Towards an effective theory of structure formation with new dark matter physics

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Department of Physics, University of Oslo, November 2014

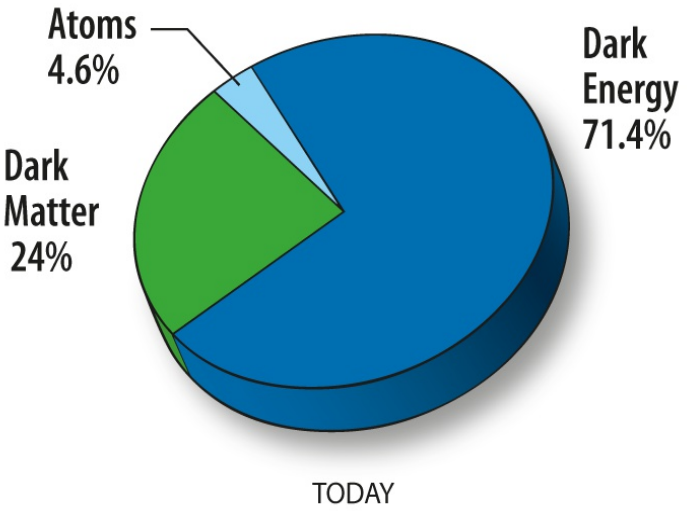
OUTLINE

- The “standard” dark matter (DM) model
  - The cold dark matter (CDM) hypothesis
  - Structure formation in CDM
- Beyond CDM
  - What do we know about the DM nature?
  - Clues from dwarf galaxies?
  - Proof of concept: structure formation in a self-interacting DM Universe
- Concluding remarks

The dark matter 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*

Luminous matter + Newtonian gravity ≠ dynamics
→ missing "dark" matter



Credit: NASA/WMAP-9 Science Team

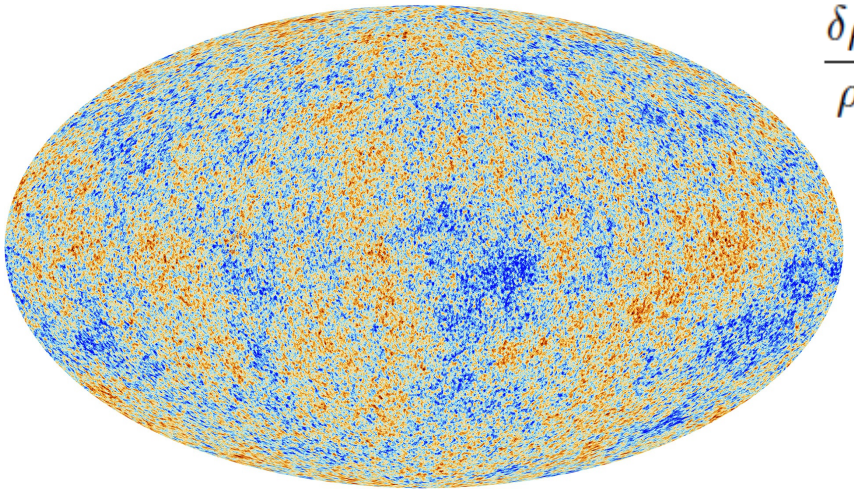
Independent astronomical observations suggest that ~80% of the matter in the Universe is dark

The “standard model” of structure formation

The particle DM hypothesis is the cornerstone of the current theory of the formation and evolution of galaxies

Credit: ESA and the Planck Collaboration

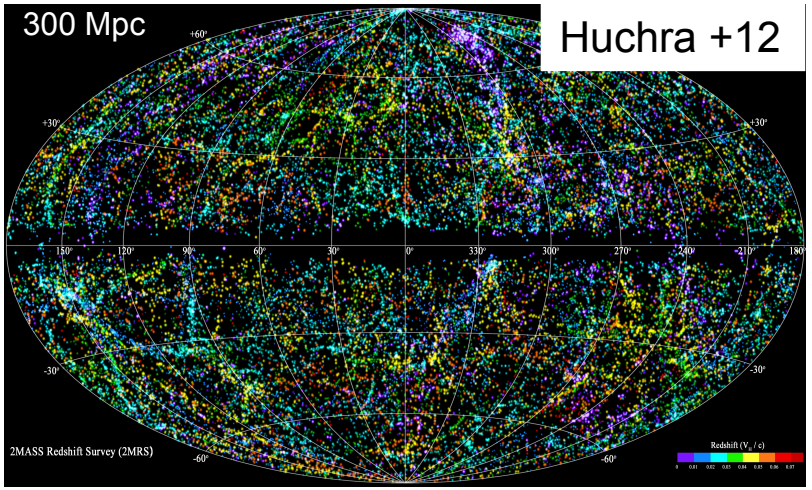
Early Universe (t ~ 0.4 Myrs)



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

Cosmic Microwave Background Radiation

Universe today (t ~ 13.8 Gyrs)



2MRS galaxy “map”, large-scale structure

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

galactic scales

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

The “standard model” of structure formation

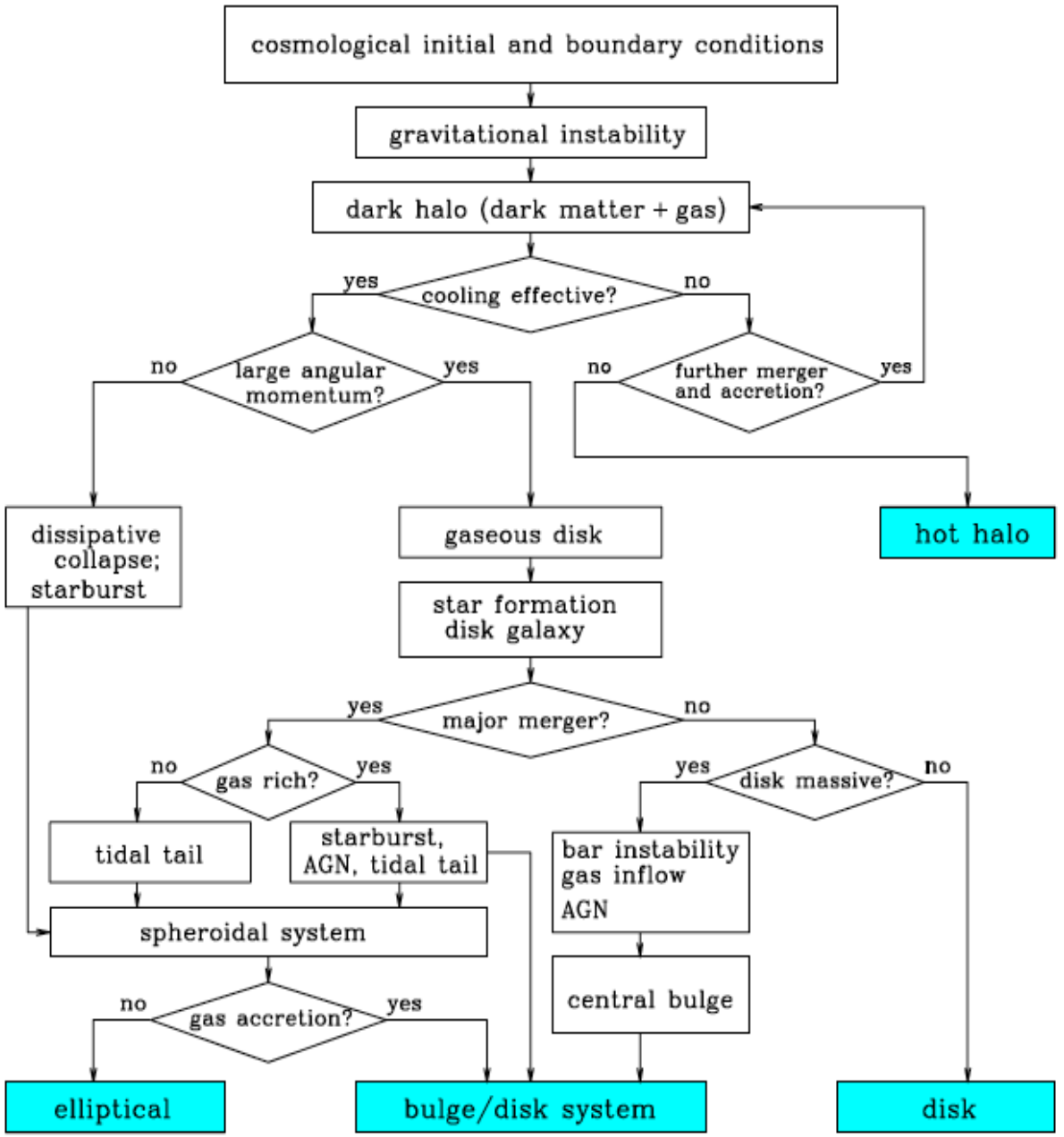


Fig. from Mo, Mao and White, 2010

formation of a DM halo

DM gravity only

Aquarius project Springel+08

“Eris” simulation Guedes+11

gas and stellar physics

formation of a galaxy

The CDM hypothesis

In the Cold Dark Matter (CDM) model,
DM is a new cold and collisionless particle

In CDM, galaxies form in a purely gravitational DM background, i.e., the nature of DM as a particle is irrelevant for galaxy formation and evolution

There is however, **no strong evidence** to support this **strong** hypothesis

A less stringent hypothesis preserves the success of CDM at large scales and predicts a distinct DM phase-space structure at smaller scales

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

Beyond CDM:

motivation for additional (i.e. non-gravitational) DM physics in structure formation

DM nature in the early Universe

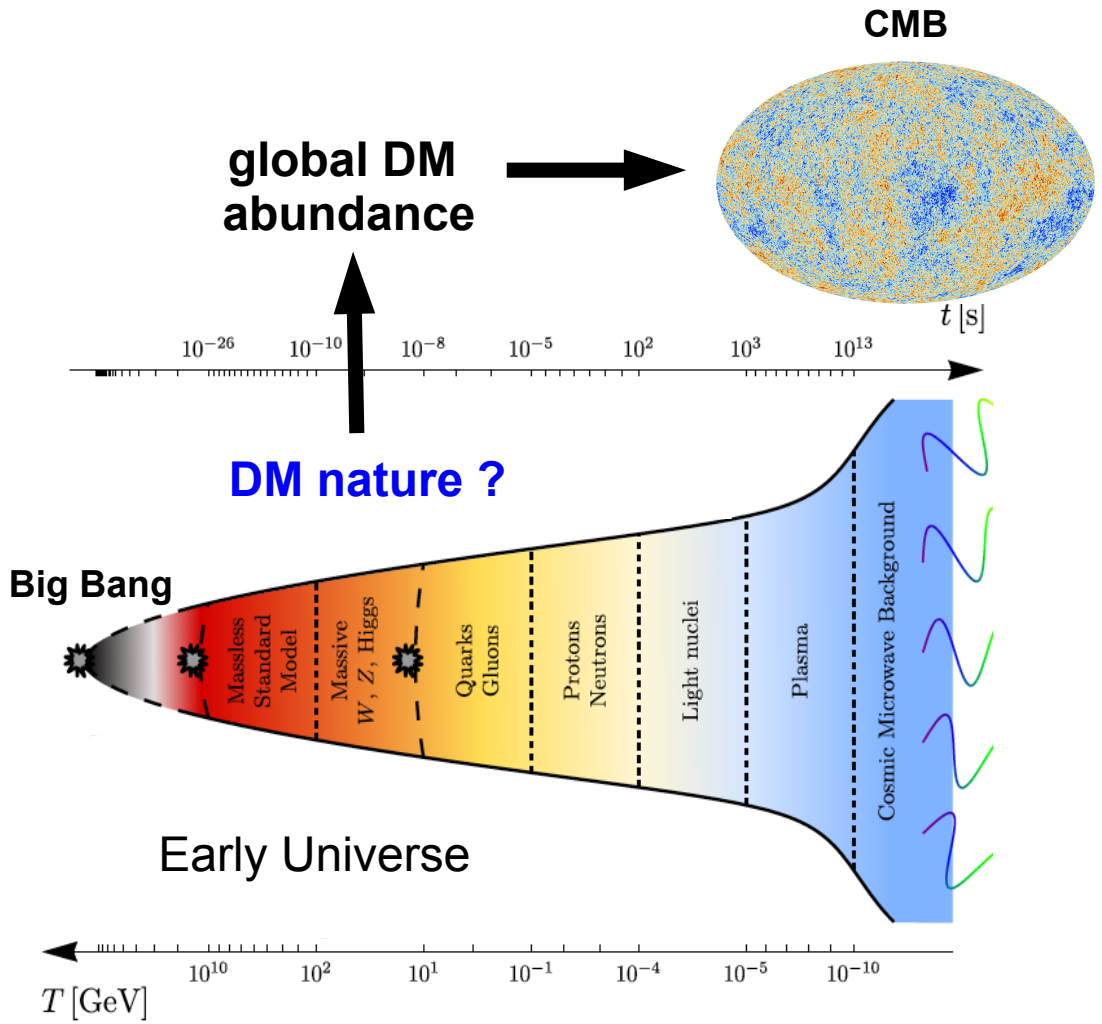
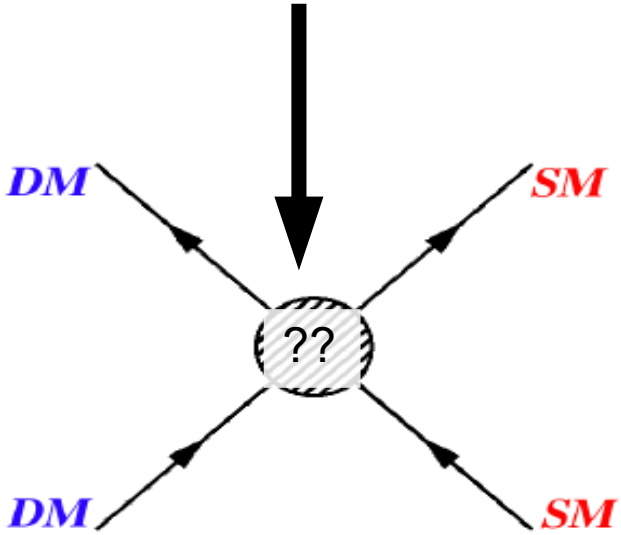


Fig. from Buchmüller 12

A guiding fundamental principle?
e.g. a new symmetry, SUSY



dark particles interacting through the **weak force** (**WIMPs**) "naturally" give the right DM abundance

WIMPs are excellent CDM candidates!

