Self-Interacting Dark Matter at the scale of dwarf galaxies

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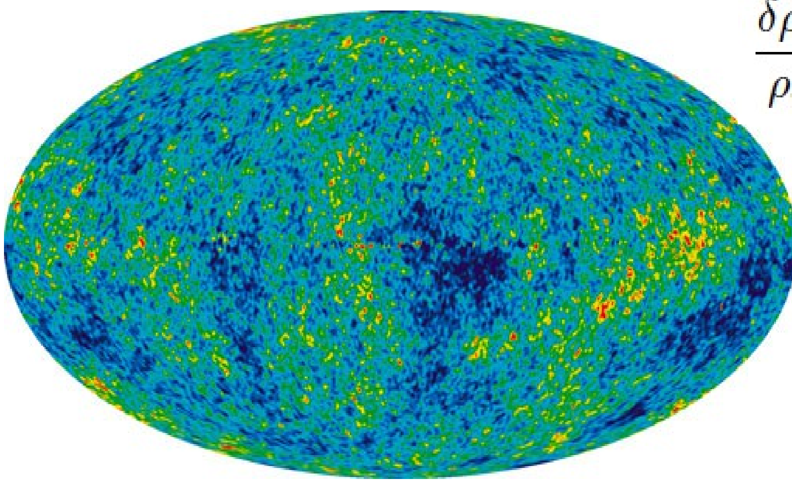
CosmoClub, UCSC, February 2014

Opening remarks

Astronomical observations at galactic and larger scales indicate that ~80% of the matter in the Universe is dark

The CDM model is the cornerstone of the current theory of structure formation

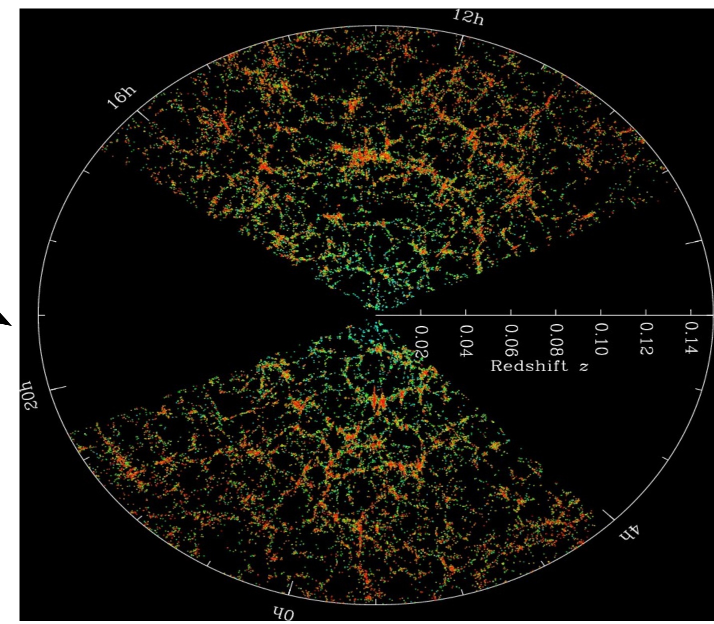
early Universe t ~ 0.4 Myrs



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

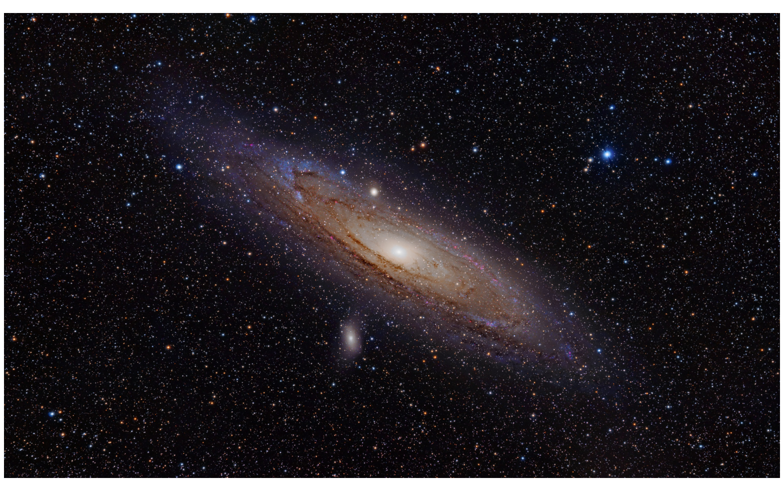
CMB

Universe today (t ~ 13.8 Gyrs)



SDSS galaxy “map”, large-scale structure

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



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

galactic scales

Opening remarks

There is no indisputable evidence that the Cold Dark Matter (CDM) paradigm is wrong, but there are reasonable physical motivations to consider alternatives: incomplete knowledge of the DM nature

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CDM = collisionless DM
(after kinetic decoupling)

What do we actually know about DM interactions?

Opening remarks

There is no indisputable evidence that the Cold Dark Matter (CDM) paradigm is wrong, but there are reasonable physical motivations to consider alternatives: incomplete knowledge of the DM nature

CDM = collisionless DM
(after kinetic decoupling)

What do we actually know about DM interactions?

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)

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

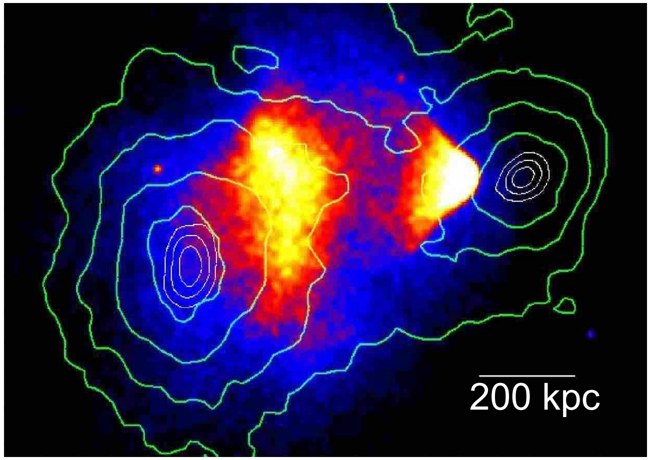
← **DM self-annihilation (reaching thermal relic value)**

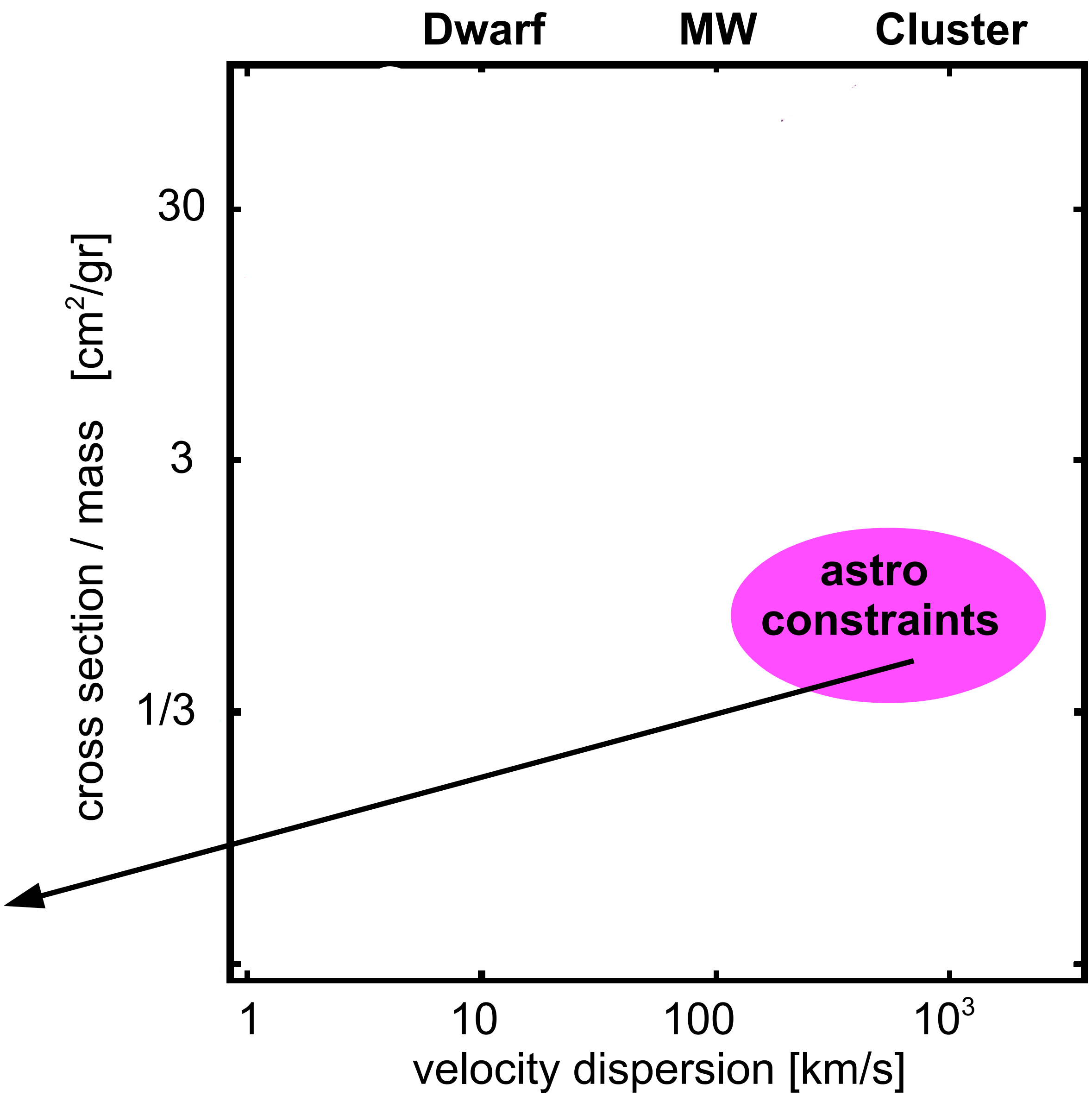
Current constraints are reaching the interaction level expected for WIMPs

Opening remarks

What about DM self-scattering?

