Lecture 3

Enduring challenges of the CDM model and alternative cosmologies

Outline:

- Challenges of the CDM model (small-scales)

  i) Overabundance of dwarf galaxies

  ii) Central densities of dwarf galaxies

- Warm Dark Matter
- Self-Interacting Dark Matter

Literature:
(i) Dark Matter Substructure and Dwarf Galactic Satellites, Kravtsov 2010, Ad. in Ast. 281913
(ii) The core-cusp problem, de Blok, 2010, Ad.in Ast. 789293
(iii) Halo Formation in Warm Dark Matter Models Bode, Ostriker & Turok, 2001, ApJ, 556, 93
(iv) Observational Evidence for Self-Interacting Cold Dark Matter, Spergel & Steinhardt, 2000, PRL, 84, 3760

A logic flow-chart for galaxy formation

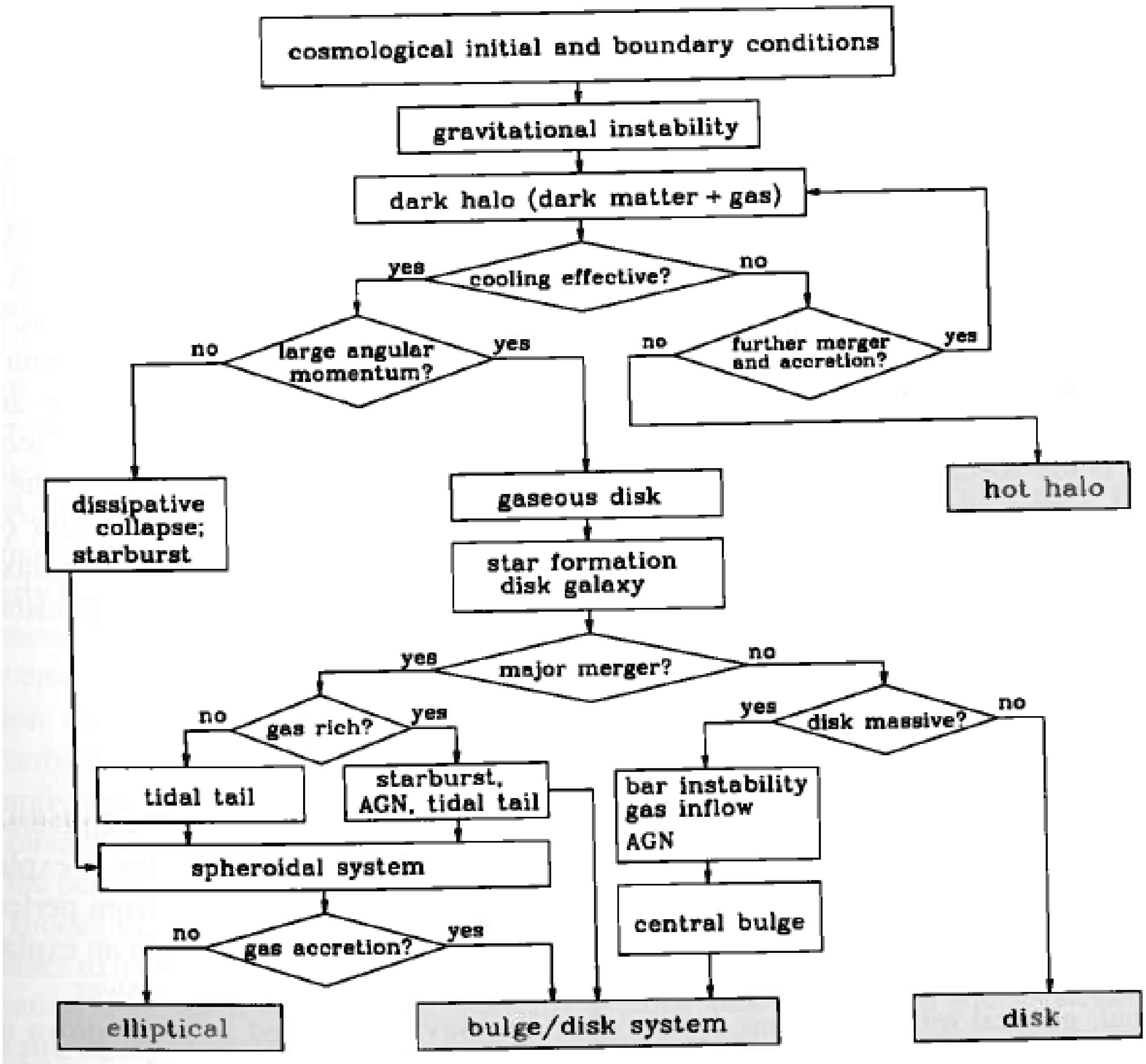
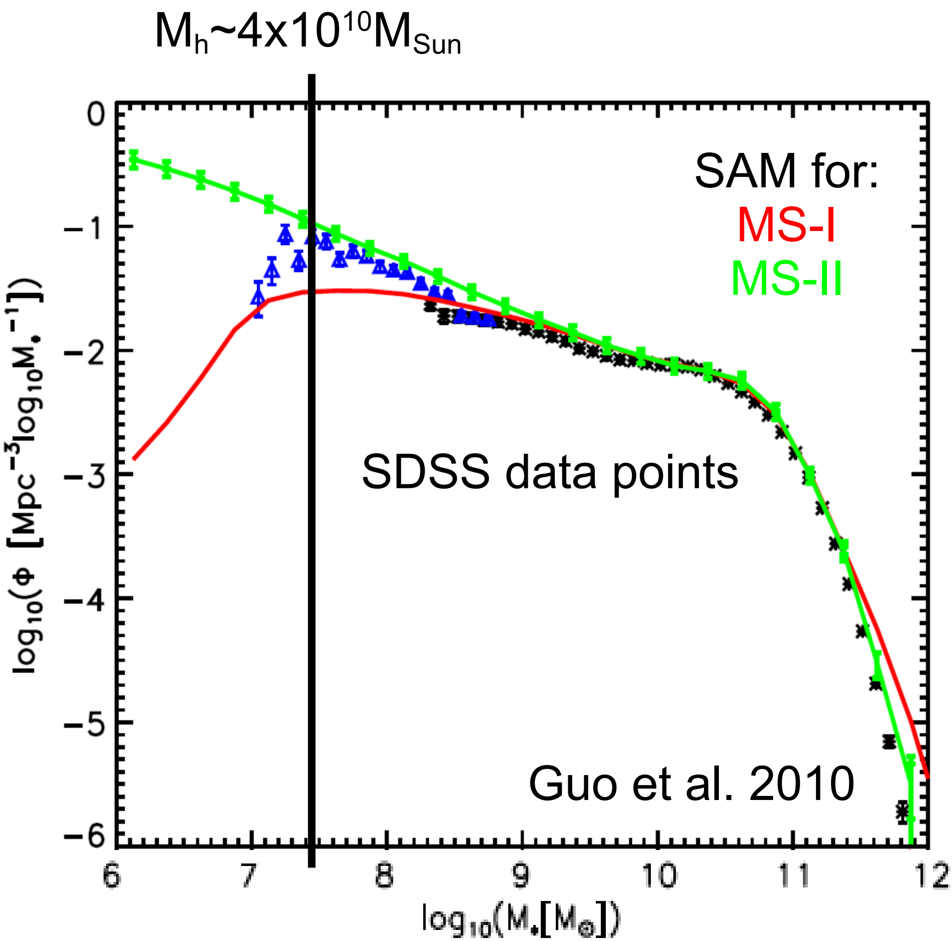


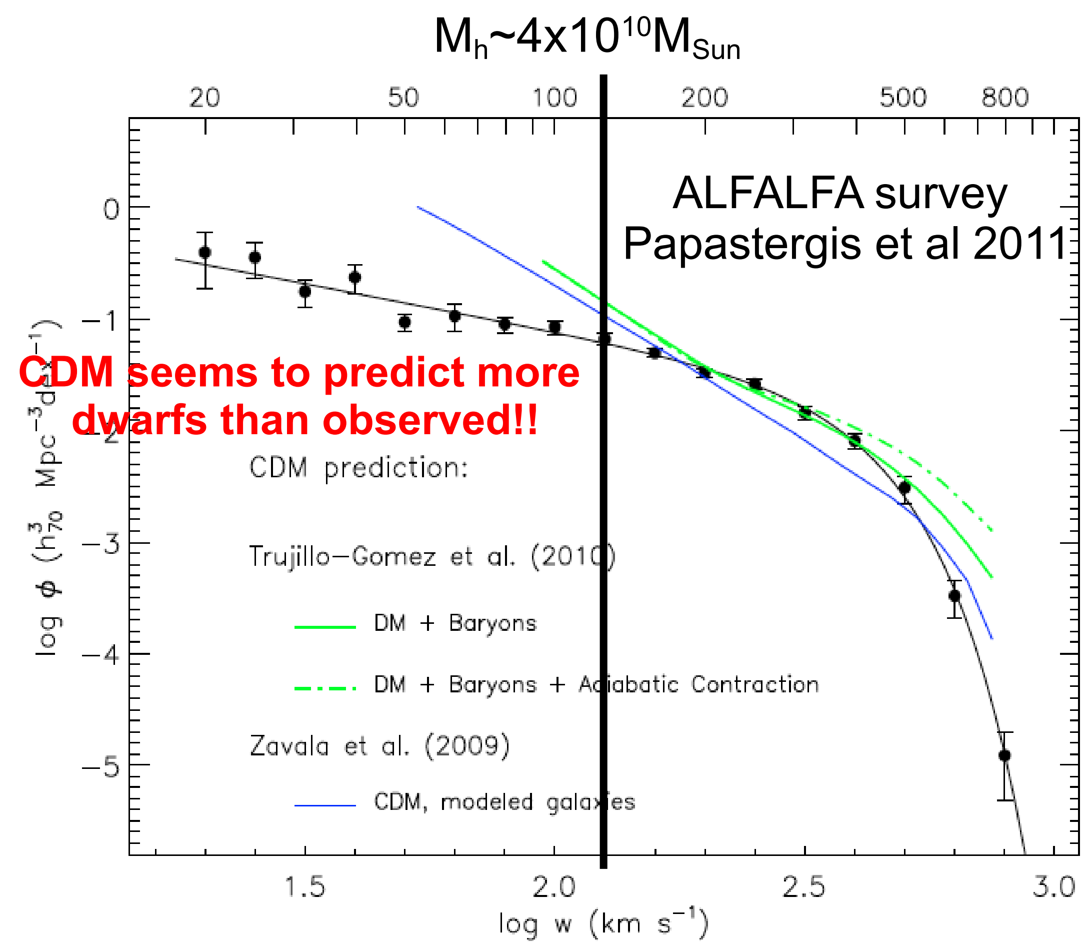
Fig. from Mo, Mao and White, 2010

The complex process of galaxy formation is studied through a combination of analytical, numerical and empirical arguments

Observed abundance of dwarf galaxies in the field



Abundance according to stellar mass: suppression of SF at low masses due mainly to SN feedback. Galaxy formation and evolution modelled by a semi-analytic model (SAM)



