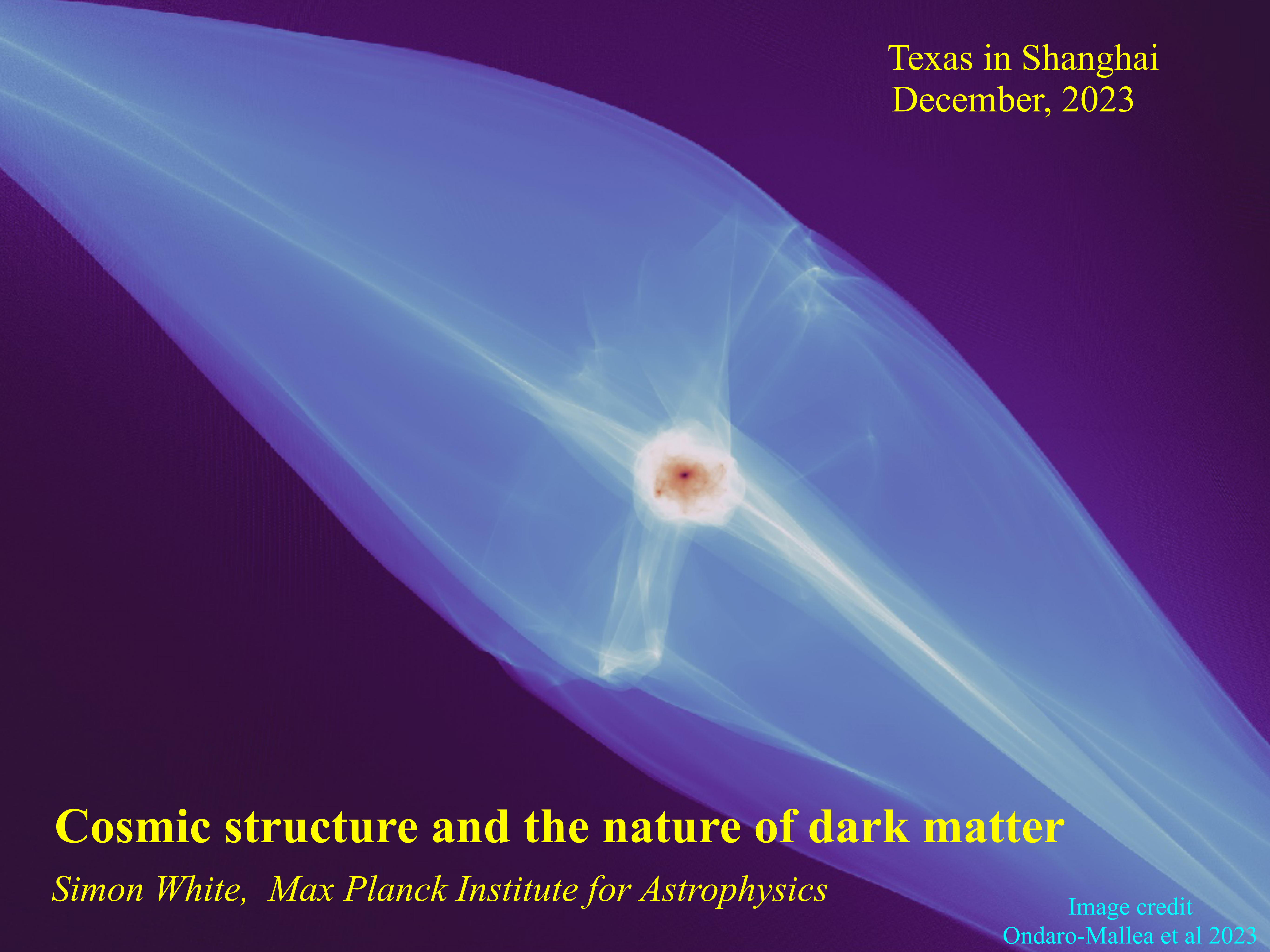
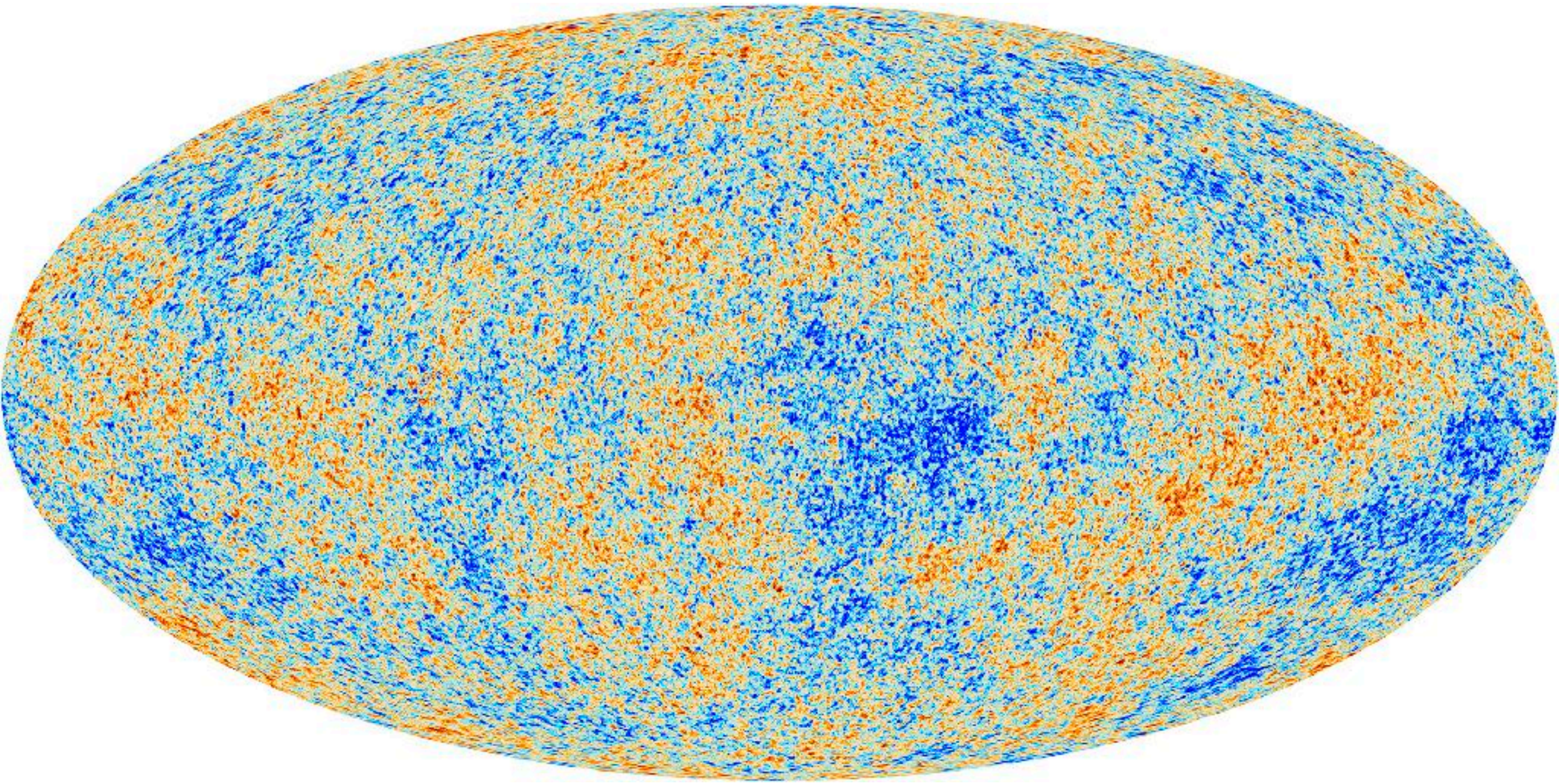
Texas in Shanghai
December, 2023



Cosmic structure and the nature of dark matter

Simon White, Max Planck Institute for Astrophysics

Image credit
Ondaro-Mallea et al 2023

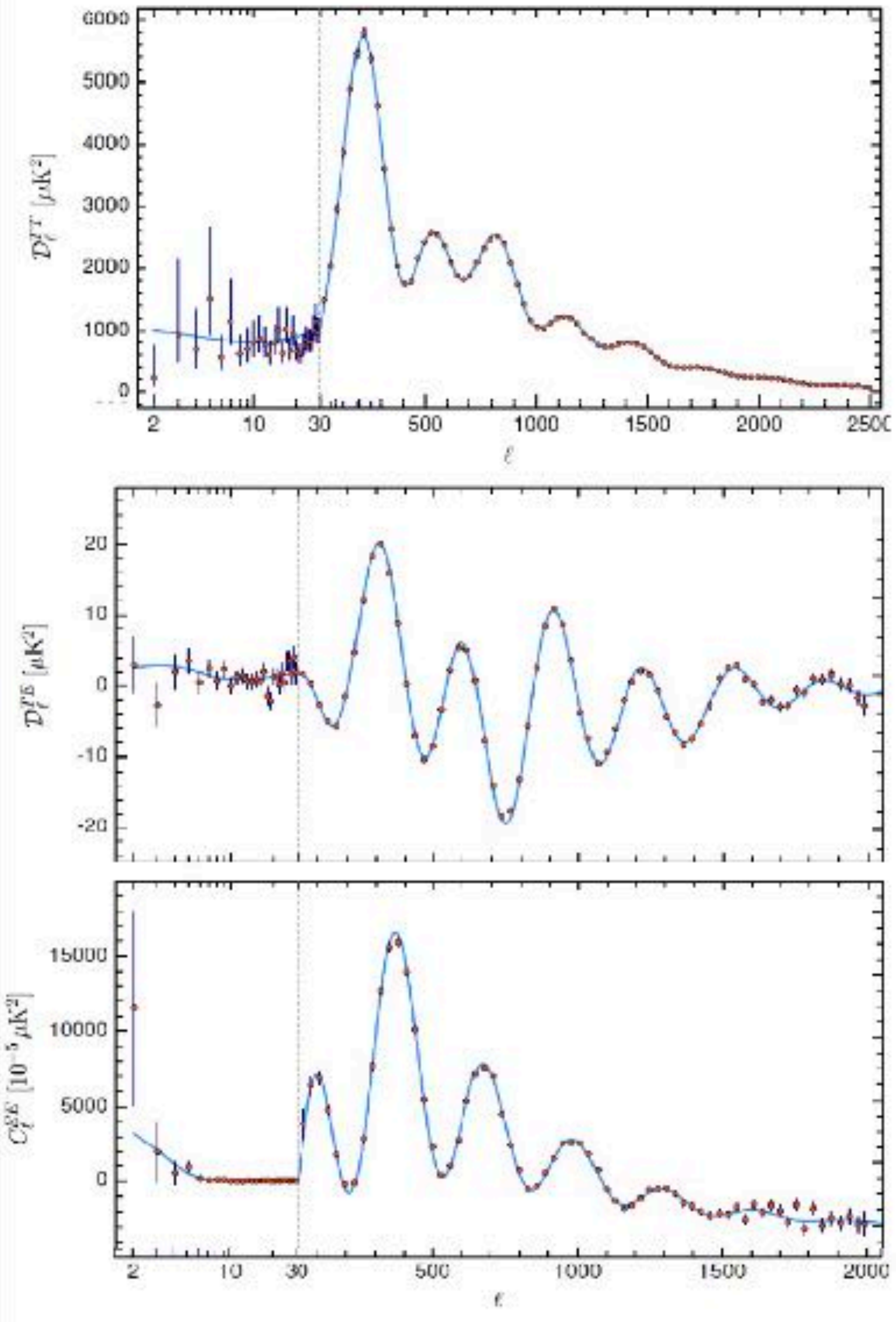


The Planck image of the Cosmic Microwave Background

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

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

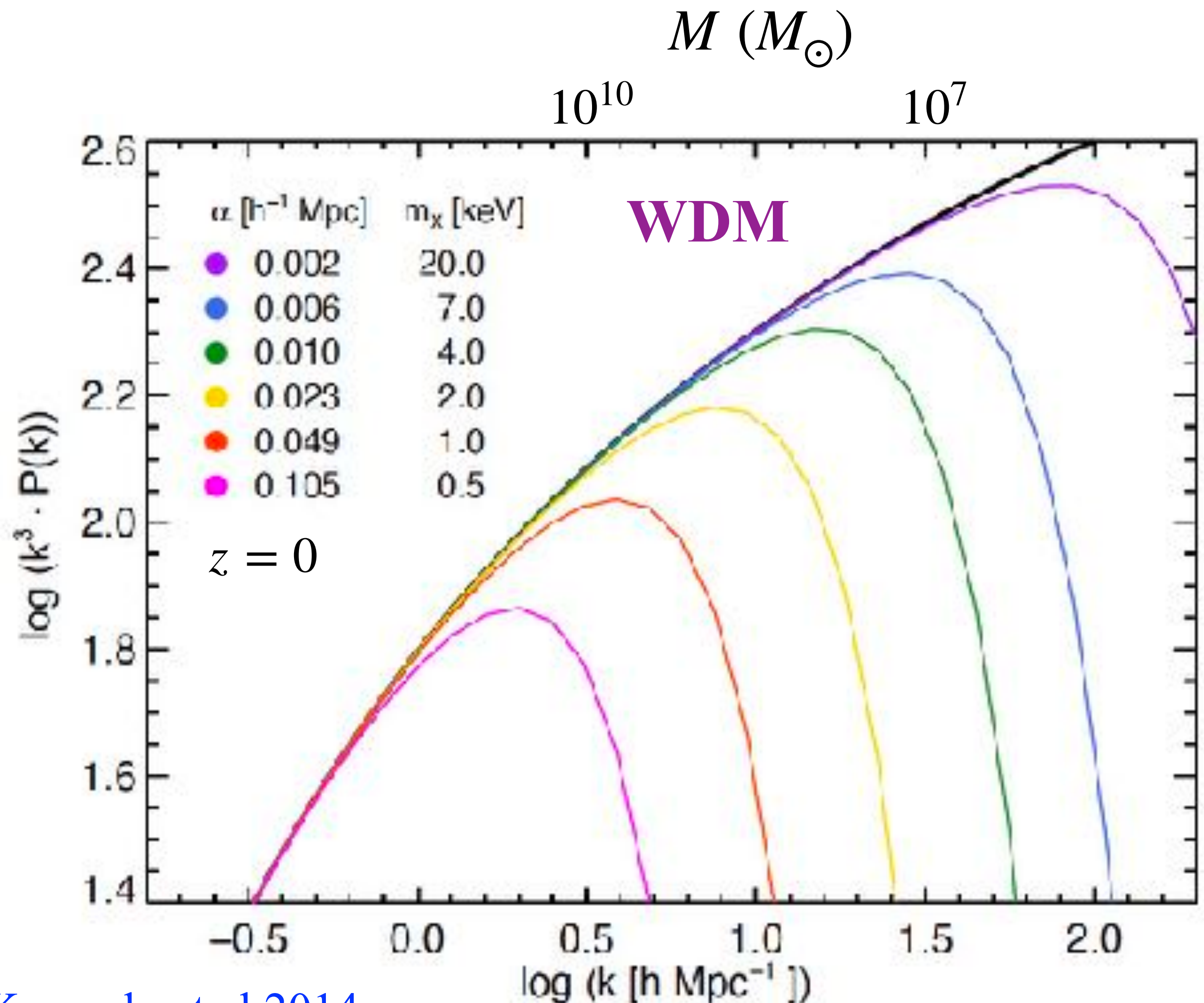
The astrophysical evidence for dark matter



