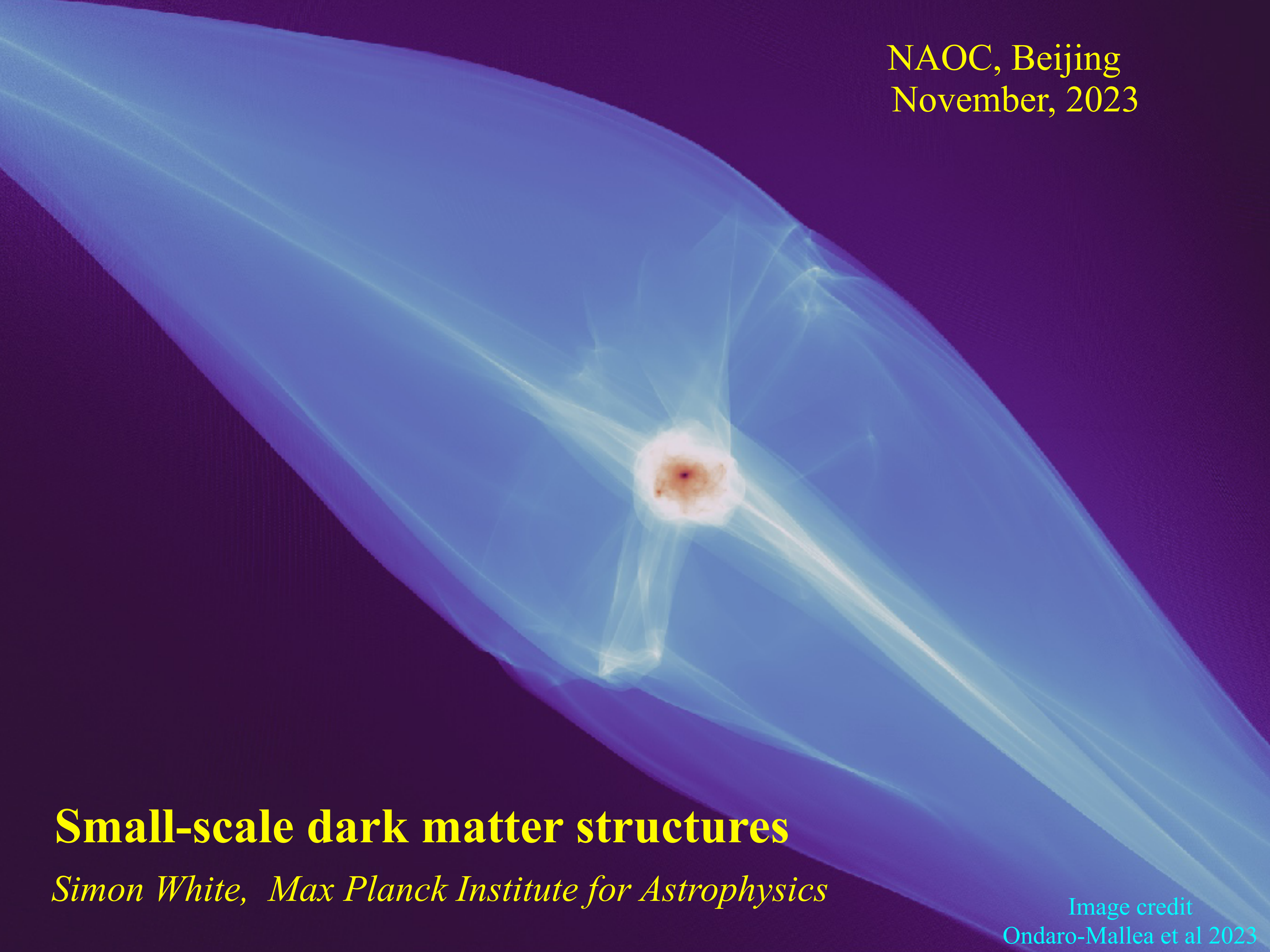
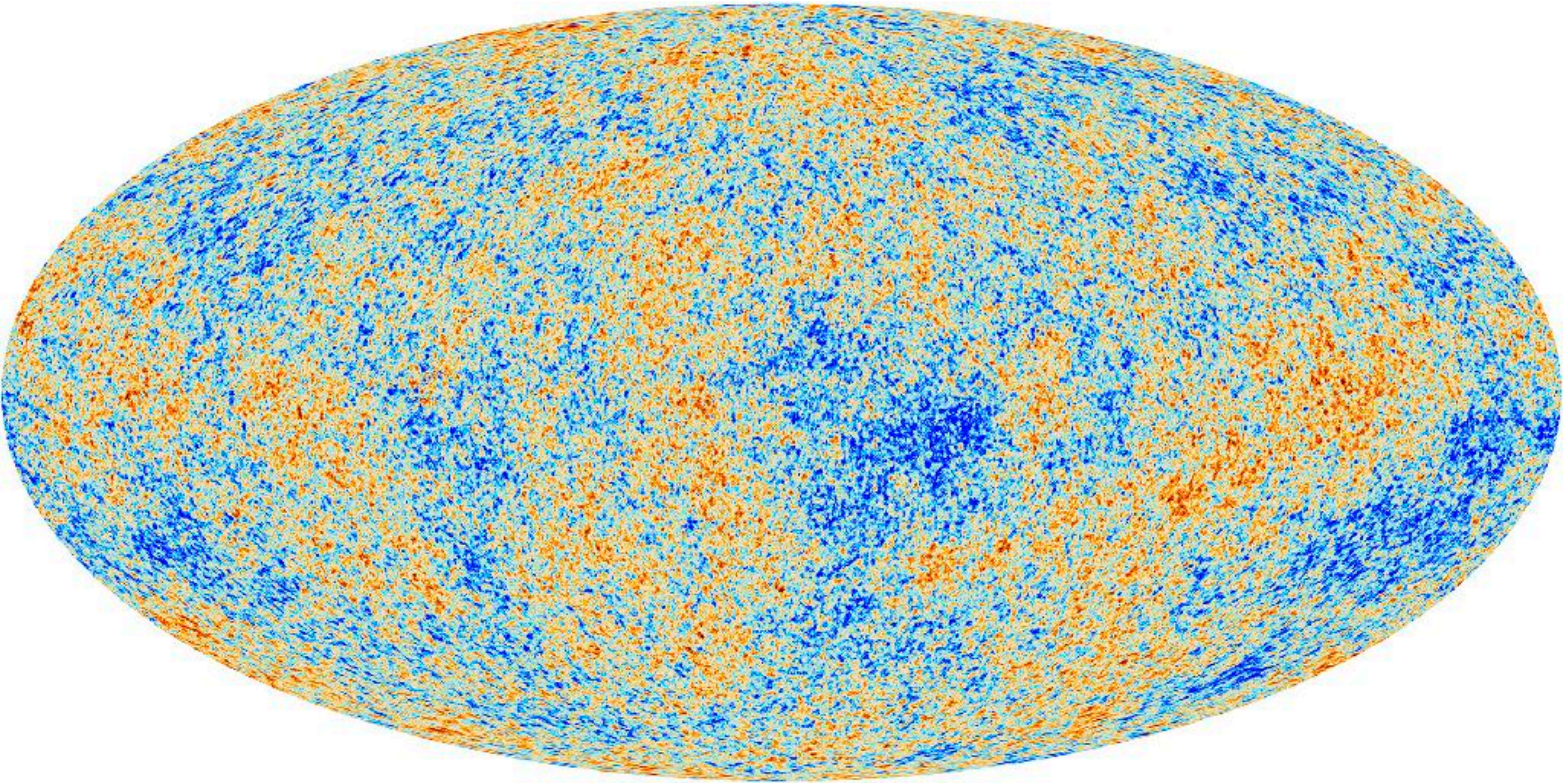
NAOC, Beijing
November, 2023



