Structure formation in a SIDM cosmology: an overview

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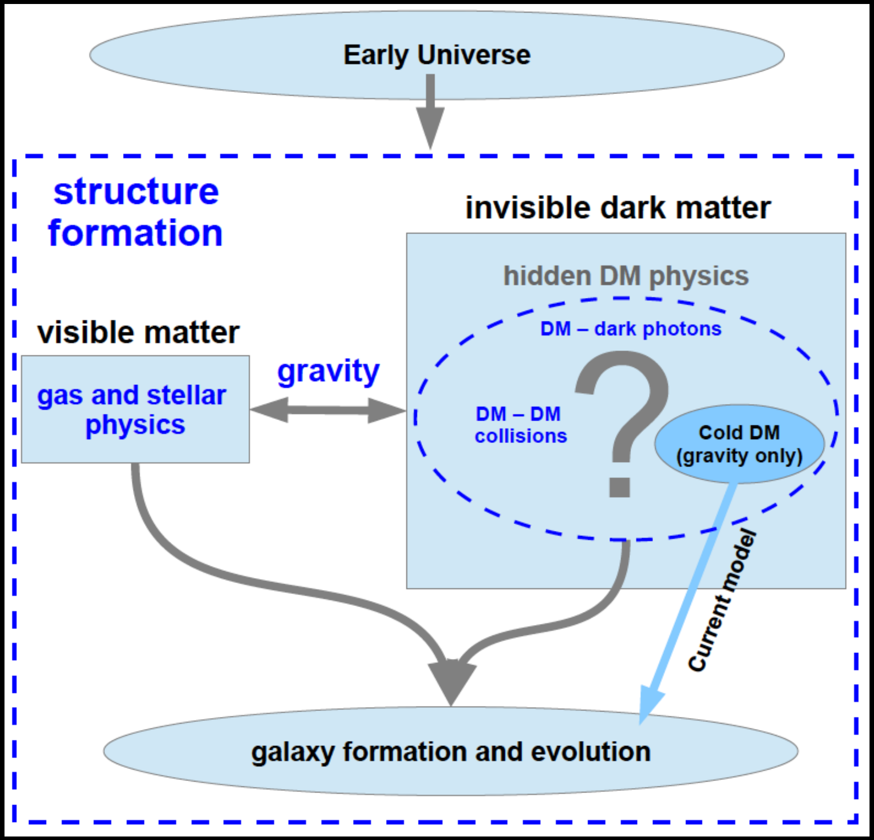
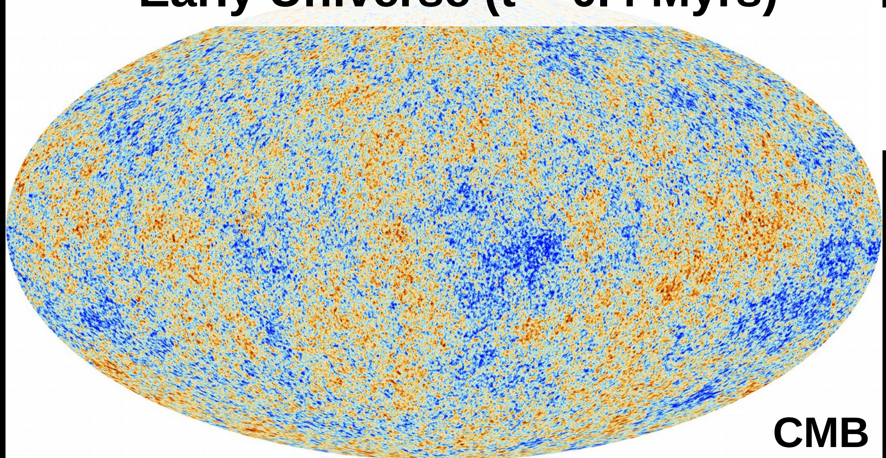


SIDM Workshop, Niels Bohr Institute, Copenhagen, August 2017

The goal of structure formation is to explain the growth of cosmic structures across time (DM is seemingly essential)

Credit: ESA and the Planck Collaboration

Early Universe (t ~ 0.4 Myrs)

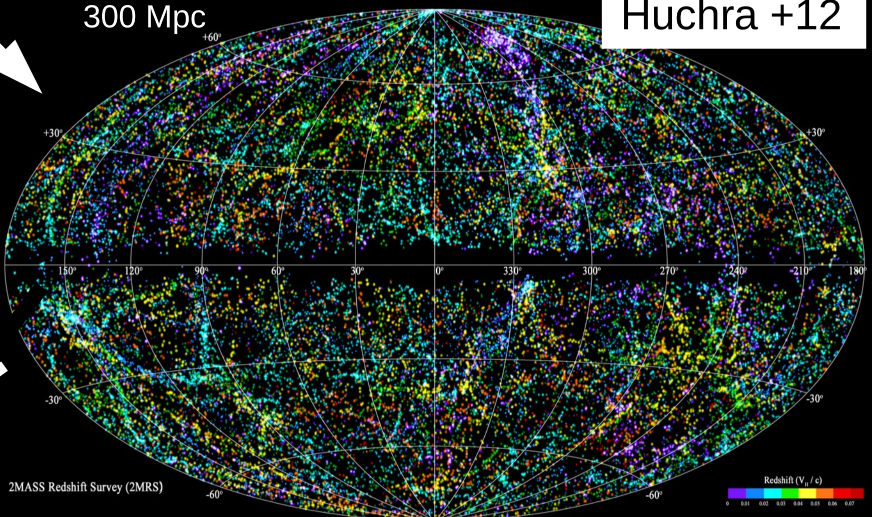


$$\frac{\delta\rho_m}{\rho_m} \sim 10^{-3}$$

Universe today (t ~ 13.8 Gyrs)

300 Mpc

Huchra +12



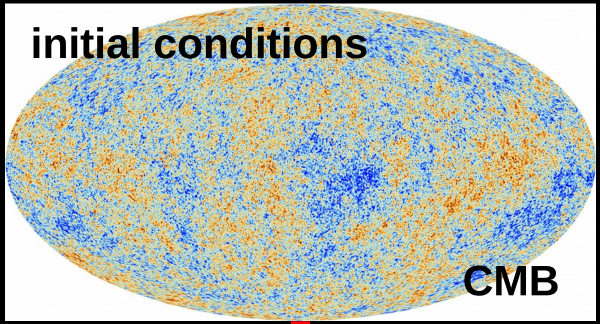
2MRS galaxy "map", large-scale structure

$$\frac{\delta\rho_m}{\rho_m} \gtrsim 1$$

$$\frac{\delta\rho_m}{\rho_m} \gg 1$$

galactic scales

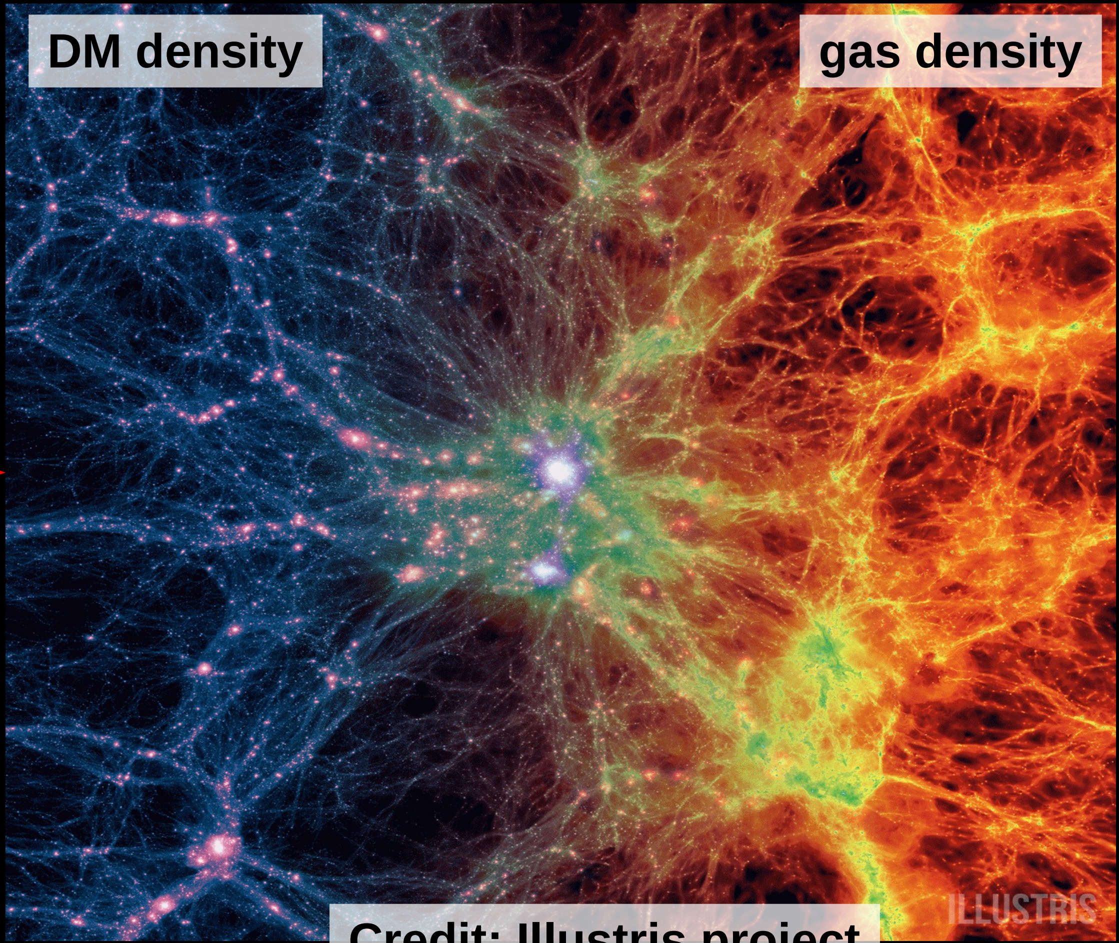
The Cold Dark Matter (CDM) hypothesis is the cornerstone of the current structure formation theory



CDM assumes that the only DM interaction that matters is gravity!!

cosmological simulations

DM gravity only
+
"baryonic" physics
(radiative cooling, gas hydrodynamics, star formation, supernova and AGN feedback,...)



100 Mpc (comoving)

2000 CPU years!!

Opening remarks

Structure formation theory has become powerful enough to predict the phase-space distribution of dark matter across time down to galactic scales.

- The Cold Dark Matter (CDM) hypothesis has been the standard for nearly three decades and implies that DM gravity is the only relevant interaction (for galactic scales and above). It implies that <u>structure formation within CDM has no free DM parameters</u>. However:

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CDM/WDM/SIDM are incomplete DM theories

They are effective structure formation theories that need completion from a particle physics model (all beyond SM: "exotic")

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- Given the current situation (obs. constraints, complexity of baryonic physics), it is timely to consider additional free DM parameters, which might play a key role in the physics of galaxies. The window is relatively narrow and within reach of upcoming observations:

SIDM transfer cross section

$$0.1\,cm^2/gr \lesssim \sigma/m \lesssim 2\,cm^2/gr$$

below this value, the behaviour is the same as CDM

above this value constraints are strong (at cluster scales)

'cutoff' halo mass at z=0

$$10^{9.5}\,M_{Sun} \lesssim M_{cut} \lesssim 10^{10.5}\,M_{Sun}$$

below this value galaxy formation Is highly supressed (reionisation)

above this value DM clustering must be as in CDM

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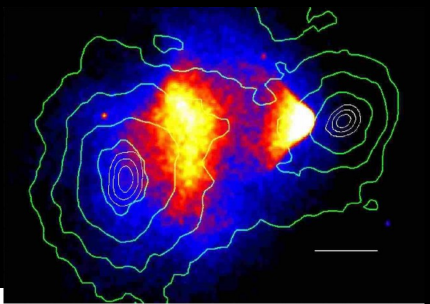
Structure formation within SIDM: could DM particles collide with themselves?

case in this talk:
<u>rare interactions,</u>
<u>large momentum transfer</u>

opposite case: afternoon session

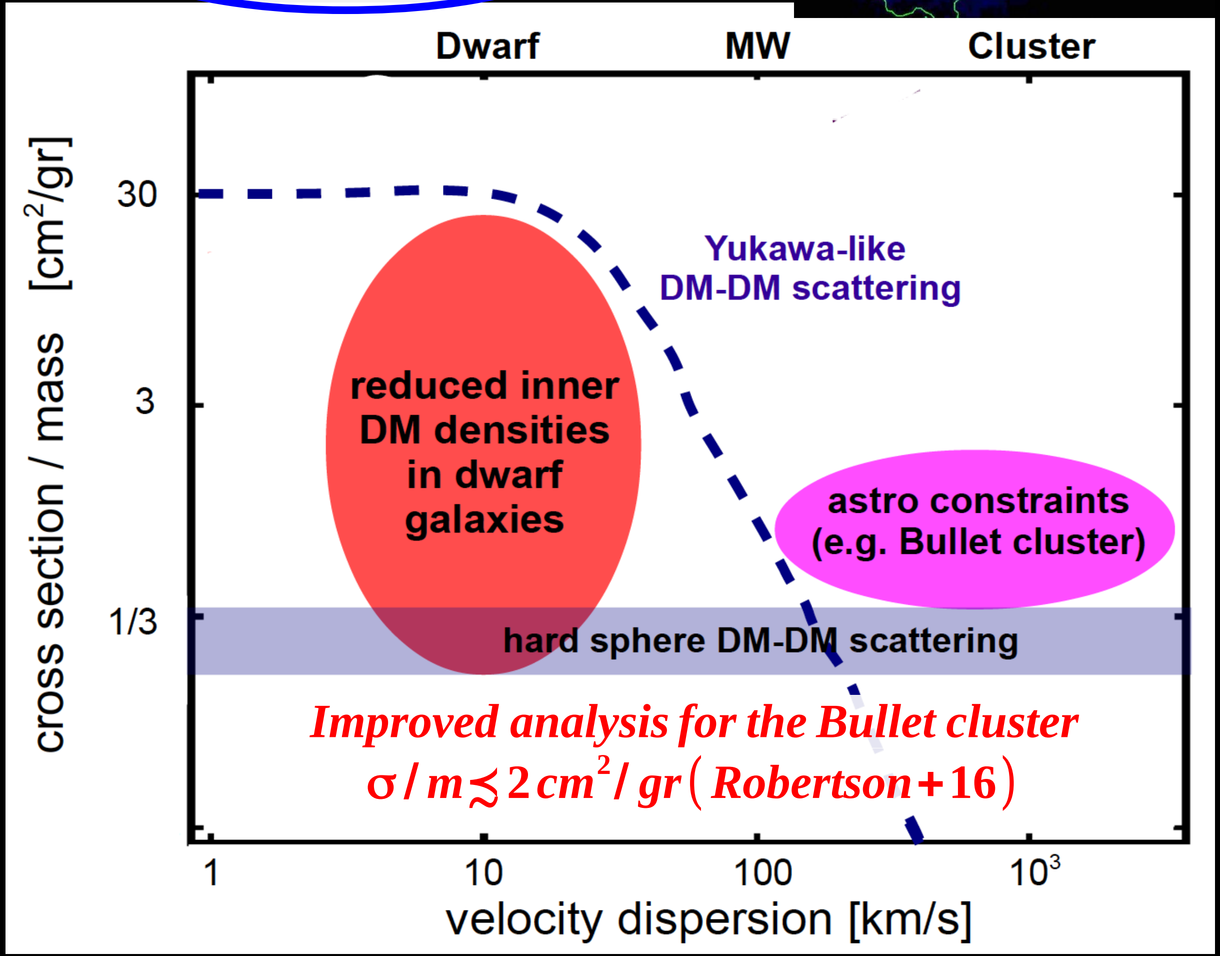
constraints allow collisional DM that is astrophysically significant in the center of galaxies



average scattering rate per particle:

$$\frac{\overline{R}_{sc}}{\Delta t} = \left(\frac{\sigma_{\rm sc}}{m_\chi}\right) \overline{\rho}_{\rm dm}\ \overline{v}_{\rm typ}$$

