Munich Joint Astronomy Colloquium
23 April 2020

The smallest dark matter halos

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The discovery of dark matter halos

Zwicky (1933) – redshifts for 9 members of the Coma cluster

Die Rotverschiebung von extragalaktischen Nebeln

von F. Zwicky.

(16. II. 33.)

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.

Smith (1936) – redshifts for 32 members of the Virgo cluster

Confirms Zwicky's result but for a different cluster

BULLETIN OF THE ASTRONOMICAL INSTITUTES OF THE NETHERLANDS

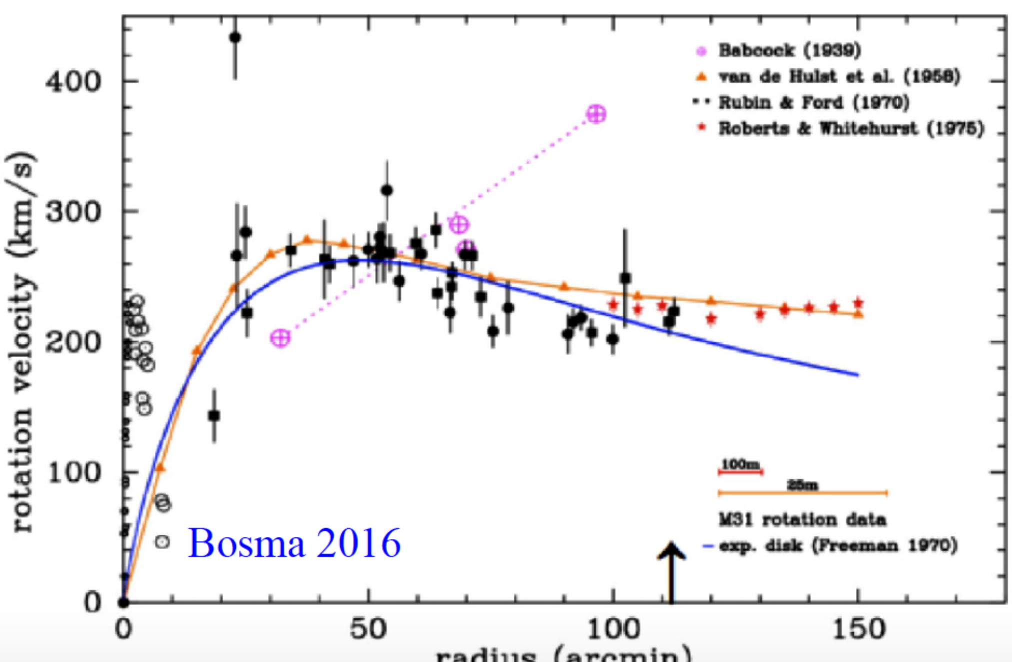
1957 NOVEMBER 9 VOLUME XIV NUMBER 480

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

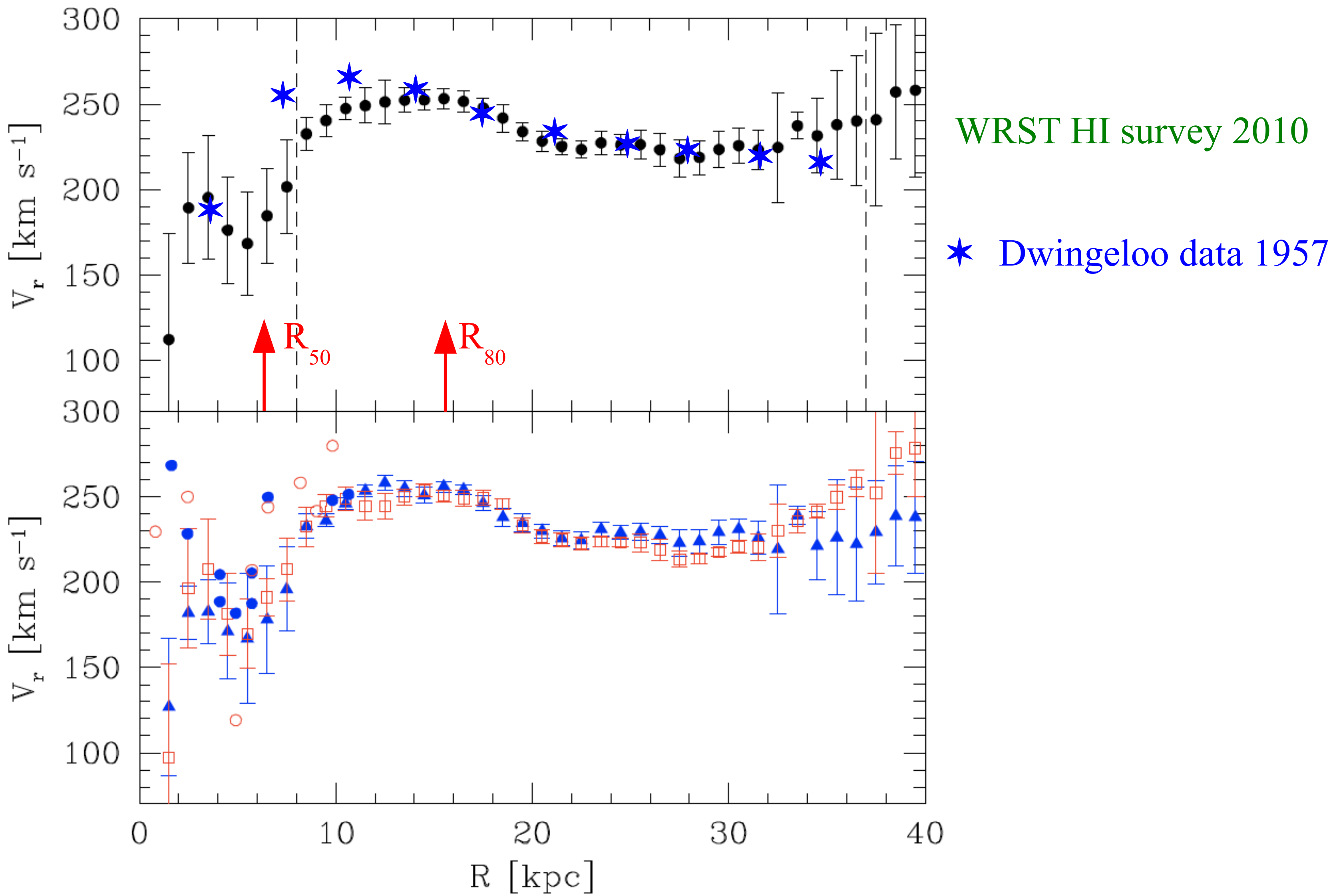


- The earliest reliable flat rotation curves (for M31) are usually credited to Rubin & Ford 1970 (optical) and Roberts & Whitehurst 1975 (radio)
- The 21cm goes to much larger radius
- The 1957 Dwingeloo curve is just as good and goes just as far

A wide-field H I mosaic of Messier 31

II. The disk warp, rotation, and the dark matter halo

E. Corbelli[1], S. Lorenzoni[1], R. Walterbos[2], R. Braun[3], and D. Thilker[4]



Dark matter halos become "mainstream"

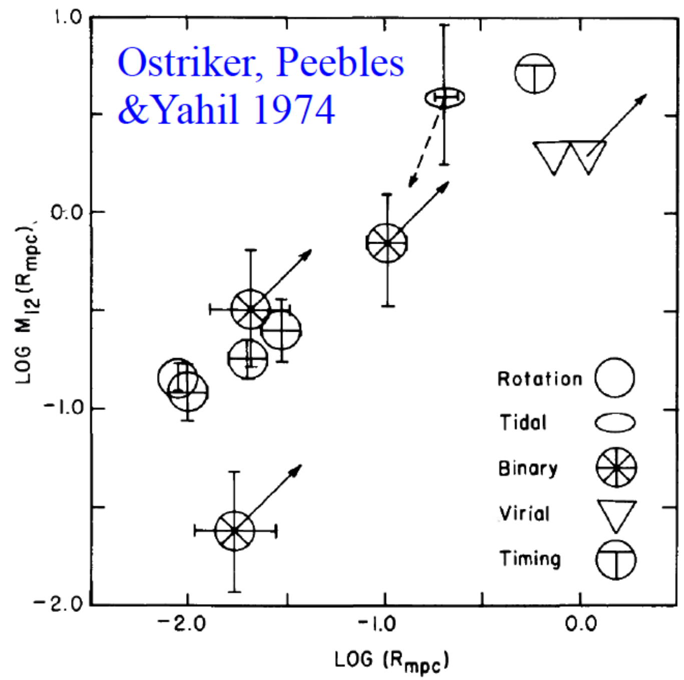


FIG. 1.—Mass (unit 10^{12} $M_\odot$) of local giant spiral galaxies within a distance (R/1 Mpc) of their centers, as determined by various methods.

Cluster M/L ratios are taken as well established

Masses for (spiral) galaxies increase linearly with scale along the sequence

- HI rotation curves
- Interacting and other binary galaxies
- Local Group timing (Kahn & Woltjer 1959)
- Other galaxy groups
- Clusters

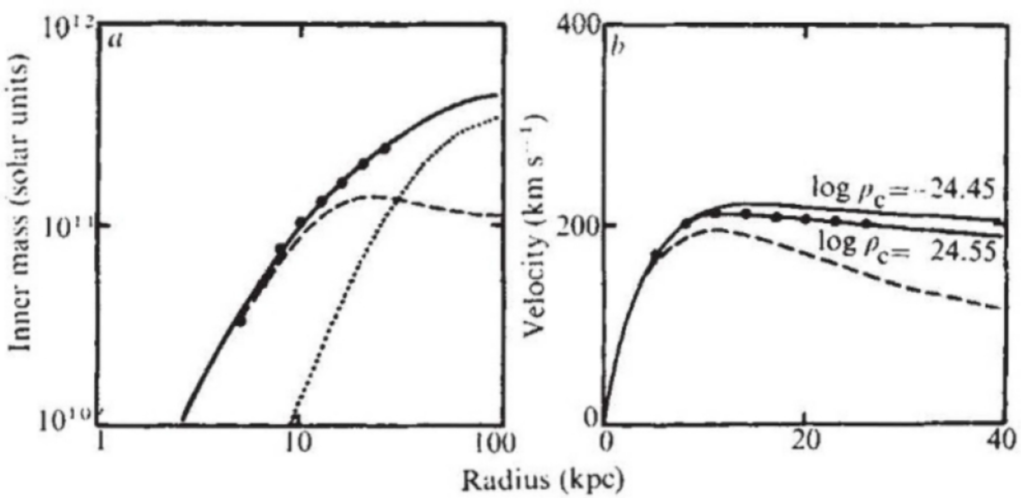


Fig. 1 The distributions of (*a*) the inner mass, $M(R)$, and (*b*) the circular velocity, V_c, in the galaxy IC342.

Einasto, Kaasik &Saar 1974

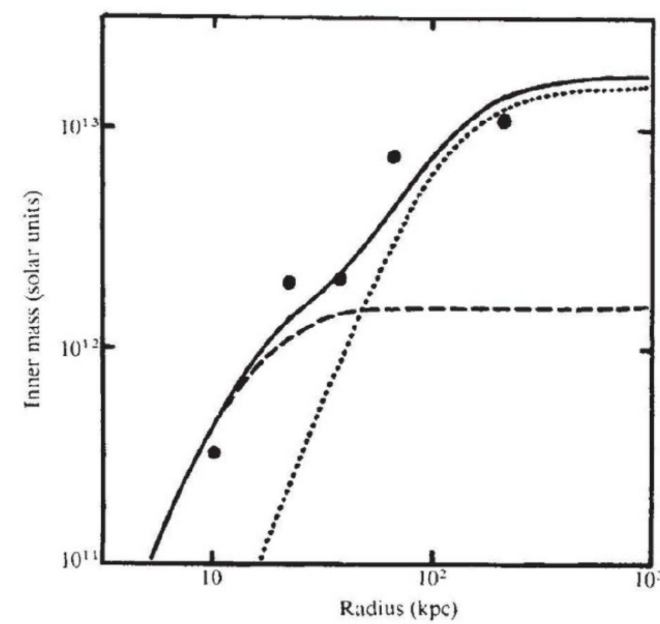


Fig. 2 The distribution of the mean inner mass, $\langle M(R)\rangle$, obtained from 105 pairs of galaxies. Symbols as in Fig. 1.

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

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

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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-

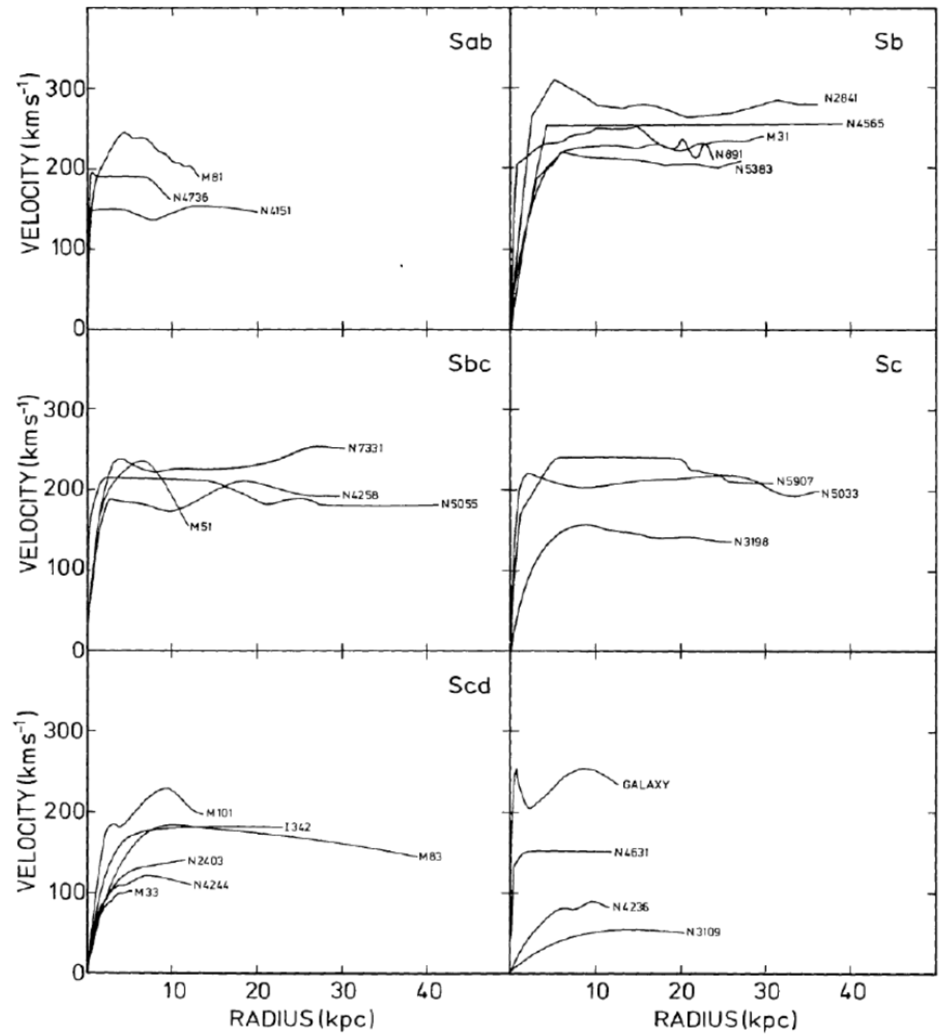


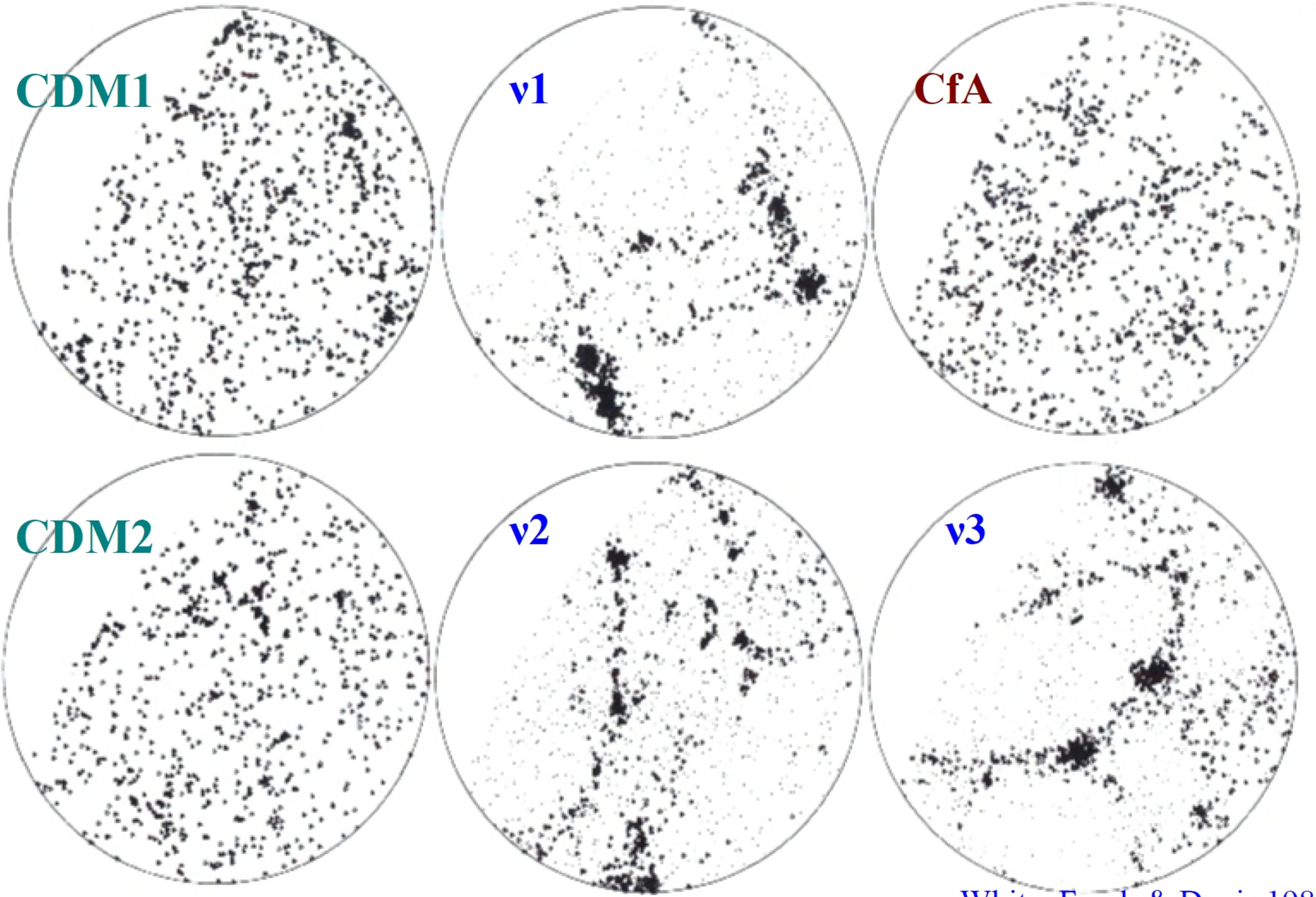
Figure 2 Rotation curves of 25 galaxies of various morphological types from Bosma (1978).

- Extended dark matter halos were broadly accepted by the end of 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

