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Constraints on self-interacting dark matter from galaxy clusters

October 1st 2019, Competing Structure Formation Models

University of Iceland

TALK OUTLINE

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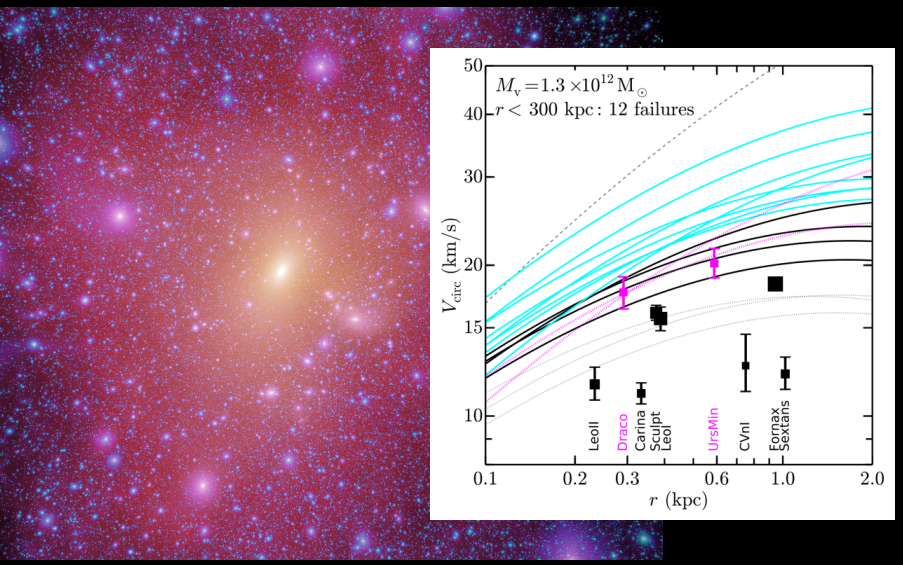
1. The motivation for SIDM



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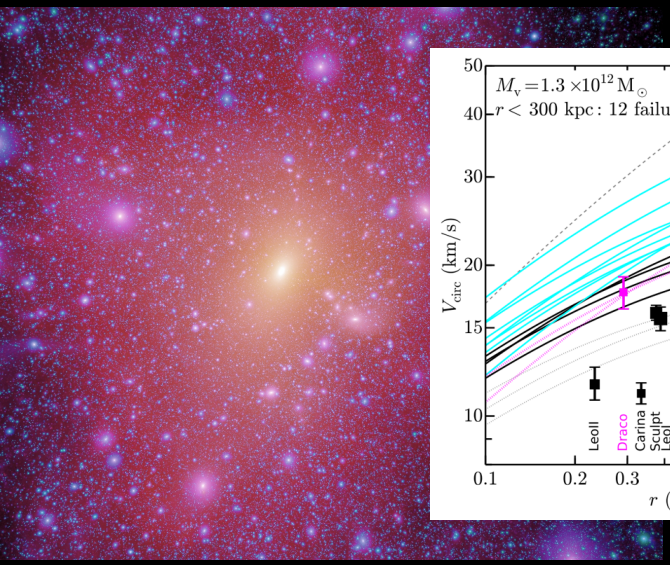
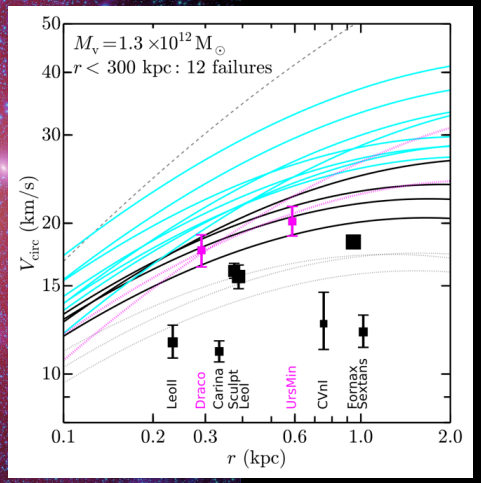
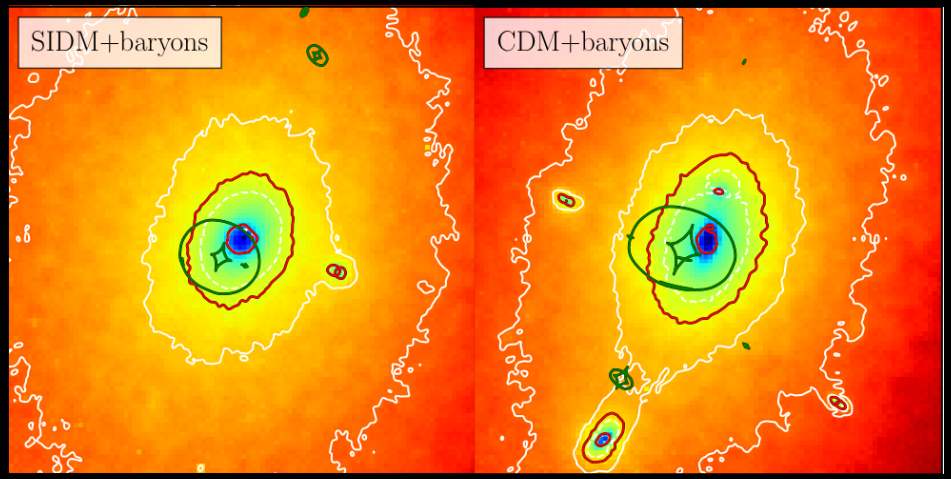




2. Individual galaxy clusters



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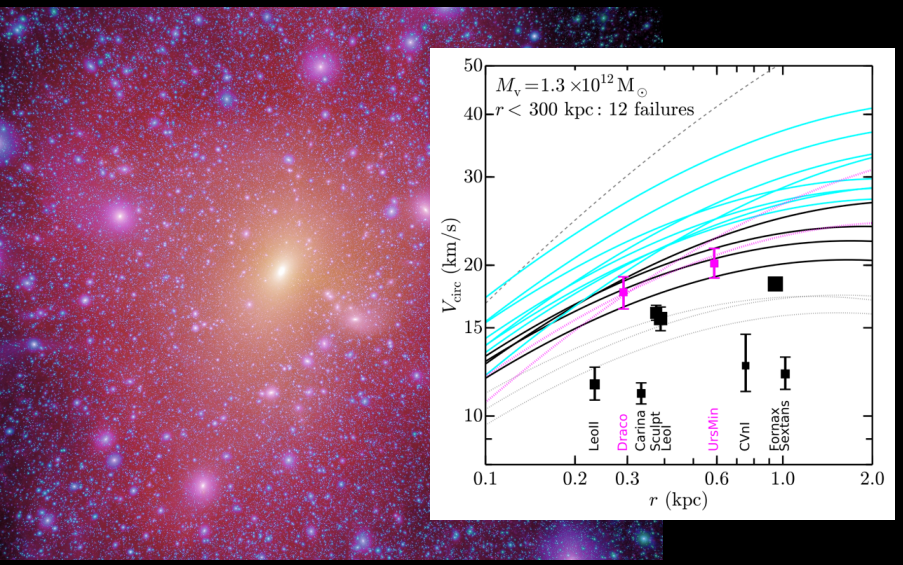

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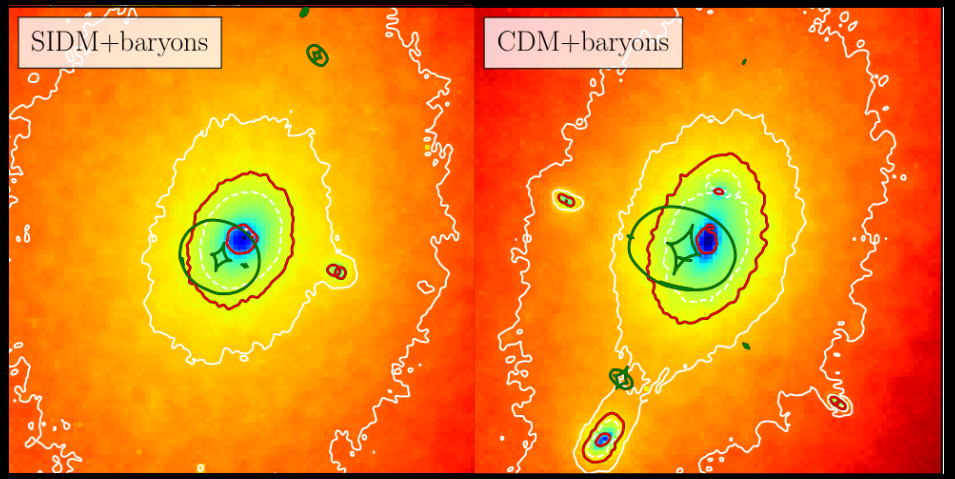
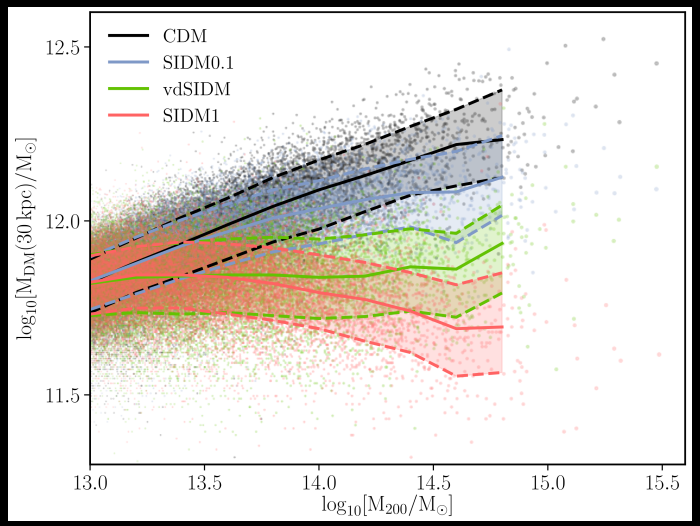


3. A simulated SIDM universe



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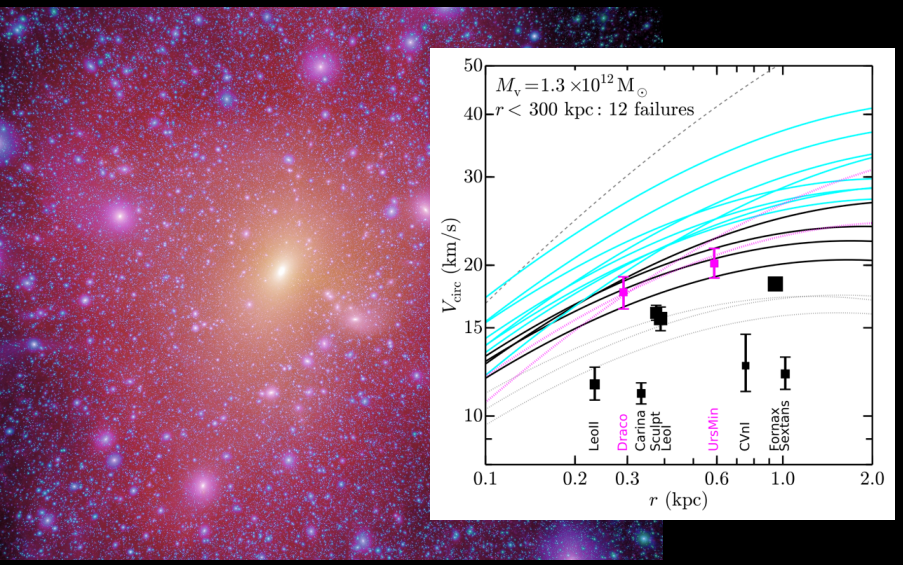

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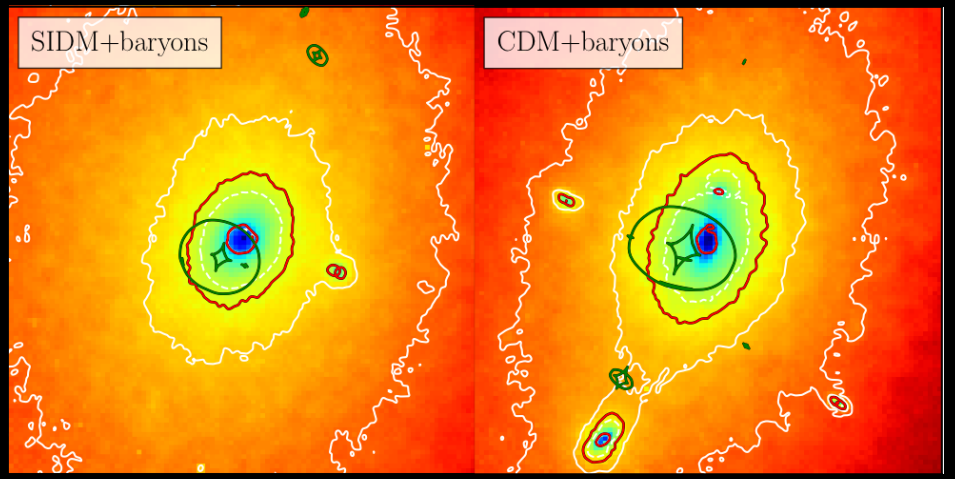

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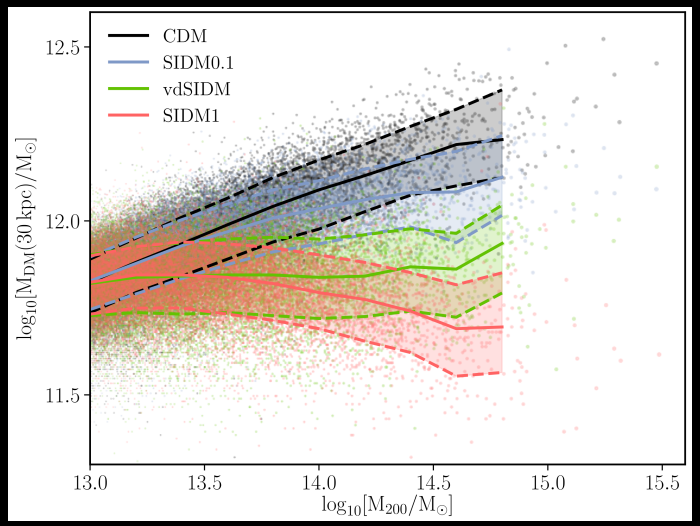
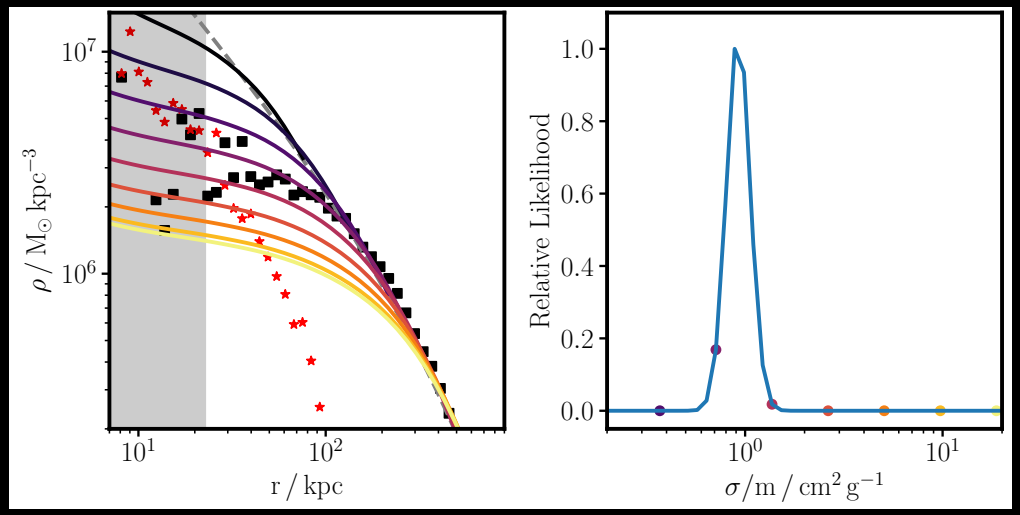
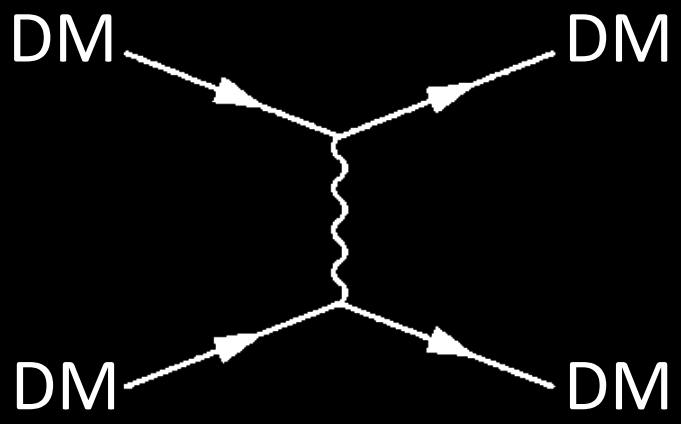


4. Analytical modelling of ρ(r)

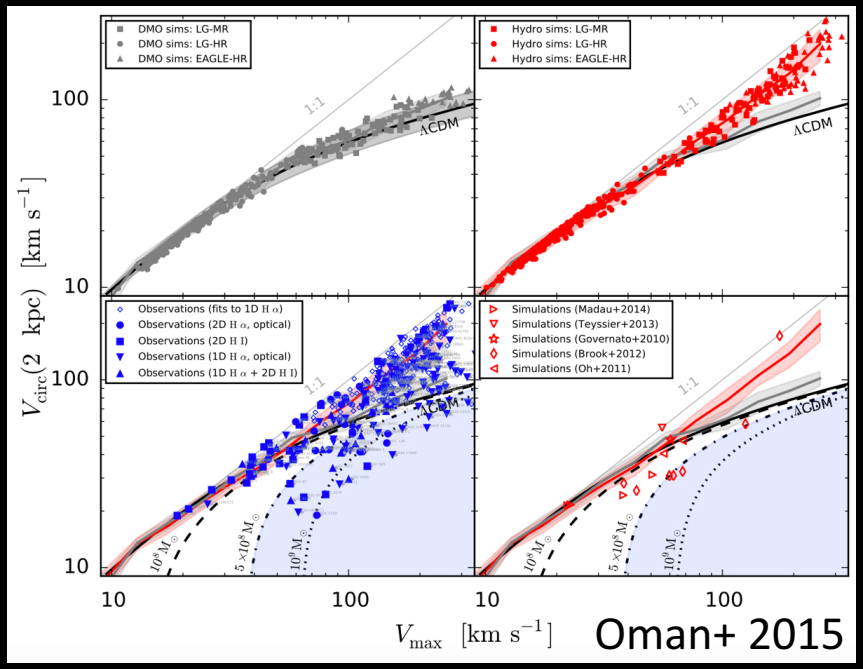


WHAT IS SIDM AND WHY SHOULD WE CARE?



Dark matter particles that can interact with one another through forces other than just gravity (at astrophysically important rates)

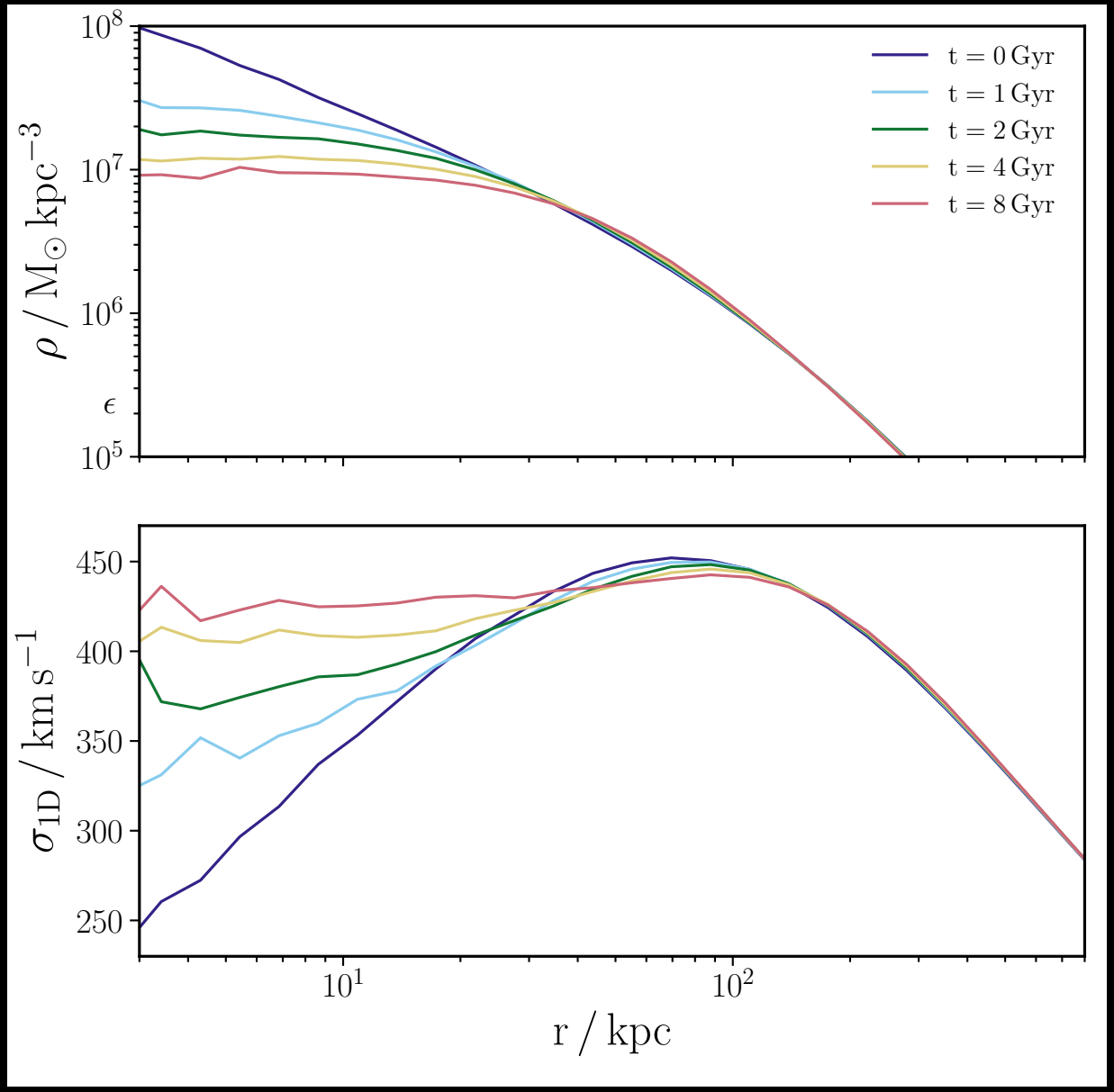
Invoked to explain 'small scale problems', i.e. core-cusp, TBTF… 'diversity'



Oman+ 2015

Chance to probe the particle nature of dark matter using astrophysical observations

SIDM CORE FORMATION



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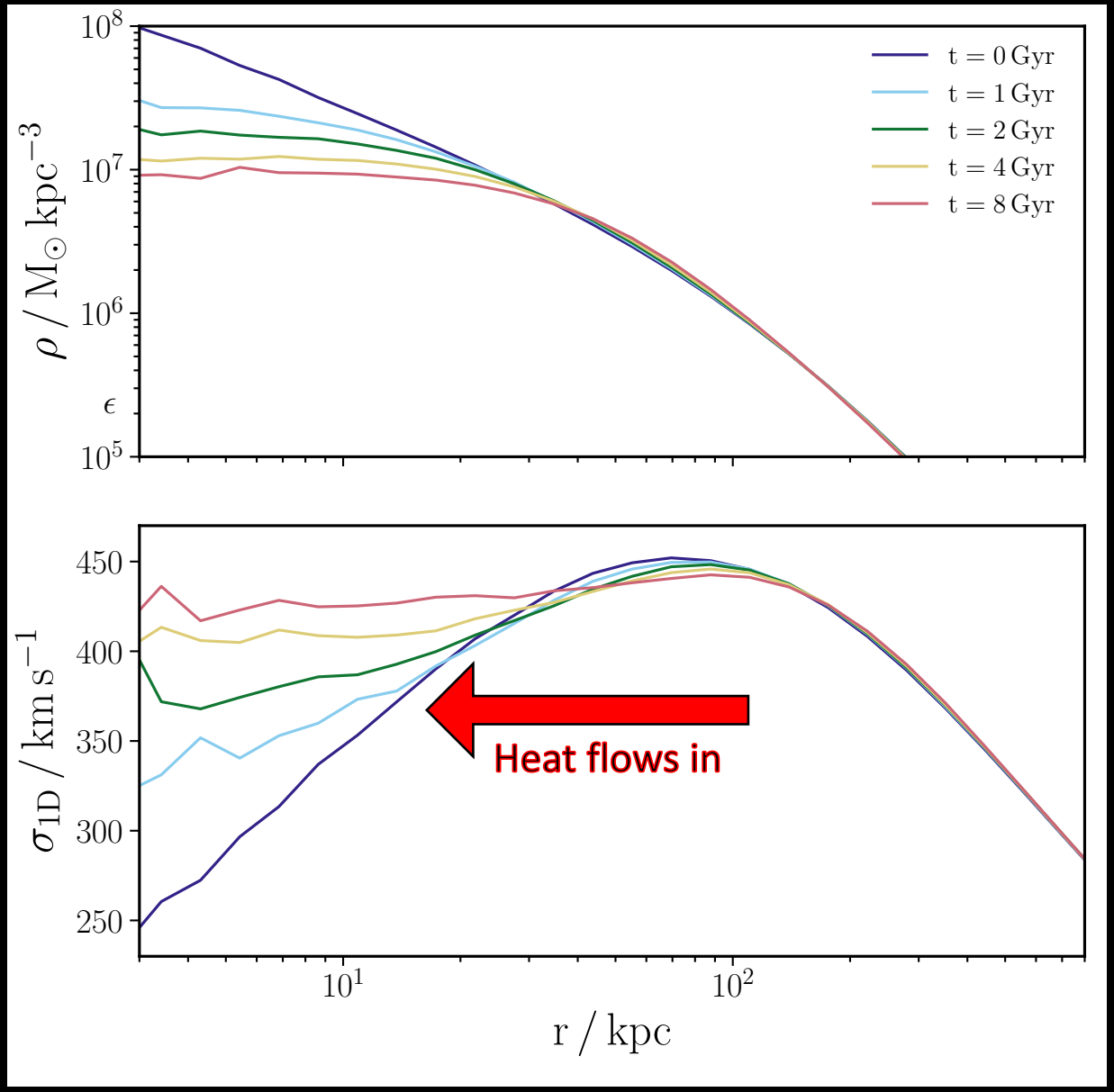

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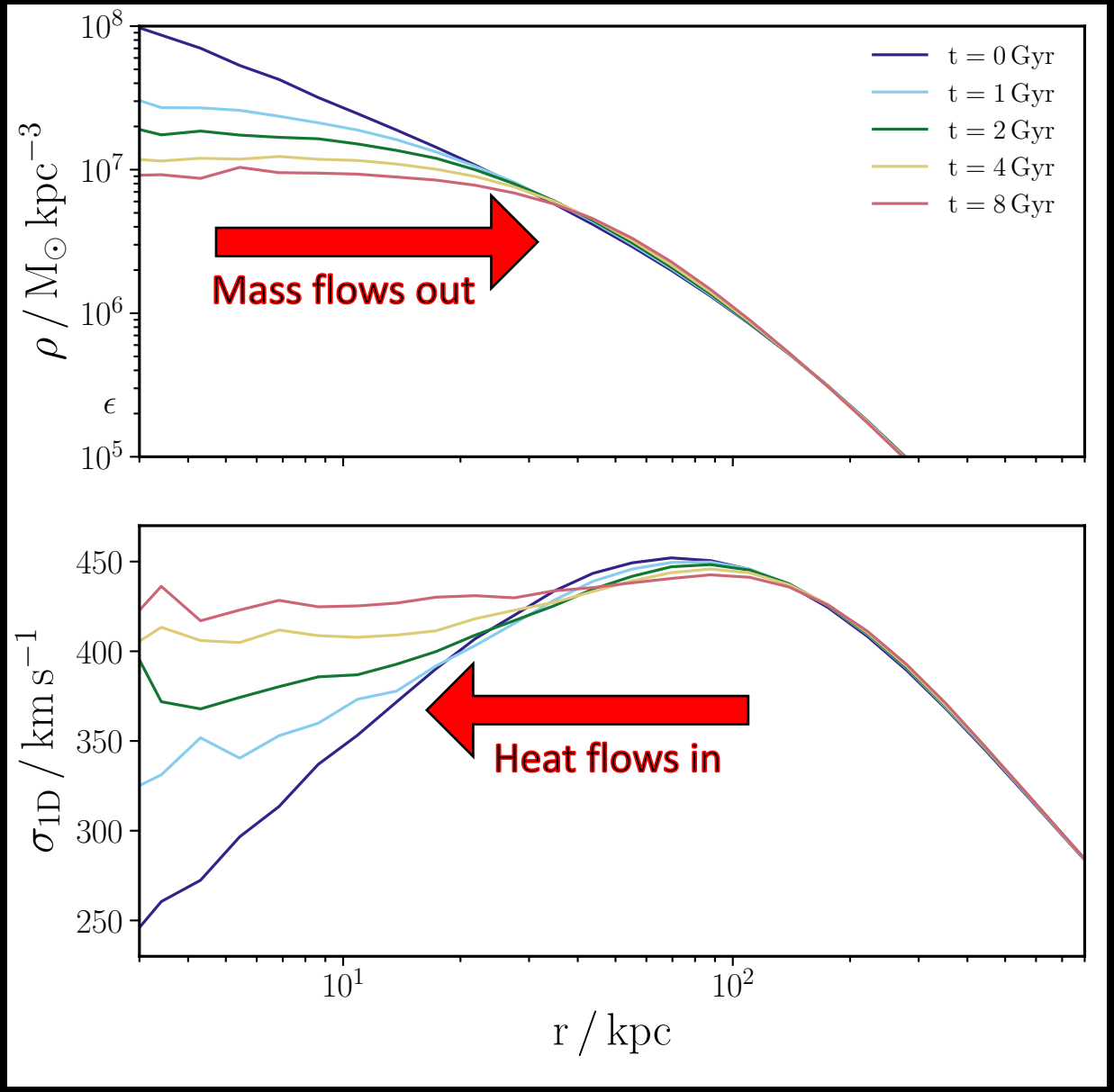
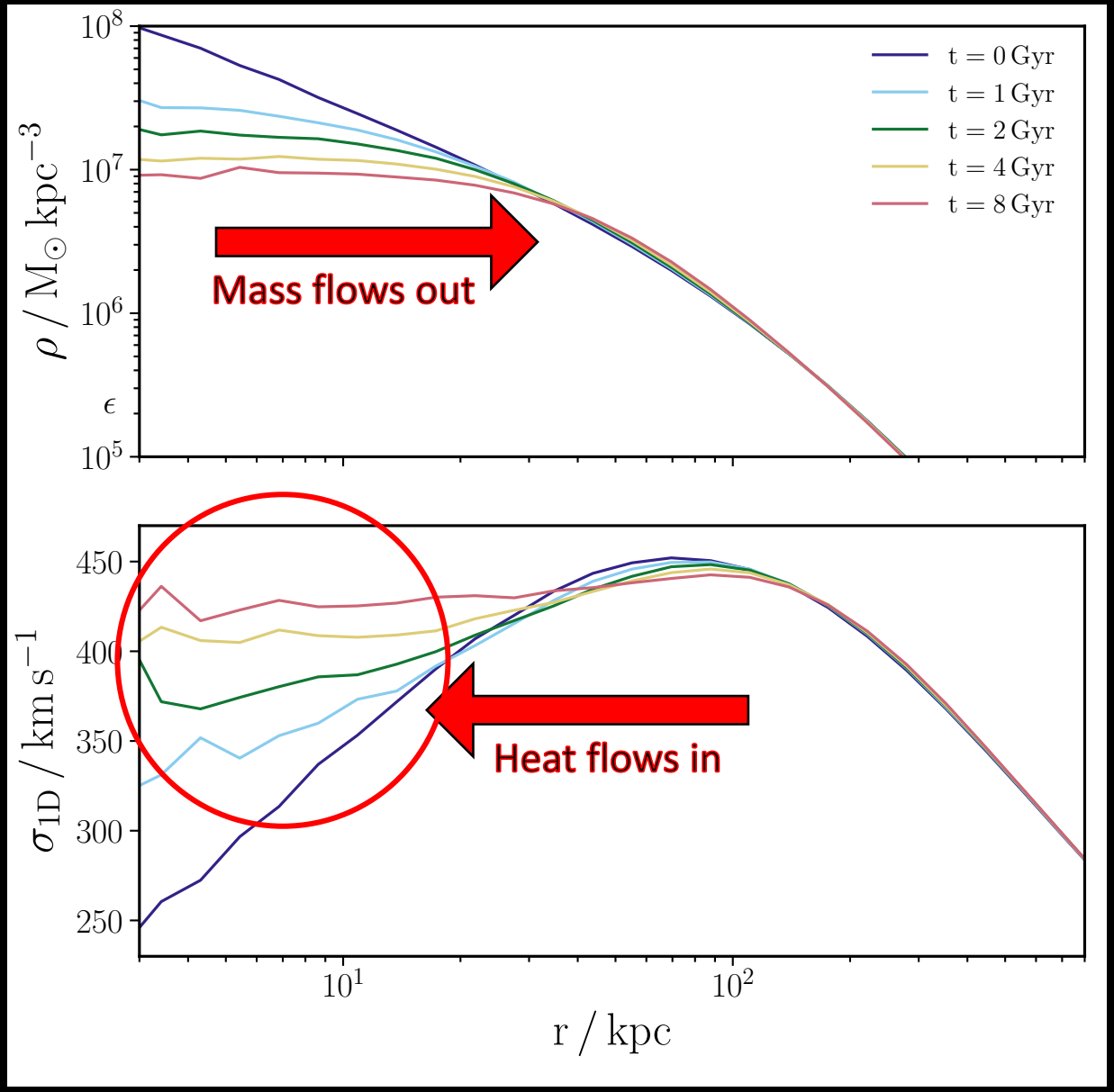


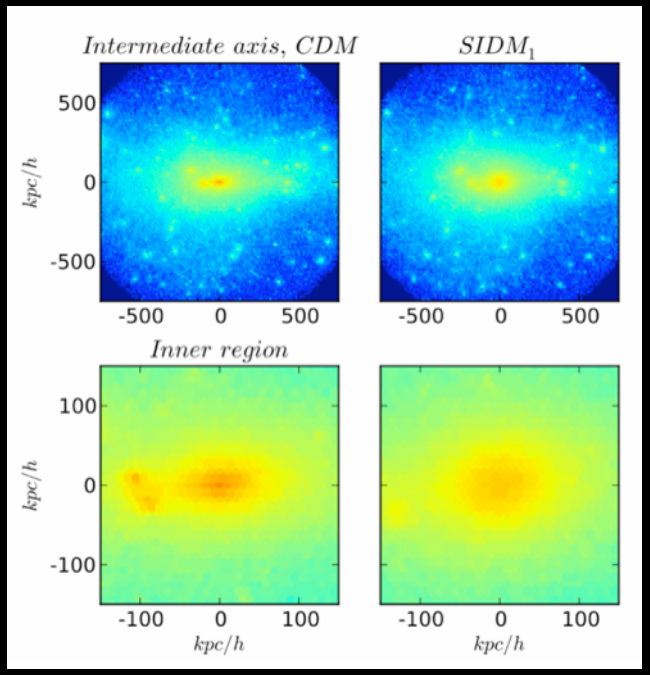
SIDM CORE FORMATION

Centre of the halo becomes ~isothermal




GALAXY CLUSTERS

PREVIOUS CLUSTER CONSTRAINTS



Halo shapes - Peter+ 2013

$$\sigma/m \lesssim 1\,\mathrm{cm}^2\,\mathrm{g}^{-1}$$

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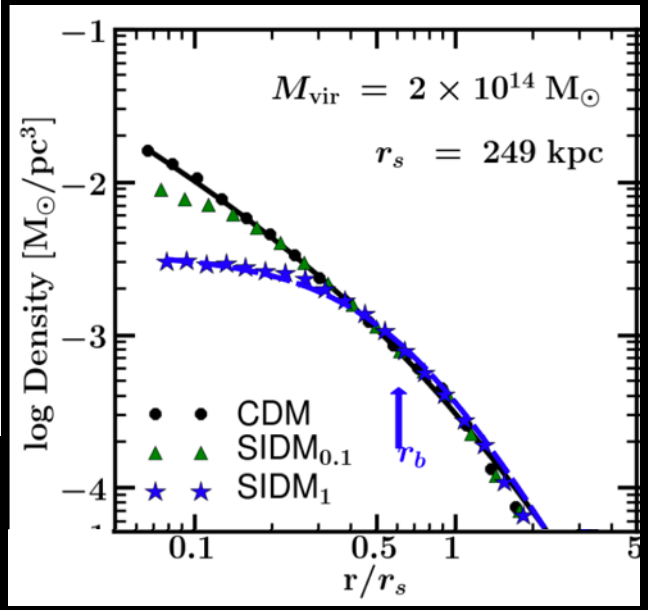
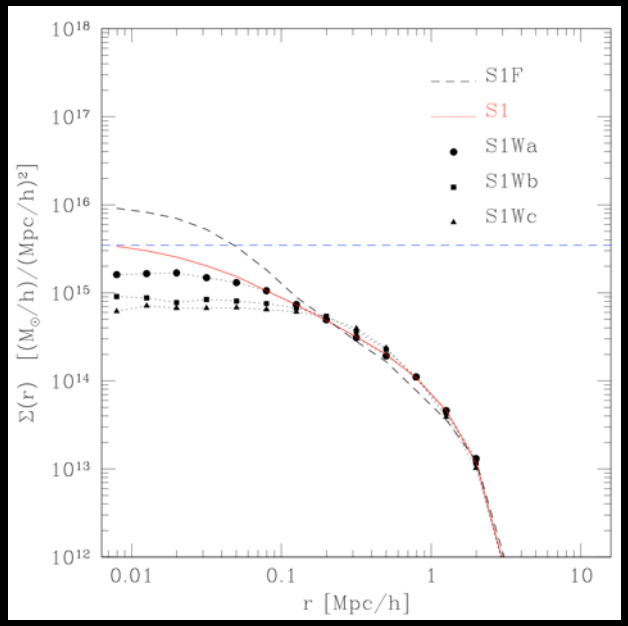
Core sizes - Rocha+ 2013





