The velocity function of galaxies in the local environment from Cold and Warm Dark Matter simulations

Jesús Zavala Franco
(CITA National Fellow)

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

In collaboration with:

Yi-Peng Jing (SHAO, Shanghai)
Andreas Faltenbacher (UWC, Cape Town)
Gustavo Yepes (UAM, Madrid)
Yehuda Hoffman (RI of P, Jerusalem)
Stefan Gottlöber (AIP, Potsdam)
Barbara Catinella (MPA, Garching)

Paper: ApJ, 700, 1779 (0906.0585)

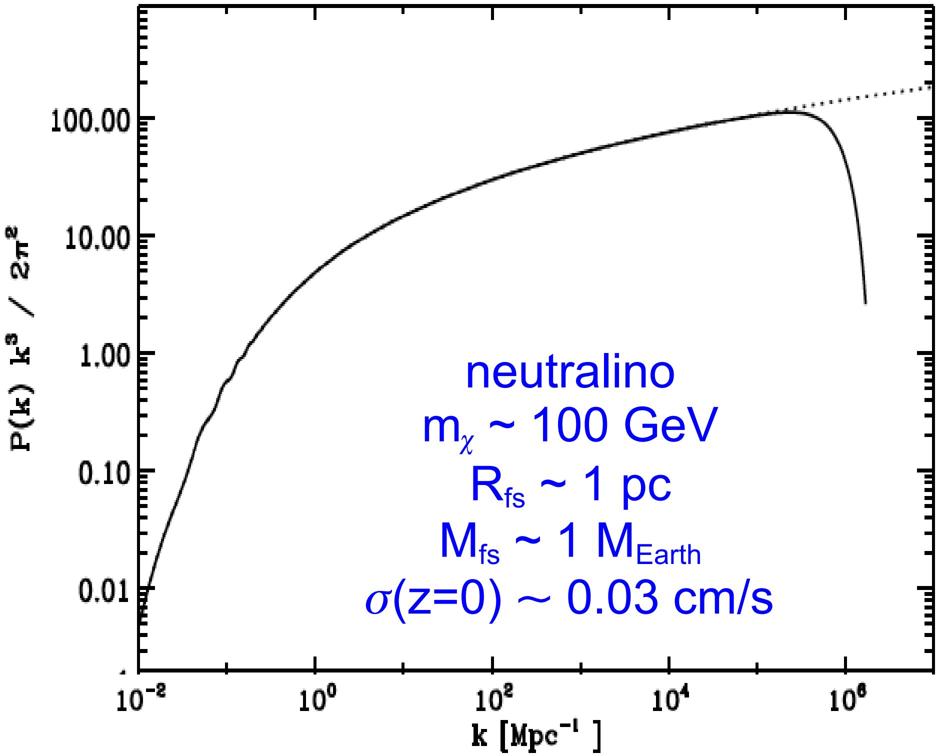
Workshop CIAS Meudon 2012

Outline

- Abundance of small scale structure: prevailing challenge for the CDM paradigm?
- Constrained CDM and WDM simulations
- Abundance of DM halos in the local universe
- Comparison with the ALFALFA H_I velocity function
- Summary and Conclusions

Is DM cold?

Angulo & White, 2010



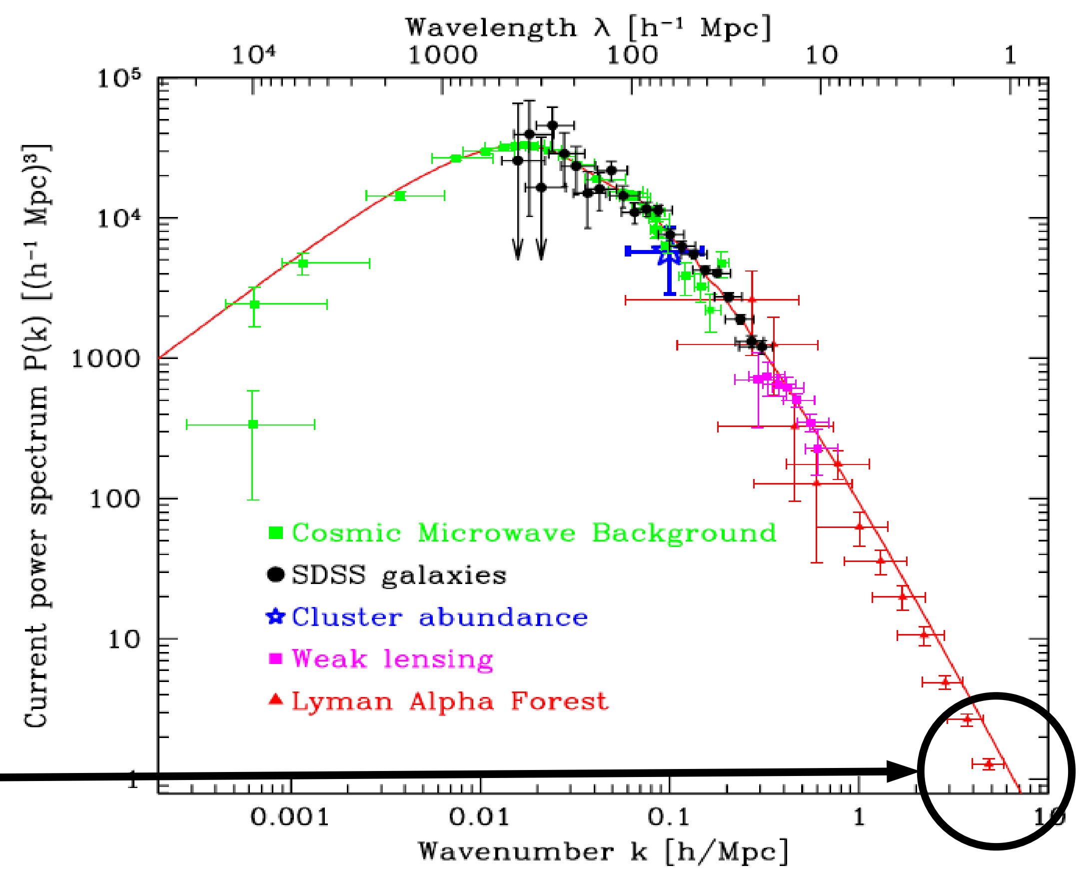
Free streaming length: $R_{\rm fs} \propto m_\chi^{-1}$

Velocity dispersion (unclustered matter):

$$\sigma_\chi \propto a^{-1} m_\chi^{-1/2}$$

e.g. Boyarsky et al. 2009

m_χ > 1 keV
R_{fs} < 500 kpc
M_{fs} < 10^{10} M_{Sun}
σ(z=0) < 0.04 km/s

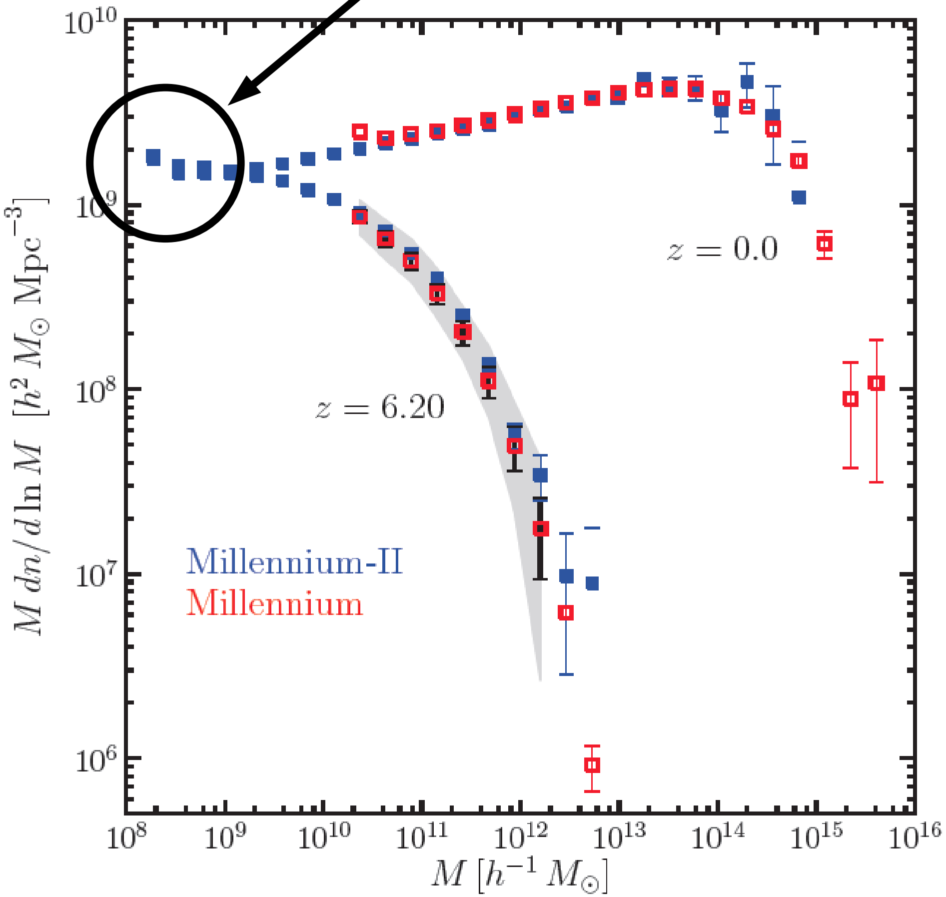


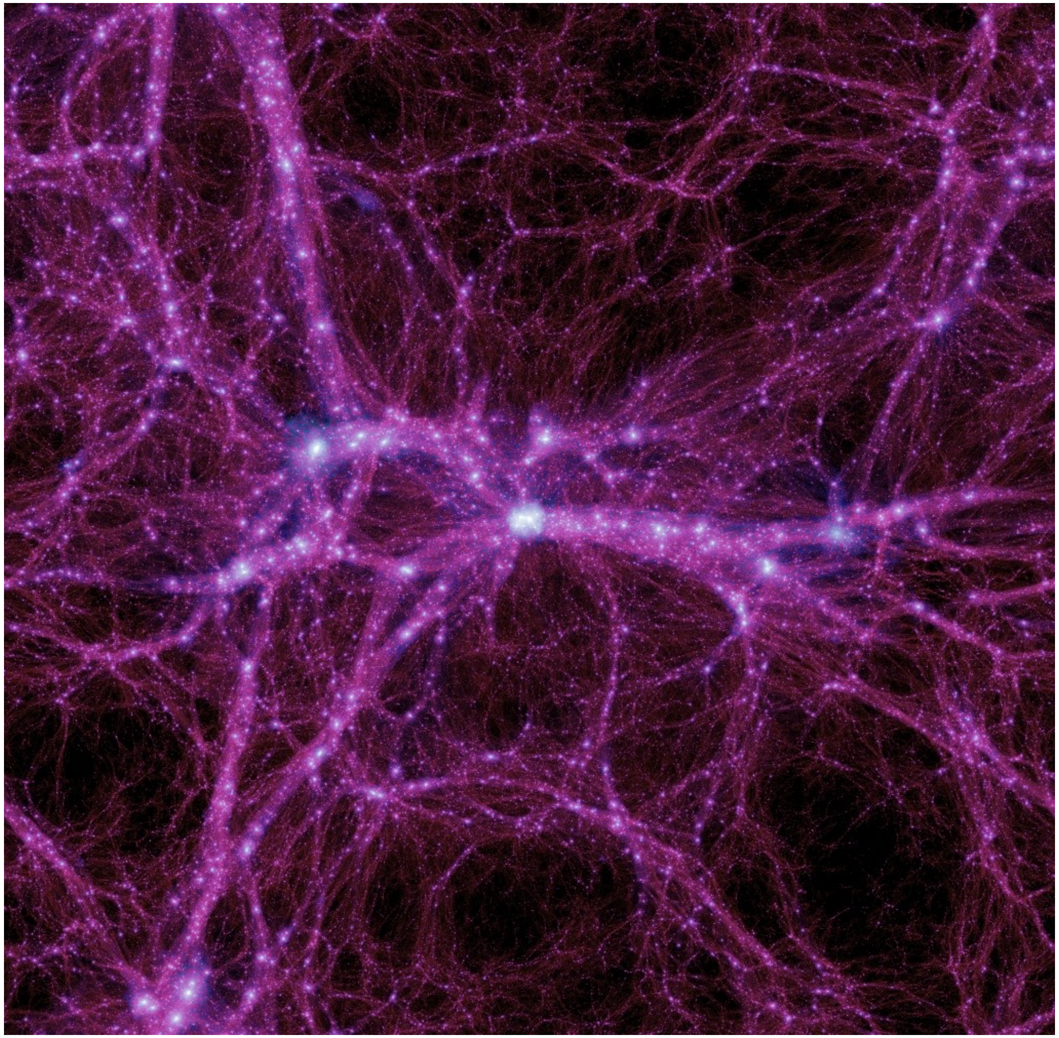
Tegmark et al. 2004

Abundance of low-mass halos in a CDM universe

Millennium II Simulation, Boylan-Kolchin et al. 2009

dn/dM ~ M^{-2}

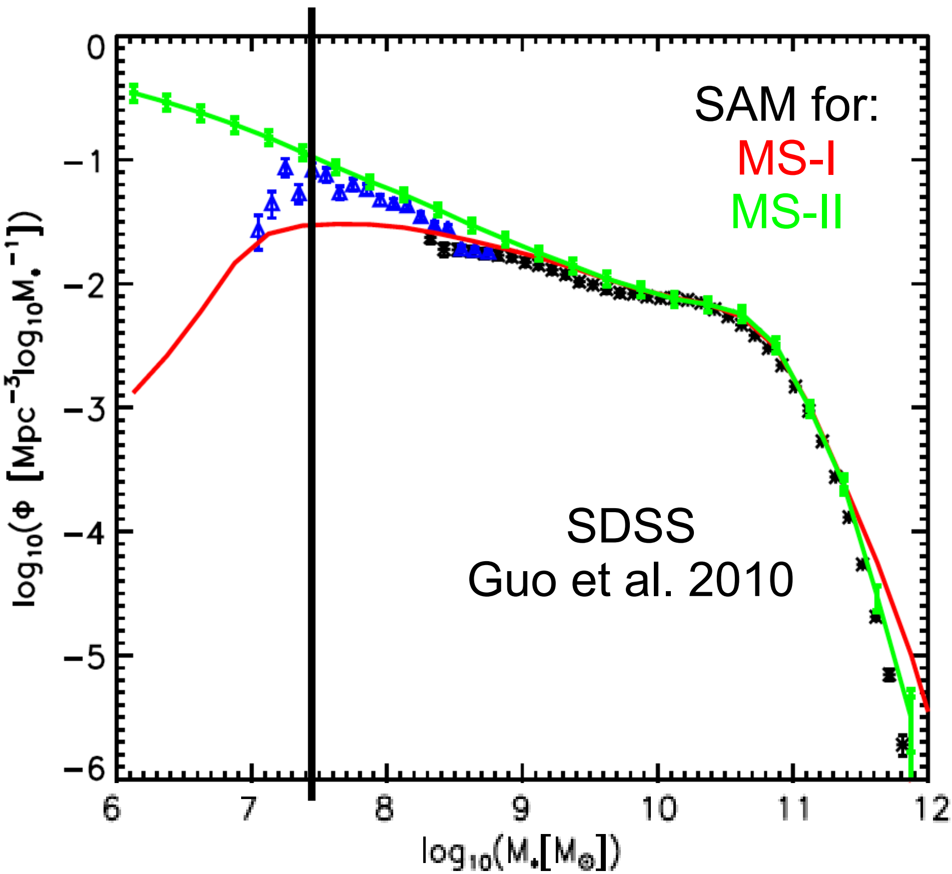




CDM free streaming length many orders of magnitude below mass resolution!

