The structure (and substructures) of dark matter haloes

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Talk objectives

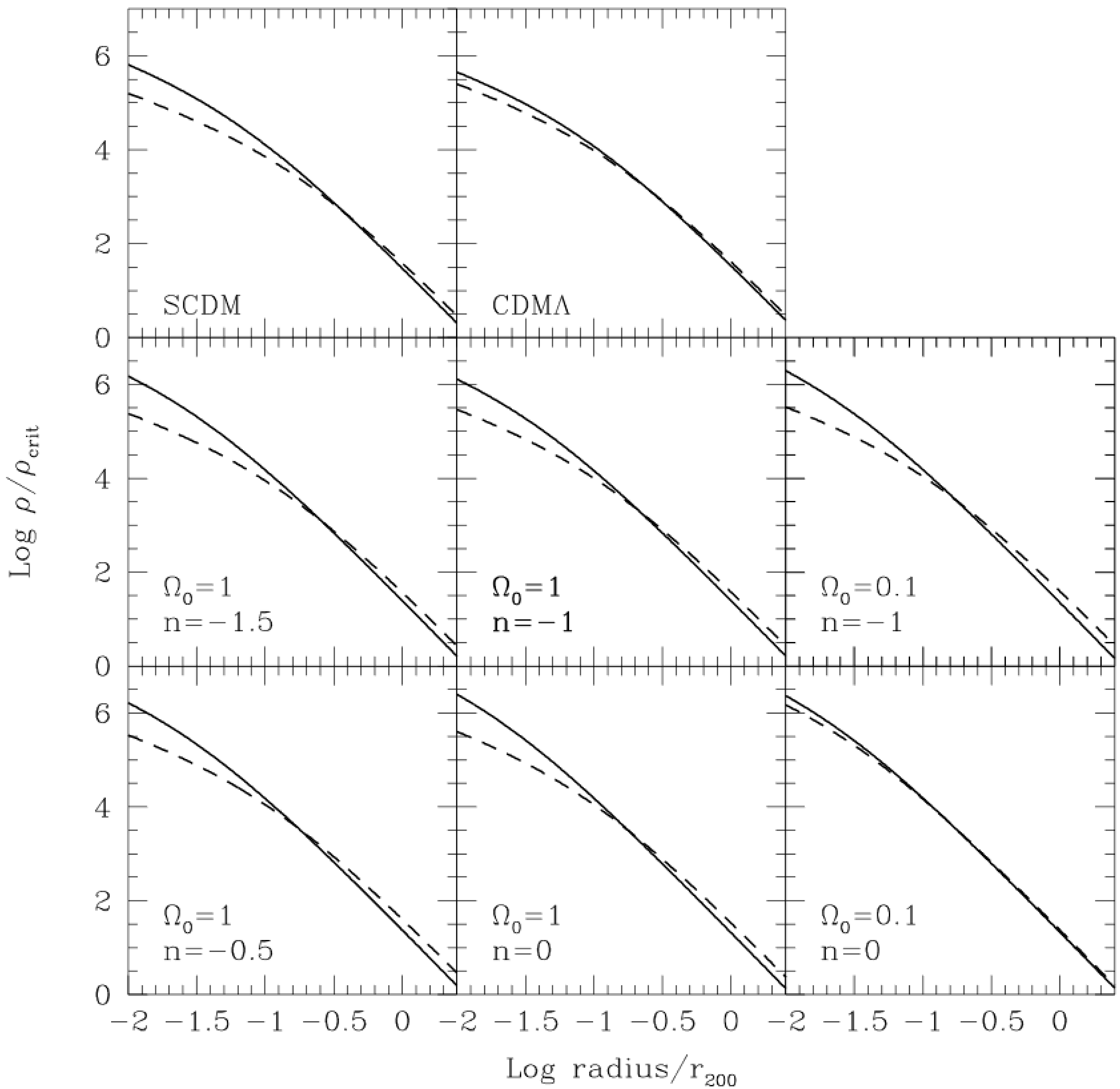
1.) Does the overall structure (radial profiles) of dark matter haloes depend on the initial conditions?

2.) How can we observationally differentiate between a universe where low-mass subhaloes are completely dark vs. one where they are not present at all?

Part 1: Structure of dark matter haloes

(Brown, IGM+2020, MNRAS, 495, 4994)

The self-similarity of dark matter haloes



When radial coordinate is normalised by virial radius, profiles are approximately self-similar.

Underpredicts the density in the inner regions, so concentration (or scale radius) must vary with halo mass.

Linked to halo formation time.

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

NFW 1997

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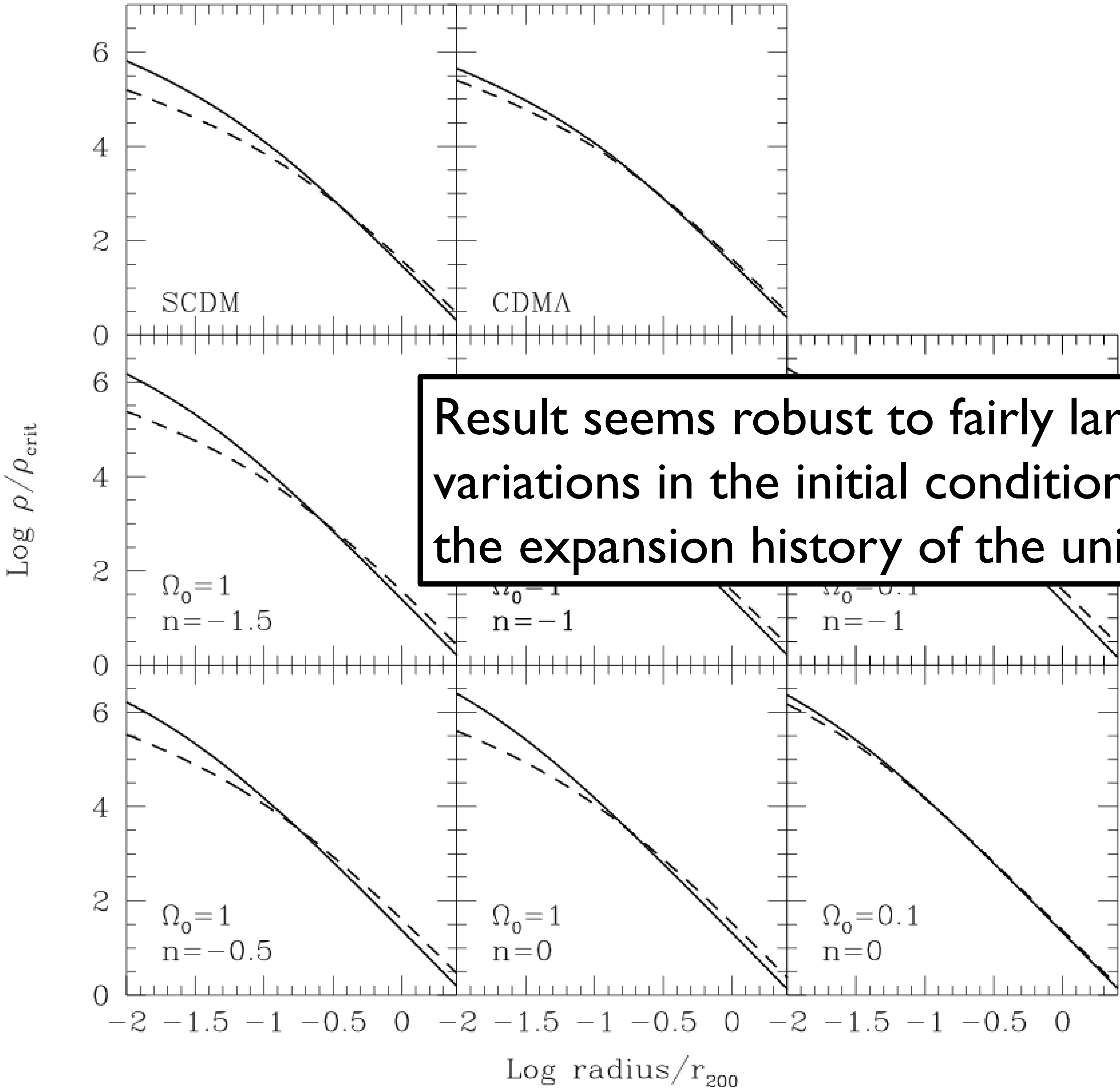

Result seems robust to fairly large variations in the initial conditions and the expansion history of the universe

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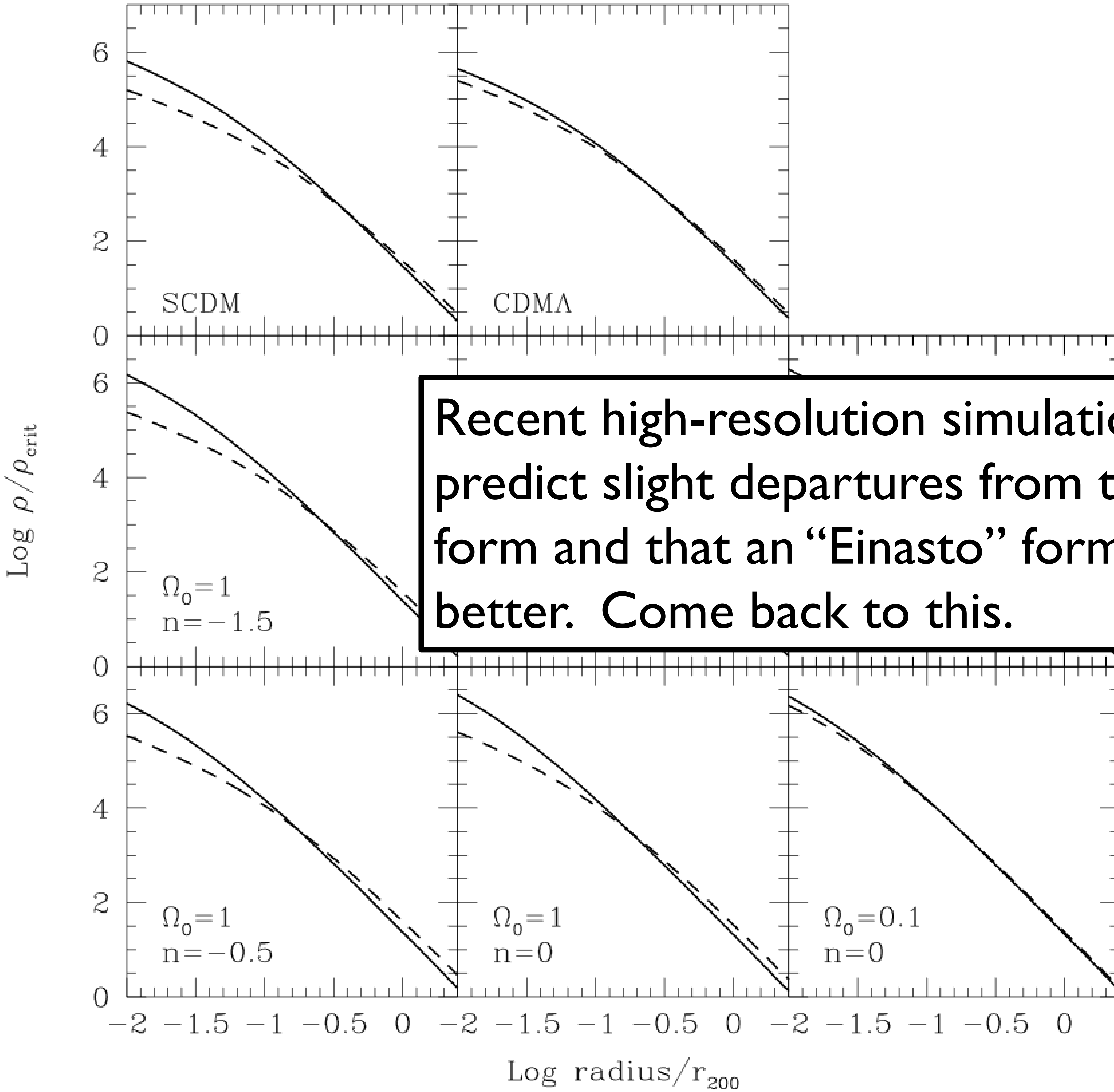

Recent high-resolution simulations predict slight departures from this form and that an “Einasto” form works better. Come back to this.

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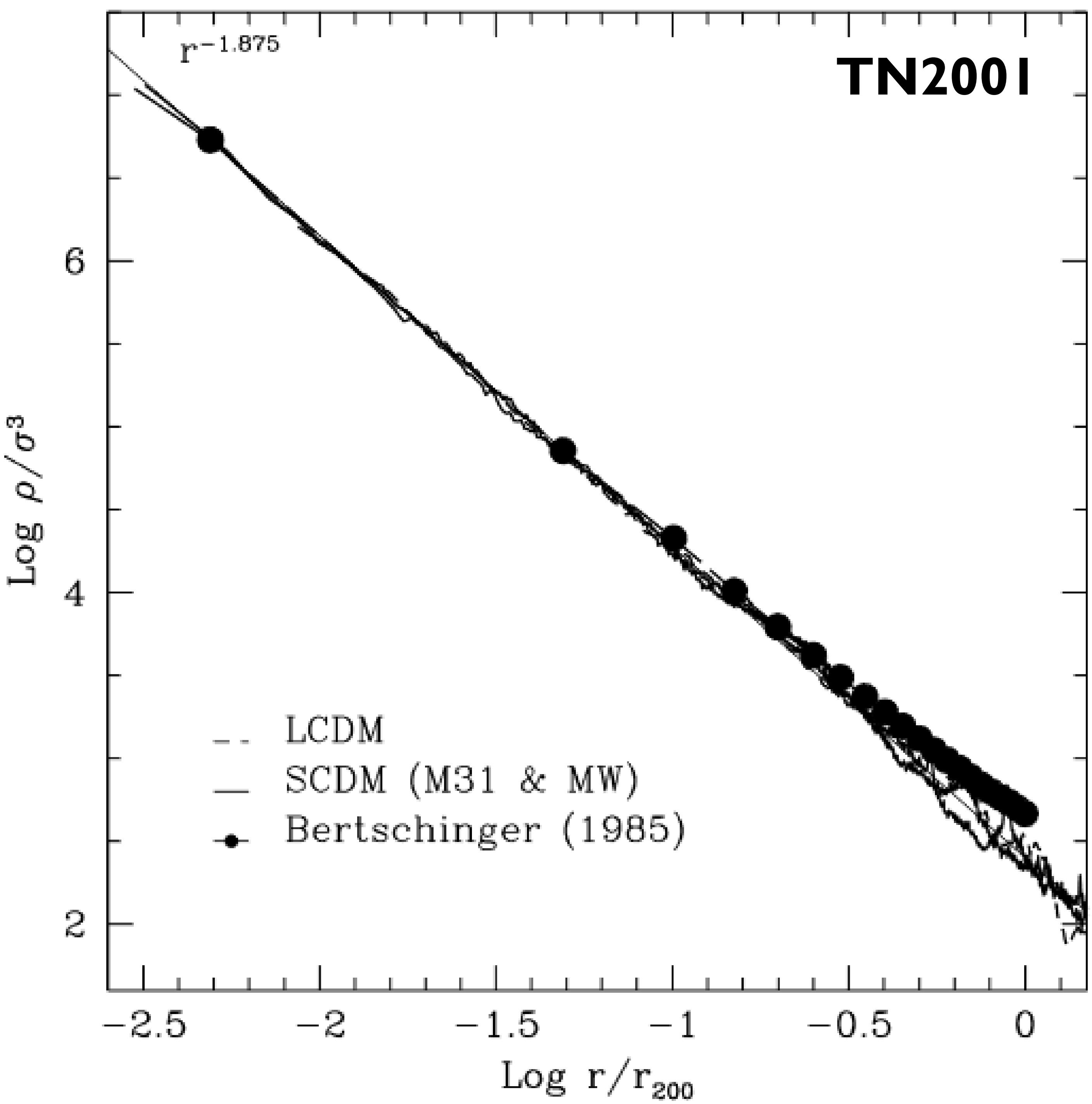
NFW 1997

The "phase-space" density of DM haloes



Curious result:

Taylor & Navarro (2001) showed that a quantity called the "phase space" density is approx. a pure power law, independent of mass.

Is this more fundamental? What sets the slope?

Why does Bertschinger (appear to) work?

Aside: "phase space" density or entropy?

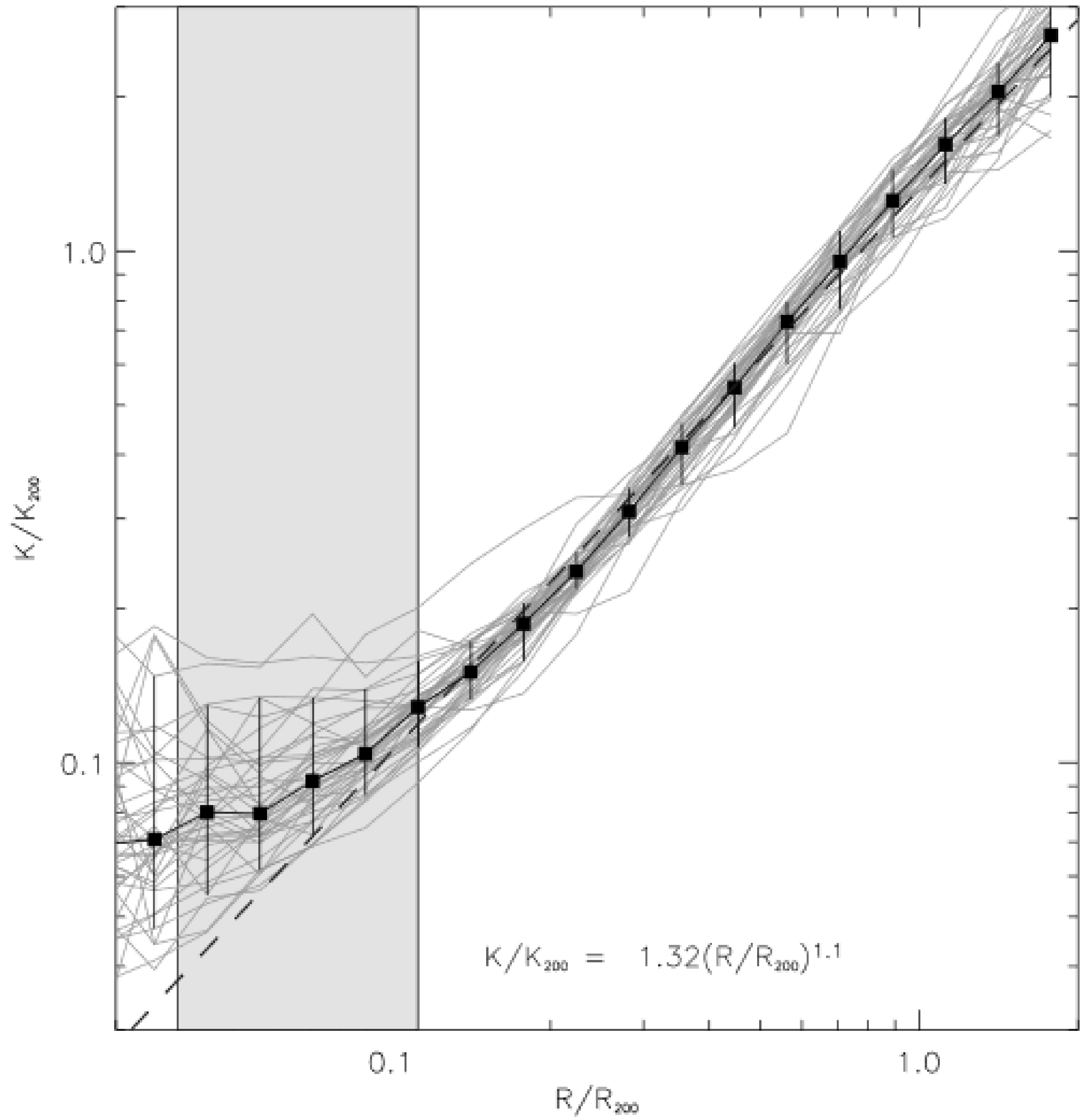
Phase space density defined as:

$$\frac{\rho}{\sigma^3}$$

Writing $\sigma^2 \rightarrow kT$ and taking to -2/3 power, one gets:

$$\frac{kT}{\rho^{2/3}}$$

Sometimes called the "entropy".



