Dark Matter Distribution In Galactic SIDM Halos

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In collaboration with:

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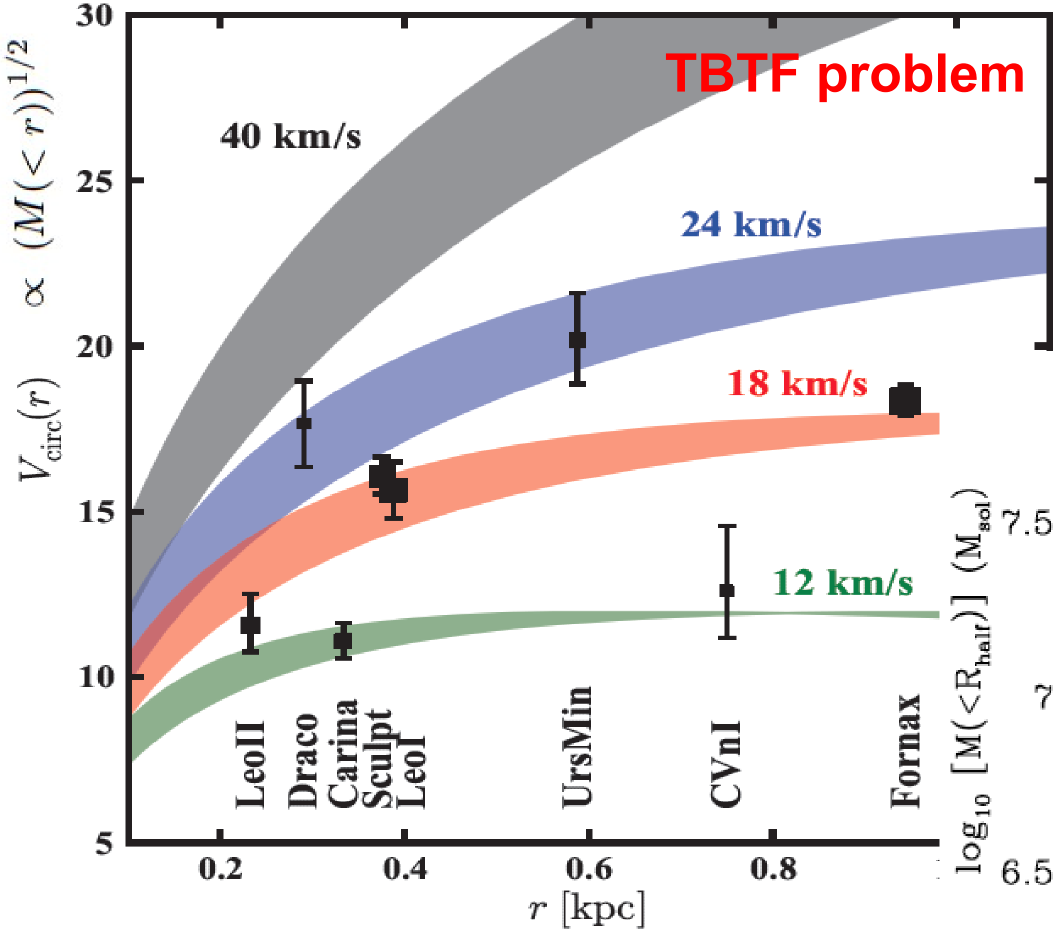
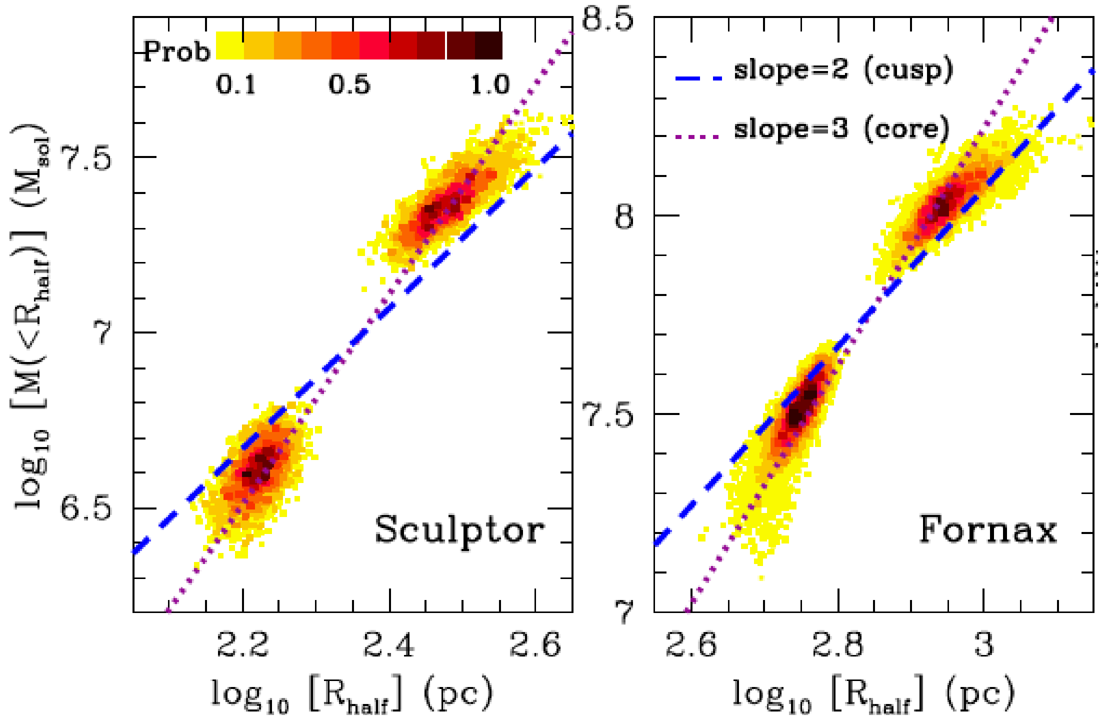
CDM challenges: clues of new DM physics or lessons on galaxy formation?

Boylan-Kolchin+ 2012



The core-cusp problem



Walker & Peñarrubia 2011

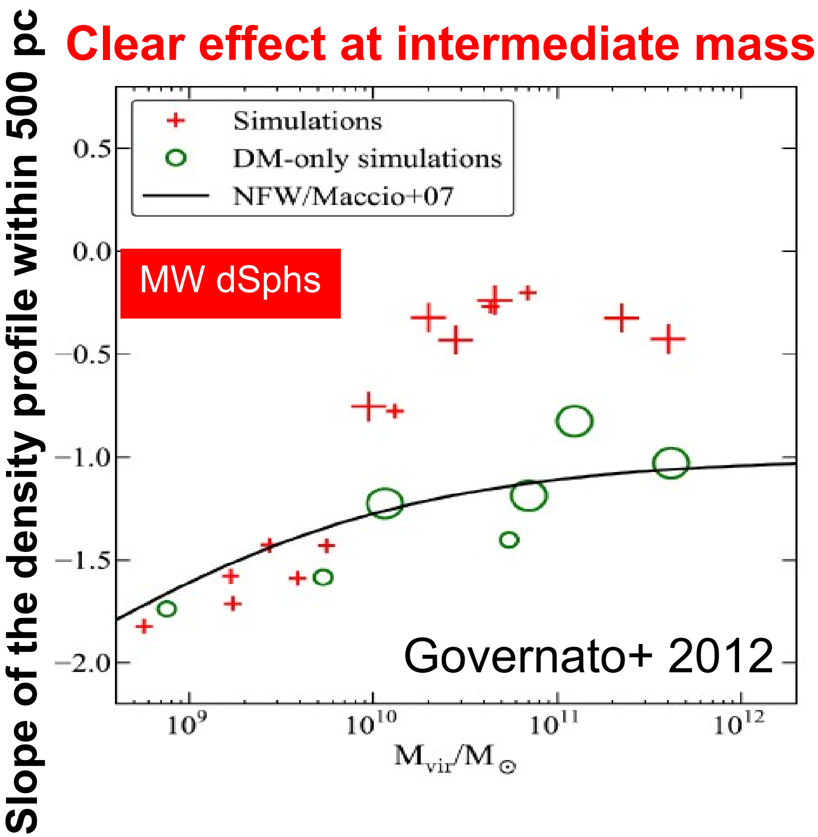
Looking at the bright side of the solution

Core-cusp problem

Early episodes of star formation and strong SN feedback

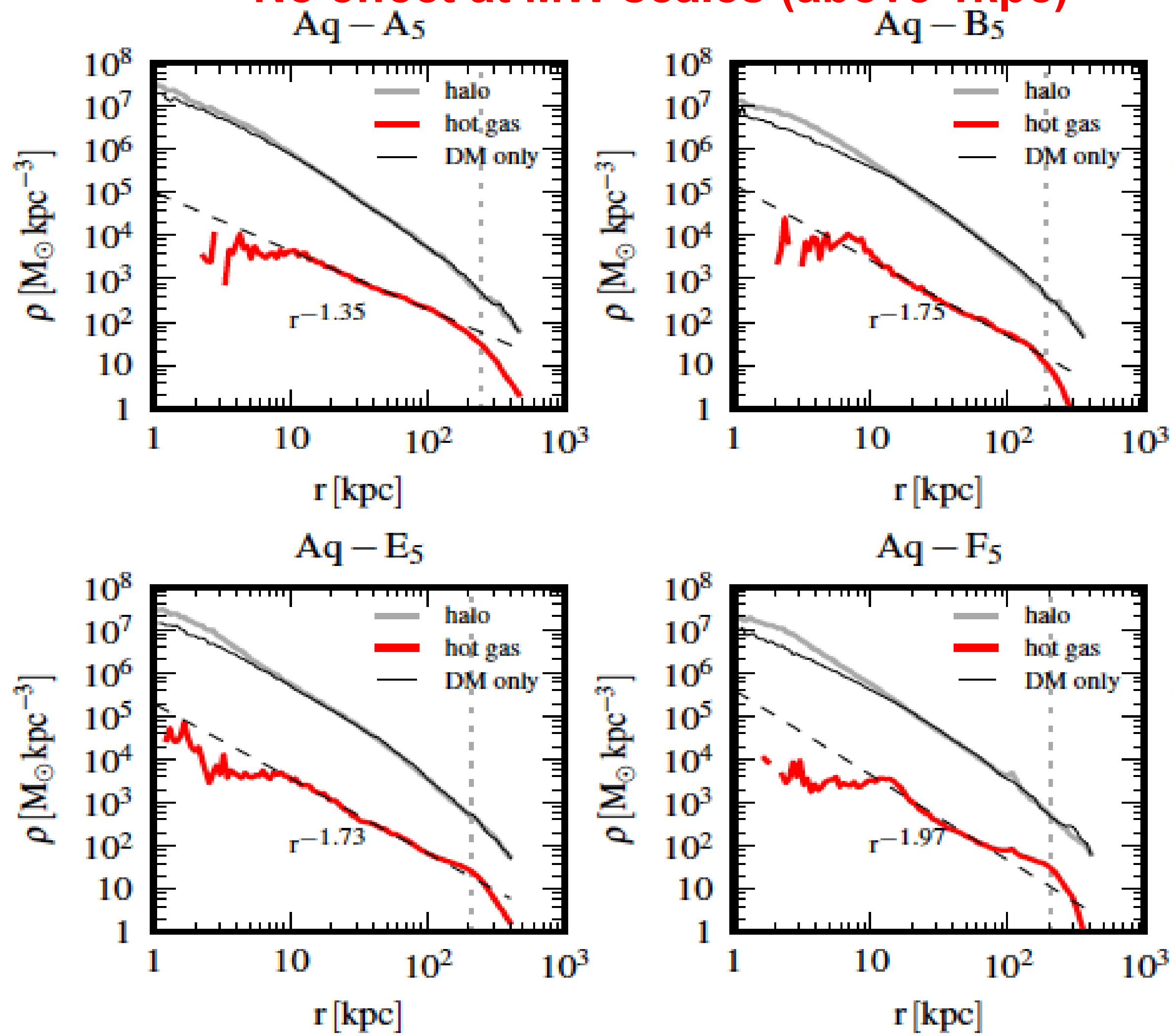
e.g. Navarro+ 1996, Governato+ 2012

Clear effect at intermediate masses



Marinacci+2013: MW-size galaxy simulations

No effect at MW scales (above 1kpc)



