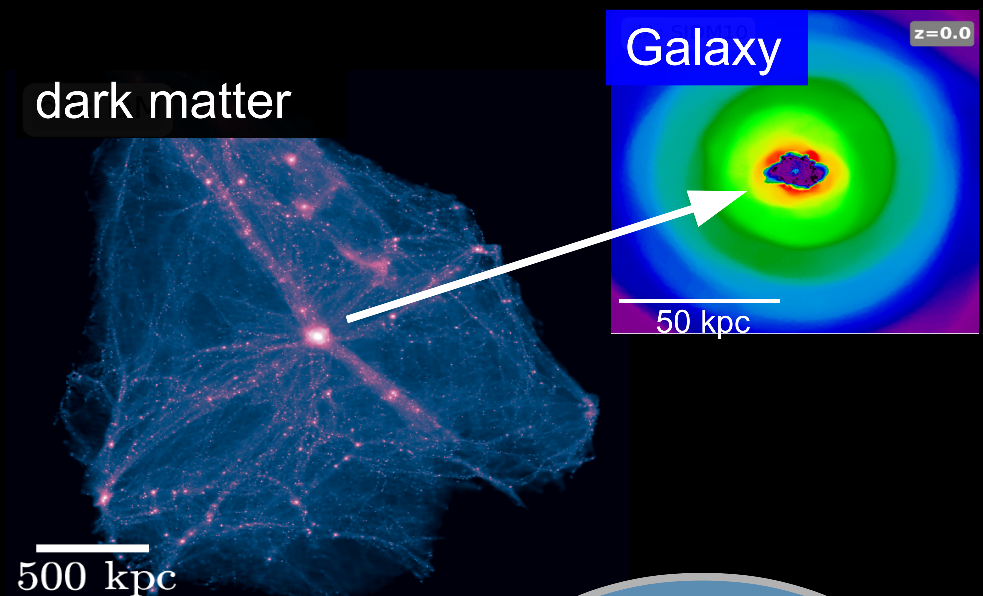
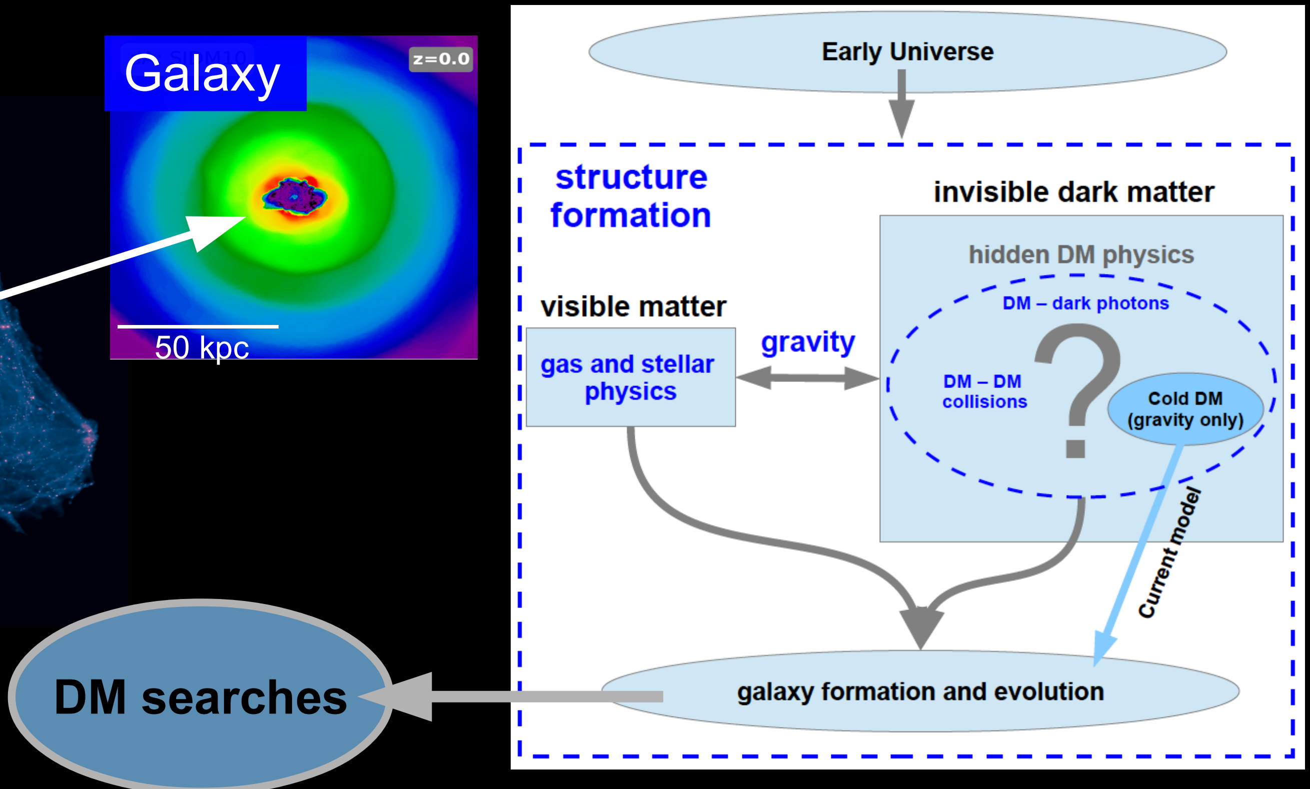
Towards an Effective THeory of Structure formation (ETHOS)

Jesús Zavala Franco
(Marie Curie Fellow)





Institute for Astronomy, Royal Observatory, Edinburgh, October 2015

OUTLINE

- The standard dark matter hypothesis (CDM)

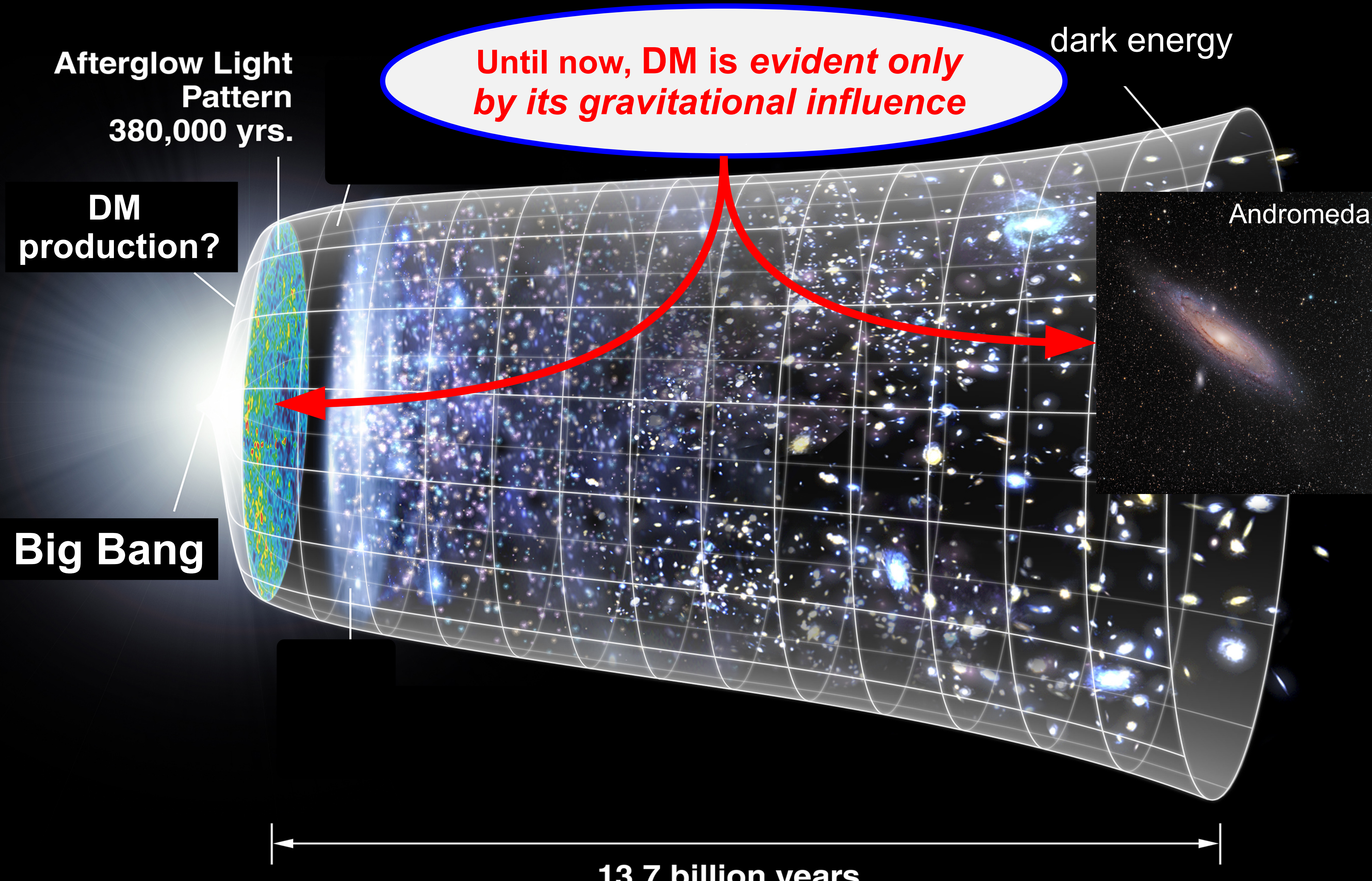
- What do we really know about non-gravitational dark matter interactions ?

- Beyond CDM: exploring new dark matter physics with astrophysics (ETHOS)

- Concluding remarks

The particle DM hypothesis:

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



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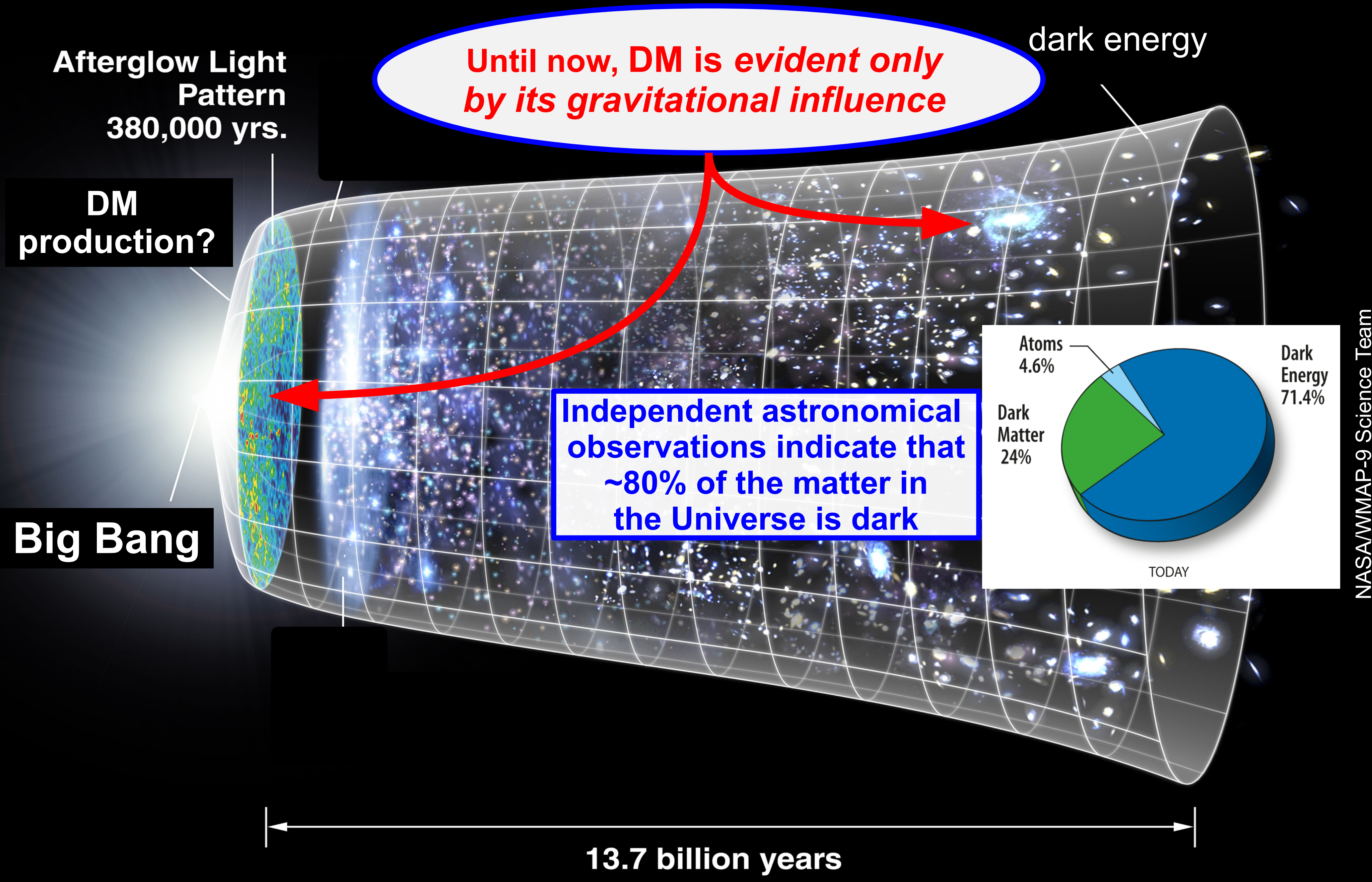
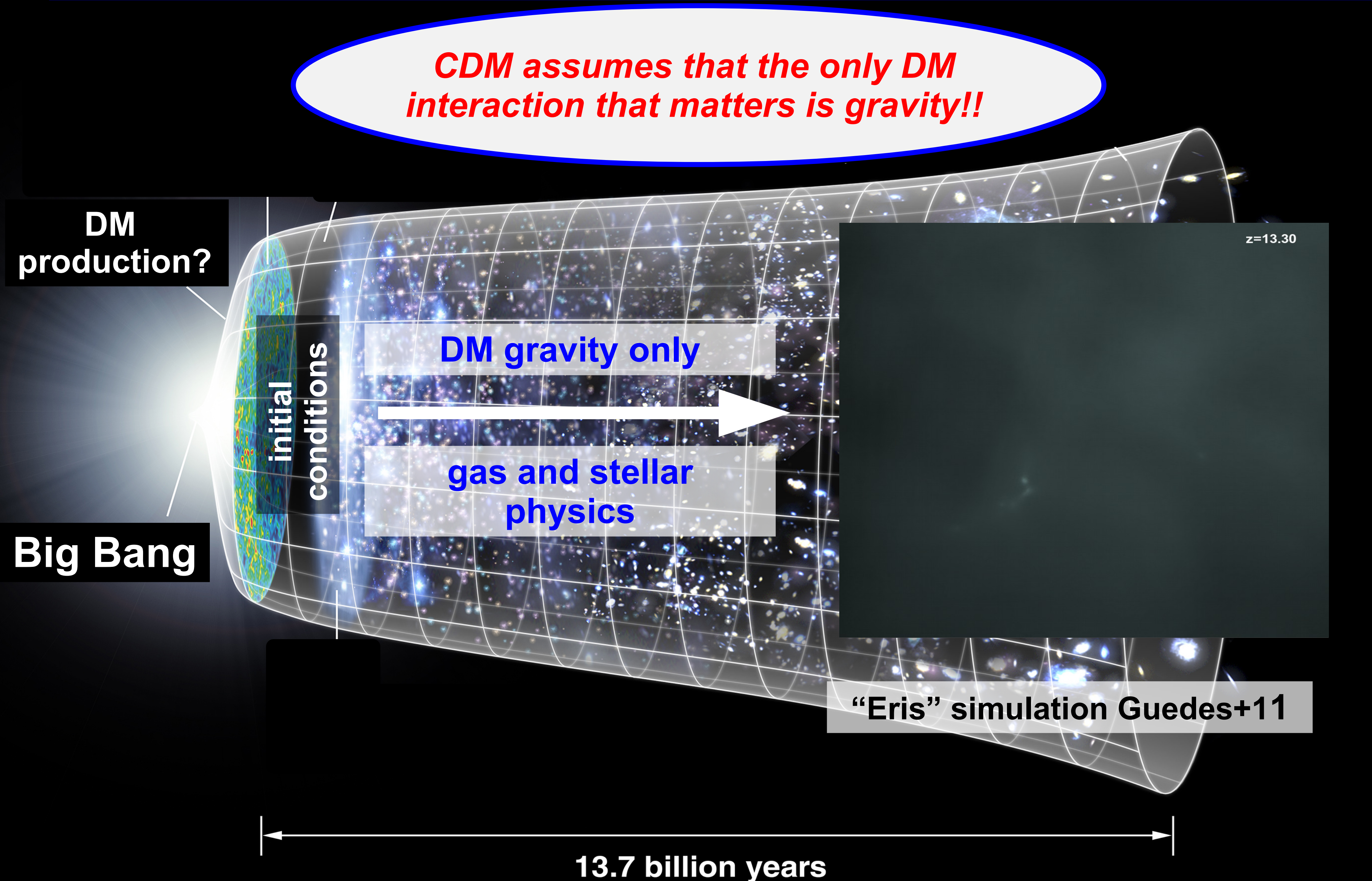