Small-scale dark matter structures

Simon White, Max Planck Institute for Astrophysics

Image credit
Ondaro-Mallea et al 2023

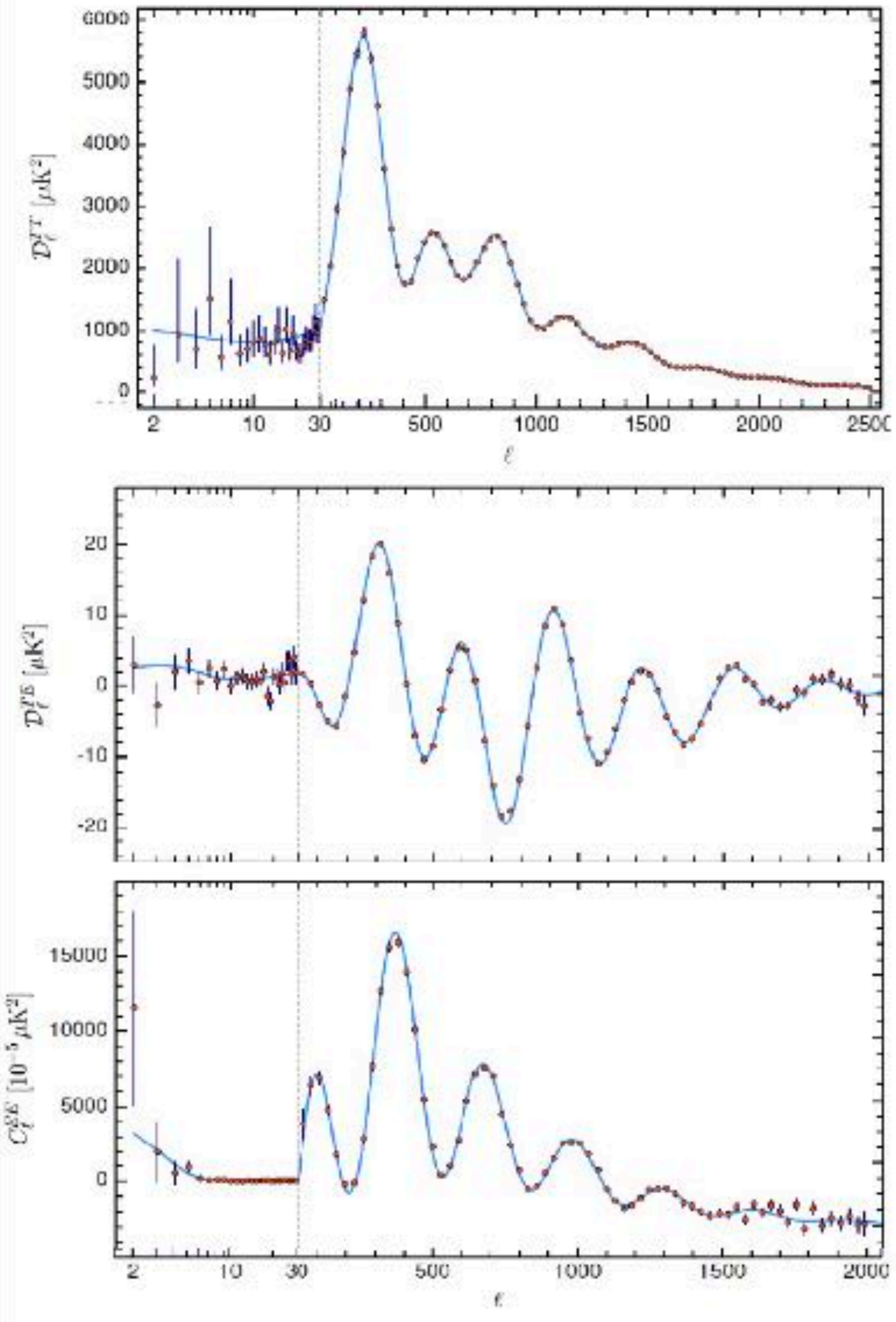


The Planck image of the Cosmic Microwave Background

The Universe at an age of 400,000 years — hot and almost uniform

The initial conditions for the formation of *all* cosmic structure

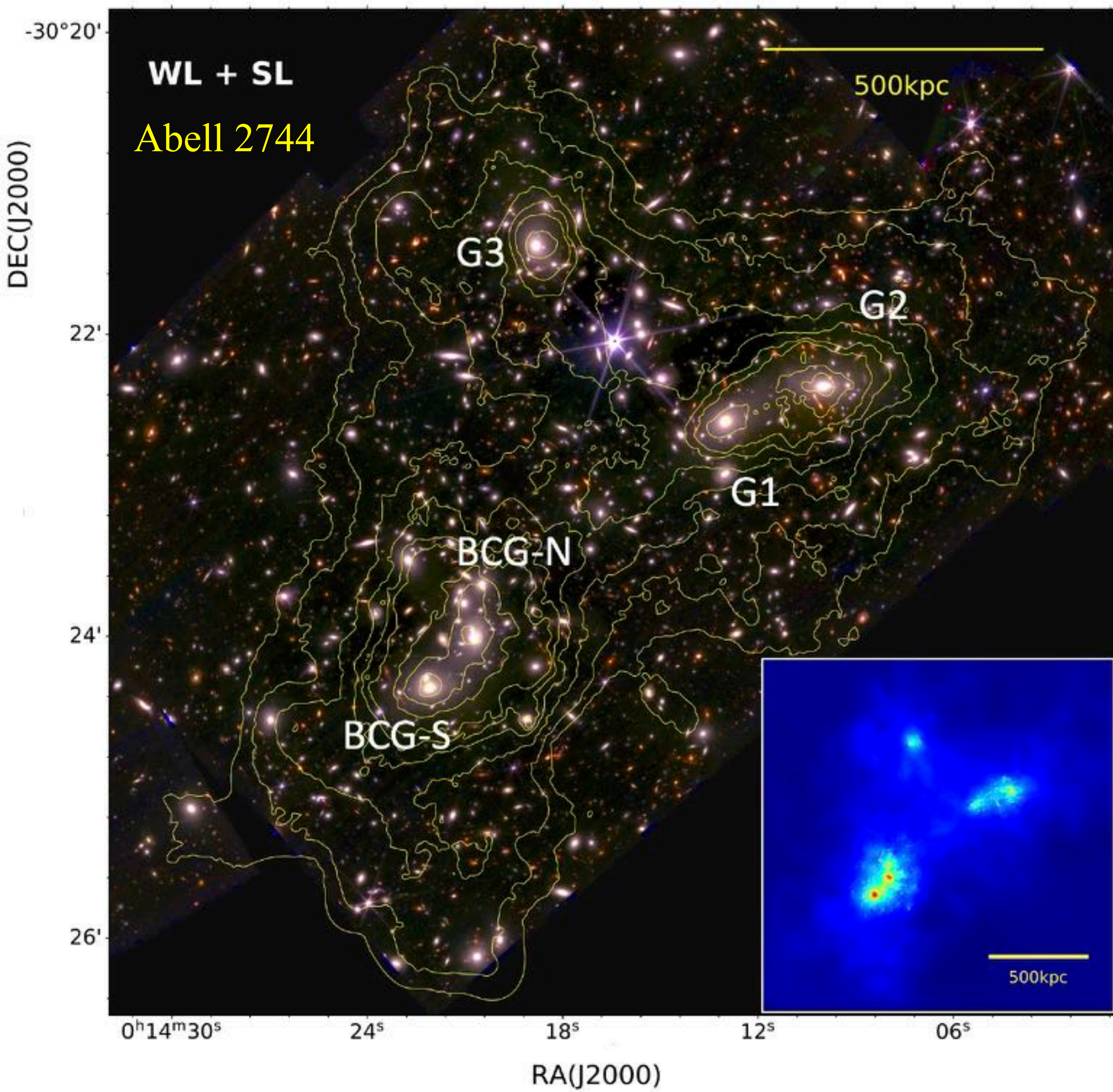
The astrophysical evidence for dark matter



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 cosmic structure formation requires extrapolation to smaller scales and later times



The mass distribution of a rich $z = 0.31$ galaxy cluster reconstructed from strong+weak gravitational lensing observations

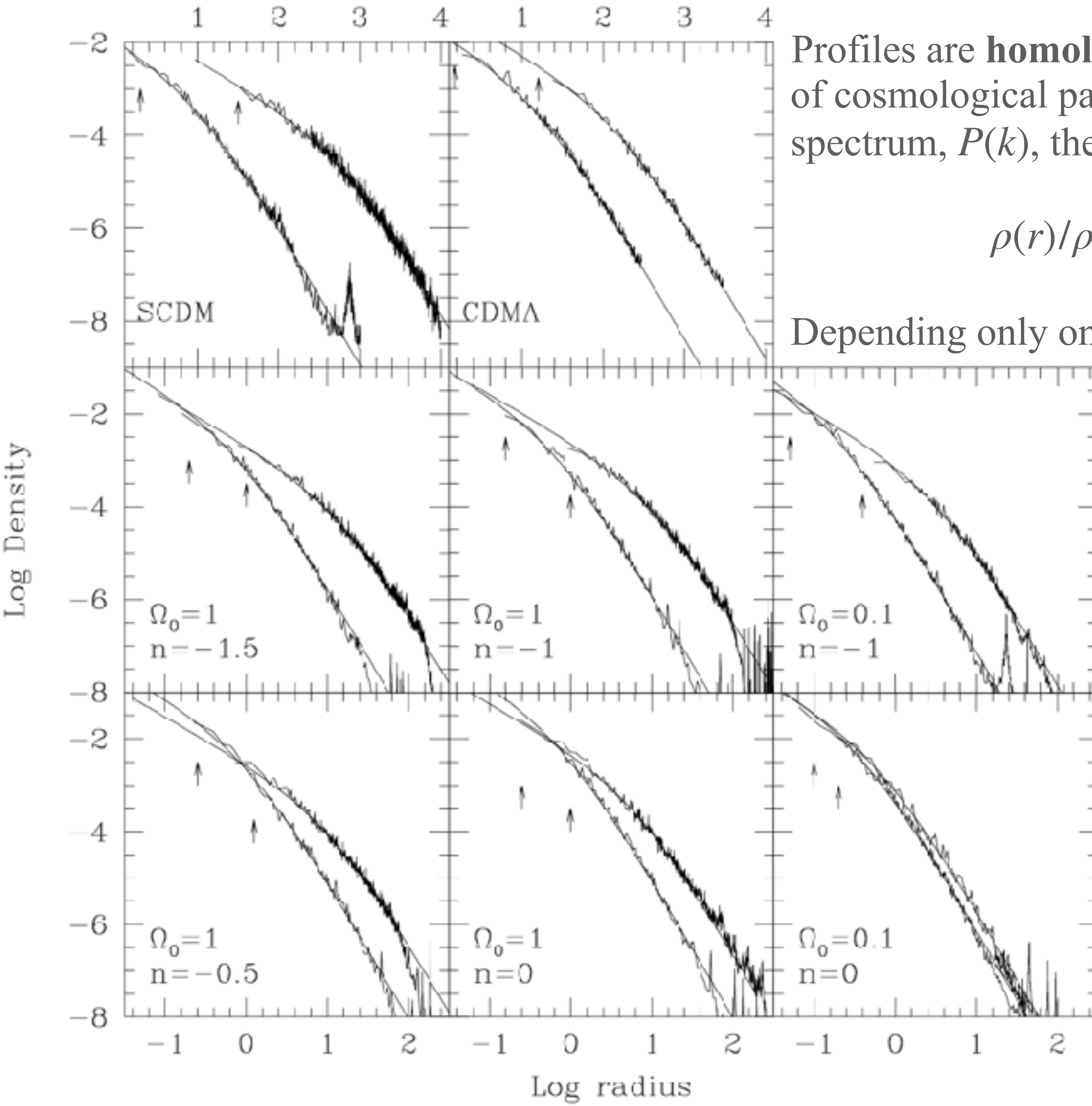
JWST data

286 SL multiple images

350 WL images/arcmin^2

Cha et al 2023

NFW claims about spherically averaged halo density profiles



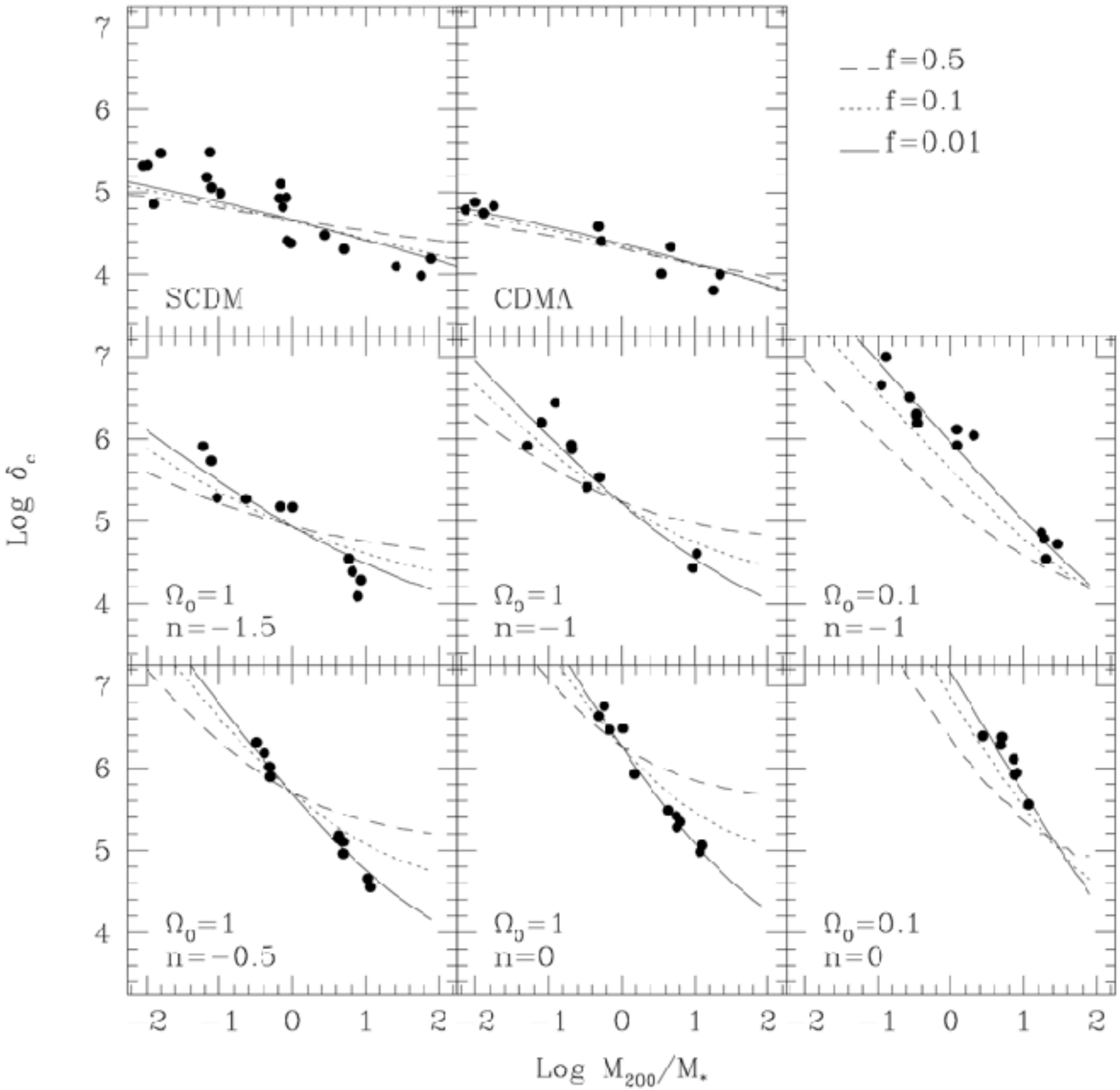
Profiles are **homologous**. Independent of halo mass, of cosmological parameters and of initial linear power spectrum, $P(k)$, they are well fit by the simple formula,

