Towards an Effective THeory Of Structure formation (ETHOS)

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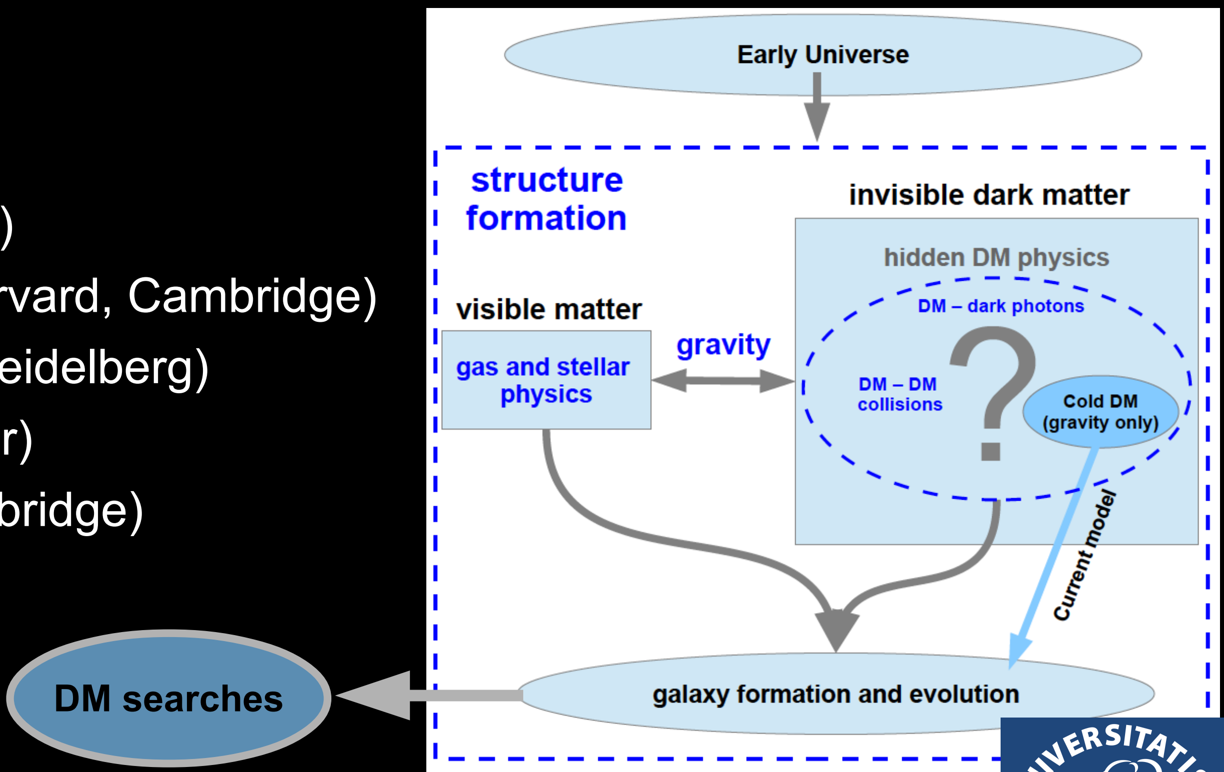
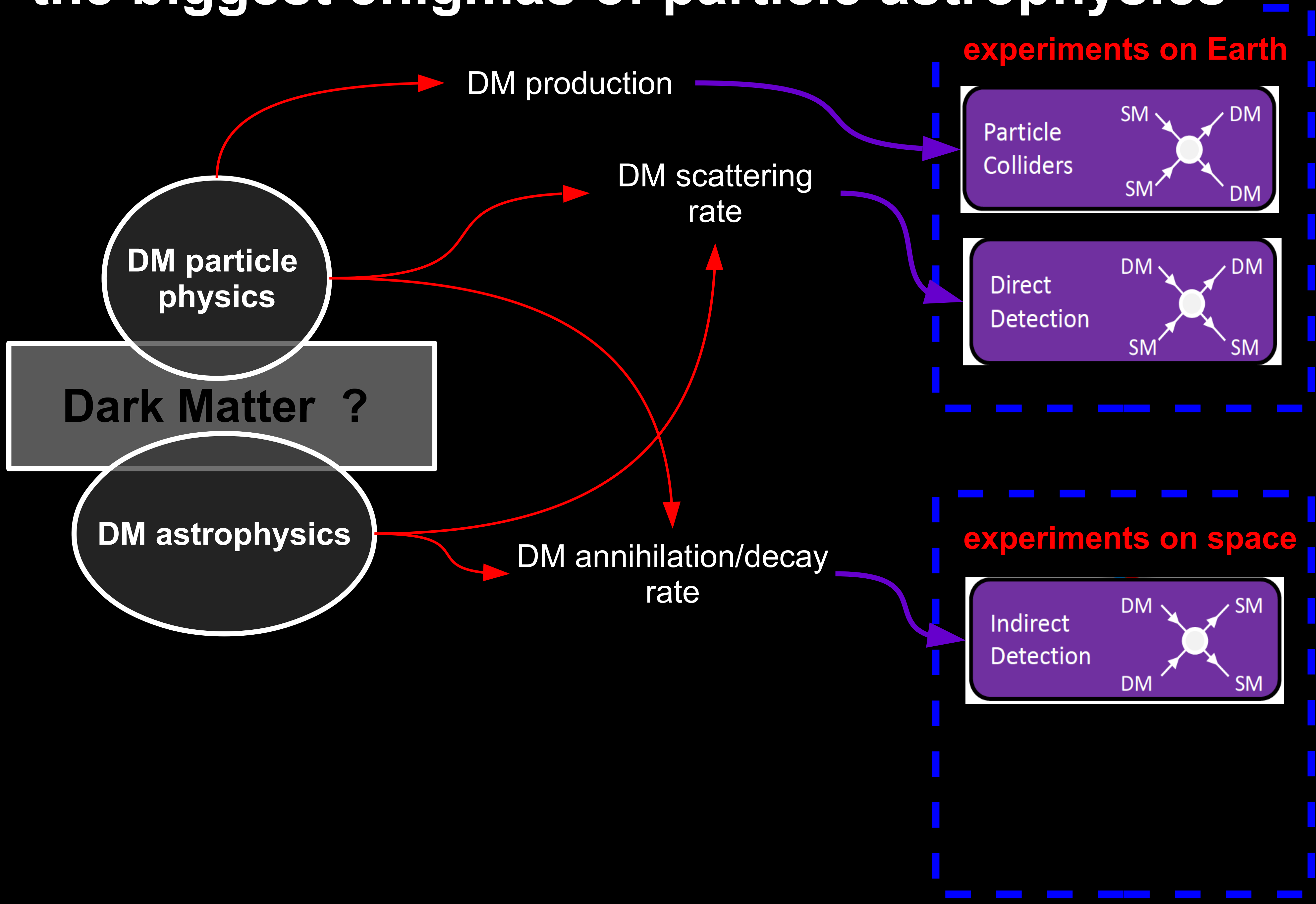


TeV Particle Astrophysics, CERN, September 2016

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



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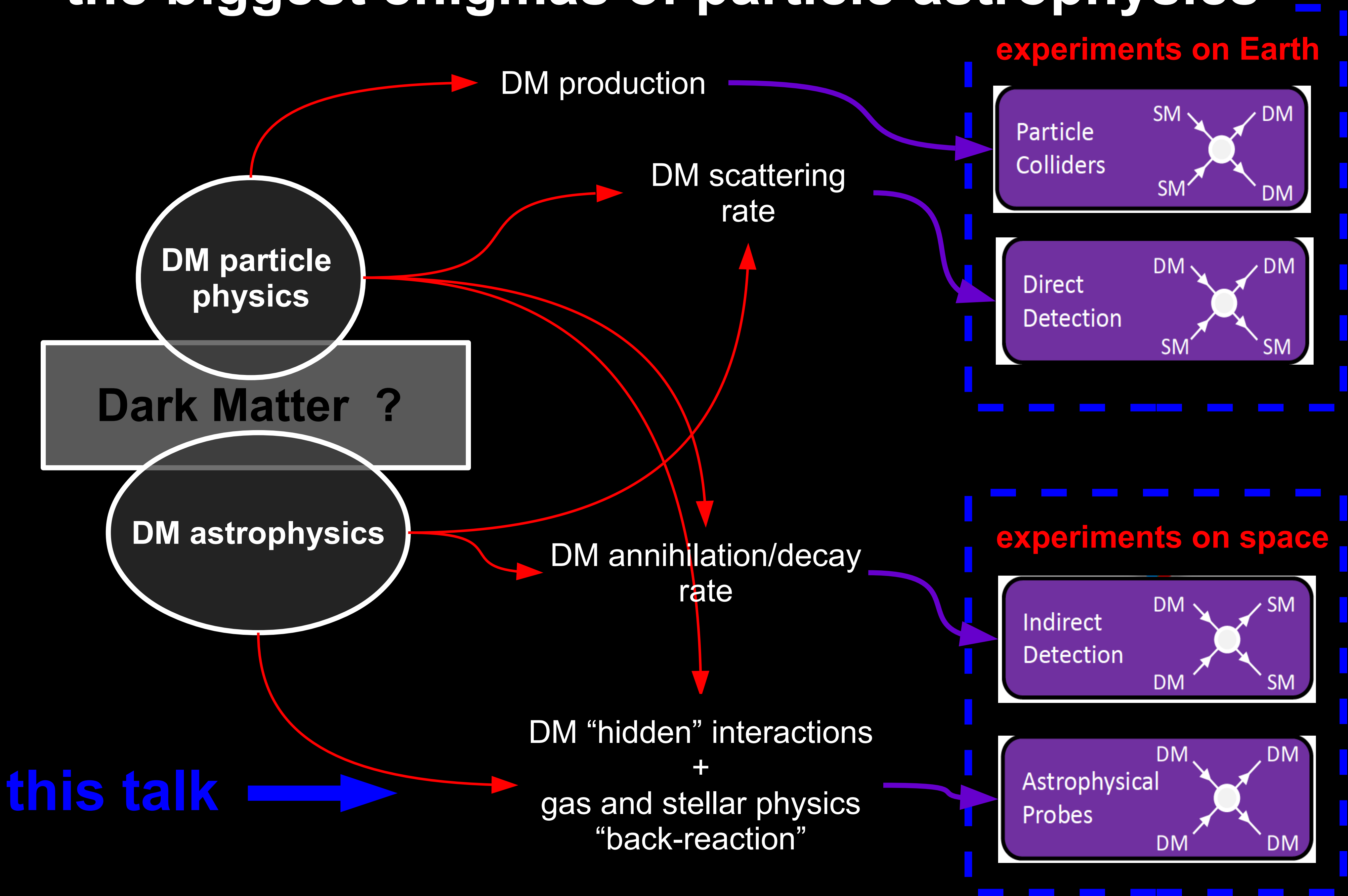


most of these efforts rely on our knowledge of the DM phase space distribution across time

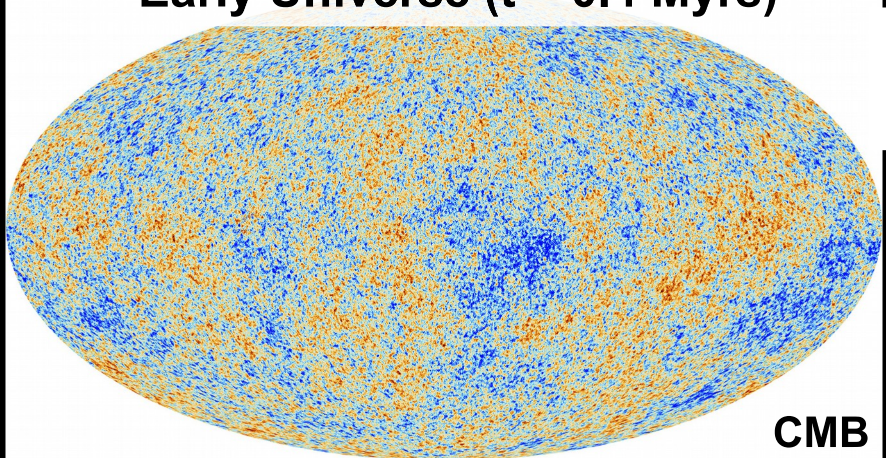
↓

structure formation theory

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

Credit: ESA and the Planck Collaboration

Early Universe (t ~ 0.4 Myrs)