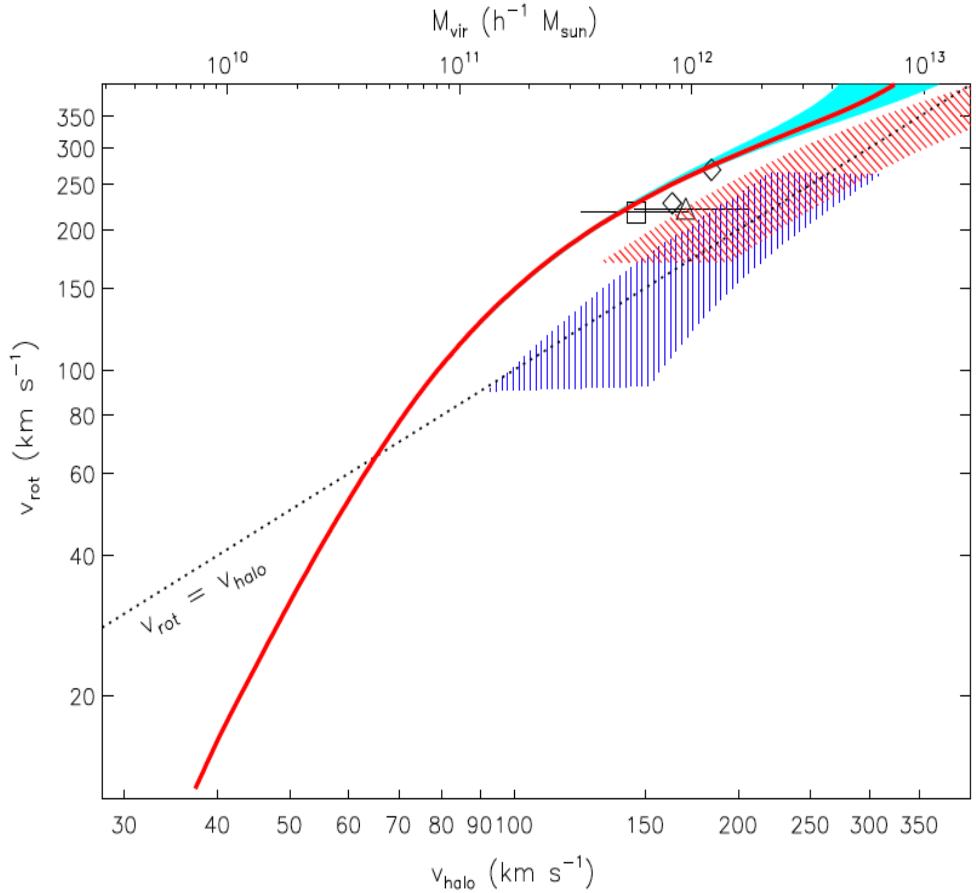
Abundance according to H_I mass: better tracer of the dynamics at large radii

Possible solutions within CDM

- Suppression of H_I in halos with M_h<$4x10^{10}M_{Sun}$ (SN-driven winds, UV photoionization M_c~$9x10^9M_{Sun}$...); Sawala et al. 2012

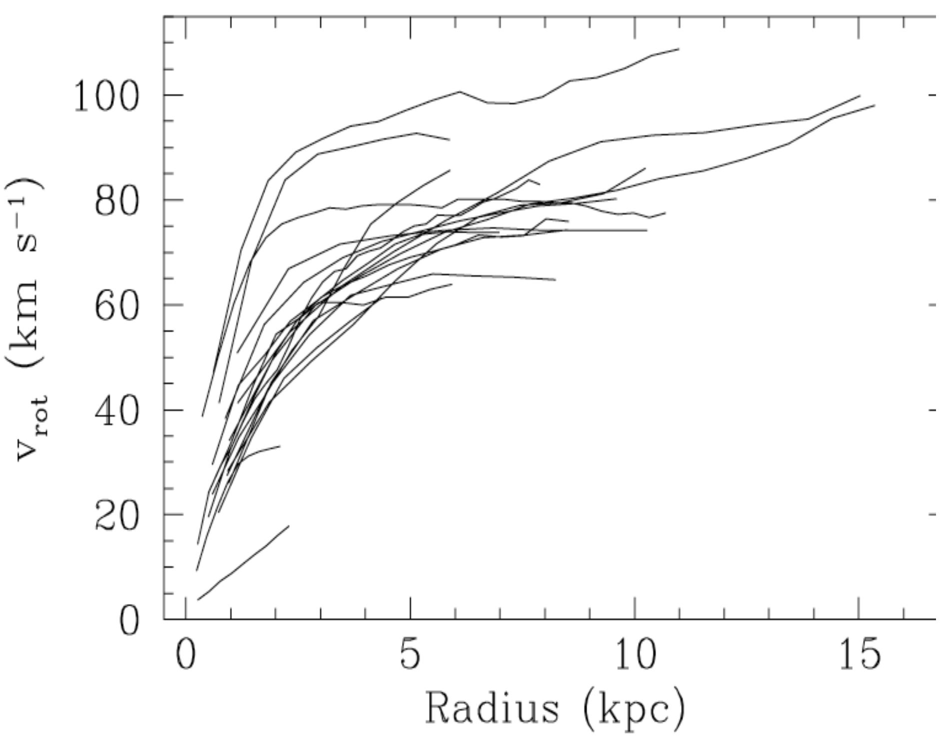
- The H_I line width underestimates the maximum rotational velocity of the halo?

Galaxy-halo Vmax relation needed to solve the overabundance problem



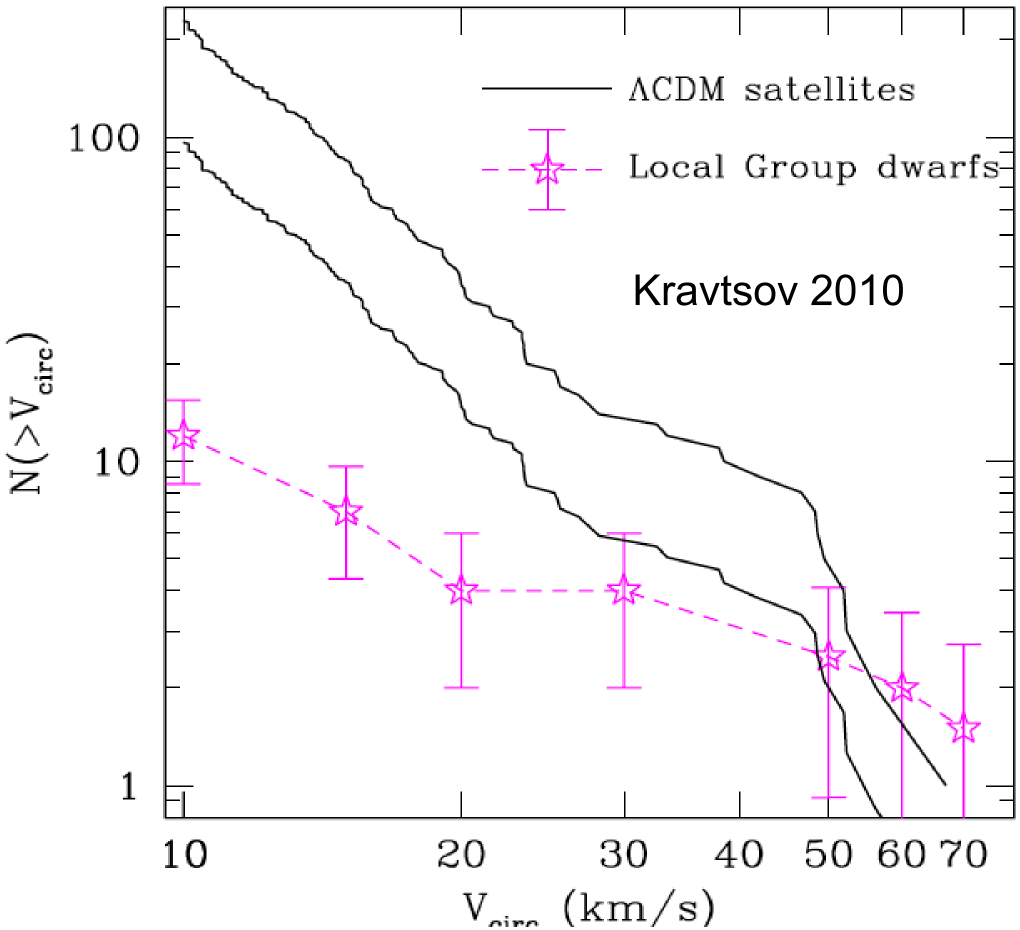
Papastergis et al. 2011

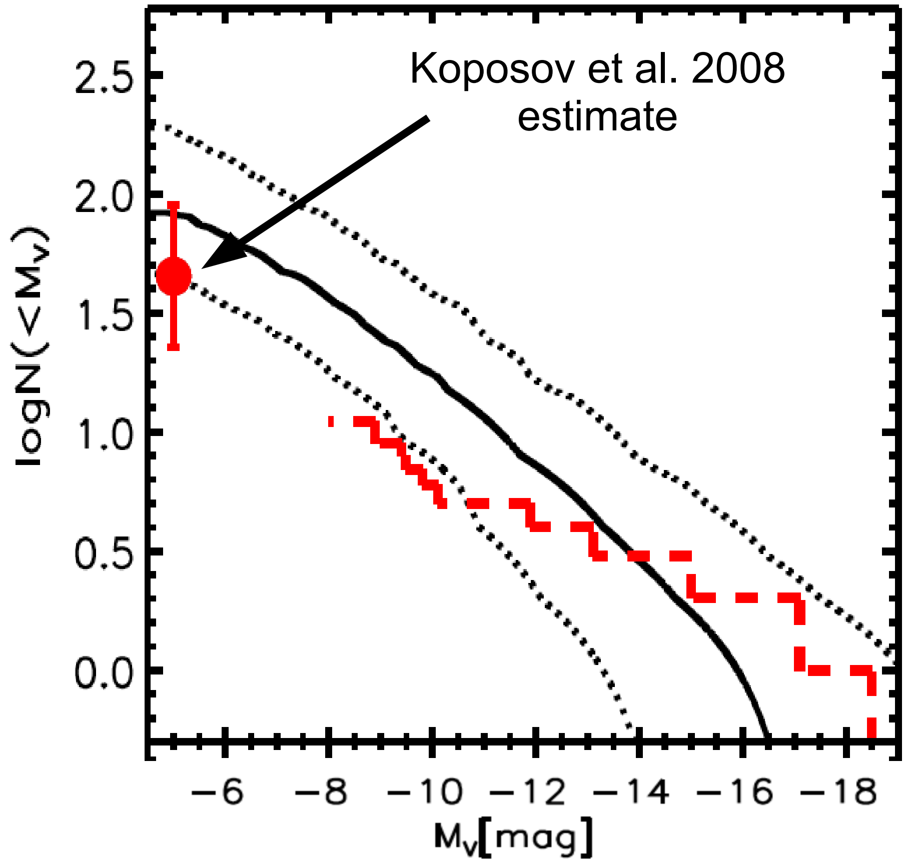
Rising rotation curves for low-mass spirals



Swaters et al. 2009

Overabundance of MW-satellites: The missing satellites problem





Guo et al. 2010 (MSII+SAM)

Considering “observational” effects (e.g. limited sky coverage) and environmental processes that suppress star formation in the satellites (e.g. ram-pressure stripping) can alleviate the problem.

