Towards an Effective THeory Of Structure formation (ETHOS)

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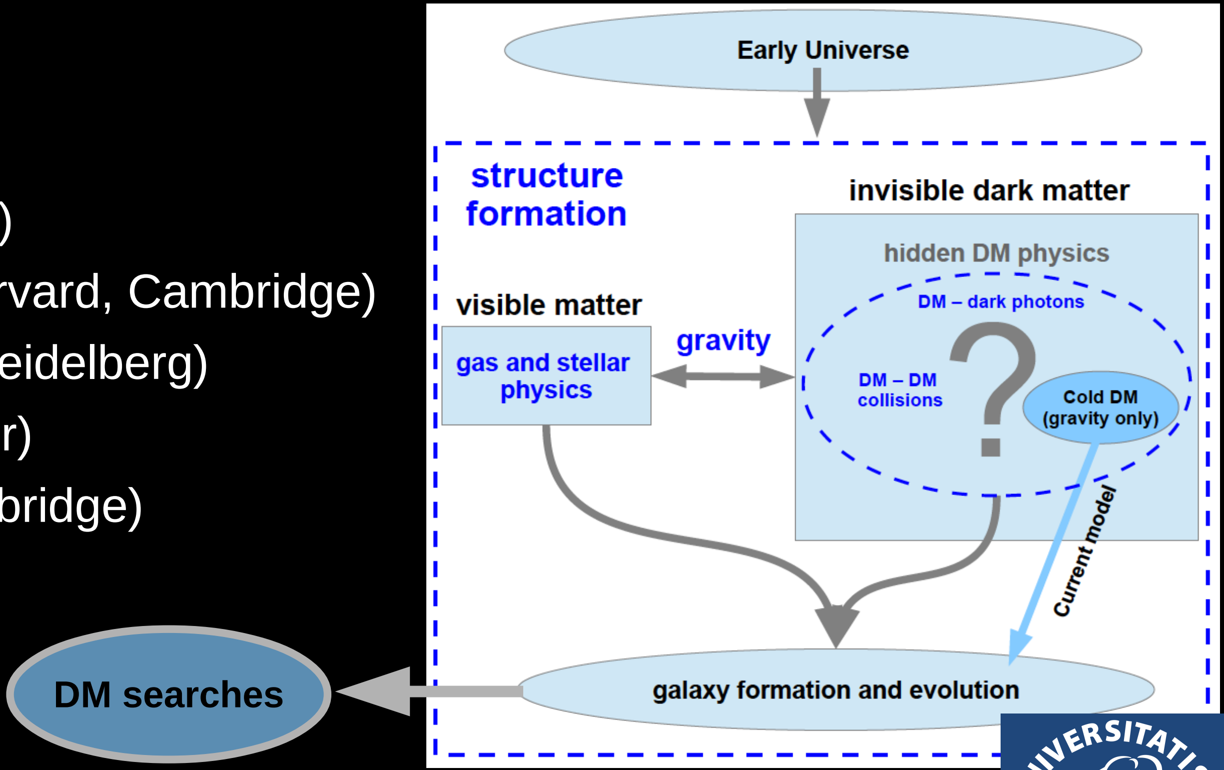


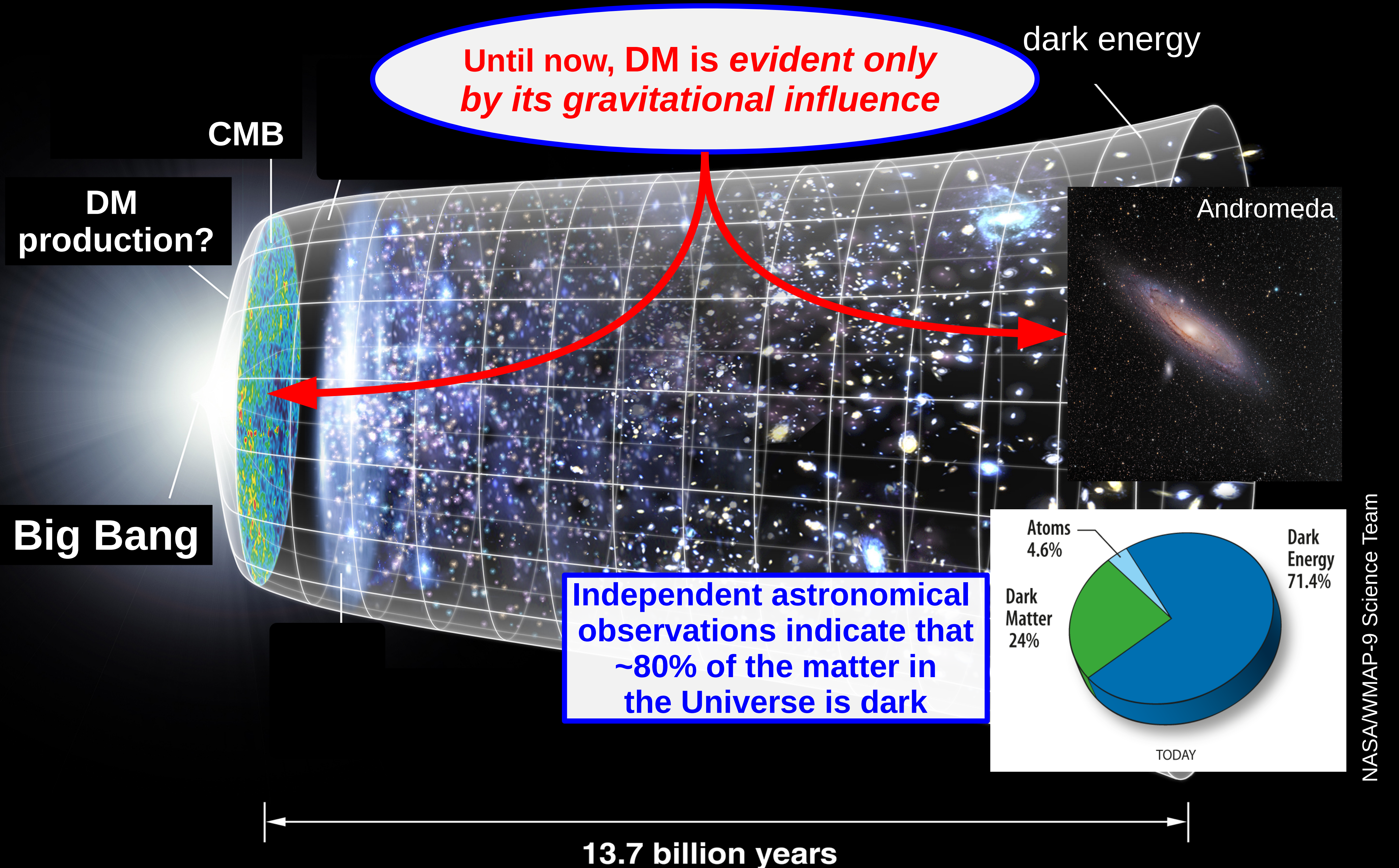
CERN TH Institute, August 2016

OUTLINE

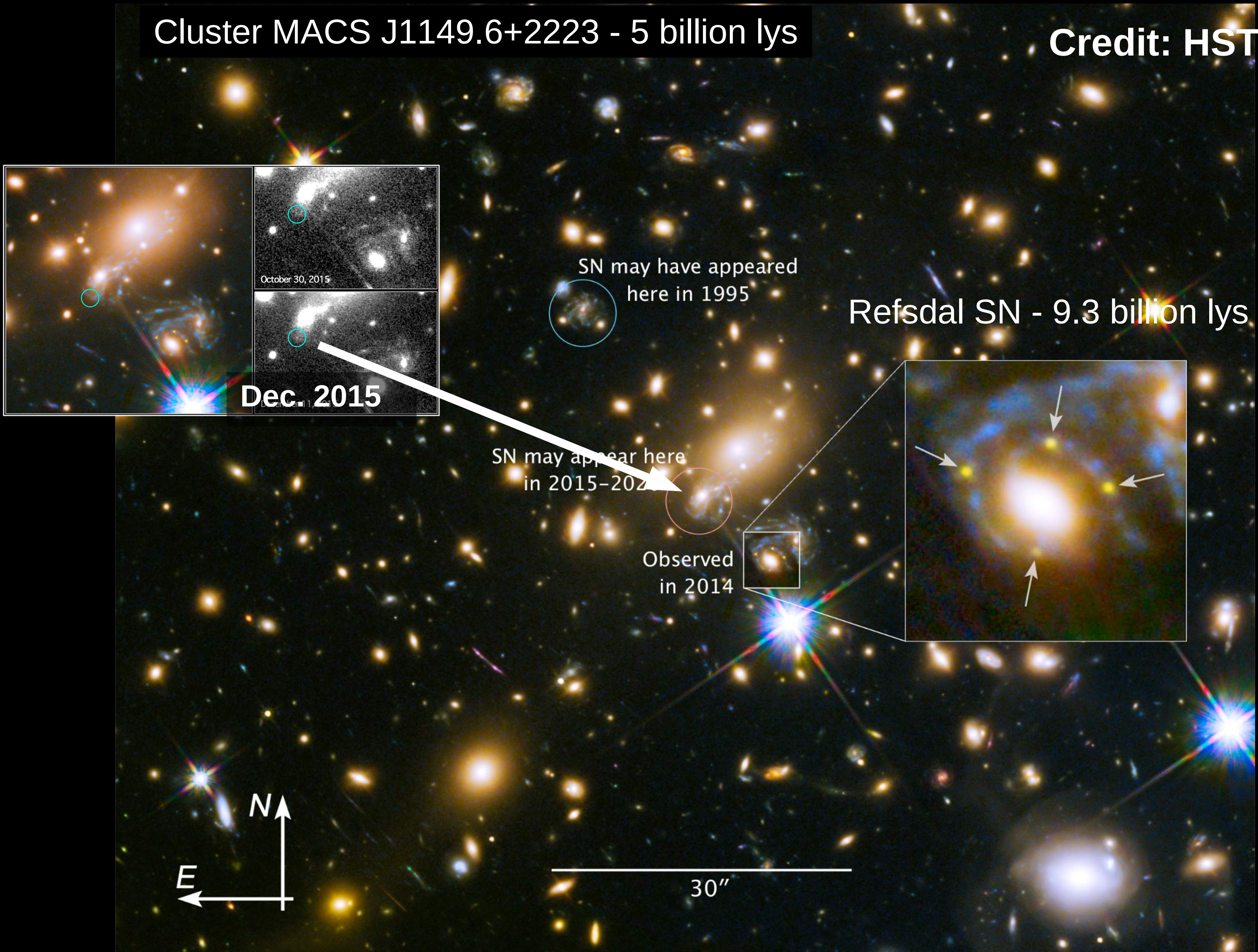
- **The dark matter hypothesis (CDM) and the standard structure formation theory**
- **Non-gravitational dark mater interactions and structure formation**
- **Beyond CDM: exploring new dark matter physics with astrophysics (ETHOS)**
- **Concluding remarks**

The particle DM hypothesis:

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



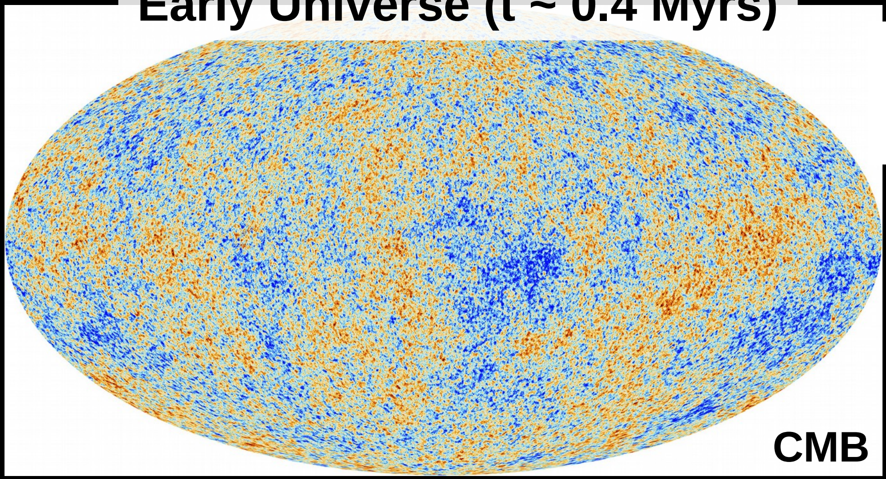
A spectacular example of a GR effect and a strong indication of the existence of DM



The particle DM hypothesis is seemingly essential to explain the growth of perturbations into the highly non-linear regime

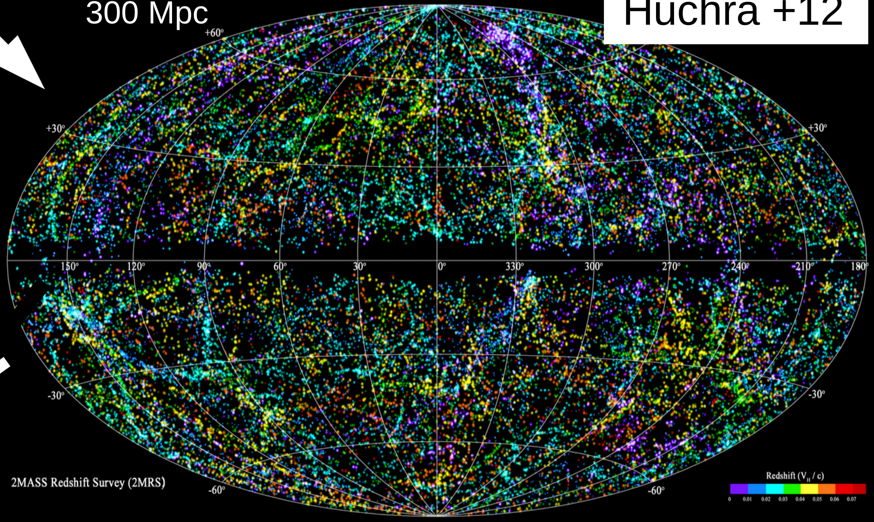
Credit: ESA and the Planck Collaboration

