Interplay between particle physics and astrophysics of dark matter

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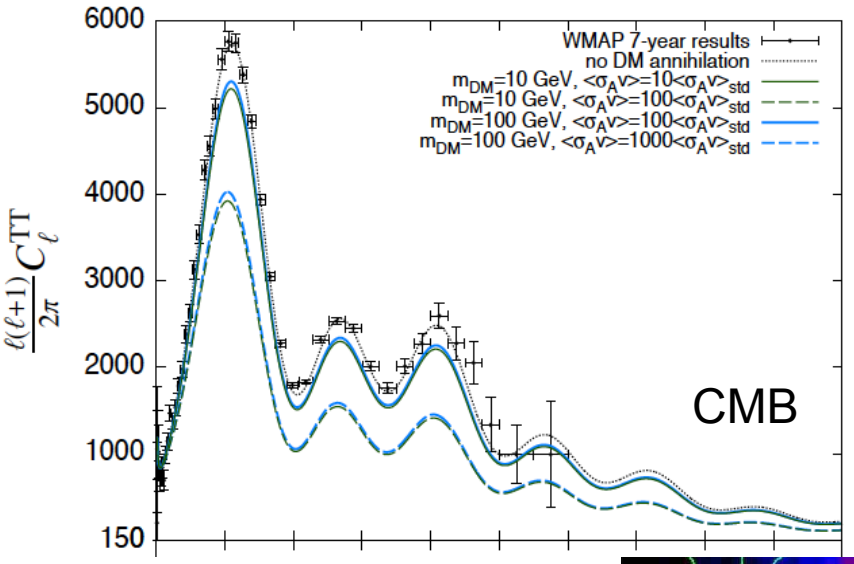
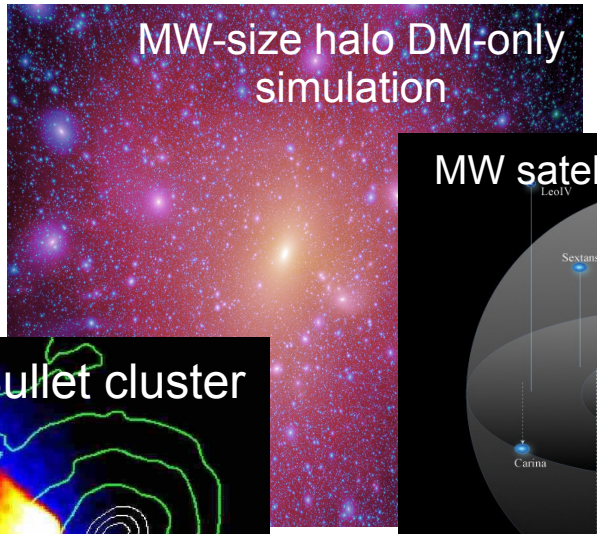
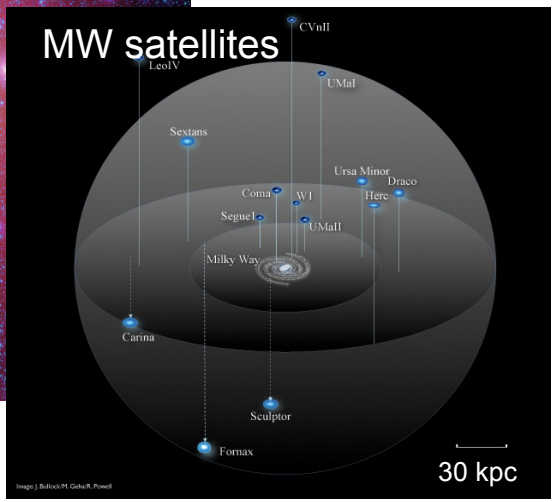
European Commission

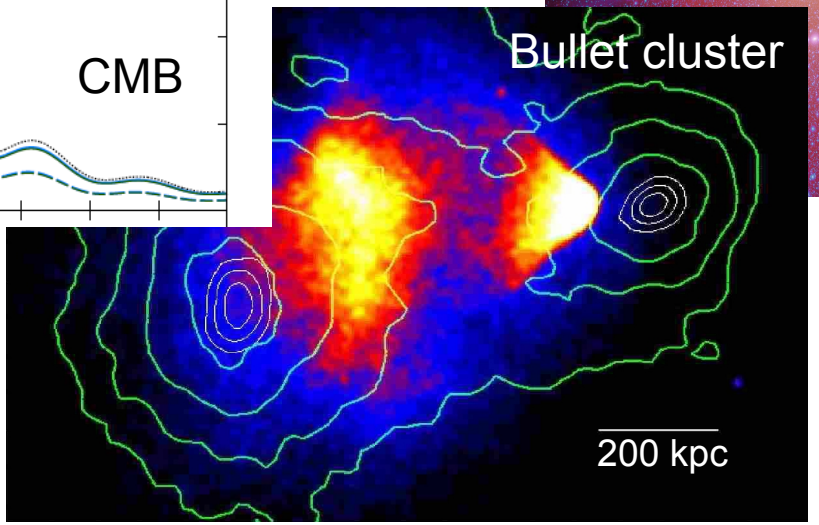
MARIE CURIE ACTIONS

Dark Cosmology Centre







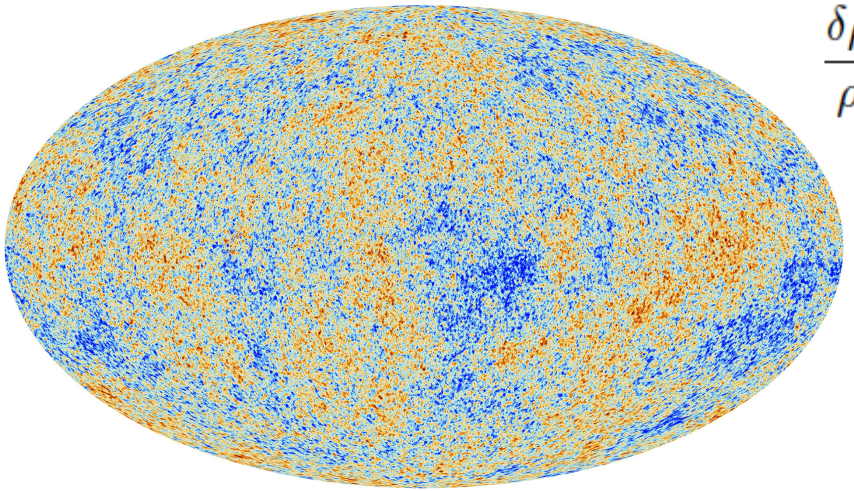


IPA 2014, Queen Mary University of London, August 2014

Dark Matter astrophysics

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

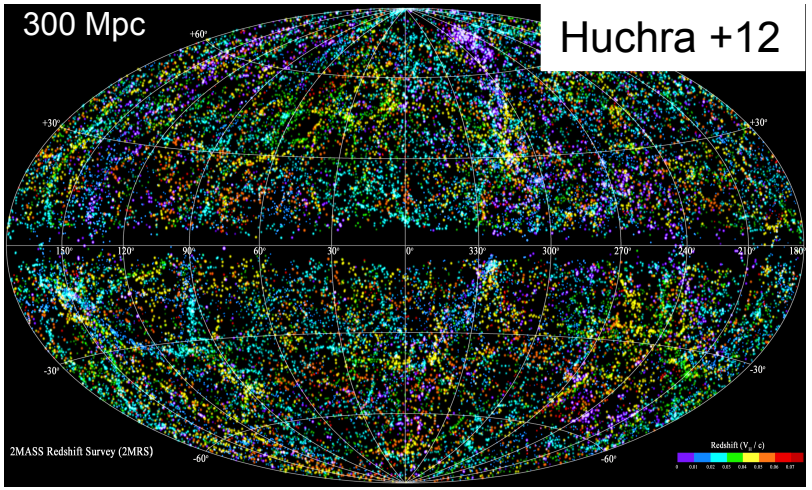
Early Universe (t ~ 0.4 Myrs)



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

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

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

Credit: ESA and the Planck Collaboration

Galaxy formation in a DM background

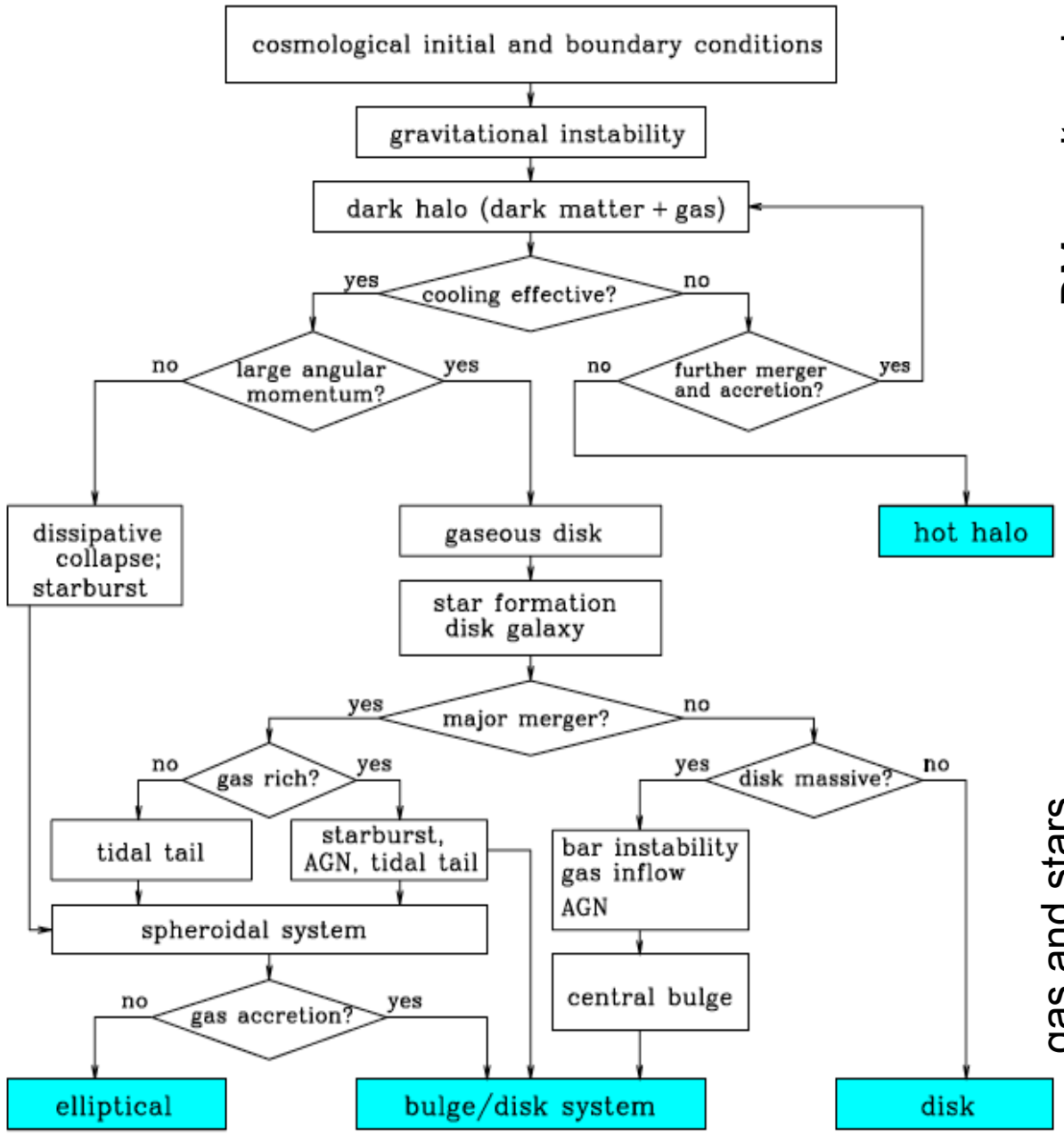
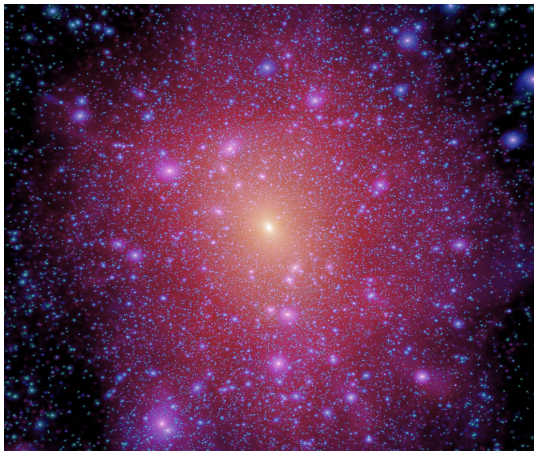