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

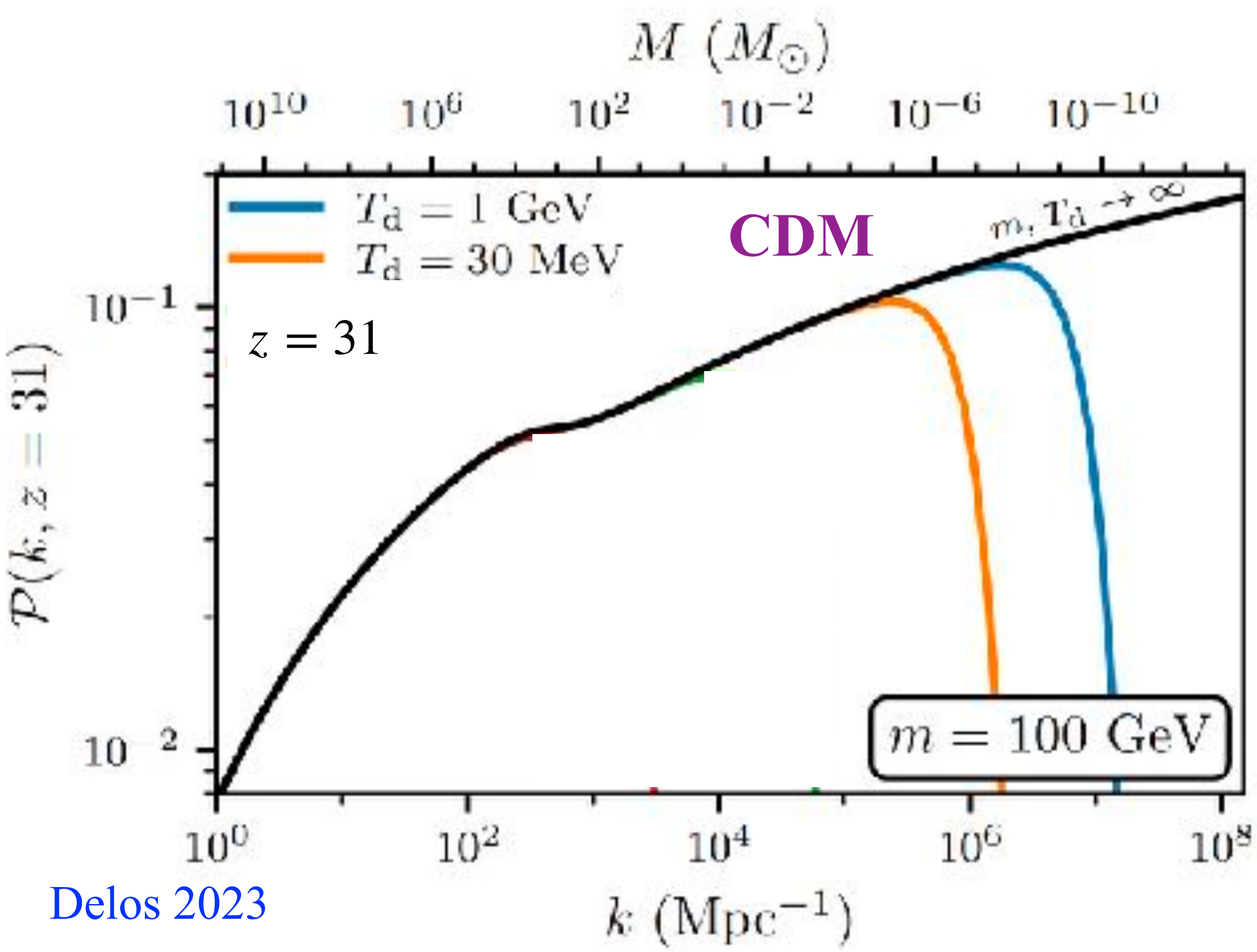
- Results from a single instrument (Planck/HFI)
- No local/low-redshift data are used
- Linear perturbation of a homogeneous medium
- No exotic/HE physics needed to set pattern
- Outside modified gravity regime
- Modelling cosmic structure formation requires extrapolation to smaller scales and later times



Kennedy et al 2014

For thermal relic Warm Dark Matter, free-streaming removes all linear structure at masses below

$$M_{\rm fs} \sim 10^{8}\ (m_\chi/3\ {\rm keV})^{-3}\ M_\odot$$



Delos 2023

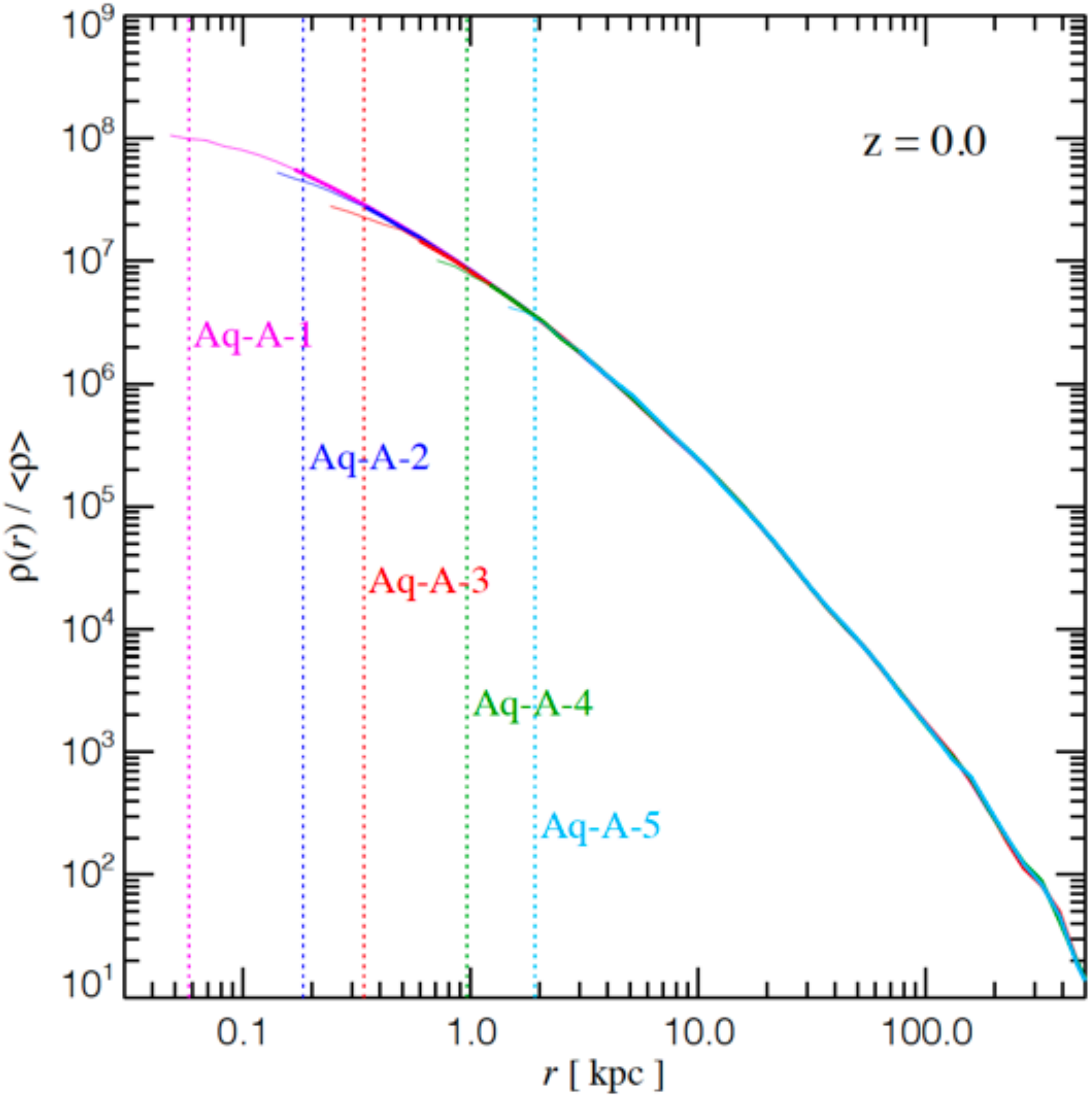
For a thermal relic Cold Dark Matter WIMP, the corresponding free-streaming mass is

$$M_{\rm fs} \sim 10^{-6}\ (m_\chi/100\ {\rm GeV}\ \ T_{\rm d}/30\ {\rm MeV})^{-3}\ M_\odot$$

where $T_{\rm d}$ is the kinetic decoupling temperature

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

Springel et al 2008

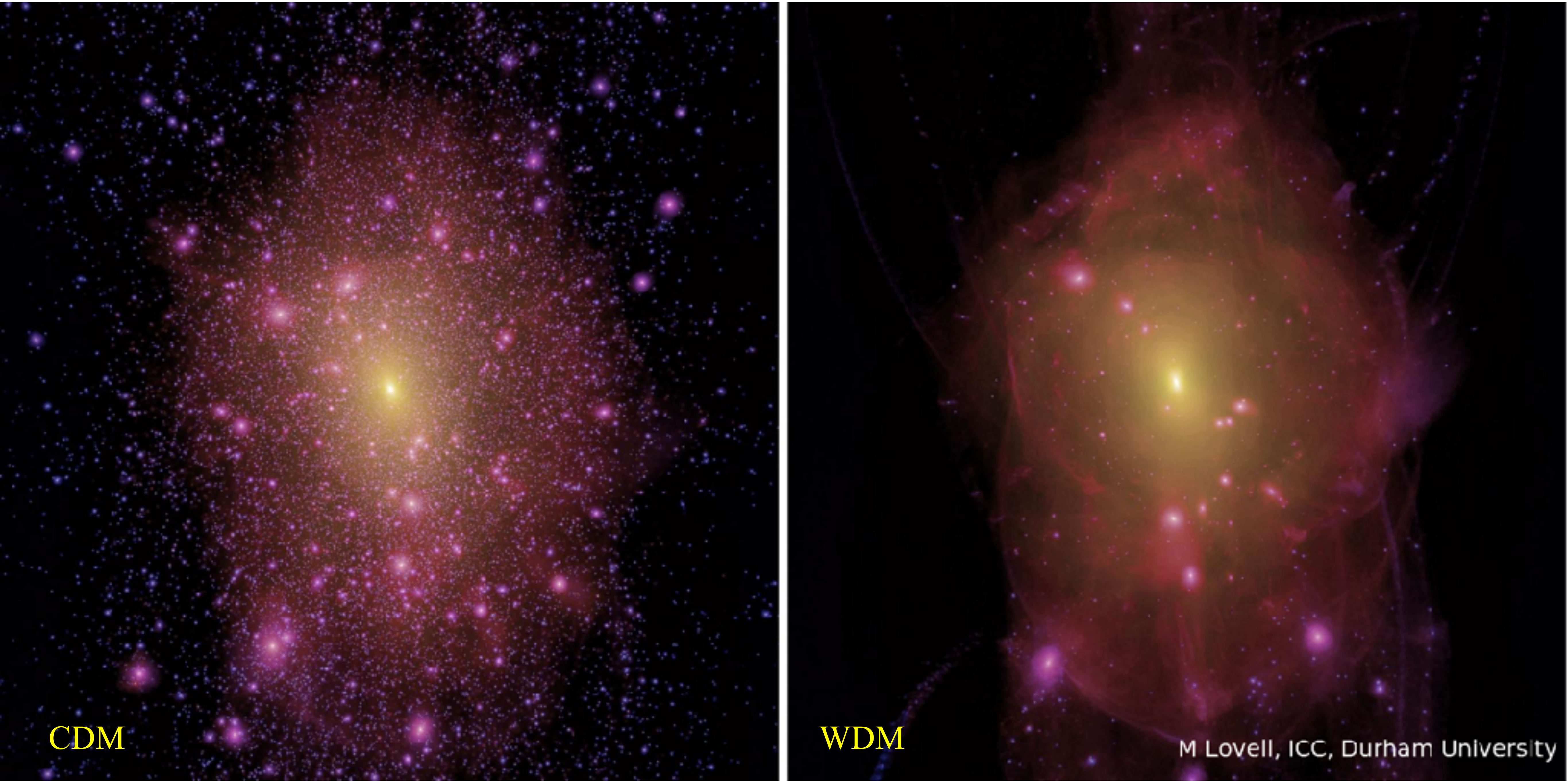


The NFW shape is a good fit over

6 orders of magnitude in density

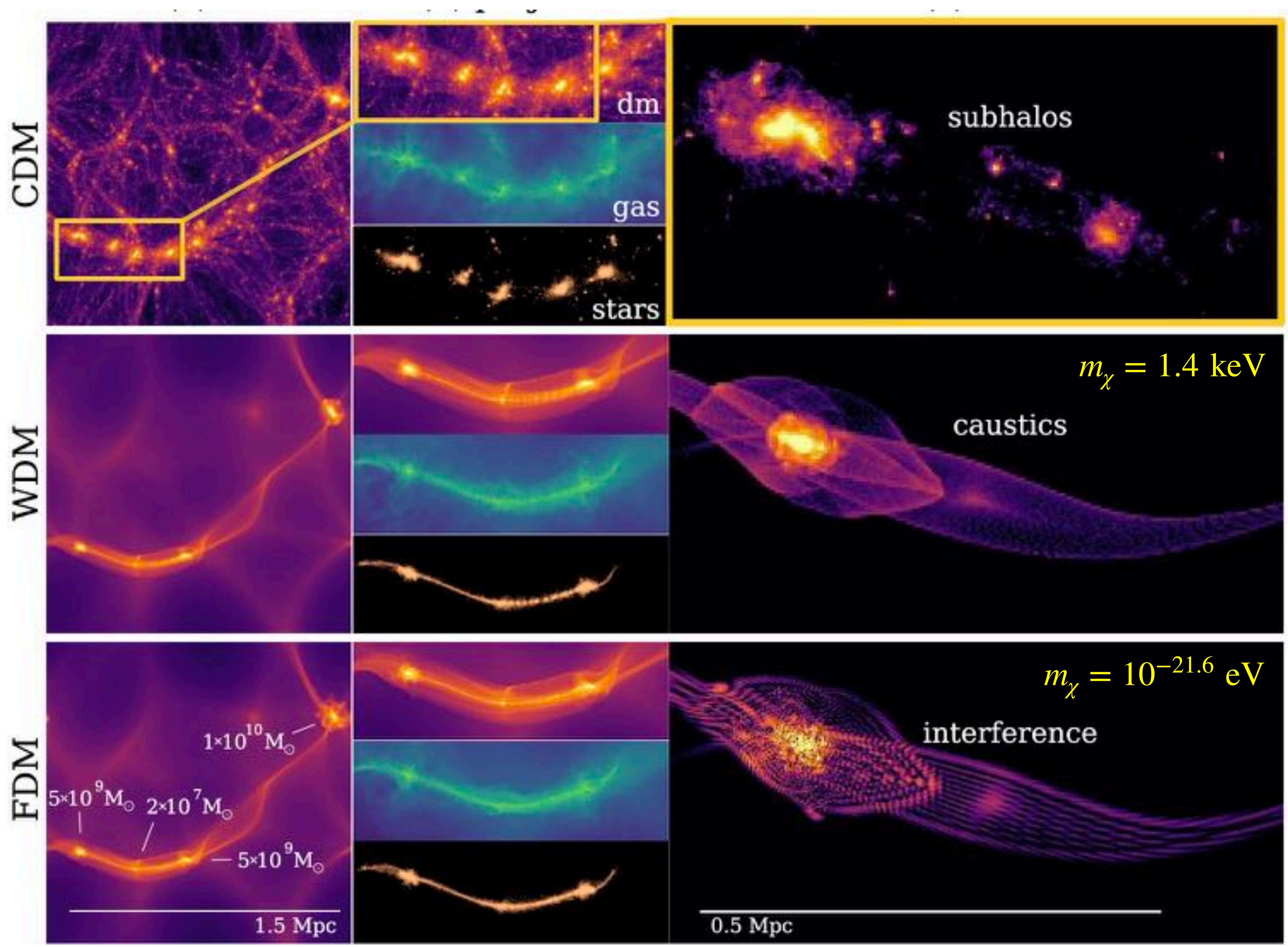
$$\rho_{\text{NFW}}(r) \approx r_{-2}^3 \rho_{-2} / r(r + r_{-2})^2$$

A Milky Way halo simulated in CDM and WDM



This WDM model assumes $m_\chi = 2$ keV, and can be excluded because of too little small-scale structure