Early Universe (t ~ 0.4 Myrs)



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

Universe today (t ~ 13.8 Gyrs)



2MRS galaxy “map”, large-scale structure

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

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

galactic scales

Standard structure formation theory (main ingredients)

- **linear regime (cosmological perturbation theory)**

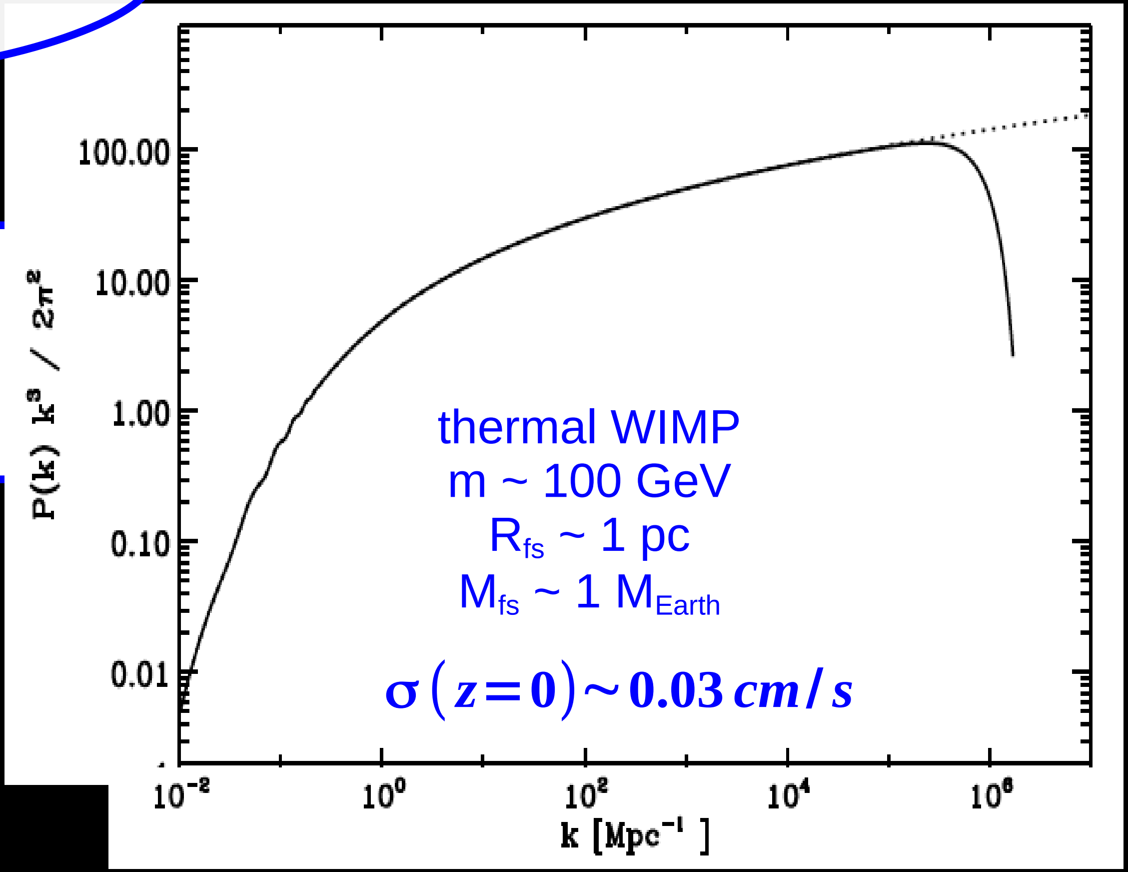
Standard hypotheses:
DM is cold and collisionless
(Cold Dark Matter model)

eqs. for DM perturbations

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

$$\dot{\theta}_\chi - c_\chi^2 k^2 \delta_\chi + \mathcal{H}\theta_\chi - k^2\psi = 0$$

Angulo & White, 2010



Standard structure formation theory (main ingredients)

- **non-linear regime (N-body simulations)**

Standard hypotheses: DM is cold and collisionless (Cold Dark Matter model) → ***the only DM interaction that matters is gravity!!***

In principle: solve Collisionless Boltzmann Equation (coupled with the Poisson equation) with the initial conditions given by linear perturbation theory

$$\frac{df}{dt}=0 \qquad \nabla^2\psi=4\pi G$$

i.e., find the local DM distribution in phase space at all points and at all times:

$$f(\vec{x},\vec{v},t)\mathrm{d}^3\vec{x}\mathrm{d}^3\vec{v}$$

In practice however, we can only compute, measure, the DM distribution averaged over a certain macroscopic scale (coarse-grained distribution)

Standard structure formation theory (main ingredients)

- **non-linear regime (N-body simulations)**

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

→

the only DM interaction
that matters is gravity!!

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

$$\hat{f}(\mathbf{x},\mathbf{v},t) = \sum_i (M_i/m) W(|\mathbf{x}-\mathbf{x}_i|; h_i)\delta^3(\mathbf{v}-\mathbf{v}_i)$$

macro-to-micro-particle mass ratio

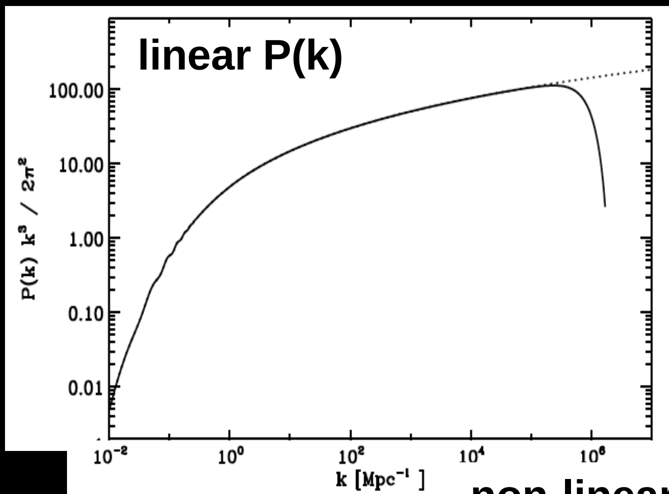
each particle is smoothed in space to give a smooth local density

each macro-particle travels at one speed

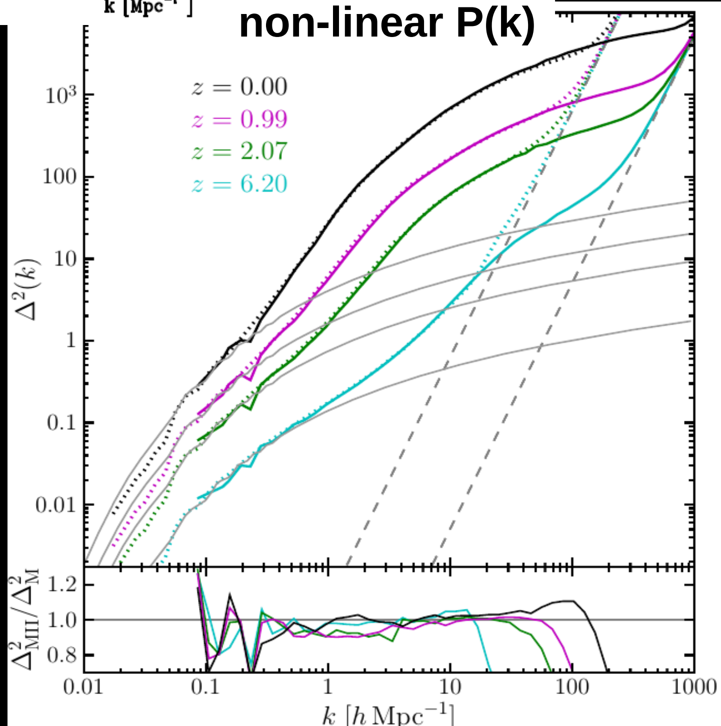
e.g. particle-mesh method: from the density assignment, the potential is found using a mesh, accelerations for each particle are calculated and the system is evolved in a timestep

Standard structure formation theory (main ingredients)

- **non-linear regime (N-body simulations)**

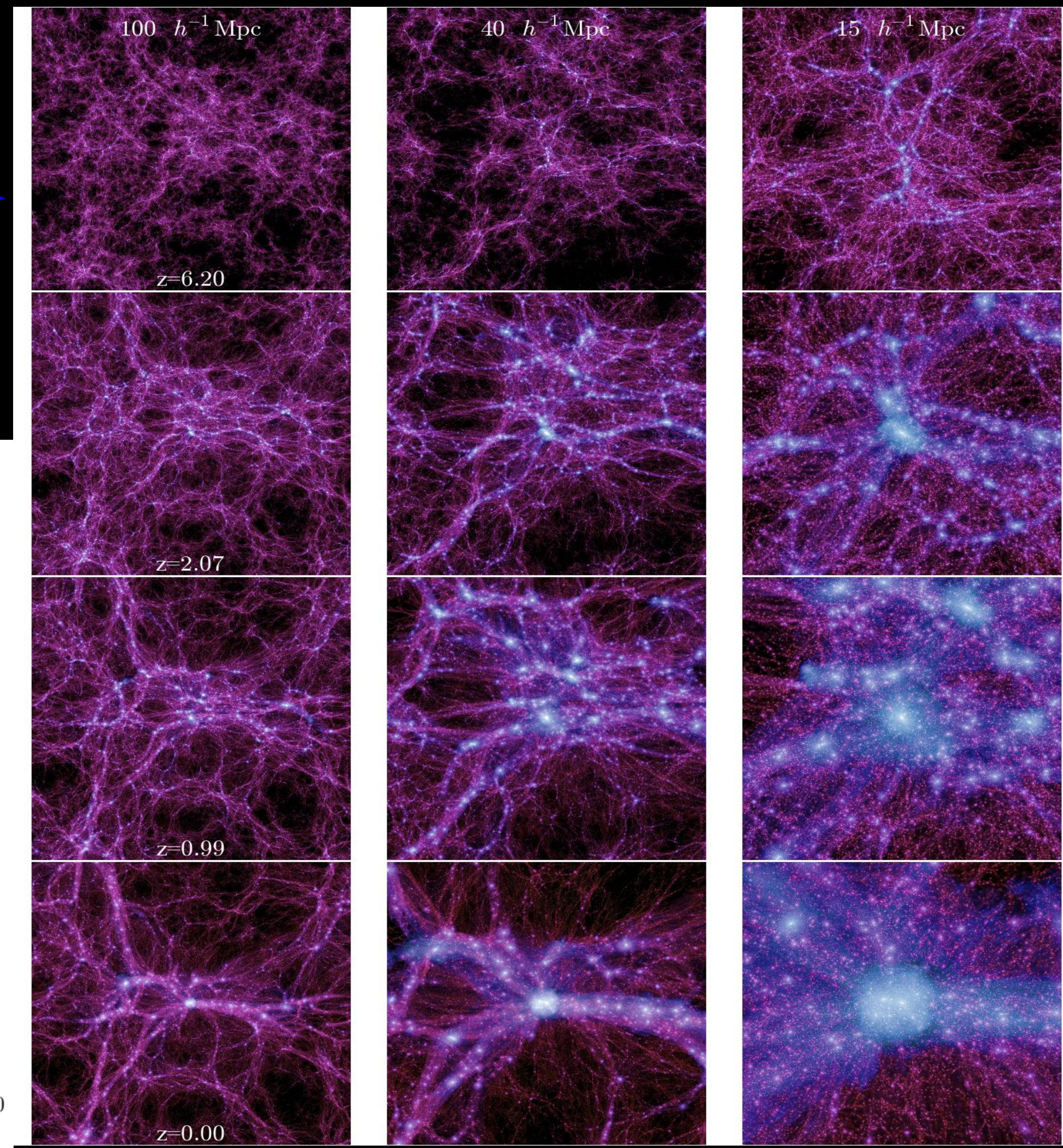


N-body



Boylan-Kolchin+09

Millennium II simulation



A sample of state-of-the-art simulations

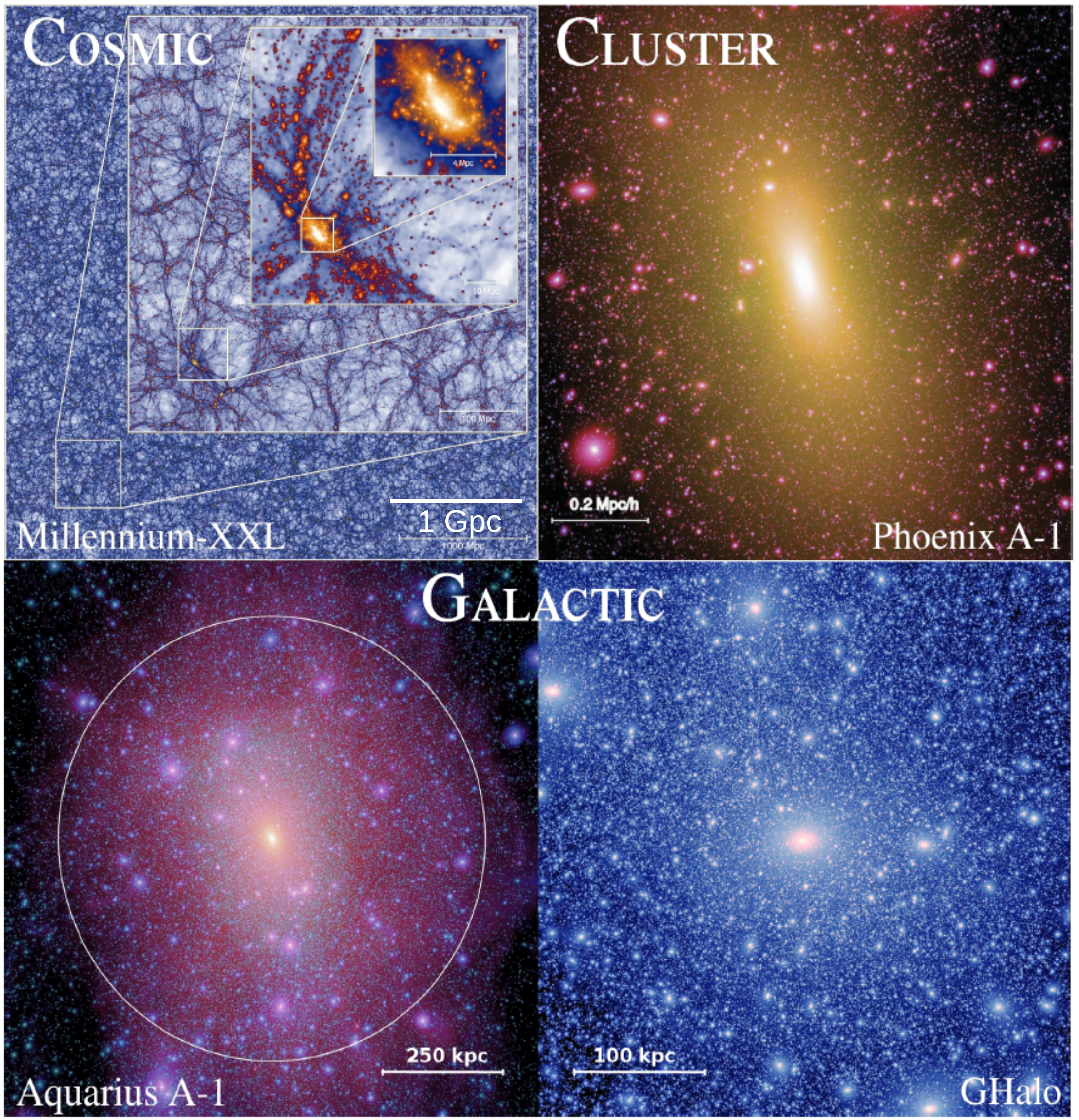
DM-only simulations

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

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

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

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



from Kuhlen+12

Standard structure formation theory (main ingredients)