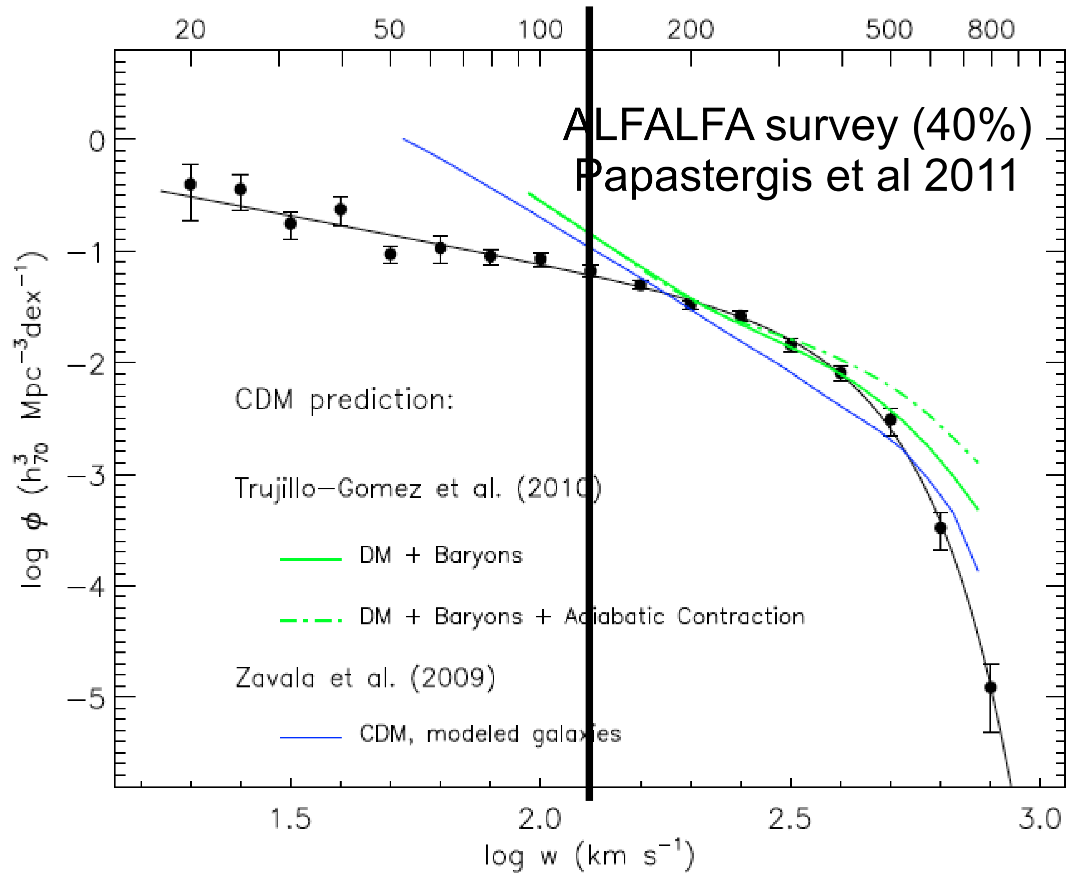
Observed abundance of dwarf galaxies

$M_h \sim 4x10^{10} M_{Sun}$



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

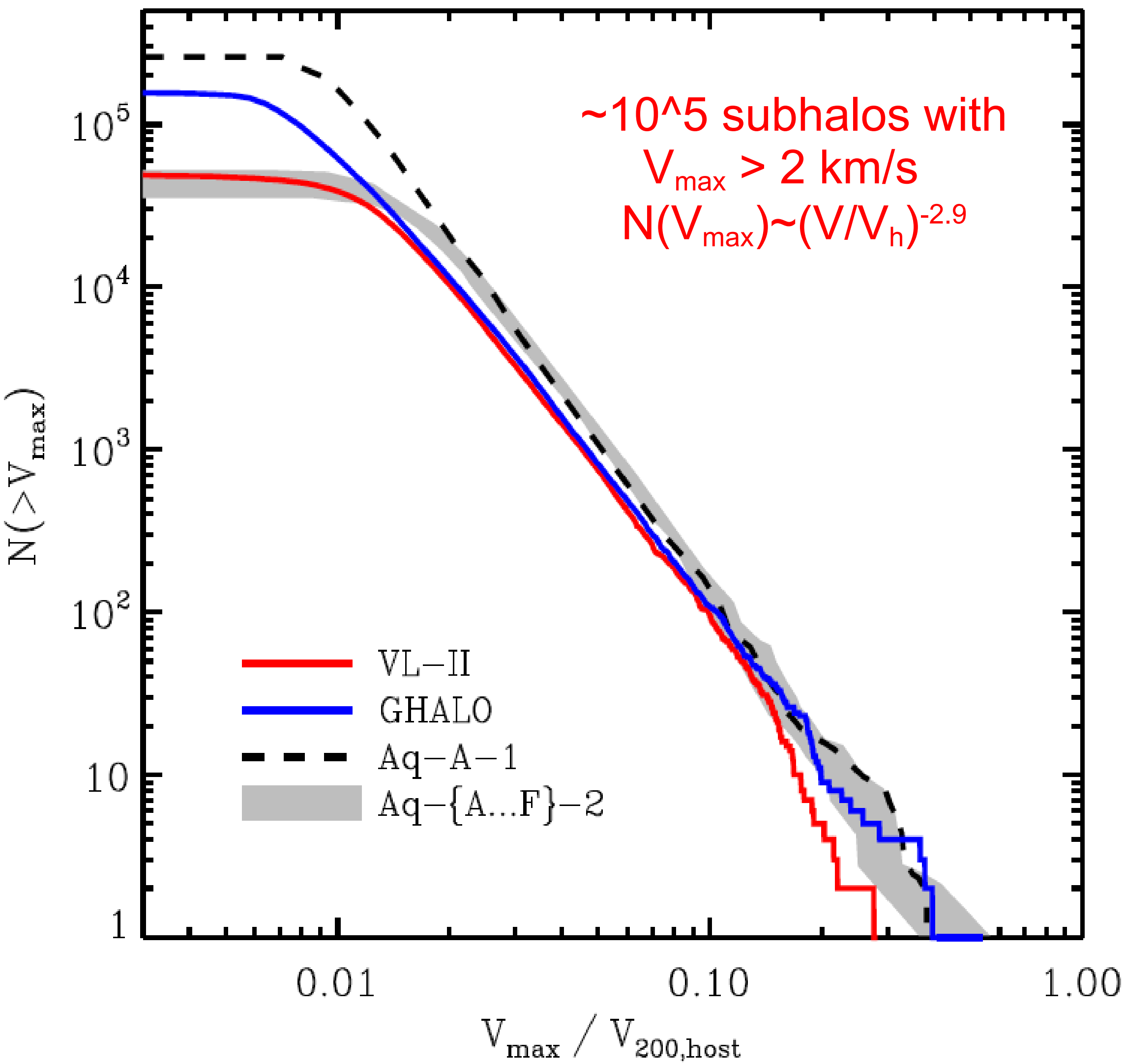
$M_h \sim 4x10^{10} M_{Sun}$



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

Abundance of low-mass subhalos in CDM

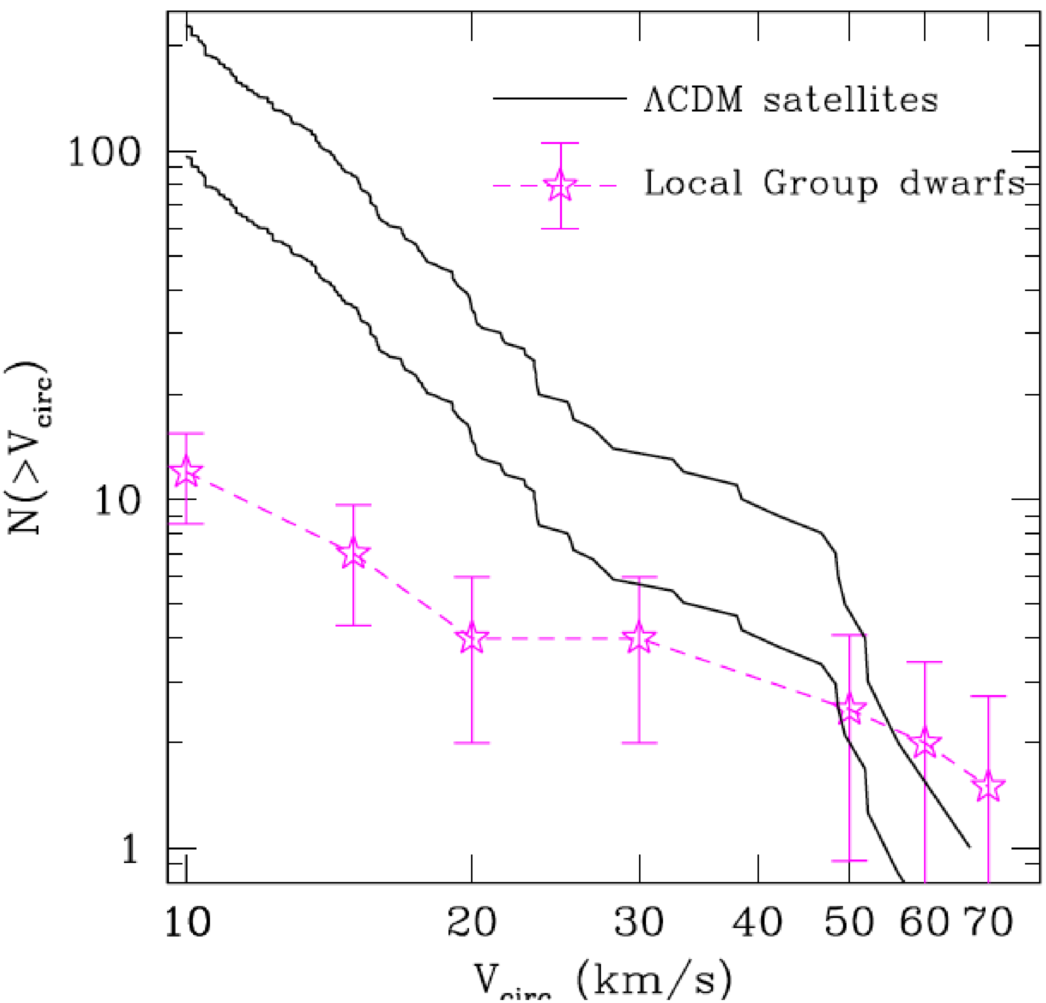
Fig. from Bullock 2010



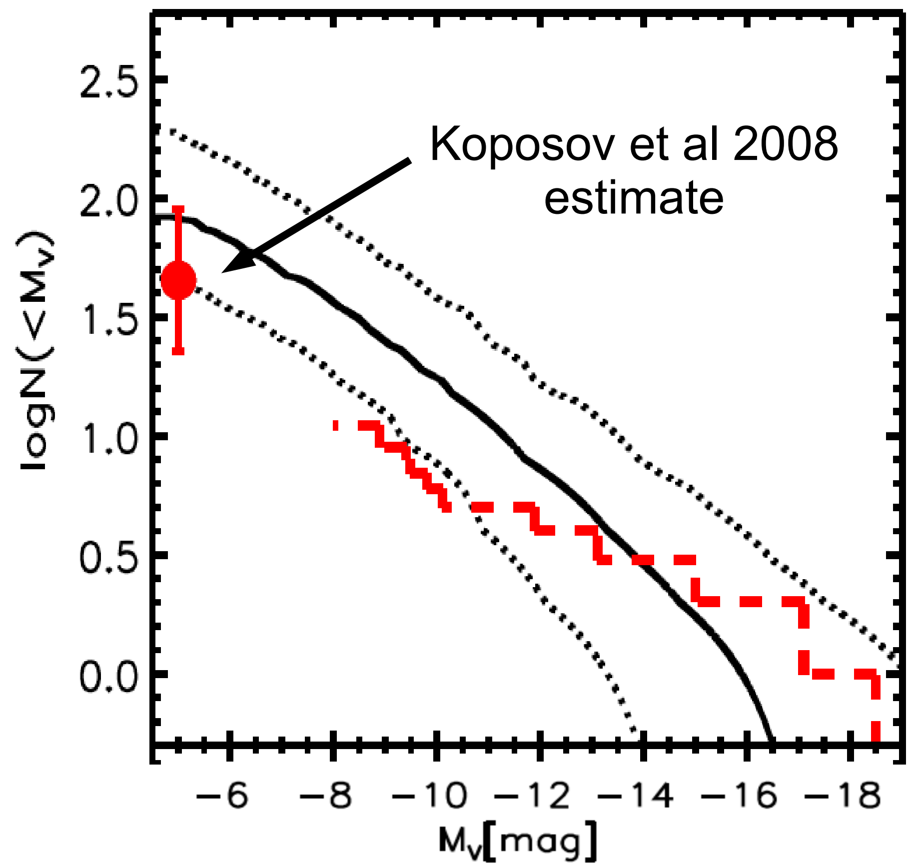
MW-size halo Aquarius project
Springel et al. 2008

Missing satellite problem?

Kravtsov 2010



Guo et al. 2010 (MSII+SAM)



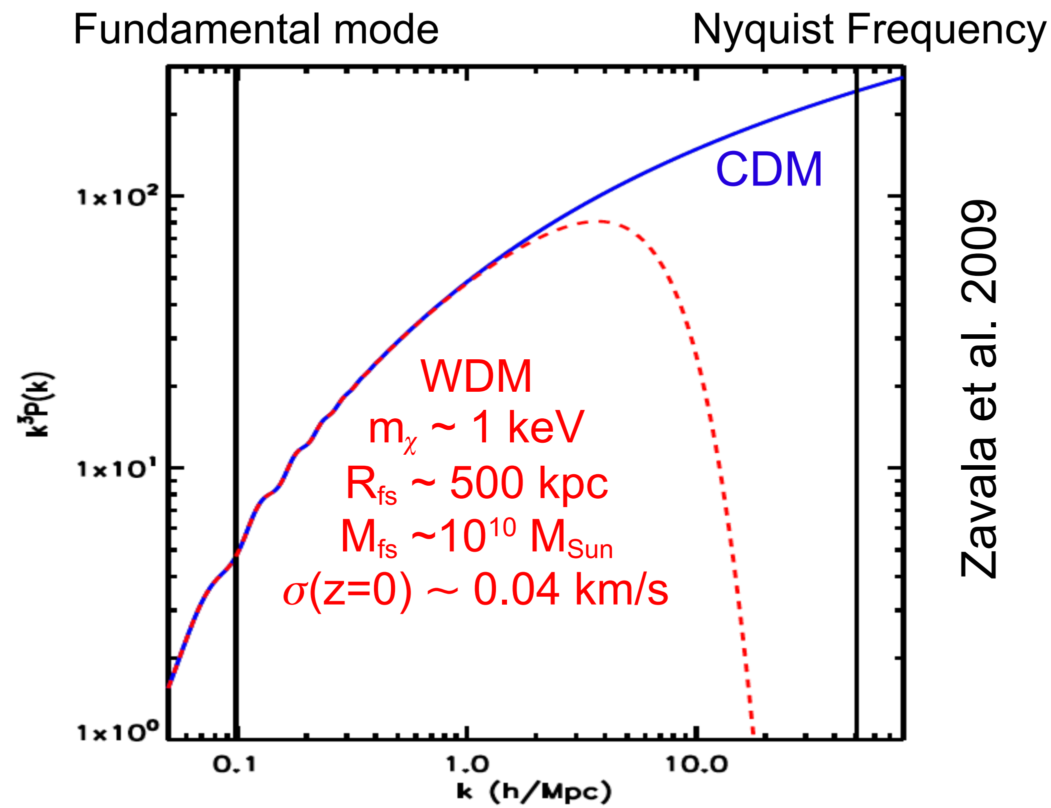
CDM and WDM constrained simulations

General setup:

WMAP3 cosmology
~88 Mpc box
~ 1 billion particles
mass resolution ~ 2e7 Msun

WDM:

Cutoff in the power spectrum
Thermal velocities not included



Constrained simulations: Constructed to reproduce the gross features (distribution and kinematics) of the nearby universe such as the local super cluster. They minimize cosmic variance present in unconstrained simulations.

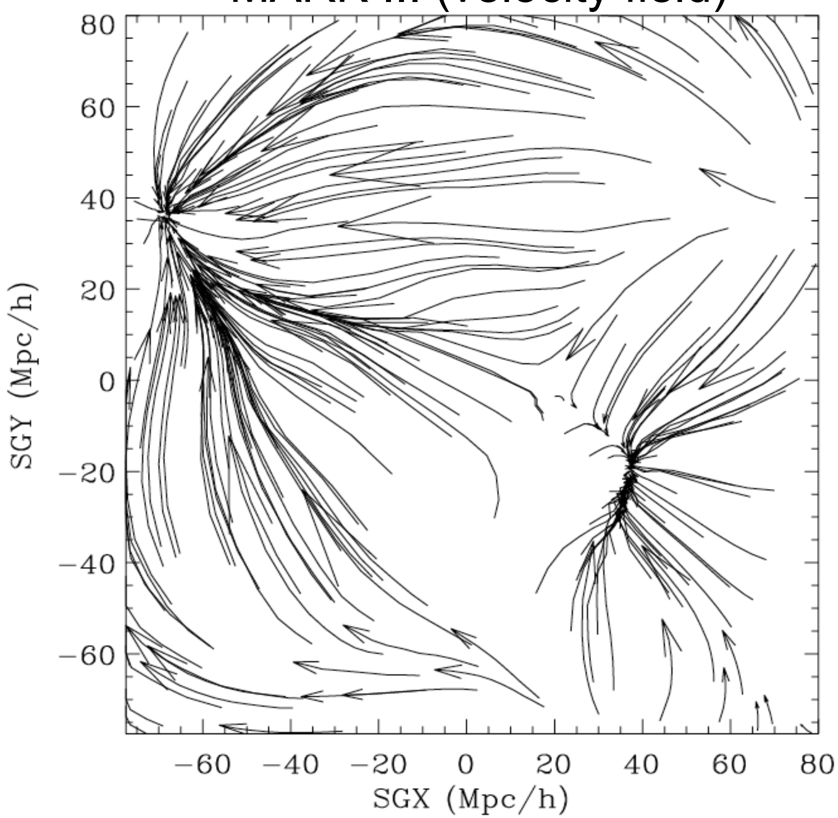
Initial conditions with constraints

Observational constraints:

Radial velocities from MARK III (Willick et al. 1997), SBF (Tonry et al. 2001) and Catalog of Neighboring Galaxies (Karachentsev et al. 2004)

Positions of nearby X-ray selected clusters (Reiprich & Böhringer 2002)

MARK III (velocity field)



Klypin et al. 2003

Reconstruct density and velocity fields from the data (Wiener Filter) assuming linear theory and a power spectrum (Hoffman and Ribak 1991, Klypin et al. 2003)