$$\rho(r)/\rho_{\text{crit}} = \delta_s r_s^3 / r(r + r_s)^2$$

Depending only on the two scale parameters, δ_s and r_s

Navarro, Frenk & White 1997

NFW claims about spherically averaged halo density profiles



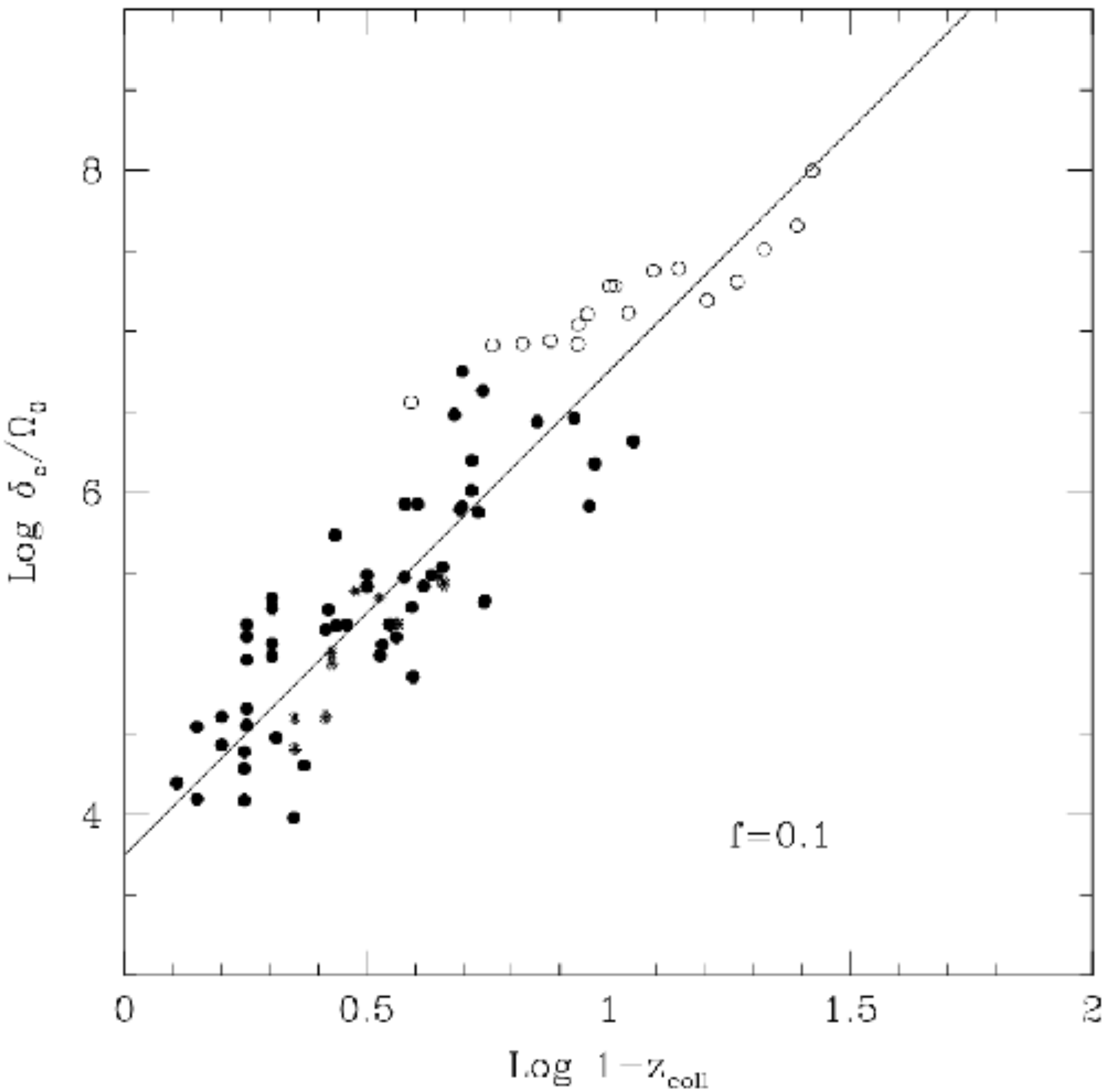
The characteristic density of a halo depends on its mass

Lower mass halos are denser

The halo mass-density relation depends strongly on cosmological parameters and on $P(k)$

Navarro, Frenk & White 1997

NFW claims about spherically averaged halo density profiles



The characteristic density of halos of all masses in all cosmologies and for all $P(k)$ is proportional to the density of the universe at the time z_{coll} when half of the total halo mass was first in significant nonlinear lumps (e.g. $> 0.1 M_{halo}$)

$$\delta_c = A\Omega_0(1+z_{coll})^3$$

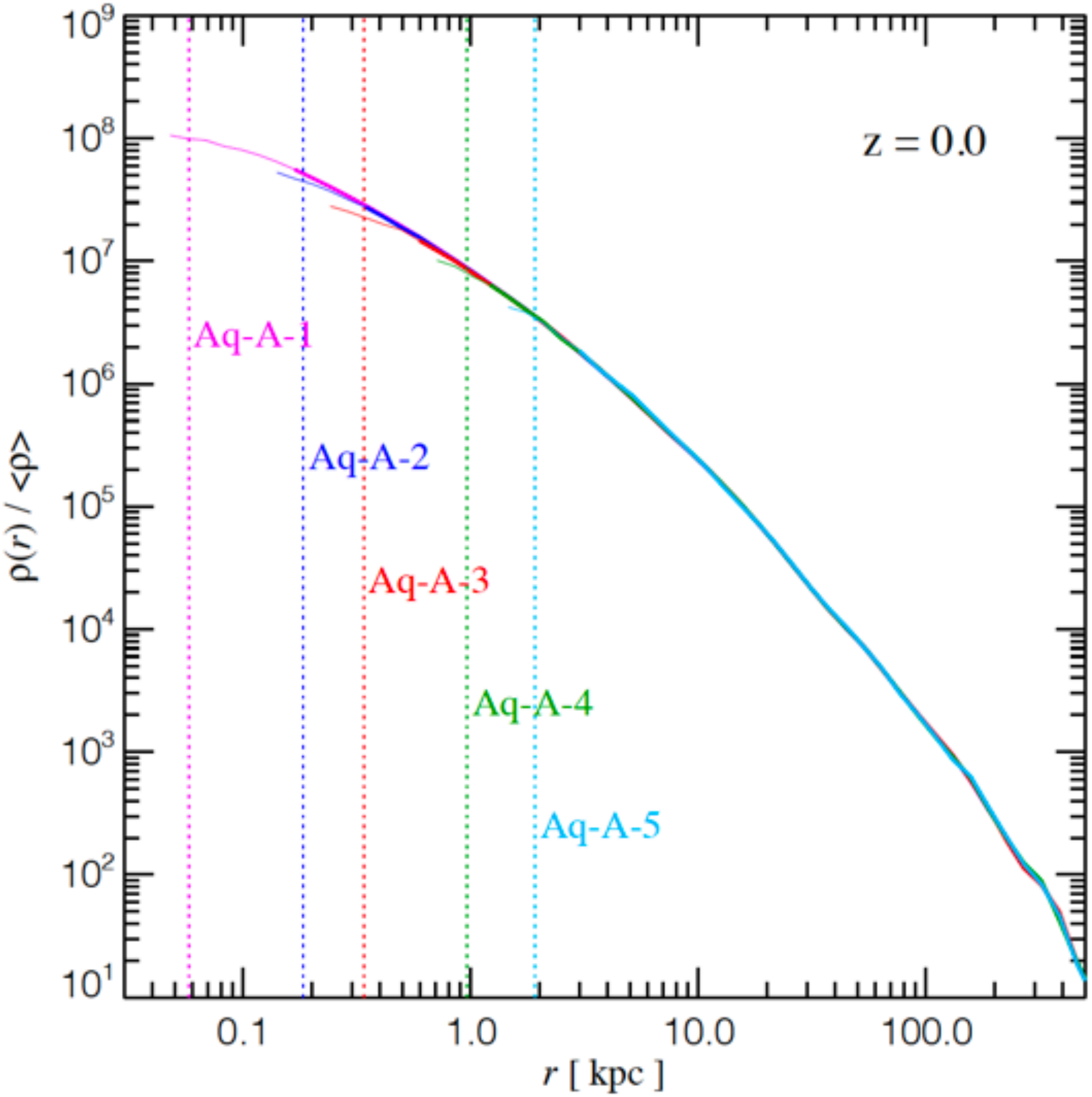
for a universal constant A

The characteristic density of halos thus reflects their assembly history

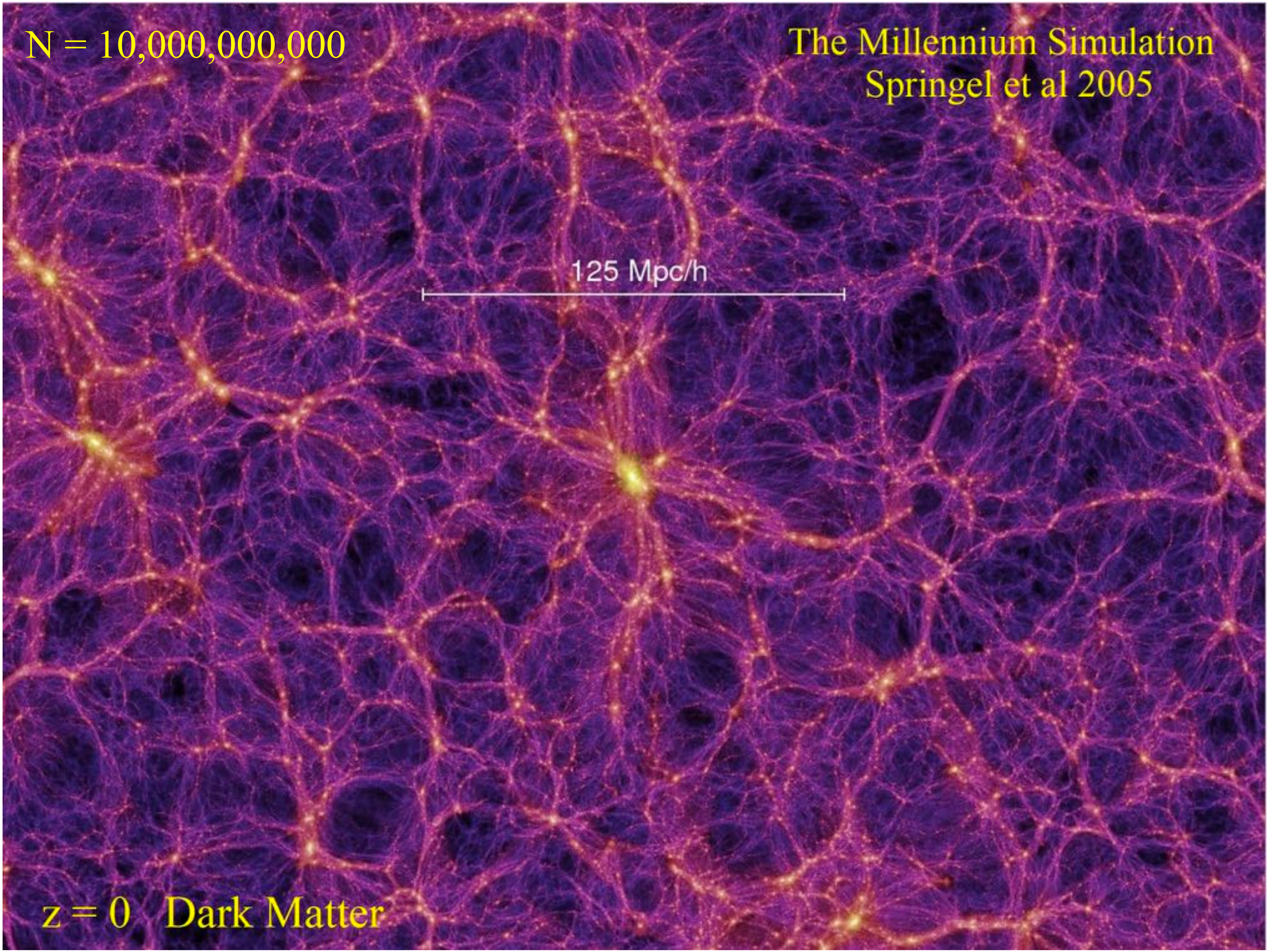
Navarro, Frenk & White 1997

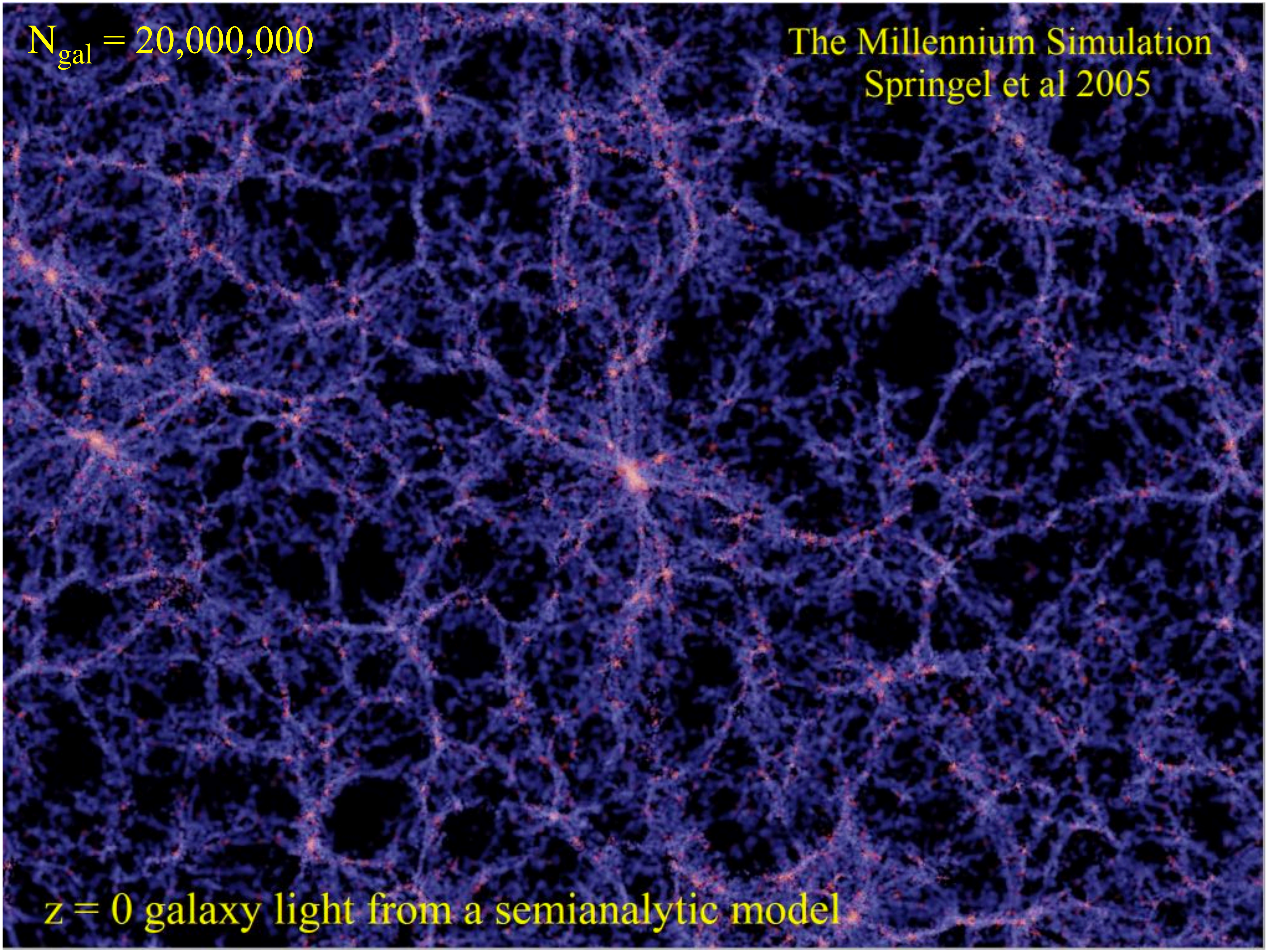
Halos converge to NFW outside $r_{\rm Power}(t_f)$

