MATERA OSCURA

- DARK MATtER(A) -

COSMOLOGY AND DARK MATTER WITHIN GALAXIES AND CLUSTERS

Wrap-up Talk

Simon White, Max Planck Institute for Astrophysics

Die Rotverschiebung von extragalaktischen Nebeln

von F. Zwicky.

(16. II. 33.)

Inhaltsangabe. Diese Arbeit gibt eine Darstellung der wesentlichsten Merkmale extragalaktischer Nebel, sowie der Methoden, welche zur Erforschung derselben gedient haben. Insbesondere wird die sog. Rotverschiebung extragalaktischer Nebel eingehend diskutiert. Verschiedene Theorien, welche zur Erklärung dieses wichtigen Phänomens aufgestellt worden sind, werden kurz besprochen. Schliesslich wird angedeutet, inwiefern die Rotverschiebung für das Studium der durchdringenden Strahlung von Wichtigkeit zu werden verspricht.

§ 5. Bemerkungen zur Streuung der Geschwindigkeiten im Coma-Nebelhaufen.

Wie aus der Zusammenstellung in § 3 hervorgeht, existieren im Comahaufen scheinbare Geschwindigkeitsunterschiede von mindestens 1500 bis 2000 km/sek. Im Zusammenhang mit dieser enormen Streuung der Geschwindigkeiten kann man folgende Überlegungen anstellen.

1. Setzt man voraus, dass das Comasystem mechanisch einen stationären Zustand erreicht hat, so folgt aus dem Virialsatz

$$\bar{\varepsilon}_k = -\tfrac{1}{2}\,\bar{\varepsilon}_p, \qquad (4)$$

wobei $\bar{\varepsilon}_k$ und $\bar{\varepsilon}_p$ mittlere kinetische und potentielle Energien, z. B. der Masseneinheit im System bedeuten. Zum Zwecke der Abschätzung nehmen wir an, dass die Materie im Haufen gleichförmig über den Raum verteilt ist. Der Haufen besitzt einen Radius R von ca. einer Million Lichtjahren (gleich 10^{24} cm) und enthält 800 individuelle Nebel von je einer Masse entsprechend 10^9 Sonnenmassen. Die Gesamtmasse M des Systems ist deshalb

$$M \sim 800 \times 10^9 \times 2 \times 10^{33} = 1.6 \times 10^{45}\ \text{gr.} \qquad (5)$$

Daraus folgt für die totale potentielle Energie Ω:

$$\Omega = -\frac{3}{5}\,\Gamma\,\frac{M^2}{R} \qquad (6)$$

Γ = Gravitationskonstante

oder

$$\bar{\varepsilon}_p = \Omega/M \sim -64 \times 10^{12}\ \text{cm}^2\,\text{sek}^{-2} \qquad (7)$$

und weiter

$$\bar{\varepsilon}_k = \overline{v^2}/2 = -\varepsilon_p/2 = 32 \times 10^{12}\ \text{cm}^2\,\text{sek}^{-2}$$

$$(\overline{v^2})^{1/2} = 80\ \text{km/sek}. \qquad (8)$$

Um, wie beobachtet, einen mittleren Dopplereffekt von 1000 km/sek oder mehr zu erhalten, müsste also die mittlere Dichte im Comasystem mindestens 400 mal grösser sein als die auf Grund von Beobachtungen an leuchtender Materie abgeleitete[1]). Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.

This is the first statement of the **concept** of dark matter as we now understand it

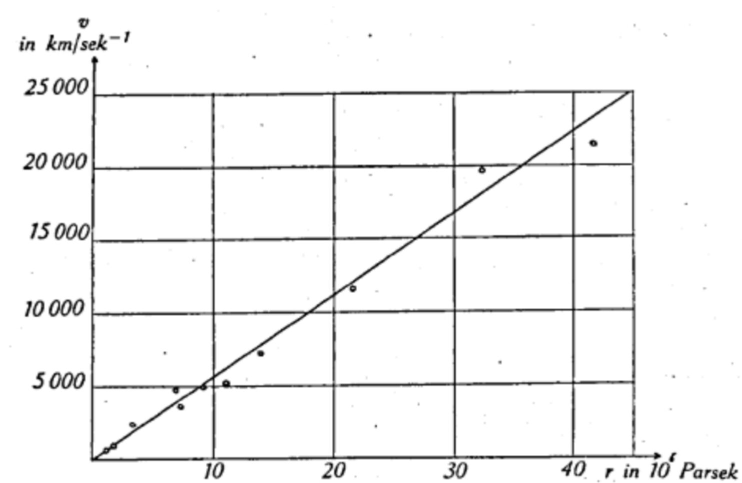


Fig. 2.

Ann. Rev. Astron. Astrophys. 1979. 17:135–87

MASSES AND MASS-TO-LIGHT RATIOS OF GALAXIES[1]

S. M. Faber[2]
Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, California 95064

J. S. Gallagher
Department of Astronomy, University of Illinois, Urbana, Illinois 61801

1 INTRODUCTION

Is there more to a galaxy than meets the eye (or can be seen on a photograph)? Many decades ago, Zwicky (1933) and Smith (1936) showed that if the Virgo cluster of galaxies is bound, the total mass must considerably exceed the sum of the masses of the individual member galaxies; i.e. there appeared to be "missing mass" in the cluster. As more data became avail-

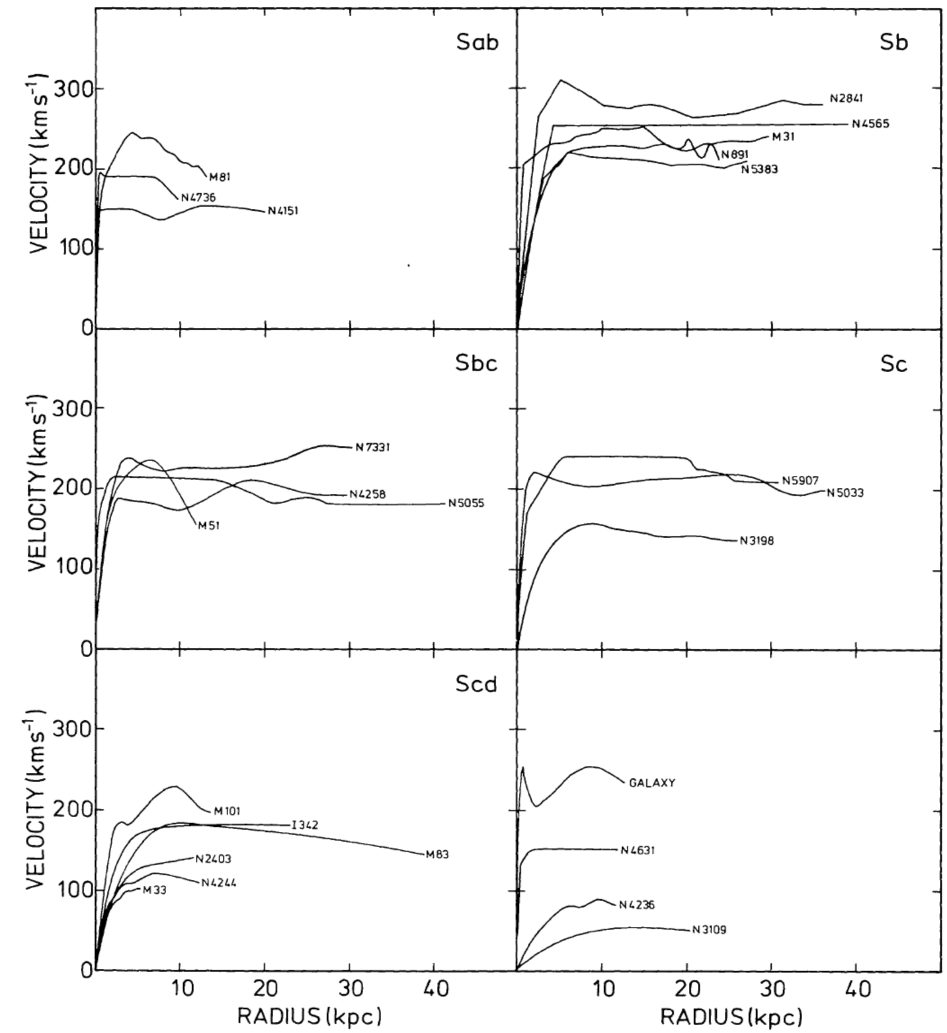


Figure 2 Rotation curves of 25 galaxies of various morphological types from Bosma (1978).

- Extended dark matter halos became part of the mainstream in the 1970's
- Rotation curves were a small part of the justification (9/54 pages in F&G79)
- The rotation curves used were mostly 21cm, rather than optical

BULLETIN OF THE ASTRONOMICAL INSTITUTES OF THE NETHERLANDS

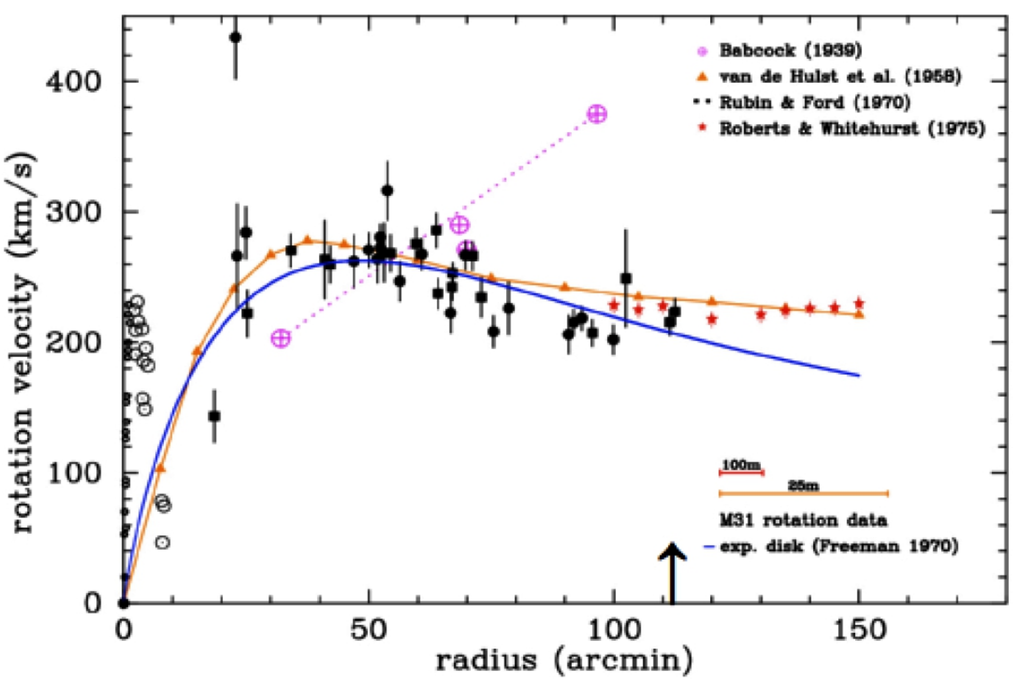
1957 NOVEMBER 9 VOLUME XIV NUMBER 480

COMMUNICATIONS FROM THE NETHERLANDS FOUNDATION FOR RADIO ASTRONOMY AND THE OBSERVATORY AT LEIDEN

ROTATION AND DENSITY DISTRIBUTION OF THE ANDROMEDA NEBULA DERIVED FROM OBSERVATIONS OF THE 21-cm LINE

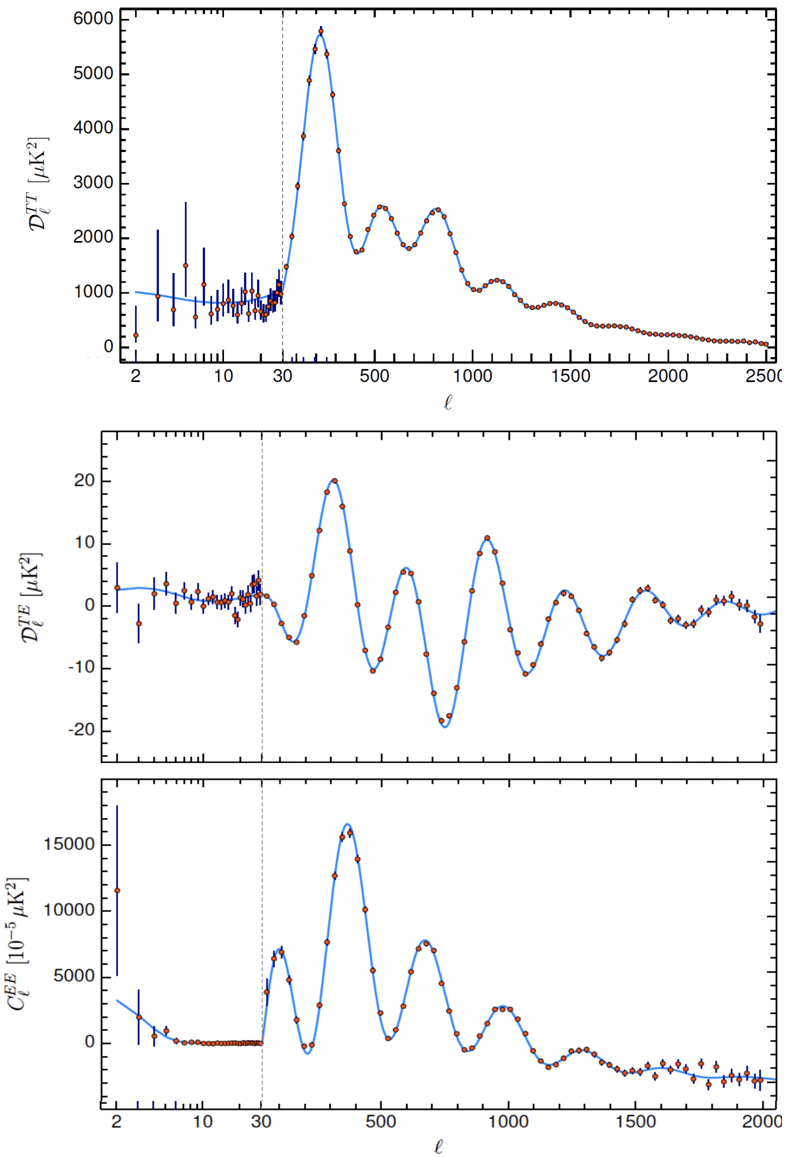
BY H. C. VAN DE HULST, E. RAIMOND AND H. VAN WOERDEN

The atomic hydrogen emission from the Andromeda nebula (M31) was observed with the 25-metre telescope at Dwingeloo; the beamwidth was 0°.6. Line profiles were measured at 20 points of the major axis (Figure 5). The mean error of the brightness temperature measured at one frequency in one direction was 0.2 to 0.3°K except in the frequency range contaminated by galactic foreground radiation. The line was observable to 2°.5 at either side of the centre. The central velocity with respect to the local standard of rest is — 296 km/sec. The velocity of rotation slowly falls from 278 km/sec at 0°.6 from the centre to 221 km/sec at 2°.5



- The earliest reliable flat rotation curves (for M31) are usually credited to Rubin & Ford 1970 (optical) and Roberts & Whitehurst 1975 (radio)
- The 21cm goes to much larger radius
- The 1957 Dwingeloo curve is just as good and goes just as far

What is the strongest astrophysical evidence for dark matter?



