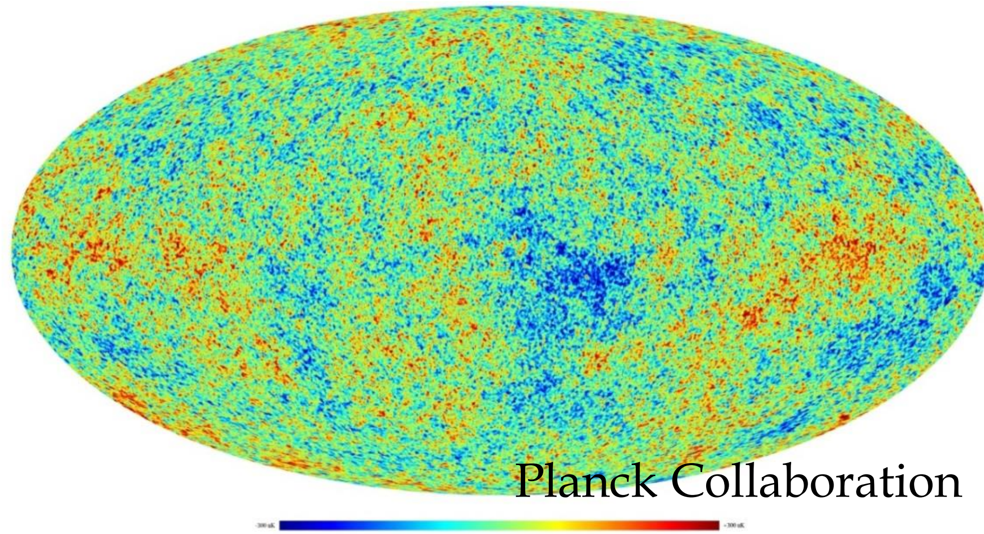
Challenges to ΛCDM

Shaun Cole (ICC, Durham)

24th July 2013

Large Scale ΛCDM successes

- Flat
- Cosmological constant
- Cold dark matter
- Adiabatic Gaussian Perturbations

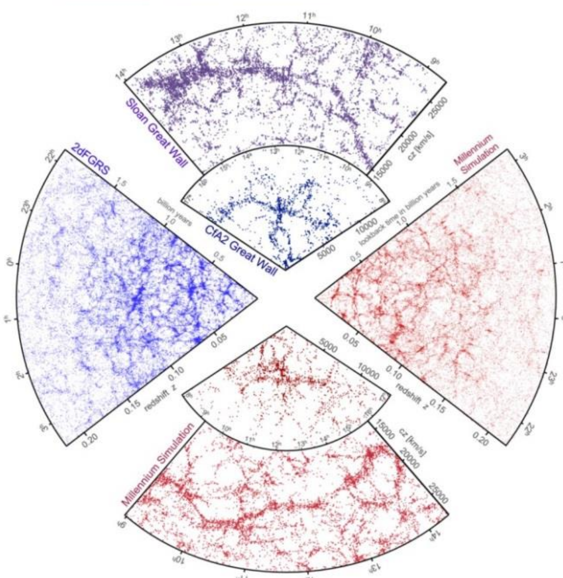


Planck Collaboration

Five Parameters

$$H_0, \Omega_m, \Omega_b, n, \sigma_8$$

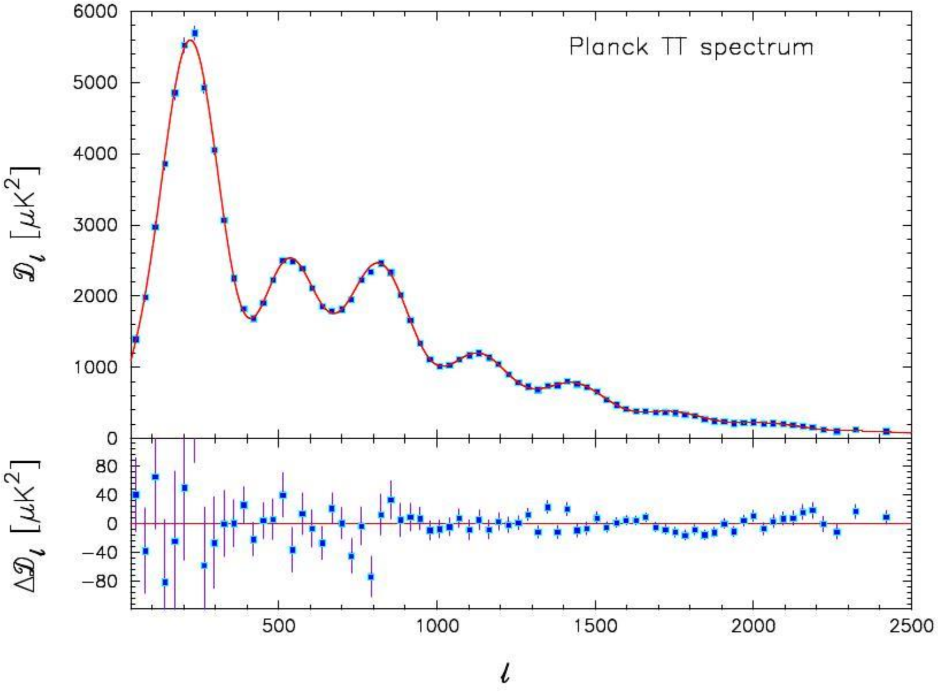
[with τ and b being effective parameters which in principle should be determined by the physics of structure/galaxy formation]



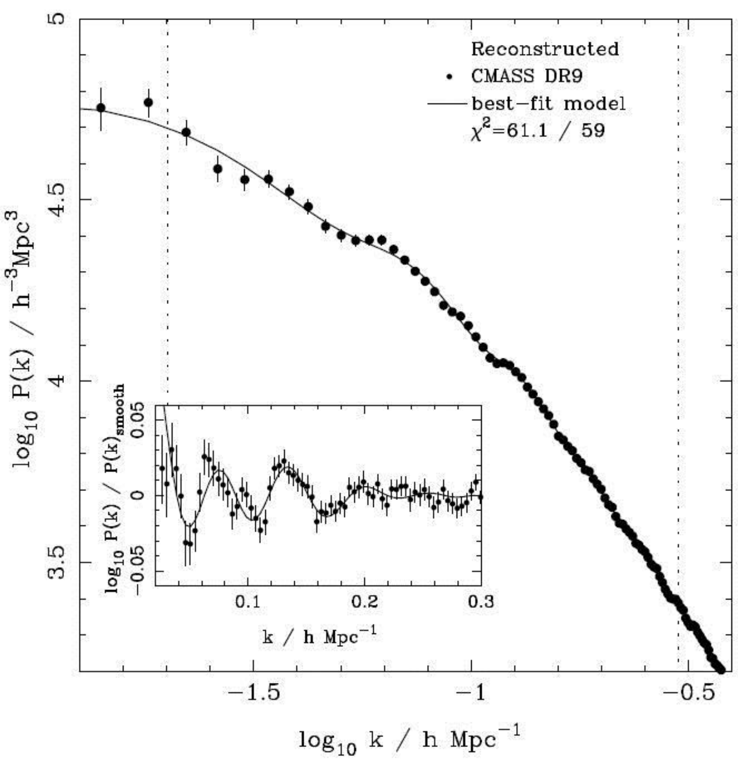
Springel et al 2006

Large Scale ΛCDM successes

$$H_0, \Omega_m, \Omega_b, n, \sigma_8, (\tau, b)$$



Planck Collaboration 2013



Anderson et al 2012 (BOSS)

Outline

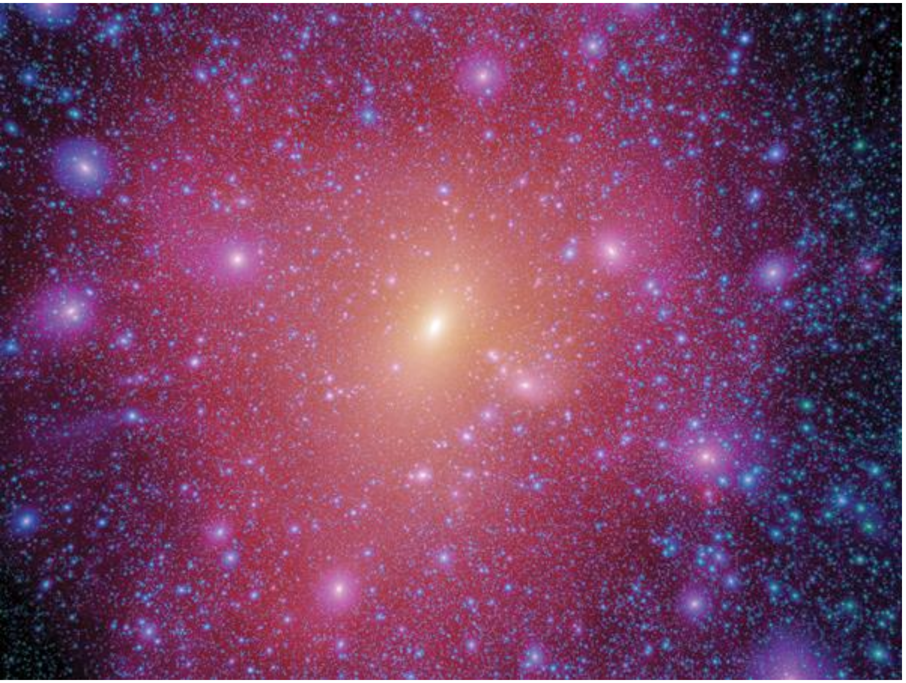
The small scale challenges for ΛCDM:

- Satellite abundance problem
- Field dwarf abundance problem
- Empty void problem
- “Too Big to Fail” problem
- Dwarf halo mass versus abundance
- Cores versus cusps
- Satellite alignments

New (astro)physics

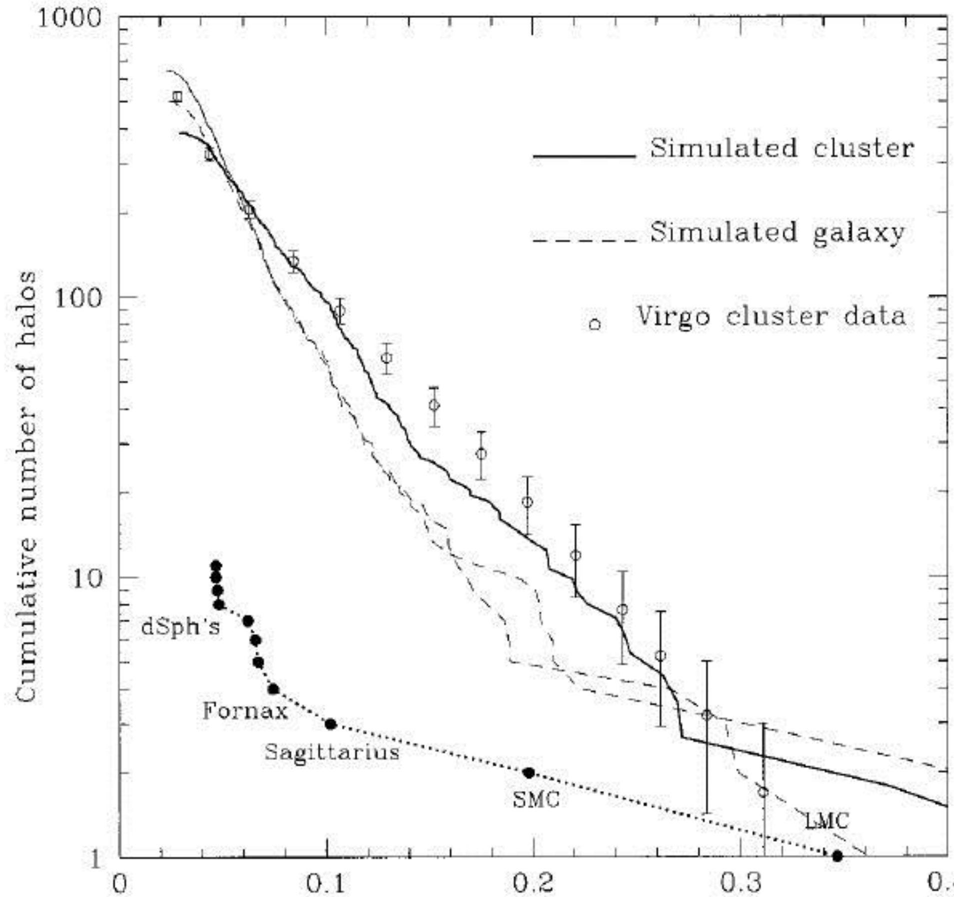
Summary

Satellite Abundance Problem



1.5 billion VIRGO Aquarius A simulation
$M_p = 1.7\times10^3 M_0$ Springel et al 2008