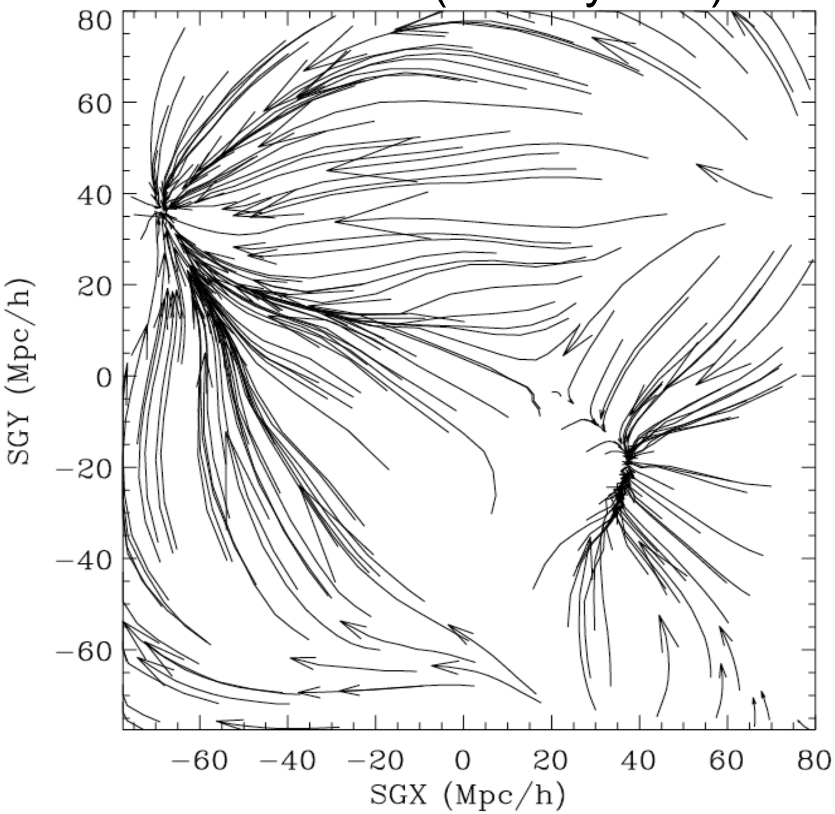
Initial conditions with constraints

Observational constraints:

Radial velocities from MARK III (Willick et al. 1997), SBF (Tonry et al. 2001) and Catalog of Neighboring Galaxies (Karachentsev et al. 2004)

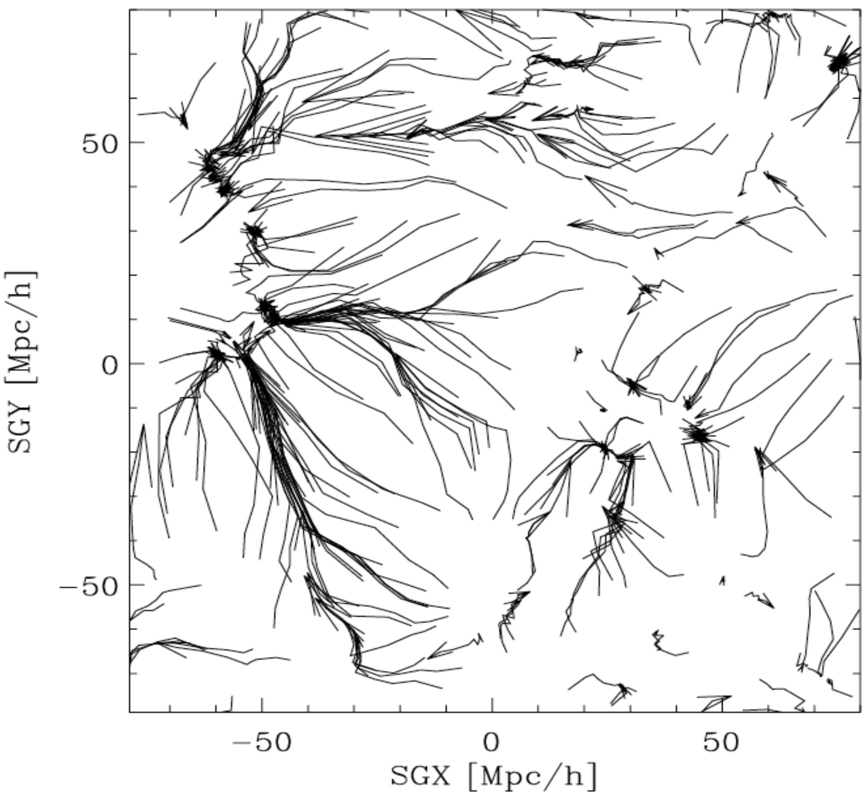
Positions of nearby X-ray selected clusters (Reiprich & Böhringer 2002)

MARK III (velocity field)



Klypin et al. 2003

Constrained Simulation



Klypin et al. 2003

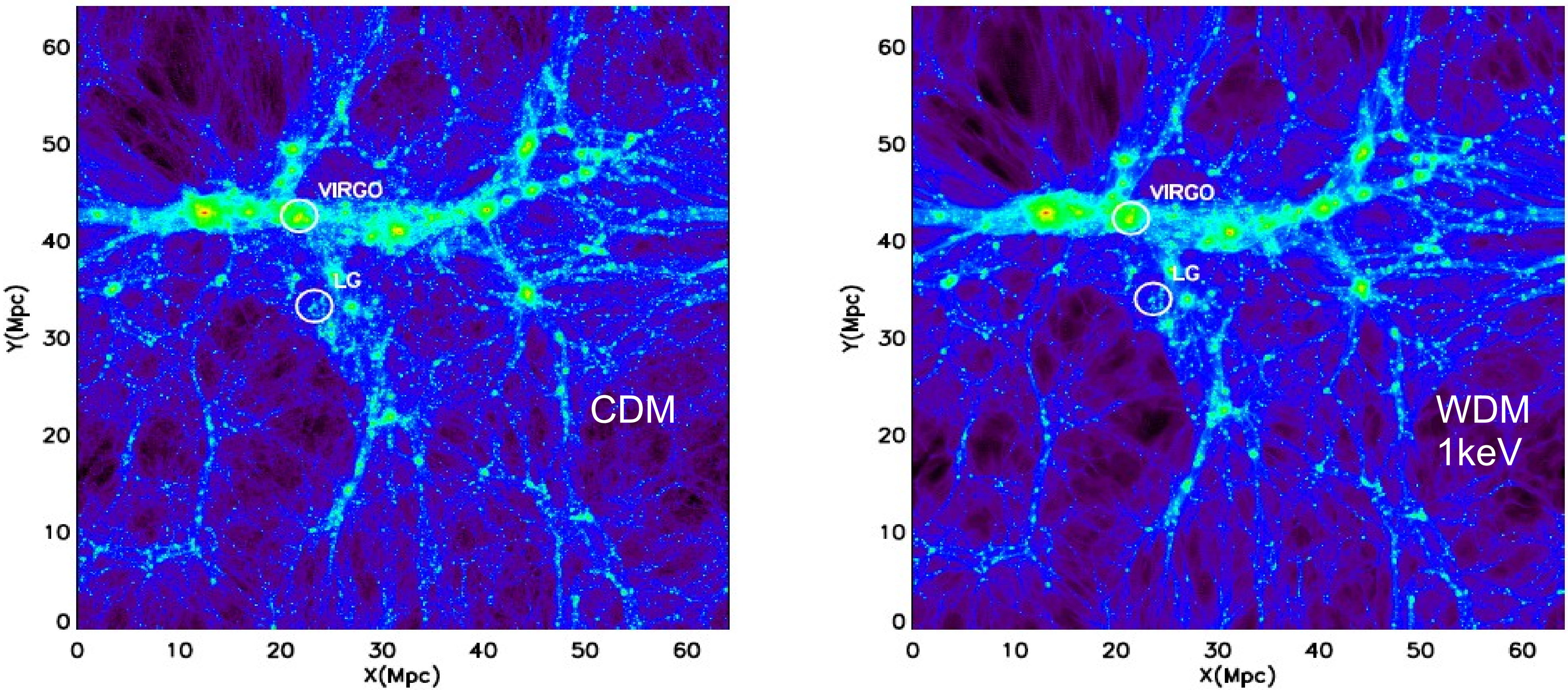
Reconstruct density and velocity fields from the data (Wiener Filter) assuming linear theory and a power spectrum (Hoffman and Ribak 1991, Klypin et al. 2003)

Scales below ~7Mpc are poorly constrained by the data: add random component to compensate for missing power.

Evolve back in time (linear theory) to get ICs.

CDM and WDM constrained simulations

Projected DM distribution at z=0 (~10Mpc thickness)

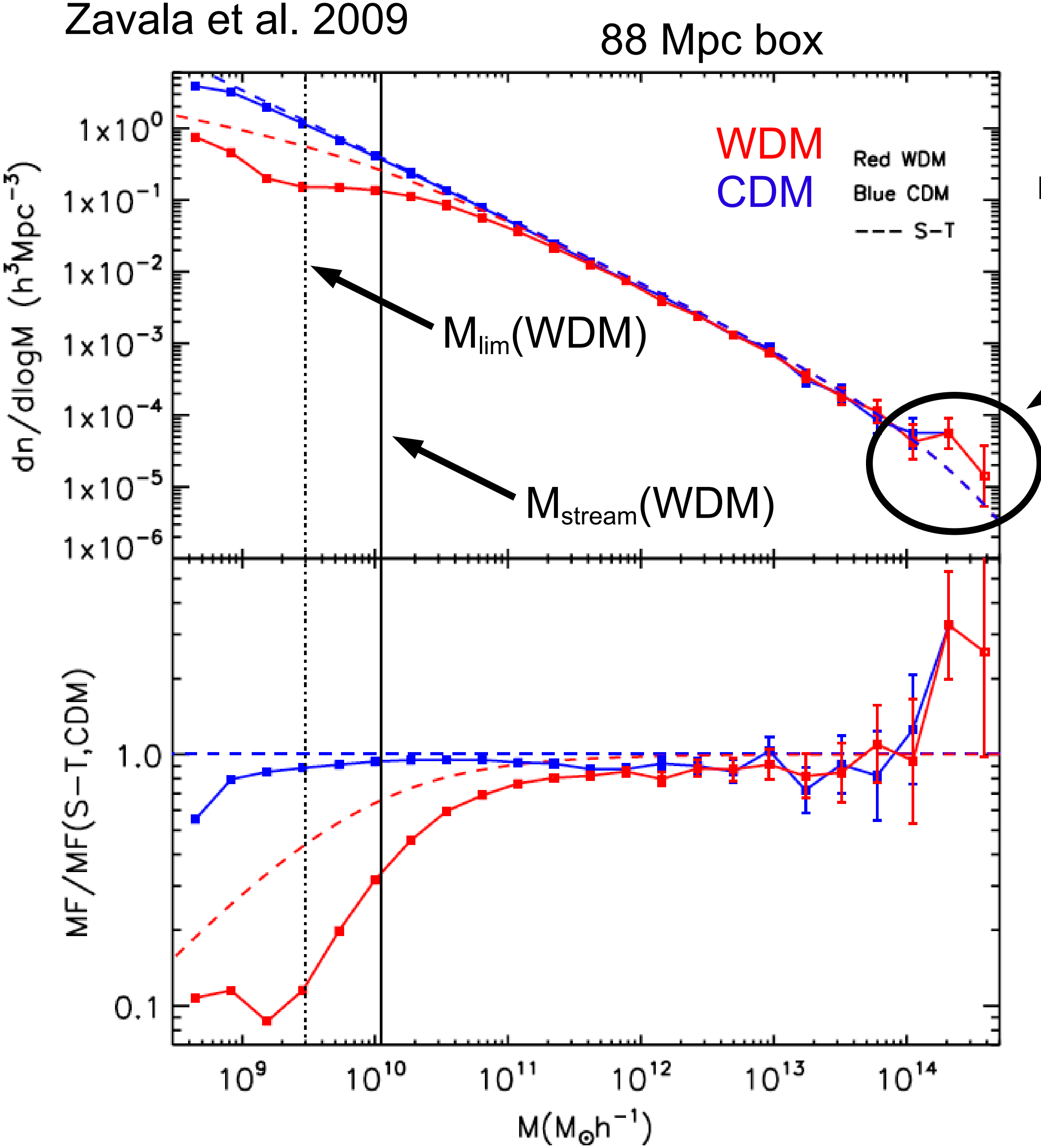


Zavala et al. 2009

The Local Super Cluster dominates the box with the Virgo cluster near a Local Group (defined with global properties of the MW and M31) close to the centre of the box

Abundance of low-mass halos in the local simulated universe

Zavala et al. 2009

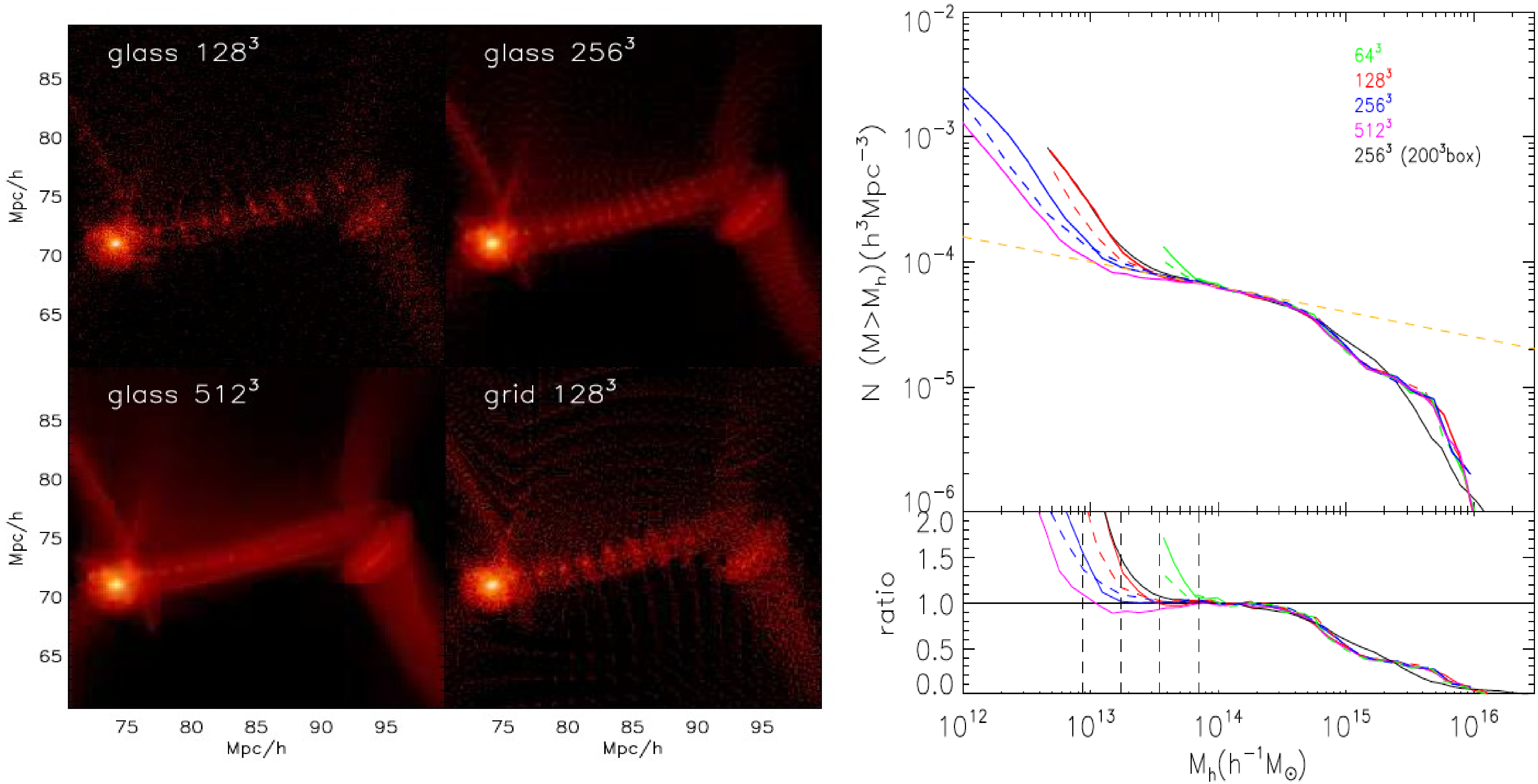


The CDM mas function within the simulated volume follows the universal mass function, except at the high mass end due to the constraints (LSC).

The WDM mas function follows CDM except at the low-mass end due to the small-scale suppression in P(k).

