A definitive test of the cold dark matter hypothesis

Carlos S. Frenk
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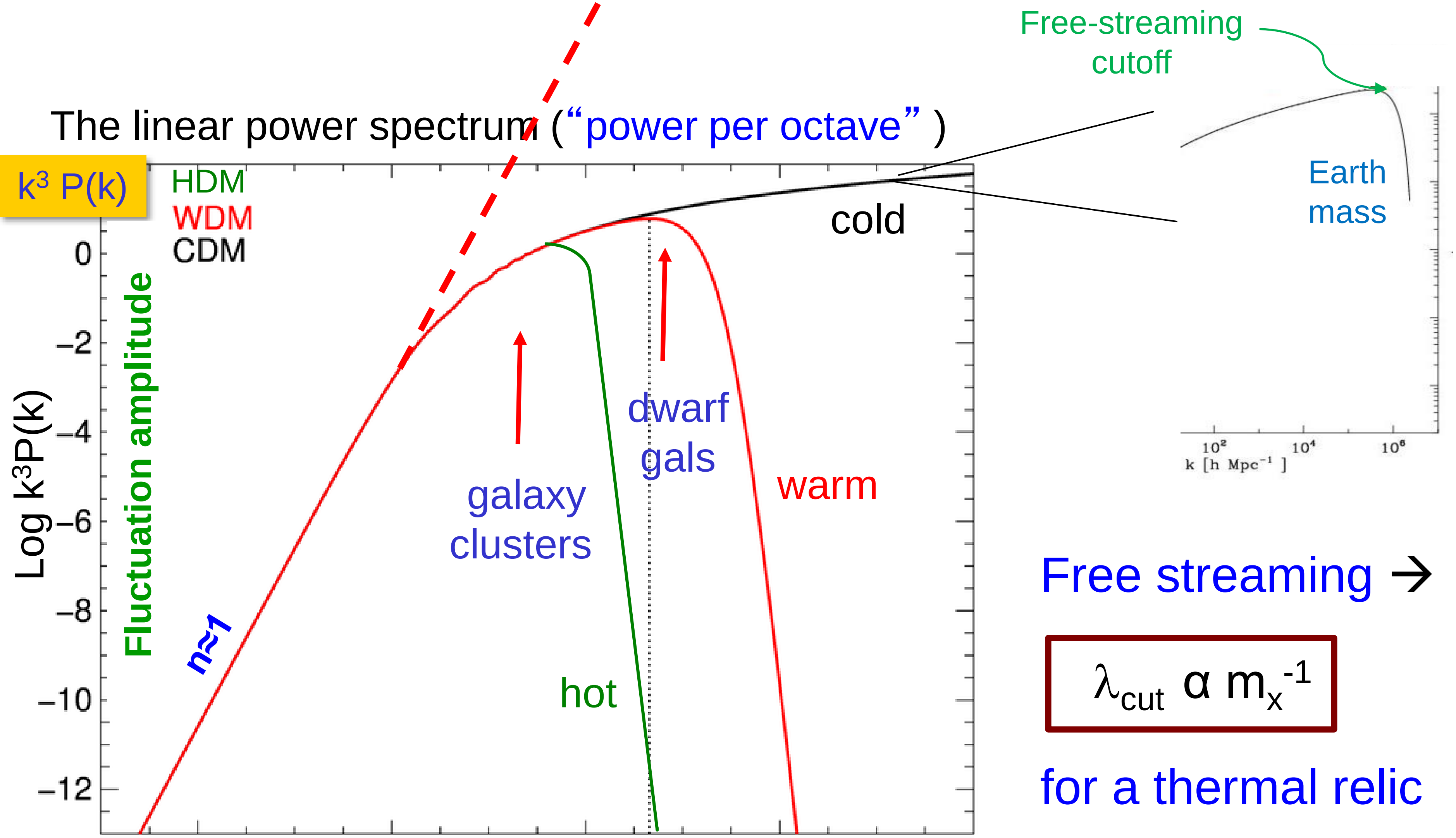
Non-baryonic dark matter candidates

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”)



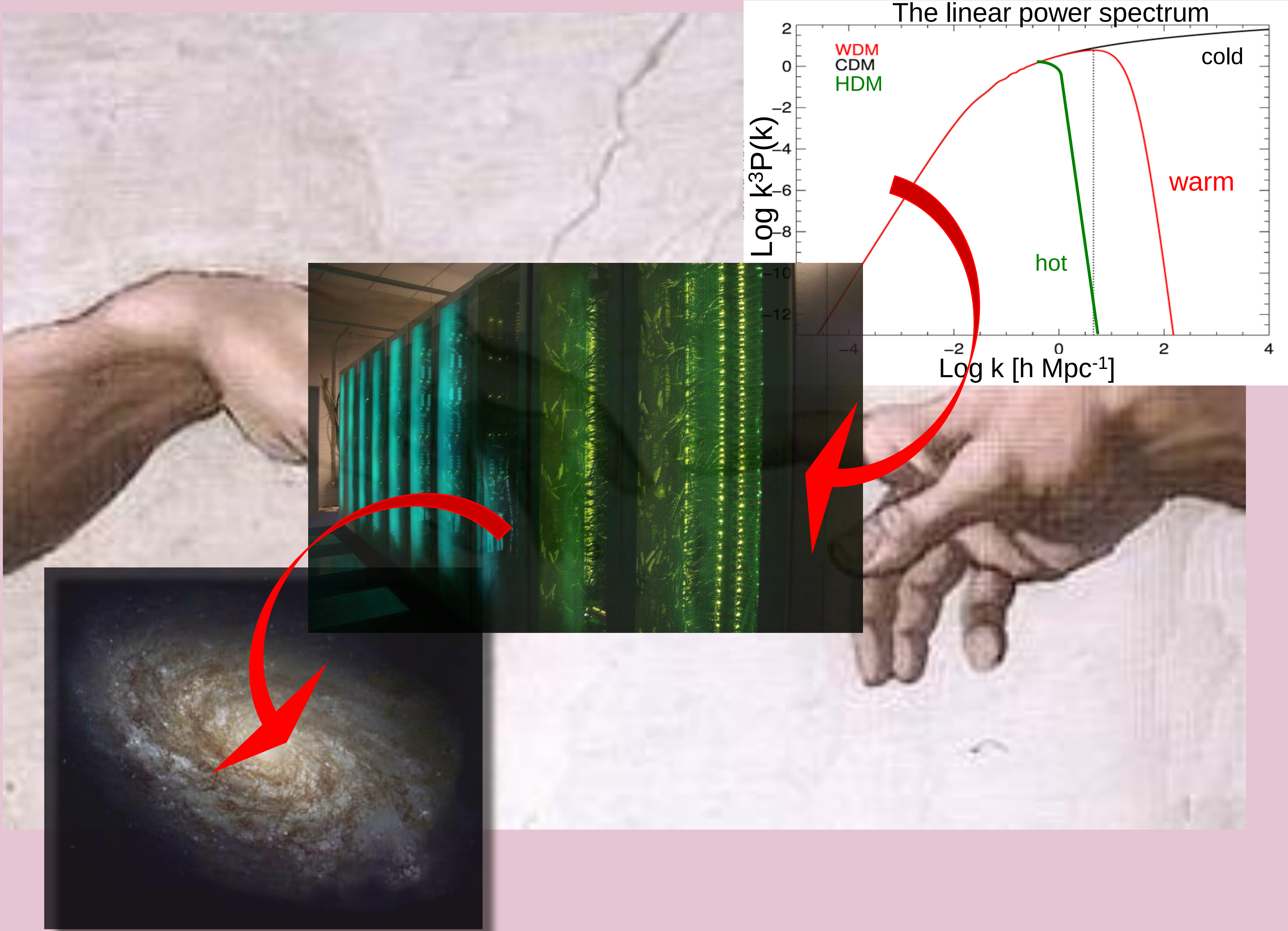
Free streaming →

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

for a thermal relic

These possibilites can be tested with astrophysics

Non-linear evolution



Non-linear evolution: simulations

Assumption about content of Universe → Initial conditions

Relevant equations:

Collisionless Boltzmann;

Poisson; Friedmann eqns;

Radiative hydrodynamics

Subgrid astrophysics

How to make a virtual universe

Hot dark matter

$m_\nu = 30$ ev → $\Omega_m = 1$

1981

HAS THE NEUTRINO A NON-ZERO REST MASS?*
(Tritium β-Spectrum Measurement)

V. Lubimov, E. Novikov, V. Nozik, E. Tretyakov
Institute for Theoretical and Experimental Physics, Moscow, U.S.S.R.

V. Kosik
Institute of Molecular Genetics, Moscow, U.S.S.R.

ABSTRACT

The high energy part of the β-spectrum of tritium in the
molecule was measured with high precision by a toroidal β-spect
meter. The results give evidence for a non-zero electron anti-
neutrino mass.

Fifty years ago Pauli introduced the neutrino to explain the β-spectrum shape. Pauli made the first estimate of the neutrino mass ($E_{3\,max} \cong$ nuclei mass defect): it should be very small or maybe zero. Up to now the study of the β-spectrum shape is the most sensitive, direct method of neutrino mass measurement.

For allowed β-transitions, if $M_\nu = 0$, then $S \simeq (E-E_o)^2$. The Kurie plot is then a straight line with the only kinematic parameter being $E_k = E_o$ (total β-transition energy). If $M_\nu \neq 0$, then $S \simeq (E_o-E)\sqrt{(E_o-E)^2-M_\nu^2}$. The Kurie plot is then distorted, especially near the endpoint.

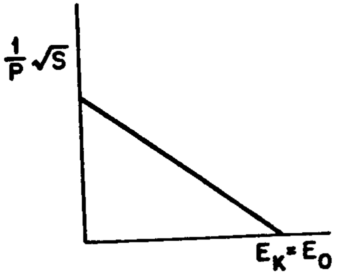


Fig. 1. Kurie plot for $M_\nu = 0$.

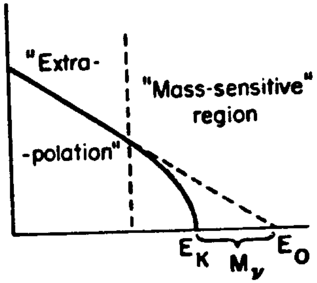


Fig. 2. Kurie plot for $M_\nu \neq 0$.

The method for the neutrino mass measurement is to obtain E_o from the extrapolation and obtain E_k from the spectrum intercept. Then $M_\nu = E_o - E_k$. Qualitatively, $M_\nu \neq 0$ if the β-spectrum near the end-point runs below the extrapolated curve.

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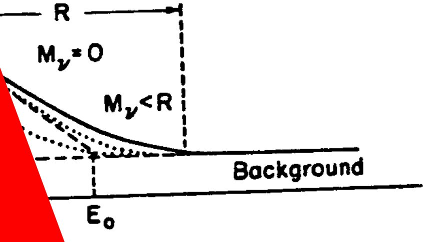
*Paper presented by Oleg Egorov.

things are more complicated. The apparatus reso-
rongly affects the spectrum endpoint and rather
e spectrum slope.



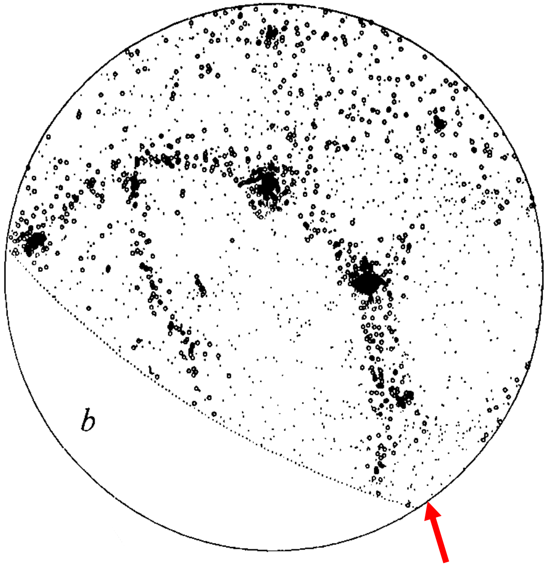
ealistic Kurie plot.

extrapolation. However, we are unable
, then once again the lack of counts near the
indicate that $M_\nu \neq 0$. If $M_\nu \leq R$, the changes due to
mass and the influence of R are indistinguishable. For M_ν
termination the knowledge of R is compulsory. The background de-
termines the statistical accuracy near the endpoint, i.e., in the
region of the highest sensitivity to the ν mass. So: 1) R should
be $\sim M_\nu$, 2) the smaller M_ν is, the smaller the background ($\sim M_\nu^2$)
must be and the higher the statistics ($\sim M_\nu^{-3}$) must be. For example,
suppose that for $M_\nu = 100$ eV we need resolution R, background Q, and
statistics N. If $M_\nu = 30$ eV, to achieve the same ΔM/M they should
be R/3, Q/10, and N × 30, respectively.

The shorter the β-spectrum, the less it is spread due to R (as
R ∿ Δp/p = const.). A classical example is ^{3}H β-decay, which has
1) the smallest $E_o \sim 18.6$ keV, 2) an allowed β-transition, simple
nucleus, and simple theoretical interpretation, 3) highly reduced
radioactivity. The first experiments with ^{3}H were by S. Curran
et al. (1948) and G. Hanna, B. Pontecorvo (1949). Using ^{3}H gas in
a proportional counter, they obtained $M_\nu \leq 1$ keV. Further progress
required magnetic spectrometer development. This allowed the reso-
lution to be improved considerably, and L. Langer and R. Moffat
(1952) obtained $M_\nu \leq 250$ eV. The best value was obtained by
K. Bergkvist (1972): R ∿ 50 eV and $M_\nu \leq 55$ eV.

The ITEP spectrometer is of a new type: ironless, with toroi-
dal magnetic field (E. Tretyakov, 1973). The principle of the tor-
oidal magnetic field focusing systems was proposed by V. Vladimirsky
et al. (An example is a "Horn" of ν-beams.) It turns out that a
rectilinear conductor (current) has a focusing ability for particles
emitted perpendicular to the rotation axis. This system has infinite
periodical focusing structure. The ITEP spectrometer is based on
this principle.

Non-baryonic dark matter cosmologies



Neutrinos
Ω=1

Frenk, White
& Davis ‘83

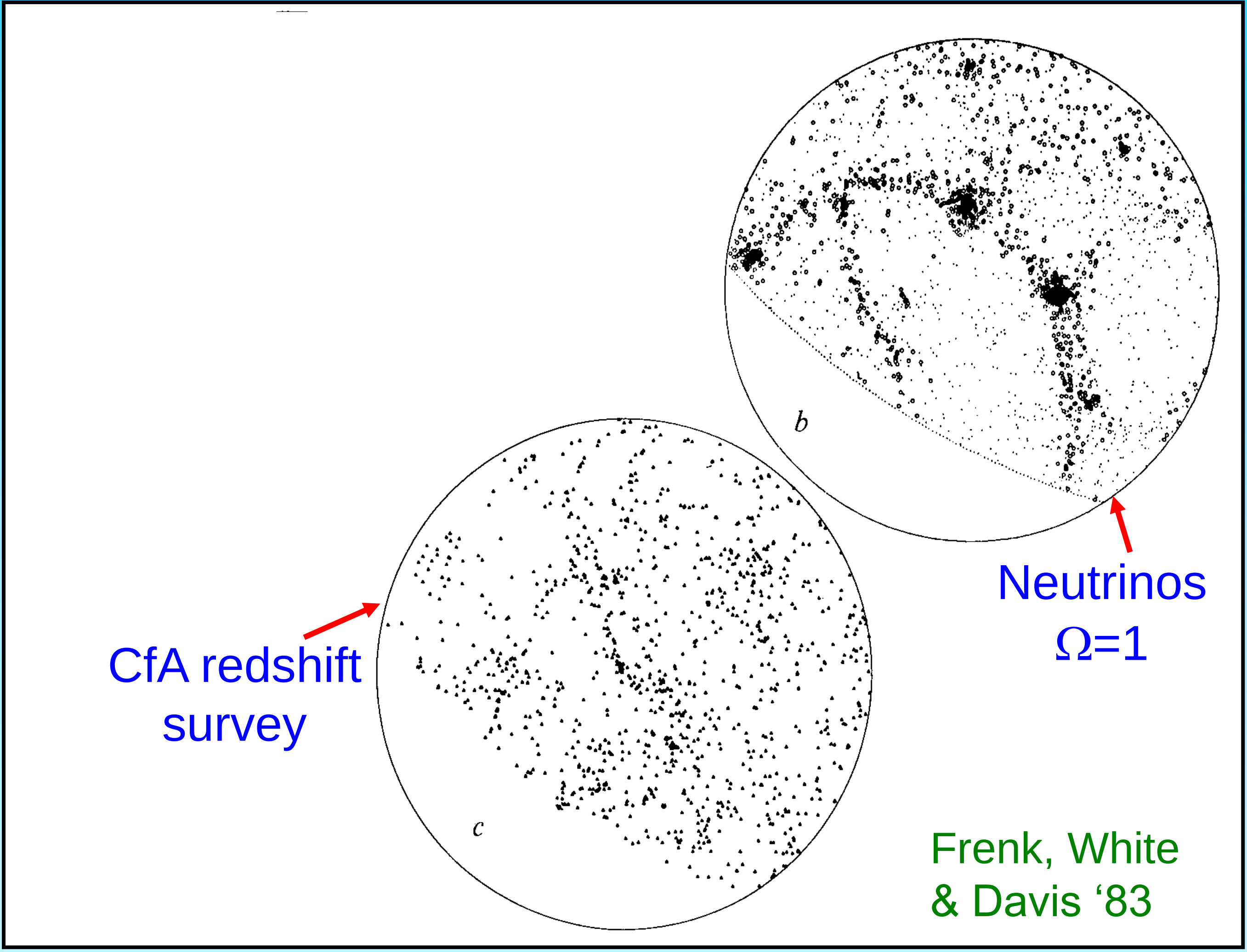
University of Durham

Non-baryonic dark matter cosmologies

Neutrino DM → wrong clustering

Neutrinos cannot make appreciable contribution to Ω

→ $m_\nu << 30$ ev



CfA redshift survey

Neutrinos Ω=1

Frenk, White & Davis ‘83

Non-baryonic dark matter cosmologies

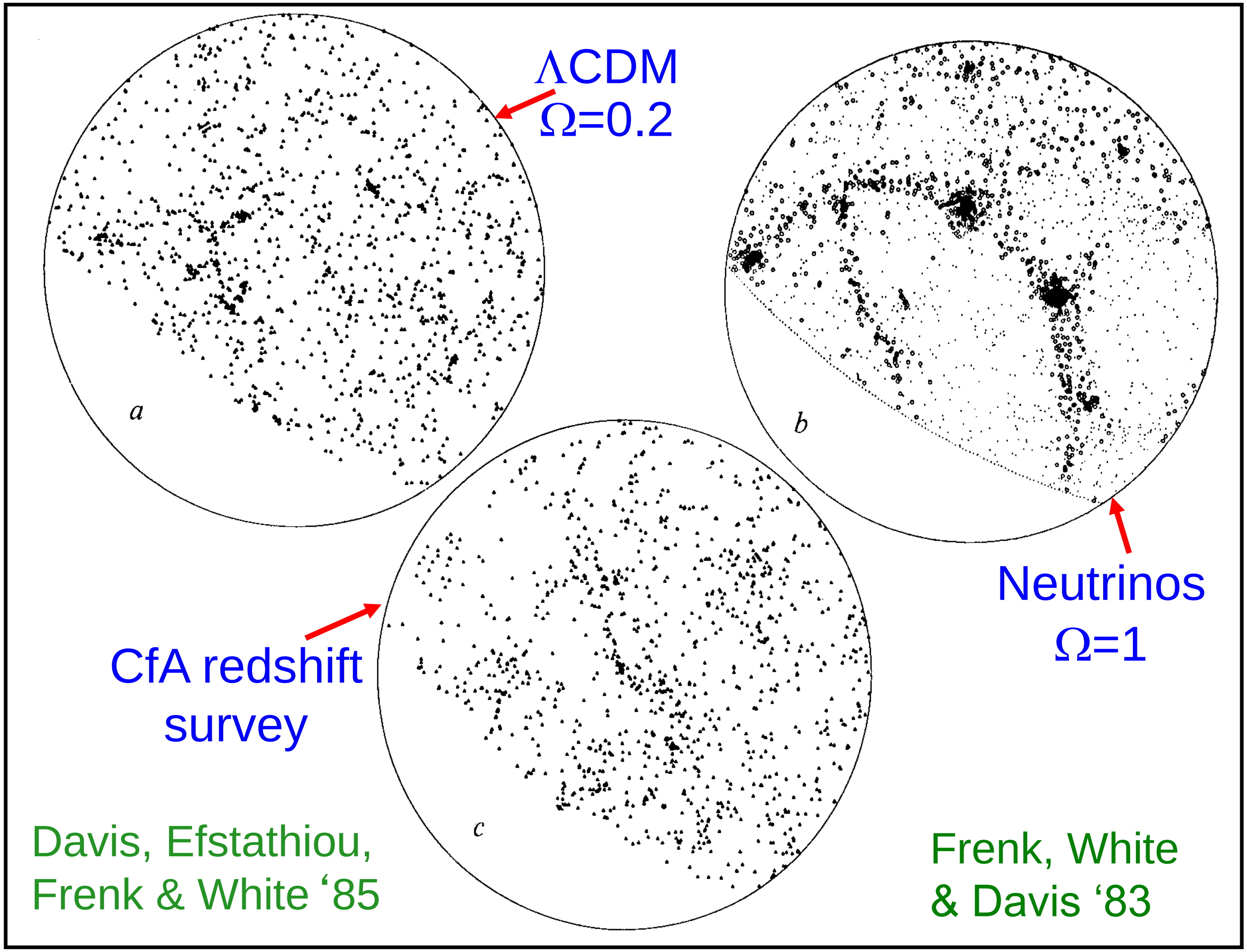
Neutrino DM → wrong clustering

Neutrinos cannot make appreciable contribution to Ω

→ m_{ν}<< 30 ev

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically



ΛCDM Ω=0.2

Neutrinos Ω=1

CfA redshift survey

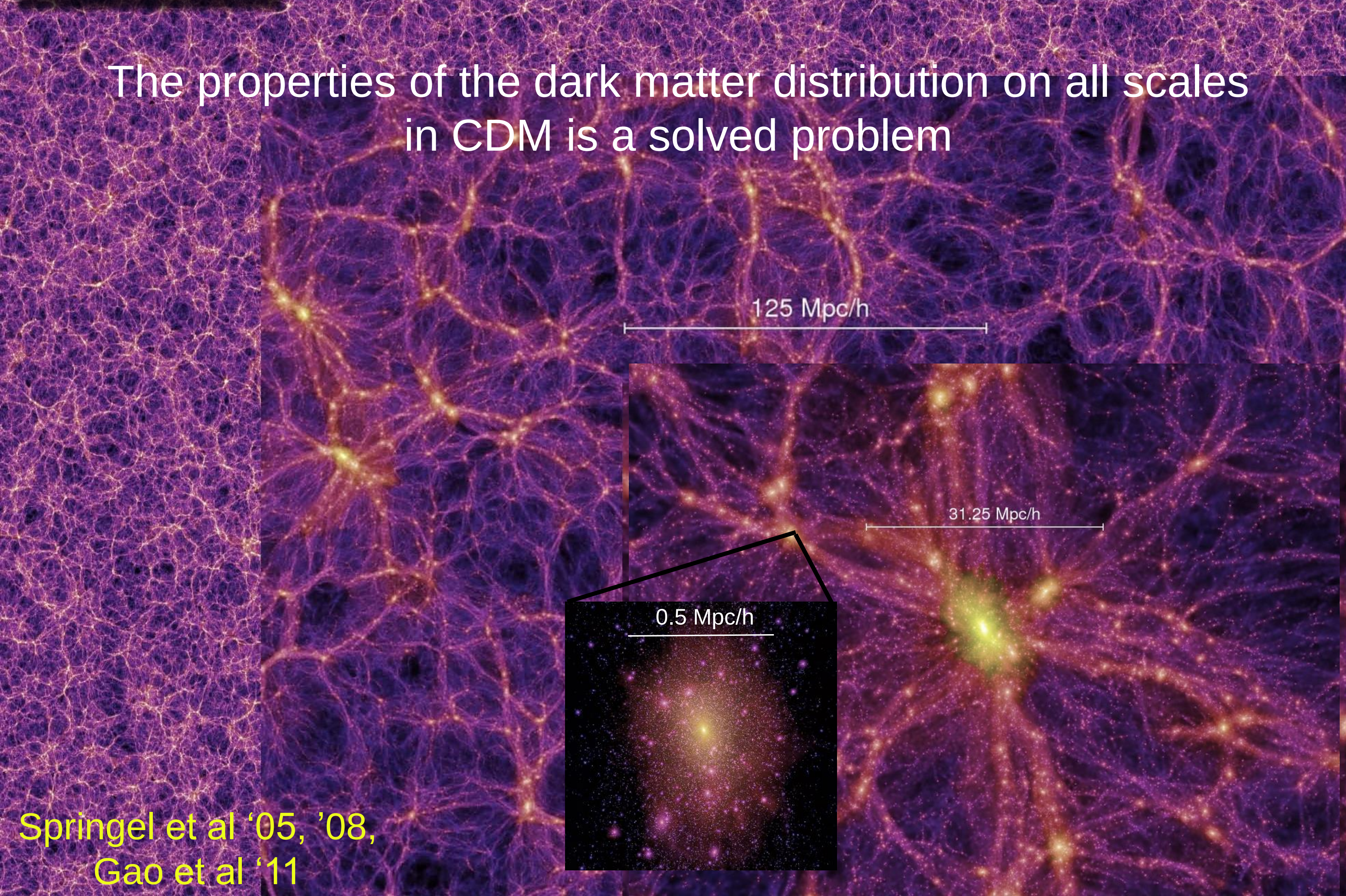
Davis, Efstathiou, Frenk & White ‘85

Frenk, White & Davis ‘83

The properties of the dark matter distribution on all scales in CDM is a solved problem

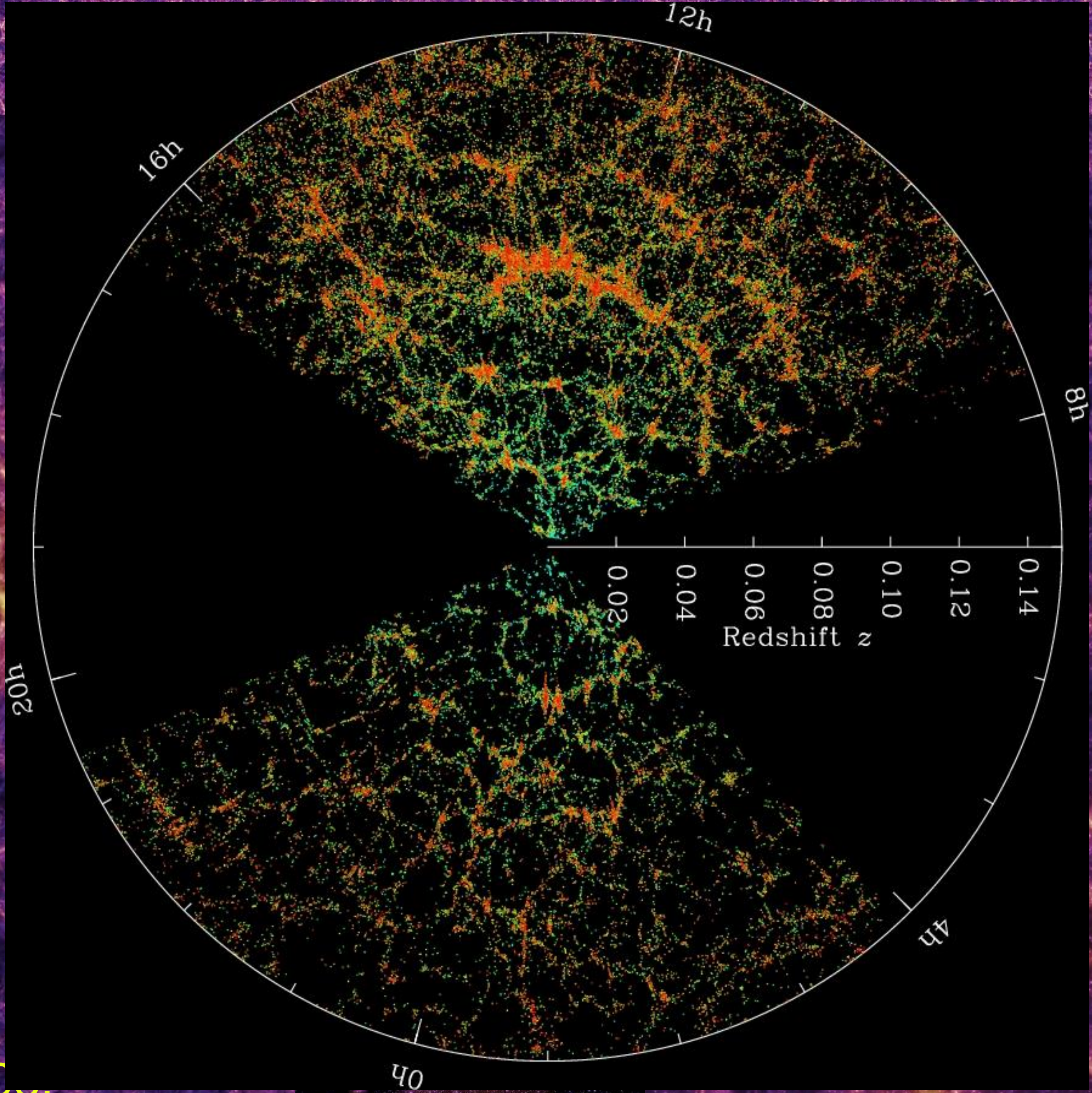
The Millennium/Aquarius/Phoenix simulation series

The properties of the dark matter distribution on all scales in CDM is a solved problem



