

Is there tension between observed
small scale structure and cold
dark matter?

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Predictions of the standard *Cold Dark Matter* model

1. Density profiles rise towards the centers of galaxies

Universal for all halo masses

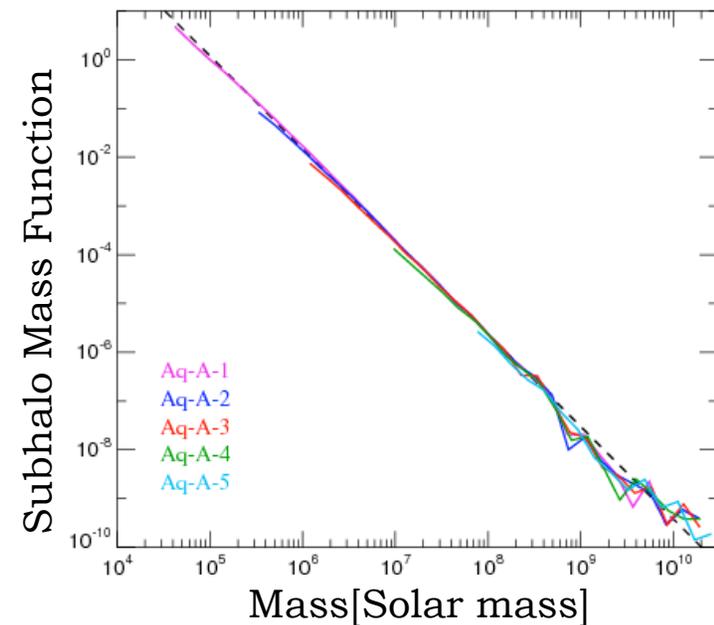
Navarro-Frenk-White (NFW) model

$$\rho(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2}$$

2. Abundance of ‘sub-structure’ (sub-halos) in galaxies

Sub-halos comprise few percent of total halo mass

Most of mass contained in highest-mass sub-halos



Problems with the standard *Cold Dark Matter* model

1. Density of dark matter halos:

Faint, dark matter-dominated galaxies *appear* less dense than predicted in simulations

General arguments: Kleyna et al. MNRAS 2003, 2004; Goerdt et al. APJ 2006; de Blok et al. AJ 2008

Dwarf spheroidals: Gilmore et al. APJ 2007; Walker & Penarrubia et al. APJ 2011; Angello & Evans APJ 2012

2. 'Missing satellites problem':

Simulations have more dark matter subhalos than there are observed dwarf satellite galaxies

Earliest papers:

Kauffmann et al. 1993; Klypin et al. 1999; Moore et al. 1999

Solutions to the issues in *Cold Dark Matter*

1. The theory is wrong

- i) Not enough physics in theory/simulations
(Talks yesterday by M. Boylan-Kolchin, M. Kuhlen) [Wadepuhl & Springel MNRAS 2011; Parry et al. MNRAS 2011; Pontzen & Governato MNRAS 2012; Brooks et al. ApJ 2012]
- ii) Cosmology/dark matter is wrong (Talk yesterday by A. Peter)

2. The data is wrong

- i) Kinematics of dwarf spheroidals (dSphs) are more difficult than assumed
- ii) Counting satellites
 - a) Many more faint satellites around the Milky Way
 - b) Milky Way is an oddball [Liu et al. 2010, Tollerud et al. 2011, Guo et al. 2011, Strigari & Wechsler ApJ 2012]