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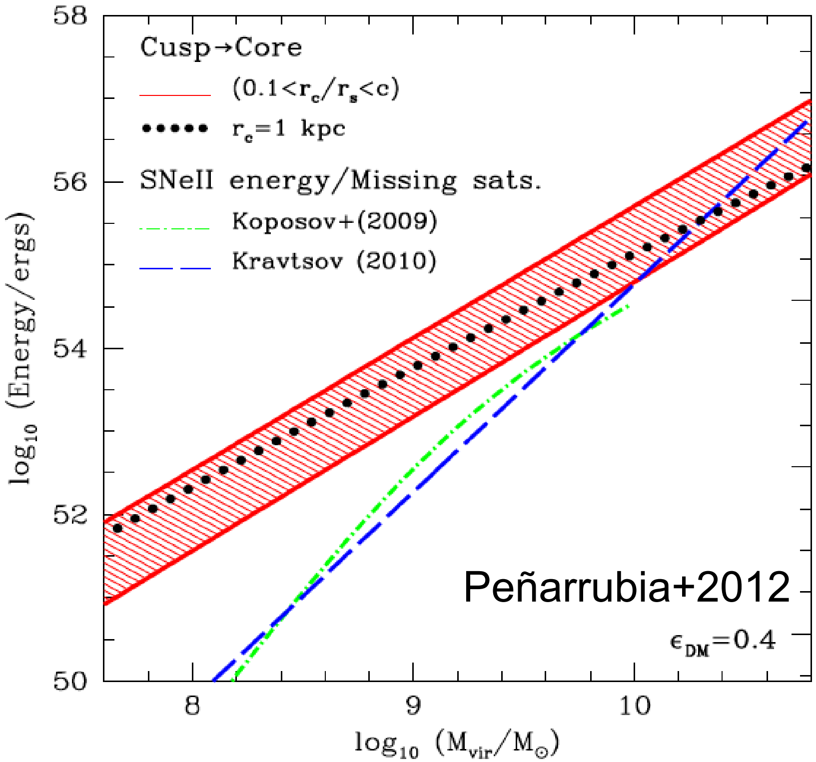


Core-cusp problem

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

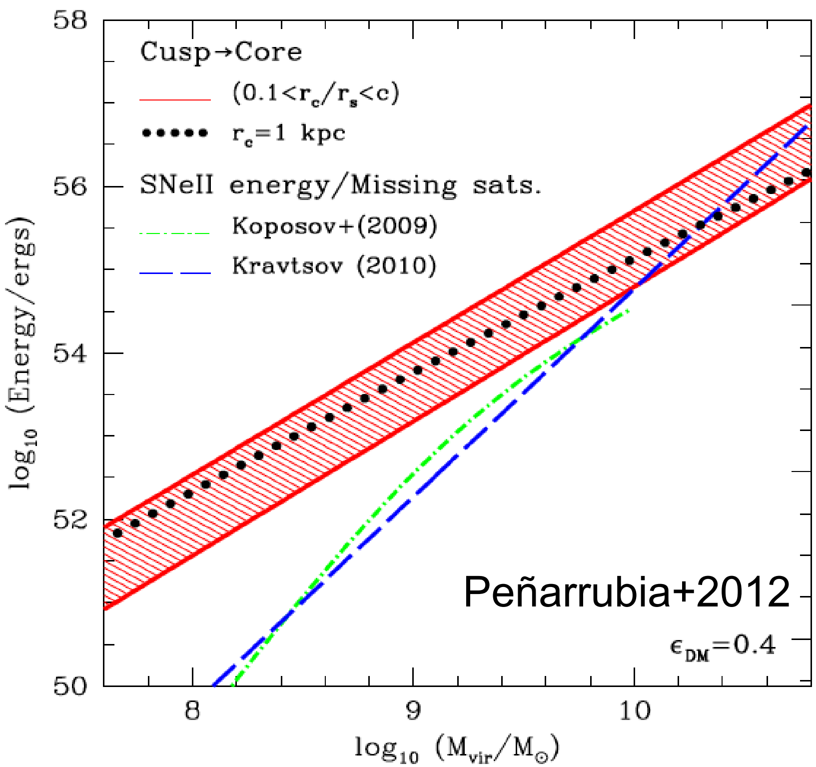
SN feedback in MW dSphs: likely insufficient for dSphs
e.g. Peñarrubia+ 2012, Garrison-Kimmel+13

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

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

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

Looking at the bright side of the solution



Core-cusp problem

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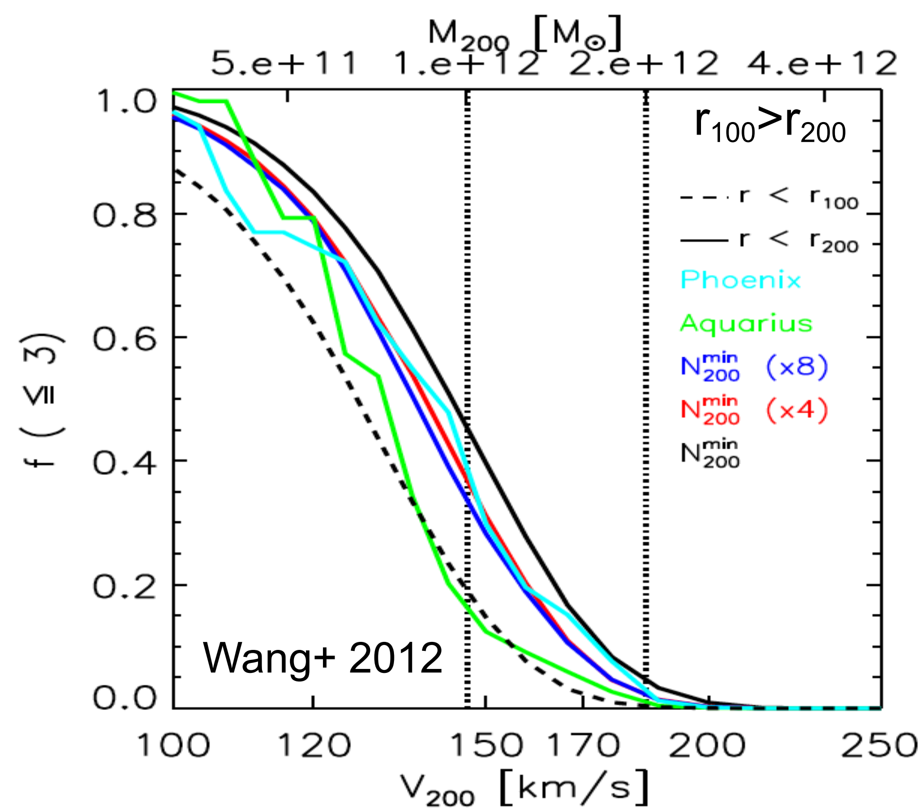
Probability that a halo contains 3 or fewer Subhaloes with V_{max} > 30 km/s



Too big to fail problem

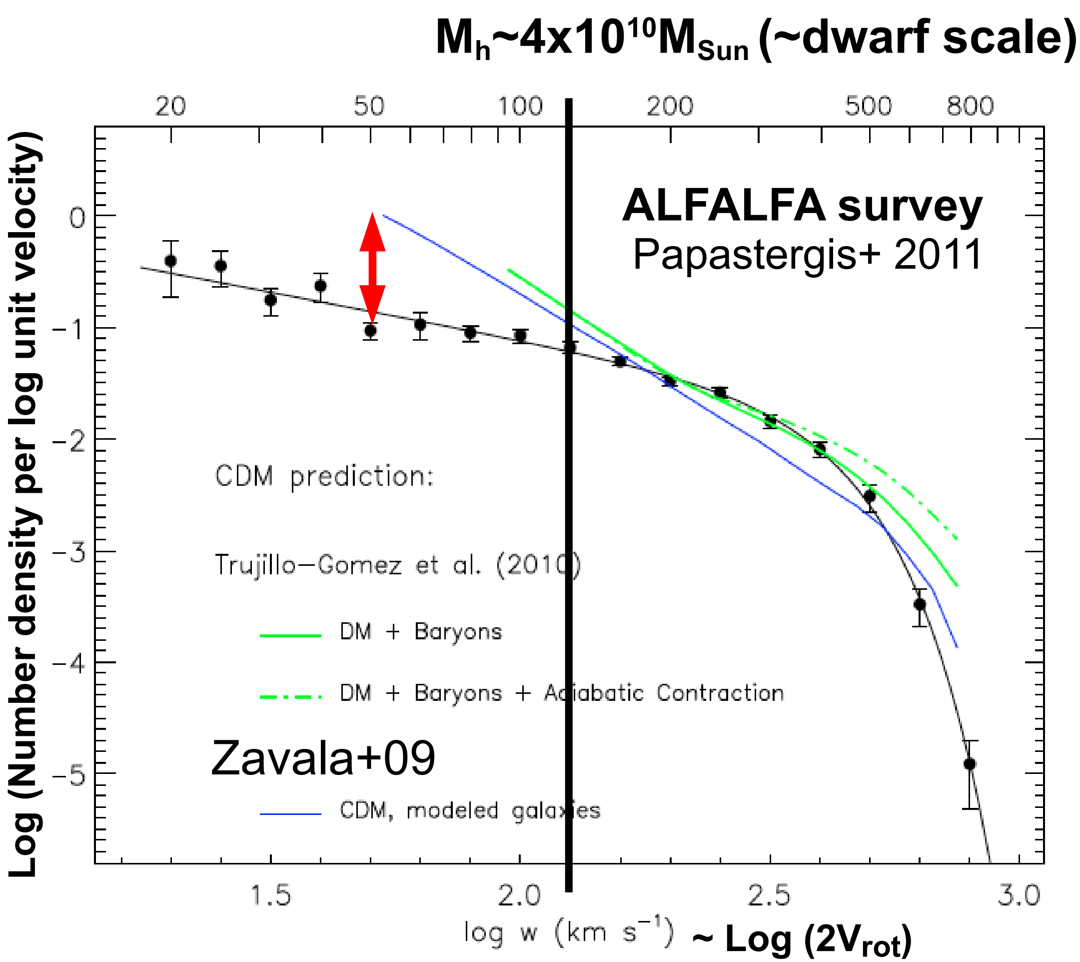
The halo of the Mily-Way is less massive than 10^{12} M_{Sun}