Inflation + particle DM gain traction in the 1980's…

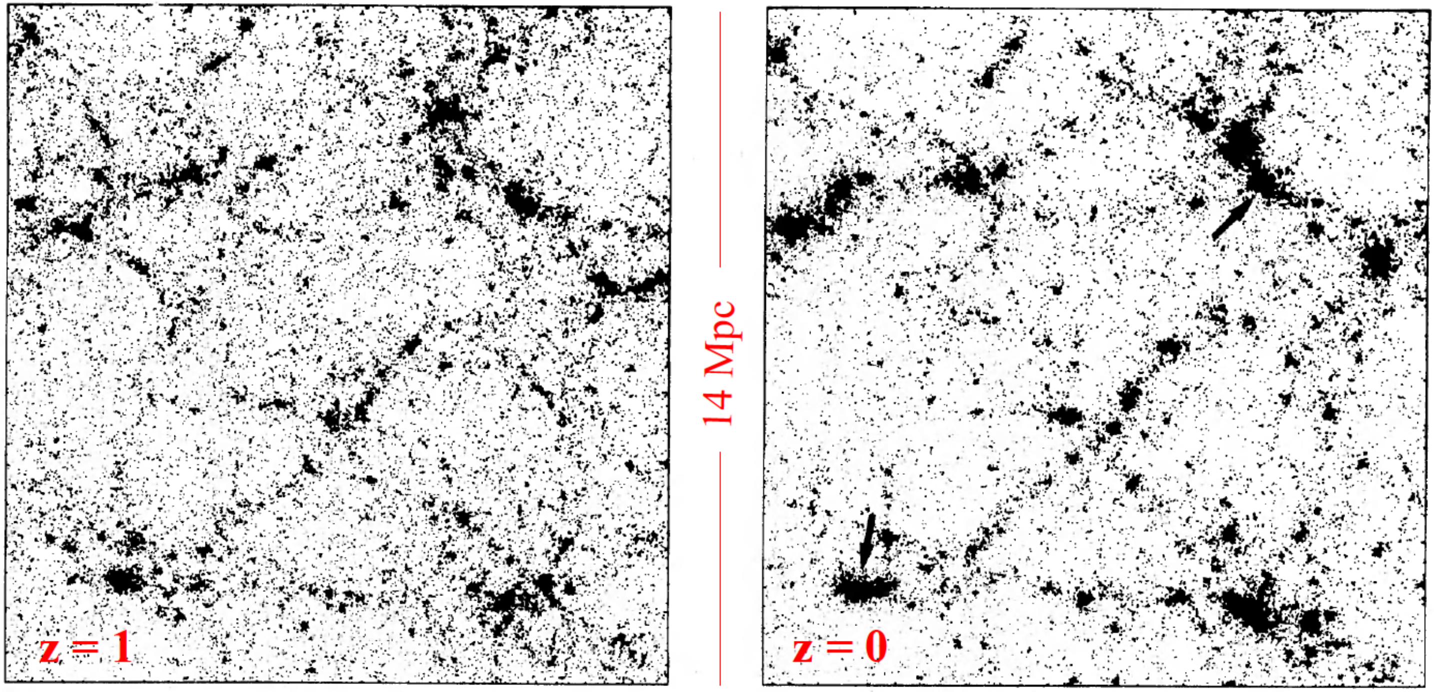
Davis, Efstathiou, Frenk & White 1985

Davis, Huchra, Latham & Tonry 1982



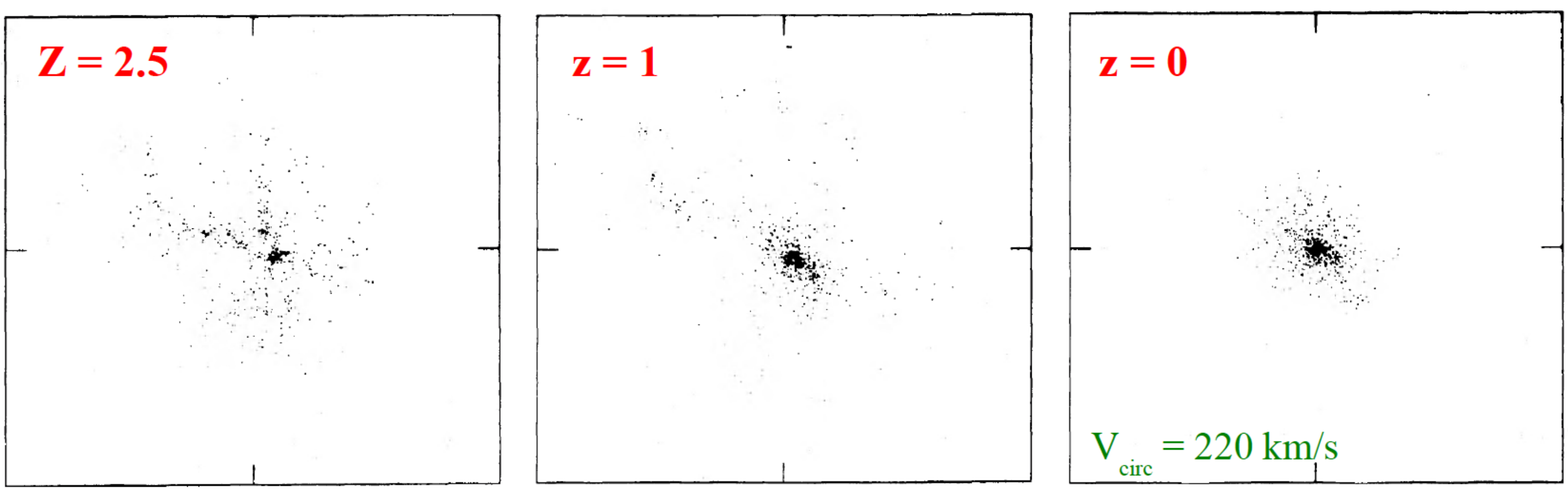
White, Frenk & Davis 1983

...leading to cosmological simulations of halo formation



Frenk, White, Davis & Efstathiou 1988

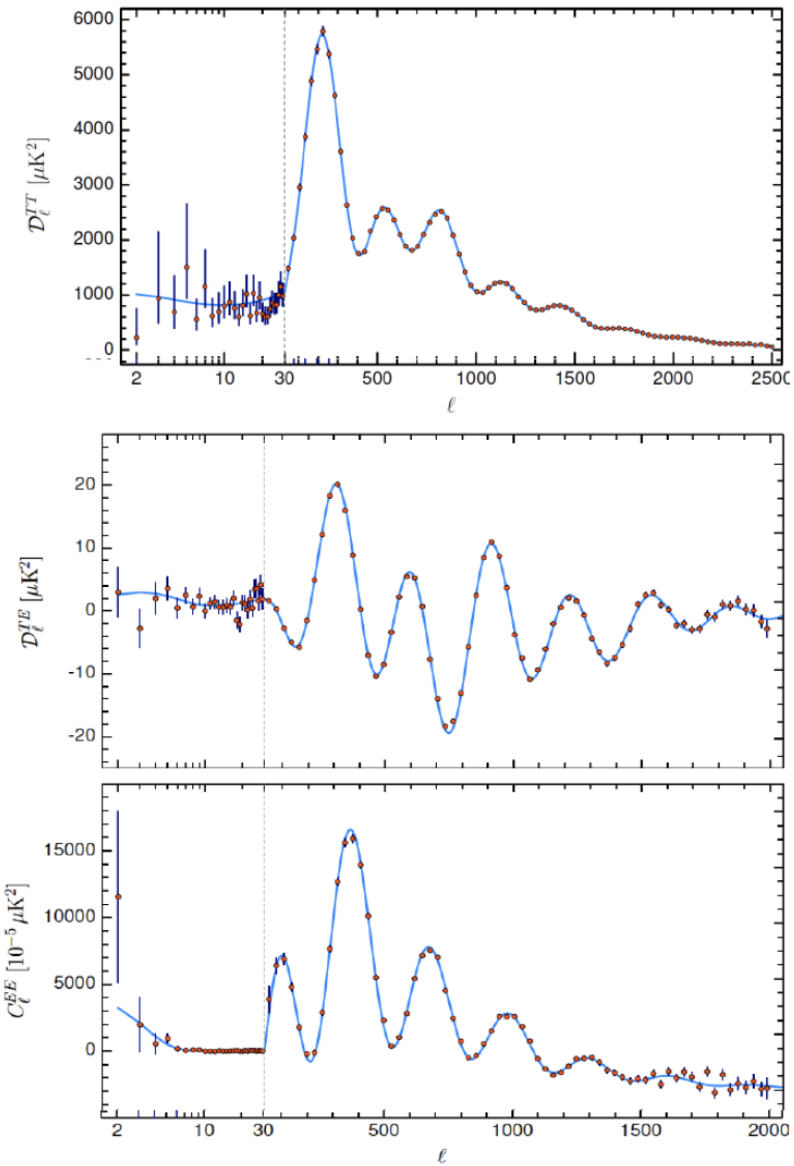
SCDM



Springel et al 2008

Newtonian “experiment” with 100 million bodies – forming a dark matter halo

What is the strongest astrophysical evidence for dark matter?

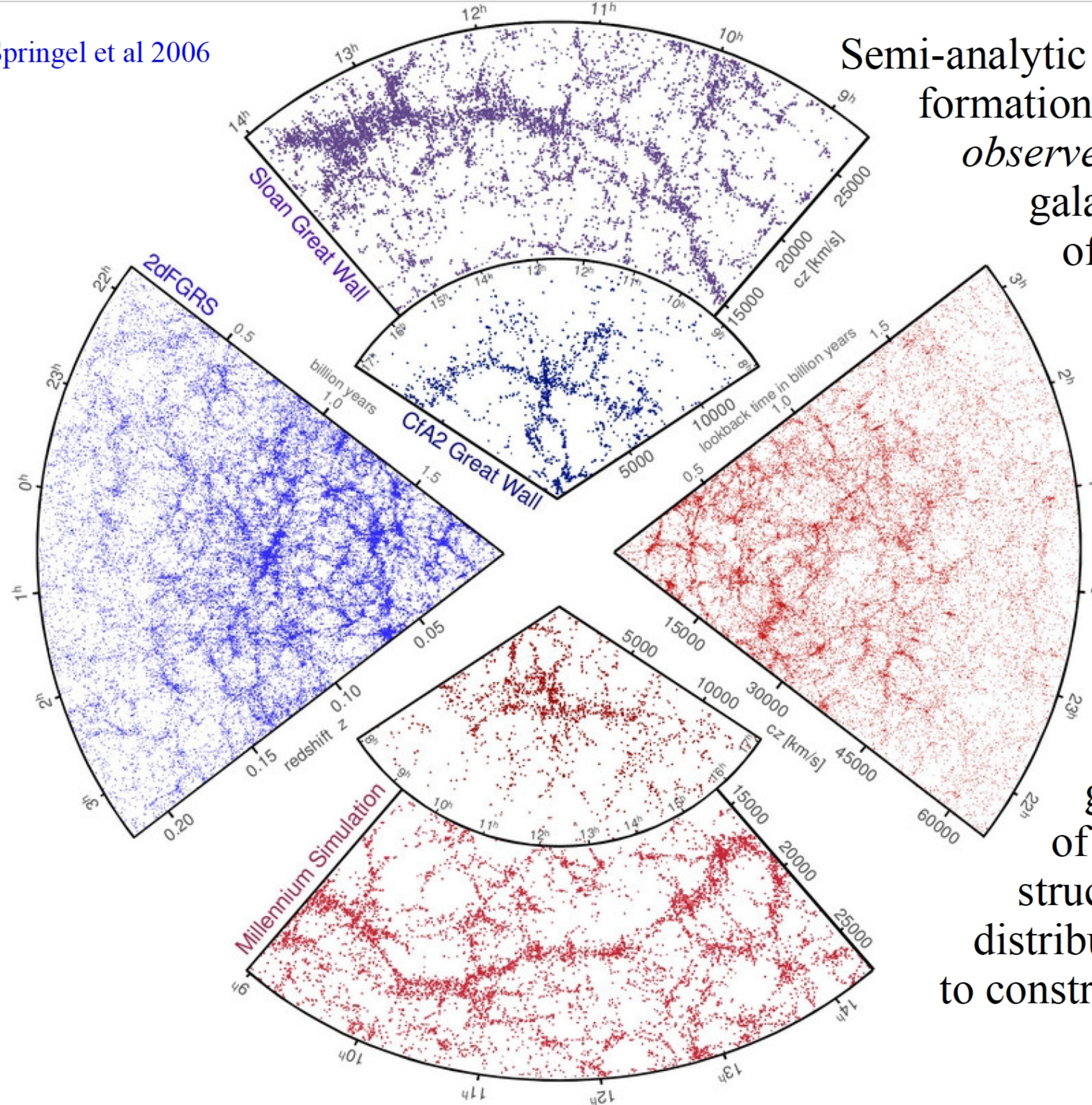


Planck Collaboration 2018

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
- Modelling halo formation requires (theoretical) extrapolation to smaller scales and later times

Springel et al 2006

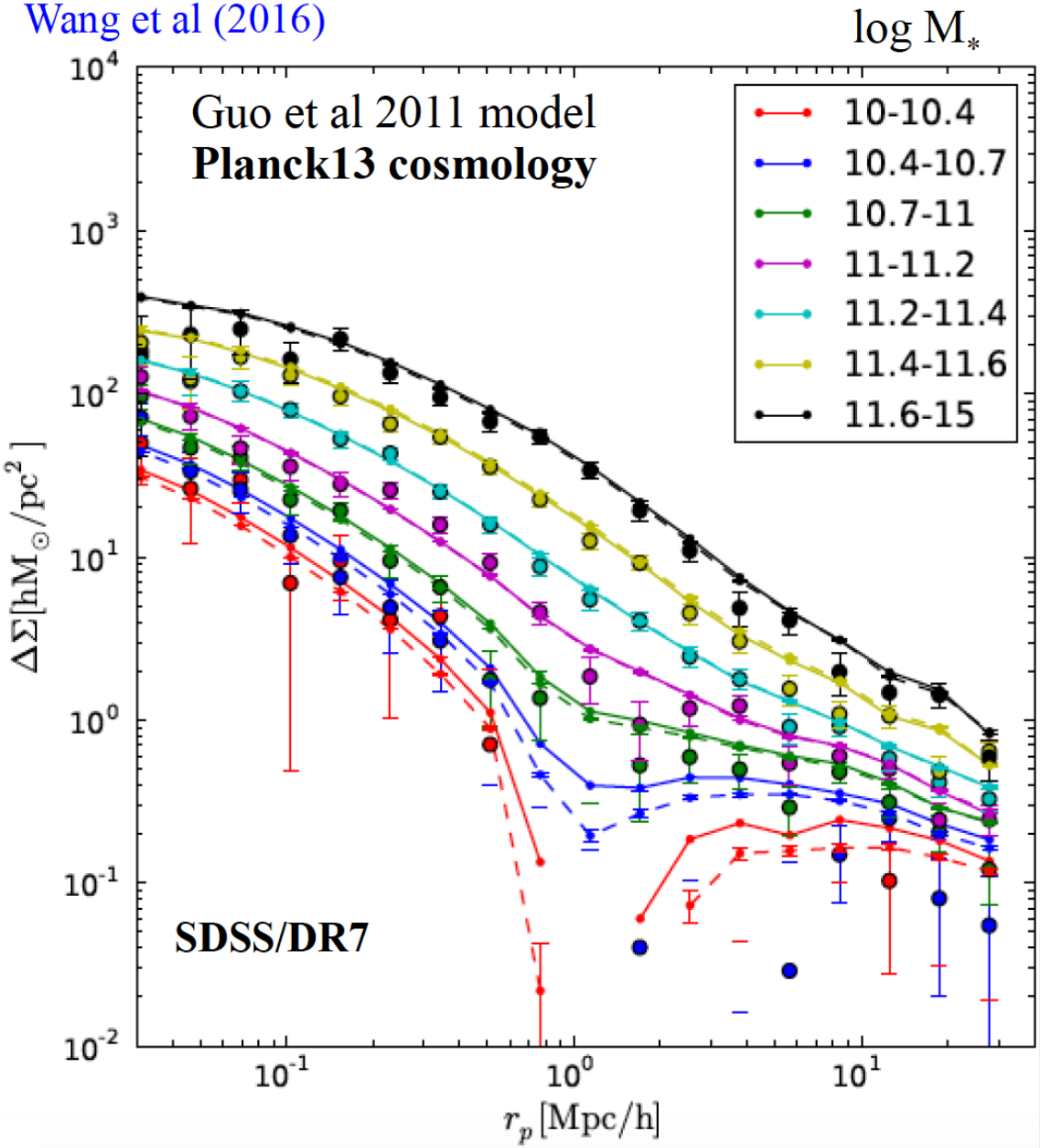


Semi-analytic models of galaxy formation in ΛCDM use the *observed* abundance of galaxies as a function of stellar mass, SFR, size, gas content, etc. to set their free parameters.

Galaxies form by cooling and condensation of gas at the centres of halos, but their structure and spatial distribution is not used to constrain parameters

Average mass profiles around bright galaxies

Wang et al (2016)



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

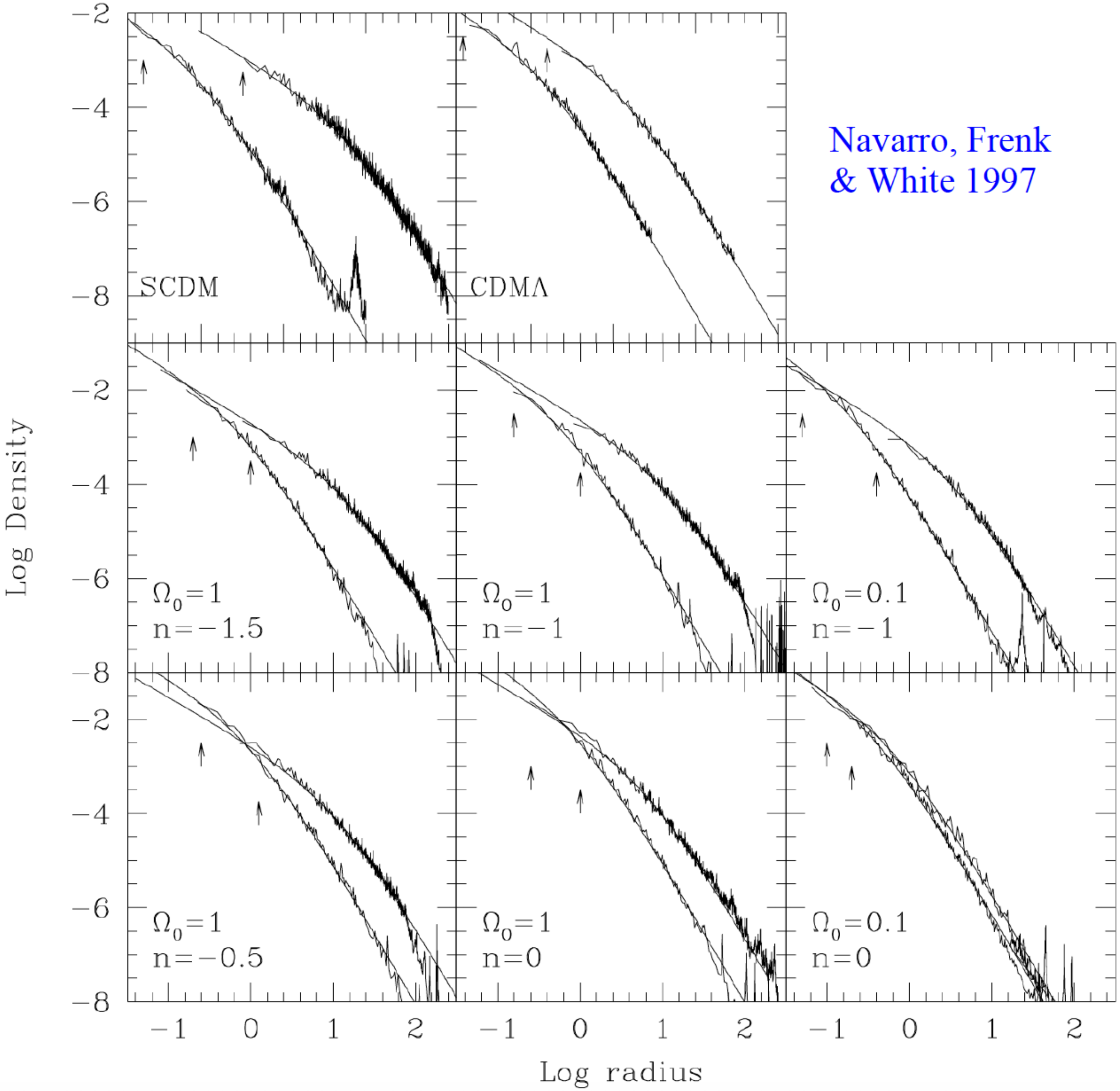
Top to bottom goes from rich clusters to "Milky Way" groups

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

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

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

"Universal" halo density profiles



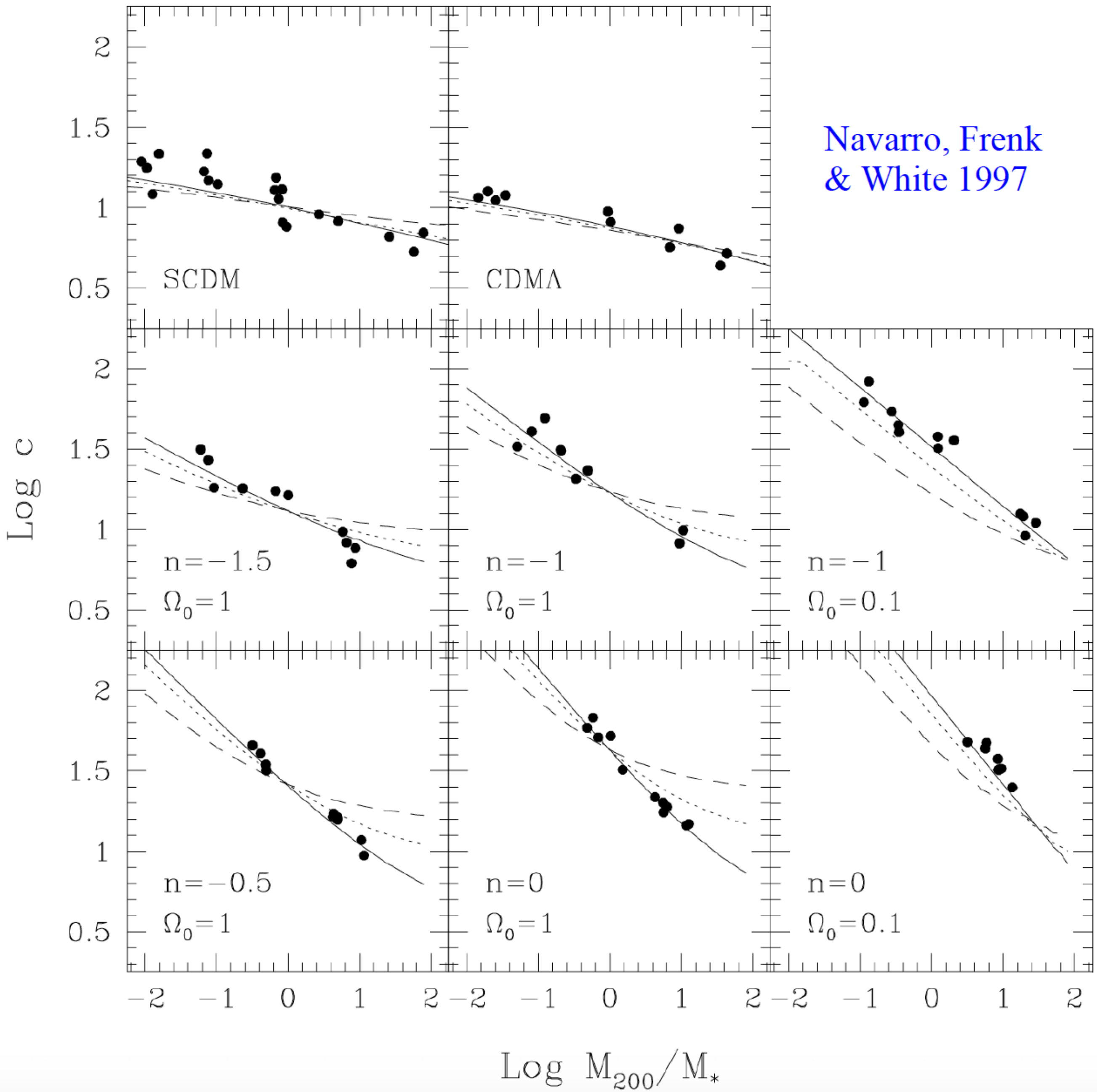
Navarro, Frenk & White 1997

The two parameter formula

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

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

"Universal" halo density profiles



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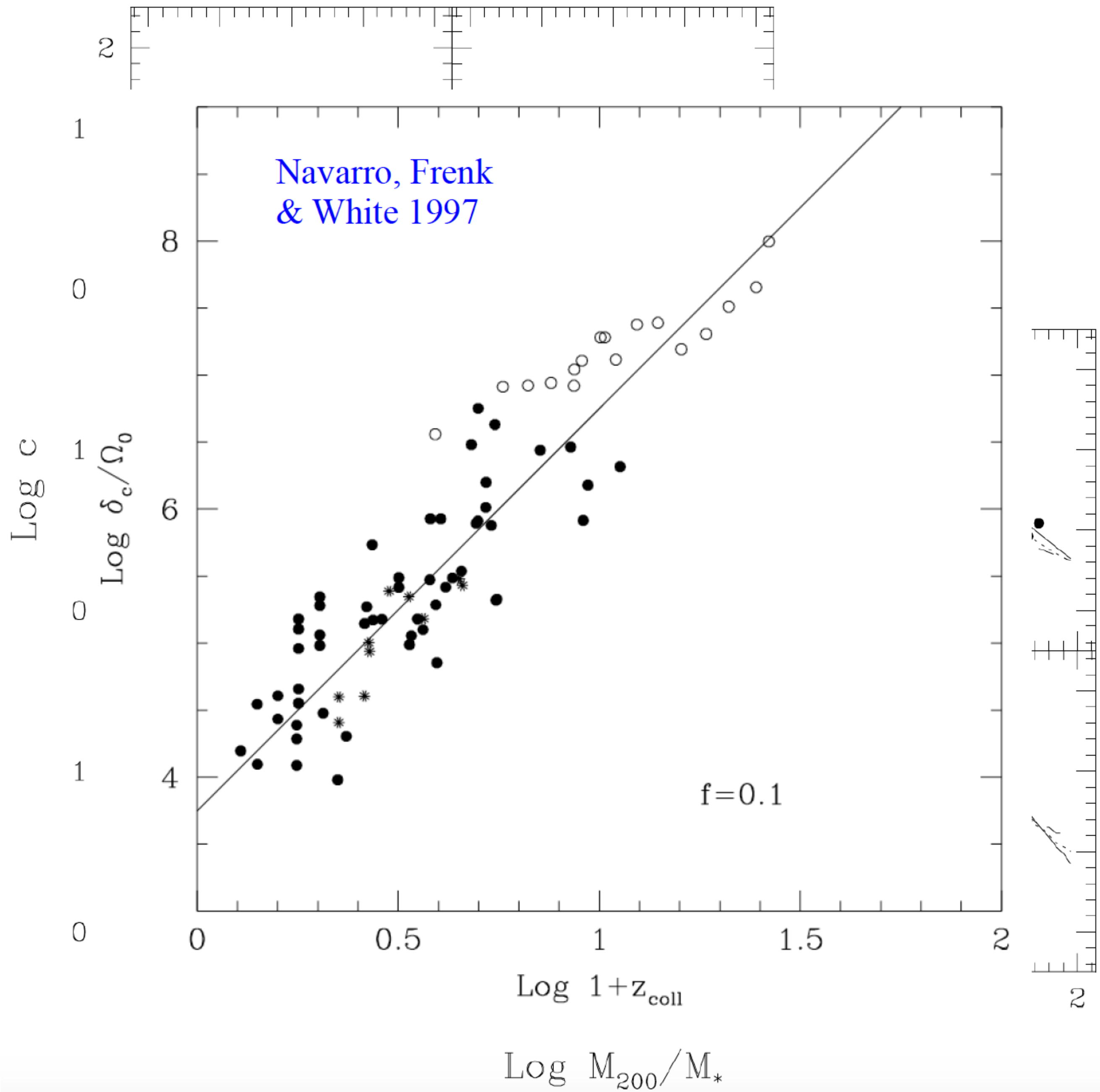
The two parameters relate to halo mass in a way that is cosmology-dependent. Halo concentration decreases as mass increases in CDM-like universes.