Dark matter solutions

1. Self-interacting dark matter

Scattering cross section much larger than standard WIMP cross section

2. Warm dark matter

Dark matter has larger velocity in the early Universe than standard WIMPs

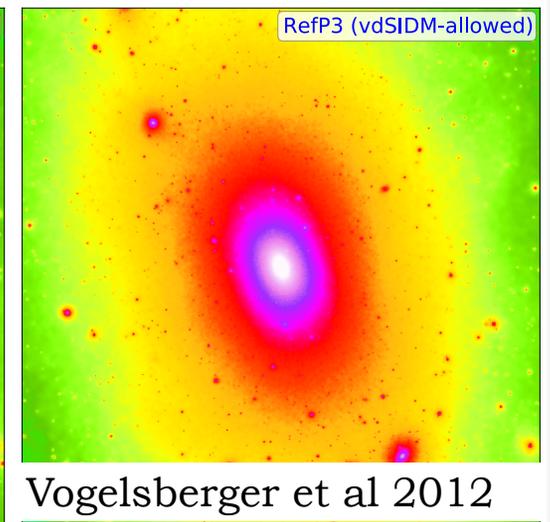
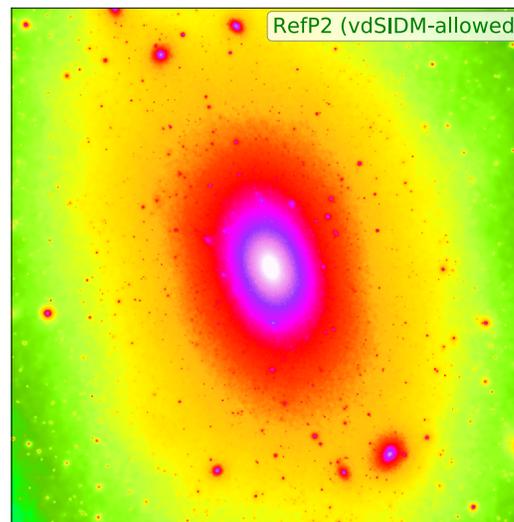
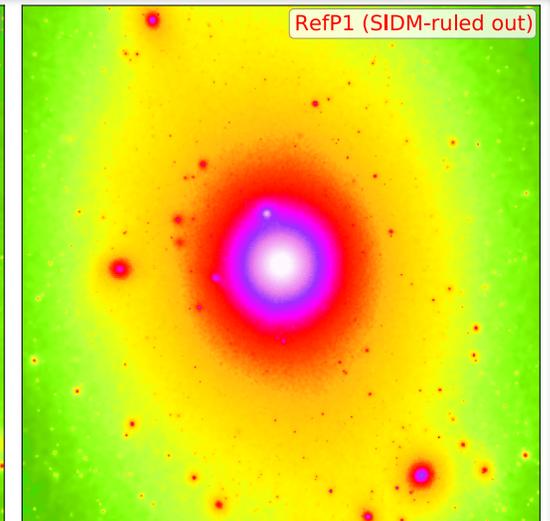
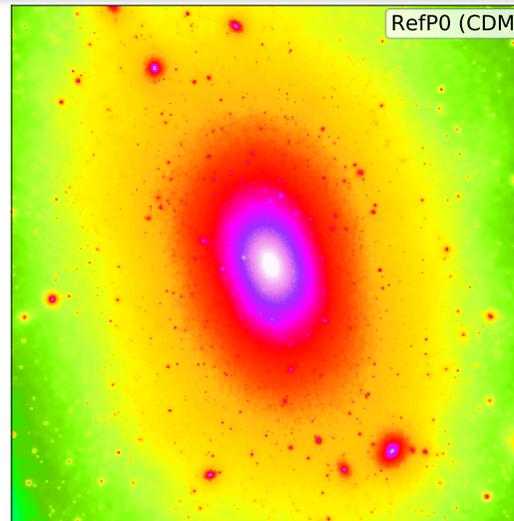
Self-interacting dark matter

- ♦ Canonical WIMP model
Interaction rate in Milky Way 10^{13} times greater than age of Universe!
- ♦ Bounds from halo shapes [Miralda-escude 2002] and galaxy cluster collisions [Markevitch et al. 2004, Randall et al. 2008, Rocha et al. 2013, Peter et al. 2013]
- ♦ Upper bound 20 orders of magnitude greater than corresponding WIMP cross section

Self-interacting dark matter simulations

♦ Halos, subhalos less dense than cold dark matter

♦ Halos, subhalos more spherical than cold dark matter

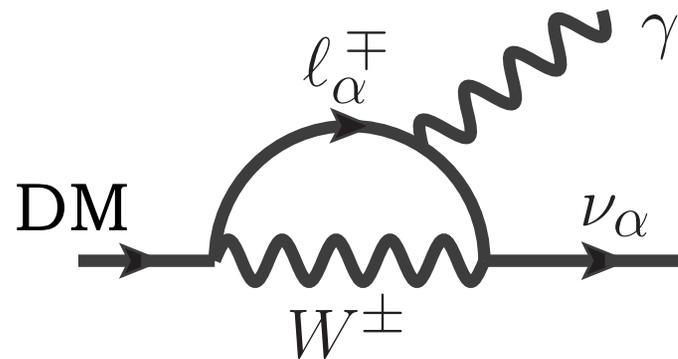


Vogelsberger et al 2012

Warm dark matter

- ◆ Particle falls out of equilibrium with large velocities
`Sterile' neutrinos with mass $\sim 1-10$ keV [Dodelson & Widrow 1994; Shi & Fuller 1999; Abazajian et al. 2012]