Voit+2005

Interestingly, the intracluster medium has the same entropy profile as the dark matter.

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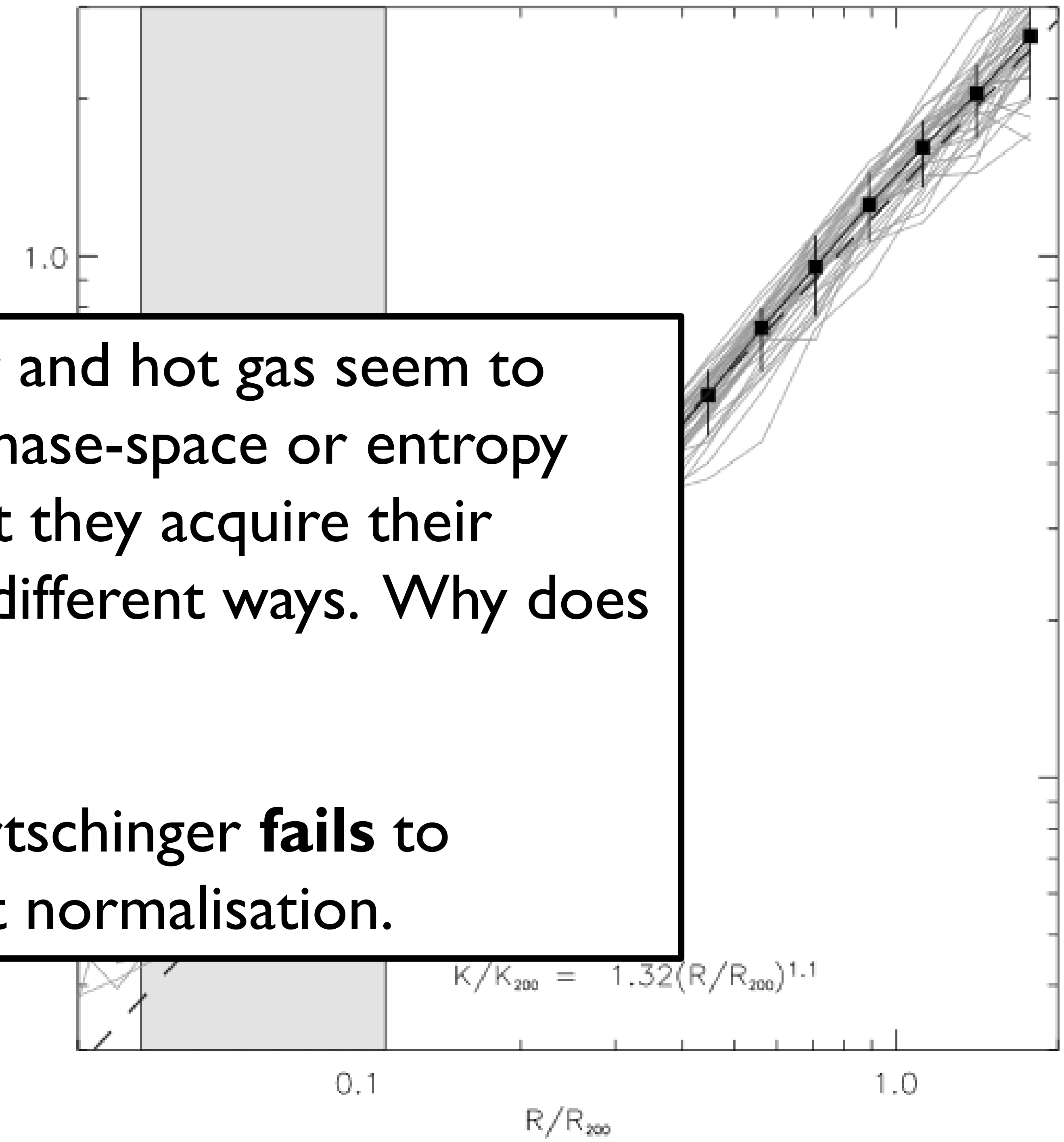


The dark matter and hot gas seem to have the same phase-space or entropy distributions. Yet they acquire their entropy in very different ways. Why does this work?

Voit showed Bertschinger **fails** to correctly predict normalisation.

Voit+2005

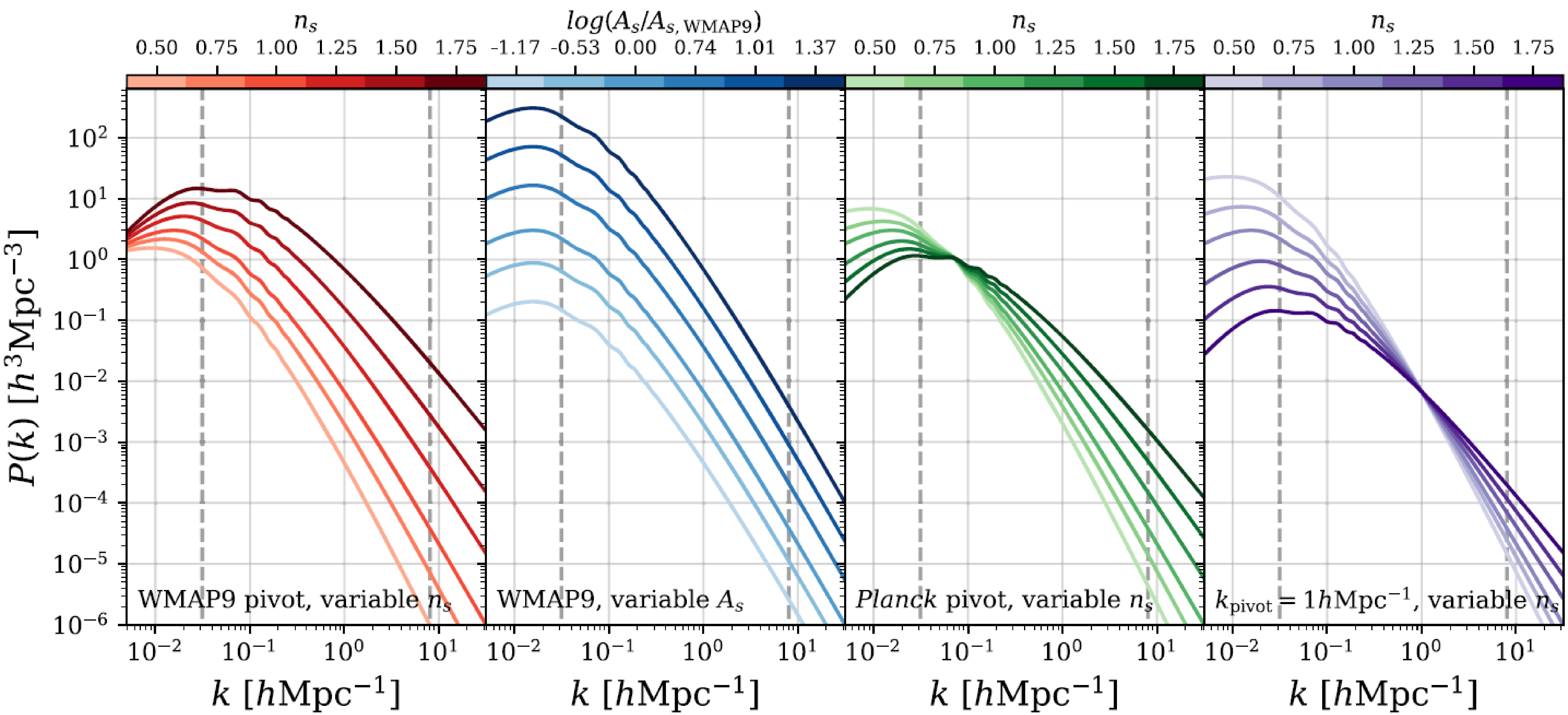
Interestingly, the intracluster medium has the same entropy profile as the dark matter.

Universal or not?

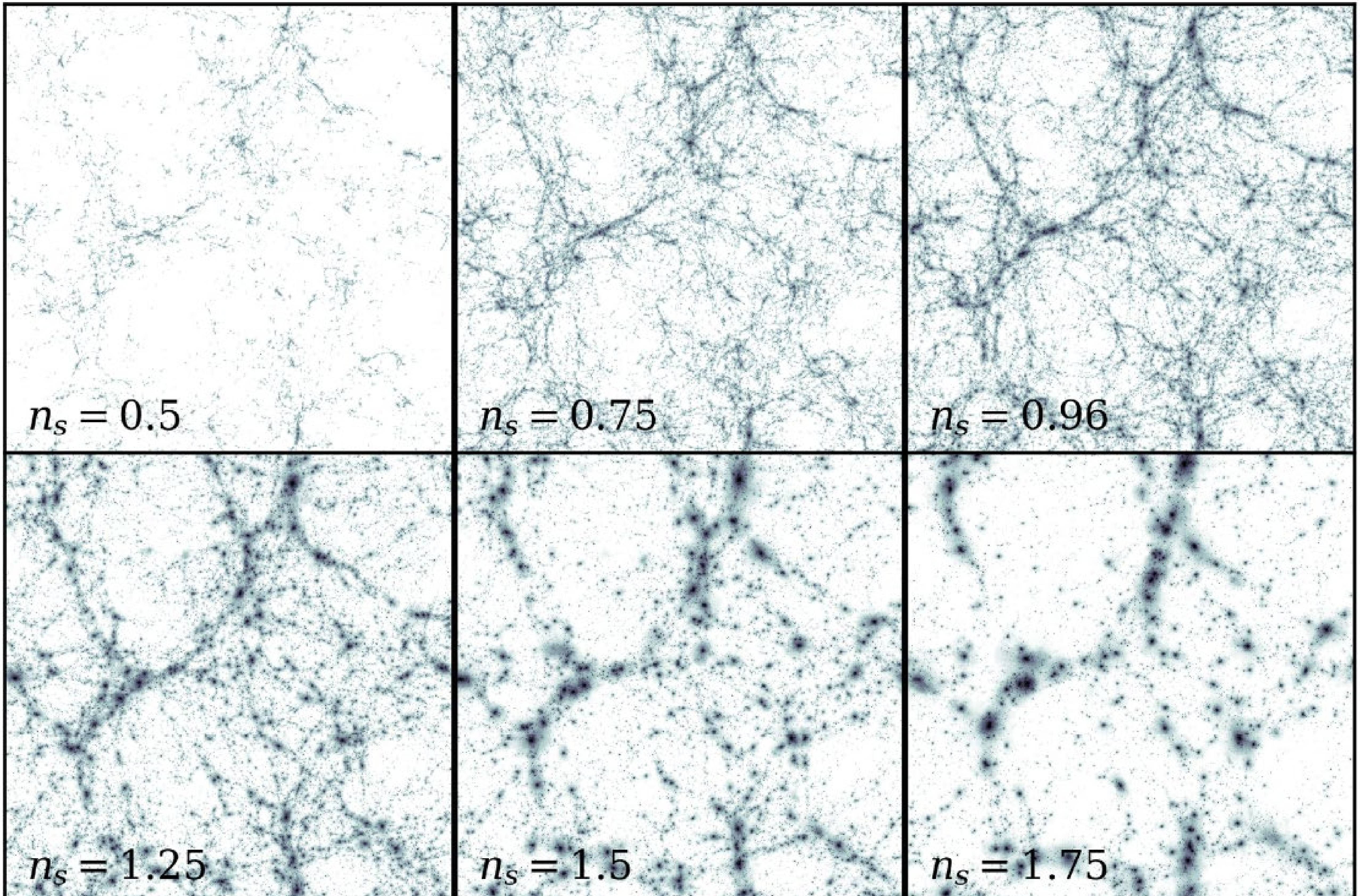
A numerical experiment:

Revisit the sensitivity to the initial conditions. **Brown+2020, MNRAS, 495, 4994**

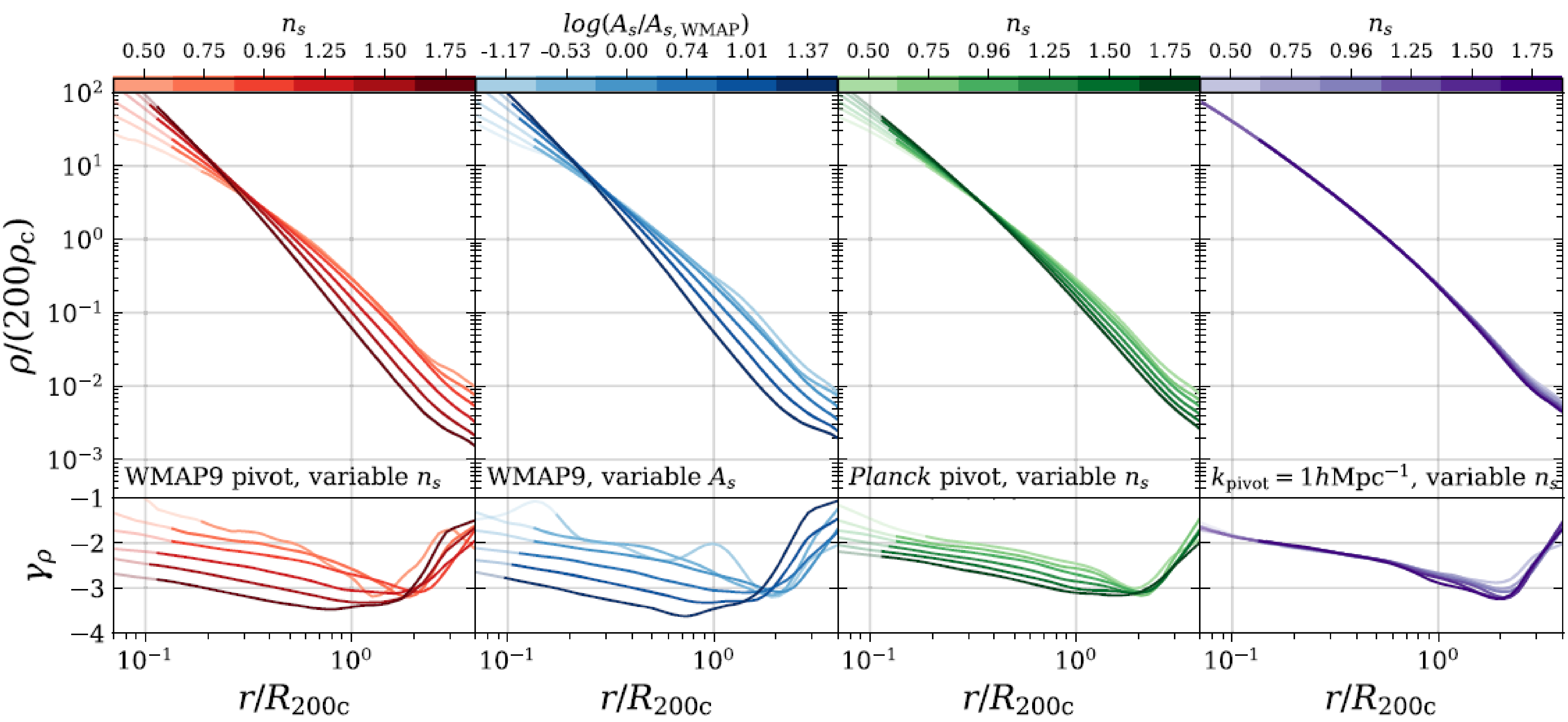
Noteworthy that previous studies did **not** explore a wide range of power spectrum normalisations (i.e., σ_8 was always ~1; "CMB-normalised").



Resulting structure (visual guide)



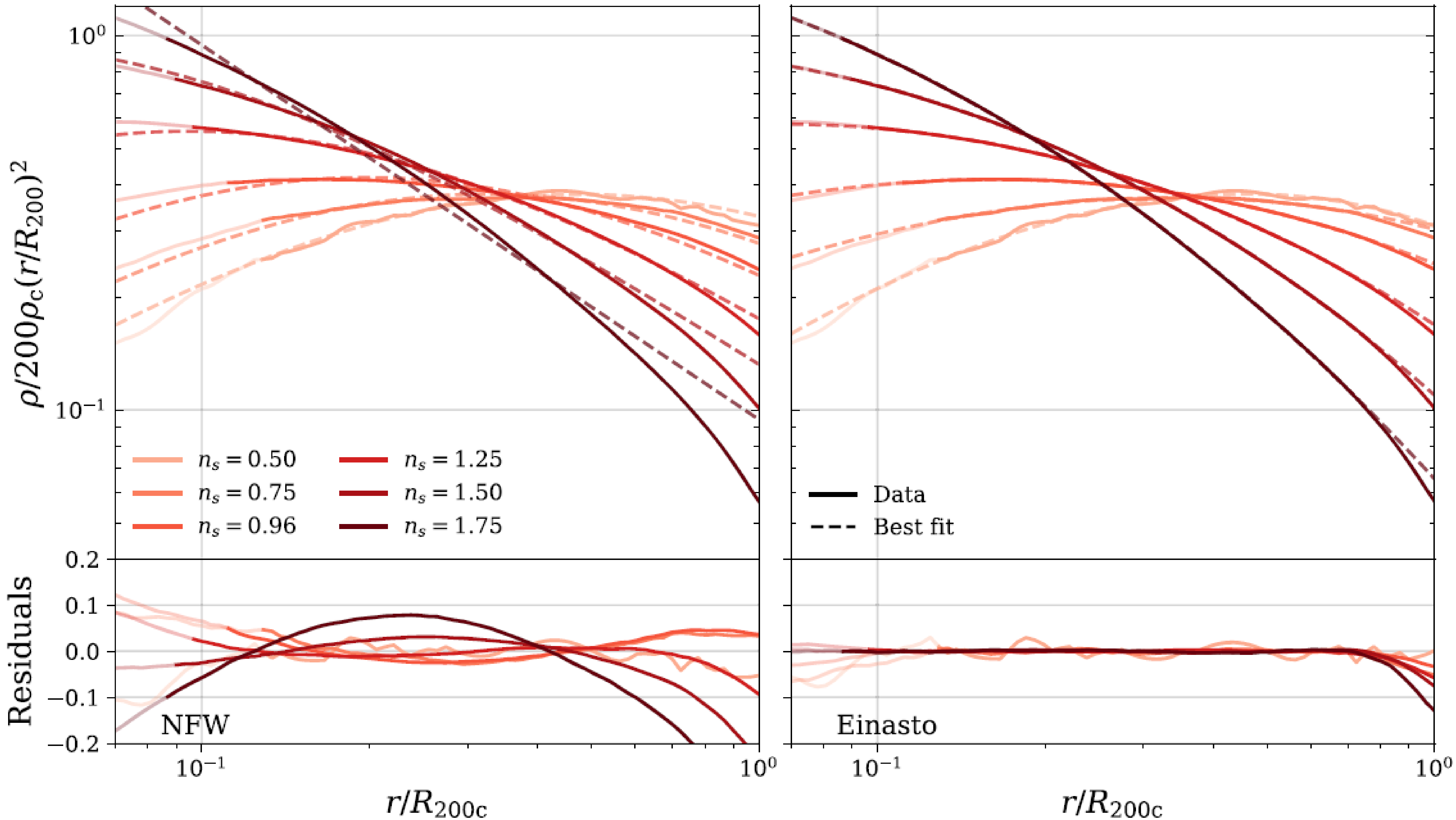
Density profiles



For haloes with $M_{200c} \sim 10^{13}\ M_\odot$

Brown, IGM+2020

Testing NFW and Einasto



For haloes with $M_{200c} \sim 10^{13}\ M_{\odot}$.