“Universal” halo density profiles



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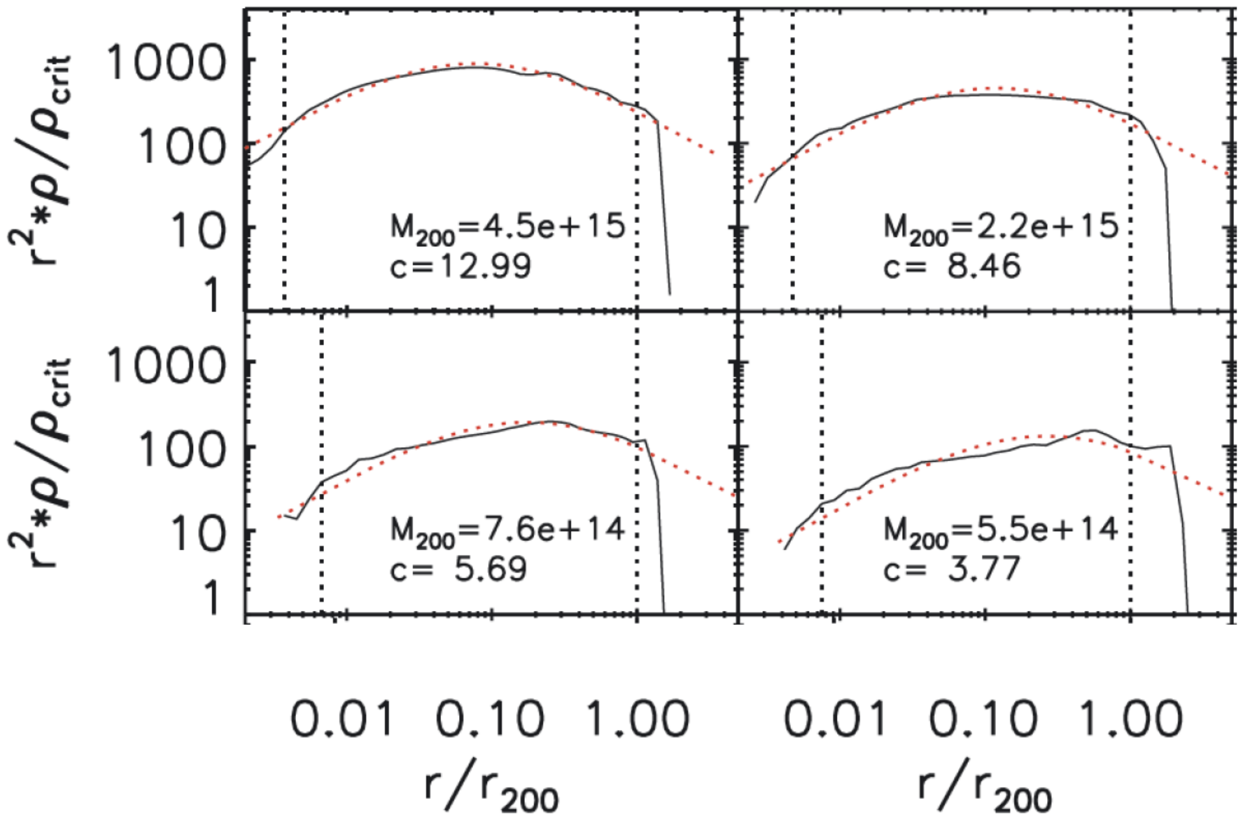
The two parameters relate to halo mass in a way that is cosmology-dependent. Halo concentration decreases as mass increases in CDM-like universes. This reflects later formation at higher mass.

“Universal” halo density profiles

Halo profiles in a Hot Dark Matter model



Wang & White 2009

The two parameter formula

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

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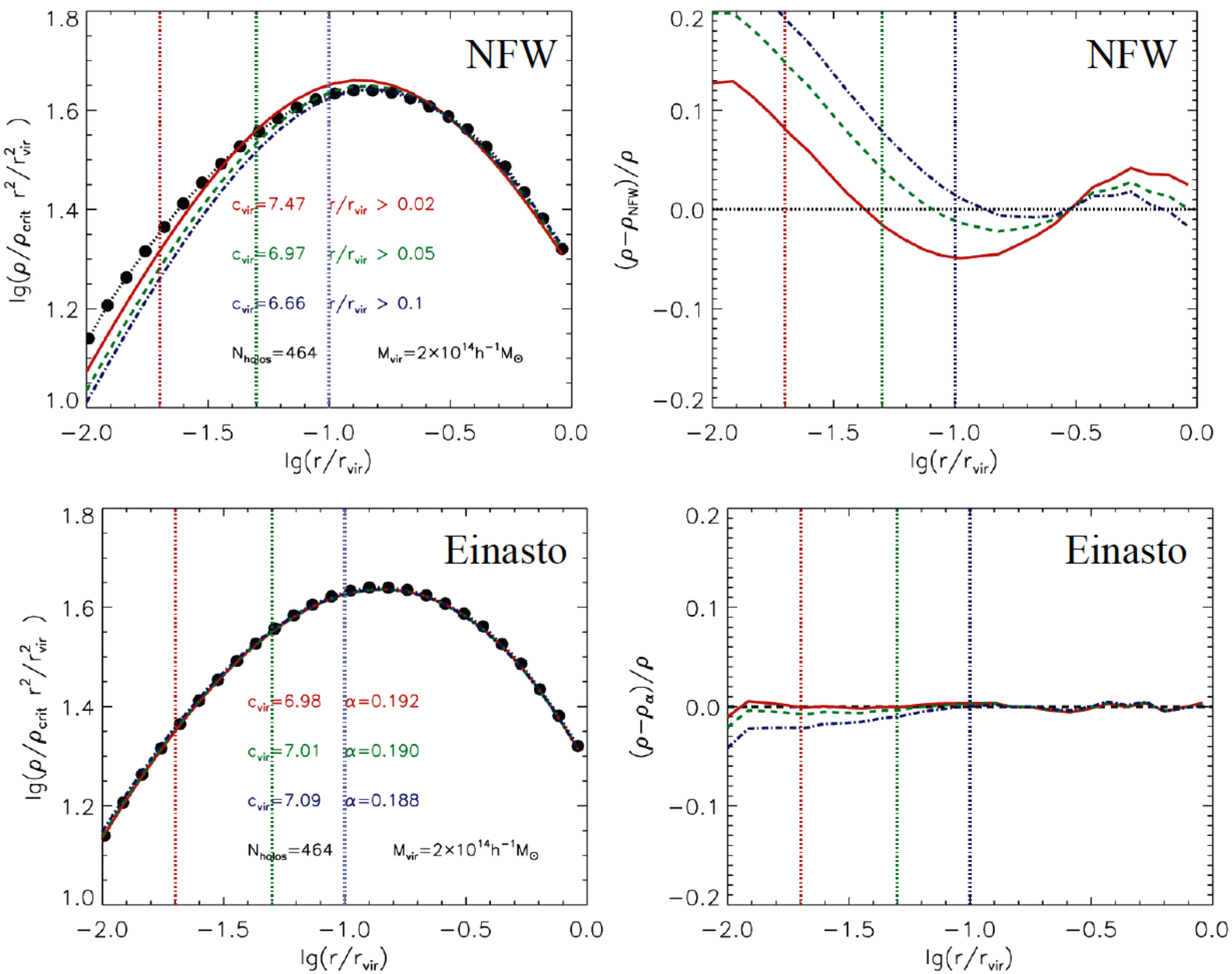
The two parameters relate to halo mass in a way that is cosmology-dependent. Halo concentration decreases as mass increases in CDM-like universes. This reflects later formation at higher mass.

HDM halos are *also* fit, but the mass-dependence of formation time and concentration reverse near the free-streaming limit

"Universal" halo density profiles

Averaged cluster mass halos fit with NFW and Einasto



Gao et al 2008

The two parameter formula

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

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

The two parameters relate to halo mass in a way that is cosmology-dependent. Halo concentration decreases as mass increases in CDM-like universes. This reflects later formation at higher mass.

HDM halos are *also* fit, but the mass-dependence of formation time and concentration reverses near the free-streaming limit

The Einasto formula

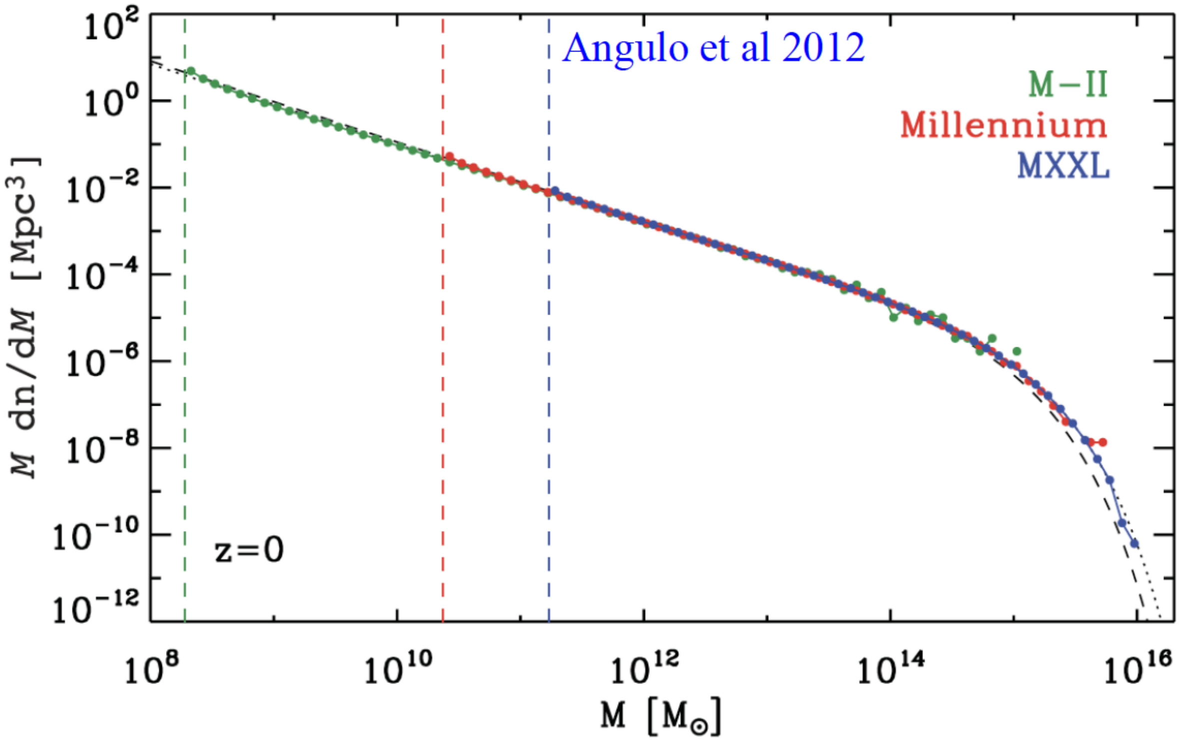
$$\ln(\rho(r)/\rho_{-2}) = (-2/\alpha)\,[(r/r_{-2})^{\alpha} - 1]$$

fits mean profiles even better

The Millennium Zoom: Springel et al 2005

In ΛCDM, the dark matter is structured in a "cosmic web" made of DM halos

How much of the dark matter is in halos?



Simulations of ΛCDM suggest that the fraction of DM in halos with

$M_{halo} > 1.8 \times 10^{11} M_\odot$ is 44%

$M_{halo} > 2.5 \times 10^{10} M_\odot$ is 50%

$M_{halo} > 2 \times 10^{8} M_\odot$ is 60%

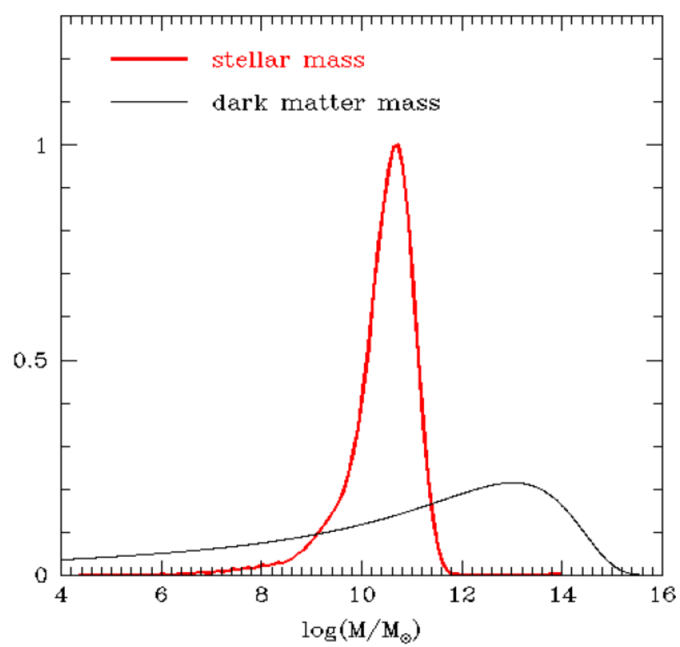
Extrapolations using theoretical mass function models suggest the corresponding fraction for

$M_{halo} > 1 M_\odot$ is $\sim$ 94%

$M_{halo} > 10^{-6} M_\odot$ is $\sim$ 98%

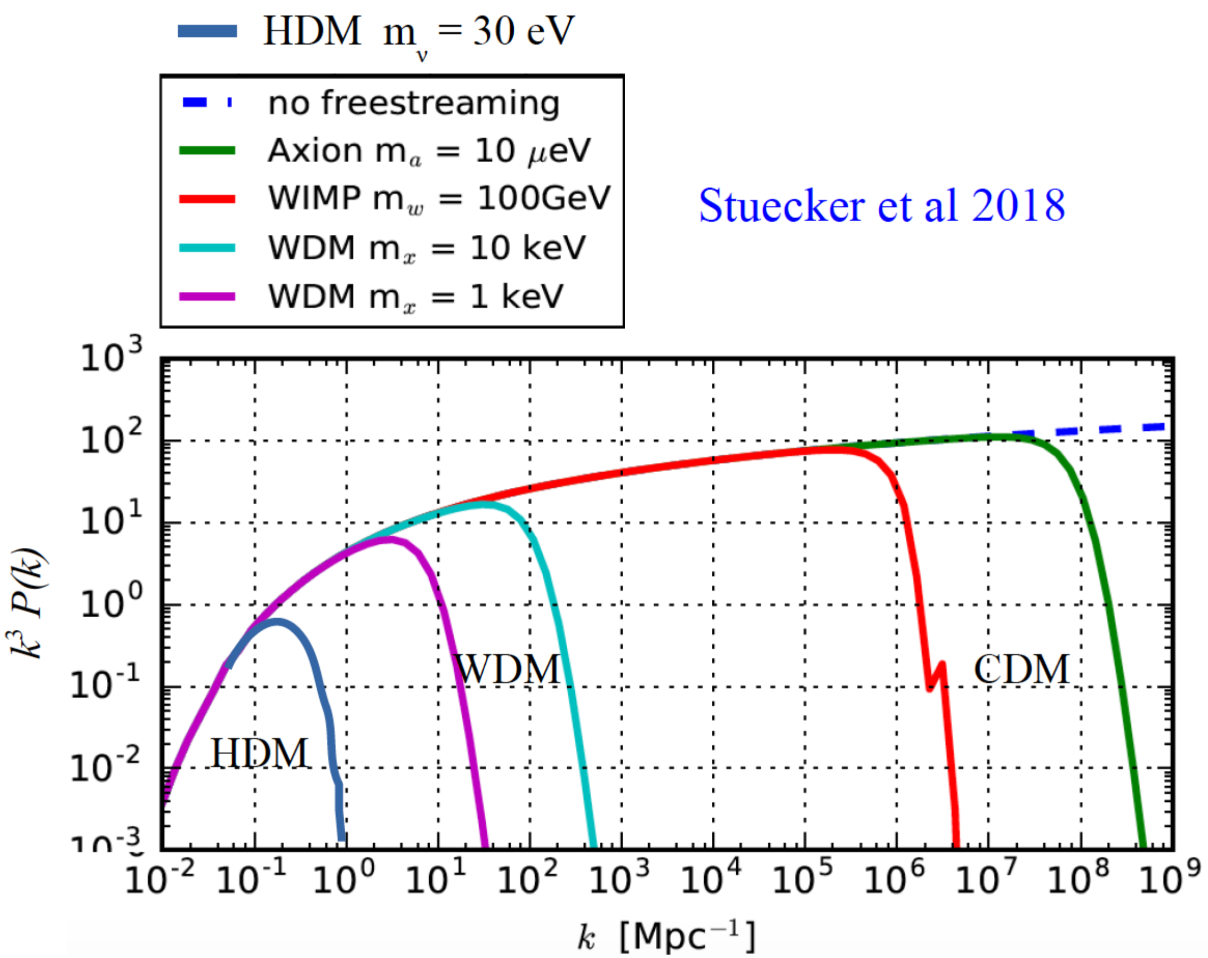
if the mass function extends this far

Distribution of cosmic DM/stars across halos/ galaxies of mass M



Since halos occupy < 1% of the Universe by volume, 99% of space has very low dark matter density

Small-scale structure and the nature of dark matter

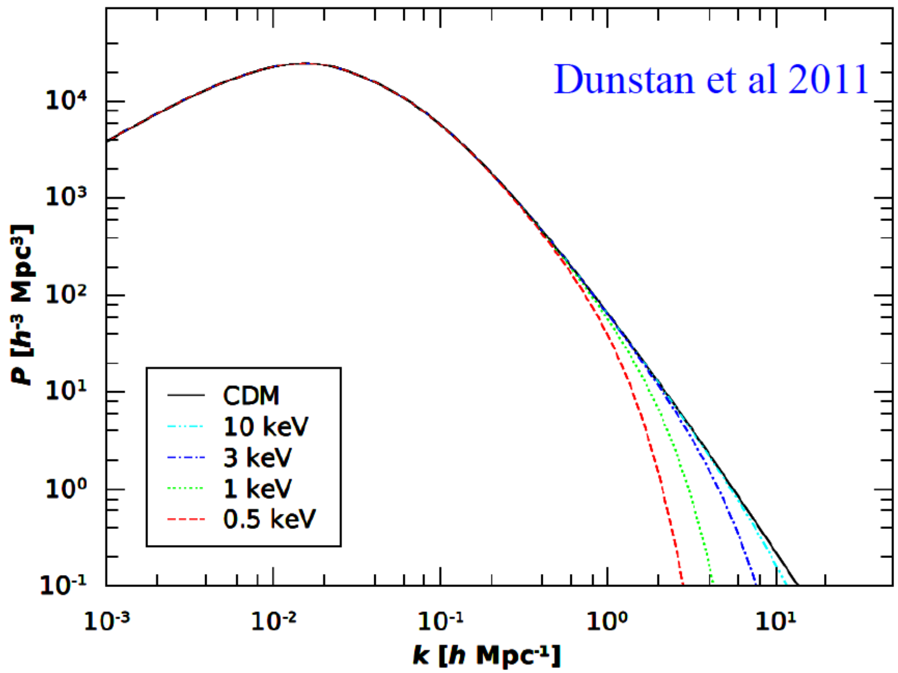


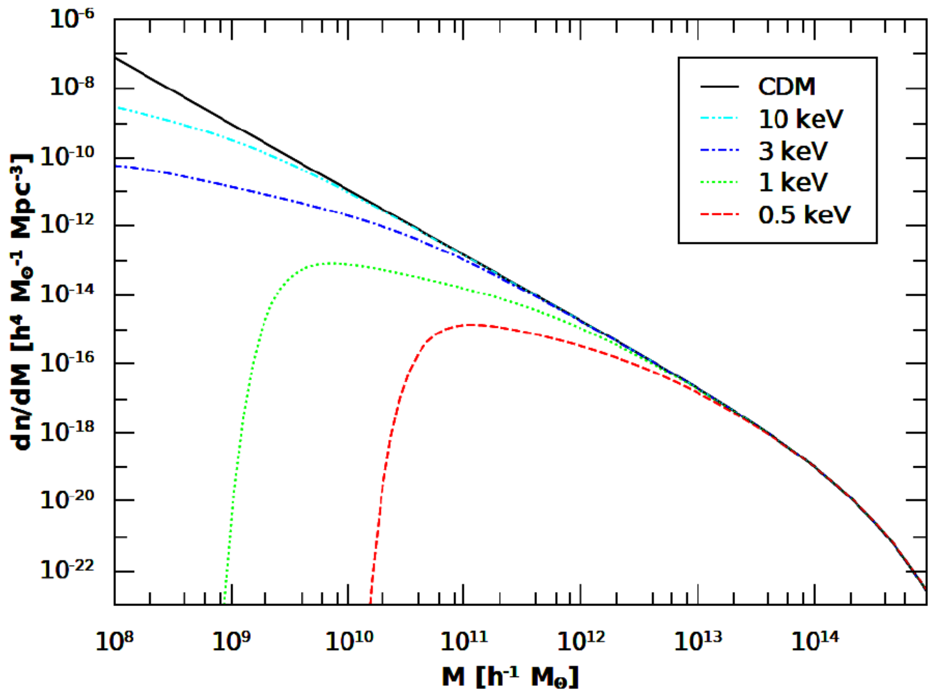
Stuecker et al 2018

Early free-streaming of collisionless dark matter erases small-scale structure

The induced scale depends on the mass of the DM particle and when/whether it thermalises

Small-scale structure and the nature of dark matter





Early free-streaming of collisionless dark matter erases small-scale structure

The induced scale depends on the mass of the DM particle and when/whether it thermalises

WDM → a halo mass cut-off, $M_{cut} \propto m_{WDM}^{-2.5}$

$m_{WDM} = 1$ keV → $M_{cut} \sim 10^{9.5} M_\odot$

$m_{WDM} = 3$ keV → $M_{cut} \sim 10^{8} M_\odot$

For CDM,

100 GeV WIMP → $M_{cut} \sim 10^{-6} M_\odot$

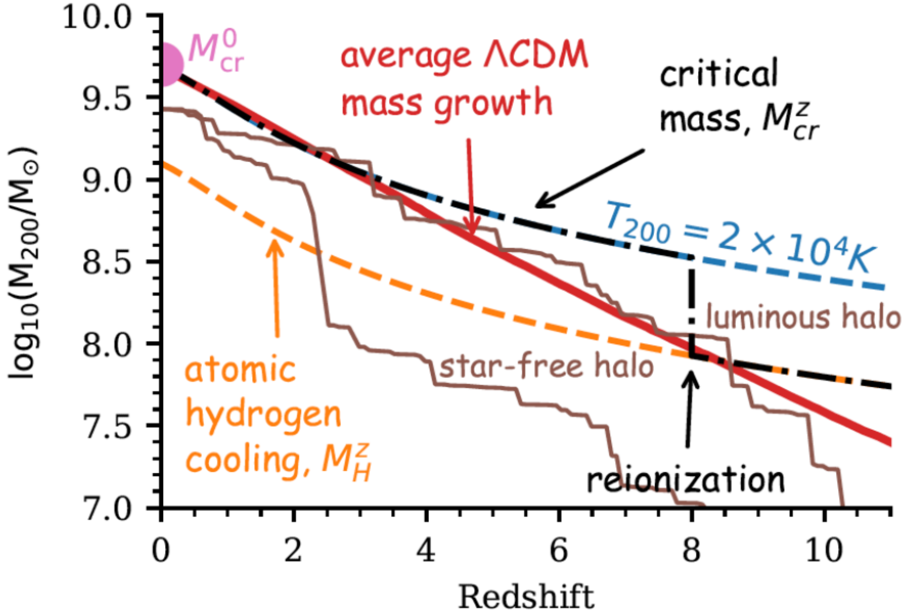
10 μeV axion → $M_{cut} \sim 10^{-12} M_\odot$