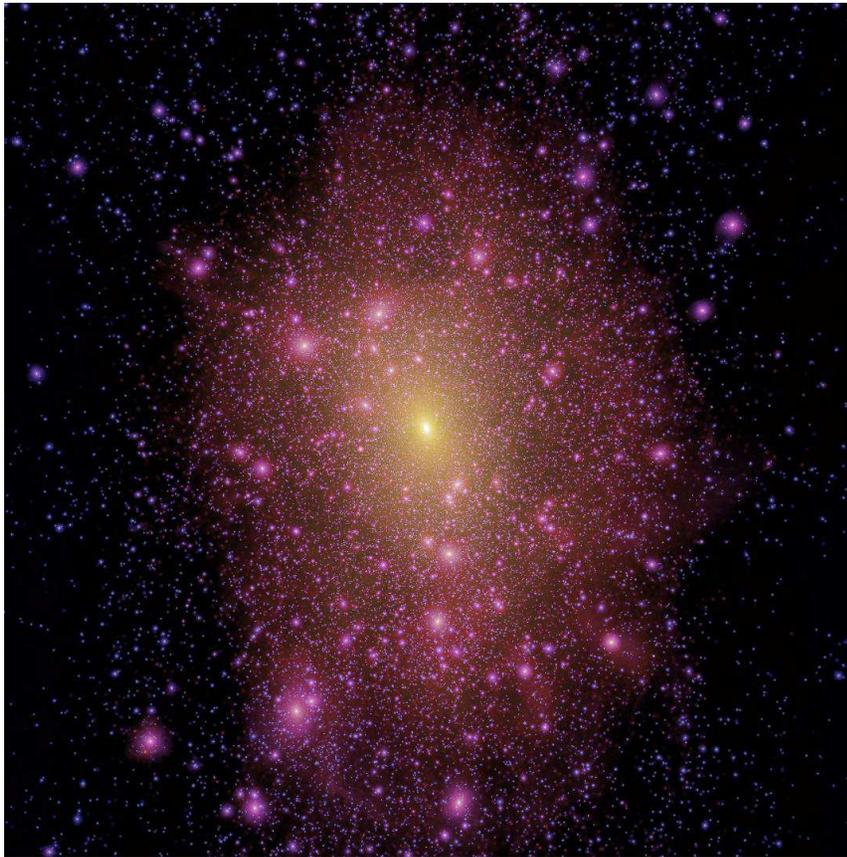
- ◆ Particles not absolutely stable
Lifetimes longer than age of Universe