Still, if CDM is right, there must be a vast amount of “dark” satellites that should be detected through lensing studies in the near future.

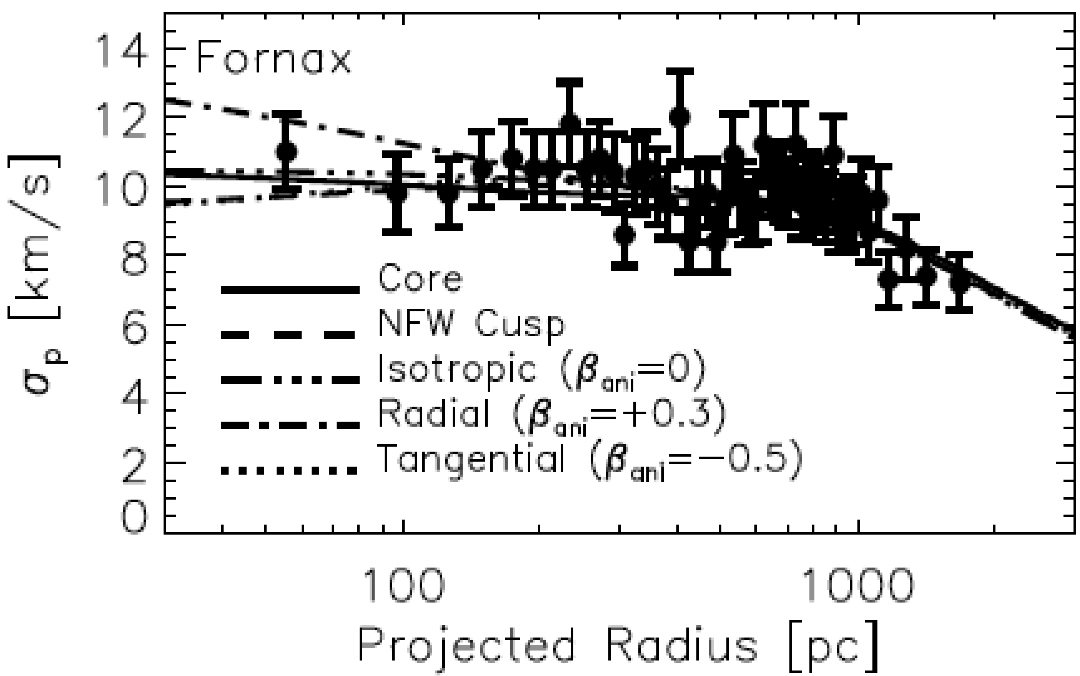
Inner density profile of MW dSphs

- The CDM model predicts DM halos that are "cuspy" in the center:

$$\rho \propto r^{-\alpha} \quad (\alpha \lesssim 1) \quad \text{for } r \to 0$$

- The assembly of the luminous galaxy modifies the inner regions of the DM distribution. In dwarf galaxies this effect is minimized since the inner dynamics are dominated by DM.

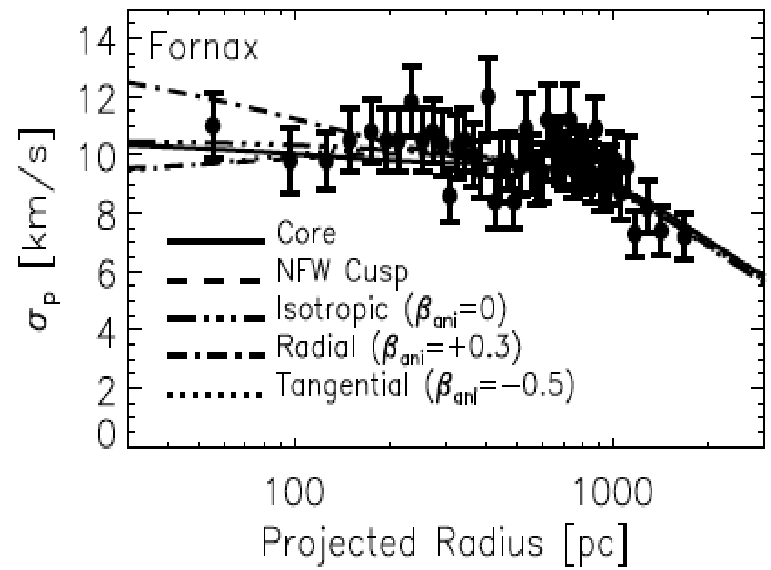
- Current observations of dSphs give an incomplete account of the 6D phase space distribution (only 2D info in space and 1D in velocity space). This creates a degeneracy between the underlying mass profile and the velocity anisotropy.

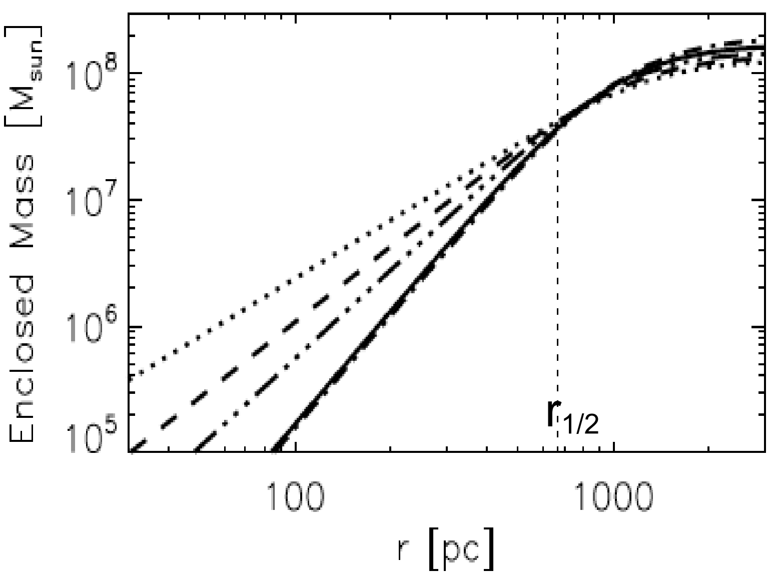


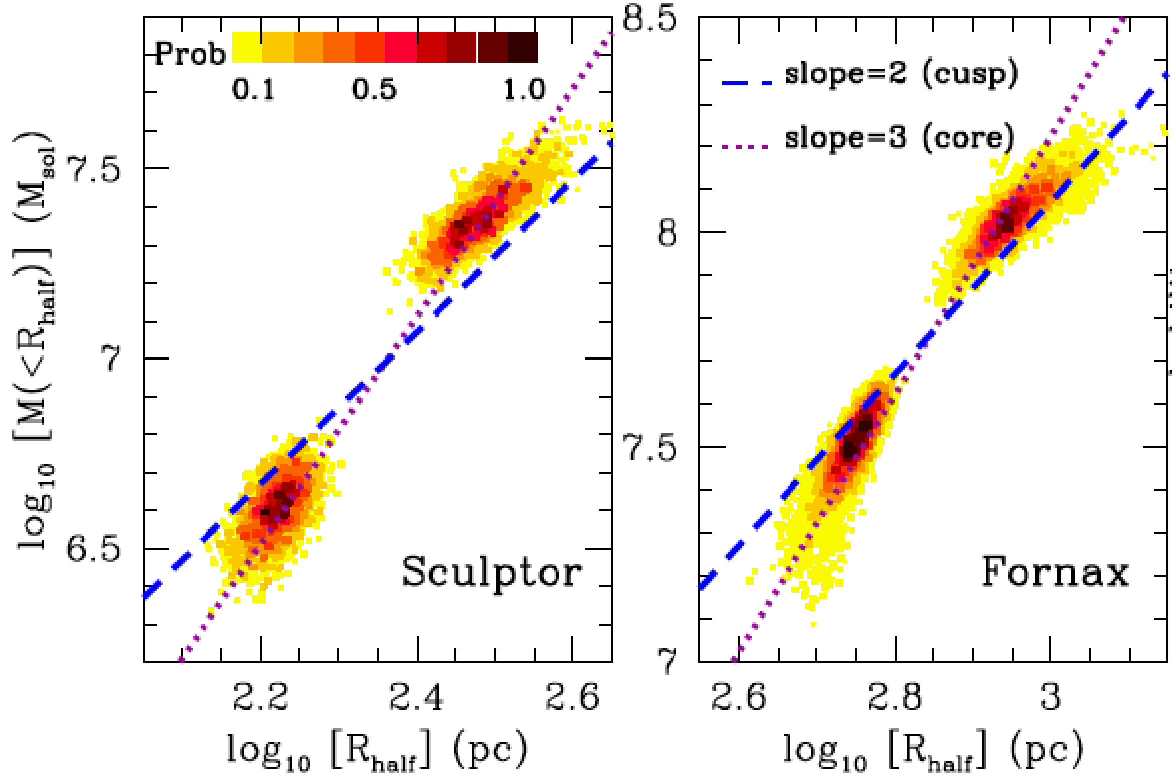
Walker and Peñarrubia 2011

Inner density profile of MW dSphs

Walker and Peñarrubia 2011







Two different stellar subcomponents provide a measurement of the slope of the mass profile:
cores are strongly favoured over cusps!!

Assumptions: spherical symmetry (halos are actually triaxial in simulations) and dynamical equilibrium

Mass-anisotropy degeneracy minimized at $r_{1/2}$
(e.g. Wolf et al. 2010)

