Andrew Robertson andrew.robertson@durham.ac.uk

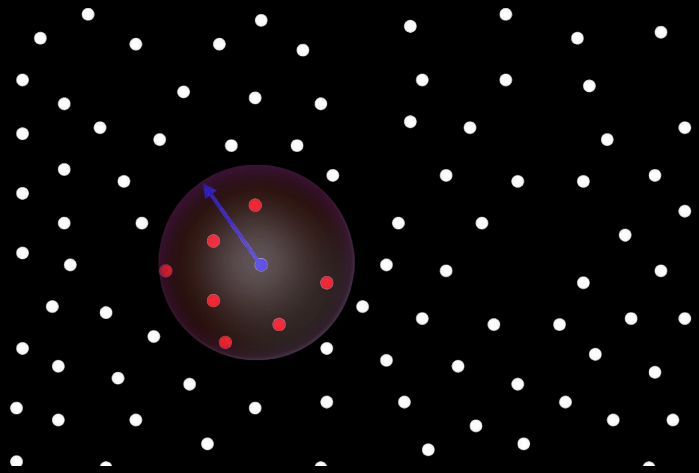
Constraining dark matter self-interactions with galaxy clusters

27th August 2021, EXPLORE Workshop: Astrophysical Laboratories of DM

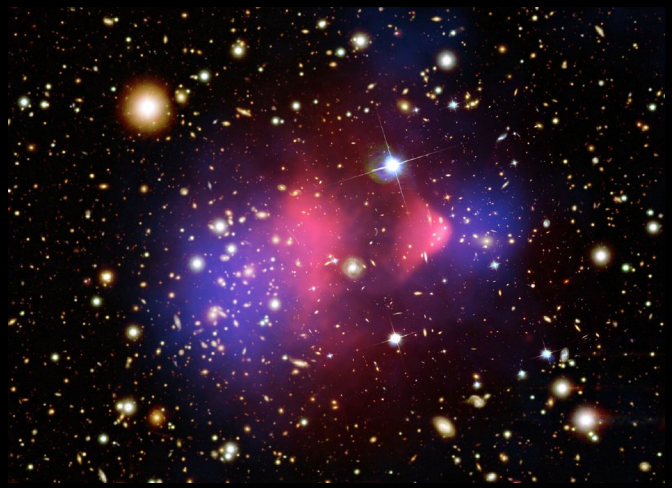
TALK OUTLINE

1. How to run a cosmological simulation

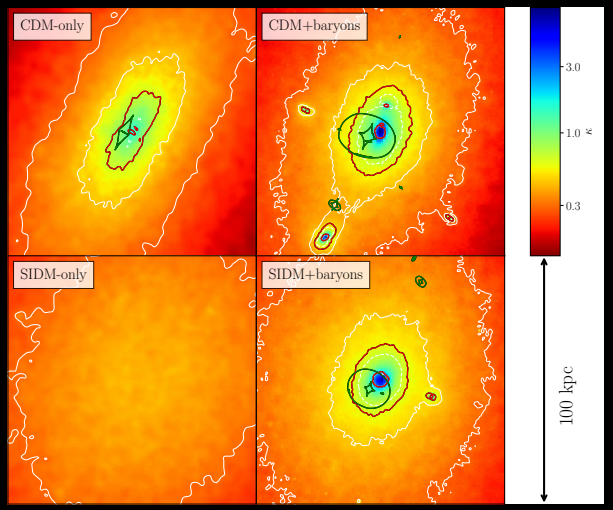
2. Simulating SIDM



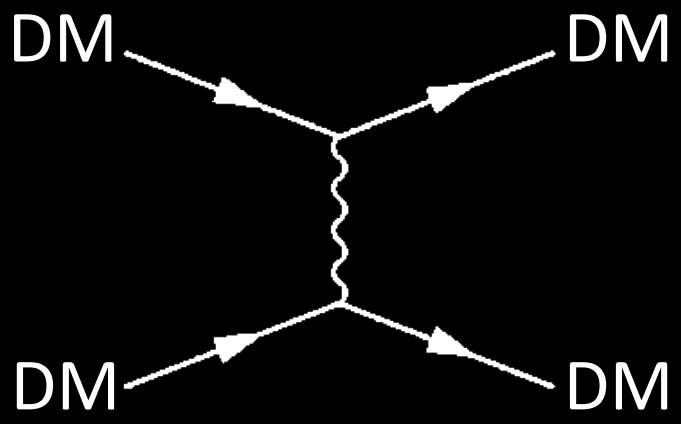
3. The Bullet Cluster with SIDM



4. Galaxy clusters with SIDM

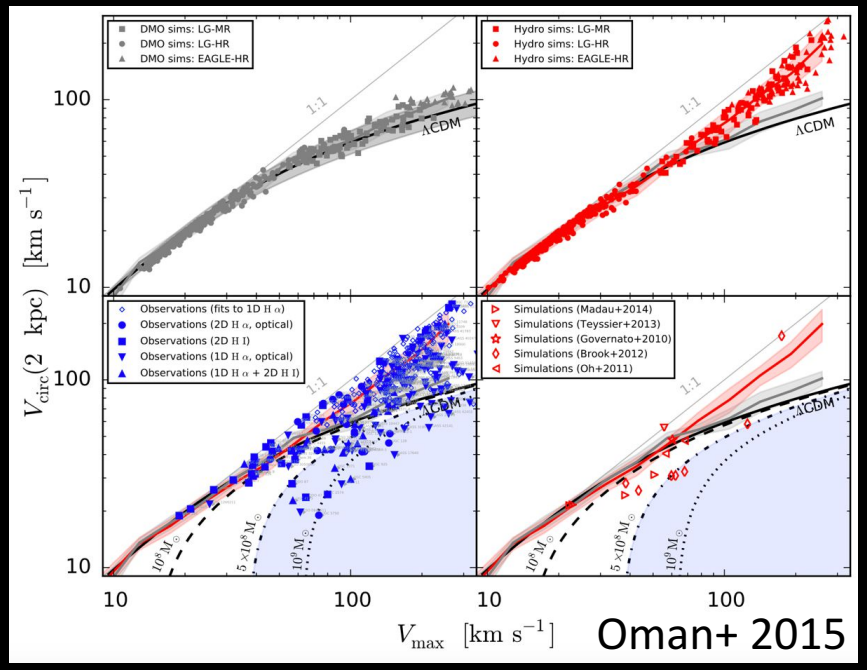


WHAT IS SIDM AND WHY SHOULD WE CARE?



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, too big to fail… 'diversity'

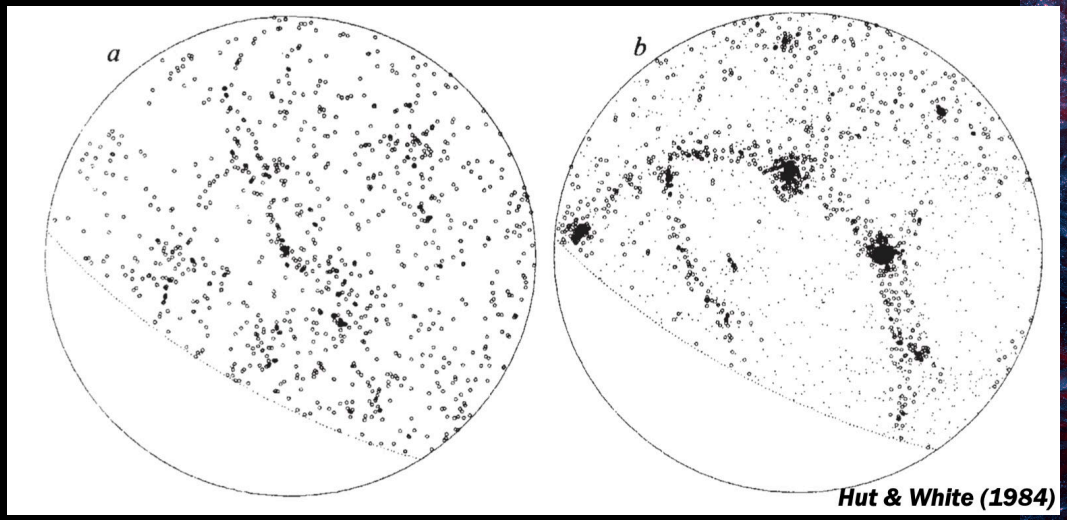


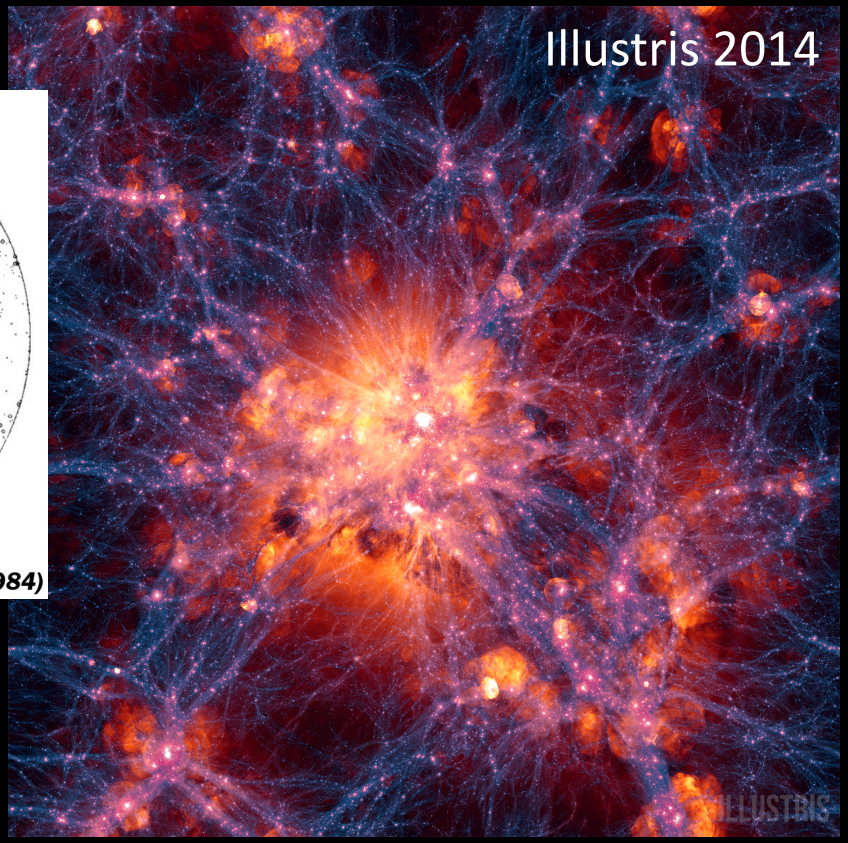
Oman+ 2015

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

A BRIEF INTRO TO COSMOLOGICAL SIMULATIONS

SIMULATIONS HAVE COME A LONG WAY IN 30+ YEARS





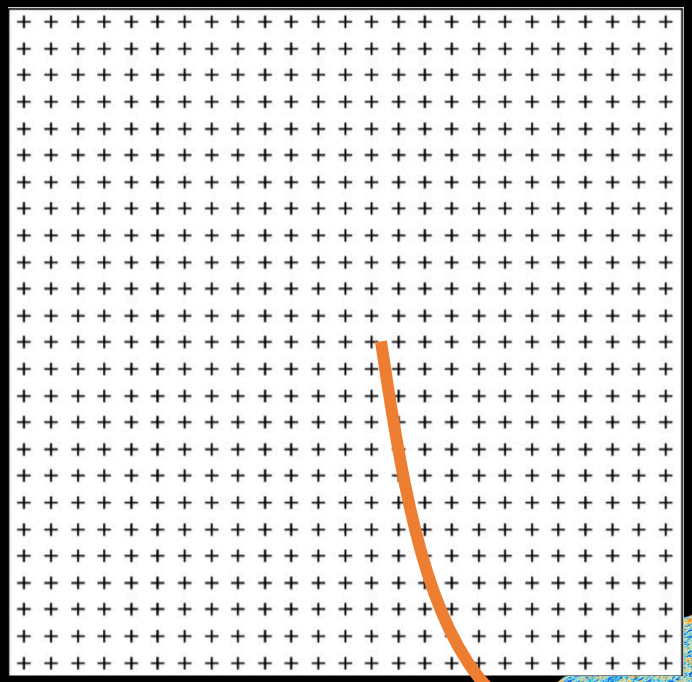
But for now let's consider simulating a dark matter-only universe

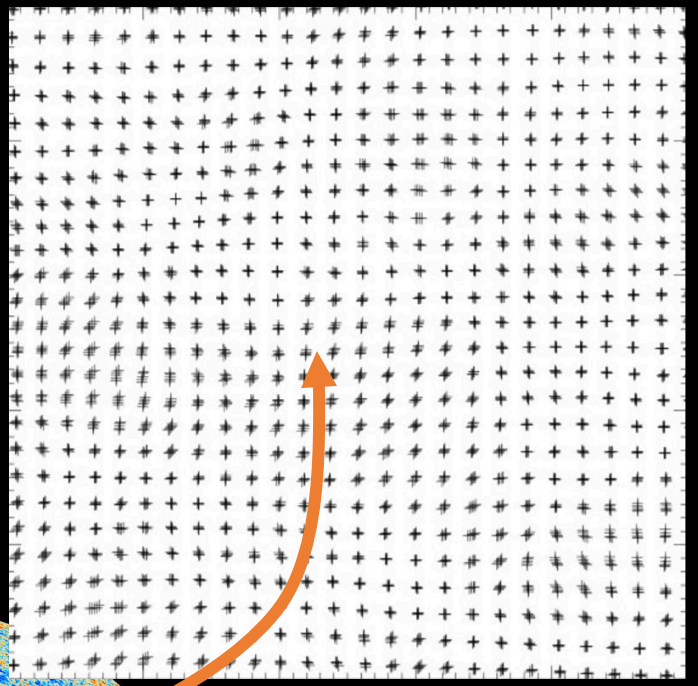
INITIAL CONDITIONS

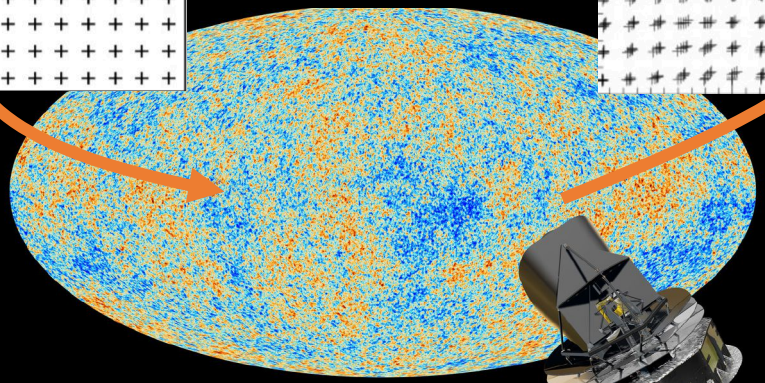
Represent the mass distribution in the universe by many discrete particles

Homogenous and isotropic

With small density fluctuations







Knebe lectures

LET GRAVITY DO ITS THING

HOW DO WE IMPLEMENT GRAVITY?