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

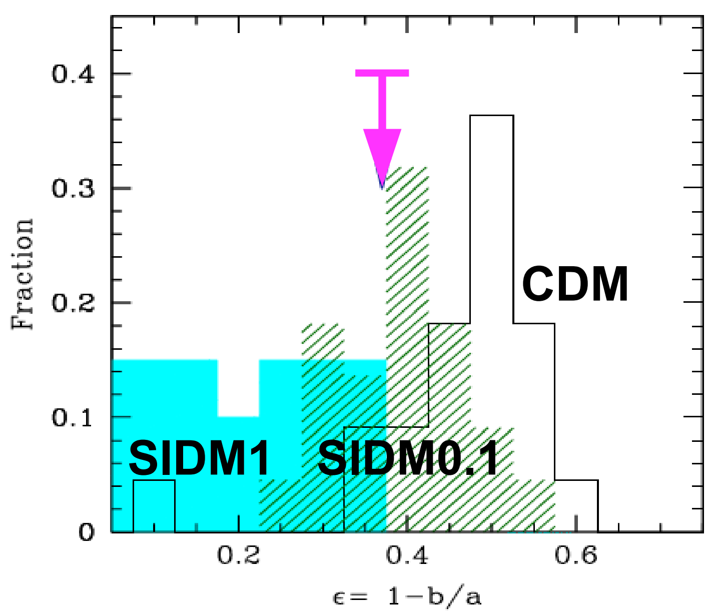


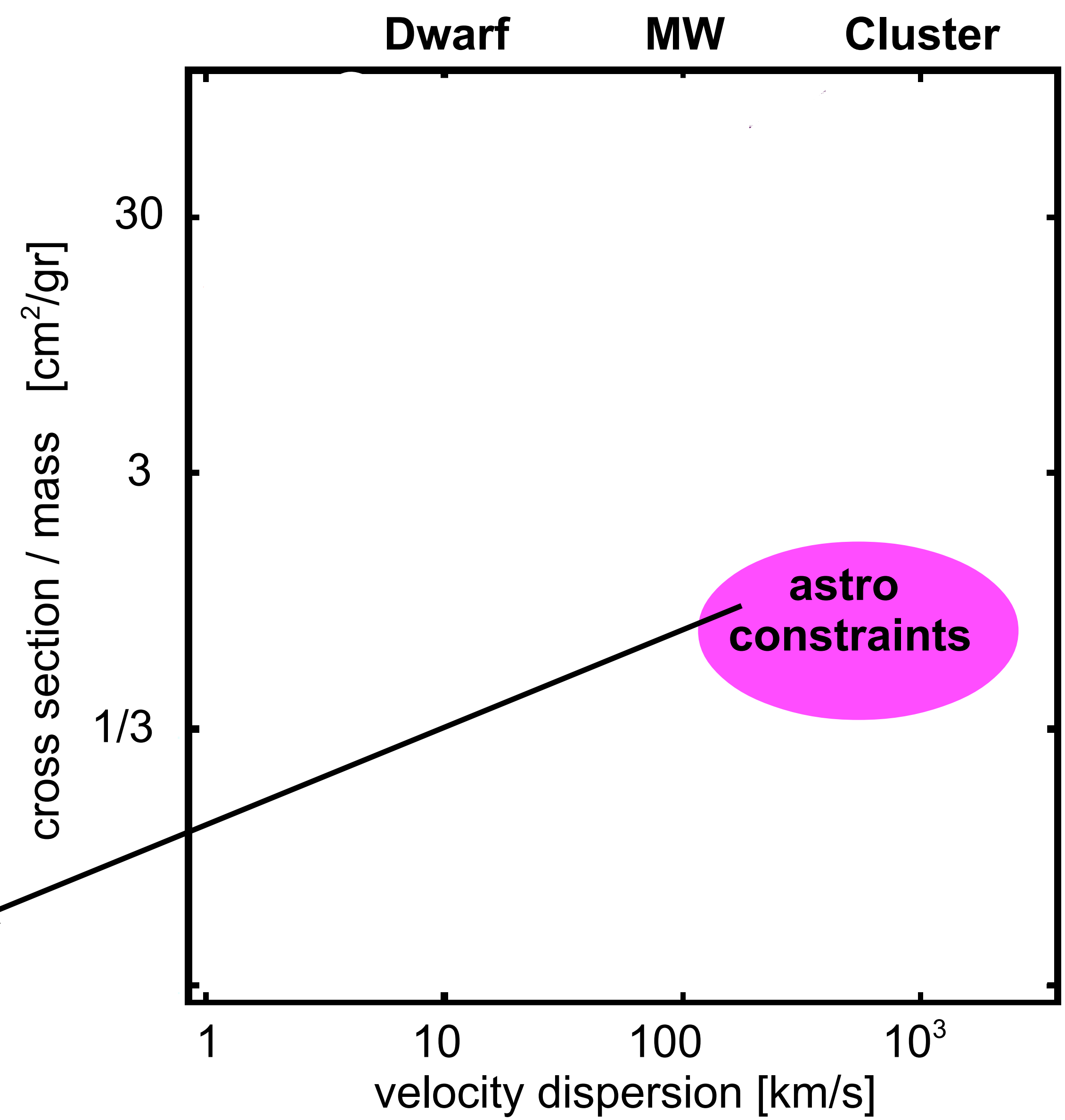


Opening remarks

What about DM self-scattering?

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





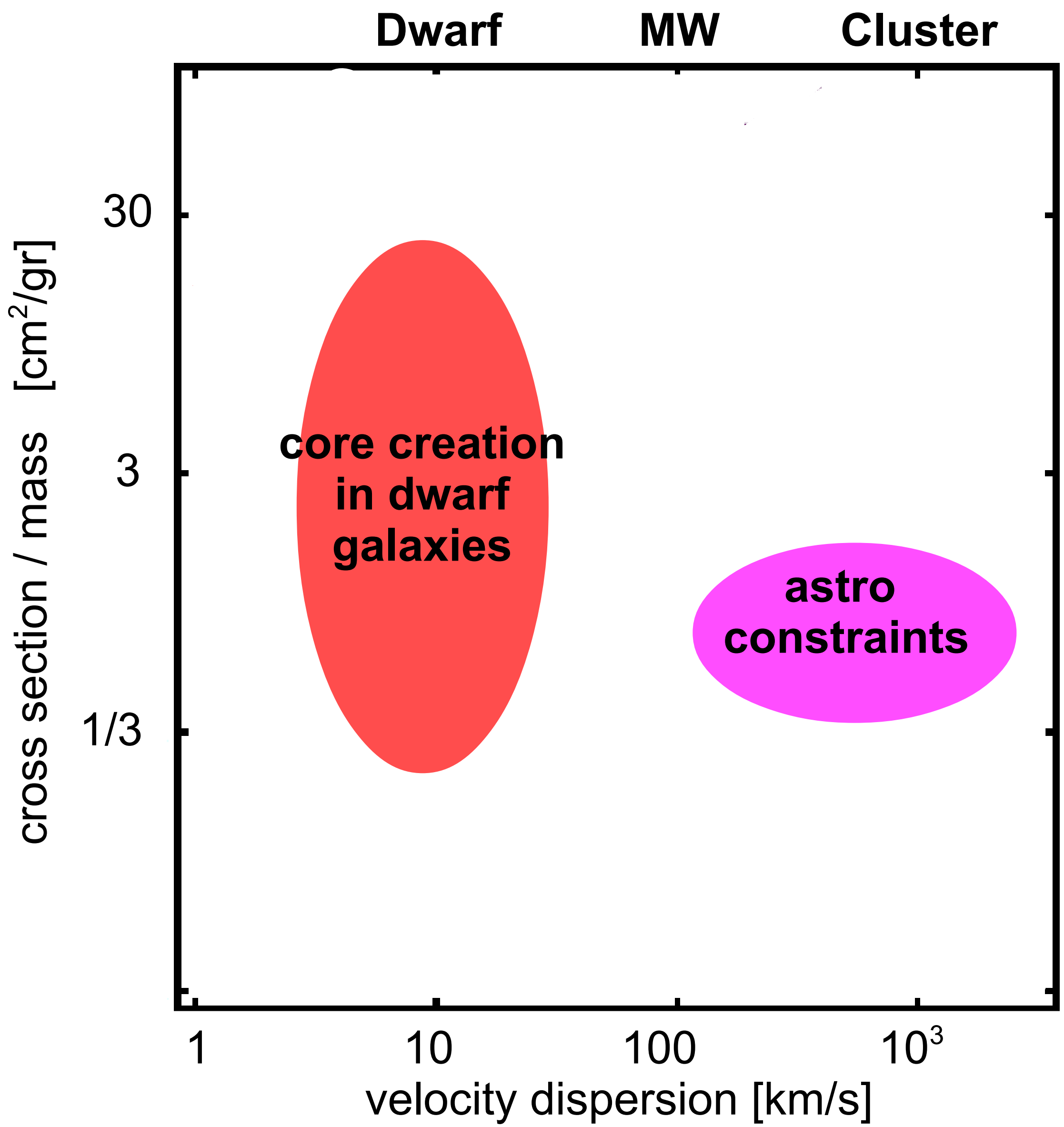
Opening remarks

What about DM self-scattering?

Constraints allow collisional DM that is astro-physically significant

~ <1 scatter/particle/t_H>

DM phase-space distribution changes

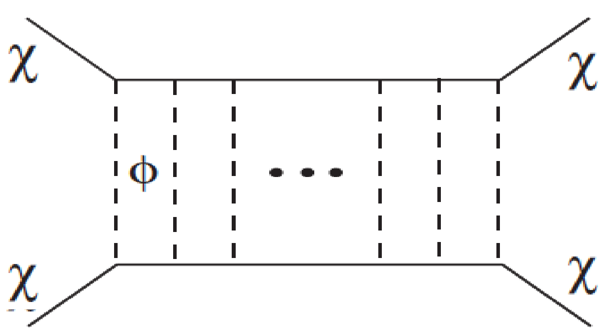


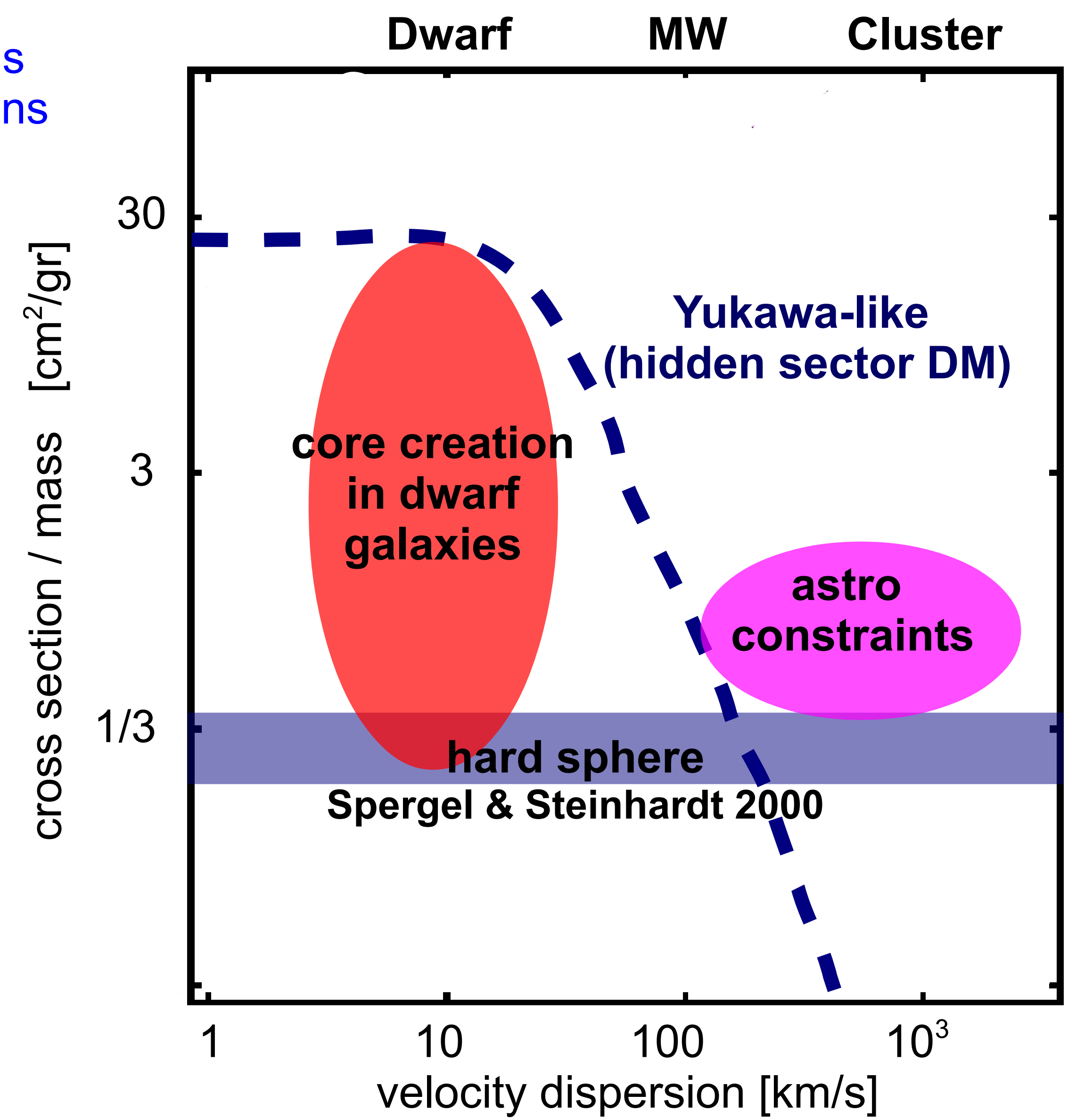
Opening remarks

What about DM self-scattering?