- **non-linear regime (galaxy formation/evolution)**

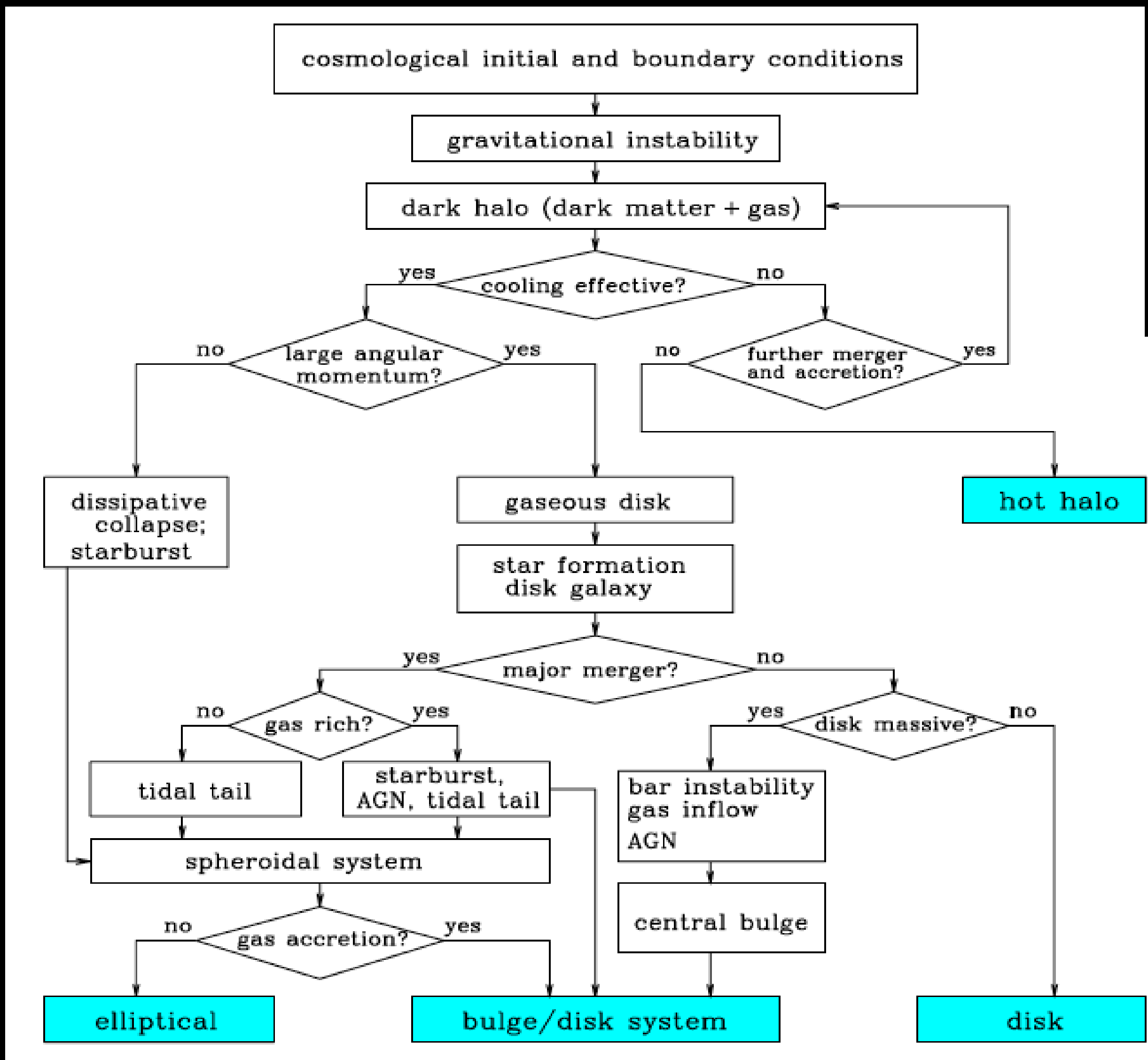
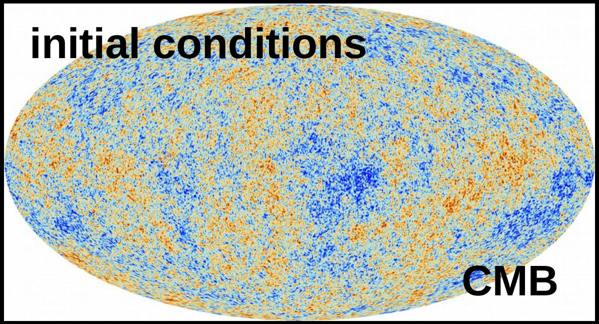


Fig. from Mo, Mao and White, 2010

DM gravity only

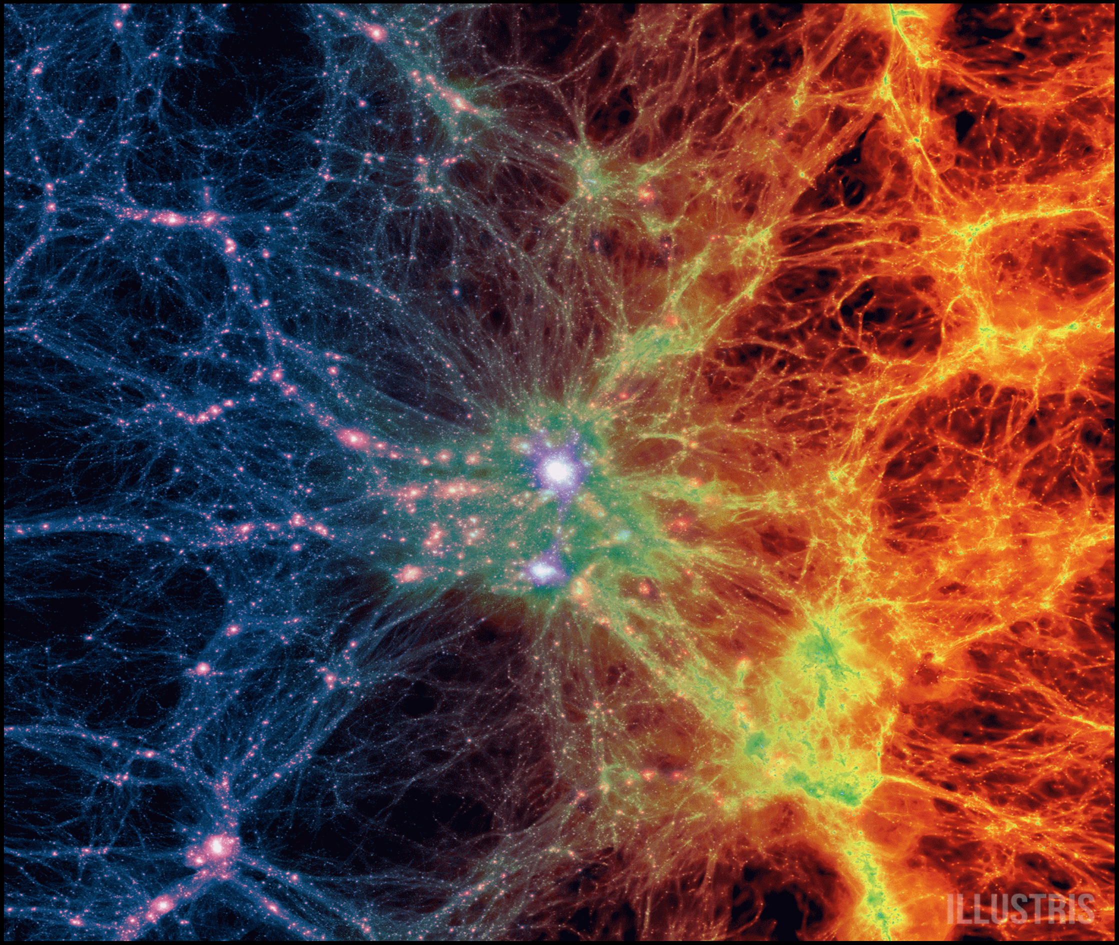
Aquarius project Springel+08

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



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

DM gravity + gas and stellar physics



Credit: Illustris project

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?

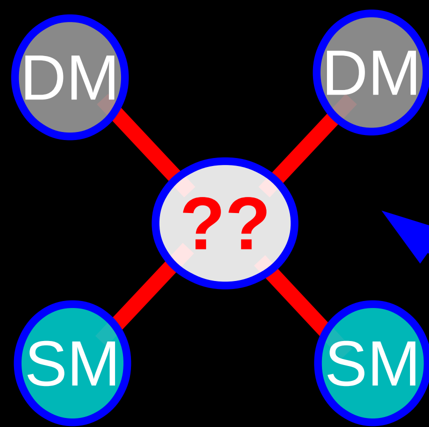
In the physics of galaxies, is gravity the only dark matter interaction that matters?

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

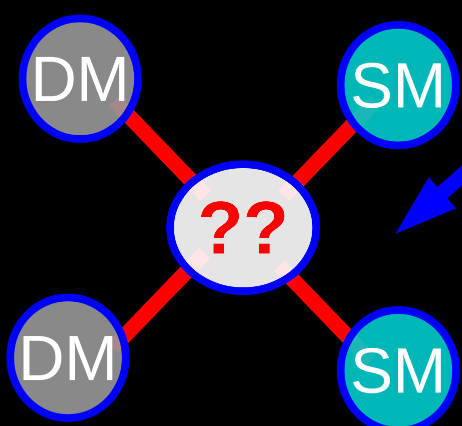
non-gravitational DM interactions and structure formation

What is the nature of dark matter?

Scattering with nuclei



DM self-annihilation



Does DM interacts with visible particles?

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)