Evolve the set of particles under the influence of their mutual gravity

$$\vec{a}_i = f(\vec{x}_i)$$

Accelerations are calculated from the particle positions

$$\vec{v}_{i+1/2} = \vec{v}_{i-1/2} + \vec{a}_i \Delta t$$

Velocities are updated based on the accelerations

$$\vec{x}_{i+1} = \vec{x}_i + \vec{v}_{i+1/2} \Delta t$$

Positions are updated based on the velocities

The acceleration of particle i is just the sum of the Gm/r^2 gravitational accelerations due to each of the other particles

$$\vec{a}_i = \sum_{j \neq i} \frac{\mathrm{G}\, m_j \, (\vec{x}_j - \vec{x}_i)}{|\vec{x}_j - \vec{x}_i|^3}$$

For N particles, there are $N(N-1)/2 \sim N^2$ pairs. With large N this would require an awfully large amount of computer time…

A "BACK OF THE ENVELOPE" CALCULATION

Potter+ 2017

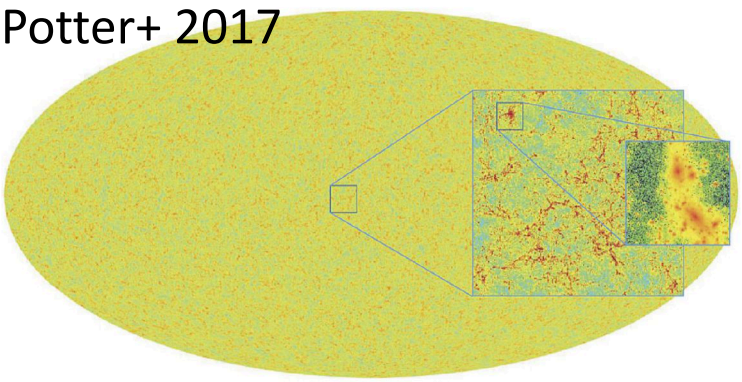


Figure 2 Simulated full-sky matter distribution from a 2 trillion particles simulation. The zoom-in quadrant shows the non-linear, filamentary structure of the universe on small scale.

2 trillion particles

400 petaflops

TECHNOLOGY

Japan's Fugaku keeps position as world's fastest supercomputer

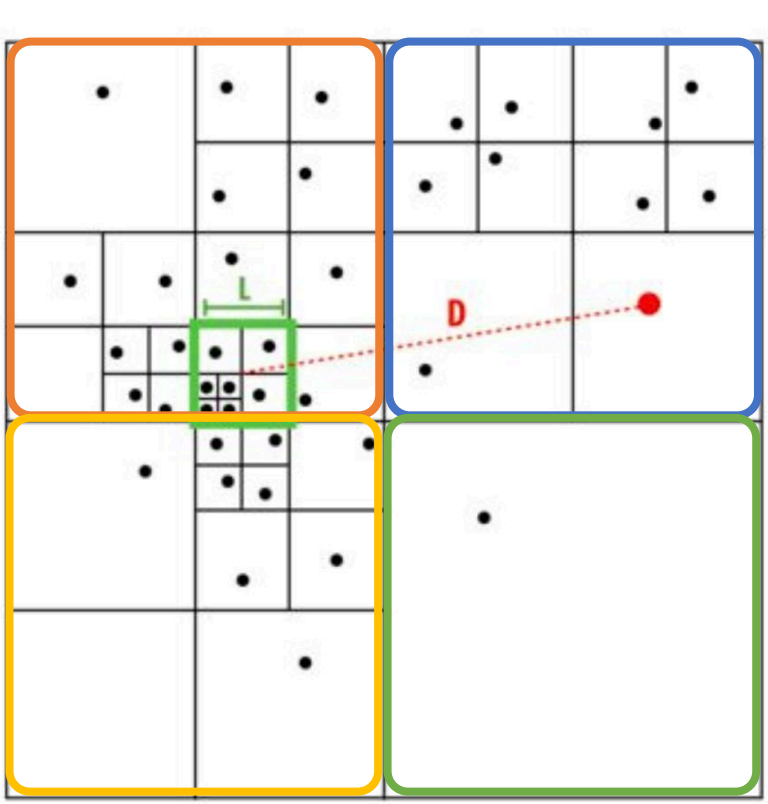
Fujitsu-Riken model also ranks highest in AI performance and big data processing

One force calculation using the "brute force" approach:

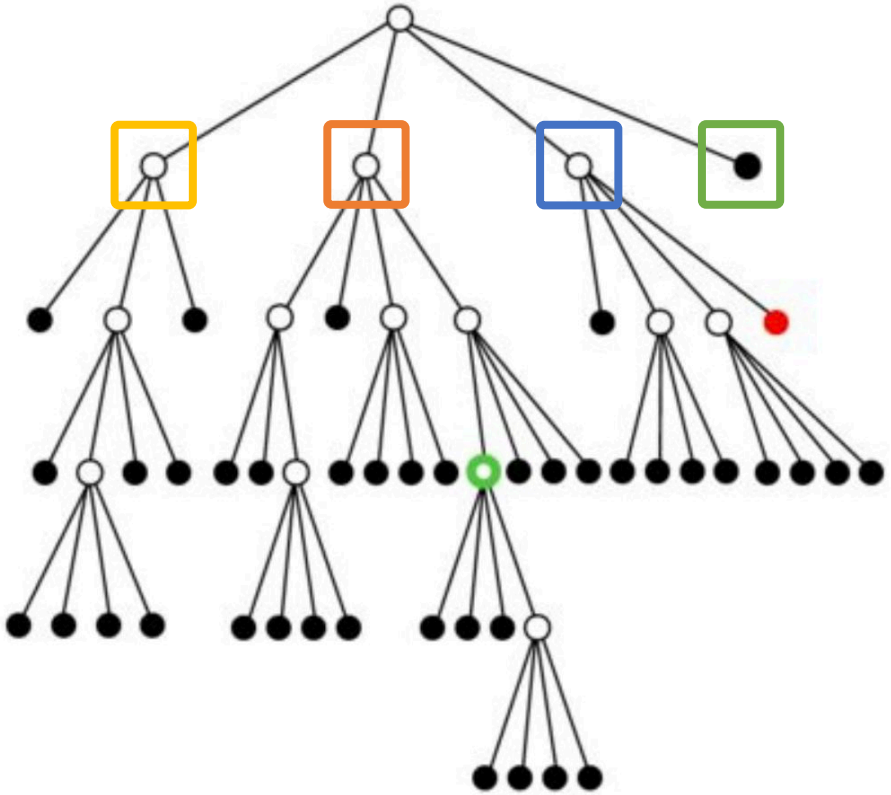
$$(2 \times 10^{12})^2 / 4 \times 10^{17}\,\mathrm{s}^{-1} = 10^7\,\mathrm{s} = 16\,\mathrm{weeks}$$

This is not how we run simulations!

BARNES-HUT TREE ALGORITHM



Spatial Domain



Quad-Tree Representation

In essence, particles that are far away do not need to be treated individually, but can instead be grouped together before calculating the force due to them

SIMULATING SIDM

SIMULATING SIDM - AN INTERMEDIATE REGIME

COLLISIONLESS (i.e. CDM)

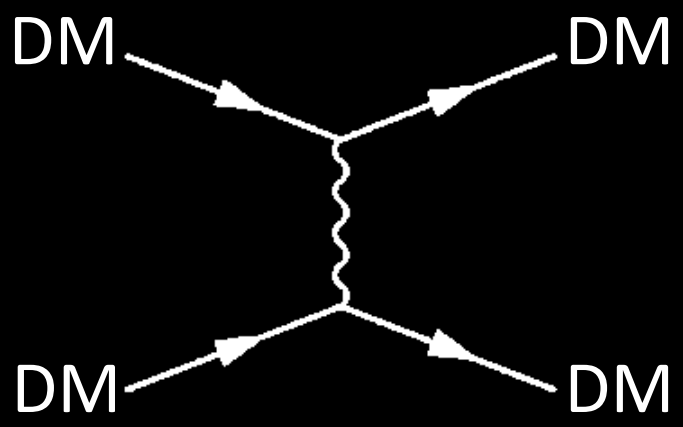
- Gravity
- Collisionless Boltzmann Equation

➔ N-body methods (Tree or Particle Mesh)

COLLISIONAL (i.e. gas)

- Gravity + Hydrodynamics
- Fluid Equations

➔ Discretize space (grid) or mass (SPH)



O(1) Collision per Hubble Time (SIDM)

- Gravity + Scattering

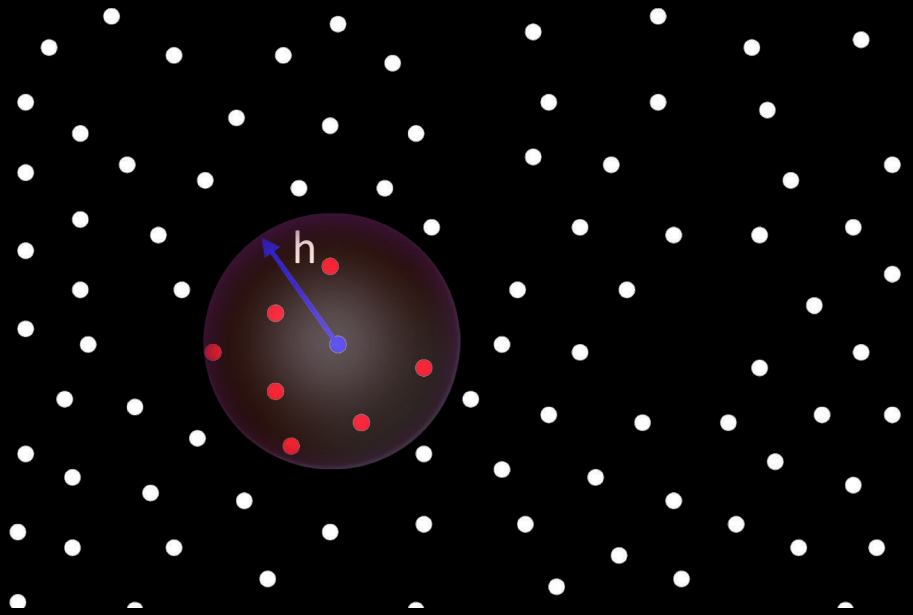
➔ N-body + Monte Carlo Scattering

CALCULATING SCATTERING PROBABILITIES

Scattering rate given by: $$\Gamma = \frac{dn}{dt} = \int f(\mathbf{v_1}) \frac{\rho\, \sigma_\chi}{m_\chi} |\mathbf{v_0} - \mathbf{v_1}|\, d^3\mathbf{v_1}$$

Probability of particle i scattering from particle j, in time Δt is:

$$P_{ij} = \frac{\frac{\sigma_\chi}{m_\chi} m_\mathrm{p} |\mathbf{v_i} - \mathbf{v_j}| \Delta t}{\frac{4\pi}{3} h^3}$$



Local density and velocity distribution estimated from region within ‘search radius’, h

At each time-step, draw a random number for each pair of particles to see if they scatter


SIDM AND
THE BULLET CLUSTER

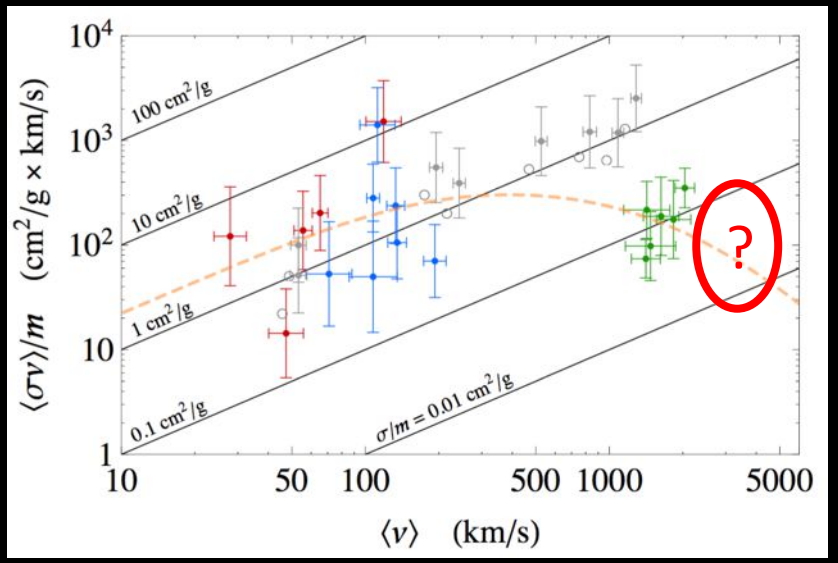
WHY LOOK AT MERGING GALAXY CLUSTERS?

Particle Collider for Dark Matter!

High speeds and densities, so large scattering rates

Particles collide preferentially along a particular axis

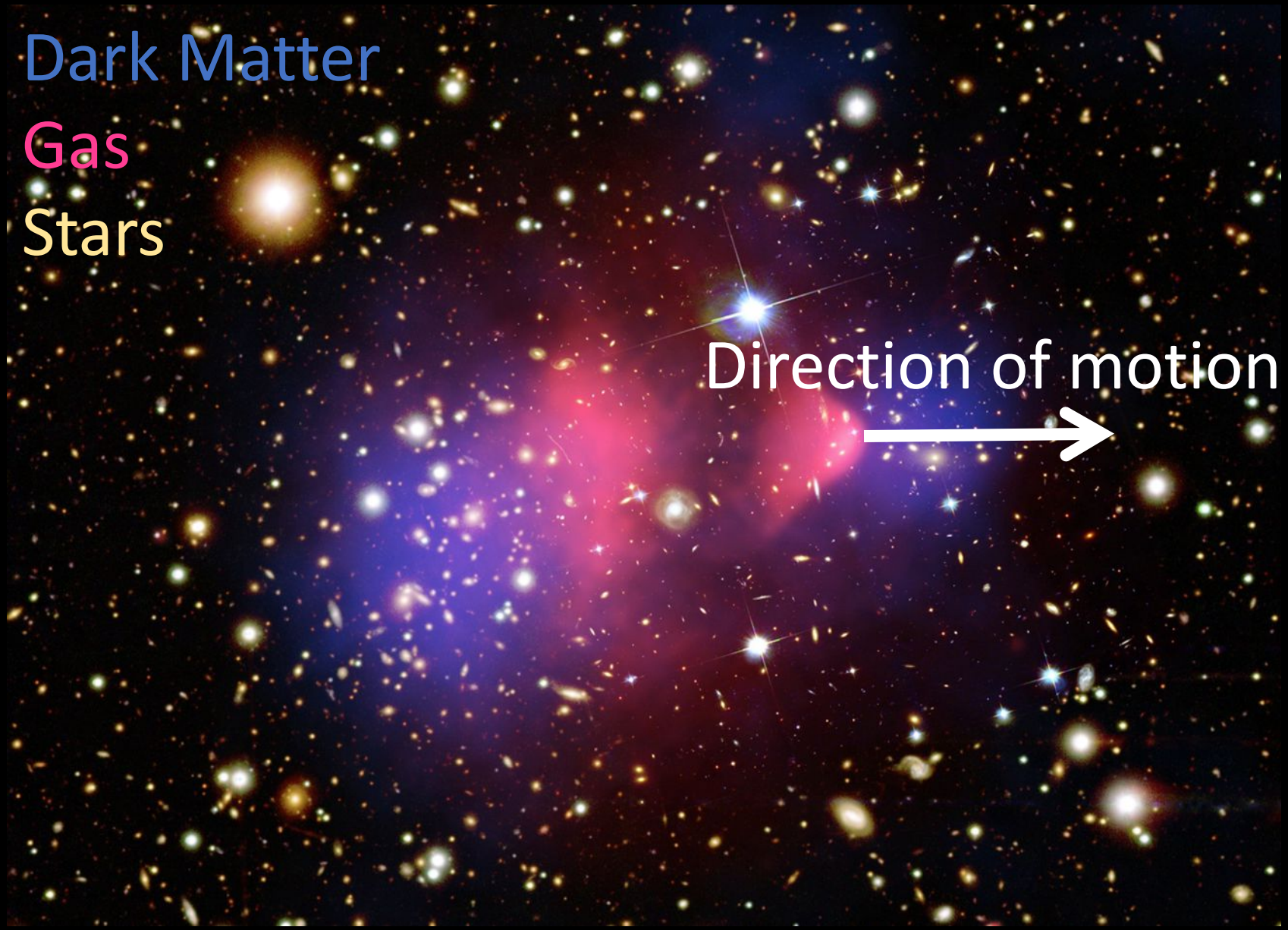
High DM-DM velocities probe the cross-section at a different energy scale



