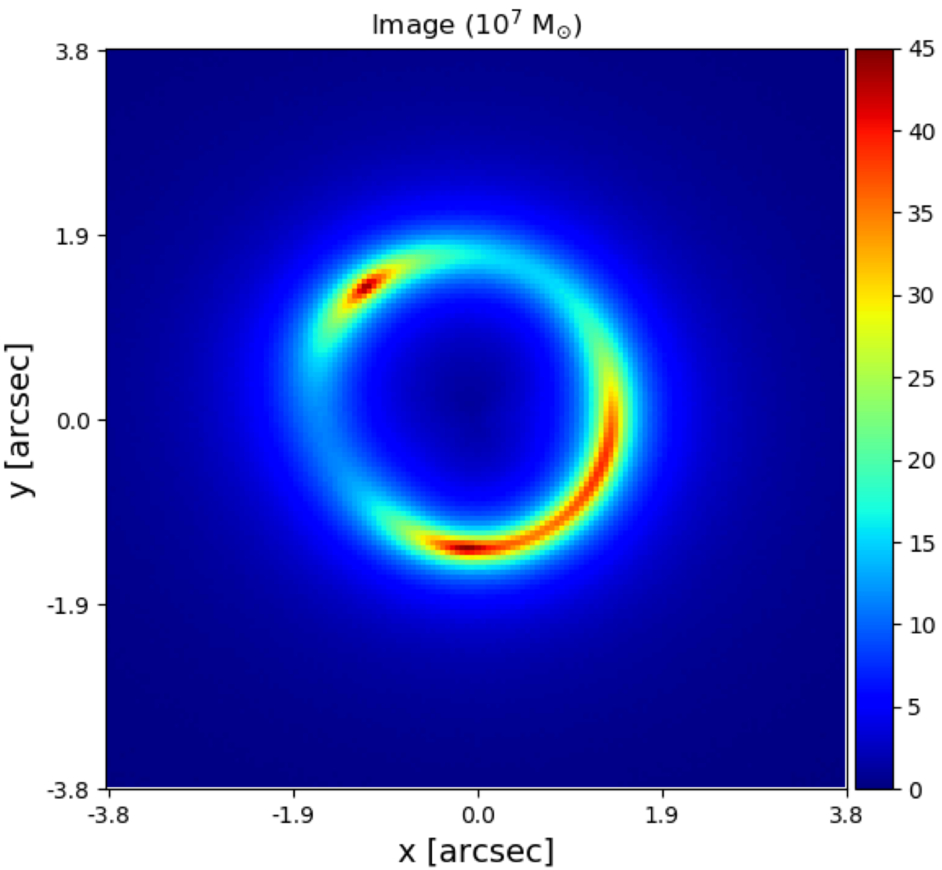
$m_{sub} = 2.8 \times 10^{10}\ M_o$

Vegetti et al '10

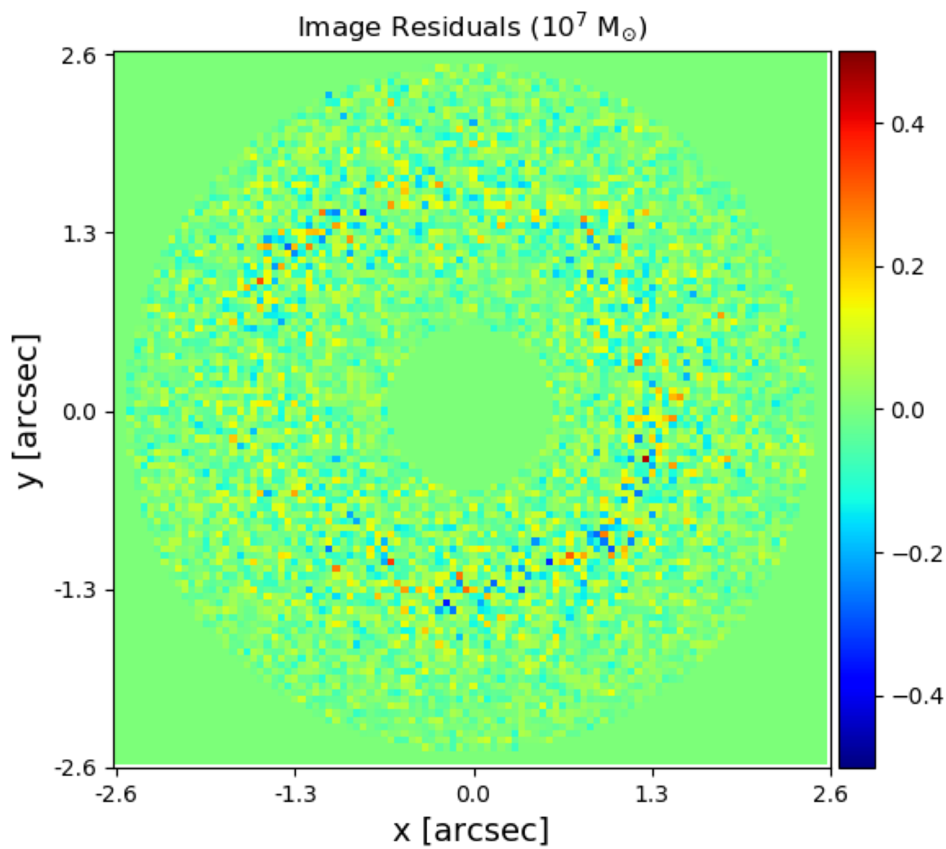
Strong lensing: detecting small halos

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

Image



Residuals (image – smooth model)

