

Dark Matter Distribution In Galactic SIDM Halos



Jesús Zavala Franco

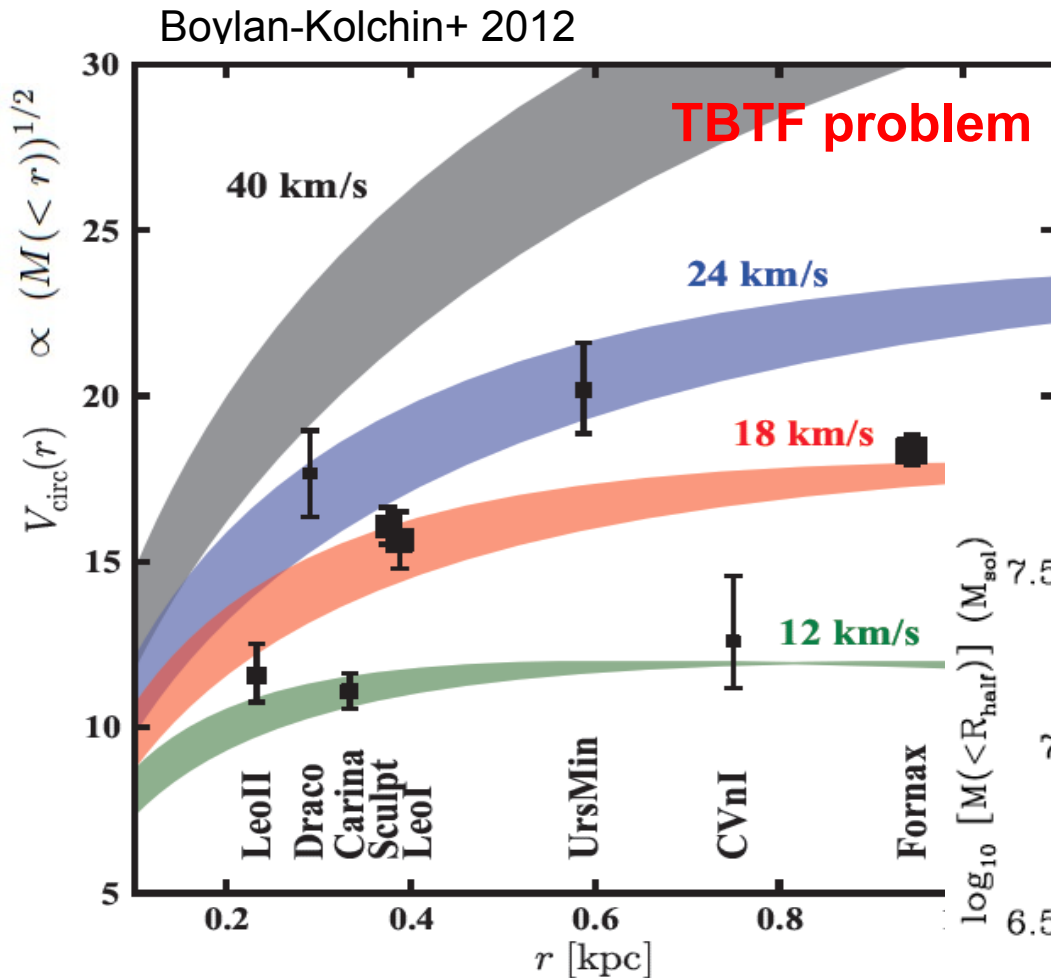


In collaboration with:

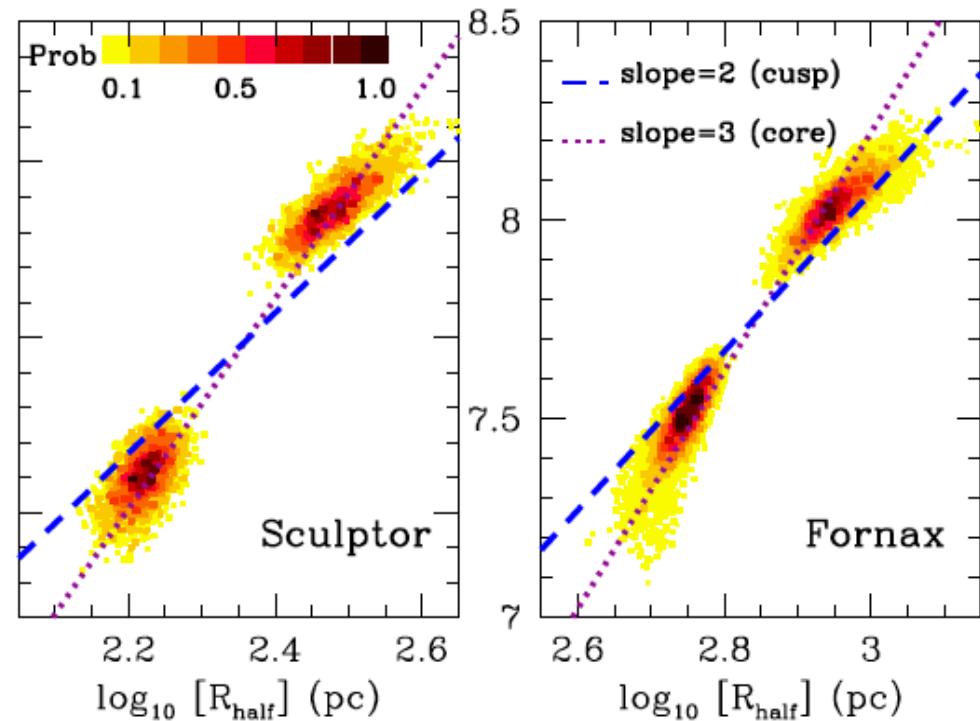
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Abraham Loeb (CfA, Cambridge)
Matt Walker (CfA, Cambridge)

Harvard SIDM Workshop, Cambridge, August 2013

CDM challenges: clues of new DM physics or lessons on galaxy formation?



The core-cusp problem



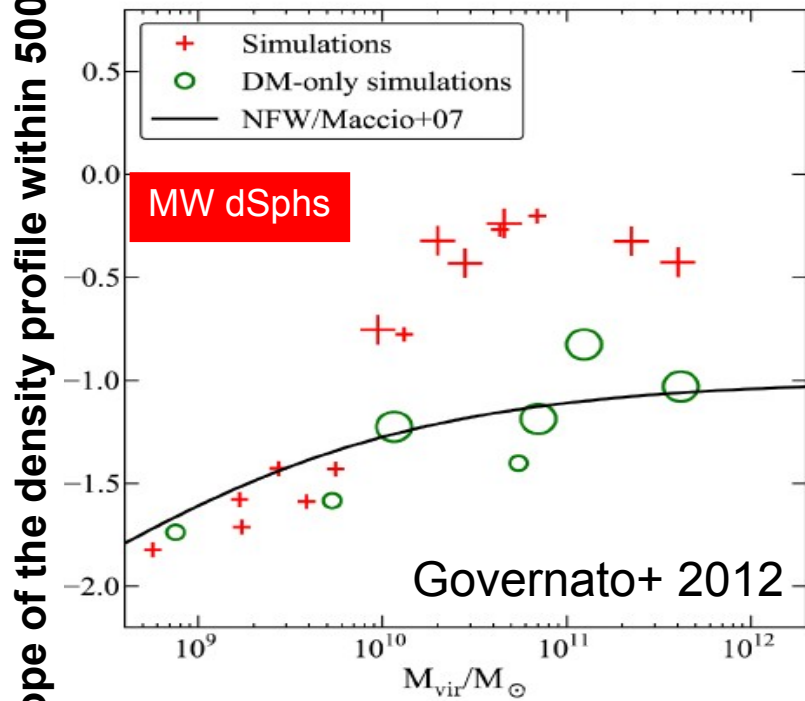
Looking at the bright side of the solution

Core-cusp problem

Early episodes of star formation and strong SN feedback

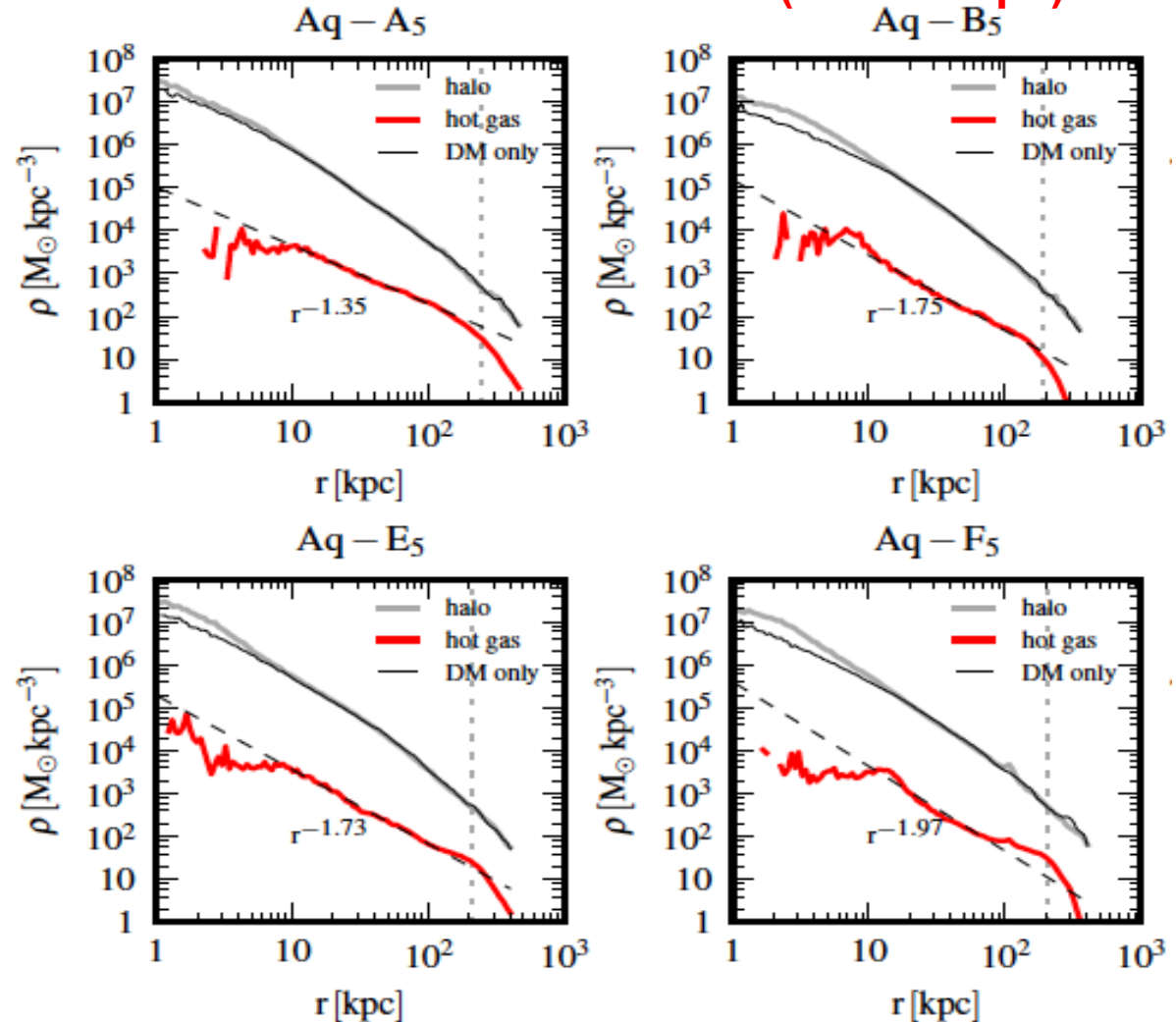
e.g. Navarro+ 1996, Governato+ 2012

Clear effect at intermediate masses

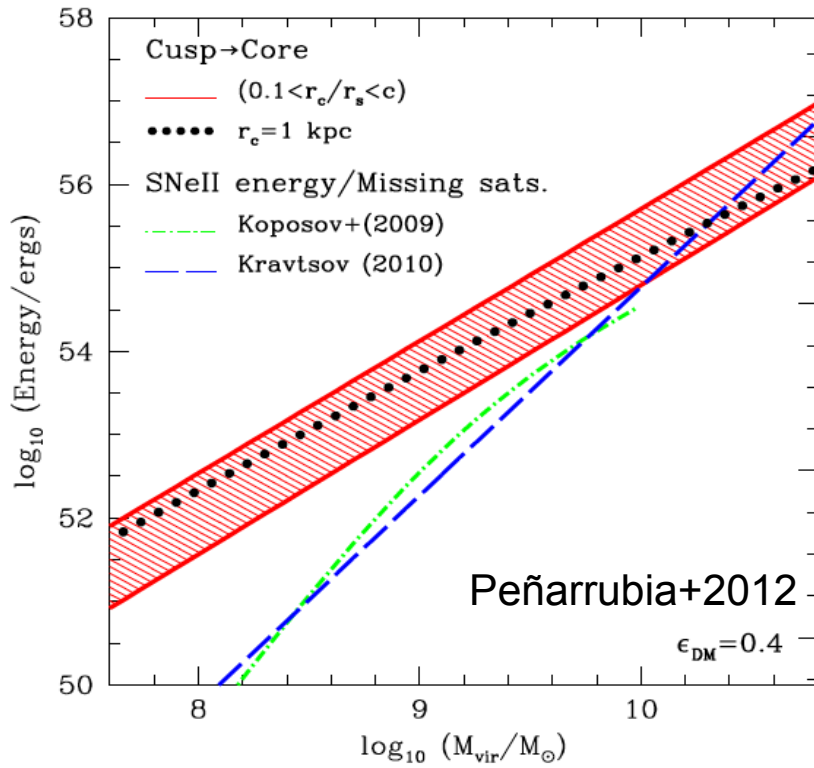


Marinacci+2013: MW-size galaxy simulations

No effect at MW scales (above 1kpc)



