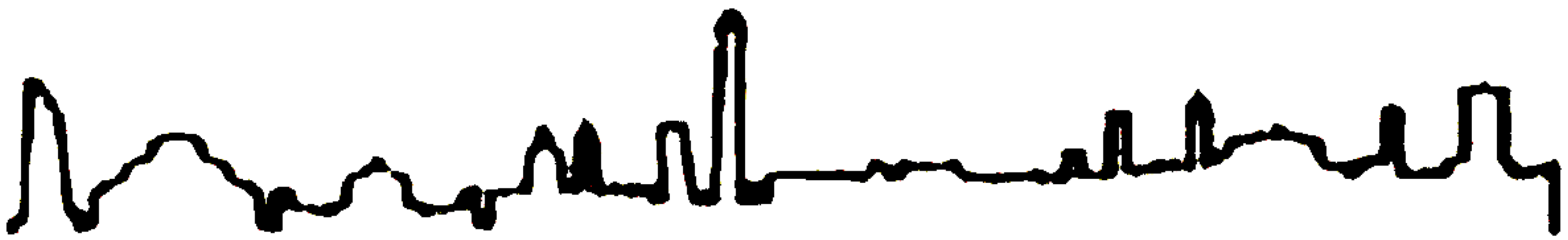
Dark Matter Halo Structural Properties: Substructures and Shapes as challenges for CDM

Galaxy Cluster Properties



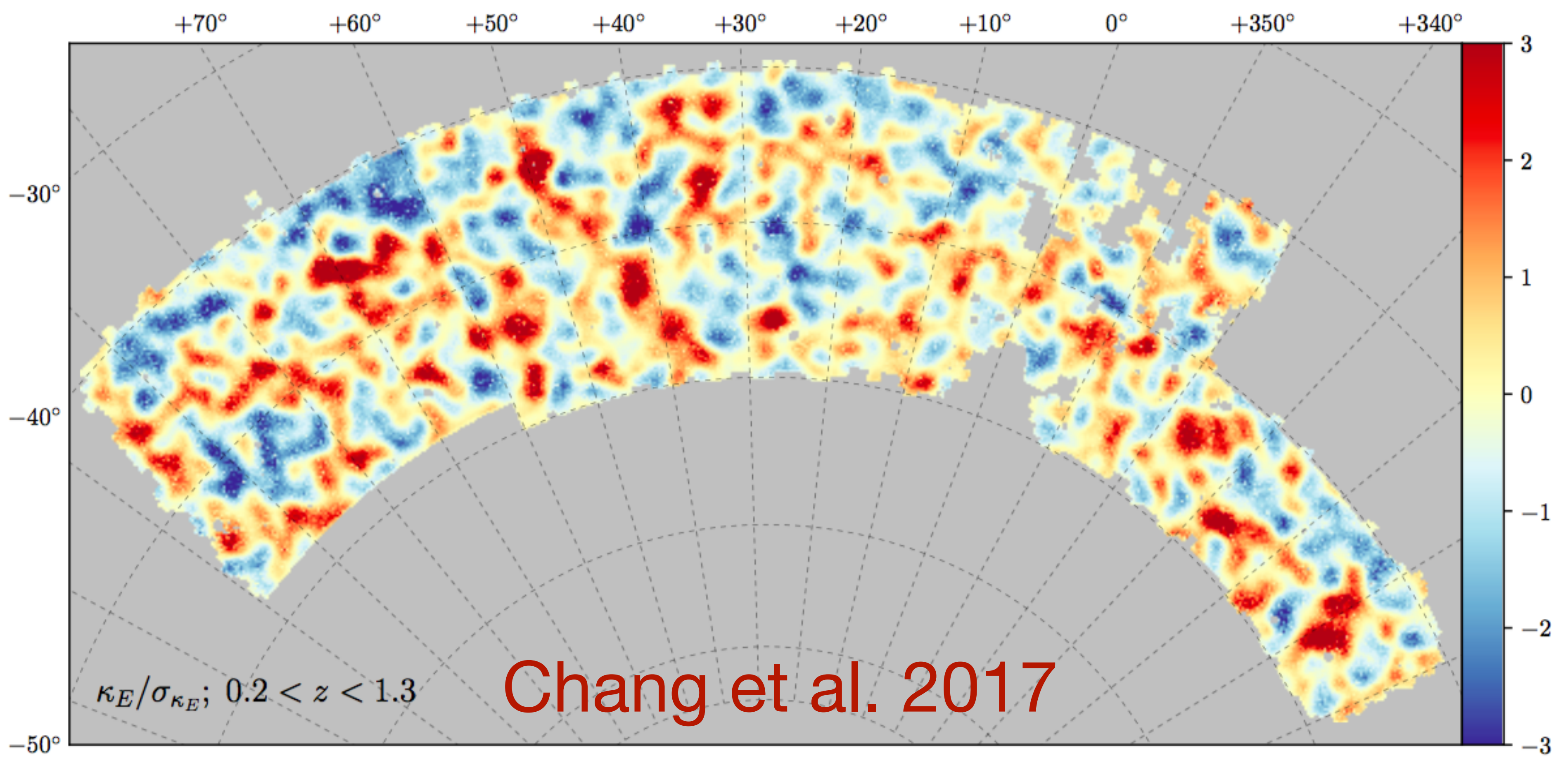
Carlo Giocoli INAF-OAS Bologna

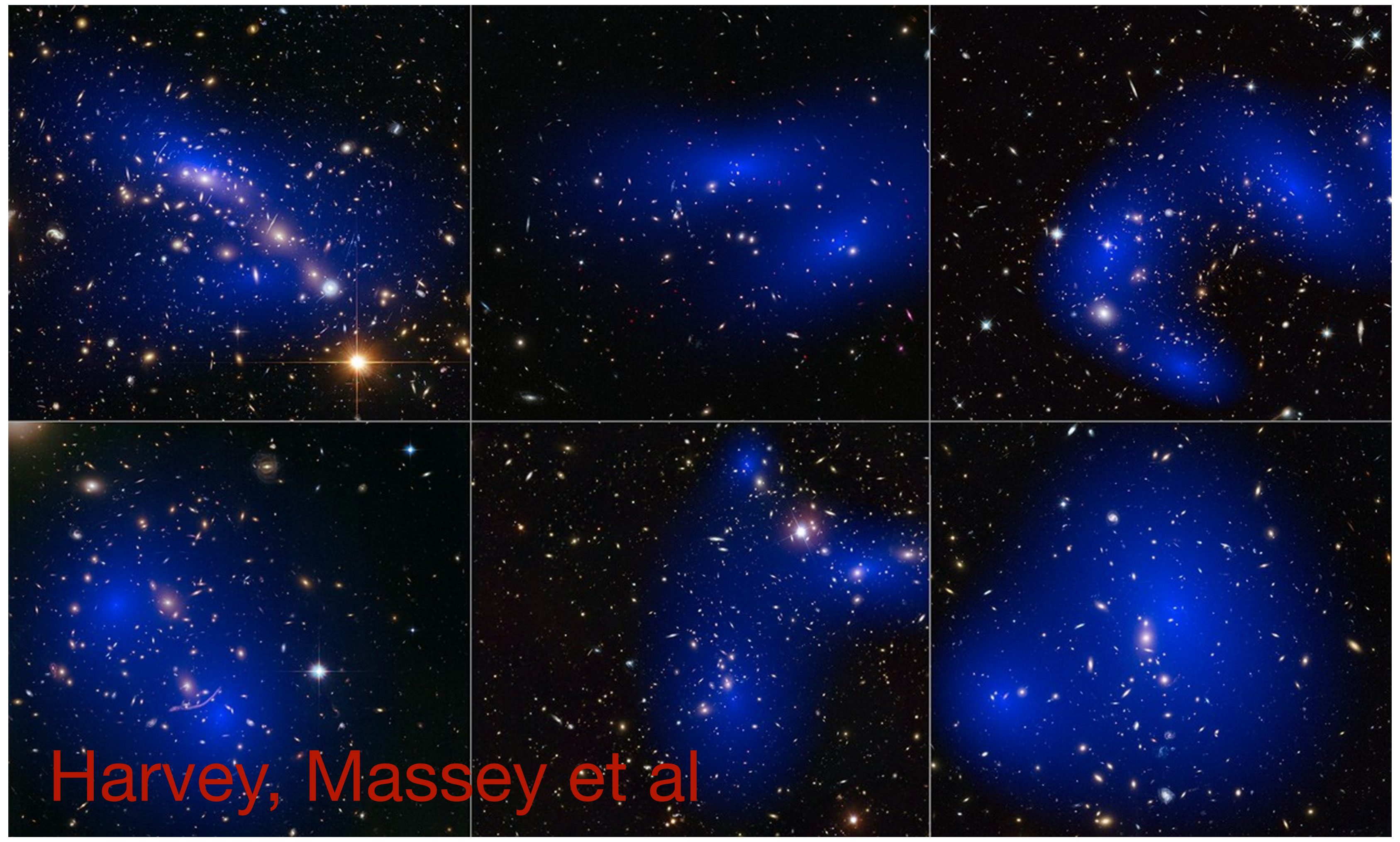
in collaboration with:
G. Despali, M. Meneghetti, L. Moscardini, A. Ragagnin, …

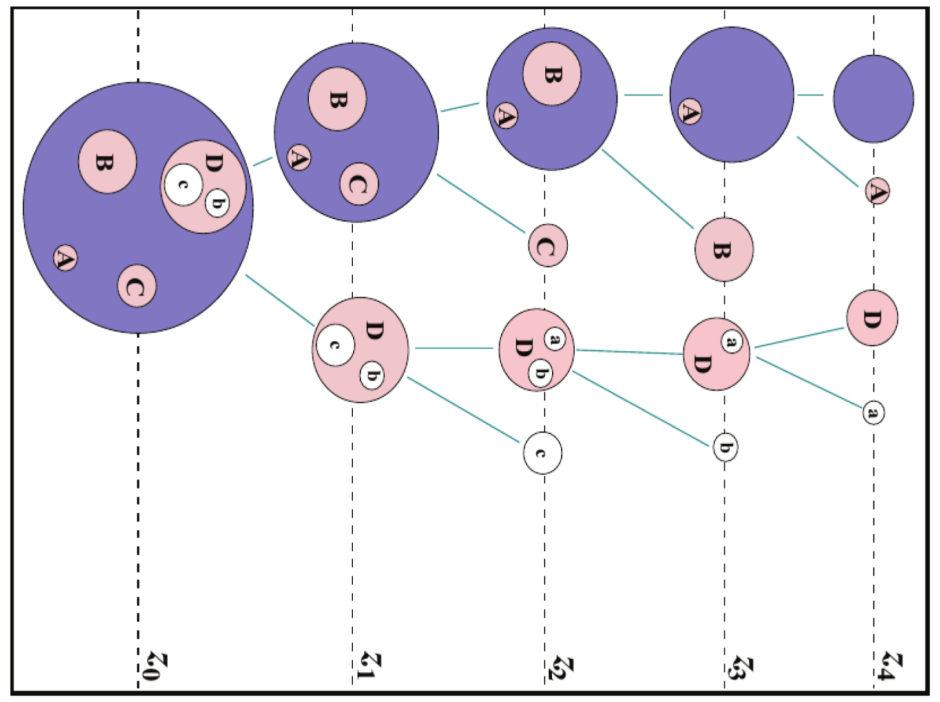
The Nature of Dark Matter

Universe constituents

- Most of the energy content of our Universe is Dark (Dark Energy and Dark Matter)
- Observations of large scale matter distribution or detiled anaysys of galaxies and clusters support the general idea that dark matter could be constituted of weakly interacting collisonless particles
- Partilcle velocity in the early universe is small to not erase the formation of small systems: Cold Dark Matter
- Structure formation processes proceed in a hierachical way







Galaxy Clusters

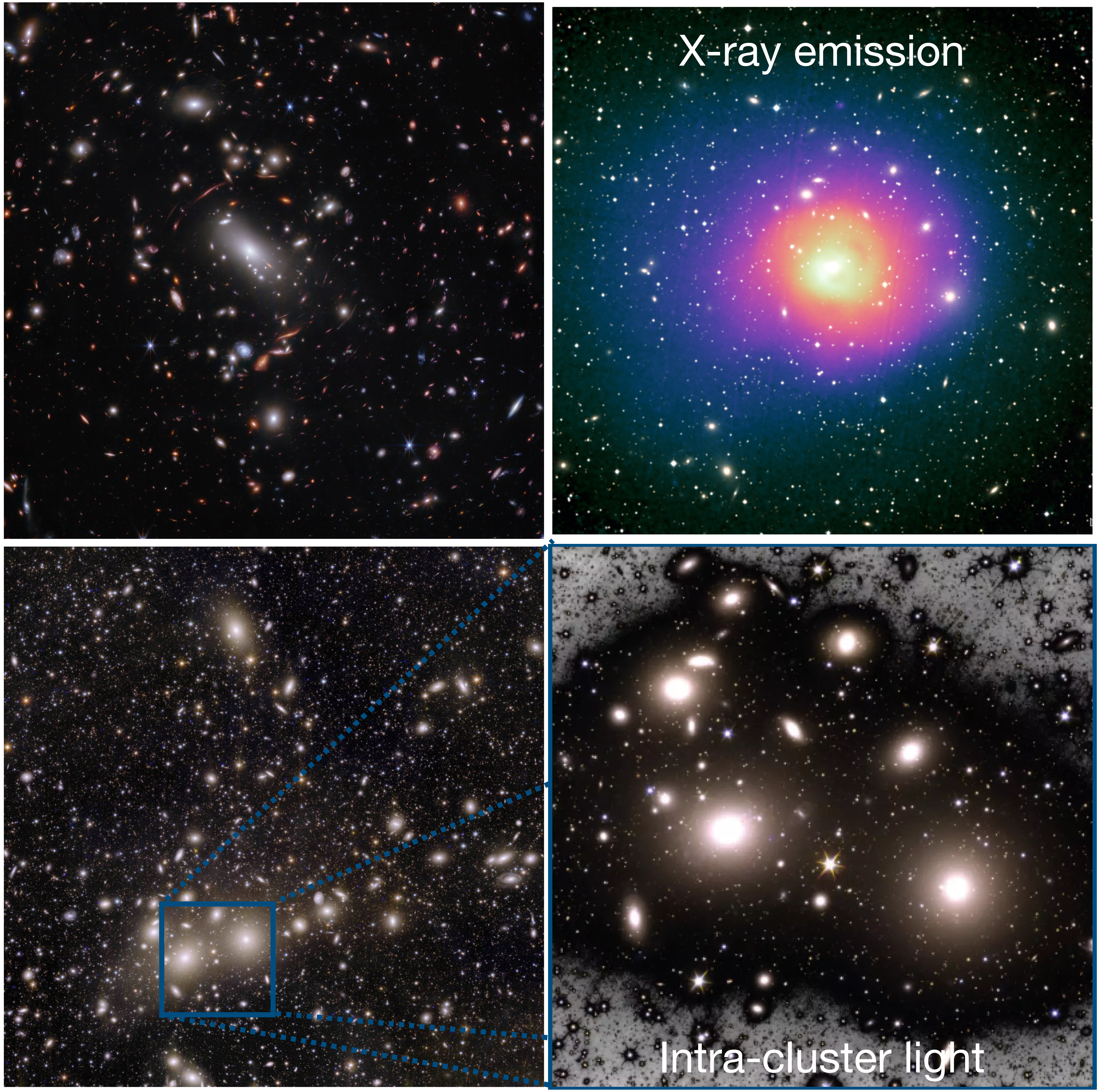
Cosmic Laboratories

Properties:

- Largest virialised objects in the Universe
- *Mass:* $10^{14}\ M_\odot < M < 10^{15}\ M_\odot$
- *Radius:* 1 Mpc < R < 5 Mpc

Detection:

- NIR & optical (member galaxies, weak lensing);
- X-rays (intra-cluster medium bremsstrahlung);
- thermal Sunyaev Zel'dovich effect.

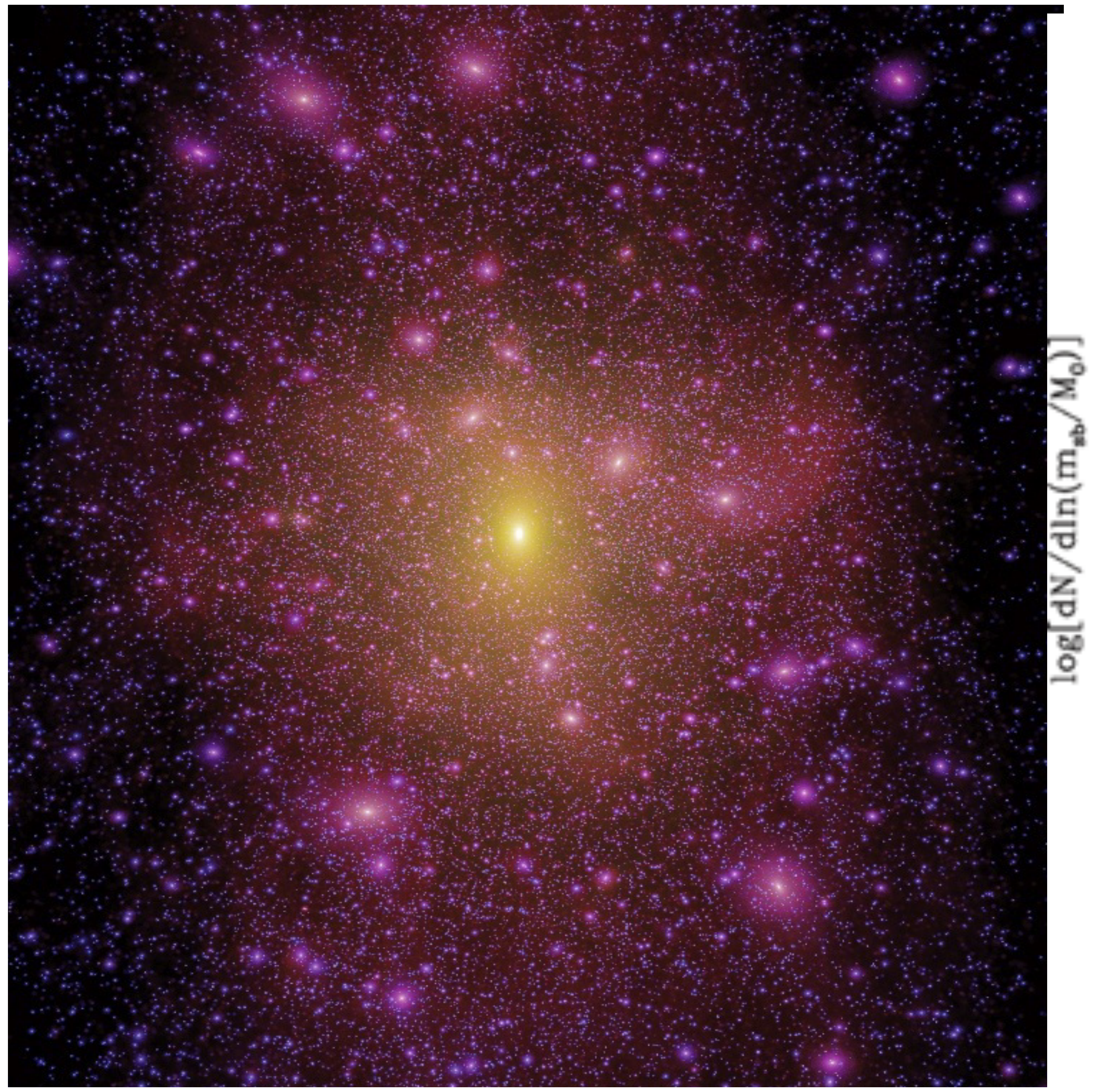


Euclid view of the Persus Cluster

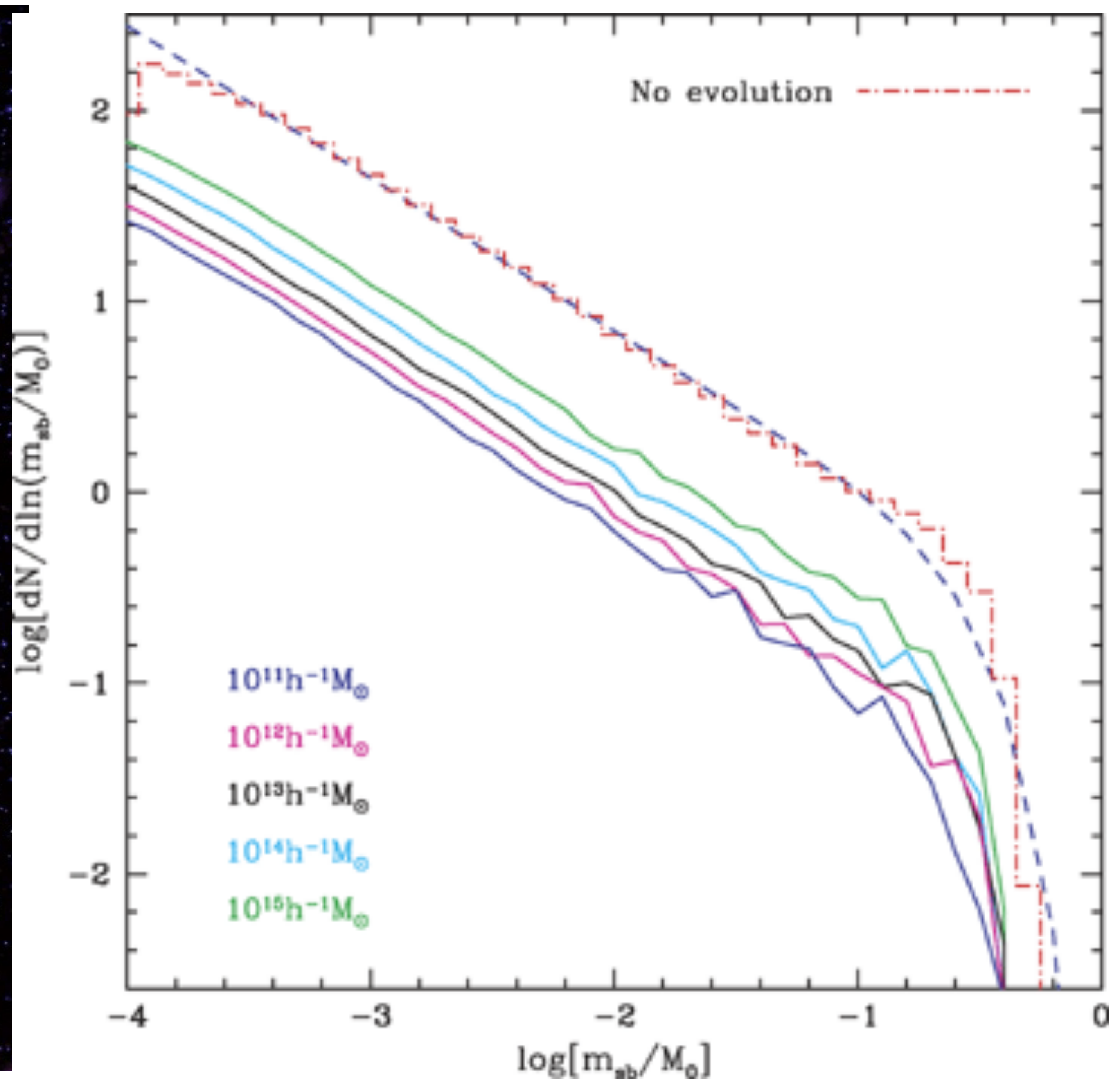
Dark Matter Substructures

Subhalo population

- Power law mass function m_{sub}/M_h, with an exponential cut-off
- Their spatial distribution is less concentrated than the underlying host dark matter, and depends on the DM model
- Their properties change when switching on the hydrodynamic