Fig. from Mo, Mao and White, 2010

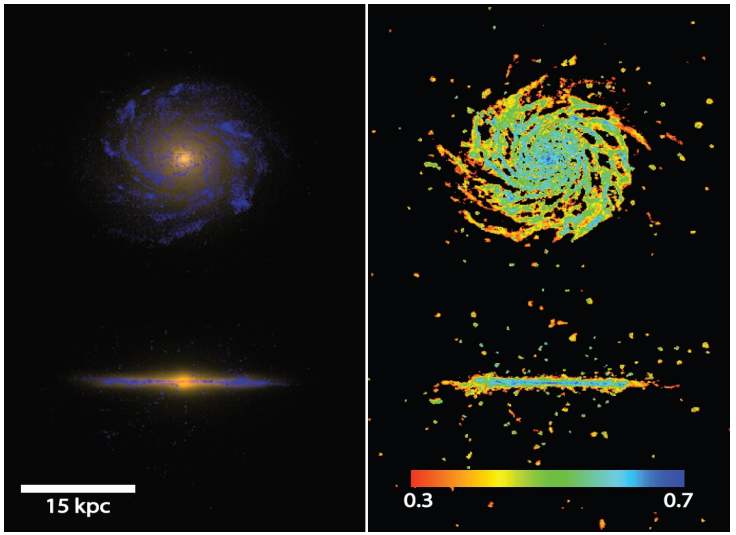
DM gravity only



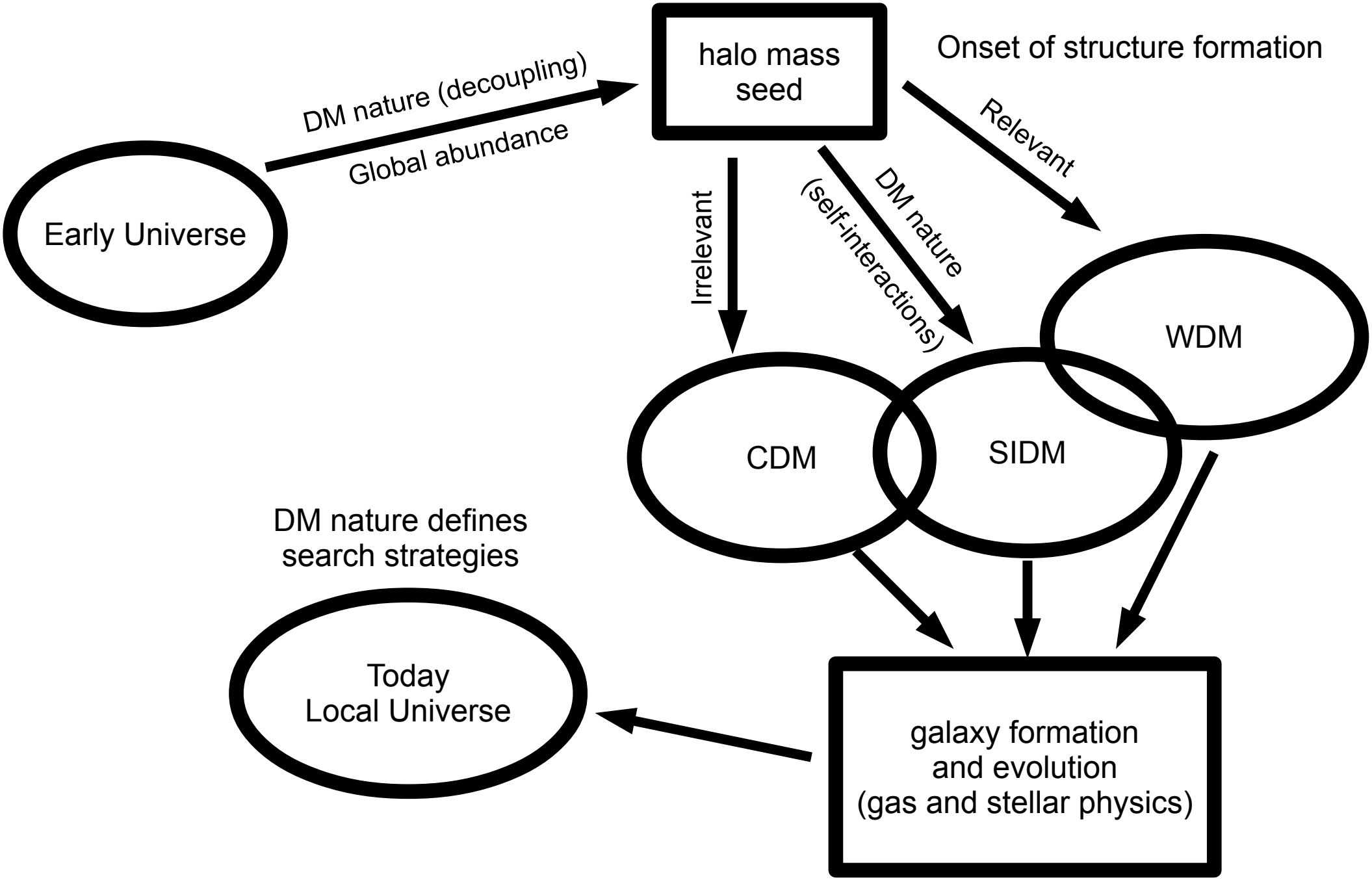
Aquarius project Springel+08

“Eris” simulation Guedes+11

gas and stars

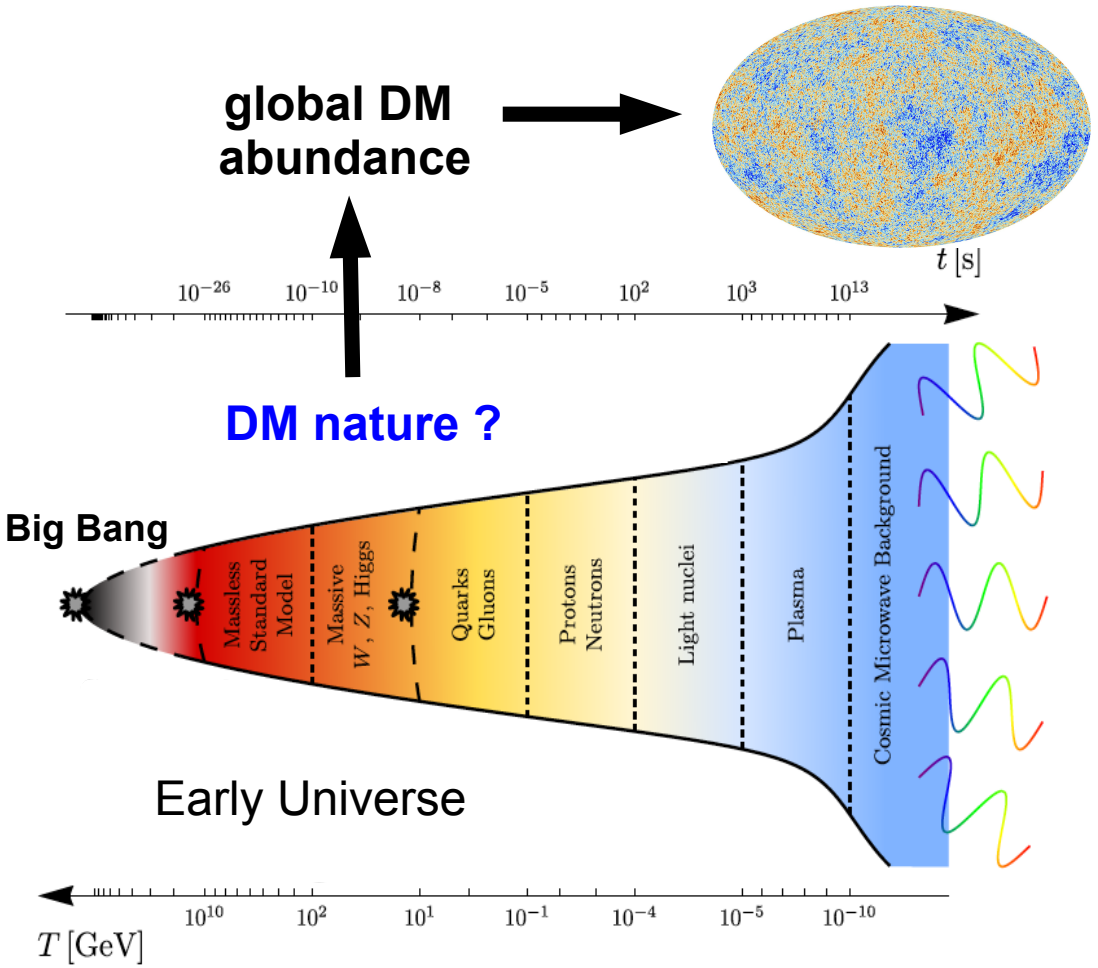


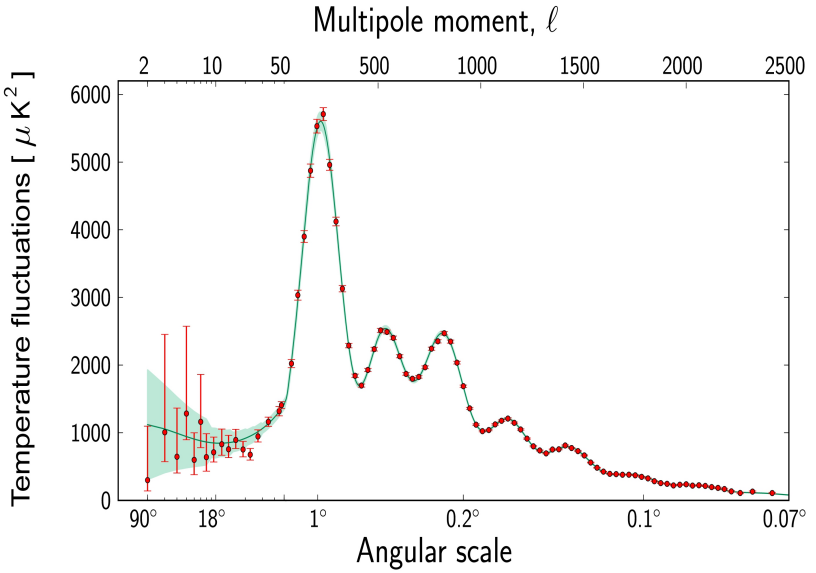
The relevance of the DM nature across time



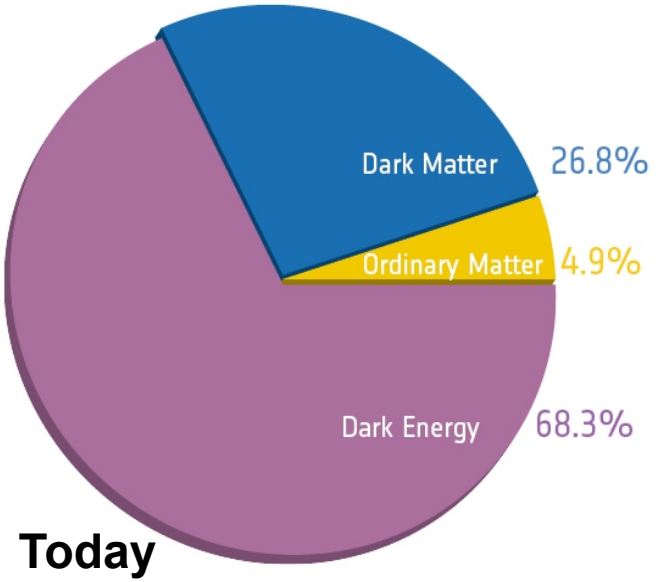
The relevance of the DM nature across time

Fig. from Buchmüller 12





Credit: ESA/Planck



Today

The relevance of the DM nature across time

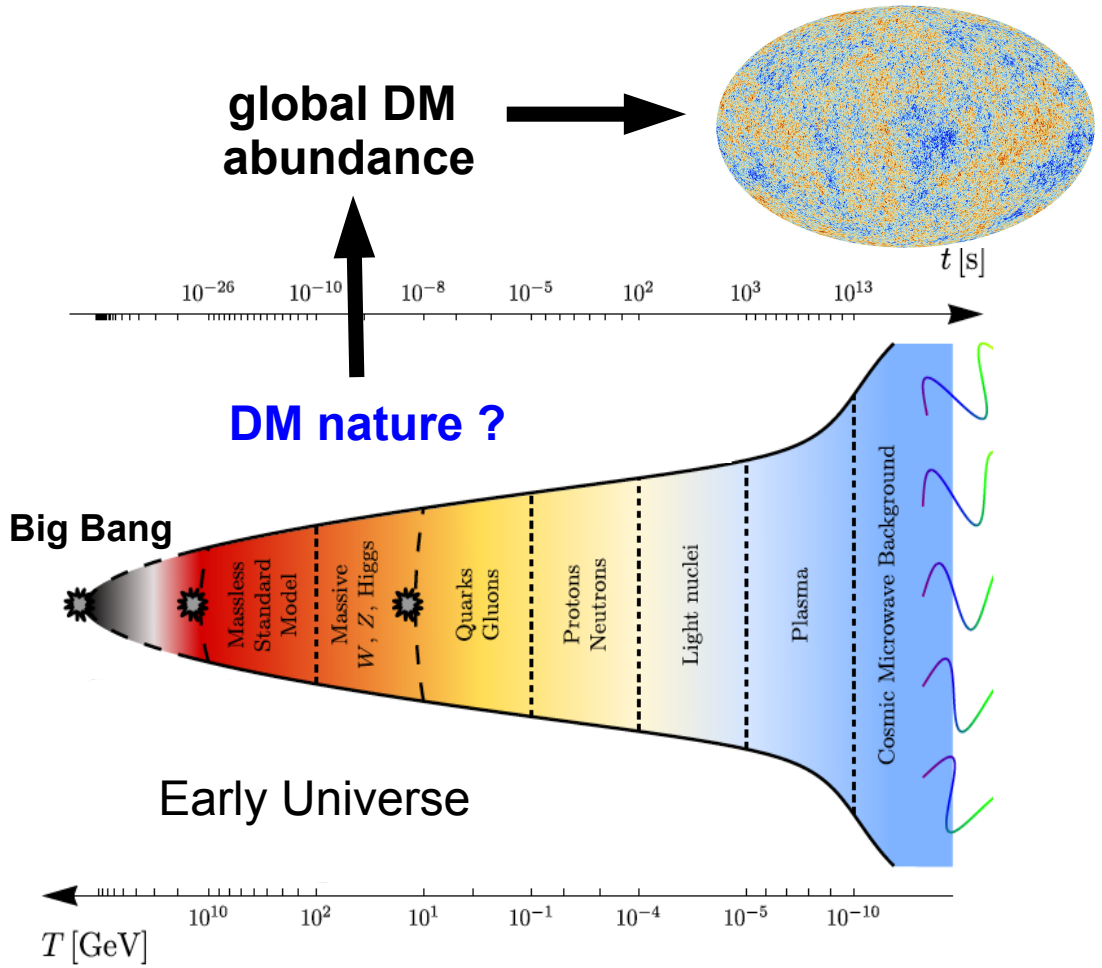
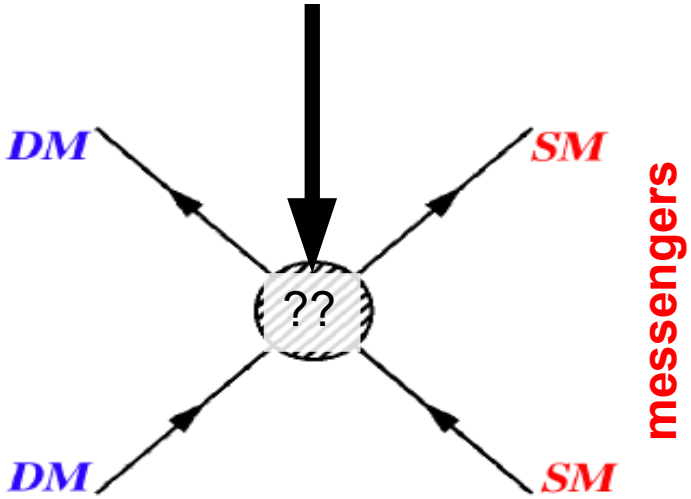


Fig. from Buchmüller 12

Multiple mechanisms of DM production

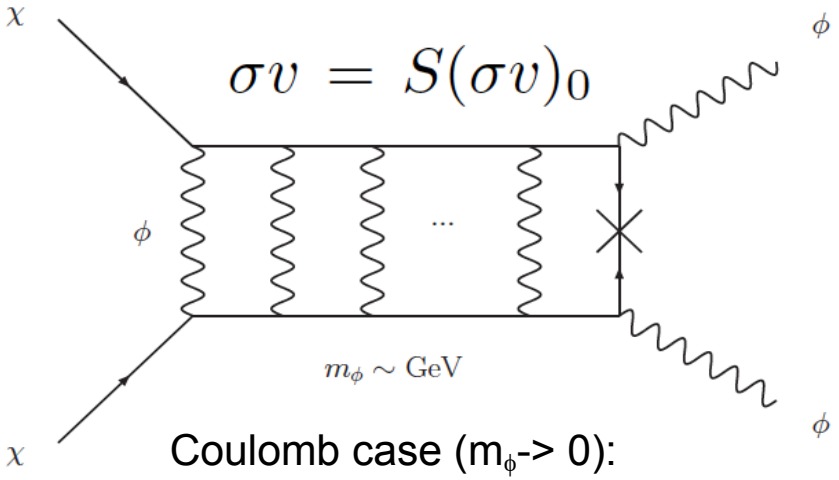
A guiding fundamental principle? e.g. a new symmetry, SUSY



Weak-scale (100 GeV) thermal dark particles (**WIMPs**) "naturally" give the right DM abundance

Relic density constraints (example: thermal Sommerfeld-enhanced)

Sommerfeld-enhanced annihilation
(e.g. Hisano +04, Arkani-Hamed +09)



$$\sigma v = S(\sigma v)_0$$

Coulomb case (m_ϕ-> 0):

$$S = \frac{\pi\alpha_c}{\beta}\left(1 - e^{-\pi\alpha_c/\beta}\right)^{-1}$$

$$S(\beta) \propto 1/\beta \quad \text{if} \quad \beta \ll \pi\alpha_c$$

β = relative velocity

Appealing to boost DM annihilation
in the MW halo to explain
e.g. excess of positrons in
Cosmic-rays (PAMELA, AMS...)

