Phys/Astro 689: Lecture 12

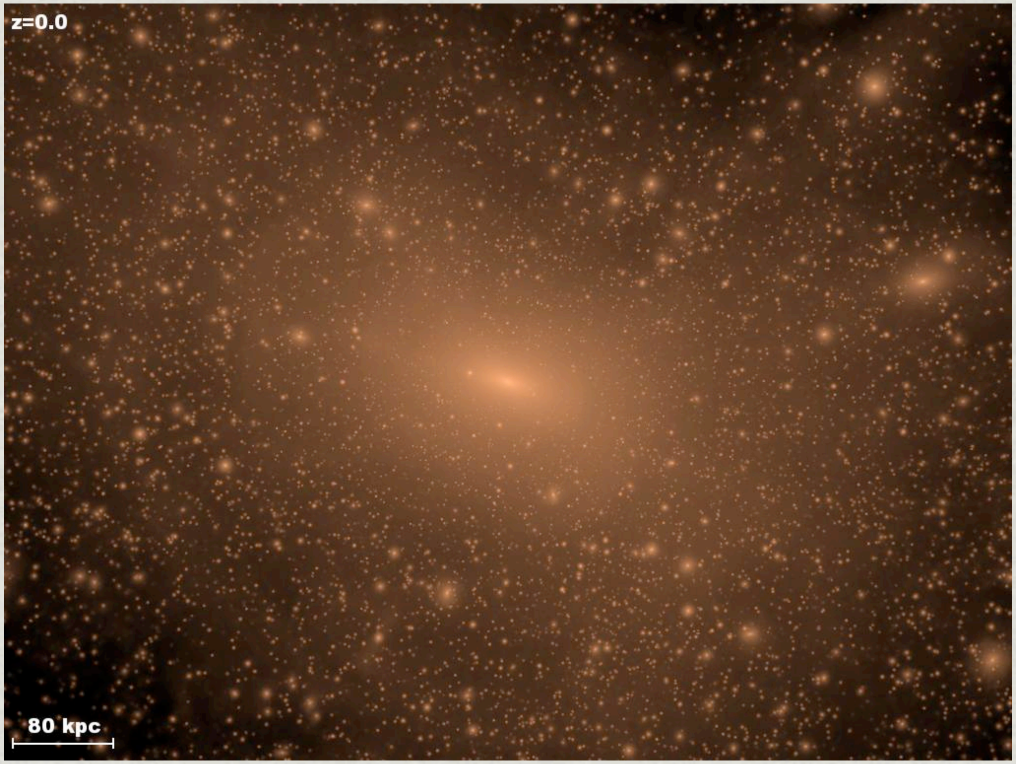
The Problems with Satellite Galaxies

The Problems with Satellites

- (1) The Missing Satellites Problem
- (2) The “Too Big to Fail” Problem
- We’ll examine potential solutions to each ***within CDM***

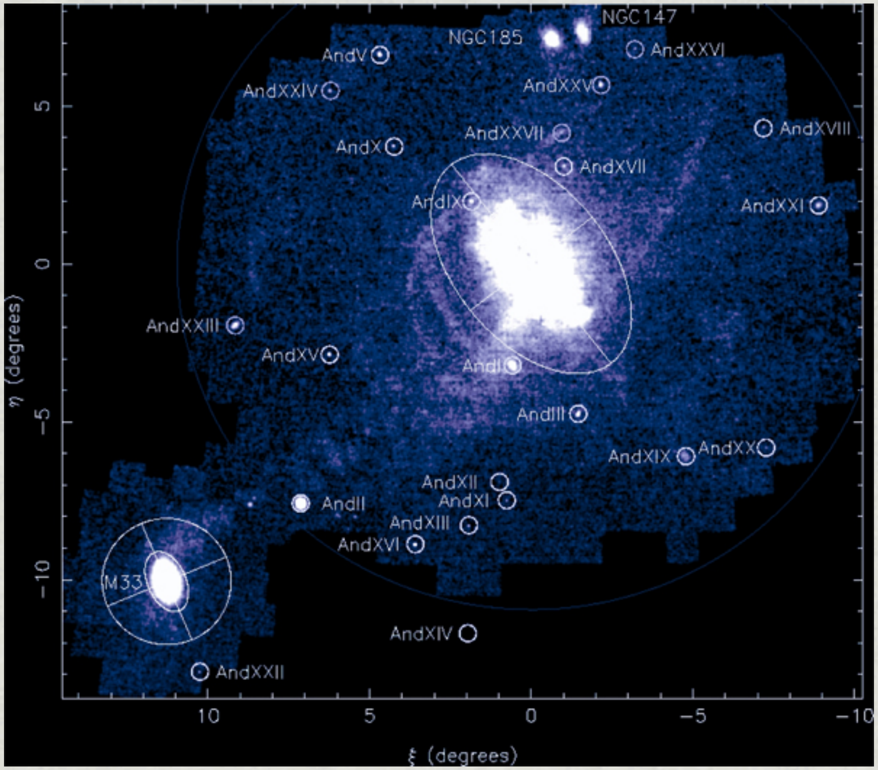
The "Missing Satellites" Problem

1000's of satellites predicted



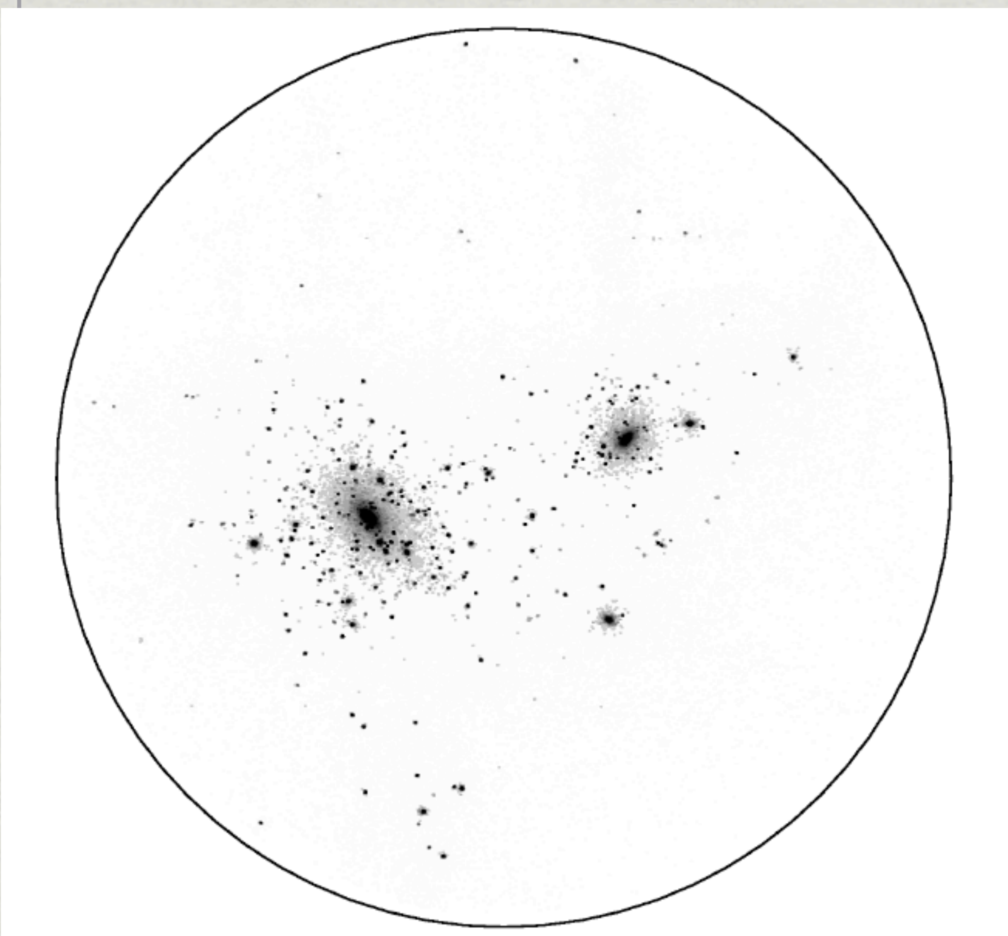
"Via Lactea" Simulation

dozens seen



Pan-ANDromeda Archeological Survey (PAndAS)

The “Missing Satellites” Problem

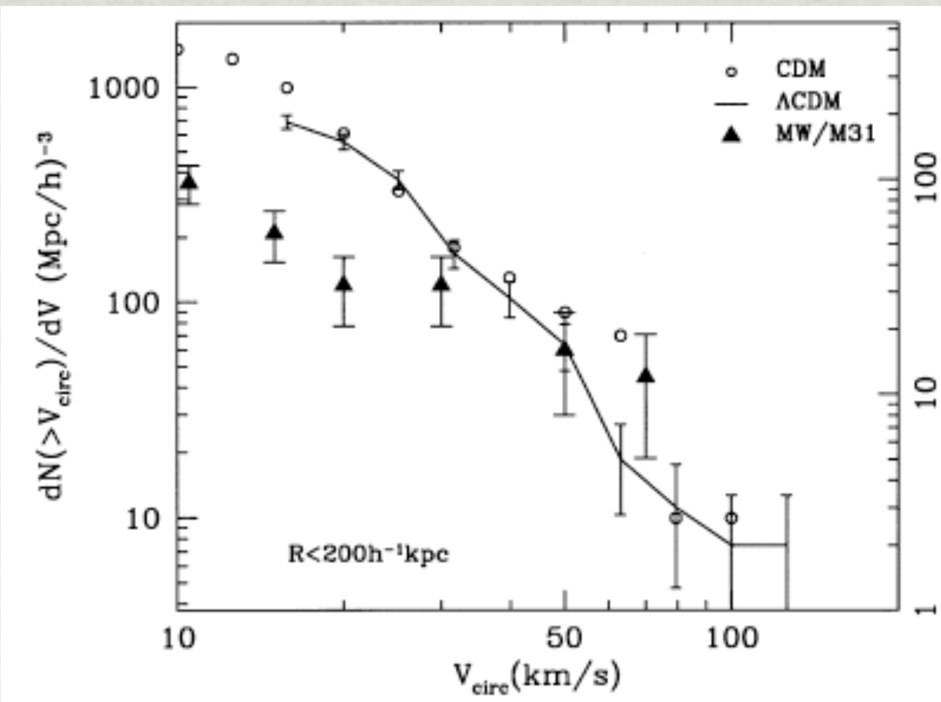


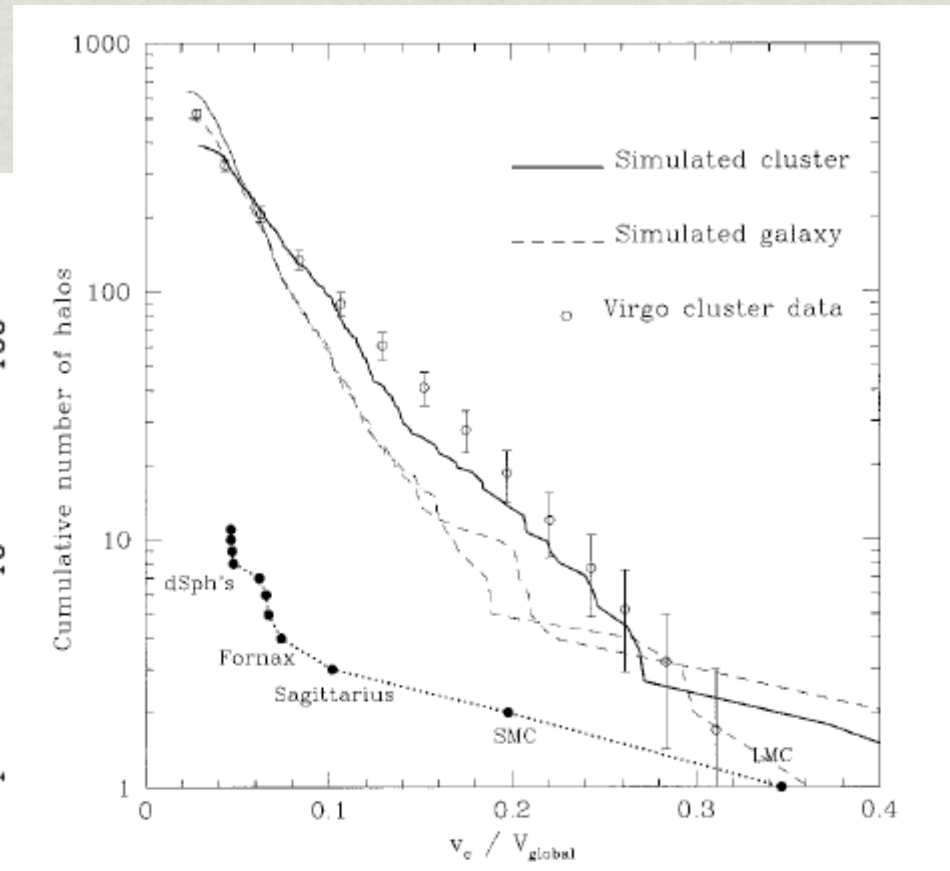
- Klypin et al. (1999)
- 281 halos with v_c > 10km/s

The “Missing Satellites” Problem

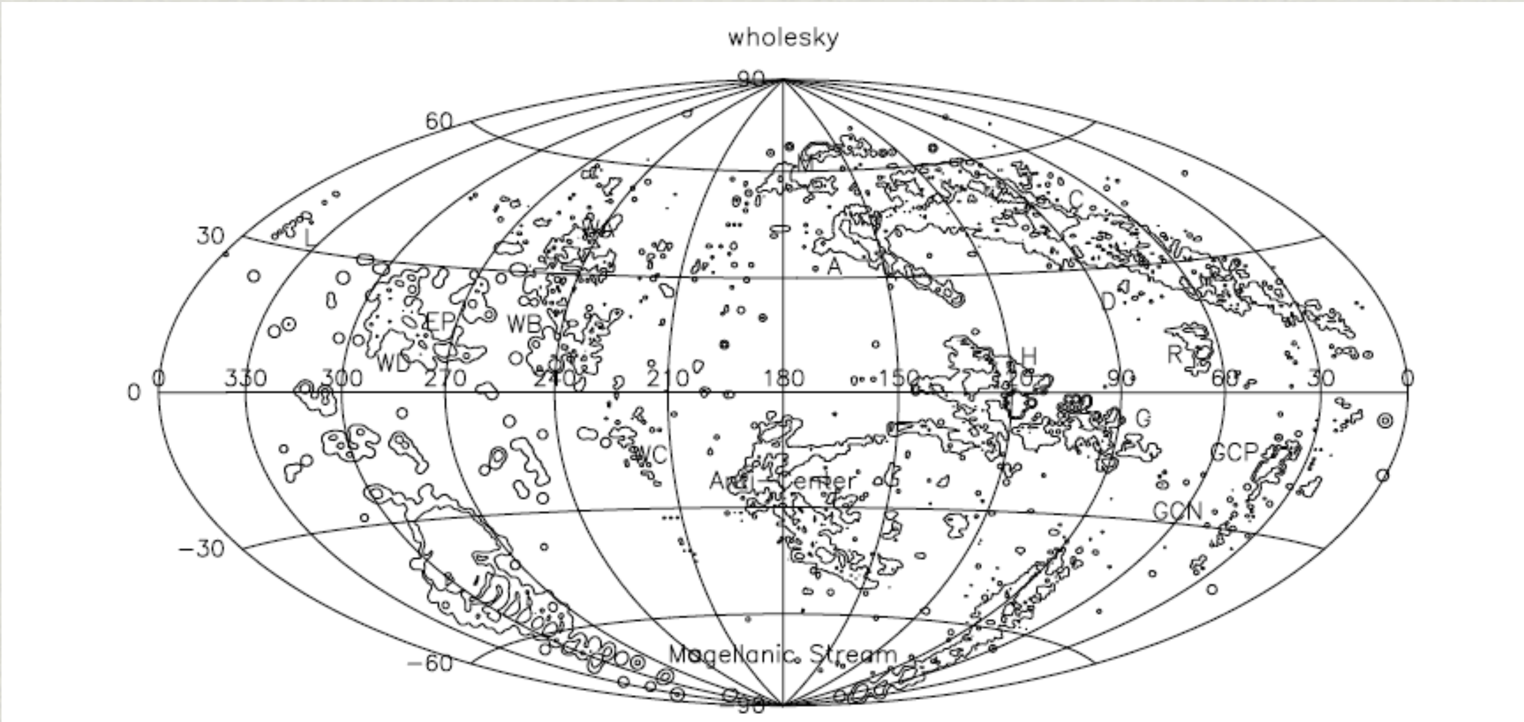
MOORE ET AL. 1999

KLYPIN ET AL. 1999





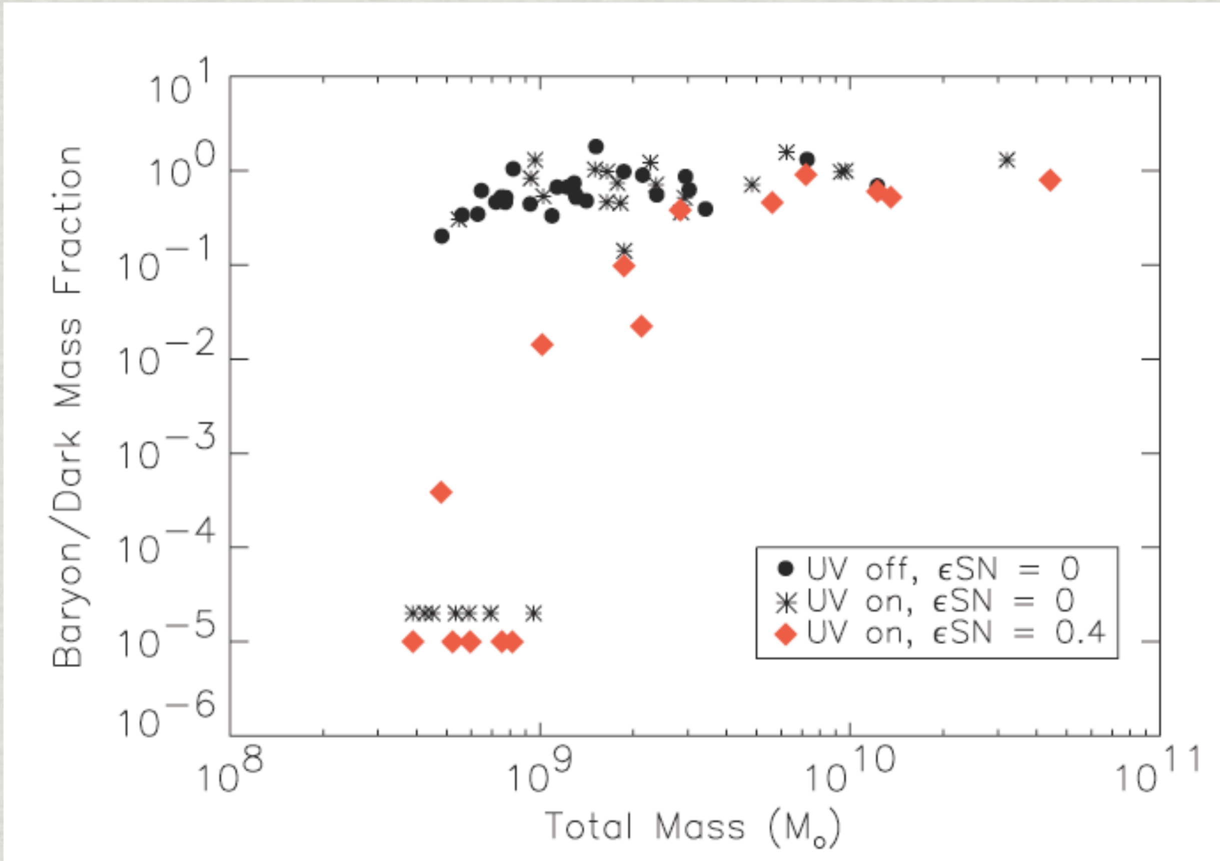
Potential Solutions: HVCs



BLITZ ET AL. 1999

- Blitz et al. 1999 simulate Local Group and suggest observed gas clouds are bound by DM
- Key: HI emission alone cannot provide a distance
- Later absorption line measurements put HVC nearby, and not massive enough to be the missing satellites.