~ 1 scatter / particle / Hubble time



Neither a fluid nor a collisionless system:
~ rarefied gas
(Knudsen number = λ_{mean}/L >~ 1)

A. Robertson's talk

structure formation theory
(linear regime)

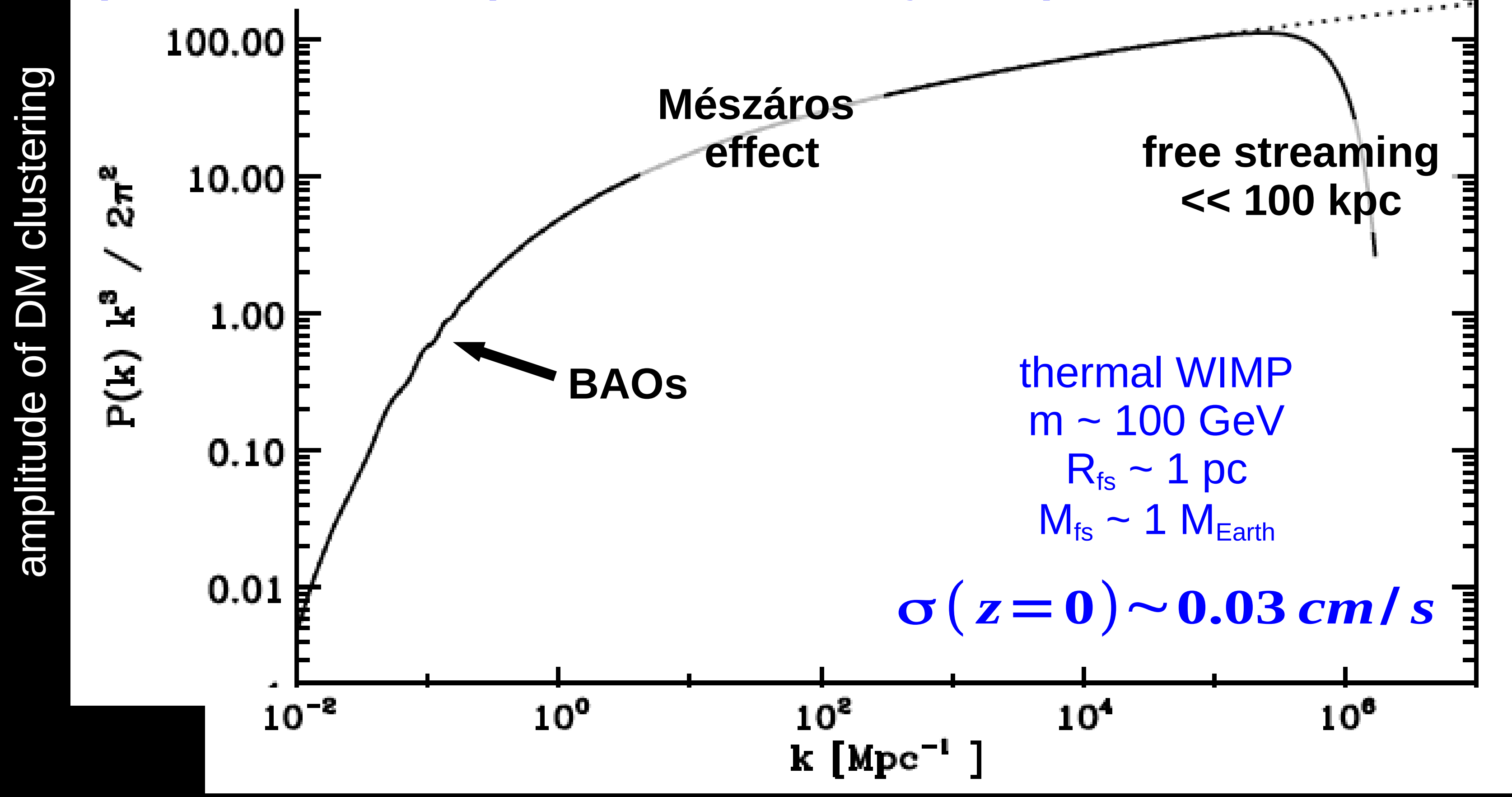
Standard structure formation theory

LINEAR REGIME (cosmological perturbation theory)

$$\delta(x,t)=\frac{\rho(x,t)-\rho_B(t)}{\rho_B(t)} \ll 1$$

Standard hypotheses:
DM is cold and collisionless
(Cold Dark Matter model)

linear power spectrum
(statistical description of the density field)



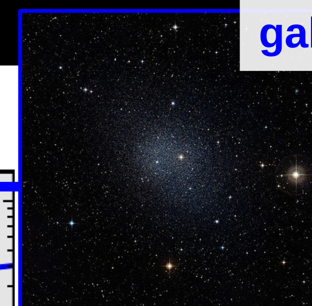
Angulo & White, 2010

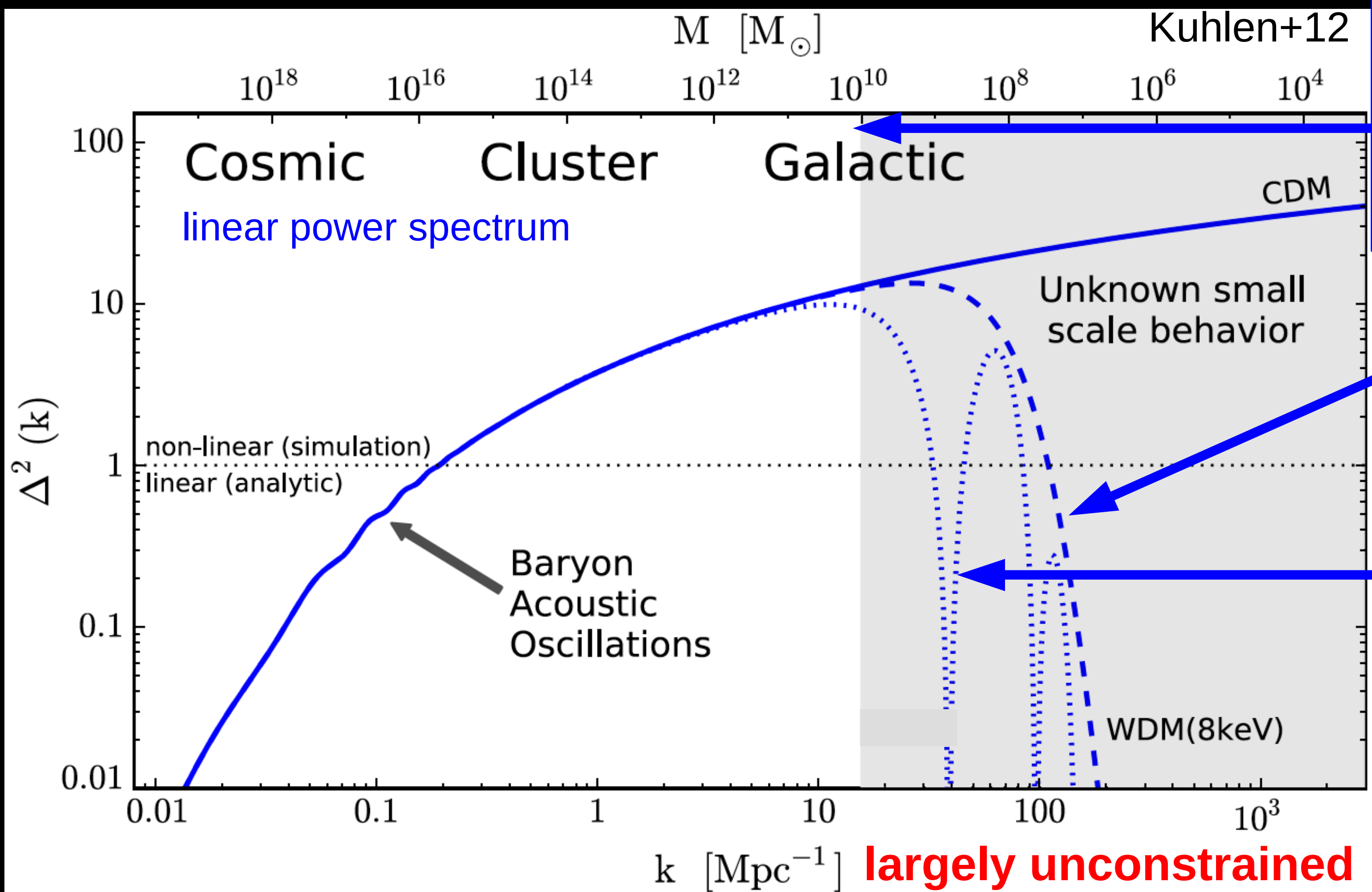
LINEAR REGIME: a ‘relevant’ P(k) cutoff ?

Unsolved question:
is the minimum mass scale for galaxy formation set by the DM nature or by gas physics (or by both)?

Observations have yet to measure the clustering of dark matter at the scale of the smallest galaxies

Dwarf galaxies





DM is relativistic at earlier times ‘thermal’ cut-off (WDM free-streaming)

DM interacts with relativistic particles at earlier times: DM-DR DAOs and Silk (collisional) damping

LINEAR REGIME: a ‘relevant’ P(k) cutoff ?

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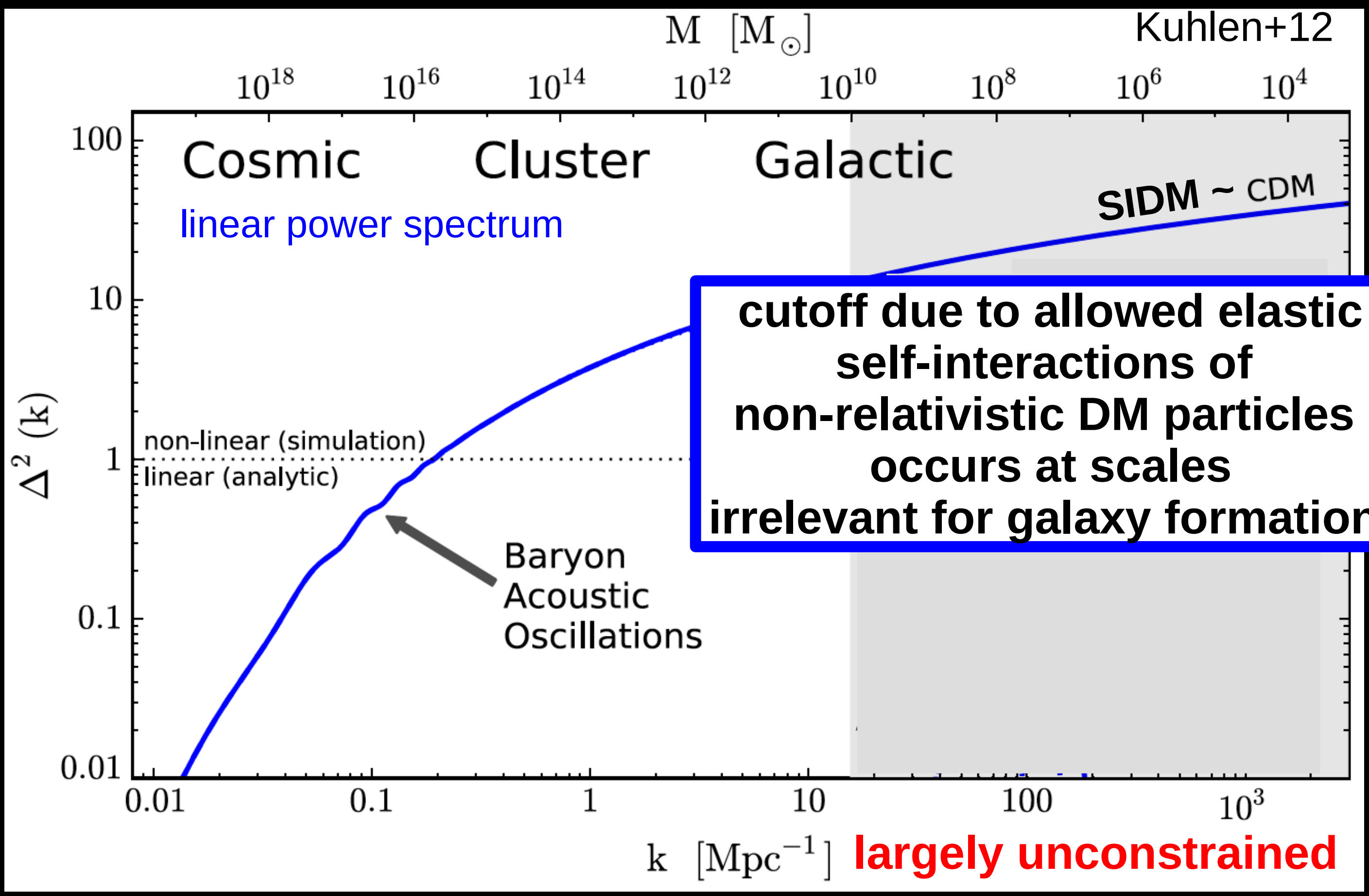


cutoff due to allowed elastic self-interactions of non-relativistic DM particles occurs at scales irrelevant for galaxy formation