Strong lensing
Meneghetti+ 2000

$$\sigma/m < 0.1\,\mathrm{cm}^2\,\mathrm{g}^{-1}$$

- Previous constraints rely on SIDM-only simulations
- Taken at face value they rule out a velocity-independent cross-section from significantly altering the DM distribution in dwarf galaxies

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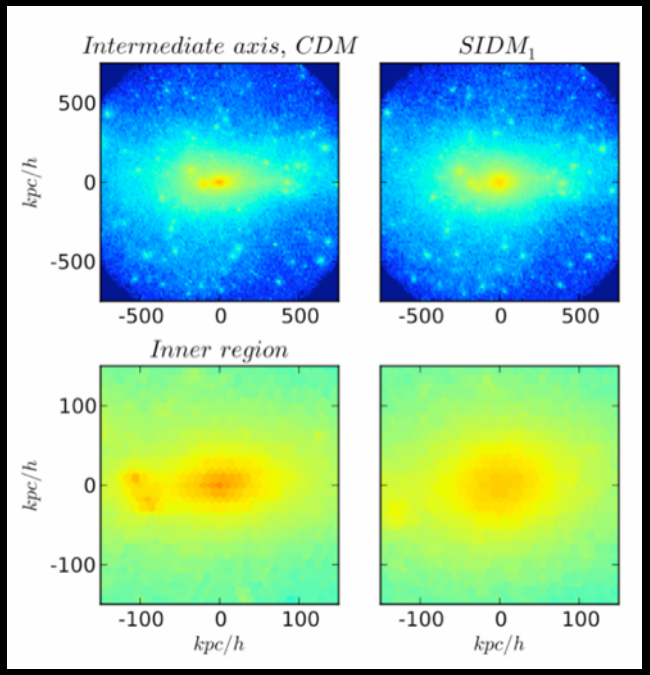

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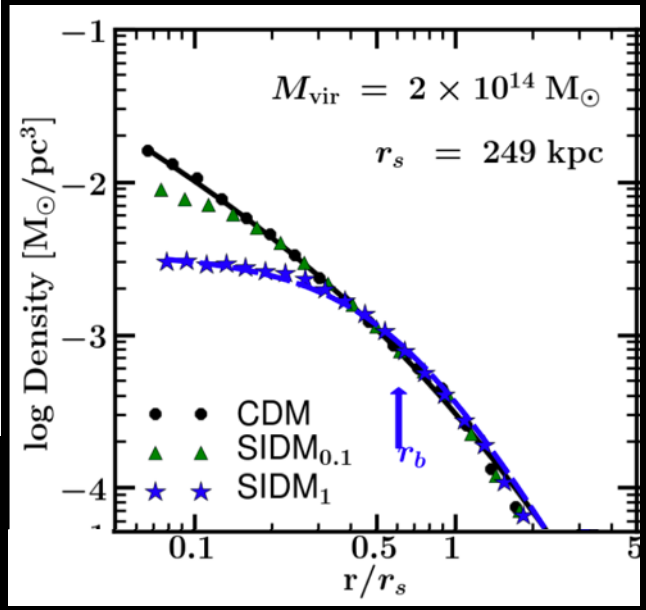

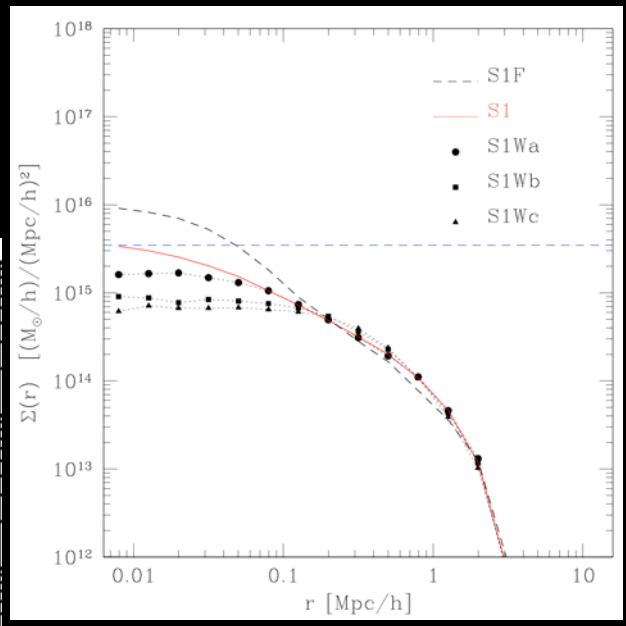

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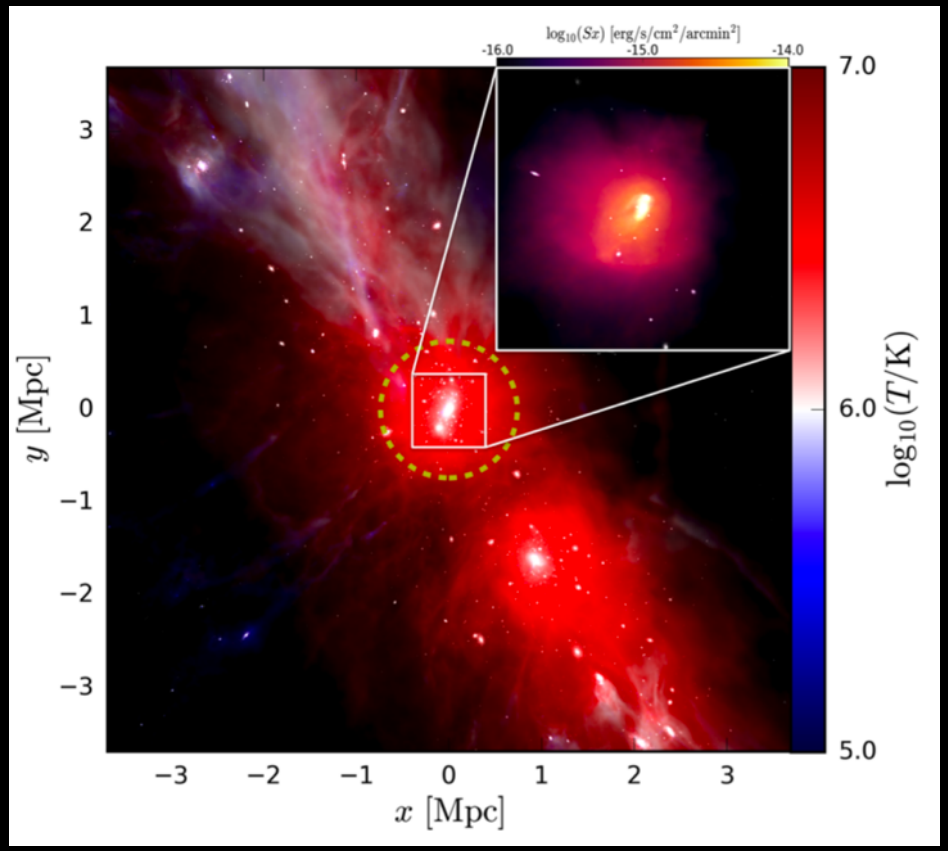
Do baryons change any of this?

Cluster-EAGLE SIDM

Zoom simulations of 2 clusters
- CE-05: 1.4x10^{14} $M_\odot$
- CE-12: 3.9x10^{14} $M_\odot$
Run with SIDM-only & SIDM+baryons

$$\sigma/m = 1\,\mathrm{cm}^2\,\mathrm{g}^{-1}$$

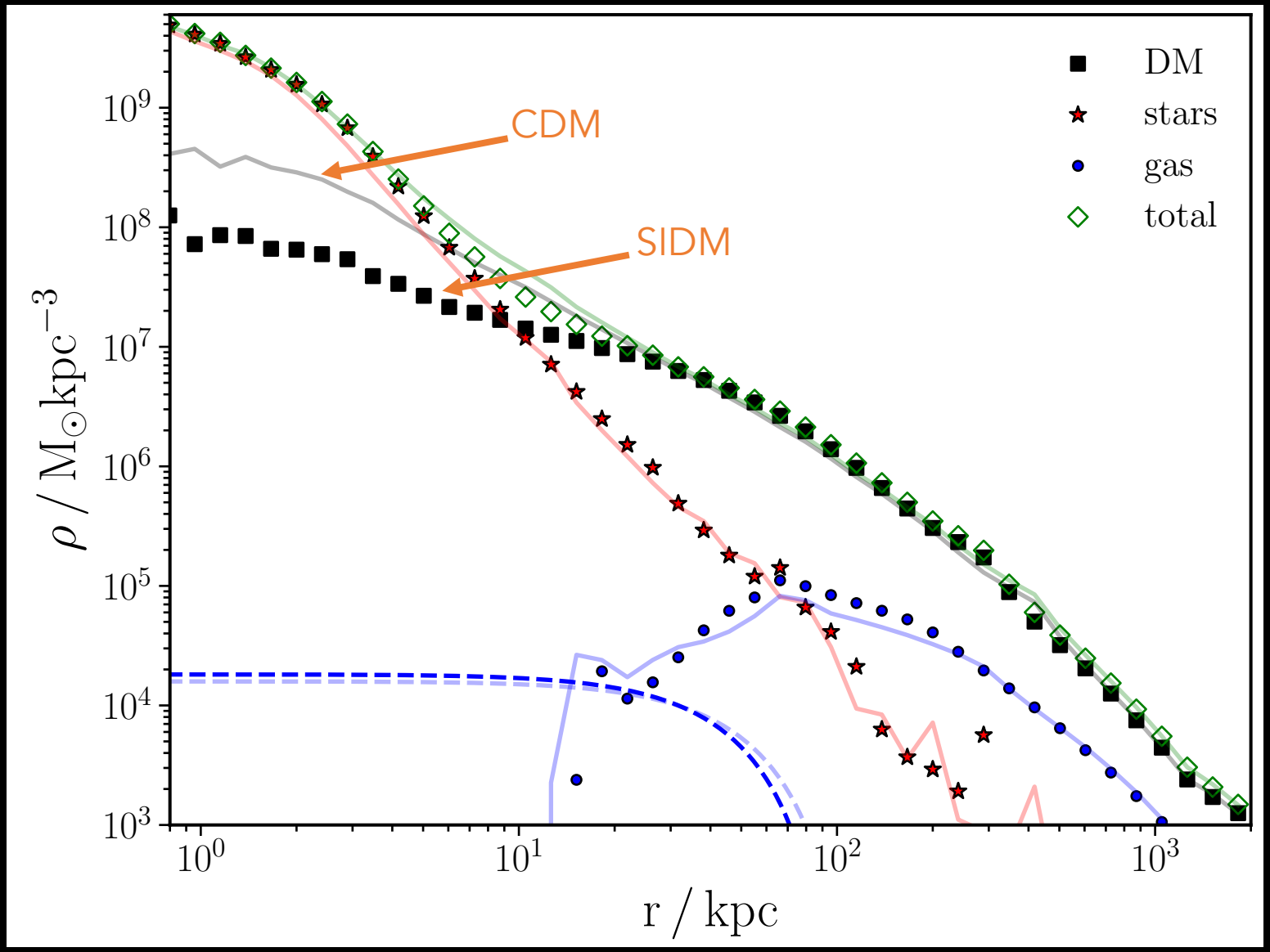
Barnes+ 2017



Gas particle mass: 1.8x10^6 $M_\odot$

The first simulated galaxy clusters with baryons plus SIDM

CE-05 DENSITY PROFILES



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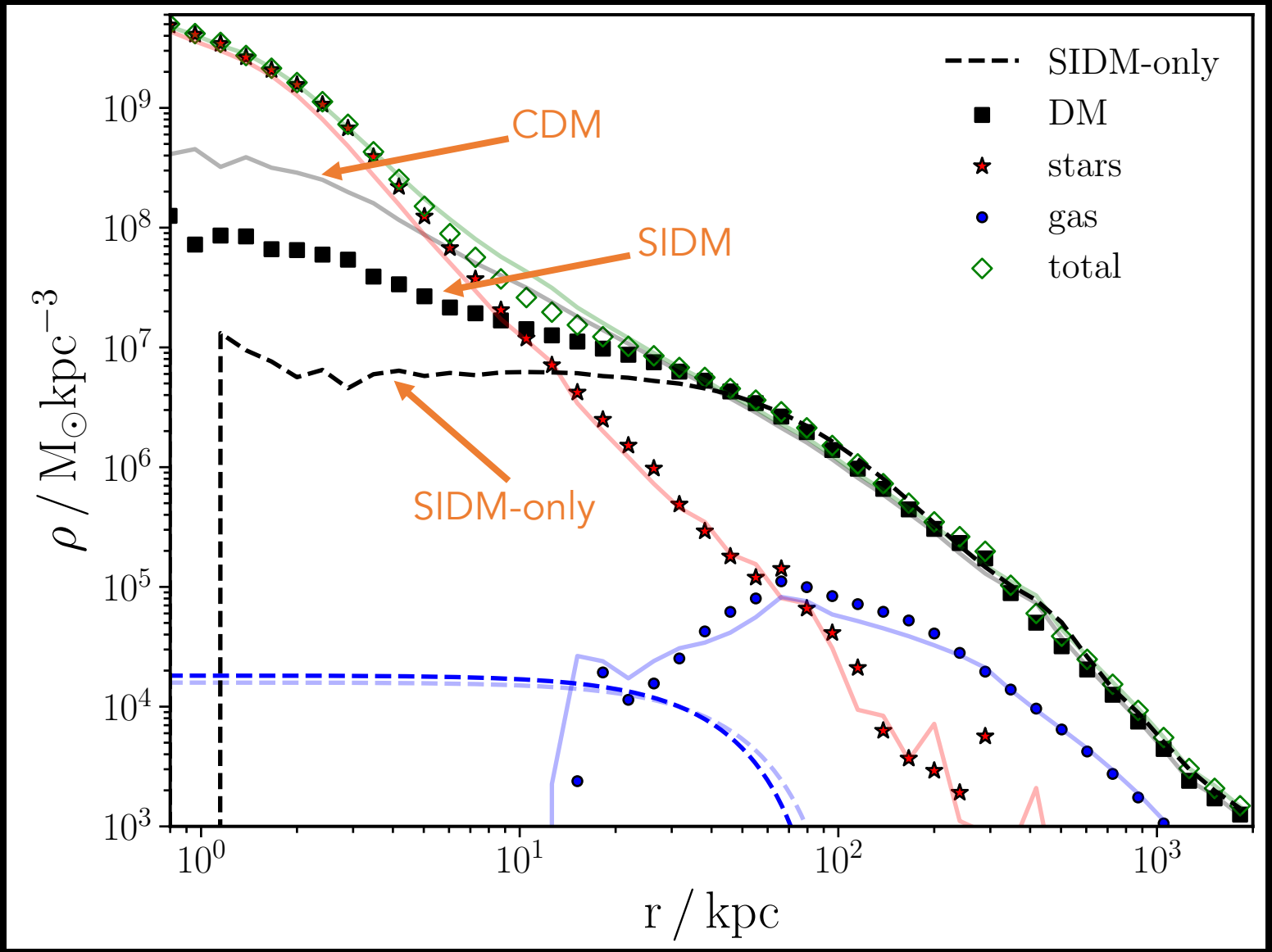
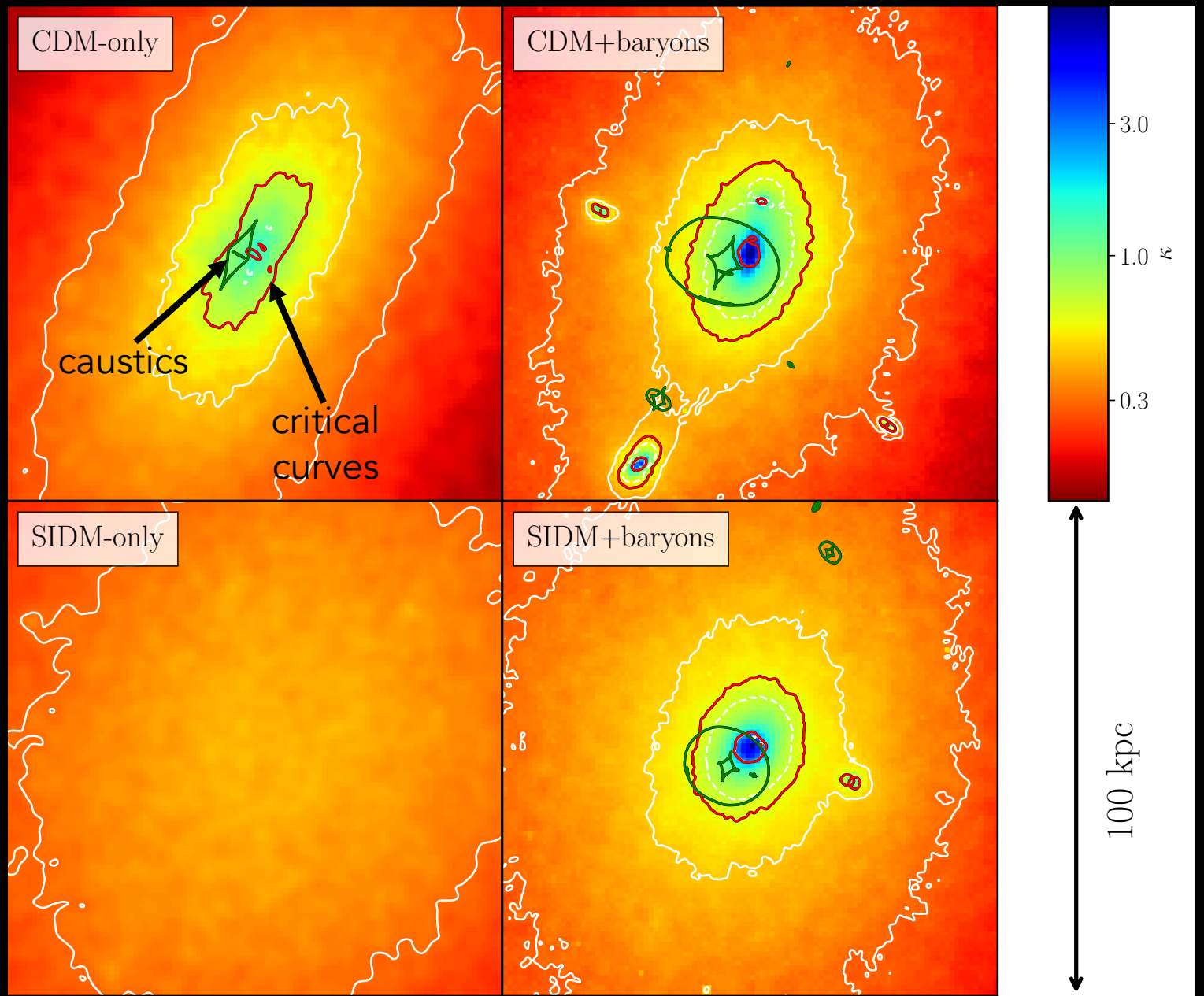


CE-05 LENSING



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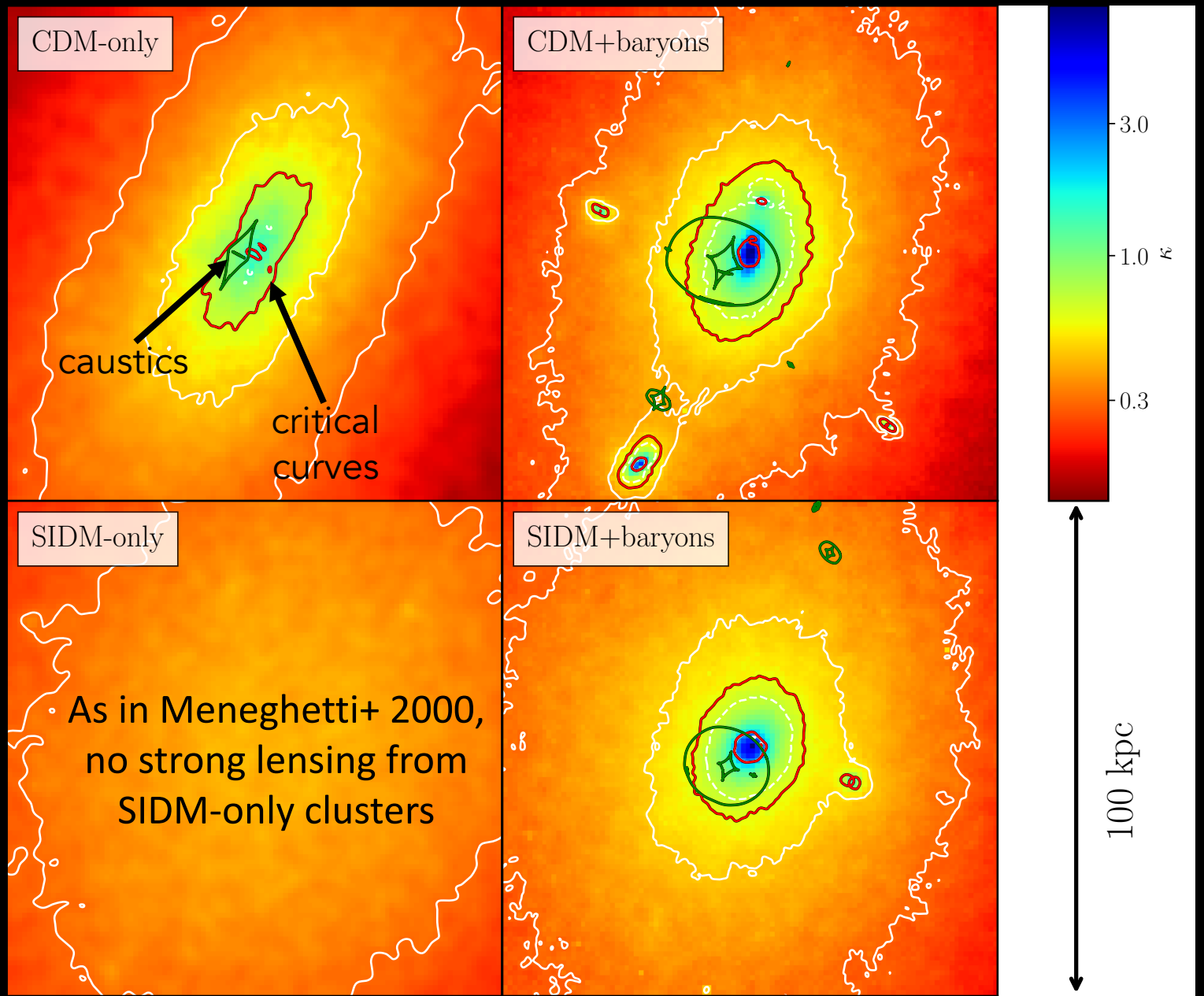
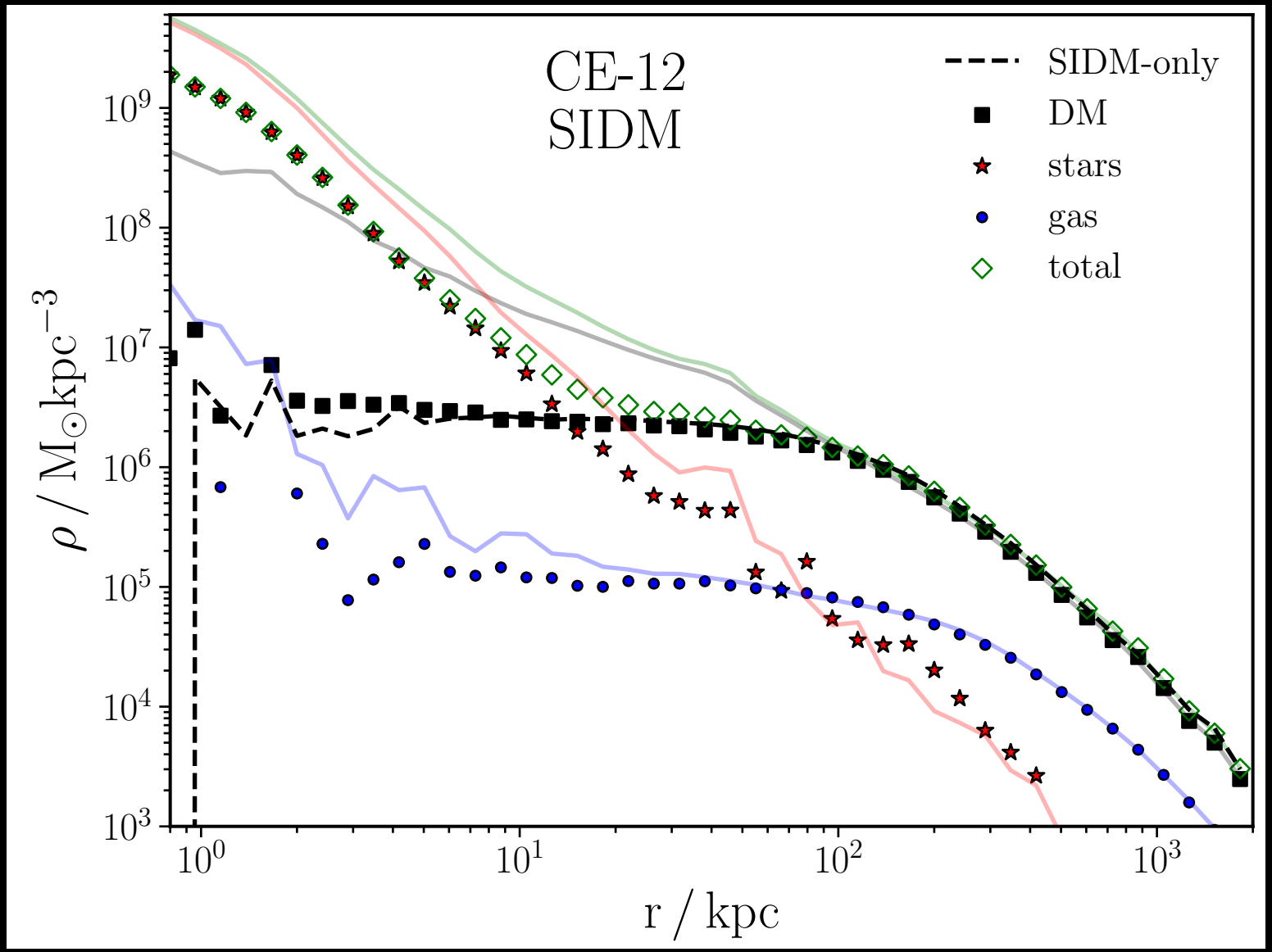
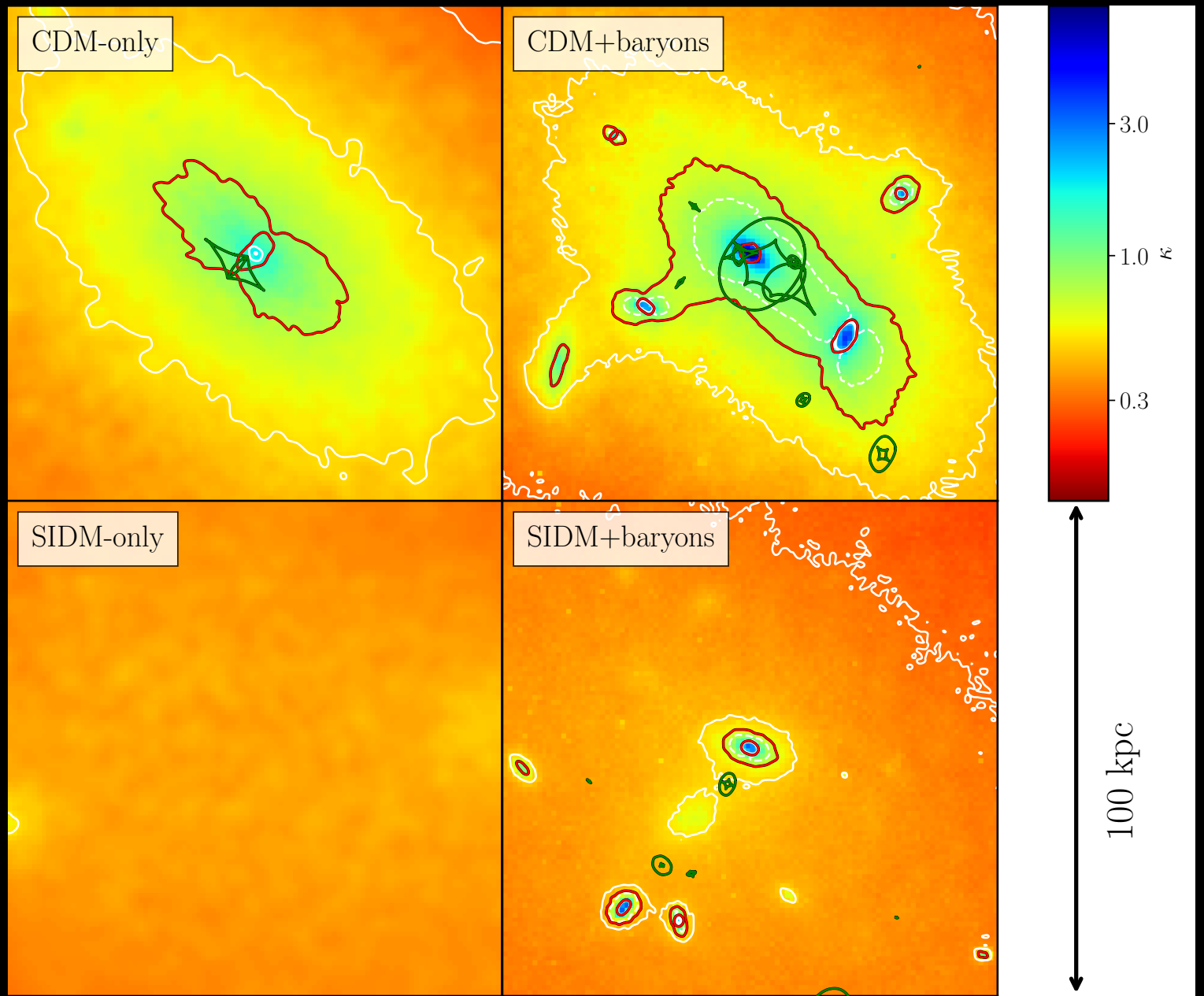


THE OTHER HALO: CE-12 DENSITY PROFILES

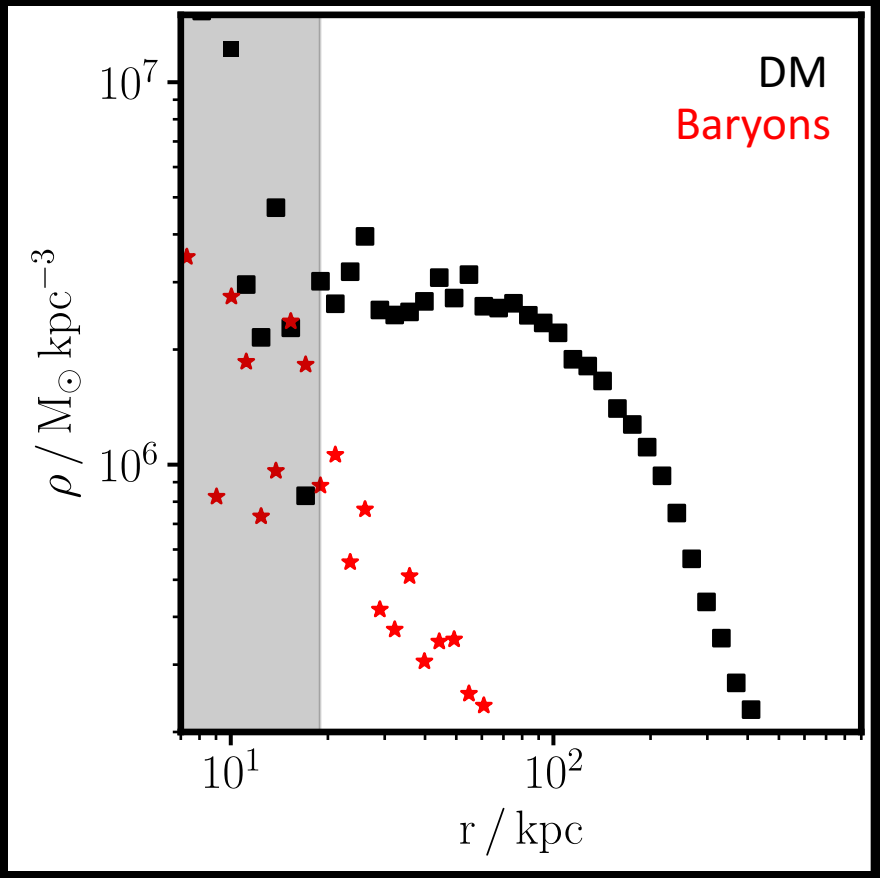


CE-12



WHY THE DIFFERENT BEHAVIOUR?