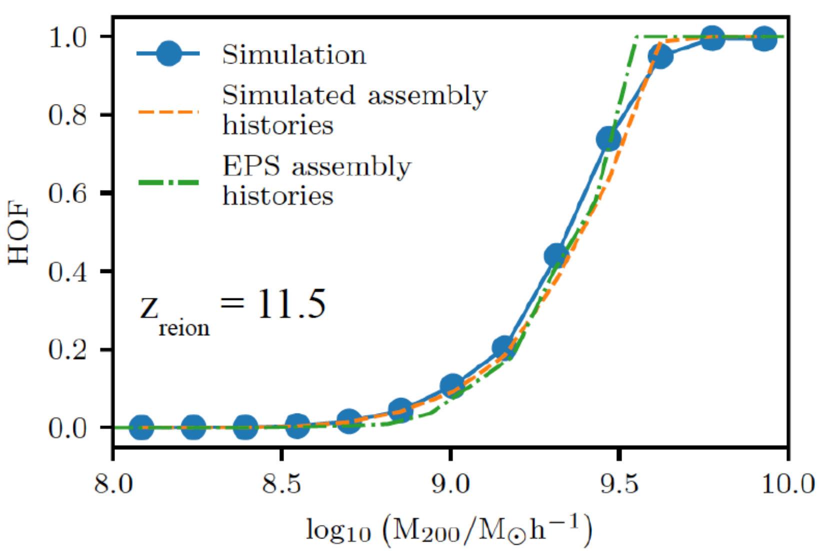
Qualitatively similar cut-offs are found for other DM models

e.g. Fuzzy DM

The smallest halos with galaxies: theory

Benitez-Llambay & Frenk 2020





Pre-reionisation

Only halos with T_{vir} high enough to ionise H (> 7000K) will be able to form stars

Post-reionisation

Only halos with $T_{vir} > T_{IGM} \sim 20000$ K will be able to form stars

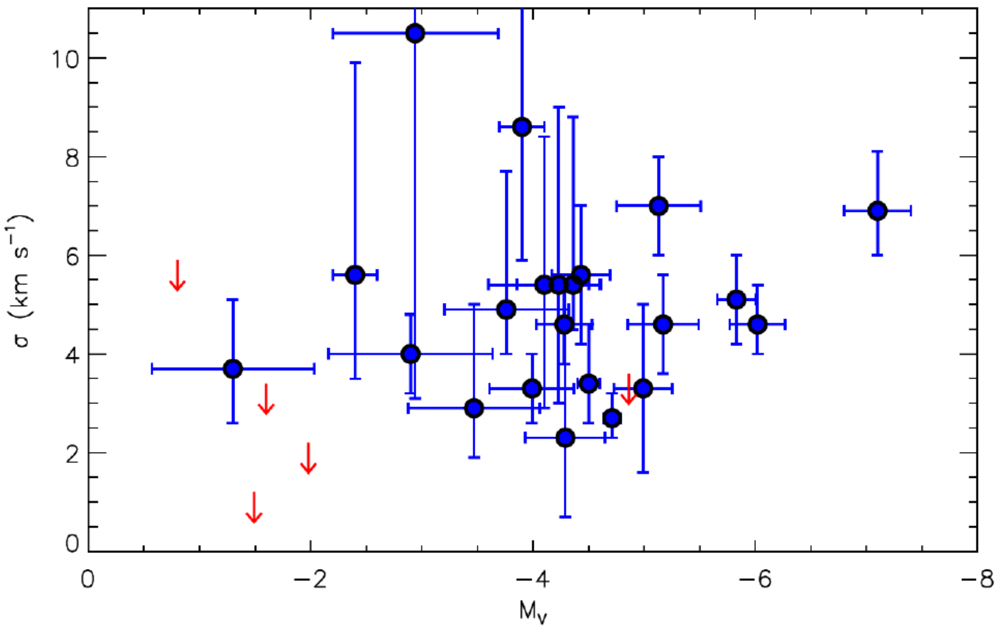
→ At the present day (z = 0)

All halos with $M > 10^{9.5} M_\odot$ should contain stars

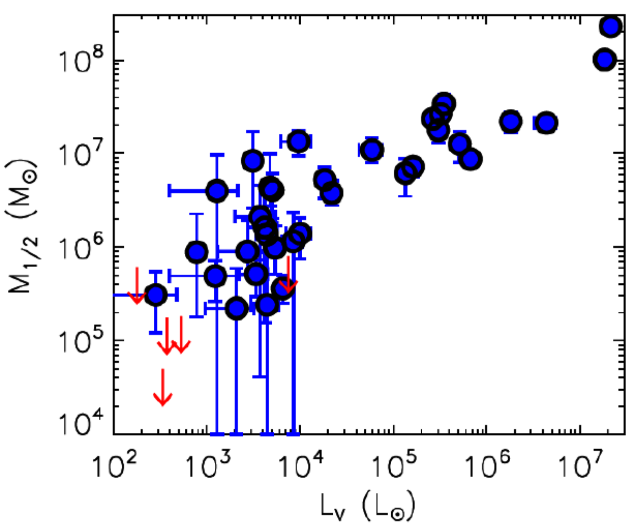
No halo with $M < 10^{8.0} M_\odot$ should contain stars

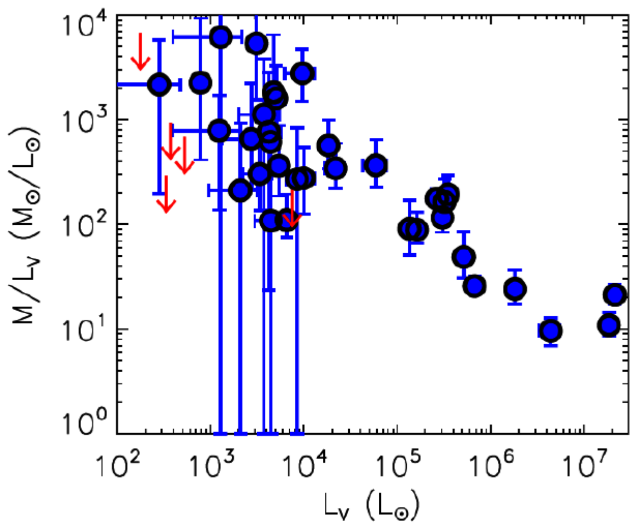
Intermediate mass halos may contain stars, depending on details of their assembly history

The smallest halos with galaxies: observation



Simon 2019





The galaxies with the smallest known stellar mass are ultrafaint satellites of the MW

$500 < L/L_\odot < 10^7$

$2 < \sigma / \mathrm{km\,s^{-1}} < 10$

$25 < R_{1/2} / \mathrm{pc} < 300$

$10 < (M_{1/2}/L_{1/2})_\odot < 5000$

Halo masses are difficult to infer because:

(i) Halos may be much more extended than the stars

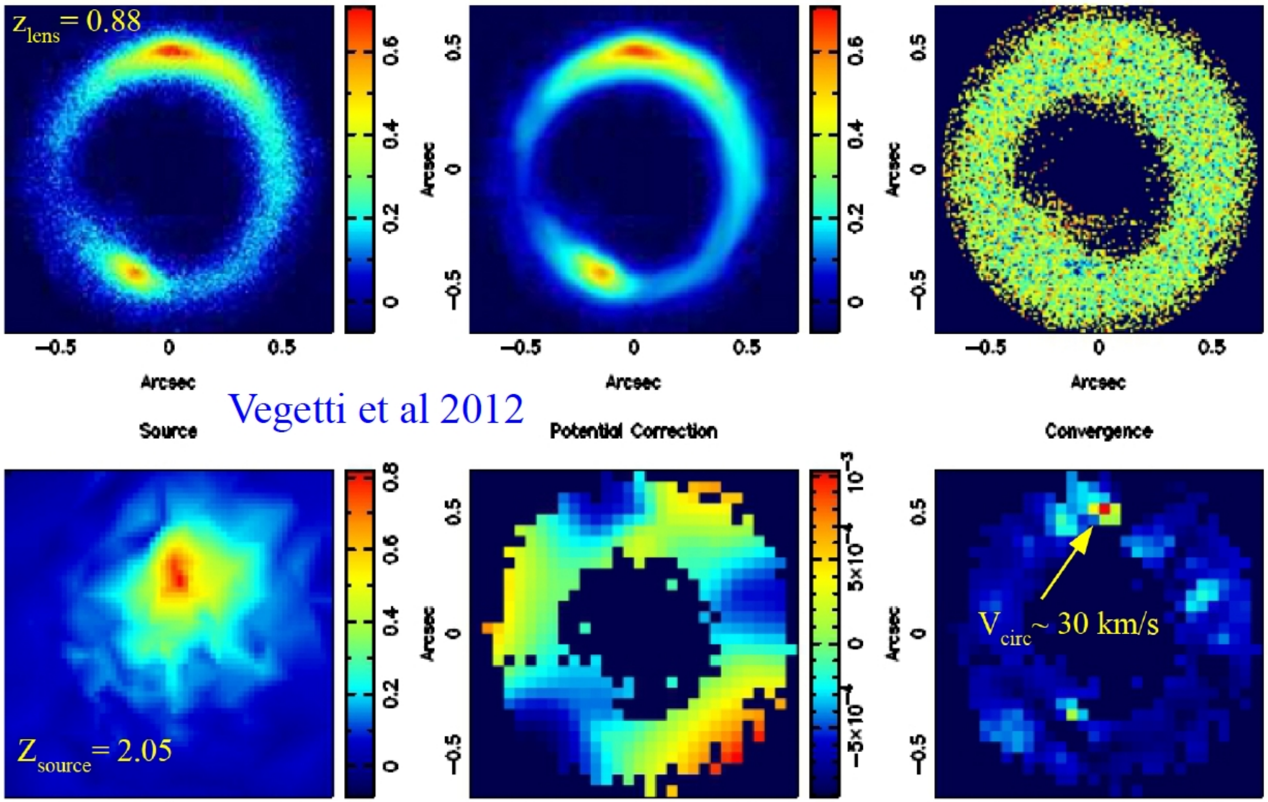
(ii) Tides will have affected their masses and radii

Currently, $M_{halo} \gg 10^6\, M_\odot$

At infall, $M_{halo} > 10^8\, M_\odot$?

How could one see smaller mass halos?

Keck AO 2.2μ



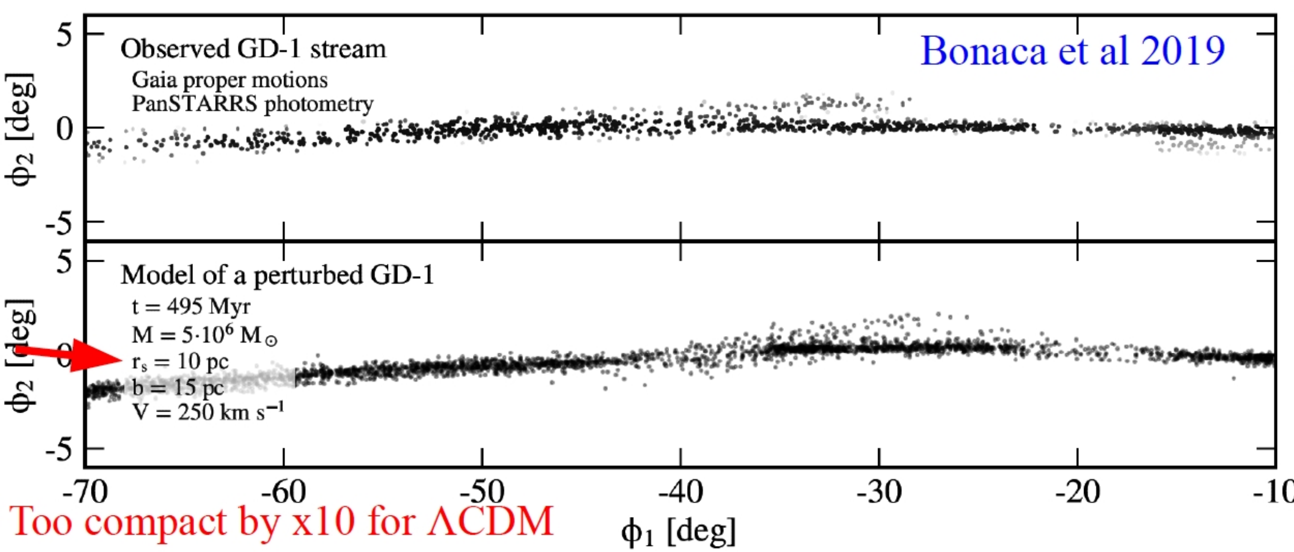
Via perturbations of strongly lensed galaxy systems

The DM halo must fall close to the l.o.s. of one of the images

Detection limit depends on S/N and resolution of the imaging

$\sim 10^6 M_\odot$ possible with VLBI

Many systems needed to survey a representative volume



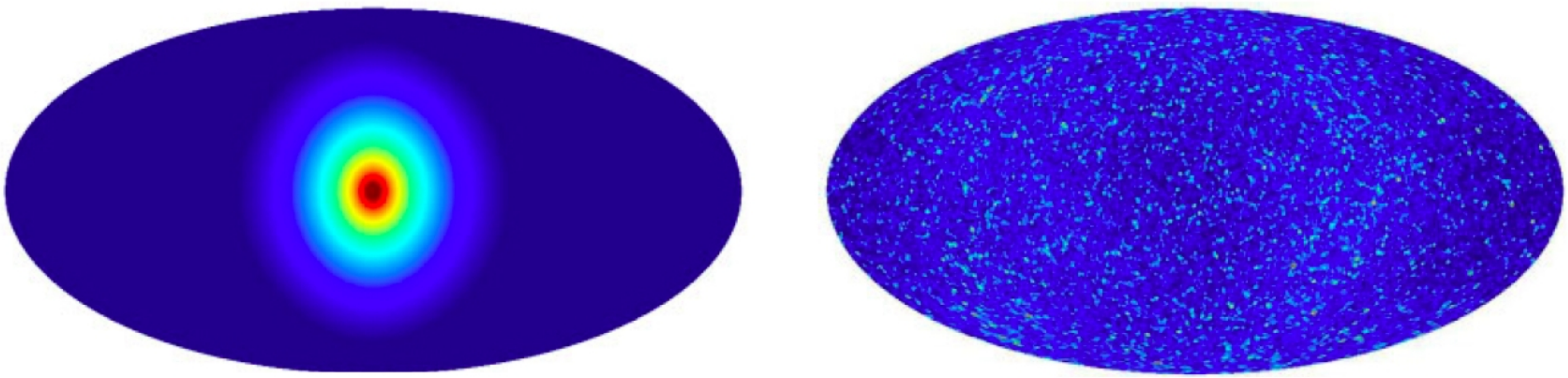
Too compact by x10 for ΛCDM

Via perturbations of stellar streams in the MW's halo

Gaia has greatly improved the fidelity of stream detection

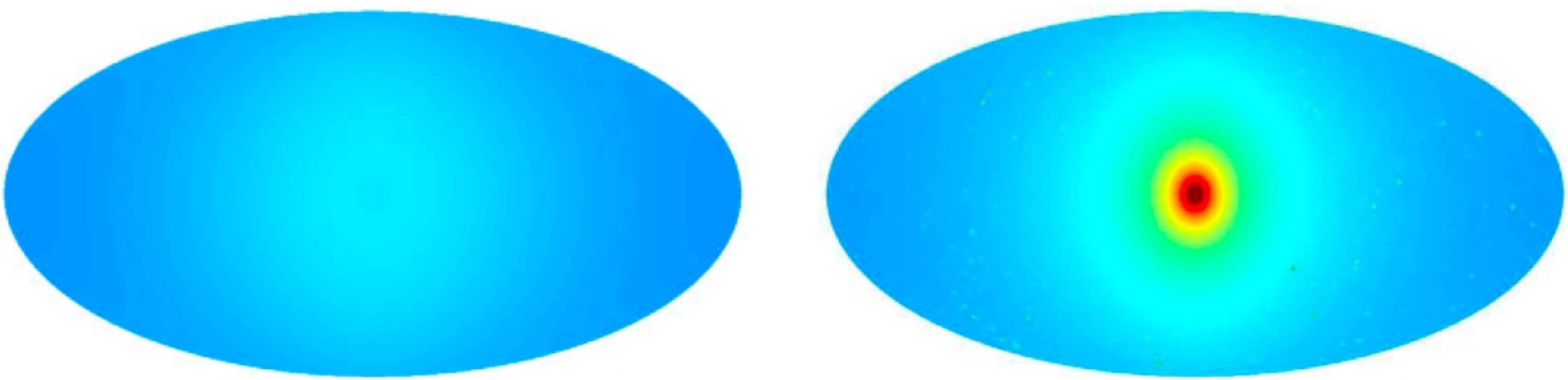
Perturbations are clearly there and could be due to encounter with mass $\sim 10^{6.7} M_\odot$

Even smaller halos might be seen by DM annihilation



Springel et al 2008

$$L_{ann} = A_{p.p.} \int \rho^2 dV = A_{p.p.} \bar{\rho} M \propto V_{max}^4 / r_{max}$$



- MW's halo annihilation flux may be dominated by that from unresolved small subhalos but this is nearly uniform over the sky
- Flux from the Galactic centre dominates that from resolved subhalos by a large factor, but relative detectability depends critically on noise sources
- The smallest halos may dominate the cosmic annihilation luminosity density

What would be the properties of the smallest halos?

For WDM

For currently popular models (e.g. sterile neutrinos)

$M_{halo,min} \sim 10^8\ M_\odot$ to $10^9\ M_\odot$

$V_{circ,max} \sim 10$ km s^{-1} to 20 km s^{-1}

$R_{200} \sim 10$ kpc to 20 kpc

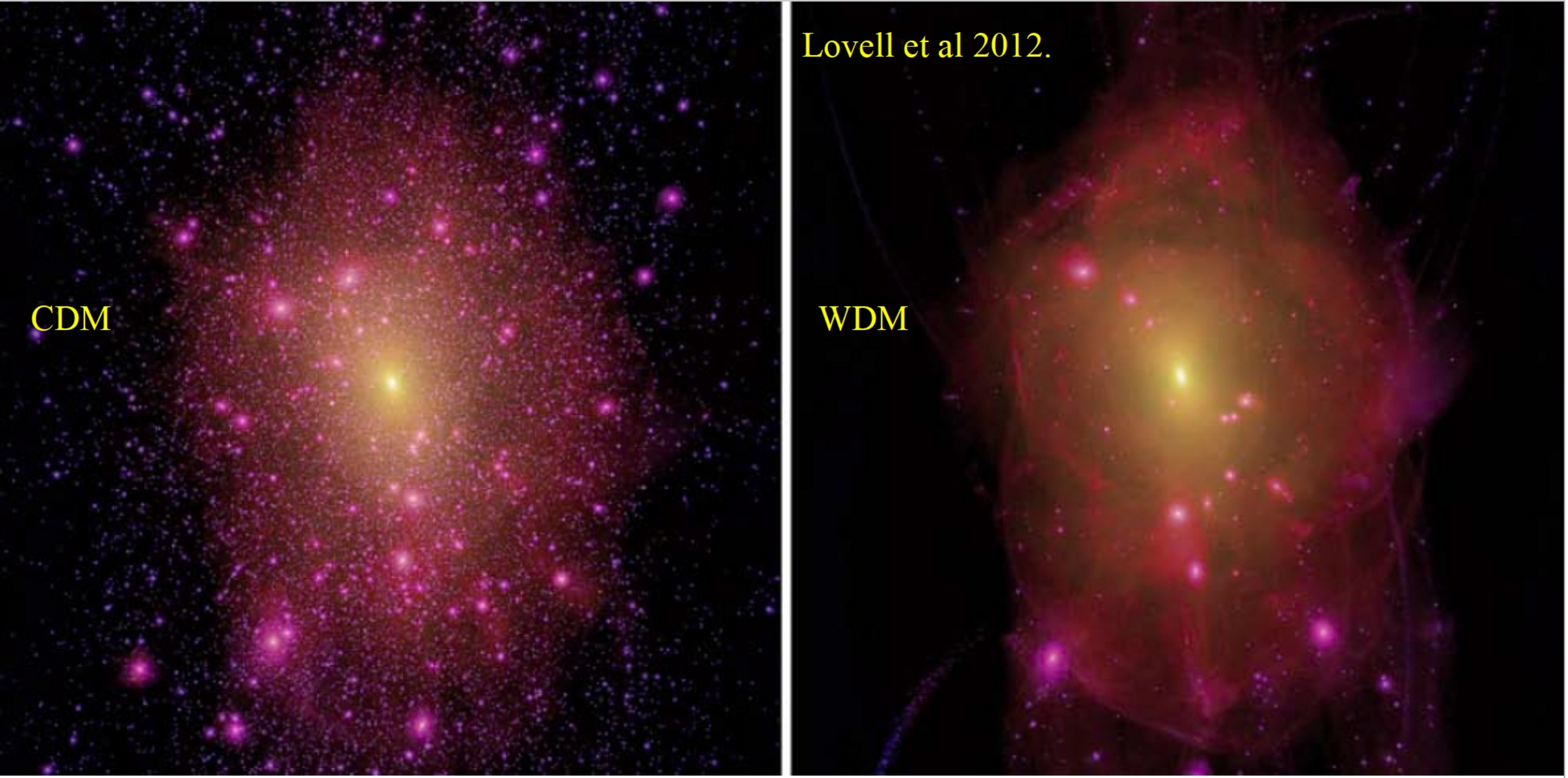
For CDM

For (formerly) popular WIMP models (e.g. the lightest SUSY particle with mass ~100 GeV)

$M_{halo,min} \sim 10^{-6}\ M_\odot \approx 1\ M_\oplus$

$V_{circ,max} \sim 20$ cm s^{-1}

$R_{200} \sim 0.2$ pc



A "Milky Way" halo in CDM and in WDM (a 1.4 keV thermal relic)

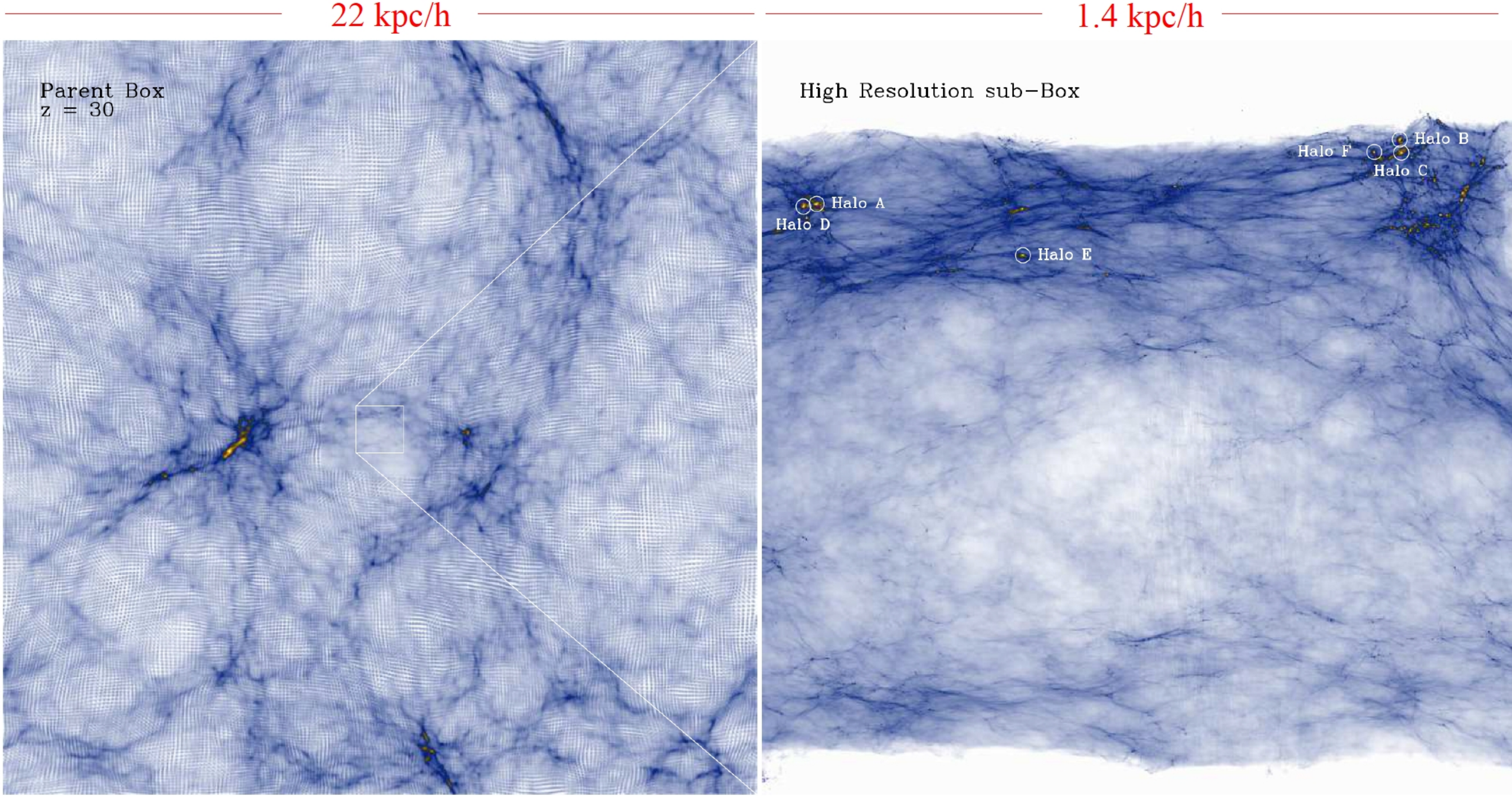
- Current simulation techniques can reach the scales of the smallest WDM halos (though the p.p. model of this illustration is already excluded by observation)