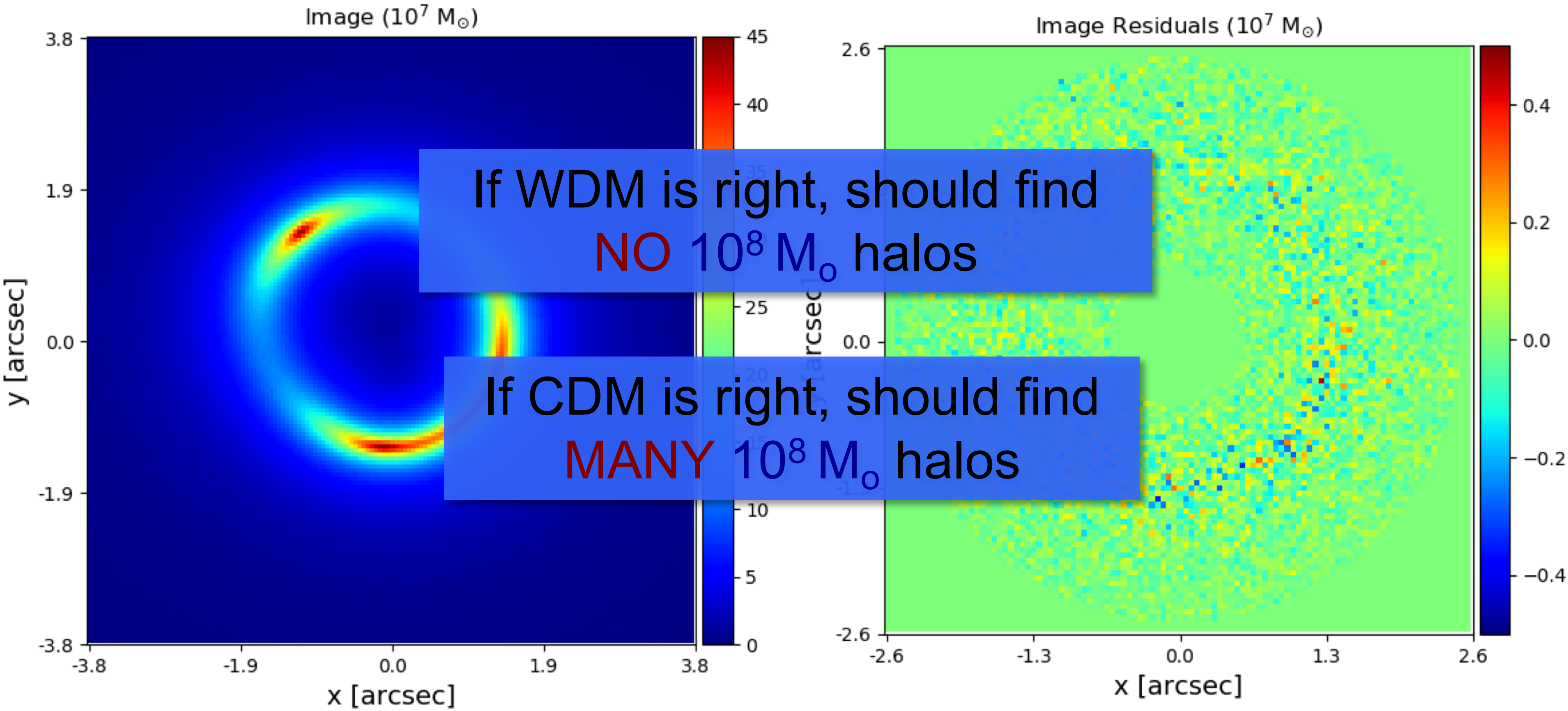


He, Li, CSF et al '19

Institute for Computational Cosmology

Detecting halos w. strong lensing

Can detect halos as small as 10^8 M_o



If WDM is right, should find NO 10^8 M_o halos

If CDM is right, should find MANY 10^8 M_o halos

He, Li, CSF et al '19

Strong lensing: statistical detection

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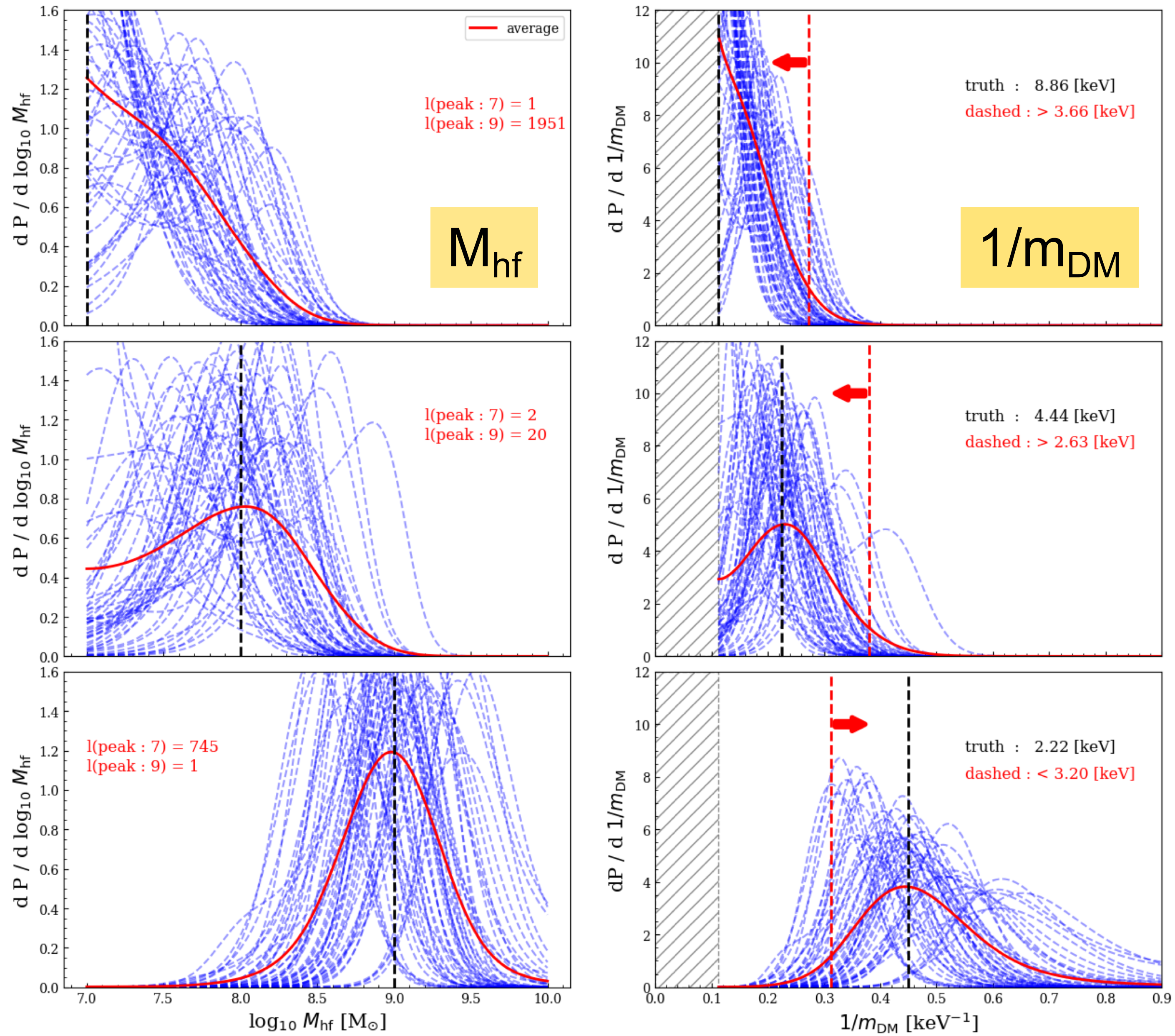
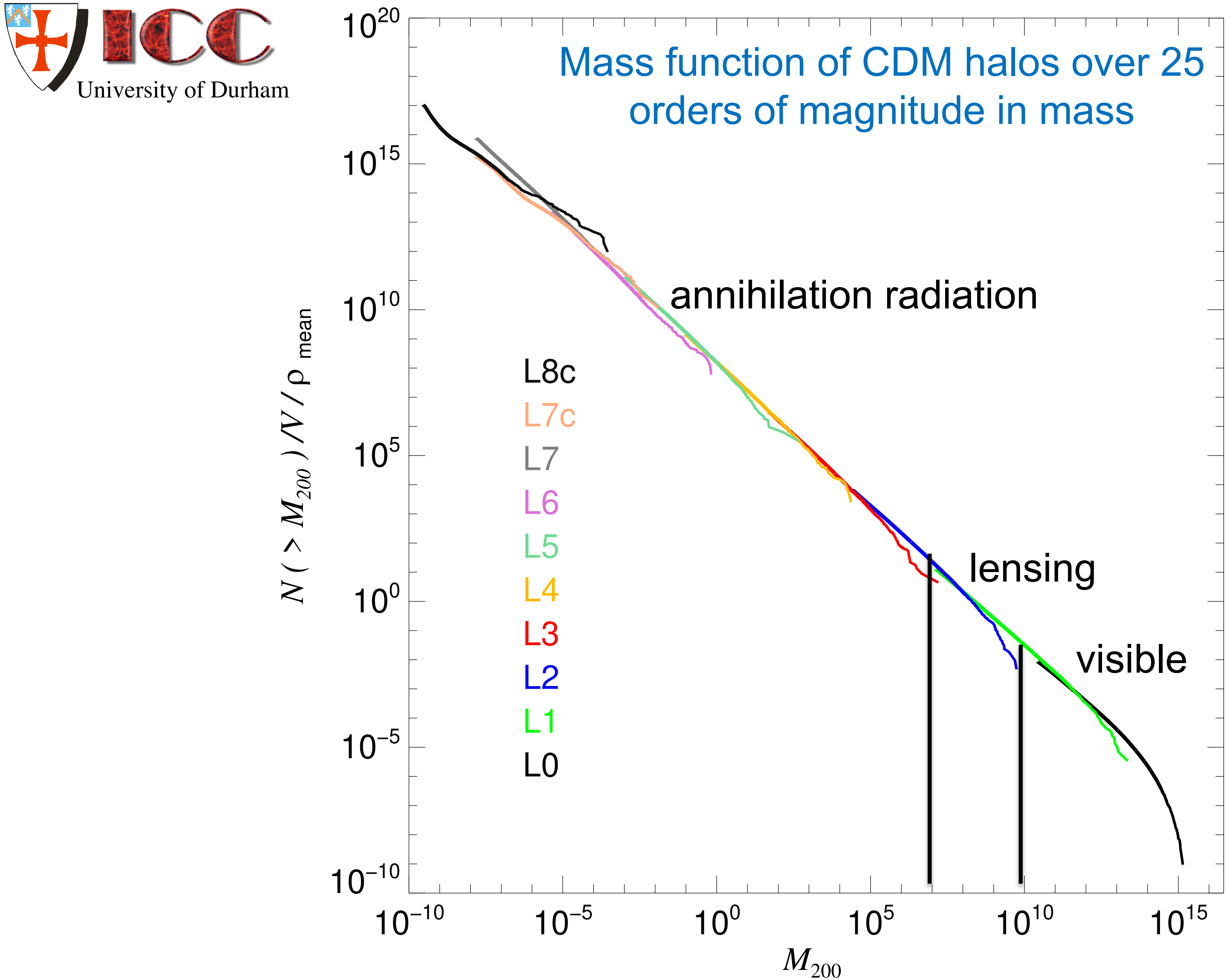
Power spectrum of residuals map

Posterior distributions (mock observations) for power spectrum of residuals



Constraints from forward modelling of 50 systems

He et al. '20



Wang, Bose, CSF, Gao, Jenkins, Springel, White - Nature 2020

University of Durham

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)