A filament at z = 5.5 in CDM, WDM and FDM

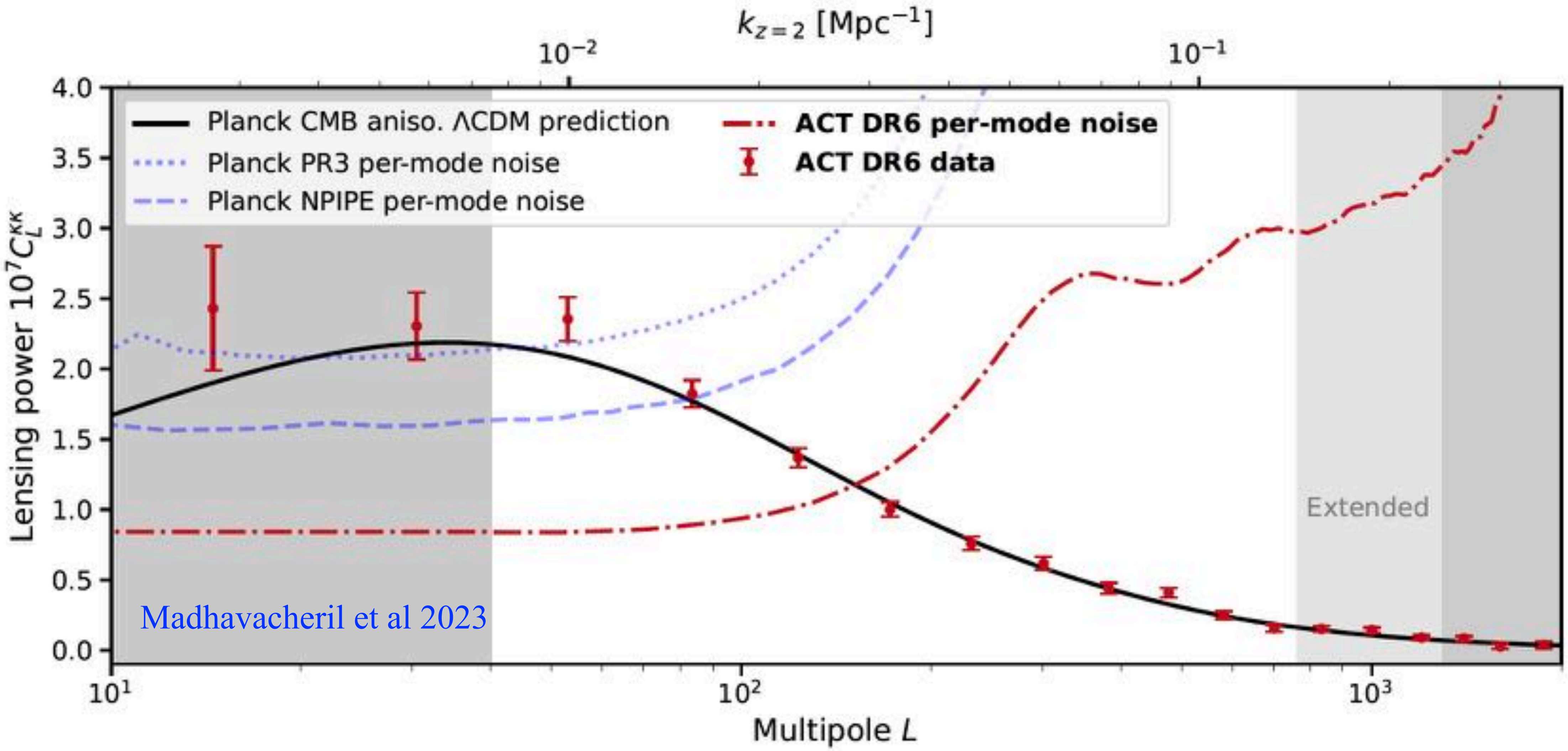


Mocz et al 2019

FDM here is an ultralight boson giving $M_{\rm fs}$ similar to the WDM case and $\lambda_{\rm deB}$ ~ a few kpc

It develops interference patterns in nonlinear regions and a central fluctuating soliton

Gravitational lensing of the CMB



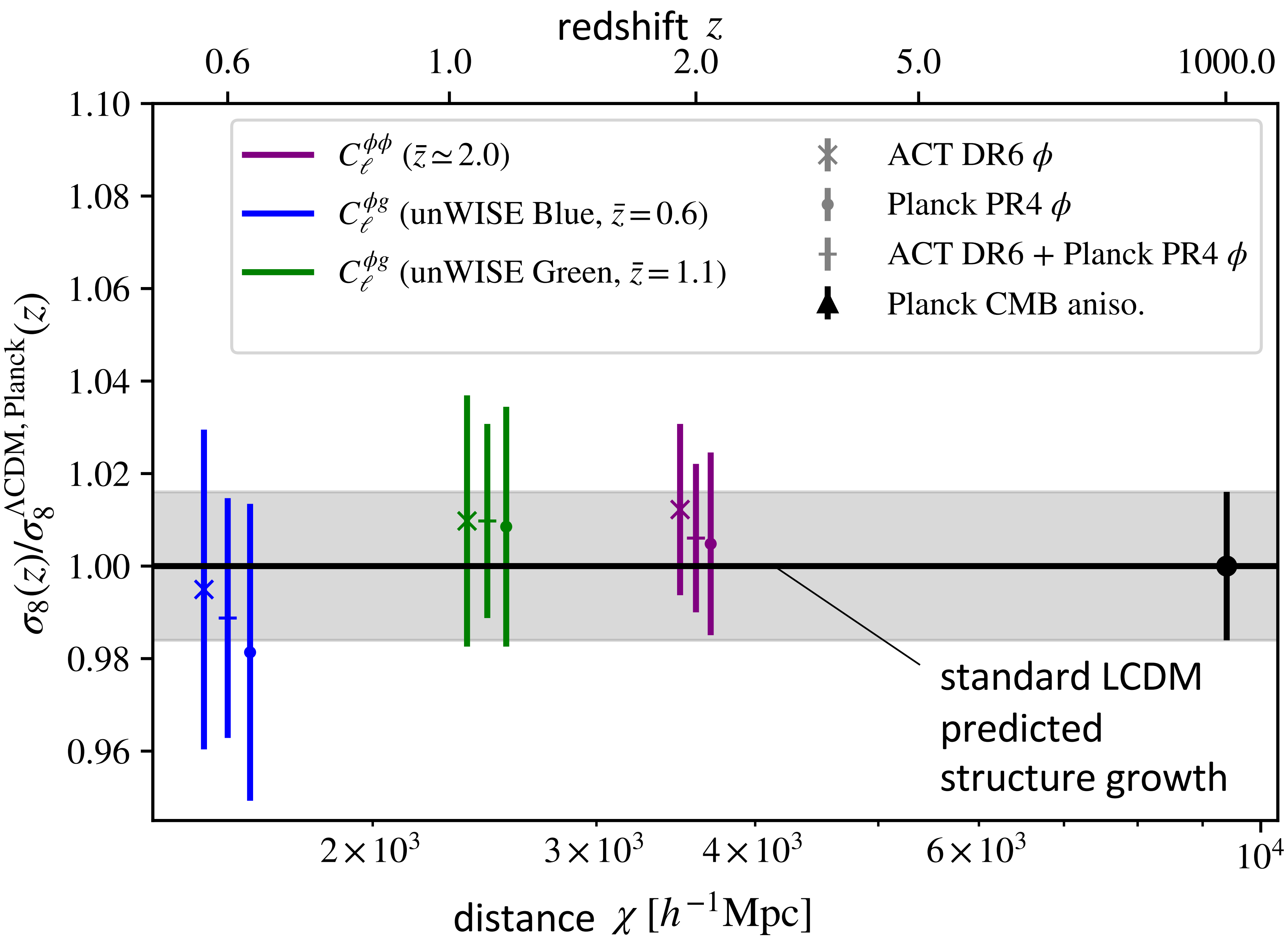
CMB lensing is sensitive to comoving scales $k^{-1} \sim 5$ to 200 Mpc averaged across $0.5 < z < 5$

Atacama Cosmology Telescope data agree perfectly with a Planck-based ΛCDM prediction

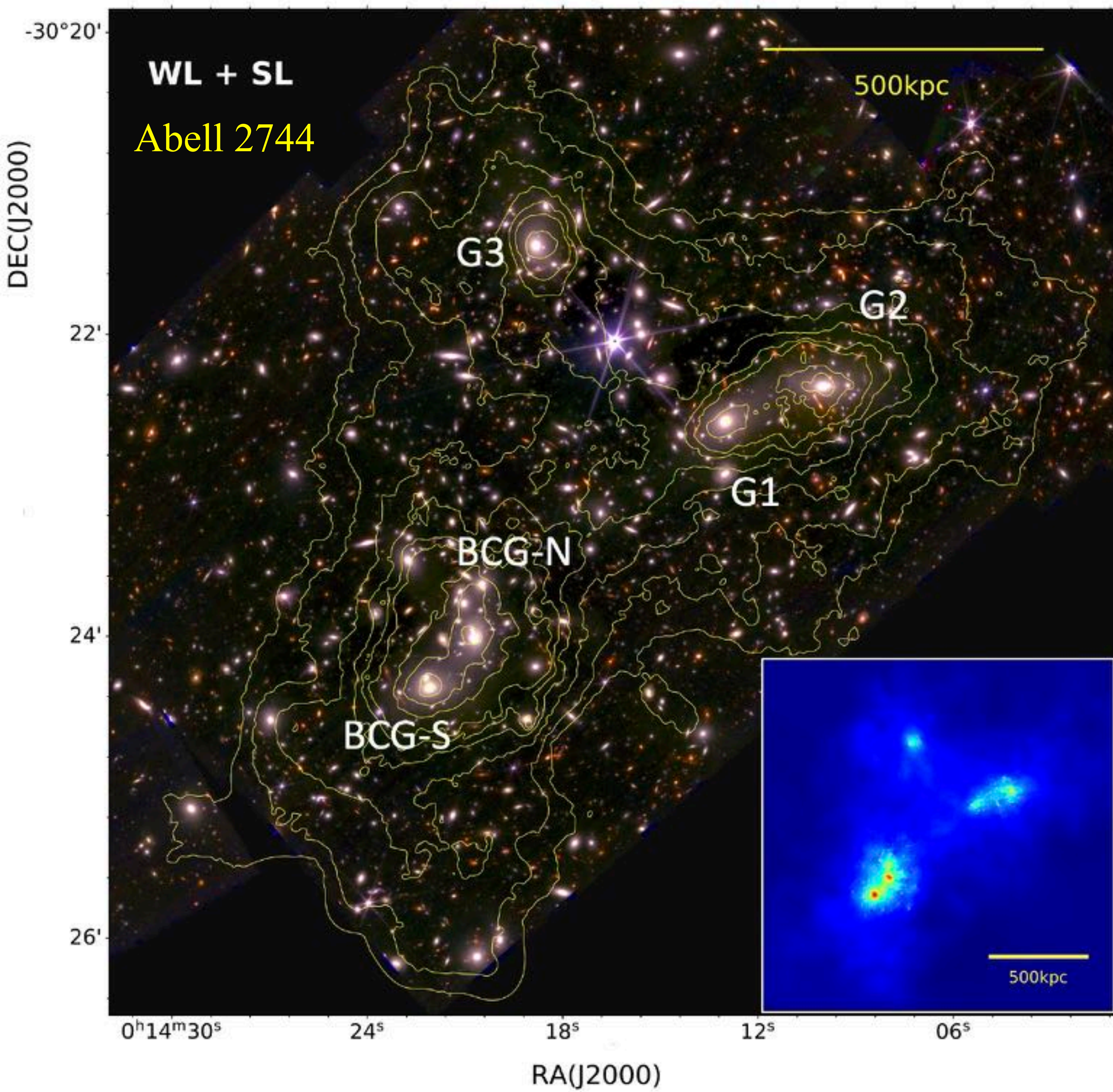
ACT lensing results summary: structure growth vs. redshift (relative to LCDM)

- Three ACT observables at different redshifts– lensing power z~2, x unWISE green z~1.1, x unWISE blue z~0.6:

- Structure growth with time follows LCDM prediction (n.b. on large scales)



Slide from Blake Sherwin



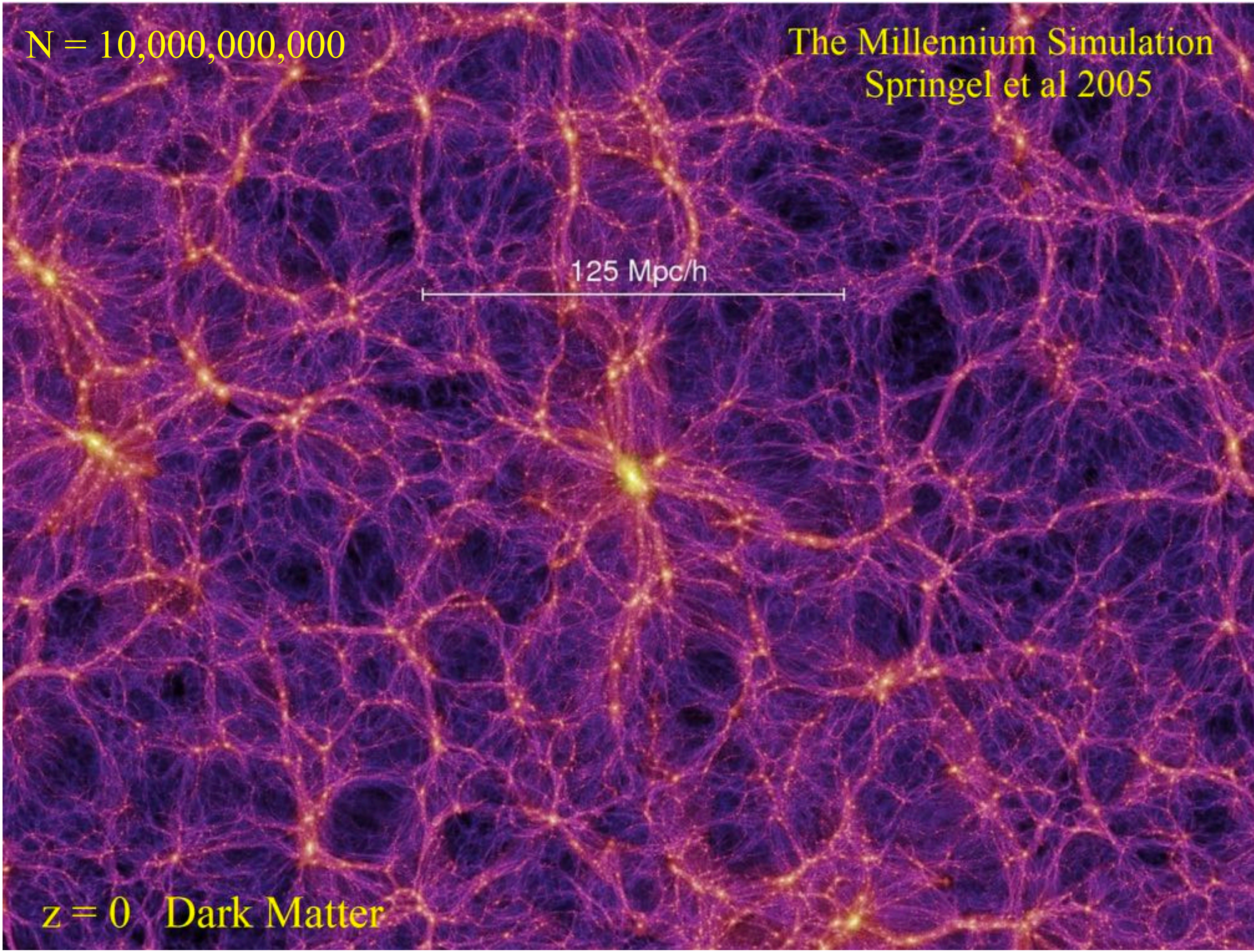
The mass distribution of a rich $z = 0.31$ galaxy cluster reconstructed from strong+weak gravitational lensing observations

