Self-Interacting and Warm Dark Matter at the scale of dwarf galaxies

Jesús Zavala Franco
(Marie Curie Fellow)

Dark Cosmology Centre

Main SIDM results in collaboration with:

Mark Vogelsberger (MIT, Cambridge)
Abraham Loeb (ITC, Cambridge)
Matt Walker (Carnegie Mellon University, Pittsburgh)

UCLA DM 2014, February 2014

Opening remarks

There is no indisputable evidence that the Cold Dark Matter (CDM) paradigm is wrong, but there are reasonable astrophysical motivations to consider alternatives:

Incomplete knowledge of the DM nature: are non-gravitational DM interactions irrelevant for galaxy formation?

Opening remarks

There is no indisputable evidence that the Cold Dark Matter (CDM) paradigm is wrong, but there are reasonable astrophysical motivations to consider alternatives:

Incomplete knowledge of the DM nature: are non-gravitational DM interactions irrelevant for galaxy formation?

Cross section σ/m_χ [cm^2/gr]	Characteristic velocity $\tilde{v}$ [km/s]
SI $\chi-$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)

← **DM-nuclei scattering (reaching minimal SUSY parameter space)**

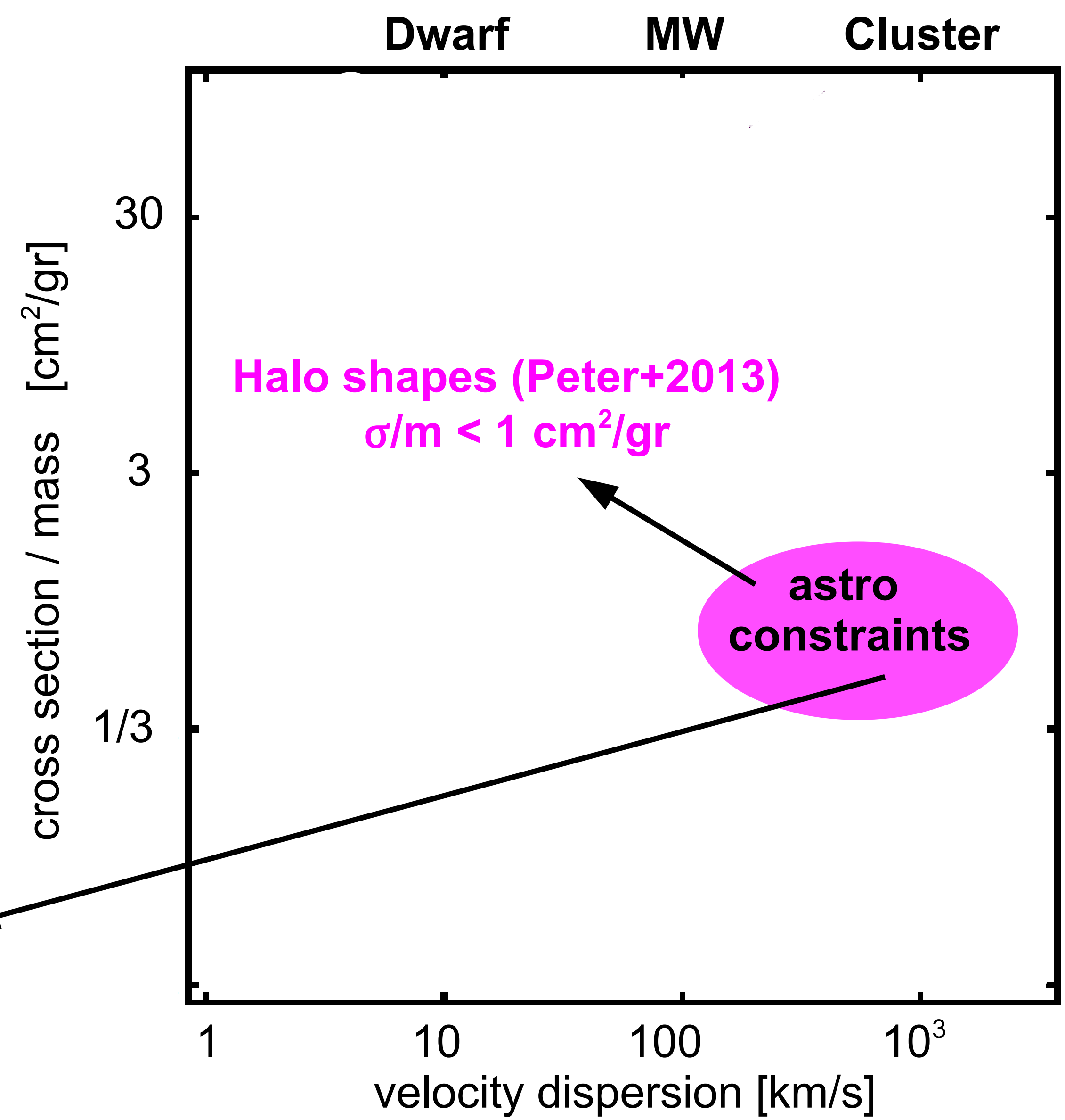
← **DM self-annihilation (reaching thermal relic value)**

annihilation and nuclei scattering are too small to impact galaxy formation!!

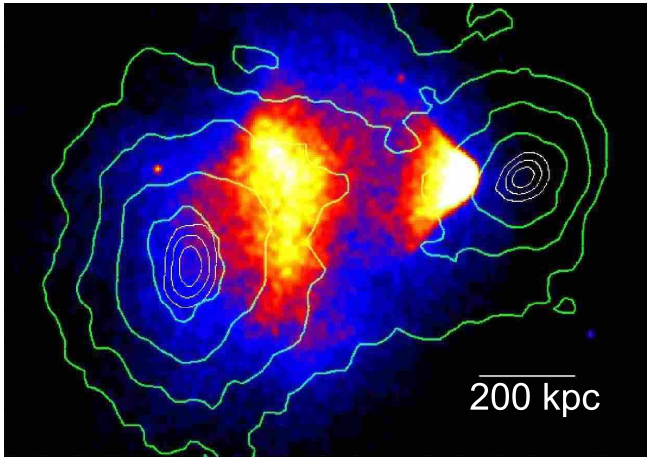
Opening remarks

Incomplete knowledge of the DM nature: are non-gravitational DM interactions irrelevant for galaxy formation?

What about DM self-scattering?