However, constraints from the
early-Universe limit the maximum boost!

$$\frac{\mathrm{d}n_\chi}{\mathrm{d}t} + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - \left(n_\chi^{EQ}\right)^2\right)$$

$$\mathrm{BF} = \frac{\langle\sigma v\rangle_0^{\Omega_{DM}} S(\sigma_{\mathrm{vel,h}})}{3\times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}} \lesssim 100$$

In the MW-halo today **Zavala+10**, Feng+10

CMB constraints (DM annihilation)

CMB energy spectrum: energy injection at $10^4<z<10^6$ produces a Bose-Einstein energy spectrum with chemical potential μ instead of a pure black body. Injection at $10^3<z<10^4$ produces a y-type distortion to (Illarionov & Sunyaev 75).

Limit by COBE/FIRAS $|\mu|<9\times10^{-5}$

$$\mu = 1.4\frac{\delta\rho_\gamma}{\rho_\gamma} = 1.4\int_{t_1}^{t_2}\frac{\dot{\rho}_\gamma}{\rho_\gamma}dt = 1.4\int_{t_1}^{t_2}\frac{f m_\chi\langle\sigma v\rangle n_\chi^2}{\rho_{\gamma,0}a^{-4}}dt,$$

weak constraints to Sommerfeld-enhanced models (Zavala+10, Hannestad & Tram 11)

(PIXIE expected-limit: $|\mu|<10^{-8}$)

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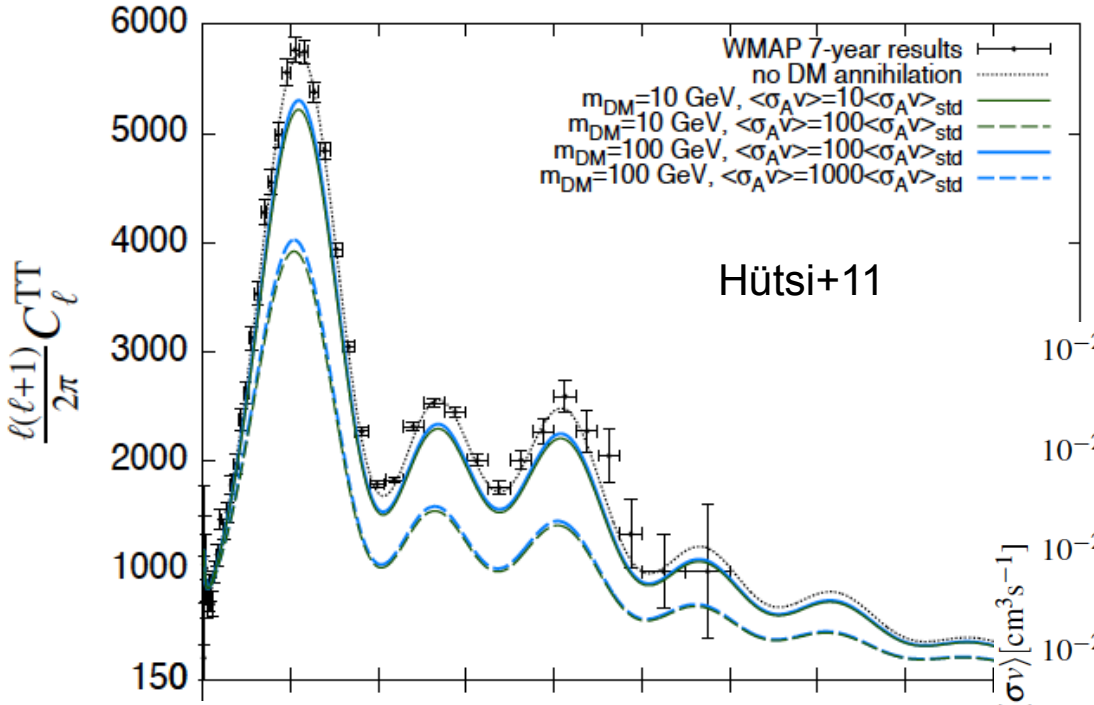
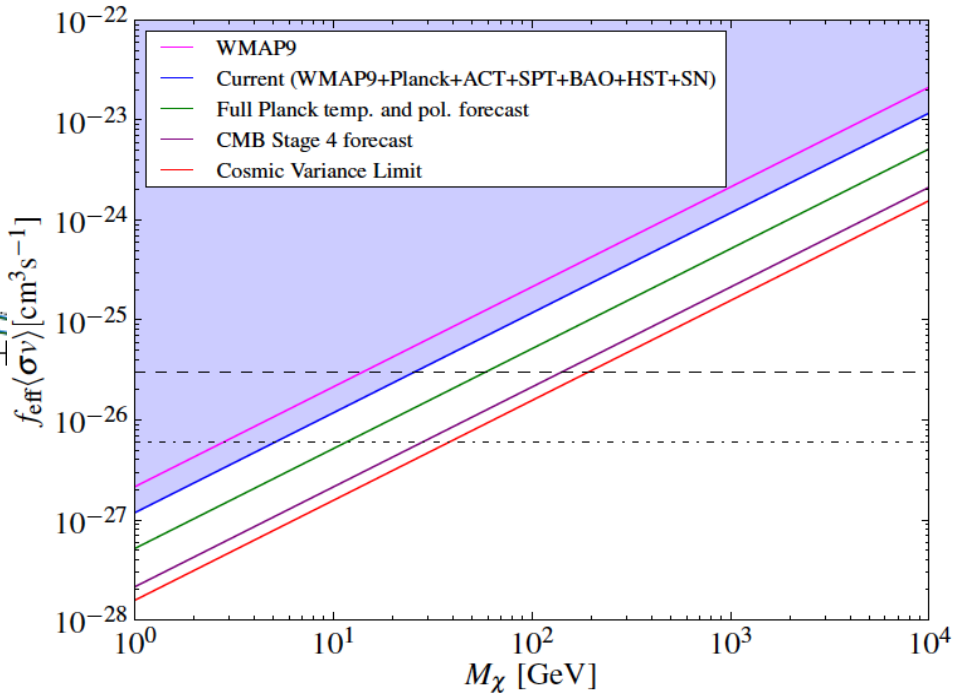


Hütsi+11

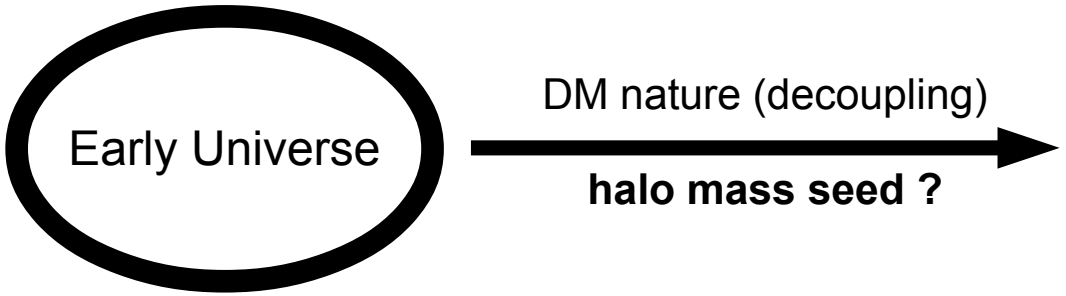
CMB power spectrum: energy injection during **recombination** broadens the surface of last scattering e.g. Padmanabhan & Finkbeiner 05, Slatyer +09...



Madhavacheril + 14

f_{eff}~0.25 for annihilation into SM particles
(electrons f_{eff}~0.7, neutrinos f_{eff}~0)

The relevance of the DM nature across time



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

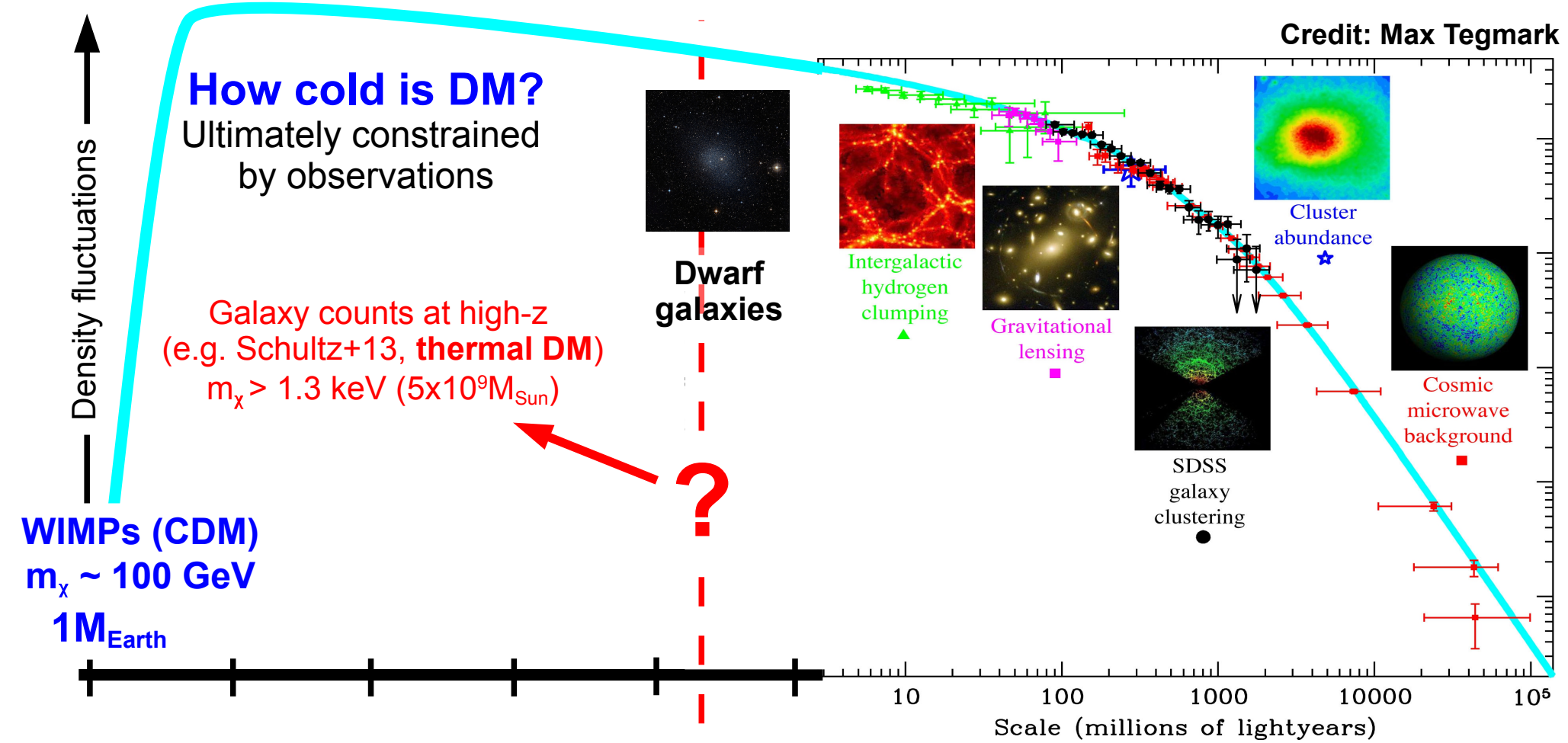
The relevance of the DM nature across time

Early Universe

DM nature (decoupling)

halo mass seed ?

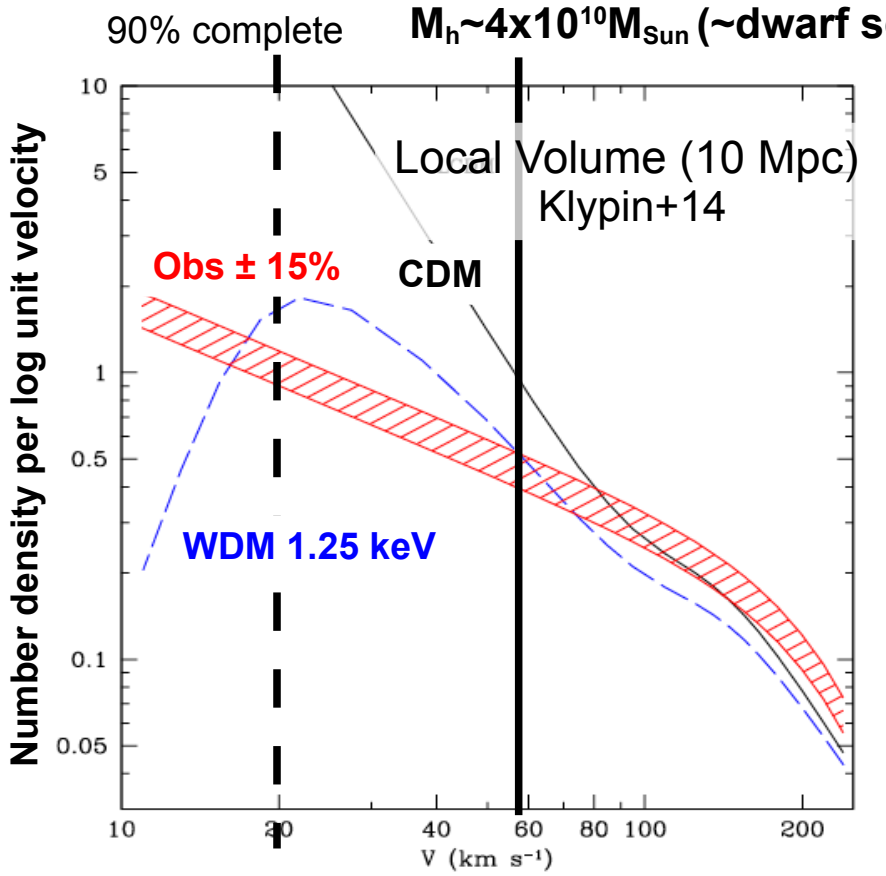
Is the minimum scale for galaxy formation set by the DM nature or by gas physics (or by both)?