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

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

Environmental effects (tidal stripping)
 Zolotov+2012, Brooks & Zolotov 2012

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

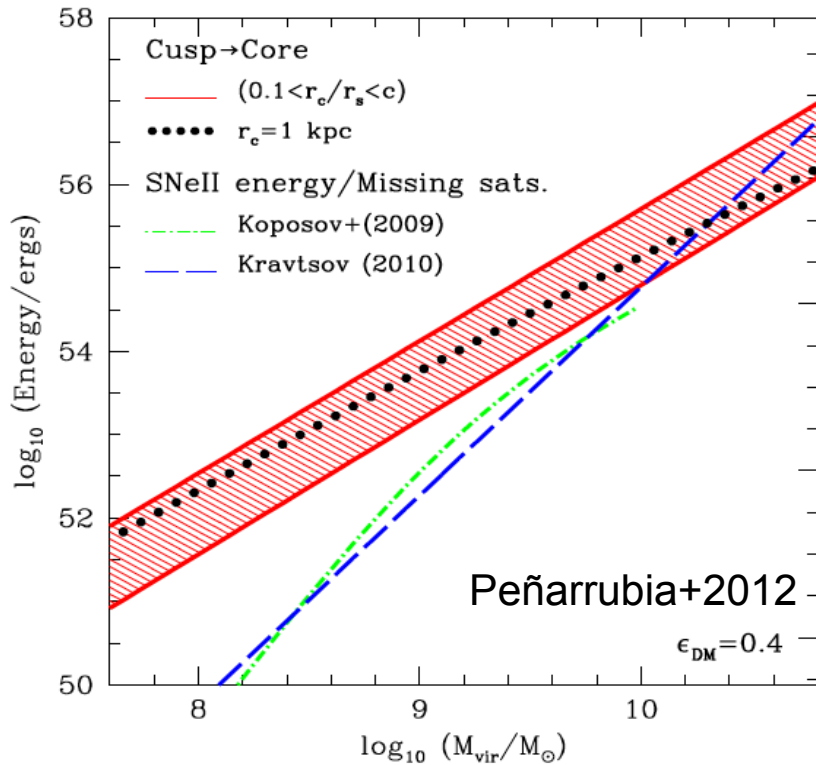
Fornax

Sculptor

$$r_{\text{peri}} / r_{\text{apo}} : 0.78^{+0.17}_{-0.50}$$

$$0.56^{+0.30}_{-0.46}$$

Looking at the bright side of the solution



Too big to fail problem

The halo of the Milky Way is less massive than $10^{12} M_{\text{Sun}}$
 e.g. Wang+ 2012, Vera-Ciro+ 2013

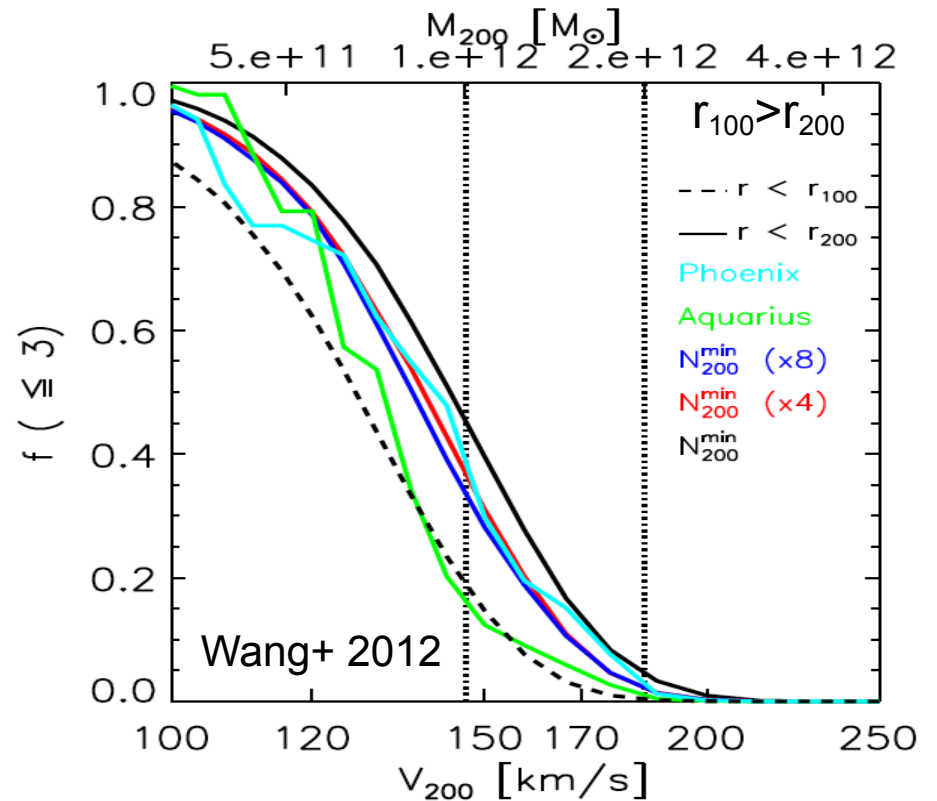
Current obs. estimates: $\sim 1-2 \times 10^{12} M_{\text{Sun}}$
 Probability of bound Magellanic Clouds:
 $\sim 20\%$ ($M_{\text{halo}} = 10^{12} M_{\text{Sun}}$)

Core-cusp problem

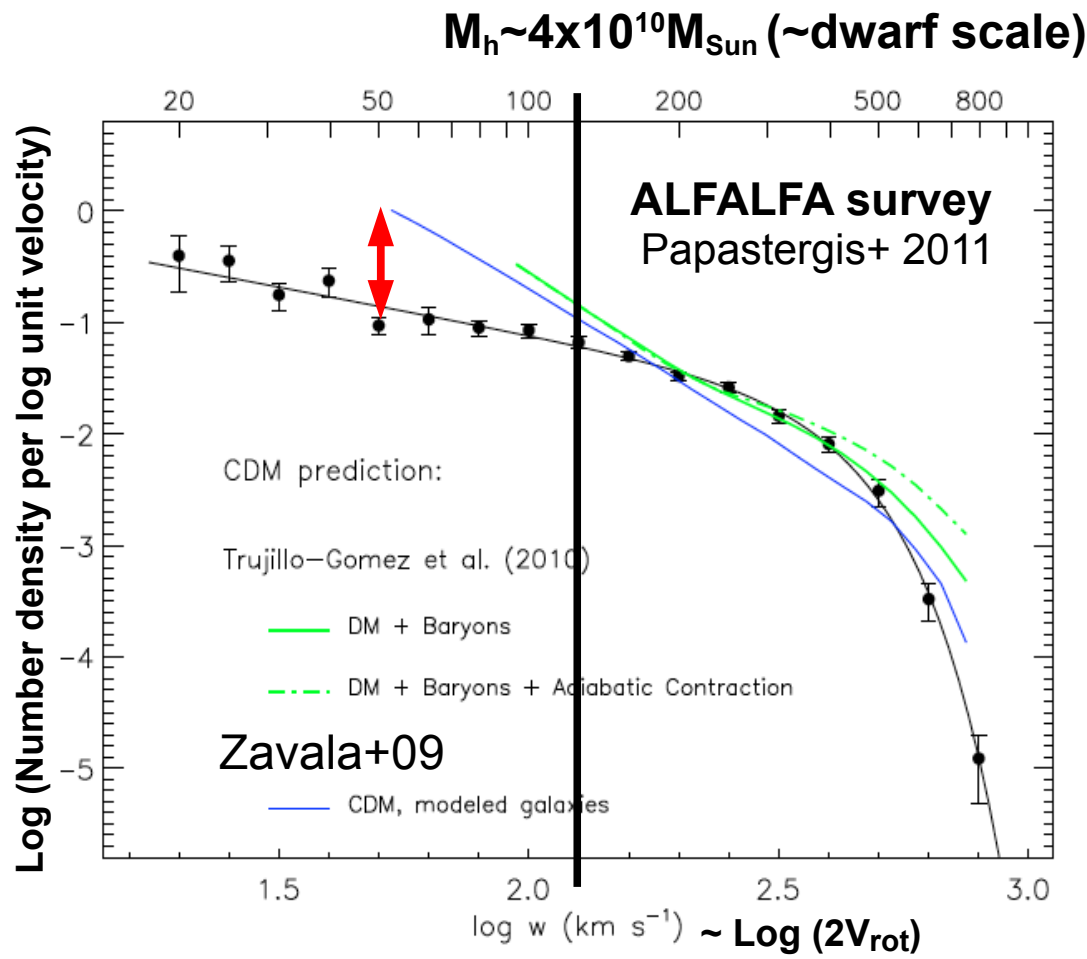
Early episodes of star formation and strong SN feedback
 e.g. Navarro+ 1996, Governato+ 2012

SN feedback in MW dSphs: likely insufficient for dSphs
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Probability that a halo contains 3 or fewer Subhaloes with $V_{\text{max}} > 30$ km/s



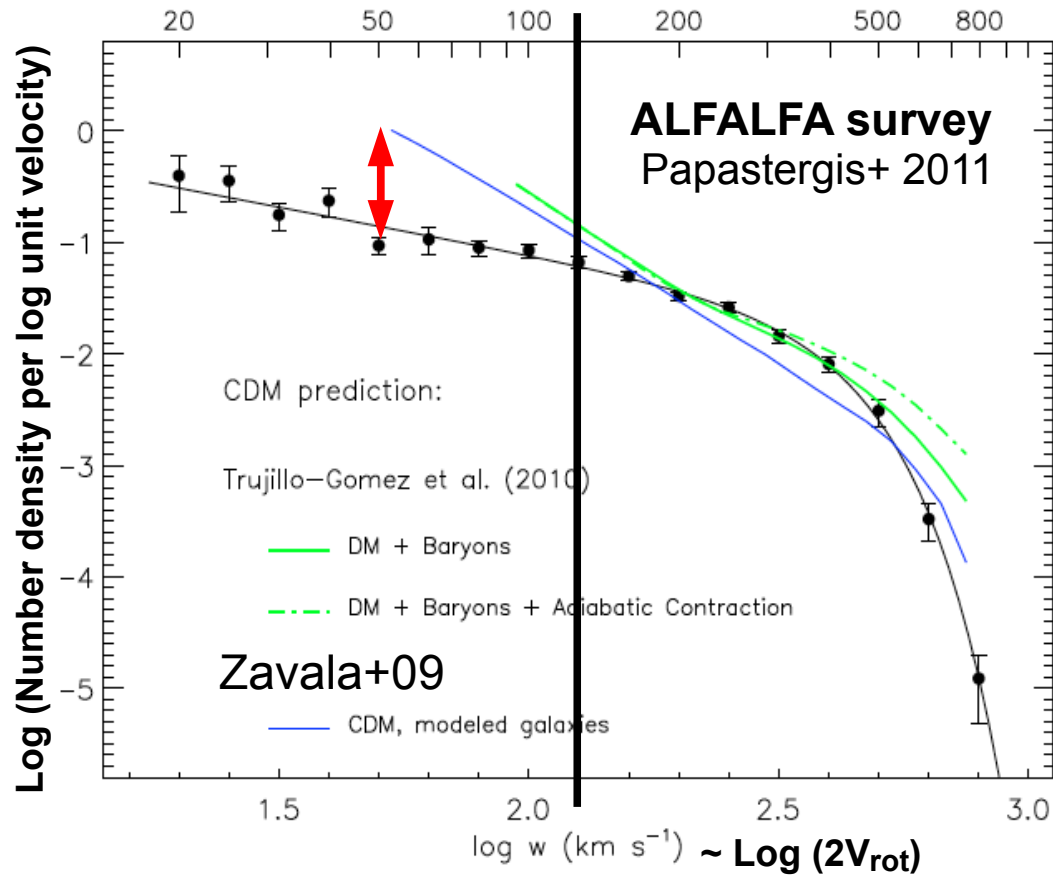
Overabundance problem in the field



CDM + several simplified form. models seem to overpredict the abundance of field dwarfs