Several particle physics DM models
can introduce significant DM collisions

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

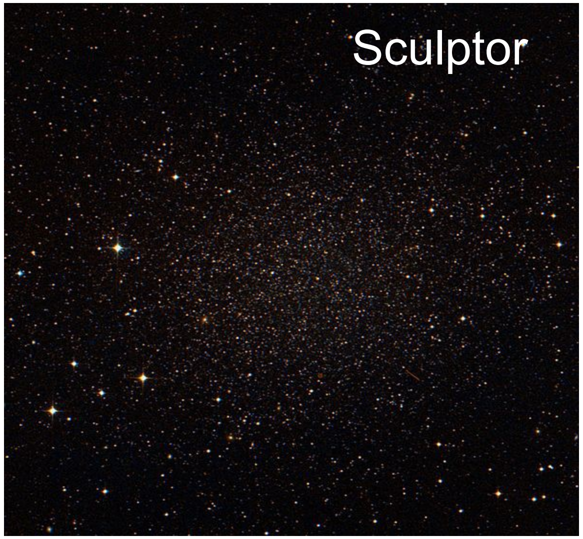


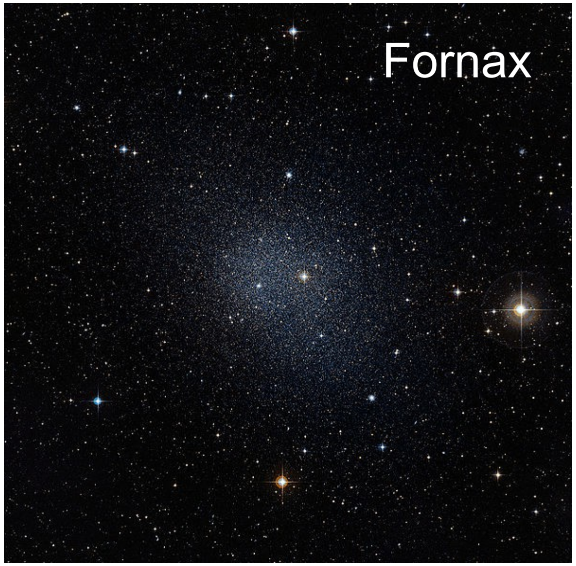


Opening remarks

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"

dwarf galaxies: largest dynamical mass-to-light ratios





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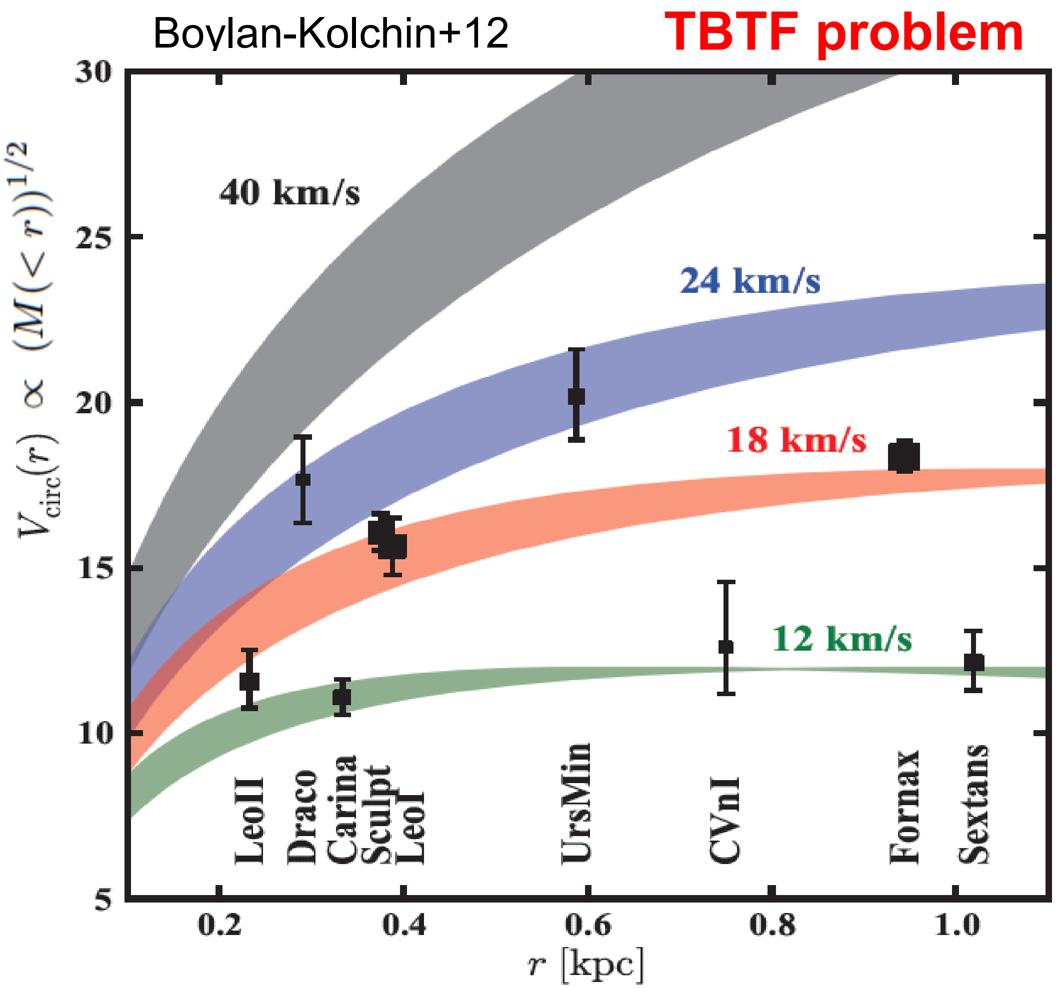
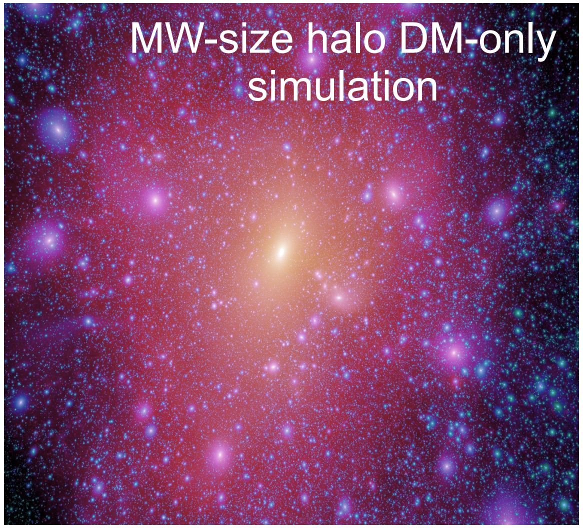
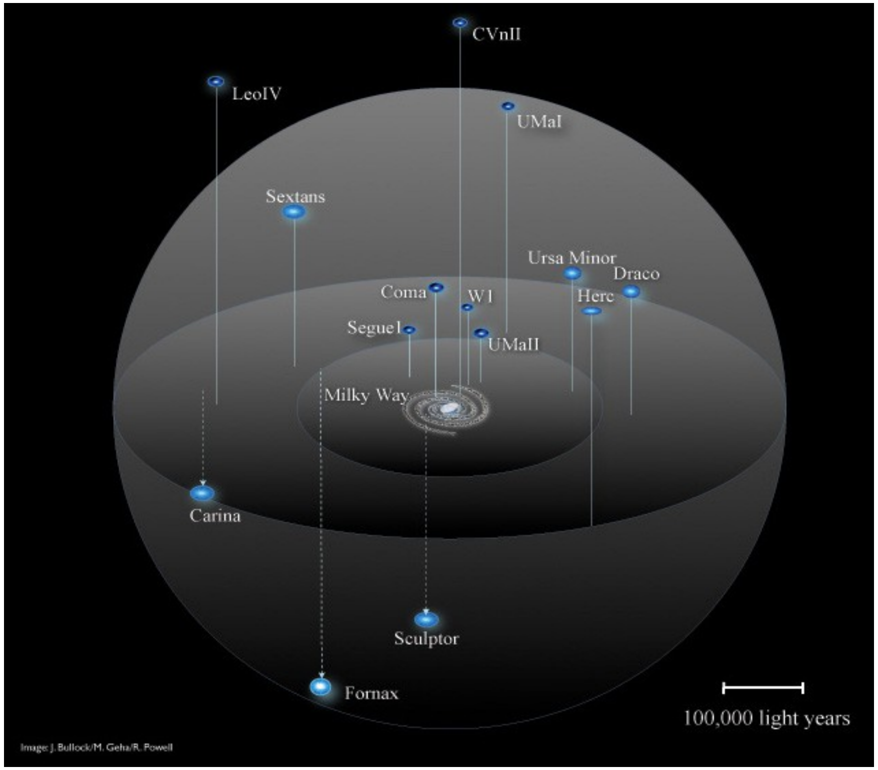


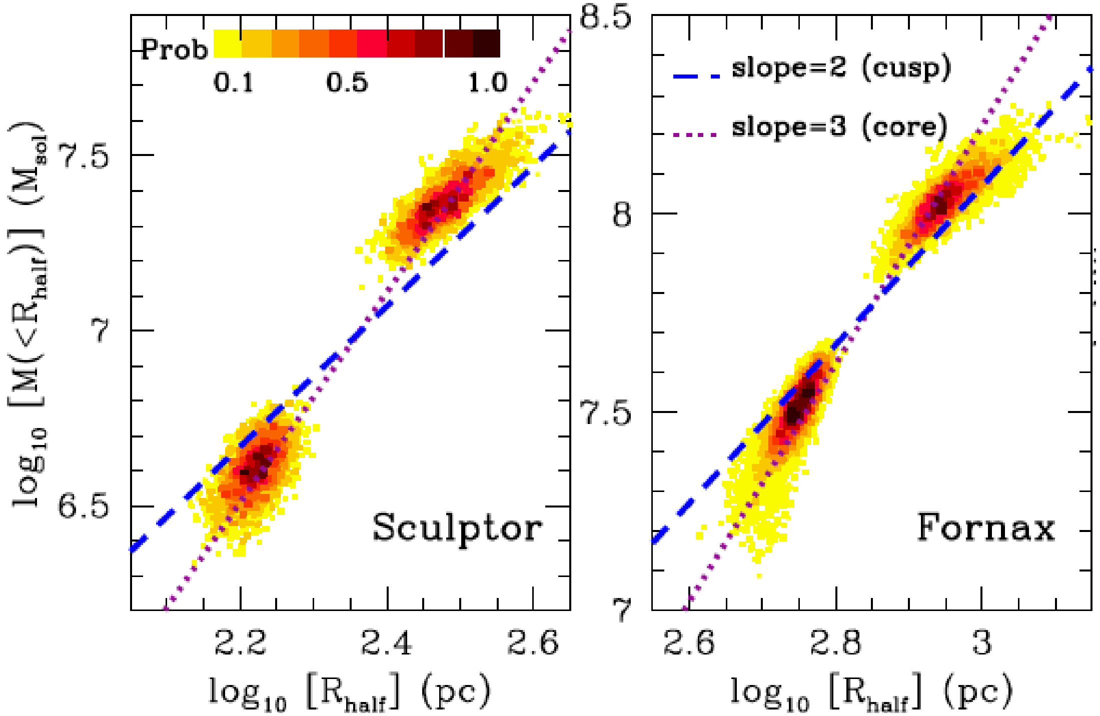




The most massive CDM-MW-subhaloes seem to be too centrally dense to host the MW dSphs

Opening remarks

The core-cusp problem



Walker & Peñarrubia 2011

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

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 **collisional**: SIDM (e.g. hidden sector DM)
    - DM might be warm: WDM (e.g. sterile neutrinos) but **current Ly-α forest constraints (m_χ > 3.3 keV, 2σ, Viel et al. 2013) make it indistinguishable from CDM at galactic scales**

Looking at the bright side of the solution

Early episodes of star formation and strong SN feedback
e.g. Navarro+ 1996, Governato+10, Governato+ 2012