Brown, IGM+2020

Predicting the trends (in hindsight)

With a high-normalisation primordial power spectrum, the simulations show logarithmic slopes steeper than -3 well within R_{200c}. Could this have been anticipated? Potentially, yes.

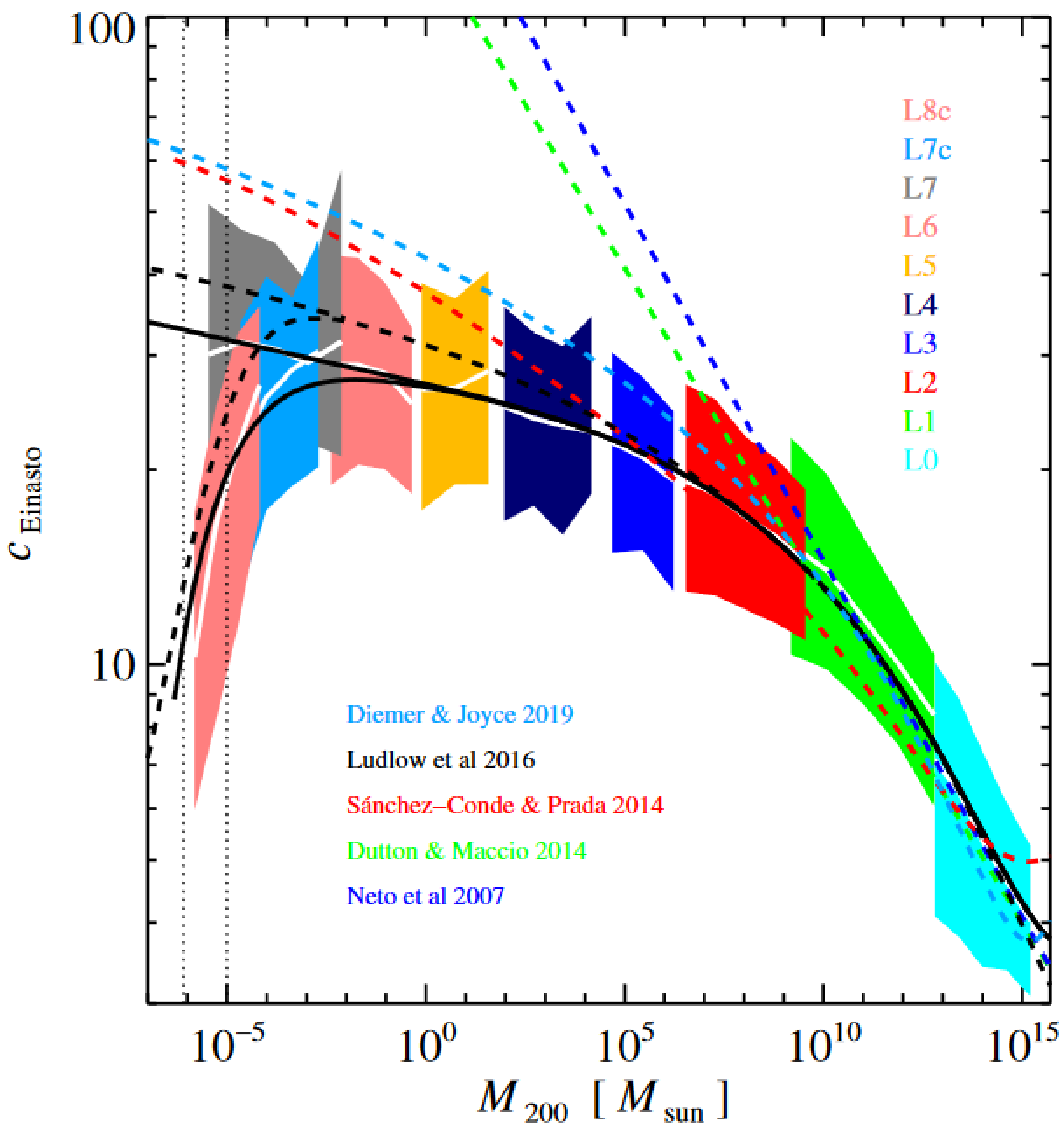
Logarithmic slope of Einasto profile is:

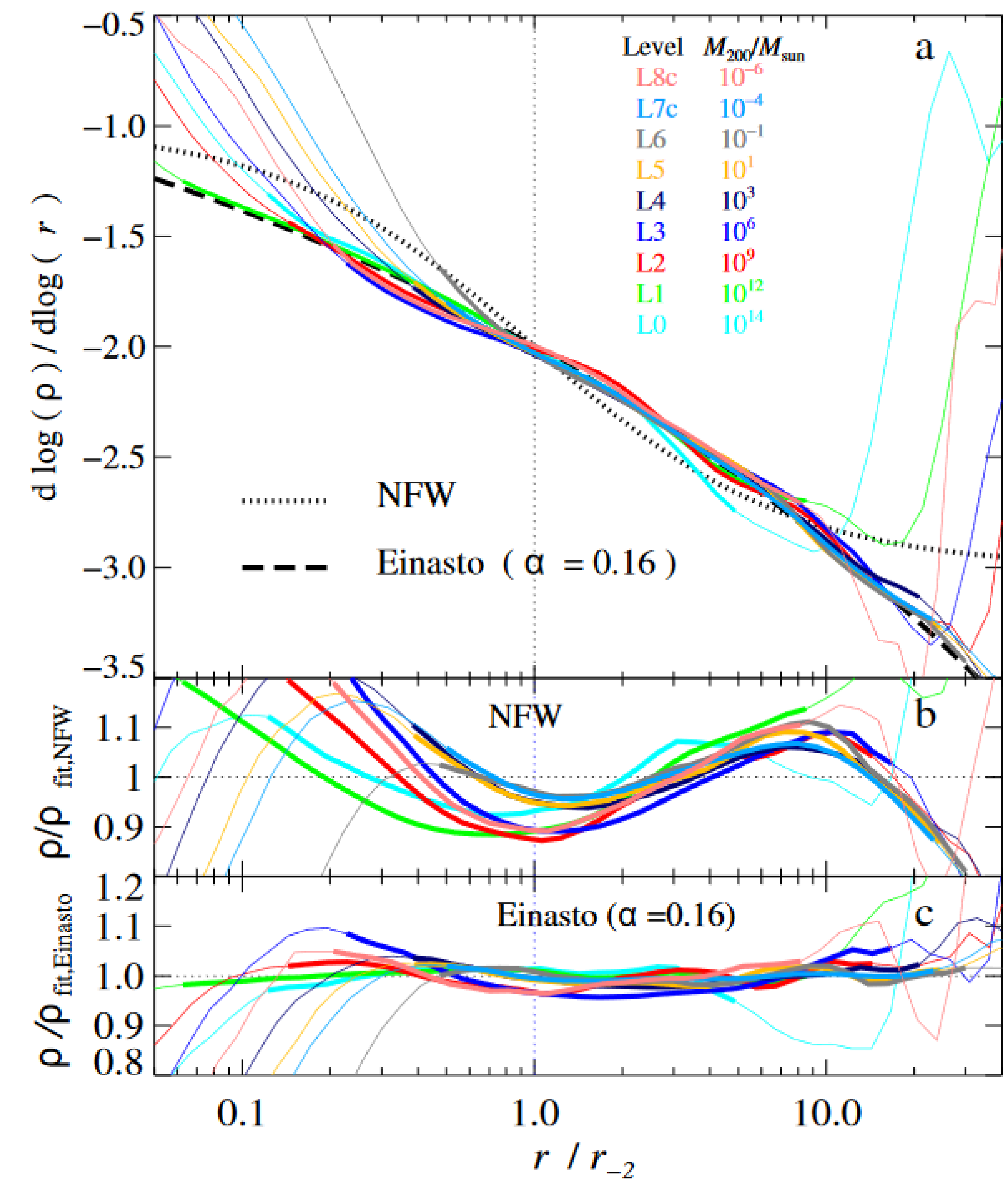
$$\gamma(r) = -2\left(\frac{cr}{R_{200c}}\right)^{\alpha}$$

Adopting $\alpha = 0.16$, one predicts $\gamma(r) < -3$ at $r = R_{200c}$ for $c > 12.6$, Einasto is correct. Simulations verify this (i.e., Einasto works well).

Does this ever happen for CMB-normalised cosmologies? Yes!

Predicting the trends (in hindsight)

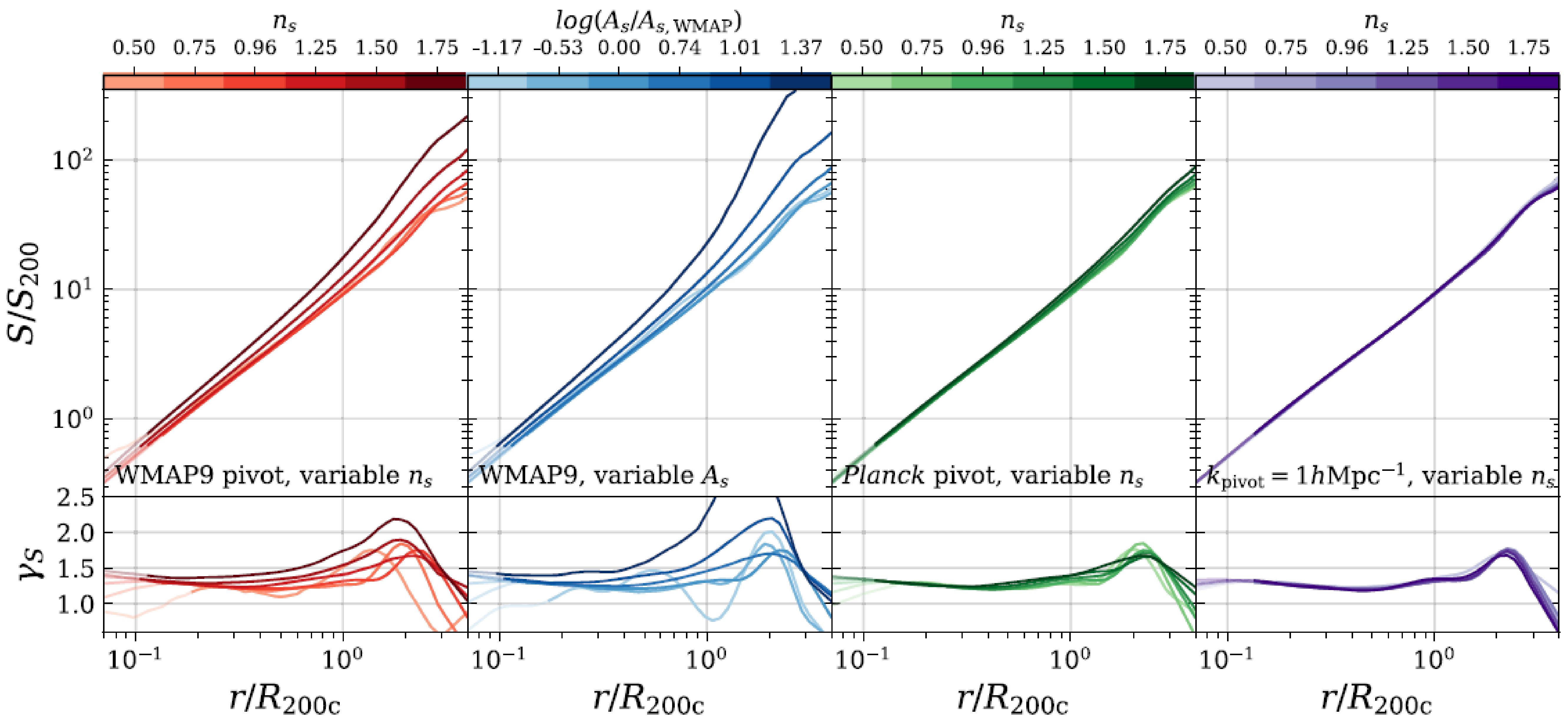




Low-mass haloes in CMB-normalised cosmologies are sufficiently concentrated to show strong departure from NFW.

Wang, Bose+2020

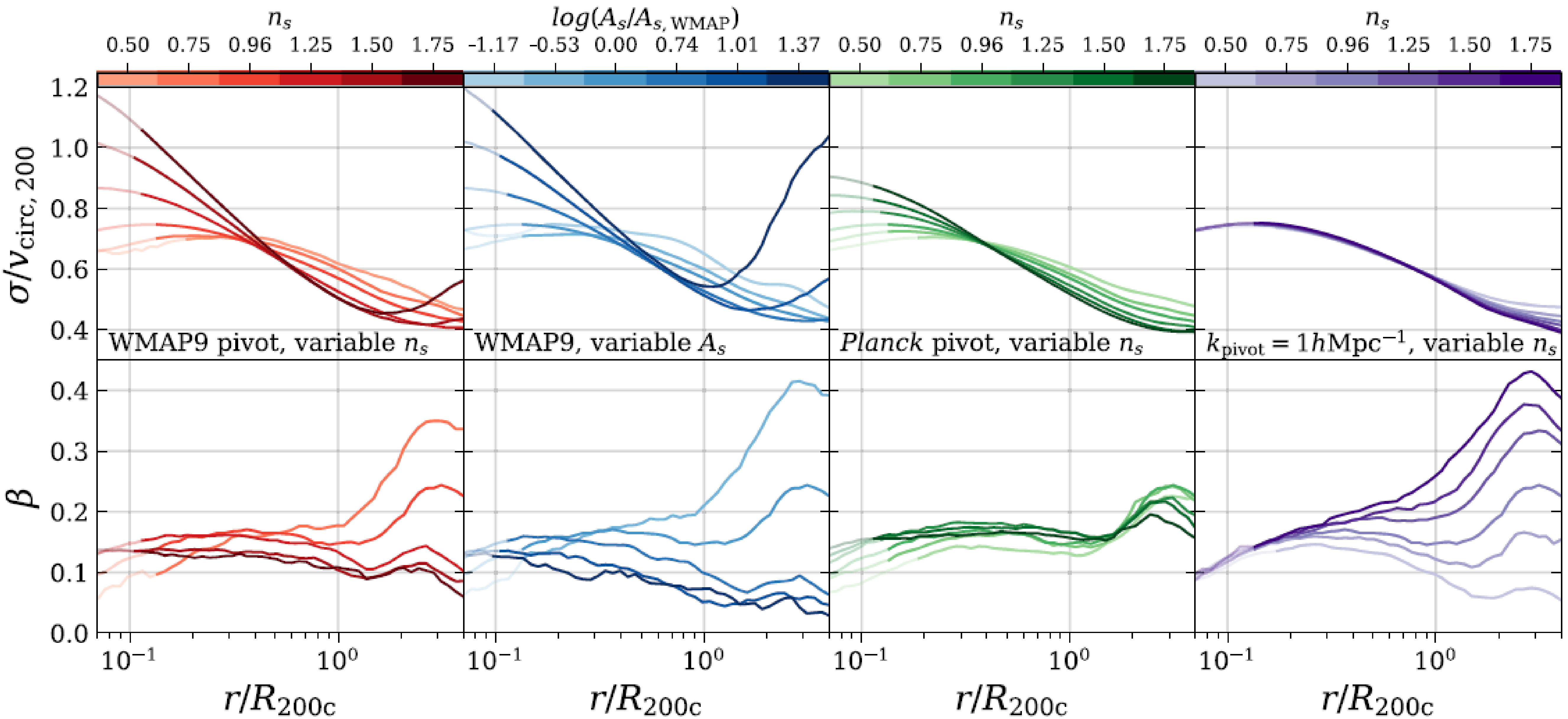
Entropy profiles



For haloes with $M_{200c} \sim 10^{13}\ M_\odot$

Brown, IGM+2020

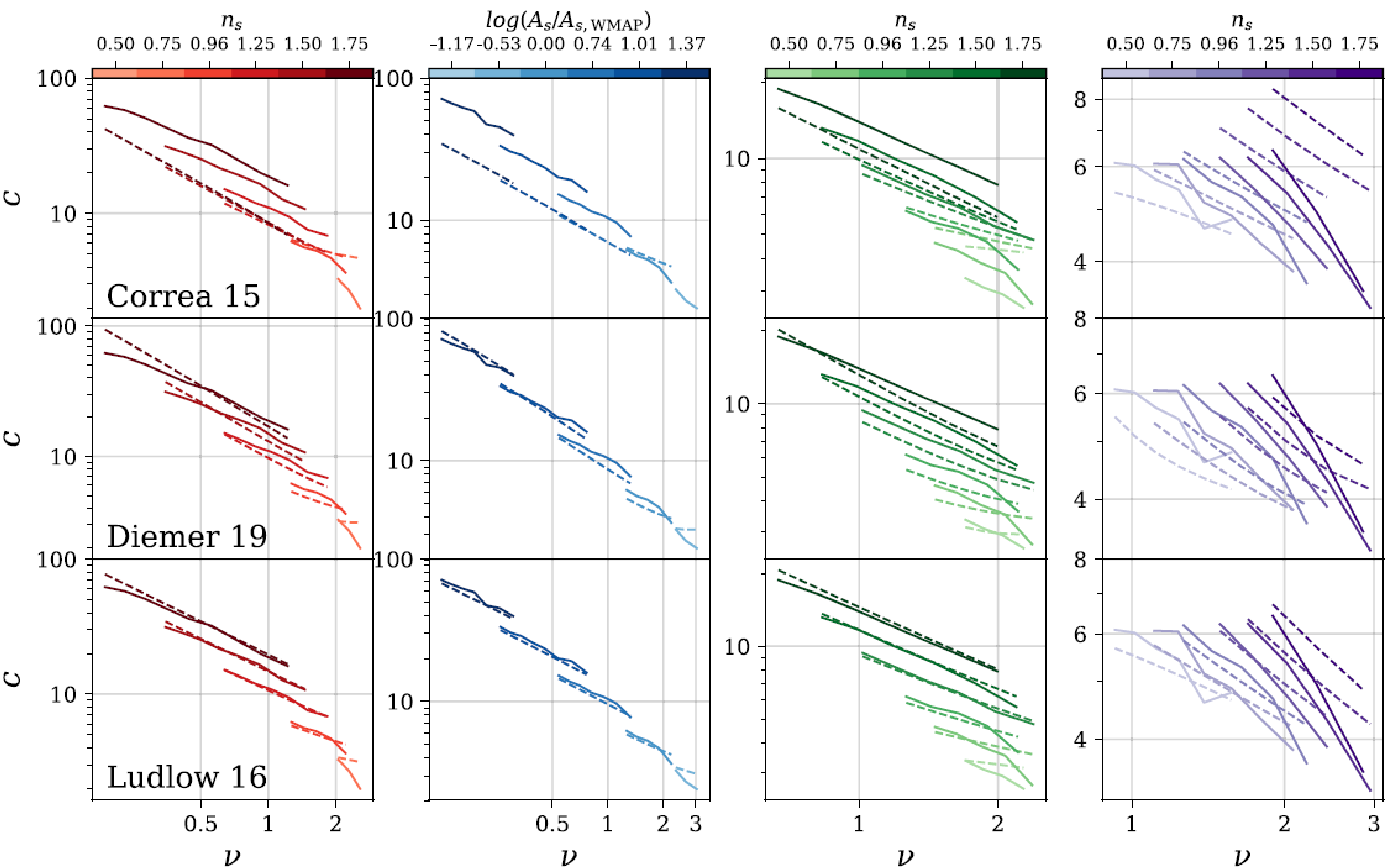
Velocity dispersion and velocity anisotropy



For haloes with $M_{200c} \sim 10^{13}\ M_{\odot}$

Brown, IGM+2020

Concentration – peak height relations



Brown, IGM+2020

Conclusions (part 1)

- The NFW form has been around for almost 25 years, appearing to be robust to changes in the expansion history and initial conditions of the Universe.
- However, previous numerical experiments were mainly limited to "CMB-normalised" cosmologies with $\sigma_8 \sim 1$, which we find to be key.
- We have shown that **the structure and kinematics of dark matter haloes depend strongly on the amplitude of the primordial power spectrum** at a characteristic wavenumber.
- Increasing (decreasing) the amplitude steepens (shallows) the density and entropy profiles. In this sense, there is no universal profile.
- The shape of the power spectrum at the characteristic wavenumber plays a secondary (but still relevant) role.