~ 1 scatter / particle / t_{age}

(scatt. rate ~ exp. rate)

self-decoupling temp. and Jeans mass

e.g. $M_J \sim 10^{-11} M_{Sun}$

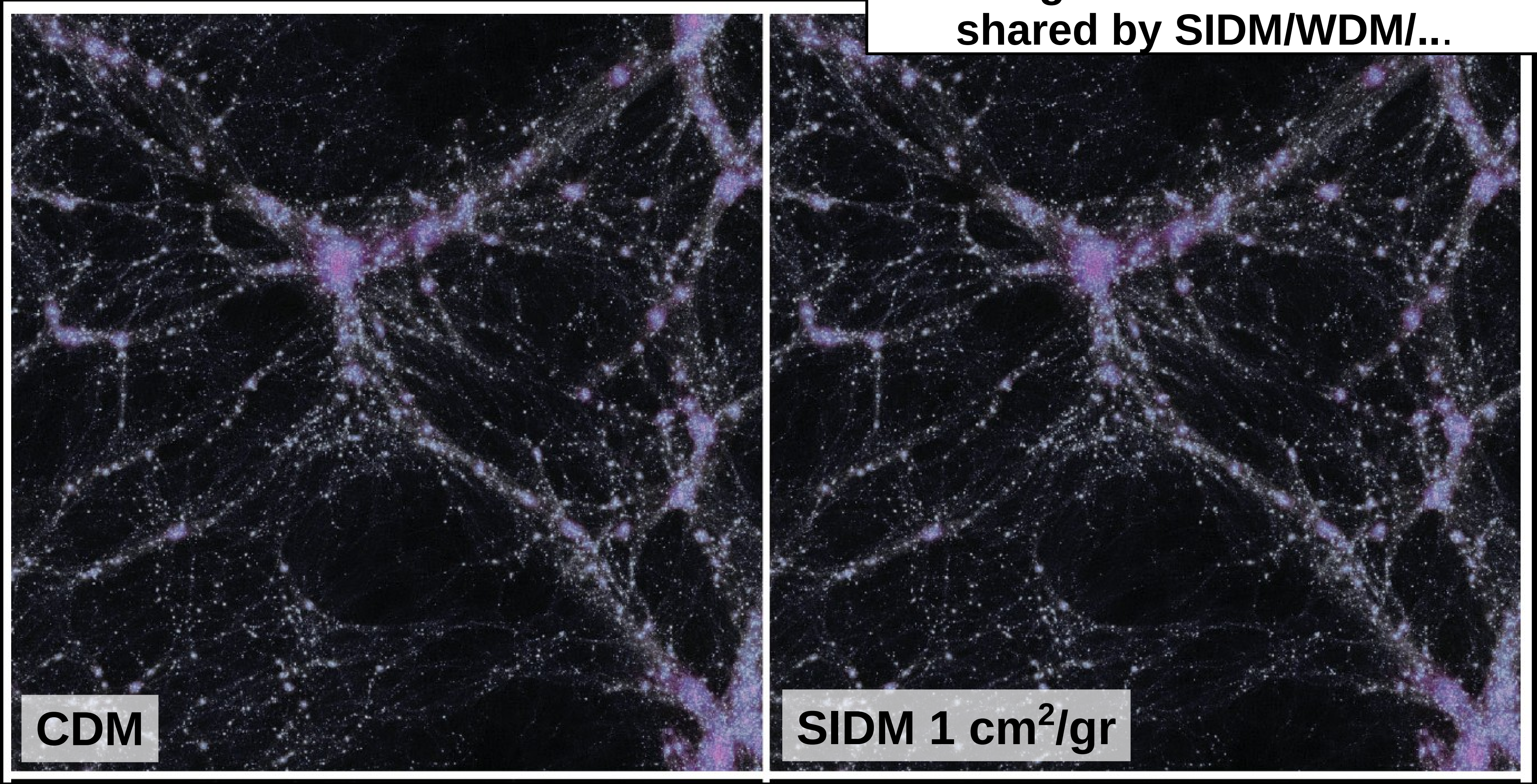
$$\sigma / m \sim 0.1\, cm^2 / gr$$

$$m \sim 100\, GeV$$

Linear evolution in SIDM is the same as in CDM (if DM is cold, and there are no additional interactions)

Rocha et al. 2013

CDM large scale successes are shared by SIDM/WDM/...



structure formation theory (non-linear regime)

Standard structure formation theory

NON-LINEAR REGIME

If $\delta(x,t) \gtrsim 1$ *perturbation theory breaks down*

Standard hypotheses:
DM is cold and collisionless
(Cold Dark Matter model)

the only DM interaction
that matters is gravity!!

In principle: solve Collisionless Boltzmann Equation (coupled with the Poisson equation) with the initial conditions given by linear perturbation theory

$$\frac{df}{dt} = 0 \qquad \nabla^2 \phi = 4 \pi G \rho$$

i.e., find the local DM distribution in phase space at all points and at all times:

$$f(\vec{x}, \vec{v}, t)\mathrm{d}^3\vec{x}\mathrm{d}^3\vec{v} \longrightarrow \rho(\vec{x}, t) = \int f(\vec{x}, \vec{v}, t) d^3\vec{v}$$

In practice however, we can only compute, measure, the DM distribution averaged over a certain macroscopic scale (coarse-grained distribution)

Standard structure formation theory

NON-LINEAR REGIME (N-body simulations)

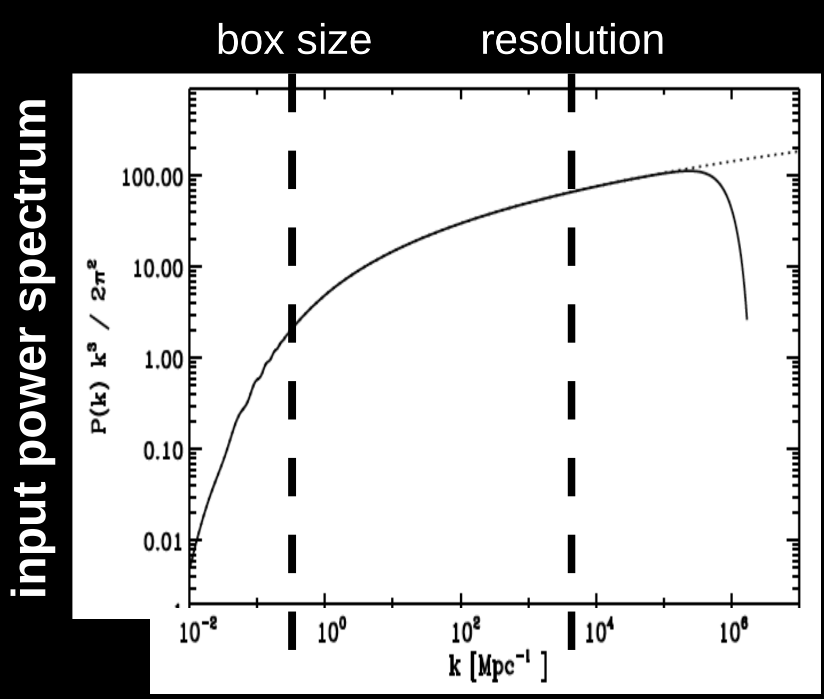
N-body sim: the coarse-grained distribution is given by a discrete representation of N particles:

macro-to-micro-particle mass ratio

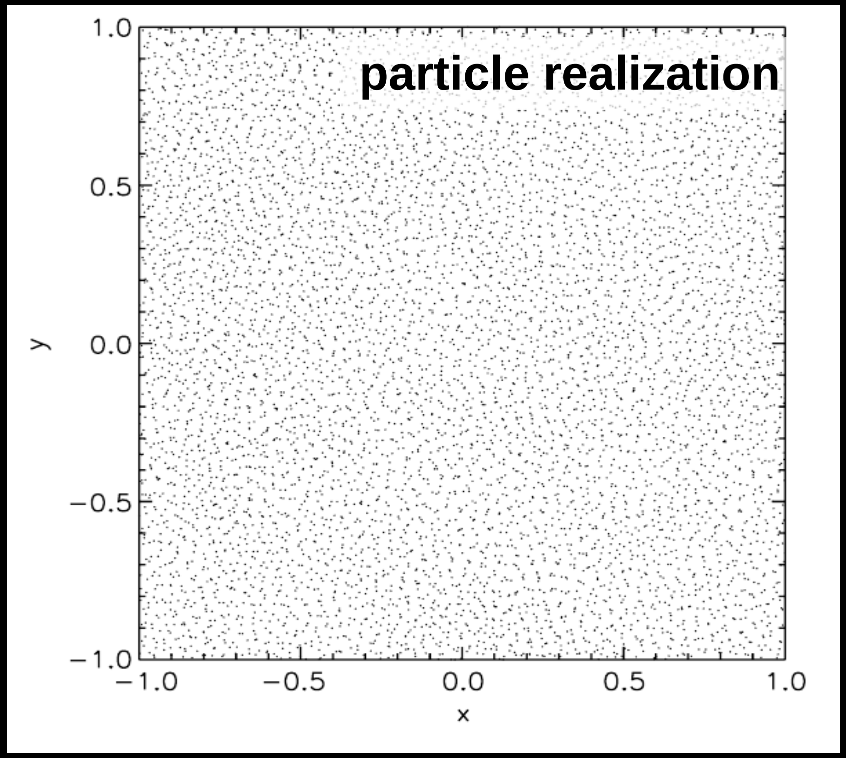
each particle is smoothed in space to give a smooth local density

each macro-particle travels at one speed

$$\hat{f}(\mathbf{x}, \mathbf{v}, t) = \sum_i (M_i/m) W(|\mathbf{x} - \mathbf{x}_i|; h_i) \delta^3(\mathbf{v} - \mathbf{v}_i)$$

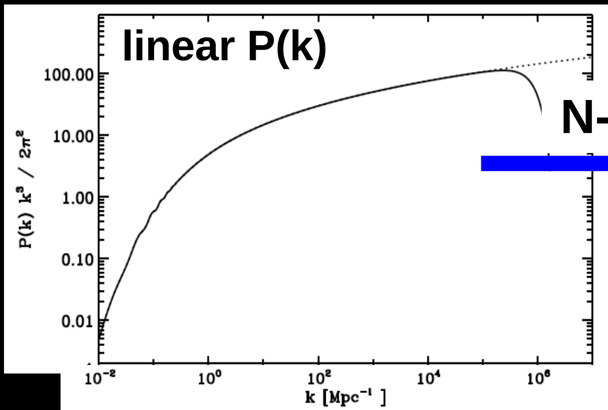


mapping

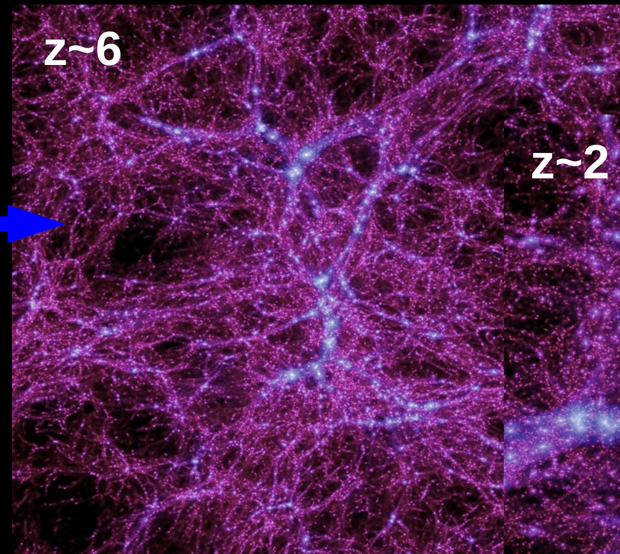


Dolag+2008

Self-gravitating DM structures: haloes



N-body

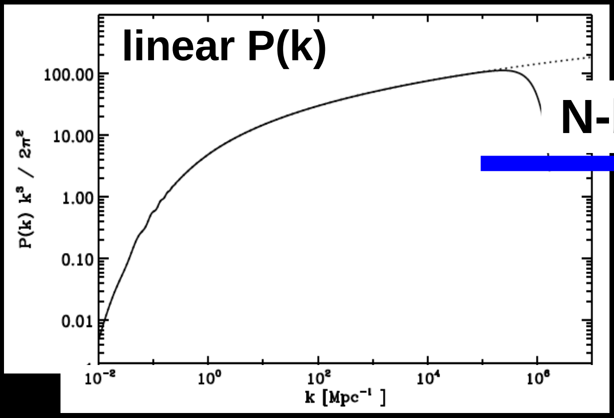


Boylan-Kolchin+2009

Milky-Way-size halo
(radius ~250 kpc)