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



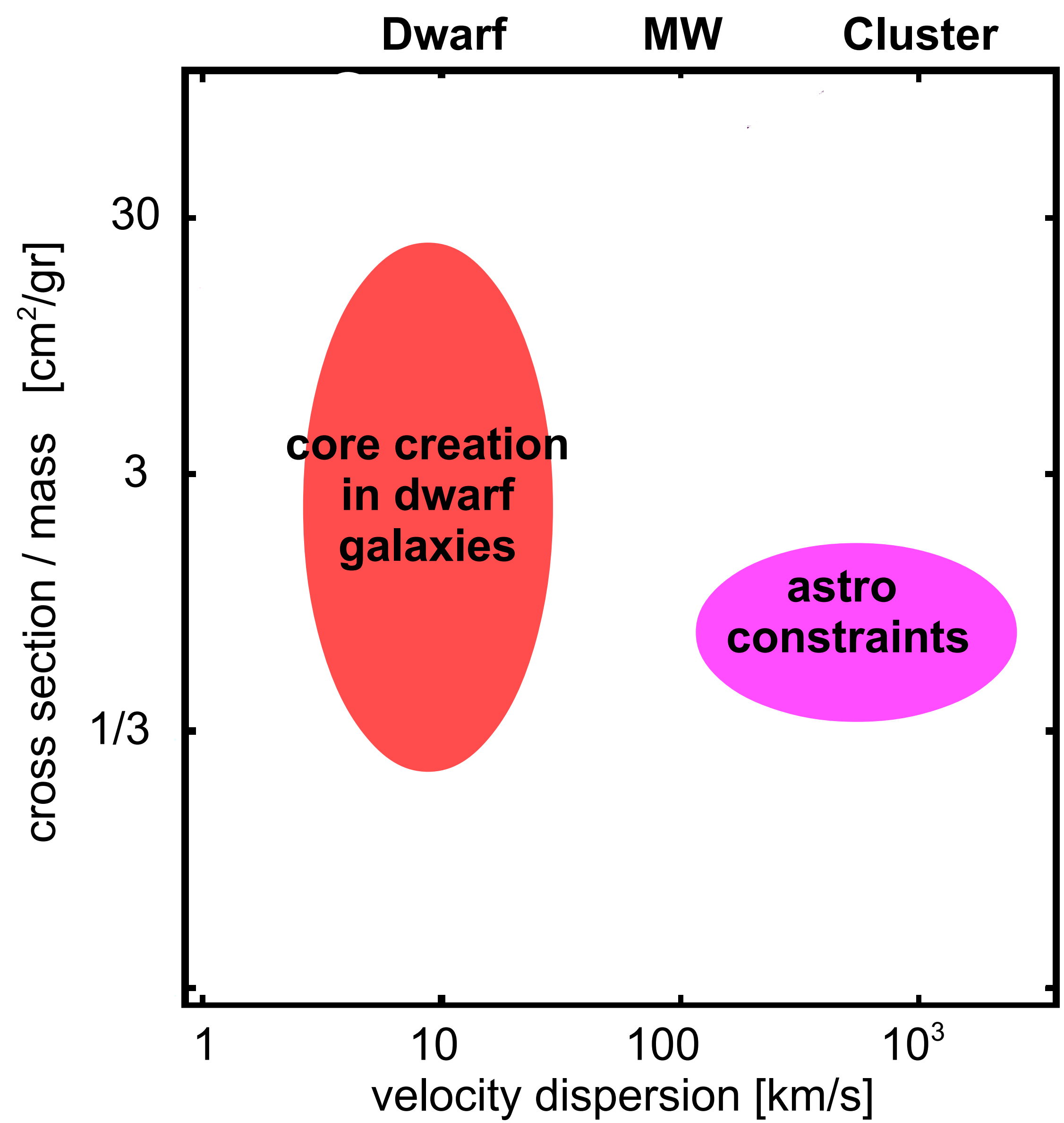
Opening remarks

Incomplete knowledge of the DM nature: are non-gravitational DM interactions irrelevant for galaxy formation?

Constraints allow collisional DM that is astrophysically significant

~ <1 scatter/particle/t_H>

DM phase-space distribution changes

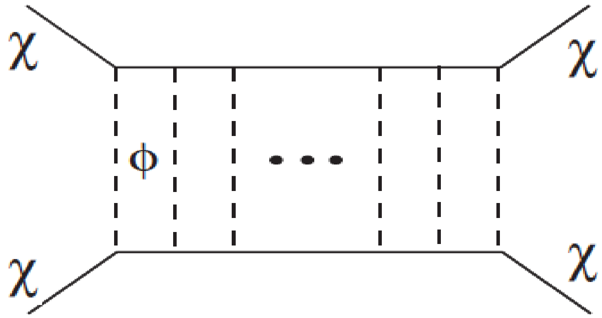


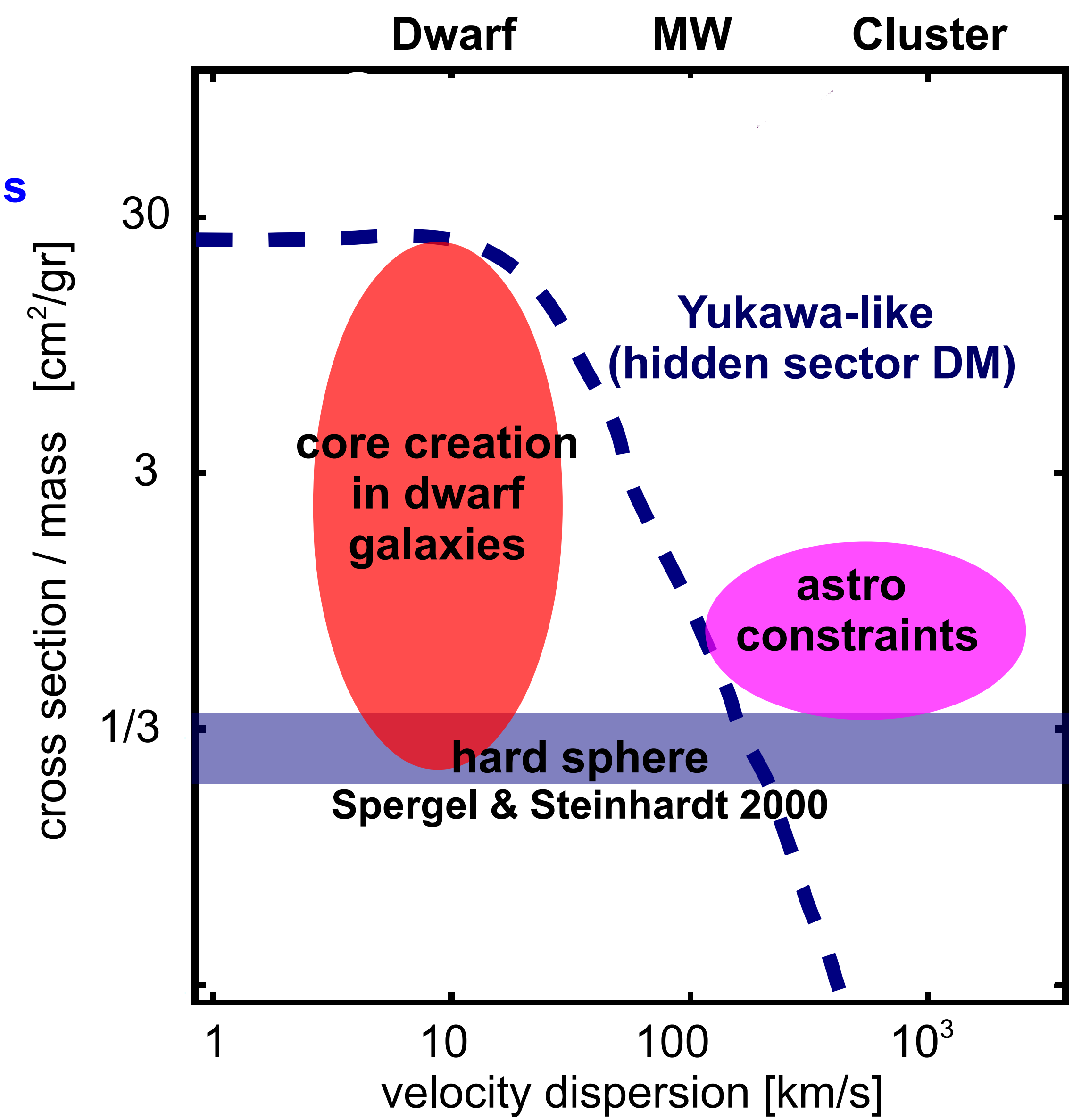
Opening remarks

Incomplete knowledge of the DM nature: are non-gravitational DM interactions irrelevant for galaxy formation?