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

The Millennium/Aquarius/Phoenix simulation series



Springel et al ‘05, ’0
Gao et al ‘11

2020s

Galaxy distribution encodes info about dark matter and dark energy

DESI already has > 10 million spectra

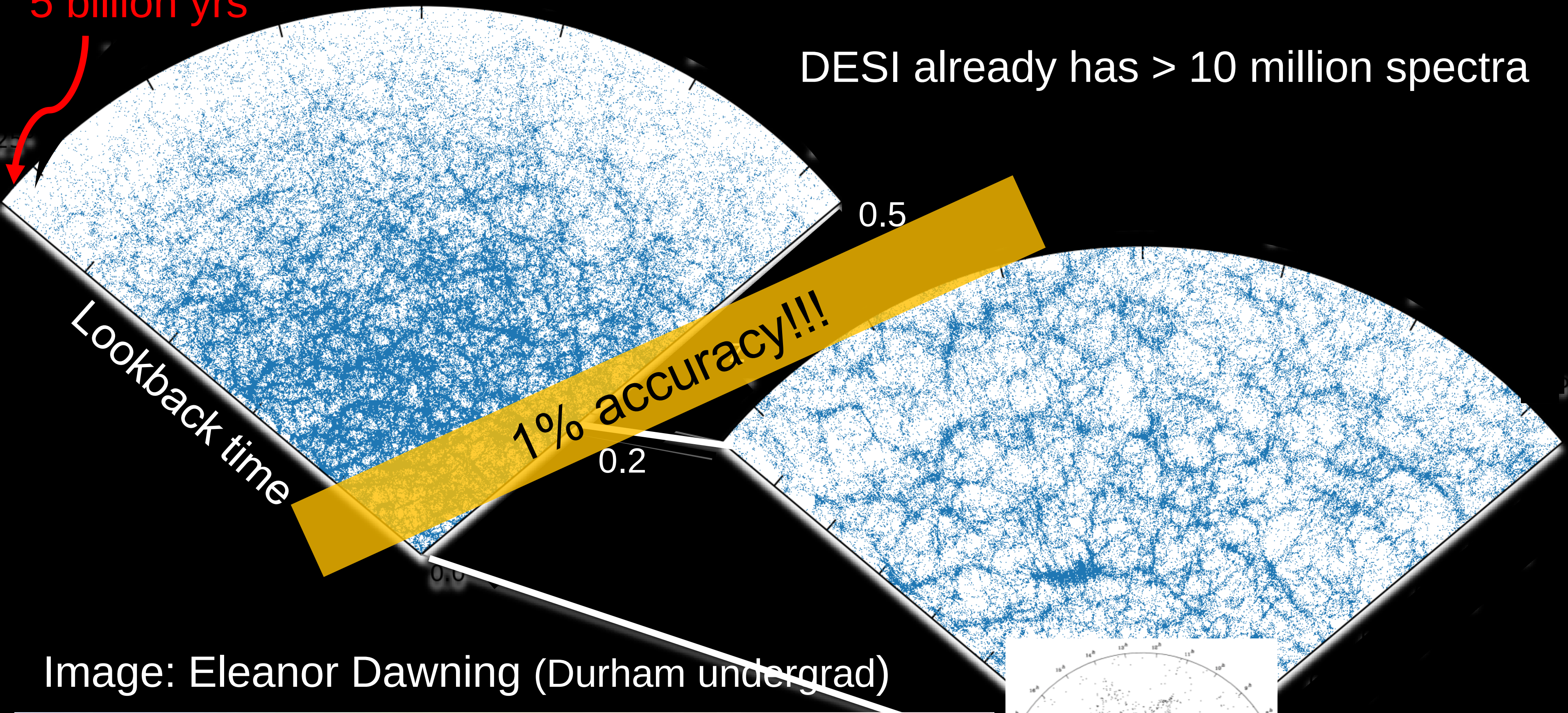
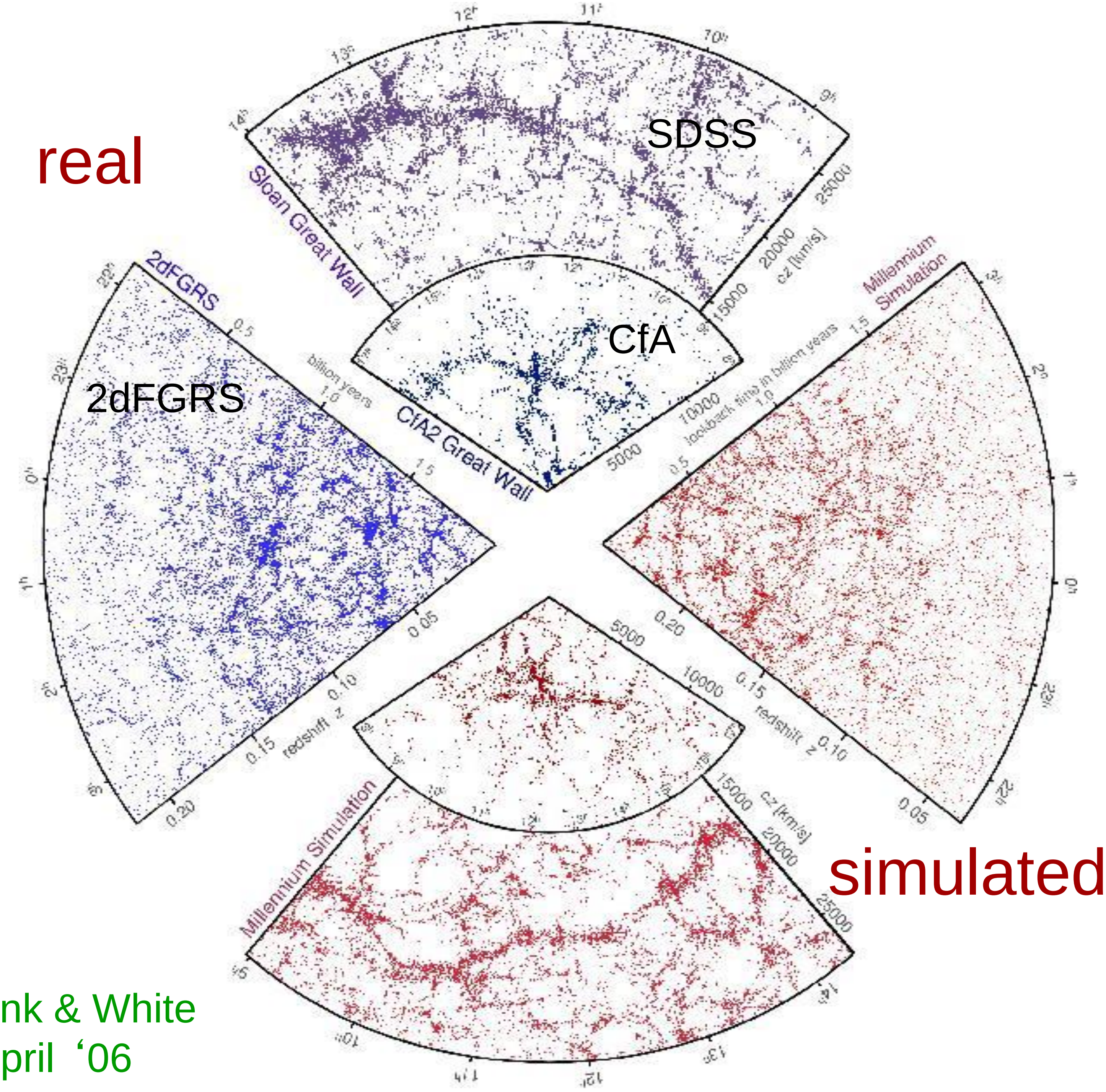


Image: Eleanor Dawning (Durham undergrad)

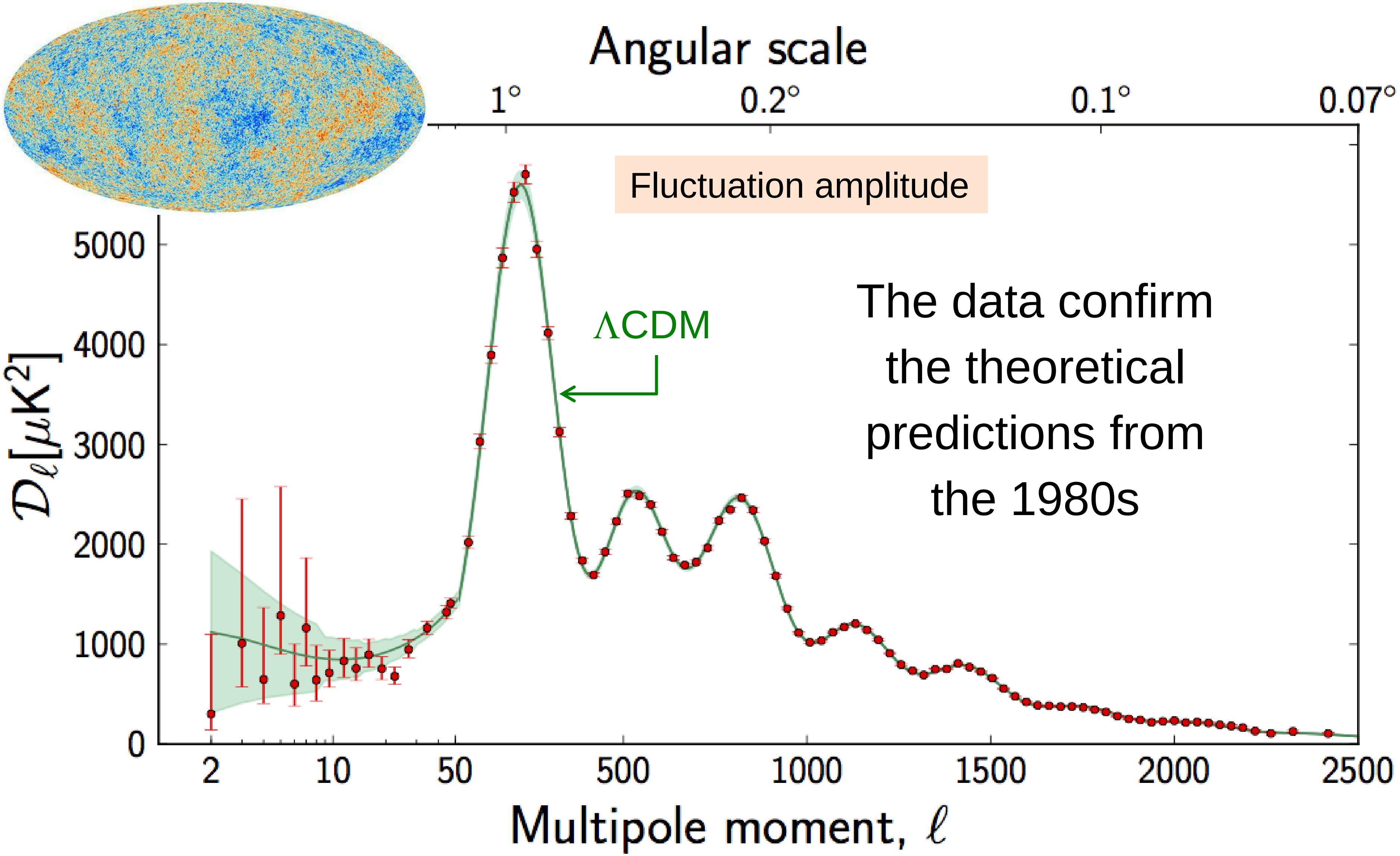
real



simulated

Springel, Frenk & White
Nature, April ‘06

Planck: CMB temperature anisotropies



The data confirm the theoretical predictions from the 1980s

Planck coll. 2015

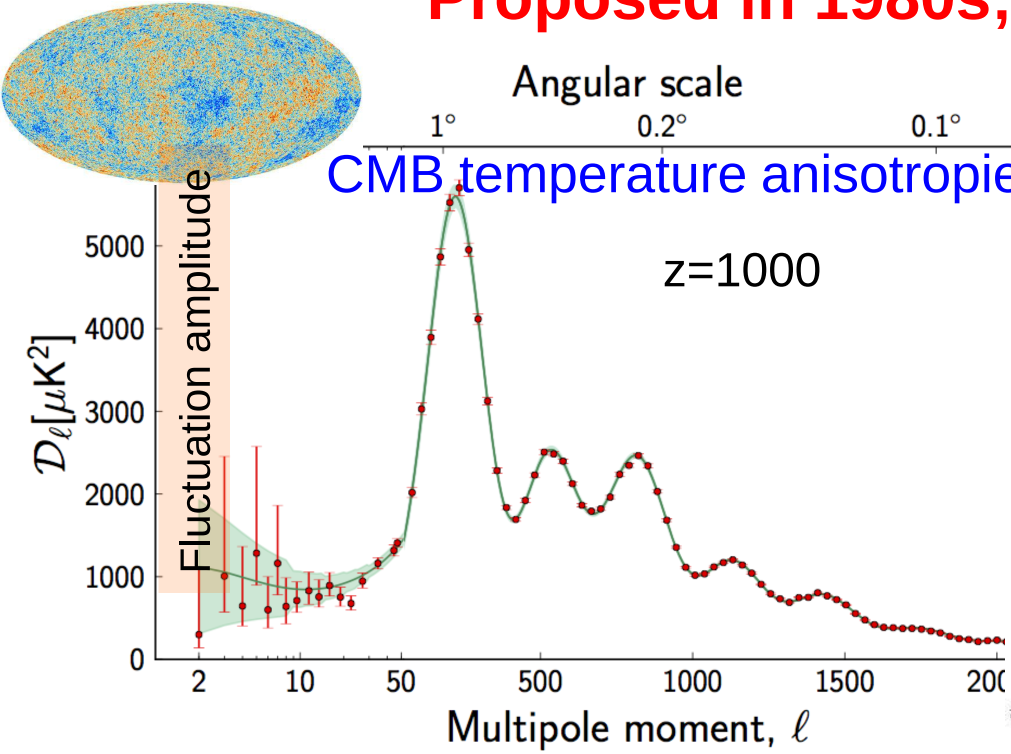
University of Durham

The ΛCDM model of cosmogony

Proposed in 1980s; now empirically supported by:

CMB temperature anisotropies

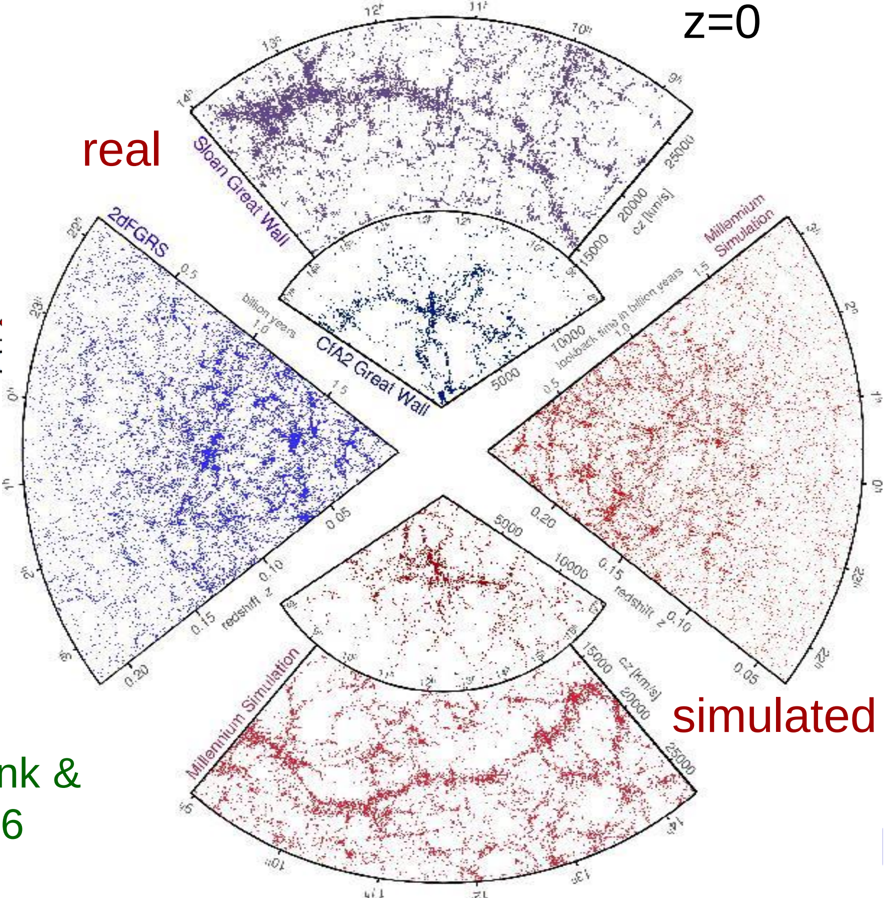
z=1000



Planck coll. 2015

Galaxy clustering

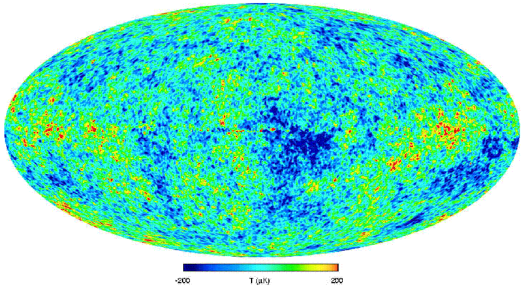
z=0



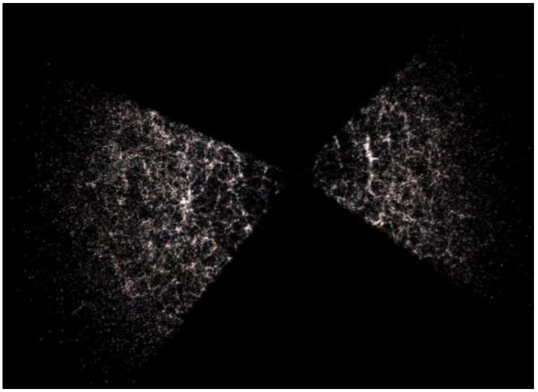
Springel, Frenk & White 2006

University of Durham

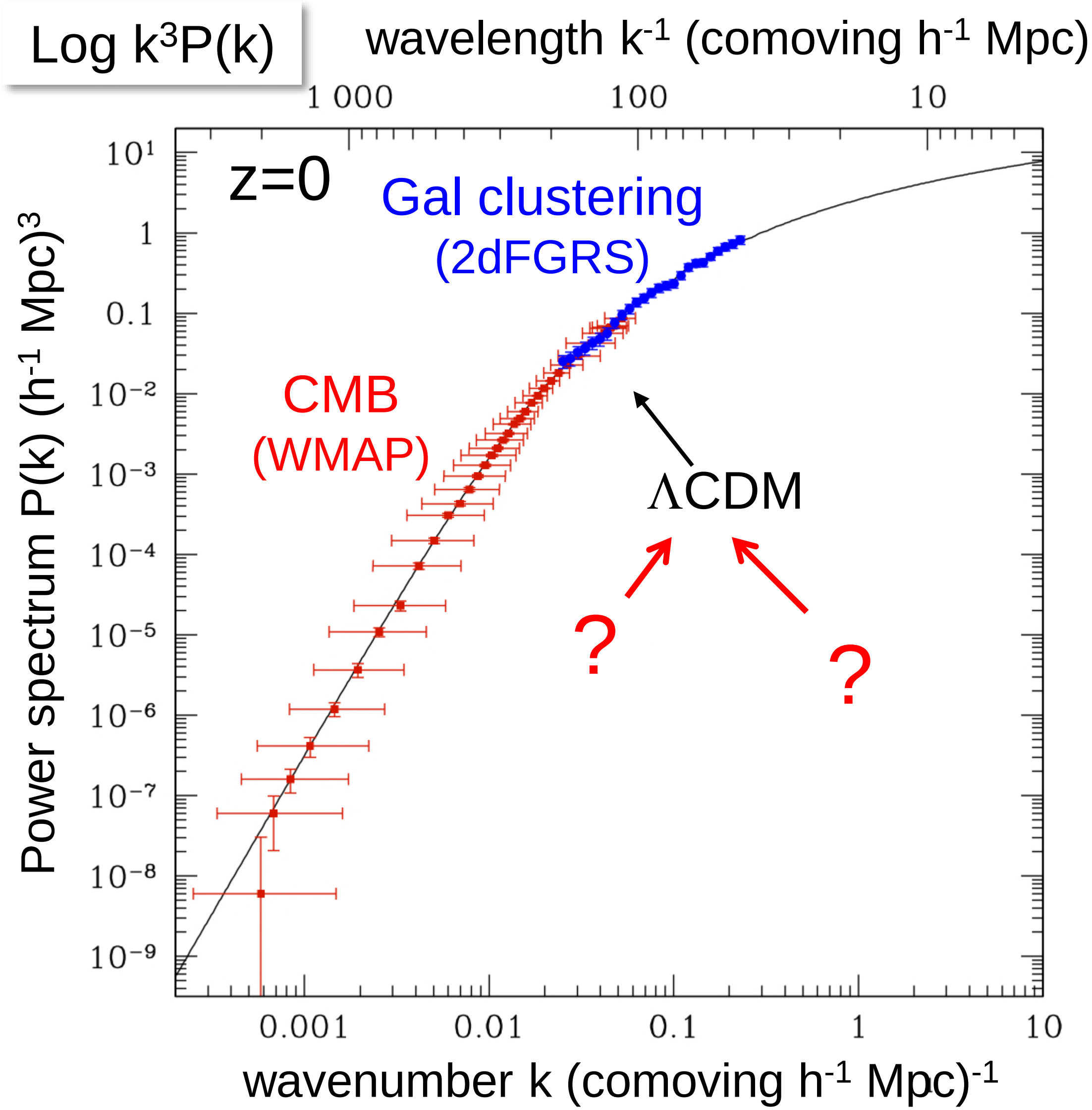
The cosmic power spectrum: from the CMB to the 2dFGRS



z~1000



z~0



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

Sanchez et al 06

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

Free streaming →

$\boxed{\lambda_{cut} \; \alpha \; m_x^{-1}}$

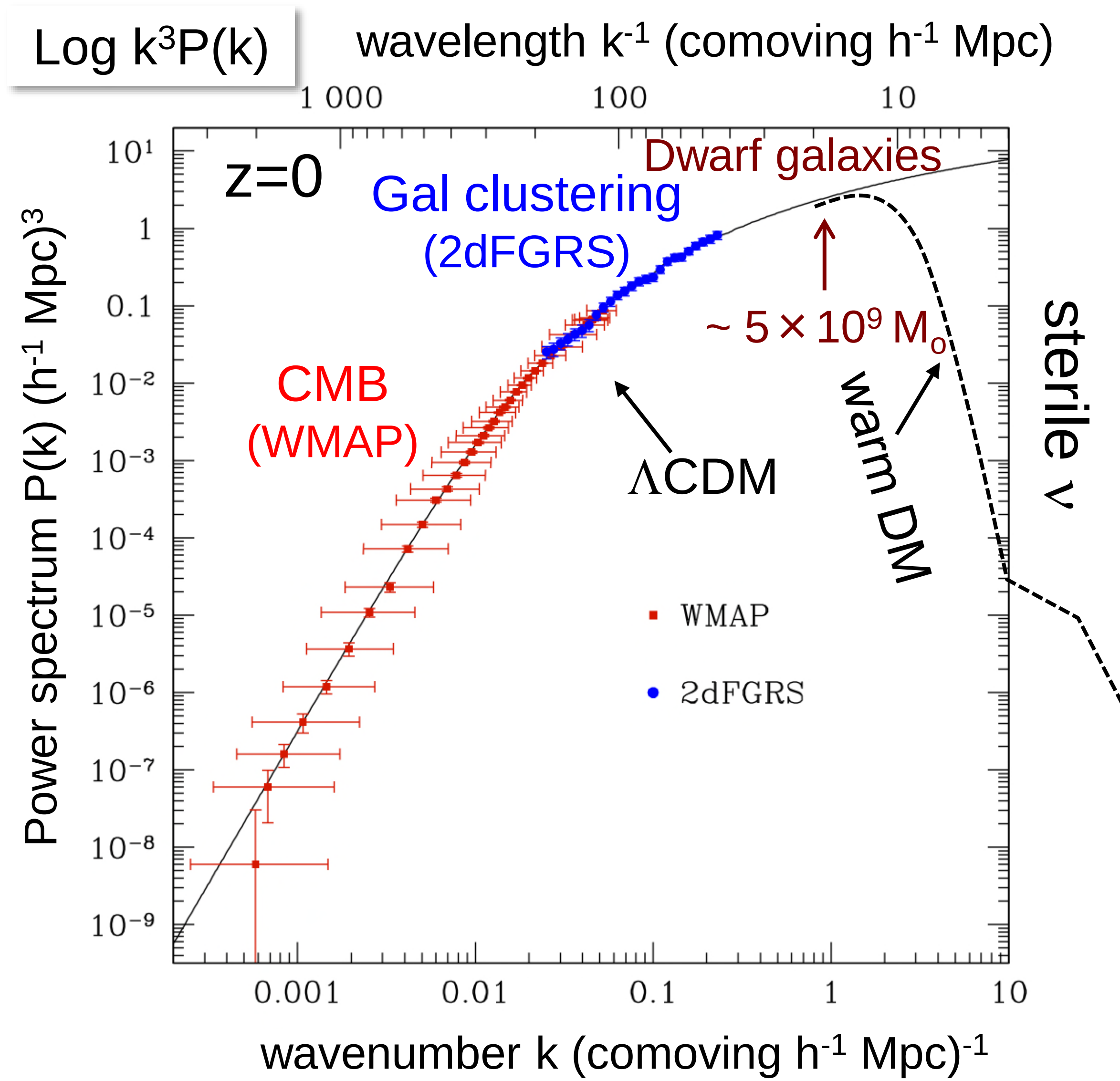
for thermal relic

m_{CDM} ~ 100GeV

susy; M_{cut} ~ 10^{-6} M_o

m_{WDM} ~ few keV

sterile ν; M_{cut}~10^9 M_o



cold dark matter

warm dark matter

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

The Millennium/Aquarius/Phoenix simulation series

The properties of the dark matter distribution on all scales
in CDM is a solved problem

We now know:

→ halo mass function down to the cutoff mas

→ the internal structure of halos of all masses

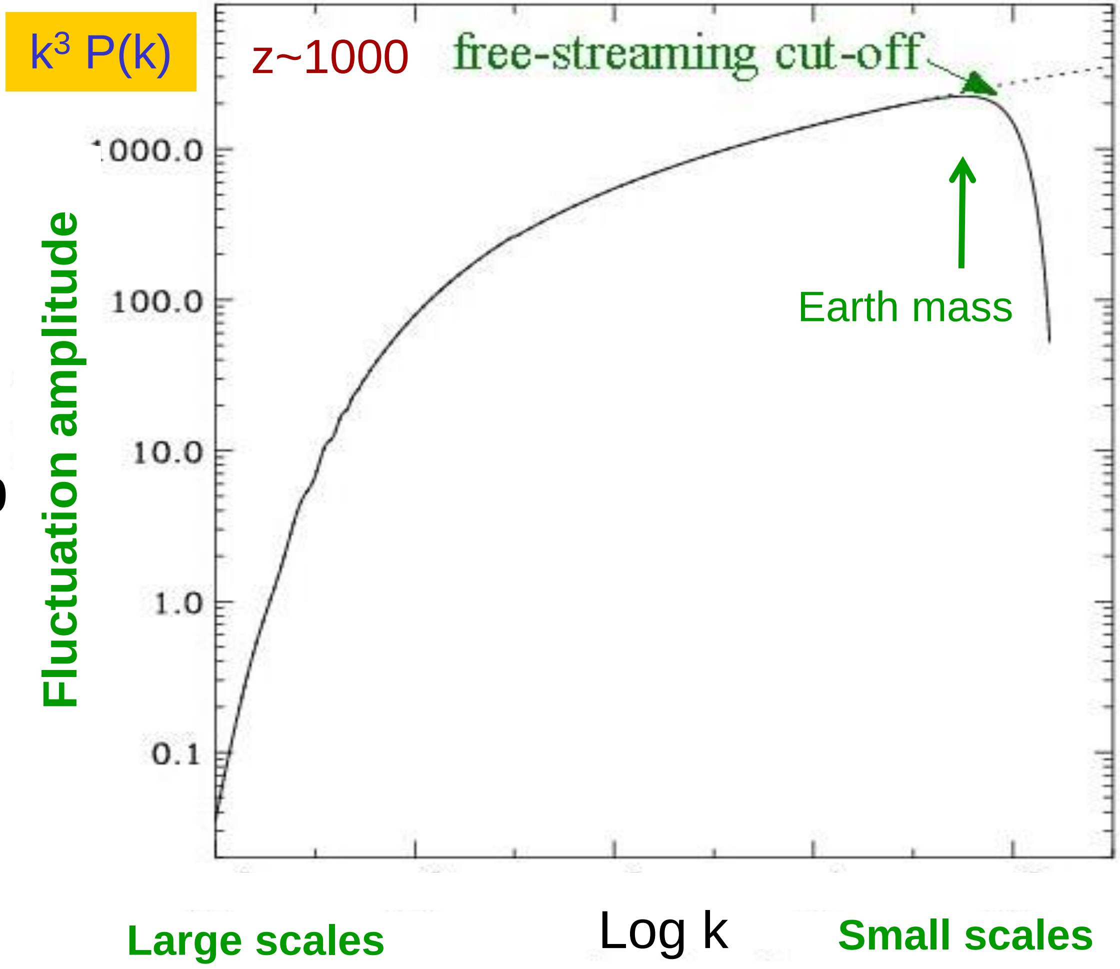
→ the spatial distribution of halos & diffuse DM

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

The cold dark matter power spectrum

The linear power spectrum
("power per octave")

Assumes a 100GeV wimp
Green et al '04



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The cold dark matter linear power spectrum