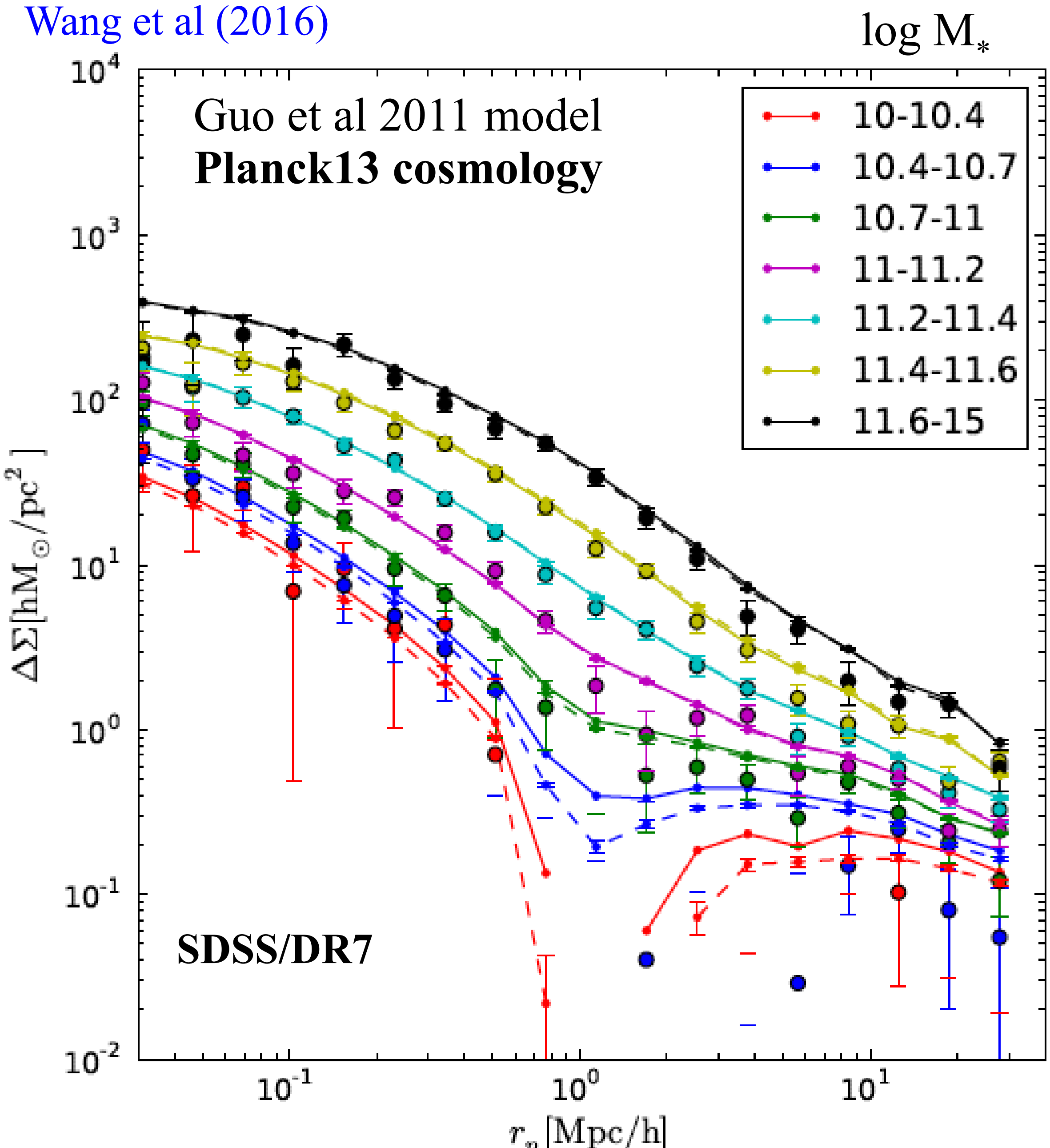
Planck Collaboration 2018

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

- Results from a single instrument (Planck/HFI)
- No local/low-redshift data are used
- Linear perturbation of a homogeneous medium
- No exotic/HE physics needed to set pattern
- Outside modified gravity regime
- Precise results applying to the whole visible Universe rather than some subregion

Average mass profiles around bright galaxies

Wang et al (2016)



The points are measured mass profiles around the central galaxies of galaxy groups

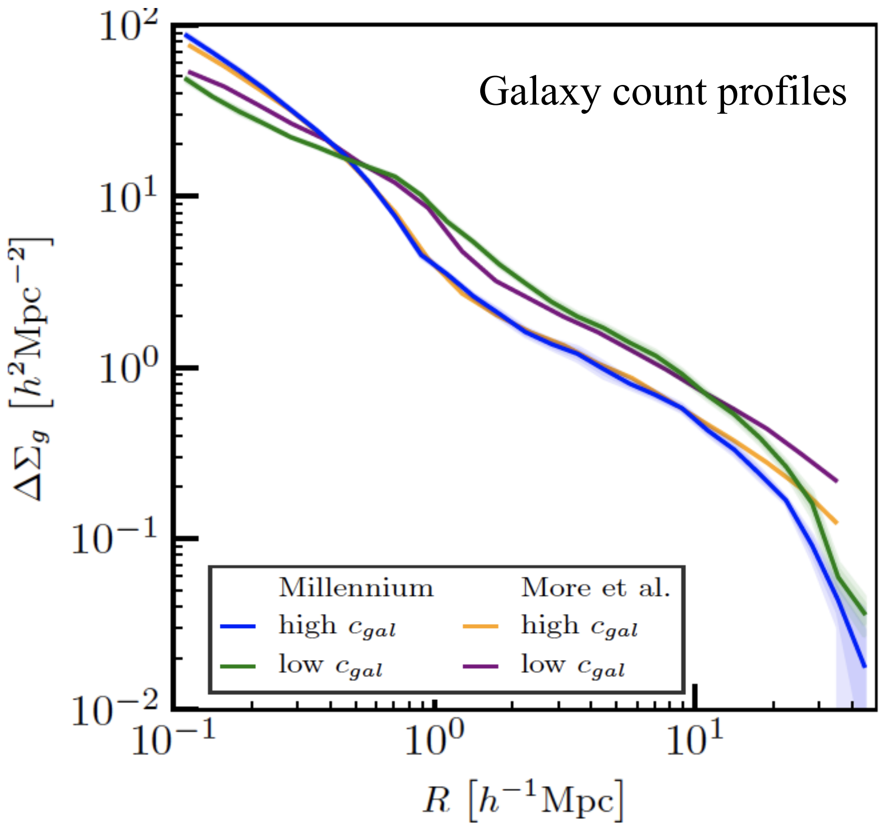
Top to bottom goes from rich galaxy clusters to poor groups

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

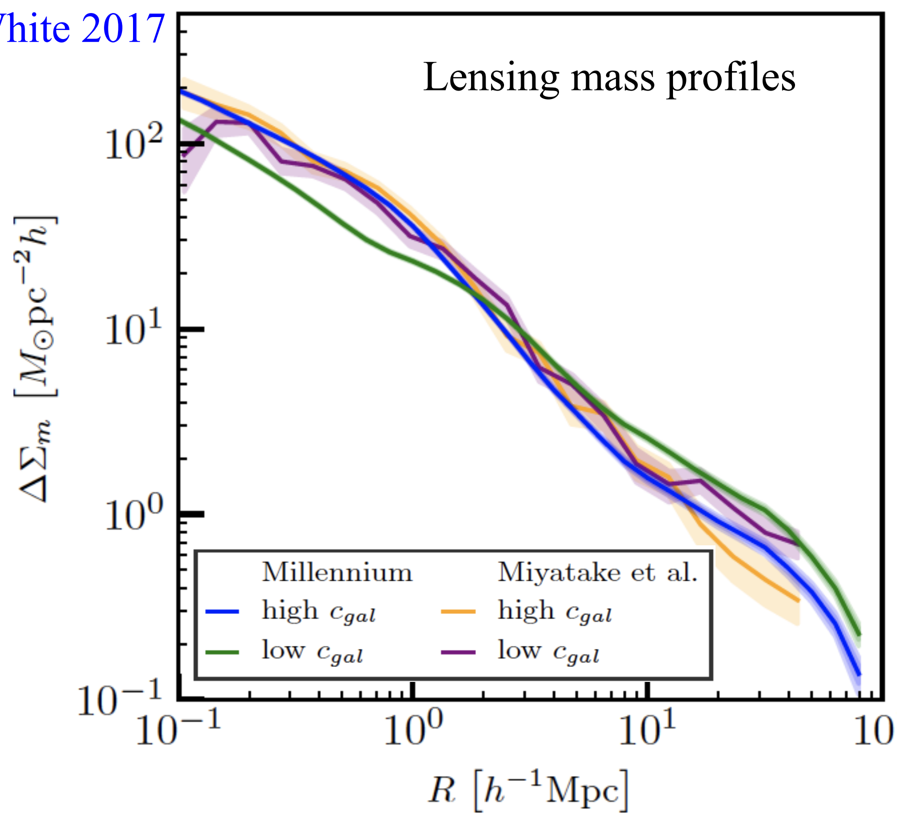
Parameters were fit using galaxy *abundances* only. **No** parameters adjusted to fit clustering

The simulation matches the mass distribution around galaxies even in regions where no light is seen!

Systematics in splashback detections



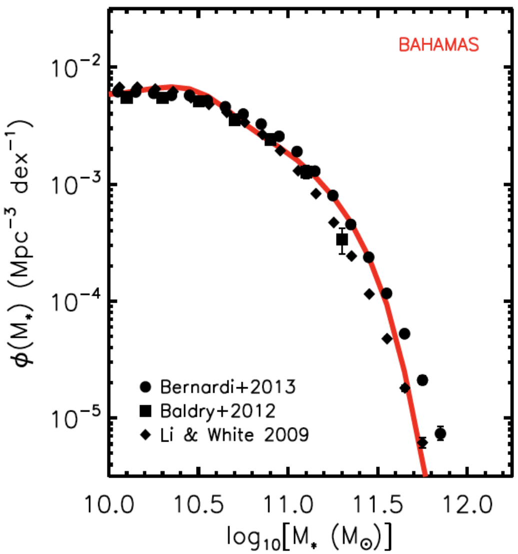
Busch & White 2017

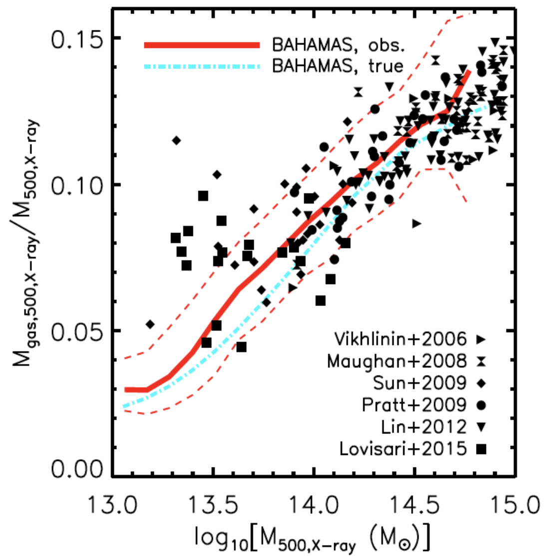


- More et al/Mitake et al (2016) saw splashback radii in SDSS/DR8 redMaPPer clusters
- The size and concentration dependence of the radii were surprising
- Comparison with mock clusters identified by a redMaPPer-like algorithm in large volume galaxy formation simulations, show this is a result of selection effects

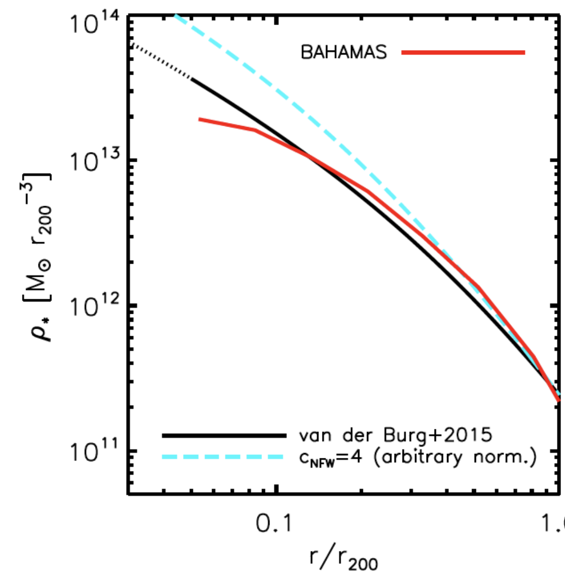
Systematics and the CMB/cluster-LSS cosmology tension

BAHAMAS McCarthy et al 2017, 2018

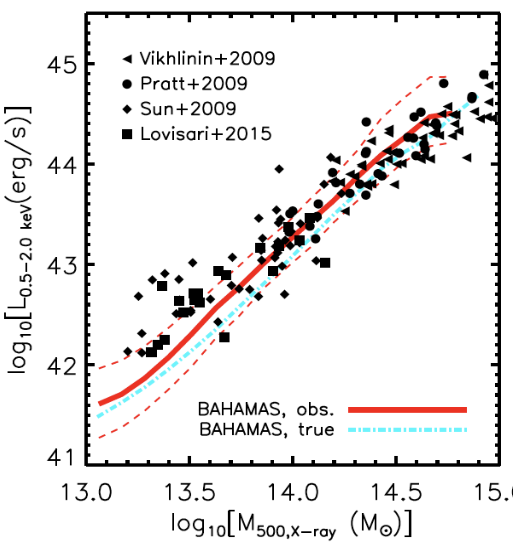


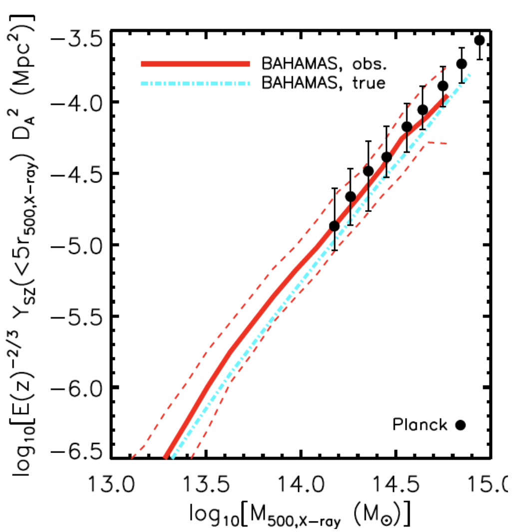


Observations calibrating the simulations



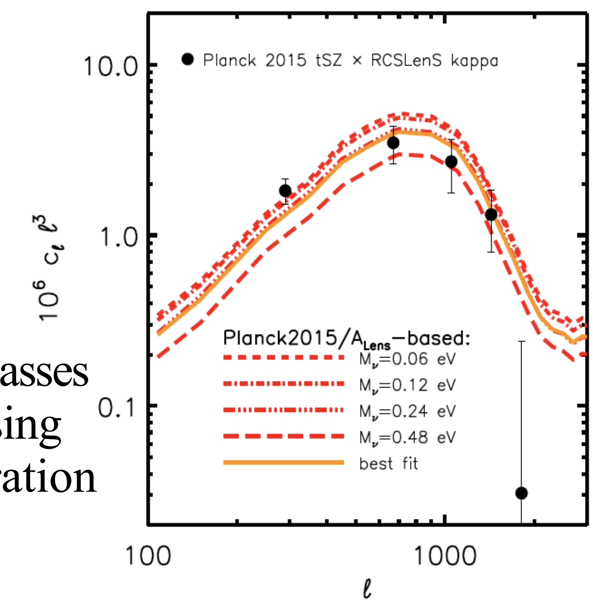
Cluster stellar mass profiles





Cluster X-ray, SZ scaling relations

Constrain sum of ν masses directly **without** passing via mass proxy calibration



Lensing shear – tSZ cross-correlation

Direct Detection Developments

WIMPs

- Scaling up existing experiments will enable reaching the ν floor, but cross-sections well below this are theoretically possible

- Paleodetection – many tons of target! Can we measure so much?
  – up to 1 Gyr exposure! What about "backgrounds"?