There are two mass scales for WDM:
A filtering mass (free streaming) ~10^{10} Msun (V_{max}~36km/s)
A limiting mass due to discreteness effects ~$4x10^9$ Msun (V_{max}~24km/s)

Discreteness effects and spurious halos (Wang & White 2007)

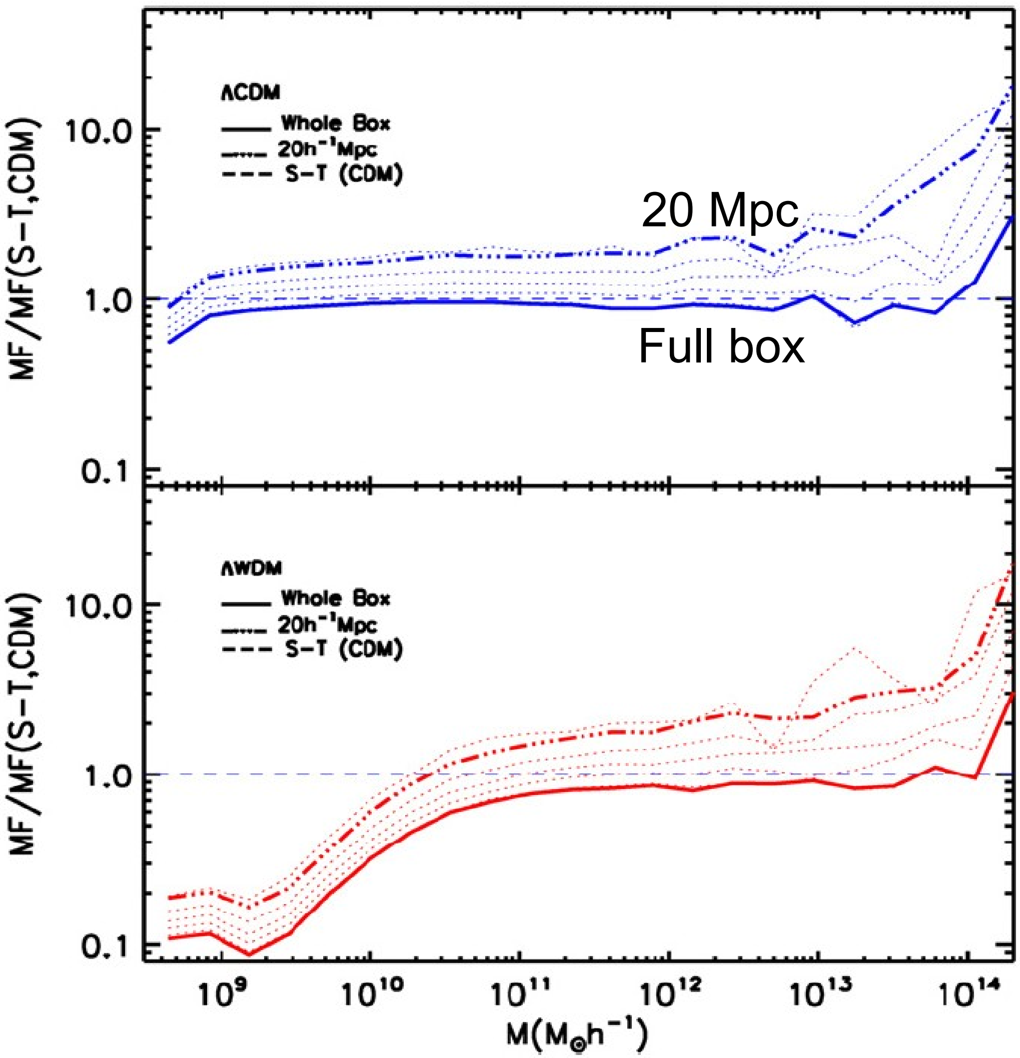


Limiting mass scale as ~ d / k^2_{peak}

$d = L / N^{1/3}$

Abundance of low-mass halos in the local simulated universe

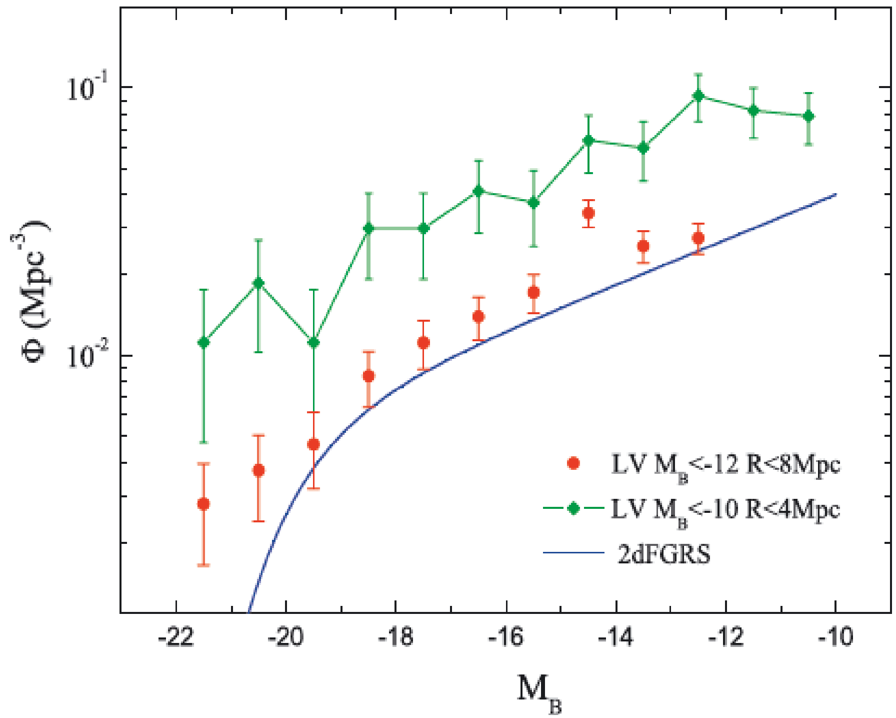
Mass function within spheres centred
In the LG from 20 Mpc to 55 Mpc



Zavala et al. 2009

The local simulated environment (20 Mpc) shows an overabundance of halos by a factor of ~2 compared to the mean "cosmic" abundance

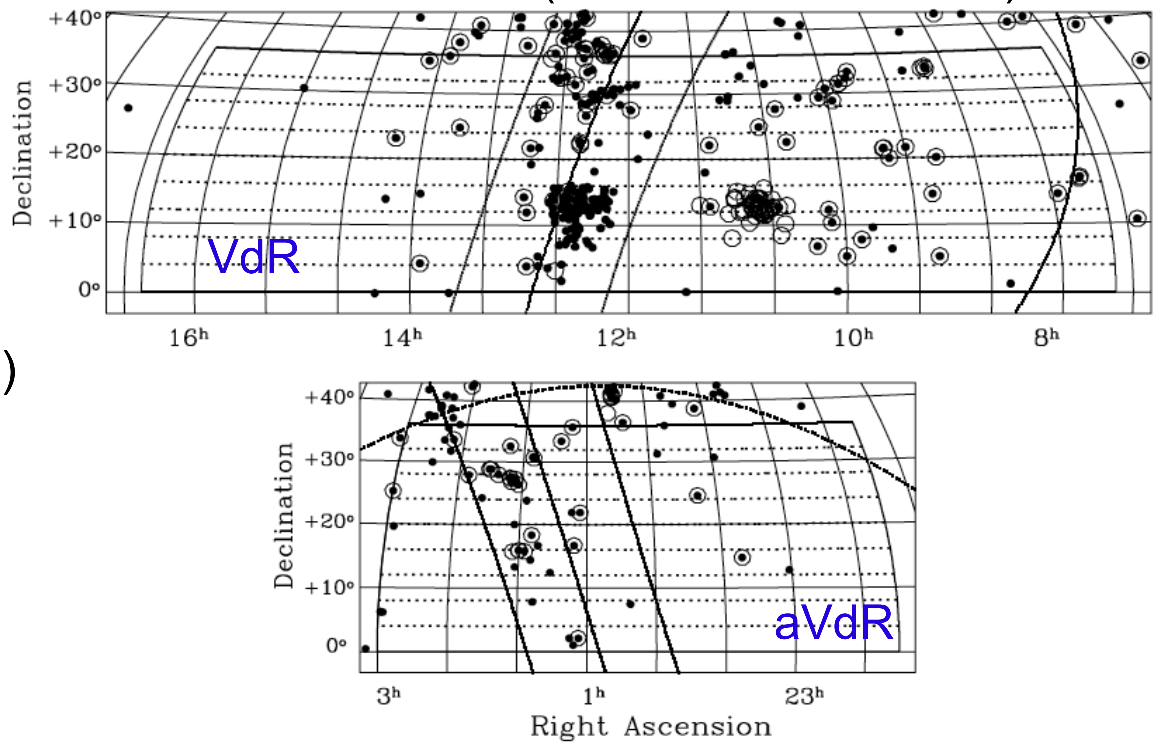
Observed LF in the local volume (8Mpc) is also overdense
(Tikhonov and Klypin 2009 based on updated sample from Karachentsev et al. 2004)



Comparison with the ALFALFA survey

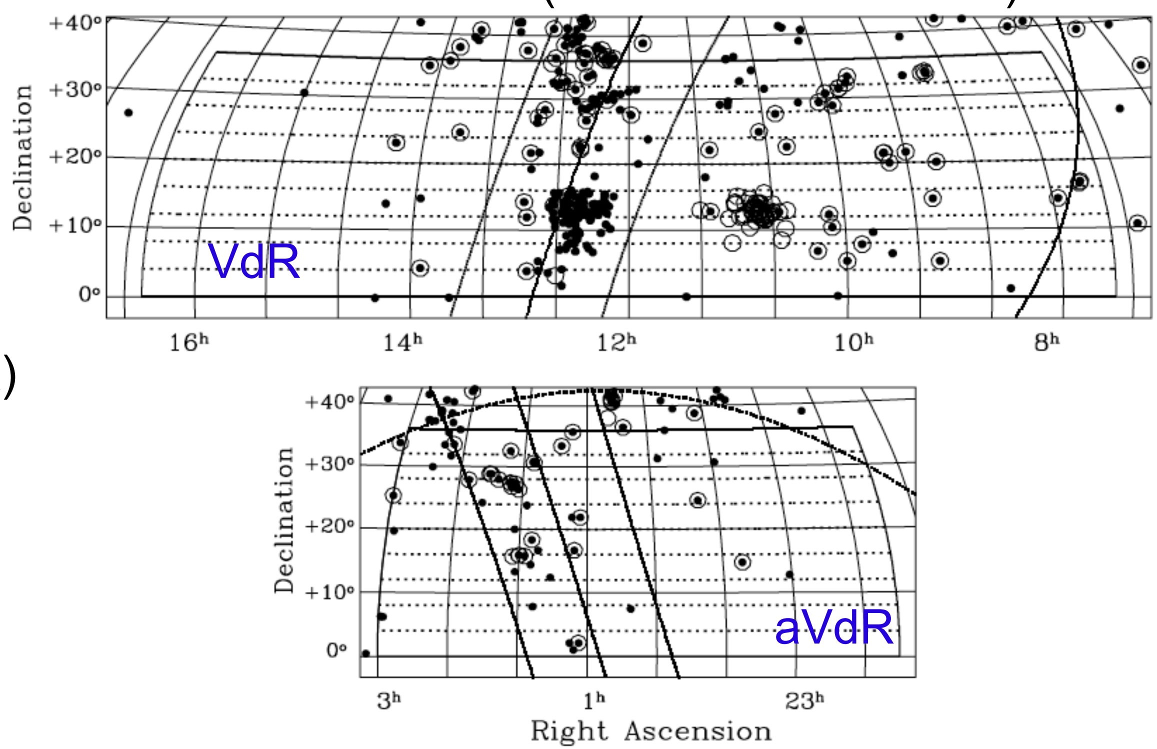
Exploring the HI local Universe
Able to detect $M_{HI} > 10^7$ Msun at $D < 27$Mpc
Two regions in the sky: Virgo- and antiVirgo-direction regions (VdR and aVdR)
(see E. Papastergis' talk)

Field of view (Giovanelli et al. 2005)



Comparison with the ALFALFA survey

Field of view (Giovanelli et al. 2005)



Exploring the HI local Universe
Able to detect $M_{HI} > 10^7$ Msun at D<27Mpc
Two regions in the sky: Virgo- and antiVirgo-direction regions (VdR and aVdR)
(E. Papastergis' talk)

The coordinate system for an observer (LG) within the simulated box

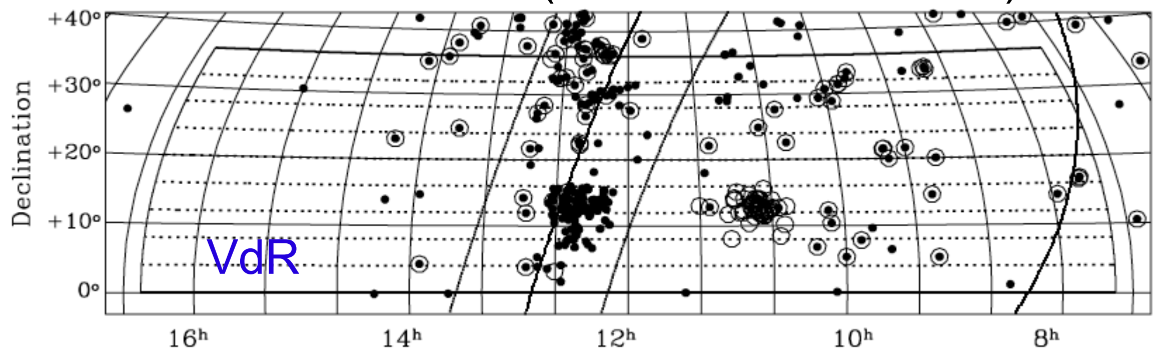
Define the supergalactic plane with the LSC (using Virgo and Ursa Major) and the LG

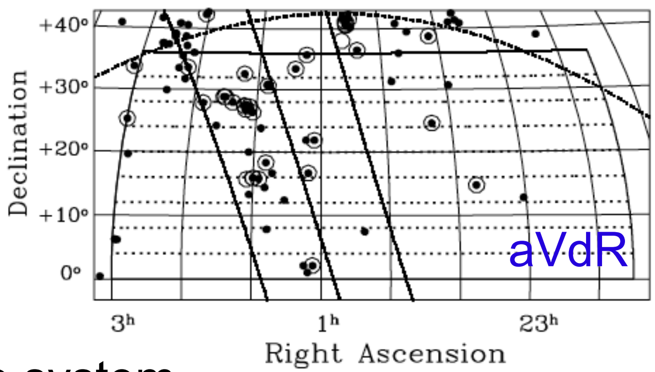
Adjustment through rotations: “better” representation of the local environment given the limitations of the method and the freedom from the constraints at scales below ~ 7Mpc

Comparison with the ALFALFA survey

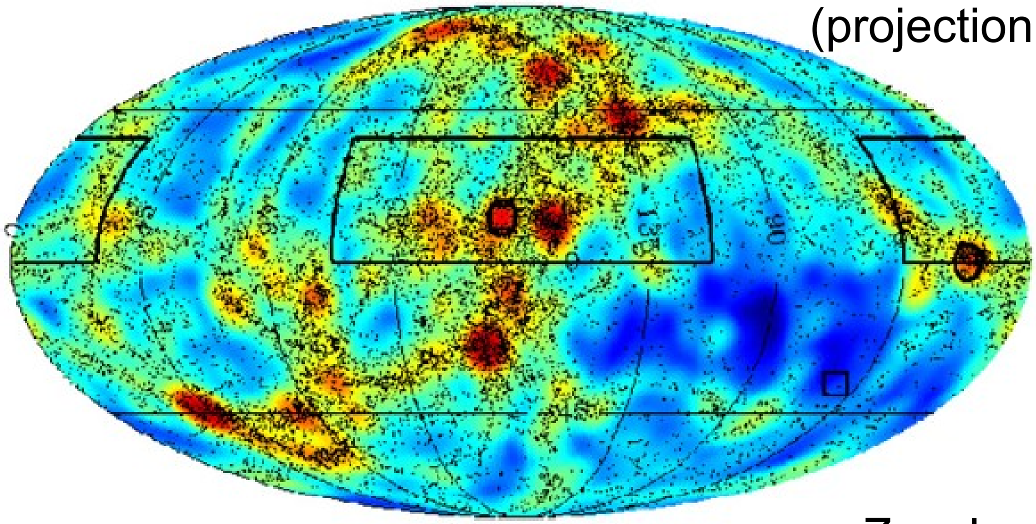
Exploring the HI local Universe
Able to detect $M_{HI} > 10^7$ Msun at D<27Mpc
Two regions in the sky: Virgo- and antiVirgo-direction regions (VdR and aVdR)
(E. Papastergis' talk)

Field of view (Giovanelli et al. 2005)



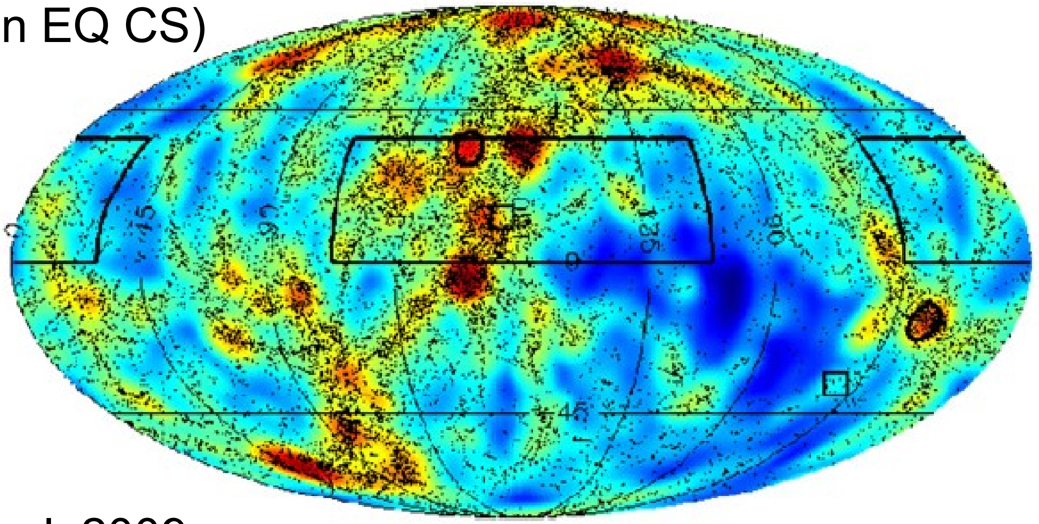


Adjusting the coordinate system
(projection in EQ CS)



SGzero

Zavala et al. 2009



SGmin

The local H_I velocity function (populating halos with galaxies)

- H_I is a good tracer of the full gravitational potential at large radii (possibly underestimated if rotation curve keeps rising)

- HI-line width provides an estimate of V_{max} (after corrections for inclination and random motions)