Springel et al 2008



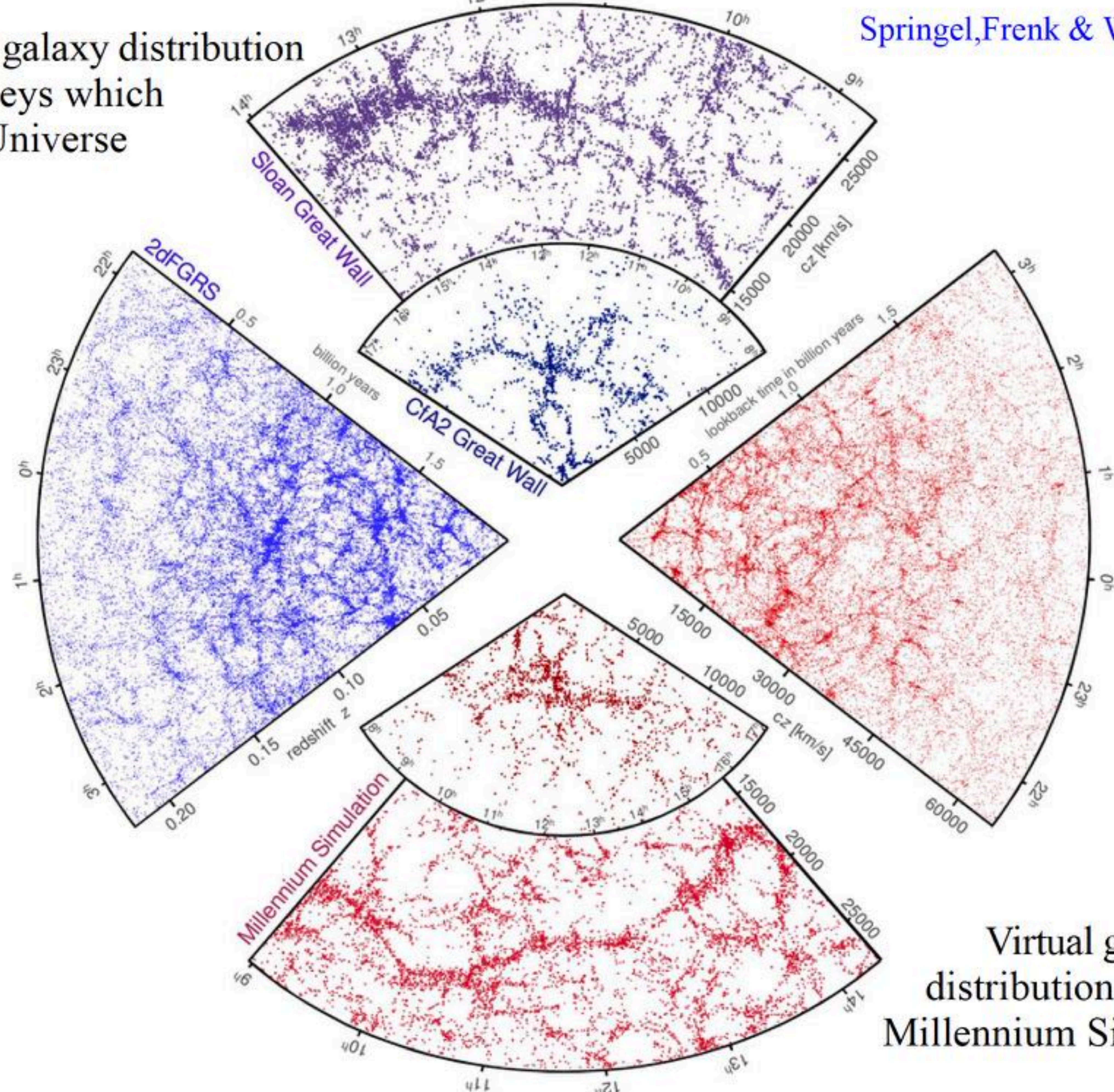
The NFW shape is not a consequence of 2-body relaxation/discreteness


N = 10,000,000,000
The Millennium Simulation
Springel et al 2005
125 Mpc/h
z = 0 Dark Matter


$N_{gal} = 20,000,000$
The Millennium Simulation
Springel et al 2005
z = 0 galaxy light from a semianalytic model

Observed galaxy distribution from surveys which map the Universe

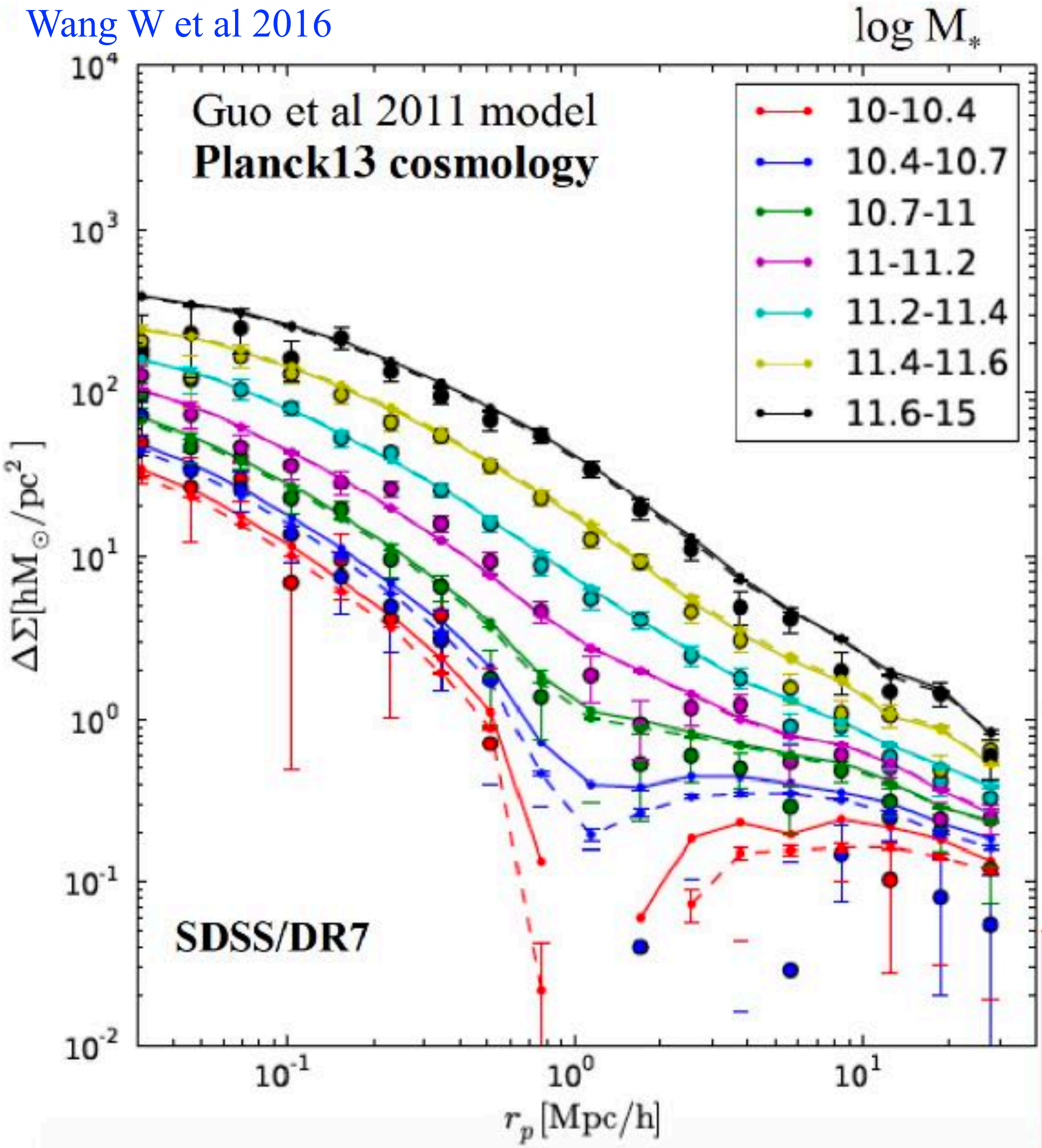
Springel,Frenk & White 2006



Virtual galaxy distribution from the Millennium Simulation

Average mass profiles around bright galaxies

Wang W et al 2016



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

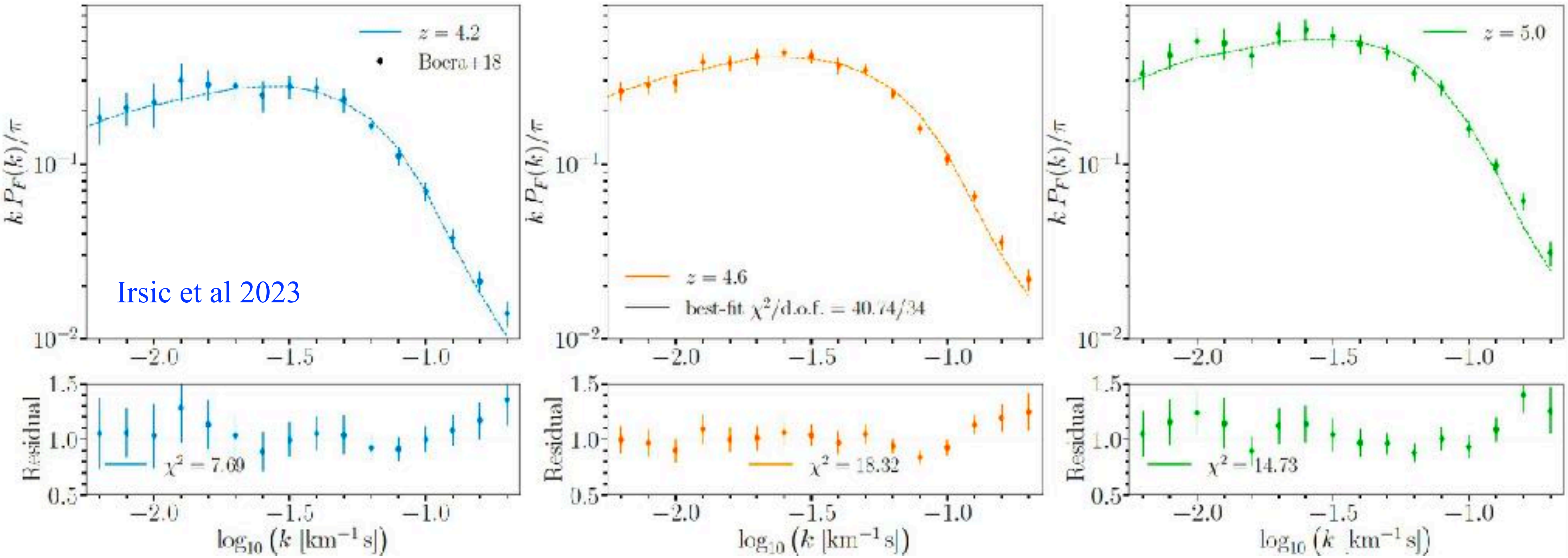
Top to bottom goes from rich clusters to "Milky Way" groups

