Perspectives on the Astrophysics of Dark Matter

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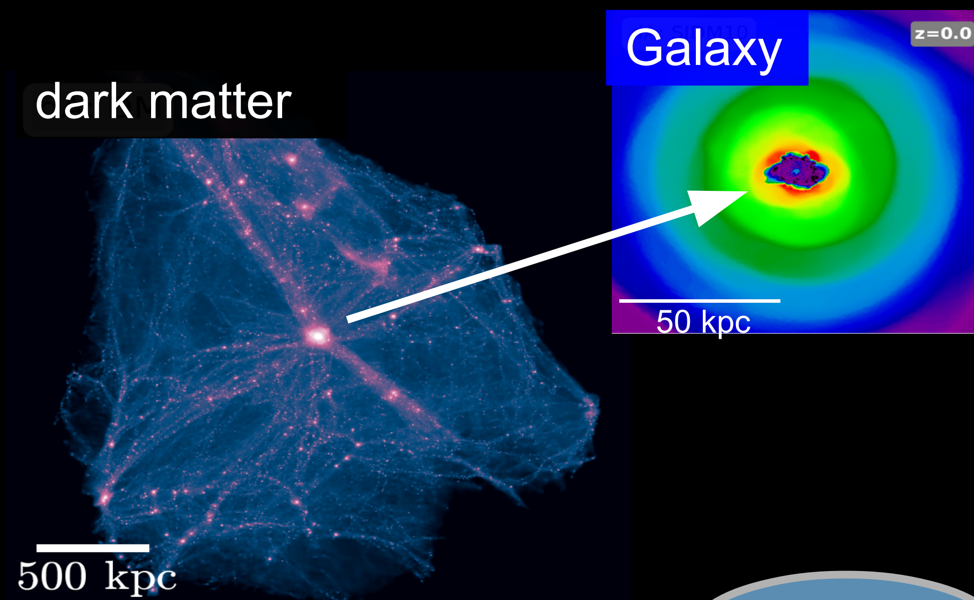
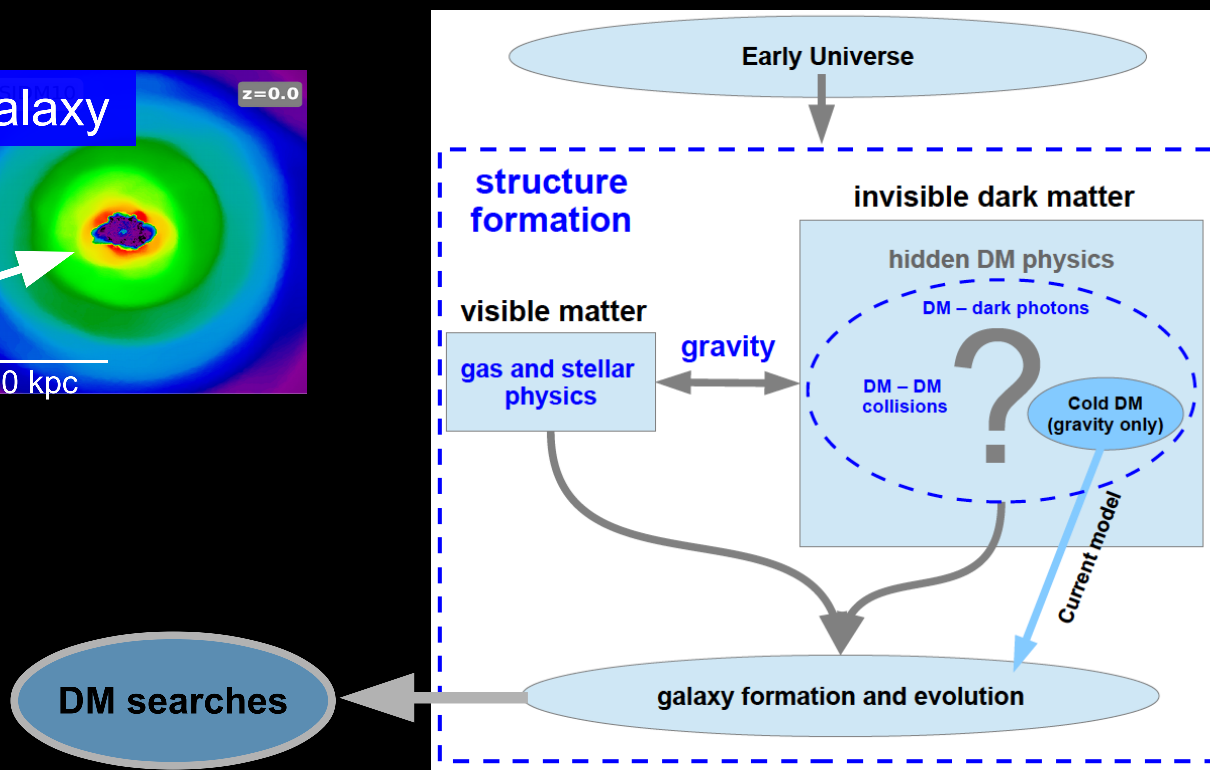




Mini Workshop on Dark Matter, Instituto de Física, UNAM, November 2016

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 implies 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

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?

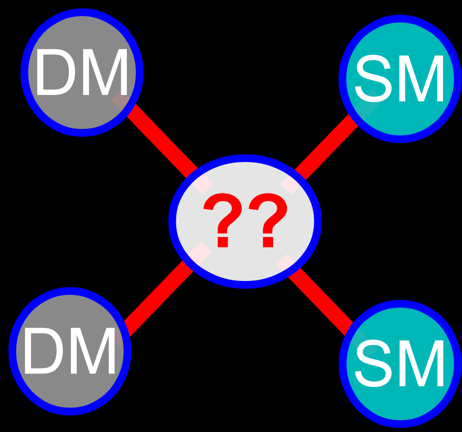
What is the mass(es) of the DM particle(s) and through which forces does it interact?

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

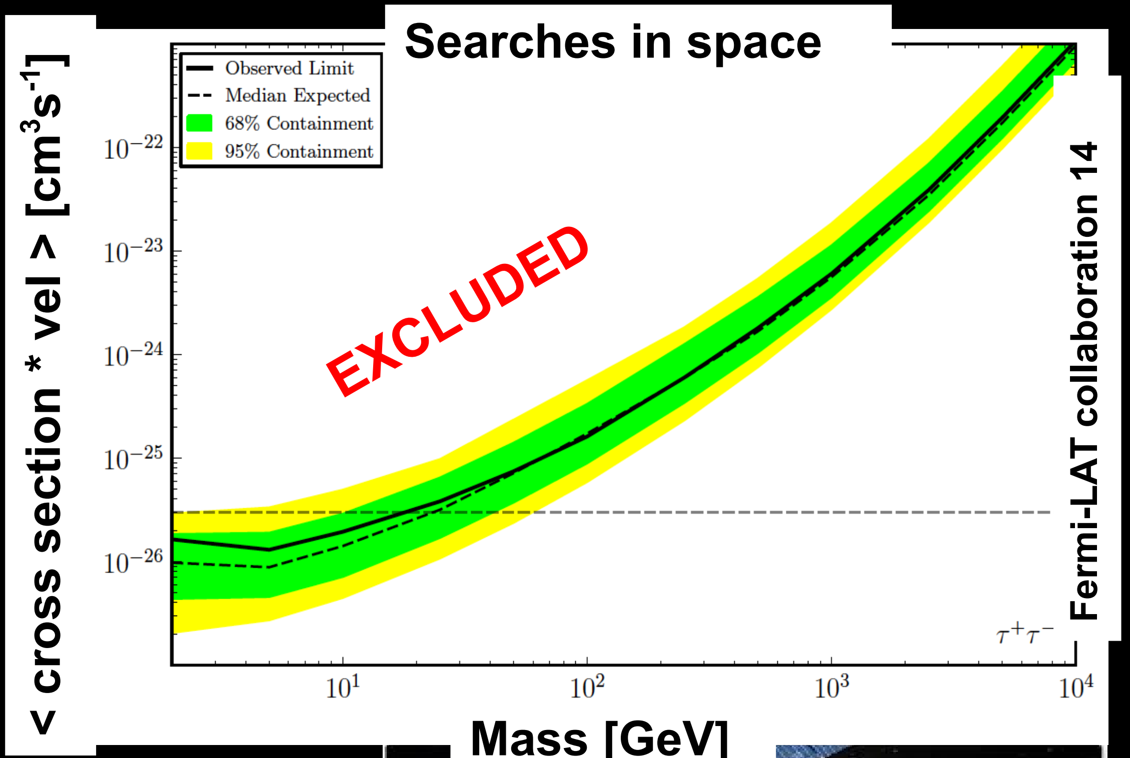
What is the nature of dark matter?

DM self-annihilation



analogous to
e^+e^- annihilation

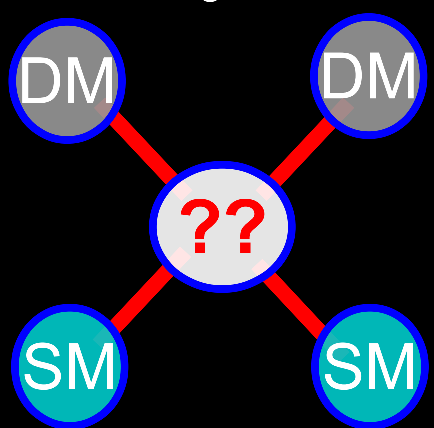
Does DM interacts with visible particles?

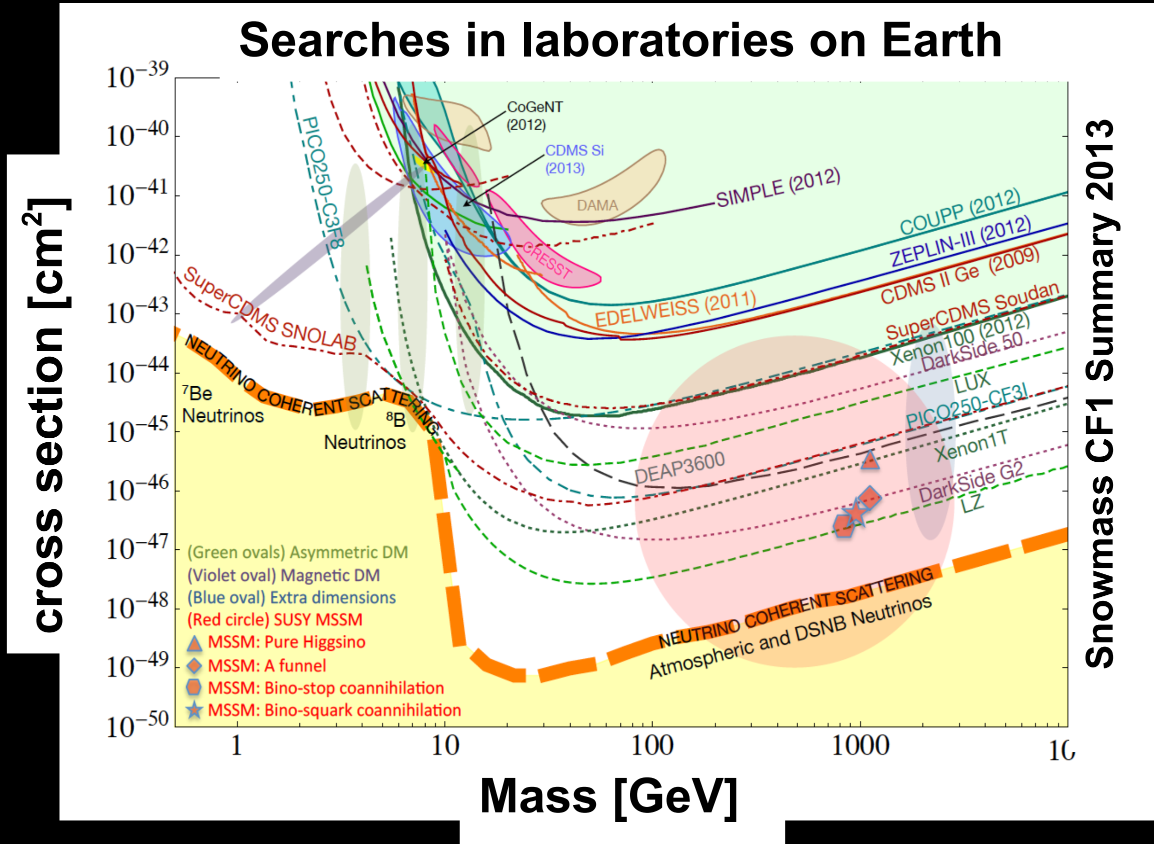


What is the nature of dark matter?

Does DM interacts with visible particles?

Scattering with nuclei





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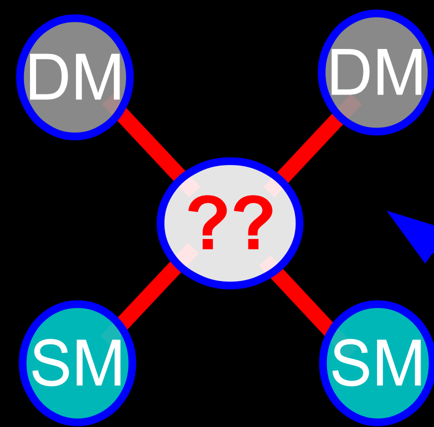
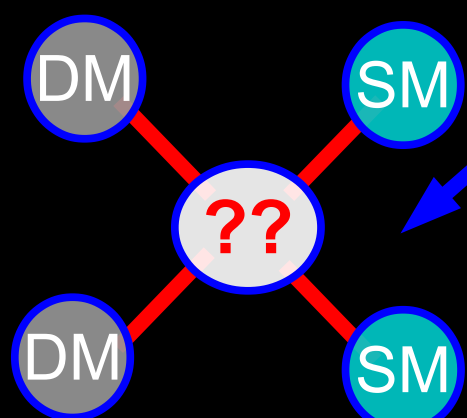


DM self-annihilation



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)

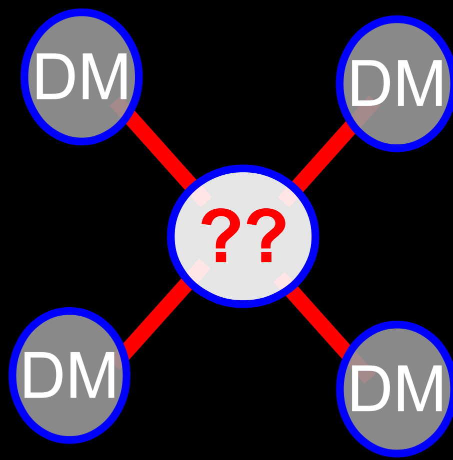
1 cm^2/g ~ 2 barns/GeV

dark matter is quite “dark” (invisible)

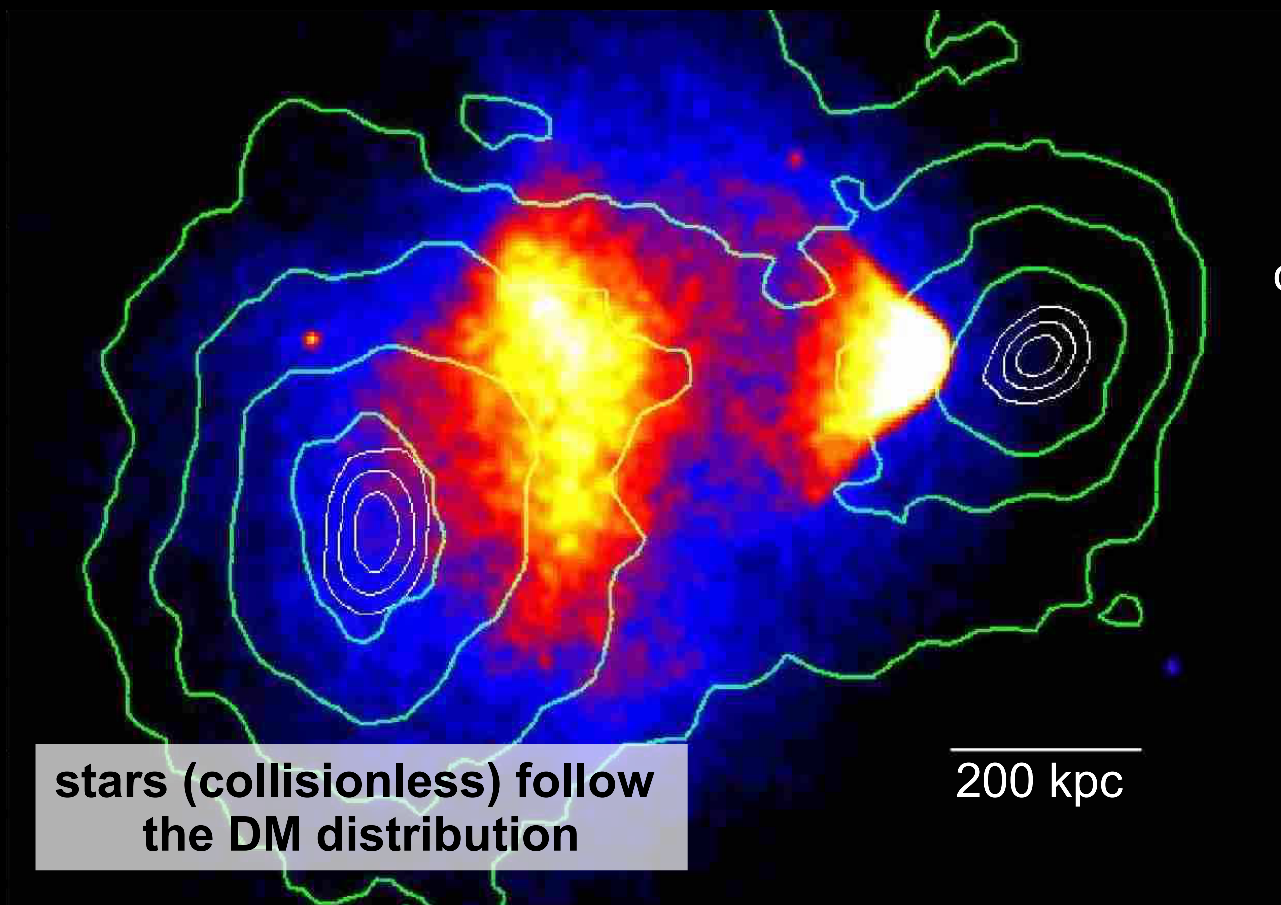
nucleon-nucleon elastic scattering: ~10 cm^2/gr

What is the nature of dark matter?

Can DM particles collide with themselves?