Potential Solutions: Reionization

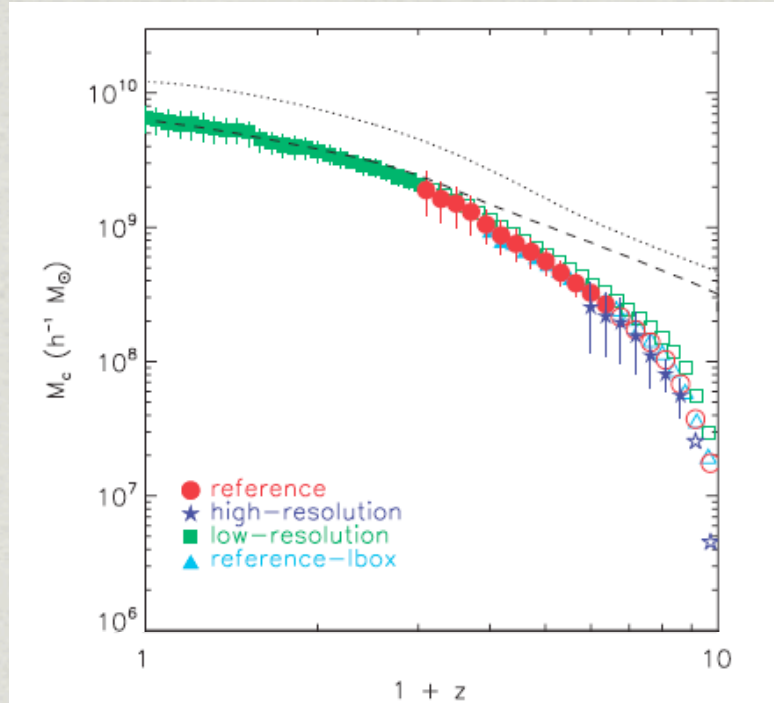


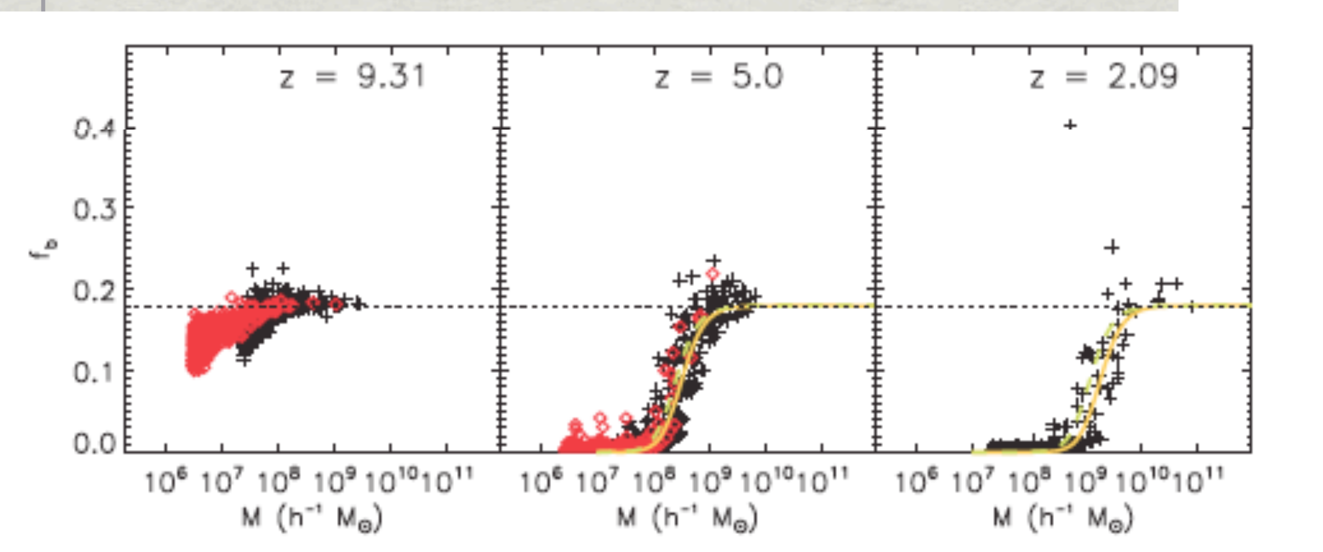
"Re-ionization" and supernovae can reproduce the number of observed satellite galaxies

Governato et al. (2007)

Potential Solutions: Reionization

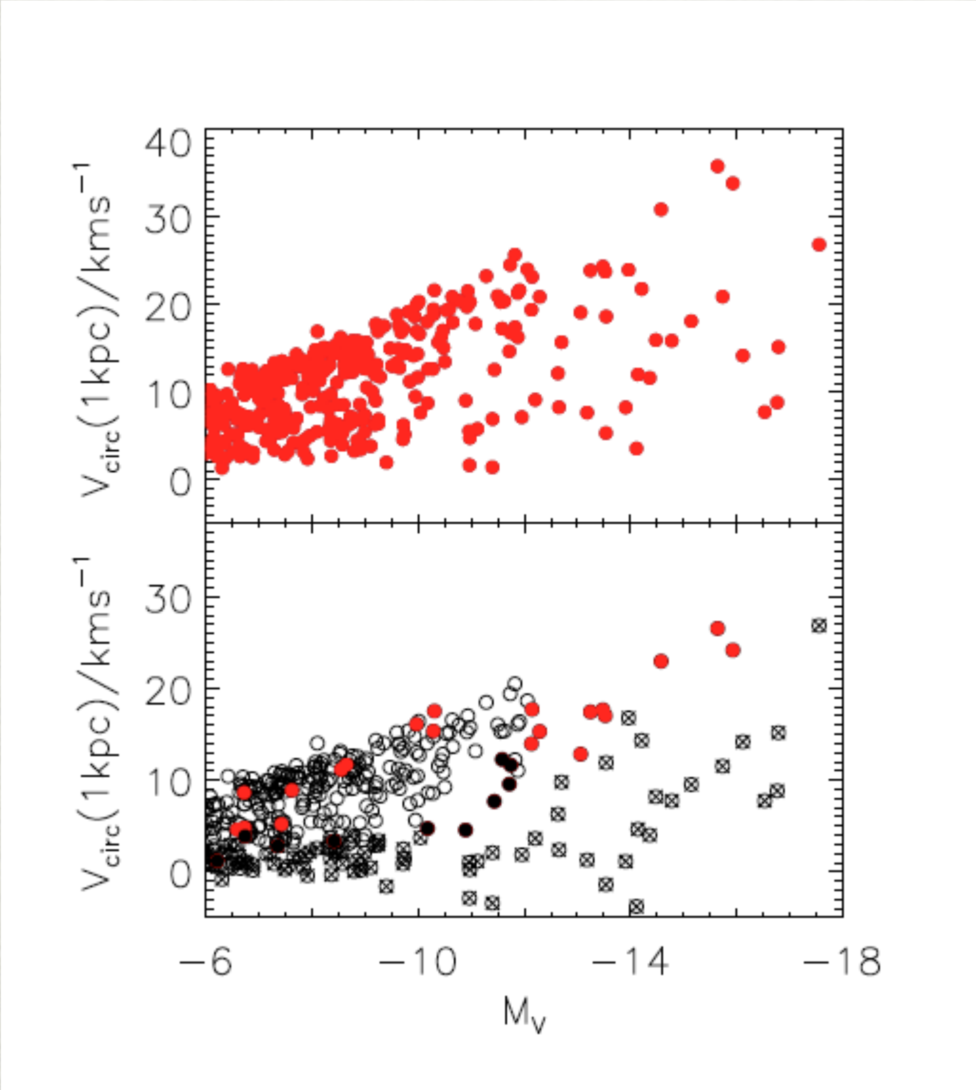
- Okamoto et al. (2008): the characteristic mass (where halos can retain 50% of their baryons) as a function of z.





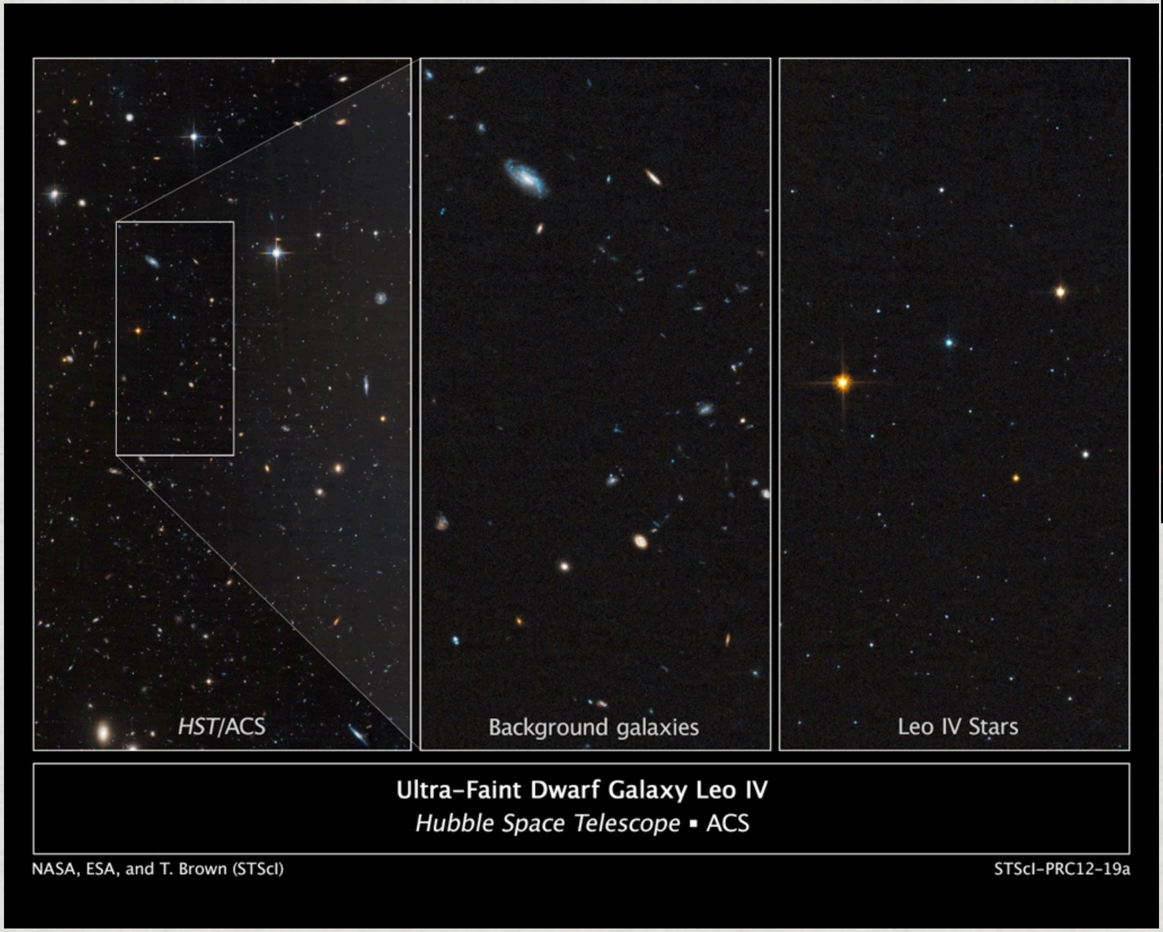
Potential Solutions: Reionization

- Results from VL2
- empty circles: not massive enough to form stars after reionization



BROOKS ET AL. 2013

Potential Solutions: Faint Galaxies



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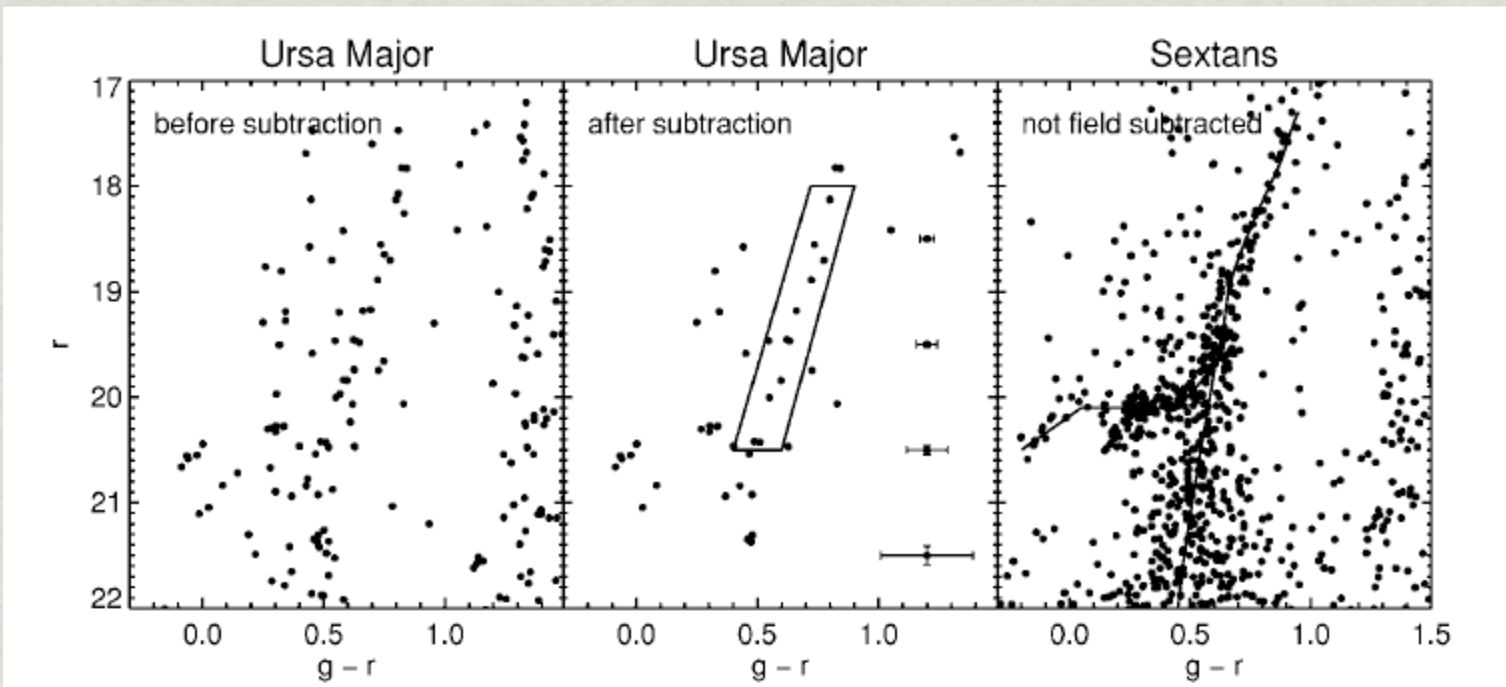
Potential Solutions: Faint Galaxies

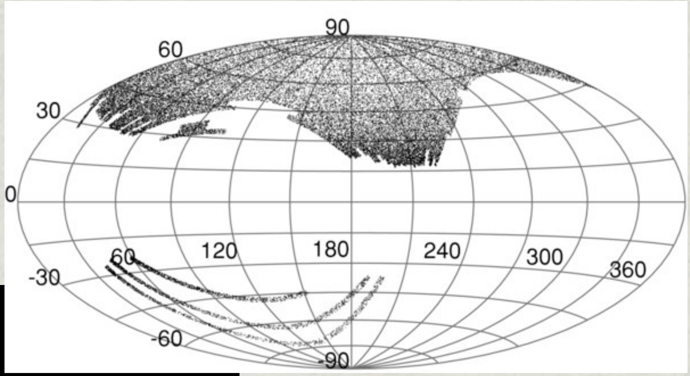
- All of the known ultra-faint dwarfs have been found by searching for overdensities in color-magnitude space