The **Cold Dark Matter (CDM) hypothesis** is the cornerstone of the current theory of the formation and evolution of galaxies



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?

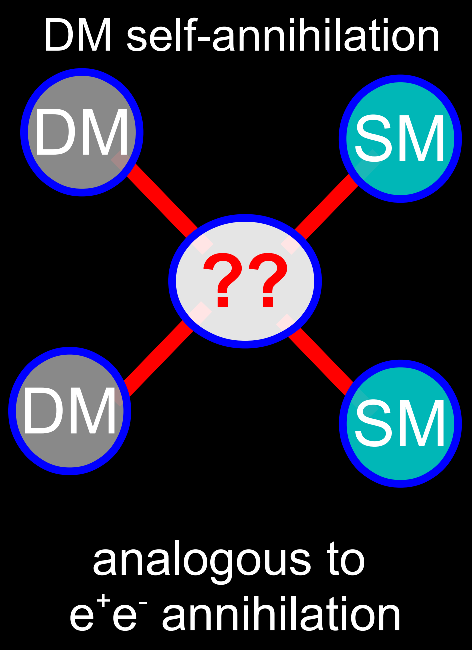
What is the mass(es) of the DM particle(s) and through which forces does it interact?

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

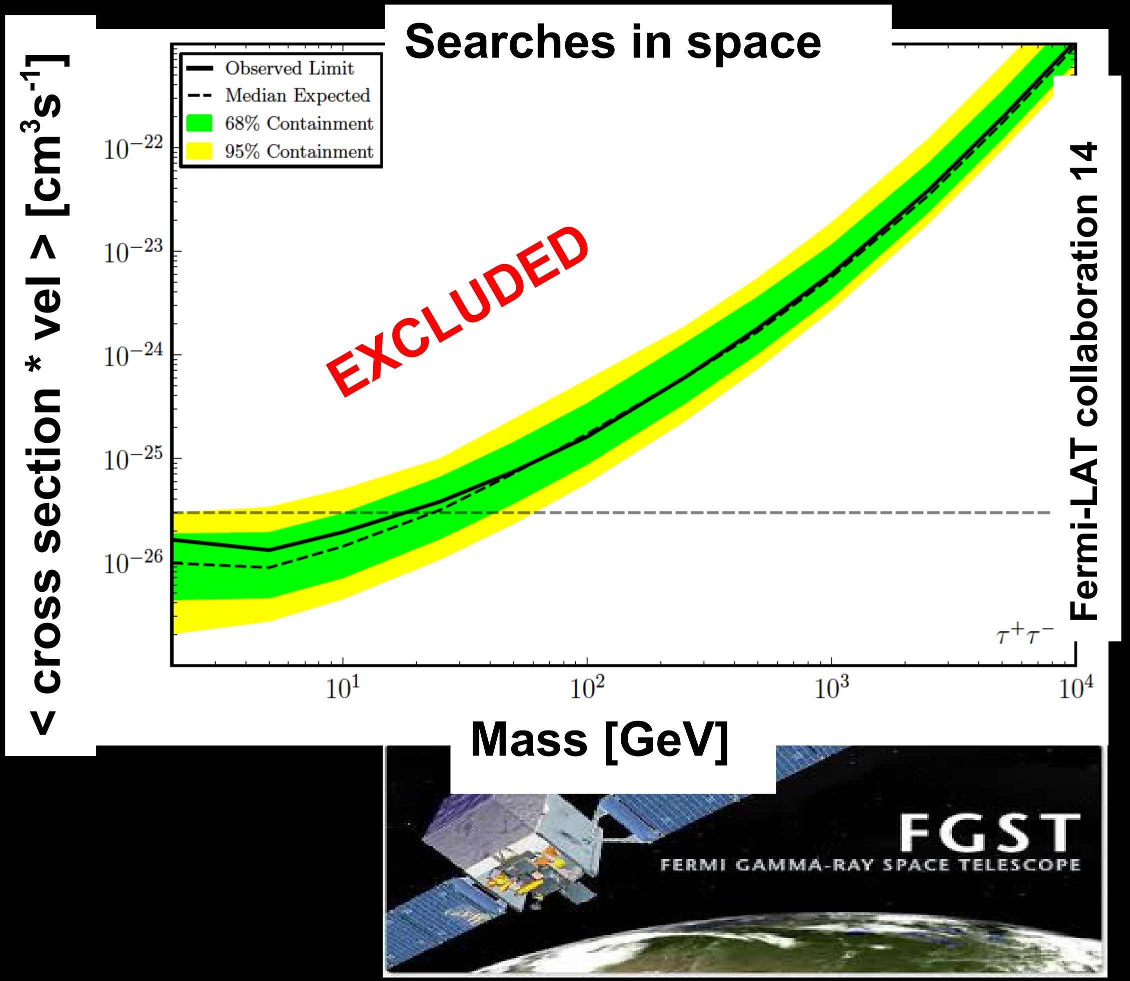
Although there is no indisputable evidence that the CDM hypothesis is wrong, there are reasonable physical motivations to consider alternatives

What do we really know about non-gravitational dark matter interactions ?

What is the nature of dark matter?



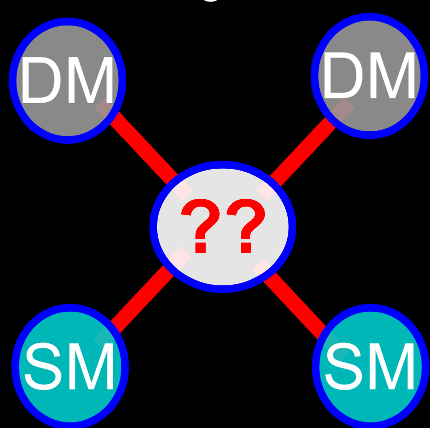
Does DM interacts with visible particles?

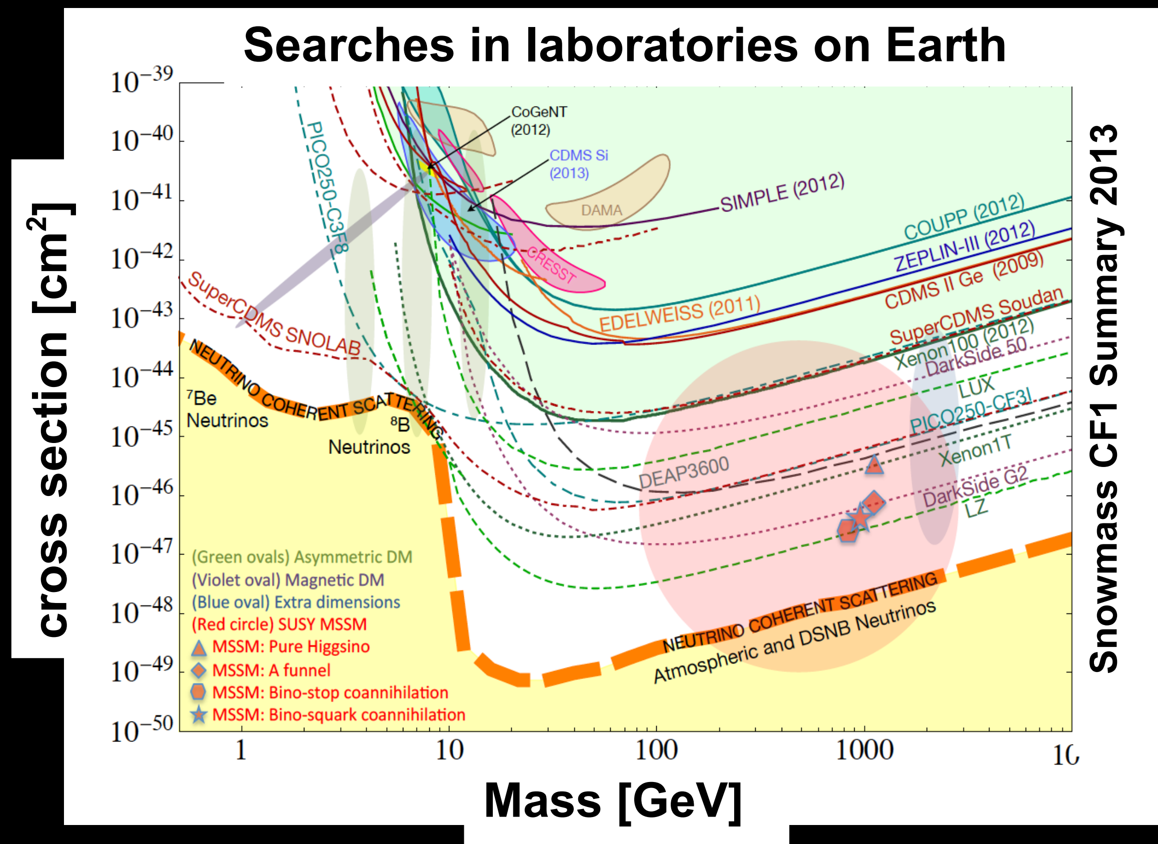


What is the nature of dark matter?

Does DM interacts with visible particles?

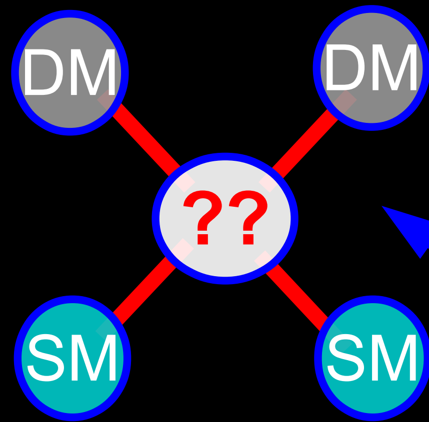
Scattering with nuclei





What is the nature of dark matter?

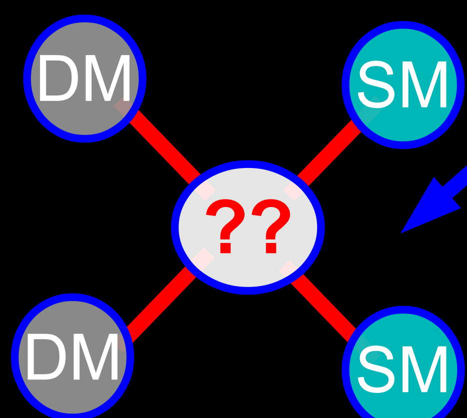
Scattering with nuclei



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

Does DM interacts with visible particles?