Overabundance problem in the field

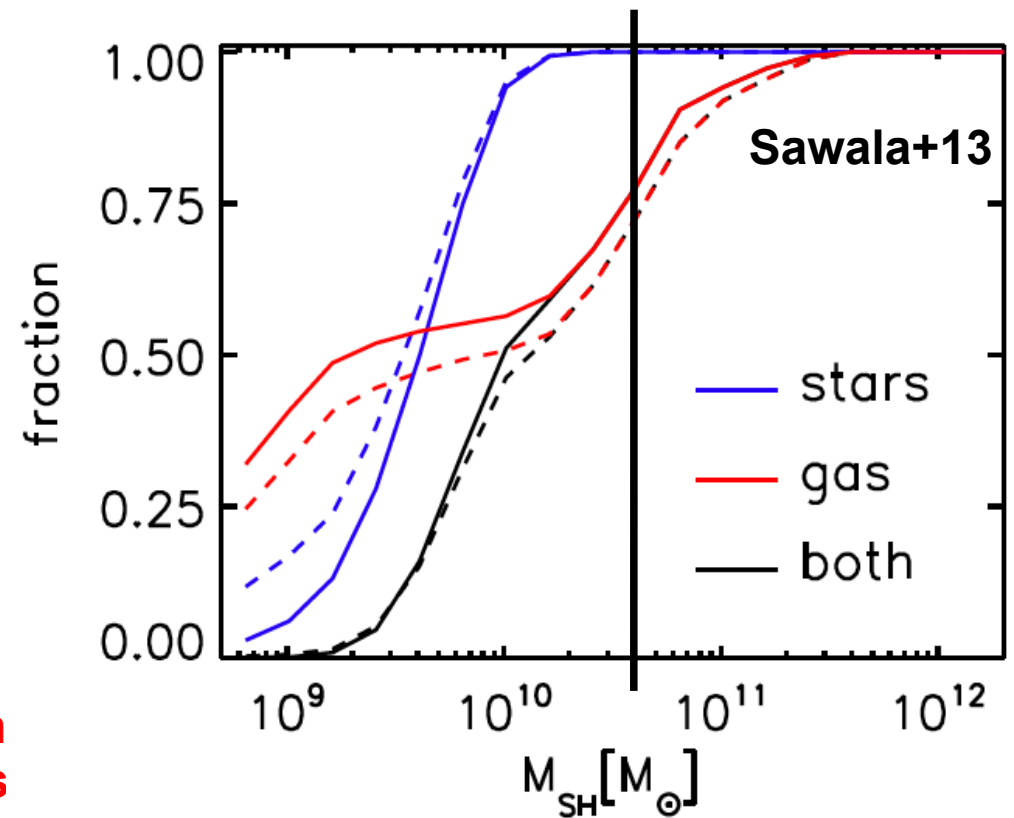
$M_h \sim 4 \times 10^{10} M_{\text{Sun}}$ (~dwarf scale)



CDM + several simplified form. models seem to overpredict the abundance of field dwarfs

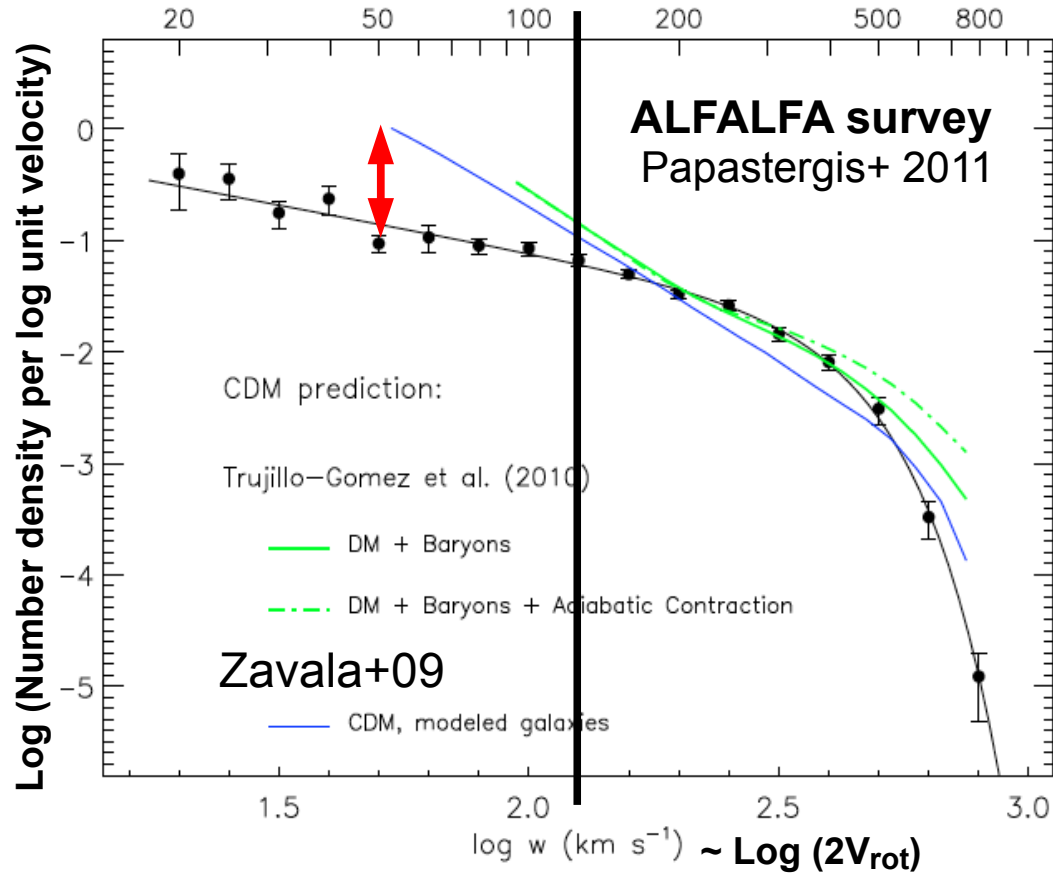
strong suppression of cold gas in dwarf-scale haloes

GIMIC simulations ("full" baryonic physics)



Overabundance problem in the field

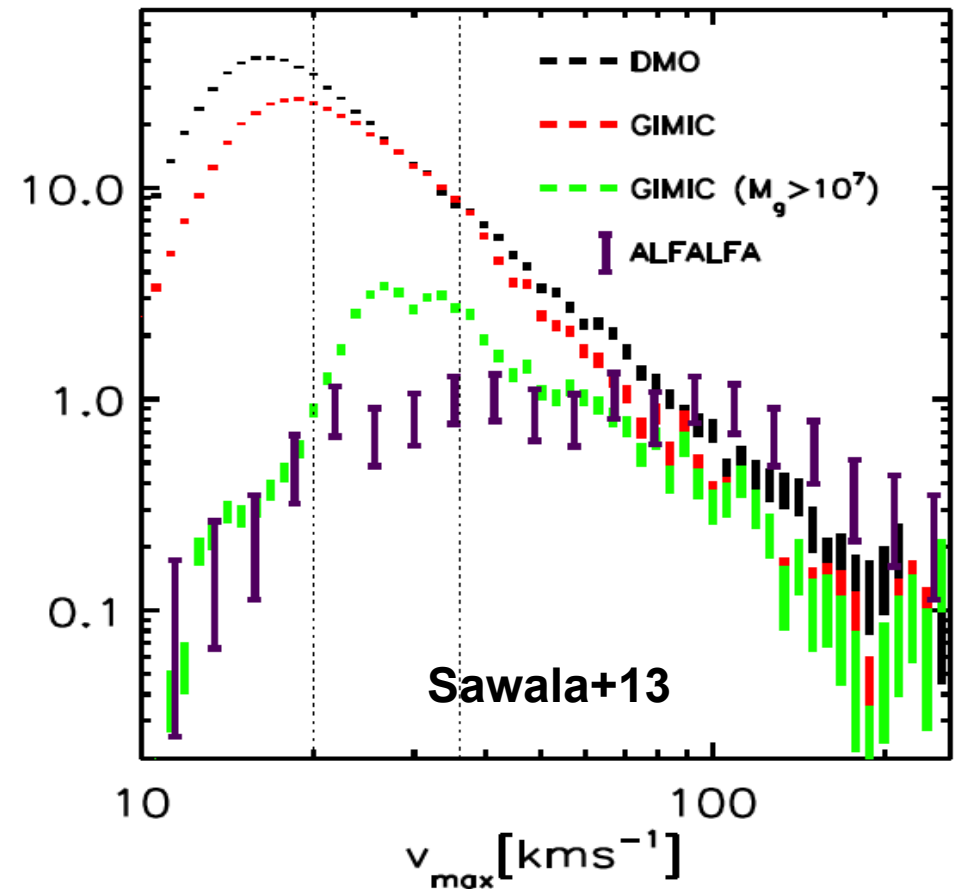
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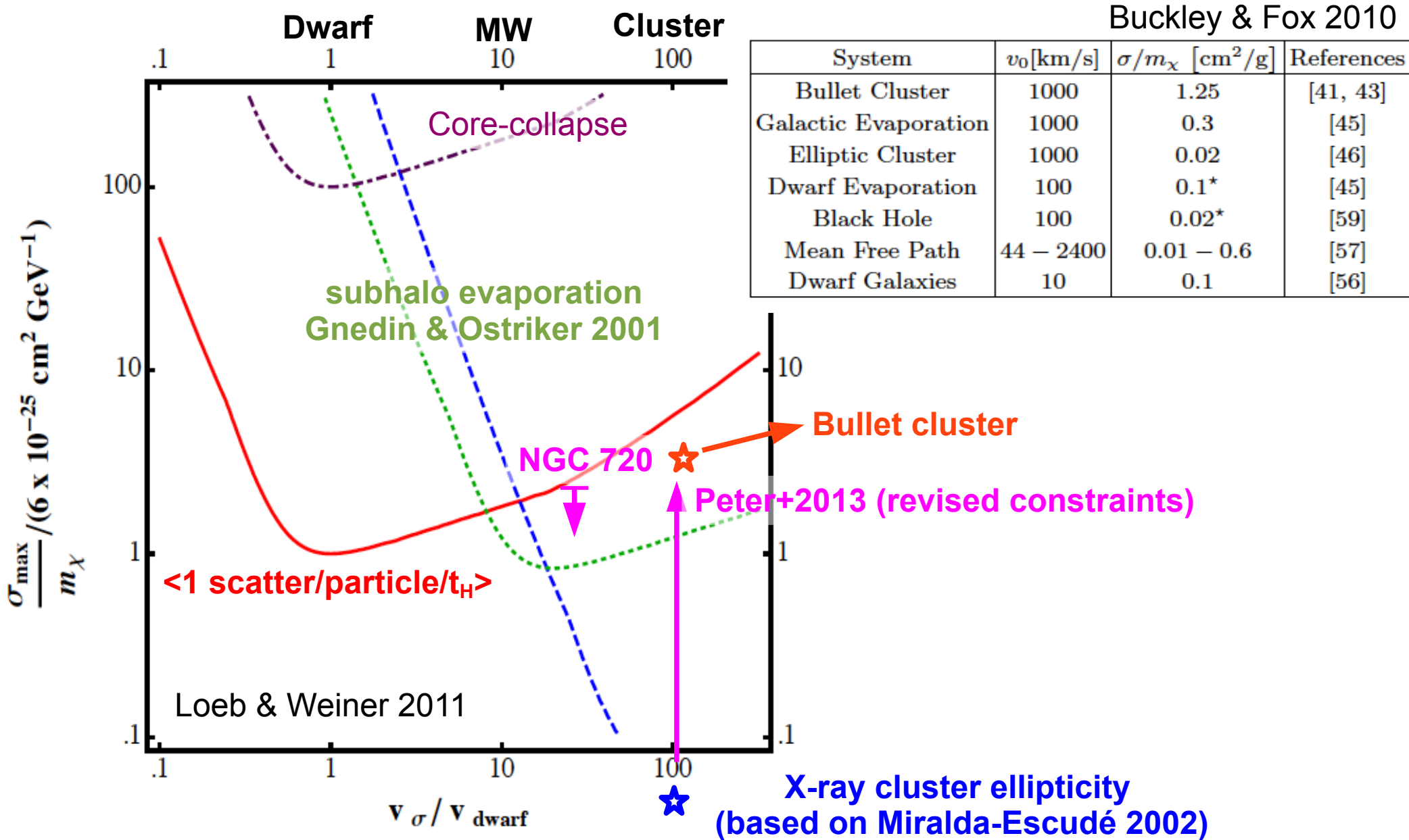
GIMIC simulations (“full” baryonic physics)