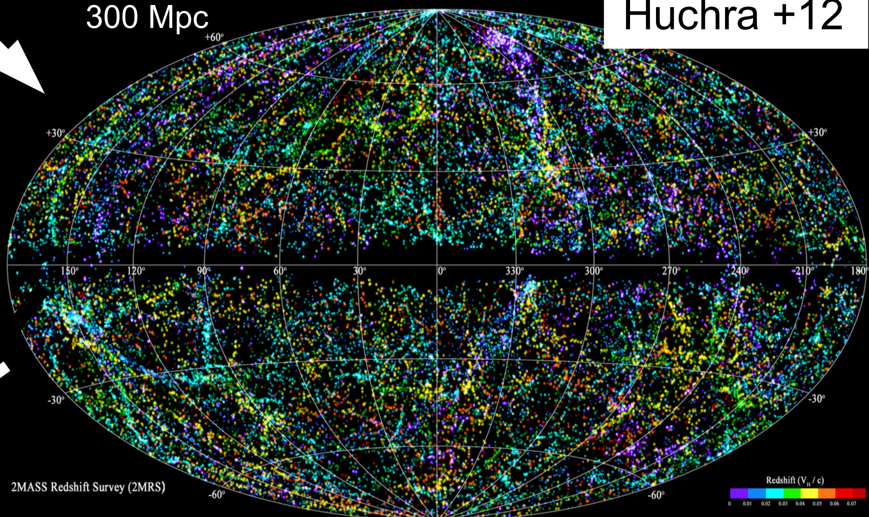


$$\frac{\delta \rho_m}{\rho_m} \sim 10^{-3}$$

Universe today (t ~ 13.8 Gyrs)

300 Mpc

Huchra +12



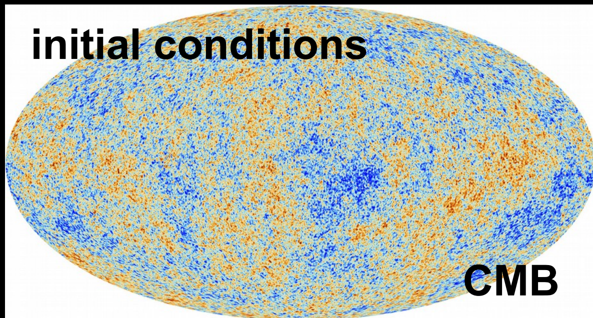
2MRS galaxy "map", large-scale structure

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

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

galactic scales

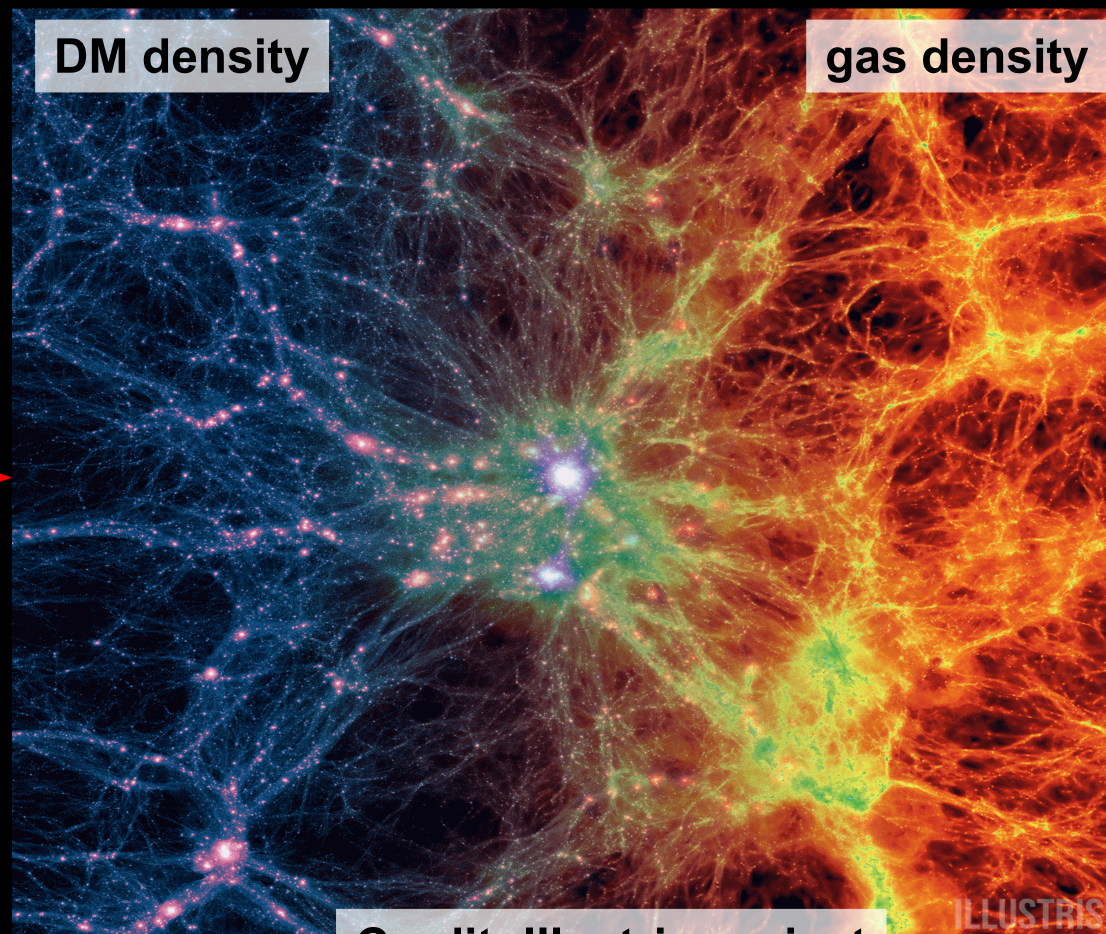
The Cold Dark Matter (CDM) hypothesis is the cornerstone of the current structure formation theory



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

cosmological simulations

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



Credit: Illustris project

100 Mpc (comoving)

2000 CPU years!!

despite the spectacular progress in developing a structure formation 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?

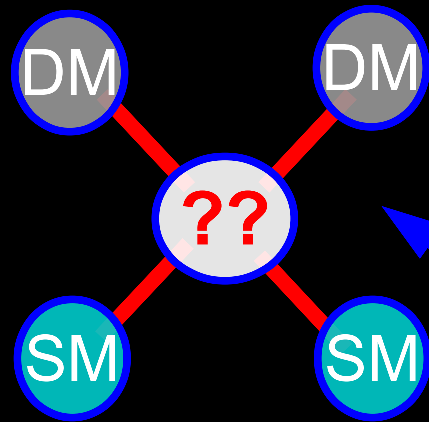
In the physics of galaxies, is gravity the only dark matter interaction that matters?

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

non-gravitational DM interactions and structure formation

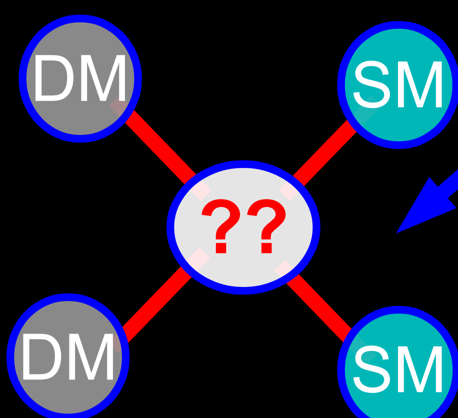
What is the nature of dark matter?

Scattering with nuclei



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)

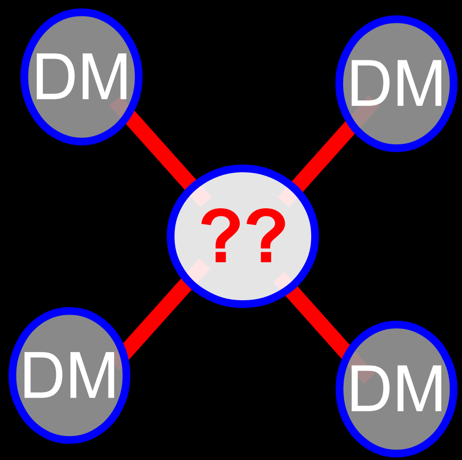
1 cm^2/g ~ 2 barns/GeV

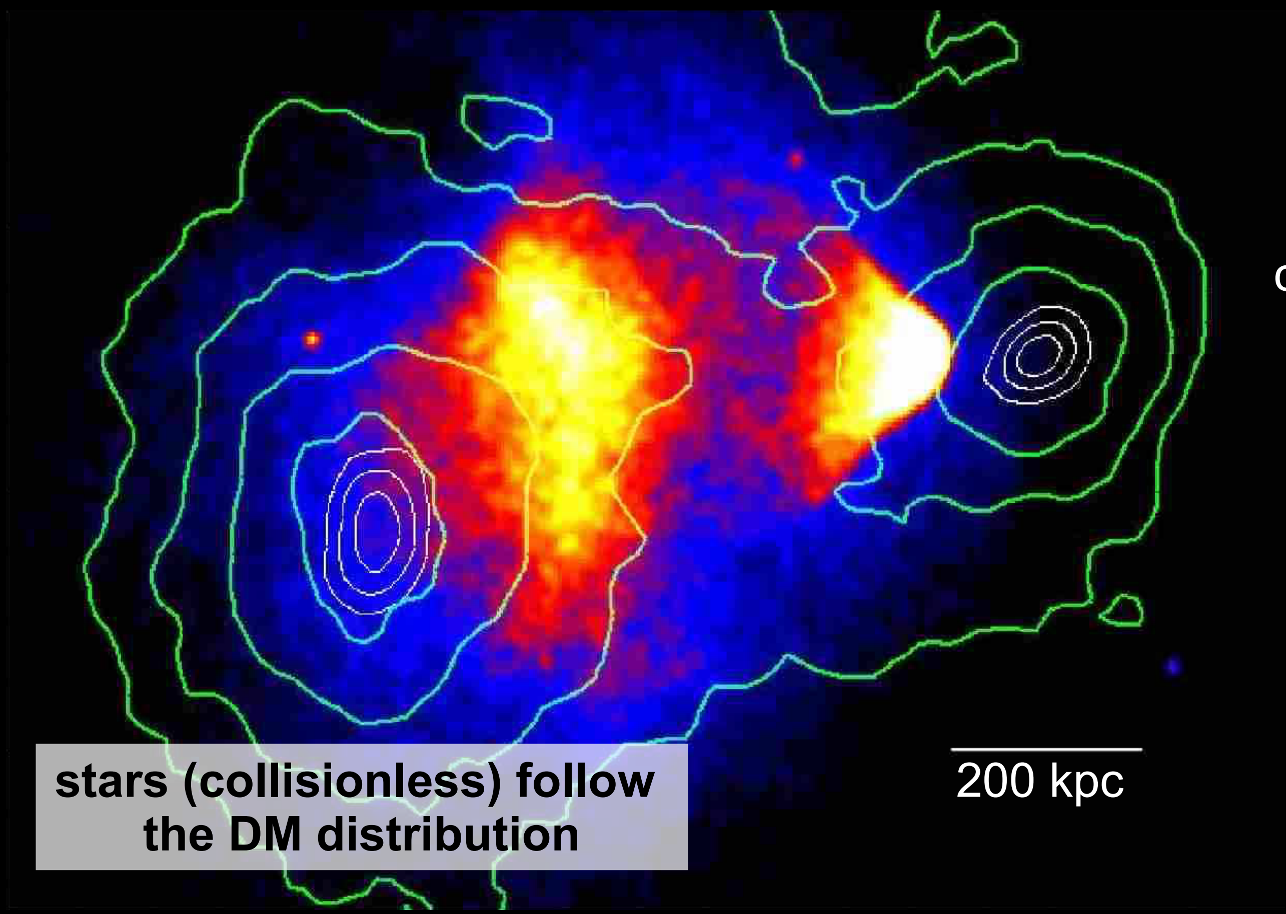
dark matter is quite “dark” (invisible)

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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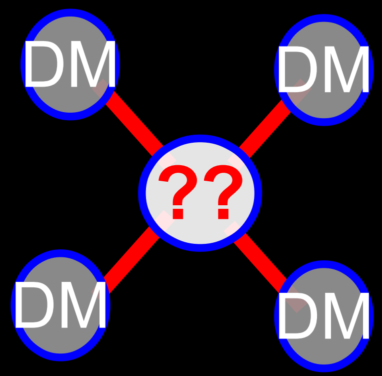