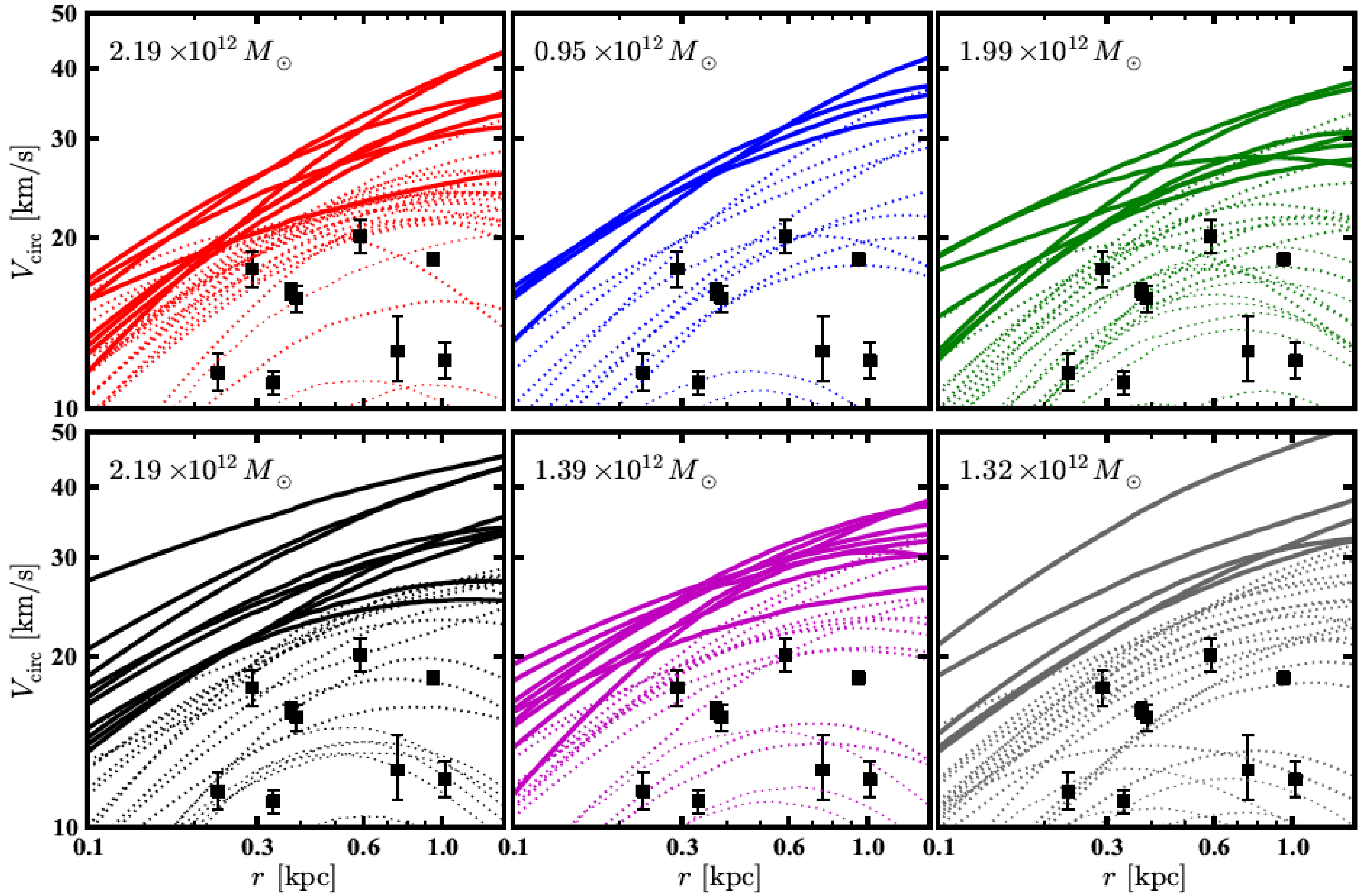
$$M_{1/2} = 3\,G^{-1}\,\langle \sigma^2_{los} \rangle\, \tilde{r}_{1/2}$$

The "too big to fail" problem

Independent(?) of the core-cusp problem, recent analysis of high resolution simulations of MW-size halos find that:

The most massive CDM subhalos seem to be too dense to host the MW dSphs!!

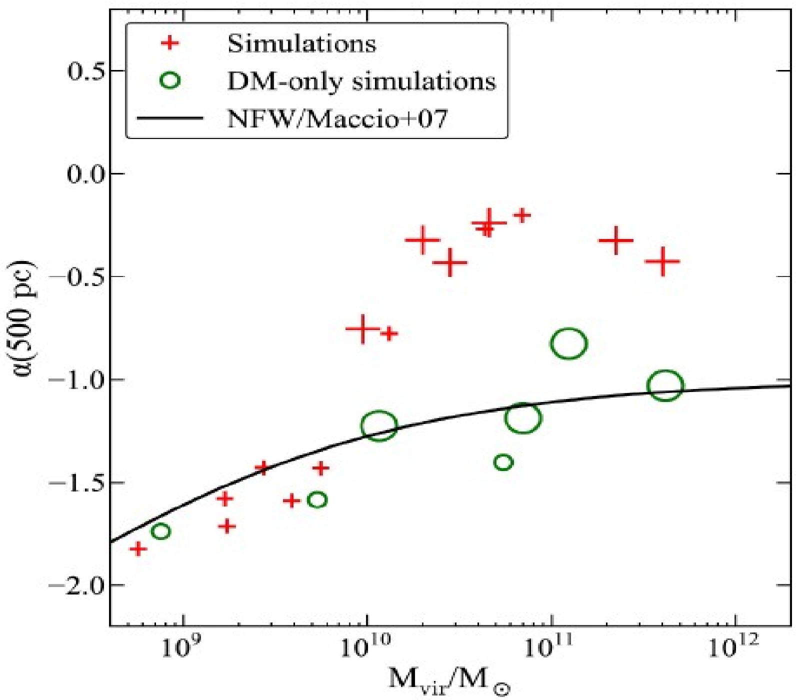
DM satellites of six MW-size halos (Aquarius project)



Boylan-Kolchin et al. 2011

Possible solutions within CDM

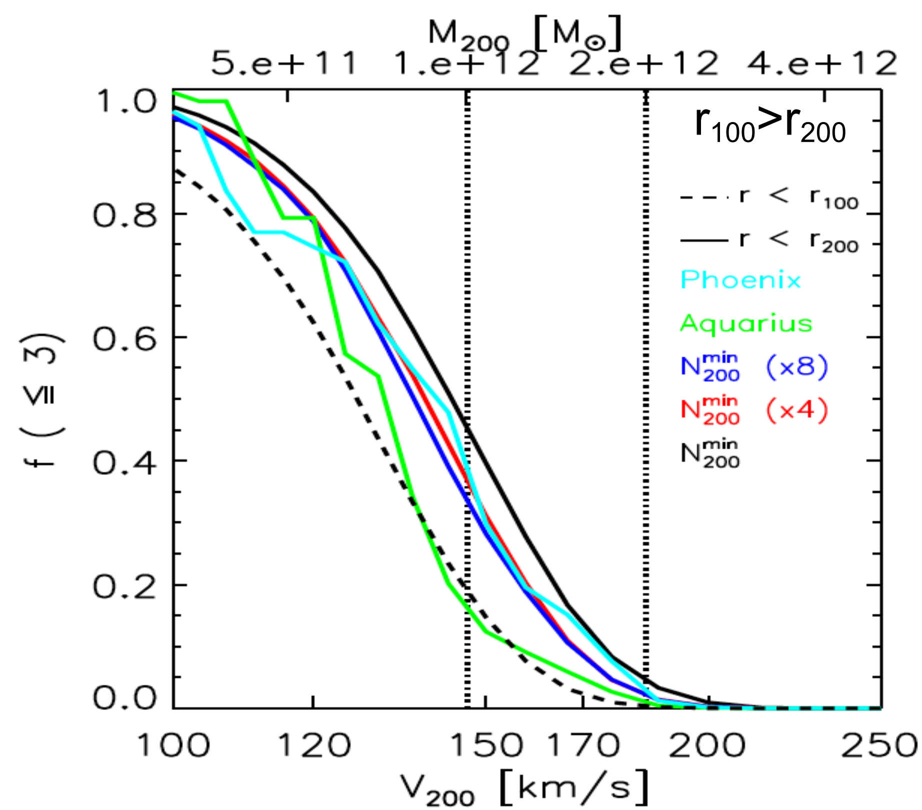
Slope of the density profile within 500 pc



Early episodes of star formation and strong SN feedback

e.g. Navarro et al. 1996, Governato et al 2012

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



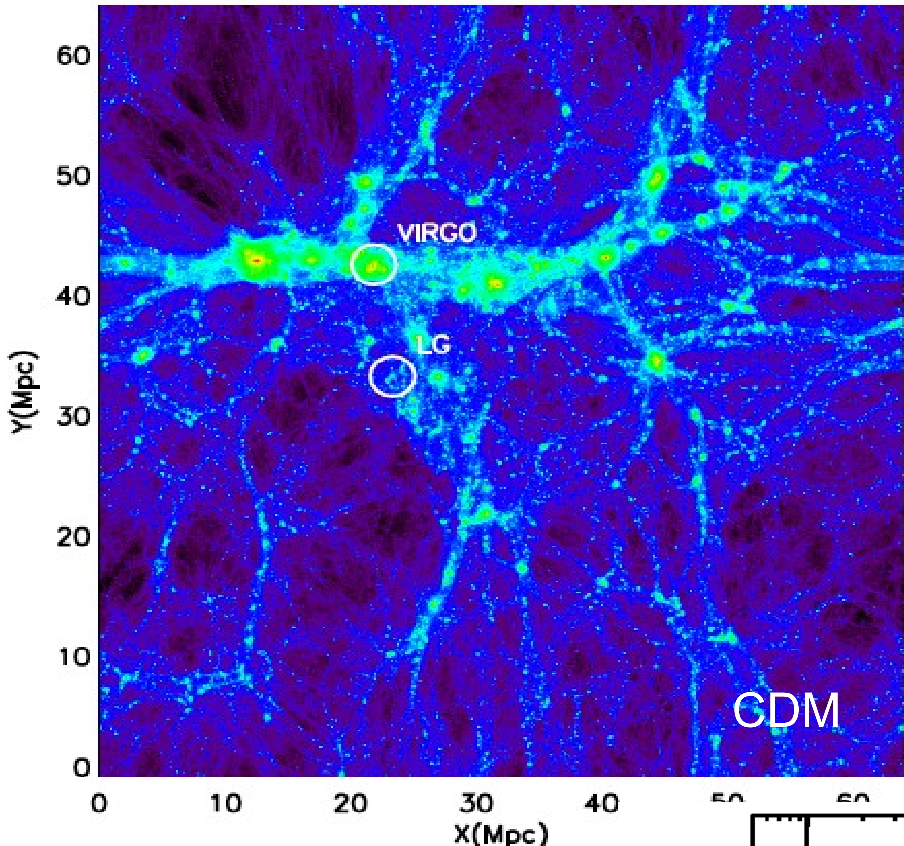
The halo of the Mily-Way is less massive than 10^{12} M_{Sun}

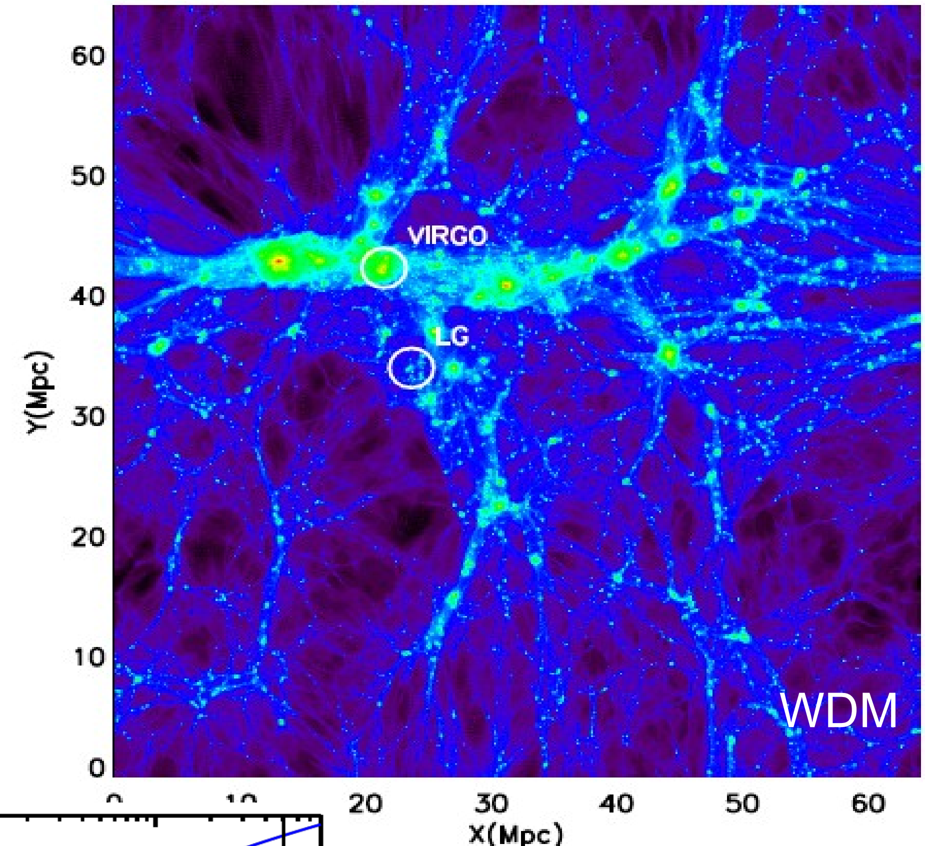
e.g. Wang et al. 2012

N_{min} is the minimum number of particles within the virial radius of the host halo needed to achieve convergence in the abundance of subhalos