Aquarius project Springel+08

Self-gravitating DM structures: haloes



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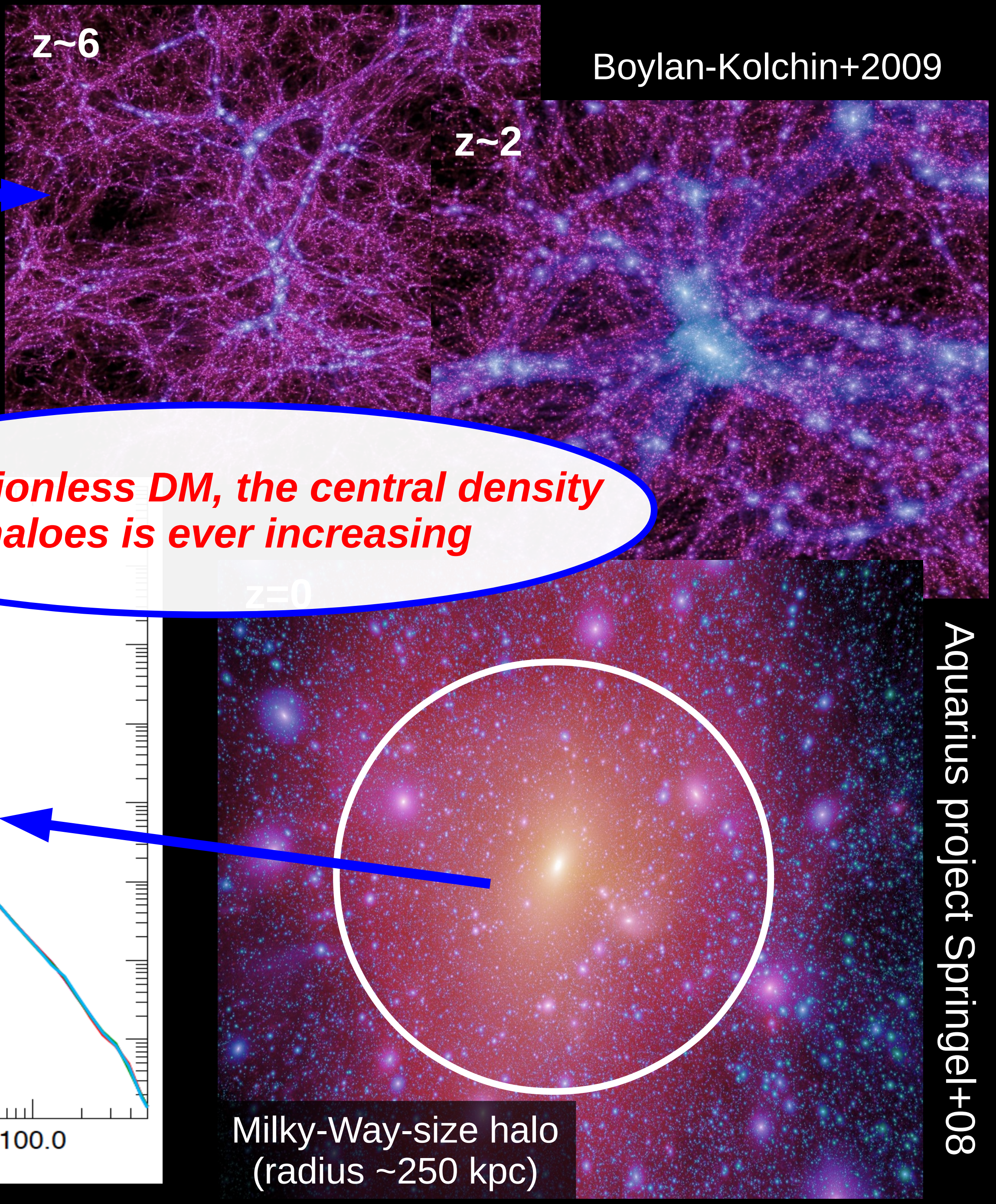
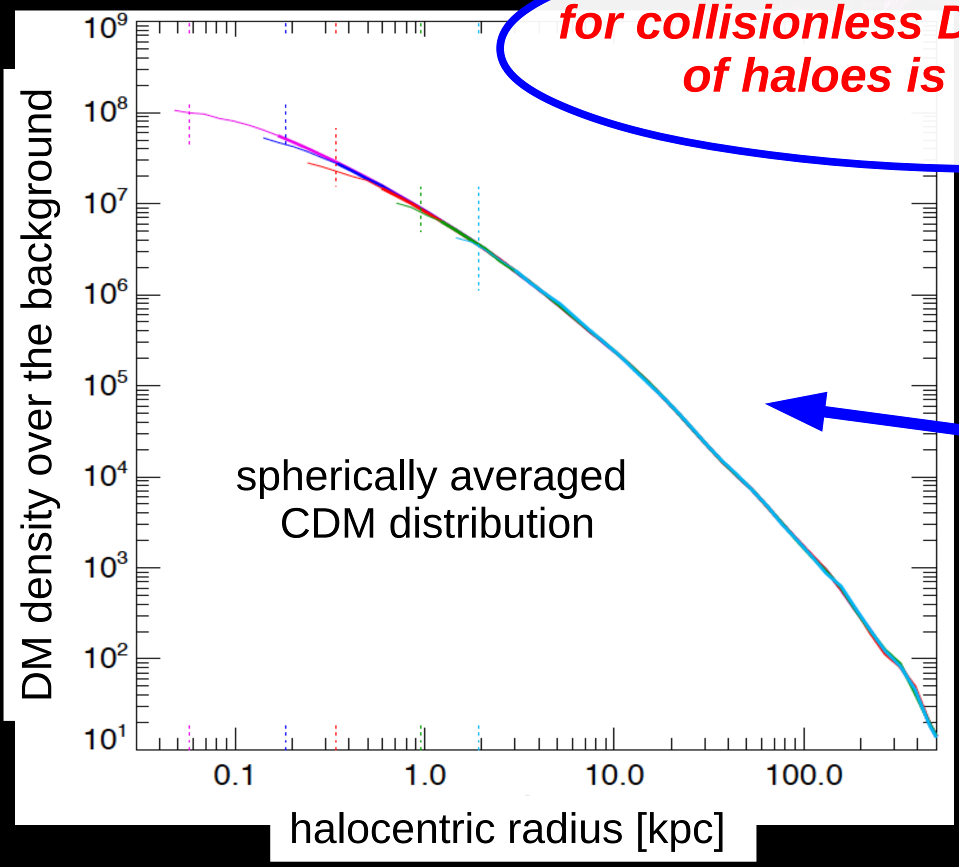


for collisionless DM, the central density of haloes is ever increasing



structure formation theory with DM self-interactions

DM self-collisions in N-body simulations (probabilistic approach)

Far from the fluid and collisionless regimes (Knudsen number = λ_{mean}/L >~ 1) → **Collisional Boltzmann equation (elastic)**

$$|\vec{v}_{\rm rel}| = |\vec{v}_1 - \vec{v}| = |\vec{v'}_1 - \vec{v'}|$$

$$\frac{Df(\mathbf{x},\mathbf{v},t)}{Dt} = \Gamma[f,\sigma]$$

$$= \int d^3\mathbf{v}_1 \int d\Omega \frac{d\sigma}{d\Omega} |\mathbf{v}-\mathbf{v}_1| \left[f(\mathbf{x},\mathbf{v}',t) f(\mathbf{x},\mathbf{v}'_1,t) - f(\mathbf{x},\mathbf{v},t) f(\mathbf{x},\mathbf{v}_1,t) \right]$$

Rate of scattered particles into phase-space patch

Differential cross section

Rate of scattered particles out of phase-space patch

Ansatz for N-body simulation: same solution for "coarse-grained" distribution function

$$\frac{D\hat{f}}{Dt} = \int d^3\mathbf{v}_1 \int d\Omega \frac{d\sigma}{d\Omega} |\mathbf{v}-\mathbf{v}_1| \left[\hat{f}(\mathbf{x},\mathbf{v}',t) \hat{f}(\mathbf{x},\mathbf{v}'_1,t) - \hat{f}(\mathbf{x},\mathbf{v},t) \hat{f}(\mathbf{x},\mathbf{v}_1,t) \right]$$

Kochanek & White 2000, Yoshida+2000,...Vogelsberger, Zavala, Loeb 2012, Rocha+2013

DM self-collisions in N-body simulations (probabilistic approach)

The coarse-grained distribution is given by a discrete representation of N particles:

$$\hat{f}(\mathbf{x},\mathbf{v},t) = \sum_i (M_i/m) W(|\mathbf{x}-\mathbf{x}_i|;h_i)\delta^3(\mathbf{v}-\mathbf{v}_i)$$

Algorithm: Gravity + Probabilistic method for elastic scattering

Consider a neighbourhood around each particle:

in pairs:

$$P_{ij} = \frac{m_i}{m_\chi} W(r_{ij},h_i)\,\sigma_T(v_{ij})v_{ij}\,\Delta t_i$$

discrete version of the collisional operator

total for a particle:

$$P_i = \sum_j P_{ij}/2$$

A collision happens if: $x \leqslant P_i$, where x is a random number between 0 and 1

sort neighbours by distance and pick the one with: $x \leqslant \sum_i^l P_{ij}$

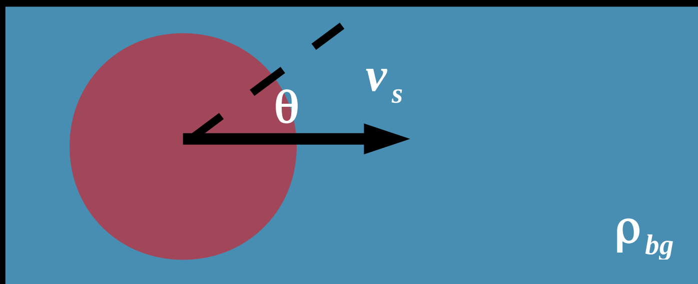
Isotropic Elastic collision:

$$\vec{v}_i = \vec{v}_{cm} + (\vec{v}_{ij}/2)\,\hat{e}$$
$$\vec{v}_j = \vec{v}_{cm} - (\vec{v}_{ij}/2)\,\hat{e}$$

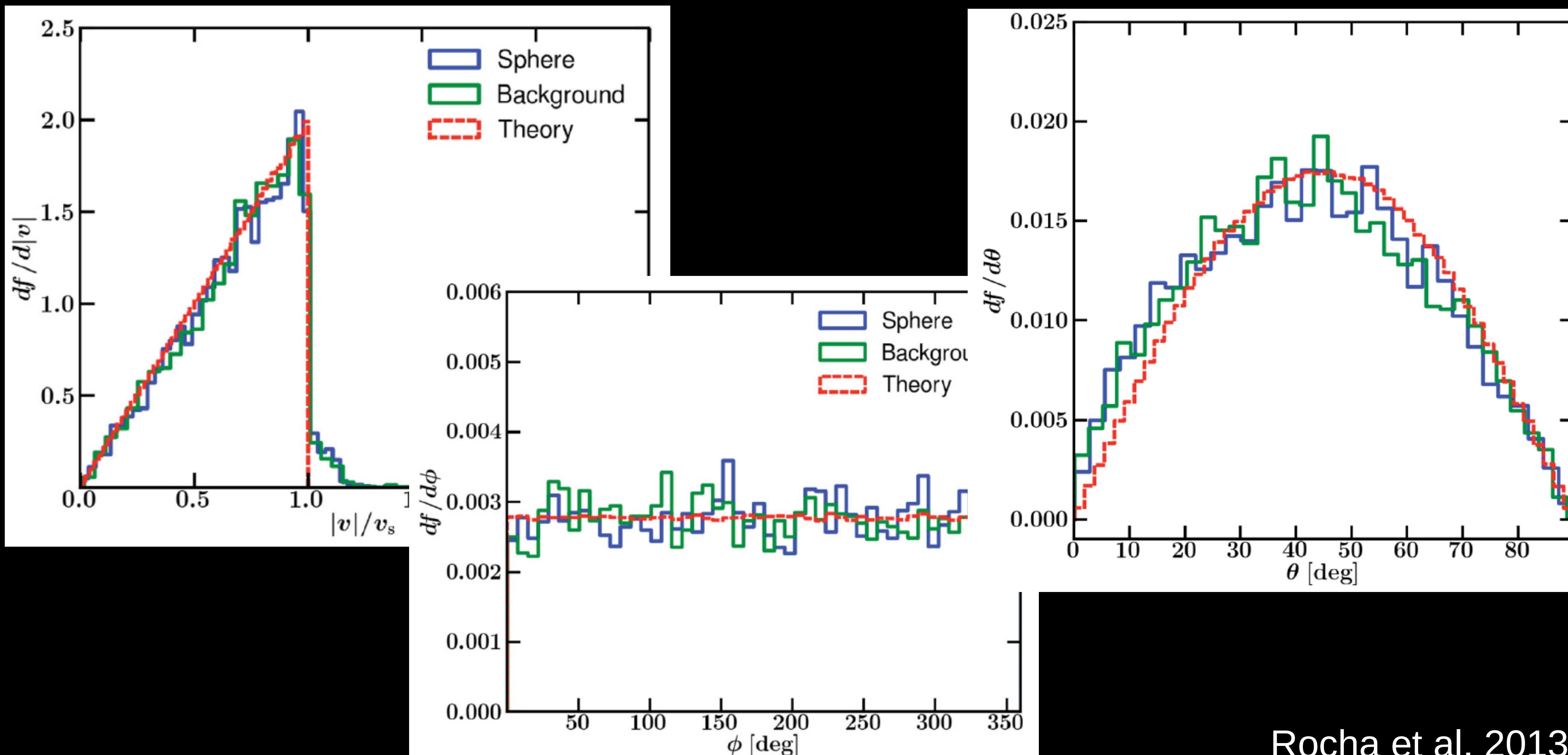
randomly scattered

Kochanek & White 2000, Yoshida+2000,...Vogelsberger, Zavala, Loeb 2012, Rocha+2013

DM self-collisions in N-body simulations (probabilistic approach: simple kinematic test)



$$N_{\rm exp}(t) = \sum_{i\in {\rm s},\, j\in {\rm bg}} P_{ij} = N_{\rm s}(\sigma/m)\rho_{\rm bg} v_{\rm s} t$$