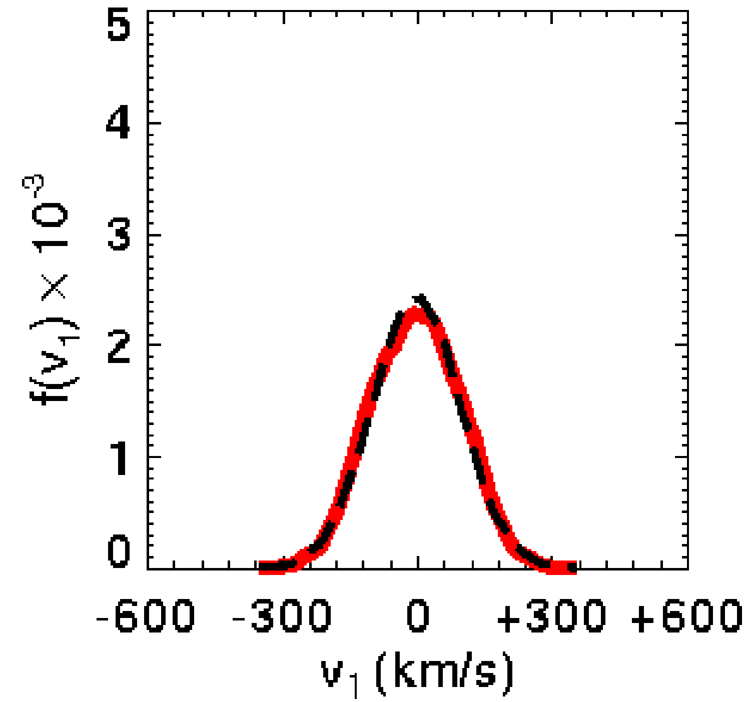
- Directional detection – nuclear emulsions
  – gaseous time projection chambers
  Can we really get below the ν floor and do ν astronomy?

P–Q Axions

- Upgrades to light-through-the-wall experiments (μ-wave lasers, supercooled transition-edge sensors) may reach required sensitivities

- MADMAX dielectric may reach sensitivity at high m_a than ADMX

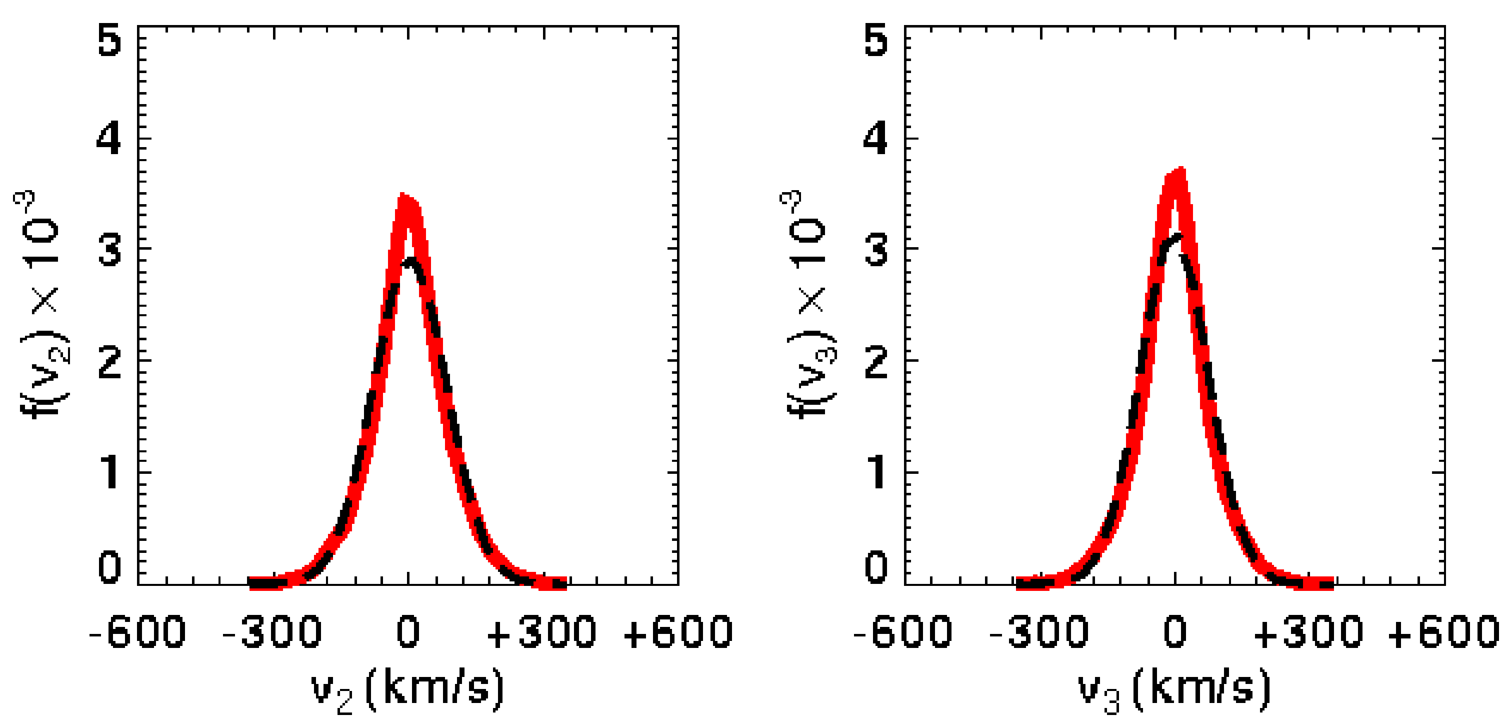
Local velocity distribution



Velocity histograms for particles in a typical $(2\text{kpc})^3$ box at R = 8 kpc

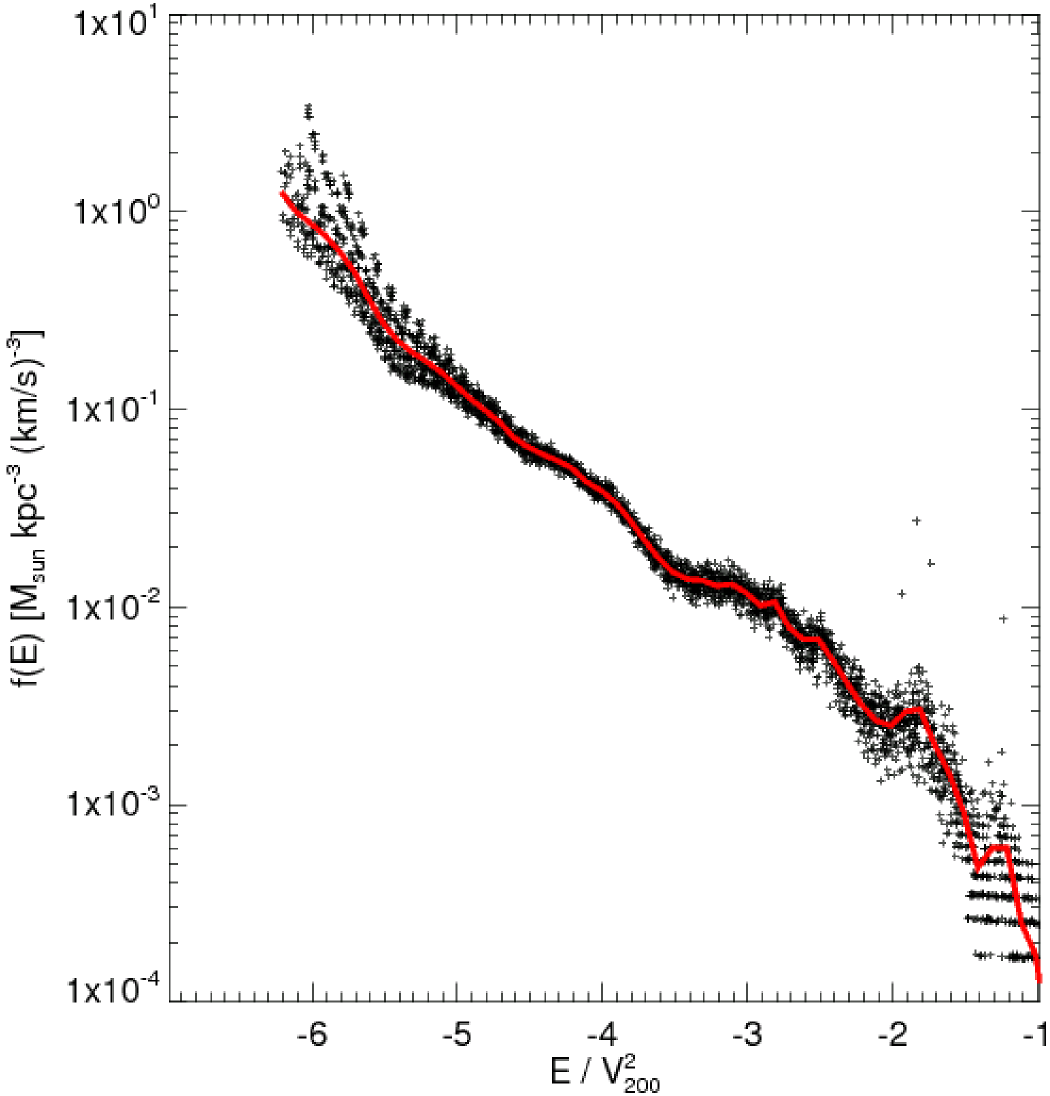
Distributions are smooth, near-Gaussian and different in different directions

No individual streams are visible



Vogelsberger et al 2009

Energy space features – fossils of formation



The energy distribution within $(2\ \mathrm{kpc})^3$ boxes shows bumps which

-- repeat from box to box

-- are stable over Gyr timescales

-- repeat in simulations of the same object at varying resolution

-- are different in simulations of different objects

These are potentially observable fossils of the formation process

Vogelsberger et al 2009

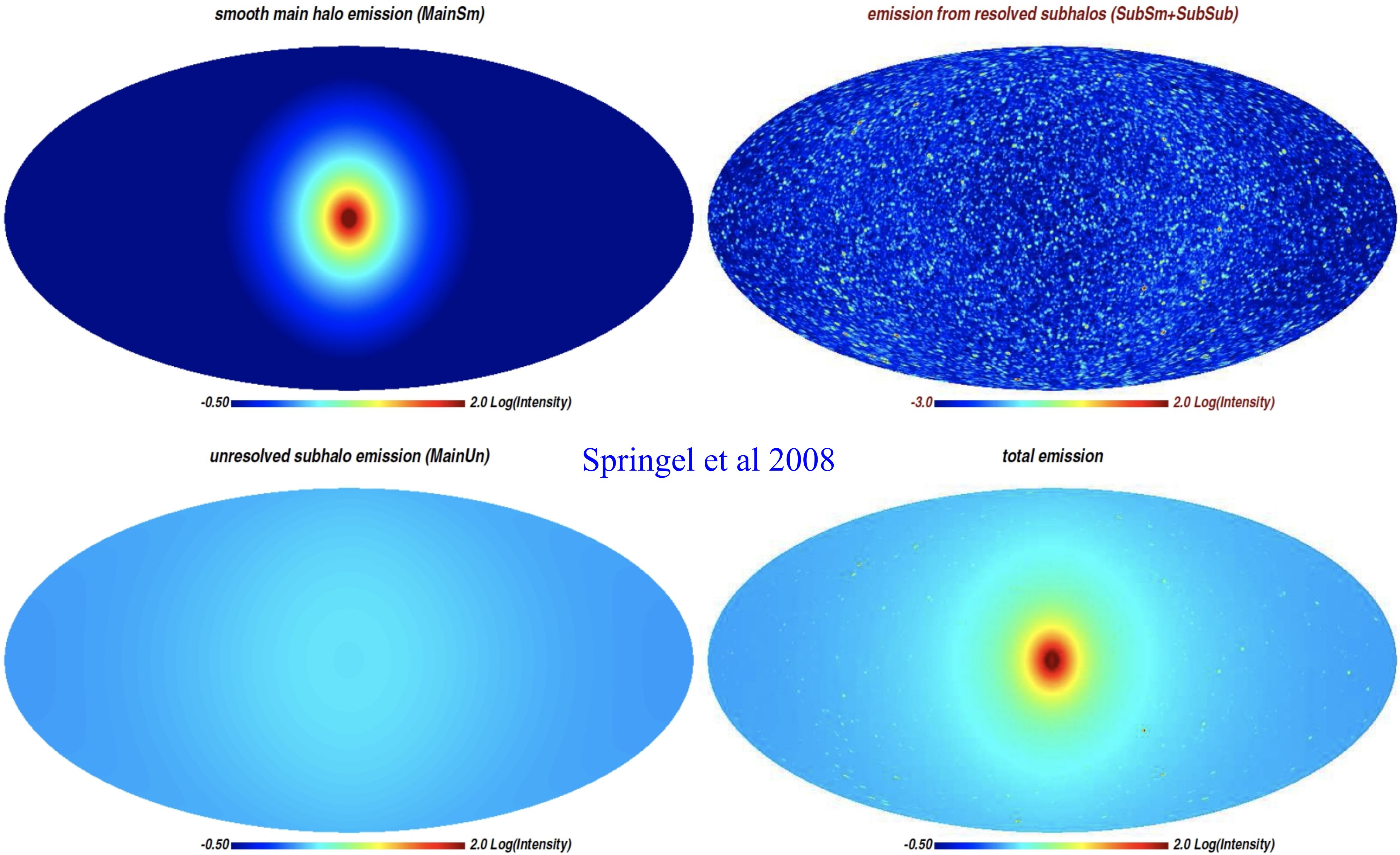
Indirect Detection Developments

3.5 keV line: Ruled out by stacking experiments – or maybe not?

Galactic Centre excess: Due to millisecond pulsars – or maybe not?
How about star-forming regions?

AMS/Pamela e^+ excess: Due to (a nearby) pulsars?