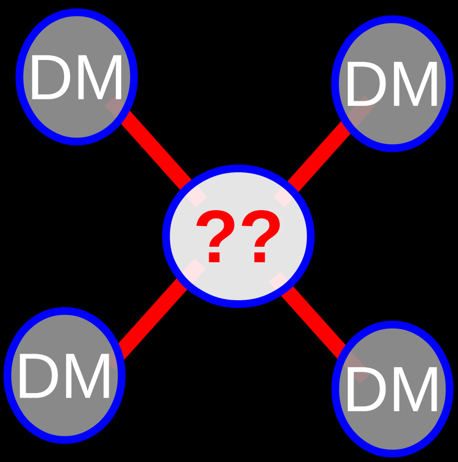
1 cm^2/g ~ 2 barns/GeV

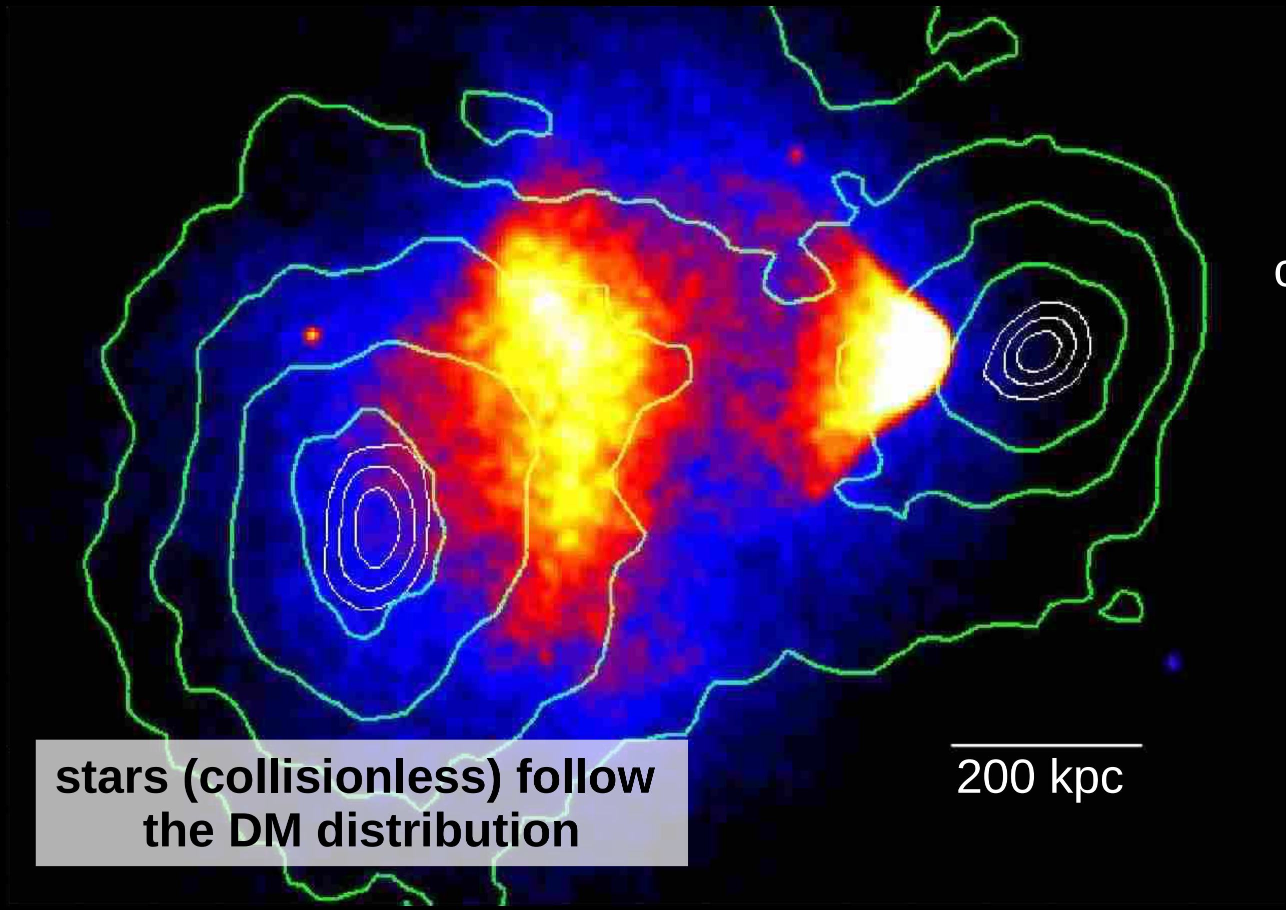
dark matter is quite “dark” (invisible)

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?

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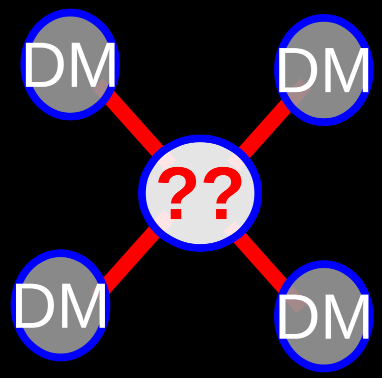

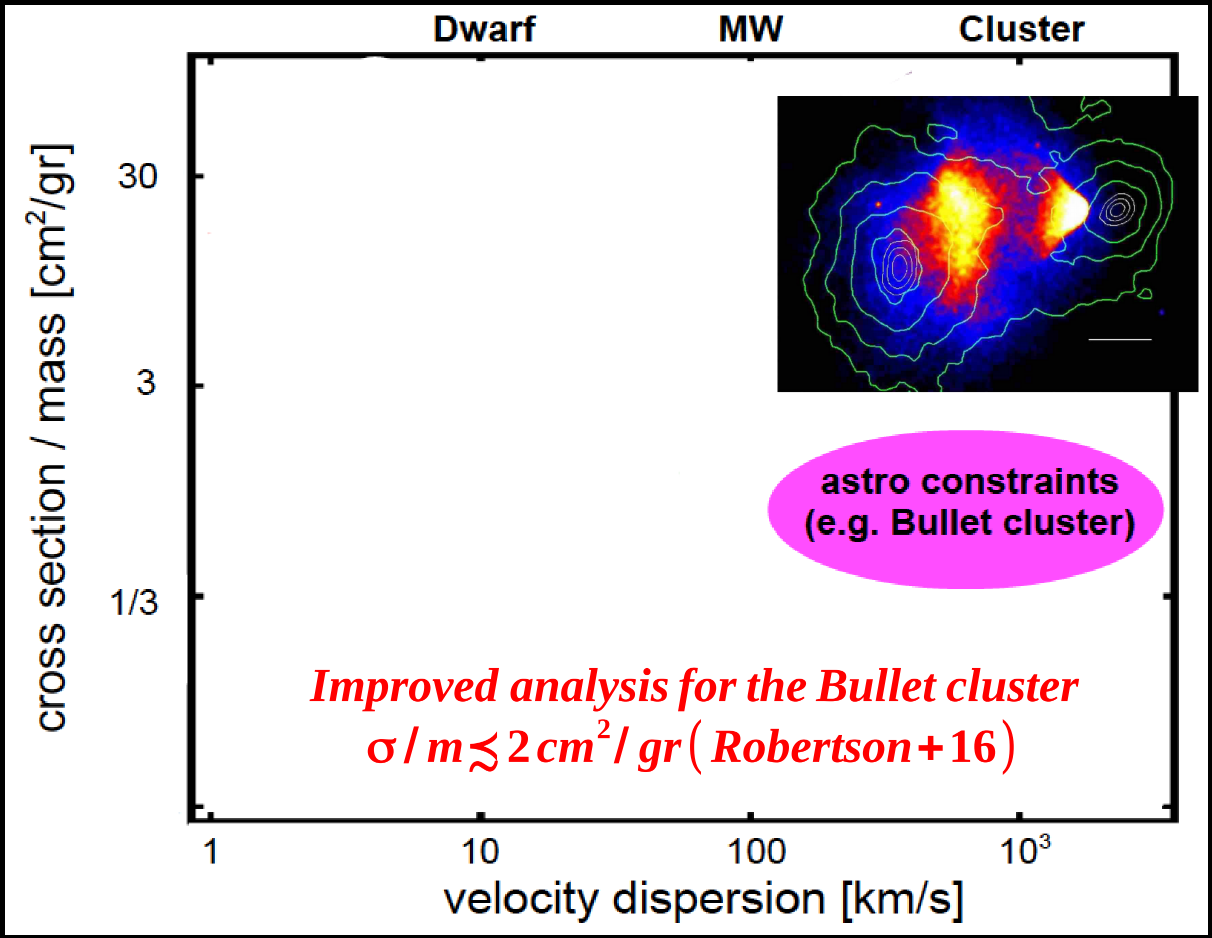

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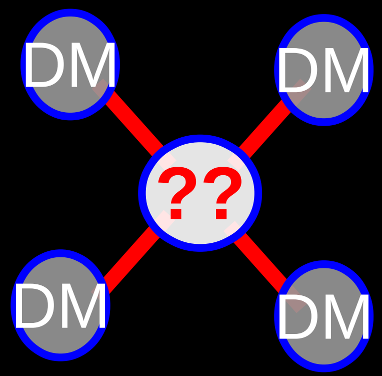


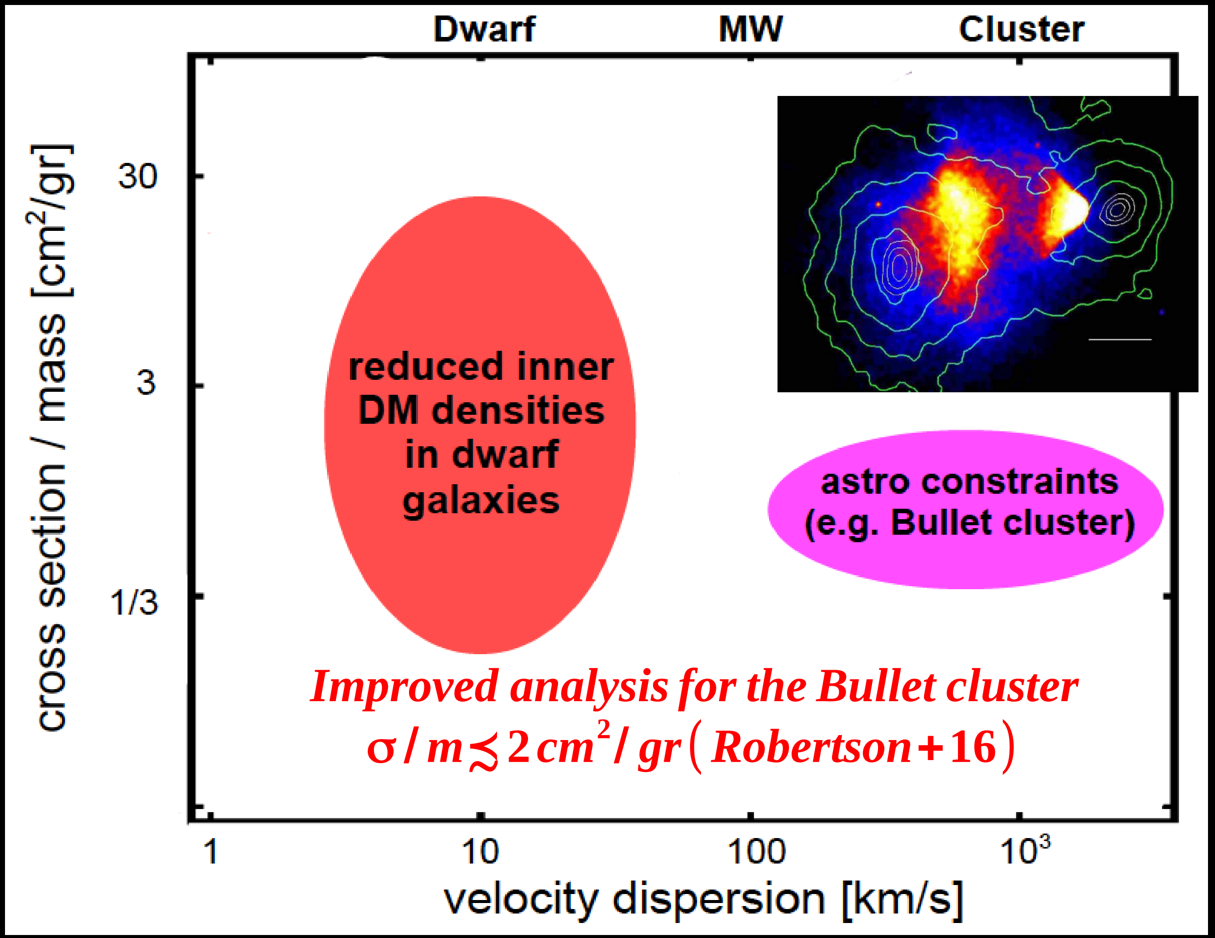
constraints allow collisional DM that is astrophysically significant in the center of galaxies:

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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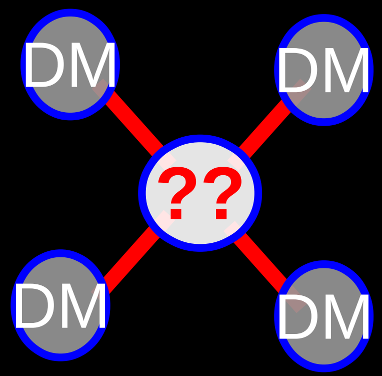

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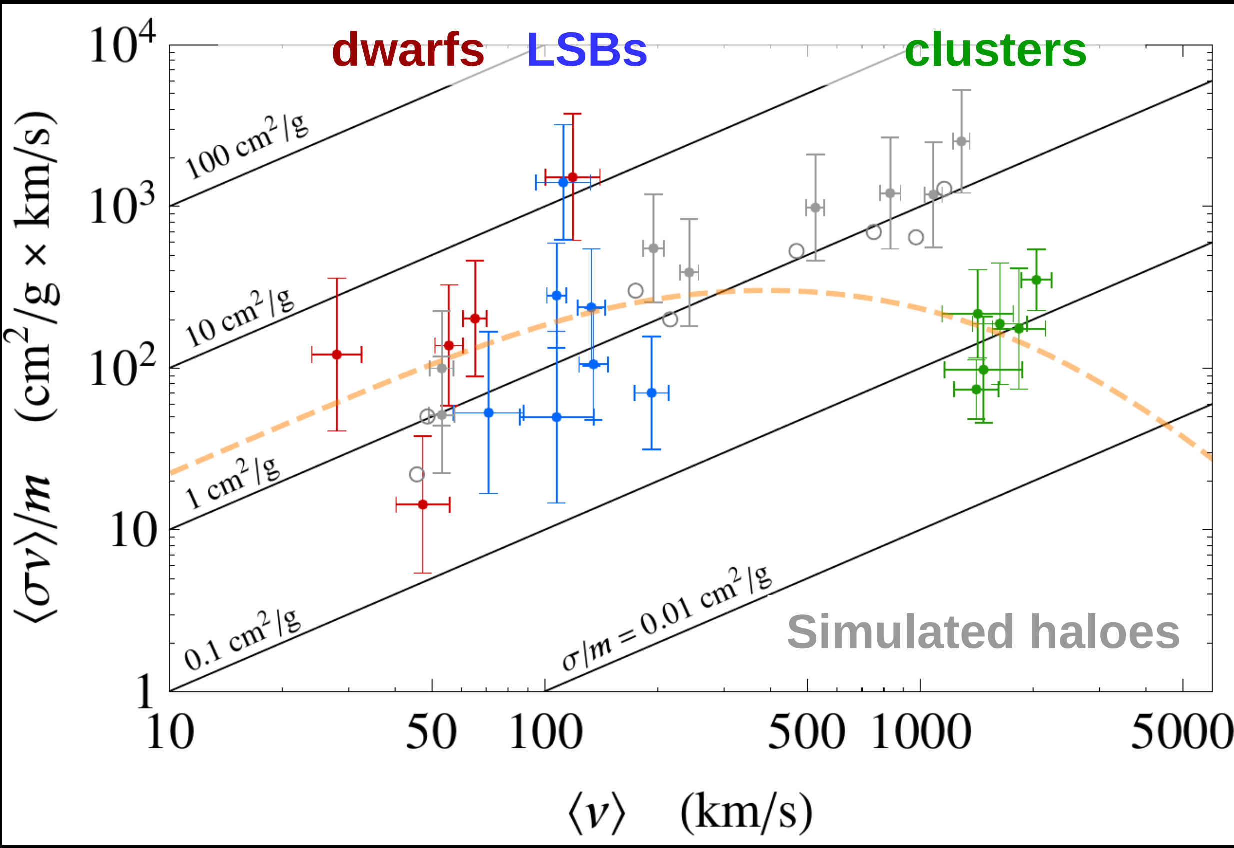


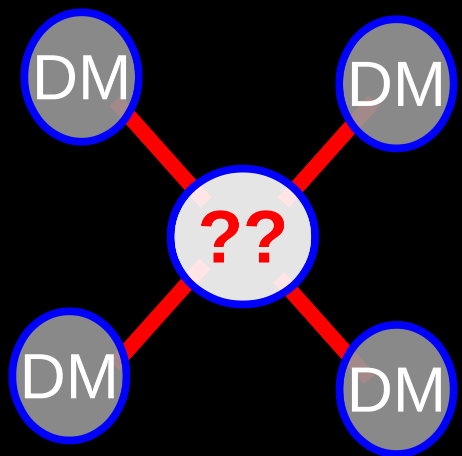
velocity-dependent models (motivated by a new force in the "dark sector") can accommodate the contraints
e.g. Yukawa-like, Feng+09, Loeb & Weiner 2011,...