Bullet Cluster (Clowe +06)



constraint on DM self-collisions

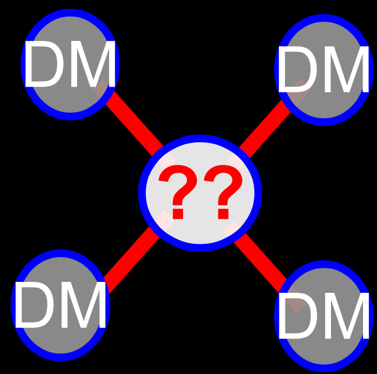
$$\sigma / m \lesssim 2\, cm^2 / gr$$

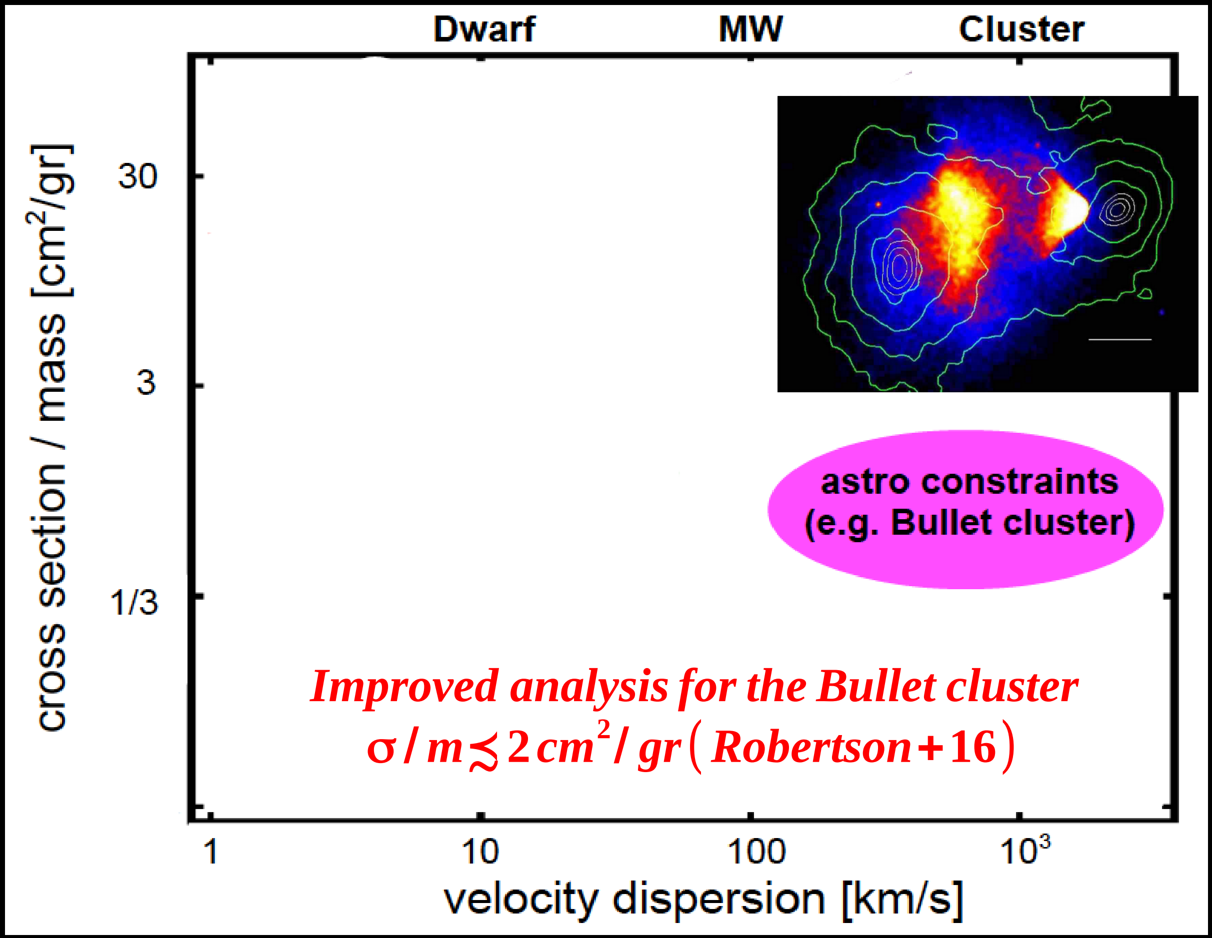
Robertson+2016

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

What is the nature of dark matter?

Can DM particles collide with themselves?





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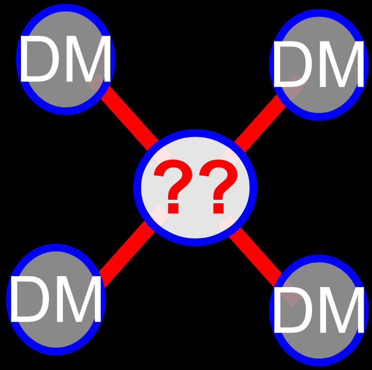


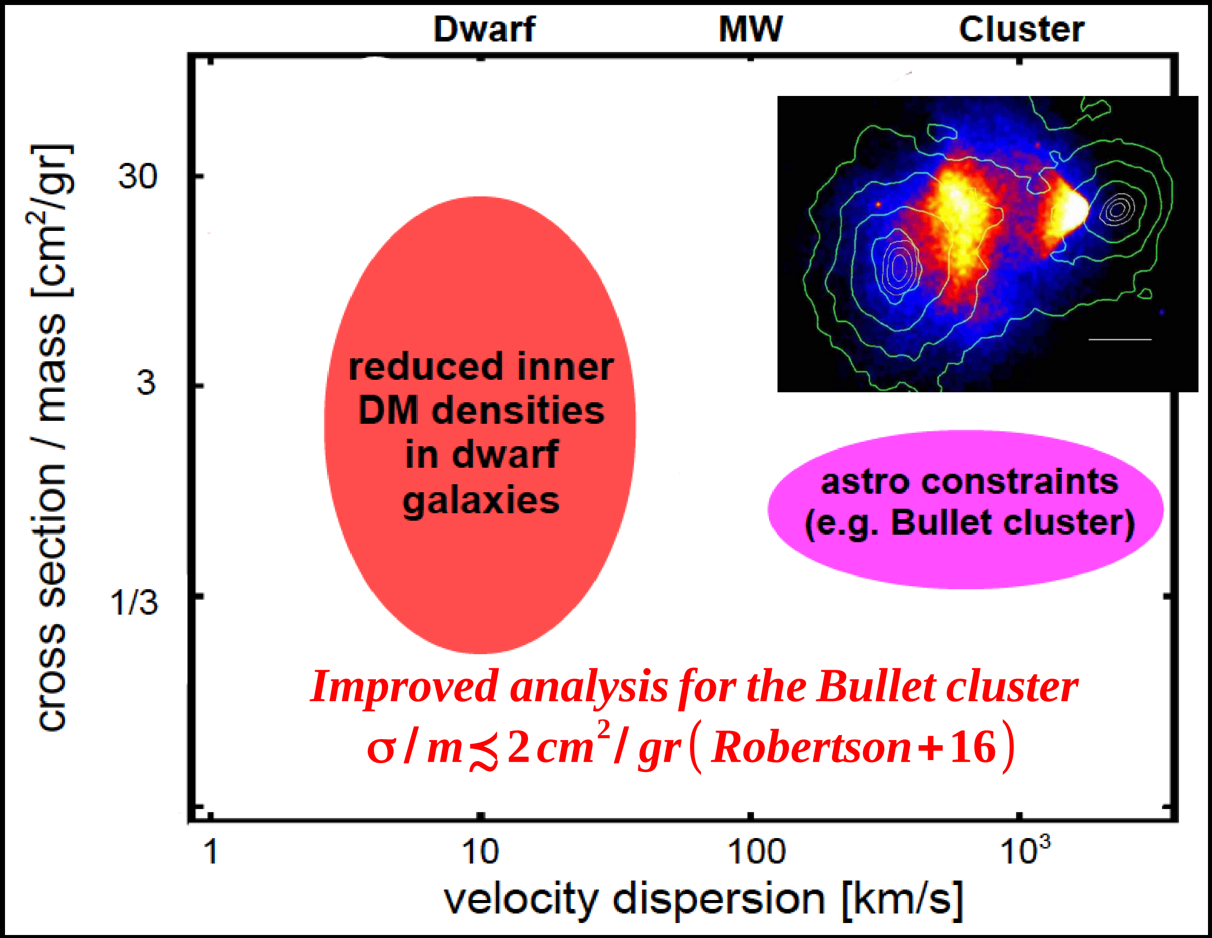
constraints allow collisional DM that is astrophysically significant in the center of galaxies:

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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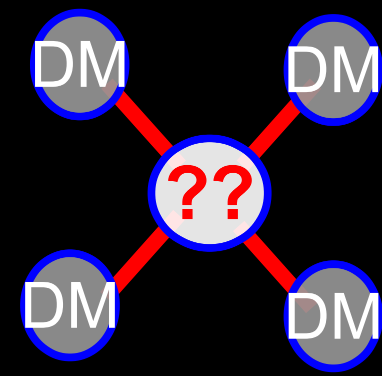
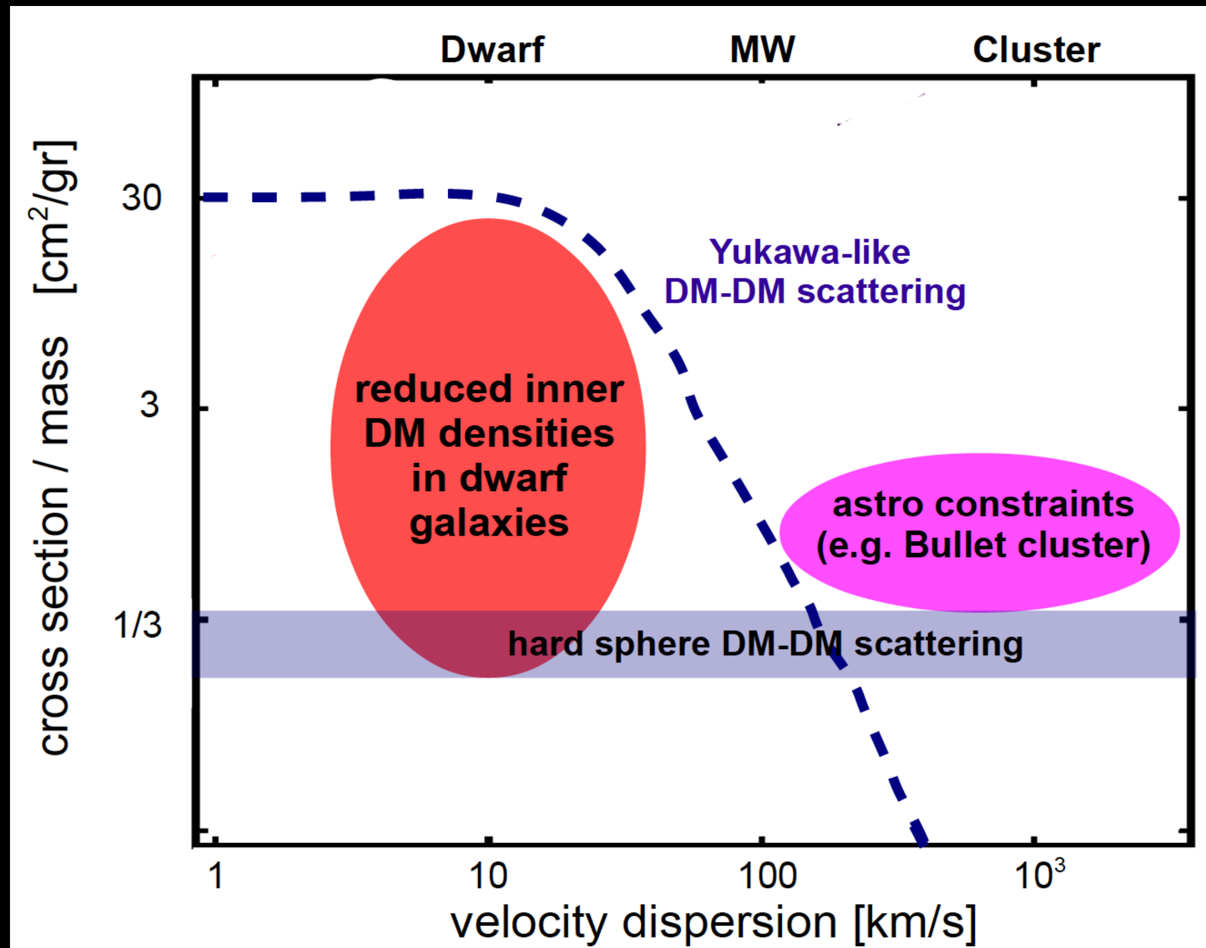


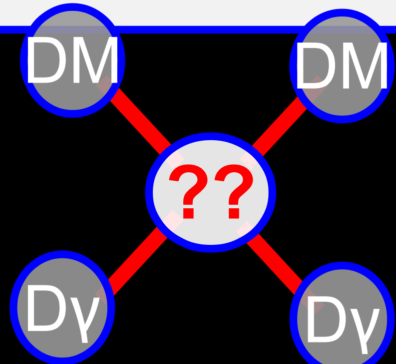
constraints allow collisional DM that is astrophysically significant in the center of galaxies:

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?



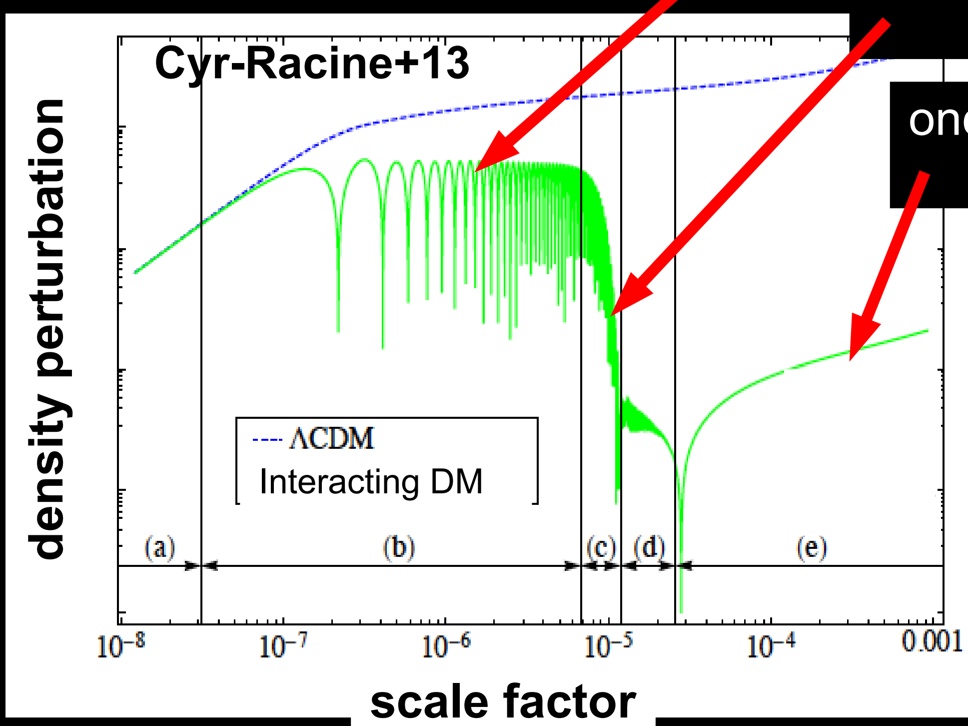
"dark photons"

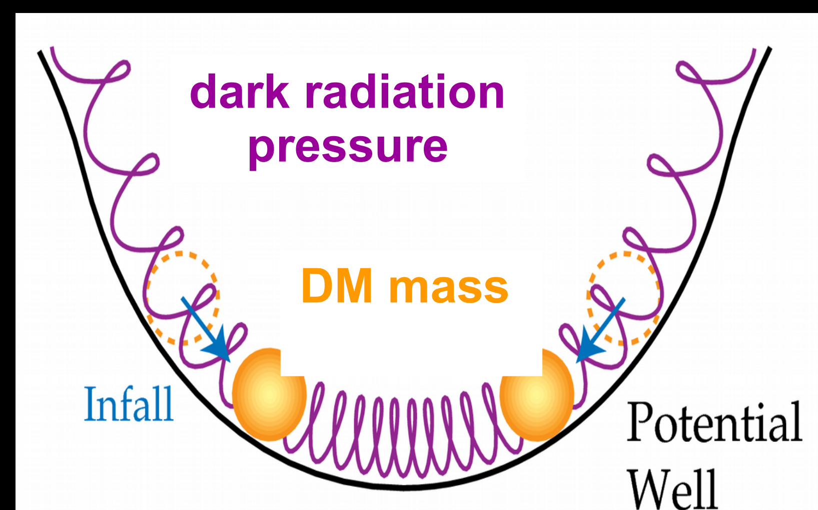
Allowed interactions between DM and relativistic particles (e.g. "dark radiation") in the early Universe introduce pressure effects that impact the growth of DM structures (phenomena analogous to that of the photon-baryon plasma)

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

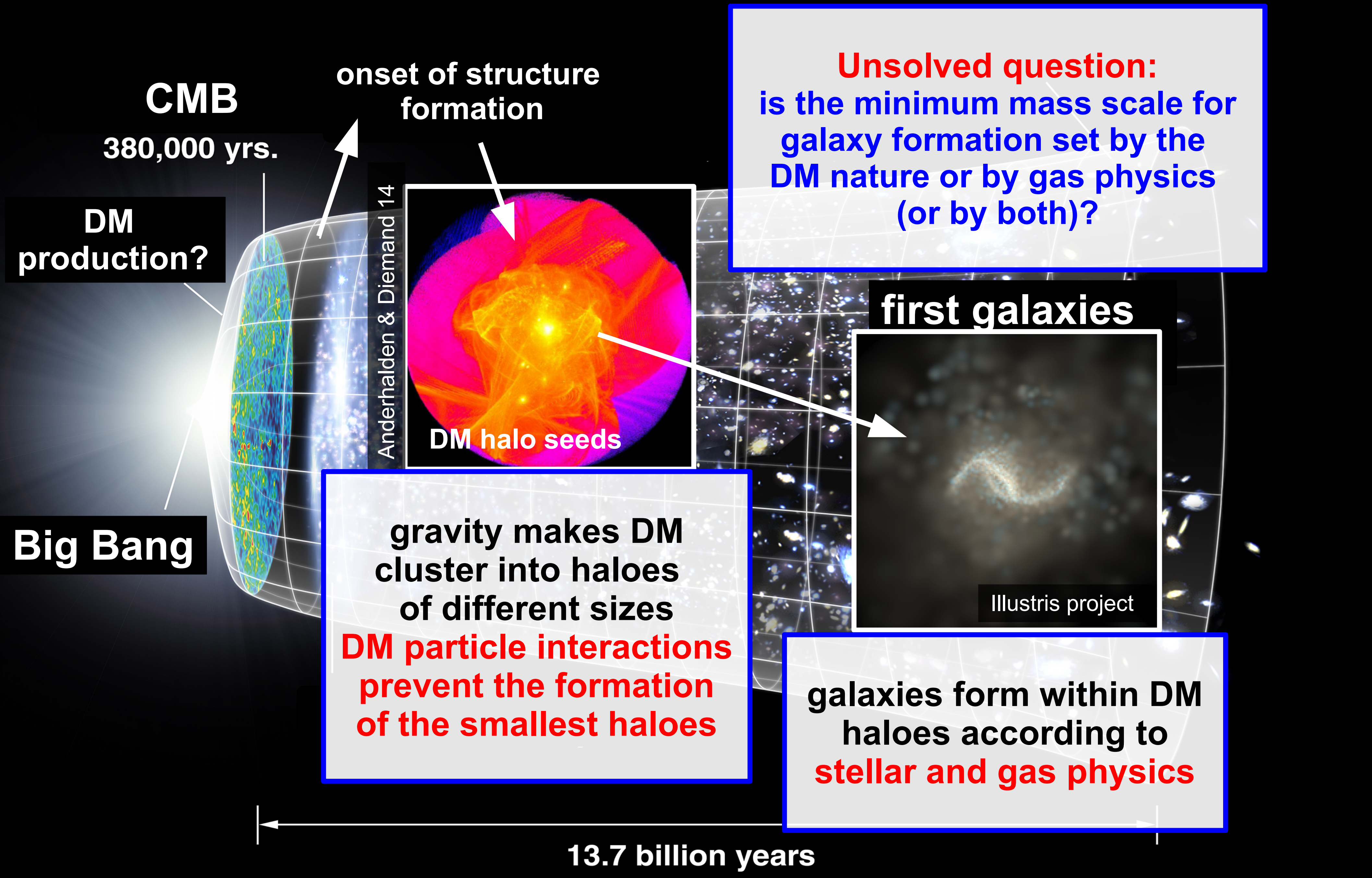
Unsolved question:
is the minimum mass scale for galaxy formation set by the DM nature or by gas physics (or by both)?