The linear power spectrum
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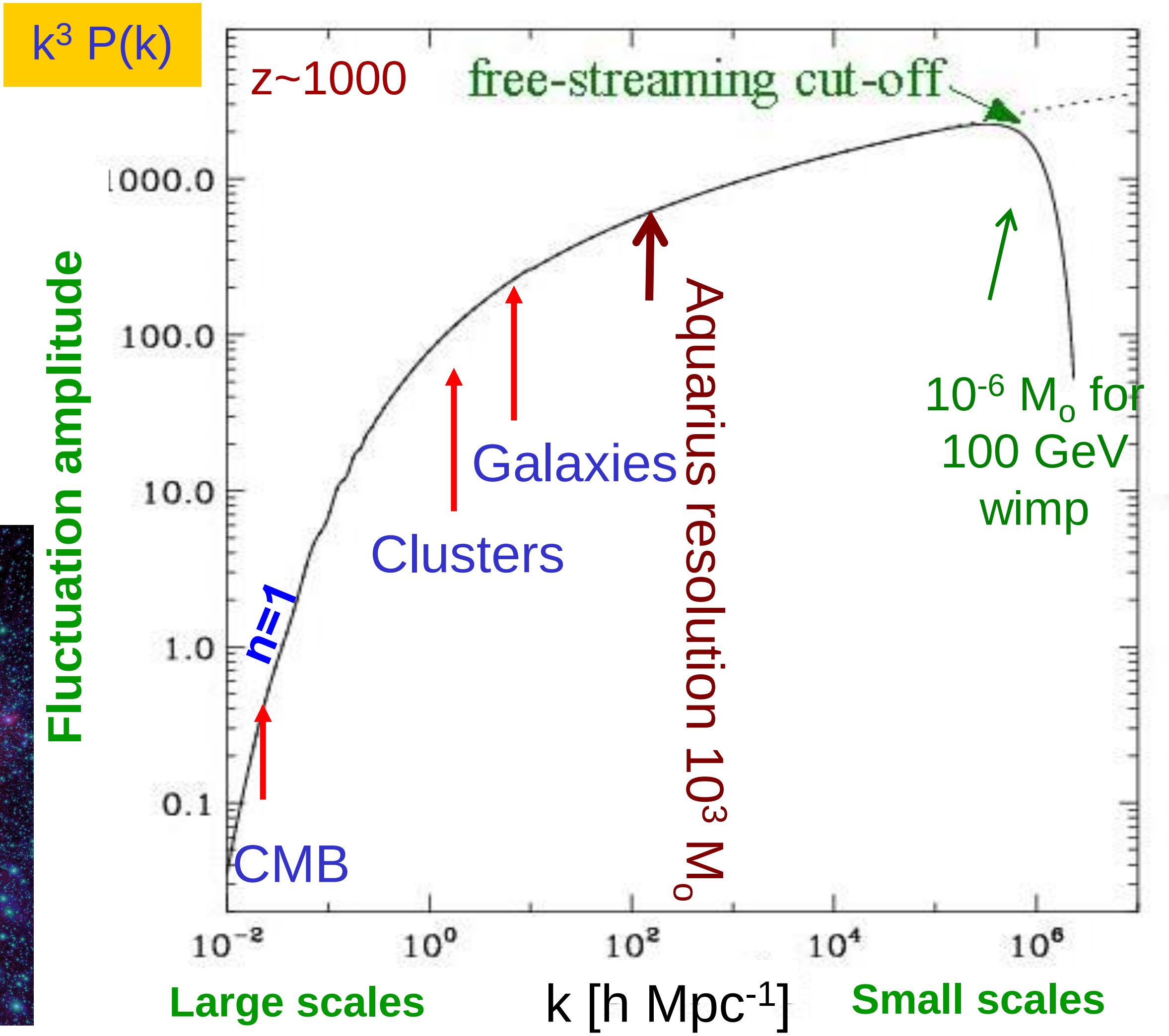
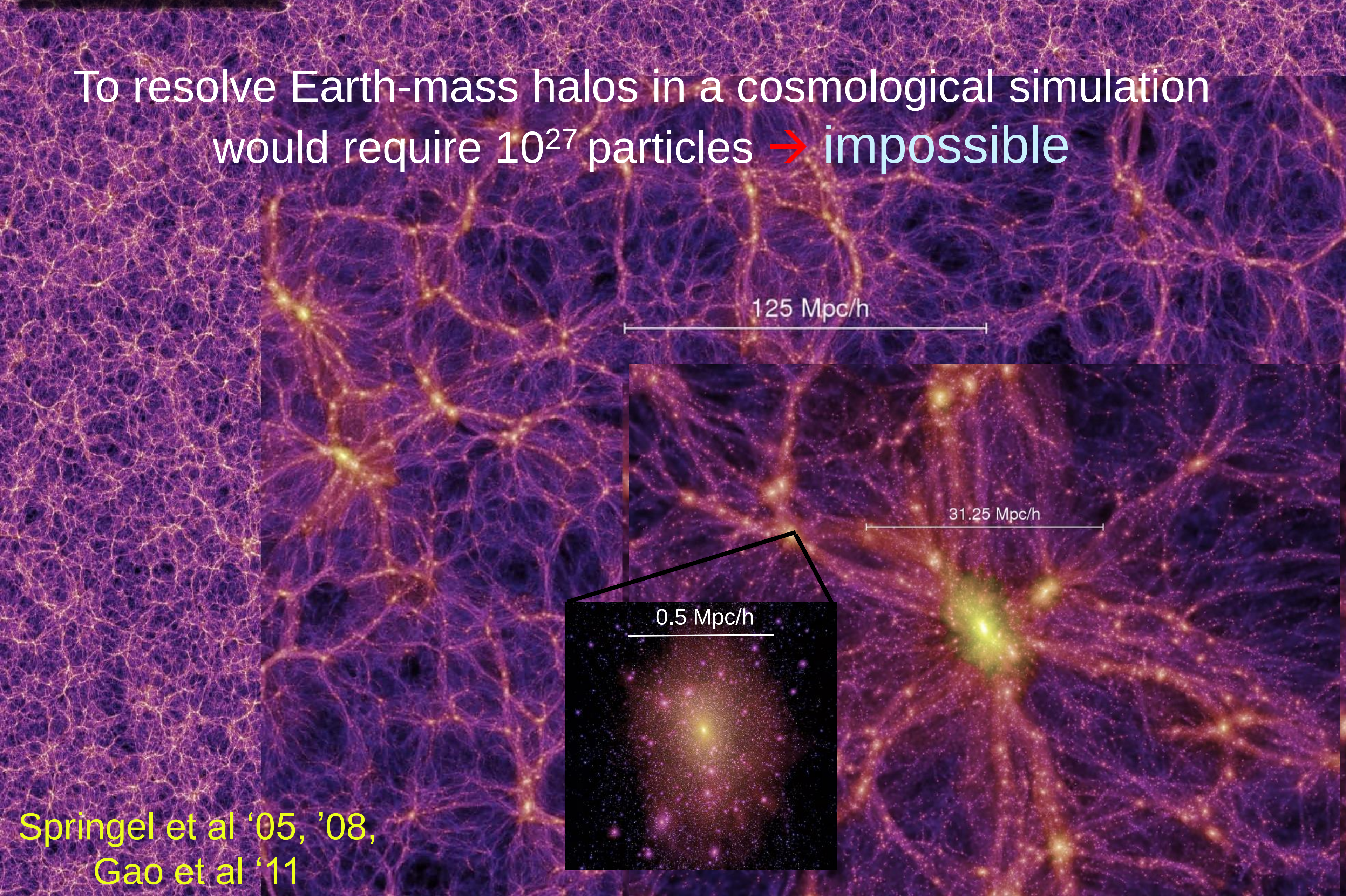
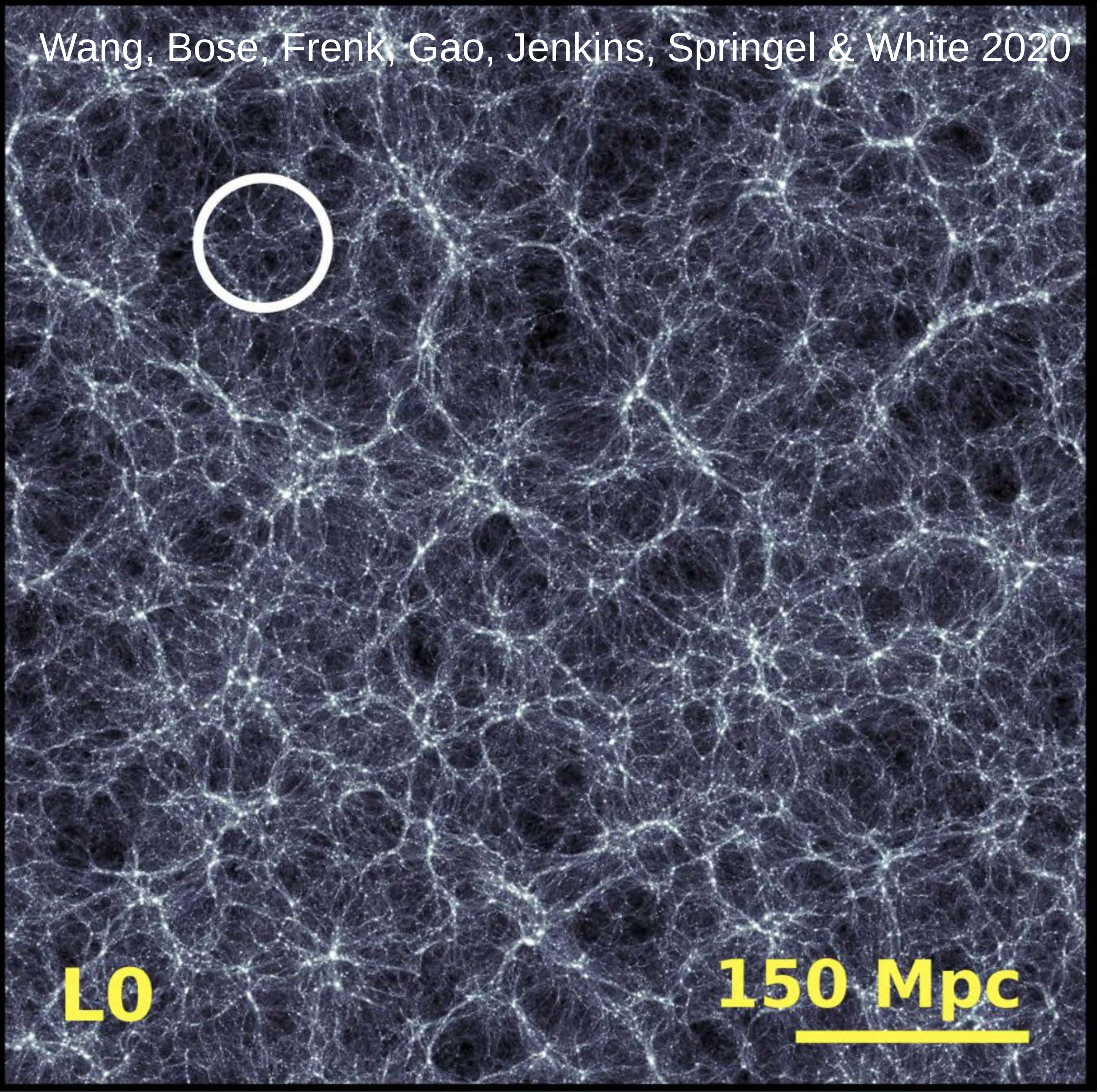


The Millennium/Aquarius/Phoenix simulation series

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

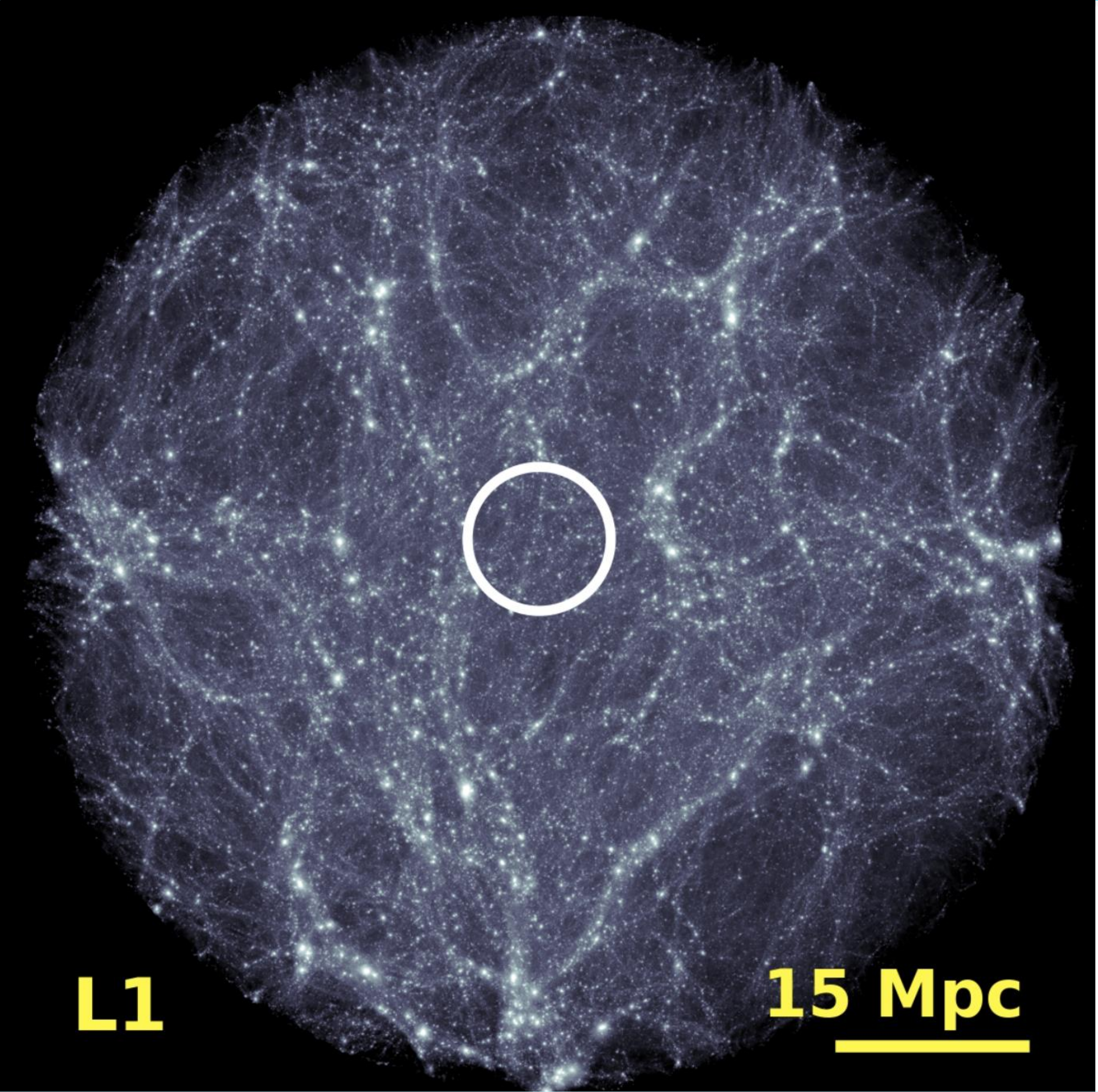
Dynamic range of 30 orders of magnitude in mass

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

Base Level

Wang, Bose et al 2020
Nature

The VVV simulation



Planck cosmology

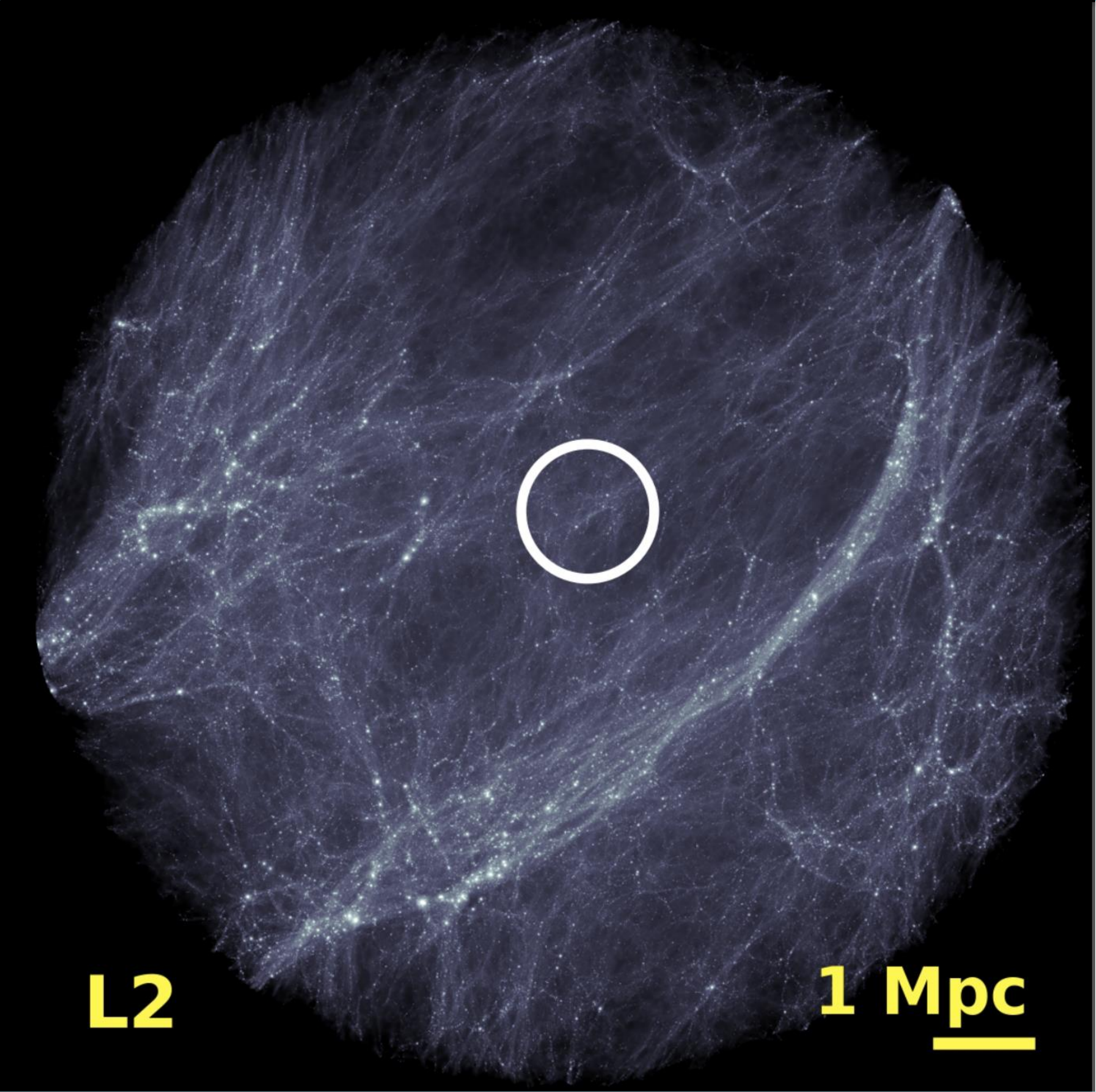
Dark matter only

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

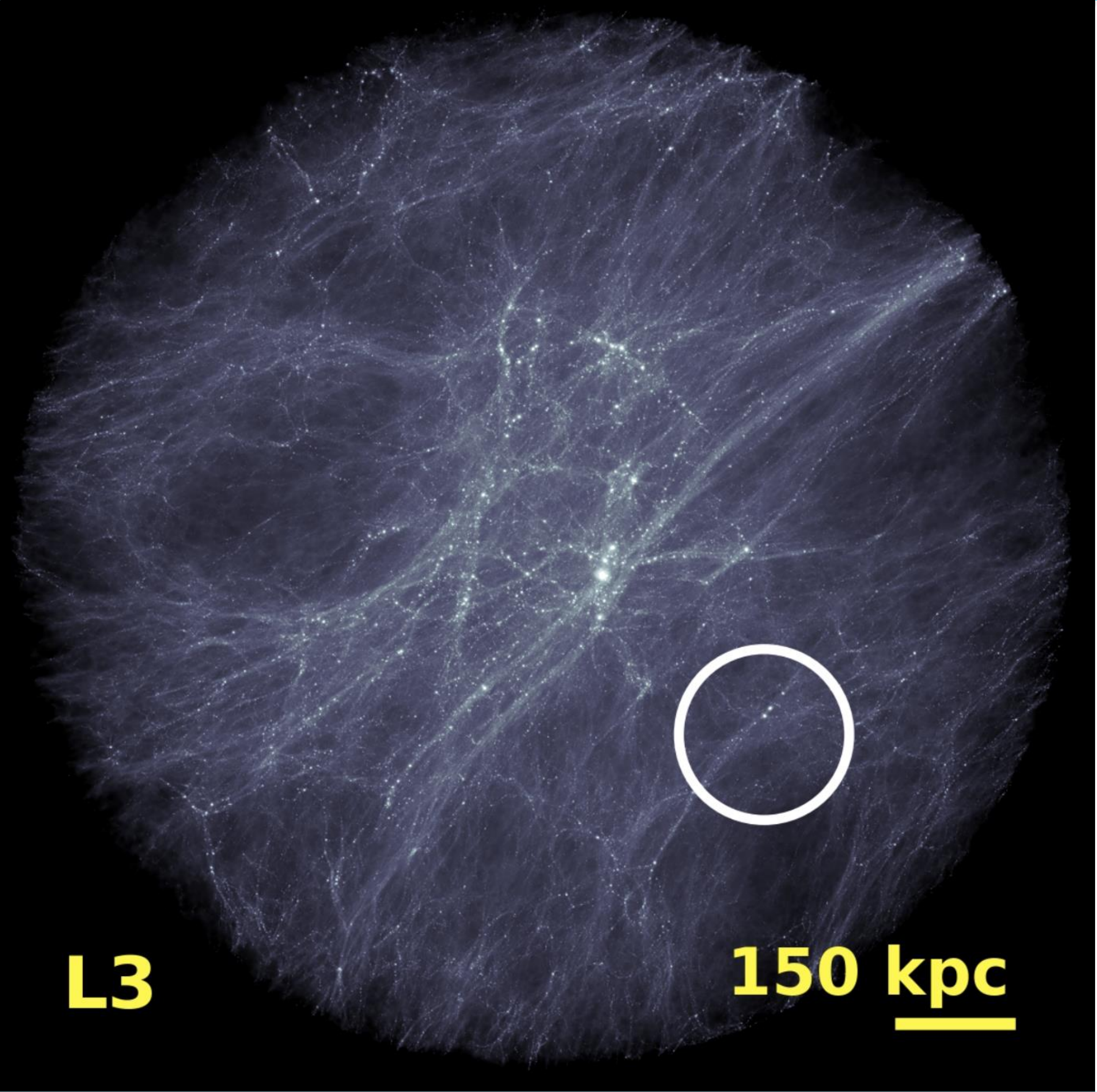
Dark matter only

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

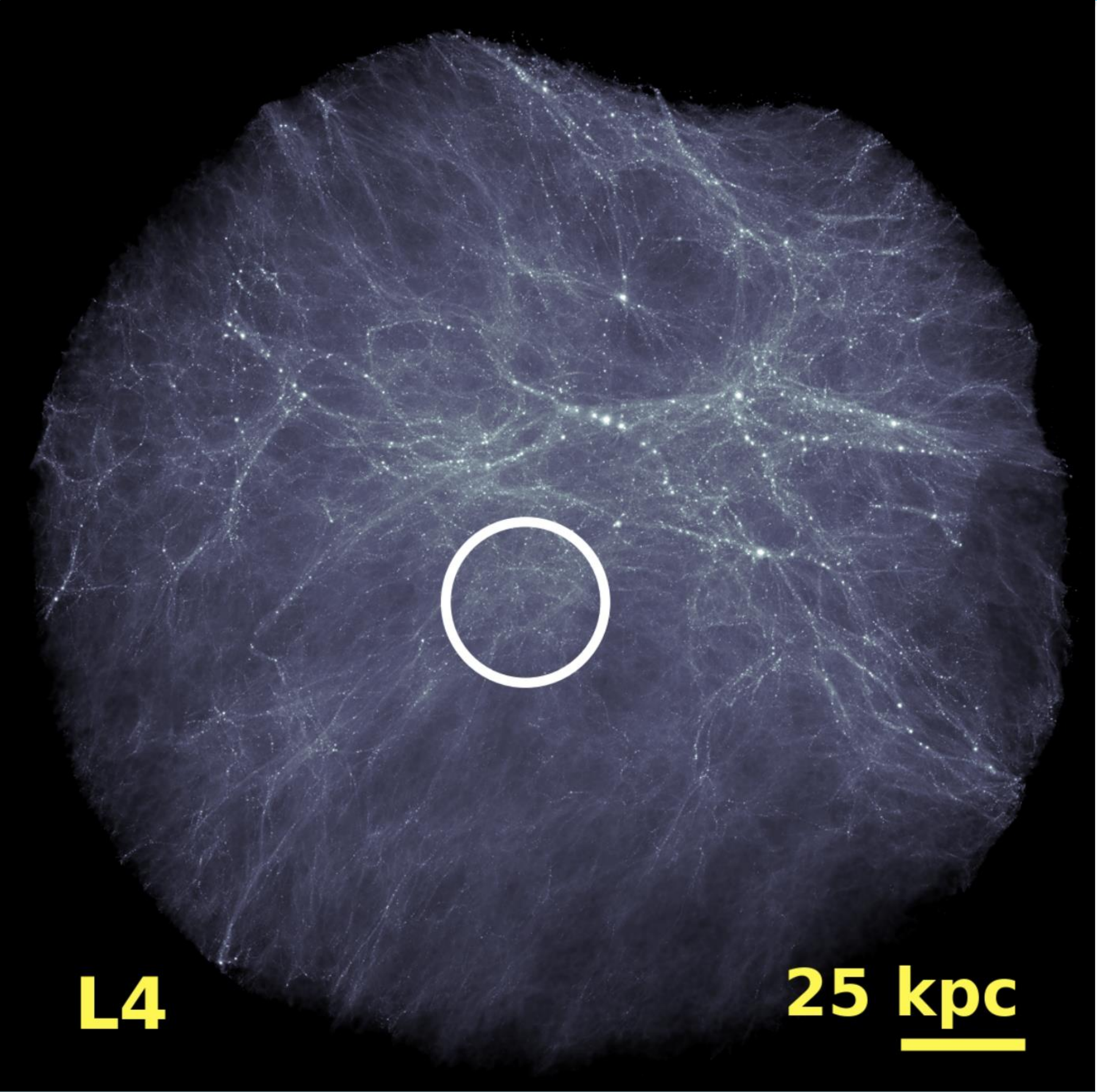
Dynamic range of 30 orders of magnitude in mass

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

Zoom Level 3

Wang, Bose et al 2020

The VVV simulation



Planck cosmology

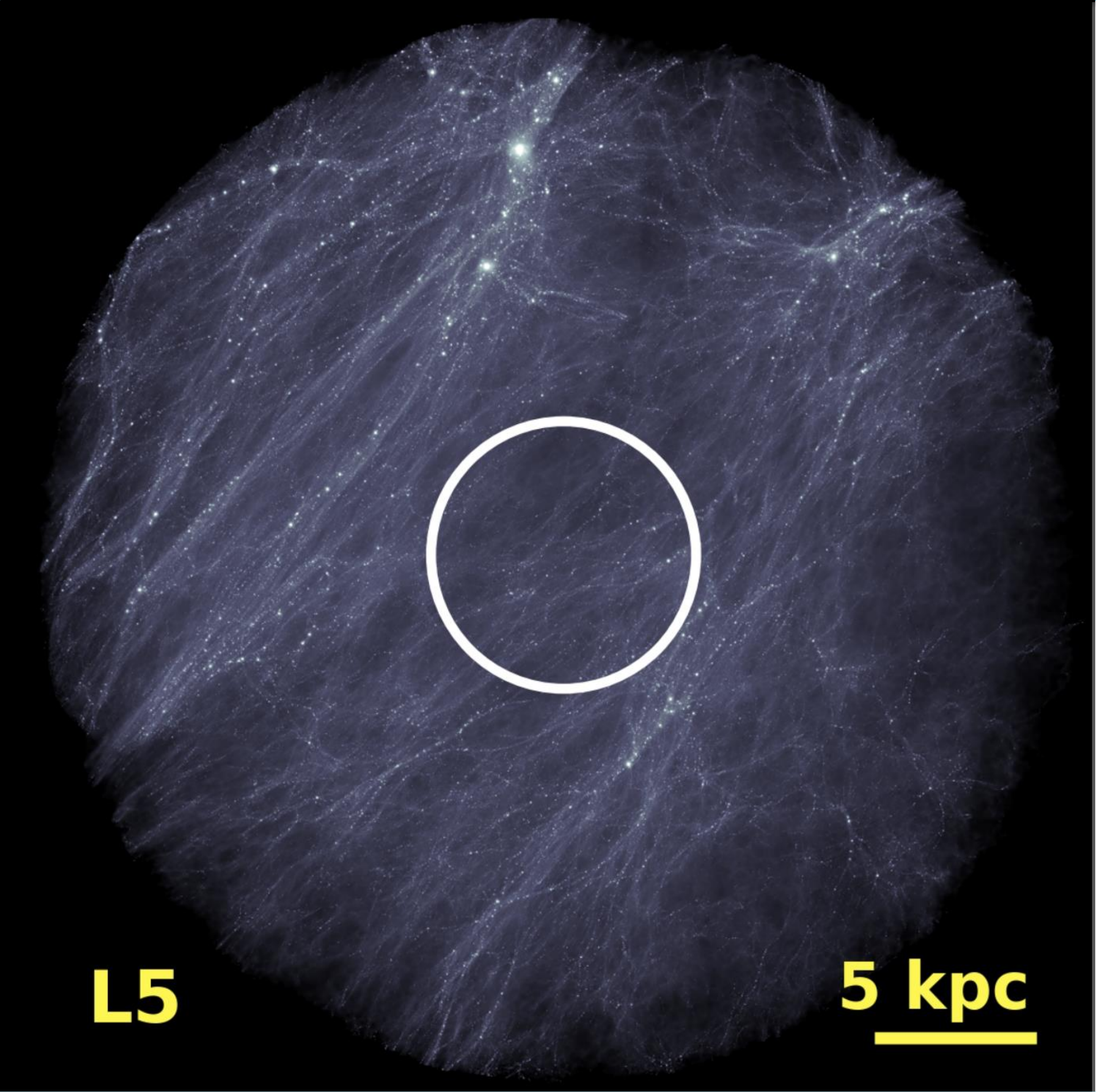
Dark matter only

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

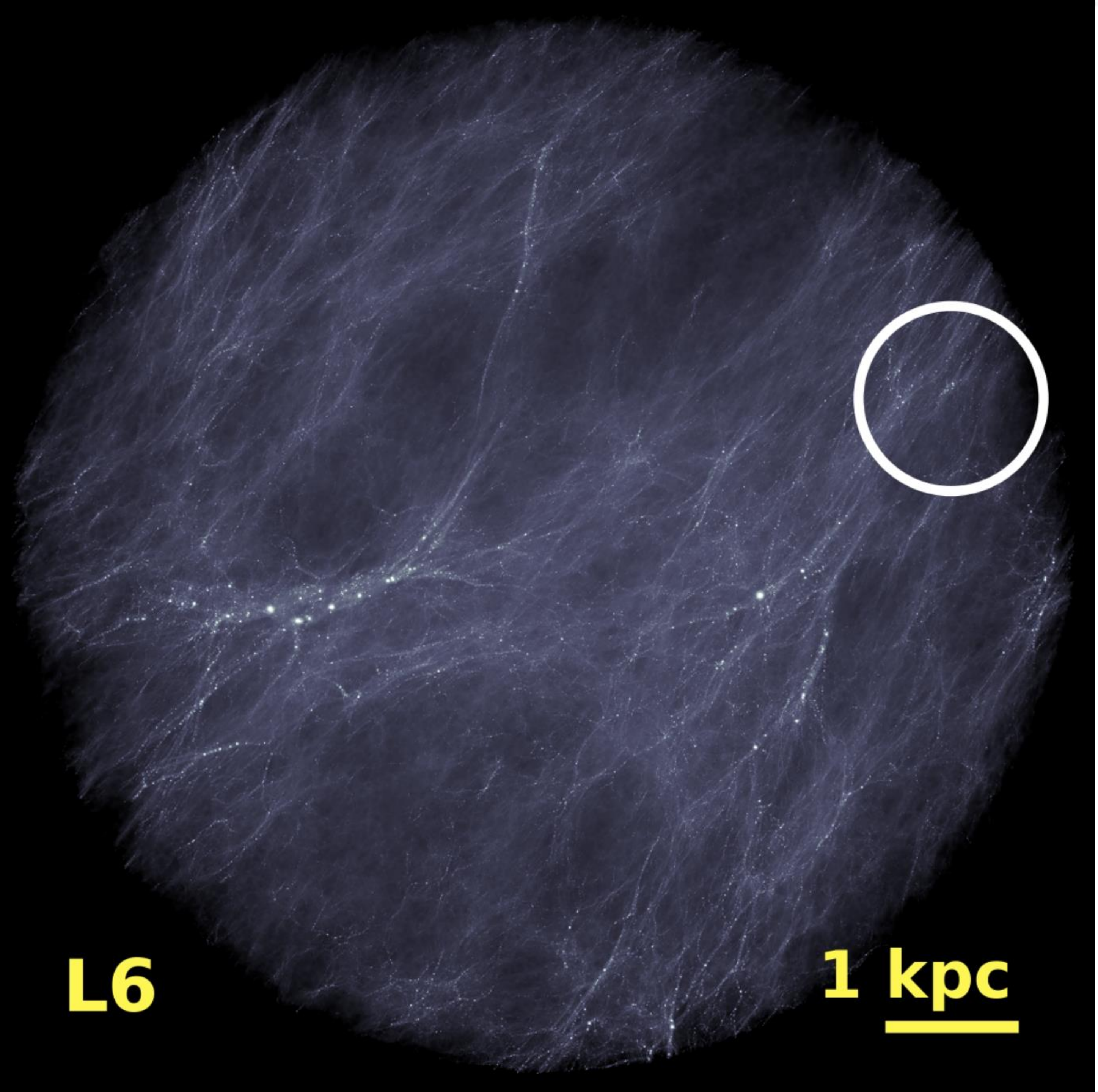
Dynamic range of 30 orders of magnitude in mass