- The smallest WDM halos are still well fit by NFW/Einasto profiles

The formation of low-mass ΛCDM halos

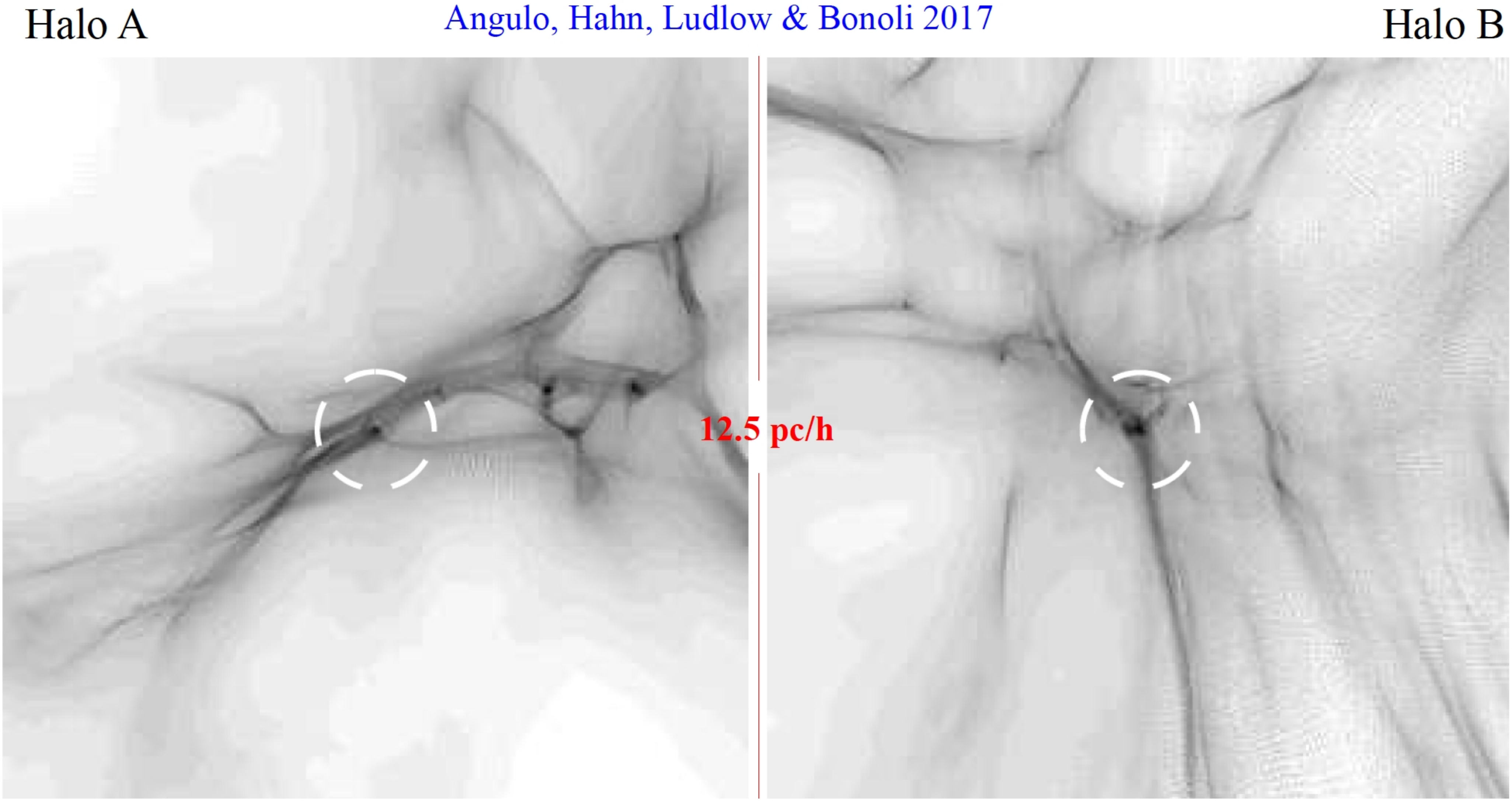
Angulo, Hahn, Ludlow & Bonoli 2017

z = 30



The evolution of low-mass ΛCDM halos

Angulo, Hahn, Ludlow & Bonoli 2017

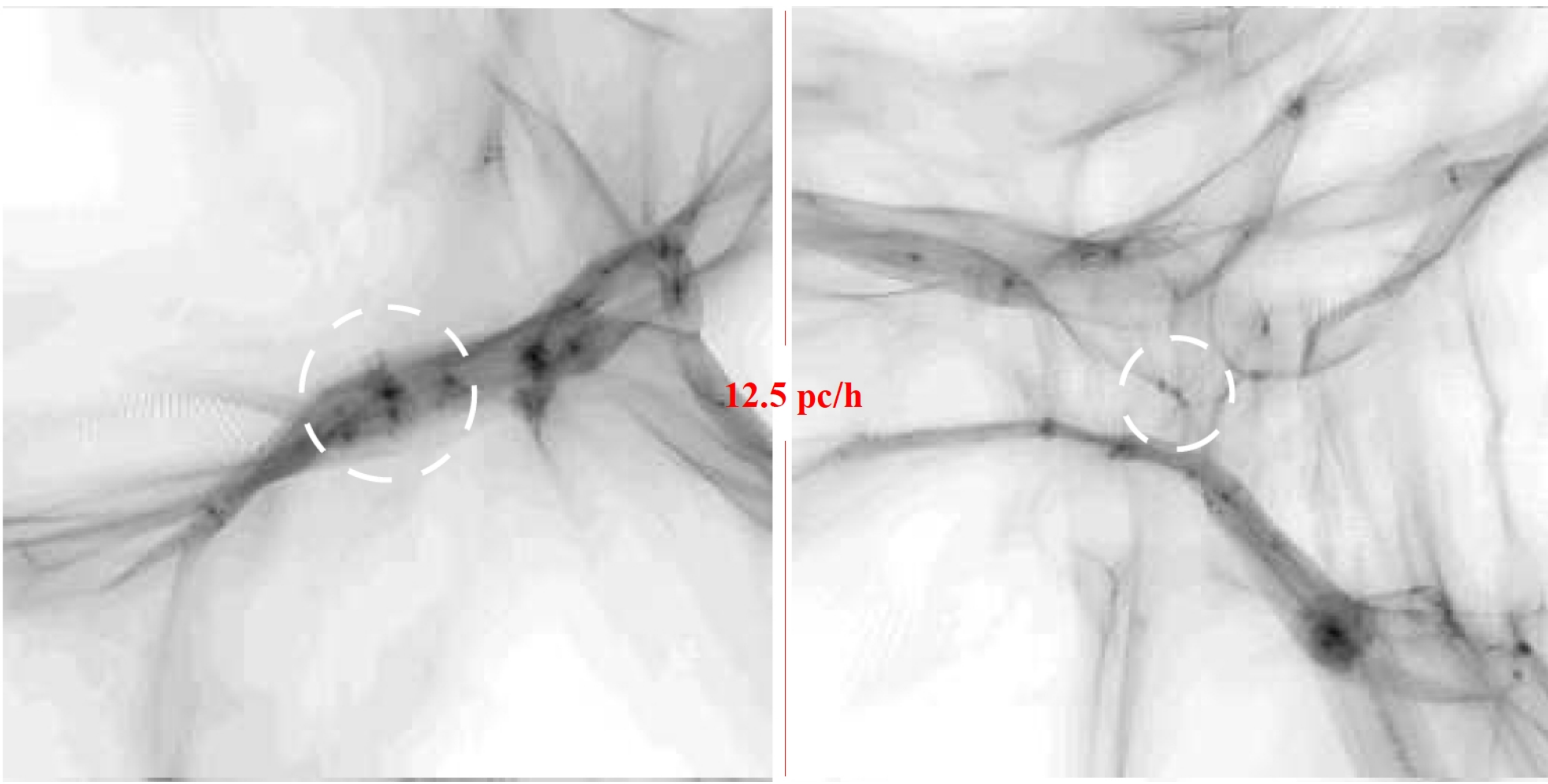


$z = 58$

R_{vir} - - - - -

The evolution of low-mass ΛCDM halos

Angulo, Hahn, Ludlow & Bonoli 2017

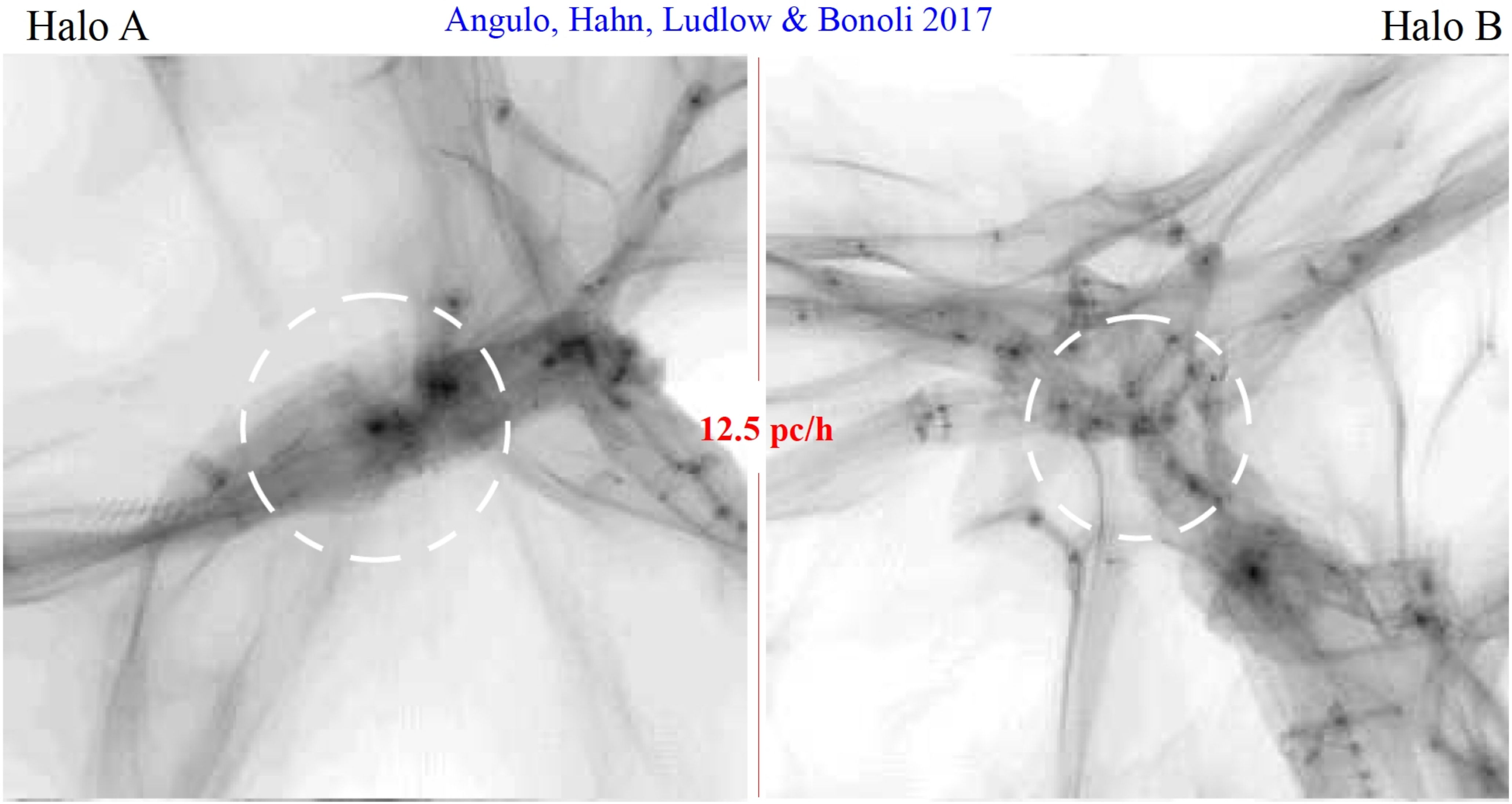


$z = 52$

R_{vir} - - - - -

The evolution of low-mass ΛCDM halos

Angulo, Hahn, Ludlow & Bonoli 2017

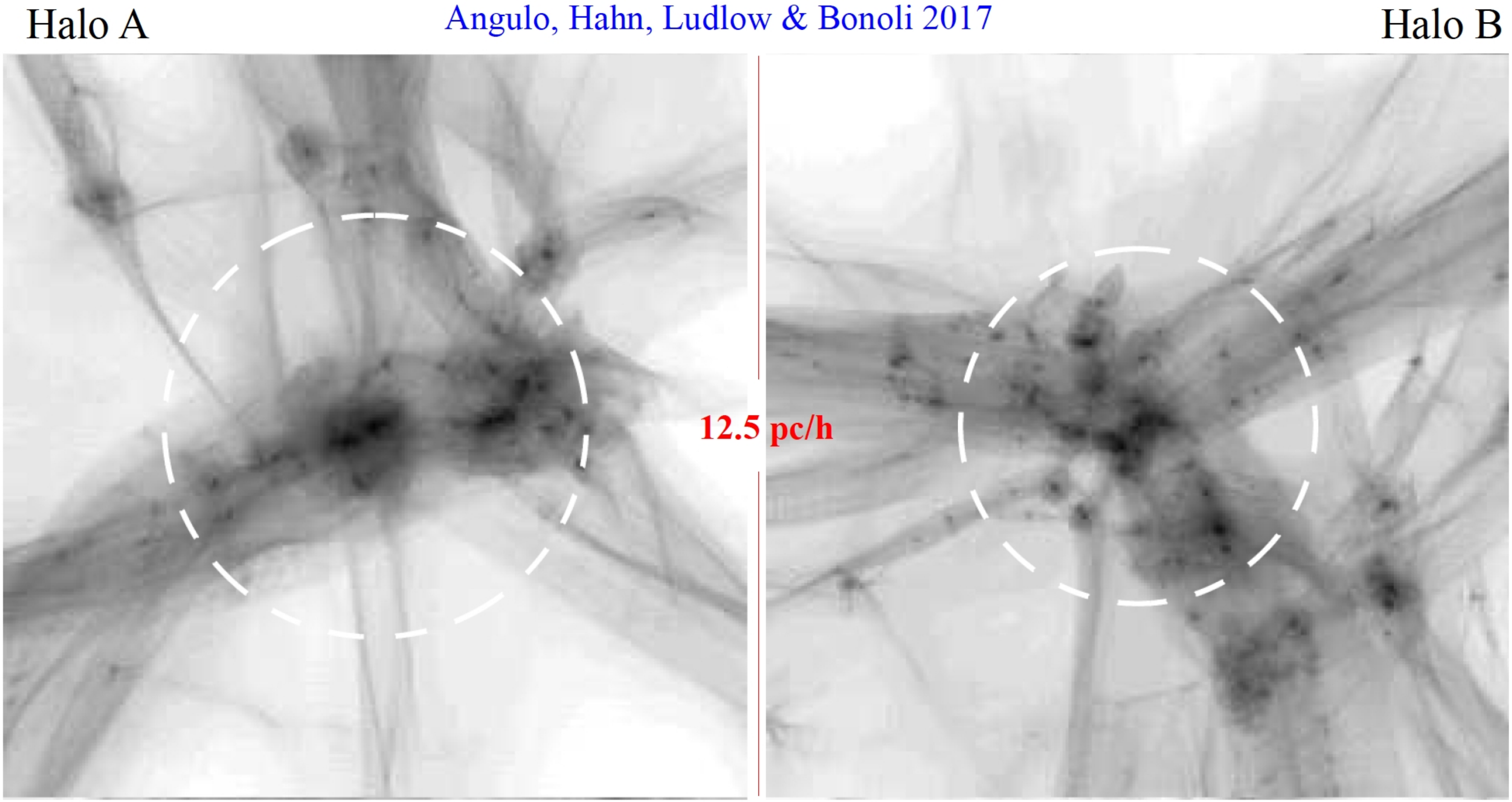


$z = 47$

R_{vir} - - - - -

The evolution of low-mass ΛCDM halos

Angulo, Hahn, Ludlow & Bonoli 2017

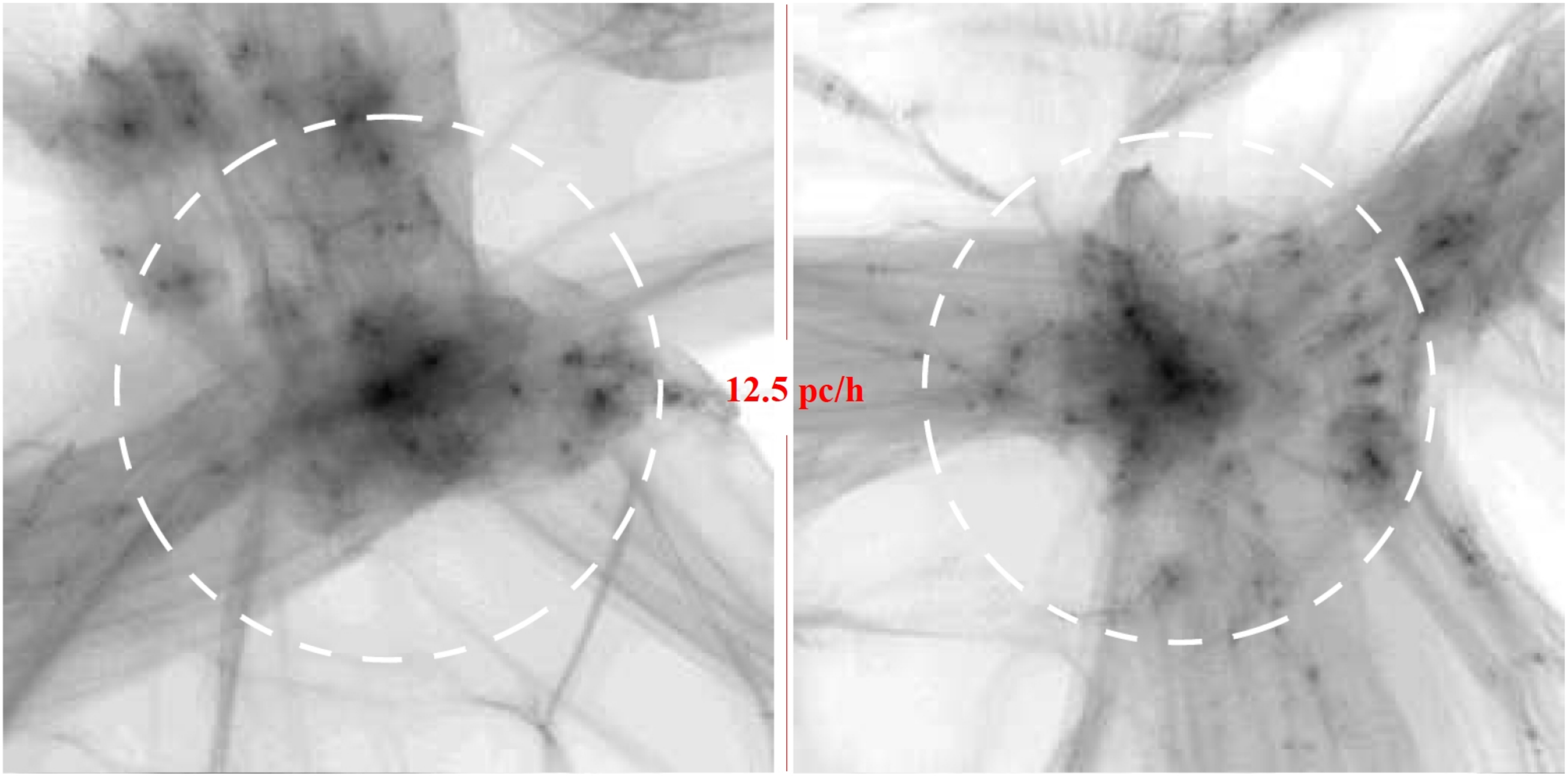


$z = 42$

R_{vir} - - - - -

The evolution of low-mass ΛCDM halos

Angulo, Hahn, Ludlow & Bonoli 2017



z = 39

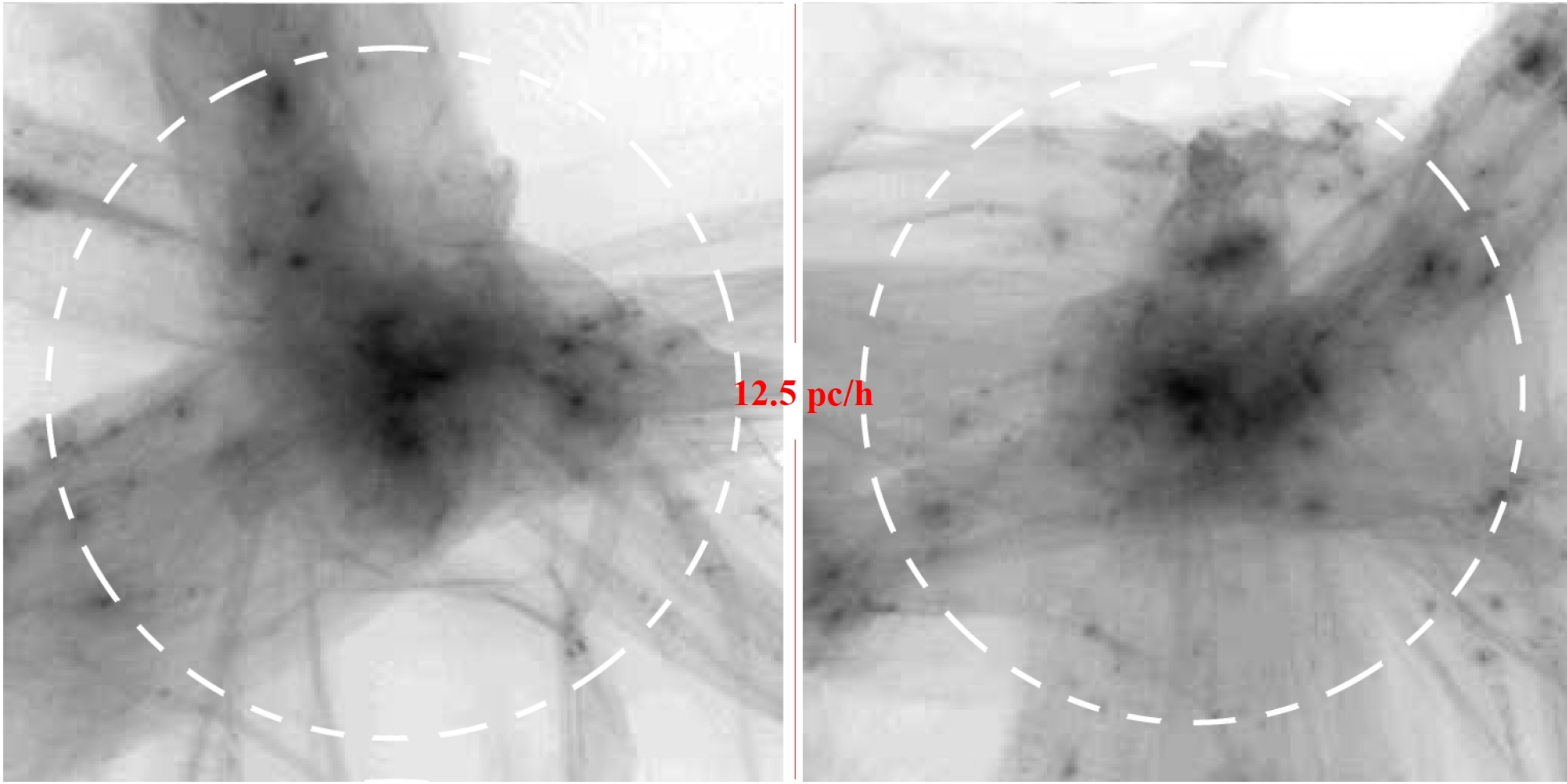
R_{vir} - - - - -

The evolution of low-mass ΛCDM halos

Angulo, Hahn, Ludlow & Bonoli 2017

Halo A