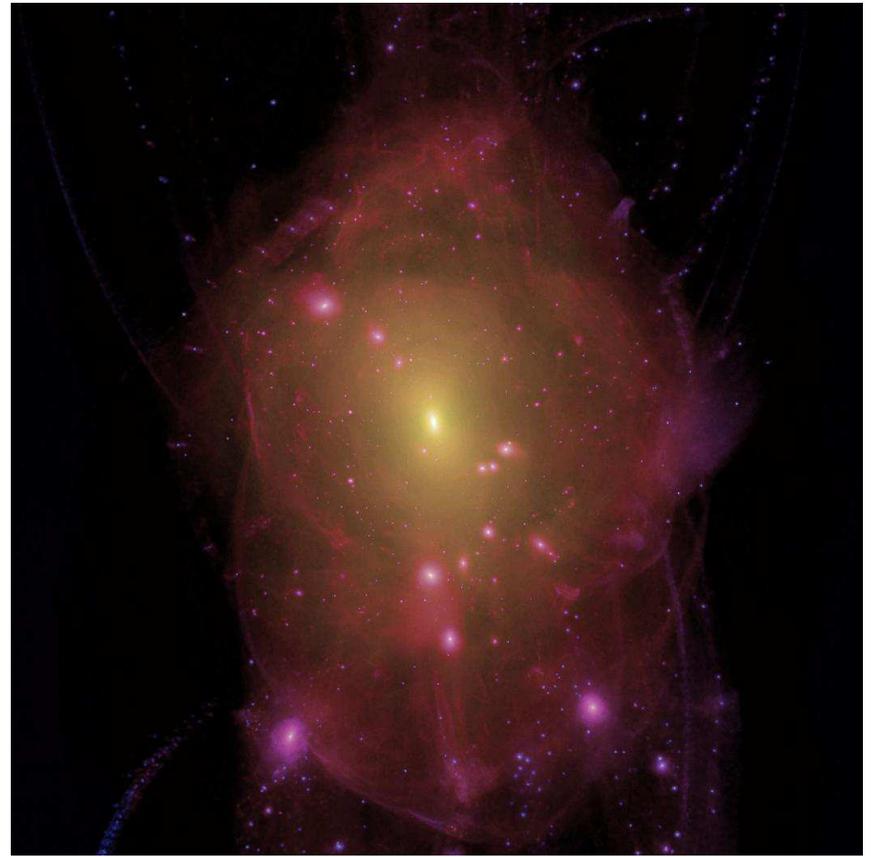
- ◆ Photons from decays be detectable in modern and forthcoming x-ray detectors

Warm dark matter simulations