Rocha et al. 2013

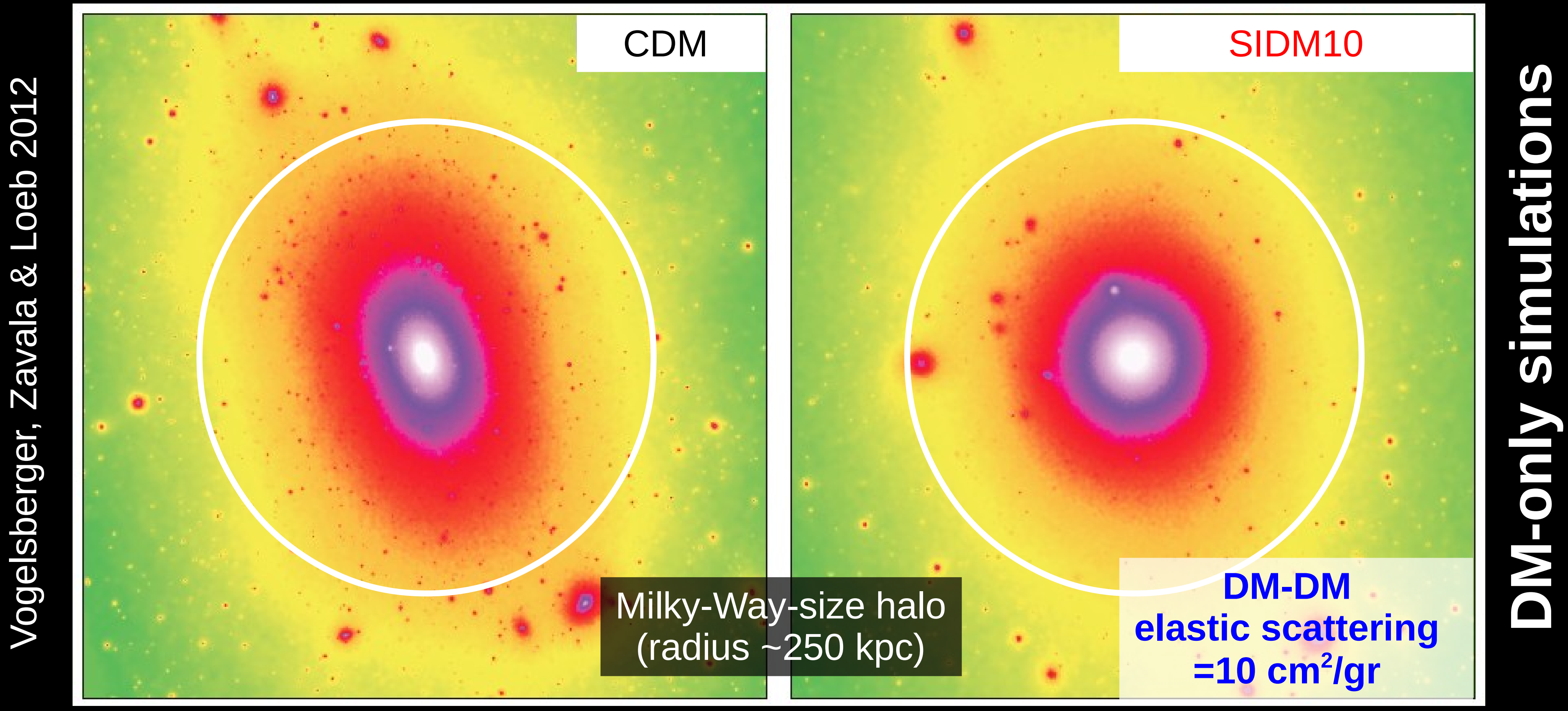
Structure of SIDM haloes

Structure of SIDM haloes

If gravity is the only relevant DM interaction, the central density of haloes is ever increasing

With strong self-interactions $\left(\sigma/m \gtrsim 0.5\, cm^2/gr\right)$ DM haloes develop nearly spherical "isothermal" cores

M. Vogelsberger's talk



(Carlson+92, Spergel & Steinhardt 00, Yoshida+00, Davé+01, Colín+02, Rocha+13, Peter+13....)

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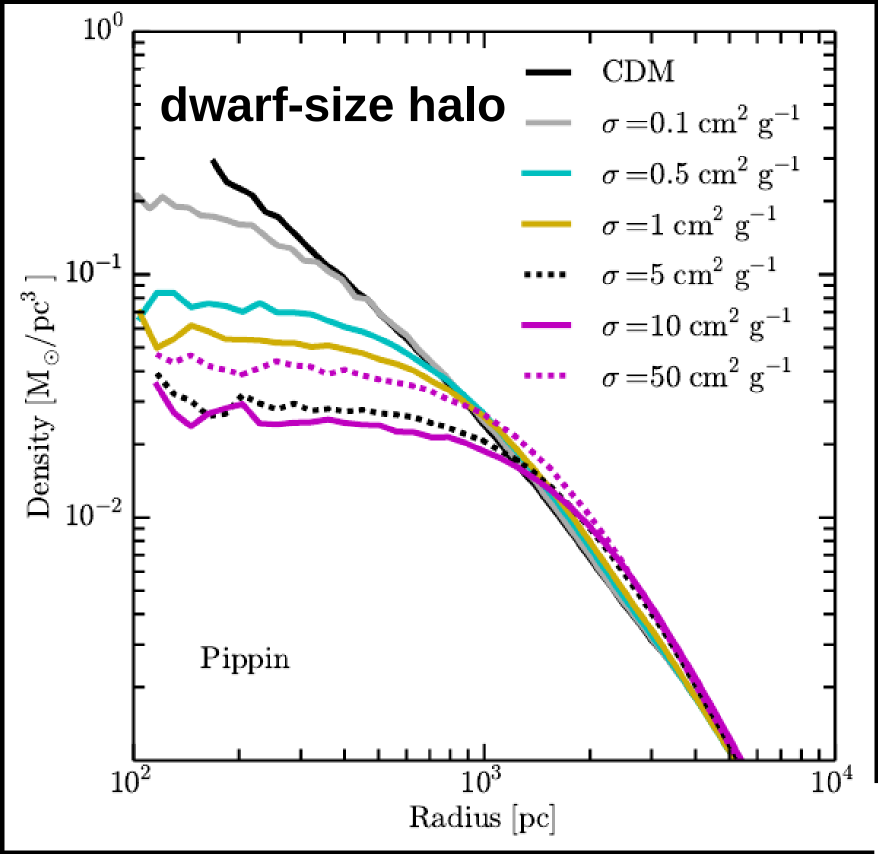
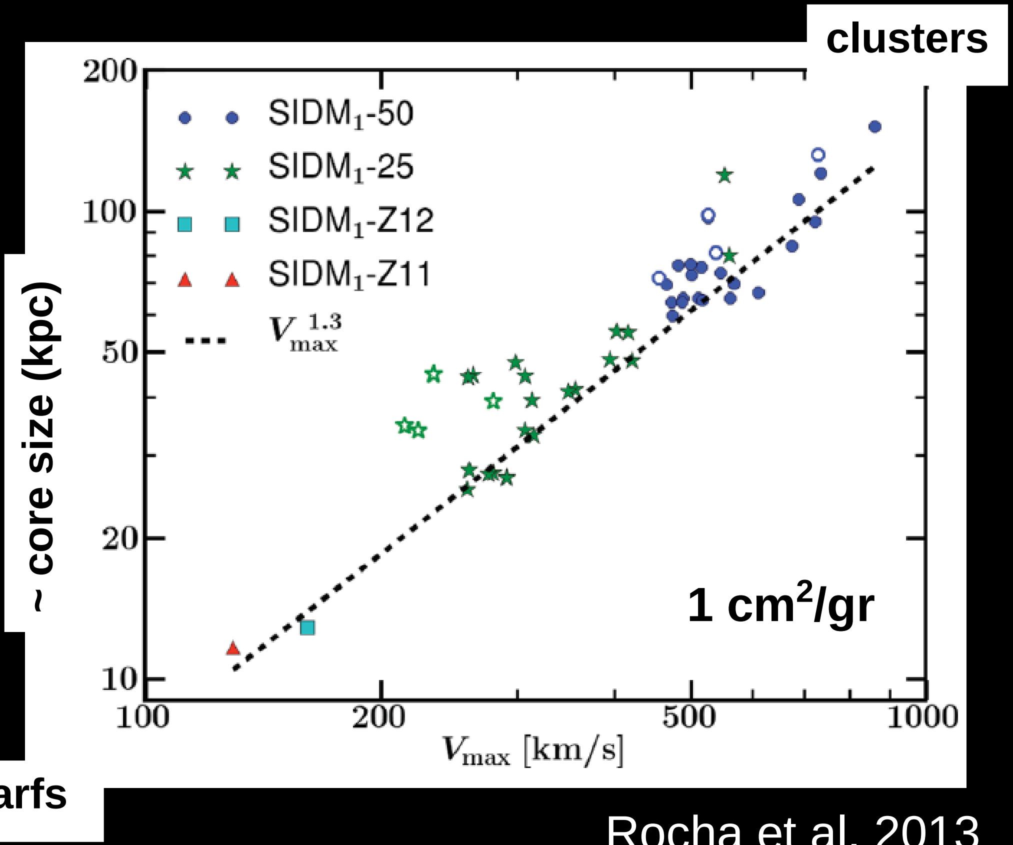
spherically averaged DM distribution

Elbert et al. 2015





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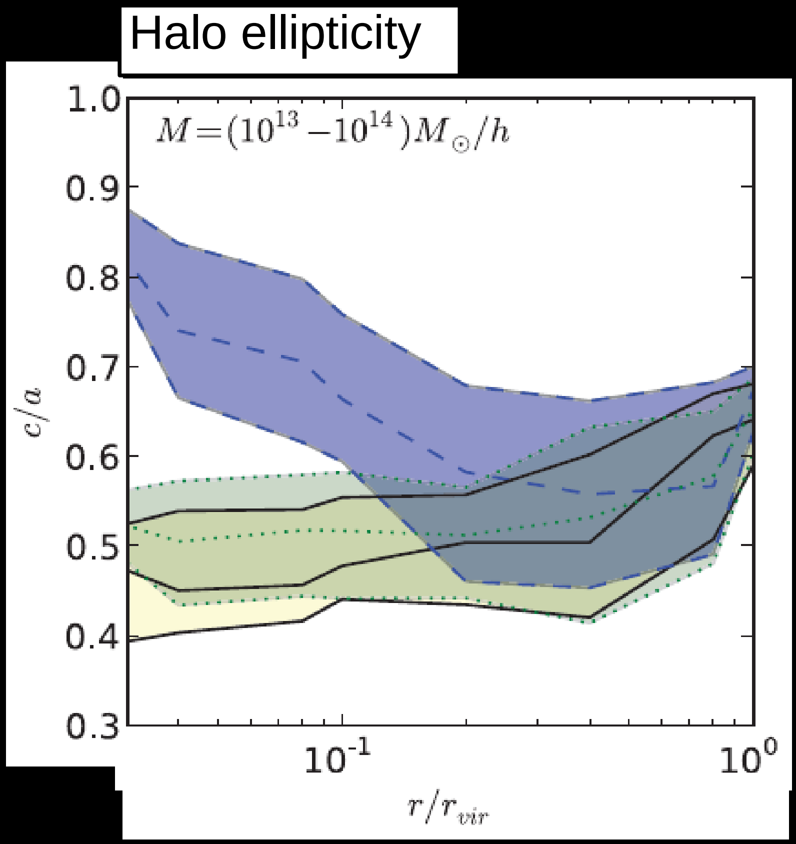
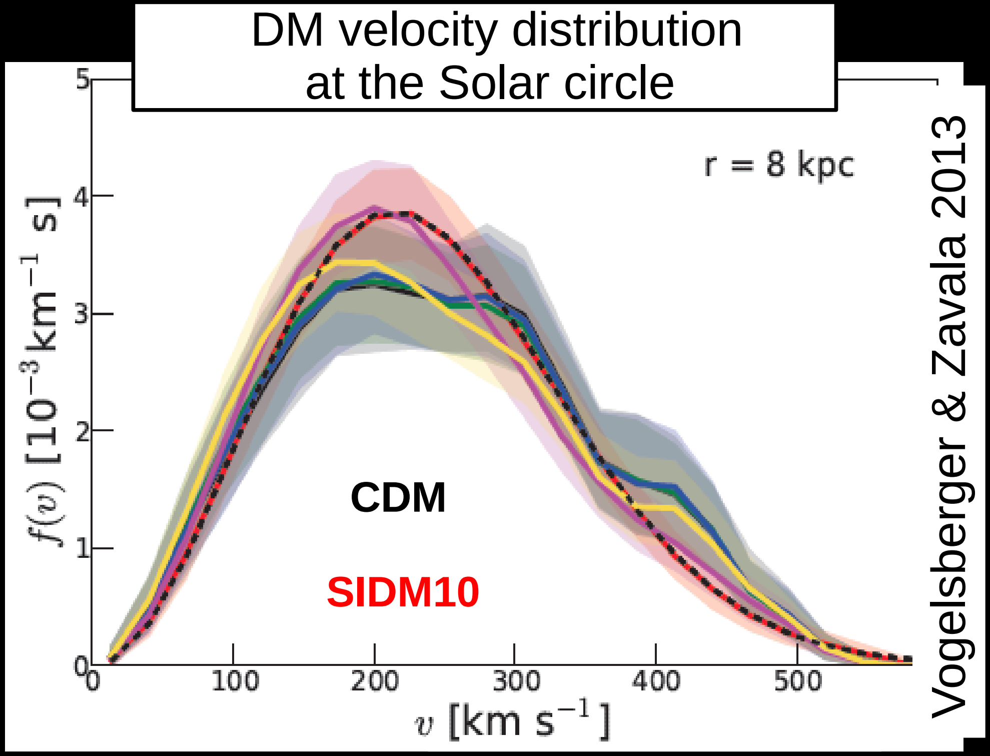
Peter et al. 2013