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

Zoom Level 5

Wang, Bose et al 2020

The VVV simulation



Planck cosmology

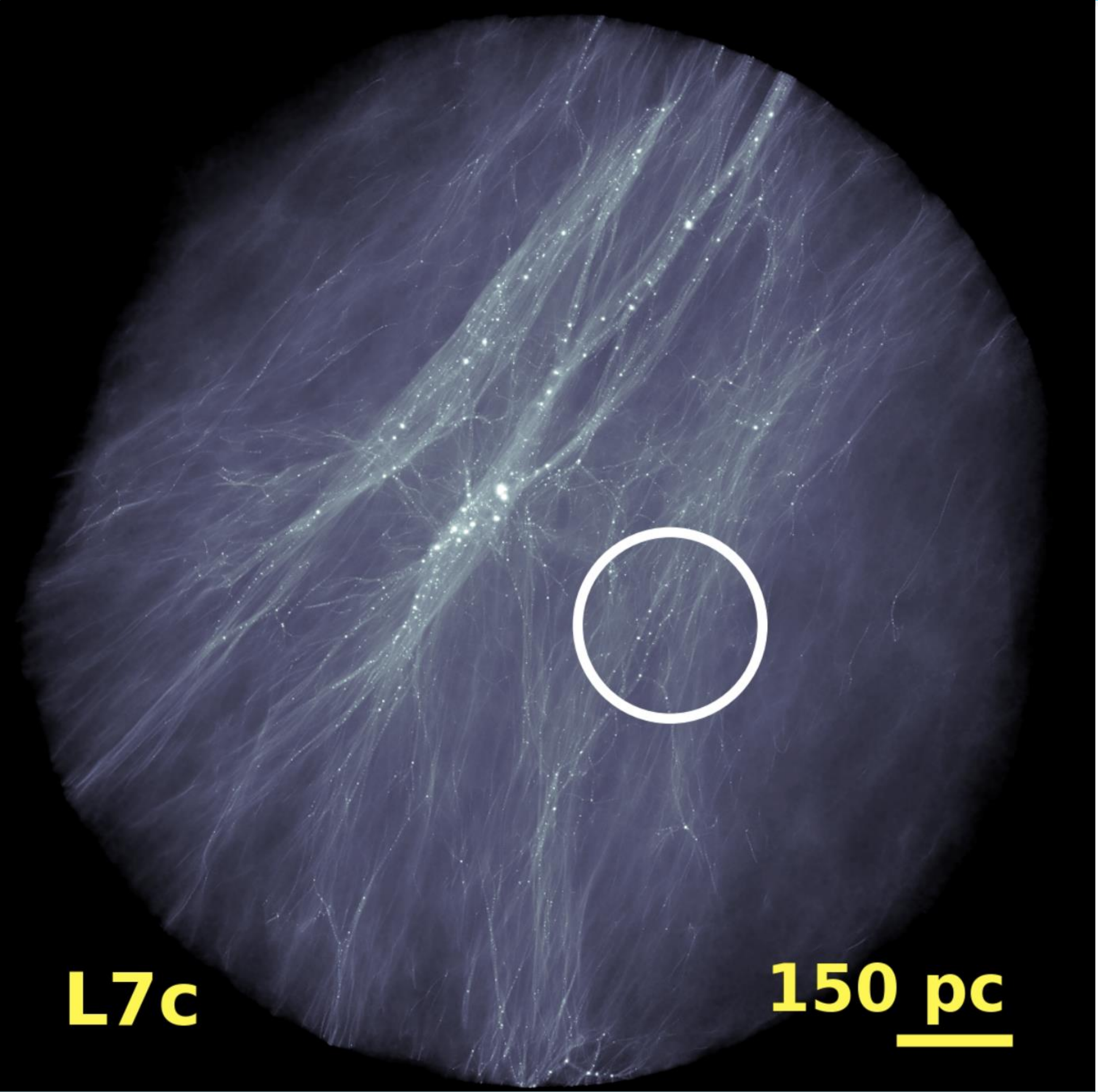
Dark matter only

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

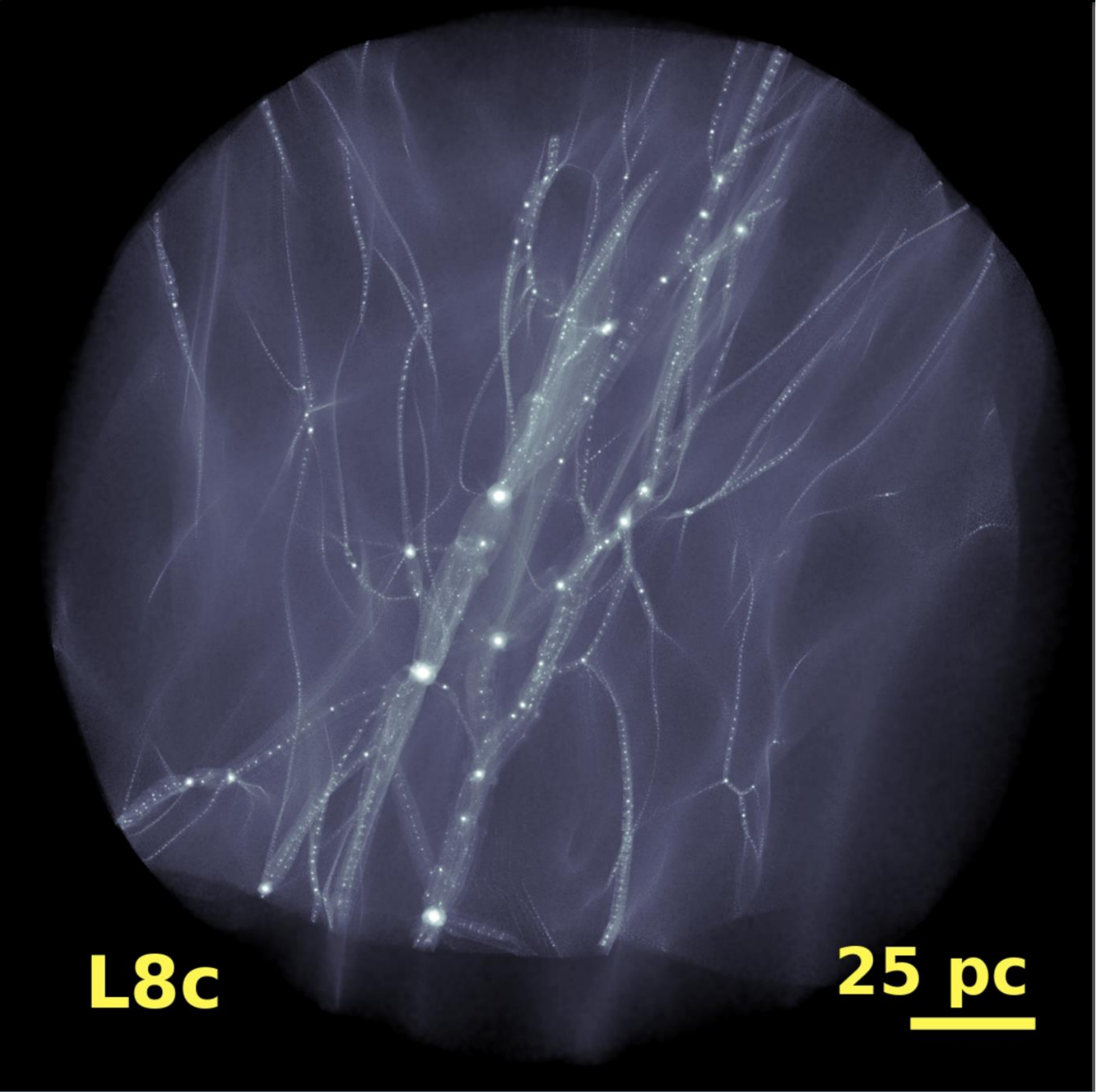
Dark matter only

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

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

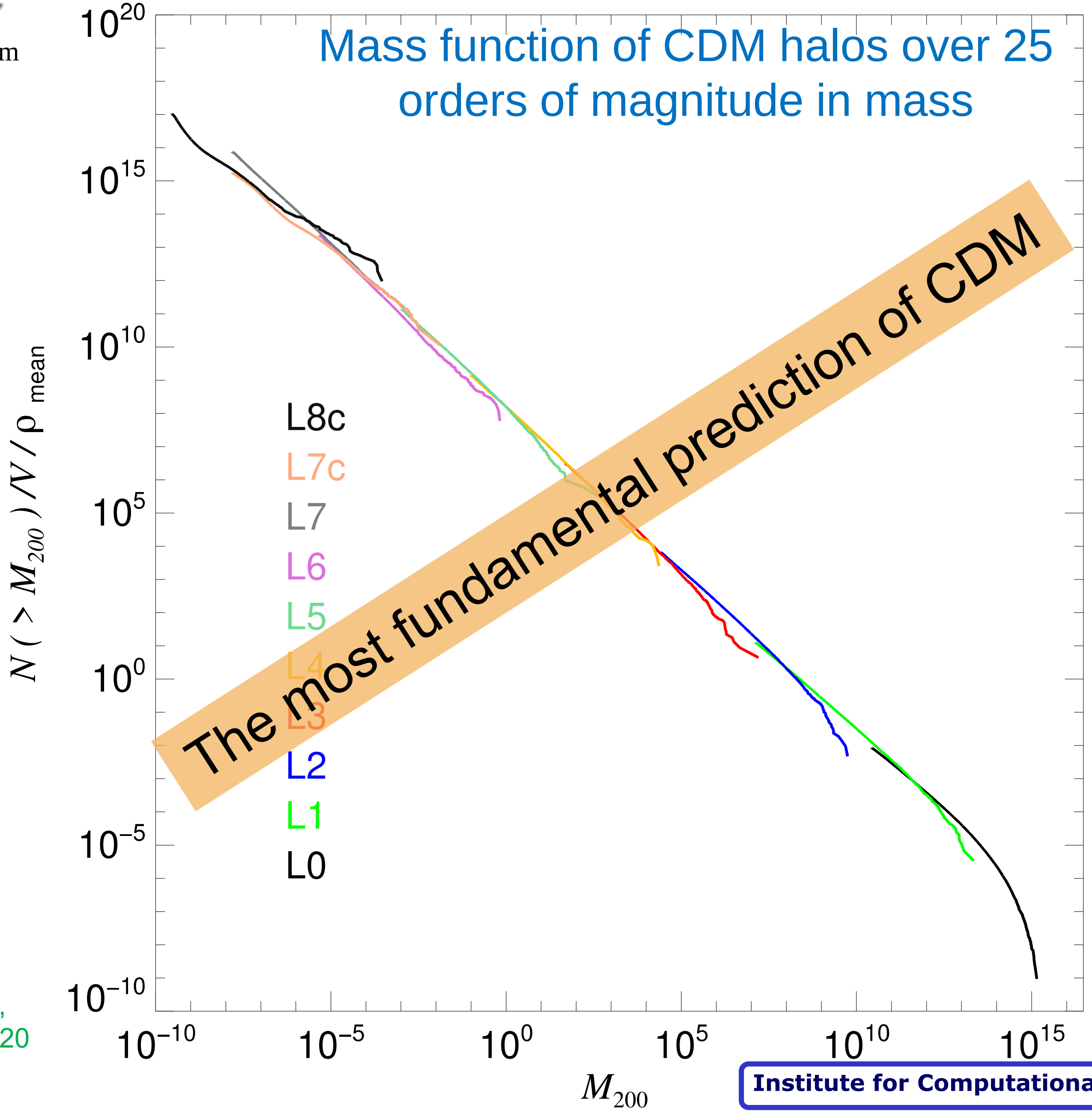
Zoom Level 8

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

Wang, Bose et al 2020

University of Durham

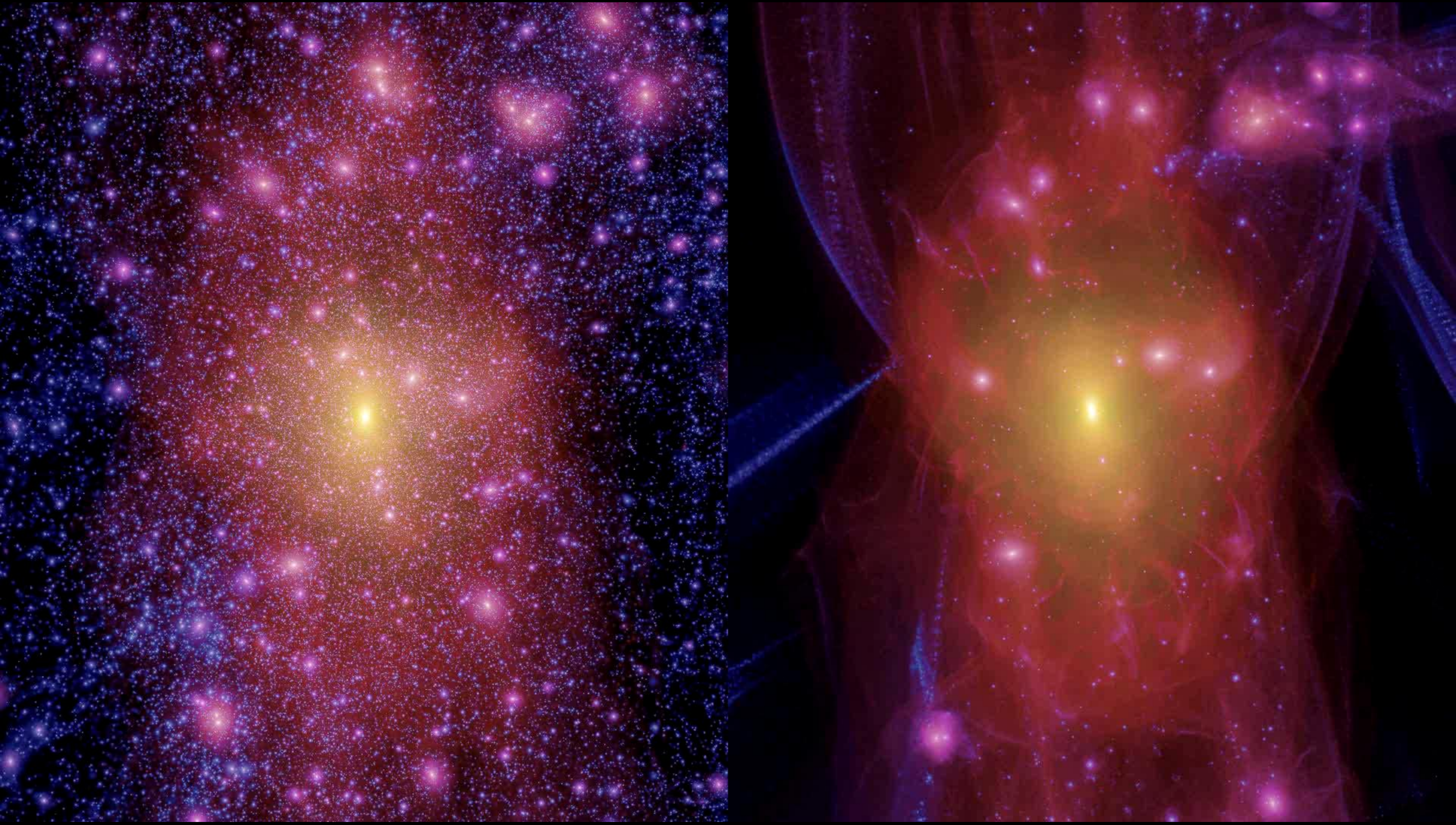
Mass function of CDM halos over 25 orders of magnitude in mass



The most fundamental prediction of CDM

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

Institute for Computational Cosmology



cold dark matter

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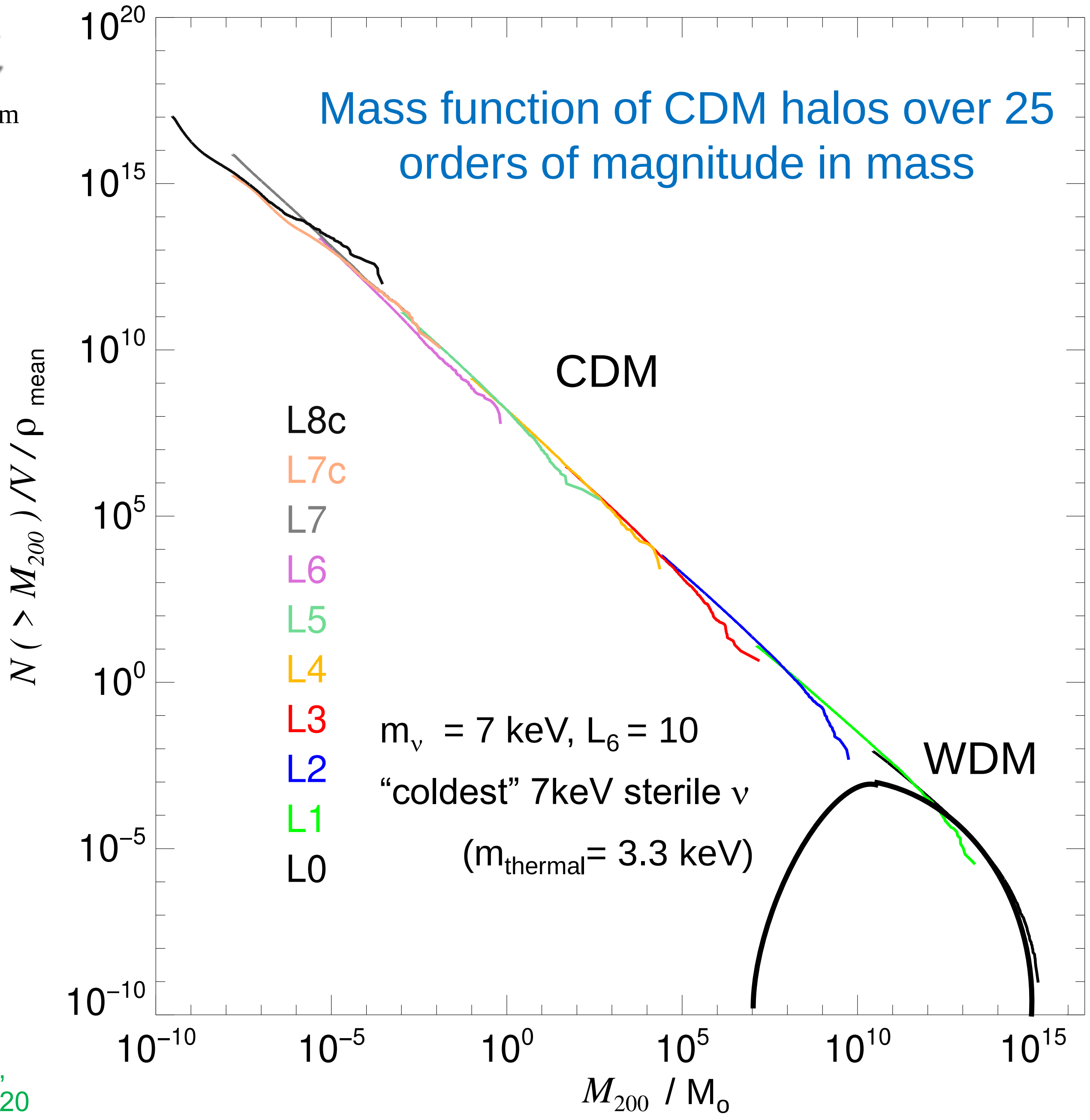
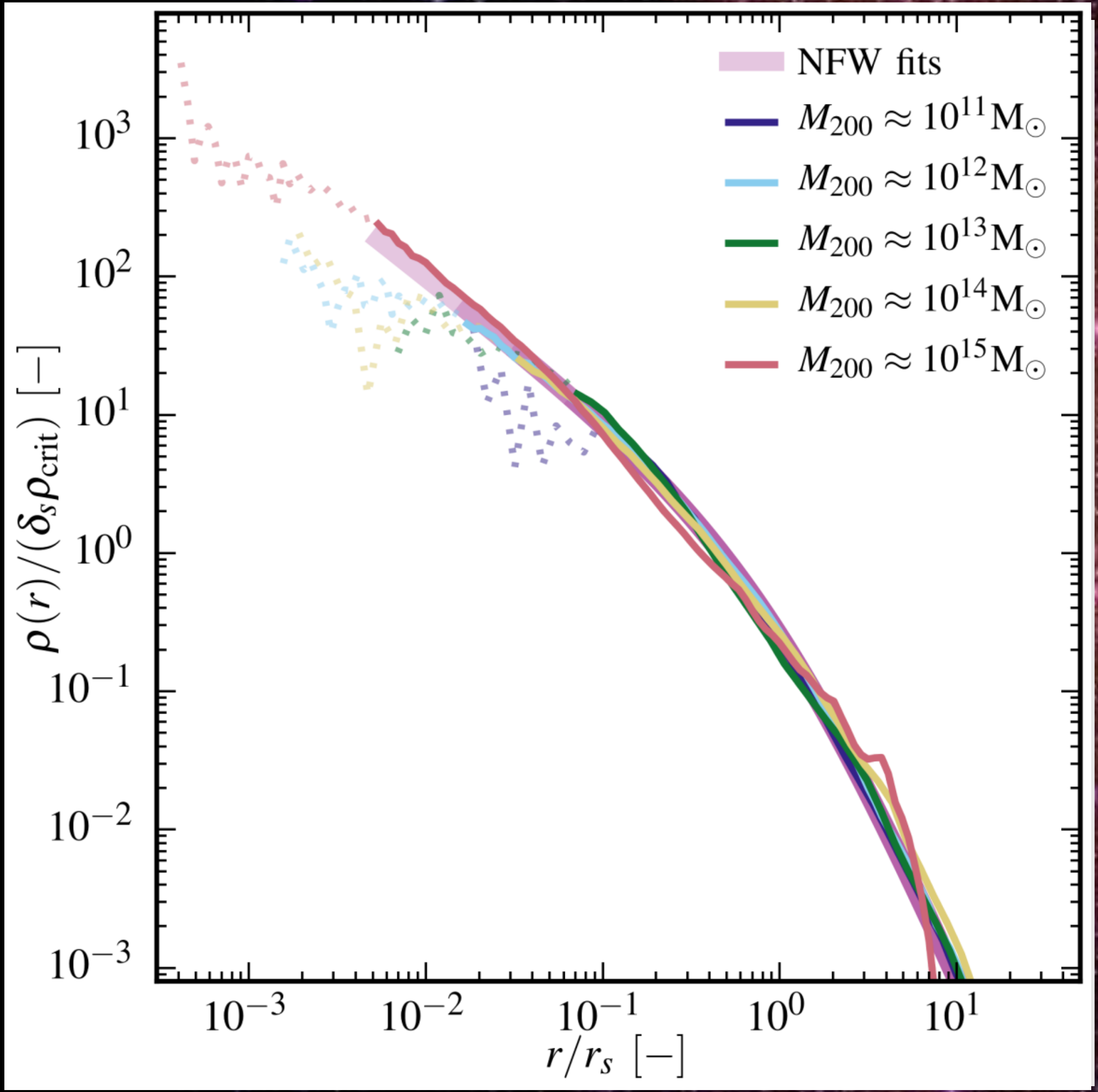


Wang, Bose, CSF, Gao, Jenkins, Springel, White '20

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)

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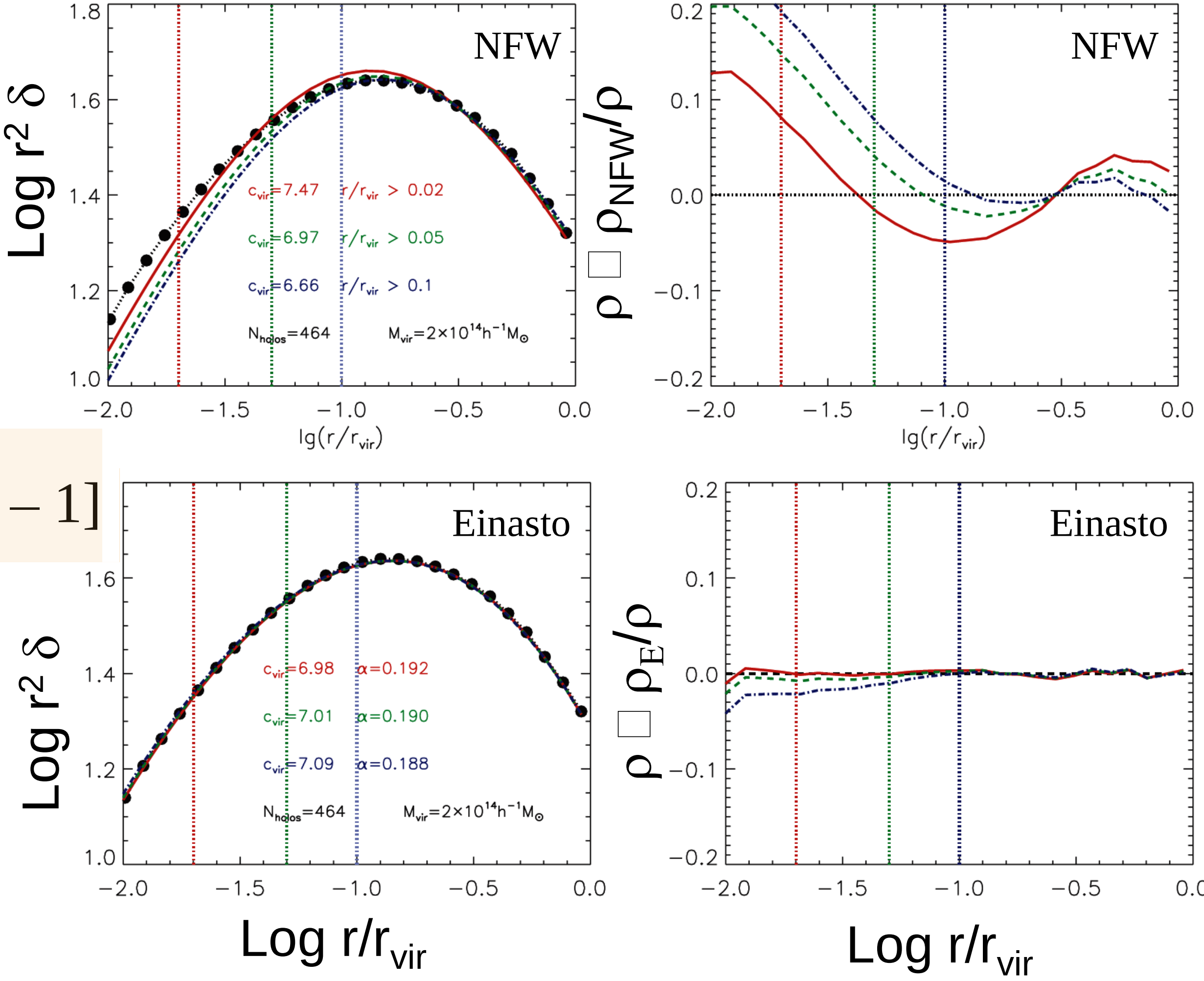
Universal halo density profiles

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

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

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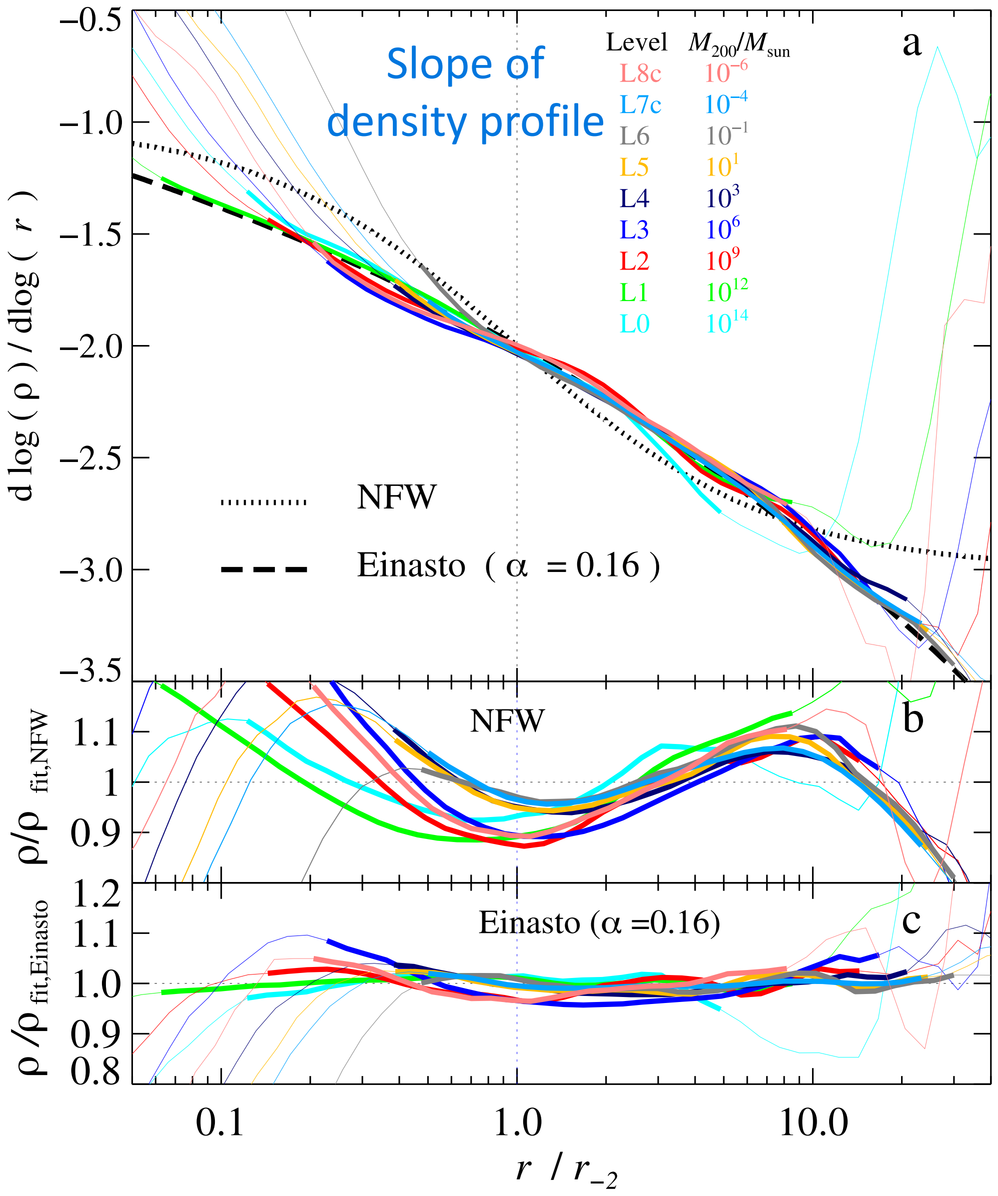
Density profile shapes