DM nature in the early Universe

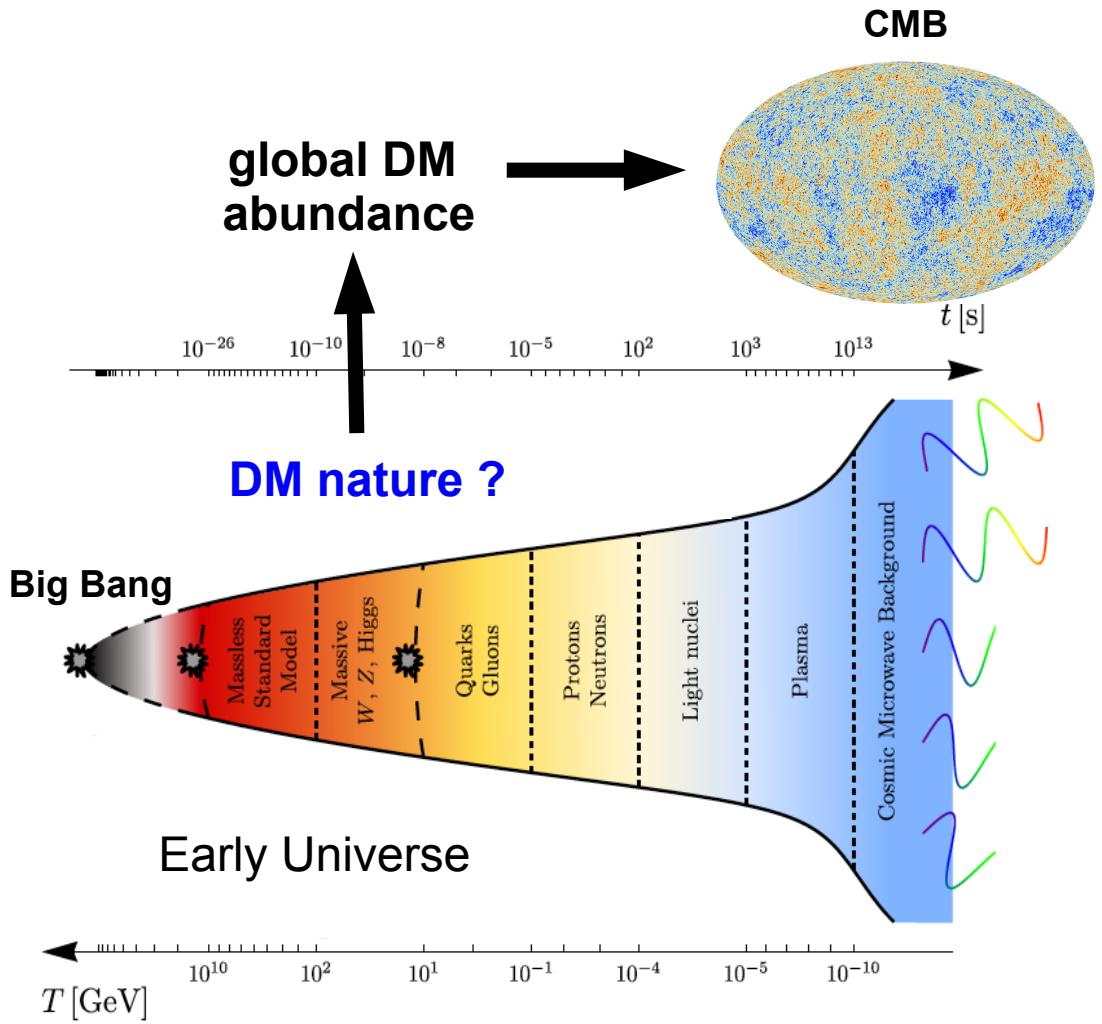


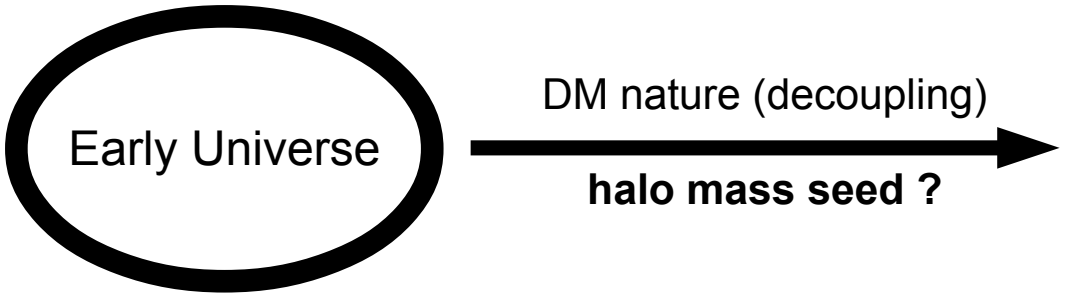
Fig. from Buchmüller 12

A guiding fundamental principle? e.g. DM is asymmetric as normal matter is

If DM is asymmetric then **much stronger interactions than the weak force** are needed to reproduce the observed DM abundance

Asymmetric DM is an example of an alternative particle model with non-CDM features!

DM nature and the first cosmic structures



Is the minimum scale for galaxy formation set by the DM nature or by gas physics (or by both)?

DM nature and the first cosmic structures

Early Universe

DM nature (decoupling)

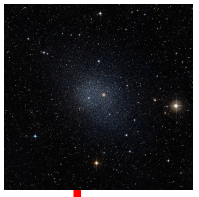
halo mass seed ?

Is the minimum scale for galaxy formation set by the DM nature or by gas physics (or by both)?

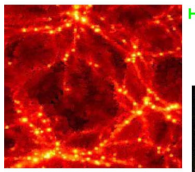
How cold is DM?

Ultimately constrained by observations

Credit: Max Tegmark

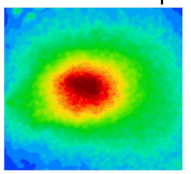


Dwarf galaxies

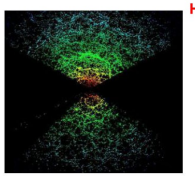


Intergalactic hydrogen clumping

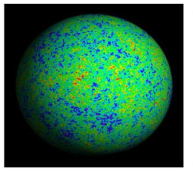
Gravitational lensing



Cluster abundance



SDSS galaxy clustering



Cosmic microwave background

Schultz+13

m_χ > 1.3 keV (thermal)

$5 \times 10^9 M_{Sun}$

WIMPs

m_χ ~ 100 GeV

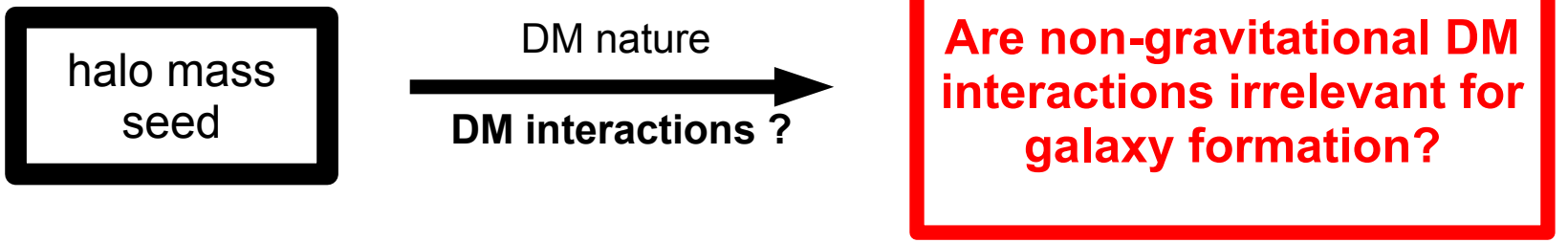
$1 M_{Earth}$

10 100 1000 10000 10^5

Scale (millions of lightyears)

Structure formation and DM interactions

Onset of structure formation



Structure formation and DM interactions

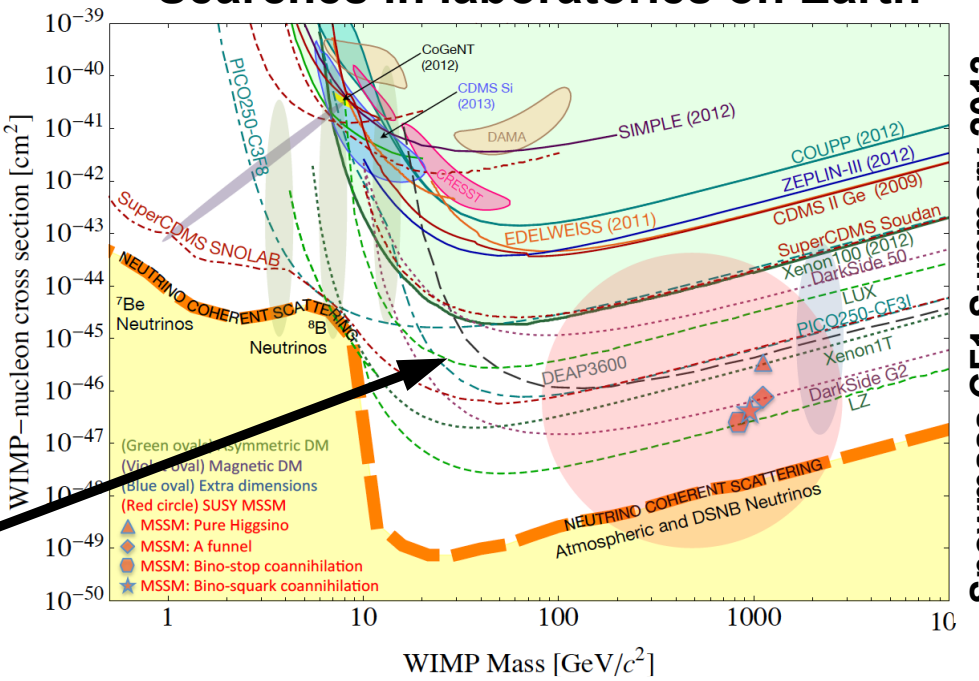
Are non-gravitational DM interactions irrelevant for galaxy formation?

DM particle interactions (weak force) **hoped** by most detection efforts!!

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

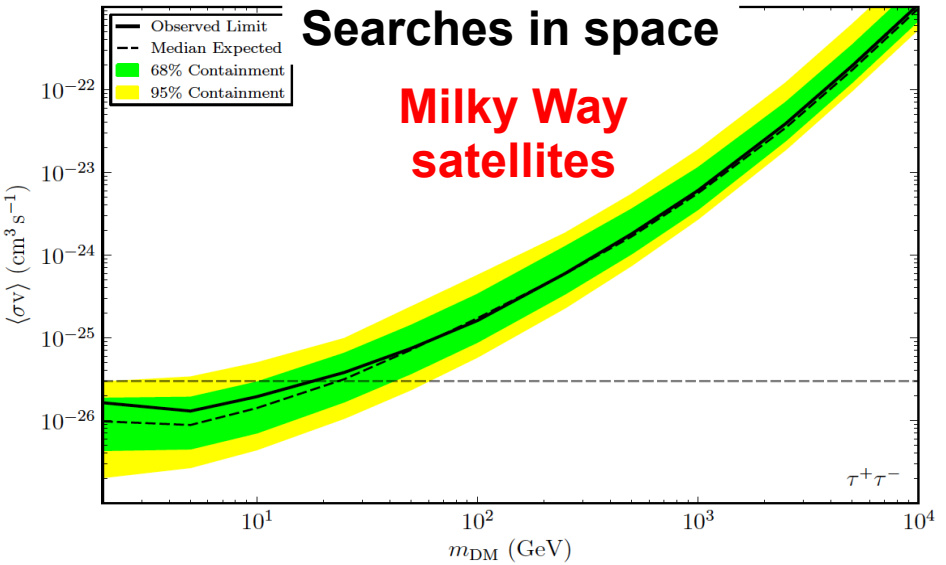
1 cm^2/g ~ 2 barns/GeV

Searches in laboratories on Earth



Snowmass CF1 Summary 2013

Searches in space



Fermi-LAT collaboration 14

Structure formation and DM interactions

Onset of structure formation

halo mass seed

DM nature

DM interactions ?