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})

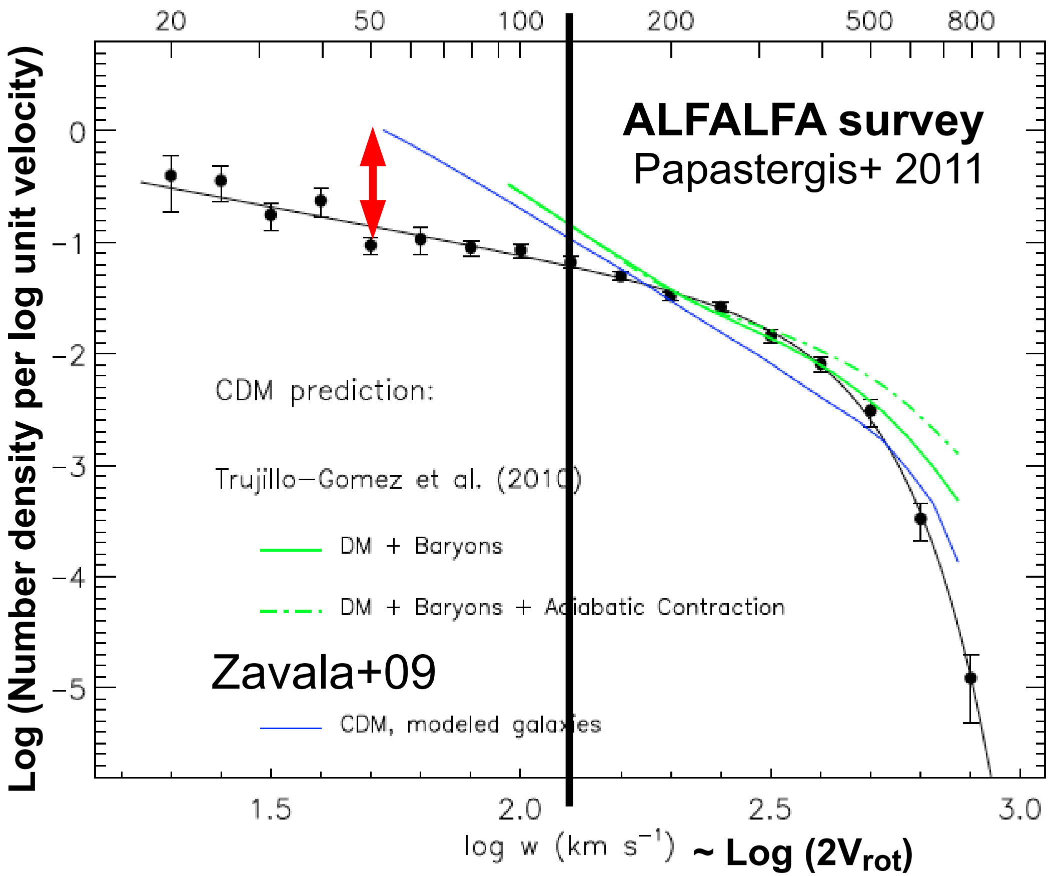
Overabundance problem in the field



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

Overabundance problem in the field

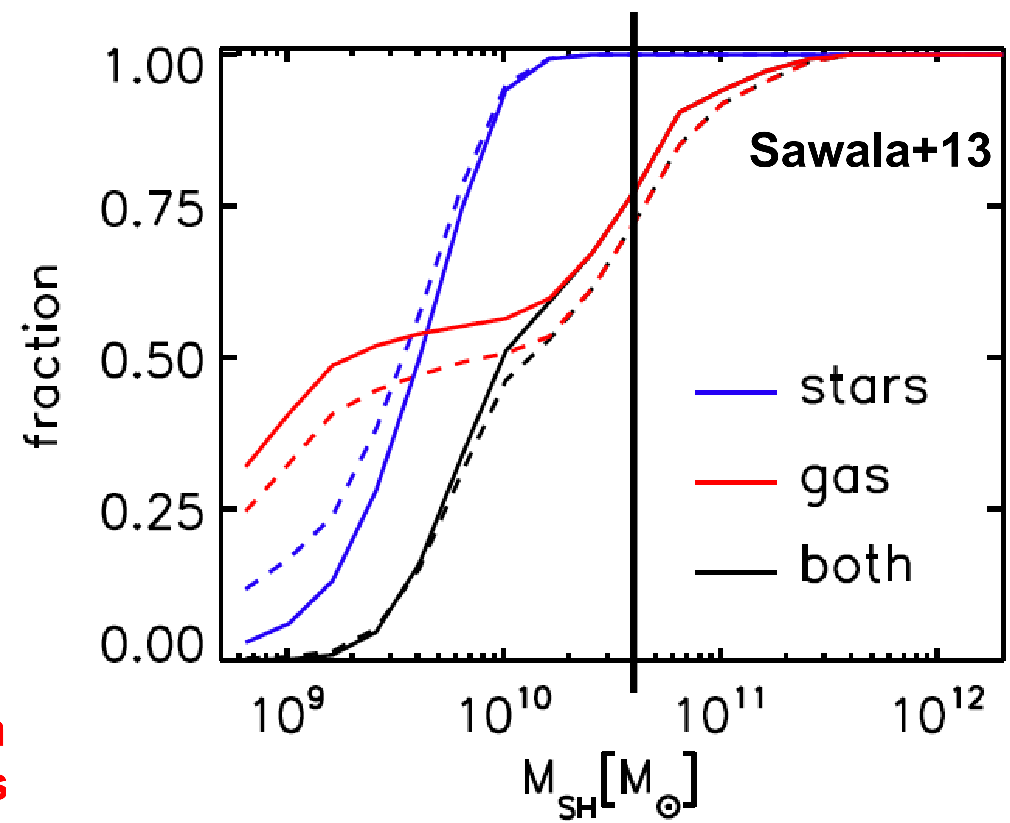
$M_h \sim 4 \times 10^{10} M_{Sun}$ (~dwarf scale)



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)



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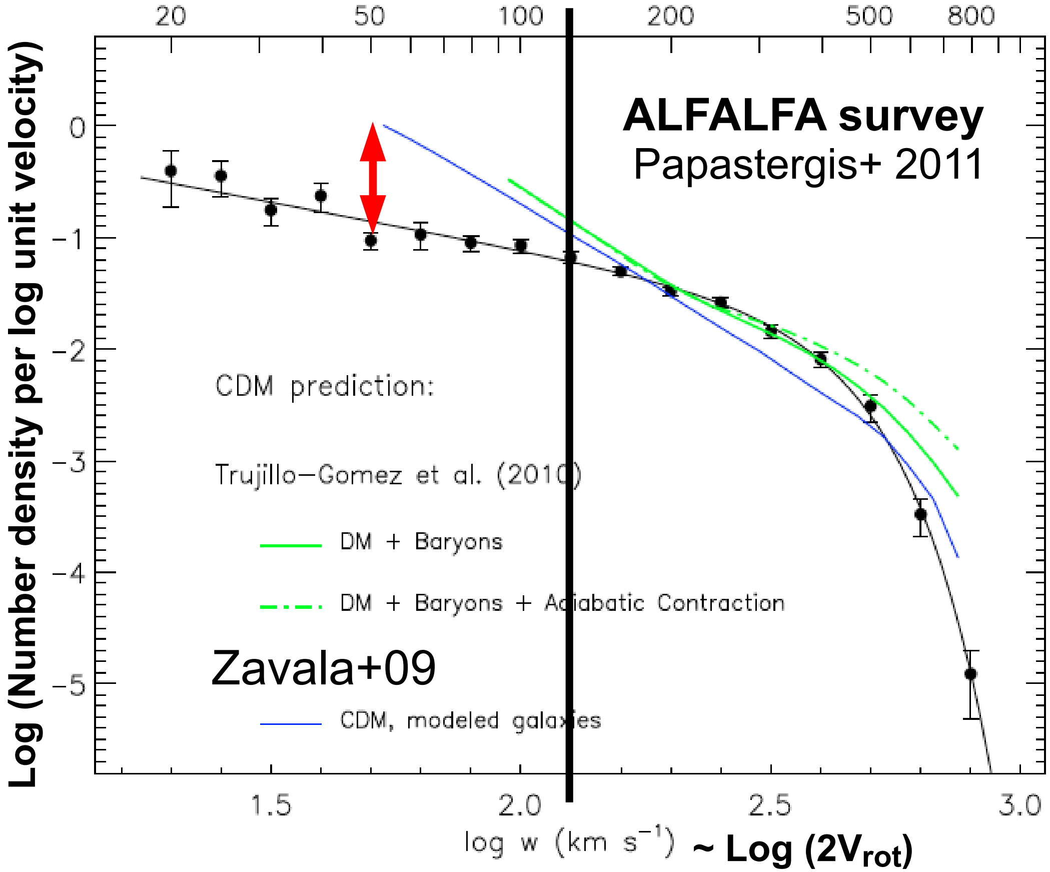