ISOTHERMAL JEANS MODELLING



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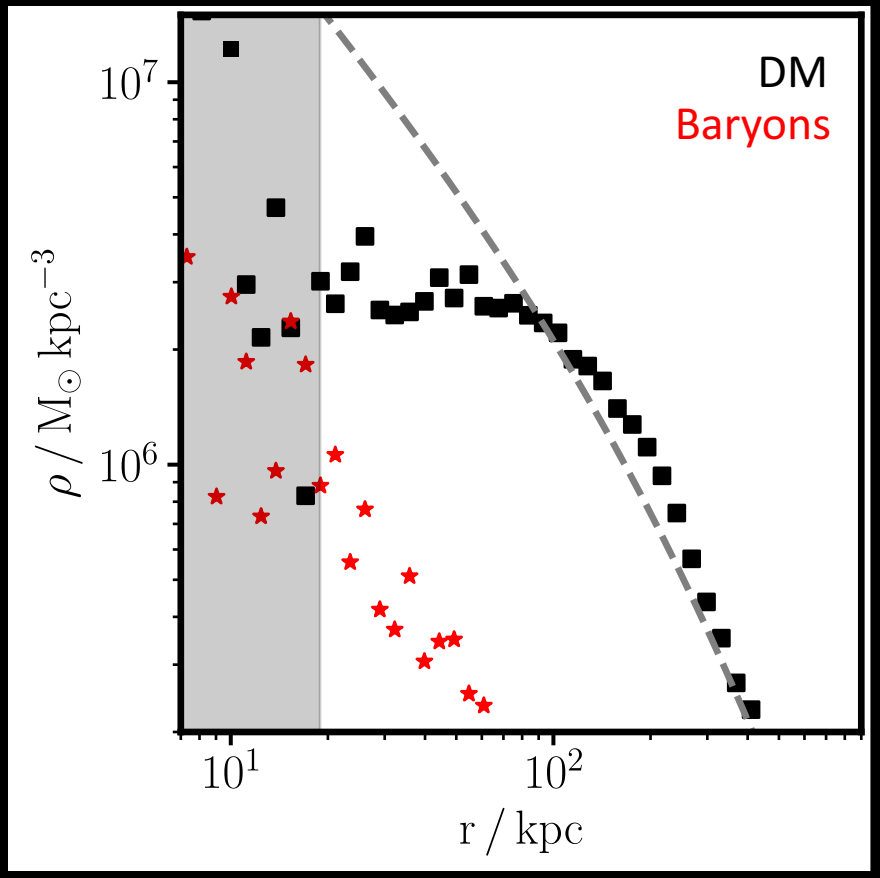
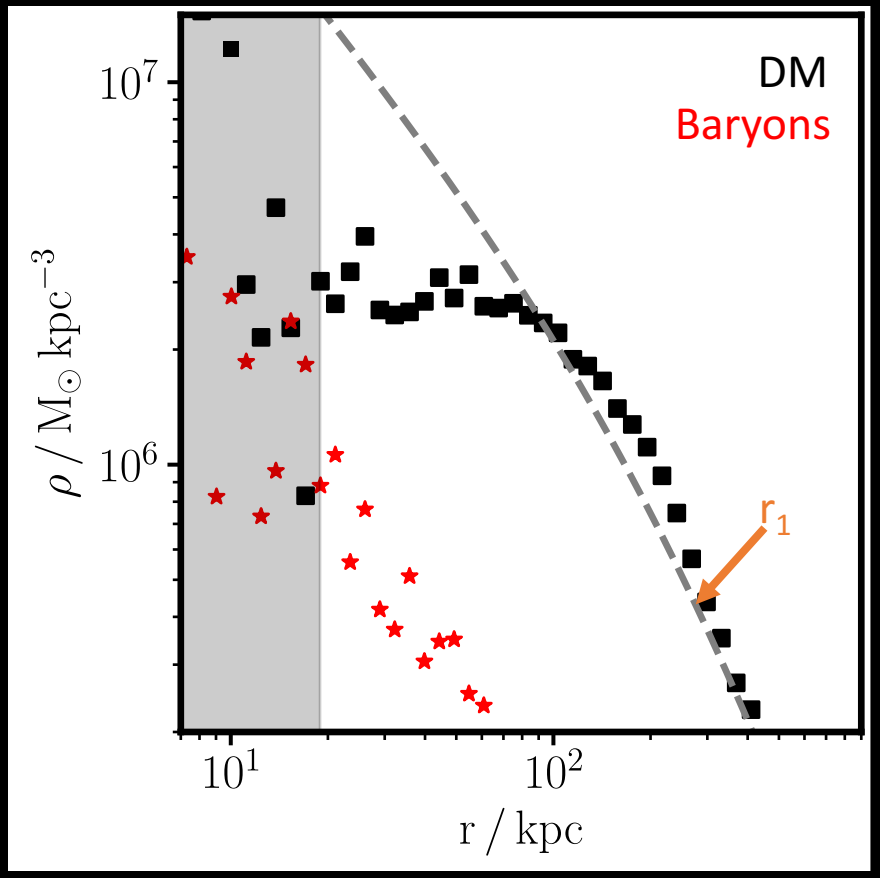


Start with some NFW profile

ISOTHERMAL JEANS MODELLING



Start with some NFW profile

For a given cross-section, find r_1, the radius at which particles have scattered once on average (in NFW)

$$\Gamma(r_1)t_{\rm age} = \rho(r_1)\ \langle v_{\rm rel}(r_1)\rangle\ \frac{\sigma}{m}\,t_{\rm age} = 1$$

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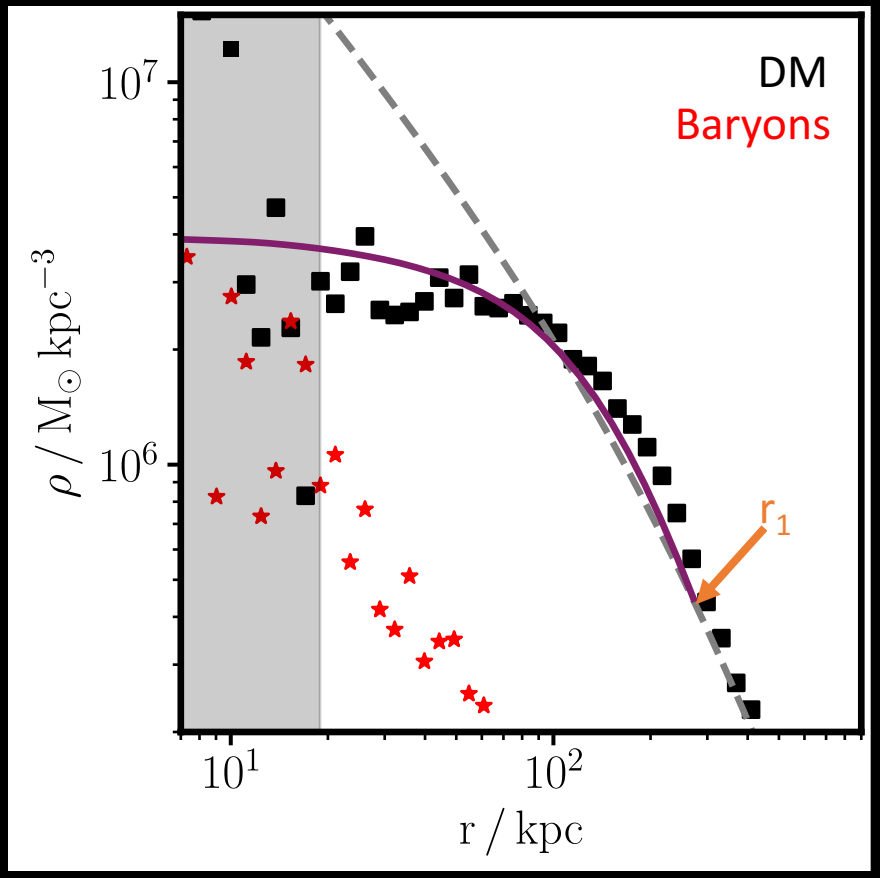

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$$\Gamma(r_1)t_{\rm age} = \rho(r_1)\ \langle v_{\rm rel}(r_1)\rangle\ \frac{\sigma}{m}\,t_{\rm age} = 1$$

Find DM temperature and central DM density, that produce a density profile that matches the density at, and mass enclosed within, r_1.

MODELLING SIDM AS AN ISOTHERMAL GAS

SIDM cross-section → r_1 – the radius at which SIDM particles would have scattered (on average) once each

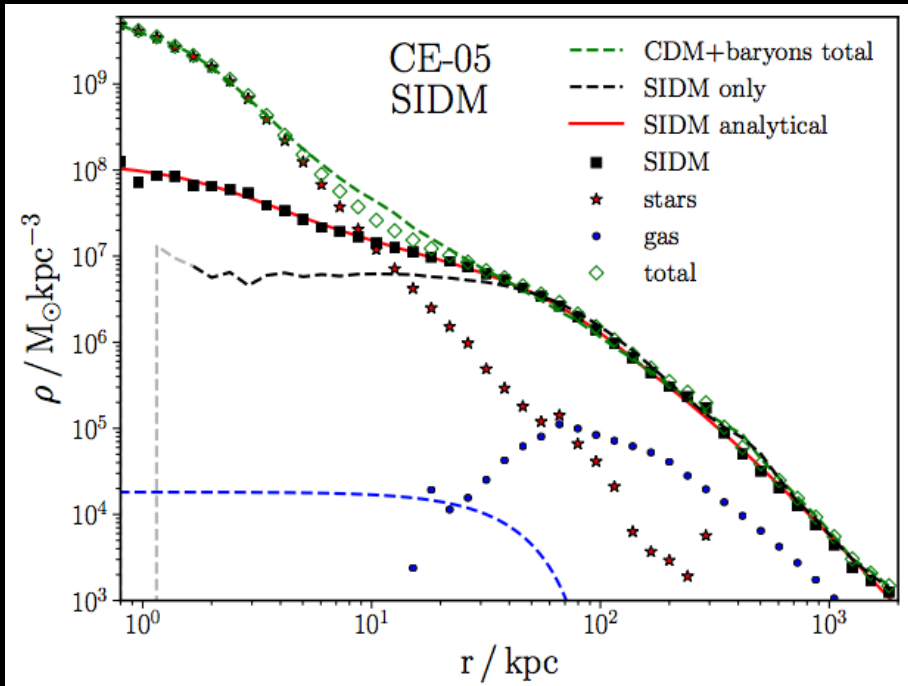
CDM-only M_{200} and c_{200} → $\rho_{SIDM}(r>r_1) = \rho_{CDM}(r>r_1)$

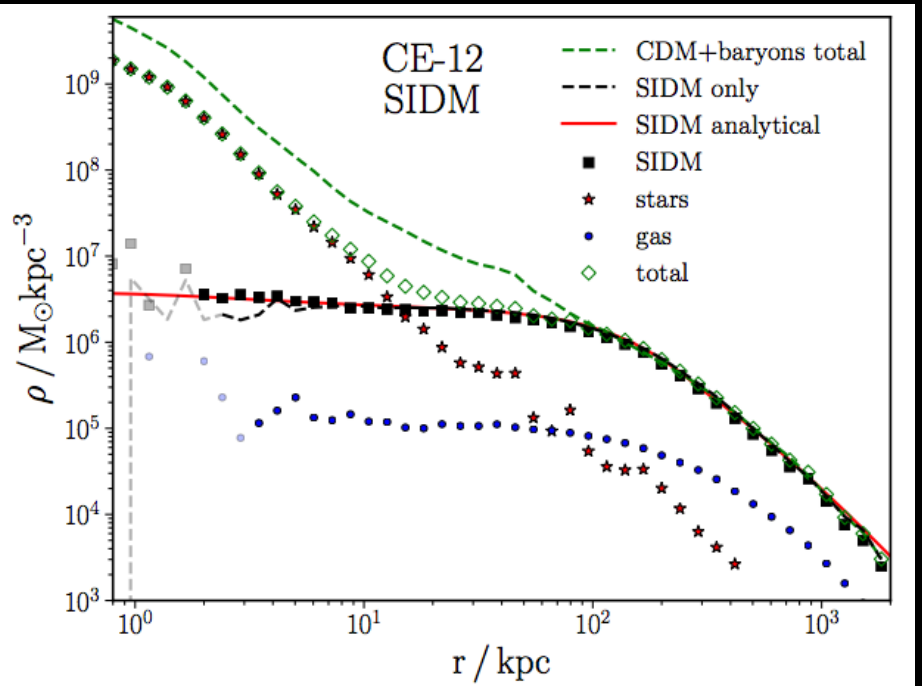
Inside of r_1 treat SIDM as an isothermal gas, and solve for hydrostatic equilibrium

$\rho_{SIDM}(r=r_1)$
$M_{SIDM}(<r_1)$

Iterate over SIDM central-density and temperature, using matching conditions at r_1

SIDM+baryons $\rho_{bar}(r)$ → $\rho_{SIDM}(r<r_1)$ ← $\rho_{SIDM}(r=0)$, T_{SIDM}





MODELLING SIDM AS AN ISOTHERMAL GAS

Total gravitational potential

Density of an isothermal species: $\rho(\mathbf{x}) = \rho_0 \exp\left(\frac{\Phi(0) - \Phi(\mathbf{x})}{\sigma_0^2}\right)$

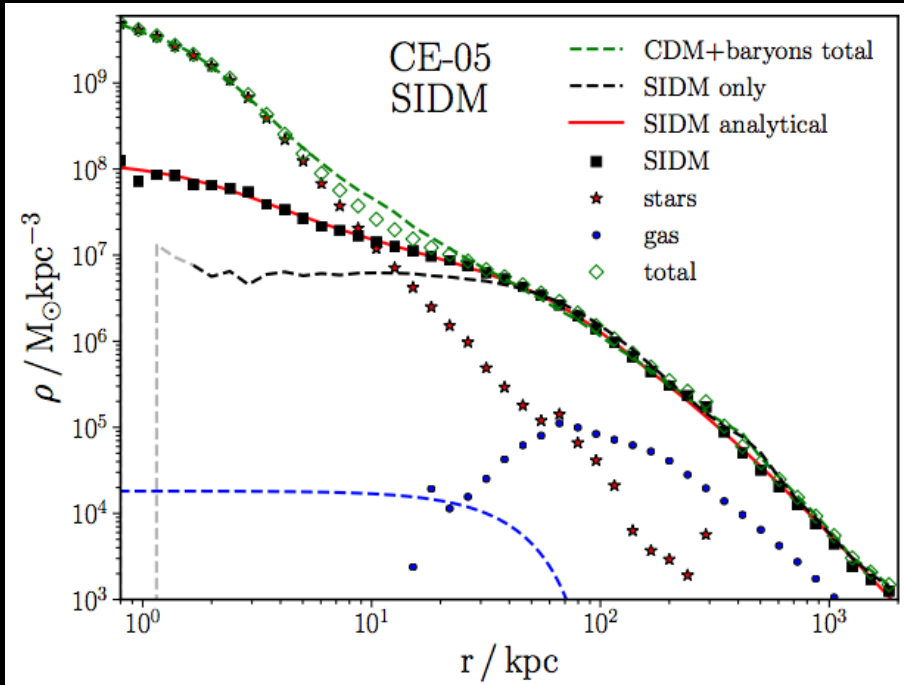
SIDM 'temperature'

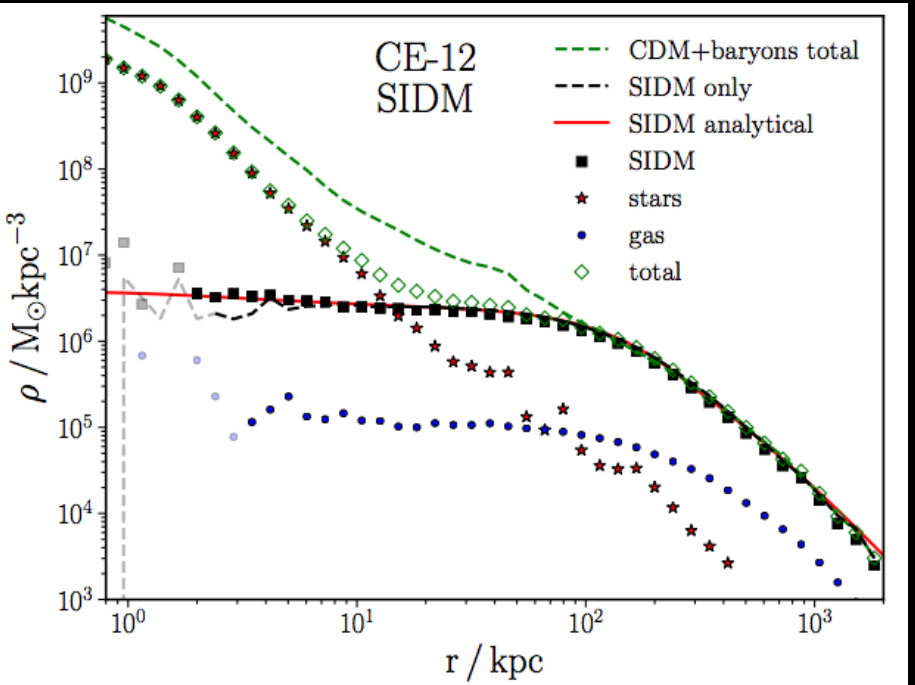
$v_{\rm max} = 848\,{\rm km\,s^{-1}}$

$\sqrt{|\Phi_{\rm B}(0)|} = 1050\,{\rm km\,s^{-1}}$

$v_{\rm max} = 1107\,{\rm km\,s^{-1}}$

$\sqrt{|\Phi_{\rm B}(0)|} = 800\,{\rm km\,s^{-1}}$

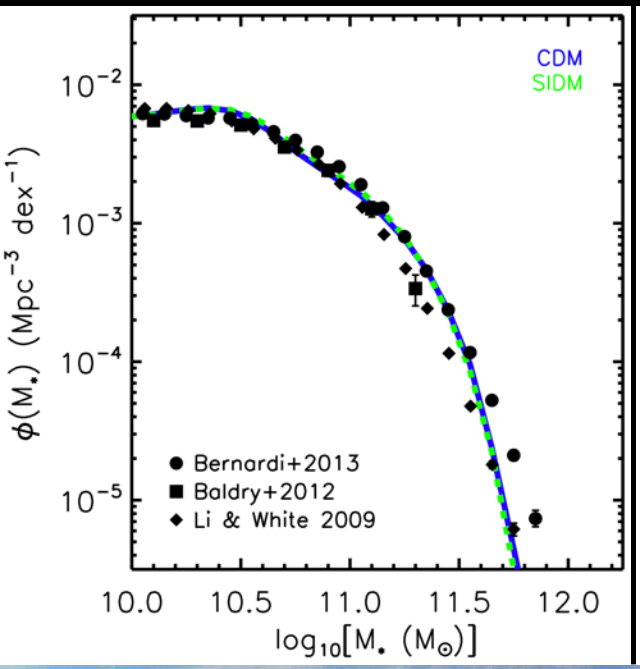


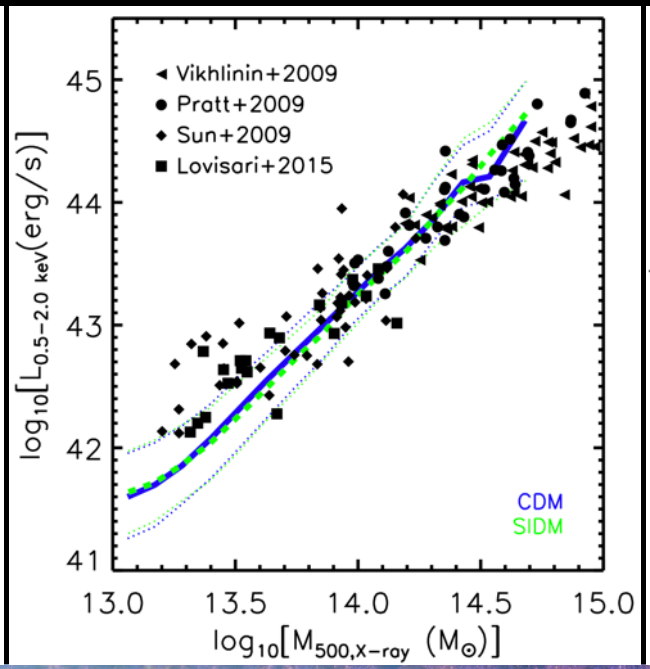


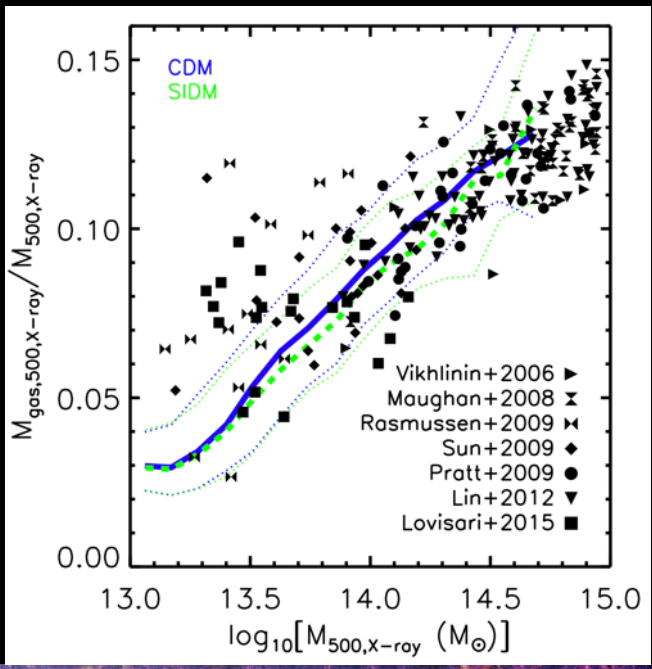
BAHAMAS – A LARGER SAMPLE OF GALAXY CLUSTERS SIMULATED WITH SIDM+BARYONS

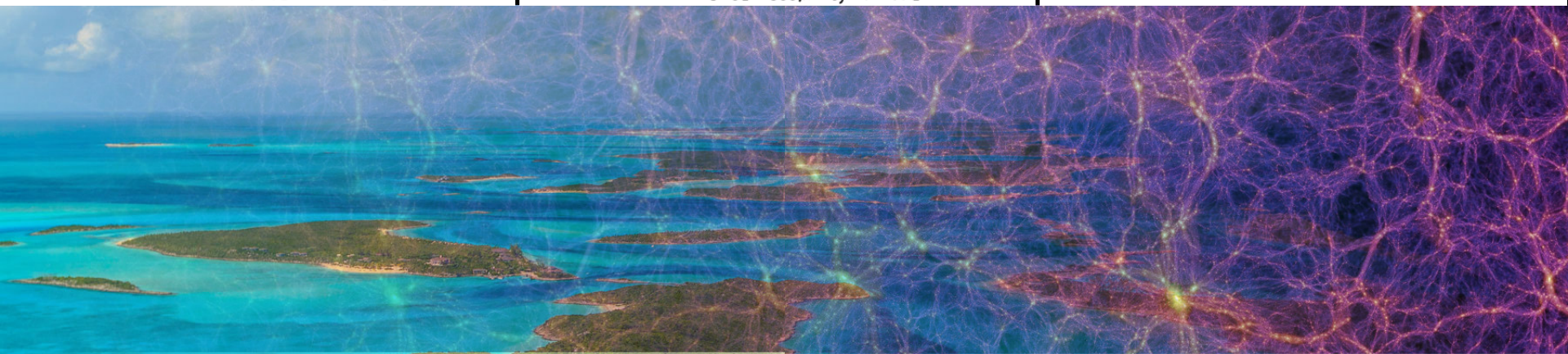
BAHAMAS

- 400 Mpc/h boxsize
- gas particle mass of $\sim 10^9 \mathrm{M}_\odot$
- Calibrated to match the galaxy stellar mass function and gas properties of clusters





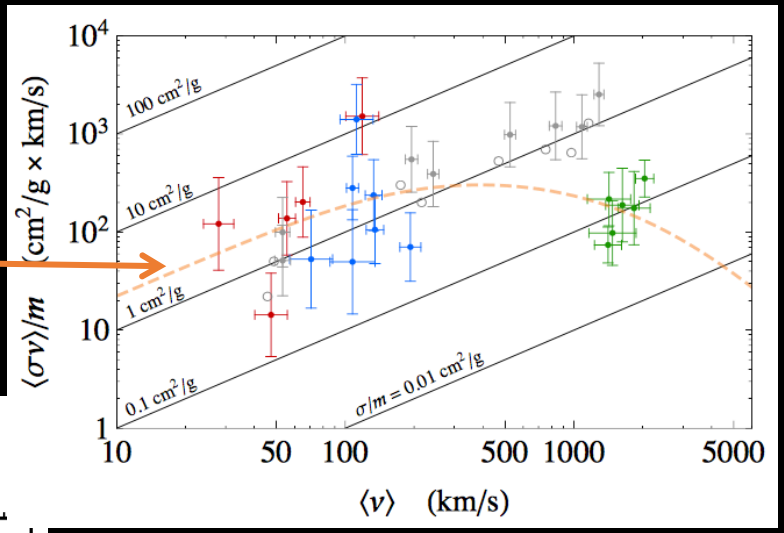




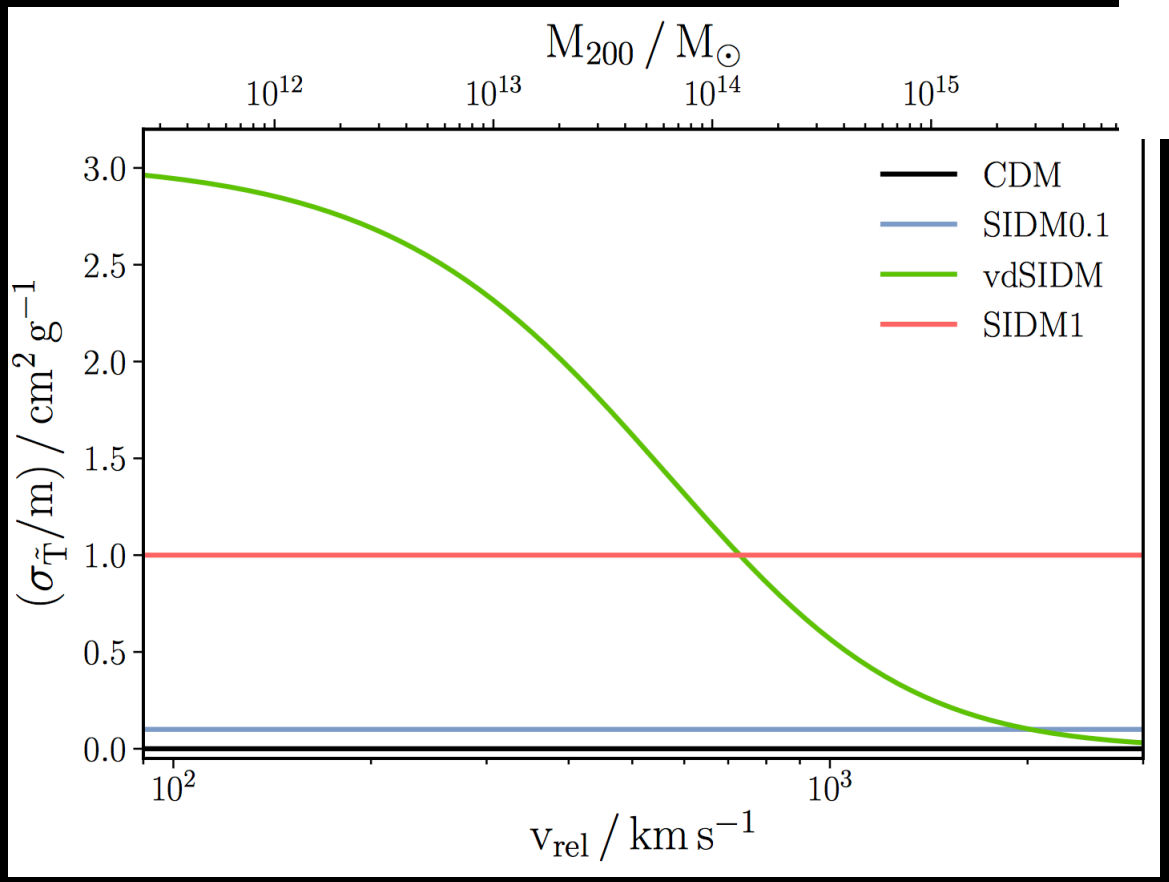
SIMULATED CROSS-SECTIONS

SIDM cross-sections:

- 1 cm^2/g
- 0.1 cm^2/g
- ~ dark photon model from Kaplinghat+2016

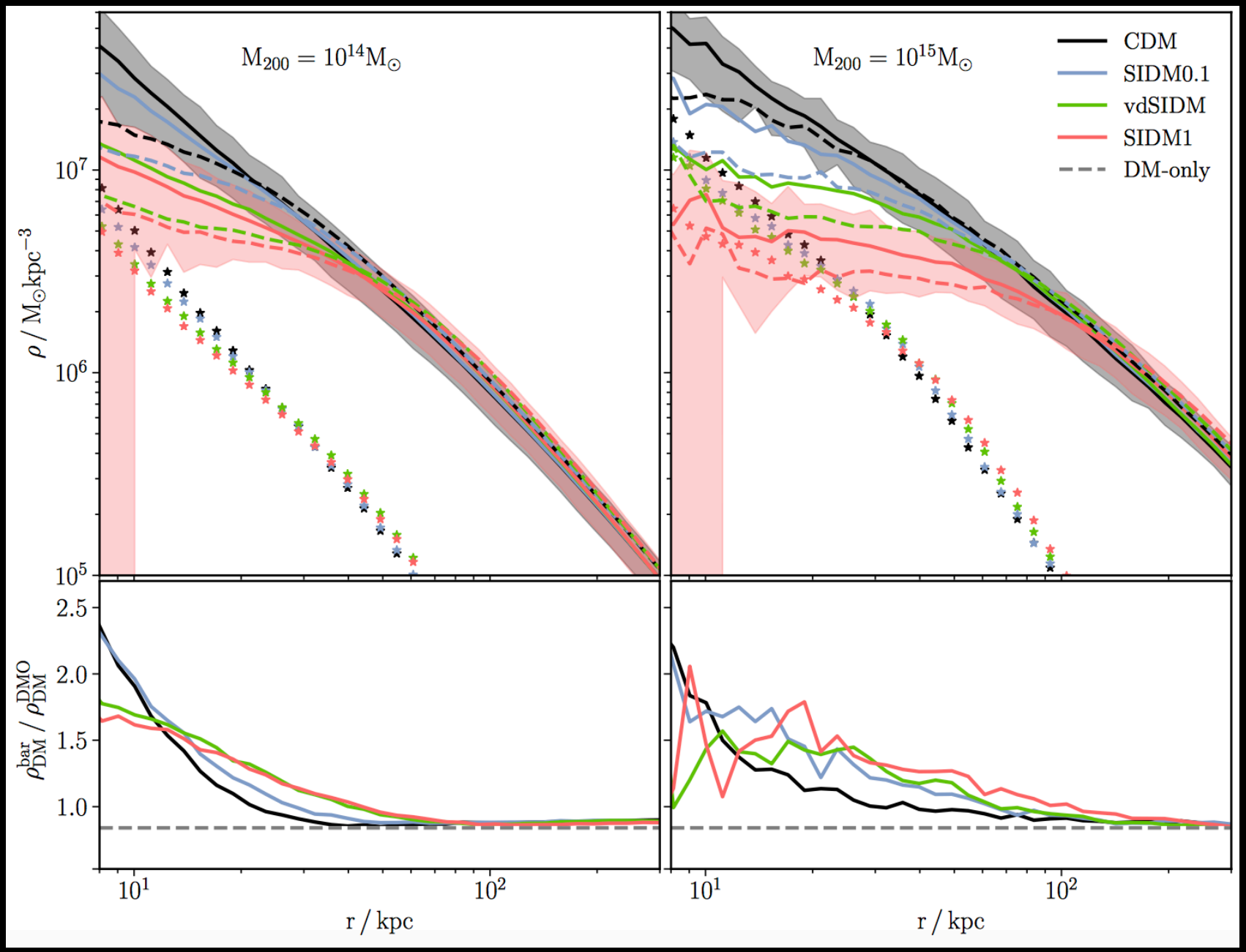


Kaplinghat+ 2016

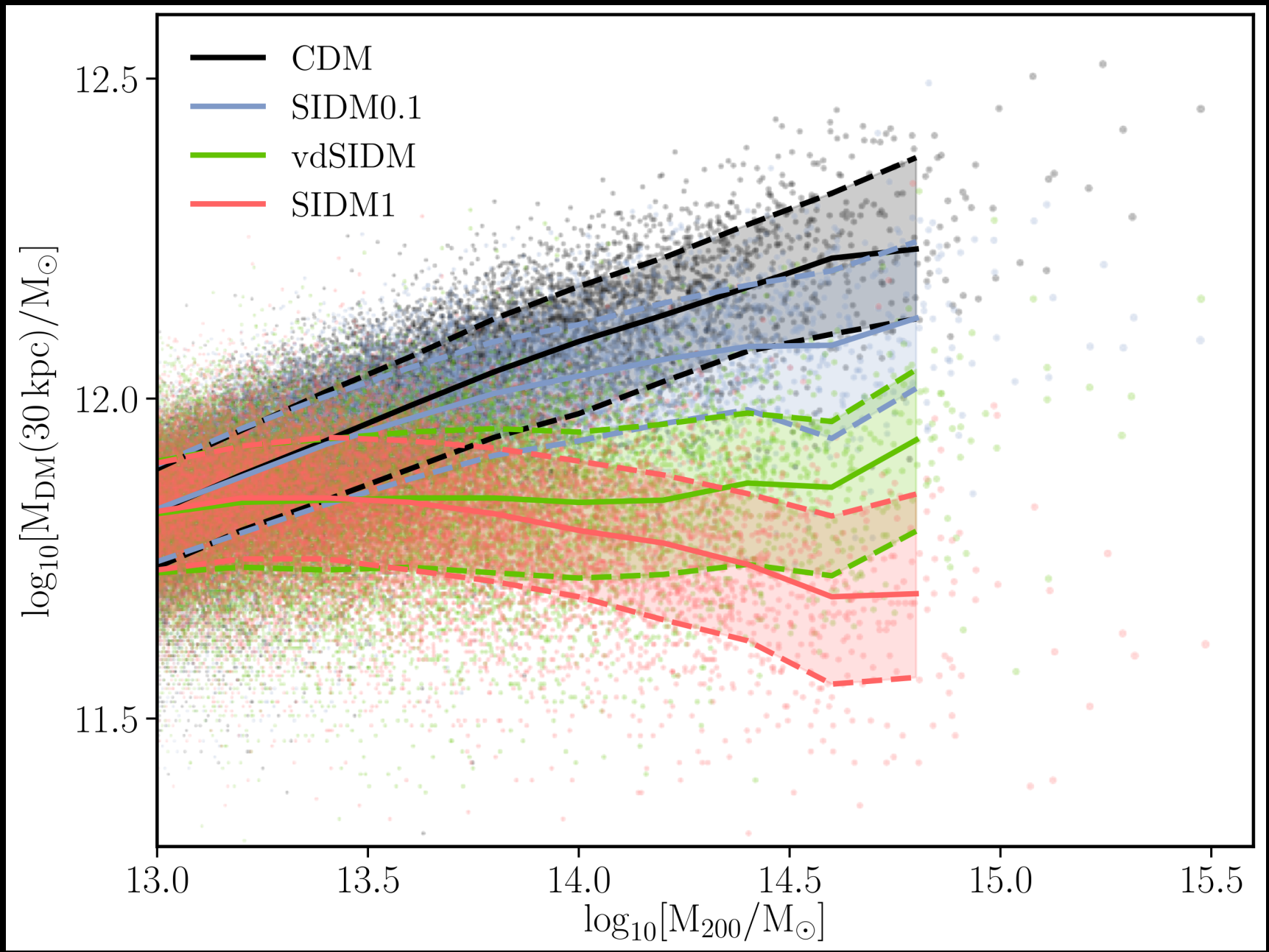


$$v = \sqrt{\frac{G\,M_{200}}{r_{200}}}$$

BAHAMAS-SIDM DENSITY PROFILES



NO OBVIOUS INCREASE IN DIVERSITY WITH SIDM



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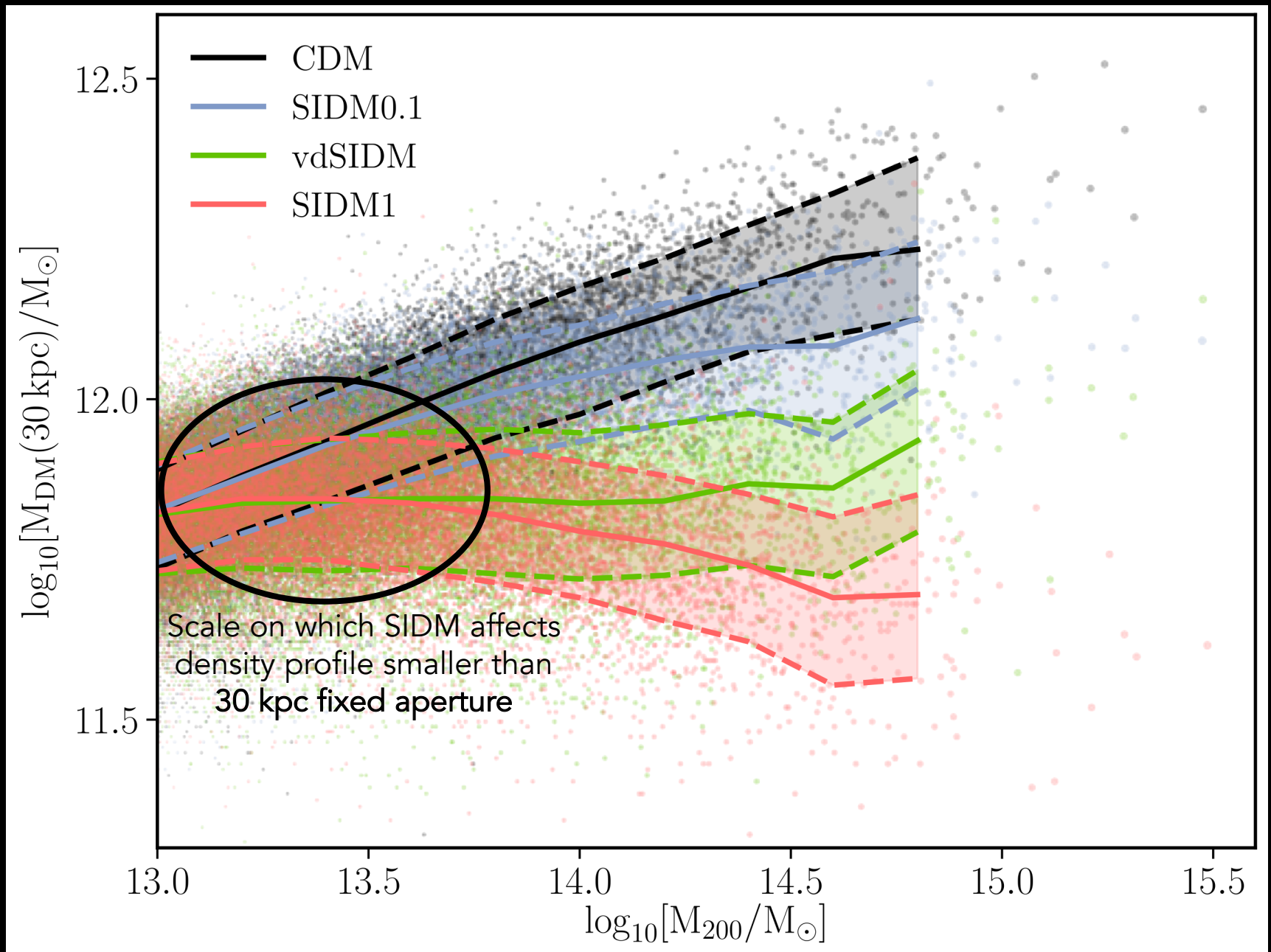