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$m_\chi \in (0.1 - 1)$ TeV	(dSphs)
Fermi-LAT	

Does it interact with ordinary matter?

χ-nucleus interactions extremely low to impact structure information

Does it interact with itself (annihilation)?

χ−χ self-annihilation extremely low to impact structure information

1 cm^2/g ~ 2 barns/GeV

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

Structure formation and DM interactions

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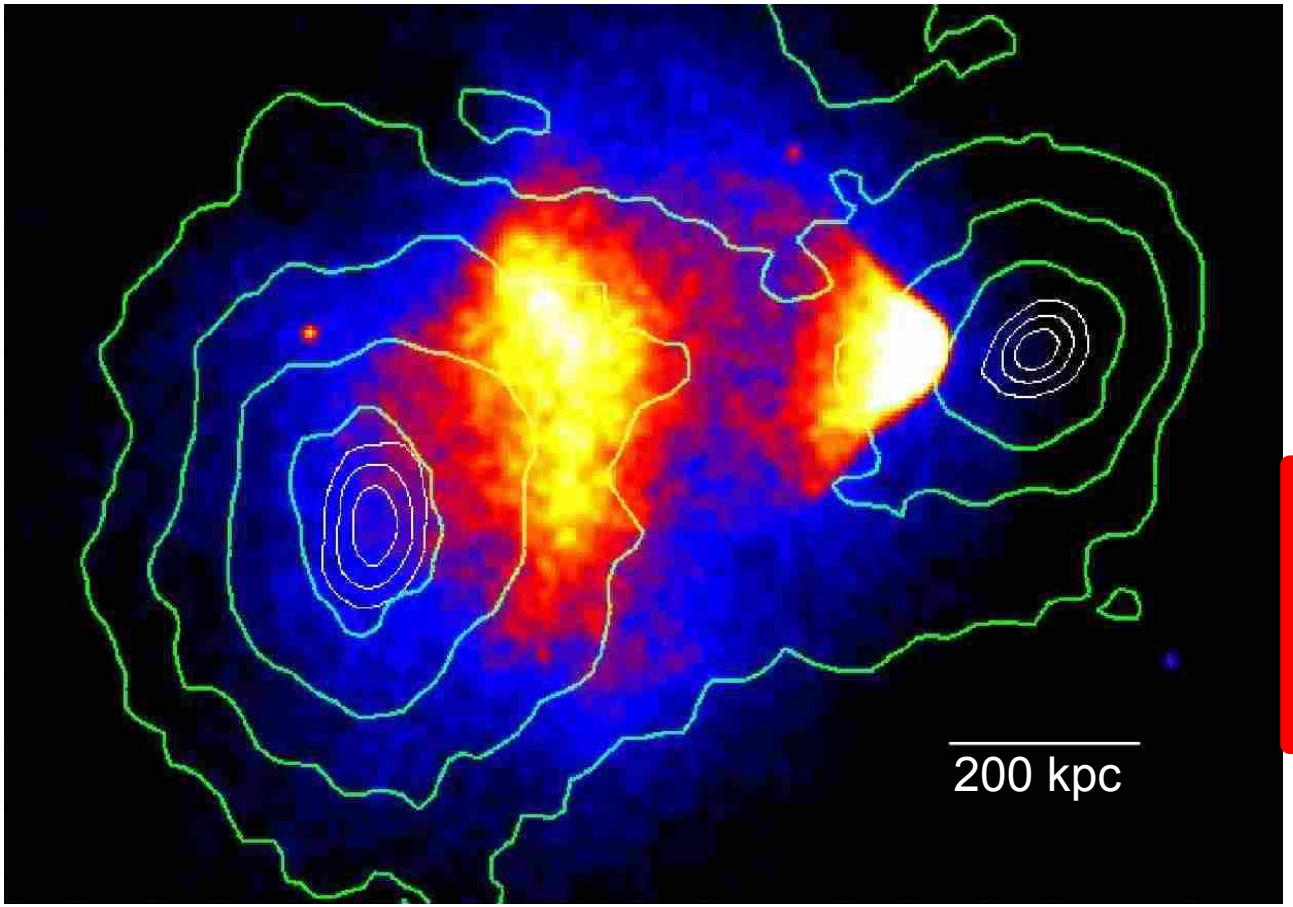
Does it interact with itself (collisions)?

Bullet Cluster (Clowe +06)



Credit: John Wise / KIPAC

$\sigma/m < 1.25$ cm^2/gr
(Randall+08)

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

Structure formation and DM interactions

Onset of structure formation

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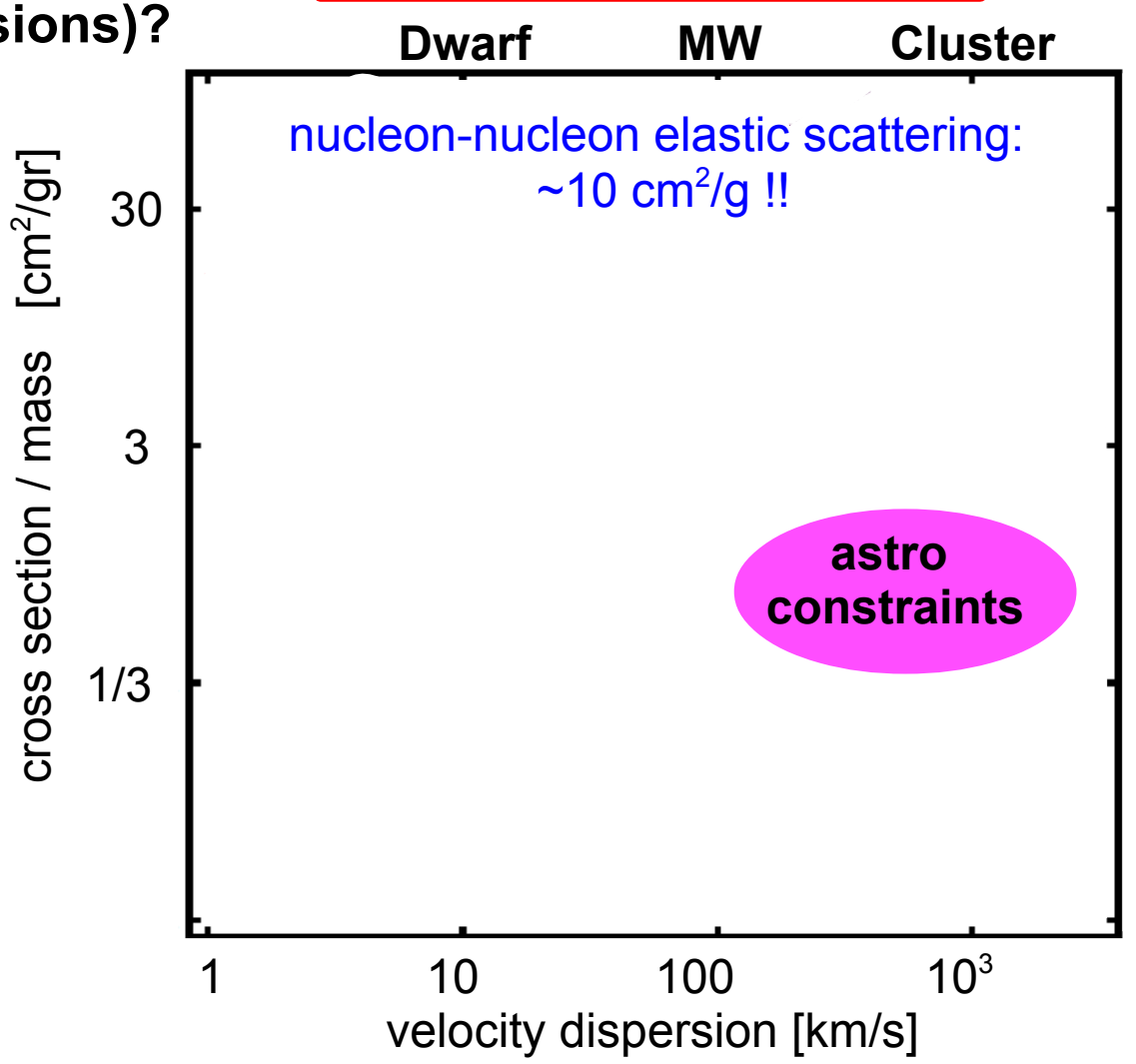
Are non-gravitational DM interactions irrelevant for galaxy formation?

Does it interact with itself (collisions)?



Structure formation and DM interactions

Onset of structure formation

halo mass seed

DM nature

DM interactions ?

Are non-gravitational DM interactions irrelevant for galaxy formation?

Does it interact with itself (collisions)?

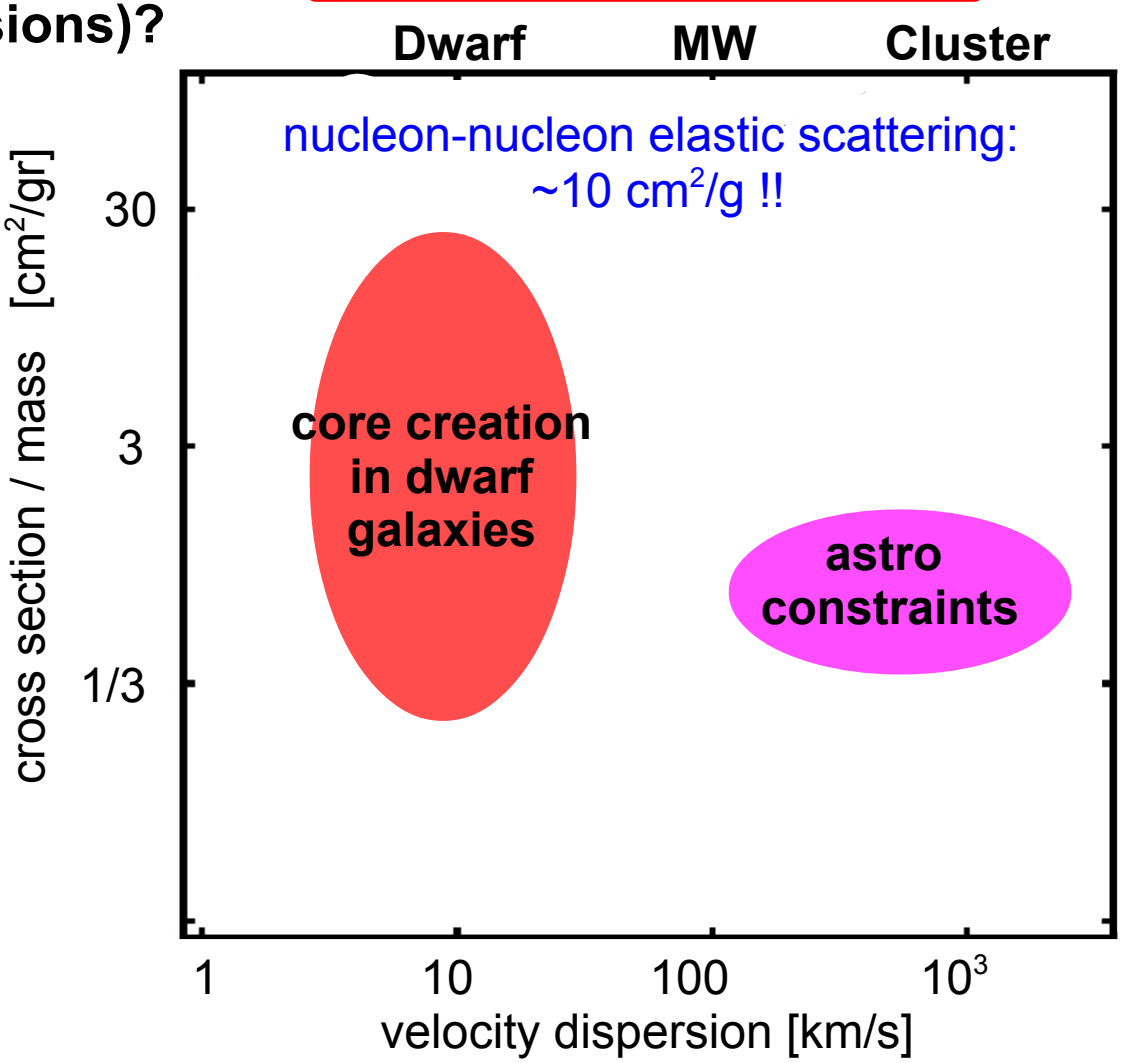
constraints allow collisional DM that is astrophysically significant in the center of galaxies:

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/t_H>

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



Structure formation and DM interactions

Onset of structure formation

halo mass seed

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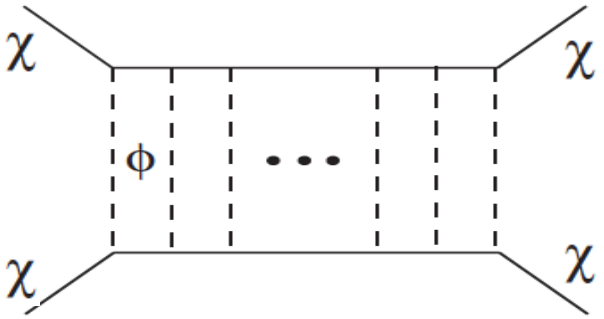
DM interactions ?

