Perspectives on the Astrophysics of Dark Matter

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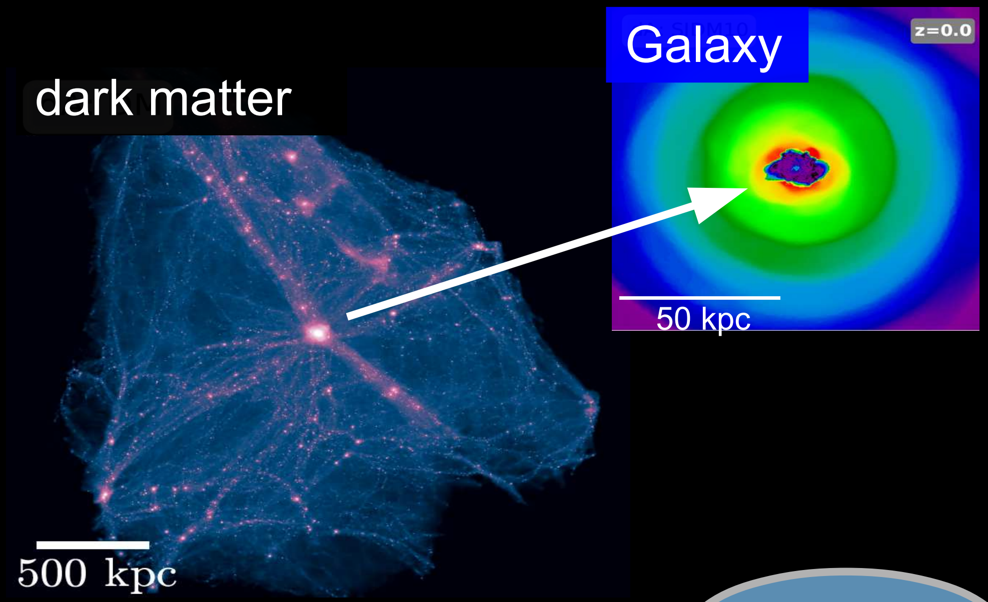
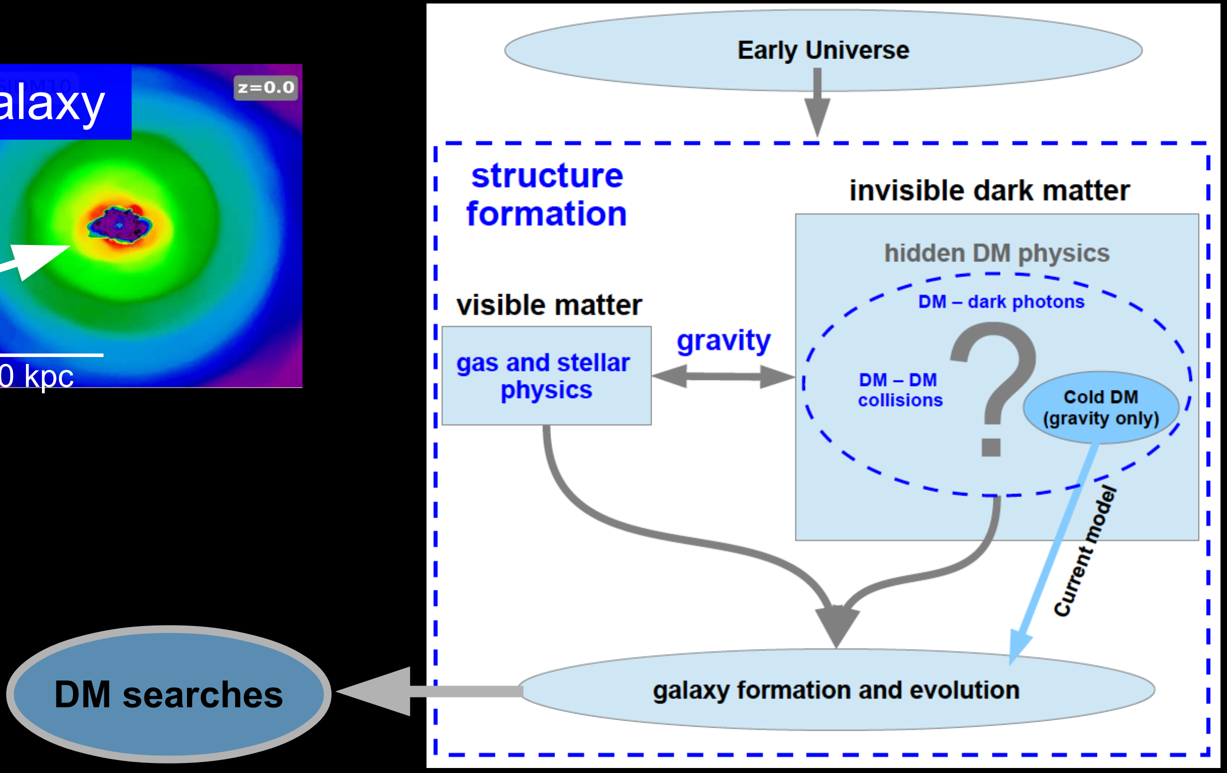




Mini Workshop on Dark Matter, Instituto de Física, UNAM, November 2016

OUTLINE

Lectures 1 and 2

- **Dark matter and structure formation**
  - ➔ Cold Dark Matter (Lecture 1)
  - ➔ Non-gravitational DM interactions (Lecture 2)
- **The sinergy between dark and 'ordinary' matter in the physics of galaxy formation and evolution**

Discussion session

- **Perspectives on the future of astrophysics to probe the DM nature: an effective theory of structure formation (ETHOS)**

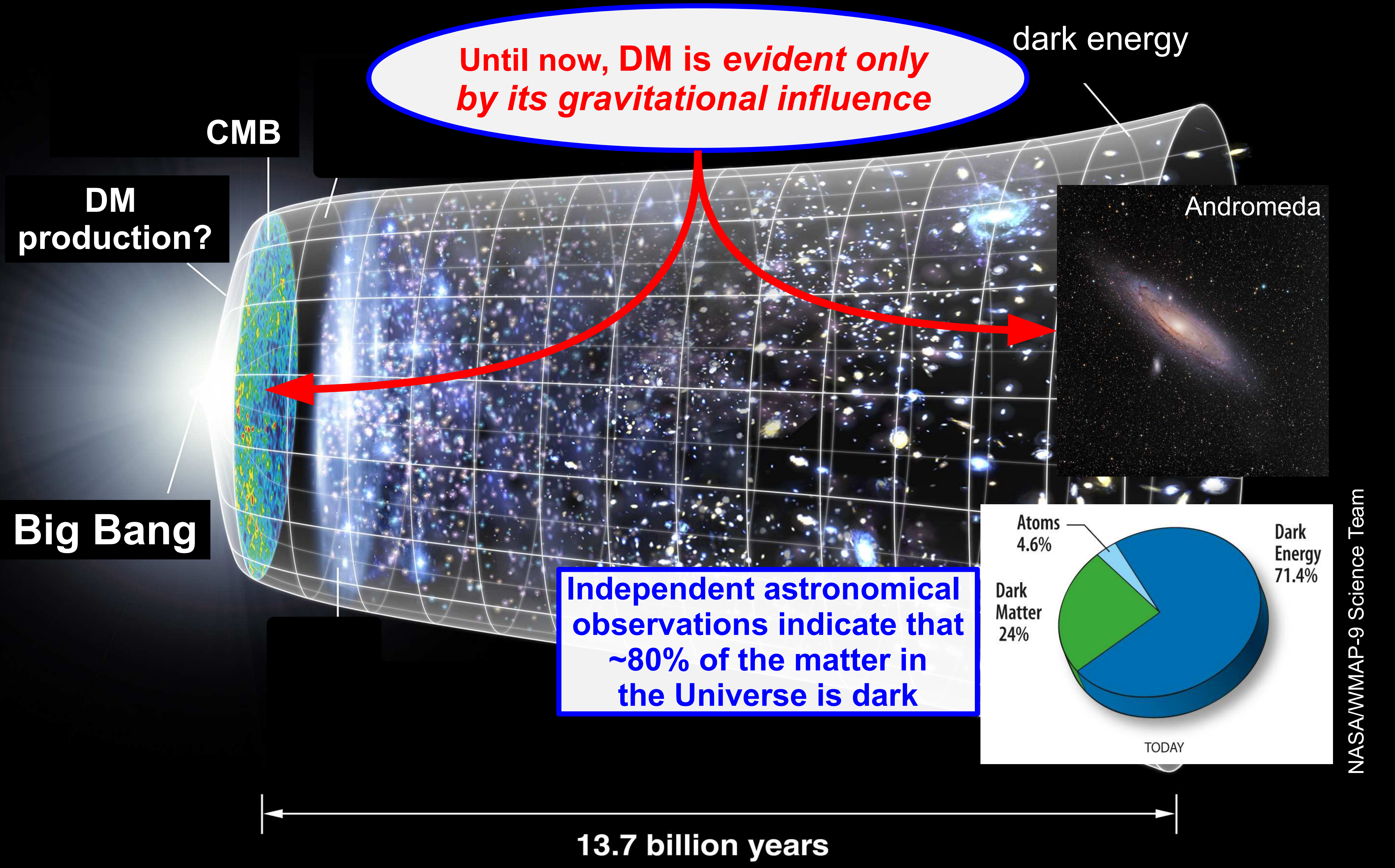
The particle DM hypothesis:

DM is made of *new* particles that do not emit electromagnetic radiation at a significant level

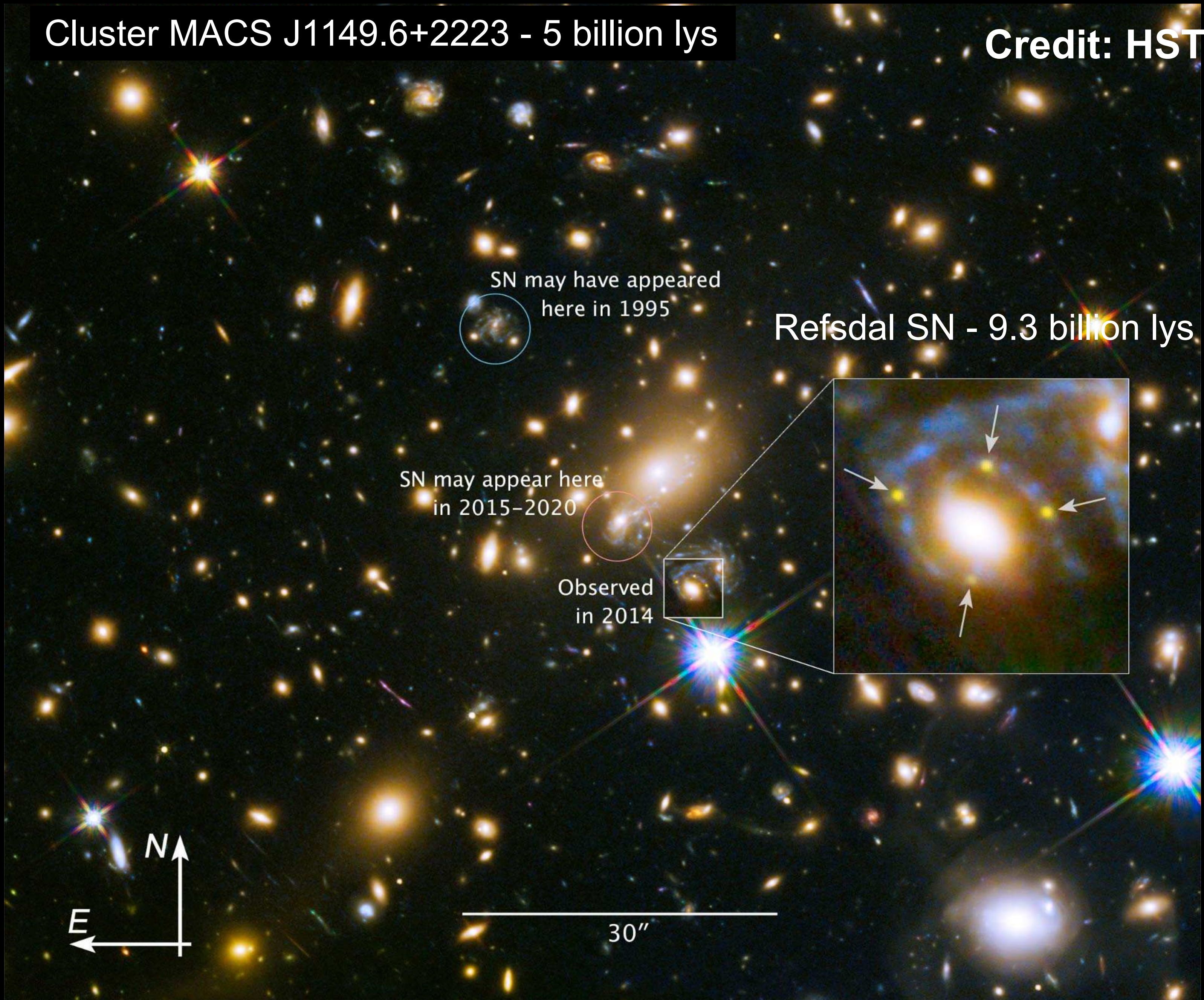
Until now, DM is *evident only by its gravitational influence*

The particle DM hypothesis:

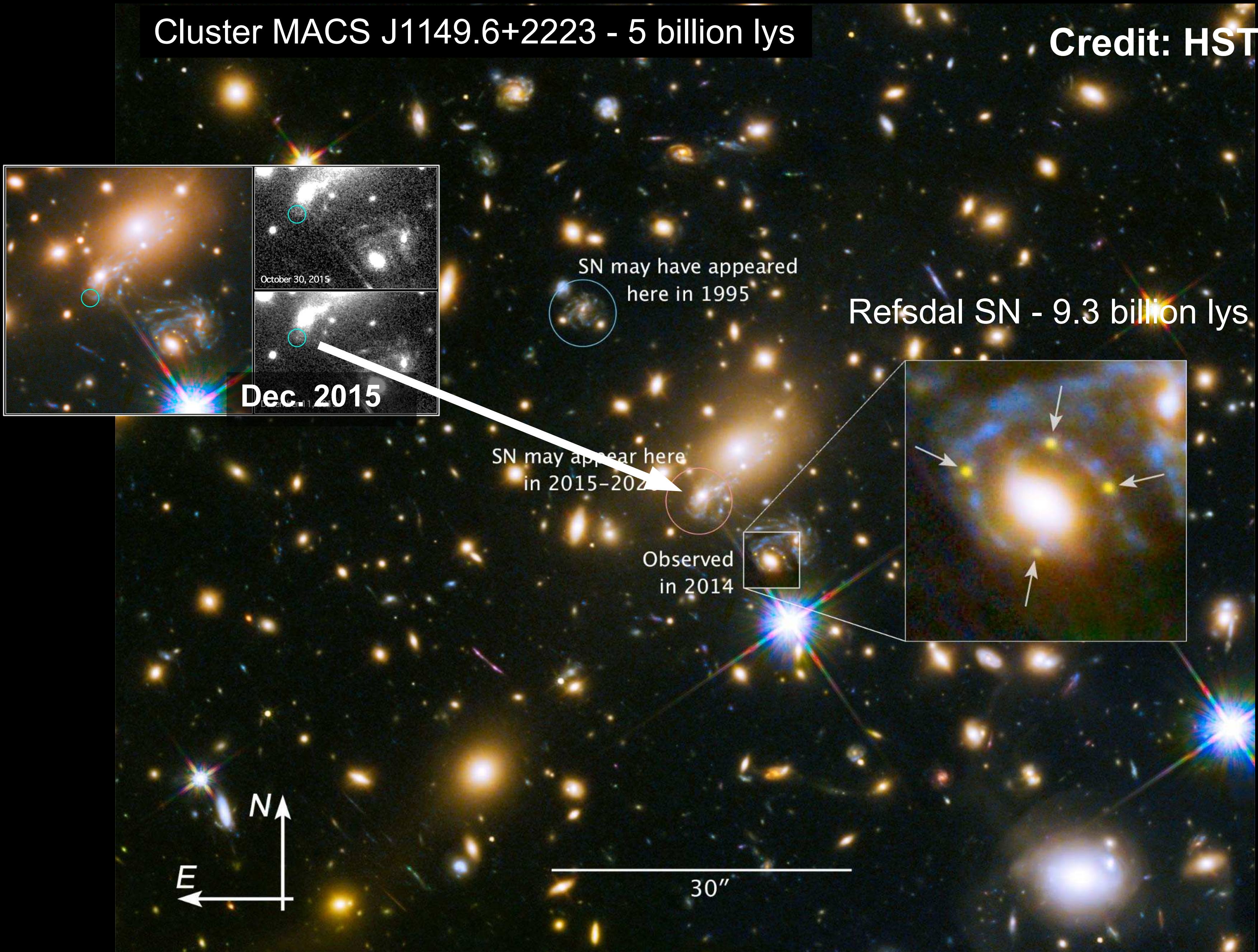
DM is made of *new* particles that do not emit electromagnetic radiation at a significant level



A spectacular example of a GR effect and a strong indication of the existence of DM



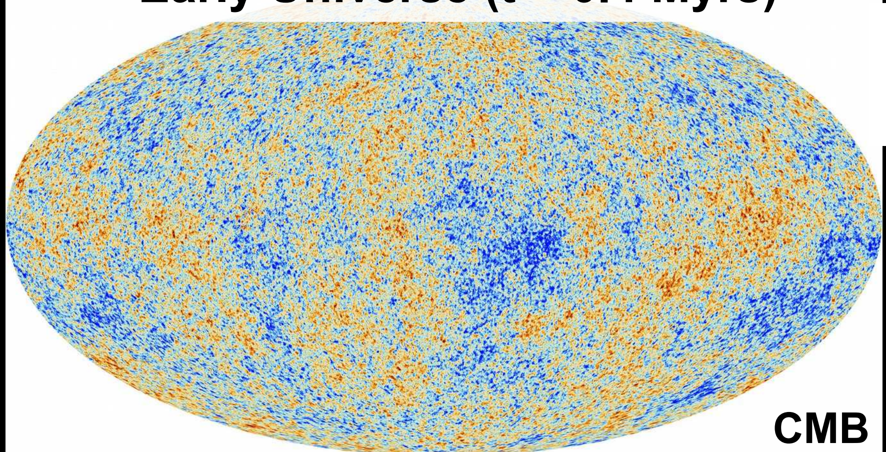
A spectacular example of a GR effect and a strong indication of the existence of DM



The particle DM hypothesis is seemingly essential to explain the growth of perturbations into the structures we see today

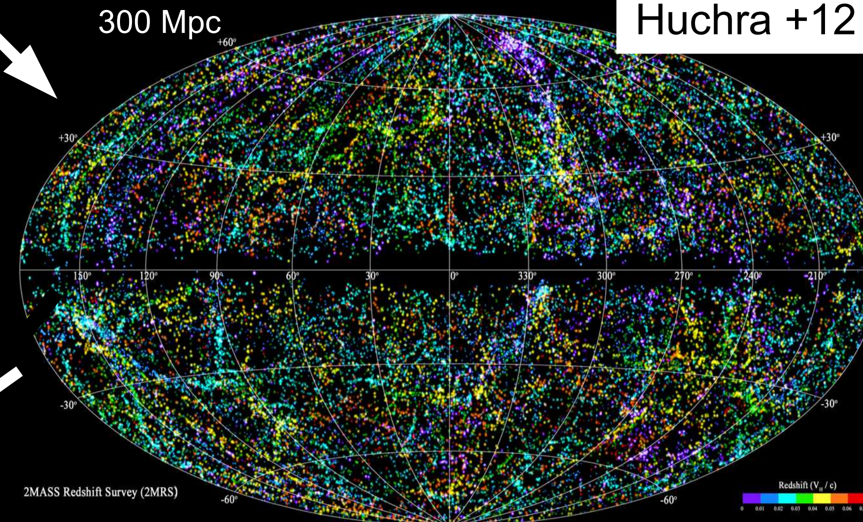
Credit: ESA and the Planck Collaboration

Early Universe (t ~ 0.4 Myrs)



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

Universe today (t ~ 13.8 Gyrs)



2MRS galaxy “map”, large-scale structure

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

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

galactic scales

structure formation theory (main ingredients)

Standard structure formation theory (main ingredients)

LINEAR REGIME (cosmological perturbation theory)

- Background evolution (flat Universe)
  - → cosmological principle, FRW metric, Friedmann eqs.
  - → global parameters constrained by the CMB,...

Standard structure formation theory (main ingredients)

LINEAR REGIME (cosmological perturbation theory)

- **Background evolution (flat Universe)**
  - ➔ cosmological principle, FRW metric, Friedmann eqs.
  - ➔ global parameters constrained by the CMB,...

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

  - ➔ initial conditions constrained by the CMB
  - ➔ perturbed FRW metric
  - ➔ ideal non-relativistic DM fluid
  - ➔ CDM hypothesis: collisionless DM "fluid" with a free streaming length much smaller than characteristic galactic scales

$$\lambda_{fs} \simeq \int_0^{t_{nr}} \frac{v_{pec}(t')}{a(t')} dt' \propto 1/m_{DM} \ll 100\, kpc$$

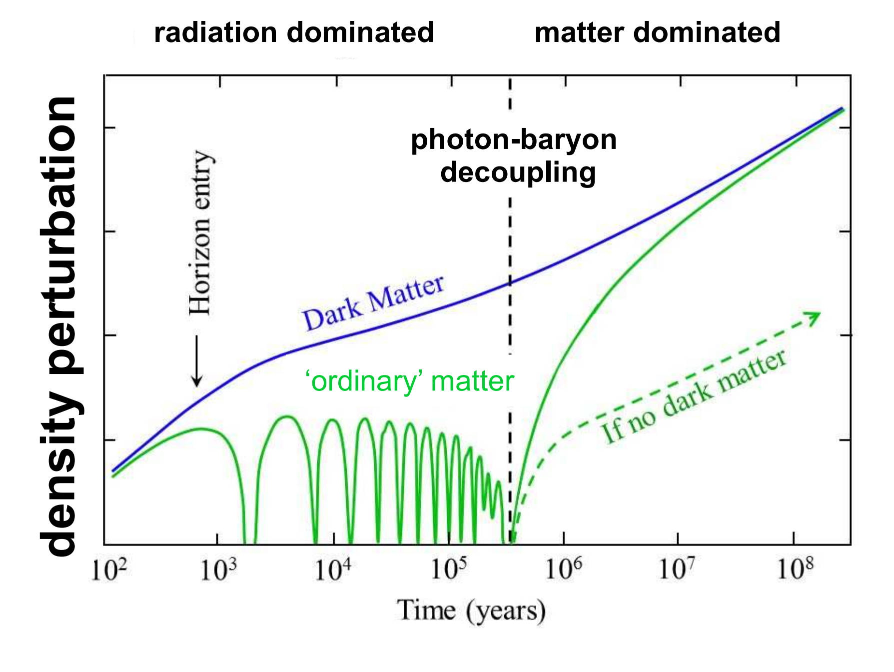
Standard structure formation theory

LINEAR REGIME (cosmological perturbation theory)

evolution eqs. are linear in this regime

↓

the perturbed density field can be expanded in plane waves with the 'k' individual modes evolving independently



eqs. for DM perturbations

$$\dot{\delta} + \theta - 3\dot{\phi} = 0 \quad \text{(Continuity)}$$

$$\dot{\theta} + \mathcal{H}\theta - k^2\phi = 0 \quad \text{(Euler)}$$

$$k^2\phi + 4\pi G a^2 \rho_{\rm B}\delta = 0 \quad \text{(Poisson)}$$

$$\theta = \nabla \cdot \vec{v}$$

$$\mathcal{H} = \frac{\dot{a}}{a}$$

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

Standard structure formation theory

LINEAR REGIME (cosmological perturbation theory)

from individual modes to the statistical description of the perpurbed density field

↓

2-point correlation function (2PCF)
(power spectrum in Fourier space)

$$\xi(|\vec{\Delta x}|) \equiv \left\langle \delta(\vec{x})\delta(\vec{x} + \vec{\Delta x}) \right\rangle$$

Standard structure formation theory

LINEAR REGIME (cosmological perturbation theory)

from individual modes to the statistical description of the perpurbed density field

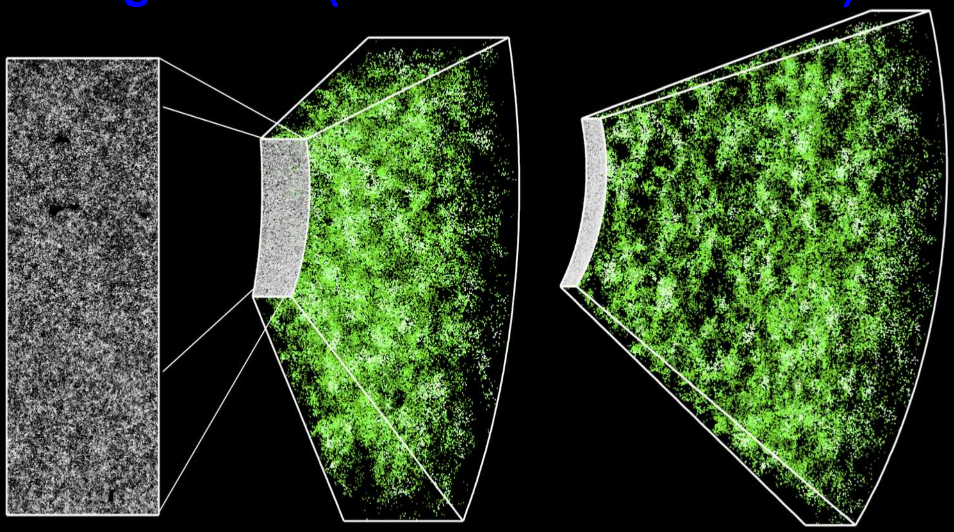
↓

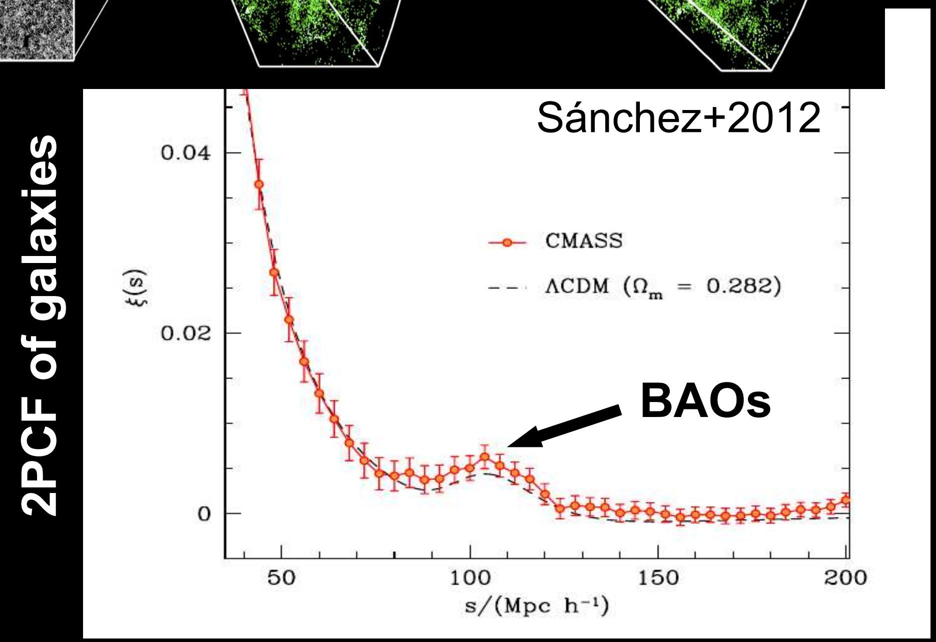
2-point correlation function (2PCF) (power spectrum in Fourier space)

$$\xi(|\vec{\Delta x}|) \equiv \left\langle \delta(\vec{x})\delta(\vec{x}+\vec{\Delta x}) \right\rangle$$

concept illustration: distribution of galaxies

3D reconstruction of the cosmc web of galaxies (SDSS-III collaboration)

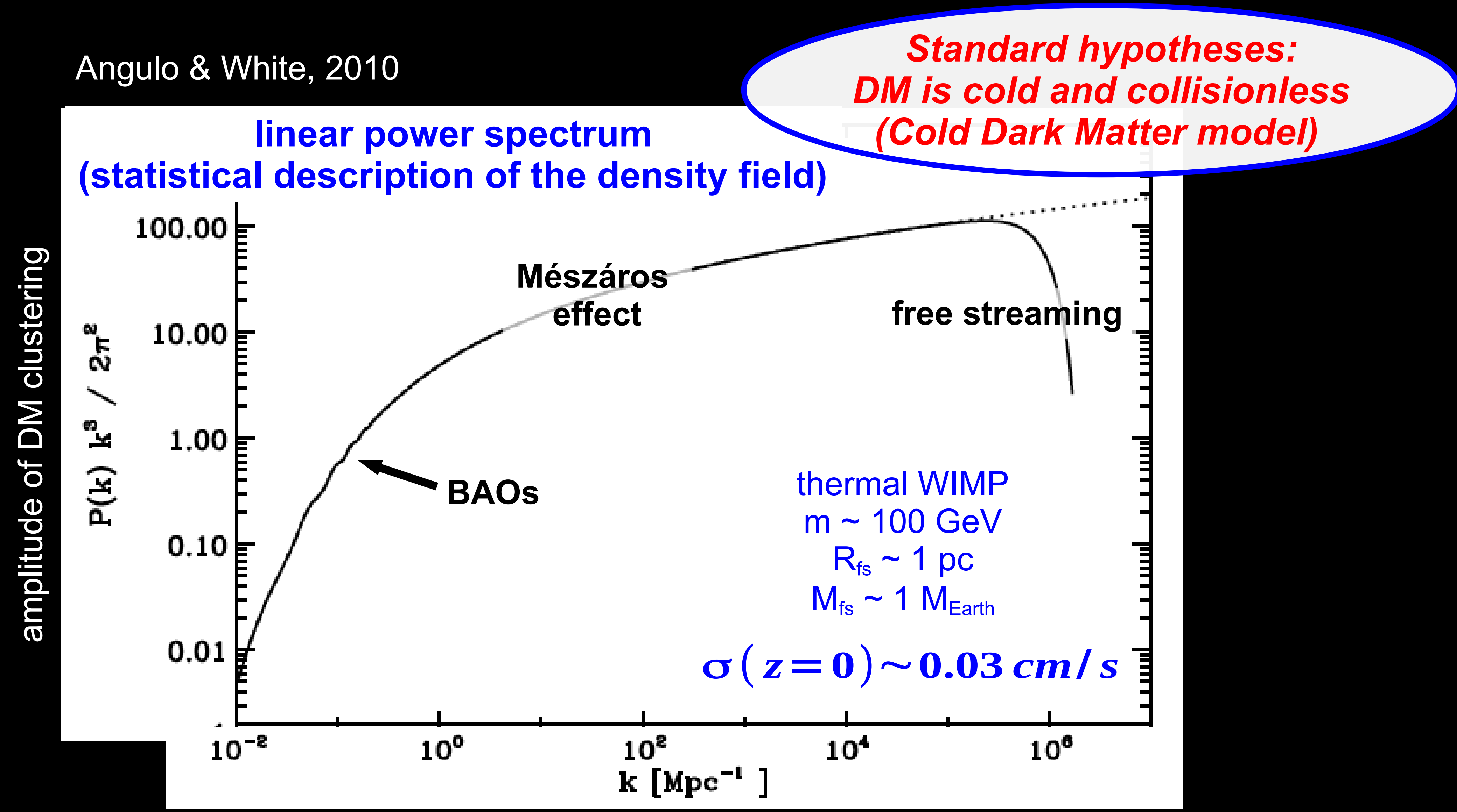




Standard structure formation theory

LINEAR REGIME (cosmological perturbation theory)

Angulo & White, 2010



Standard structure formation theory

NON-LINEAR REGIME (N-body simulations)

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:

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

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)

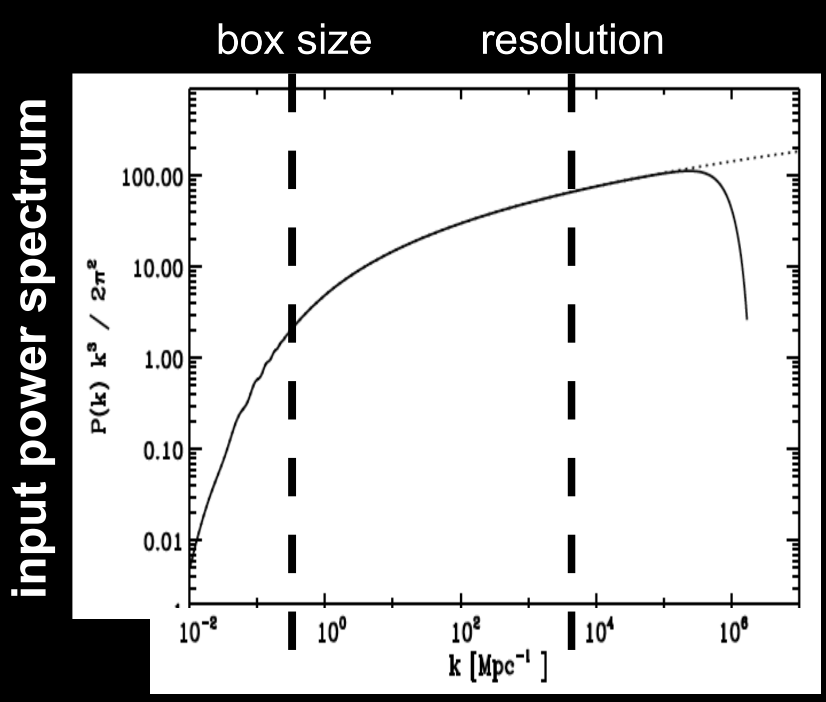
N-body sim: the coarse-grained distribution is given by a discrete representation of N particles:

macro-to-micro-particle mass ratio

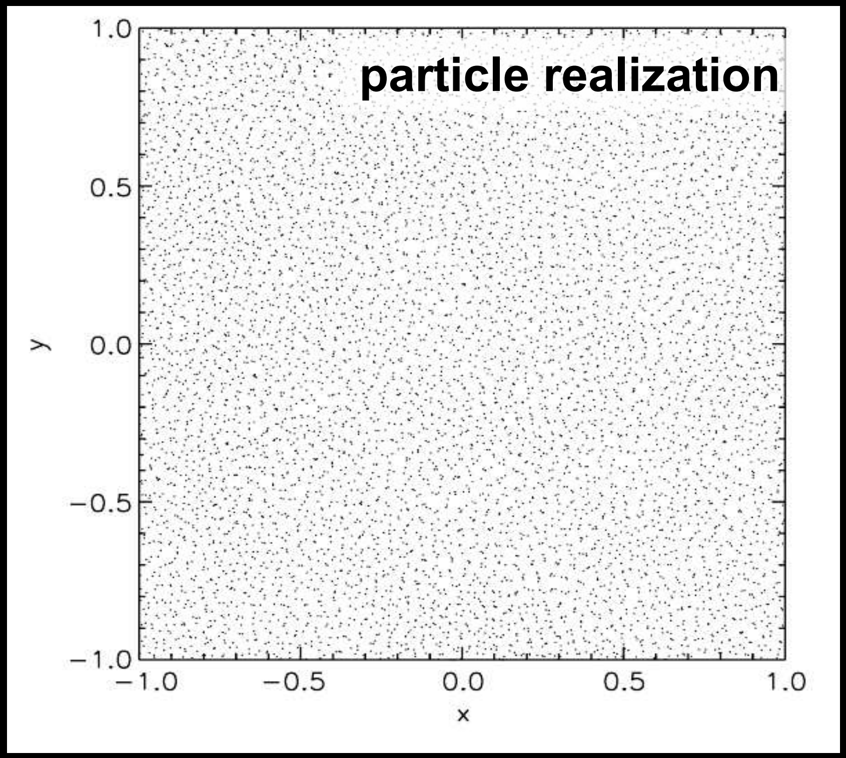
each particle is smoothed in space to give a smooth local density

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

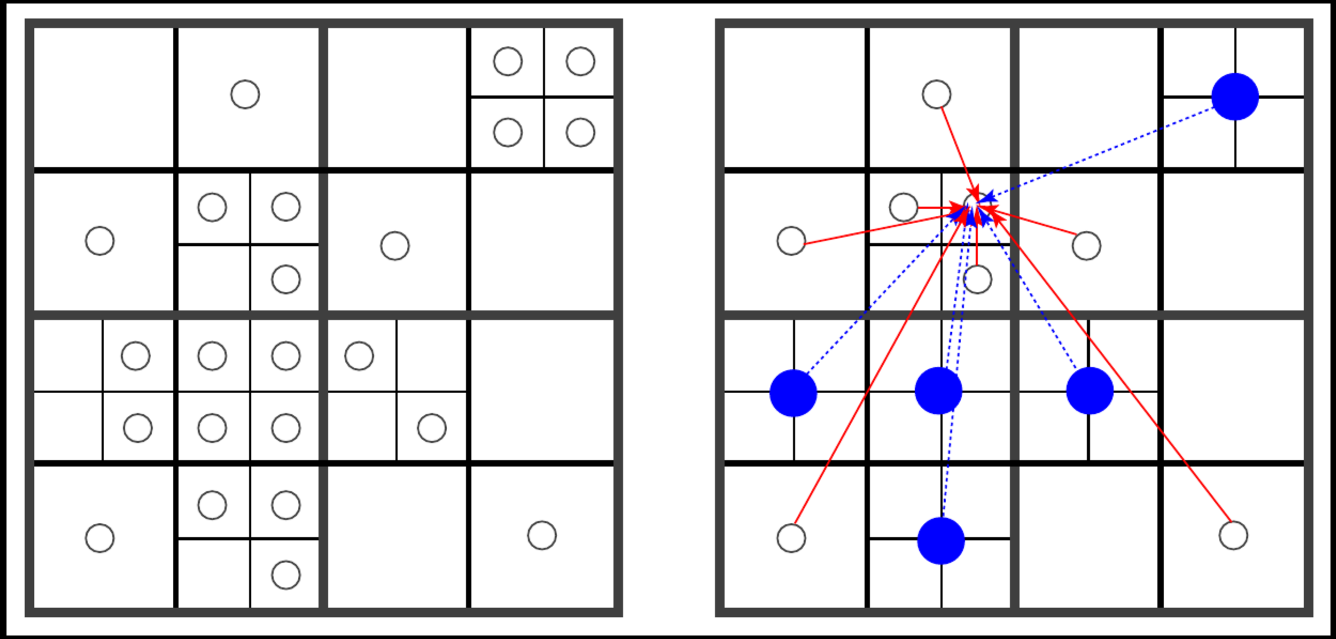
Standard structure formation theory

NON-LINEAR REGIME (N-body simulations)

time evolution is simply given by Newtonian gravity in an expansing background

a large number of simulated particles is needed to have a realization of cosmological size and sufficient resolution to study DM clustering at subgalactic scales

example of N-body method: three algorithm



Ishiyama+2015

to reduce the number of force calculations, a hierarchical multipole expansion is used to account for distant group of particles