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

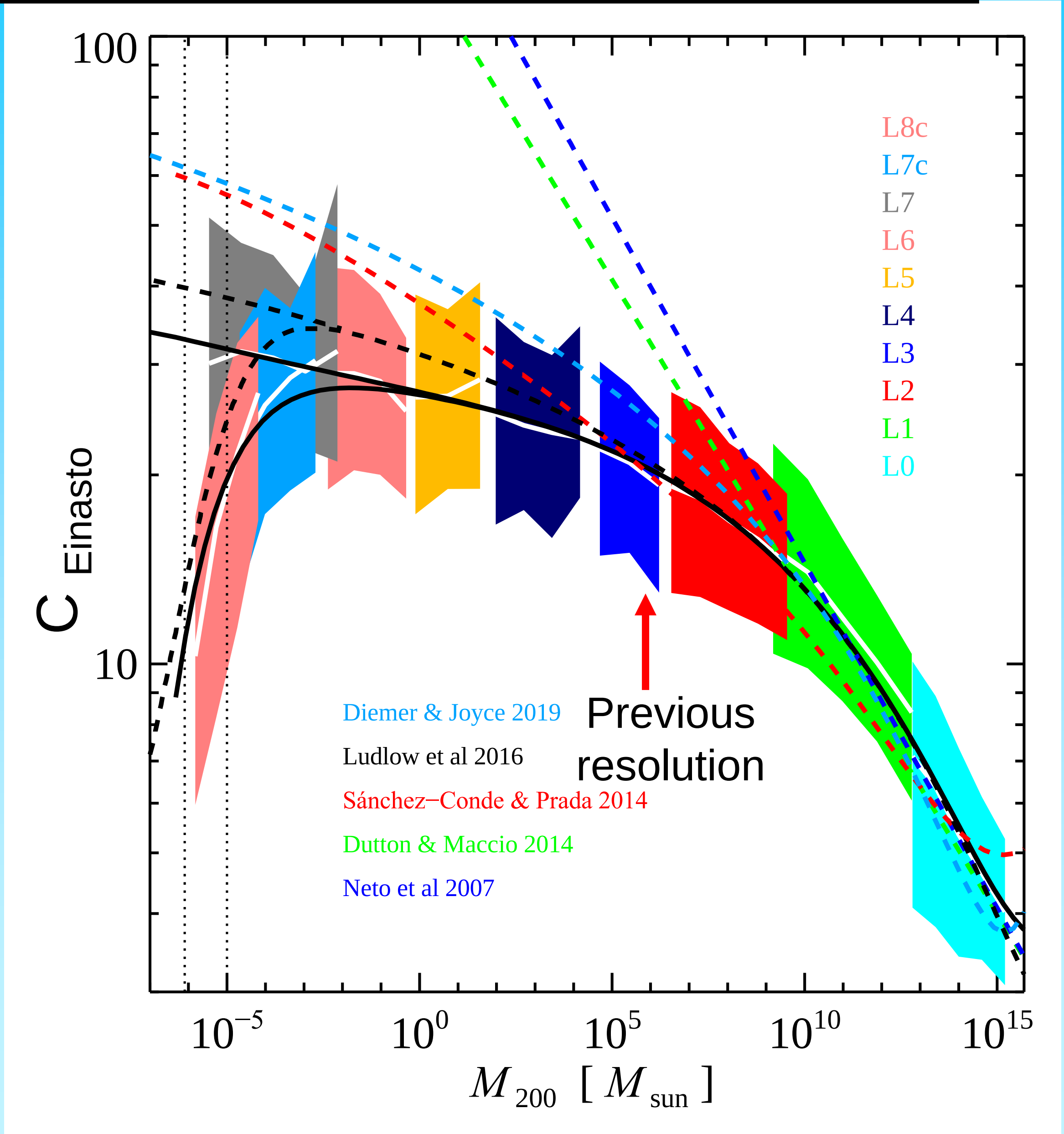
University of Durham

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

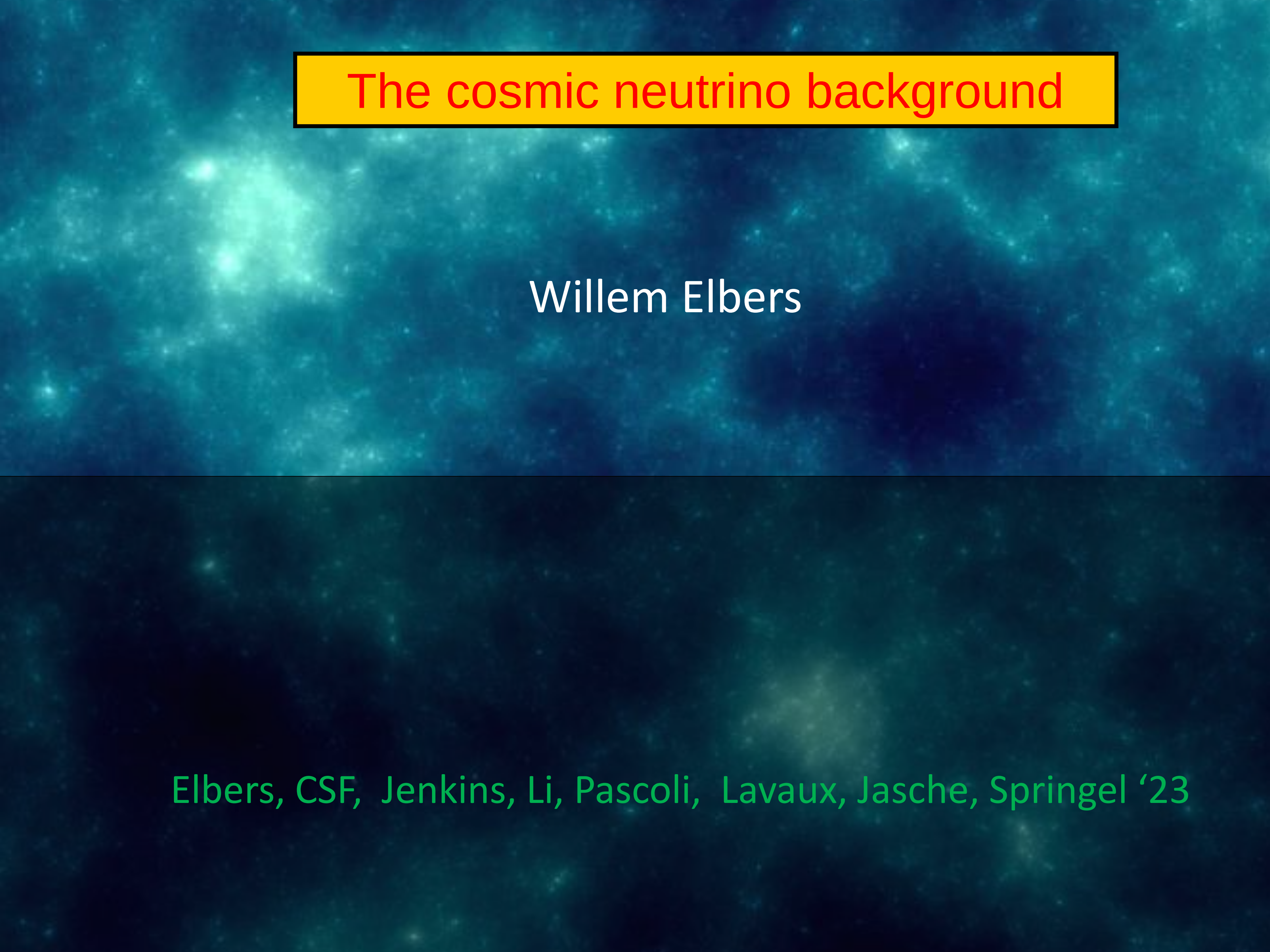
A digression: the cosmic neutrino background

Neutrinos are the only non-baryonic form of dark matter known!

The make on a small contribution, ~ 1%, to the dark matter

Cosmic neutrinos were produced a few seconds after the Big Bang and produce a cosmic background today

May be detected by Ptolomy experiment



The cosmic neutrino background

Willem Elbers

Elbers, CSF, Jenkins, Li, Pascoli, Lavaux, Jasche, Springel ‘23

Constrained realization simulations

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

Constrained by 2MASS++ survey

Sawala, CSF+ 2022; MaAlpine, Sawala, CSF+ 2022

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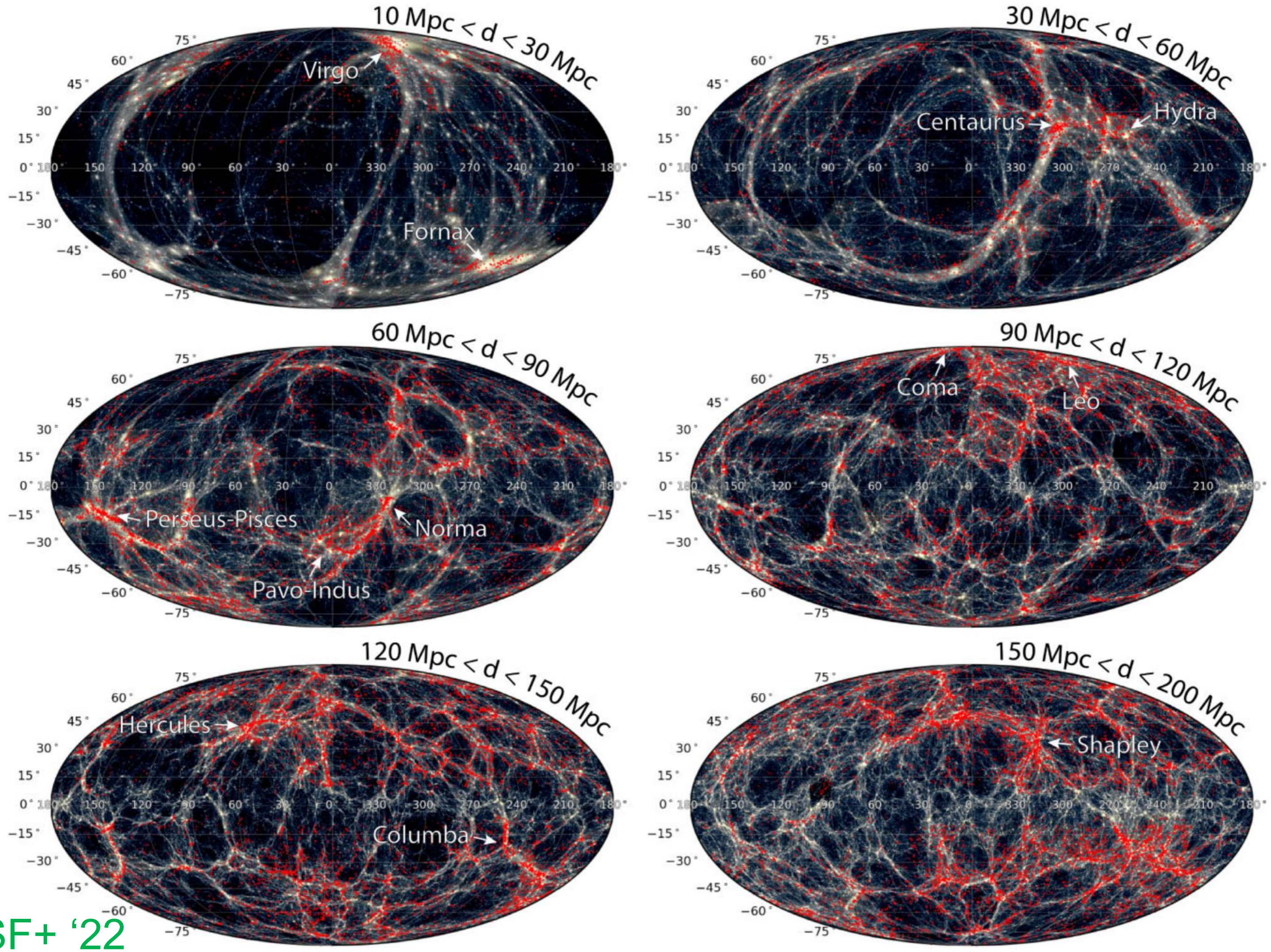
Constrained simulations

SIBELIUS DARK

Grey: dark matter in SIBELIUS DARK

Red: galaxies in 2M++ survey, used for reconstruction



Mcalpine, Sawala , CSF+ ‘22

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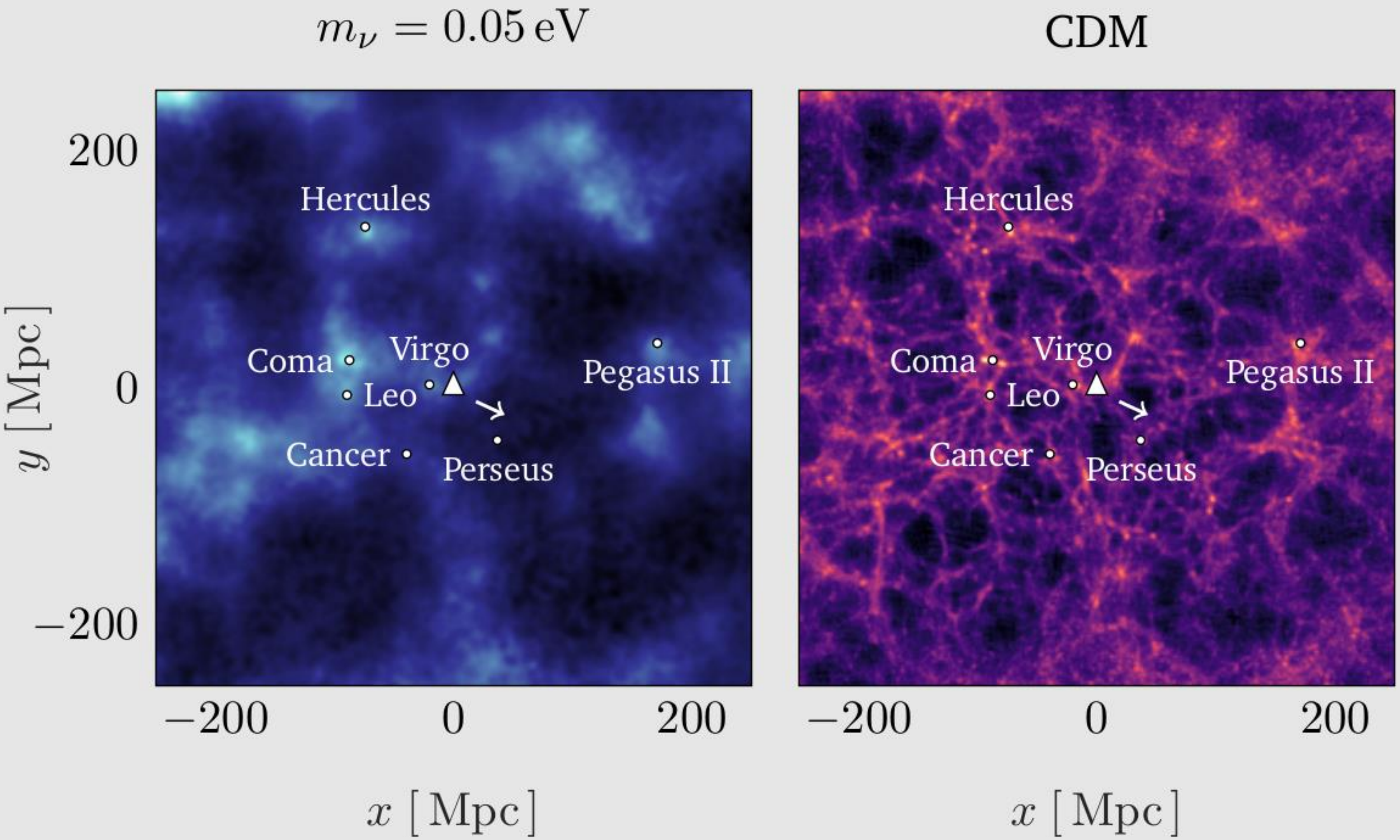
Constrained simulations with νs

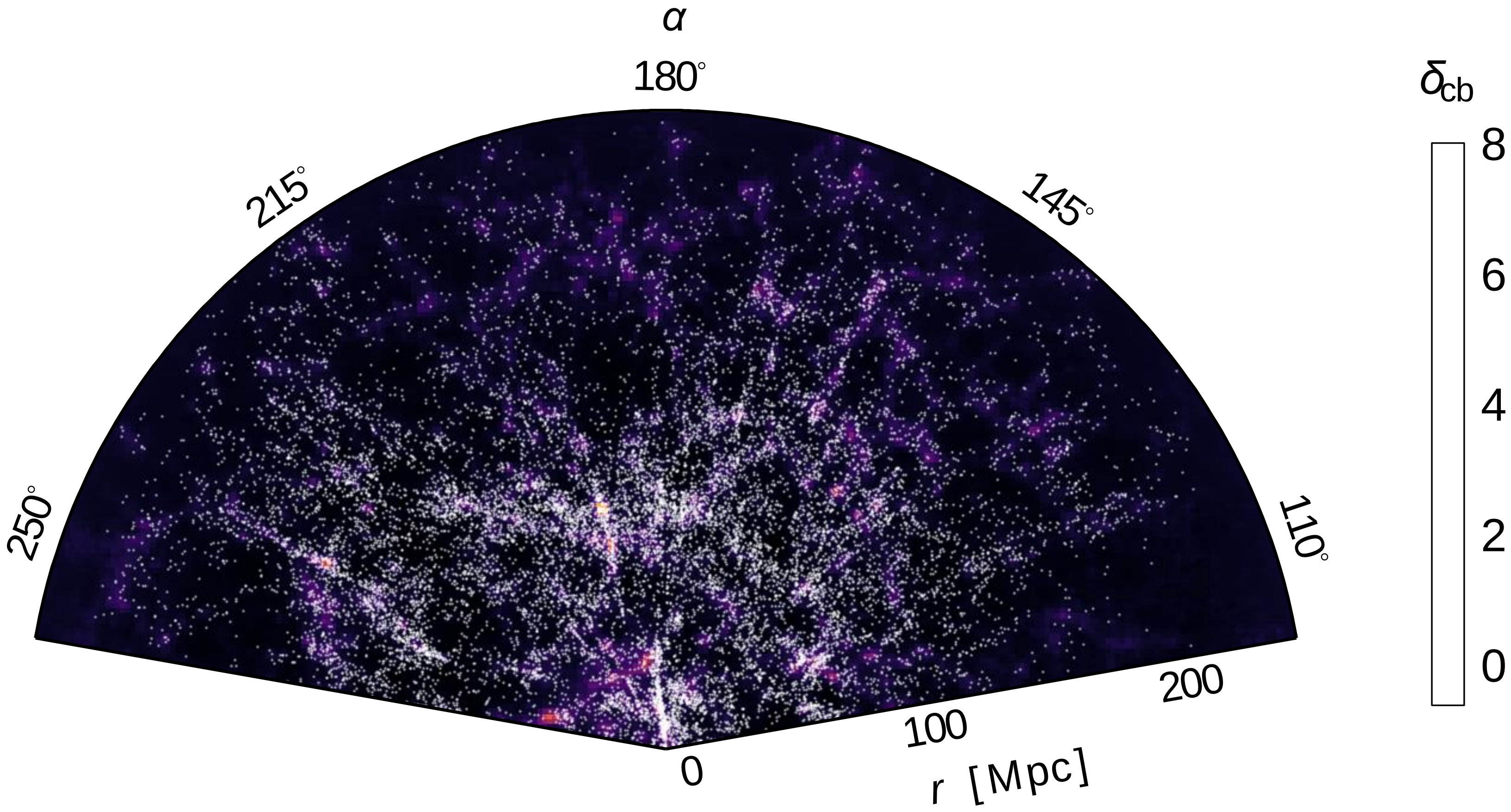


The position of the Milky Way is indicated by a white triangle

and the dipole direction by an arrow

Elbers, CSF+ '23

Local CDM distribution in z-space



Elbers, CSF+ ‘23

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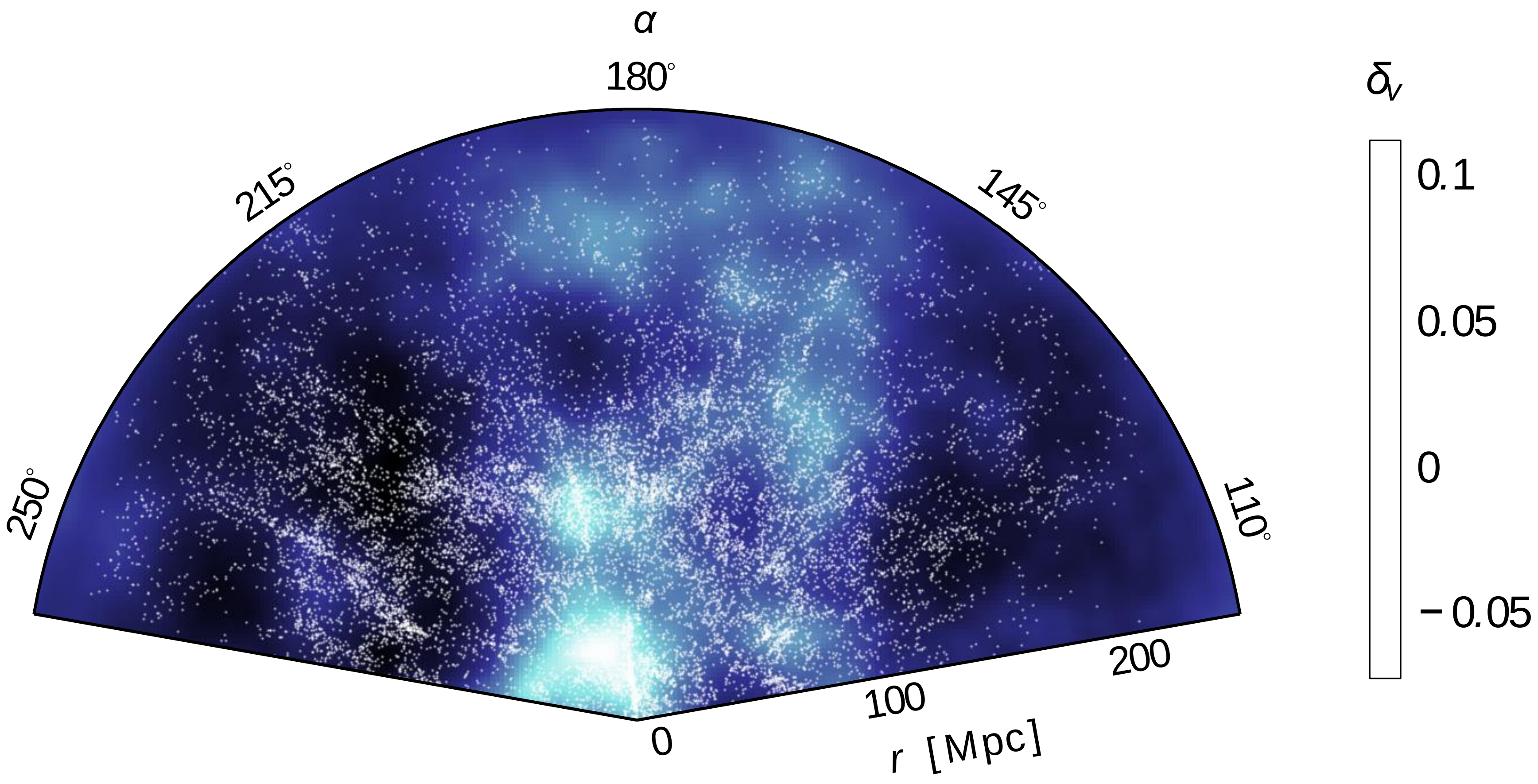
Local ν distribution in z-space

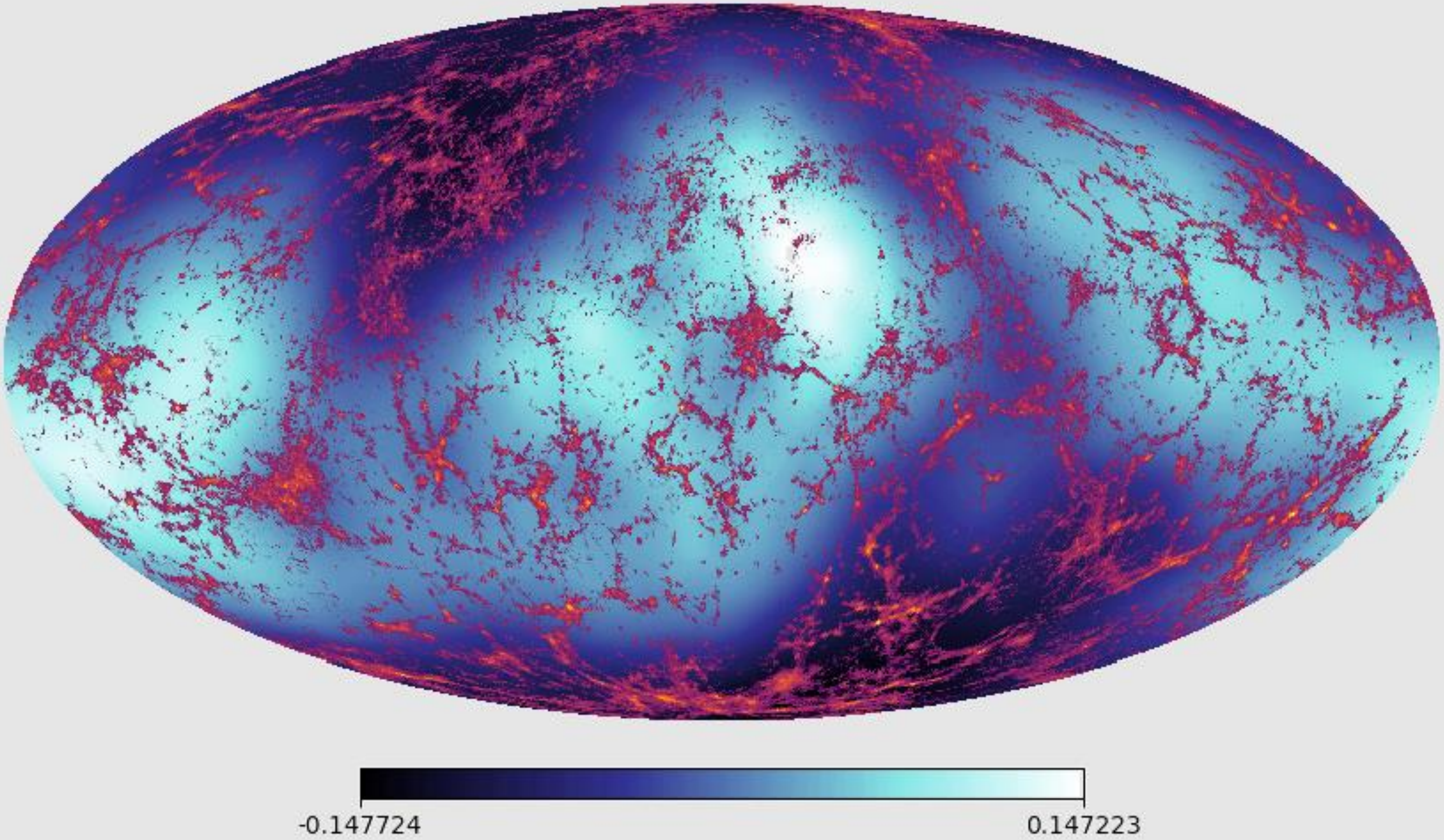


Elbers, CSF+ ‘23

Institute for Computational Cosmology

Angular anisotropies

Local neutrino density perturbations without dipole:



Elbers, CSF+ ‘23

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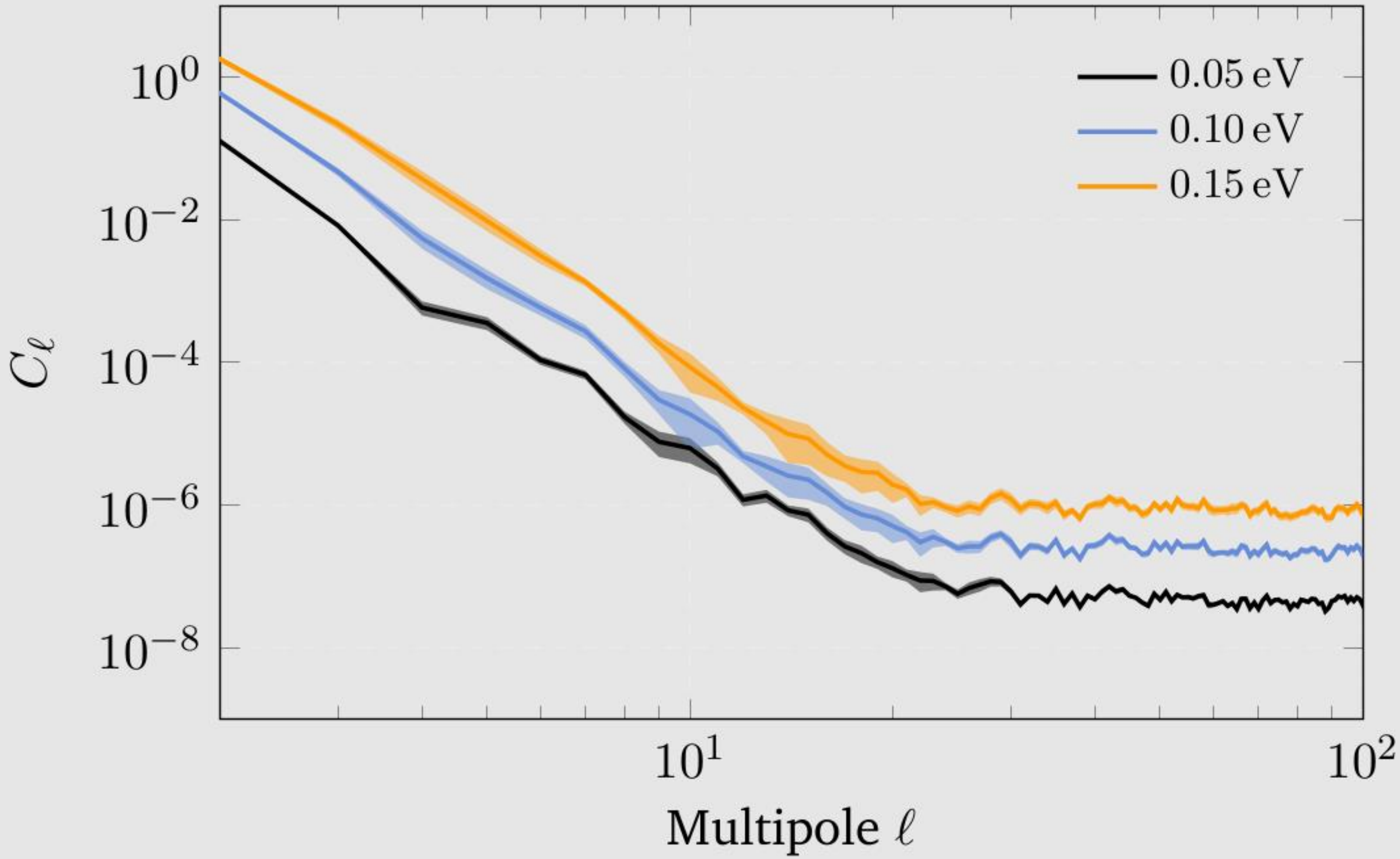
Angular power spectrum of ν perturbations