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

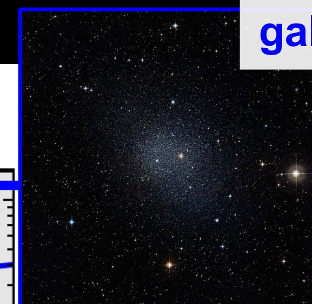


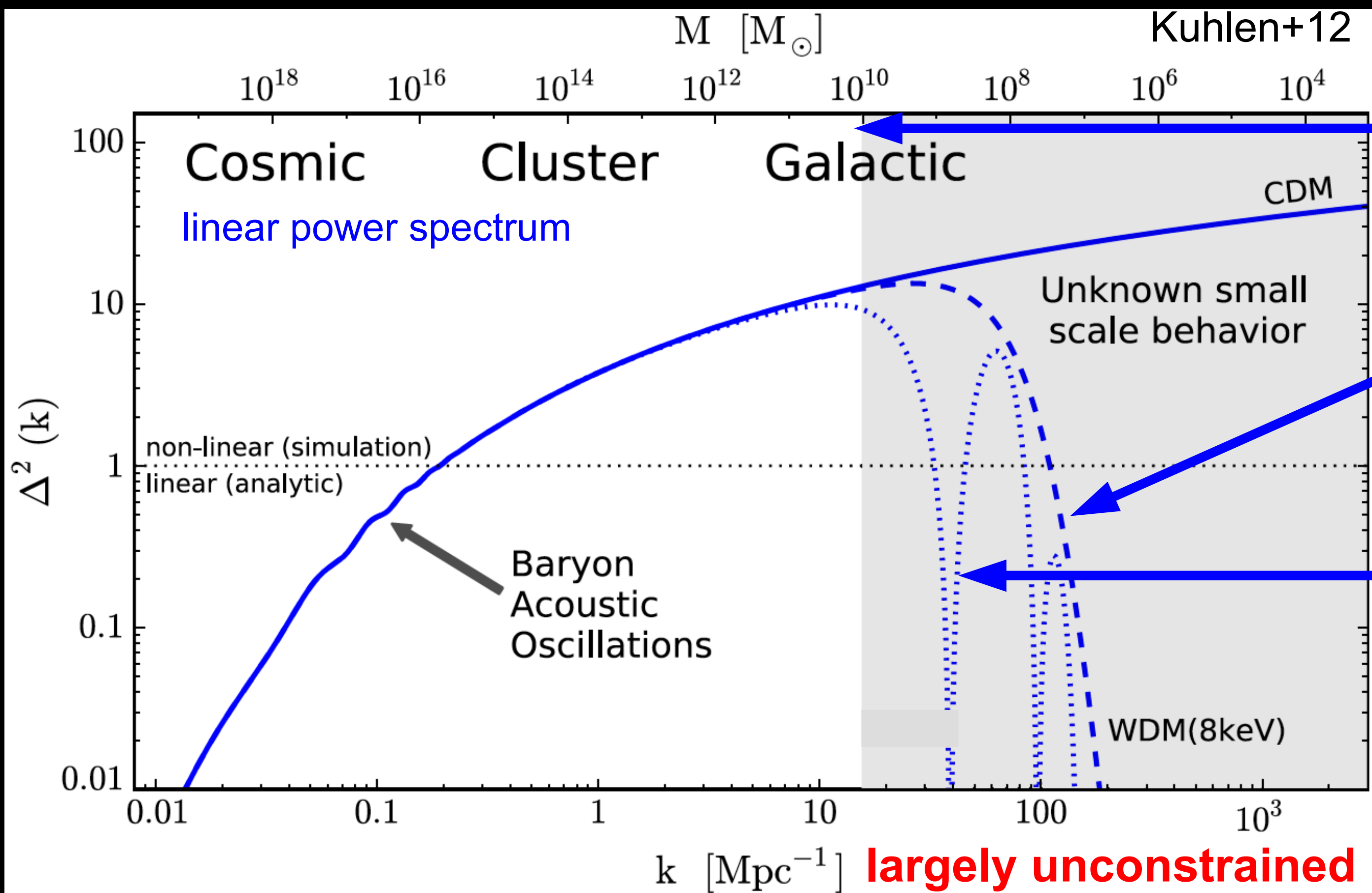
The nature of dark matter and the first galaxies

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

Dwarf galaxies

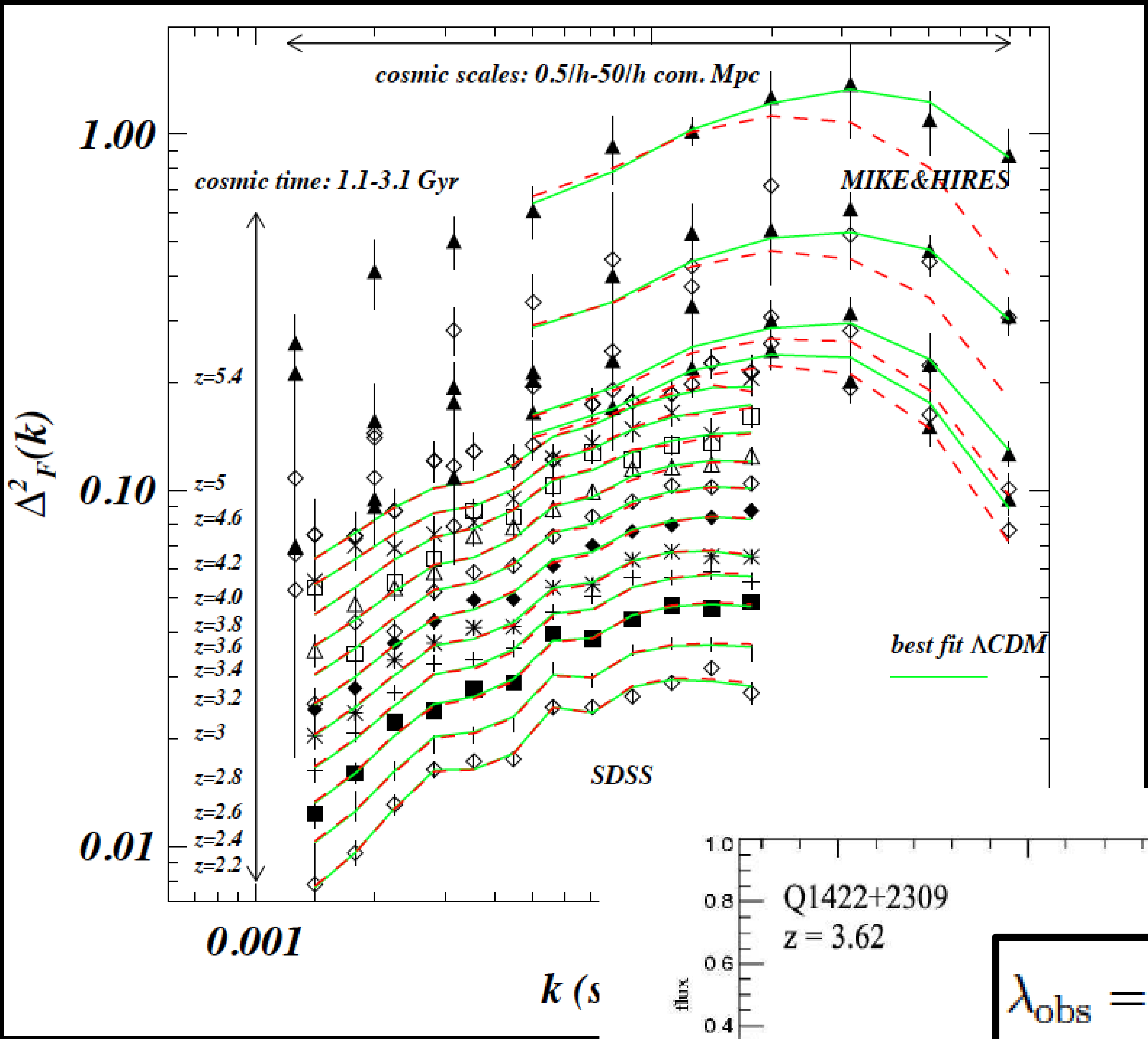




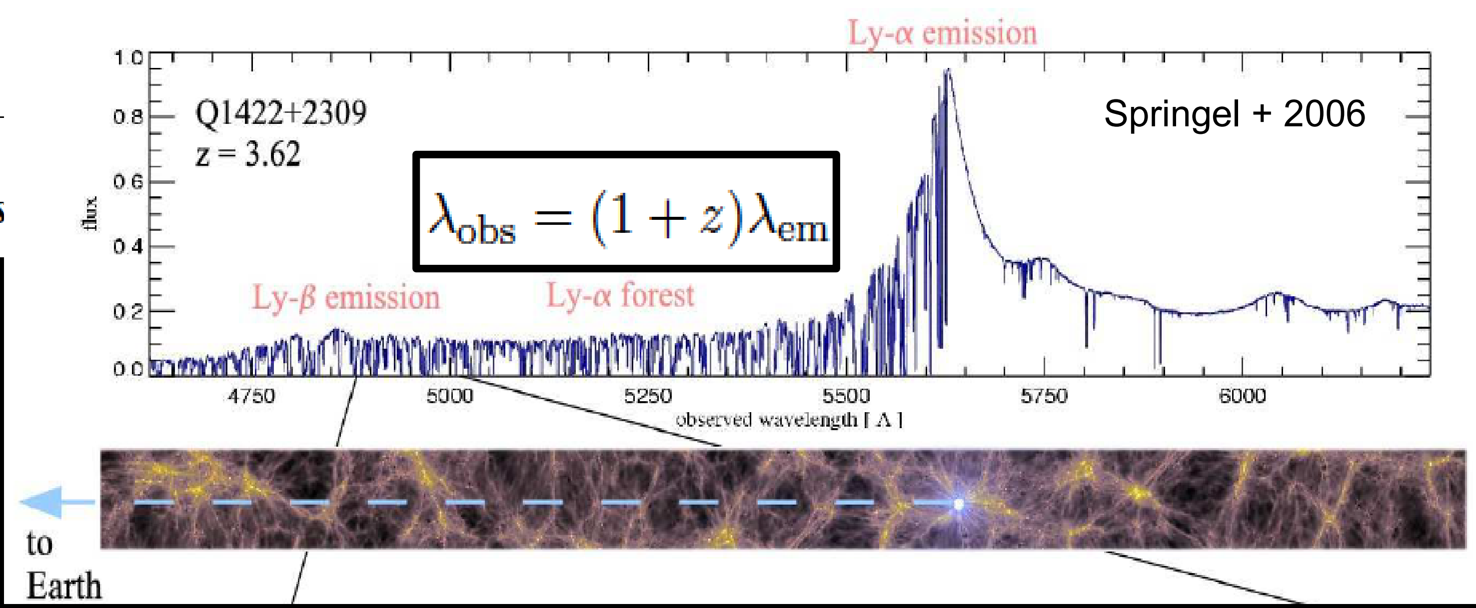
DM is relativistic at earlier times thermal cut-off (free-streaming)

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

(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

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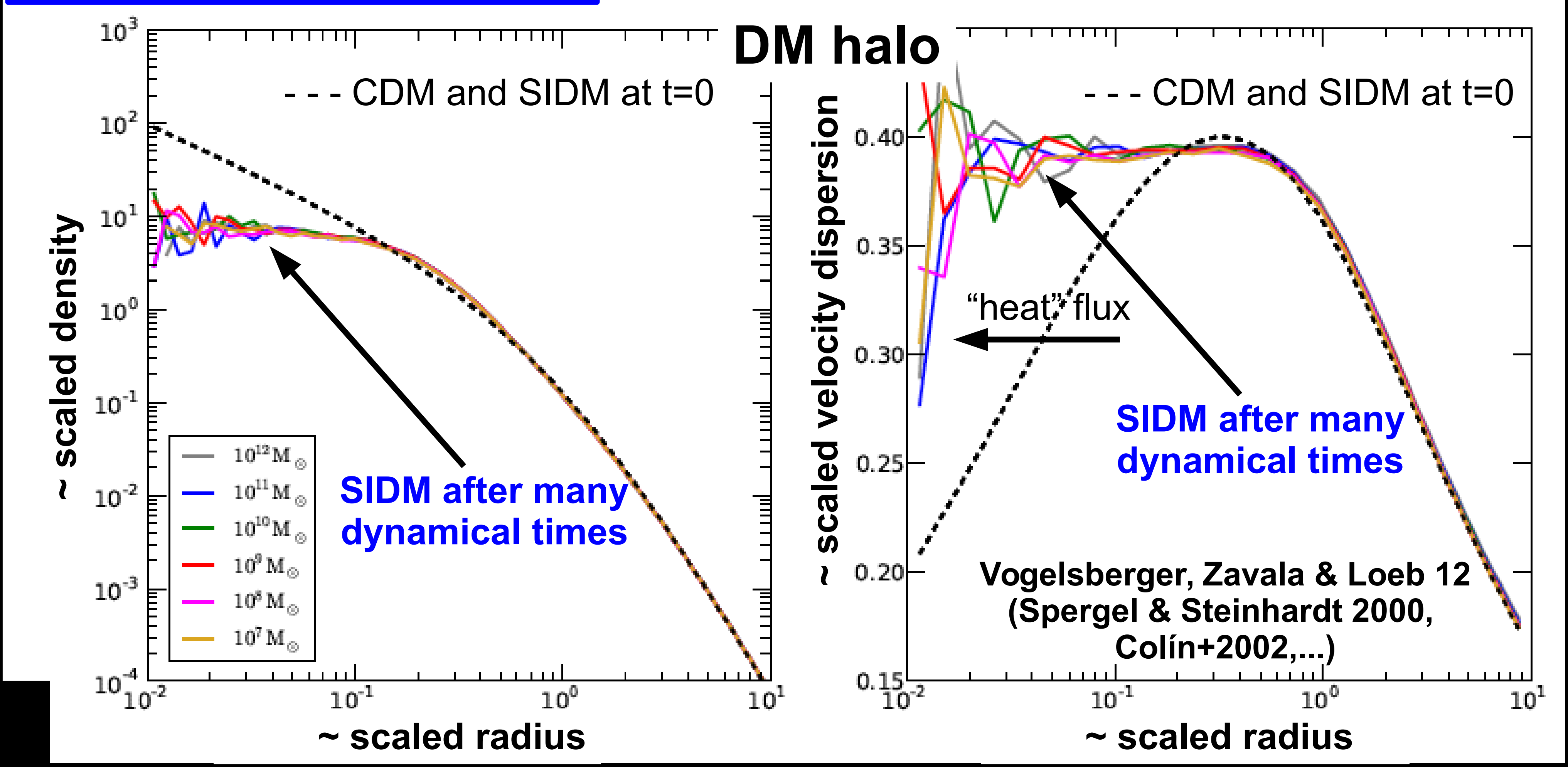
The nature of dark matter (evolution of structures)

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

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



Vogelsberger, Zavala & Loeb 12 (Spergel & Steinhardt 2000, Colín+2002,...)

The nature of dark matter (evolution of structures)

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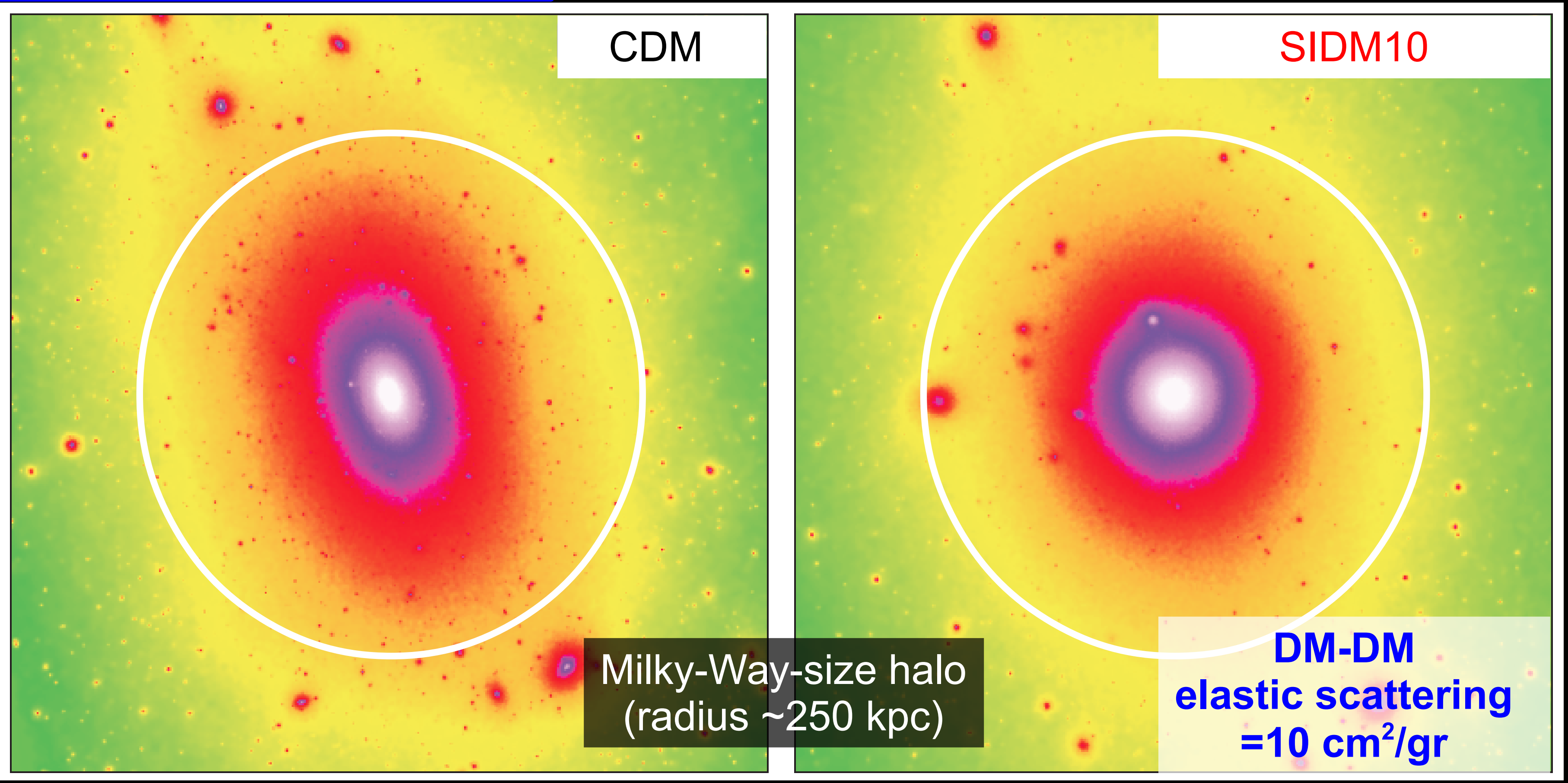
If gravity is the only relevant DM interaction, the central density of haloes is ever increasing

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....)