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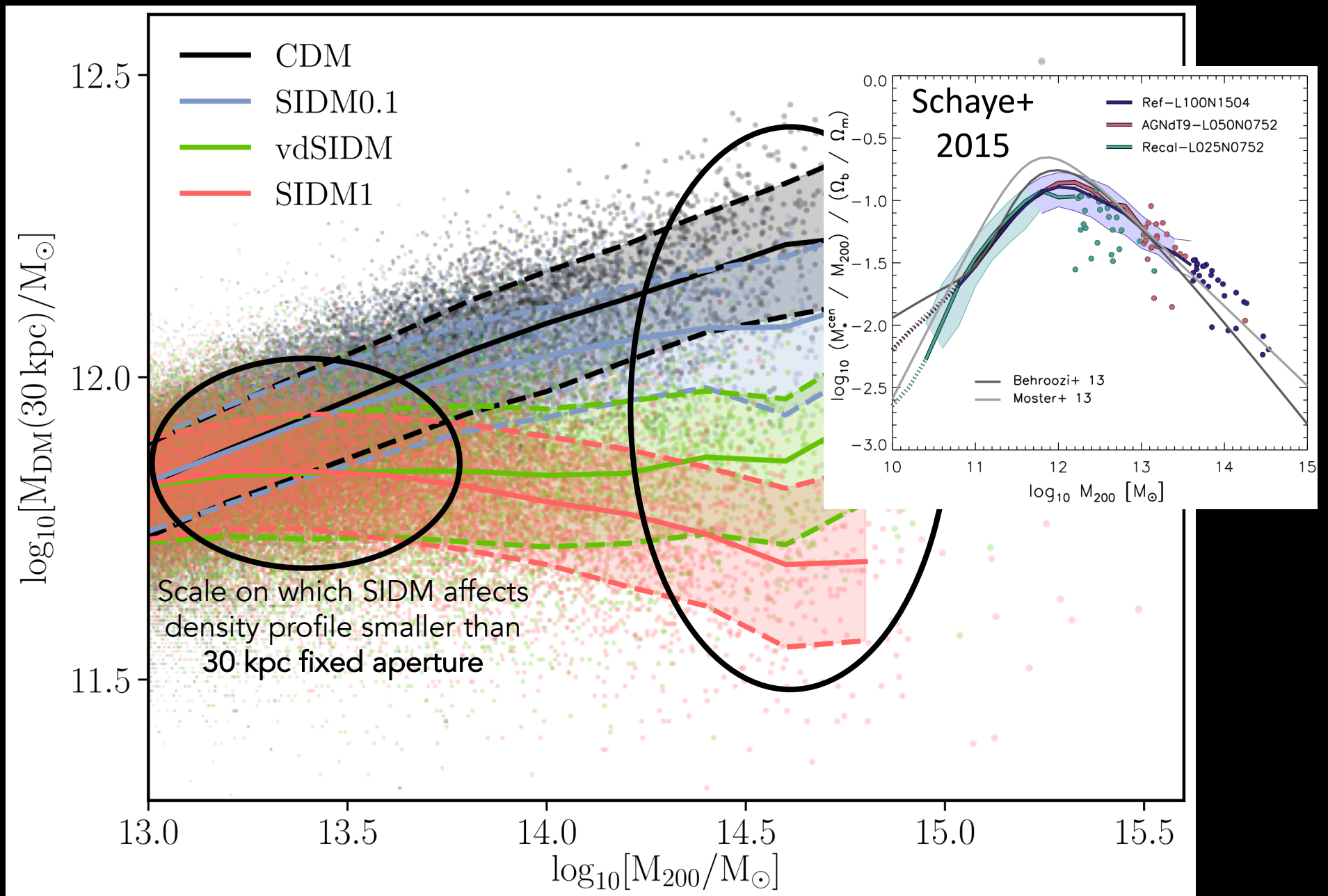
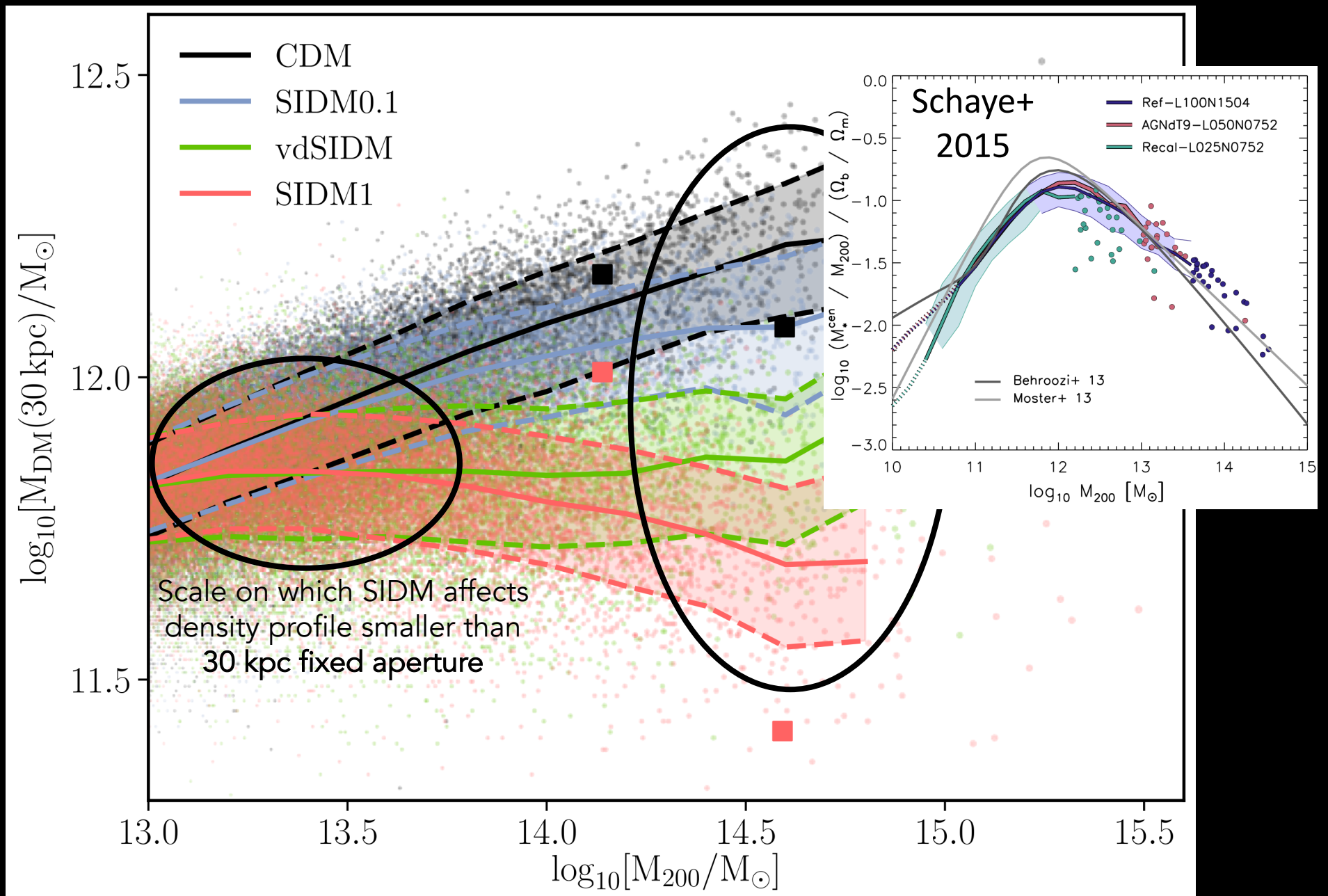
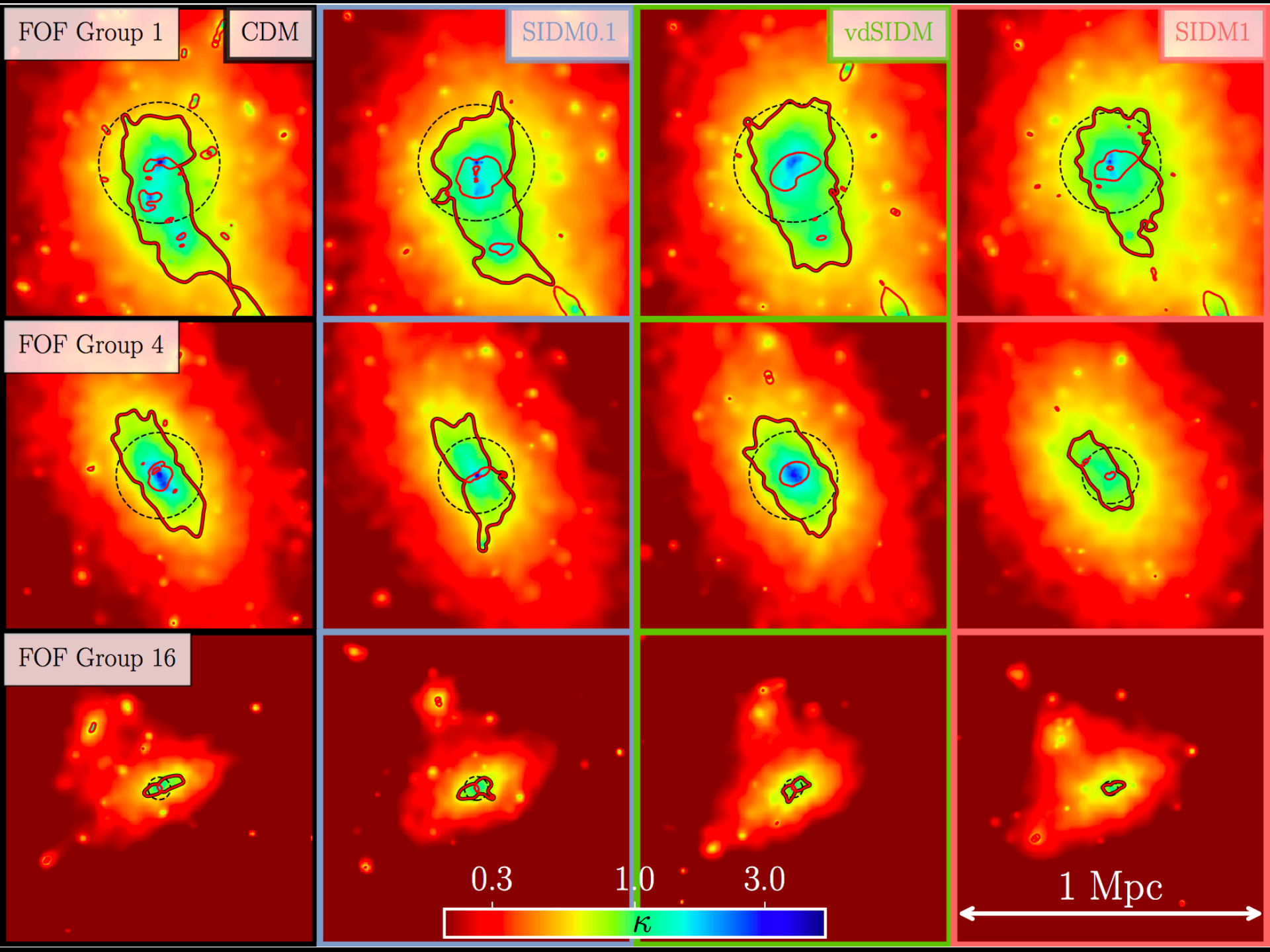
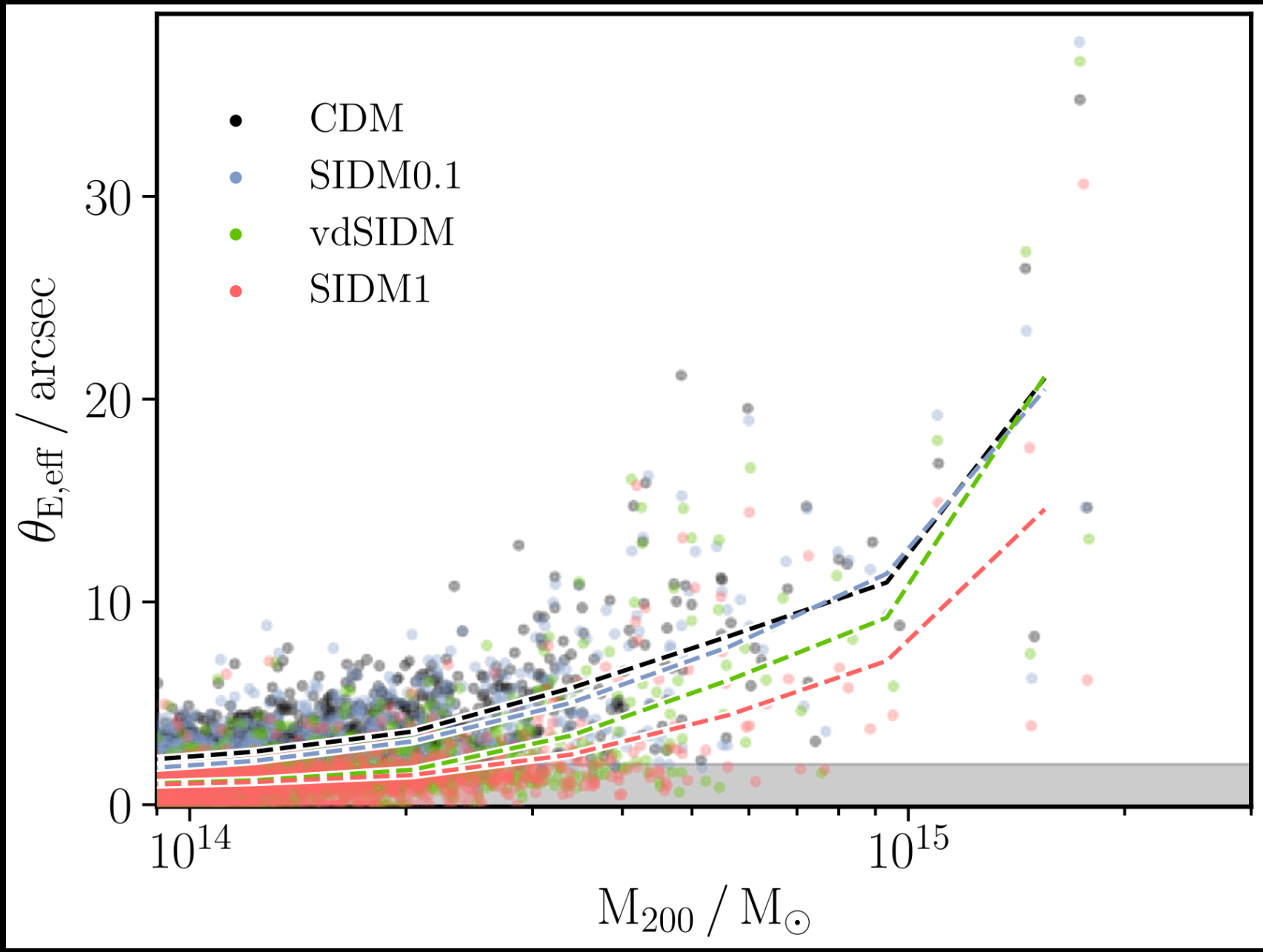


WHAT WAS GOING ON WITH THE 2 ZOOMS?

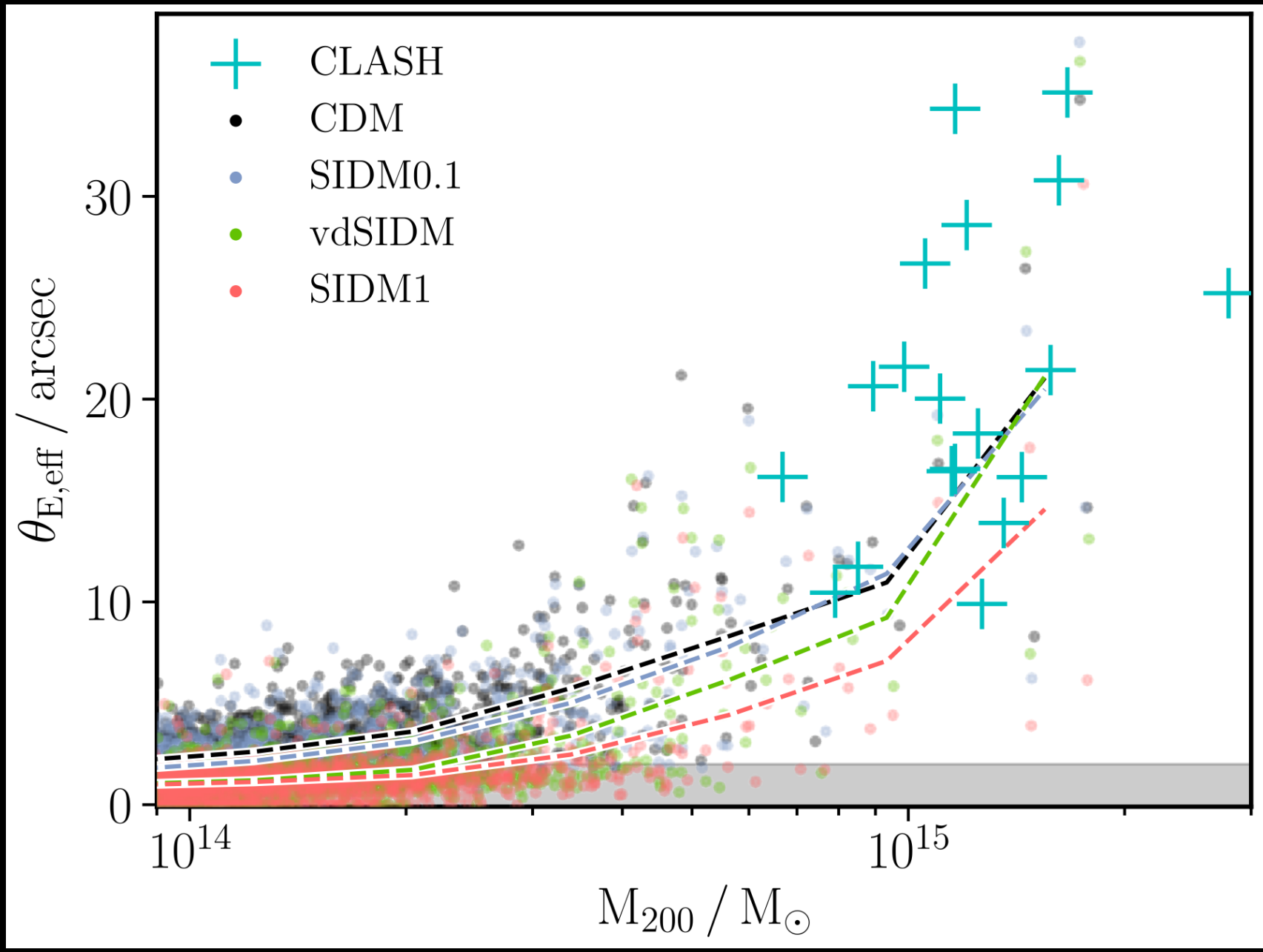



FOF Group 1
CDM
SIDM0.1
vdSIDM
SIDM1
FOF Group 4
FOF Group 16
0.3
1.0
3.0
κ
1 Mpc

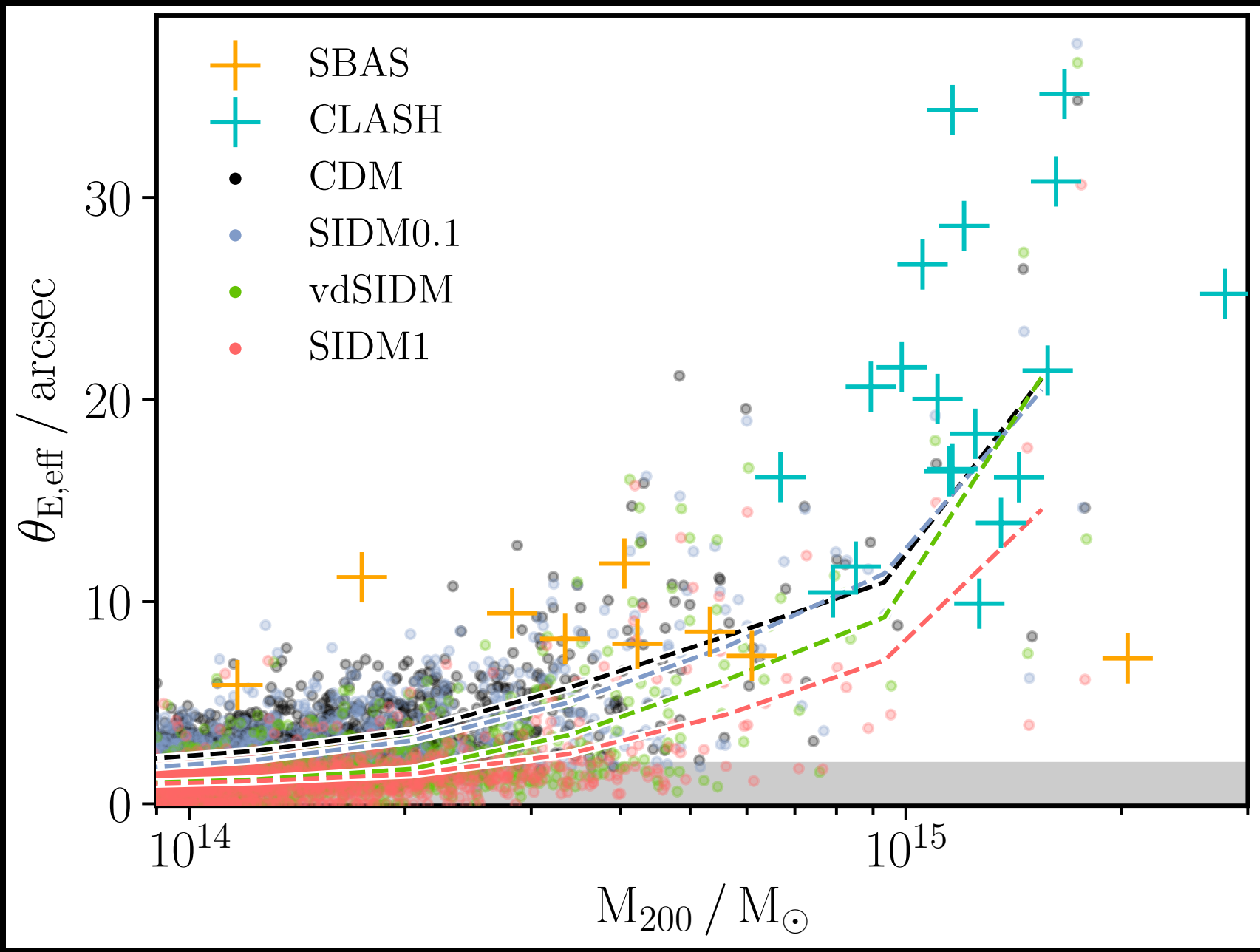
BAHAMAS-SIDM EINSTEIN RADII



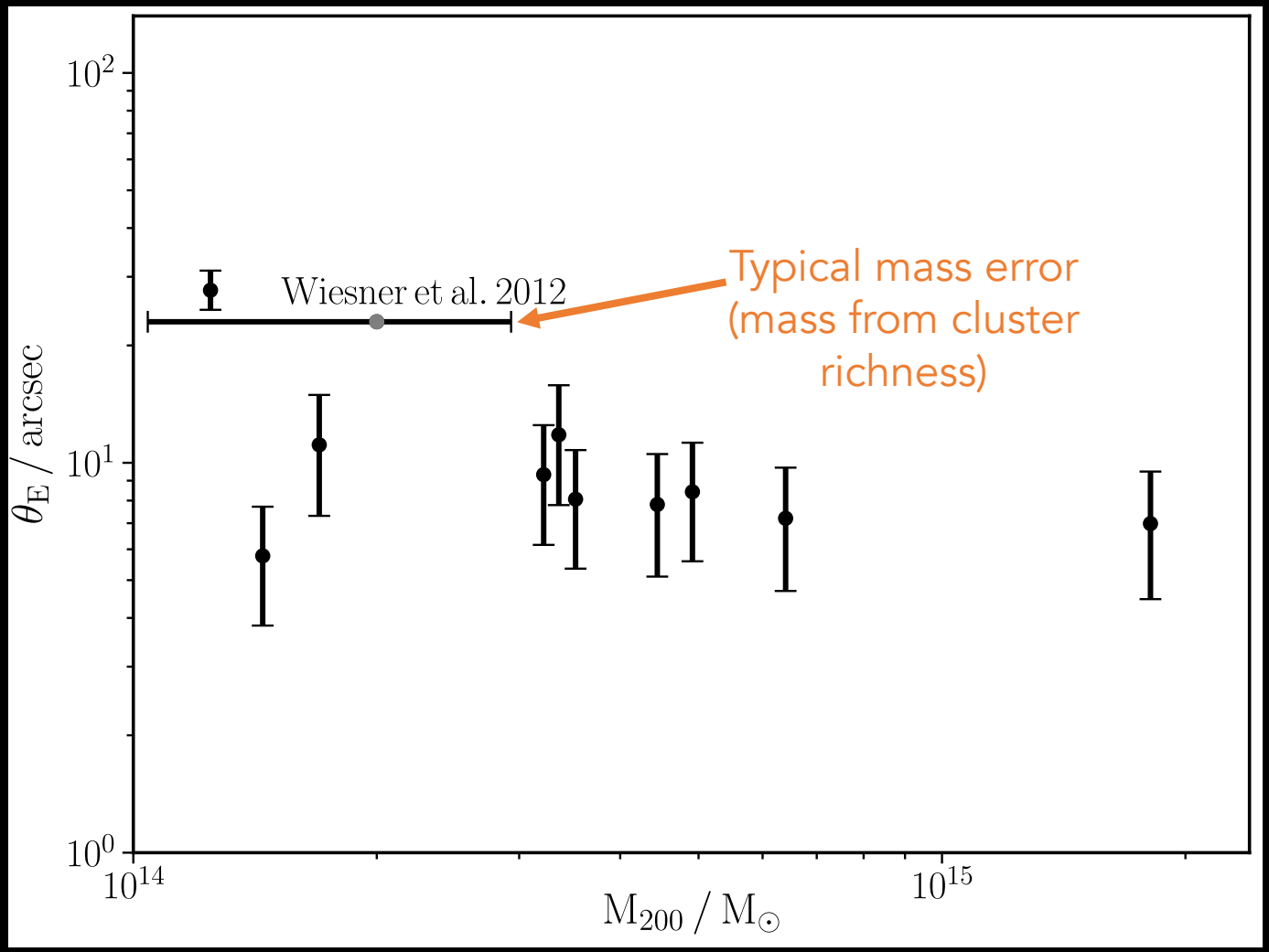
BAHAMAS-SIDM EINSTEIN RADII

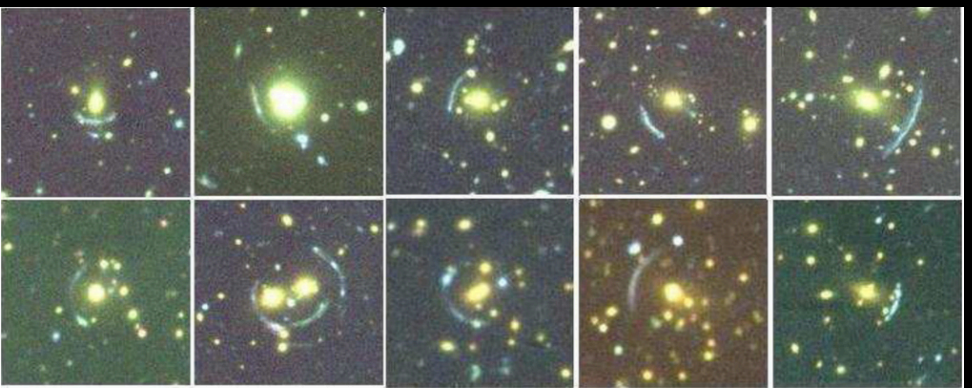


BAHAMAS-SIDM EINSTEIN RADII



FORGETTING ABOUT SIDM FOR A SECOND…





The Sloan Bright Arcs Survey
- Found 19 spectroscopically verified strong lensing systems in SDSS
- Obtained deeper follow-up data for 10 of these 19 systems

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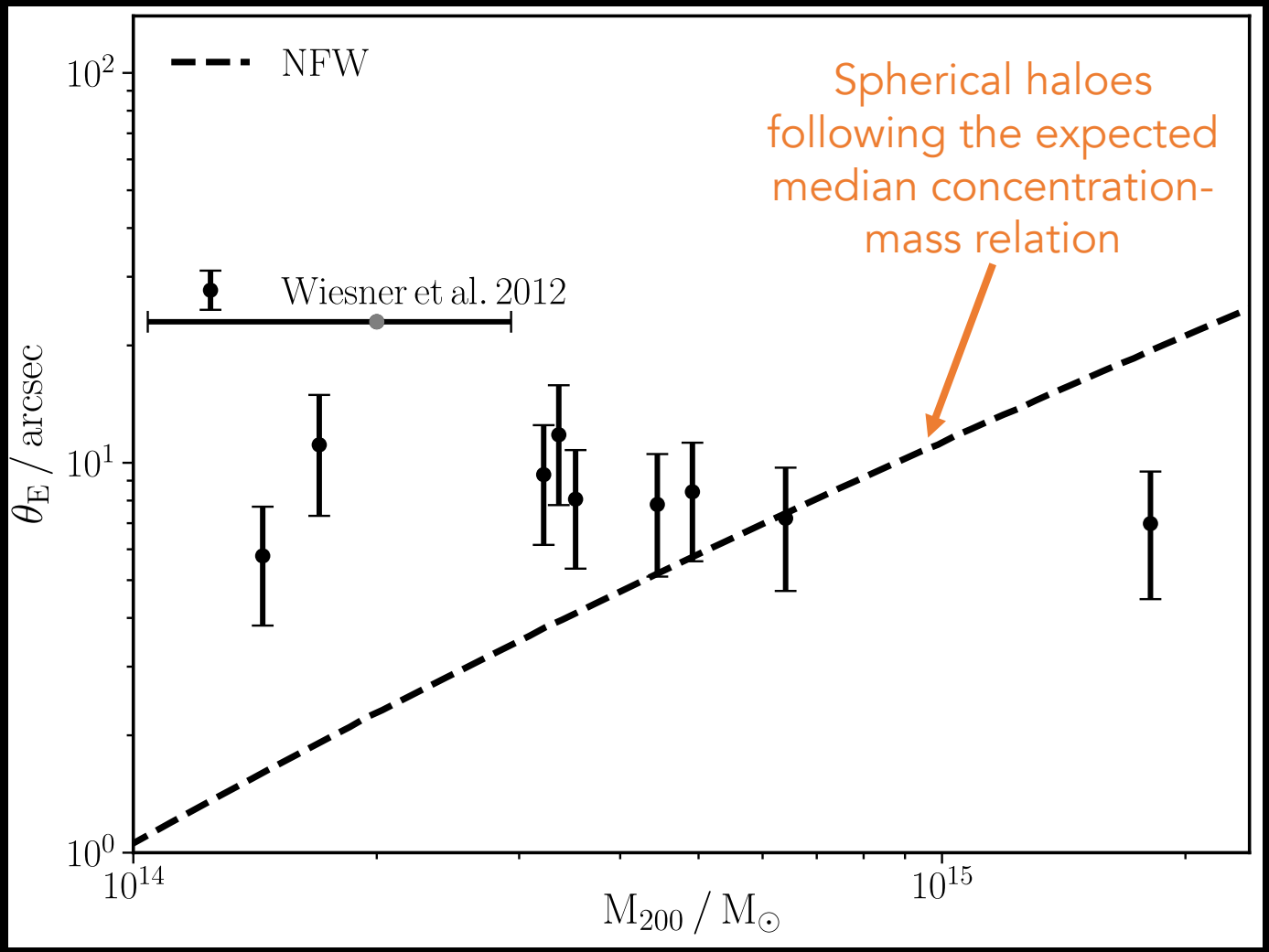

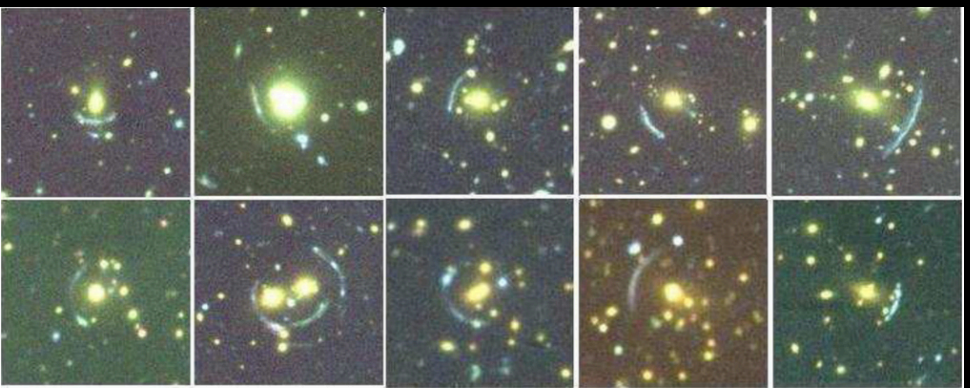

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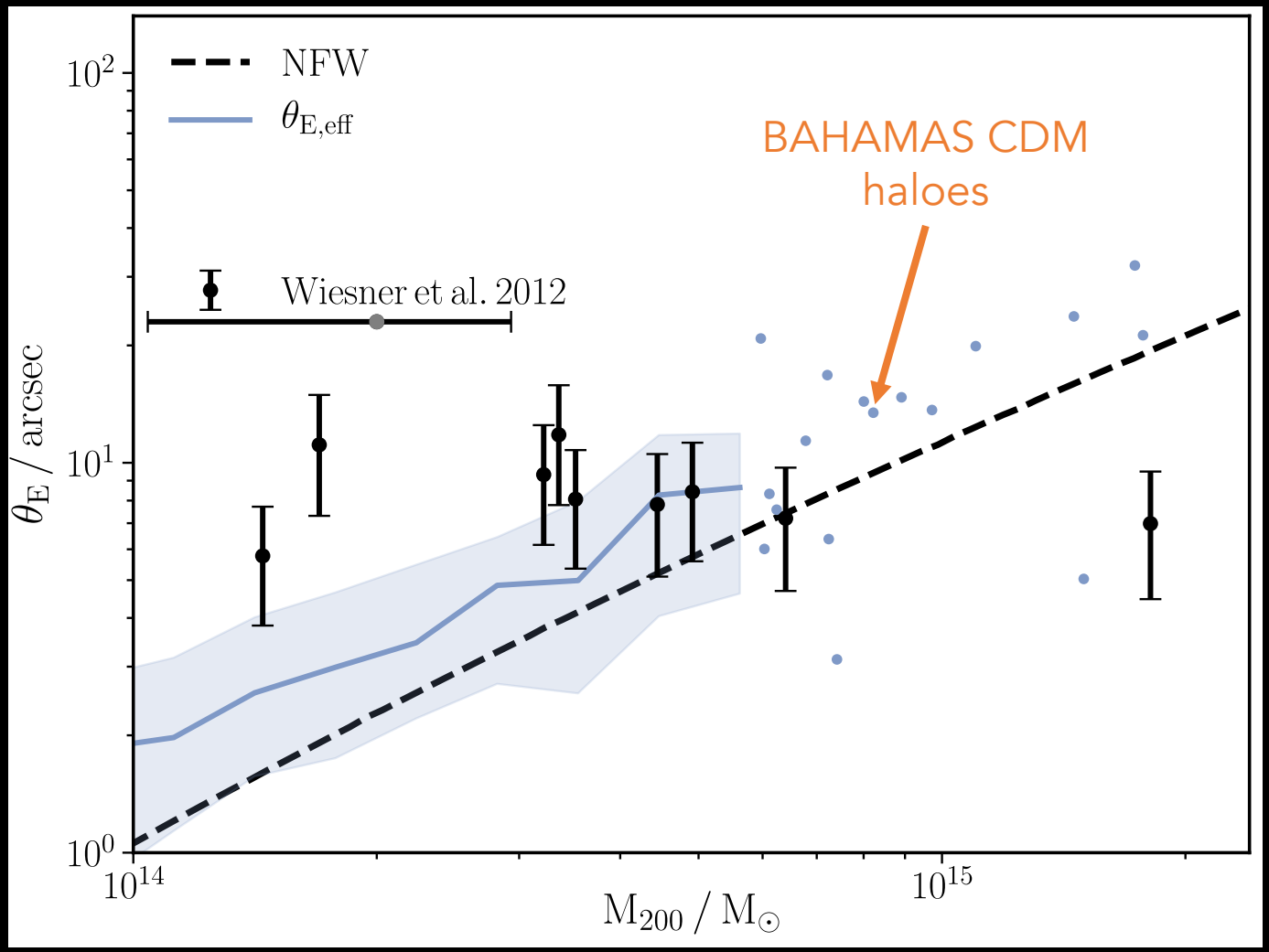