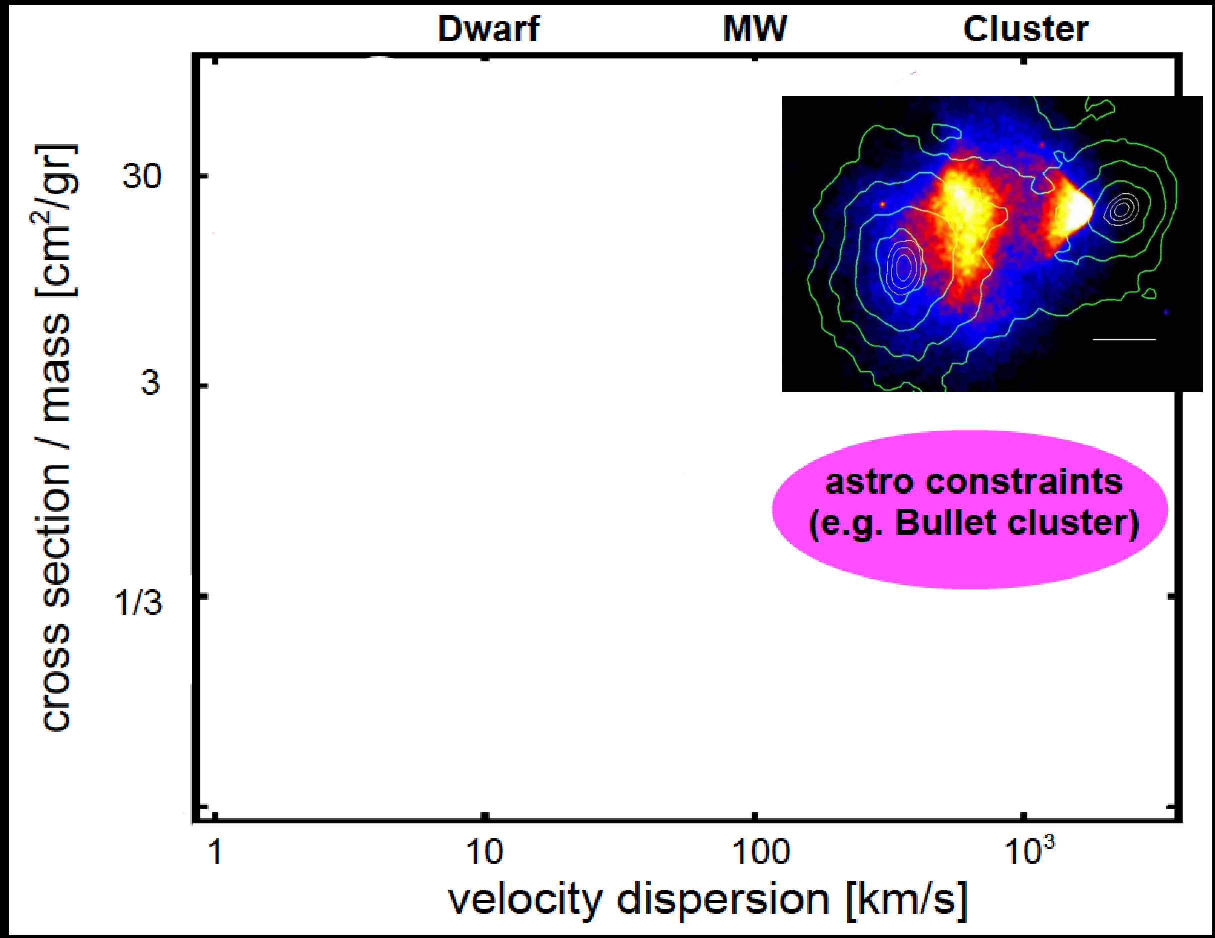

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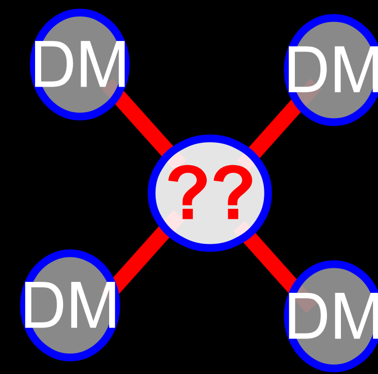


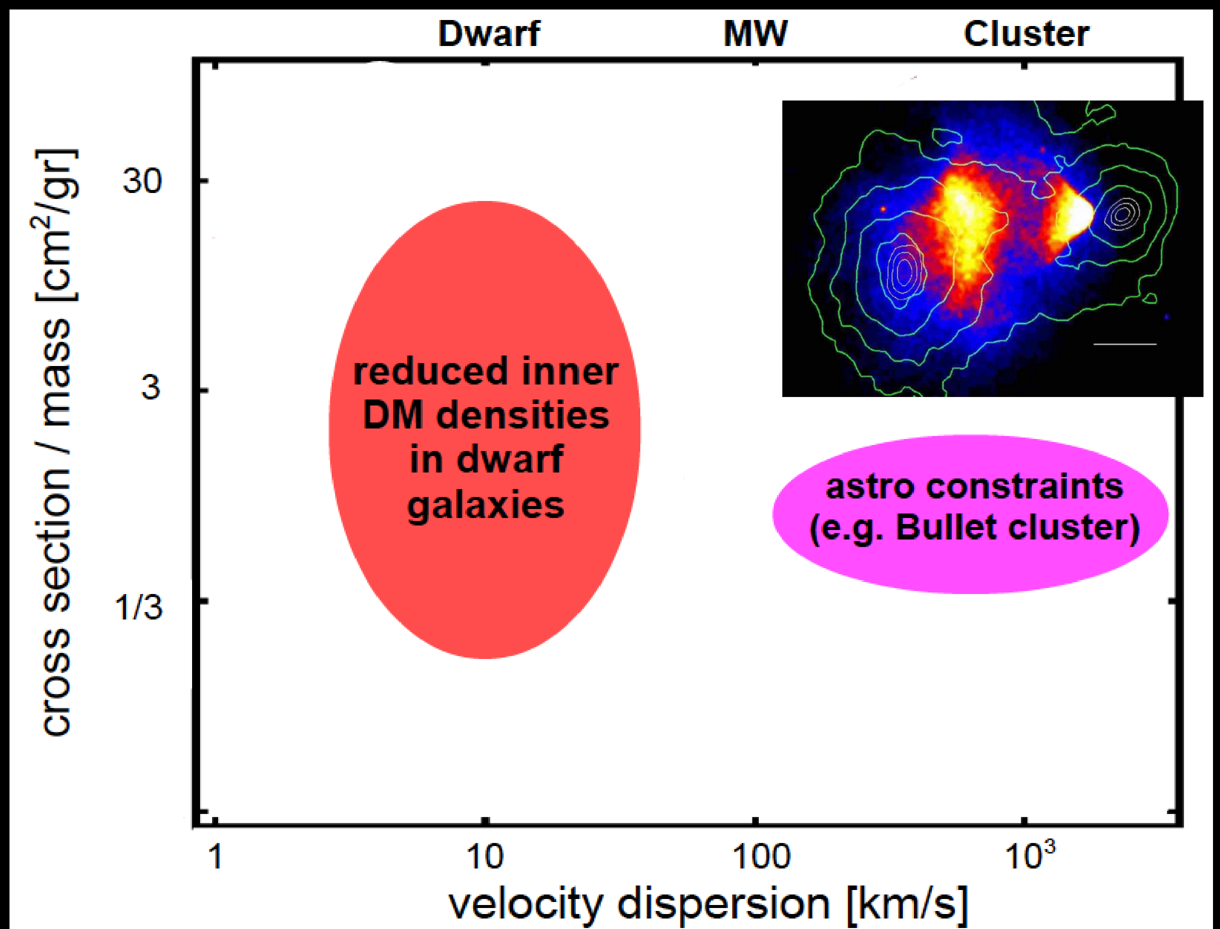
constraints allow collisional DM that is astrophysically significant in the center of galaxies:

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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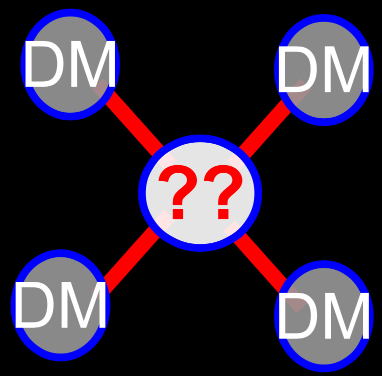
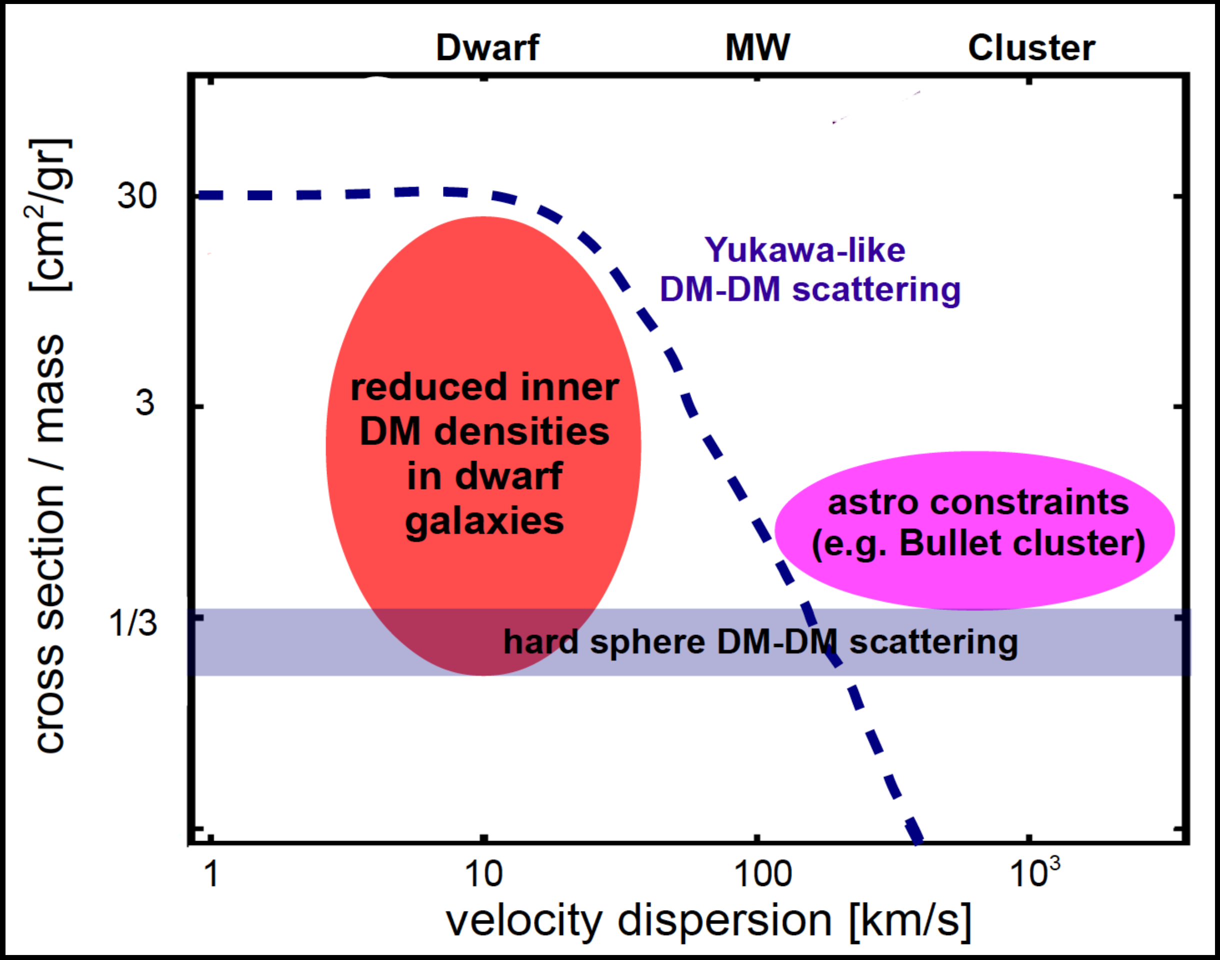


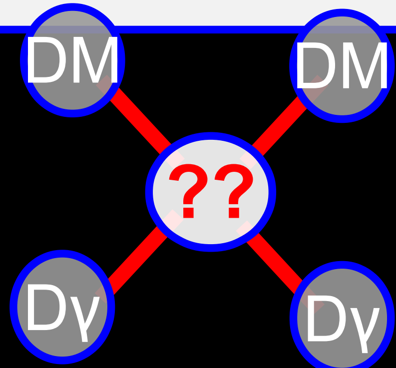
constraints allow collisional DM that is astrophysically significant in the center of galaxies:

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?