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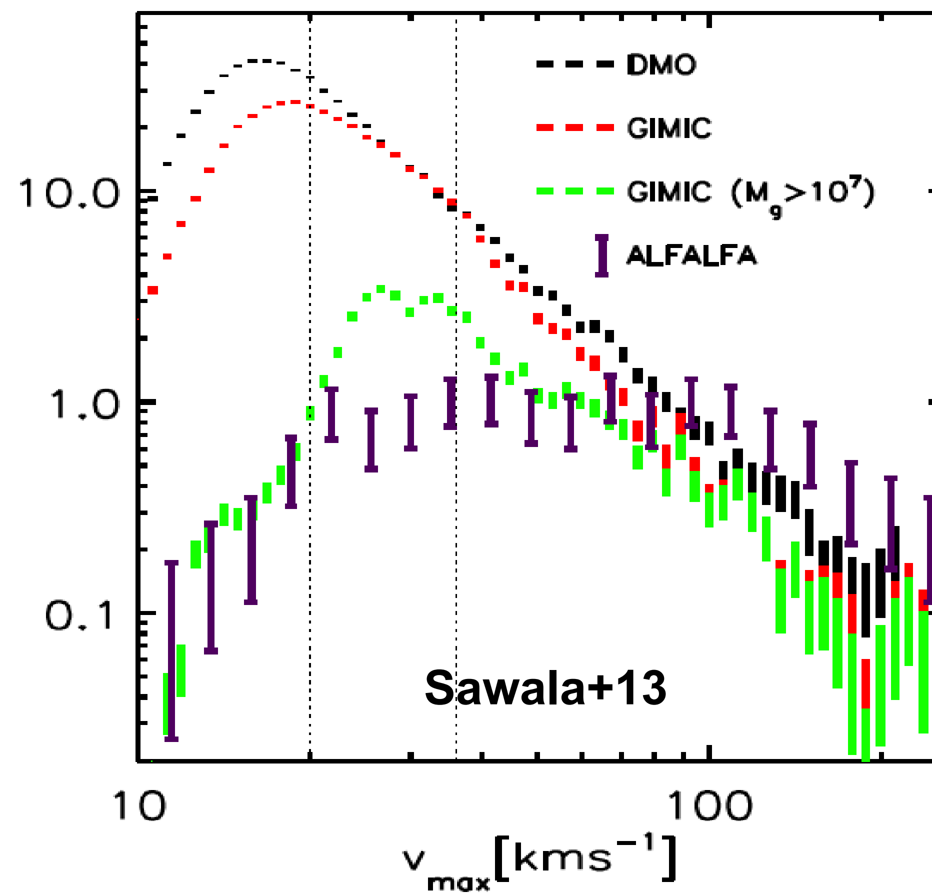
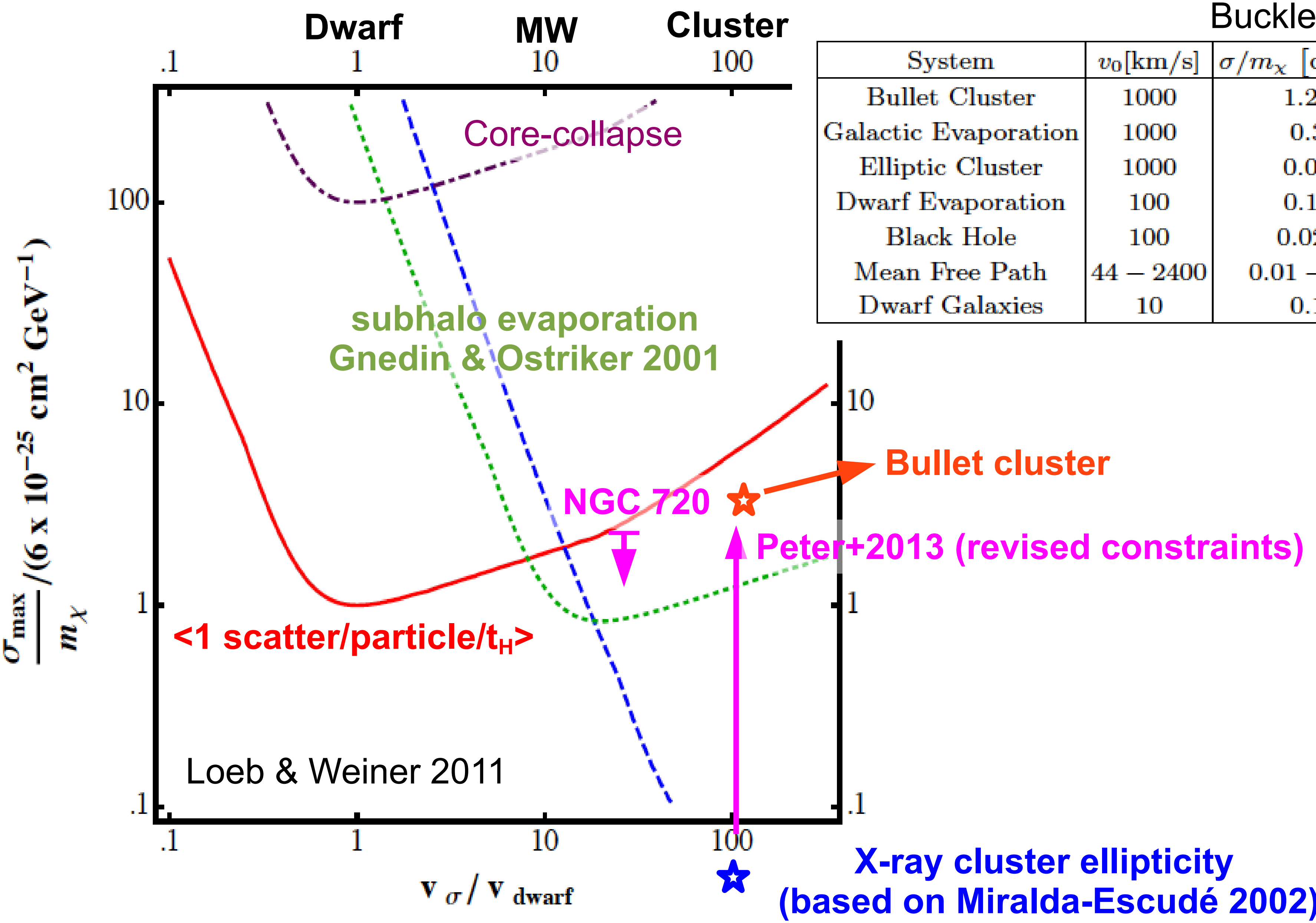


Another possibility: underestimation of the true DM potential (hints in Swaters+ 2009)

Constraints on collisional DM

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



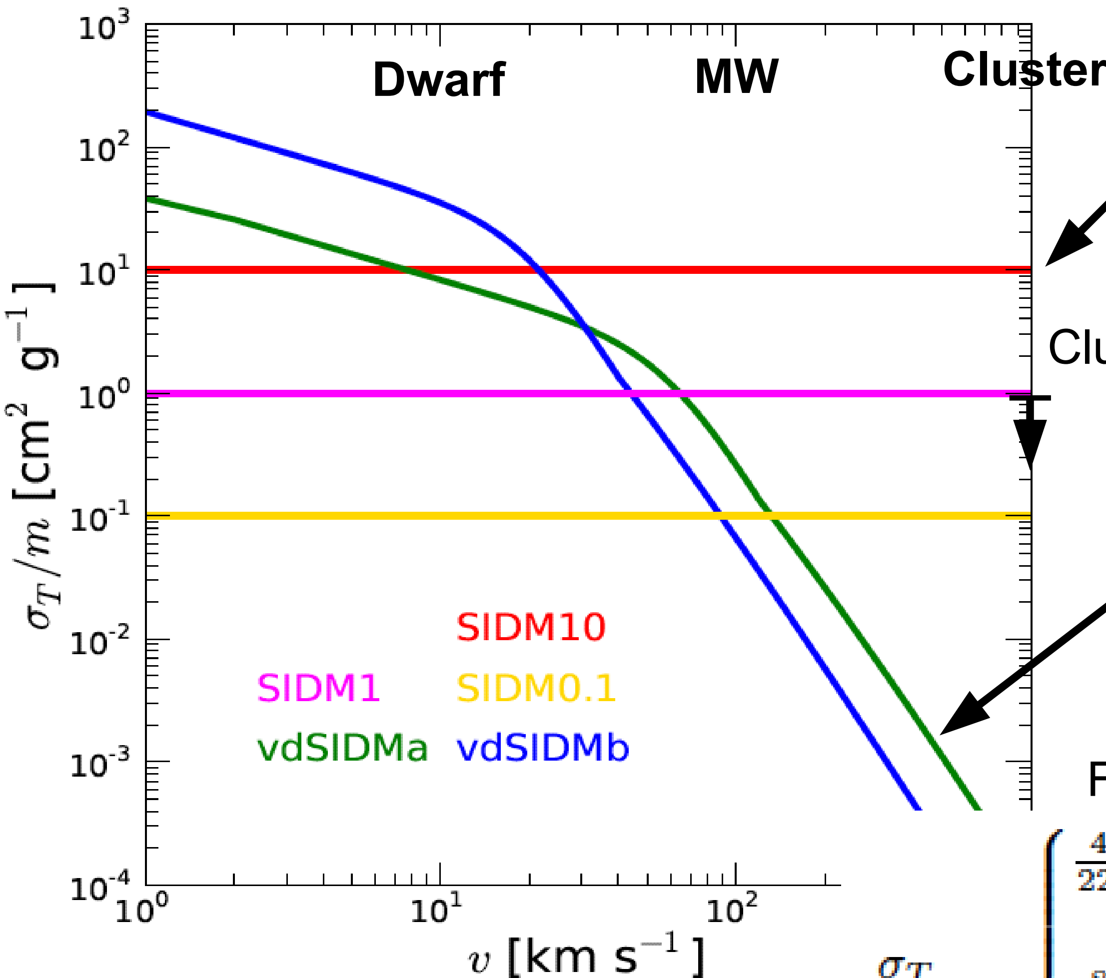
Buckley & Fox 2010

System	v_0[km/s]	σ/m_χ [cm^2/g]	References
Bullet Cluster	1000	1.25	[41, 43]
Galactic Evaporation	1000	0.3	[45]
Elliptic Cluster	1000	0.02	[46]
Dwarf Evaporation	100	0.1*	[45]
Black Hole	100	0.02*	[59]
Mean Free Path	44 – 2400	0.01 – 0.6	[57]
Dwarf Galaxies	10	0.1	[56]

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)