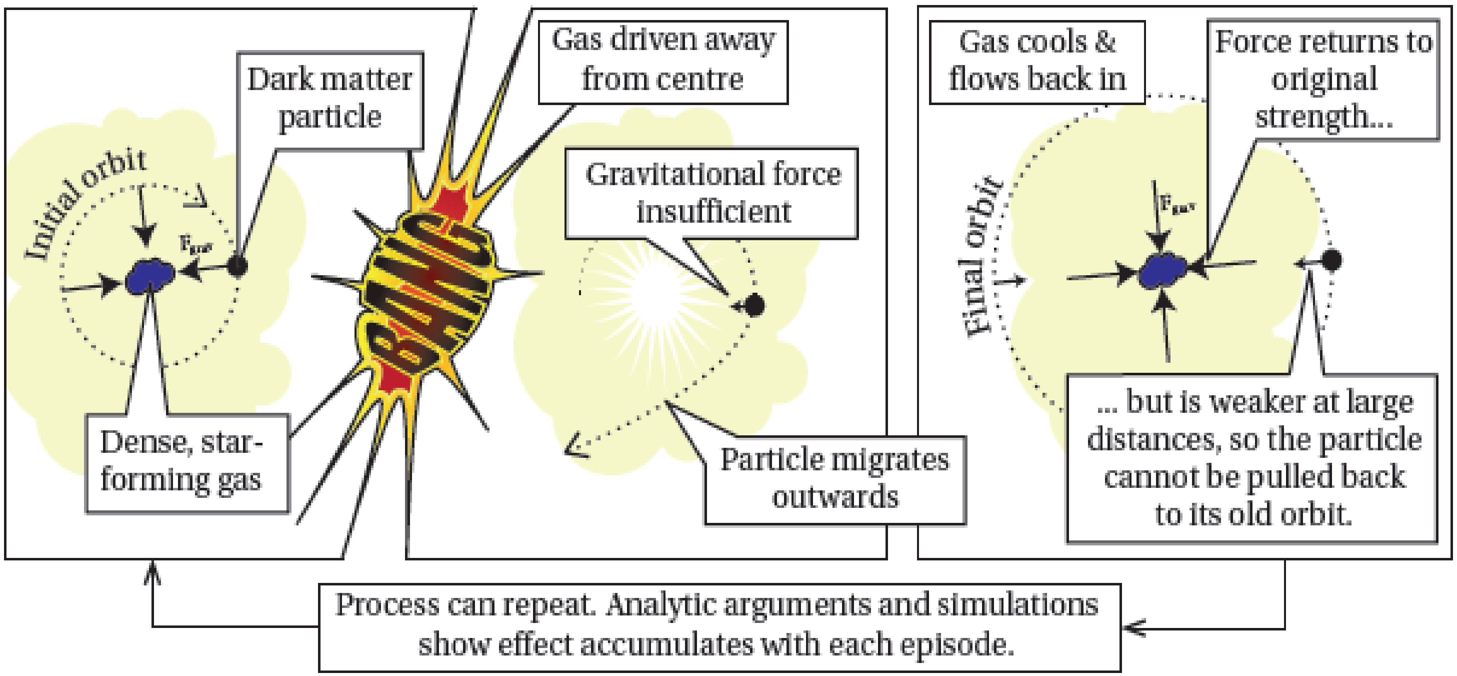
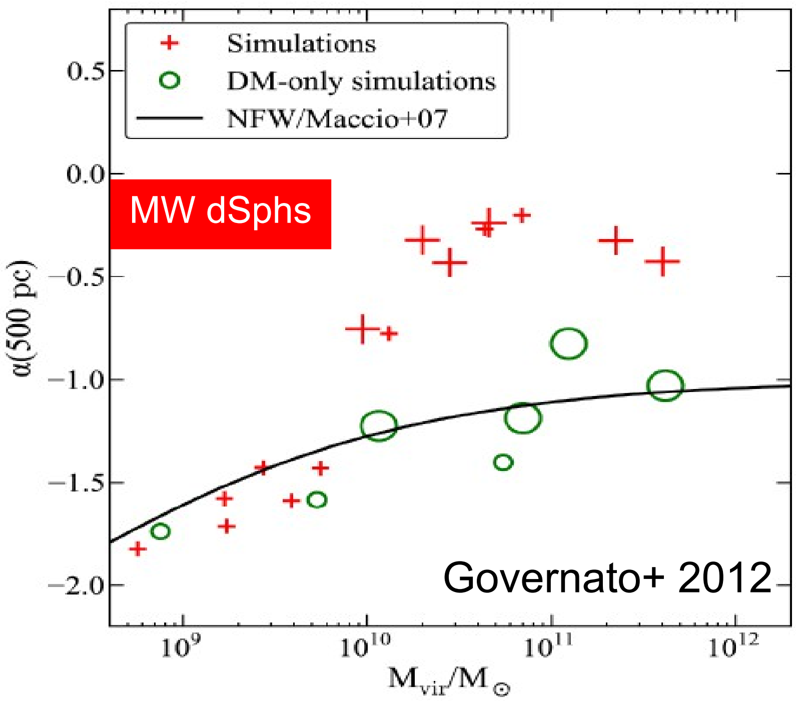


Fig. From Pontzen and Governato 2014

Also, radiation pressure from massive stars can lower the DM central densities (e.g. Trujillo-Gomez+13)

Looking at the bright side of the solution



Core-cusp problem

SN feedback in MW dSphs: likely insufficient for dSphs

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

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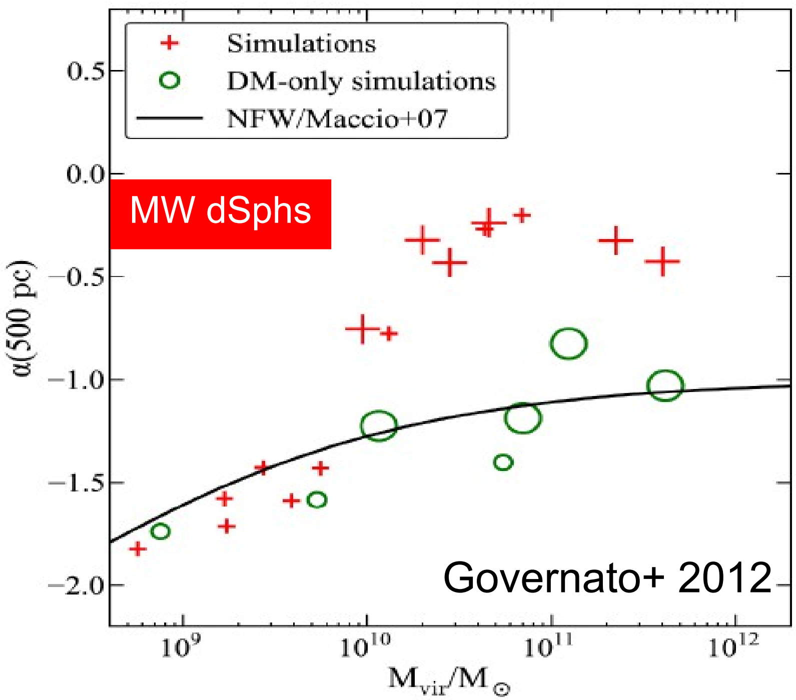


Core-cusp problem

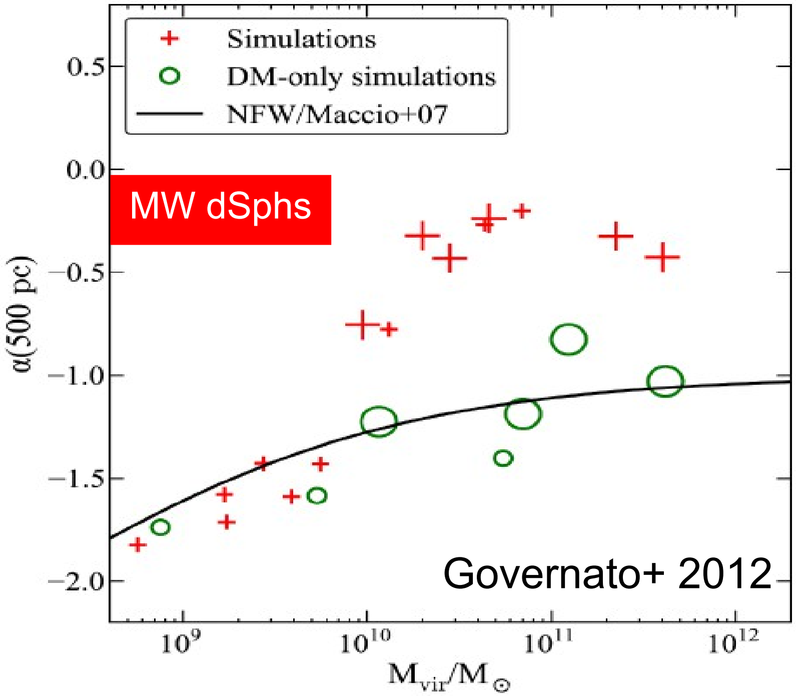
SN feedback in MW dSphs: likely insufficient for dSphs
e.g. Peñarrubia+ 2012, Garrison-Kimmel+13

Environmental effects (tidal heating due to MW disk)
Zolotov+2012, Brooks & Zolotov 2012

dSphs orbits from proper motions (HST data)
Piatek+2006,+2007

	Fornax	Sculptor
r_{peri}/r_{apo} :	$0.78^{+0.17}_{-0.50}$	$0.56^{+0.30}_{-0.46}$

Looking at the bright side of the solution



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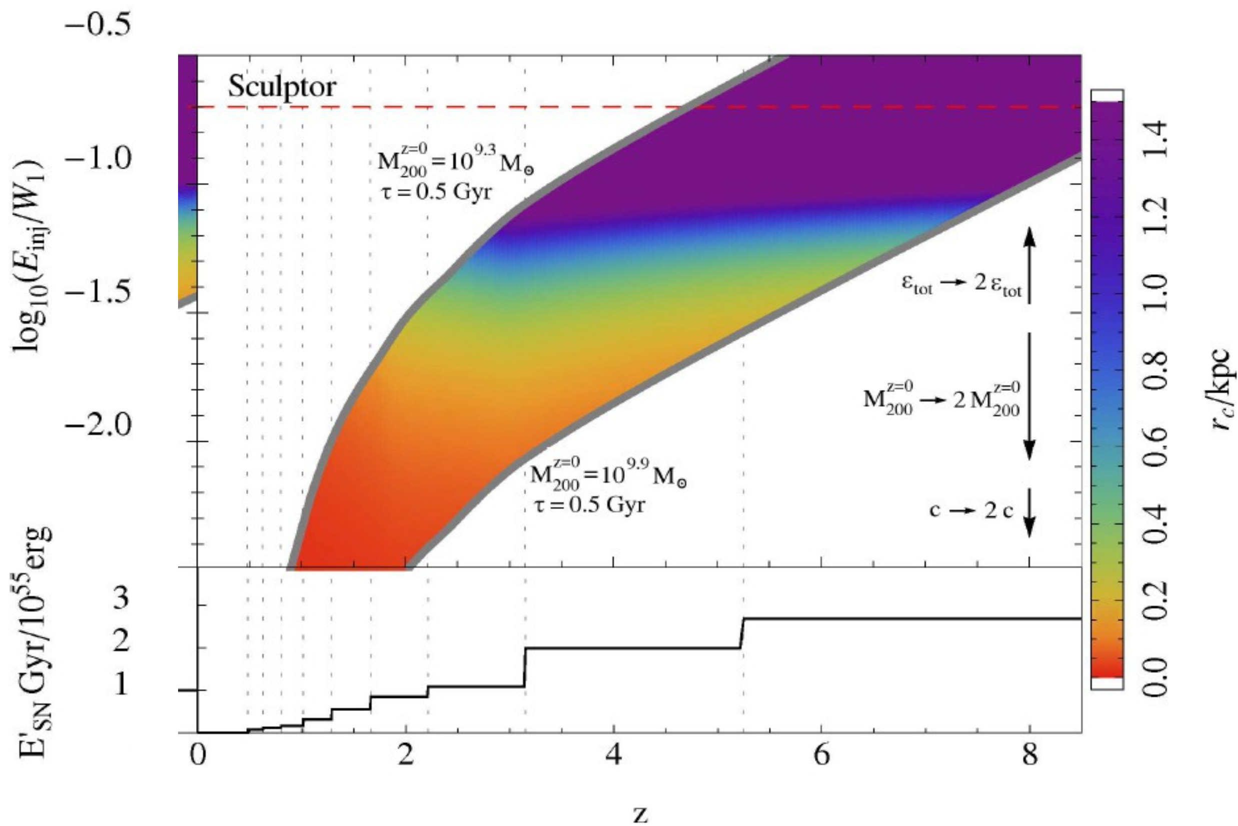
early SN feedback in MW dSphs
Amorisco, Zavala & de Boer 2013

How "bursty" is the SF history of dwarfs?

How many early DM cores can survive subsequent mergers?