Dark matter might not be cold: WDM as an alternative

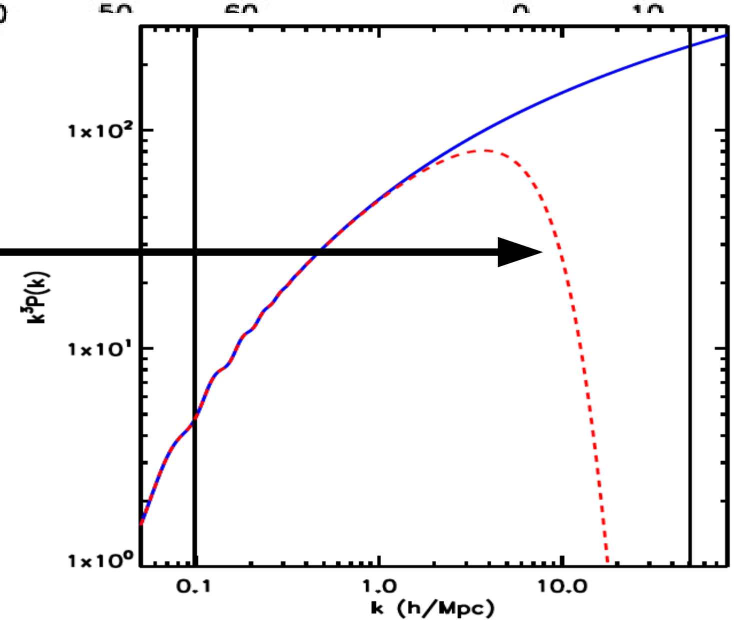
Halo abundance in the WDM model





Zavala et al. 2009

$m_\chi \sim 1$ keV
$R_{fs} \sim 500$ kpc
$M_{fs} \sim 10^{10}\ M_{Sun}$
$\sigma(z=0) \sim 0.04$ km/s

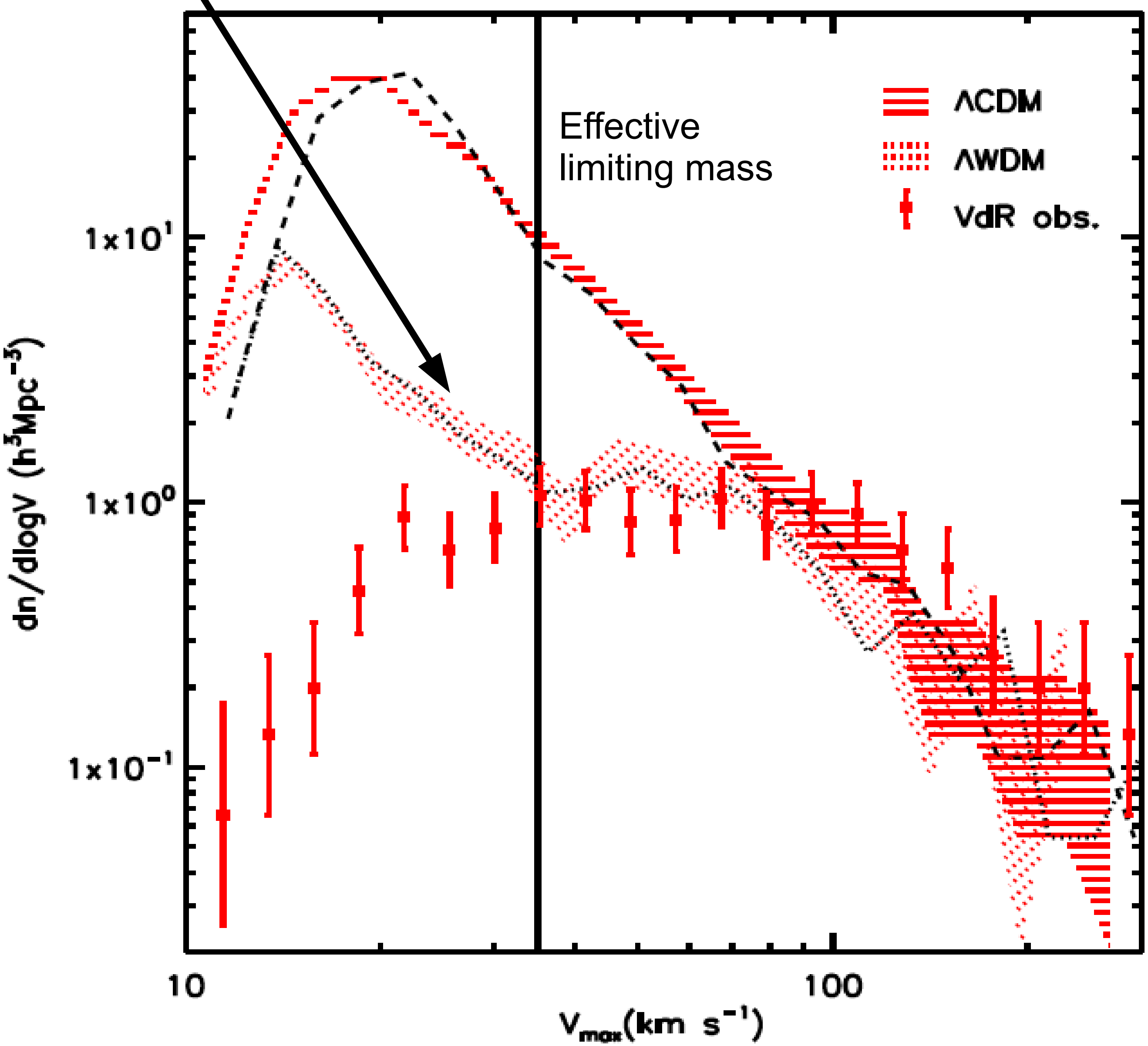


Some classic studies on halo abundance in WDM:
Colín et al. 2000,
Bode et al. 2001,
Avila-Reese et al. 2001...

The H_I velocity function (comparison with the H_I ALFALFA survey)