See talk by Hai-Bo Yu later today

Kaplinghat, Tulin & Yu 2016

What is the nature of dark matter?

Can DM particles collide with themselves?



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

Cluster Abell 3827 (Massey +15)

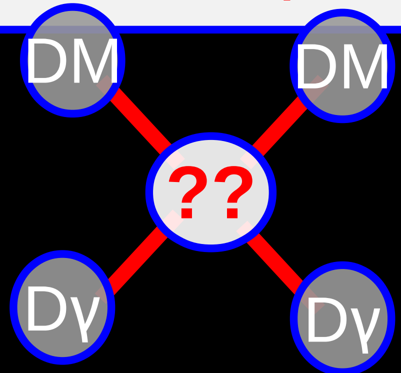
$\sigma/m \sim 1.5\ cm^2/gr$

(Kahlhoefer+15)

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

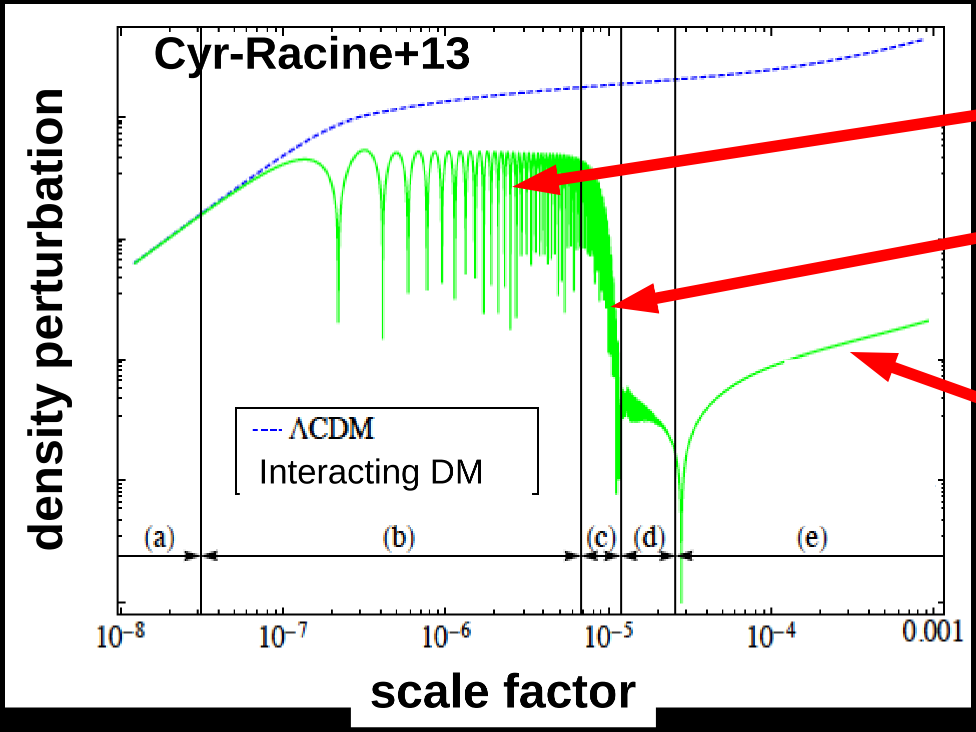
What is the nature of dark matter?

Can DM particles 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

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

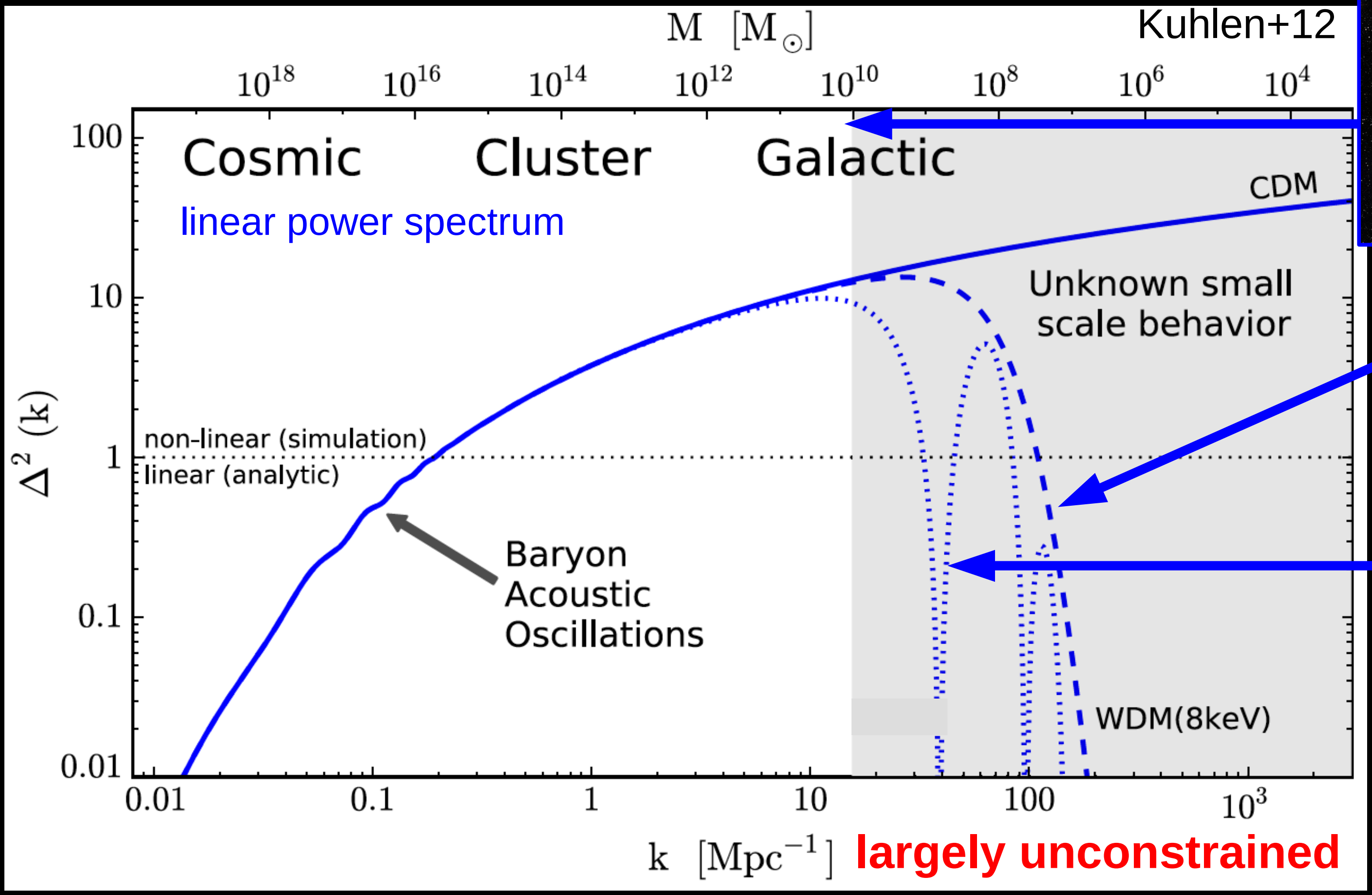
Pursuing them, will either confirm the standard model or unveil a fundamental DM property

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



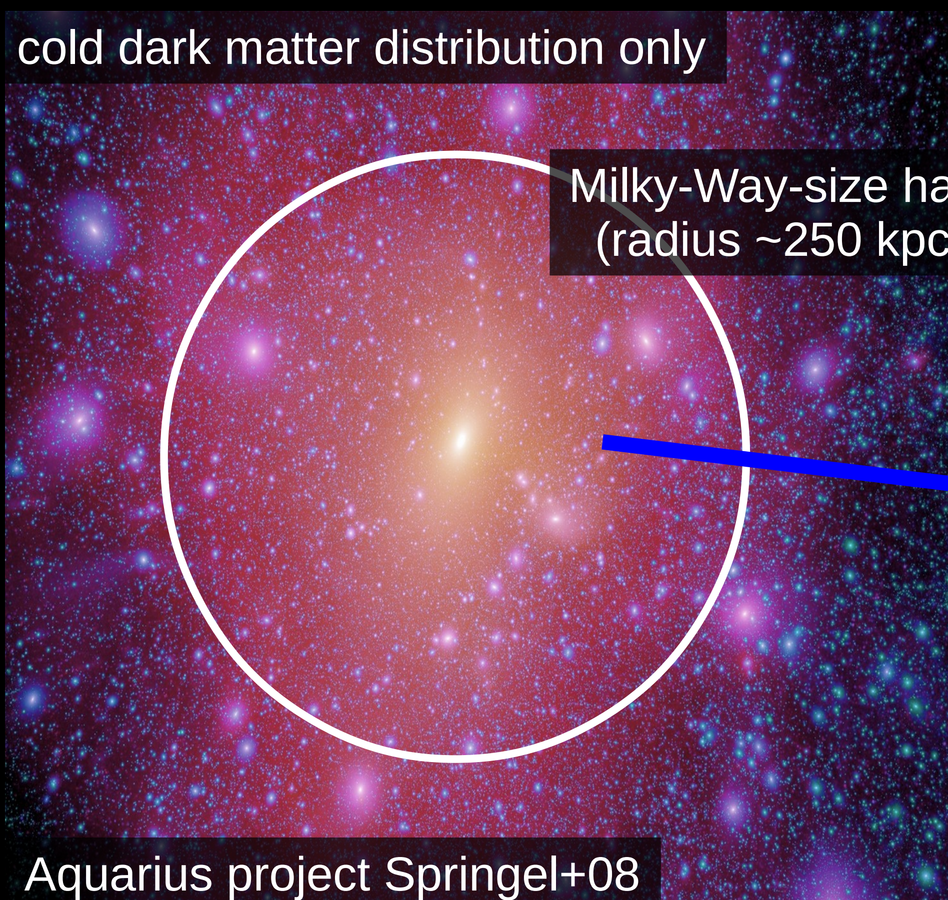
DM is relativistic at earlier times thermal cut-off (free-streaming)

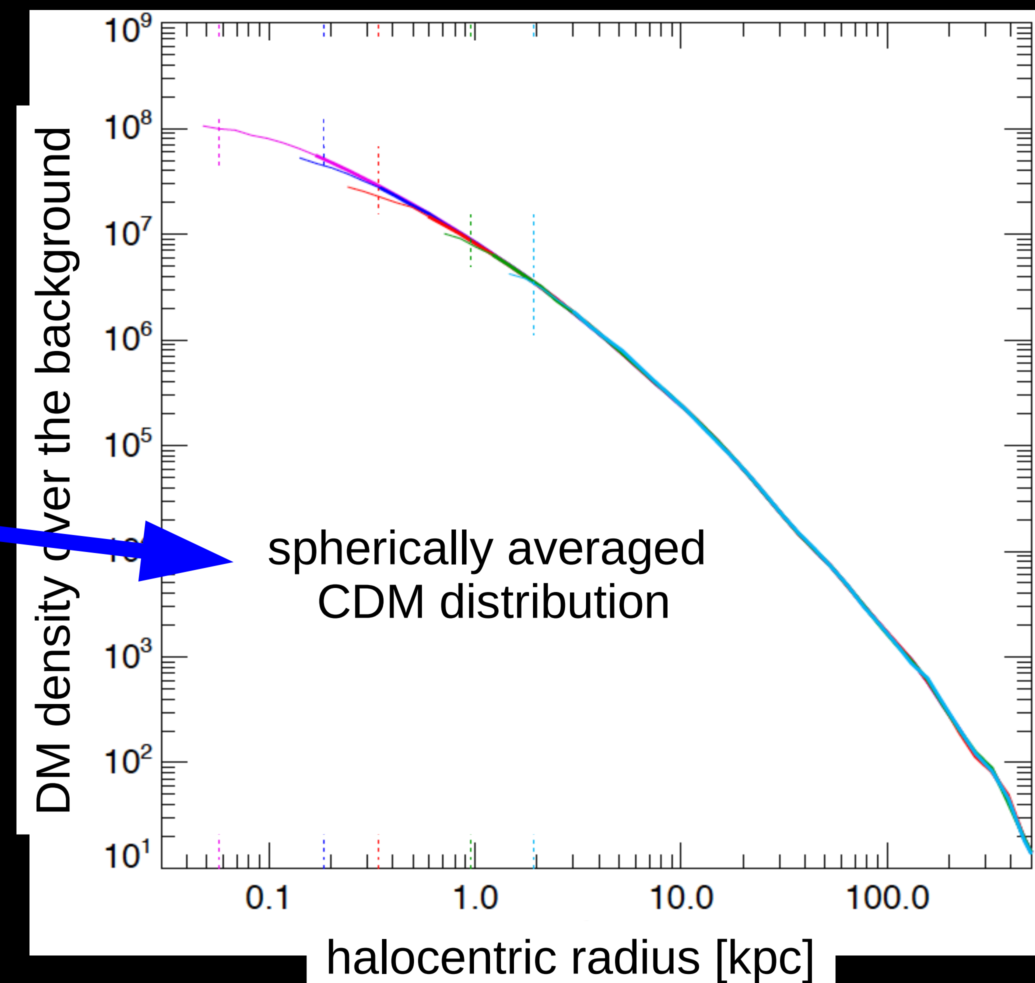
DM interacts with relativistic particles at earlier times: DM-DR DAOs and Silk (collisional) damping