The nature of dark matter (evolution of structures)

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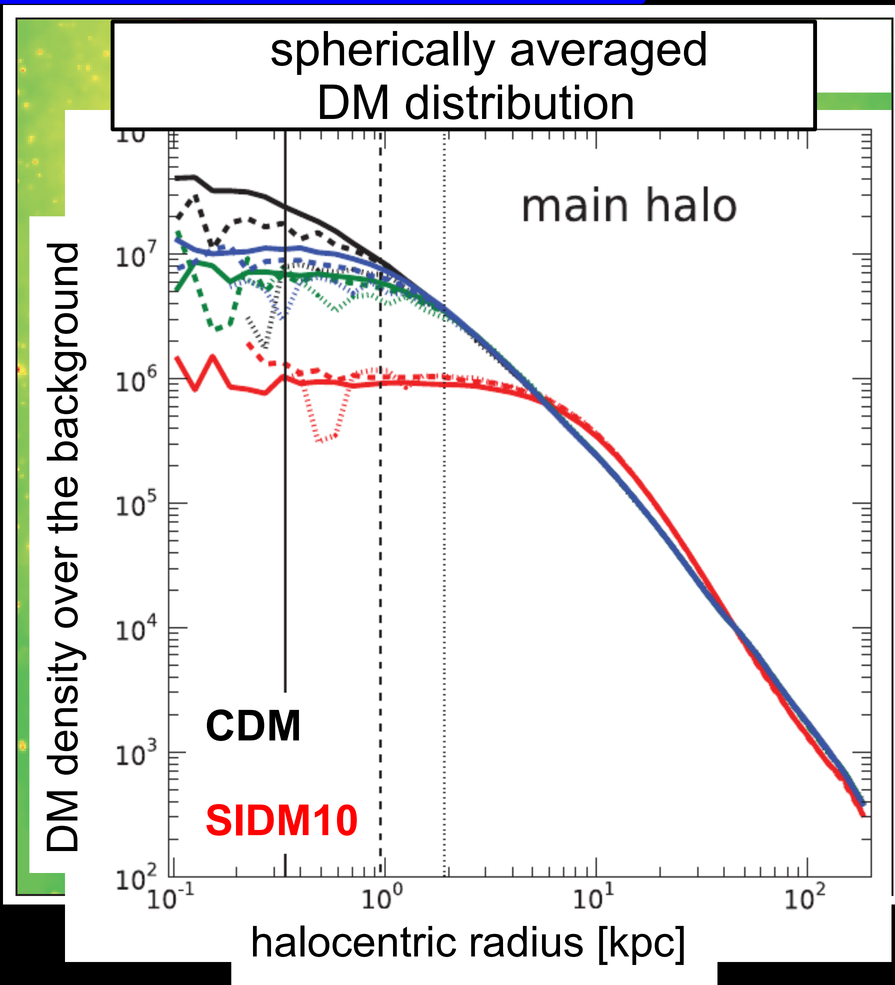
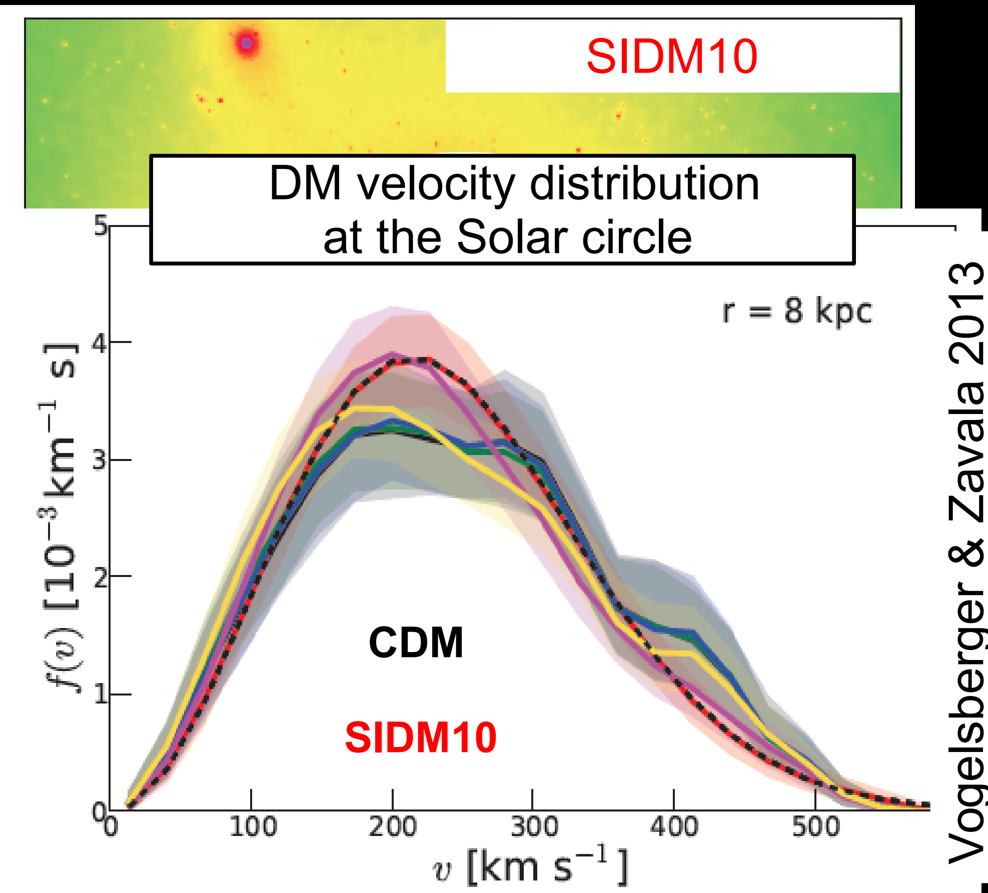


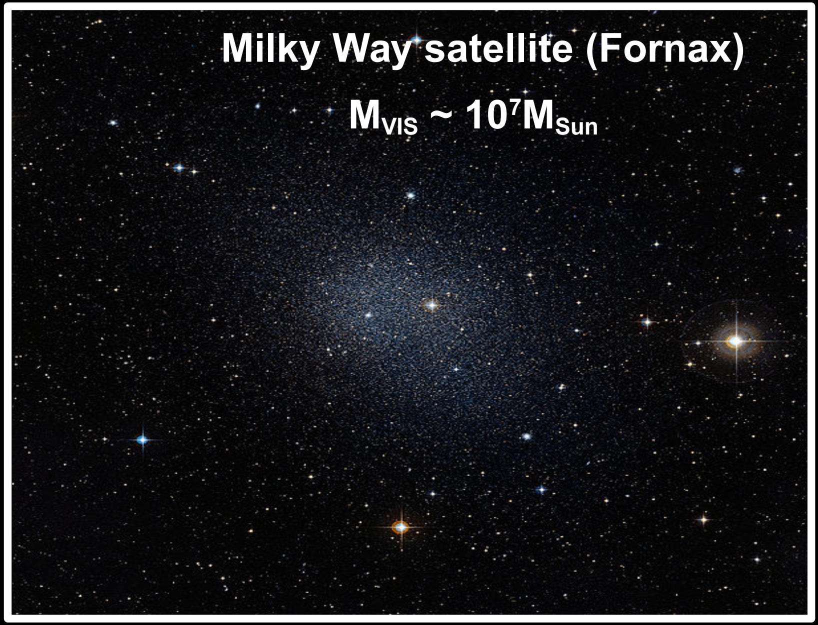


Vogelsberger & Zavala 2013

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

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

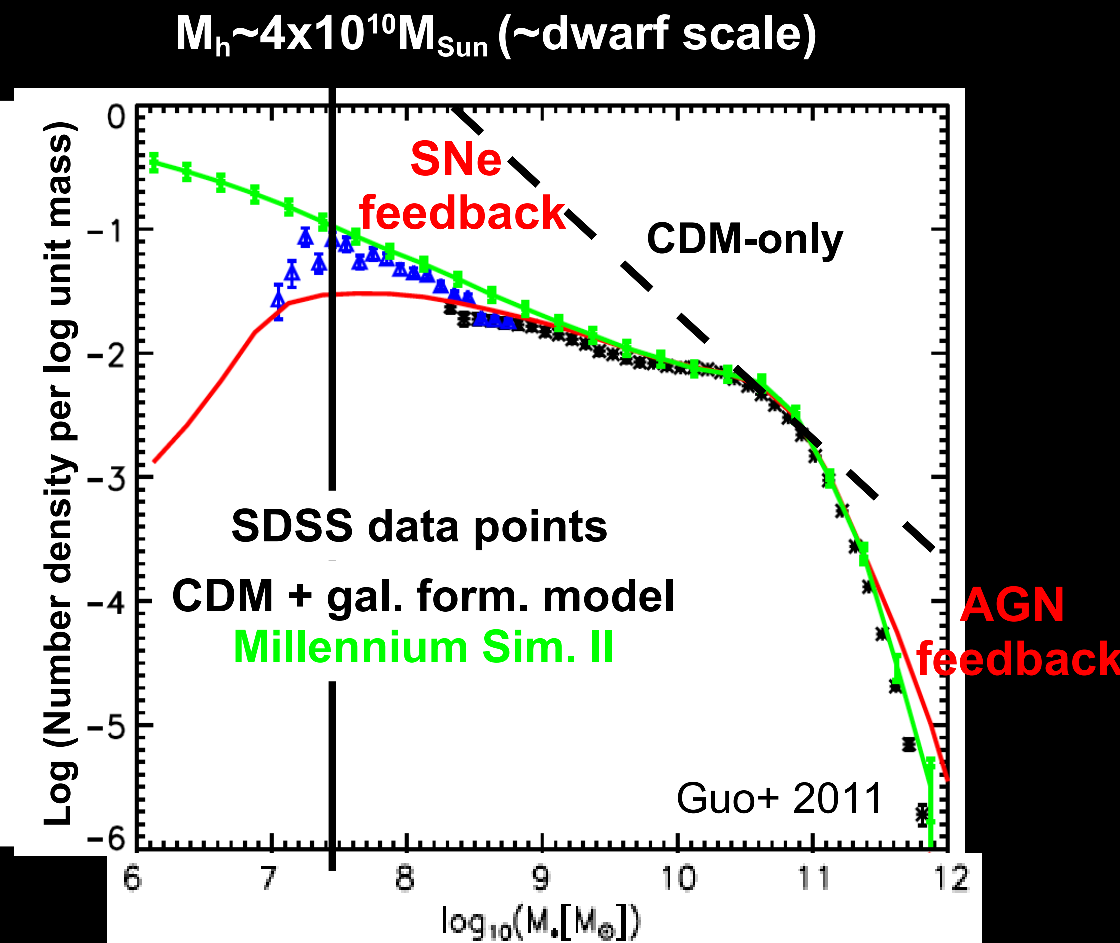
$$\beta = 1 - \left(\sigma_t/\sigma_r\right)^2$$

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

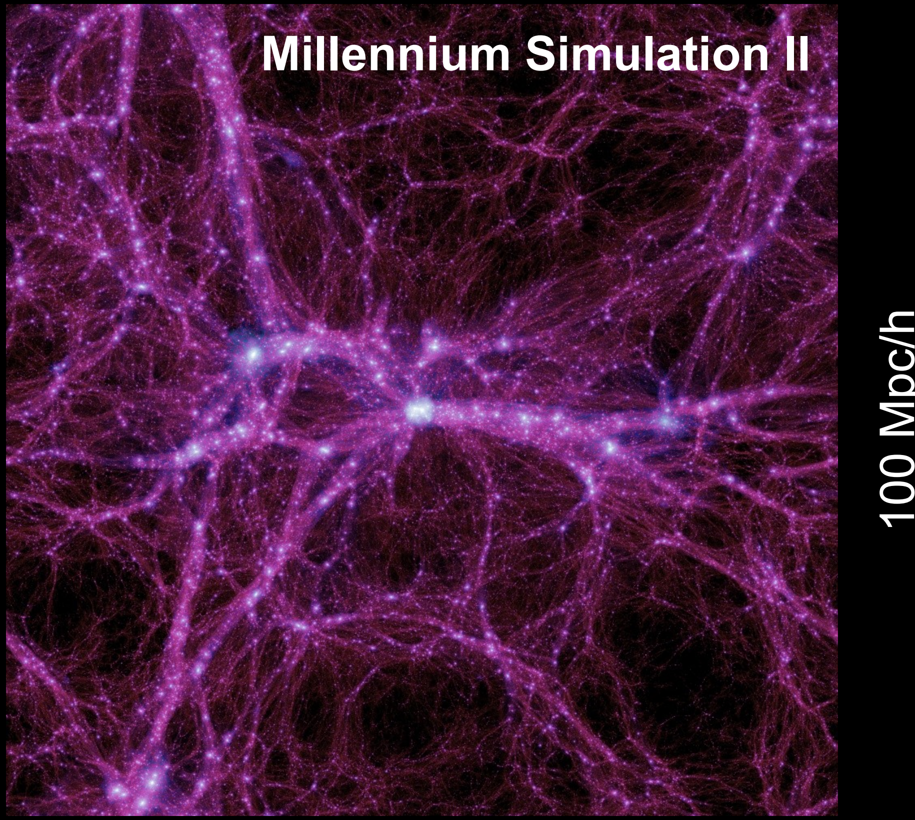
CBE + steady-state
+ spherical symmetry

"Optimal" dynamical DM detectors

Observed abundance of dwarf galaxies in the field



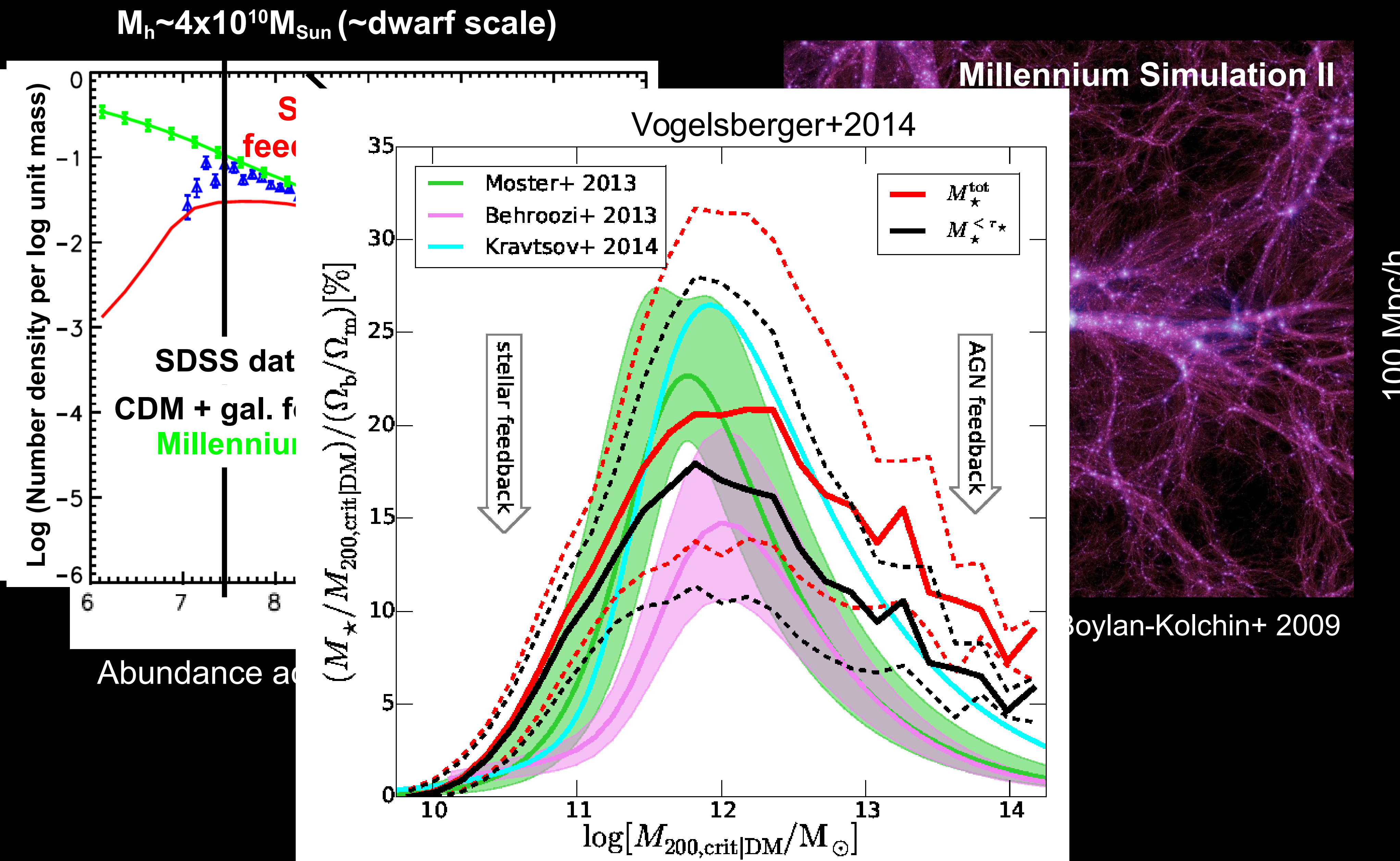
Abundance according to stellar mass



Boylan-Kolchin+ 2009

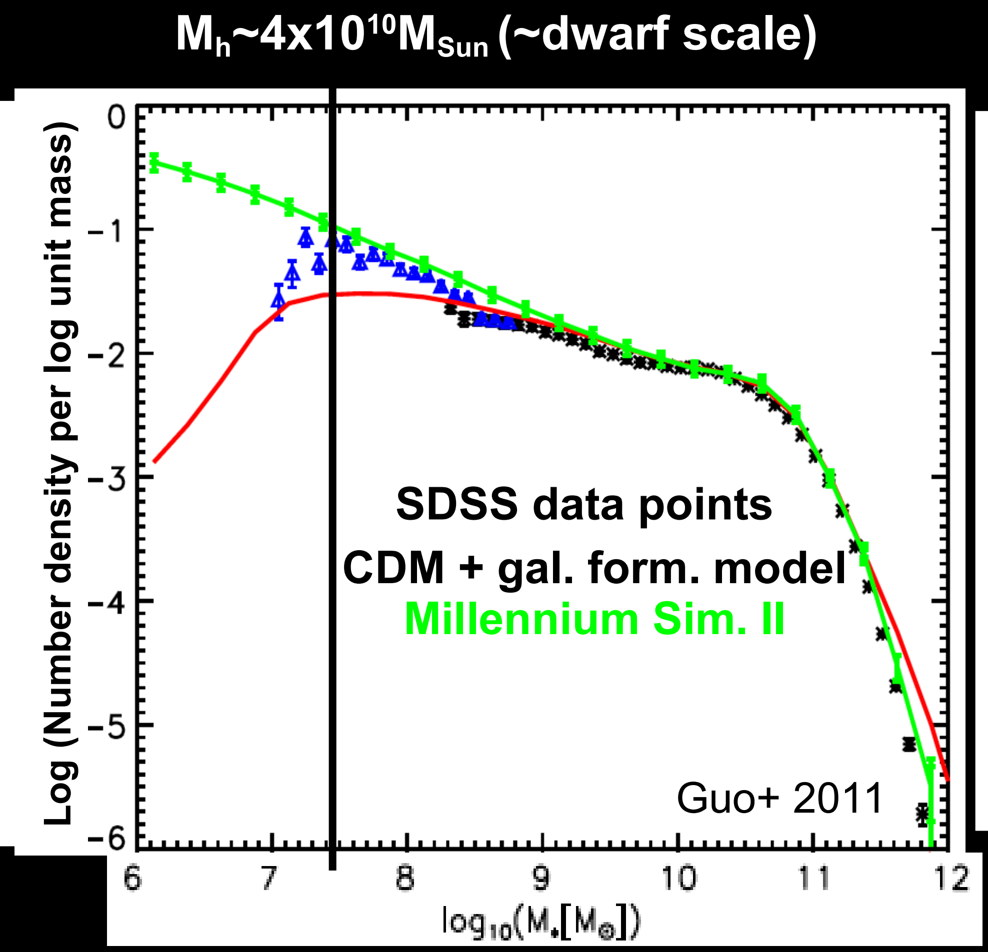
Galaxy formation and evolution modifies the DM-only prediction