Cold dark matter



Warm dark matter



Lovell et al 2011

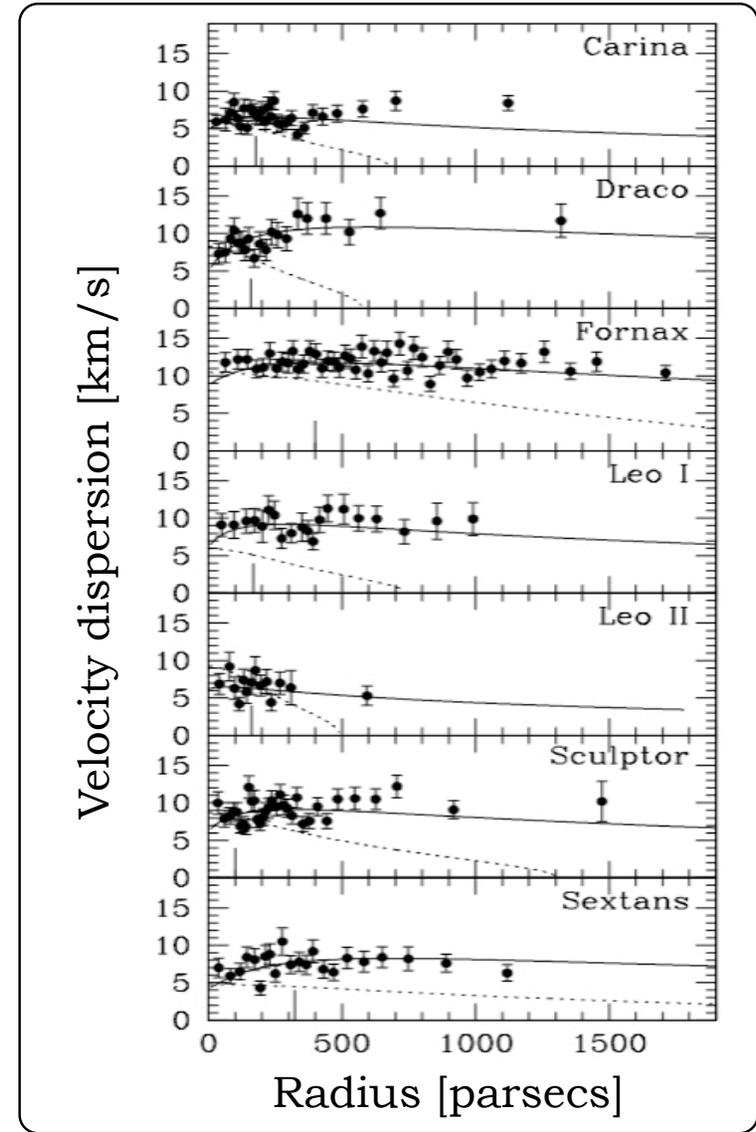
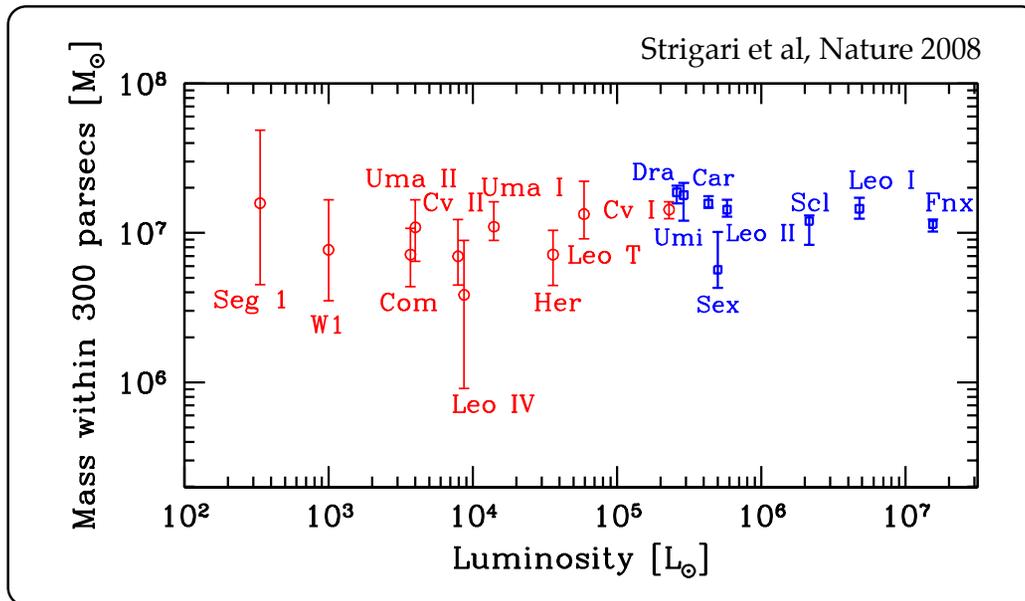
Theory and observations