Looking at the bright side of the solution

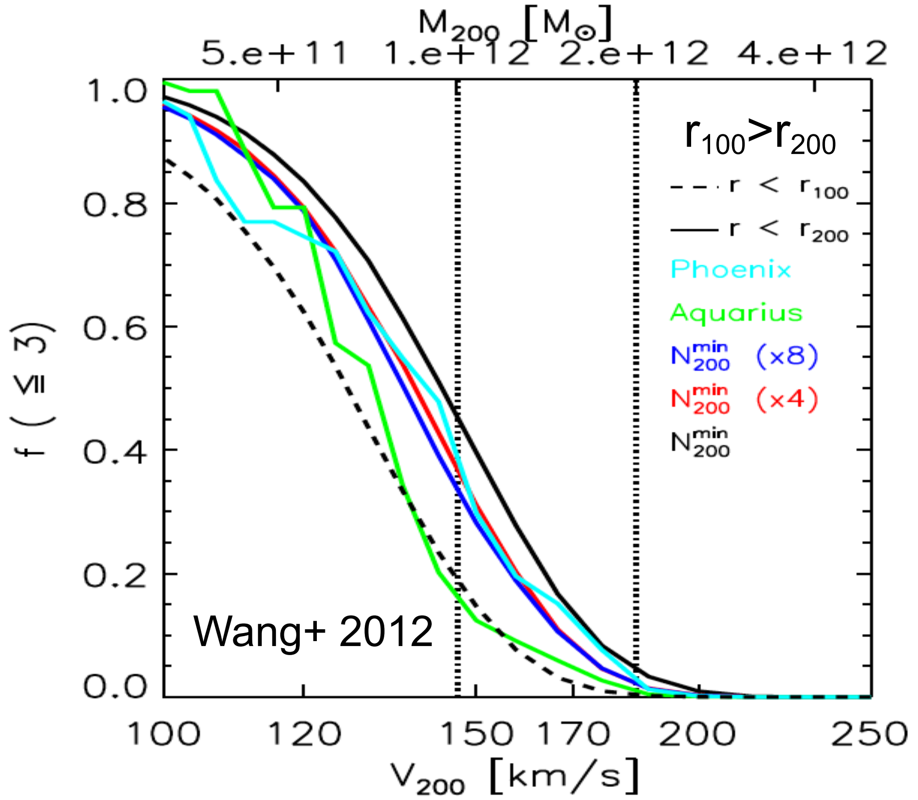
Too big to fail problem

The halo of the Mily-Way is less massive than 10^{12} M_{Sun}

e.g. Wang+ 2012, Vera-Ciro+ 2013

Current obs. estimates: ~ 1-2 x 10^{12} M_{Sun}
Probability of bound Magellanic Clouds: ~20 % (M_{halo} = 10^{12} M_{sun}), also a halo of this mass has too low V_{vir}

Probability that a halo contains 3 or fewer Subhaloes with V_{max} > 30 km/s

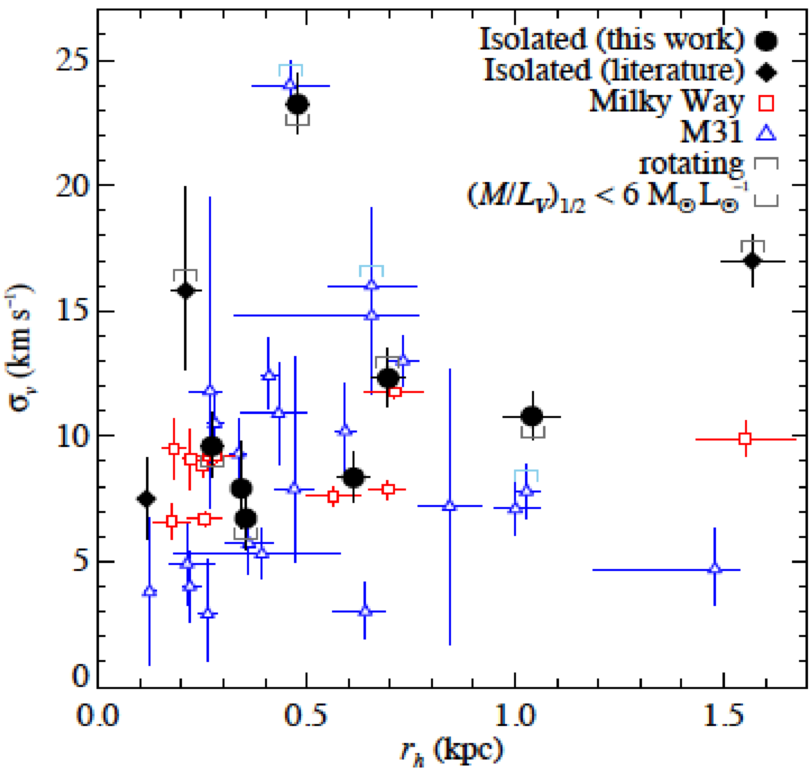


Looking at the bright side of the solution

Too big to fail problem

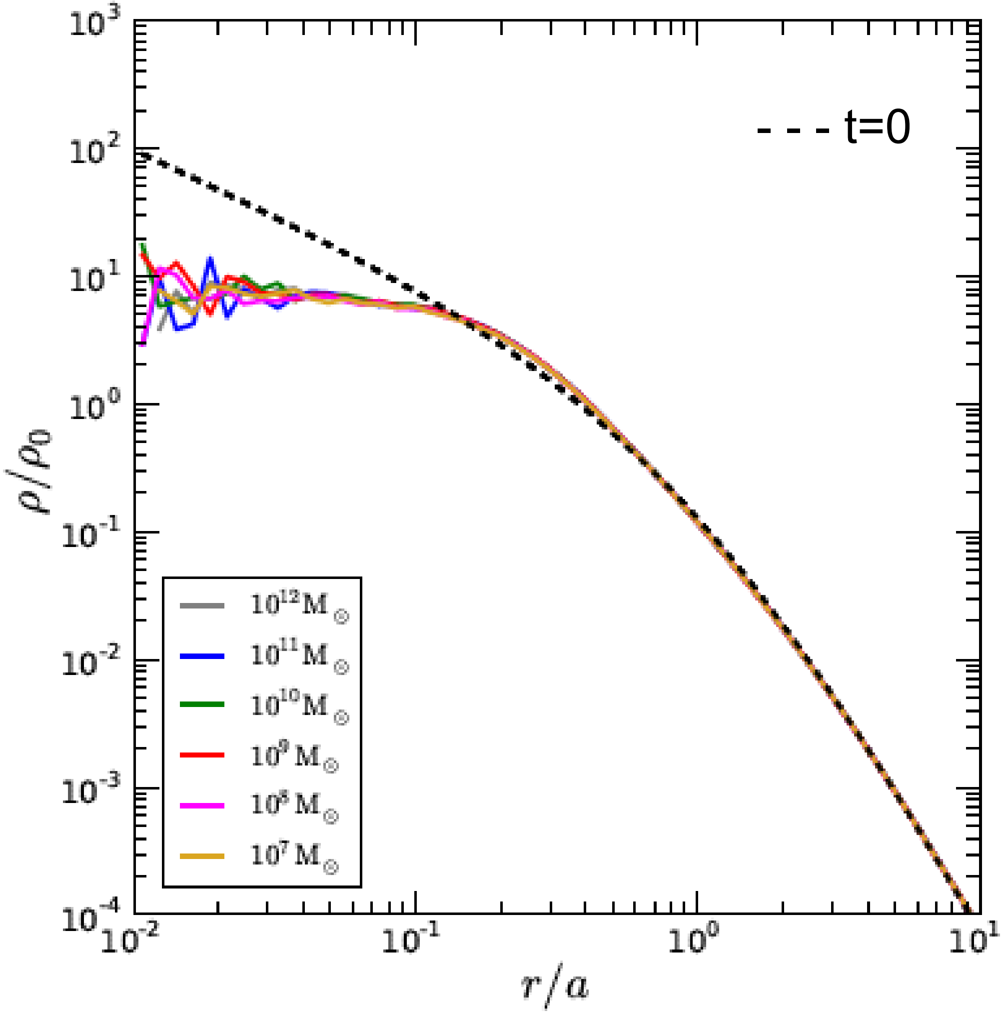
Kirby+ 14

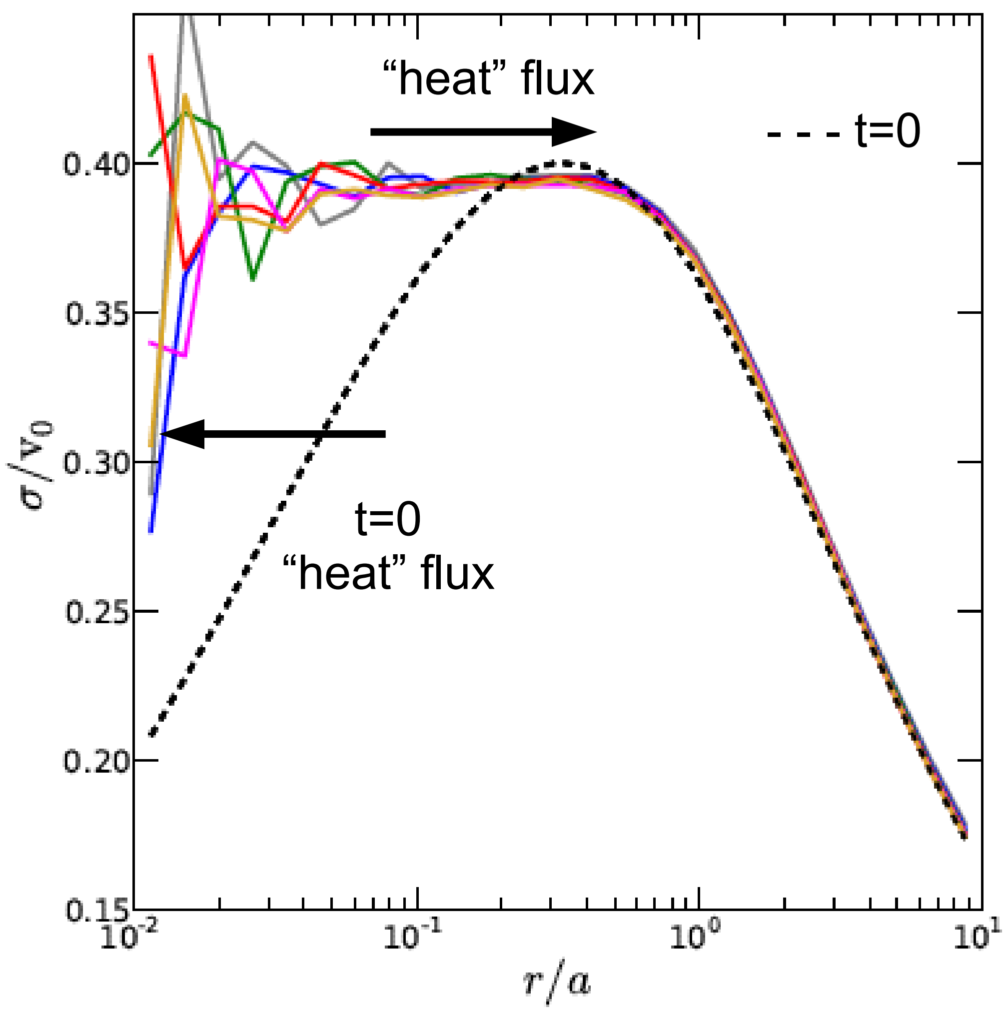
Environmental effects?
no obvious distinction between satellites and isolated dwarfs in the TBTF plane