Elbers, CSF+ ‘23

A conclusive test of CDM

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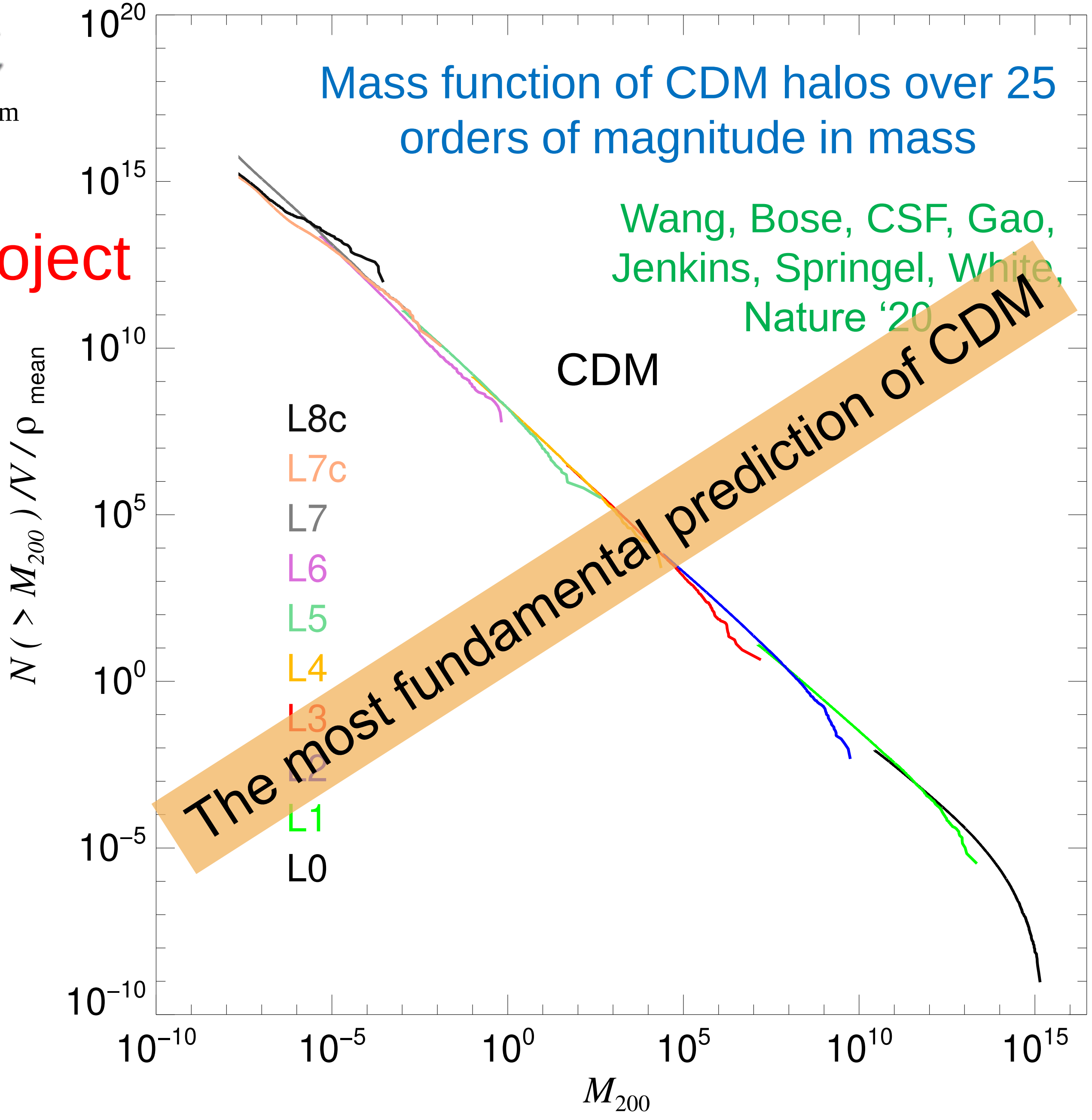
The VVV project



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

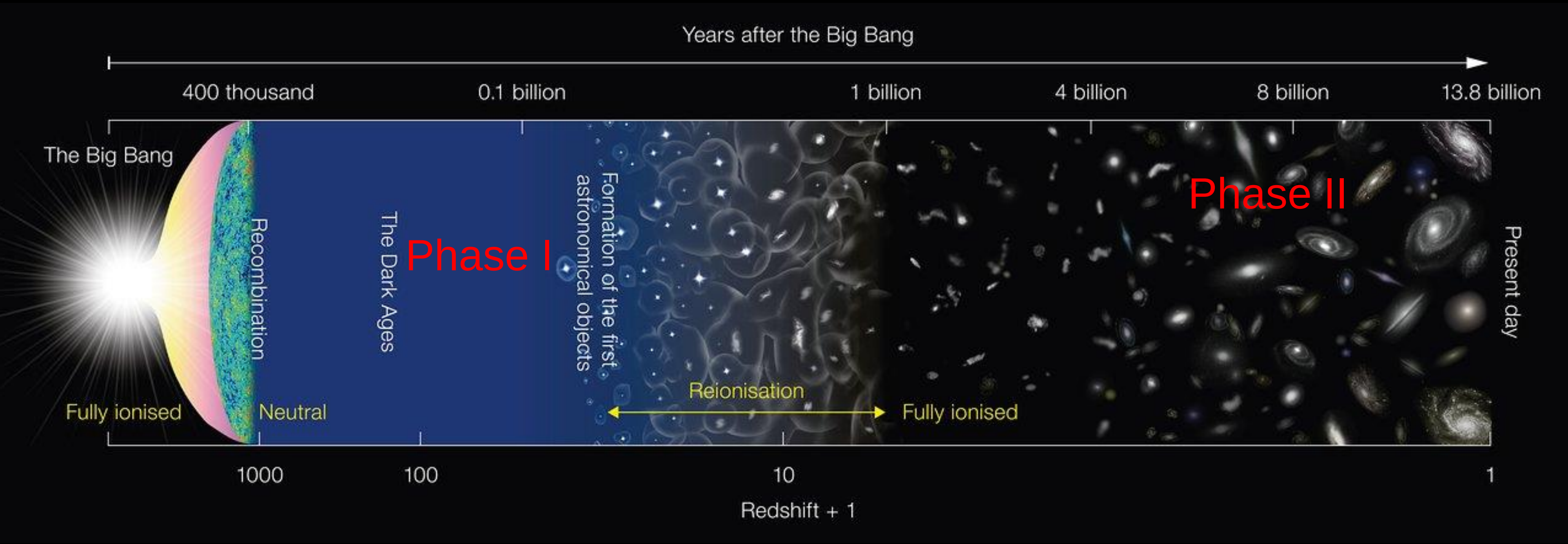
Wang, Bose, CSF, Gao, Jenkins, Springel, White, Nature '20

The most fundamental prediction of CDM

CDM

Most subhalos never make a galaxy!

The two phases of galaxy formation



Phase I: H gas is neutral → can only cool in halos $m > m_{thr,1}$

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

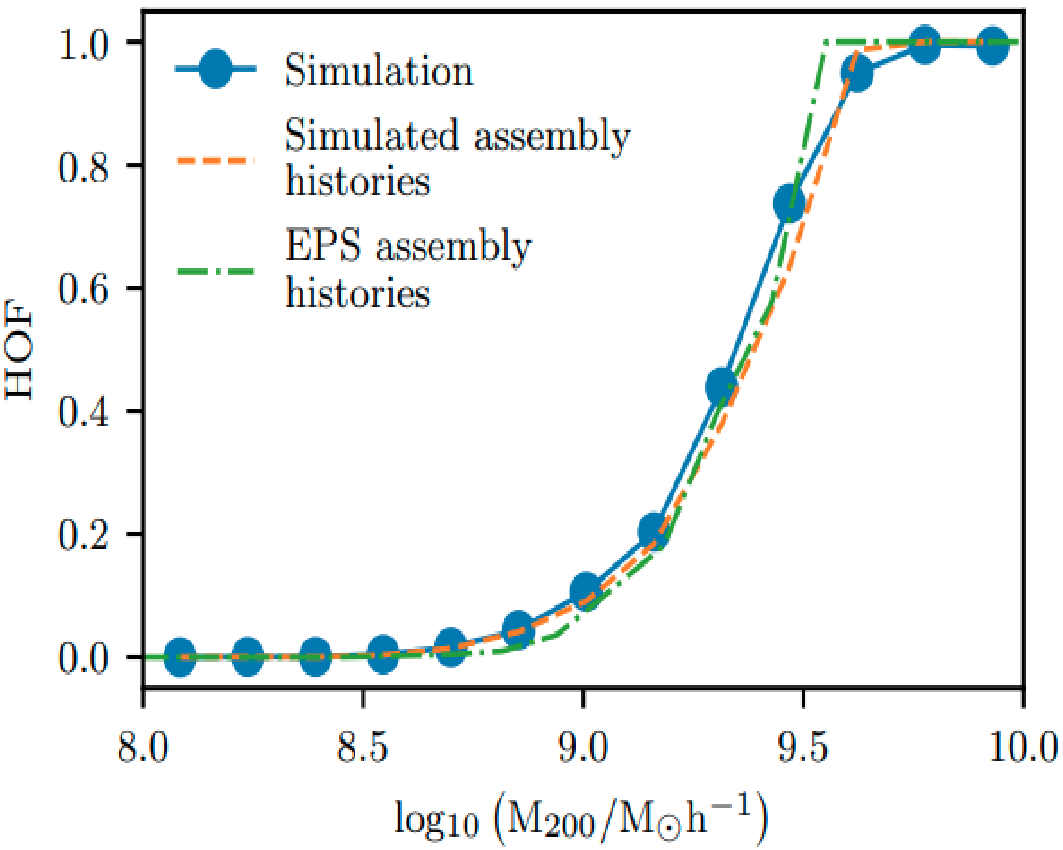
Phase II: H Gas is ionized ("T_{vir}" > 10^4)

→ can only cool in halos $m > m_{thr,2}$

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



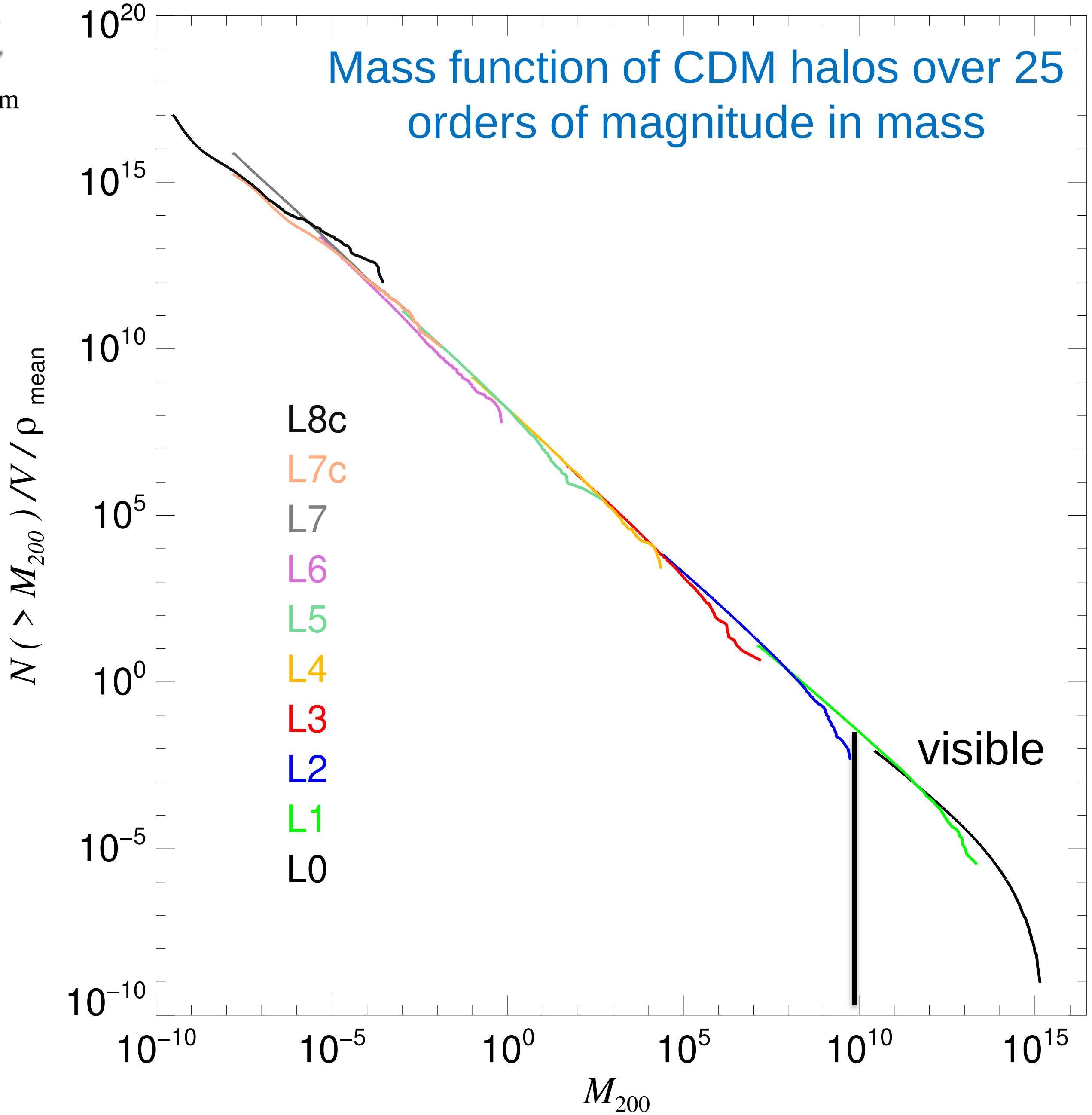
$M<3\times10^8 M_o$
→ dark

$M>3\times10^9 M_o$
→ visible

Benitez-Llambay & CSF ‘20

University of Durham

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



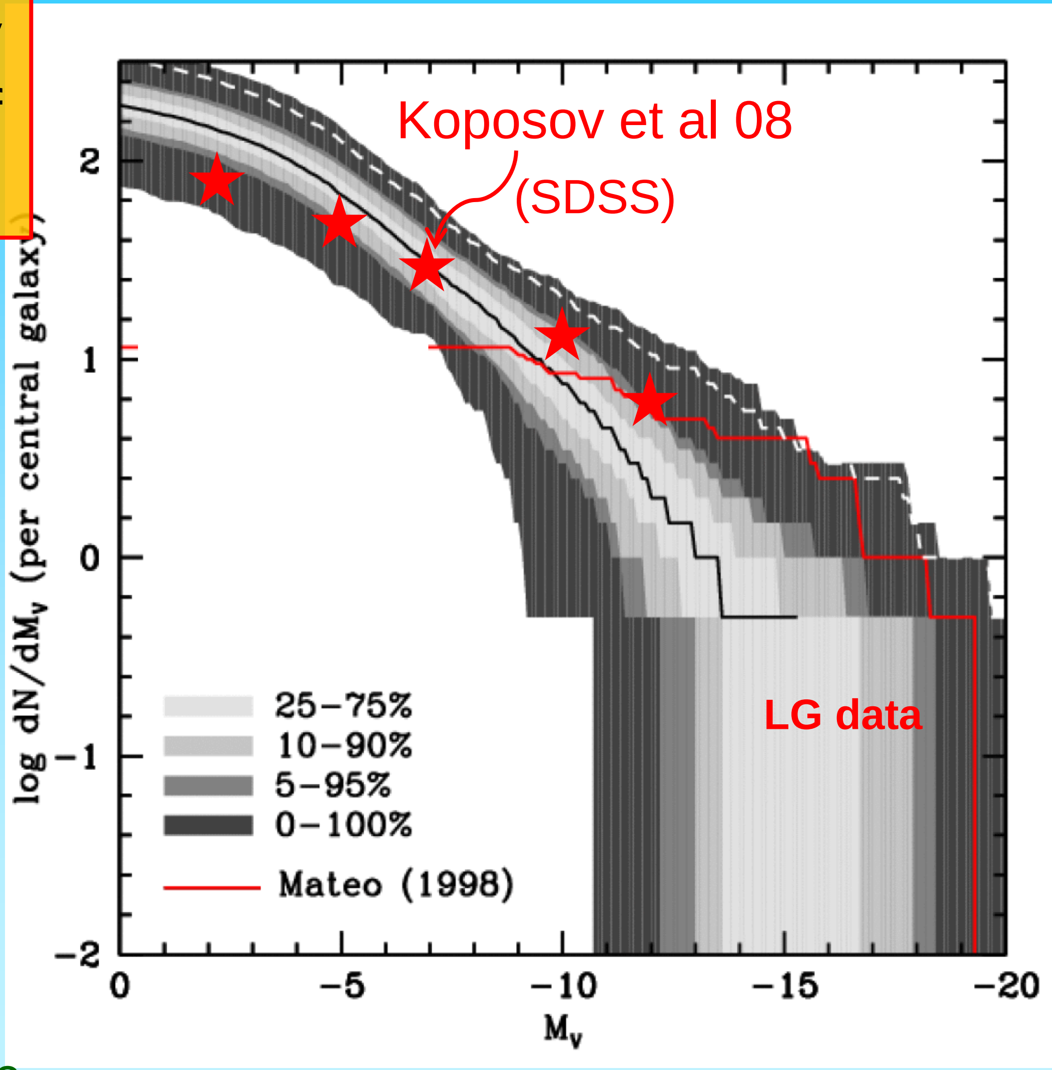
Wang, Bose, CSF, Gao, Jenkins, Springel, White - Nature 2020

Luminosity Function of Local Group Satellites

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

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

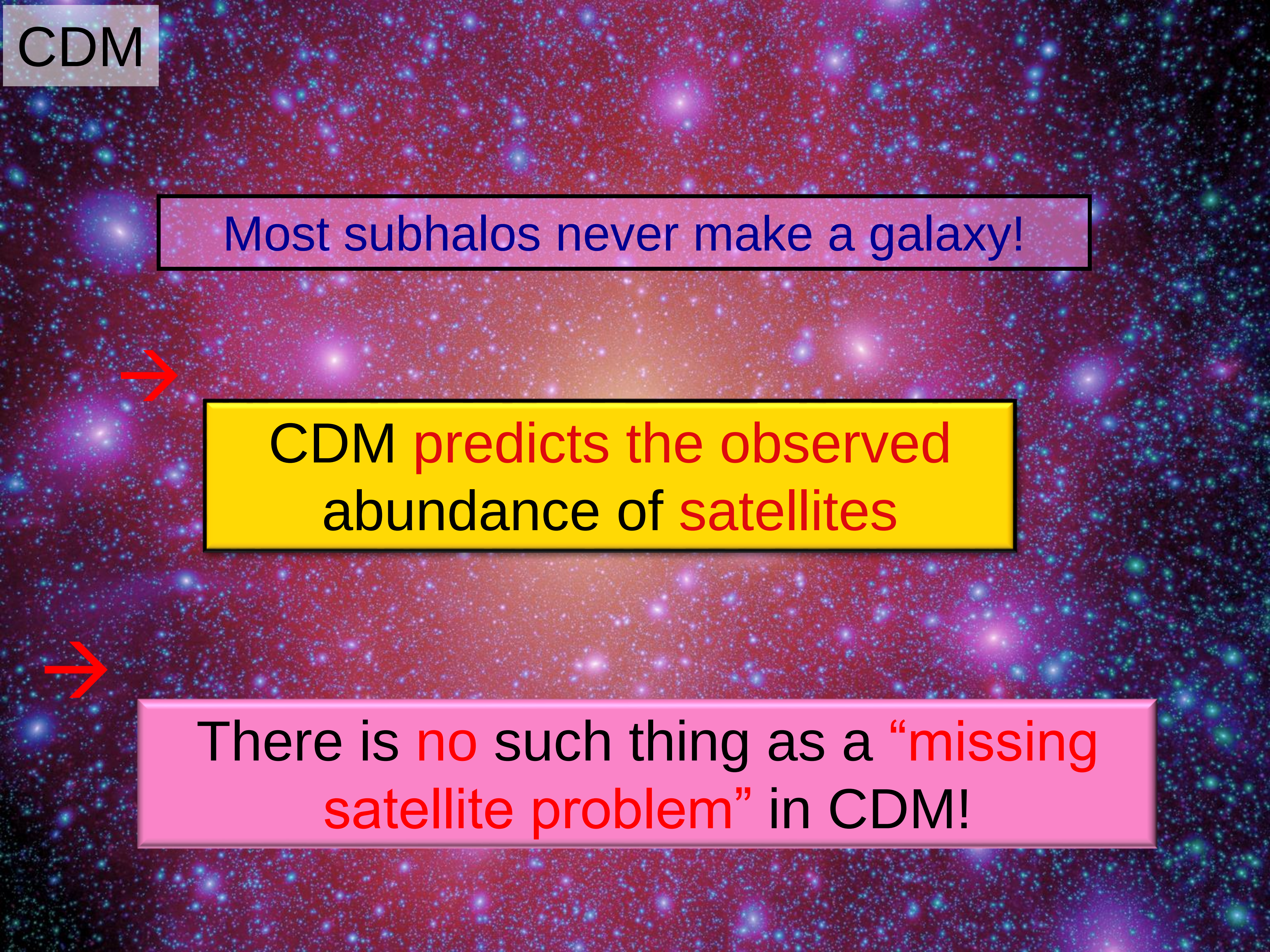
- Model predicts many, as yet undiscovered, faint satellites



Koposov et al 08 (SDSS)

LG data

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

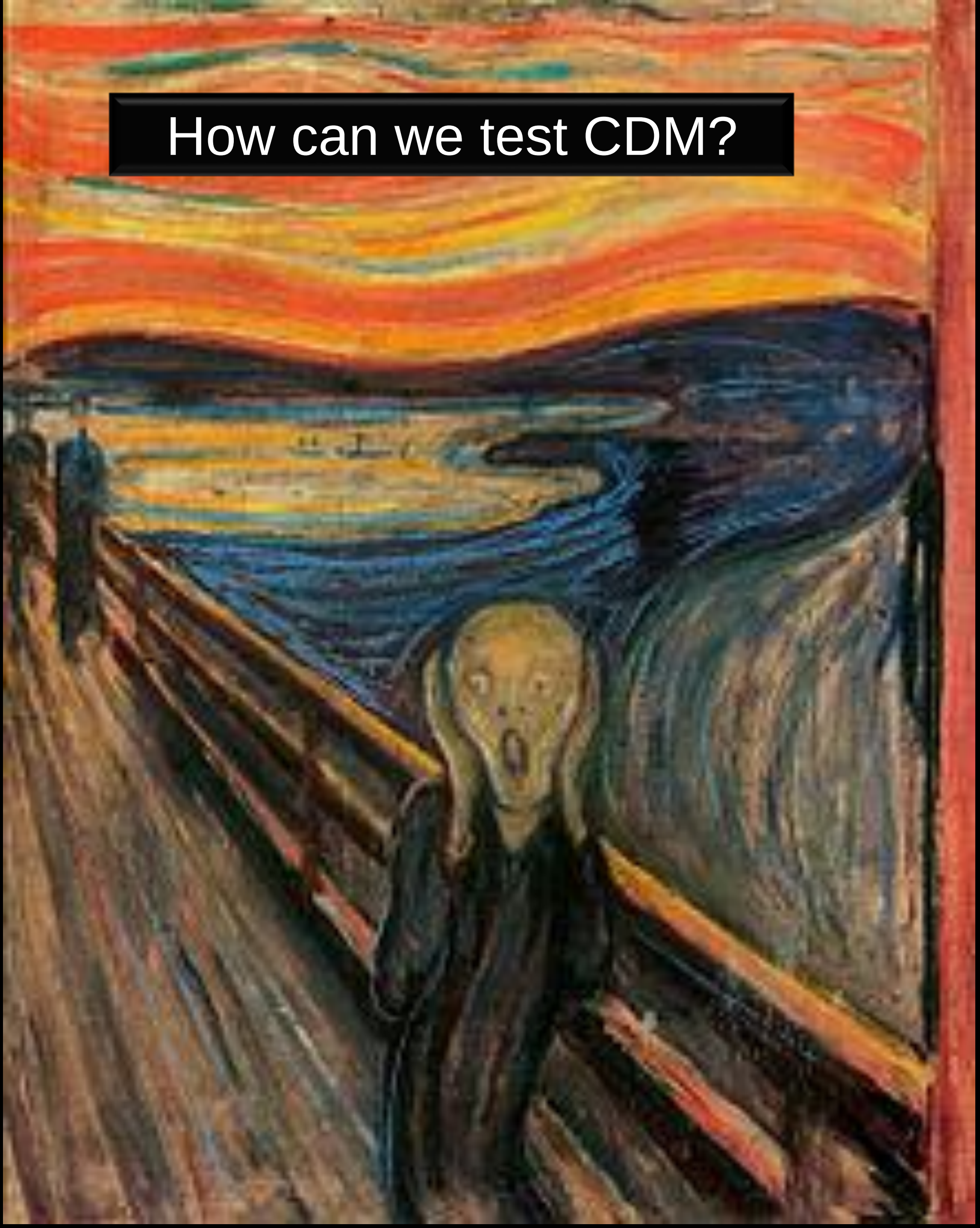


CDM

Most subhalos never make a galaxy!

→ CDM predicts the observed abundance of satellites

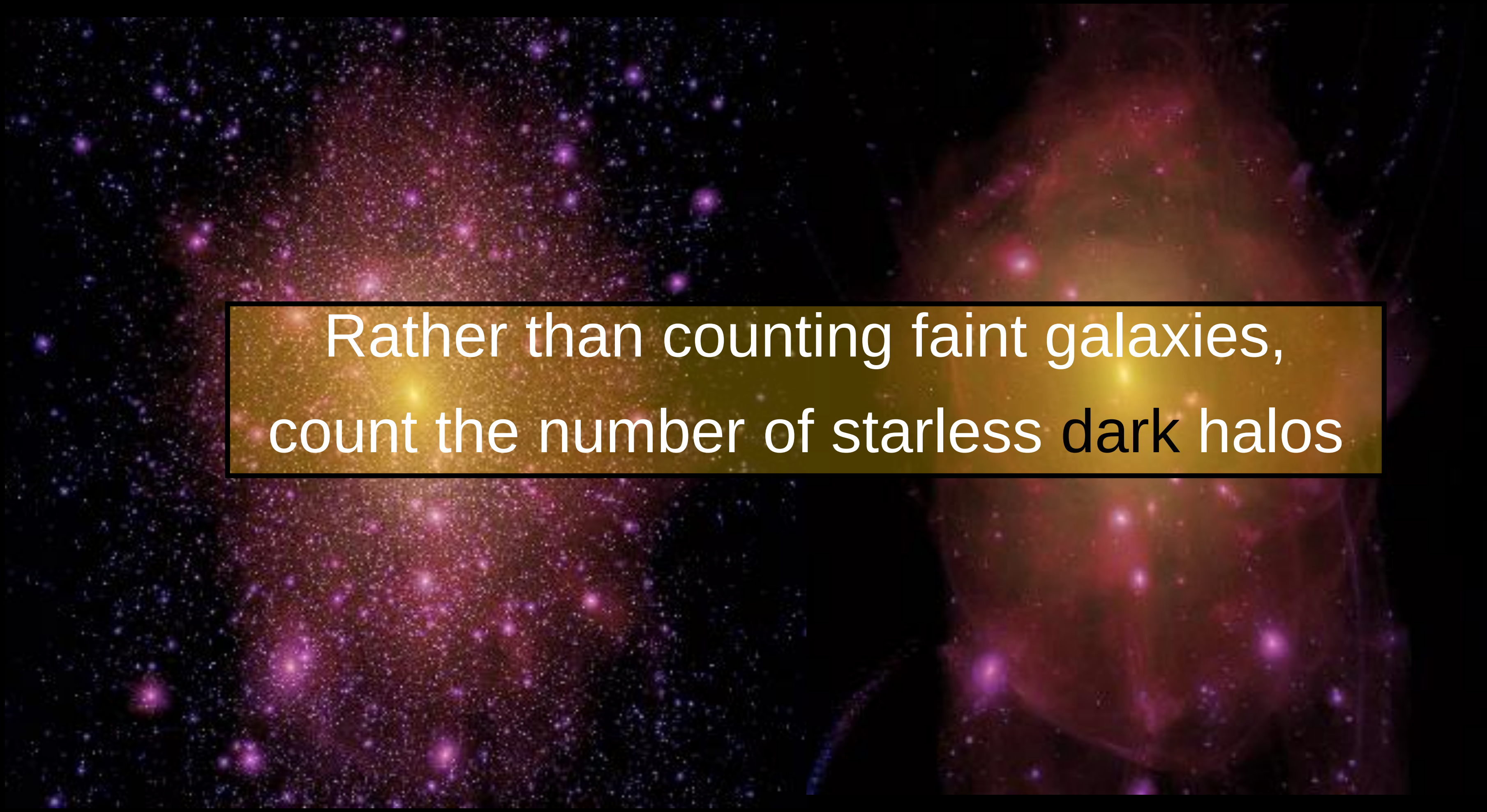
→ There is no such thing as a "missing satellite problem" in CDM!



How can we test CDM?

… and distinguish CDM/WDM?

… and distinguish CDM/WDM?



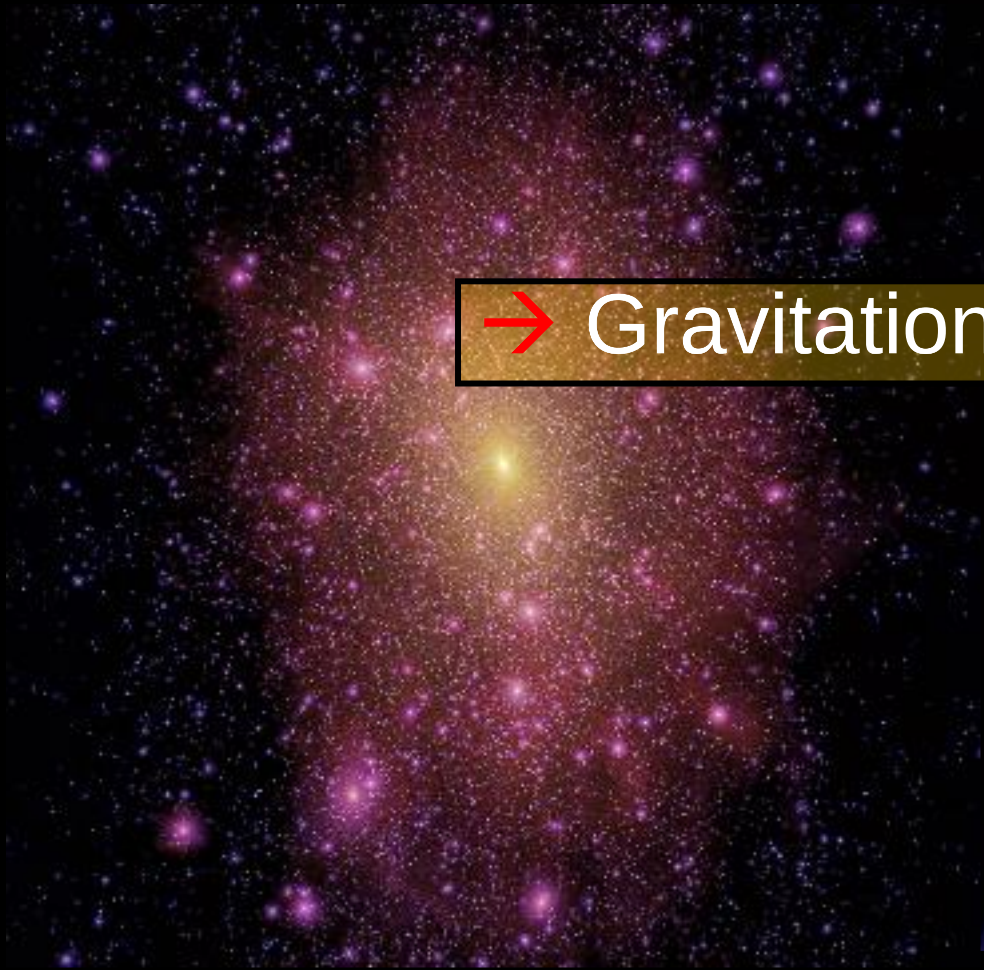
cold dark matter

warm dark matter

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

Can we count dark haloes?