Springel et al. 2008



Giocoli et al. 2008

Despali et al. 2017

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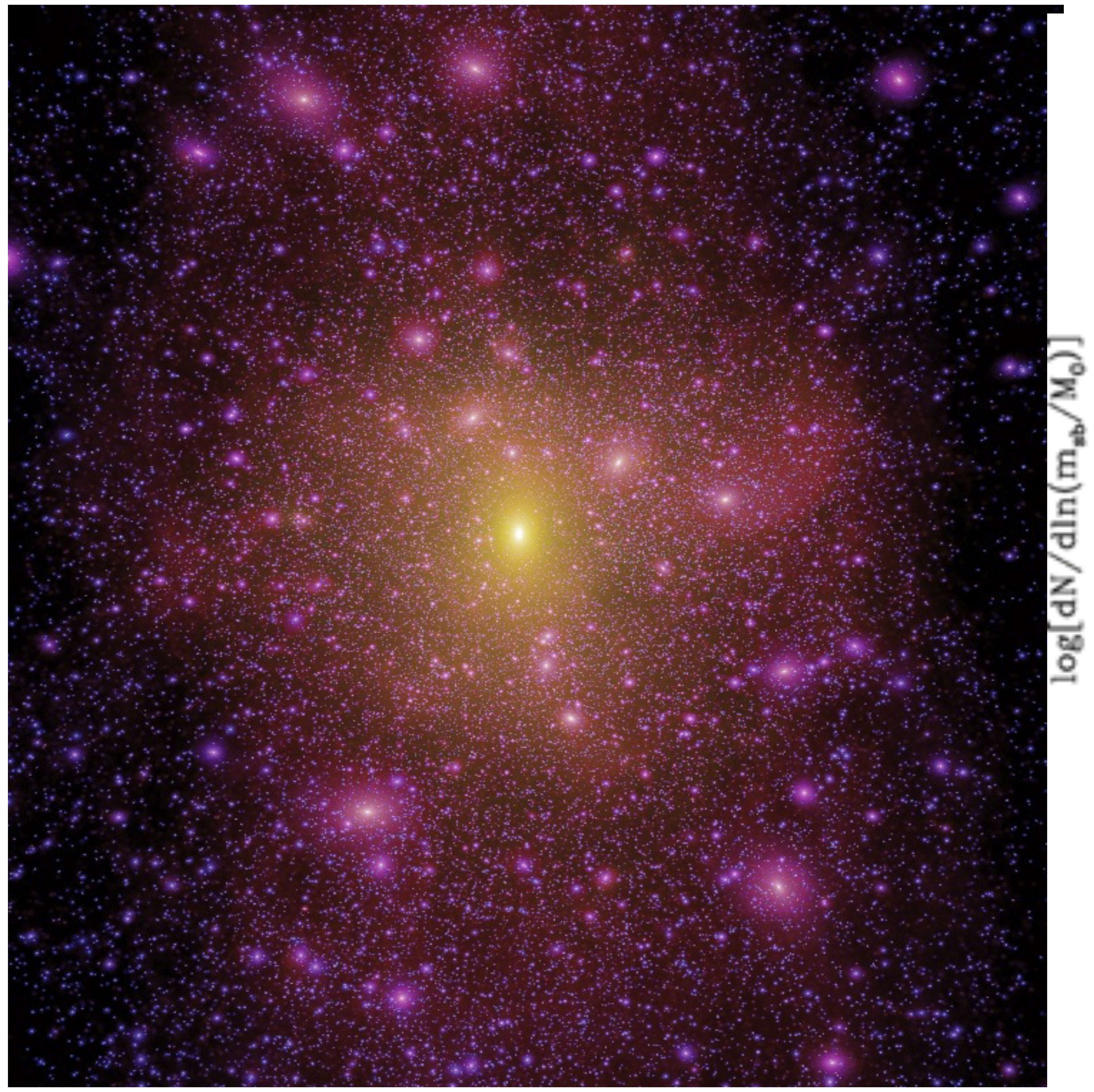

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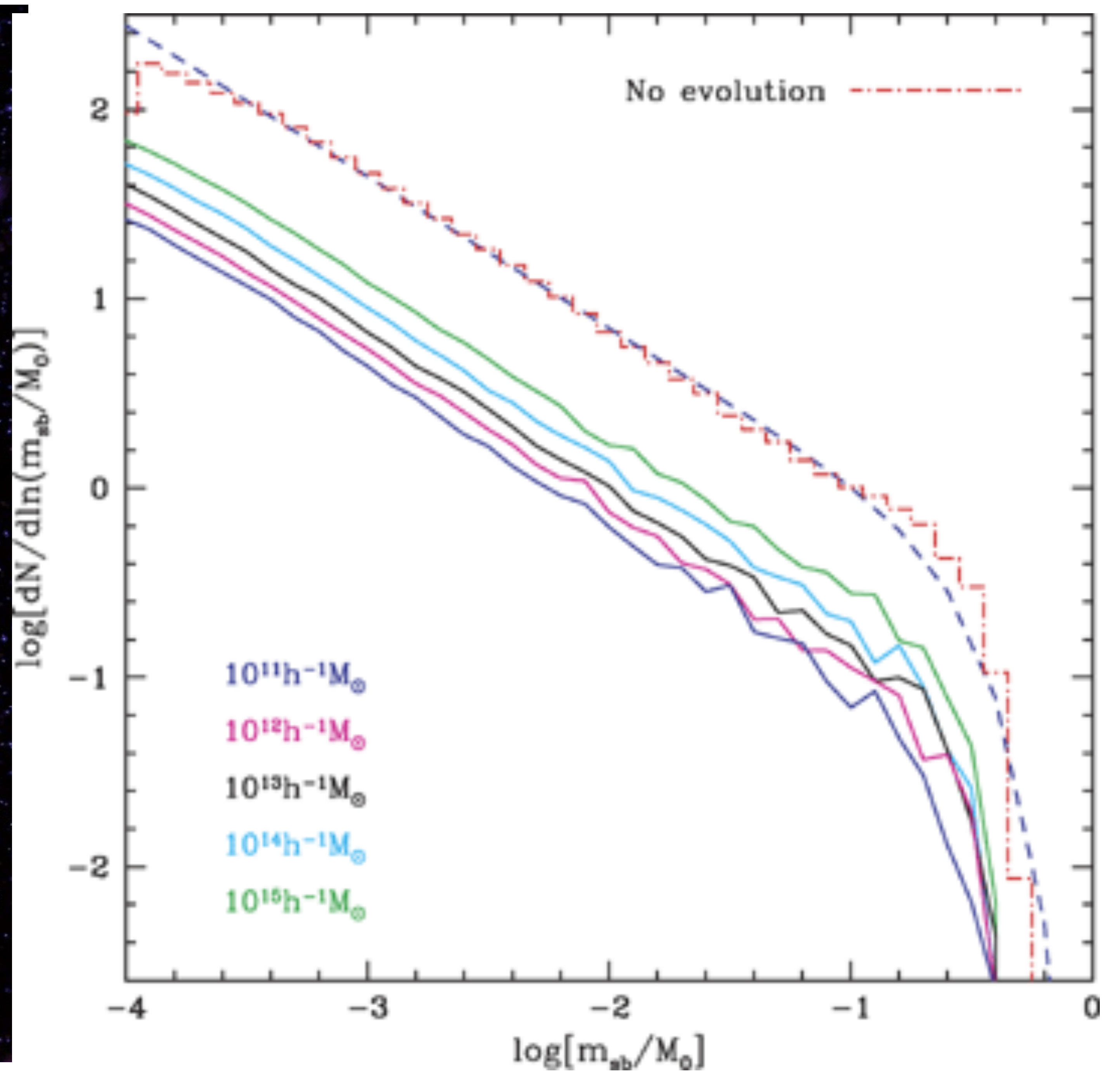

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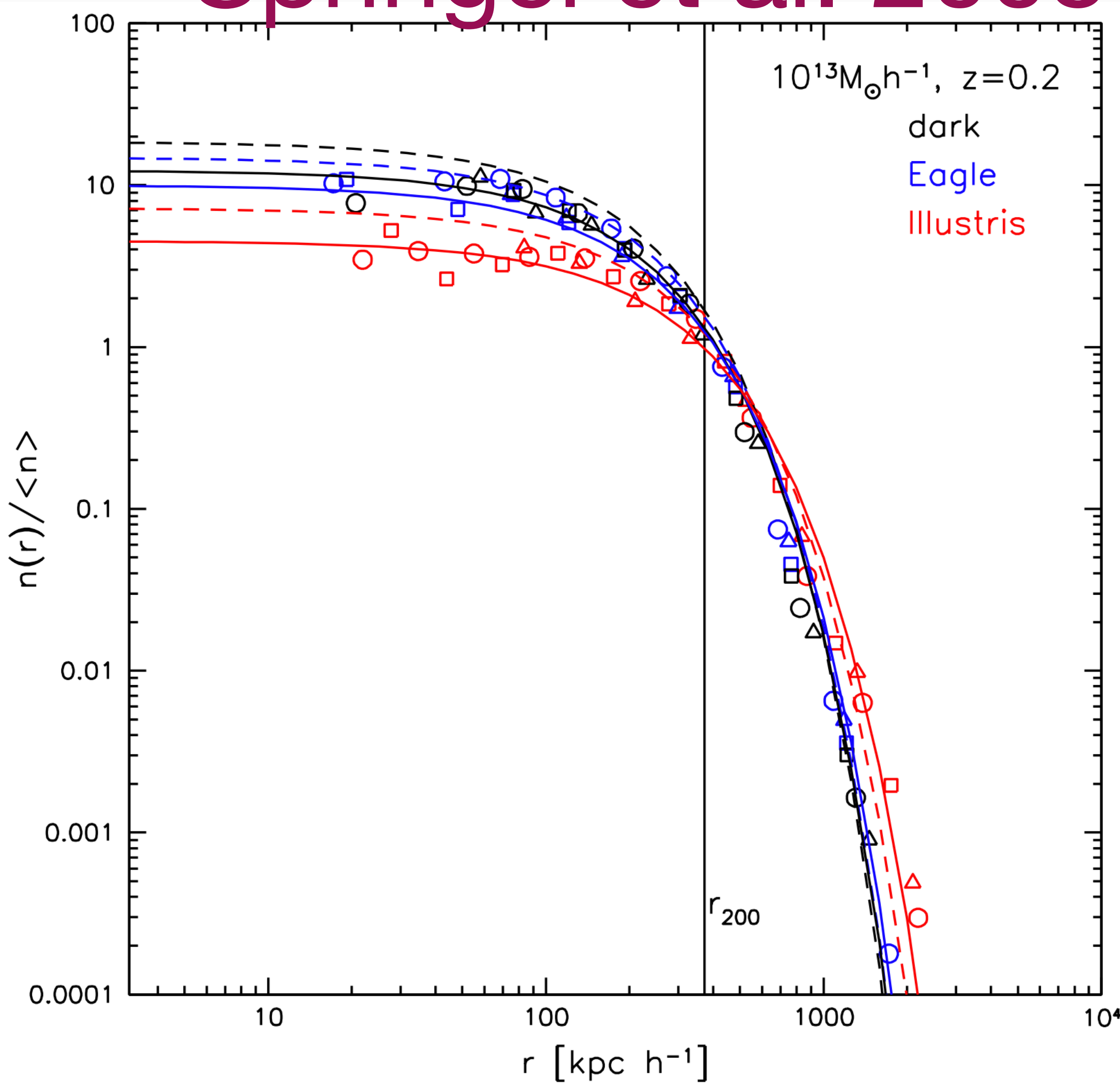
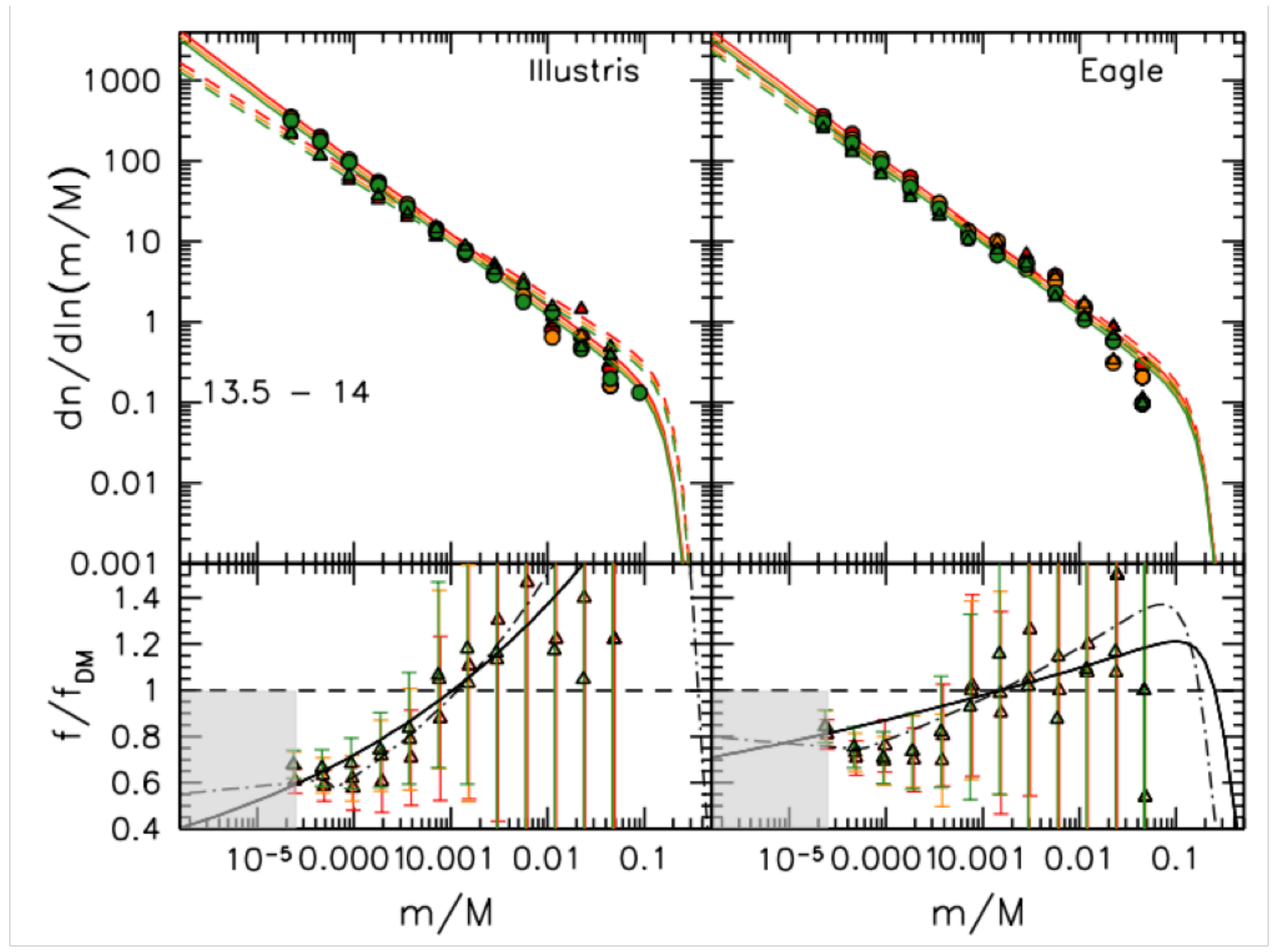
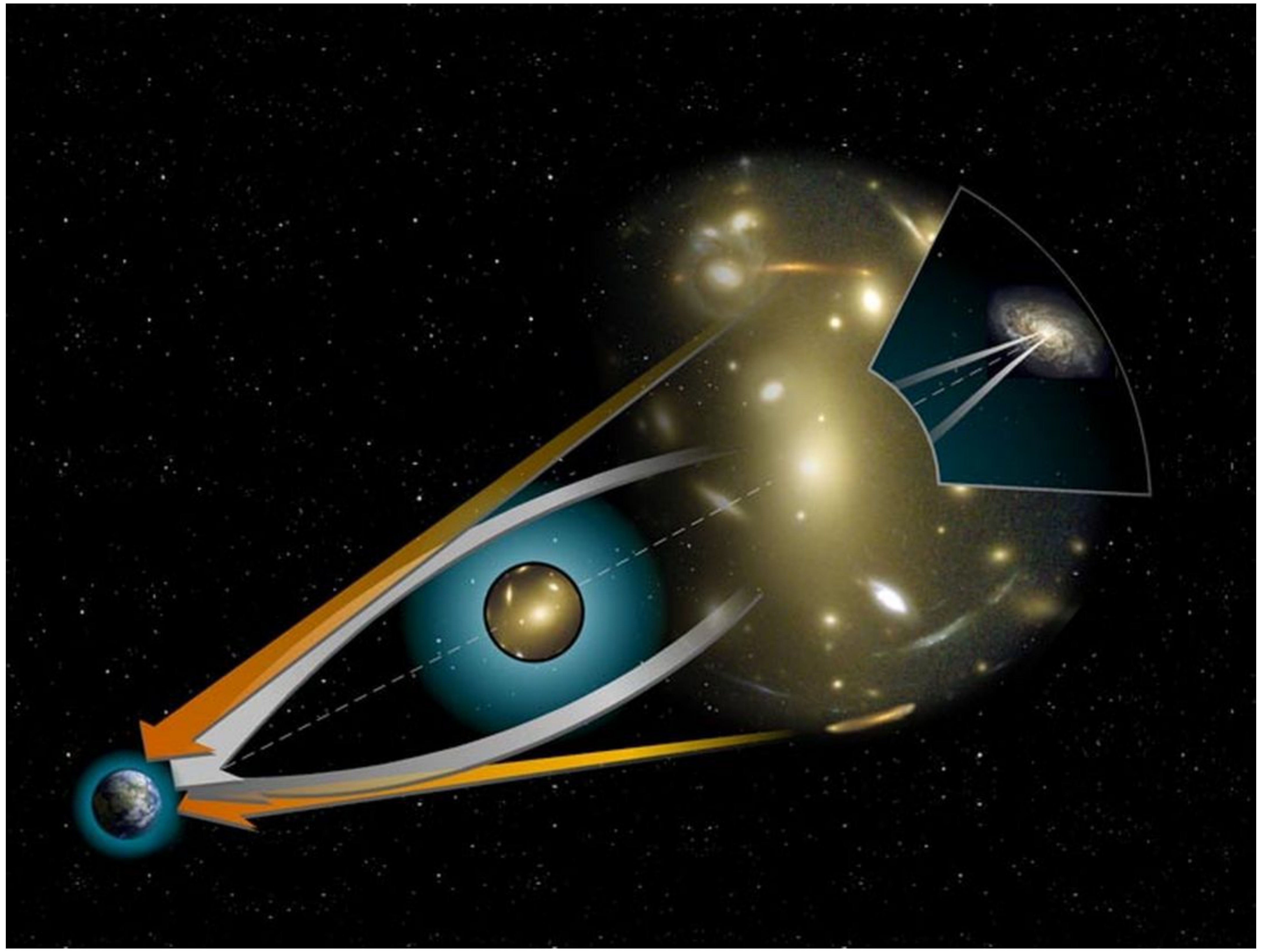




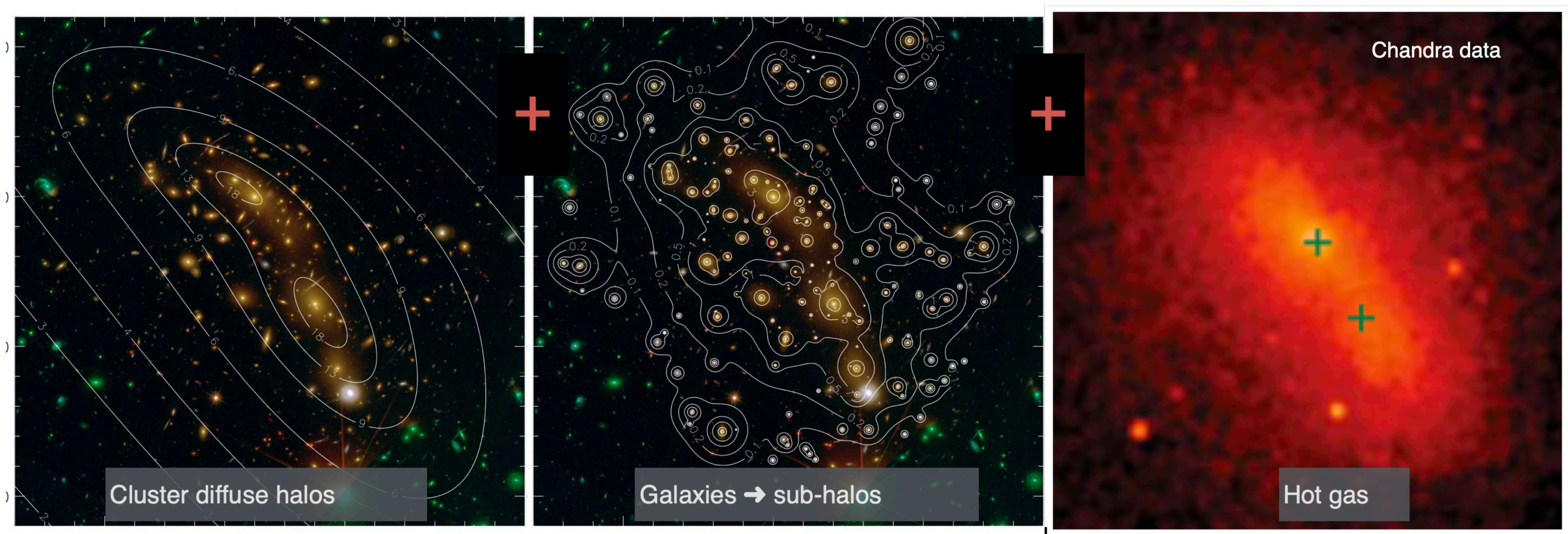
Despali et al. 2017

Reconstructing the Projected Mass via Strong Lensing

Probing Dark Matter Properties



Clusters of galaxies are complicated multi-mass and -scale components. An efficient and fast parametric mass model represents the best way to reconstruct their projected mass distribution



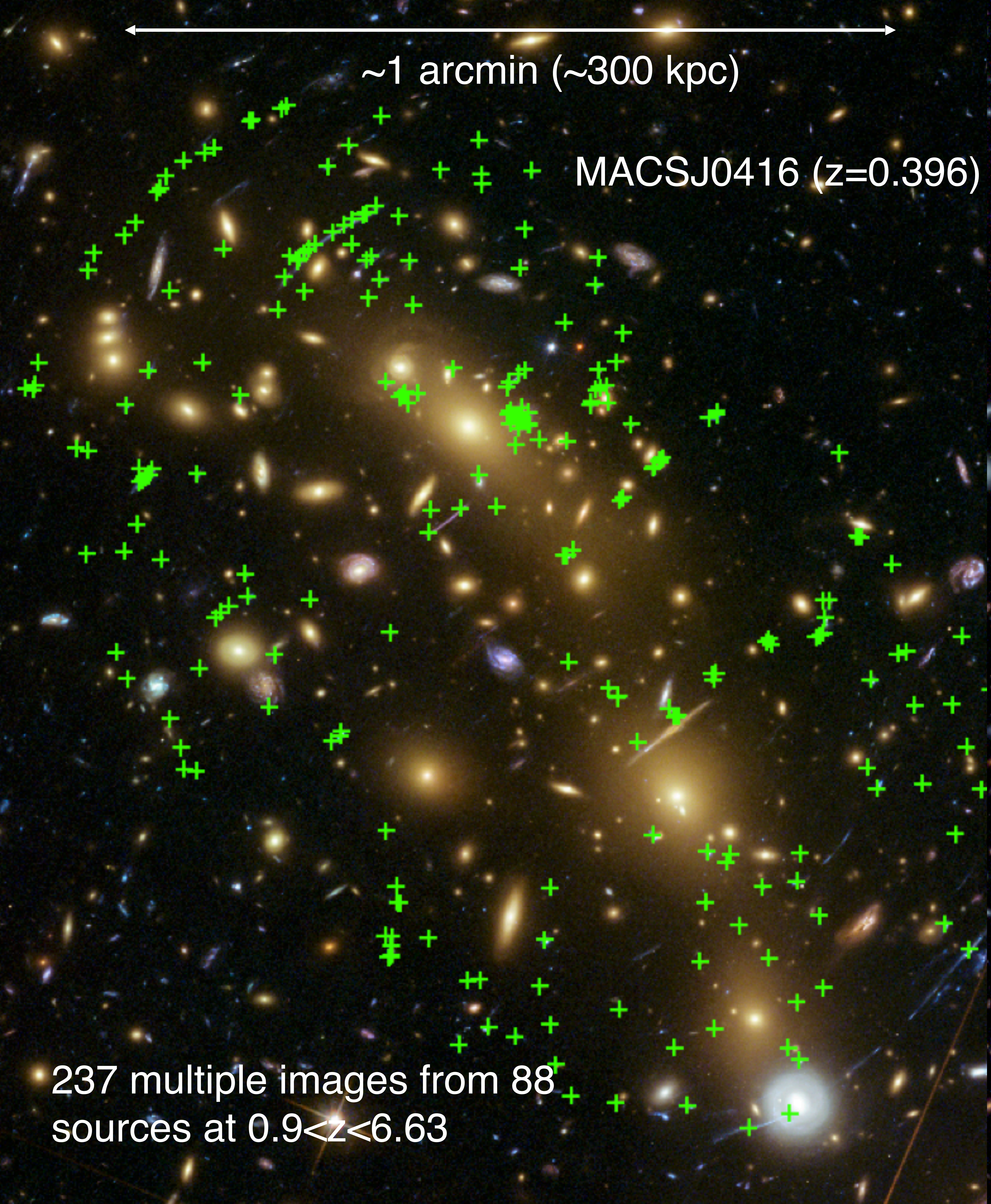
$$\phi_{tot} = \sum_{i=1}^{N_h} \phi_i^{halo} + \sum_{j=1}^{N_{gas}} \phi_j^{gas} + \sum_{k=1}^{N_{gal}} \phi_k^{gal} + \sum_{k=1}^{N_{pert}} \phi_k^{pert} + \phi_{shear}$$