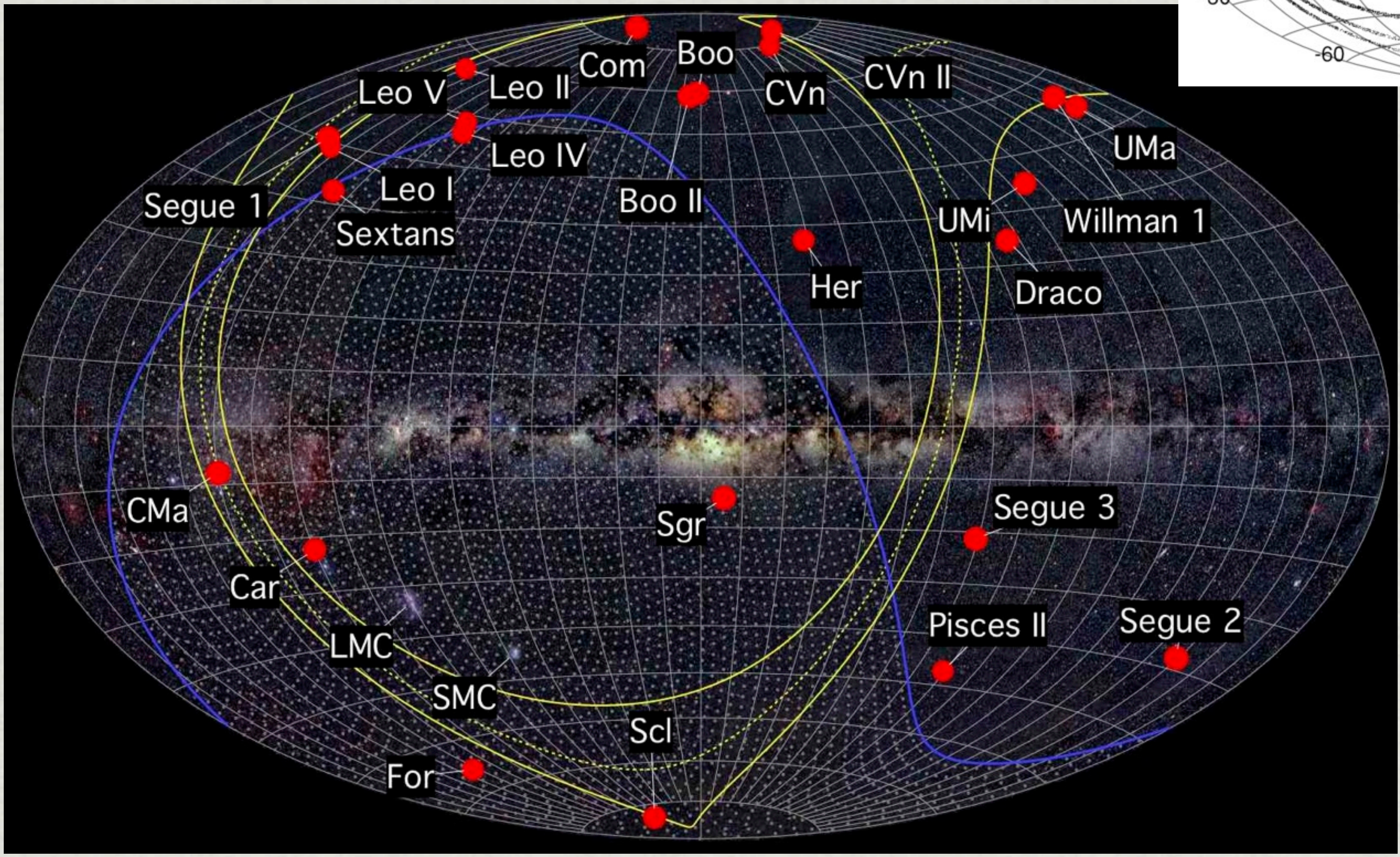


WILLMAN ET AL 2005

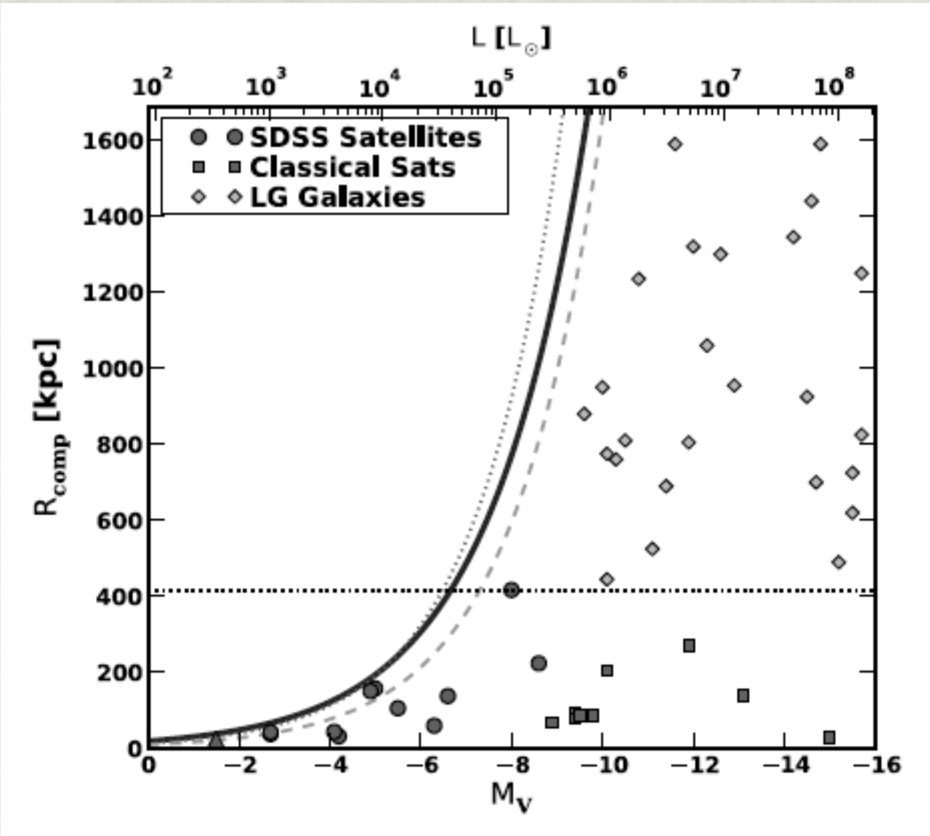
Potential Solutions: Faint Galaxies

- All of the known ultra-faint dwarfs were found in SDSS

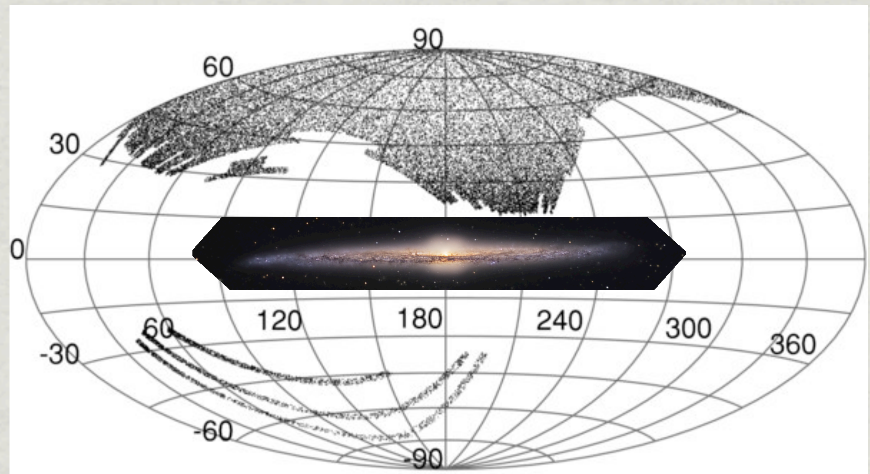




WE PROBABLY CAN'T SEE A LOT OF SATELLITES



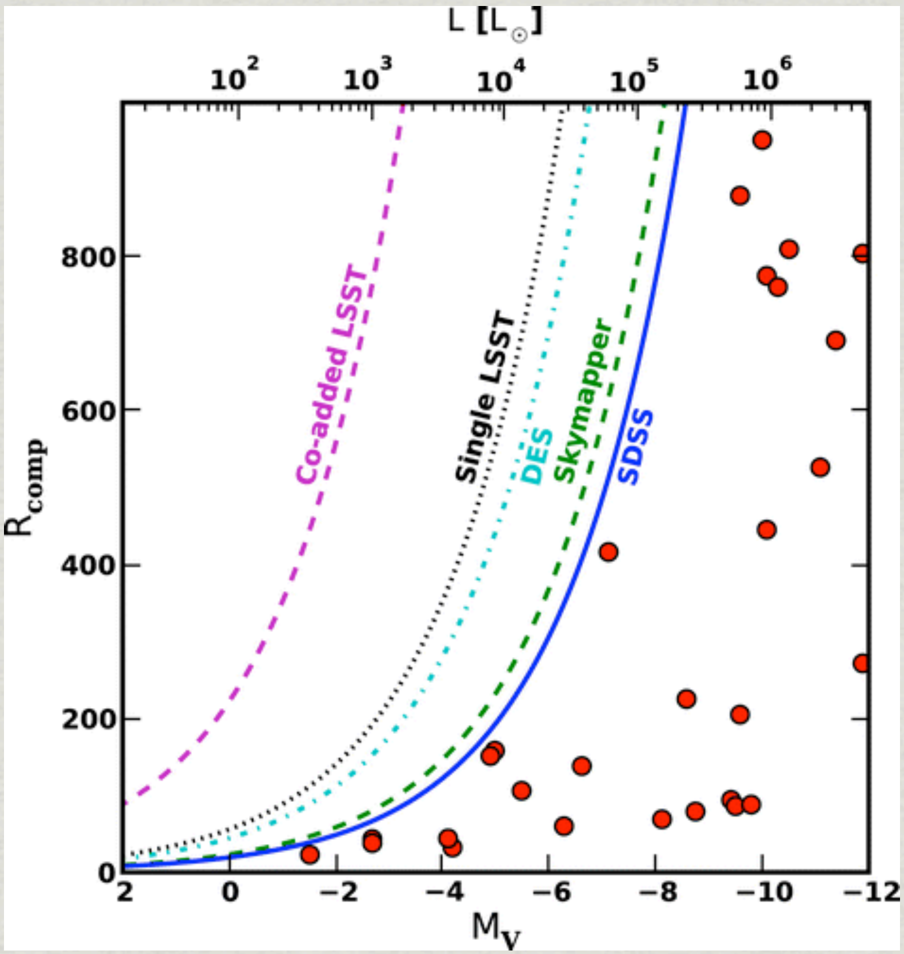
The SDSS "footprint"

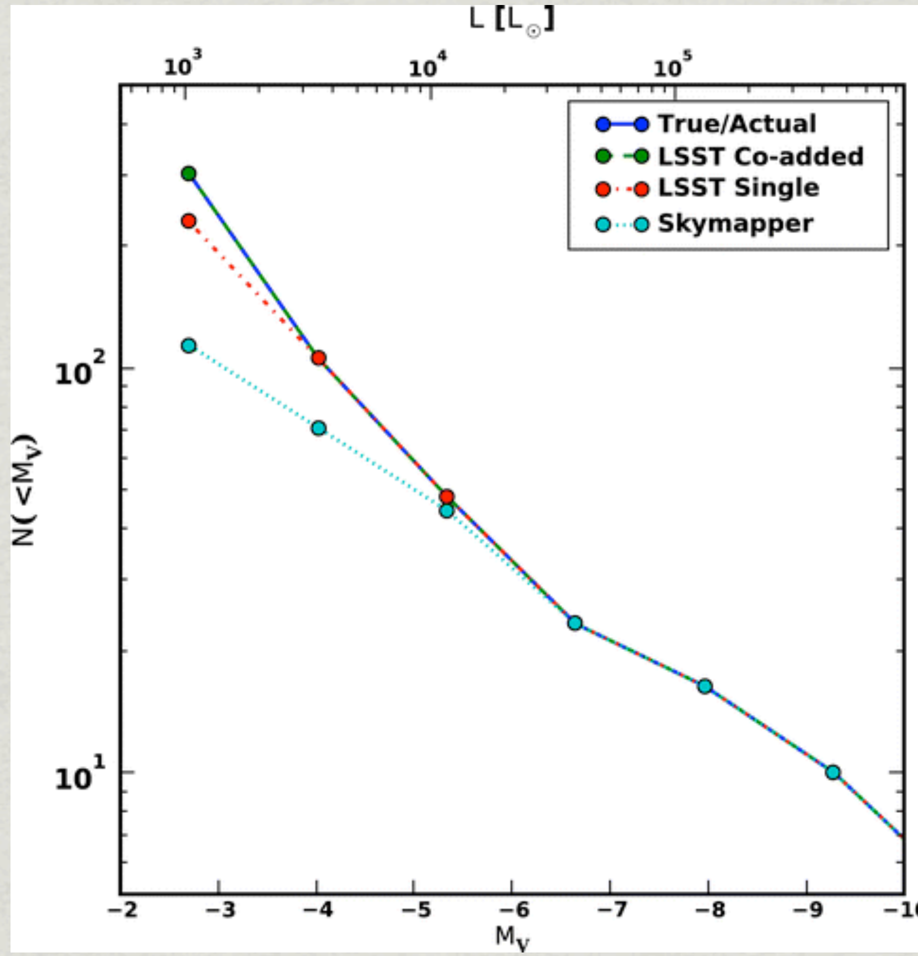


But that doesn't mean they aren't there

Tollerud et al. (2008)

Potential Solutions: Faint Galaxies



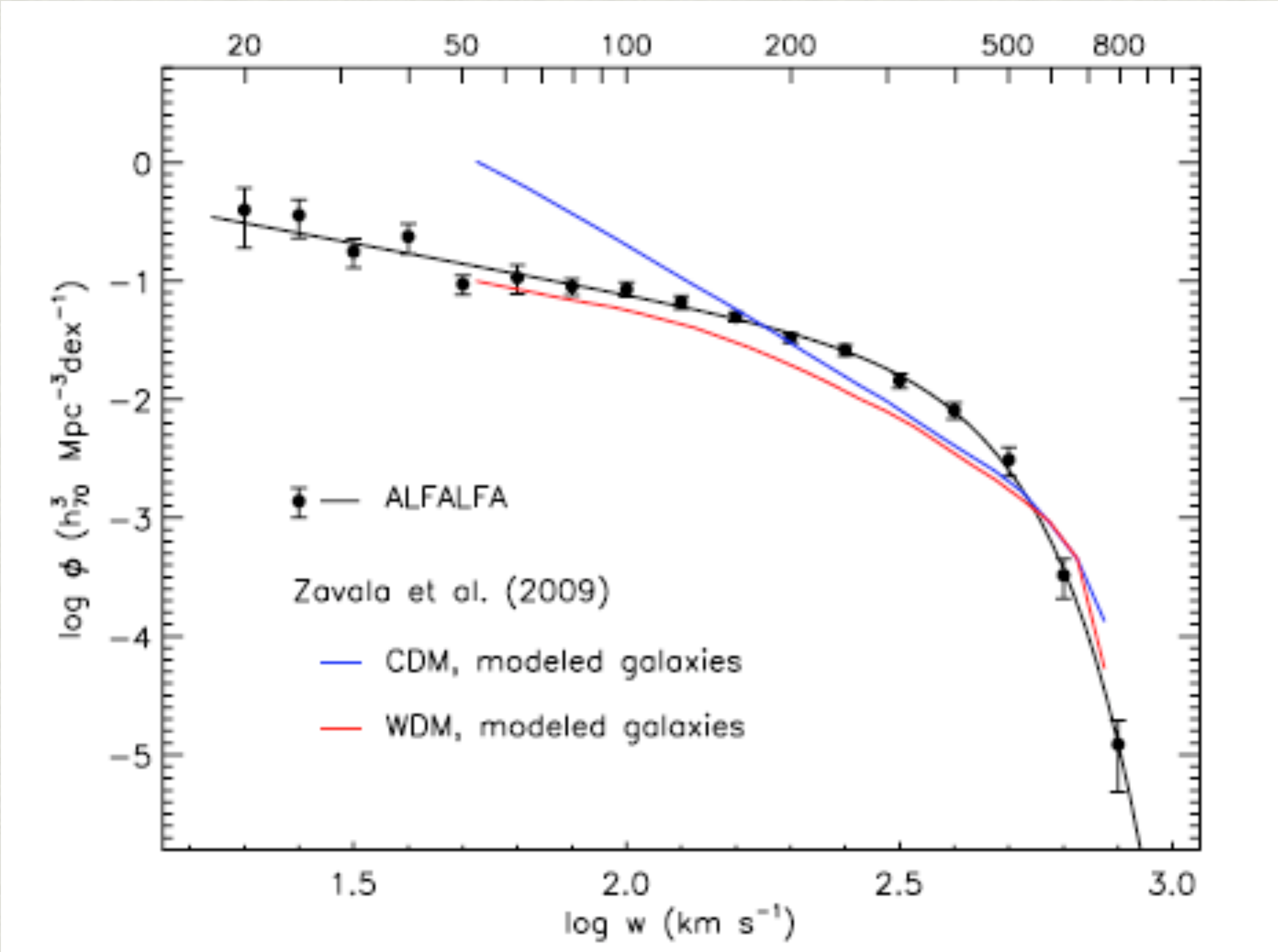


Tollerud et al. (2008)

Summary: MSP

- Between faint galaxies and reionization, we have solved the Missing Satellites Problem, yes?
- Not so fast: missing field dwarfs?
- Not so fast: Too Big to Fail