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

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

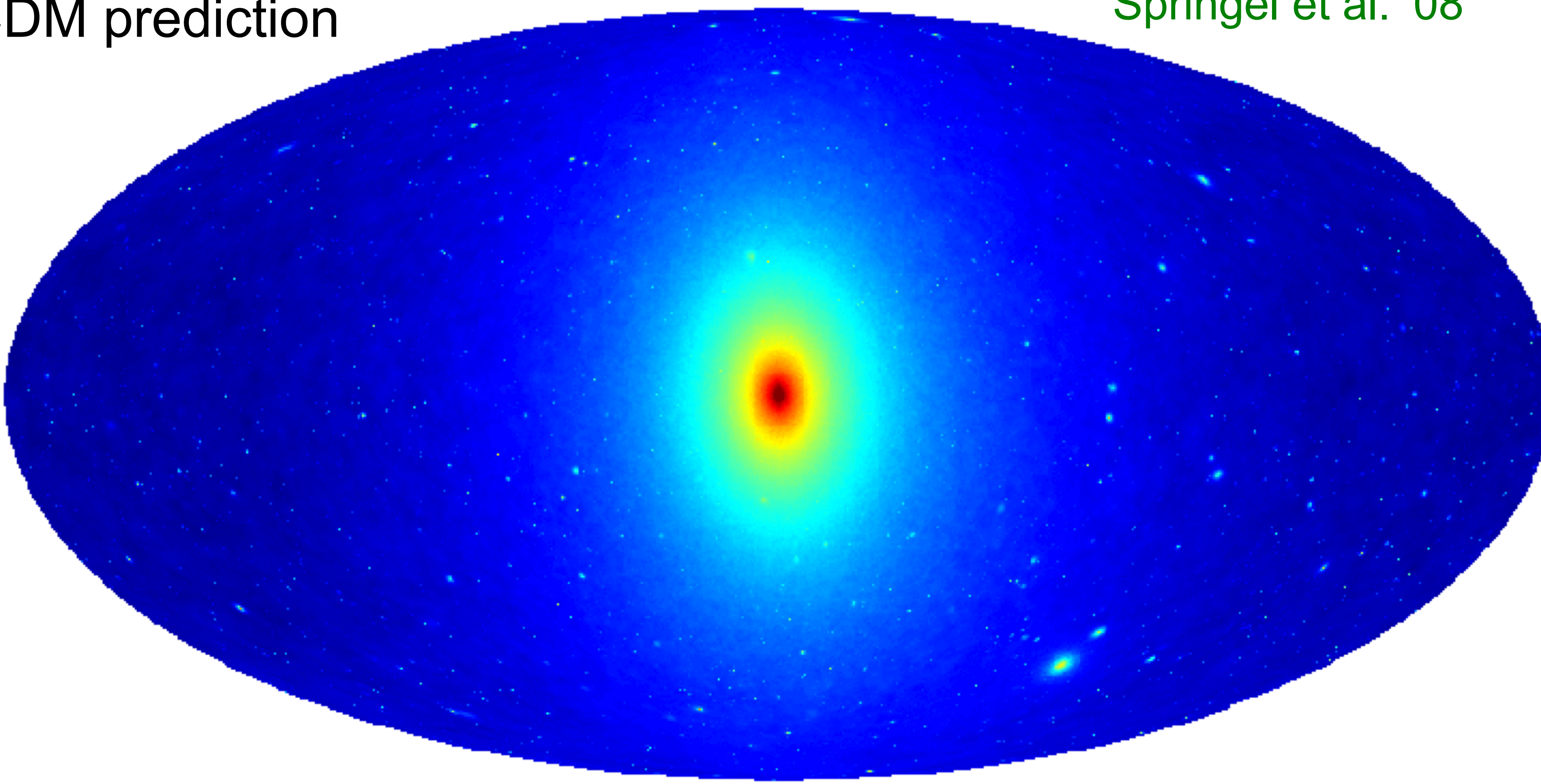
The Milky Way seen in annihilation radiation

University of Durham

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

CDM prediction

Springel et al. '08



MW's halo annihilation flux may be dominated by unresolved small subhalos but this is nearly uniform over the sky

Concentration-mass relation

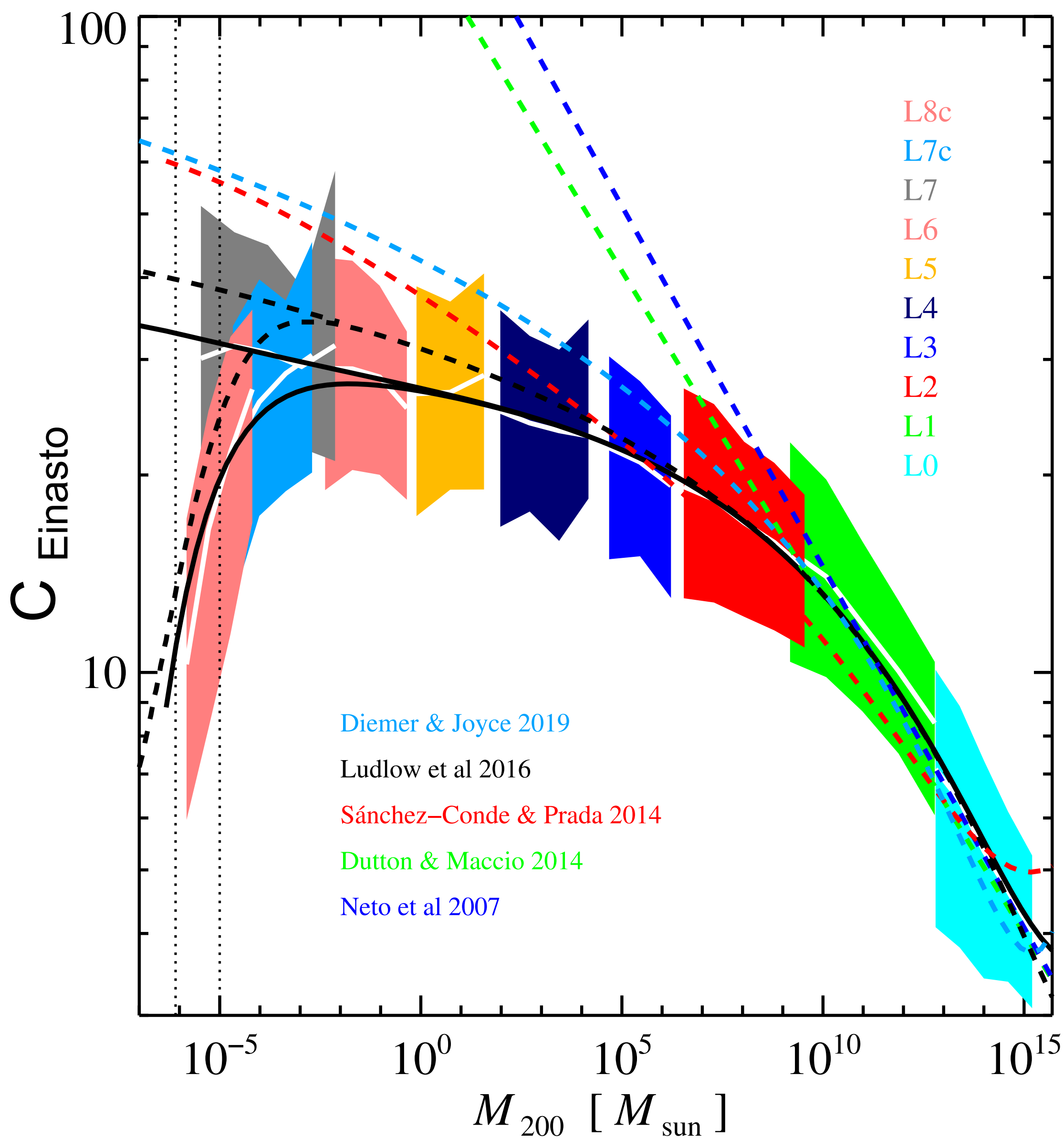
University of Durham

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

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

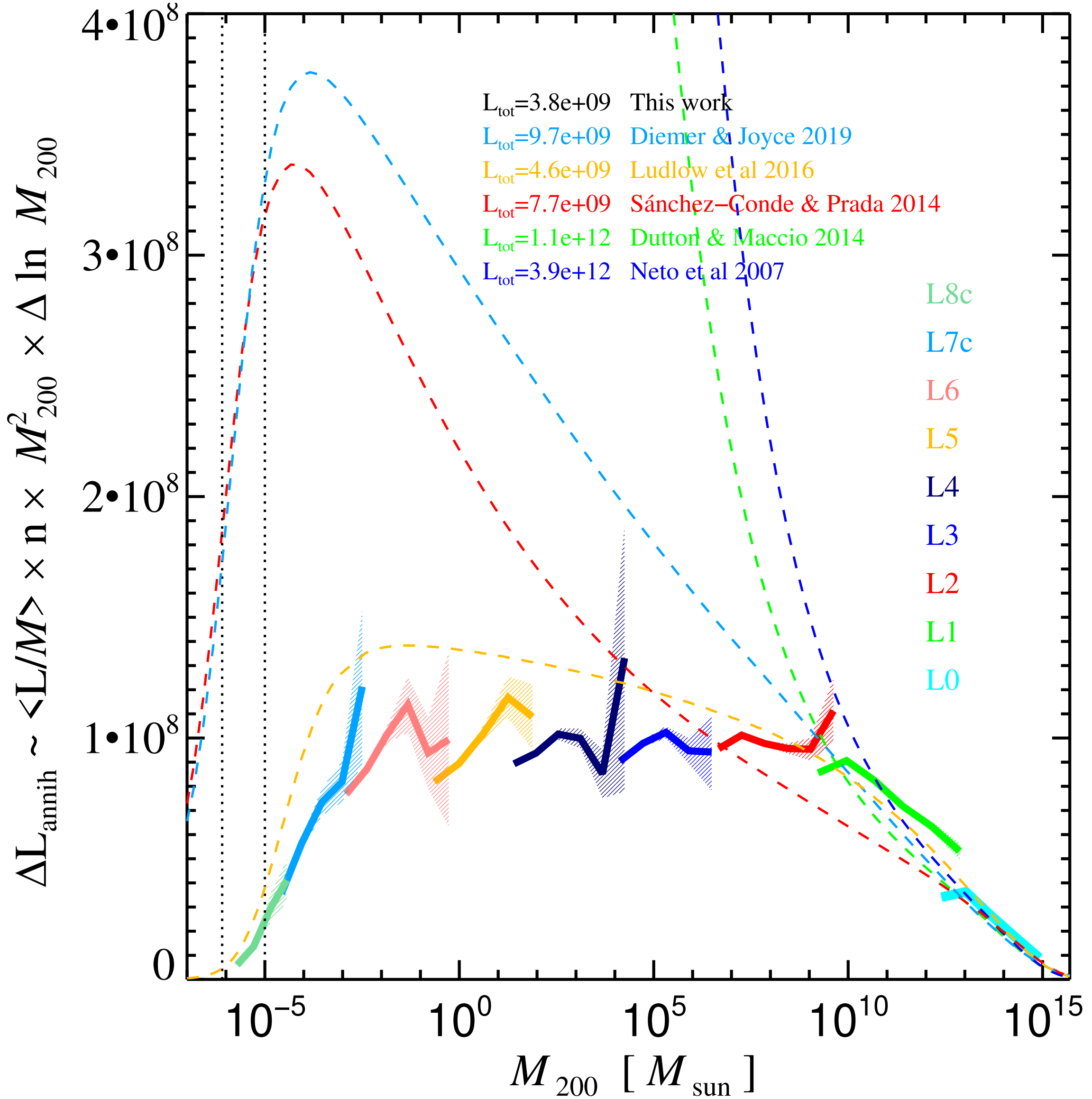
$10^{-4}\ M_\odot < M_{halo} < 10^{12}\ M_\odot$