Another possibility: underestimation of the true DM potential (hints in Swaters+ 2009)

Constraints on collisional DM

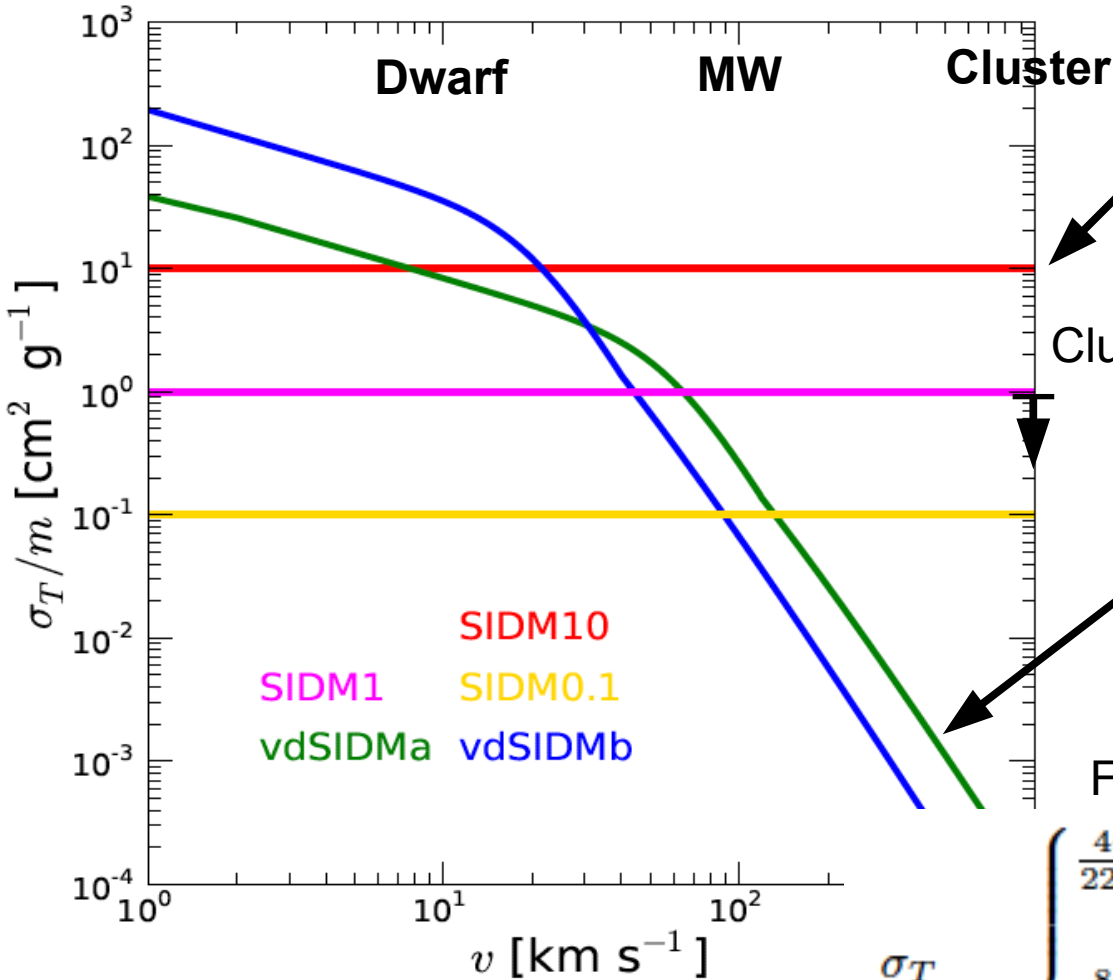
How collisionless DM is, and at what scales, ultimately depends on observations



SIDM N -body simulations

Elastic scattering cross section (SIDM microphysics)

Vogelsberger, Zavala & Loeb 2012



“hard-sphere”
original idea introduced by
Spergel & Steinhardt 2000

Cluster constraints
(Peter+ 2013)

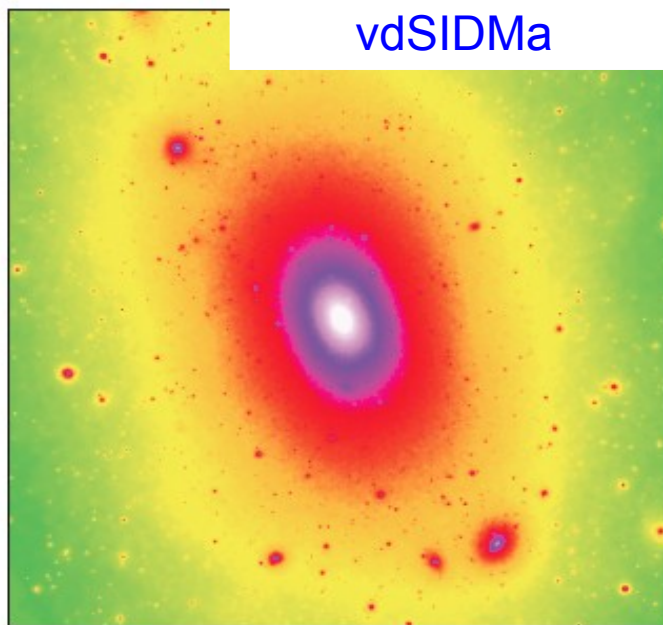
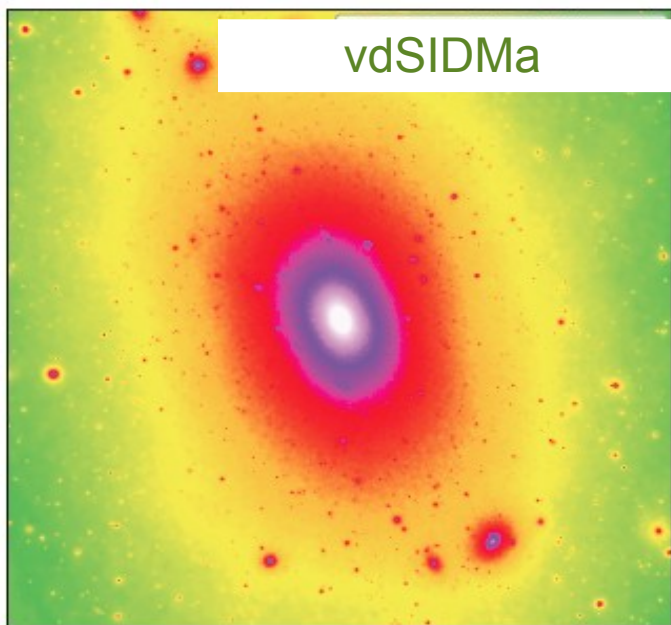
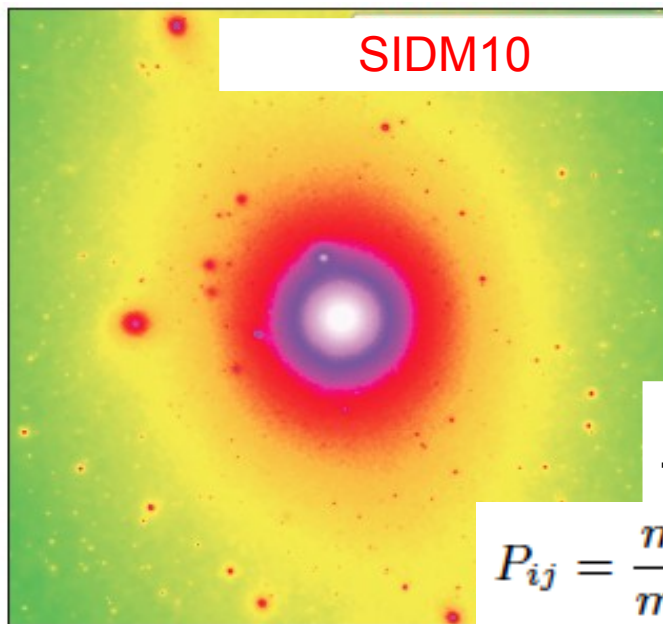
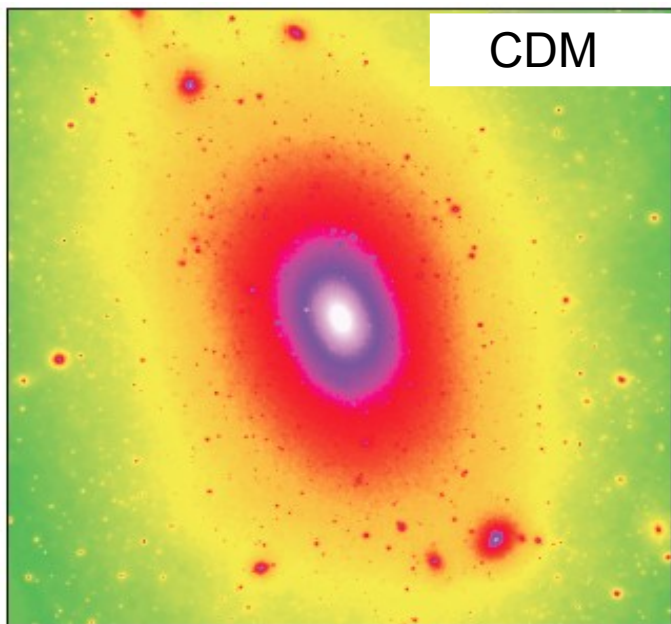
**vdSIDM models motivated by a
new force in the “dark sector”,**
e.g. Yukawa-like, (e.g. Feng+09,
Feng+10, Loeb & Weiner 2011)

From plasma physics (Khrapak+03+04)

$$\frac{\sigma_T}{\sigma_{T\max}} \approx \begin{cases} \frac{4\pi}{22.7} \beta^2 \ln(1 + \beta^{-1}), & \beta < 0.1 \\ \frac{8\pi}{22.7} \beta^2 (1 + 1.5\beta^{1.65})^{-1}, & 0.1 < \beta < 10^3 \\ \frac{\pi}{22.7} (\ln\beta + 1 - \frac{1}{2}\ln^{-1}\beta)^2, & \beta > 10^3, \end{cases}$$