The Missing Dwarfs Problem

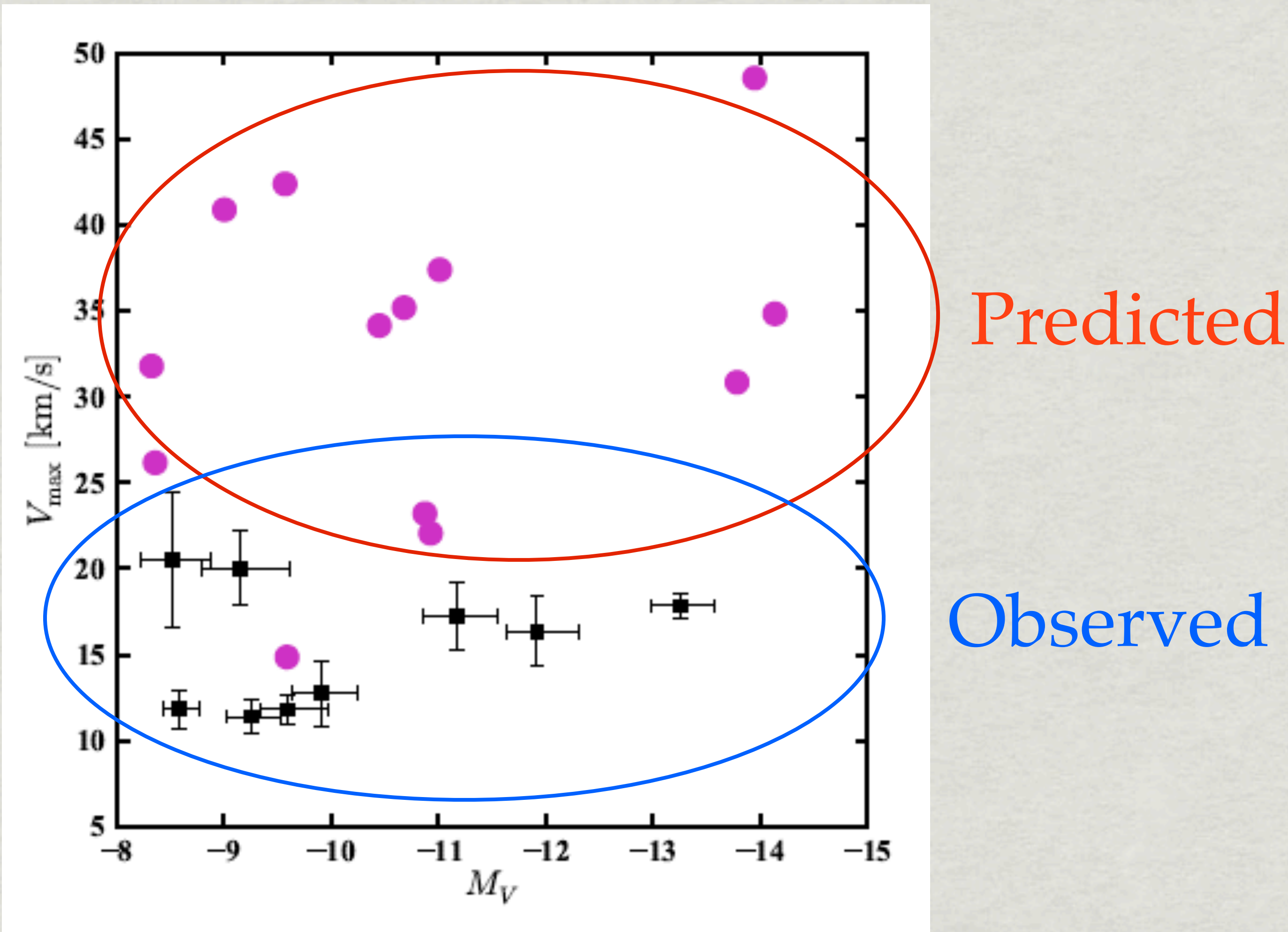


PAPASTERGIS ET AL. 2011

Summary: MSP

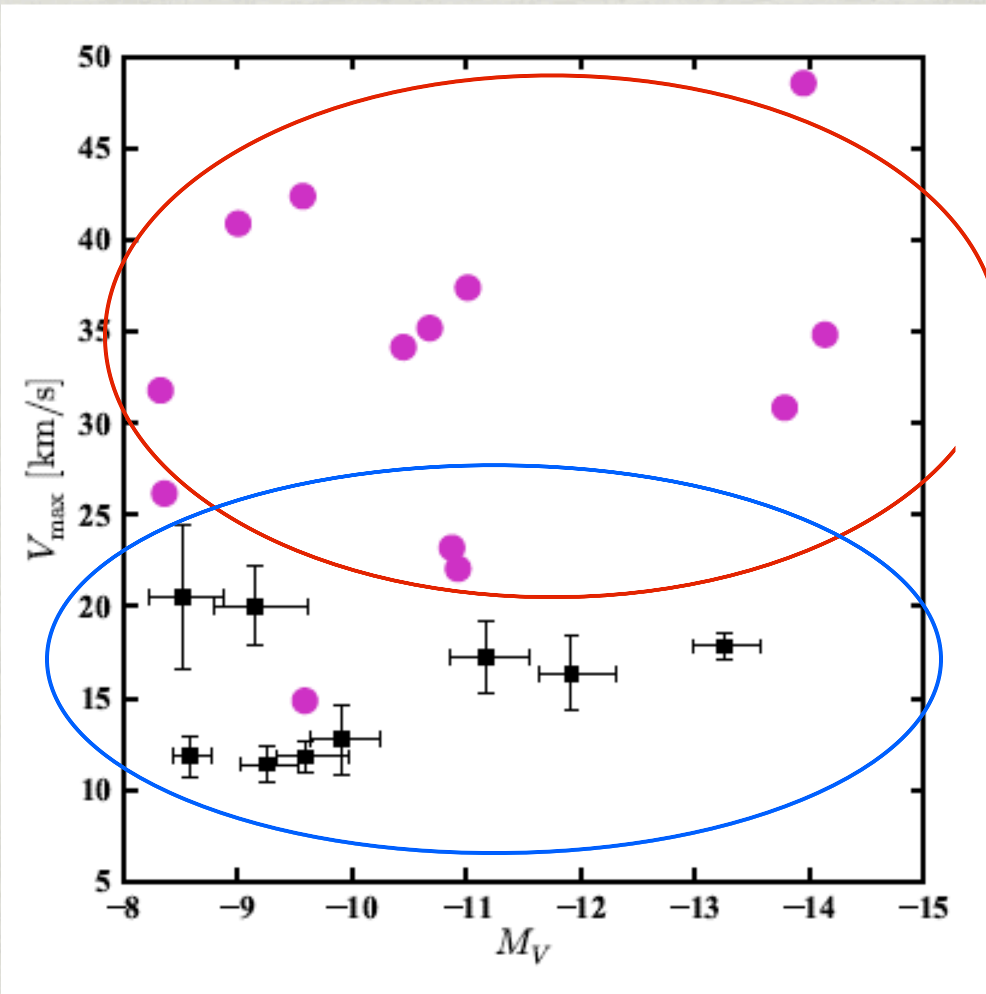
* Between faint galaxies and reionization, we have solved the Missing Satellites Problem, yes?
* Not so fast: missing field dwarfs?
* Not so fast: Too Big to Fail

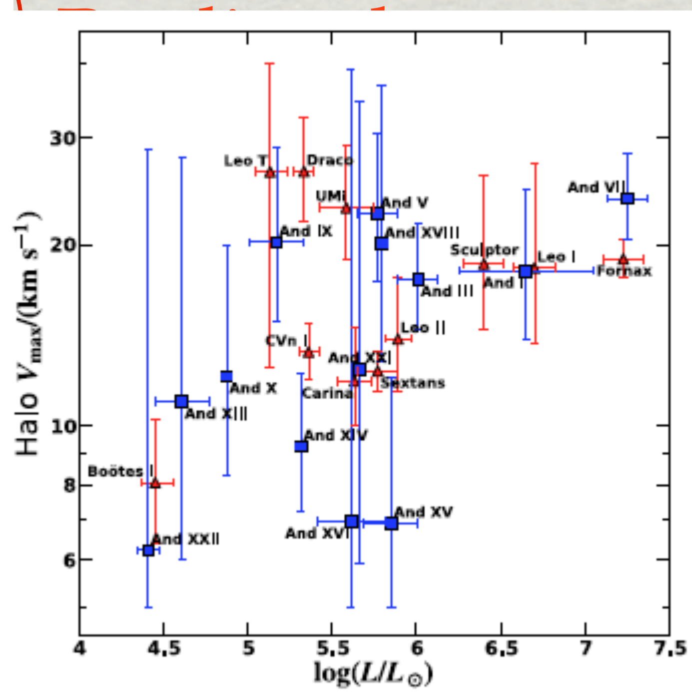
Too Big to Fail: Predicted Satellites are too massive



Boylan-Kolchin et al. (2012)

Too Big to Fail: Predicted Satellites are too massive

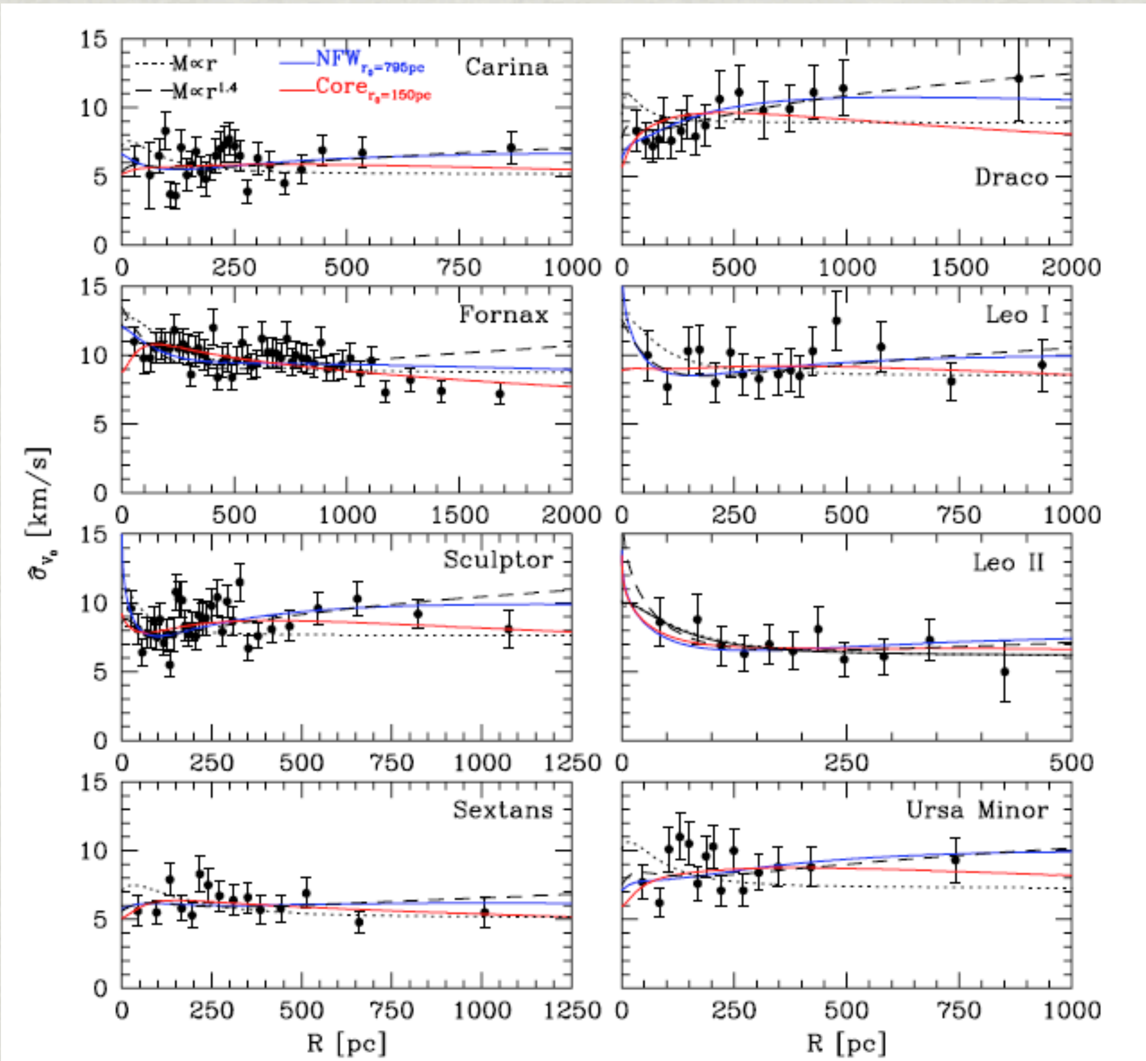




TOLLERUD ET AL. 2012

Boylan-Kolchin et al. (2012)

Dwarf Spheroidal Kinematics



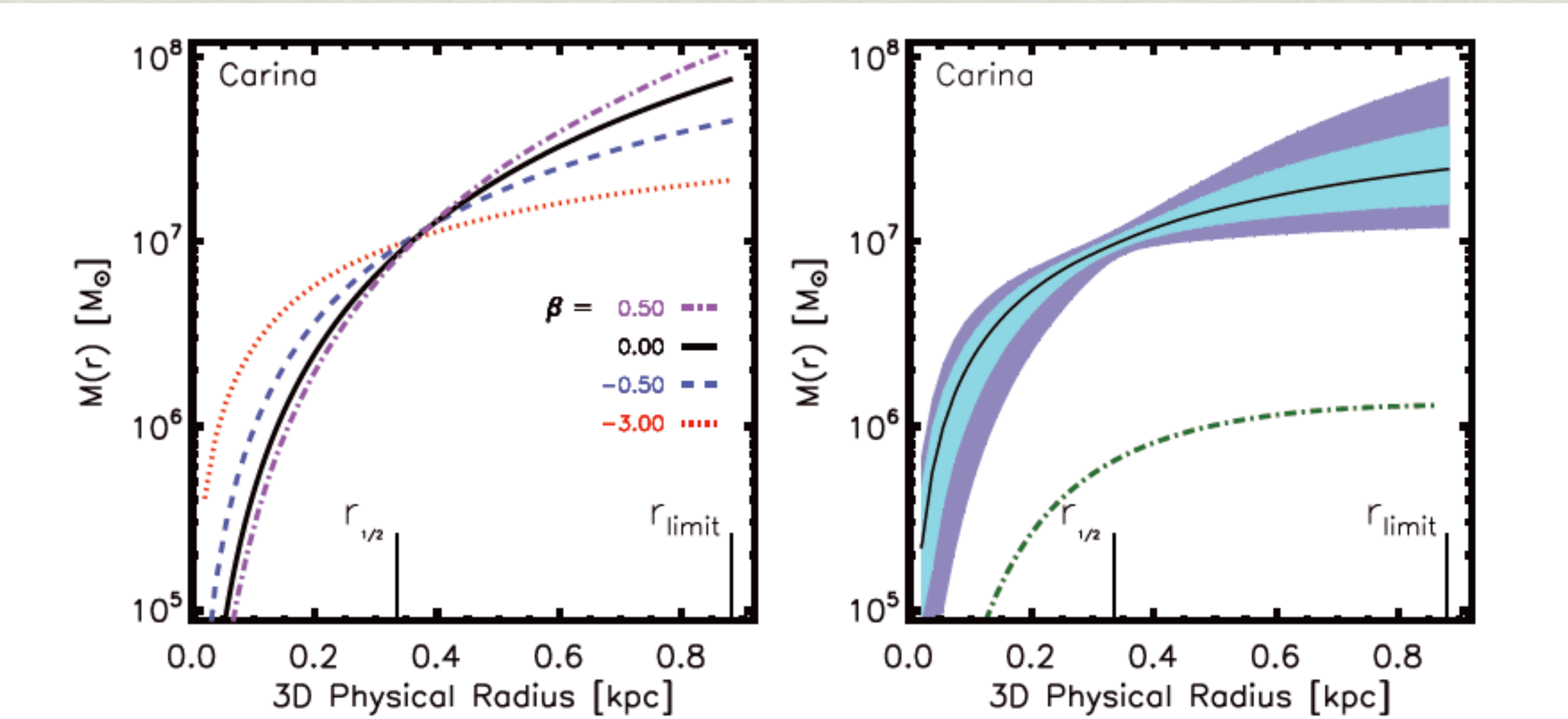
- Actually, we measure velocity dispersions
- $v_c = \sqrt{3\sigma 2}$
- Profiles are generally flat