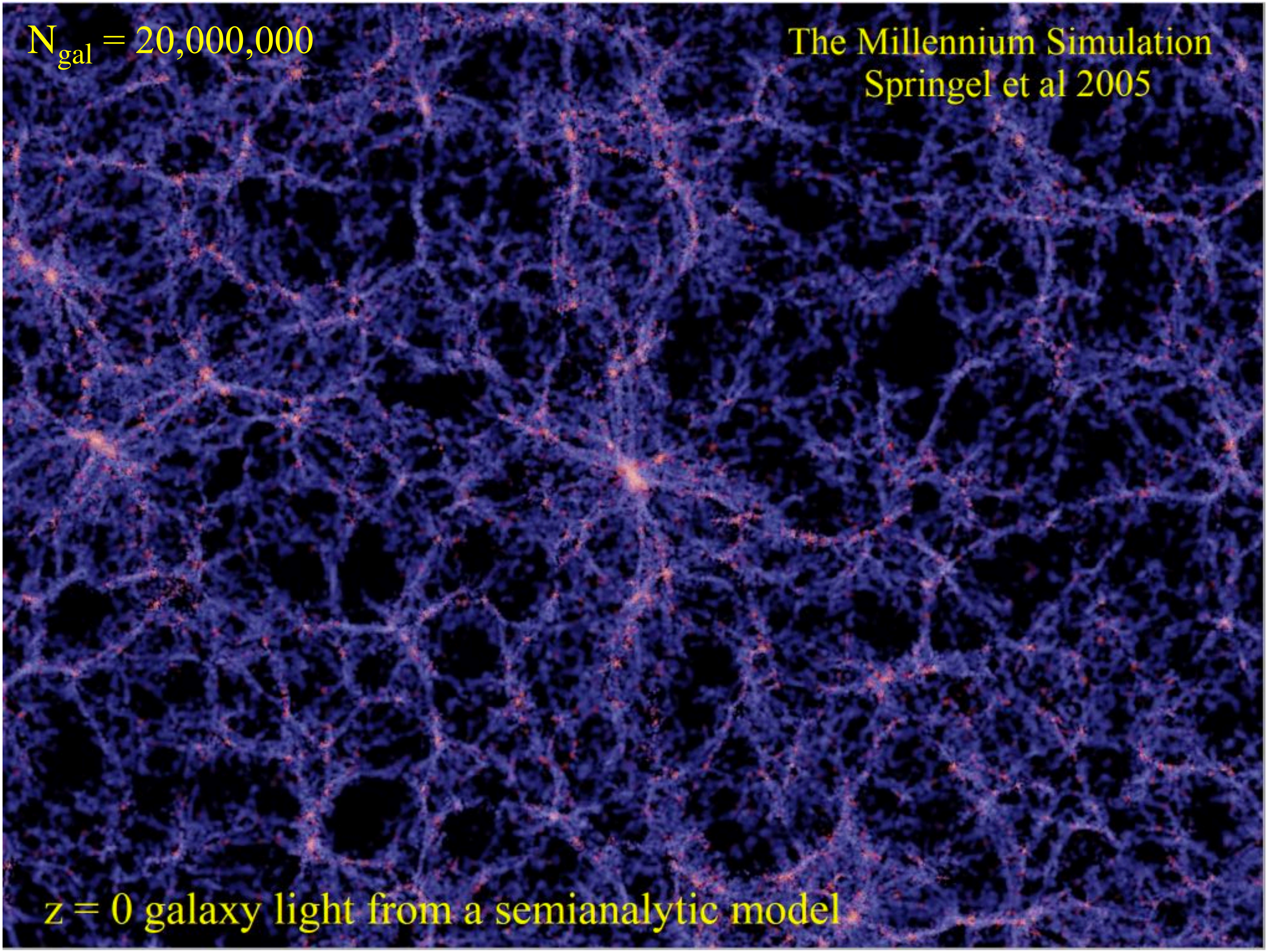
JWST data

286 SL multiple images

350 WL images/arcmin^2

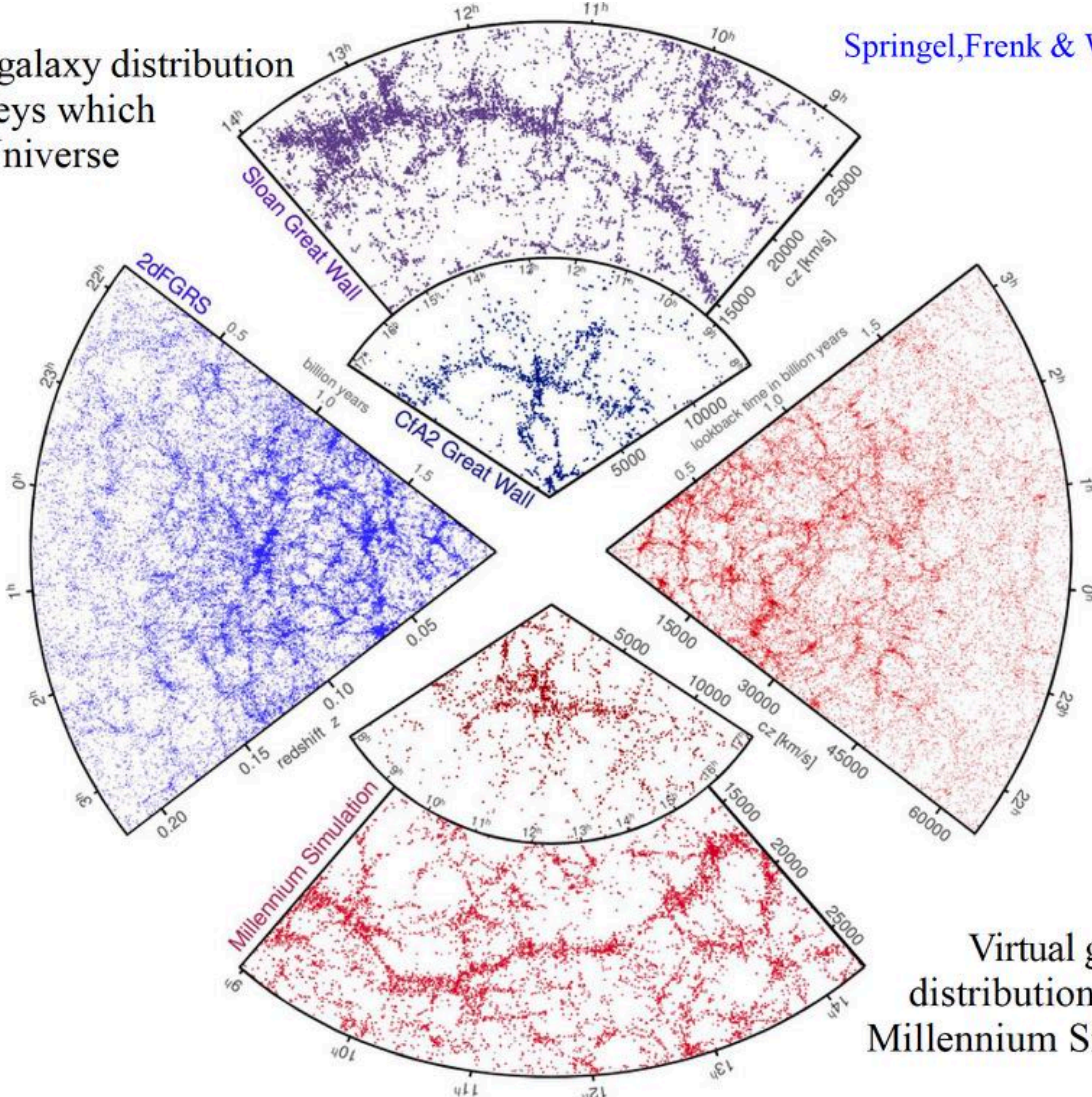
Cha et al 2023


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

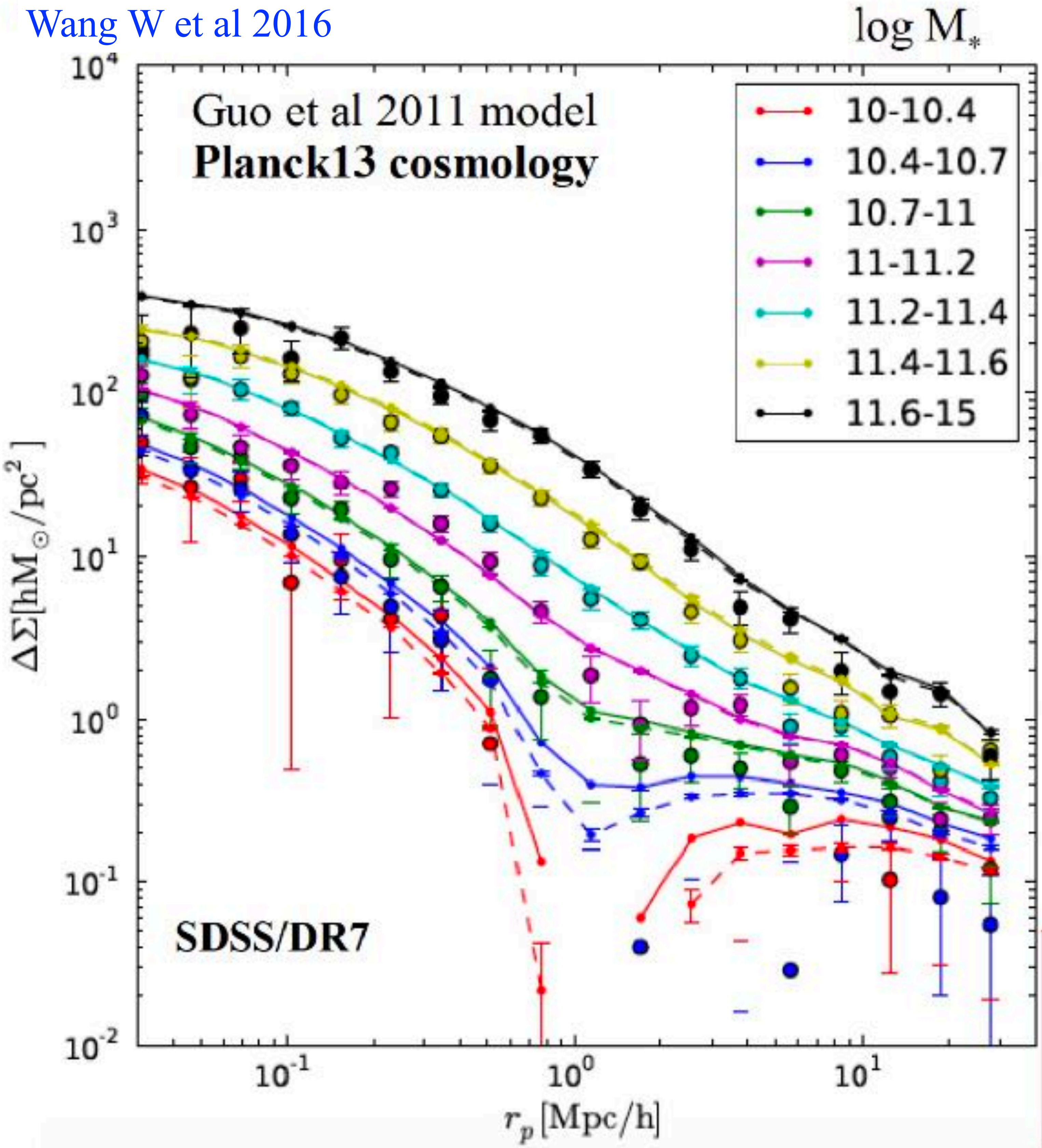
Springel,Frenk & White 2006



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

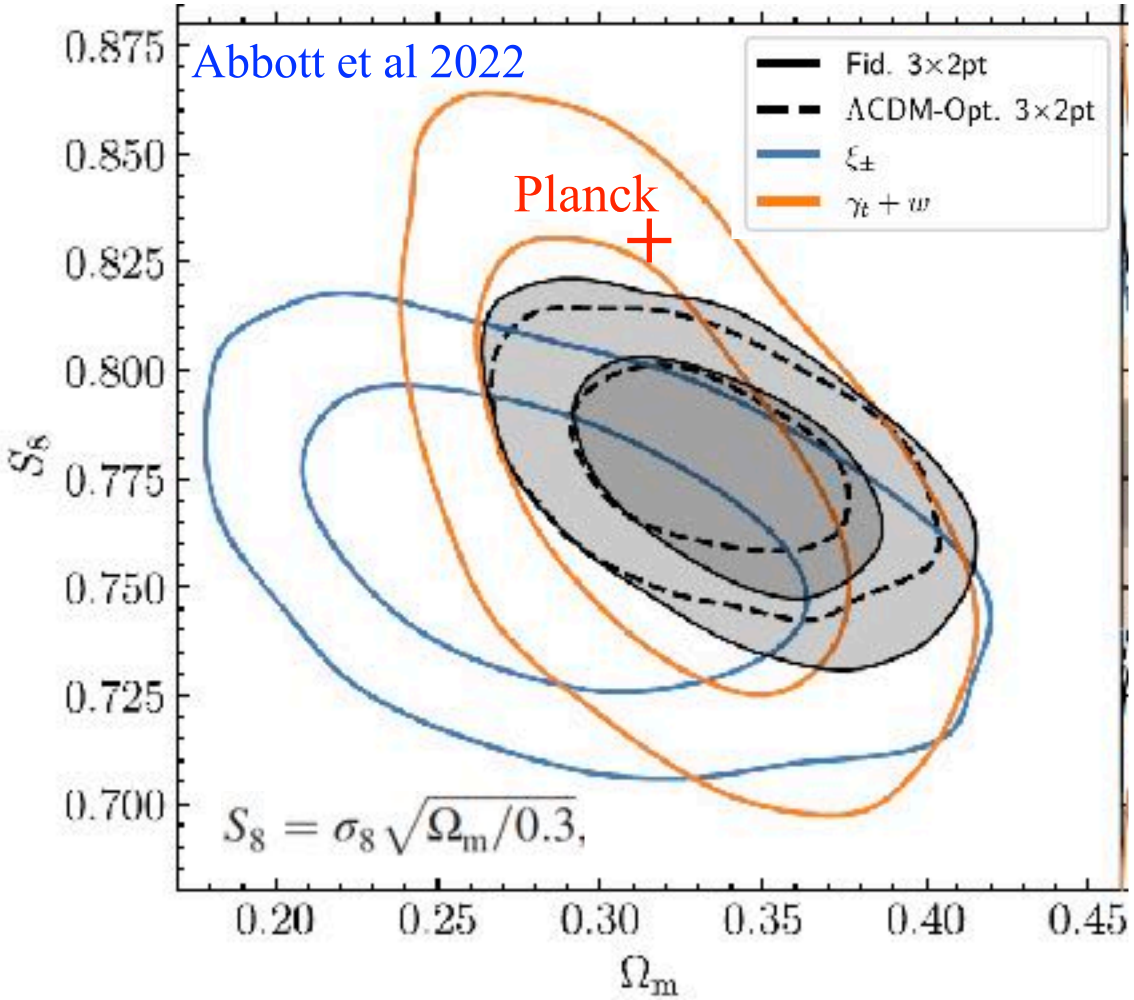
Top to bottom goes from rich clusters to "Milky Way" groups

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

Large-scale structure in the ΛCDM cosmology



Useful to estimate cosmological parameters, here the DES year 3 results for Ω_m and σ_8 derived from cosmic shear, galaxy-galaxy lensing and galaxy clustering.