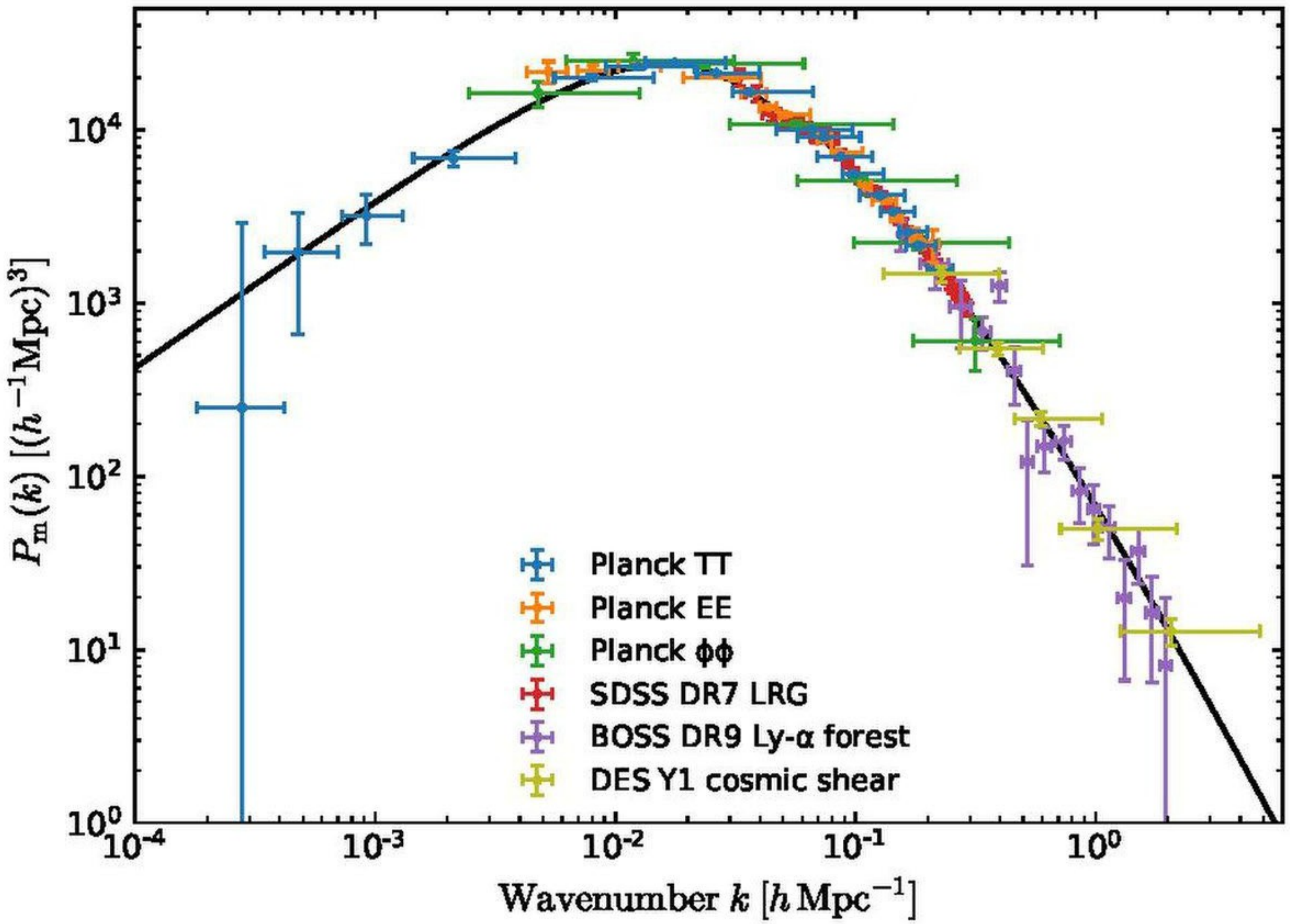
Part II: Substructures of dark matter haloes

(IGM+2020, MNRAS, 499, 3255)

The ΛCDM model

The standard model of cosmology posits:

- GR is the correct theory of gravity
- Universe is isotropic, homogeneous, and spatially flat.
- Constituent energy components are: radiation, baryons, dark matter, dark energy
- Dark matter is assumed to interact only via gravity and is "cold"



In general, has had **remarkable success on "large" scales**.

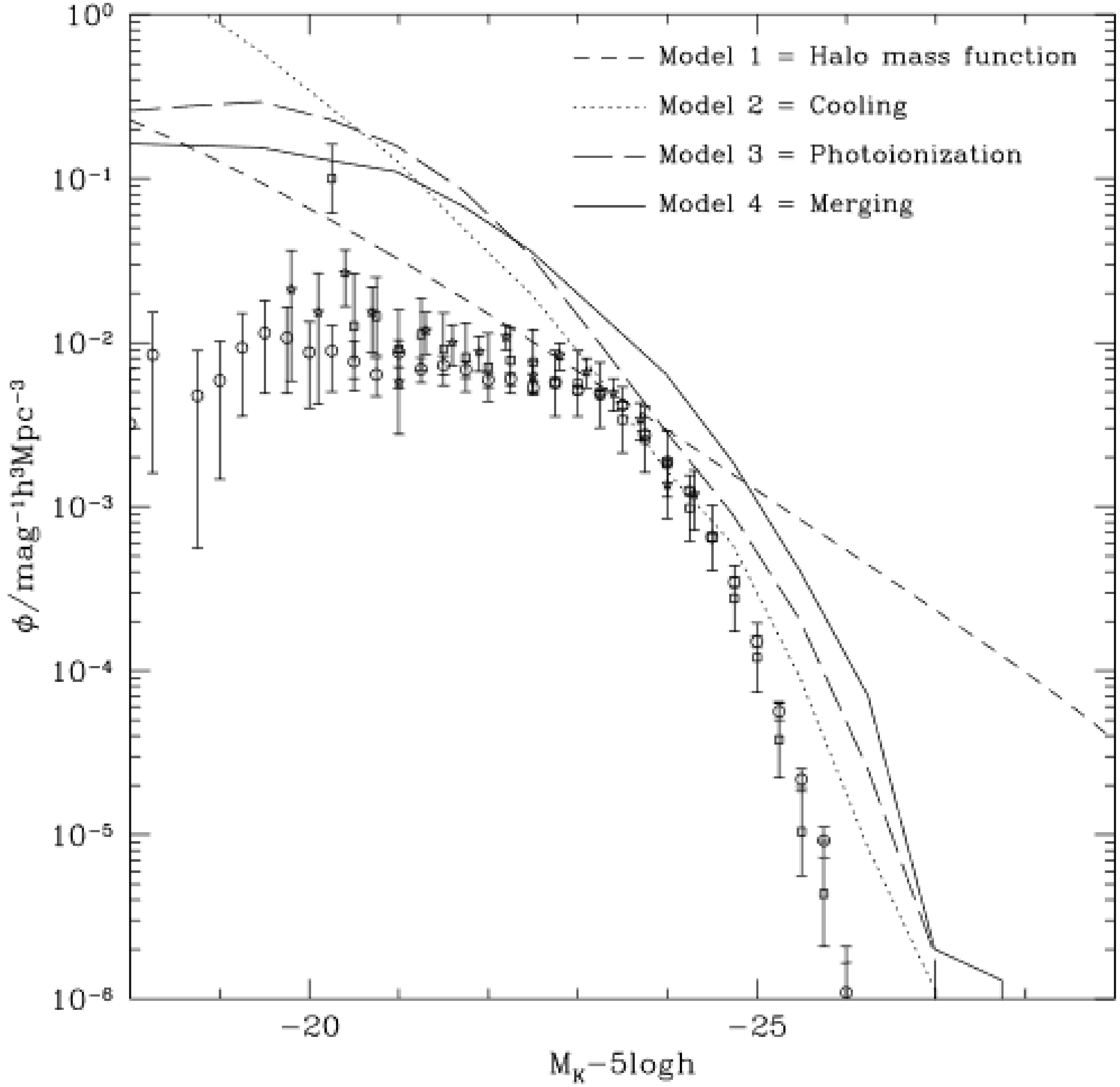
Great, but what does that mean?

Predictions on small scales

Springel+2008

A typical Milky Way-mass halo

Impact of galaxy formation

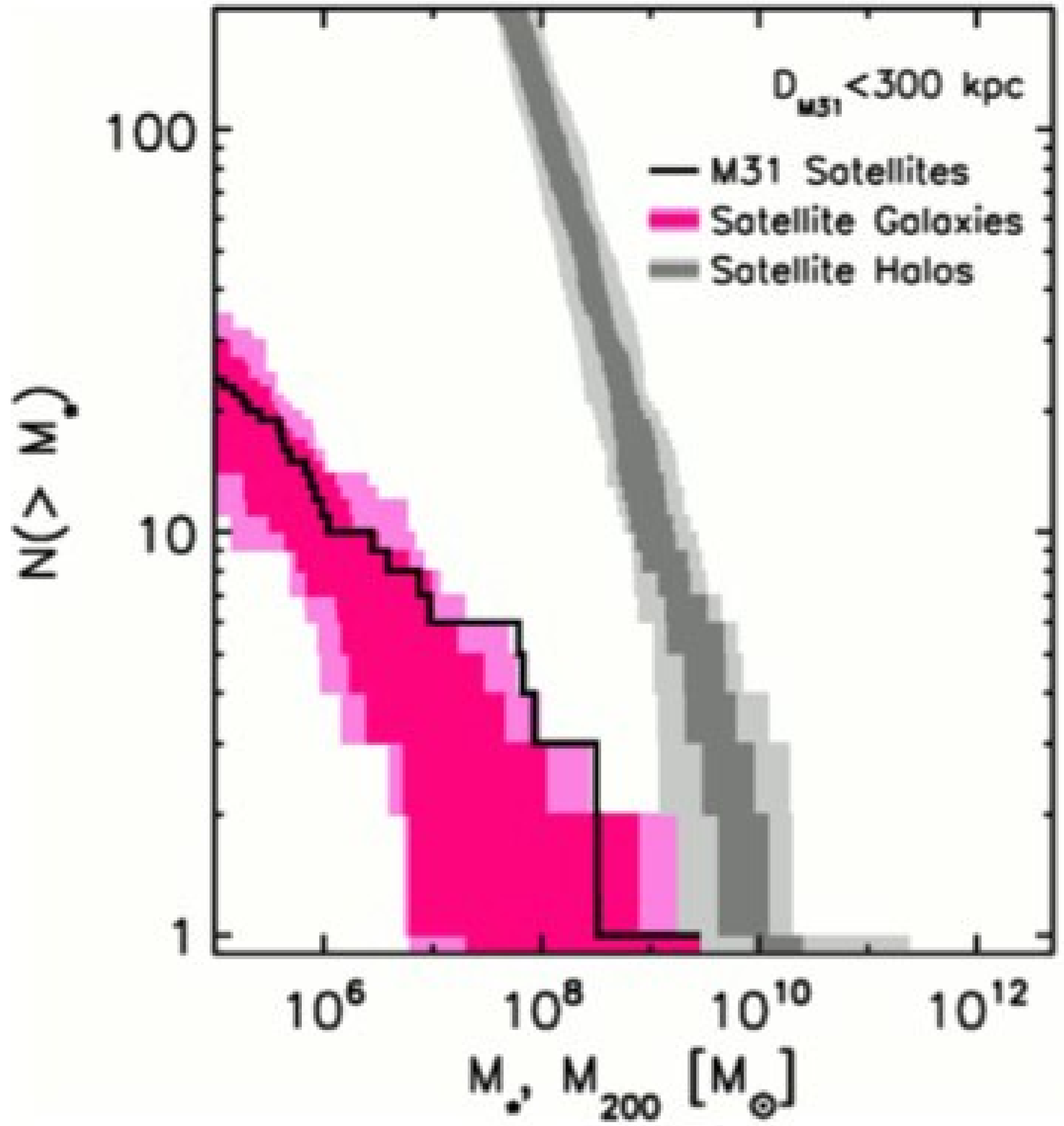


Photoionisation and stellar feedback combine to prevent significant star formation in low-mass subhaloes.

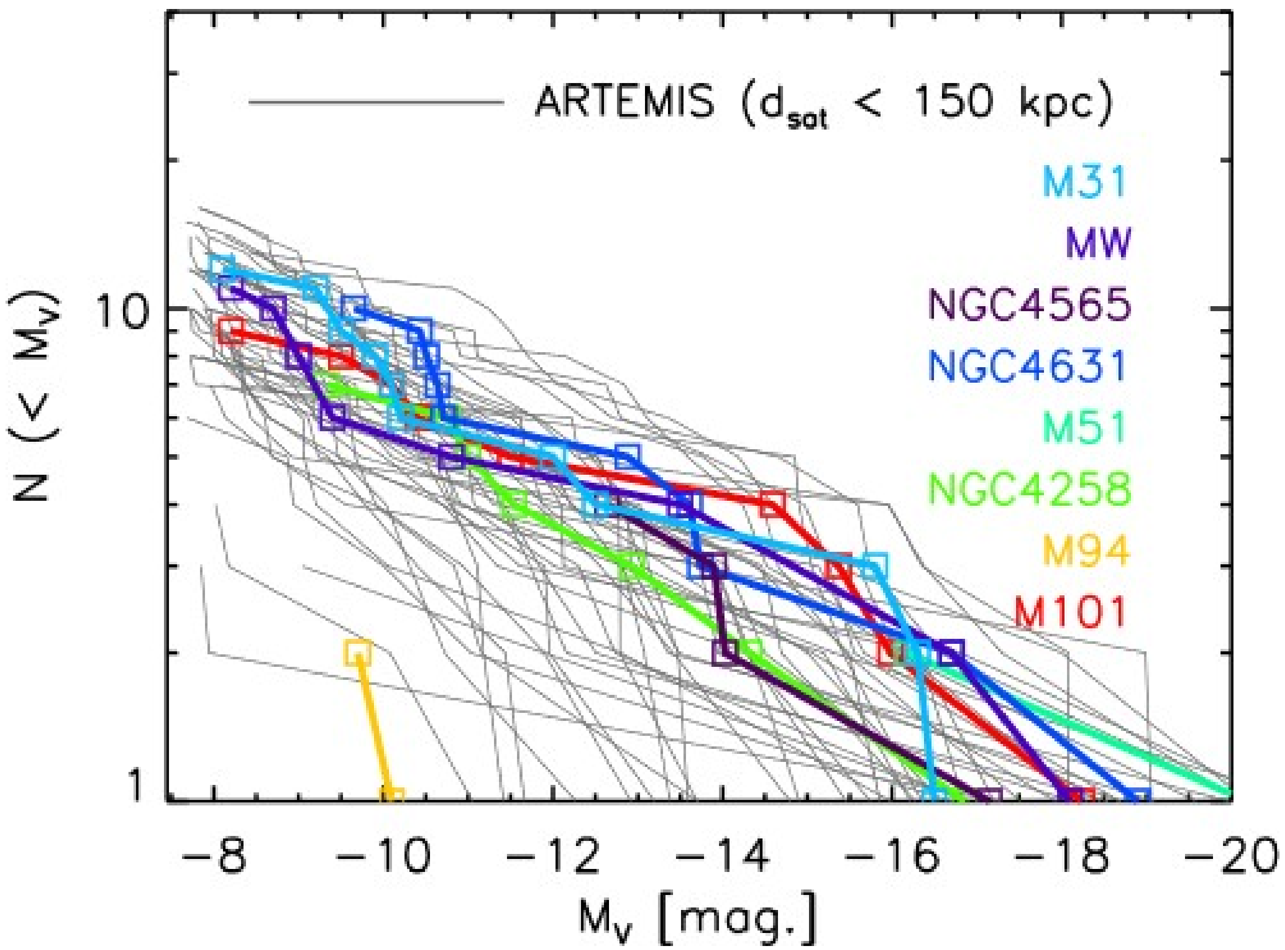
Photoionisation is particularly effective for haloes with circular velocities <~ 10 km/s

Benson+2003

Impact of galaxy formation



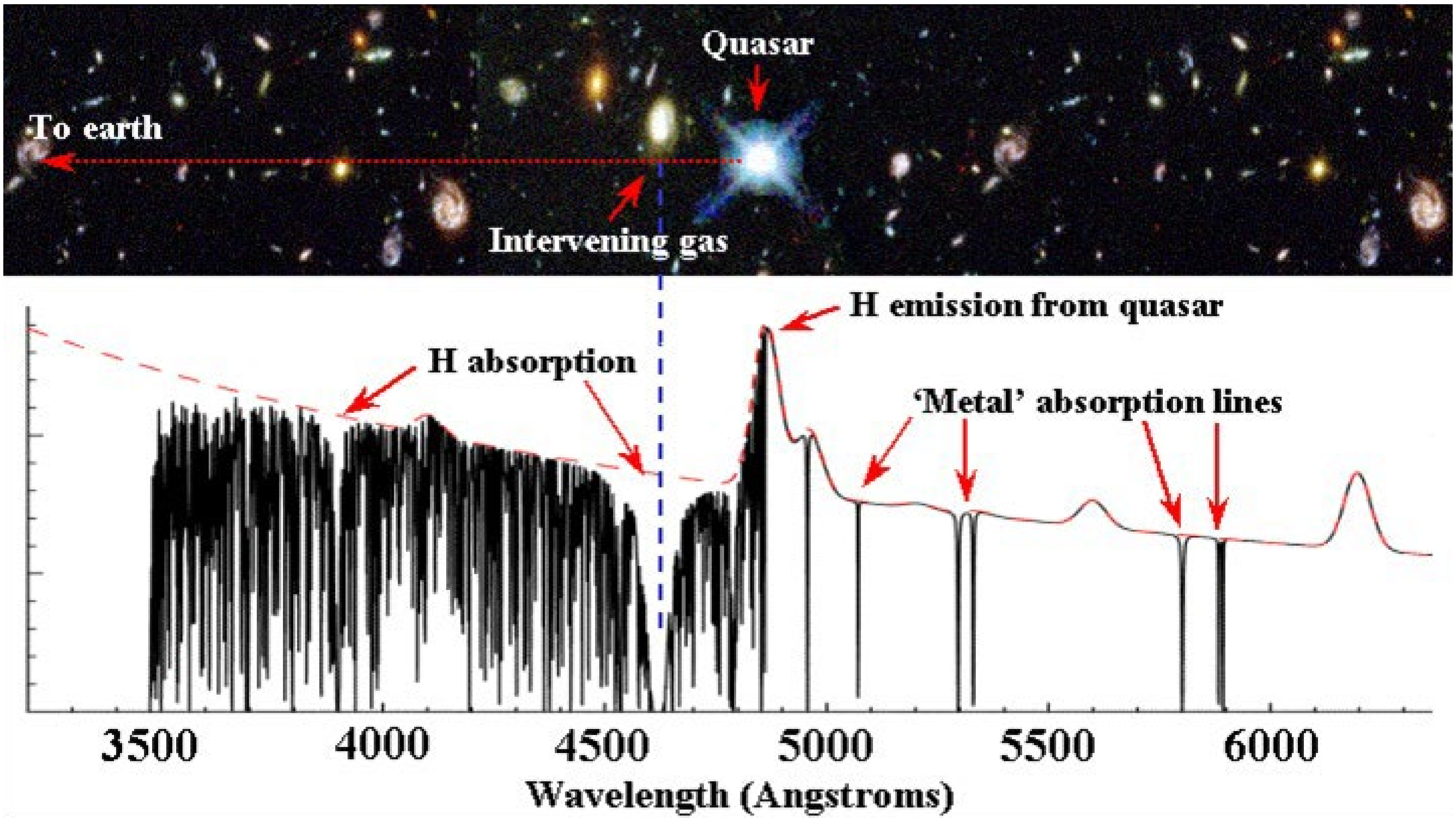
APOSTLE simulations (Sawala+2016)