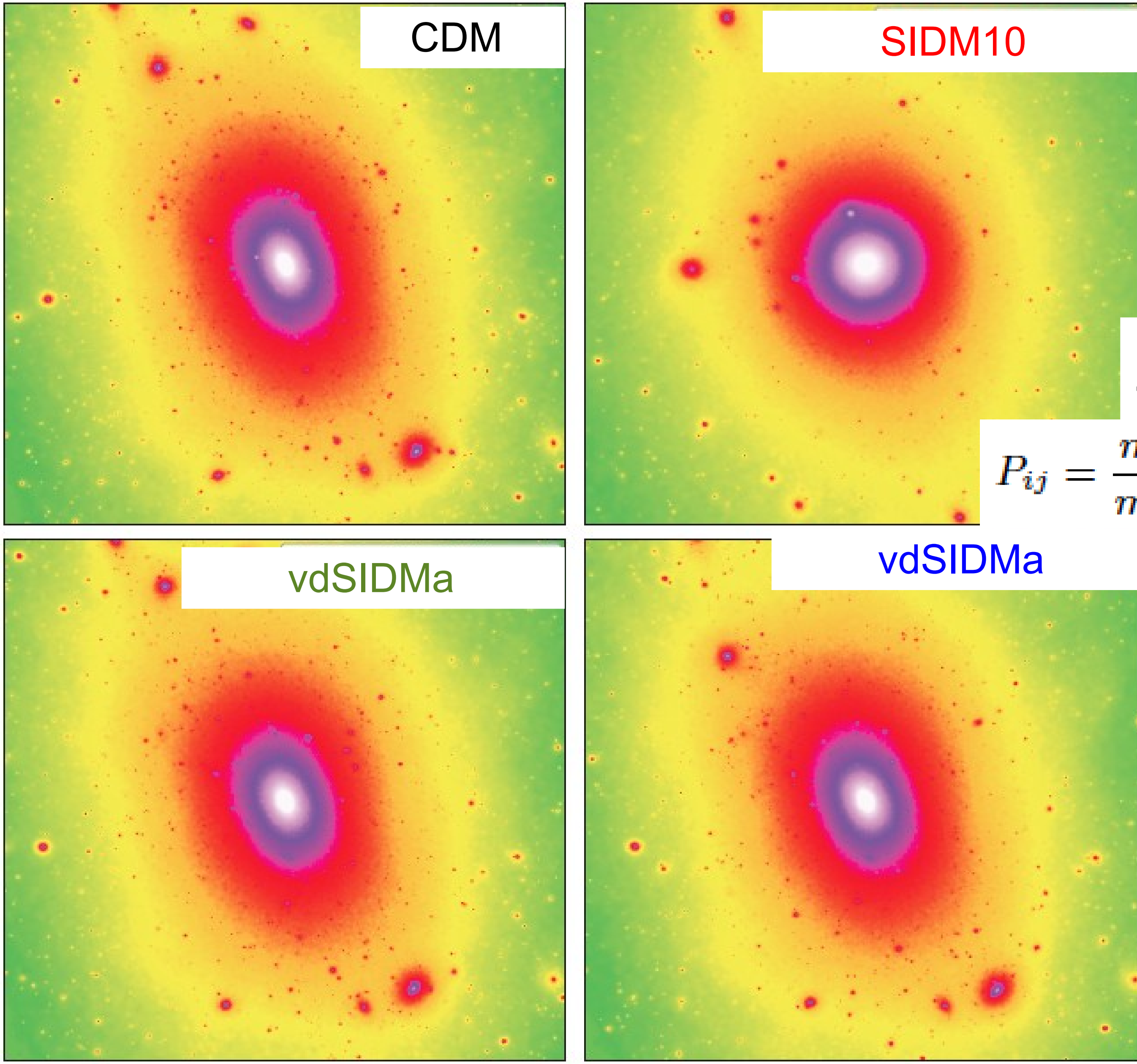
vdSIDM models motivated by a new force in the "dark sector", e.g. Yukawa-like, (e.g. Feng+09, Feng+10, Loeb & Weiner 2011)

From plasma physics (Khrapak+03+04)

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

SIDM *N*-body simulations

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



Probabilistic method for elastic scattering

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

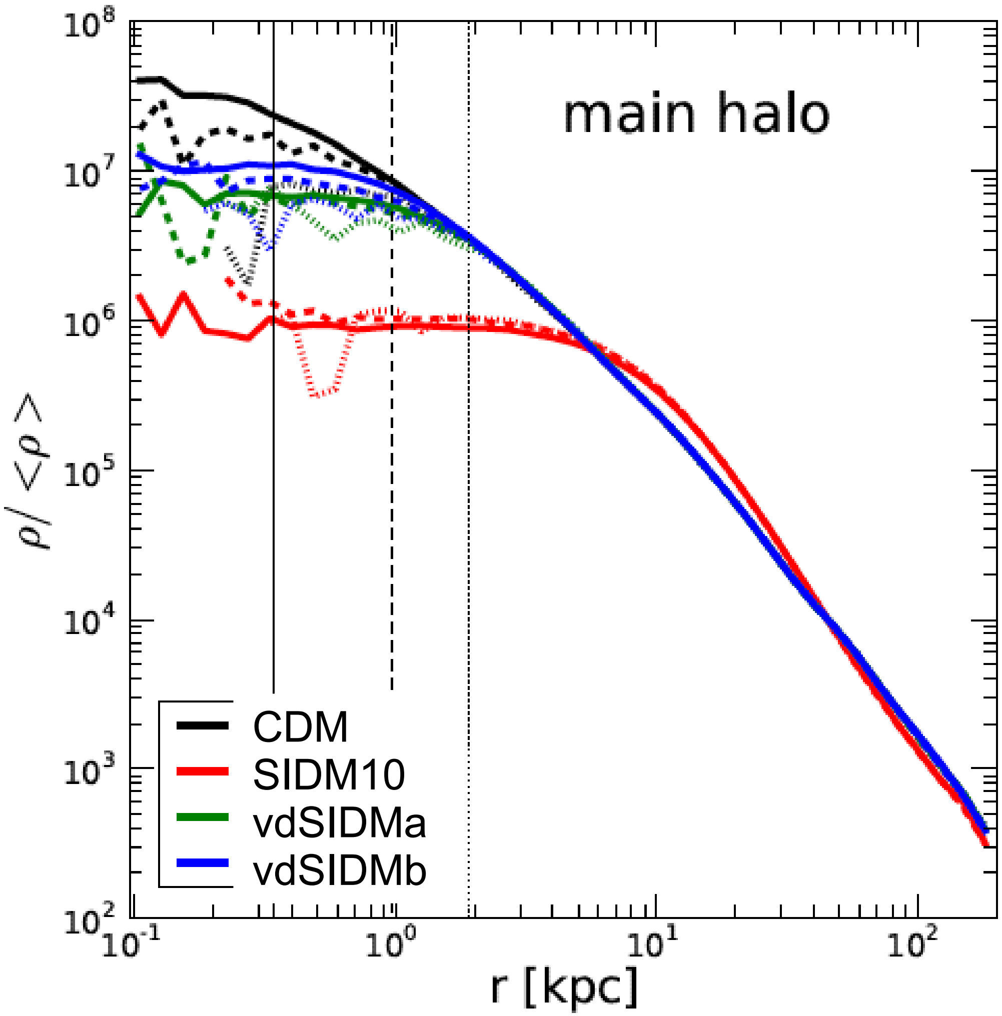
Resolution

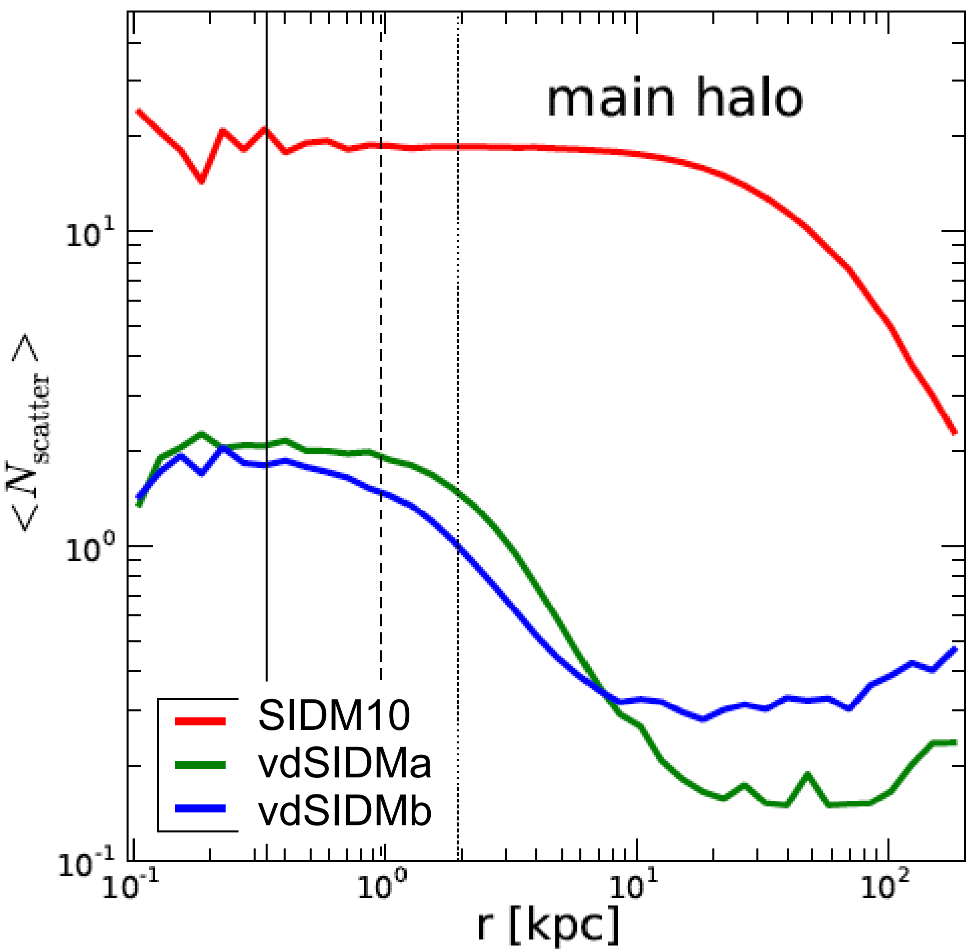
$m_{\rm p}[{\rm M}_\odot]$	$\epsilon[{\rm pc}]$
4.911×10^4	120.5

$M_{200}[{\rm M}_\odot]$	$r_{200}[{\rm kpc}]$
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