SIDM N -body simulations

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



Probabilistic method
for elastic scattering

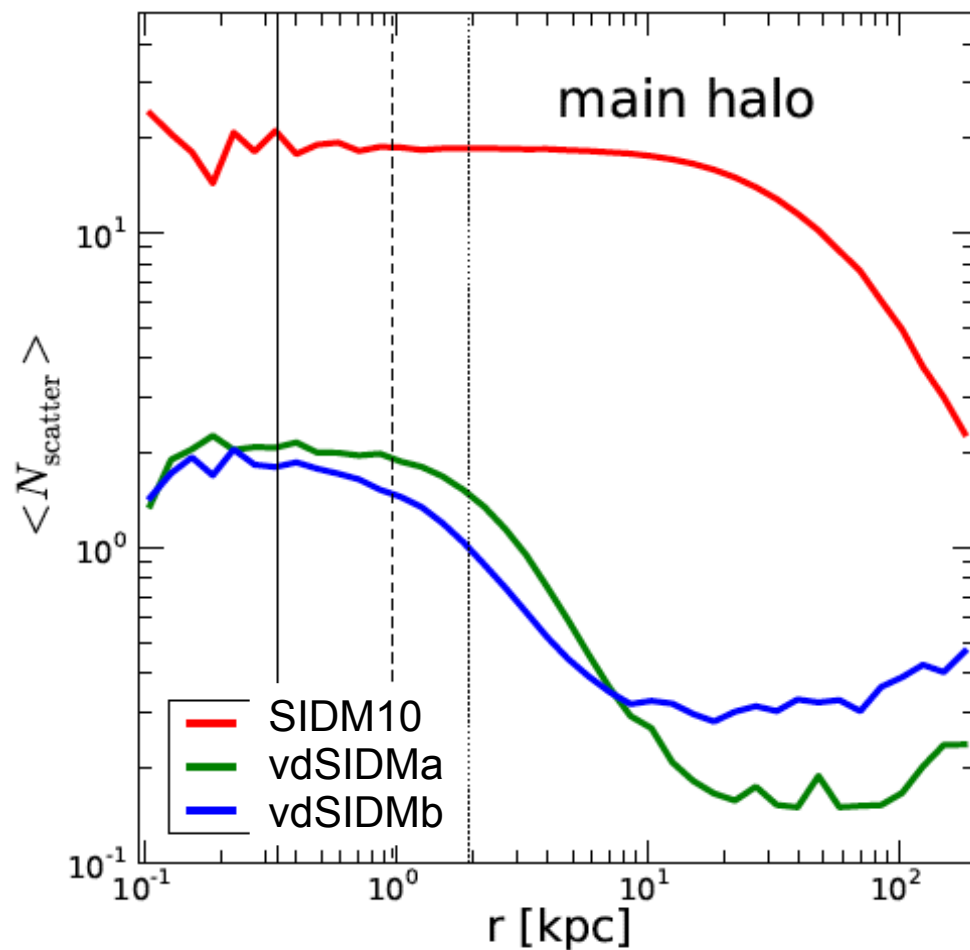
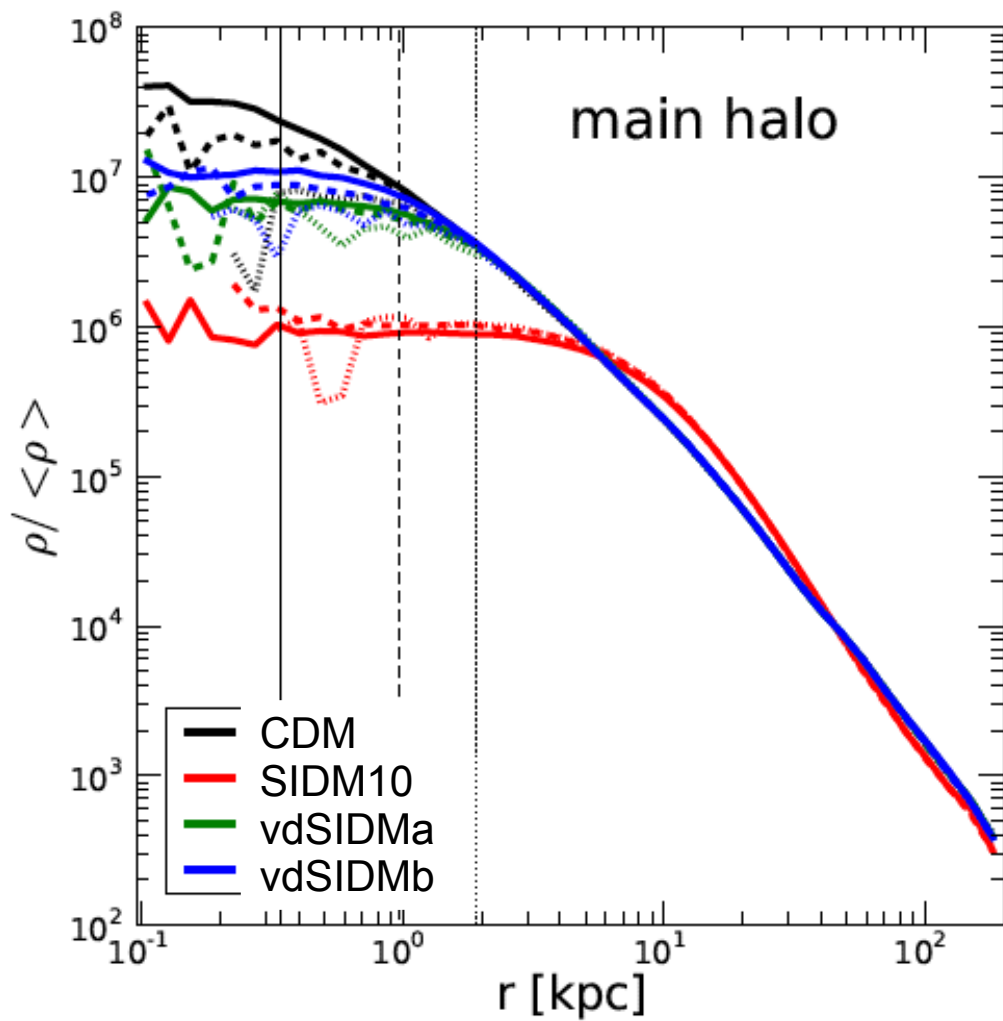
$$P_{ij} = \frac{m_i}{m_\chi} W(r_{ij}, h_i) \sigma_T(v_{ij}) v_{ij} \Delta t_i$$

Resolution

$m_p [M_\odot]$	$\epsilon [\text{pc}]$
4.911×10^4	120.5
$M_{200} [M_\odot]$	$r_{200} [\text{kpc}]$
1.836×10^{12}	245.64

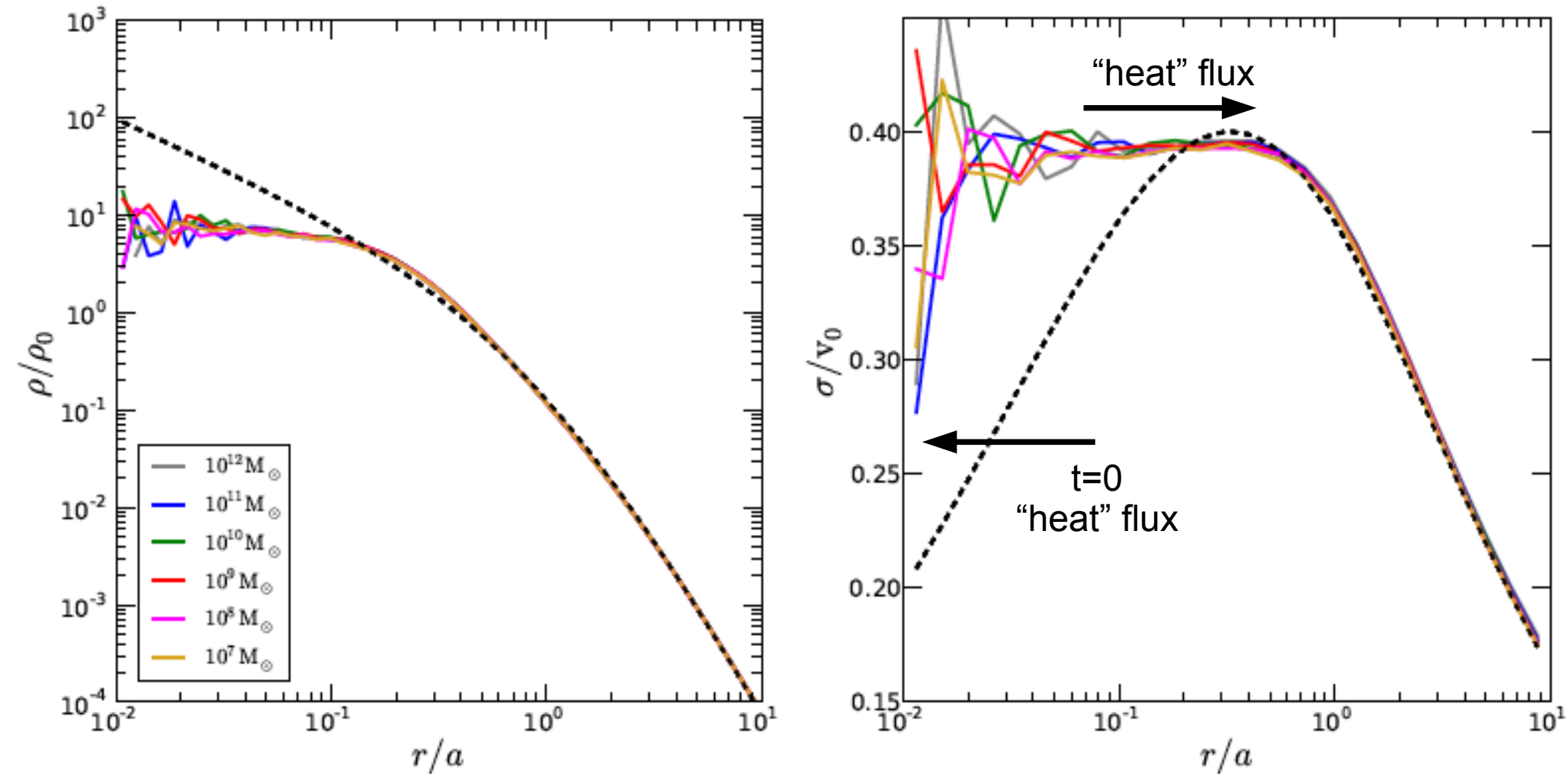
DM collisions (~ a few per particle in a Hubble time in the denser regions)
create density cores and isotropize the orbits