- ♦ CDM, and non-CDM models now in better position to provide testable predictions
- ♦ Put aside theoretical aspects. Consider observational systematics
 - ♦ Masses of dwarf spheroidals (dSphs)
 - ♦ Count satellites

Masses of dwarf spheroidals

Dark matter in satellite galaxies (dwarf spheroidals)

- ♦ Velocity dispersion $\sim 5\text{-}10$ km/s
- ♦ Uncertainties $\sim 1\text{-}2$ km/s
- ♦ Common densities over observed scales [Strigari et al. 2008]

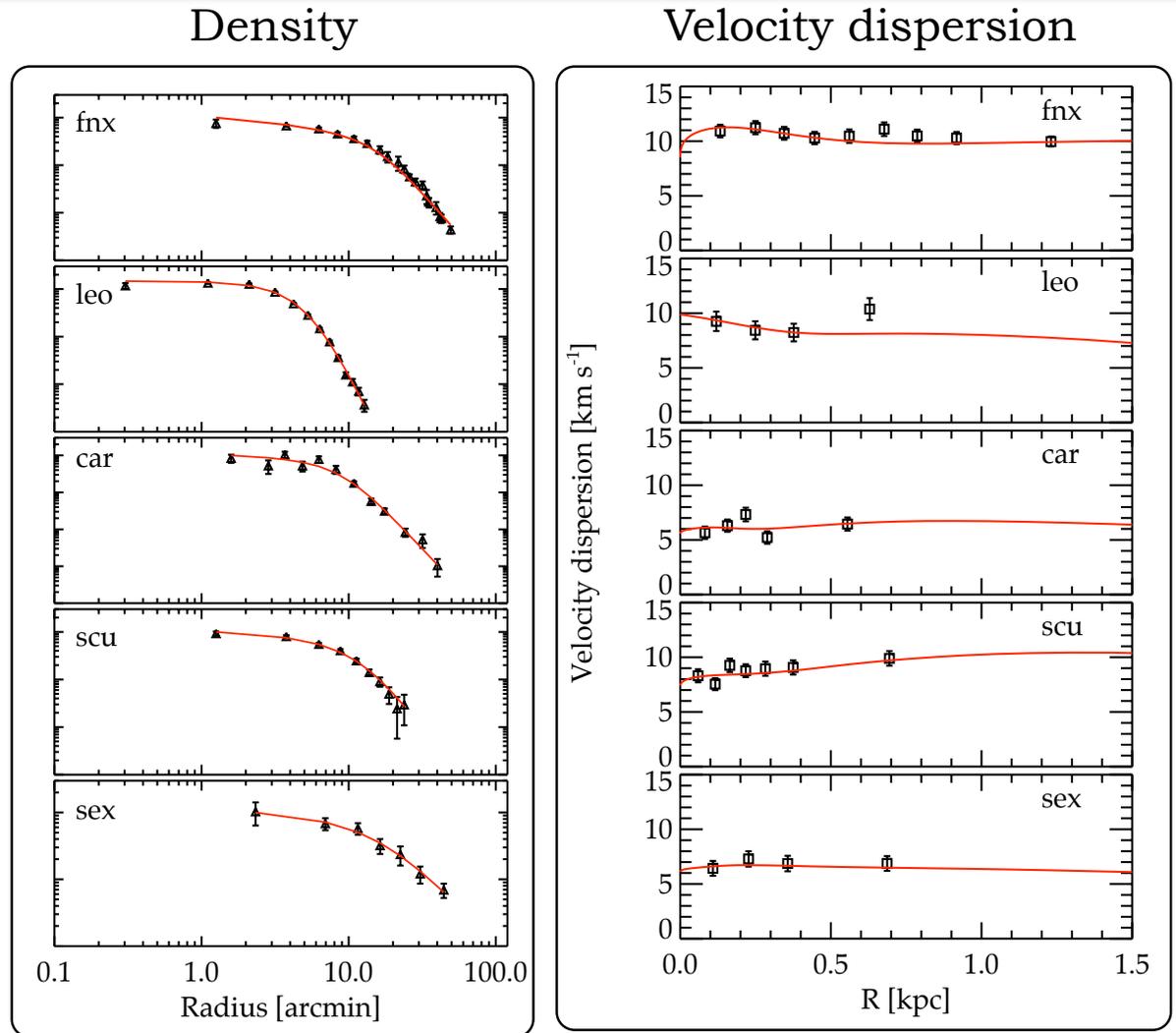


Densities of dwarf spheroidalals

♦ Parameter space is very degenerate. CDM-based NFW models fit all dwarf spheroidalals