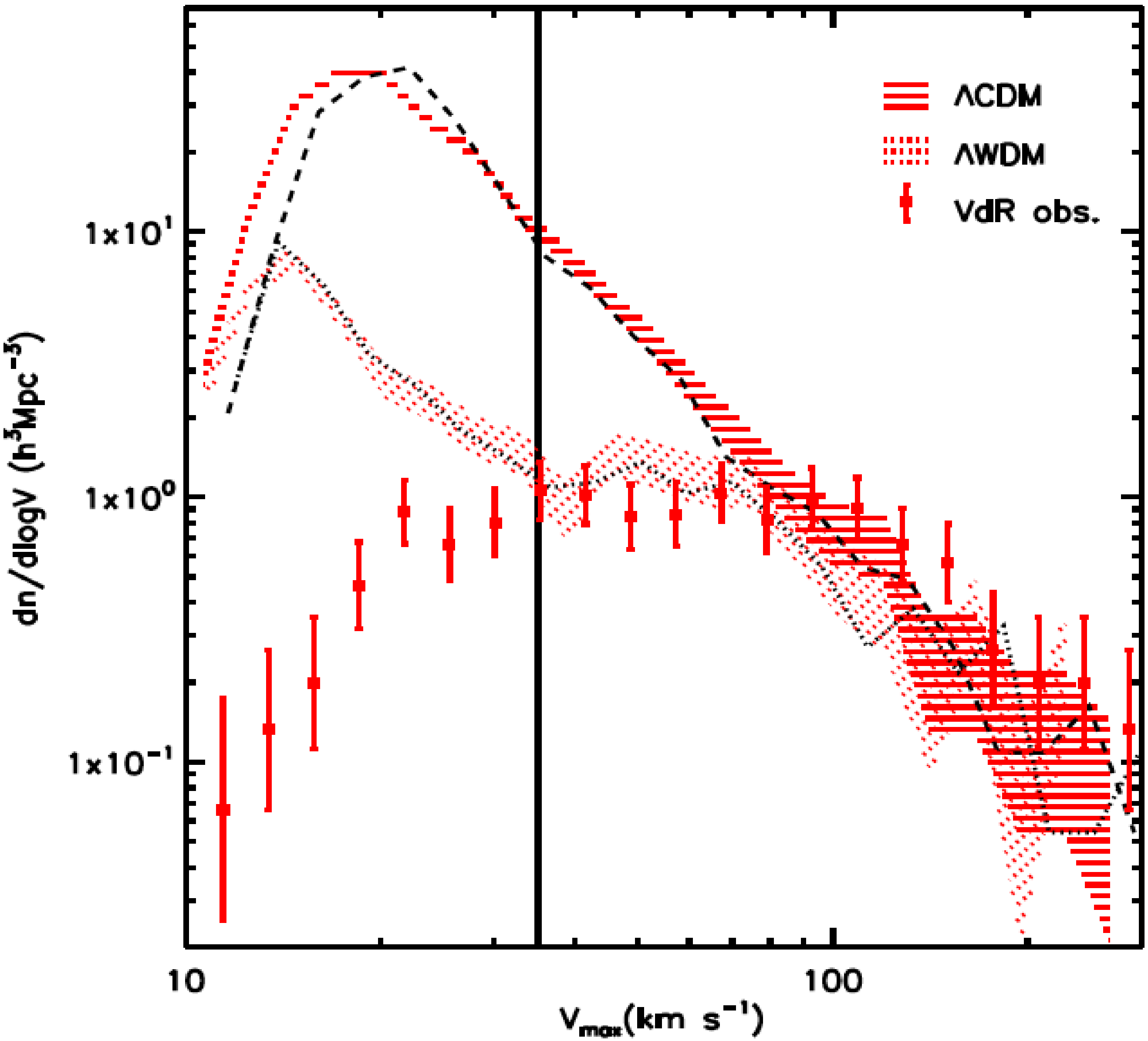
- The VF provides a cleaner comparison between simulations and observations on the abundance of halos than the luminosity/stellar-mass function

The local H_I velocity function (populating halos with galaxies)

- H_I is a good tracer of the full gravitational potential at large radii (possibly underestimated if rotation curve keeps rising)
- HI-line width provides an estimate of V_{max} (after corrections for inclination and random motions)
- The VF provides a cleaner comparison between simulations and observations on the abundance of halos than the luminosity/stellar-mass function
- Halo occupation (main focus low-mass population):
- Only central galaxies (main halos), satellites (substructure) are likely to be HI deficient (undetected by ALFALFA). Possible underestimate of the VF less than ~30% in sims (Klypin et al. 2011). ALFALFA likely missing a similar fraction (Zavala et al. 2009)
- V_{max}(halo) to V_{max}(disc) from simple model of adiabatic contraction (Mo et al. 1998) based on conservation of specific angular momentum and $J_{disc}/M_{disc} = J_{halo}/M_{halo}$ (key assumptions for realistic disc in sims Zavala et al. 2008). Less relevant for low-mass systems (DM-dominated)

The H_I velocity function

Zavala et al. 2009

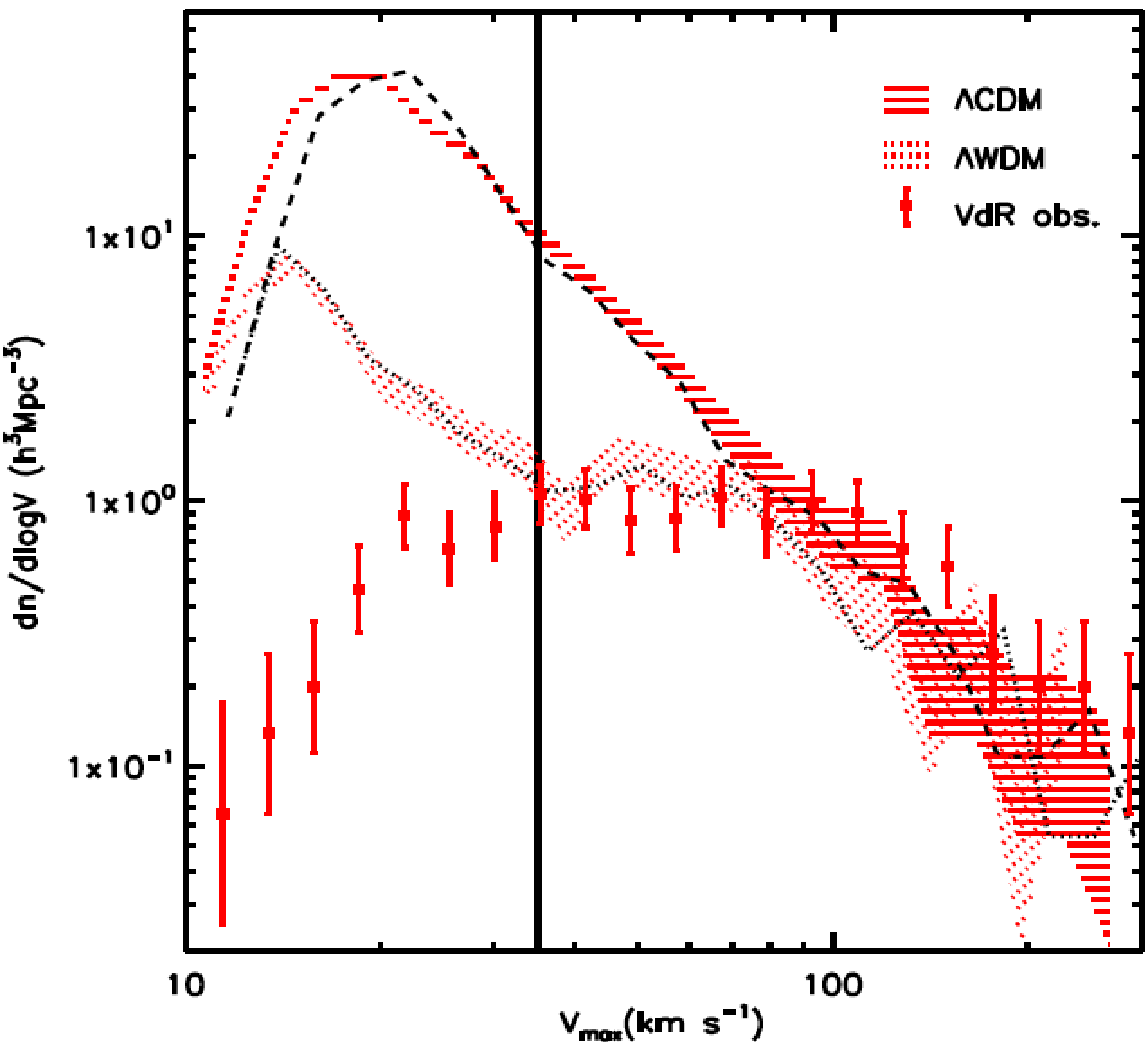


Comparison made only with the first public catalogs (~6% of the final volume within ~27 Mpc)

Constrained simulations match the abundance at high velocities (~10 times higher than the whole box)

The H_I velocity function

Zavala et al. 2009

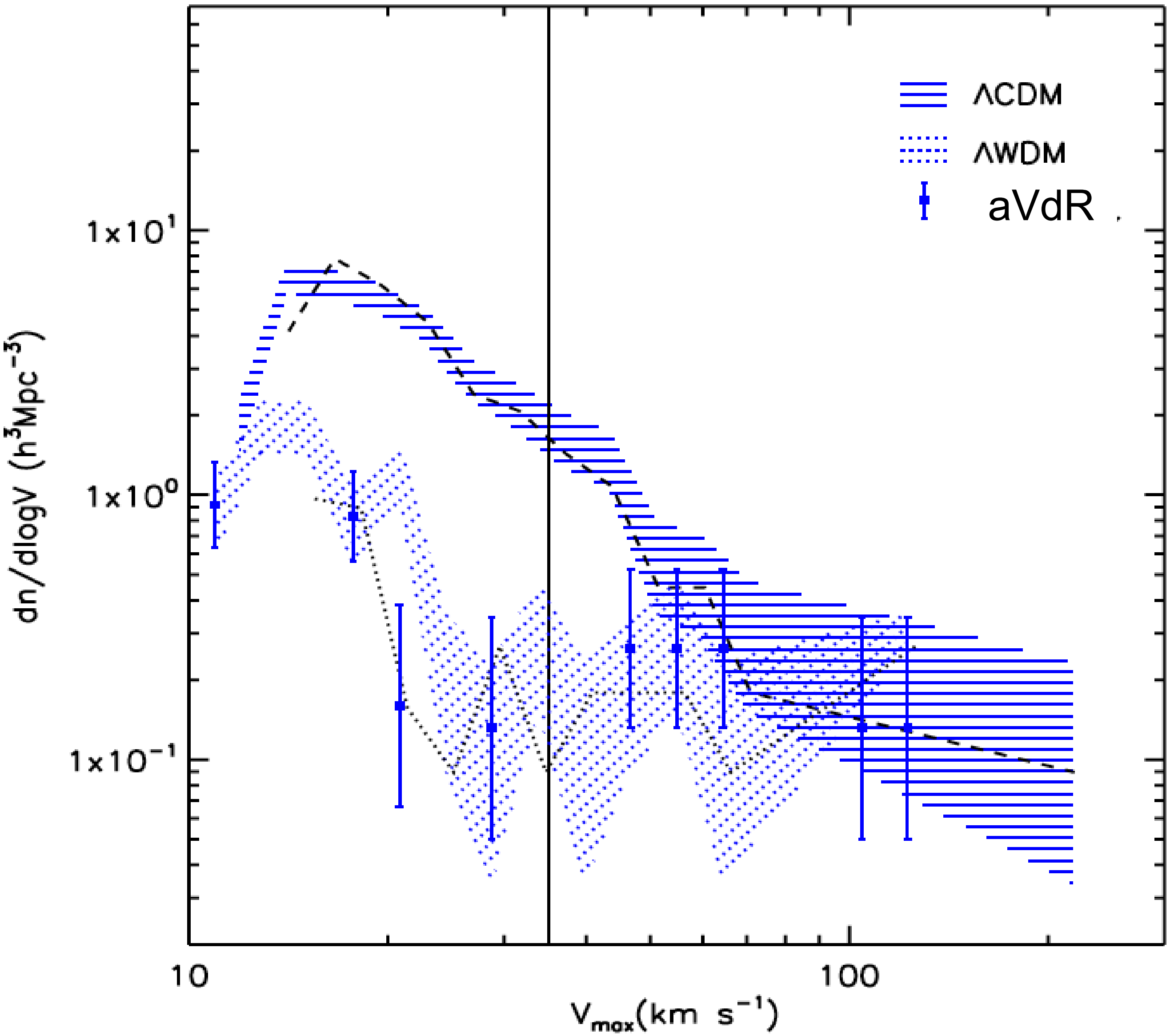


Comparison made only with the first public catalogs (~6% of the final volume within ~27 Mpc)

Constrained simulations match the abundance at high velocities (~10 times higher than the whole box)

The H_I velocity function

Zavala et al. 2009



Comparison made only with the first public catalogs (~6% of the final volume within ~27 Mpc)

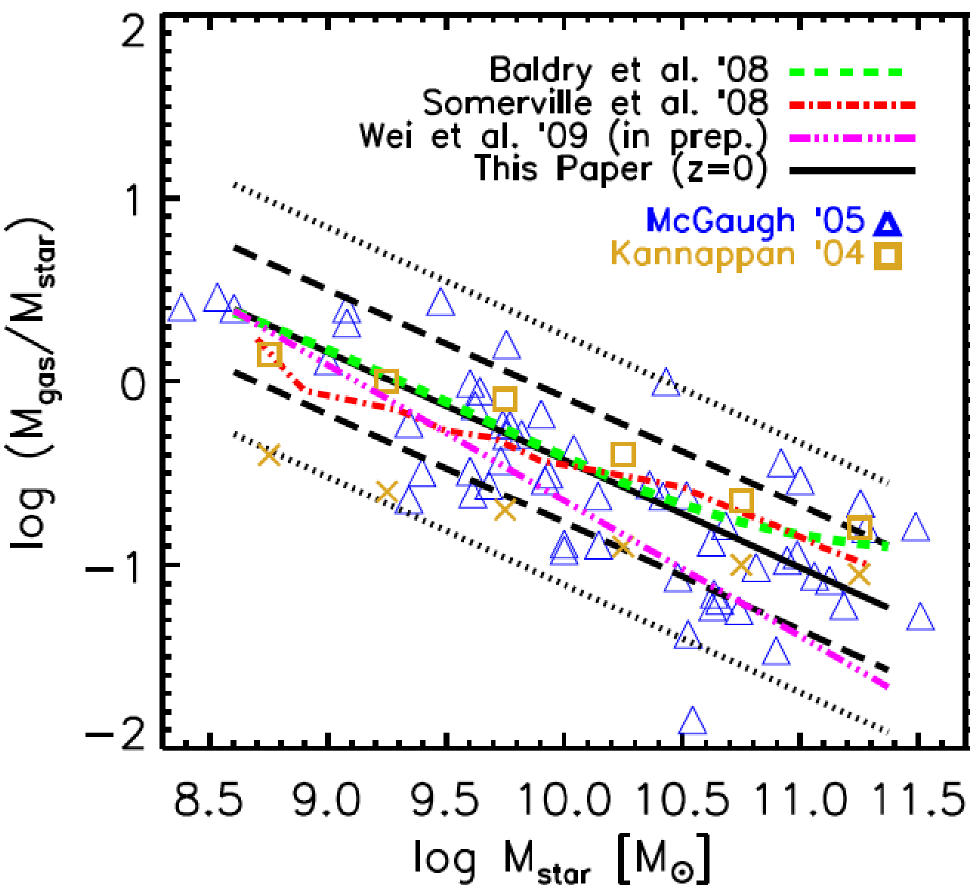
Constrained simulations match the abundance at high velocities for the aVdR as well

Is ALFALFA missing halos at the plateau?

- Robust comparison with sims for V_{max}>35km/s (M_{halo}>8e9Msun): M_{HI}/M_{halo} needs to be ~ 0.16% for a halo of this mass to be missed at D~27 Mpc.

- Isolated dwarf galaxies are typically gas rich.