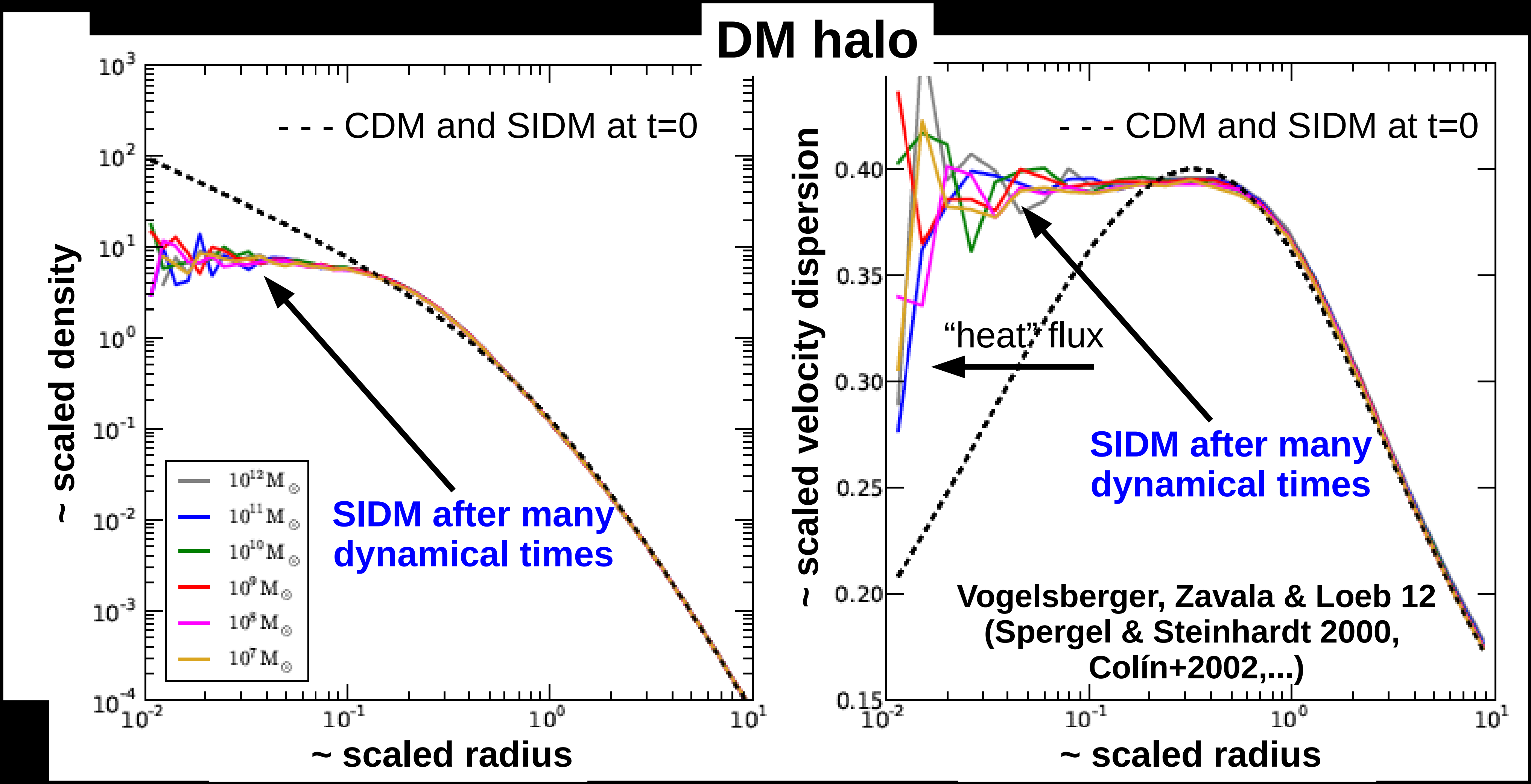




Vogelsberger & Zavala 2013

T. Brinckmann's talk

Core formation with DM self-collisions



DM self-collisions (gravothermal fluid approximation)

spherically symmetric ideal gas in hydrostatic equilibrium
Lynden-Bell & Eggleton 1980

$$\frac{\partial(\rho \nu^2)}{\partial r} = -\frac{GM\rho}{r^2}$$

isotropic Jeans equation

heat flux

$$\frac{L}{4\pi r^2} = -\kappa \frac{\partial T}{\partial r}$$

conductivity

$$\frac{\partial L}{\partial r} = -4\pi \rho r^2 \nu^2 \left(\frac{\partial}{\partial t}\right)_M \ln \frac{\nu^3}{\rho},$$

mass shell

1st law

$$\kappa \sim (3k/2m)\rho \lambda^2/\tau$$

$$\tau \equiv relaxation \quad time$$

since Kn~1 conductivity is found as an empirical interpolation between fluid and collisionless regimes

$$\lambda \rightarrow l_{mean} = 1/(\rho \sigma) \qquad Kn \ll 1$$

$$\lambda \rightarrow \lambda_J^2 = \nu^2/(4\pi G \rho) \qquad Kn \gg 1 \ (LBE)$$

requires callibration from N-body sims

e.g. Balberg, Shapiro & Inagaki 2002, Koda & Shapiro 2011, Pollack, Spergel & Steinhardt 2015

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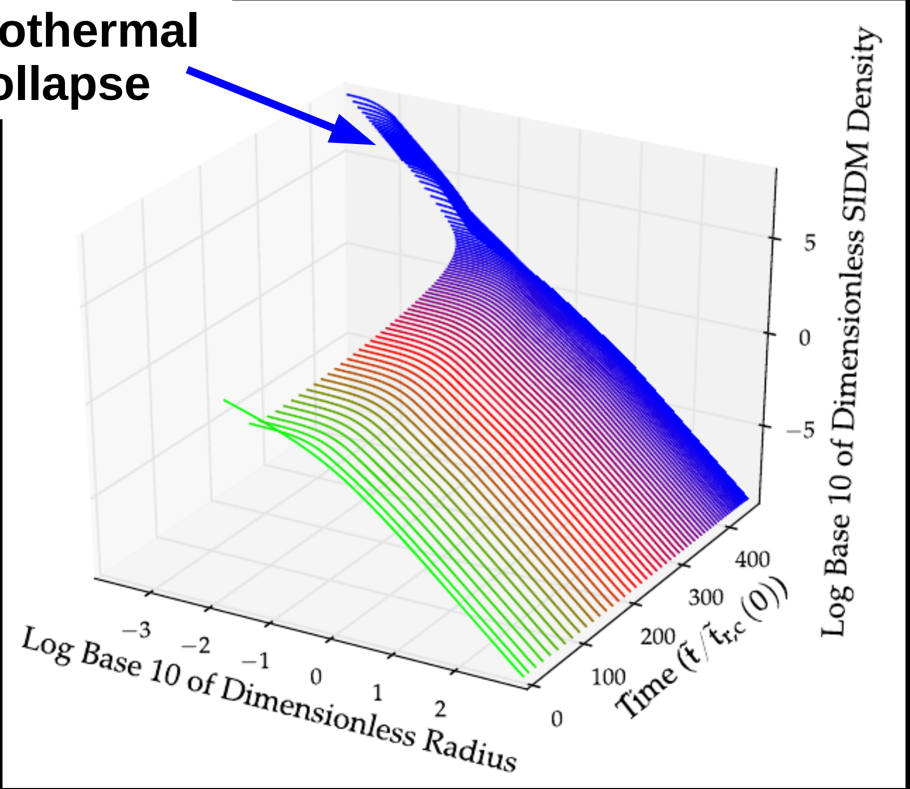
gravothermal collapse



Pollack, Spergel & Steinhardt 2015

e.g. Balberg, Shapiro & Inagaki 2002, Koda & Shapiro 2011, Pollack, Spergel & Steinhardt 2015

DM self-collisions
(isothermal solution to ‘relaxed’ SIDM haloes)

isotropic
Jeans equation

$$\frac{\partial\left(\rho\nu^2\right)}{\partial r} = -\frac{GM\rho}{r^2}$$

+

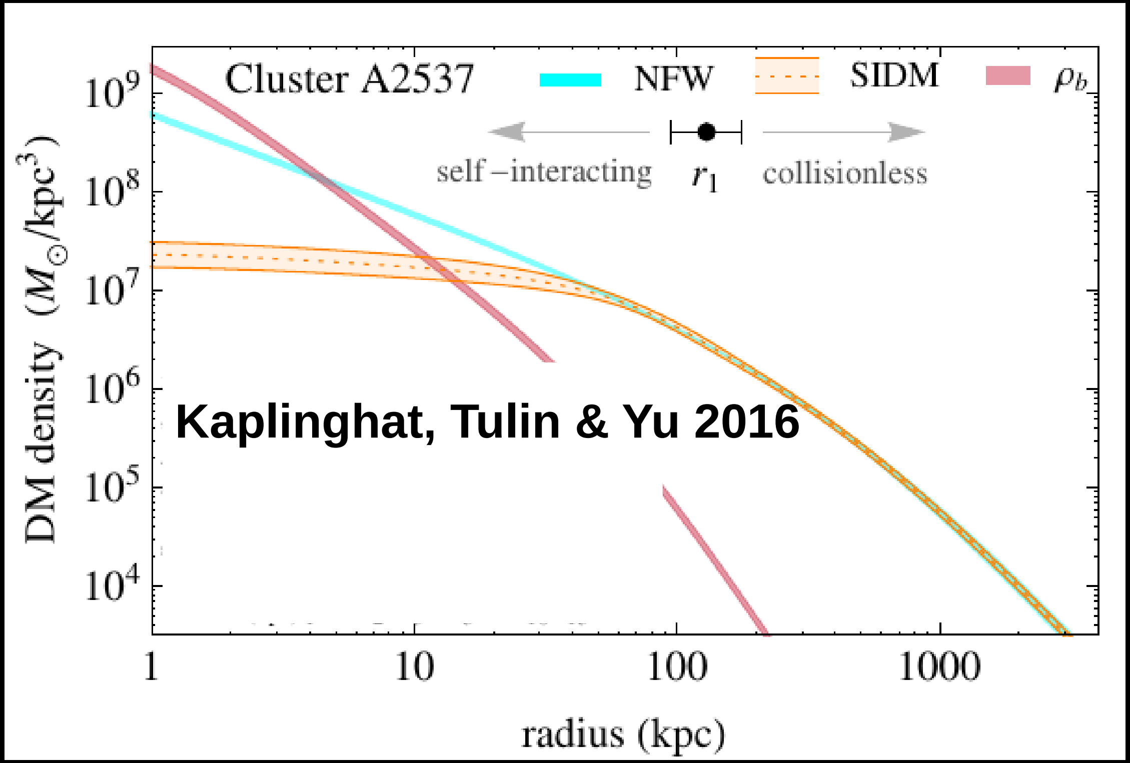
isothermal core

+

DM is eff. collisionless beyond r_1, which is given by the condition:

~ 1 scatter / particle / Hubble time

$$\rho_{\rm dm}(r) = \begin{cases} \rho_{\rm iso}(r)\,, & r < r_1 \\ \rho_{\rm NFW}(r)\,, & r > r_1 \end{cases}$$



O(10-15%) level agreement with N-body

straightforward to add a baryonic component

Rocha et al. 2013, Kaplinghat et al. 2014, Kaplinghat, Tulin & Yu 2016

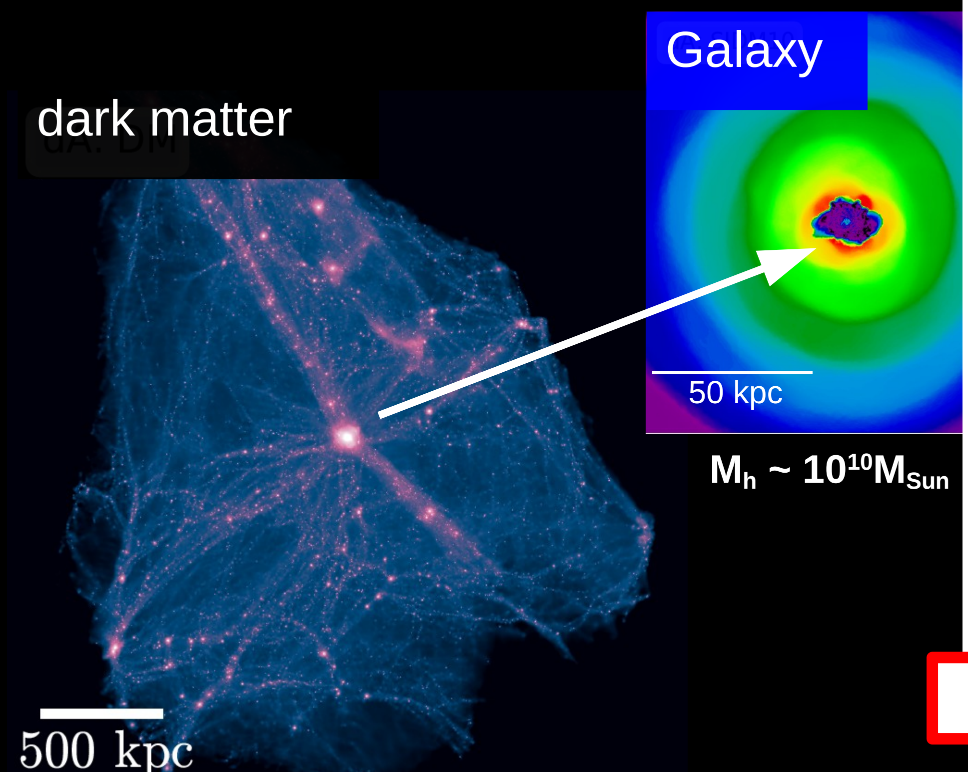
SIDM structure formation theory: beyond DM physics

Full structure formation theory in SIDM (self-scattering DM + baryonic physics)

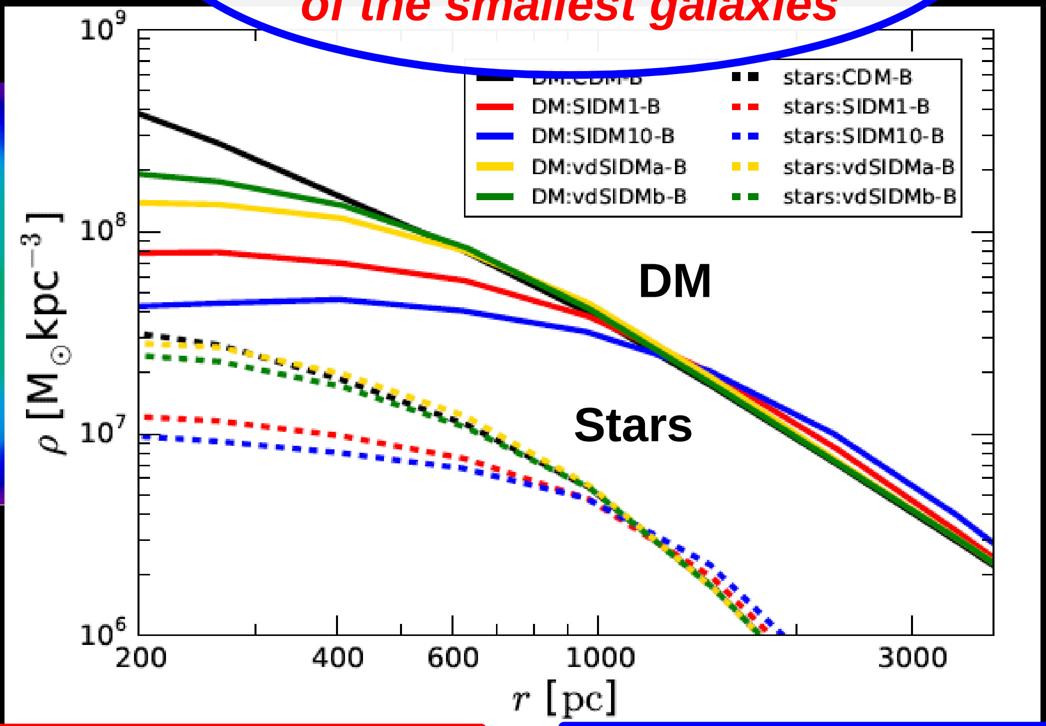
“baryonic physics”: hydrodynamics, radiative cooling of gas, stellar population modelling, SNe feedback (non-bursty)

simulation of a galaxy in Self-Interacting DM (Vogelsberger, Zavala +14)