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

Small-scale structure in the high-z Lyman α forest



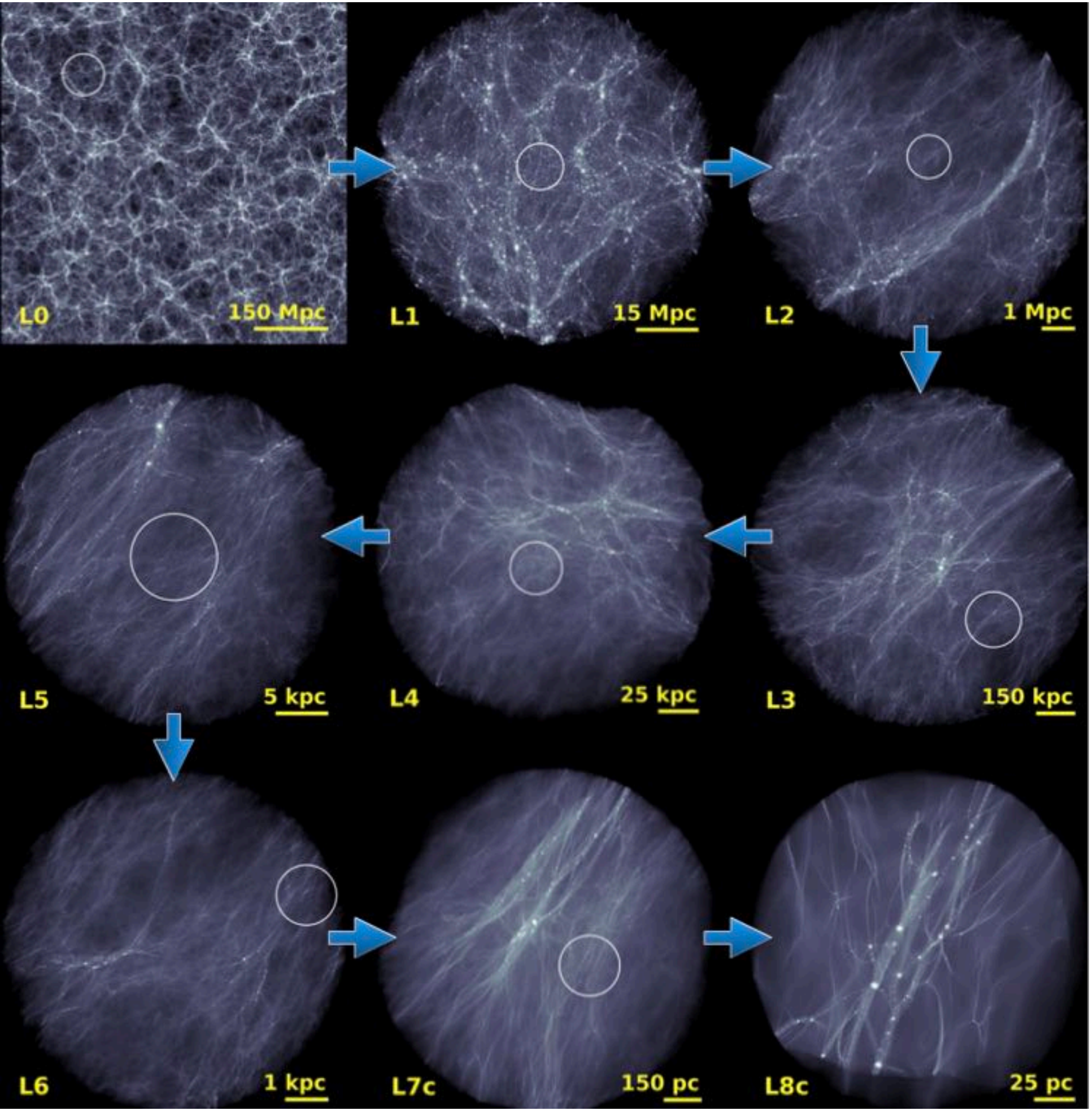
HI absorption in front of high-z QSOs allows measurement of small-scale structure in the IGM

The measured $P(k)$ is consistent with ΛCDM with Planck parameters

Warm Dark Matter is excluded for $m_{\rm thermal} < 5.7$keV at 2σ

The standard ΛCDM paradigm is validated down to the scales of small dwarf galaxies

[redacted]

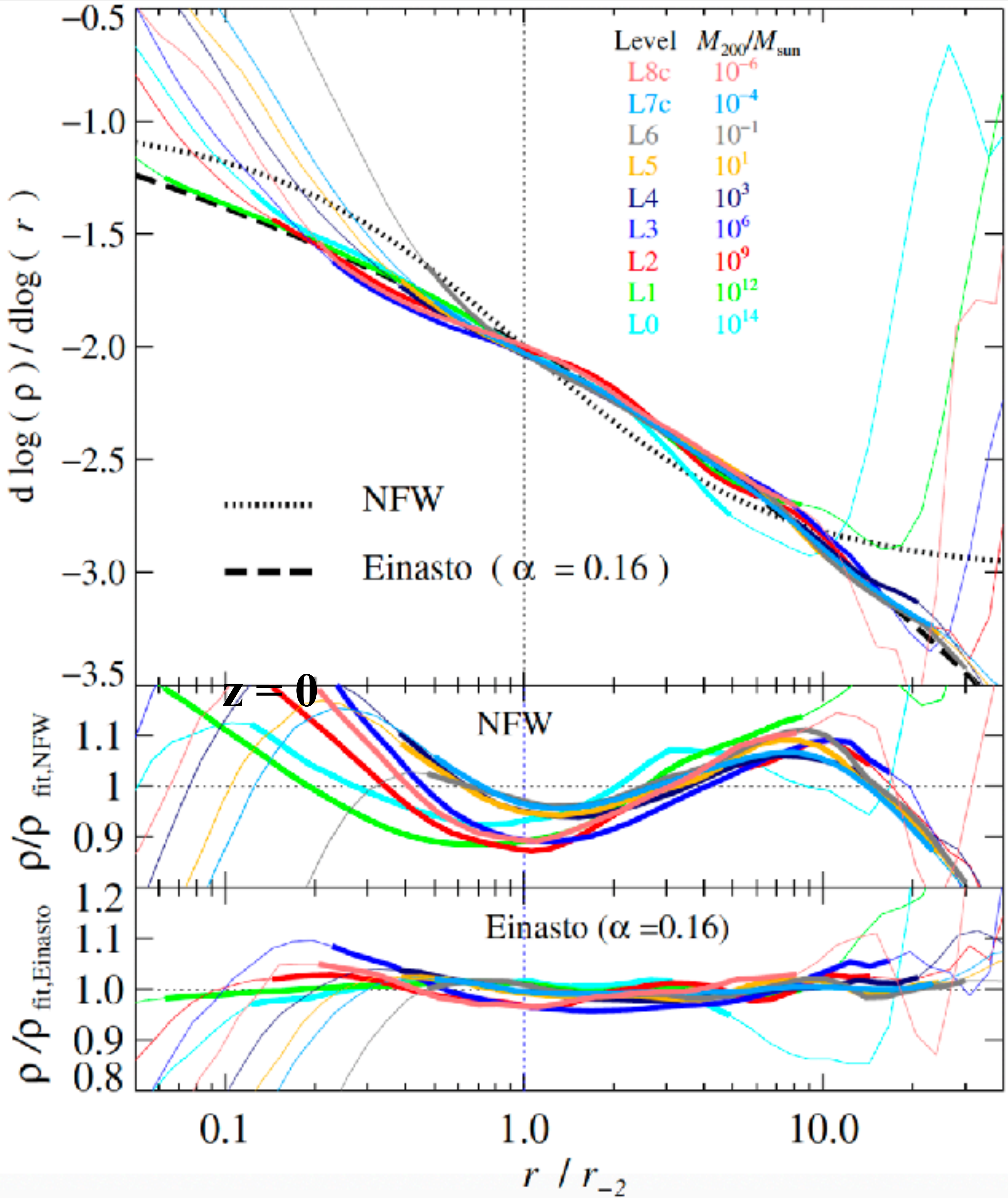


The VVV simulation suite zooms into a low-density region of a z=0 ΛCDM universe by a factor 4.10^6