Discreteness effects
Wang and White 2007

Zavala et al. 2009

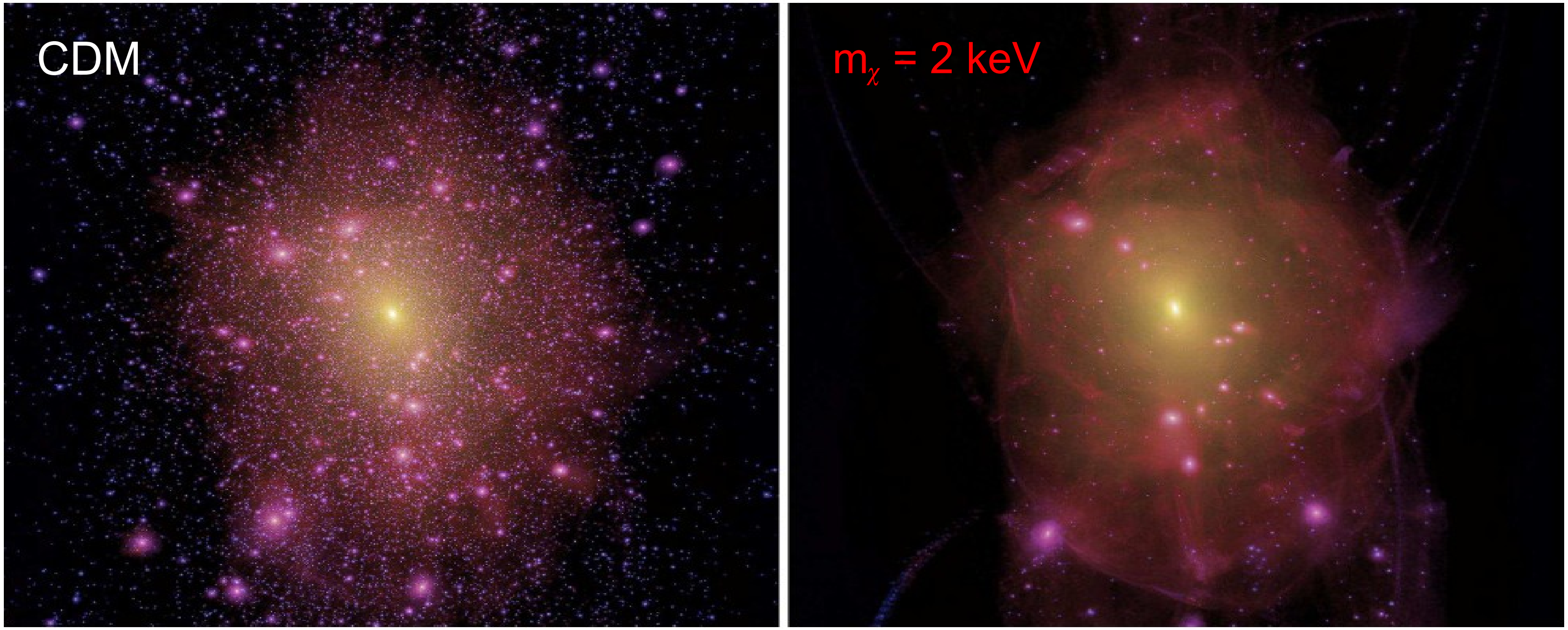


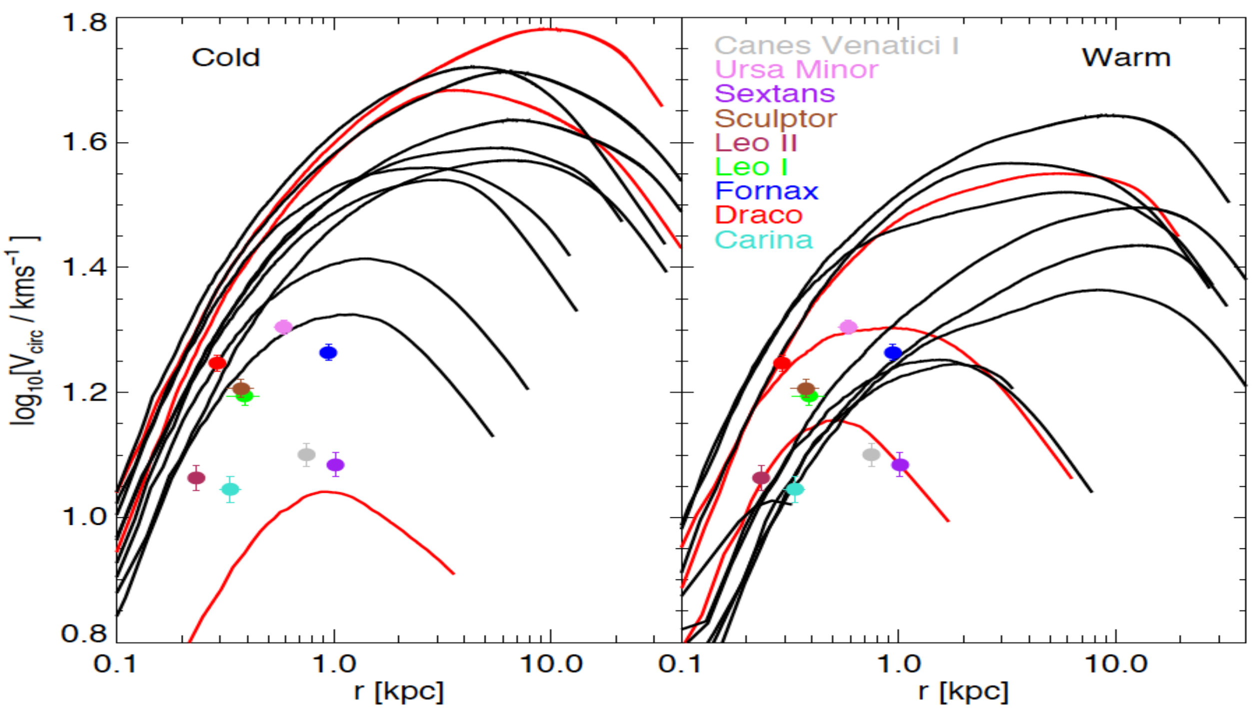
CDM is overabundant by a factor of ~10 at V_{max}~30 km/s WDM (1keV) fits nicely but:

In marginal tension with current Ly-α forest constraints

Inner density profile of WDM subhalos

MW-size halo simulations (Lovell et al. 2012)





WDM halos are still well fitted by a NFW profile, but halos are less concentrated:

WDM alleviates the “too big too fail” problem!!

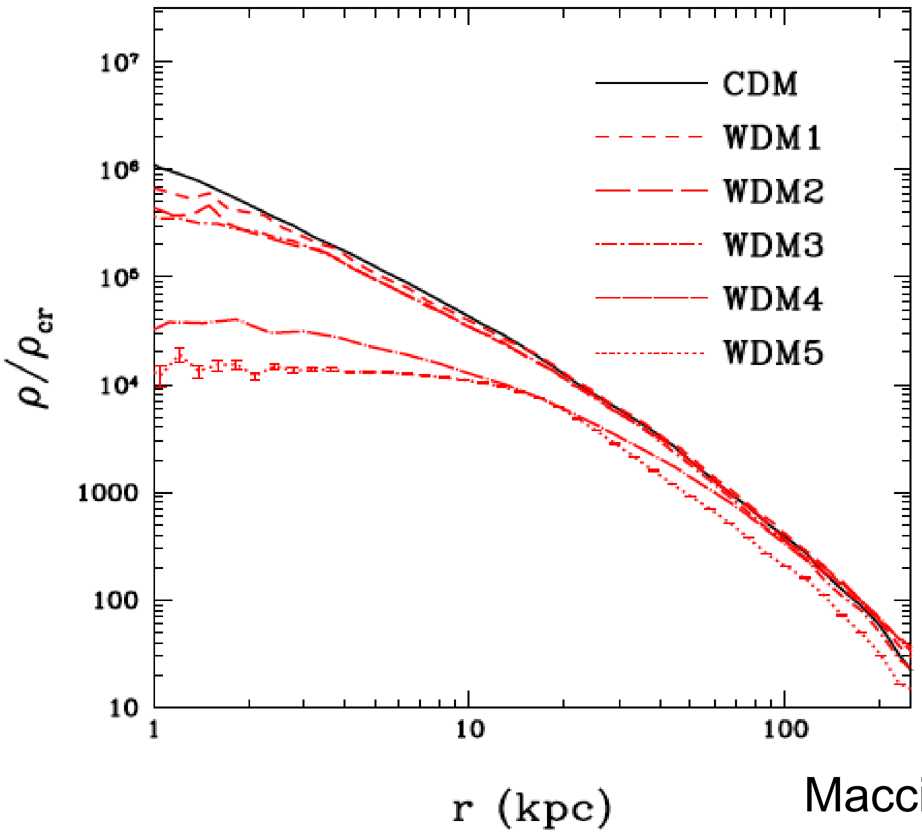
Cores in WDM halos

(e.g. Kuzio de Naray et al. 2010, Maccio et al. 2012)

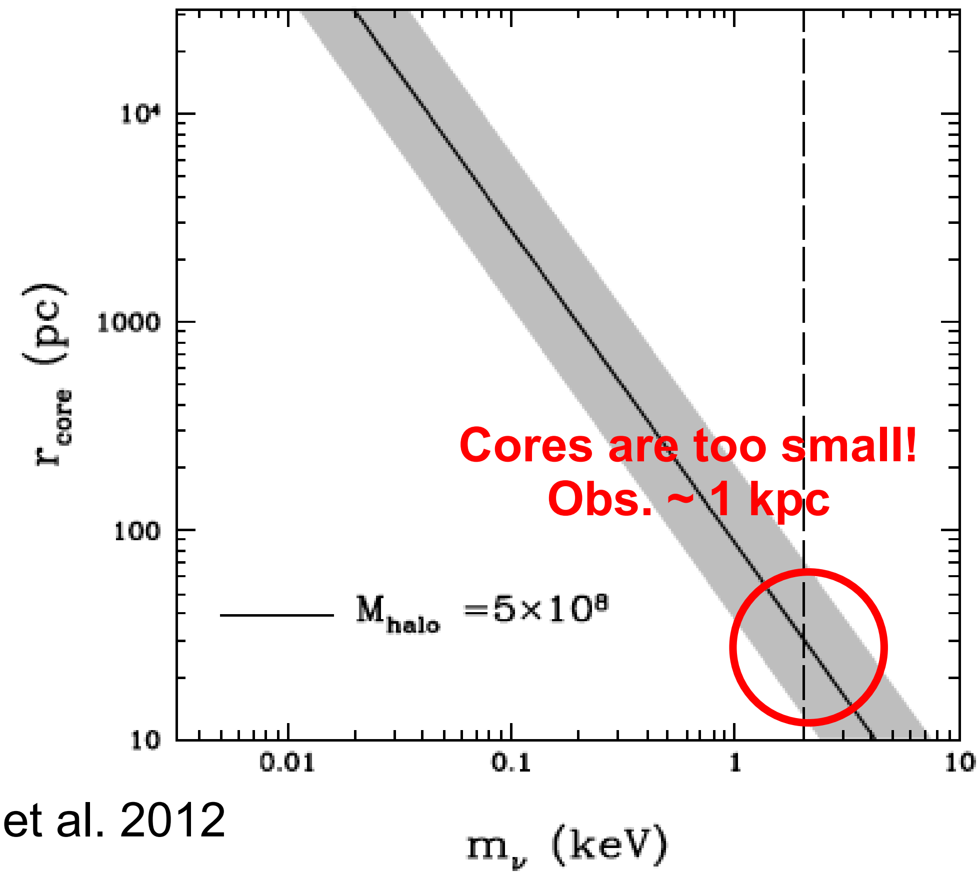
Coarse-grained phase-space density: $Q = \rho/\sigma^3$

Thermal velocities at decoupling set a maximum value to Q that translates into a central density core (this value depends on the mass of the DM particle)

MW halo (sim)



Typical MW subhalo (estimate)



Maccio et al. 2012

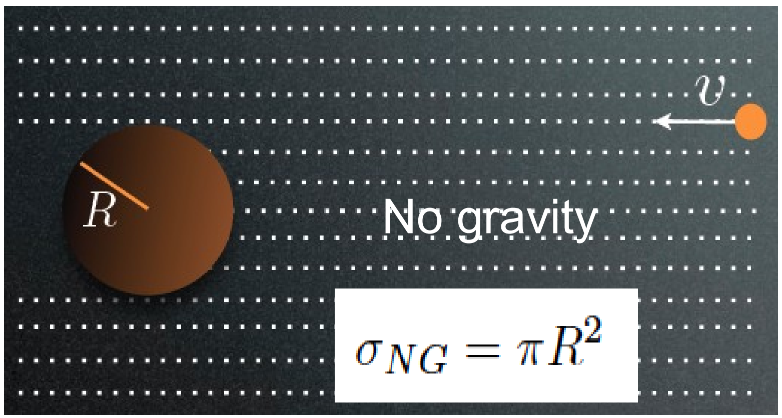
Still, no simulation to date has been able to resolve the central kpc region of the subhalos of a WDM MW-size halo (WDM sims are quite challenging!!)

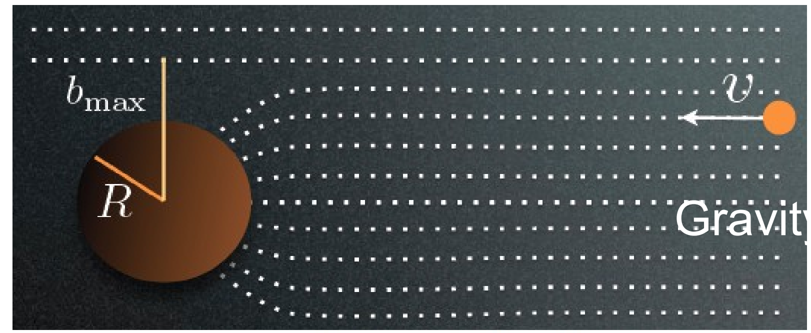
Dark matter might not be collisionless: Self-Interacting DM as an alternative

Velocity-dependent SIDM models (vdSIDM) (Sommerfeld enhancement)

- Classical analog:

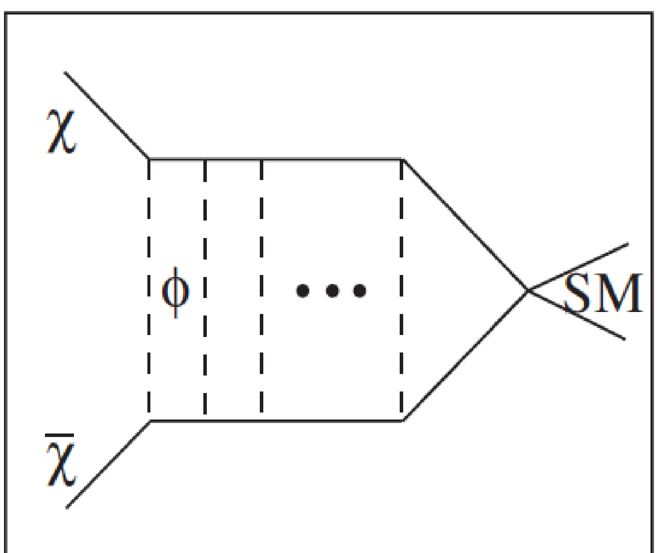
Figs. from M. Cirelli, DMV, Cambridge 2011