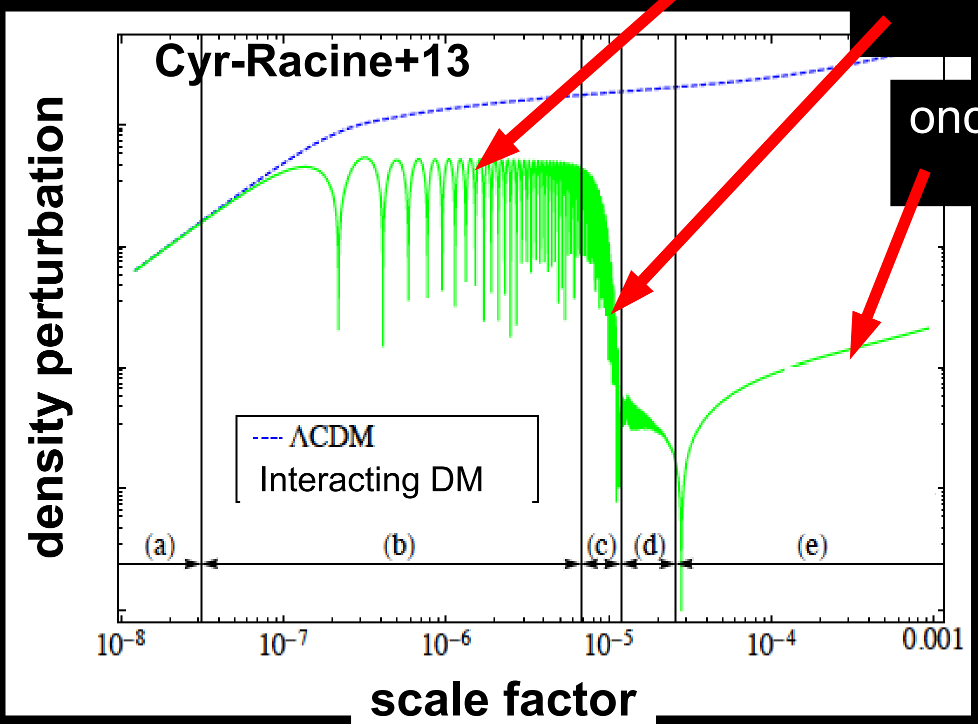
“dark photons”

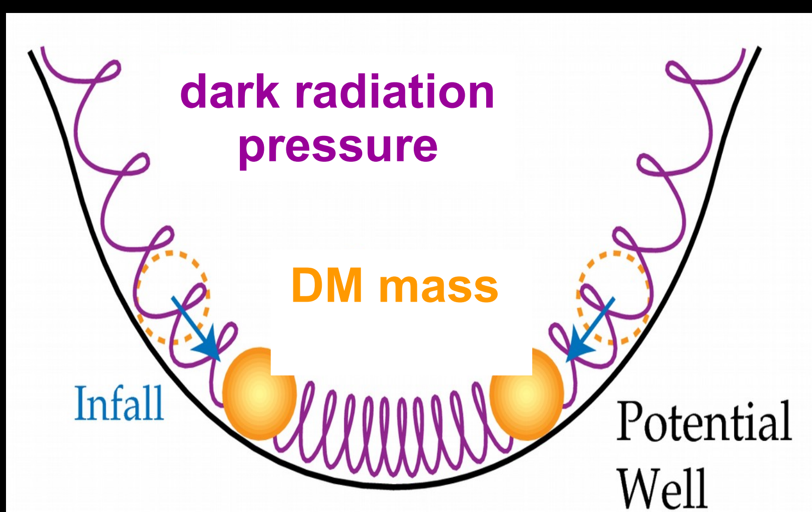
Allowed interactions between DM and relativistic particles (e.g. “dark radiation”) in the early Universe introduce pressure effects that impact the growth of DM structures (phenomena analogous to that of the photon-baryon plasma)

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

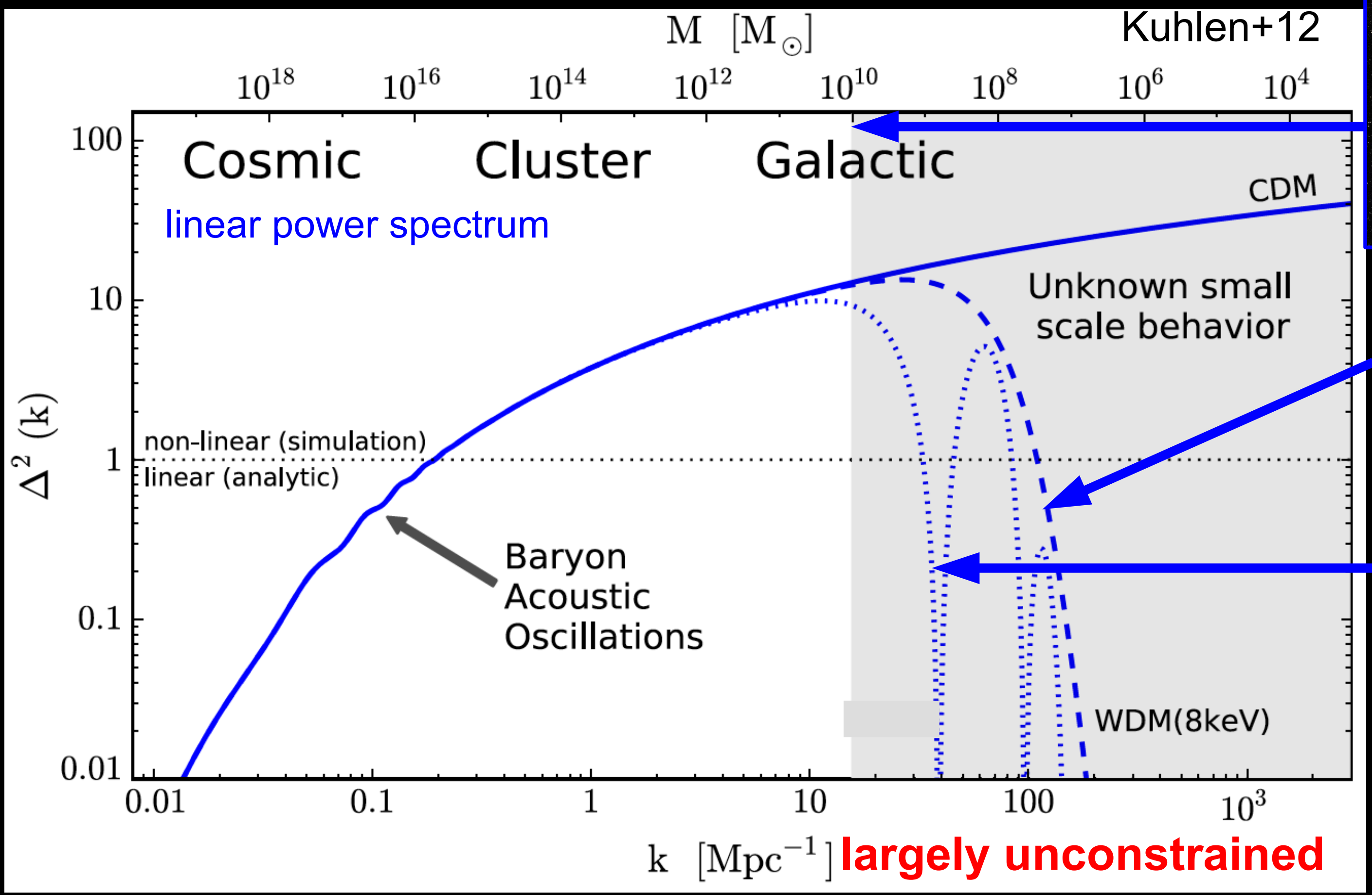
Pursuing them, will either confirm the standard model or unveil a fundamental DM property

The nature of dark matter and the first galaxies

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

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

Dwarf galaxies



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

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

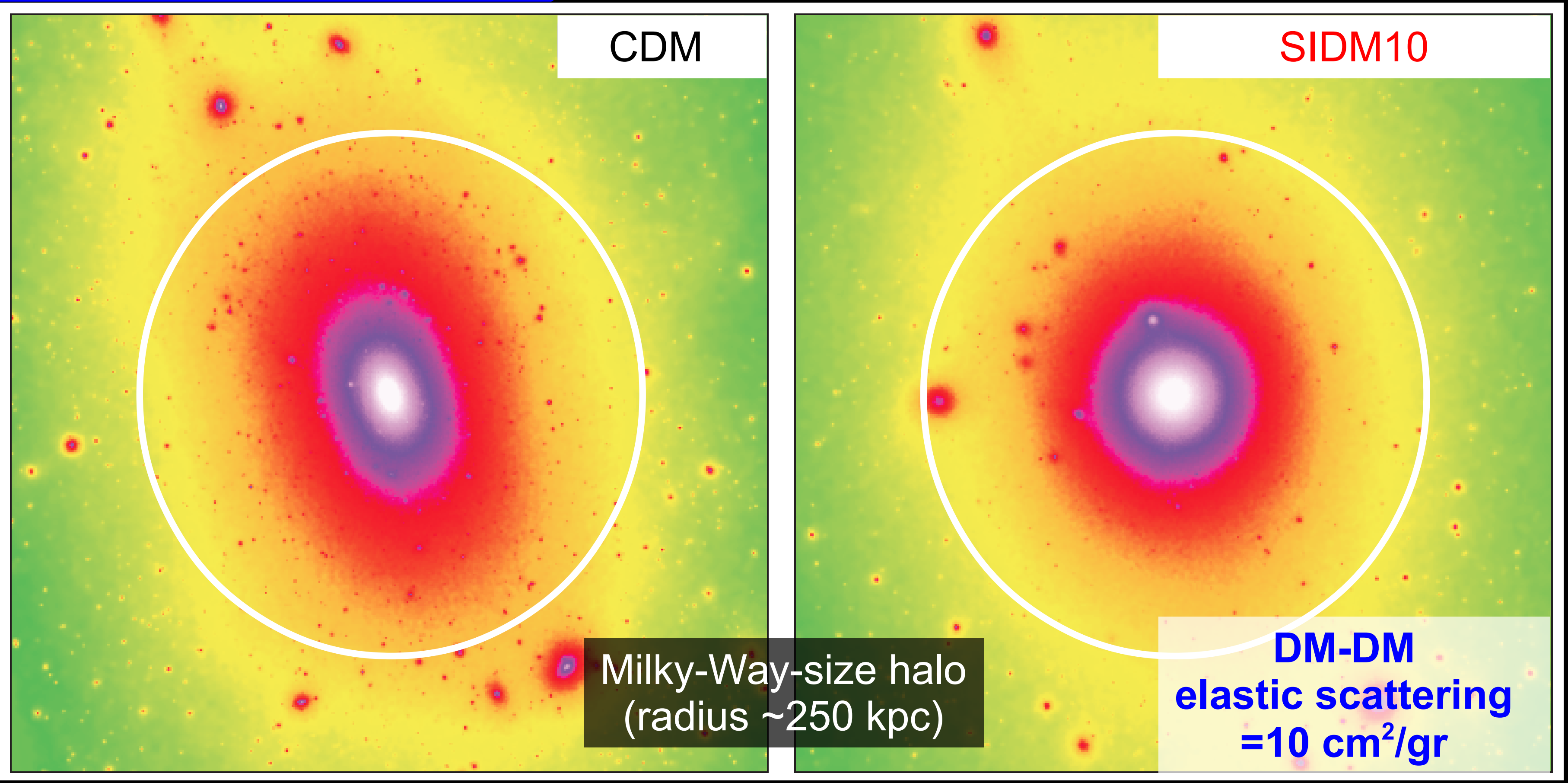
The nature of dark matter (evolution of structures)

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

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....)

The nature of dark matter (evolution of structures)