LOS perturbers

Bergamini et al. 2022,2023

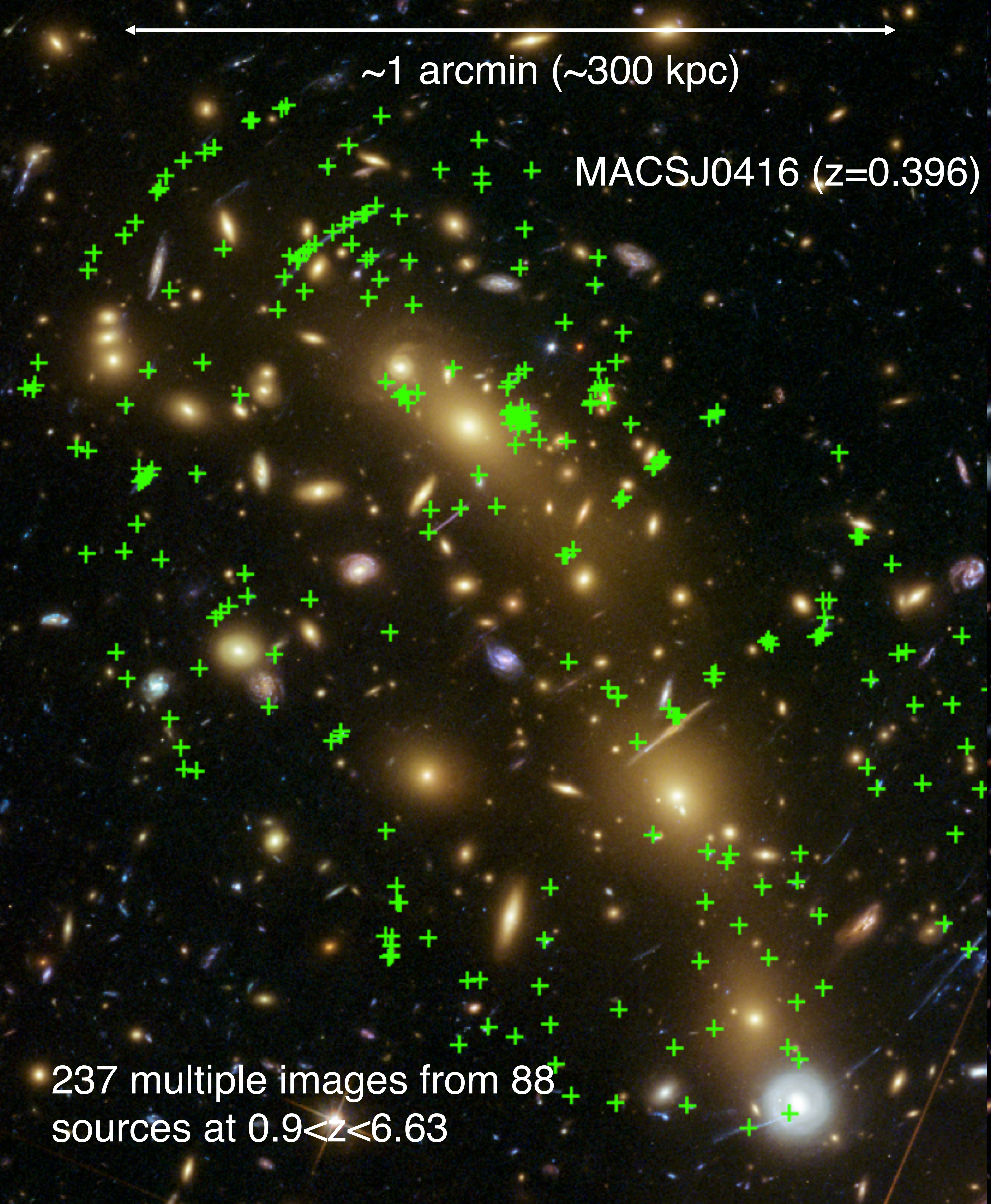
Bonamigo et al. 2017,2018

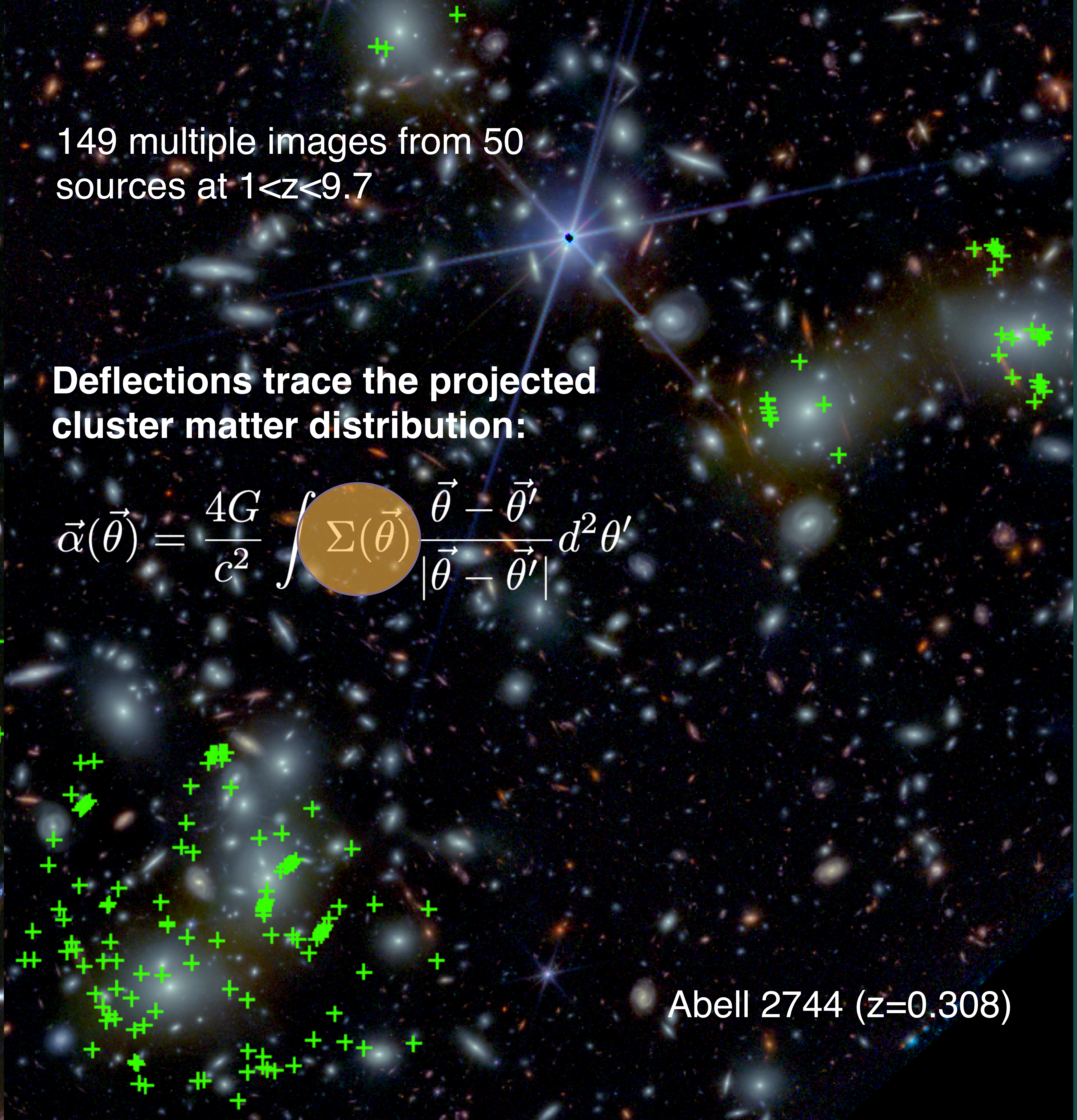

~1 arcmin (~300 kpc)
MACSJ0416 (z=0.396)
Abell 2744 (z=0.308)


~1 arcmin (~300 kpc)
MACSJ0416 (z=0.396)
237 multiple images from 88
sources at 0.9<z<6.63

Abell 2744 (z=0.308)


~1 arcmin (~300 kpc)
MACSJ0416 (z=0.396)
237 multiple images from 88
sources at 0.9<z<6.63
149 multiple images from 50
sources at 1<z<9.7
Abell 2744 (z=0.308)



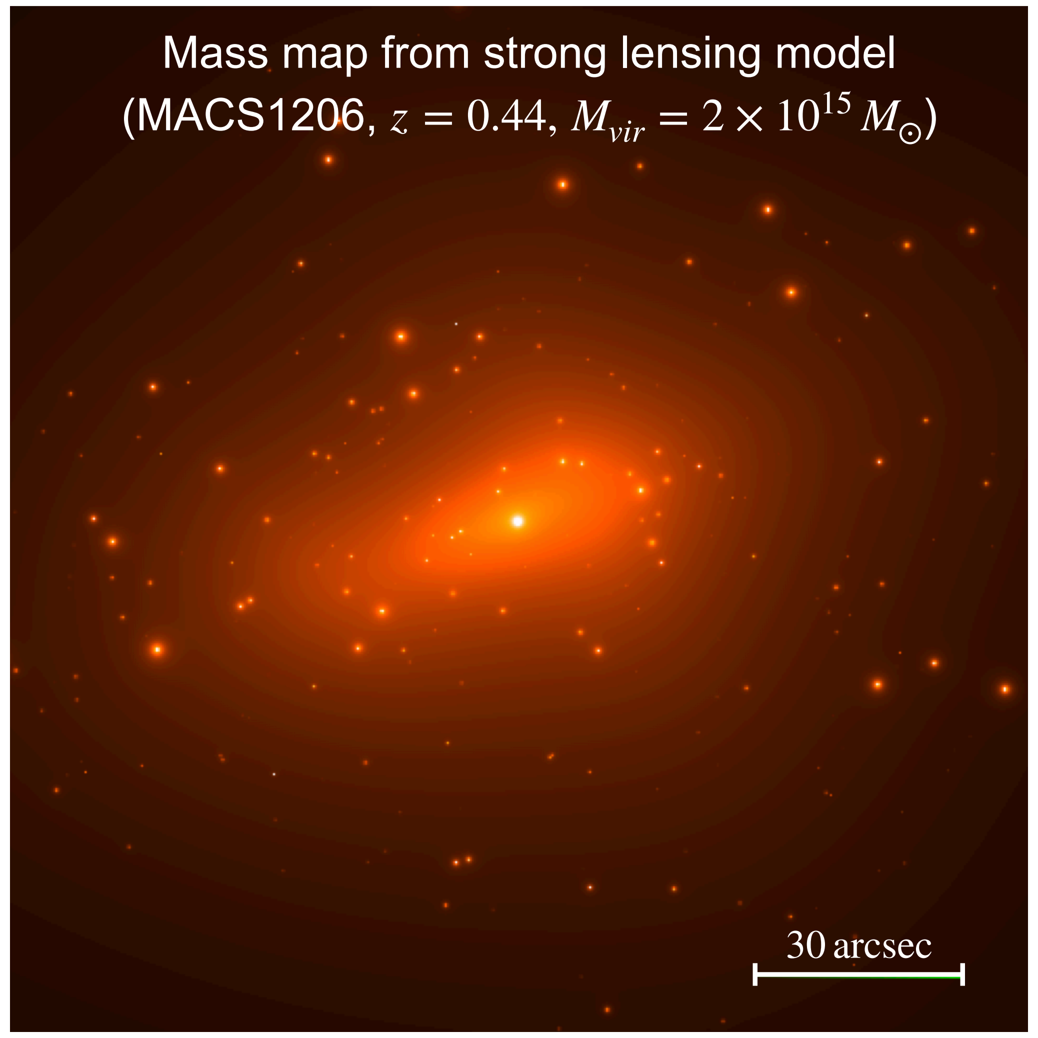


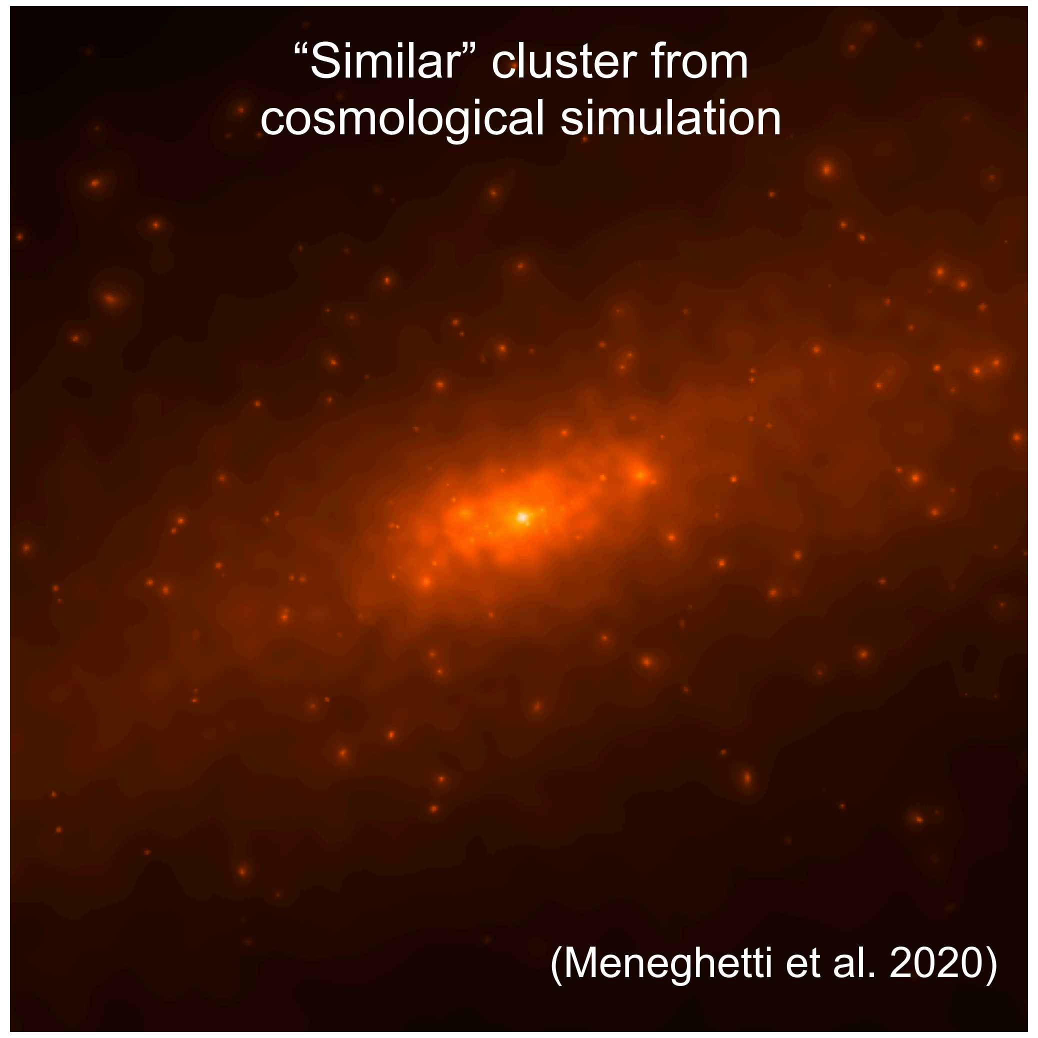
Deflections trace the projected cluster matter distribution:

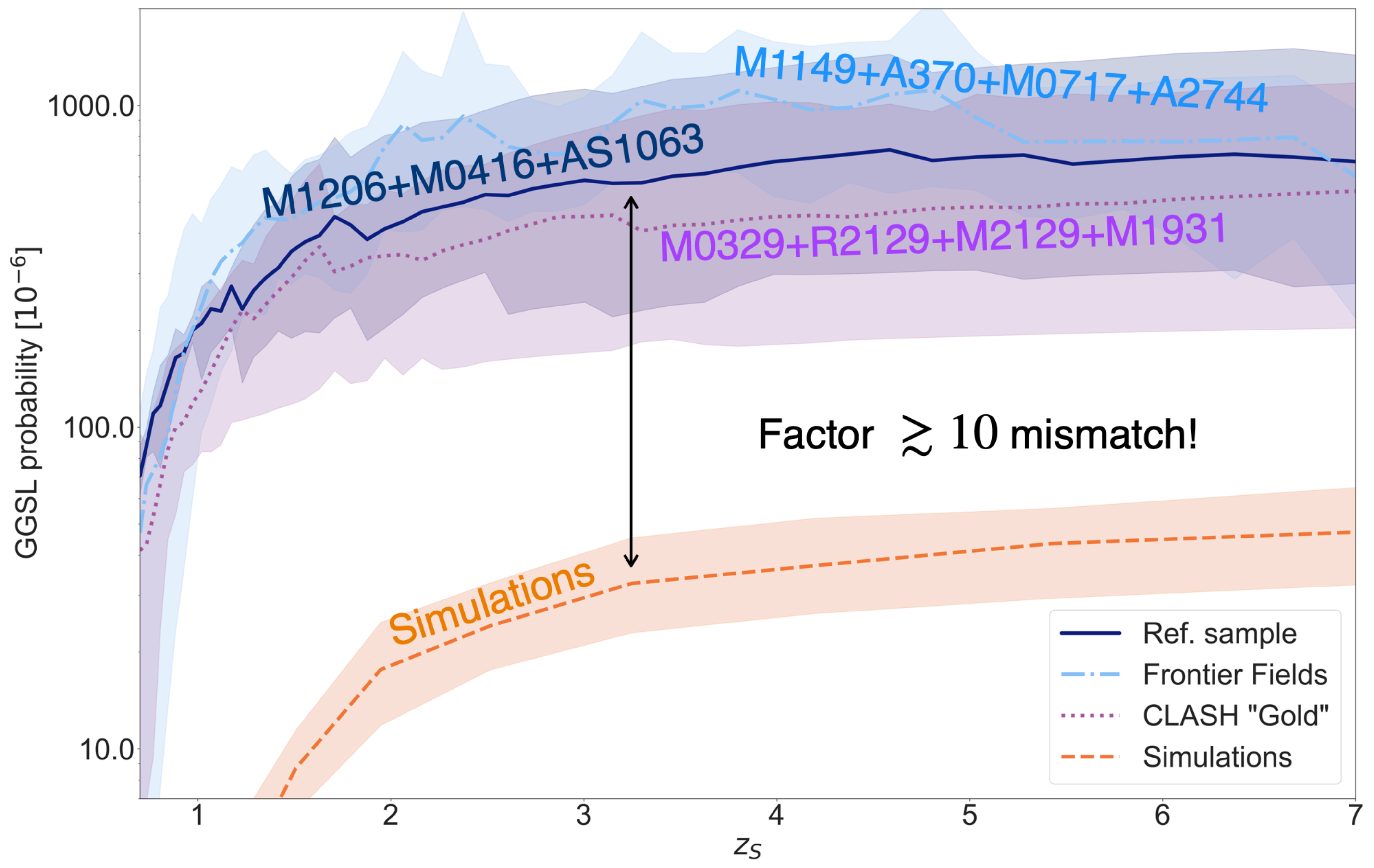
$$\vec{\alpha}(\vec{\theta}) = \frac{4G}{c^2} \int \Sigma(\vec{\theta}) \frac{\vec{\theta} - \vec{\theta}'}{|\vec{\theta} - \vec{\theta}'|} d^2\theta'$$

Subhalo internal properties

Comparing projected mass reconstruction with simulations







Meneghetti et al. 2020, 2023

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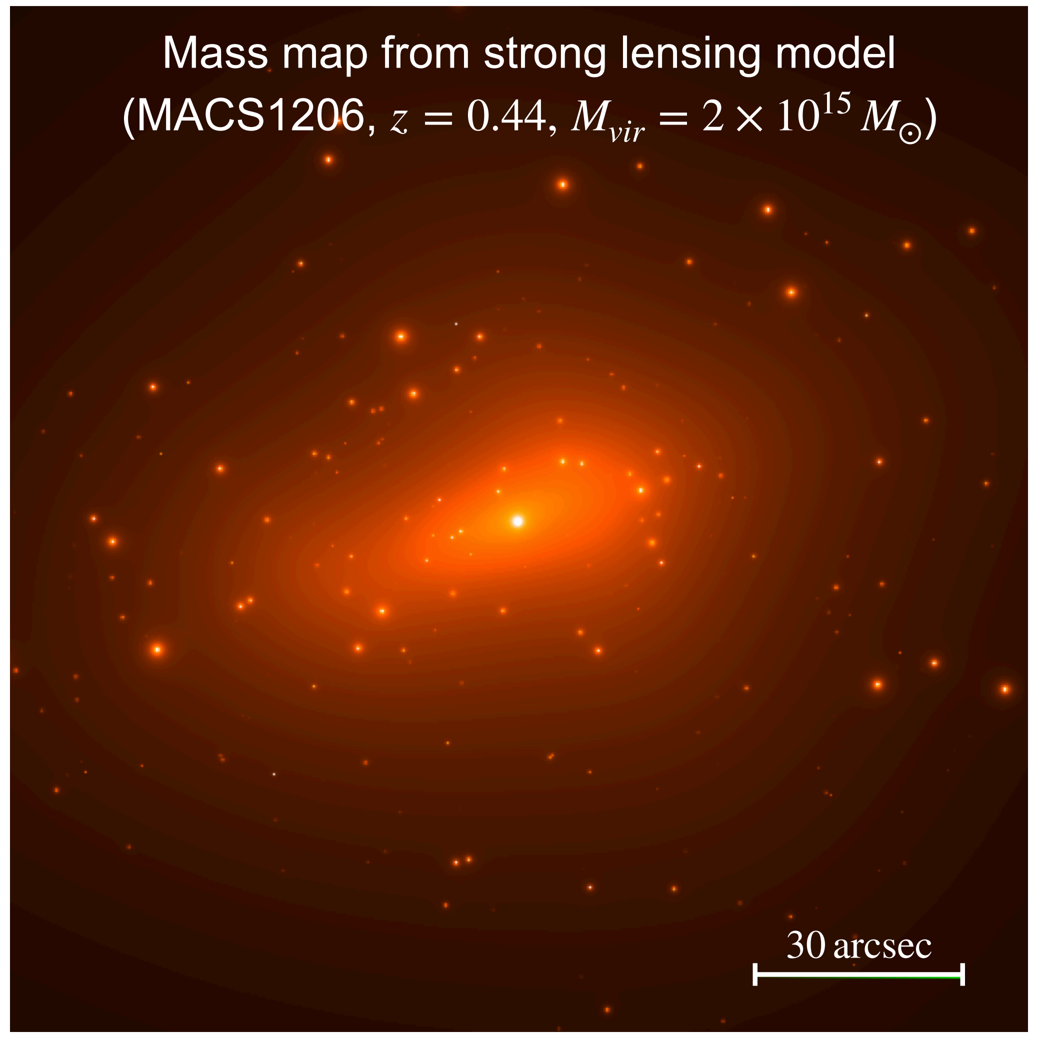