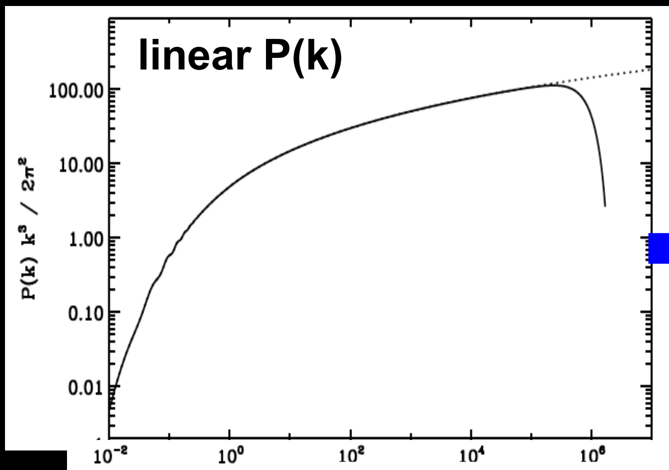
Standard structure formation theory

NON-LINEAR REGIME (N-body simulations)

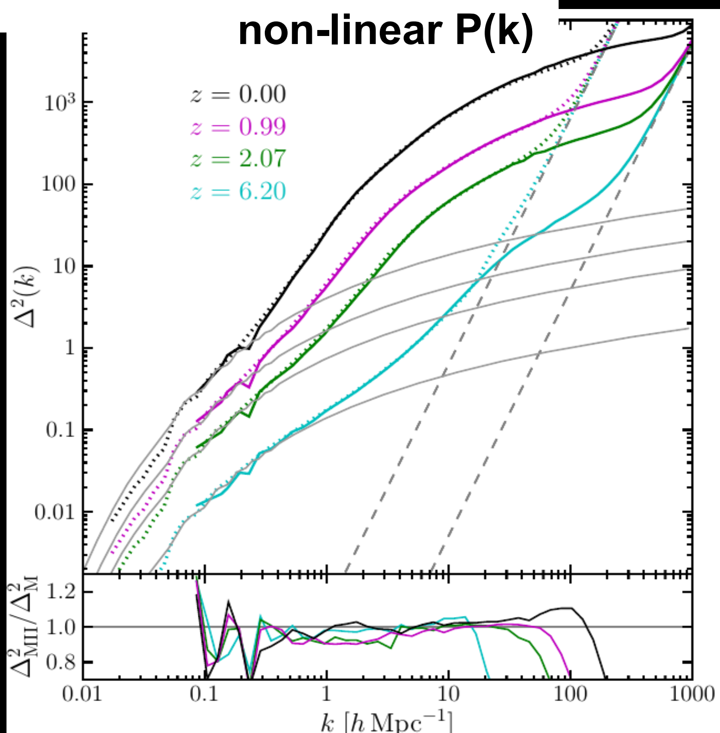
Aquarius Project 2008
Credit: Volker Springel

Standard structure formation theory

NON-LINEAR REGIME (N-body simulations)

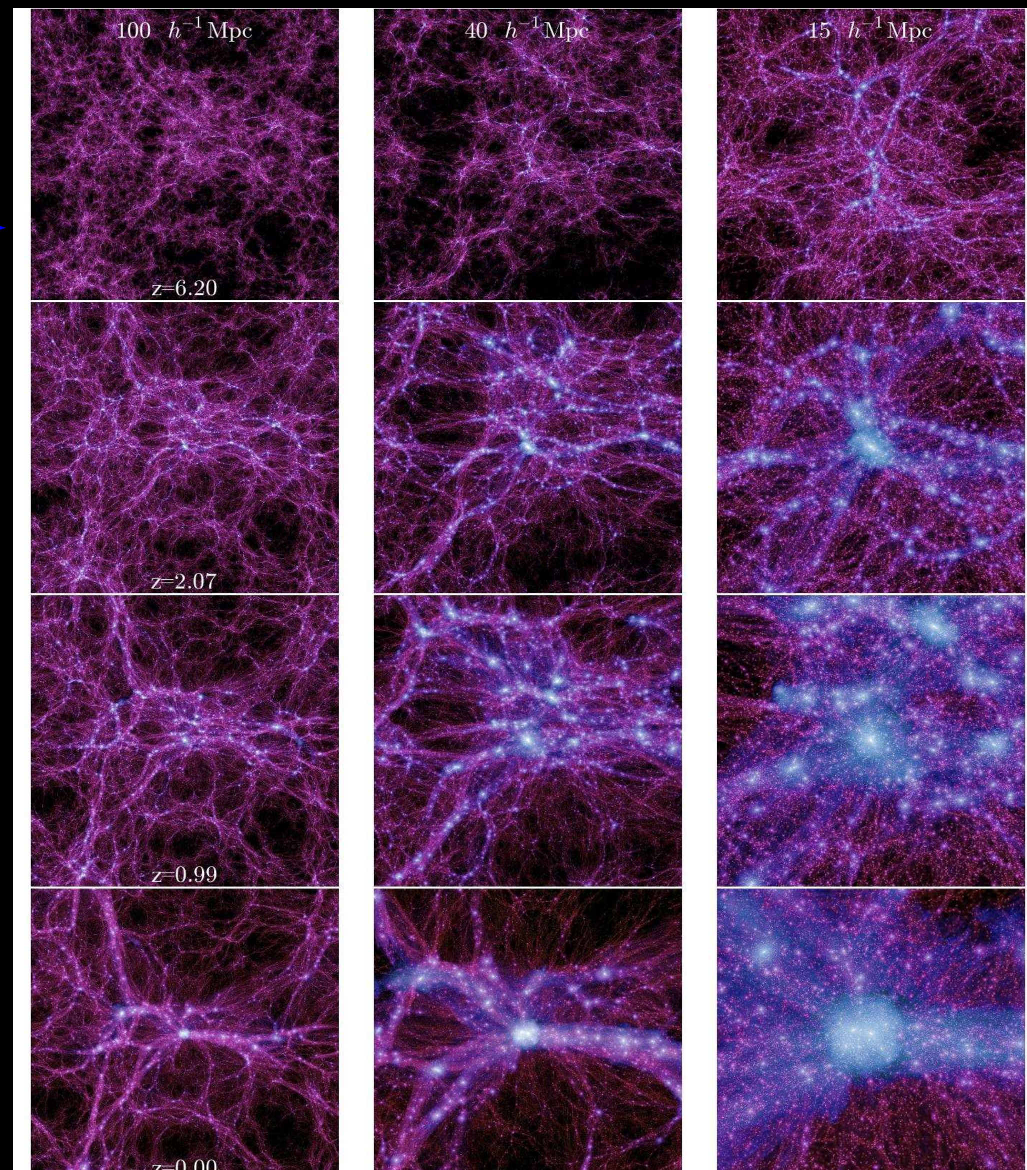


N-body



Boylan-Kolchin+09

Millennium II simulation



Time

A sample of state-of-the-art simulations (circa 2012)

from Kuhlen+12

DM-only simulations

COSMIC

Name	Code	L_{box} [h^{-1}Mpc]	N_p [10^9]	m_p [h^{-1} $M_{\odot}$]	ϵ_{soft} [h^{-1}kpc]
DEUS FUR	RAMSES-DEUS	21000	550	1.2×10^{12}	40.0†
Horizon Run 3	GOTPM	10815	370	2.5×10^{11}	150.0
Millennium-XXL	GADGET-3	3000	300	6.2×10^{9}	10.0
Horizon-4Π	RAMSES	2000	69	7.8×10^{9}	7.6†
Millennium-II	GADGET-3	100	10	6.9×10^{6}	1.0
MultiDark Run1	ART	1000	8.6	8.7×10^{9}	7.6†
Bolshoi	ART	250	8.6	1.4×10^{8}	1.0†

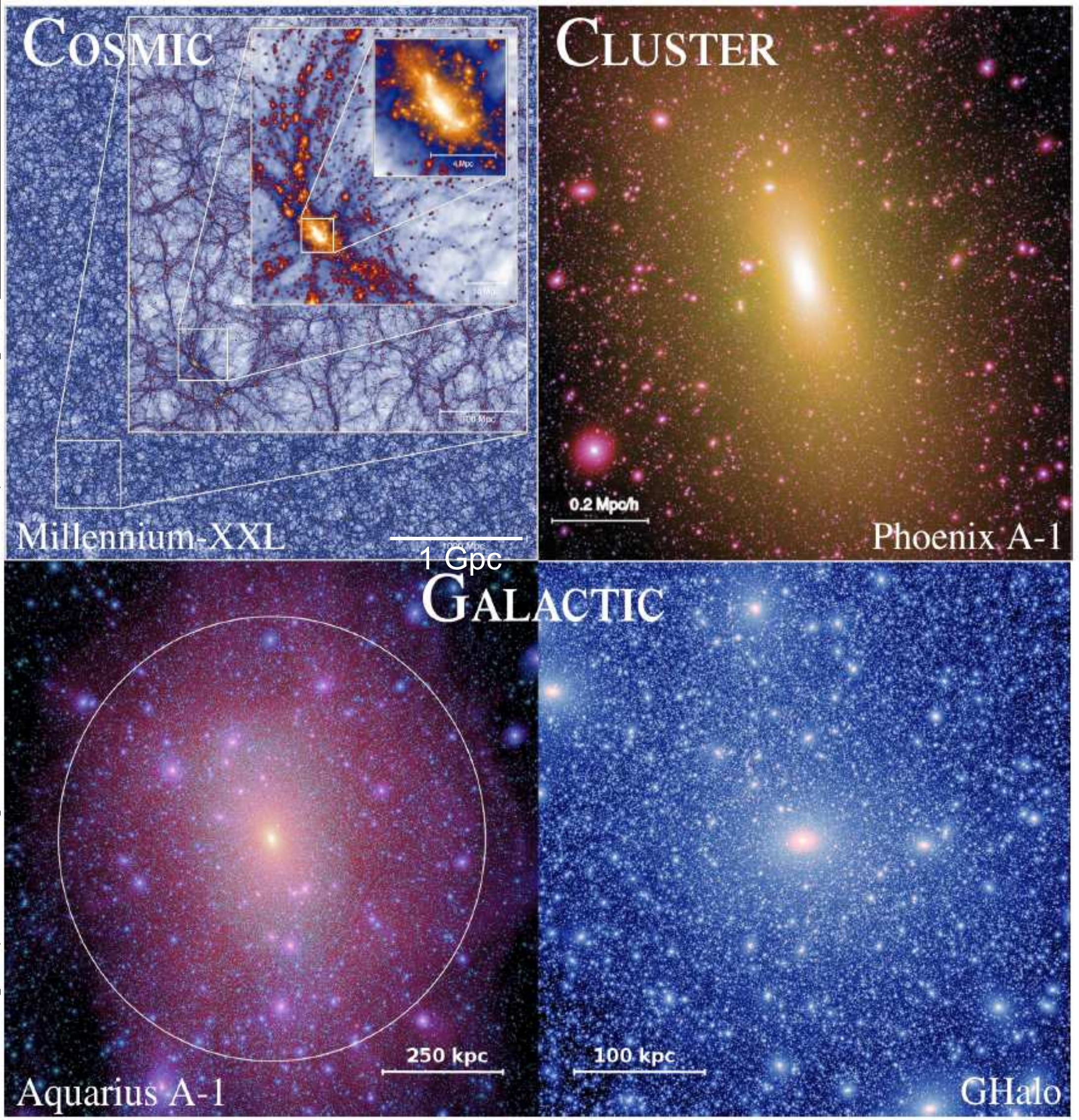
†For AMR simulations (RAMSES, ART) ϵ_{soft} refers to the highest resolution cell width.

CLUSTER

Name	Code	L_{hires} [h^{-1}Mpc]	$N_{p,hires}$ [10^9]	$m_{p,hires}$ [h^{-1} $M_{\odot}$]	ϵ_{soft} [h^{-1}kpc]
Phoenix A-1	GADGET-3	41.2	4.1	6.4×10^{5}	0.15

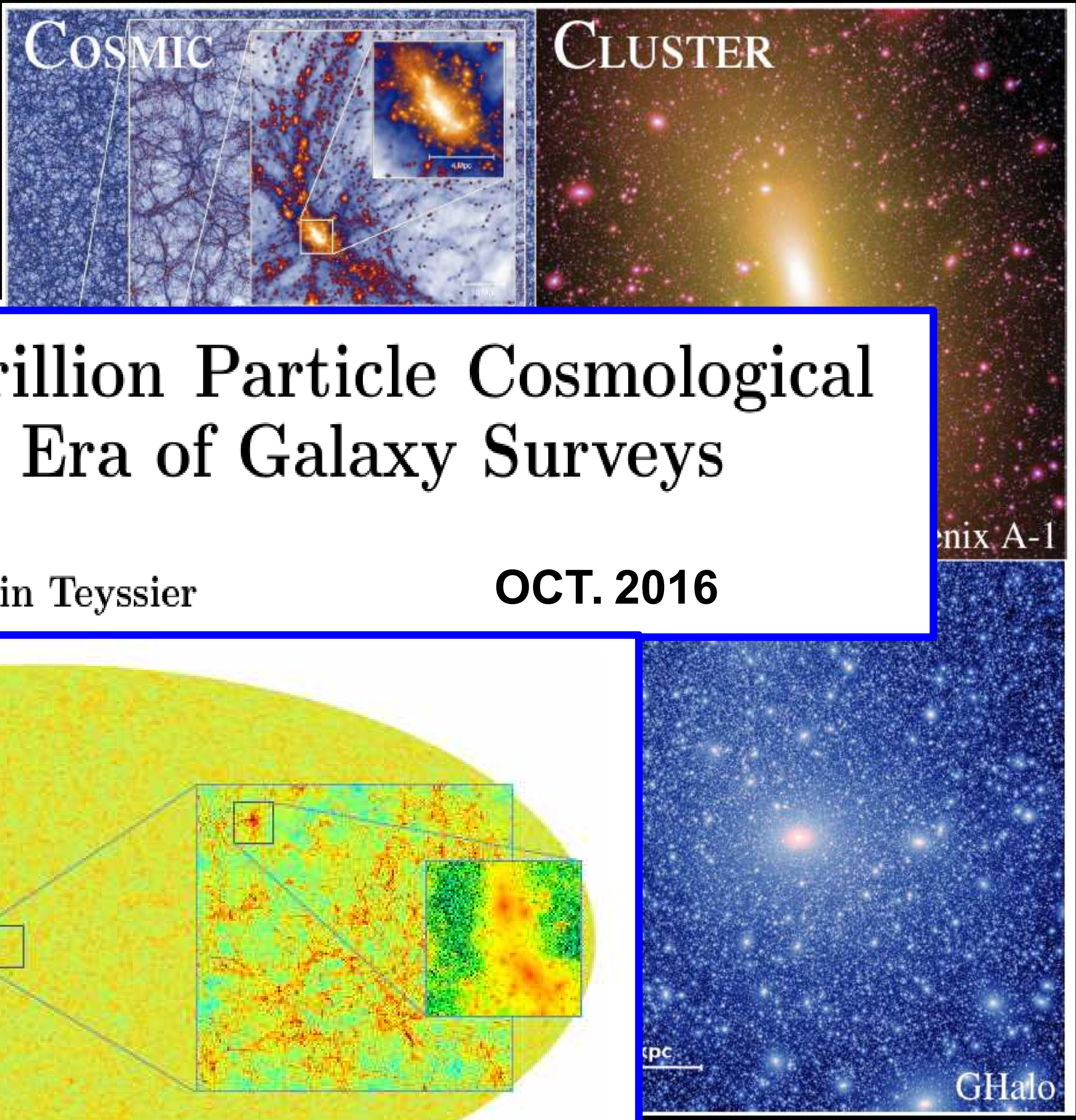
GALACTIC

Name	Code	L_{hires} [Mpc]	$N_{p,hires}$ [10^9]	$m_{p,hires}$ [$M_{\odot}$]	ϵ_{soft} [pc]
Aquarius A-1	GADGET-3	5.9	4.3×10^{9}	1.7×10^{3}	20.5
GHalo	PKDGRAV2	3.89	2.1×10^{9}	1.0×10^{3}	61.0
Via Lactea II	PKDGRAV2	4.86	1.0×10^{9}	4.1×10^{3}	40.0



A sample of state-of-the-art simulations (circa 2012)

from Kuhlen+12



COSMIC		
Name		
DEUS FU		
Horizon Ru		
Millennium-X		
Horizon-4		
Millennium-II	GADGET-3	
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†For AMR simulations (RAMSES, ART) ϵ_{soft} re

CLUSTER		
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GALACTIC		
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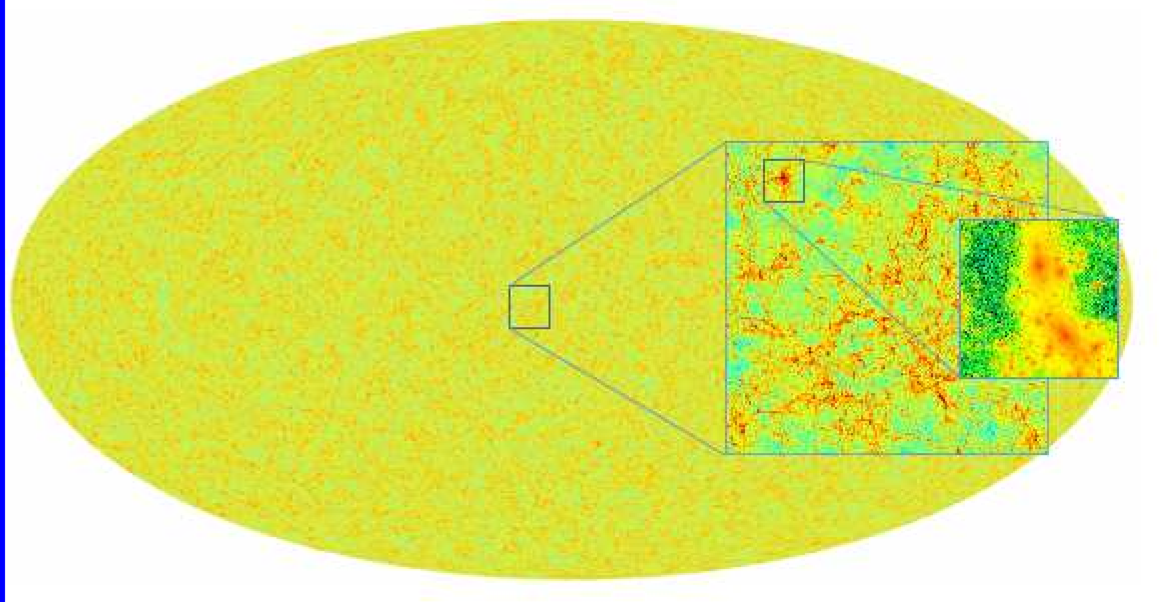
GHalo	PKDGRAV2	
Via Lactea II	PKDGRAV2	

PKDGRAV3: Beyond Trillion Particle Cosmological Simulations for the Next Era of Galaxy Surveys

Douglas Potter · Joachim Stadel · Romain Teyssier

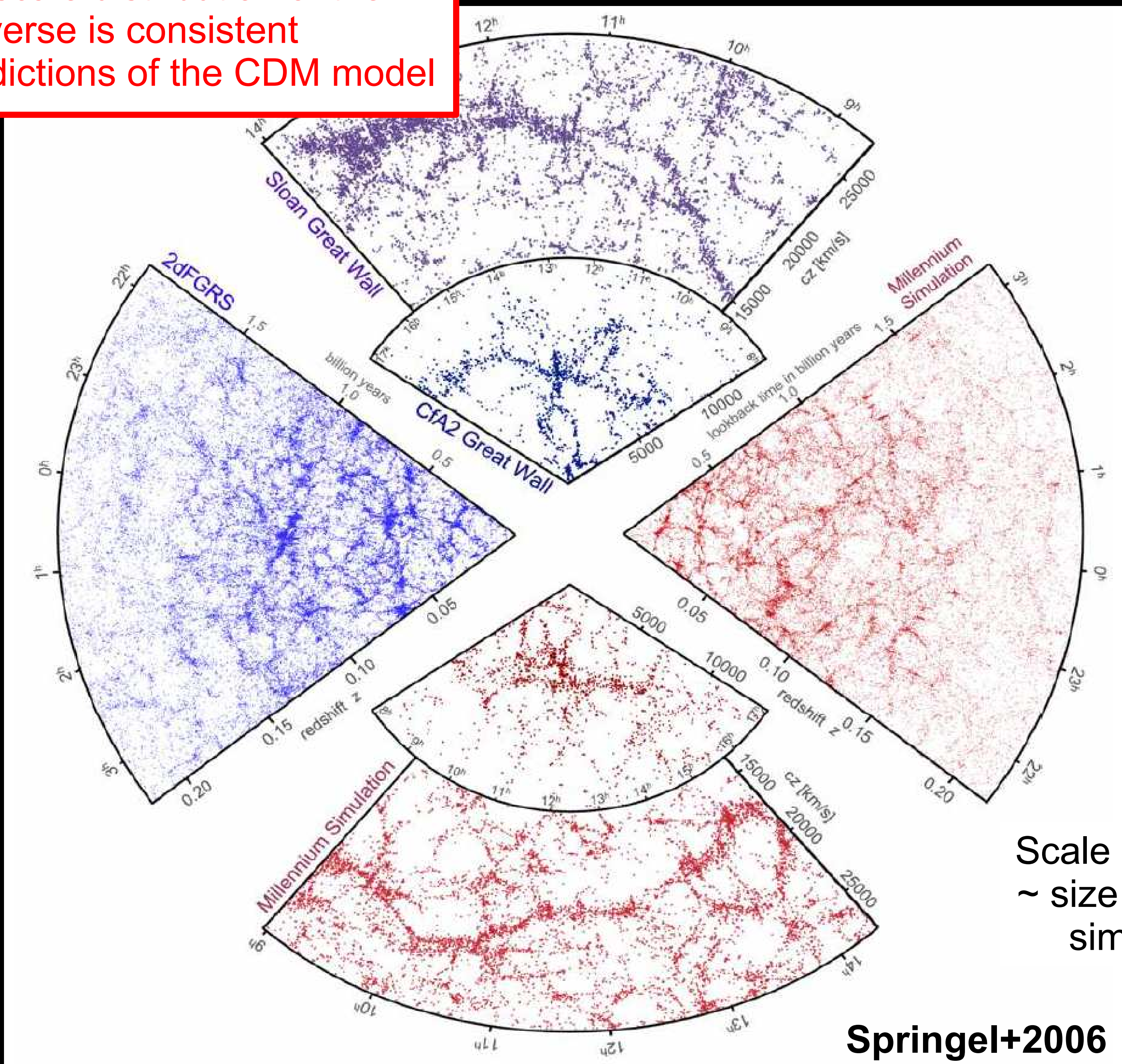
OCT. 2016



DM spatial distribution
(comments on near-universal behaviour)

Large-scale structure

the large-scale distribution of the Universe is consistent with the predictions of the CDM model

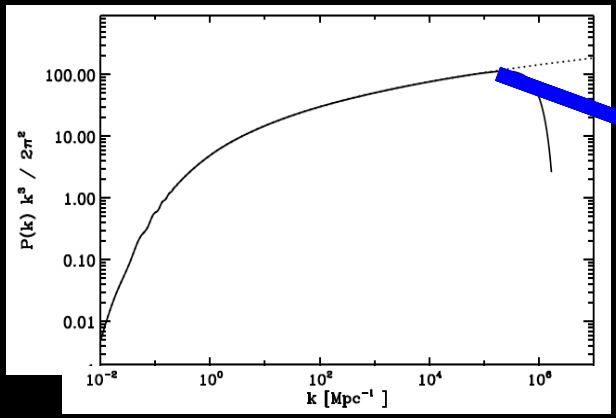


Scale ~400-600 Mpc ~ size of Millennium simulation box

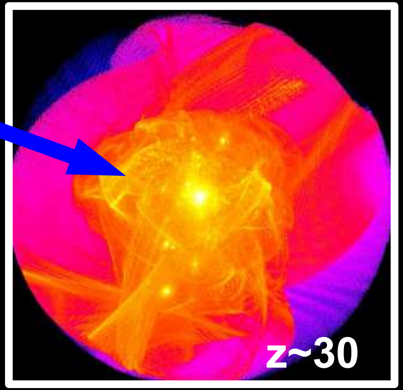
Springel+2006

Self-gravitating DM structures: haloes

CDM predicts a hierarchichal growth of structures



DM halo seeds



Anderhalden & Diemand 14

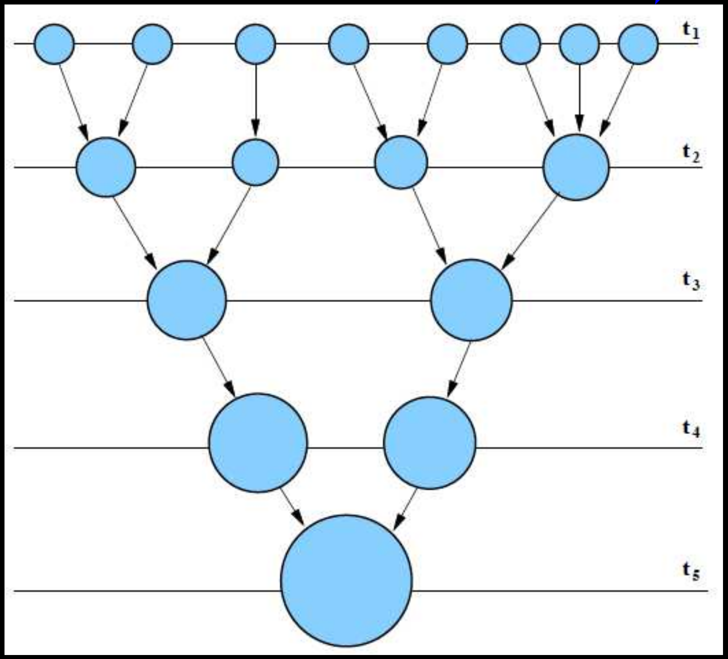


Fig. from Baugh 2006

Self-gravitating DM structures: haloes

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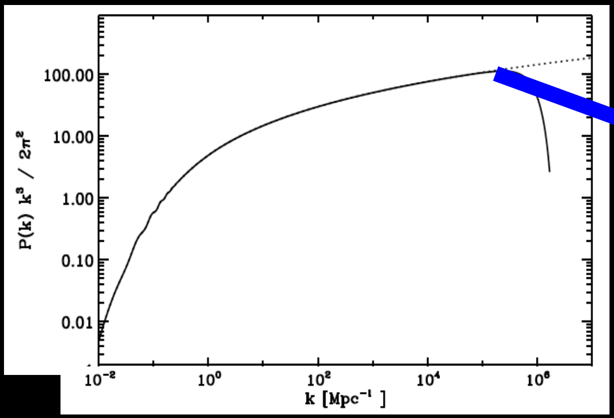
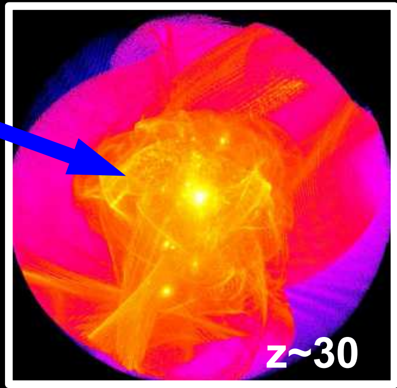


DM halo seeds



Anderhalden & Diemand 14

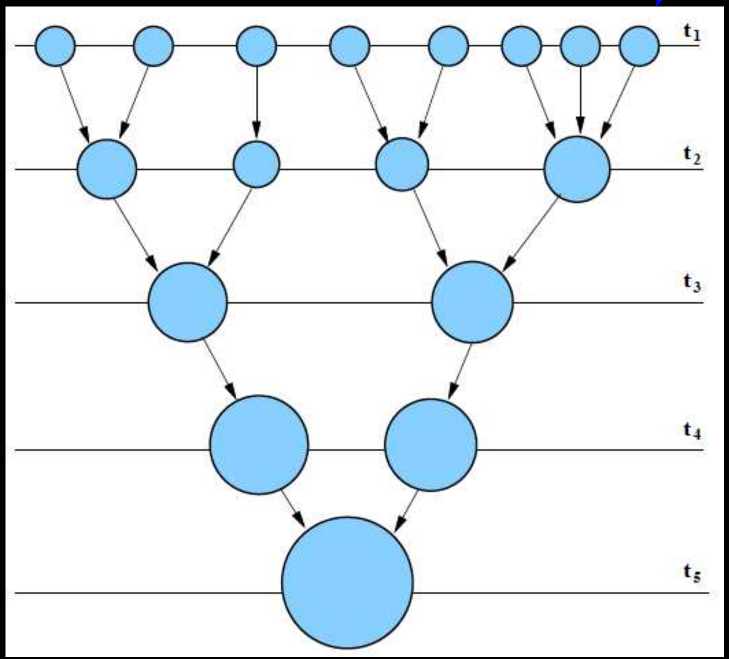
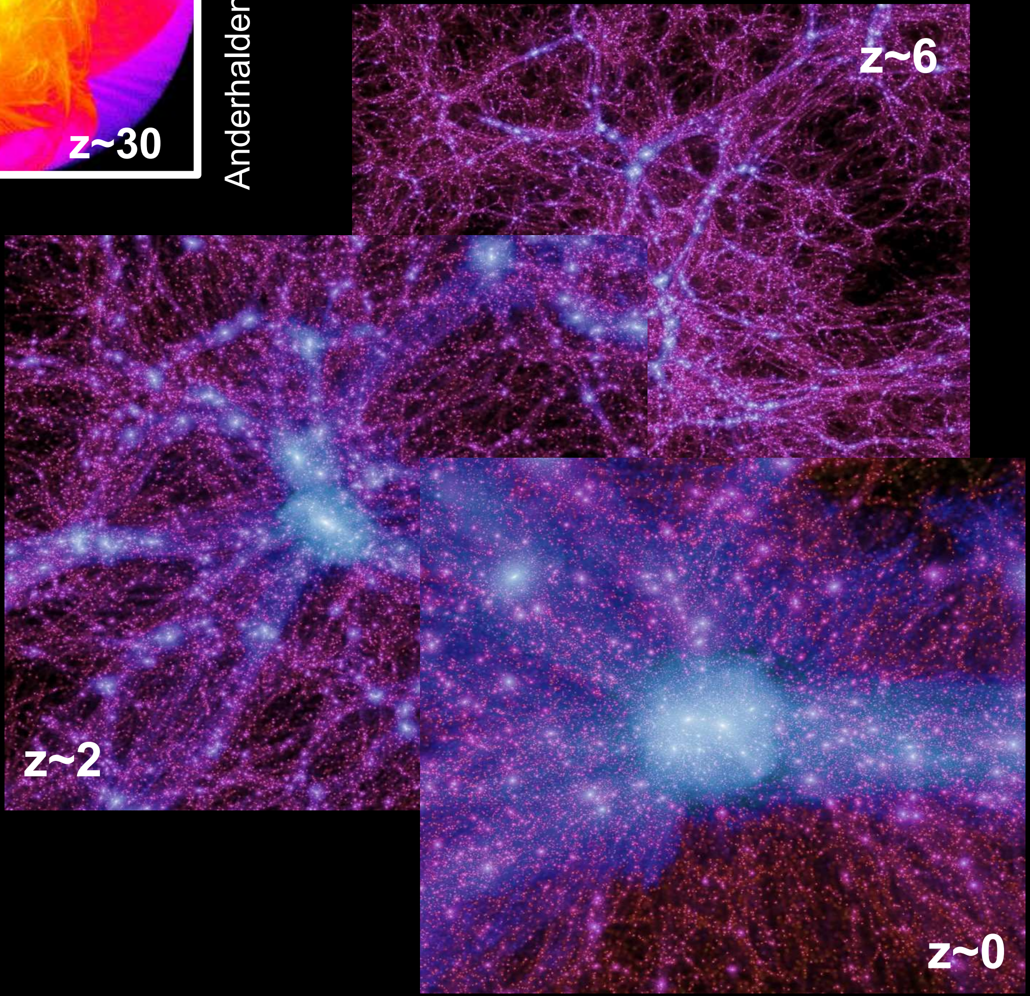


Fig. from Baugh 2006

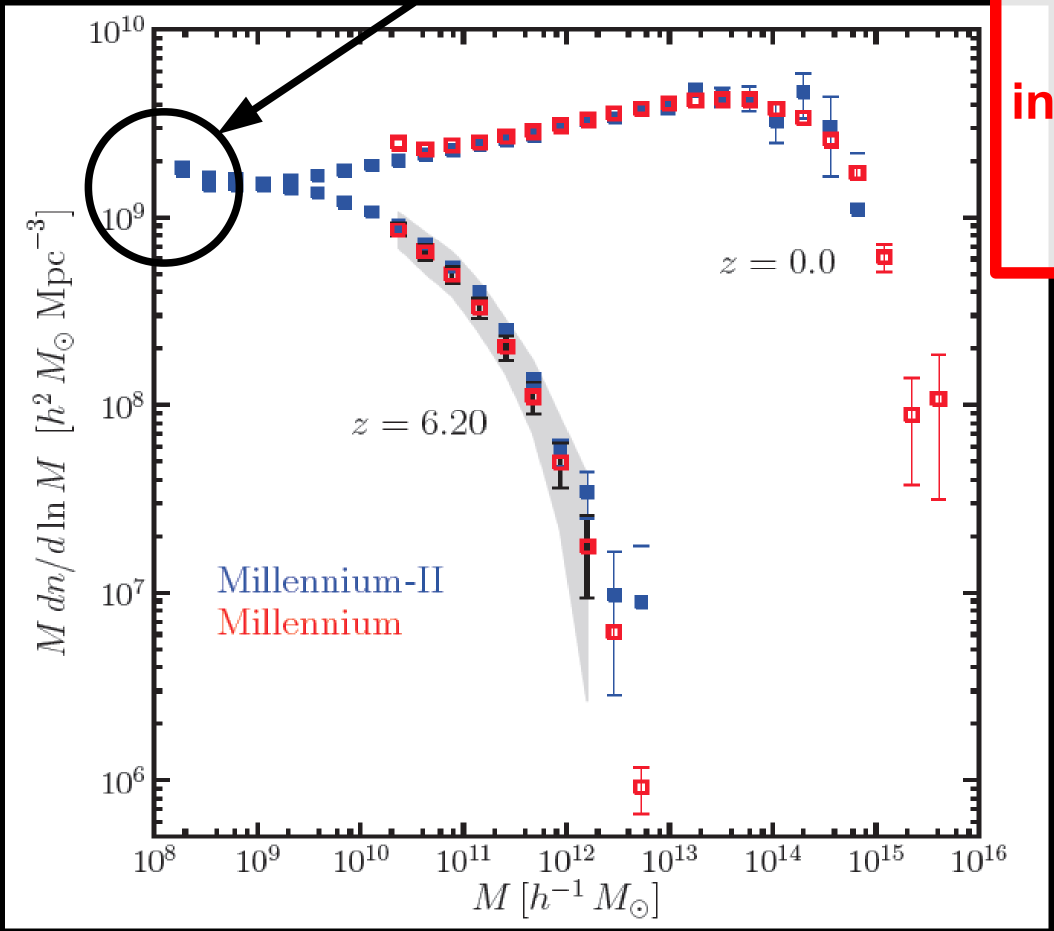
Boylan-Kolchin+2009



Abundance of DM haloes

Mass function (dn/dM): number of haloes per comoving volume and per mass range.
It evolves with redshift according to the CDM hierarchical scenario

dn/dM ~ $M^{-1.9}$ (at small masses)



Boylan-Kolchin+2009

If gravity is the only relevant DM interaction, the abundance of low-mass haloes is ever increasing (down to the free-streaming scale)

Minimum halo mass in CDM particle models many orders of magnitude below mass resolution of current simulations!