Alternative solution: DM might be self-interacting

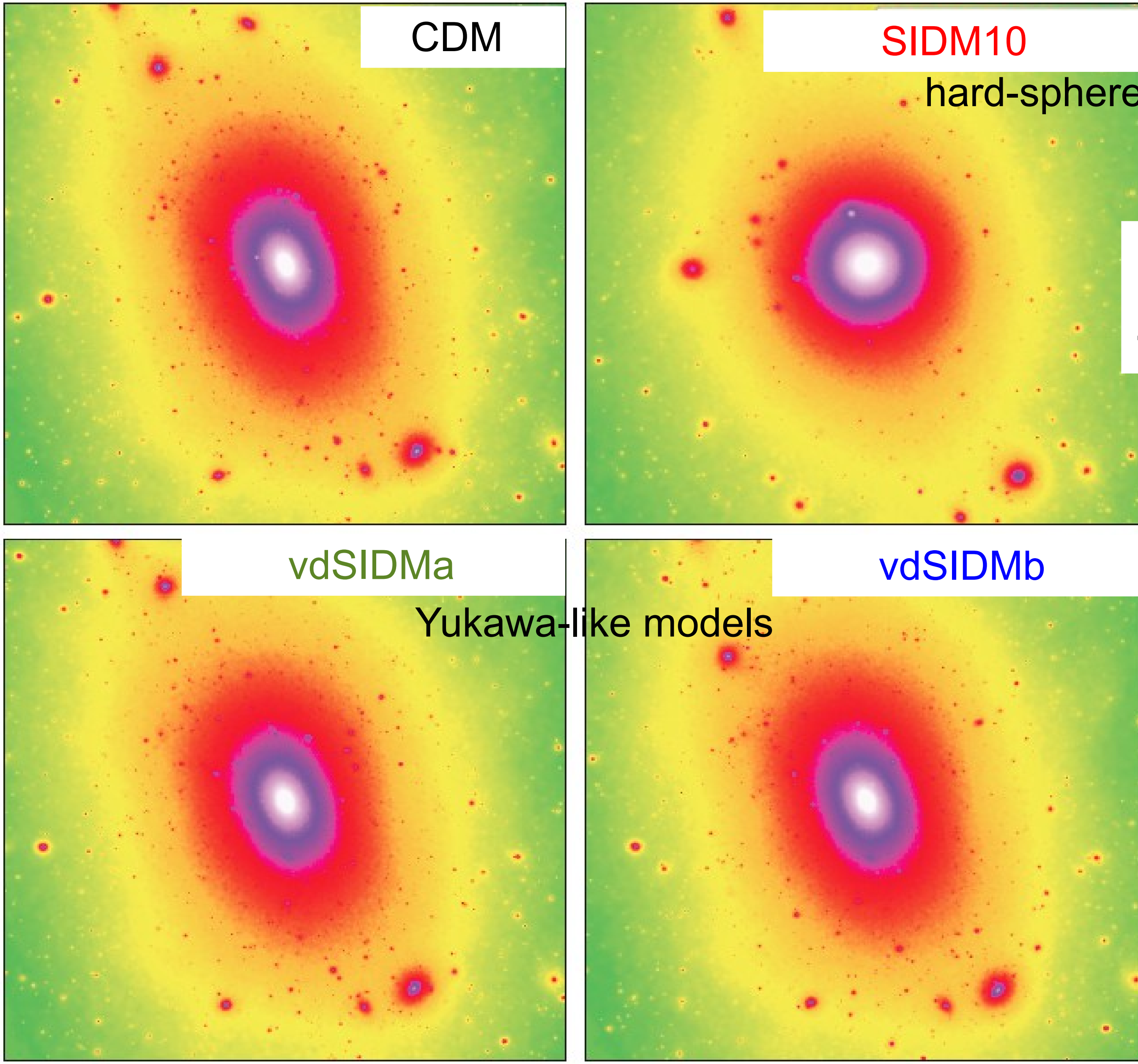
DM self-scattering
SIDM: forming a core through collisions





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

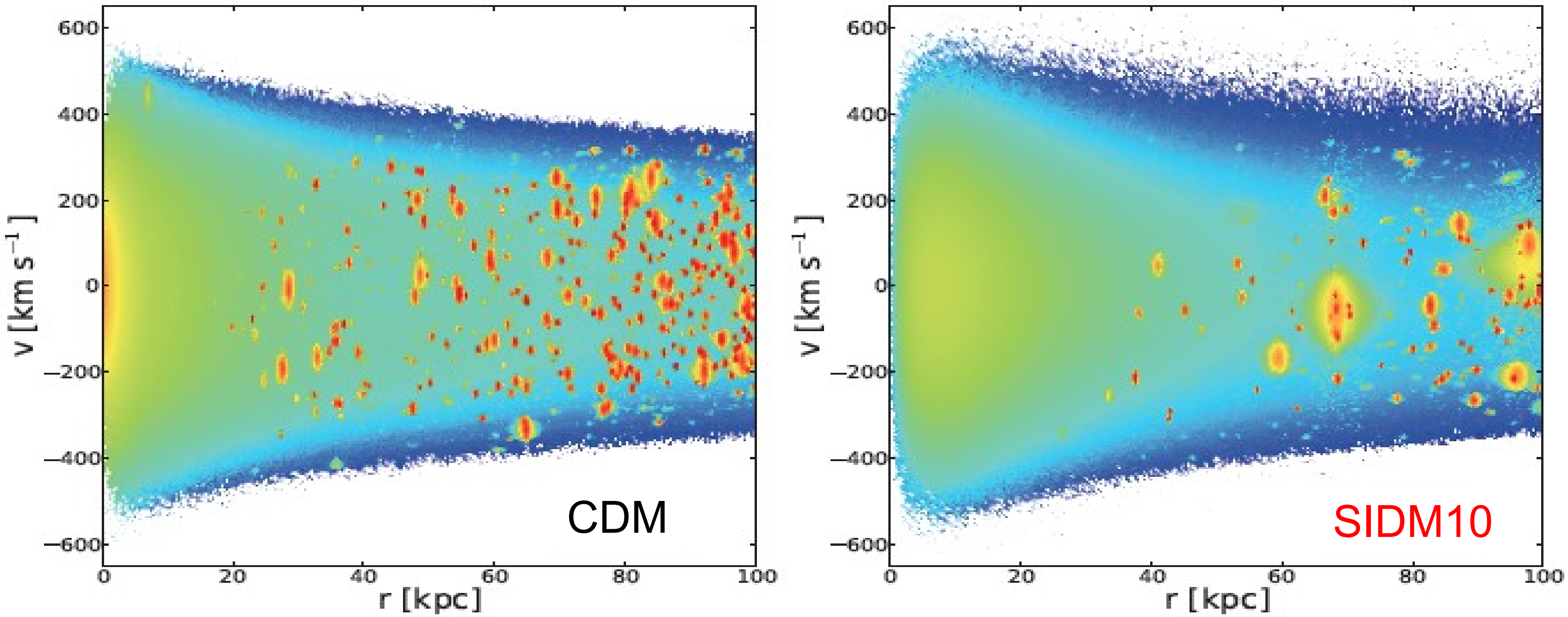
$M_{200} [M_\odot]$	r_{200}[kpc]
1.836×10^{12}	245.64

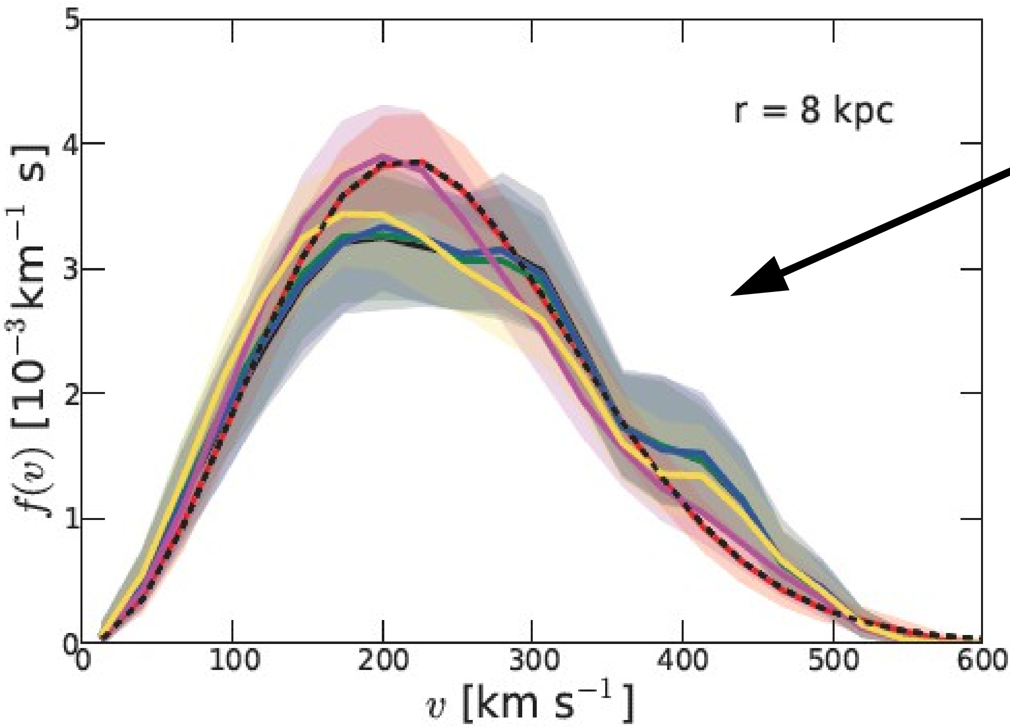
Another group has also been very active in recent SIDM sims: (see Rocha+13)

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

Phase-space distribution in SIDM

Vogelsberger & Zavala 2013





“Local” DM velocity distribution for observers at the solar circle

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

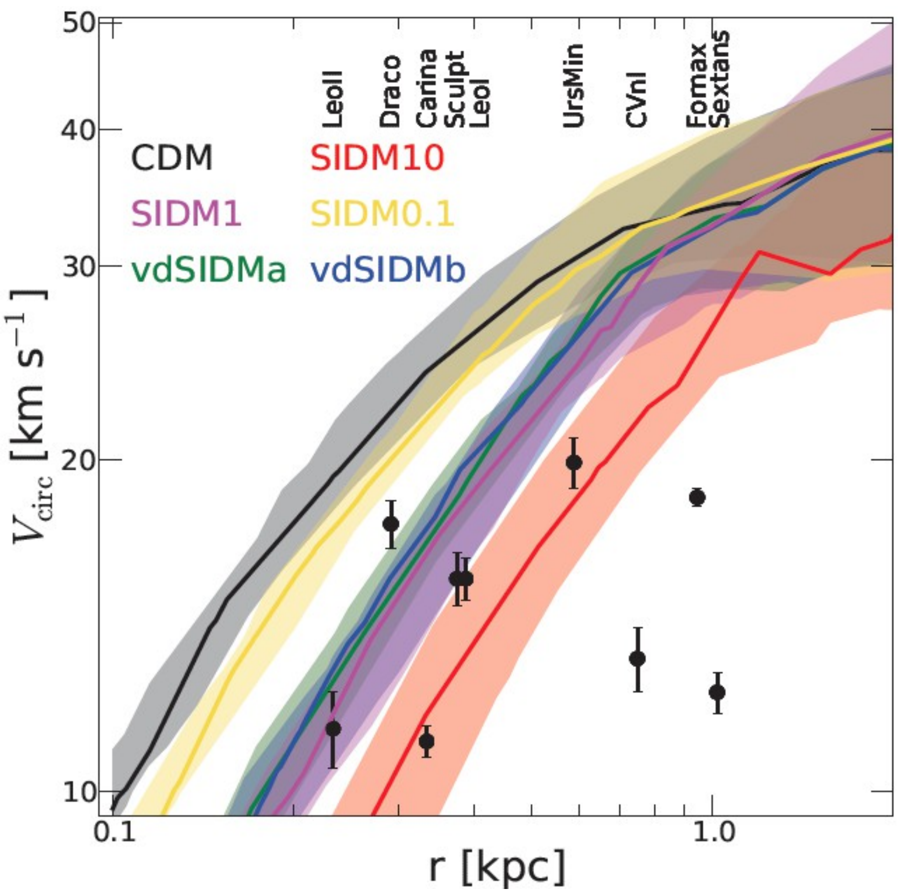
Key results: densities of MW-like subhaloes

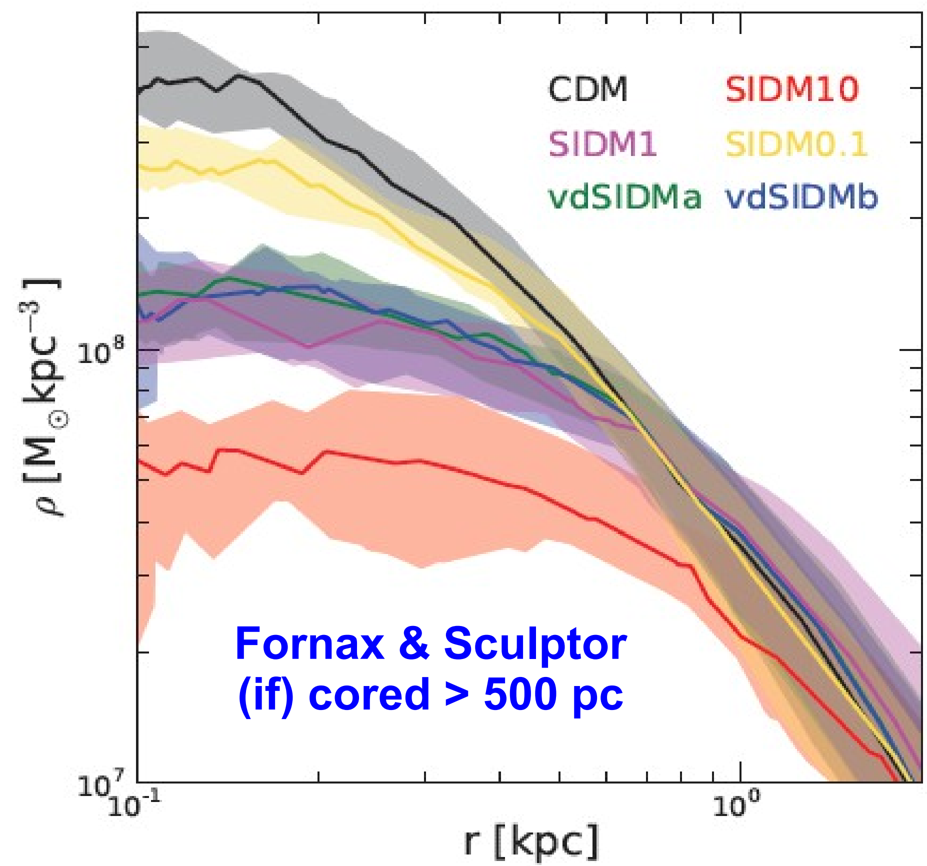
- Allowed vdSIDM (expected in hidden sector models) avoids cluster-constraints, does not have the “too big to fail” even for a “high” MW halo mass (~2×10^{12}Msun), and produces O(1kpc) cores in MW satellites (Vogelsberger, Zavala & Loeb 2012)