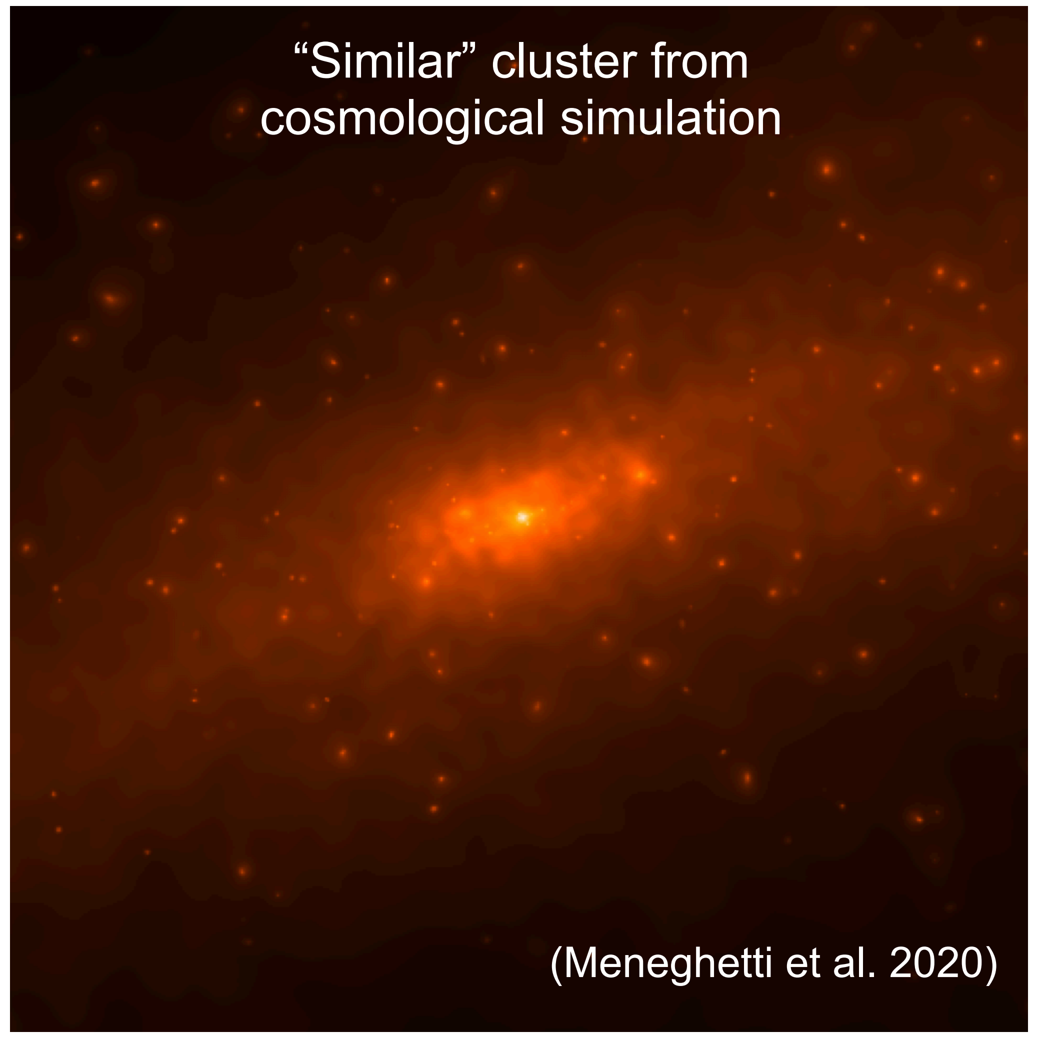

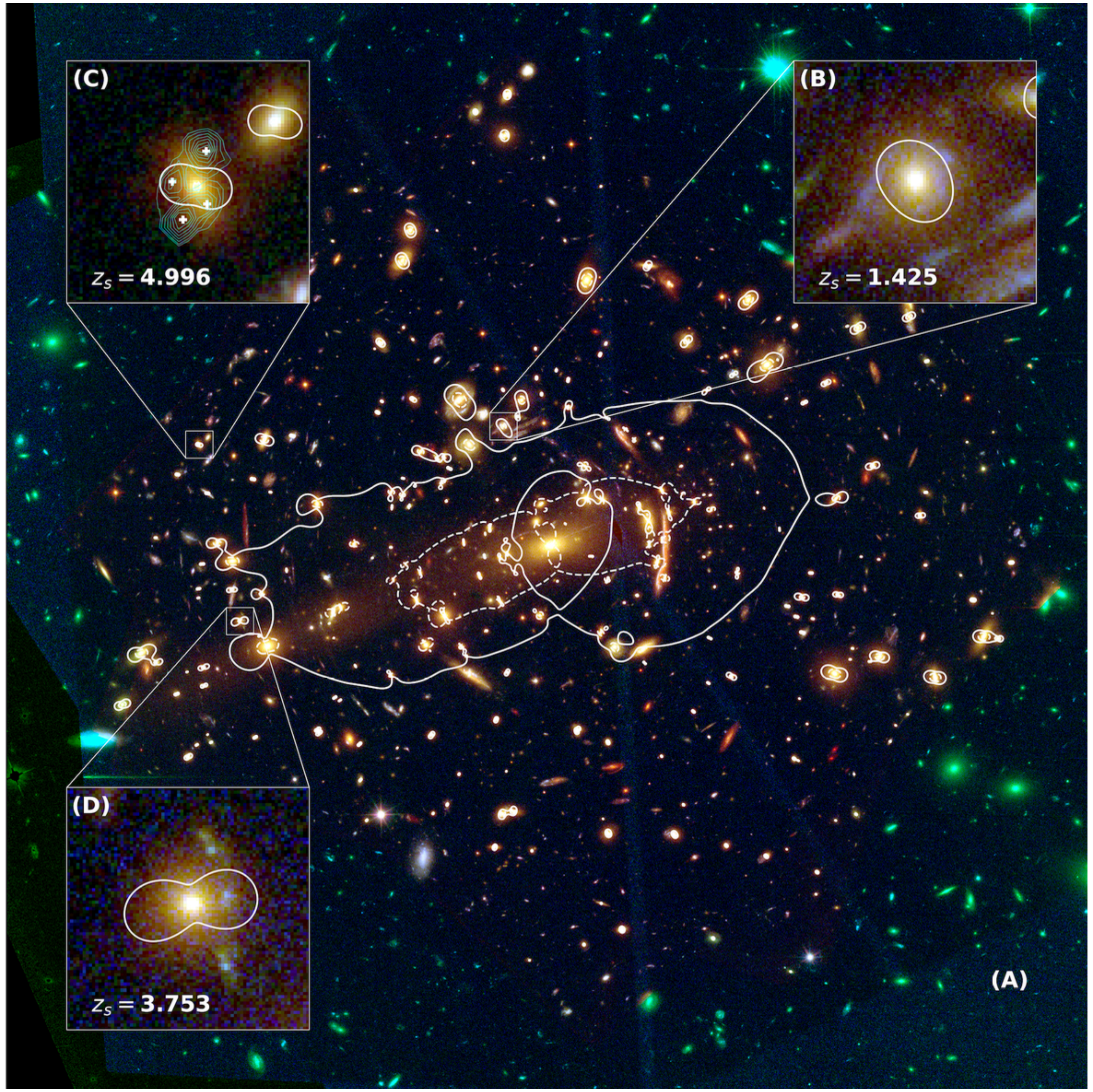

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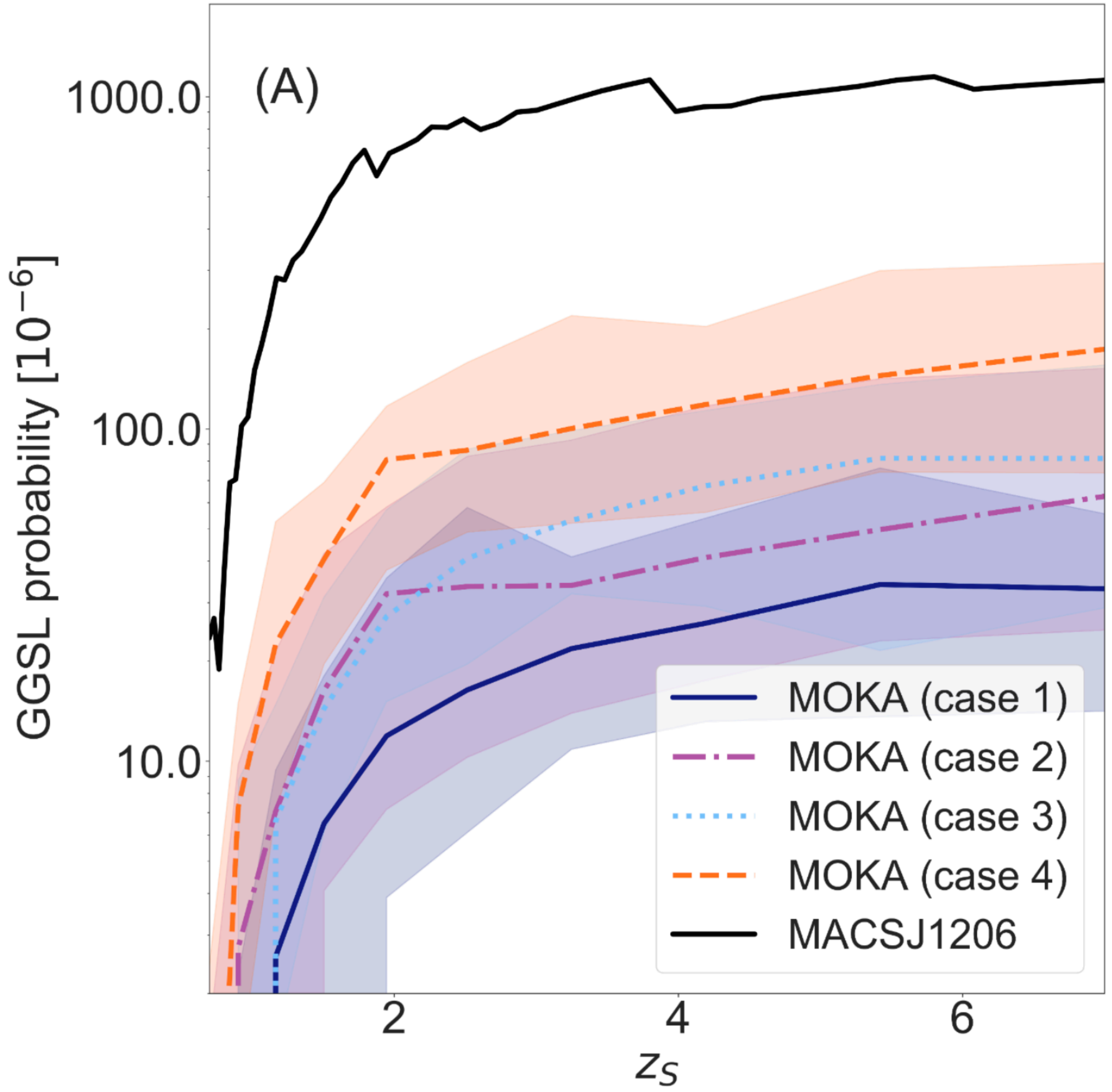

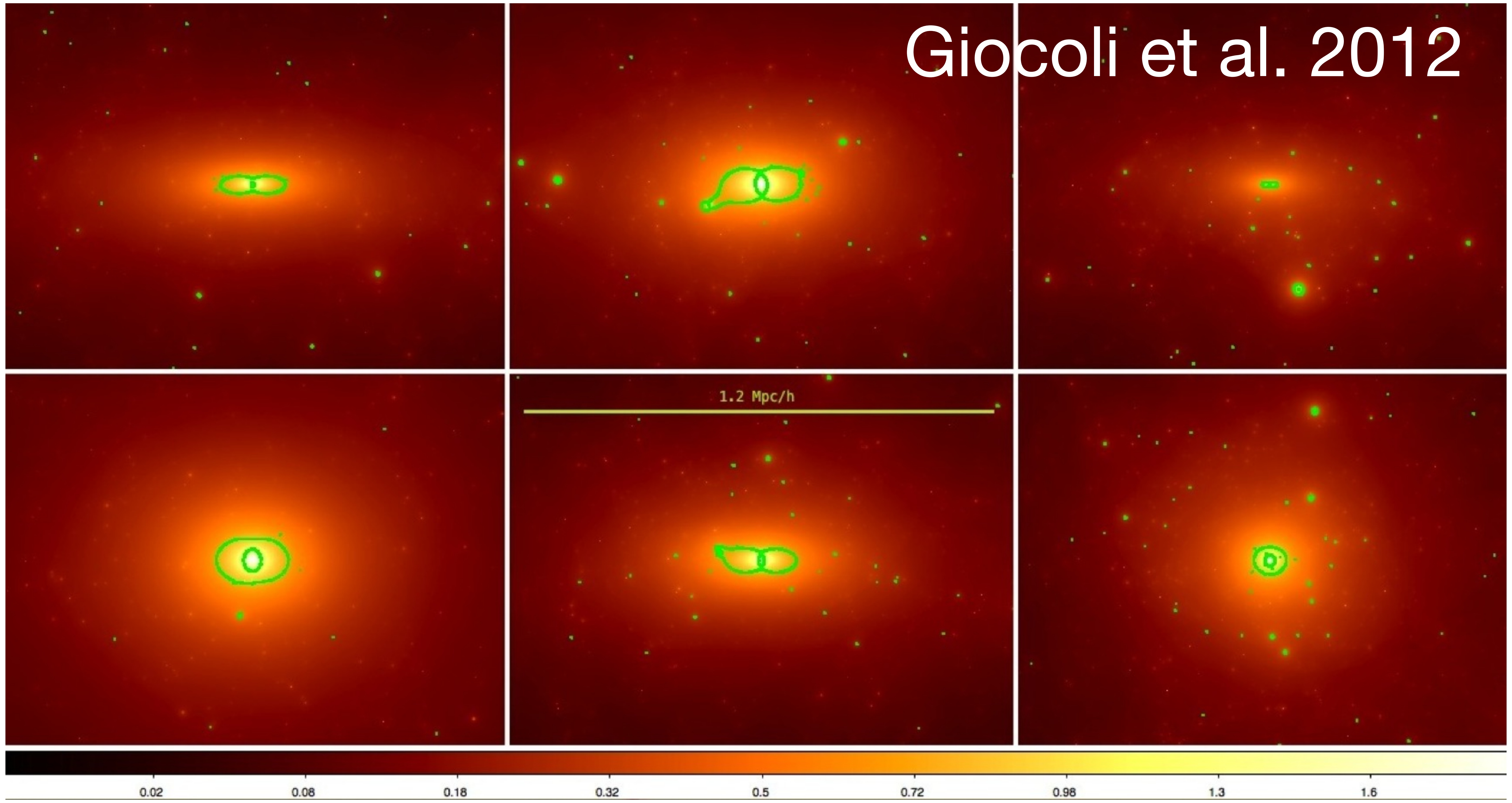

We have created different cluster realisations, even when extreme subhalo populations and distributions. (MOKA)

Meneghetti et al. 2020, 2023

Cluster Substructures

Tension for CDM model?

Meneghetti et al. 2020, 2023

Cluster Substructures

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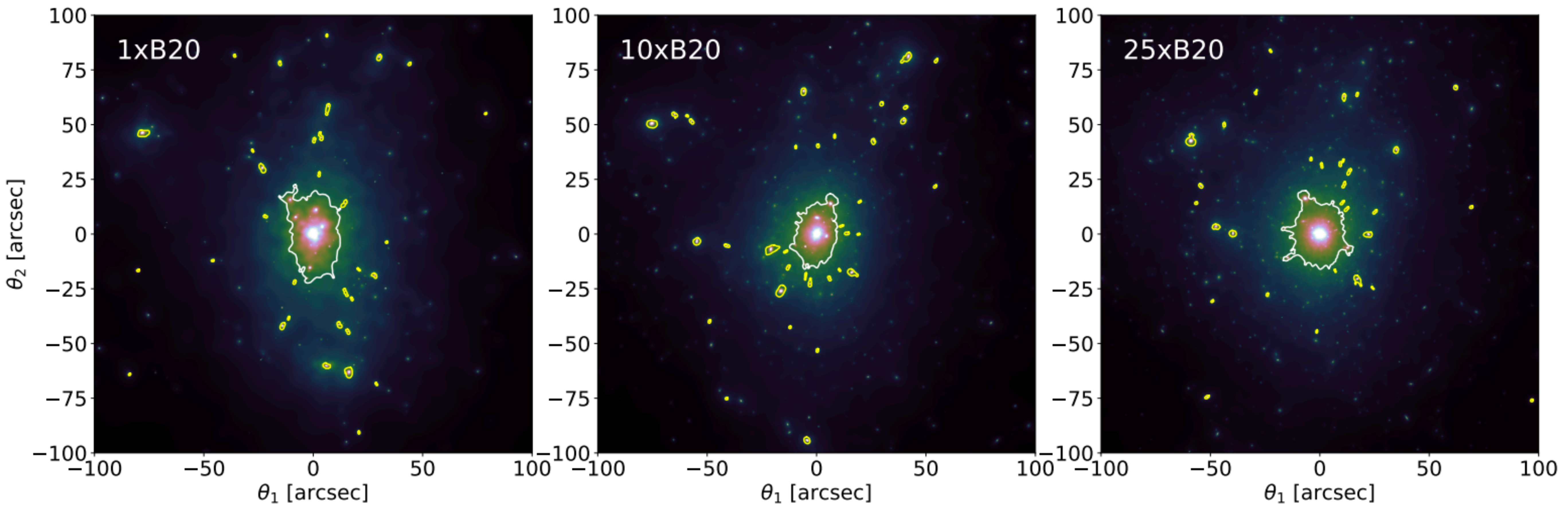
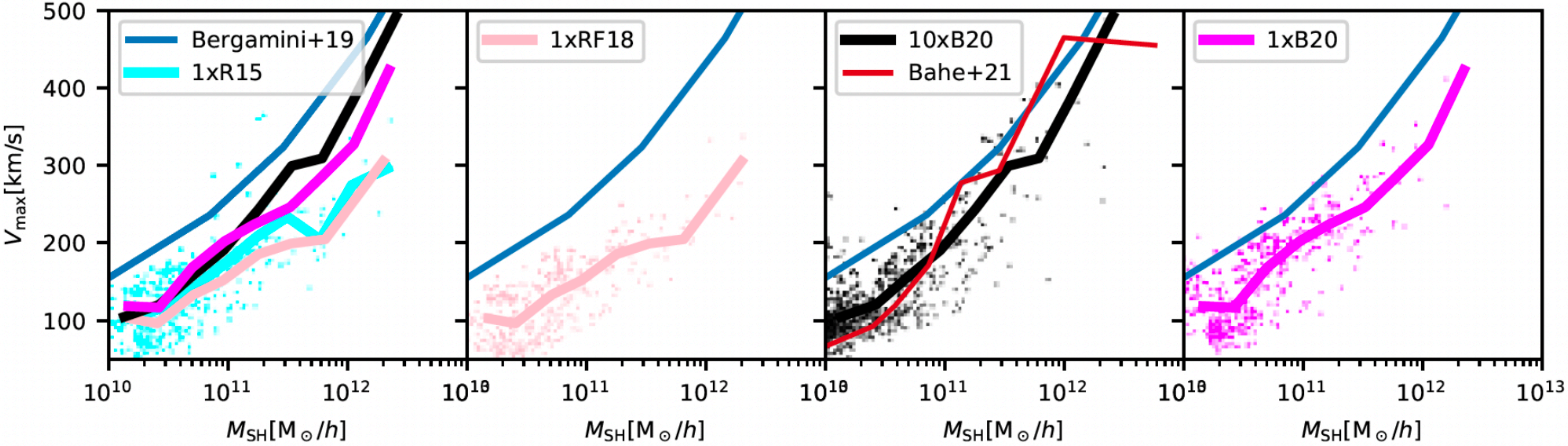




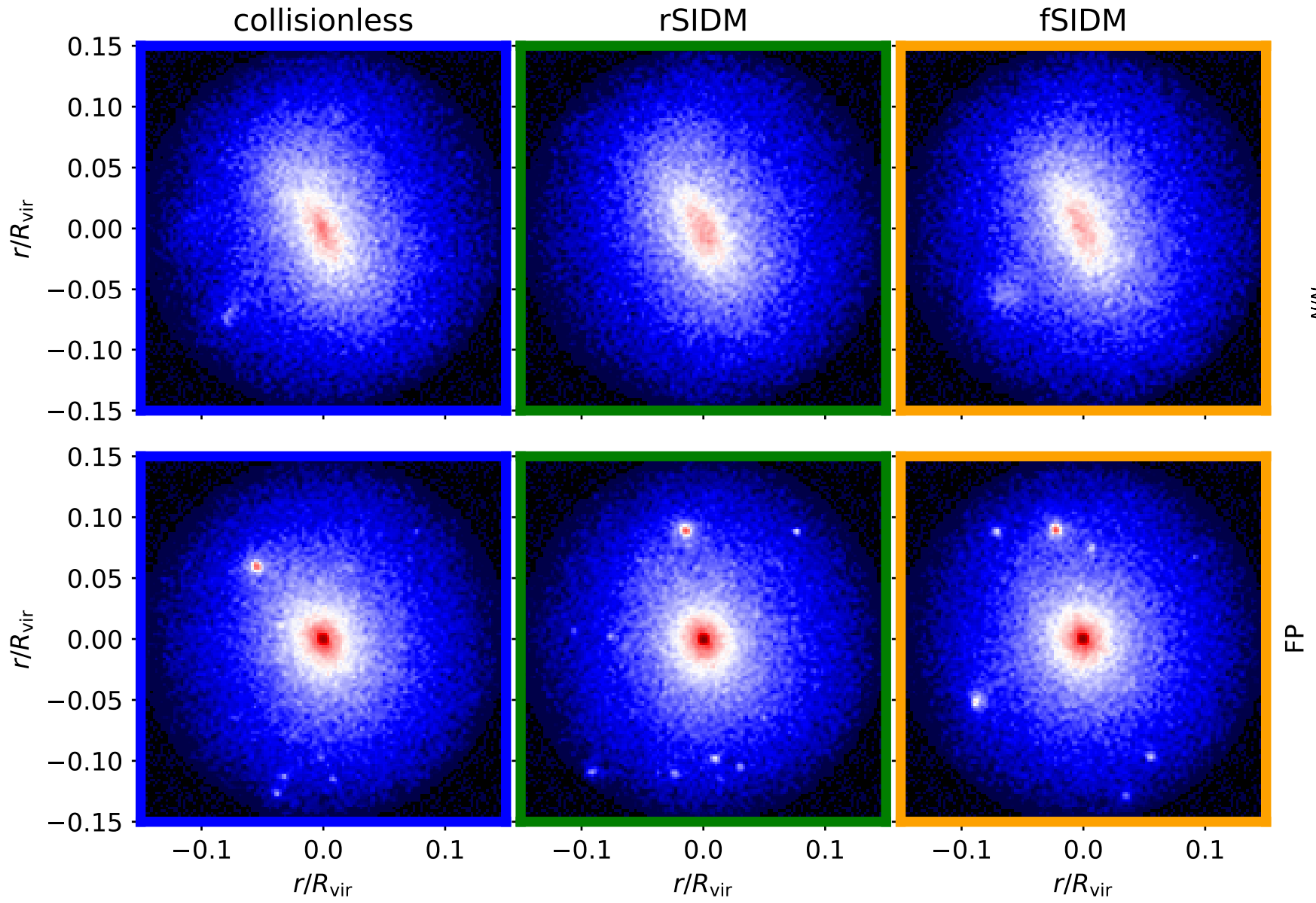
Convergence tests

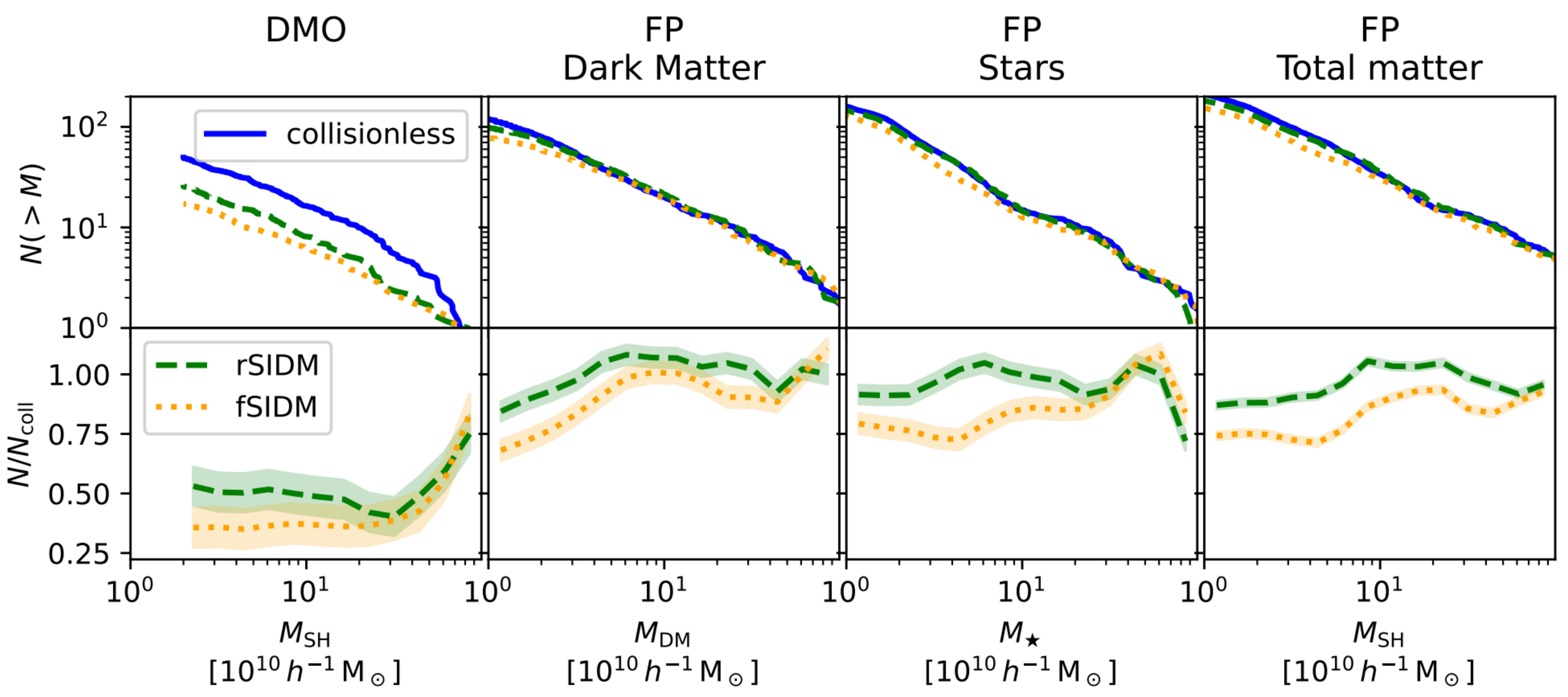
GGSL tension between Models from Observations and Simulations