Resolves dark matter halos over a mass range of 10^{20}

Wang J et al 2020

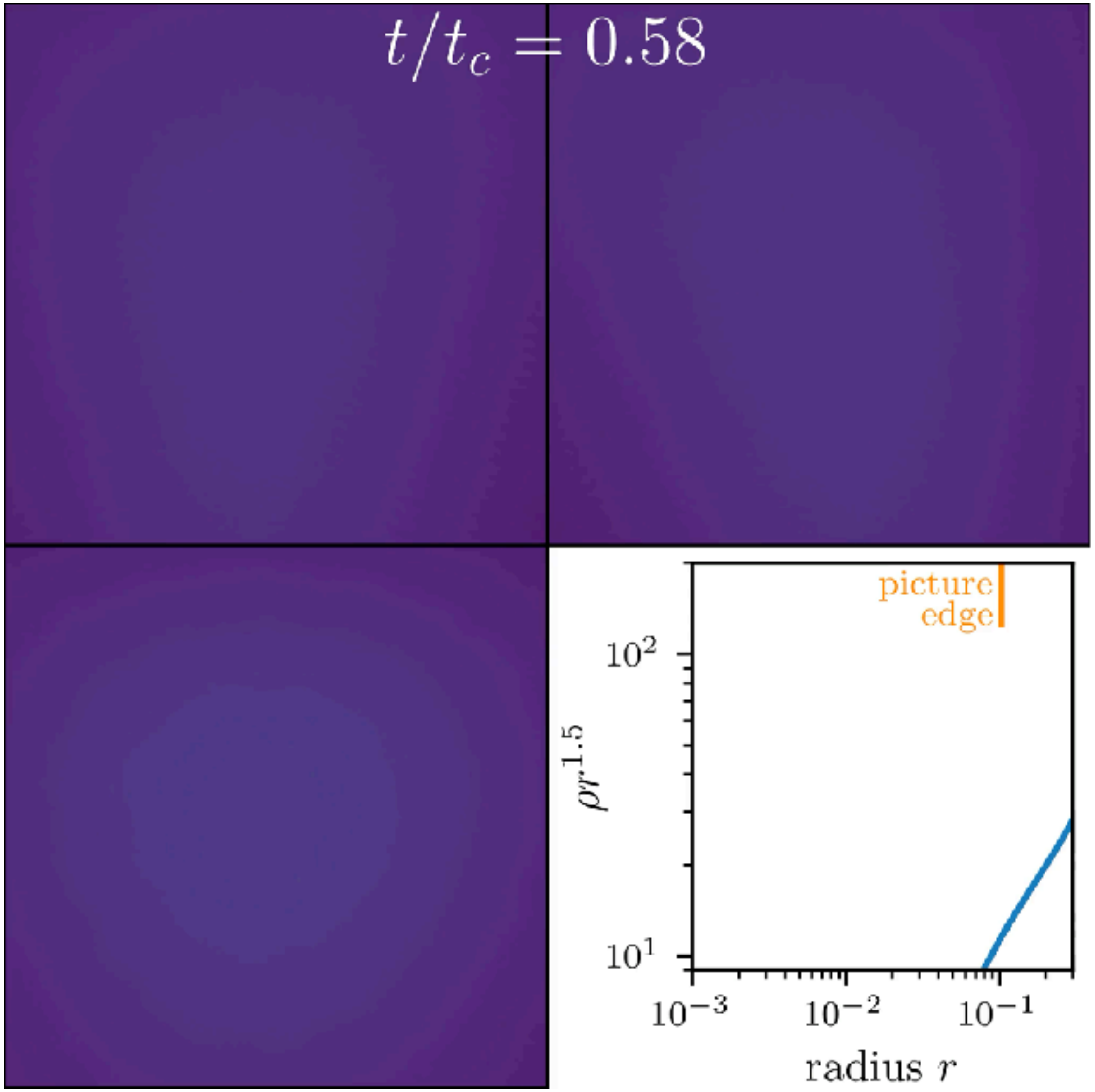
Density profile shapes



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 J et al 2020

Prompt cusp formation in a ΛCDM density peak

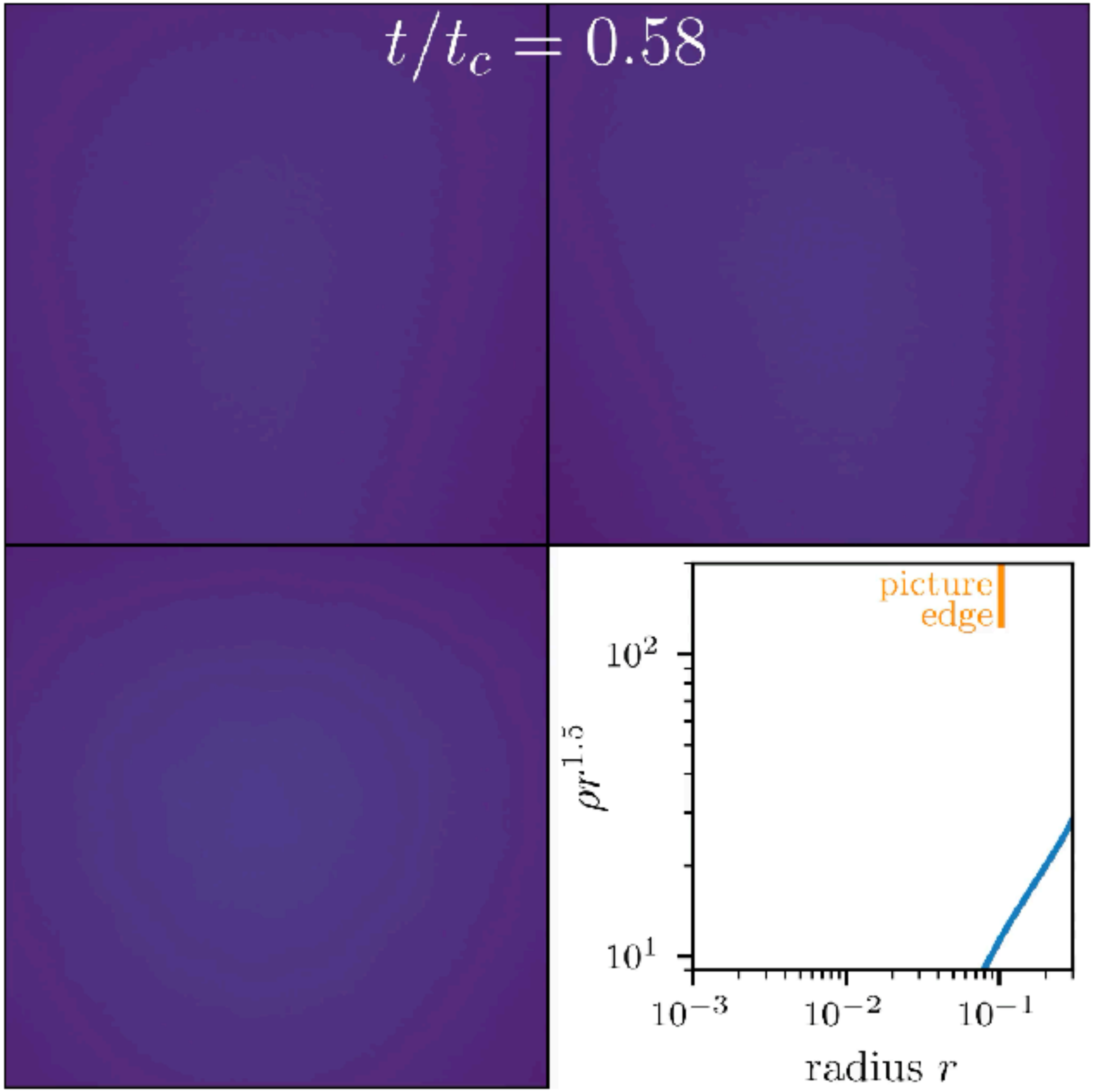


$t_c \longrightarrow z = 87$

$M_{pk} \sim 10^{-6} M_{\text{sun}}$

Delos & White 2023

Prompt cusp formation in a ΛCDM density peak



$t_c \rightarrow z = 87$

$M_{pk} \sim 10^{-6} M_{\rm sun}$

Prompt cusp formation differs qualitatively from "normal" halo formation

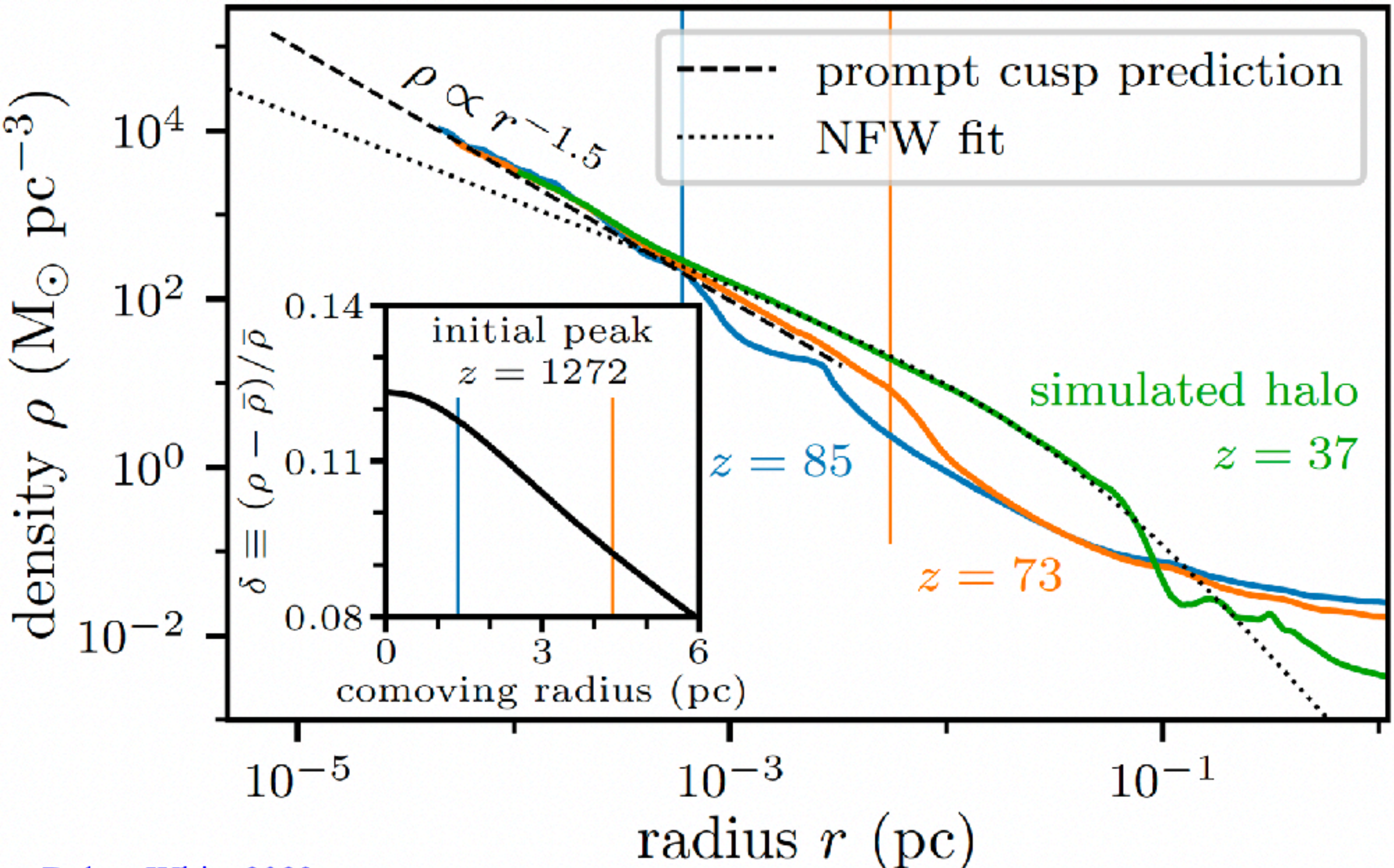
Violent relaxation is important

No close link of profile to cusp growth history

A "universal" profile *different* from NFW

Delos & White 2023

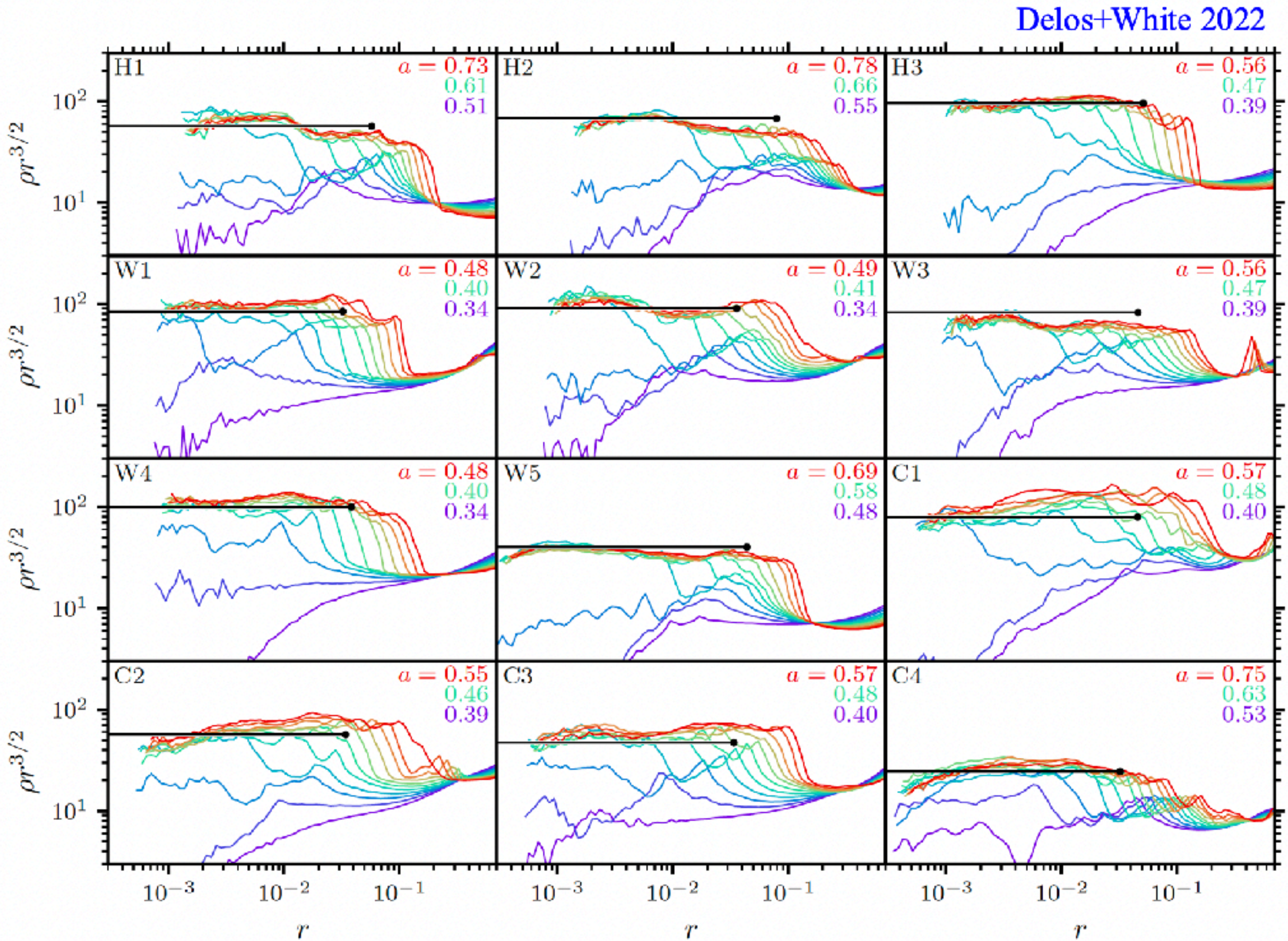
Prompt cusp and subsequent halo growth for a peak with $z_{coll} = 87$