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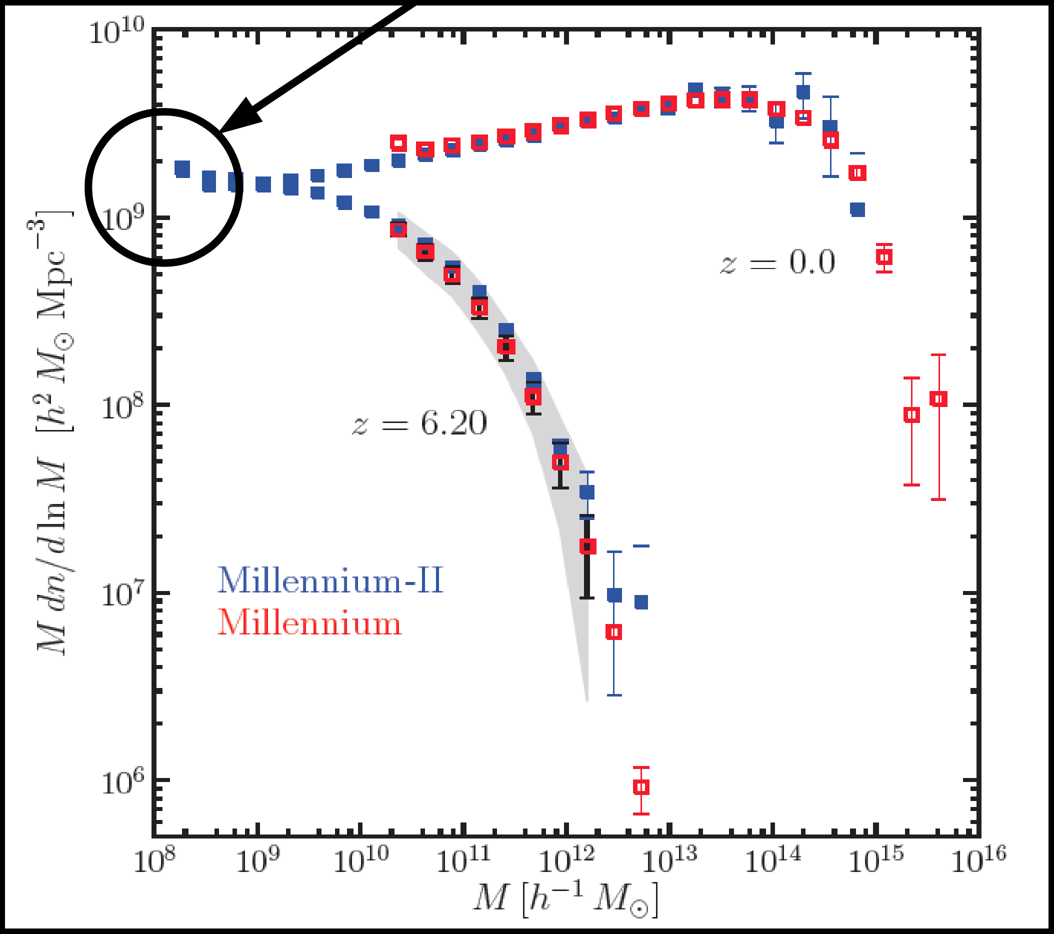
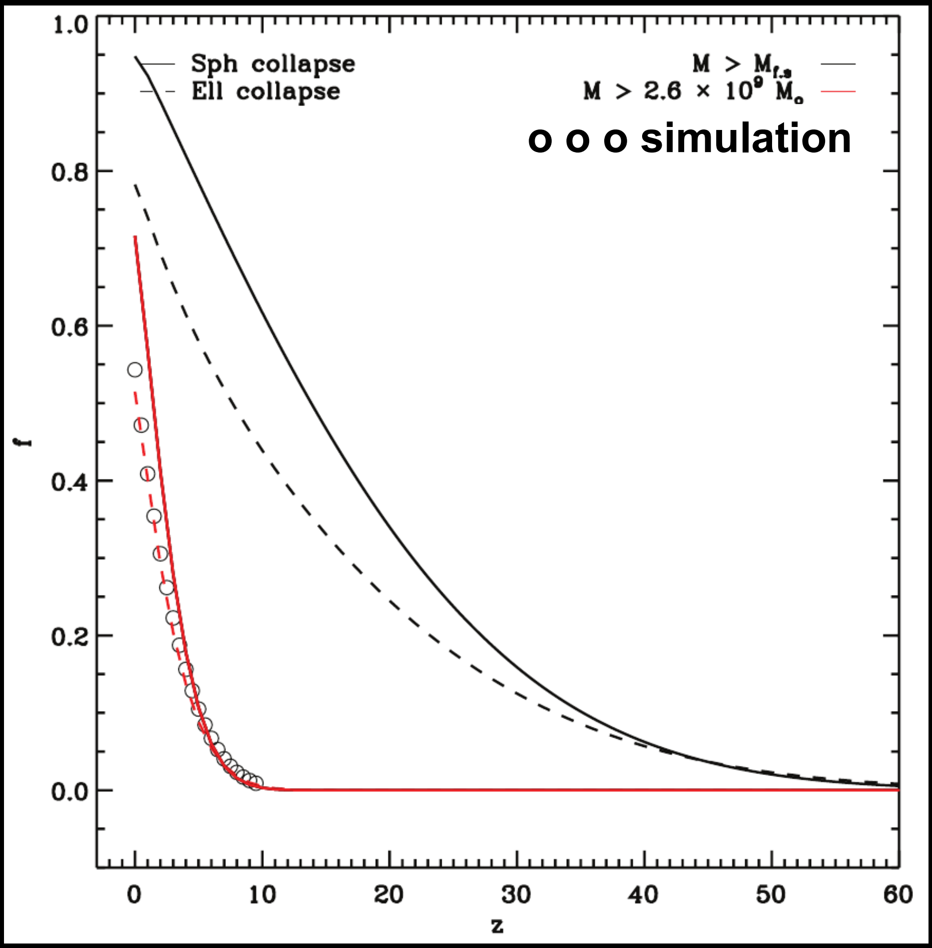
Angulo & White 10

Boylan-Kolchin+2009



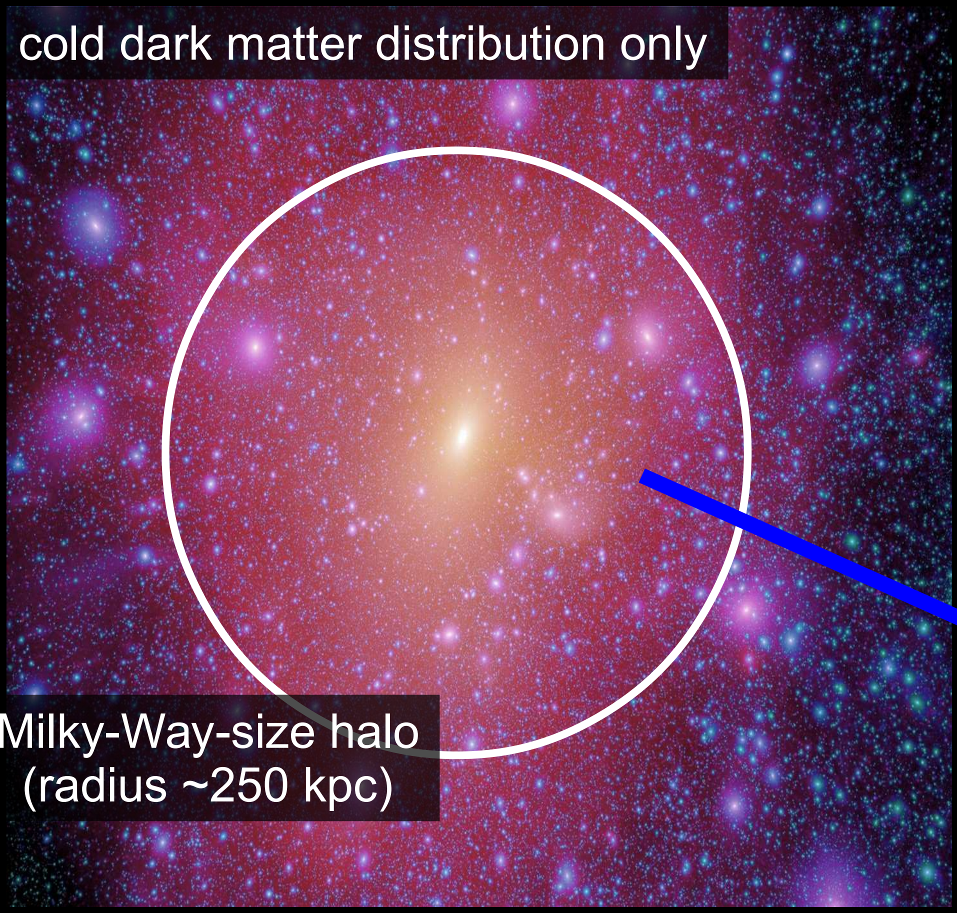


Minimum halo mass in CDM particle models many orders of magnitude below mass resolution of current simulations!

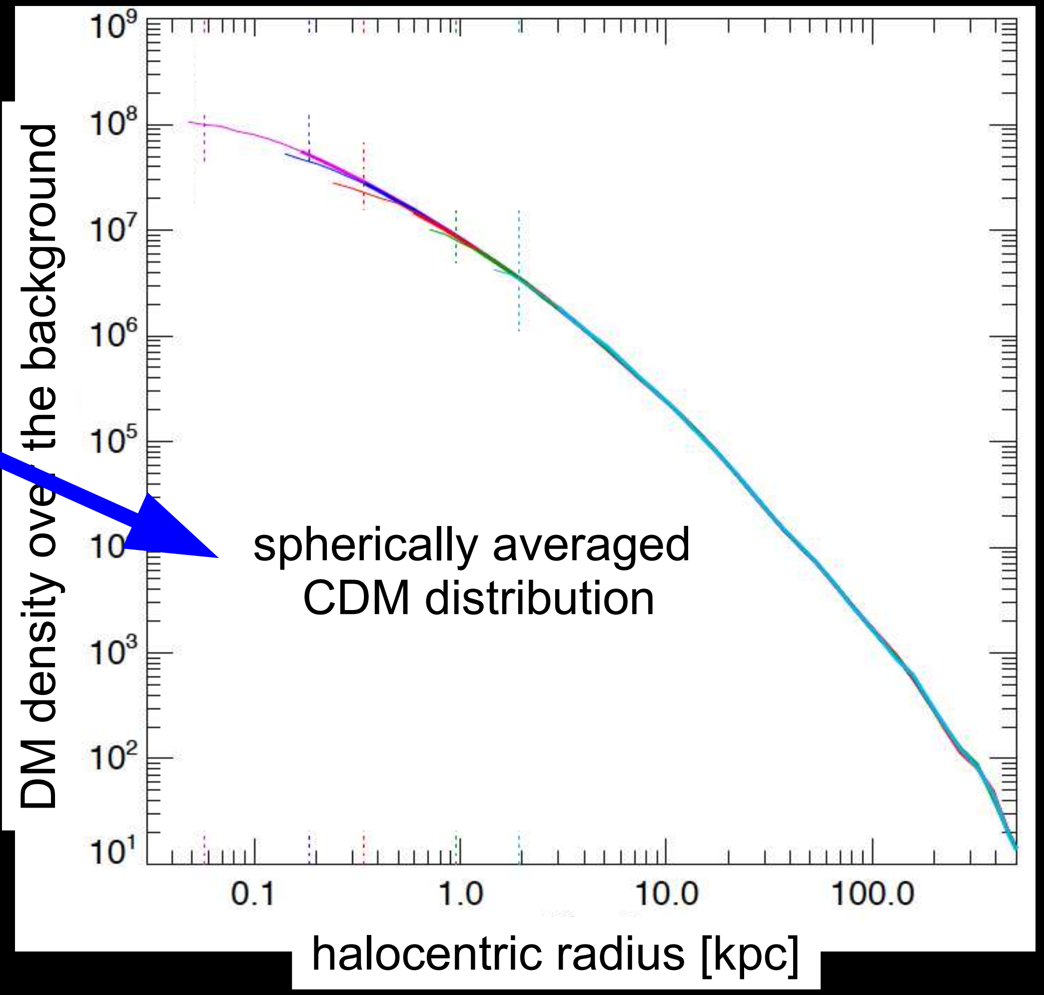
Not all dark matter is in haloes!

Inner structure of DM haloes (smooth distribution)

Aquarius project Springel+08



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

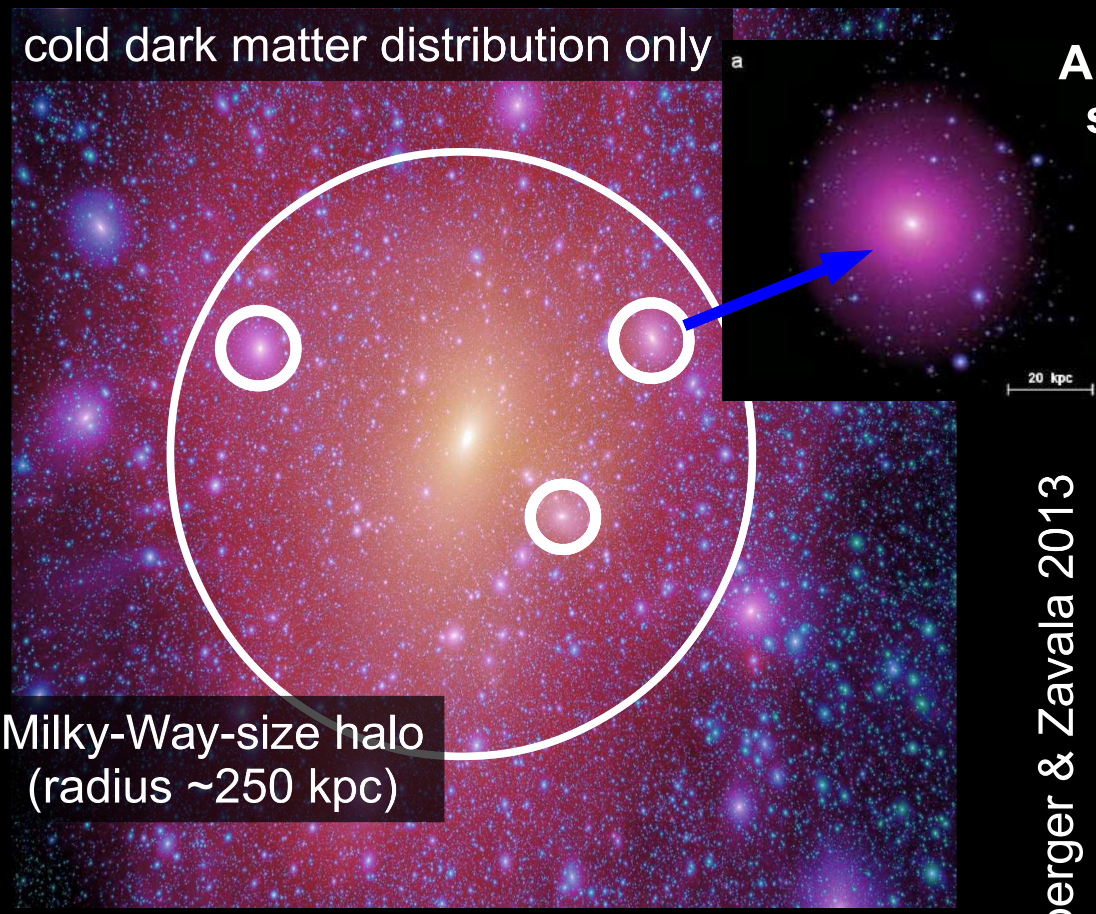


Universality famously known as the Navarro-Frenk-White (NFW) profile

Inner structure of DM haloes (subhaloes)

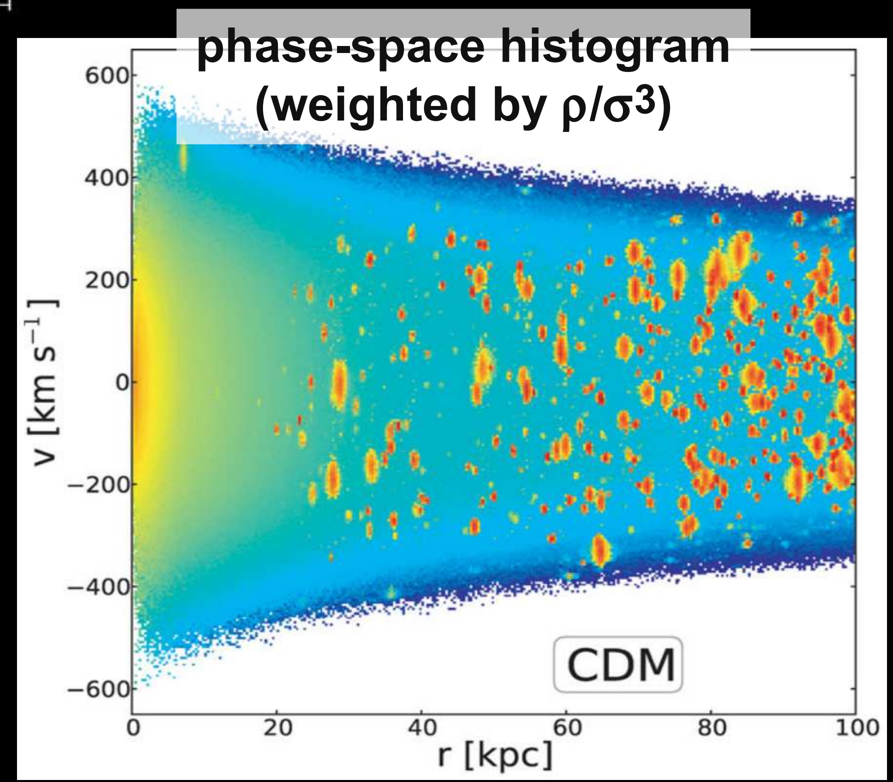
→ DM self-bound clumps within a host halo

Aquarius project Springel+08



Abundance (mass function) and inner structure (density profile) share the near-universality of the hosts

substructure in phase space

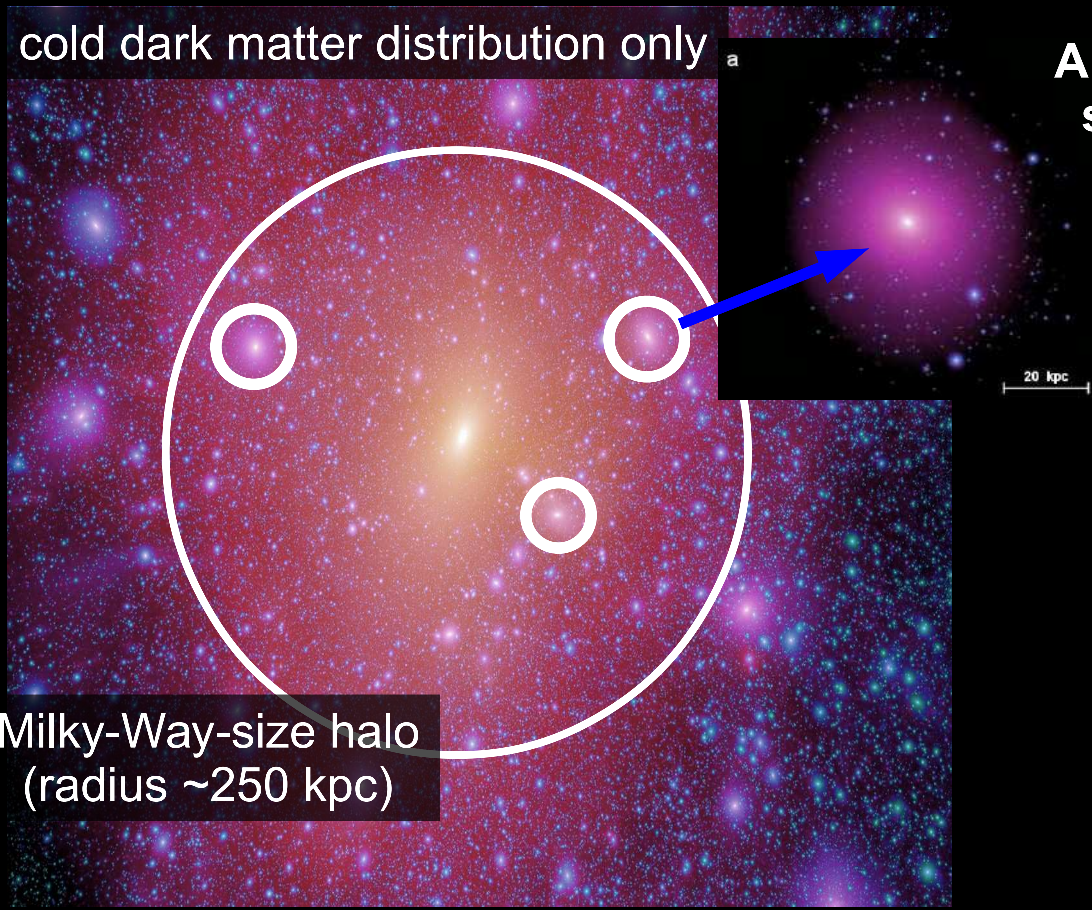


Vogelsberger & Zavala 2013

Inner structure of DM haloes (subhaloes)

→ DM self-bound clumps within a host halo

Aquarius project Springel+08



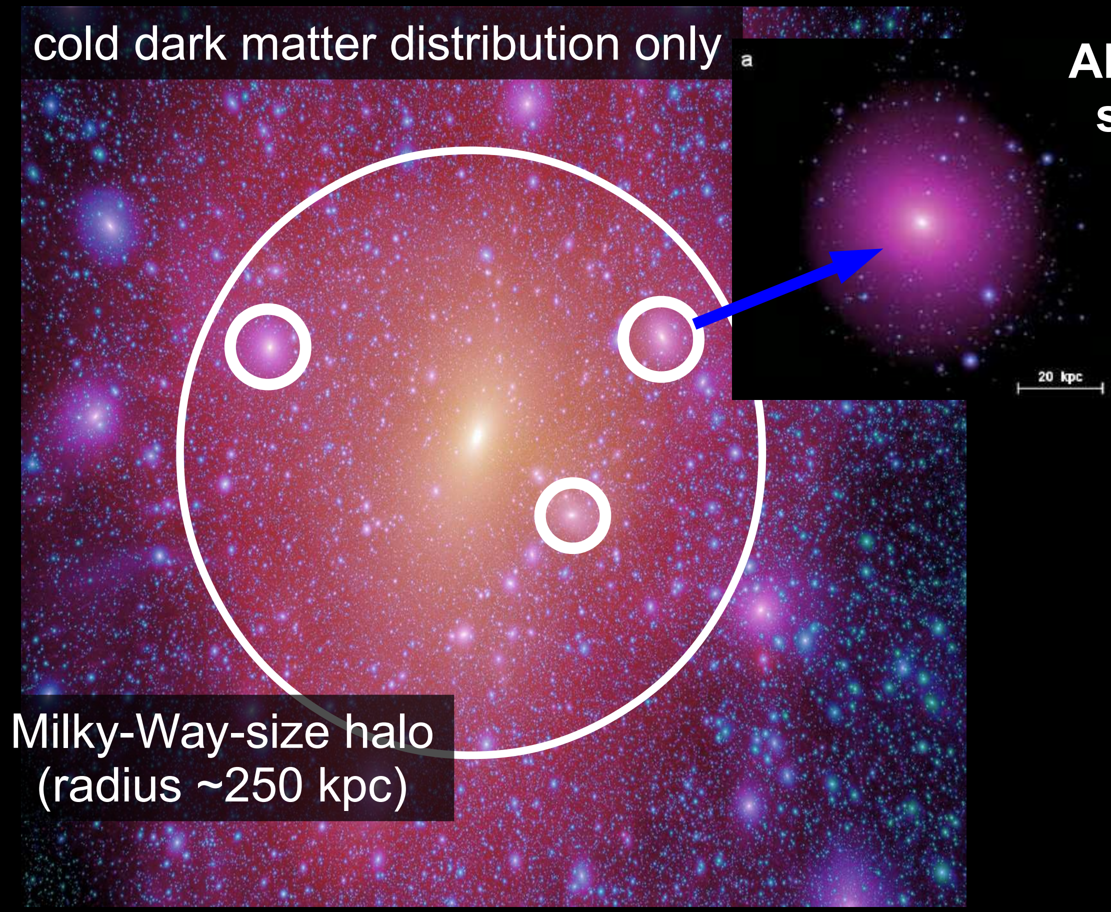
Abundance (mass function) and inner structure (density profile) share the near-universality of the hosts

<u>two mechanisms become important for subhaloes:</u>

Inner structure of DM haloes (subhaloes)

→ DM self-bound clumps within a host halo

Aquarius project Springel+08



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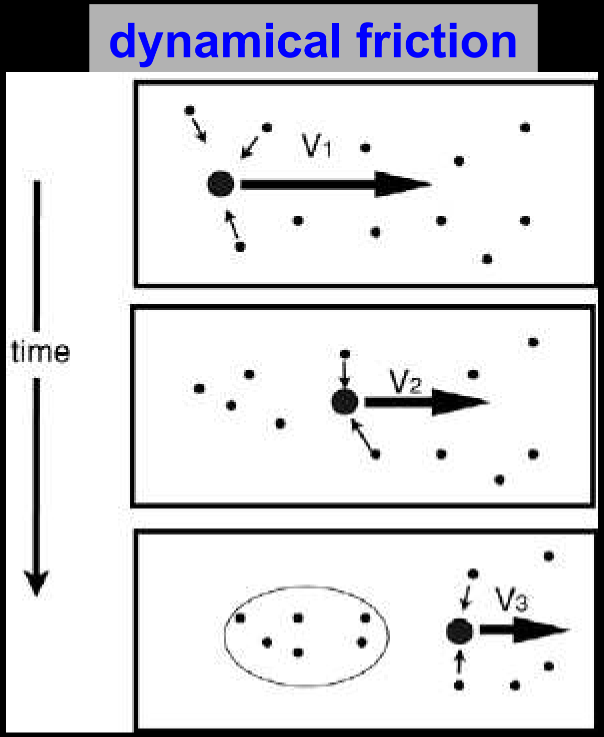
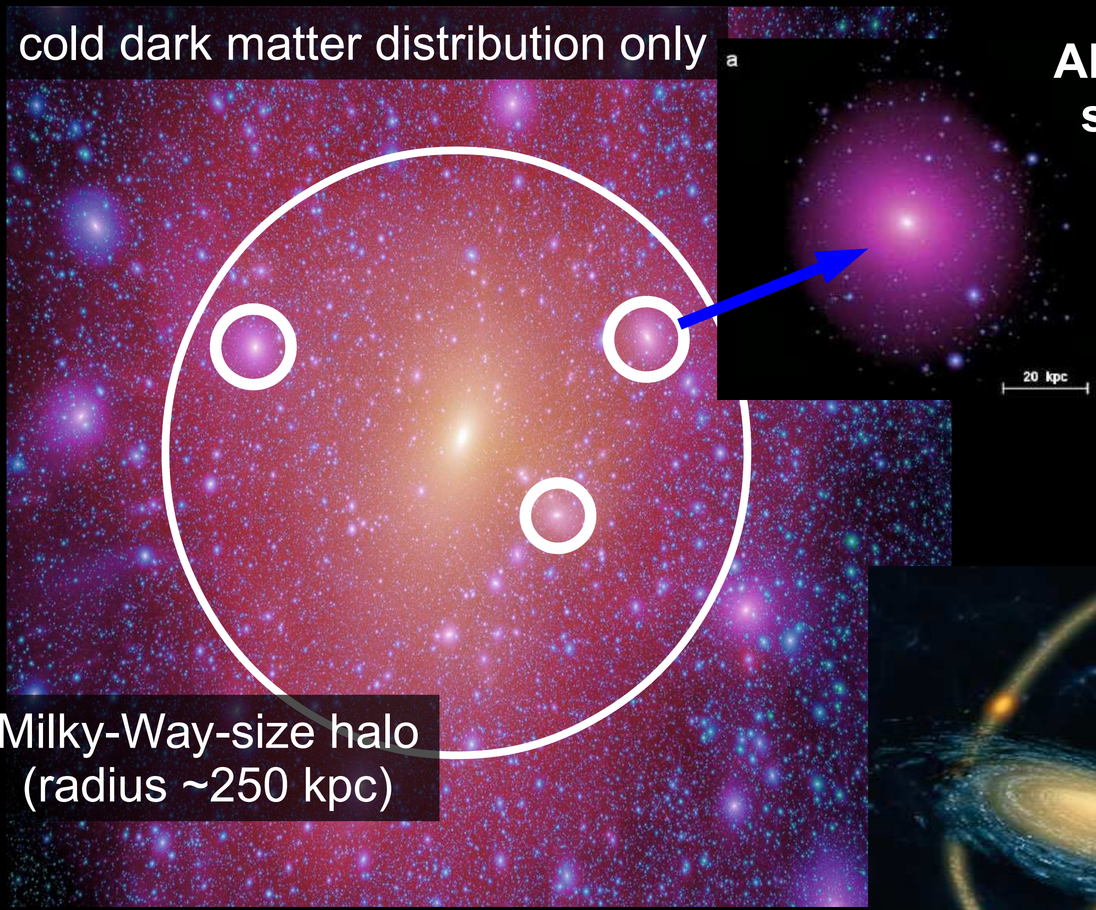


the orbital angular momentum of the subhalo is transferred into the host, the subhalo graduallly sinks into the centre of the host

Inner structure of DM haloes (subhaloes)

DM self-bound clumps within a host halo

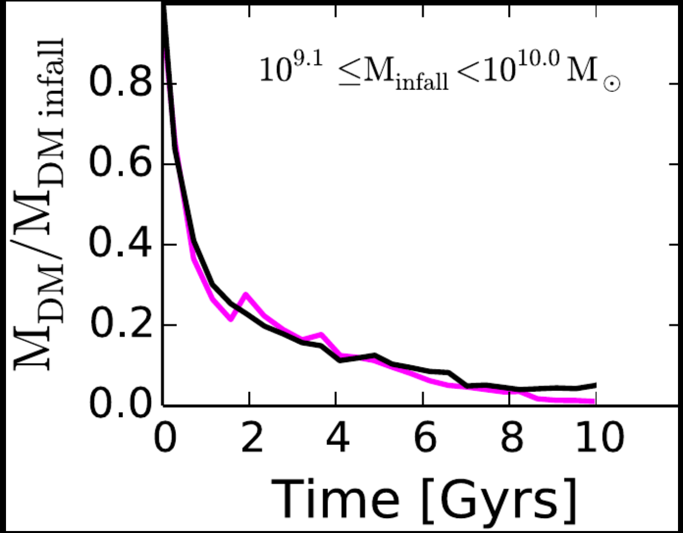
Aquarius project Springel+08



Abundance (mass function) and inner structure (density profile) share the near-universality of the hosts

two mechanisms become important for subhaloes:

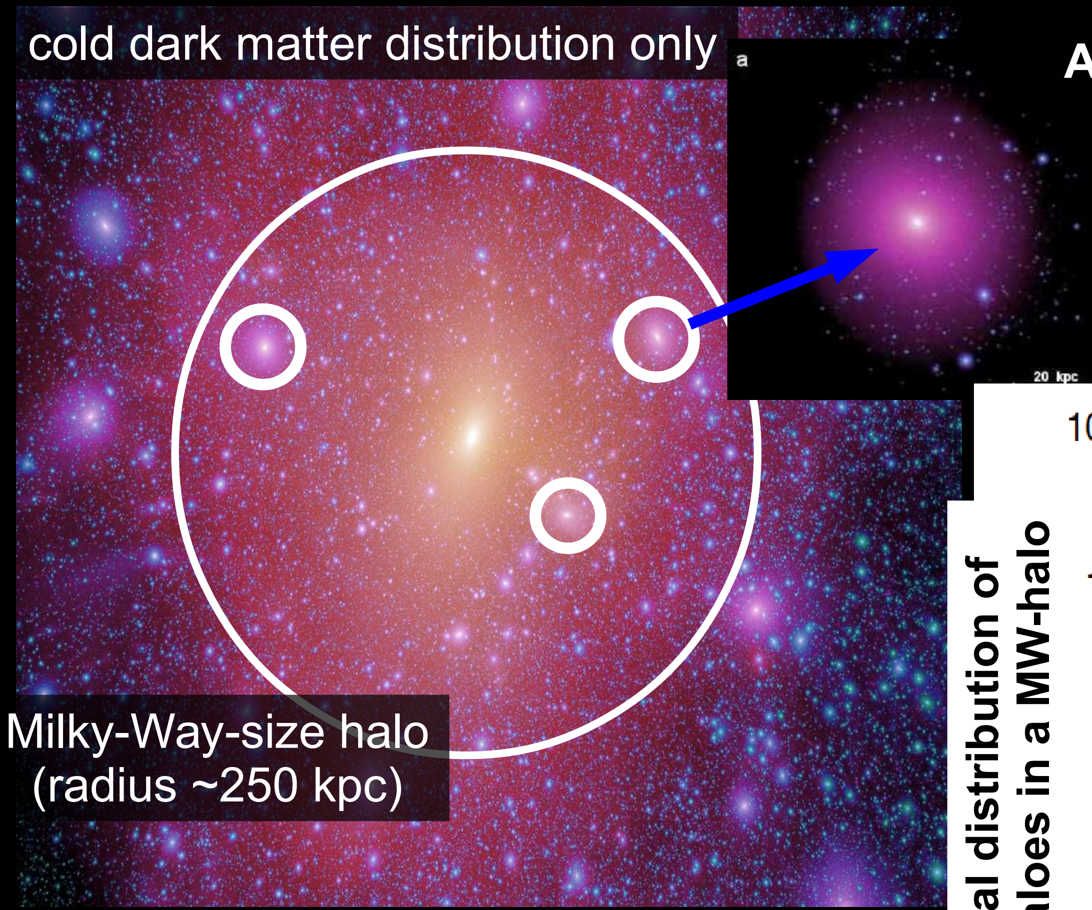
tidal stripping



Inner structure of DM haloes (subhaloes)

DM self-bound clumps within a host halo

Aquarius project Springel+08



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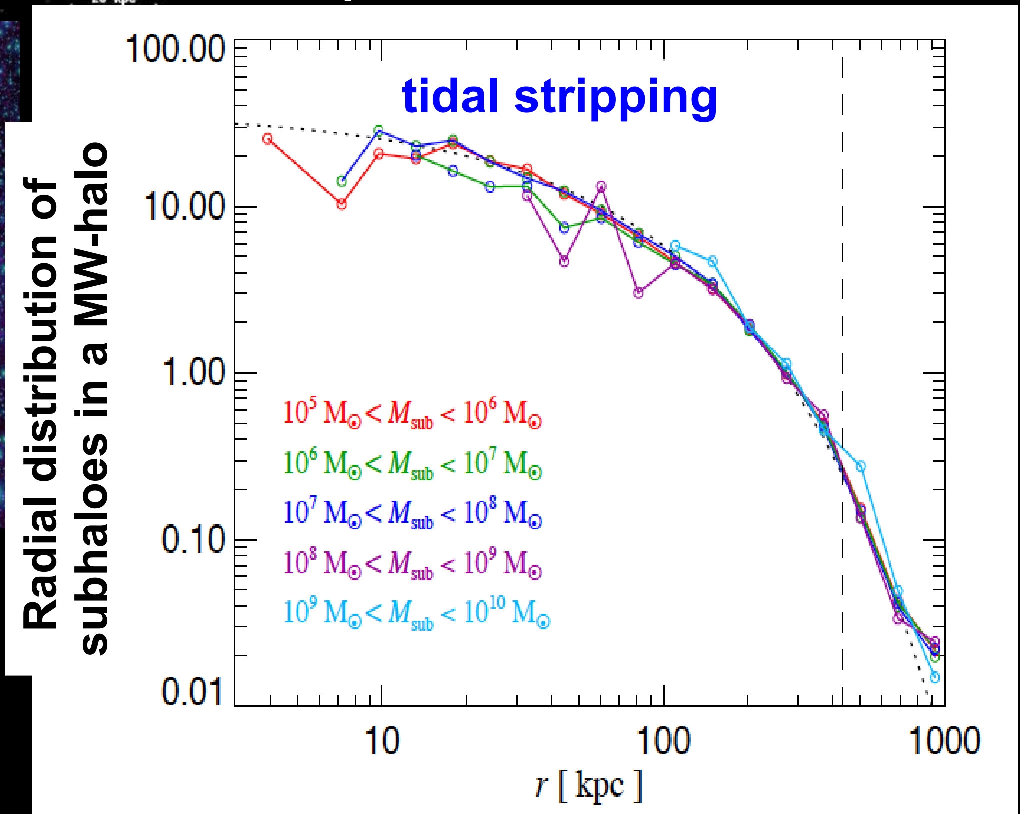
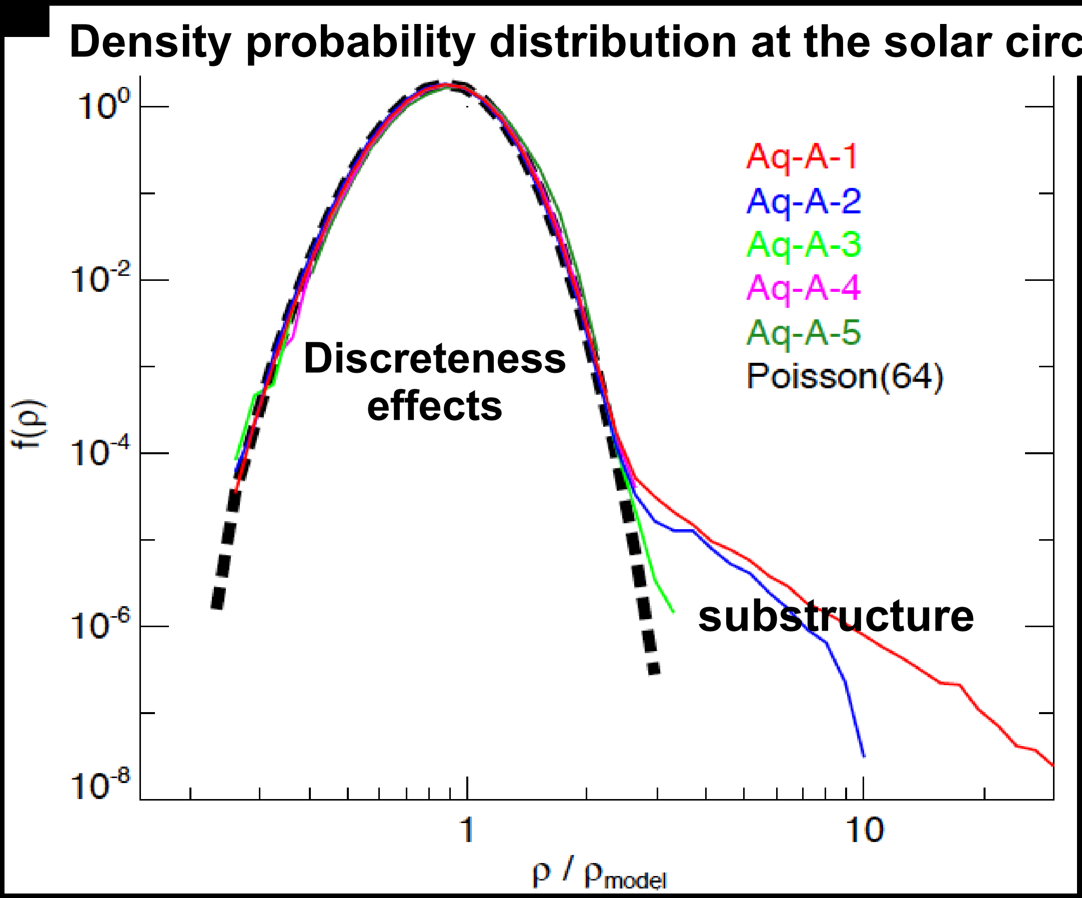


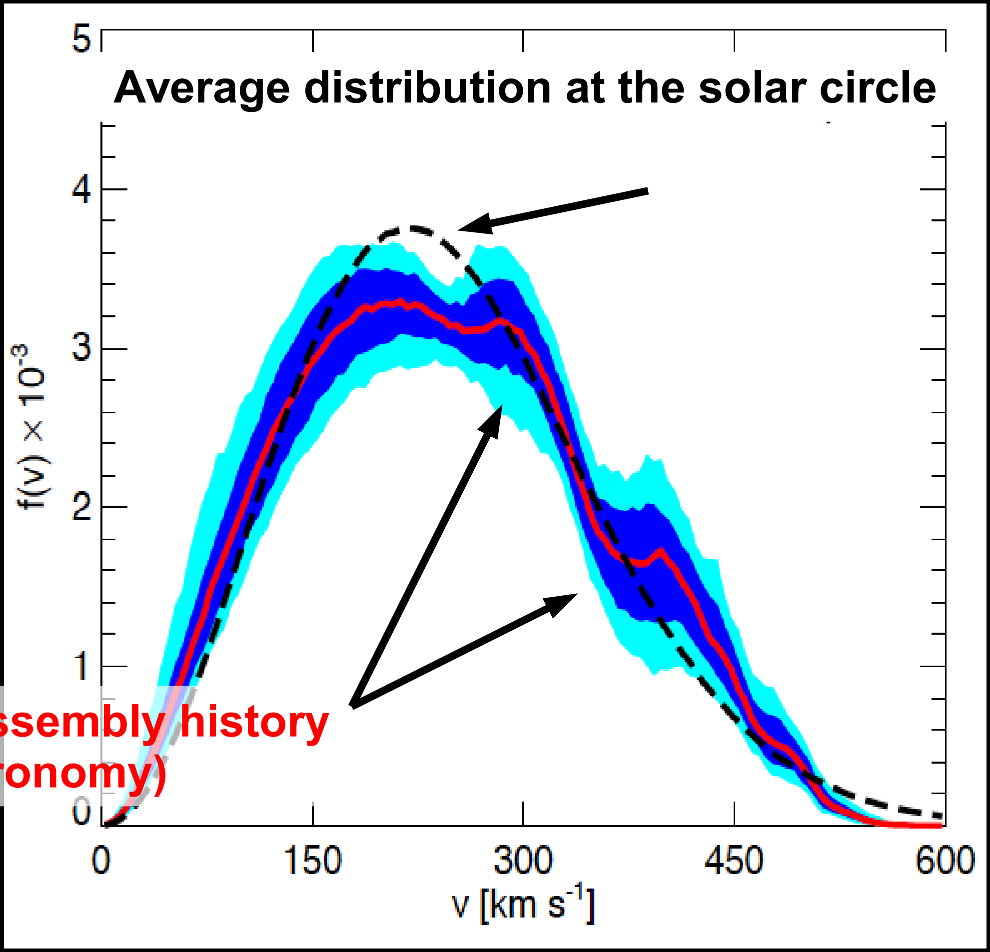
subhaloes are underabundant towards the centre compared to the ‘smooth’ distribution