The signature of DM collisions could be imprinted in the stellar distribution of the smallest galaxies



$M_h \sim 10^{10} M_{Sun}$

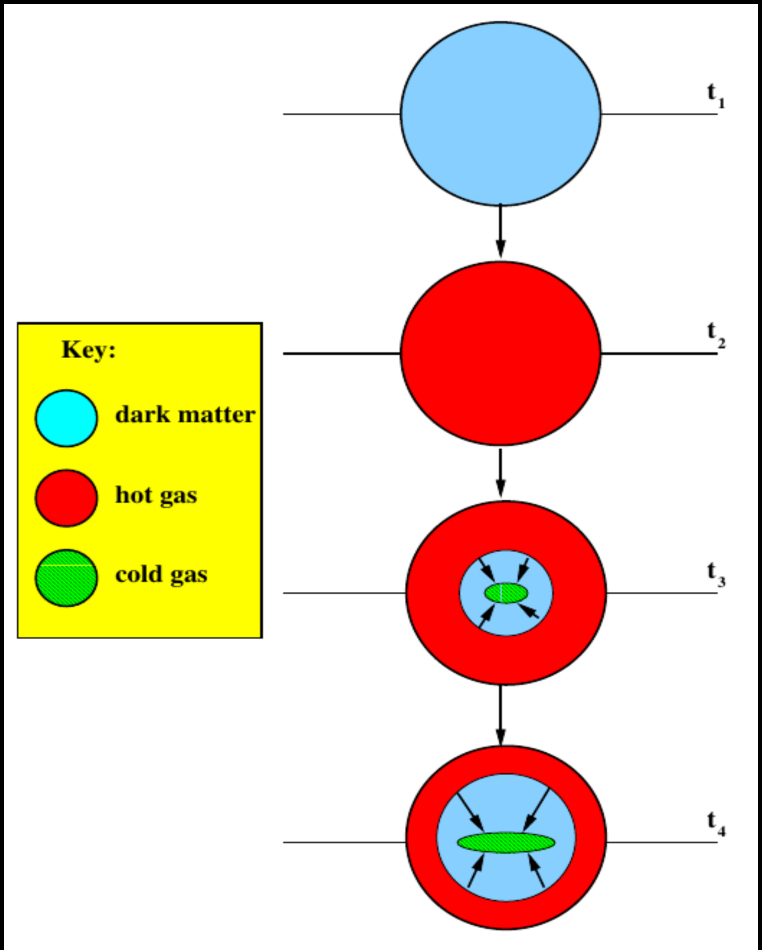


$\sigma/m = 1\ cm^2/gr$

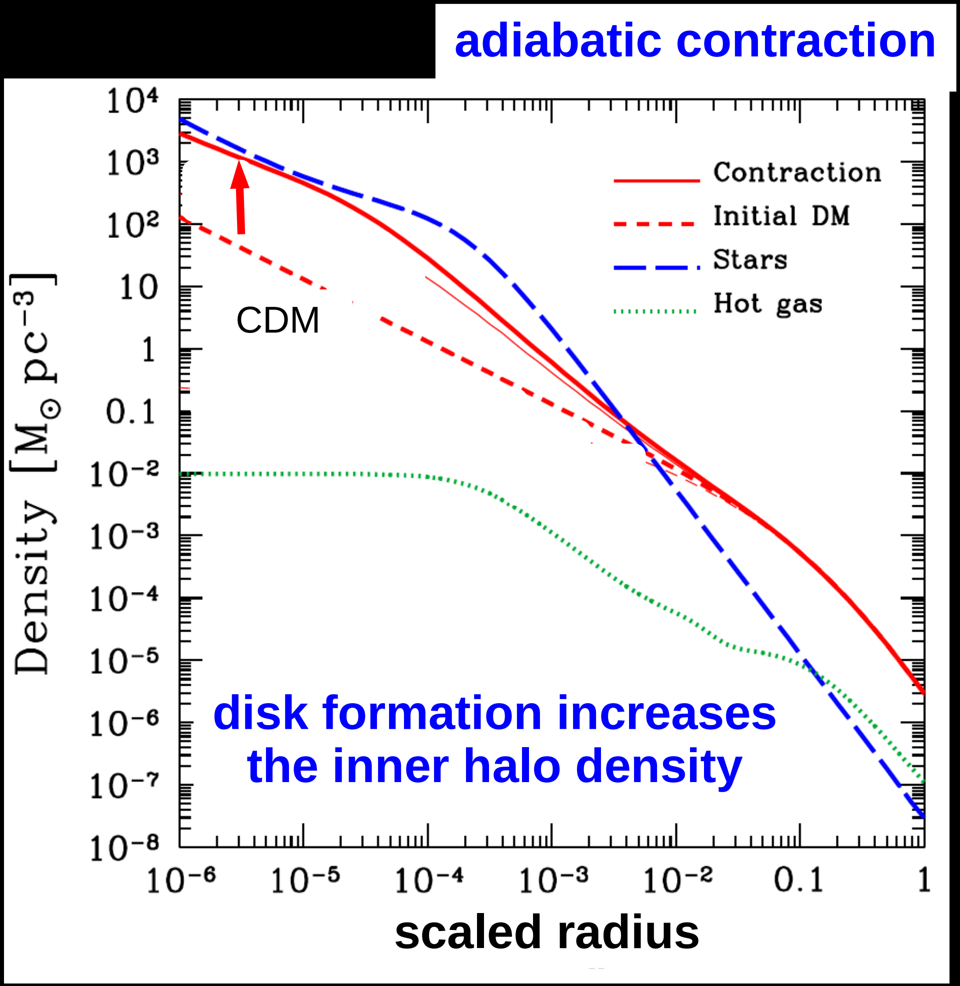
$\sigma/m = 10\ cm^2/gr$

The challenging interplay between DM/baryonic physics

Baugh 2006



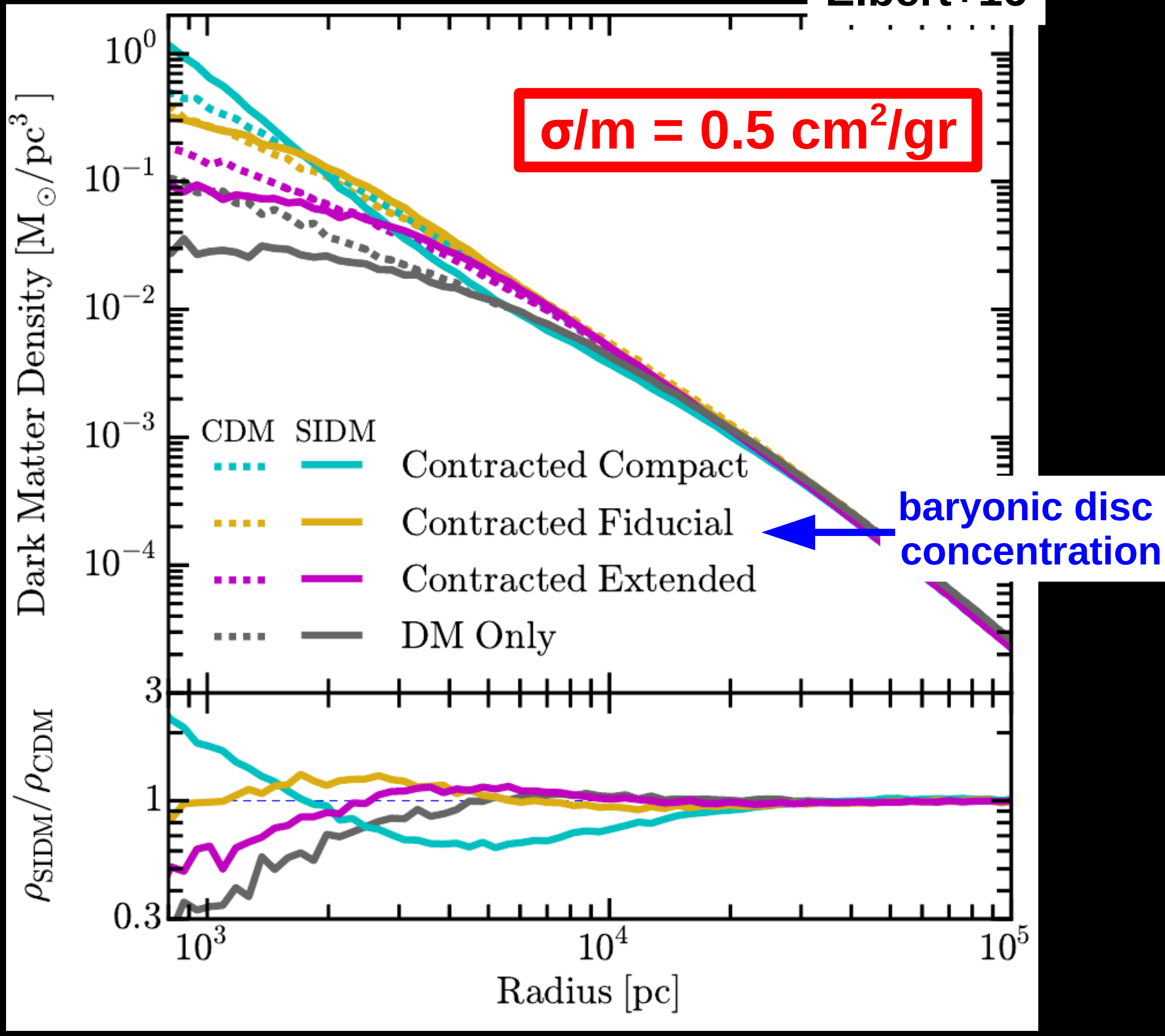
adiabatic contraction



The challenging interplay between DM/baryonic physics

If DM self-collisions are important, a strong contraction due to a compact massive disc, can lead to core collapse

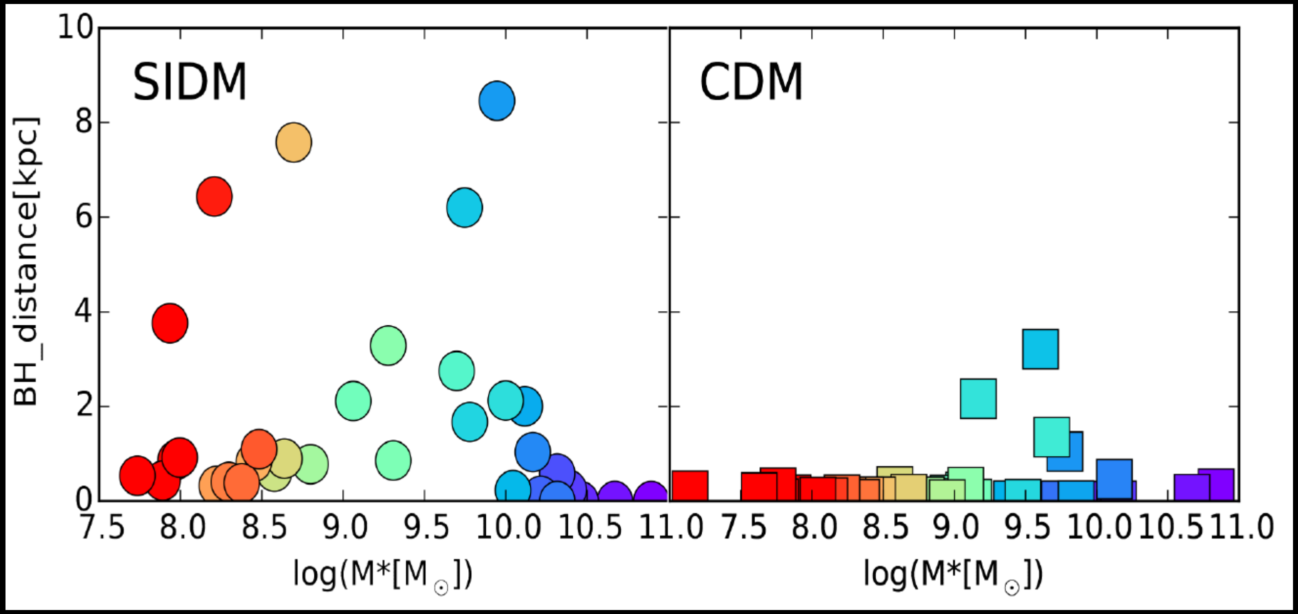
Elbert+16



Milky-Way-size simulation: DM and stars (by hand)

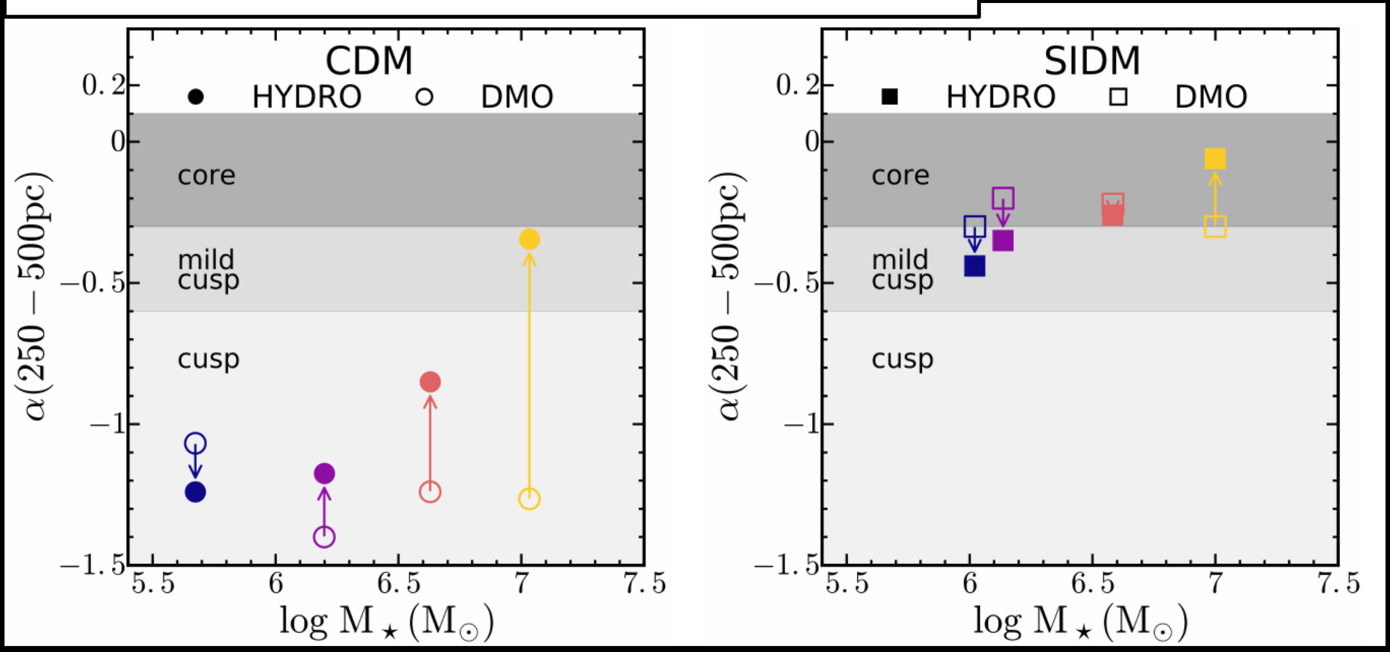
Disentangling dark from baryonic physics