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



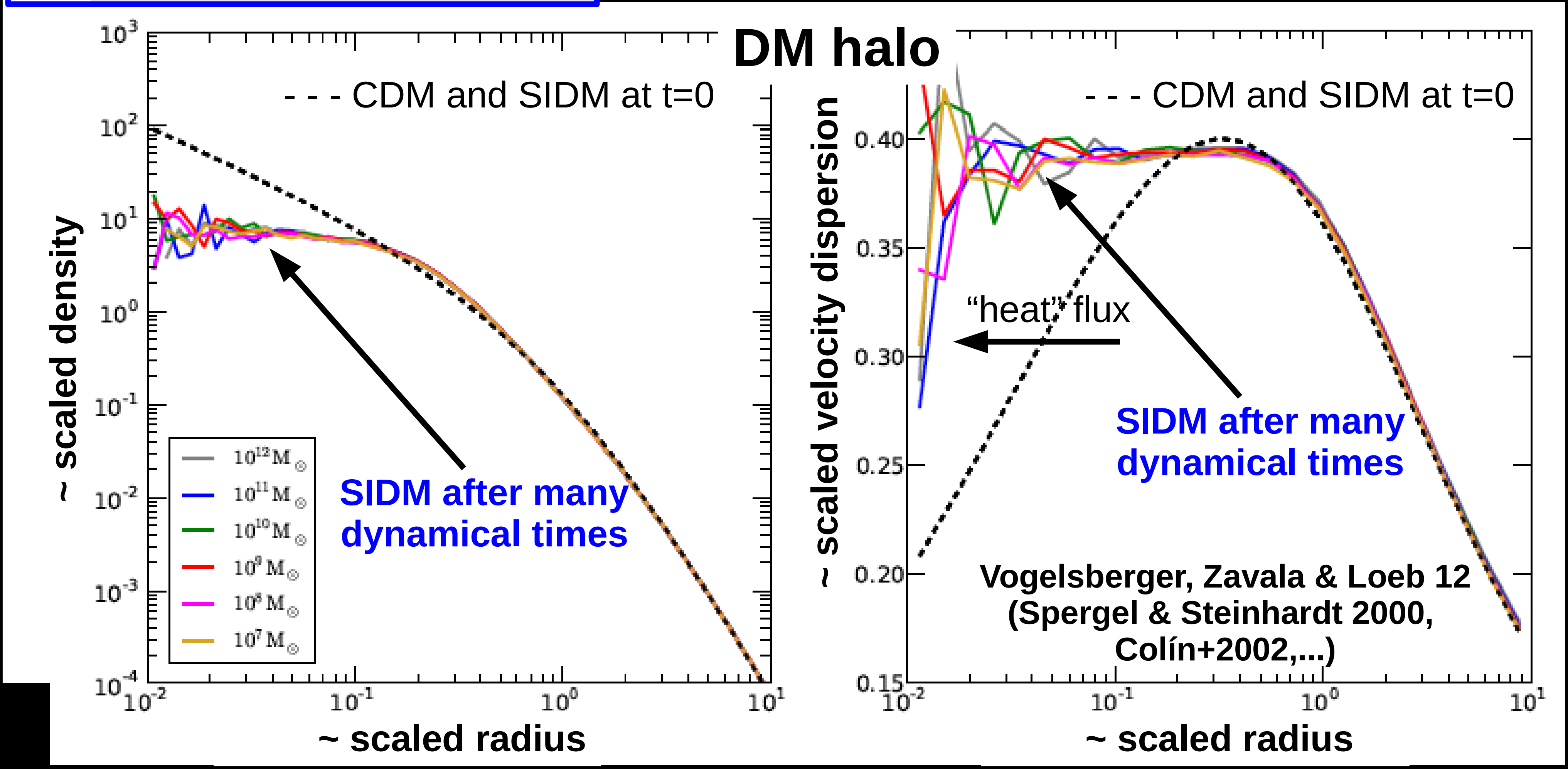


The nature of dark matter (evolution of structures)

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

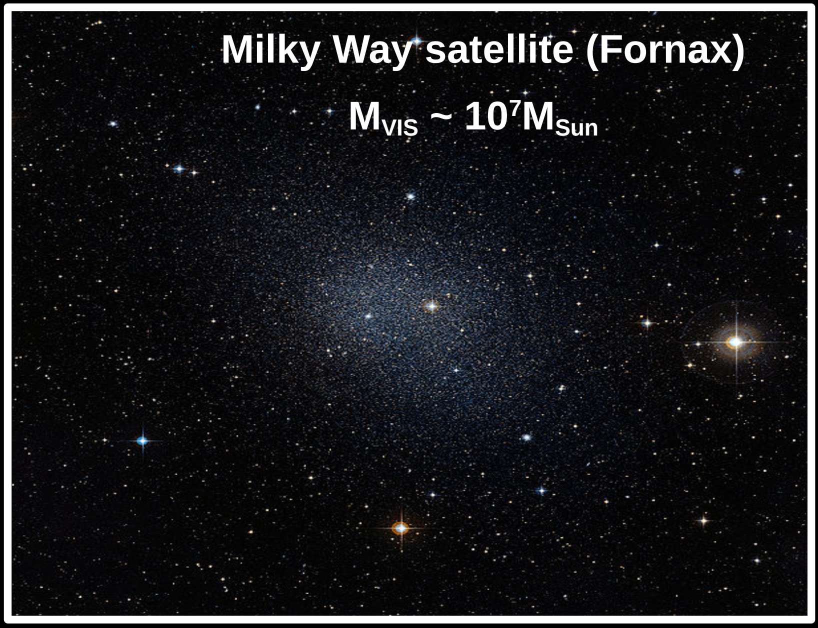
Observations are still inconclusive on the diversity of cores/cusps across haloes

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



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

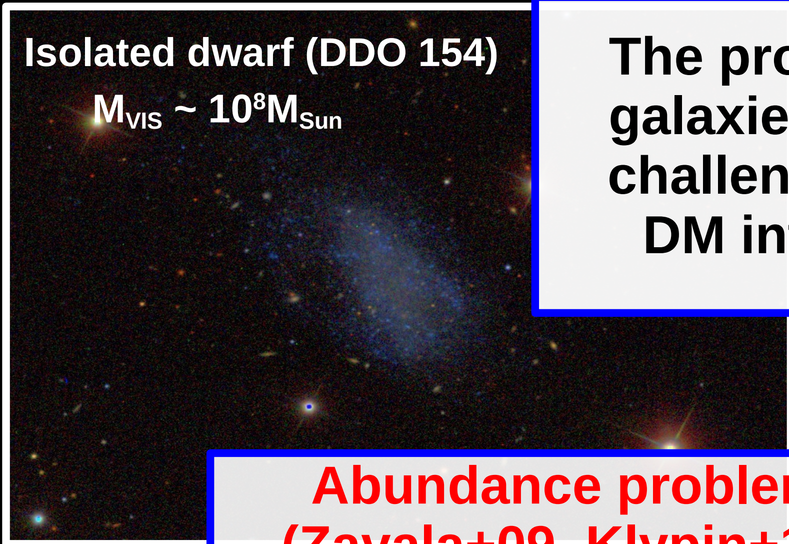
$$\frac{df}{dt} = 0$$

CBE + steady-state + spherical symmetry

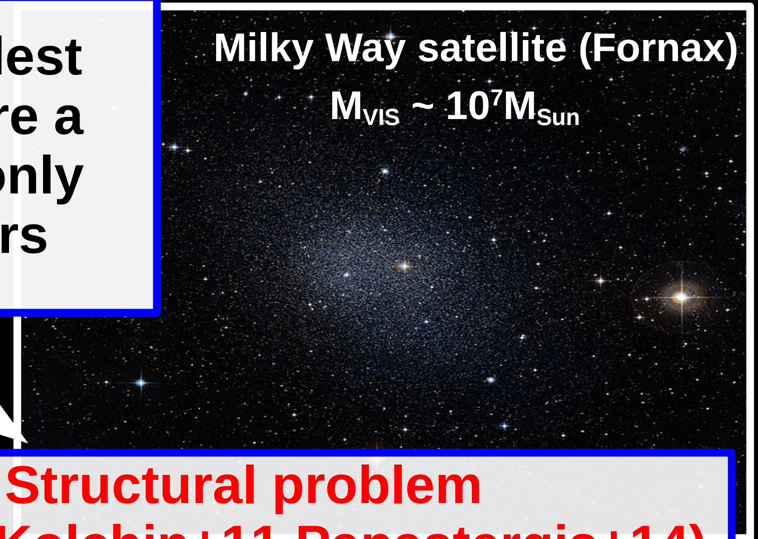
$$\frac{d\left(\rho_{st}\sigma_r^2\right)}{dr} + 2\frac{\beta}{r}\rho_{st}\sigma_r^2 \simeq -\rho_{st}\frac{d\phi_{DM}}{dr}$$

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

Clues of new DM physics from dwarf galaxies?

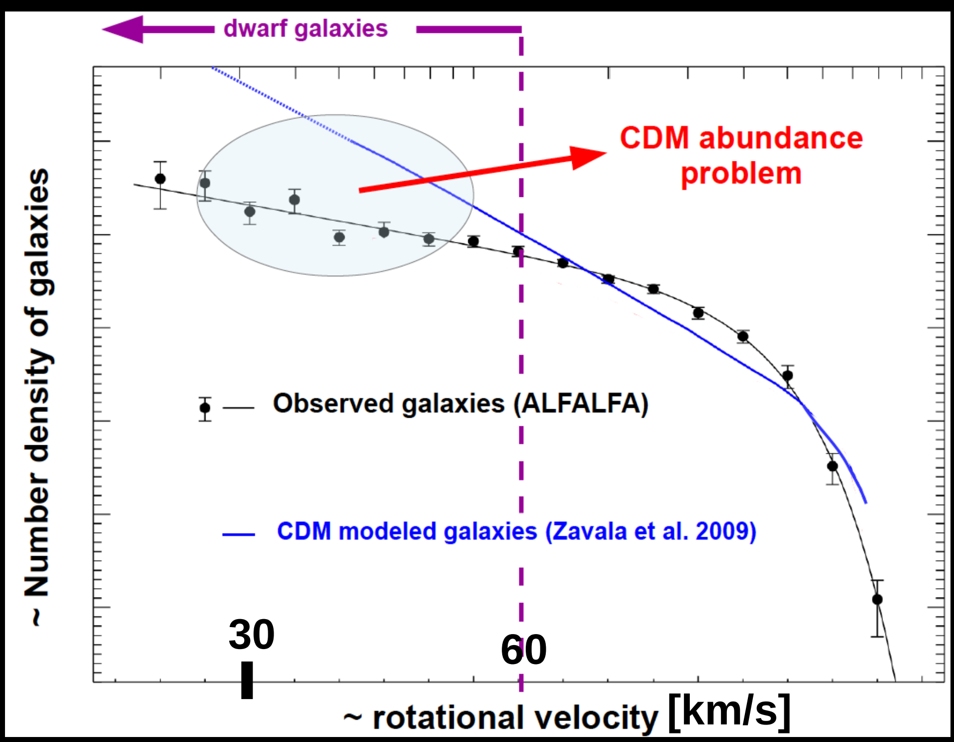


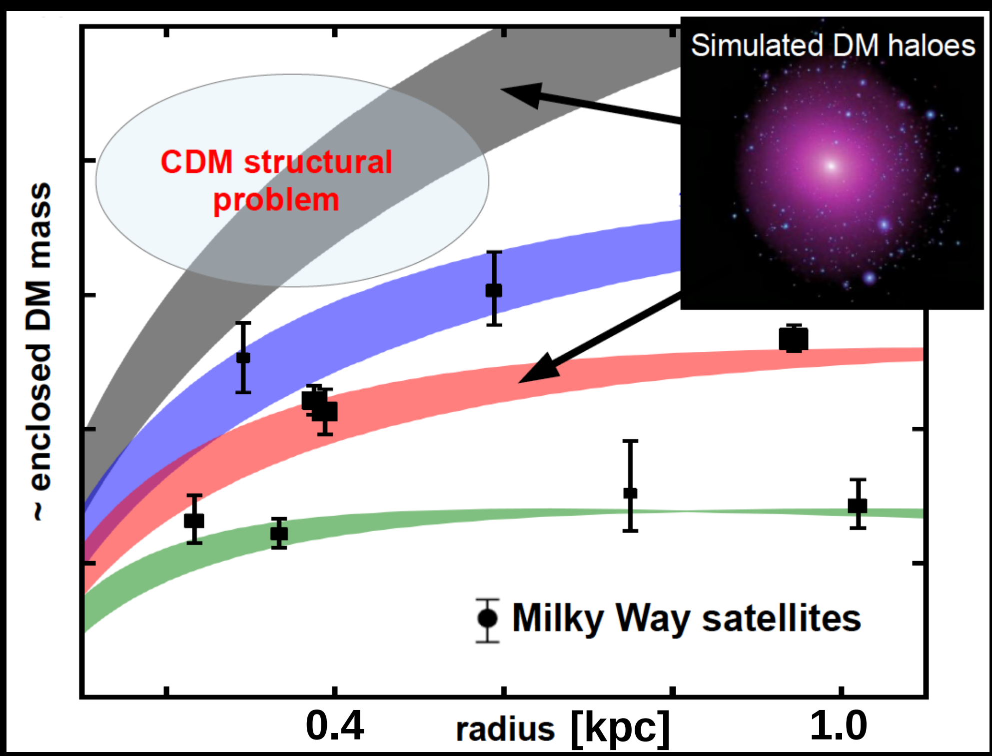
The properties of the smallest galaxies observed today are a challenge if gravity is the only DM interaction that matters