The relevance of the DM nature across time

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

A clue from the abundance of dwarf galaxies?



Unsolved problem in CDM!!

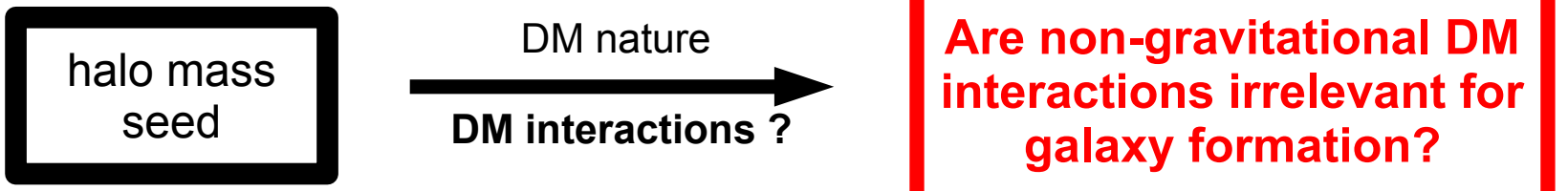
CDM + current benchmark gal. form. models overpredict the abundance of field dwarfs (**Zavala+09**,Papastergis+11,Klypin+14)

Strong suppression of gas and star formation by SNe-driven winds alleviates but **does not yet** solve the tension in a CDM model

A suppression in the original DM power spectrum might hold the key...

The relevance of the DM nature across time

Onset of structure formation



Are non-gravitational DM interactions irrelevant for galaxy formation?

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?

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

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

Virtually all direct and indirect searches assume CDM structure formation!!

Structure formation and DM interactions

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halo mass seed

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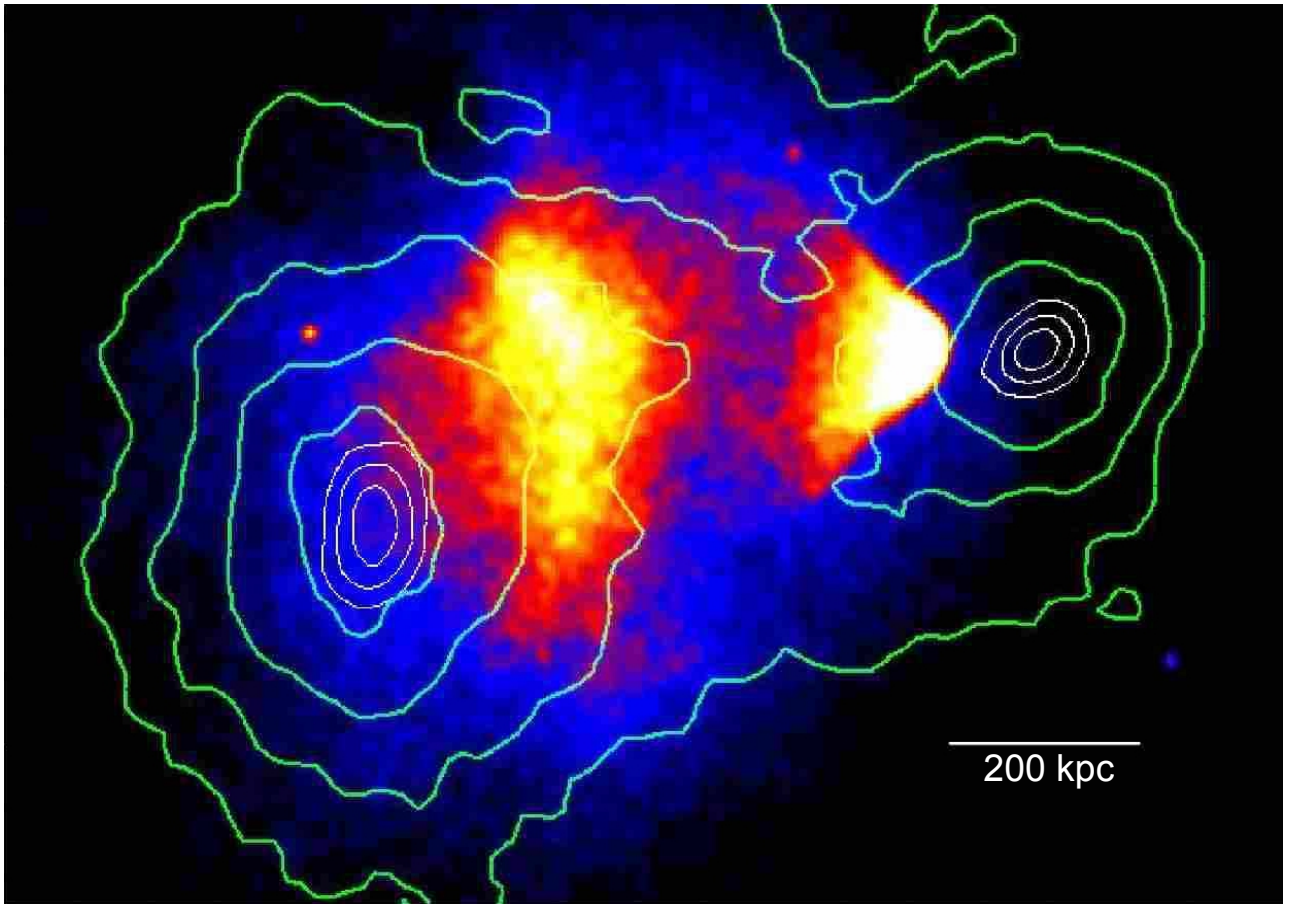
Are non-gravitational DM interactions irrelevant for galaxy formation?

Does it interact with itself (collisions)?



Bullet Cluster (Clowe +06)

(Randall+08)

$\sigma/m < 1.25\ cm^2/gr$

Caveat: DM-only simulation gas and stars might weaken the constraint

Structure formation and DM interactions

Onset of structure formation

halo mass seed

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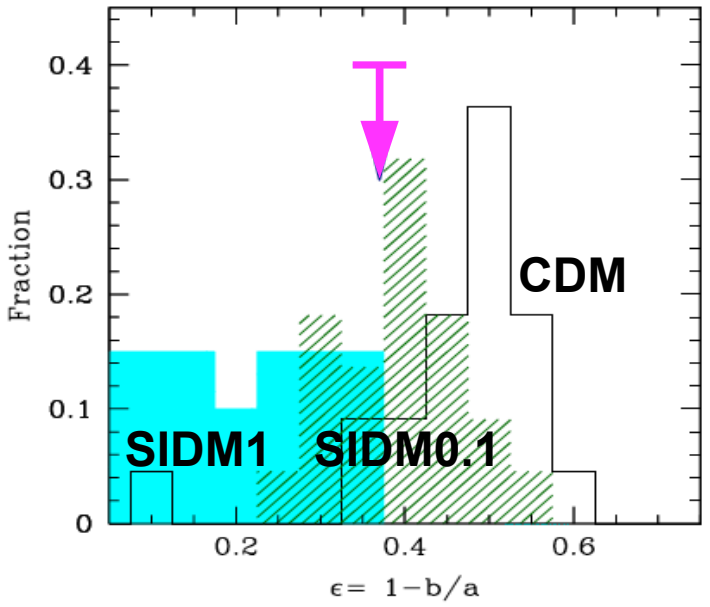
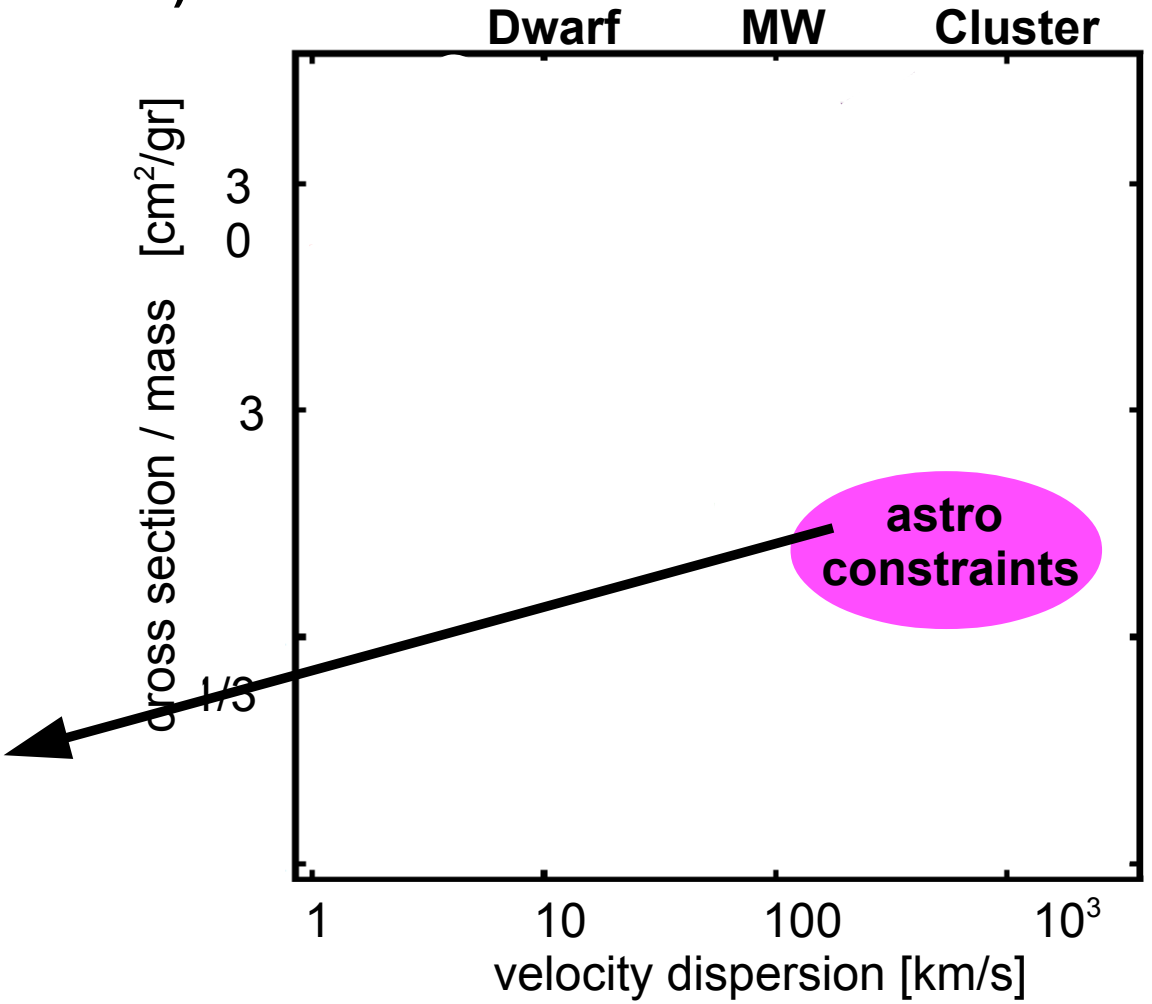
Does it interact with itself (collisions)?

ellipticity constraint
NGC 720 (Peter+2013)
$\sigma/m < 1\ cm^2/gr$





Structure formation and DM interactions

Onset of structure formation

halo mass seed

DM nature

DM interactions ?

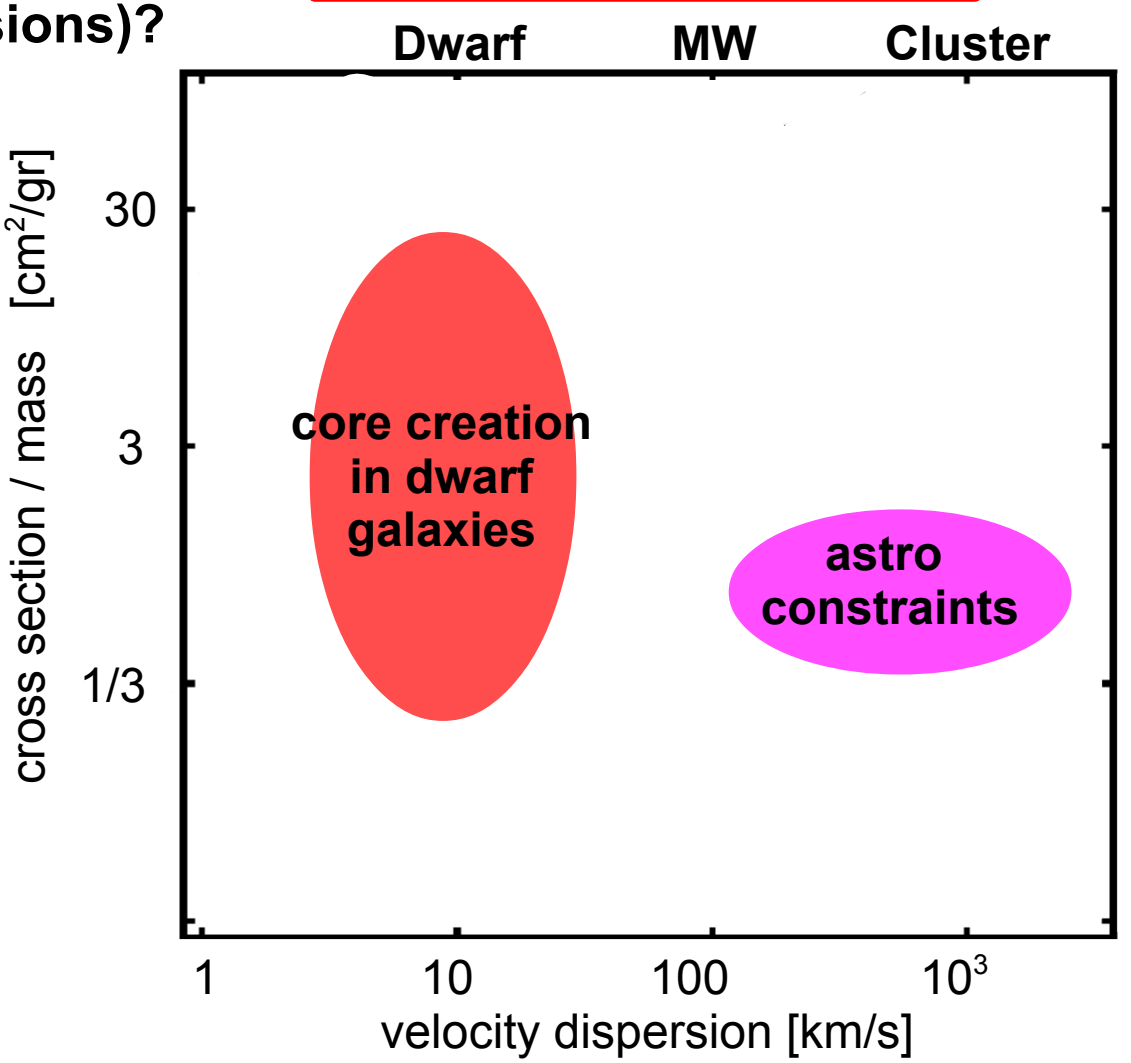
Are non-gravitational DM interactions irrelevant for galaxy formation?