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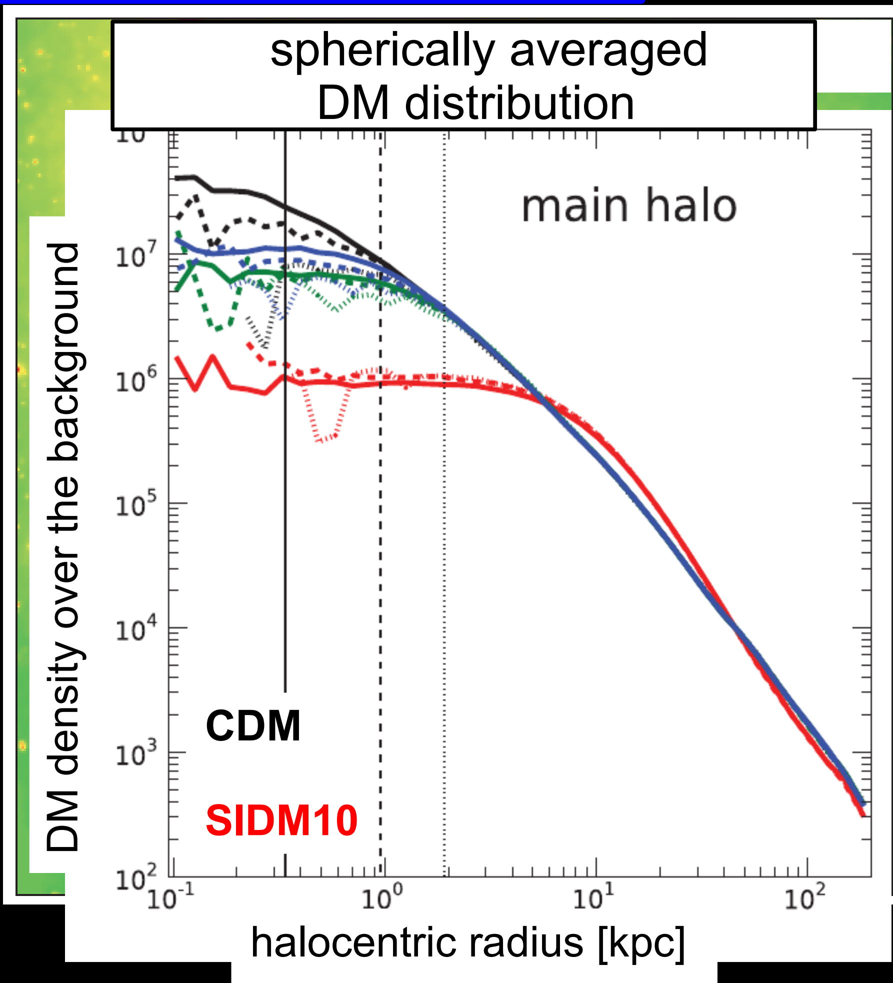
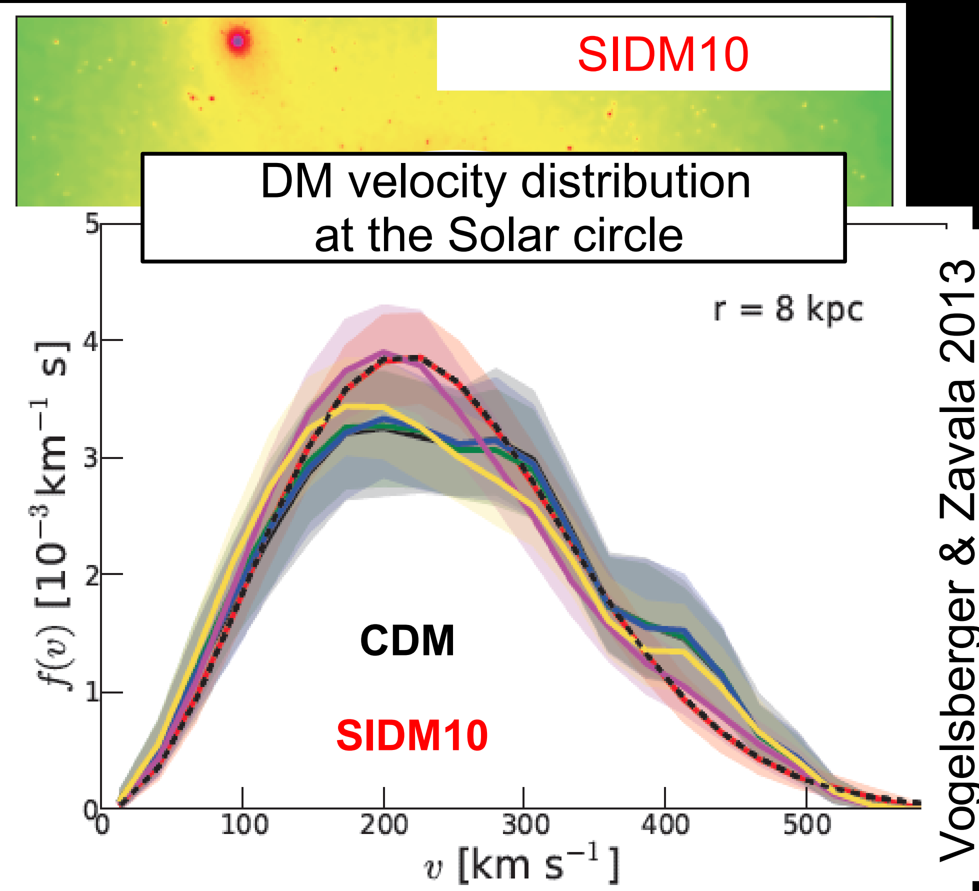
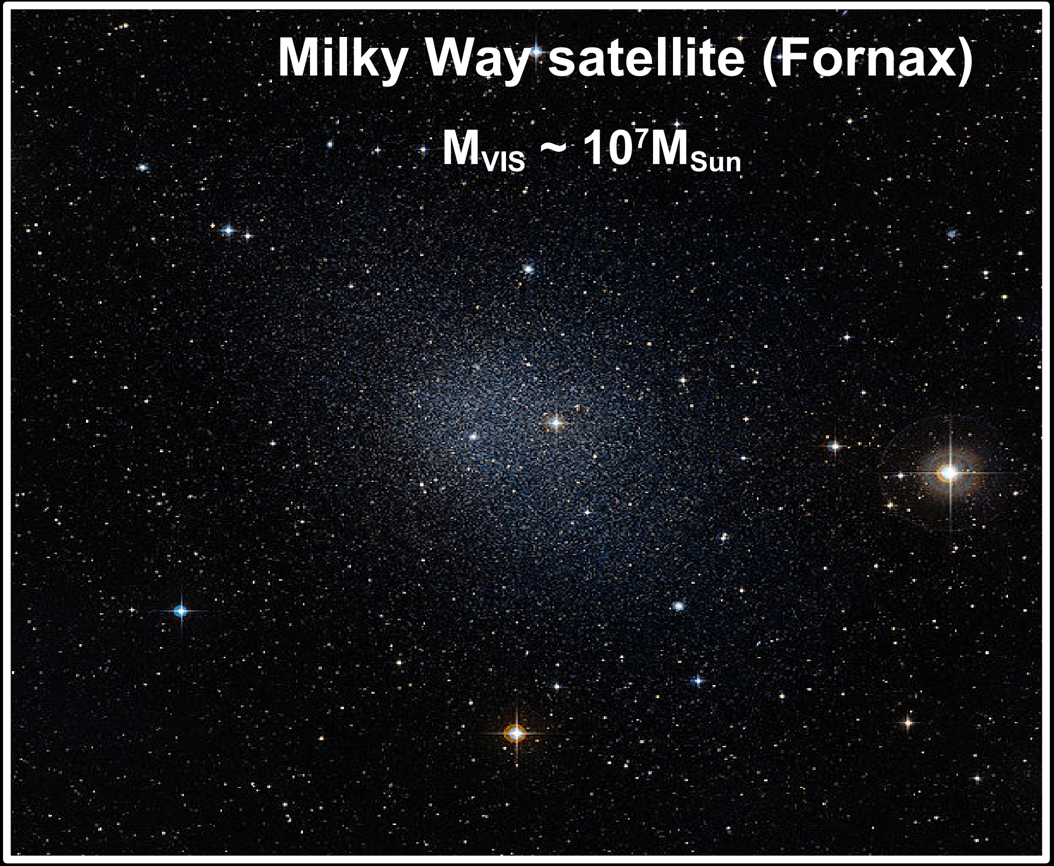




Vogelsberger & Zavala 2013

Clues of new DM physics from dwarf galaxies?

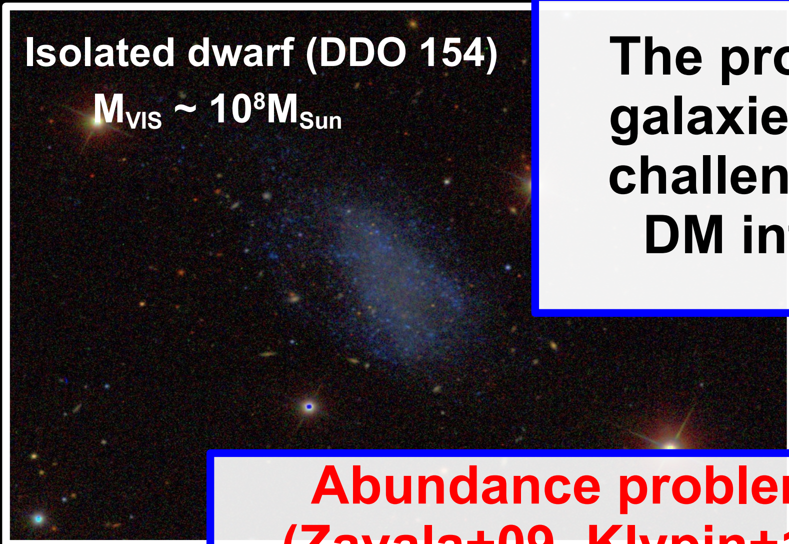
Dwarf galaxies:
most DM-dominated systems: $M_{DM} > 10\ M_{VIS}$
(ordinary matter is less dynamically relevant)



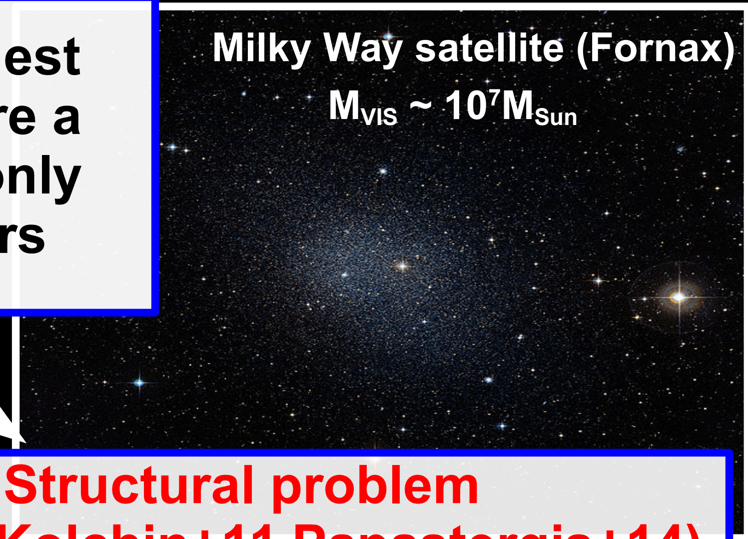
The stellar dynamics is simplified and the underlying DM distribution can be more easily constrained

"Optimal" dynamical DM detectors

Clues of new DM physics from dwarf galaxies?

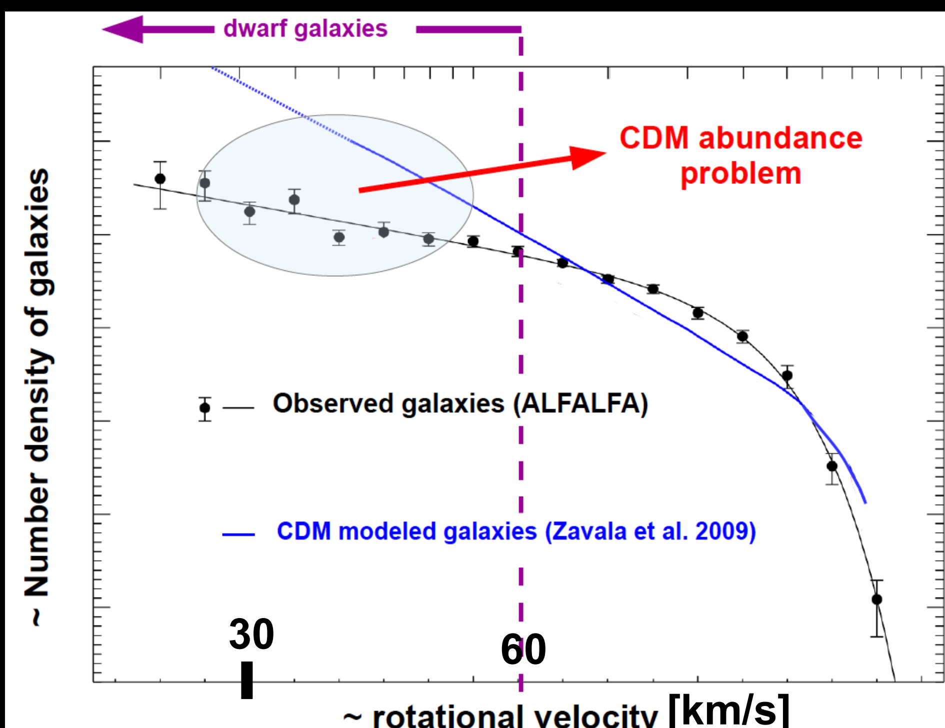


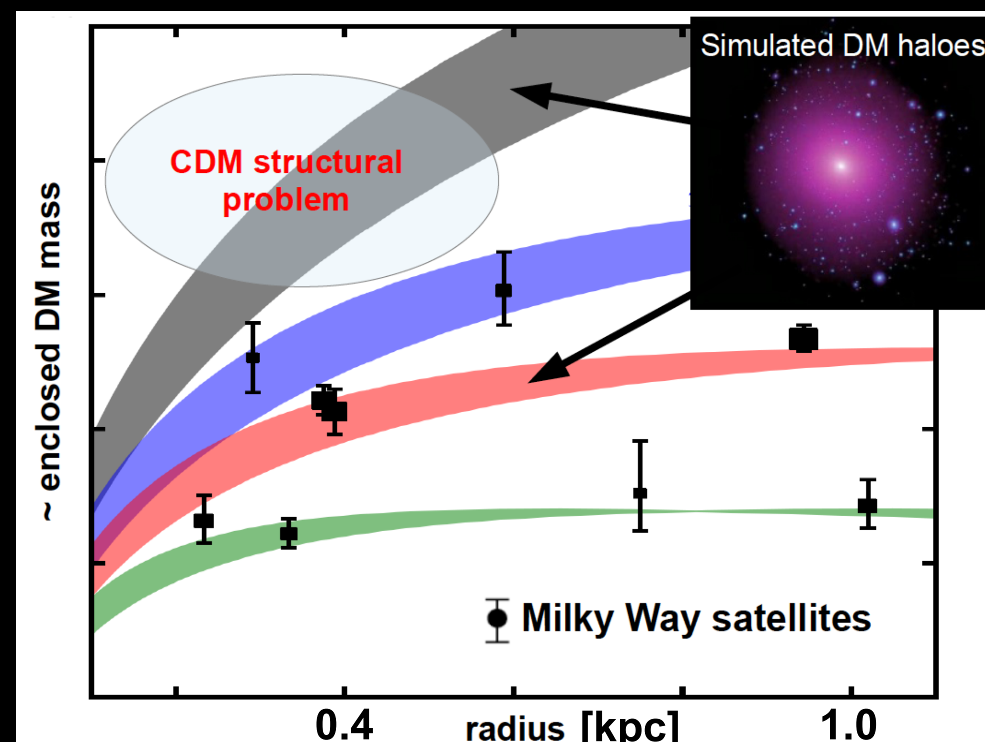
The properties of the smallest galaxies observed **today** are a challenge if gravity is the only DM interaction that matters