Several particle physics models can introduce significant DM collisions

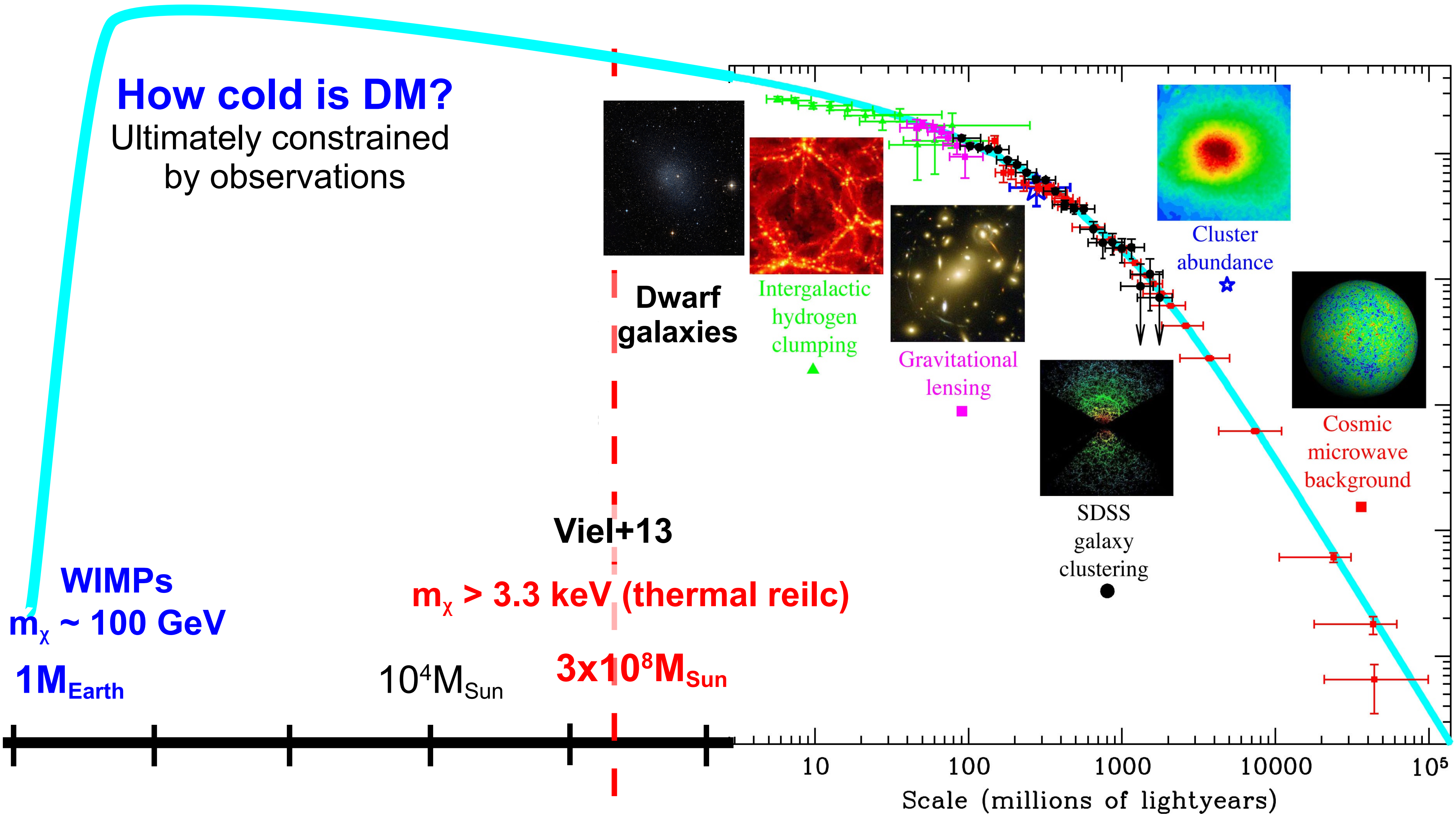
vdSIDM models motivated by a new force in the "dark sector", e.g. Yukawa-like, Feng+09





Opening remarks

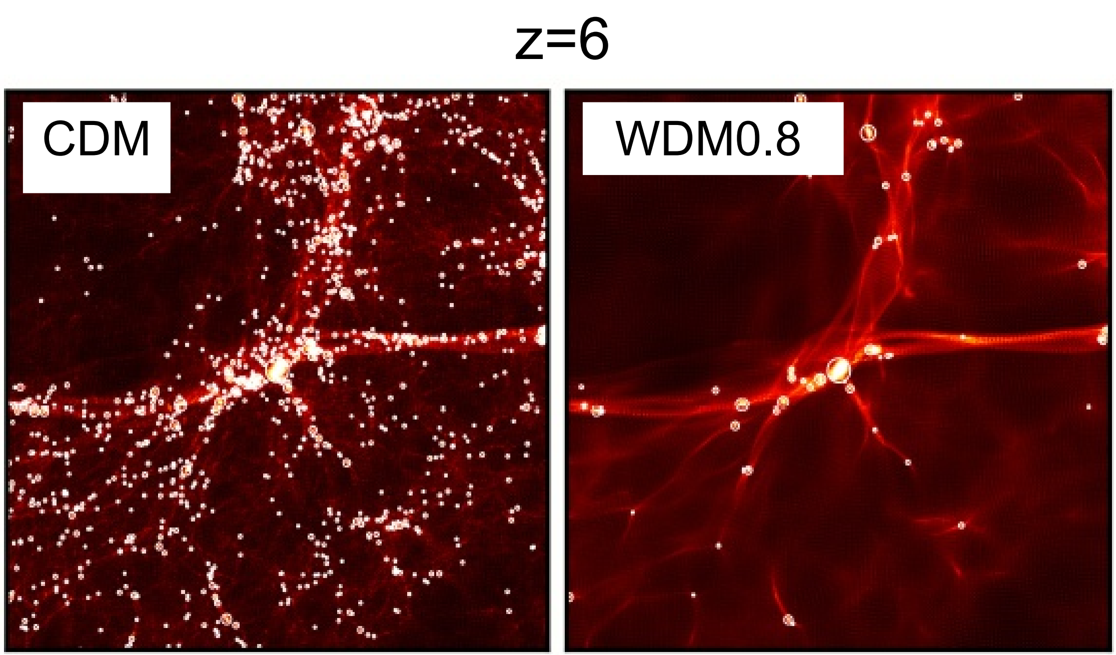
Incomplete knowledge of the DM nature: is the minimum scale for galaxy formation set by the DM nature or by gas physics (or by both)?



Opening remarks

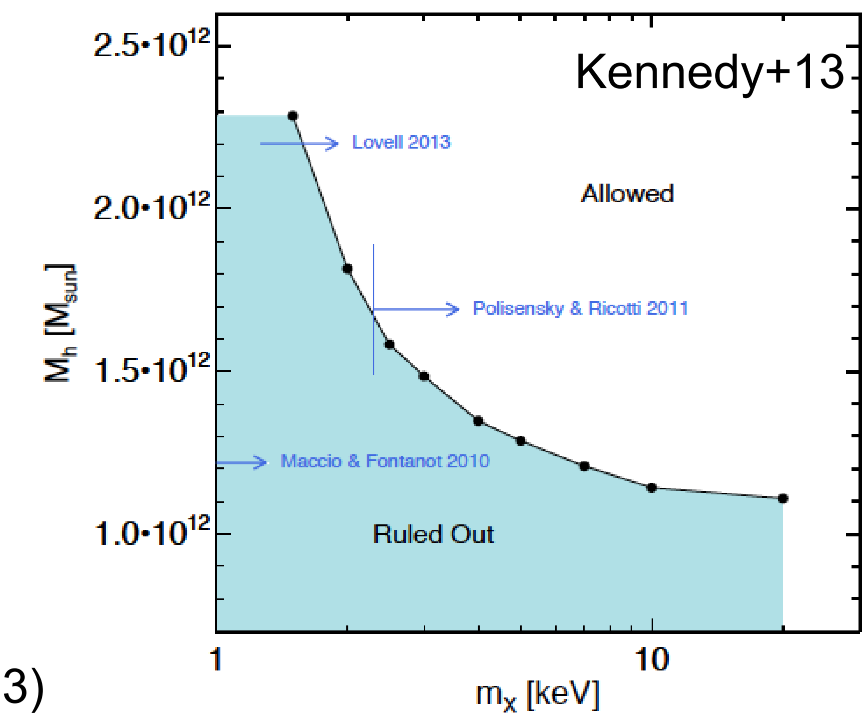
Incomplete knowledge of the DM nature: is the minimum scale for galaxy formation set by the DM nature or by gas physics (or by both)?