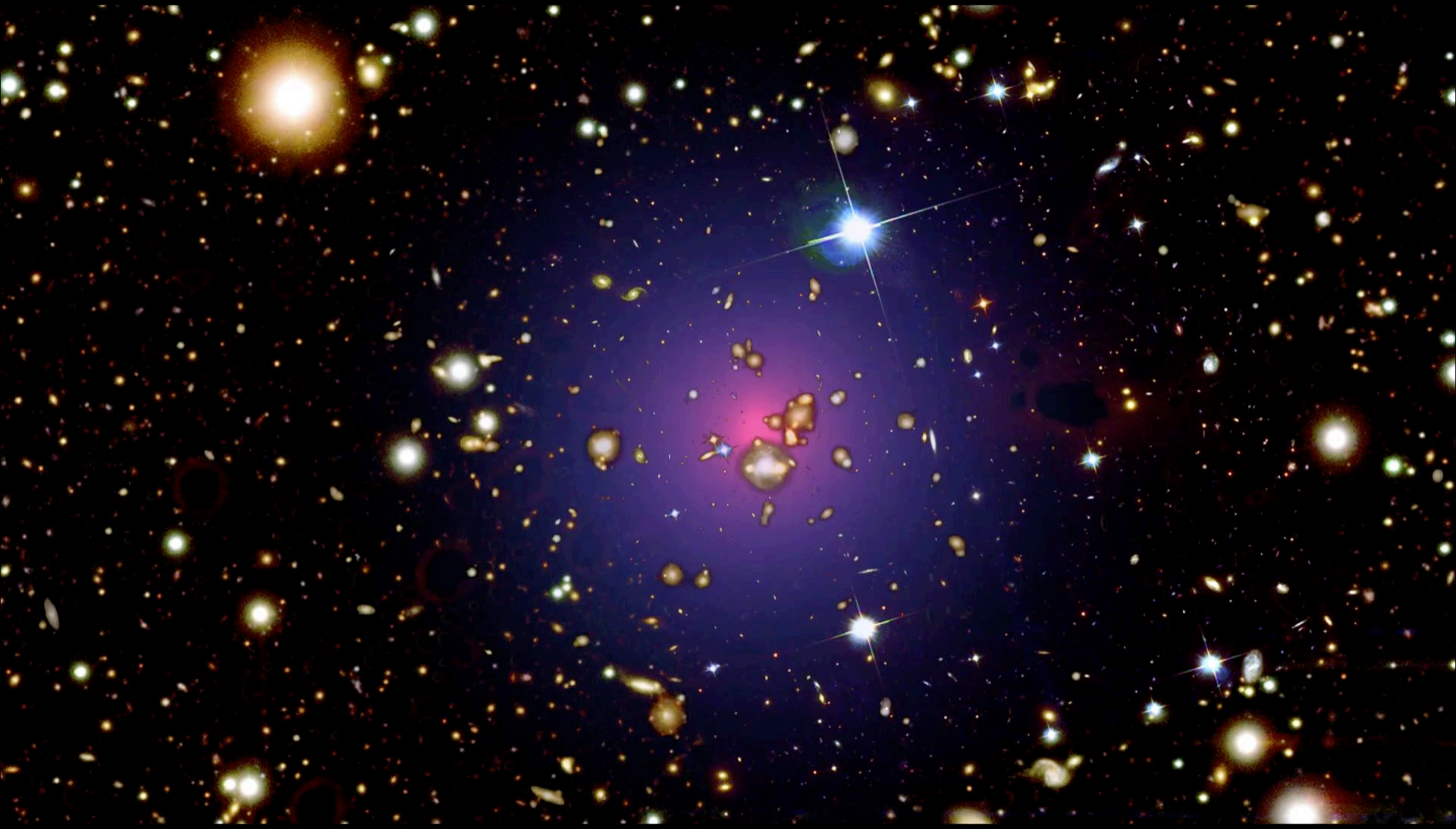
Kaplinghat+ 2016

If DM has a velocity dependent cross-section, then information on DM scattering at different velocities provides complementary information

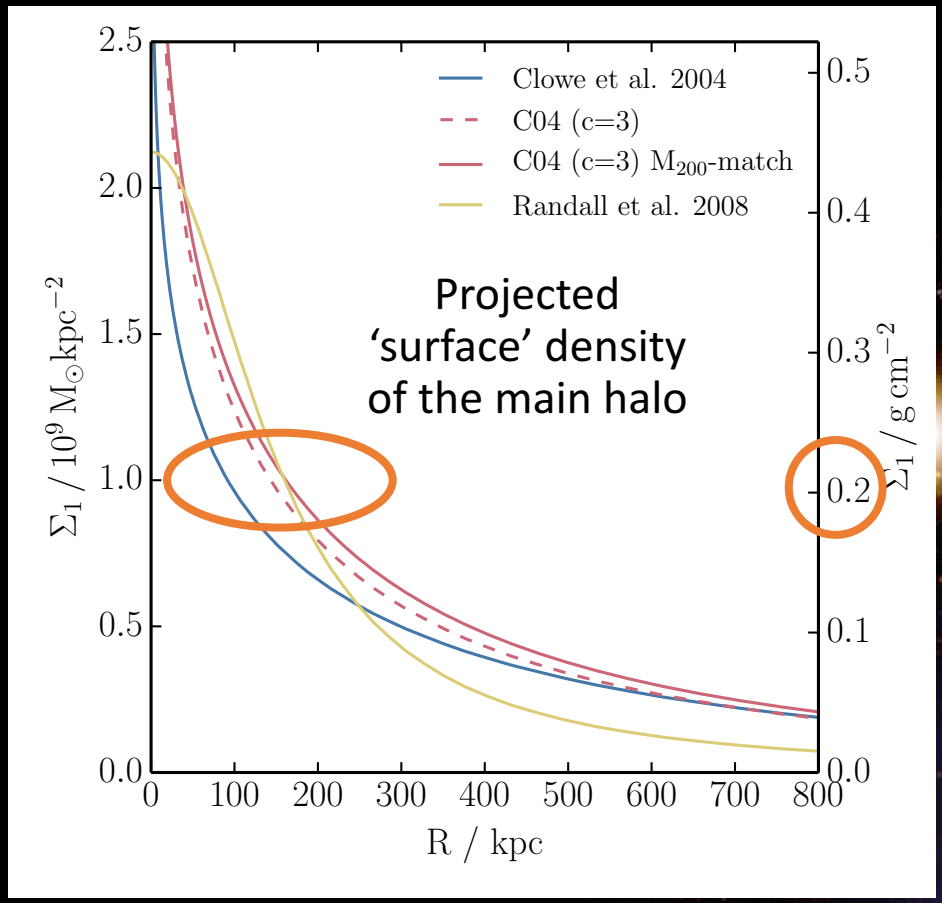
COSMIC PARTICLE COLLIDERS



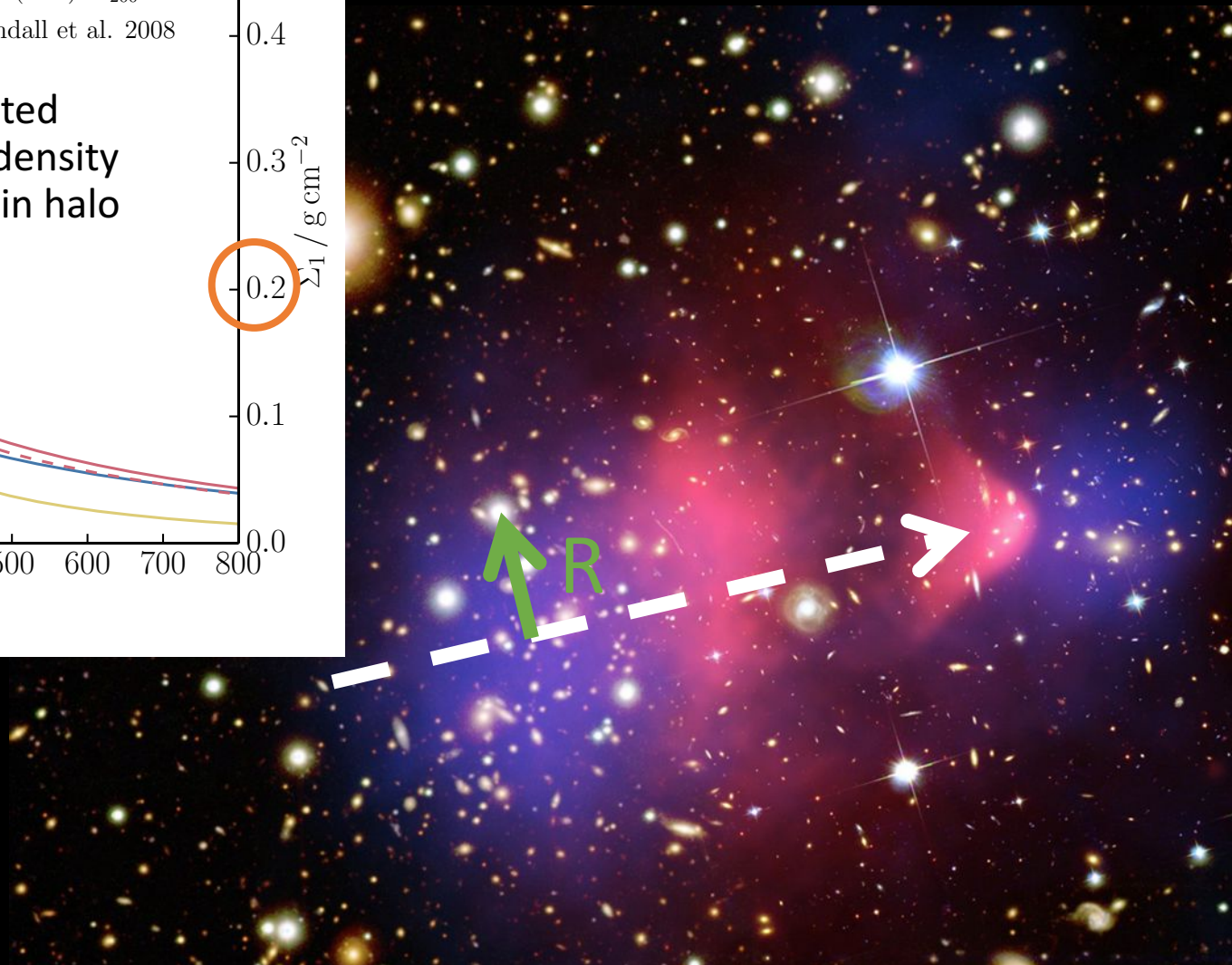
THE BULLET CLUSTER WITH COLLISIONLESS DM