WALKER ET AL. 2009

Mass Modeling of a Dwarf Spheroidal

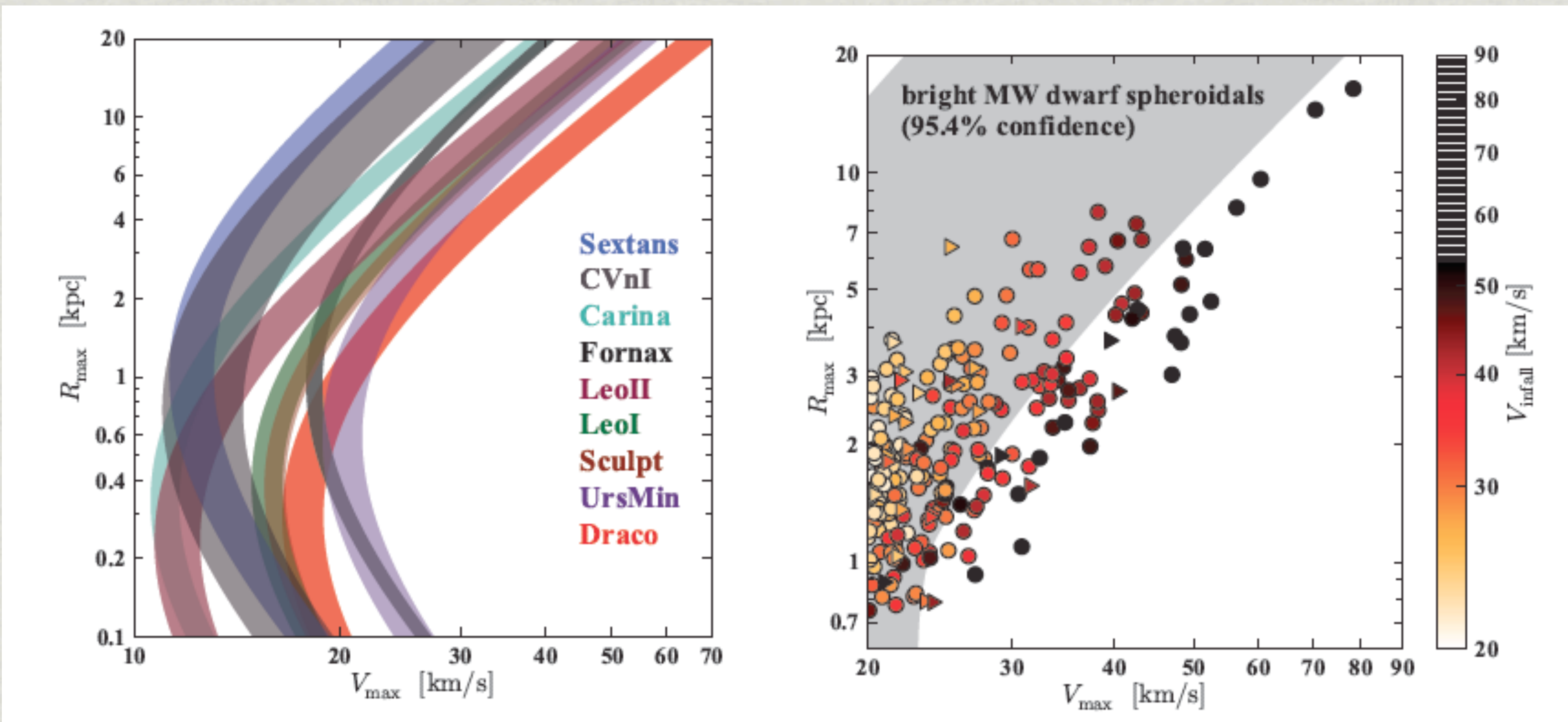
- Note: these are gas-free galaxies that are velocity dispersion supported
- Jeans modeling of the mass profile; the spherical Jean equation (assumes spherically symmetric system) is: $-n_\star \frac{\mathrm{d}\Phi}{\mathrm{d}r} = \frac{\mathrm{d}(n_\star \sigma_r^2)}{\mathrm{d}r} + 2\frac{\beta\, n_\star \sigma_r^2}{r}$
- Or, in terms of mass profile: $M(r) = \frac{r\sigma_r^2}{G}(\gamma_\star + \gamma_\sigma - 2\beta)$
- Only $\gamma_{☆}$ is known from observations

Mass Modeling of a Dwarf Spheroidal



* Assumptions about (unknown) anisotropy are minimized at the half light radius (see also Walker et al 2009)

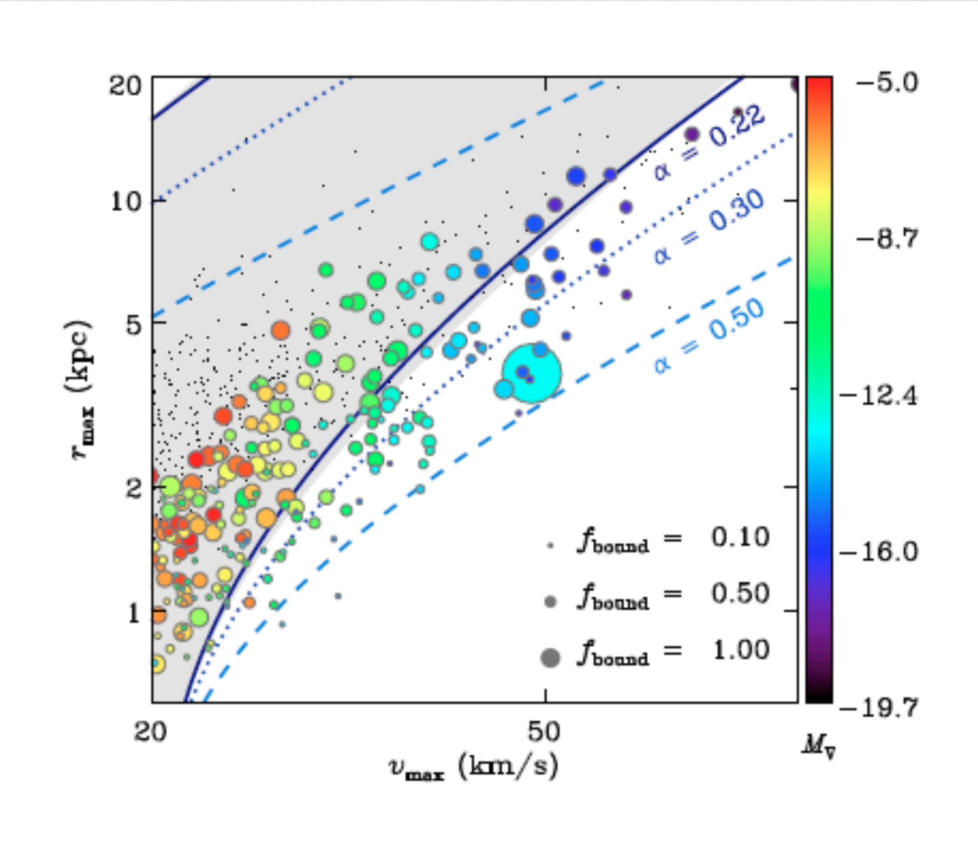
Mass Modeling of a Dwarf Spheroidal



BOYLAN-KOLCHIN ET AL. 2011

- Simulations have Rmax too small compared to observed dwarfs: simulated satellites are too dense

Possible Solutions: Einasto DM profile



VERA-CIRO ET AL. 2013

$$m(r) = 4\pi r_{-2}^3 \rho_{-2} g(r/r_{-2}),$$

$$g_{\rm NFW}(x) = 4\ln(1+x) - \frac{4x}{1+x},$$

$$g_{\rm Einasto}(x) = \frac{1}{\alpha}\exp\left(\frac{3\ln\alpha + 2 - \ln 8}{\alpha}\right)\gamma\left(\frac{3}{\alpha}, \frac{2x^\alpha}{\alpha}\right),$$

Possible Solutions: The Mass of the Milky Way

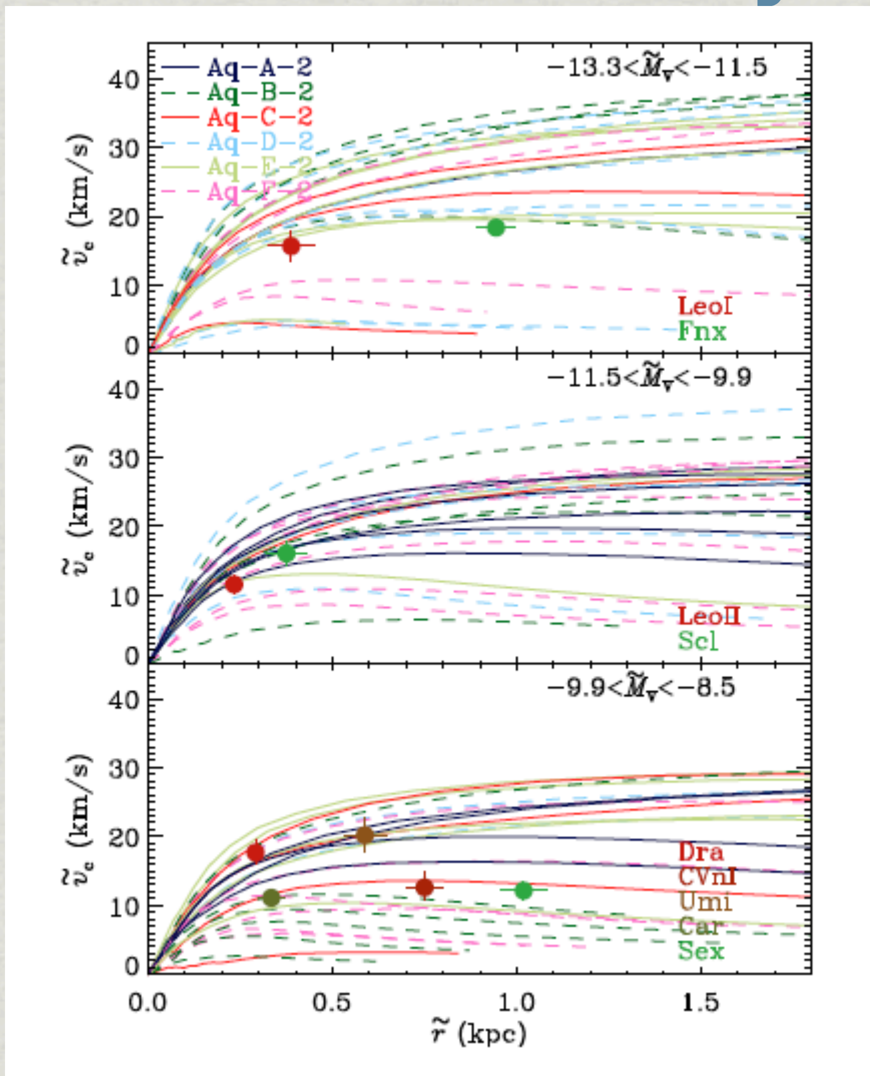
- Merger-trees are self-similar with mass
- Hence, if you reduce the mass of the parent halo, the mass of the most massive satellite reduces by a similar factor

$$\tilde{m} = m\frac{M_{\rm MW}}{M_{\rm Aq}} \equiv \mu m.$$

$$\tilde{r} = \mu^{1/3} r,$$

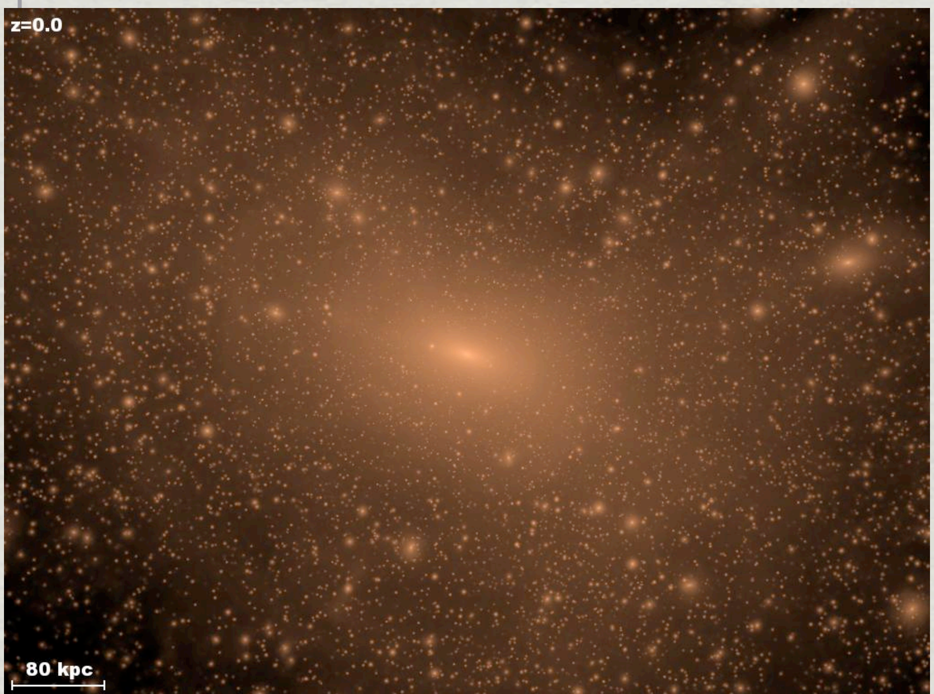
$$\tilde{v_c} = \left(\frac{G\tilde{m}}{\tilde{r}}\right)^{1/2} = \mu^{1/3} v_c.$$

Possible Solutions: The Mass of the Milky Way



VERA-CIRO ET AL. 2013

Possible Solutions: Tidal Stripping (with a disk)

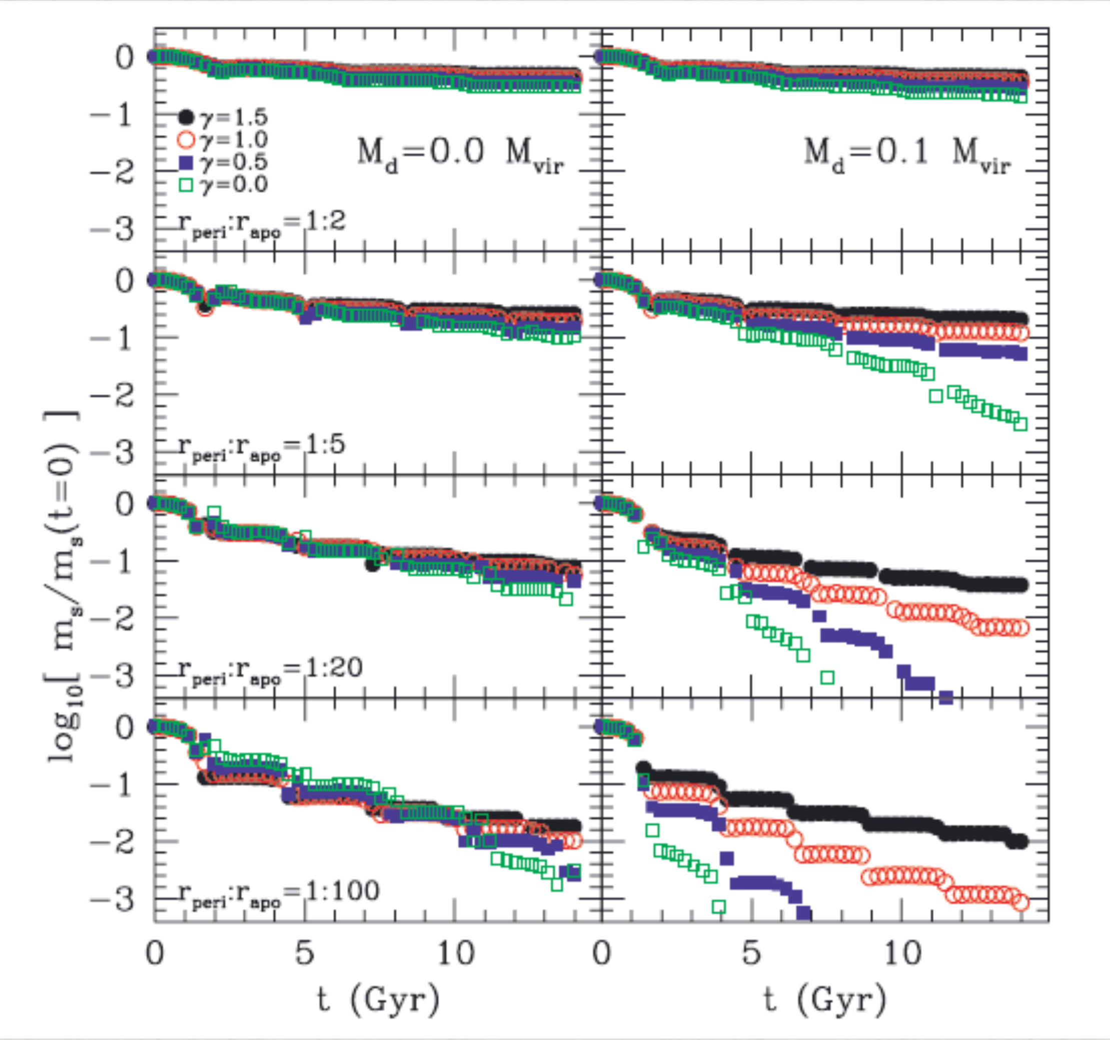


Dark Matter

Baryons
(or any central baryonic concentration)
Chang et al. (2012)

Baryons Make a Disk (Dark Matter Doesn't)

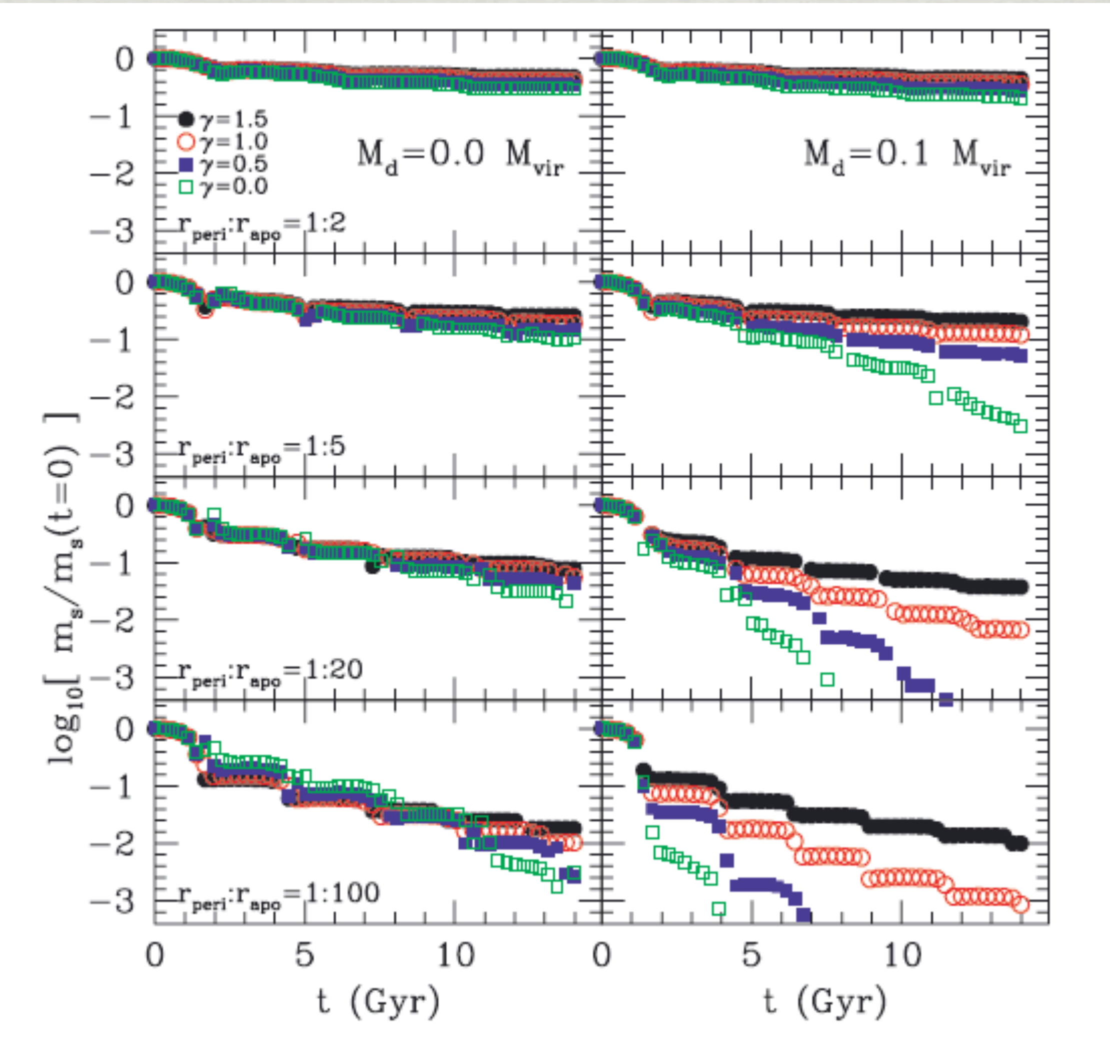
Possible Solutions: Tidal Stripping (with a disk)