Ragagnin et al. 2022

Cluster Substructures

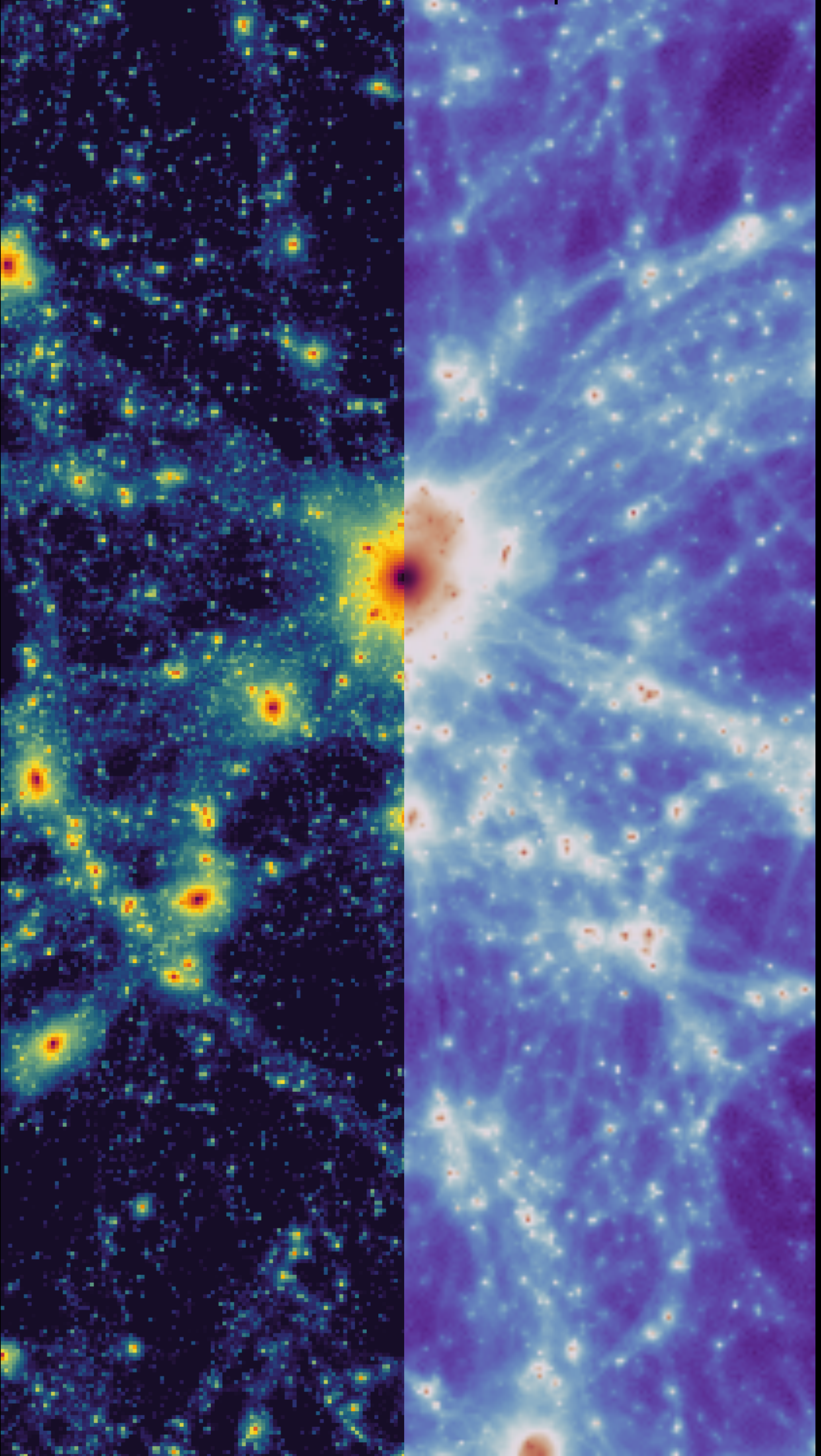
rSIDM and fSIDM Cluster Simulations





SIDM models generate a broader range of subhalo concentration values, including a tail of more diffuse subhaloes in the outskirts of galaxy clusters and a population of more compact subhaloes in the cluster cores.

Ragagnin et al. 2024



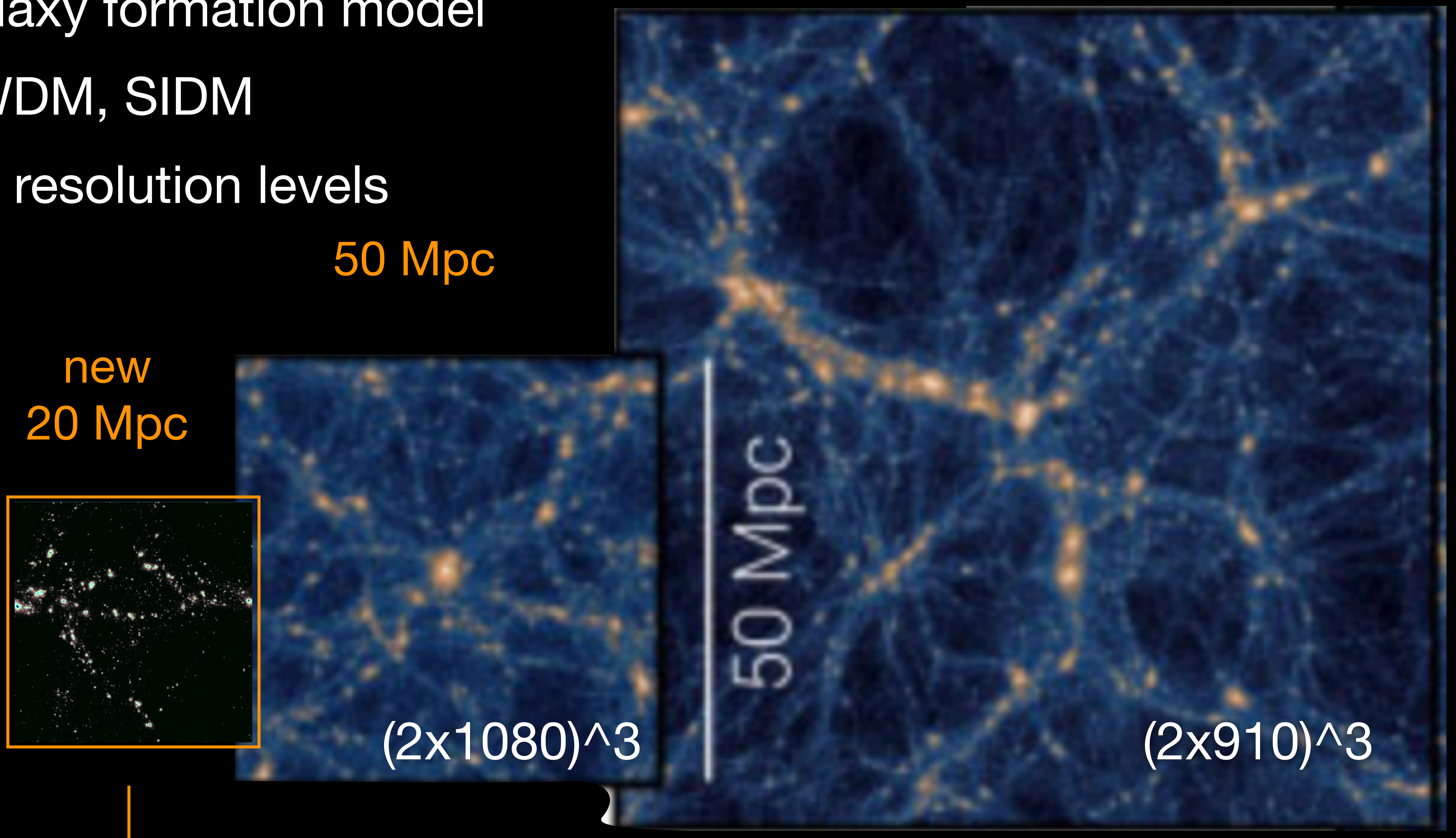
AIDA-TNG SIMULATIONS

- ✓ three cosmological boxes
- ✓ AREPO - moving mesh
- ✓ TNG galaxy formation model
- ✓ CDM, WDM, SIDM
- ✓ multiple resolution levels

100 Mpc

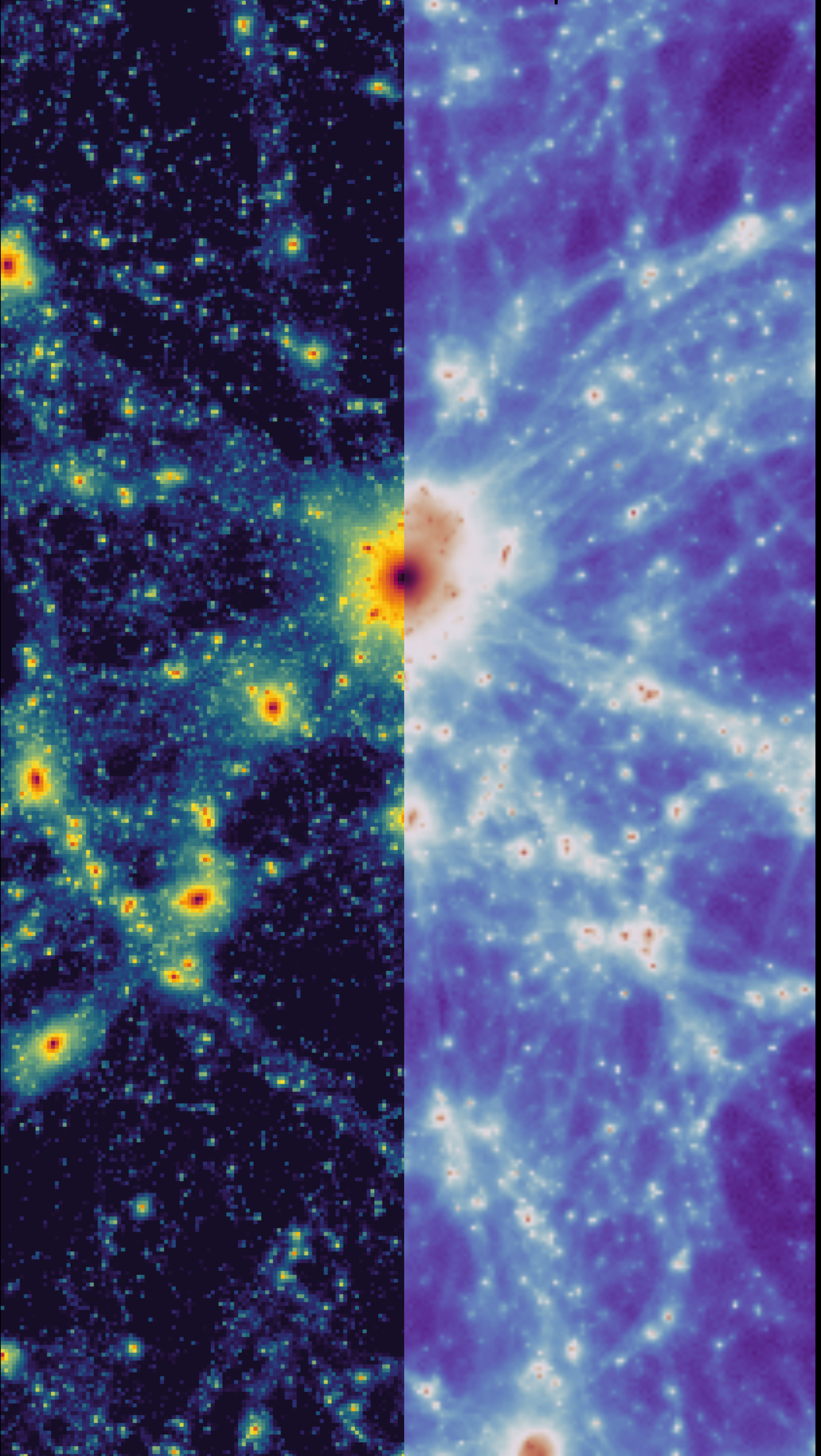
50 Mpc

new
20 Mpc



max resolutuion:
4 x 10^5 M⊙
280 pc
(2x1024)^3

Despali et al. 2025



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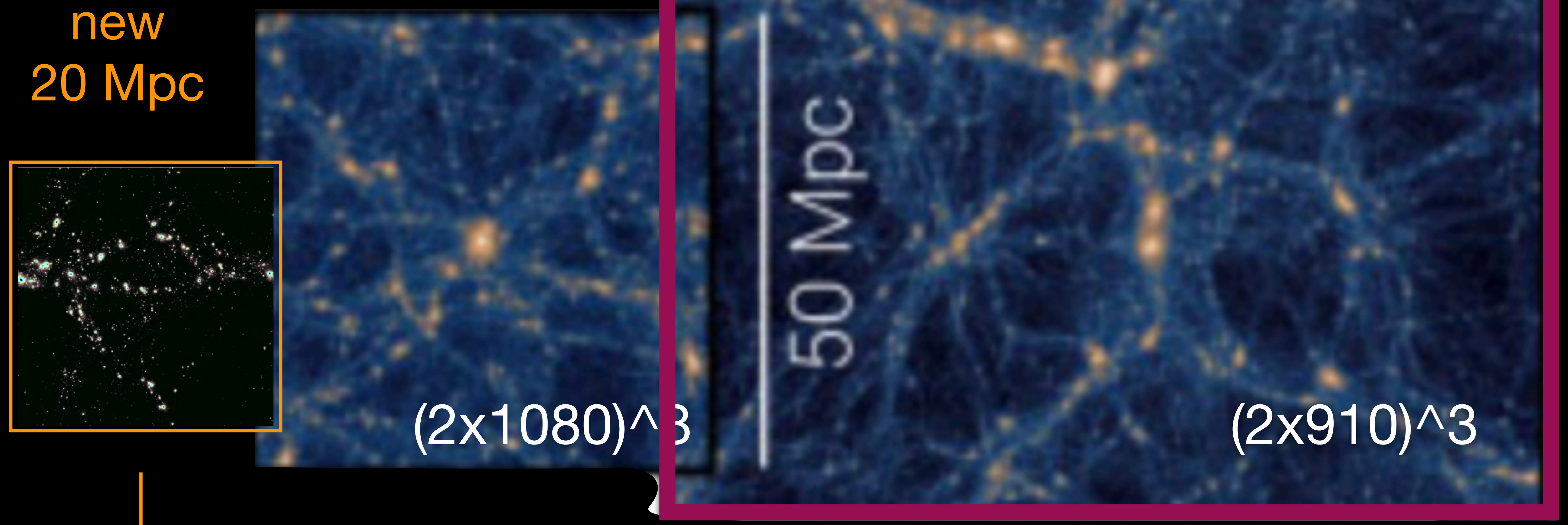

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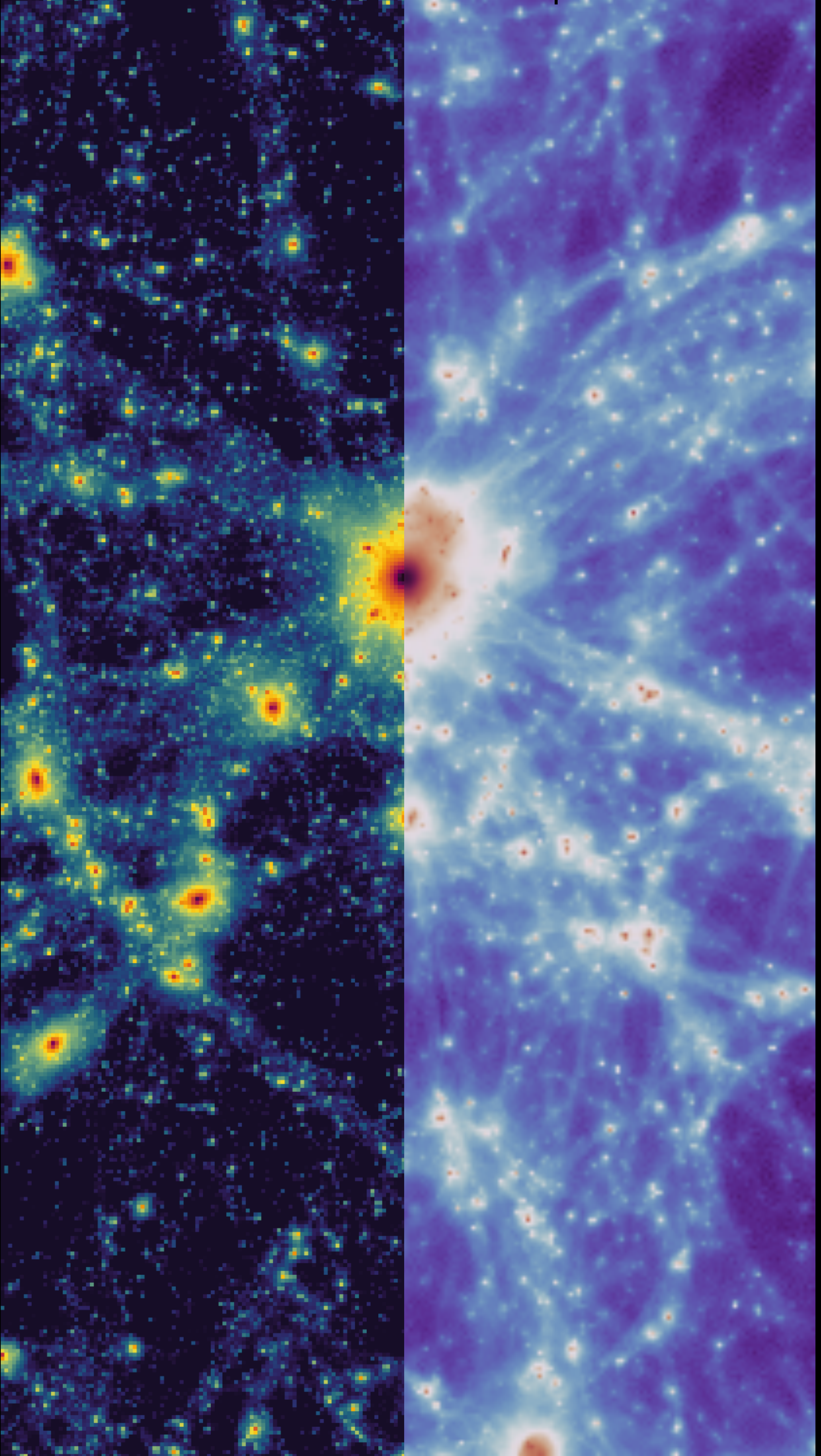