SURVIVAL OF THE BULLET HALO

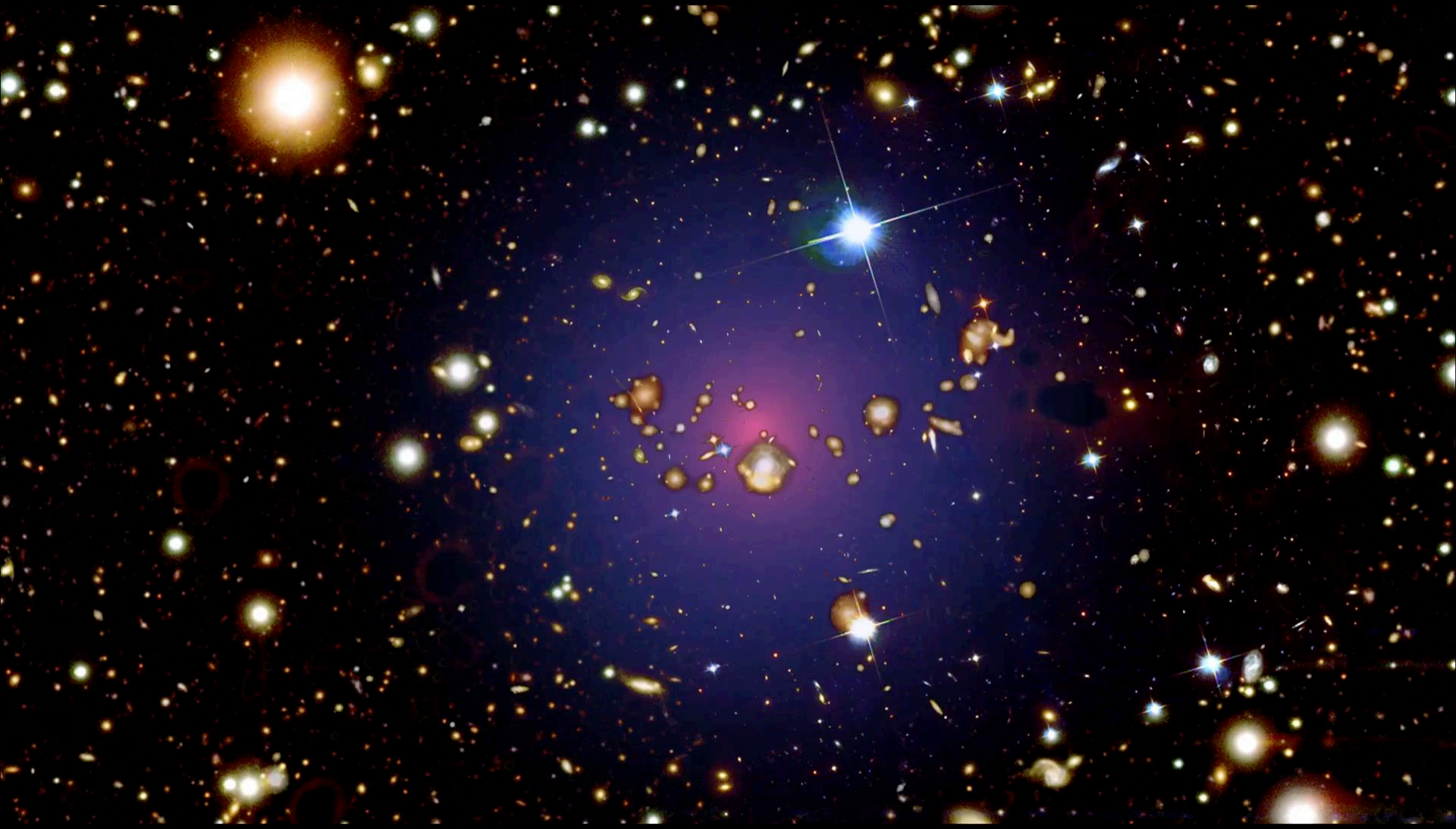


$$\sigma/m \lesssim 5\,\mathrm{cm}^2\,\mathrm{g}^{-1}$$

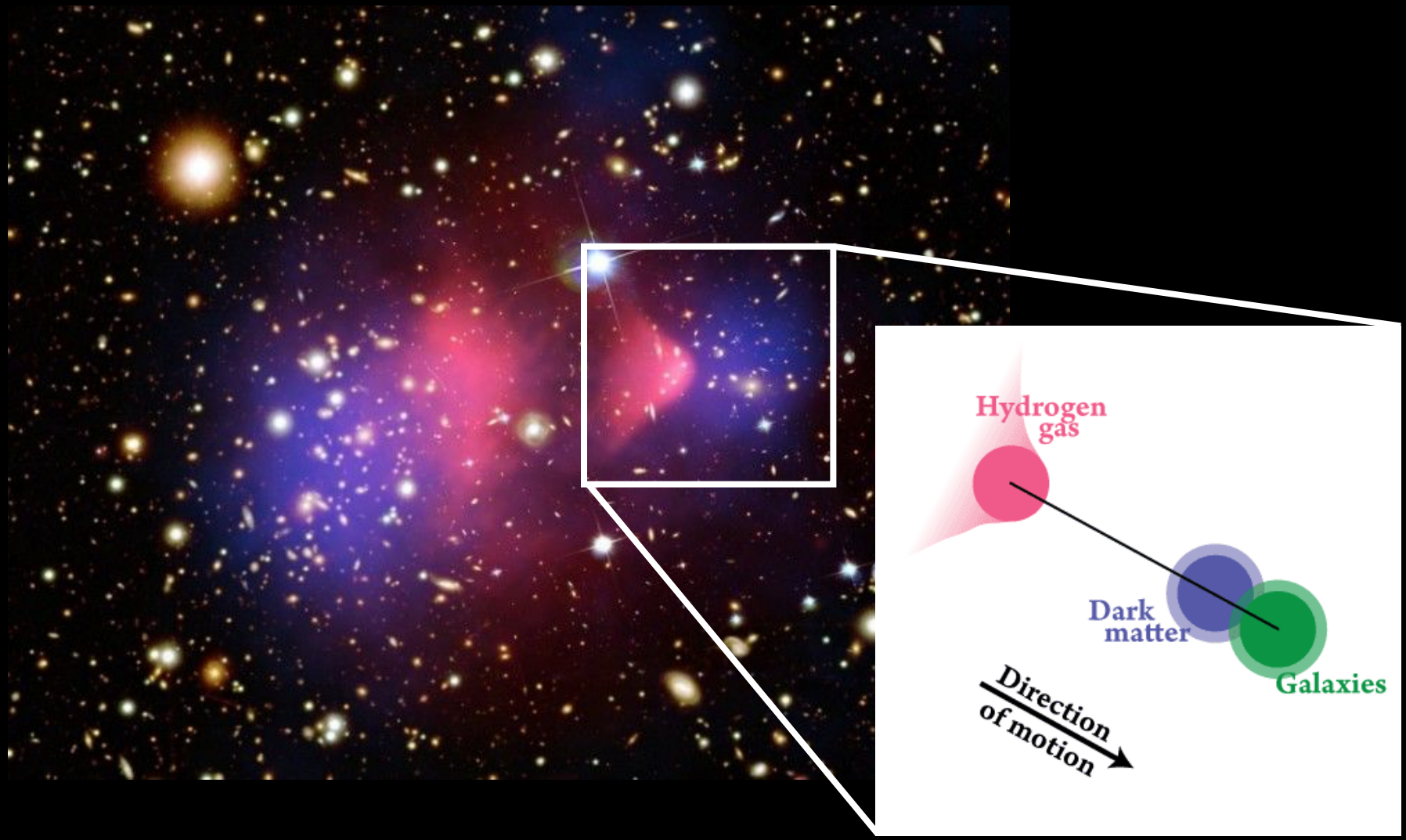


$$\tau = \Sigma \frac{\sigma}{m}$$

INCLUDING SIDM WITH A LARGE CROSS-SECTION

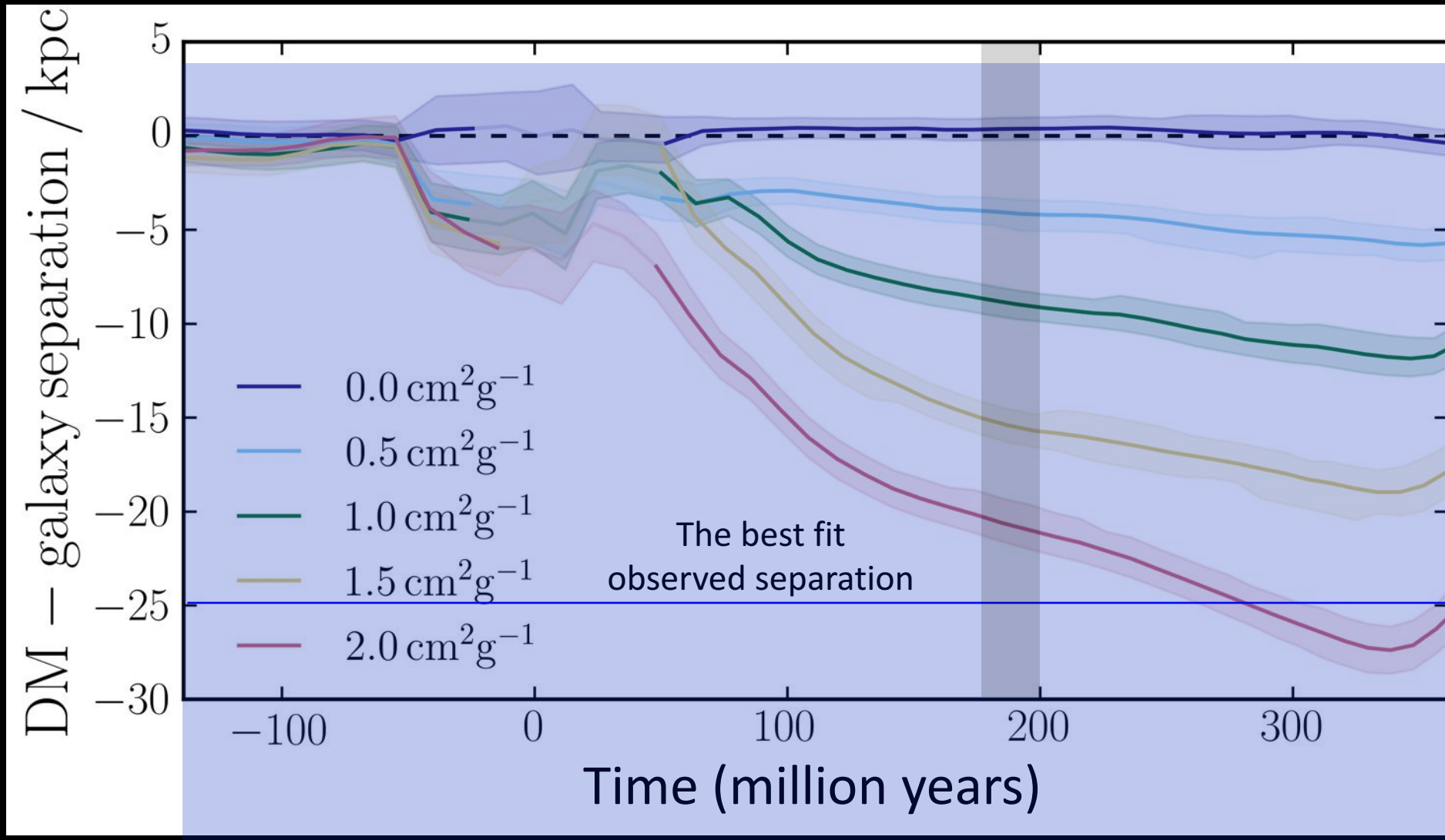


THE BULLET CLUSTER – A TOY MODEL



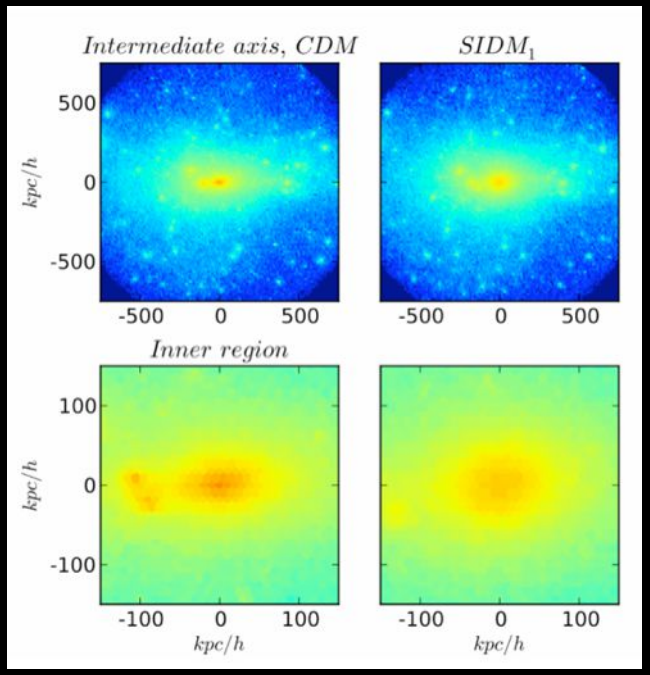
Harvey+ 2014

DM–GALAXY OFFSETS




ISOLATED
GALAXY CLUSTERS

PREVIOUS CLUSTER CONSTRAINTS

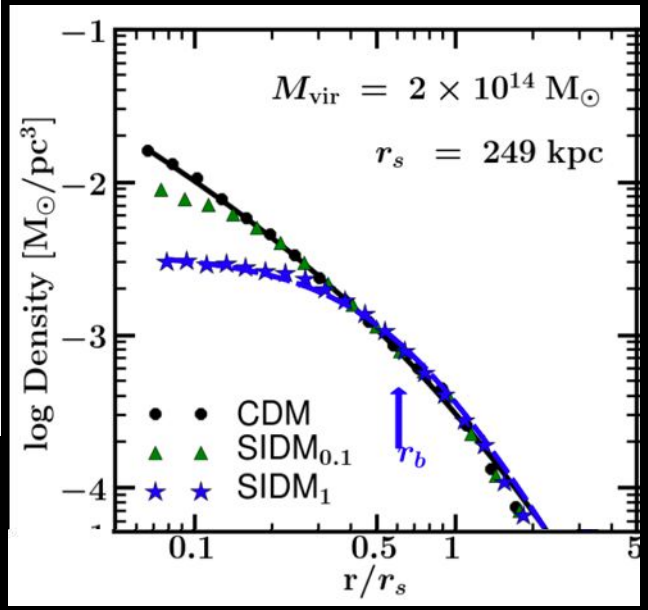


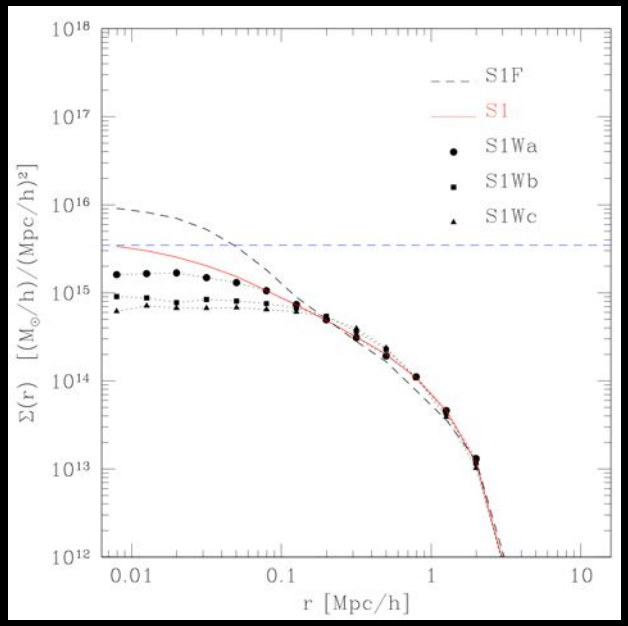
Halo shapes - Peter+ 2013

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

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

Core sizes - Rocha+ 2013





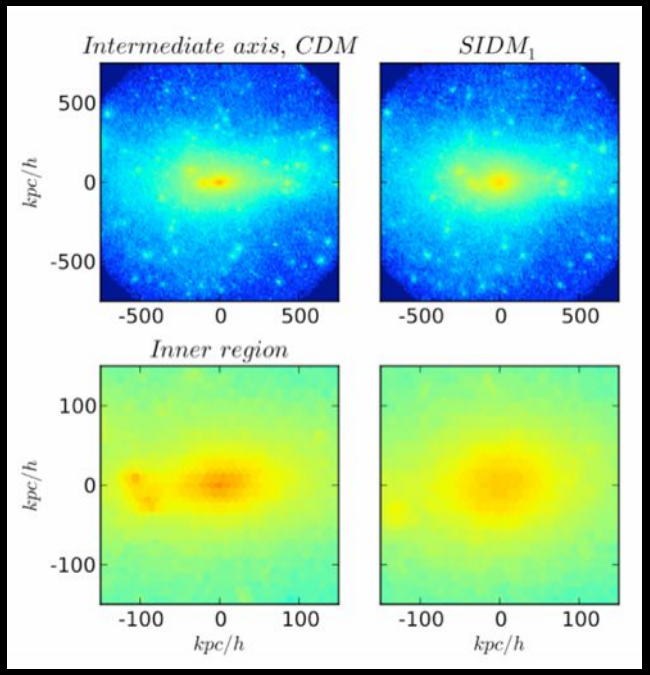
Strong lensing

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