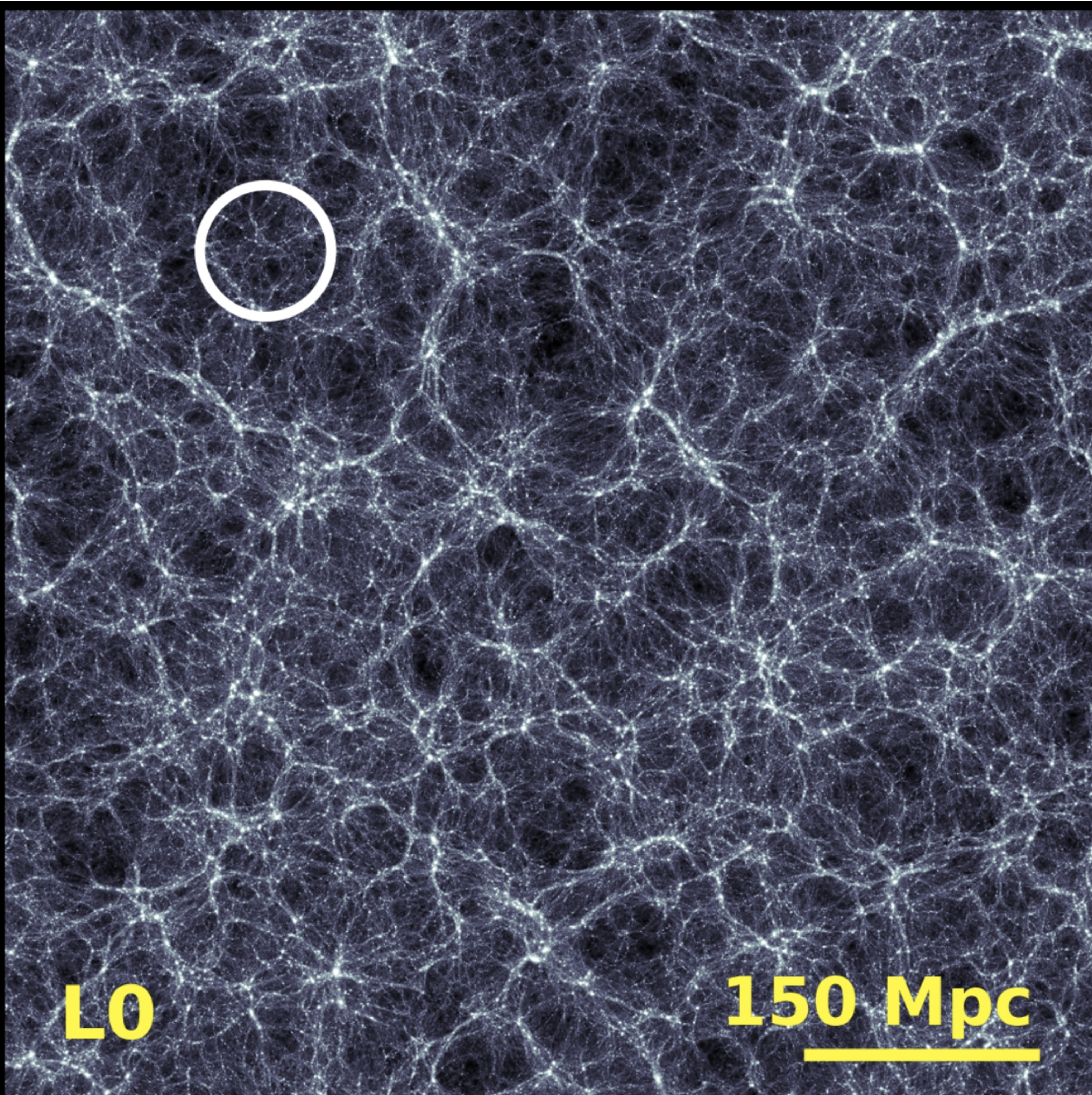
Continuum annihilation radiation: Do we know "J-factors"



For CDM, halo annihilation luminosity is dominated by $<1\ M_\odot$ subhalos at large r

e.g. the above Aquarius predictions for the MW's luminosity seen from the Sun

→ "J-factor" calculations based on the main halo profile are meaningless!



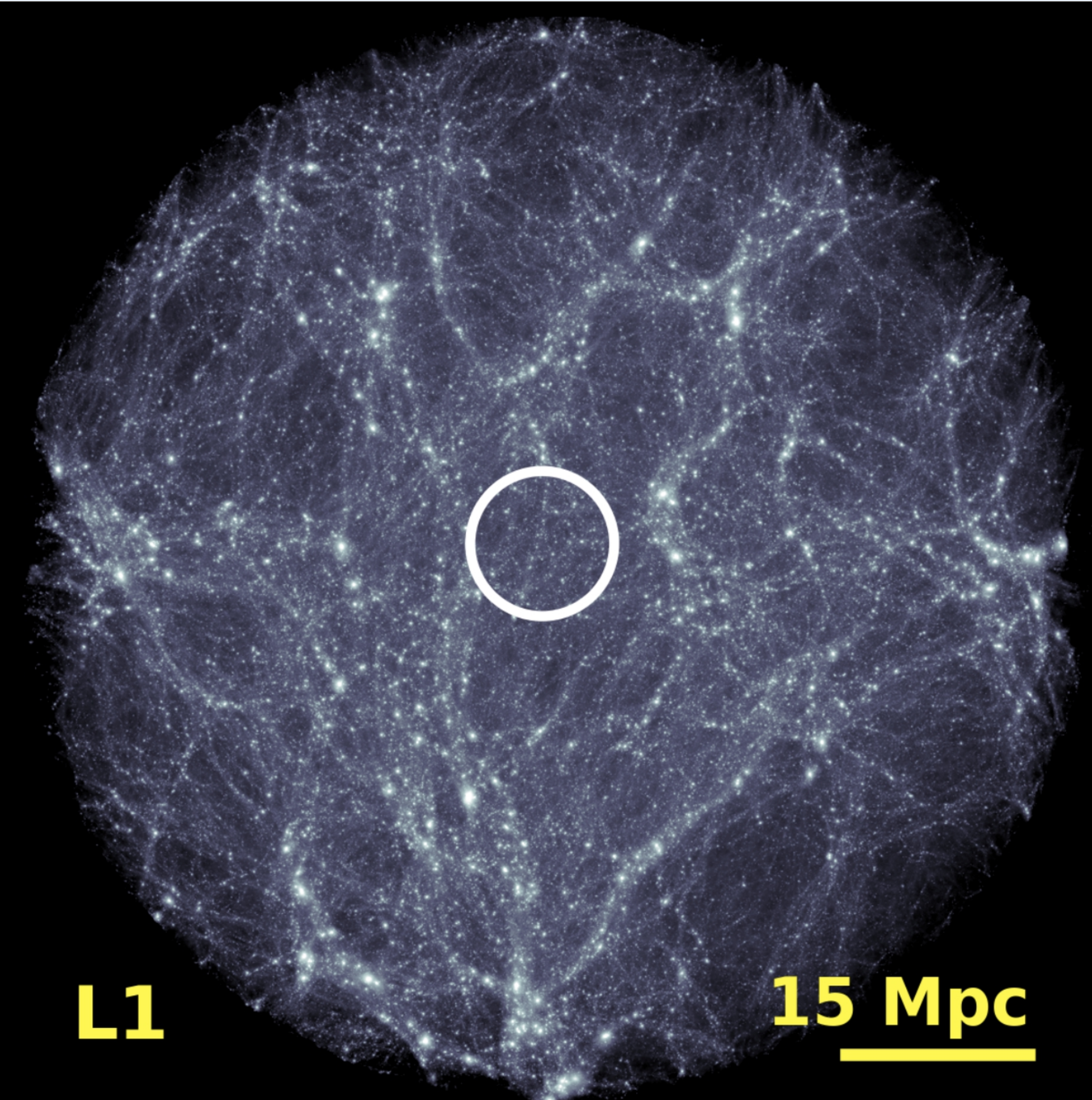
The VVV simulation

Planck cosmology

Dark matter only

Dynamic range of 30 orders of magnitude in mass

Base Level



The VVV simulation

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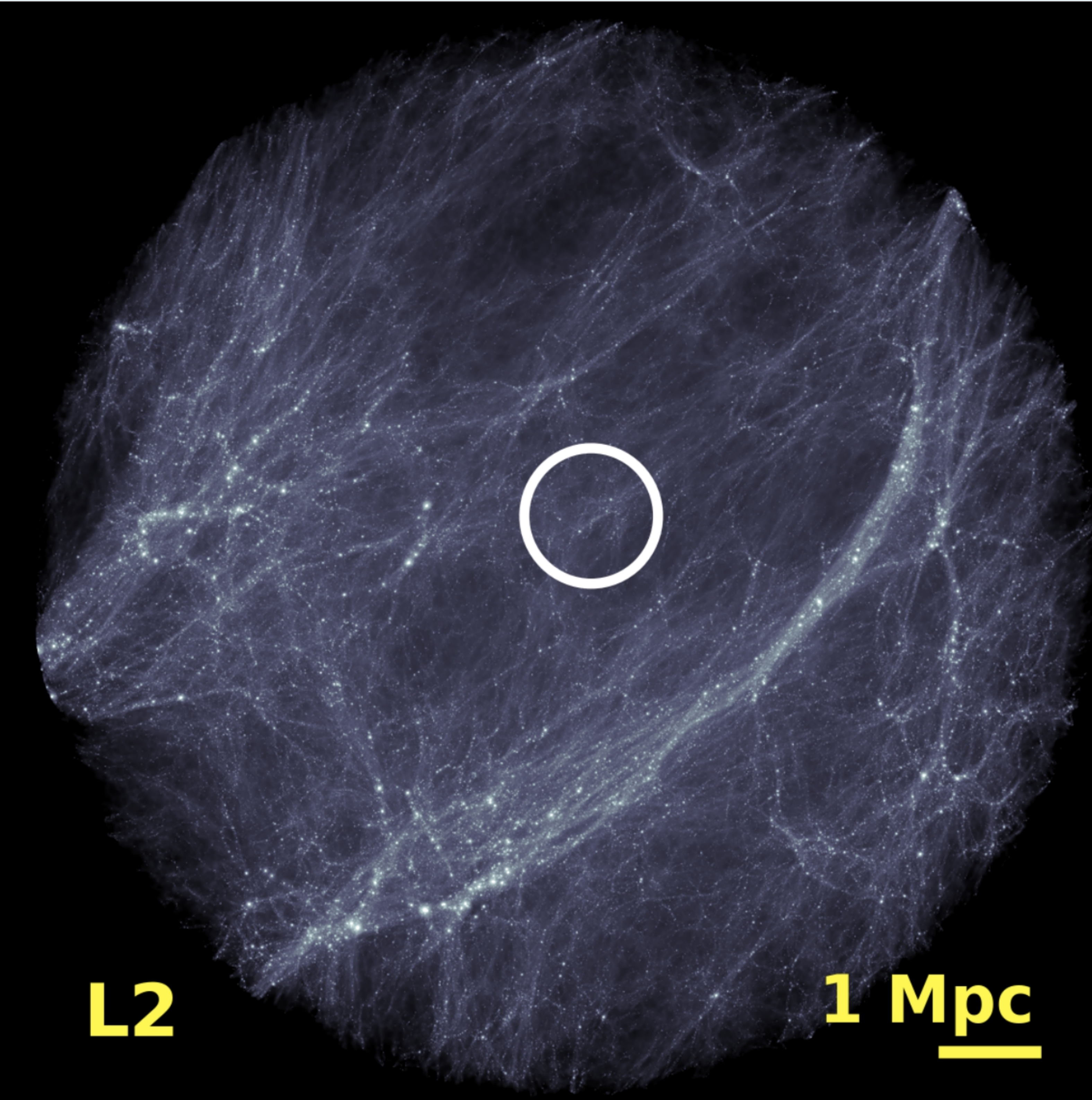
Dynamic range of 30 orders of magnitude in mass

Zoom Level 1

Tormen et al 1997



The VVV simulation

Planck cosmology

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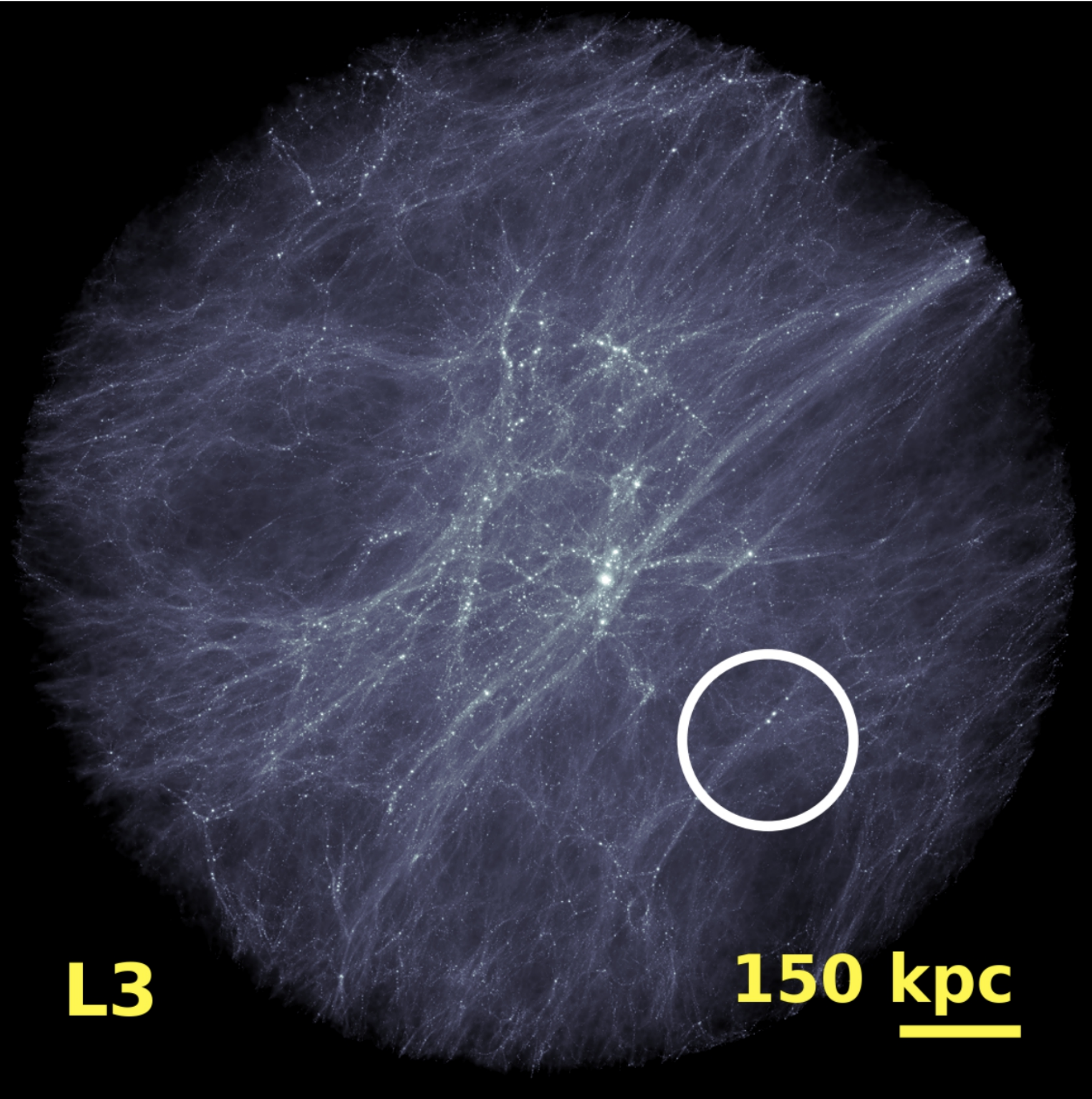
Dynamic range of 30 orders of magnitude in mass