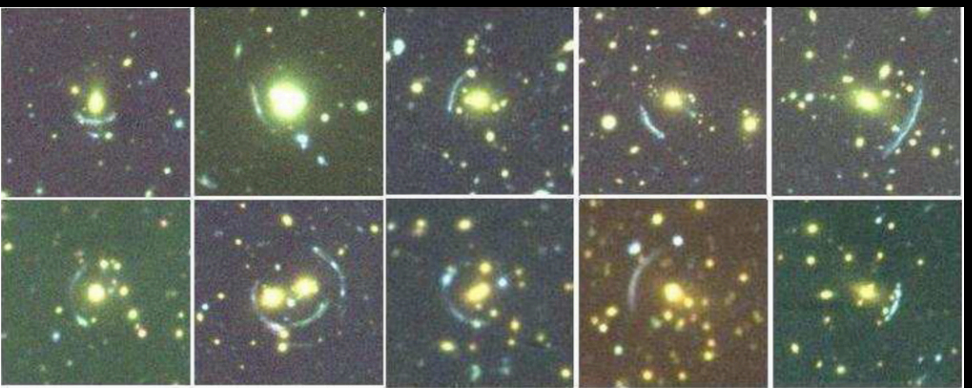

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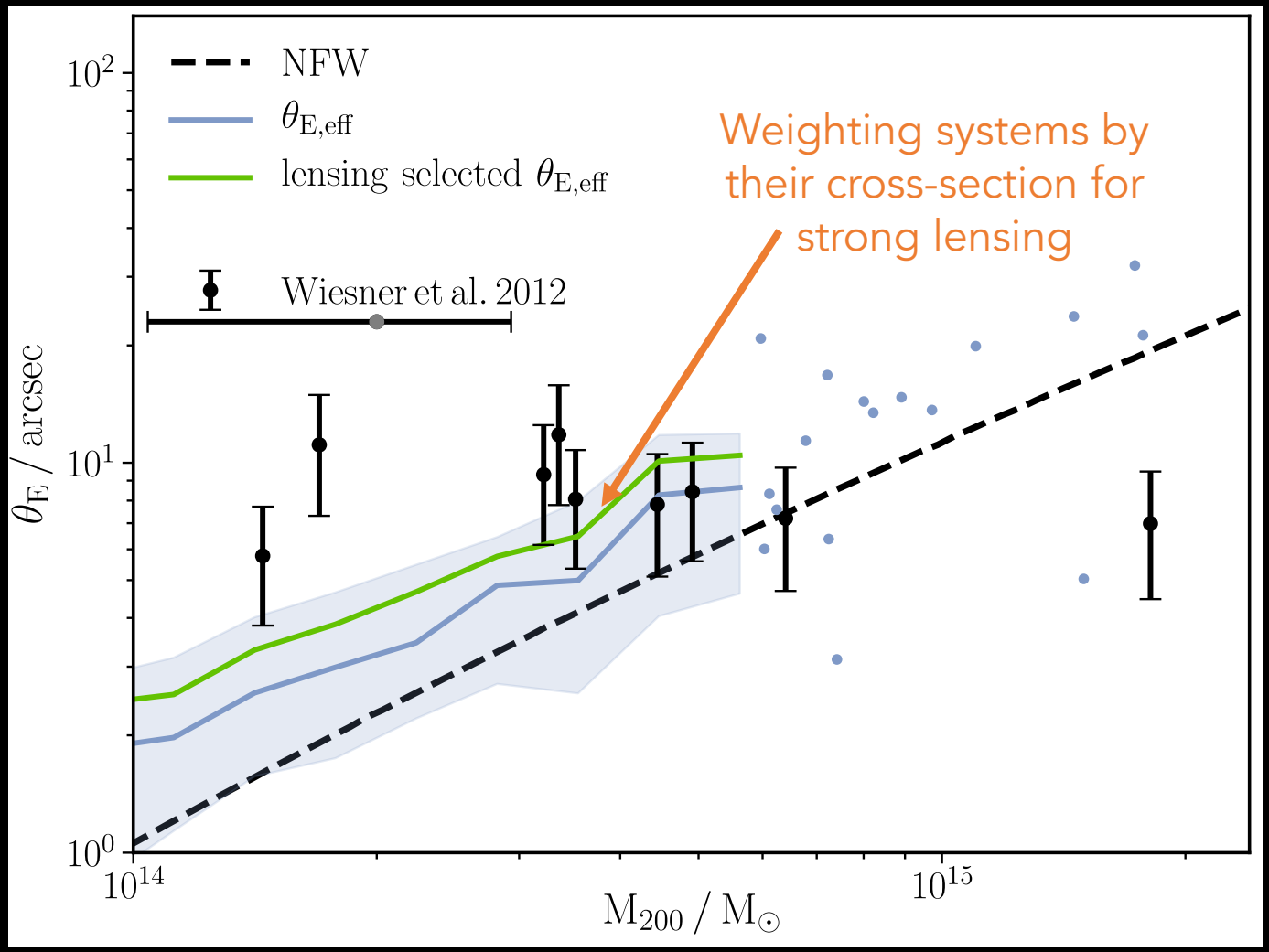

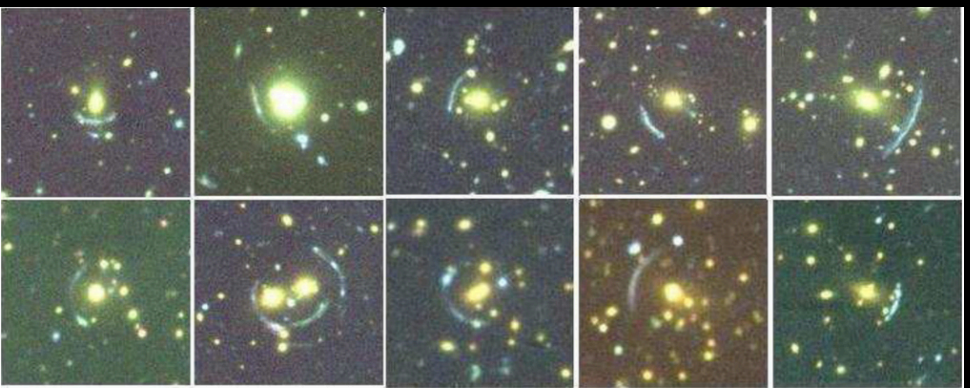

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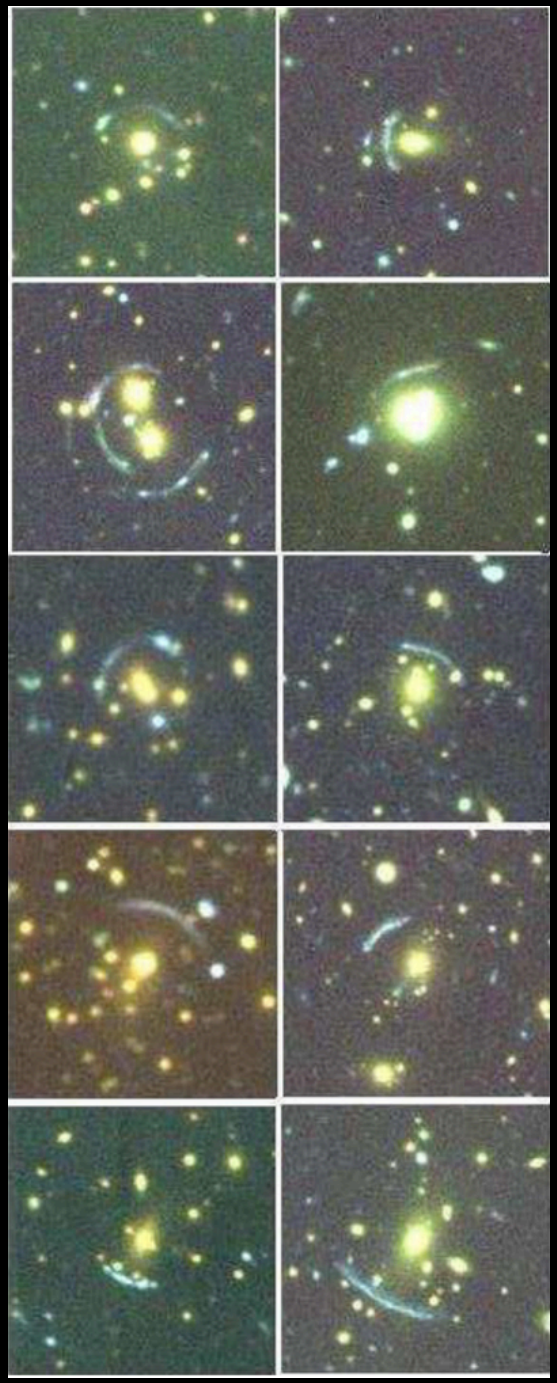
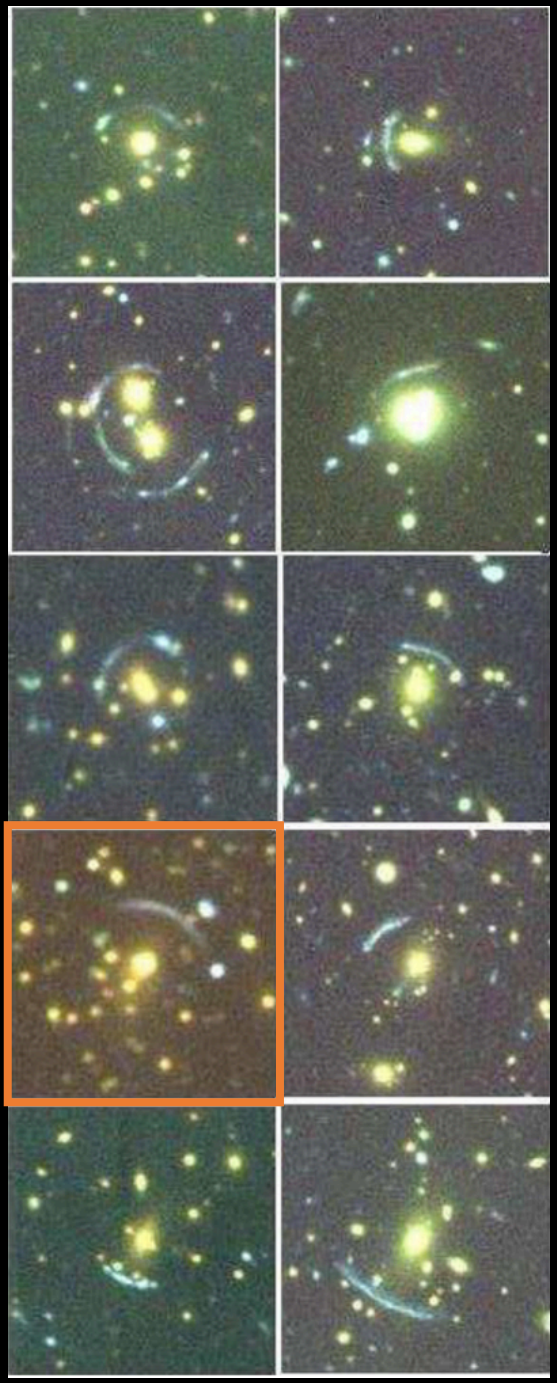
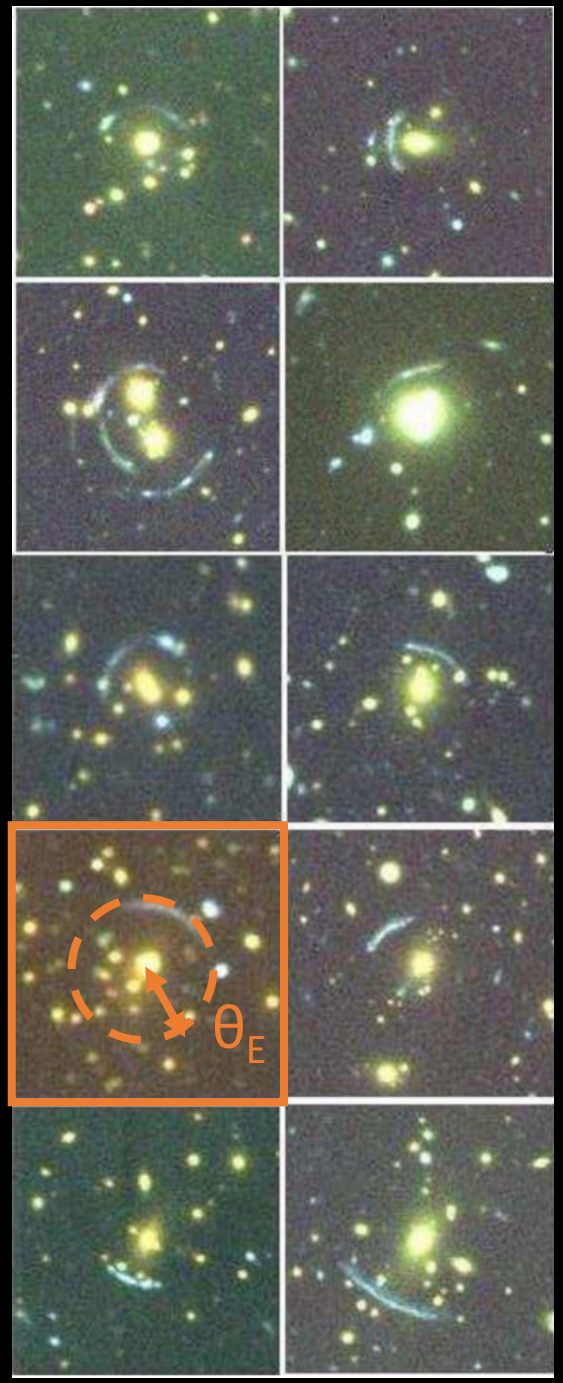


EINSTEIN RADII FROM ARC CURVATURE



EINSTEIN RADII FROM ARC CURVATURE



EINSTEIN RADII FROM ARC CURVATURE

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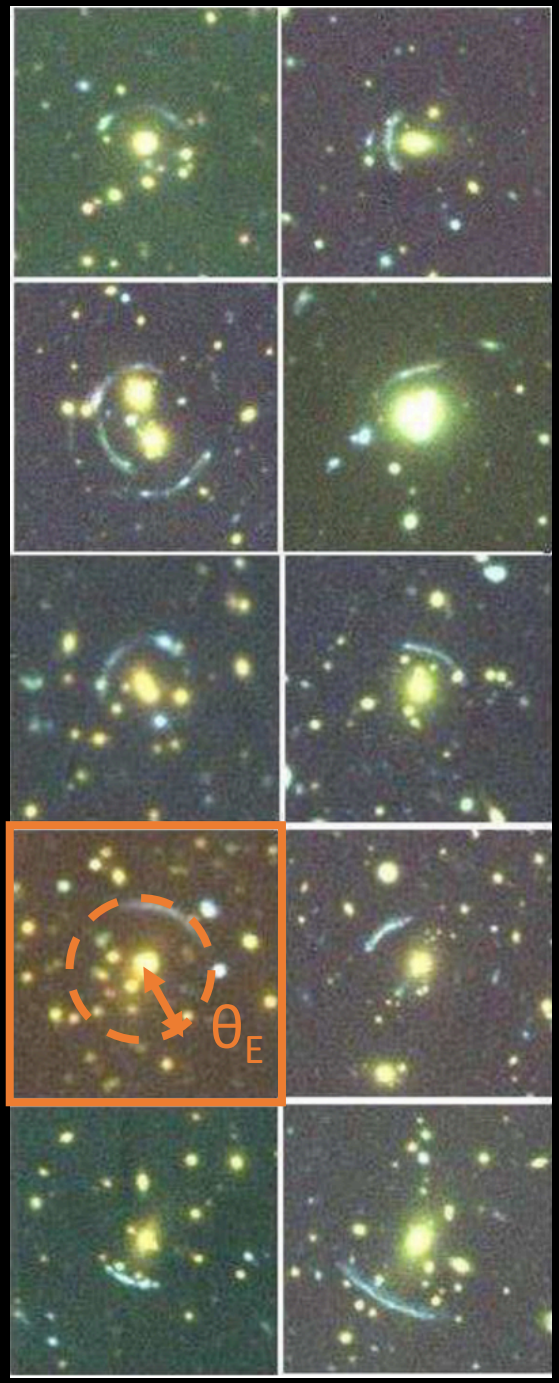

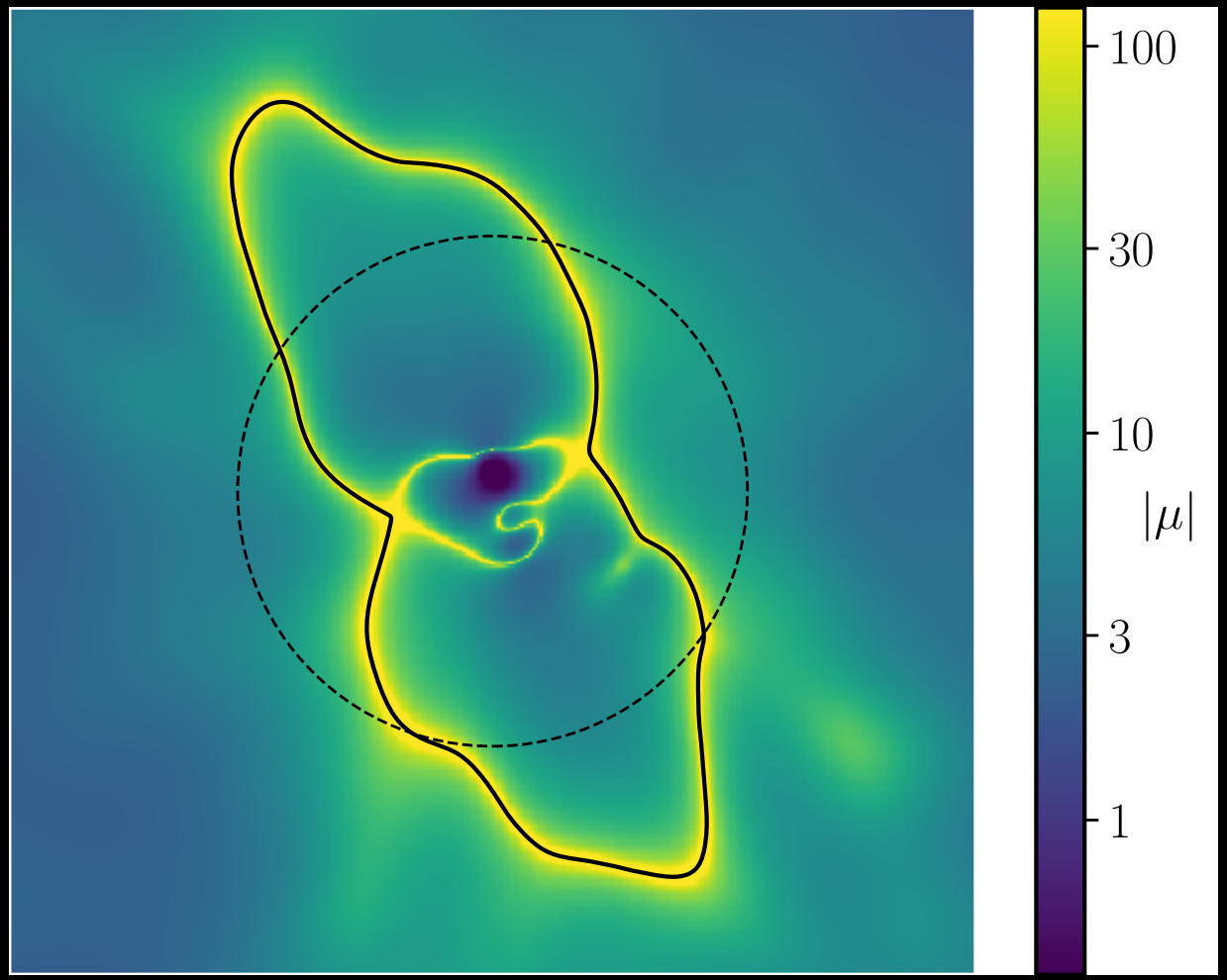

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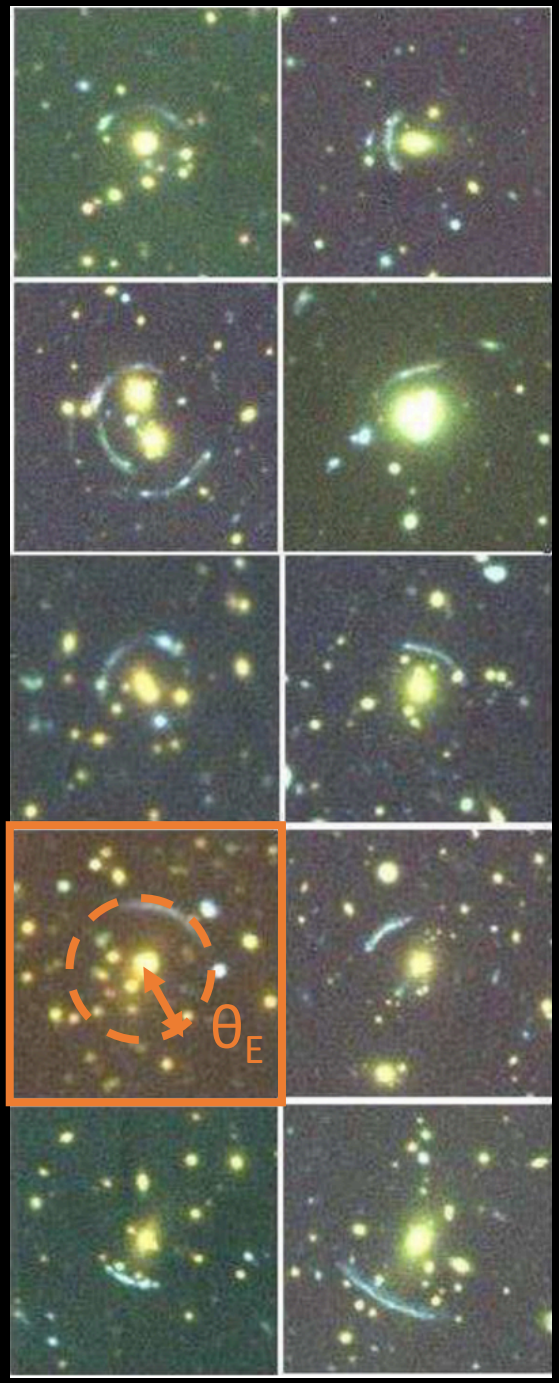
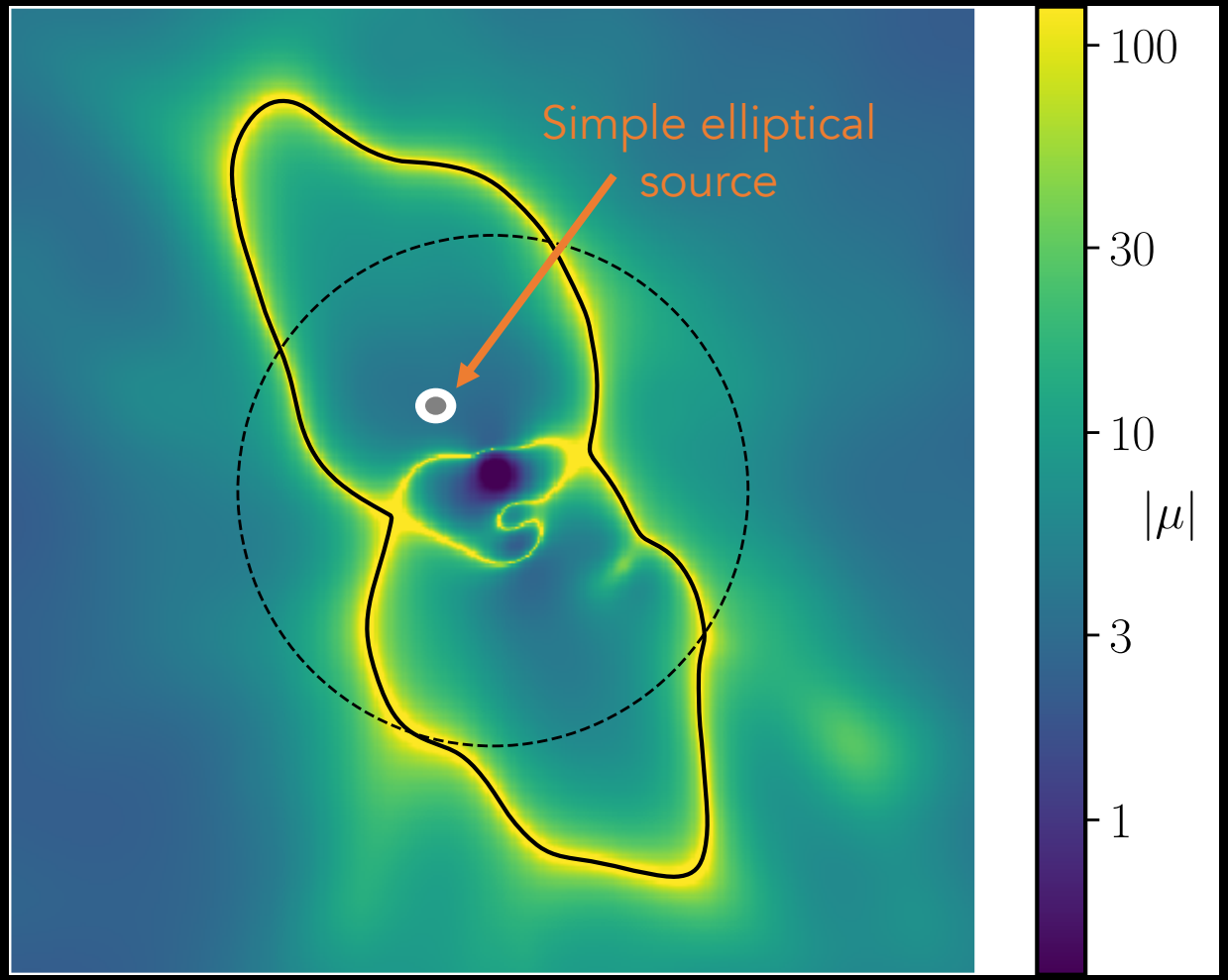
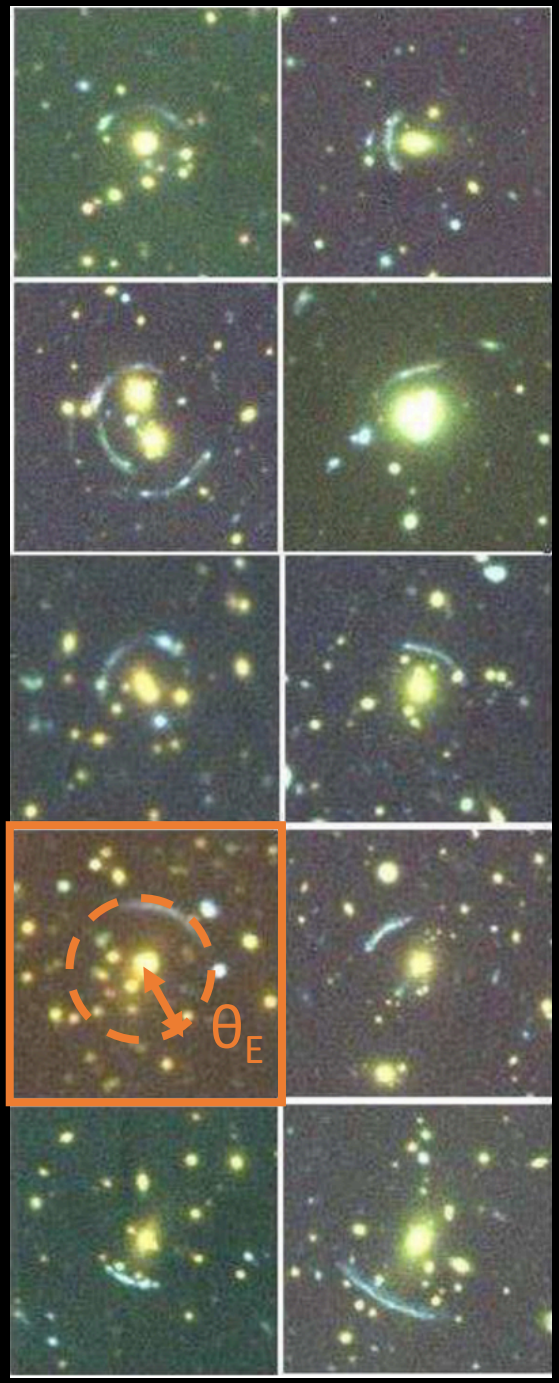
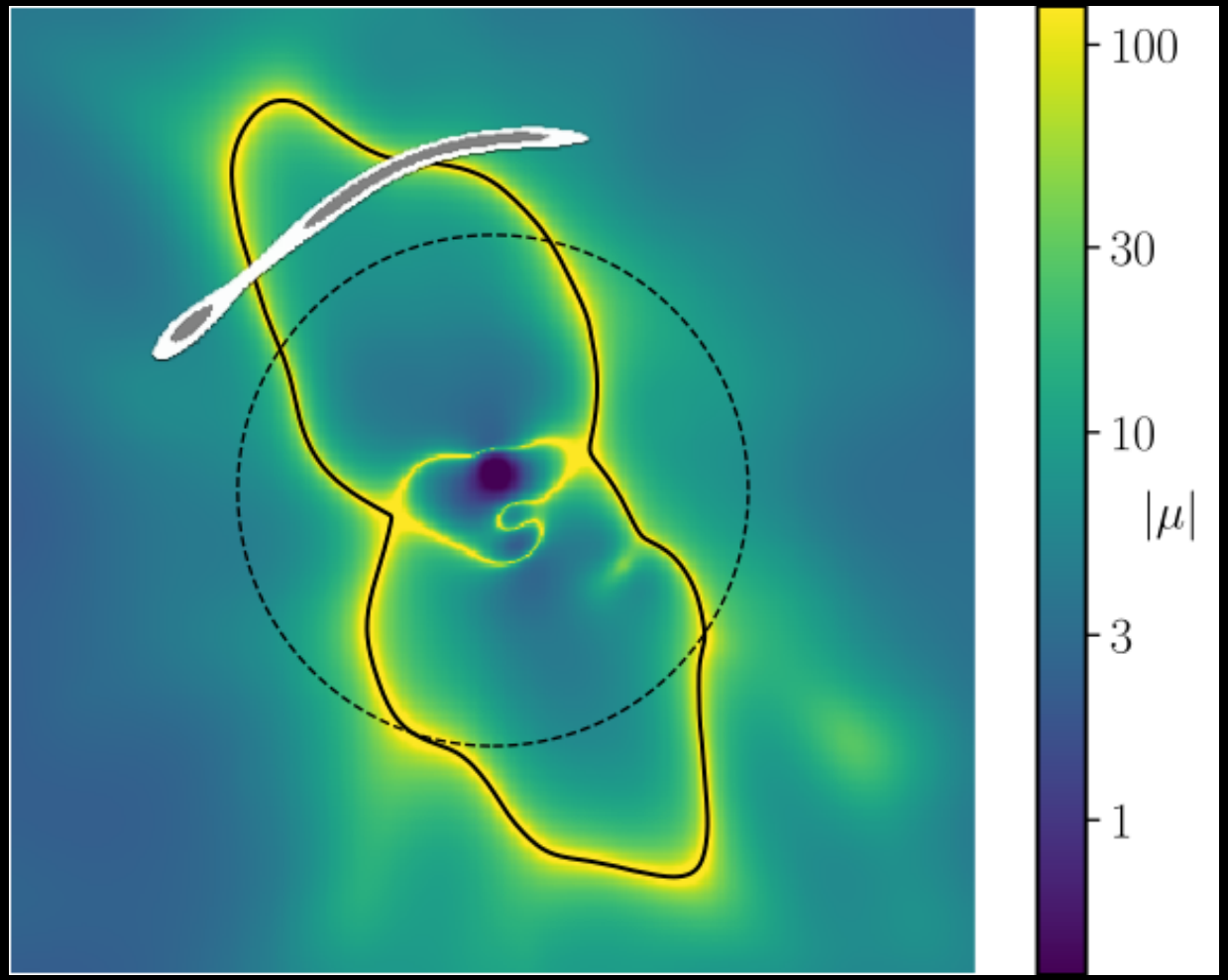