Halo B



$z = 36$

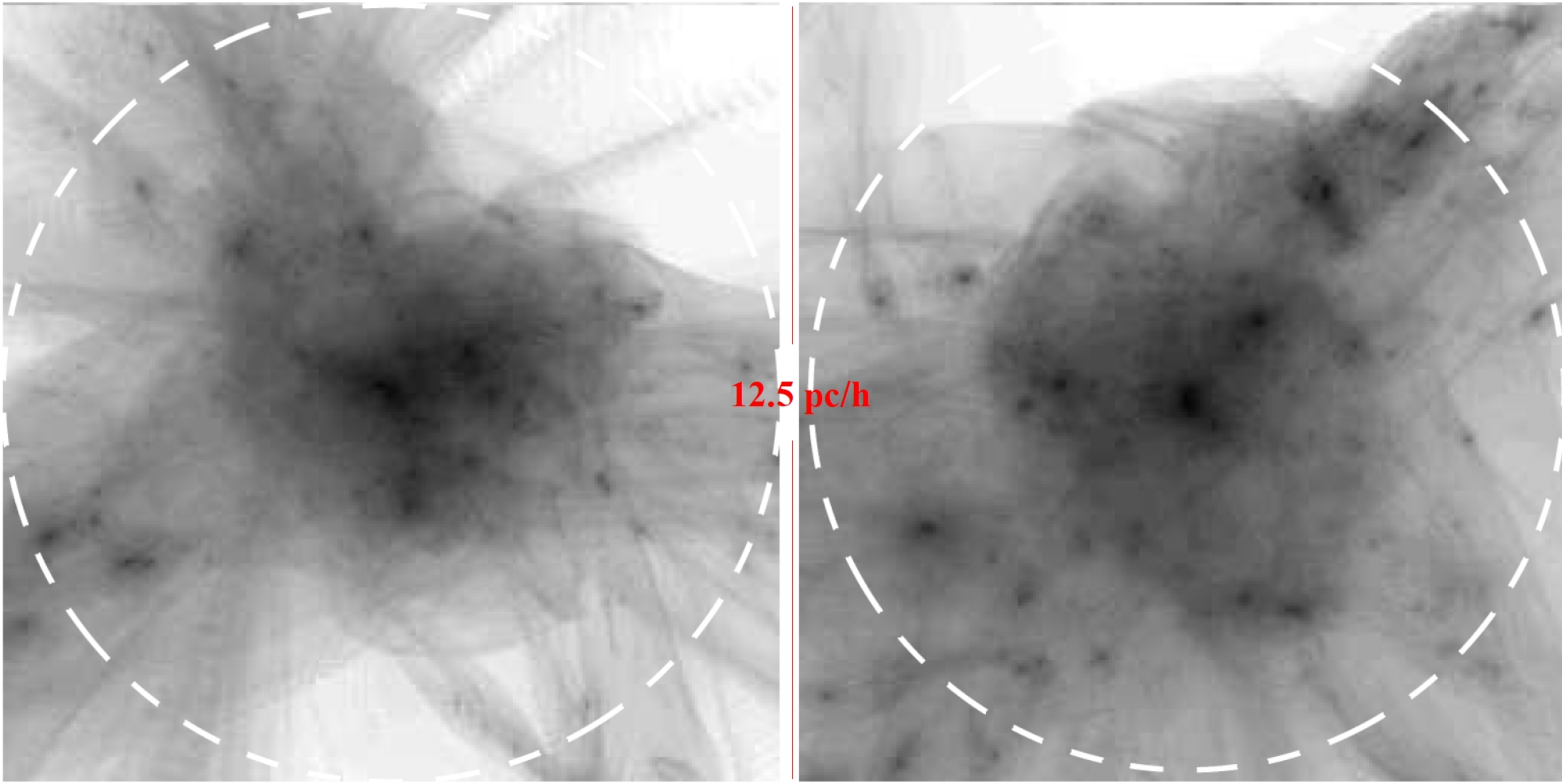
R_{vir} - - - - -

The evolution of low-mass ΛCDM halos

Halo A

Angulo, Hahn, Ludlow & Bonoli 2017

Halo B

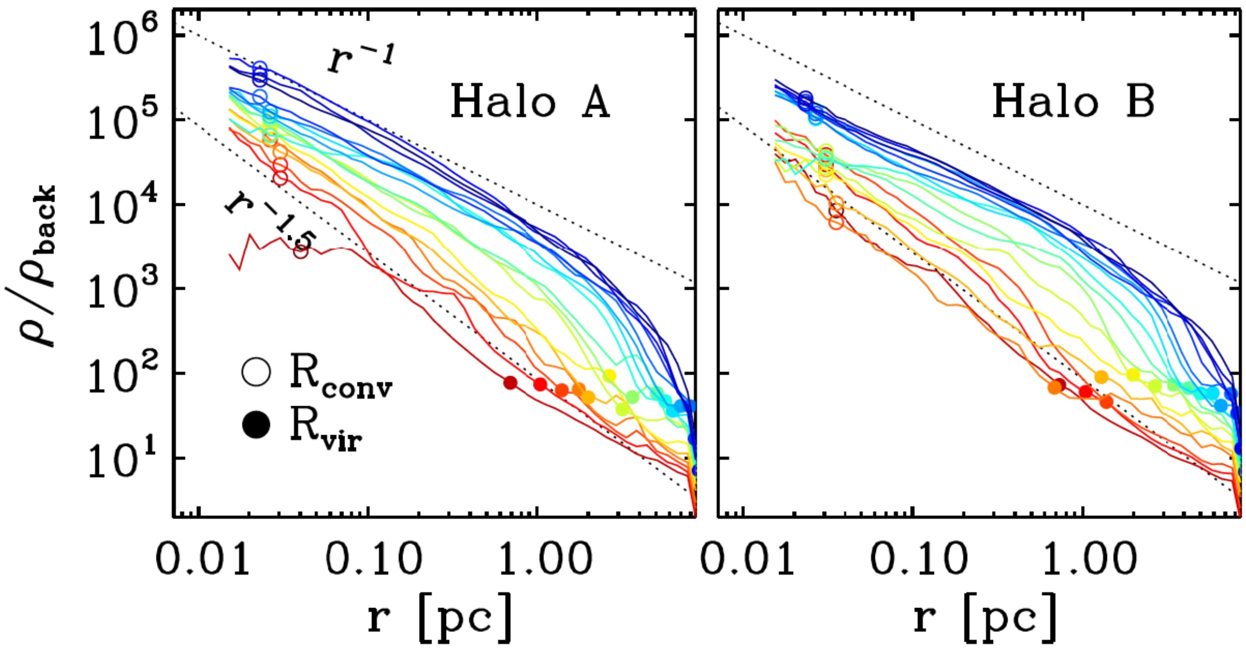


z = 33

R_{vir} - - - - -

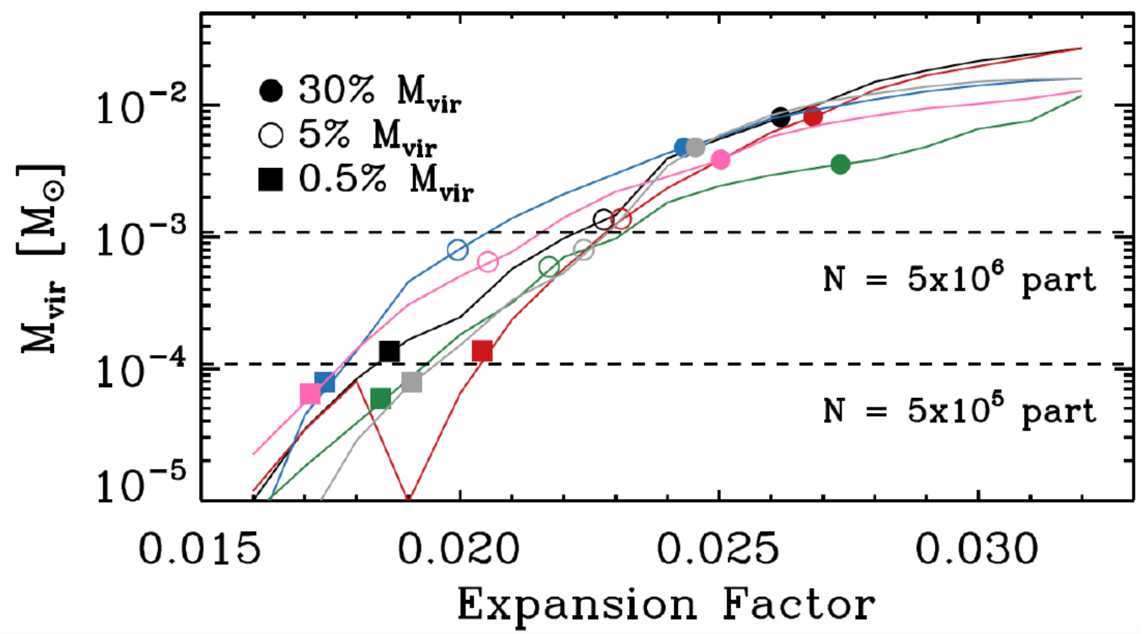
The evolution of low-mass ΛCDM halos

Angulo, Hahn, Ludlow & Bonoli 2017



Density profiles at formation are irregular but, in the mean, are power-laws with $\gamma = -1.5$

They later evolve to be NFW-like

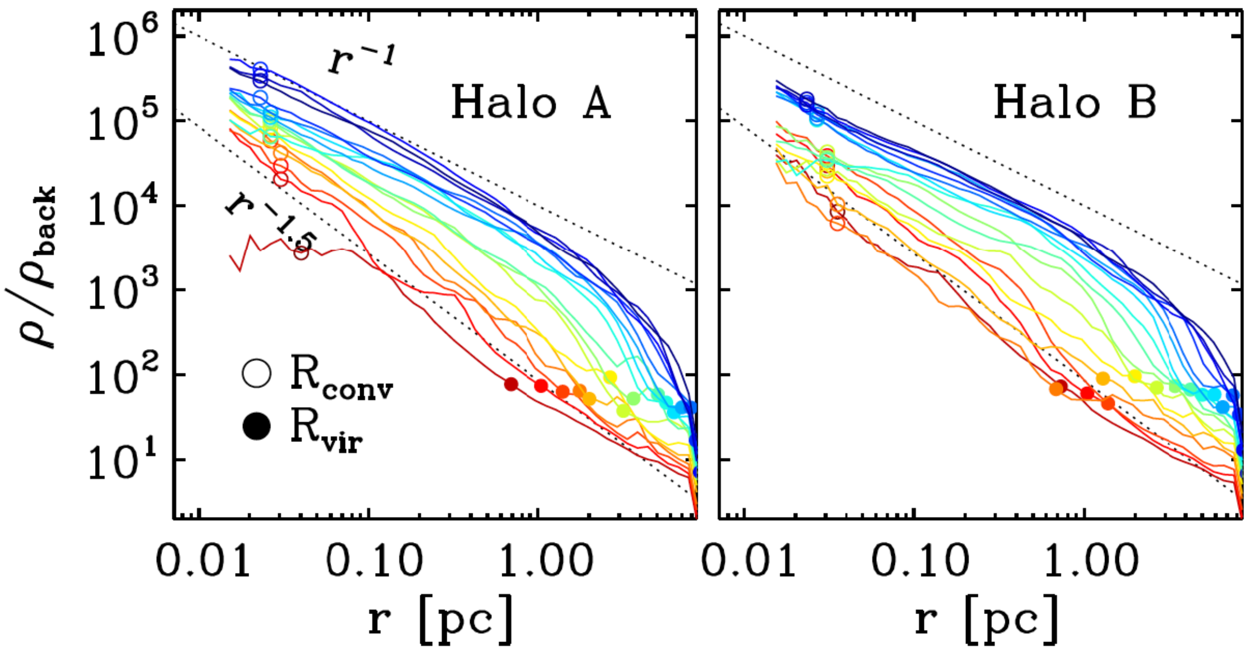


Halo growth is extremely fast – a factor of ~ 1000 in mass between z = 60 and z = 30

The simulation has to stop at z ~ 30 because the whole simulated region goes nonlinear

The evolution of low-mass ΛCDM halos

Angulo, Hahn, Ludlow & Bonoli 2017



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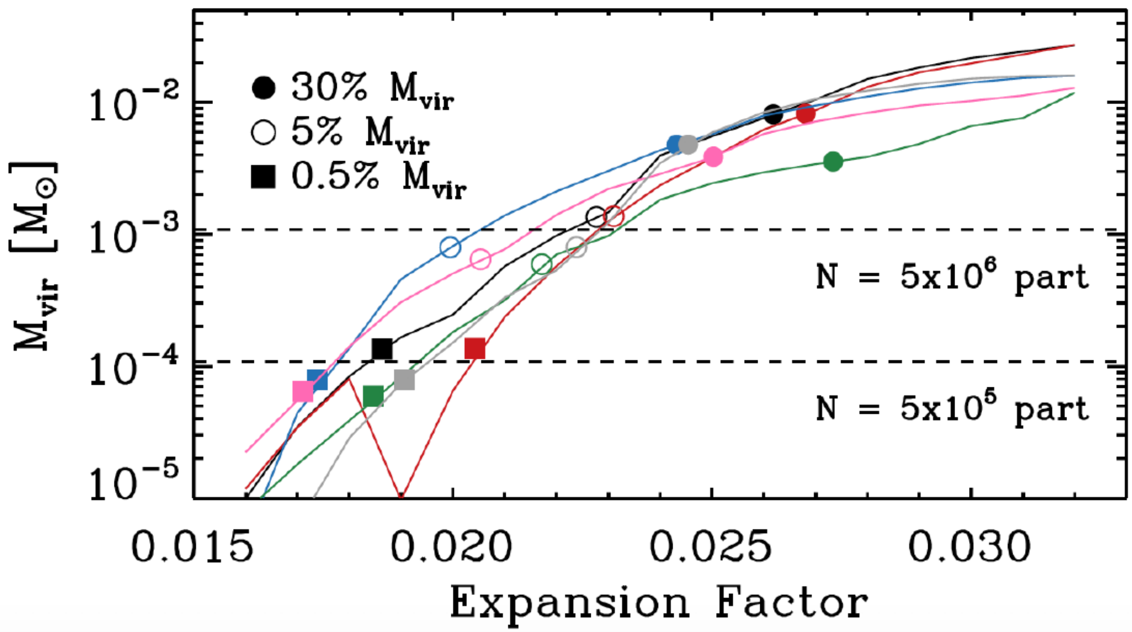

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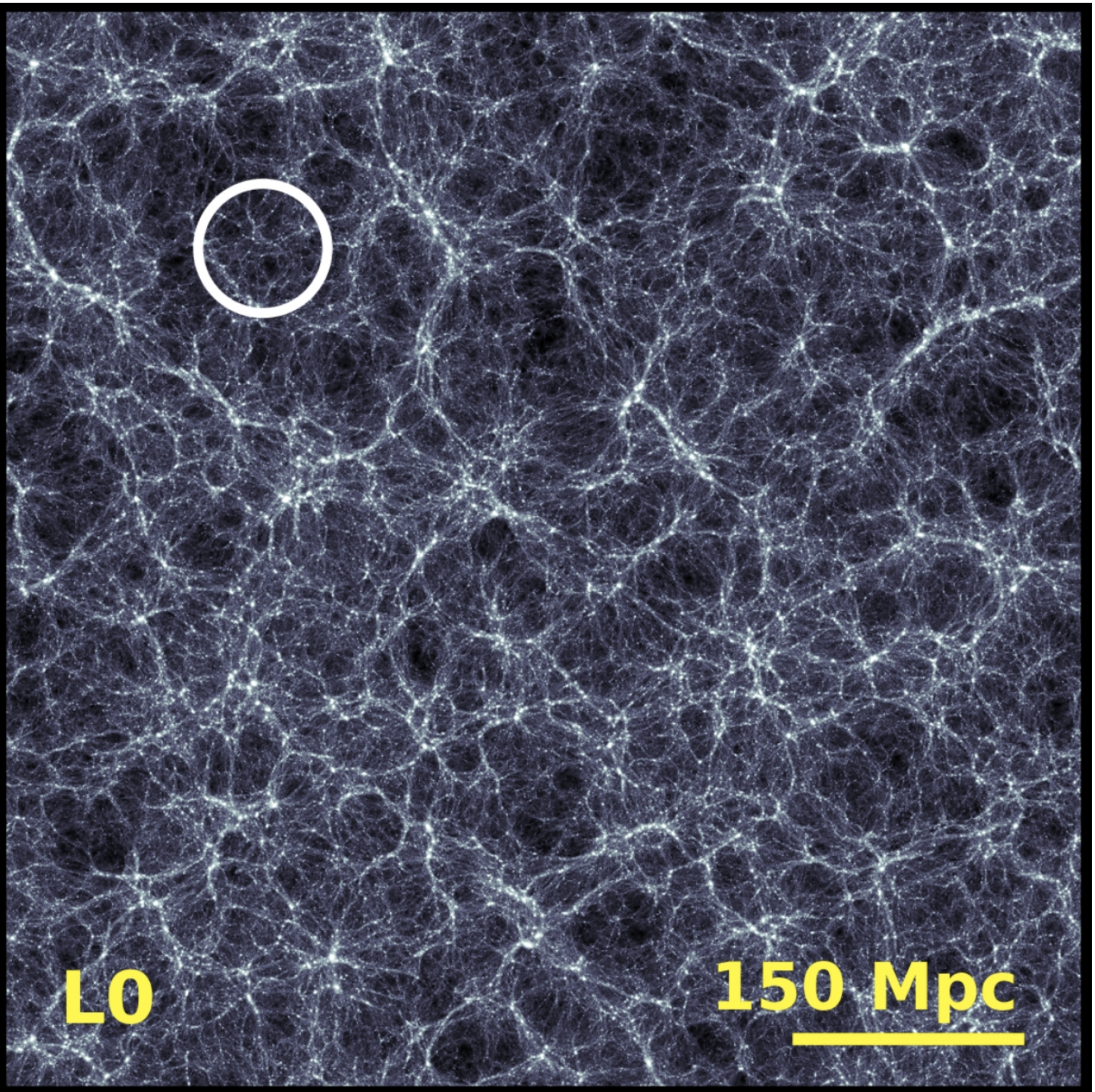
What about low-mass halos at z = 0?