DM distribution at the solar circle

local (average) DM density distribution very smooth
(chance of the Sun within a subhalo ~ 10^{-4})



Velocity distribution is not
fully Maxwellian
(influence on direct detection rates)



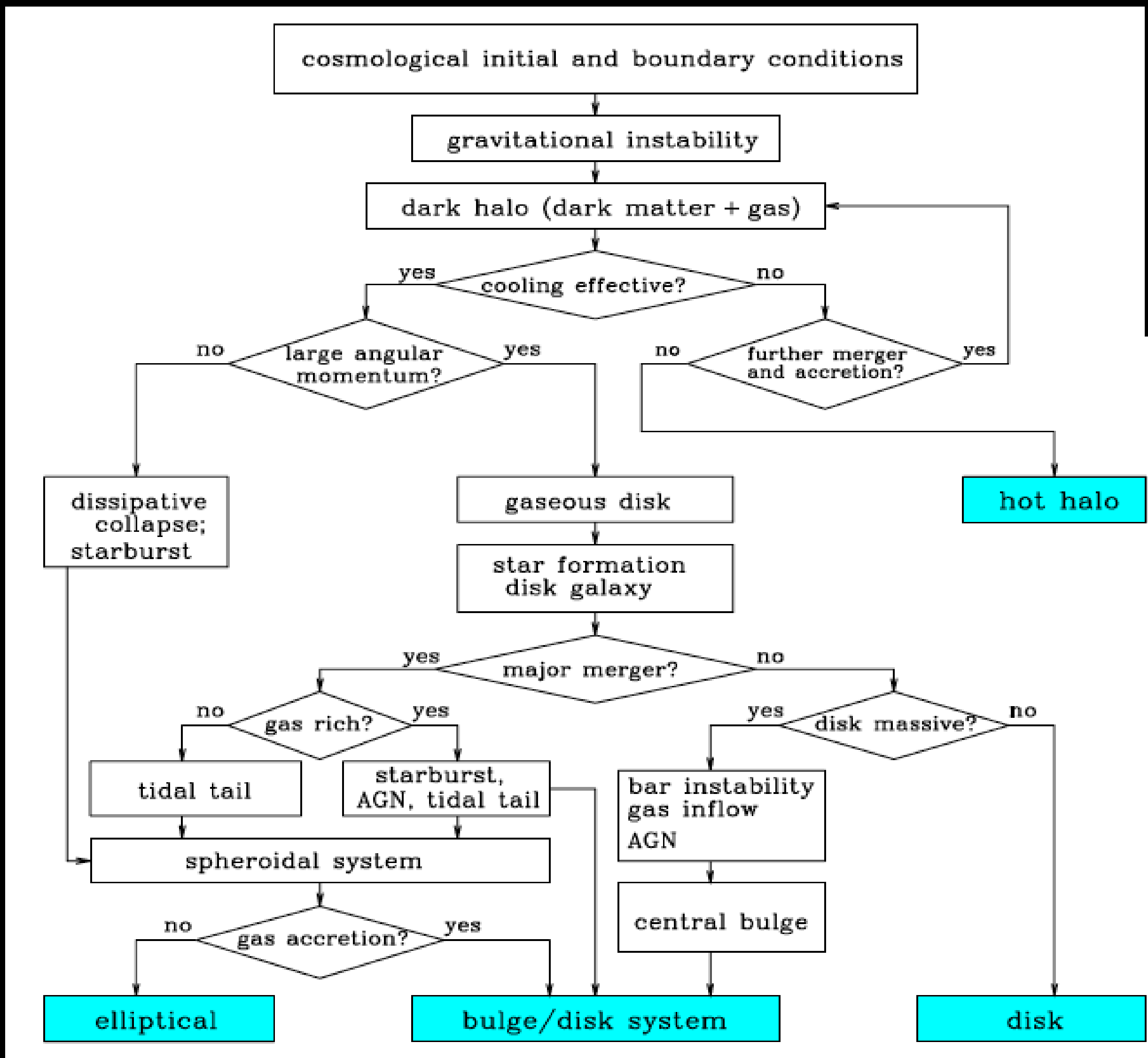
Related to individual assembly history
(future: DM astronomy)

Vogelsberger+09

Standard structure formation theory

NON-LINEAR REGIME (gas and stellar physics)

Fig. from Mo, Mao and White, 2010



DM gravity only

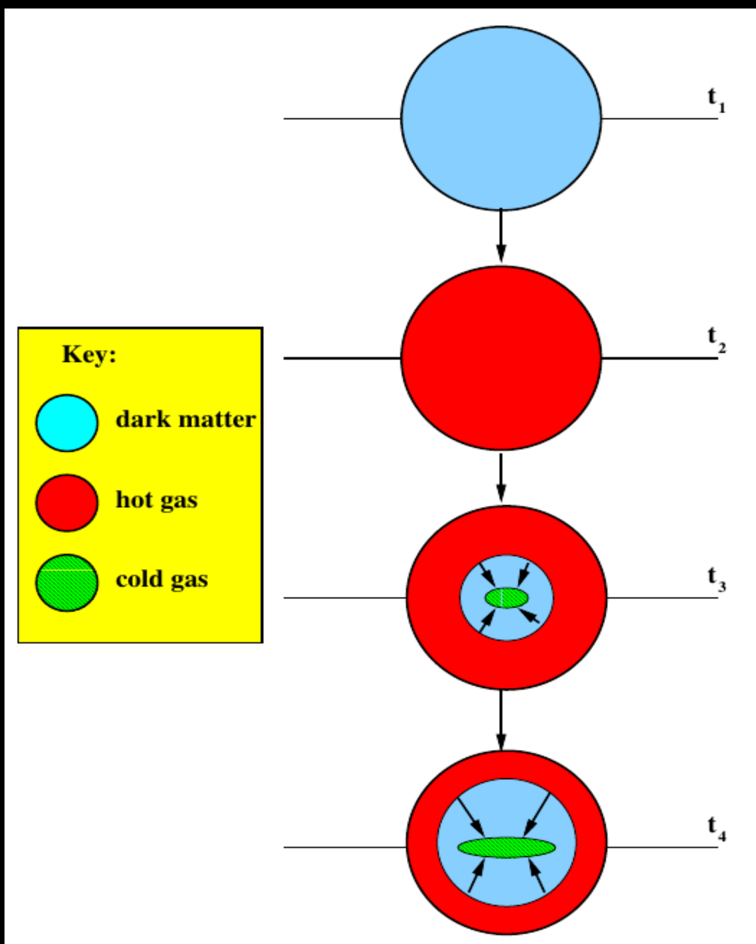
Aquarius project Springel+08

Standard structure formation theory

NON-LINEAR REGIME (gas and stellar physics)

- Gas hydrodynamics (shocks, instabilities)
- Radiative cooling (galactic disk formation)

Baugh 2006



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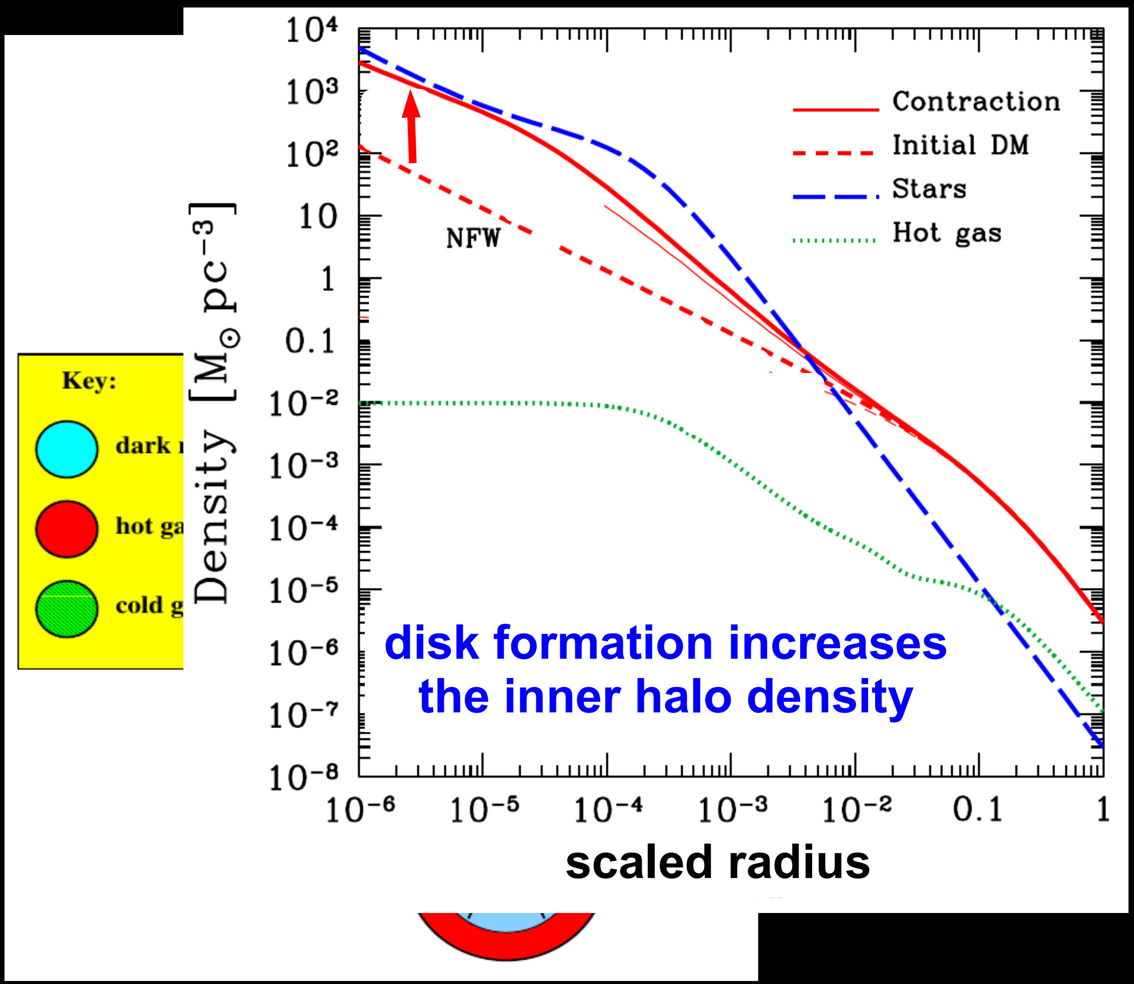


DM gravity only

Aquarius project Springel+08

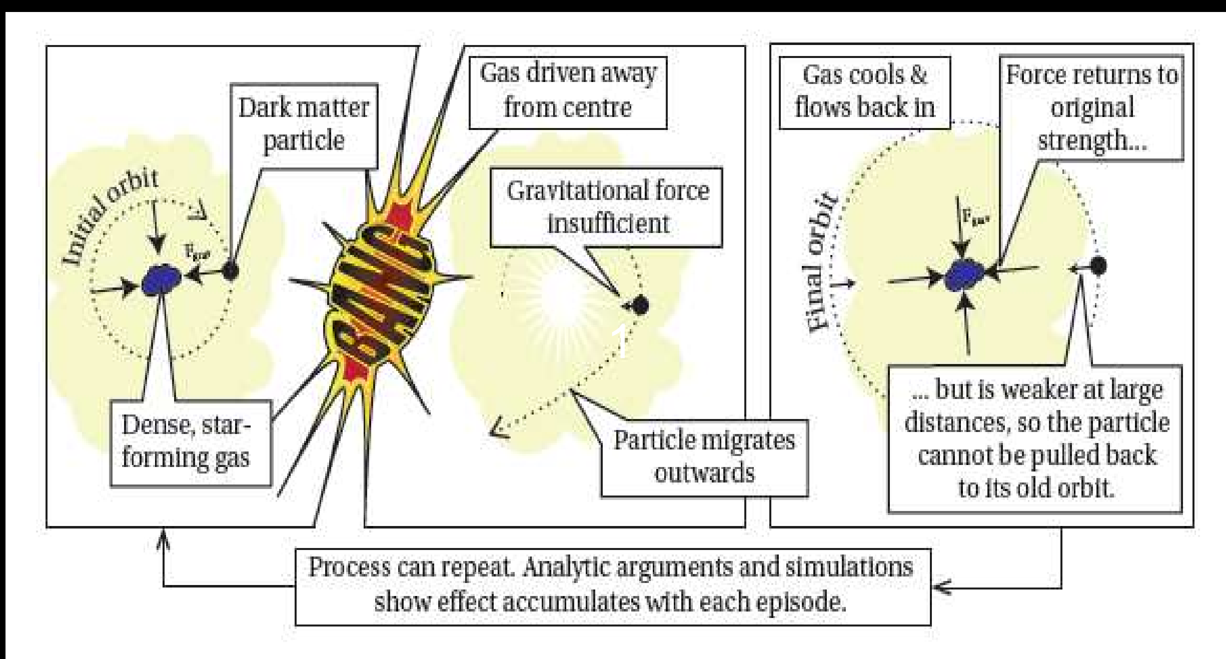
Standard structure formation theory

NON-LINEAR REGIME (gas and stellar physics)

- Gas hydrodynamics (shocks, instabilities)
- Radiative cooling (galactic disks formation)
- Formation, evolution, and death of stars

DM gravity only

Aquarius project Springel+08

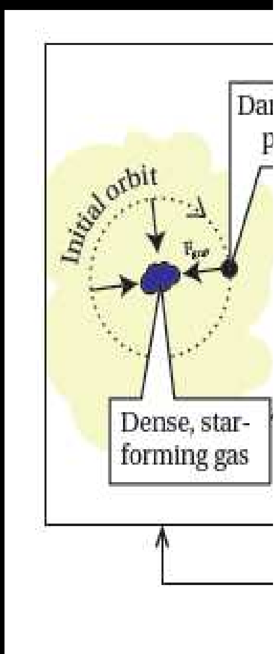


Pontzen & Governato 2014

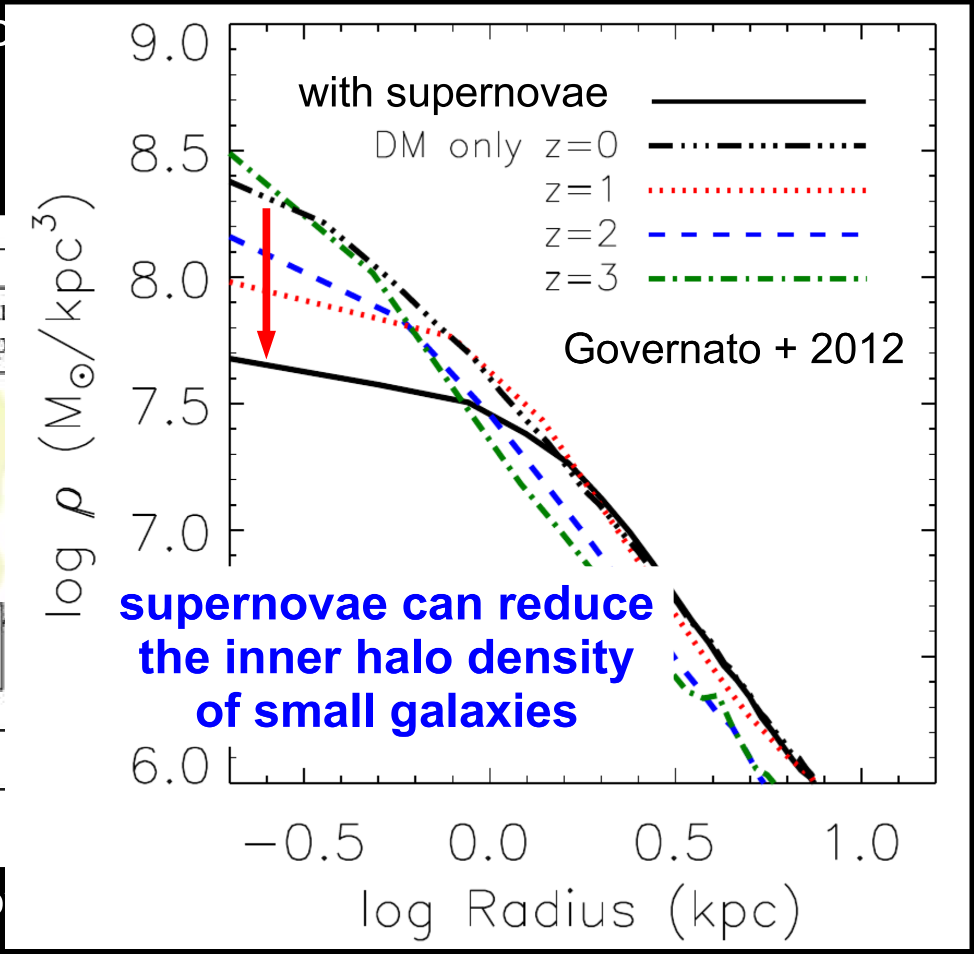
Standard structure formation theory

NON-LINEAR REGIME (gas and stellar physics)

- Gas hydrodynamics (shocks, instabilities)
- Radiative cooling (galactic disks formation)
- Formatio



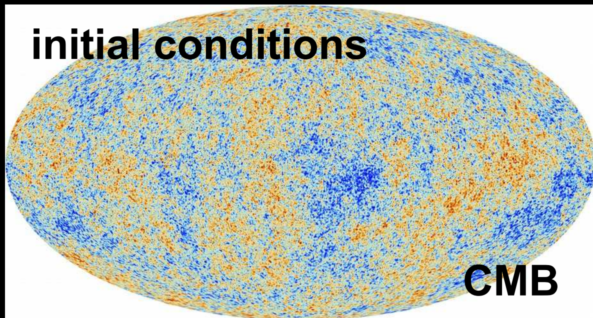
Pontzen & Go



DM gravity only

Aquarius project Springel+08

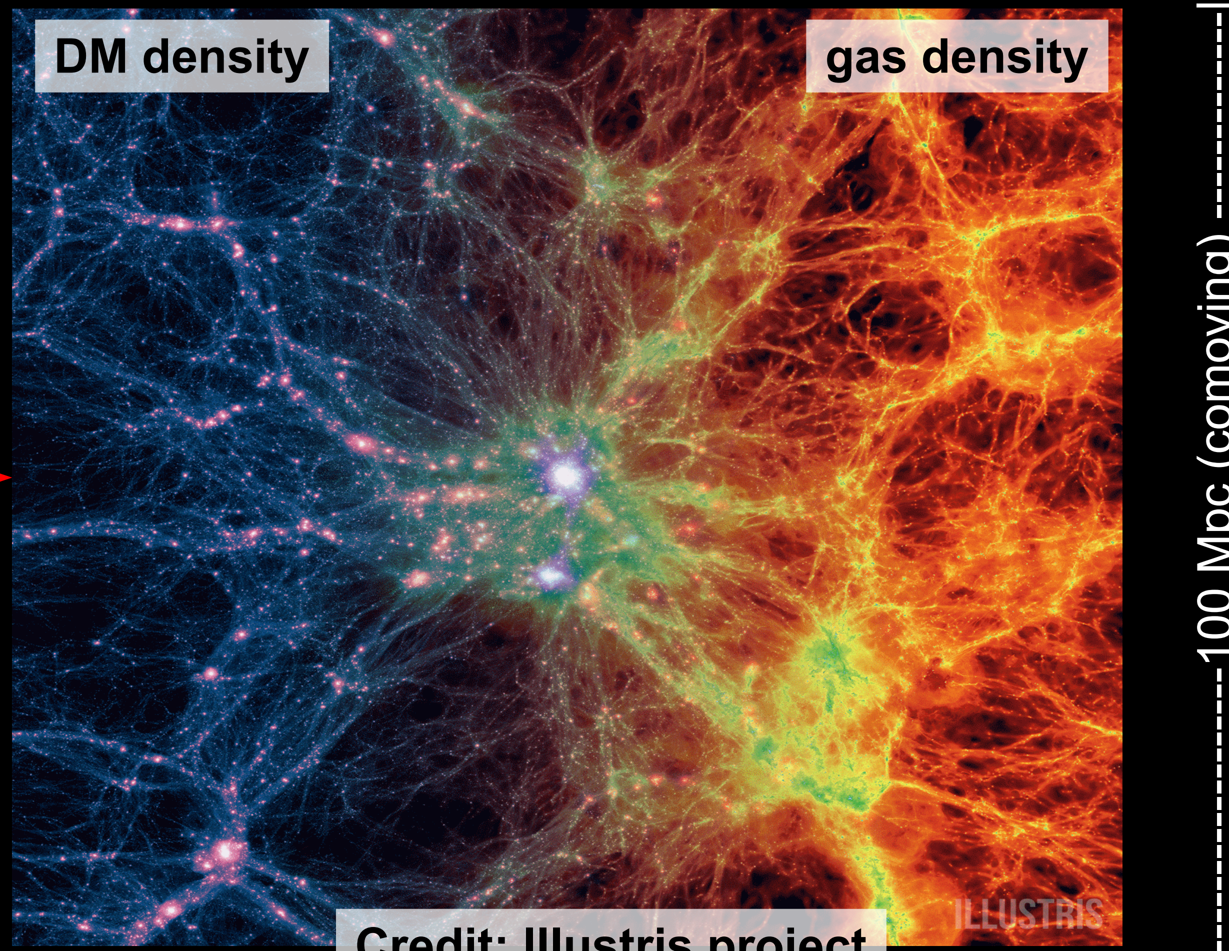
The Cold Dark Matter (CDM) hypothesis is the cornerstone of the current structure formation theory



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,...)



Credit: Illustris project

2000 CPU years!!

Concluding Remarks (Lecture 1)

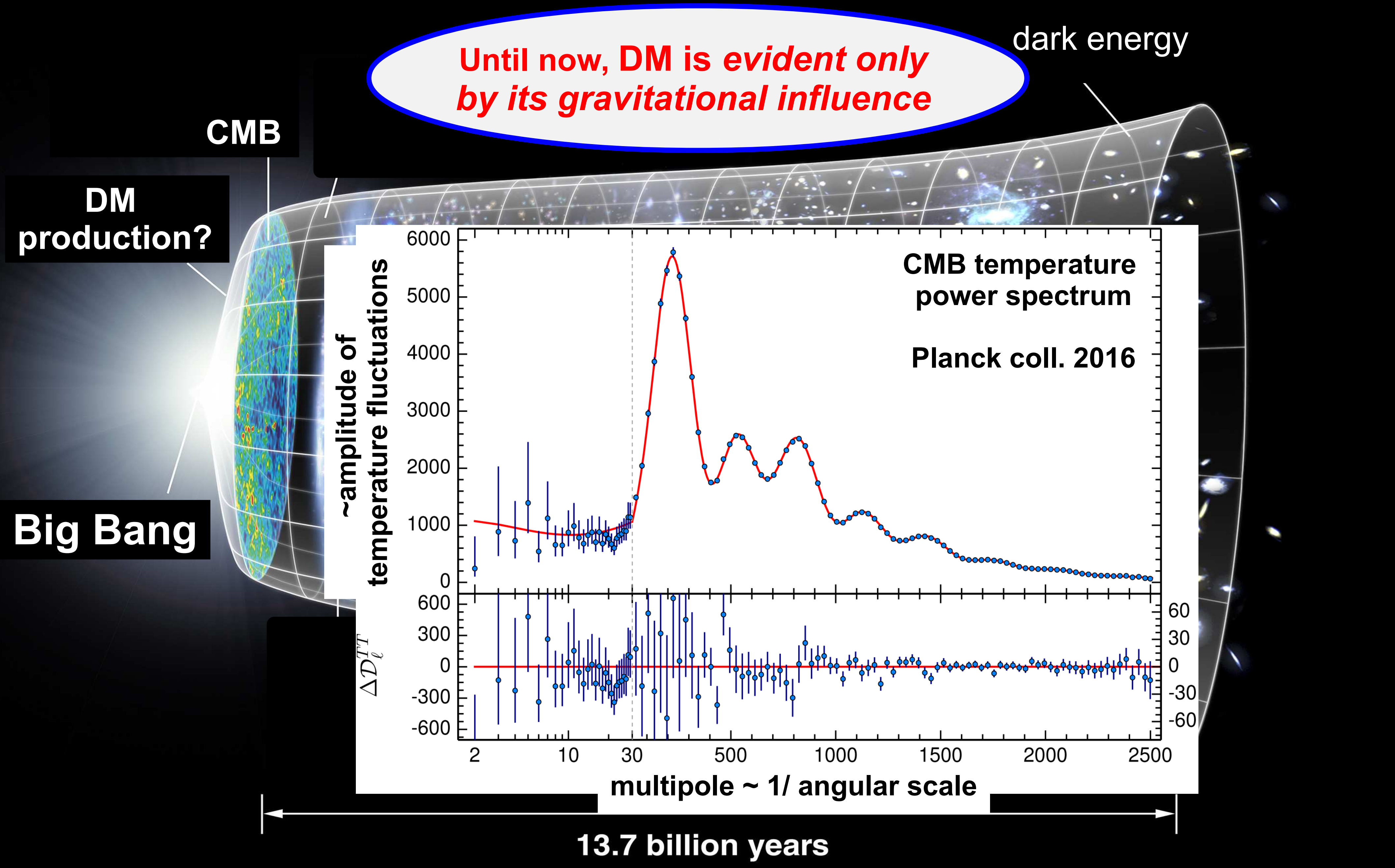
Structure formation theory has become powerful enough to predict the phase-space distribution of dark matter across time down to galactic scales.

- The Cold Dark Matter (CDM) hypothesis has been the standard for over two decades and implies that DM gravity is the only relevant interaction (for galactic scales and above). It impleas that structure formation within CDM has no free DM parameters
- The CMB puts stringent constraints on the initial conditions at large scales
- The linear regime of the evolution ($\delta \ll 1$) is very well understood
- N-body simulations are the most powerful approach to follow the non-linear regime of the evolution
- The CDM model makes predictions on the abundance and inner DM structure, which can be probed with astrophysical observations, but:
  the physics of gas and stars has a still uncertain impact on the DM distribution

EXTRA SLIDES

The particle DM hypothesis:

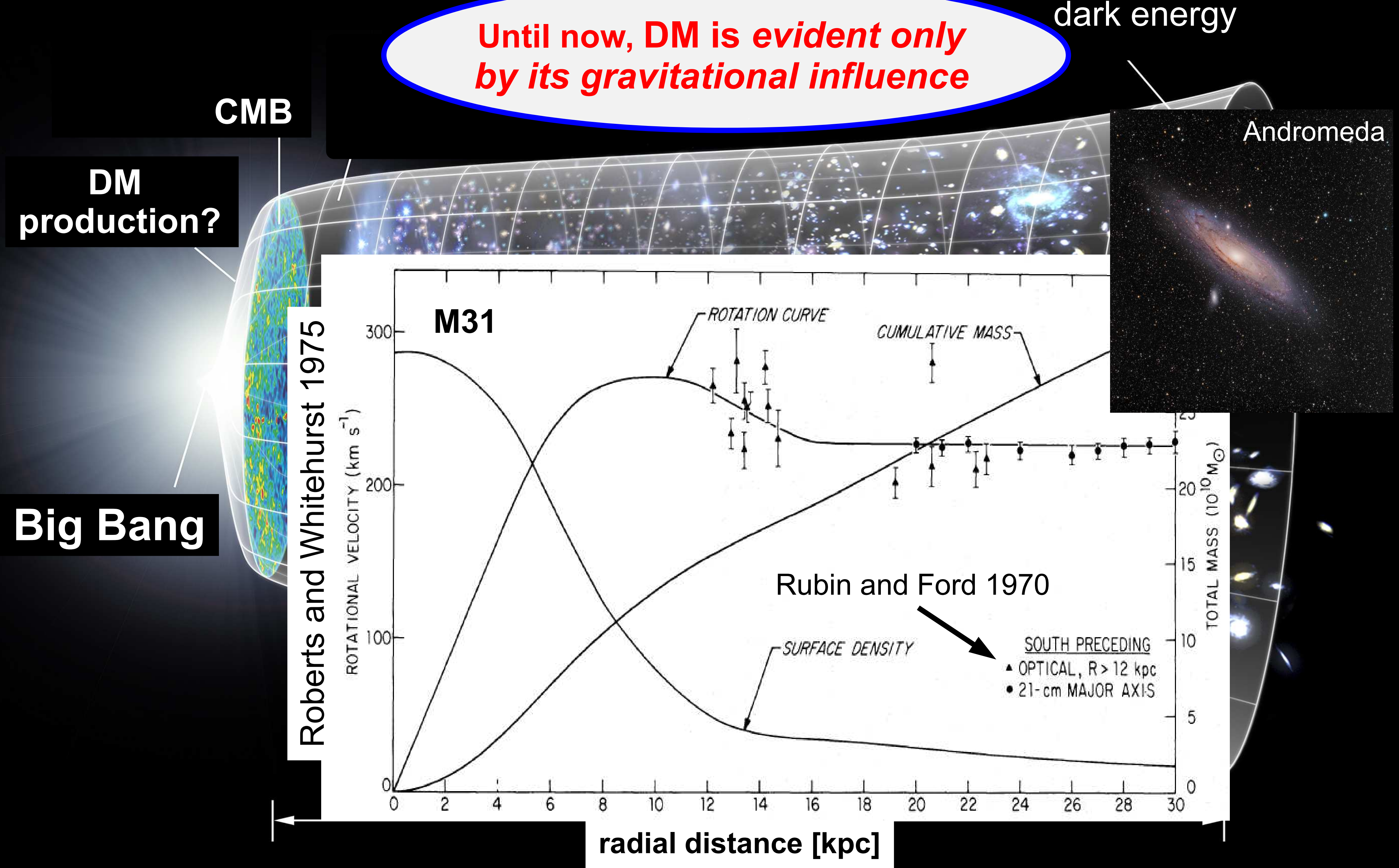
DM is made of *new* particles that do not emit electromagnetic radiation at a significant level



The particle DM hypothesis:

DM is made of *new* particles that do not emit electromagnetic radiation at a significant level

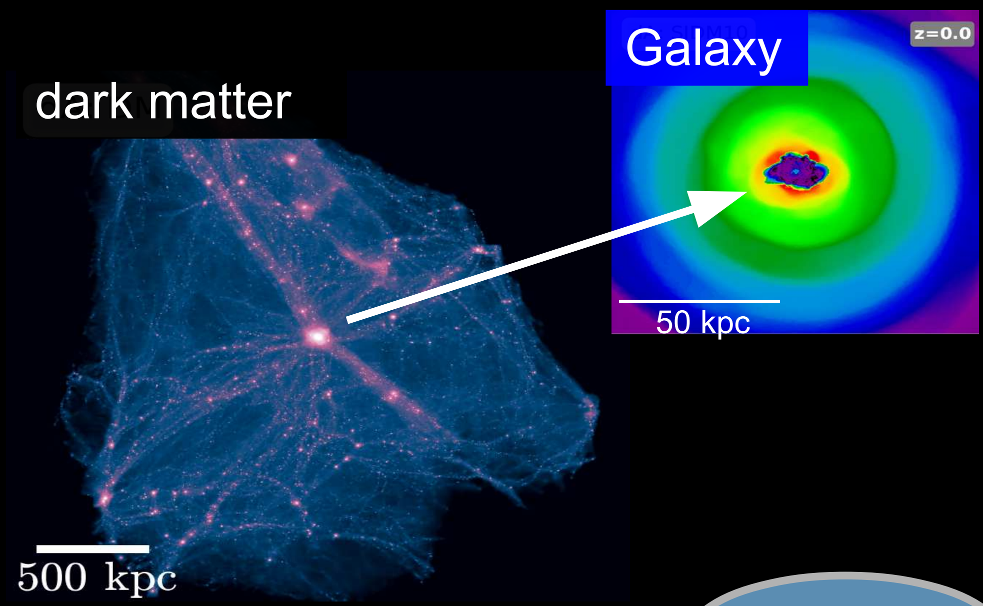
Until now, DM is *evident only by its gravitational influence*

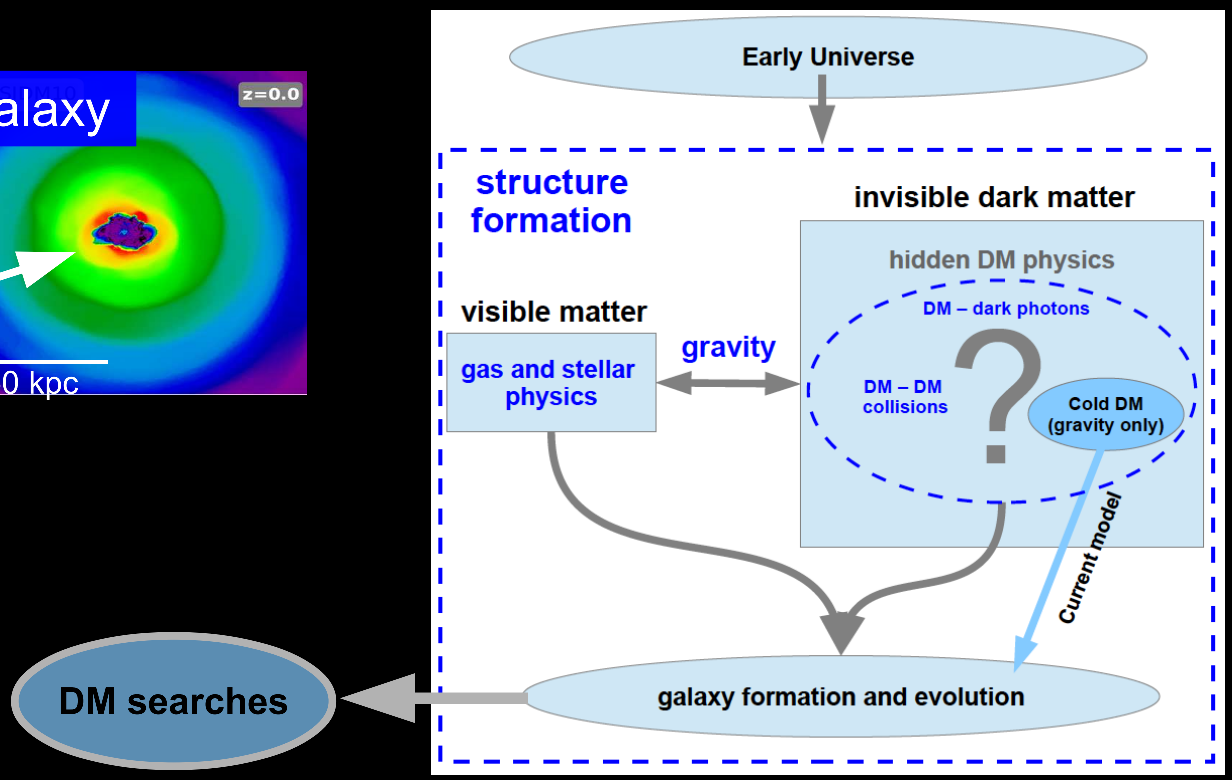


Perspectives on the Astrophysics of Dark Matter

Jesús Zavala Franco

Faculty of Physical Sciences, University of Iceland





Mini Workshop on Dark Matter, Instituto de Física, UNAM, November 2016

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  the physics of gas and stars has a still uncertain impact on the DM distribution

Lecture 2

non-gravitational DM interactions and structure formation

despite the spectacular progress in developing a galaxy formation/evolution theory, it remains incomplete since we still don't know:

what is the nature of dark matter?

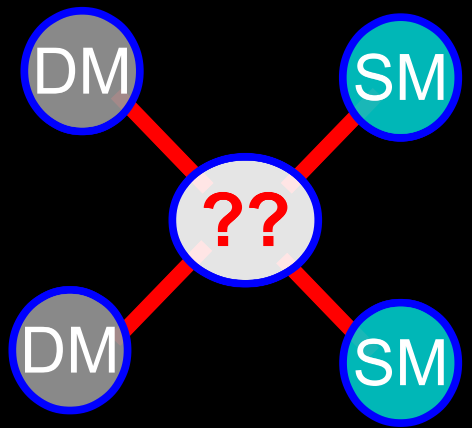
What is the mass(es) of the DM particle(s) and through which forces does it interact?

In the physics of galaxies, is gravity the only dark matter interaction that matters?

Although there is no indisputable evidence that the CDM hypothesis is wrong, there are reasonable physical motivations to consider alternatives

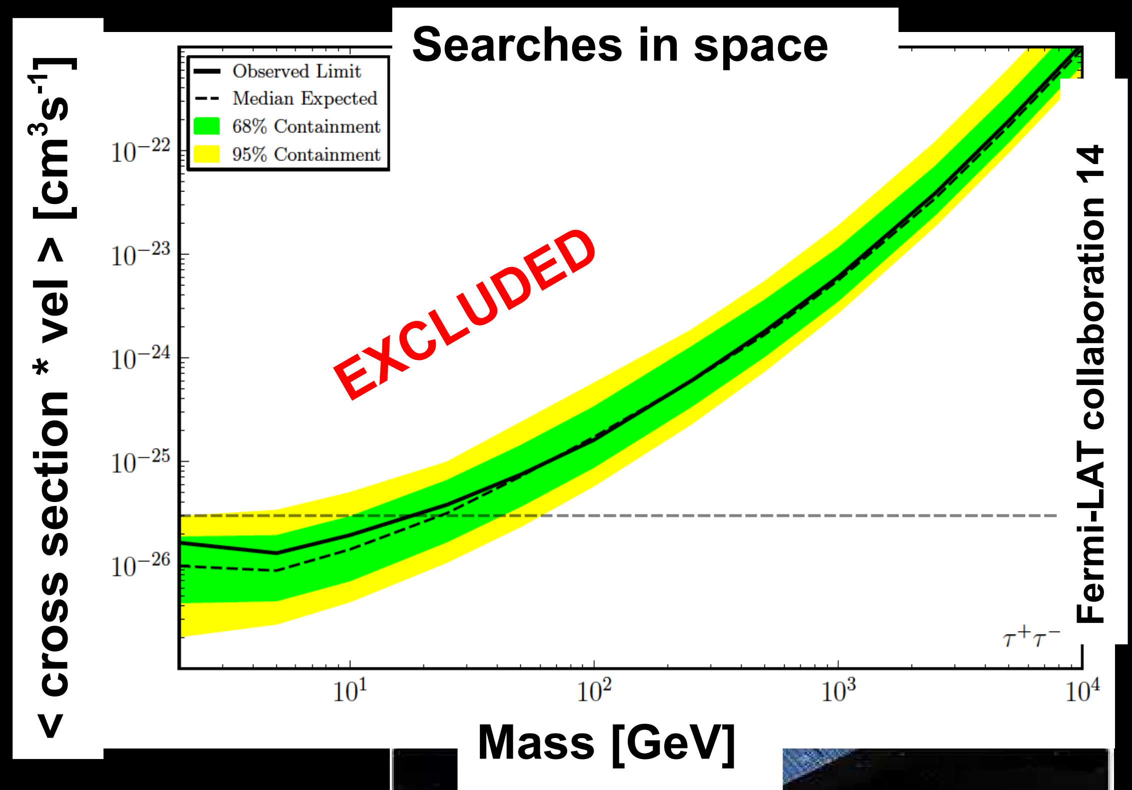
What is the nature of dark matter?