More CDM substructures within galactic DM haloes than satellite galaxies – to given circular velocity



V_c / V_{global}

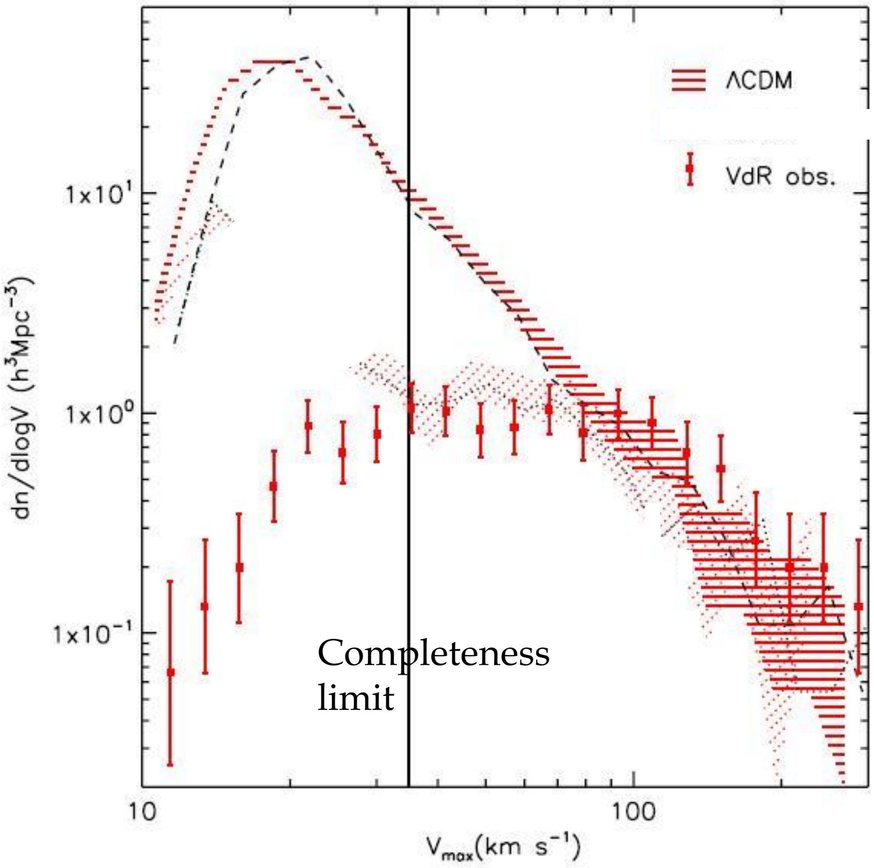
Moore et al 1999

Also Klypin et al 1999

Field Dwarf Abundance Problem

ALFALFA HI survey (Giovanelli et al 2005) in the Virgo direction (<20 Mpc) compared to dwarf haloes in constrained simulations.

Dwarfs overabundant
For v=35-80 km/s

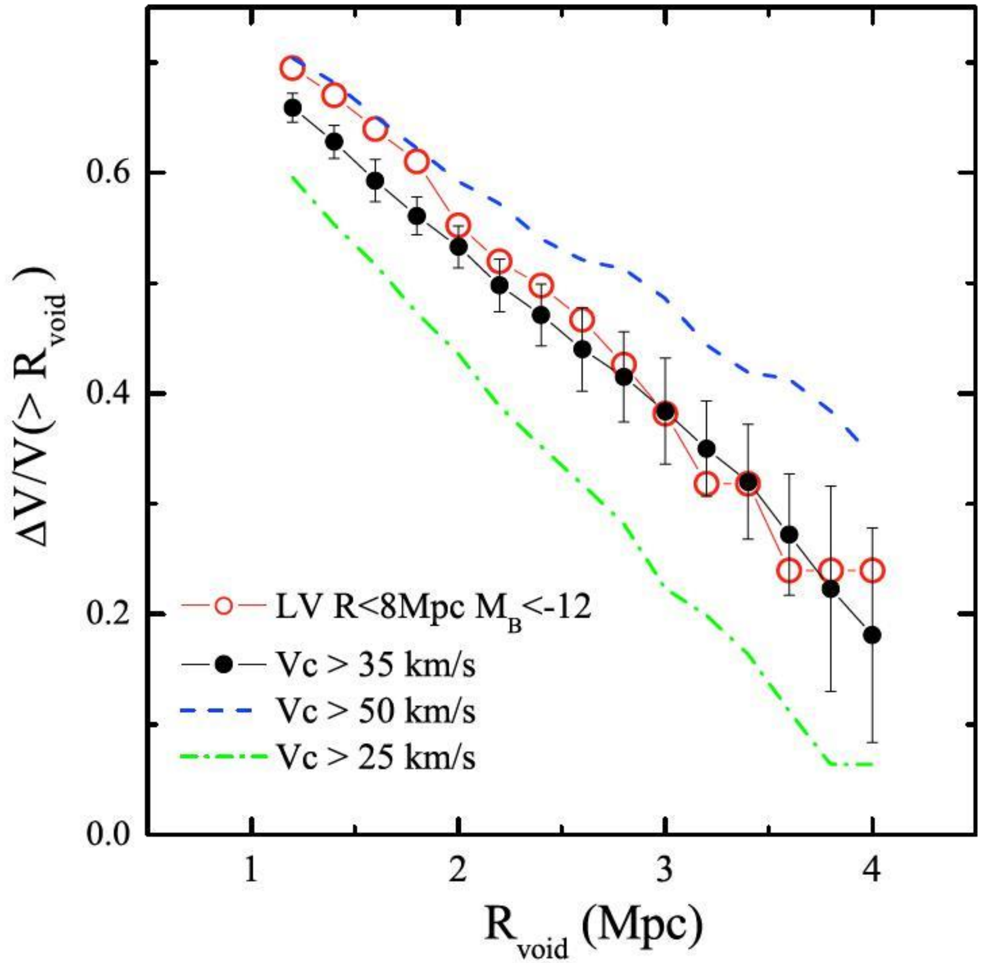


Zavala et al 2009

Empty void problem

Fraction of space occupied by voids with radii larger than R.

Voids too small unless haloes with v<35 km/s are excluded, but then not consistent with many galaxies having HI v< 25 km/s.



Tikhonov & Klypin 2009

"Too big to fail"

Boylan-Kolchin 2011,2012

Stellar kinematics can robustly constrain

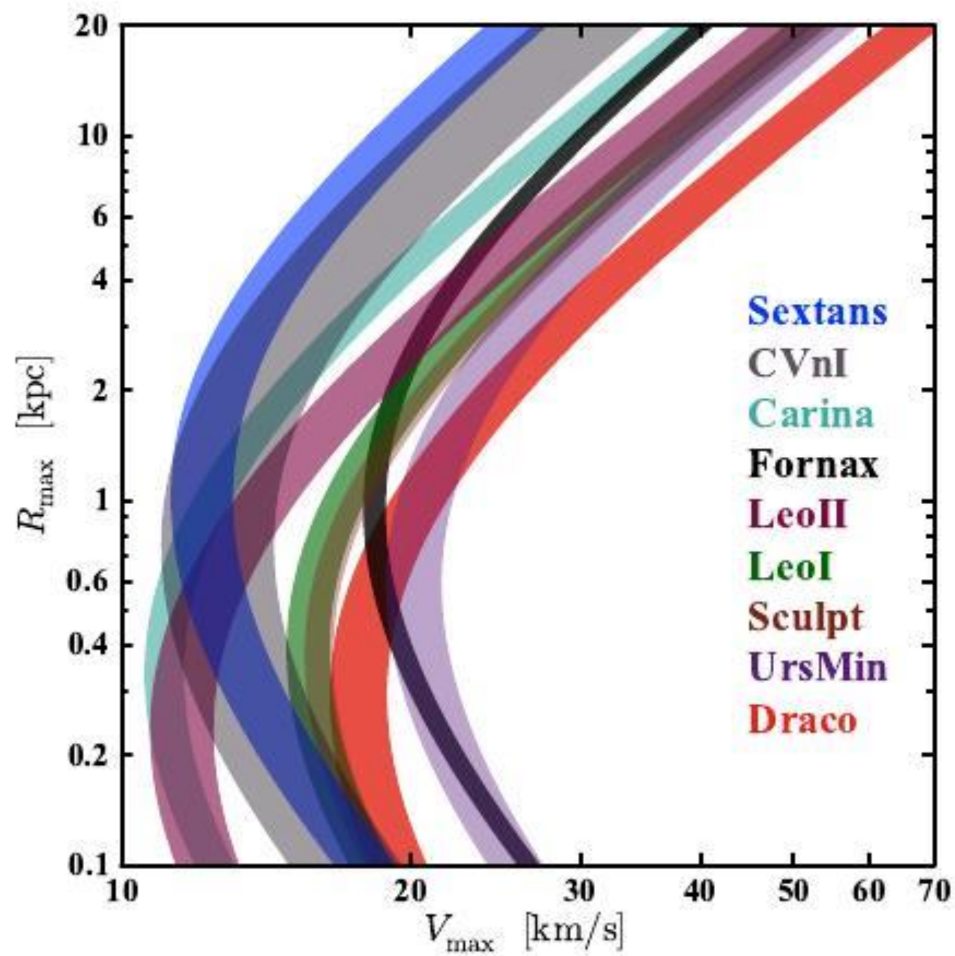
$$M_{tot}(r_{1/2}) = \kappa r_{1/2} \sigma^2$$

(Walker et al 2009,
Wolf et al 2010)

Fit by NFW and results in constraints on

$$R_{max} - V_{max}$$

Excludes the LMC, SMC and Sag satellites



“Too big to fail”

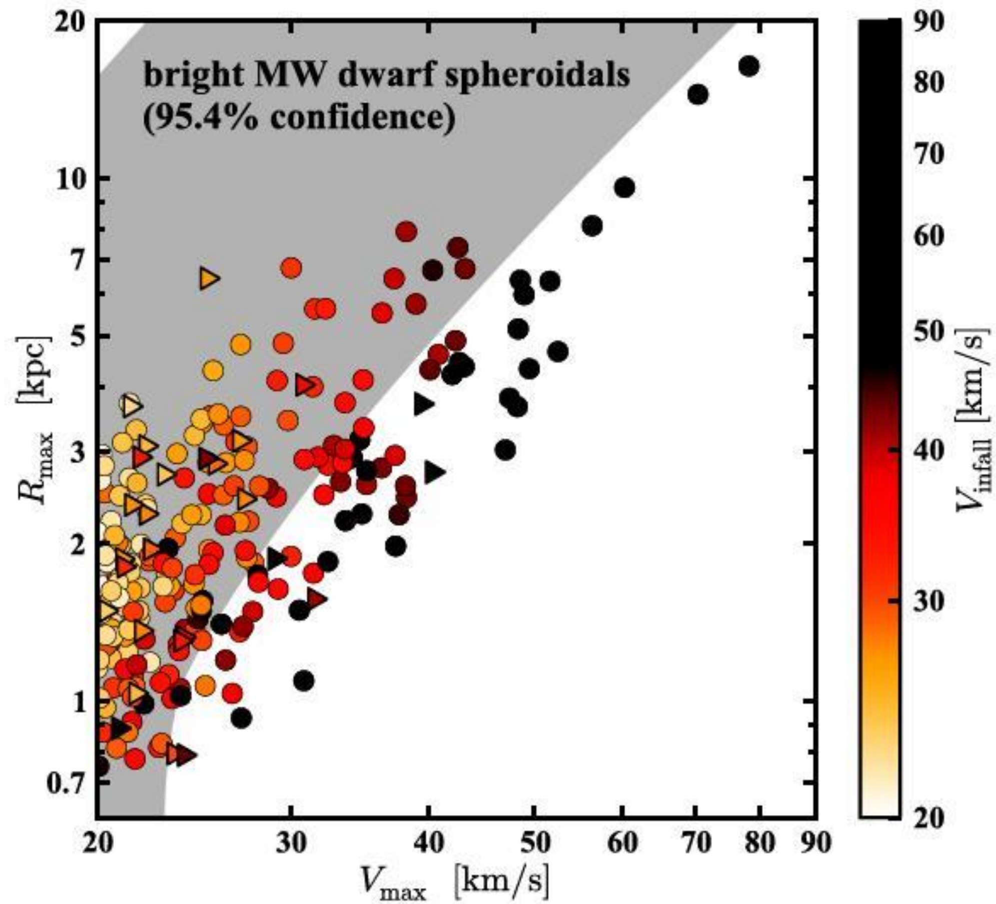
Boylan-Kolchin 2011,2012

Compare the “observed locus” with the

$$R_{\max} - V_{\max}$$

locus of substructures in the Virgo Aquarius simulations of MW haloes.