The VVV simulation



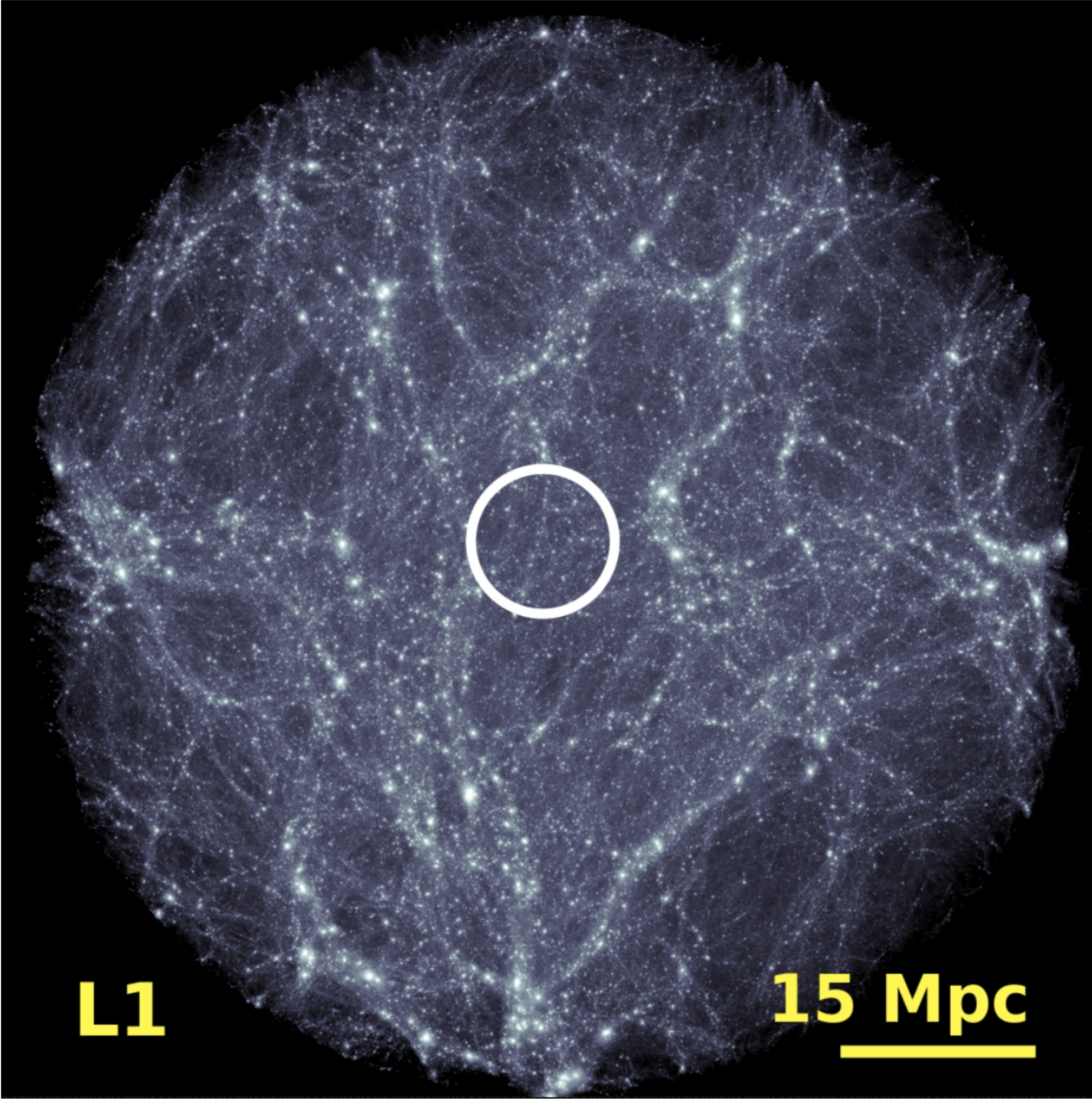
Planck cosmology

Dark matter only

Dynamic range of 30 orders of magnitude in mass

Base Level

Wang, Bose et al 2020



The VVV simulation

Planck cosmology

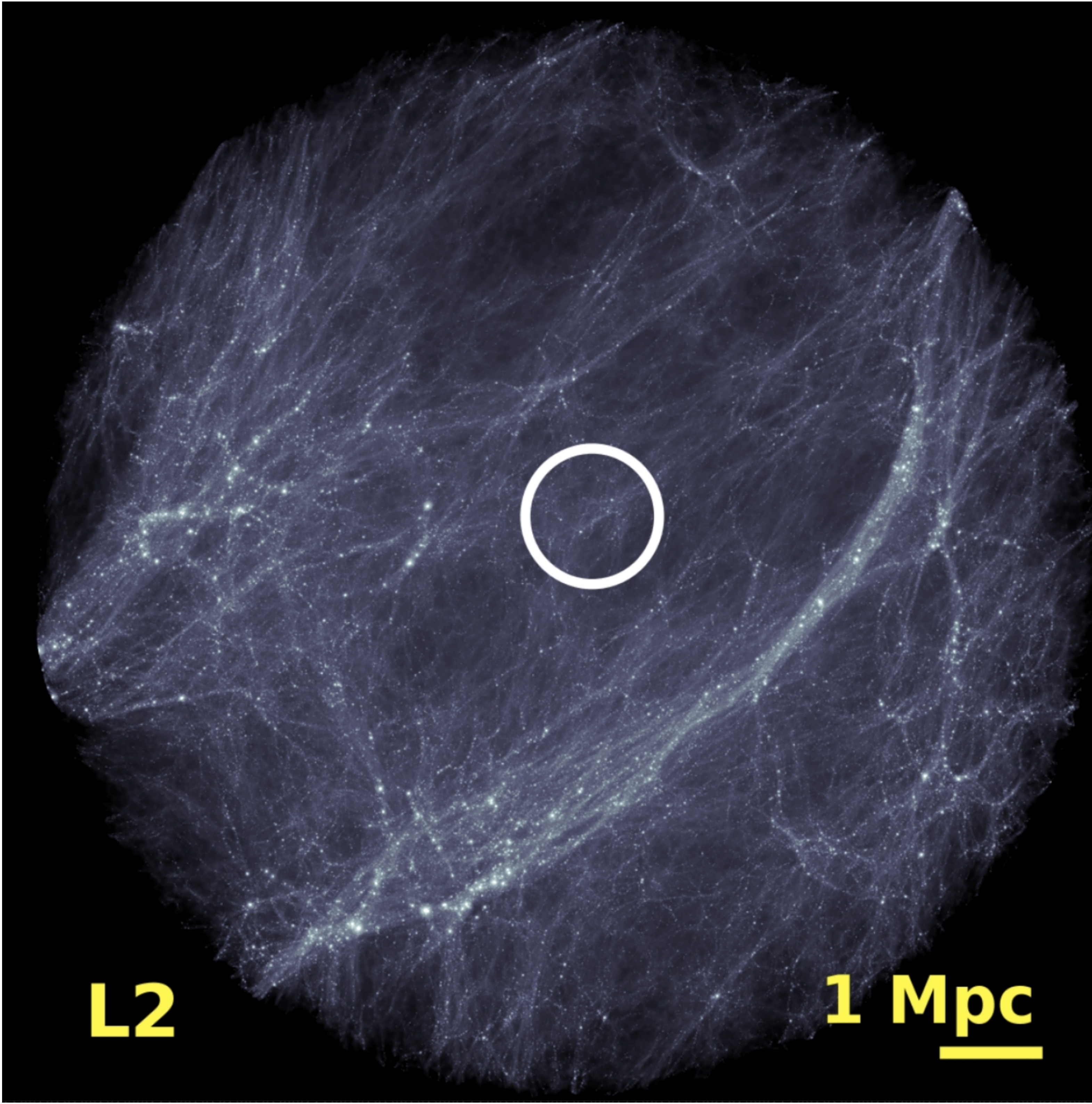
Dark matter only

Dynamic range of 30 orders of magnitude in mass

Zoom Level 1

Wang, Bose et al 2020

The VVV simulation



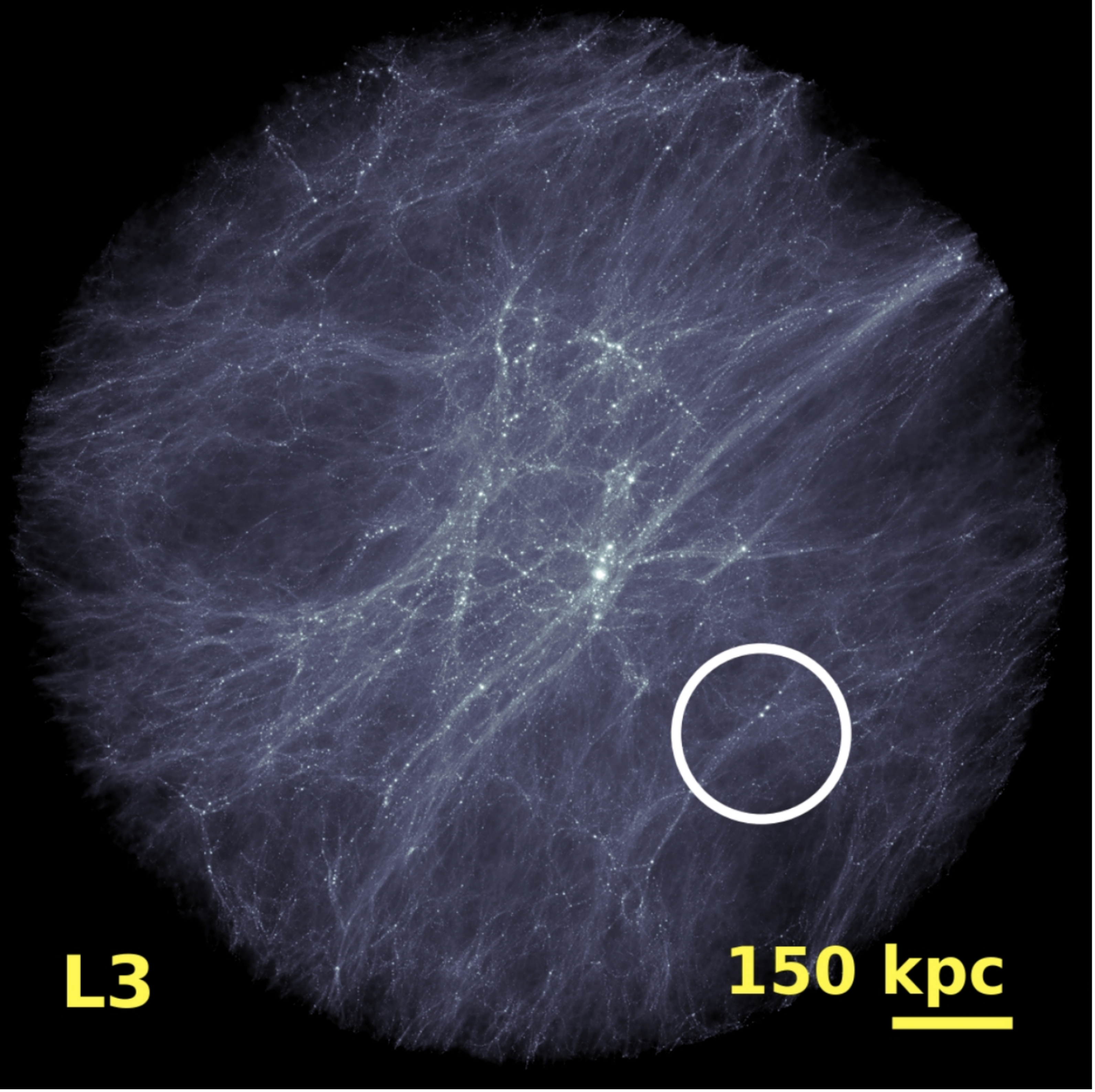
Planck cosmology

Dark matter only

Dynamic range of 30 orders of magnitude in mass

Zoom Level 2

Wang, Bose et al 2020



The VVV simulation

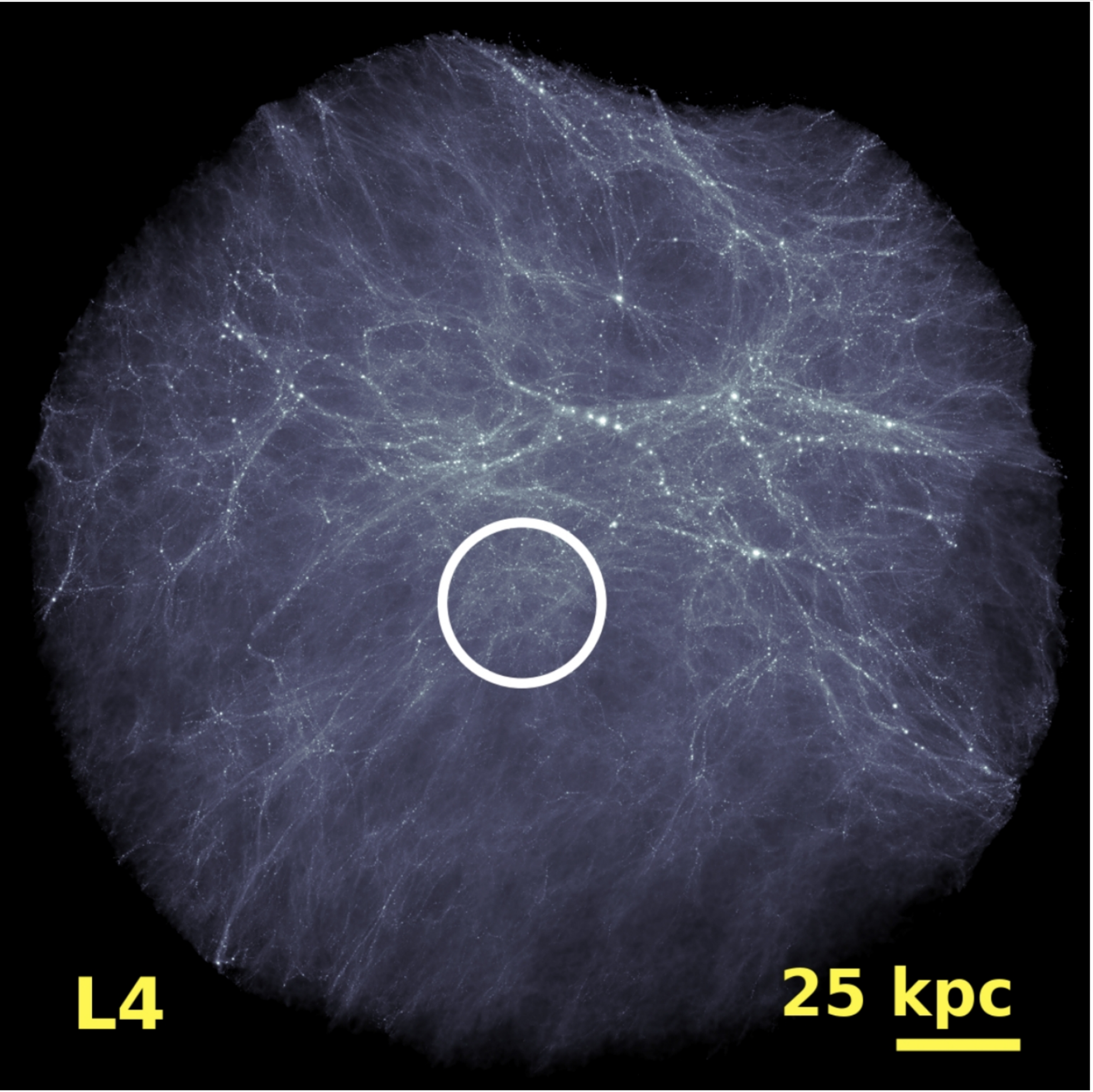
Planck cosmology

Dark matter only

Dynamic range of 30 orders of magnitude in mass

Zoom Level 3

Wang, Bose et al 2020



The VVV simulation

Planck cosmology

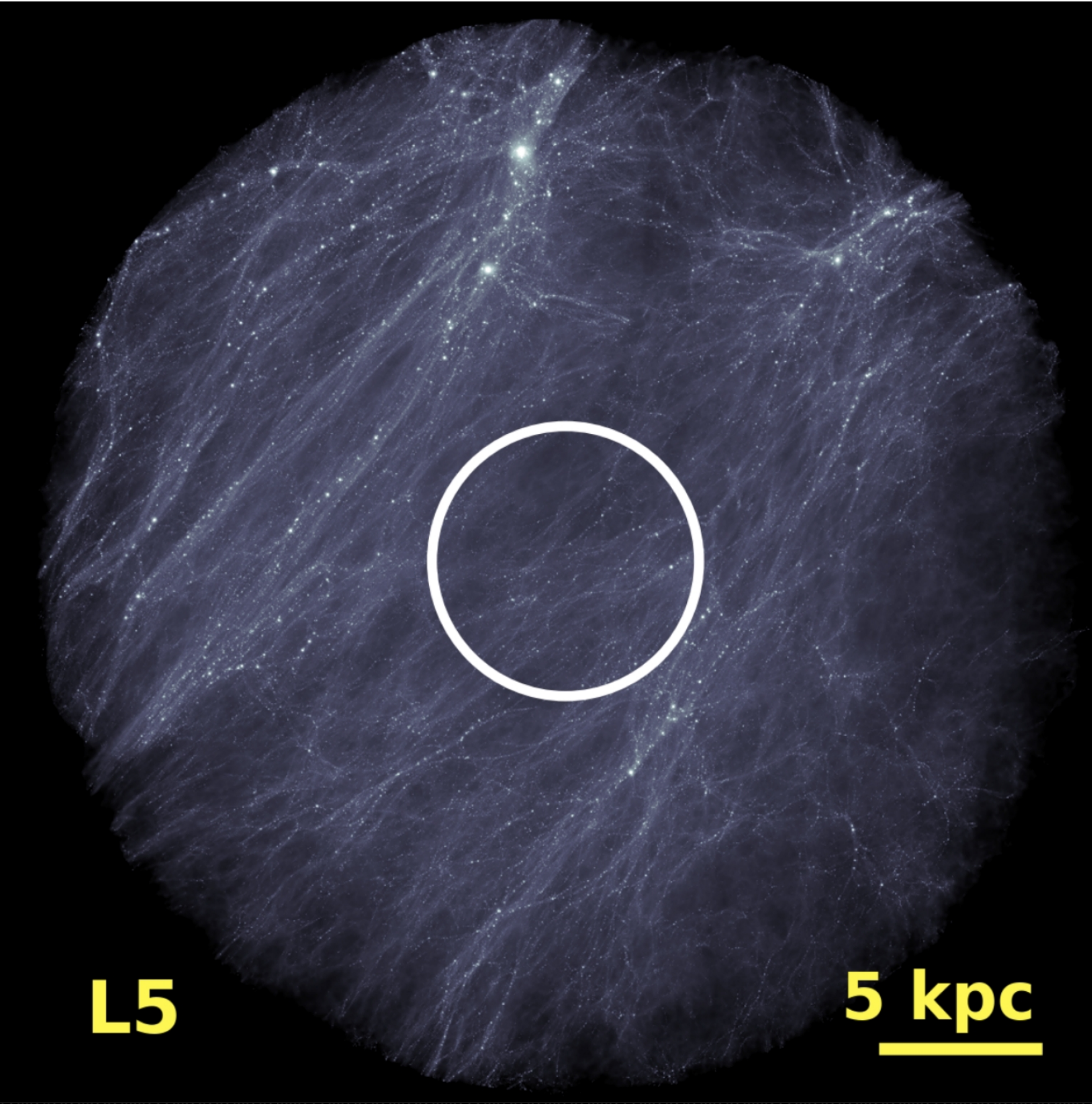
Dark matter only

Dynamic range of 30 orders of magnitude in mass

Zoom Level 4

Wang, Bose et al 2020

The VVV simulation



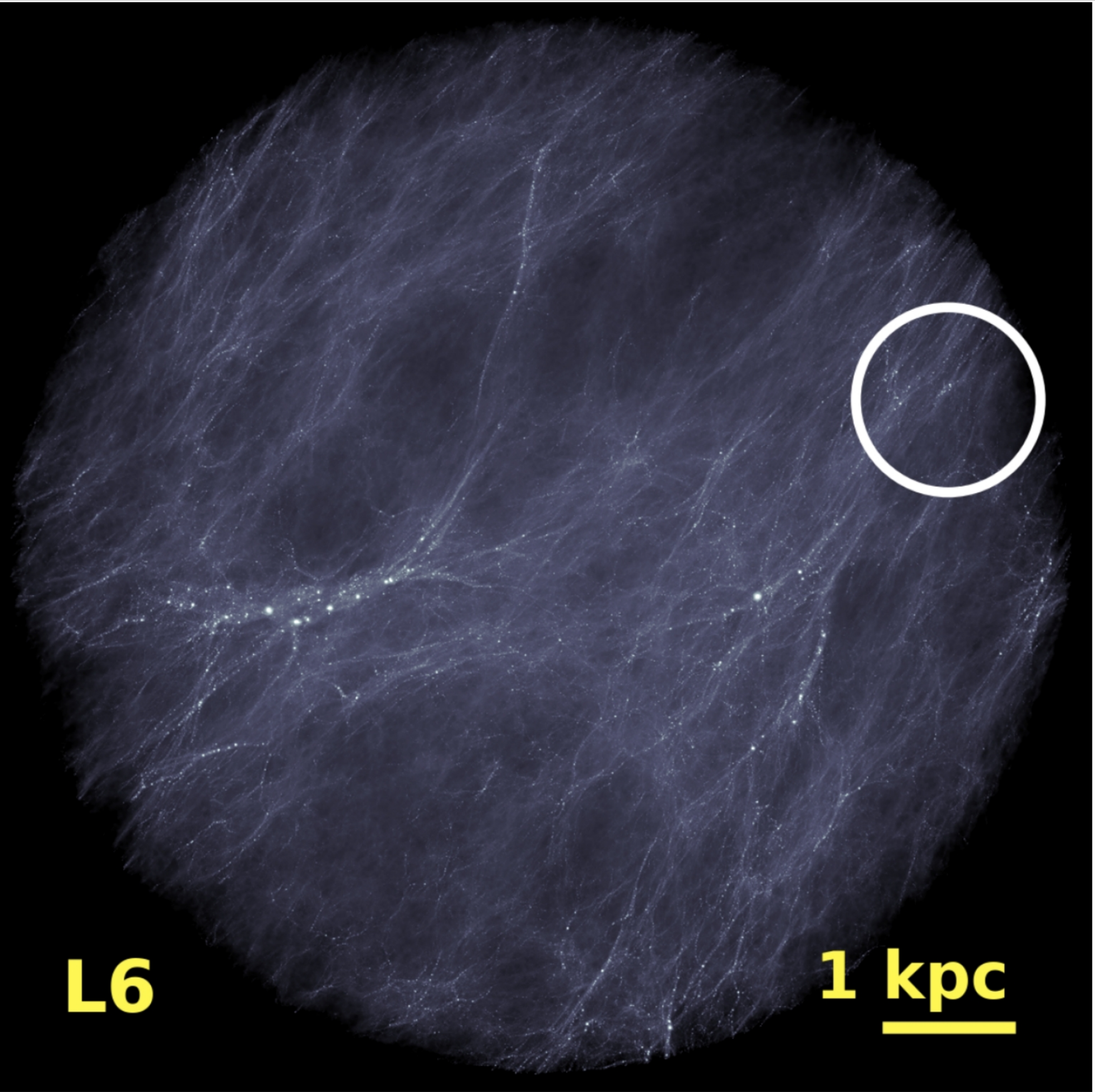
Planck cosmology

Dark matter only

Dynamic range of 30 orders of magnitude in mass

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

Zoom Level 6

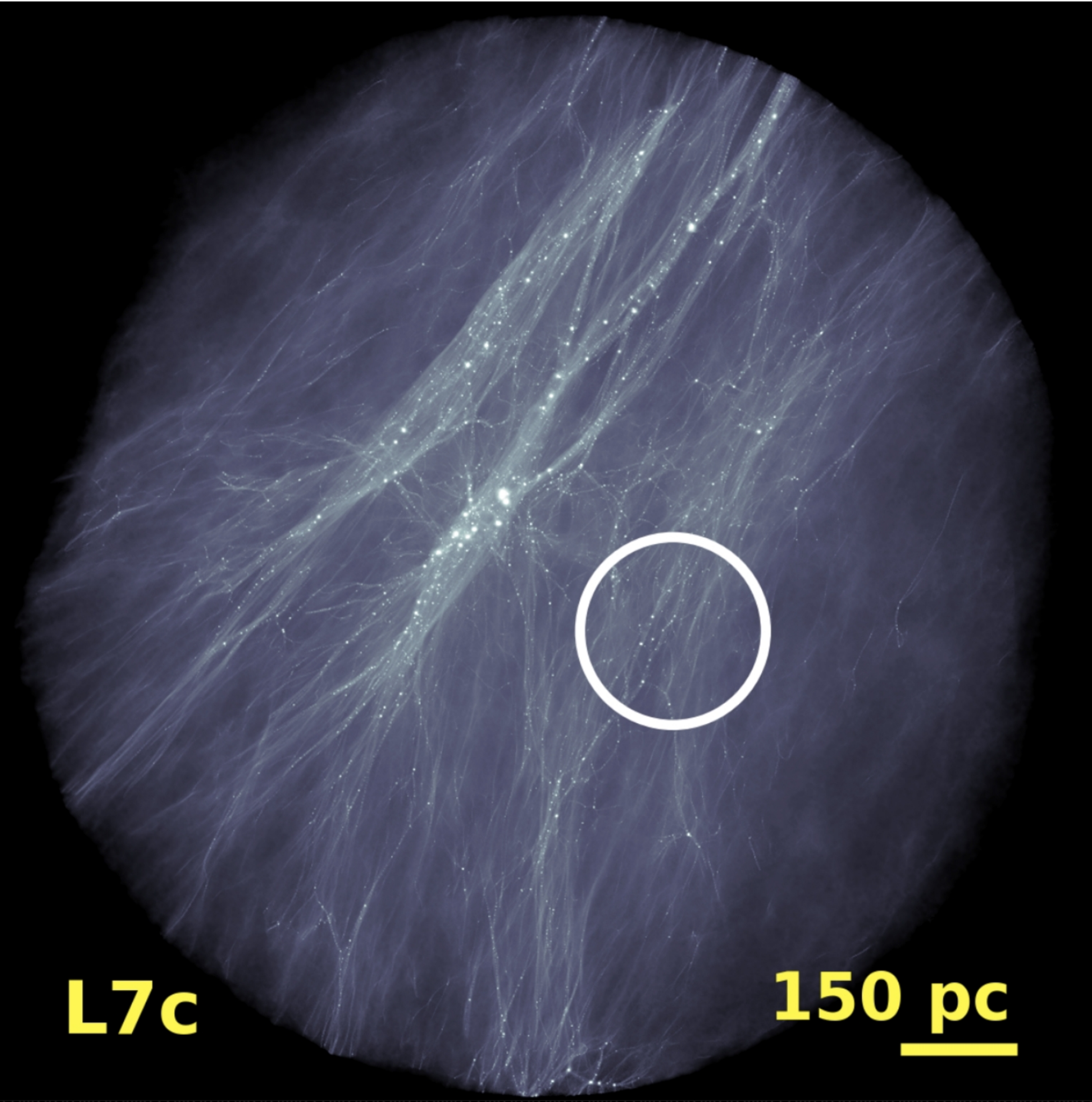
Wang, Bose et al 2020

The VVV simulation

Planck cosmology

Dark matter only

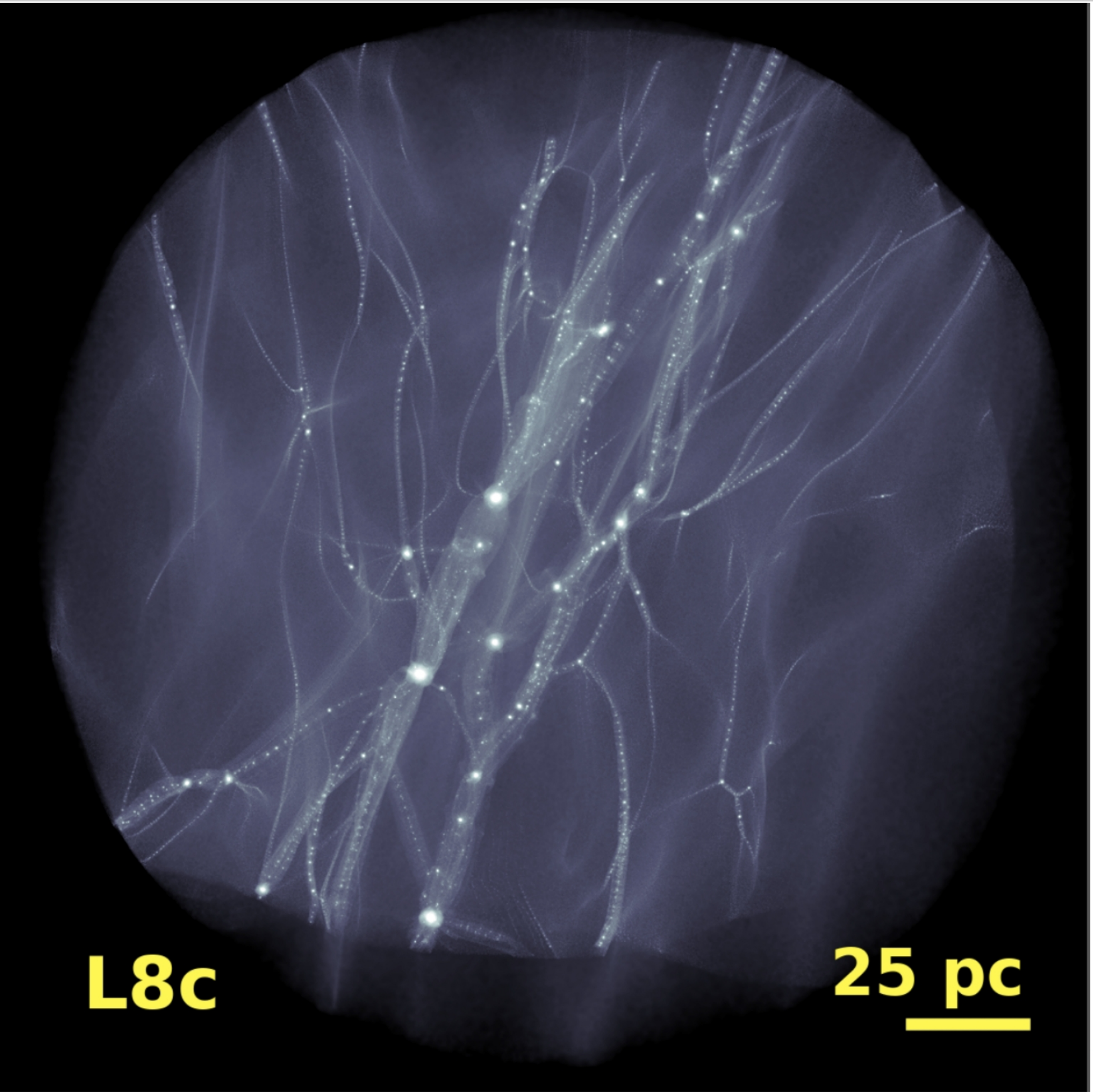
Dynamic range of 30 orders of magnitude in mass