Observed abundance of dwarf galaxies in the field

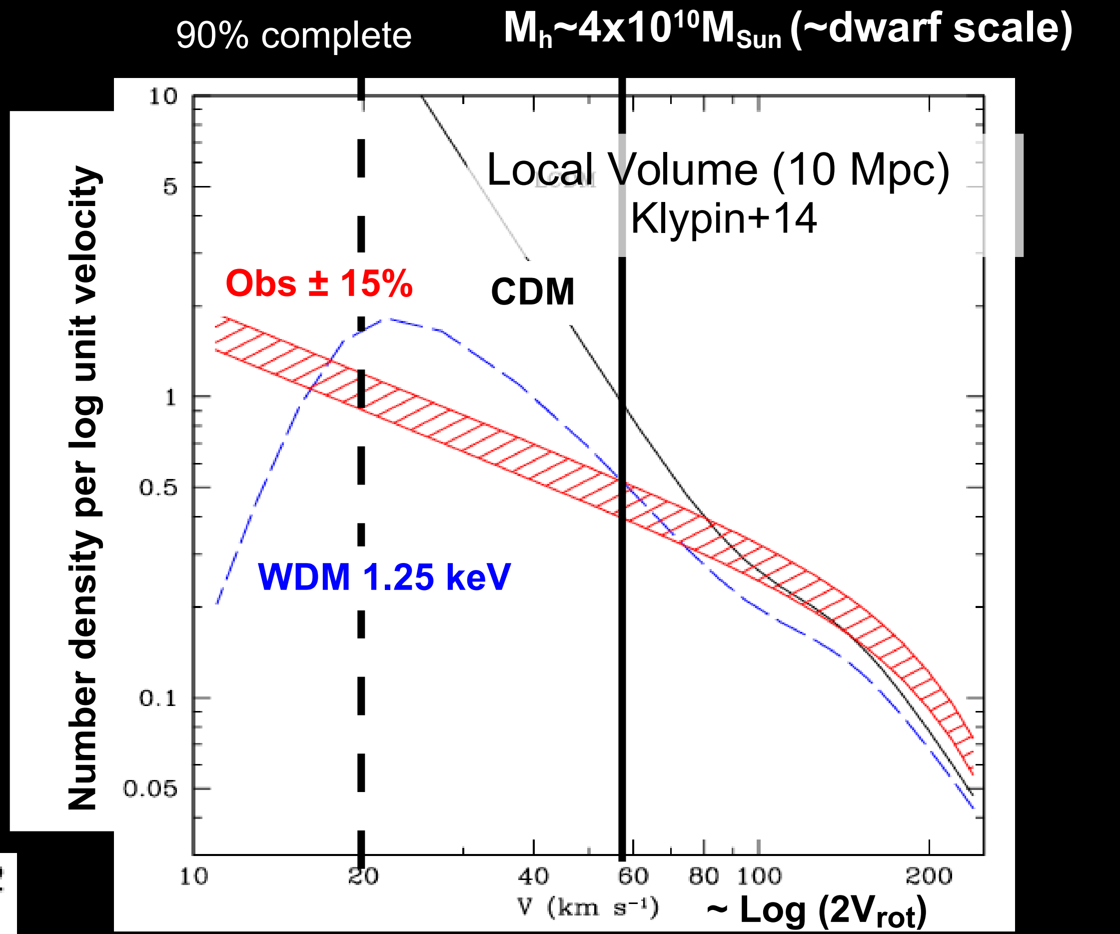


Galaxy formation is quite inefficient!!

Observed abundance of dwarf galaxies in the field



Abundance according to stellar mass



Abundance according to global rotation

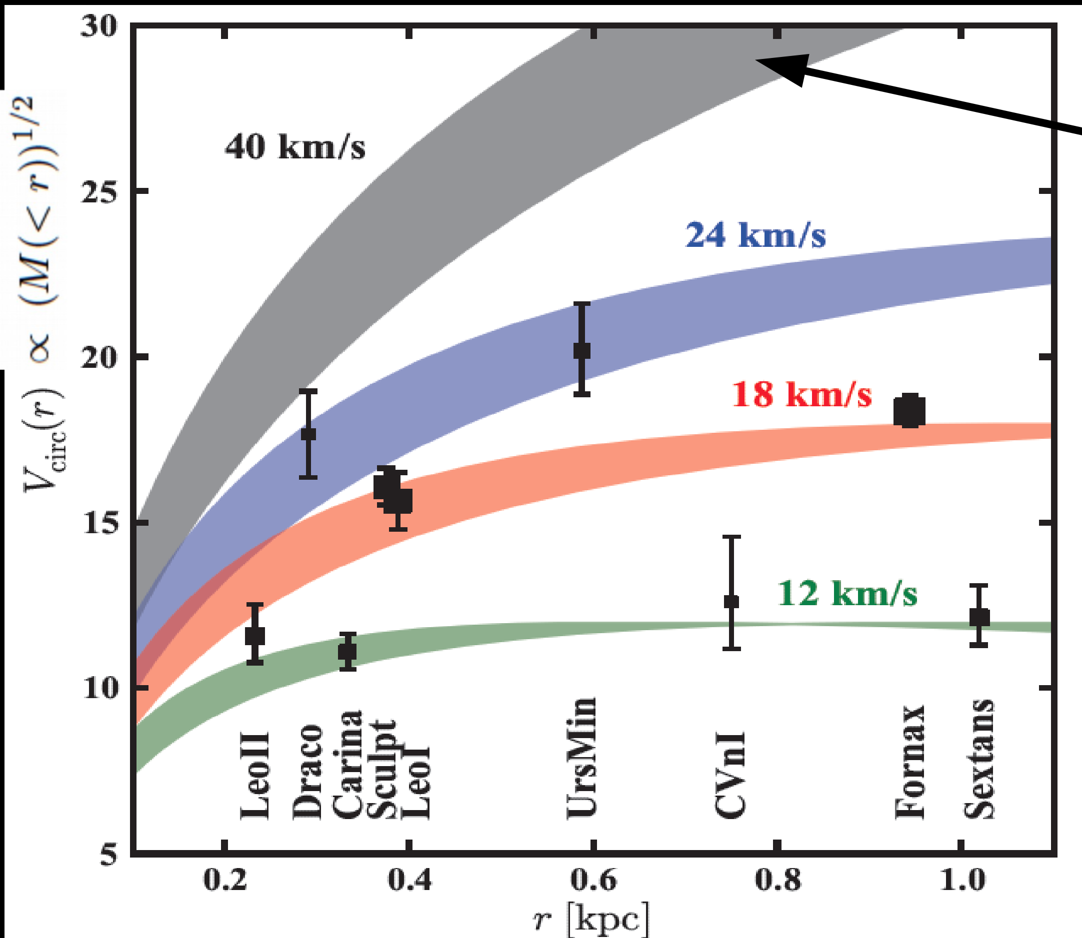
CDM + current gal. form. models overpredict the abundance of field dwarfs (Zavala+09,Papastergis+11,Klypin+14)

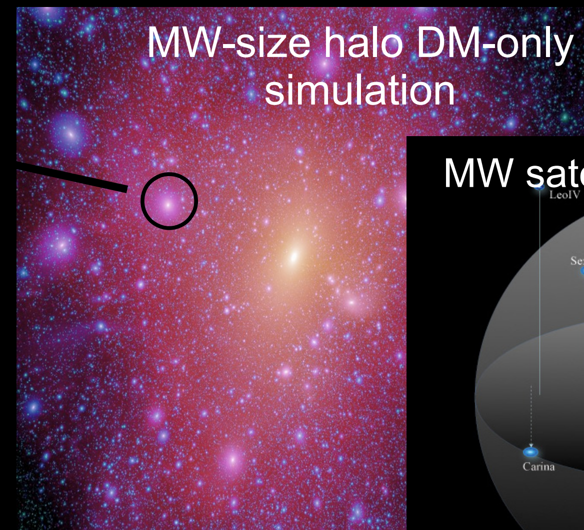
Missing satellite problem (is not really a problem in CDM

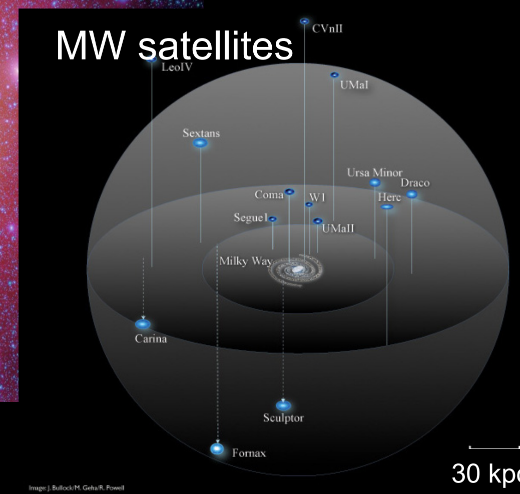
Missing isolated dwarfs (is an unsolved problem in CDM)

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

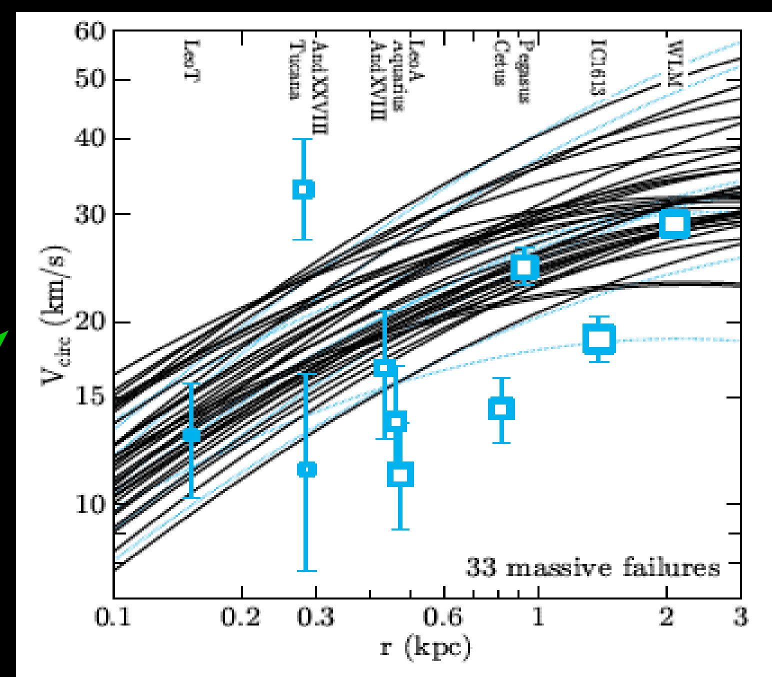
Boylan-Kolchin+12







Garrison-Kimmel+14

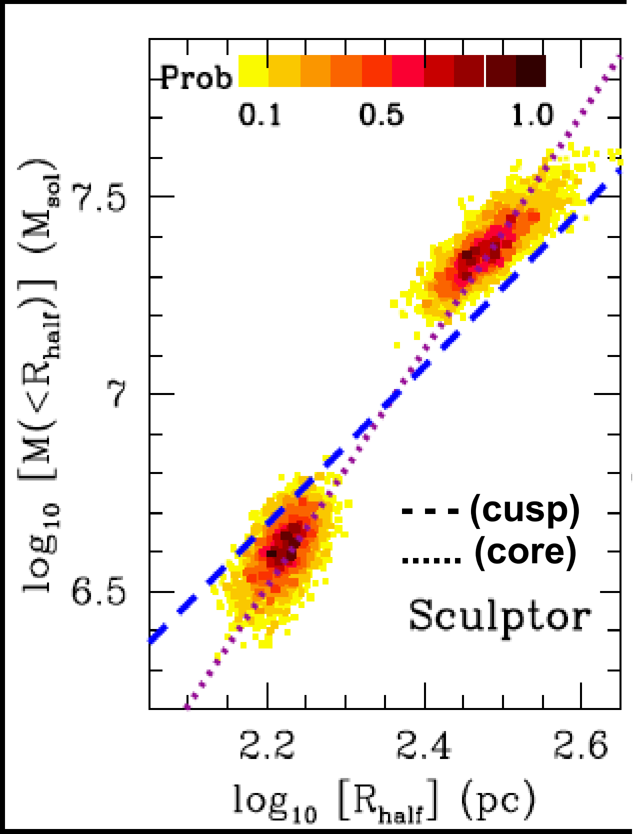


The most massive CDM-MW-subhaloes seem to be too centrally dense to host the MW dSphs (problem extends to LG)

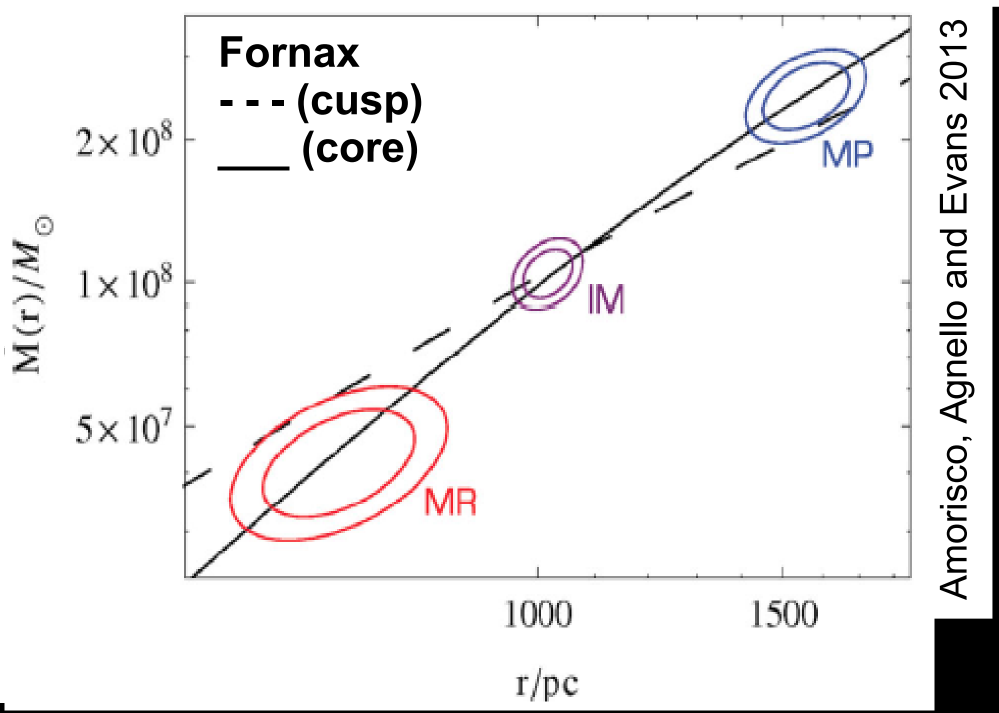
Unsolved problem in CDM!!

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

Walker & Peñarrubia 2011



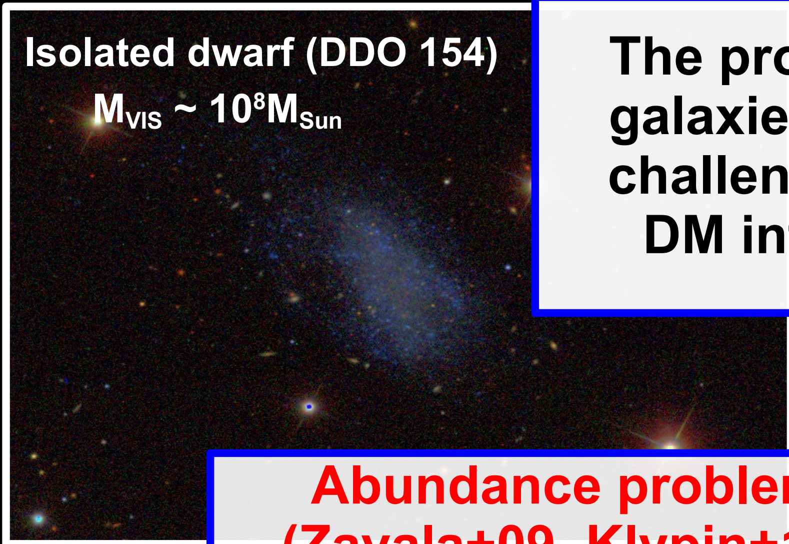
Different stellar subcomponents provide an estimate of the slope of the mass profile:
cores seem favoured over cusps



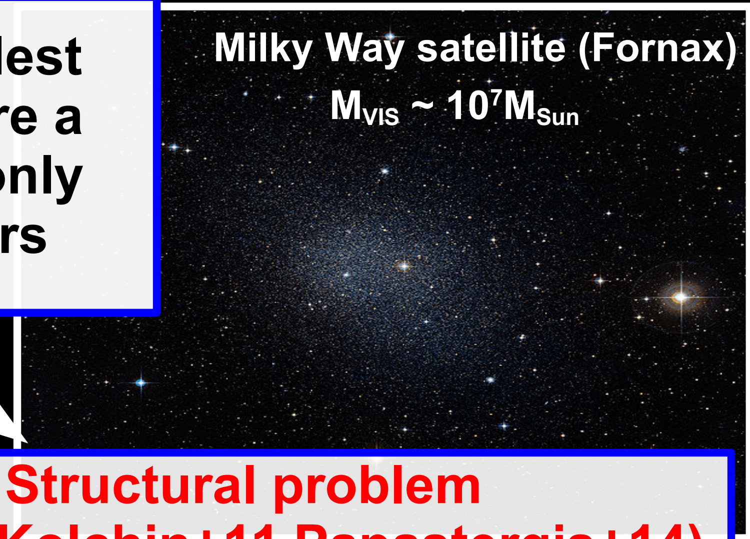
Other analysis suggest that **both cores and cusps can fit the data**
(e.g. Breddels & Helmi 13, Richardson & Fairbairn 14, Strigari, Frenk & White 14)

Controversial issue in CDM!!

Clues of new DM physics from dwarf galaxies?