DM self-annihilation



Cross section σ/m_χ [cm^2/gr]	Characteristic velocity $\tilde{v}$ [km/s]
SI $\chi-$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)

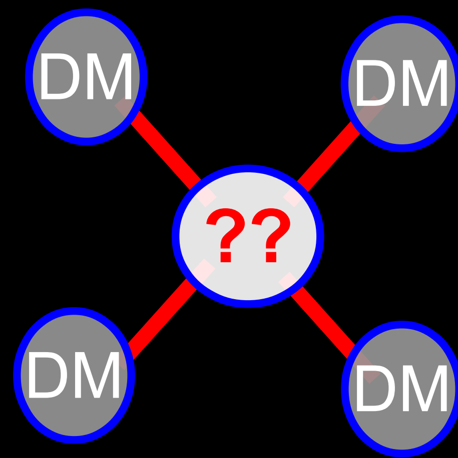
1 cm^2/g ~ 2 barns/GeV

dark matter is quite “dark” (invisible)

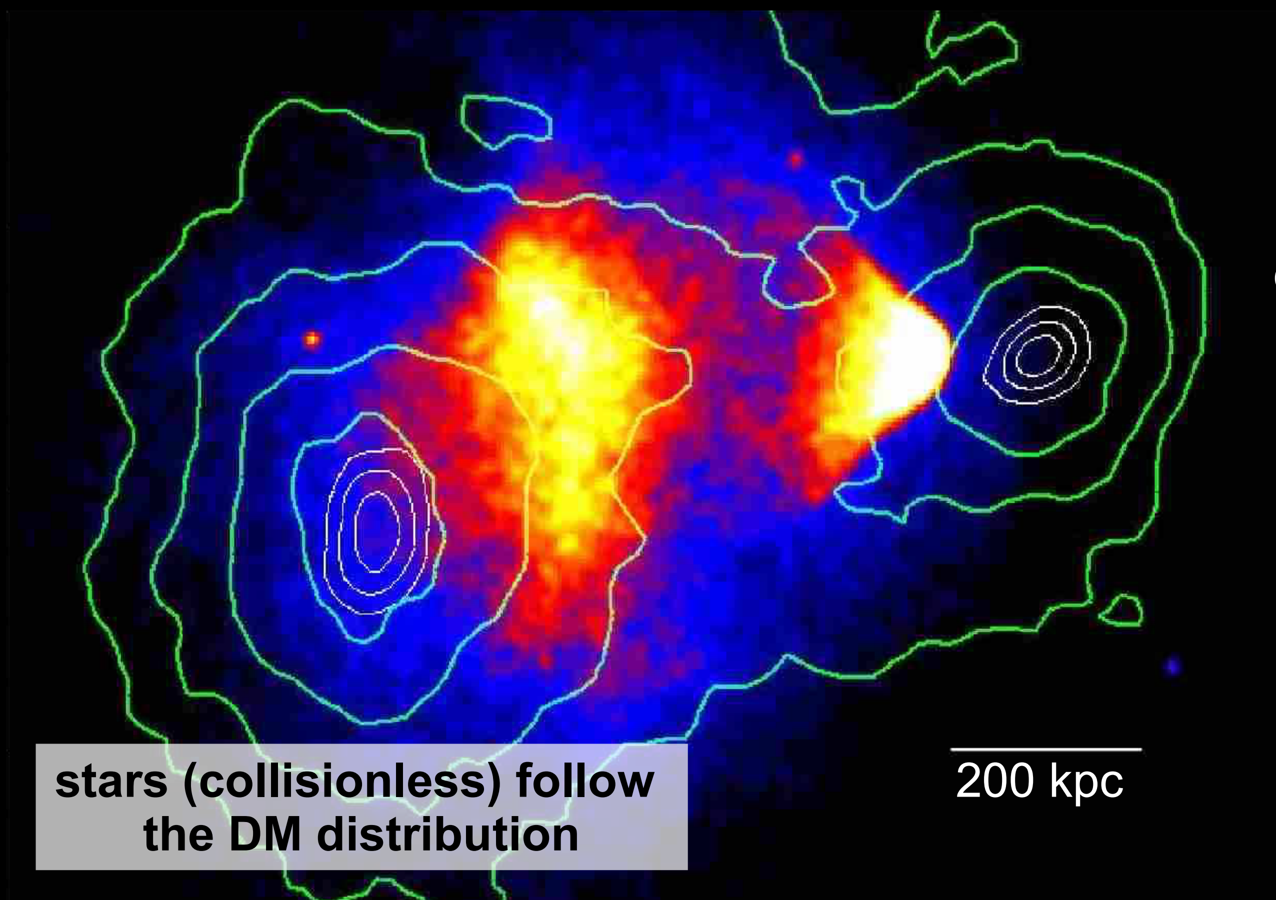
nucleon-nucleon elastic scattering: ~10 cm^2/gr

What is the nature of dark matter?

Can DM particles collide with themselves?



Bullet Cluster (Clowe +06)



constraint on DM self-collisions

s/m < 1.25 cm^2/gr

(Randal+08)

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

What is the nature of dark matter?

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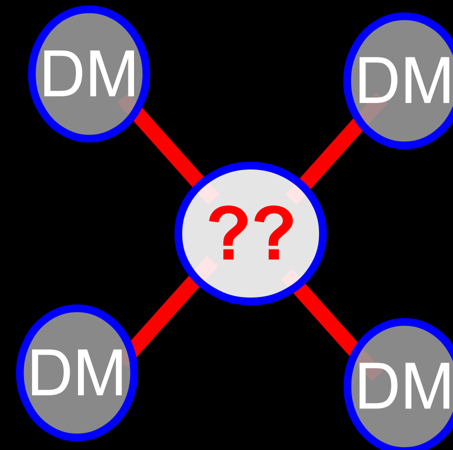


claimed detection of ~1.6 kpc offset between the stars and DM centroids of elliptical galaxy N1

Cluster Abell 3827 (Massey +15)

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

(Kahlhoefer+15)

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

What is the nature of dark matter?

Can DM particles collide with themselves?

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

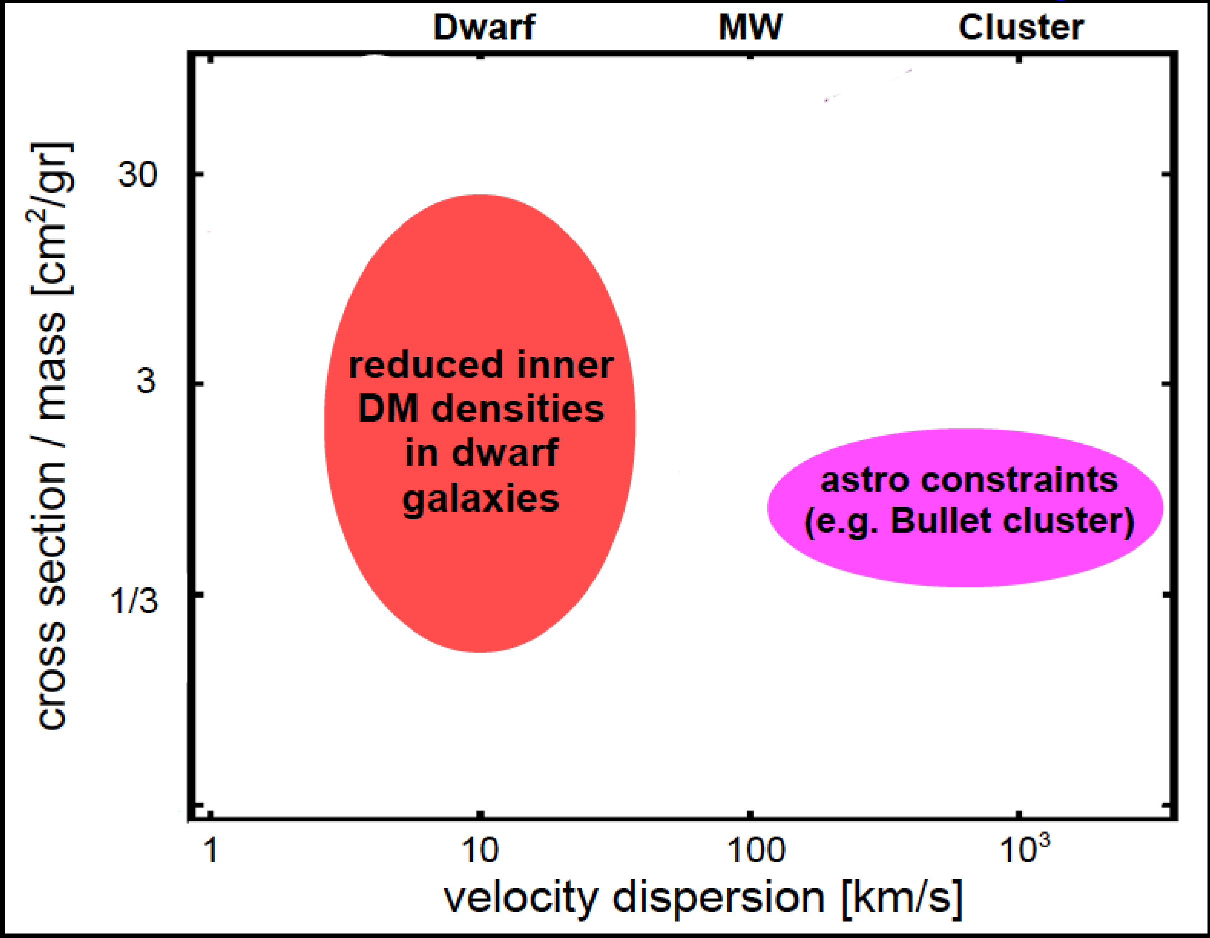
average scattering rate per particle:

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

~ 1 scatter / particle / 14Gyr

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

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

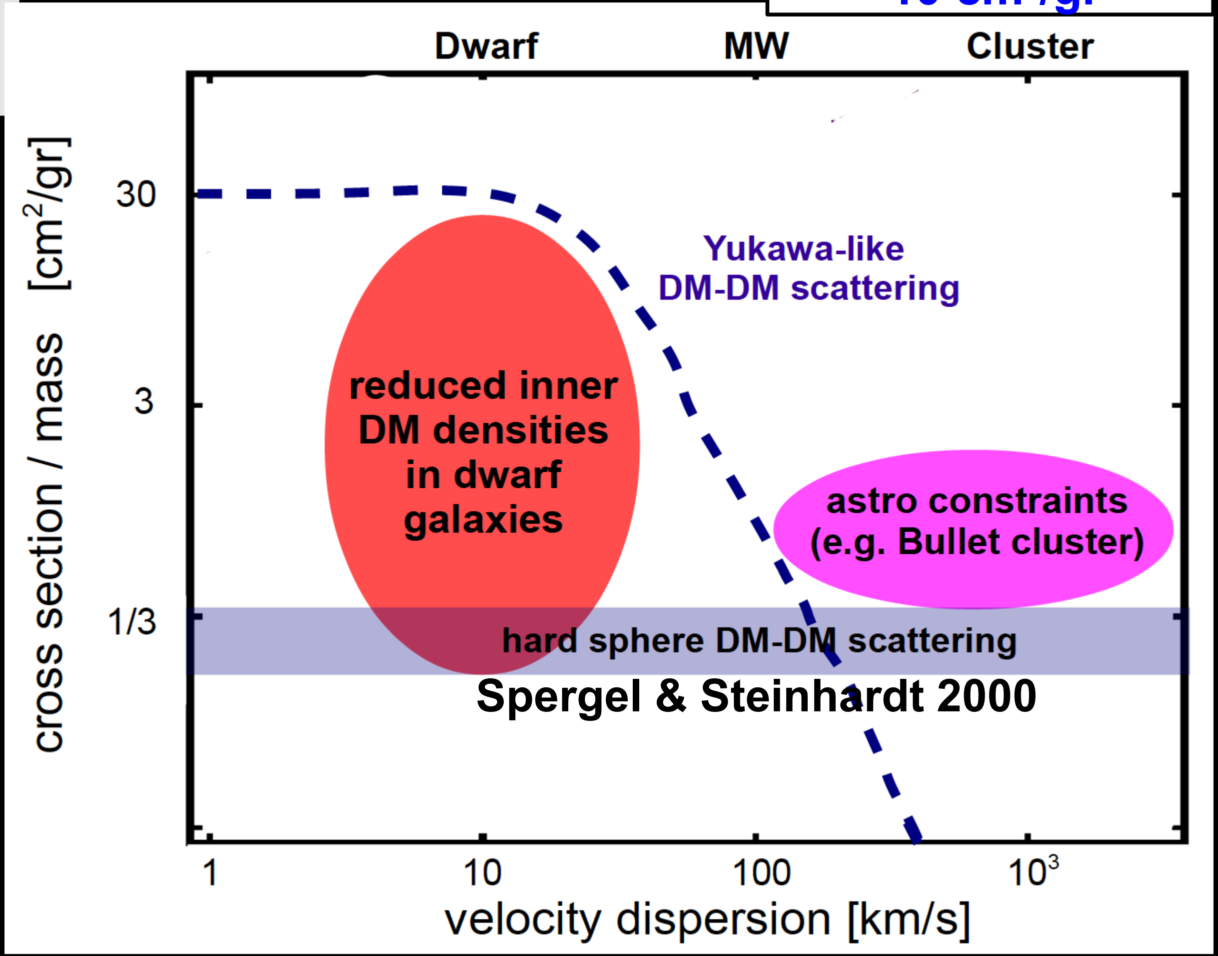


What is the nature of dark matter?

Can DM particles collide with themselves?

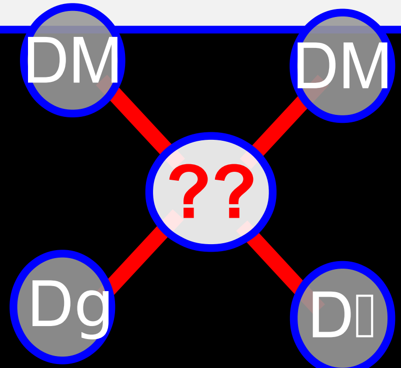
velocity-dependence motivated by a new force in the "dark sector" (analogous to Rutherford scattering)
e.g. Yukawa-like, Feng+09

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



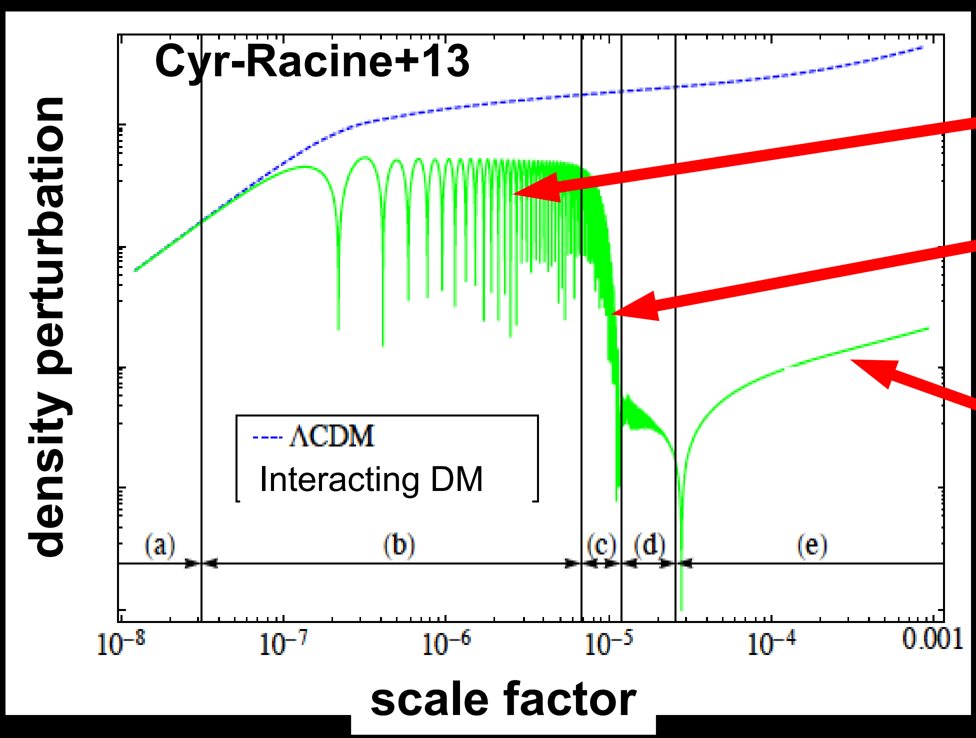
What is the nature of dark matter?