Zoom Level 2



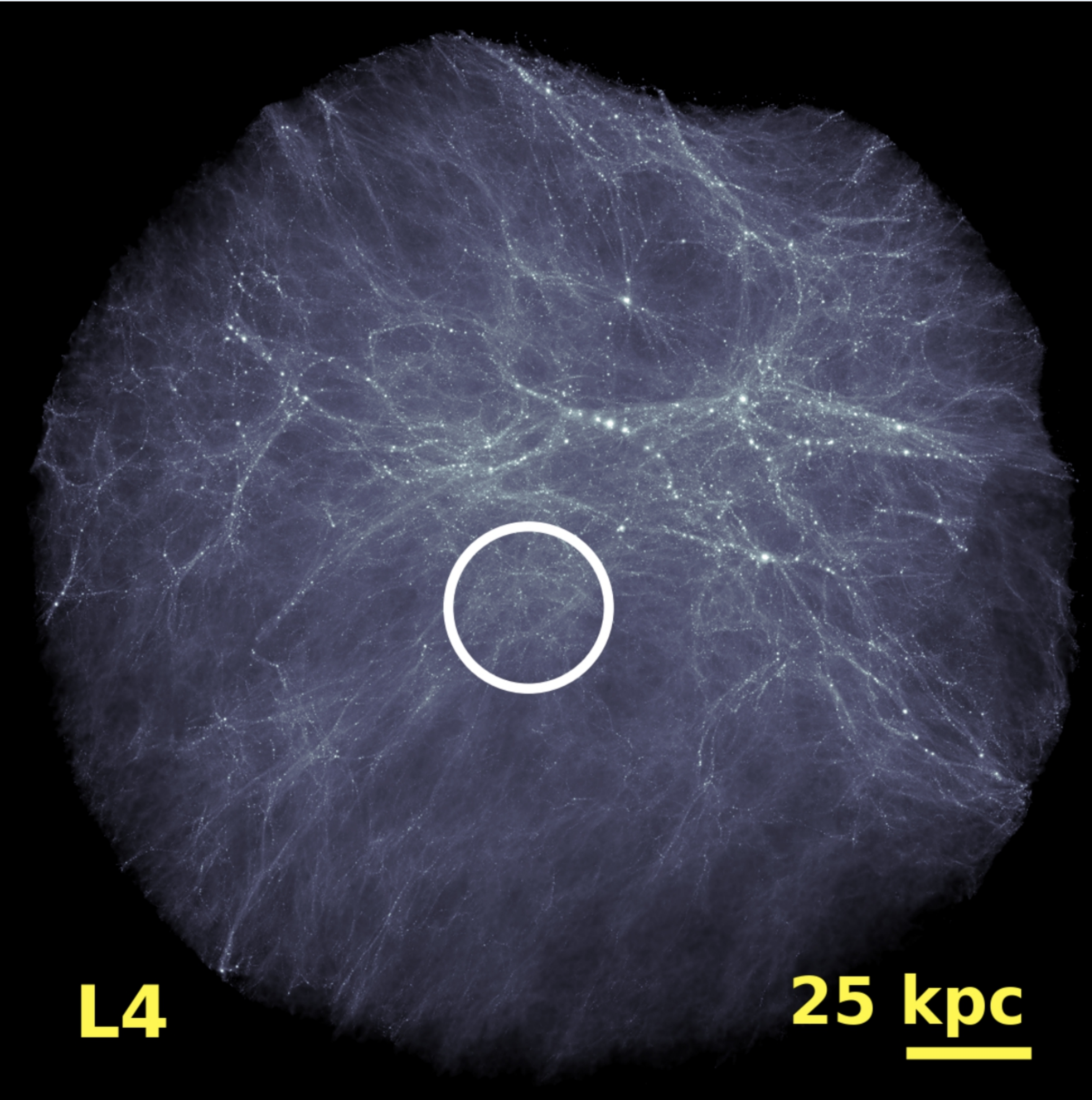
The VVV simulation

Planck cosmology

Dark matter only

Dynamic range of 30 orders of magnitude in mass

Zoom Level 3



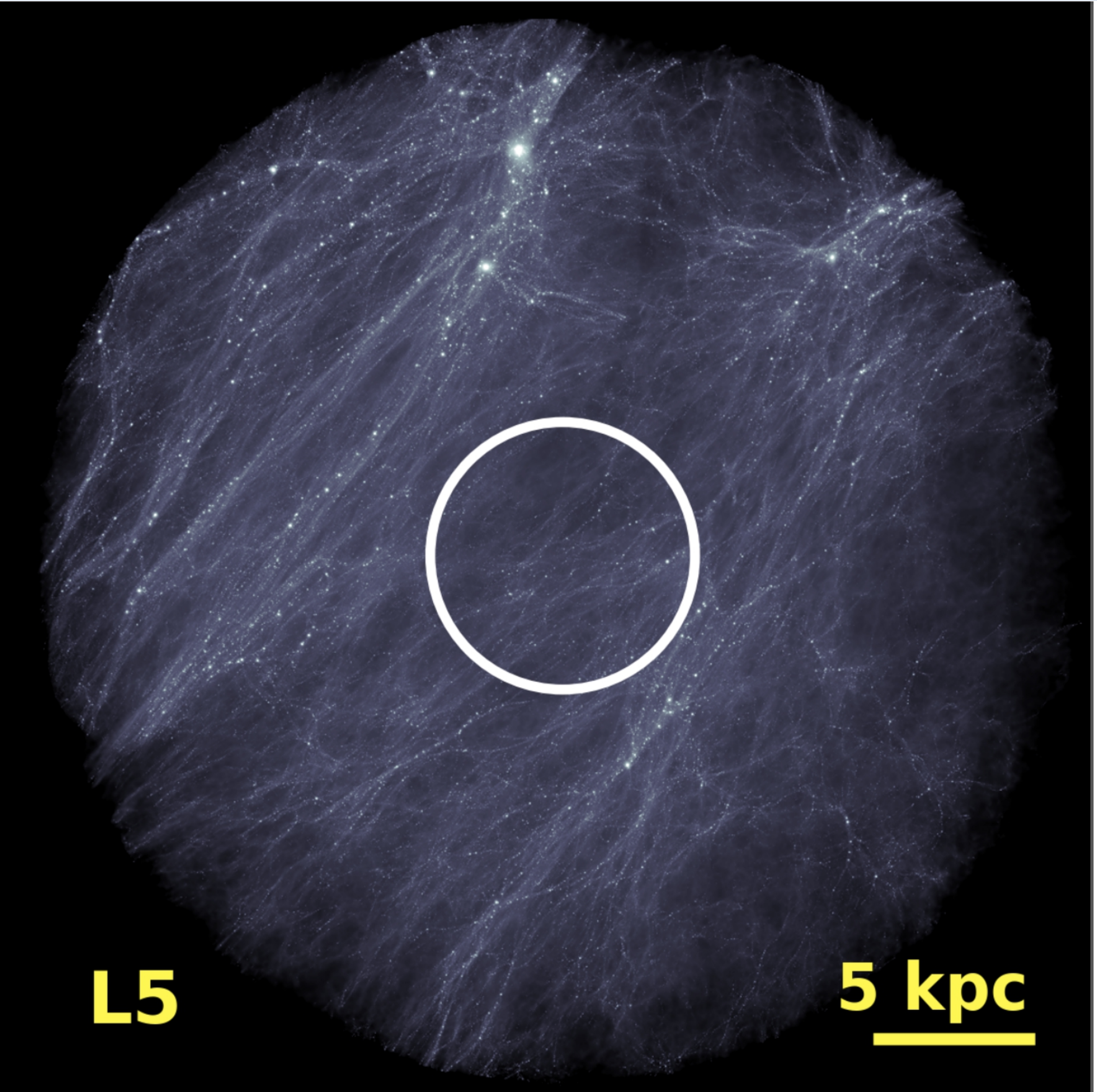
The VVV simulation

Planck cosmology

Dark matter only

Dynamic range of 30 orders of magnitude in mass

Zoom Level 4



The VVV simulation

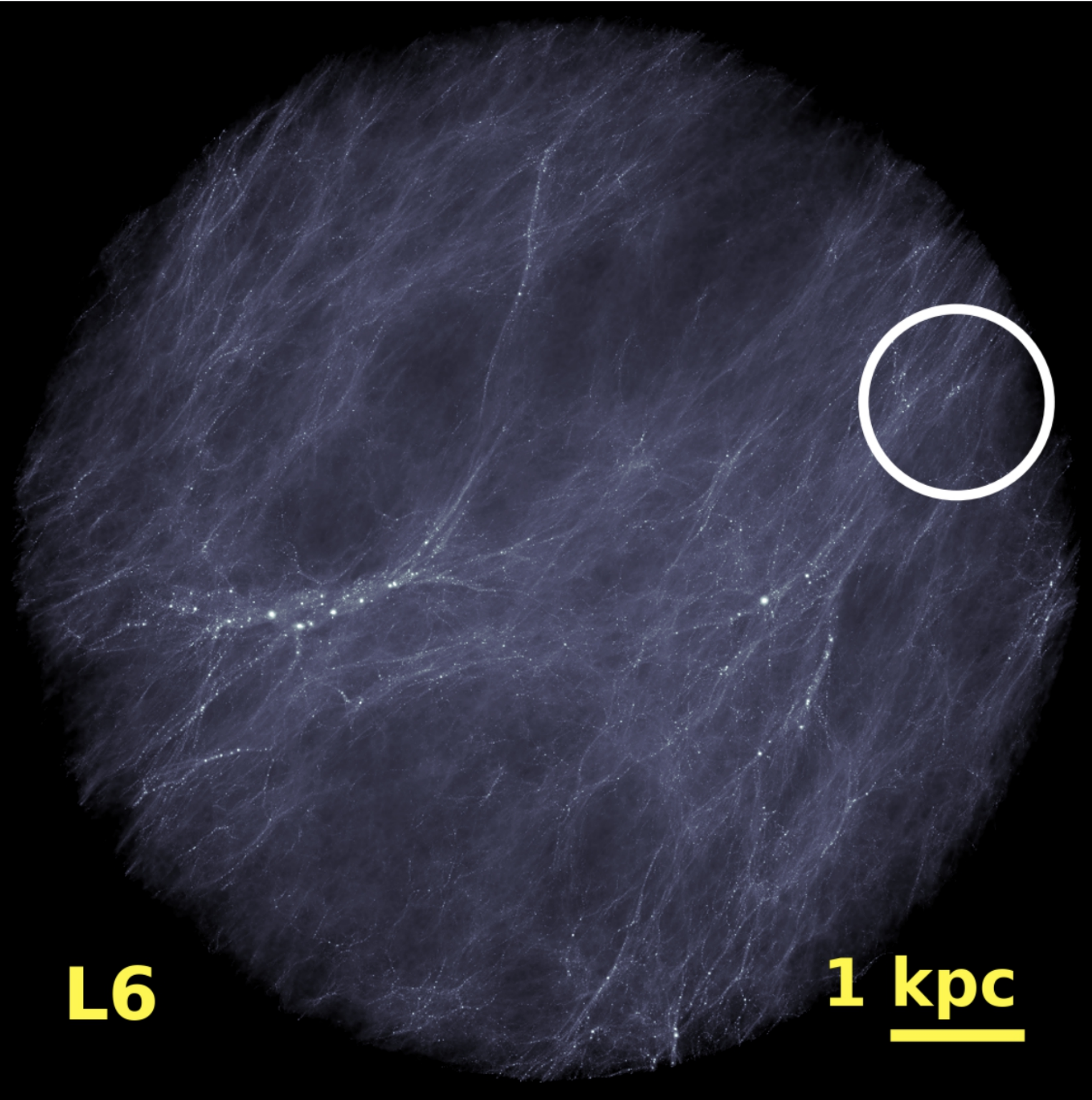
Planck cosmology

Dark matter only

Dynamic range of 30 orders of magnitude in mass

Zoom Level 5

The VVV simulation

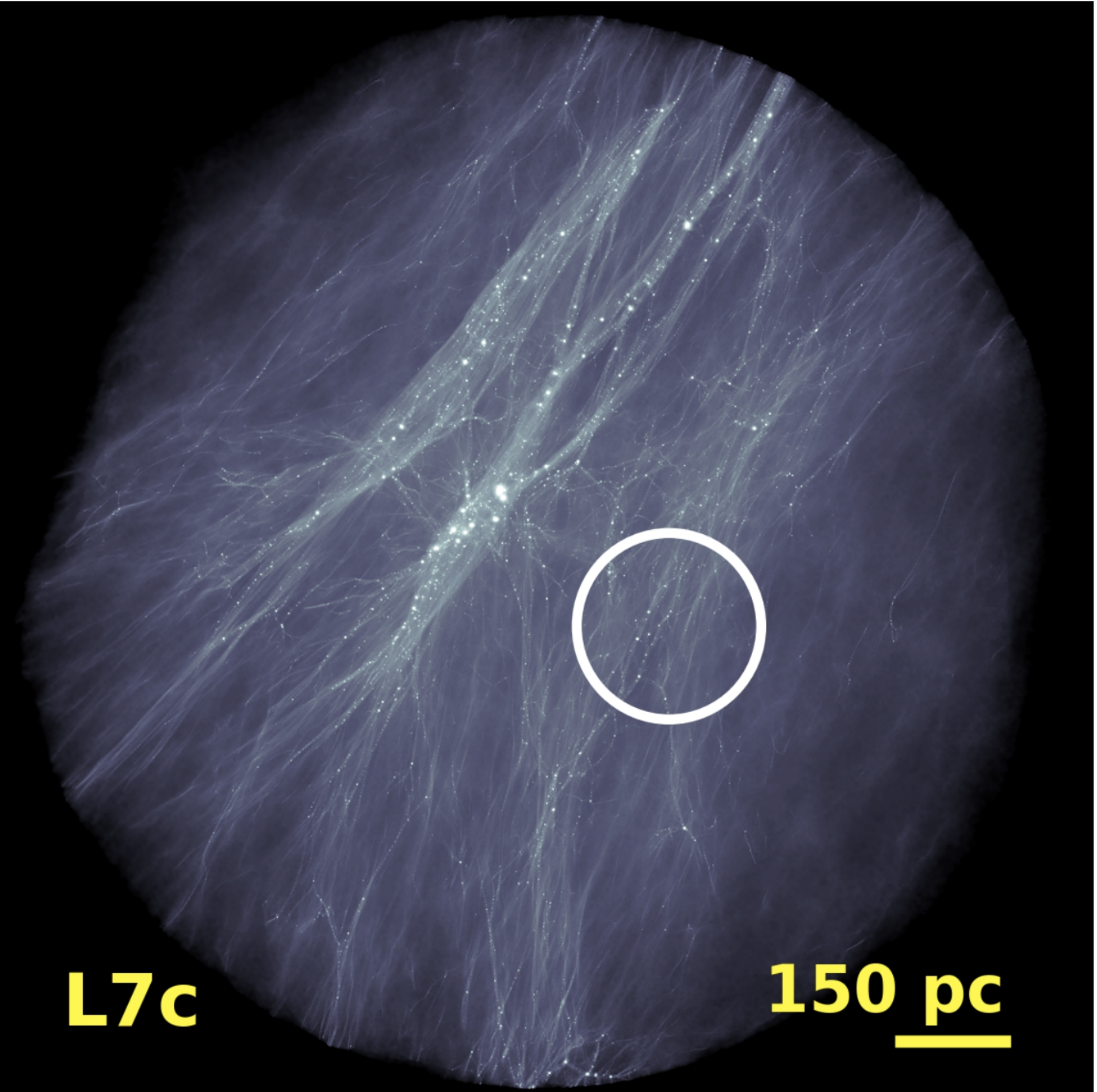


Planck cosmology

Dark matter only

Dynamic range of 30 orders of magnitude in mass

Zoom Level 6



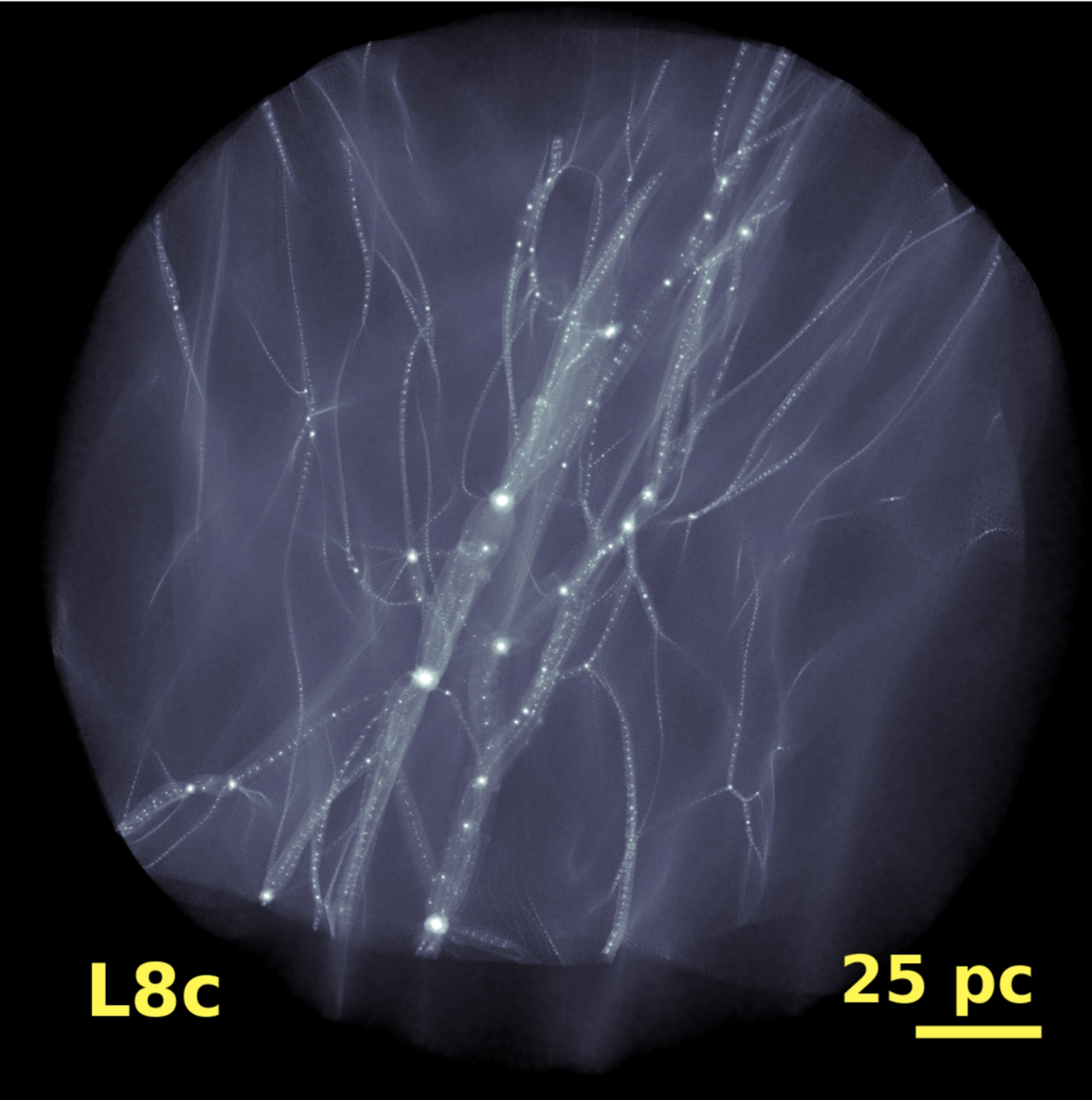
The VVV simulation

Planck cosmology

Dark matter only

Dynamic range of 30 orders of magnitude in mass

Zoom Level 7



The VVV simulation

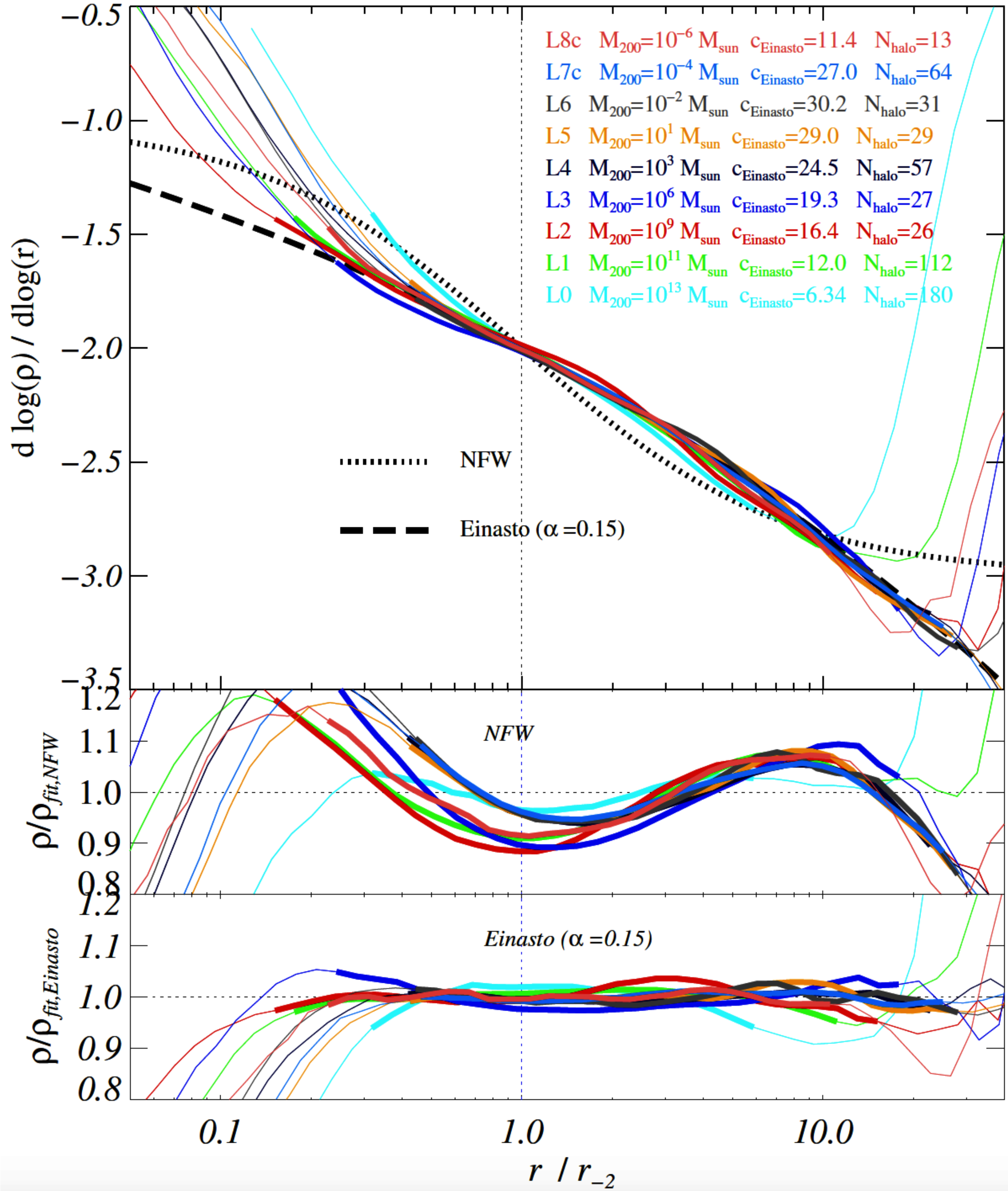
Planck cosmology

Dark matter only