Does it interact with itself (collisions)?

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

~ <1 scatter/particle/t_H>

DM phase-space distribution changes



Structure formation and DM interactions

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halo mass seed

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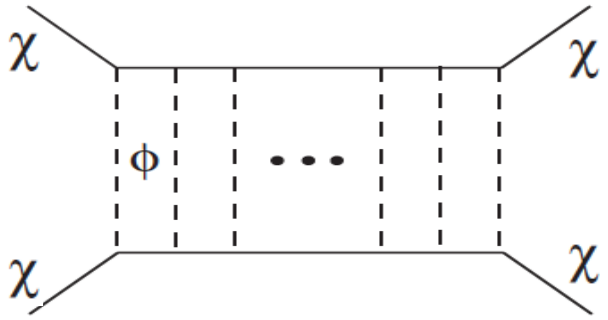
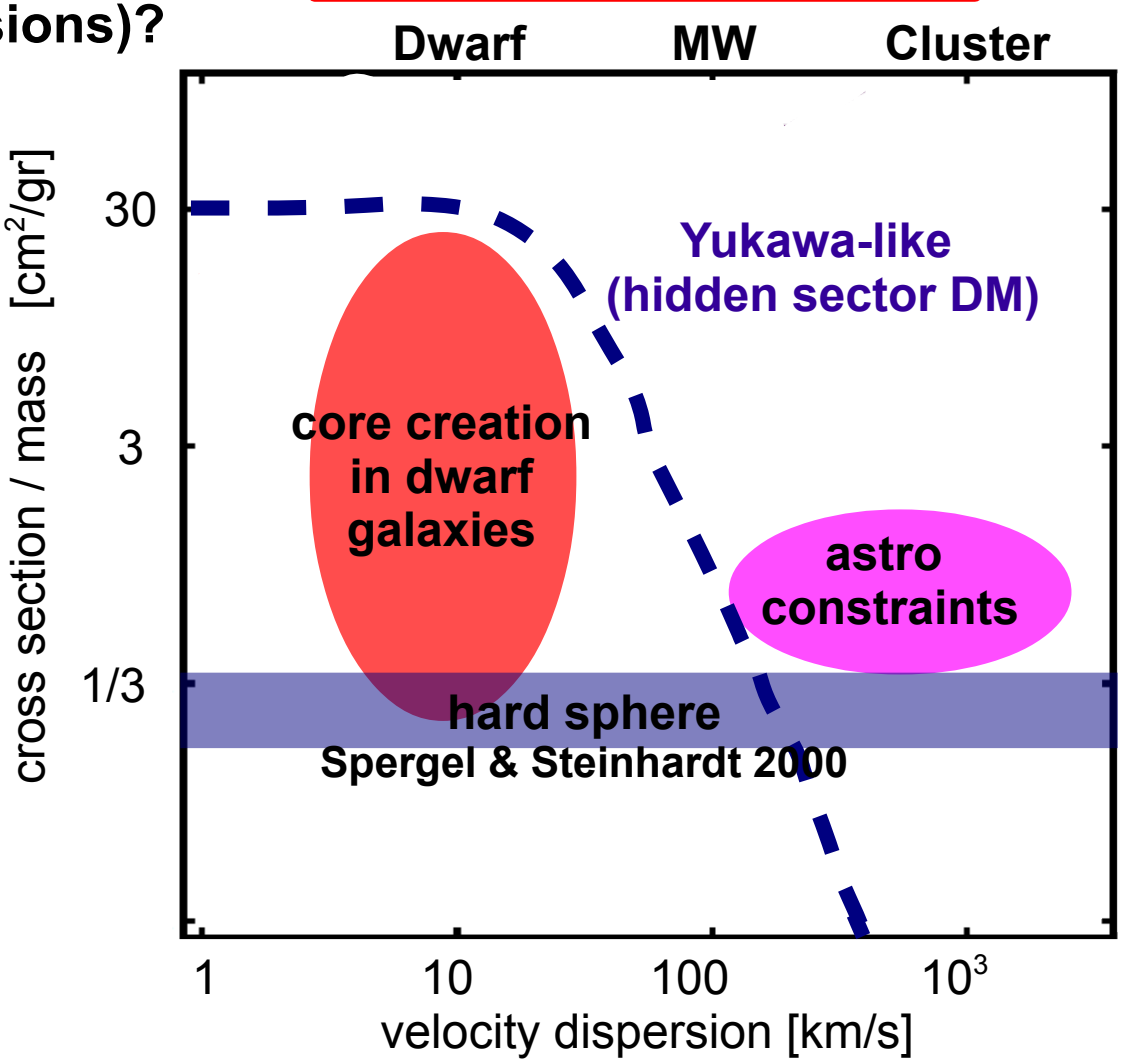
vdSIDM models motivated by a new force in the "dark sector", e.g. Yukawa-like, Feng+09



nucleon-nucleon elastic scattering: ~10 cm^2/g !!

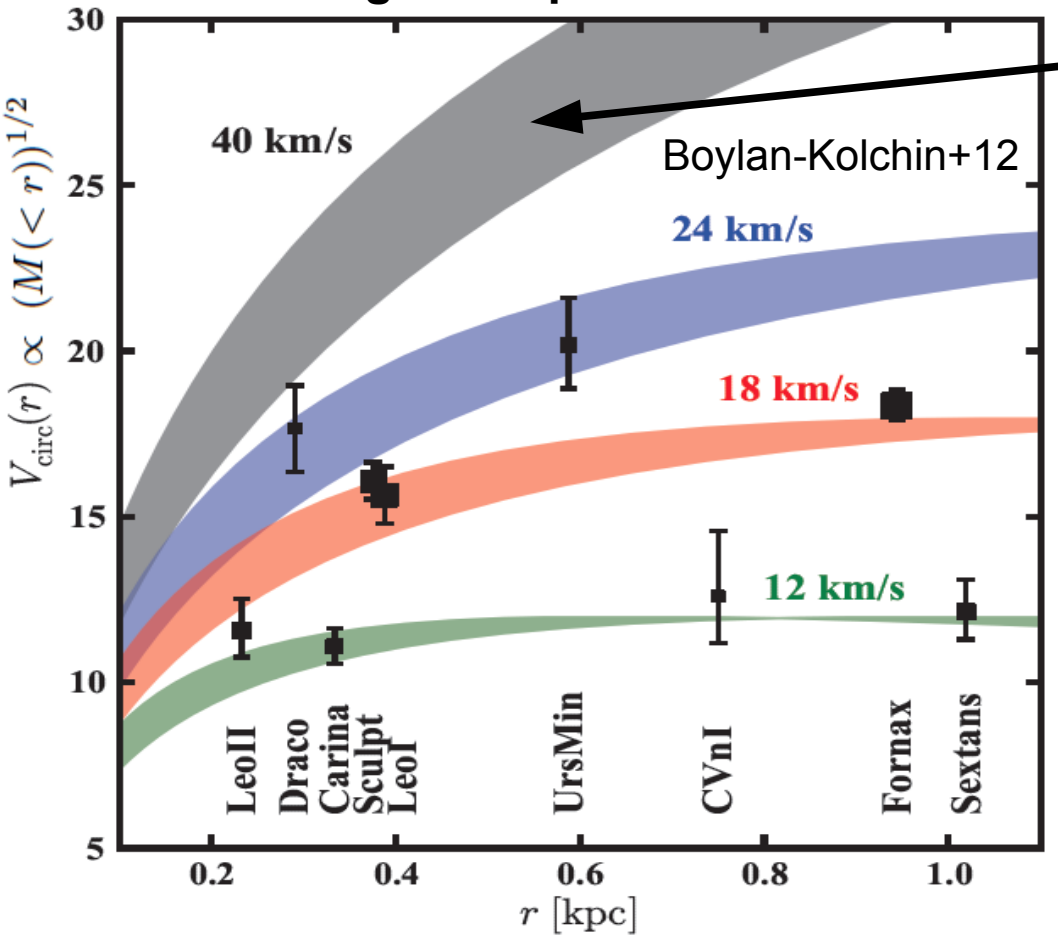


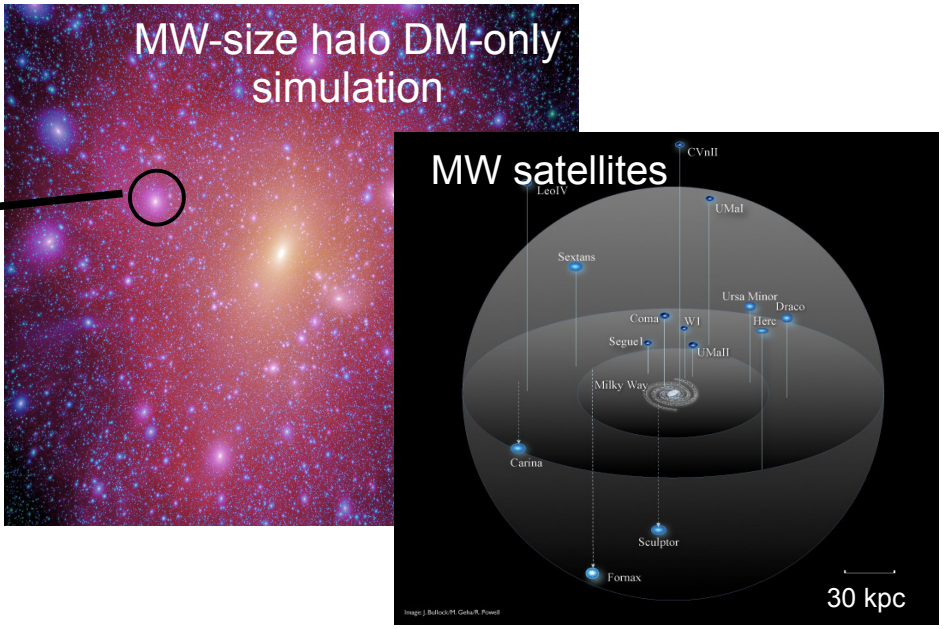
Structure formation and DM interactions

Are non-gravitational DM interactions irrelevant for galaxy formation?

A clue from the structure of dwarf galaxies?

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 Garrison-Kimmel+14, Papastergis+14)

Unsolved problem in CDM!!

The relevance of the CDM nature across time

Early Universe

DM nature (decoupling)

Global abundance

halo mass seed

Onset of structure formation

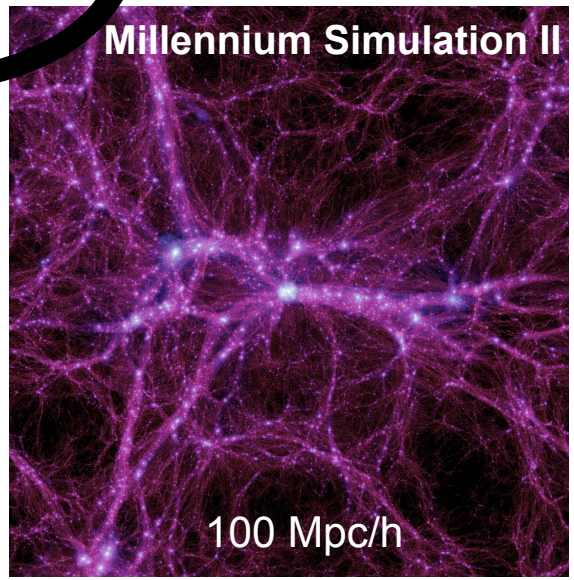
DM nature Irrelevant

CDM

galaxy formation and evolution (gas and stellar physics)

DM nature defines search strategies

Today Local Universe



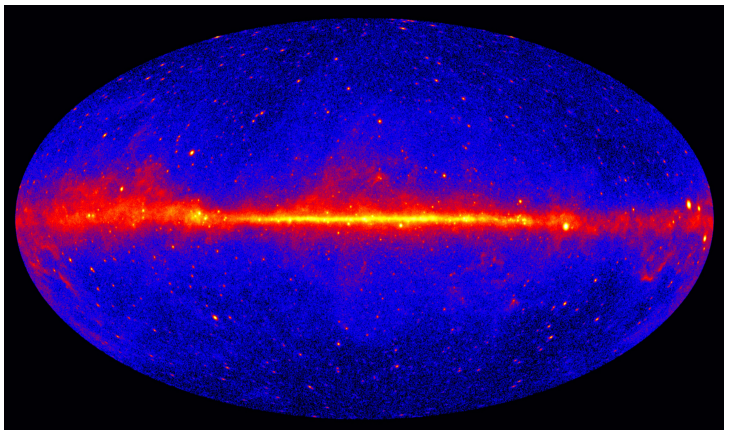
Boylan-Kolchin+ 2009

Uncertainties for predictions of DM signals in a CDM background

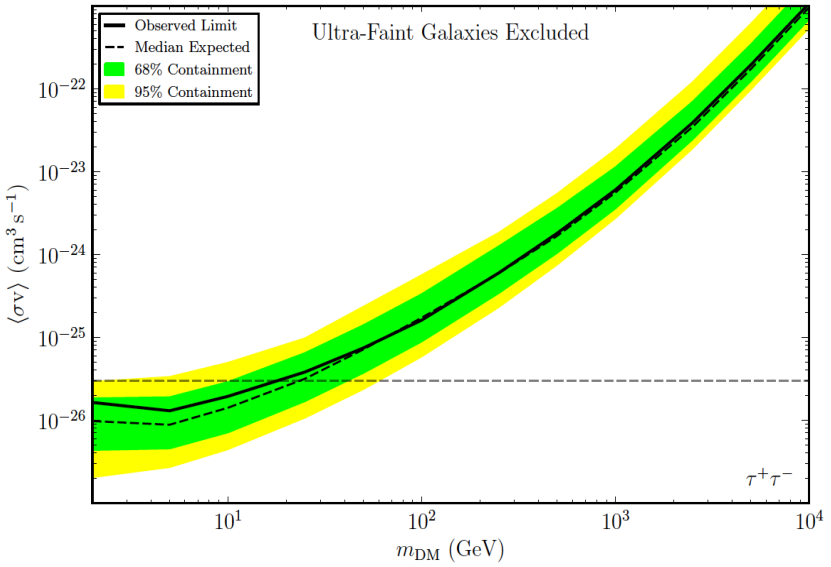
- Minimum clustering scale ($\sim 10^{-6} M_\odot$ for "vanilla" WIMPs)
- "Unresolved" DM phase-space structure
- Gravitational impact on DM by galaxy formation and evolution