- All satellites lose mass in tidal stripping
- Satellites with closer r_{peri} lose more mass
- Satellites that have been orbiting longer lose more mass

Penarrubia et al. (2010), see also Arraki et al. (2012)

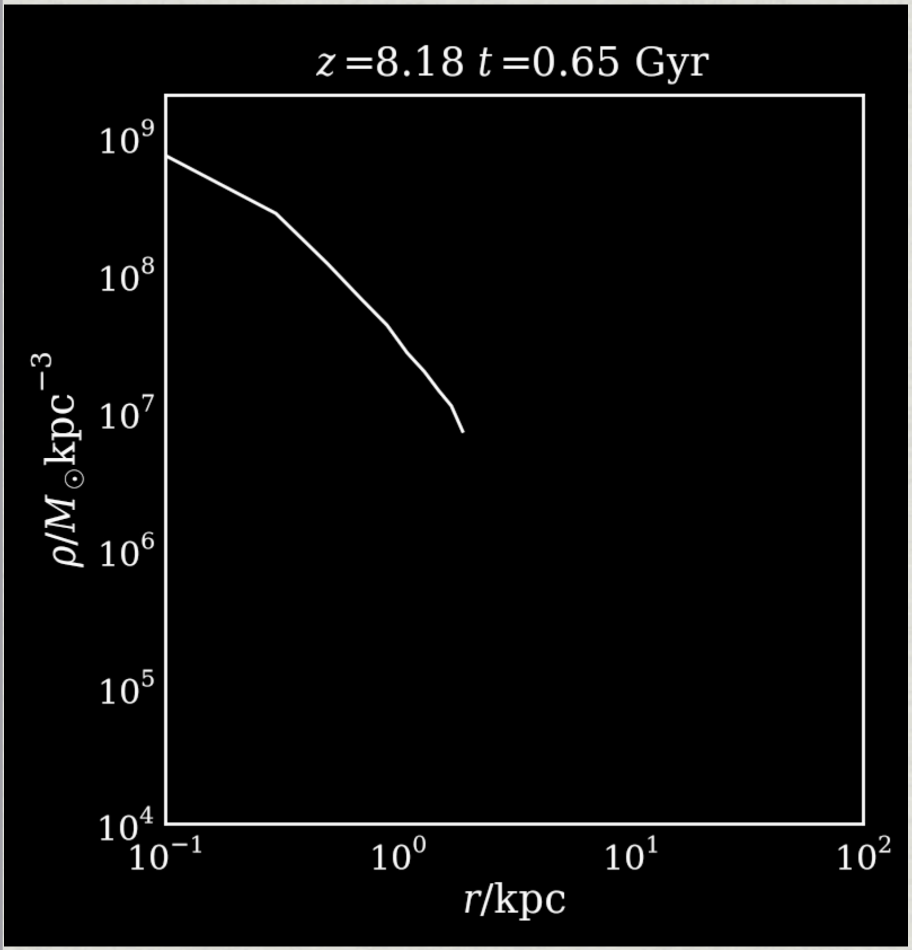
Possible Solutions: Tidal Stripping (with a disk)

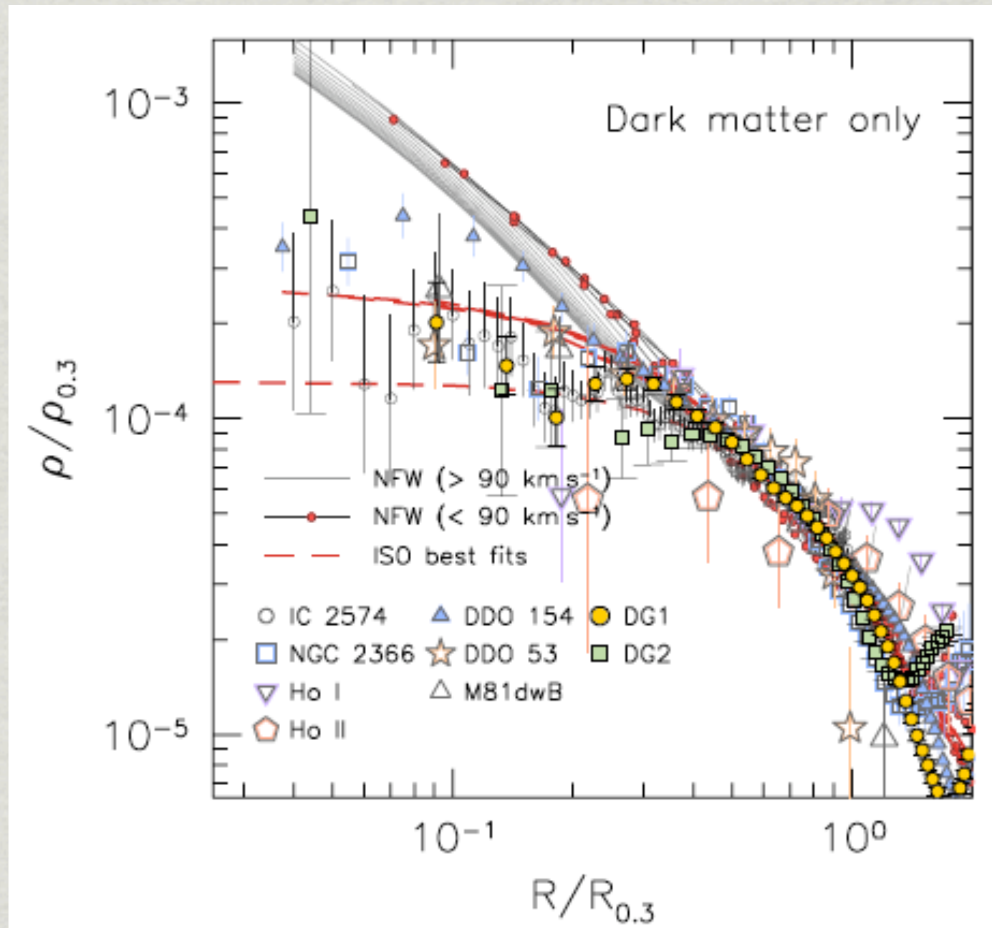


- All satellites lose MORE mass when a disk potential is included
- Bonus: "cored" satellites lose a LOT more mass

Penarrubia et al. (2010),
see also Arraki et al. (2012)

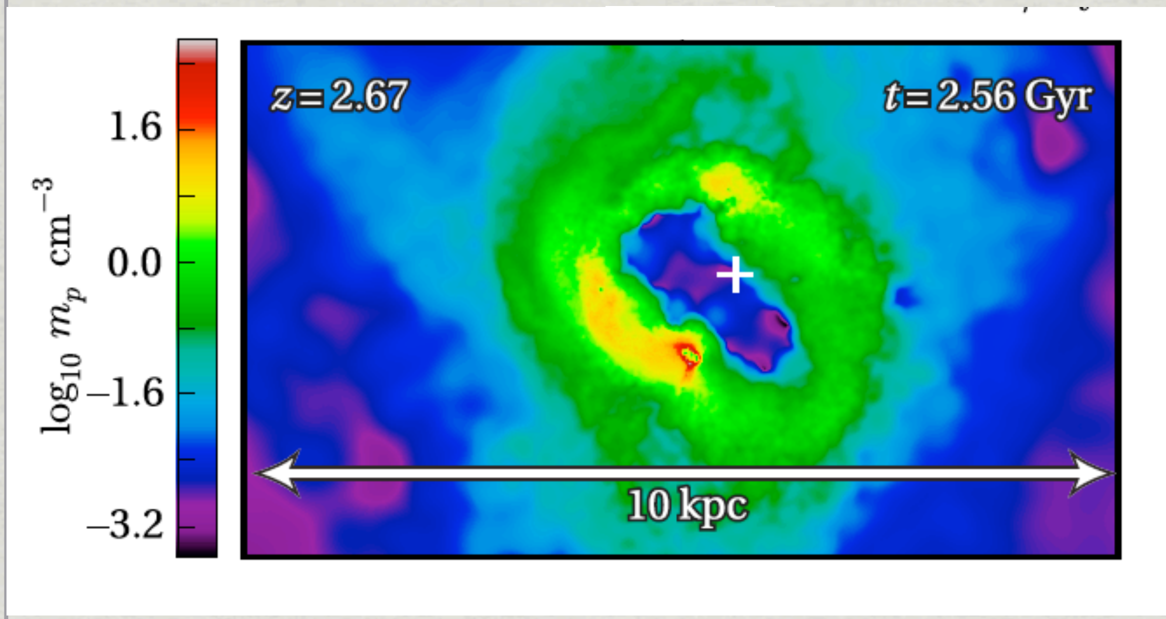
Recall that baryons can create DM cores

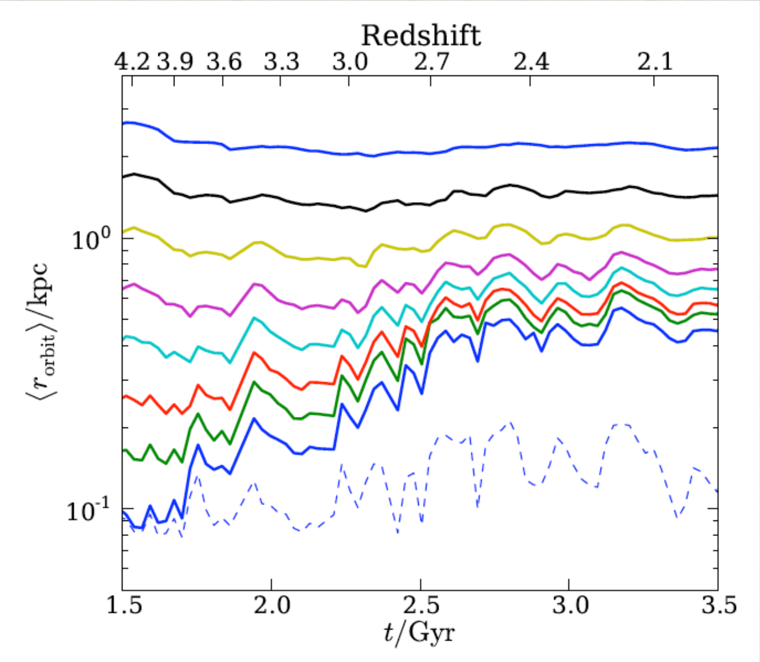




Oh et al., 2011, AJ, 142, 24

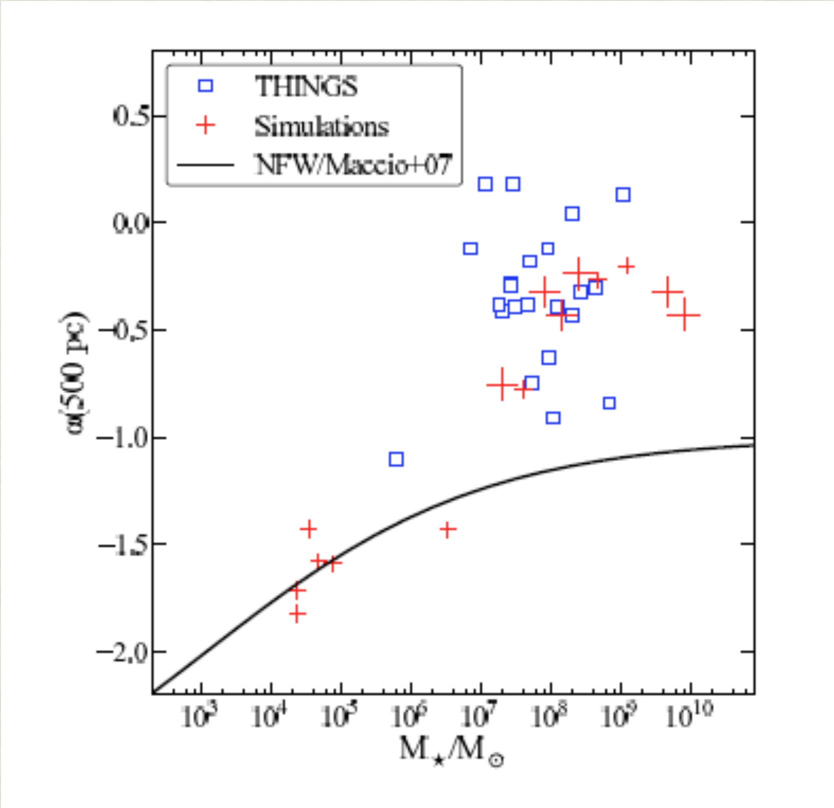
Recall that baryons can create DM cores

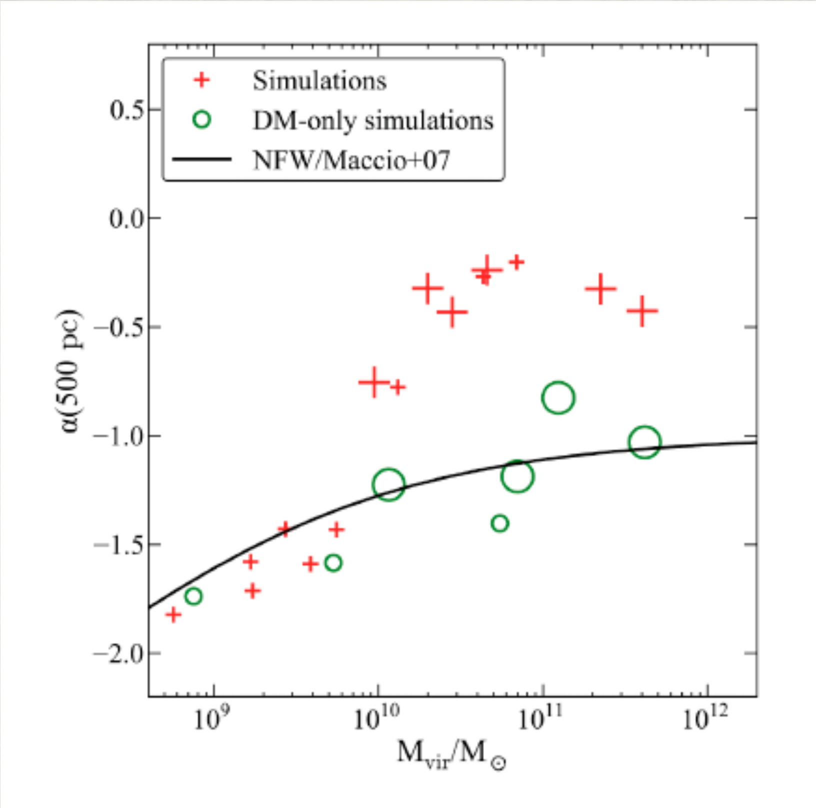




Pontzen & Governato (2012), MNRAS, 421, 3464, arXiv:1106.0499

Core Creation varies with Mass!