Are non-gravitational DM interactions irrelevant for galaxy formation?

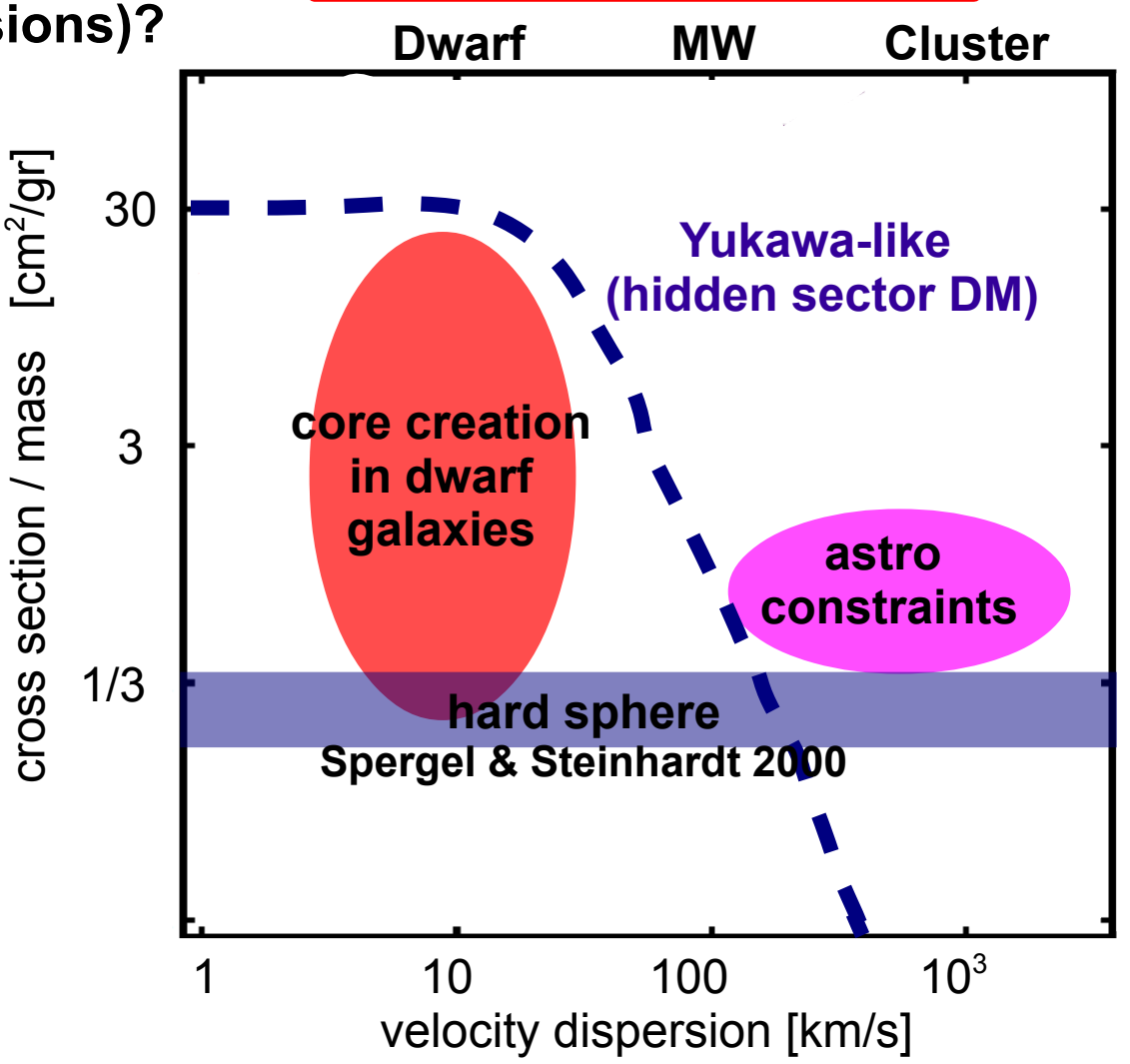
Does it interact with itself (collisions)?

velocity-dependence motivated by a new force in the "dark sector" (analogous to Rutherford scattering)

e.g. Yukawa-like, Feng+09



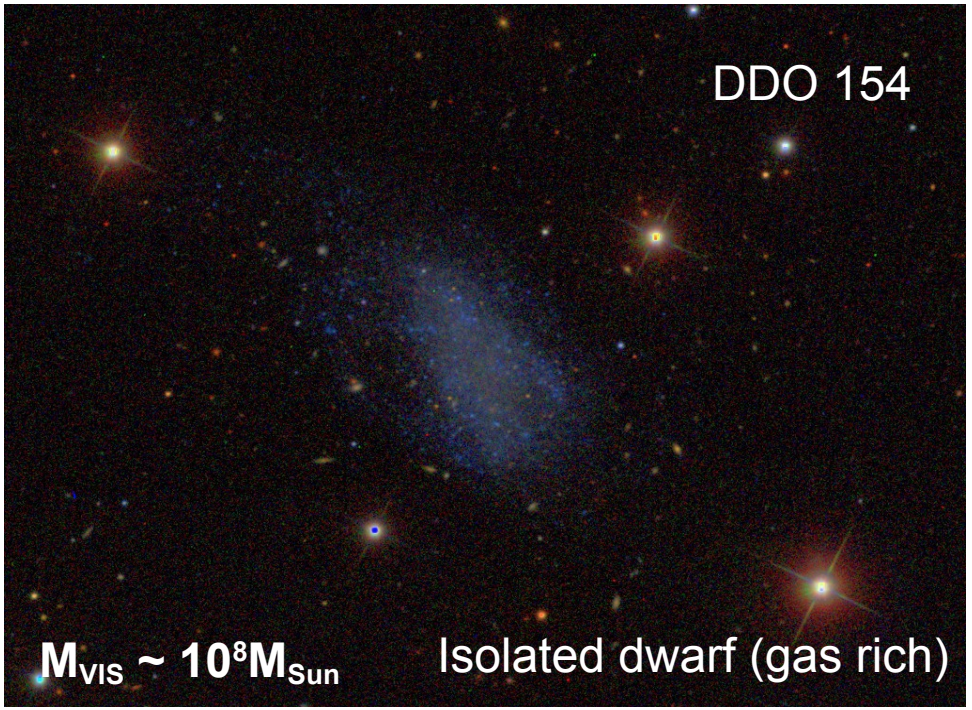
Asymmetric DM is a case model for such interactions

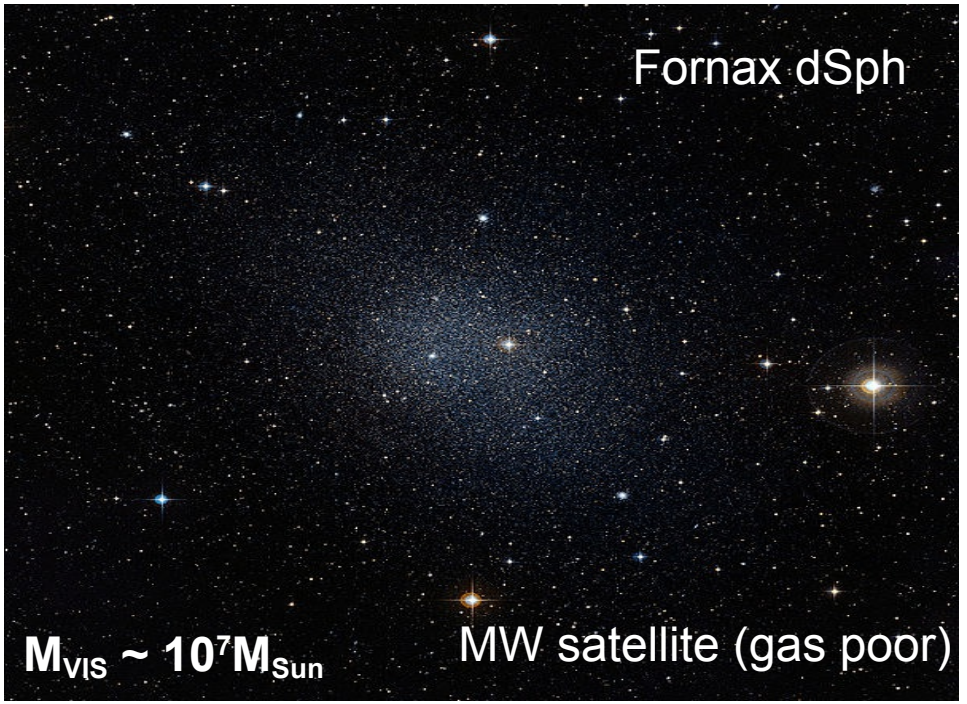


Beyond CDM:

from a purely phenomenological perspective, the CDM hypothesis is just a restricted case of allowed DM microphysics

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)

Theoretical modelling of the galaxy population

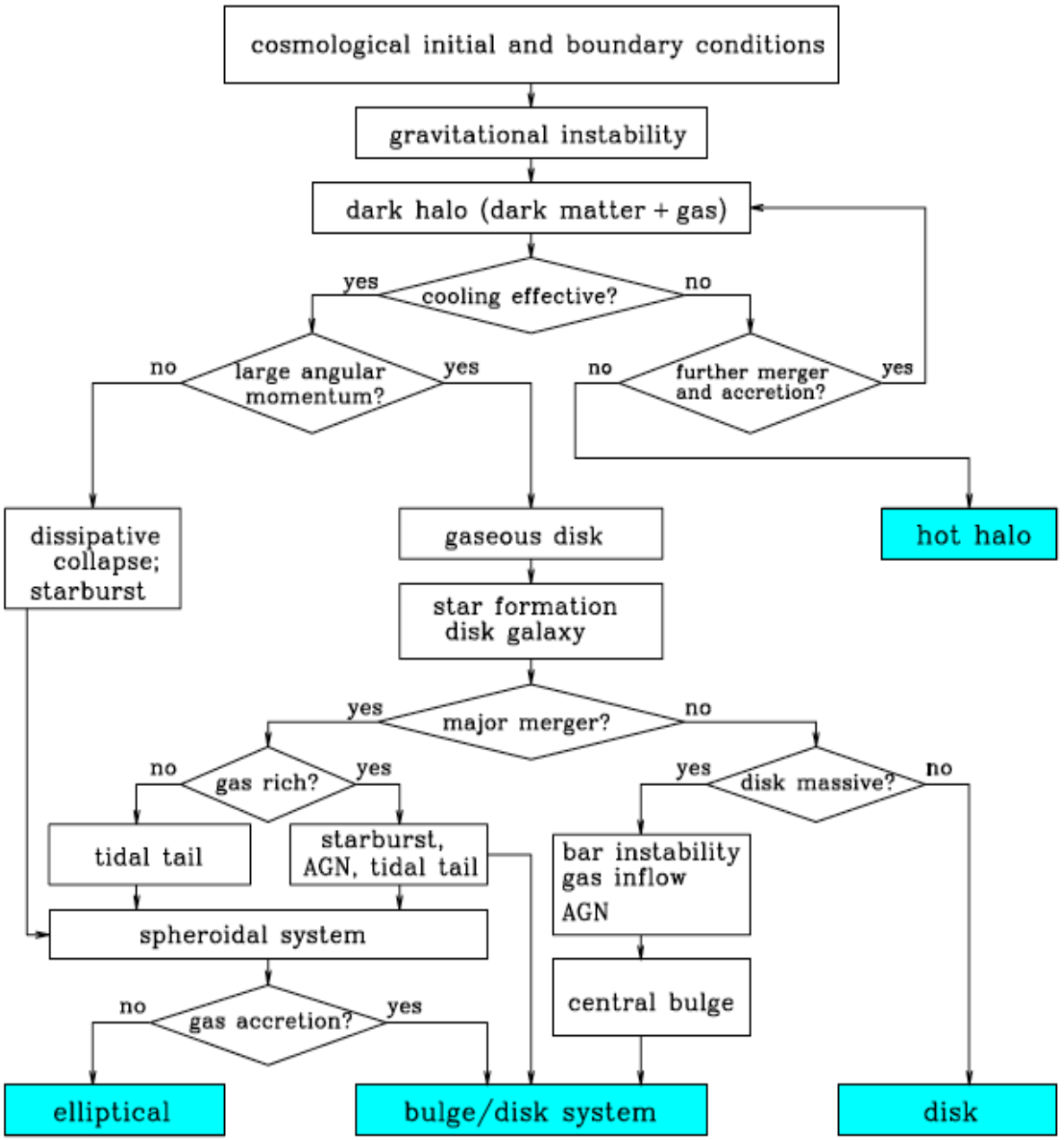
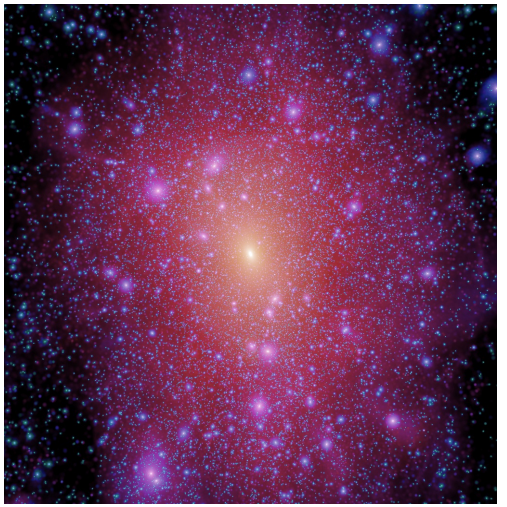