Ly-α forest constraints are sensitive to assumptions on the thermal history. Consider other independent constraints.



Galaxy counts at high redshift (m_χ > 1.3 keV, Schultz+13)

MW-satellite counts

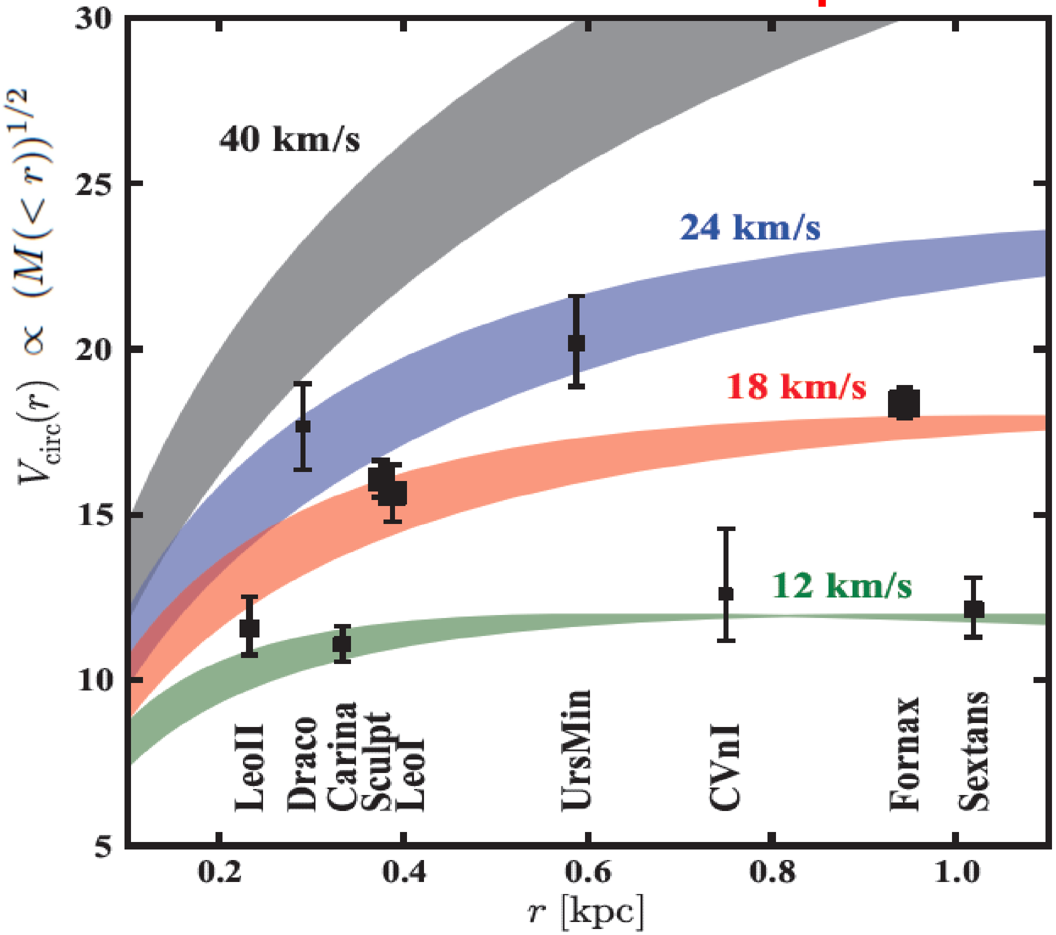


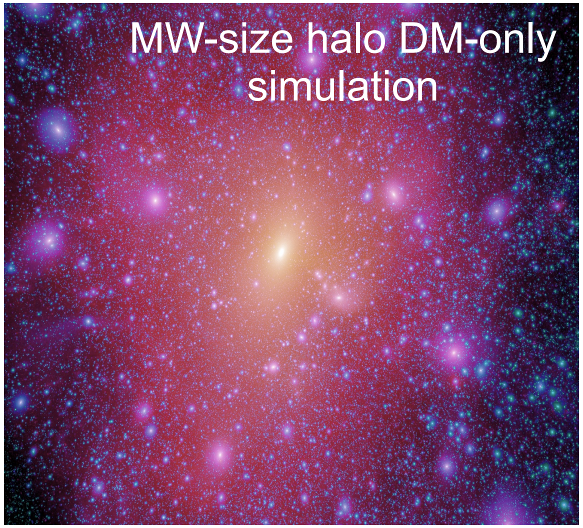
Also, subhalo-satellite counts on M31 (m_χ > 1.8 keV, Horiuchi+13)

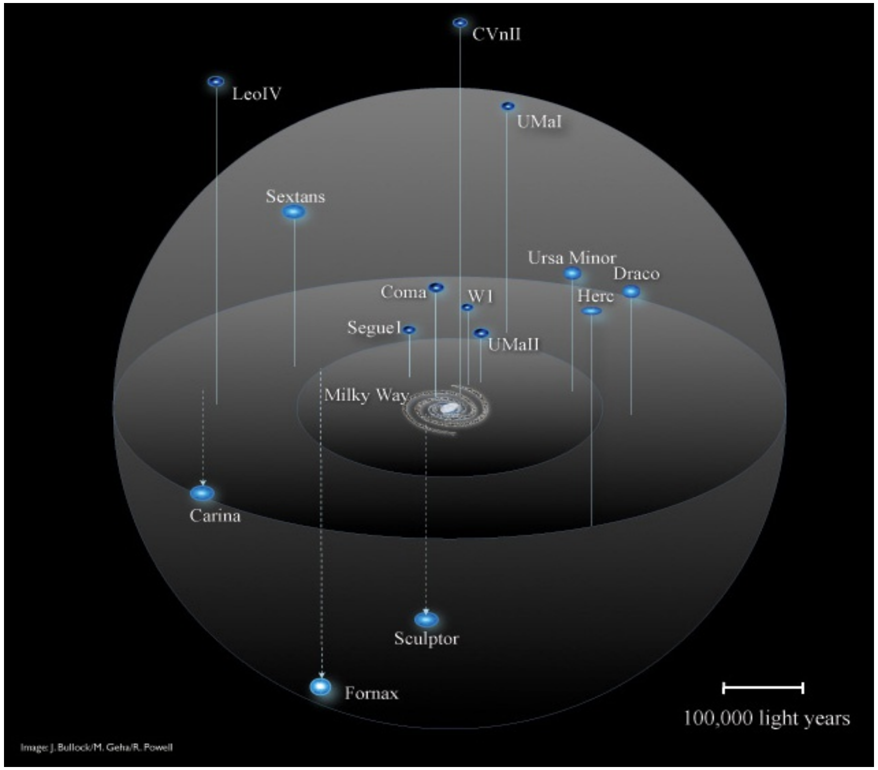
Opening remarks

There is no indisputable evidence that the Cold Dark Matter (CDM) paradigm is wrong, but there are reasonable astrophysical motivations to consider alternatives: dwarf-scale "challenges"