Can DM particles collide 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

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

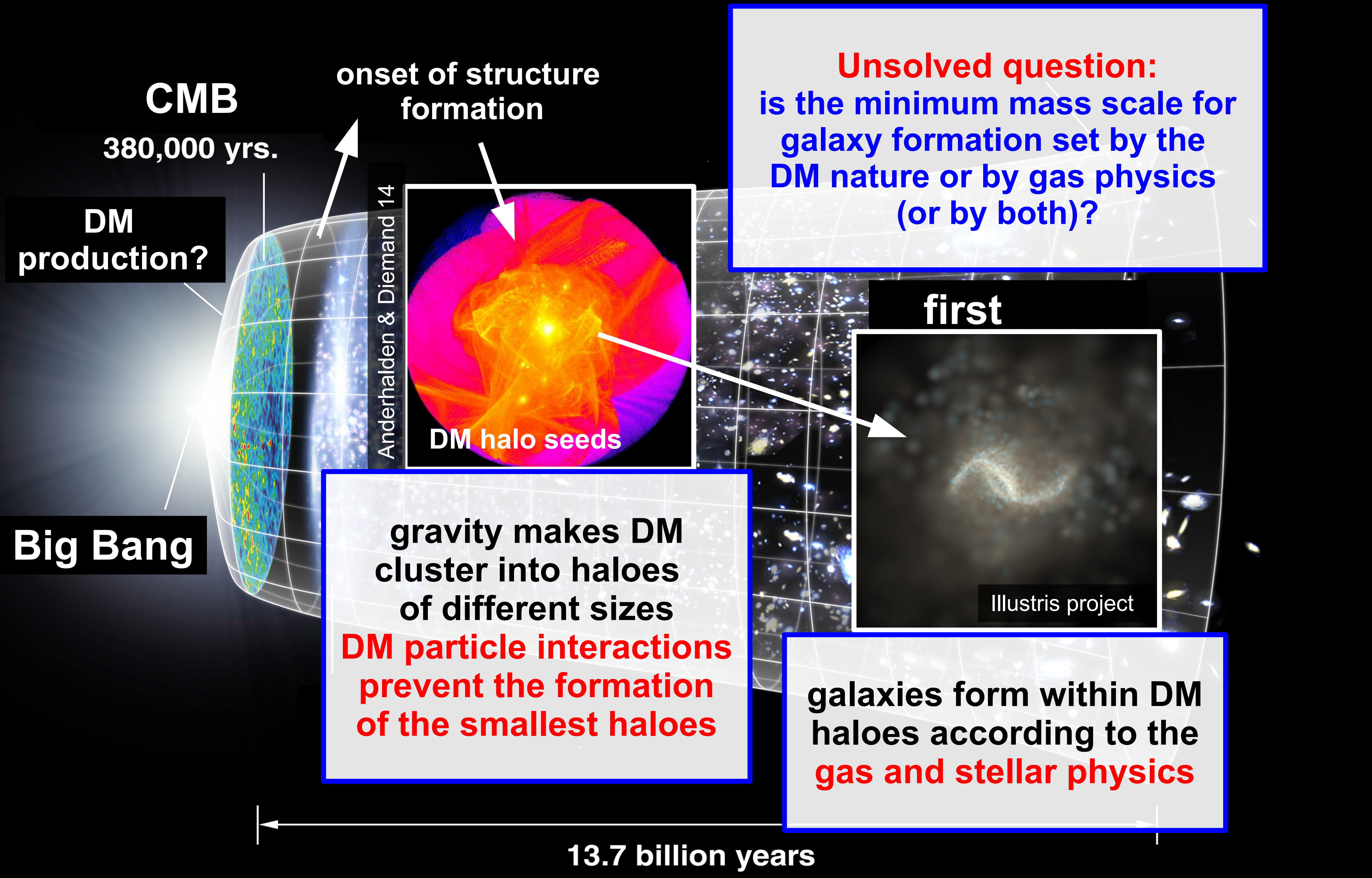
Unsolved question:
is the minimum mass scale for galaxy formation set by the DM nature or by gas physics (or by both)?

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

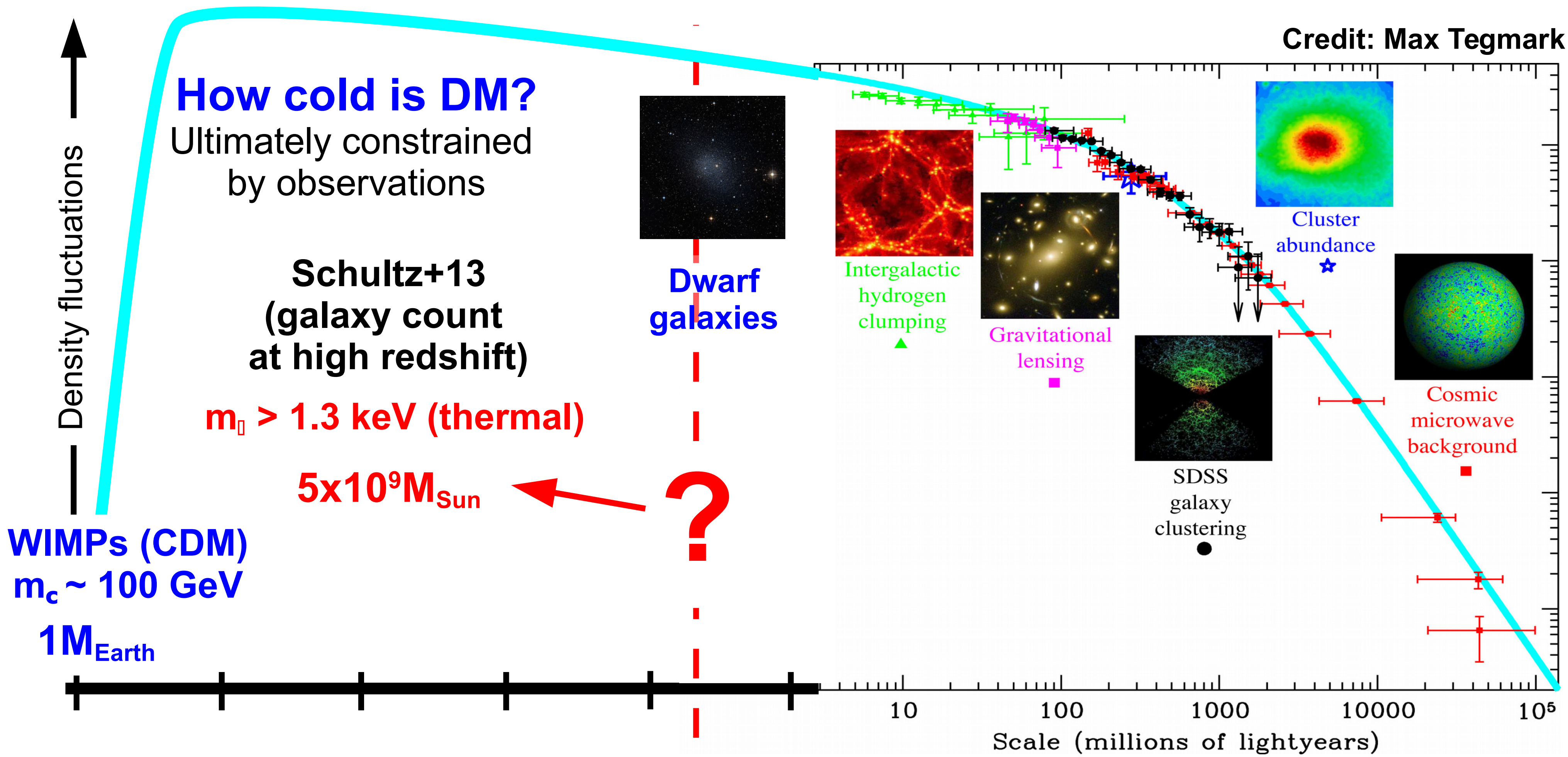
The nature of dark matter and the first galaxies



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)?

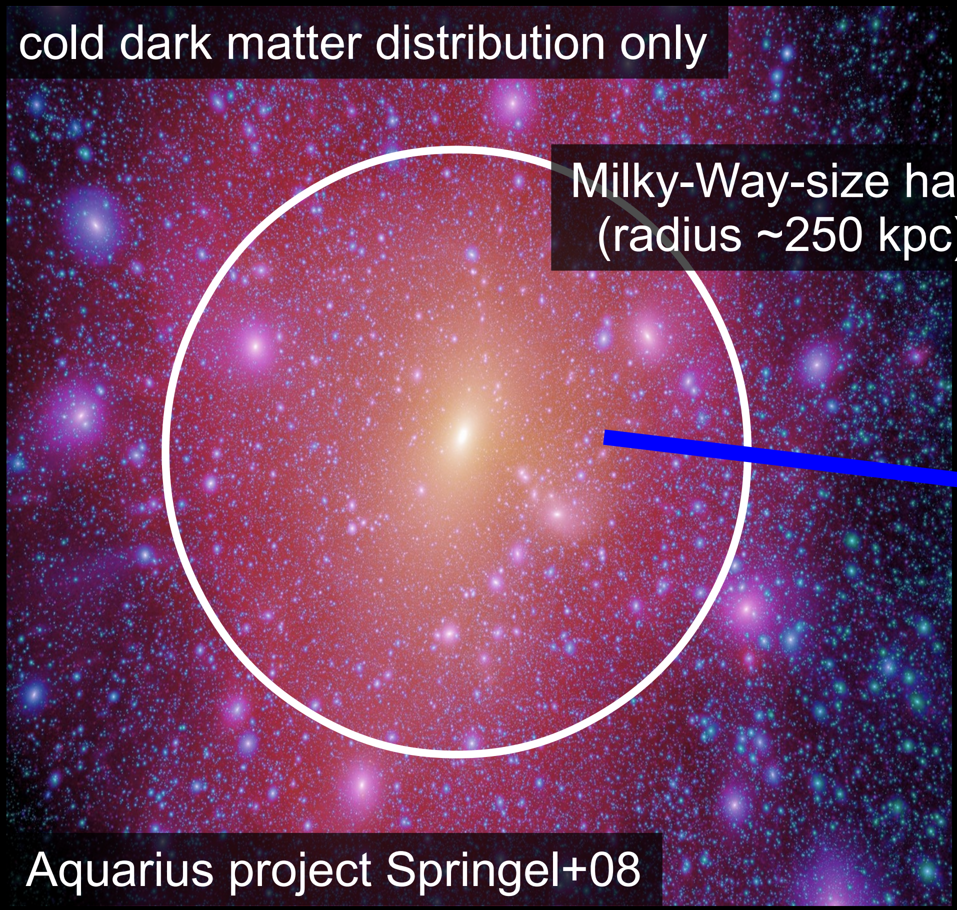
Observations have yet to measure the clustering of dark matter at the scale of the smallest galaxies

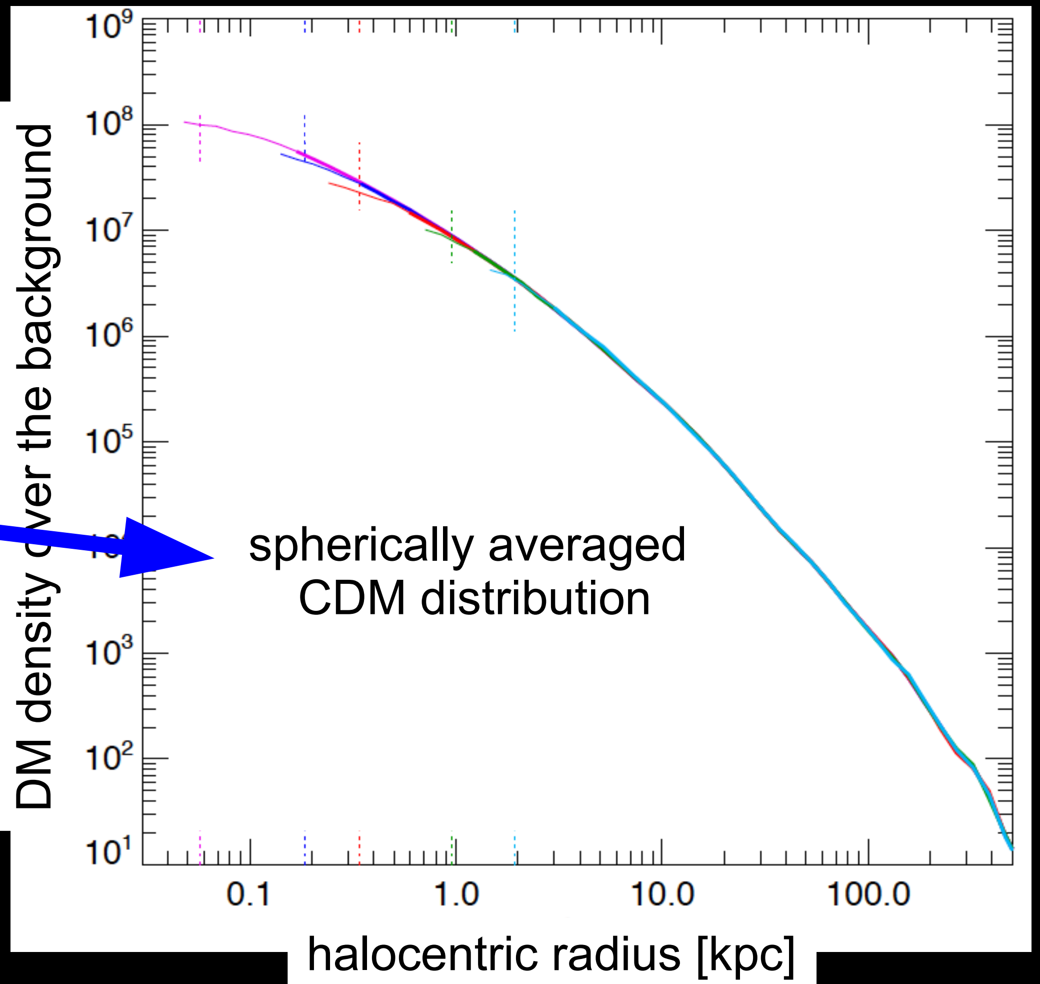


The nature of dark matter (evolution of structures)