CDM + WIMPs (looking for a signal in γ-rays)

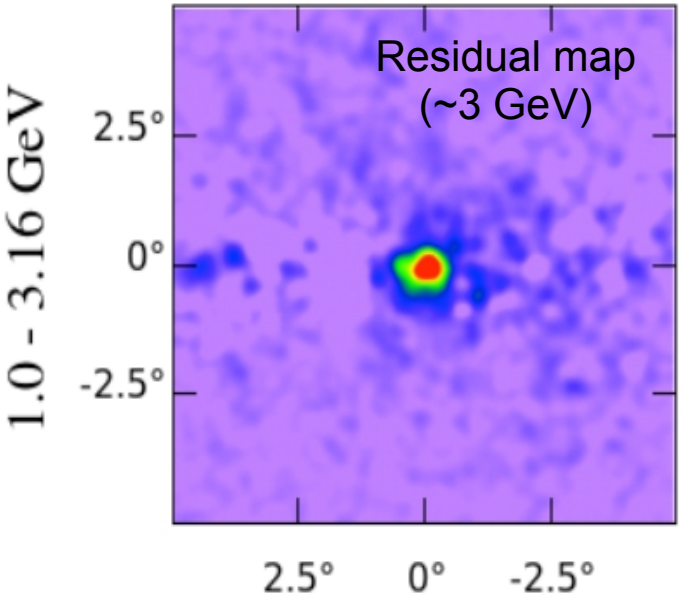
Credit: NASA/Fermi-LAT (5 years)



Search for DM annihilation in dSphs
(Fermi-LAT collaboration 14)



A possible signal in the inner galaxy
(Daylan+14)



- ~ thermal cross section (m_χ ~ 35 GeV)
- spherical morphology
- inner DM profile steeper than CDM (adiabatic contraction)
- some models in tension with antiproton/positron data from PAMELA/AMS-02 (Bringmann+14)

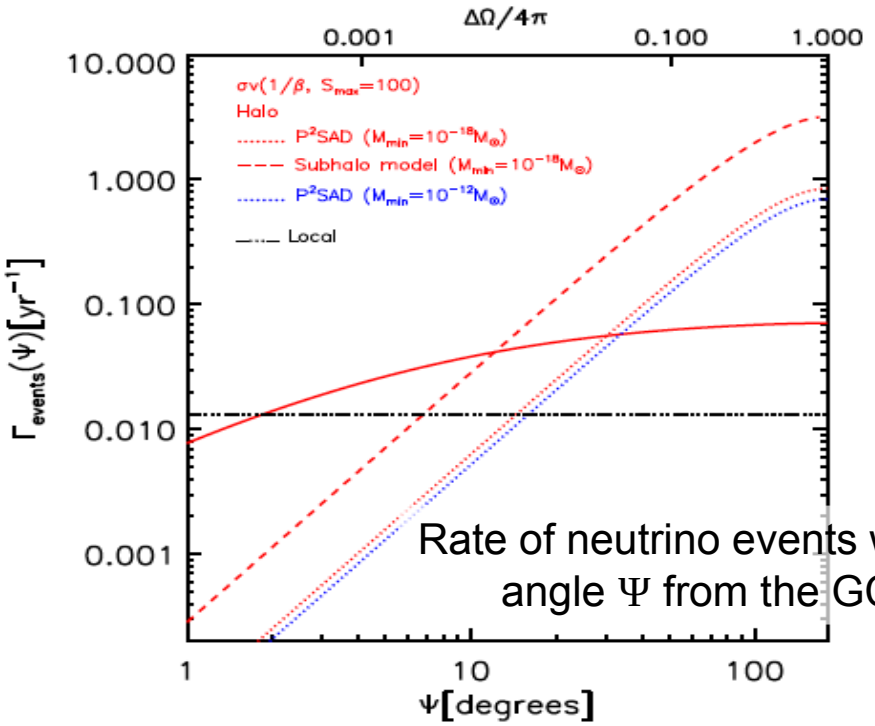
MW satellites

main "nuisance":
inner DM structure in dSphs

(PeV neutrinos as DM messengers)

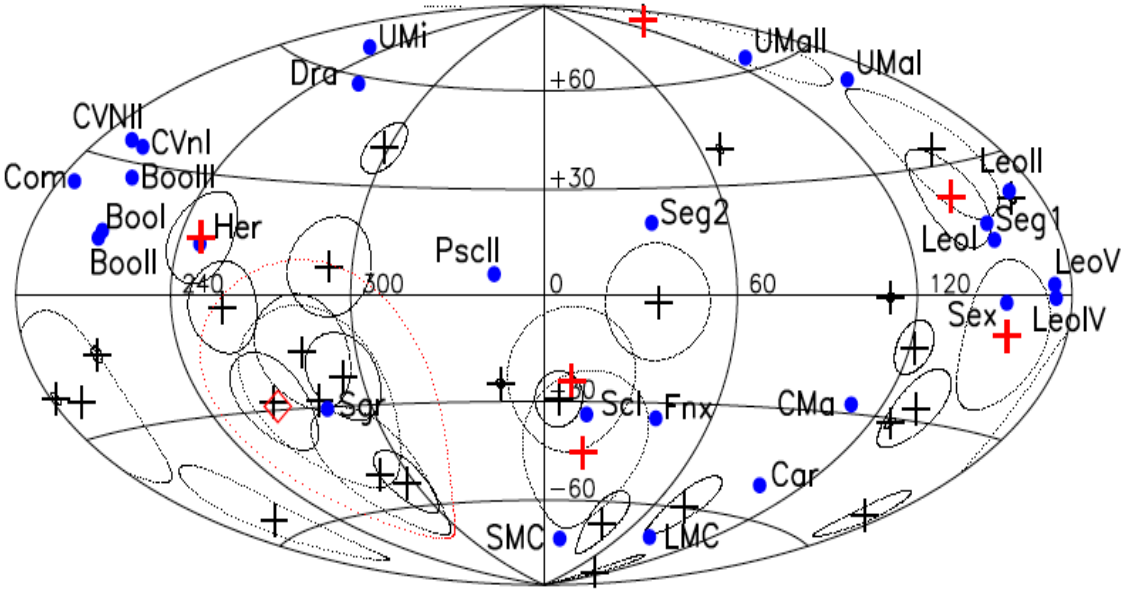
- IceCube discovery of high-energy cosmic neutrinos (including 3PeV events) (IceCube collaboration 13-14)

- **PeV DM is a possibility:**
  - **DM-decay e.g. Feldstein+13)**
  - **First proposal of DM-annihilation (Zavala 14)**



Rate of neutrino events within angle Ψ from the GC

Zavala 14 (arXiv:1404.2932)



IceCube cosmic neutrinos
MW satellites
coincident events

DM annihilation signal would be expected to show correlation with MW subhaloes

Intriguing, but random coincidence is likely

Structure formation in a non-CDM Universe

In the standard Cold Dark Matter paradigm
galaxies form in a purely gravitational DM background

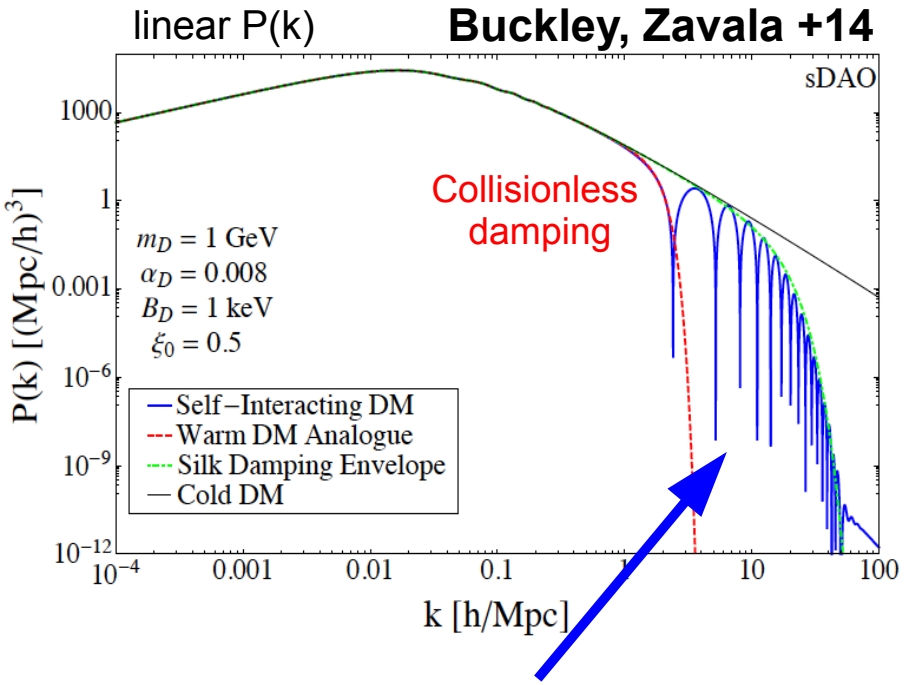
The nature of DM as a particle is therefore
irrelevant for galaxy formation and evolution

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

If DM is effectively warm and/or collisional then predictions
for DM signals need to consider the synergy between the
DM nature and structure formation

A richer DM (initial) power spectrum

Reducing small-scale power suppresses the formation of low-mass haloes and delays that of massive ones: WDM (e.g. Bode+01) CDM+interactions (e.g. Boehm+02)



Collisional damping:

e.g. photons (γCDM, Boehm+14), dark radiation (ADM, Cyr-Racine+13)

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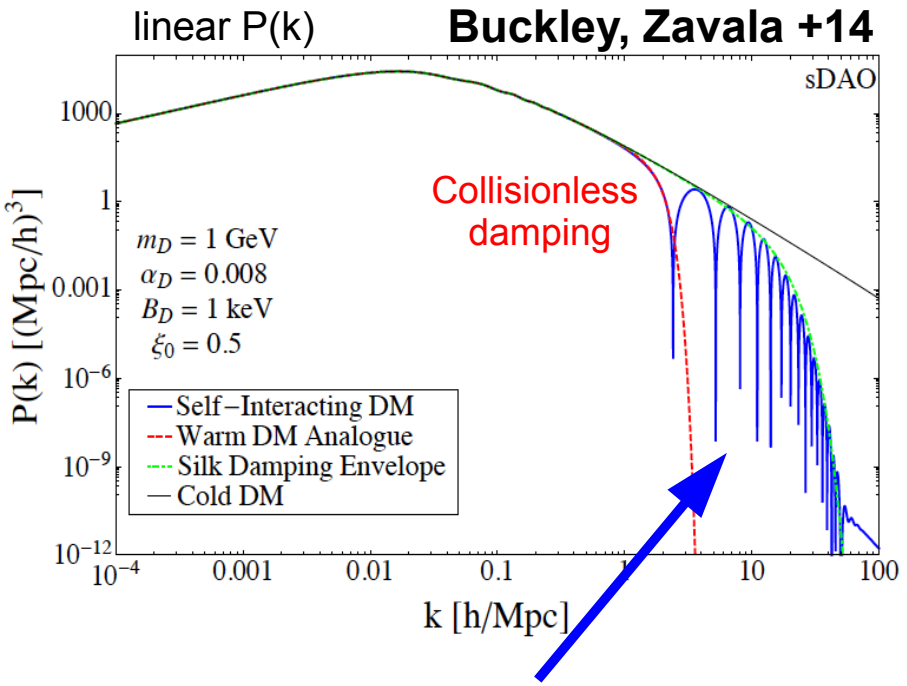

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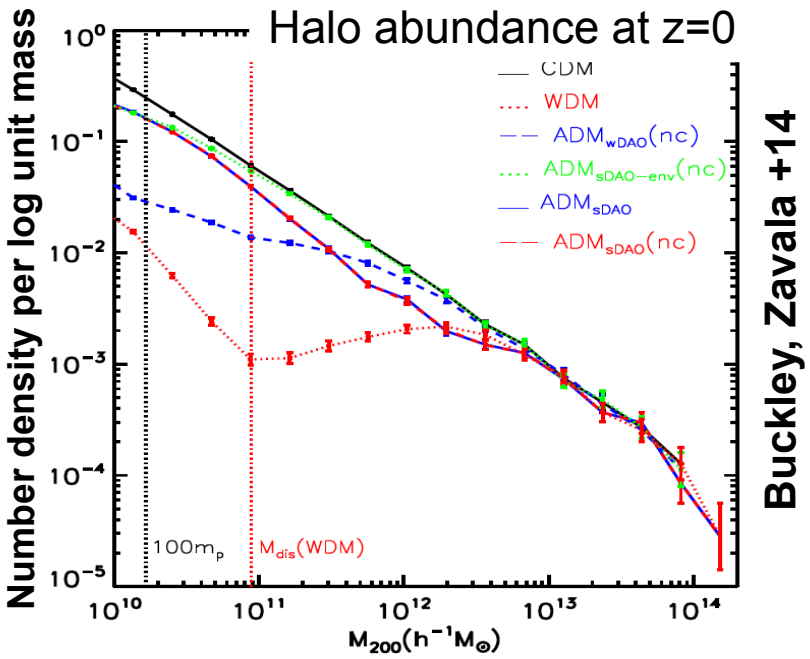
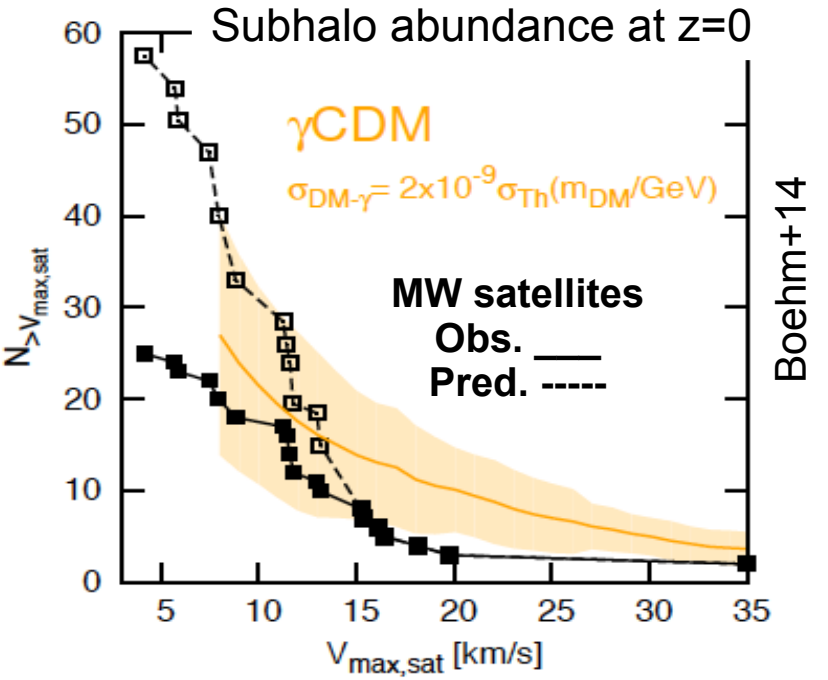
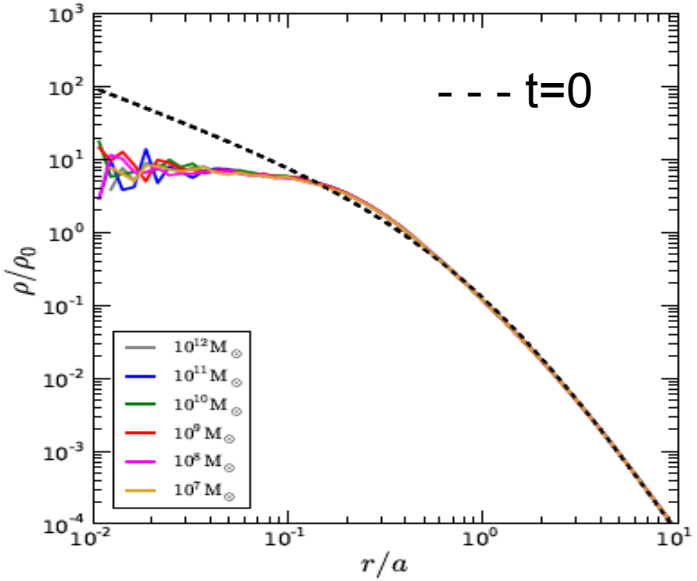
NON-LINEAR EVOLUTION (N-body simulations)