Similarly BAO measurements constrain D.E. parameters

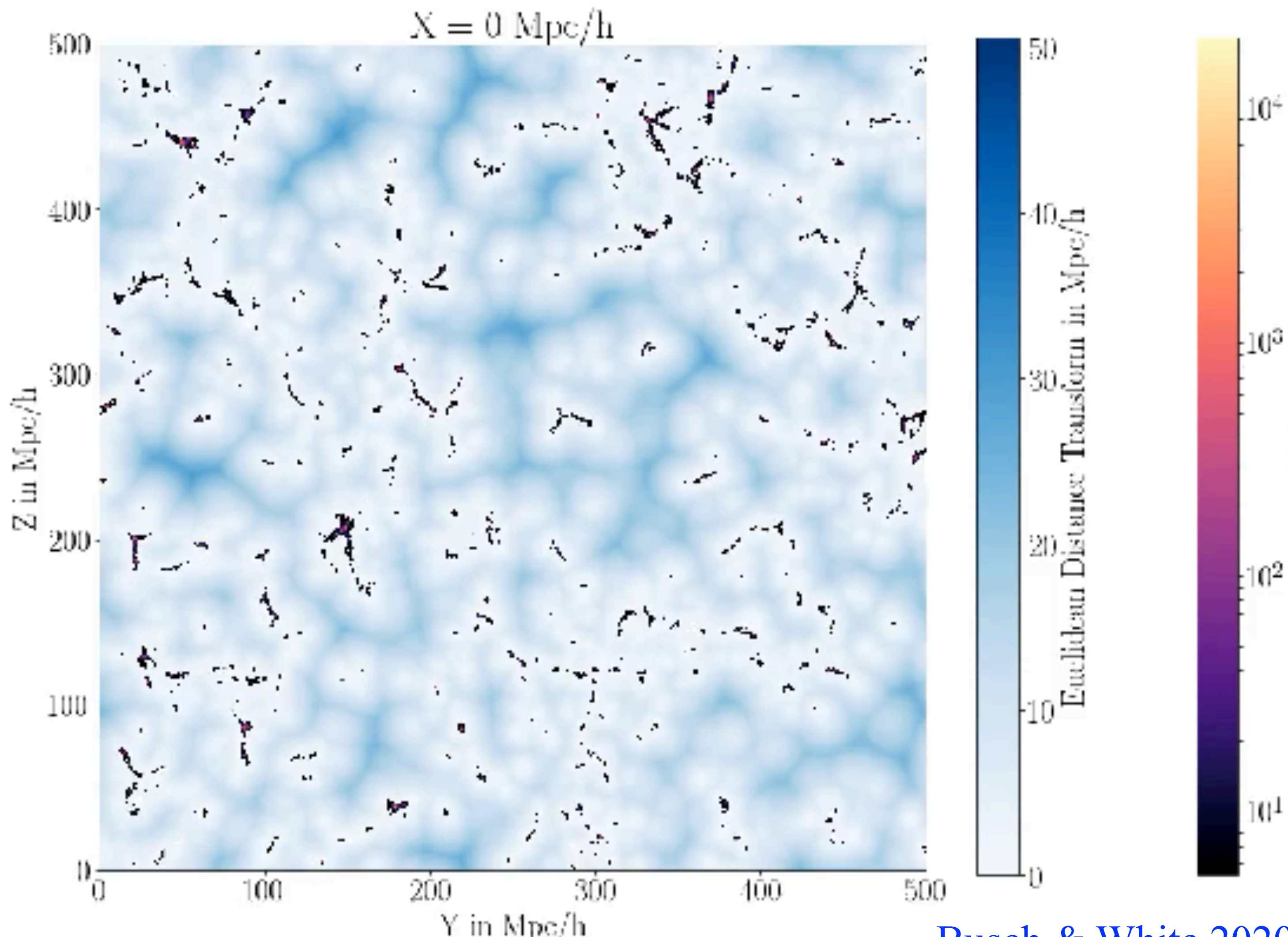
Clustering will soon constrain/measure Σm_ν

Present-day LSS is nonlinear and nongaussian

Here the largest single connected object with local $\rho/\bar{\rho} > 5$ is shown in black where it intersects a thin slice through the simulation

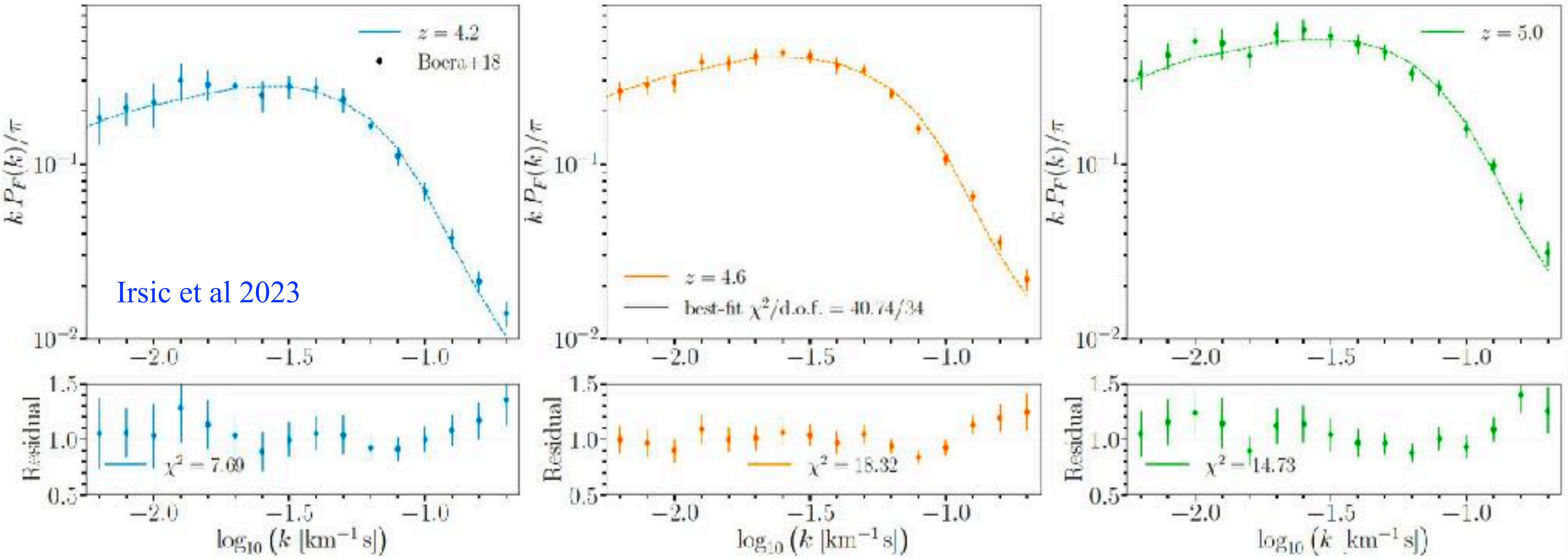
$f_{\rm mass} = 0.35 \qquad f_{\rm volume} = 0.006$

The cosmic web is very filamentary, but does not constrain viable DM models



Busch & White 2020

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

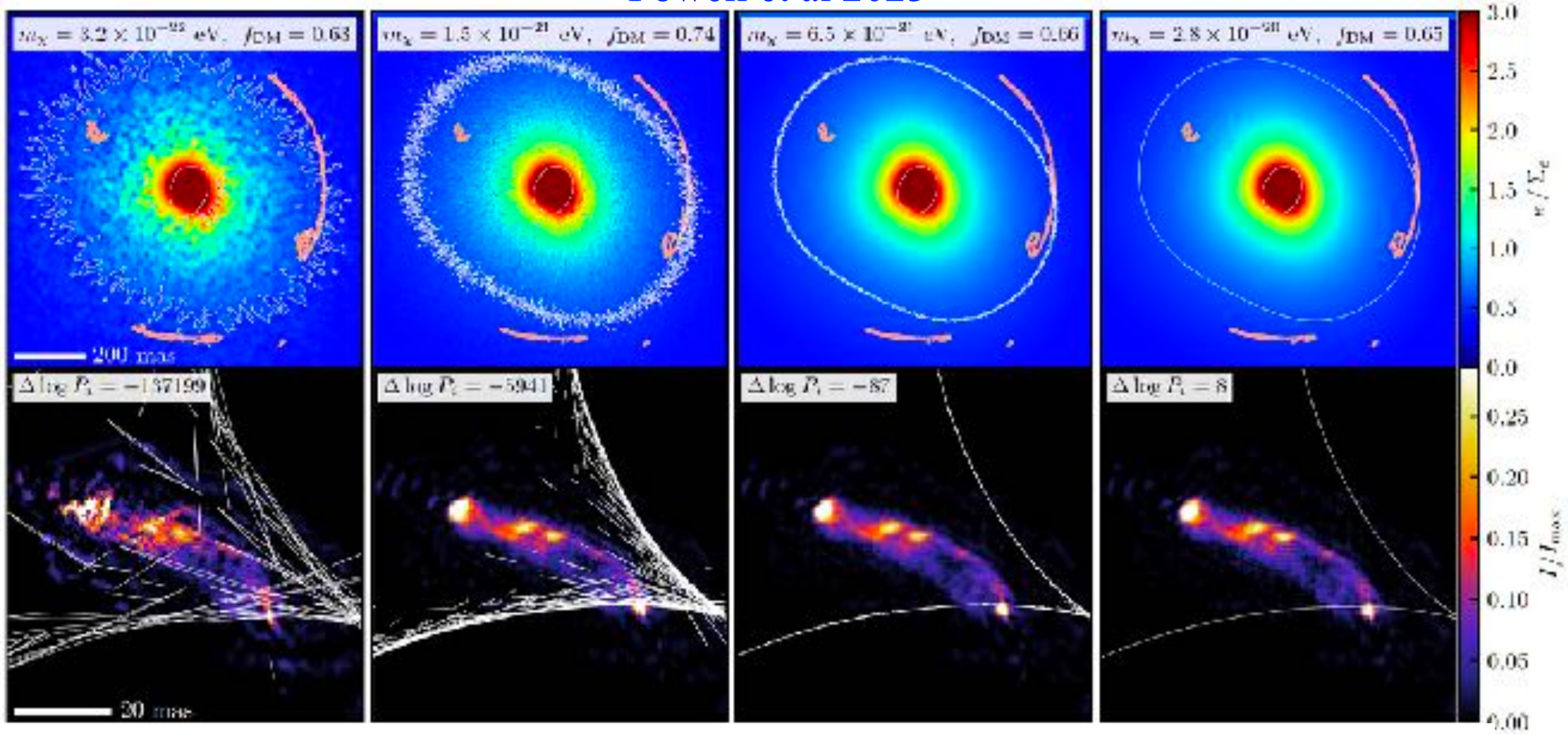
Warm Dark Matter is excluded for $m_\chi <$ 5.7 keV at 2σ Irsic et al 2023

Fuzzy Dark Matter is excluded for $m_\chi <$ $2\ 10^{-20}$eV at 2σ Rogers & Peiris 2021

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

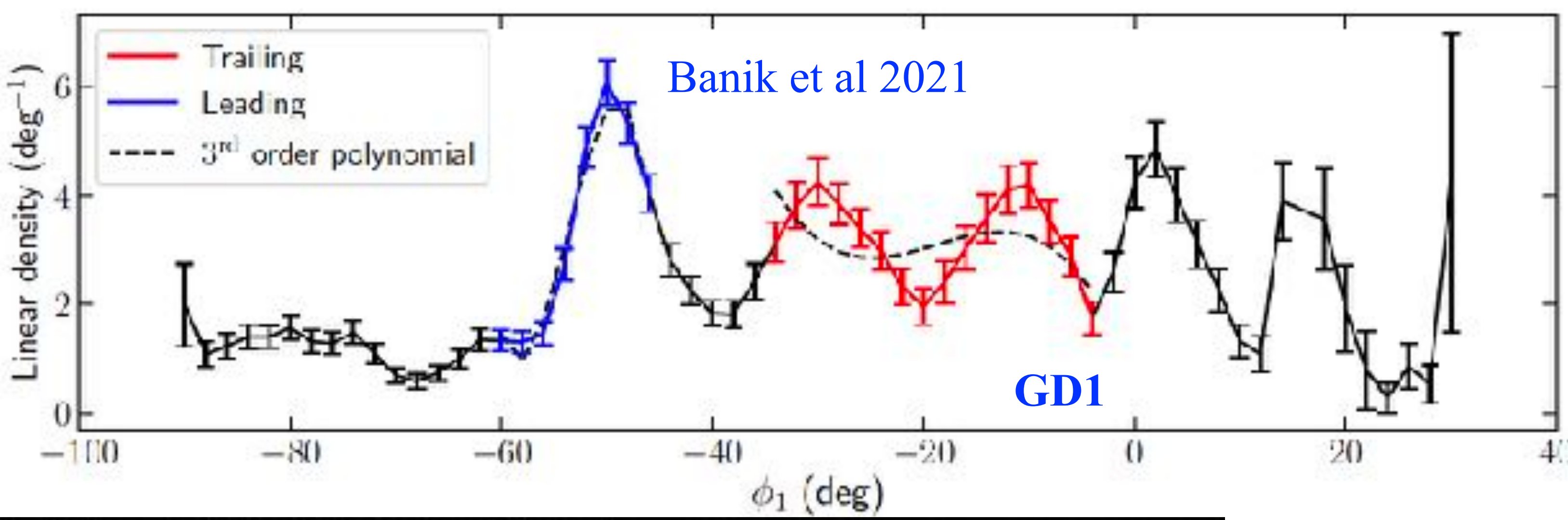
FDM constraints

Powell et al 2023



VLBI image of a strongly lensed radio source

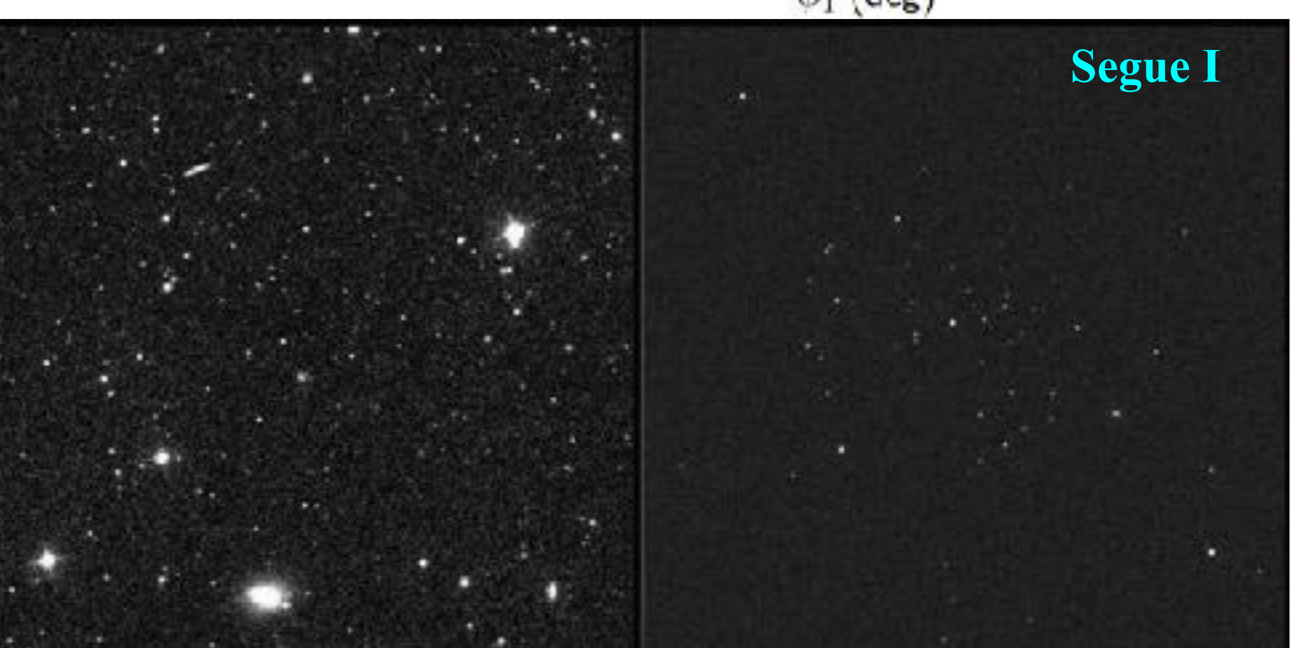
$$m_\chi > \; 4.4 \; 10^{-21} \text{ eV at } 2\sigma$$