PREVIOUS CLUSTER CONSTRAINTS

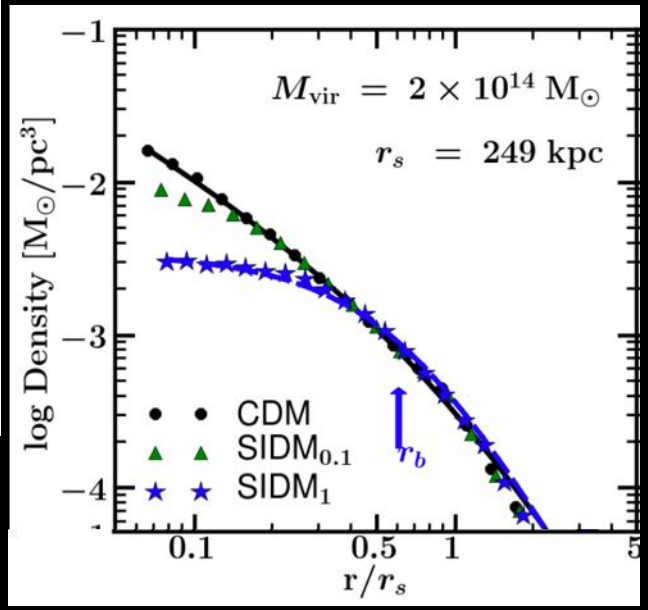


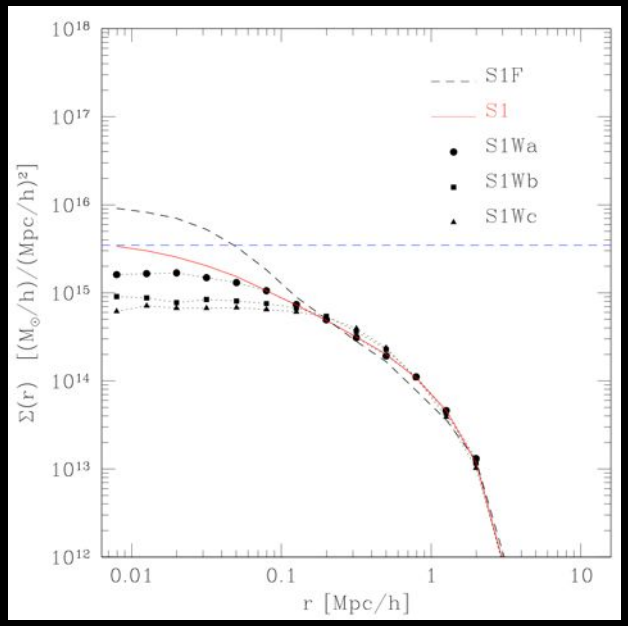
Halo shapes - Peter+ 2013

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

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

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

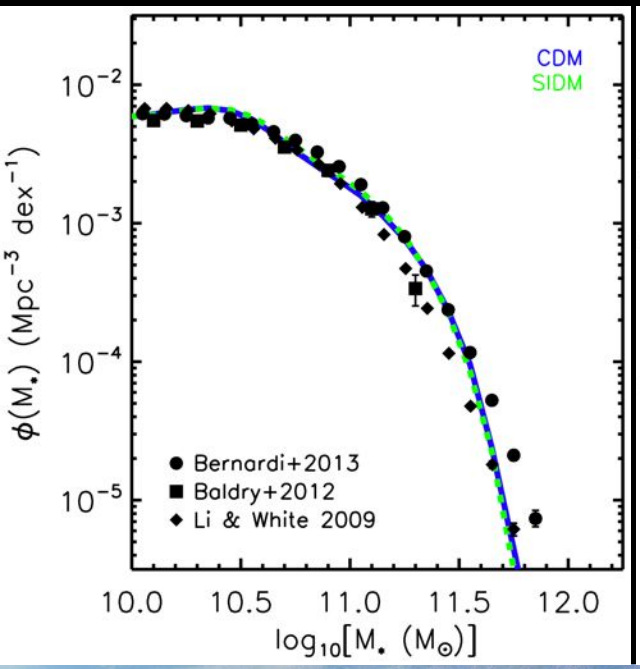
Do baryons change any of this?

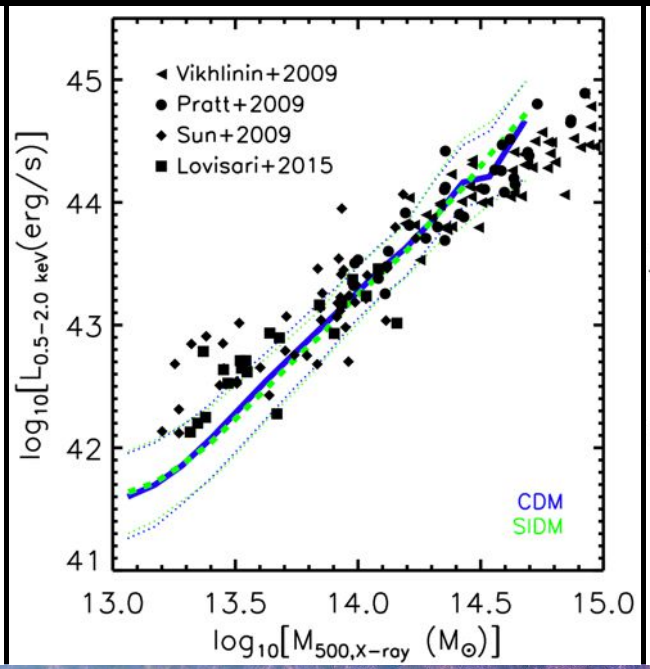
BAHAMAS-SIDM

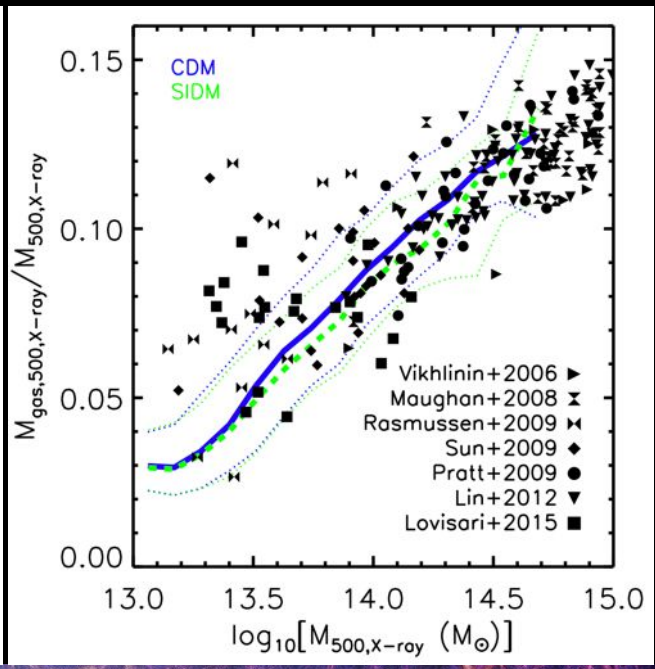
A LARGE SAMPLE OF GALAXY CLUSTERS SIMULATED WITH SIDM+BARYONS

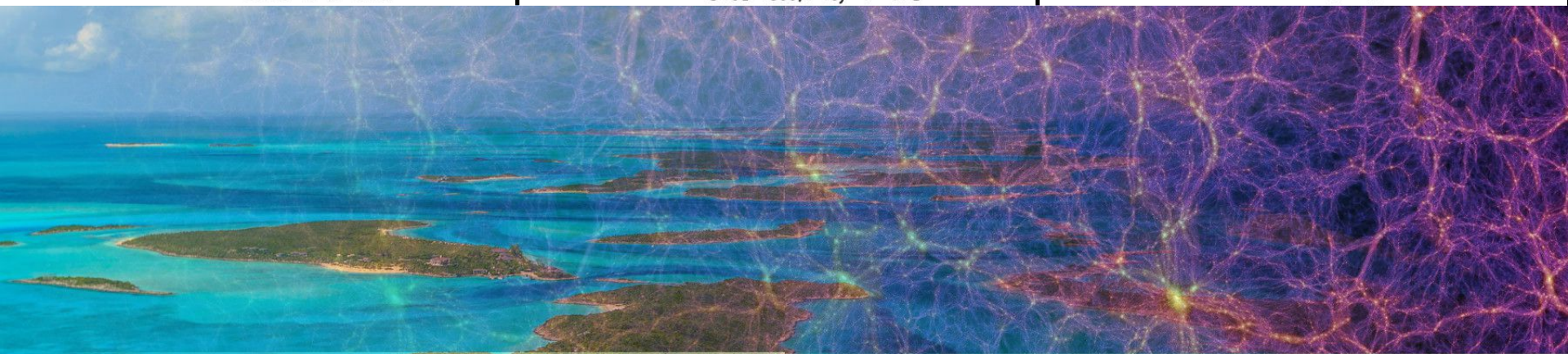
BAHAMAS

- 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





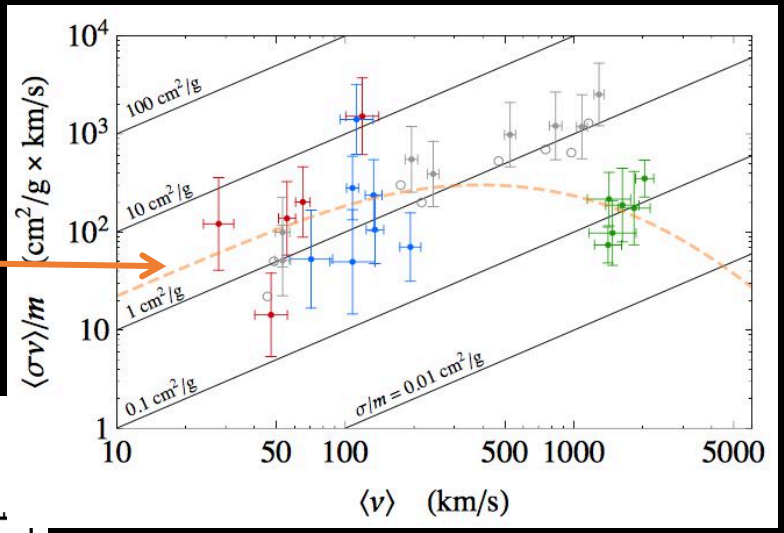




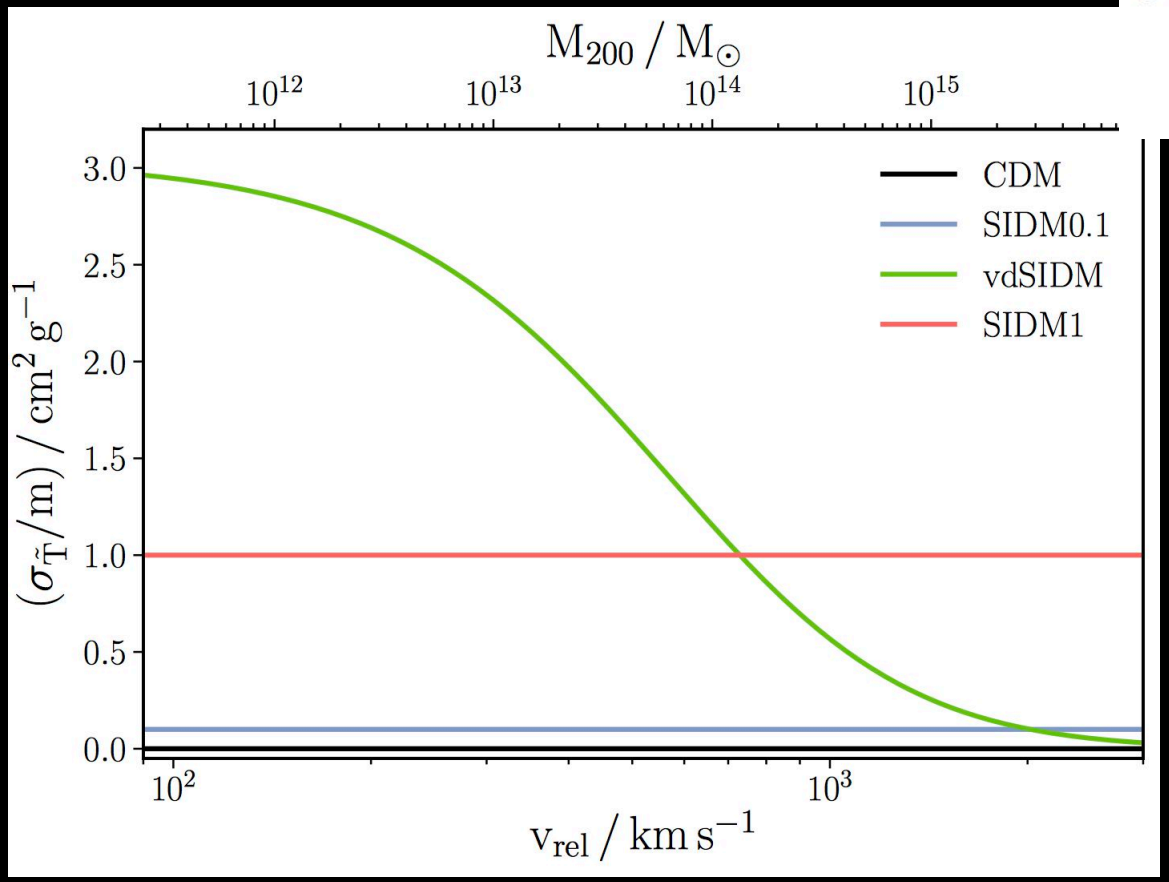
SIMULATED CROSS-SECTIONS

SIDM cross-sections:

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

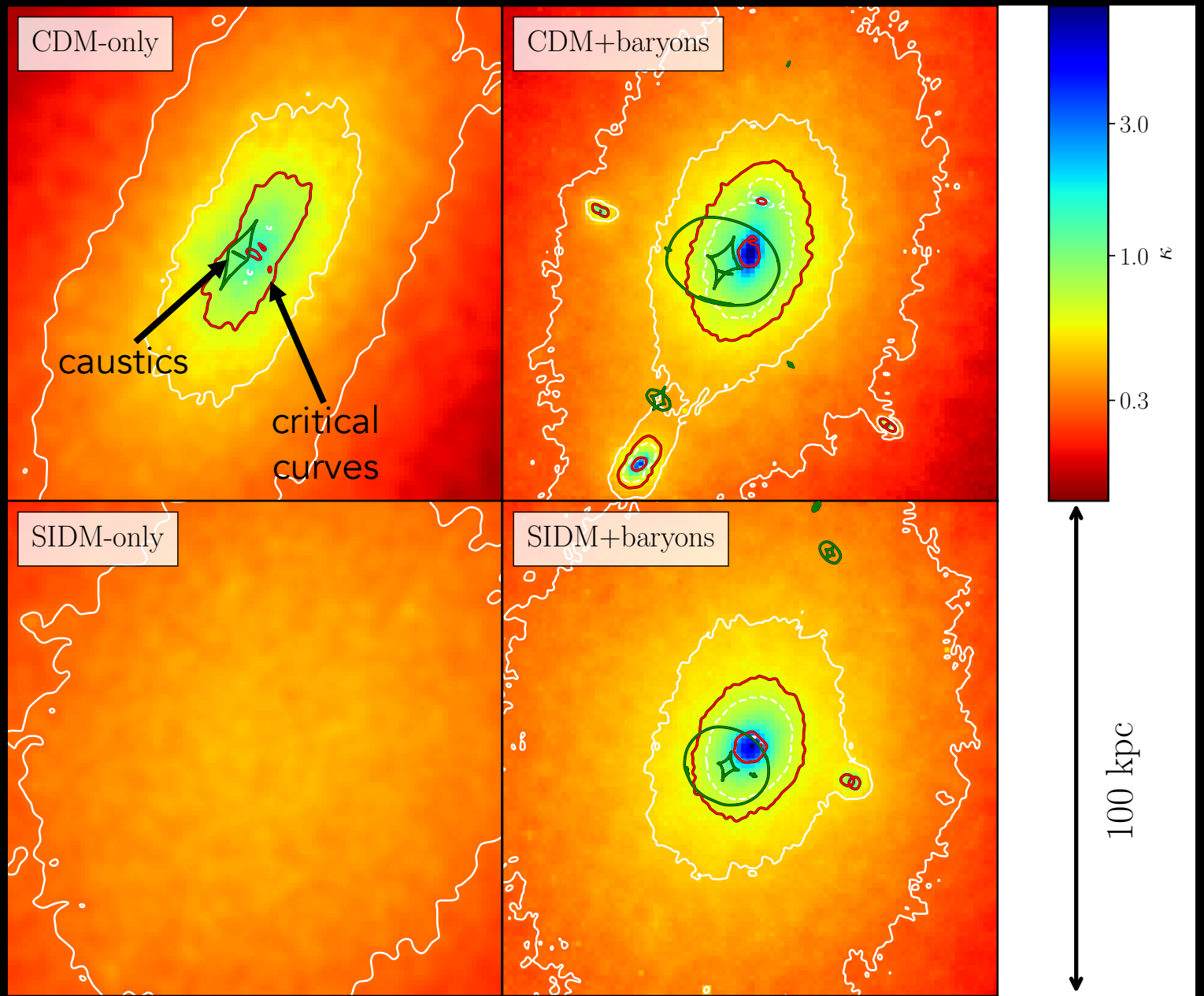


Kaplinghat+ 2016

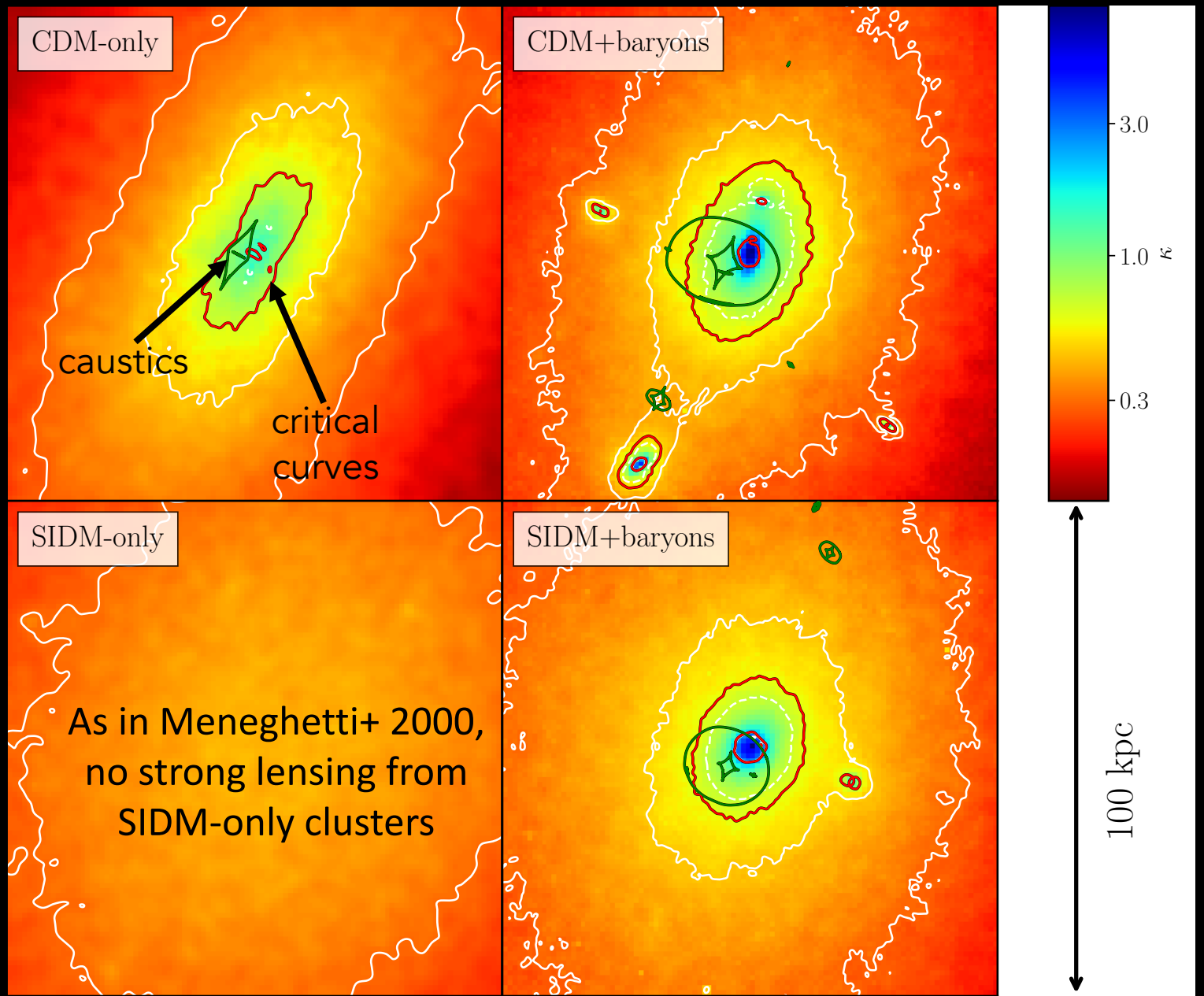


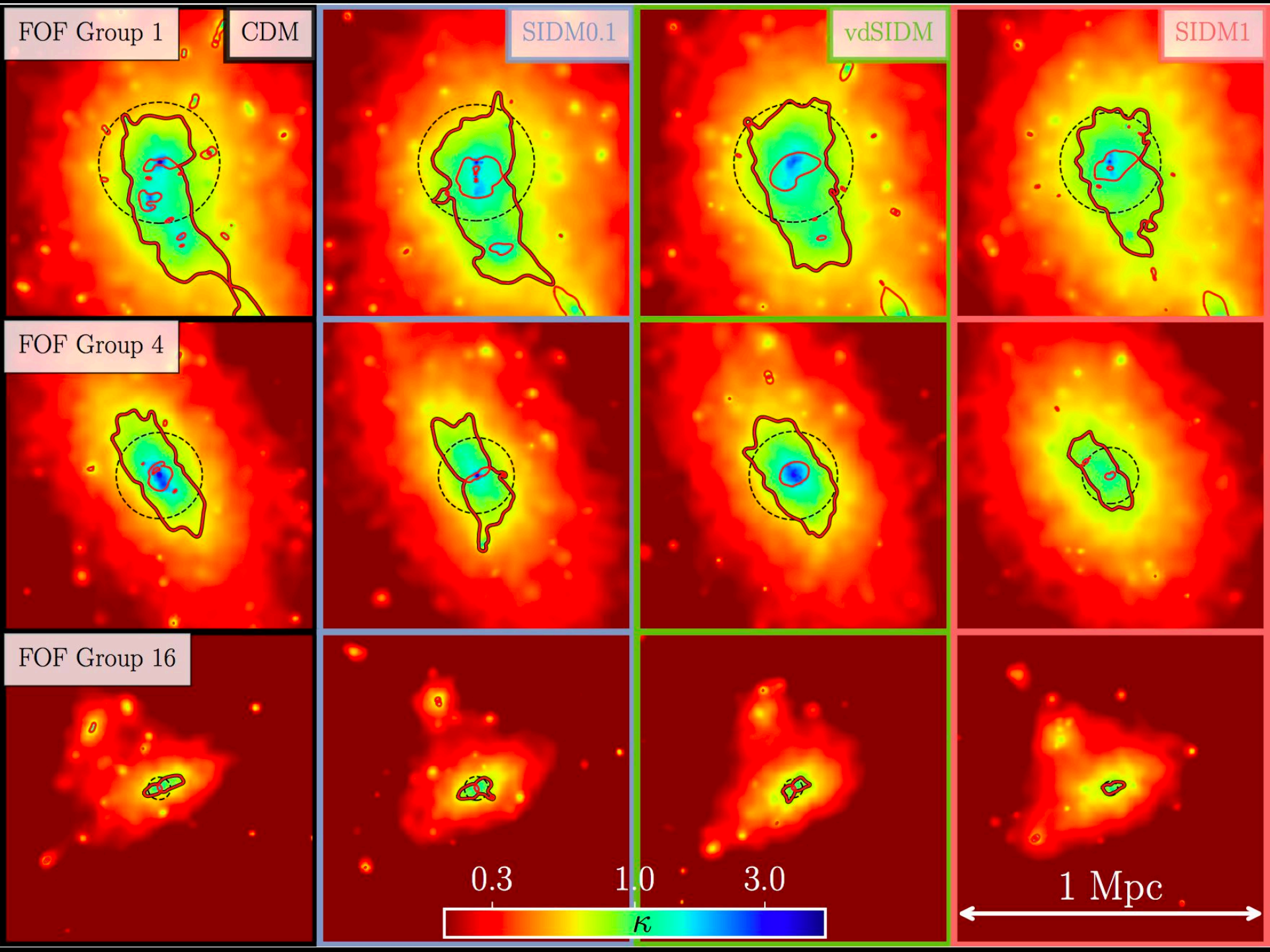
$$v = \sqrt{\frac{G\,M_{200}}{r_{200}}}$$

LENSING BY A SIMULATED CLUSTER

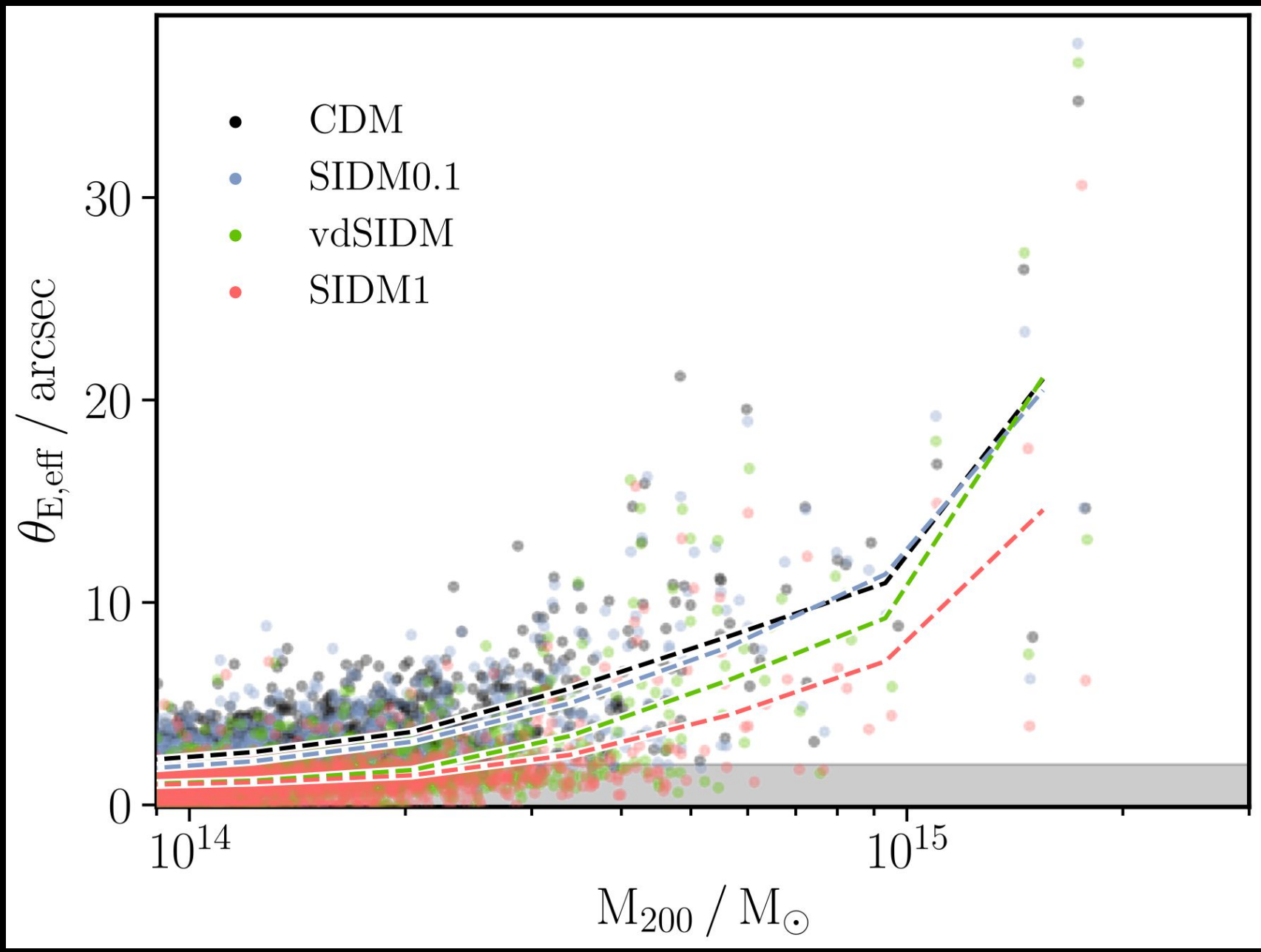


LENSING BY A SIMULATED CLUSTER

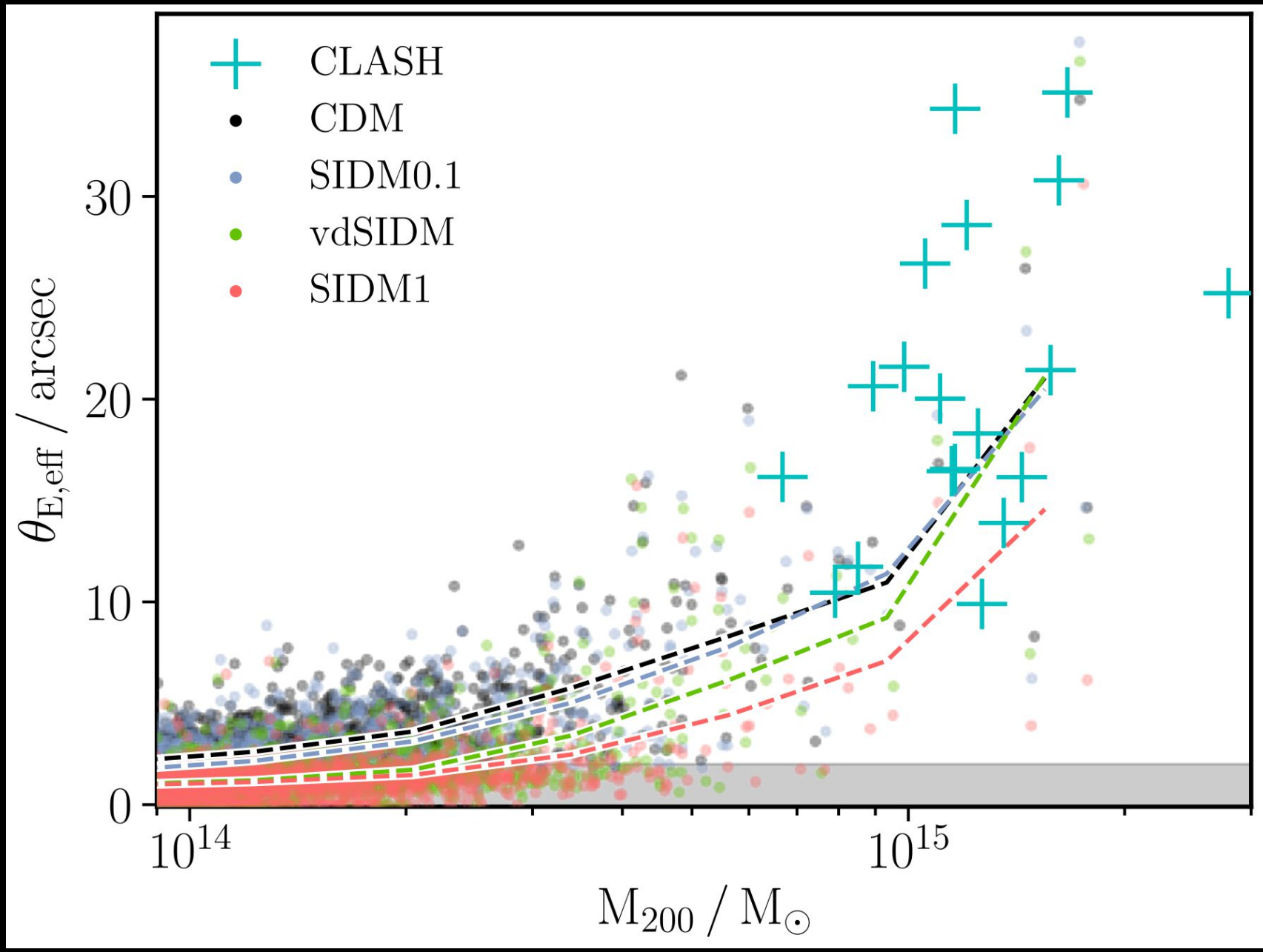



FOF Group 1
CDM
SIDM0.1
vdSIDM
SIDM1
FOF Group 4
FOF Group 16
0.3
1.0
3.0
κ
1 Mpc