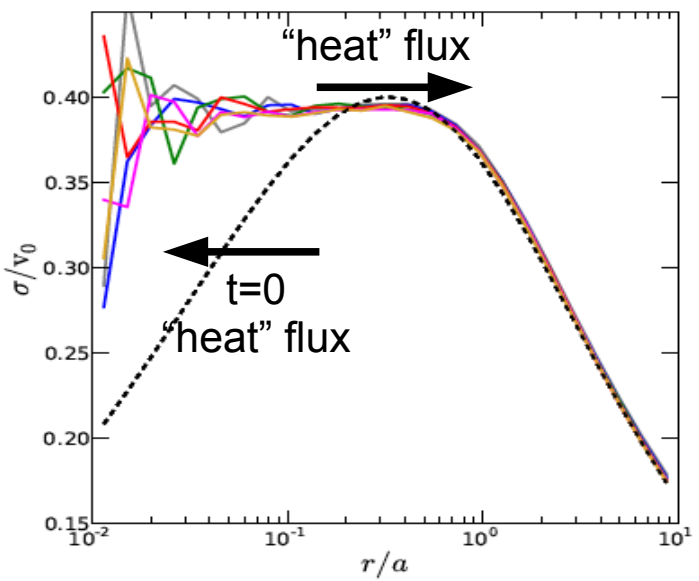




Structure formation in a SIDM Universe

SIDM haloes develop an isothermal (MB) core





Collisional Boltzmann equation

$$\frac{df}{dt} = C[f, \sigma_{\rm sc}]$$

$$\rightarrow \qquad \frac{d\rho_\chi}{dt} \sim -\rho_\chi^2 \left(\frac{\sigma_{\rm sc}}{m_\chi}\right) \sigma_{\rm vel}$$

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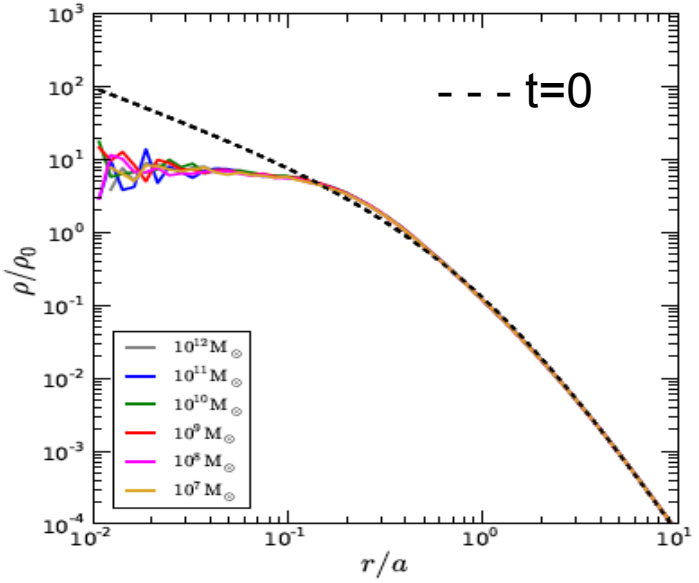

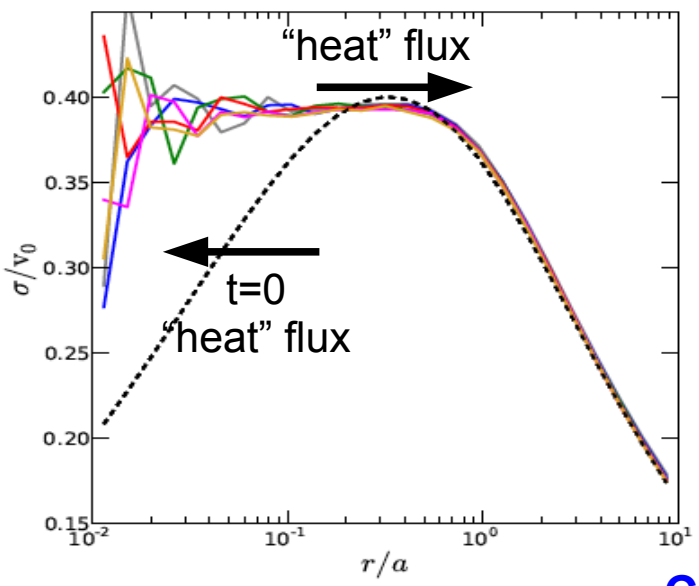

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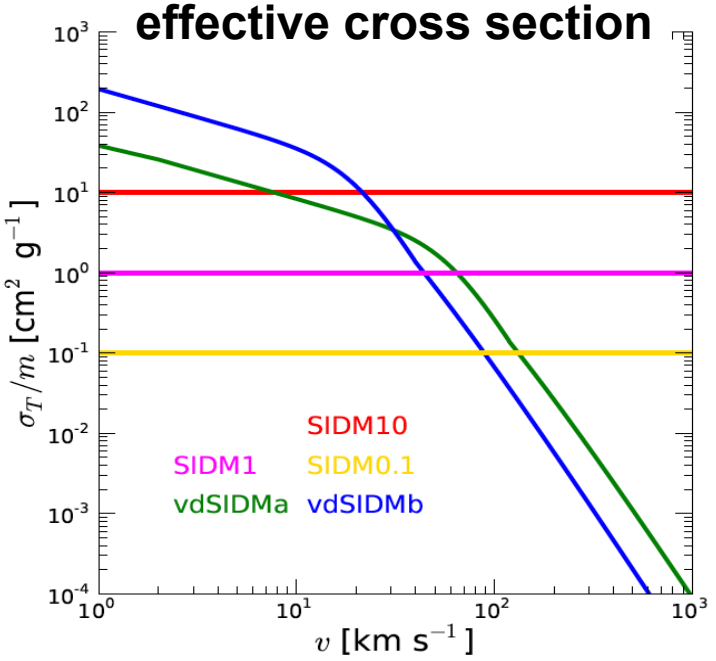
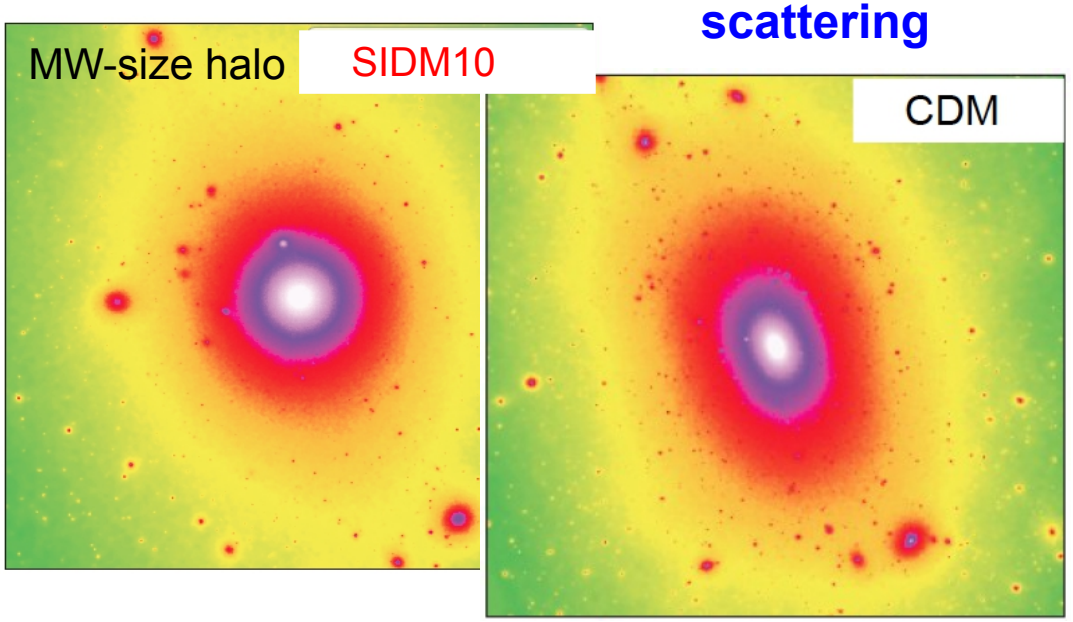
Vogelsberger, Zavala & Loeb 12

effective cross section



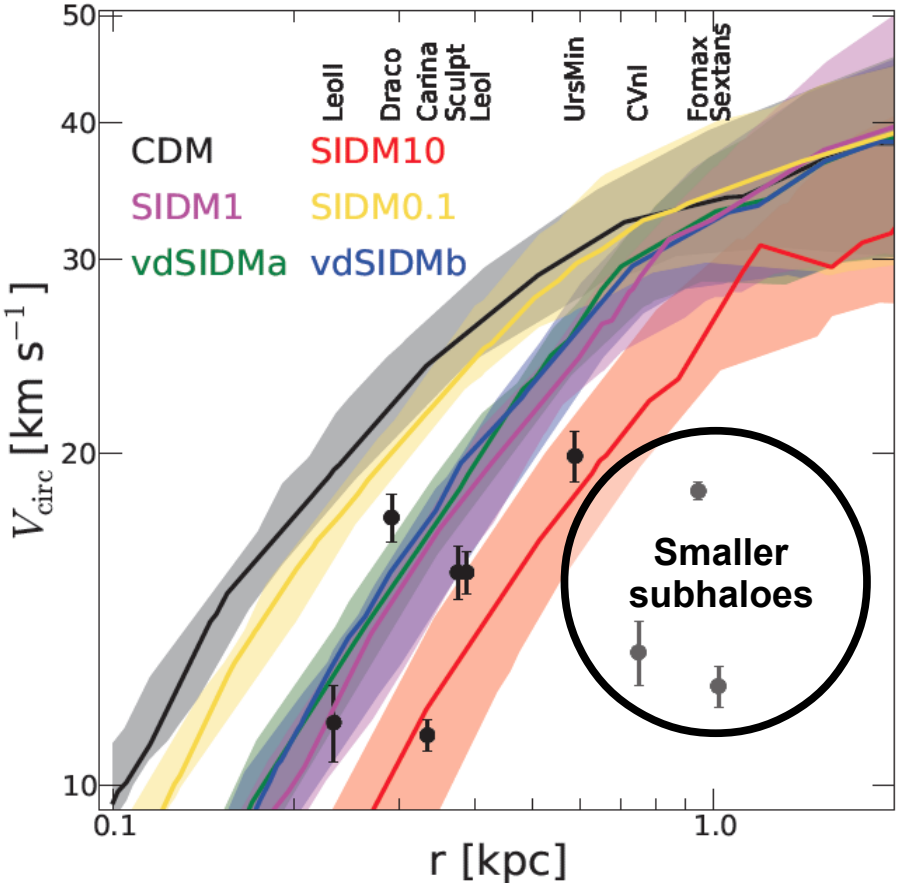
Cosmological Simulations with gravity + elastic scattering



Structure formation in a SIDM Universe

The dark satellites of a MW-size halo DM-only simulation

Zavala, Vogelsberger & Walker 13



Allowed SIDM models do not have the inner structure "problems" of CDM

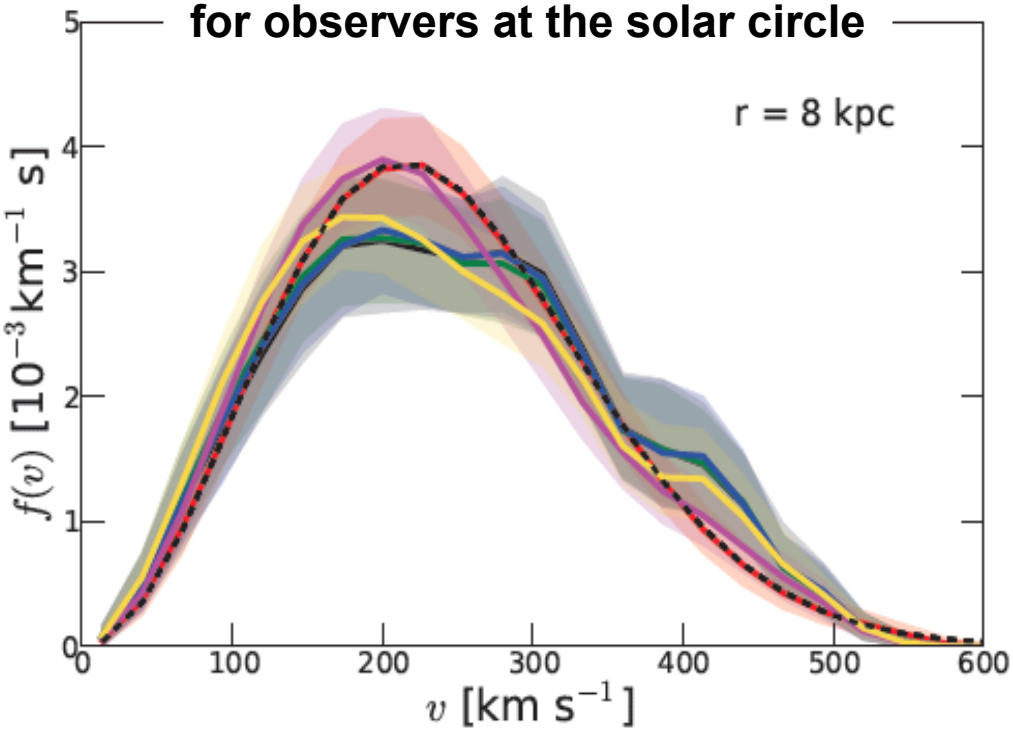
SIDM only works as a ***distinct DM-only*** alternative to CDM

if 0.6 cm^2/g < σ / m < 1 cm^2/g

or velocity-dependent

DM self-scattering affects predictions from direct detection experiments (~20% effect)

"Local" DM velocity distribution for observers at the solar circle



Concluding remarks

- decisive decade for the “standard” DM model (CDM + WIMPs):
  experiments reaching the “expected” WIMP cross sections (Fermi, LUX,...)