⇨ There are many substructures with V_{max} too large to host the observed satellites.

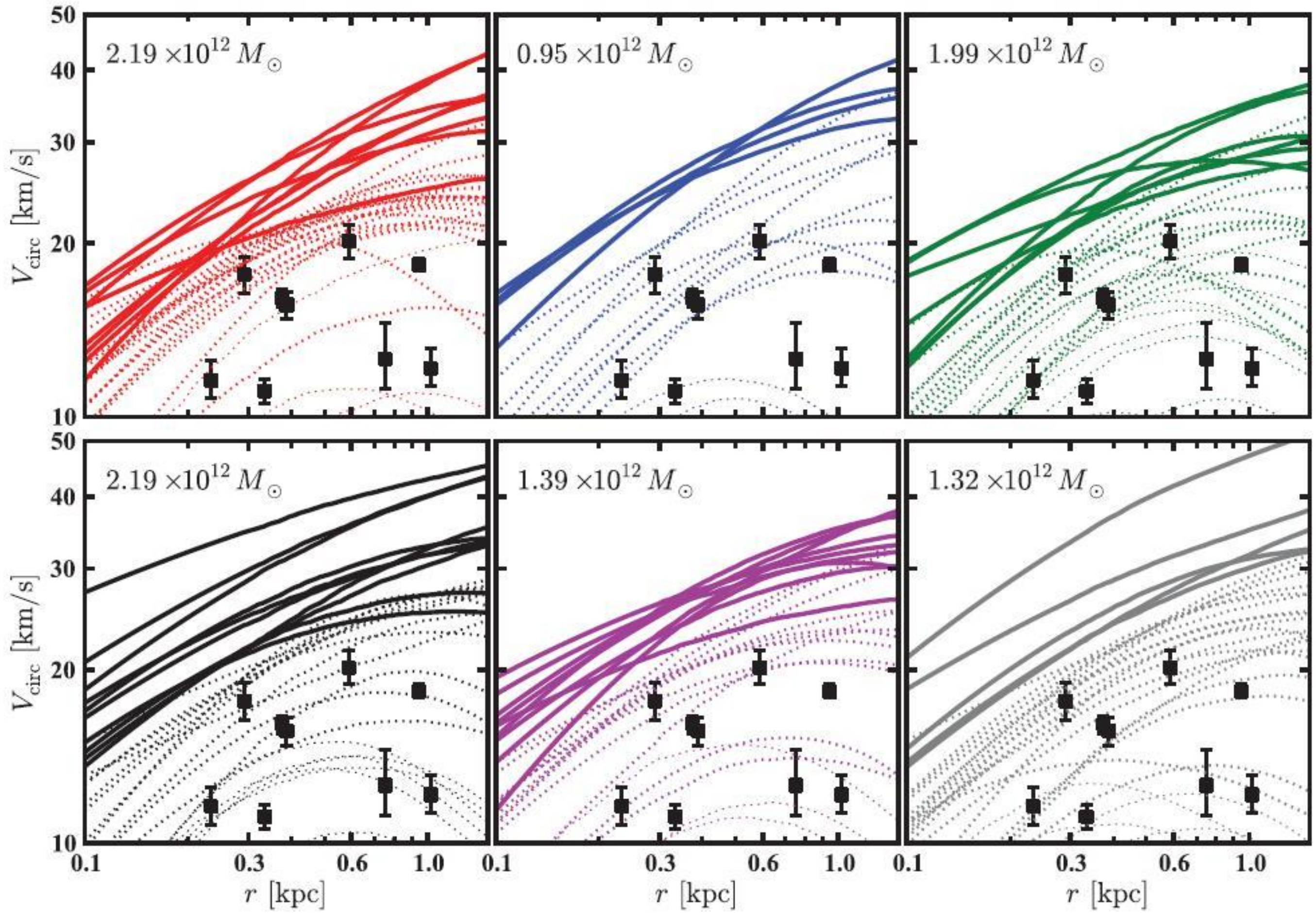


"Too big to fail"

The same discrepancy can be seen using the simulation circular velocity curves directly and without resorting to fitting NFW profiles.

Solid curves are more than 2σ from all dSph points.

Analogues of the Magellanic Clouds , (V_{infall}>60 V_{max}>40 km/s) already removed.



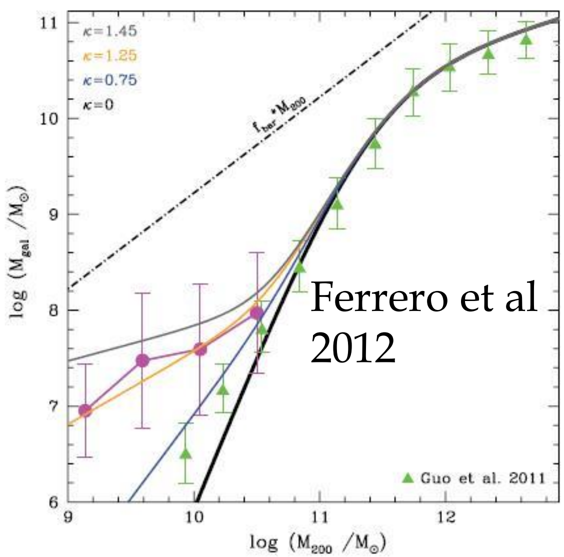
Boylan-Kolchin et al 2012

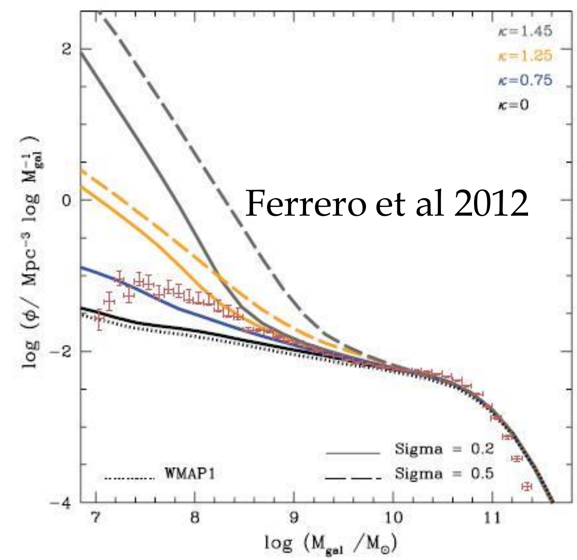
Dwarf Masses

(sub)Halo abundance matching (e.g. Vale & Ostriker 2006),

$$n_{\mathrm{gal}}(>m_{\mathrm{star}}) = n_{\mathrm{halo}}(>m_{\mathrm{halo}})$$

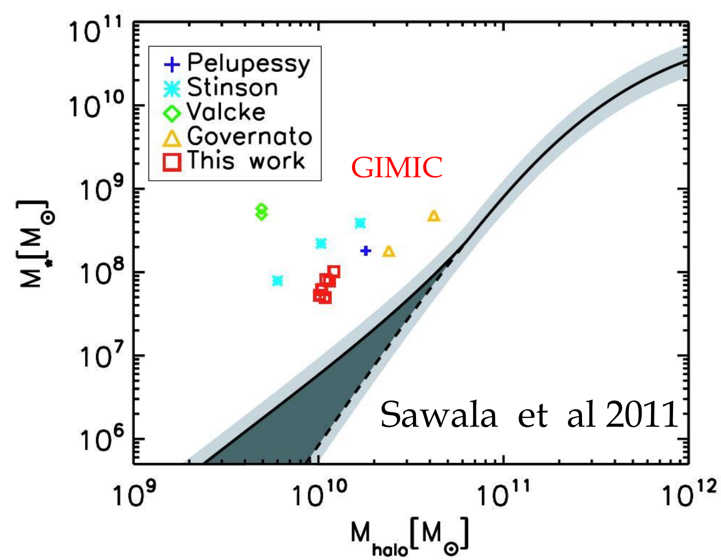
can be used to predict the stellar mass content of halo e.g. Guo et al (2010).





Under this assumption Ferrero et al (2012) show that measured dwarf masses (NFW fits to kinematic data) are not consistent with the measured luminosity function.

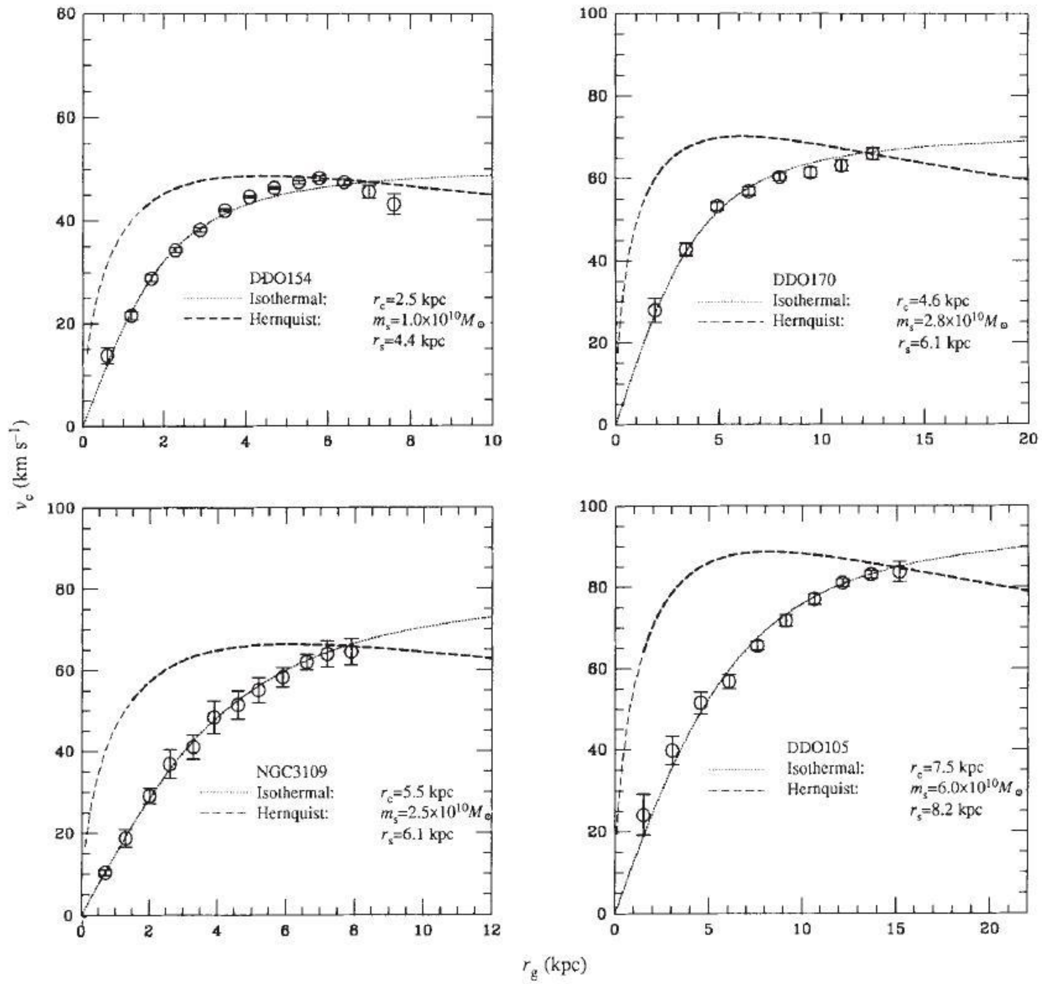
Sawala et al (2011) show that the predicted stellar masses similarly disagree with "state-of-the-art" simulations.



Cores versus Cusps

High mass to light ratios imply dwarfs are dark matter dominated beyond 1 kpc.