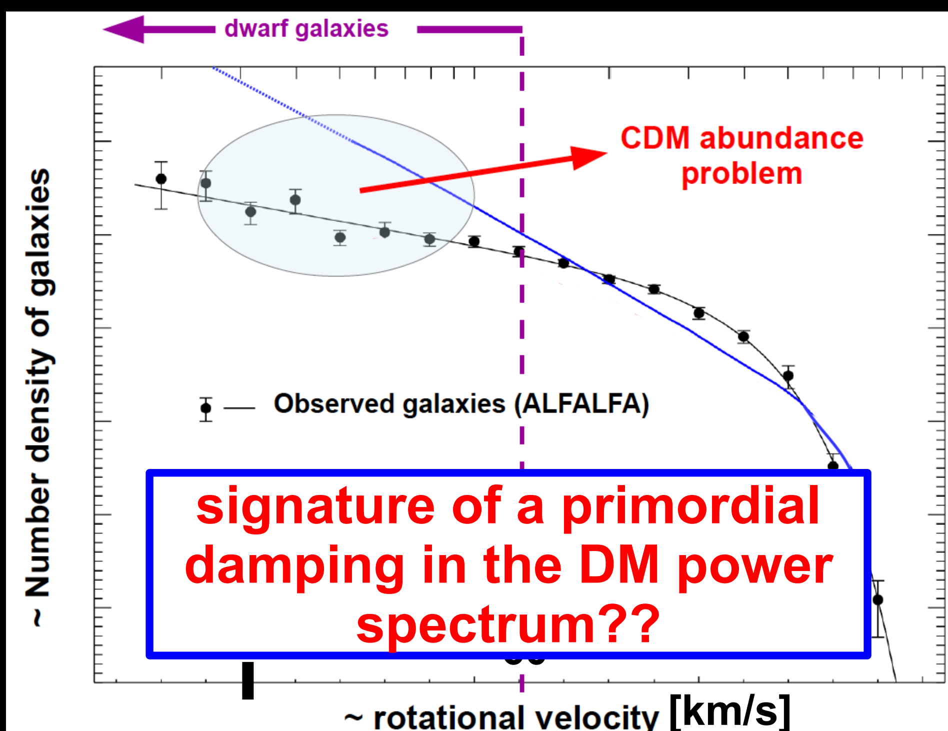


The properties of the smallest galaxies observed **today** are a challenge if gravity is the only DM interaction that matters

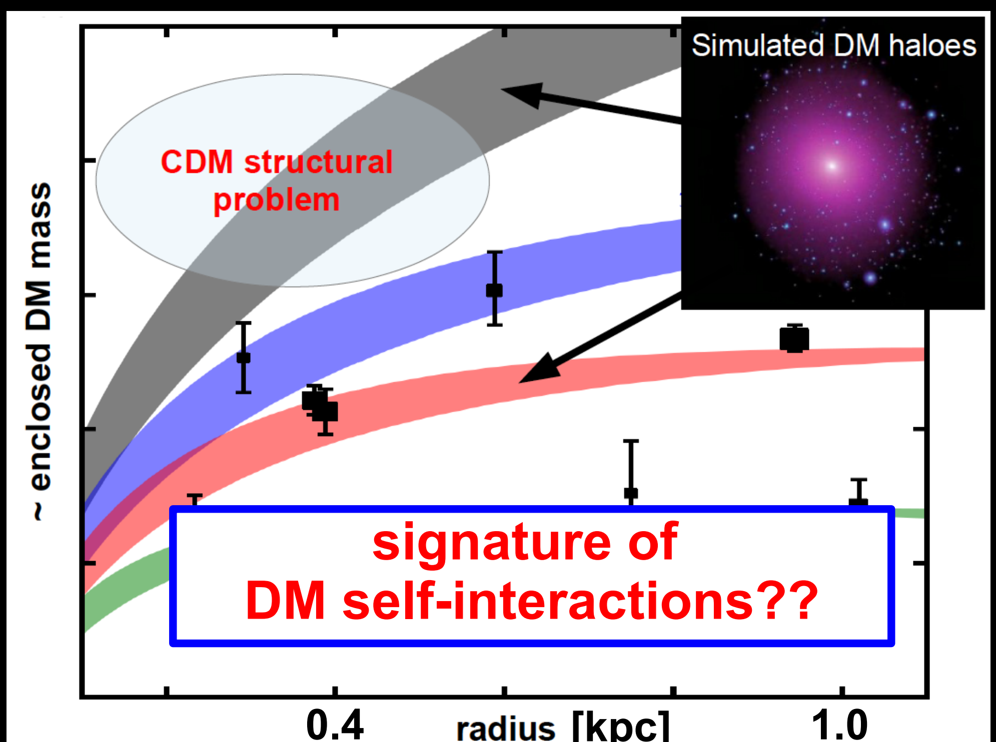


Abundance problem (Zavala+09, Klypin+15)

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



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

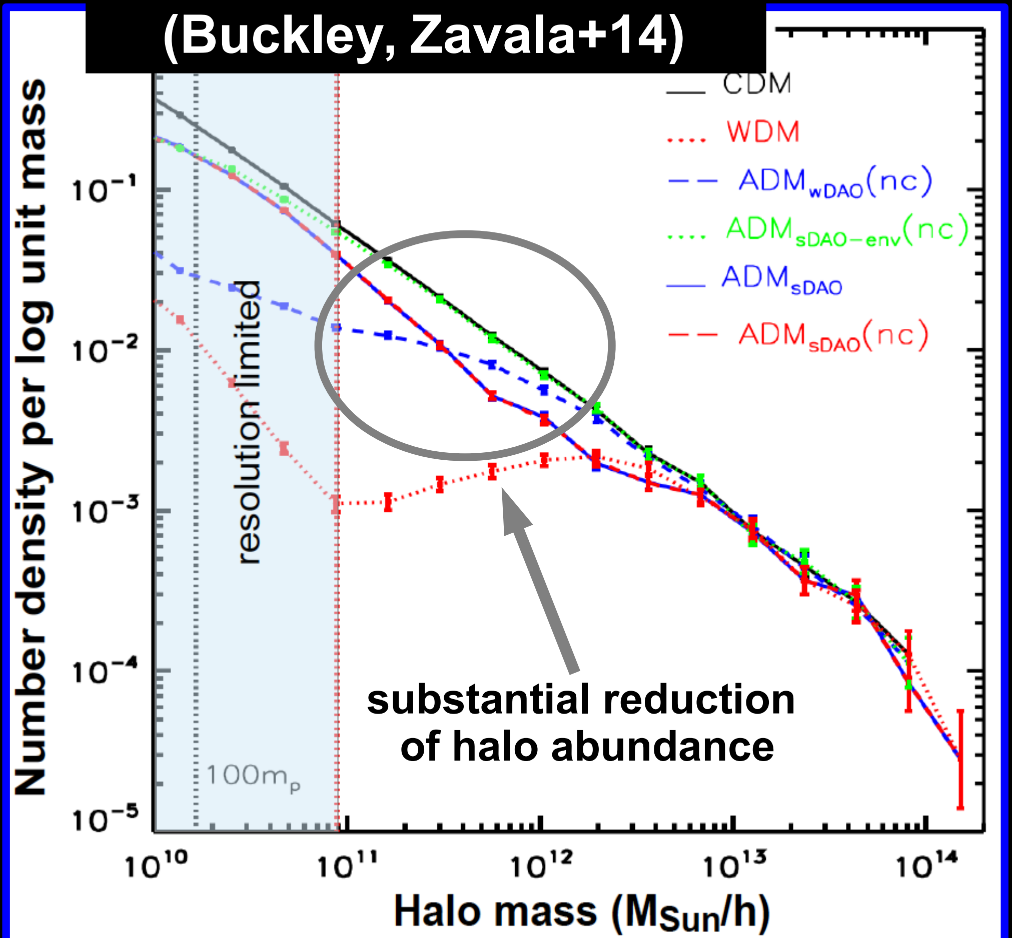


signature of DM self-interactions??

Structure formation in a universe with new dark matter interactions

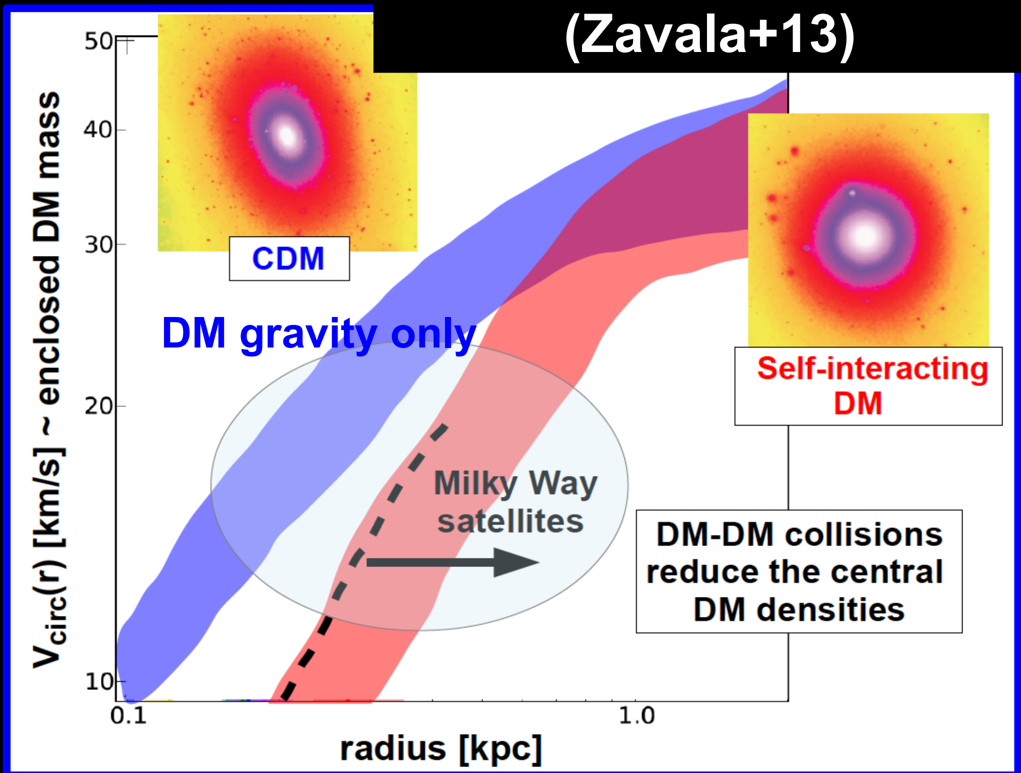
The abundance and structural problems of the smallest galaxies might be solved with new DM interactions

Abundance of DM haloes (Buckley, Zavala+14)



interactions between DM and dark radiation

DM content in DM haloes (Zavala+13)

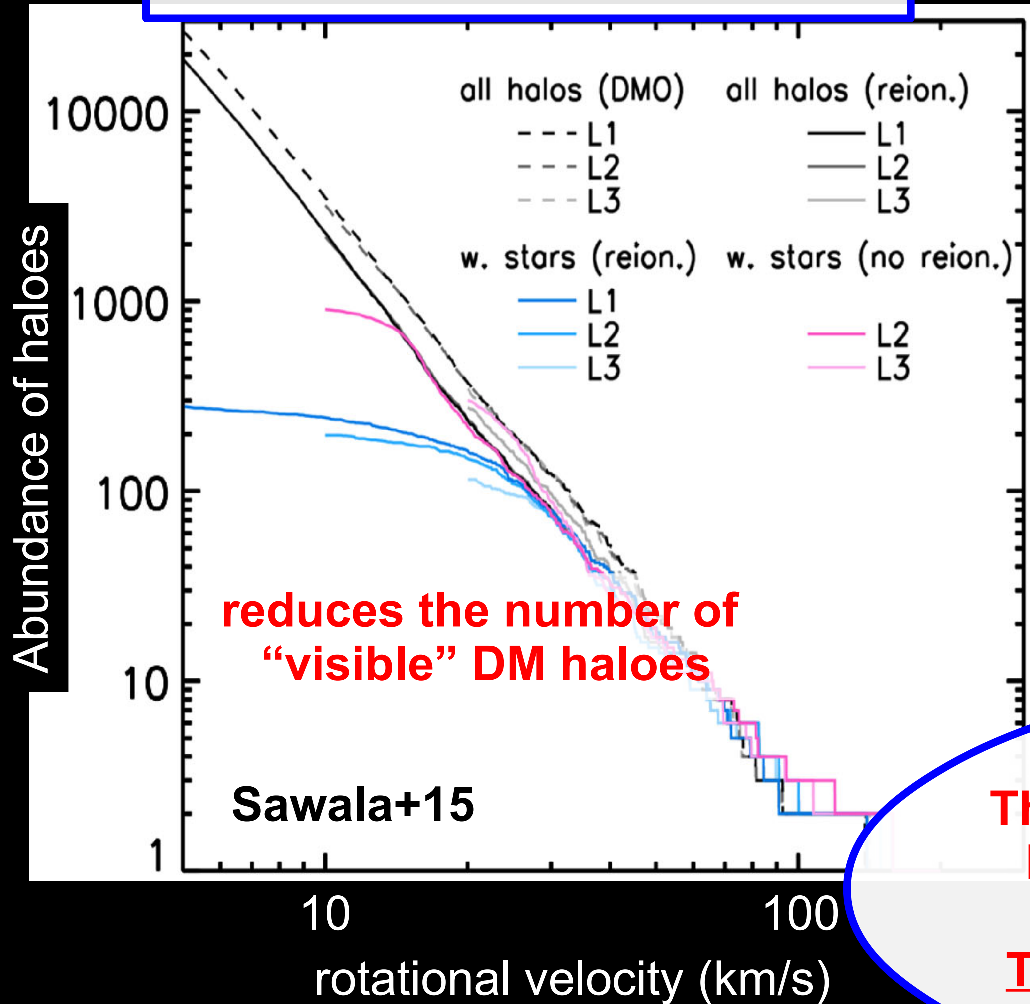


DM self-interactions

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

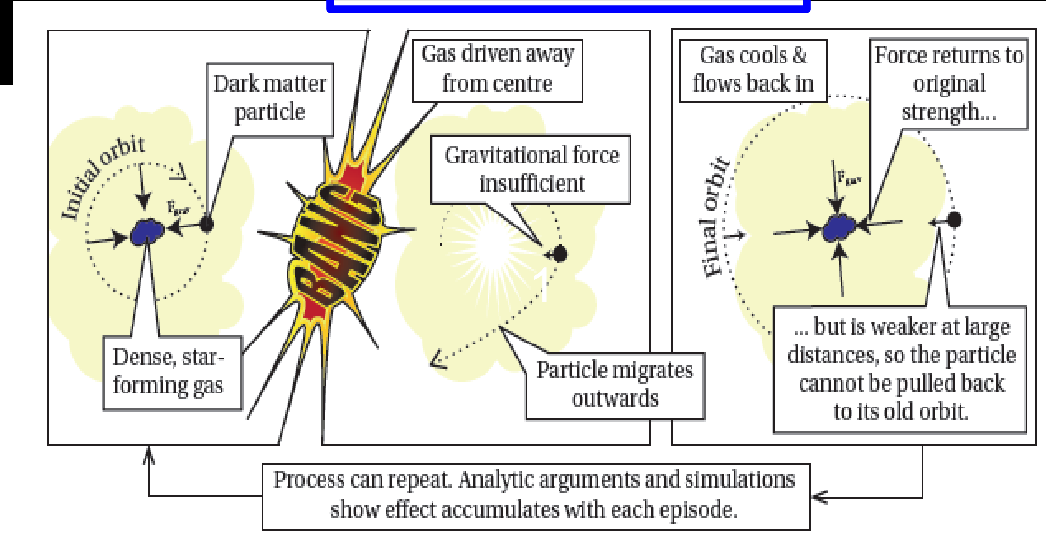
Or... the complexity of gas and stellar physics

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

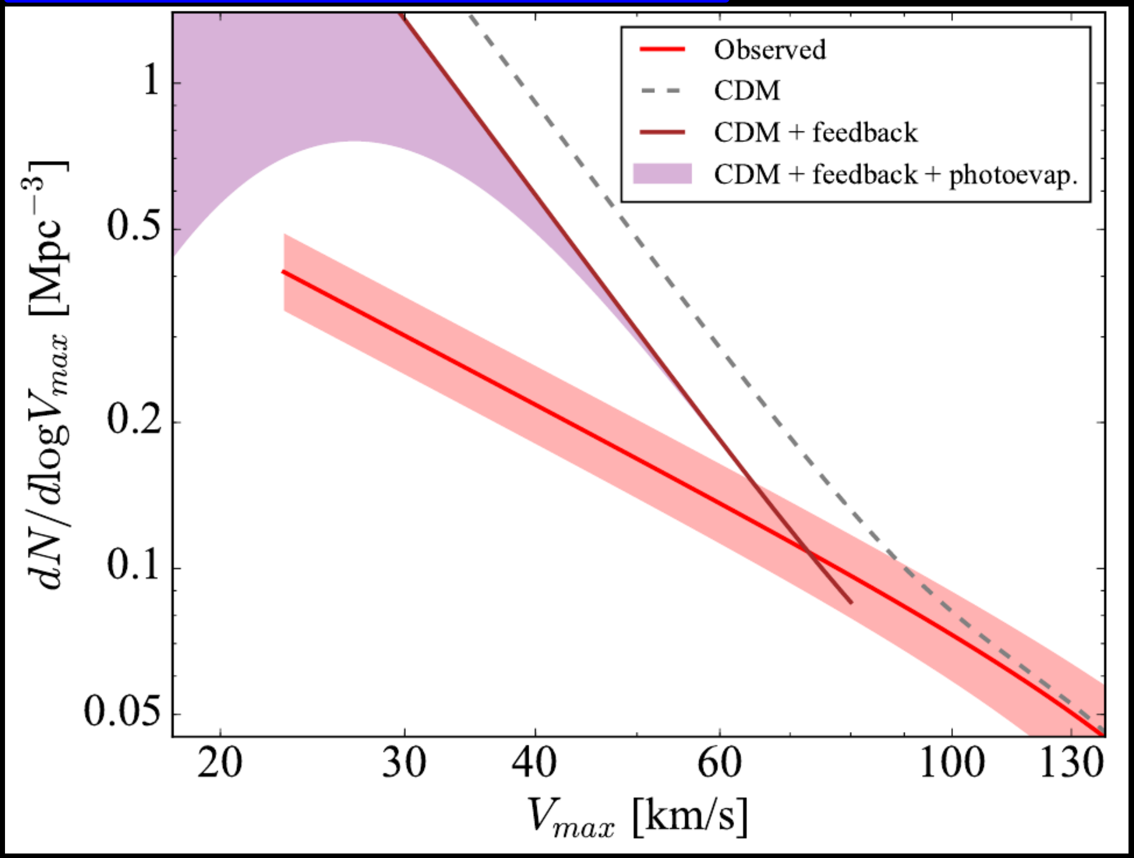
<u>To some extent, they are degenerate with new DM physics</u>

Or... the complexity of gas and stellar physics

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

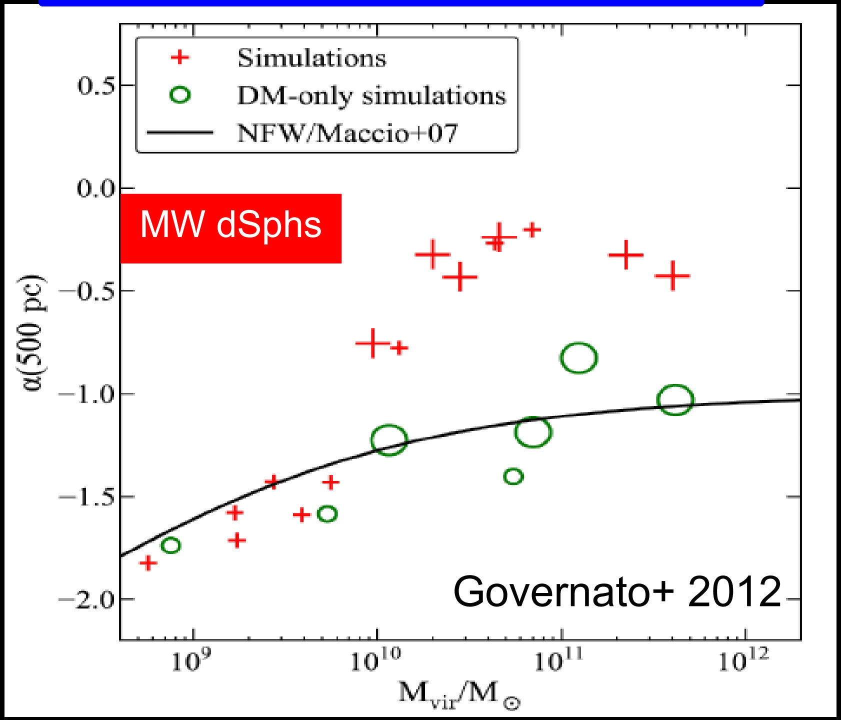
Gas and DM heating through supernovae

Abundance problem



Trujillo-Gomez+06

Core-cusp problem



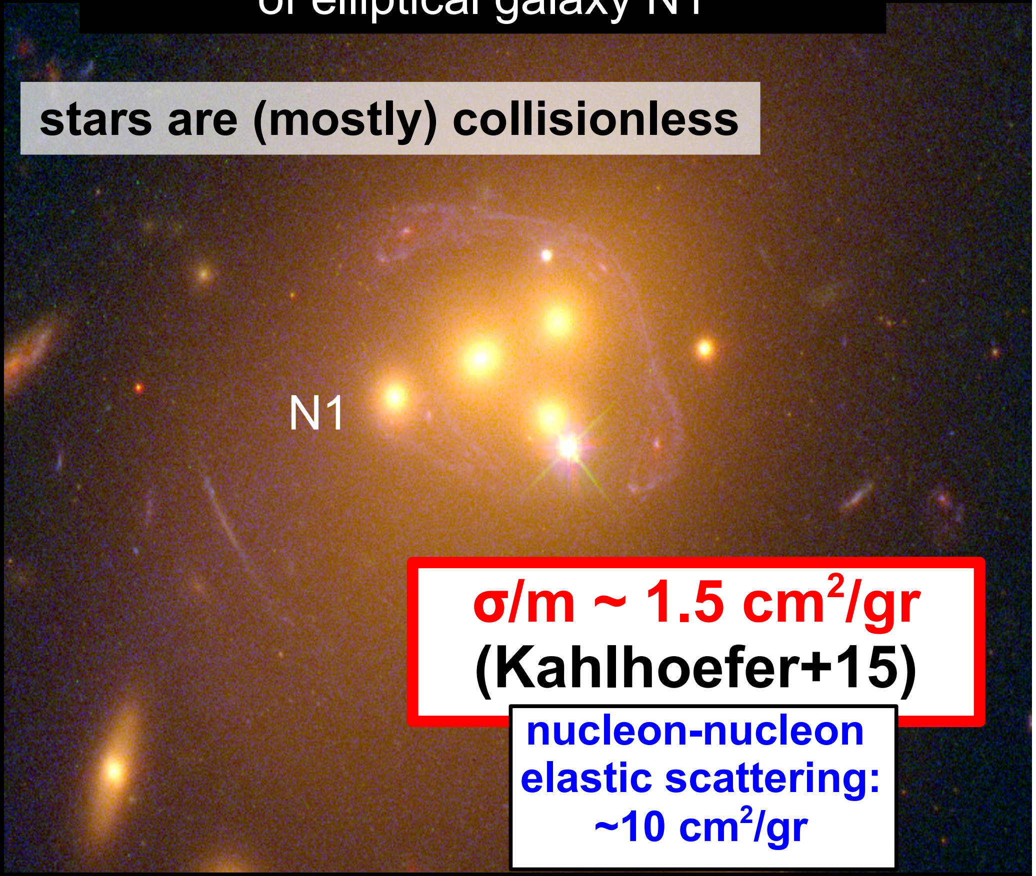
SN feedback in MW dSphs:
likely insufficient for dSphs

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

Clues on new DM physics at other scales?