DM self-annihilation



analogous to e^+e^- annihilation

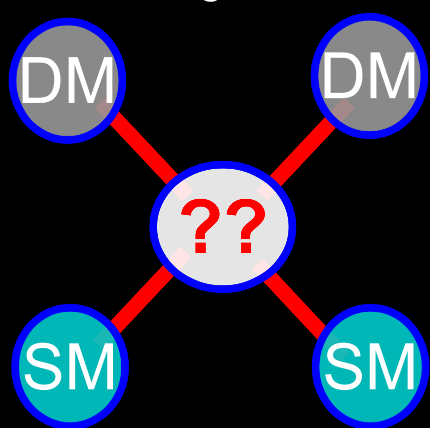
Does DM interacts with visible particles?

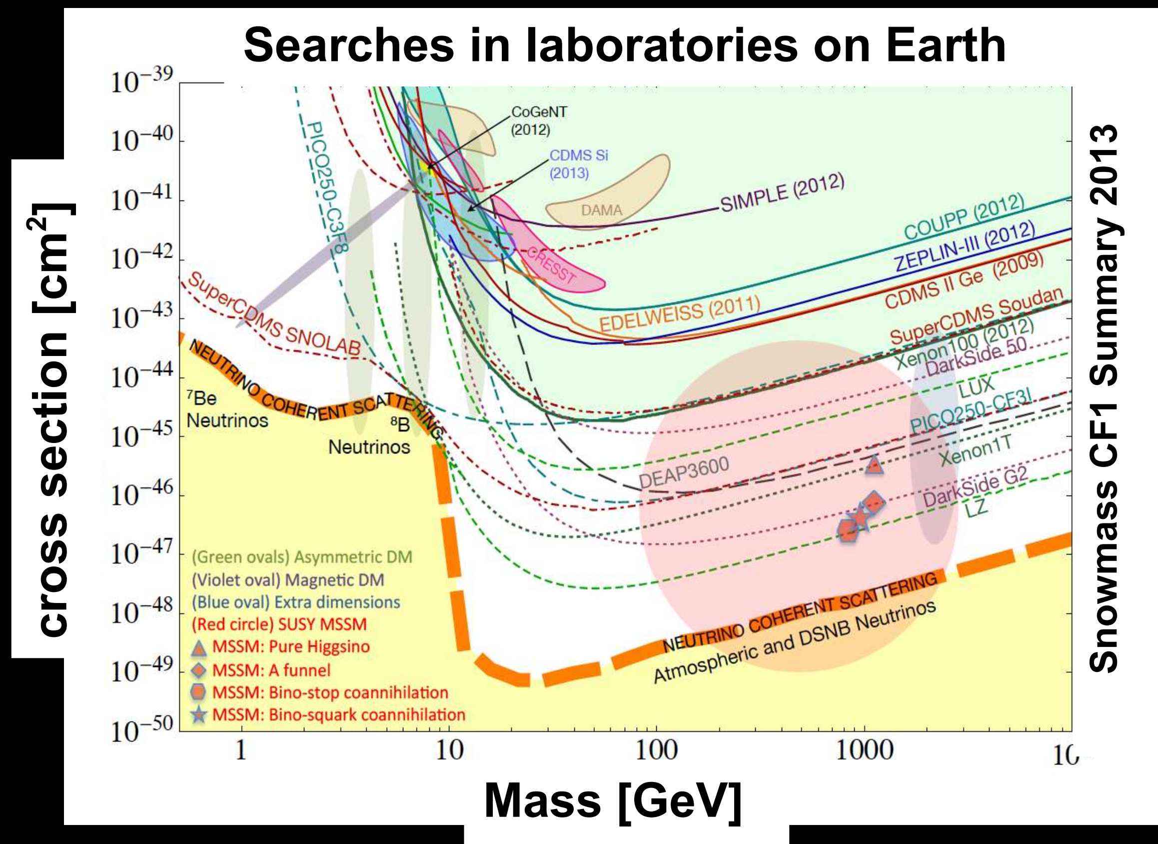


What is the nature of dark matter?

Does DM interacts with visible particles?

Scattering with nuclei





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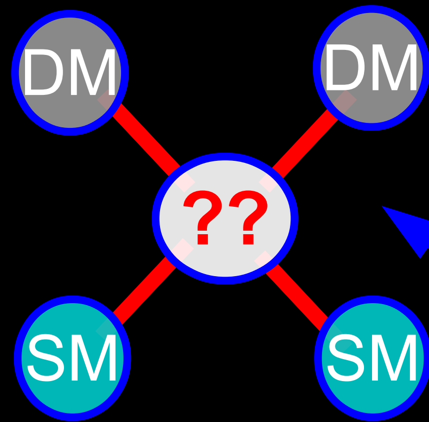
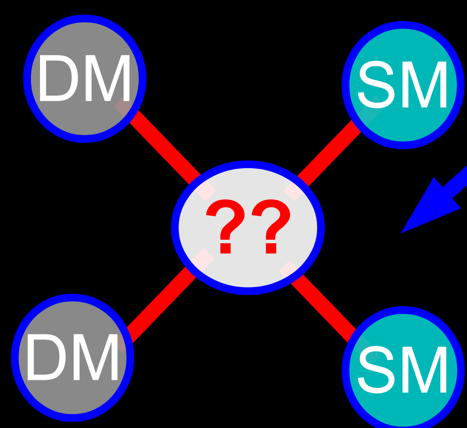


Does DM interacts with visible particles?

DM self-annihilation



Interactions with visible particles are too weak to impact galaxy formation/evolution

Cross section σ/m_χ [cm^2/gr]	Characteristic velocity $\tilde{v}$ [km/s]
SI χ−nucleon $\lesssim 10^{-23}$ $m_\chi \in (0.1-5)$ TeV LUX	~ 200 (local halo)
$\chi\chi \to b\bar{b}$ $\lesssim 10^{-10}$ $m_\chi \in (0.1-1)$ TeV Fermi-LAT	~ 10 (dSphs)

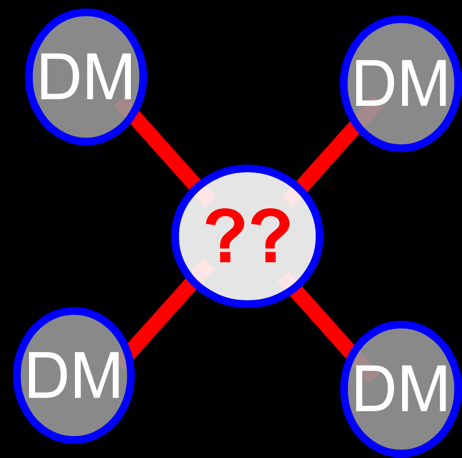
1 cm^2/g ~ 2 barns/GeV

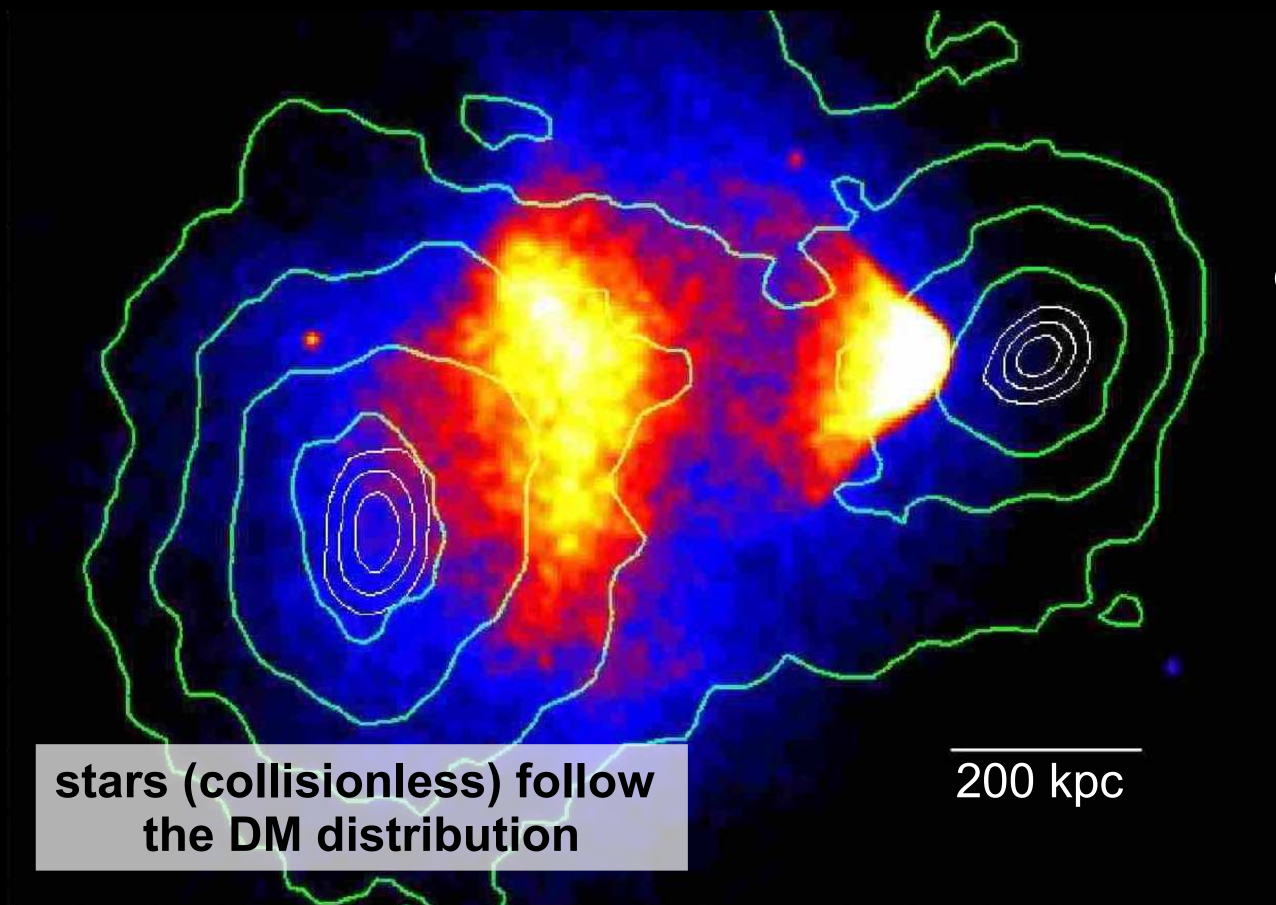
dark matter is quite "dark" (invisible)

nucleon-nucleon elastic scattering: ~10 cm^2/gr

What is the nature of dark matter?

Can DM particles collide with themselves?





Bullet Cluster (Clowe +06)

constraint on DM self-collisions

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

Robertson+2016

nucleon-nucleon elastic scattering: ~10 cm^2/gr

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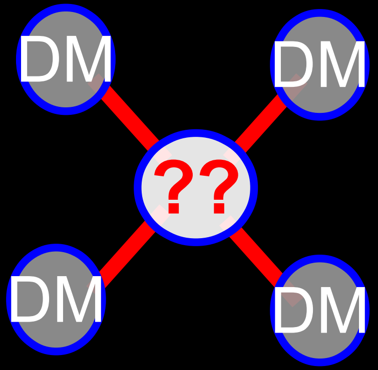
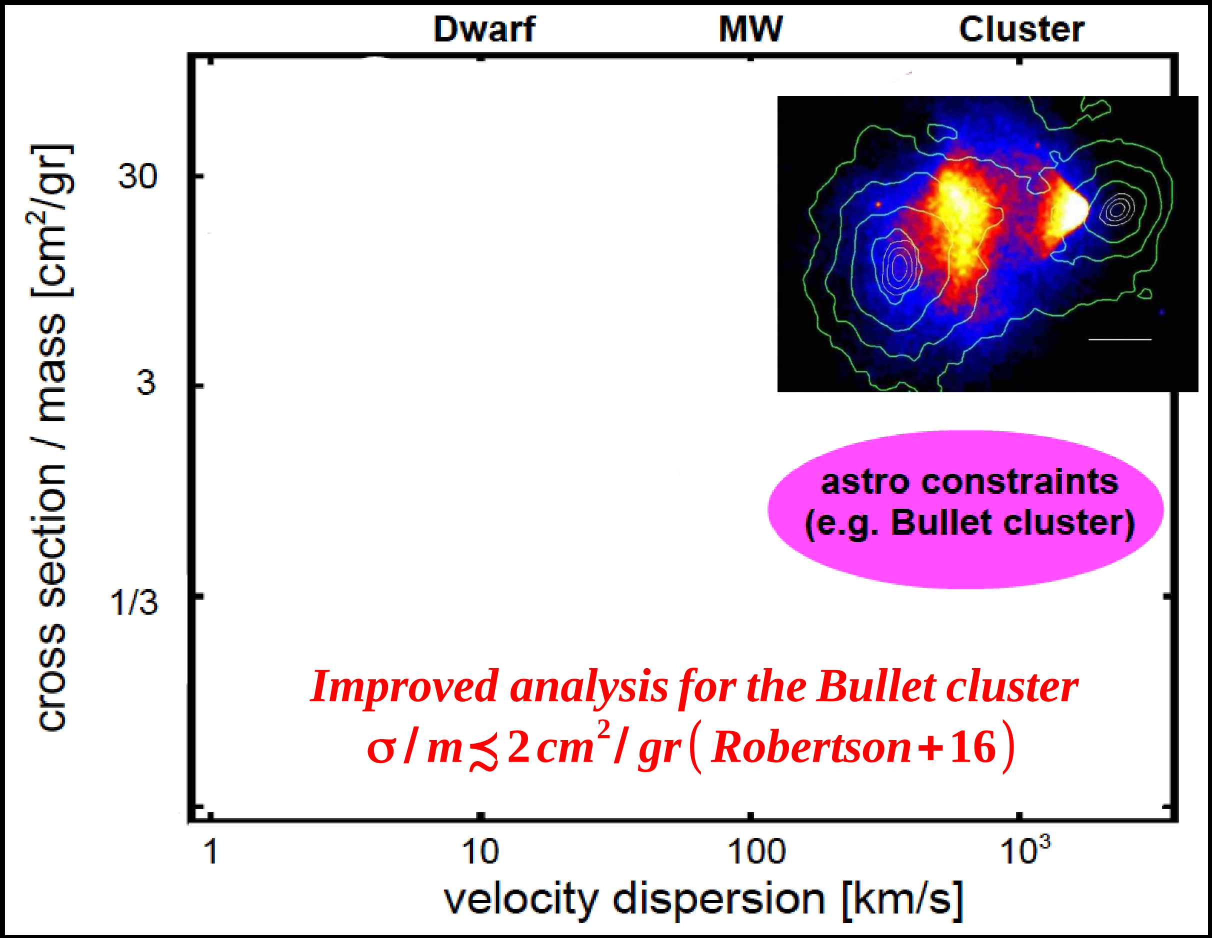
Can DM particles collide with themselves?





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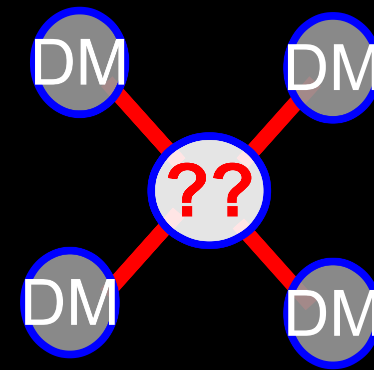


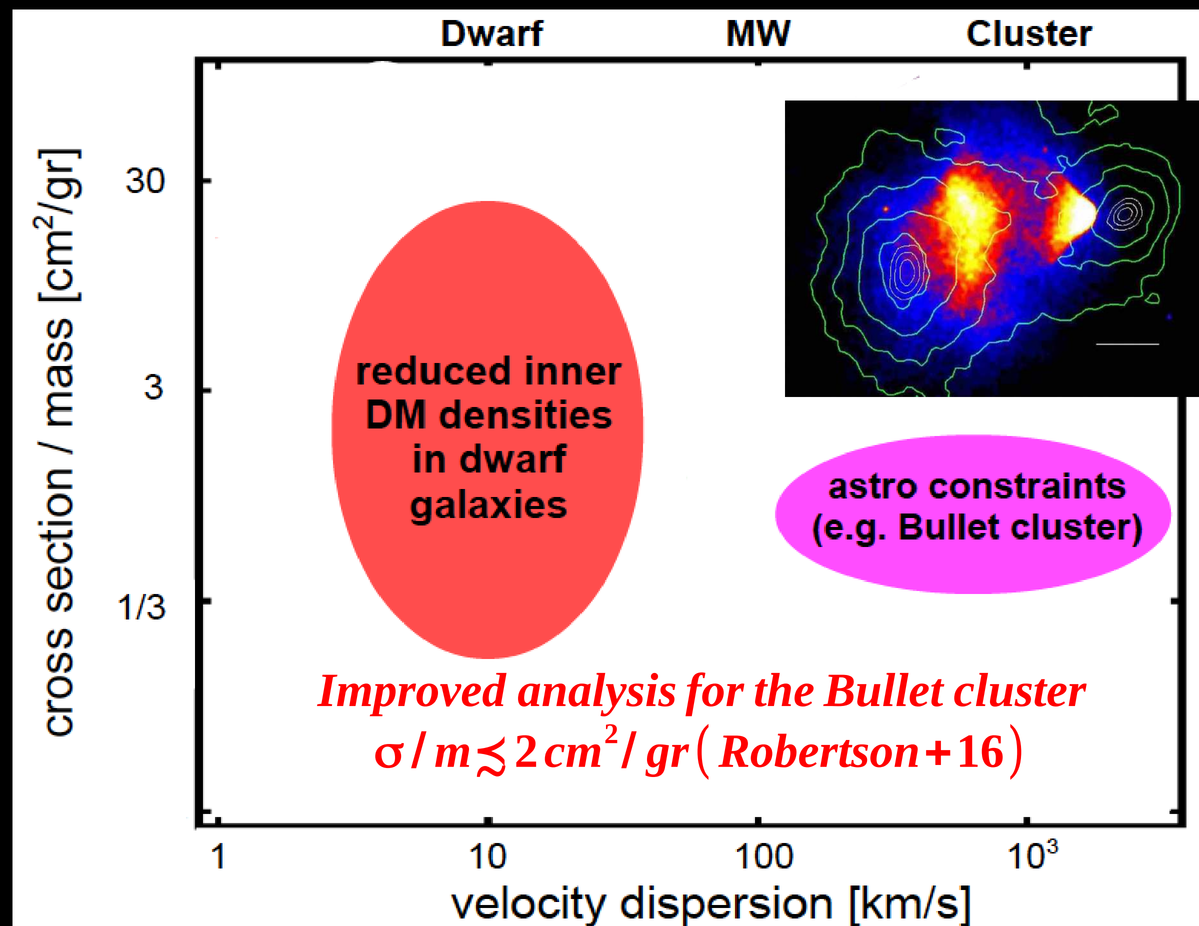
constraints allow collisional DM that is astrophysically significant in the center of galaxies:

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)



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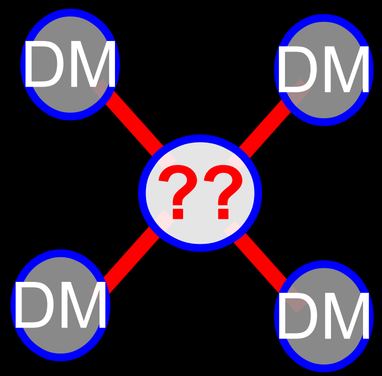
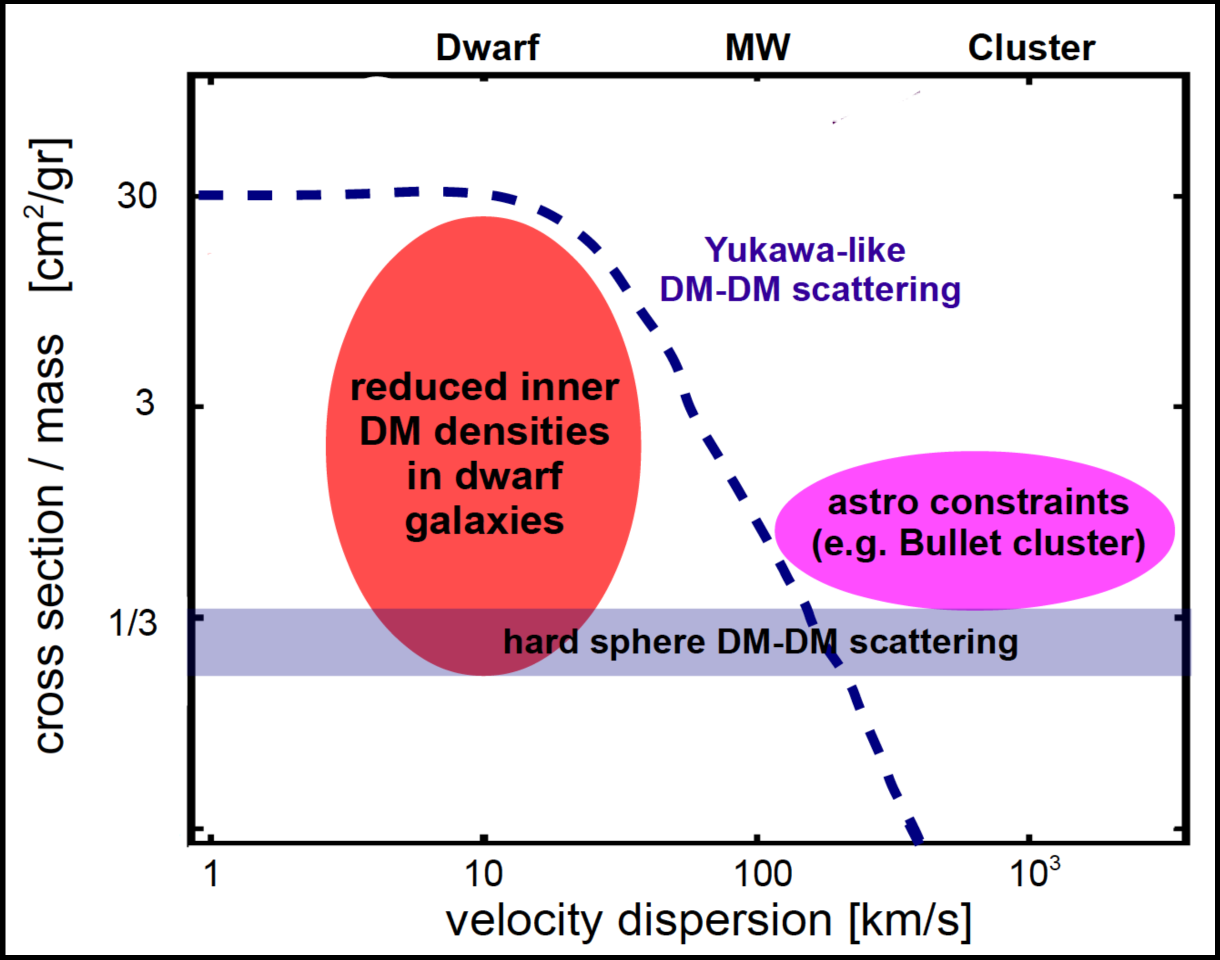


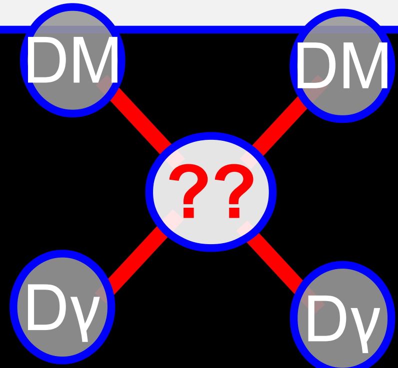
constraints allow collisional DM that is astrophysically significant in the center of galaxies:

velocity-dependent models (motivated by a new force in the "dark sector") can accommodate the constraints
e.g. Yukawa-like, Feng+09, Loeb & Weiner 2011,...



What is the nature of dark matter?

Can DM particles interact with other "dark" particles?



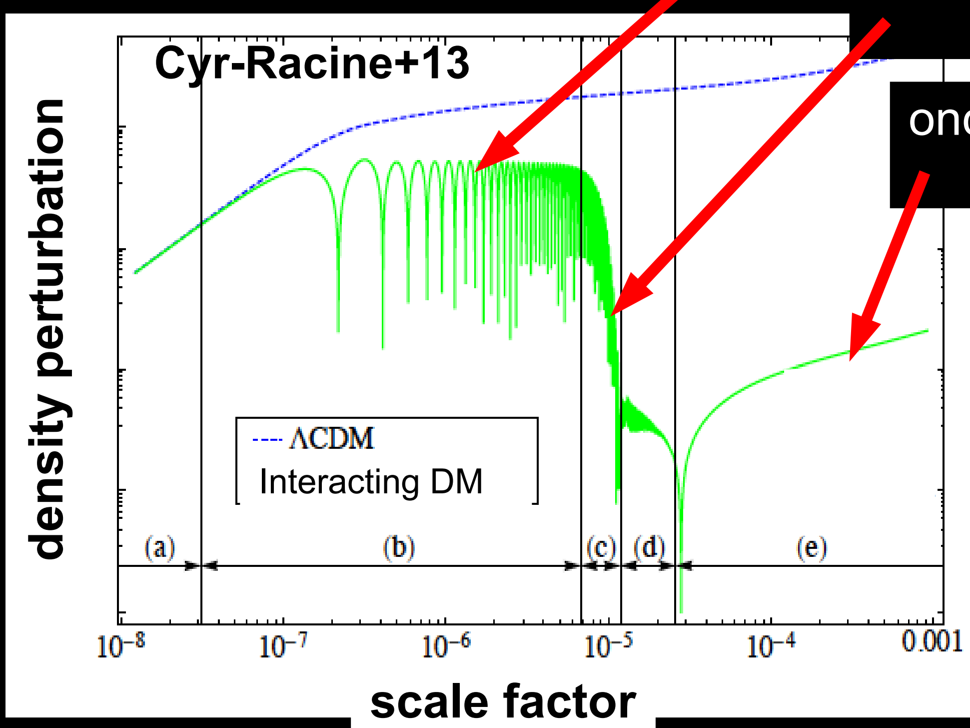
"dark photons"

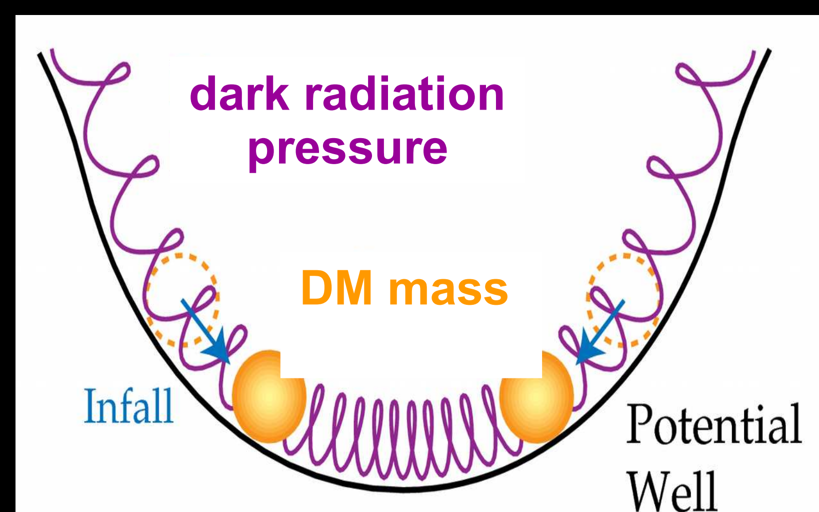
Allowed interactions between DM and relativistic particles (e.g. "dark radiation") in the early Universe introduce pressure effects that impact the growth of DM structures (phenomena analogous to that of the photon-baryon plasma)

dark radiation pressure counteracts gravity creating "dark acoustic oscillations"

diffusion (Silk) damping can effectively diffuse-out DM perturbations

once kinetic decoupling (DM-DR) occurs DM behaviour is like CDM





Credit: Wayne Hu (U. Of Chicago)

What is the nature of dark matter? (summary)

The search for visible byproducts of DM interactions continues

dark matter is quite dark (invisible)

From a purely phenomenological perspective, it is possible that non-gravitational DM interactions play a key role in the physics of galaxies

dark matter might not be as “inert” as is commonly assumed

Beyond CDM: exploring new dark matter physics with astrophysics

From a purely phenomenological perspective, it is possible that non-gravitational DM interactions play a key role in the physics of galaxies

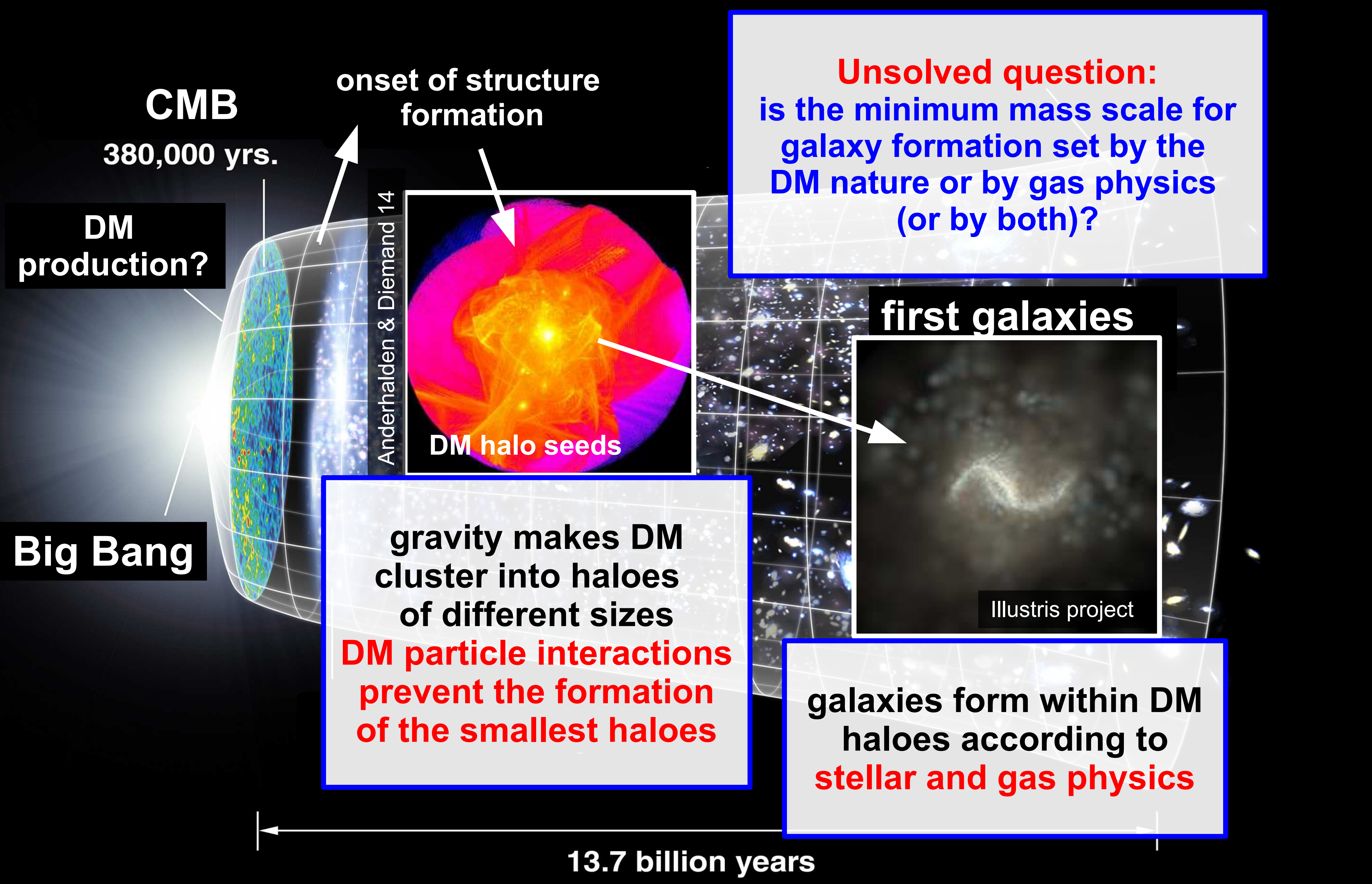
Unsolved question:
is the minimum mass scale for galaxy formation set by the DM nature or by gas physics (or by both)?

Unsolved question:
are non-gravitational DM interactions irrelevant for galaxy evolution?

These questions go beyond the "standard" DM model for the formation and evolution of galaxies

Pursuing them, will either confirm the standard model or unveil a fundamental DM property

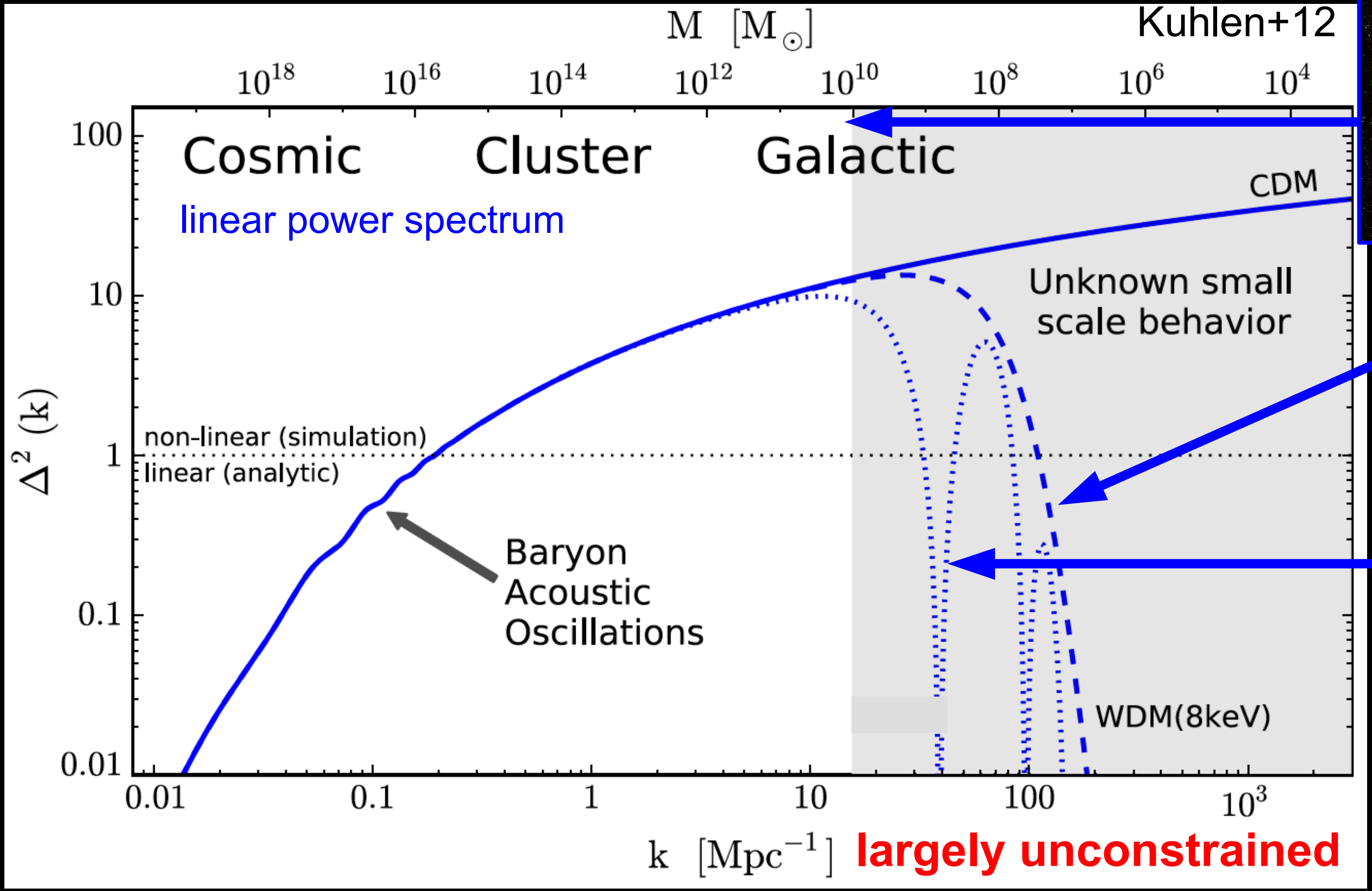
The nature of dark matter and the first galaxies



The nature of dark matter and the first galaxies

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

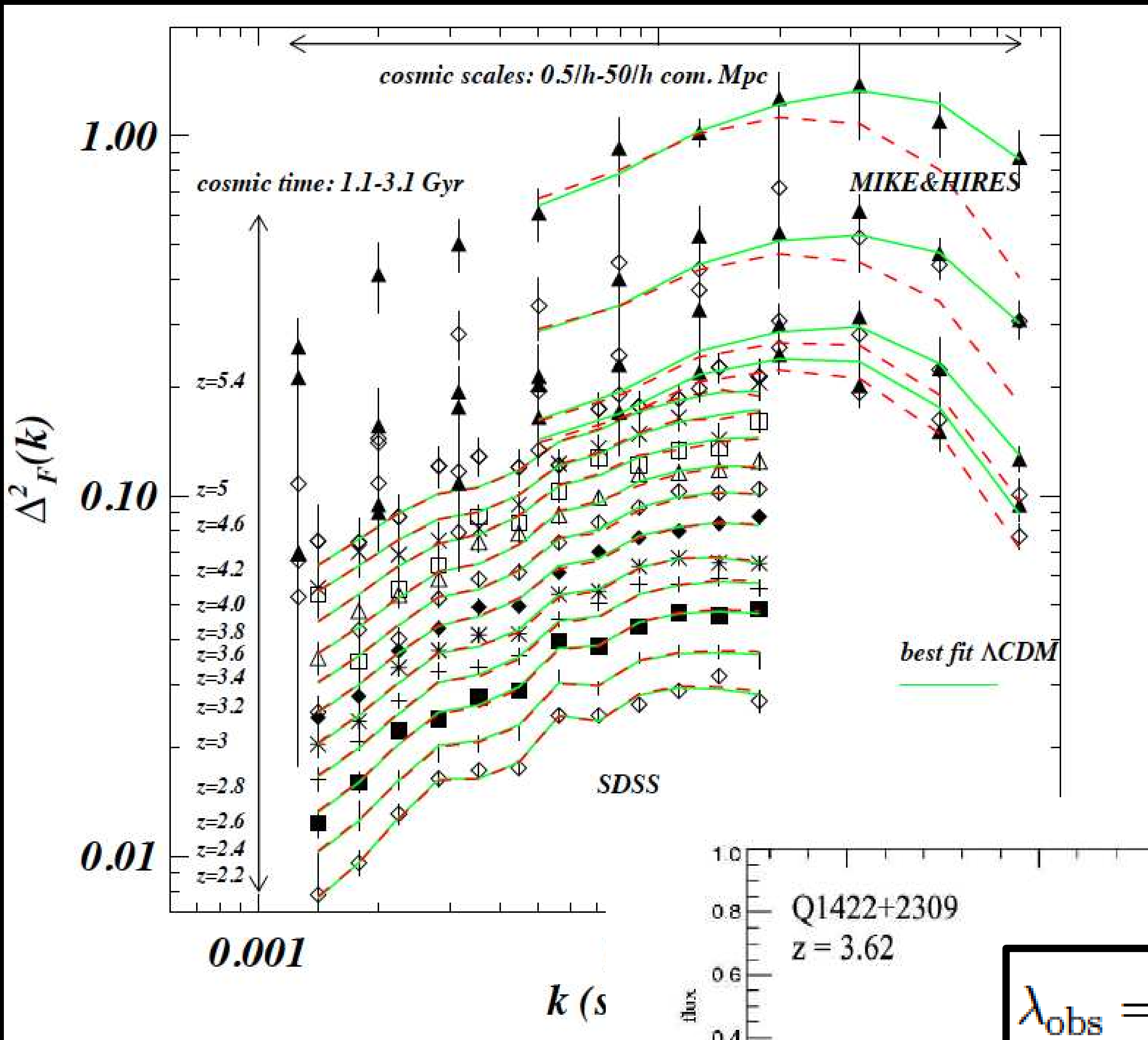
Observations have yet to measure the clustering of dark matter at the scale of the smallest galaxies