EINSTEIN RADII FROM ARC CURVATURE





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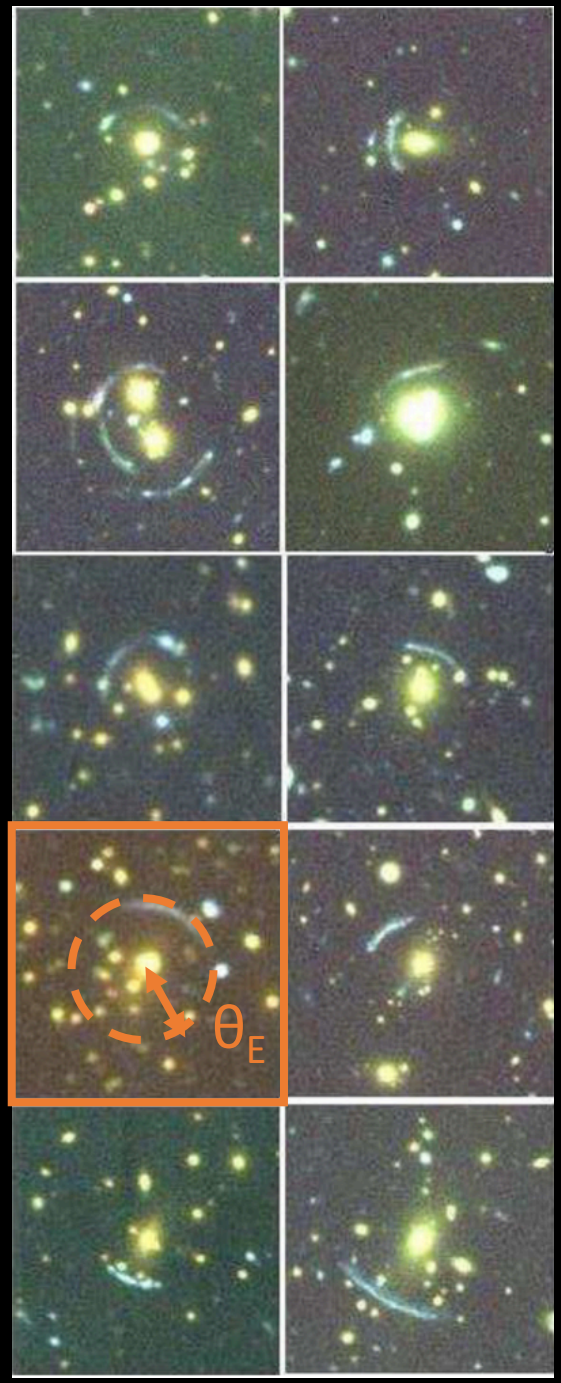
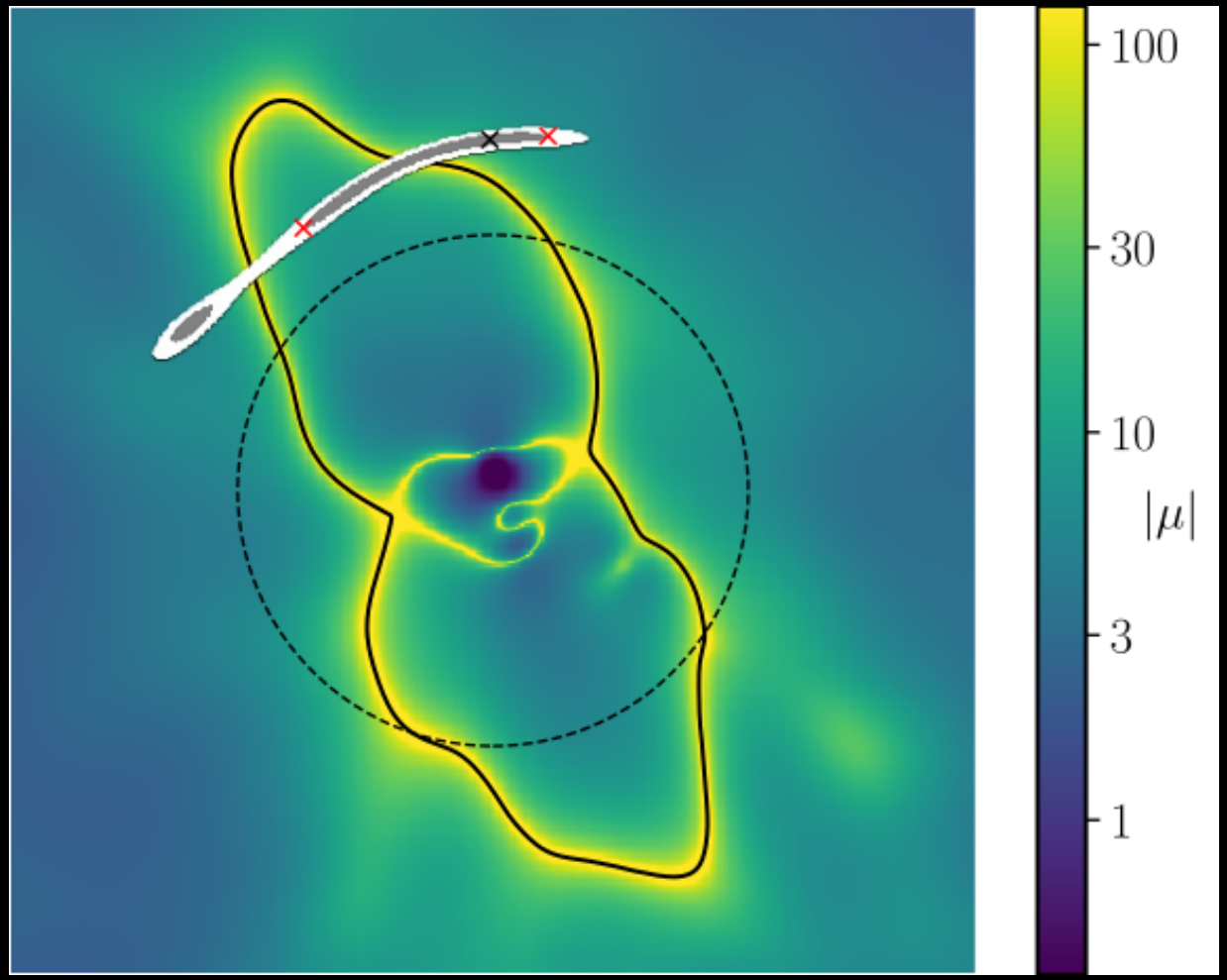
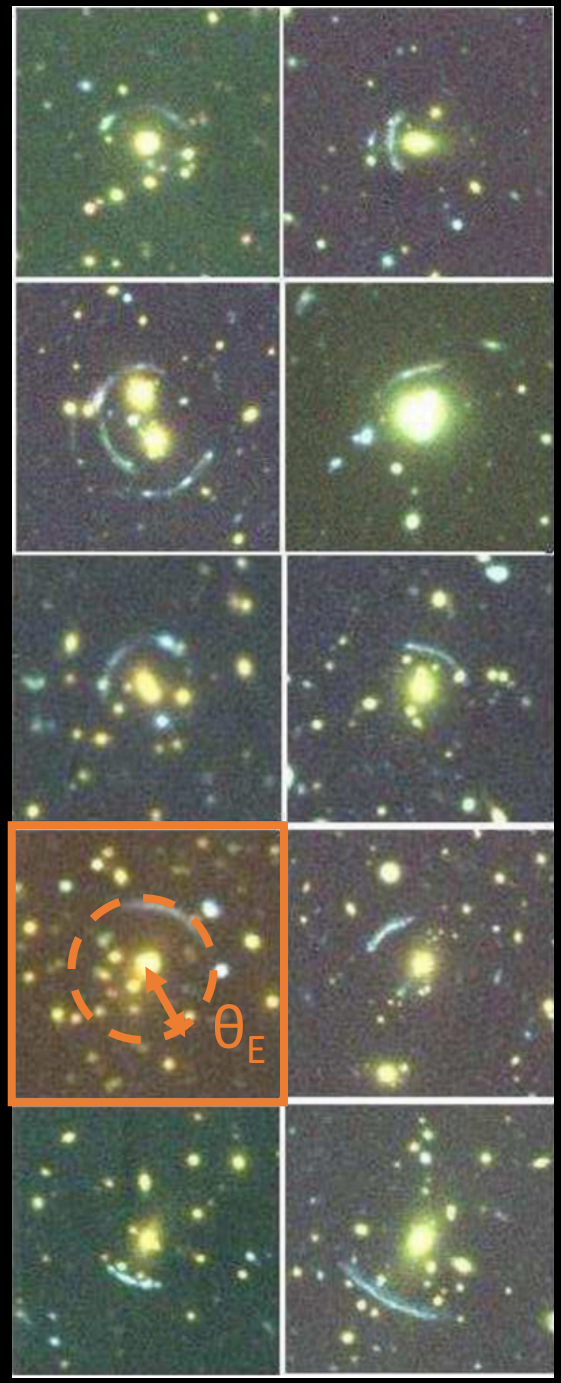
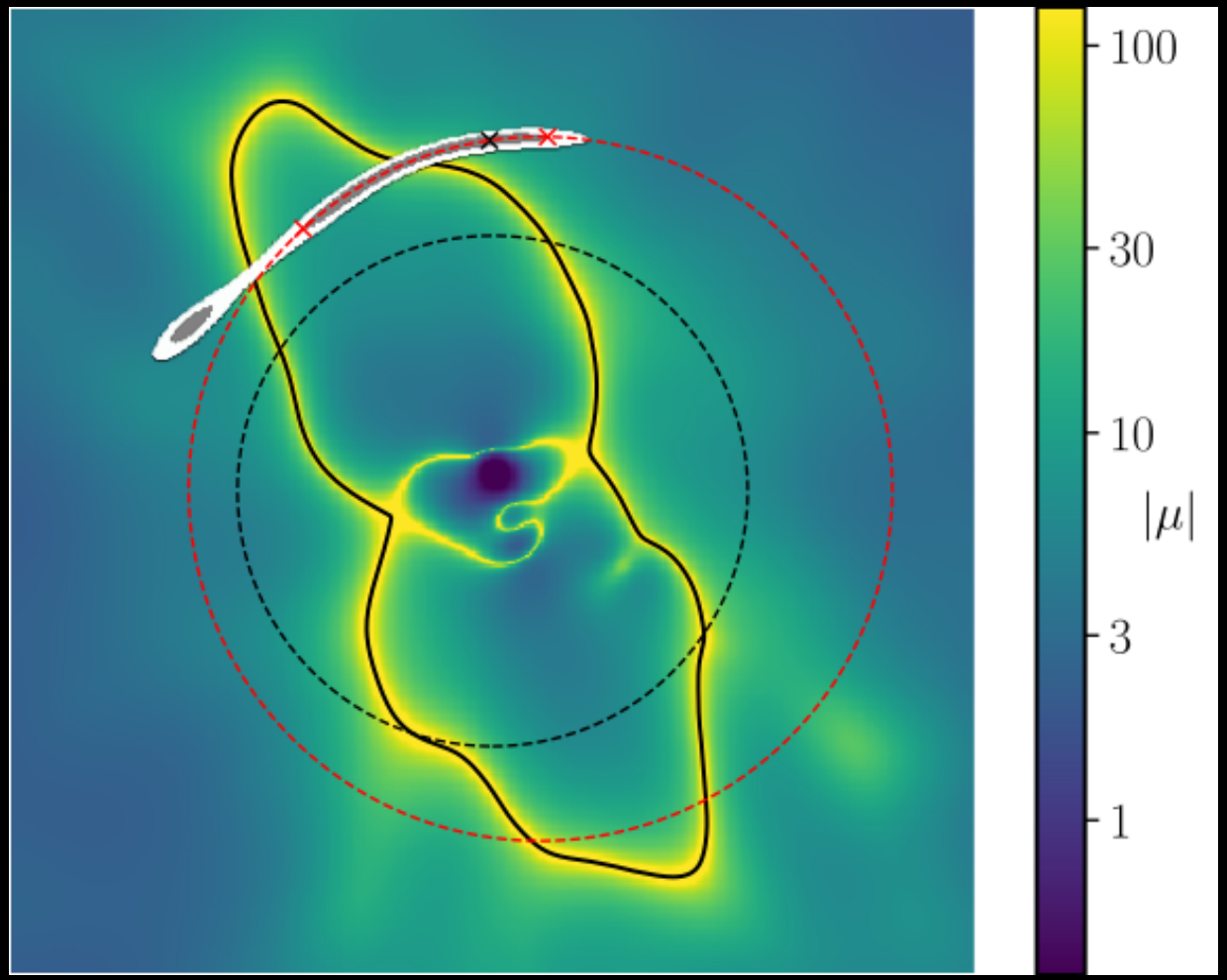




EINSTEIN RADII FROM ARC CURVATURE





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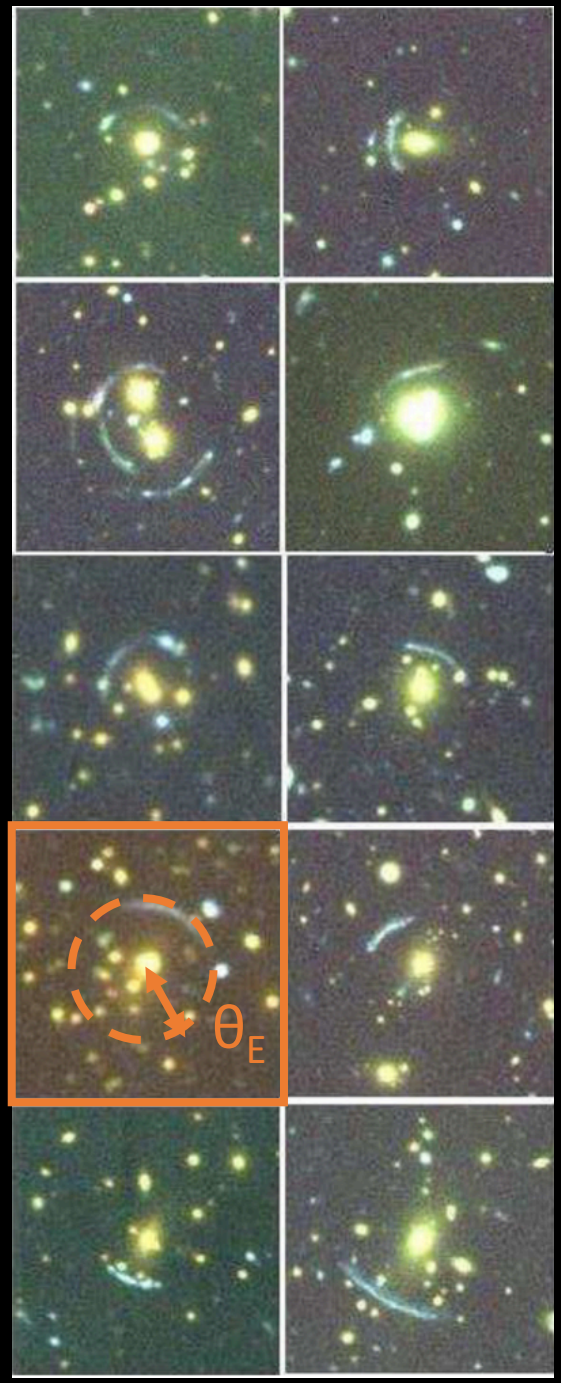
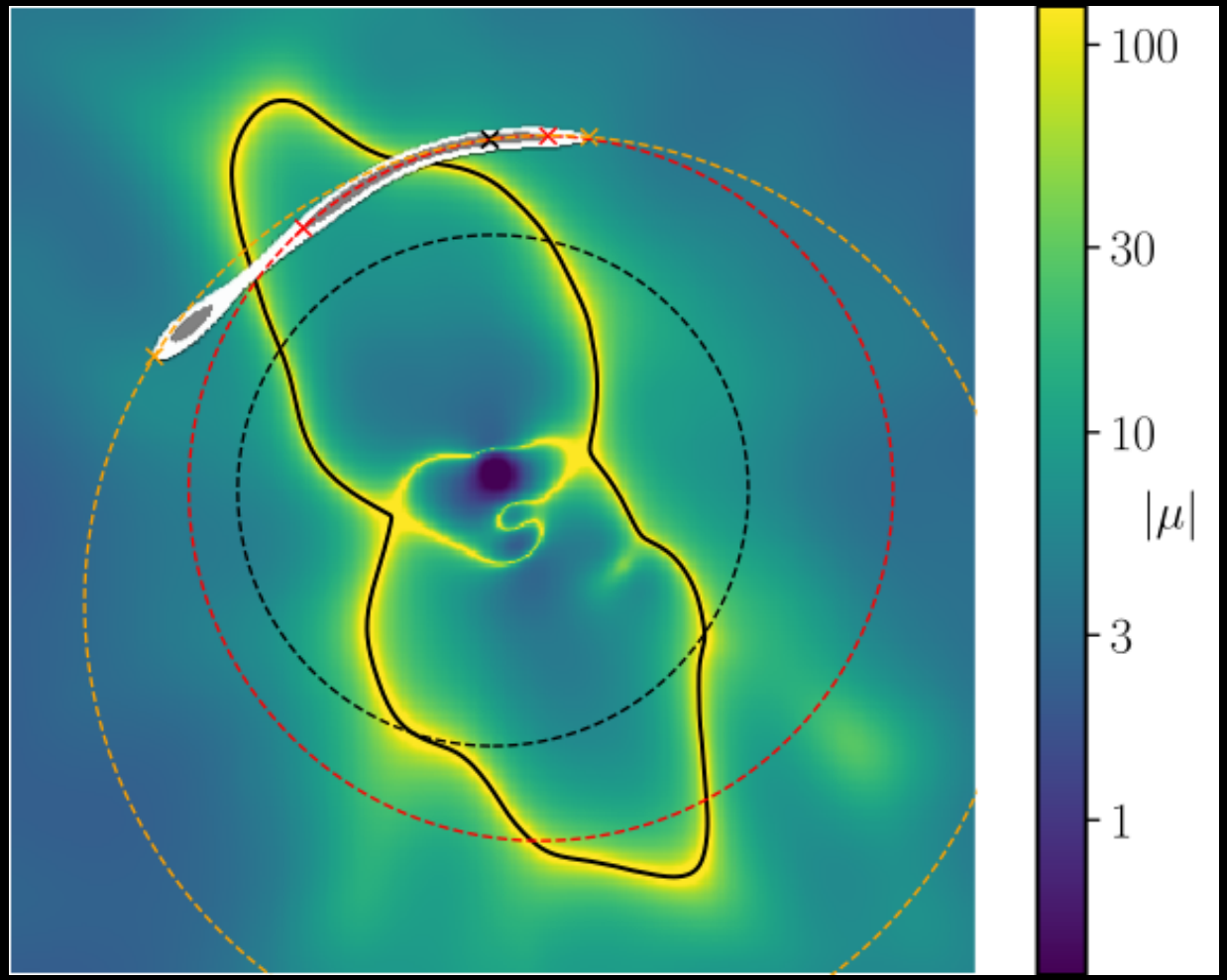
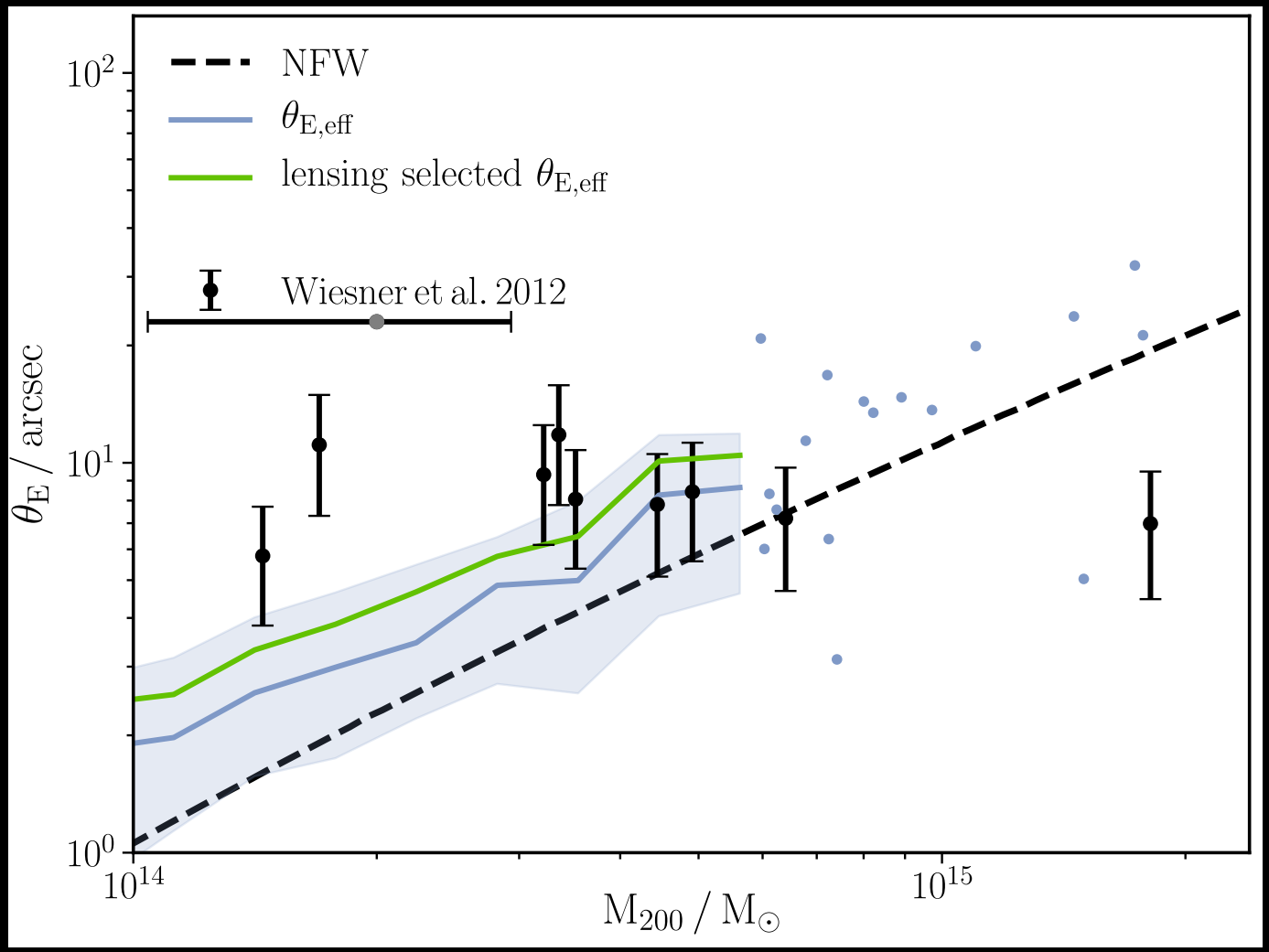
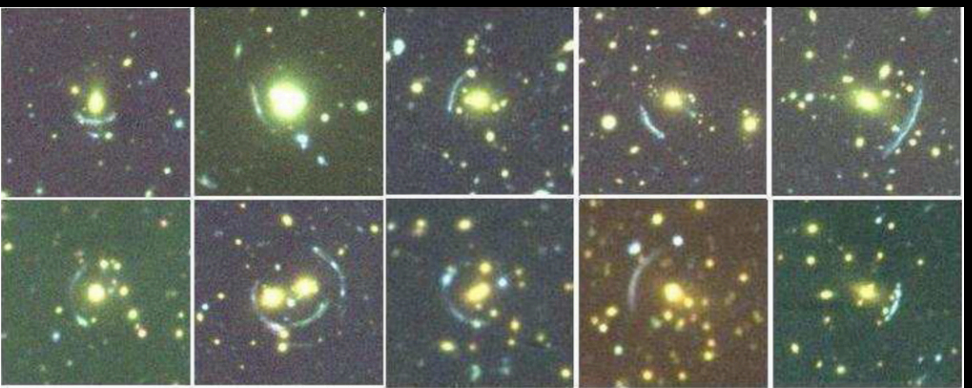




FORGETTING ABOUT SIDM FOR A SECOND…





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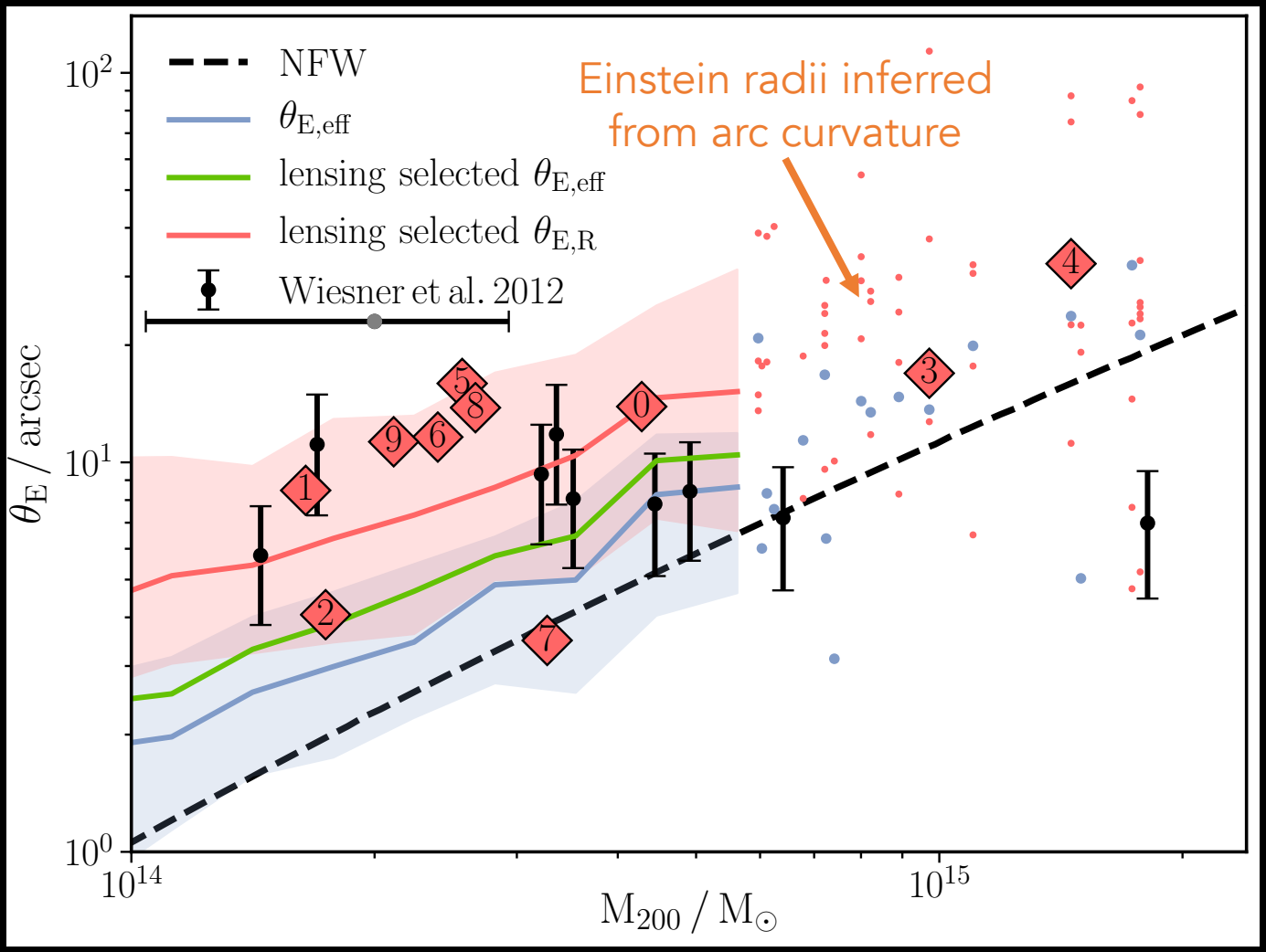
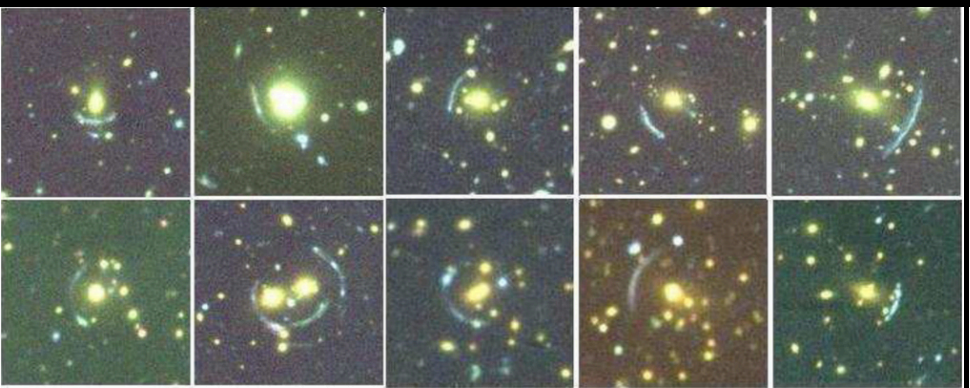
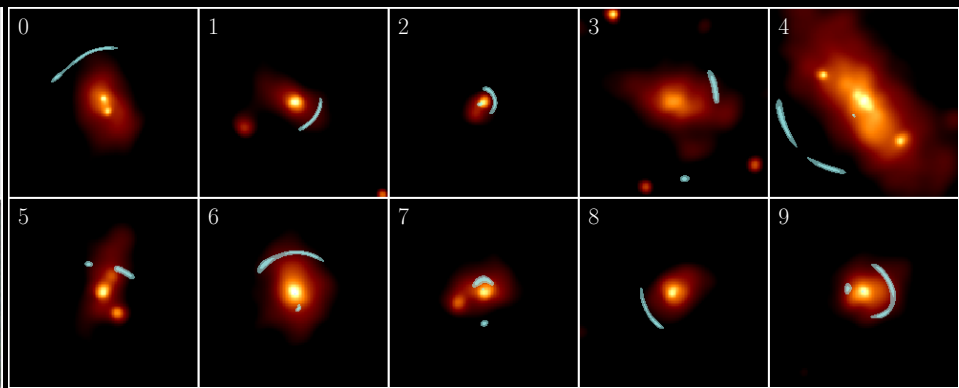
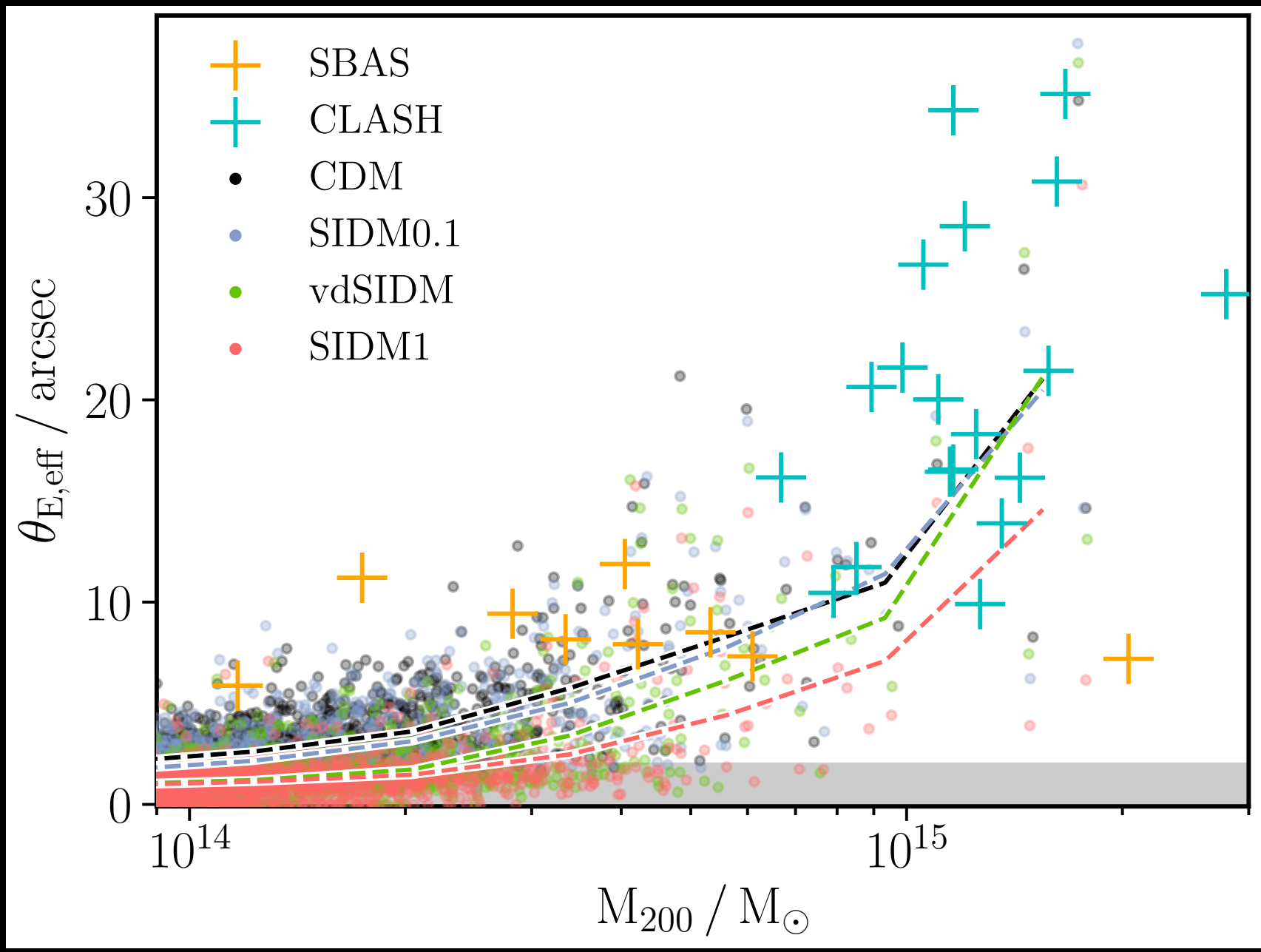


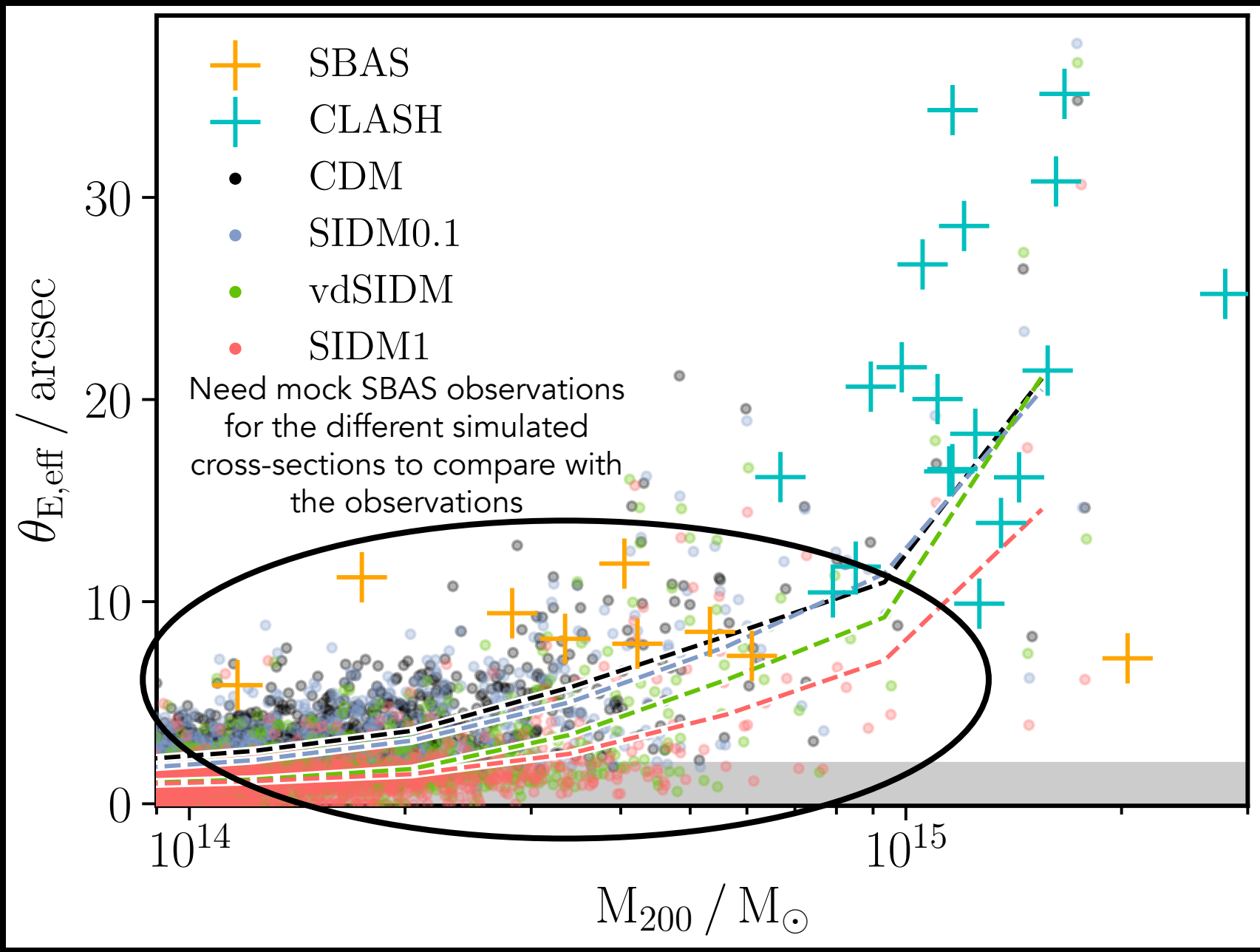




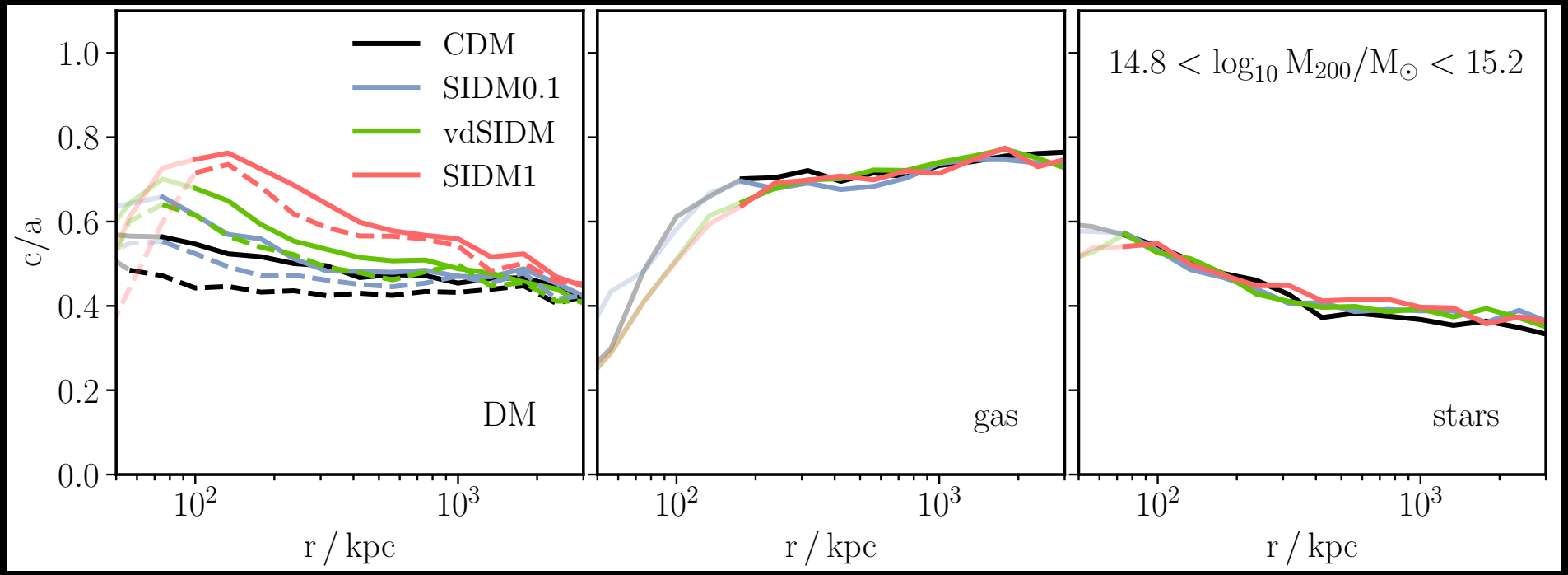
… BACK TO SIDM


SBAS
CLASH
CDM
SIDM0.1
vdSIDM
SIDM1
$\theta_{\mathrm{E,eff}}$ / arcsec
0
10
20
30
10^{14}
10^{15}
M_{200} / $M_\odot$

… BACK TO SIDM


SBAS
CLASH
CDM
SIDM0.1
vdSIDM
SIDM1
Need mock SBAS observations for the different simulated cross-sections to compare with the observations
$\theta_{E,eff}$ / arcsec
M_{200} / $M_\odot$
0
10
20
30
10^{14}
10^{15}