Dynamic range of 30 orders of magnitude in mass

Zoom Level 8

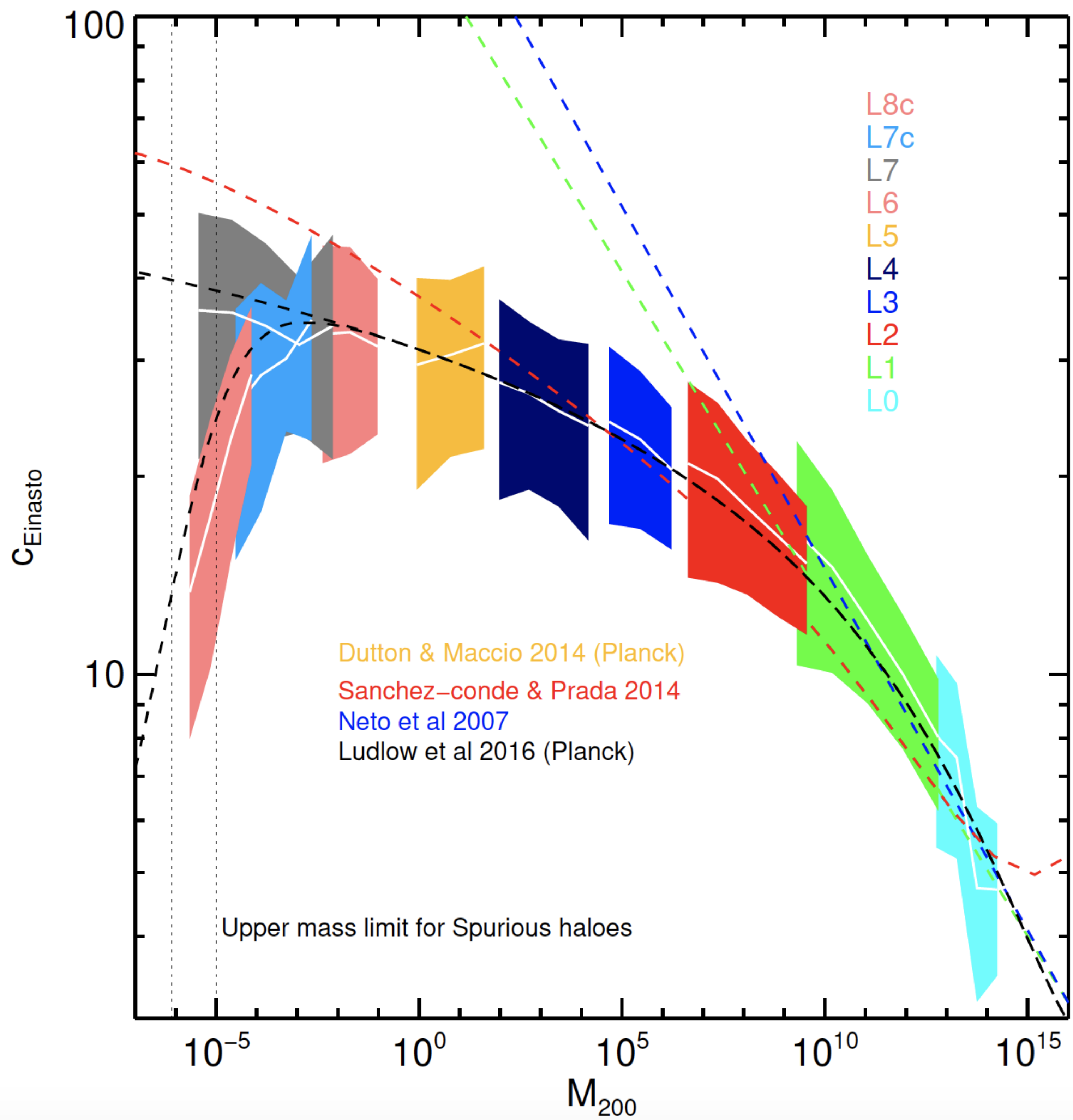
The density of this region is only 0.4% of the cosmic mean



Density profile shapes

Over 19 orders of magnitude in halo mass and 4 orders of magnitude in halo density, the mean density profiles of halos are fit by NFW to within 20% and by Einasto with α = 0.15 to within 7%

Wang, Bose et al 2019



Concentration-mass relation

Over the full 20 orders of magnitude probed, the relation of Ludlow et al (2016) is followed quite closely.

There is a turndown at 1000 Earth masses due to the free-streaming limit.

The scatter does not depend strongly on halo mass.

Wang, Bose et al 2019

The standard small-scale “problems” of ΛCDM

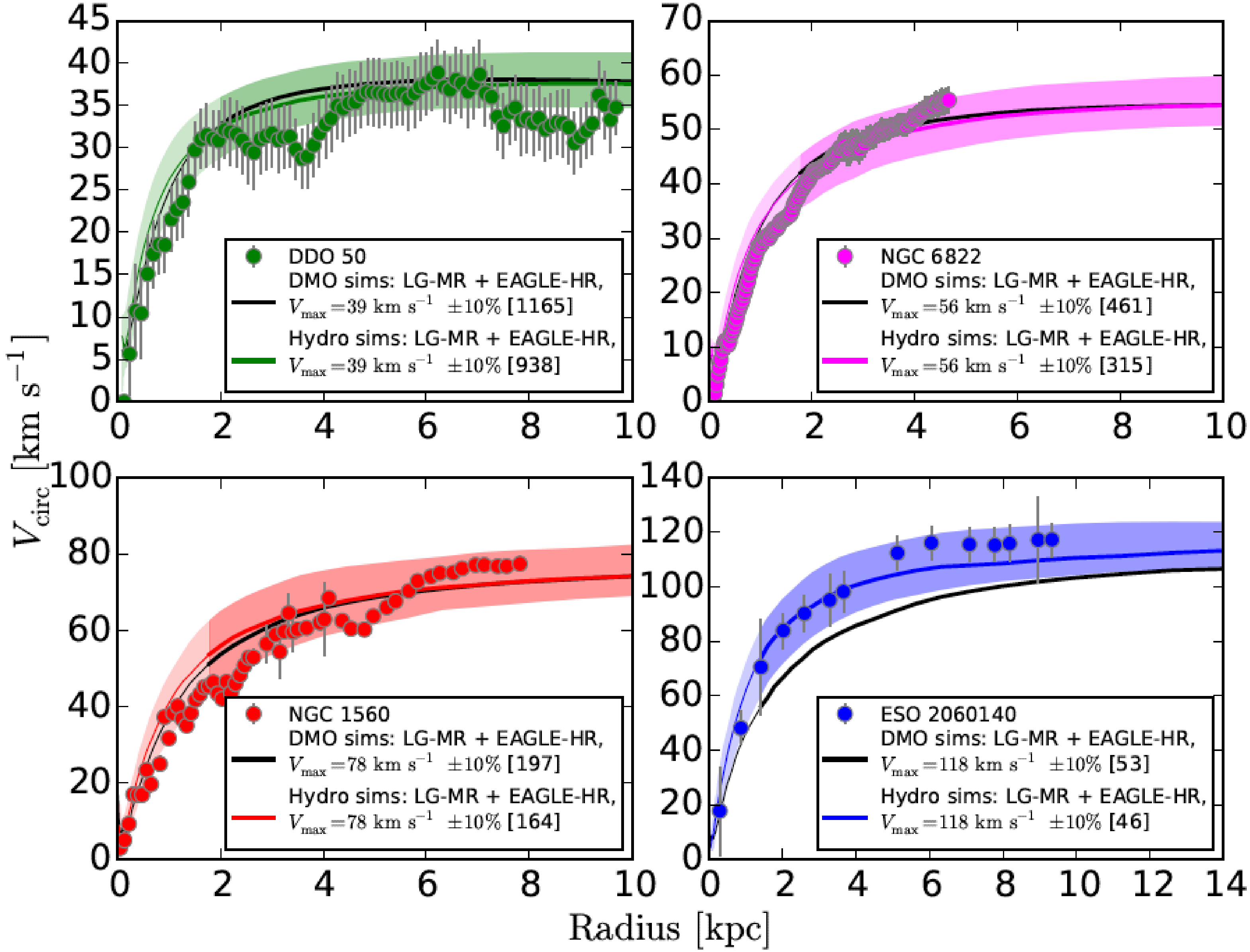
- The core-cusp problem
- The missing satellite problem
- The Too-Big-To-Fail problem

All potentially solved by baryon effects?