Abundance problem (Zavala+09, Klypin+15)

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





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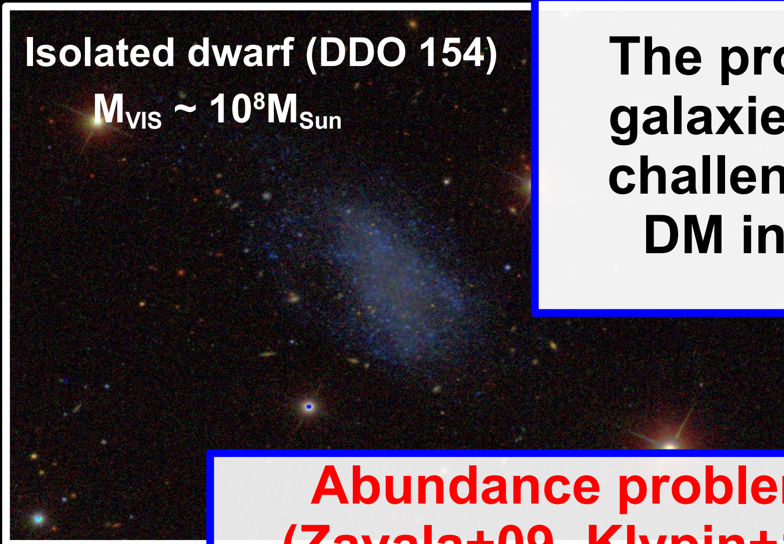

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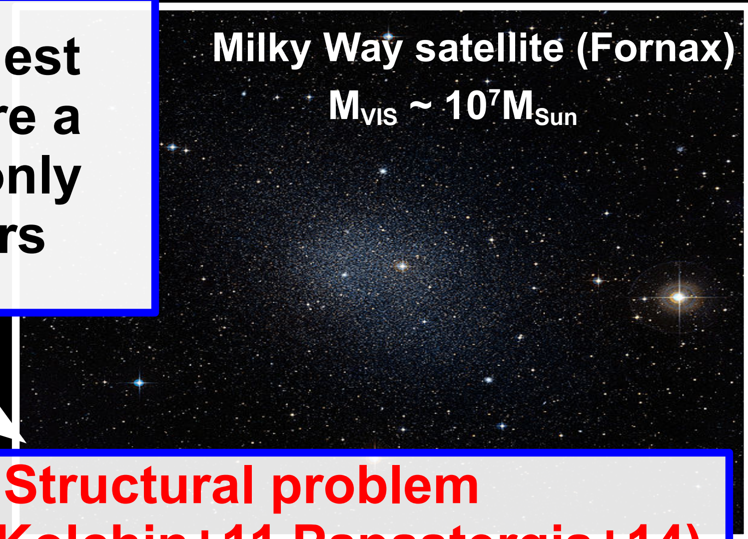

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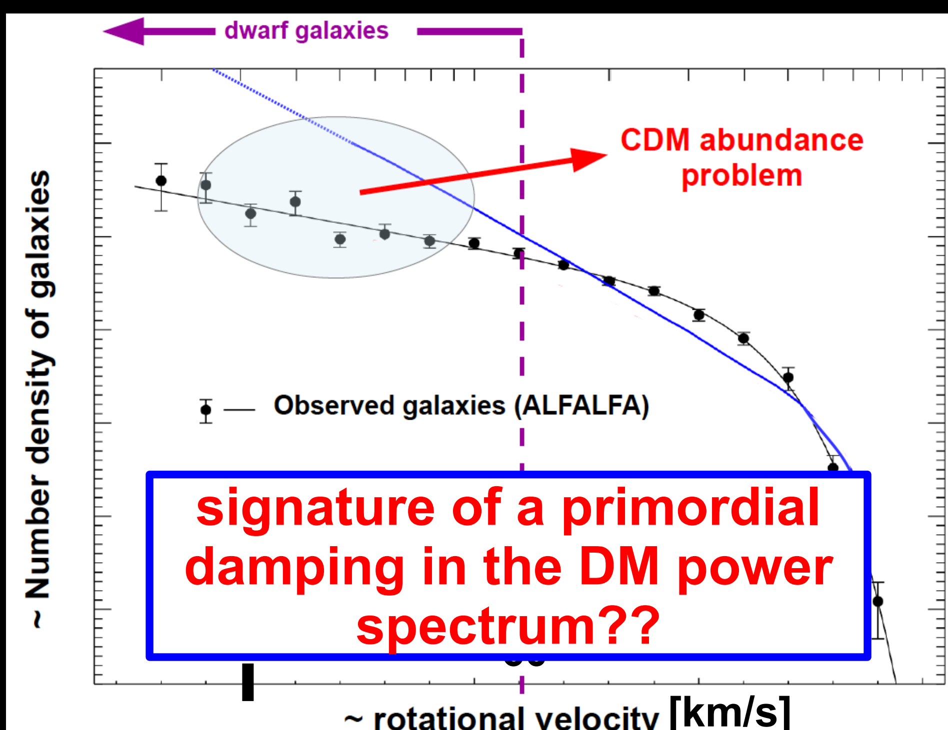
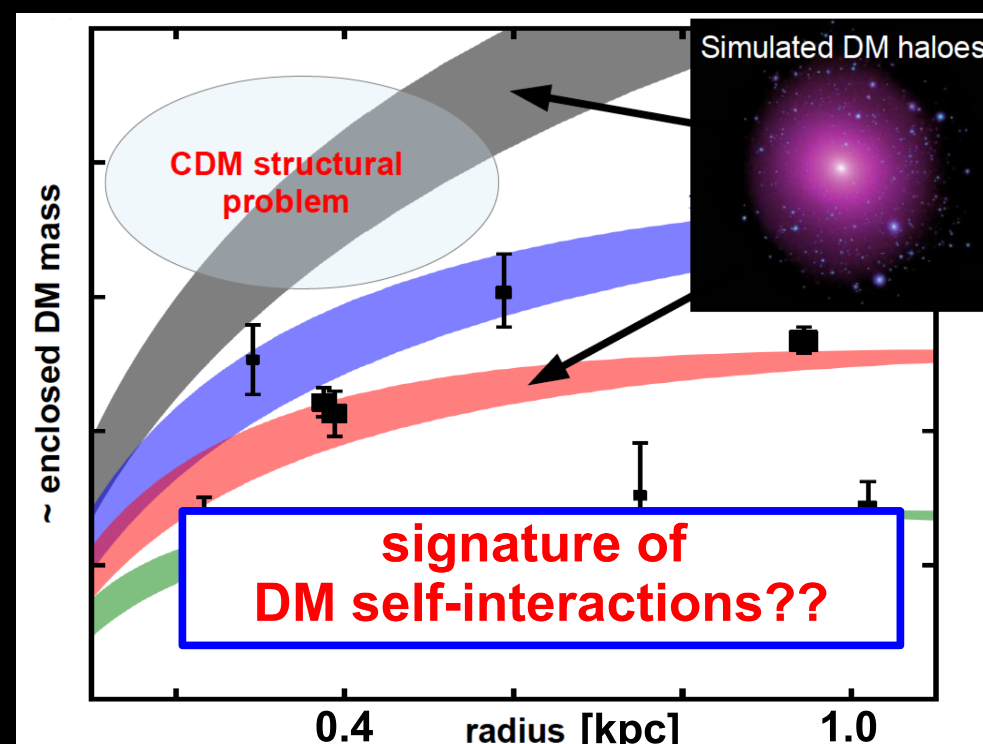


signature of a primordial damping in the DM power spectrum??

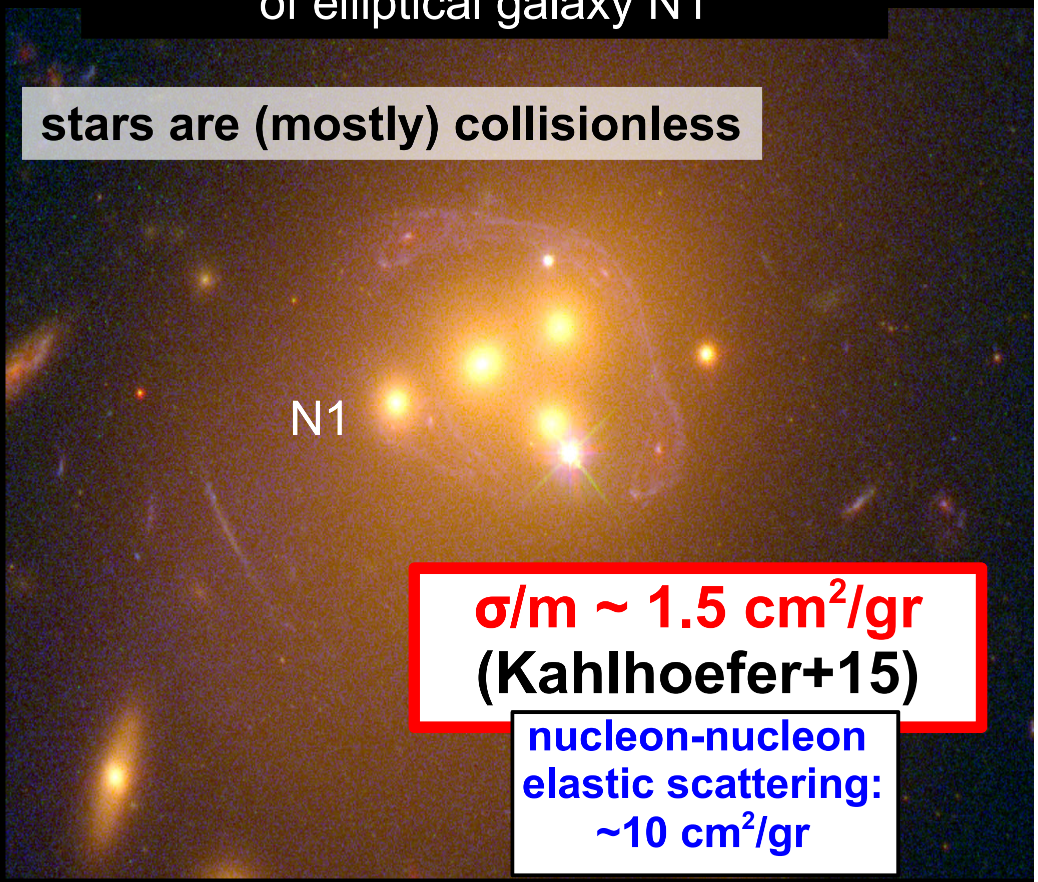


signature of DM self-interactions??

Clues on new DM physics at other scales?