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

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

Zavala, Vogelsberger & Walker 2013

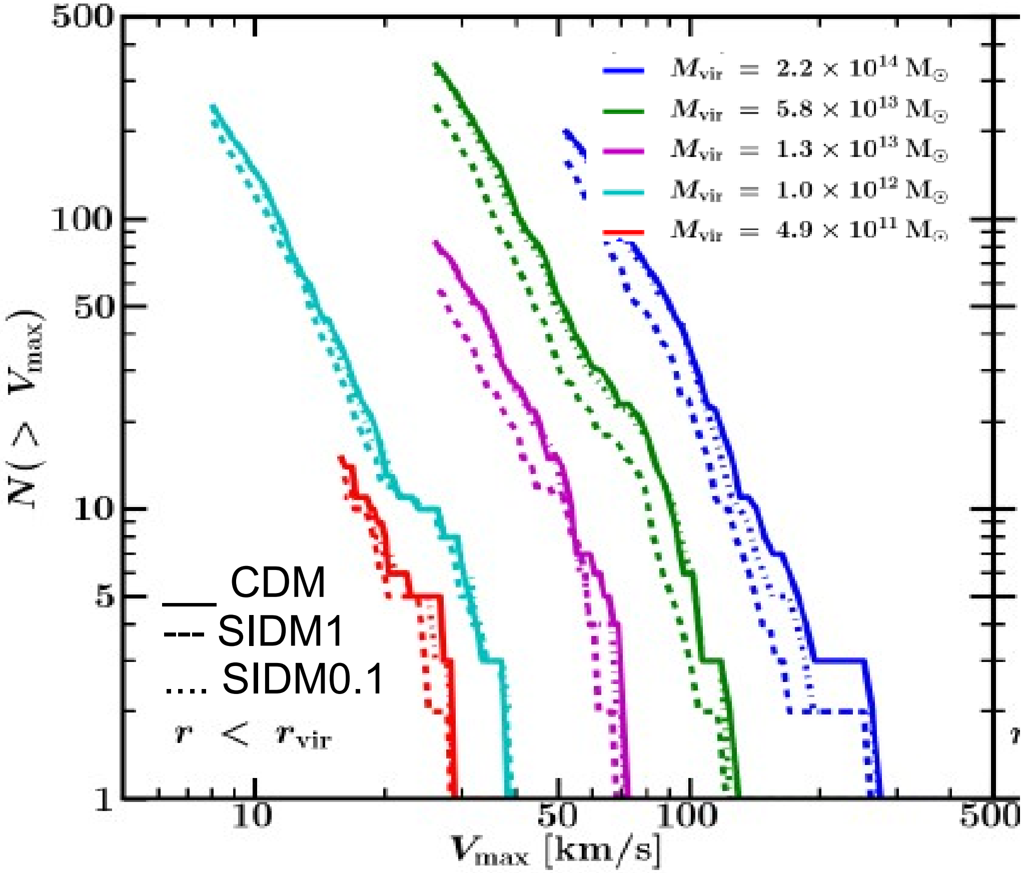




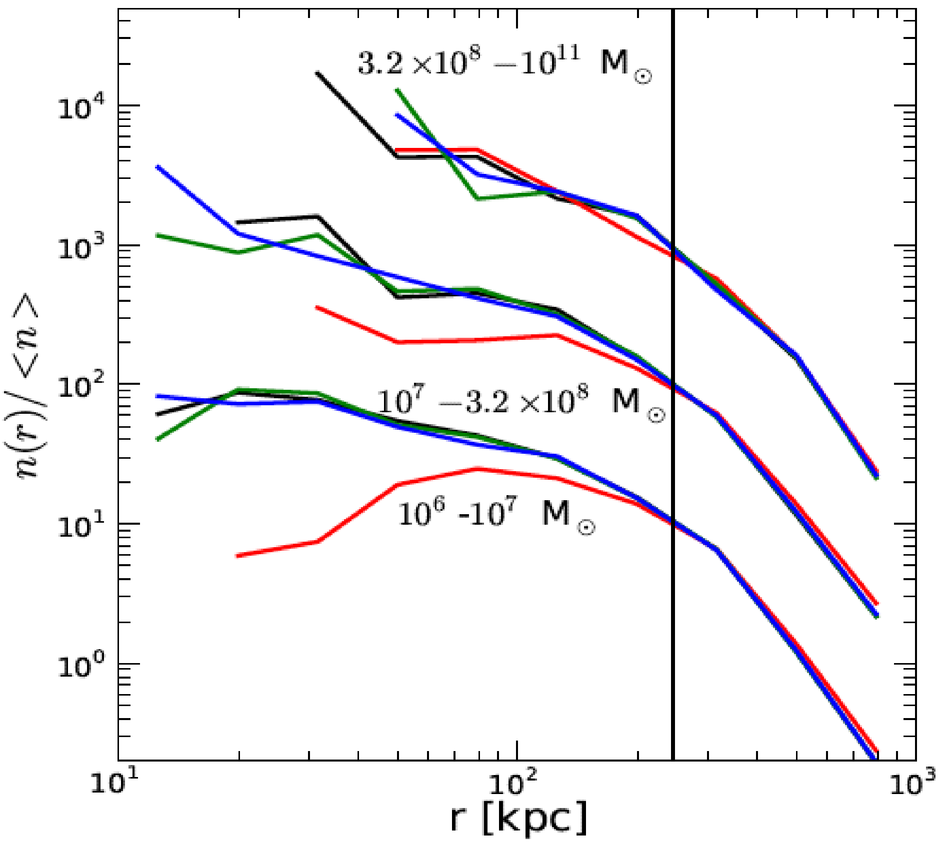
Key results: subhalo abundance

(allowed) elastic SIDM gives the same abundance as CDM

Subhalo mass function Rocha+13



MW subhalo radial distribution

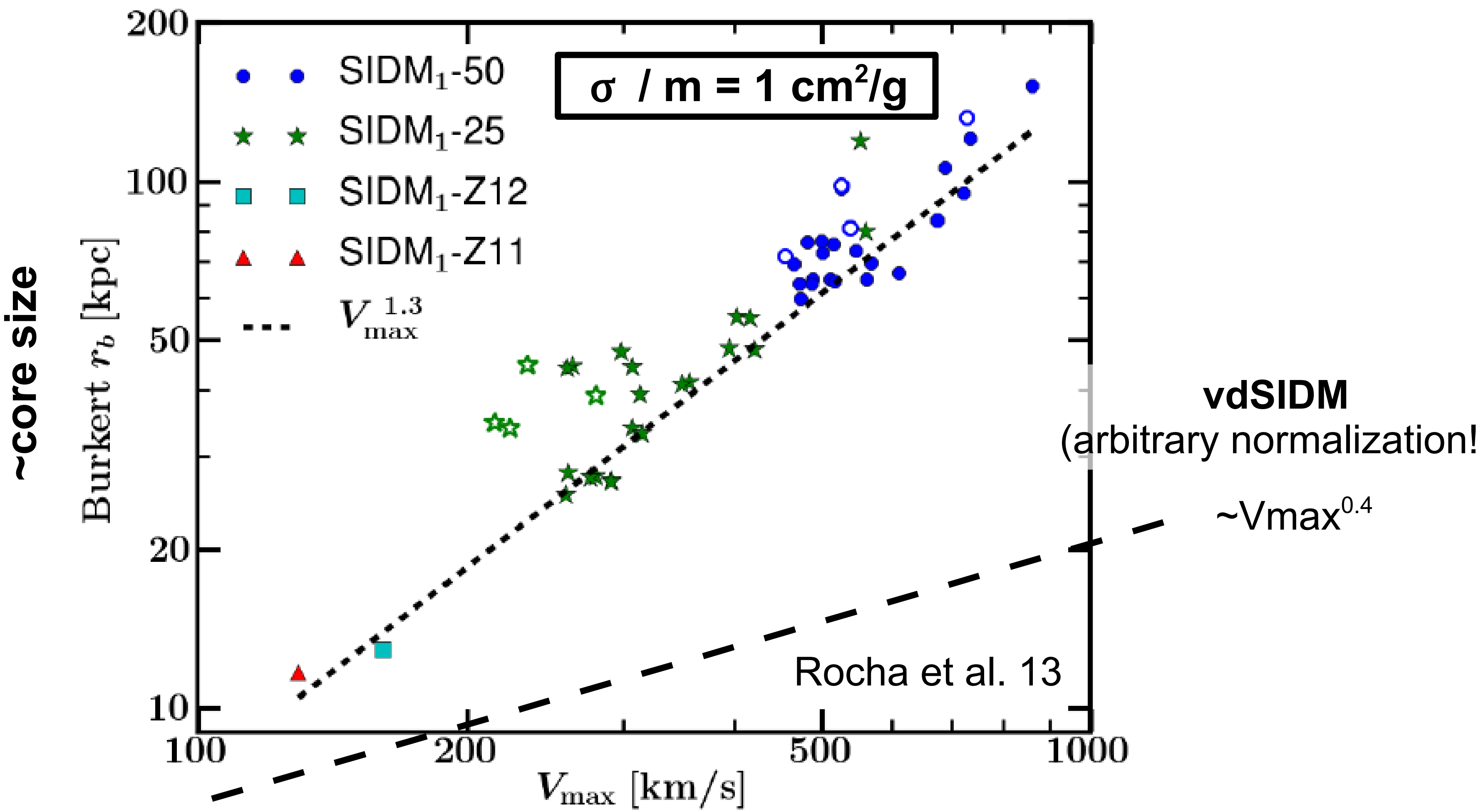


Vogelsberger, Zavala & Loeb 2012

Inelastic scattering (excited states of DM) might lead to the evaporation of low-mass subhaloes (Loeb & Weiner 2011)

Open questions

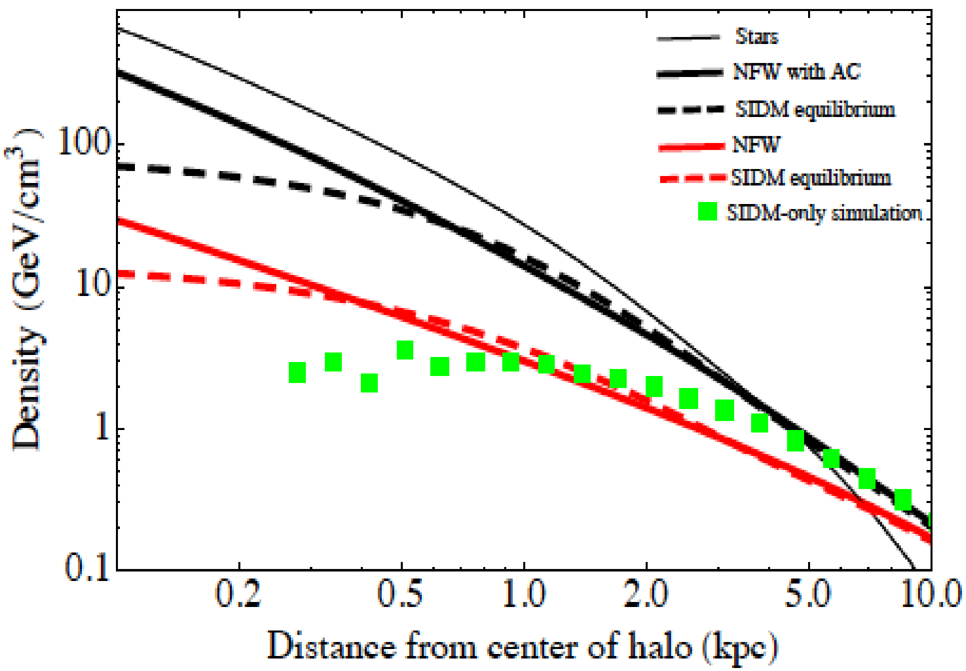
Are there other testable predictions of SIDM models (e.g. scaling relation between the core size and the DM halo mass)?