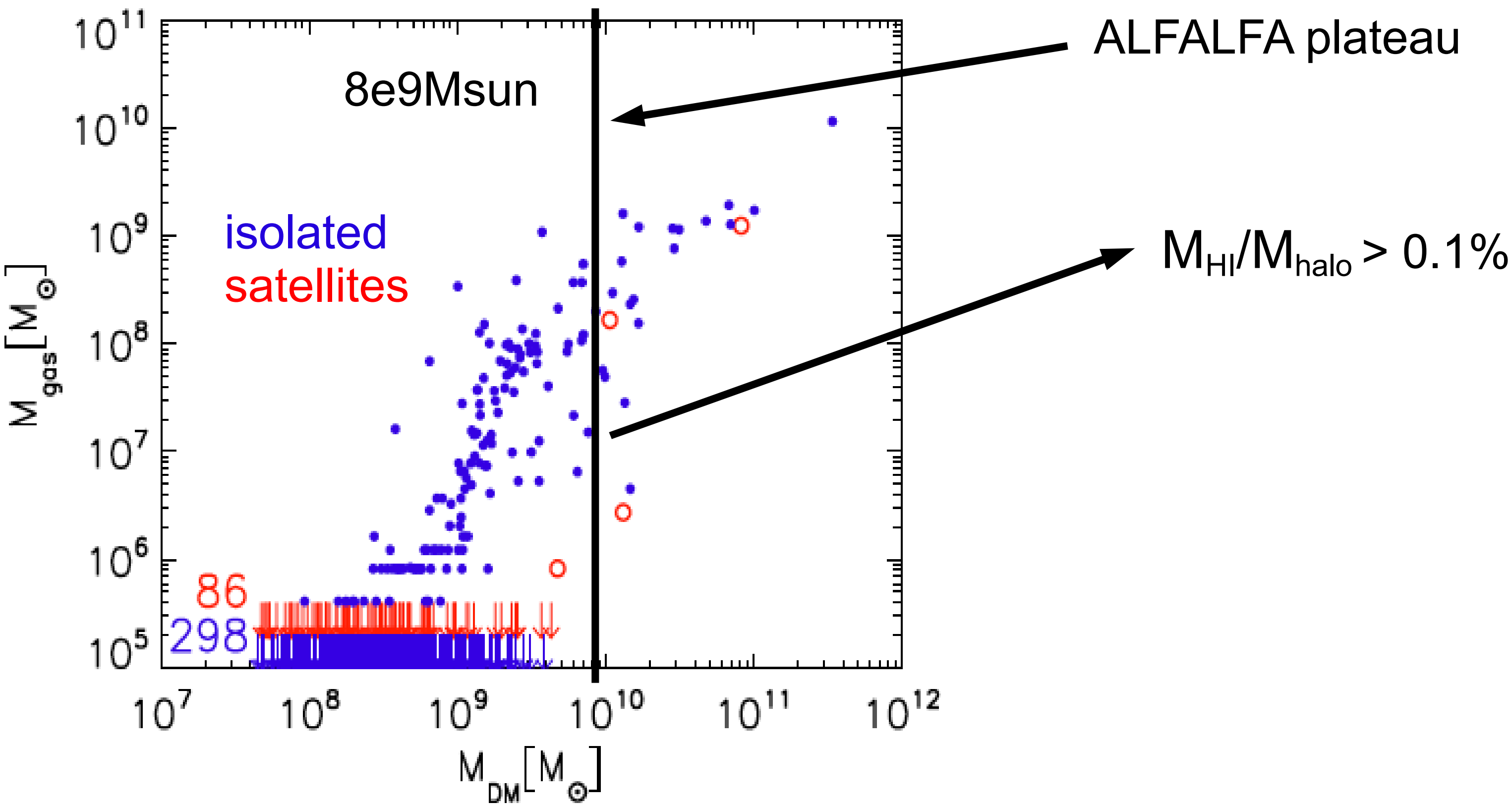
Stewart et al. 2009



We estimated $f_{gas}=M_{HI}/(M_{HI}+M_{star})$ for ¾ of the galaxies we used from ALFALFA and found that 90% of the ones with V_{max}<100 km/s have f_{gas}>0.1 (typically larger than 1 at low masses)

Is ALFALFA missing halos at the plateau?

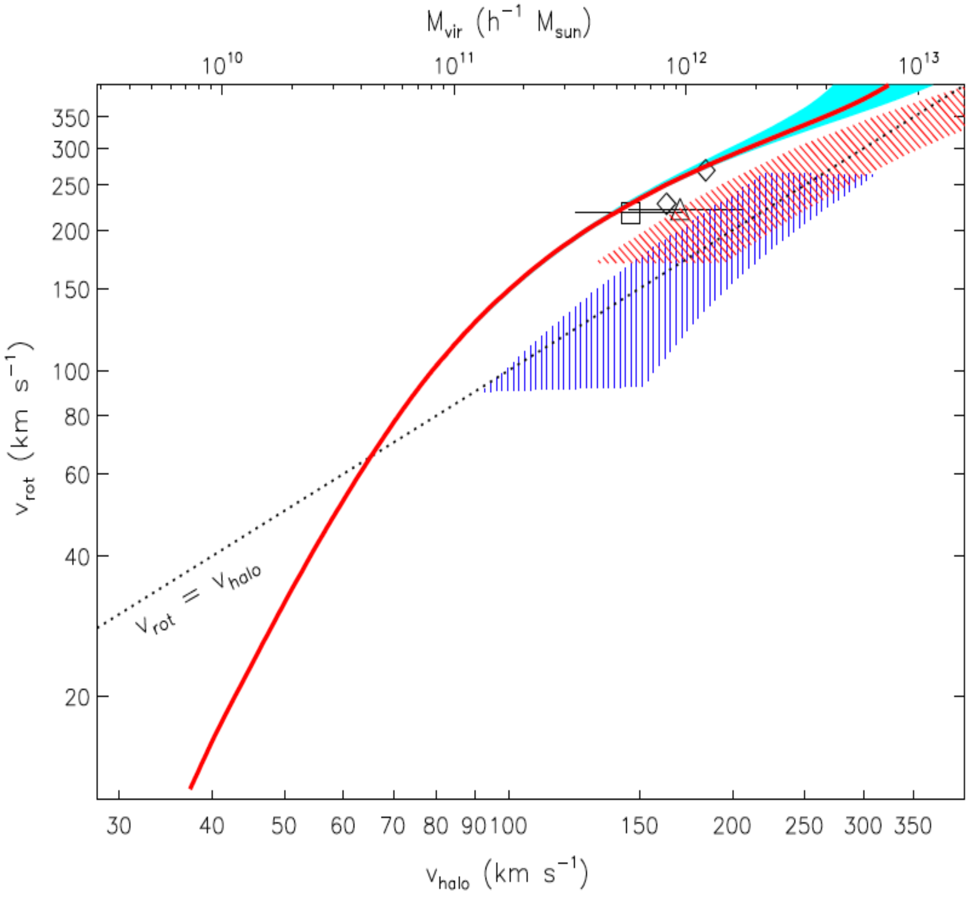
- Robust comparison with sims for V_{max}>35km/s (M_{halo}>8e9Msun): M_{HI}/M_{halo} needs to be ~ 0.16% for a halo of this mass to be missed at D~27 Mpc.
- Isolated dwarf galaxies are typically gas rich.
- Suppression of H_I in low-mass halos: SN-driven winds, UV photoionization typically very effective in simulations at M_c~$5x10^9M_{Sun}$



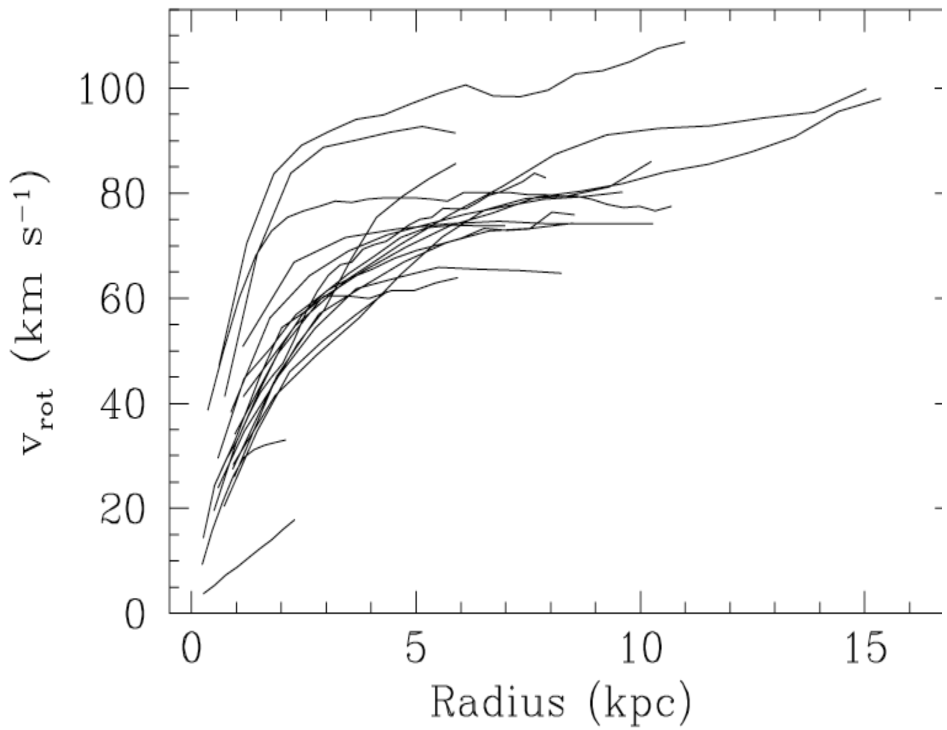
Sawala et al. 2012

The HI line width might underestimate the maximum rotational velocity of the halo

Papastergis et al 2011



Swaters et al. 2009



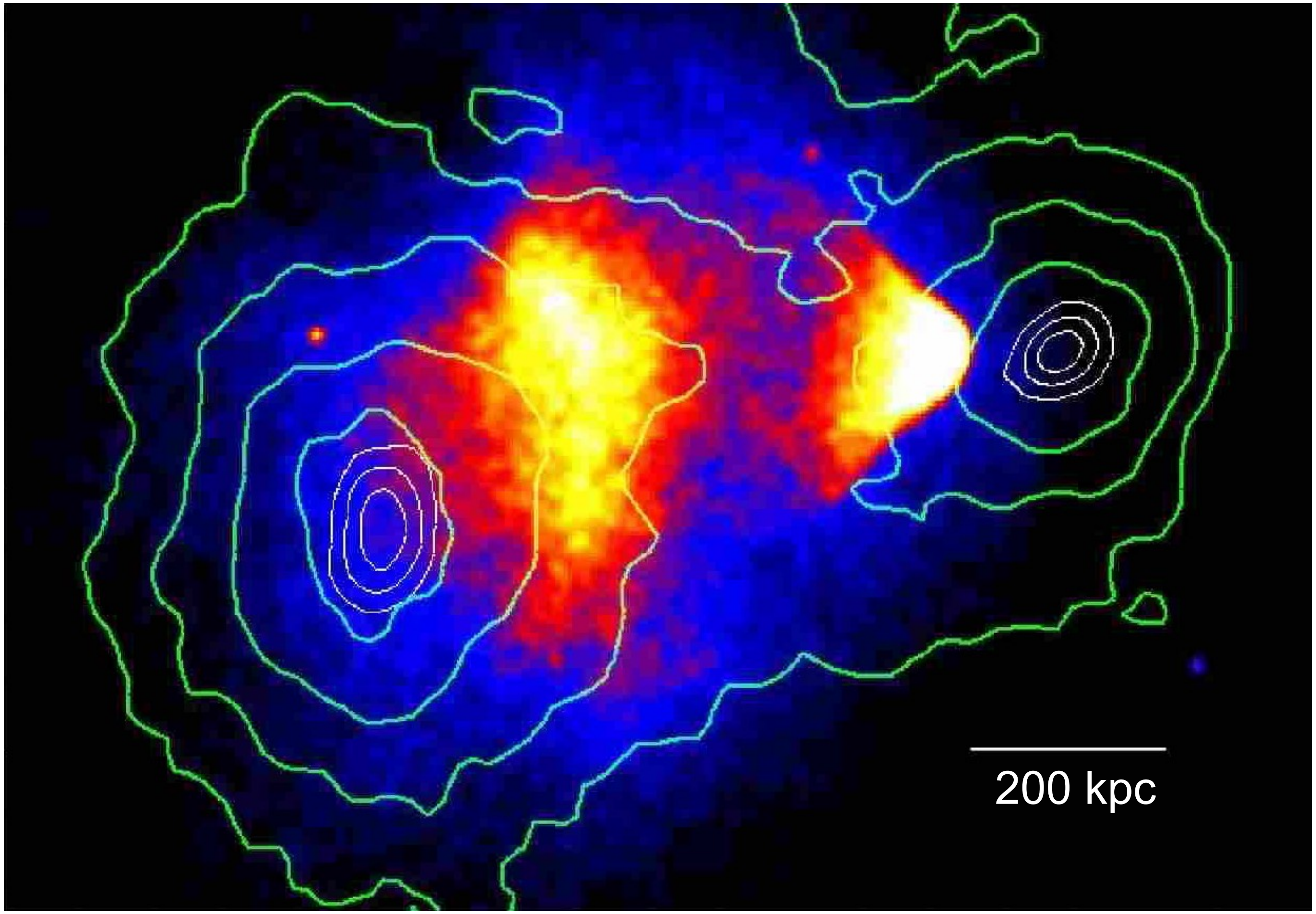
Summary and Conclusions

- Constrained simulations are a powerful tool to make detailed comparisons in our local environment.
- Observations on the abundance of DM-dominated galaxies still challenge the CDM model.
  - Abundance of MW satellites can be consistent with gal-form models.
  - Abundance of dwarfs in the field (H_I ALFALFA) remains challenging.
- A systematic underestimation of V_{max}(halo) by the measurement of the HI-line width is a possible solution within CDM.
- WDM is a viable alternative but: current constraints from Ly - α semm to barely admit a viable solution.
- WDM halos are less concentrated so this might also solve the “too big to fail” problem (Marc Lovell's talk). However, they seem to have cores that are too small compared to the ones that are apparently found in some dSphs (Jorge Peñarrubia's talk).

SELF INTERACTING DARK MATTER

Is DM collisionless?

Bullet Cluster (Clowe et al. 2006)



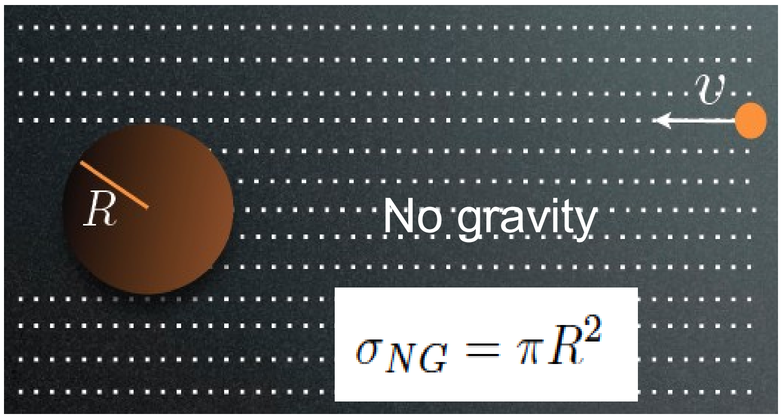
σ / m < 1.25 cm^2/g

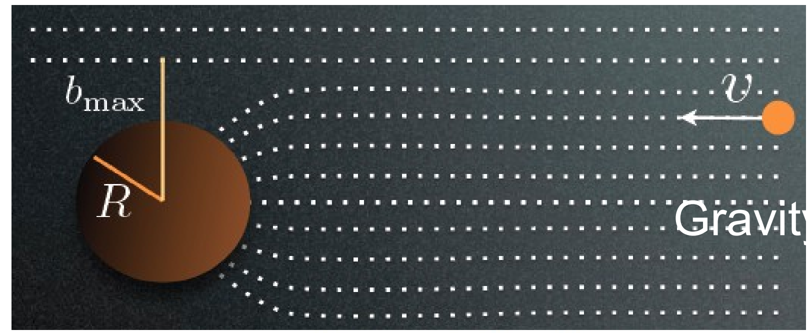
(for relative velocities of O(1000km/s) Randall et al. 2008)

Velocity-dependent SIDM models (Sommerfeld enhancement)

- Classical analog:

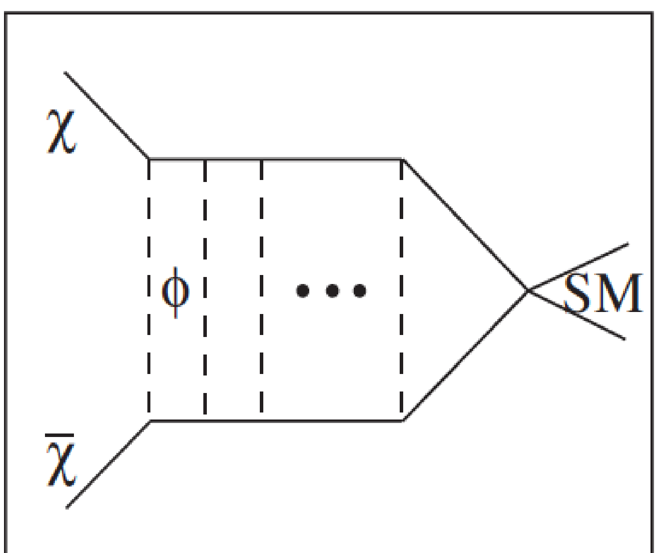
Figs. from M. Cirelli, DMV, Cambridge 2011