Rotation curves are inconsistent with the cuspy steep inner density profiles predicted for CDM.



core

$$\rho \propto \frac{1}{(r_c^{\,2}+r^2)},\;\; v \propto r \text{ as } r \rightarrow 0$$

cusp (NFW)

$$\rho = \frac{\rho_0}{(1+r/r_s)^2\, r/r_s},\;\; v \propto \sqrt{r} \text{ as r} \rightarrow 0$$

Moore 1994

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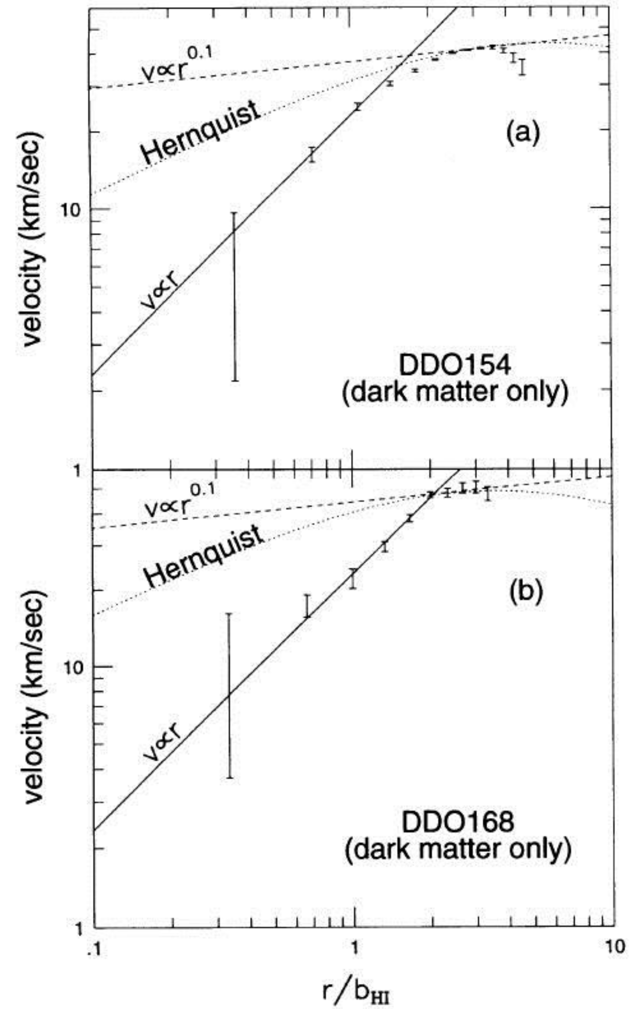


Flores & Primack 1994

Cores versus Cusps

Cores have also been reported in lower mass systems, the dSph satellites of the MW.

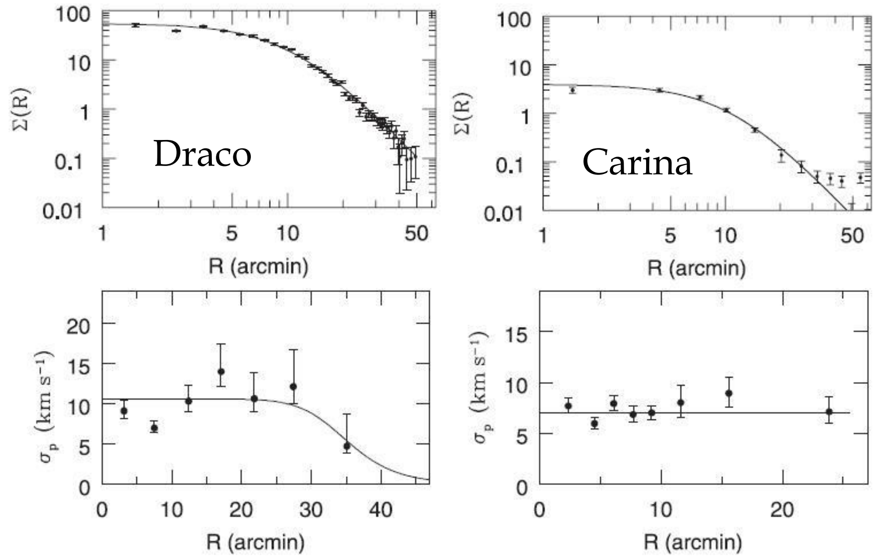
(Goerdt et al 2006; Sanchez-Salcedo 2006; Gilmore et al 2007; Angus & Diaferio 2009)

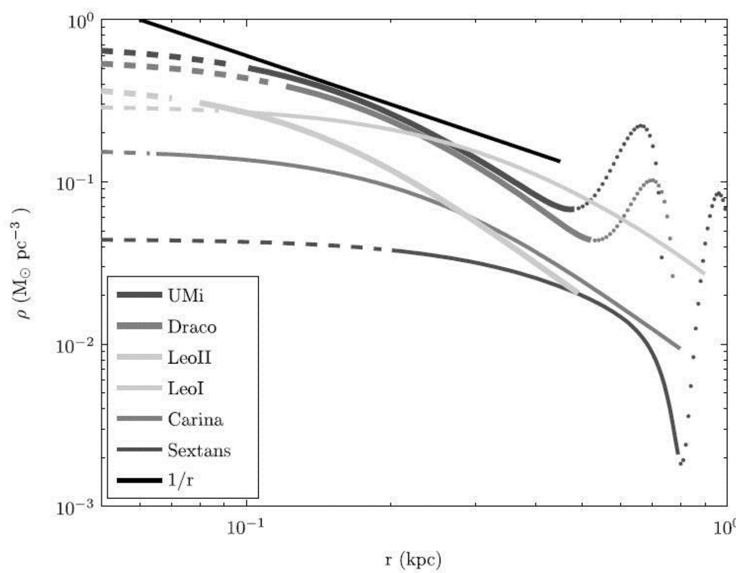
The approach in Gilmore et al was to fit the velocity dispersion , σ, and surface density profiles by smooth functions and then use Jeans analysis to infer the mass profiles.

$$M(r) = -\frac{r^2}{G}\left(\frac{1}{\nu}\frac{d\nu\,\sigma_r^2}{dr} + 2\frac{\beta\sigma_r^2}{r}\right)$$

Assume isotropy, β=0.

Find cores with radii of around 100pc.





Gilmore et al 2007

Cores versus Cusps

Sub haloes from the Aquarius simulations

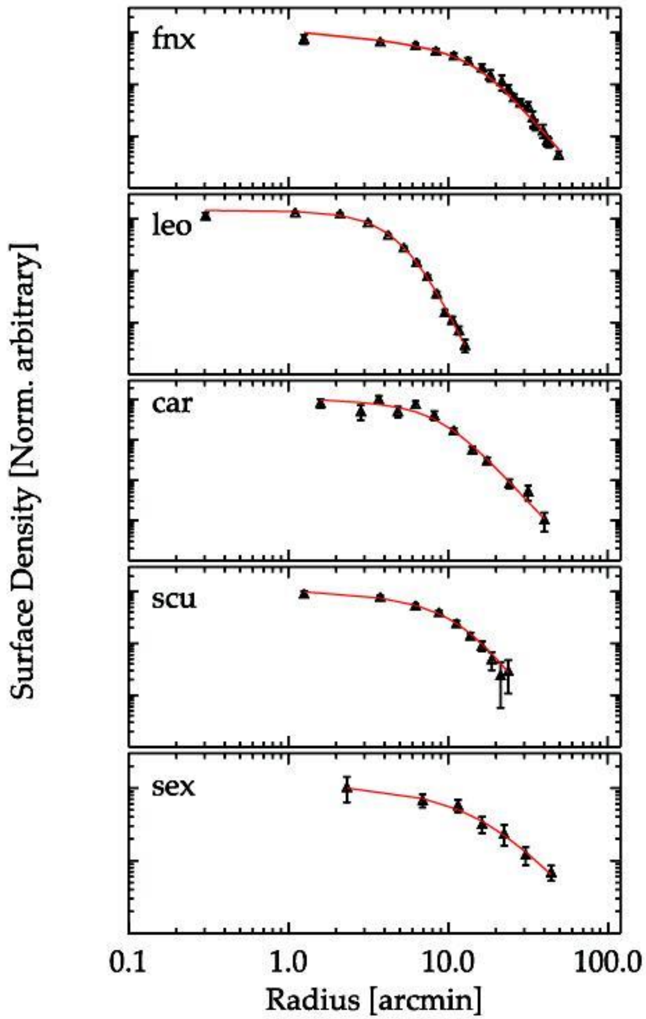
Fit projected surface density profiles

For each subhalo determine the velocity dispersion profile that is consistent with this profile (assuming isotropic velocity dispersion). Find which subhalo best reproduces the measured velocity dispersion profile.

4 out of 5 dSph fit very well

Also predict full velocity distribution and find the observed kurtosis is reproduced quite well.

Data not inconsistent with LCDM cusps!



Strigari et al 2010

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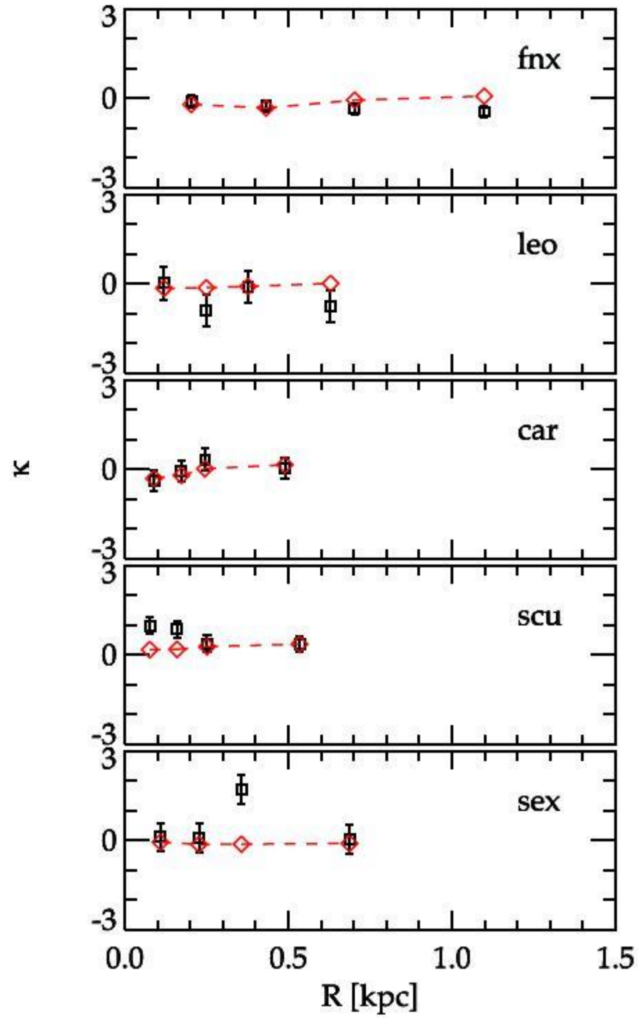


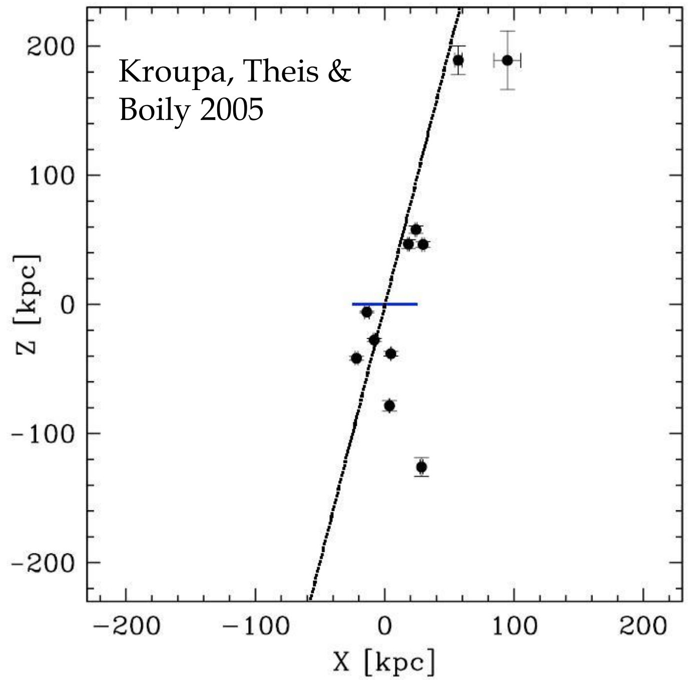
Strigari et al 2010

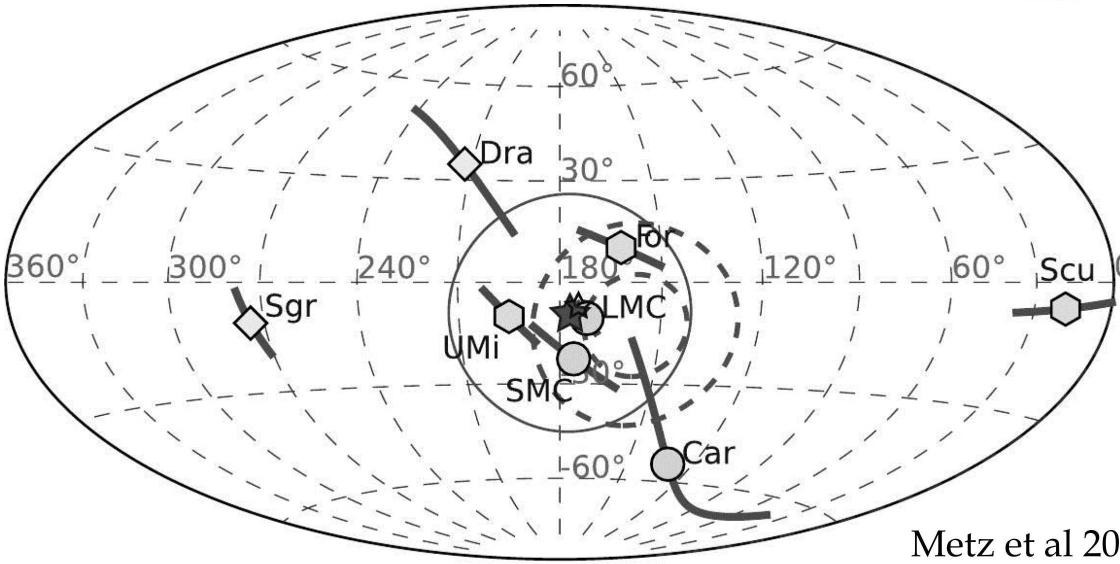
Satellite Alignments

The Milky Way

The 11 classical satellites form a very flattened distribution.