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 $\longrightarrow$ $h(\vec{r}) = \ln(\rho(\vec{r})/\rho_0)$

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

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

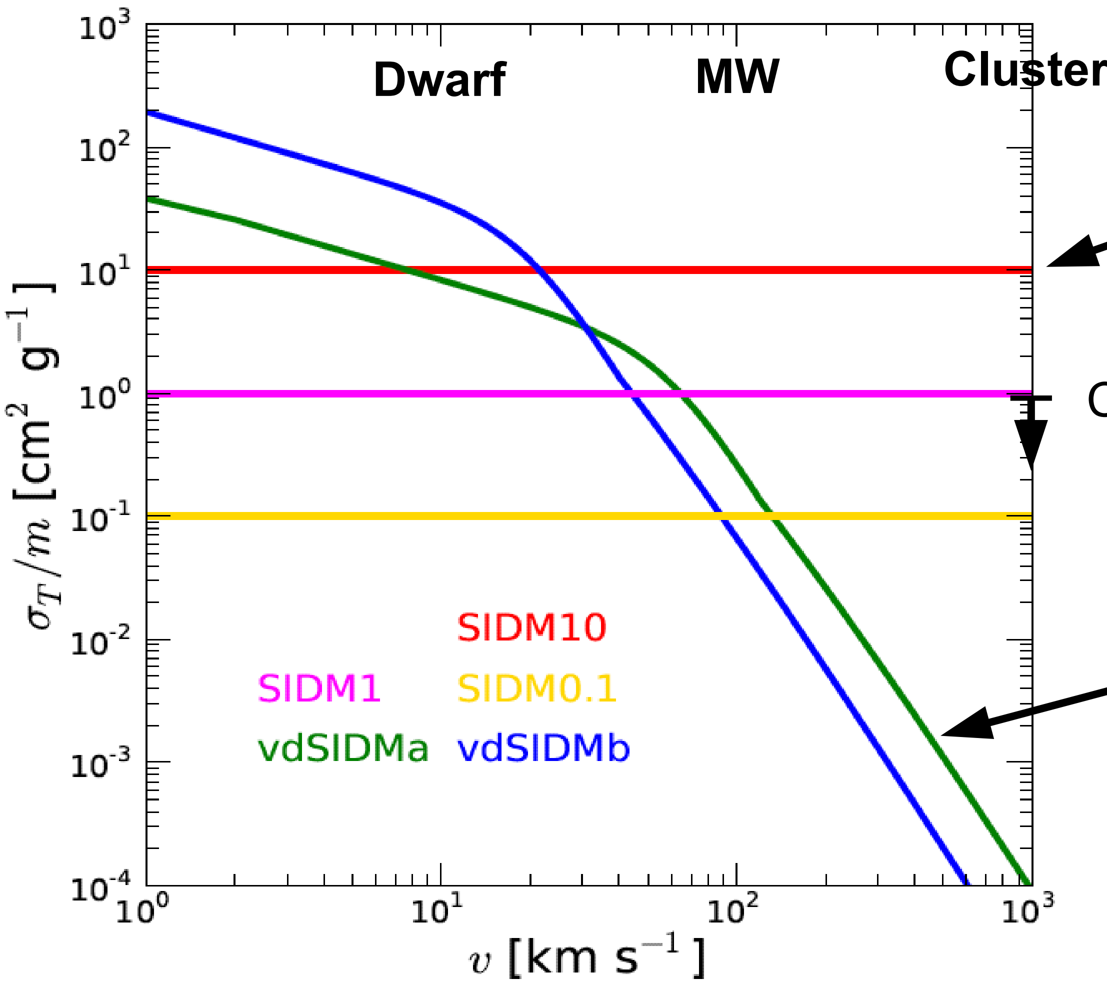
Concluding remarks

- **If** dwarf galaxies point to new DM physics, DM might be **collisional:**
  - DM cores, central spherical halo shapes, near-Maxwellian velocity distributions, are generic predictions of “astrophysically interesting” SIDM models
  - allowed vdSIDM (expected in hidden sector models) avoids cluster-constraints, solves the TBTF and core-cusp problems
  - cSIDM only works if $0.6\ cm^2/g < \sigma / m < 1\ cm^2/g$ (caveat: no baryonic effects)
  - elastic scattering does not reduce the abundance of dwarf-size haloes
  - the synergy between baryonic physics and DM collisions is an open question

EXTRA SLIDES

SIDM *N*-body simulations

Elastic scattering cross section (DM microphysics)

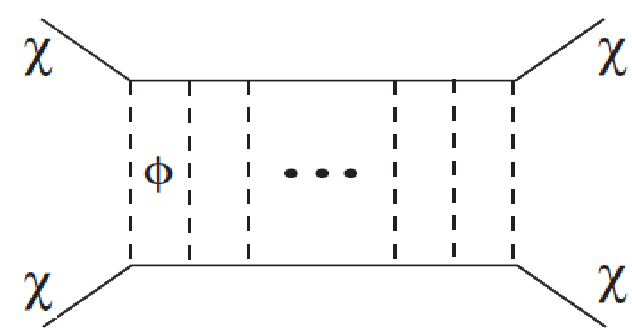


Vogelsberger, Zavala & Loeb 2012

"hard-sphere"
original idea introduced by
Spergel & Steinhardt 2000

Cluster constraints
(Peter+ 2012)

vdSIDM models motivated by a
new force in the "dark sector", e.g.
Yukawa-like, Loeb & Weiner 2011



SIDM *N*-body simulations: 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:

$$P_i = \sum_j P_{ij}/2$$

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

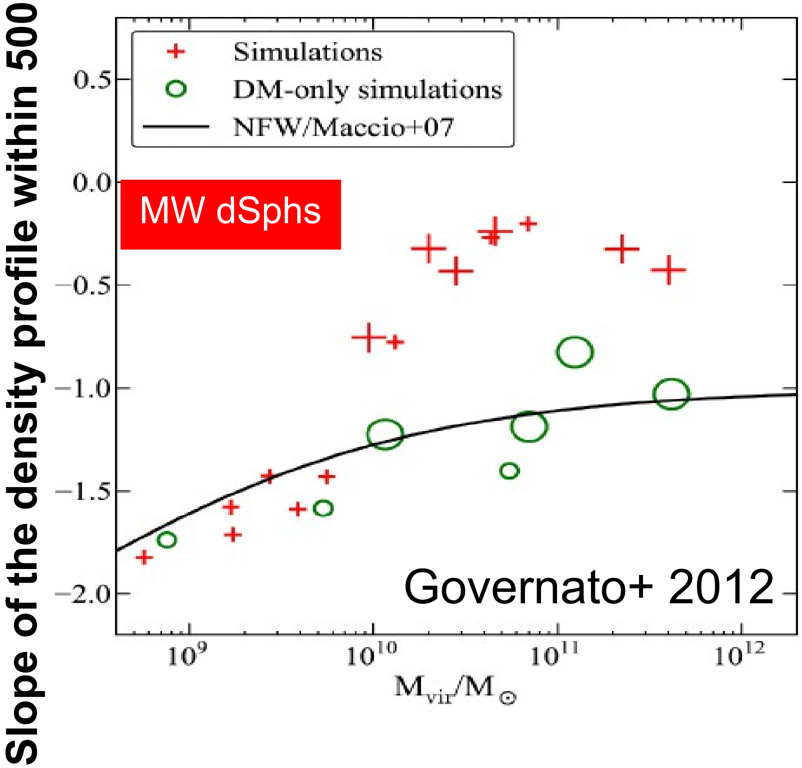
Looking at the bright side of the solution

Core-cusp problem

Early episodes of star formation and strong SN feedback

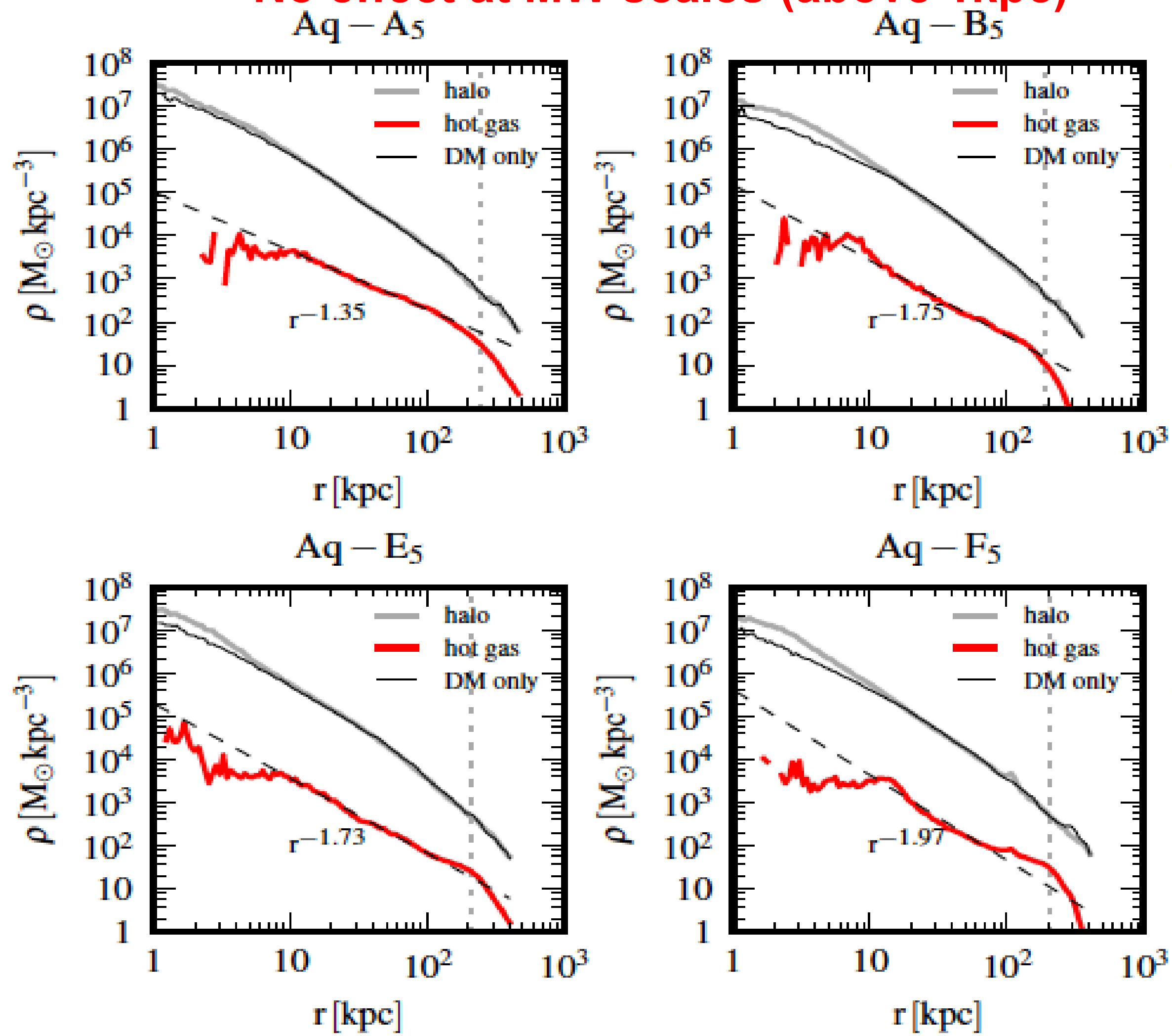
e.g. Navarro+ 1996, Governato+ 2012

Clear effect at intermediate masses



Marinacci+2013: MW-size galaxy simulations

No effect at MW scales (above 1kpc)



Convergence: inner subhalo distributions