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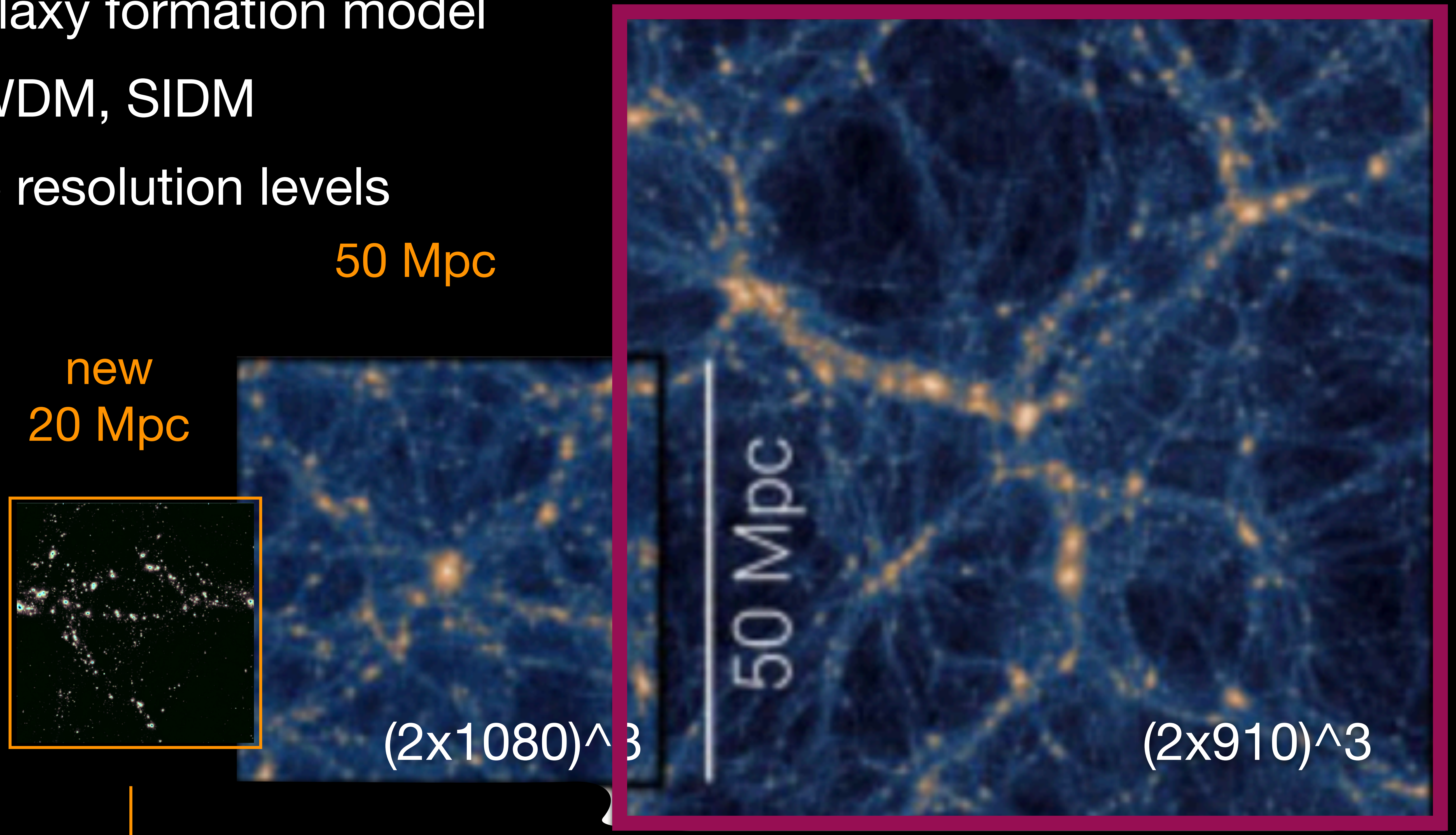


max resolutuion:
4 x 10^5 M⊙
280 pc
(2x1024)^3

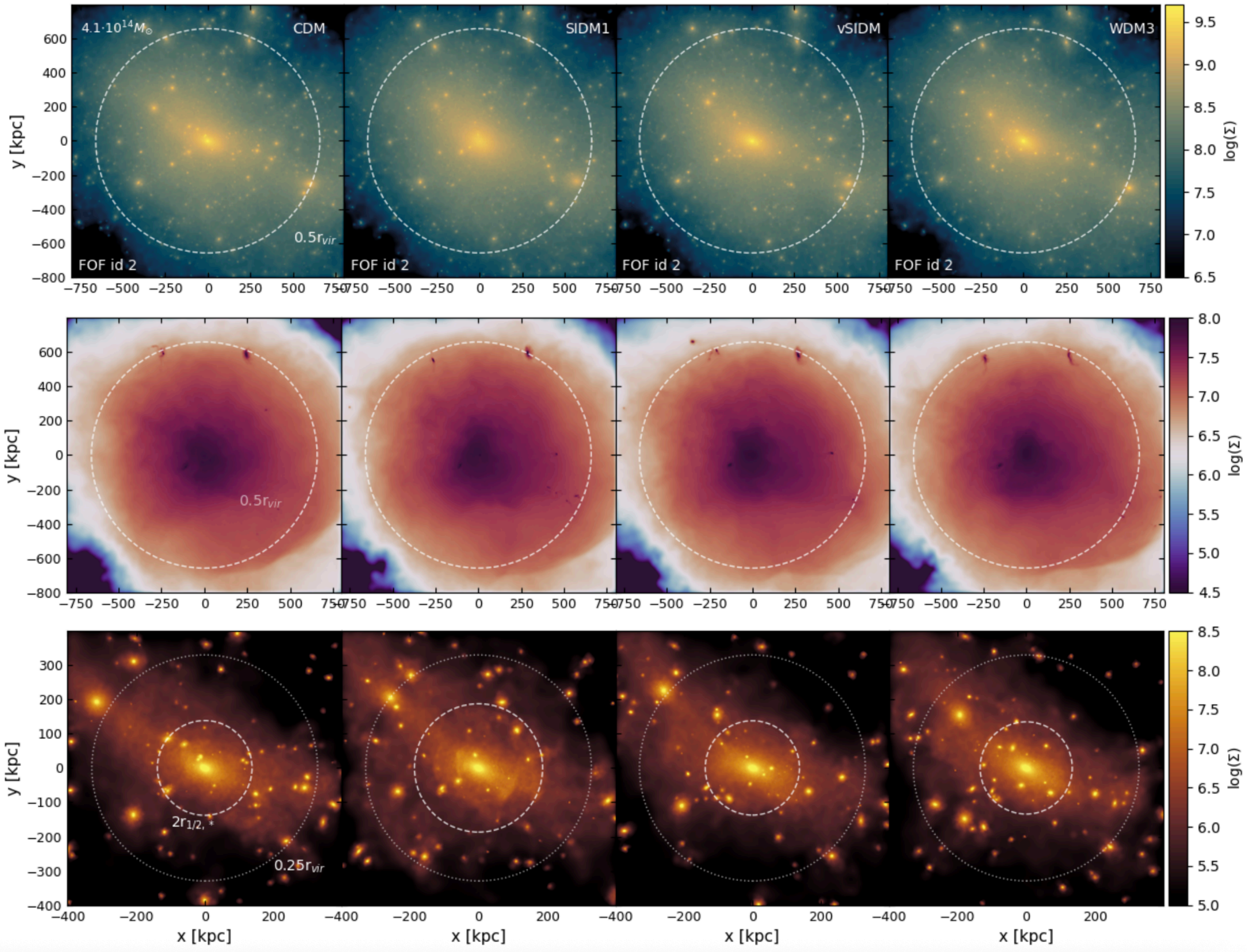
each hydro simulation has a corresponding DM-only reference run

Despali et al. 2025

AIDA-TNG Simulation

A Galaxy Cluster

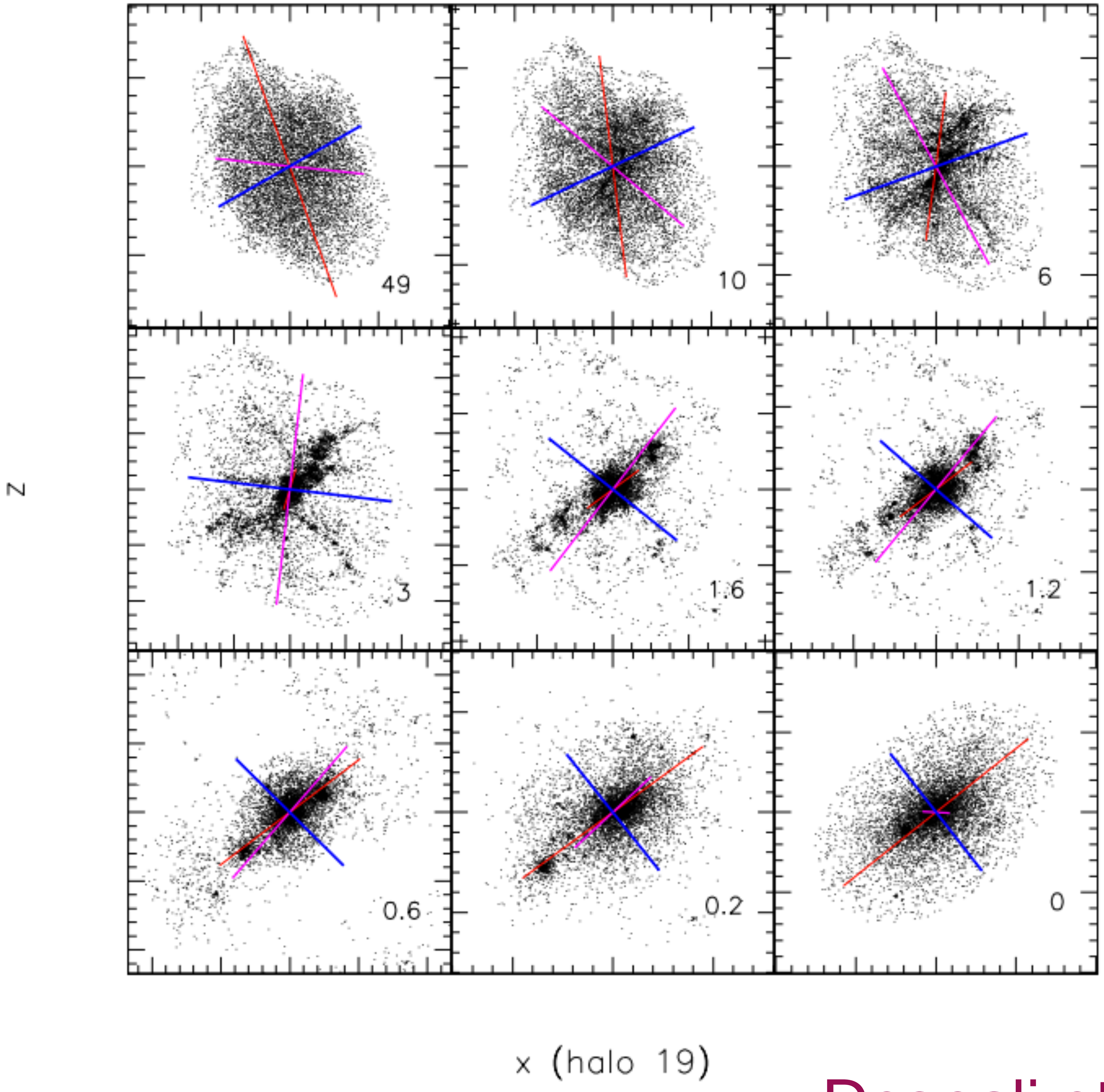
A large variety of systems with different morphological properties.
We can separate the varius compoments and study their shape characteristics and compare them to the refernce run case



Dark Matter Halo Shape

Triaxiality Properties

- dark matter haloes are triaxial systems
- the surrounding matter density distribution stretch and shear them
- the shape is a function of the radius
- larger haloes are more spherical than the smaller ones

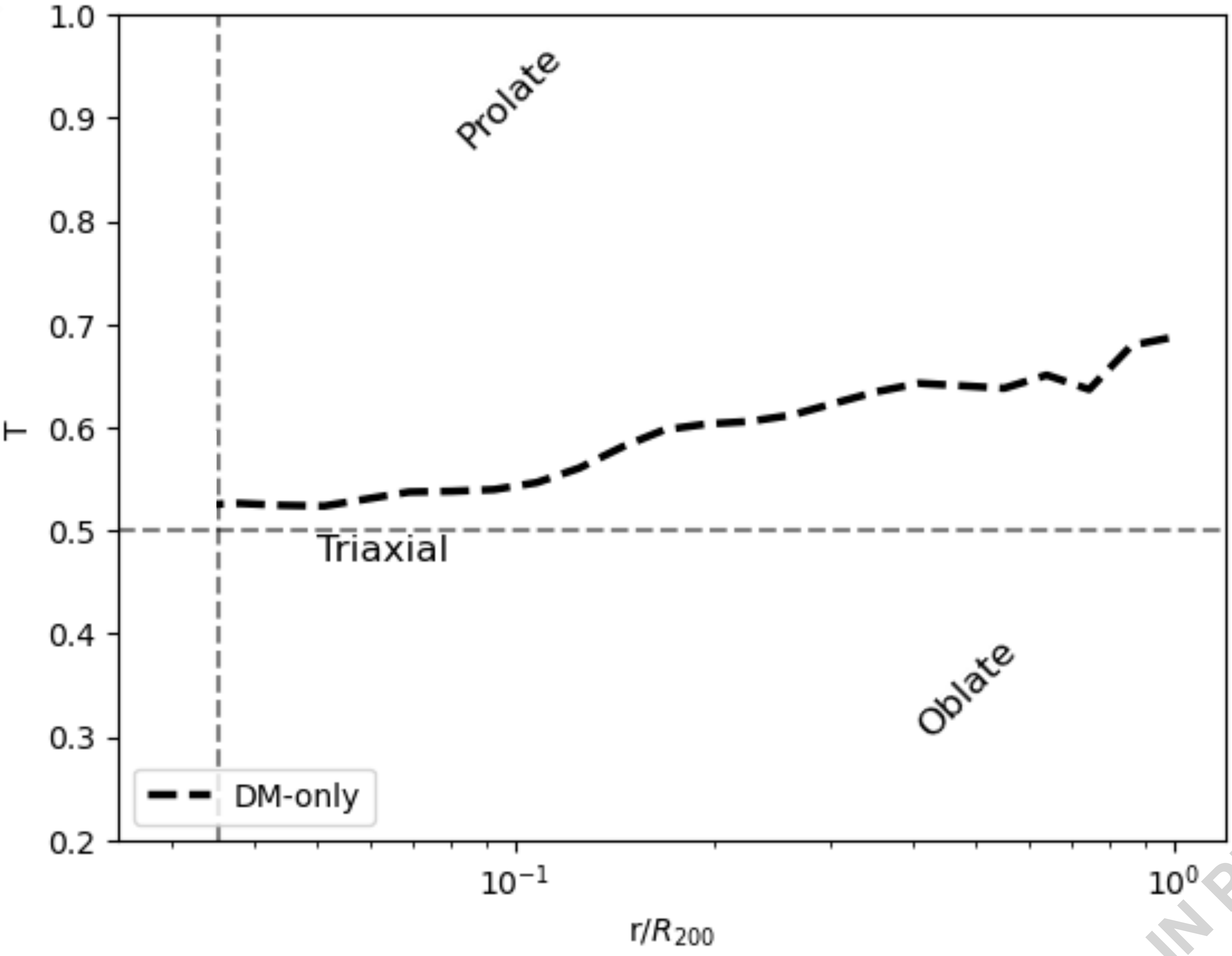


Some like it triaxial

Despali et al. 2012

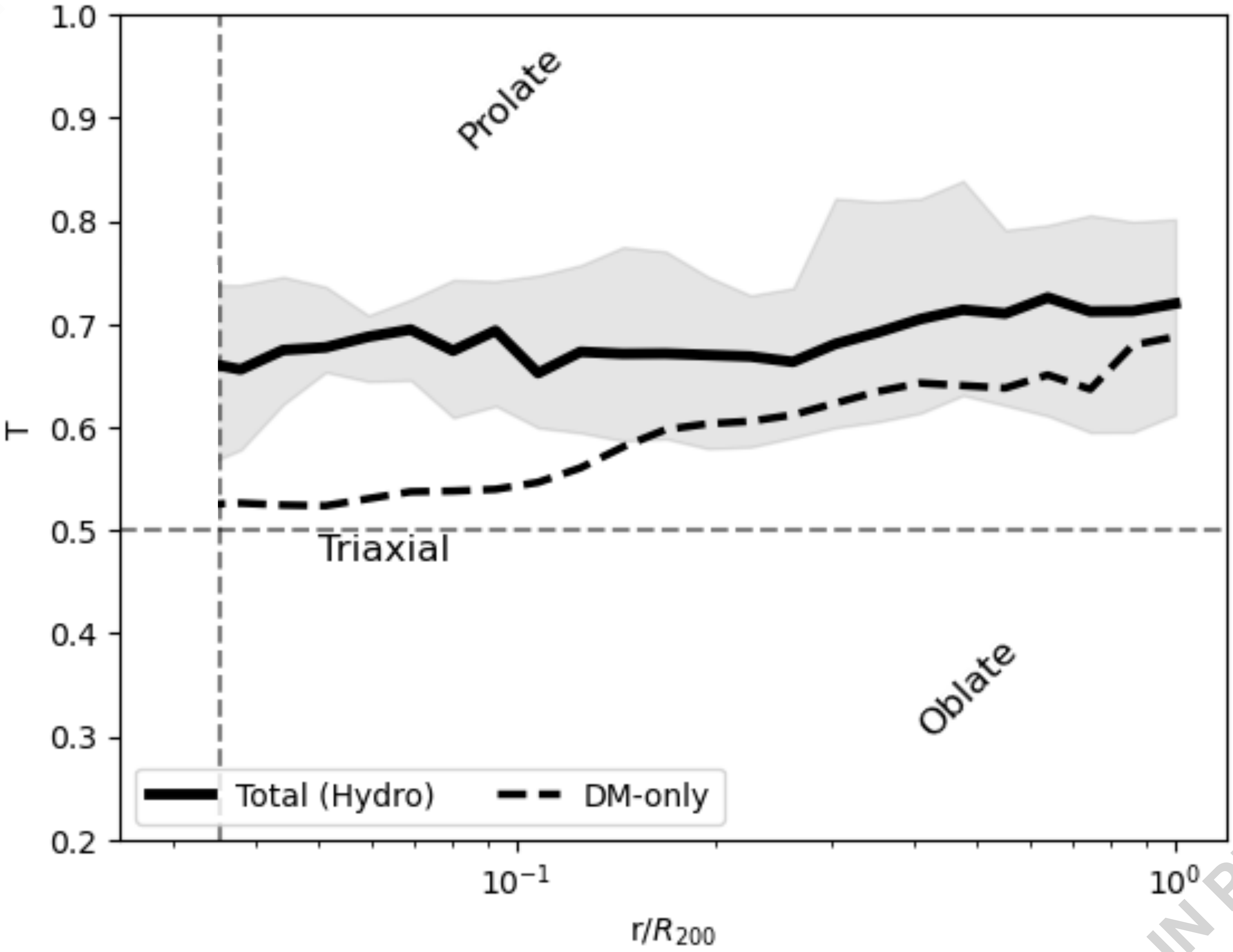
$$T = \frac{a^2 - b^2}{a^2 - c^2}$$

$$a > b > c$$



CDM

$M_{200} \gtrsim 7 \times 10^{13} h^{-1} M_{\odot}$



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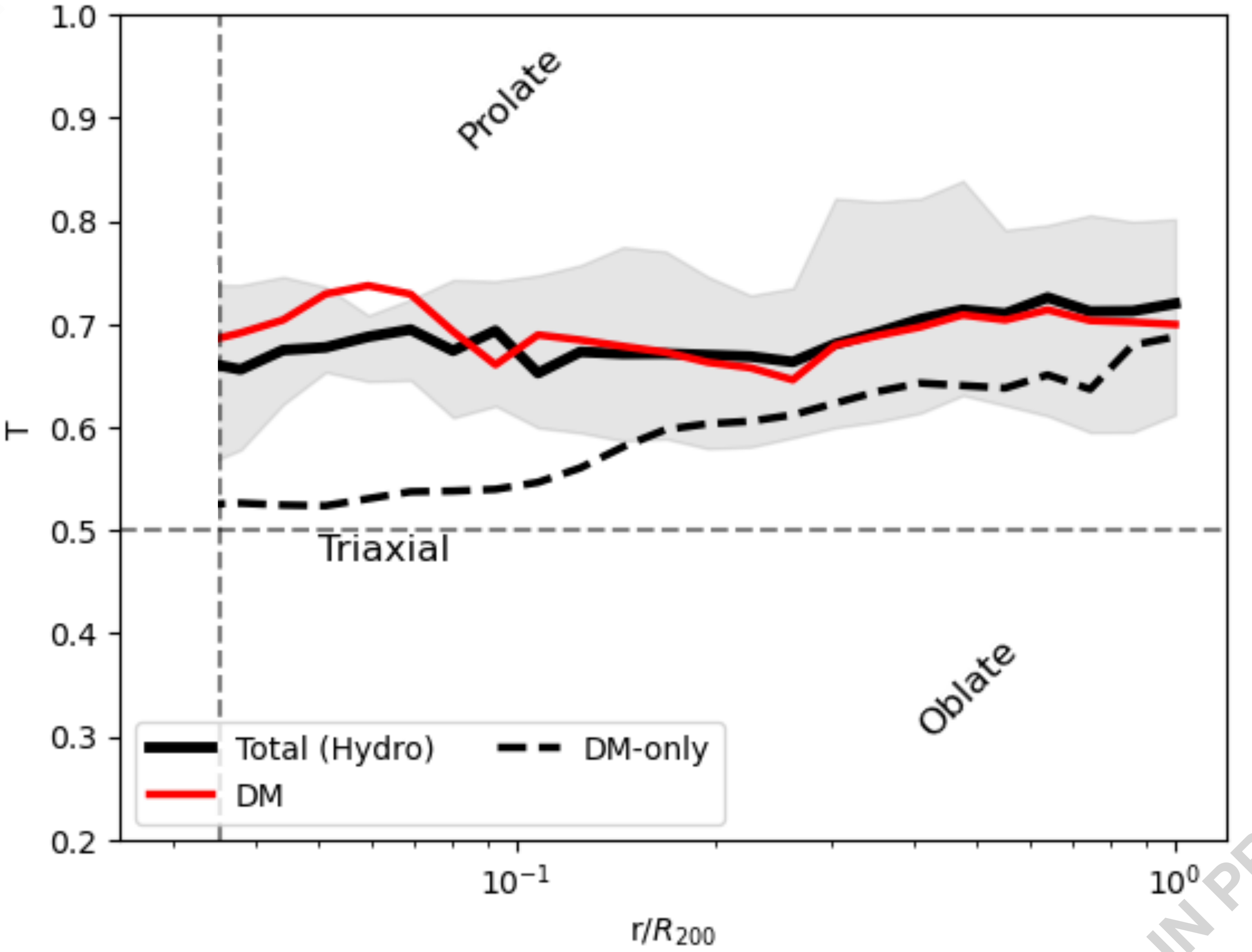

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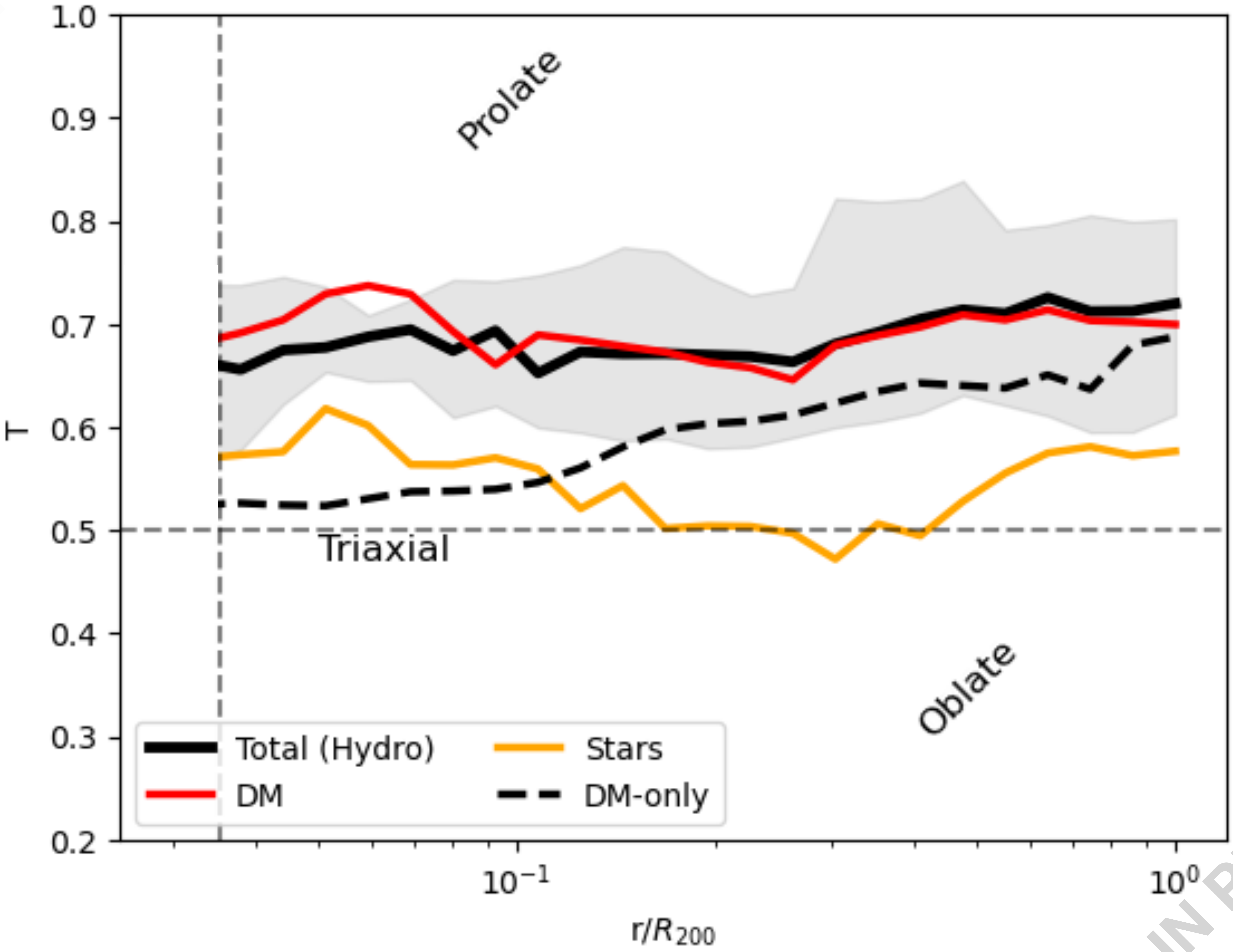