ARTEMIS simulations (Font+2020)

But the basic prediction is unchanged… there should be gazillions of subhaloes

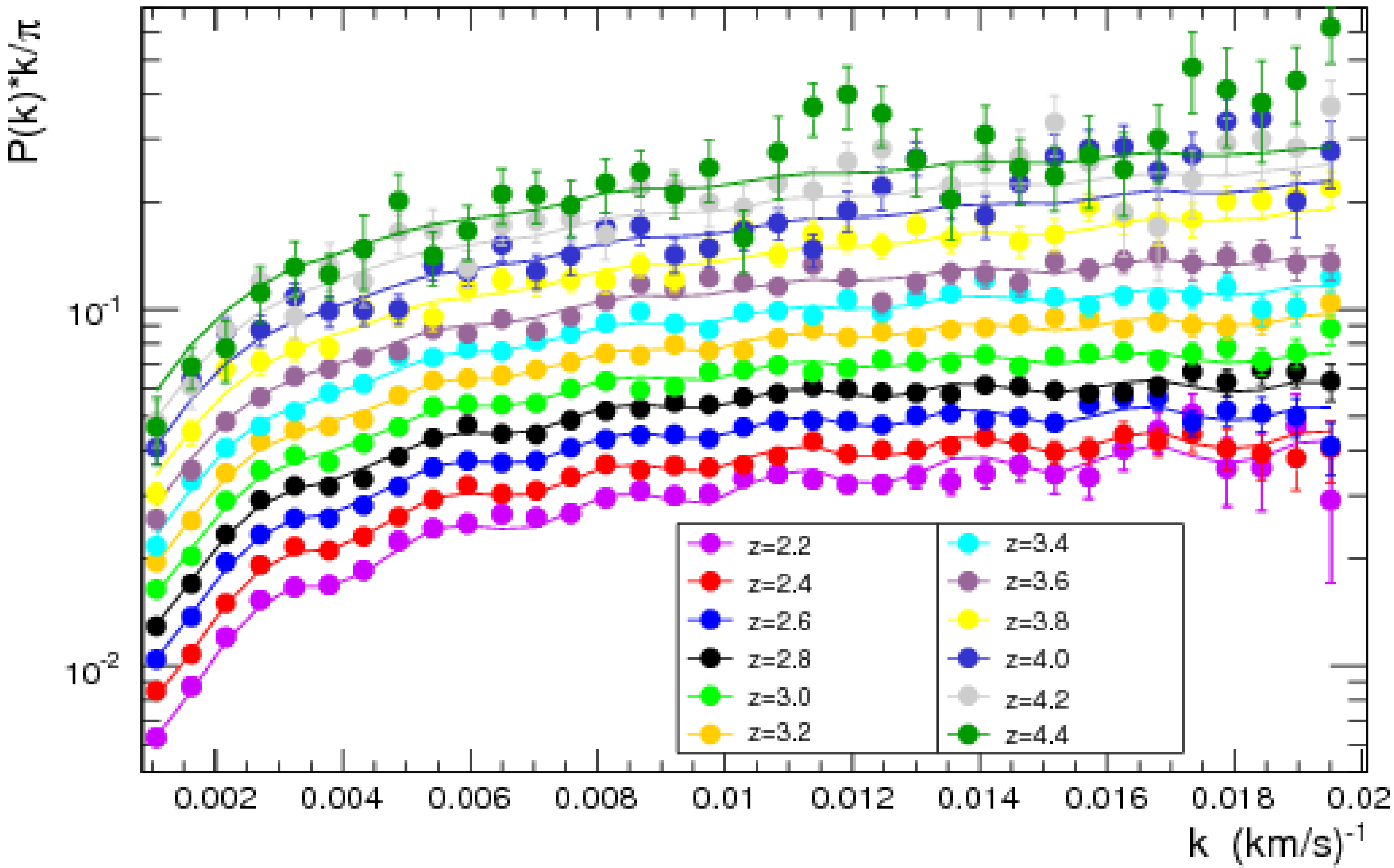
Current observational tests of dark subhaloes



Lyman-alpha forest

Current observational tests of dark subhaloes

(e.g.,Viel+2005, Palanque-Delabrouille+2013)



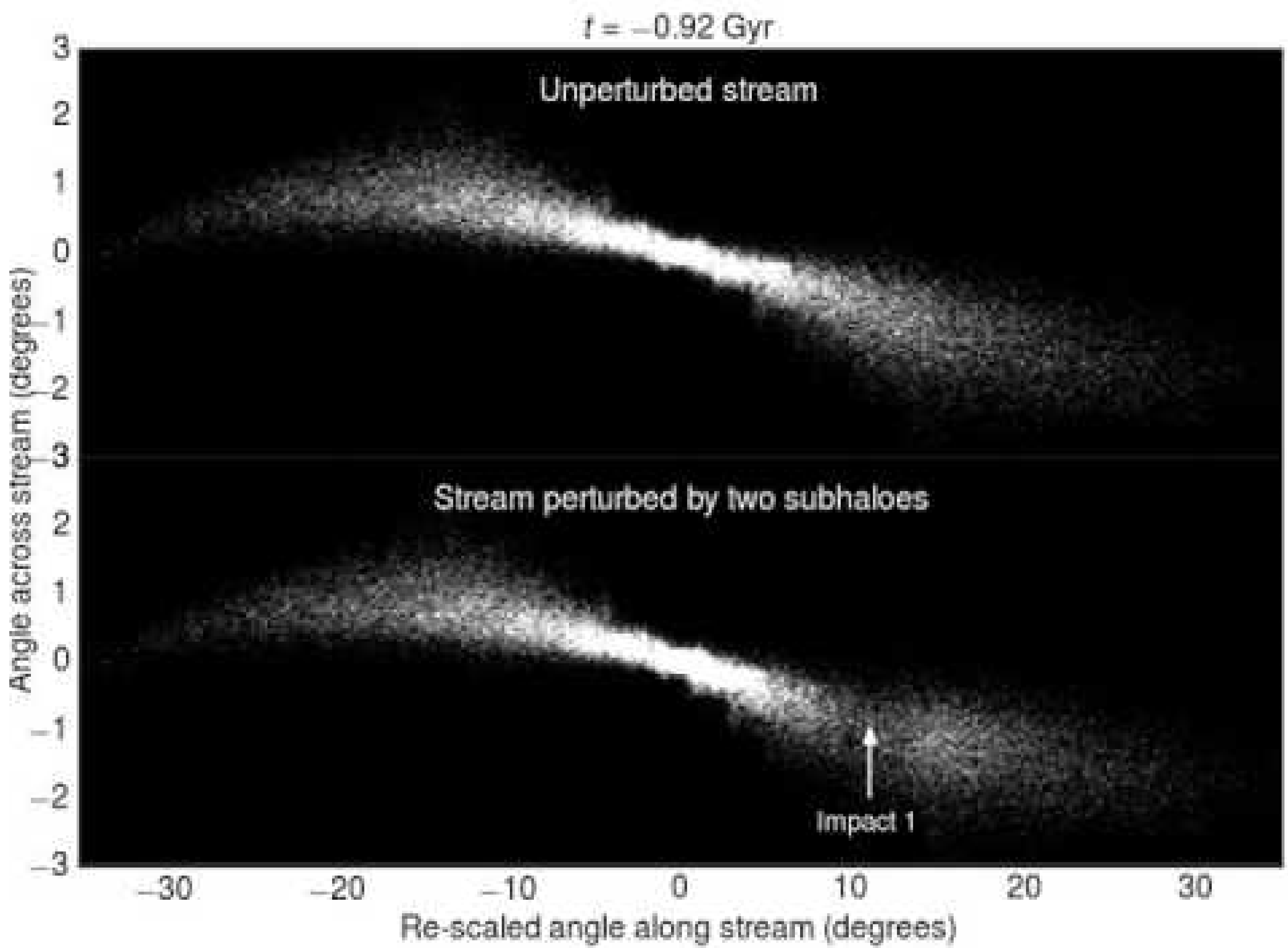
Lyman-alpha forest flux power spectrum → matter power spectrum. Constraint on nature of dark matter. Complex and limited.

Current observational tests of dark subhaloes

(e.g., Koopmans 2005)

Perturbations of strong lensing arcs

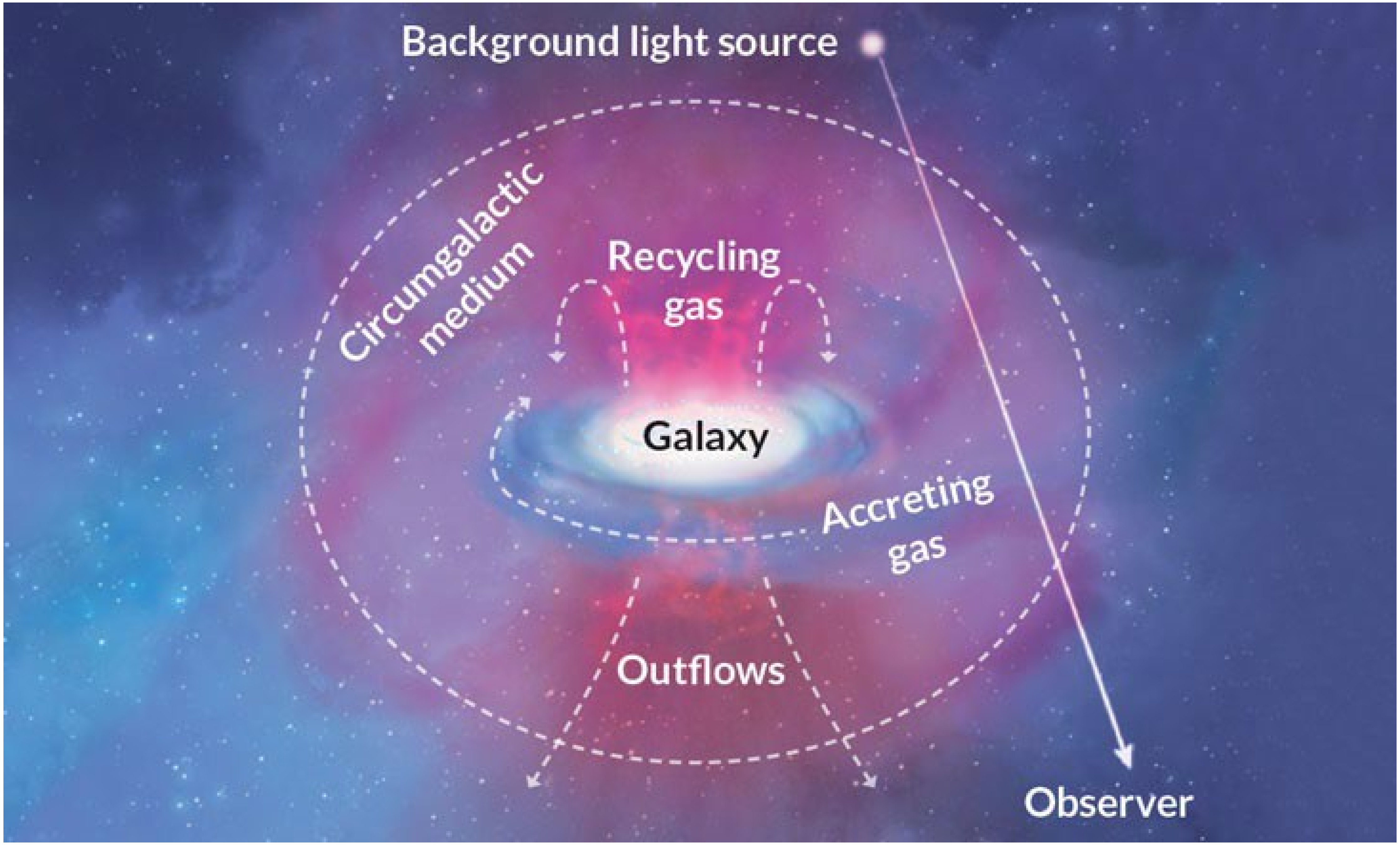
Current observational tests of dark subhaloes



(e.g., Erkal & Belokurov 2015)

Perturbations of stellar streams

Proposal: fluctuations in the CGM



Advantages: most baryons are in hot phase. Volume-filling.
Disadvantages: not easy to observe and CGM is dynamic.

CGM fluctuations: the physics

Gas that is flowing over the top of a subhalo will try to satisfy HSE:

$$\frac{dP_{\rm cgm}(r)}{dr} = -\frac{GM_{\rm grav}(<r)\rho_{\rm cgm}(r)}{r^2}$$

So long as the flow is not supersonic, HSE will be about right. Also, **compression will be adiabatic**. Under these conditions, one can derive the density enhancement profile centred on a subhalo:

$$\frac{\rho_{\rm cgm}(r)}{\rho_0} = \left[1 + \frac{4}{5}\frac{T_{200}}{T_0}\ln\left(\frac{R}{r}\right)\right]^{3/2}$$

where

$$\frac{k_B T_{200}}{\mu m_H} = \frac{GM_{200}}{2r_{200}}$$

Depends only on the ratio of the subhalo gravitational temperature (T_{200}) to the CGM temperature (T_0), not on the density of the CGM itself.

Fall off with radius depends on dark matter profile (assumed isothermal here).

IGM+2020

Idealised hydrodynamical simulations

SPH With Inter-dependent Fine-grained Tasking

Run with new **SWIFT** code (Schaller et al.)

Fiducial setup:

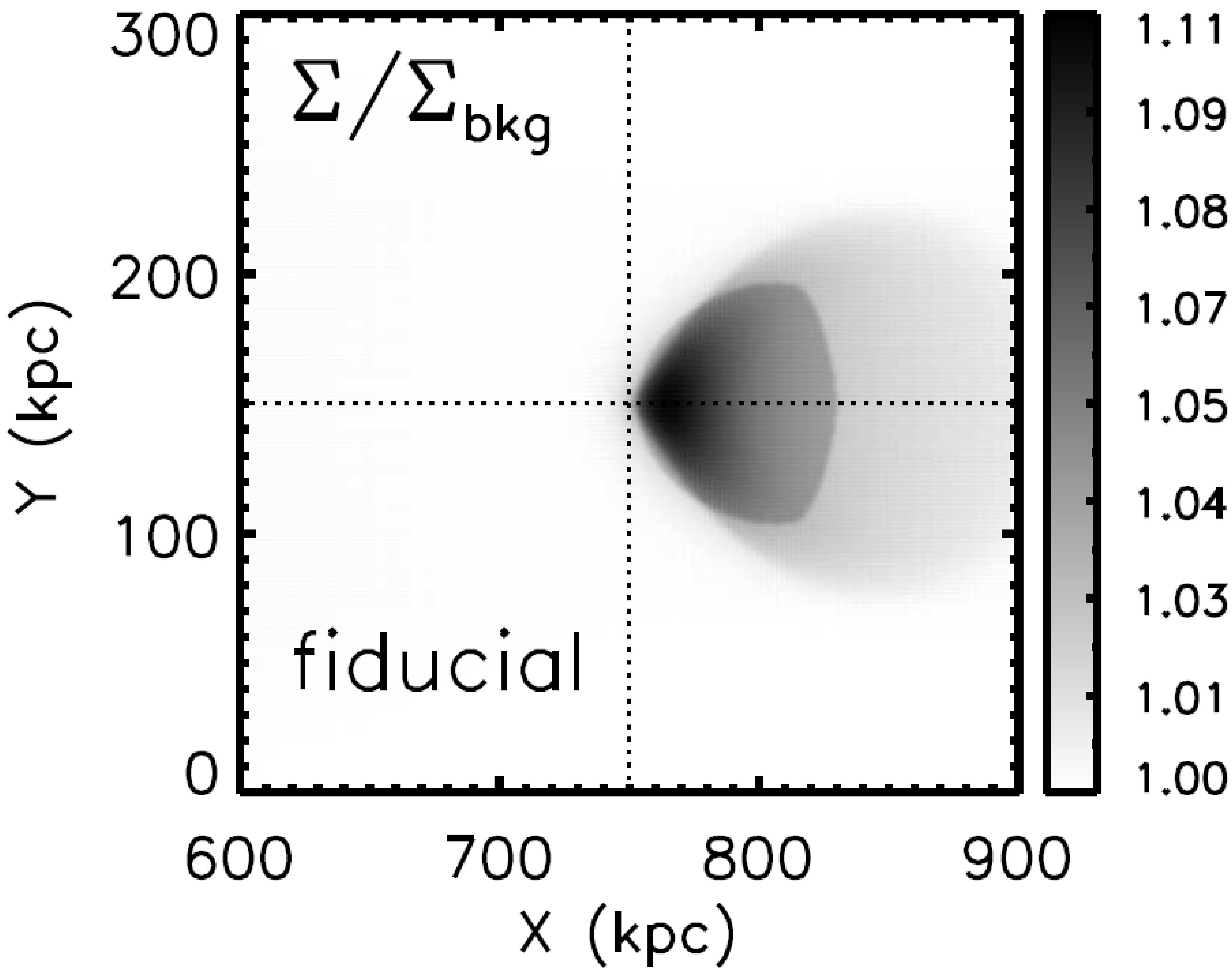
- $M_{sub} = 10^{10}\ M_{sun}$
- $T_{cgm} = 10^6$ K
- $V_{sub} = 200$ km/s
- $n_{cgm} = 10^{-4}$ g/cm^3 (doesn't matter)
- Very high resolution!

Run on only 32 cores for about 5 hours!

Vary subhalo mass, CGM temperature, relative velocity.