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

Zoom Level 8

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

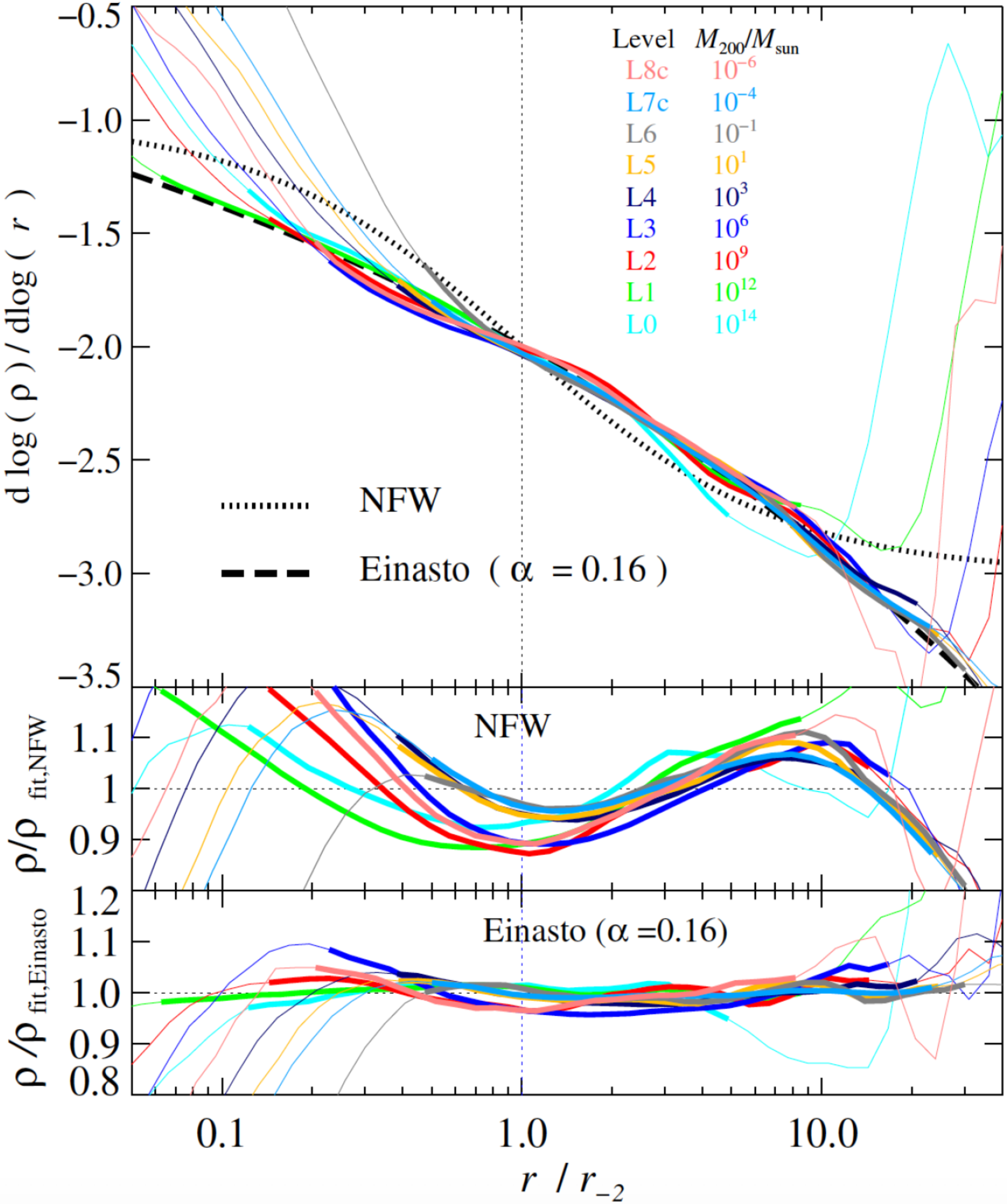
Wang, Bose et al 2020

The various levels of the VVV* simulation

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

level	$R_{\rm high}$ [Mpc]	$n_{\rm p}$	ε [kpc]	$m_{\rm p}$ [$M_\odot$]	$\sigma(M_{\rm tot}, z=0)$	$\langle\rho\rangle/\rho_{\rm mean}$	$M_{\rm char}$ [$M_\odot$]	$N_{\rm char}$	$z_{\rm form}$	$f_{\rm vir}$
L0	738	1.0×10^{10}	7.4	1.5×10^{9}		1.0	10^{14}	127	0.94	0.92
L1	52	1.0×10^{10}	4.4×10^{-1}	7.4×10^{5}	0.34	0.39	10^{12}	59	1.66	0.91
L2	8.8	5.4×10^{9}	5.6×10^{-2}	1.5×10^{3}	1.66	0.082	10^{9}	29	1.91	0.93
L3	1.0	1.8×10^{9}	8.3×10^{-3}	2.8	4.22	0.036	10^{6}	27	2.61	0.94
L4	0.27	2.0×10^{9}	1.0×10^{-3}	5.5×10^{-3}	6.96	0.026	10^{3}	59	4.44	0.94
L5	0.035	1.5×10^{9}	2.2×10^{-4}	5.8×10^{-5}	9.36	0.024	10	30	4.68	0.94
L6	0.0066	1.7×10^{9}	3.8×10^{-5}	2.6×10^{-7}	12.12	0.014	10^{-1}	35	4.84	0.94
L7	0.0011	2.5×10^{9}	5.3×10^{-6}	8.6×10^{-10}	15.06	0.016	10^{-4}	201	5.21	0.96
L7c	0.0011	2.5×10^{9}	5.3×10^{-6}	8.6×10^{-10}	15.06	0.016	10^{-4}	202	4.83	0.97
L8c	0.00024	1.5×10^{9}	1.4×10^{-6}	1.6×10^{-11}	17.60	0.028	10^{-6}	24	1.96	0.94

* VVV = "voids-in-voids-in-voids"

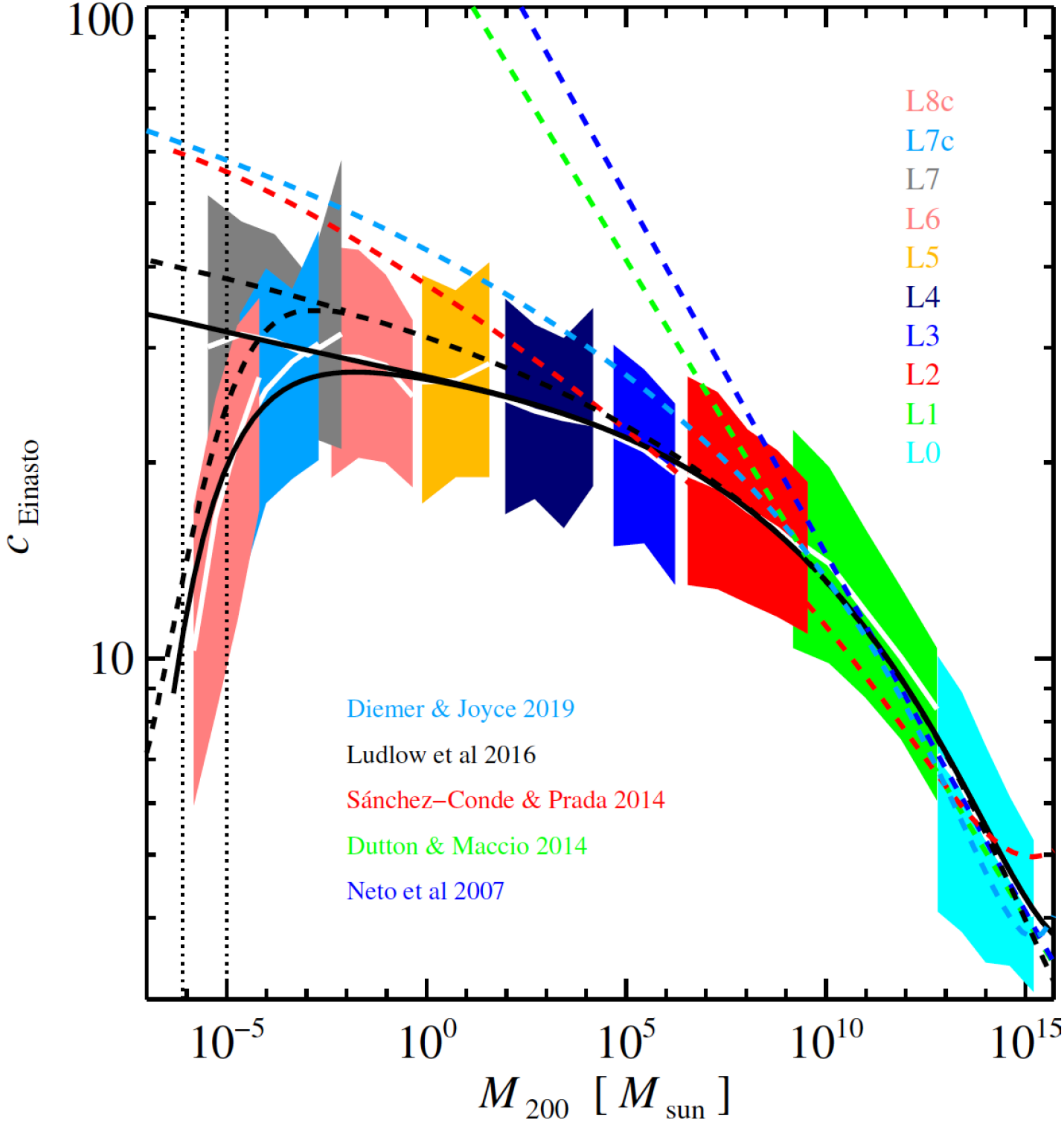


Density profile shapes

Over 19 orders of magnitude in halo mass and 4 orders of magnitude in density, the mean density profiles of halos are fit by NFW to within 20% and by Einasto (with α = 0.16) to within 7%

Wang, Bose et al 2020

Concentration-mass relation

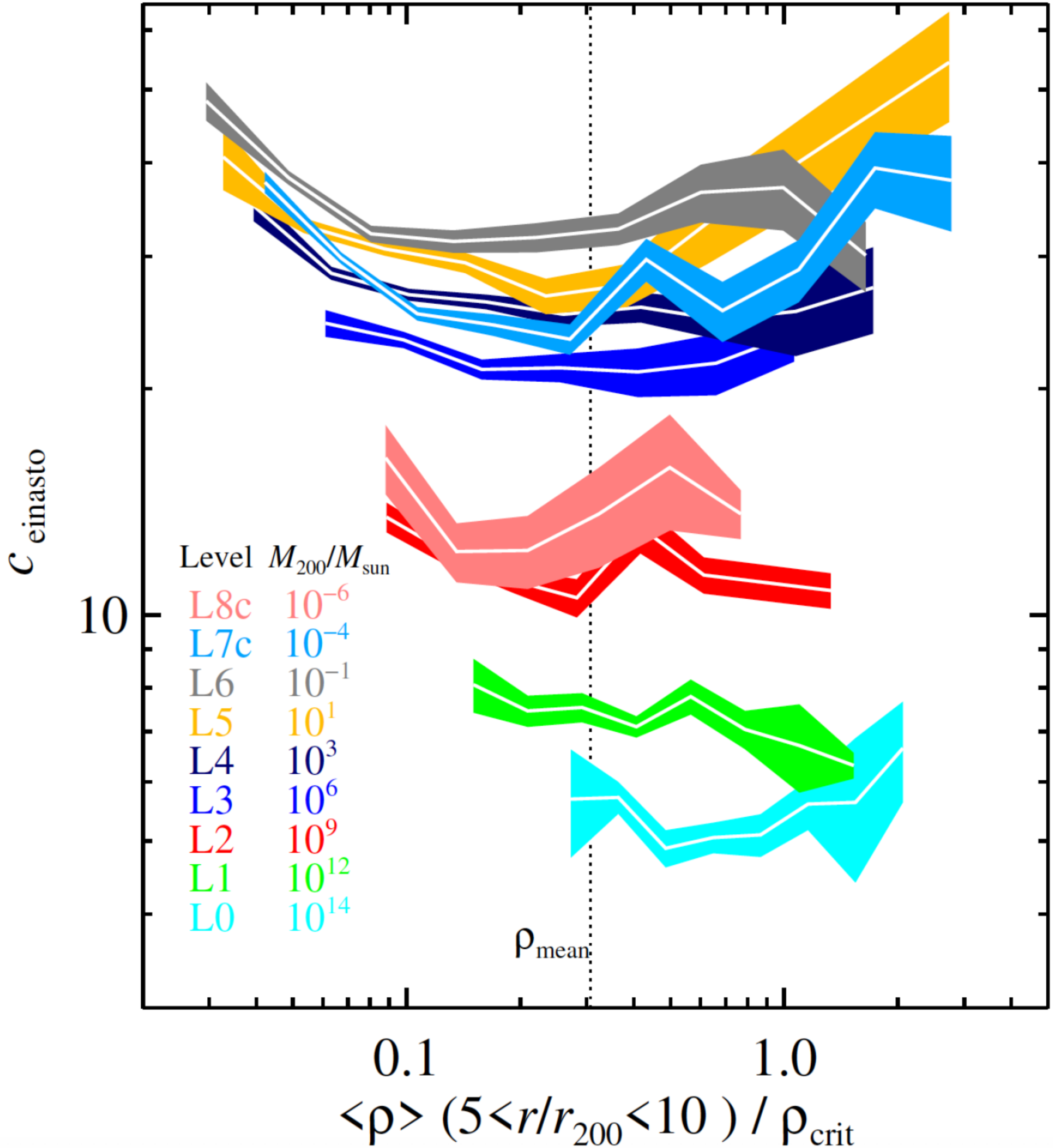


Concentrations at small mass are lower than all previous extrapolations by up to factors of tens

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

The scatter depends only weakly on halo mass.

Wang, Bose et al 2020



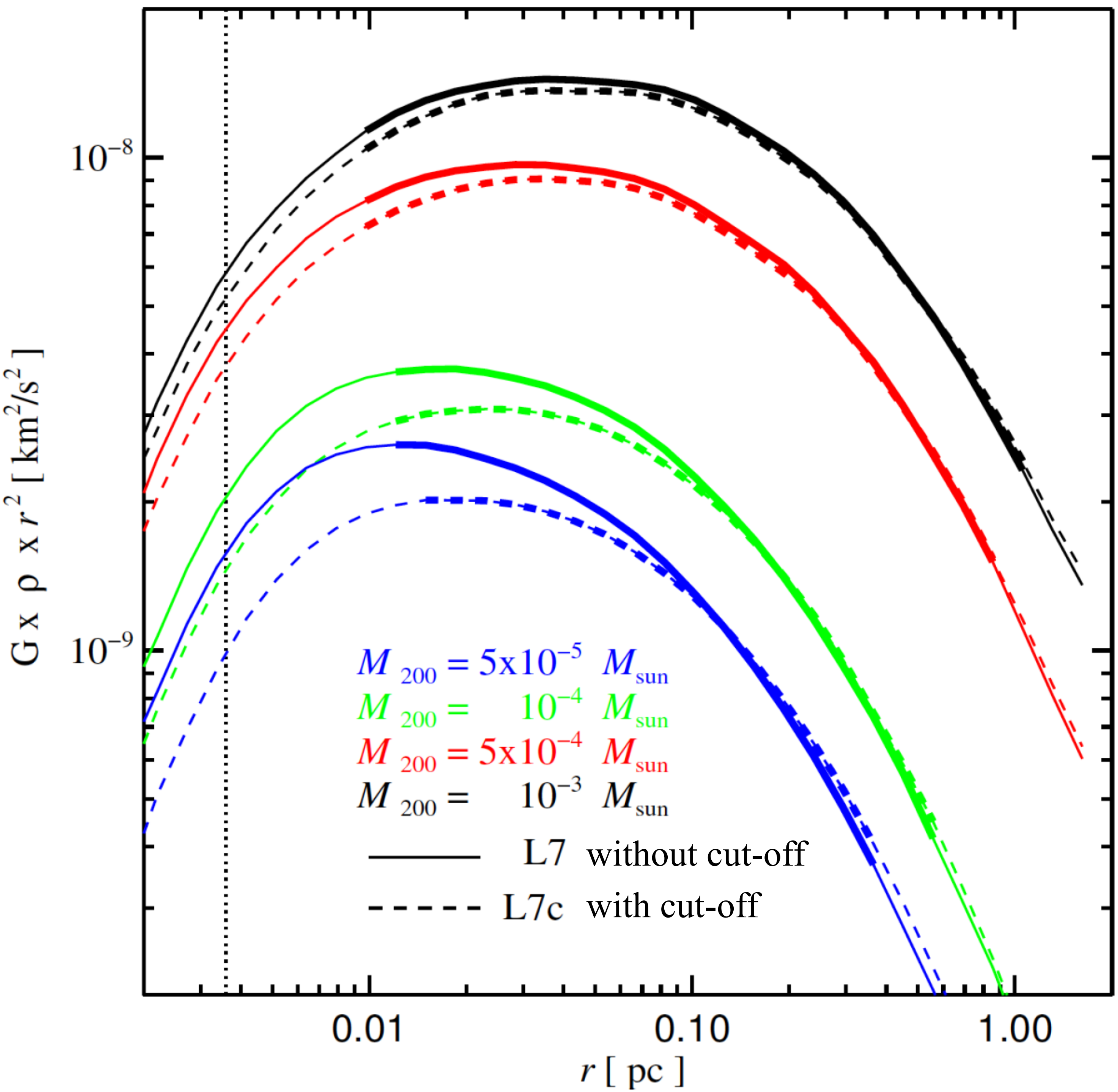
Concentration-density relation

At given halo mass, concentration does not depend on *local* environment density.

The *range* of local environment density does not depend strongly on halo mass

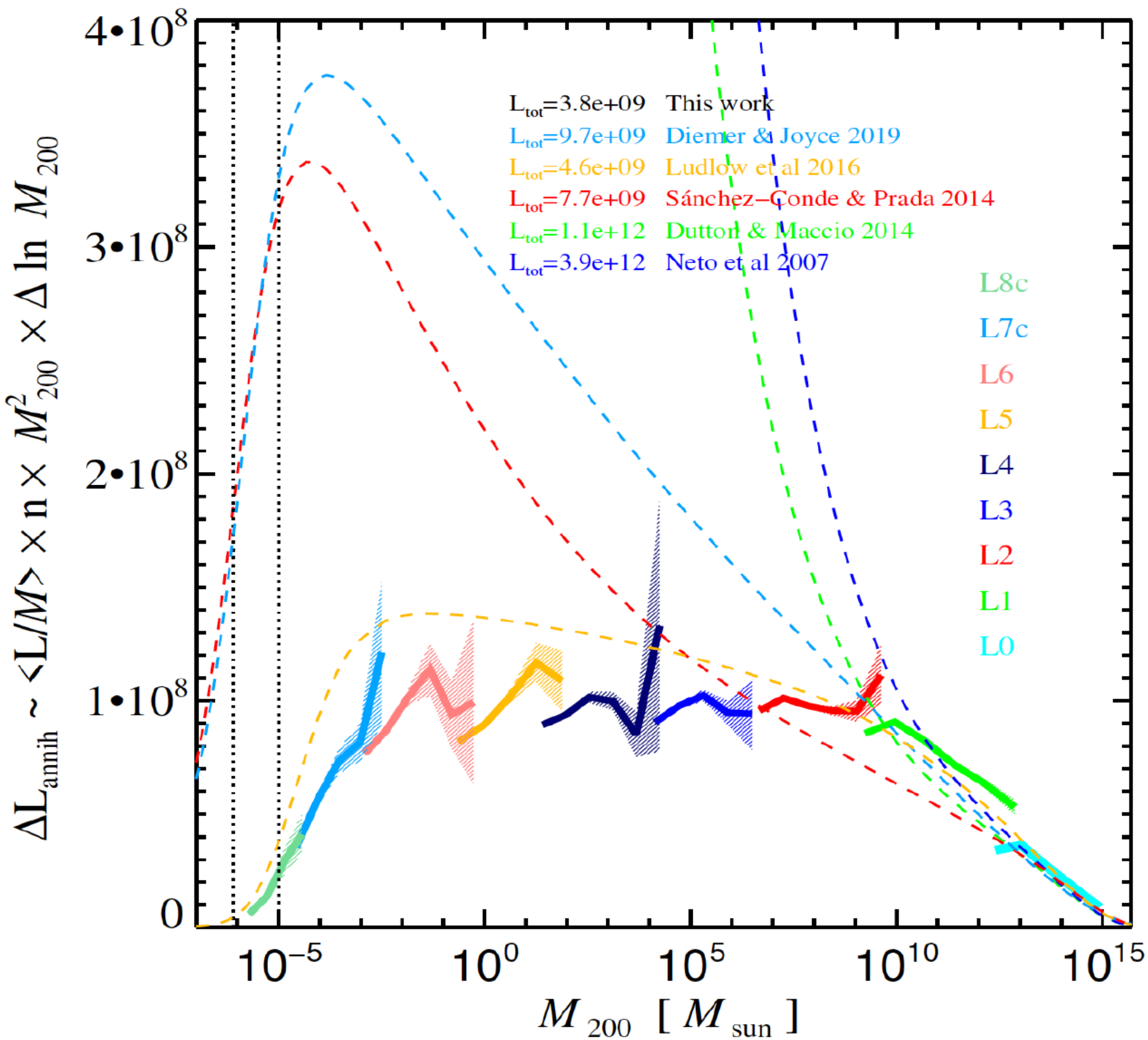
Wang, Bose et al 2020

Free-streaming effects on halo density profiles



The concentration of halos near the cut-off mass is reduced by free-streaming

Wang, Bose et al 2020



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

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

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

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

This still neglects the substructure contribution to halo luminosity

Wang, Bose et al 2020

Take-home messages

- The abundance and structure of small halos is sensitive to the *nature* of dark matter
- Halos of collisionless dark matter have universal density profiles at low redshift on all mass scales.
- Free streaming of collisionless dark matter induces a small-scale cut-off in the halo mass function. This can be on dwarf galaxy scales for WDM but is much smaller for CDM
- Near the cut-off, free-streaming reduces halo concentration
- Very small (sub)halos can dominate the annihilation luminosity
- Low-mass halos identified at z=0 do not form from typical regions of the early Universe, but rather from the rare regions that are not incorporated into a higher mass halo