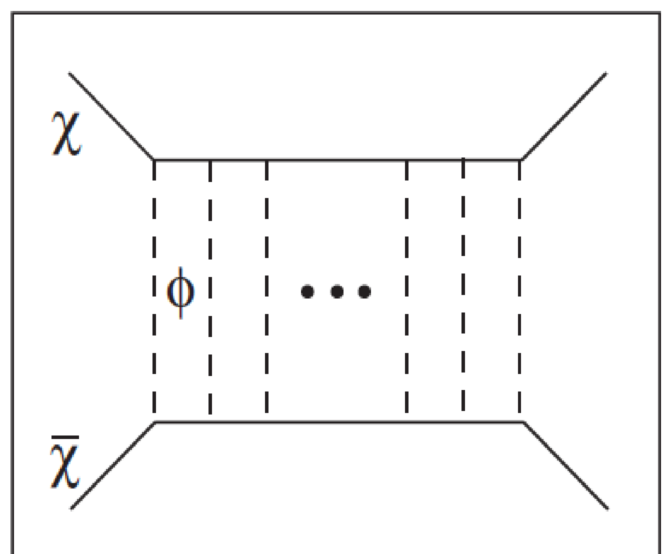




$$\sigma_N = \sigma_{NG}\left(1 + \frac{v_{esc}^2}{v^2}\right) = \pi b_{max}^2$$

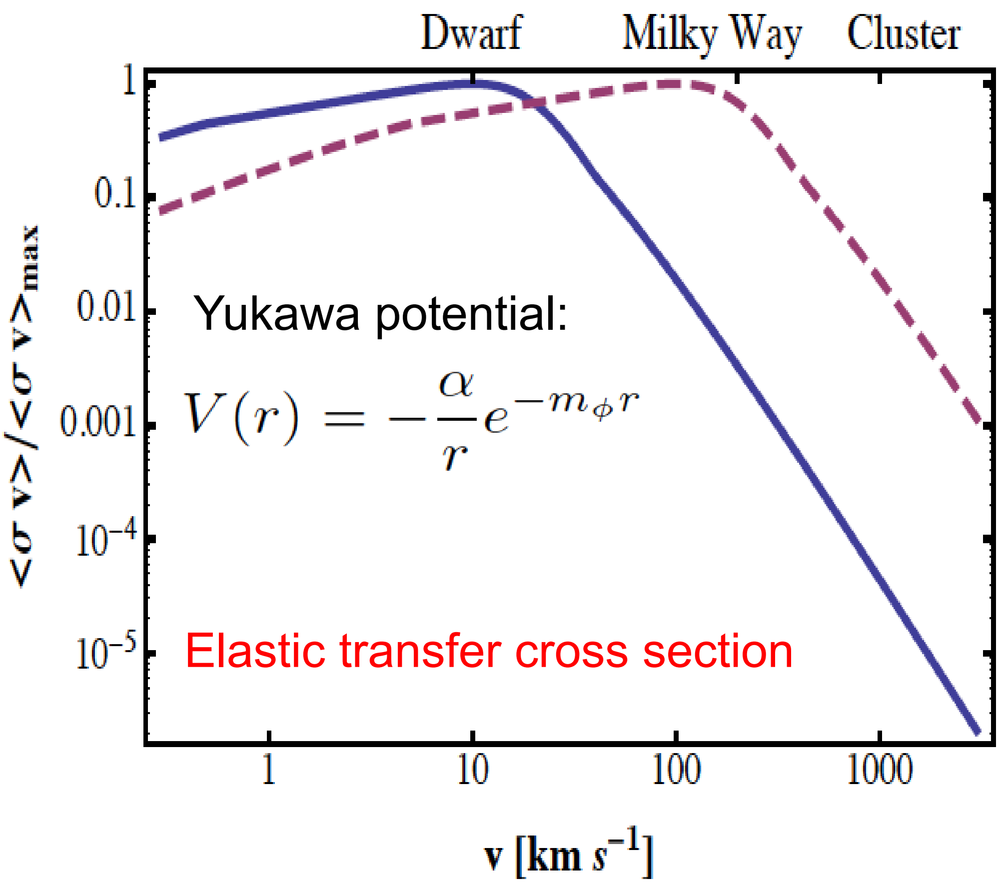
- Annihilation and self-scattering enhancement (e.g. Buckley and Fox 2010)





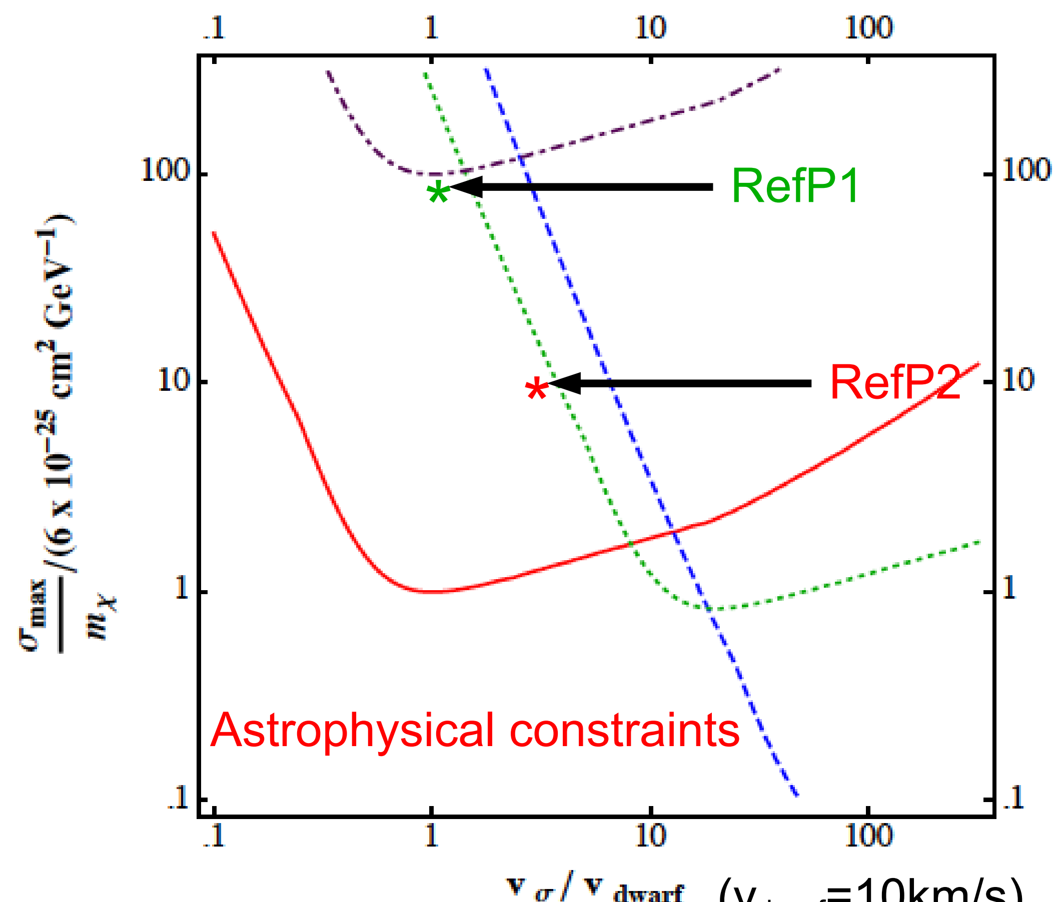
Velocity-dependent elastic SIDM models

Loeb and Weiner 2011



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

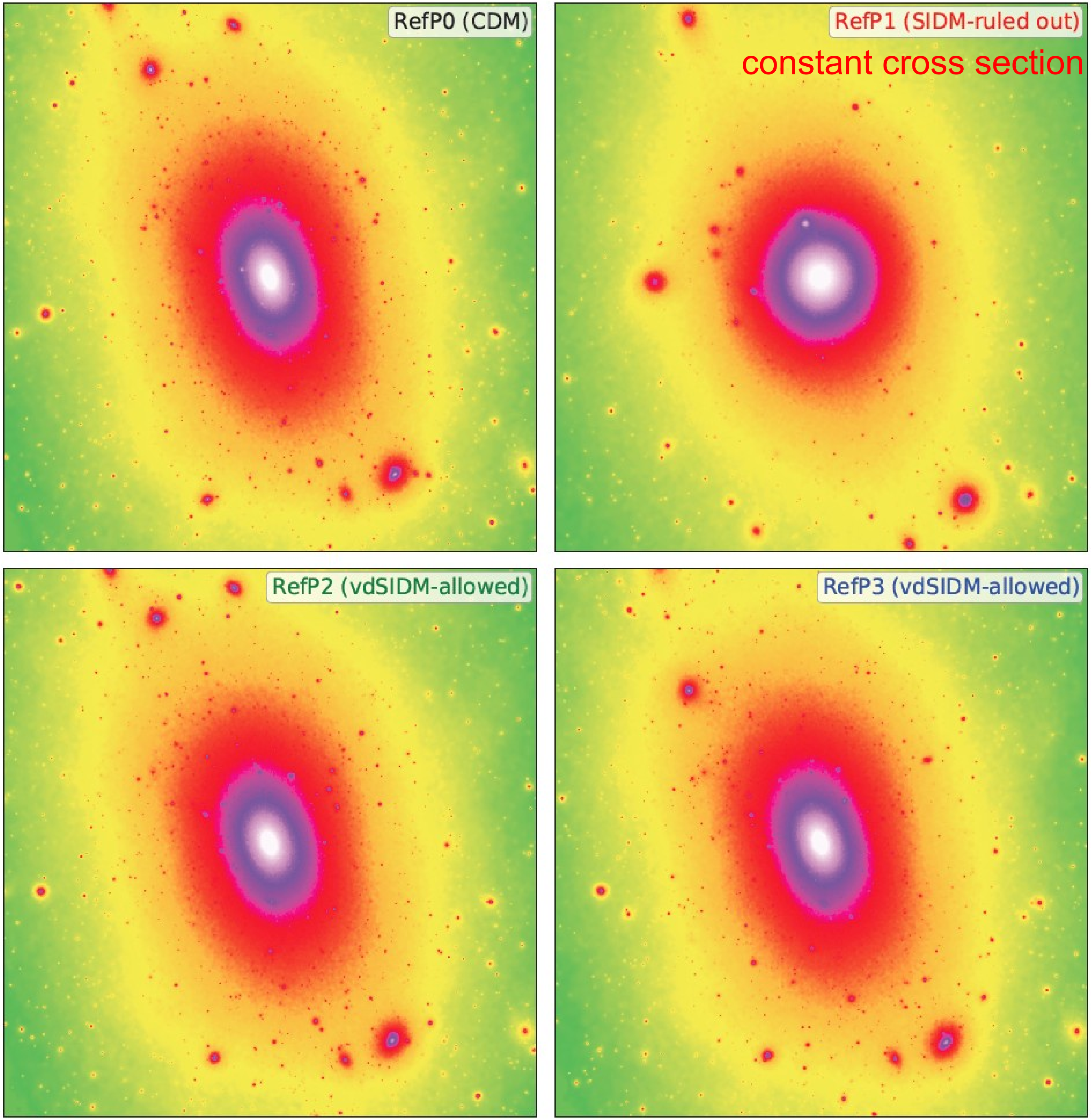
$$\sigma_{max} = 22.7 / m_\phi^2$$



(v_{dwarf}=10km/s)

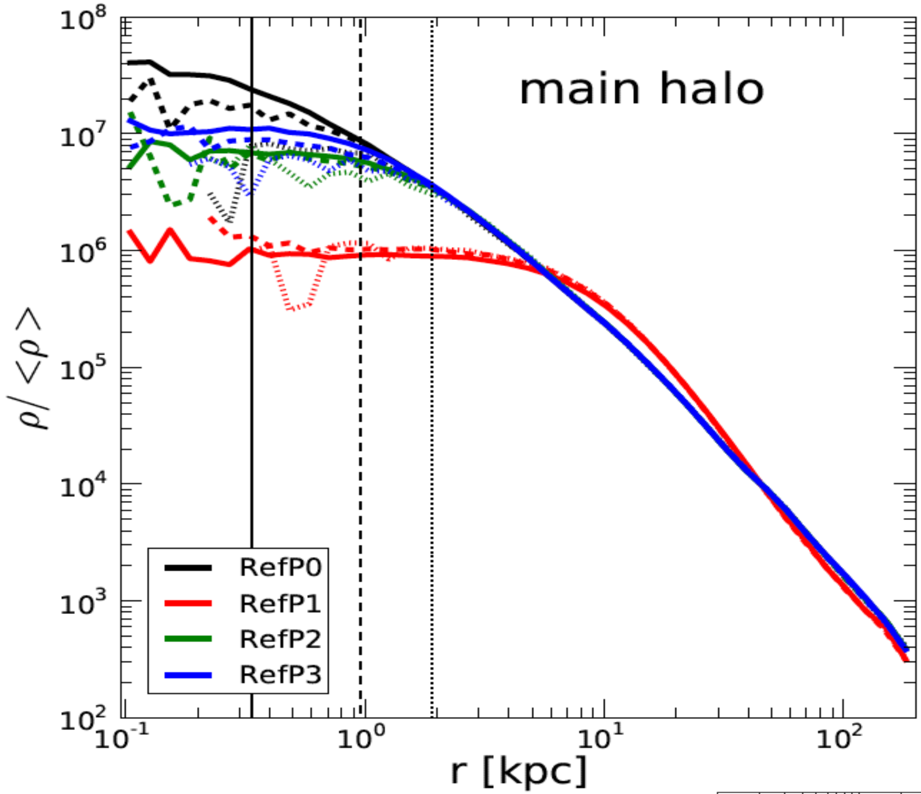
vdSIDM (re-simulate Aquarius MW-size halo)

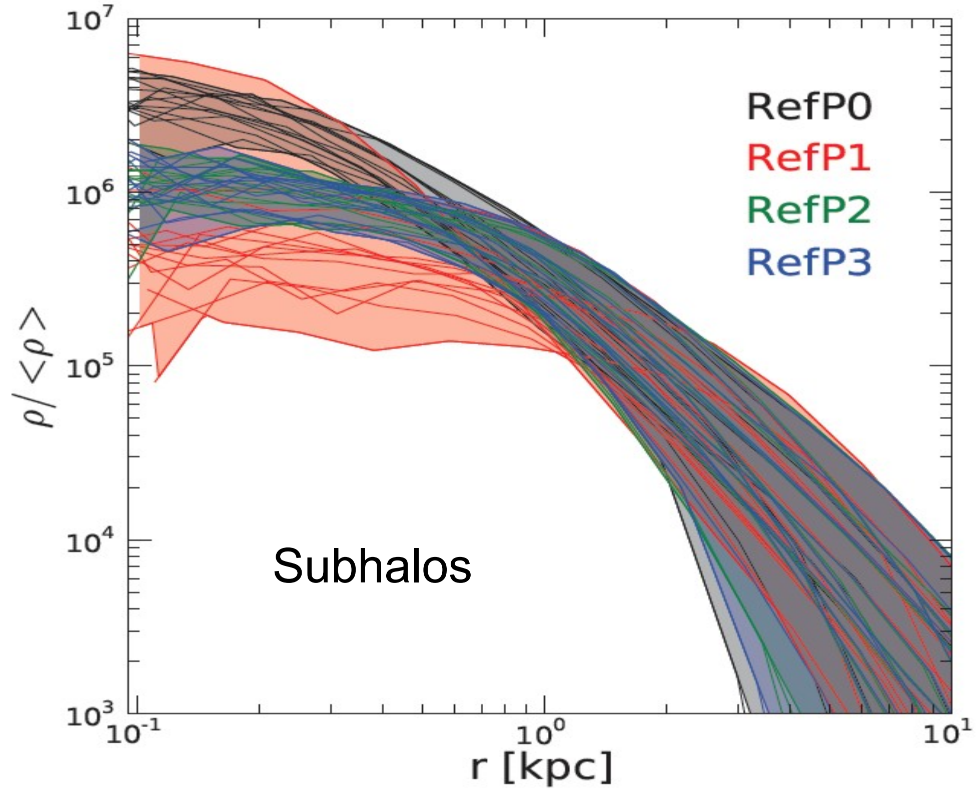
Vogelsberger, JZ & Loeb 2012

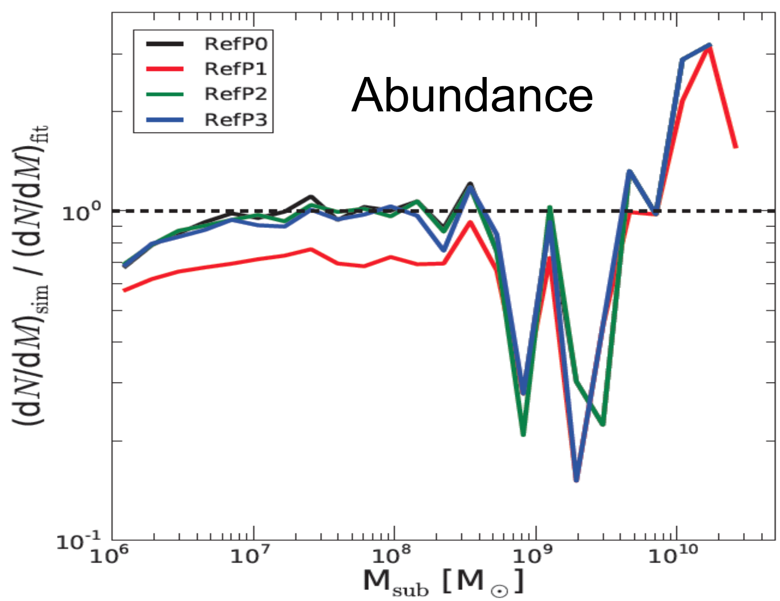


vdSIDM (MW-size halo)