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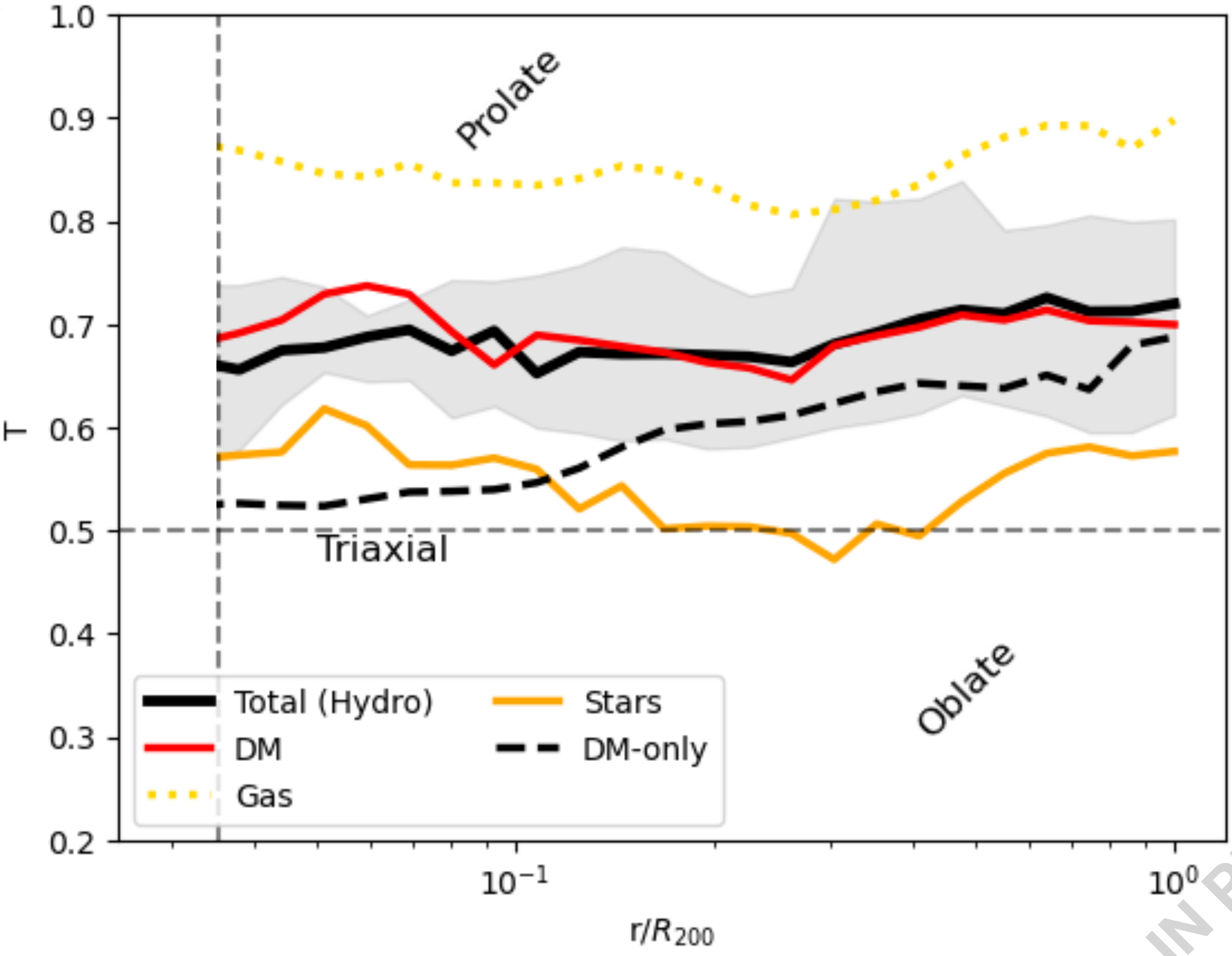
IN PREPARATION



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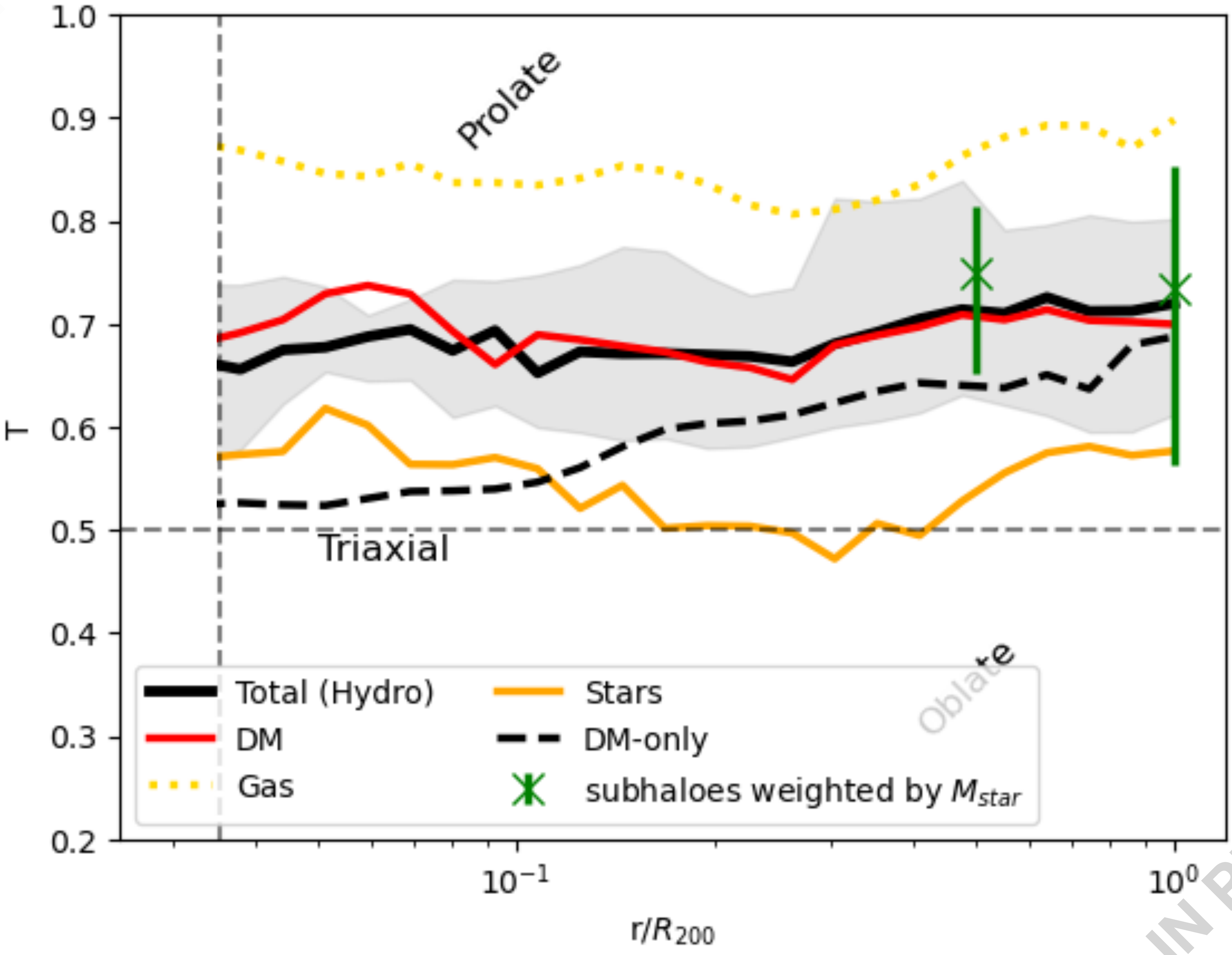

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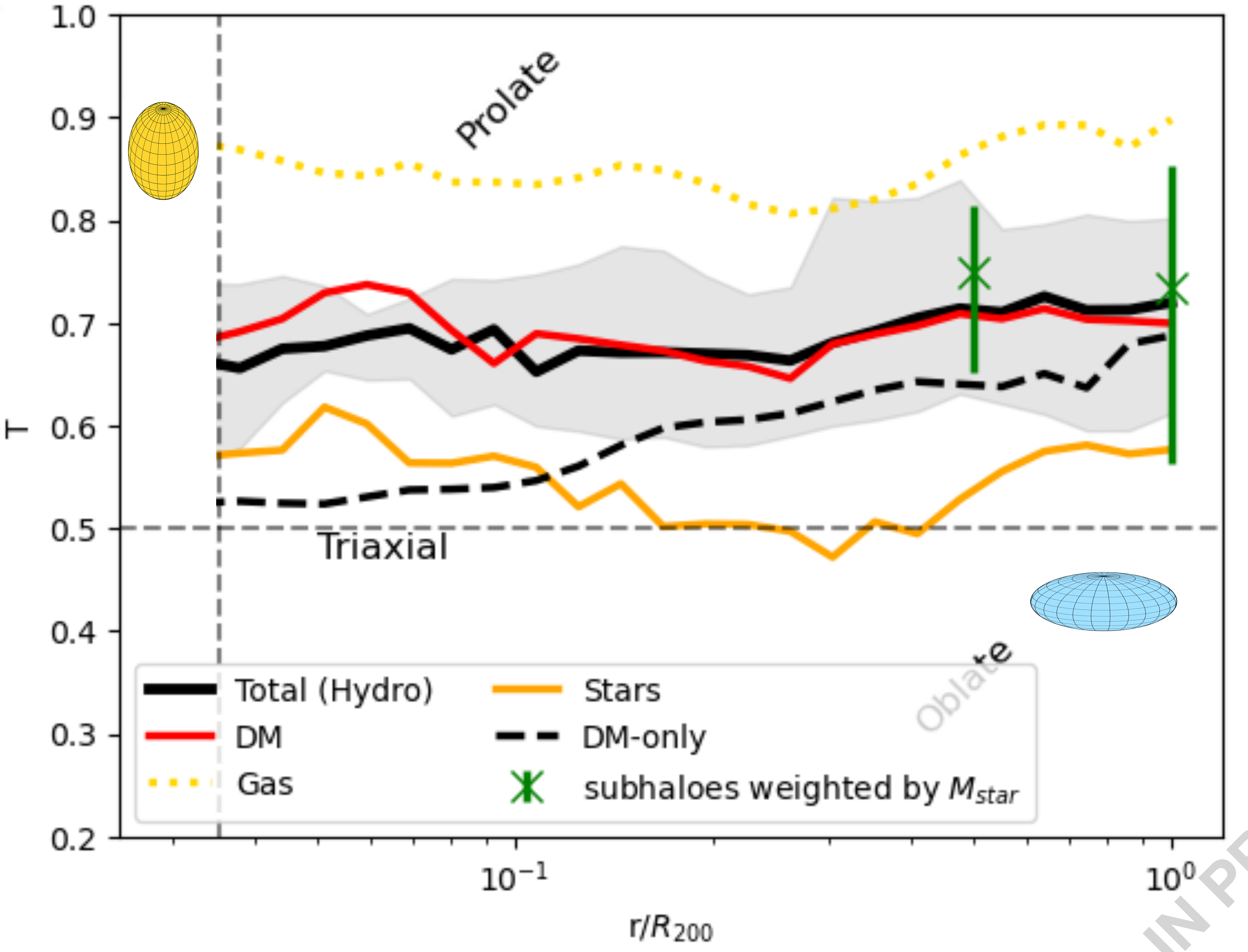
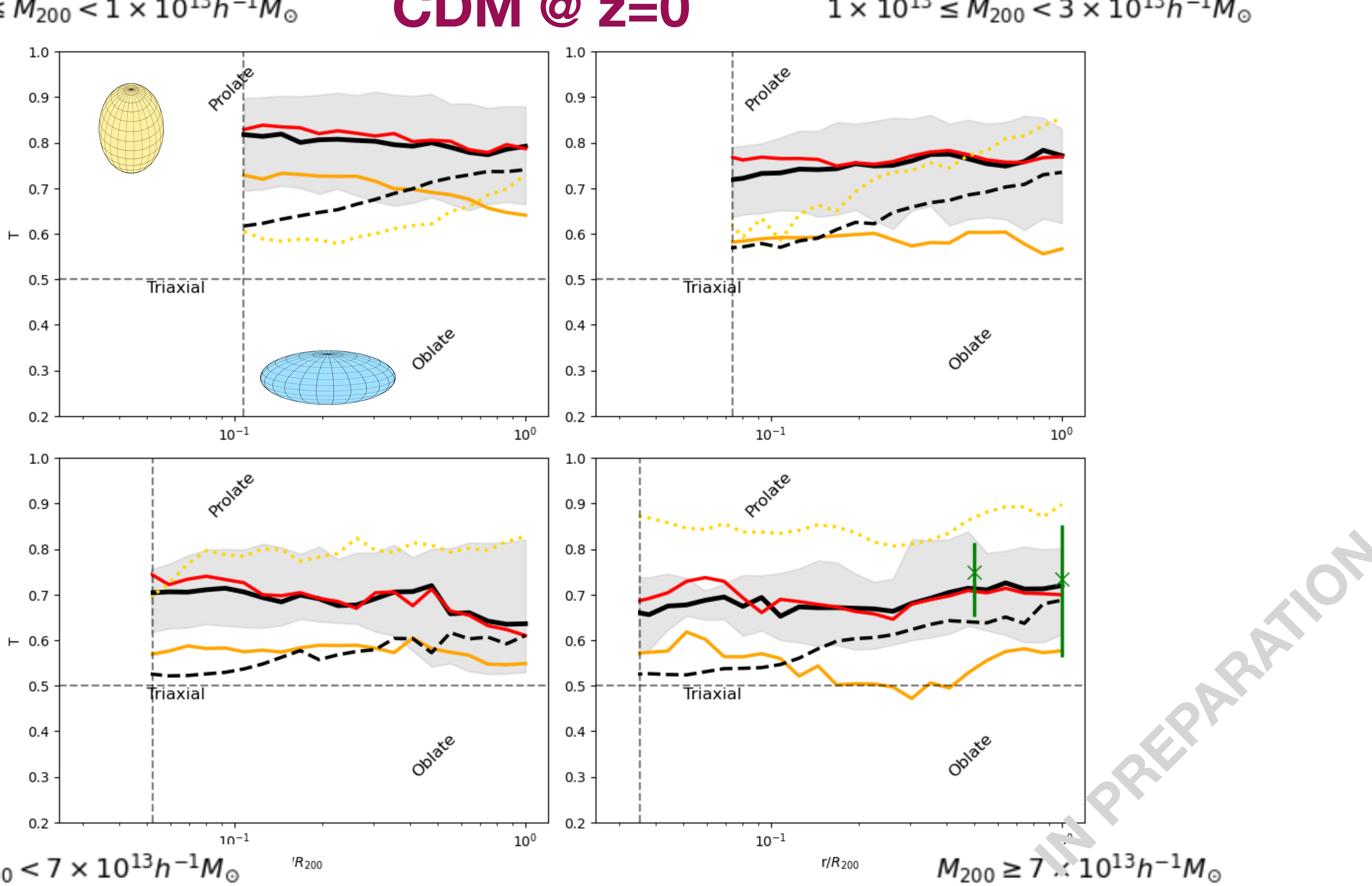


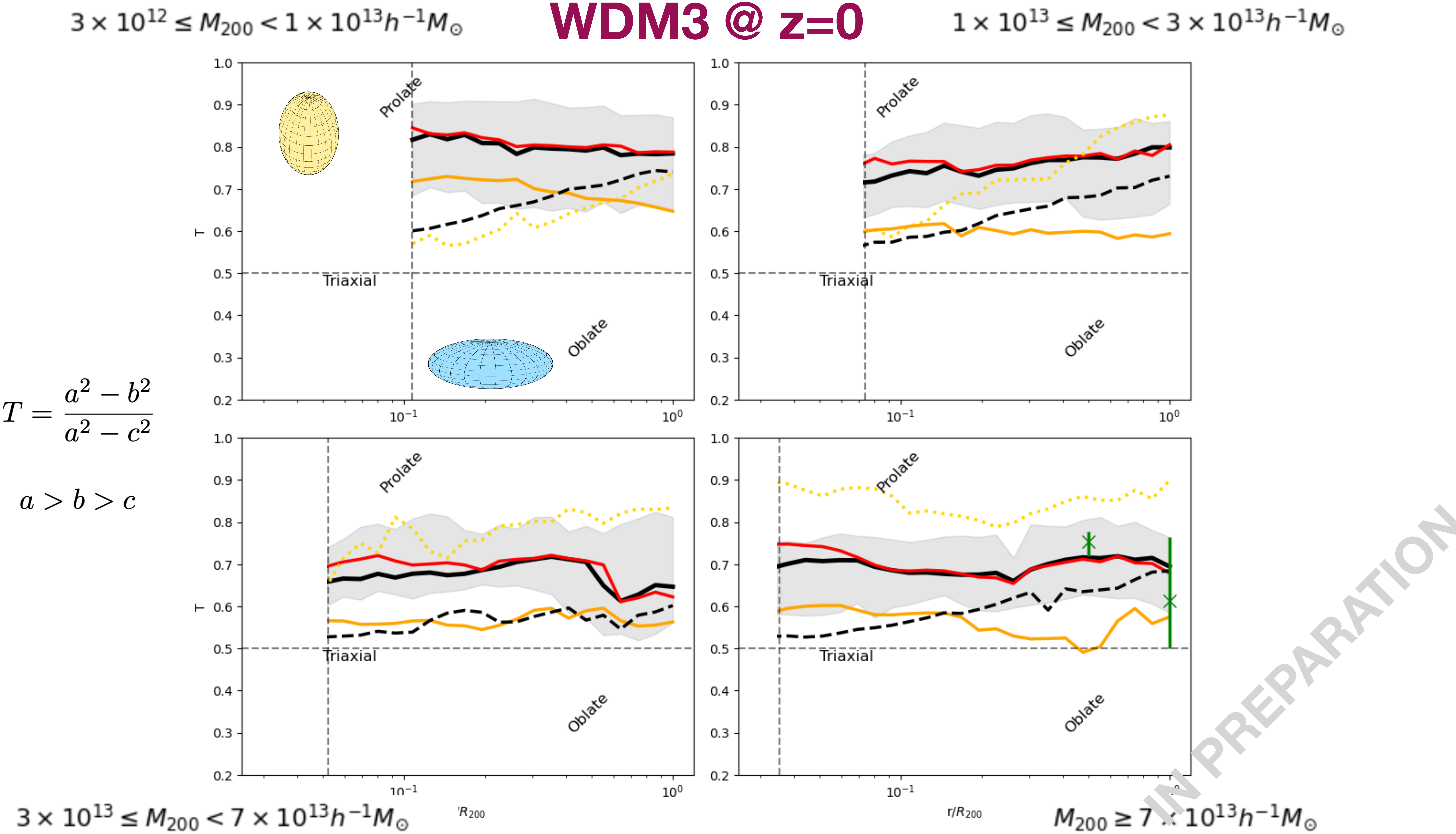
CDM @ z=0

$$T = \frac{a^2 - b^2}{a^2 - c^2}$$

$$a > b > c$$



WDM3 @ z=0



$$T = \frac{a^2 - b^2}{a^2 - c^2}$$

$$a > b > c$$

SIDM @ z=0

$$T = \frac{a^2 - b^2}{a^2 - c^2}$$

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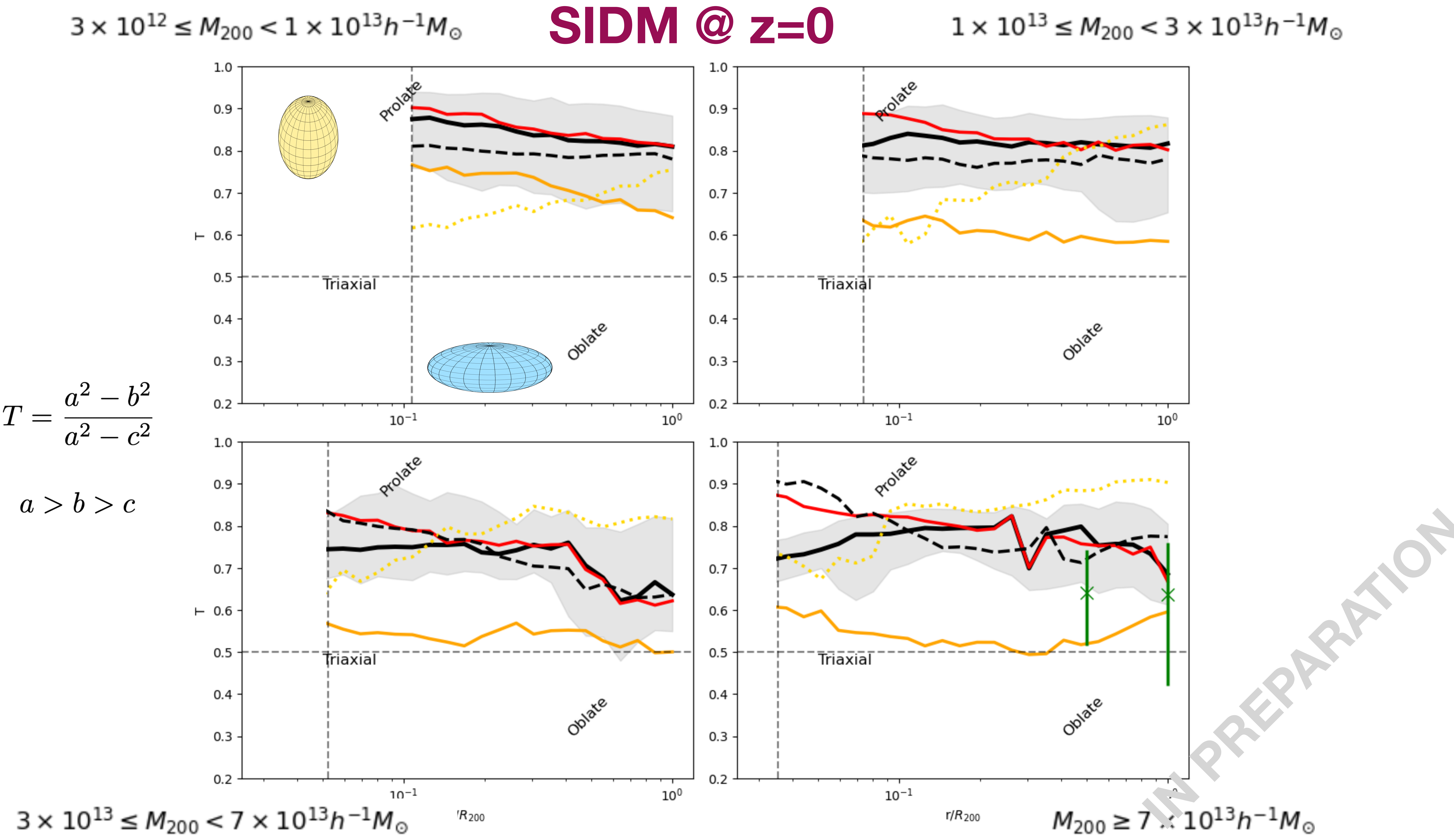
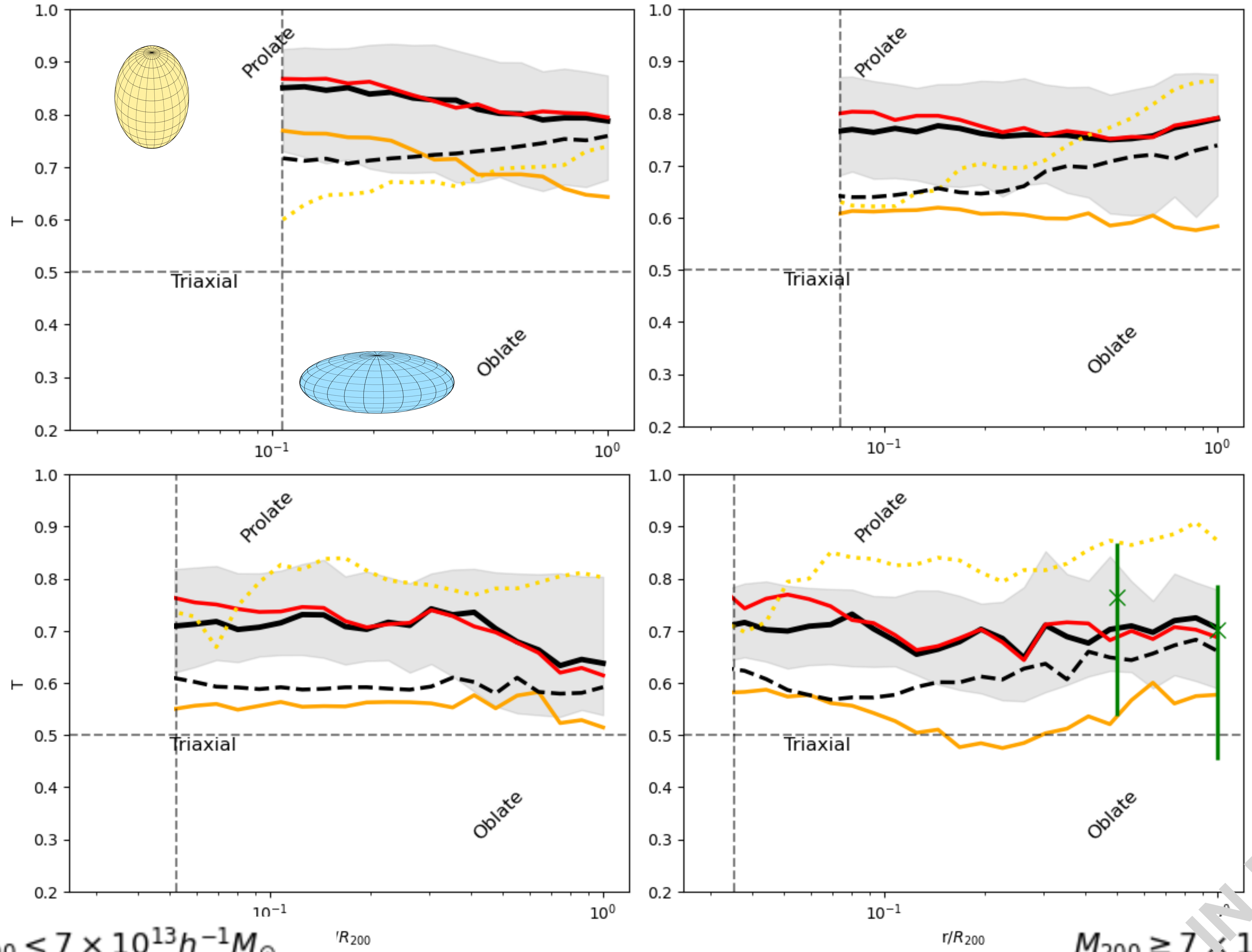