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

the central density of CDM haloes is ever increasing

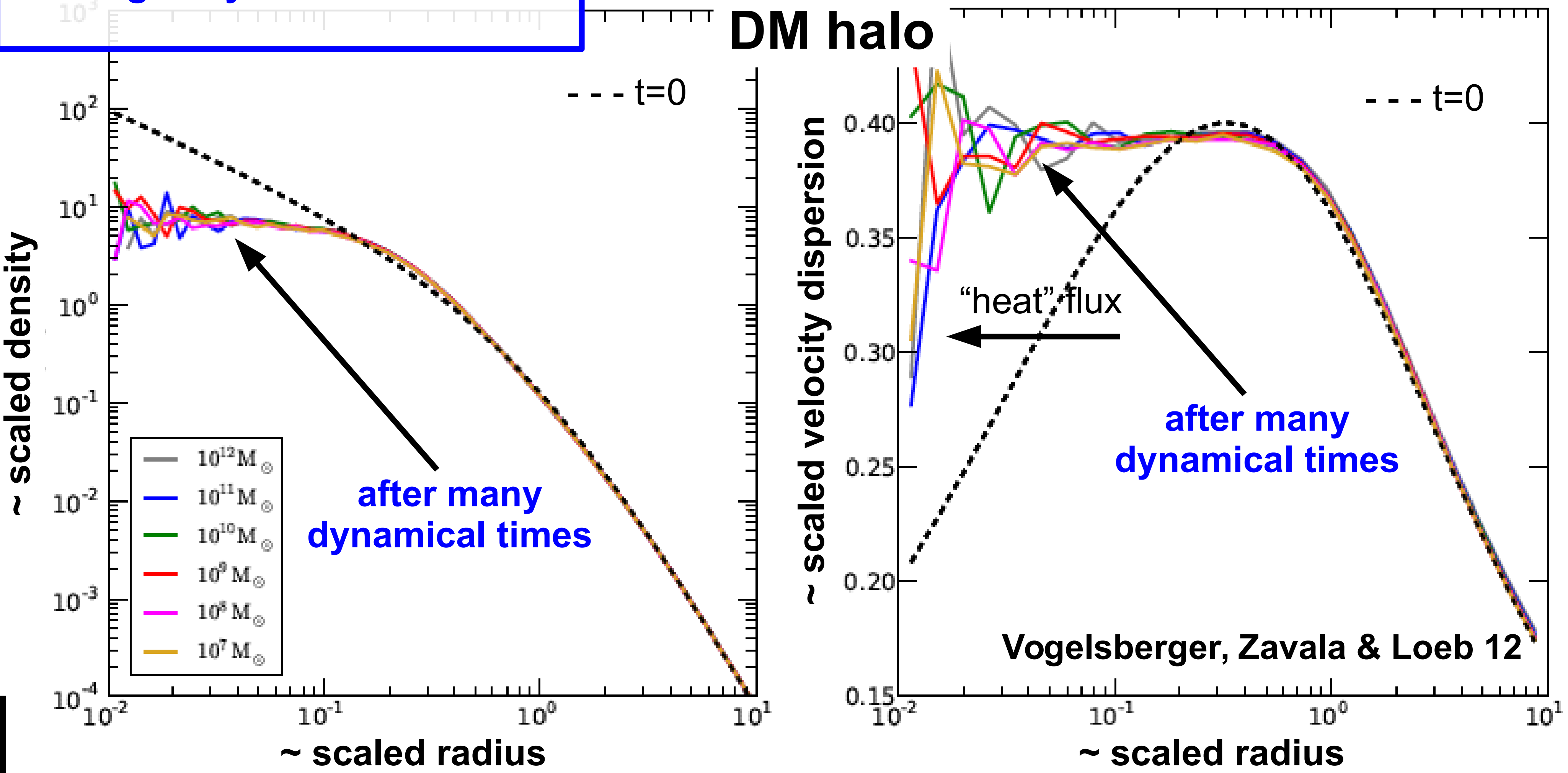




The nature of dark matter (evolution of structures)

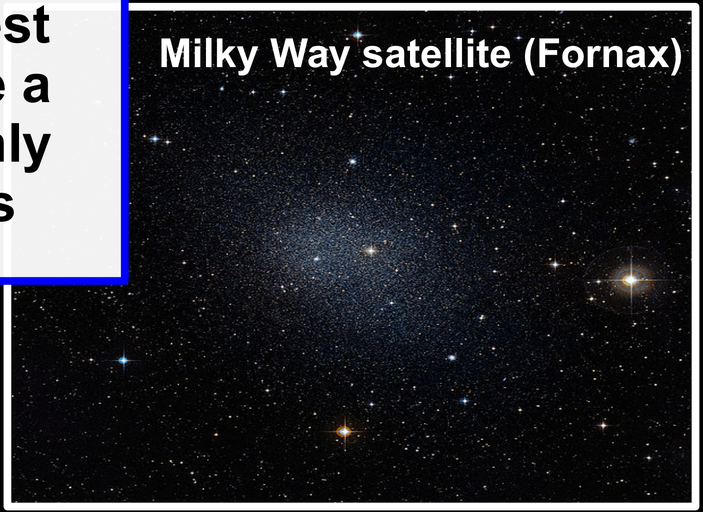
Unsolved question:
are non-gravitational DM interactions irrelevant for galaxy evolution?

with strong interactions (σ/m ~ 1 cm²/gr), galactic haloes develop central cores (~kpc)



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



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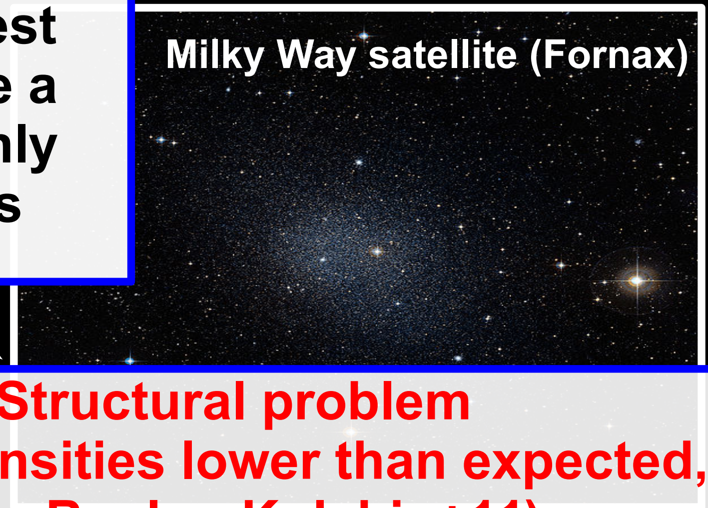
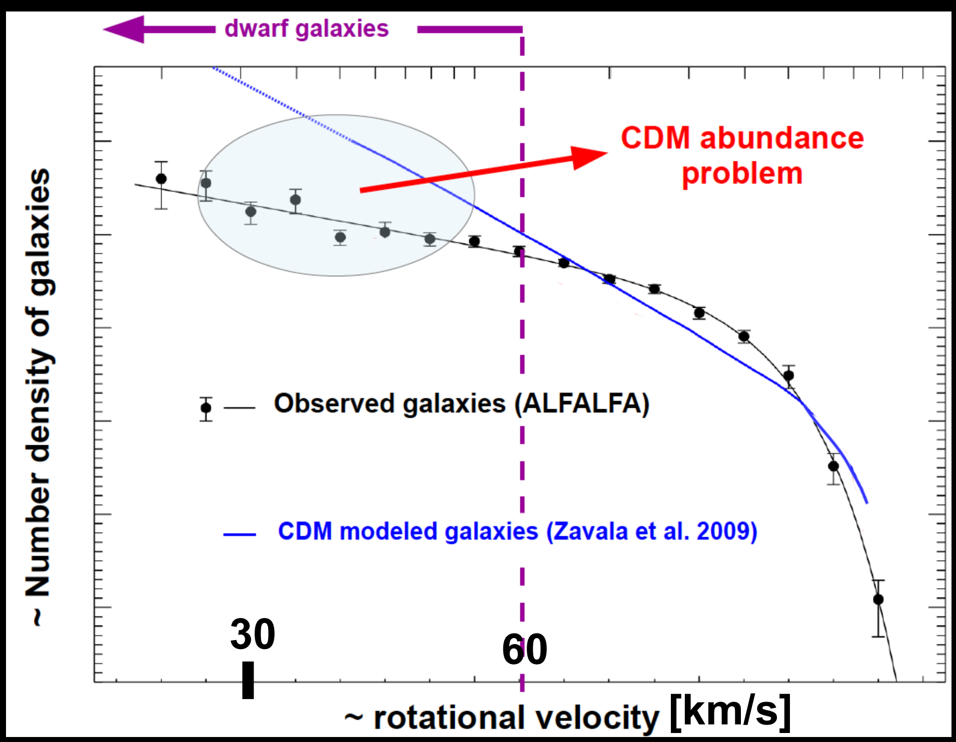
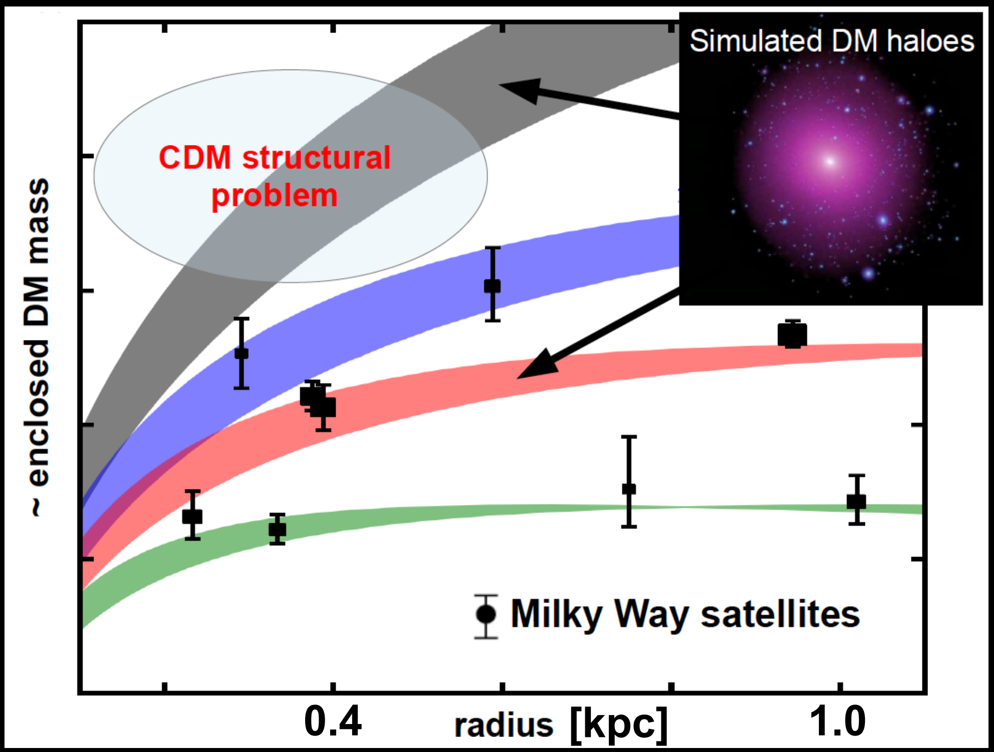


Abundance problem (Zavala+09, Klypin+14)

Structural problem (inner densities lower than expected, e.g. Boylan-Kolchin+11)





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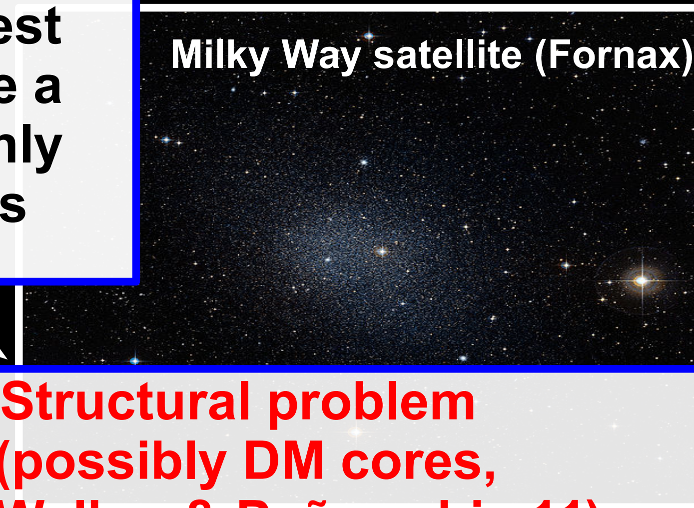
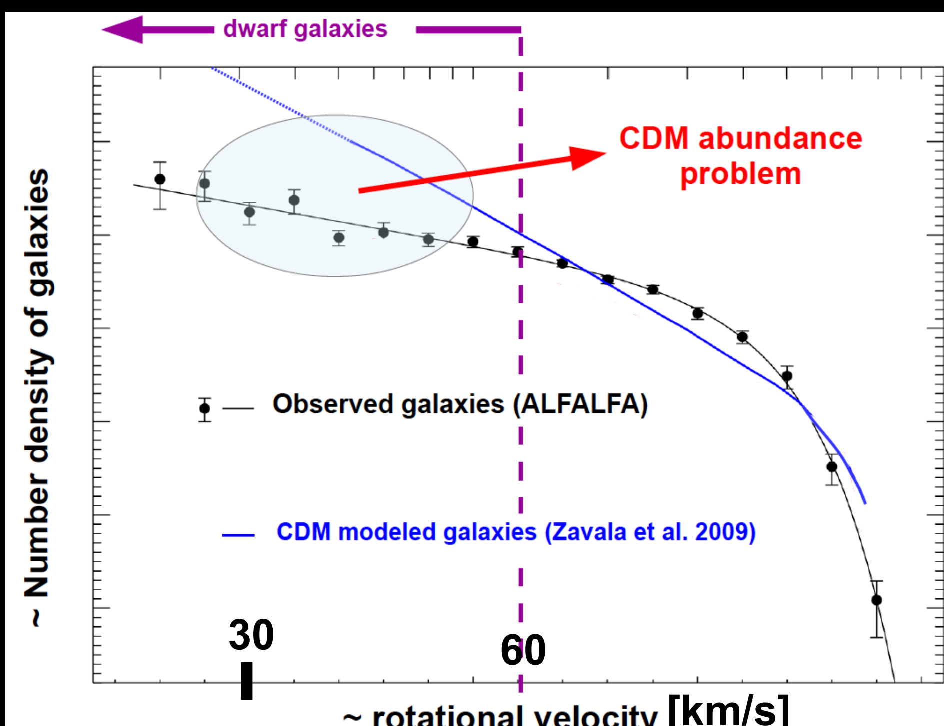
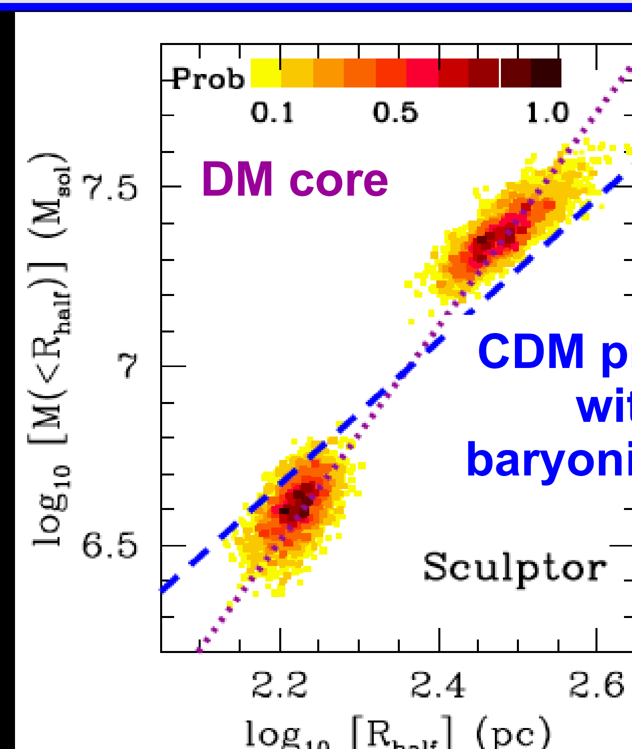


Abundance problem (Zavala+09, Klypin+14)

Structural problem (possibly DM cores, e.g. Walker & Peñarrubia 11)





Clues of new DM physics from dwarf galaxies?