Proper motion measurements indicate that the majority (5 out of 8 measured) have orbital poles that are consistent with falling in a 30deg radius circle, close to the pole of their plane.





Metz et al 2008,2009

Satellite Alignments

Satellites of Andromeda

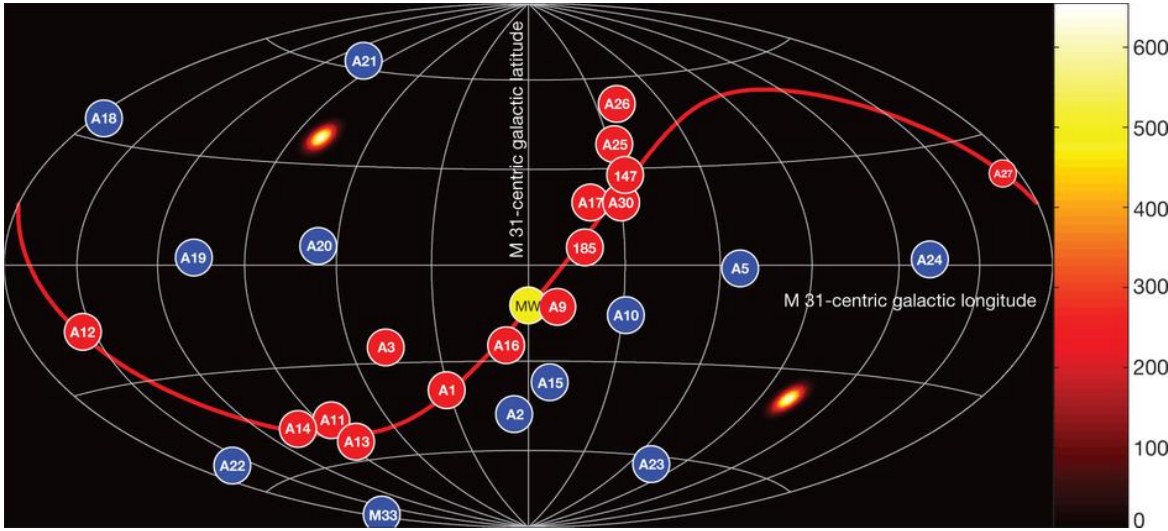
15 of the 27 satellites from the homogeneously surveyed, PANDAS (Ibata et al 2013), region lie close to a great circle as viewed from Andromeda .

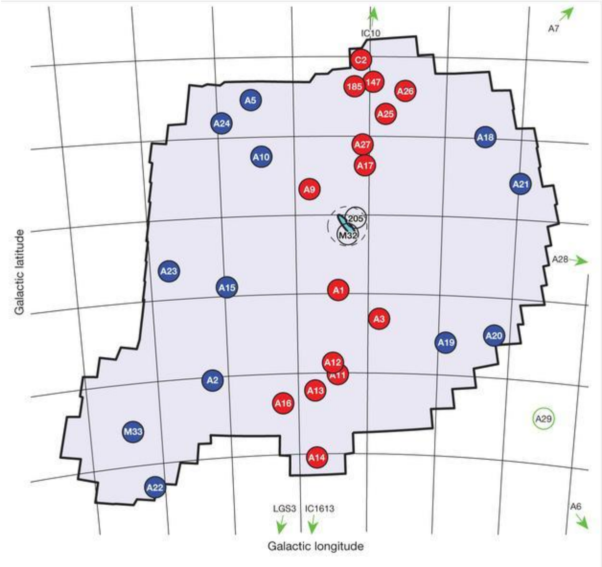
0.13% chance for an isotropic distribution.

Of these 15, 13 show coherent rotation as indicated by their line of sight velocities

1.4% chance for random

(see today's talk by Annette Ferguson)





Ibata et al 2013

Satellite Alignments

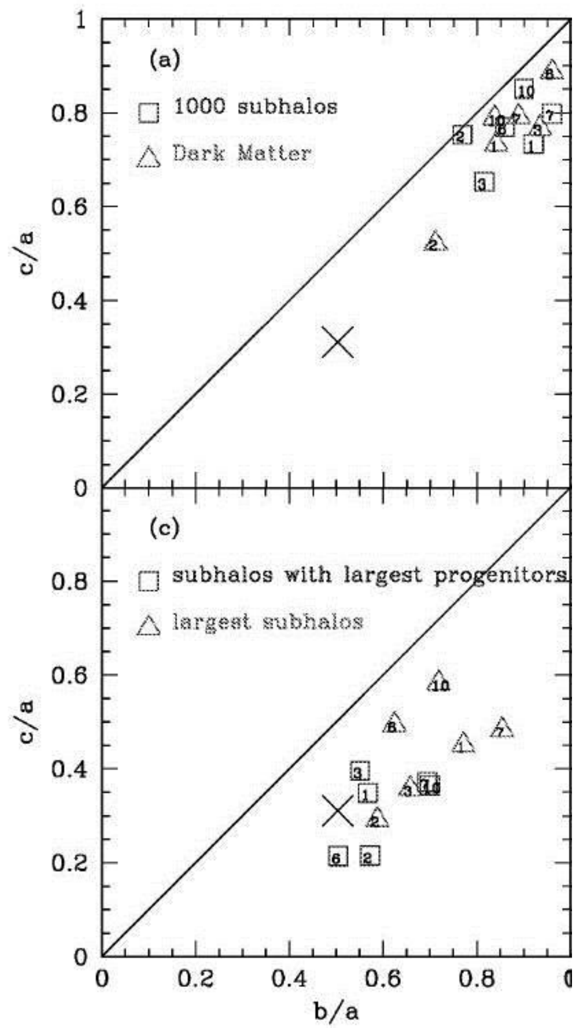
<u>LCDM expectation</u>

LCDM haloes, while not being spherical, have typical axis ratios c/a=0.6 to 0.9

MW satellite distribution has
c/a=0.3.

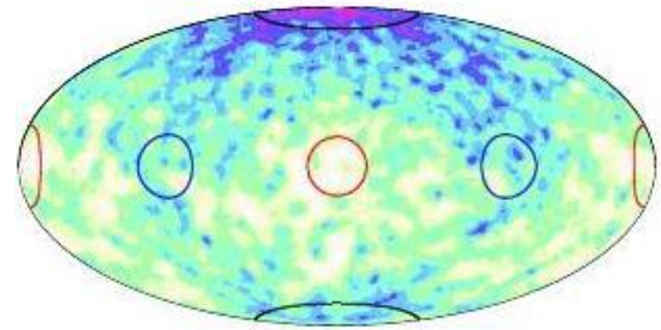
But, the most massive subhalos are accreted preferentially along the central spines of filaments and have a more flattened distribution.
(Libeskind et al 2005, Zentner et al 2005)

Axial Ratios

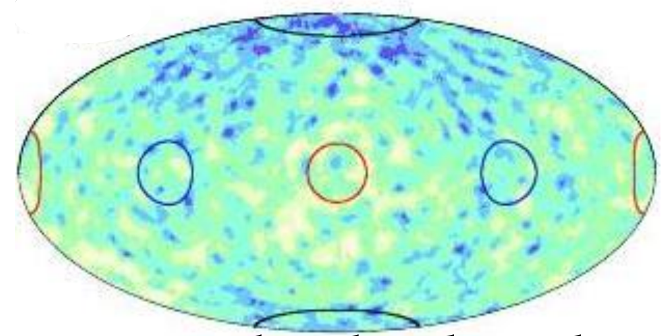


Libeskind et al 2005

Alignment of orbitalpoles



11 most massive sats.



Replaced with random DM particles

35% chance of 3 within 30deg
5% chance of 5 within 30deg

Libeskind et al 2008

Satellite Alignments

Often several satellite orbits have angular momenta clustered around a common pole, though generally not coincident with the pole of the overall halo.

Would the presence of Andromeda in simulations select a preferred direction?

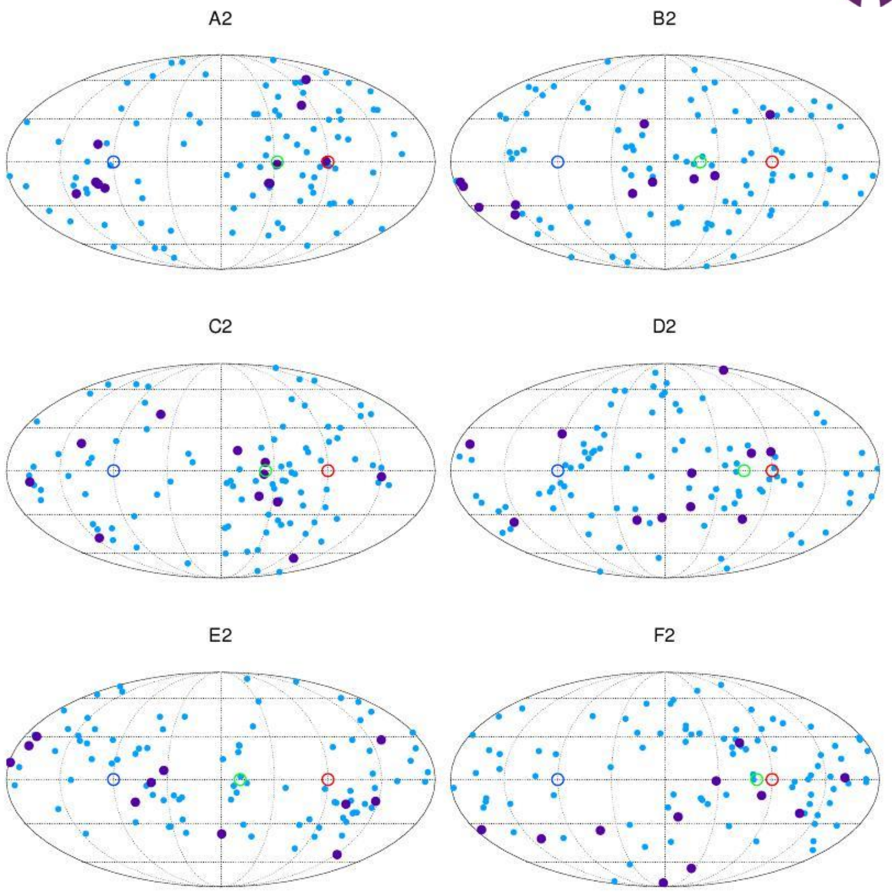


Fig: Orbital poles of the 11 (and 100) most massive satellites in the 6 Aquarius MW simulations relative to the direction of the total angular momentum of each halo.