Opening remarks



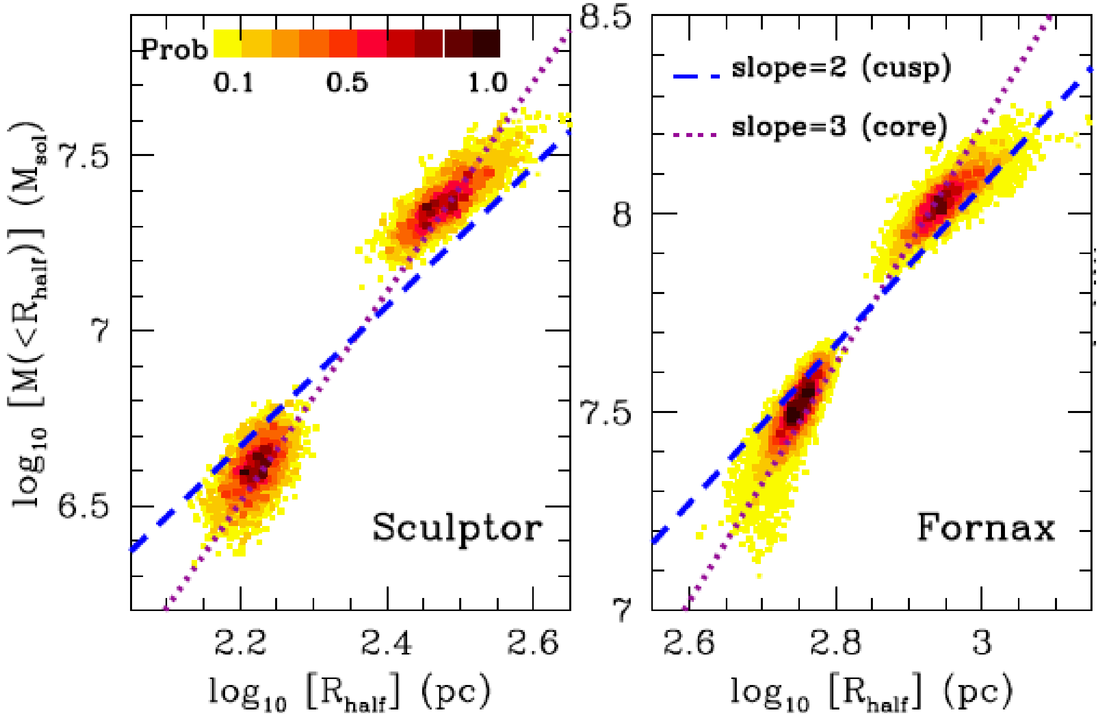




The most massive CDM-MW-subhaloes seem to be too centrally dense to host the MW dSphs

Opening remarks

The core-cusp problem



Walker & Peñarrubia 11

Different stellar subcomponents provide an estimate of the slope of the mass Profile (e.g.Walker & Peñarrubia 11, Amorisco+13): **cores seem to be favoured over cusps**

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

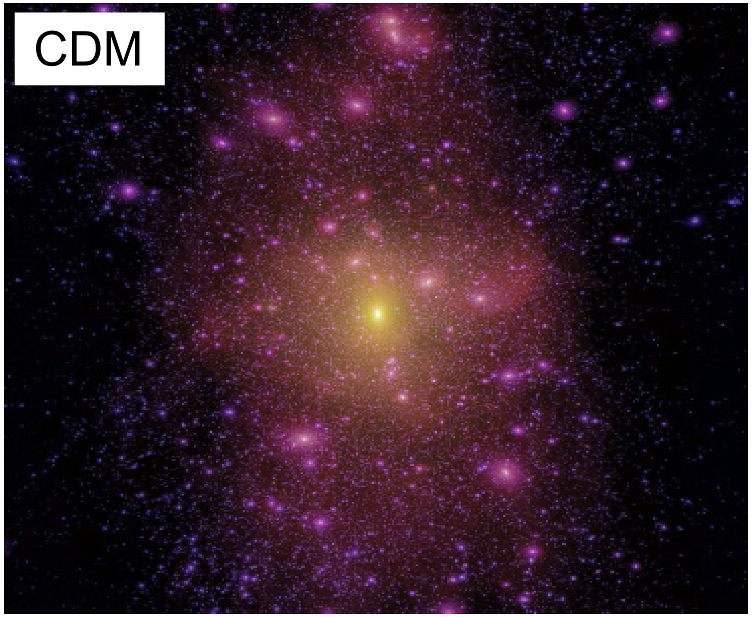
Opening remarks

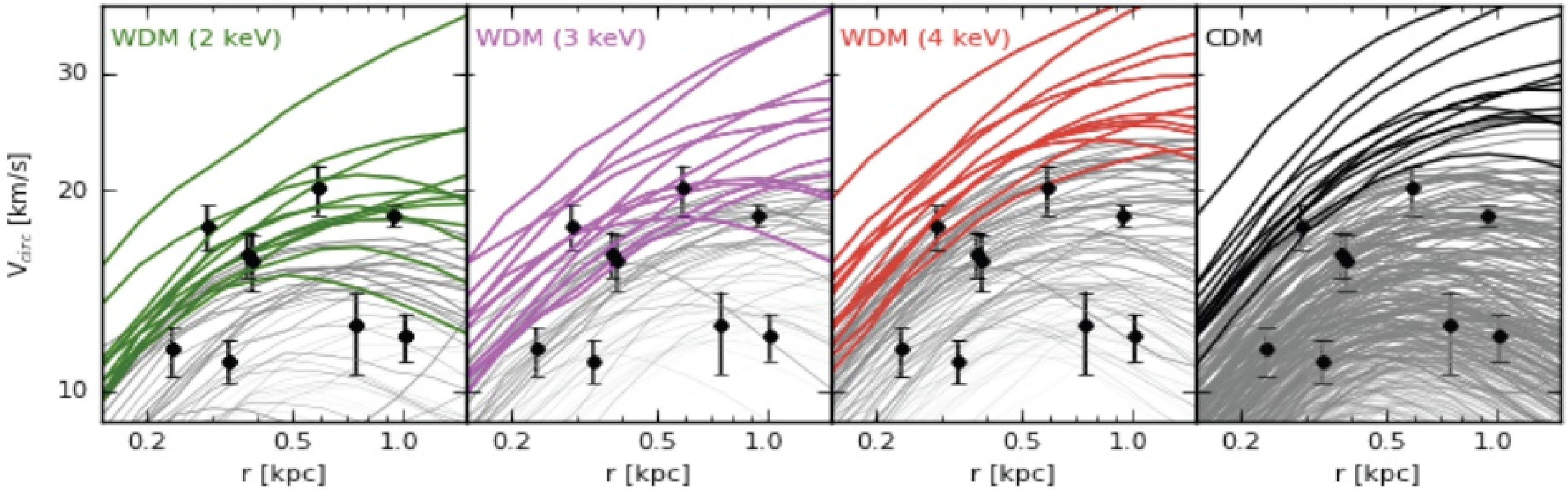
There is no indisputable evidence that the Cold Dark Matter (CDM) paradigm is wrong, but there are reasonable astrophysical motivations to consider alternatives: dwarf-scale “challenges”

- These challenges could be related to:
  - **Misinterpretation of observational data** (incomplete reconstruction of the phase-space distribution, low MW-halo mass,...)
  - **Incomplete knowledge of galaxy formation** (energy injection into the DM halo by feedback, environmental effects like tidal stripping,...)
  - **New DM physics**:
    - DM might be warm: WDM (e.g. sterile neutrinos)
    - DM might be **collisional**: SIDM (e.g. hidden sector DM)

DM distribution in WDM subhaloes

MW-size halo simulations (Lovell+12, Schneider+13)





Narrow window for WDM models to solve the TBTF problem:
only if P(k) has a sharp cutoff + strongly dependent on MW halo mass!!

Cores in WDM haloes?