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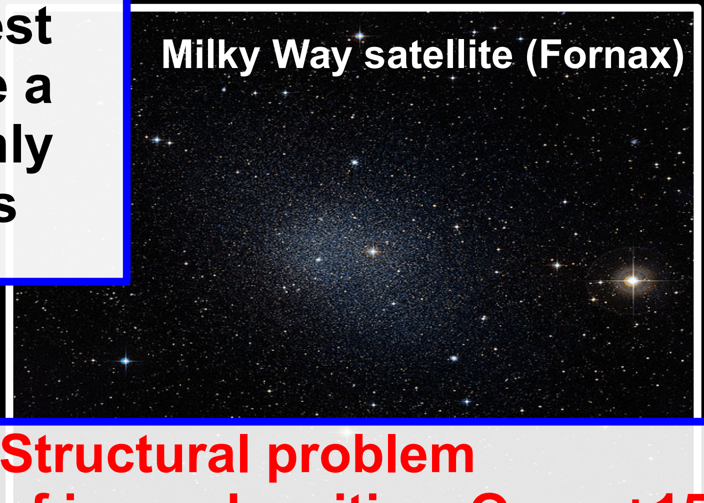

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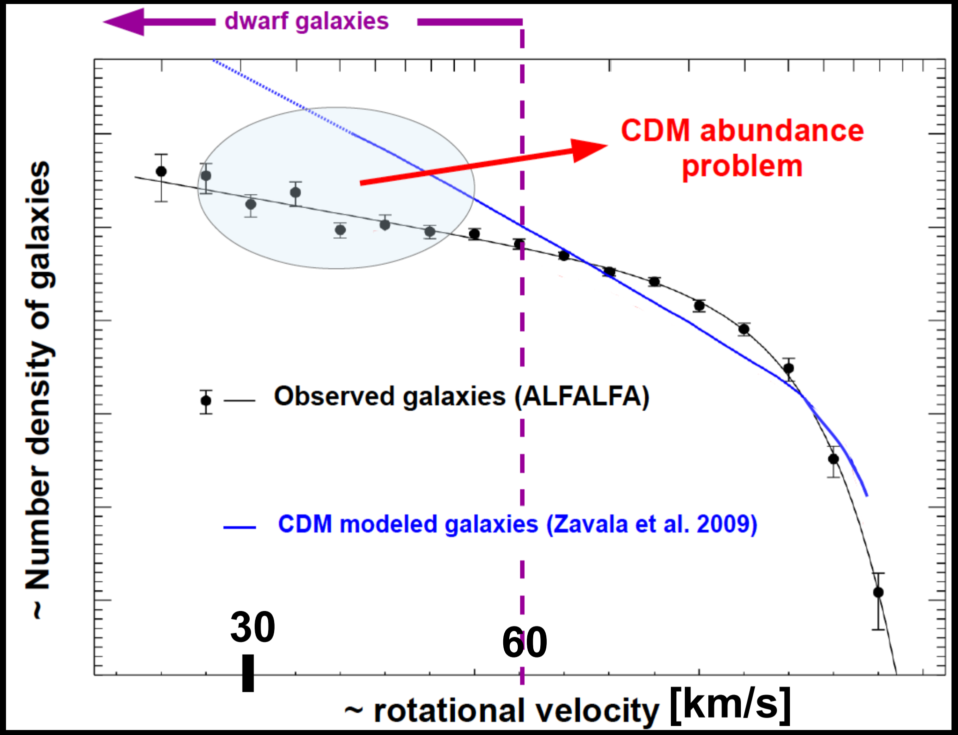
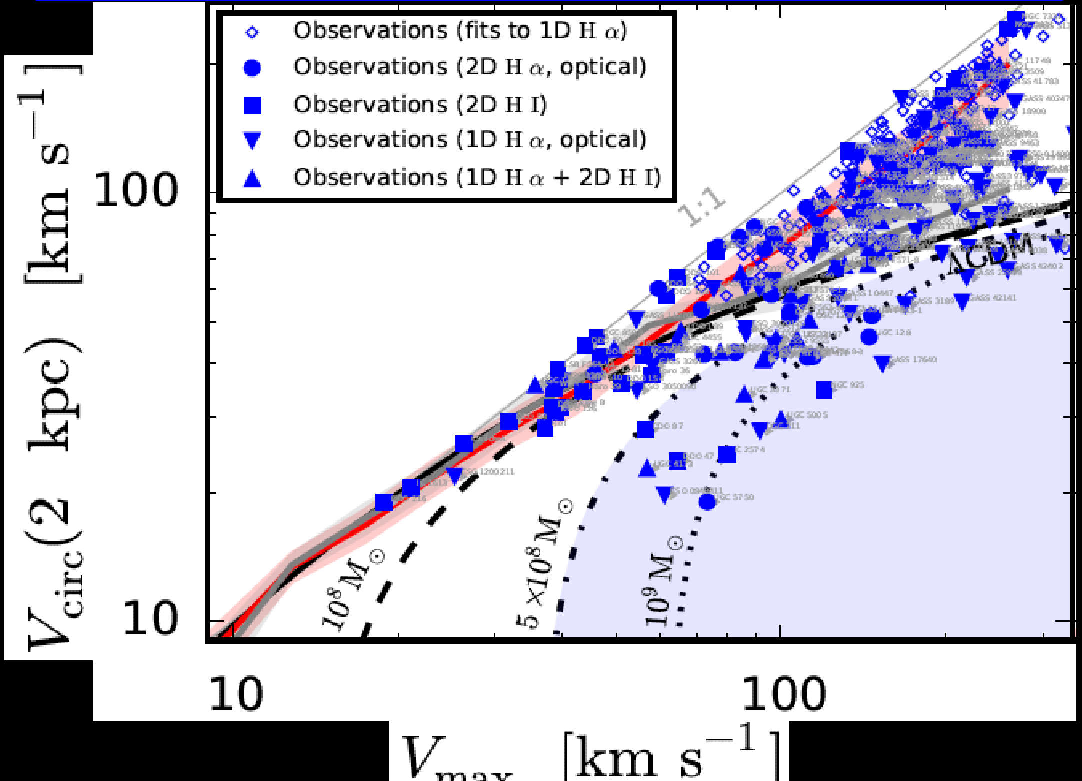
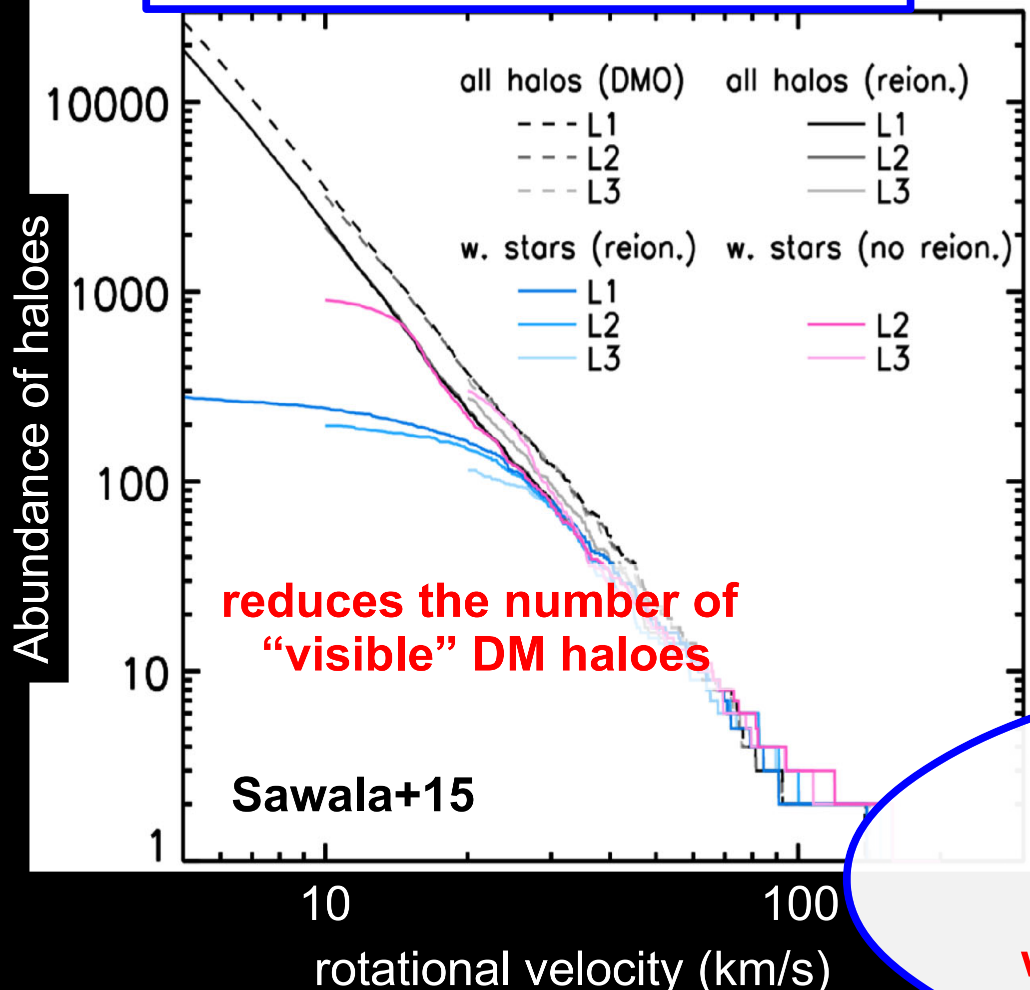


Structural problem (diversity of inner densities, Oman+15)



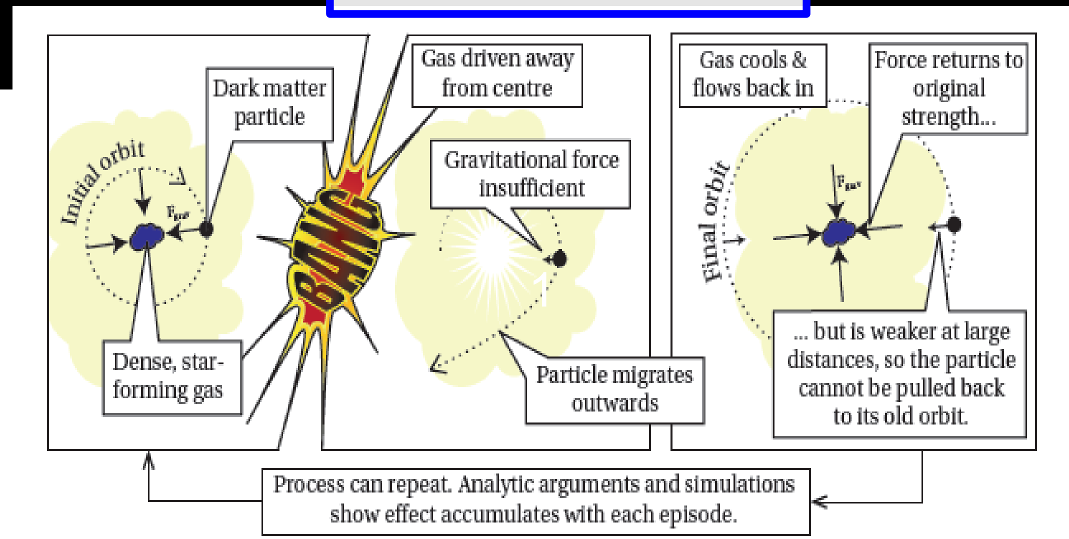
The complexities of gas and stellar physics