Perturbations of stellar streams in the Milky Way's halo

$$m_\chi > \; 1.4 \; 10^{-21} \text{ eV at } 2\sigma$$

but this *ignores* interference effects



Structure of the ultrafaint dwarf galaxy, Segue I

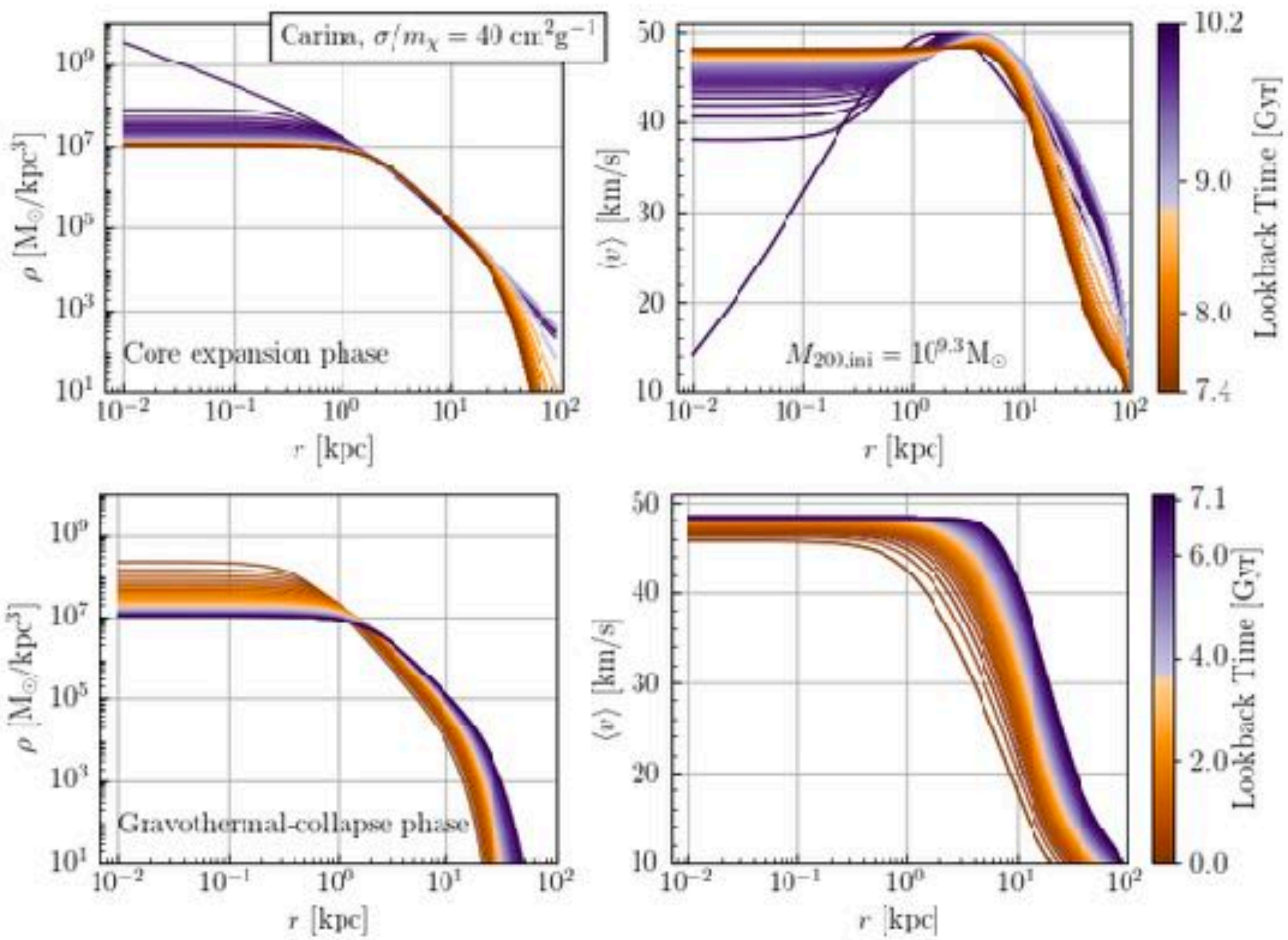
$$R_{1/2} = 24 \text{ pc}, \quad M_* \sim 200 \; M_\odot, \quad \sigma = 4 \text{ km/s}$$

$$m_\chi > \; 4 \; 10^{-19} \text{ eV at } 2\sigma$$

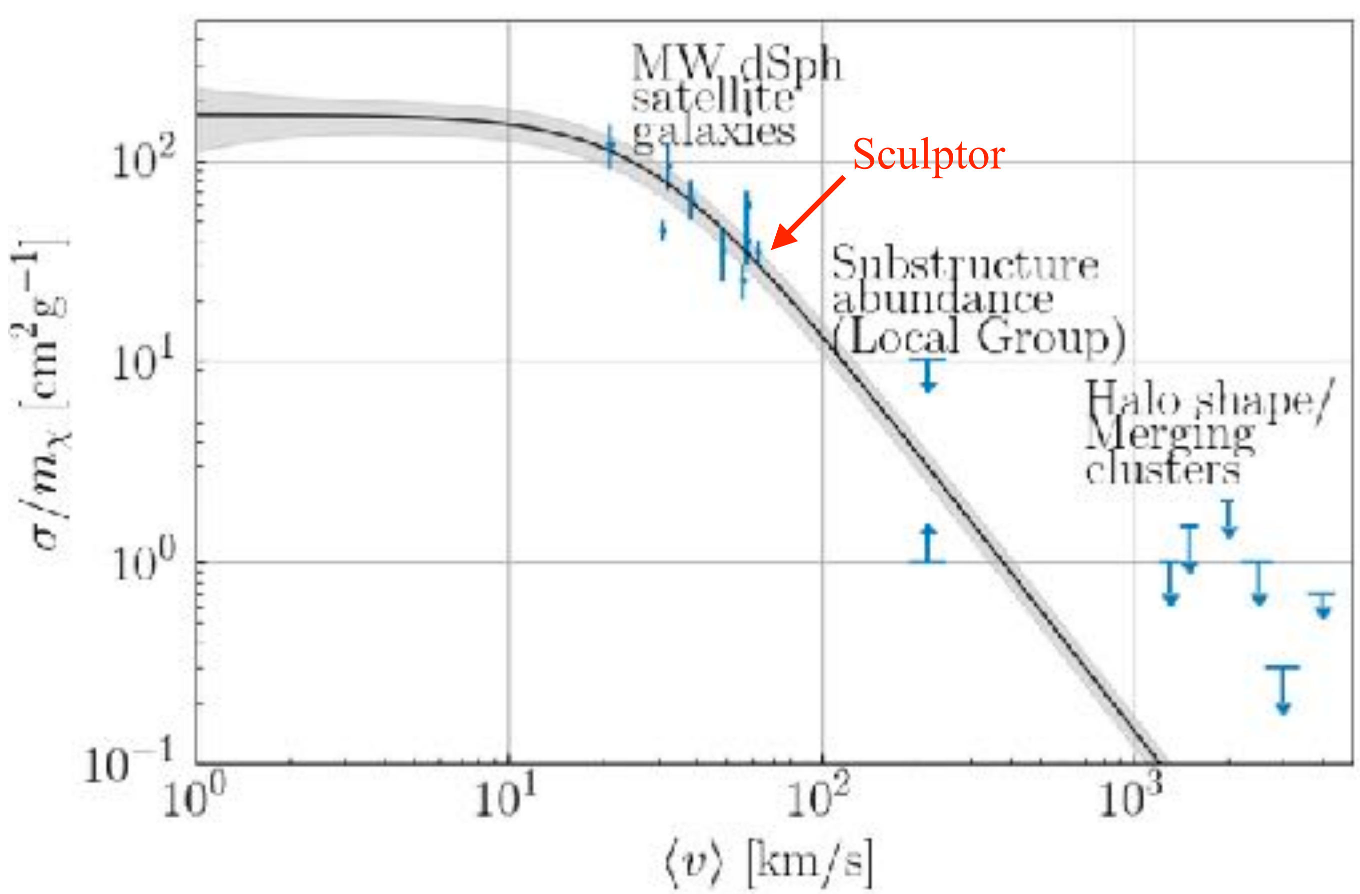
Dalal & Kravtsov 2022

c.f. Xinyu Li on Tuesday

Self-interacting Dark Matter



Correa 2021



$t_{\mathrm{coll}} \propto (\rho\ \langle\sigma/m\rangle\ v)^{-1}$ ⟶ the strongest cross-section constraints come from massive clusters.

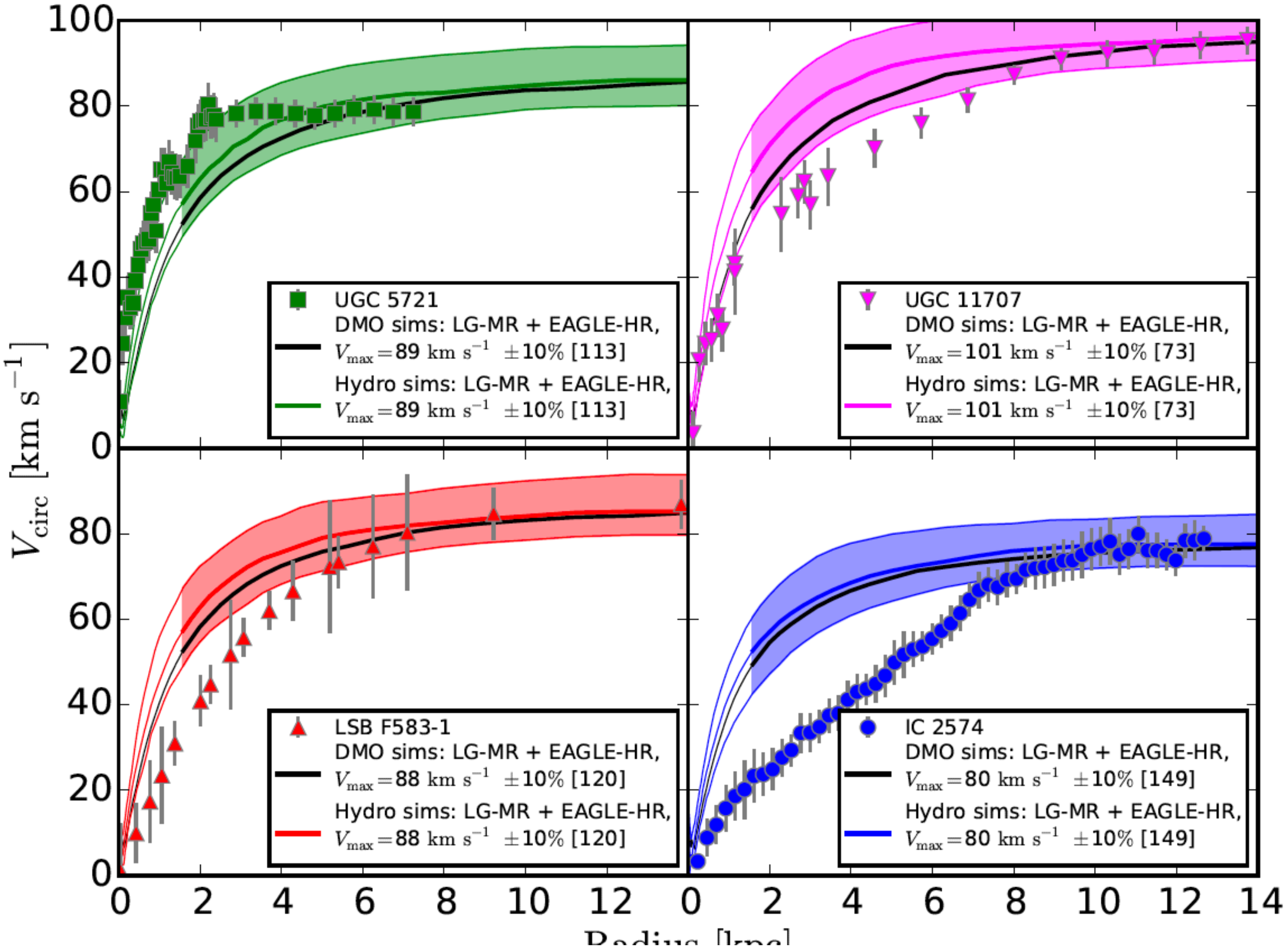
The absence of collisional effects in clusters ⟶ $\langle\sigma/m\rangle \propto v^{-1}$ is necessary to get core formation or core collapse in dwarf halos.

There is no consensus that cores are needed in the *halos* of the MW's dwarf satellite galaxies — NFW halos also fit the observations —

No clear evidence prefers SIDM over CDM

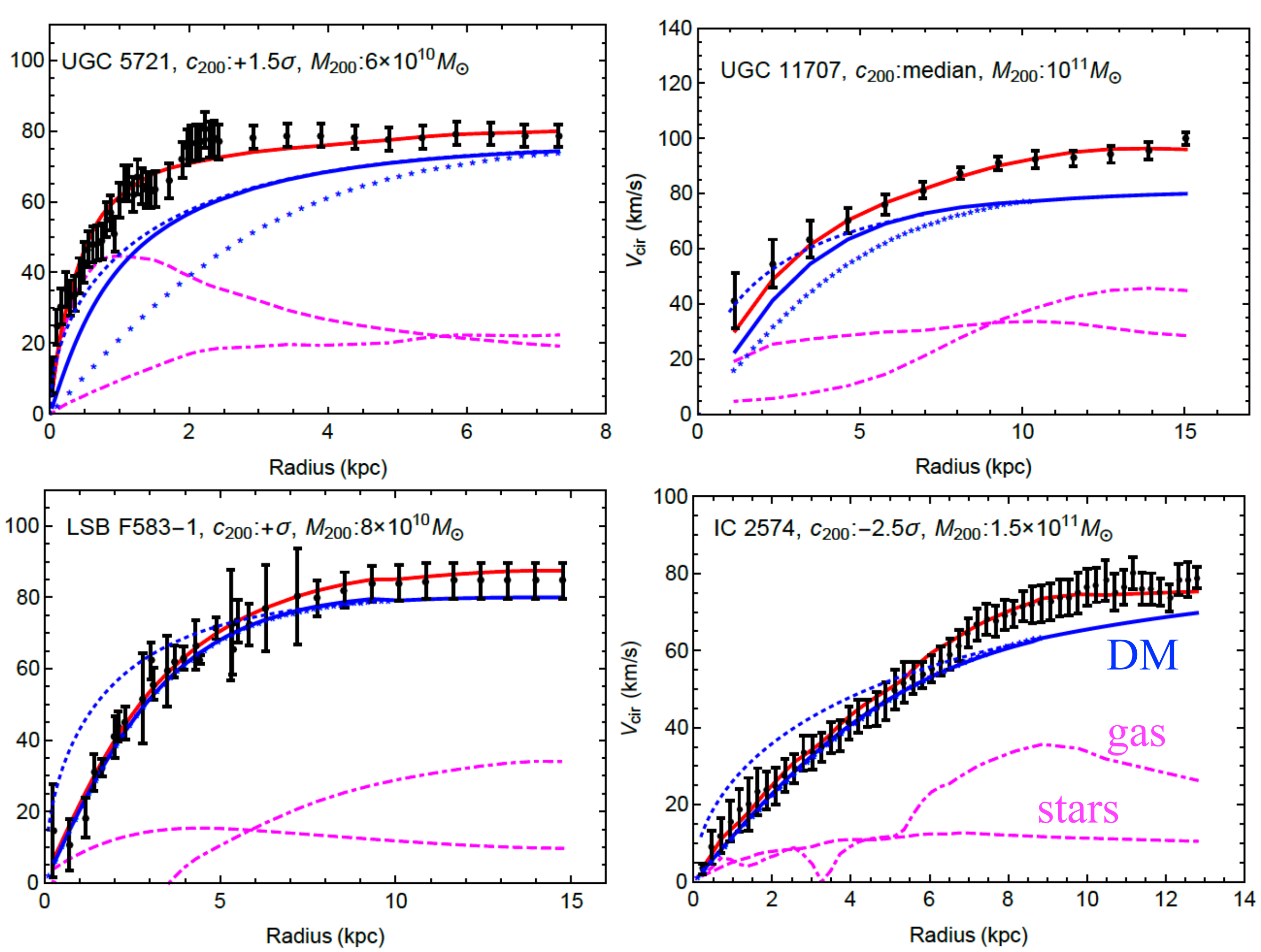
c.f. Haibo Yu on Tuesday

Rotation curve diversity



Rotation curves of dwarf spiral galaxies with similar maximum values can have very different shape