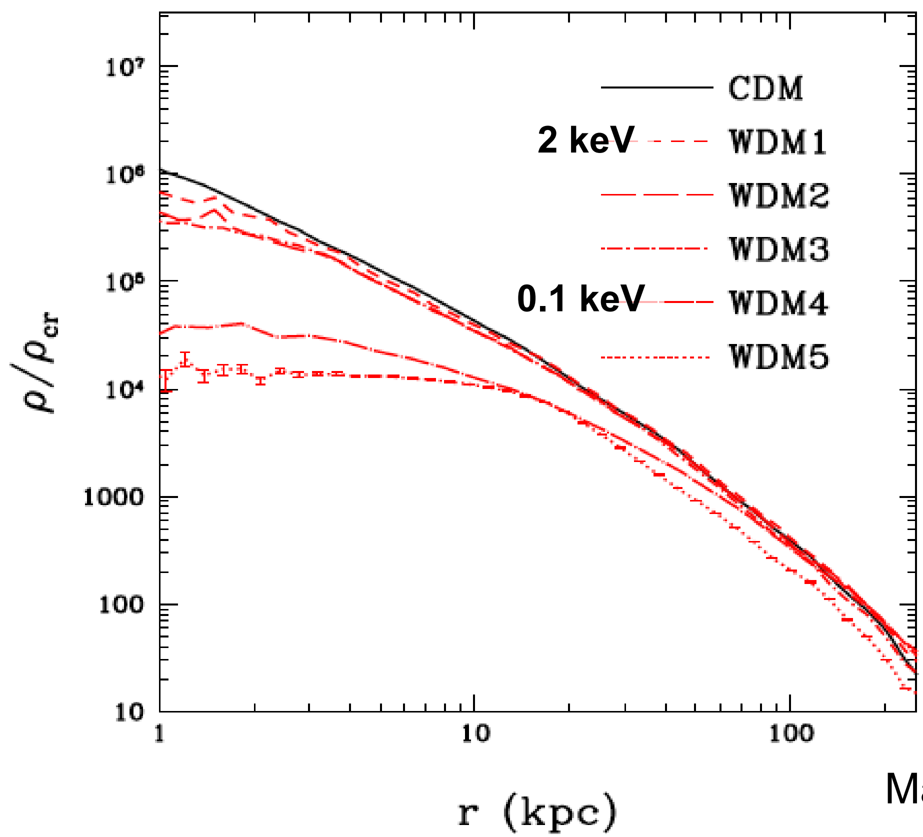
Coarse-grained
pseudo phase-space density:

$$Q = \rho/\sigma^3$$

Thermal velocities at decoupling set a maximum value to Q that translates into a typical core radius today

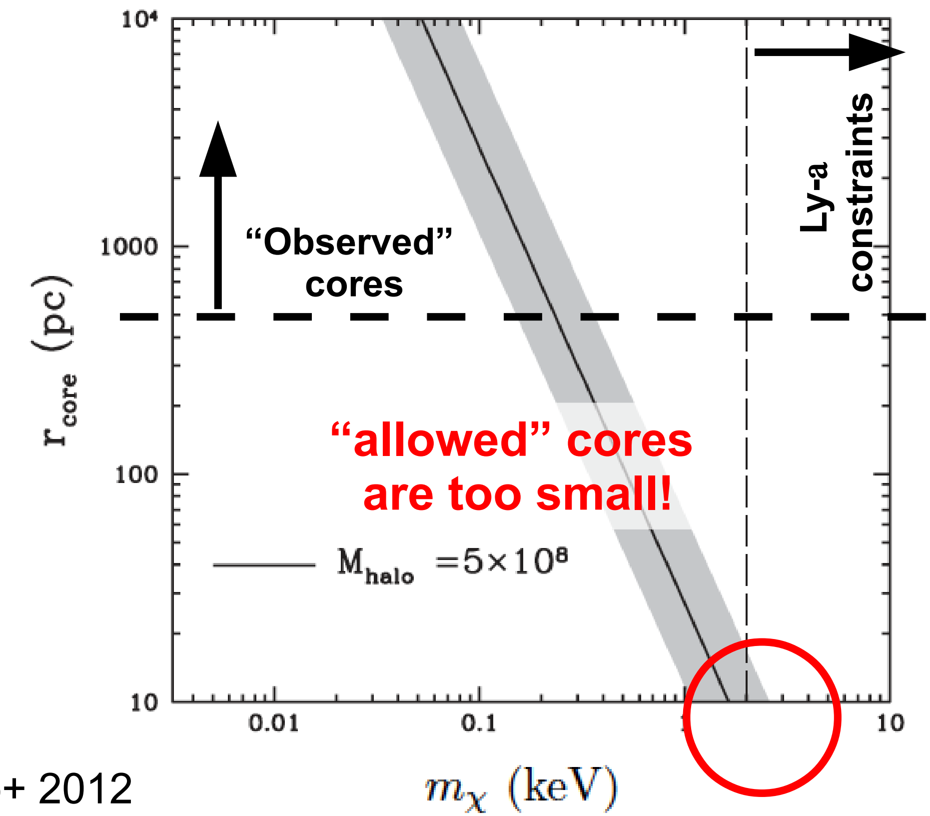
$$Q_{\max} \propto m_\chi^4 \qquad r_c^2 \propto (Q_{\max}\sigma_c)^{-1}$$

MW halo (sim)



Maccio+ 2012

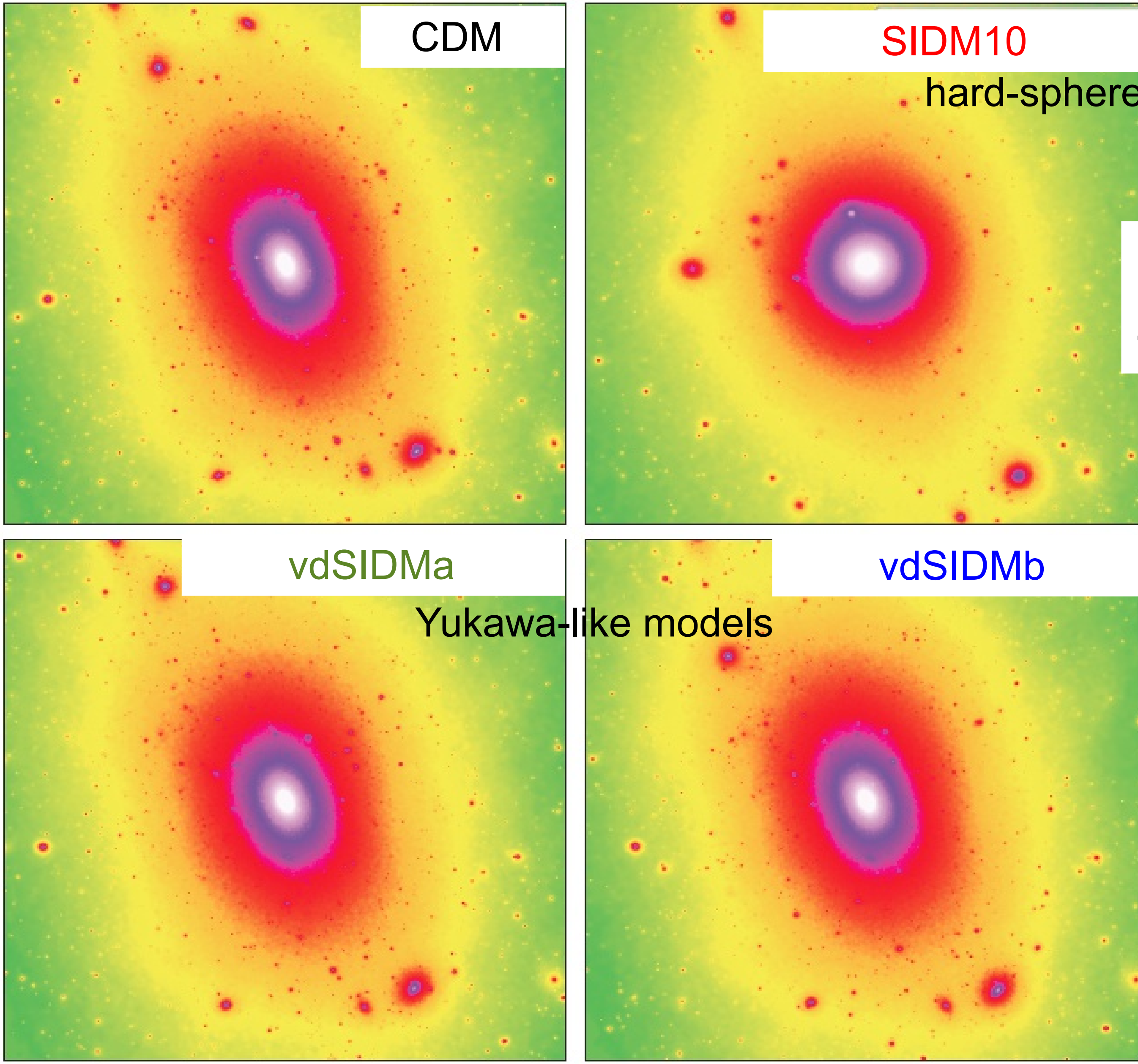
Typical MW subhalo (estimate)