BAHAMAS-SIDM HALO SHAPES



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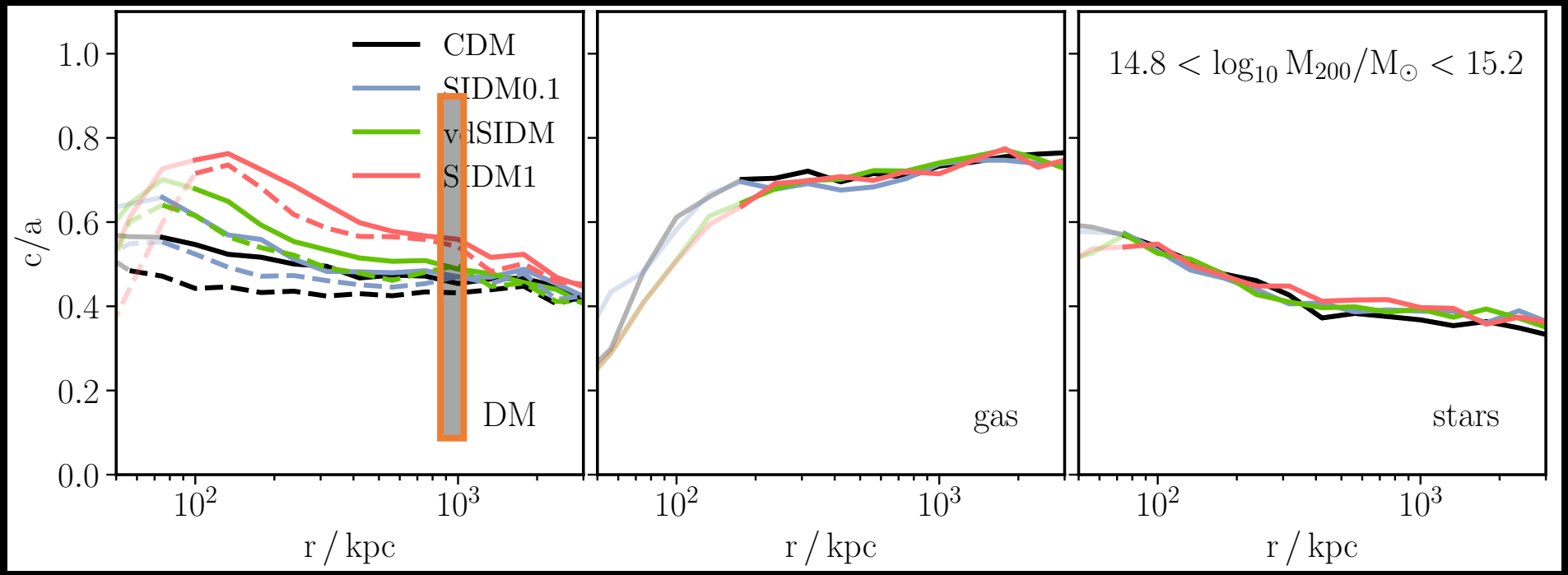

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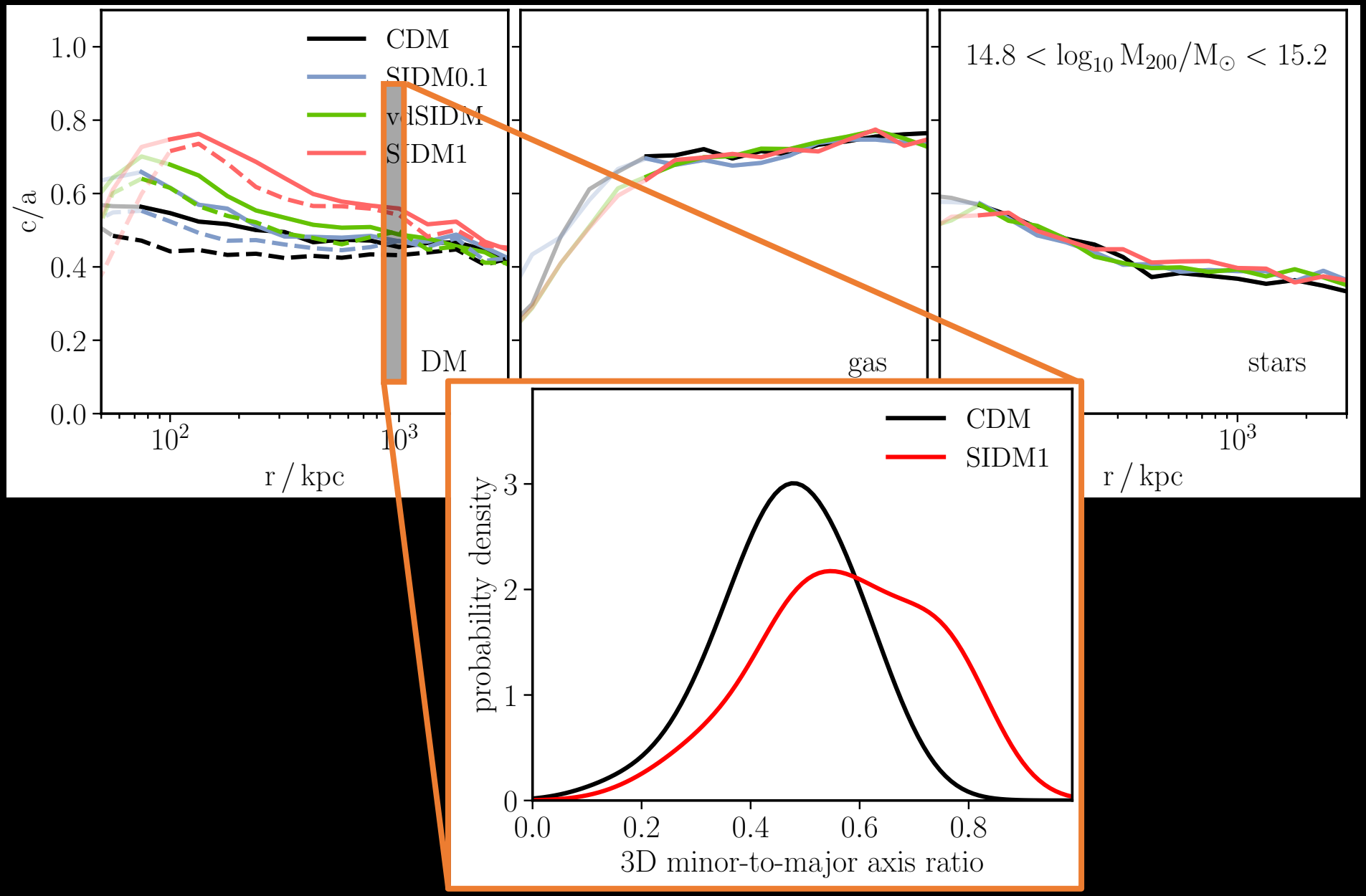

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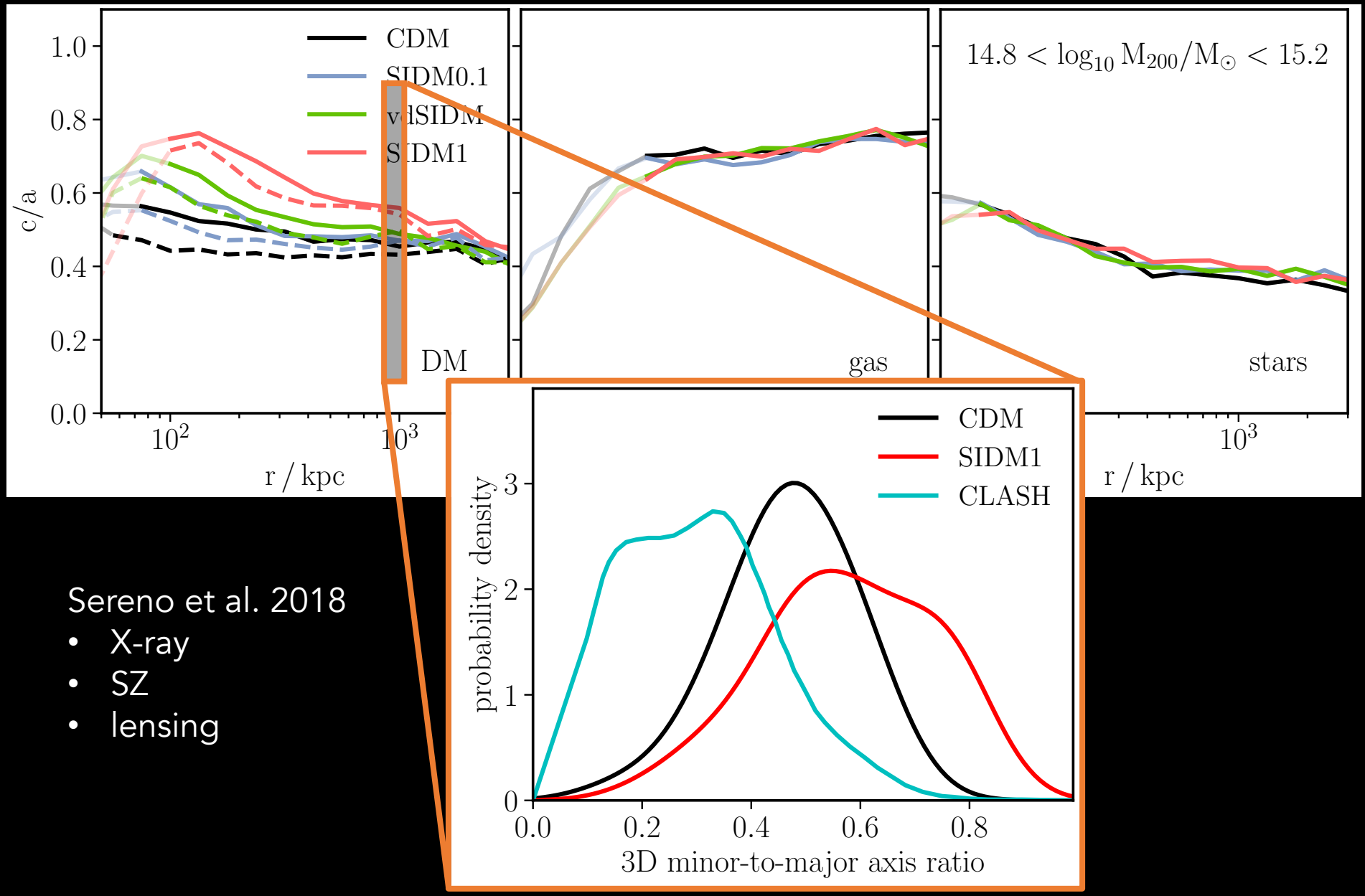
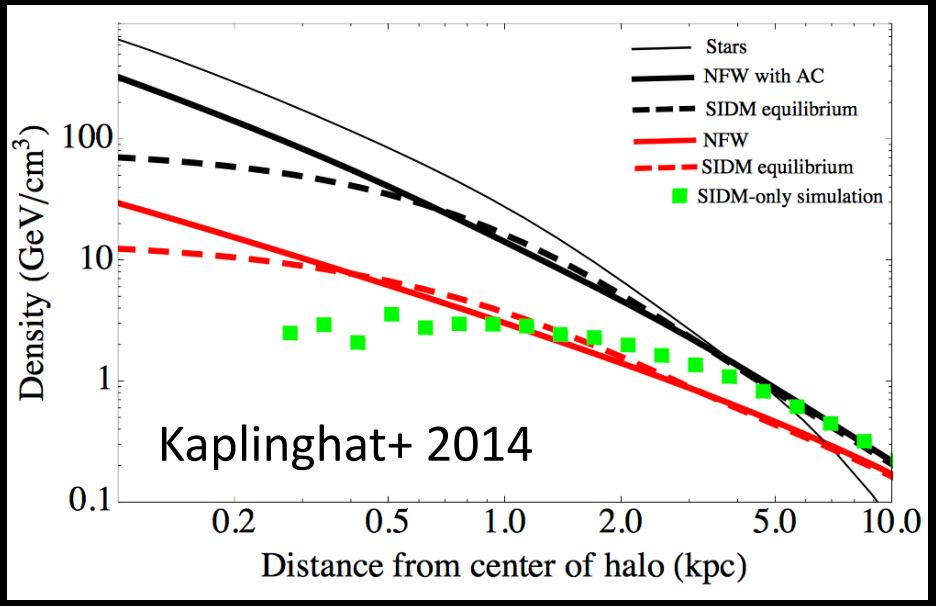
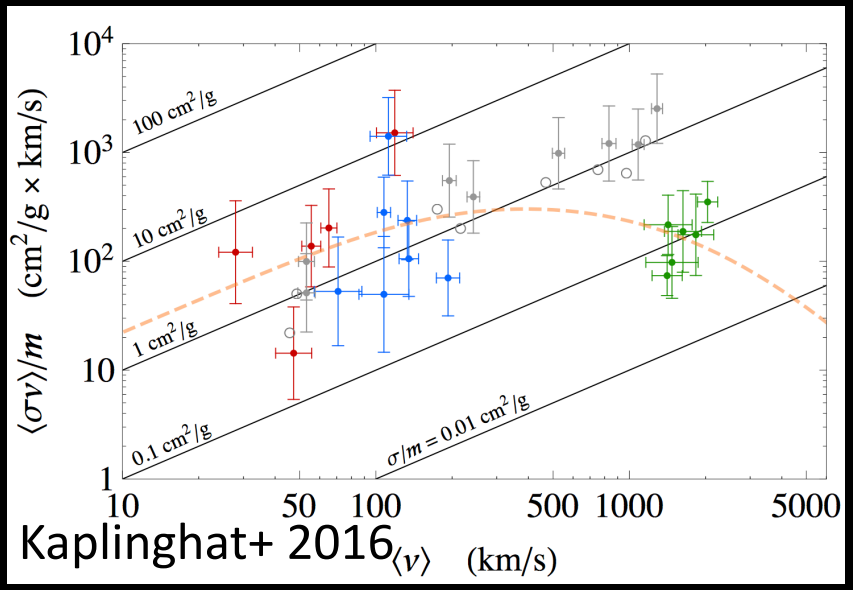


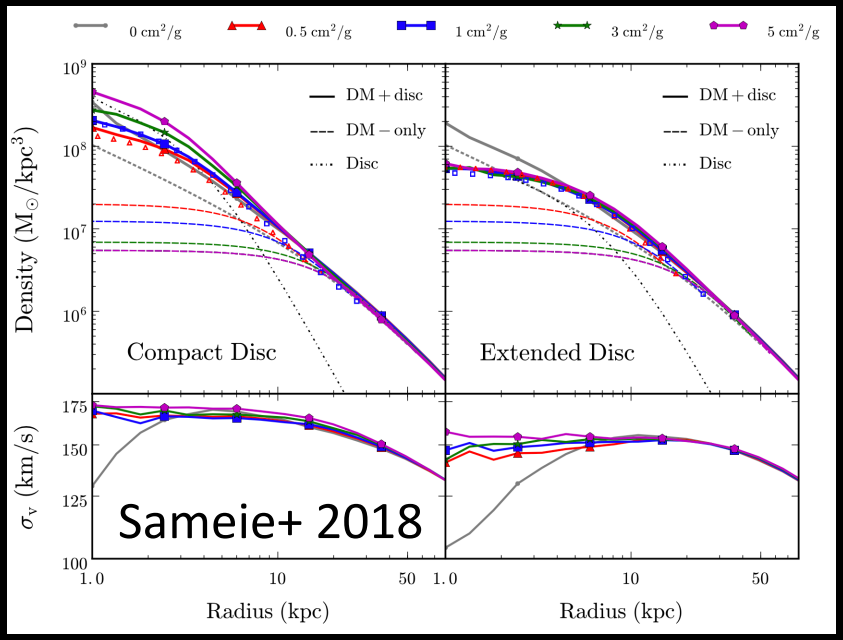
Sereno et al. 2018

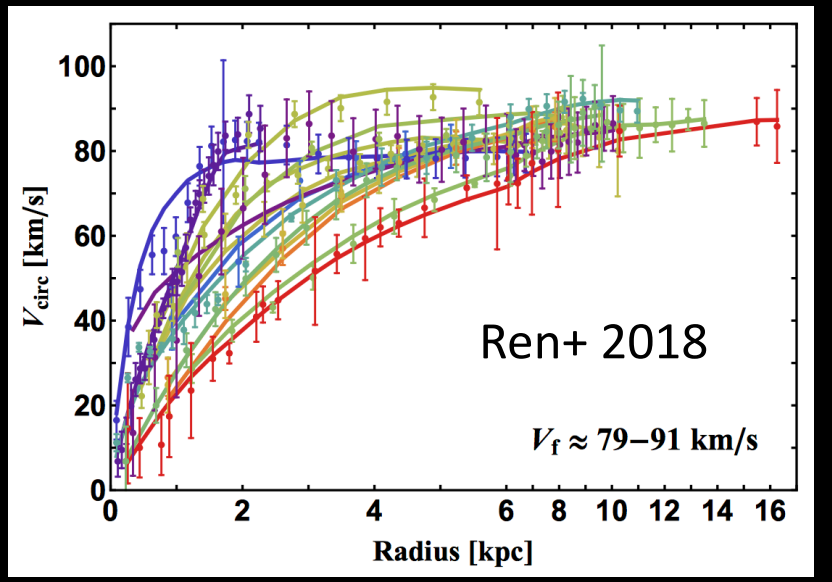
- X-ray
- SZ
- lensing



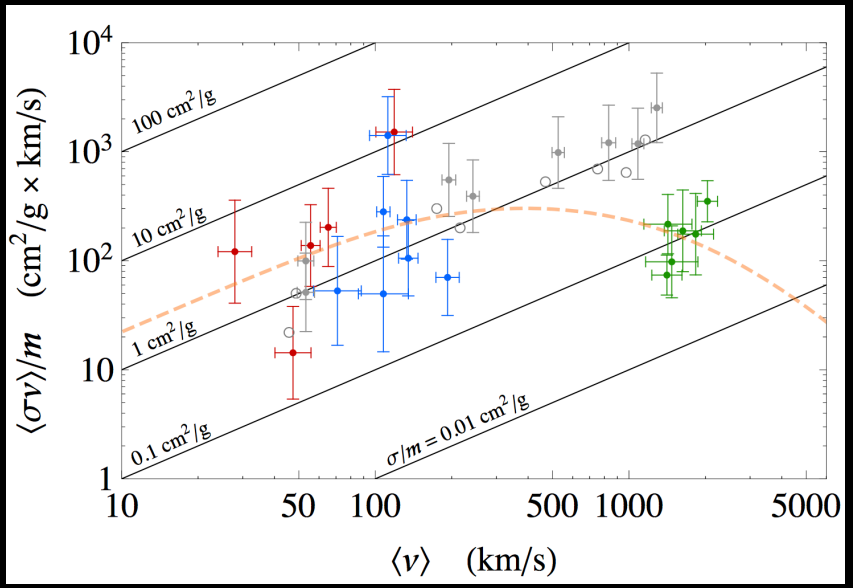


ISOTHERMAL JEANS MODELLING





ISOTHERMAL JEANS MODELLING ON REAL CLUSTERS



Kaplinghat+ 2016

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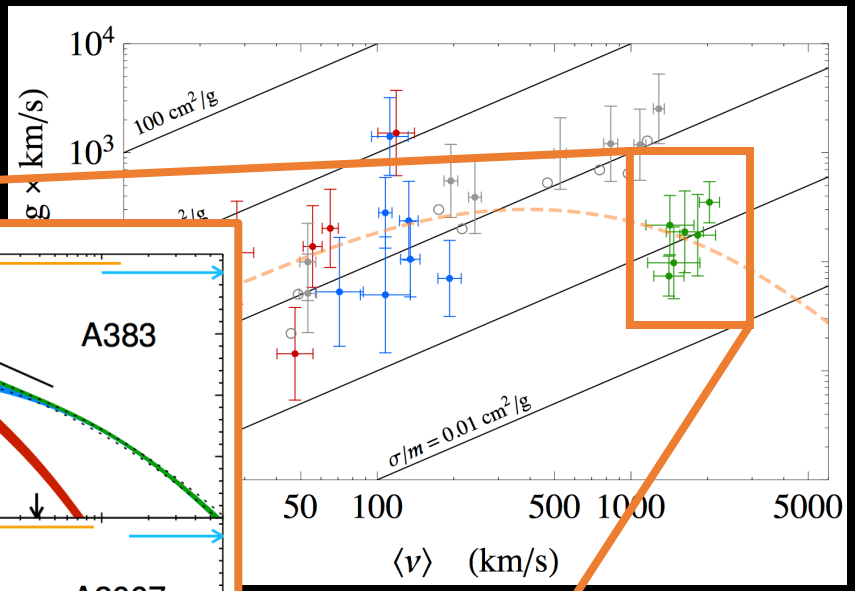
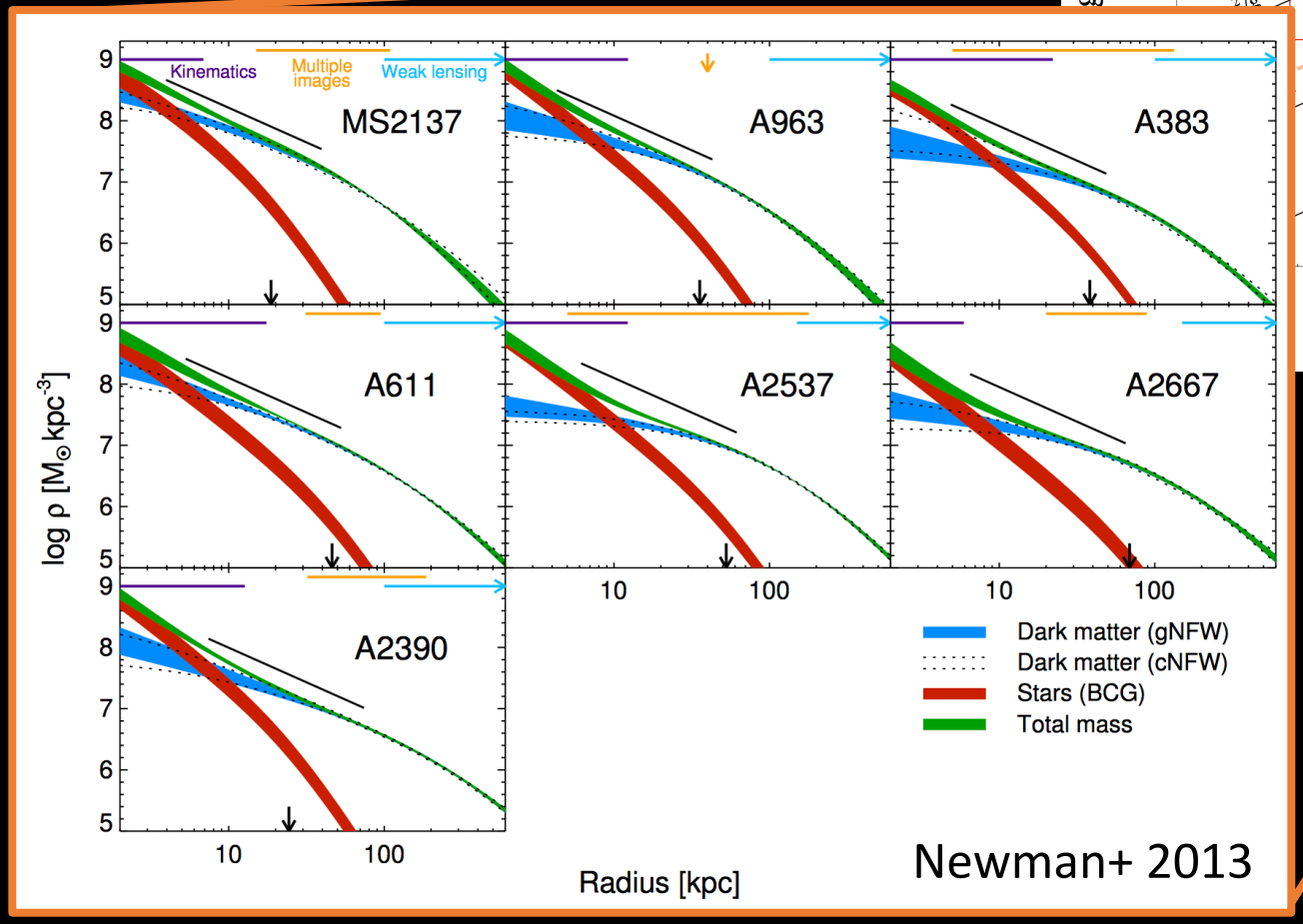
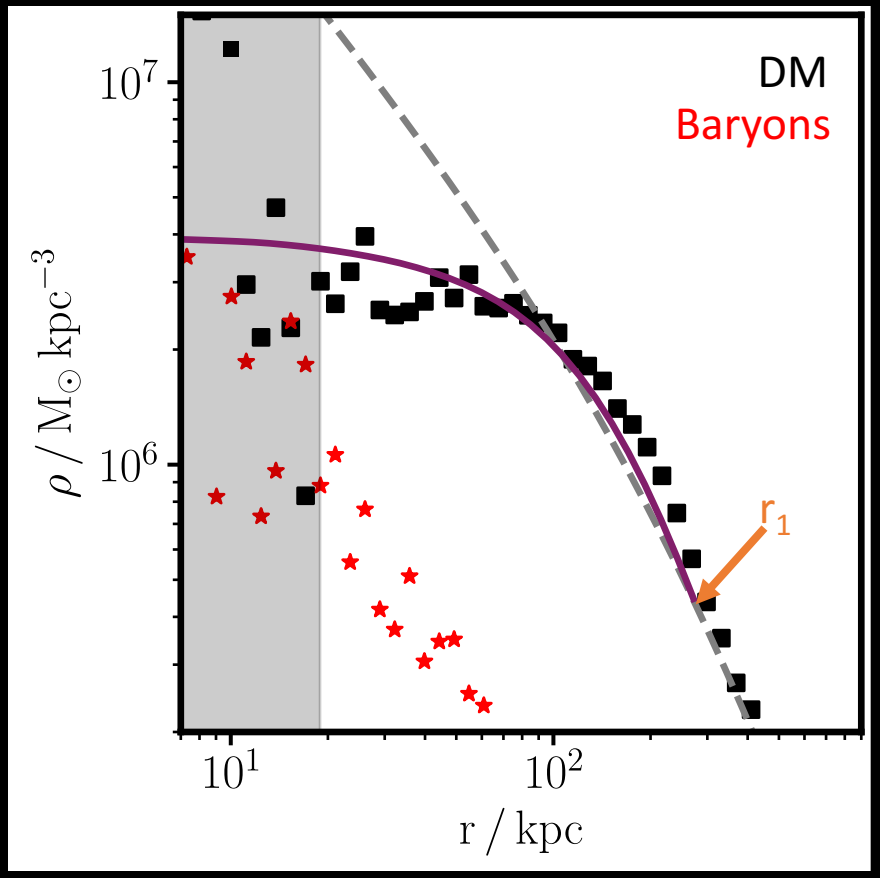


Kaplinghat+ 2016



Newman+ 2013

ISOTHERMAL JEANS MODELLING



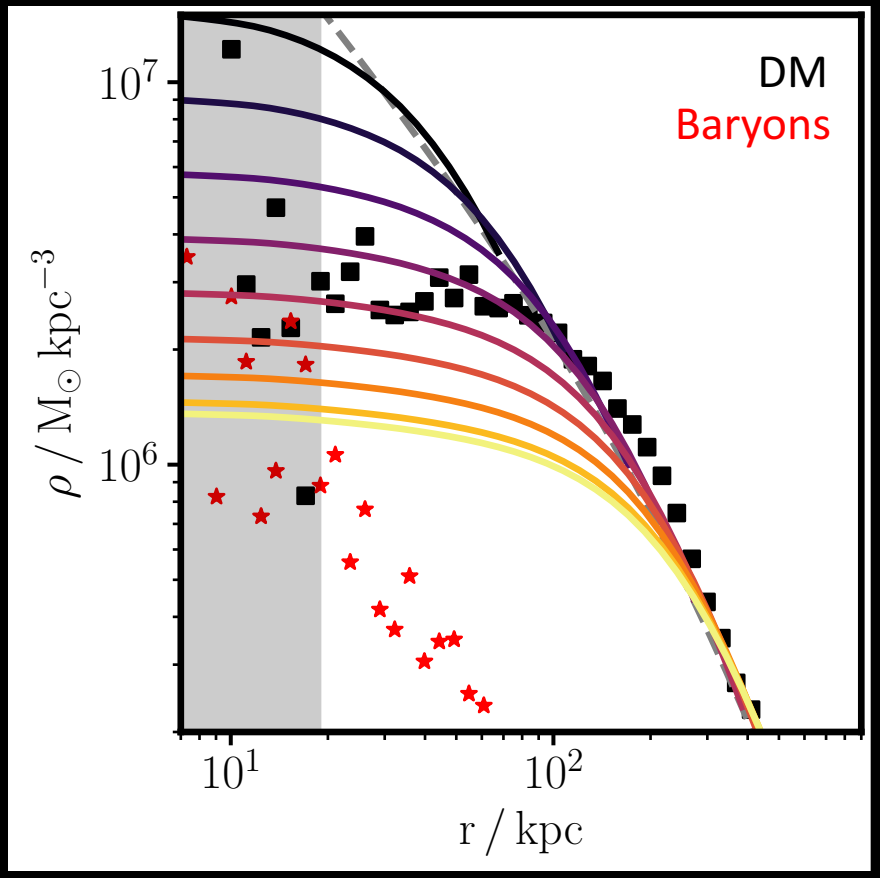
Fit NFW profile (at the moment to M_{200} and $M(<f*r_{200})$, with $f=0.1$)

For a given cross-section, find r_1, the radius at which particles have scattered once on average (in NFW)

$$\Gamma(r_1)t_{\rm age} = \rho(r_1)\ \langle v_{\rm rel}(r_1)\rangle\ \frac{\sigma}{m}\,t_{\rm age} = 1$$

Find DM temperature and central DM density, that produce a density profile that matches the density at, and mass enclosed within, r_1.

ISOTHERMAL JEANS MODELLING



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Try for different cross-sections

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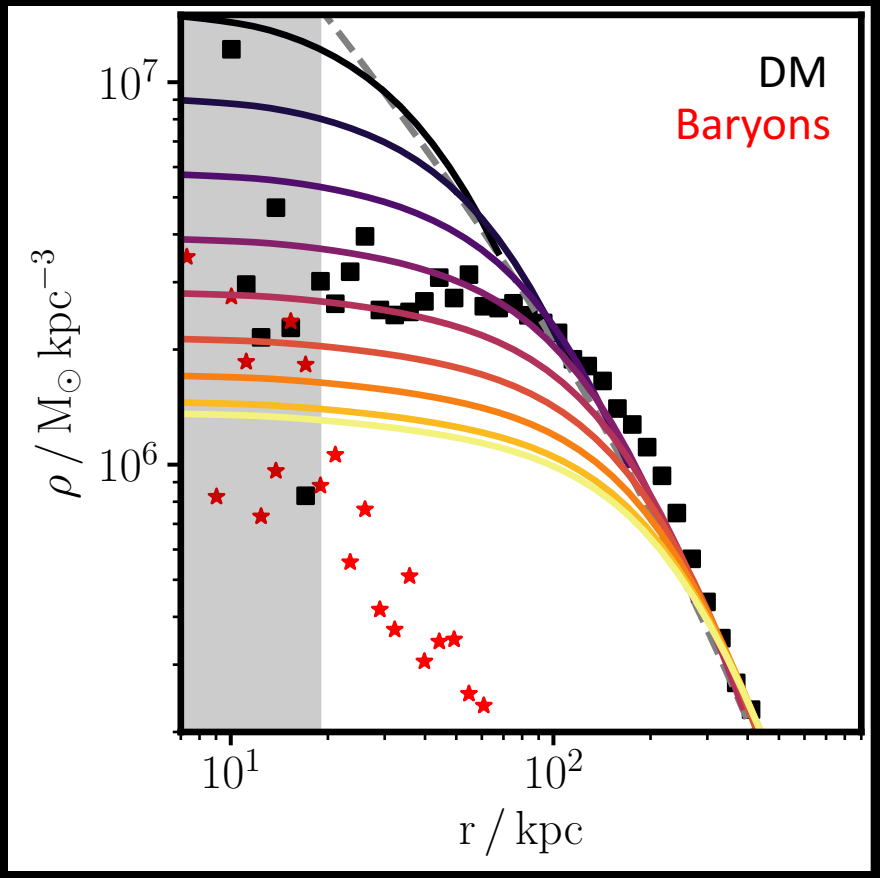

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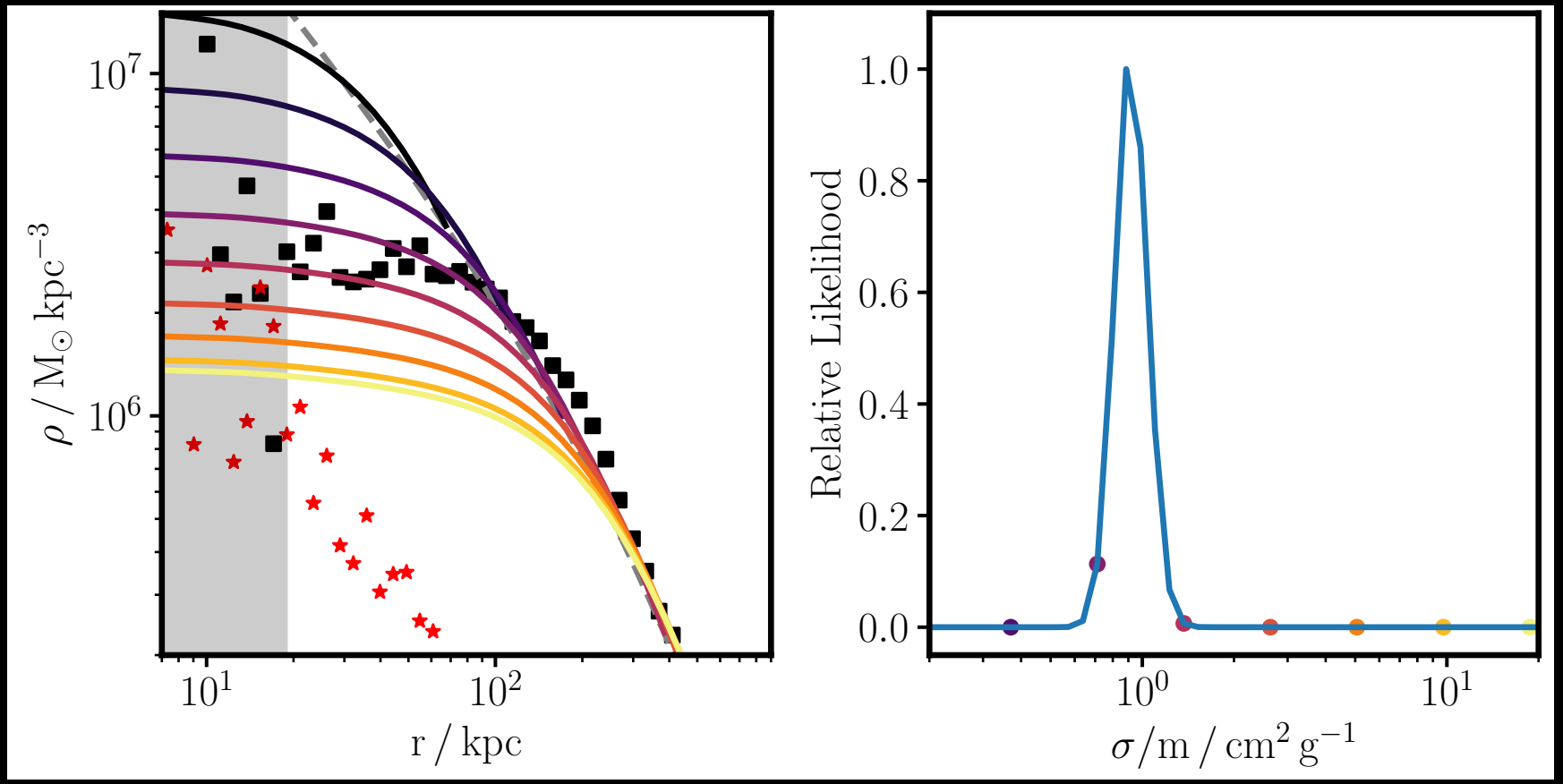
Log-spaced radial bins

$$\chi^2 = \sum_{0.01<r/r_{200}<1} \frac{(\log\rho_{\rm sim} - \log\rho_{\rm model})^2}{(\delta\log\rho)^2}$$

0.1 dex

Decide what constitutes a 'good fit' (currently ~ what looks best on a log(r) – log(ρ) plot!)