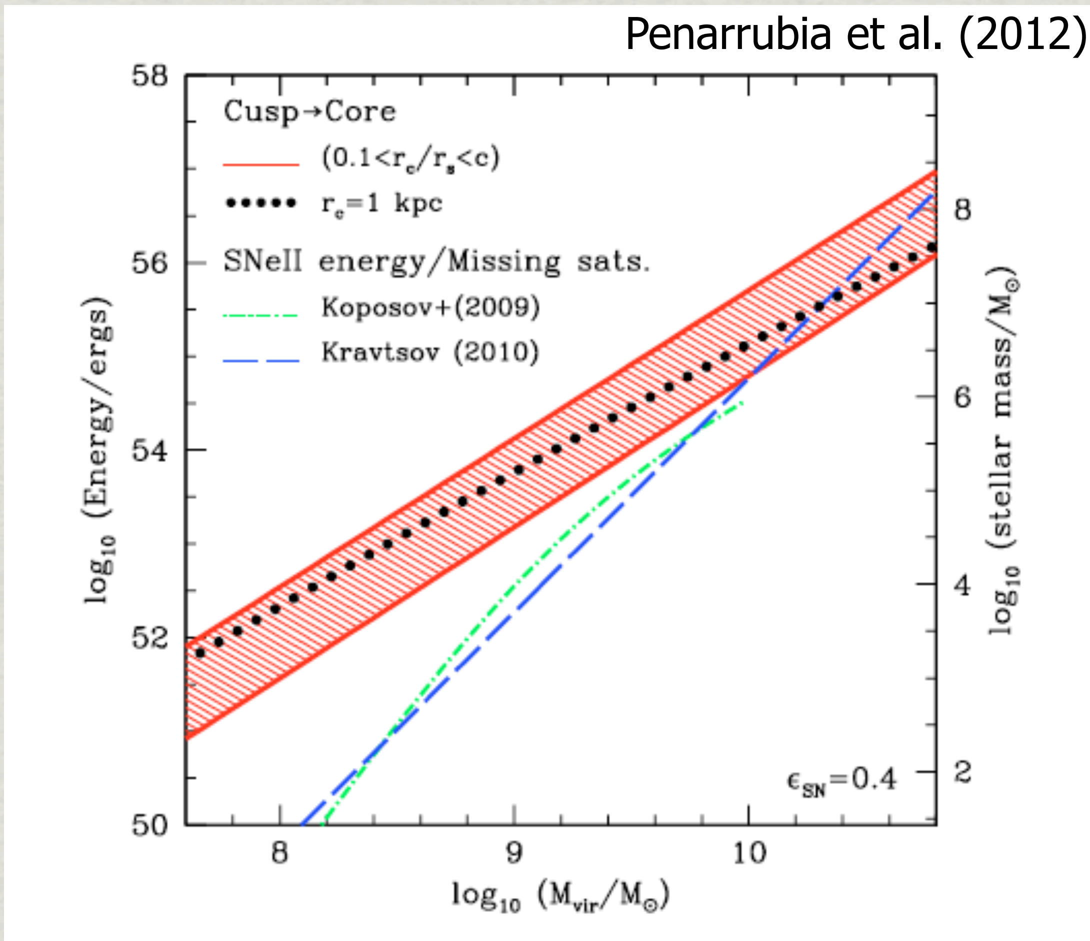


Galaxies with $M_{star} < 10^7\ M_{sun}$ do not release enough energy to create large DM cores

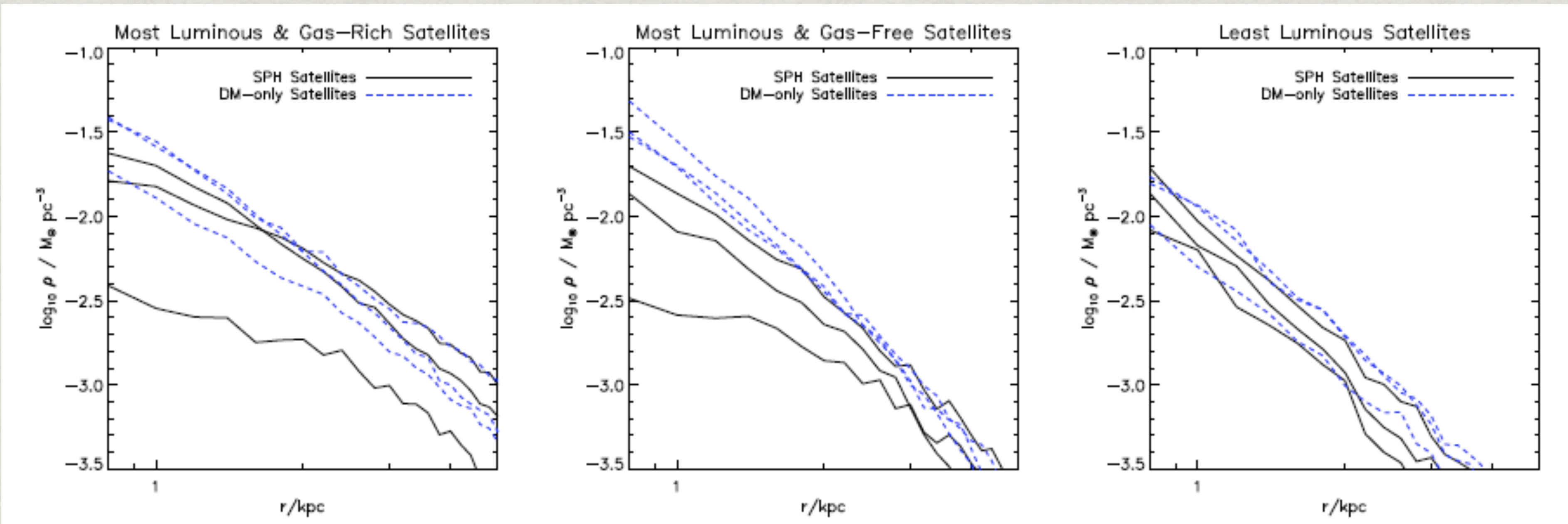
Governato et al., 2012, MNRAS, 422, 1231

Core Creation varies with Mass!

- Analytic arguments and simulations agree

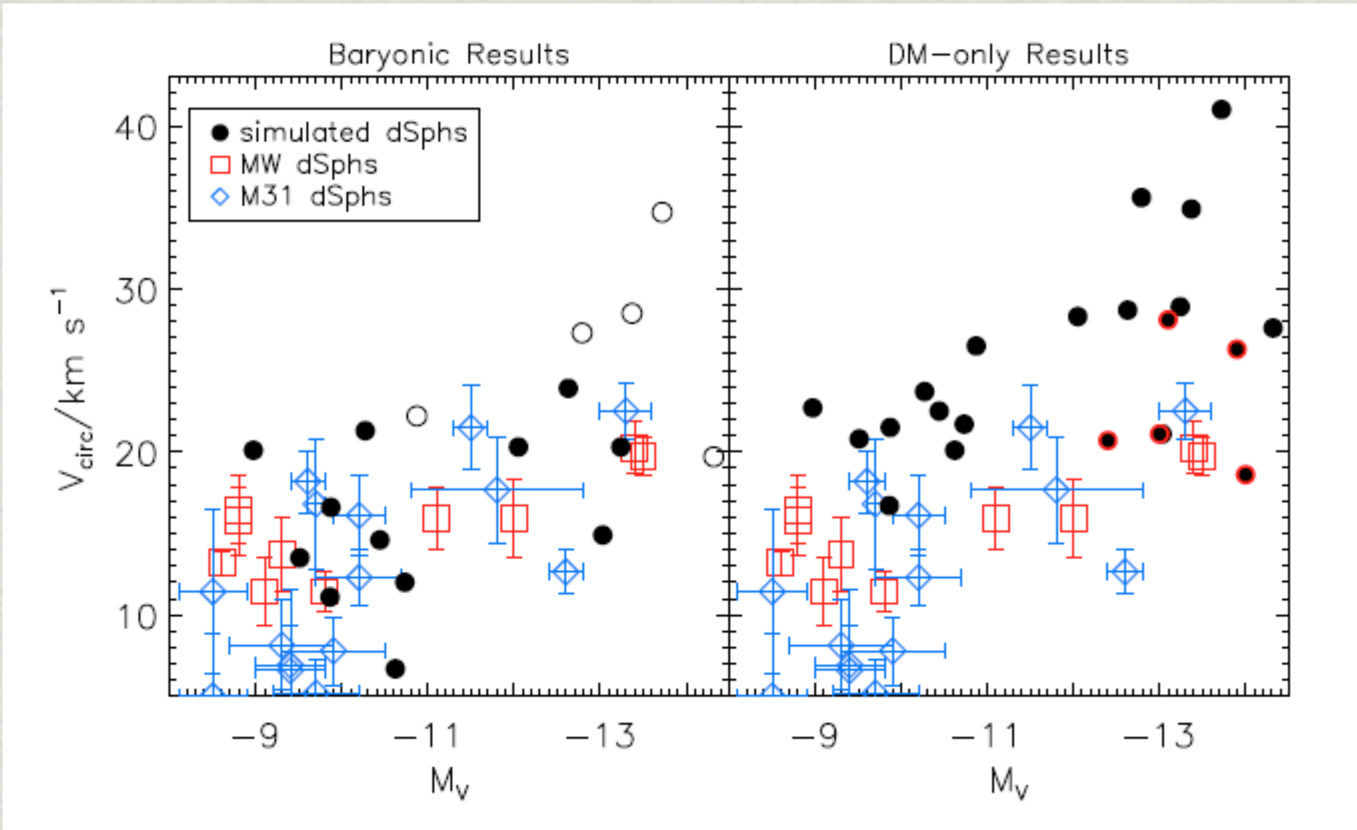


Large DM cores can be created in the brightest satellites



Zolotov, Brooks, et al., 2012, ApJ, 761, 71, arXiv:1207.0007

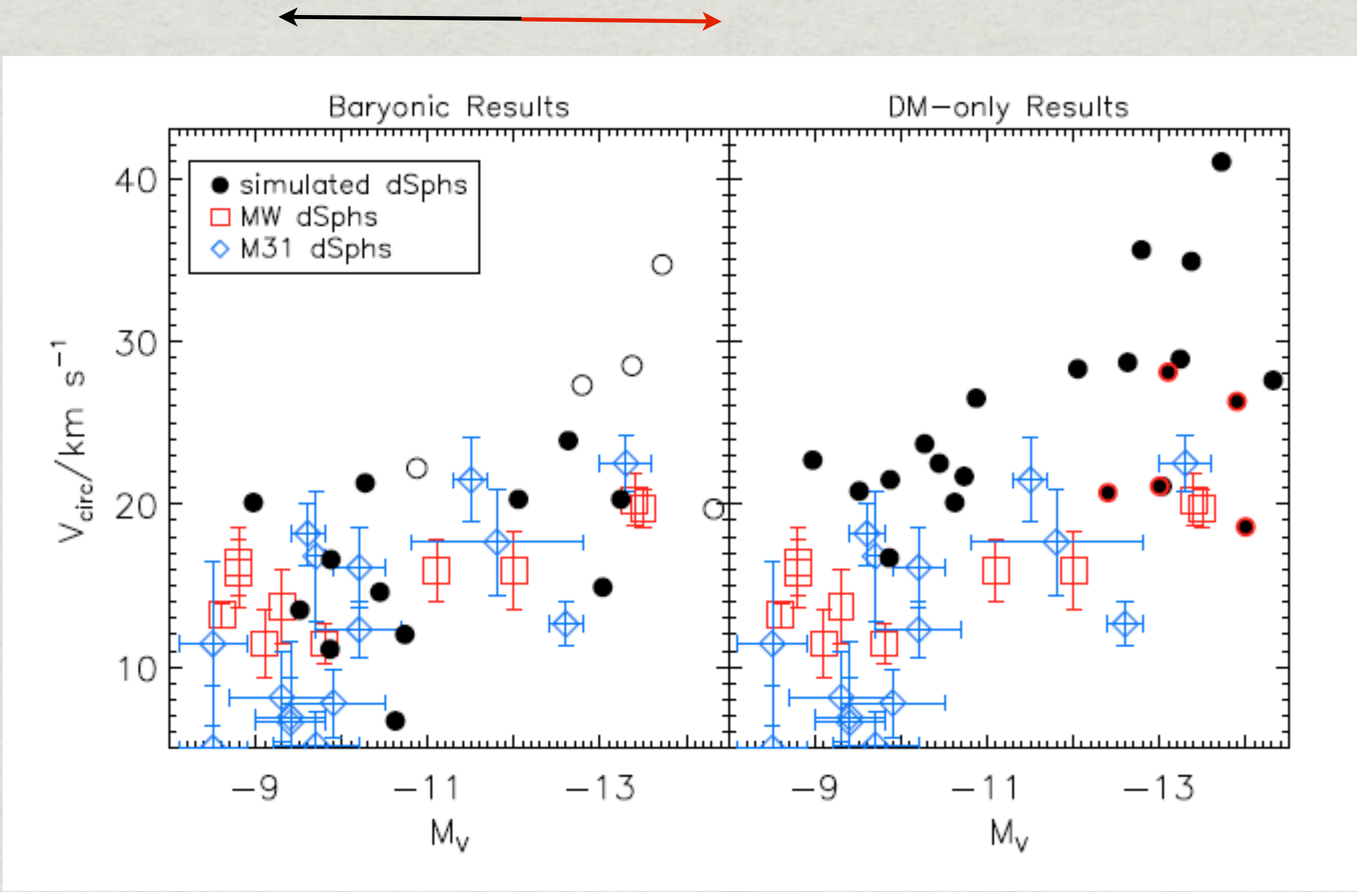
Possible Solutions: Tidal Stripping (with a disk) combined with DM core creation



BROOKS & ZOLOTOV (2013)

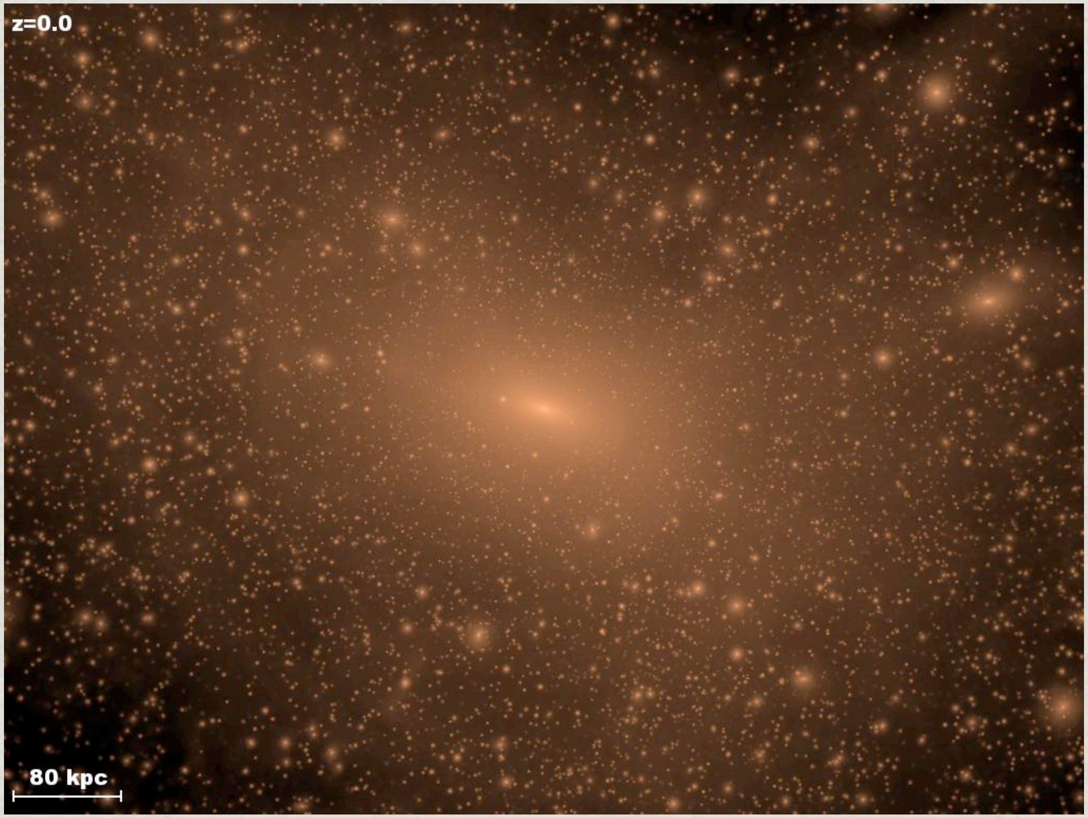
Mass loss due to tidal stripping in presence of disk

Large DM cores in satellites brighter than M_V = -12;
cores + tides = even greater mass loss



BROOKS & ZOLOTOV (2013)

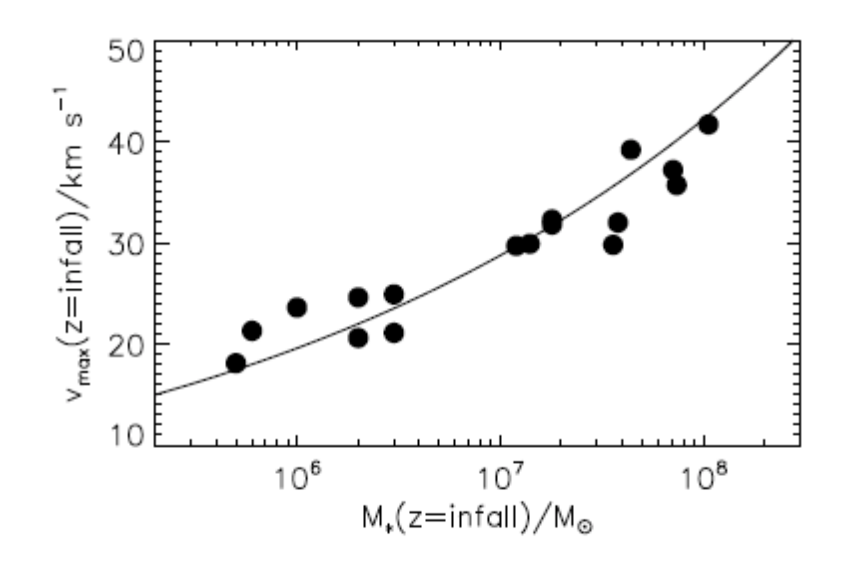
Bonus: Solving the Missing Satellites Problem by Solving the Too Big to Fail Problem