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

This still neglects the substructure contribution to halo luminosity

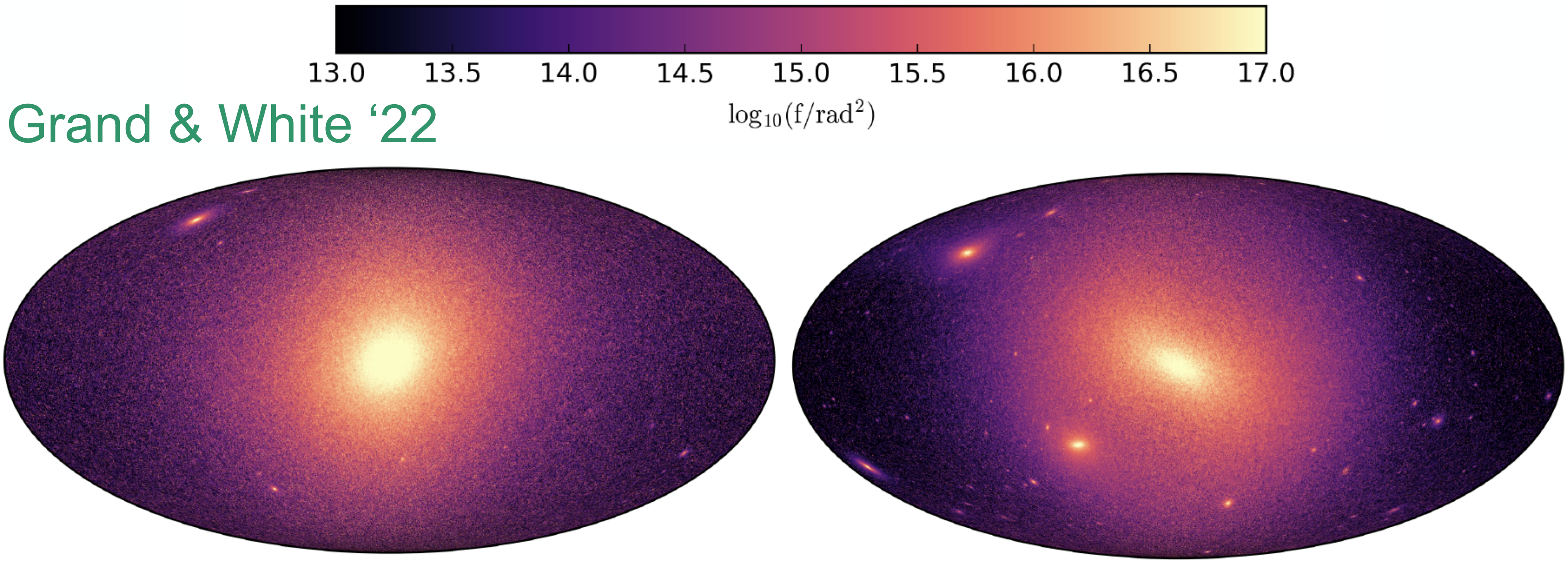
Wang, Bose, CSF + '20

Annihilation luminosity per unit cosmological volume



The Milky Way seen in annihilation radiation

Grand & White ‘22



“Full physics” Dark matter only

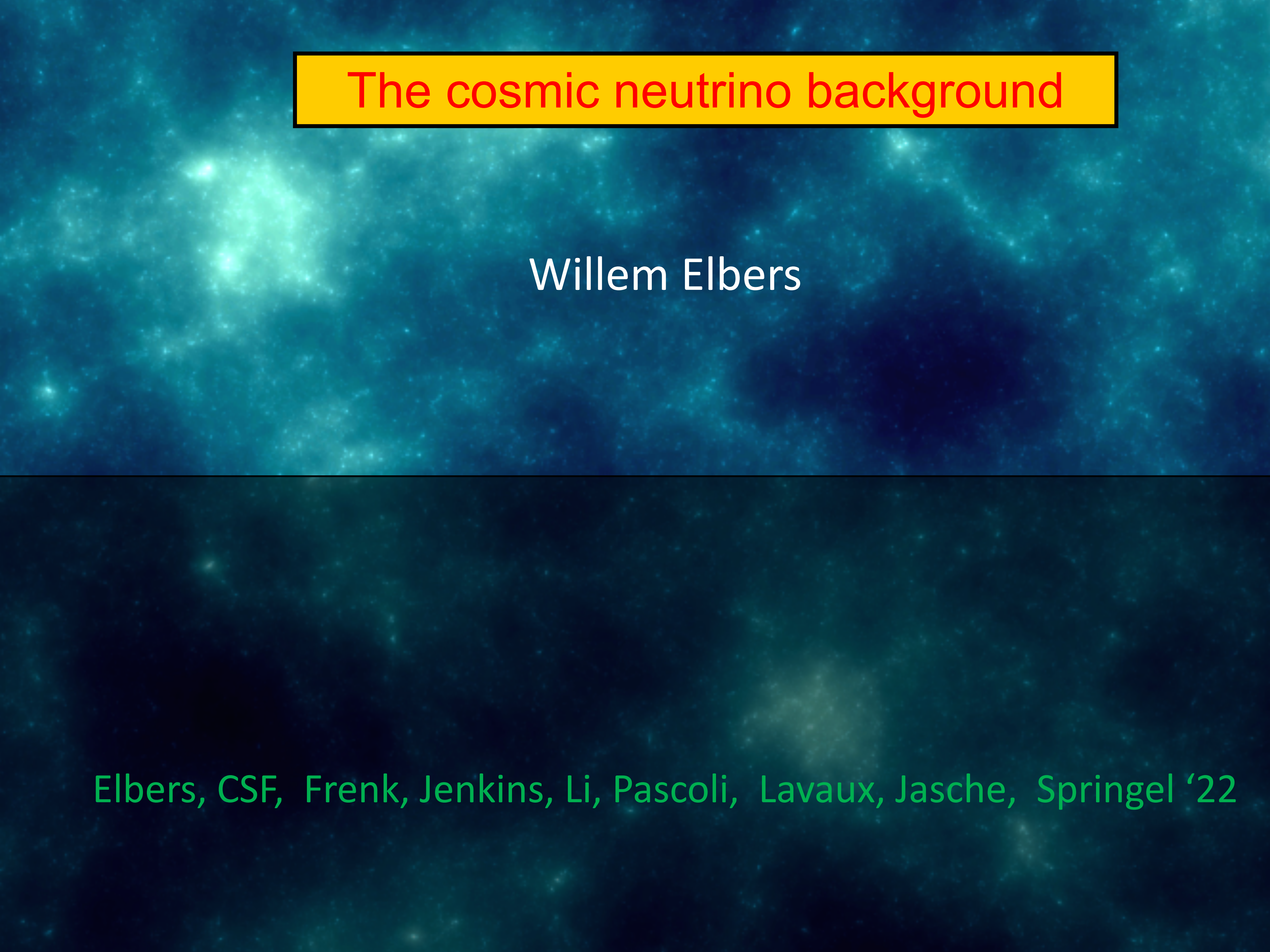
Include baryons and effect of small subhalos