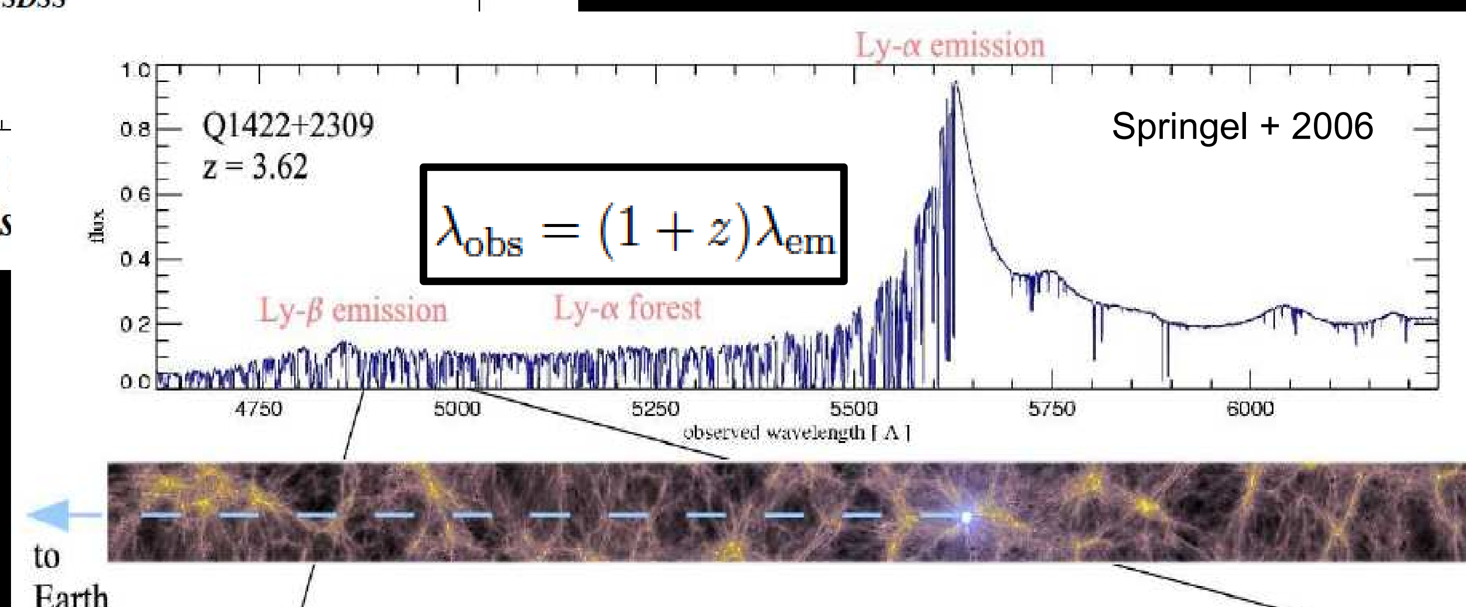
DM is relativistic at earlier times thermal cut-off (free-streaming)

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

(e.g. Ly-α forest constraints)



DM power spectrum – IGM connection



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DM self-collisions in N-body simulations

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

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

in pairs:

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

total for a particle:

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

discrete version of the collisional operator

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: $x \leqslant \sum_i^l P_{ij}$

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

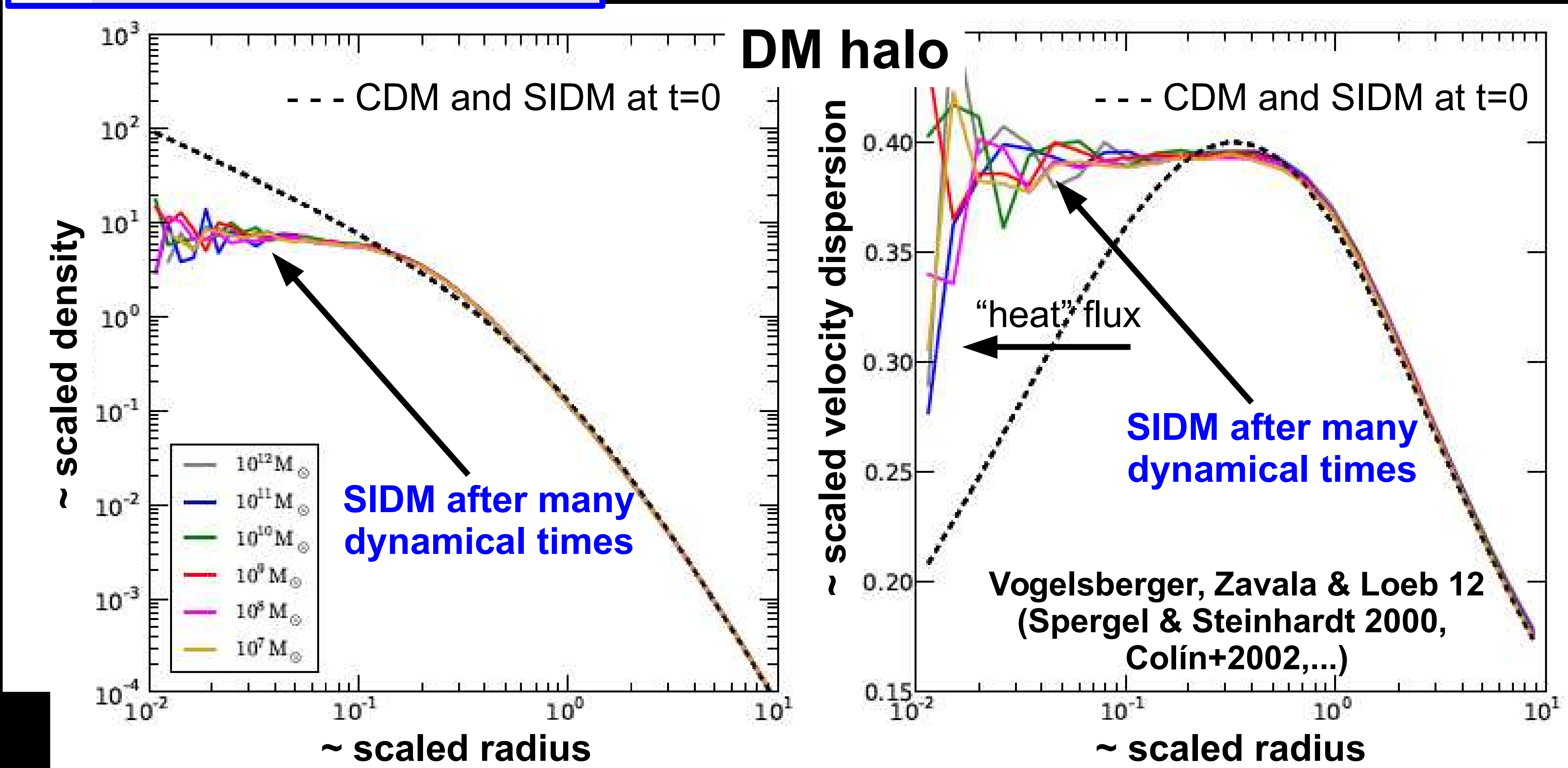
Kochanek & White 2000, Yoshida+2000,...Vogelsberger, Zavala, Loeb 2012, Rocha+2013

)

The nature of dark matter (evolution of structures)

Unsolved question:
are non-gravitational DM interactions irrelevant for galaxy evolution?

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



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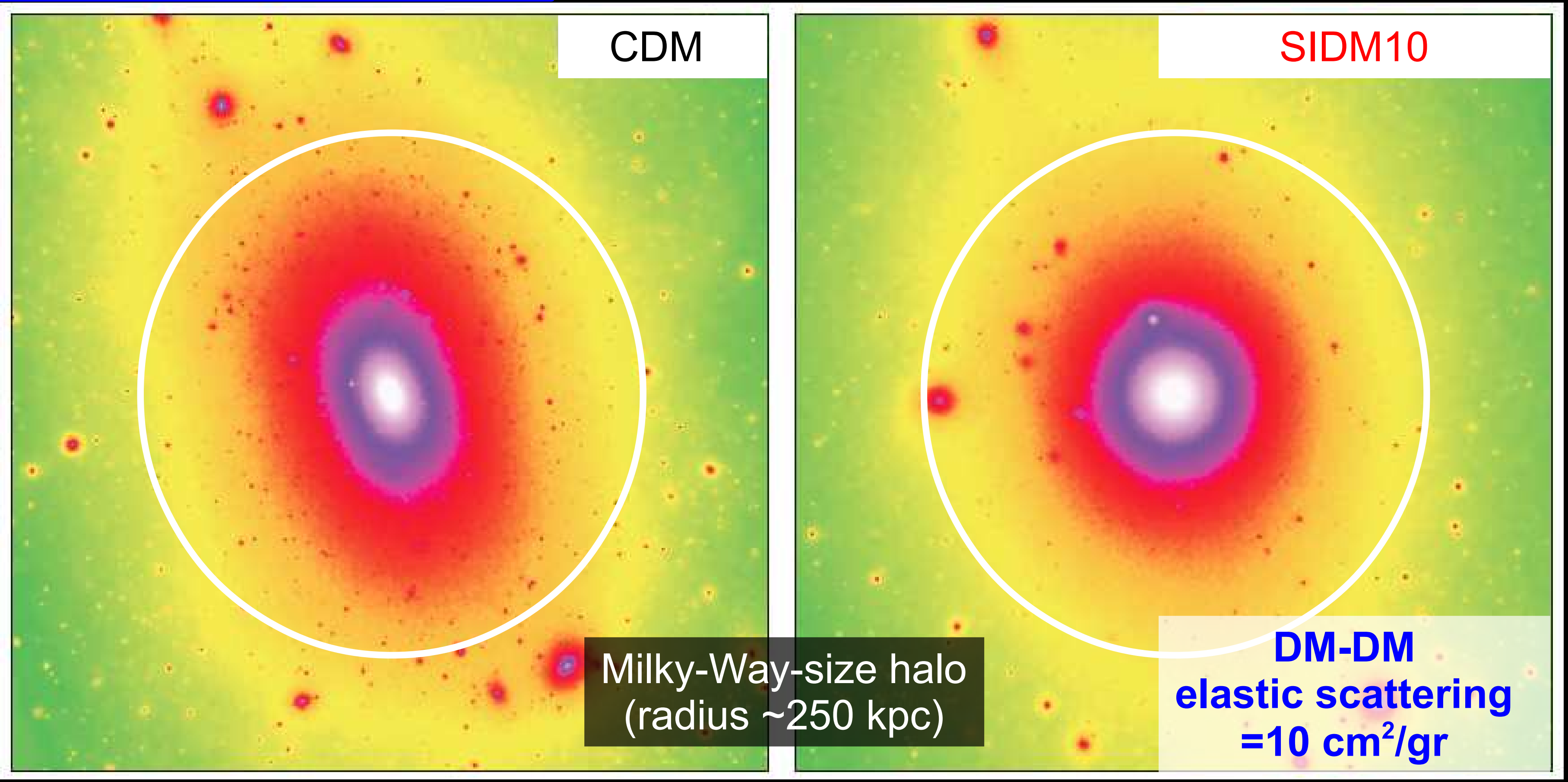
If gravity is the only relevant DM interaction, the central density of haloes is ever increasing

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

Vogelsberger, Zavala & Loeb 2012



DM-only simulations

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

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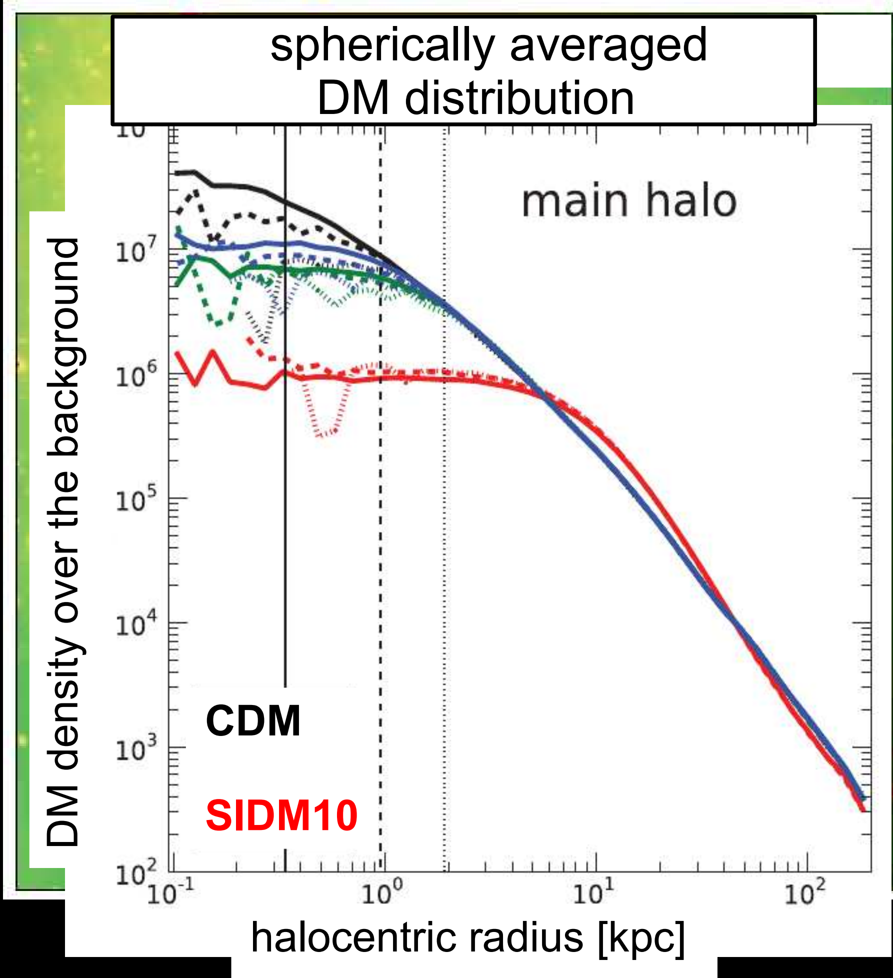
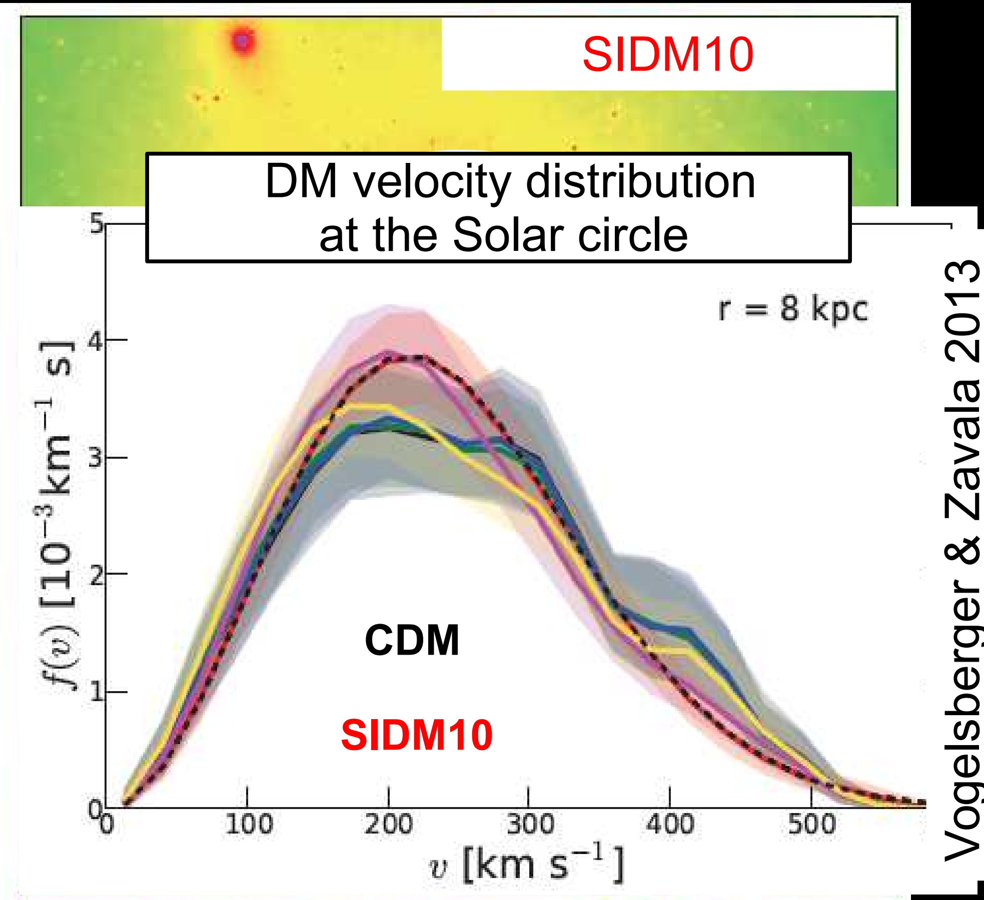


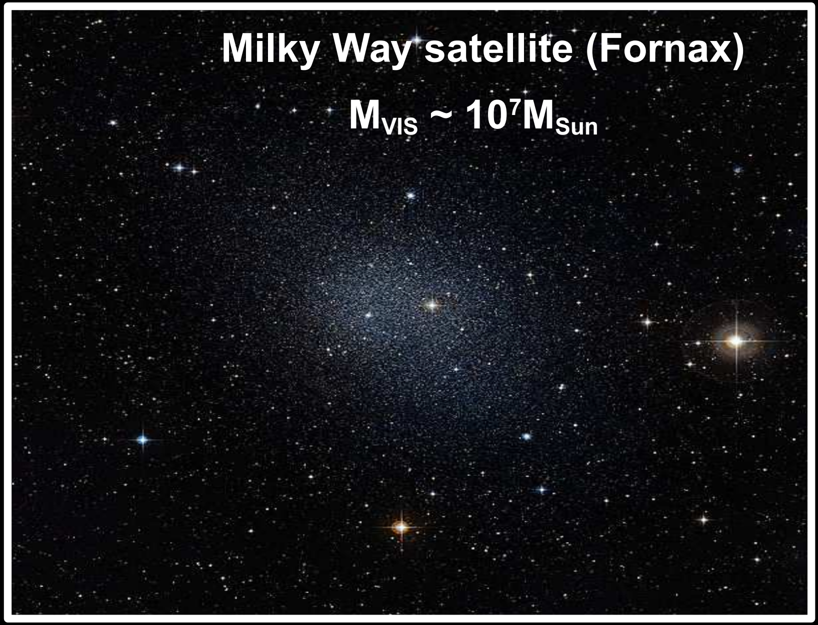


Vogelsberger & Zavala 2013

relevant to particle DM searches

Clues of new DM physics from dwarf galaxies?

Dwarf galaxies:
most DM-dominated systems: $M_{DM} > 10\ M_{VIS}$
(ordinary matter is less dynamically relevant)



The stellar dynamics is simplified and the underlying DM distribution can be more easily constrained

radial Jeans equation

$$\frac{d\left(\rho_{st}\sigma_r^2\right)}{dr} + 2\frac{\beta}{r}\rho_{st}\sigma_r^2 \simeq -\rho_{st}\frac{d\phi_{DM}}{dr}$$

$$\beta = 1 - \left(\sigma_t/\sigma_r\right)^2$$

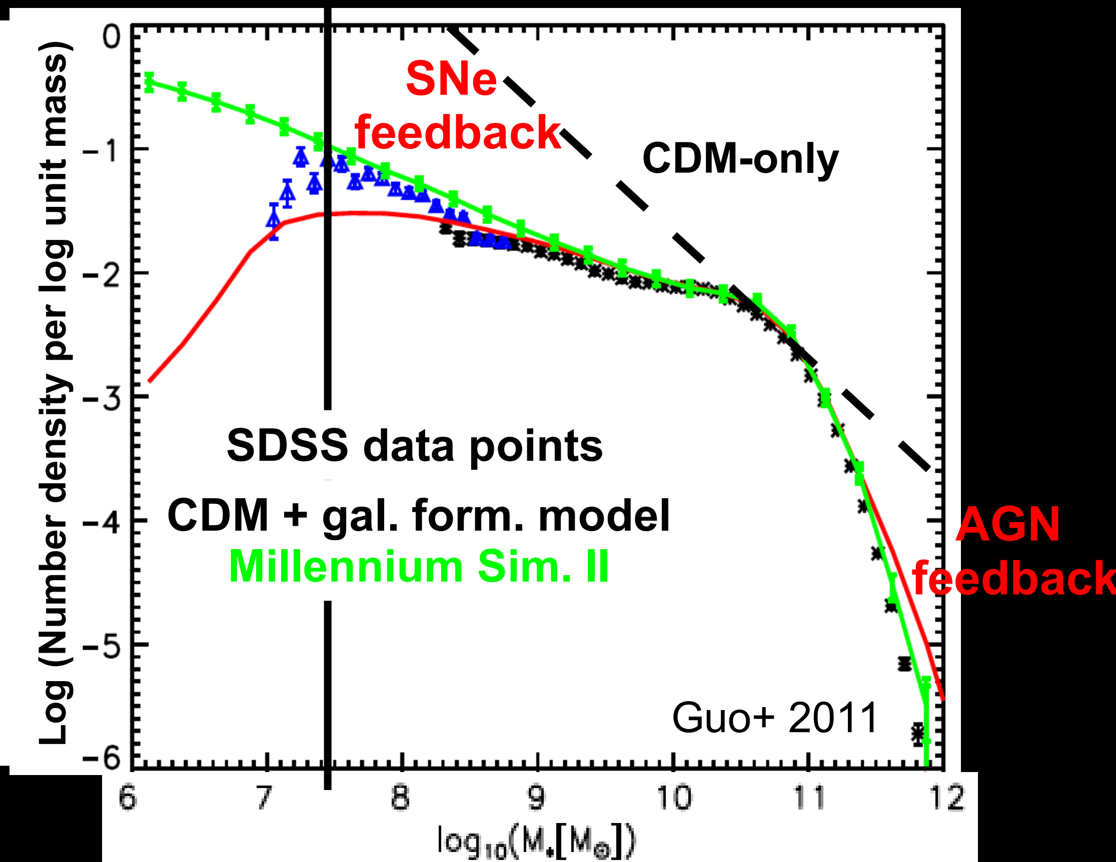
$$\frac{df}{dt} = 0$$

CBE + steady-state
+ spherical symmetry

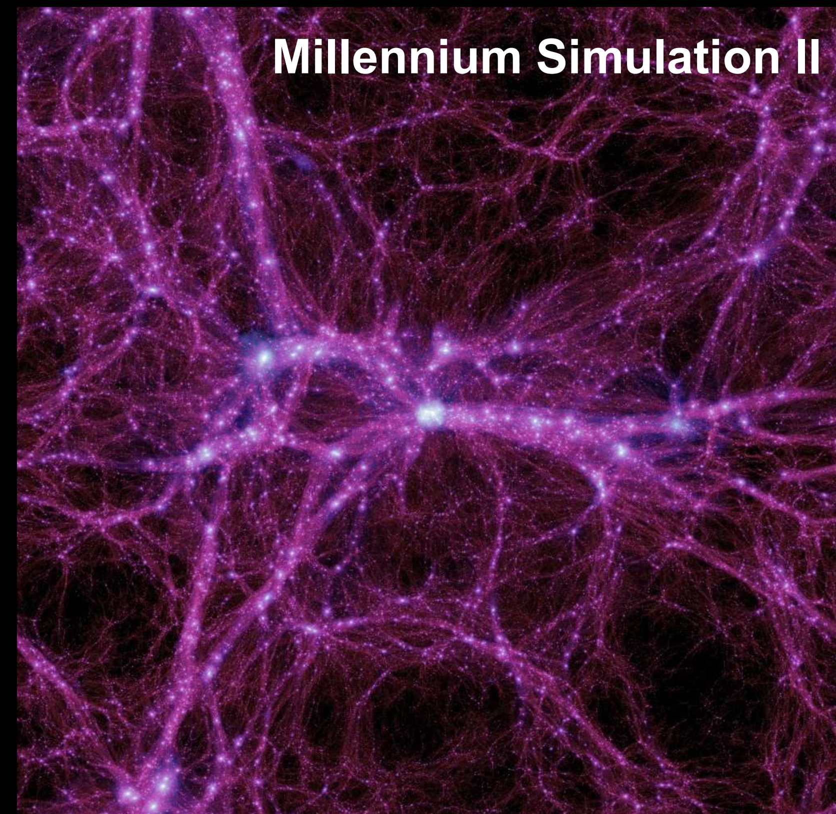
"Optimal" dynamical DM detectors

Observed abundance of dwarf galaxies in the field

$M_h \sim 4 \times 10^{10} M_{Sun}$ (~dwarf scale)



Abundance according to stellar mass



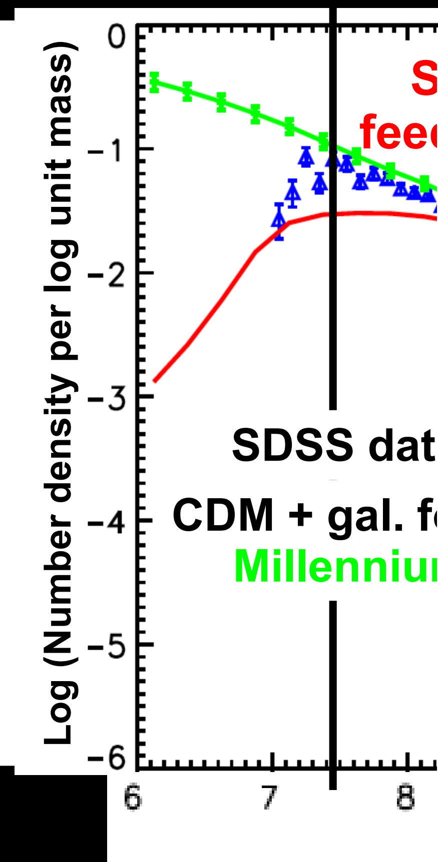
100 Mpc/h

Boylan-Kolchin+ 2009

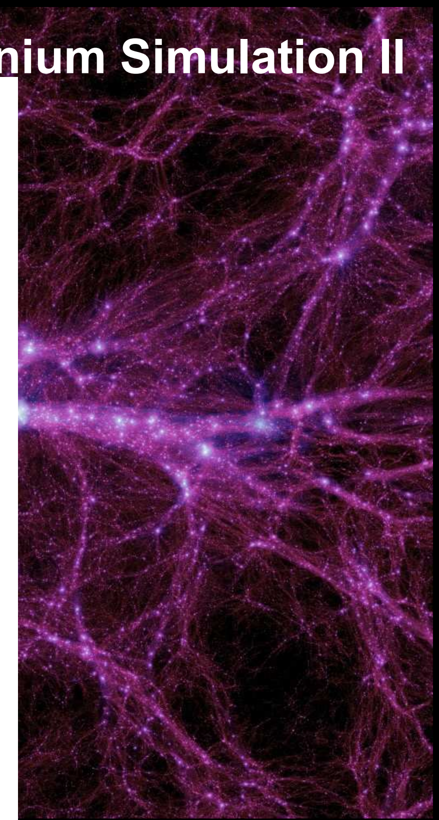
Galaxy formation and evolution modifies the DM-only prediction

Observed abundance of dwarf galaxies in the field

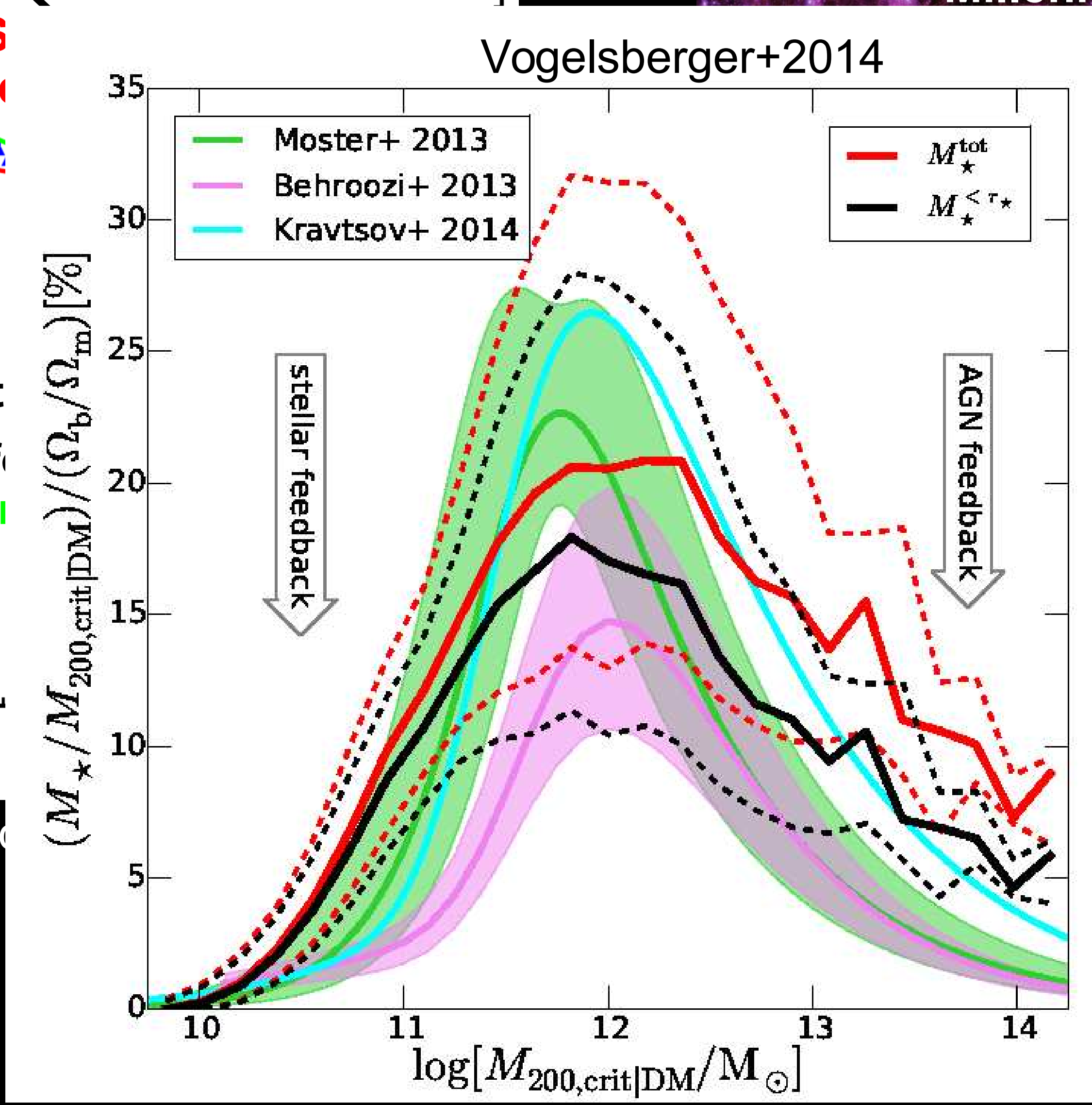
$M_h \sim 4 \times 10^{10} M_{Sun}$ (~dwarf scale)



Abundance ac



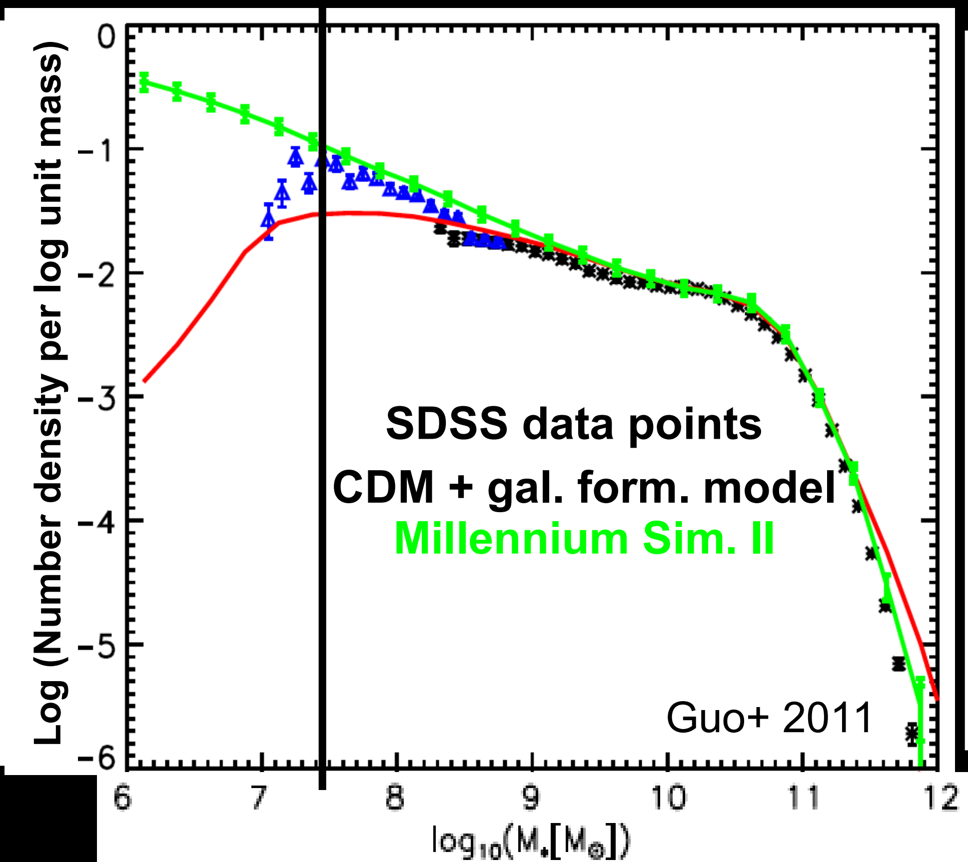
Boylan-Kolchin+ 2009



Galaxy formation is quite inefficient!!