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

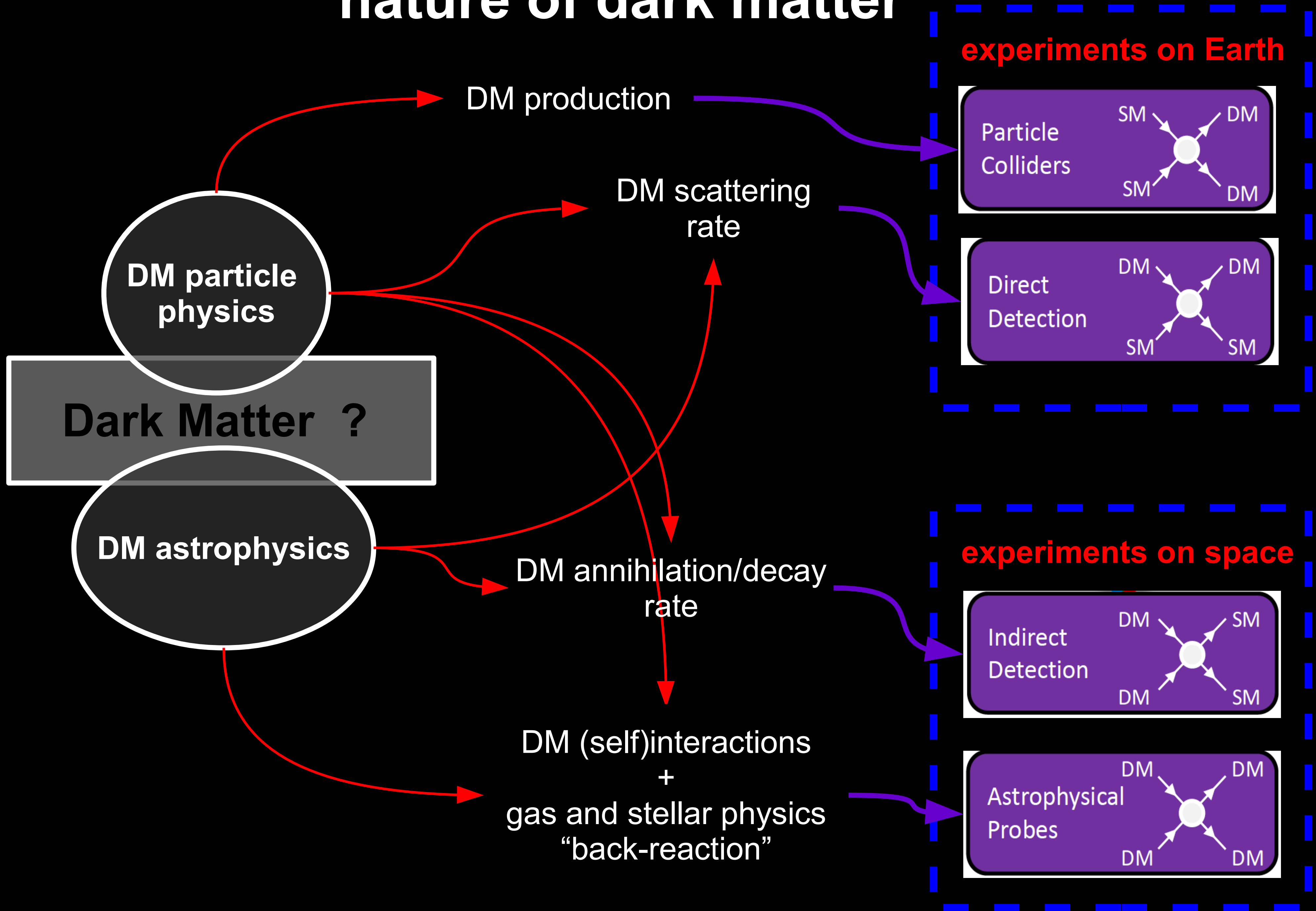
reduces the inner density of DM haloes

these mechanisms are energetically challenging for the smallest galaxies (e.g. Peñarrubia+12)

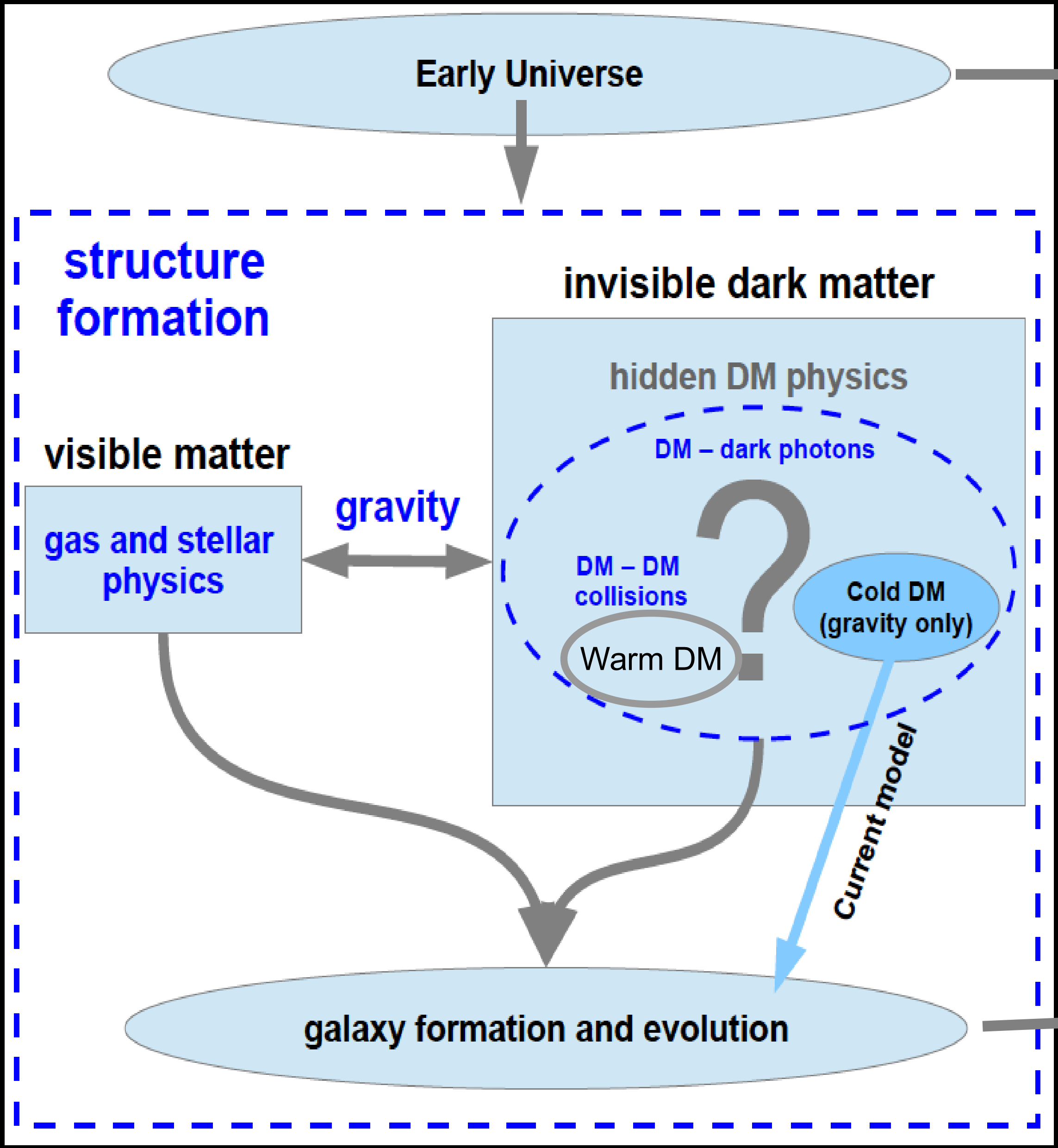
whether or not they are viable solutions to the CDM problems remains unclear

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

Complimentary approaches to elucidate the nature of dark matter



Towards an Effective THeory of Structure formation (ETHOS)



DM production mechanism (verify consistency with global DM abundance and colliders)

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

proof of concept to avoid the CDM challenges

DM interactions with relativistic particles in the early Universe

+

DM-DM self-scattering in the late Universe

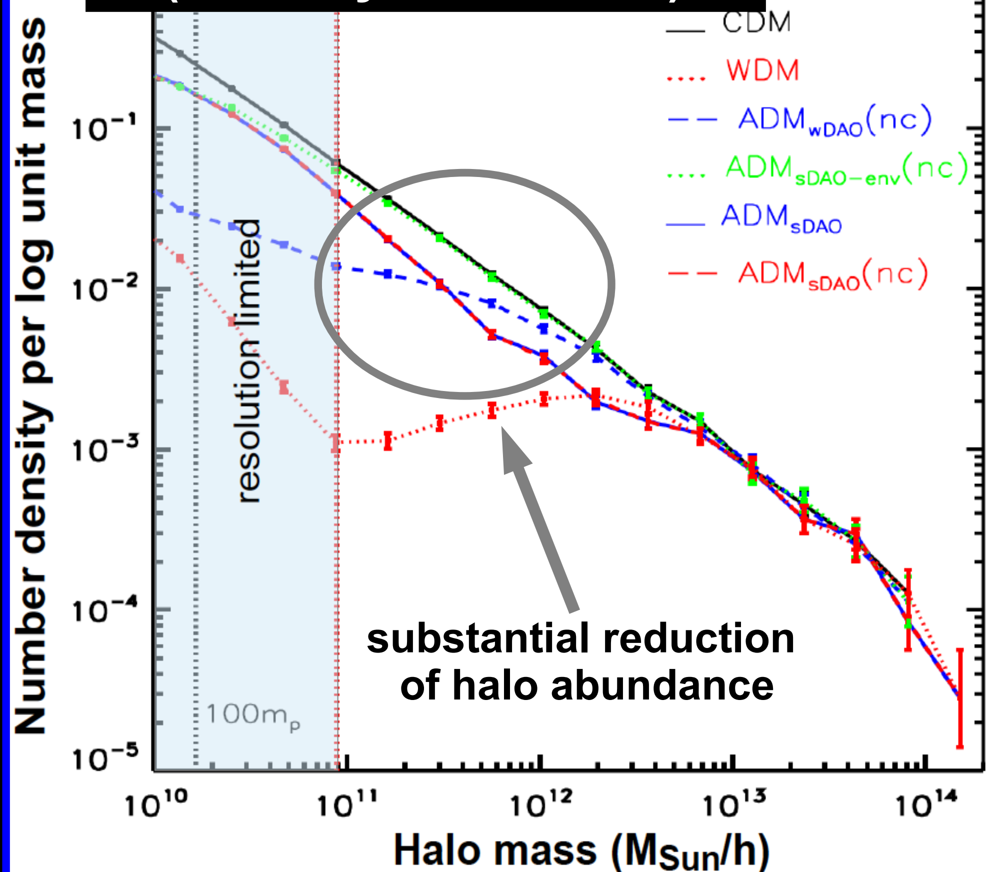
Published results mainly in collaboration with:

Mark Vogelsberger (MIT, Cambridge)
Abraham Loeb (ITC, Cambridge)
Matt Walker (Carnegie Mellon University, Pittsburgh)
Kris Sigurdson (UBC, Vancouver)
Francis-Yan Cyr-Racine (Caltech, Pasadena)
Matthew Buckley (Rutgers, Piscataway)

Structure formation in a universe with new dark matter interactions

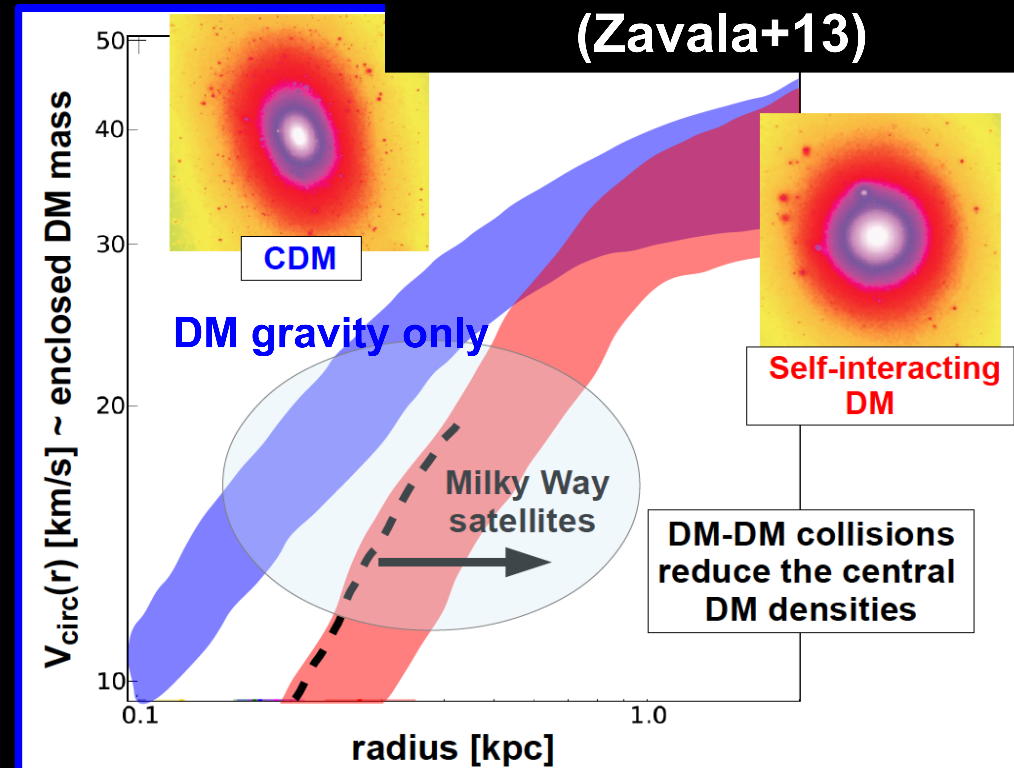
The abundance and structural problems of the smallest galaxies might be solved with new DM interactions

Abundance of DM haloes (Buckley, Zavala+14)



interactions between DM and dark radiation

DM content in DM haloes (Zavala+13)