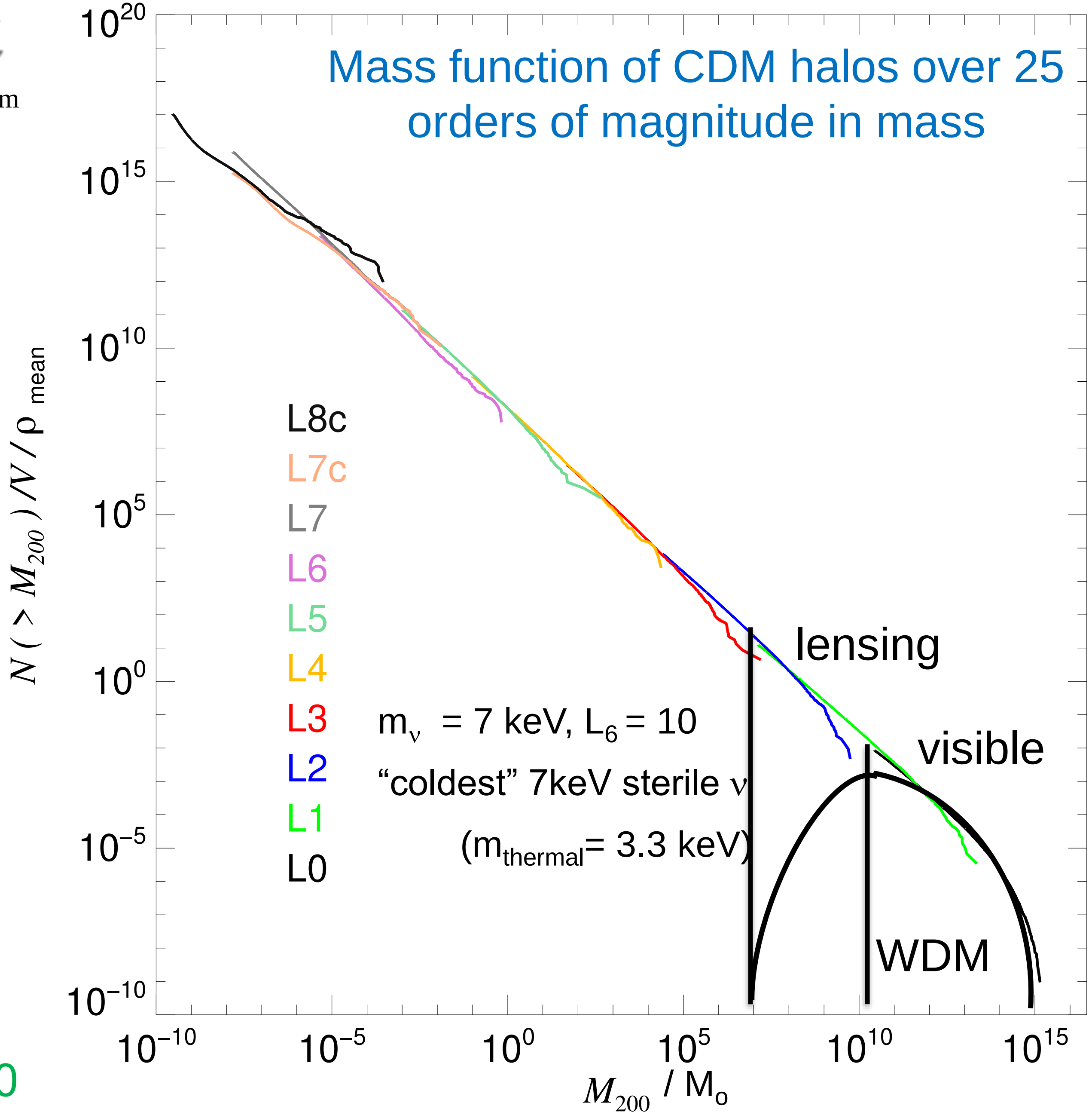
cold dark matter



warm dark matter

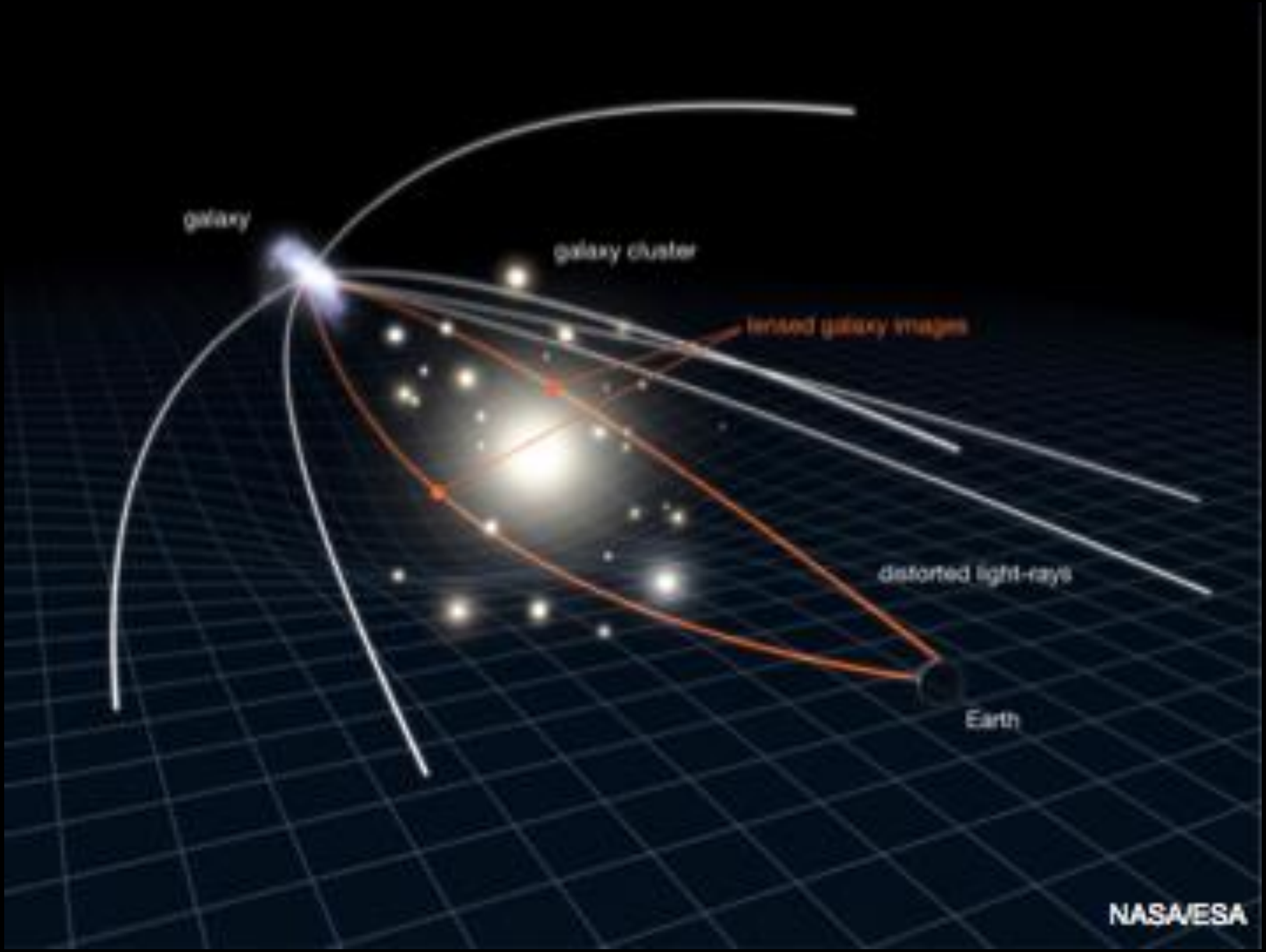
→ Gravitational lensing

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



Wang et al ‘20

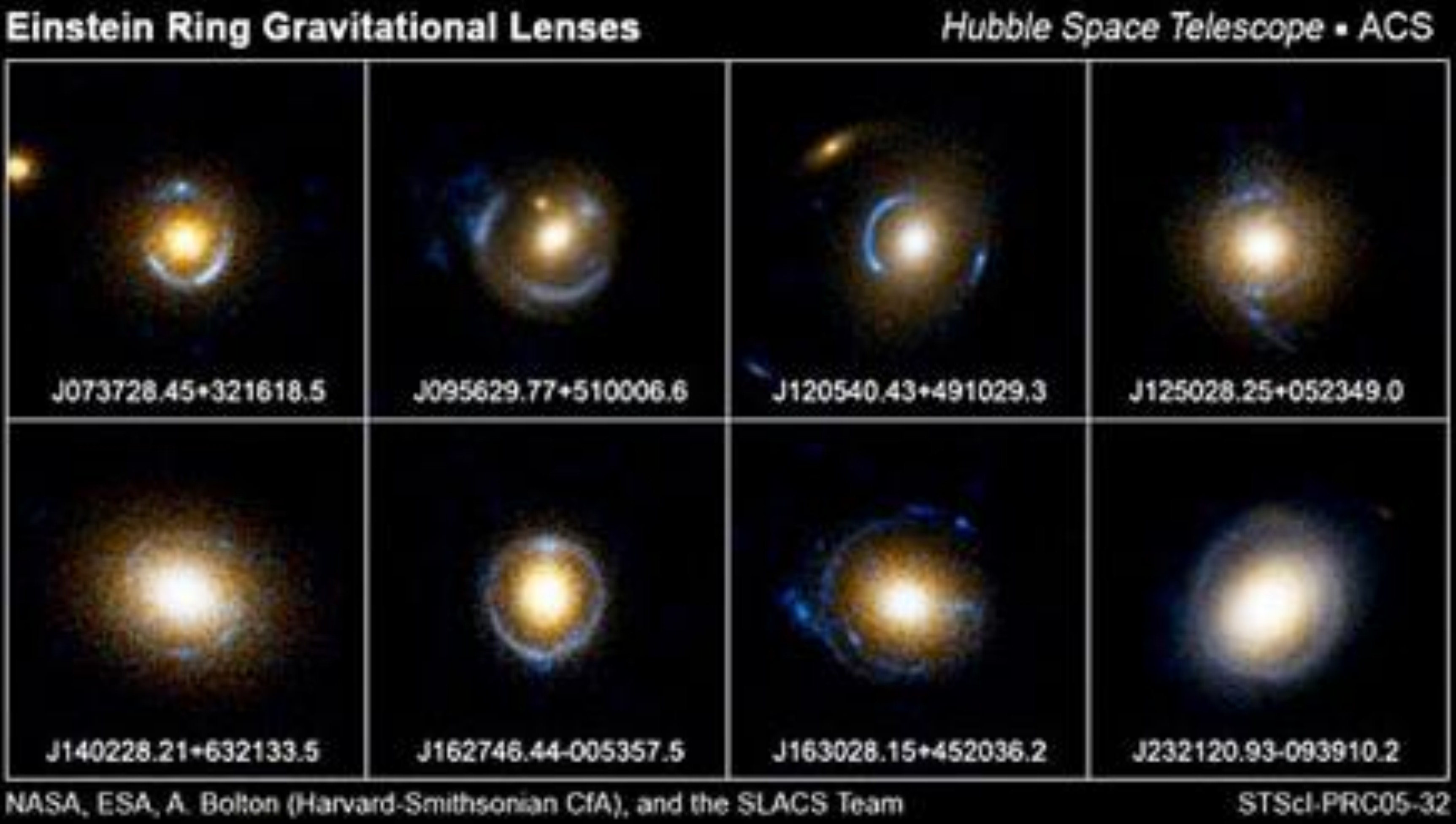
Gravitational lensing: Einstein rings



NASA/ESA

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

SLAC sample of strong lenses



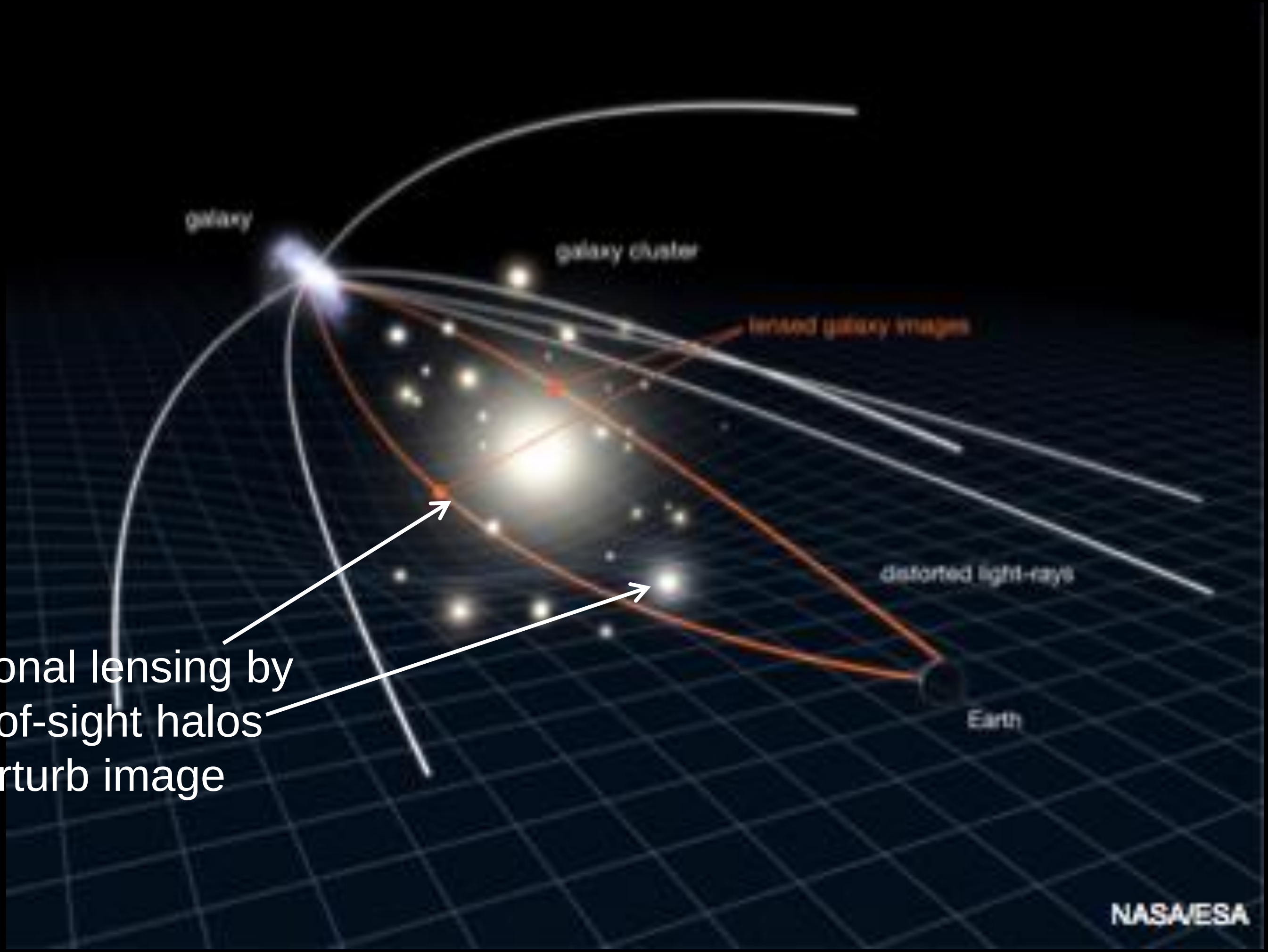
Einstein Ring Gravitational Lenses

Hubble Space Telescope • ACS

NASA, ESA, A. Bolton (Harvard-Smithsonian CfA), and the SLACS Team

STScI-PRC05-32

Gravitational lensing: Einstein rings



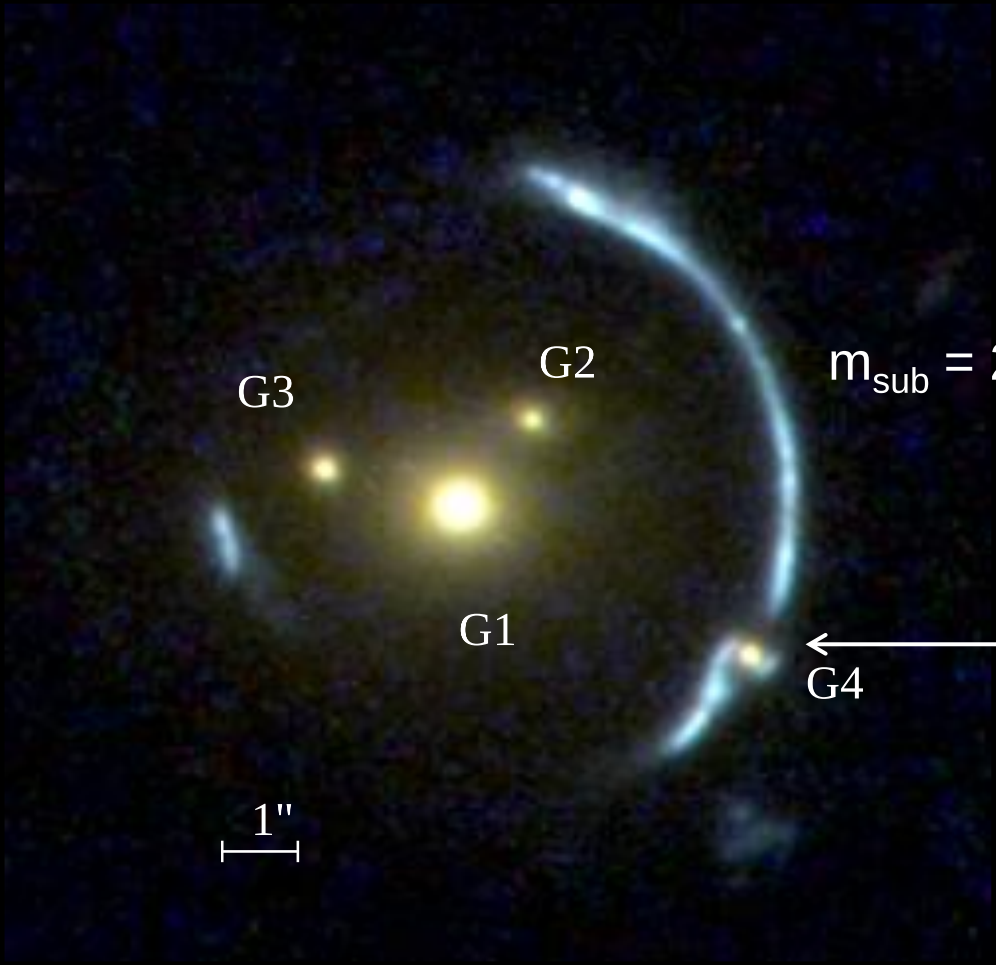
NASA/ESA

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

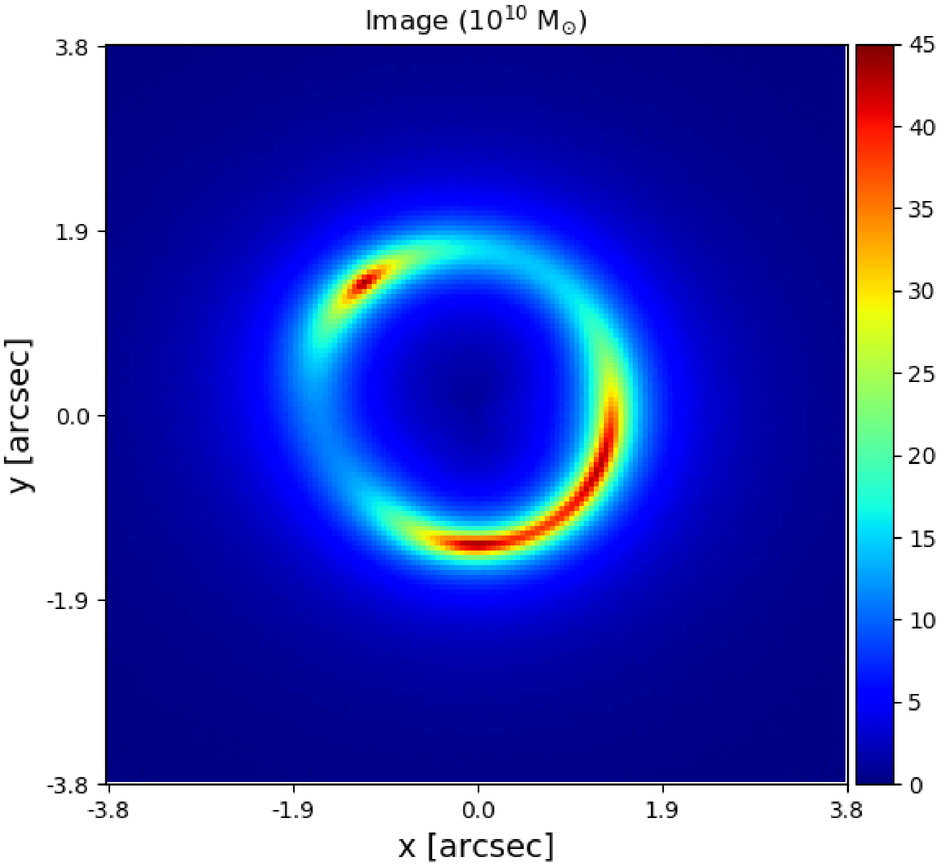
University of Durham

Gravitational lensing: Einstein rings

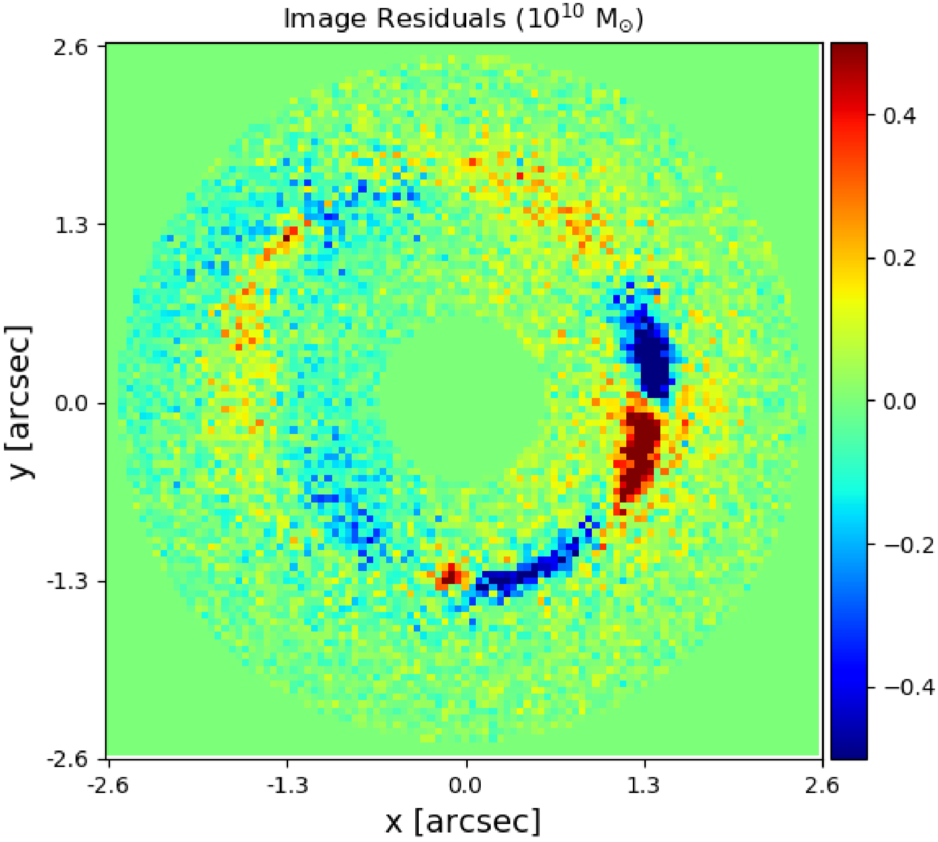
HST “data”: z_{source}=1; z_{lens}=0.2

$10^{10}M_o$ halo – easy to spot

Image

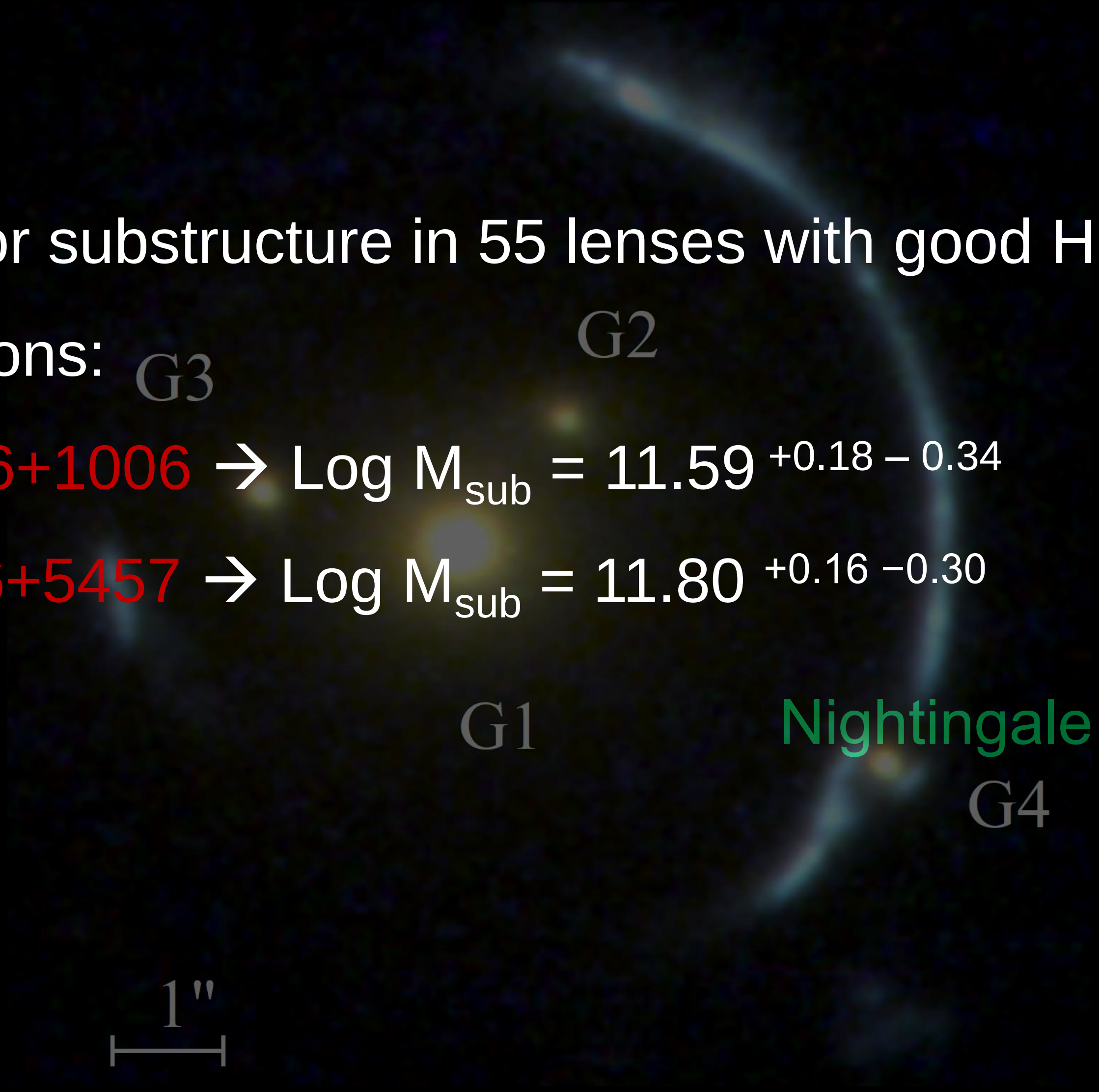


Residuals



He, Li, CSF et al ‘19

Gravitational lensing: substructures



Searched for substructure in 55 lenses with good HST imaging

→ 2 detections:

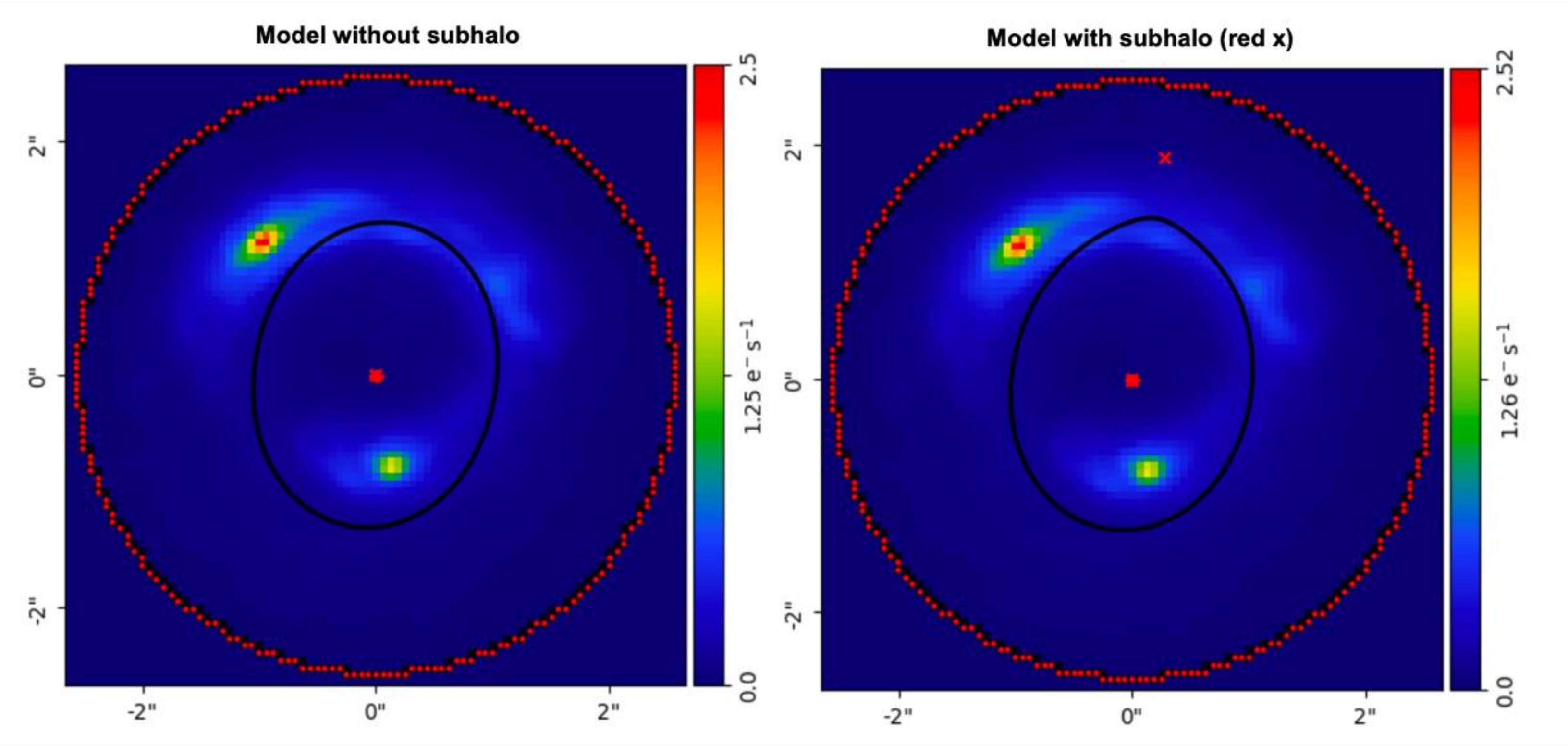
SLACS0946+1006 → $\mathrm{Log}\ M_{\mathrm{sub}} = 11.59^{+0.18 - 0.34}$

BELLS1226+5457 → $\mathrm{Log}\ M_{\mathrm{sub}} = 11.80^{+0.16 -0.30}$

Nightingale + ‘22

Gravitational lensing: substructures

JWST



And another one in JWST data:

→ Log $M_{sub} = 11.59^{+0.18 - 0.34}$

Lange, Nightingale, CSF+ '23

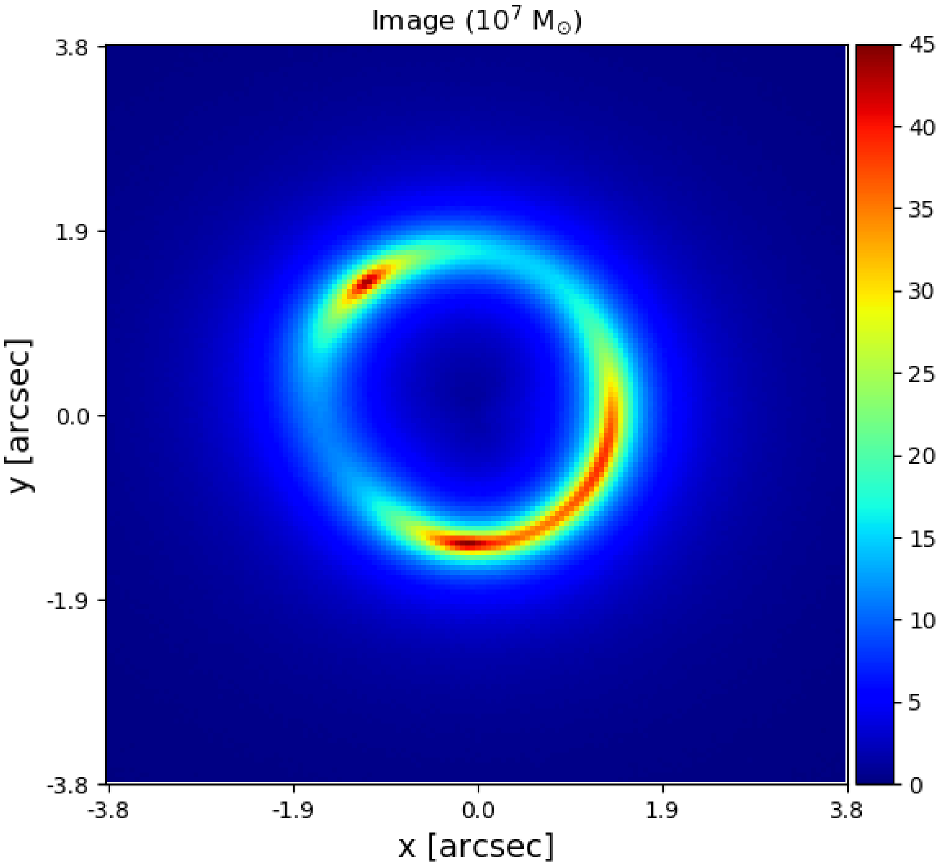
University of Durham

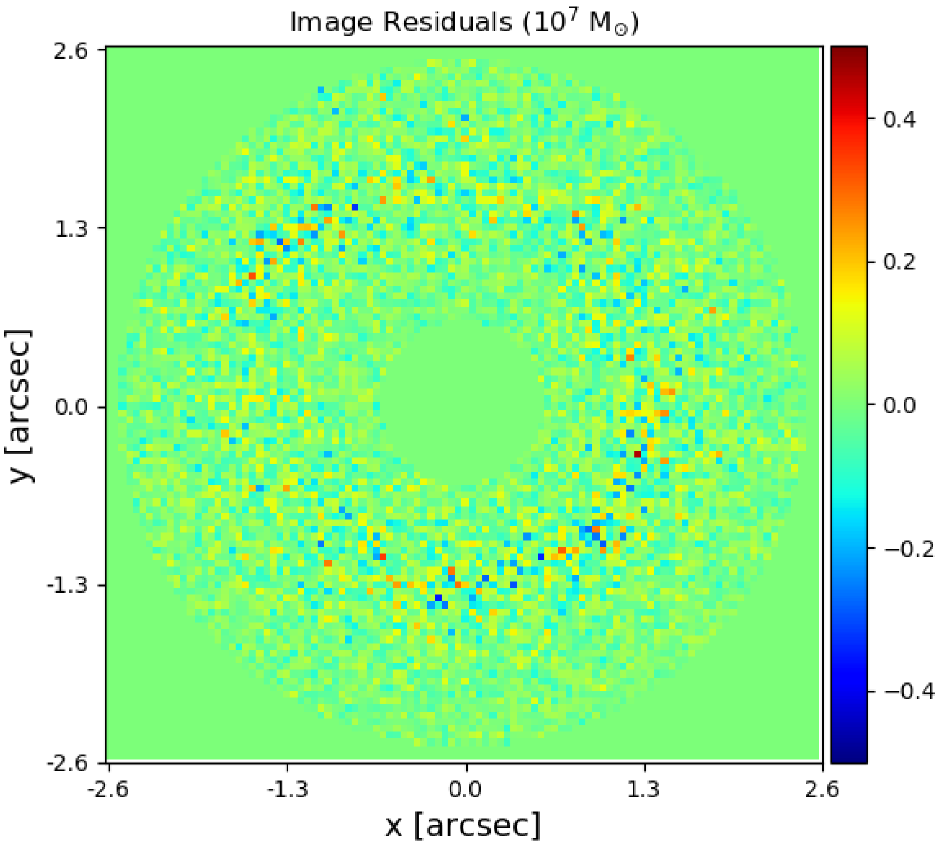
Strong lensing: detecting small halos

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

Image

Residuals (image – smooth model)

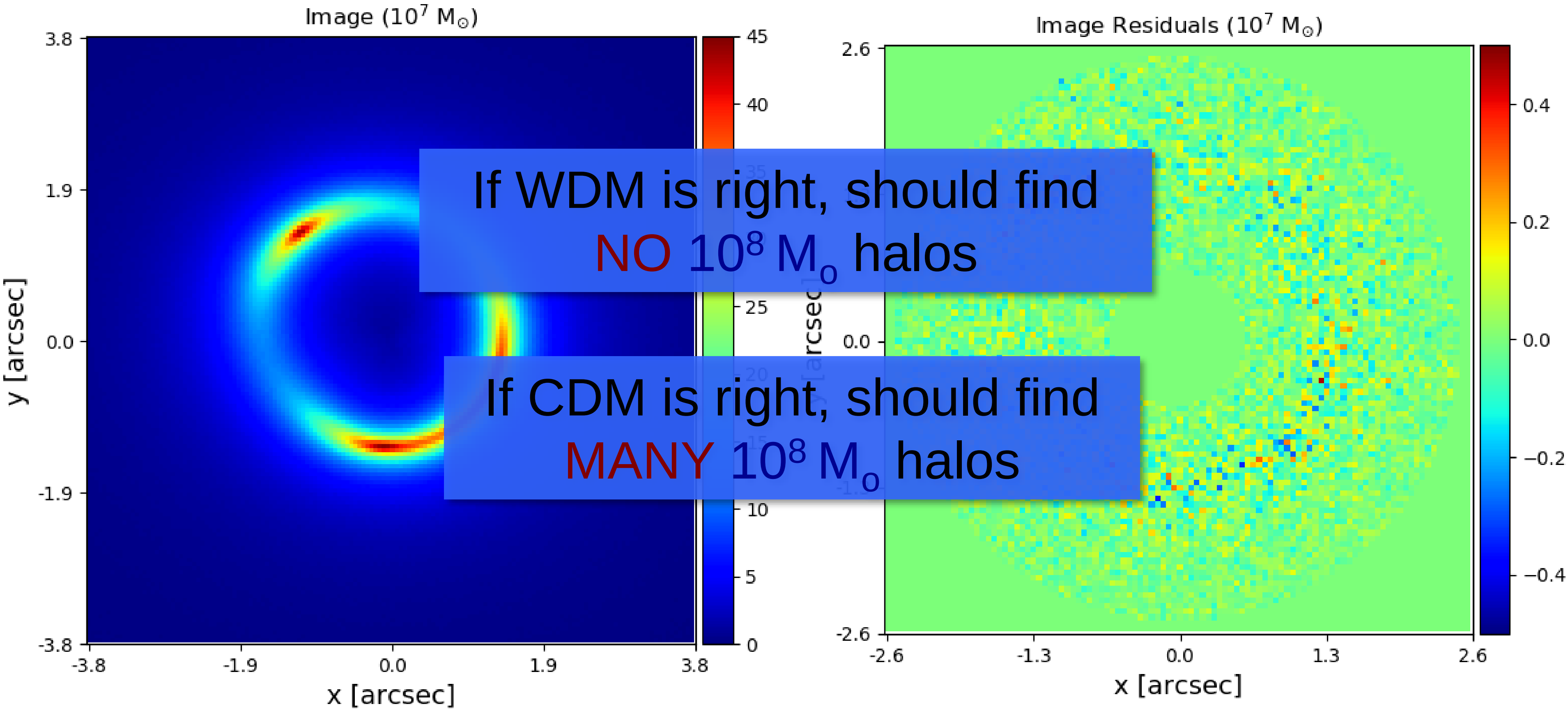




He, Li, CSF et al ‘19

Detecting halos w. strong lensing

Can detect halos as small as 10^7 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

ICC
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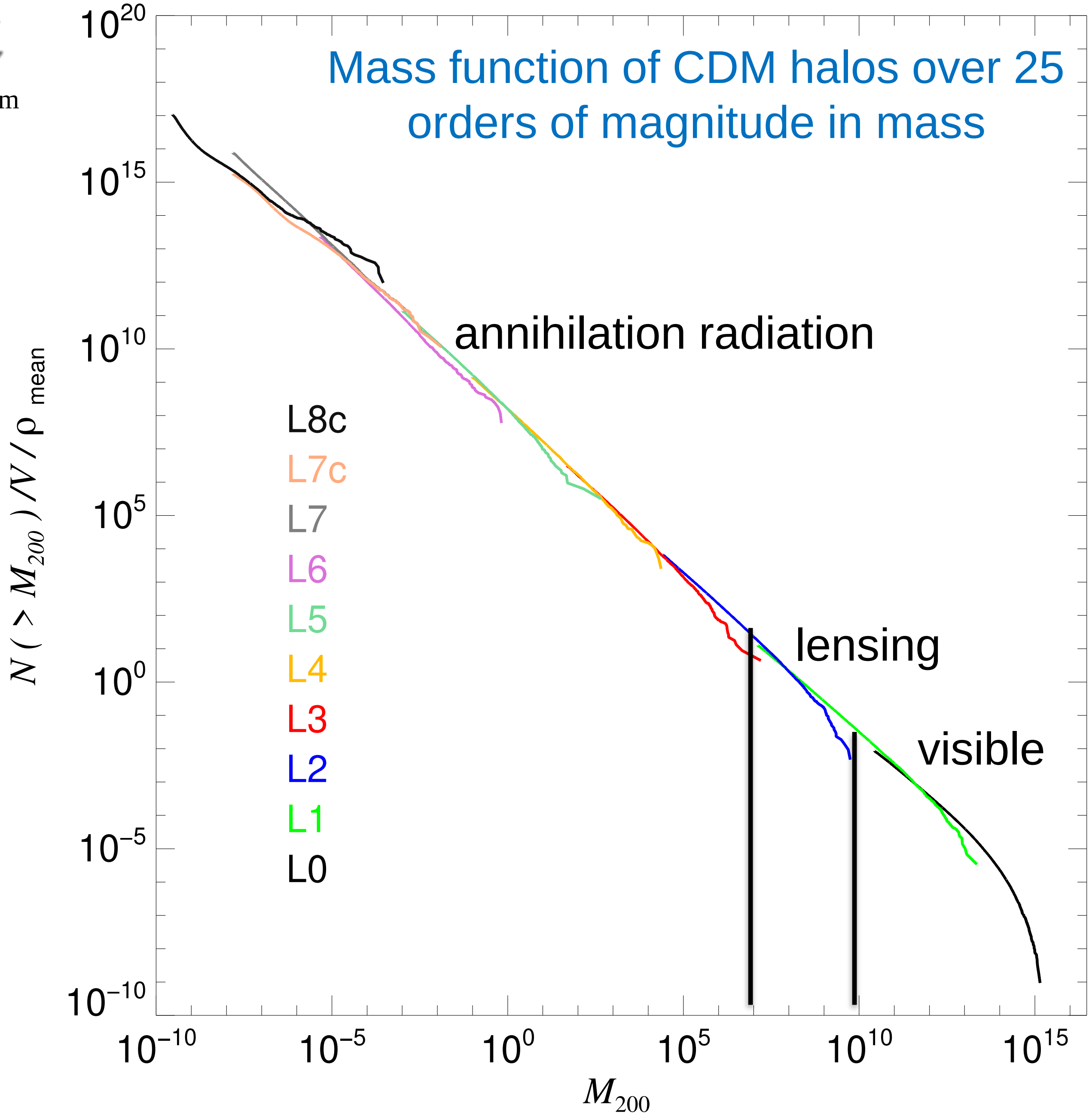

Wang, Bose, CSF, Gao, Jenkins, Springel, White - Nature 2020

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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)

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

cross-section (particle physics)

$\langle\sigma v\rangle = 3\times10^{-26}\,cm^3 s^{-1}$ → 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

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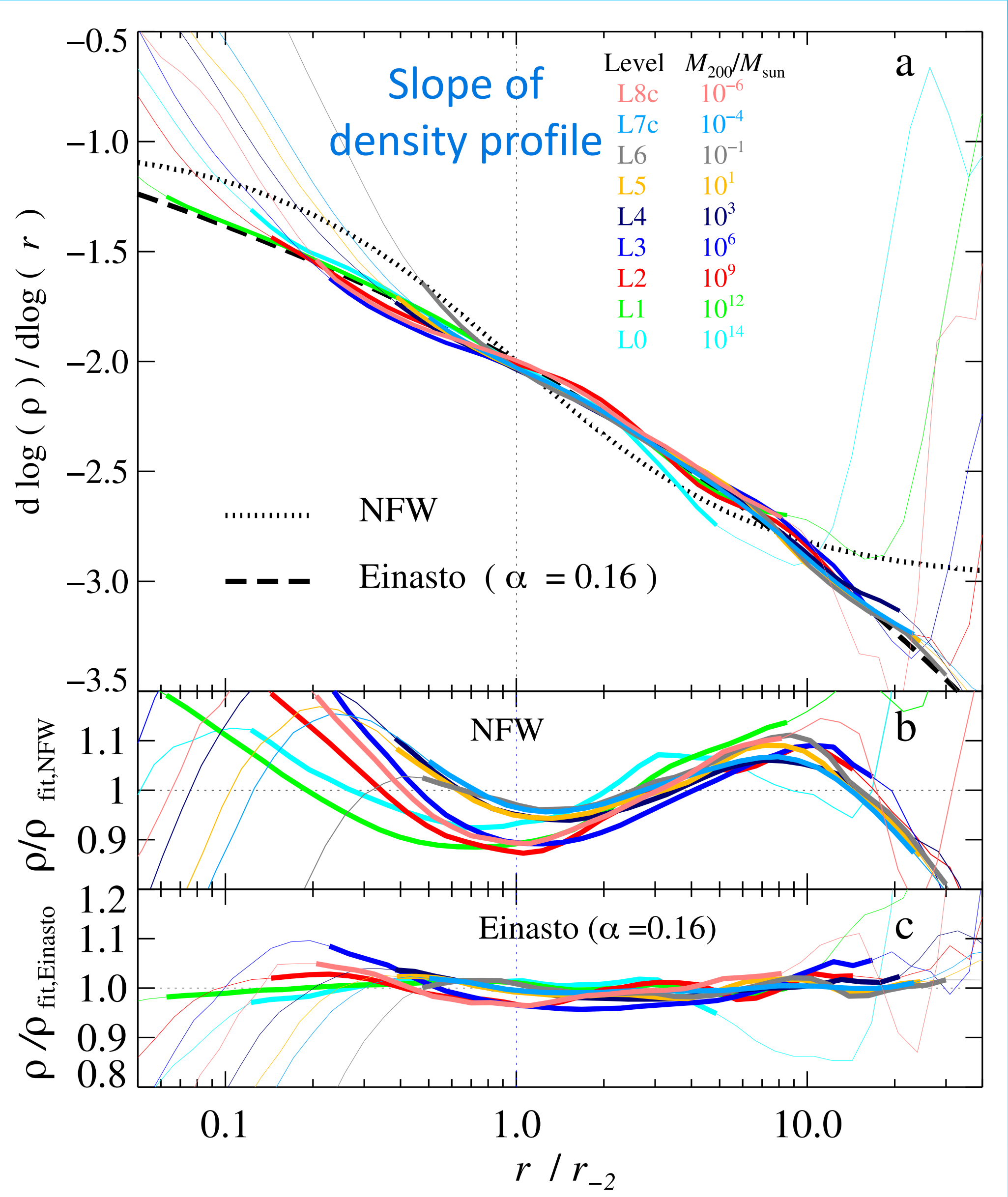
Density profile shapes

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%

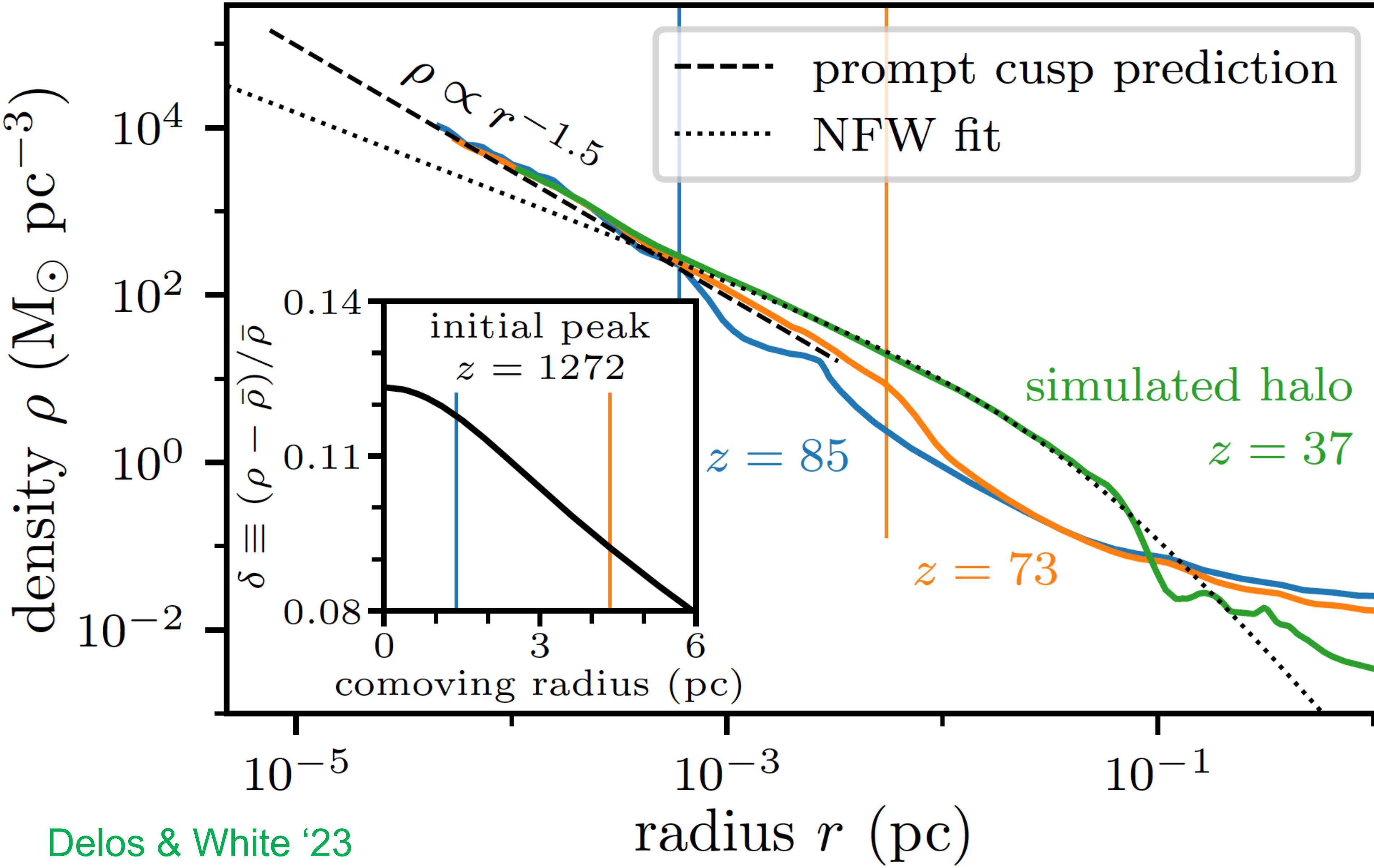


Earth-mass halo

Wang, Bose, CSF + ‘20

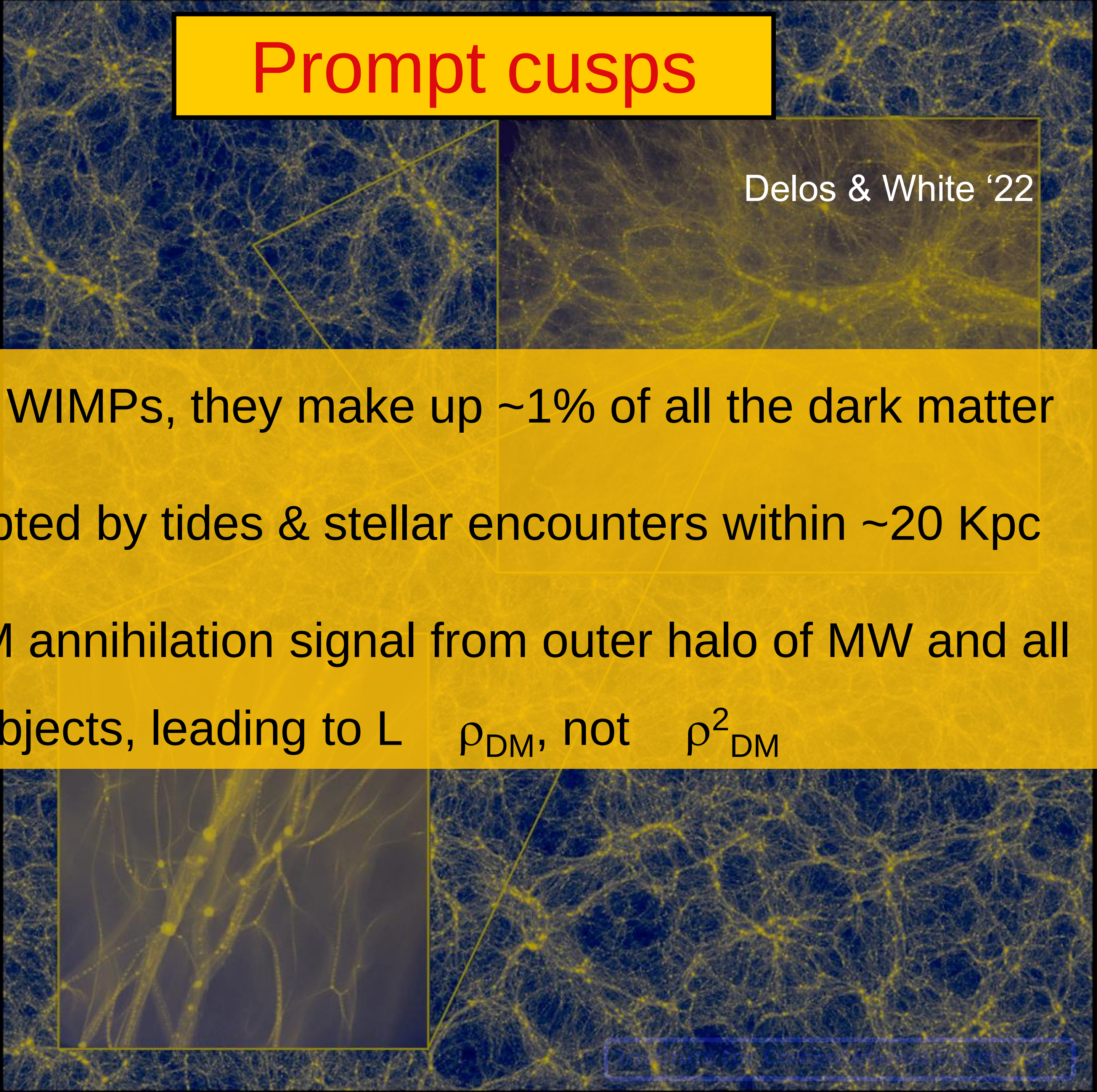
Earth-mass halo

Prompt cusp and subsequent halo growth for a peak with $z_{\mathrm{coll}} = 87$



Delos & White '23

Prompt cusps



Delos & White ‘22

- For standard WIMPs, they make up ~1% of all the dark matter
- In MW, disrupted by tides & stellar encounters within ~20 Kpc
- Dominate DM annihilation signal from outer halo of MW and all extragalactic objects, leading to L ρ_{DM}, not ρ^2_{DM}

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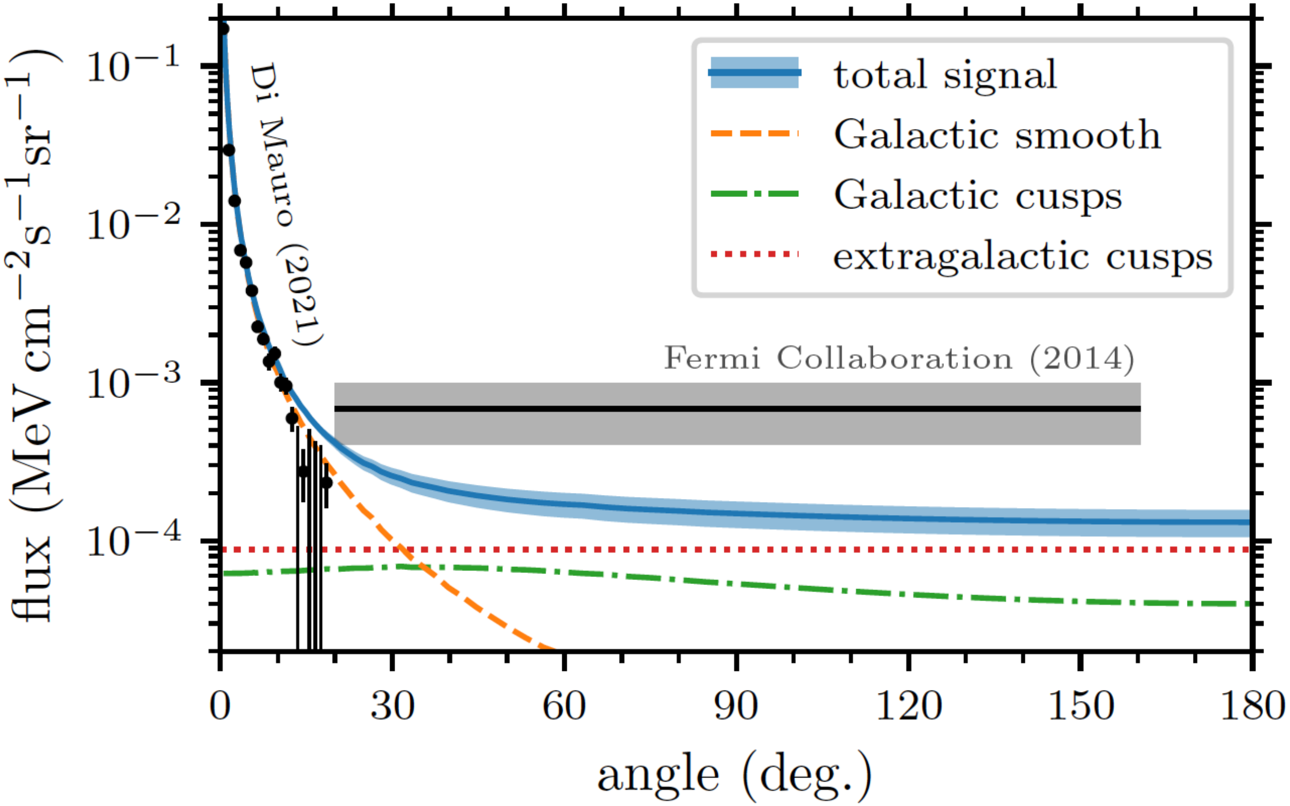
The Galactic Centre excess

Cusp emission dominates at >20^0 from centre

Surface brightness from MW halo comparable to that from halos of external galaxies

Prompt cusps dominate the 1 – 10 Gev background

Delos & White '23



Only just consistent with γ-ray background

Conclusions

- The properties CDM (no baryons) on all scales - solved problem
- The abundance & structure of CDM halos (down to Earth's mass) and of WDM (no halos of mass $<10^8$ M_o) is now known
- CDM (and WDM) halos of all masses have NFW density profiles (except in very inner parts for halos near the cutoff)
- There is NO "small-scale" crisis in CDM
- Local large-scale structure is reflected in the cosmic neutrino background. MW dipole & angular PS depend in the ν mass
- Distortions of strong gravitational lenses offer a clean test of CDM *vs* WDM → and can potentially rule out CDM!
- Prompt cusps of Earth mass dominate the annihilation radiation from outer halo of MW and extragalactic objects