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

The subhalos become fainter

→ Consistent with Fermi excess

The cosmic neutrino background



Willem Elbers

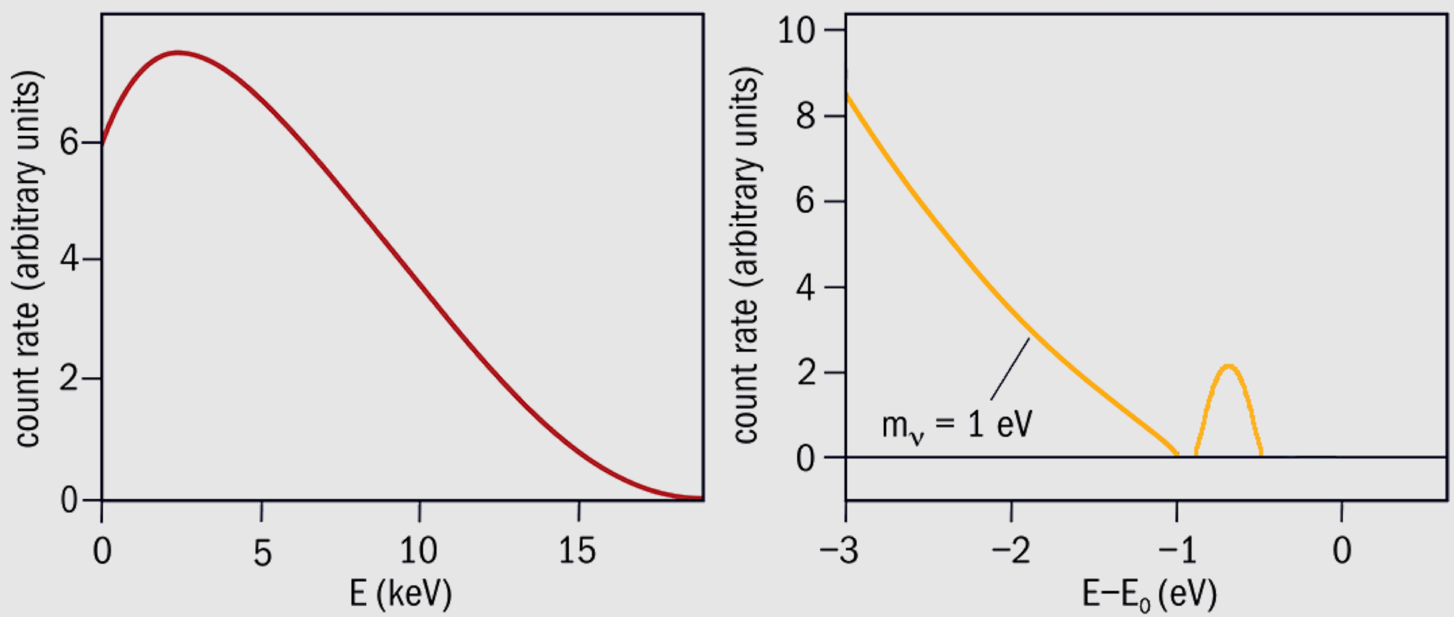
Elbers, CSF, Frenk, Jenkins, Li, Pascoli, Lavaux, Jasche, Springel '22

The cosmic neutrino background

Cosmic neutrino background detection possible through neutrino capture on nuclei

Katrin, Ptolemy

$$\nu_e + {}^3H \rightarrow {}^3He + e^-$$



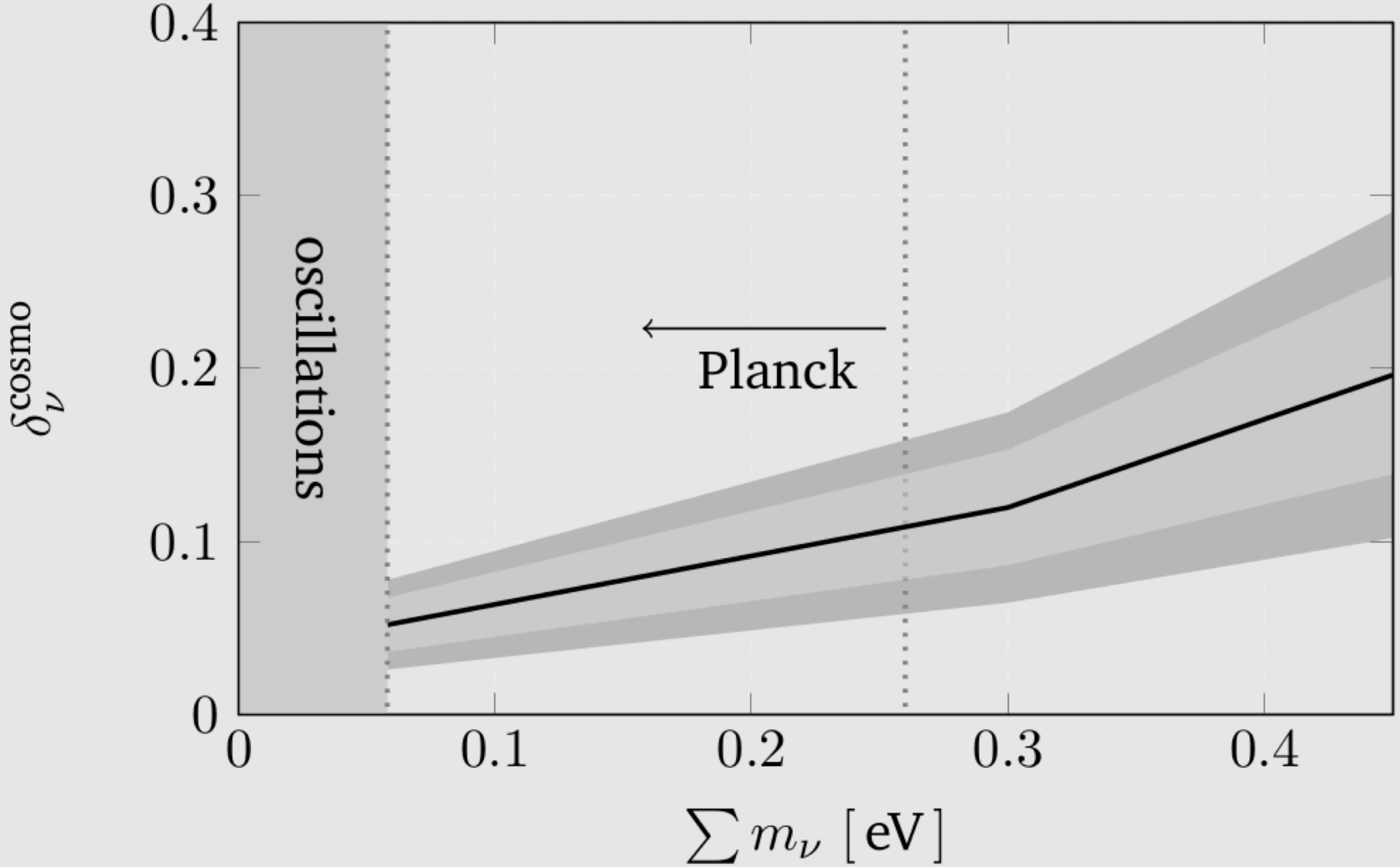
Credit CERN

Local neutrino density

Local density enhancement

$$\delta_{\nu,i} = \delta_{\nu,i}^{\text{halo}} + \delta_{\nu,i}^{\text{cosmo}}$$

→ Depends on the neutrino mass



Constrained realization simulations

Simulations from CDM initial conditions, with phases adjusted to reproduce the local observed galaxy clustering

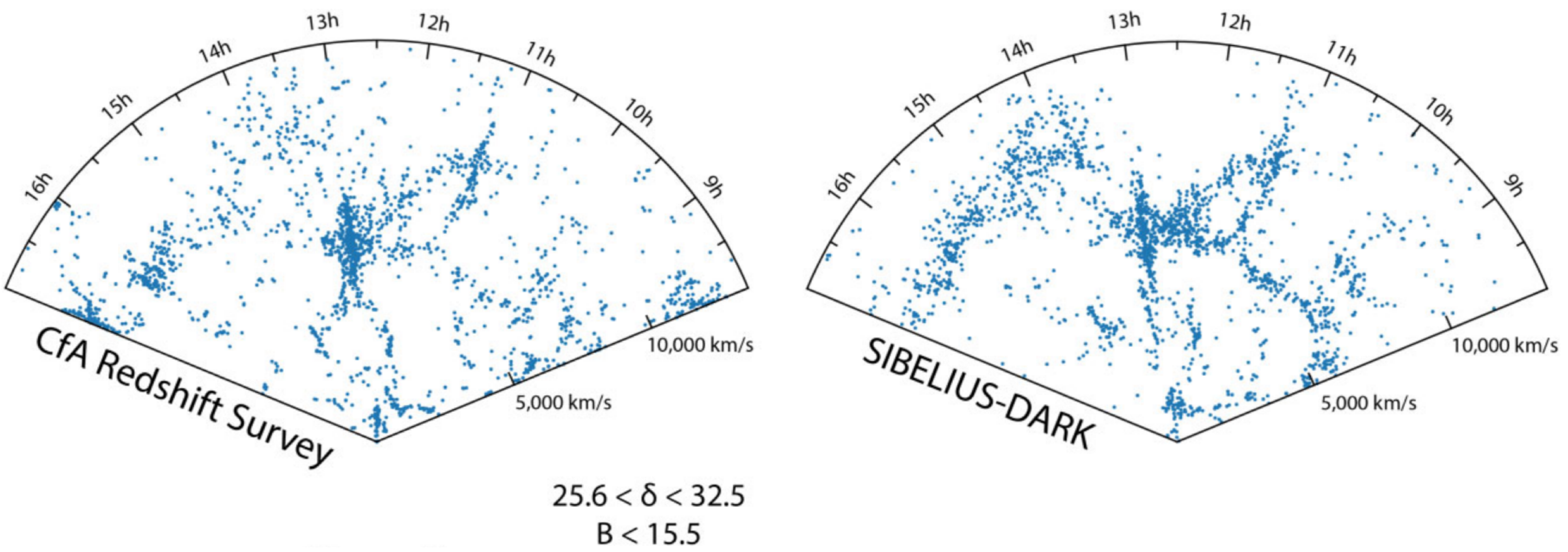
Sibelius project → Bayesian Origin Reconstruction with Galaxies (BORG)