Delos+White 2023

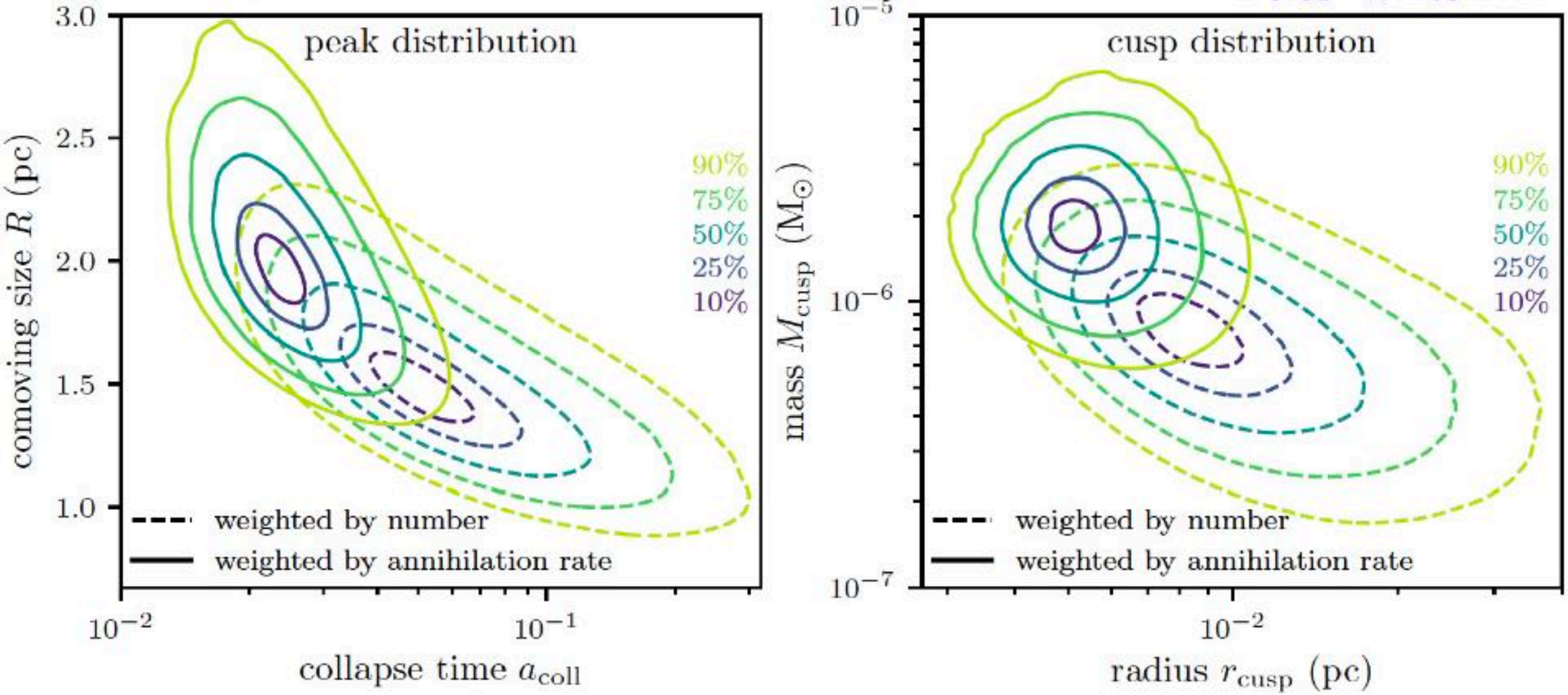
Prompt Cusps

- ...are relevant whenever $P(k)$ is sharply truncated at high k
- ...form promptly as each initial density peak collapses
- ...have density profiles, $\rho(r) \approx 24\,\bar{\rho}\,(r / R)^{-1.5}$, where $\bar{\rho}$ is the mean cosmic DM density and $R = a_c(\delta / \nabla^2\delta)^{1/2}$ is the size of the linear overdensity peak (both measured at t_c, the time of peak collapse)
- ...have, by 1.2 t_c, mass, $M_{cusp} \sim 7\,R^3\,\bar{\rho}$, and size, $r_{cusp} \sim 0.1\,R$
- ...have an inner core radius set by phase-space constraints, thus dependent on the nature and cosmological origin of the DM
- ...suffer late-time tidal disruption only in star-dominated regions of galaxies (through encounters with individual stars)
- ...dominate the dark matter annihilation signal in all but the very densest regions of galaxies


Delos+White 2022
H1
a = 0.73
0.61
0.51
H2
a = 0.78
0.66
0.55
H3
a = 0.56
0.47
0.39
W1
a = 0.48
0.40
0.34
W2
a = 0.49
0.41
0.34
W3
a = 0.56
0.47
0.39
W4
a = 0.48
0.40
0.34
W5
a = 0.69
0.58
0.48
C1
a = 0.57
0.48
0.40
C2
a = 0.55
0.46
0.39
C3
a = 0.57
0.48
0.40
C4
a = 0.75
0.63
0.53
$\rho r^{3/2}$
r
10^{-3}
10^{-2}
10^{-1}
10^{1}
10^{2}