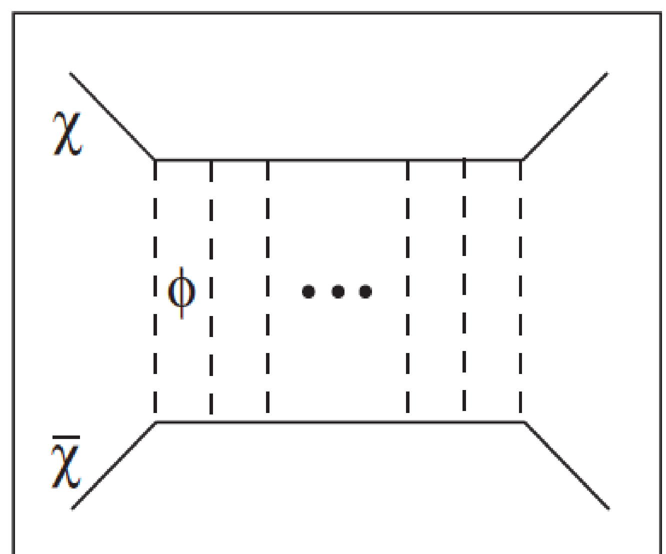




$$\sigma_N = \sigma_{NG}\left(1 + \frac{v_{esc}^2}{v^2}\right) = \pi b_{max}^2$$

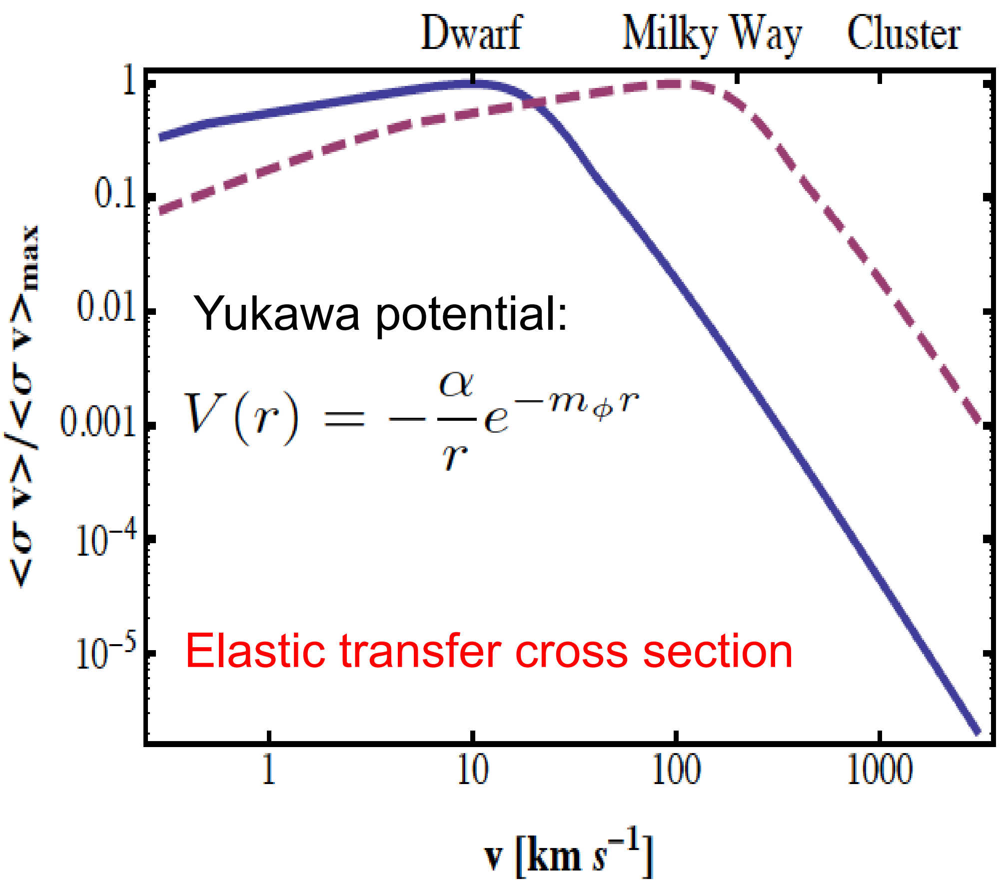
- Annihilation and self-scattering enhancement (e.g. Buckley and Fox 2010)