Constraints from CMASS+ survey

Sibelius dark → r=200 Mpc sphere with ~10^7 $M_\odot$ particles

Sawala+ 2022; MaAlpine+ 2022

SIBELIUS dark

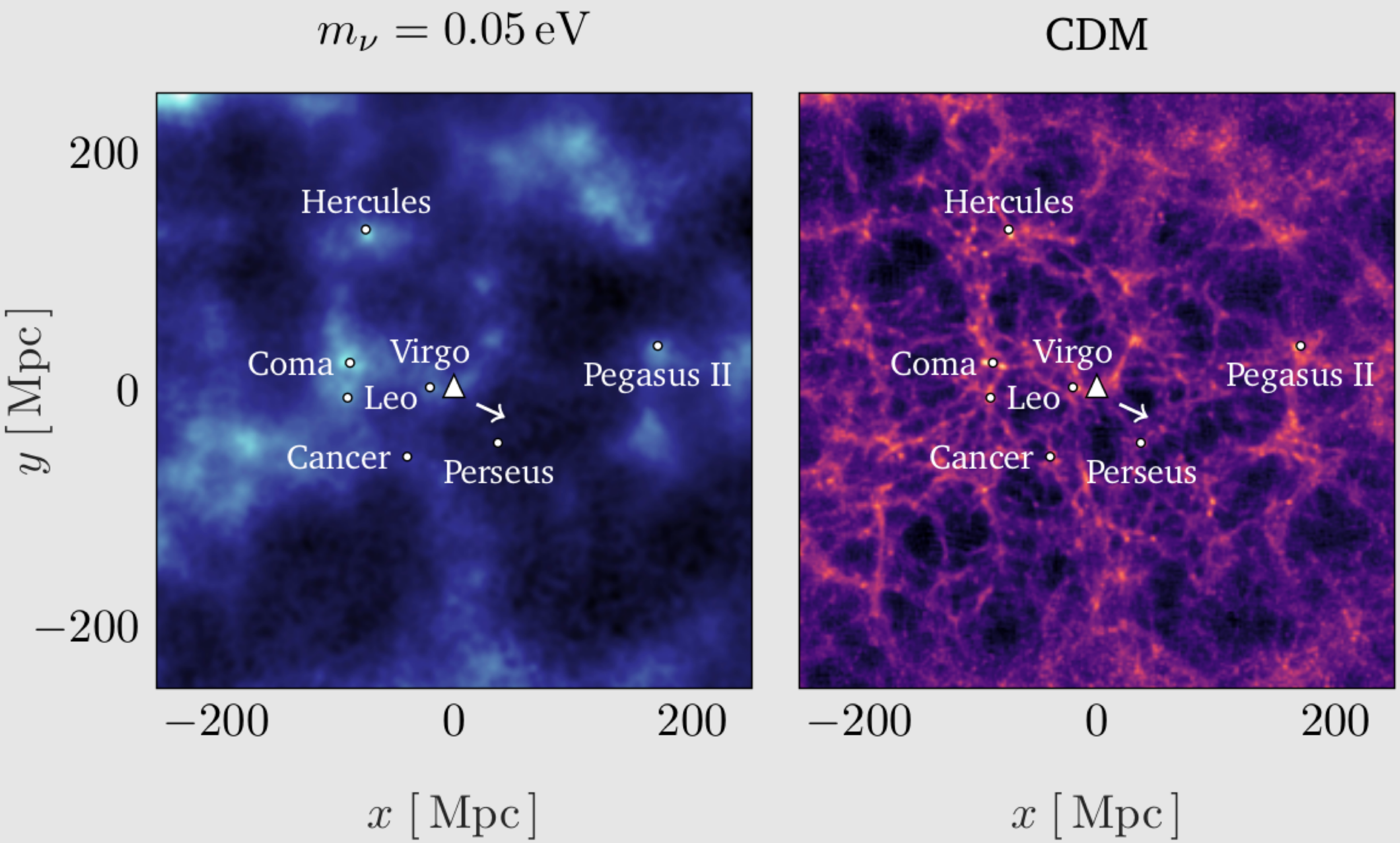


SIBELIUS dark follows growth of known objects in Local Universe

Constrained simulations test cosmology beyond cosmic-variance-limited statistics, turning each individual object into a test case

McAlpine+ 2022

Constrained simulations with νs



The position of the Milky Way is indicated by a white triangle and the dipole direction by an arrow

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Neutrino dipole

Dipoles of CMB (measured) and CNB (predicted)

	l	*b*	*v* [km/s]
CMB	276 °	30 °	627 ± 22
0.05 eV	302 °	48 °	246 ± 6
0.10 eV	310 °	43 °	347 ± 15
0.15 eV	315 °	38 °	442 ± 26

Elbers, CSF" '22

Local CDM distribution in z-space

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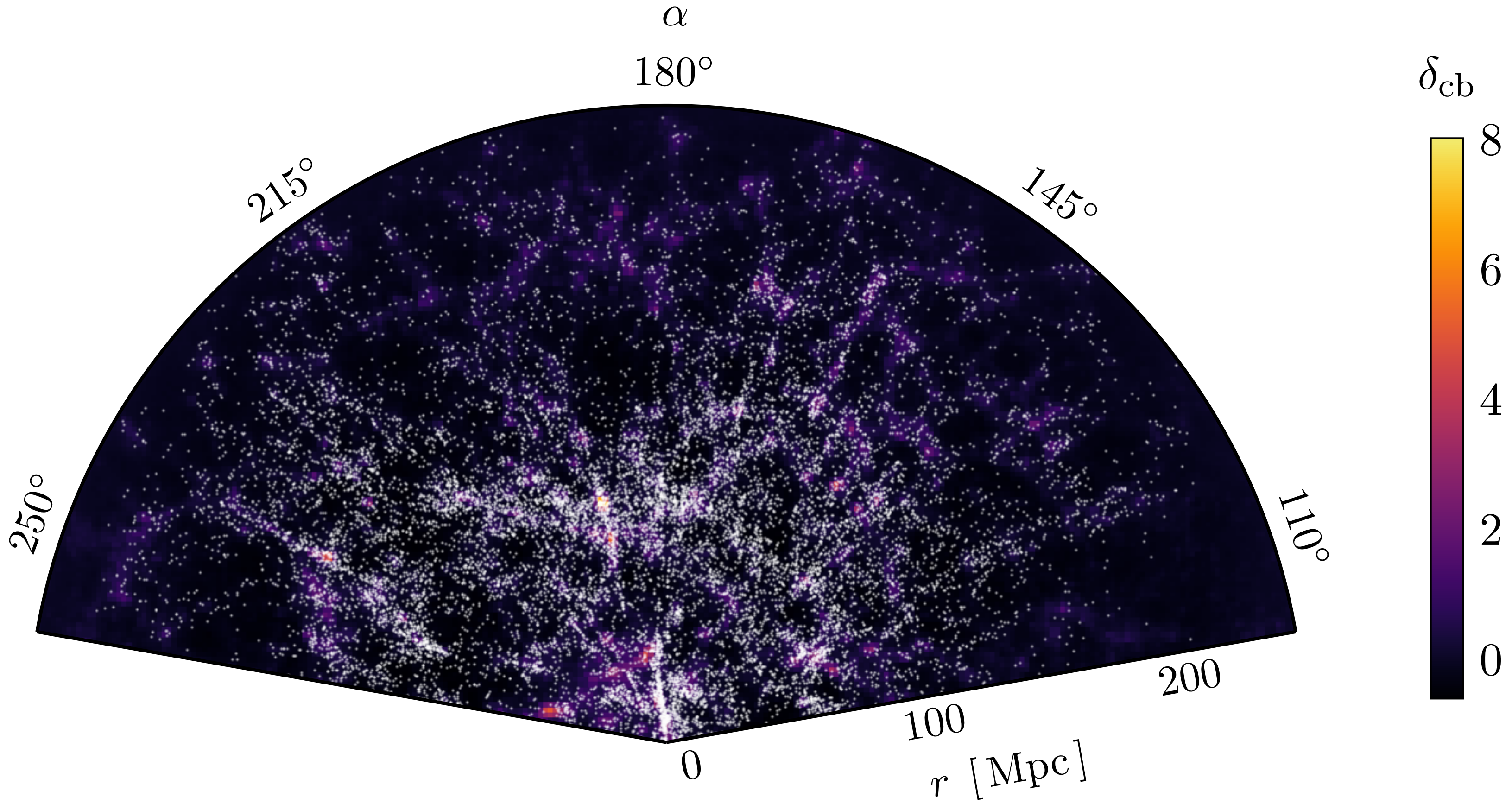