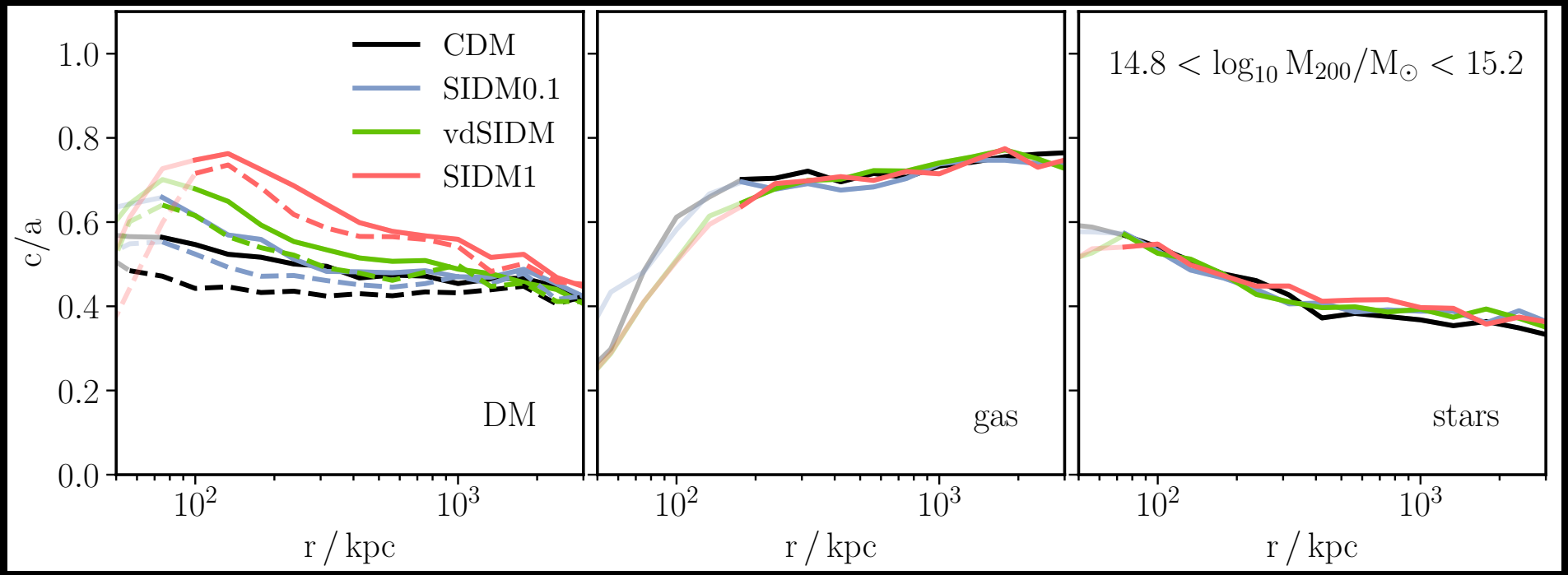
BAHAMAS-SIDM EINSTEIN RADII



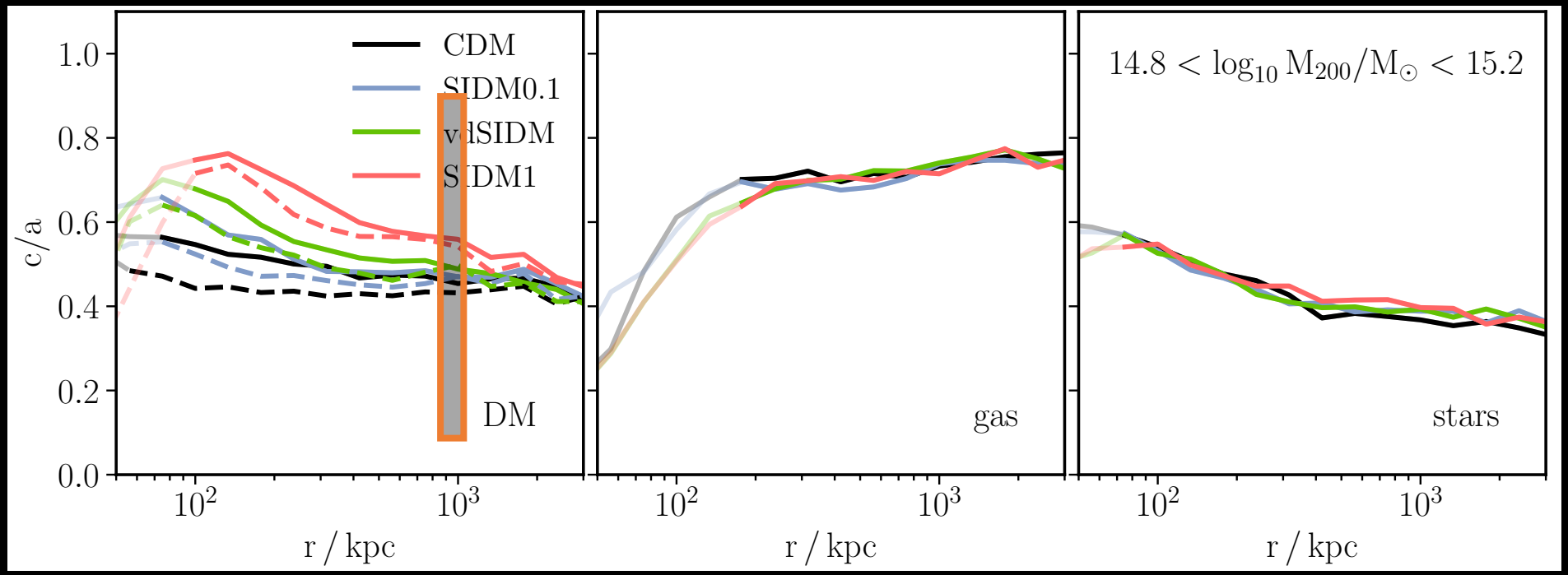
BAHAMAS-SIDM EINSTEIN RADII



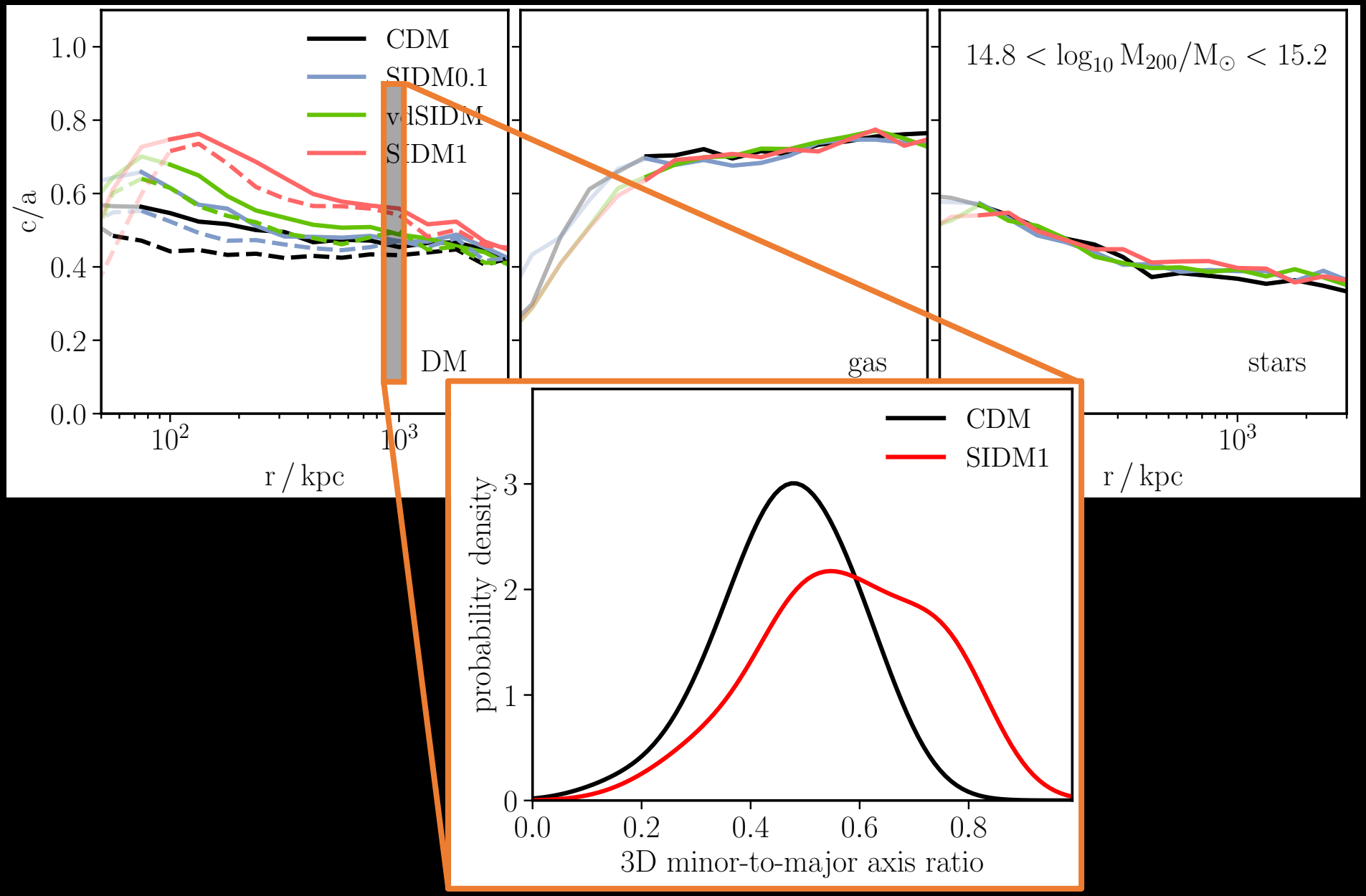
BAHAMAS-SIDM HALO SHAPES



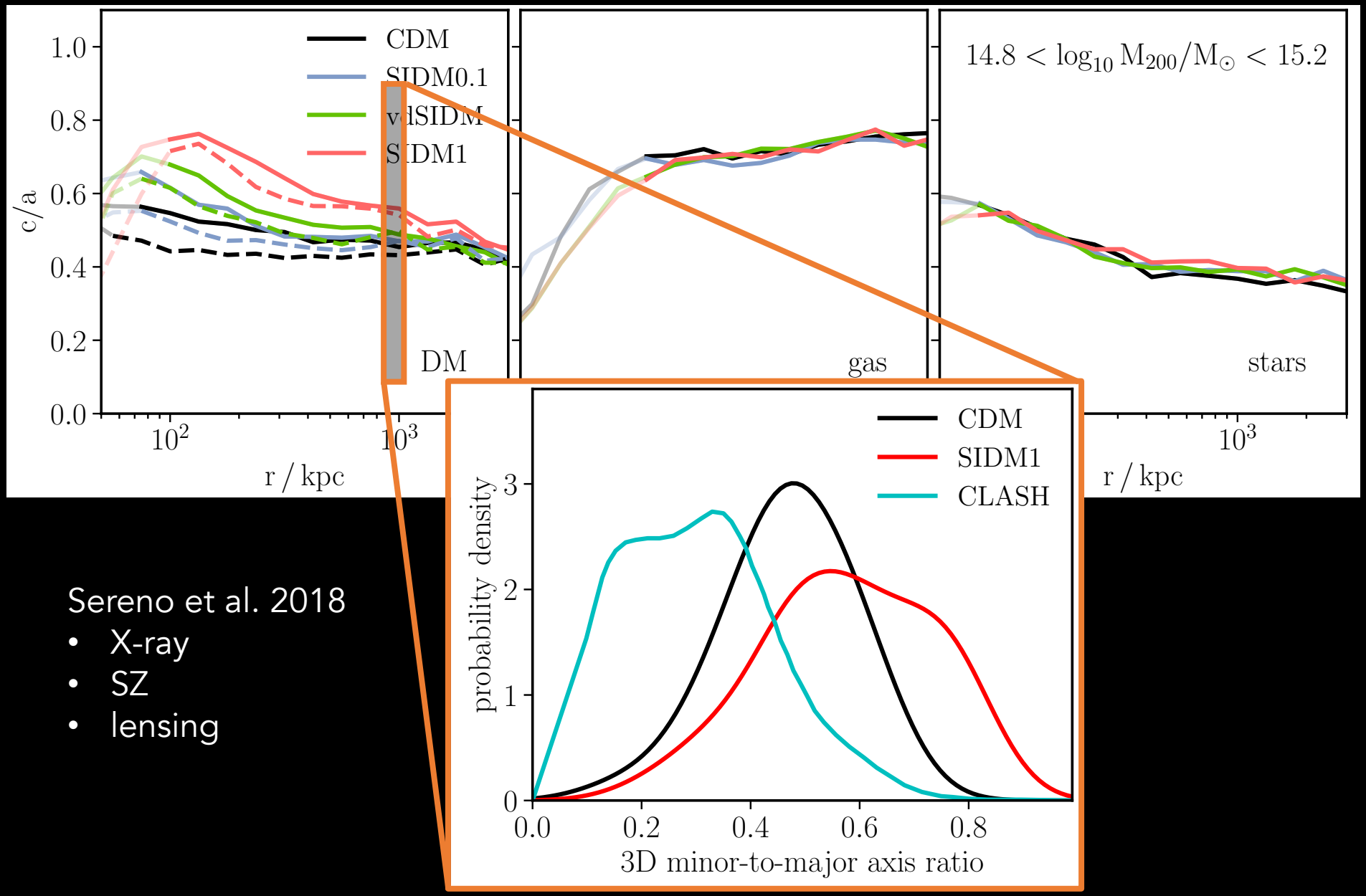
BAHAMAS-SIDM HALO SHAPES



BAHAMAS-SIDM HALO SHAPES



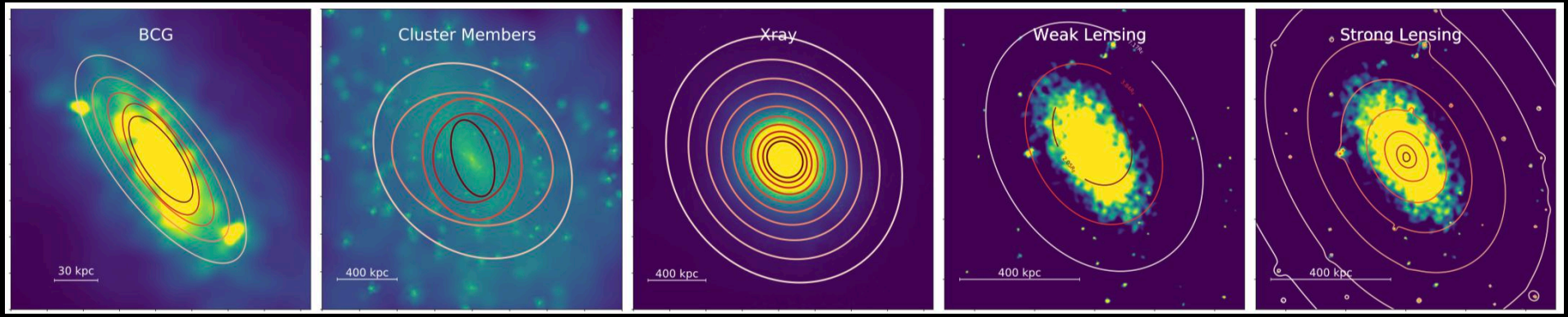
BAHAMAS-SIDM HALO SHAPES

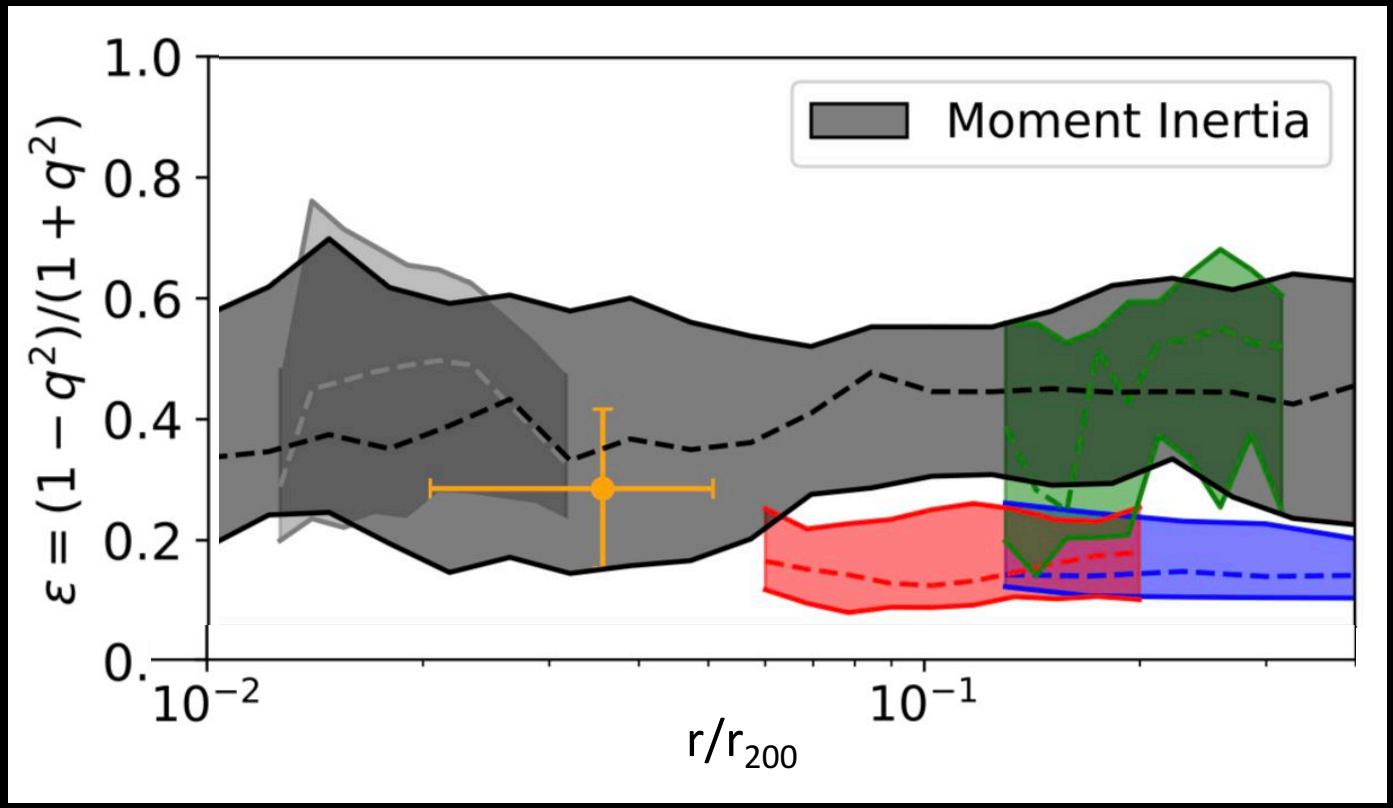


Sereno et al. 2018

- X-ray
- SZ
- lensing

MEASURING SHAPES IS HARD!





SUMMARY

HOPEFULLY YOU HAVE LEARNT A BIT ABOUT HOW WE RUN LARGE COSMOLOGICAL SIMULATIONS

GALAXY CLUSTERS CAN PLACE COMPETITIVE CONSTRAINTS ON THE SIDM CROSS-SECTION, THOUGH THEY ARE TYPICALLY WEAKENED BY THE INCLUSION OF BARYONS

STRONG LENSING BY GALAXY CLUSTERS IS SENSITIVE TO THE SIDM CROSS-SECTION, BUT WE NEED A LARGE NUMBER OF SIMULATED SYSTEMS TO CORRECTLY MODEL SELECTION EFFECTS

HALO SHAPES ALSO DEPEND ON THE SIDM CROSS-SECTION, BUT AGAIN MORE WORK IS REQUIRED TO ROBUSTLY INFER THE CROSS-SECTION FROM OBSERVATIONS

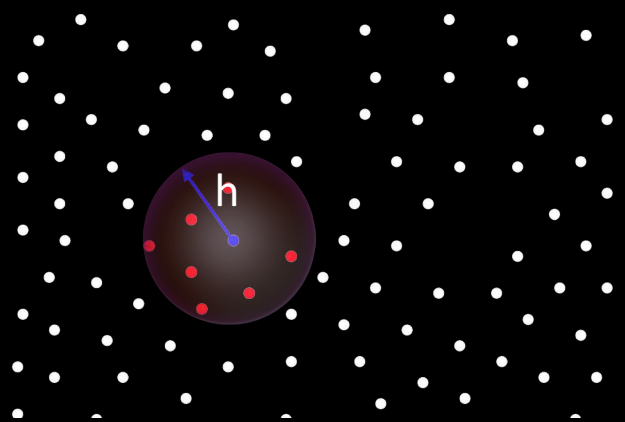
Additional Slides…

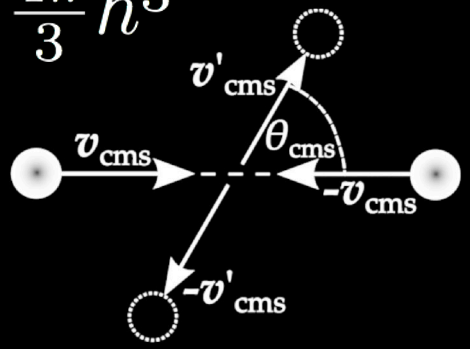
SCATTERING WITH A GENERAL DIFERENTIAL CROSS-SECTION

Tulin+ 2013

Cross-section can be a function of $|\mathbf{v_i} - \mathbf{v_j}|$

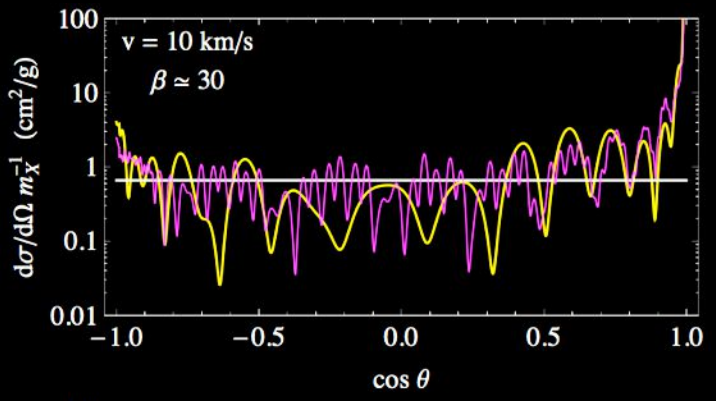