Fig. from Mo, Mao and White, 2010

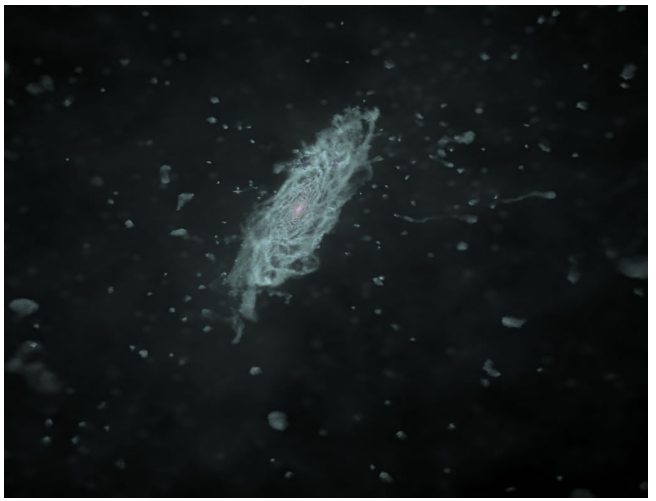
DM gravity only



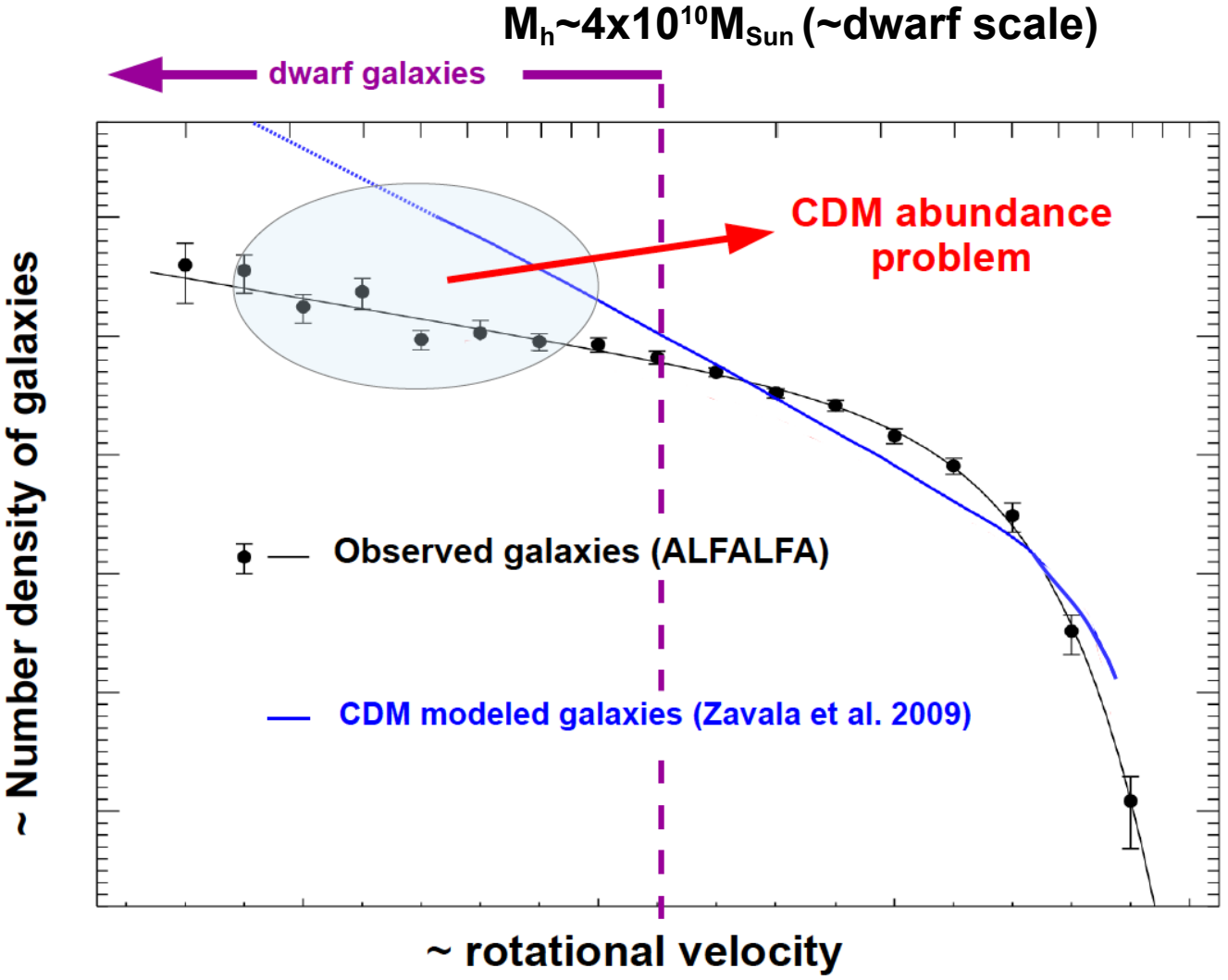
Aquarius project Springel+08

"Eris" simulation Guedes+11

gas and stellar physics



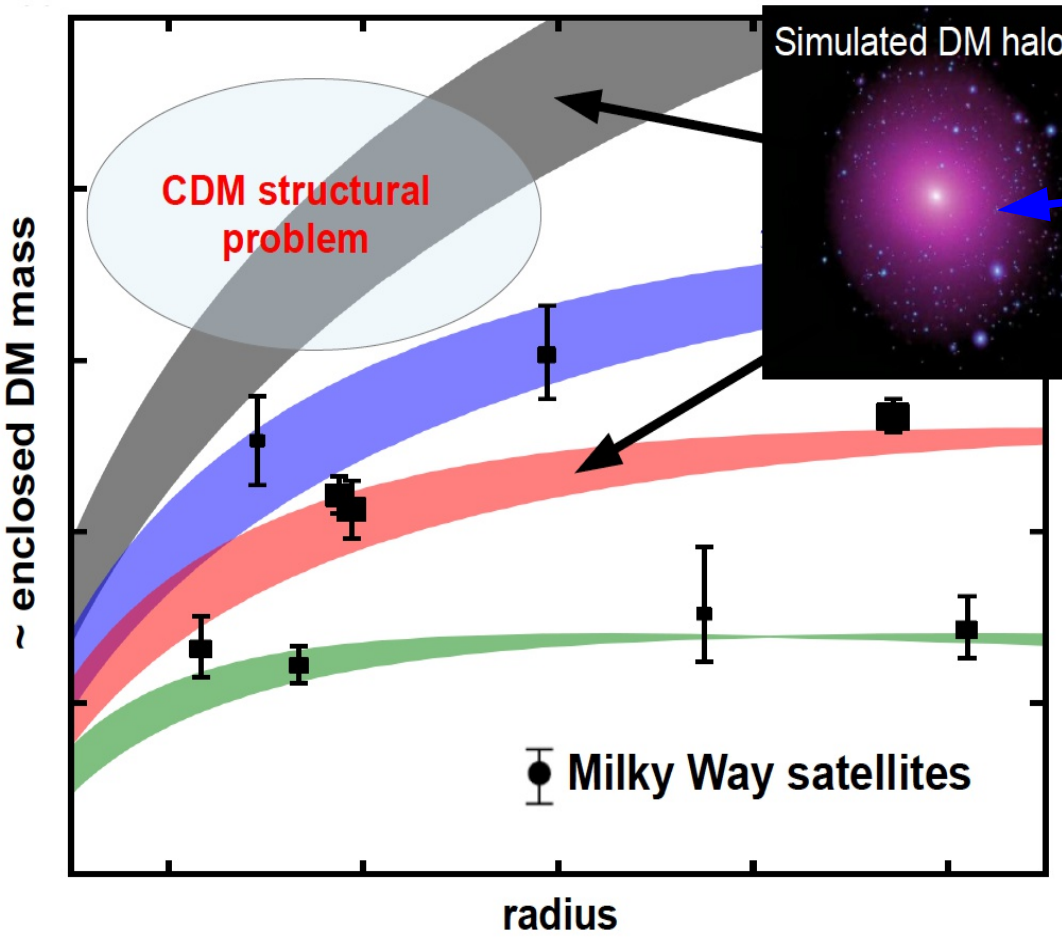
Observed abundance of isolated dwarf galaxies

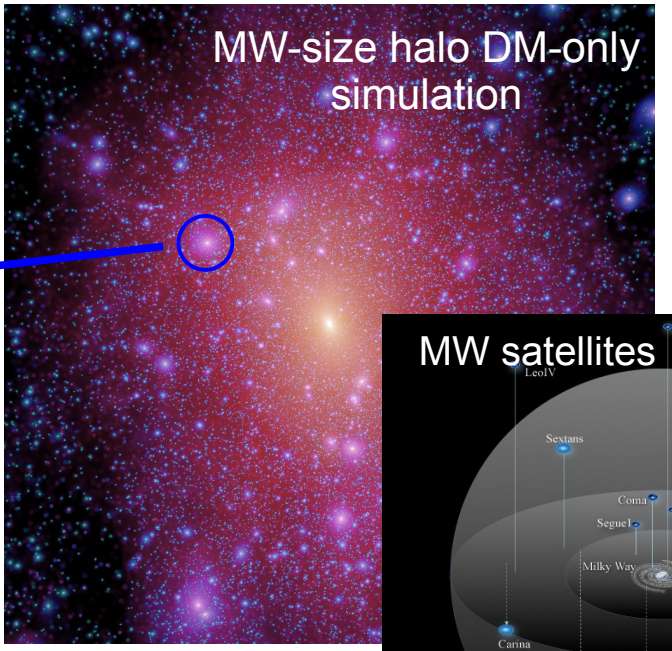


CDM + **simple** gal. form. models clearly overpredict the abundance of field dwarfs

This an unsolved problem within CDM!

The “too big to fail” problem

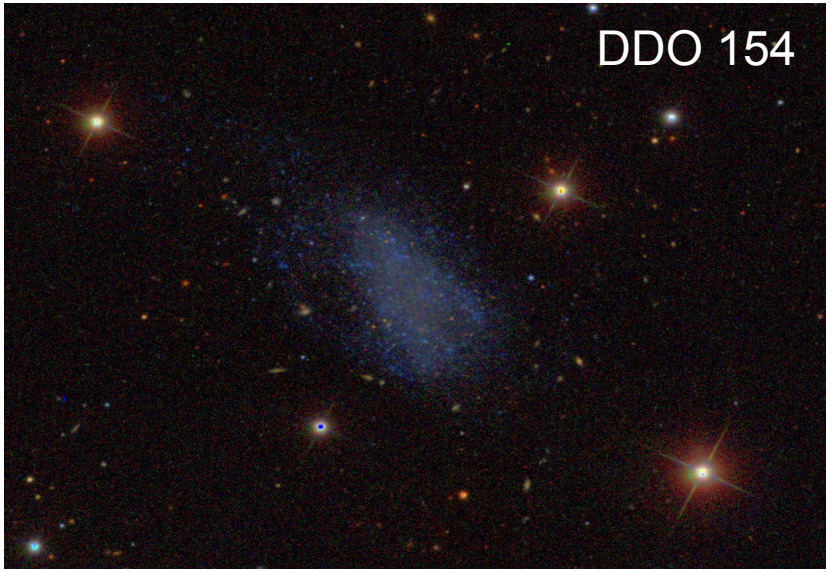


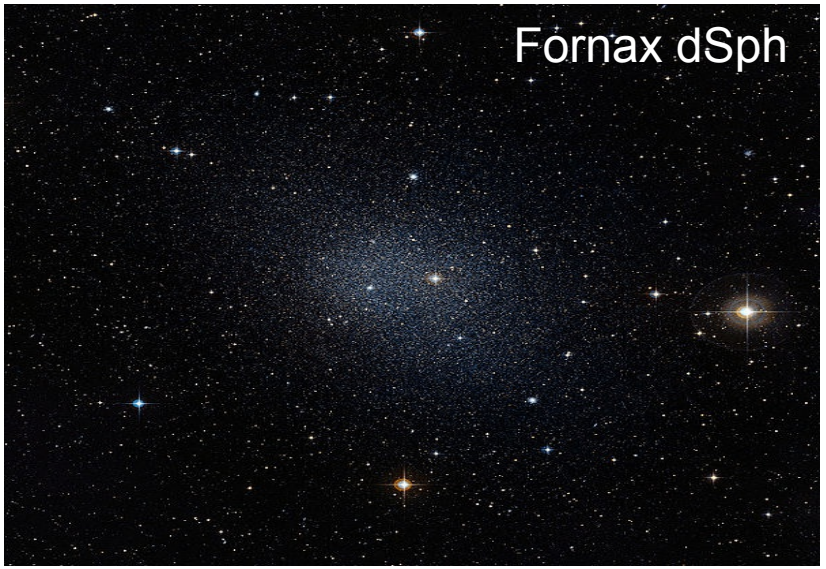


The most massive CDM-MW-subhaloes seem to be too centrally dense to host the MW dSphs
(problem extends beyond MW: Ferrero+12, Garrison-Kimmel+14, Papastergis+14)

Unsolved problem in CDM!!