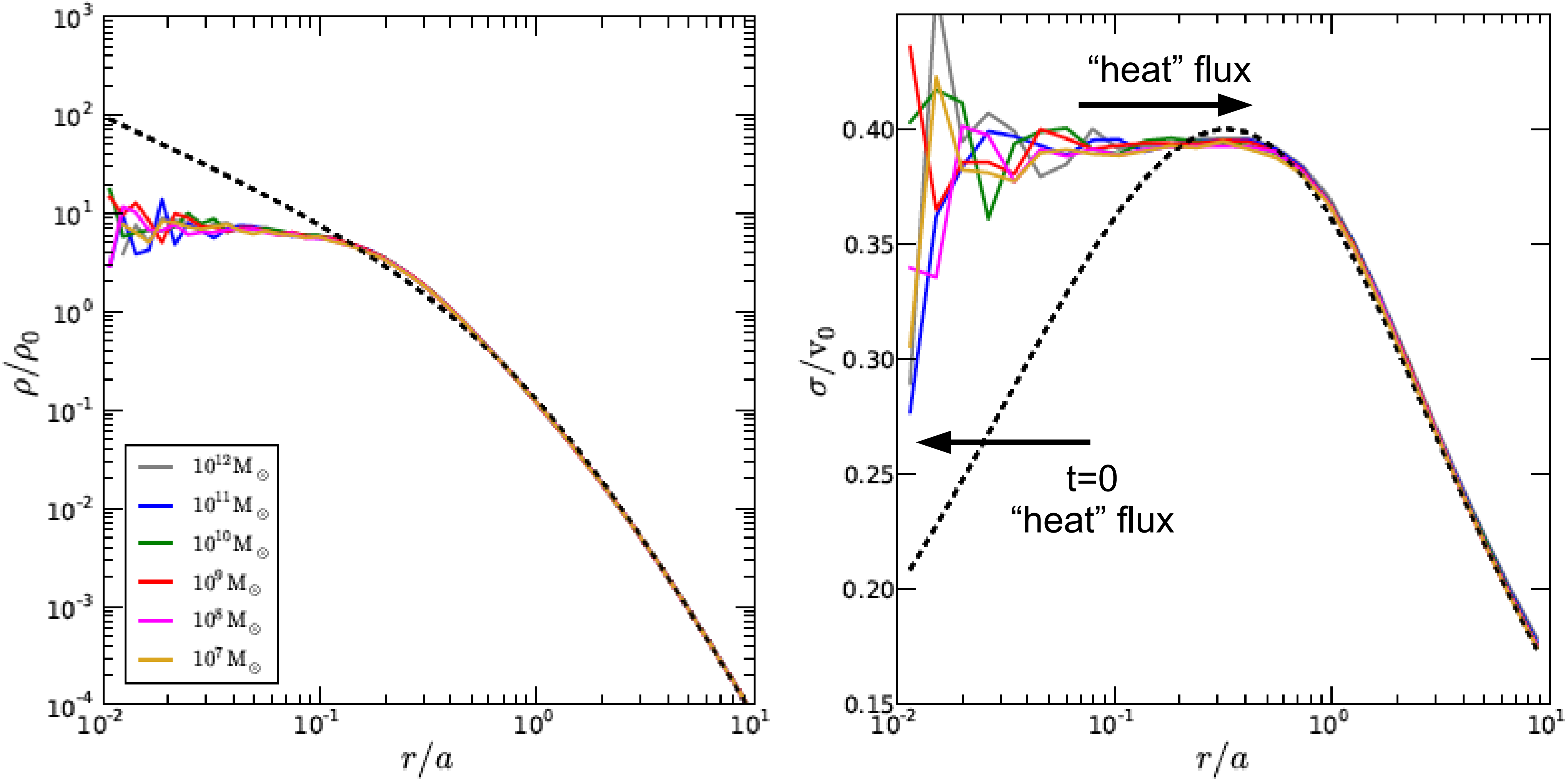




Vogelsberger, Zavala & Loeb 2012

Forming a core through collisions

Constant cross section case

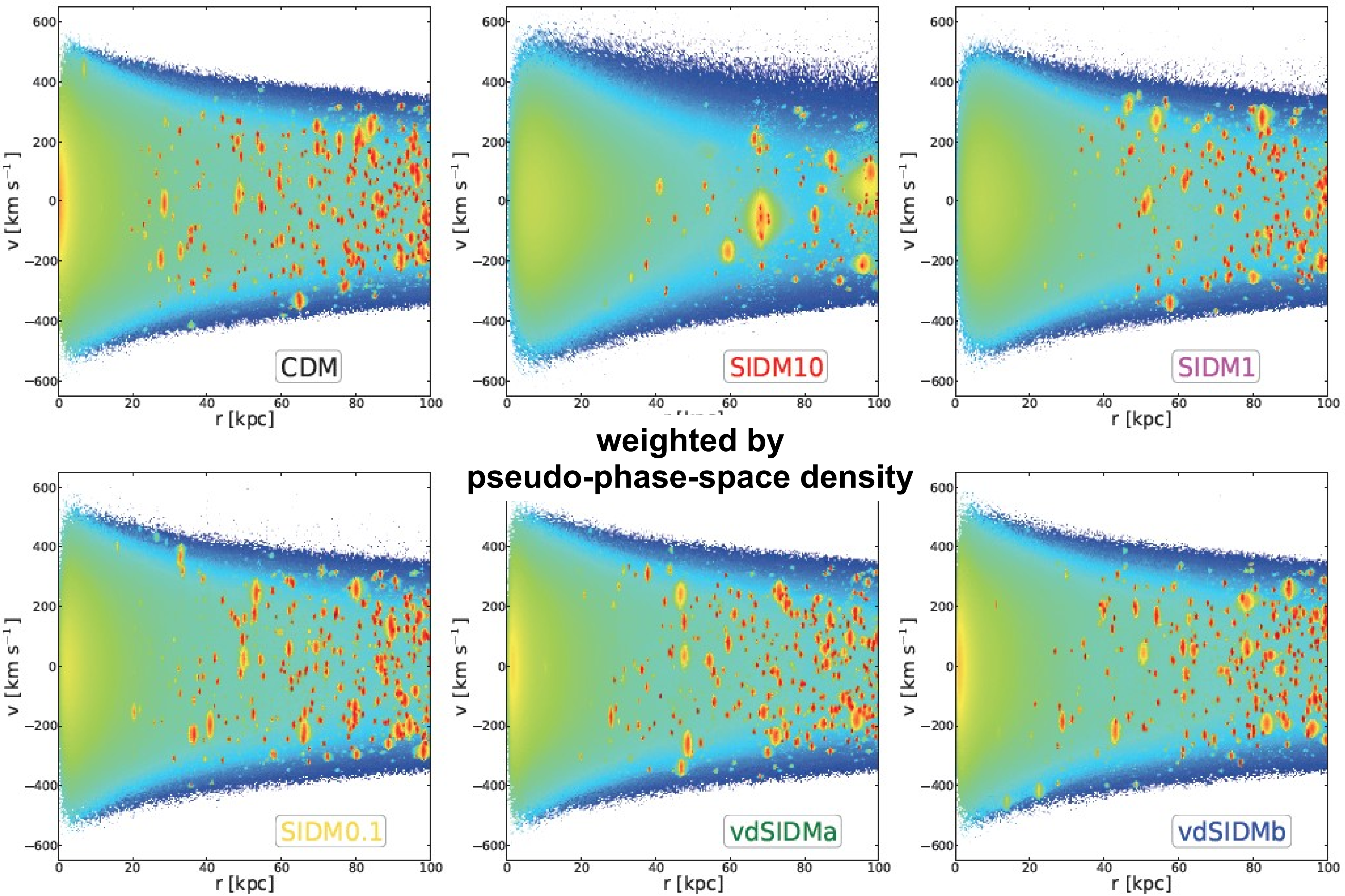


Vogelsberger, Zavala & Loeb 2012

Nicely described in Colín+02

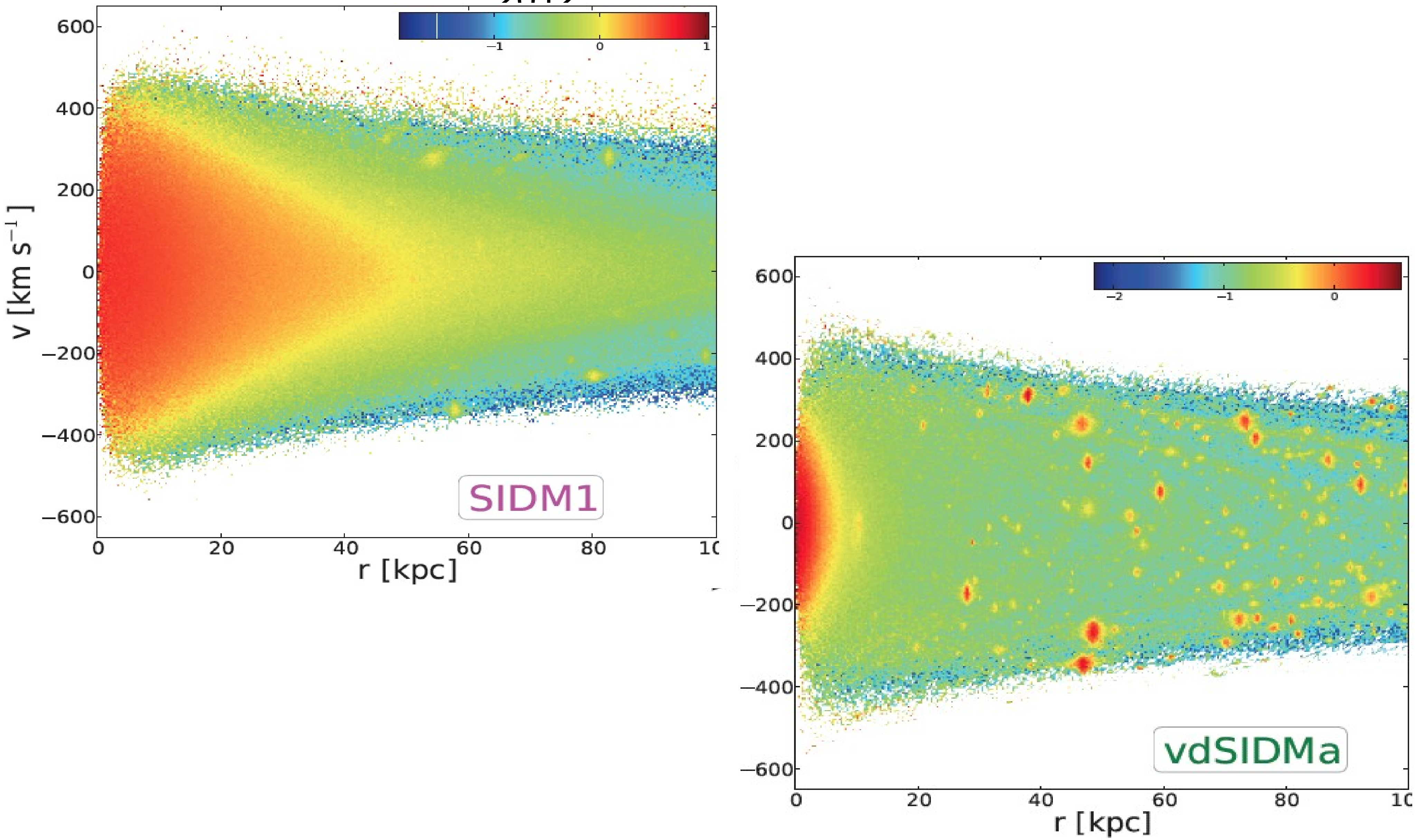
Phase-space distribution in SIDM

Vogelsberger & Zavala 2012



Distribution of scattering events in SIDM

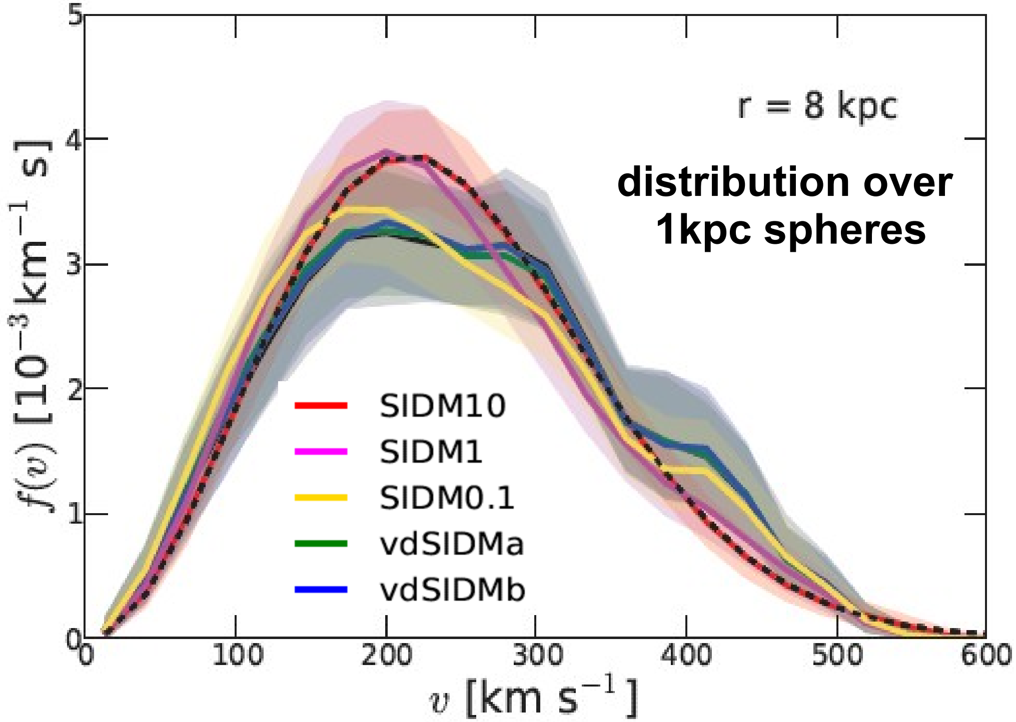
Vogelsberger & Zavala 2012



Weighted by average # scatters

"Local" SIDM velocity distribution: impact on direct detection

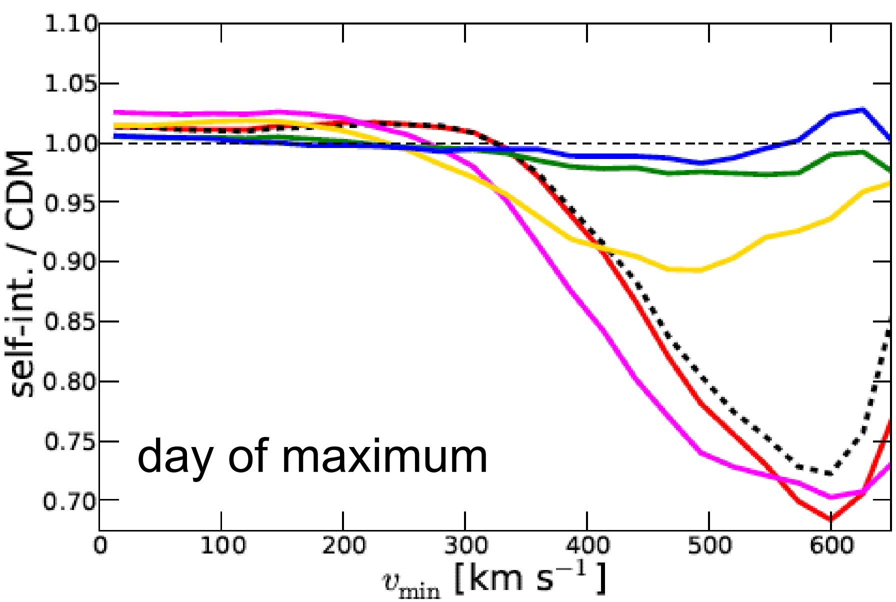