Cluster Abell 3827 (Massey +15)

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



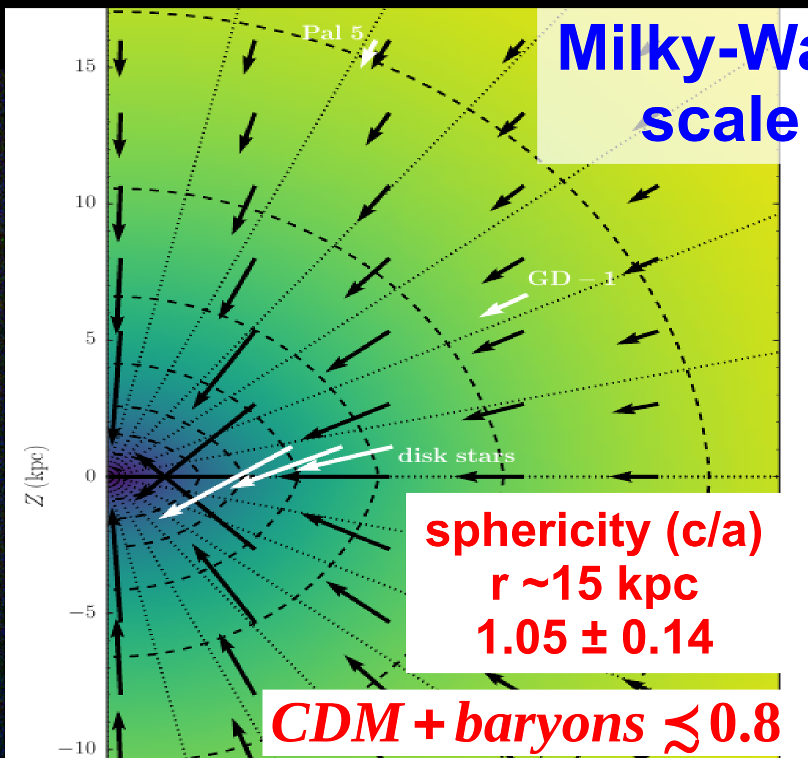
stars are (mostly) collisionless

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

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

Cluster scales

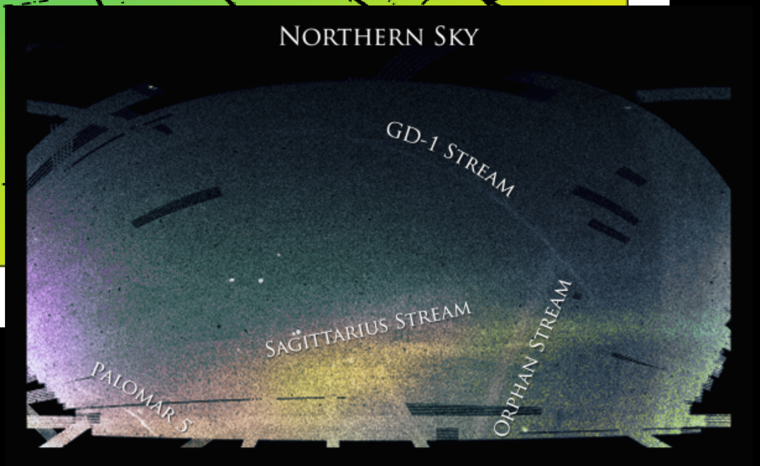
reconstruction of the gravitational field in the MW using phase-space data from stellar tidal streams



Milky-Way scale

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

$CDM + baryons \lesssim 0.8$



Bovy et al. 2016

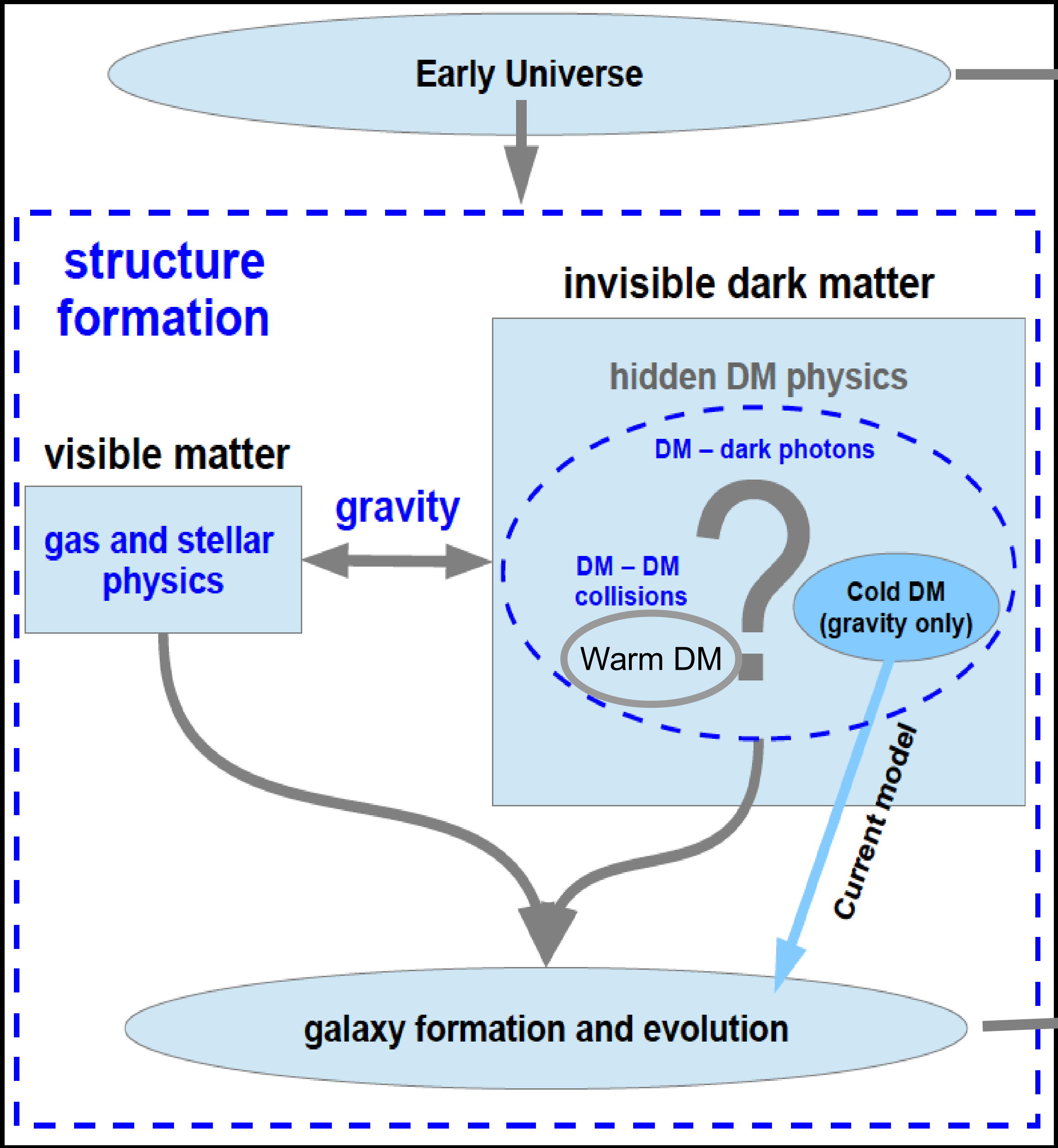
CDM + current galaxy modelling are successful in reproducing several properties of the galaxy population but:

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...

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)

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

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

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

effective parameters

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

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

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, ...)

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

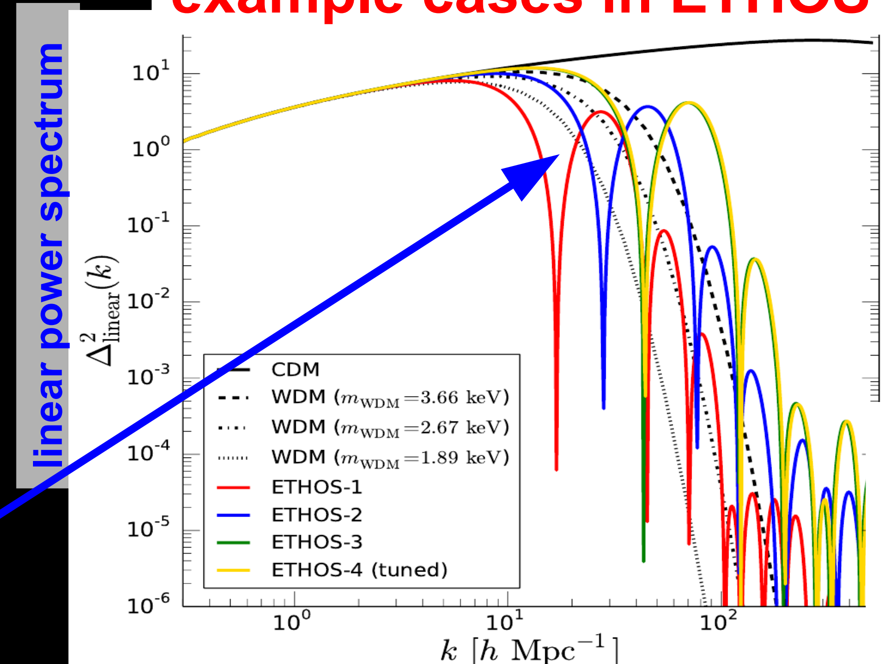
growth of structures (linear regime) with additional physics: DM-DR-induced DAOs and Silk damping