vSIDM @ z=0

$3\times10^{12} \le M_{200} < 1\times10^{13} h^{-1} M_\odot$

$1\times10^{13} \le M_{200} < 3\times10^{13} h^{-1} M_\odot$



$3\times10^{13} \le M_{200} < 7\times10^{13} h^{-1} M_\odot$

$M_{200} \ge 7\times10^{13} h^{-1} M_\odot$

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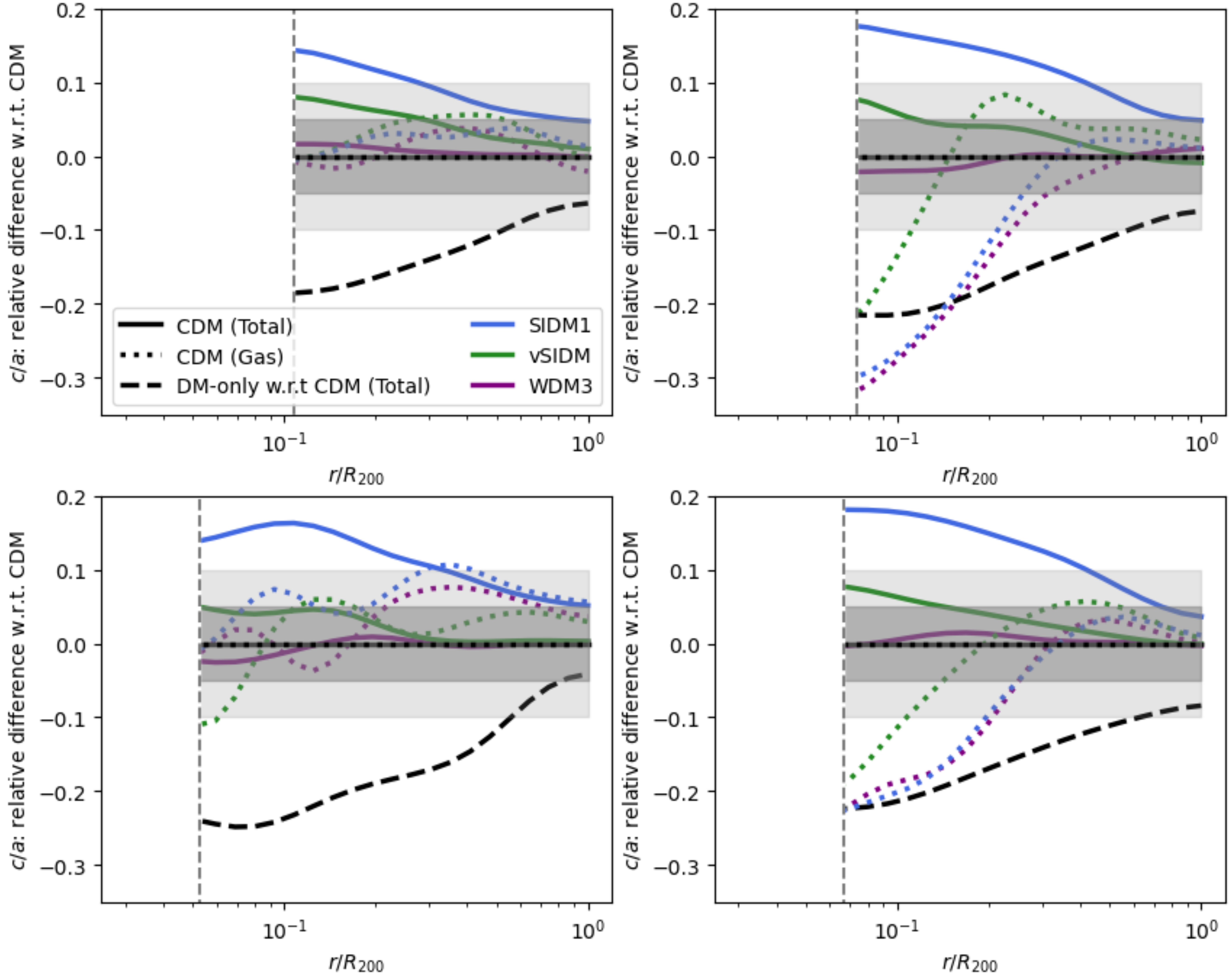
Dark Matter Halo Shape

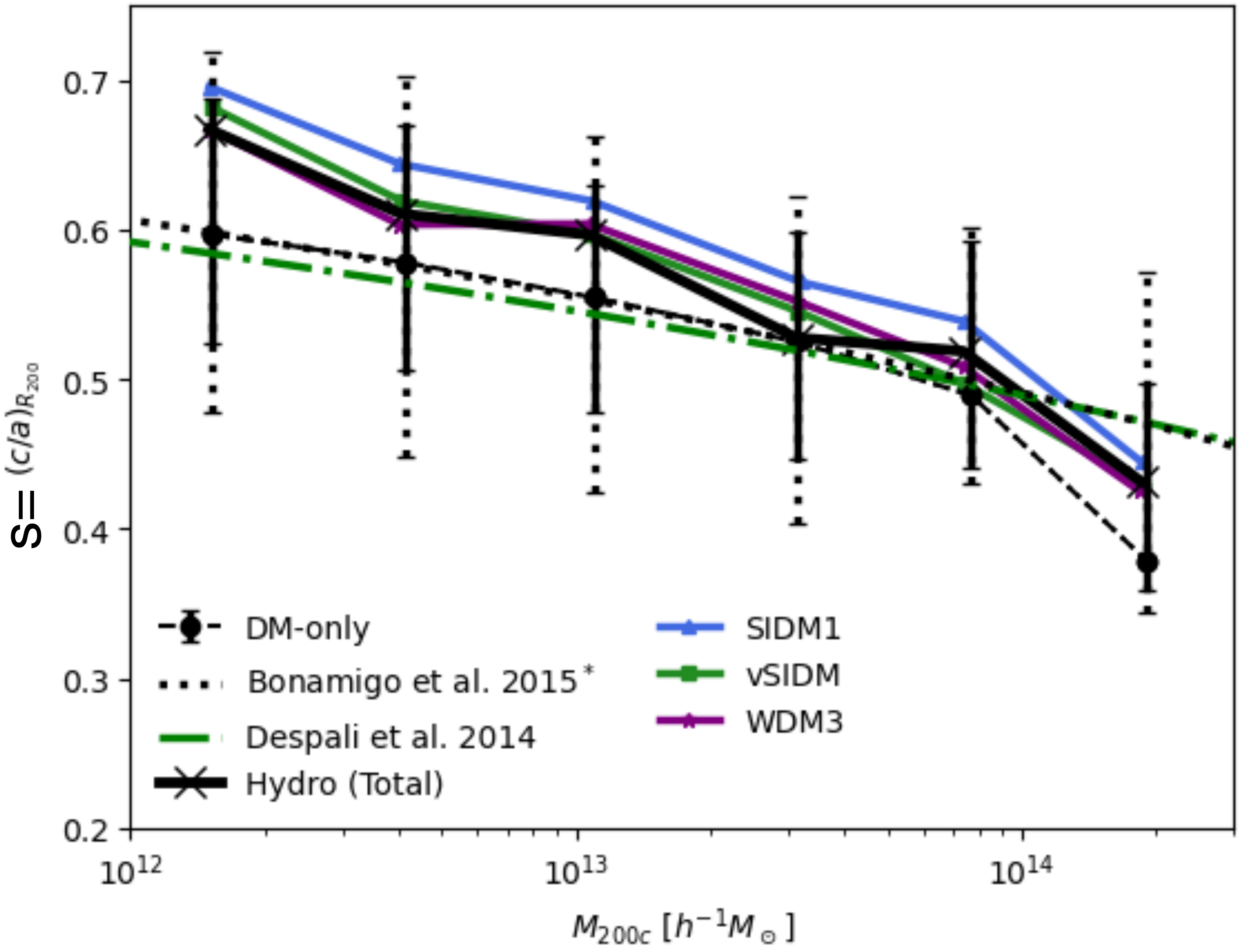
Triaxiality Properties



Dark Matter Halo Shape

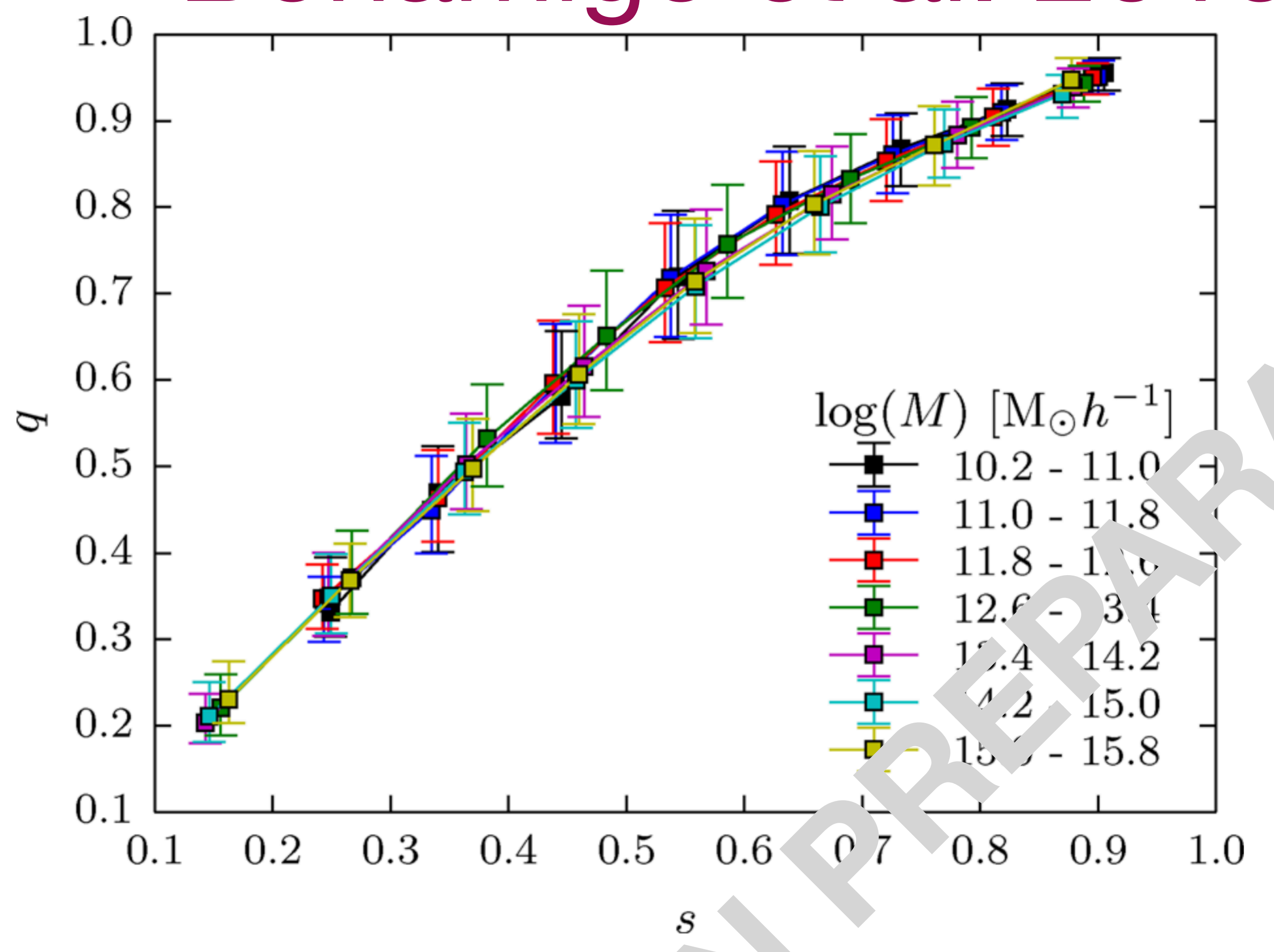
Triaxiality Properties

Total Matter Shape



The **triaxiality** of dark matter haloes is a key structural property that describes their **3D shape**, and it provides insight into their **formation history and dynamics.**
It affects **gravitational lensing**, **satellite orbits**, and the interpretation of **galaxy dynamics.**
Gas cools and collapses toward the center, dragging DM inward via **adiabatic contraction,** and **rounds** the potential.
Repeated gas inflows/outflows **heat the dark matter**, potentially making it less concentrated and more spherical.
A dense stellar component exerts a **symmetric gravitational pull**, smoothing the DM distribution.

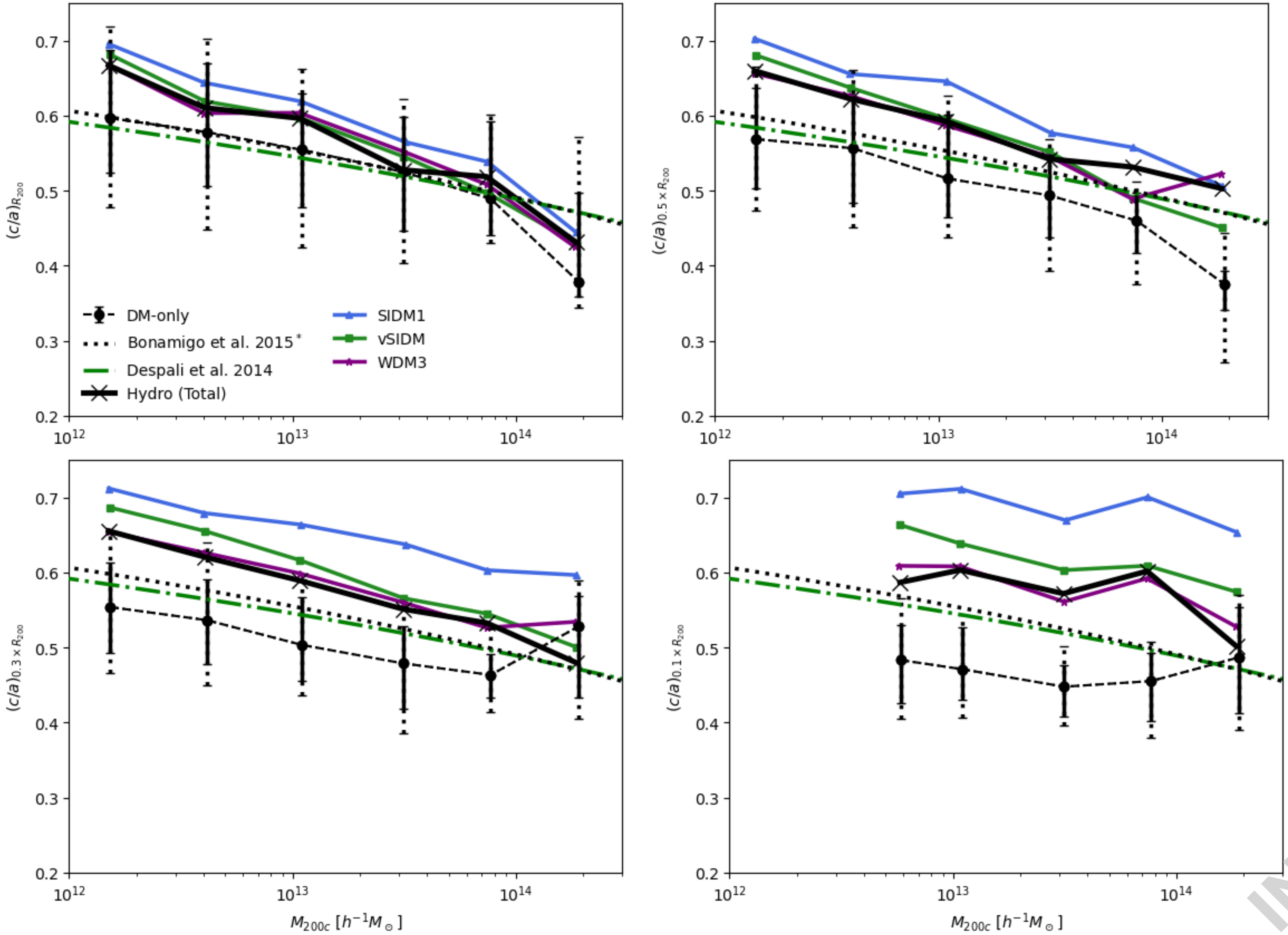
Bonamigo et al. 2015



IN PREPARATION

Dark Matter Halo Shape

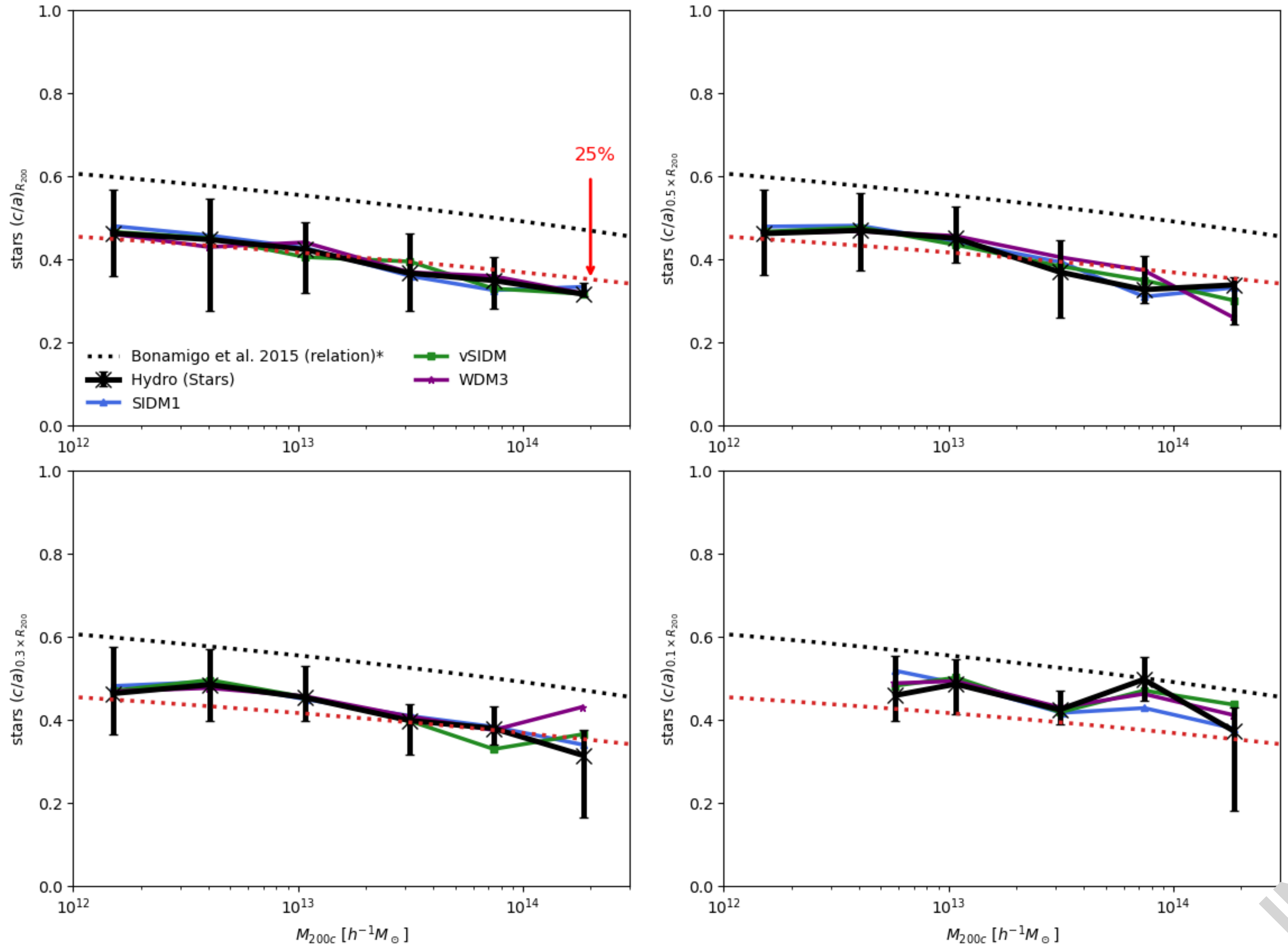
Total Matter Shape



IN PREPARATION

Dark Matter Halo Shape

Stars Shape



Summary & Conclusions

Structural Halo Properties are Challenging for CDM

- A **persistent excess of galaxy-galaxy strong lensing** is observed in galaxy clusters, challenging predictions from standard Cold Dark Matter (CDM) models.
- Efforts to attribute this excess to uncertainties in the **galaxy formation models** used in current hydrodynamical simulations have not resolved the discrepancy, suggesting that baryonic physics alone is insufficient to explain the observations.
- This tension highlights the need for **further investigation into the limitations of existing simulations** and motivates the exploration of alternative dark matter scenarios, such as **self-interacting dark matter (SIDM)**.
- The **shapes of dark matter halos** emerge as a key diagnostic for testing the nature of dark matter, offering complementary constraints to those from lensing statistics.
- Full hydrodynamical simulations predict **rounder halos** due to the impact of baryonic processes, consistent across different implementations.
- In particular, the **central regions of halos show distinctive signatures of the underlying dark matter physics**: SIDM models produce systematically rounder cores, offering a promising avenue for distinguishing between CDM and alternative dark matter candidates.
- The combined study of **strong lensing, halo shapes, and next-generation simulations** will be critical to advancing our understanding of dark matter and resolving current tensions with observations.