ISOTHERMAL JEANS MODELLING



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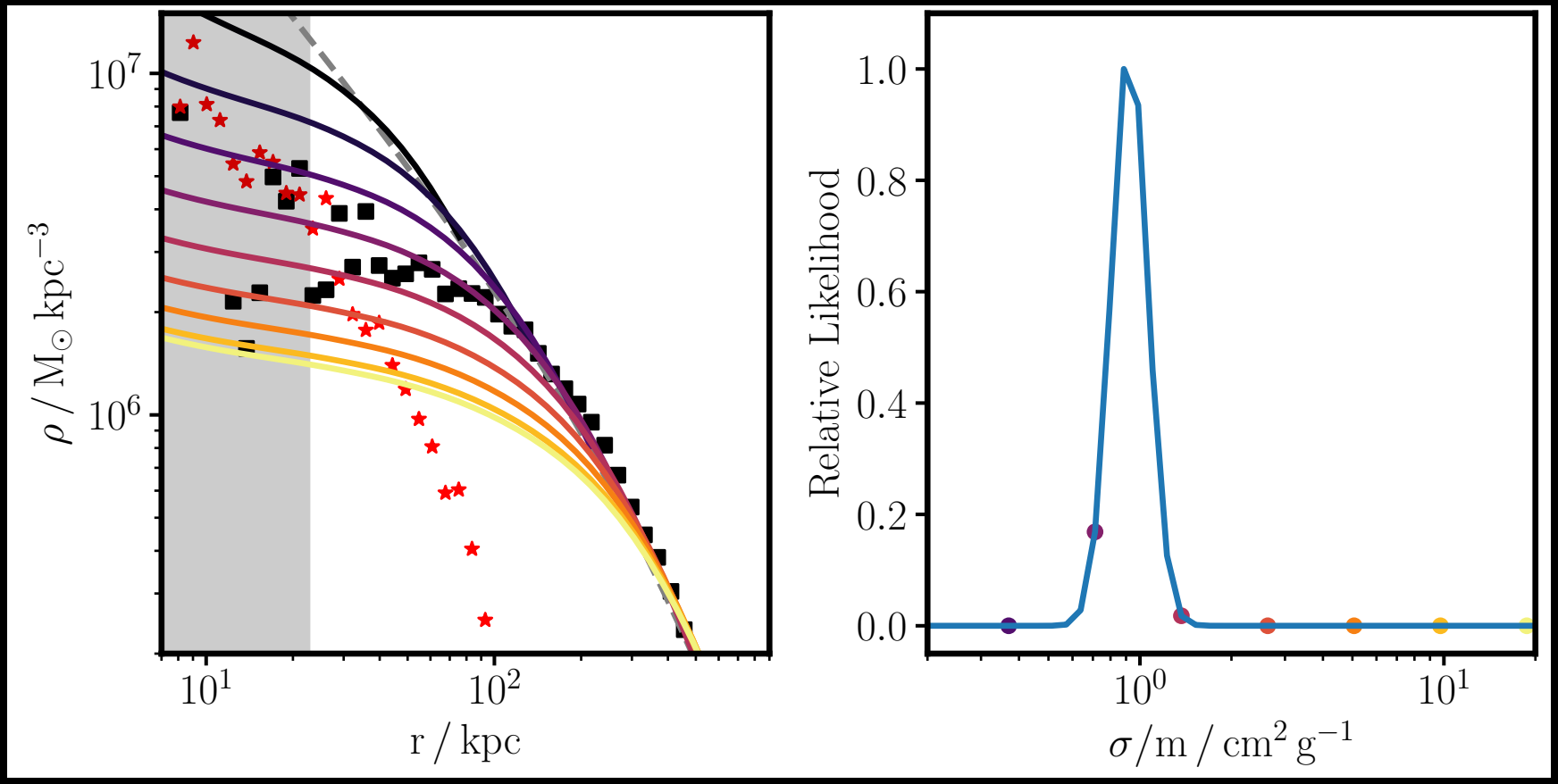
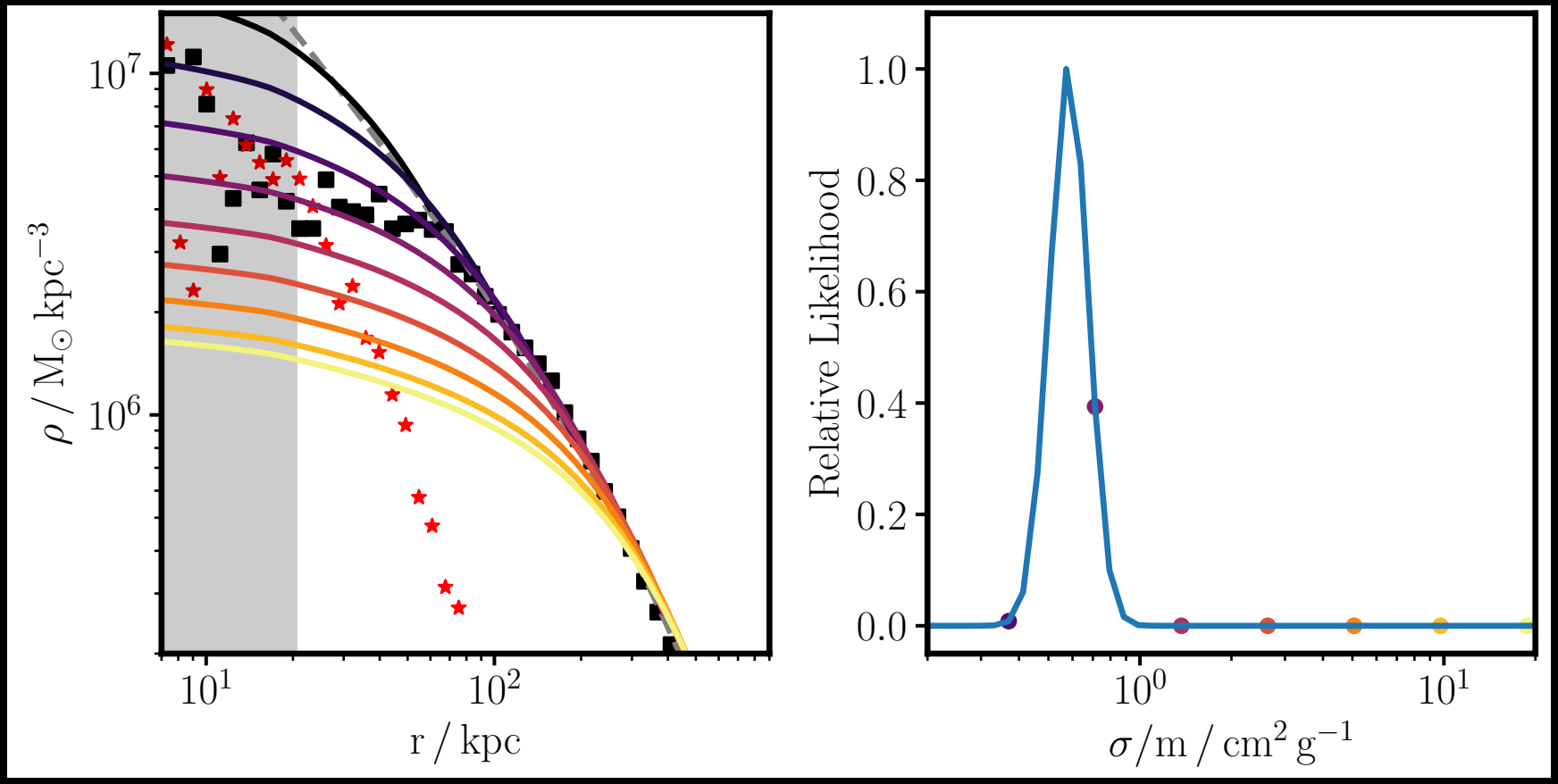
Decide what constitutes a 'good fit' (currently ~ what looks best on a log(r) – log(ρ) plot!)

OTHER EXAMPLES



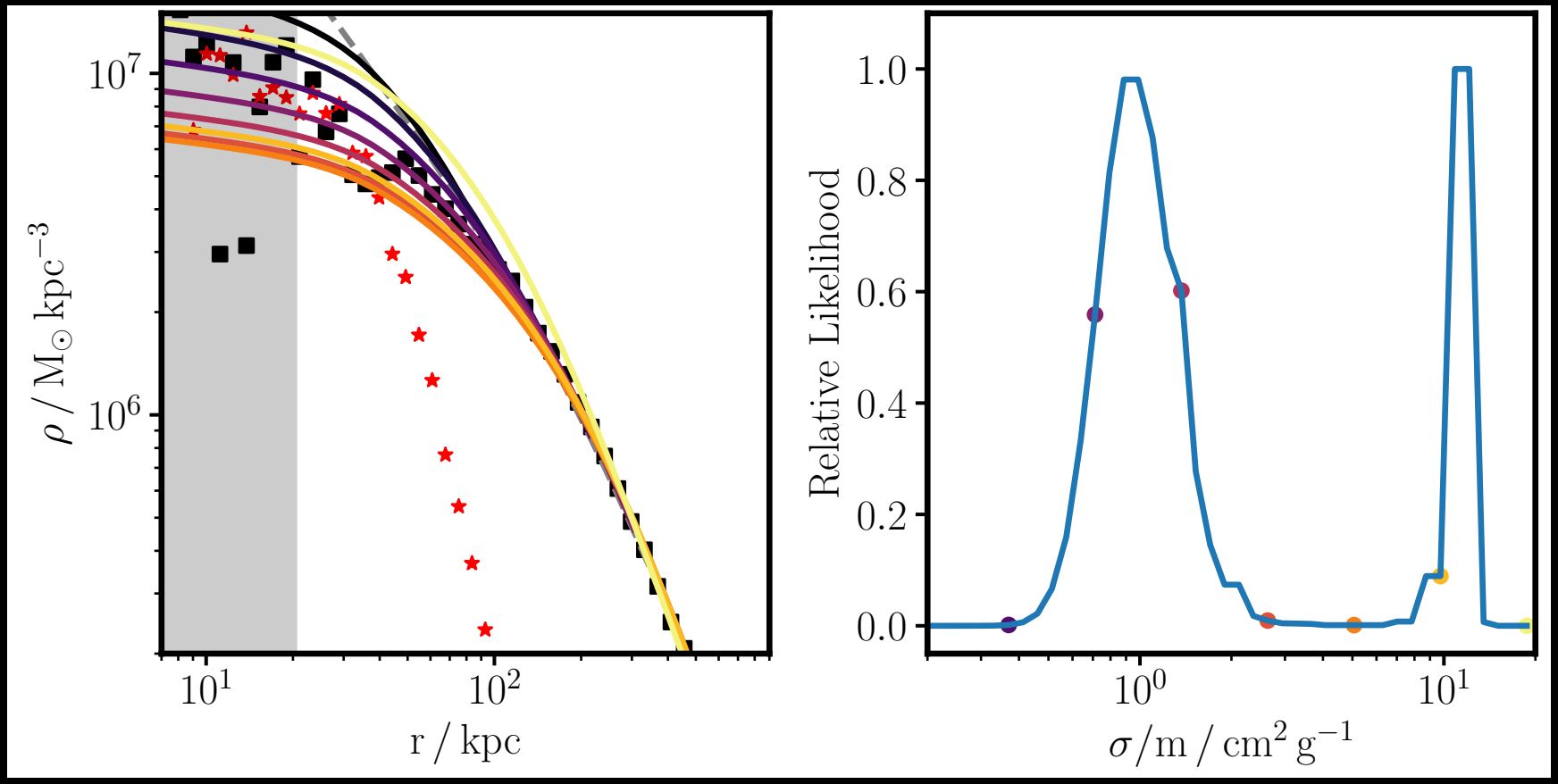
Denser baryonic (stellar) distribution – SIDM halo no longer ‘cored’

OTHER EXAMPLES



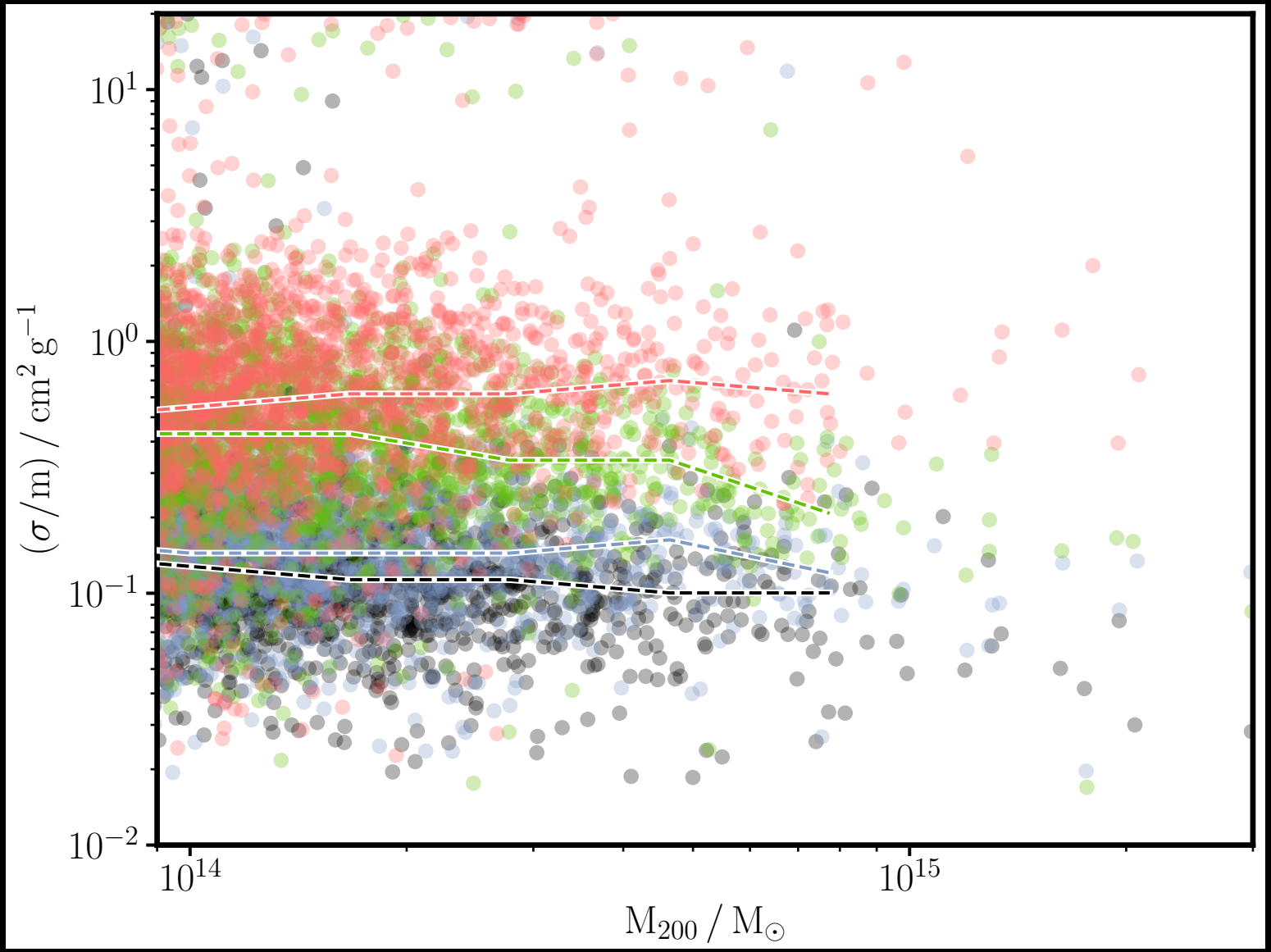
Best-fit cross-section low compared with true one

OTHER EXAMPLES

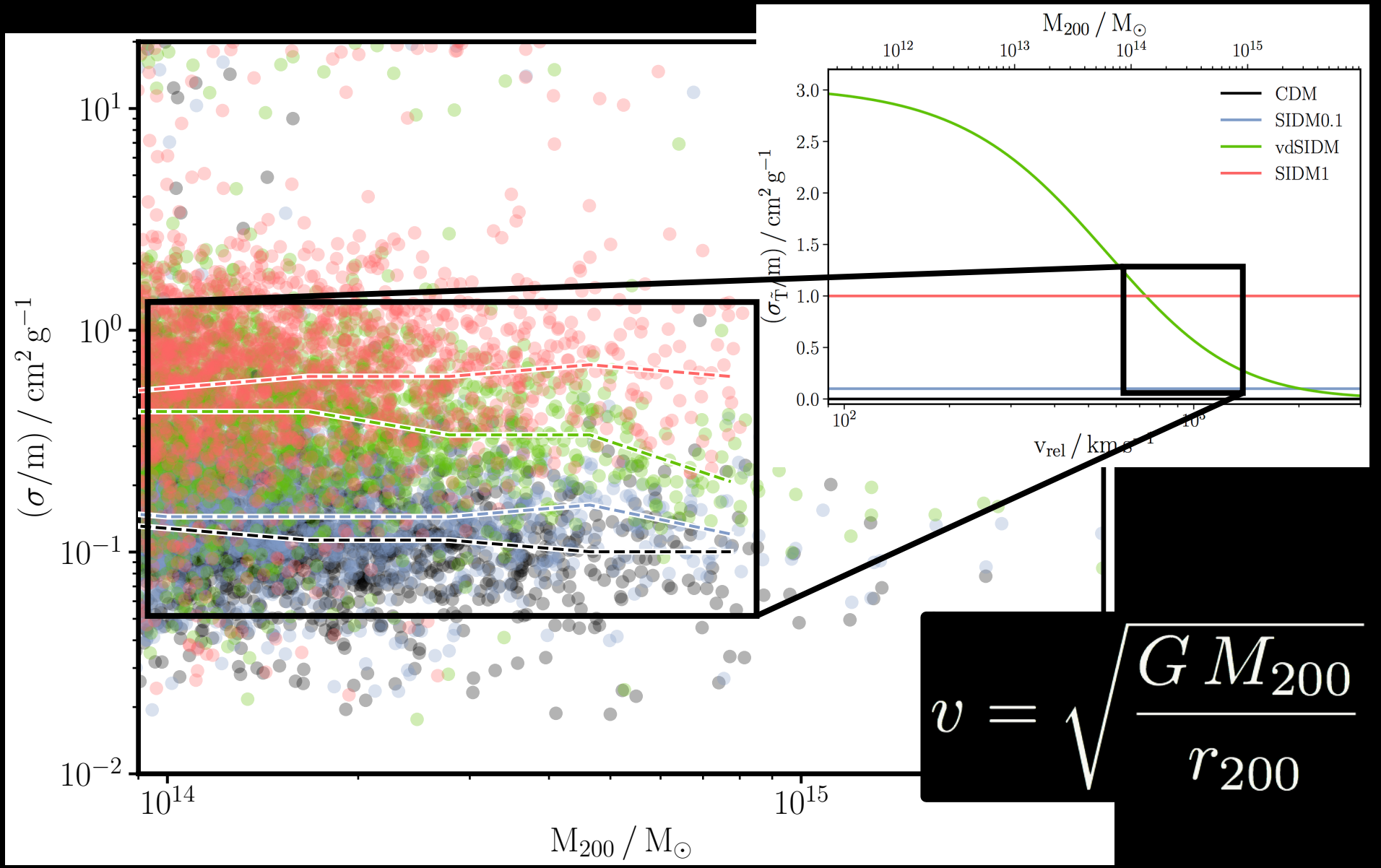


2nd 'core-collapsing' good-fit solution

APPLYING TO ALL HALOES

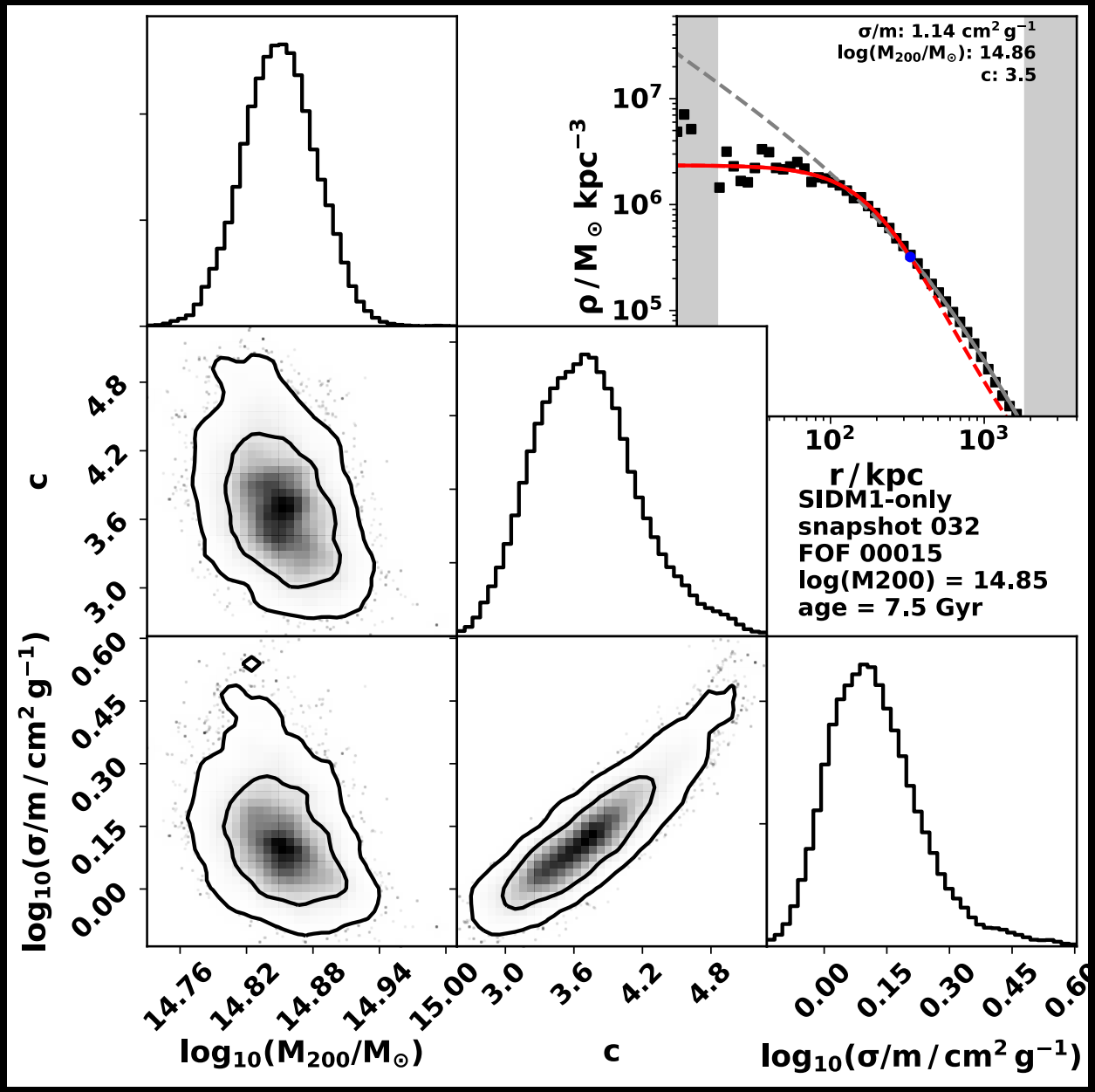


APPLYING TO ALL HALOES

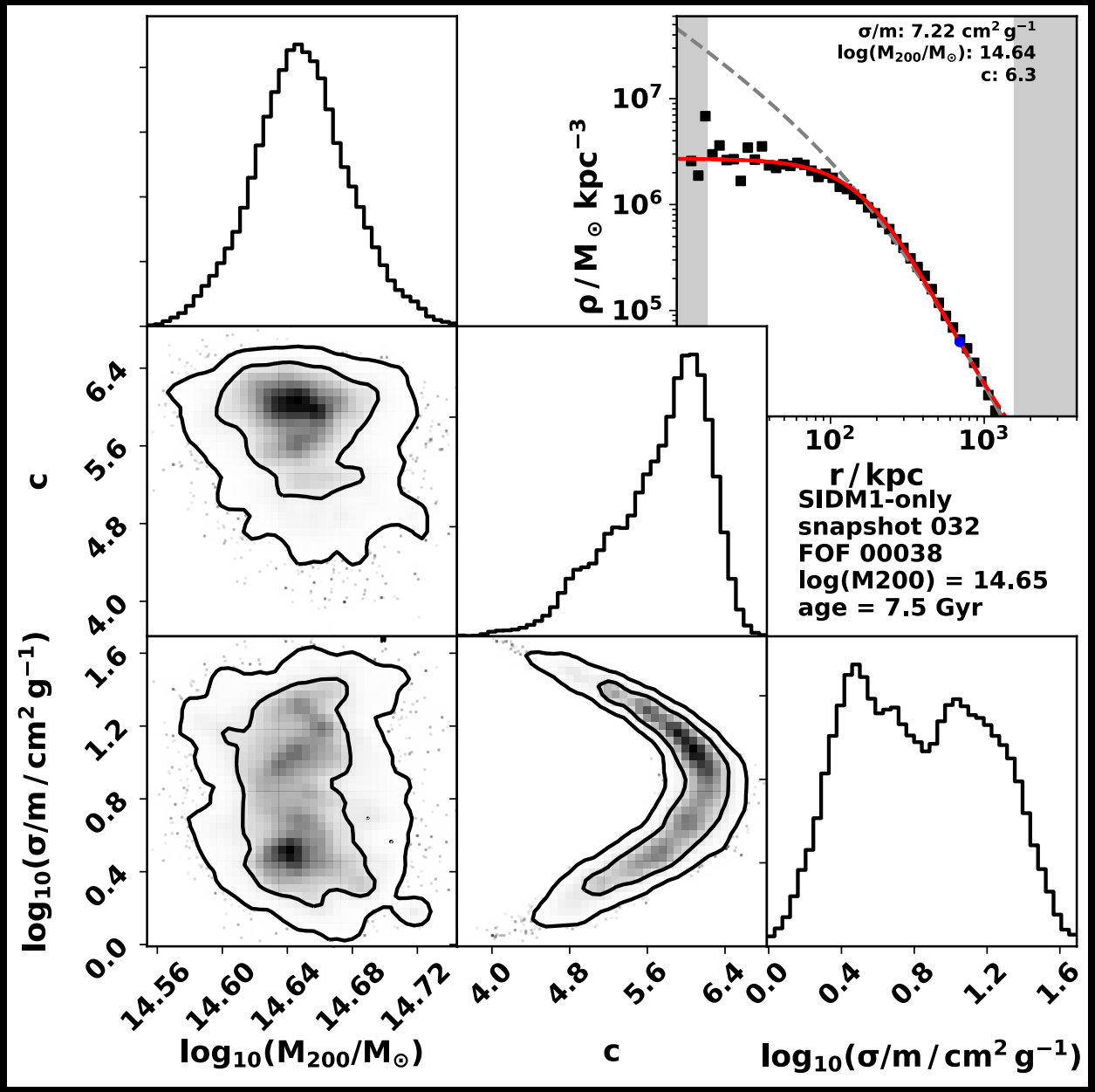


$$v = \sqrt{\frac{G\,M_{200}}{r_{200}}}$$

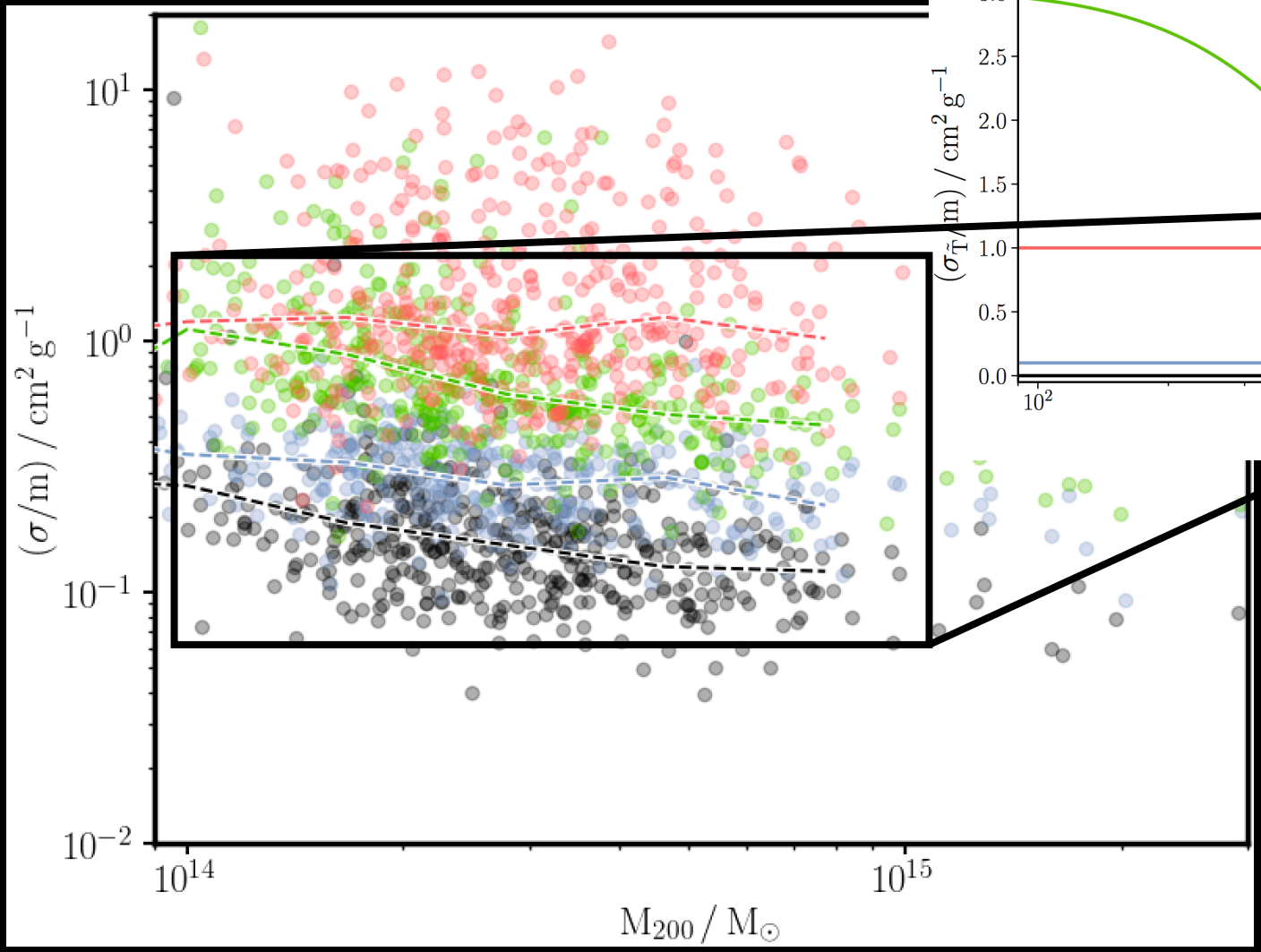
SIMULTANEOUSLY FIT M_{200}, C_{200}, AND σ/m

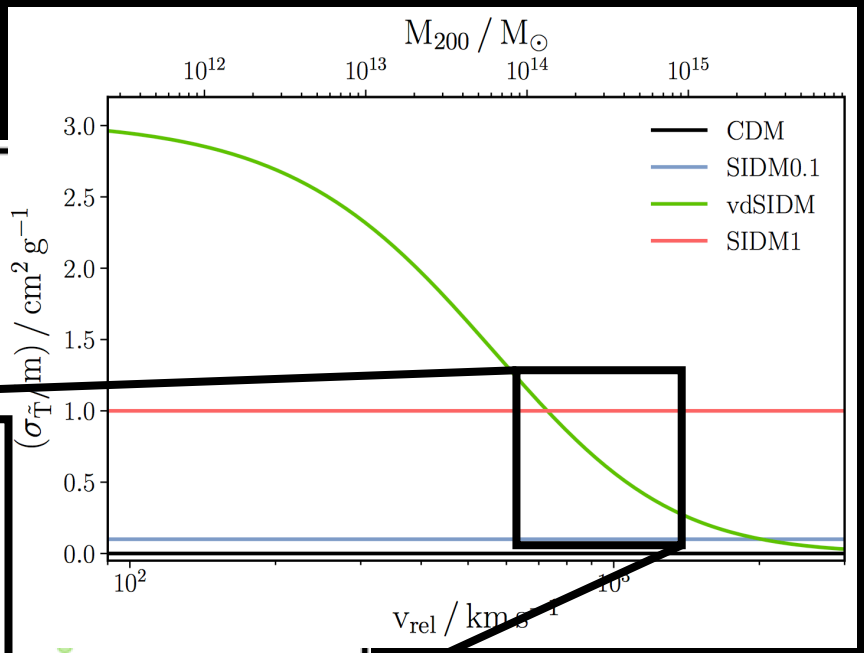


MANY SYSTEMS HAVE BROAD σ/m POSTERIORS

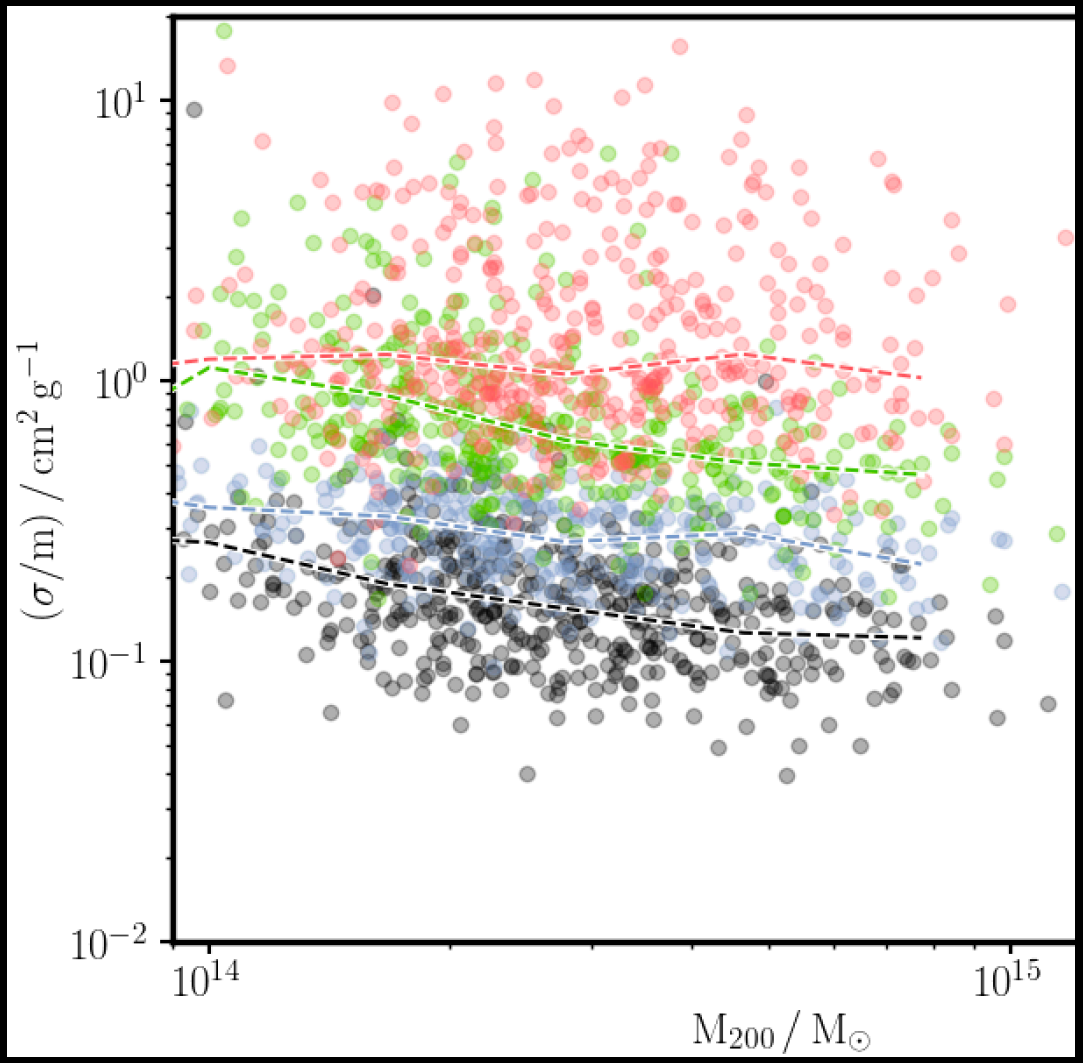


SIDM1 FITS NOW SCATTER AROUND 1CM²/G





TO DO



Perform 3 parameter fits on hydro versions of BAHAMAS

Use SIDM EAGLE and SIDM APOSTLE to extend over a wide range of halo masses

Fit to observationally-motivated quantities
- lensing constraints
- stellar kinematics

Make mock data

Suggestions?

SUMMARY

GALAXY CLUSTERS WITH SIDM+BARYONS DO NOT APPEAR TO HAVE ESPECIALLY DIVERSE MASS DISTRIBUTIONS

STRONG LENSING PROPERTIES AND HALO SHAPES ARE PROMISING PROBES OF SIDM IN CLUSTERS

A THOROUGH INVESTIGATION OF ISOTHERMAL JEANS MODELLING IS HOPEFULLY ON THE WAY ☺

FINDING ρ_0 AND σ_0