SMBH offsets



Di Cintio et al. 2017

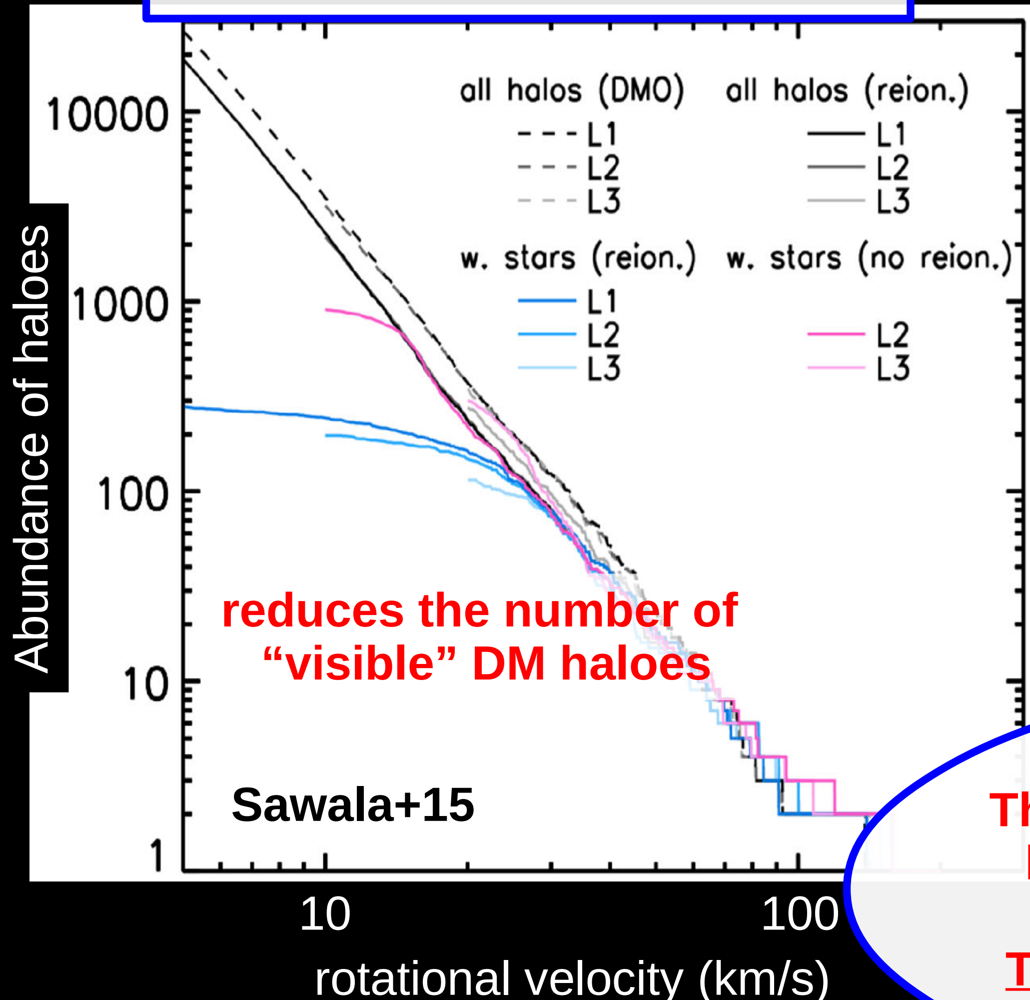
SNe-driven DM cores inneficient at low M*⁎*



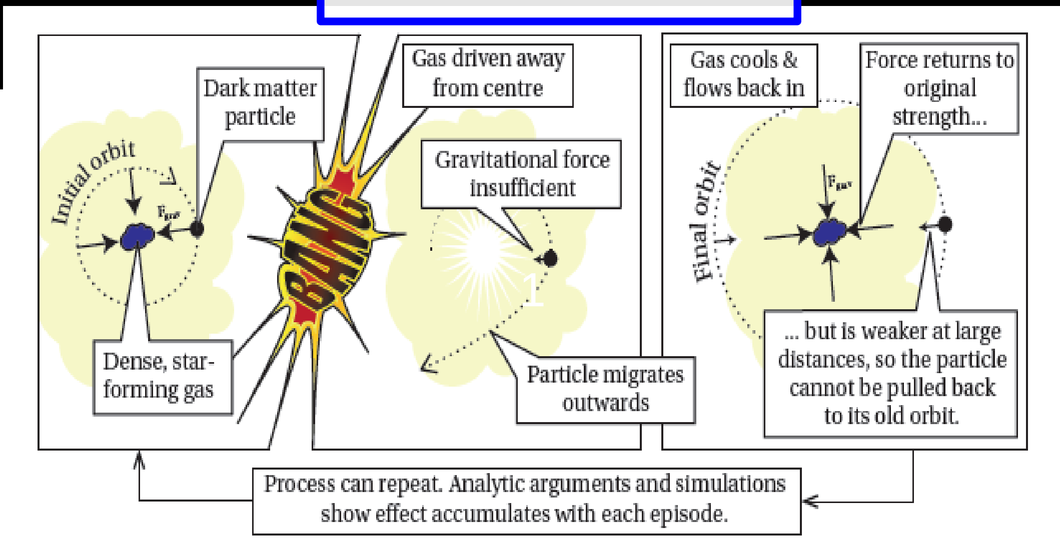
Robles t al. 2017

The complexity of gas and stellar physics

Gas heating (UV background from first generation of stars/galaxies)



Gas and DM heating through supernovae



Credit: Pontzen & Governato 2014

reduces the inner density of DM haloes

These mechanisms are certainly there, but how efficient they are remains unclear

<u>To some extent, they are degenerate with new DM physics</u>

Concluding remarks

- The window for the DM particle nature to be relevant for structure formation is narrow and within reach of upcoming observations

SIDM transfer cross section

$$0.1\,cm^2/gr \lesssim \sigma/m \lesssim 2\,cm^2/gr$$

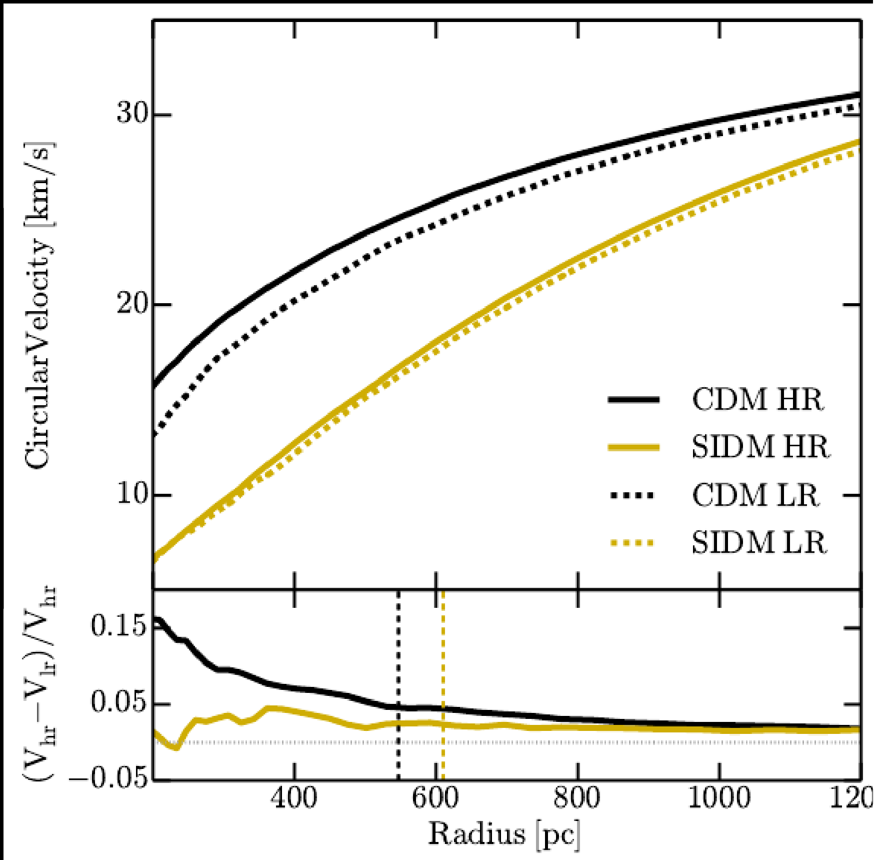
'cutoff' halo mass at z=0

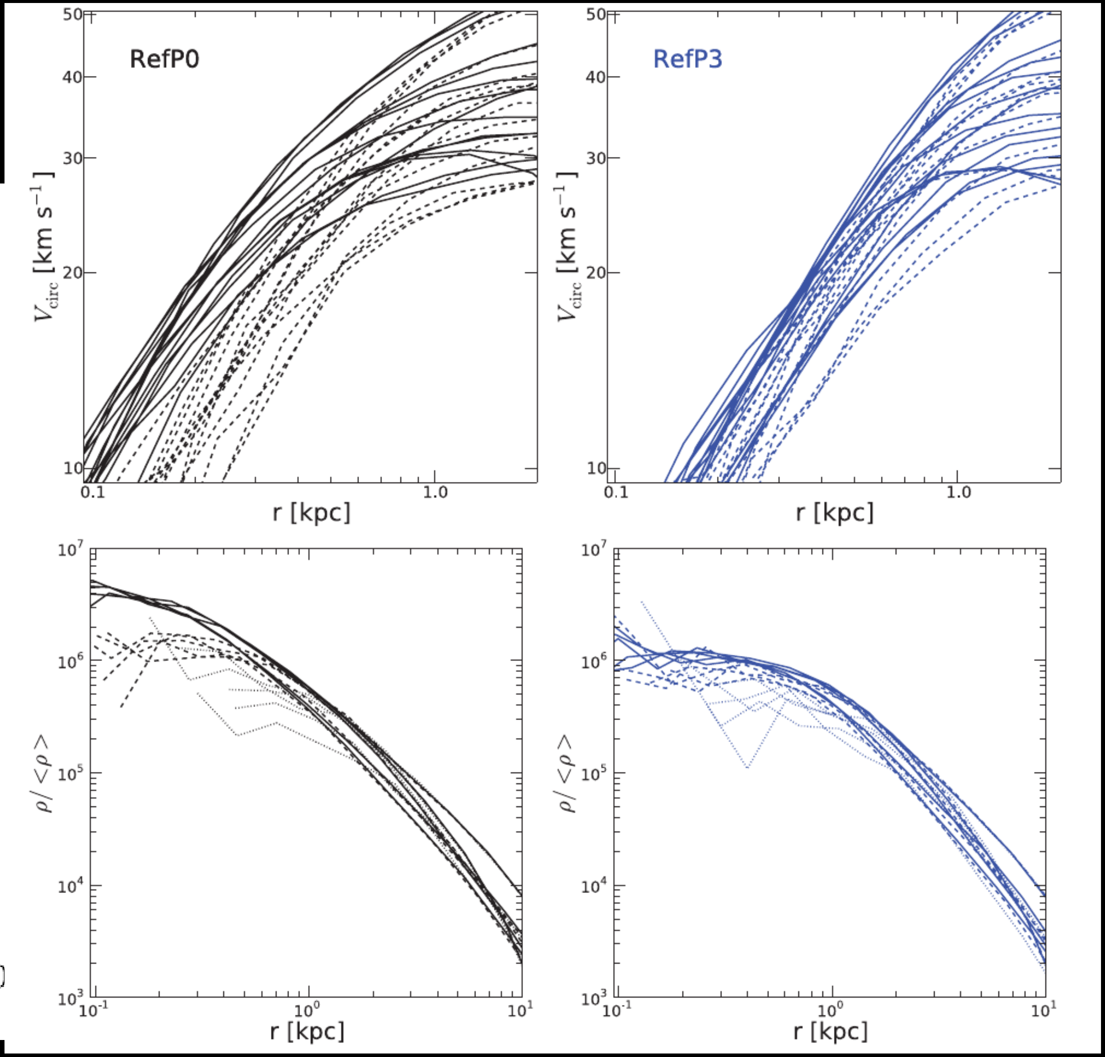
$$10^{9.5}\,M_{Sun} \lesssim M_{cut} \lesssim 10^{10.5}\,M_{Sun}$$

- DM self-collisions could have an impact in the non-linear evolution of haloes:
  - Spherical, Maxwellian DM cores of size $\sim r_{max}$ are the quasi-equilibrium stage of SIDM haloes if the central scattering rate per particle is $\sim 1/t_H$
  - Gravothermal collapse is the natural outcome for large time scales (and/or σ/m)
  - The DM/baryonic physics synergy remains largely unexplored: possible degeneracies in observational comparisons, albeit undesirable, reflect our current incomplete knowledge of the DM nature and galaxy formation/evolution
  - Looking for subtle changes beyond r_{max} is a promising avenue to avoid the complexities of baryonic physics (T. Brinckmann's talk)

DM self-collisions in N-body simulations (probabilistic approach: convergence)

Elbert et al. 2015





Vogelsberger et al. 2012