Allowed WDM models have lower concentrations but NFW-like profiles

SIDM *N*-body simulations

MW-size halo (same ICs from Aquarius)
Vogelsberger, Zavala & Loeb 2012



Gravity + Probabilistic method for elastic scattering

Resolution

$m_p[M_\odot]$	ϵ[pc]
4.911×10^4	120.5

$M_{200}[M_\odot]$	r_{200}[kpc]
1.836×10^{12}	245.64

Another group has also been very active in recent SIDM sims: (see Rocha+13)

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

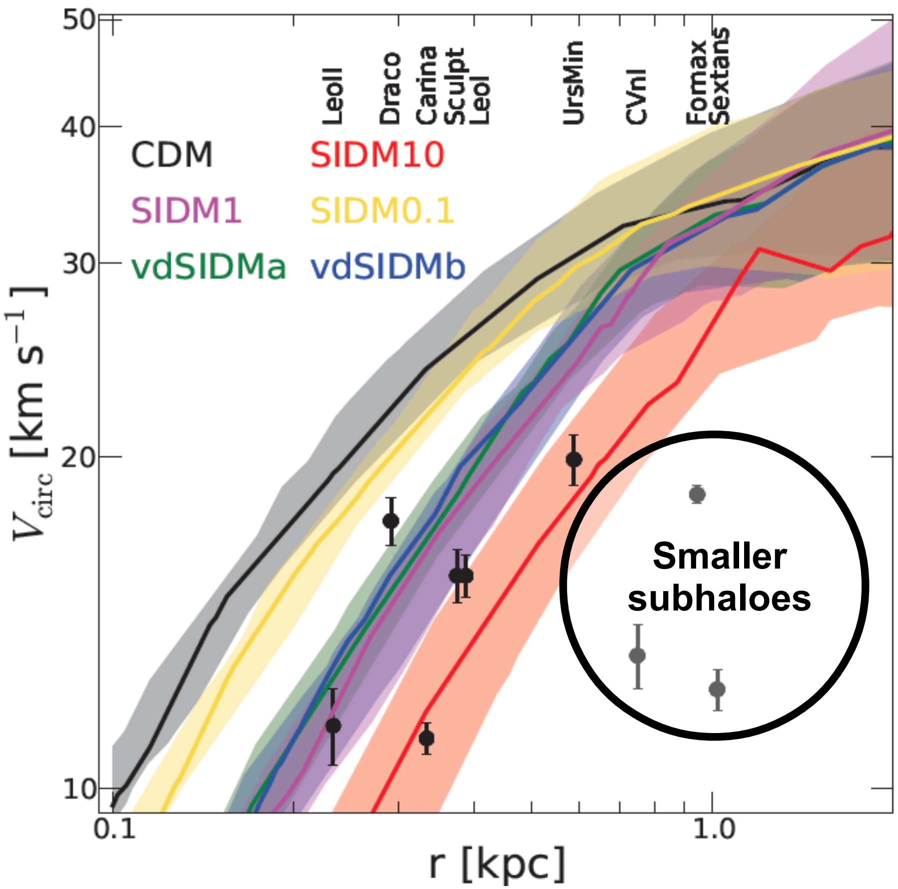
Key results: densities of MW-like subhaloes

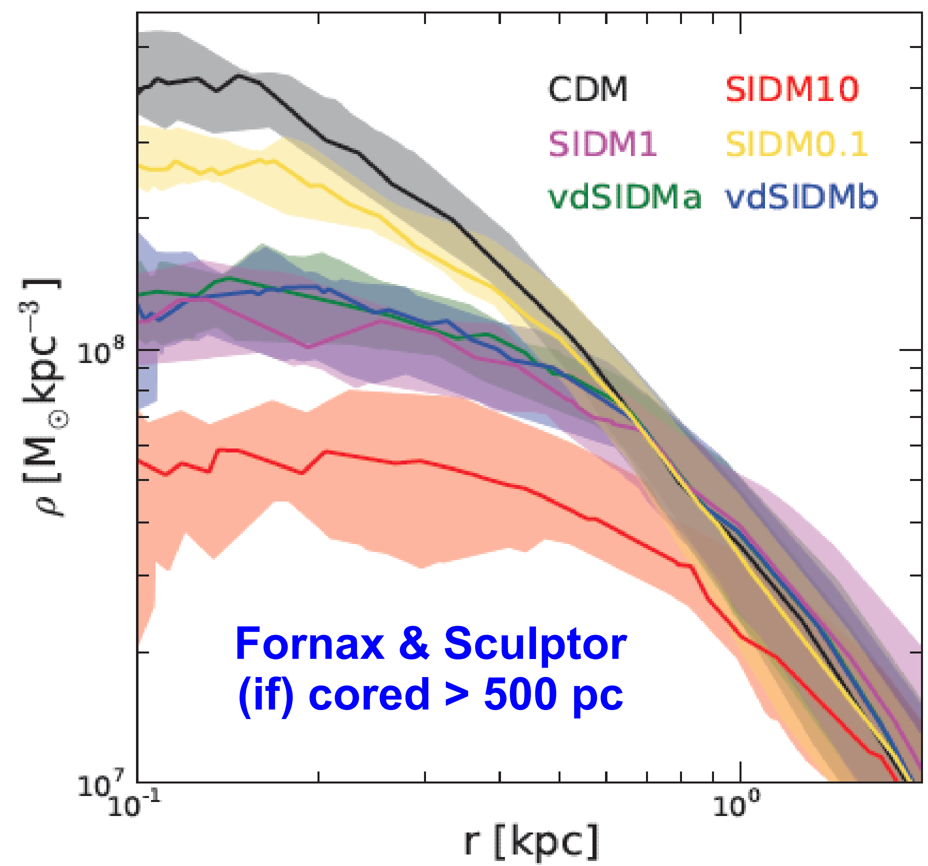
- Allowed vdSIDM (expected in hidden sector models) avoids cluster-constraints, does not have the “too big to fail” even for a “high” MW halo mass (~2×10^{12}Msun), and produces O(1kpc) cores in MW satellites (Vogelsberger, Zavala & Loeb 2012)

- cSIDM only works as a ***distinct*** alternative to CDM if 0.6 $cm^2/g < \sigma / m < 1$ cm^2/g (Zavala, Vogelsberger & Walker 2013)