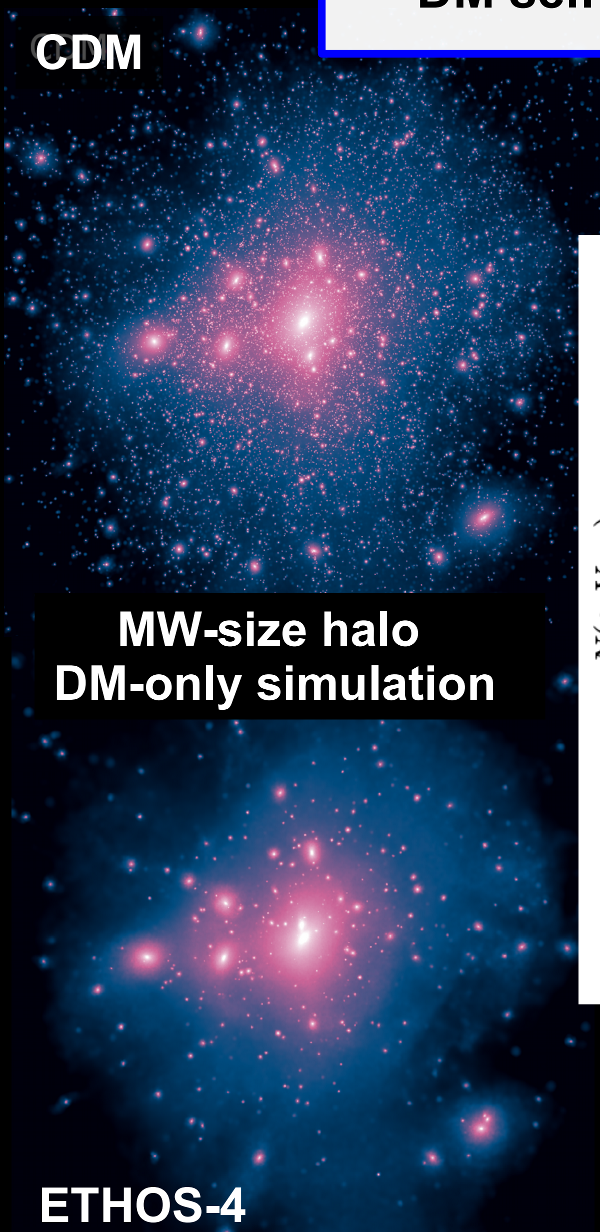


DM self-interactions

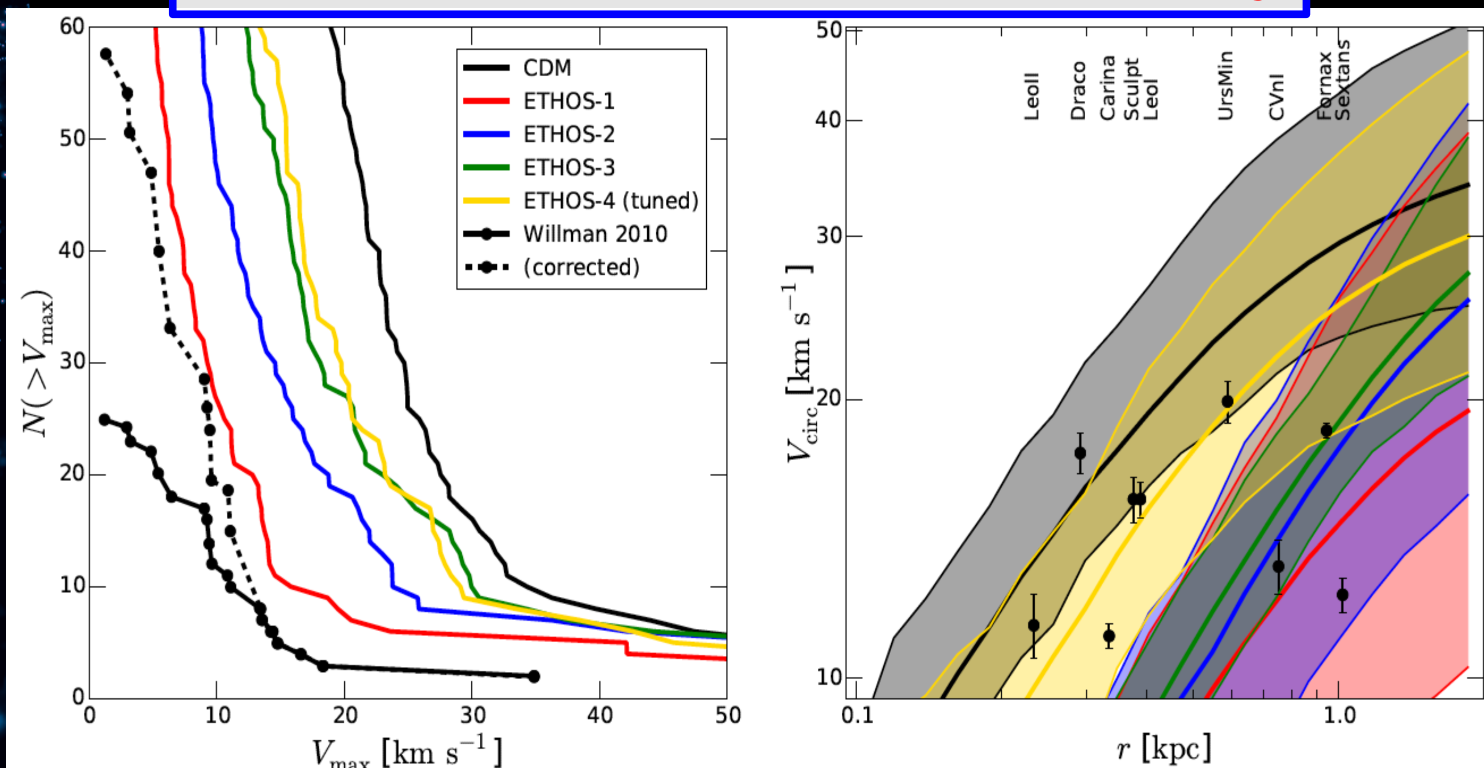
$s/m \sim 1.5\ cm^2/gr$

Preliminary results from ETHOS

DM self-scattering + DM-dark-radiation interactions



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



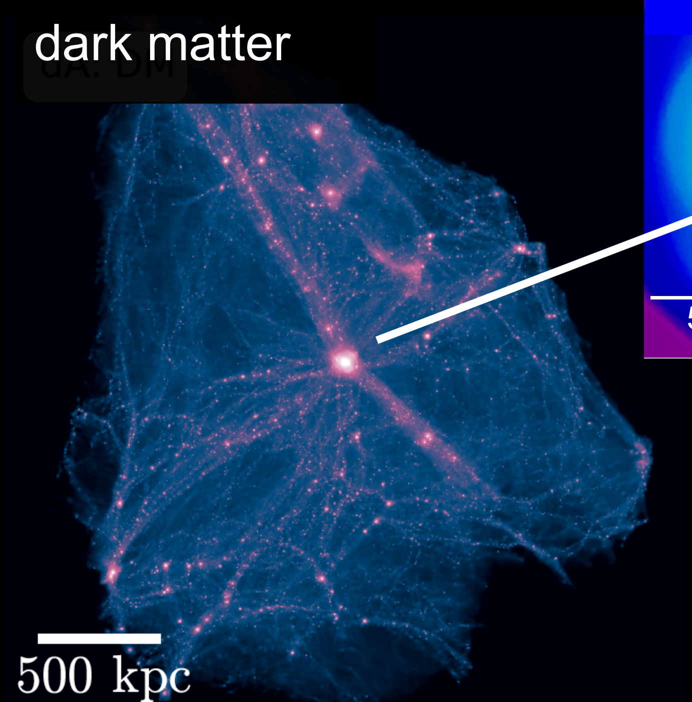
In collaboration with:
Mark Vogelsberger, Francis-Yan Cyr-Racine,
Christoph Pfrommer, Torsten Bringmann and Kris Sigurdson

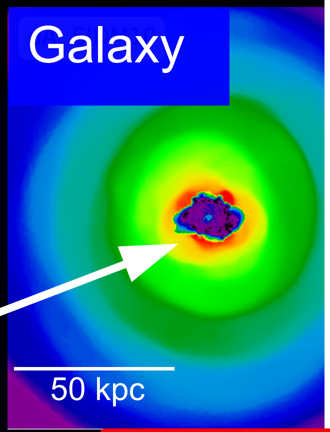
Developing ETHOS
(self-scattering DM + baryonic physics)

The properties of DM as a particle (mass, interactions) impact the properties of DM haloes, and thus, those of the galaxies they host

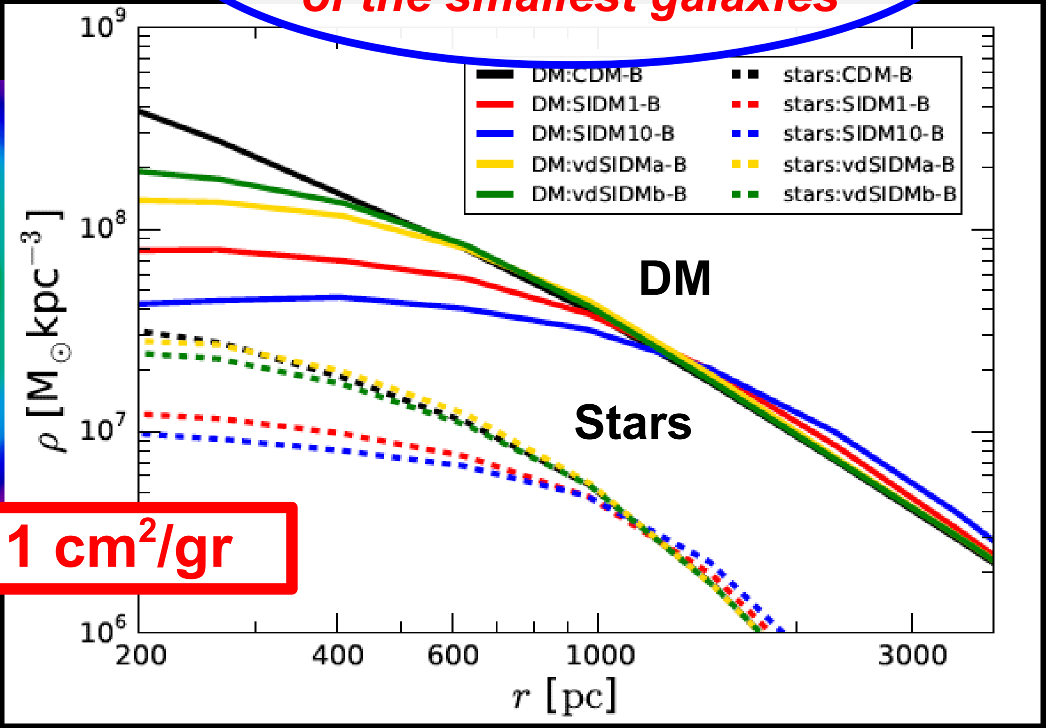
simulation of a galaxy in Self-Interacting DM
(Vogelsberger, Zavala +14)

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





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



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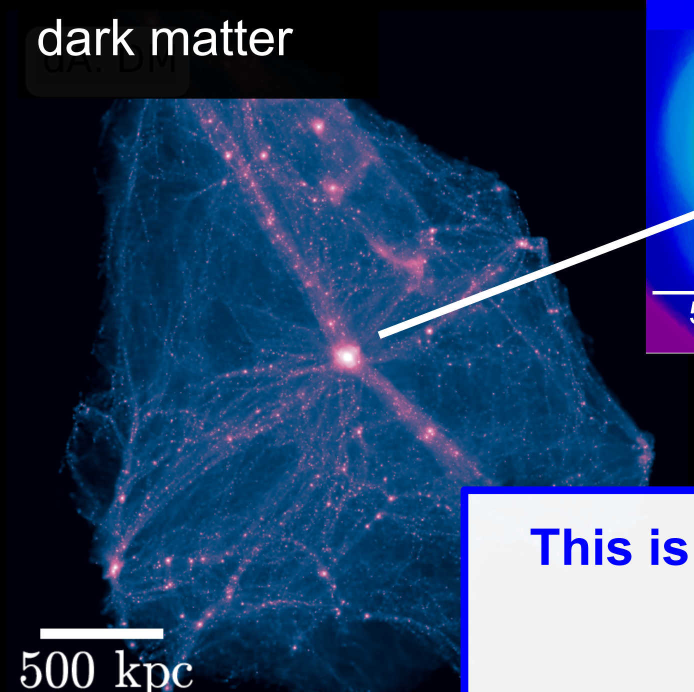

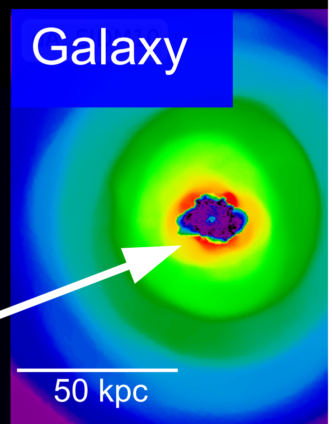

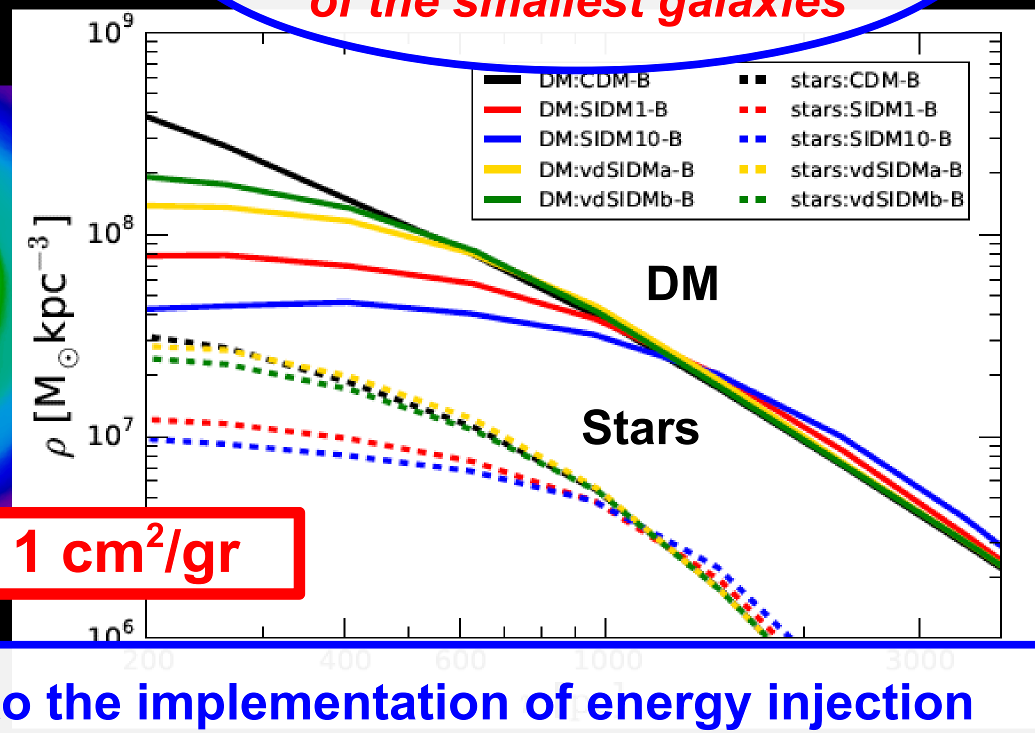

σ/m = 1 cm^2/gr

This is sensitive to the implementation of energy injection (efficiency and timescales) from SNe
(see Fry+15 for the highly efficient case)

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):

- it preserves the large-scale successes of CDM and “naturally” alleviates most of its small-scale (dwarf galaxies) challenges

- first galaxy simulations in Self-interacting dark matter indicate that galaxy formation and evolution proceeds in a similar way as in CDM (nothing catastrophic!)

- the effect of DM collisions might be imprinted in the phase-space distribution of stars in dwarf galaxies at an observable level: **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