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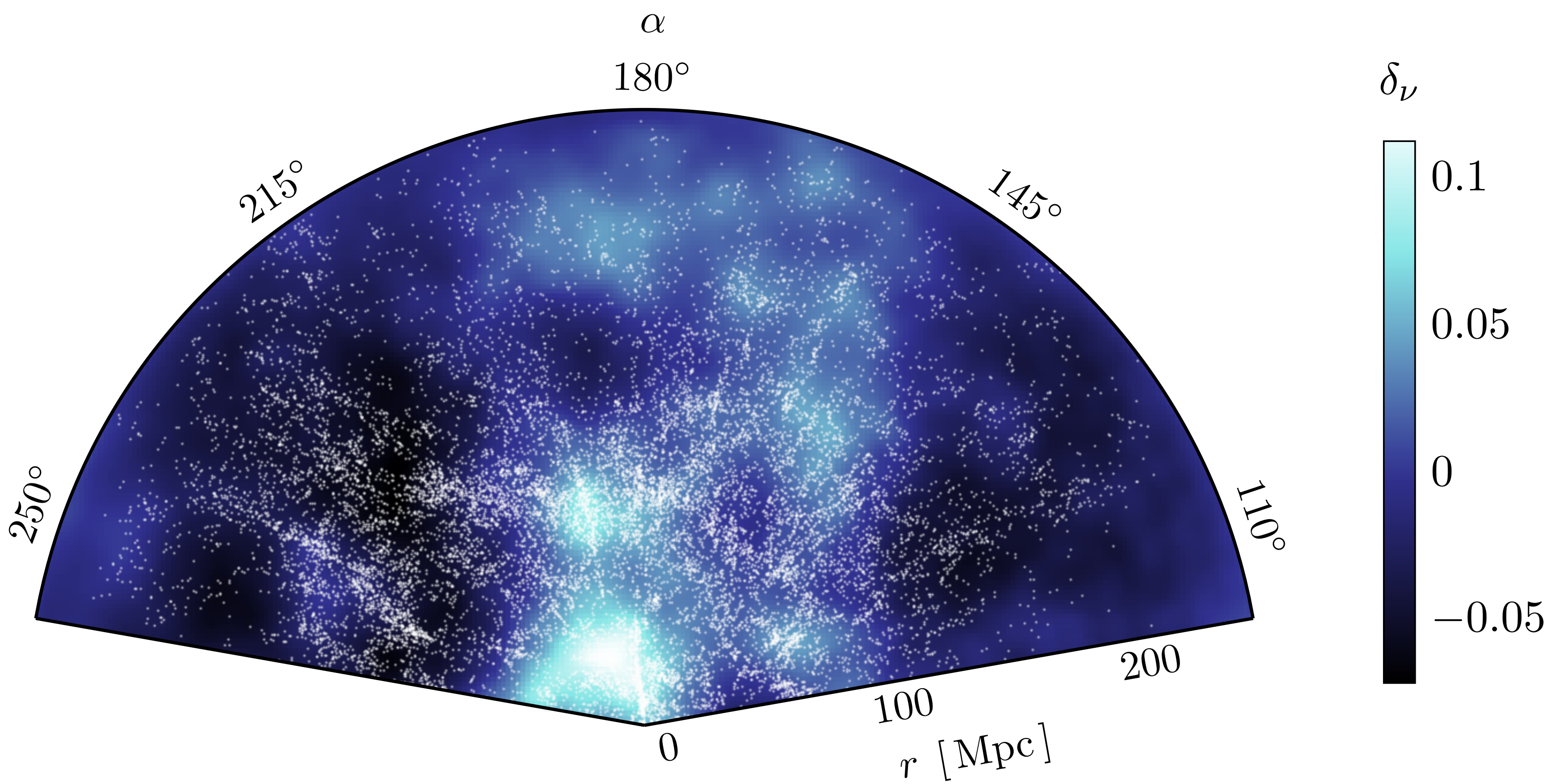
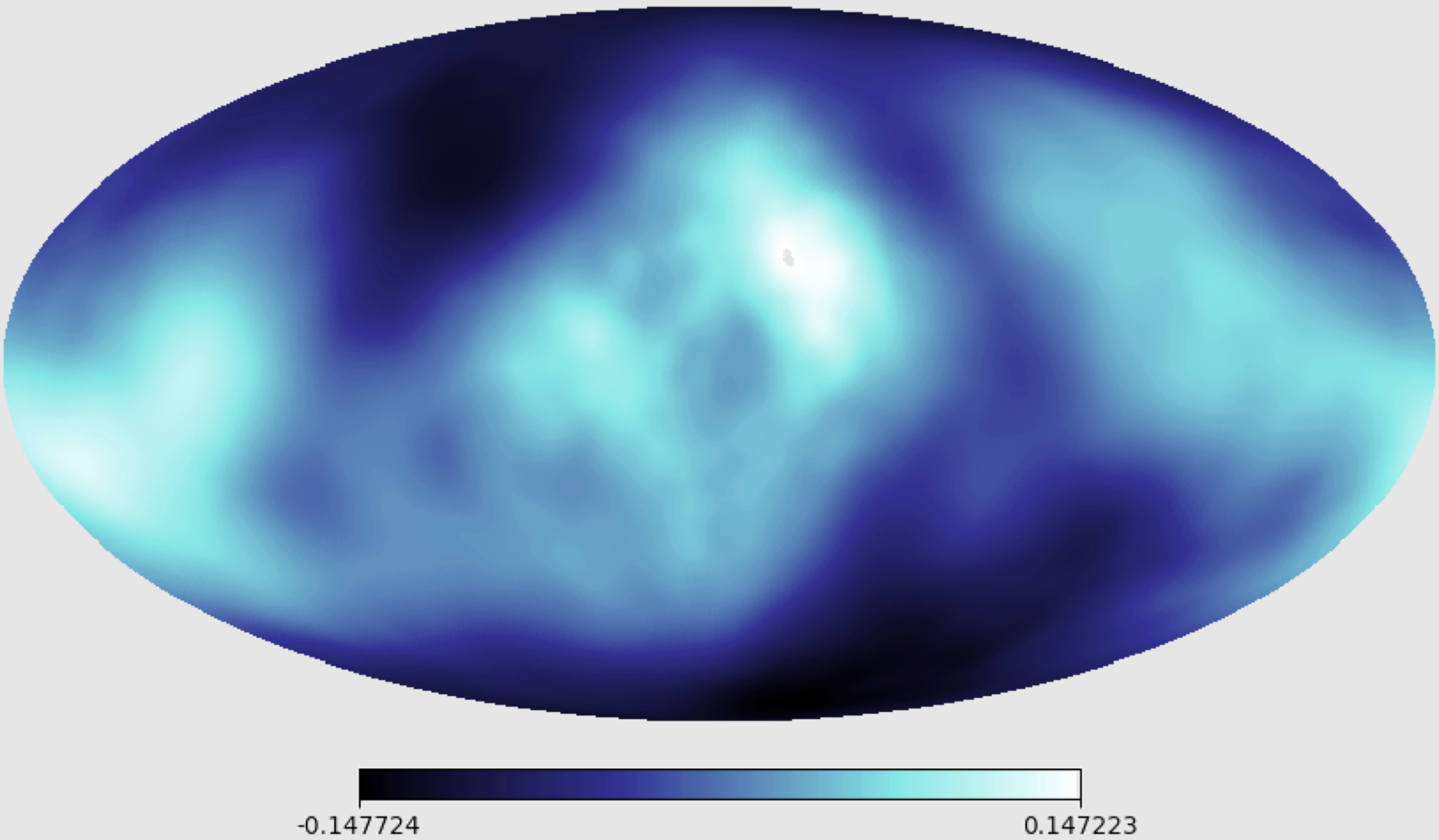
Local ν distribution in z-space



Angular anisotropies

University of Durham

Local neutrino density perturbations without dipole



Angular anisotropies

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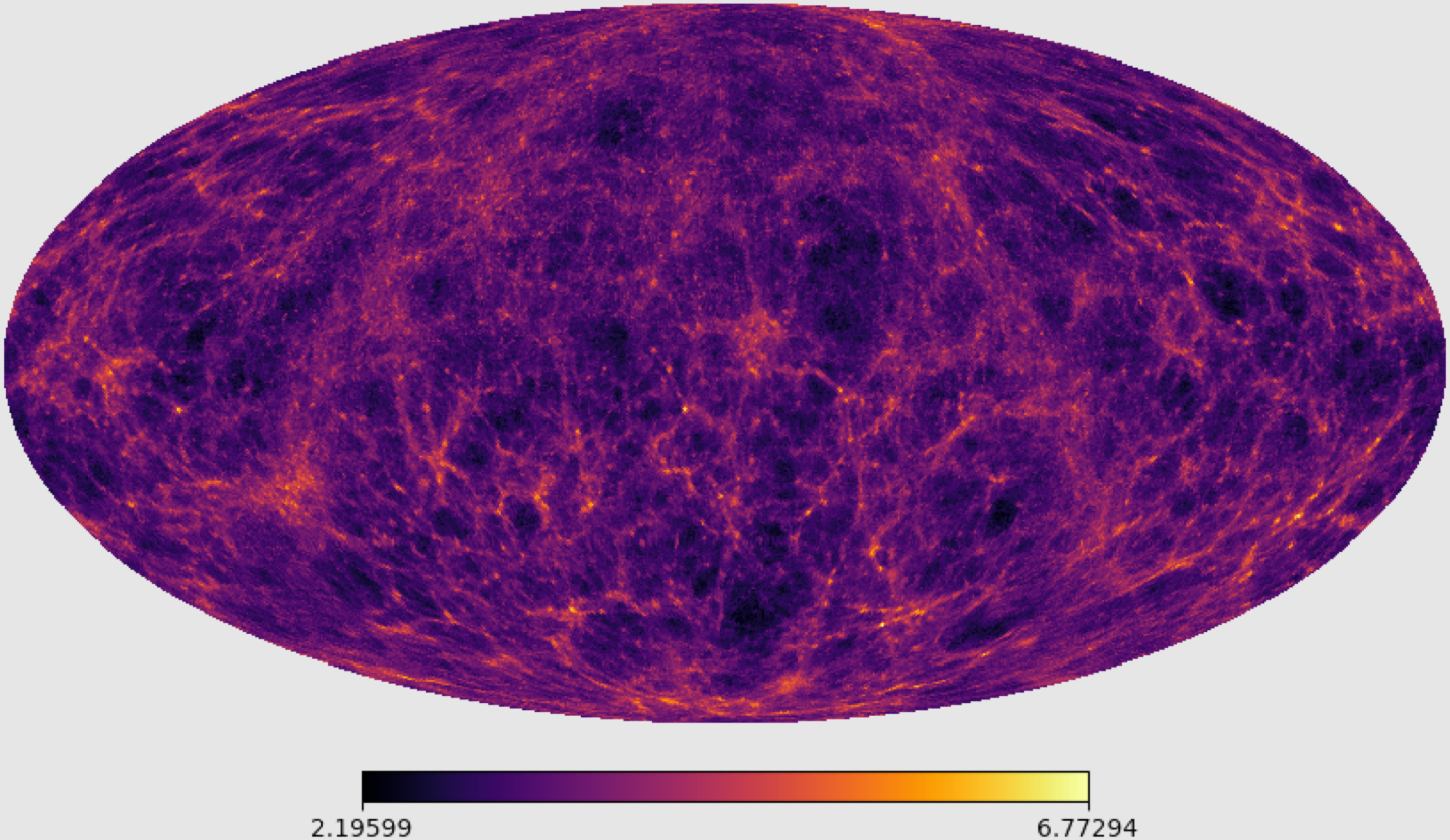
The integrated dark matter density within 200 Mpc