IGM+2020

Idealised hydrodynamical simulations



IGM+2020

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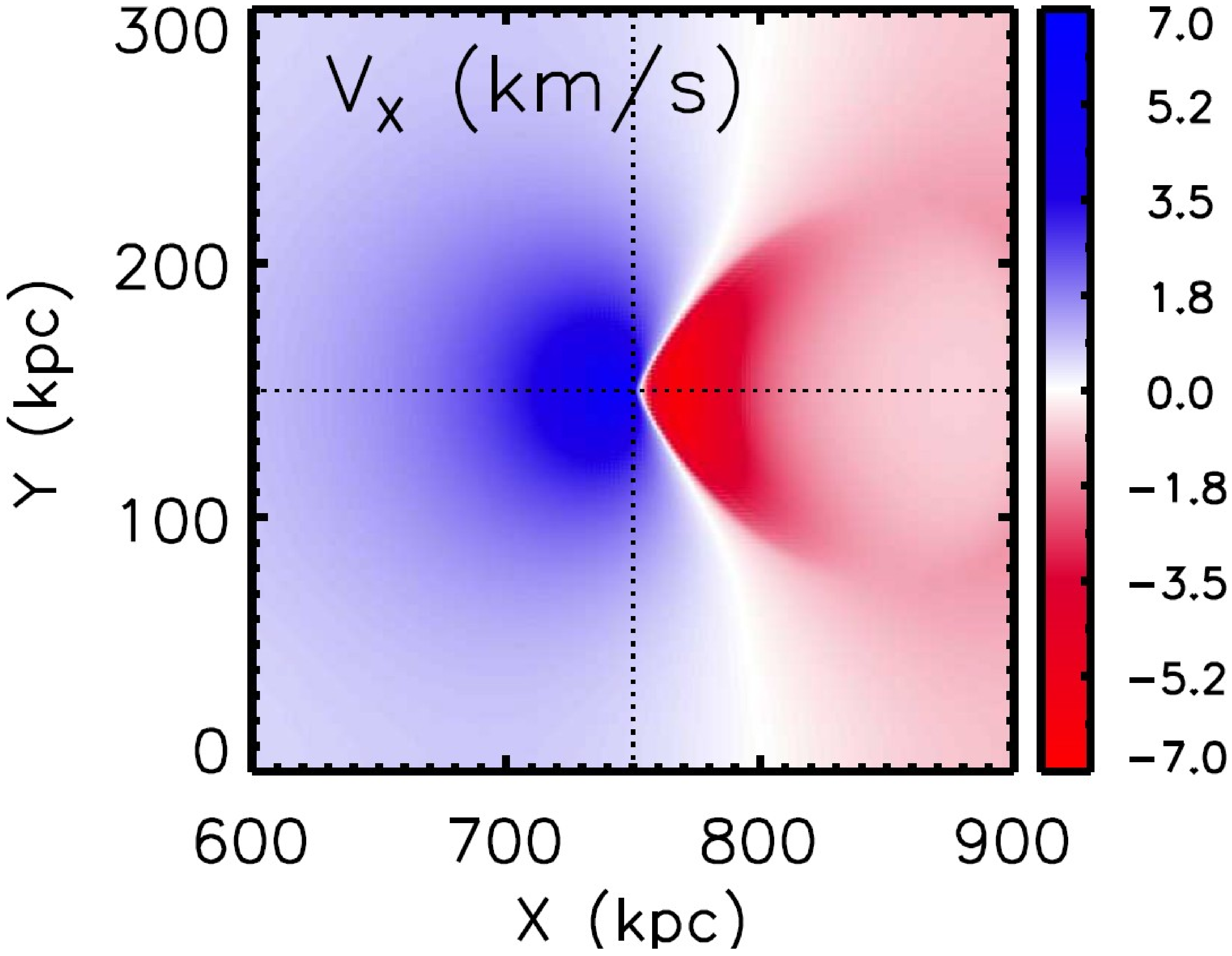


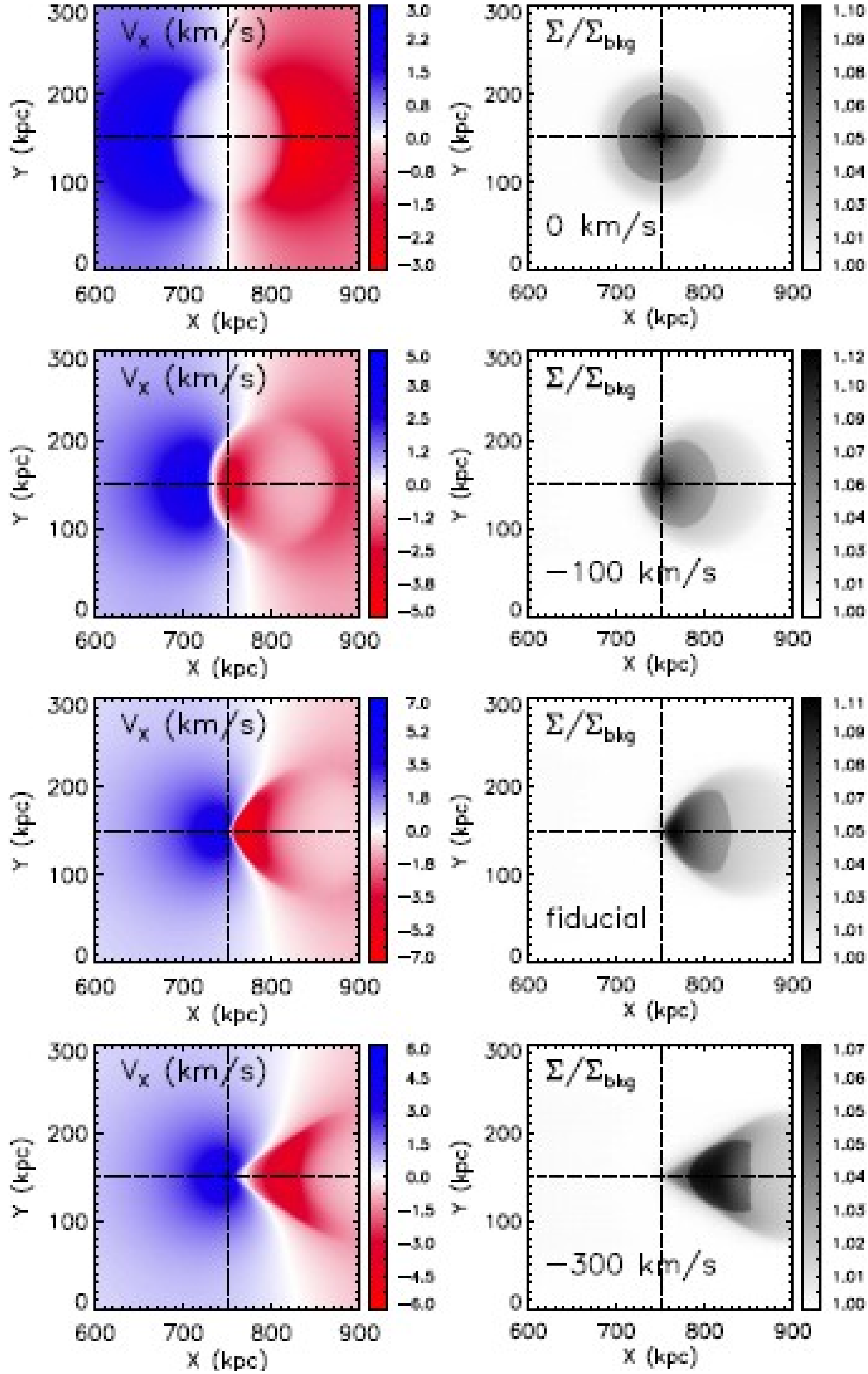
IGM+2020

Varying the relative velocity

Faster the motion the larger the offset is between the subhalo and the CGM enhancement.

Morphology changes.

Amplitude of the effect is only mildly altered.



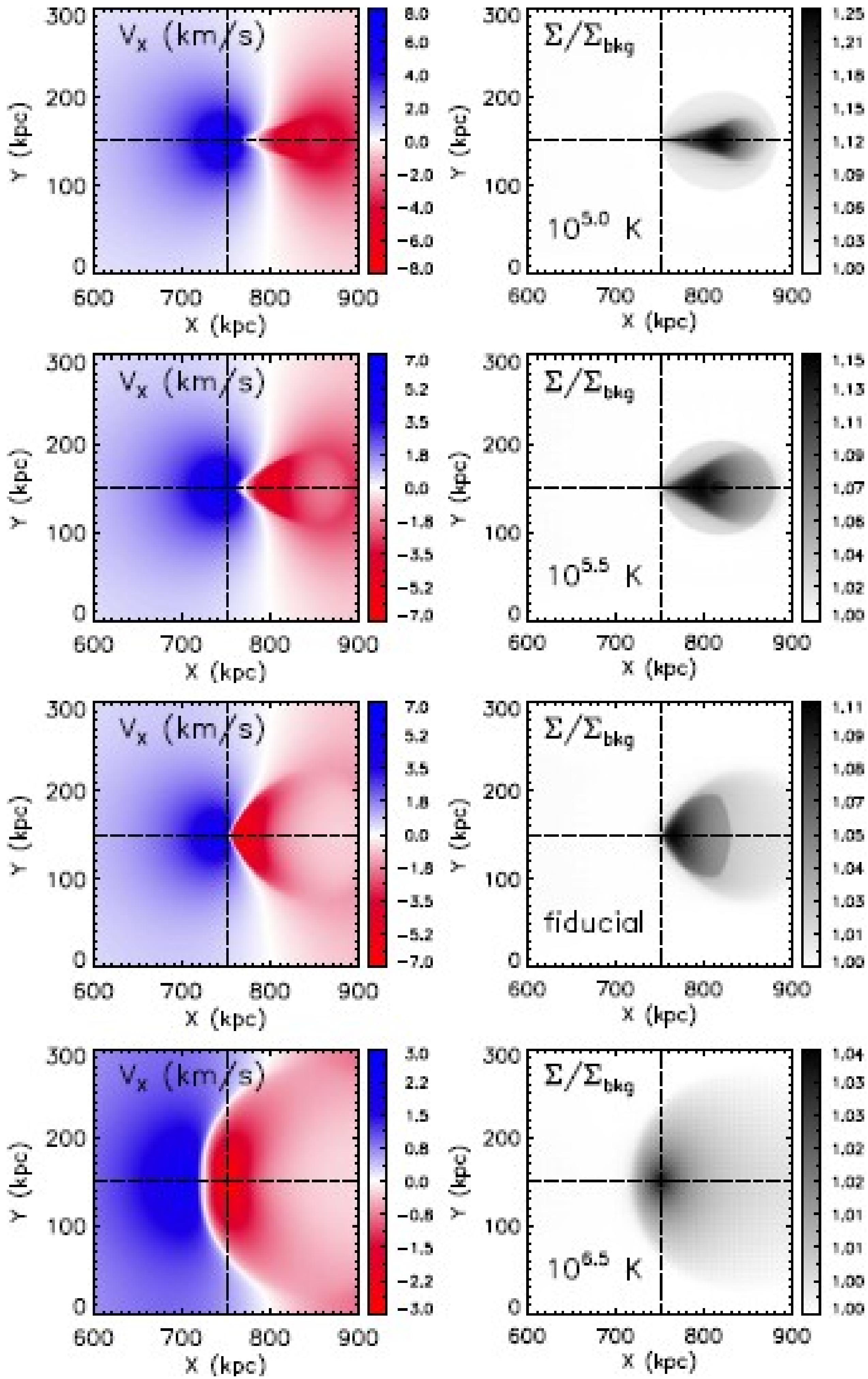
IGM+2020

Varying the CGM temperature

Cooler the CGM the larger the offset is between the subhalo and the CGM enhancement.

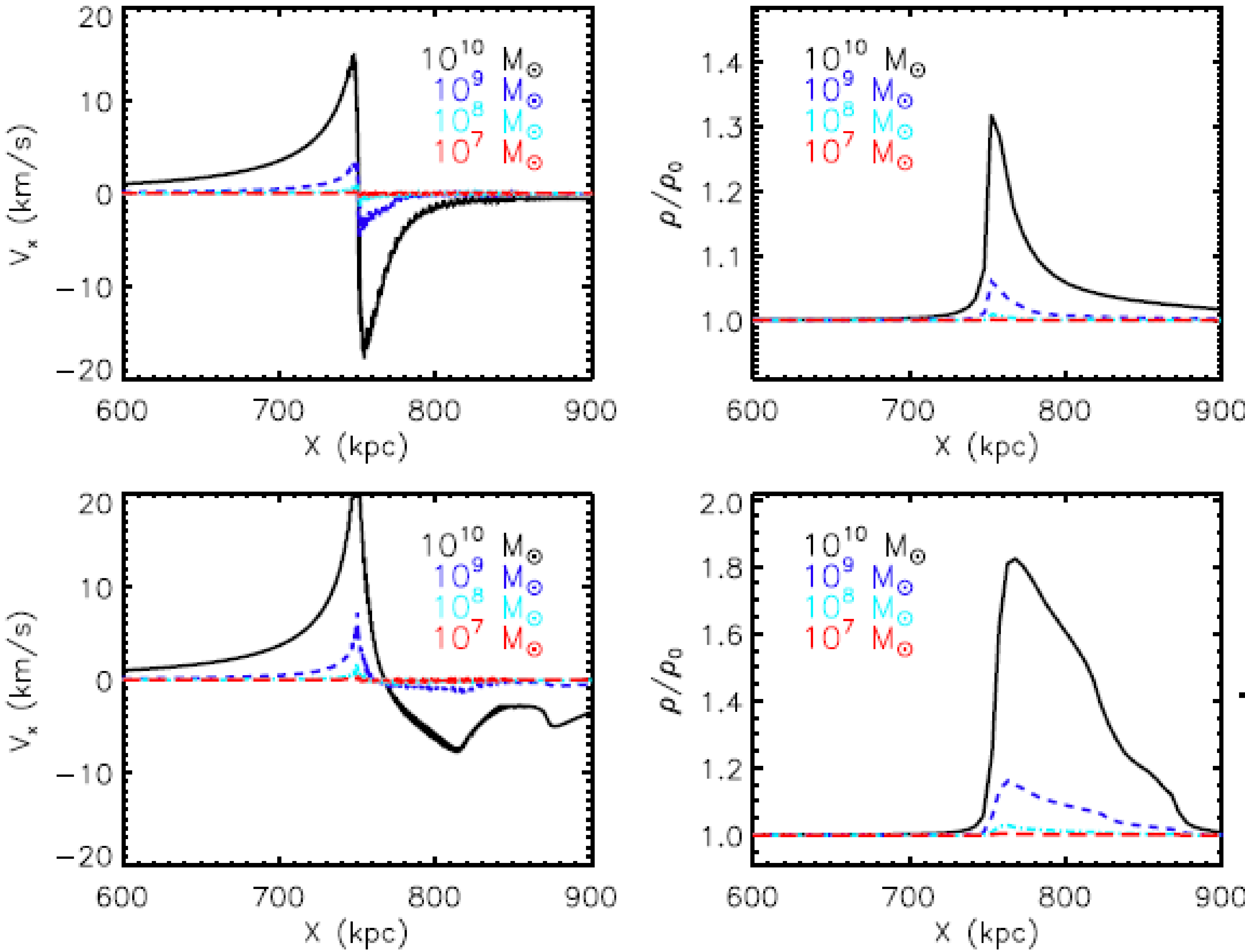
Morphology changes.

Amplitude of the effect is strongly altered (as expected based on analytics). Cooler CGM is more easily compressed.



IGM+2020

Idealised hydrodynamical simulations



T_{cgm}=10^6 K

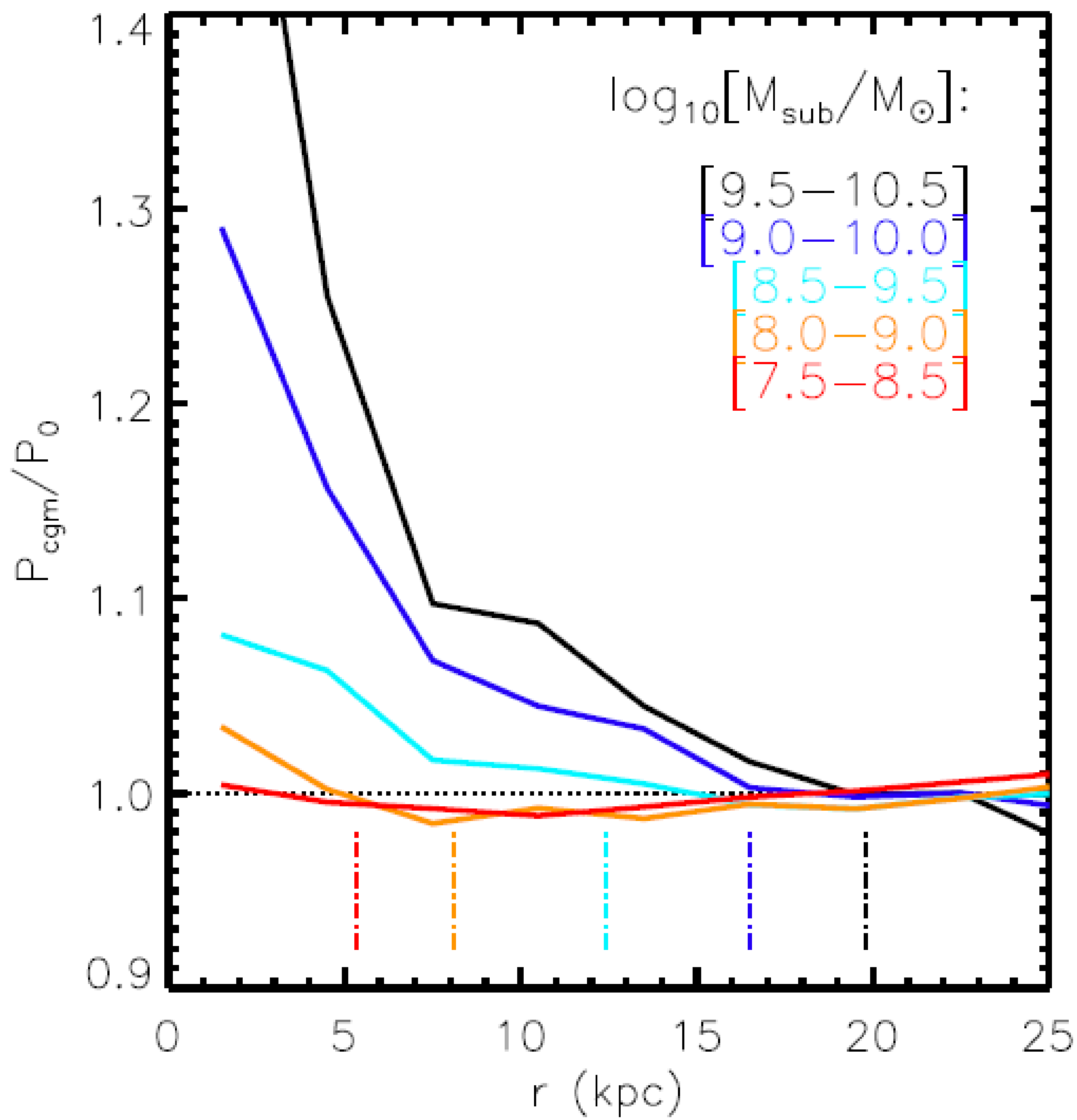
T_{cgm}=10^5 K

IGM+2020

Cooler phase of CGM is best hope.