Vogelsberger, JZ & Loeb 2012



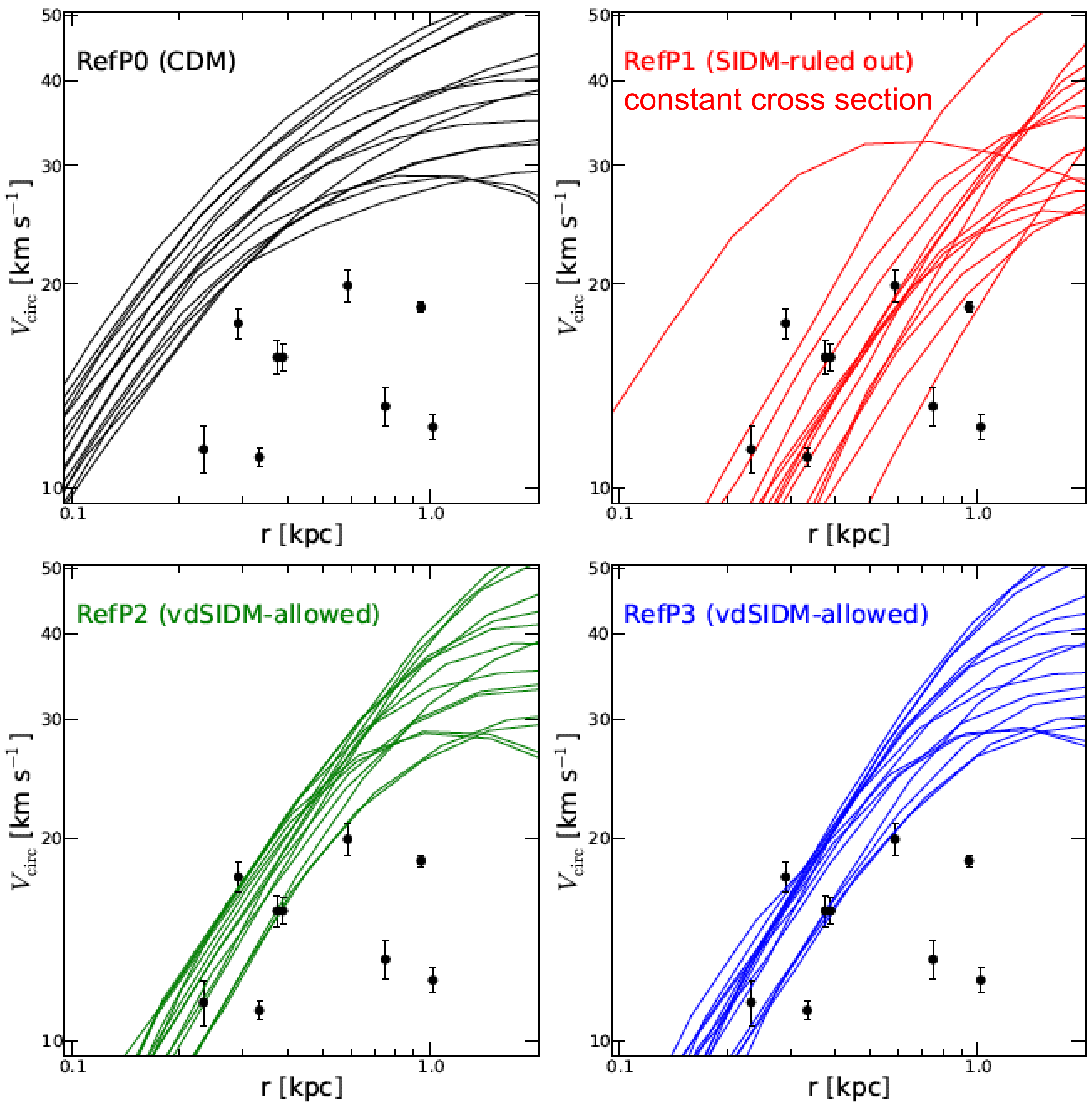




Abundance unchanged in elastic vdSIDM models

vdSIDM subhalos and the bright MW dSphs

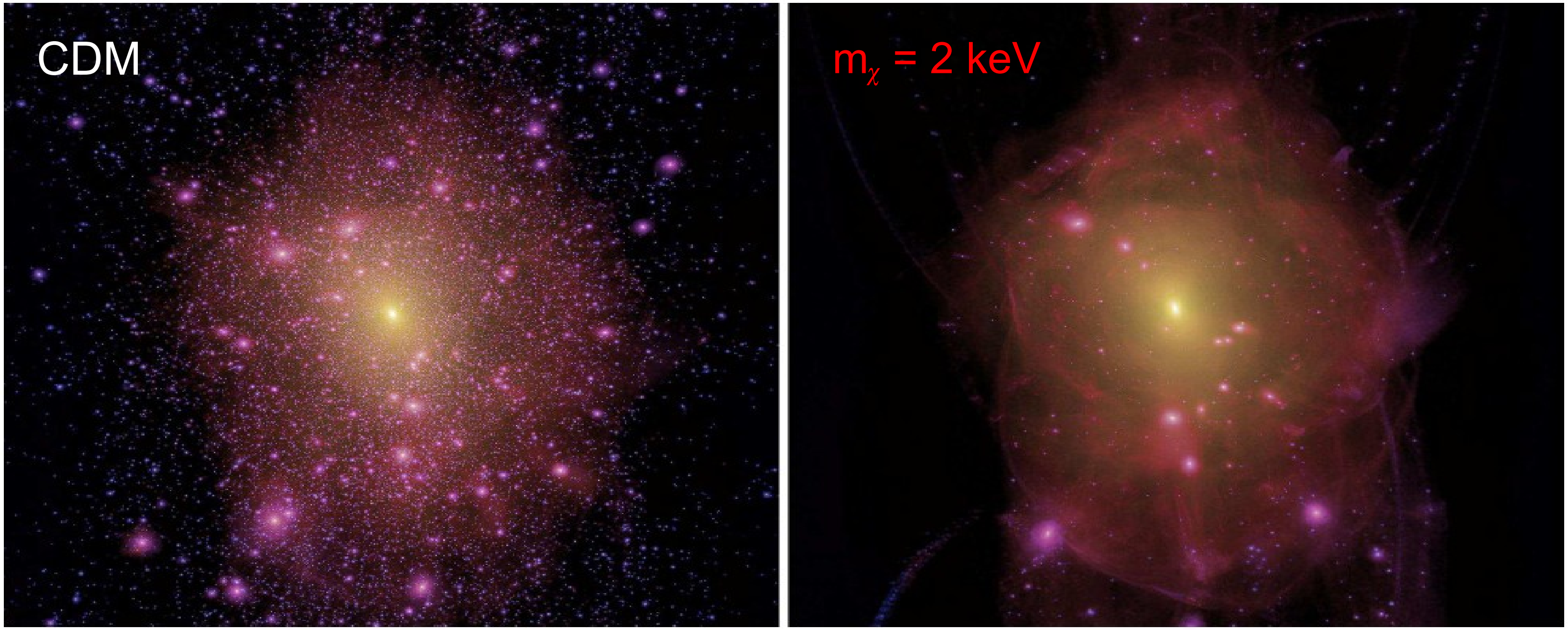
Vogelsberger, JZ & Loeb 2012

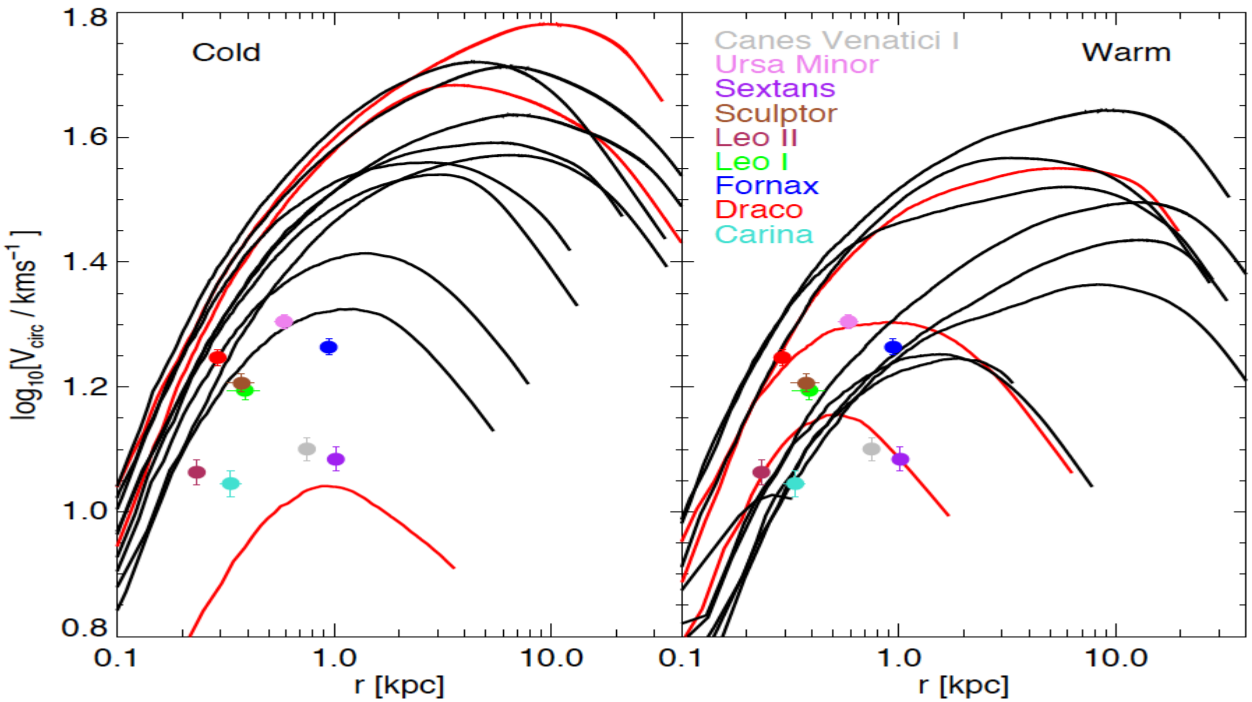


EXTRA SLIDES

Inner density profile of WDM subhalos

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



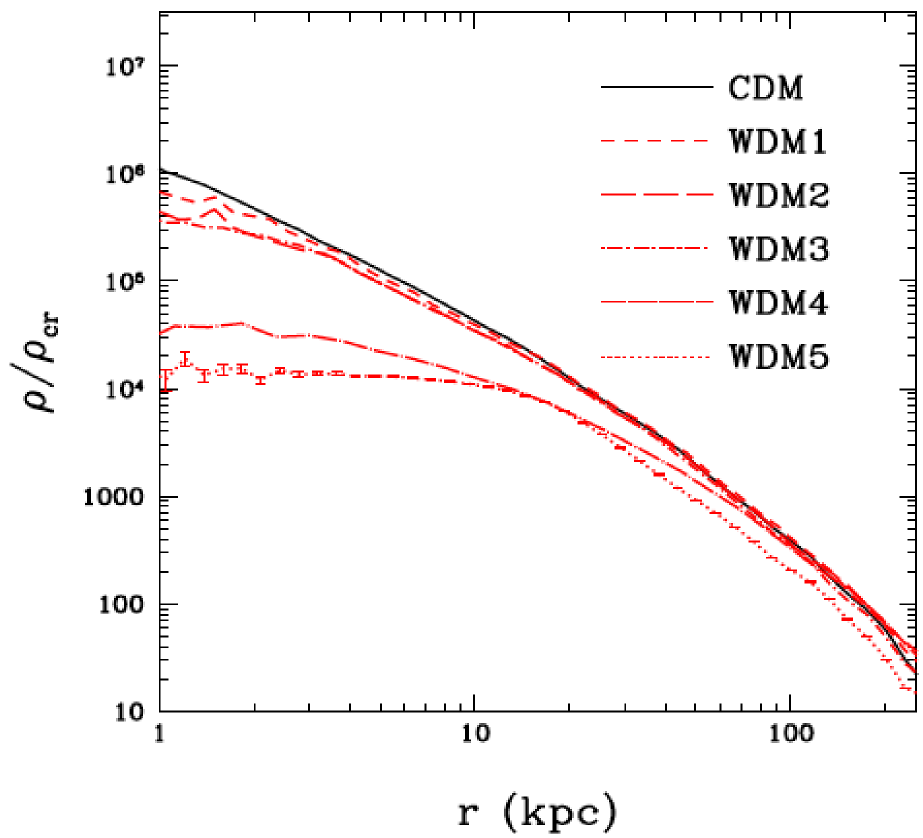


Cores in WDM halos

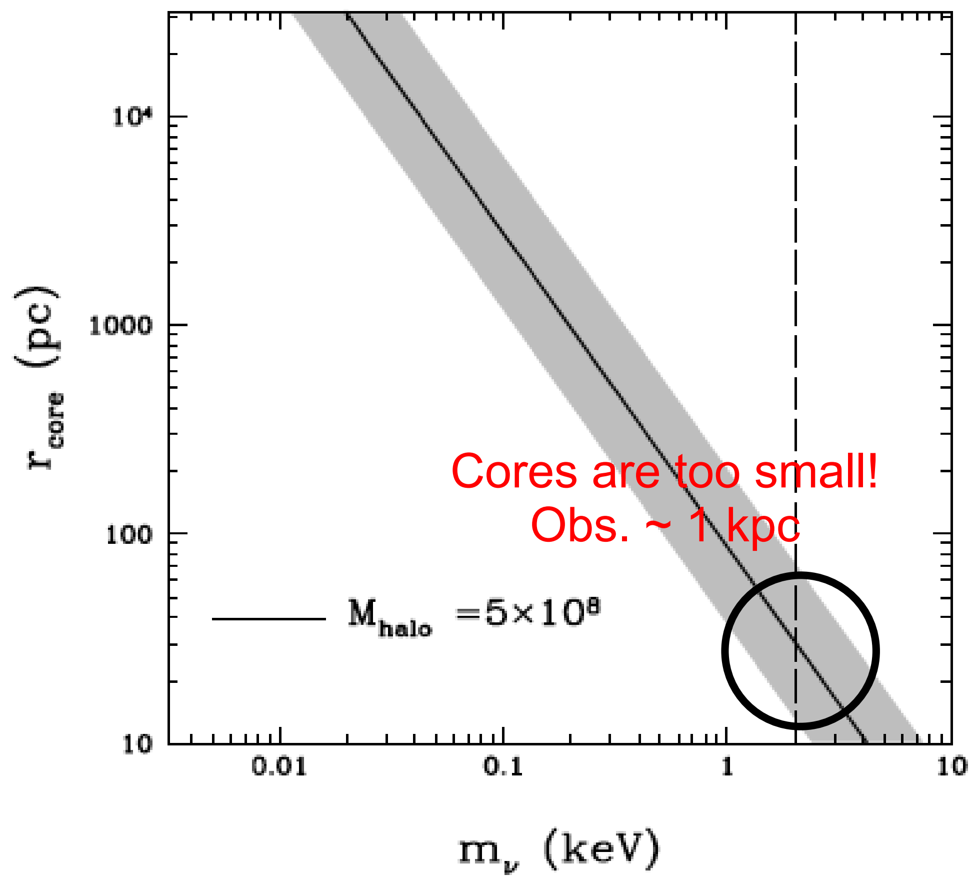
Kuzio de Naray et al. 2010, Maccio et al. 2012 ....

$Q=\rho/\sigma^3$ ⟶ Thermal velocities at decouple set a maximum value to Q that translates into a central density core

MW halo (sim)

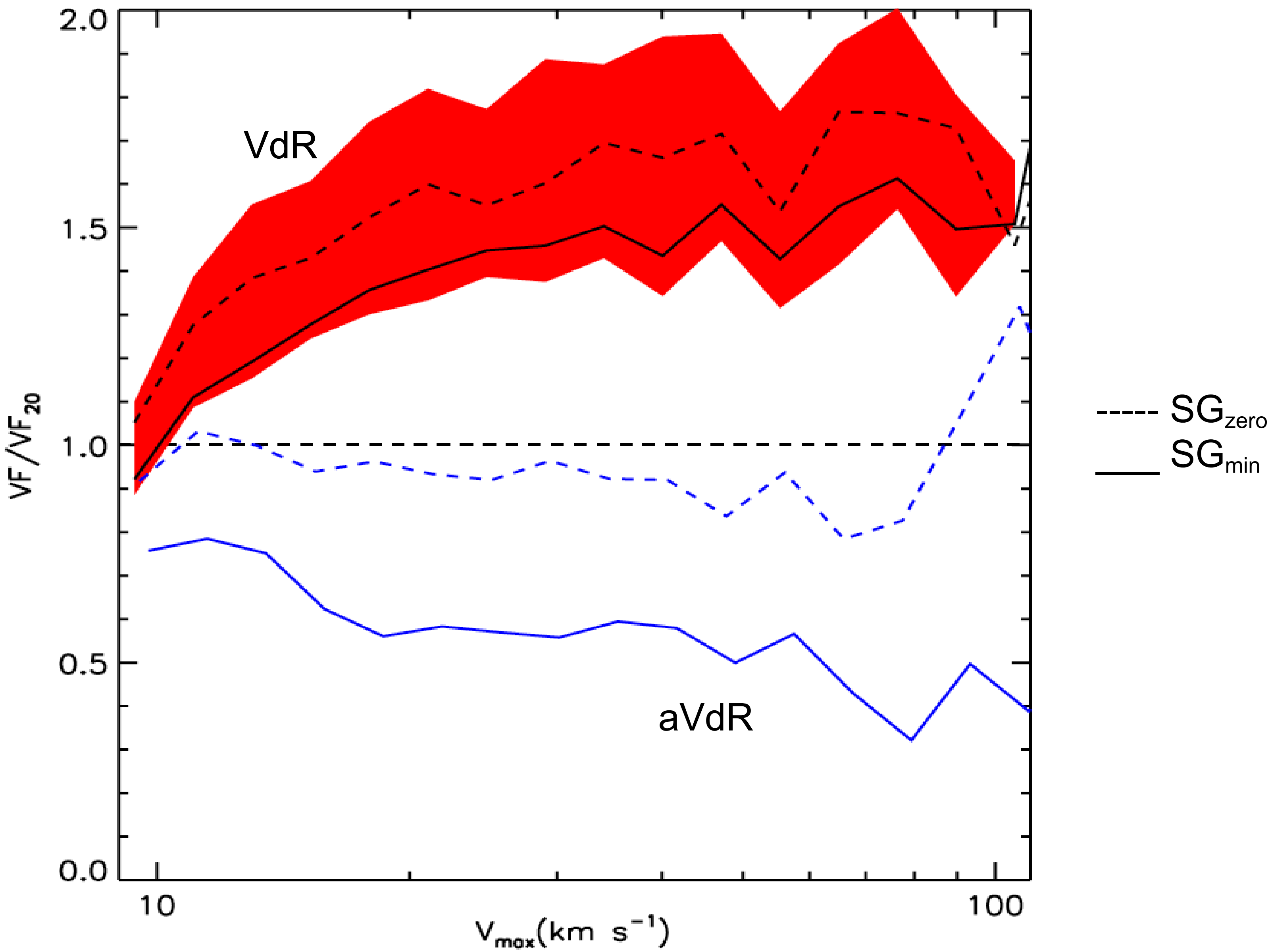


Typical MW subhalo (estimate)



Maccio et al. 2012

Effect of the rotation of the coordinate system (up to 20deg around SG_{zero} in SGB and SGL)



Full volume within 27 Mpc in the two regions