Lovell et al 2010

New (Astro)Physics

- **Halo mass-abundance mismatch**
- **Cuspy profiles**
- **Satellite alignment**

The solution to these challenges could be the exotic or the complex

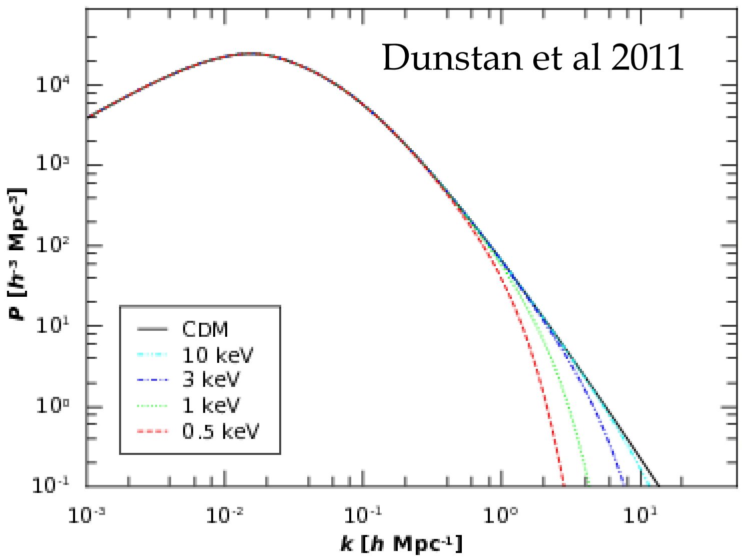
Changes to LCDM

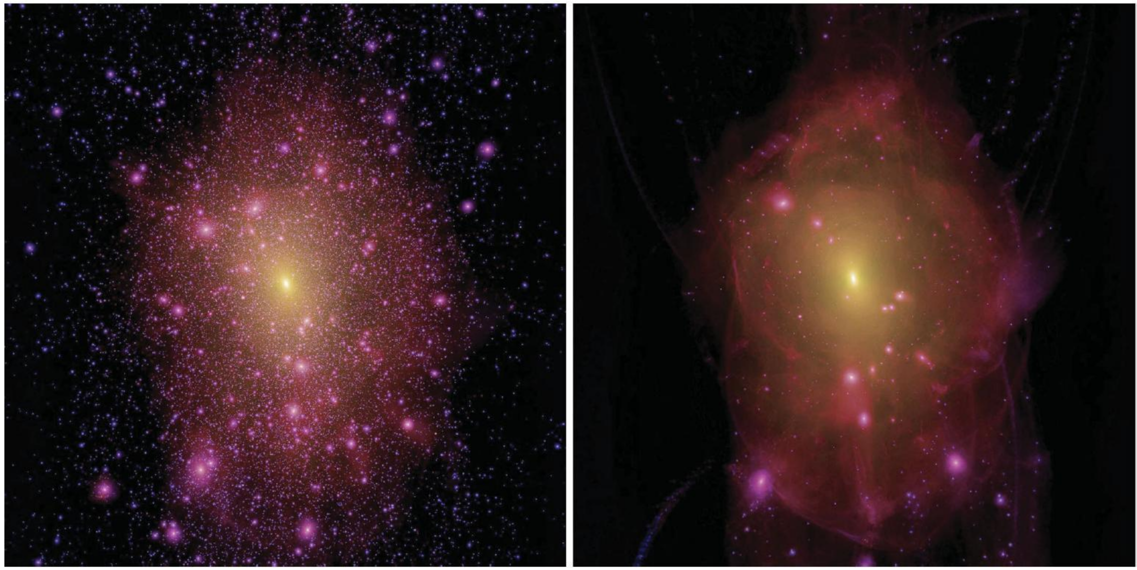
Warm Dark Matter
Self-interacting Dark Matter
Modified Gravity

Complex Astrophysics

Baryonic – Dark Matter interactions
Star Formation and Feedback

ΛWDM and satellite abundance





Lovell et al 2012

If the DM is a keV particle, e.g. a sterile neutrino, its relativistic velocity at decoupling leads to the erasure of small scale density perturbations due to free streaming. For a ~2 keV thermal neutrino the cutoff results in first structures formed being the mass of dwarf galaxies.

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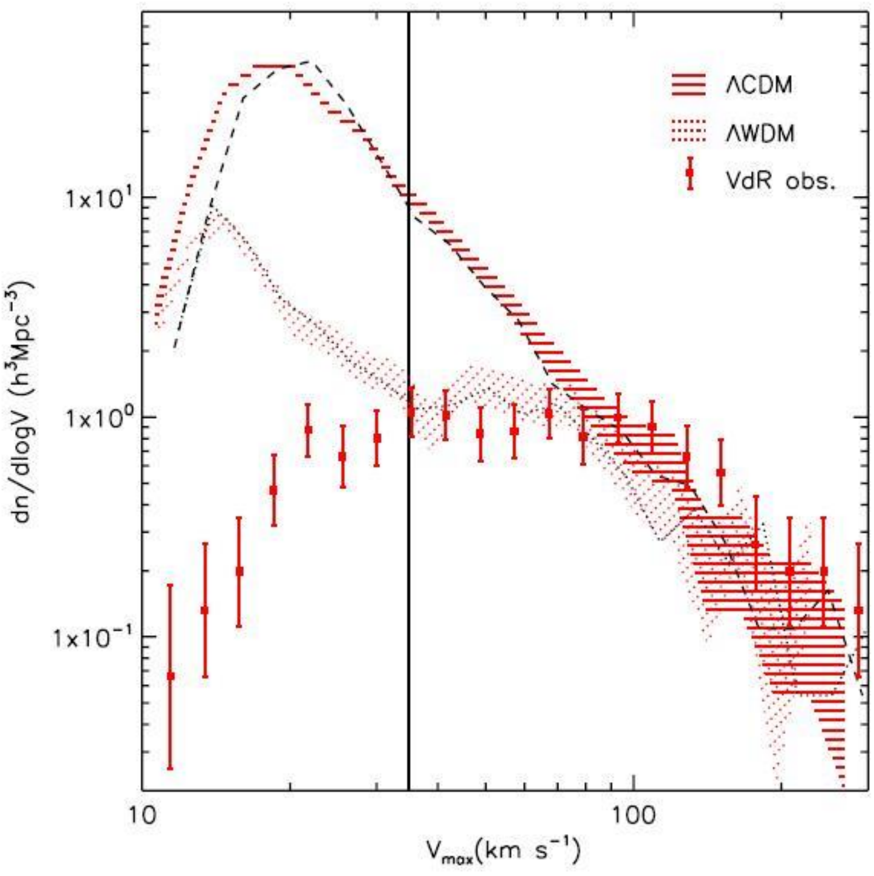
See Monday's talks by Carlos Frenk and Mark Lovell

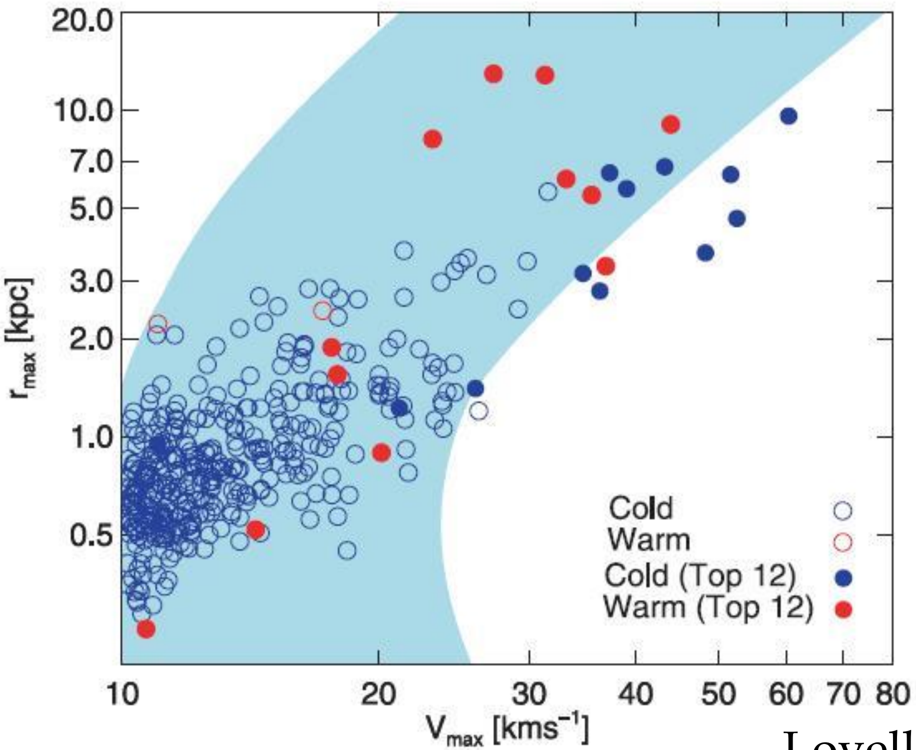
ΛWDM and dwarf mass-abundance

The same reduction in the number of low mass halos also solves the local dwarf abundance problem



Zavala et al 2009

ΛWDM and too big to fail



Lovell et al 2012

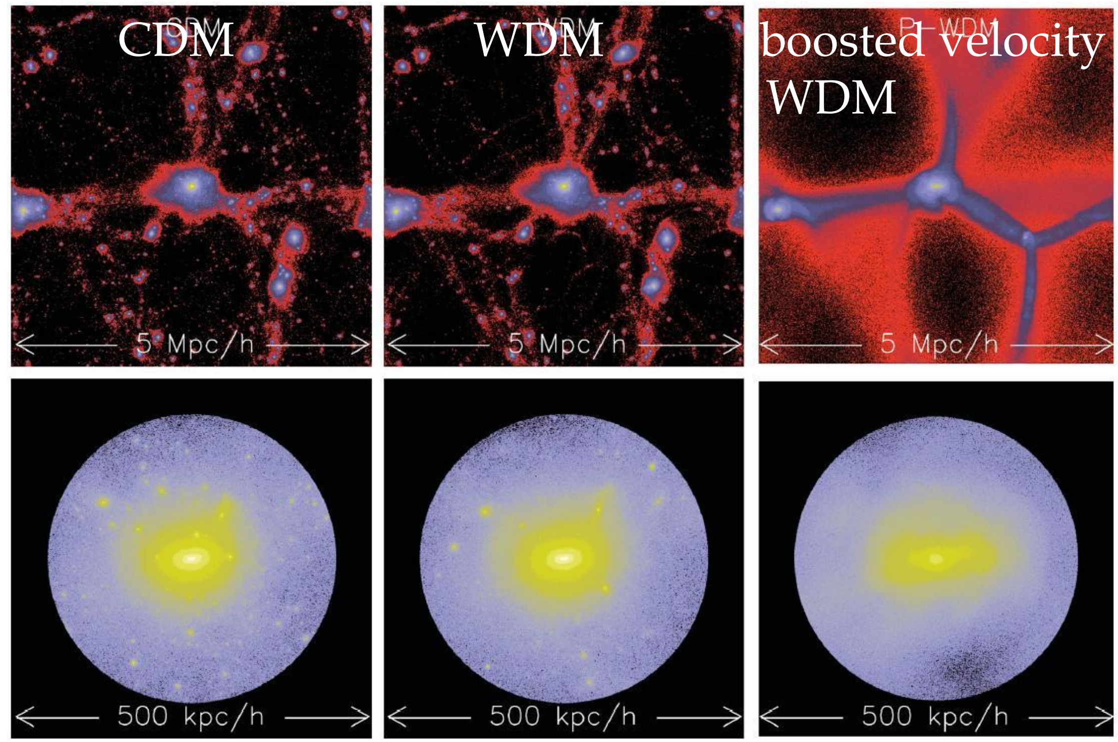
There is pretty much a one-to-one correspondence between the largest CDM substructures and the WDM substructures. However the WDM counterparts are less concentrated due to forming later.
This results in a Vmax-Rmax distribution much more consistent with that of the local dSph.

ΛWDM and cores

Cores in WDM haloes resulting from the initial Fermi-Dirac velocity distribution

Simulations (Shao et al 2013)
5 Mpc/h boxes
256^3 particles, m=2 keV

Simulation with velocities boosted by 270 so that the resulting core can be resolved with the achievable resolution.