Full cosmological simulations: ARTEMIS

CGM pressure profiles centred on dark subhaloes of ARTEMIS host haloes



IGM+2020

Full cosmological simulations: ARTEMIS

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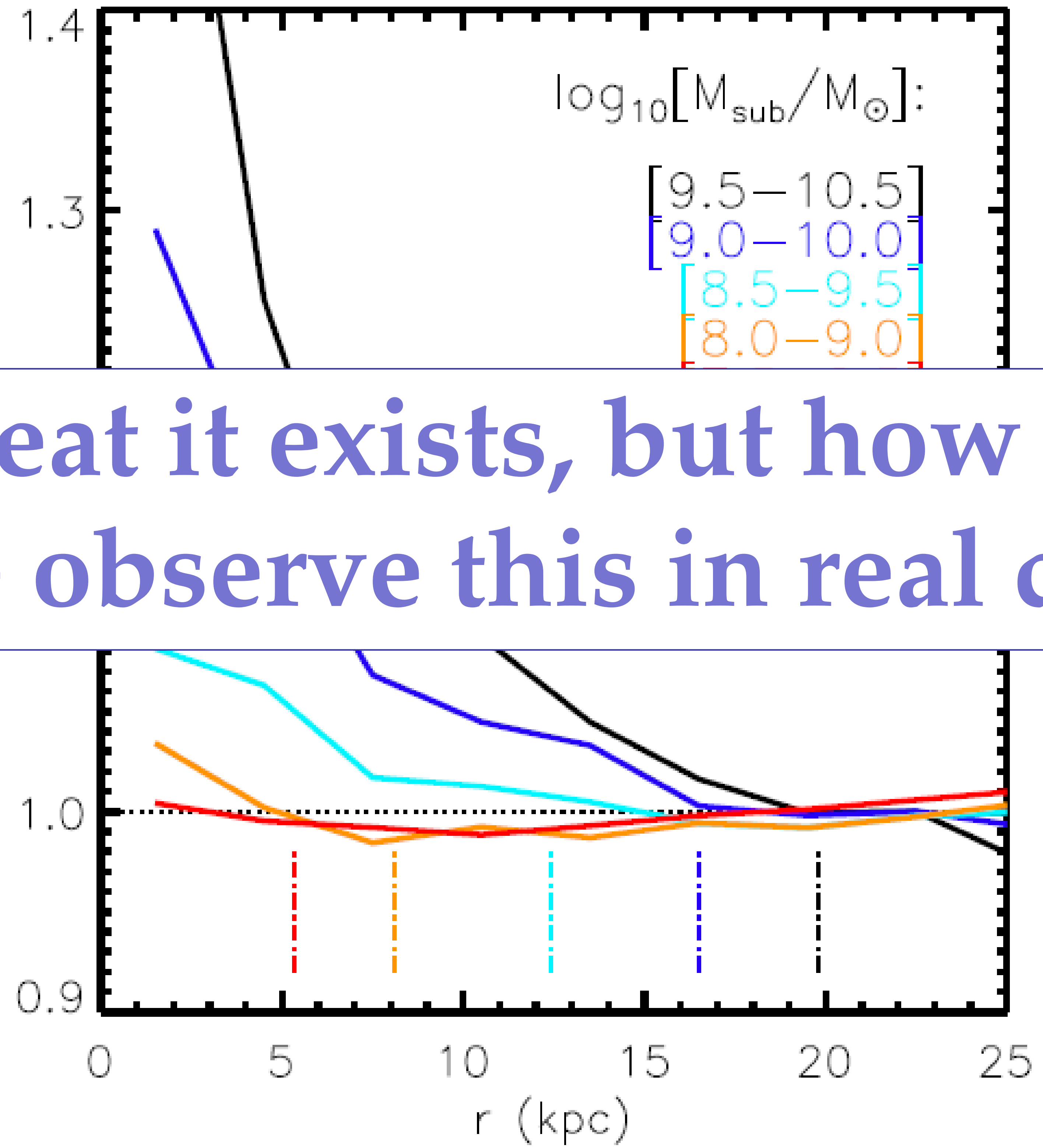
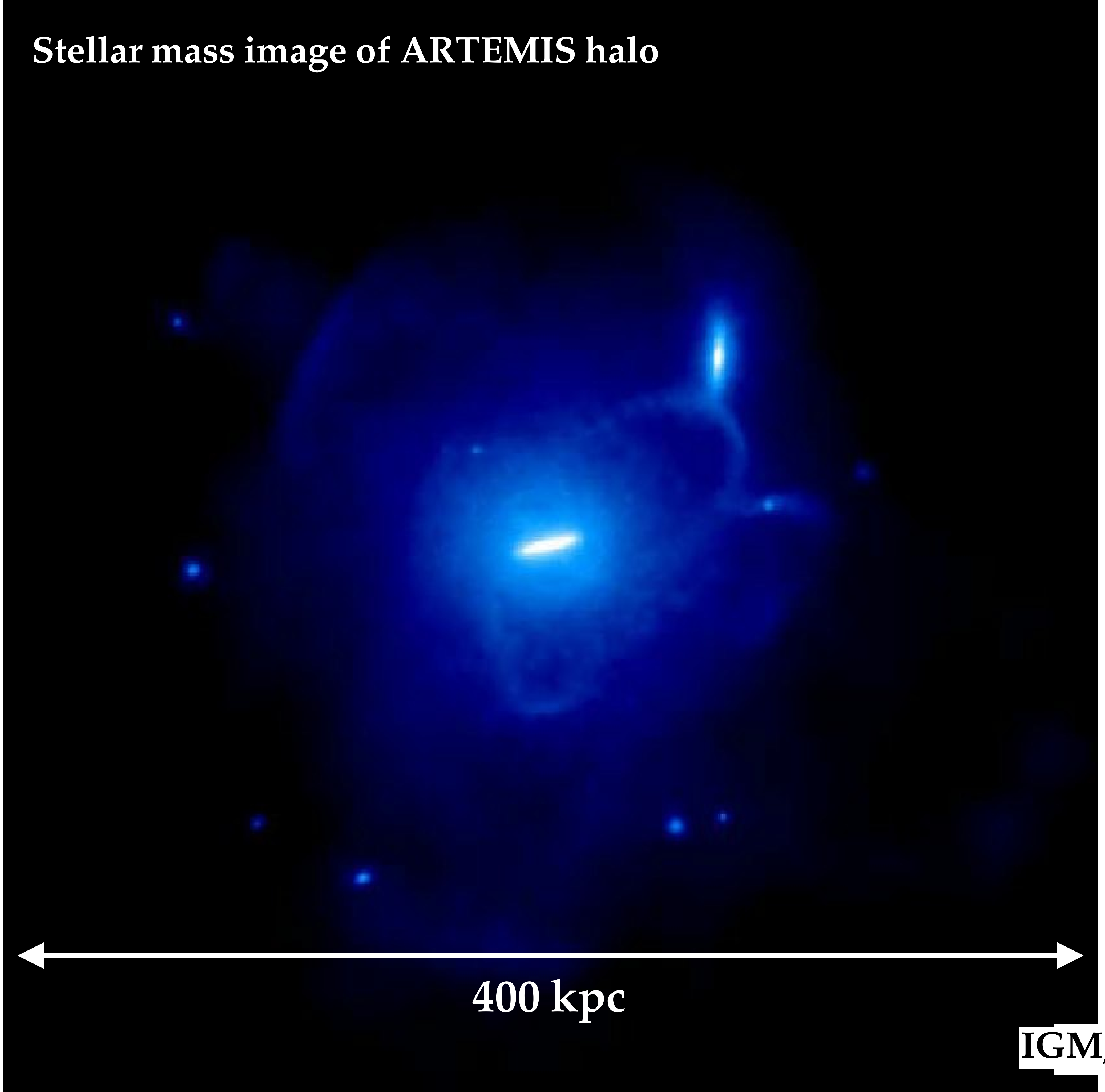
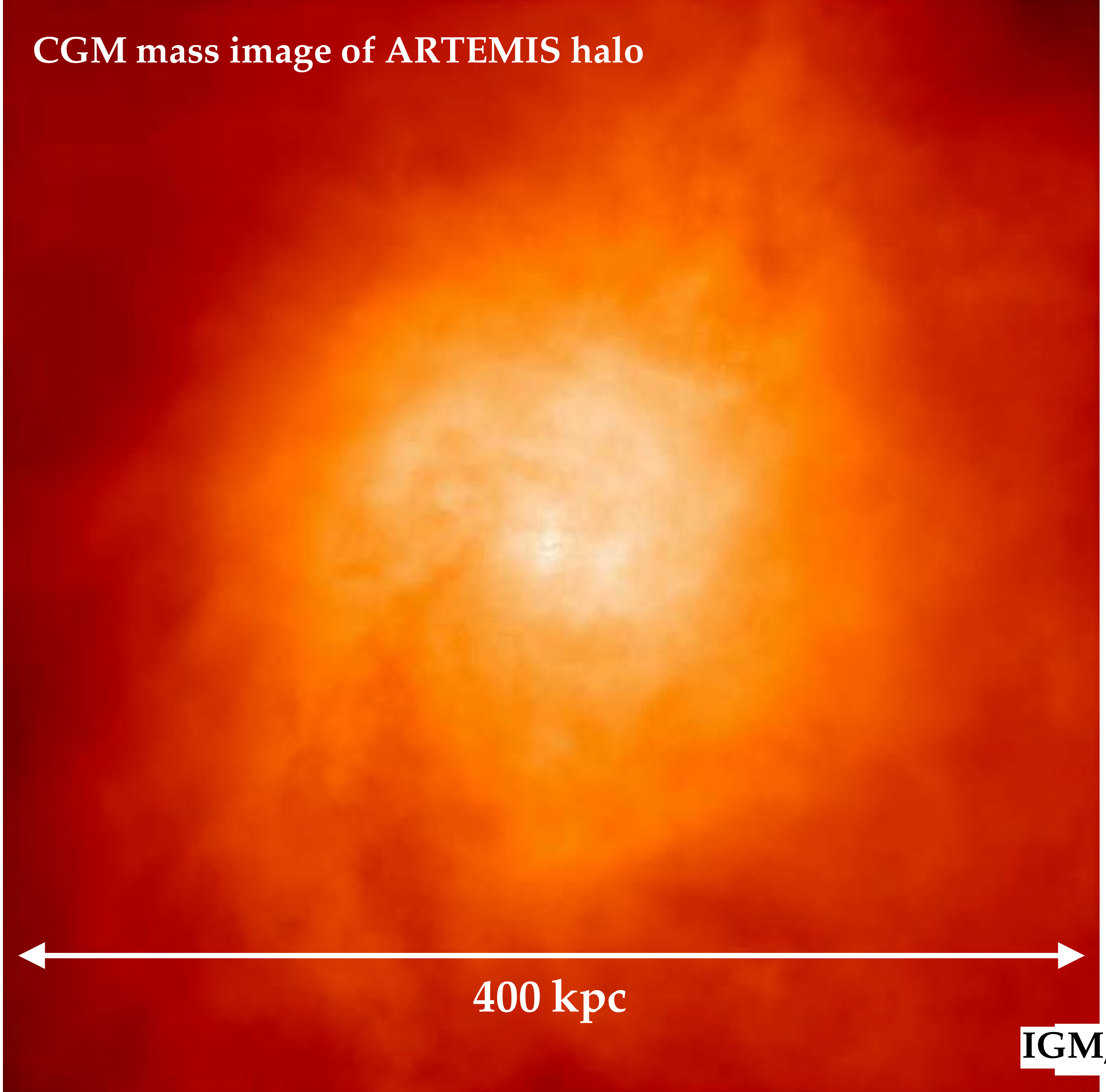


Great it exists, but how do we observe this in real data?

IGM+2020



IGM, in prep



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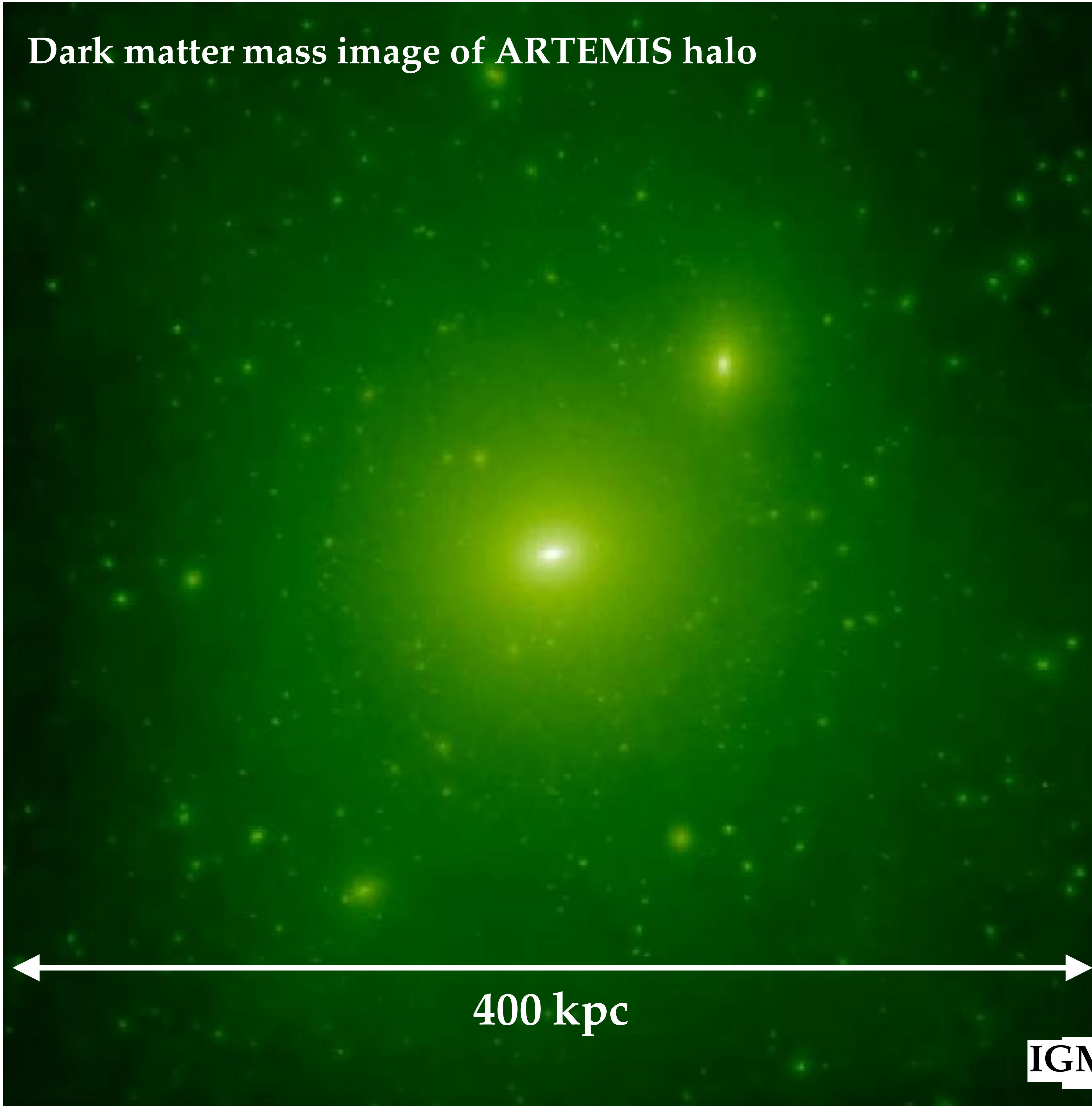
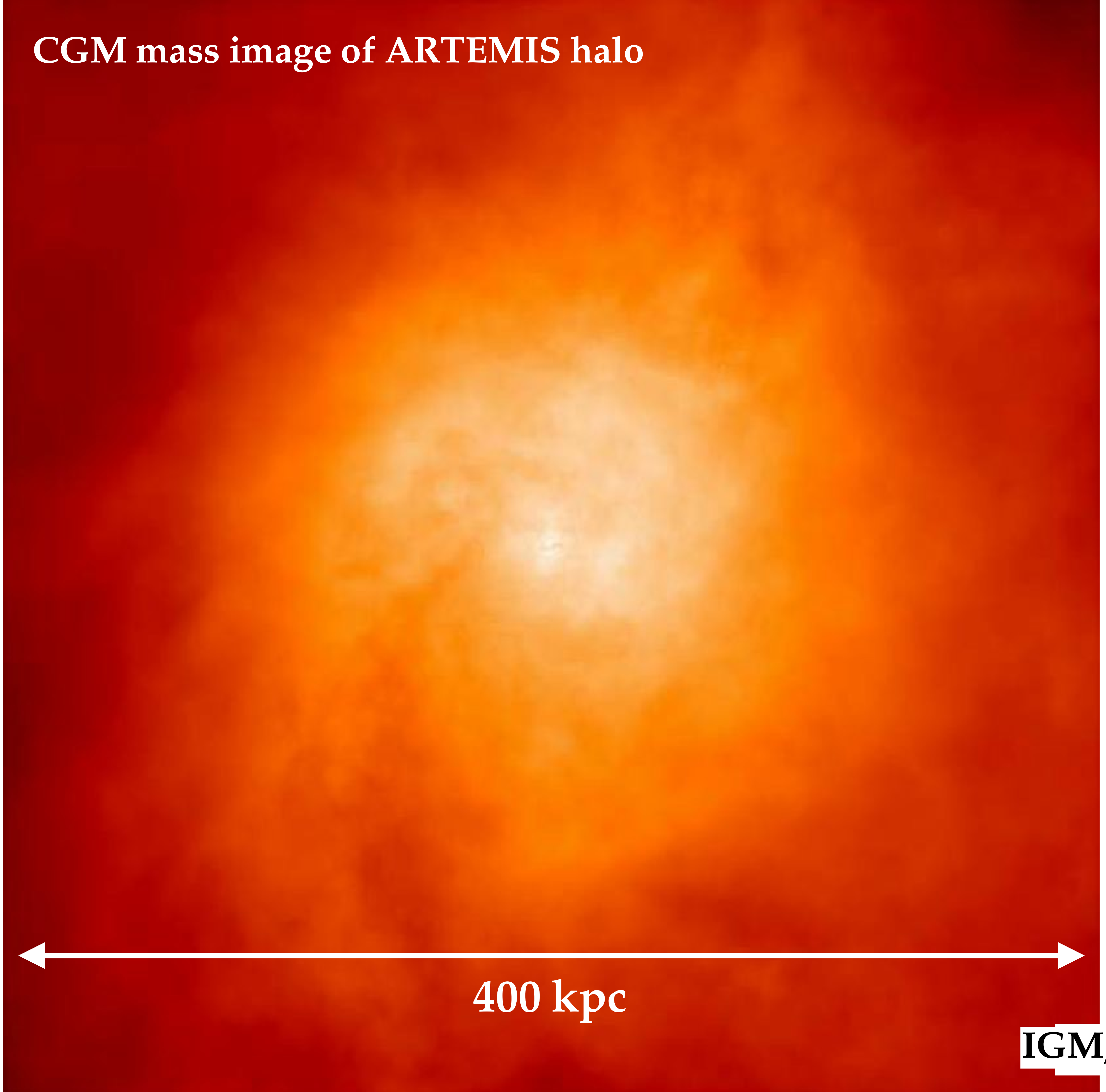
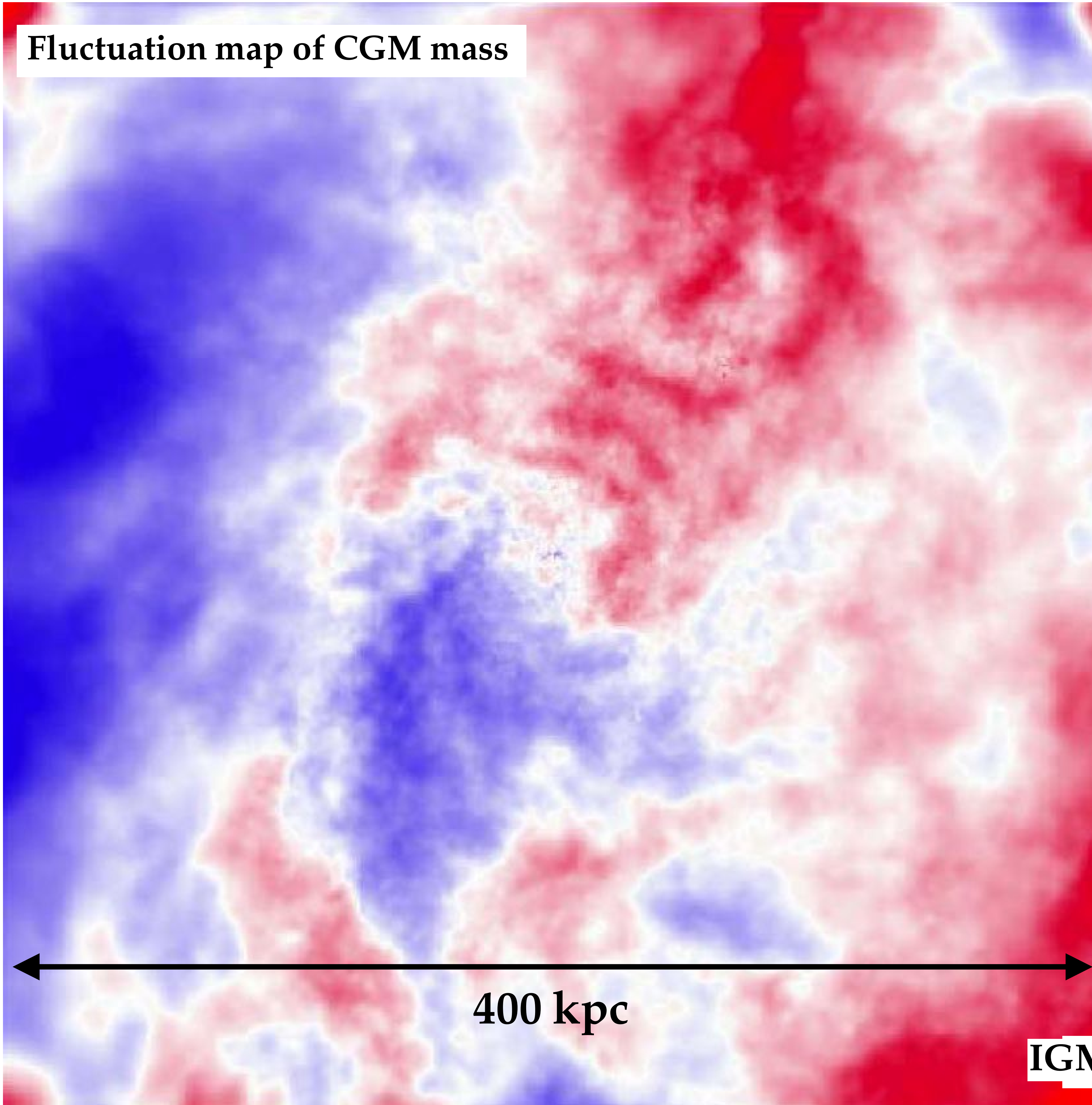
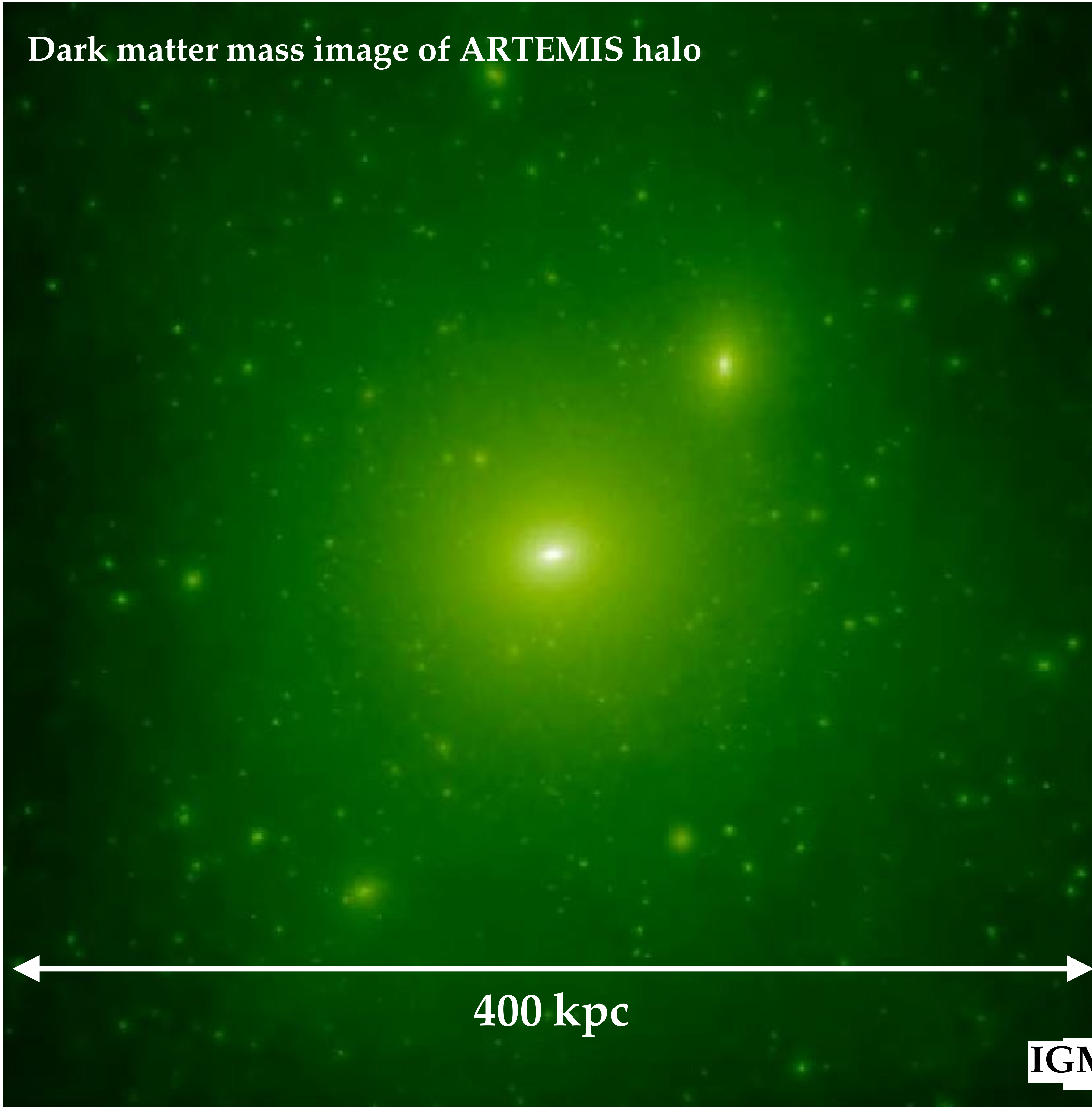