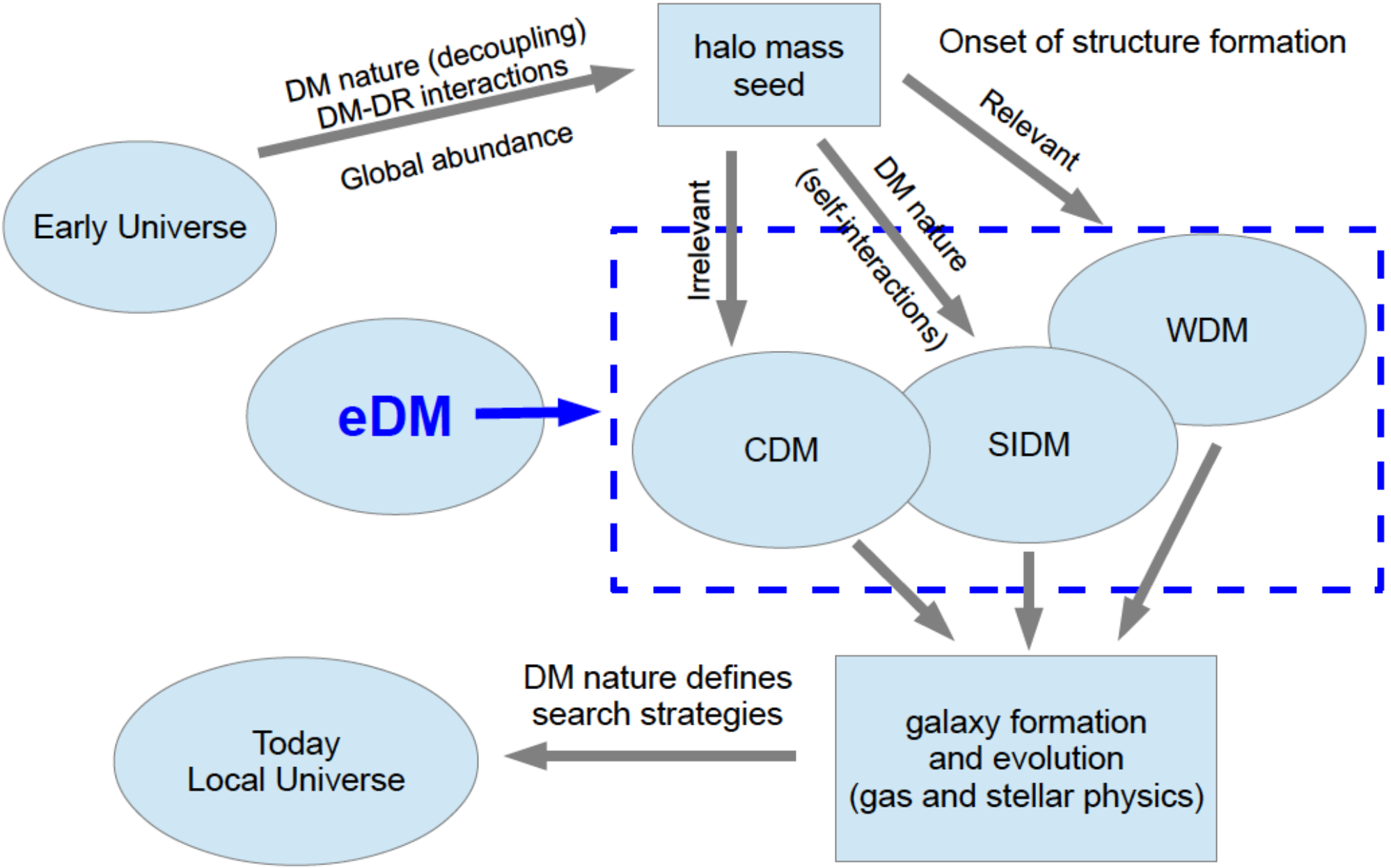
Clues of new DM physics from dwarf galaxies?





- The dwarf-scale challenges could be related to:
  - **Misinterpretation of observational data** (e.g. incomplete reconstruction of the phase-space distribution,...)
  - **Incomplete knowledge of galaxy formation** (e.g. Indirect energy injection into the DM halo by supernovae,...)
  - **New DM physics**: DM might be **collisional**: SIDM (e.g. hidden sector DM)

Towards an effective theory of structure formation



Proof of concept to avoid CDM challenges:

(i) abundance of dwarfs in the field
(ii) too big to fail problem
(iii) core-cusp problem

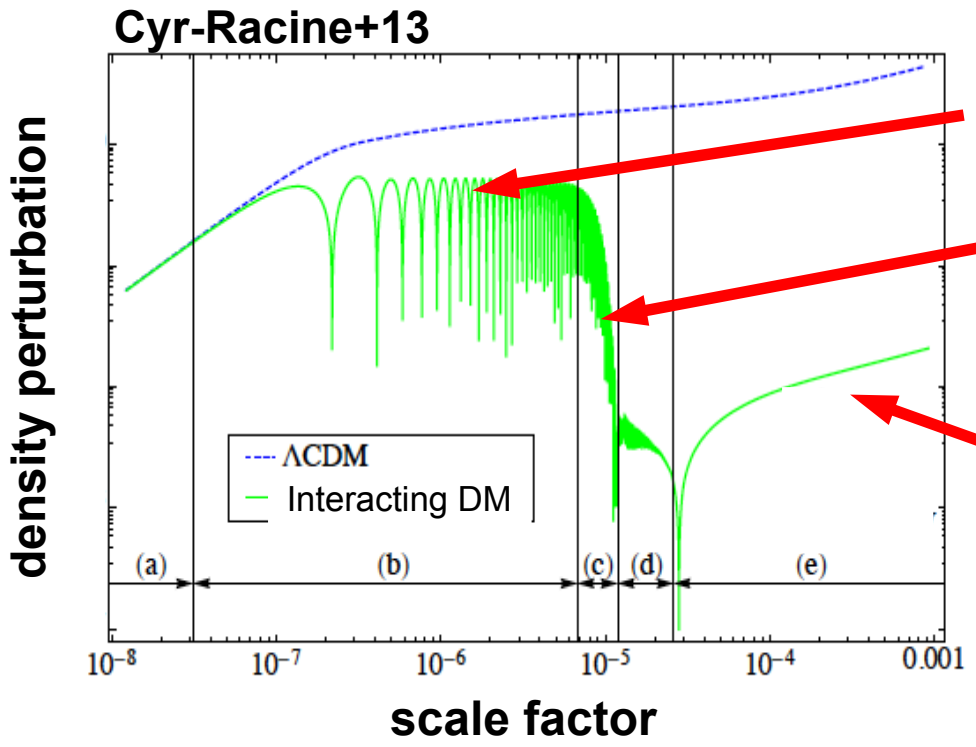
DM interactions with relativistic particles in the early Universe

+

DM-DM self-scattering in the late Universe

A richer growth of DM perturbations

Interactions between DM and relativistic particles (e.g. dark radiation) in the early Universe introduce collisional damping and "dark" acoustic oscillations (DAOs) to the linear growth of primordial DM perturbations (phenomena analogous to that of the photon-baryon plasma)

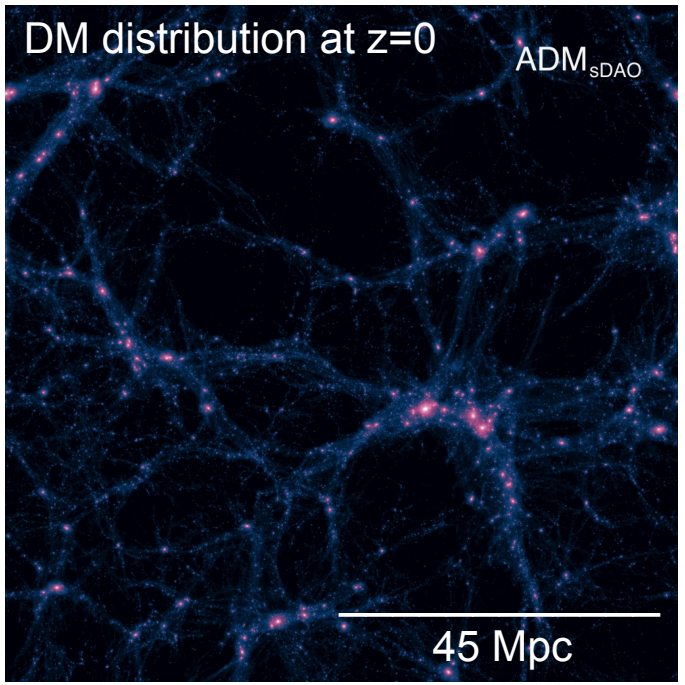


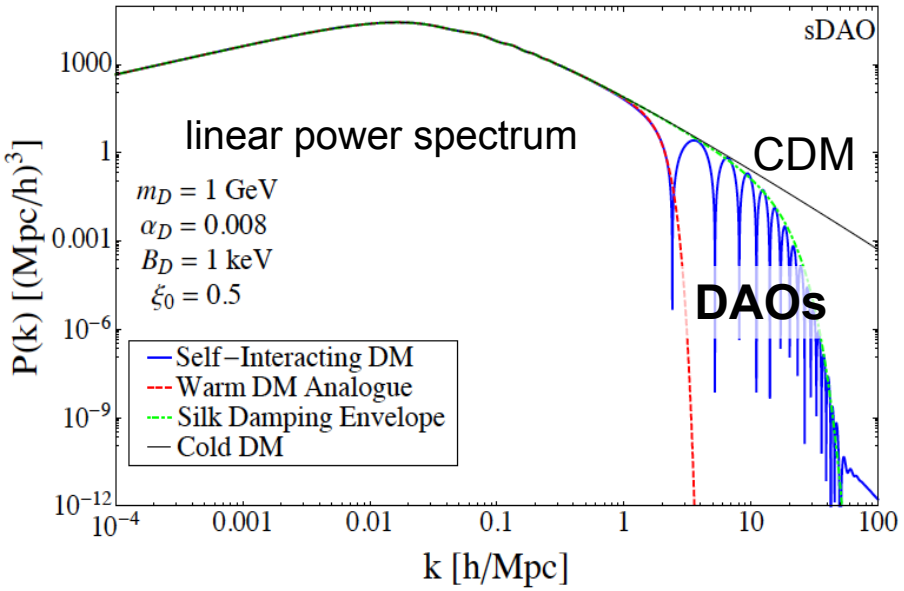
dark radiation pressure counteracts gravity creating DAOs

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

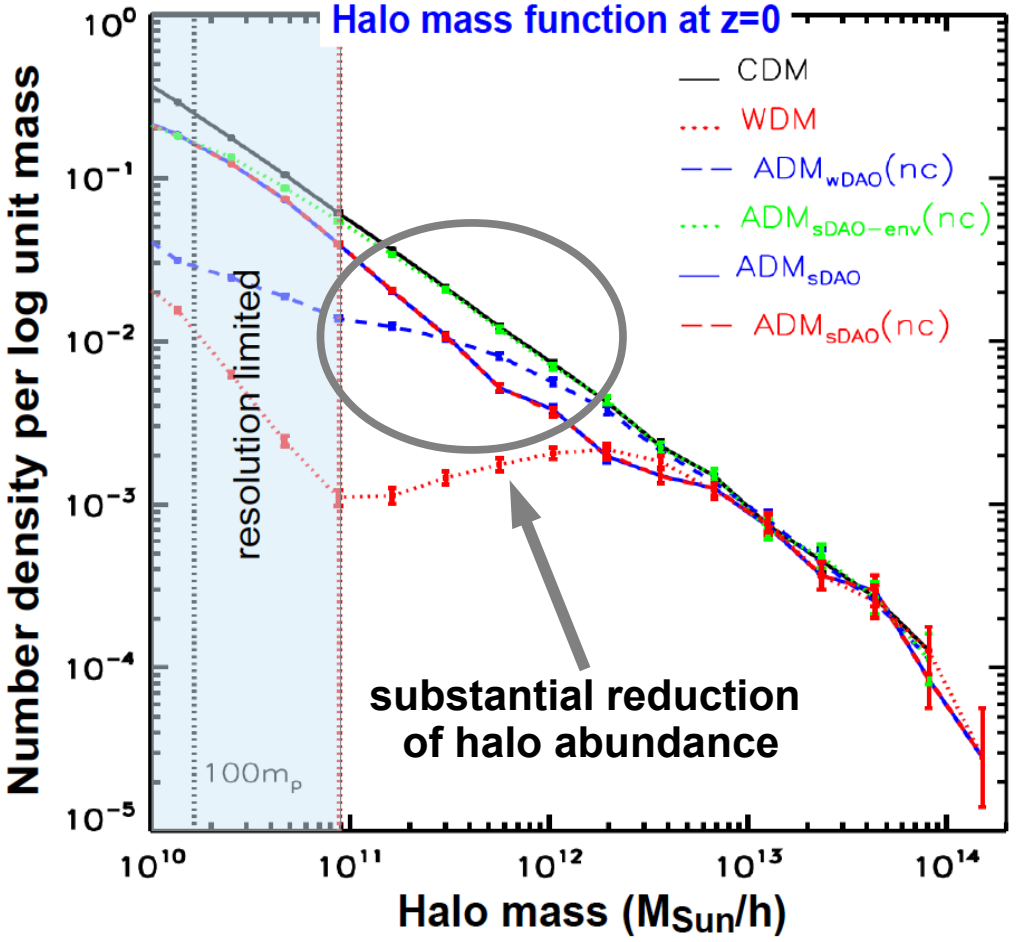
once kinetic decoupling (DM-DR) occurs DM behaviour is like CDM