These do not appear to be reproduced by ΛCDM simulations of galaxy formation Oman et al 2015

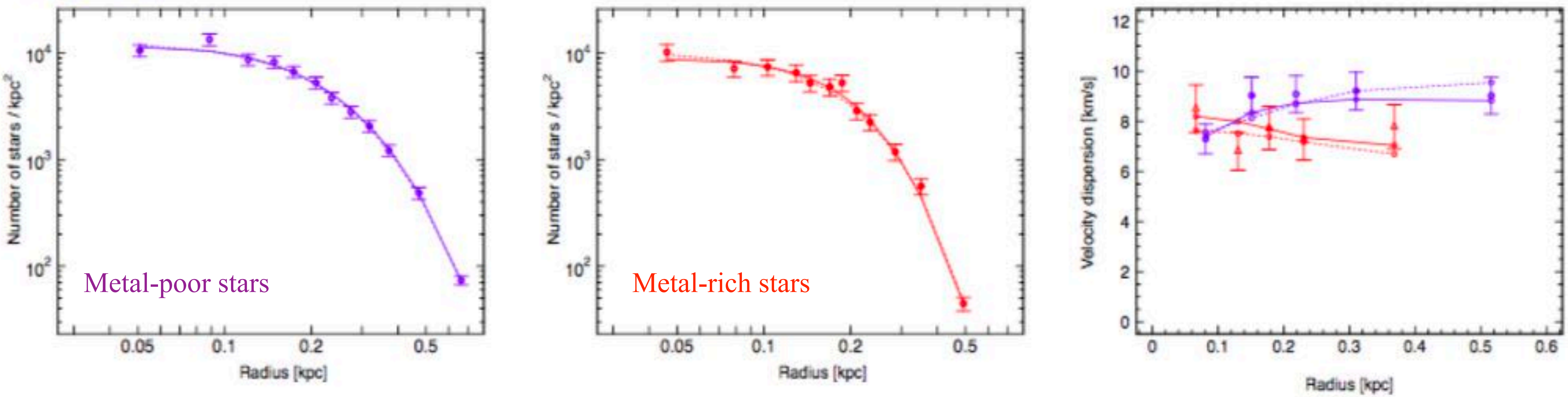


They can be accomodated by SIDM simulations with $\langle \sigma/m \rangle = 3\ \mathrm{g/cm^2}$ Kamada et al 2016

Rotation curve interpretation is difficult because the galaxies are irregular with noncircular motions

Two population fits to the stellar kinematics of Sculptor

Strigari et al 2017



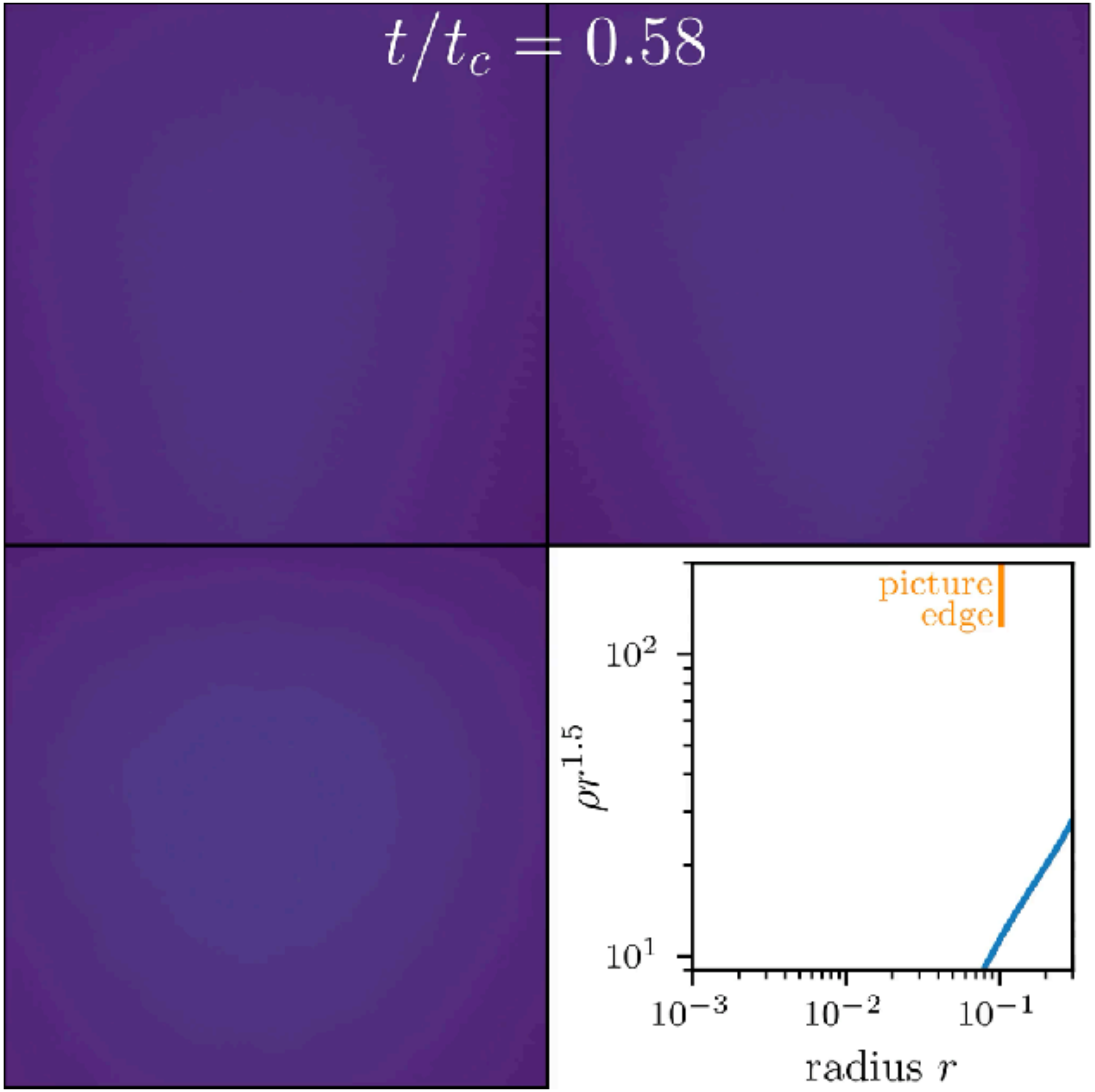
Good simultaneous fits can be found to the star count and velocity dispersion data from WP11 for both MR and MP stars

WP11 = Walker & Penarrubia 2011

The fits for cored (Burkert) and cusped (NFW) potentials are equally good

The parameters found for NFW profiles are consistent with those expected from simulations of the standard ΛCDM model

Prompt cusp formation in a ΛCDM density peak



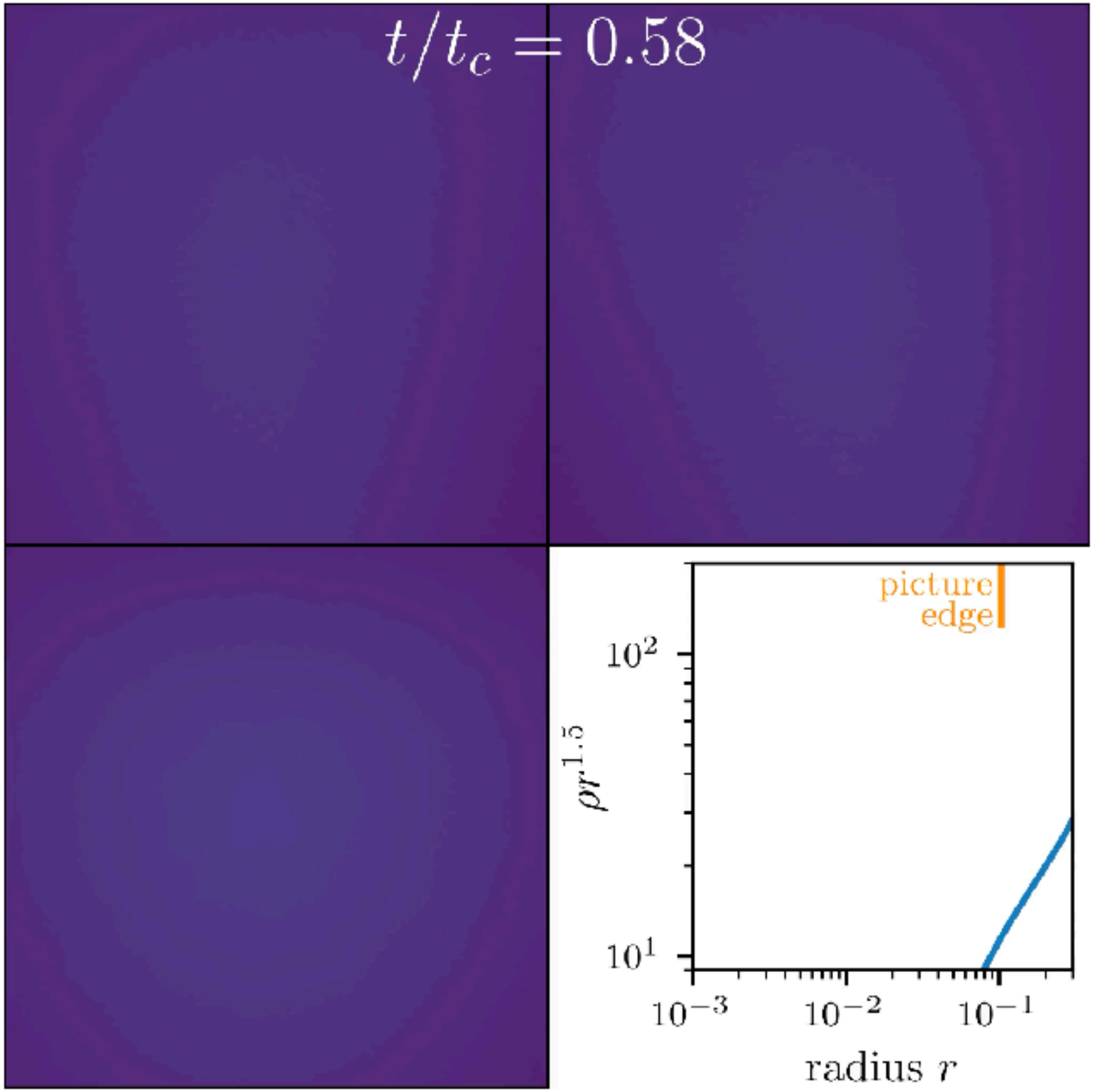
$t_c \longrightarrow z = 87$

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

Delos & White 2023

See talk by Sten Delos

Prompt cusp formation in a ΛCDM density peak



Delos & White 2023

$t_c \longrightarrow z = 87$

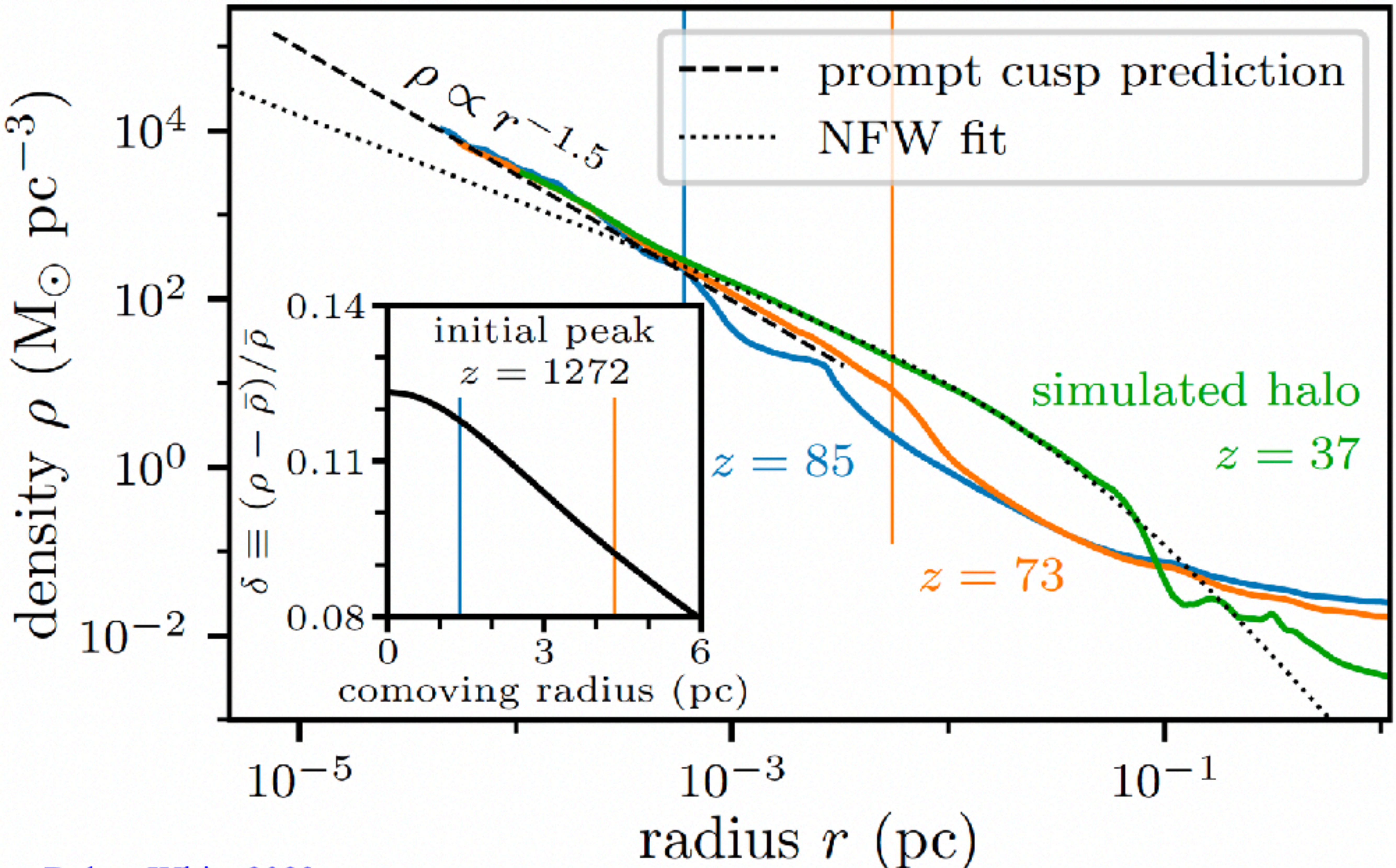
$M_{pk} \sim 10^{-6} M_{\rm sun}$

Prompt cusp formation differs from that of “normal” dark matter haloes

It is not hierarchical, involves no mergers, and produces universal structure which is **not** NFW