DM “solutions” have other problems or are insufficiently understood

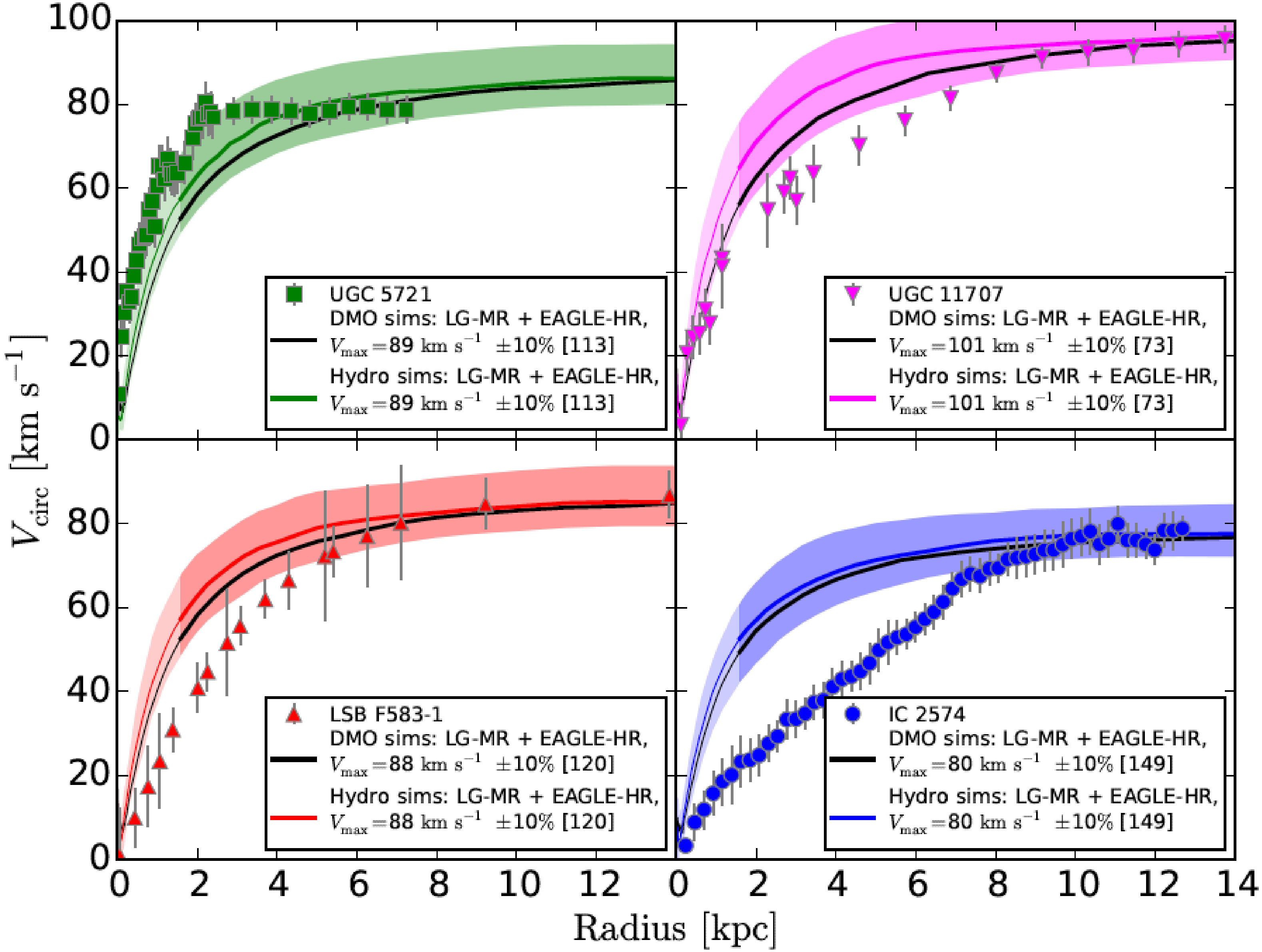
- **WDM** Abundance of hi-z galaxies? Ly-α forest? flux-ratio anomalies?
- **SIDM** V-dependent X-section needed, complex interaction with G.F.
- **FDM** Not yet explored enough to know
- **Emergent DM** A fully calculable theory has yet to emerge

Dwarf galaxy rotation curves: cusps vs cores



Many dwarf galaxies have rotation curves that fit ΛCDM predictions well

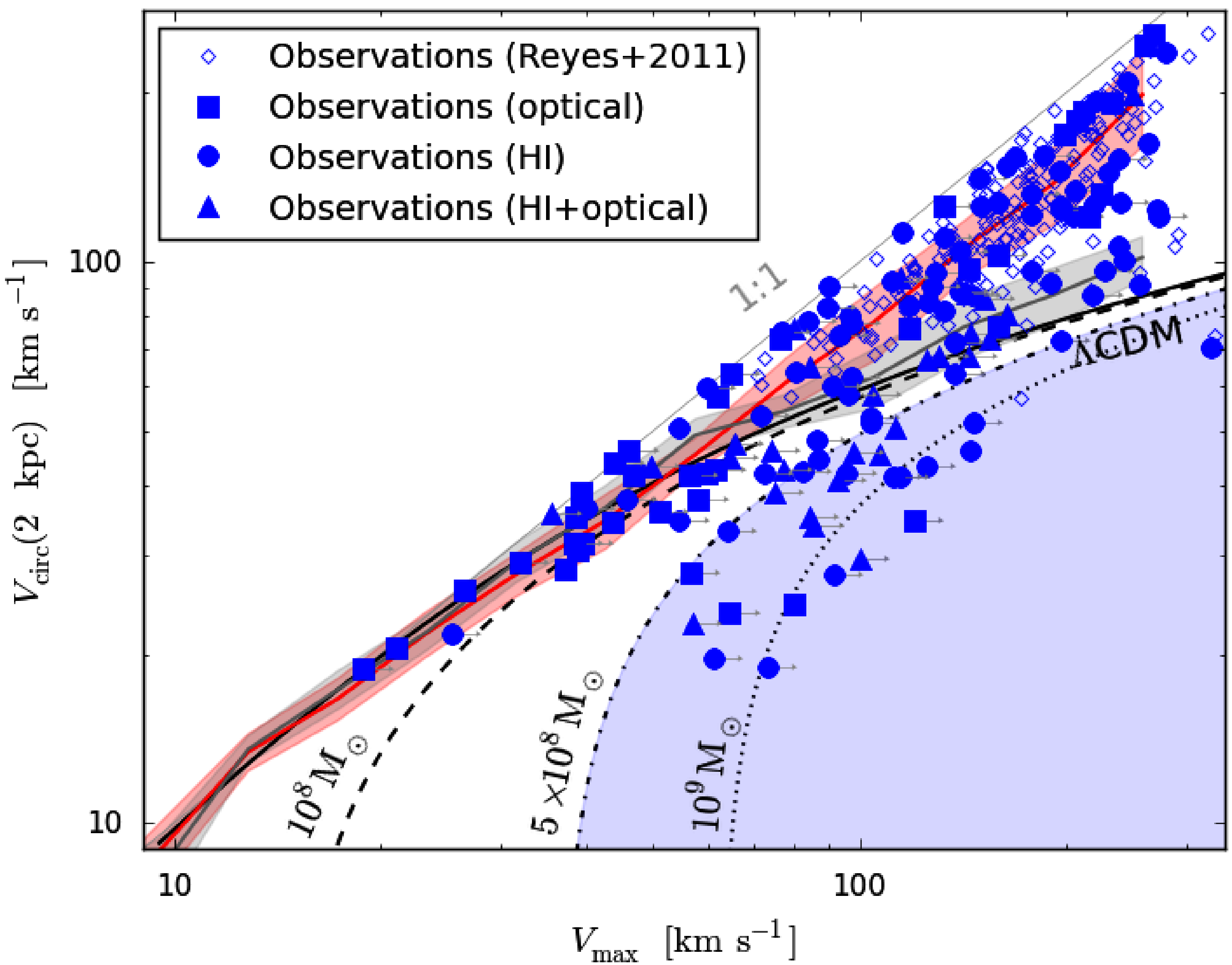
Dwarf galaxy rotation curves: cusps vs cores



Many others fail dramatically to fit ΛCDM predictions.

"Cores" from: (i) DM properties? (ii) Baryon effects? (iii) Incorrect modelling?

V_{circ}(2 kpc) versus V_{max} for observed dwarfs



Enormous apparent <u>diversity:</u>

Too large for baryon effects proposed so far?

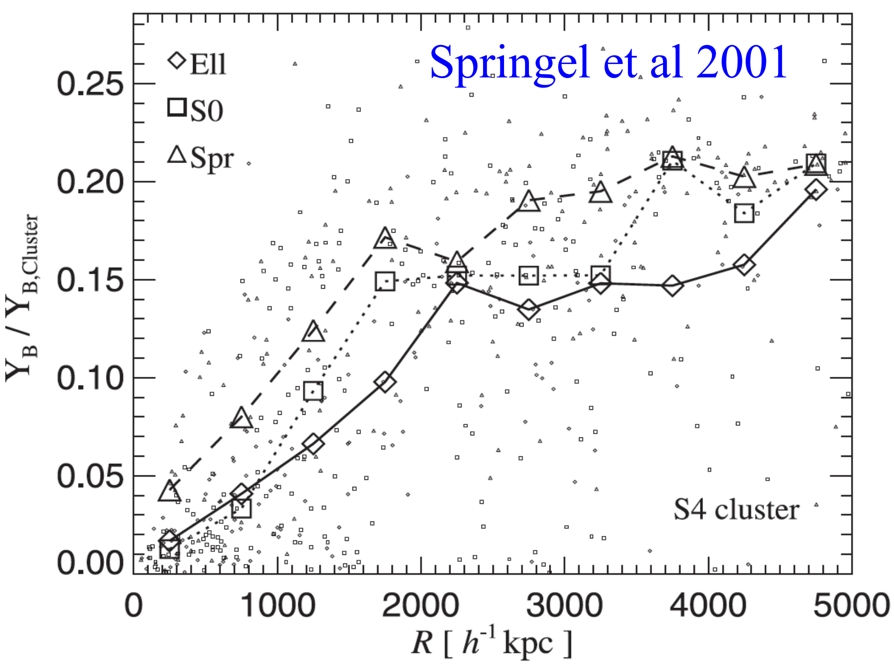
Too large to reflect DM properties alone?

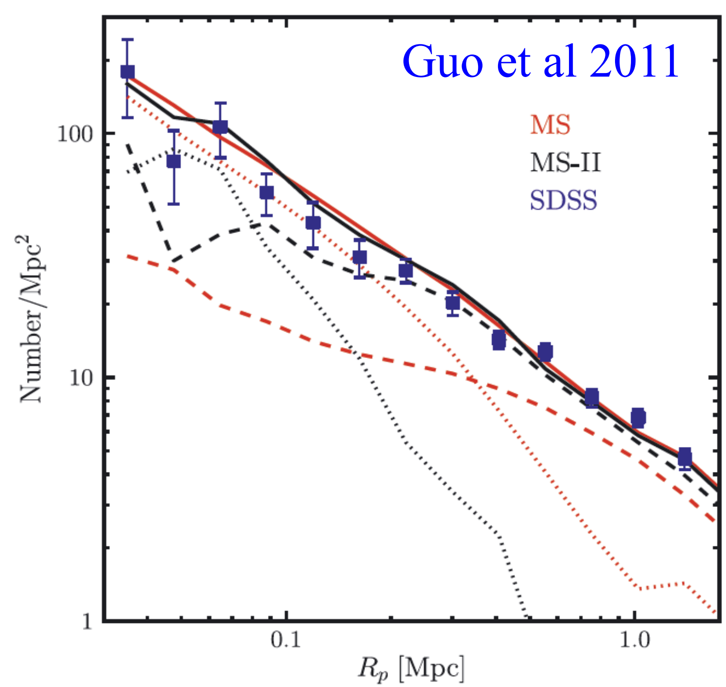
Oman et al 2015

Strong and weak lensing constraints on substructure

In **clusters** the datasets have dramatically improved

- Lens modelling should include the expected variation of M/L with *r*
- Hydro simulations must reproduce observed stellar mass functions, radial profiles **and** M_*–R_{eff} relations for clusters as a function of M_{halo}
- Examples with abundant radial arcs should constrain SIDM strongly