Velocity-dependent elastic SIDM models

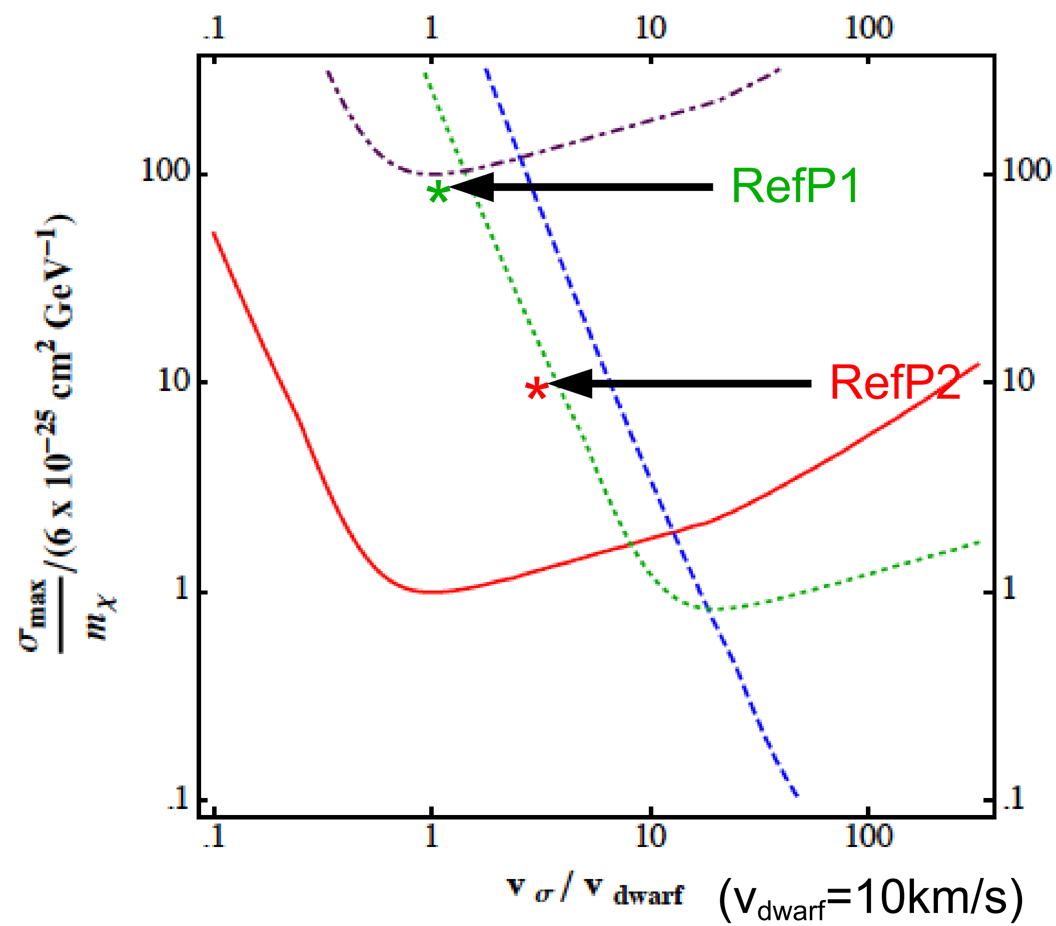
Loeb and Weiner 2011



$$v^2_{\rm max} = 2\alpha_c m_\phi / (\pi m_\chi)$$

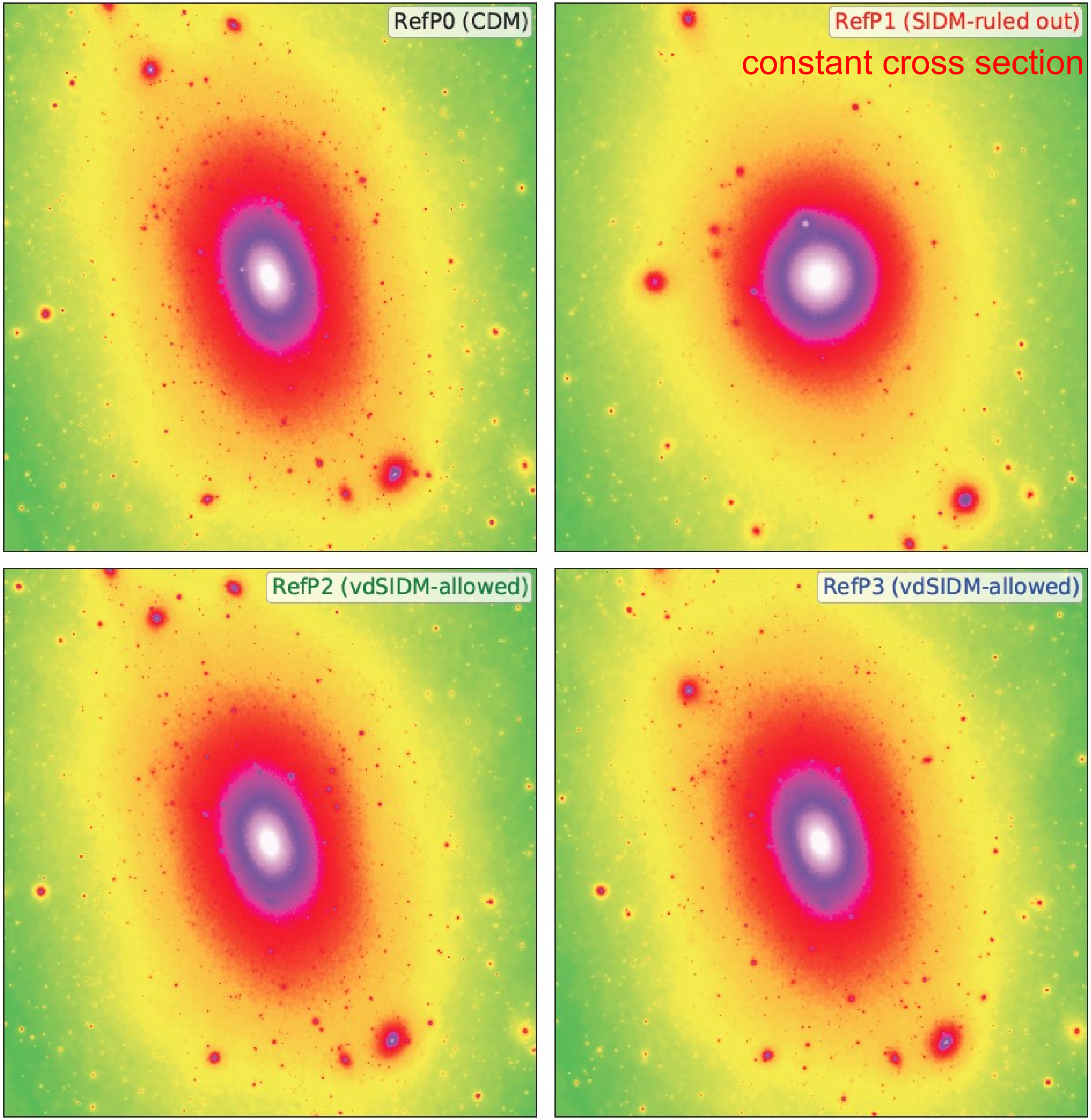
$$\sigma_{\rm max} = 22.7/m^2_\phi$$

Astrophysical constraints
Cluster ellipticities
Subhalo evaporation



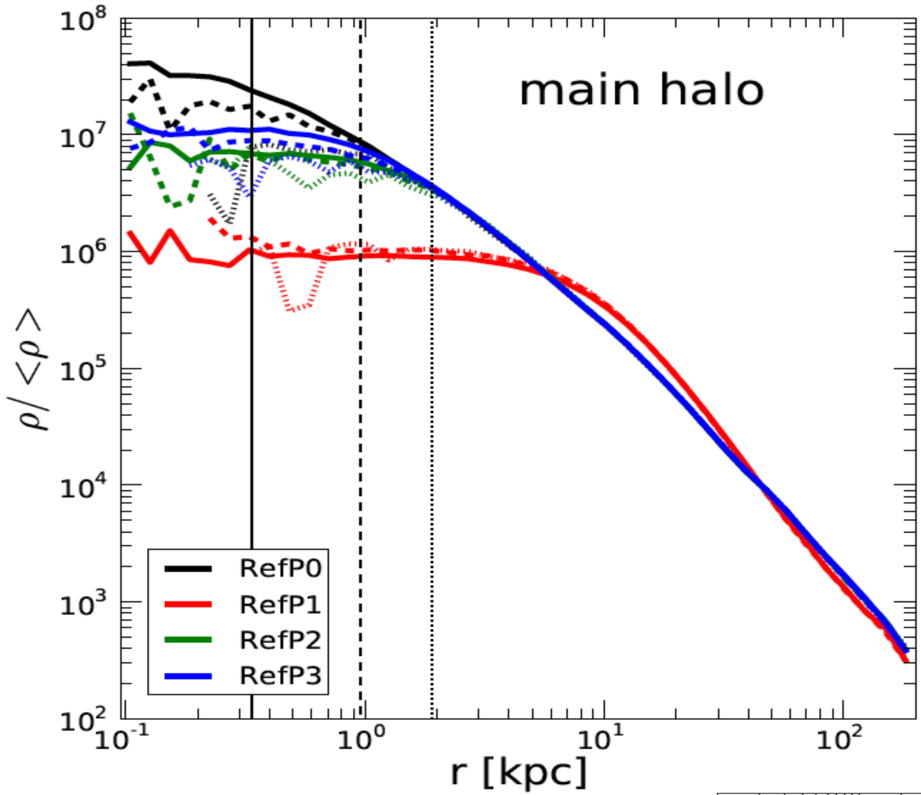
vdSIDM (re-simulate Aquarius MW-size halo)

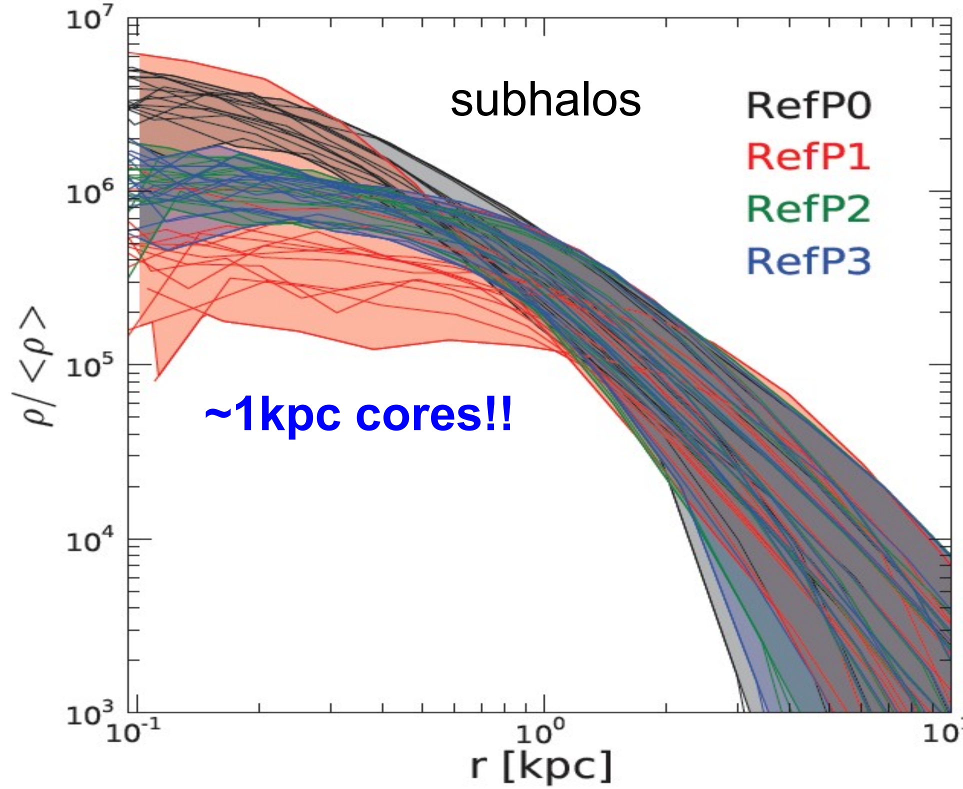
Vogelsberger, JZ & Loeb 2012



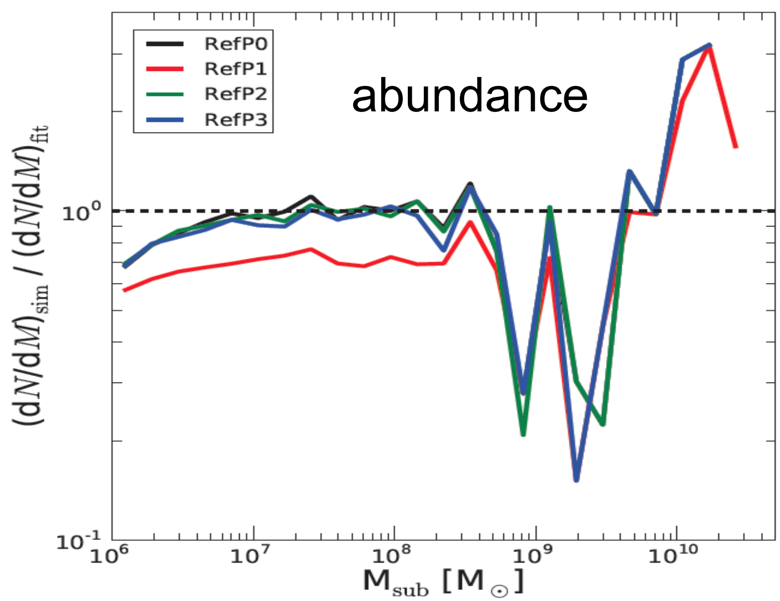
vdSIDM (MW-size halo)

Vogelsberger, JZ & Loeb 2012

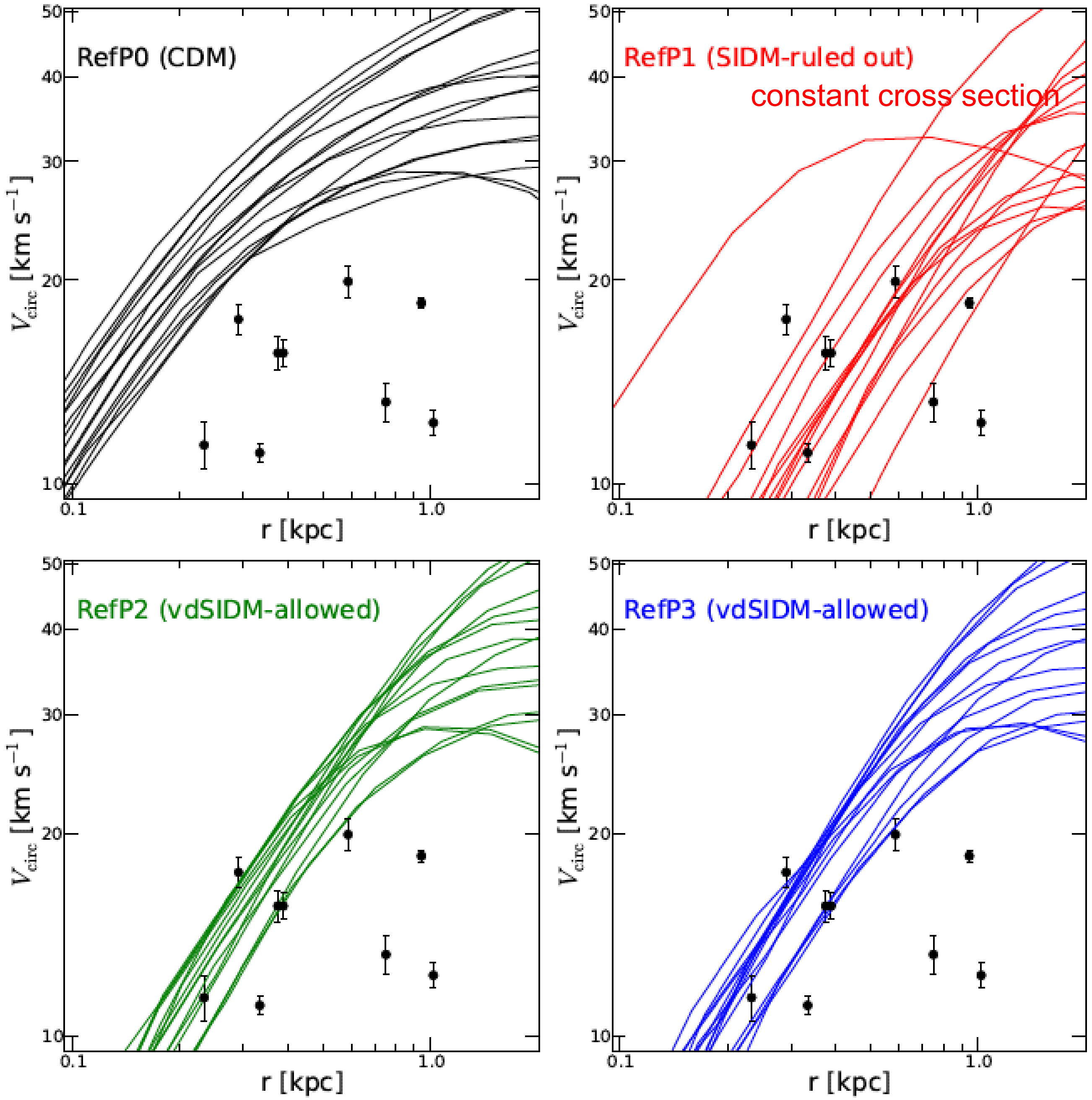




Abundance unchanged in elastic vdSIDM models



vdSIDM subhalos and the bright MW dSphs



Vogelsberger, JZ & Loeb 2012

vdSIDM halos naturally develop sizeable cores without violating current constraints

vdSIDM alleviates the “too big too fail” problem!!