Vogelsberger & Zavala 2012



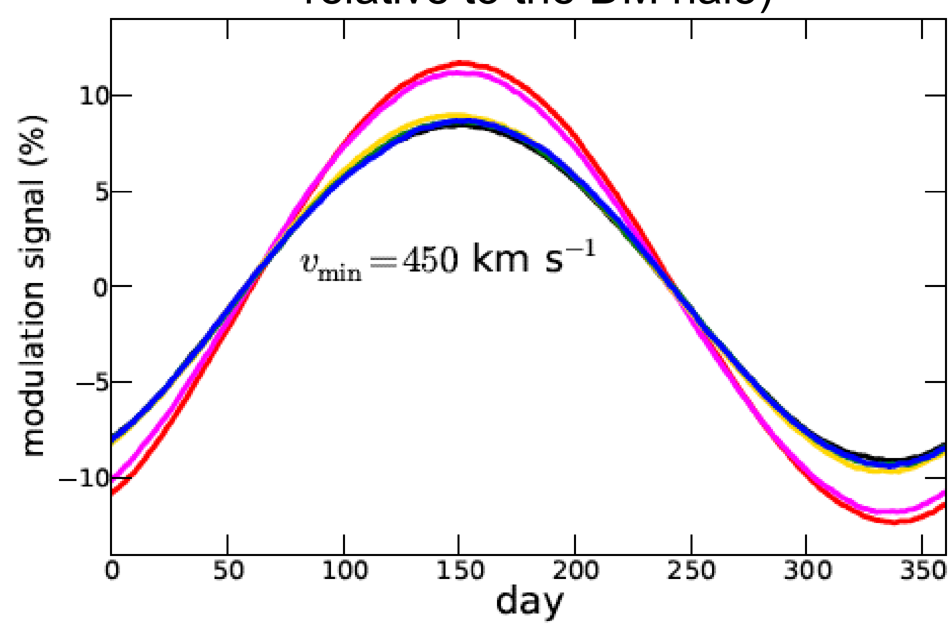
$$T(v_{\min}(E),t)=\int_{v_{\min}(E)}^{\infty}\frac{f_v(t)}{v}\,\mathrm{d}v$$

Elastic collision, E=nucleus recoil energy

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



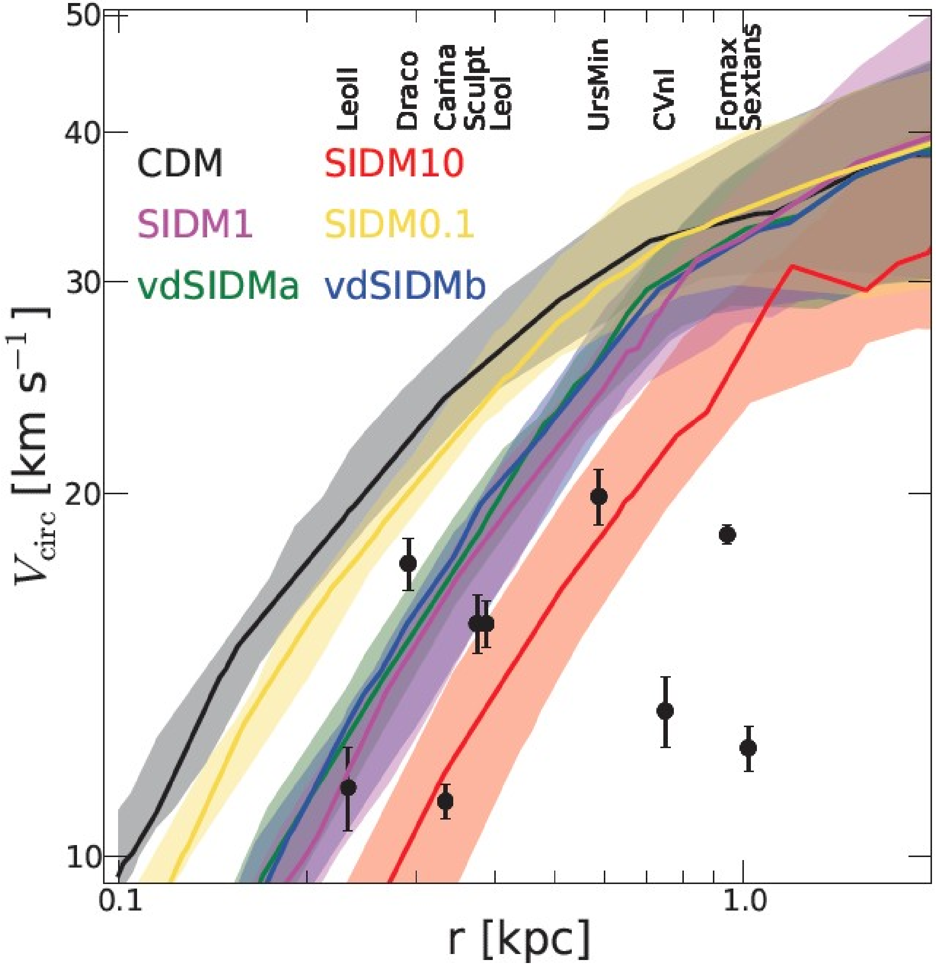
Modulation signal relative to average over the year (due to Earth's motion relative to the DM halo)

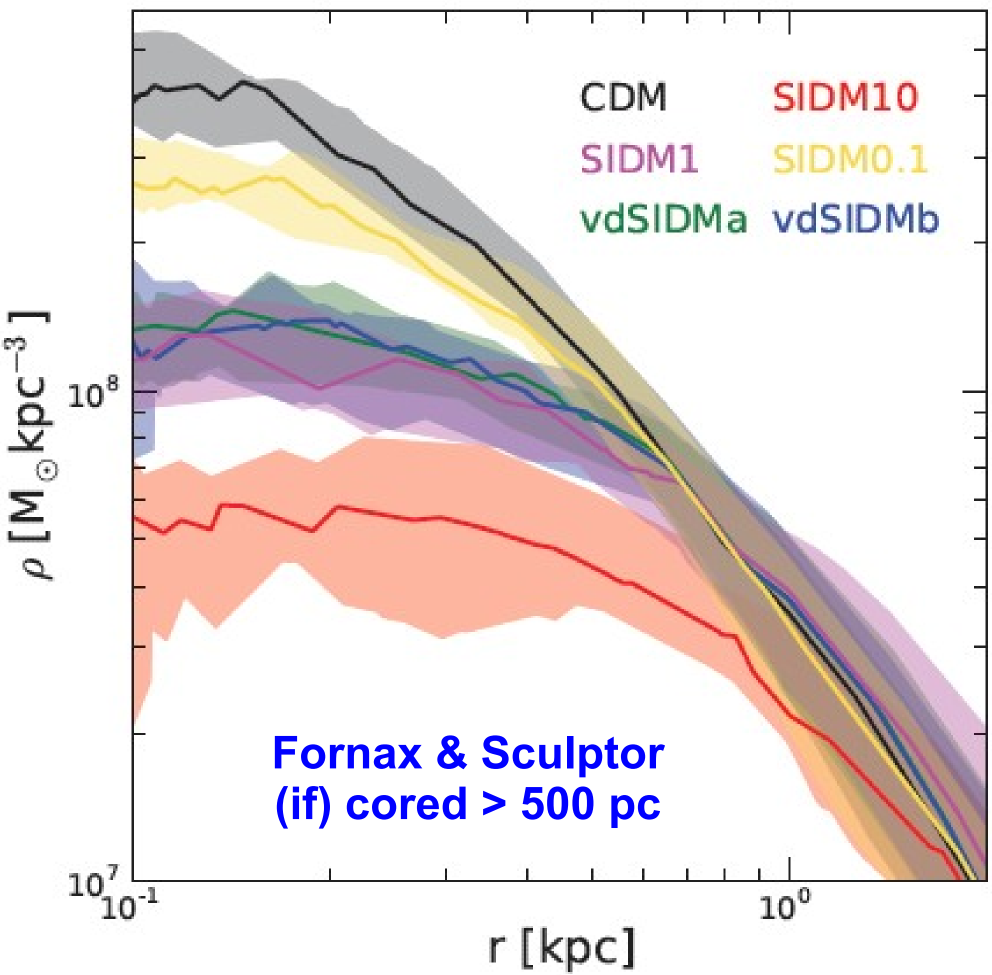


DM distribution in SIDM subhaloes

Clusters/ellipticals put an upper limit to the cross section ~ 1 cm^2/g,
the MW satellites put a lower limit on SIDM as a distinct alternative to CDM