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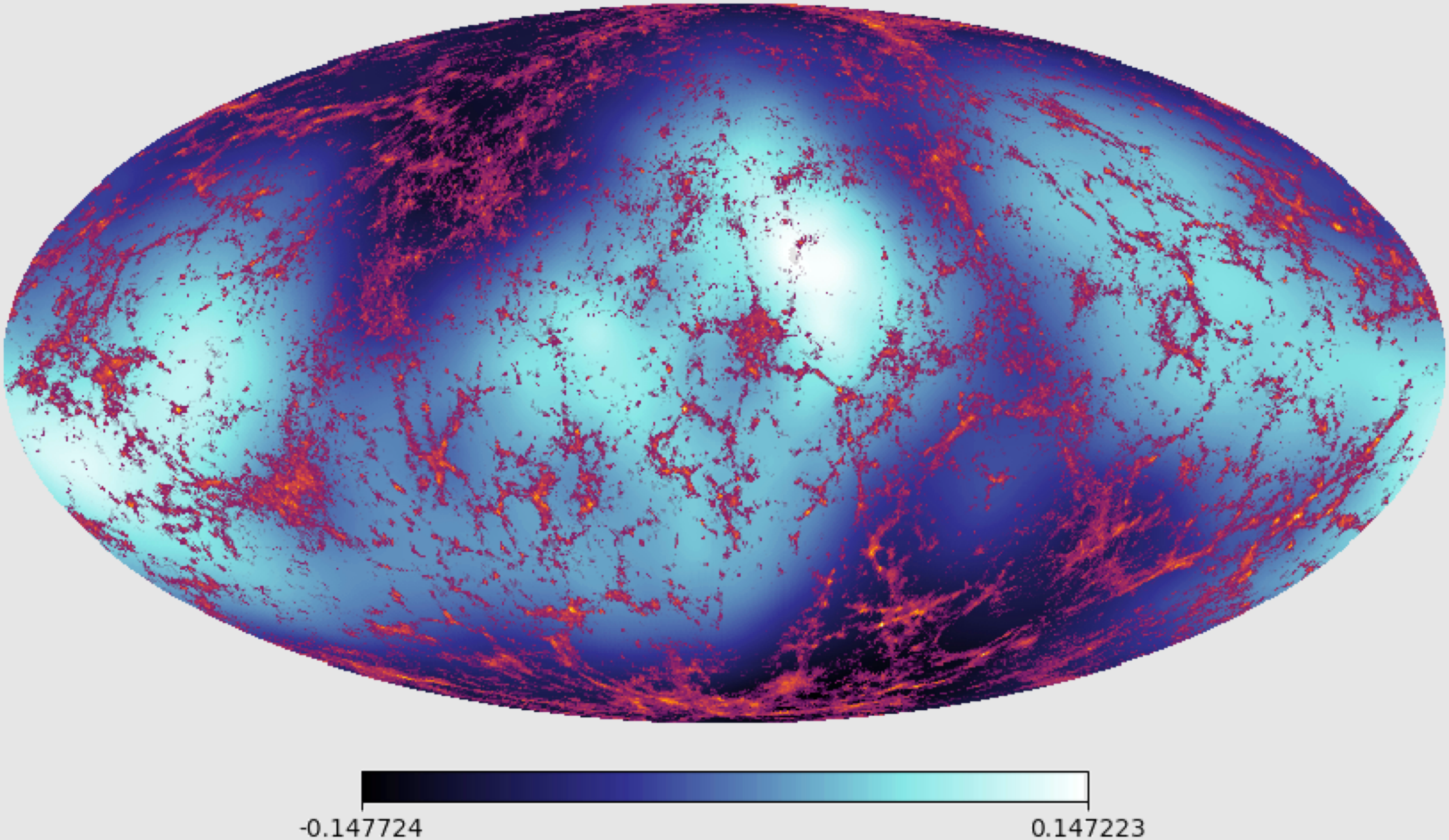
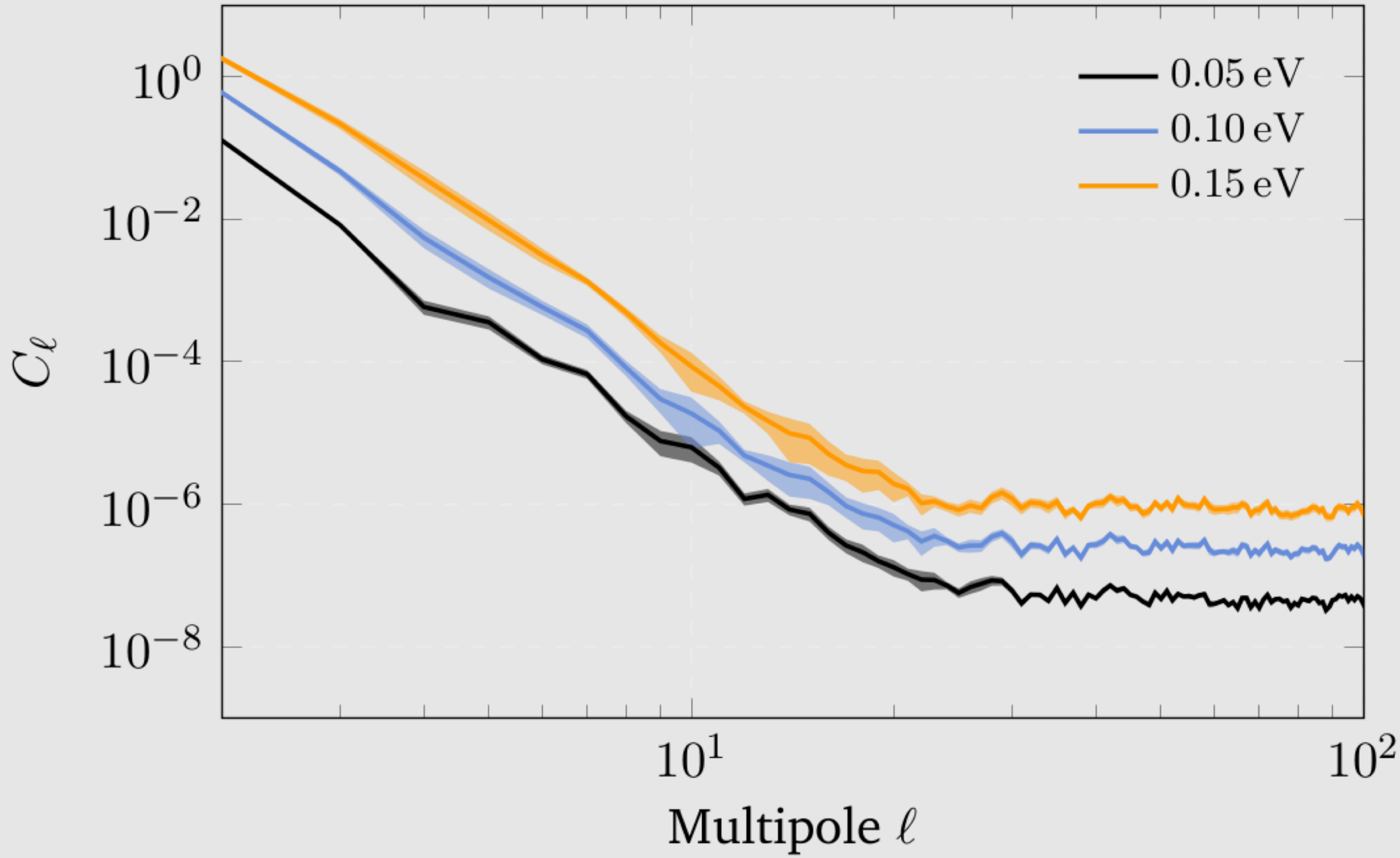
Angular anisotropies

Local neutrino density perturbations without dipole:



Angular power spectrum of ν perturbations



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Conclusions

- The abundance & structure of CDM halos (down to Earth's mass) and for WDM (no halos of mass <10^8 M_o) is now known
- CDM (and WDM) halos of all masses have NFW density profiles
- CDM and WDM predict the observed number of MW satellites
- Distortions of strong gravitational lenses offer a clean test of CDM *vs* WDM → and can potentially rule out CDM!
- The Fermi excess is consistent with CDM predictions for the anihilation radiation; subhalos are too faint to be detectable
- The local large-scale structure is reflected in the cosmic neutrino background. The MW dipole and the angular PS depend in the ν mass