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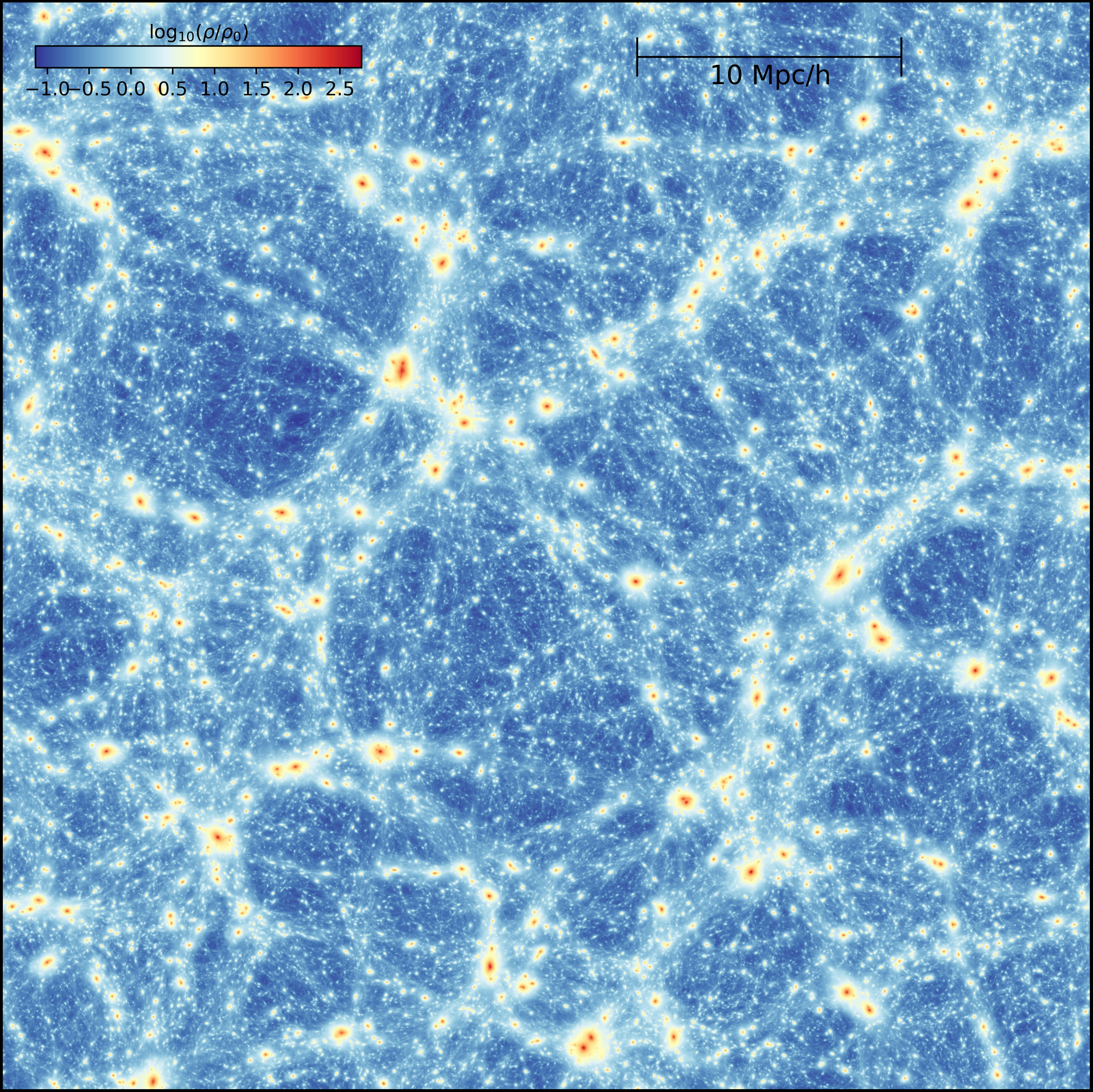
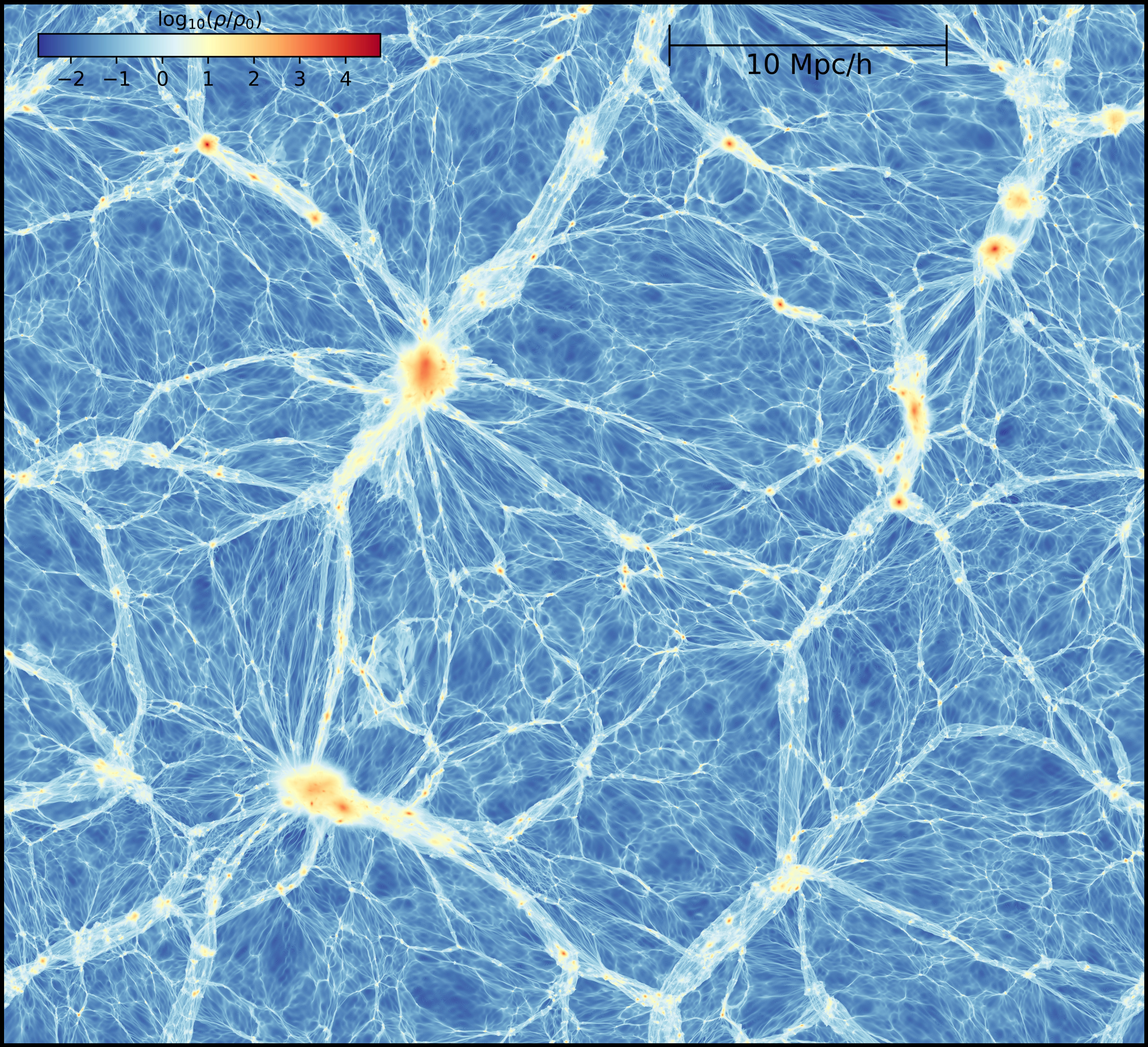
In **galaxies**

- The realisation that l.o.s. structures are the dominant perturbers in many observed situations is a game changer – both their abundance and their structure are more robustly known, and there are more of them
- Advent of ALMA, VLBI and 10m adaptive optics methods allows constraints to be placed to lower substructure masses

→ Both WDM **and/or** CDM can be ruled out with realistic samples

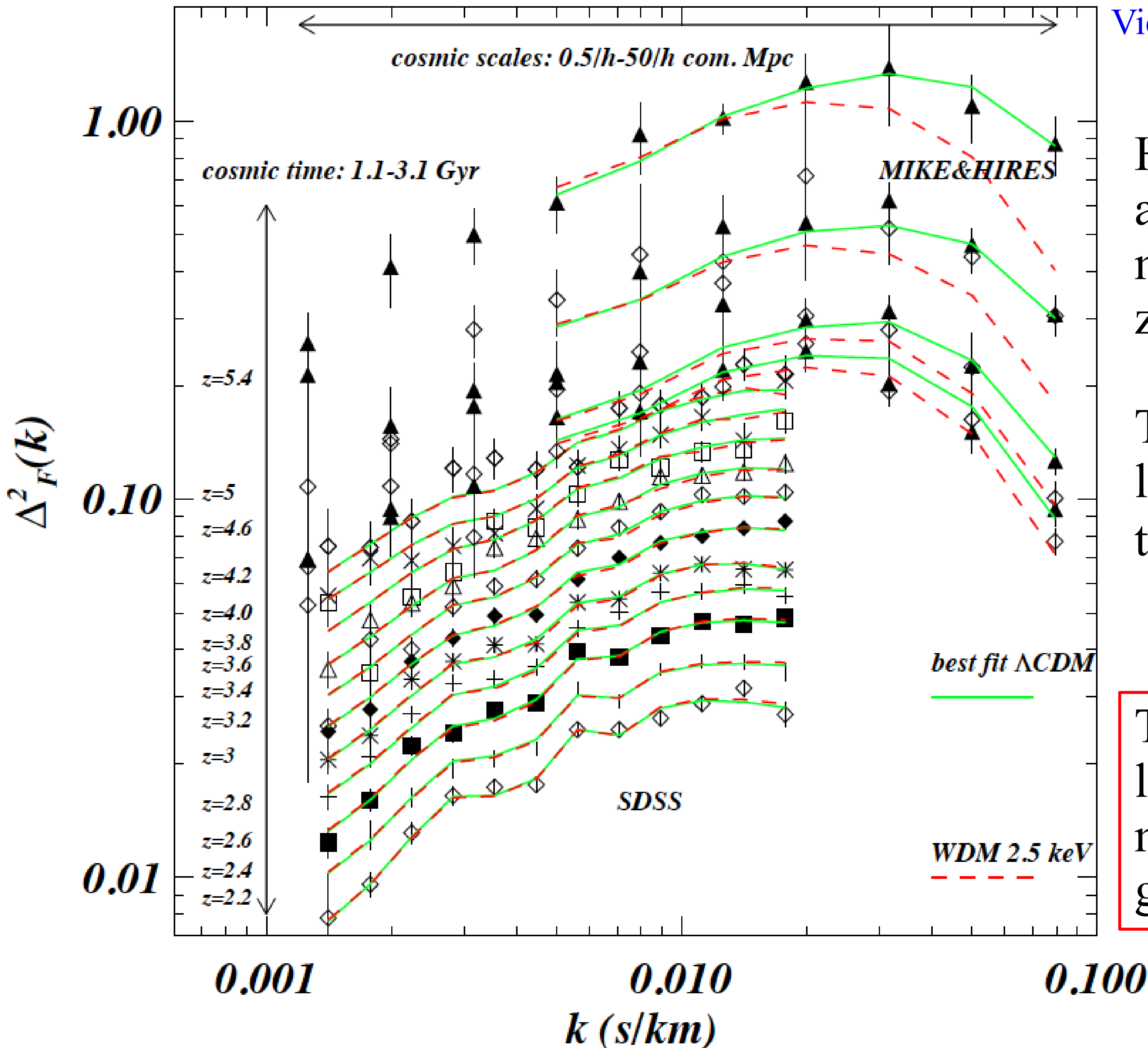


$\log_{10}(\rho/\rho_0)$
−1.0 −0.5 0.0 0.5 1.0 1.5 2.0 2.5
10 Mpc/h



log10(ρ/ρ0)
−2 −1 0 1 2 3 4
10 Mpc/h

Lyman α forest spectra for WDM relative to CDM



Viel, Becker, Bolton & Haehnelt 2013

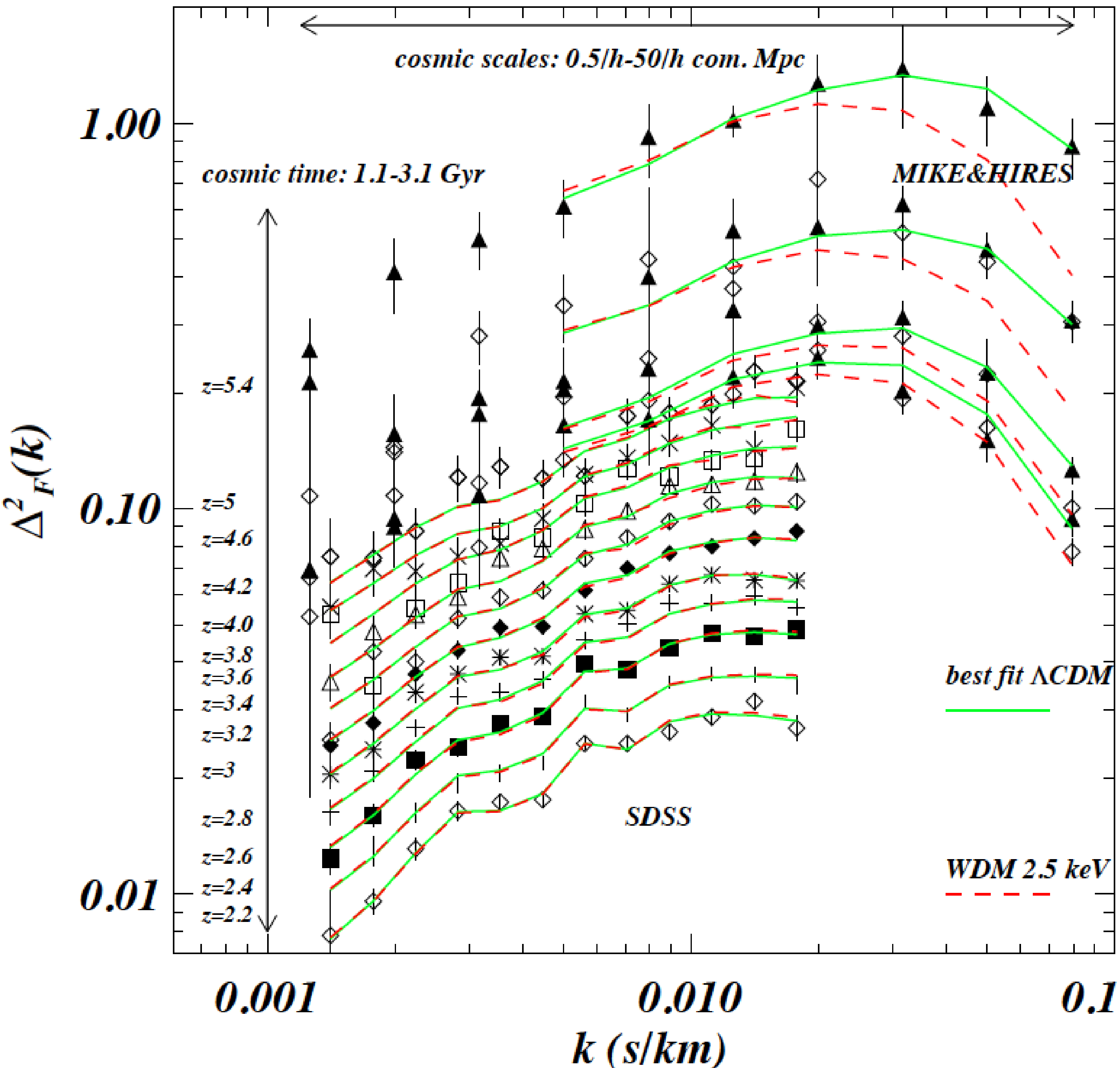
High-resolution Keck and Magellan spectra match ΛCDM up to z = 5.4

This places a 2σ lower limit on the mass of a thermal relic

$m_{WDM} > 3.3$ keV

This lower limit is too large for WDM to have much effect on dwarf galaxy structure

Lyman α forest spectra for WDM relative to CDM



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Flux-ratio anomalies give a similar constraint

Thanks to the organisors for a great meeting!