SIDM N -body simulations: the main halo



Forming a core through collisions

Constant cross section case

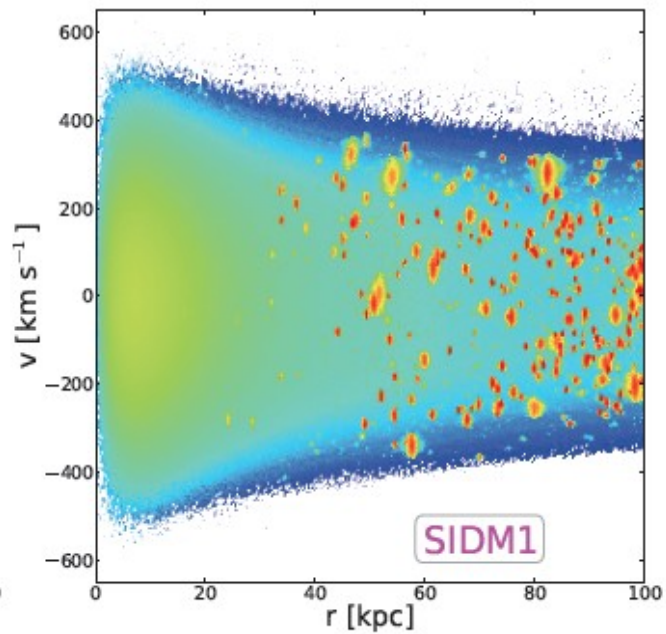
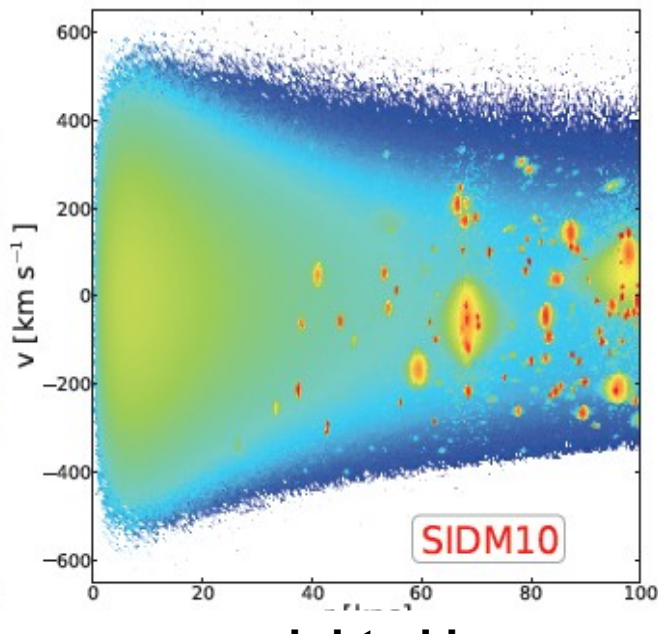
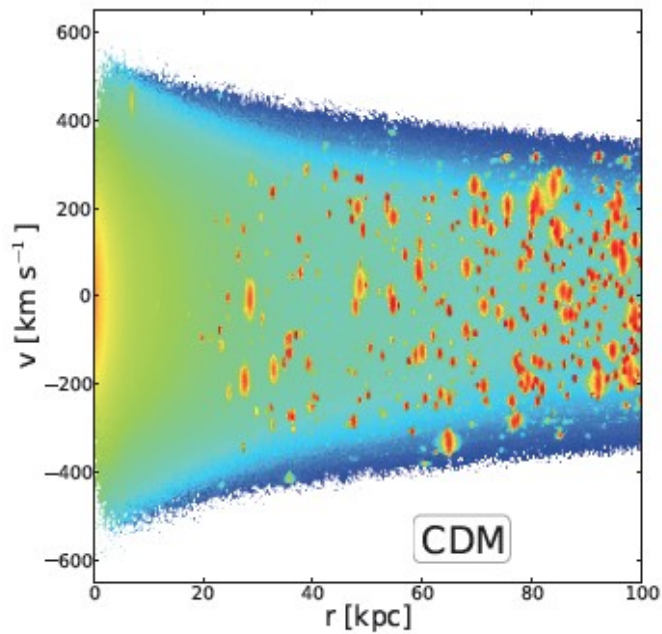


Vogelsberger, Zavala & Loeb 2012

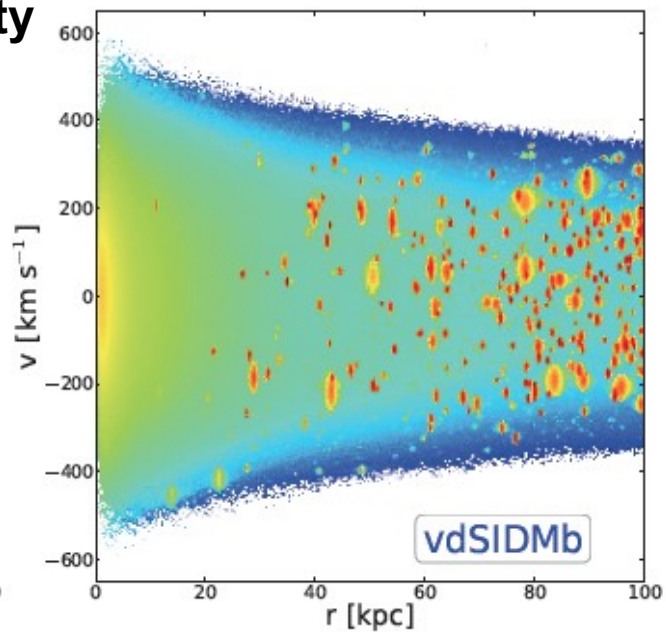
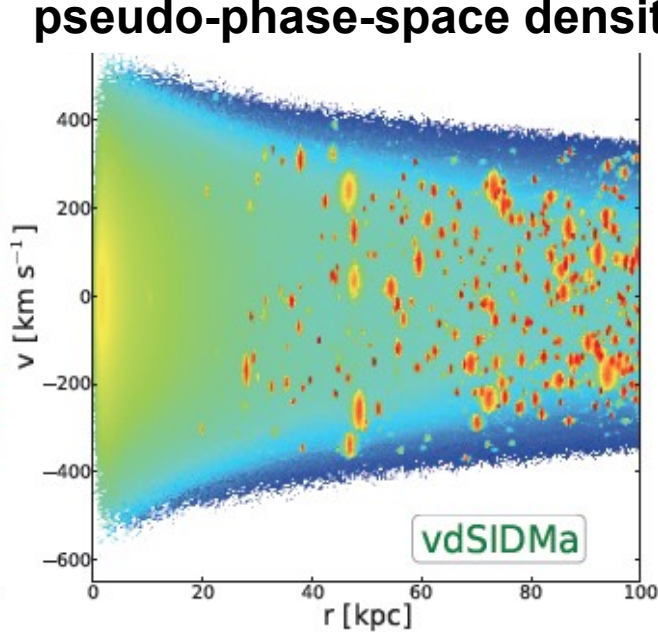
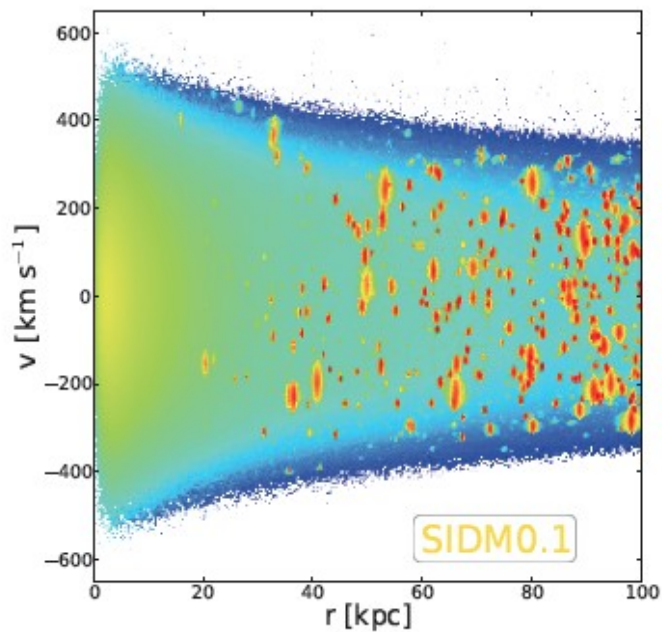
Nicely described in Colín+02

Phase-space distribution in SIDM

Vogelsberger & Zavala
2012

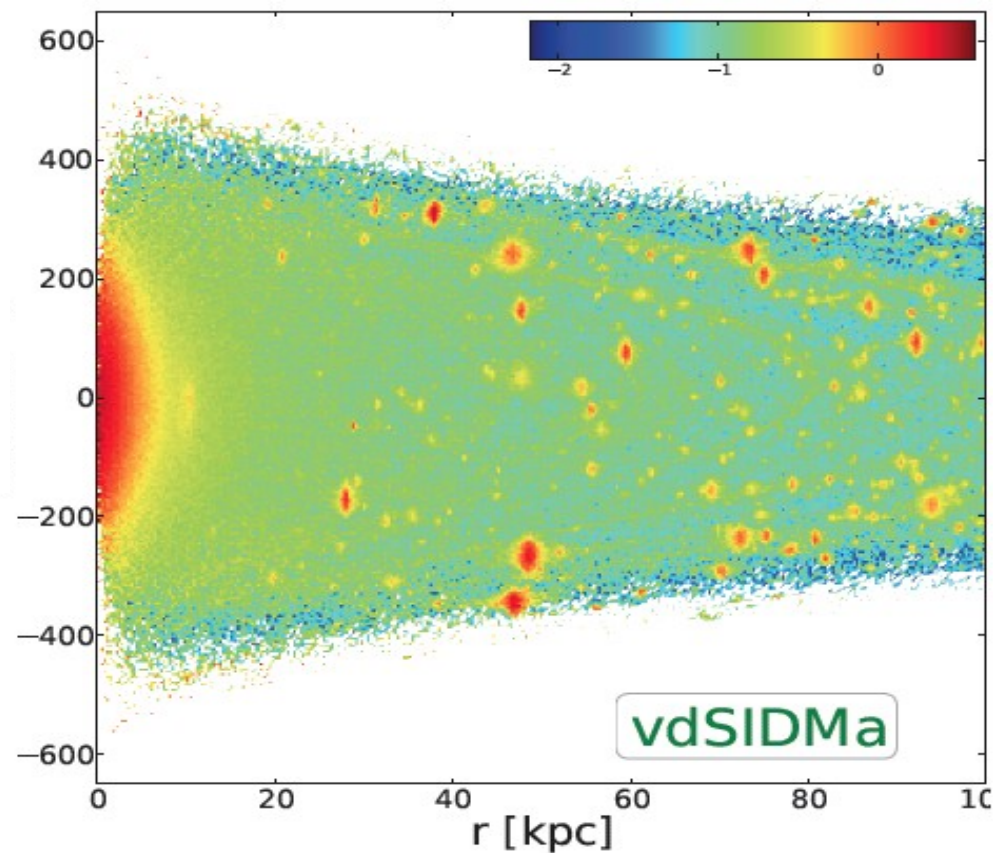
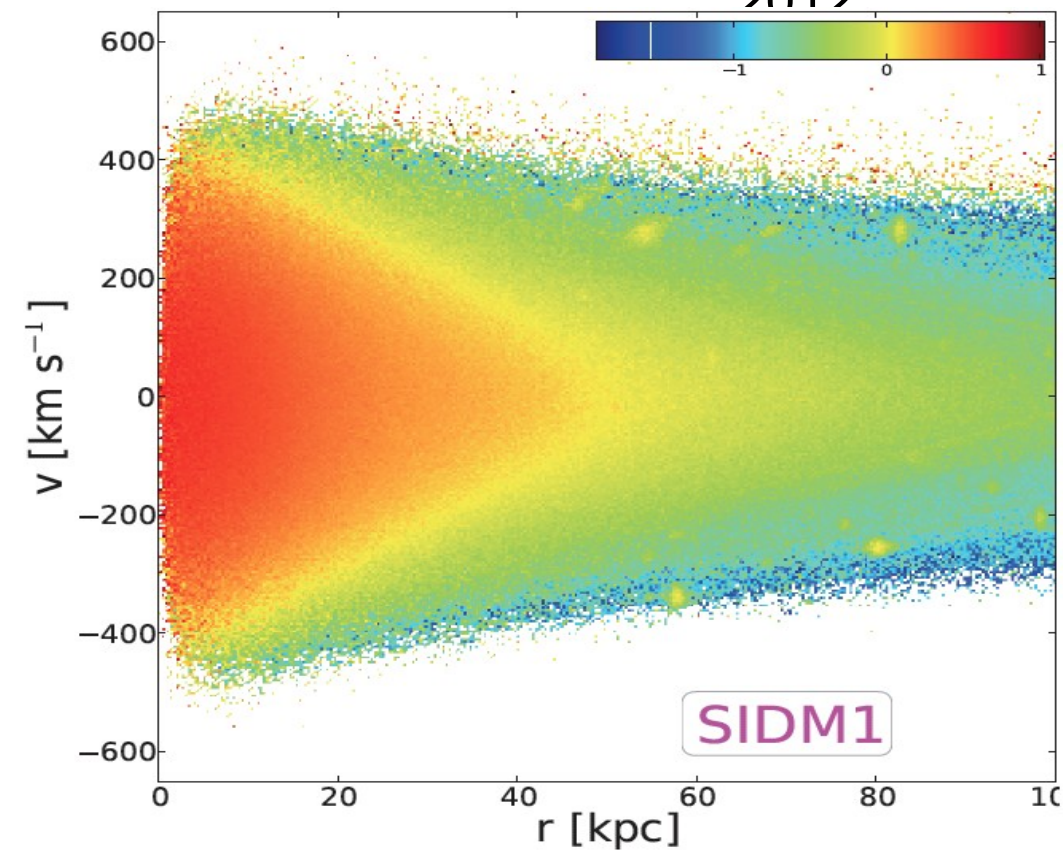