BBKS-predicted peak and cusp distributions in ΛCDM

Delos+White 2023

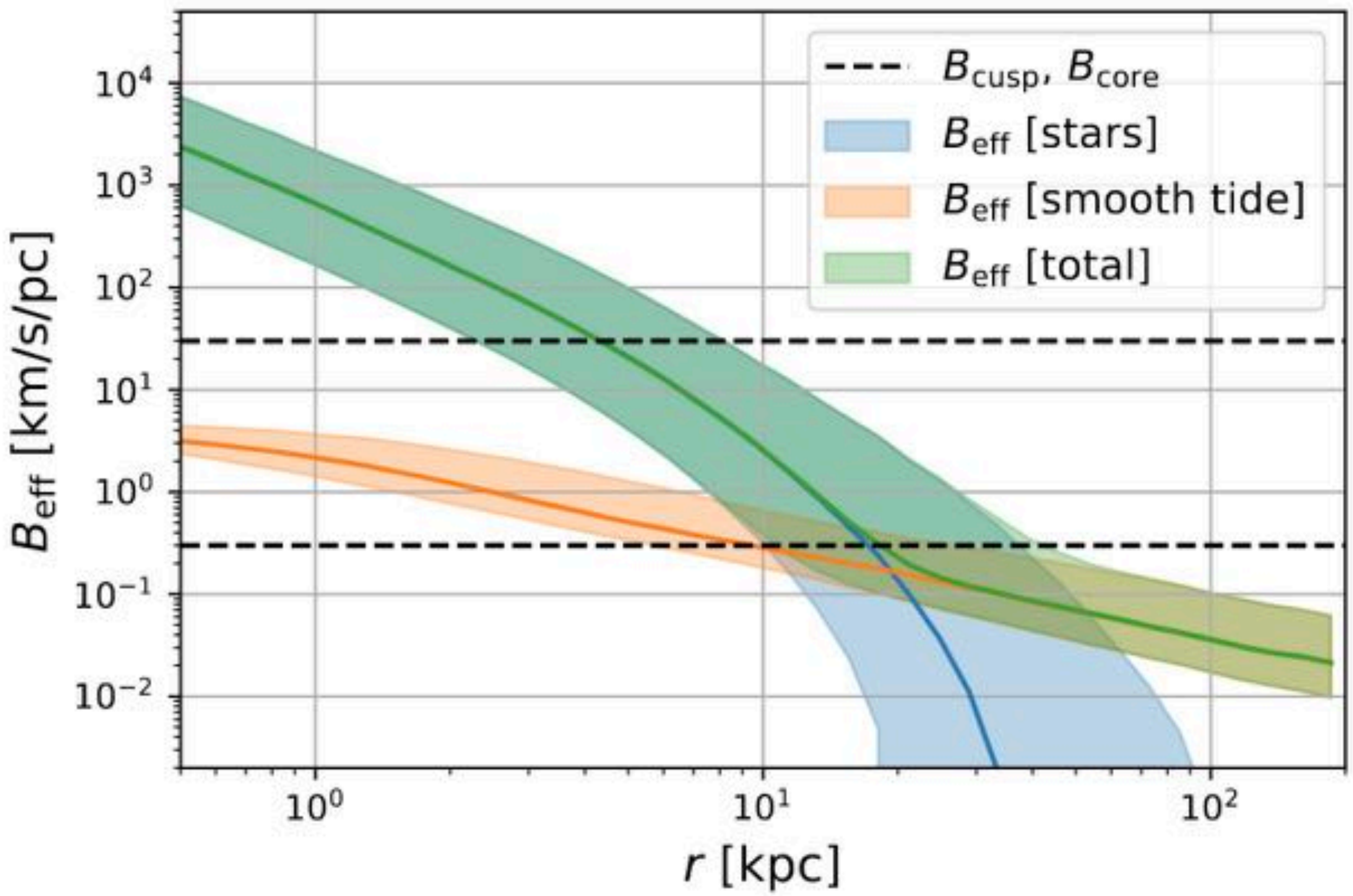


$m_\chi = 100$ GeV, $T_{kd} = 30$ MeV

$J \quad \int \rho^2 \, dV$

Tidal effects on prompt cusps in the Milky Way

Stücker et al 2023

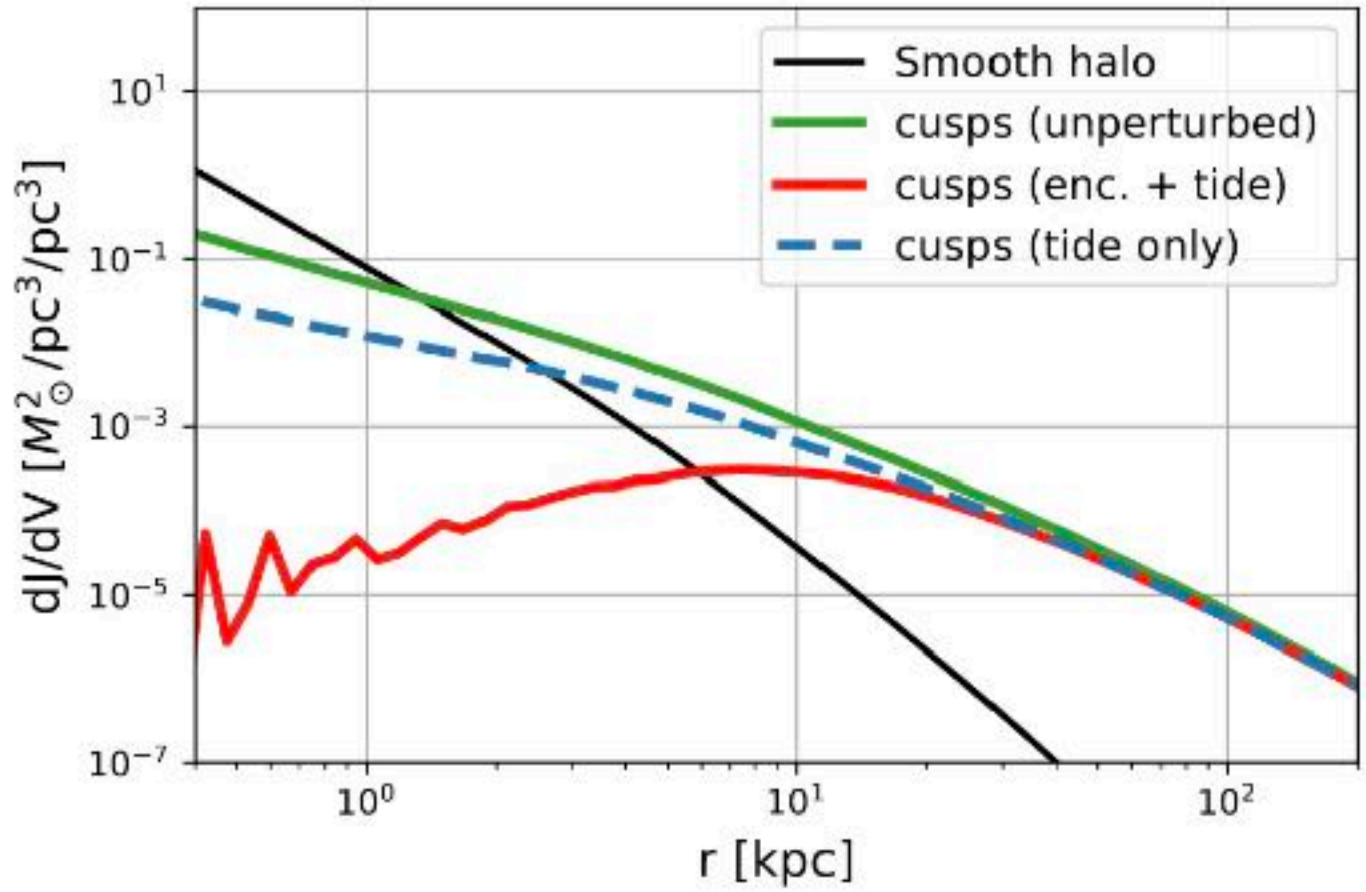


A impulsive stellar encounter is characterised by strength, $B = 2GM_*/Vb^2$

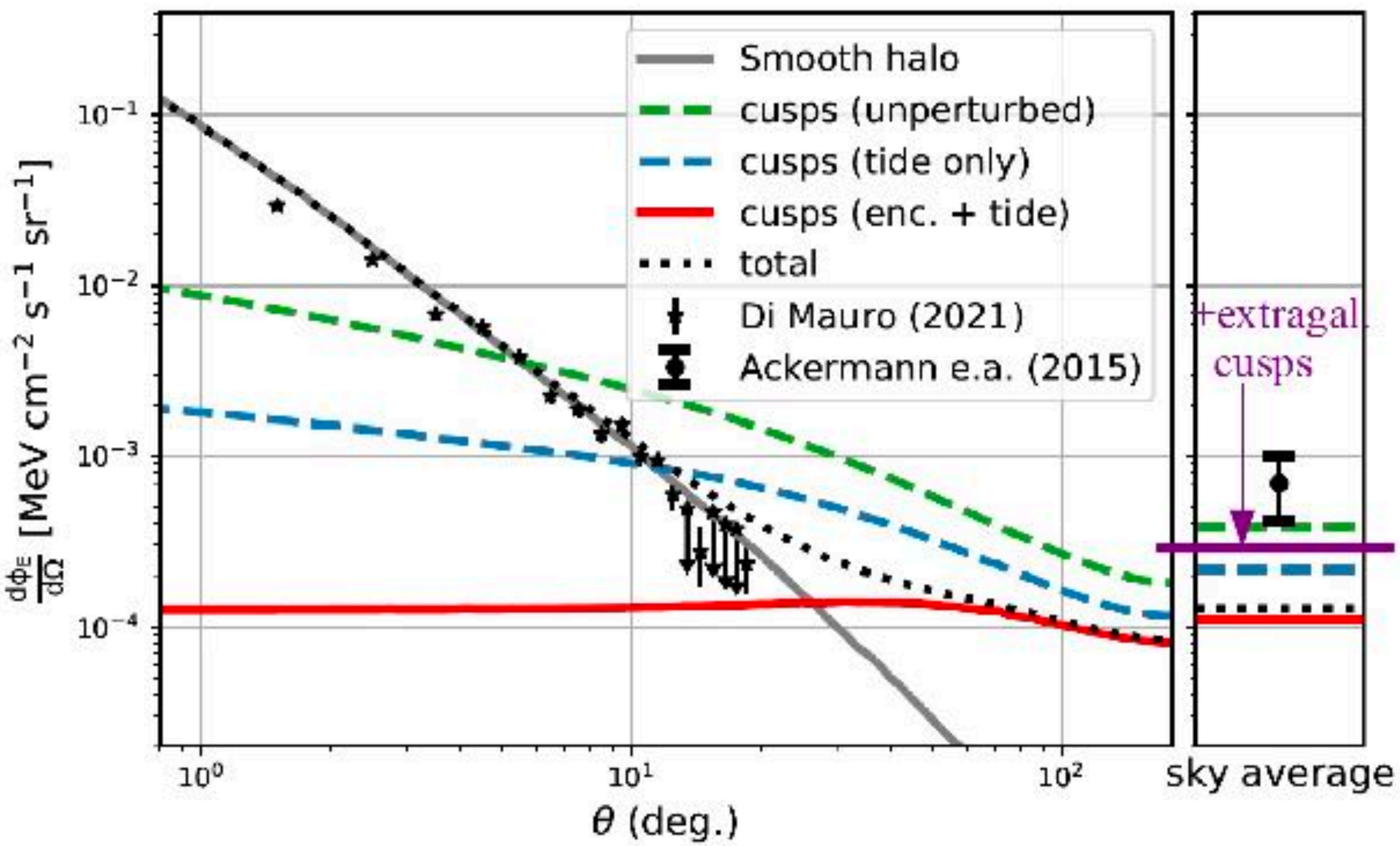
For a given cusp, $d\bar{N}/dB = 2\pi G B^{-2} \int \rho_*(\mathbf{x}(t))\, dt$; $\quad B_{eff} = (\Sigma\, B_i^{1.2})^{1/1.2}$

Mean field truncation is approximated by $B_{mean} = (42.2\, |r^{-2}\, \partial_r\, r^2\, \partial_r\, \Phi|_{peri}\,)^{1/2}$

Milky Way annihilation radiation profiles



Stücker et al 2023

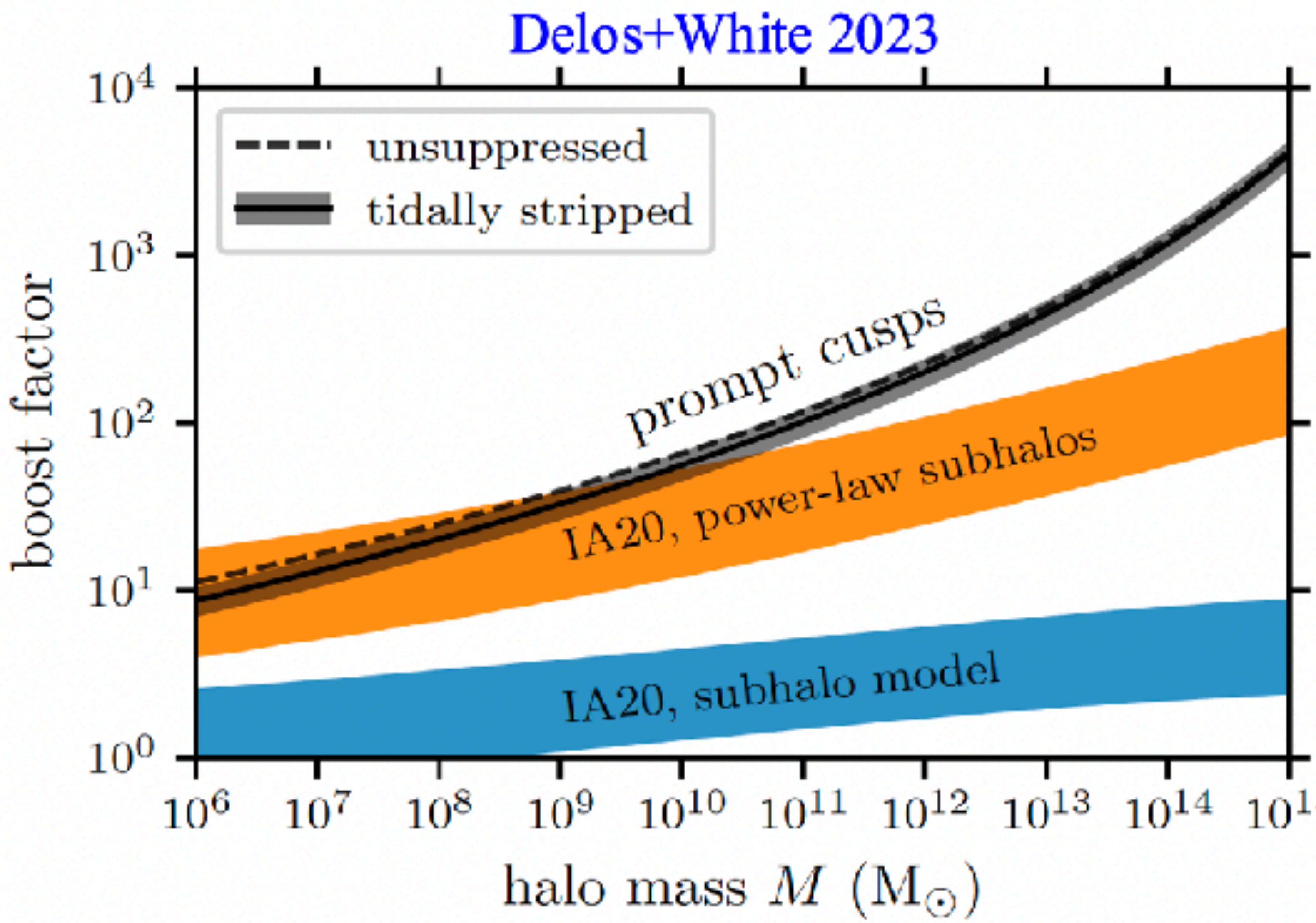


The profile due to cusps is much shallower than that due to the smoothly distributed dark matter

Cusp emission dominates at >1 kpc neglecting tides, at >3 kpc including the mean tide, and at >7 kpc including stellar encounters also

Prompt cusps do not affect the Fermi Galactic Centre Excess, but if this is due to annihilation then they contribute much of the 1 – 10 GeV background

Annihilation radiation boosts in field halos

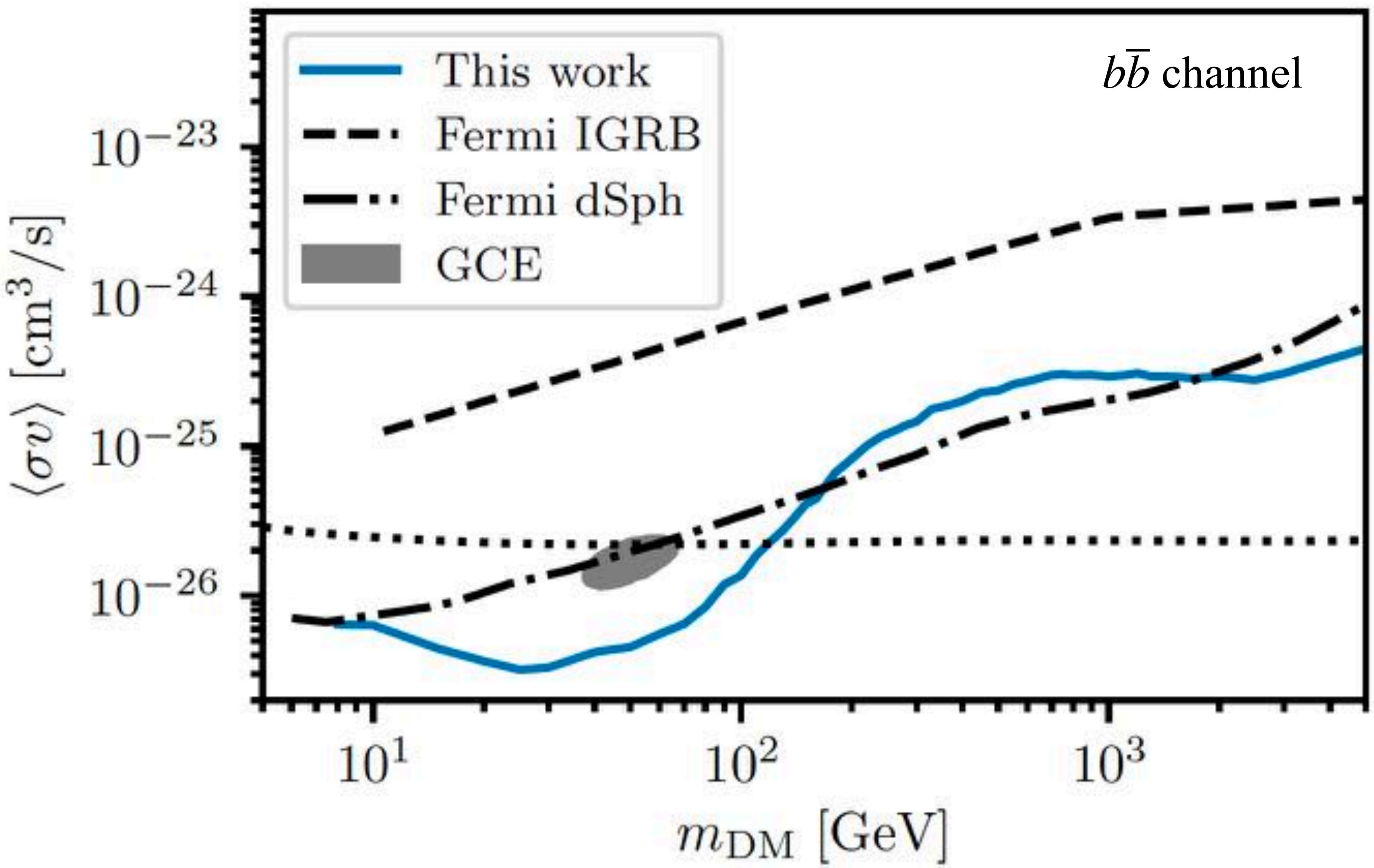


Prompt cusps boost the emission from distant halos by factors ~20 (small dwarfs) ~200 (MW-like galaxies) and ~2000 (rich clusters)

These are much larger than recent estimates of the boost due to substructure made by extrapolating results of high-resolution halo simulations .

Isotropic γ-ray background constraints on DM annihilation

Delos et al 2023



95% upper limit without prompt cusps

with prompt cusps

Expected cross-section for a thermal WIMP

- Prompt cusps tighten the upper limits on annihilation cross-sections by a factor of 30
- Standard thermal WIMPS with $m_{\rm DM} < 120$ GeV are excluded at 95% confidence
- Production of the Galactic Centre Excess by annihilation is inconsistent with the IGRB
- The IGRB limit is stronger than that from dSph galaxies for much of the $m_{\rm DM}$ range

Prompt cusps

- The formation mechanism and structure of prompt cusps differ from those of "normal" halos
- For a m = 100 GeV, Tkd = 30 GeV WIMP, prompt cusps have Earth mass and are a million times more abundant than Earth-mass planets in the Milky Way, accounting for a percent or two of all dark matter
- In the Milky Way they are significantly disrupted both by tides and (particularly) by stellar encounters within ~20 kpc
- They have no observable dynamical or gravitational lensing effects
- They dominate the dark matter annihilation signal from the outer halo of the Milky Way and from all extragalactic objects, leading to a local luminosity density that is proportional to $\bar{\rho}_{dm}$ rather than $\bar{\rho}_{dm}^2$