Zavala, Vogelsberger & Walker 2013



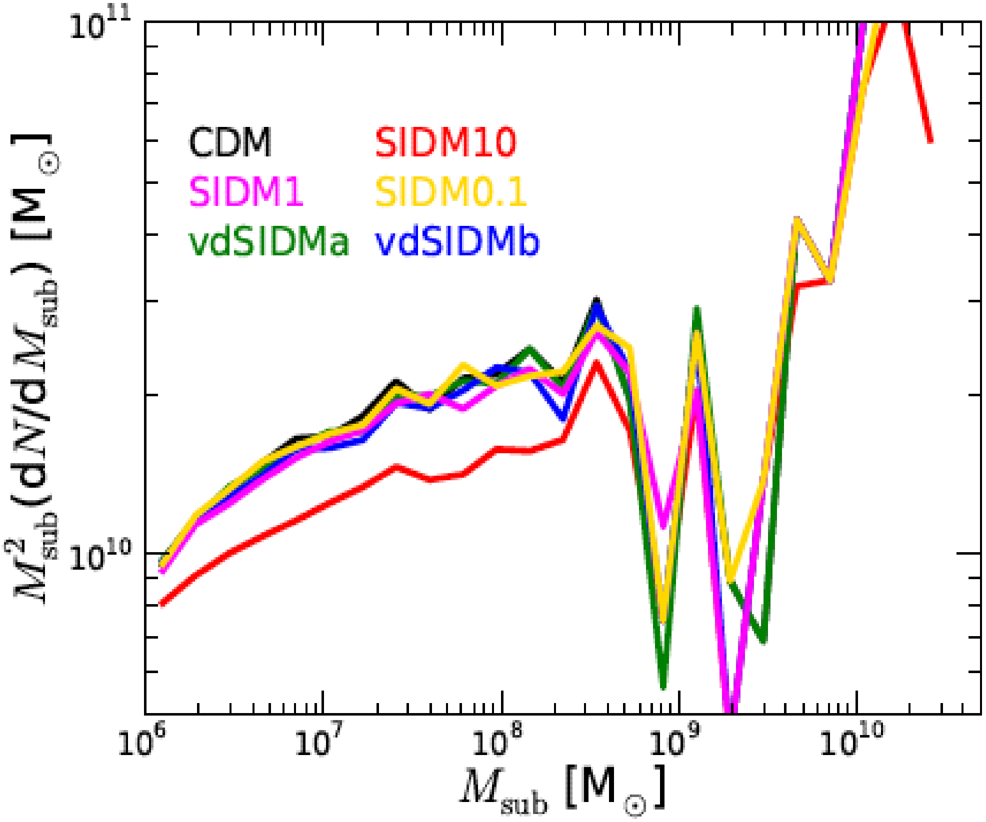


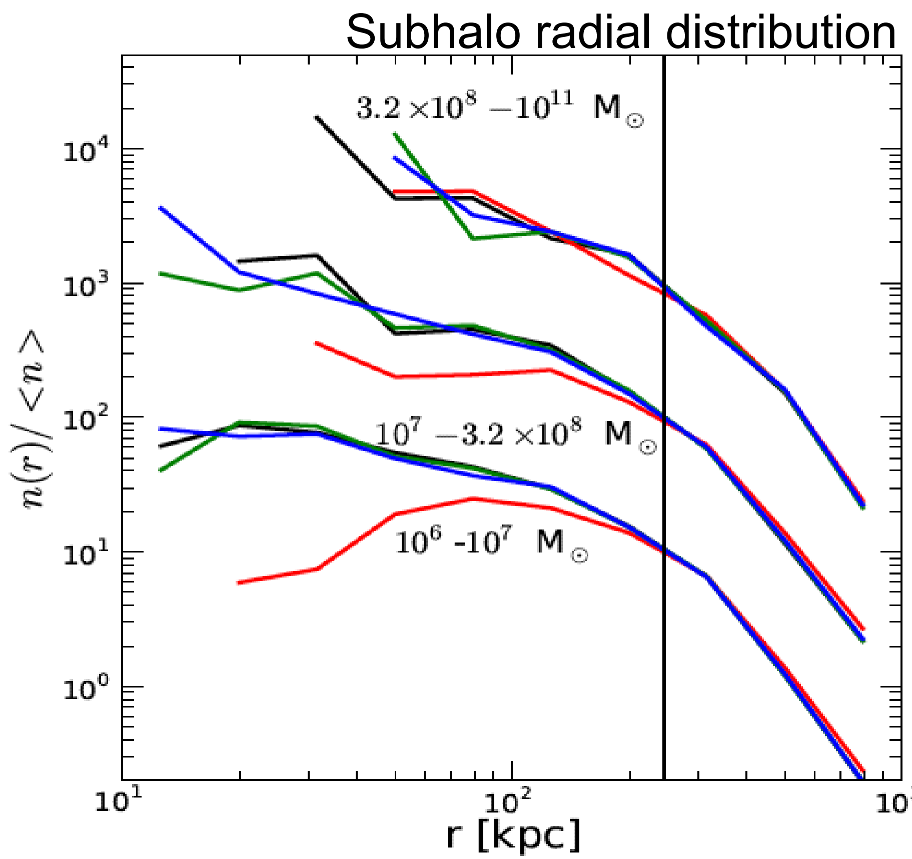
We show that SIDM solves the too big to fail problem and the core-cusp problem
only if 0.6 $cm^2/g < \sigma / m < 1$ cm^2/g or velocity-dependent cross section

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

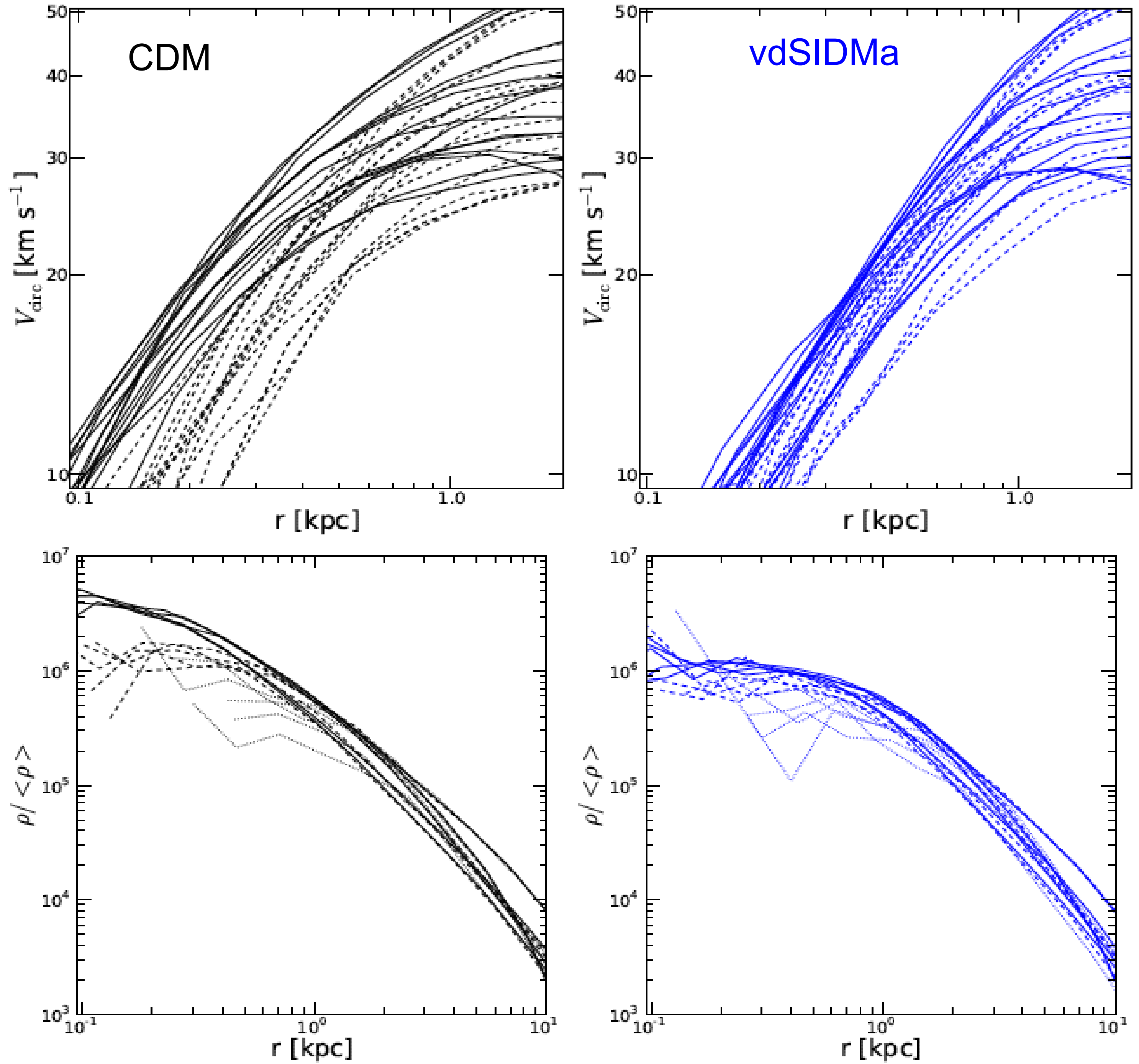




Inelastic scattering (excited states of DM) might lead to the evaporation of low-mass subhaloes

$$\chi\chi^* \rightarrow \chi\chi \qquad \sqrt{\delta/m} \sim v_{esc}$$

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 $cm^2/g < \sigma / m < 1\ cm^2/g$ (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)