Abundance problem (Zavala+09, Klypin+15)

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





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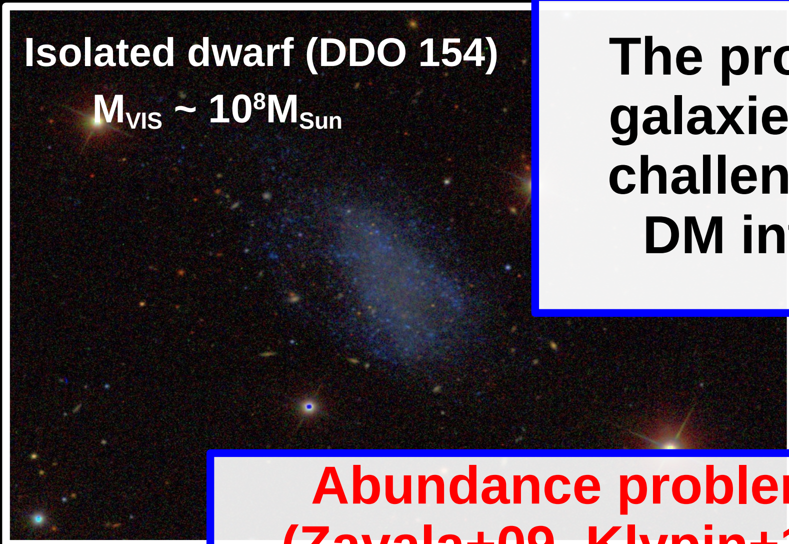
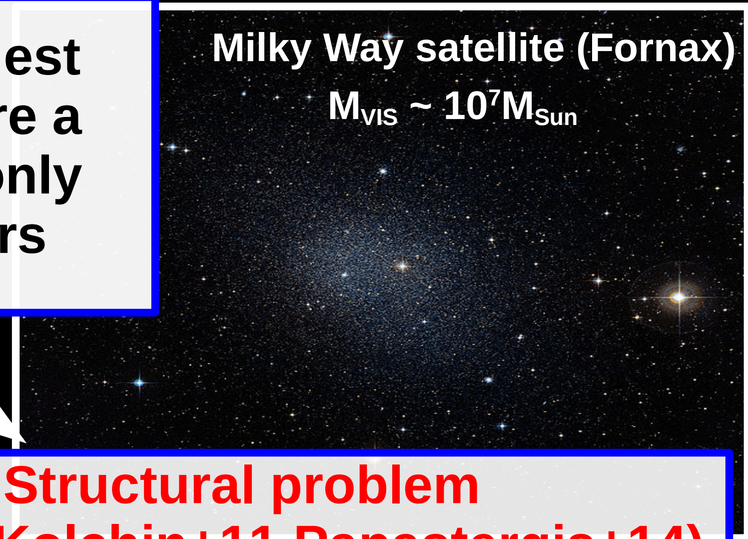


The properties of the smallest galaxies observed **today** are a challenge if gravity is the only DM interaction that matters



Abundance problem (Zavala+09, Klypin+15)

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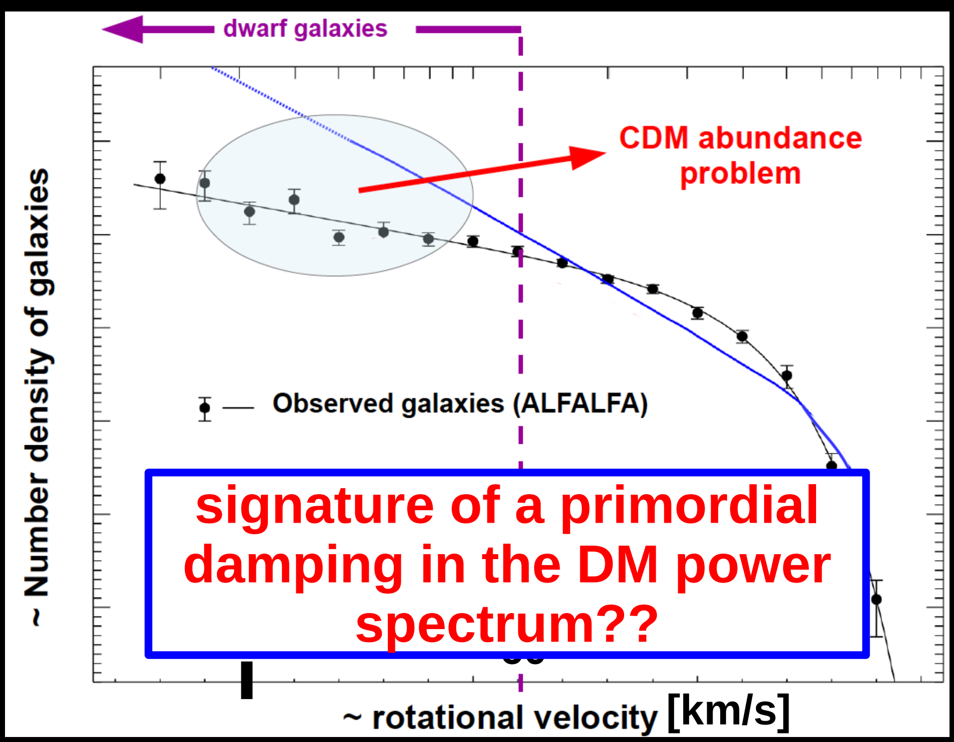
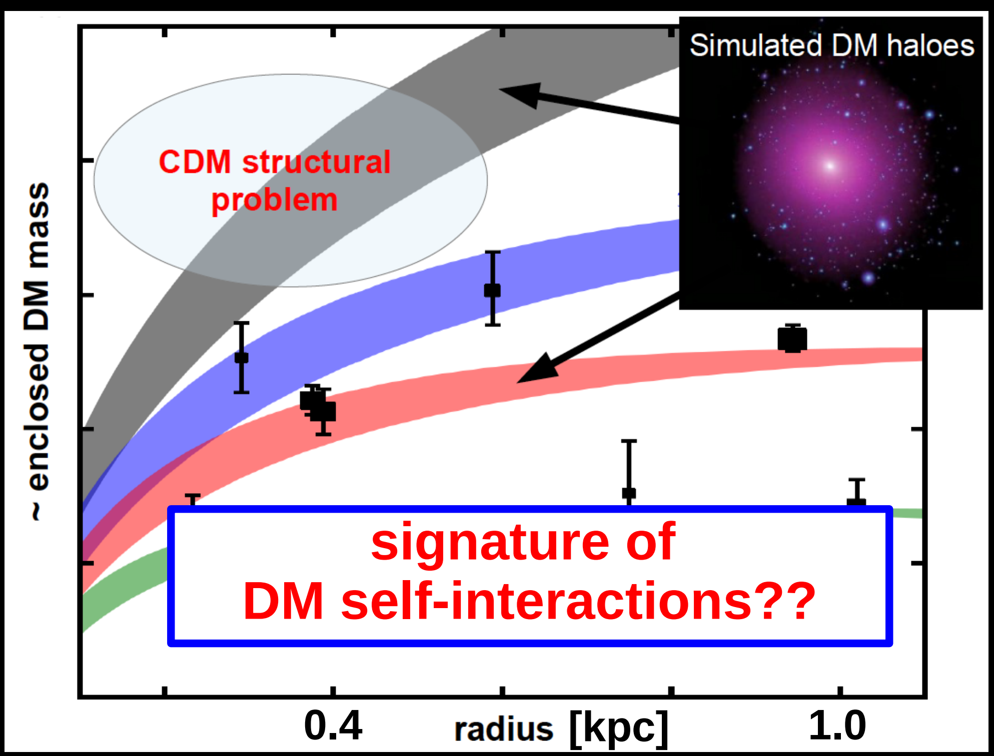
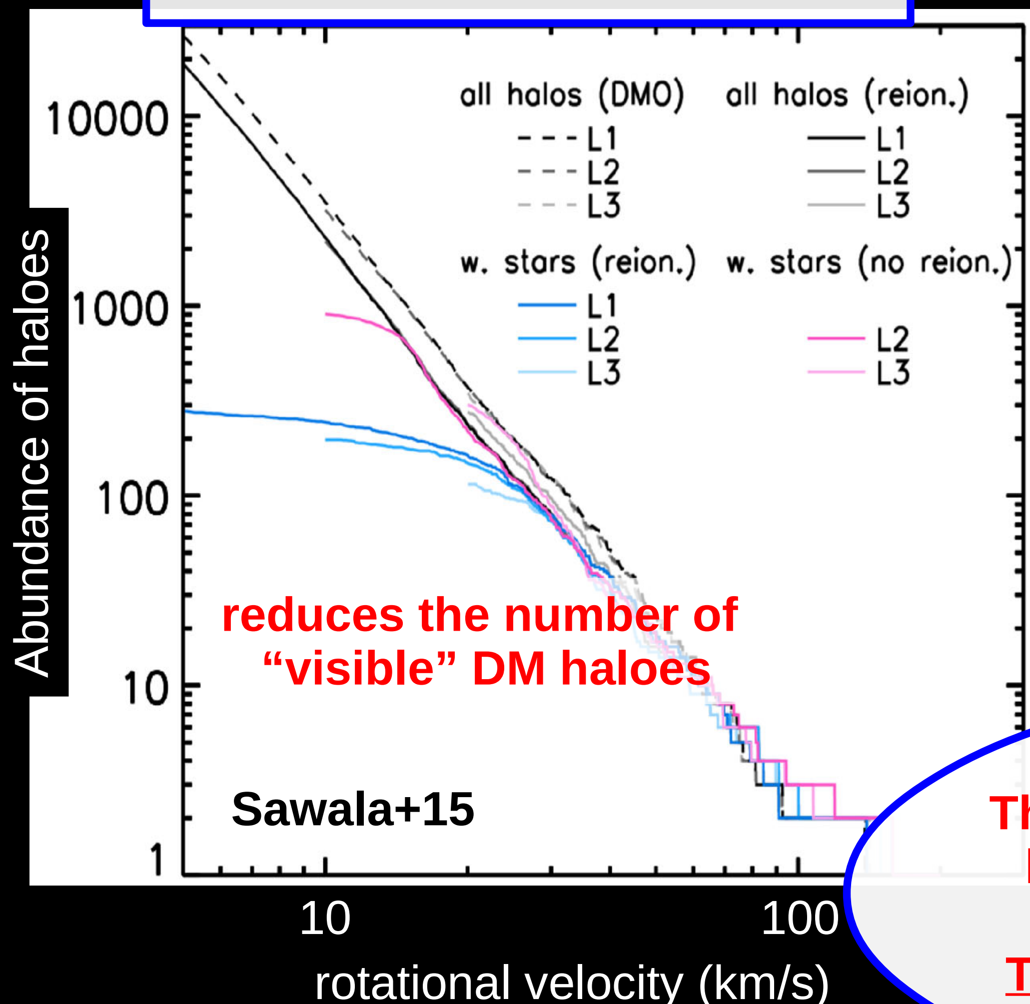




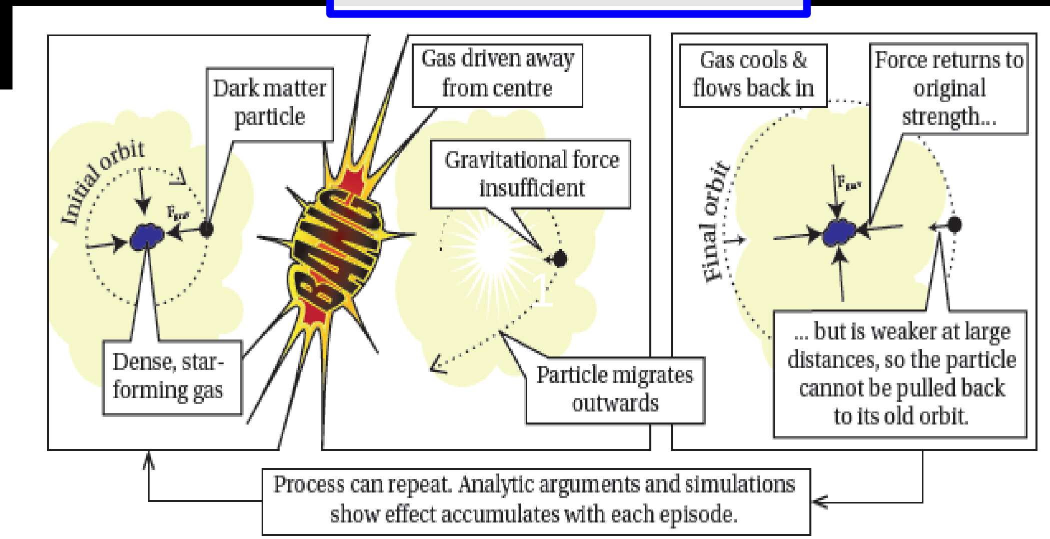
Or... the complexity of gas and stellar physics