See talk by Sten Delos

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

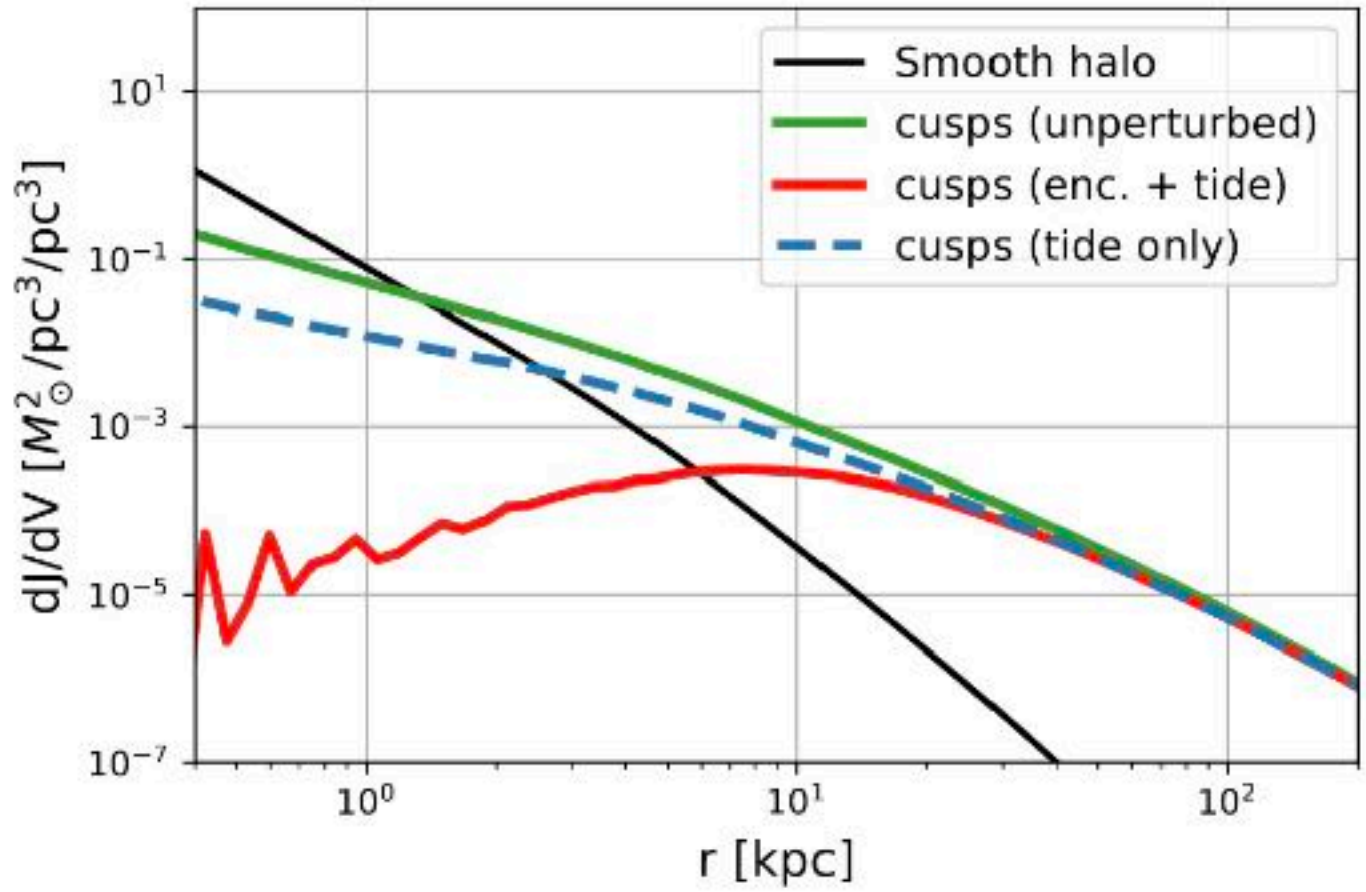


Delos+White 2023

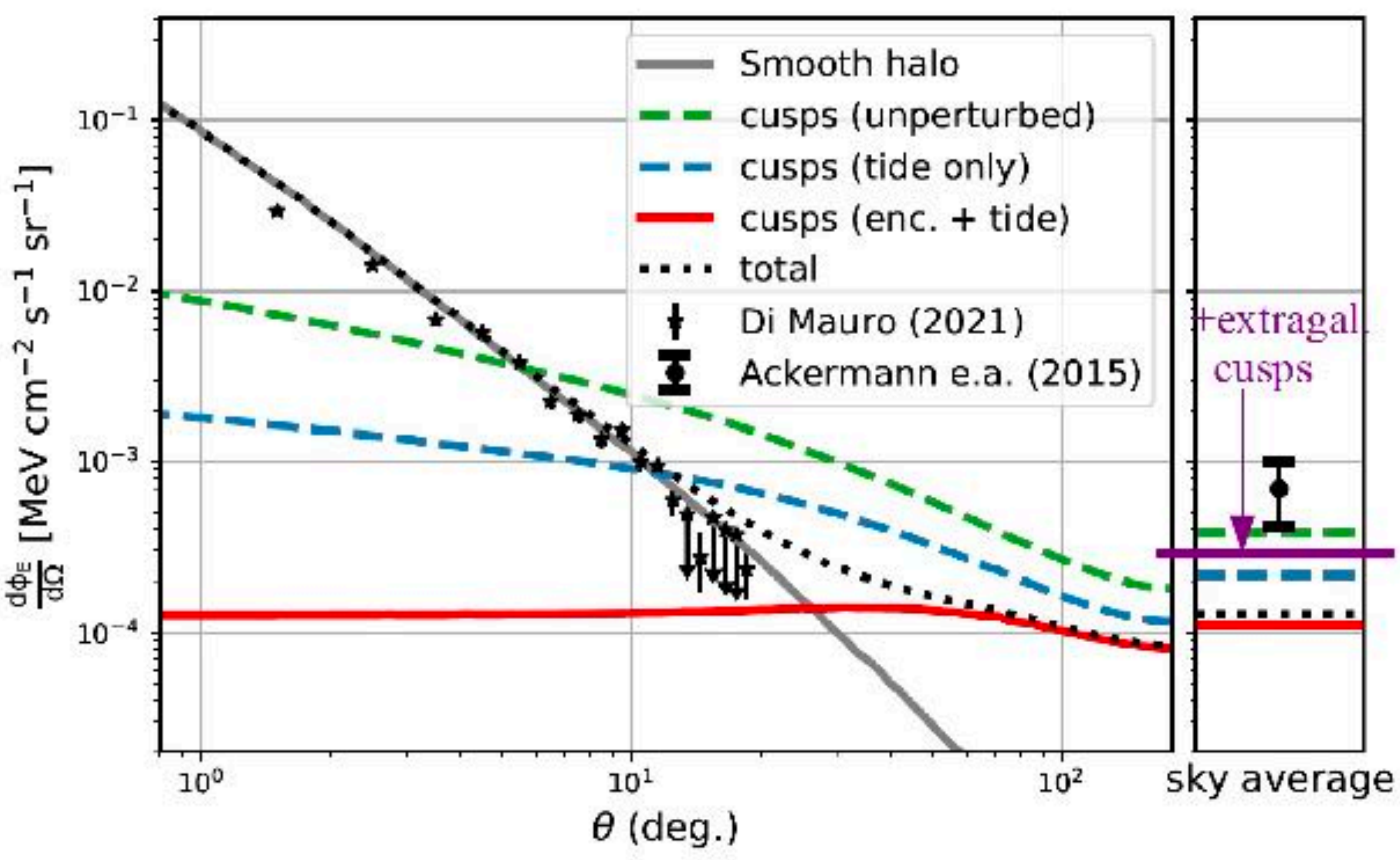
Prompt Cusps

- ...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

Milky Way annihilation radiation profiles



Stücker et al 2023

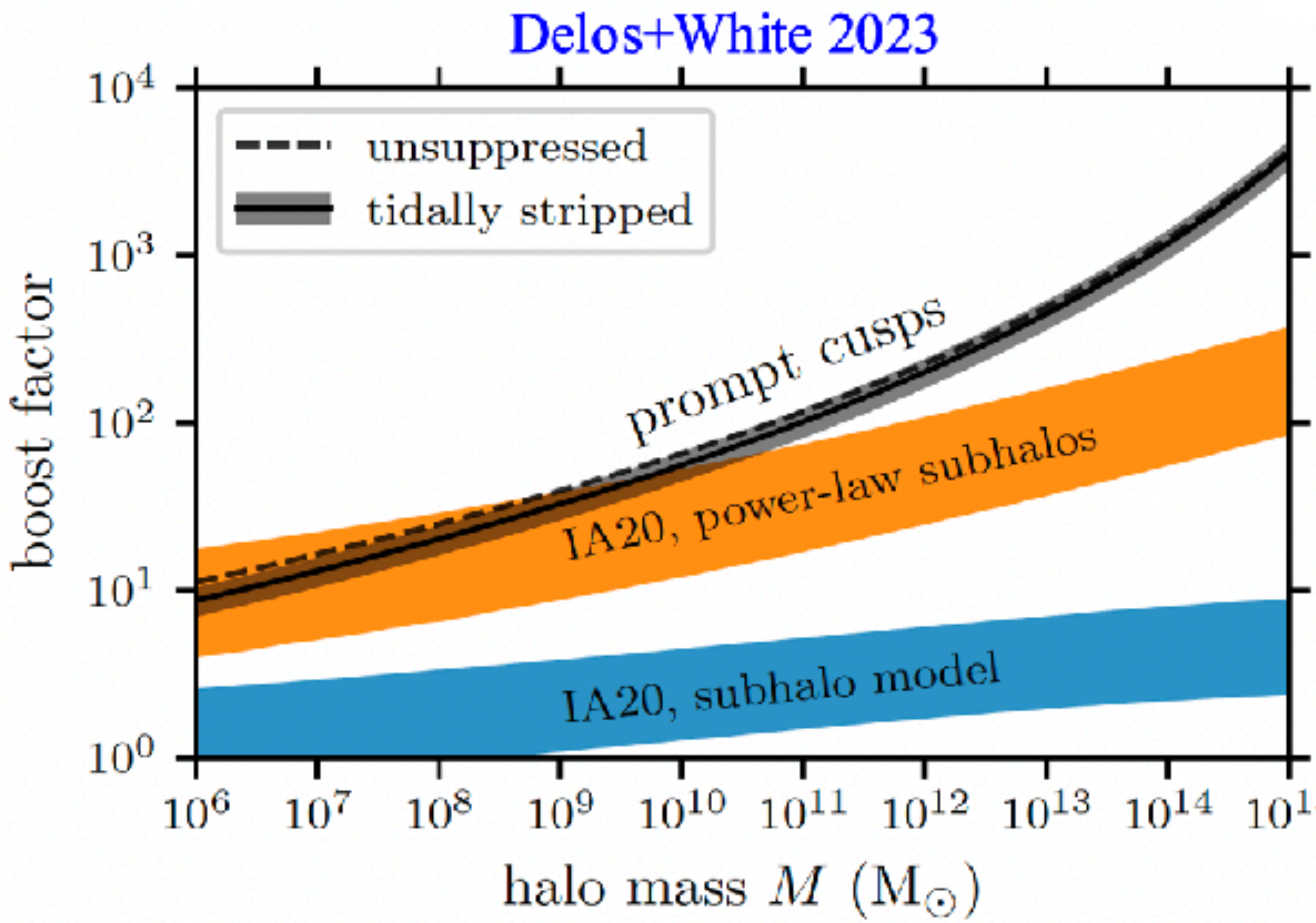


The profile due to cusps is much shallower than that due to the smoothly distributed dark matter

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

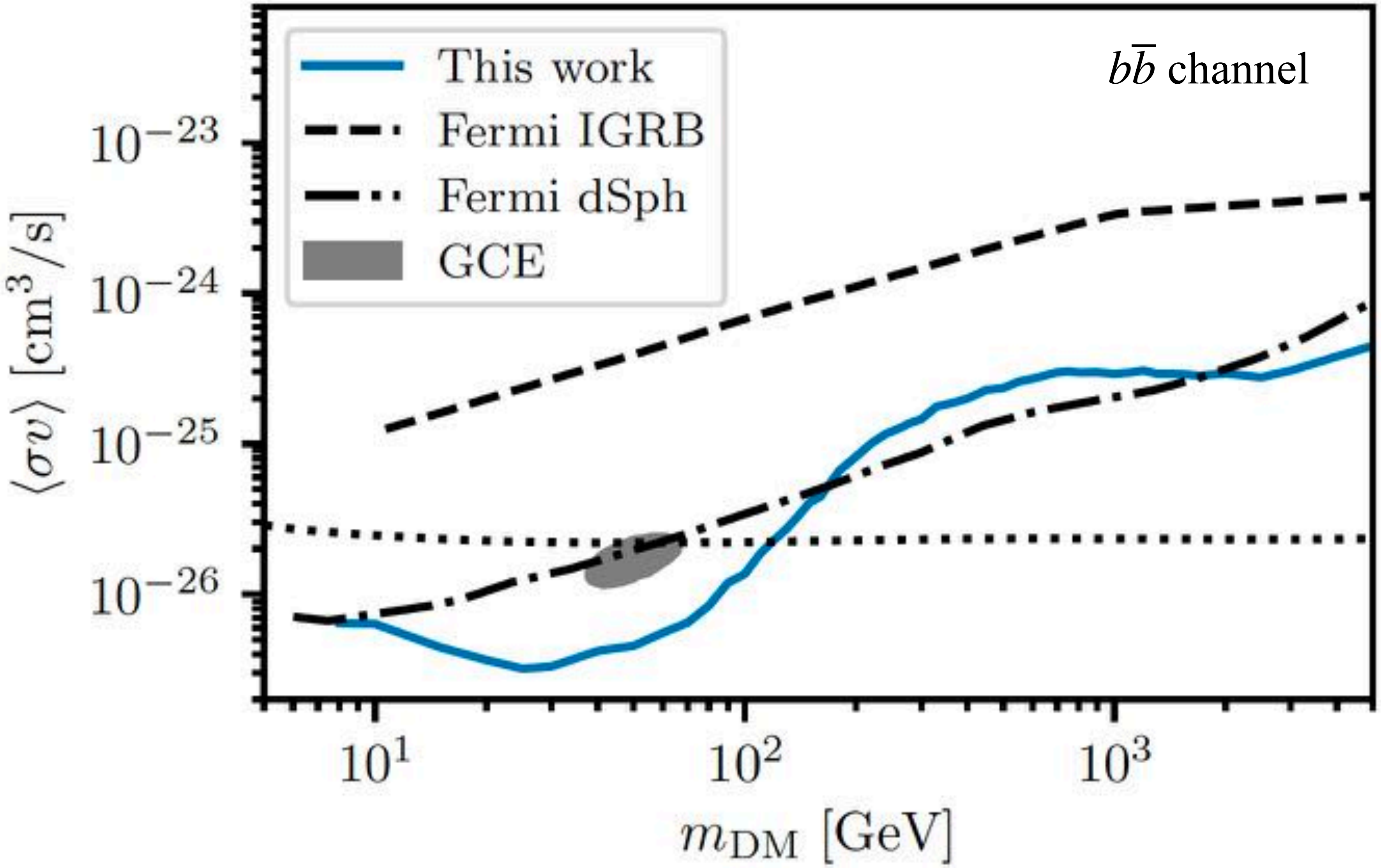


Prompt cusps boost the emission from distant halos by factors ~20 (small dwarfs) ~200 (MW-like galaxies) and ~2000 (rich clusters)

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 may be inconsistent with the IGRB
- The IGRB limit is stronger than that from dSph galaxies for much of the $m_{\rm DM}$ range

In summary…..

- The CMB provides the most direct, robust and precise evidence for the existence of DM

- ΛCDM evolution from CMB initial conditions reproduces quantitatively the cosmic mass distribution at all later times on galactic, cluster and LSS scales

- For both WDM and FDM, observational lower limits on the particle mass m_χ are now so tight that their astrophysical phenomenology is almost indistinguishable from CDM

- SIDM is of astrophysical interest only if $\langle \sigma / m_\chi \rangle$ is a strongly decreasing function of v, but there is still no evidence that unambiguously favours such SIDM over CDM

- Prompt cusps dominate DM annihilation radiation from extragalactic structures and modify its expected sky distribution. The implied upper limit on $\langle \sigma v \rangle$ from the IGRB is in tension with an annihilation origin for the Galactic Centre Excess seen by Fermi