Shao et al 2013

$$P_{\rm WDM}(k) = P_{\rm CDM}(k)T^2(k),$$

$$T(k) = (1+(\alpha k))^{-5}$$

Bode et al (2001)

$$\alpha = 0.05\left(\frac{\Omega_{\rm WDM}}{0.3}\right)^{0.15}\left(\frac{h}{0.72}\right)^{1.3}\left(\frac{m}{\rm keV}\right)^{-1.15} h^{-1}{\rm Mpc}$$

--- Power spectrum cutoff scale

$$v = 0.012(1+z)\left(\frac{\Omega_{\rm WDM}}{0.3}\right)^{1/3}\left(\frac{h}{0.65}\right)^{2/3}\left(\frac{m}{\rm keV}\right)^{-4/3} {\rm kms}^{-1}$$

---Characteristic thermal velocity

ΛWDM and cores

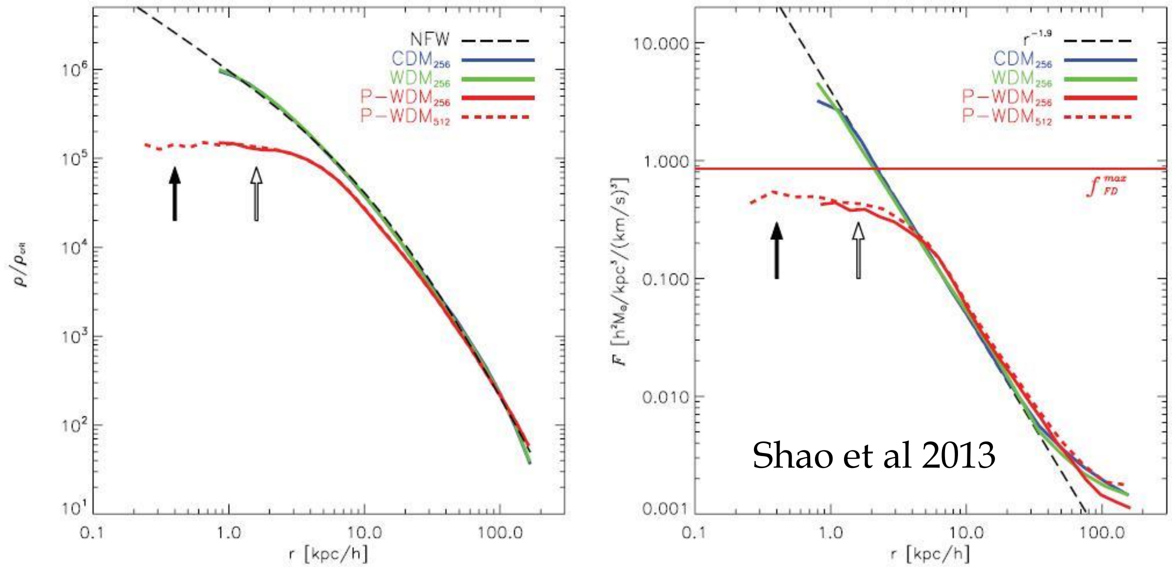
Standard WDM and CDM almost the same and well fitted by NFW and power law.

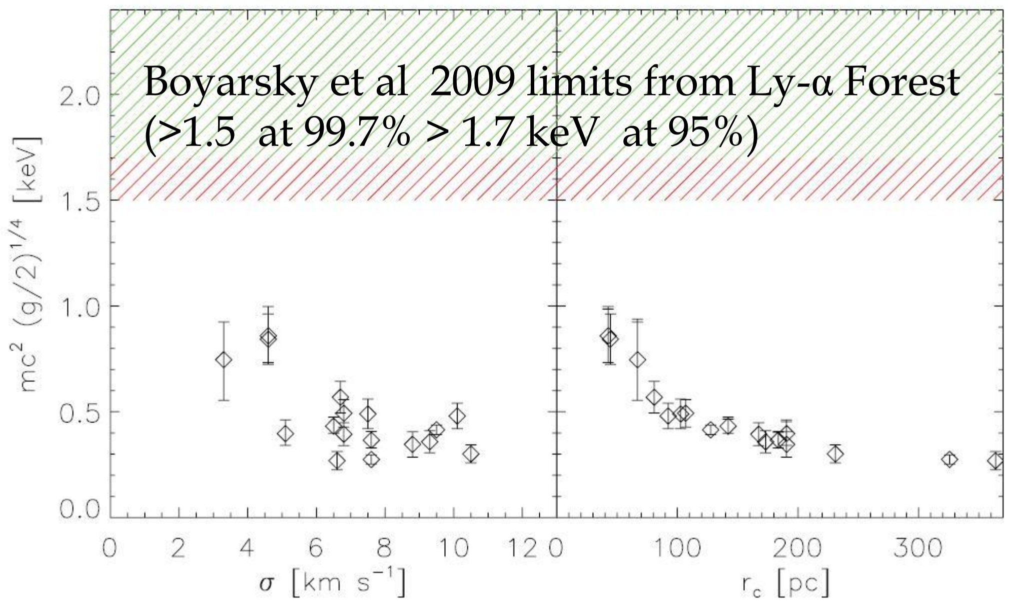
With boosted velocities resolved cores are produced.

Coarse grained phase space density (ENBID, Sharma & Steinmetz 2006) close to theoretical fine grained upper bound.

Match inferred central phase space density of MW dSph and estimate the required WDM particle mass.

➡ To produce cores in MW dSph would need m =0.5 keV which is ruled out by the Ly-α Forest limits





Baryon Physics: Creation of cores

Rapid changes in the gravitational potential caused by SN ejecting baryons on a timescale shorter than the local dynamical time can irreversibly transfer energy from the baryons to the DM.

Navarro, Eke & Frenk 1996 showed that imposing and then suddenly removing a massive disk potential generates a core in an originally cuspy DM profile.

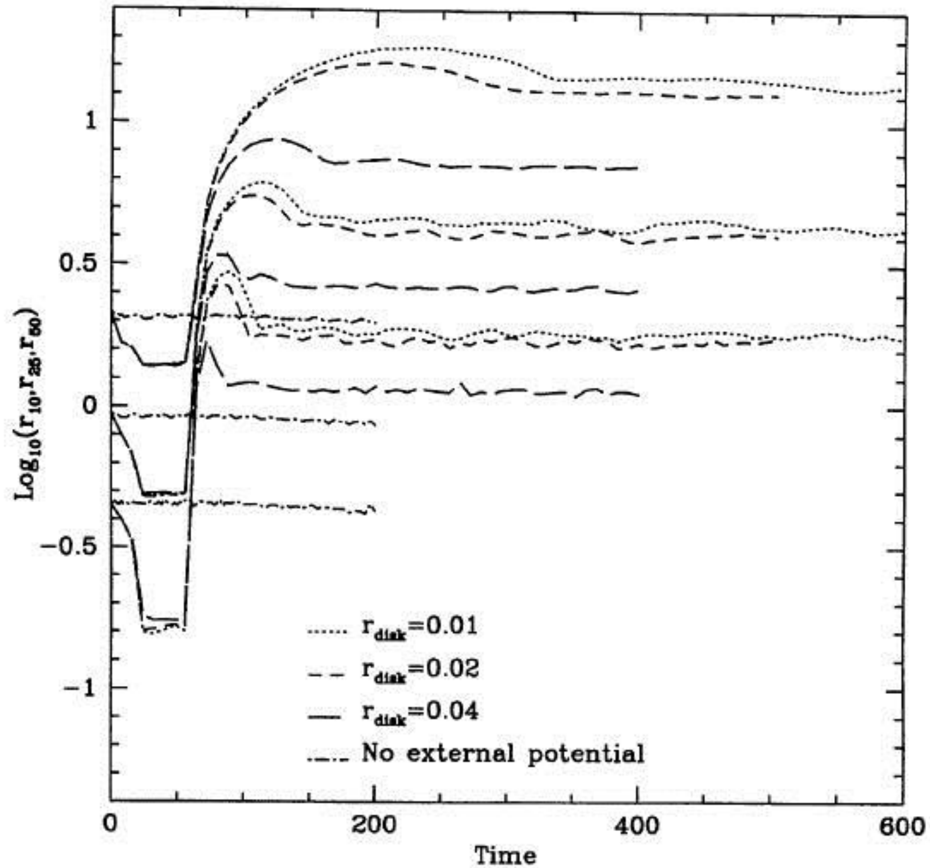


Figure 1. The evolution of radial mass shells in a Hernquist model run in isolation (dot–dashed lines), or subject to the collapse and removal of an exponential disc potential of mass $M_{disc} = 0.2$, and $r_{disc} = 0.01$, 0.02 and 0.04 (dotted, short-dashed and long-dashed lines, respectively).

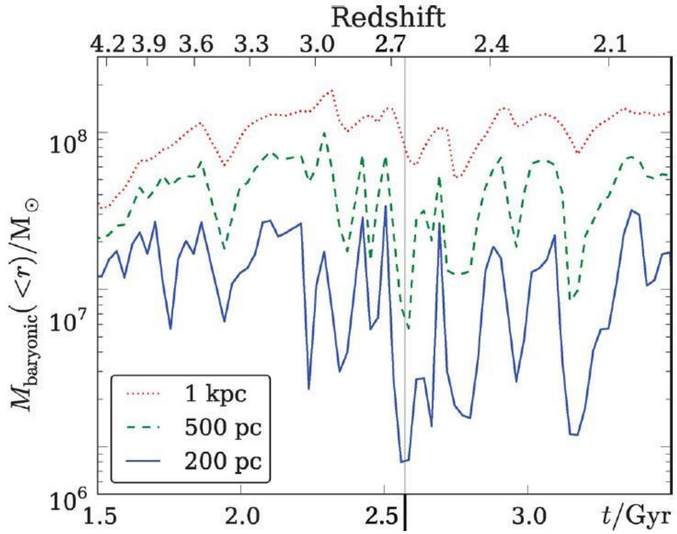
Navarro, Eke & Frenk 1996

Baryon Physics: Creation of cores

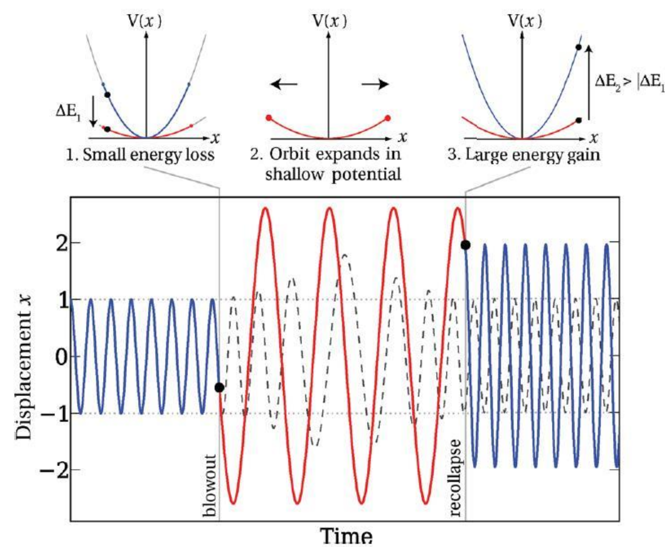
A less extreme version has been shown to operate in the full SPH star formation+feedback simulations of Governato et al 2012

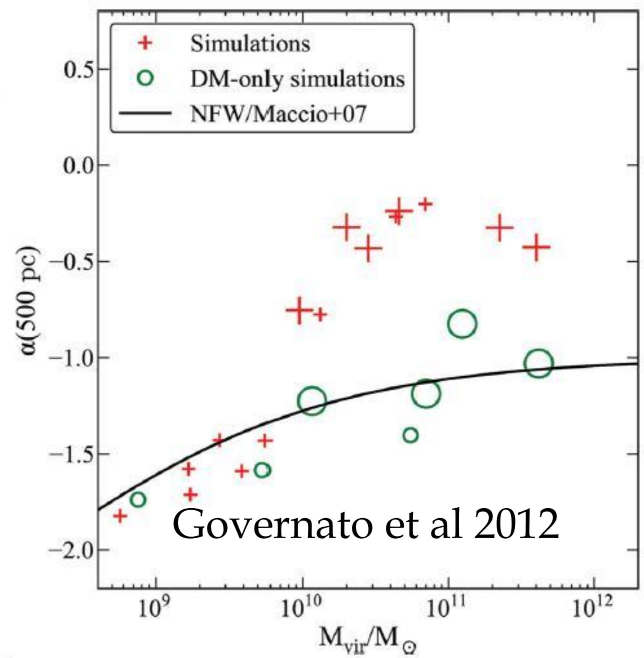
Here star formation only occurs in very dense gas and then initiates strong SN feedback. These results in rapid fluctuations flows in the inner regions.

Pontzen & Governato present an analytic model for how this results in energy transfer.