IGM, in prep


CGM mass image of ARTEMIS halo
400 kpc
IGM, in prep



IGM, in prep



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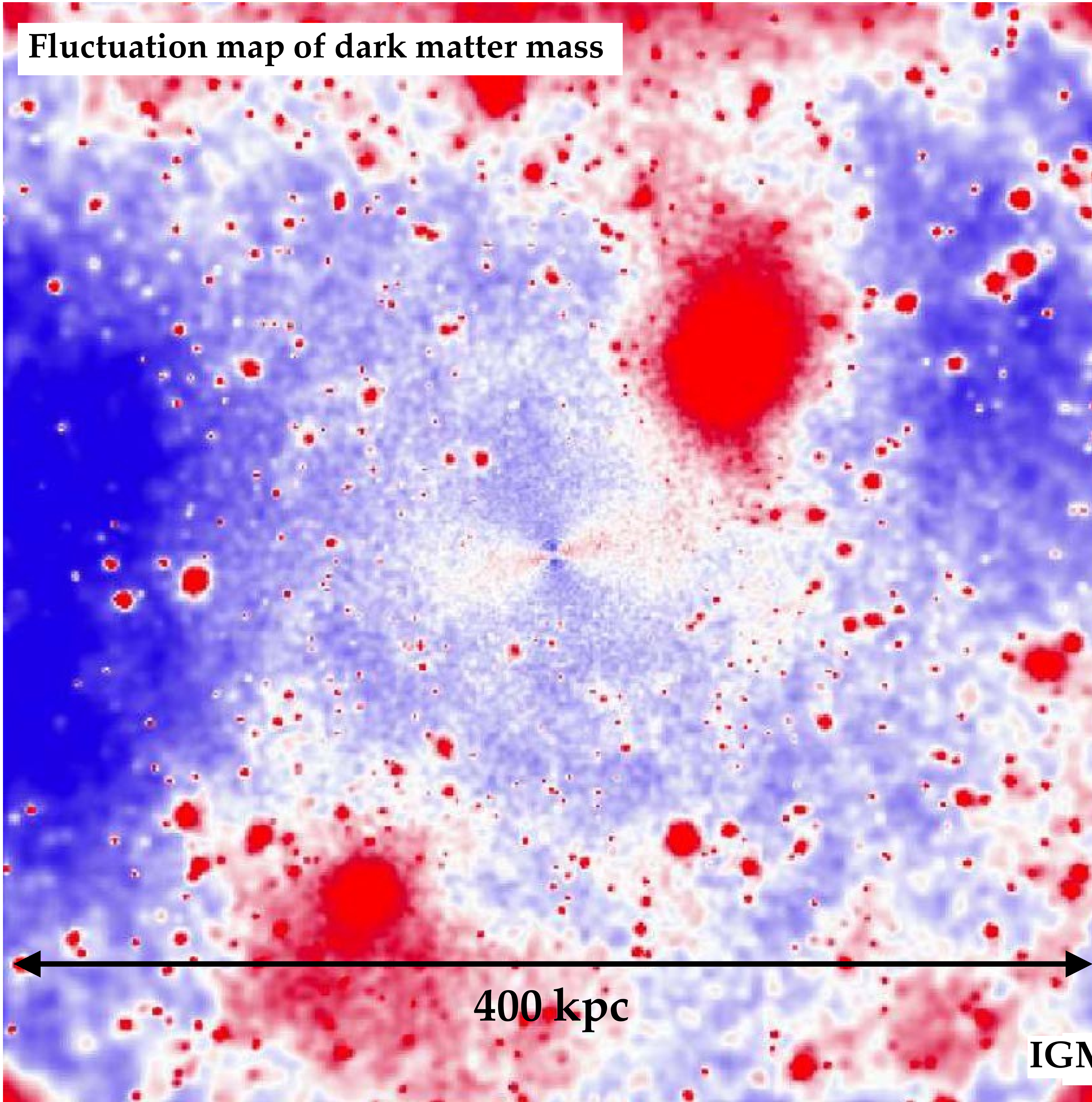

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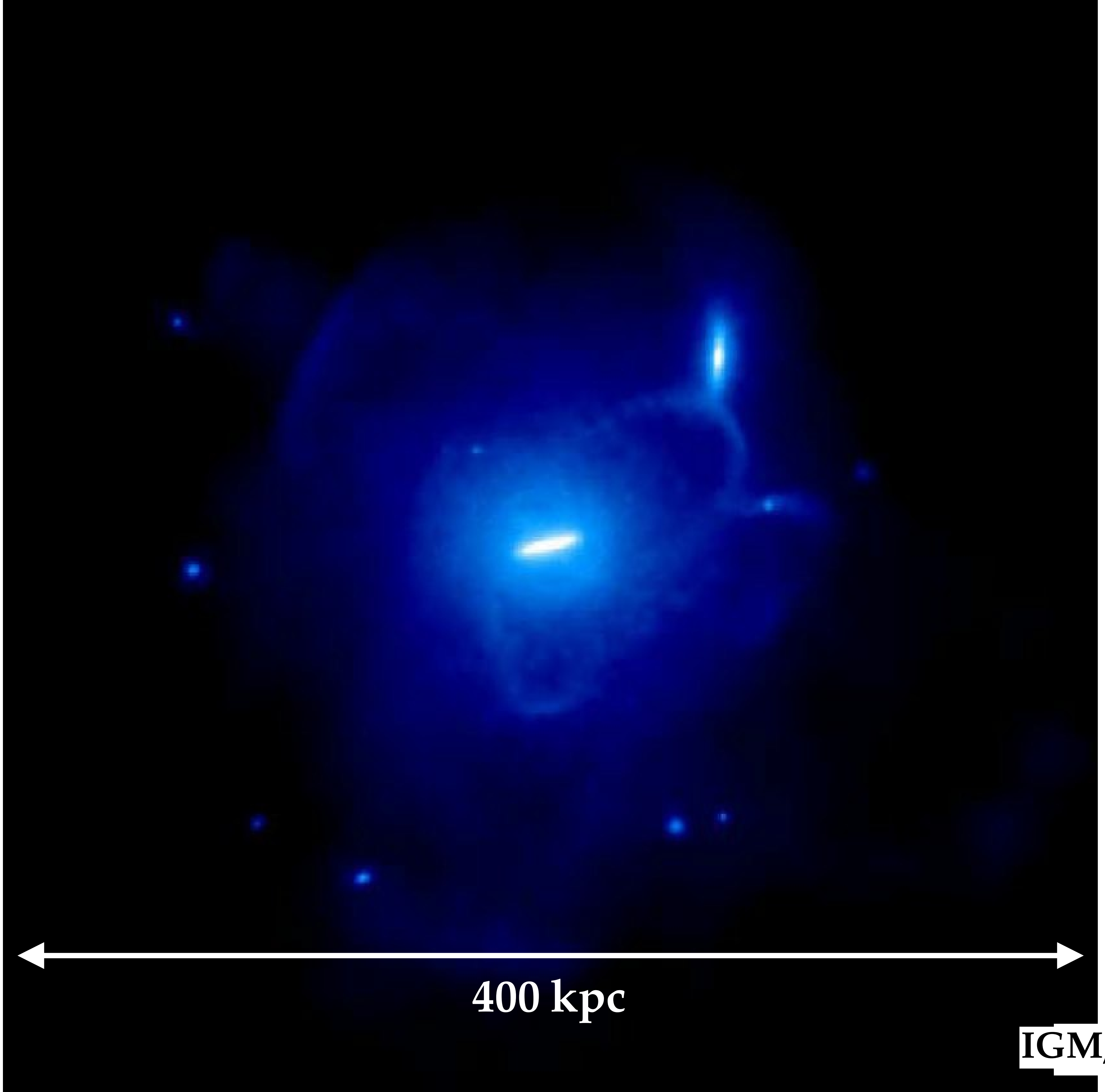
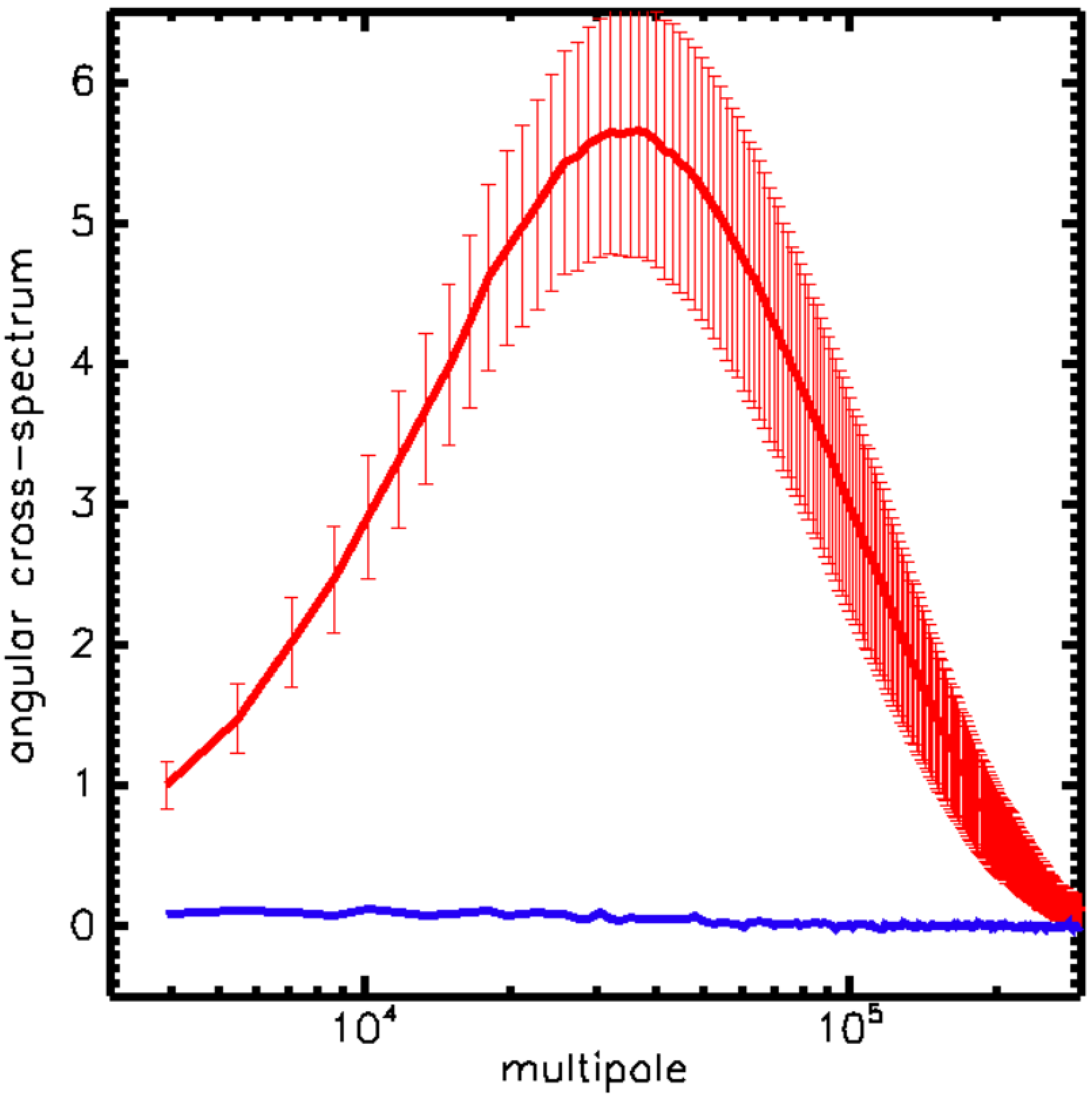


IGM, in prep

CGM-dark matter angular cross-spectrum



IGM, in prep

Conclusions (part 2)

- If ΛCDM is correct, there should be countless dark matter subhaloes around galaxies like the Milky Way.
- Galaxy formation (feedback) provides a plausible explanation for why most of them are dark. **But how can we distinguish between being present and dark or just not being present?**
- Recent searches for dark subhaloes have relied on stellar mass/cool gas. Requires a bit of fortune.
- **New proposal:** CGM has most of the mass and is volume-filling.
- Effect is indeed present at few percent up to tens of percent (in density).
- Observations that probe the CGM (X-ray, tSZ, absorption/emission line studies, and radio dispersion) can potentially measure the fluctuation power spectrum.