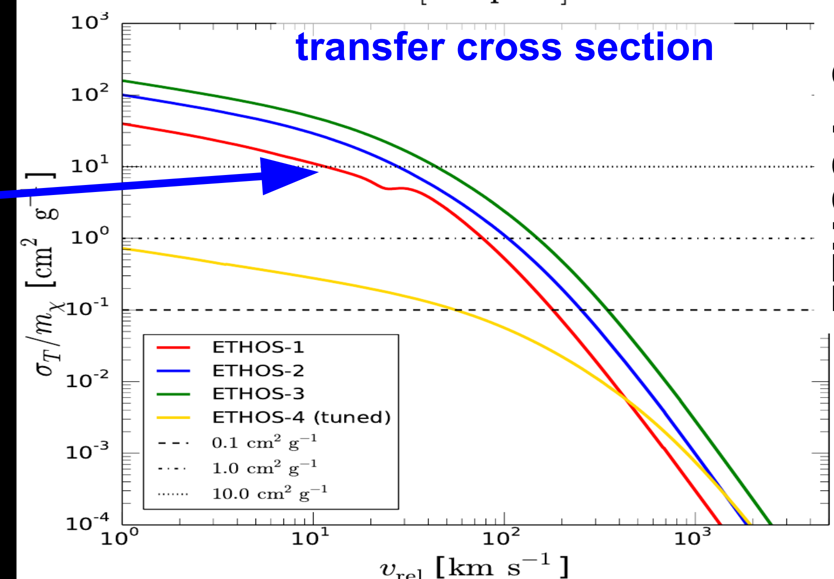
effective parameters

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

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

example cases in ETHOS

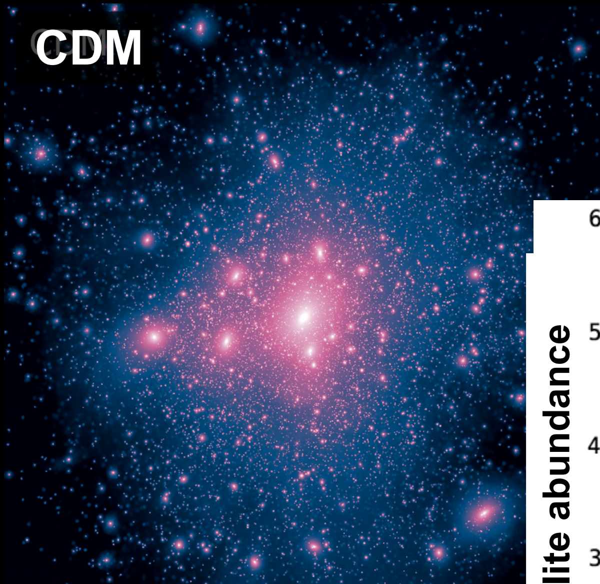




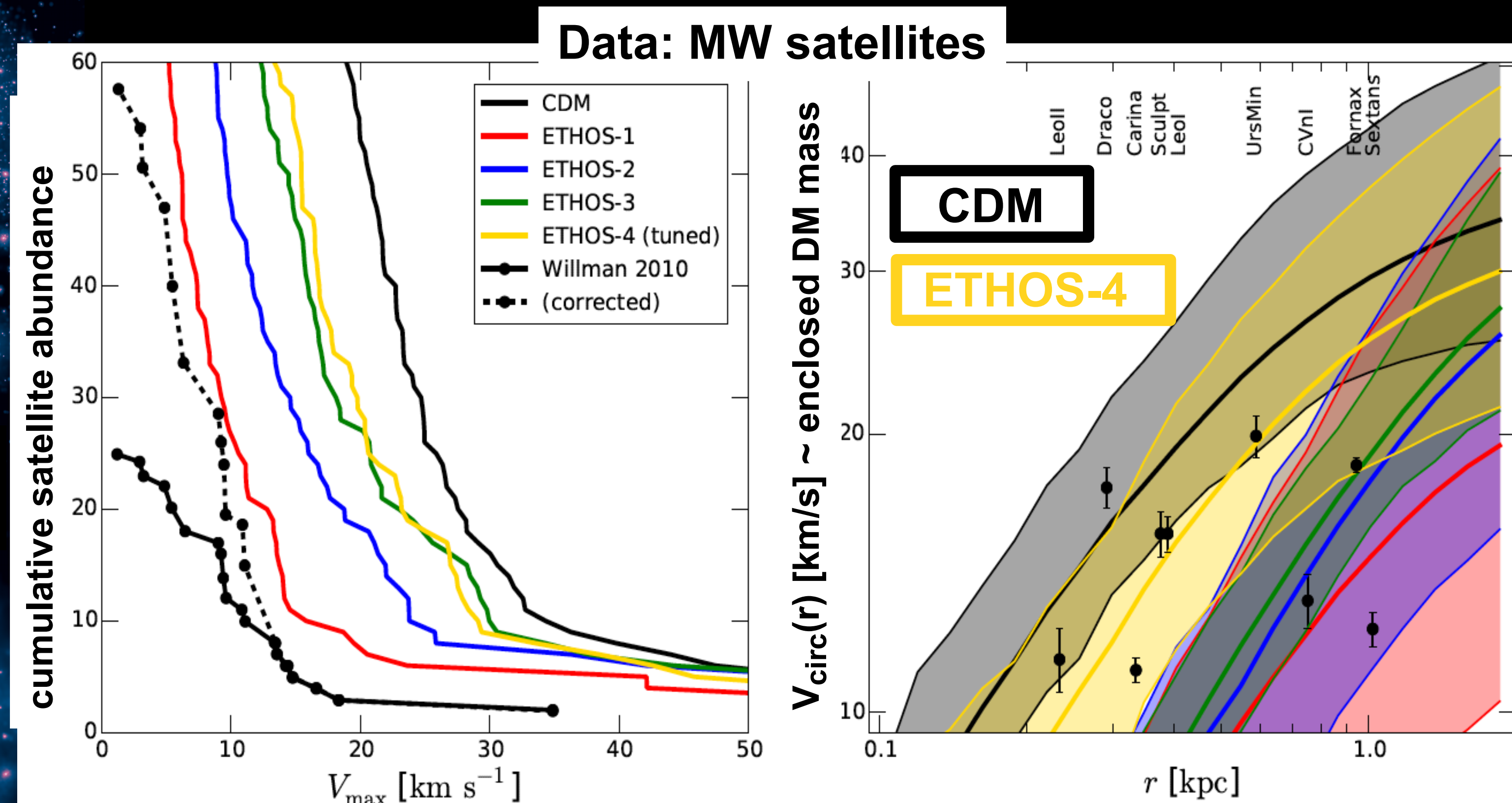
ETHOS I: Cyr-Racine+16

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



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

DM self-interactions reduce the central DM densities of haloes

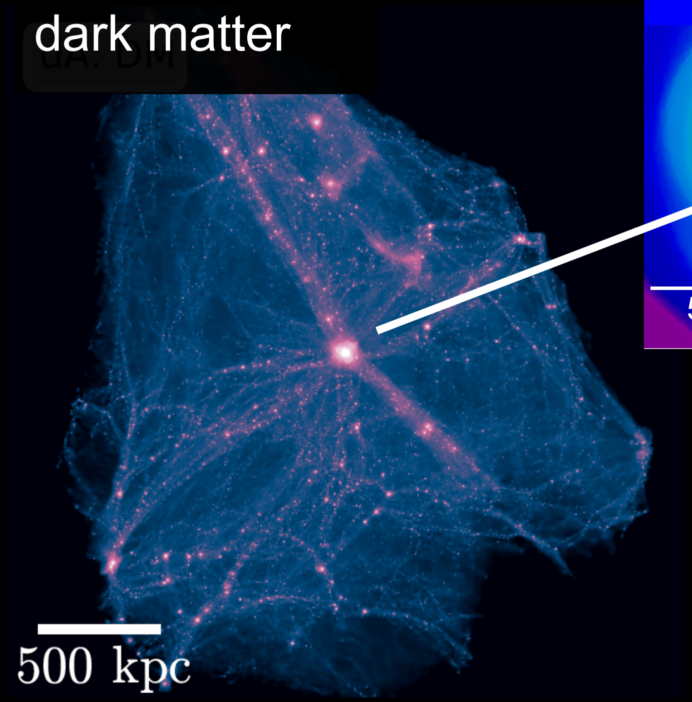
ETHOS II: Vogelsberger+16

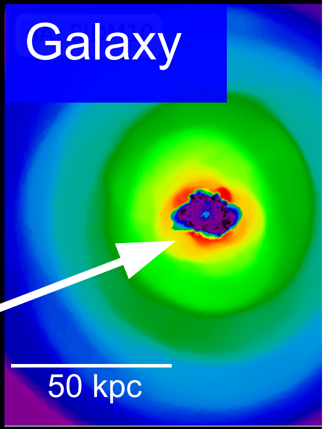
Developing ETHOS
(self-scattering DM + baryonic physics)

"baryonic physics": hydrodynamics, radiative cooling of gas, stellar population modelling, SNe feedback (AREPO code)

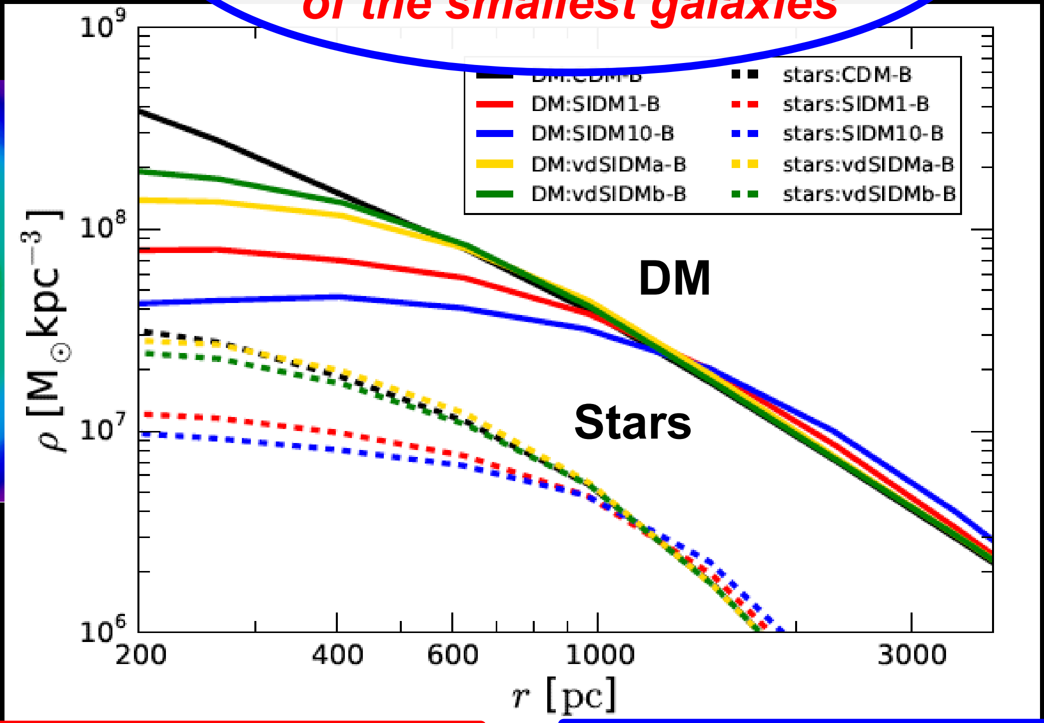
simulation of a galaxy in Self-Interacting DM
(Vogelsberger, Zavala +14)

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





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



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

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

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

EXTRA SLIDES

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)

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

eqs. for DM perturbations

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

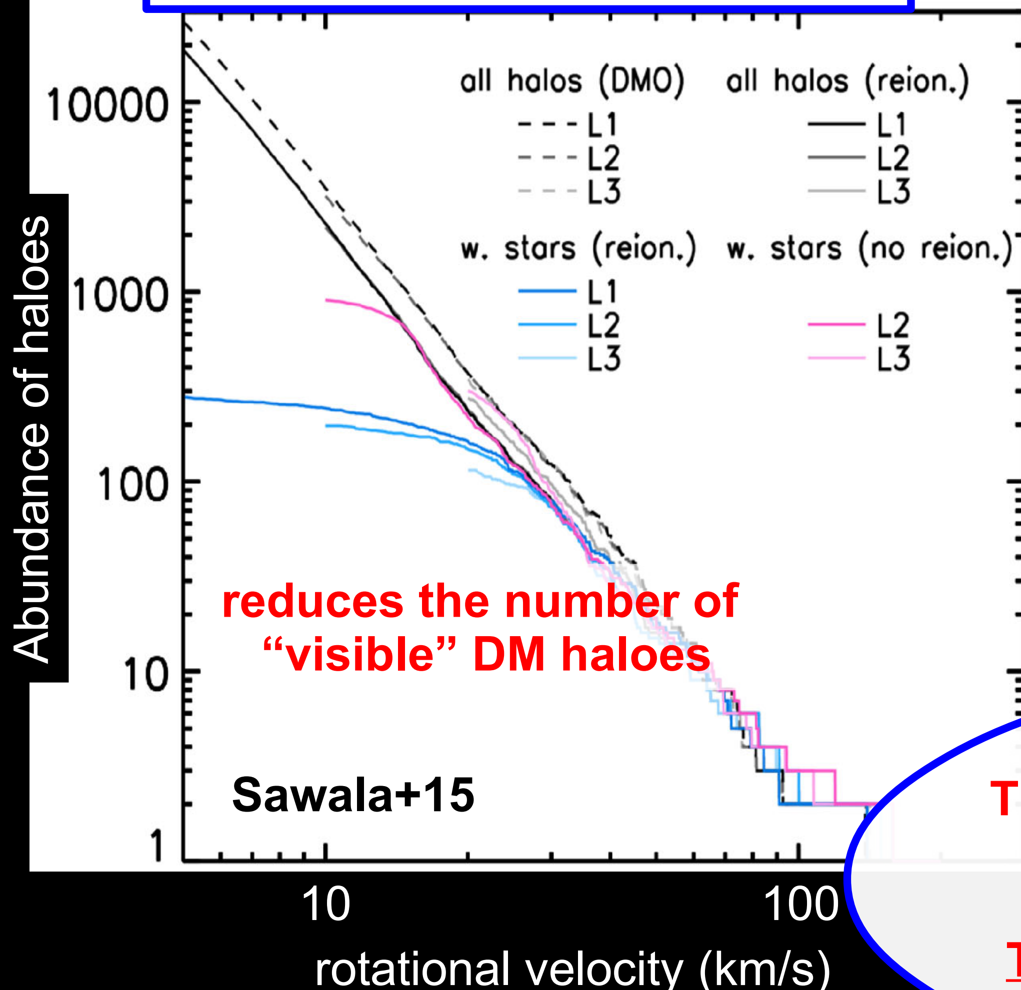
$$\dot{\theta}_\chi - c_\chi^2 k^2 \delta_\chi + \mathcal{H}\theta_\chi - k^2\psi = \dot{\kappa}_\chi[\theta_\chi - \theta_{\mathrm{DR}}]$$

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

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

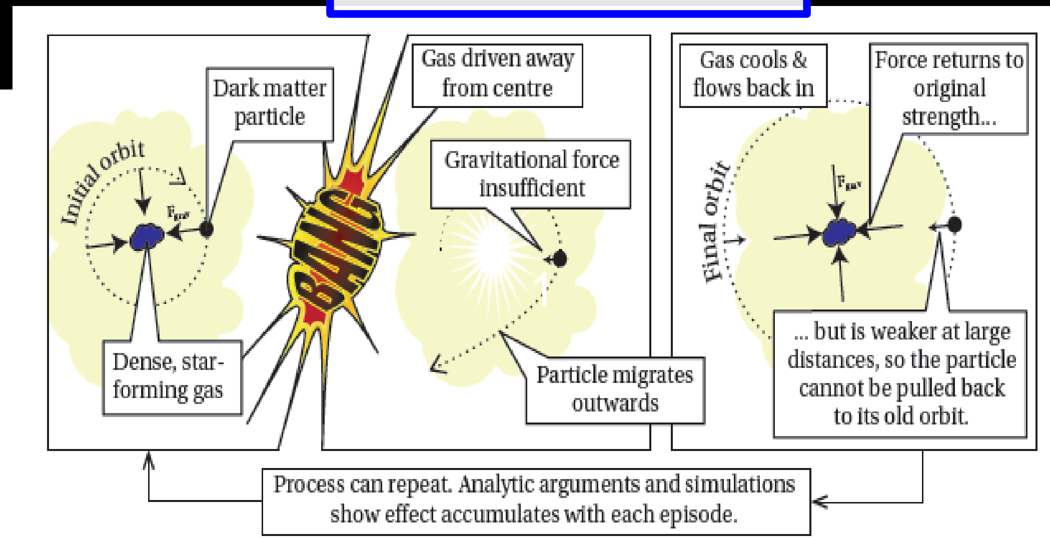
Or... the complexity of gas and stellar physics

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