A richer growth of DM perturbations





Buckley, Zavala + 2014

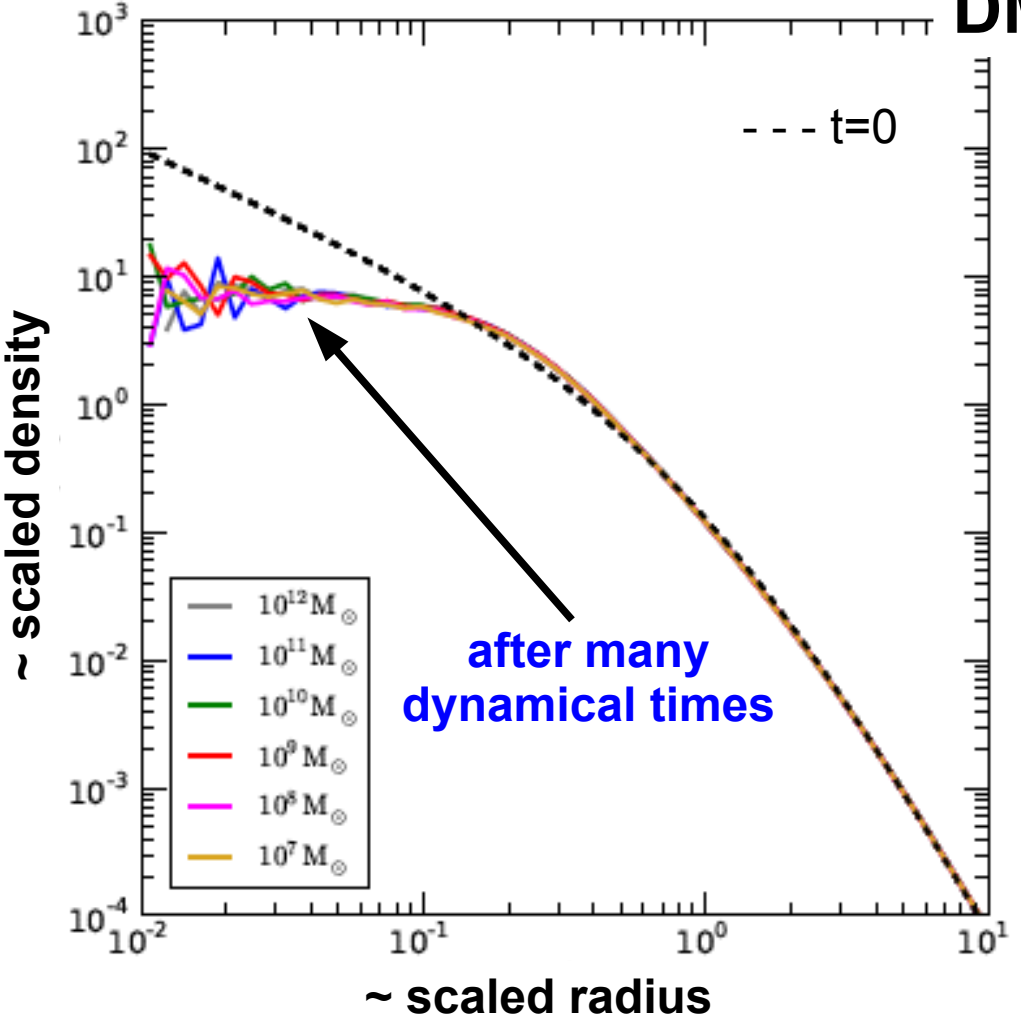


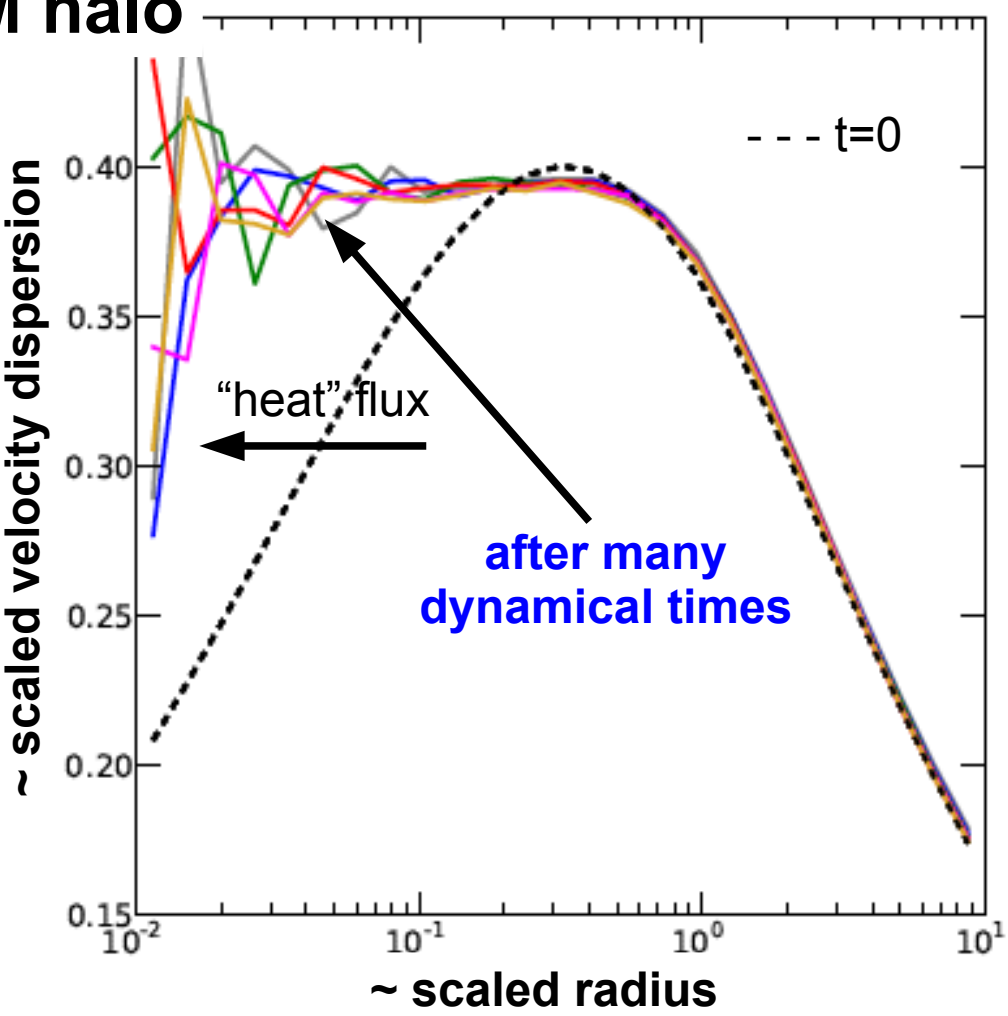
Interactions between DM and relativistic particles in the early Universe introduce collisional damping and DAOs to the linear power spectrum.

Their effects are still visible at z=0!!
potential to solve the CDM abundance problem
(proof of concept only)

DM self-scattering: forming a core through collisions

DM halo





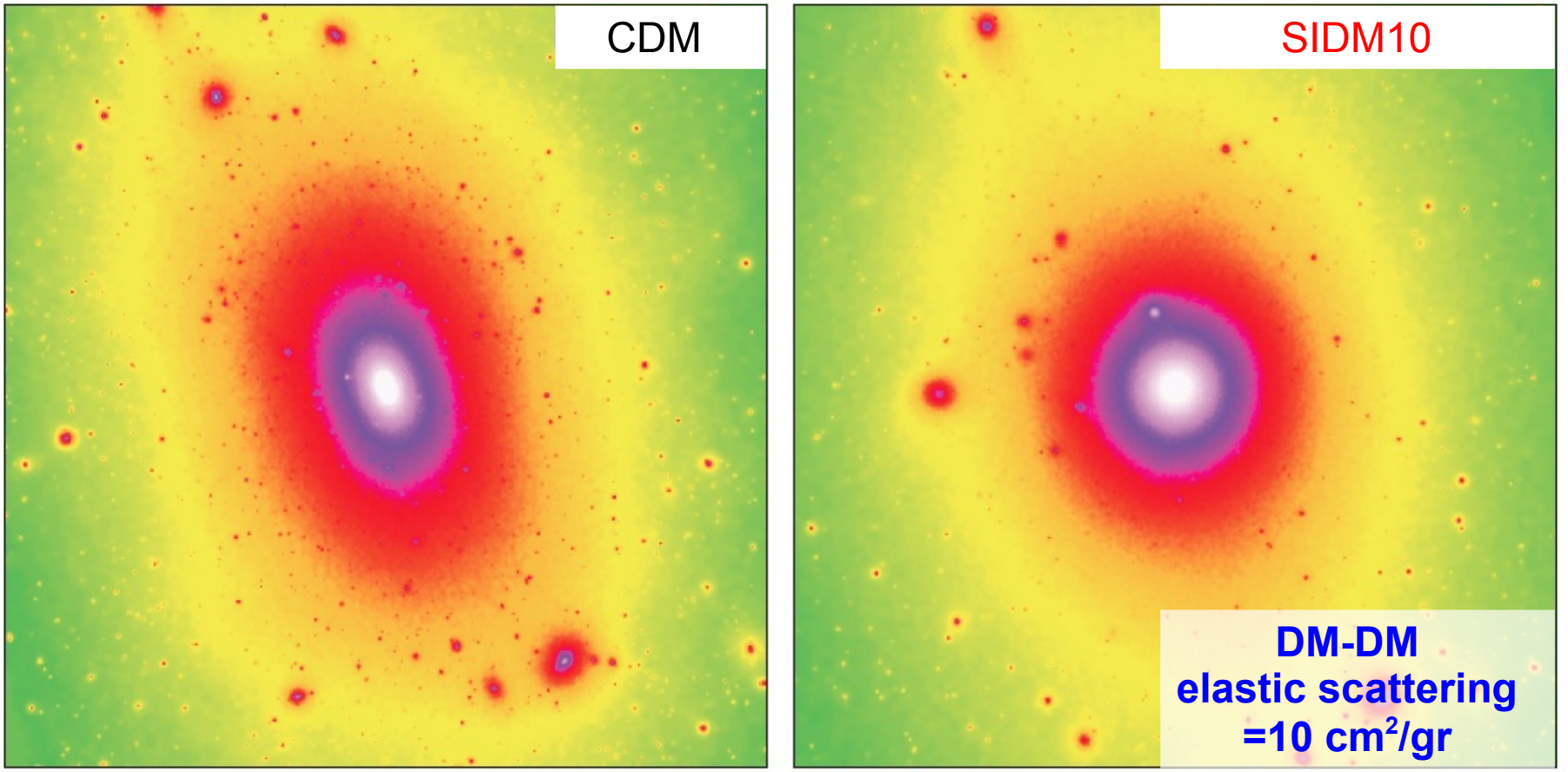
Collisional Boltzmann equation

$$\frac{df}{dt} = C[f, \sigma_{\rm sc}] \quad \rightarrow \quad \frac{d\rho_\chi}{dt} \sim -\rho_\chi^2 \left(\frac{\sigma_{\rm sc}}{m_\chi}\right) \sigma_{\rm vel}$$

N-body simulations with DM collisions: Self-Interacting DM (SIDM)

Probabilistic method for elastic scattering on top of code for gravitational interactions