- potential signals must be examined with a multidisciplinary approach:
  - consistency with multi-epoch astrophysical observations
  - theoretically viable in particle physics models

- absence of signals and/or inconsistency with CDM might lead
  to a paradigm shift

- astrophysical constraints are weak enough for the DM nature to play
  a major role in the formation and evolution of galaxies

- **the central structure of DM haloes might hide a clue of a fundamental guiding principle for a complete DM theory**

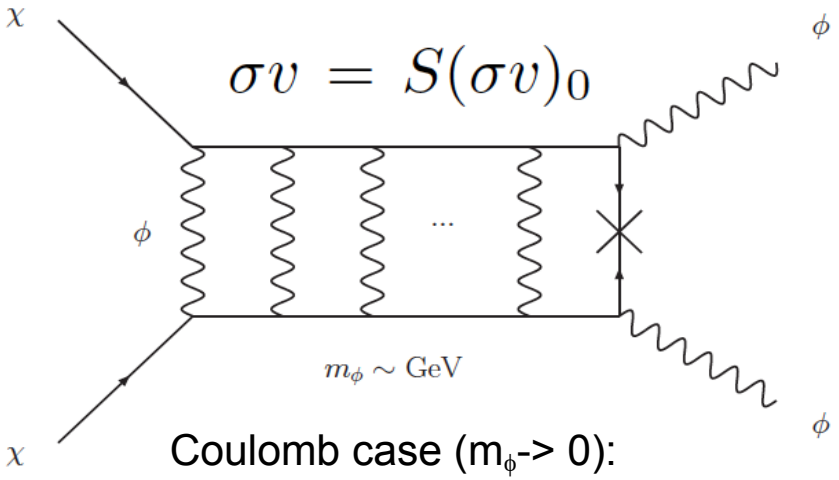
EXTRA SLIDES

Relic density constraints (example: thermal Sommerfeld-enhanced)

Collisional Boltzmann equation: $$\frac{\mathrm{d}n_\chi}{\mathrm{d}t} + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - \left(n_\chi^{EQ}\right)^2\right)$$

$$\langle\sigma v\rangle = \langle\sigma v\rangle_S \mathcal{S}(x) \qquad \boxed{\mathcal{S}(x) \propto x^{1/2} \propto \sigma_v^{-1}}$$

Sommerfeld-enhanced annihilation
(e.g. Hisano +04, Arkani-Hamed +09)



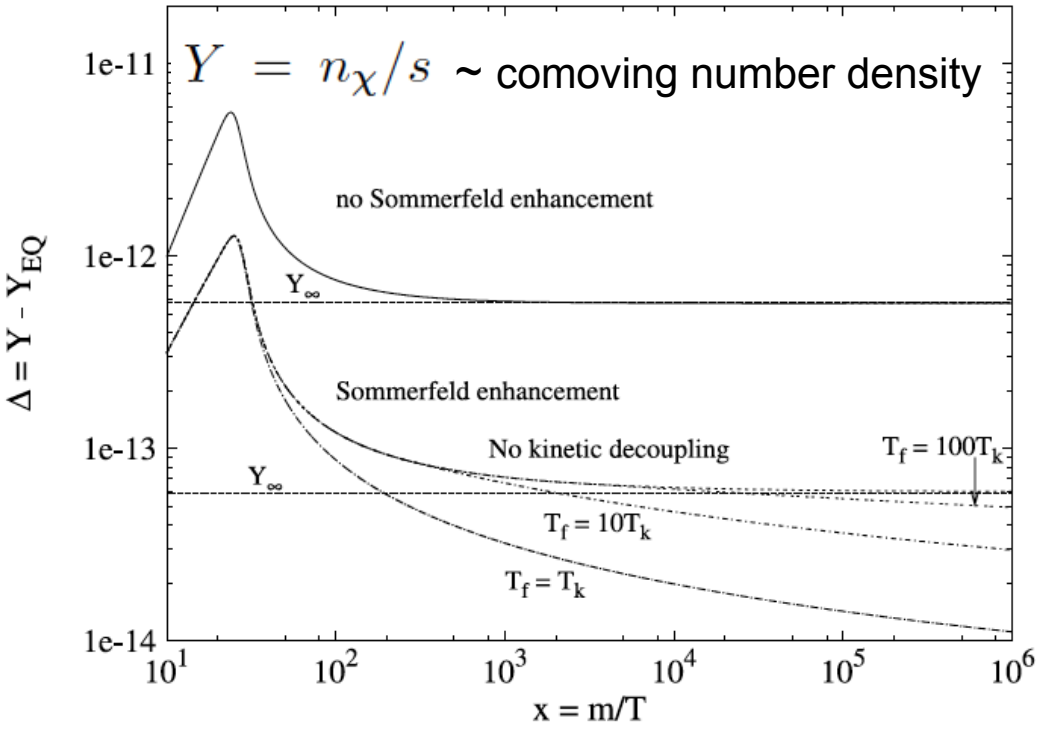
$$\sigma v = S(\sigma v)_0$$

Coulomb case (m_ϕ-> 0):

$$S = \frac{\pi\alpha_c}{\beta}\left(1 - e^{-\pi\alpha_c/\beta}\right)^{-1}$$

$$\boxed{S(\beta) \propto 1/\beta \quad \text{if} \quad \beta \ll \pi\alpha_c}$$

β = relative velocity



$$\mathrm{BF} = \frac{\langle\sigma v\rangle_0^{\Omega_{DM}} S(\sigma_{\mathrm{vel,h}})}{3\times10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}} \lesssim 100$$

In the MW-halo today **Zavala+10**, Feng+10

Relic density constraints (example: thermal Sommerfeld-enhanced)

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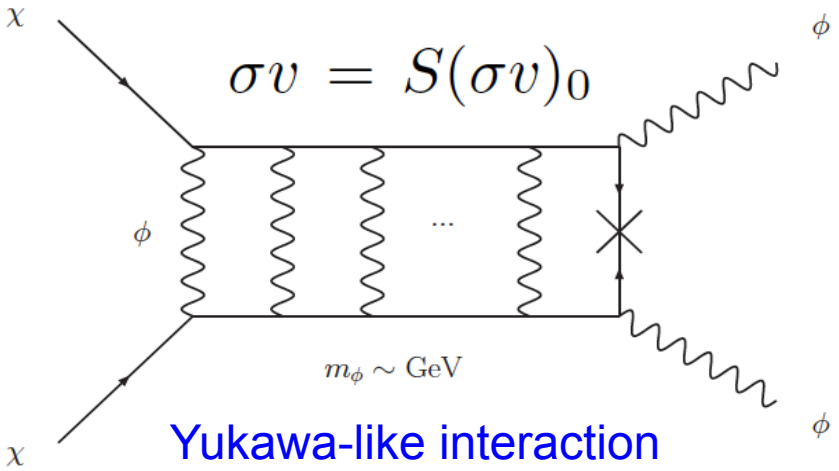
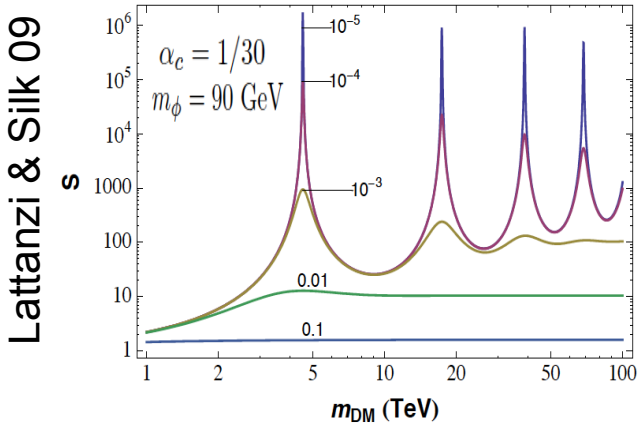
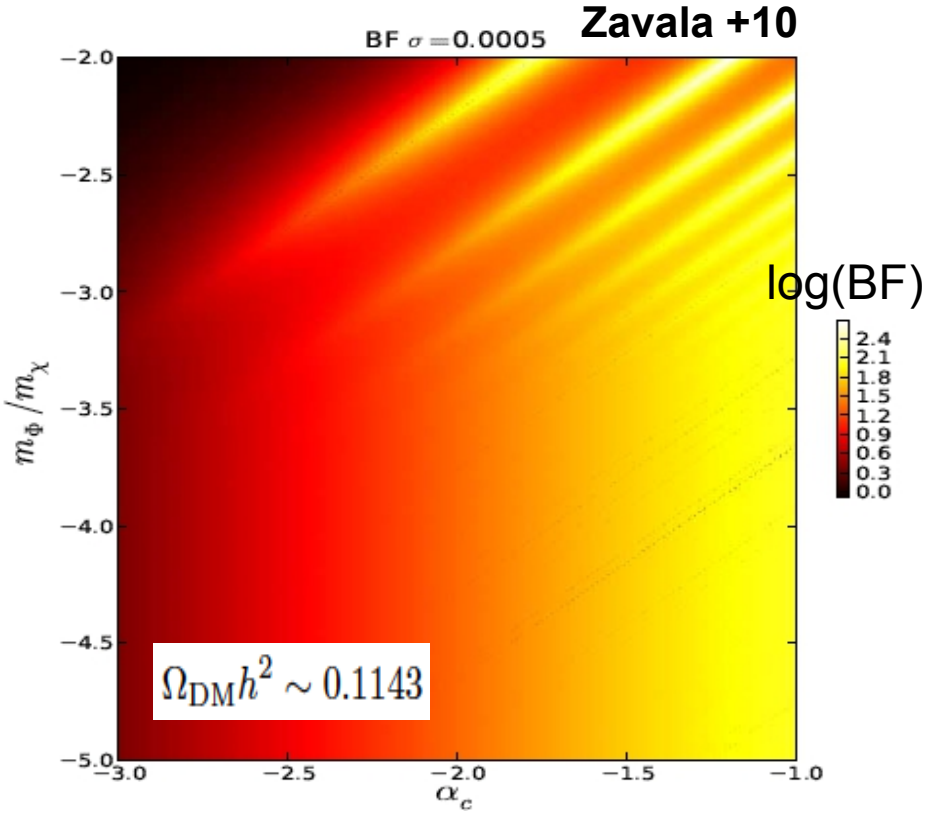


Yukawa-like interaction



Zavala +10

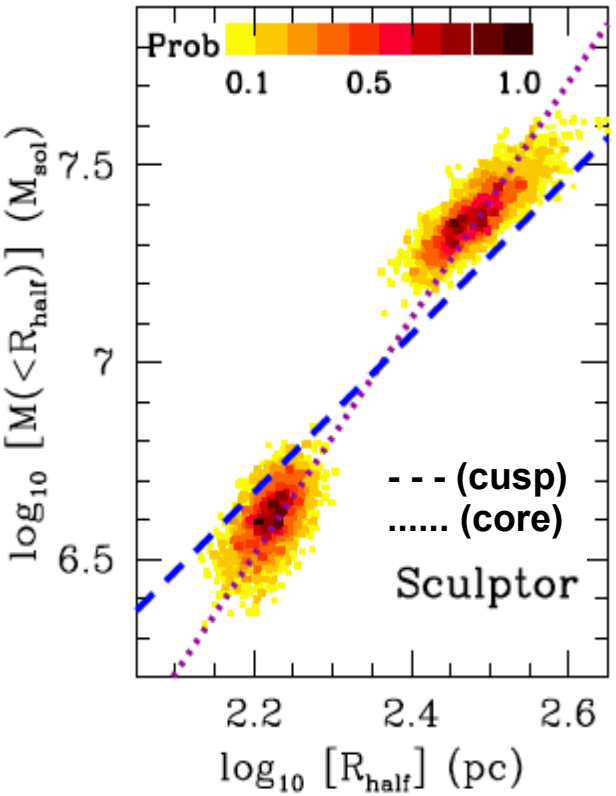


$$\mathrm{BF} = \frac{\langle\sigma v\rangle_0^{\Omega_{DM}} S(\sigma_{\mathrm{vel,h}})}{3\times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}} \quad < 300$$

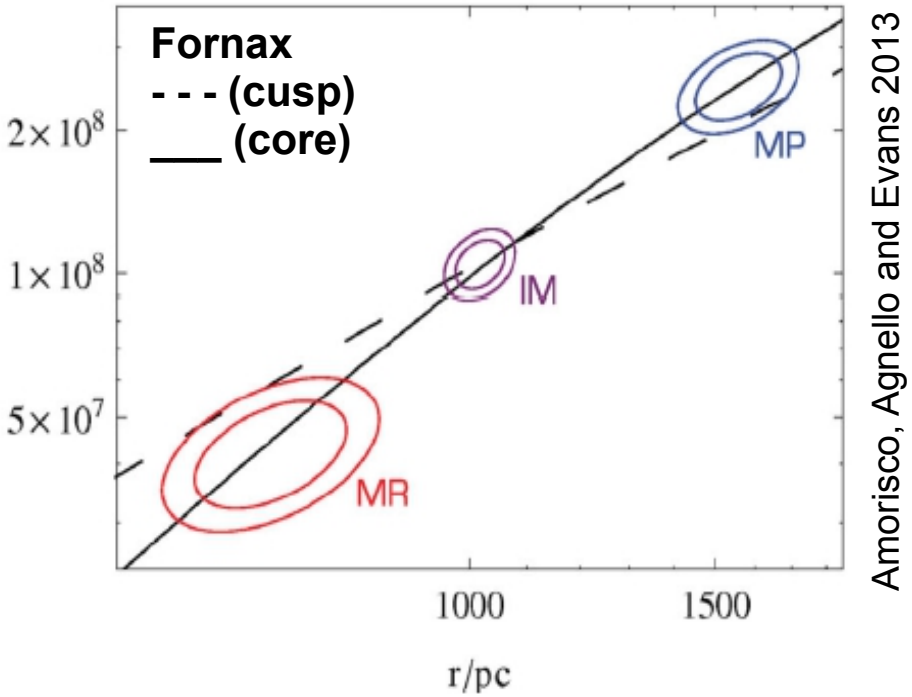
Zavala+10, Feng+10

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



Amorisco, Agnello and Evans 2013

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!!