$$P_{ij} = \frac{\frac{\sigma_\chi}{m_\chi} m_p |\mathbf{v_i} - \mathbf{v_j}| \Delta t}{\frac{4\pi}{3} h^3}$$

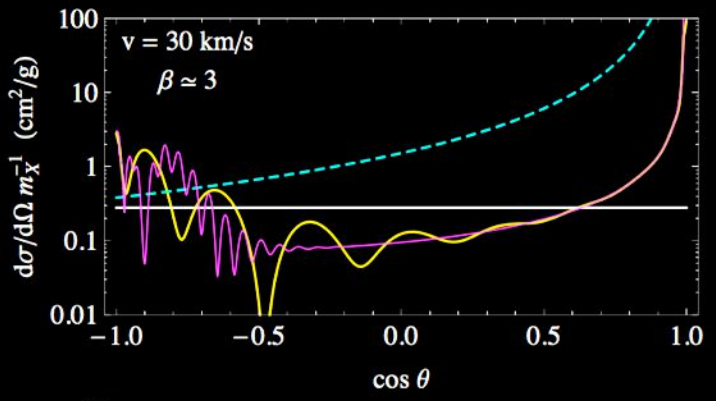


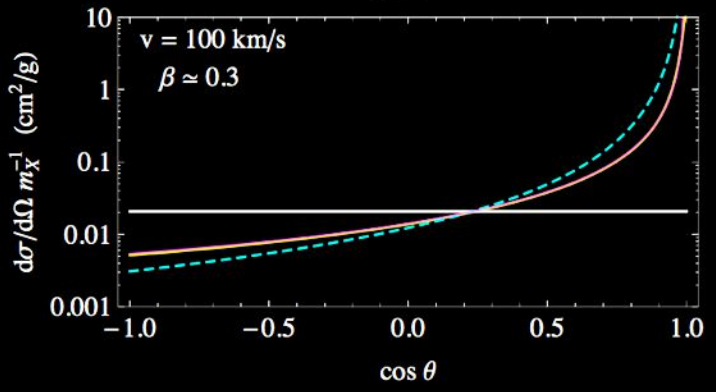


Kahlhoefer+ 2014

When two particles scatter, draw θ from the relevant probability distribution (which can change with relative velocity)







WHICH INTEGRATED CROSS-SECTION IS RELEVANT?

Complete description of interaction

$$\sigma \equiv \int \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\,\mathrm{d}\Omega$$

Total cross-section

$$\sigma_T \equiv \int (1-\cos\theta)\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\,\mathrm{d}\Omega$$

Momentum transfer cross-section

$$\sigma_{\tilde{T}} \equiv \int (1-|\cos\theta|)\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\,\mathrm{d}\Omega$$

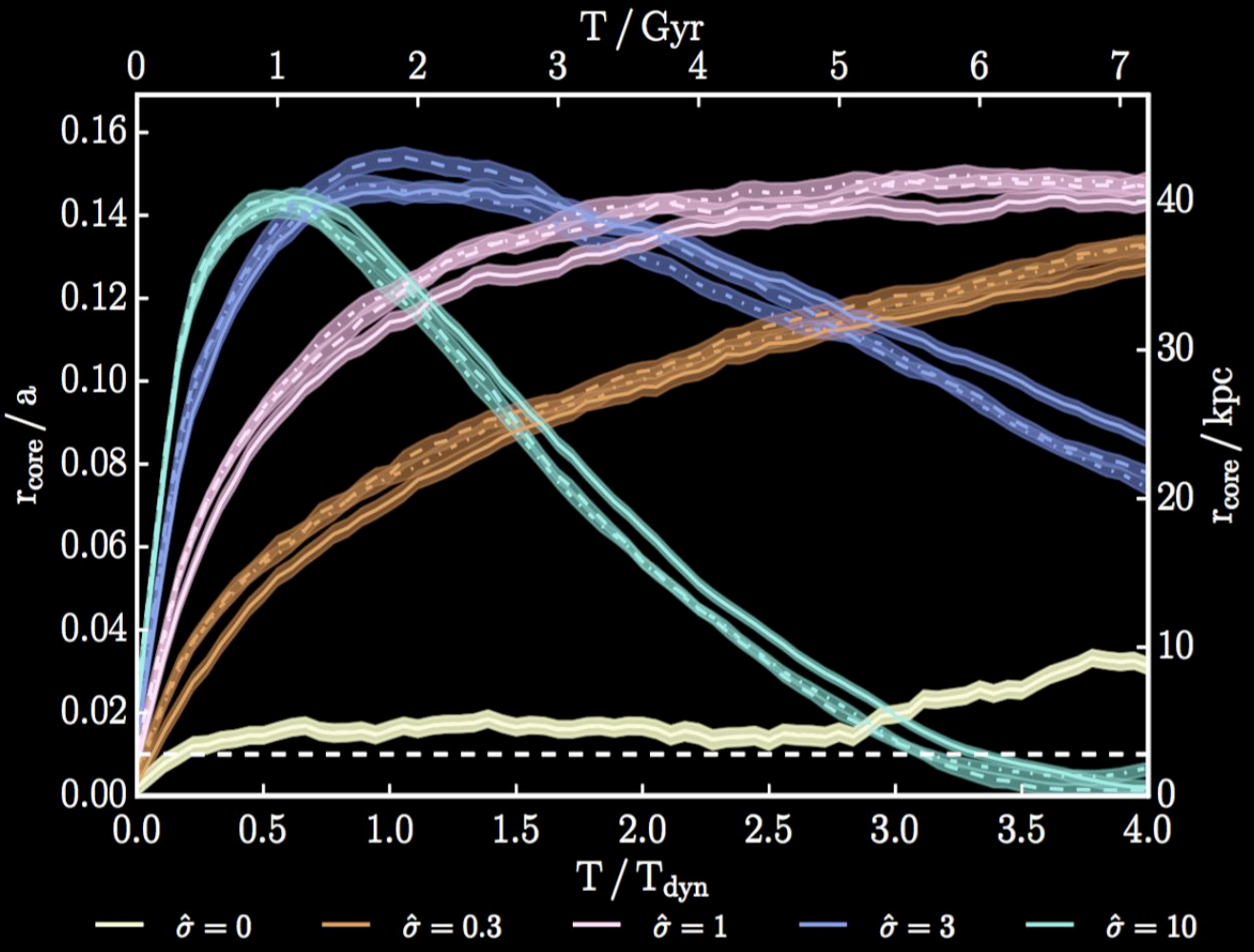
Kahlhoefer+ 2014

$$\sigma_V \equiv \int \sin^2\theta\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\,\mathrm{d}\Omega$$

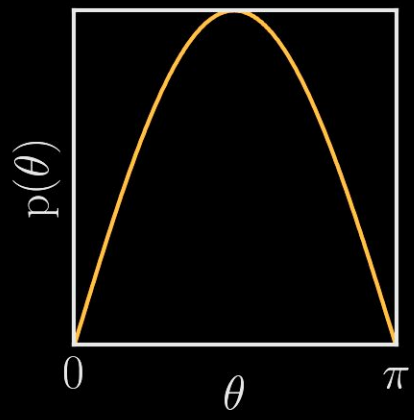
Viscosity cross-section

WHICH INTEGRATED CROSS-SECTION IS RELEVANT

Matched by $\sigma_{\tilde{T}} \equiv \int (1 - |\cos\theta|) \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} \mathrm{d}\Omega$



Isotropic scattering



Anisotropic DM

5x more scattering