Pontzen & Governato 2012





Governato et al 2012

Inner density profile slopes are reduced. Much closer to cored profiles and compatible with kinematic data from THINGS (Walter et al 2008).
Too few stars form for this mechanism to work in dSph

Baryon Physics: abundances and masses

Abundance matching matches galaxies to halos in Dark Matter only simulations, but haloes whose properties we measure in the real Universe did not form in a Dark Matter only universe.

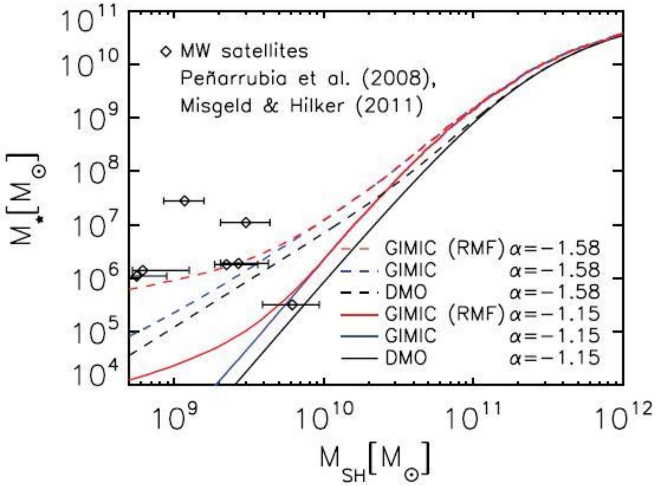
$$M_{\text{halo,measured}} \neq M_{\text{halo,DMonly}}$$

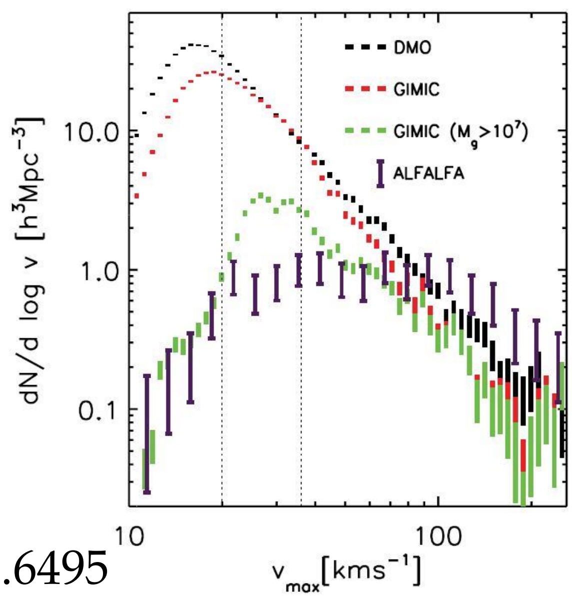
GIMIC (VIRGO, Crain et al 2009)

Full SPH star formation and feedback simulation of cosmologically representative regions with mass resolution of order 1 million Msun.

By no means definitive (e.g. galaxy stellar mass function not a good fits to observations), but illustrative of the effect that baryonic processes can have on dark matter.

Analysis here by Sawala et al 2013.





1206.6495

Baryon Physics: abundances and masses

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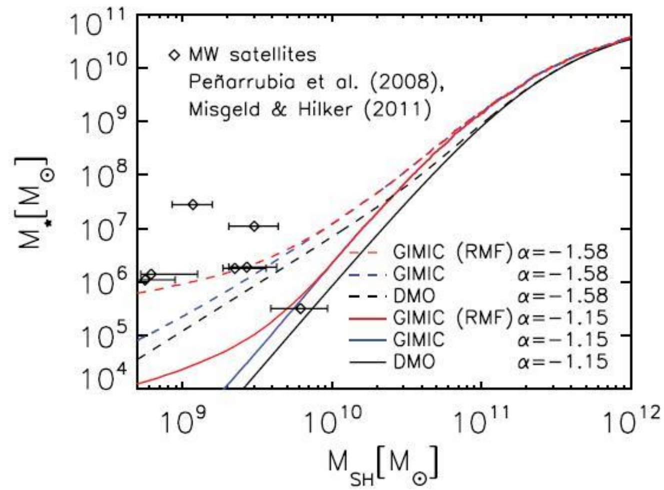
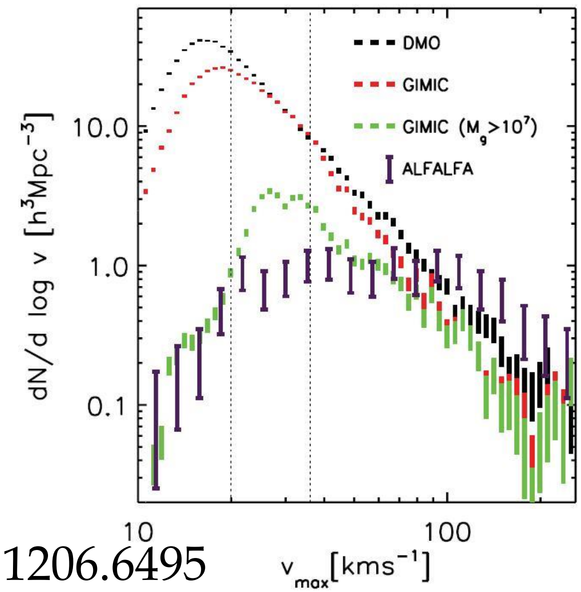
$$M_{\text{halo,measured}} \neq M_{\text{halo,DMonly}}$$

This is reasonable approximation at galaxy cluster mass scales, where haloes retain most of their baryons, but on the scales of dwarf galaxies feedback winds can expel most of the baryons.

$$M_{\text{halo,measured}} = \frac{\Omega_{\text{dm}}}{\Omega_{\text{dm}} + \Omega_{\text{b}}} M_{\text{halo,DM only}} ?$$

This difference would already effect comparisons but as the early loss of baryons effects the subsequent growth of halos the differences in the two masses can be even larger.

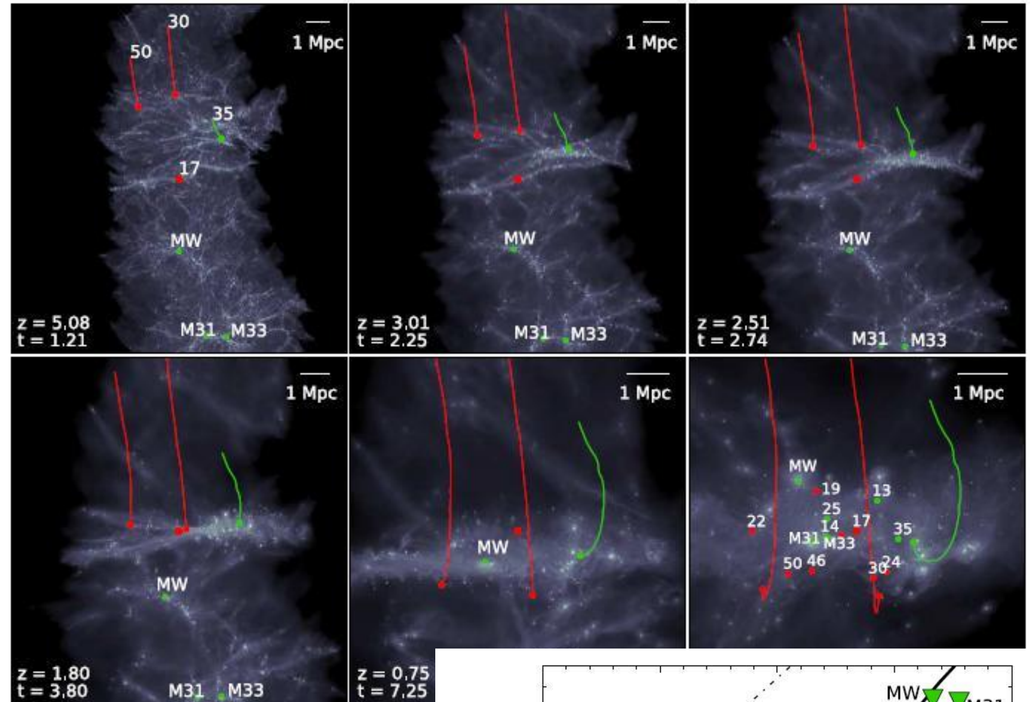




See Poster #15: Till Sawala and/or Sawala et al 2013 arXiv 1206.6495

Baryon Physics

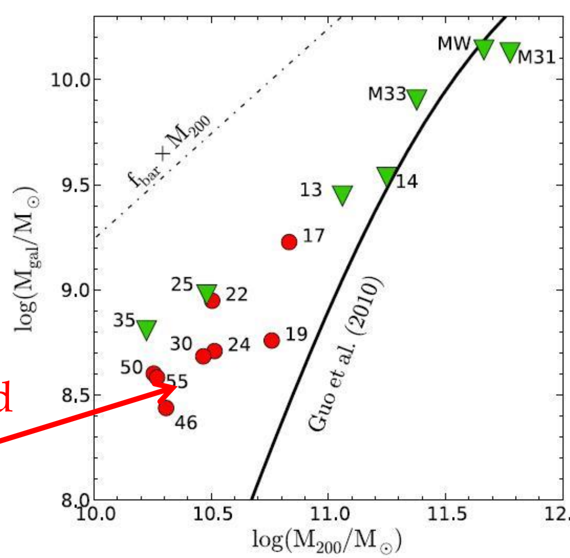
CLUES (Gottlober et al 2010) high resolution zoom simulations $\left[M_p = 3.5\times10^5 M_O\right]$ constrained to match the local group (MW,M31 and M33)



Satellite halos can be stripped by interactions with the cosmic web (passing through a pancake) during the formation of the main halo.

Benitez-Llambay et al 2013

~80% of baryons lost resuliting in masses much closer to the abundance matching prediction.



Dwarfs whose star formation was truncated after being stripped at z~2

Could effect just certain orbits and hence alter the alignment and rotation of the remaining (visible) satellites.

Summary

ΛCDM Challenges	ΛWDM	Baryon Physics
Satellite Abundance	✓	✓
Dwarf/LSB cores	✗	✓
dSph cores (?)	✗	✗ ?
TBTF	✓	✓ ?
Satellite Alignments	✗	?
Dwarf mass-abundance	✓	✓?

Cores versus Cusps

Sub haloes from the Aquarius simulations

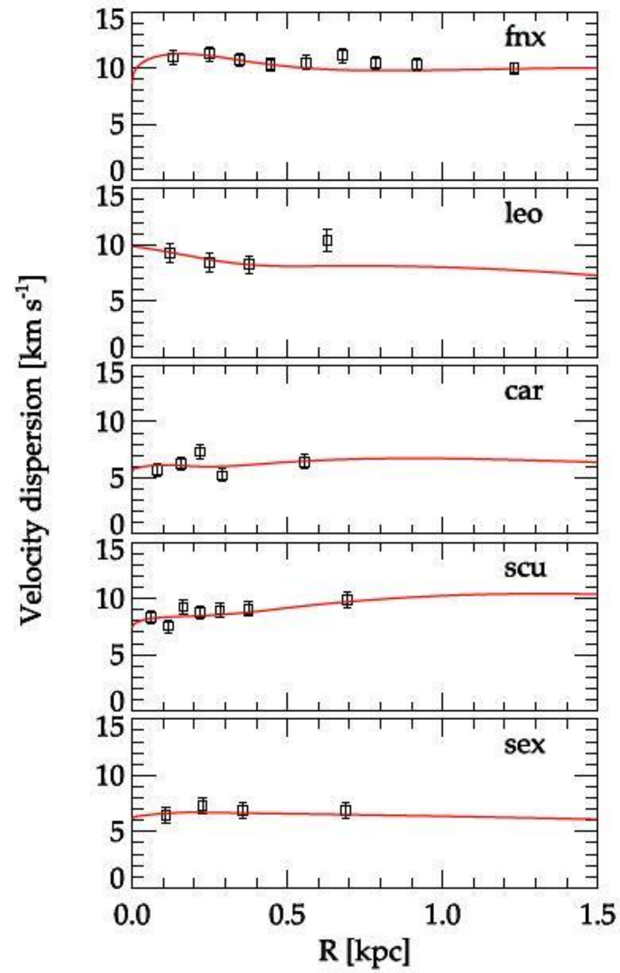
Fit projected surface density profiles

For each subhalo determine the velocity dispersion profile that is consistent with this profile (assuming isotropic velocity dispersion). Find which subhalo best reproduces the measured velocity dispersion profile.

4 out of 5 dSph fit very well

Also predict full velocity distribution and find the observed kurtosis is reproduced quite well.

Data not inconsistent with LCDM cusps!



Strigari et al 2010