Milky-Way-size halo: Vogelsberger, **Zavala** & Loeb 2012



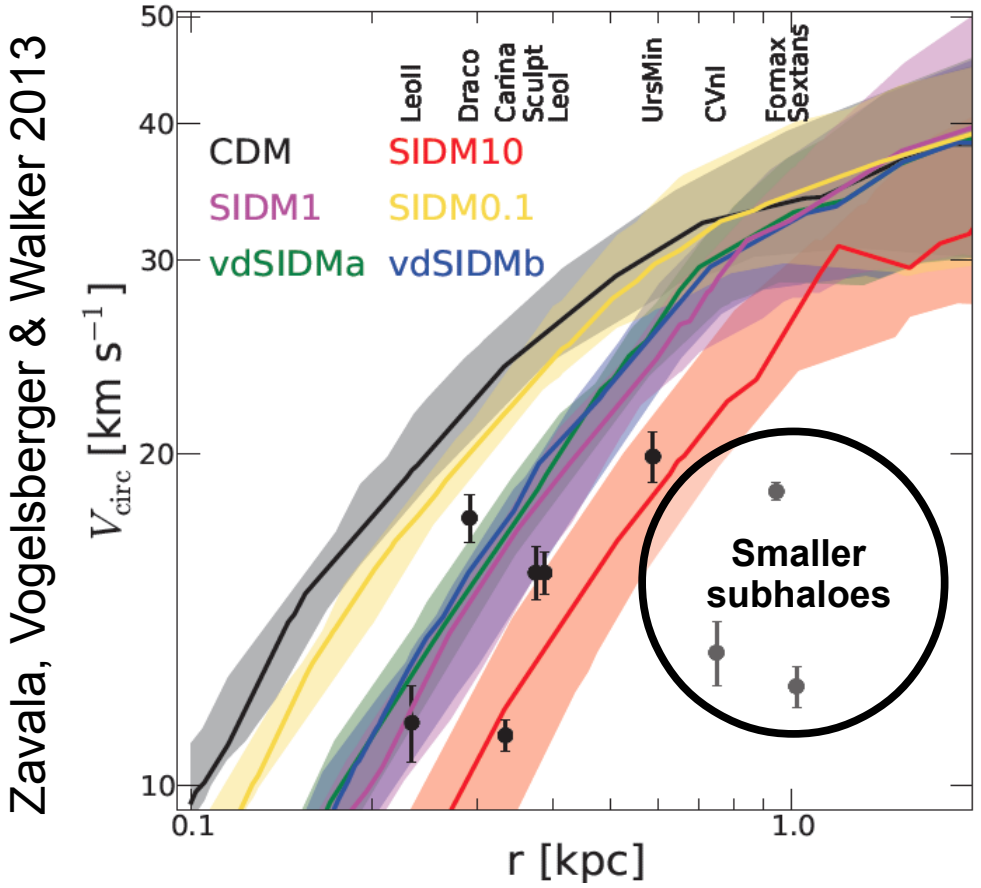
DM collisions (~ a few per particle in a Hubble time in the denser regions) create density cores and isotropize the orbits

Inner structure of SIDM dark satellites

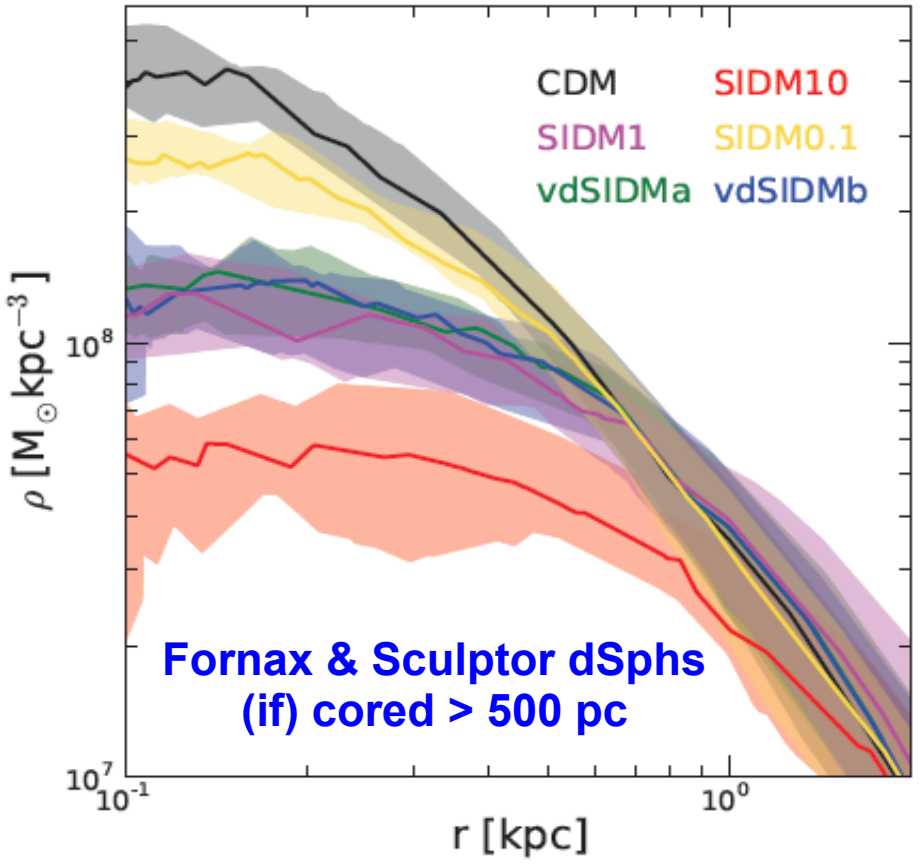
- **Allowed *elastic* SIDM models significantly reduce the structure CDM problems: (Vogelsberger, Zavala & Loeb 2012)**

- **Elastic SIDM only works as a distinct DM-only alternative to CDM if 0.6 cm^2/gr < s / m < 1 cm^2/gr or velocity-dependent (MW-halo-mass-dependent) (Zavala, Vogelsberger & Walker 2013)**

SIDM can avoid the too big to fail problem

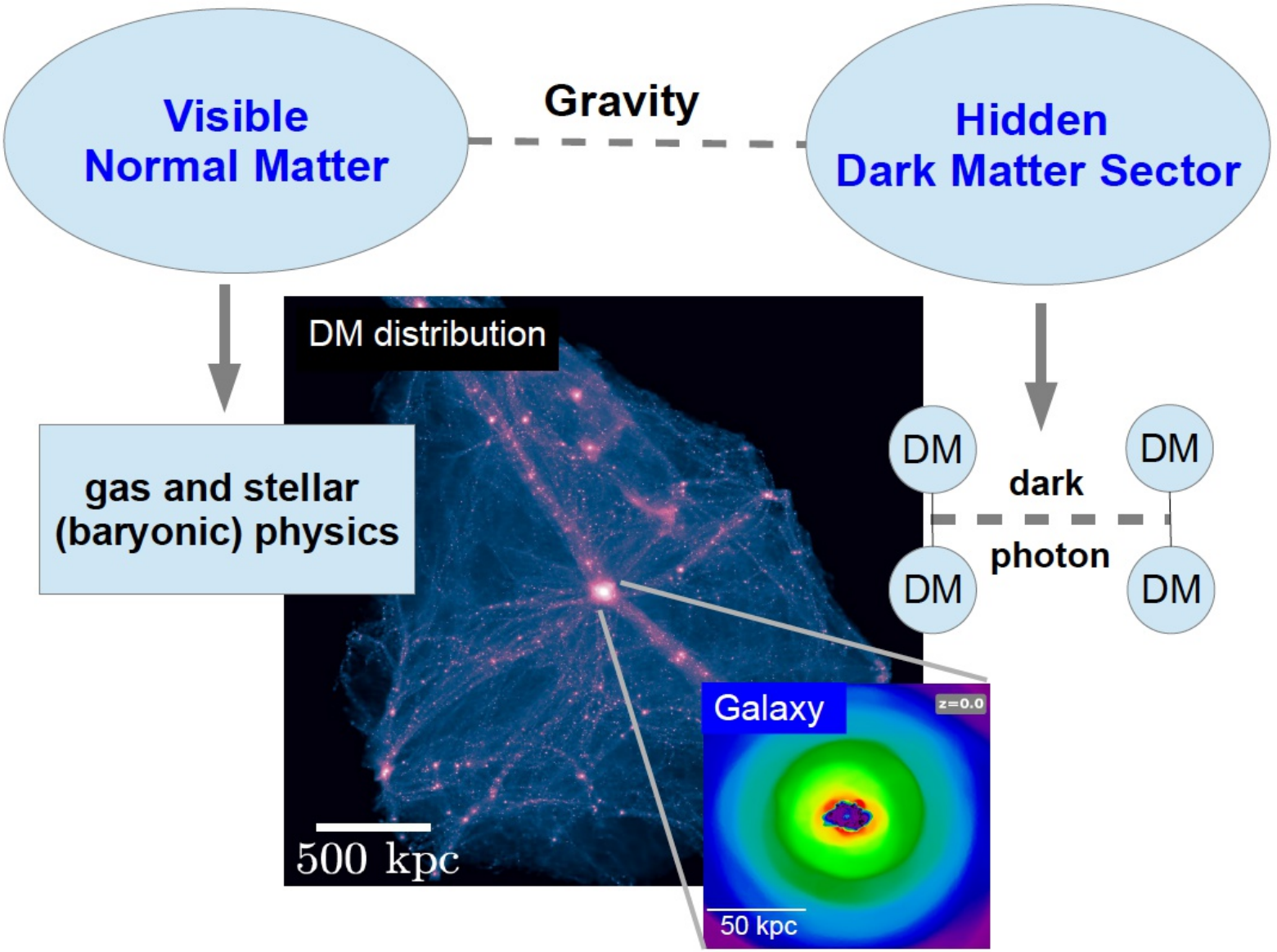


SIDM predicts sizeable DM cores



Galaxies in a SIDM Universe

How does galaxy formation occurs in SIDM? Will the coupling of baryonic physics and DM collisionality help (or hinder) constrain SIDM models?



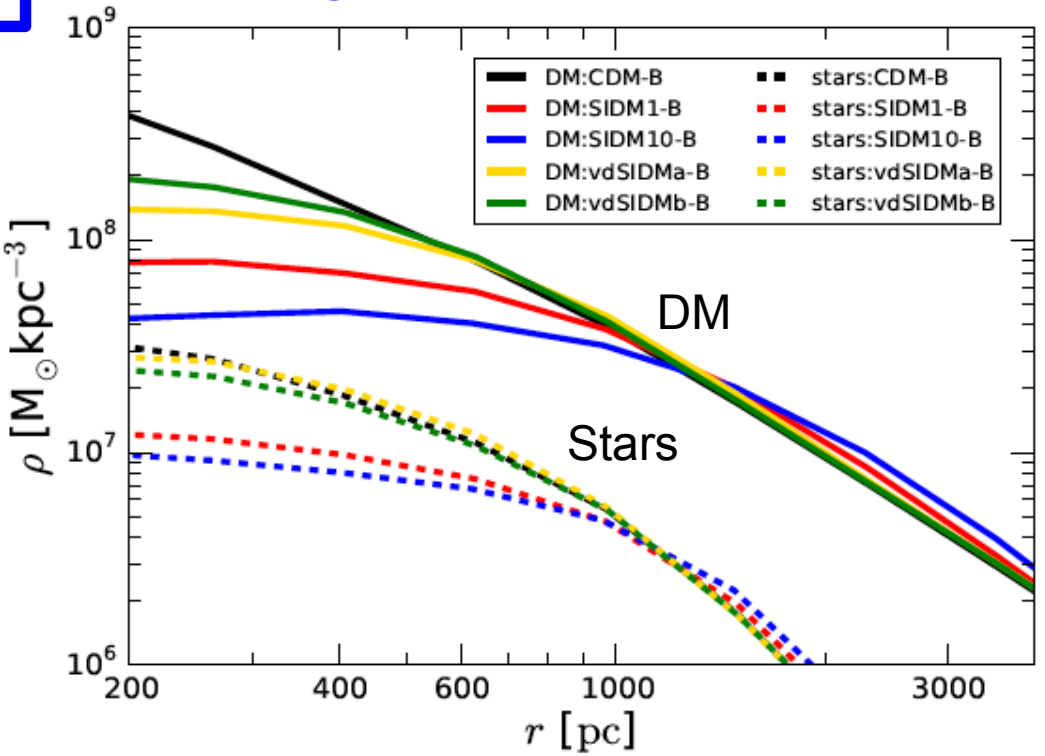
Galaxies in a SIDM Universe

First hydrodynamical simulation of a galaxy in a SIDM cosmology

Vogelsbeger, Zavala+14

- baryonic physics implementation (Illustris): hydrodynamics, star formation, SNe feedback
- effective "non-bursty" star formation history (inefficient baryon → DM energy injection)
- **global galaxy properties <u>similar</u> (<10%) to CDM**

Stellar cores tied to SIDM cores in DM-dominated systems (signature of DM collisions)



A signature of DM collisions might be hidden in the distribution of stars in dwarf galaxies

Concluding remarks

An effective (more generic) theory of structure formation **must consider a broader range of allowed DM phenomenology** (DM interactions, different P(k)...) coupled with our developing knowledge of galaxy formation/evolution

First highlights of the effective theory:

- it preserves the large-scale successes of CDM and “naturally” avoids most of its small-scale (dwarf galaxies) challenges (**partially proof of concept only**)
- first hydro simulations in SIDM 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