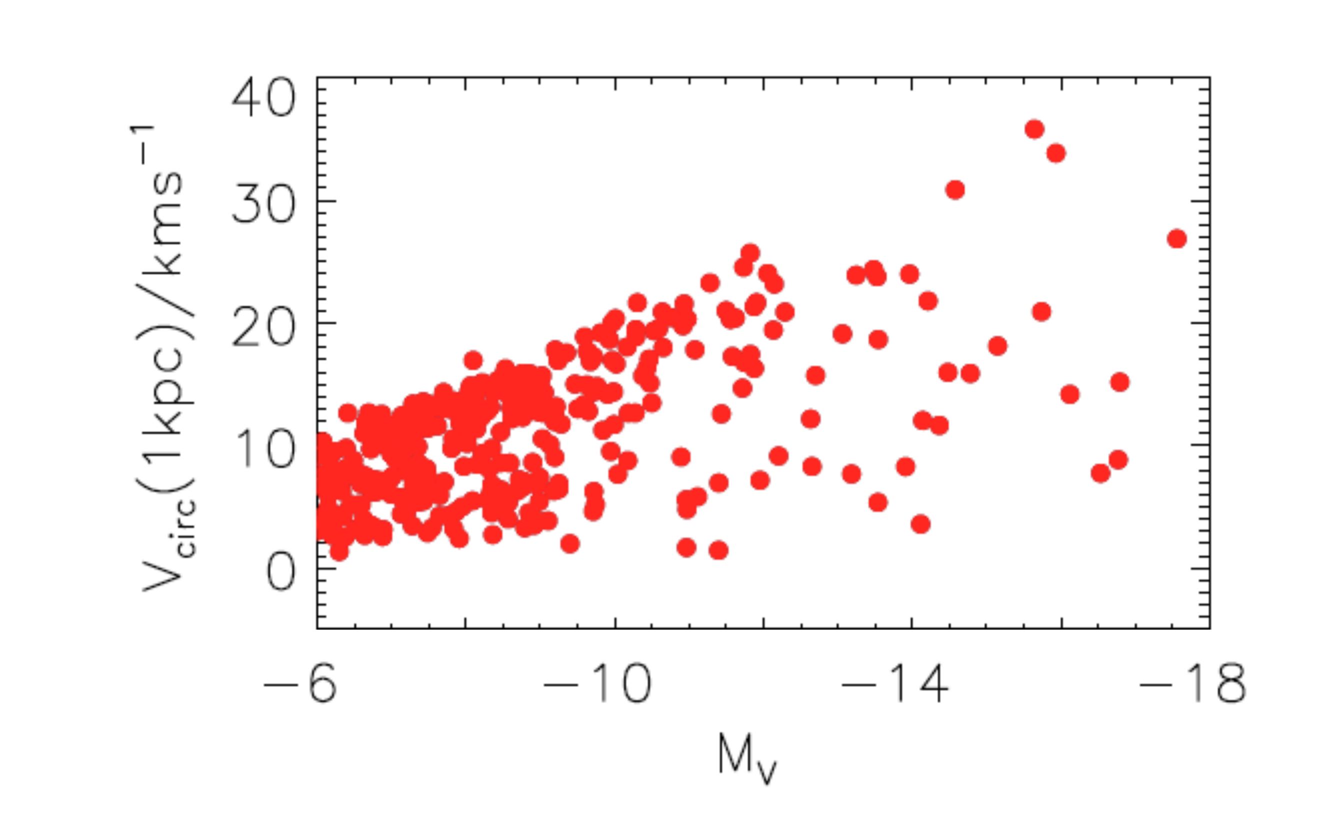
- Let's apply the tidal stripping + DM core creation model to Via Lactea II

Assume

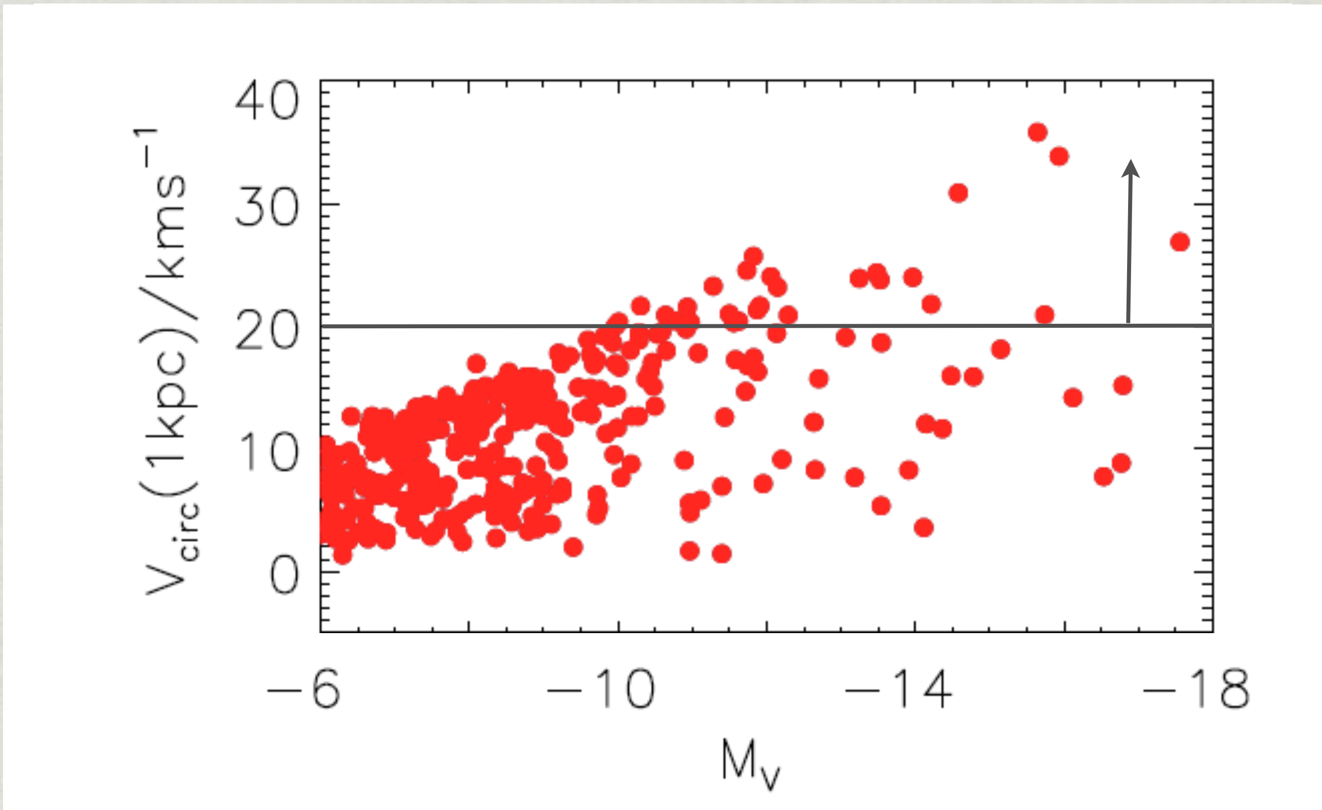
v_{peak} -- M_{star} relation



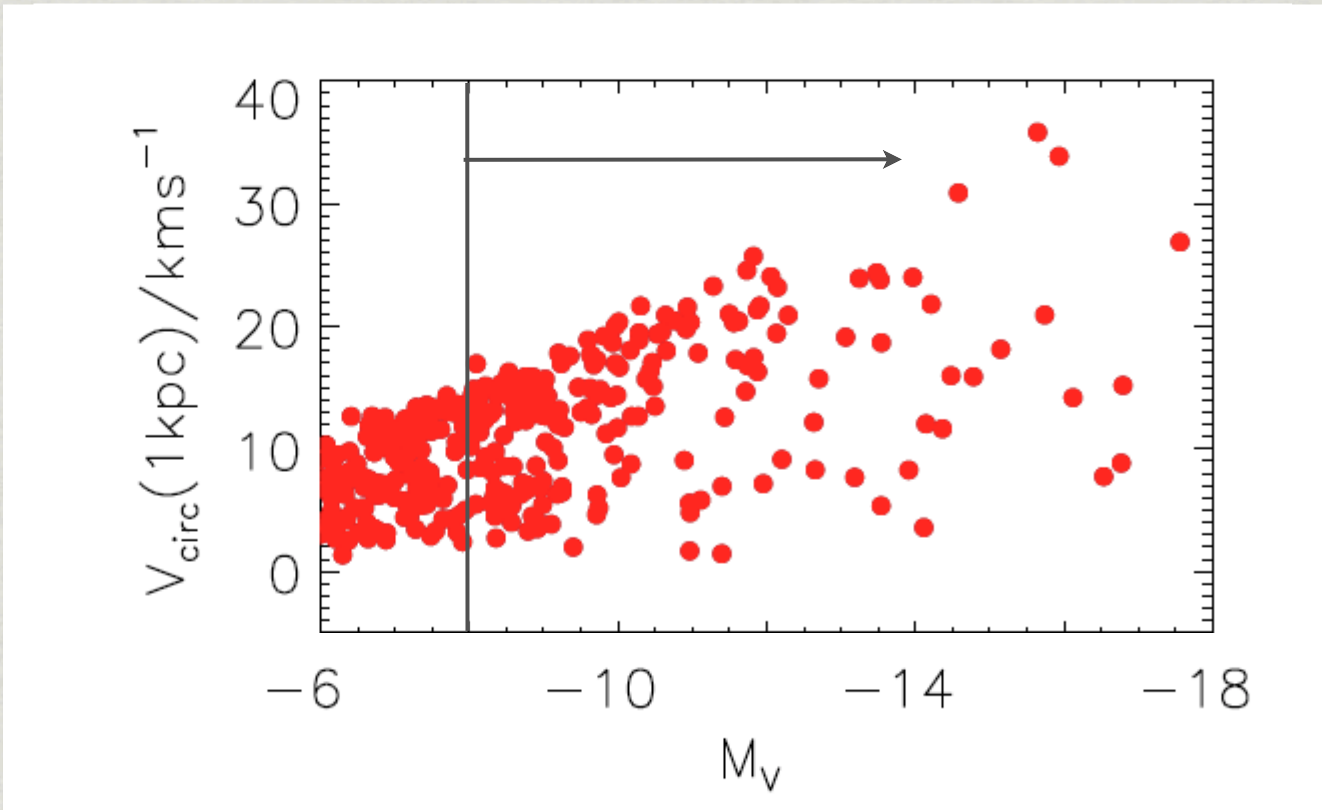
SATELLITES IN VL2



Too many satellites!



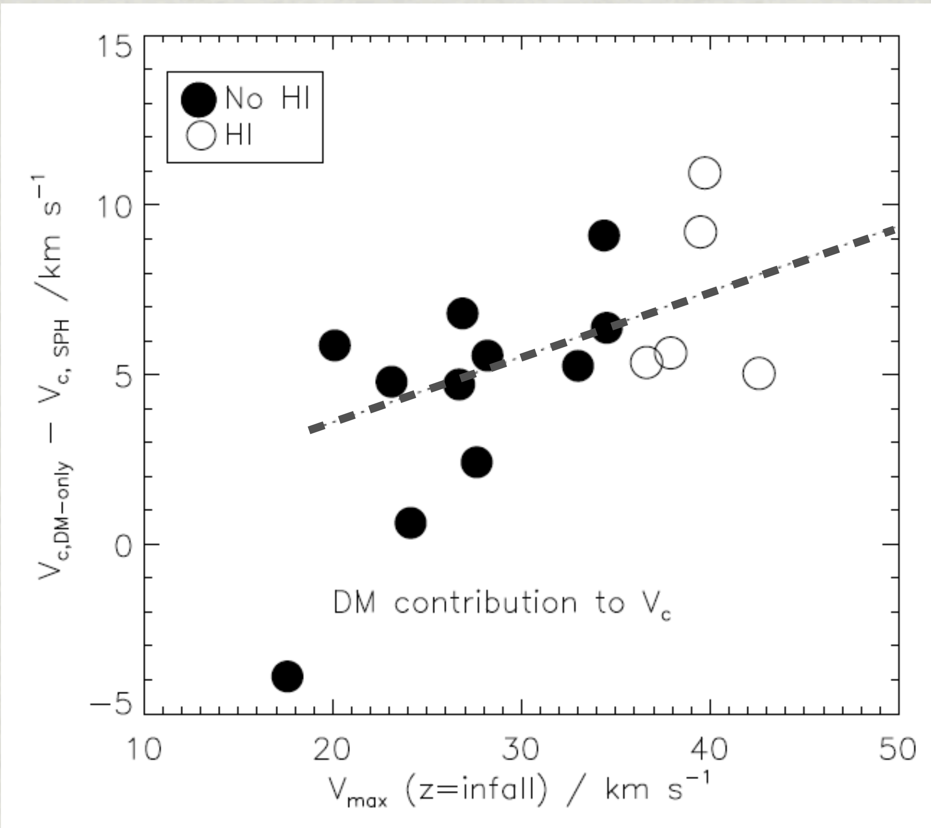
Too many massive satellites!



Too many bright satellites!

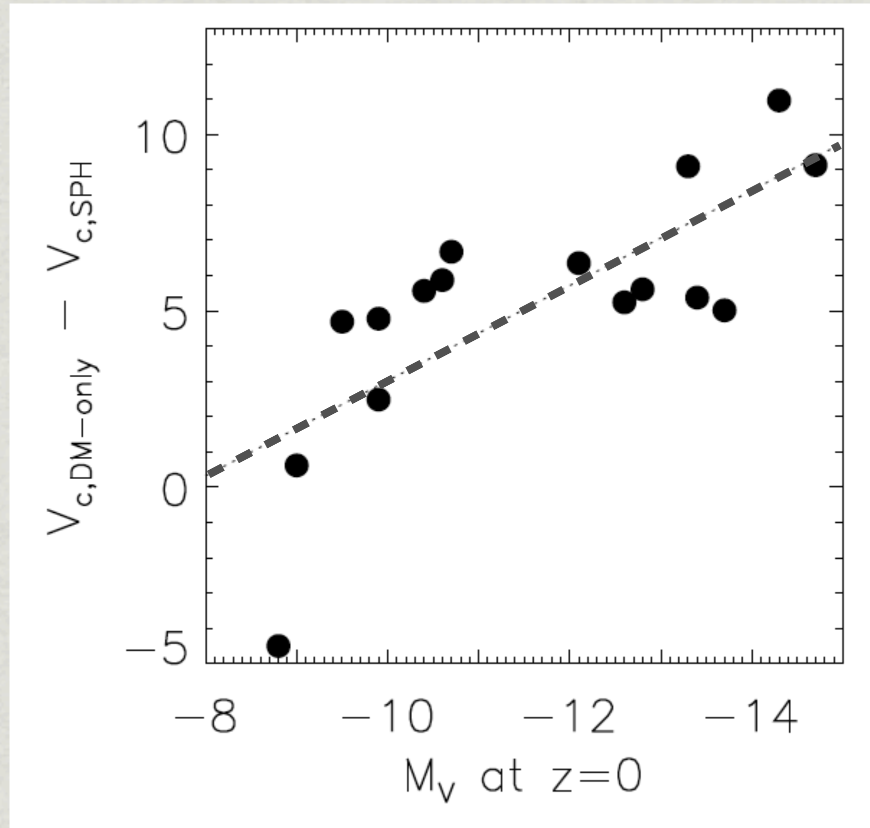
Corrections to DM-only DATA

Theory space:



$\Delta(v_c, 1kpc) = 0.2 v_{peak,DM-only} - 0.26$

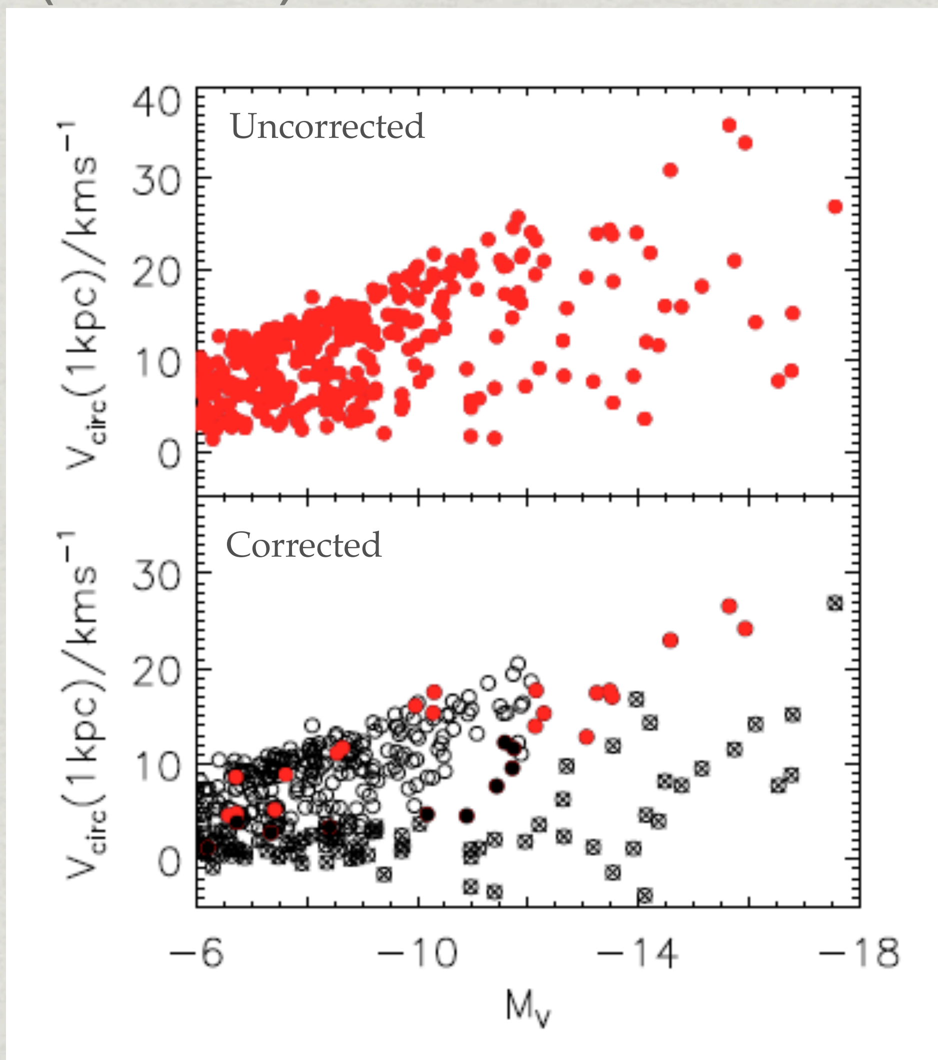
Observer space:



$\Delta(v_{c,1kpc}) = -10.47 - 1.35 \times M_V$

Zolotov et al. (2012)

- Considering tidal stripping (in the presence of a disk) + reionization can make the both the kinematic and luminosity distribution of VL2 look like the MW (or M31)



Brooks, Kuhlen, Zolotov, & Hooper (2012), ApJ, 765, 22, arXiv:1209.5394

THE BIGGER PICTURE:
THE SMALL SCALE "CRISIS" OF CDM

- Bulge-less disk galaxies
- The cusp/core problem
- The dense satellites problem
- The "Missing Satellites" problem

I've shown you that baryons have the potential to solve all of these problems simultaneously!