weighted by
pseudo-phase-space density



Distribution of scattering events in SIDM

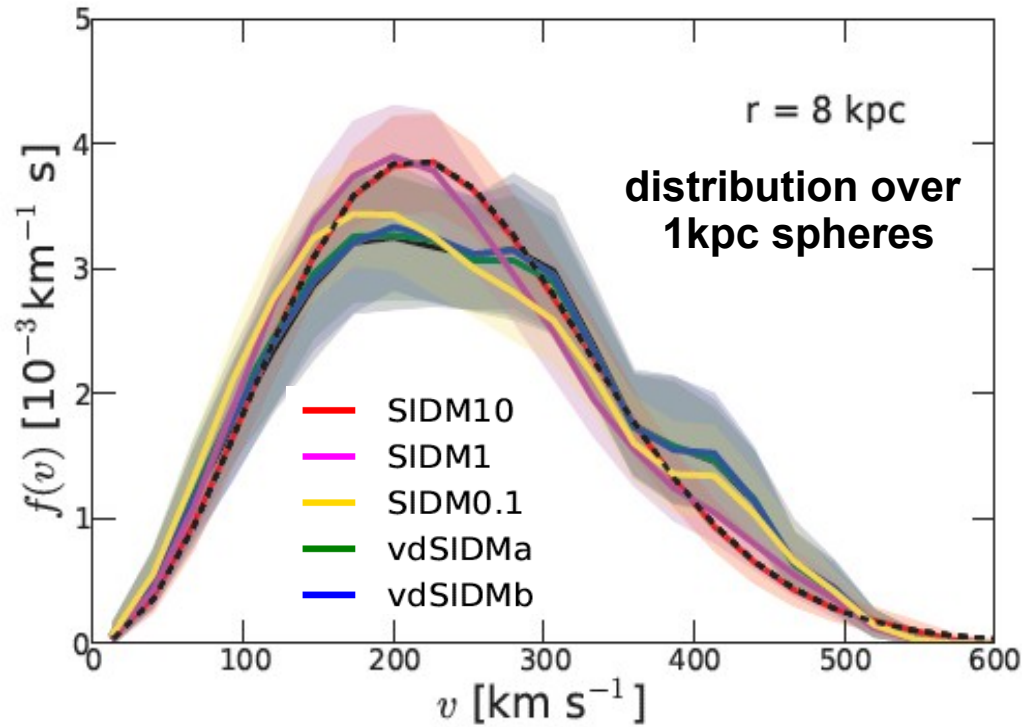
Vogelsberger & Zavala
2012



Weighted by average # scatters

“Local” SIDM velocity distribution: impact on direct detection

Vogelsberger & Zavala 2012

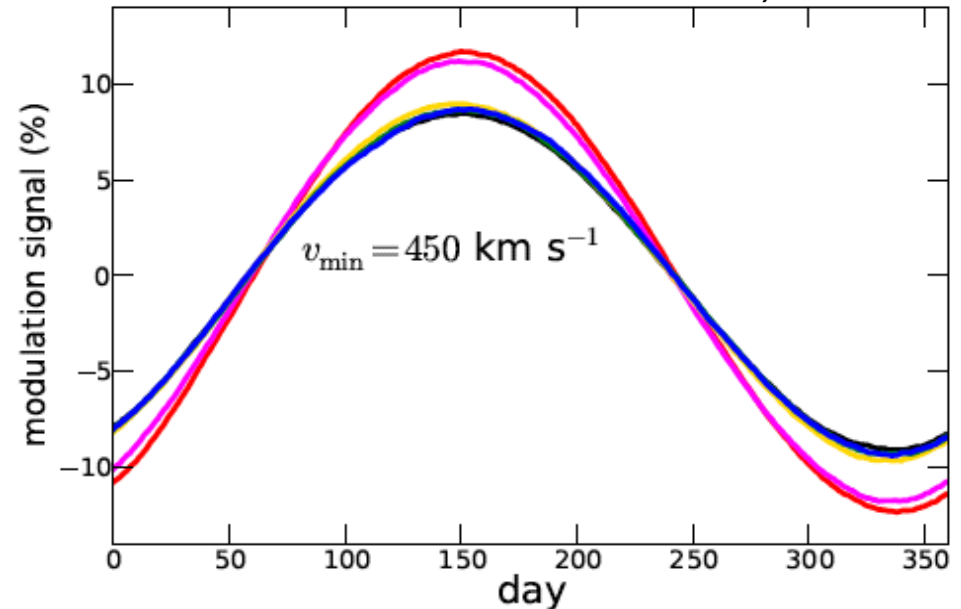
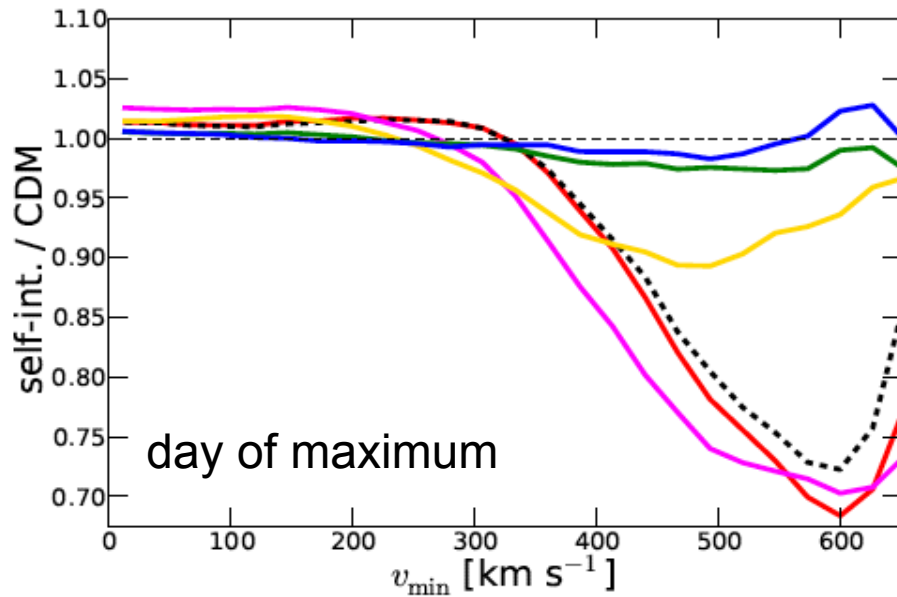


$$T(v_{\min}(E), t) = \int_{v_{\min}(E)}^{\infty} \frac{f_v(t)}{v} dv$$

Elastic collision, E =nucleus recoil energy

$$v_{\min}(E) = \left(\frac{E (m_\chi + m_N)^2}{2m_\chi^2 m_N} \right)^{1/2}$$

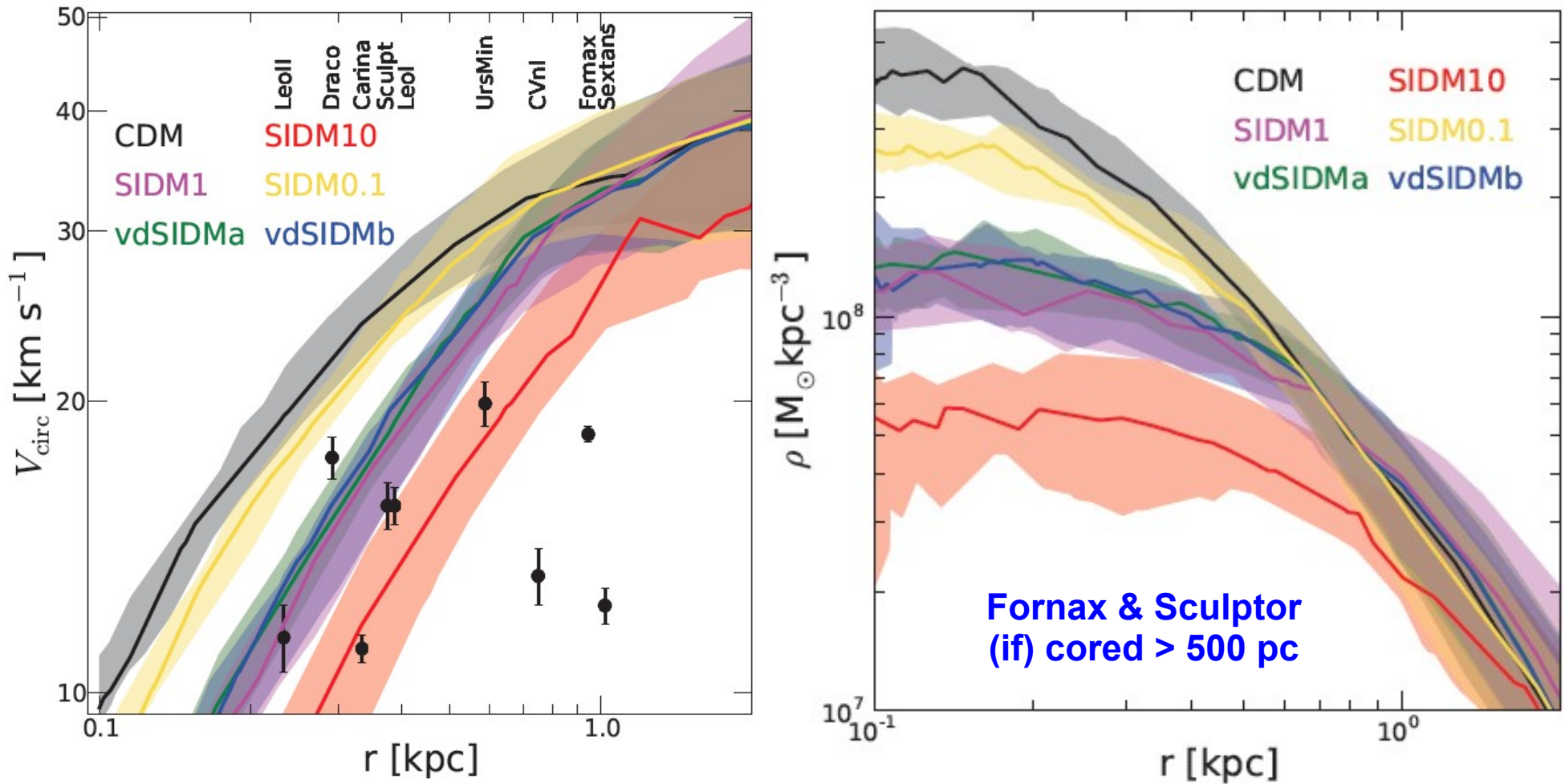
Modulation signal relative to average over the year (due to Earth's motion relative to the DM halo)



DM distribution in SIDM subhaloes

Clusters/ellipticals put an upper limit to the cross section $\sim 1 \text{ cm}^2/\text{g}$,
the MW satellites put a lower limit on SIDM as a distinct alternative to CDM