Observed abundance of dwarf galaxies in the field

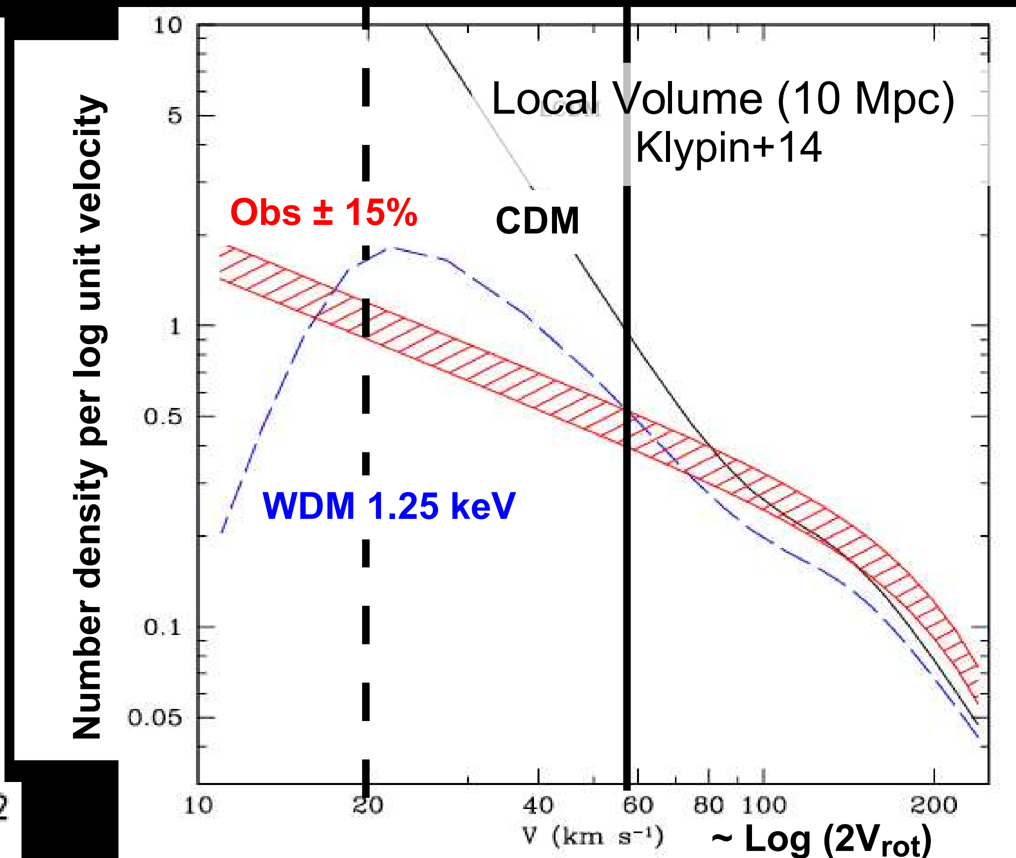
$M_h \sim 4 \times 10^{10} M_{Sun}$ (~dwarf scale)



Abundance according to stellar mass

90% complete

$M_h \sim 4 \times 10^{10} M_{Sun}$ (~dwarf scale)



Abundance according to global rotation

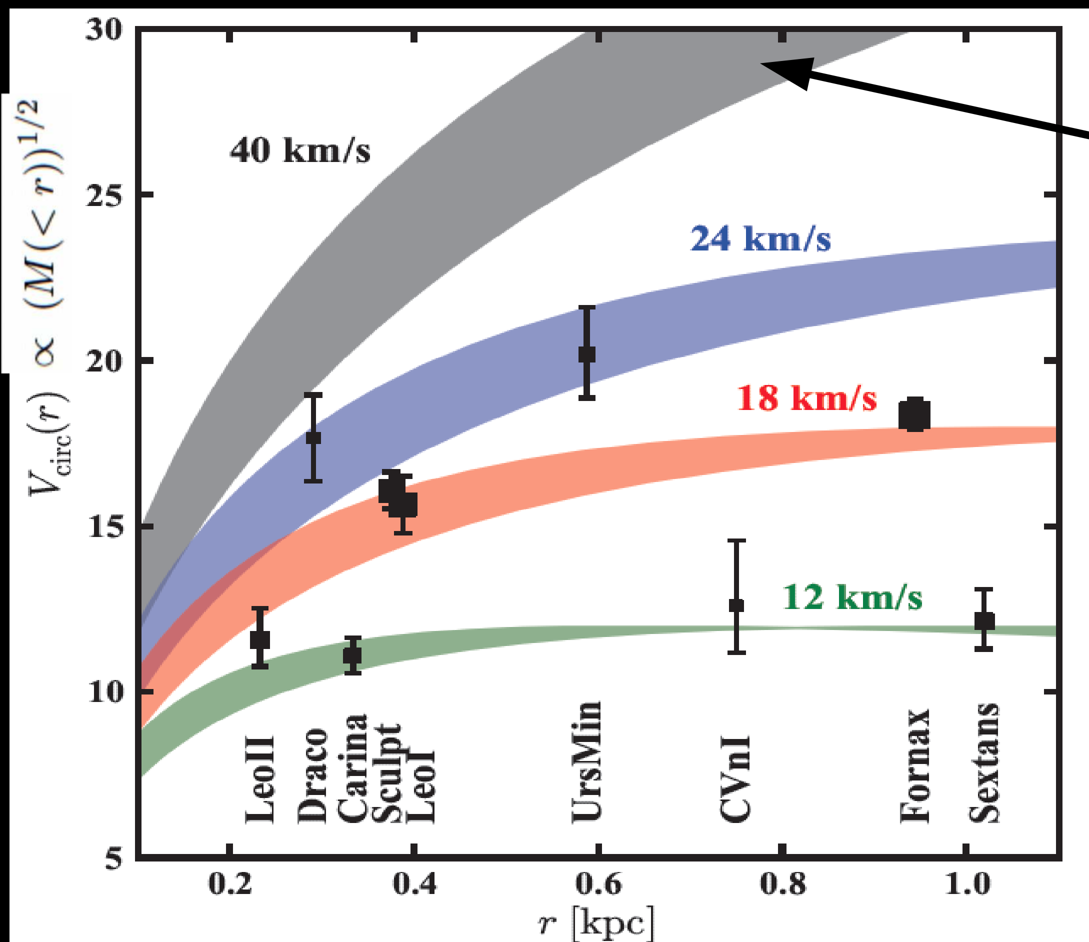
CDM + current gal. form. models overpredict the abundance of field dwarfs (Zavala+09,Papastergis+11,Klypin+14)

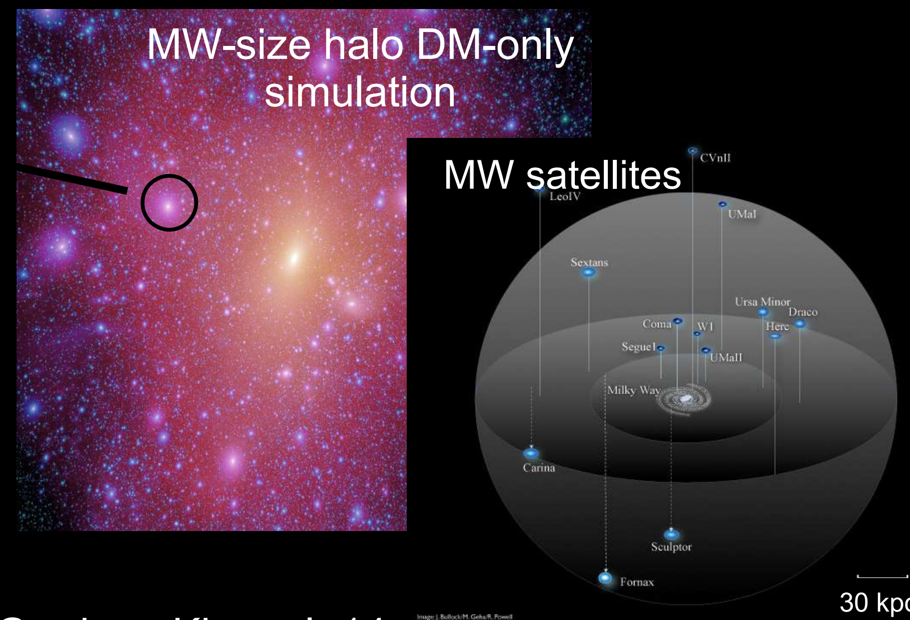
Missing satellite problem (is not really a problem in CDM

Missing isolated dwarfs (is an unsolved problem in CDM)

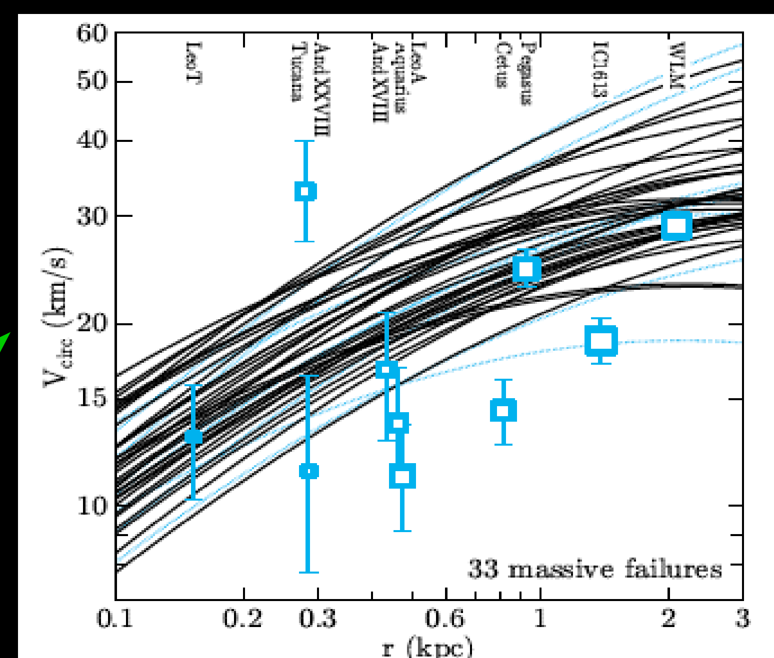
DM distribution in the MW satellites: The “Too Big to Fail” problem

Boylan-Kolchin+12





Garrison-Kimmel+14

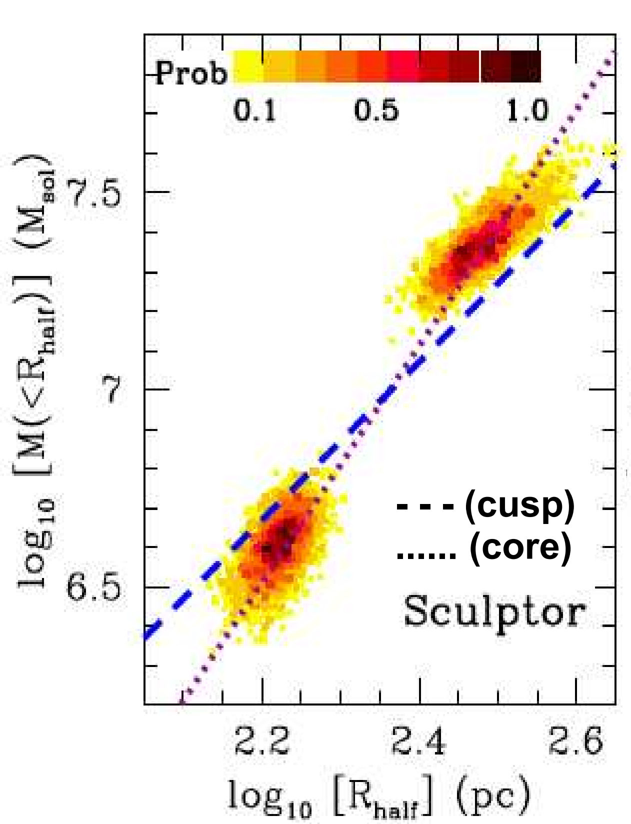


The most massive CDM-MW-subhaloes seem to be too centrally dense to host the MW dSphs (problem extends to LG)

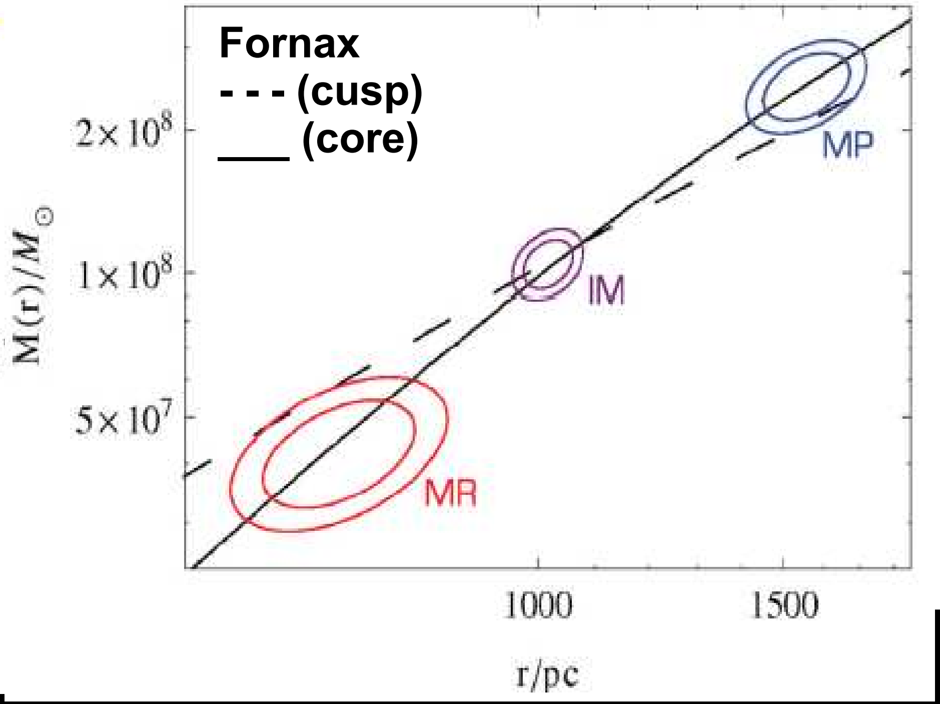
Unsolved problem in CDM!!

DM distribution in the MW satellites: the core-cusp problem

Walker & Peñarrubia 2011



Different stellar subcomponents provide an estimate of the slope of the mass profile:
cores seem favoured over cusps

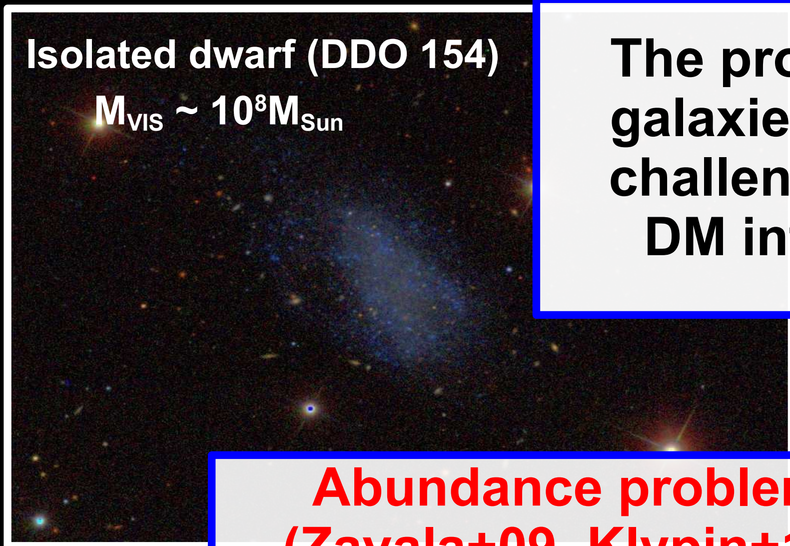


Amorisco, Agnello and Evans 2013

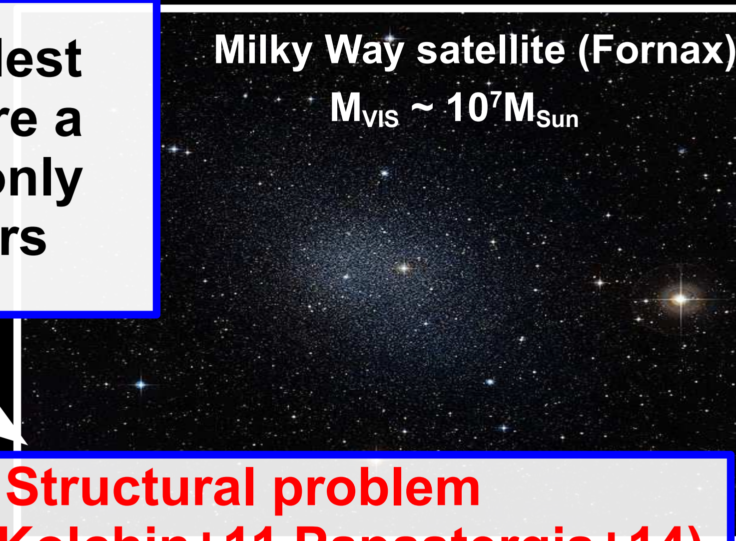
Other analysis suggest that **both cores and cusps can fit the data**
(e.g. Breddels & Helmi 13, Richardson & Fairbairn 14, Strigari, Frenk & White 14)

Controversial issue in CDM!!

Clues of new DM physics from dwarf galaxies?

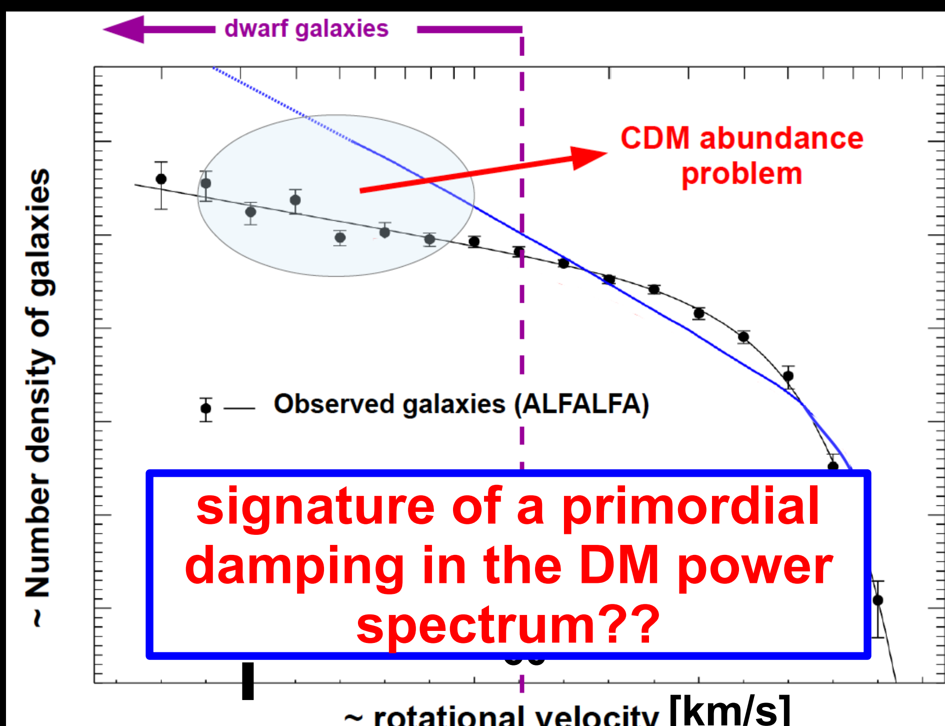


The properties of the smallest galaxies observed **today** are a challenge if gravity is the only DM interaction that matters

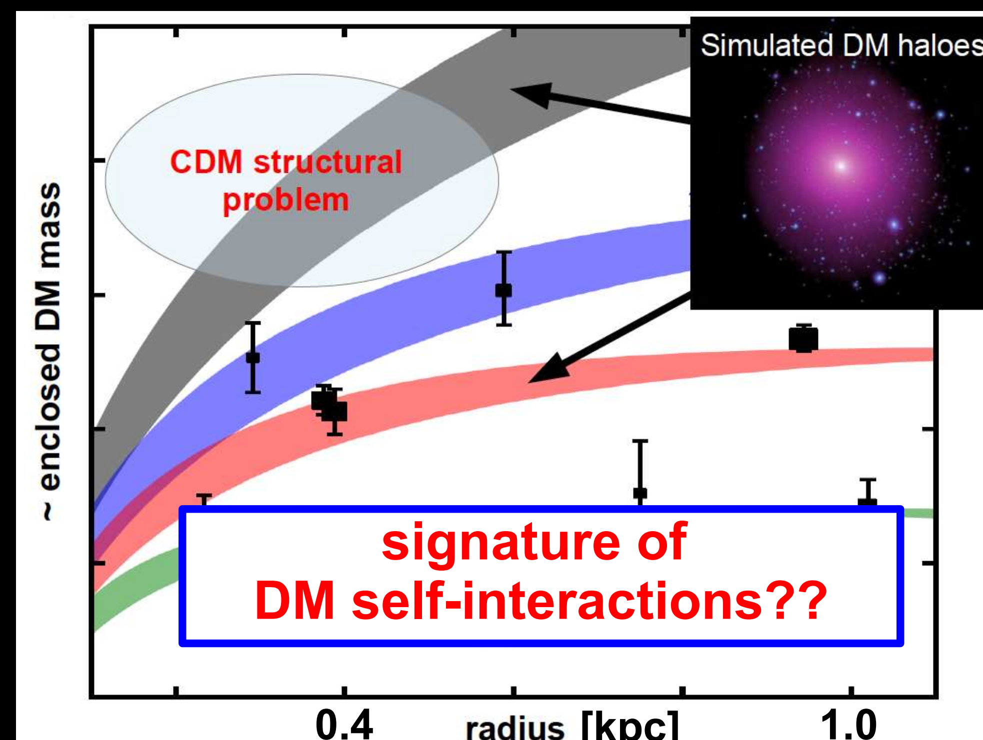


Abundance problem (Zavala+09, Klypin+15)

Structural problem (Boylan-Kolchin+11, Papastergis+14)



signature of a primordial damping in the DM power spectrum??

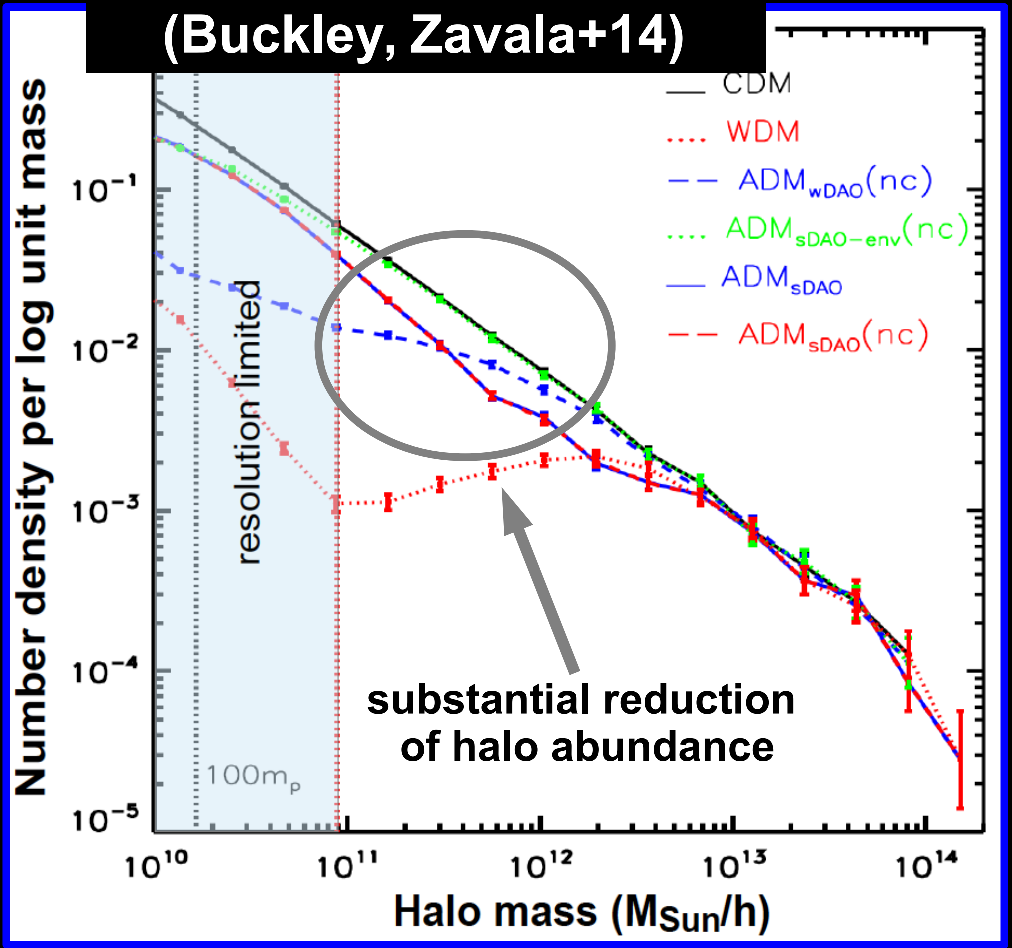


signature of DM self-interactions??

Structure formation in a universe with new dark matter interactions

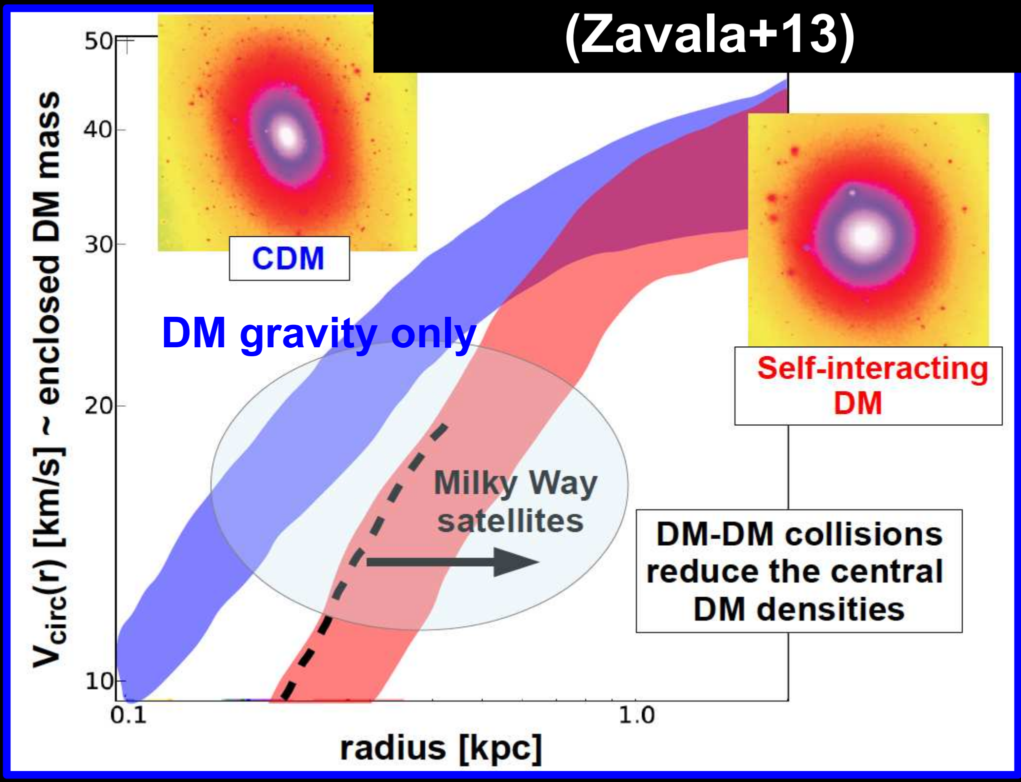
The abundance and structural problems of the smallest galaxies might be solved with new DM interactions

Abundance of DM haloes (Buckley, Zavala+14)



interactions between DM and dark radiation

DM content in DM haloes (Zavala+13)

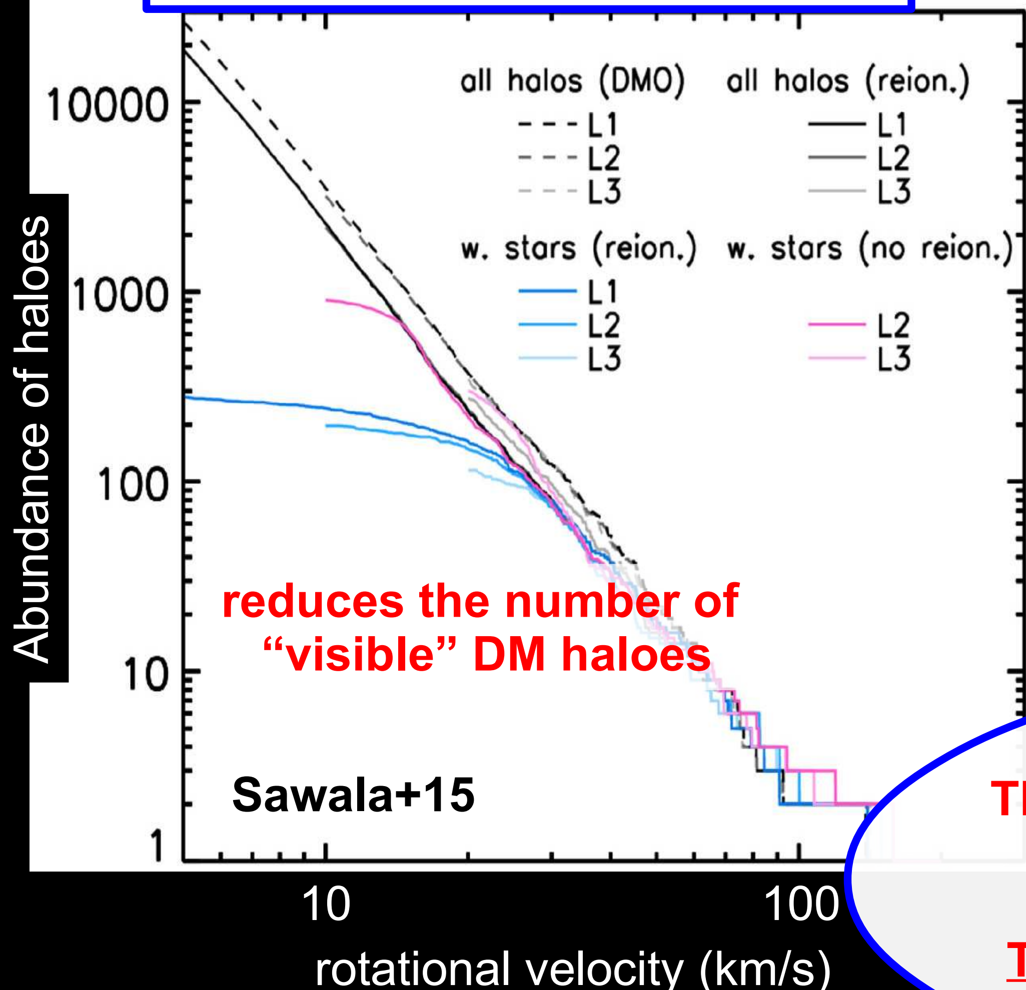


DM self-interactions

$\sigma/m \sim 1.5\ cm^2/gr$

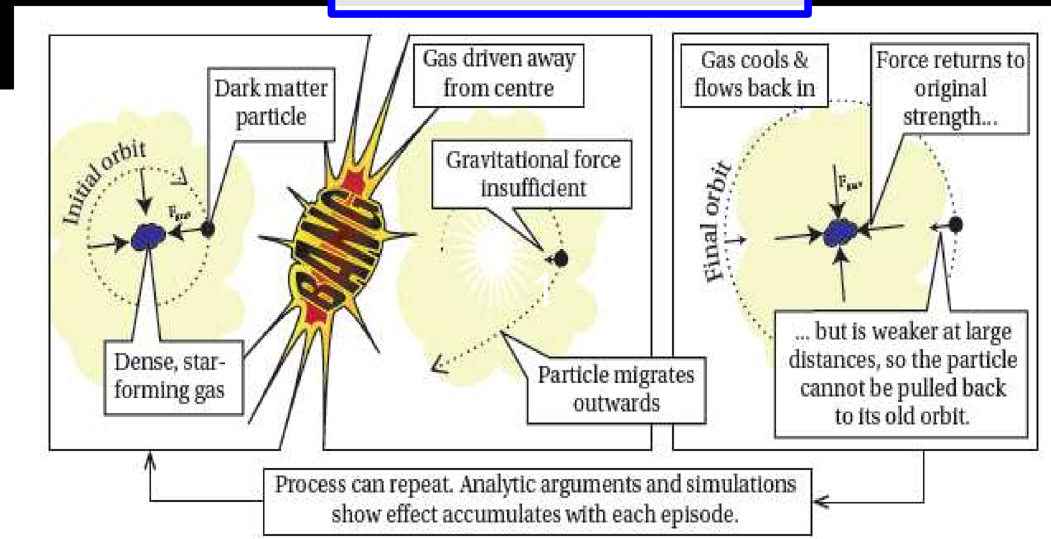
Or... the complexity of gas and stellar physics

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



reduces the number of "visible" DM haloes

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

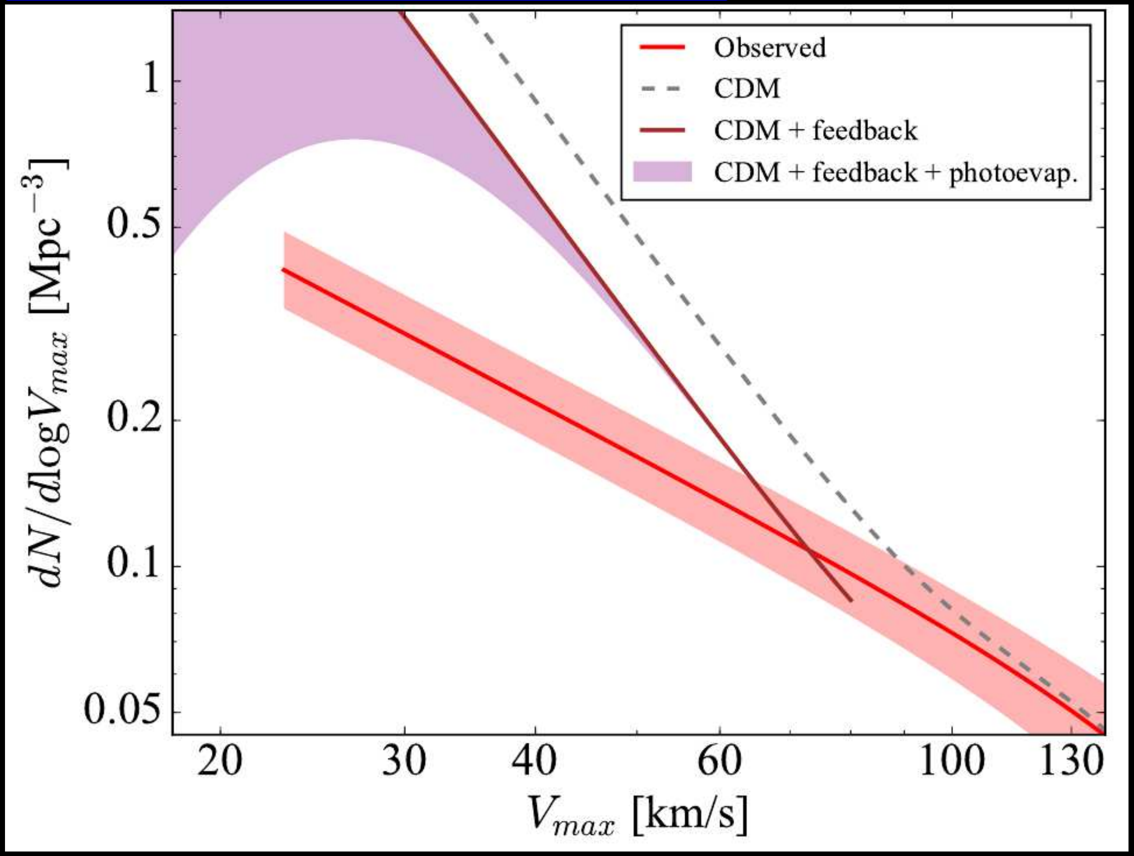
To some extent, they are degenerate with new DM physics

Or... the complexity of gas and stellar physics

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

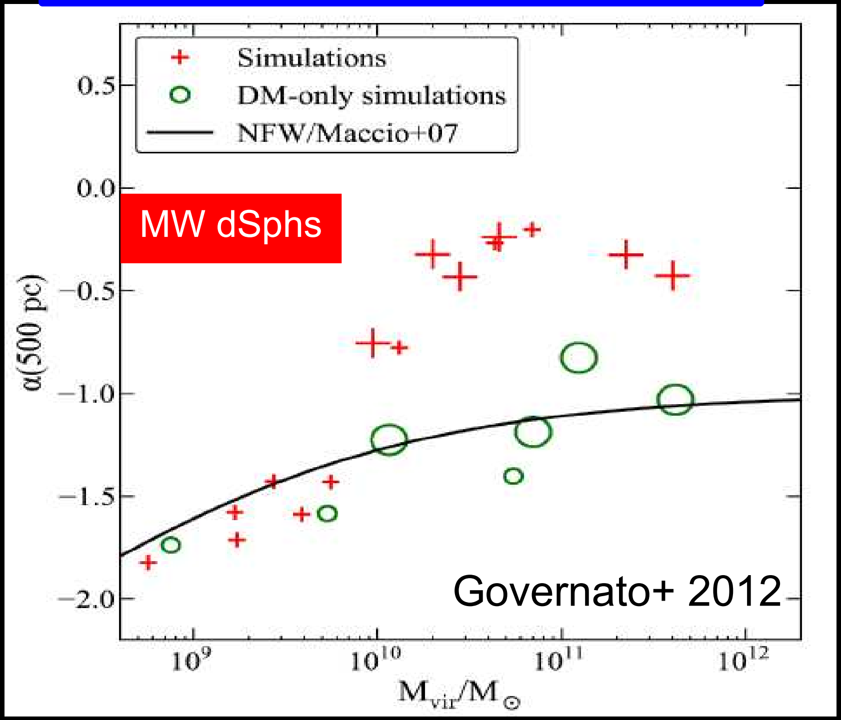
Gas and DM heating through supernovae

Abundance problem



Trujillo-Gomez+06

Core-cusp problem



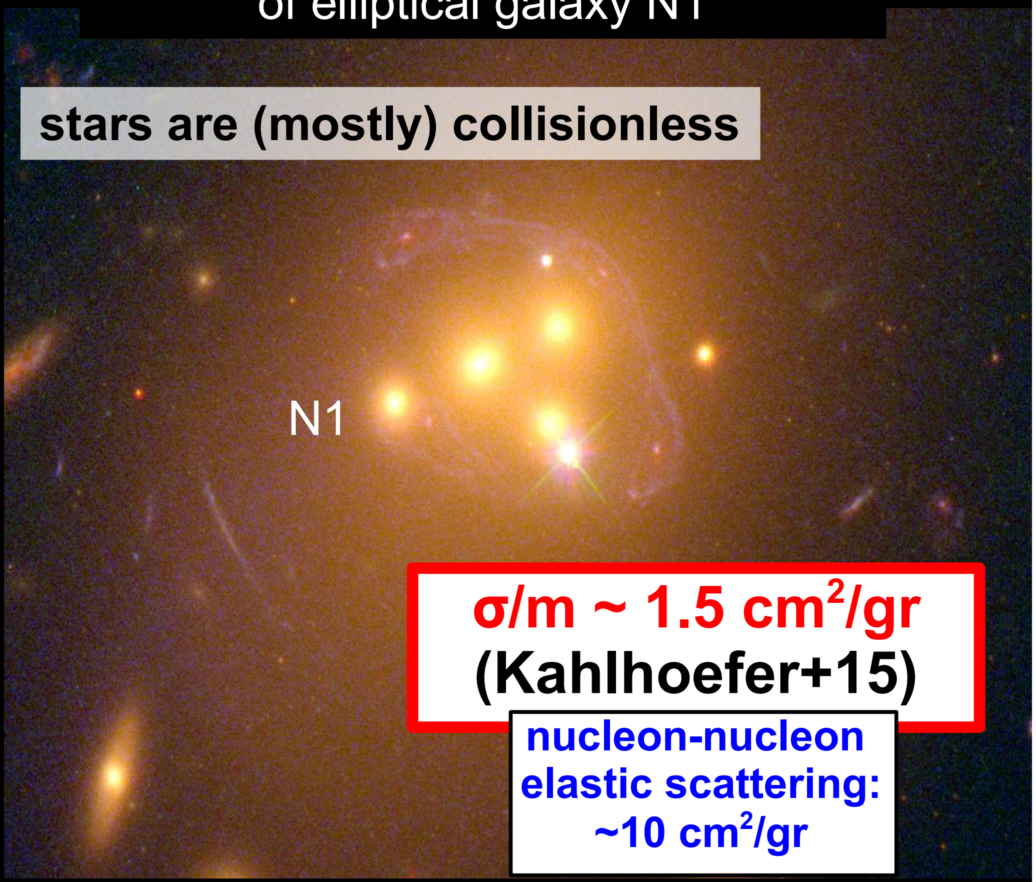
SN feedback in MW dSphs: likely insufficient for dSphs

e.g. Peñarrubia+ 2012, Garrison-Kimmel+13

Clues on new DM physics at other scales?

claimed detection of ~1.6 kpc offset between the stars and DM centroids of elliptical galaxy N1

Cluster Abell 3827 (Massey +15)



stars are (mostly) collisionless

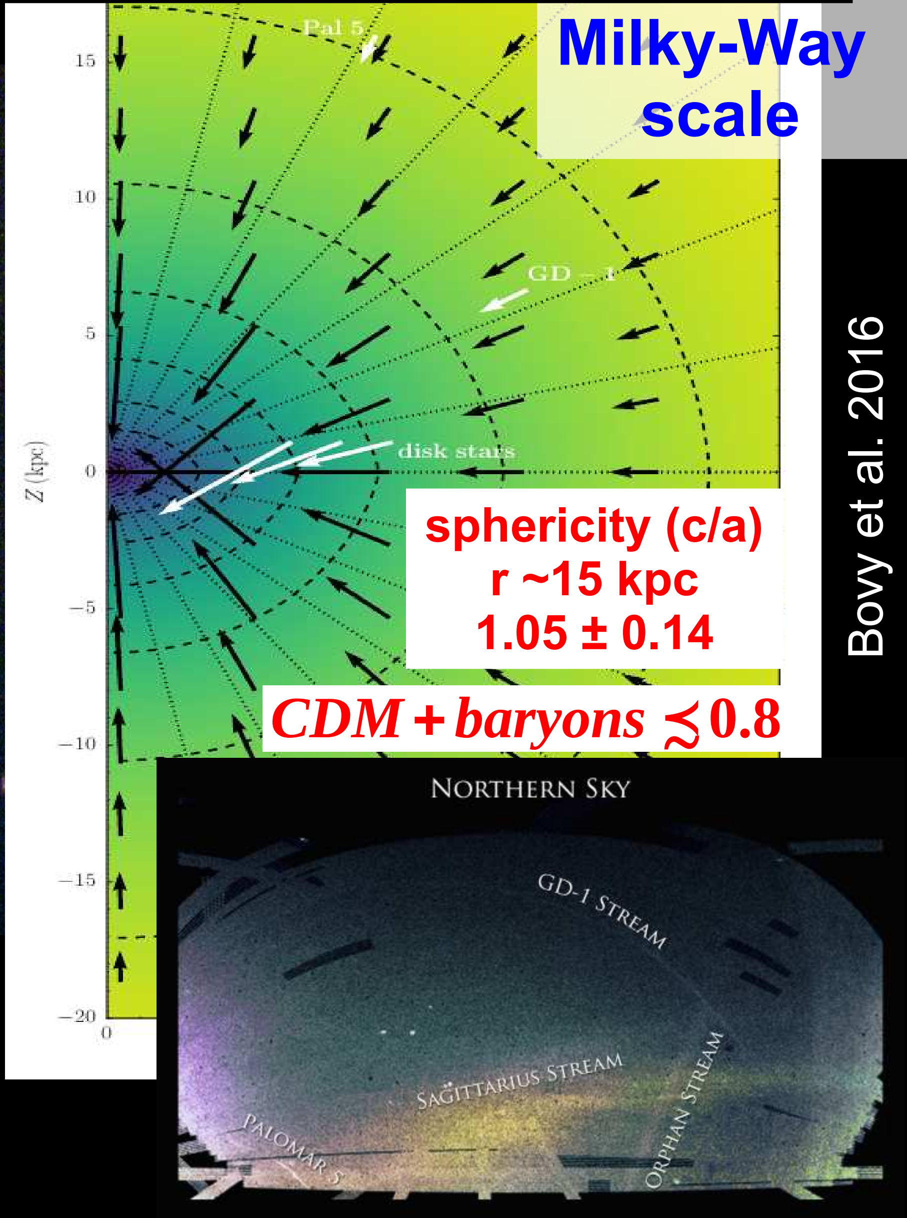
$\sigma/m \sim 1.5\ cm^2/gr$
(Kahlhoefer+15)

nucleon-nucleon elastic scattering: $\sim 10\ cm^2/gr$

Cluster scales

reconstruction of the gravitational field in the MW using phase-space data from stellar tidal streams