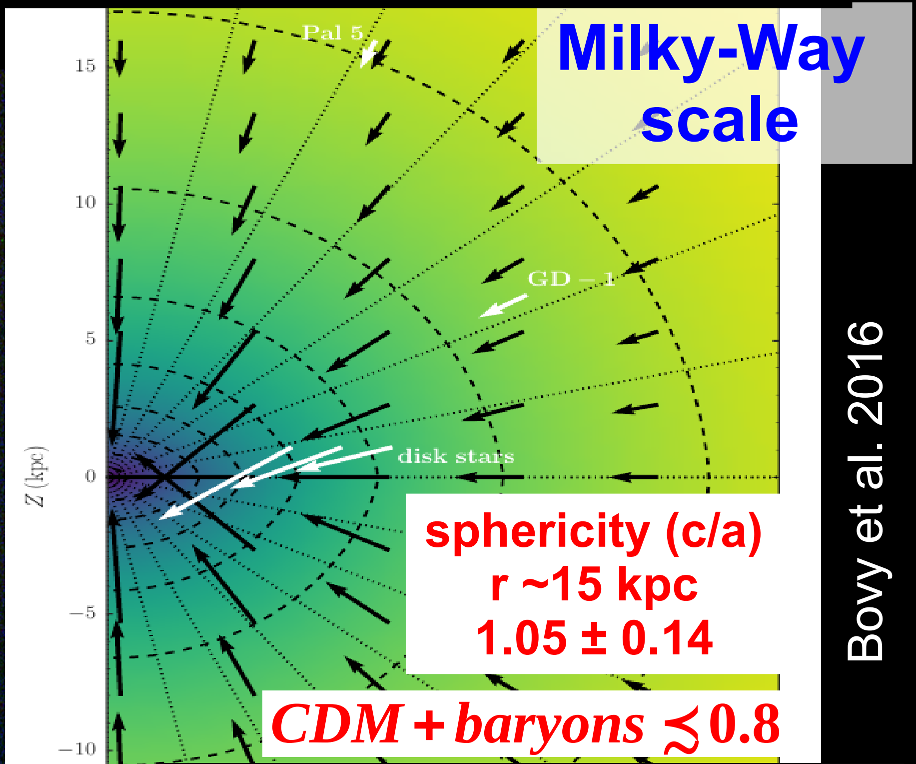
claimed detection of ~1.6 kpc offset between the stars and DM centroids of elliptical galaxy N1

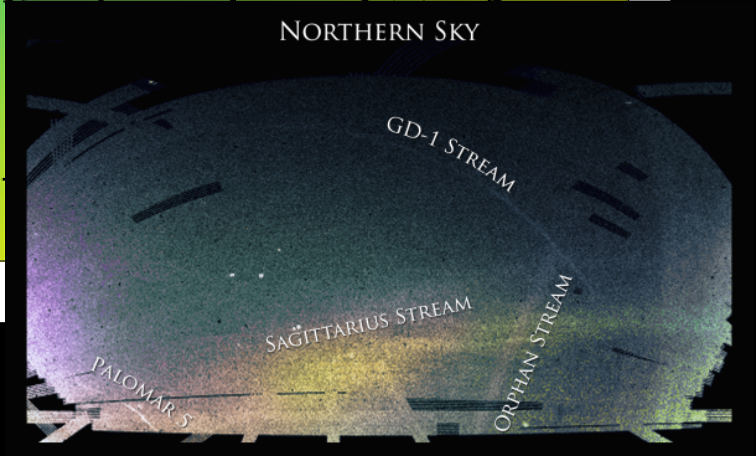
Cluster Abell 3827 (Massey +15)



Cluster scales

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





Bovy et al. 2016

Lecture 3

Towards an Effective THeory Of Structure formation (ETHOS)

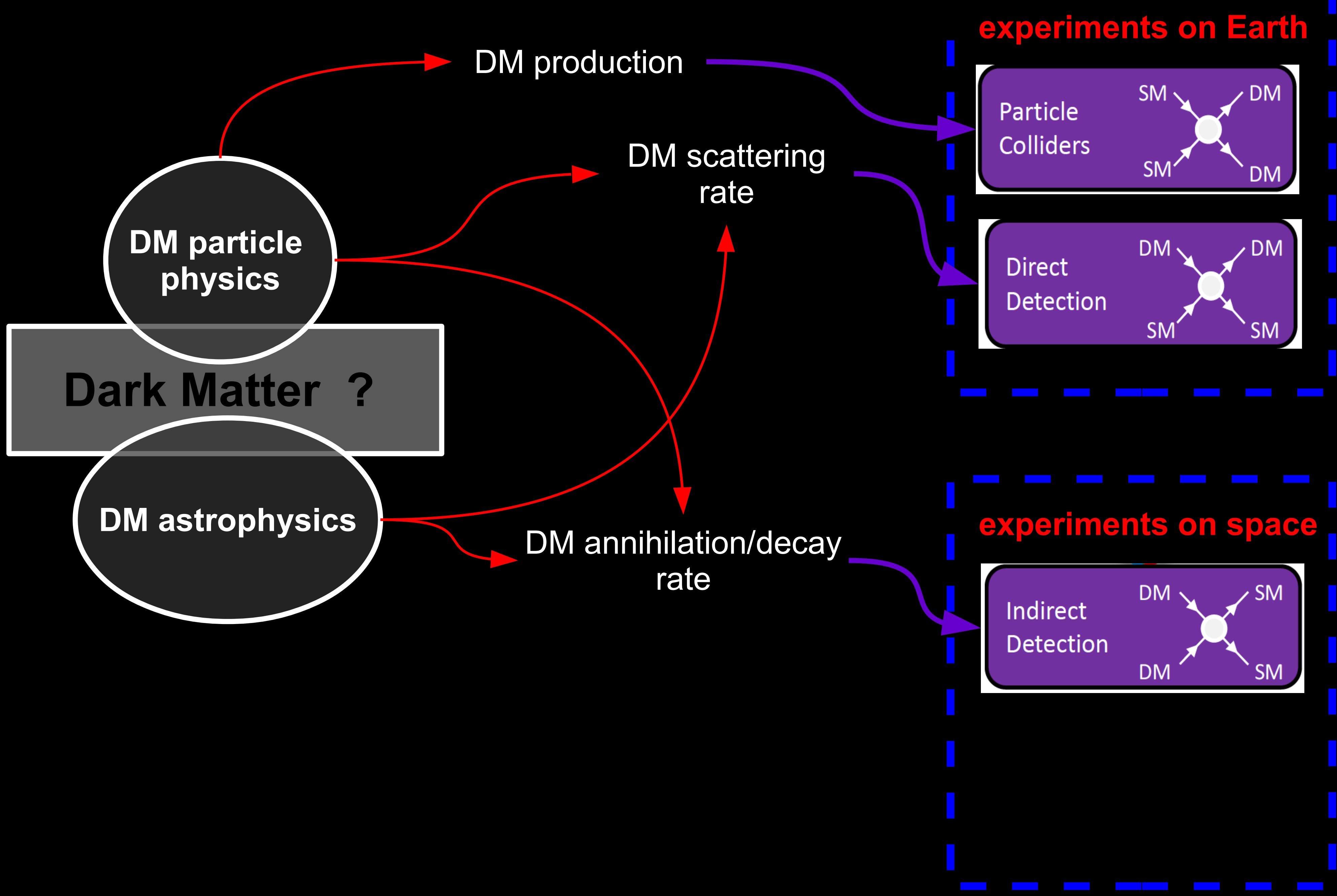
CDM + current galaxy modelling are successful in reproducing several properties of the galaxy population but:

uncertain gas and stellar physics

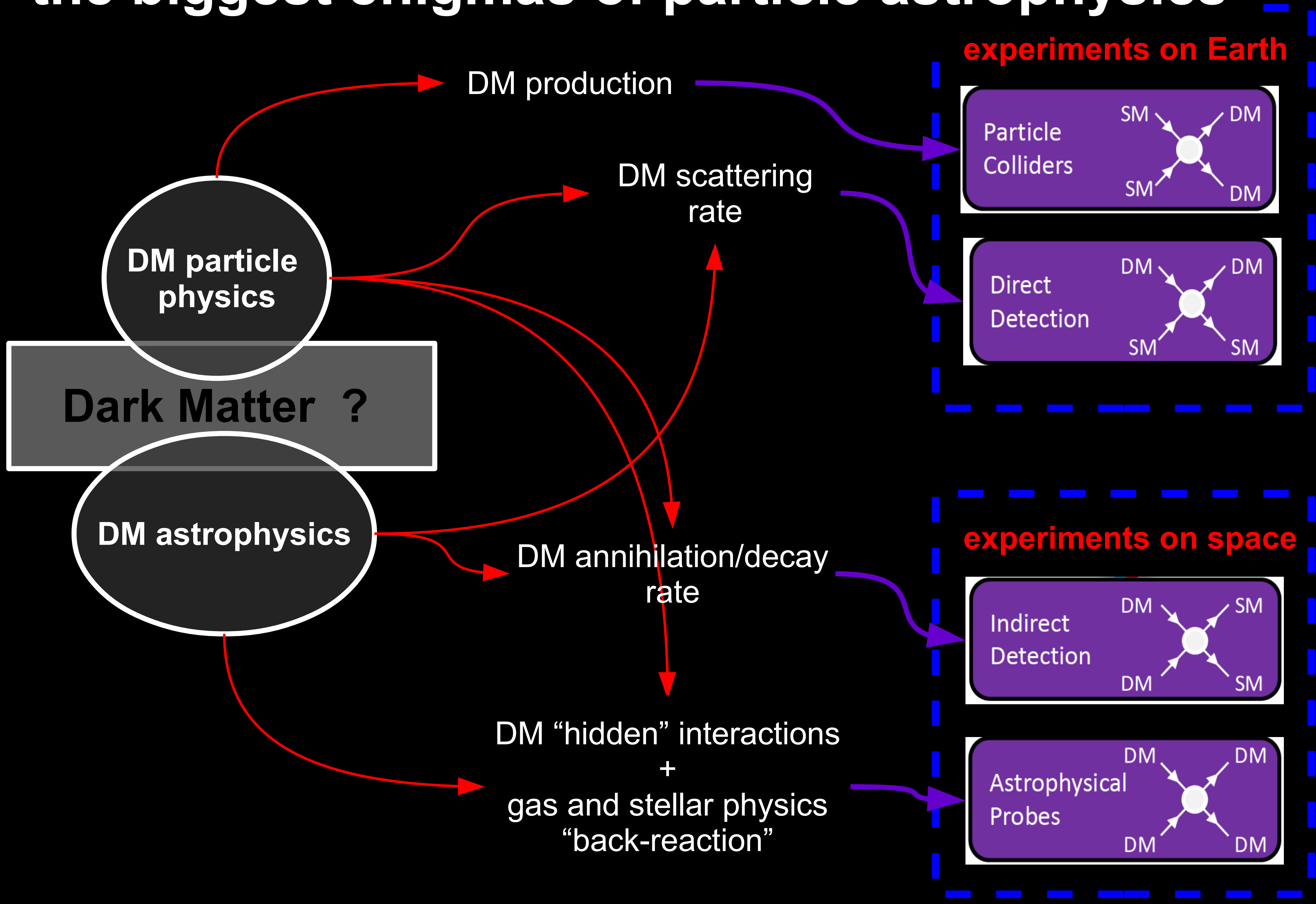
outstanding challenges at the scale of the smallest (dwarf) galaxies

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

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

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

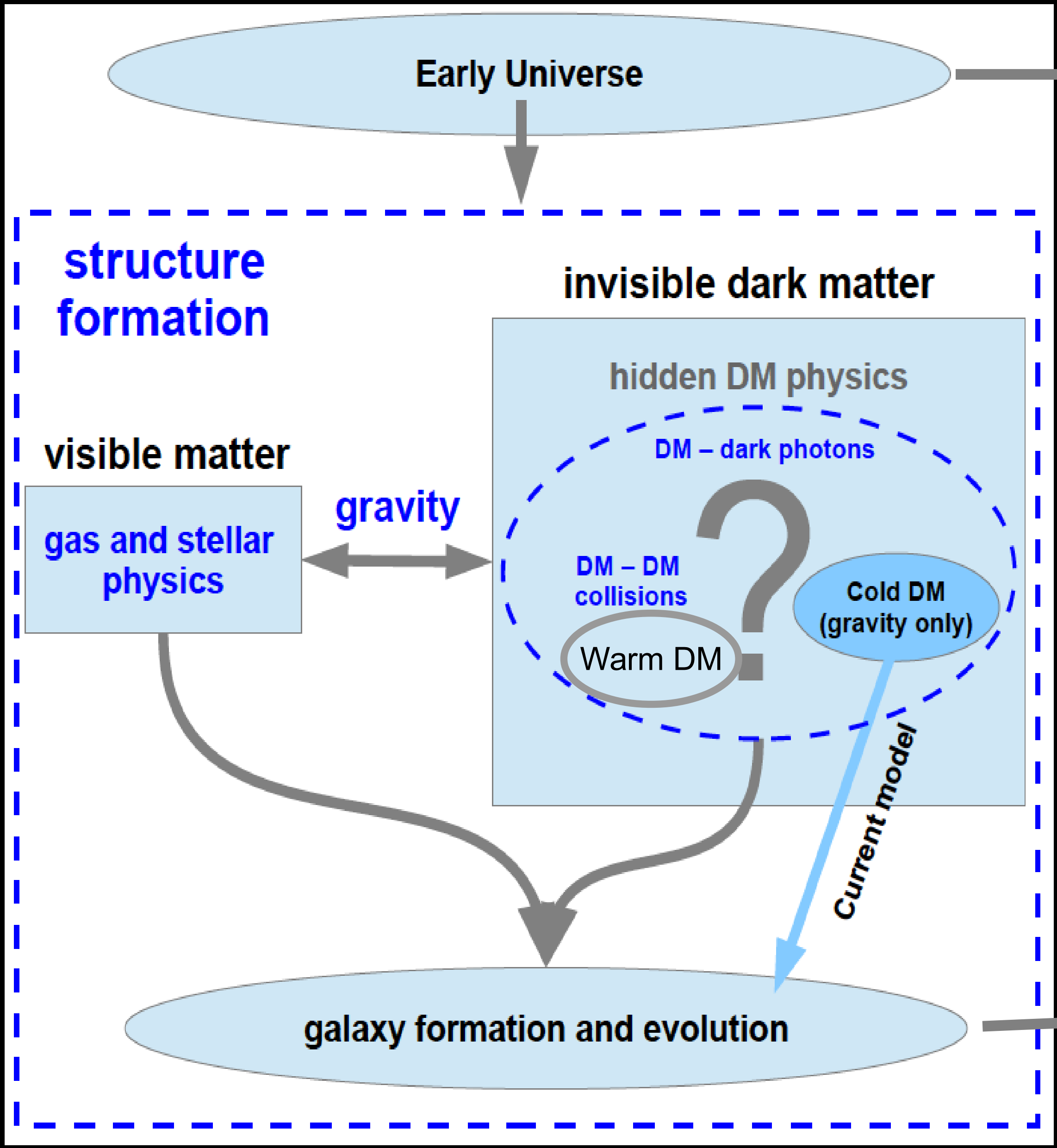
below this value, the behaviour is the same as CDM

above this value constraints are strong (at cluster scales)

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 (masses, couplings, ...)

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(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

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

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

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
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DM-DR-induced DAOs and Silk damping

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

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

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, ...)