Zavala, Vogelsberger & Walker 2013

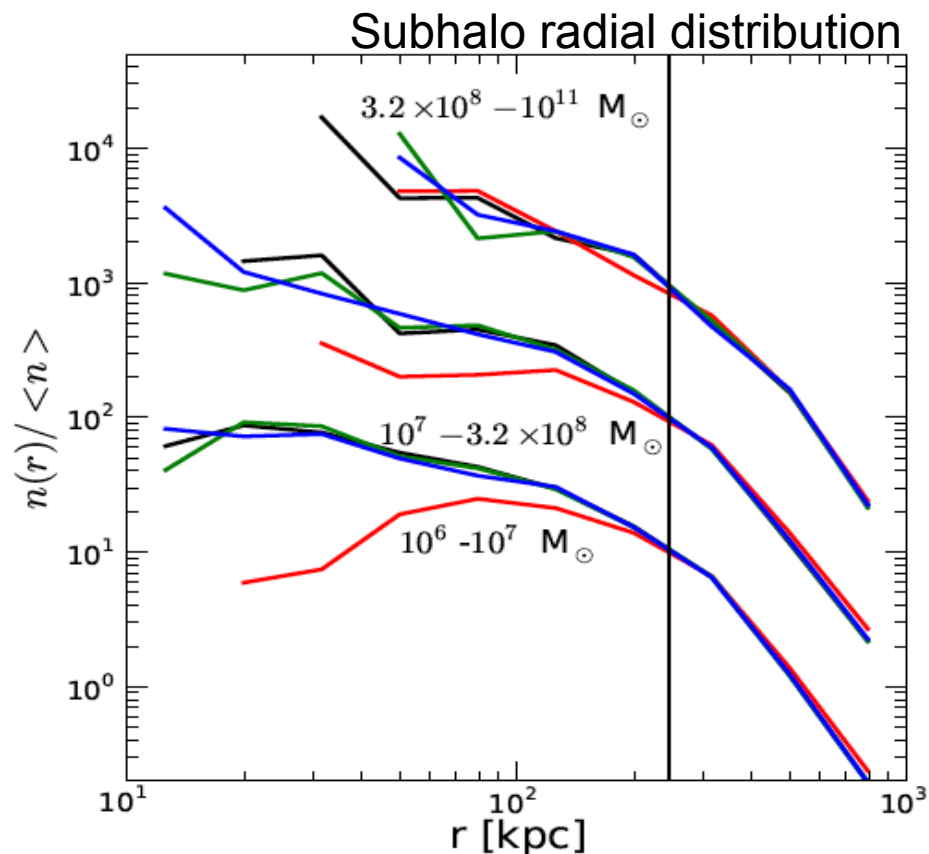
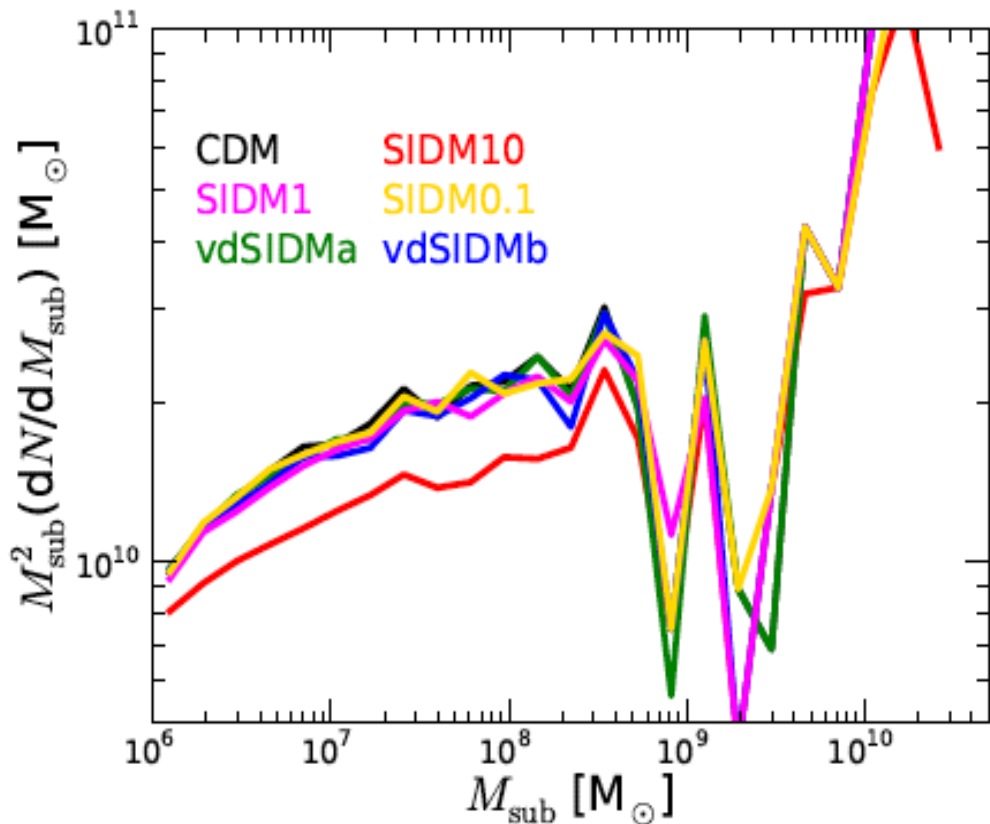


We show that SIDM solves the too big to fail problem and the core-cusp problem
only if $0.6 \text{ cm}^2/\text{g} < \sigma / m < 1 \text{ cm}^2/\text{g}$ or velocity-dependent cross section

Caveat: DM-only simulations!!

Subhalo abundance in SIDM

(allowed) elastic SIDM gives the same abundance as CDM:
it does NOT solve the missing satellite problem

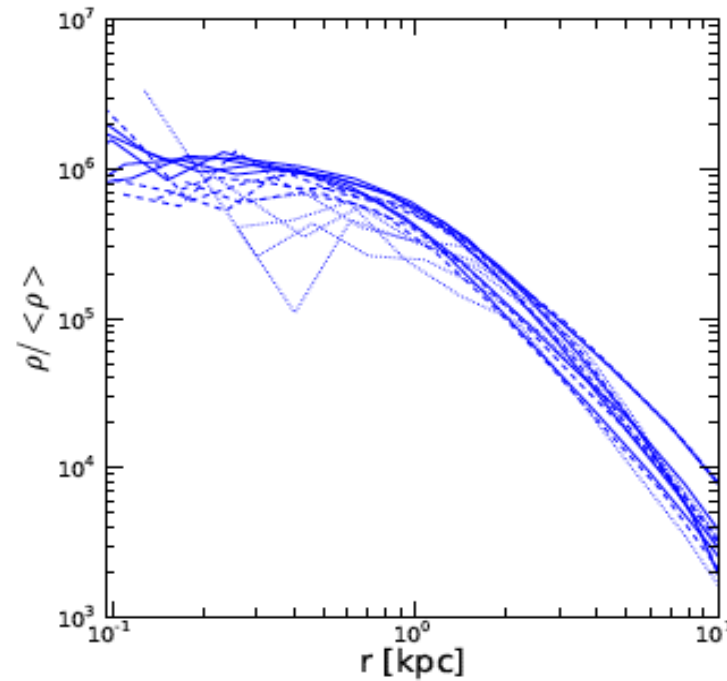
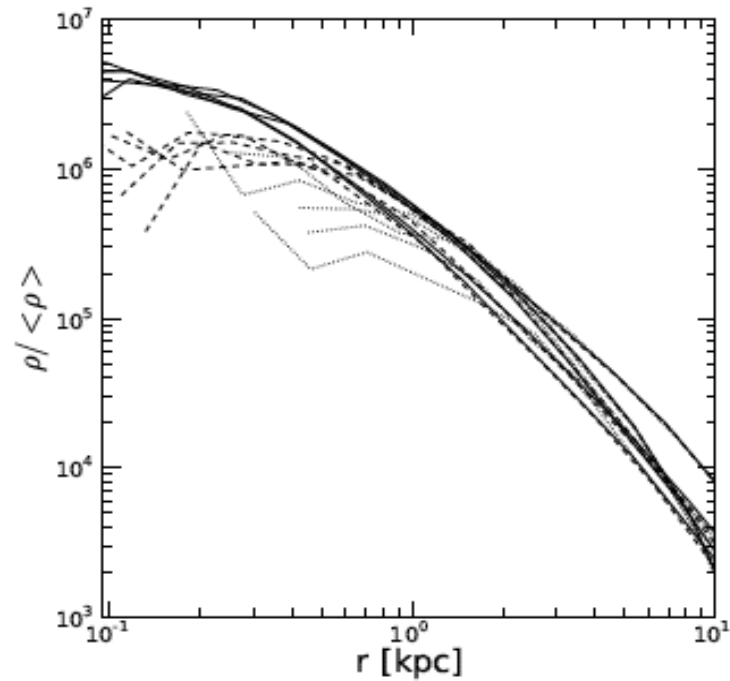
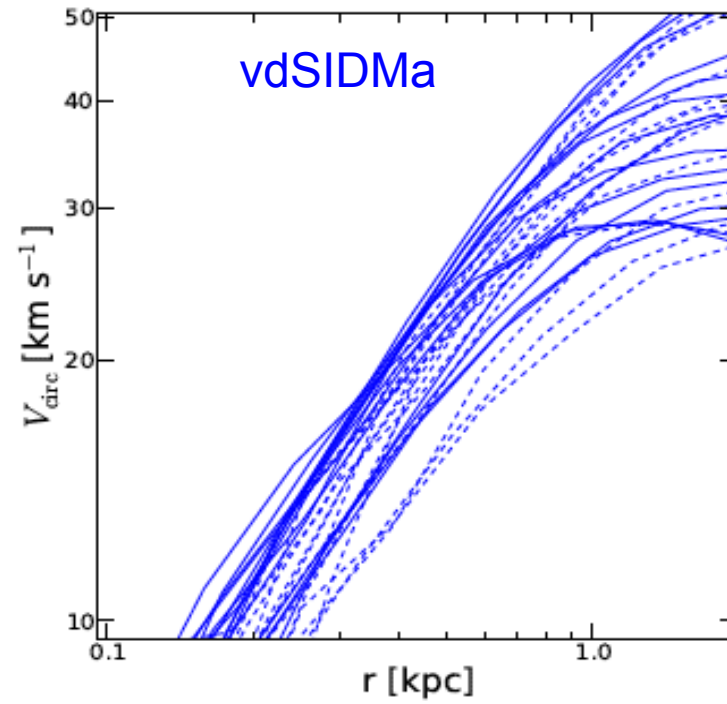
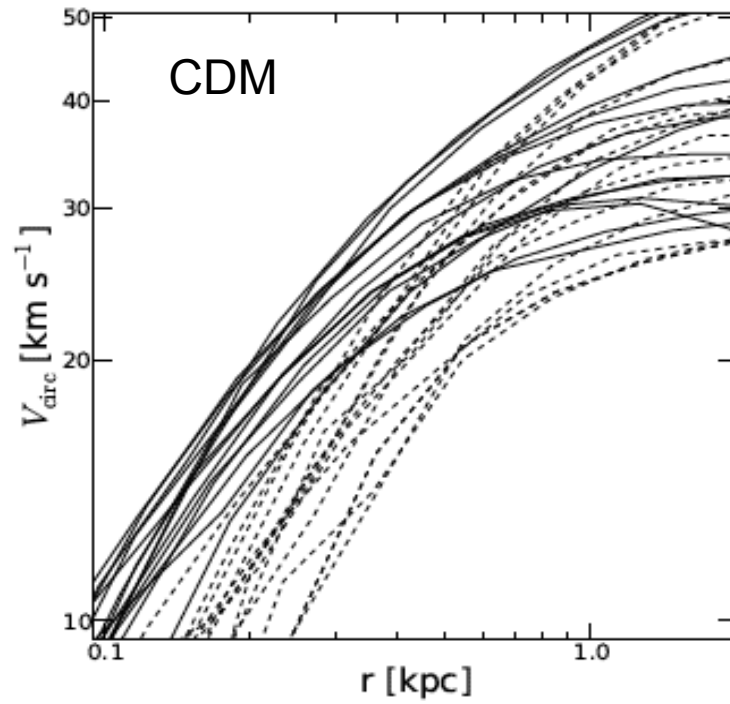


Inelastic scattering (excited states of DM) might lead to
the evaporation of low-mass subhaloes

$$\chi\chi^* \rightarrow \chi\chi$$

$$\sqrt{\delta/m} \sim v_{\text{esc}}$$

Convergence: inner subhalo distributions



Concluding remarks

- Challenging times for the standard DM model (CDM + WIMPs)
 - experiments reaching the “expected” WIMP cross sections (Fermi, Xenon100,...)
 - **dwarf-scale challenges** (TBTF problem, core-cusp problem)
- The bright side:
 - **Extreme?** energy injection into DM, low MW-halo mass, environment??
- Do dwarf galaxies point to new DM physics?
 - DM might be **collisional**: SIDM (e.g. hidden sector DM)
 - **vdSIDM naturally avoids cluster-constraints, solves the TBTF and core-cusp problems**
 - cSIDM only works if $0.6 \text{ cm}^2/\text{g} < \sigma / m < 1 \text{ cm}^2/\text{g}$
(caveat: no feedback effects)
 - elastic scattering does not reduce the abundance of dwarf-size haloes
 - DM collisions modify the local velocity distribution (impact on direct detection)