Milky-Way scale



sphericity (c/a)
r ~15 kpc
1.05 ± 0.14

$\mathit{CDM + baryons} \lesssim 0.8$

Bovy et al. 2016

Lecture 3

Towards an Effective THeory Of Structure formation (ETHOS)

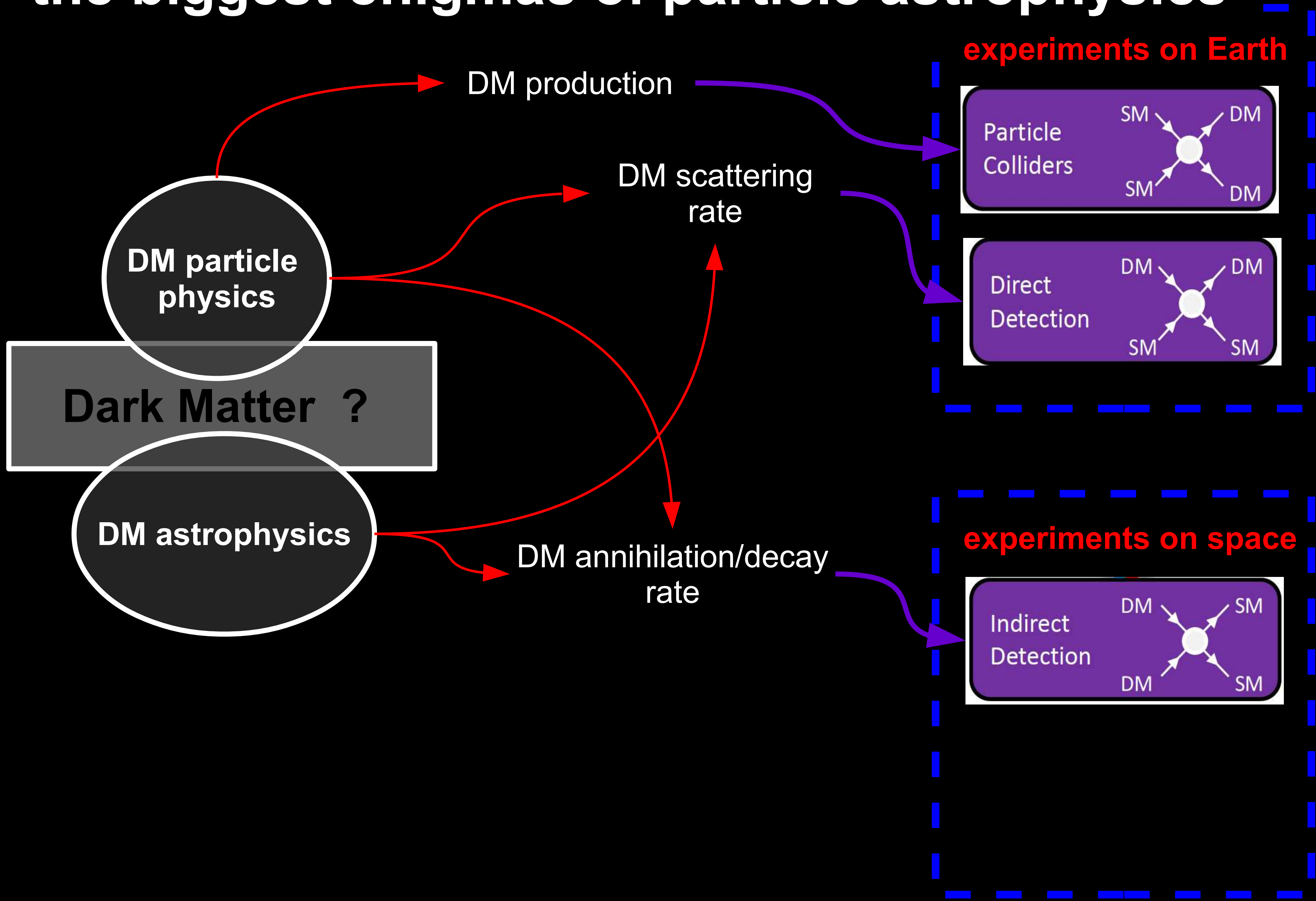
CDM + current galaxy modelling are successful in reproducing several properties of the galaxy population but:

uncertain gas and stellar physics

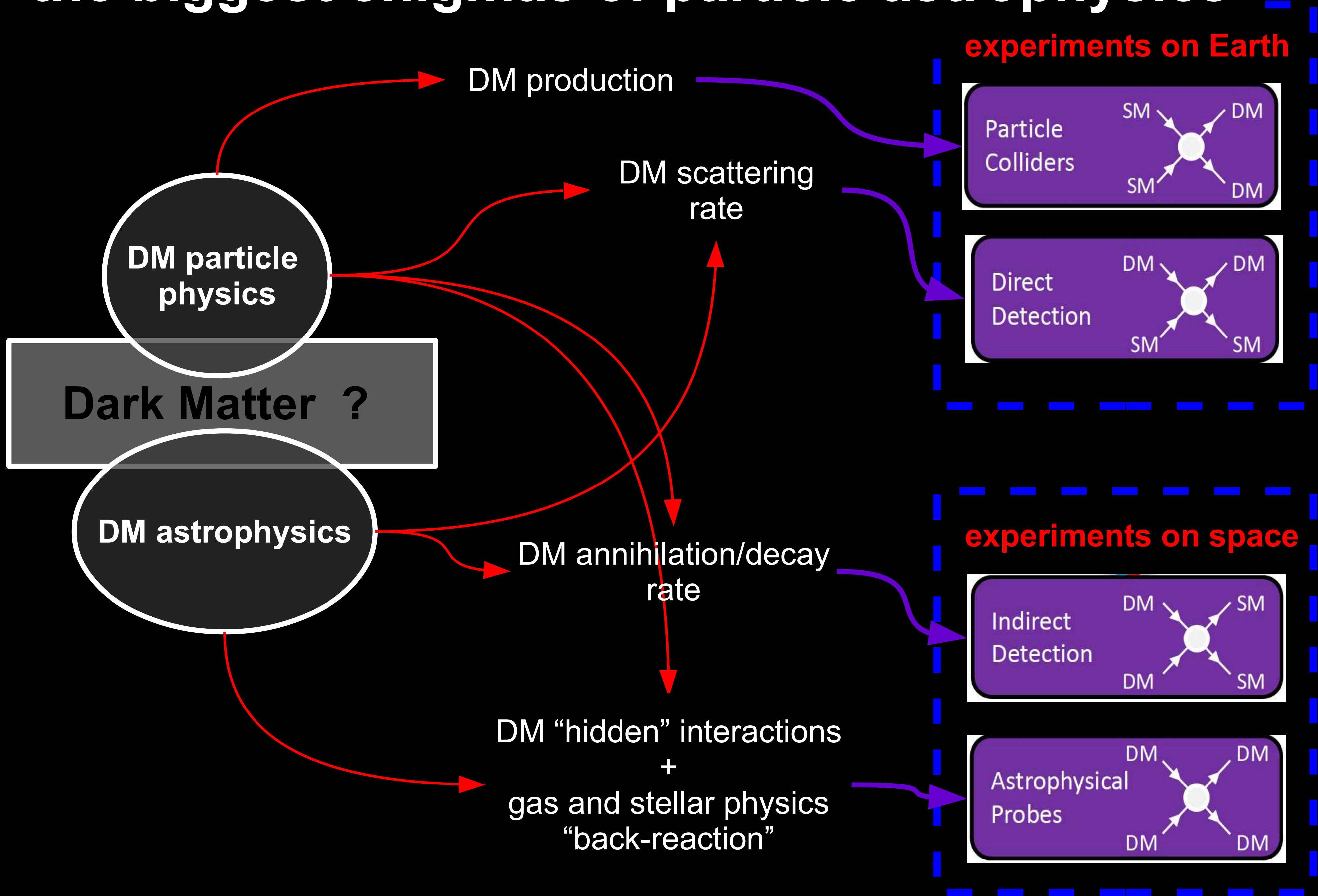
outstanding challenges at the scale of the smallest (dwarf) galaxies

the current situation offers an opportunity to approach the dark matter problem from a broader perspective...

The particle nature of dark matter is one of the biggest enigmas of particle astrophysics



The particle nature of dark matter is one of the biggest enigmas of particle astrophysics



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

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

below this value, the behaviour is the same as CDM

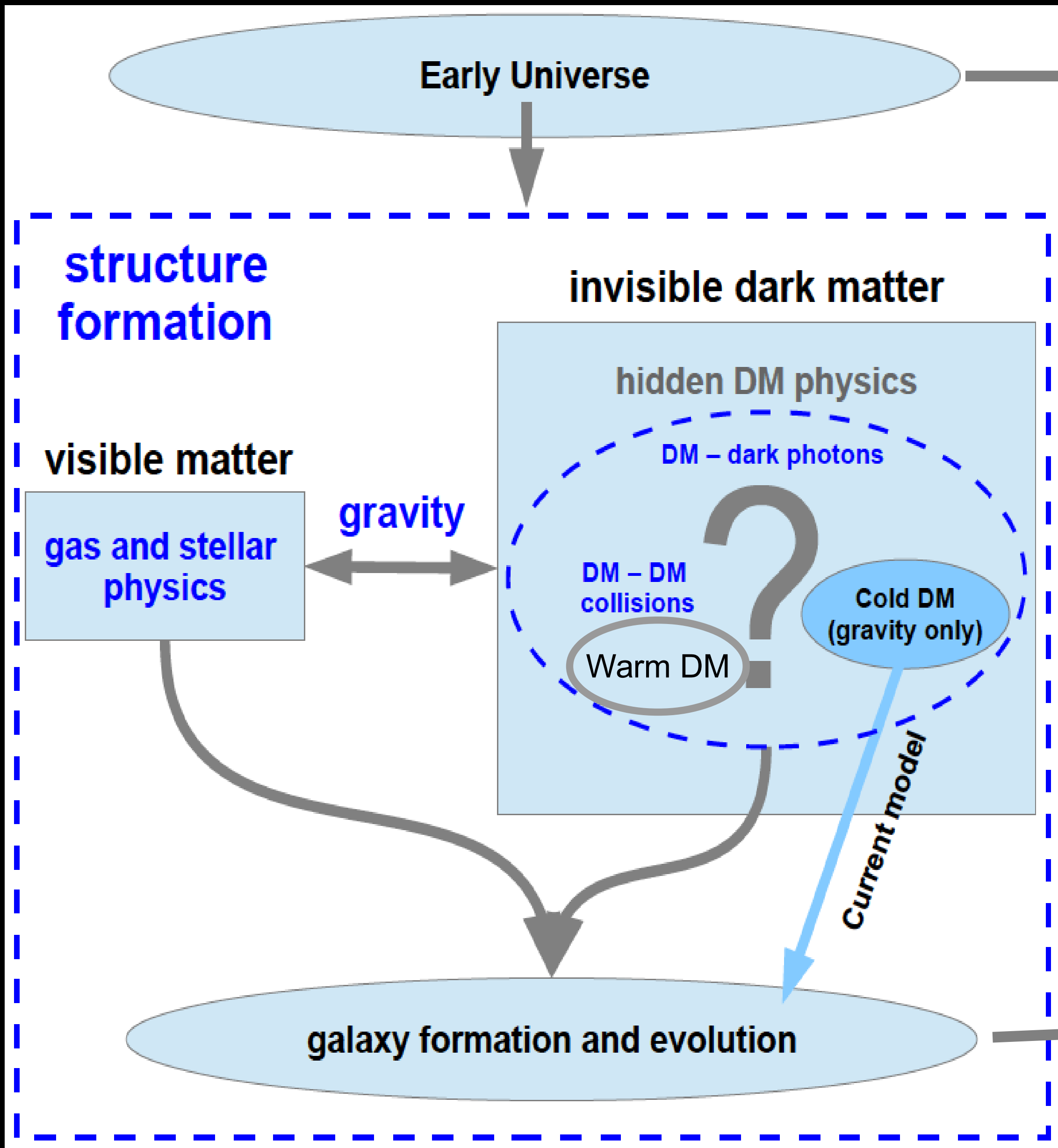
above this value constraints are strong (at cluster scales)

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

below this value galaxy formation Is highly supressed

above this value DM clustering must be as in CDM

Towards an Effective THeory Of Structure formation (ETHOS)



DM production mechanism (verify consistency with global DM abundance)

Generalize the theory of structure formation (CDM) to include **a broader range of allowed DM phenomenology** coupled with our knowledge of galaxy formation/evolution

Signatures of non-gravitational DM interactions (dynamical, visible byproducts)

Developing ETHOS

DM interactions with relativistic particles in the early Universe

+

DM-DM self-scattering in the late Universe

In collaboration with:

Torsten Bringmann (UiO, Oslo)
Franncis-Yan Cyr-Racine (Harvard, Cambridge)
Christoph Pfrommer (HITS, Heidelberg)
Kris Sigurdson (UBC, Vancouver)
Mark Vogelsberger (MIT, Cambridge)

ETHOS I:
Cyr-Racine, Sigurdson, Zavala +16
(arXiv:1512.05349)

ETHOS II:
Vogelsberger, Zavala +16
(arXiv:1512.05344)

ETHOS: classify DM models according to their effective parameters for structure formation

particle physics parameters
(masses, couplings, ...)

$$\left\{ m_\chi, \{g_i\}, \{h_i\}, \xi \right\}$$

select a particle physics model
e.g. DM interacting with masless neutrino-like fermion via massive mediator
(e.g. van der Aarssen, Bringmann+12)

DR to CMB temperature at z=0

growth of structures
(linear regime) with additional physics:
DM-DR-induced DAOs and Silk damping

ETHOS: classify DM models according to their effective parameters for structure formation

particle physics parameters
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growth of structures
(linear regime) with additional physics:
DM-DR-induced DAOs and Silk damping

eqs. for DM perturbations

$$\dot{\delta}_\chi + \theta_\chi - 3\dot{\phi} = 0,$$

$$\dot{\theta}_\chi - c_\chi^2 k^2 \delta_\chi + \mathcal{H}\theta_\chi - k^2\psi = \dot{\kappa}_\chi[\theta_\chi - \theta_{\rm DR}]$$

related to DR opacity to DM scattering
(parameterize the collisional term of the Boltxmann eq.)

$$C_{\chi\tilde{\gamma}\leftrightarrow\chi\tilde{\gamma}}[f_\chi, f_{\rm DR}]$$

ETHOS: classify DM models according to their effective parameters for structure formation

particle physics parameters
(masses, couplings, ...)

$$\left\{ m_\chi, \{g_i\}, \{h_i\}, \xi \right\}$$

select a particle physics model
e.g. DM interacting with masless neutrino-like fermion via massive mediator
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growth of structures
(linear regime) with additional physics:
DM-DR-induced DAOs and Silk damping

eqs. for DM perturbations

$$\dot{\delta}_\chi + \theta_\chi - 3\dot{\phi} = 0,$$

$$\dot{\theta}_\chi - c_\chi^2 k^2 \delta_\chi + \mathcal{H}\theta_\chi - k^2\psi = \dot{\kappa}_\chi[\theta_\chi - \theta_{\rm DR}]$$

related to DR opacity to DM scattering
(relative to early-time evolution)

effective parameters

$$\Xi_{\rm ETHOS} = \left\{ \omega_{\rm DR}, \{a_n, \alpha_l\}, \left\{ \frac{\langle \sigma_T \rangle_{v_{M_i}}}{m_\chi} \right\} \right\}$$

$$\omega_{\rm DR} \equiv \Omega_{\rm DR} h^2$$

DM self-scattering
(relevant for late-time evolution)

ETHOS: classify DM models according to their effective parameters for structure formation

particle physics parameters
(masses, couplings, ...)

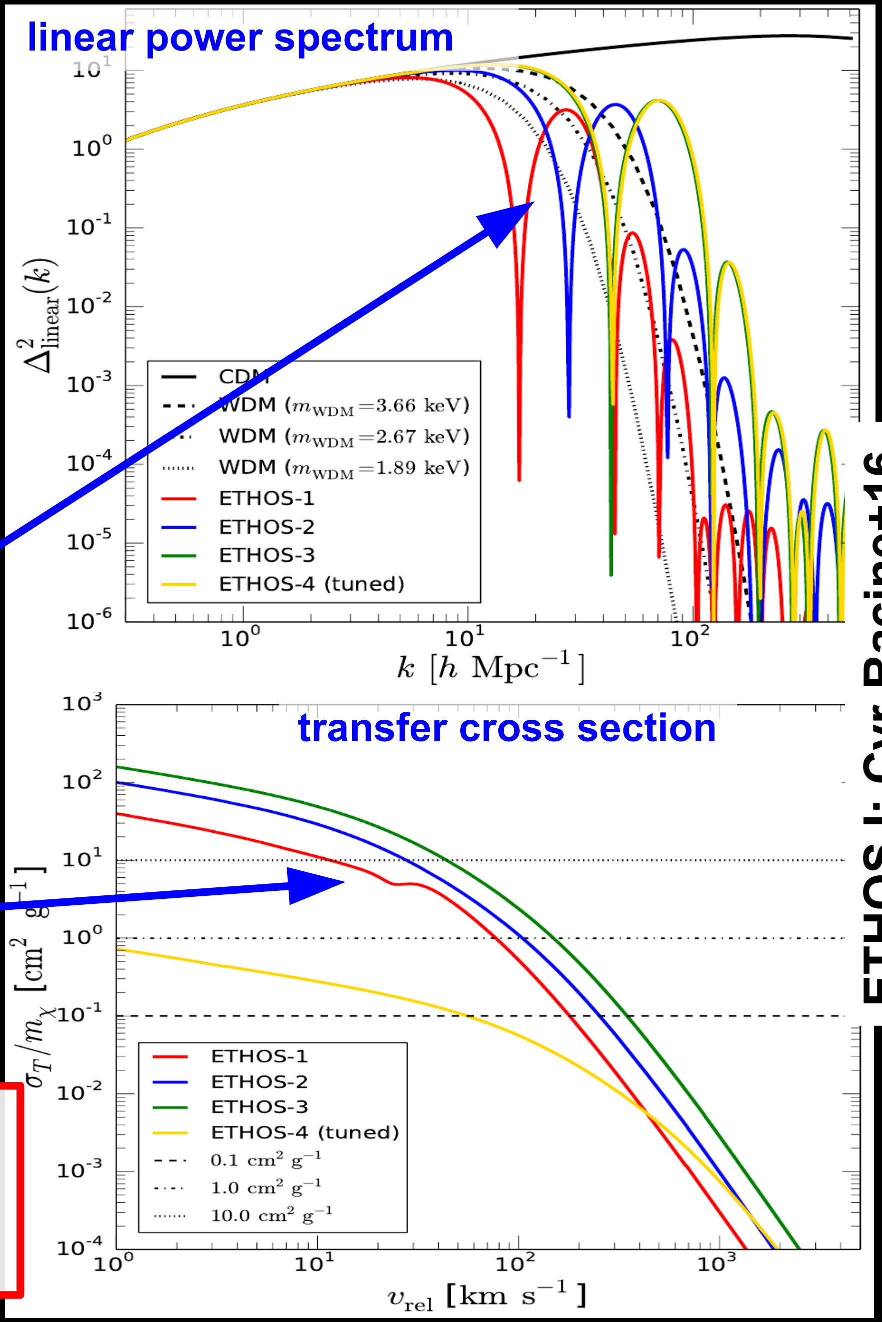
$$\left\{ m_\chi, \{g_i\}, \{h_i\}, \xi \right\}$$

growth of structures
(linear regime) with additional physics:
DM-DR-induced DAOs and Silk damping

effective parameters

$$\Xi_{\rm ETHOS} = \left\{ \omega_{\rm DR}, \{a_n, \alpha_l\}, \left\{ \frac{\langle \sigma_T \rangle_{v_{M_i}}}{m_\chi} \right\} \right\}$$

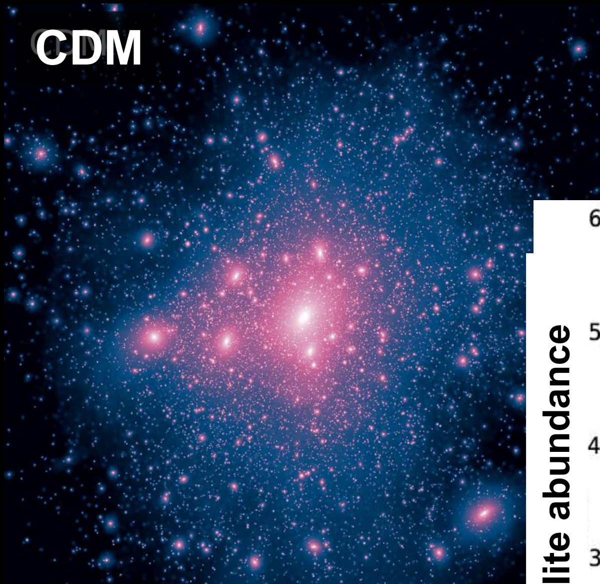
All DM particle physics models that map into the same ETHOS parameters can be studied (constrained) at the same time



ETHOS I: Cyr-Racine+16

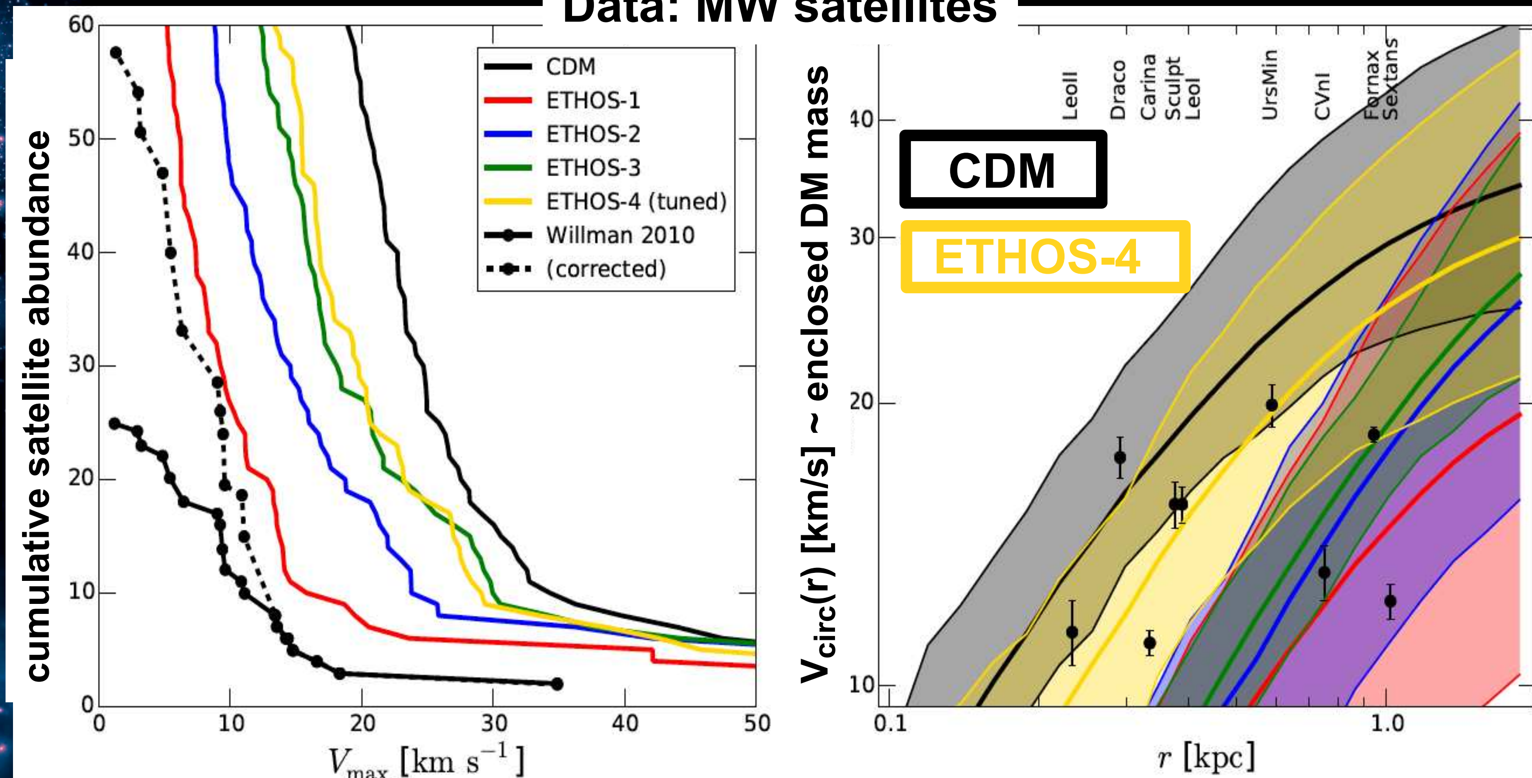
ETHOS application: non-linear regime with N-body simulations and the CDM challenges

Both CDM abundance and structural "problems" can be alleviated *simultaneously*



MW-size halo
DM-only simulation

Data: MW satellites



DM-dark radiation interactions suppress/delay the formation of small haloes (galaxies)

DM self-interactions reduce the central DM densities of haloes

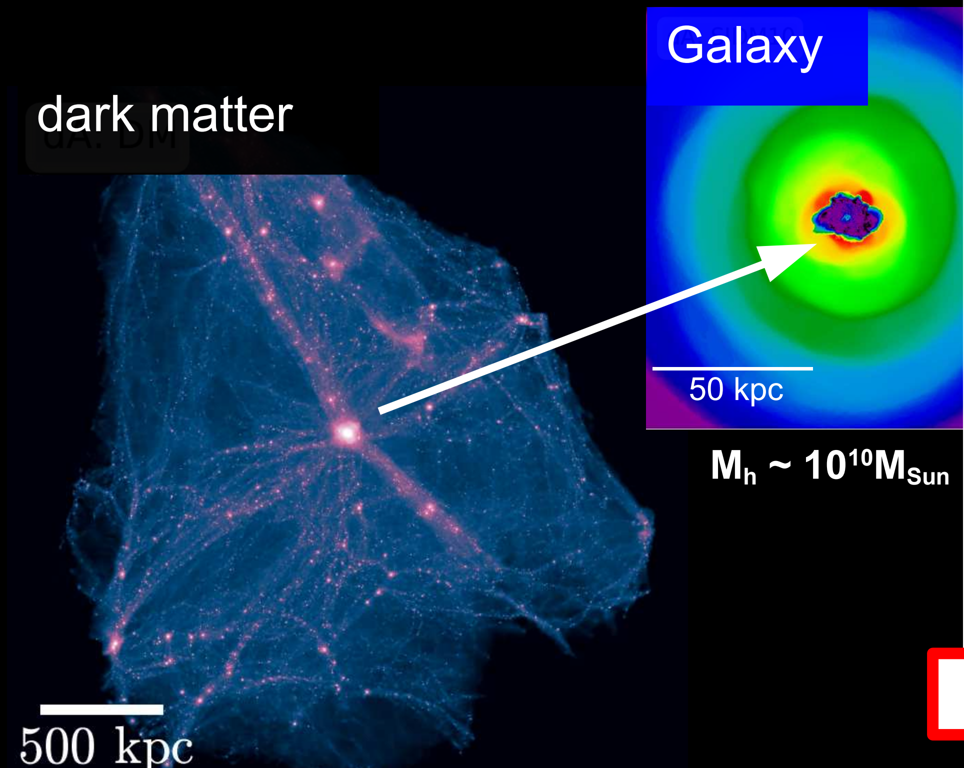
ETHOS II: Vogelsberger+16

Developing ETHOS
(self-scattering DM + baryonic physics)

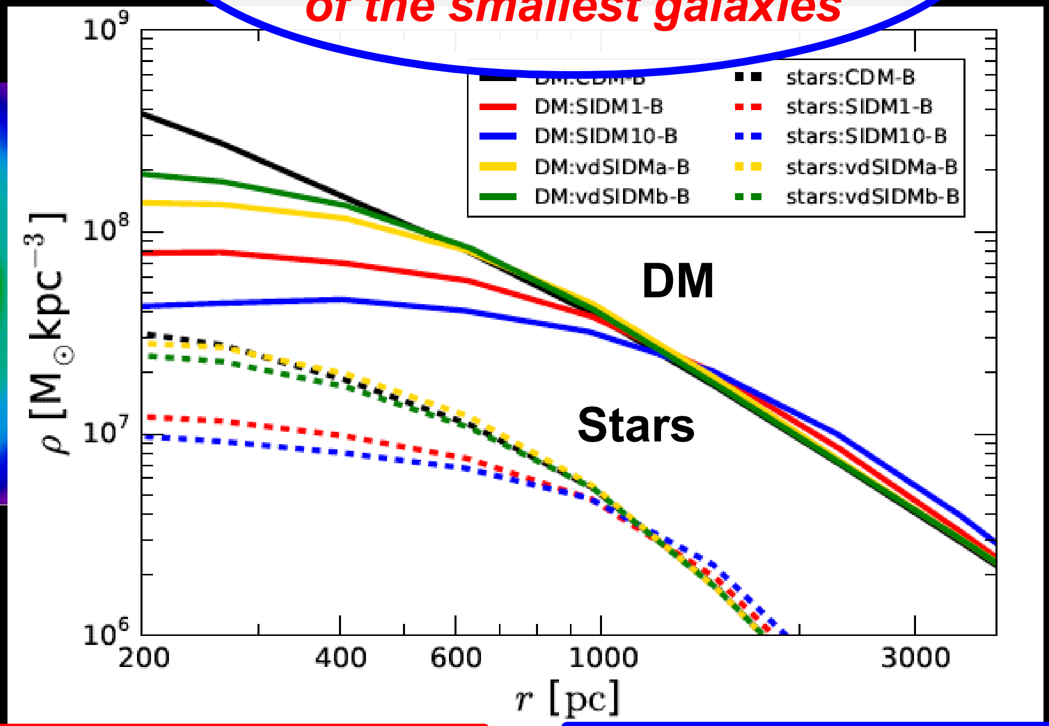
"baryonic physics": hydrodynamics, radiative cooling of gas, stellar population modelling, SNe feedback

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



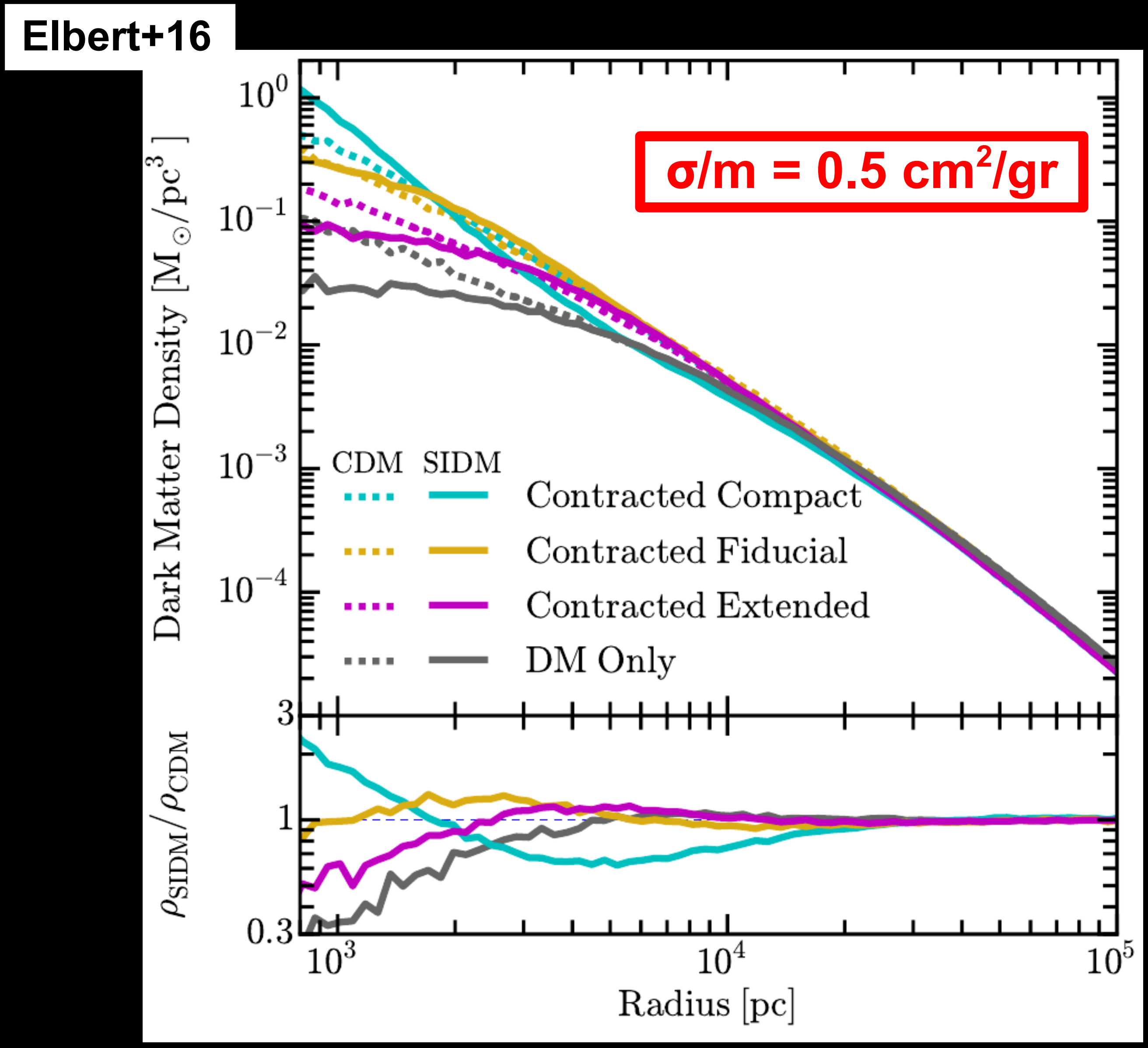
$M_h \sim 10^{10} M_{Sun}$



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

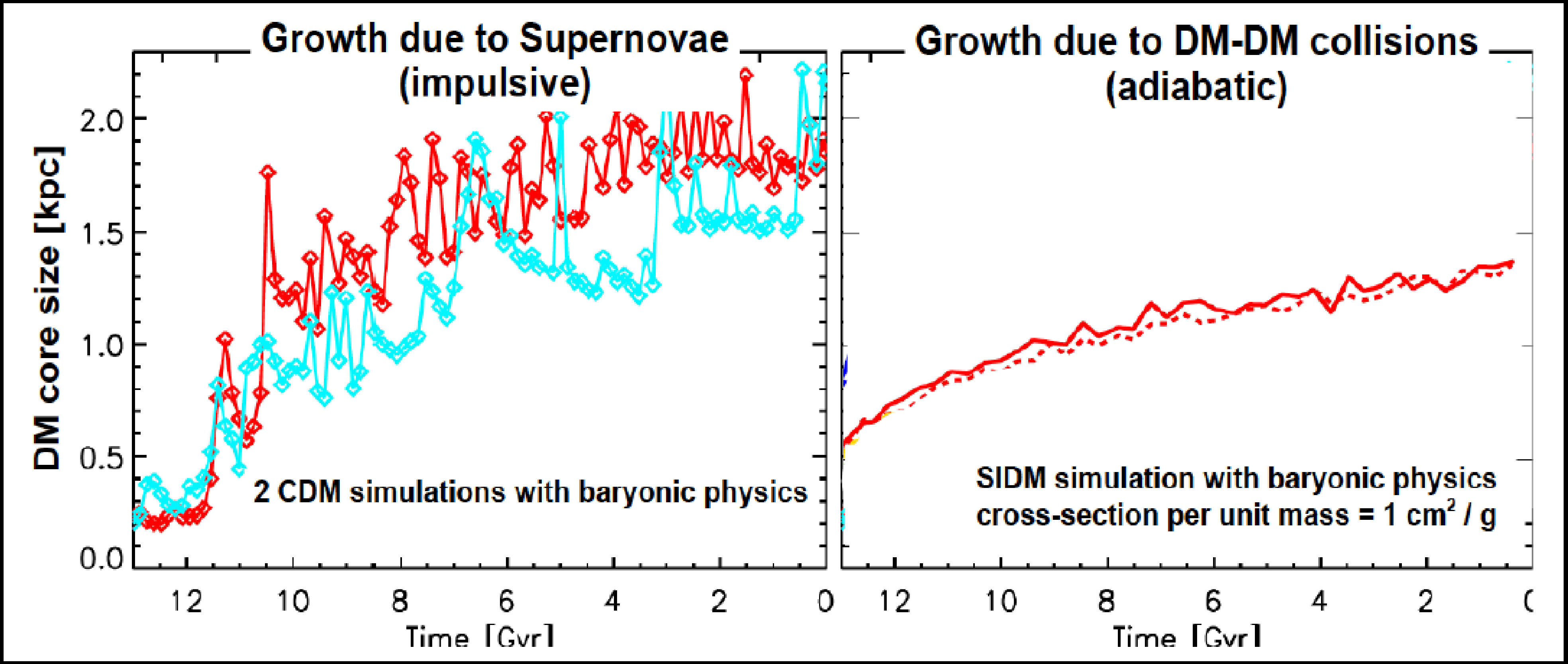
$\sigma/m = 10\ cm^2/gr$

The challenging interplay between DM/baryonic physics



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

The challenging interplay between DM/baryonic physics



How to distinguish a DM core formed by Supernovae from one formed by DM collisions?

Concluding remarks

An Effective (more generic) THeory Of Structure formation (ETHOS) **must consider a broader range of allowed DM phenomenology** coupled with our developing knowledge of galaxy formation/evolution

First highlights of the effective theory (ETHOS):

- Mapping between the particle physics parameters of a generic DM-DR interaction into effective parameters for structure formation (P(k) and σ_T/m)

- All DM particle physics models that map into the same ETHOS parameters can be studied (constrained) at the same time

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

$$0.1\, cm^2/gr \lesssim \sigma/m \lesssim 2\, cm^2/gr \qquad 10^{9.5} M_{Sun} \lesssim M_{cut} \lesssim 10^{10.5} M_{Sun}$$

- **dwarf galaxies might hide a clue of a fundamental guiding principle for a complete DM theory**

Possible degeneracies in observational comparisons, albeit undesirable, reflect our current incomplete knowledge of the DM nature and galaxy formation/evolution