- **Caveat: DM-only simulations!!**

Zavala, Vogelsberger & Walker 2013

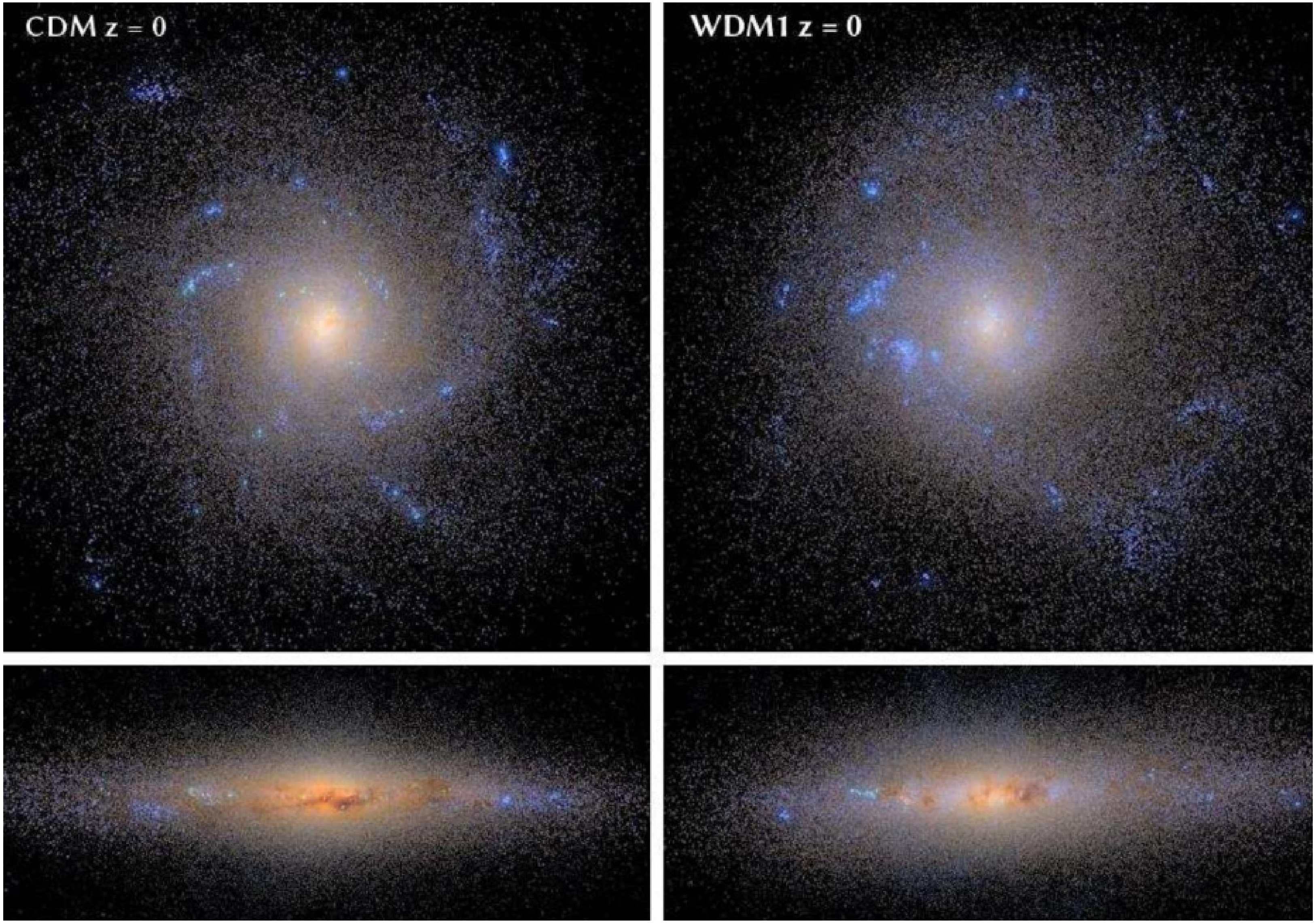




Open questions

How does galaxy formation occurs in WDM?

Herpich+14 $6x10^{11}$ M_{Sun} halo

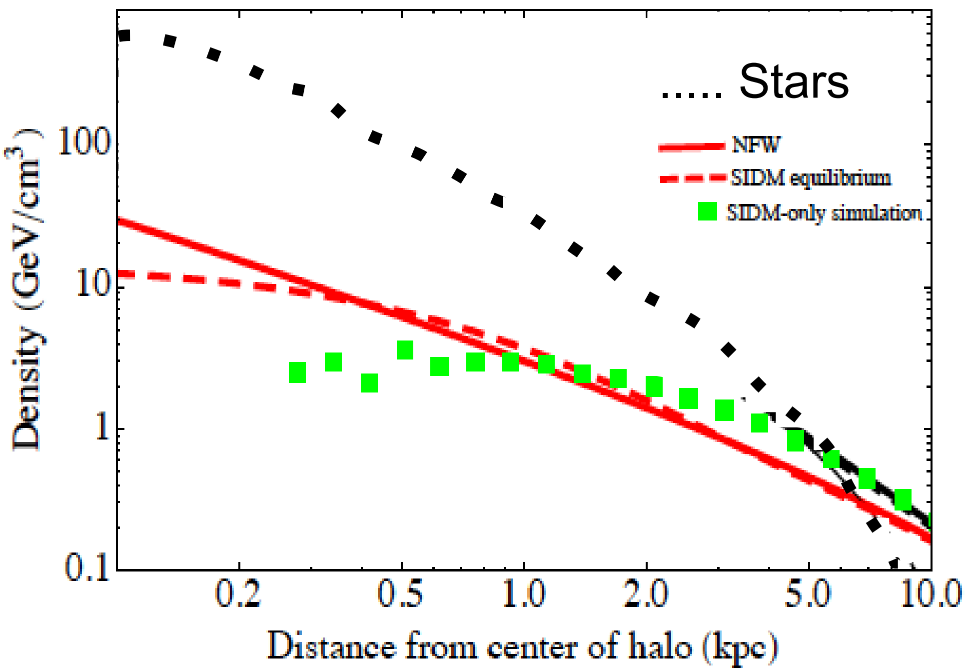


Late galaxy evolution much more sensitive to feedback assumptions than WDM cosmology (for $m_\chi > 2$ keV)

Open questions

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

Kaplinghat+13 **MW-size system**



Analytic treatment: enforce isothermal core and find equilibrium solution for the DM given a final stellar distribution

baryons ↓

$$\nabla_x^2\left(h(\vec{x}) + \Phi_B(\vec{x})/\sigma_0^2\right) + \frac{4\pi G_N \rho_0 r_0^2}{\sigma_0^2}\exp\left(h(\vec{x})\right) = 0$$

DM → $h(\vec{r}) \; = \; \ln(\rho(\vec{r})/\rho_0)$

SIDM core sizes smaller and central densities larger in baryon-dominated systems

How significant are these effects in DM-dominated systems like dwarfs?

Concluding remarks

Are dwarf galaxies less centrally dense than CDM-only predictions? **Yes**

- It is plausible to reduce DM densities through gas outflows driven by feedback, but, it is not clear there is enough energy for $M<10^{10}M_{Sun}$
- Both allowed SIDM-only and WDM-only models solve this issue

Do dwarf galaxies ($M<10^{10}M_{Sun}$) have cores or cusps? **Controversial**

- If cored:
  - even more energetically demanding for feedback-driven outflows
  - WDM-only models do not form a sizeable core
  - SIDM-only ($\sigma/m \sim 1\ cm^2/g$ or velocity-dependent) models form ~1kpc cores

- If cuspy or a distribution:
  - Very relevant for the stellar assembly history of dwarf galaxies
  - Can this help to constrain WDM and SIDM models?

The synergy between baryonic physics and warm DM or collisional DM in dwarf galaxies is an open question