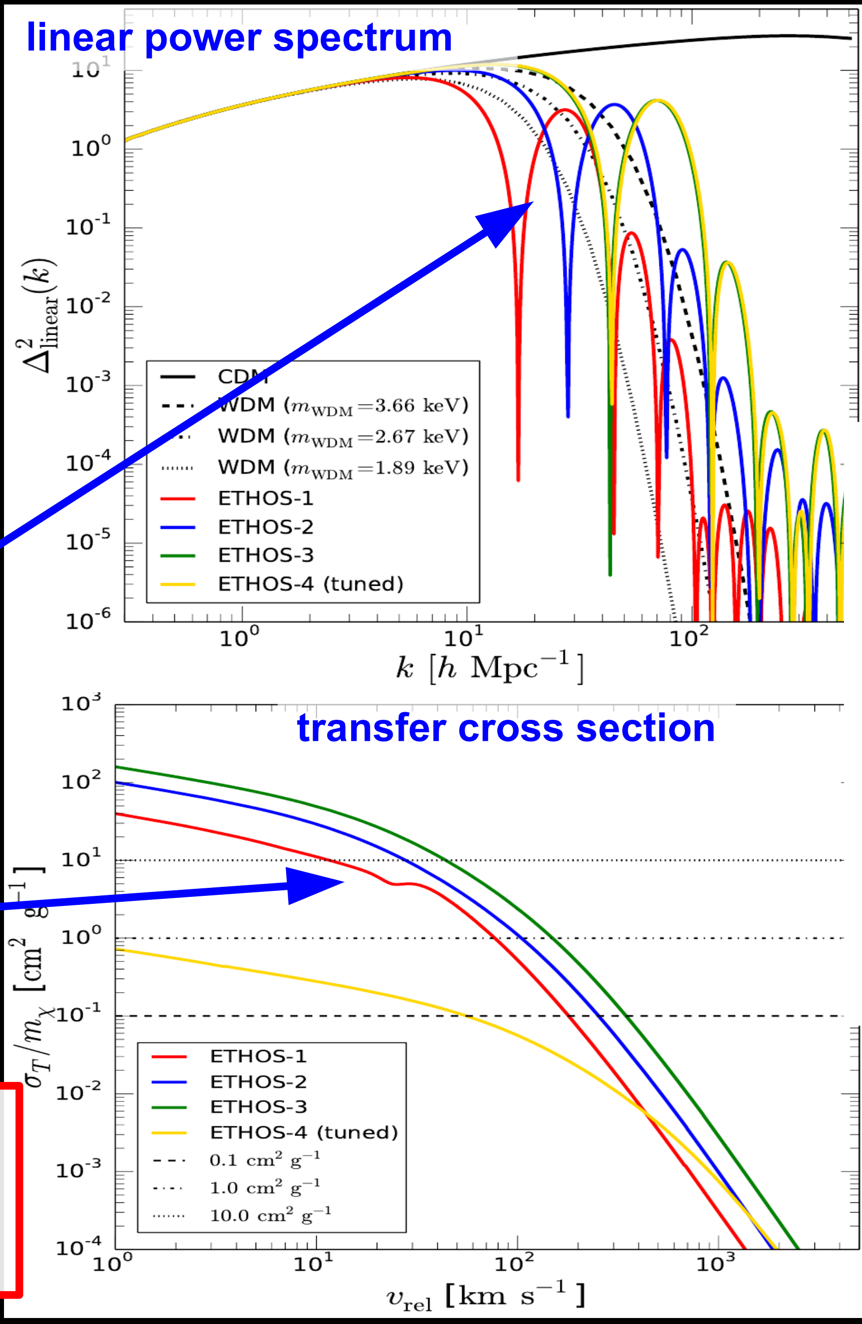
$$\left\{ m_\chi, \{g_i\}, \{h_i\}, \xi \right\}$$

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

effective parameters

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

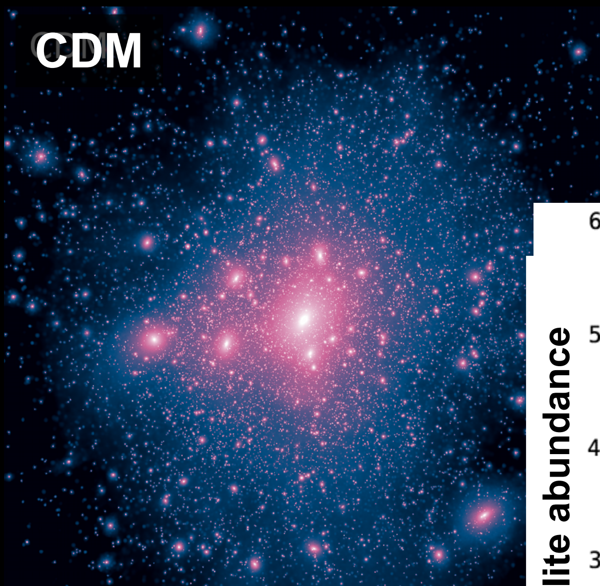
All DM particle physics models that map into the same ETHOS parameters can be studied (constrained) at the same time



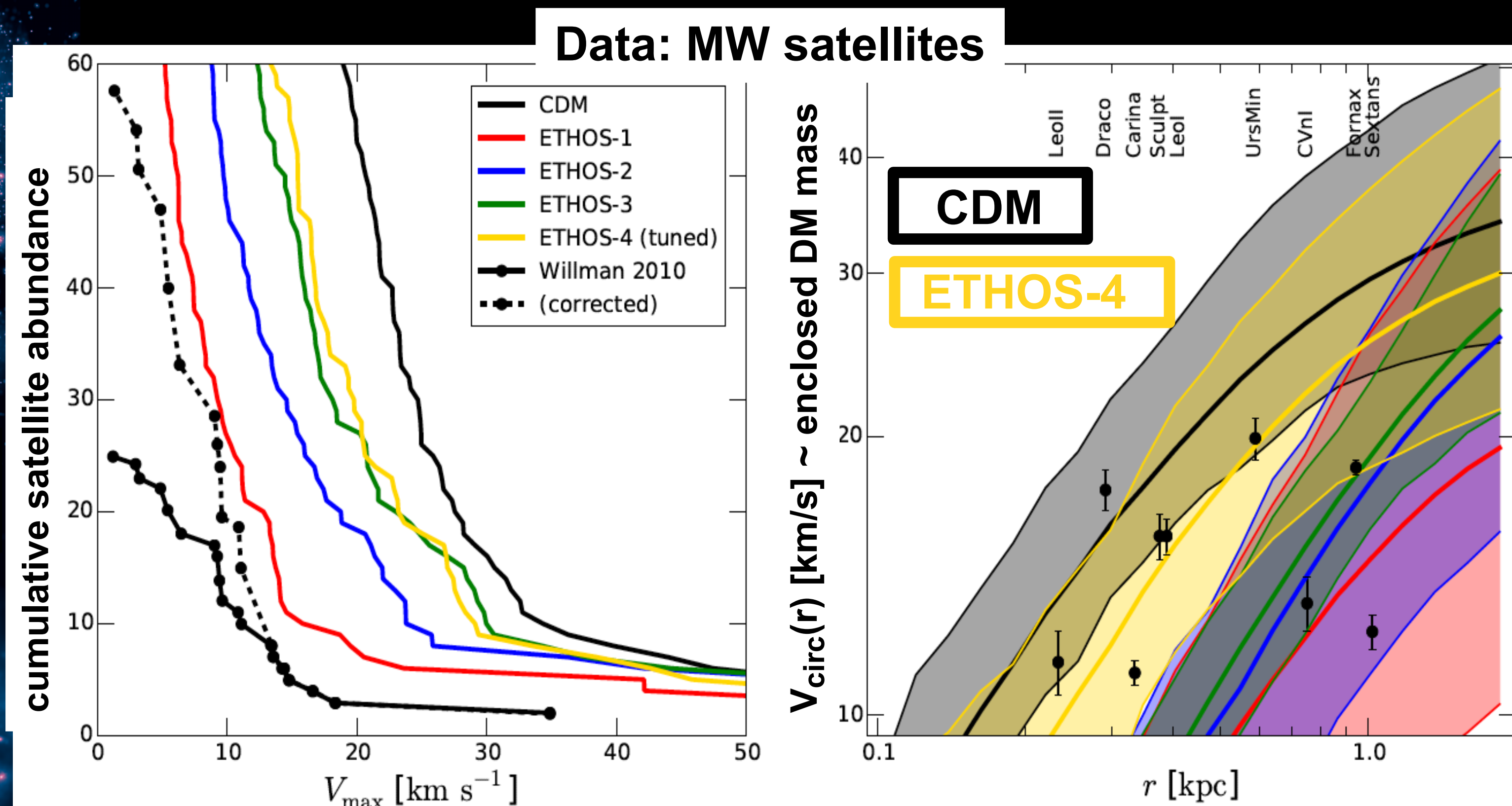
ETHOS I: Cyr-Racine+16

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



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

DM self-interactions reduce the central DM densities of haloes

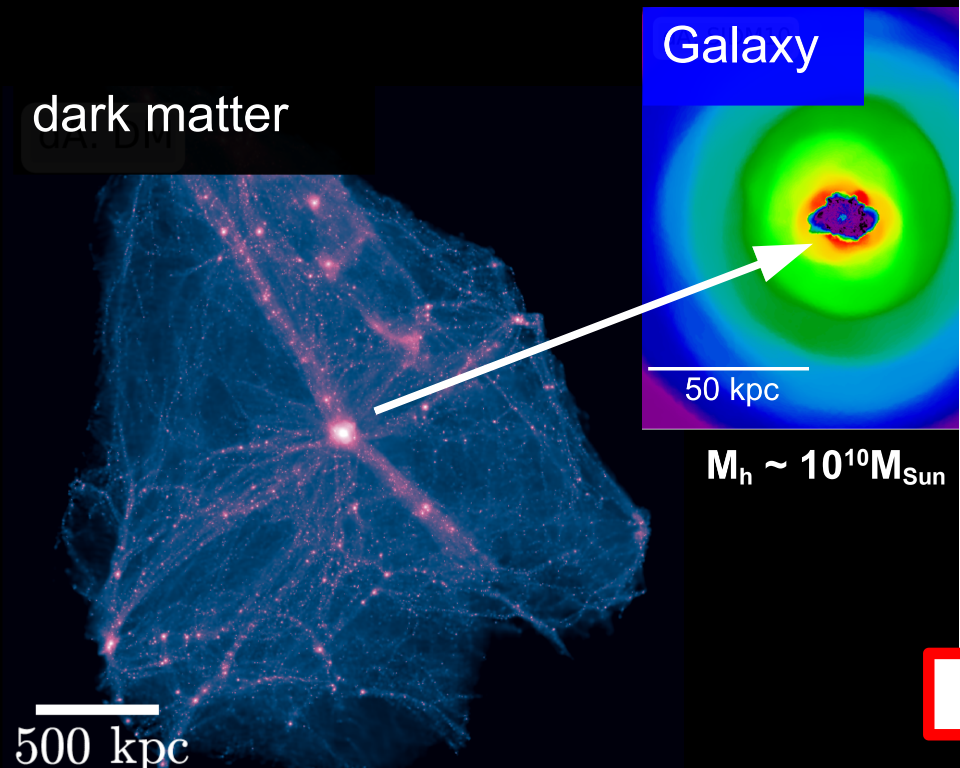
ETHOS II: Vogelsberger+16

Developing ETHOS
(self-scattering DM + baryonic physics)

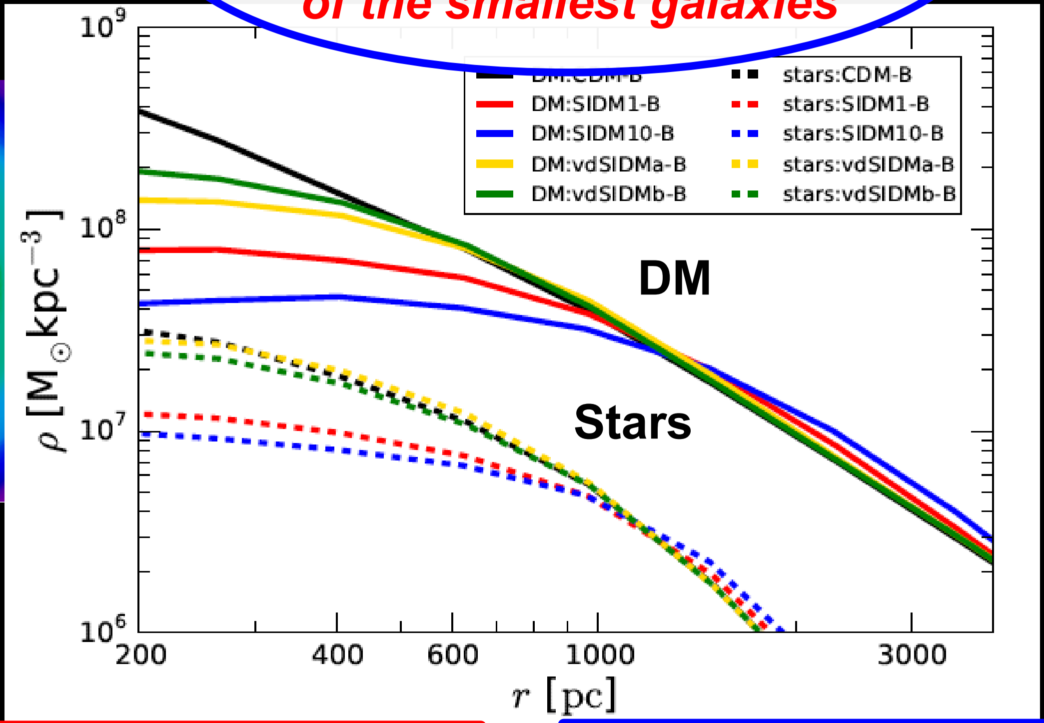
"baryonic physics": hydrodynamics, radiative cooling of gas, stellar population modelling, SNe feedback

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

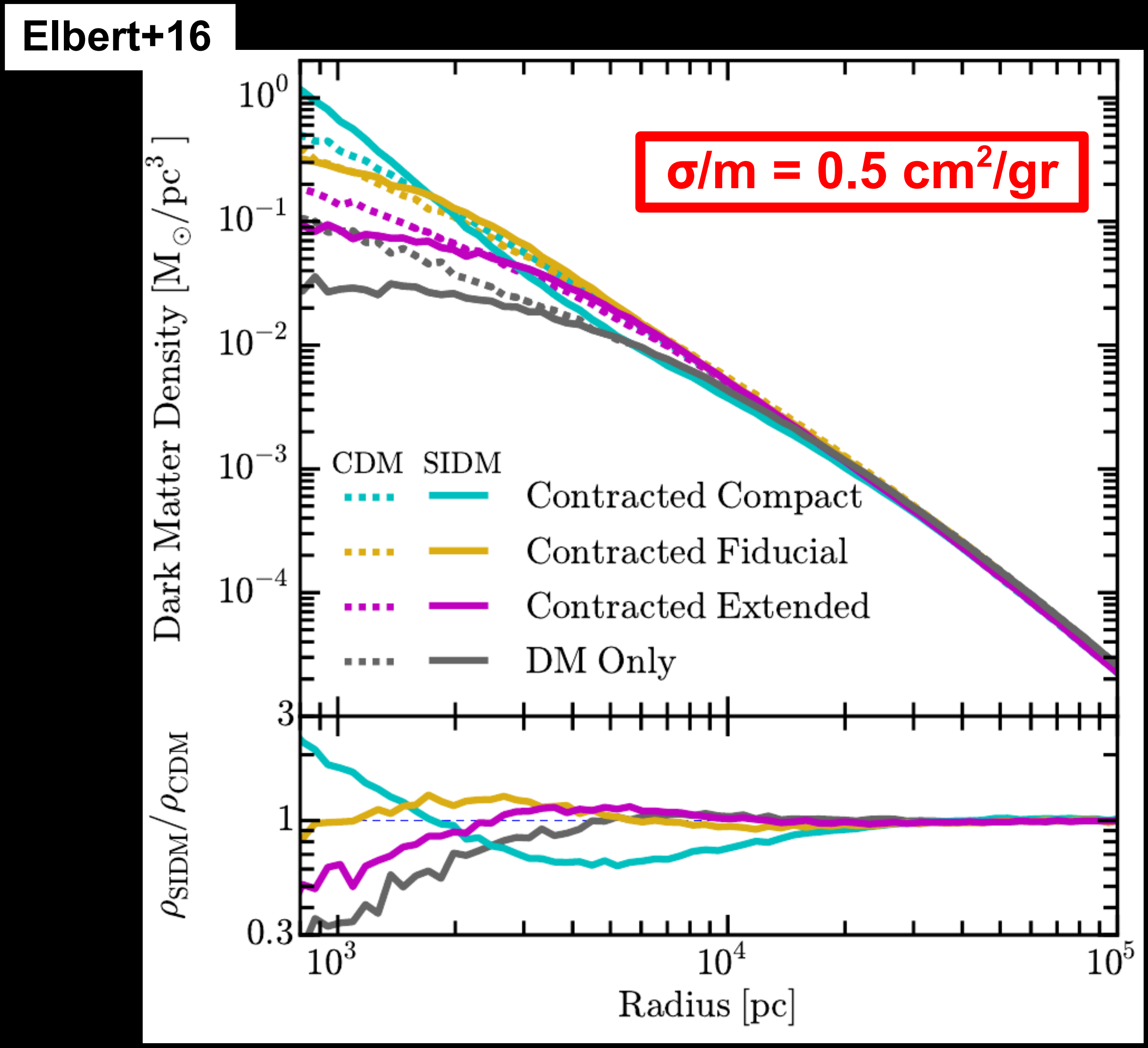


$M_h \sim 10^{10} M_{Sun}$



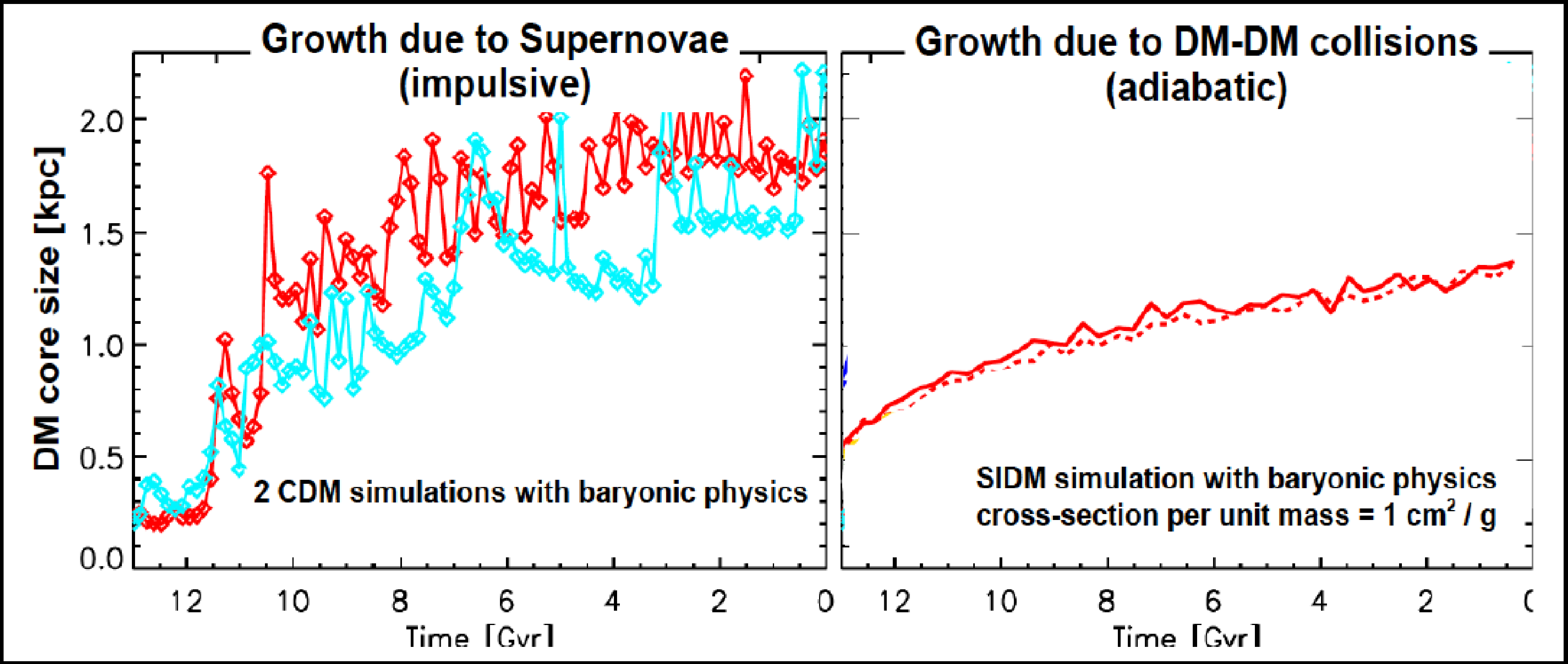
$\sigma/m = 1\ cm^2/gr$ **$\sigma/m = 10\ cm^2/gr$**

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