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>

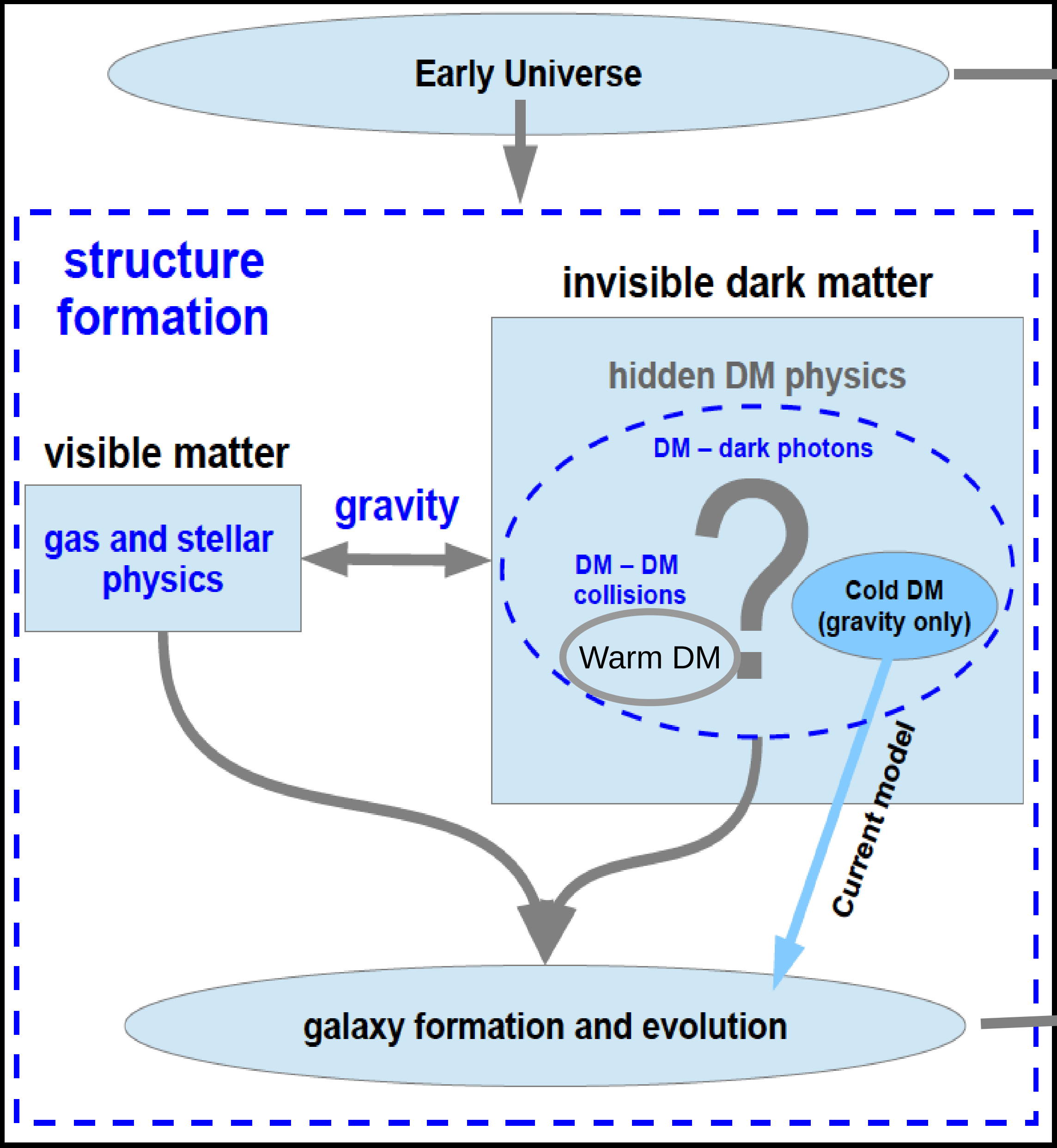
CDM + current galaxy modelling are successful in reproducing several properties of the galaxy population but:

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)

DR to CMB temperature at z=0

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

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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.)

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

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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)

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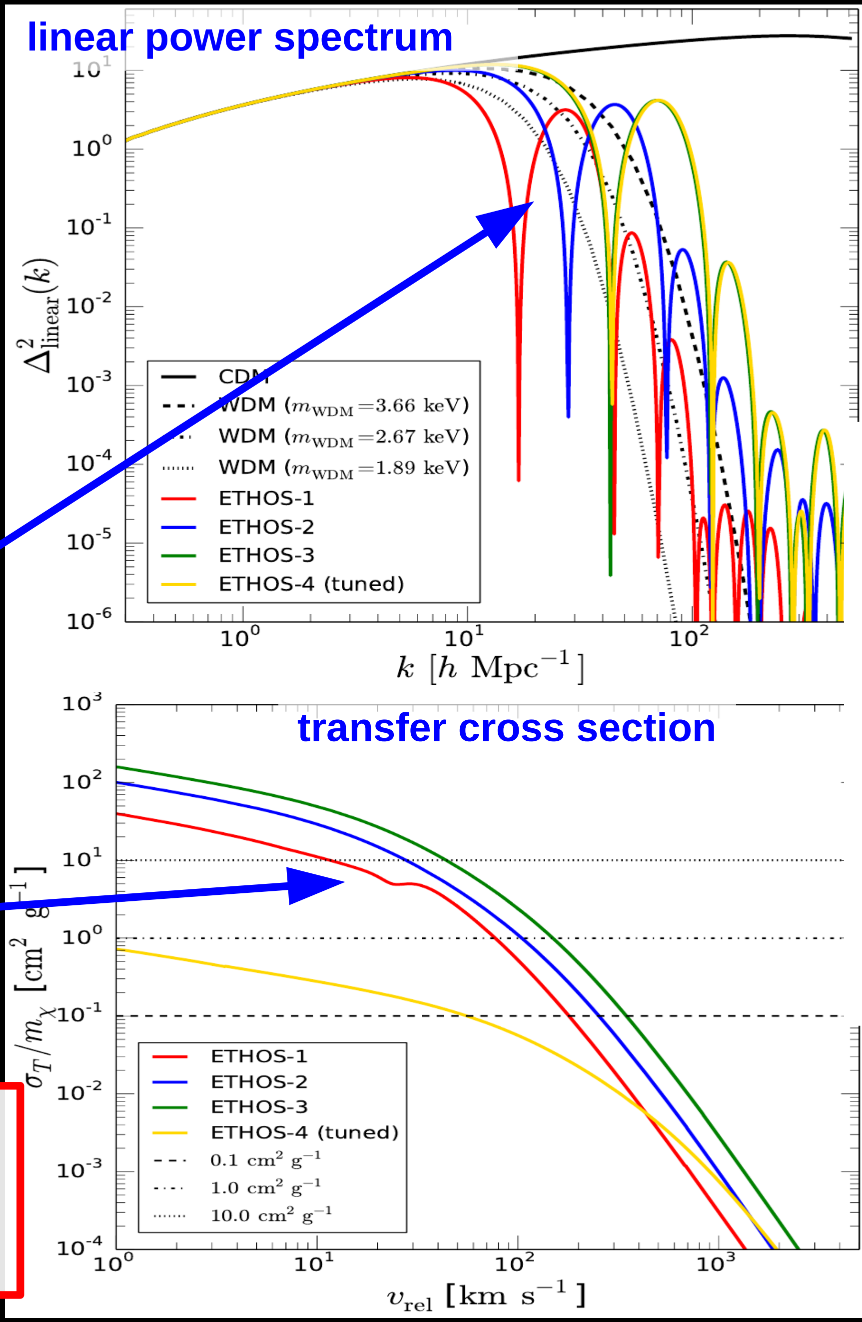
All DM particle physics models that map into the same ETHOS parameters can be studied (constrained) at the same time



ETHOS I: Cyr-Racine+16

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:

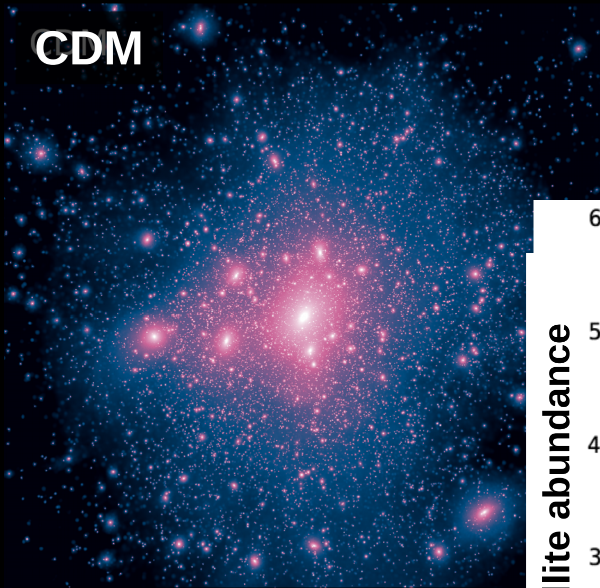
$$\vec{v}_i = \vec{v}_{cm} + (\vec{v}_{ij}/2)\,\hat{e}$$
$$\vec{v}_j = \vec{v}_{cm} - (\vec{v}_{ij}/2)\,\hat{e}$$

randomly scattered

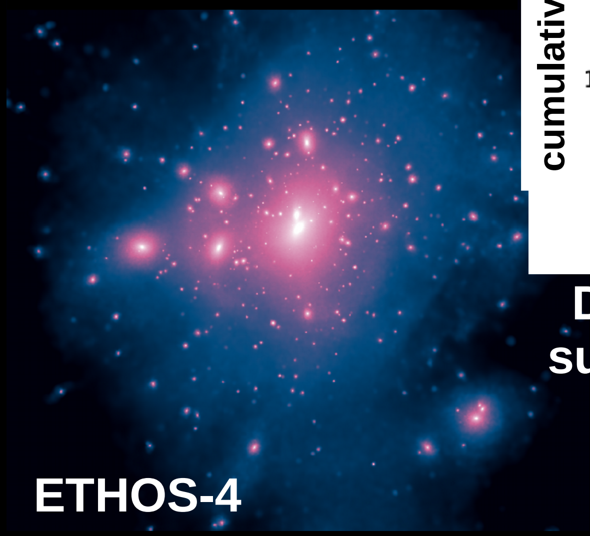
Kochanek & White 2000, Yoshida+2000,...Vogelsberger, Zavala, Loeb 2012, Rocha+2013

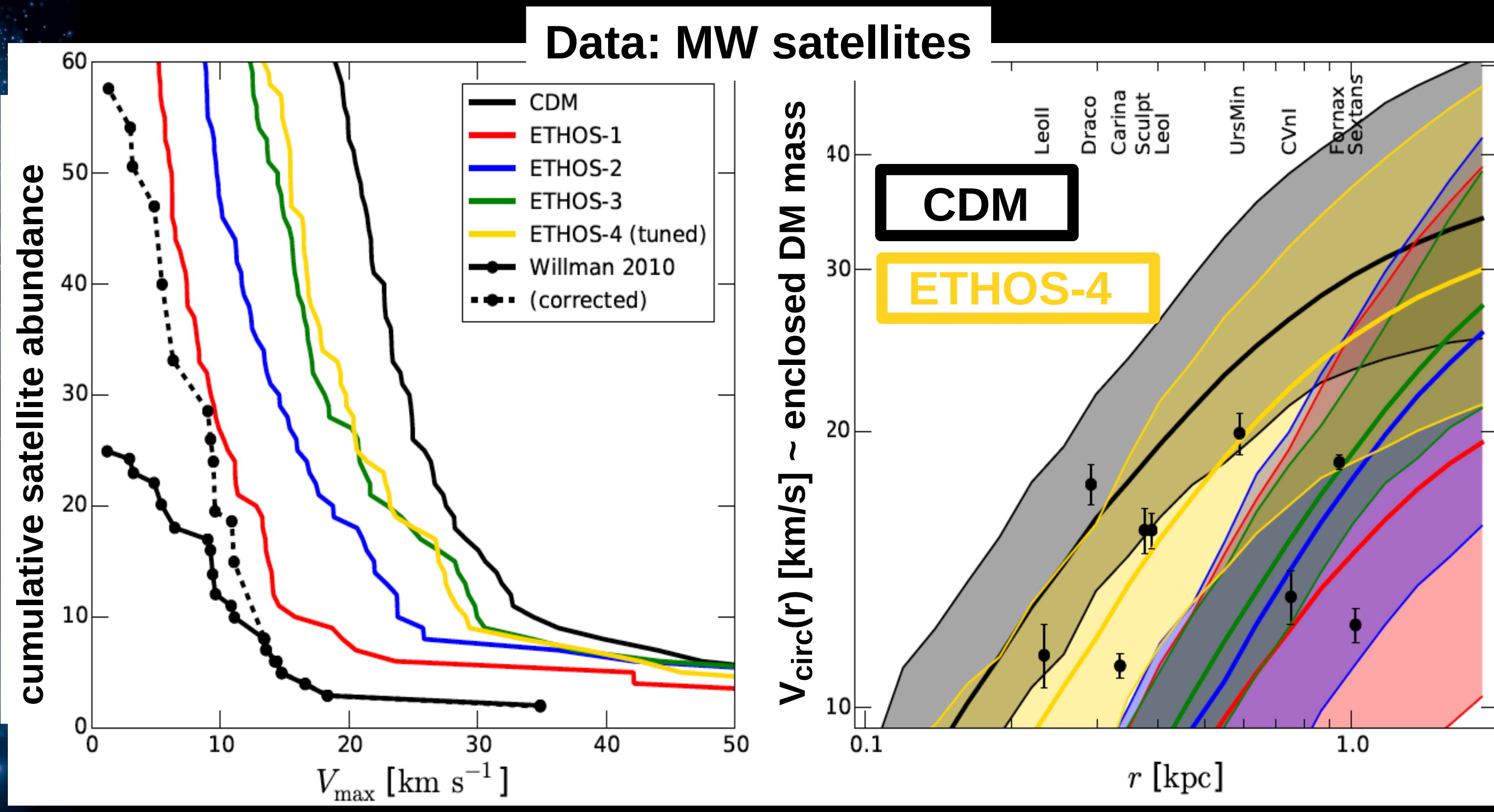
ETHOS application: non-linear regime with N-body simulations and the CDM challenges

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

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

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

- 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