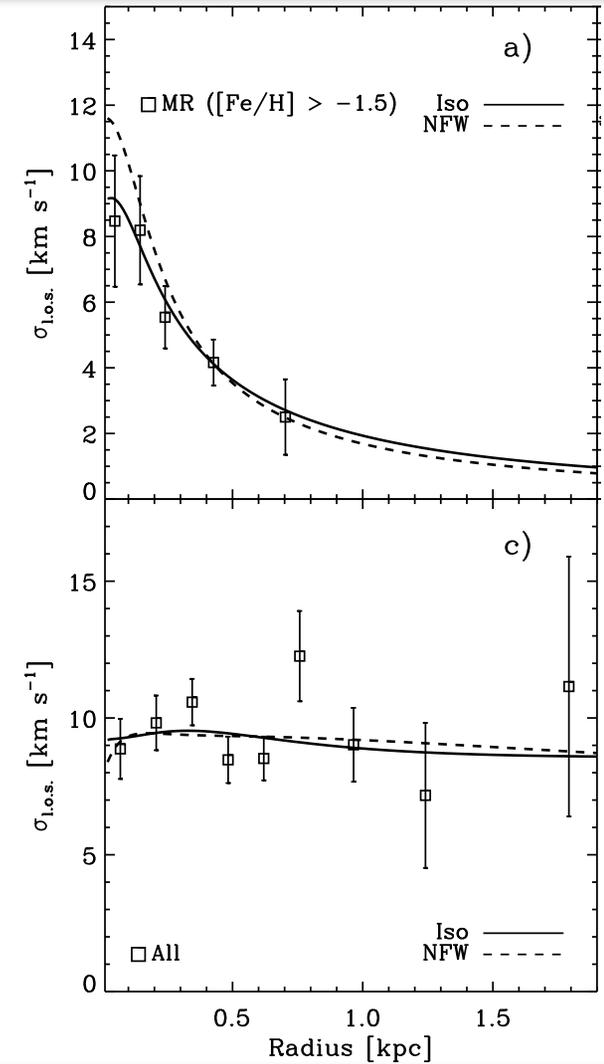
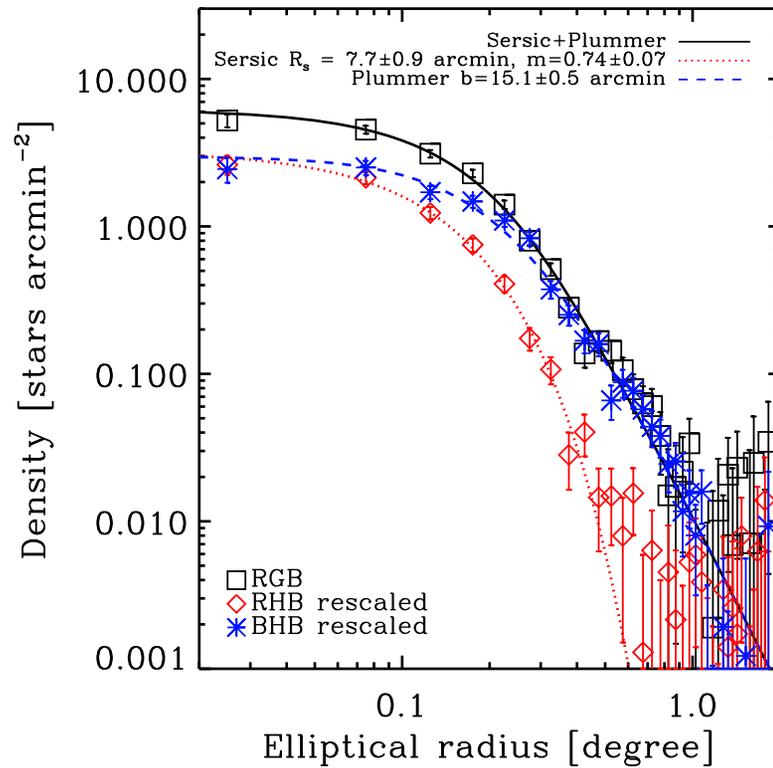
♦ Future measurements of photometry and velocities will test these solutions

Strigari, Frenk, White
MNRAS 2010



Multiple populations in Sculptor dwarf spheroidal

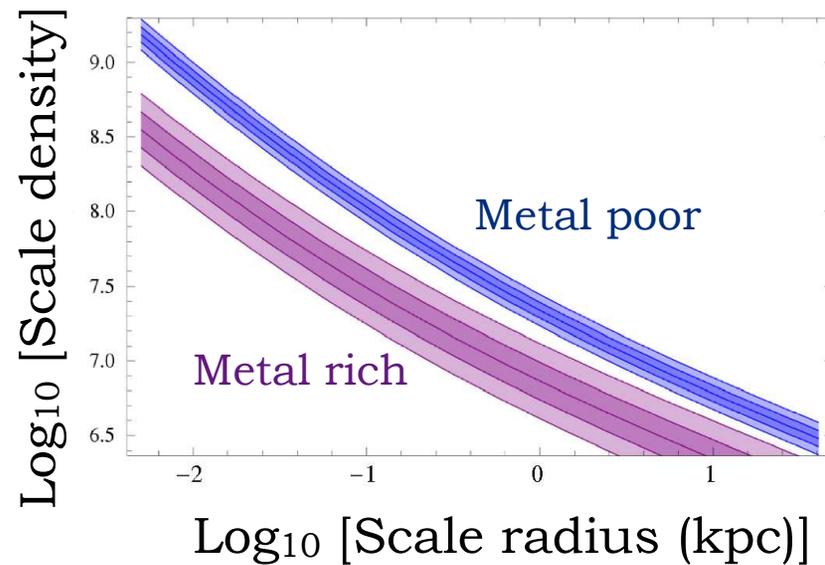
Metal Rich (MR) and Metal Poor (MP) population
(Battaglia et al 2008)



Multiple populations in Sculptor dwarf spheroidal

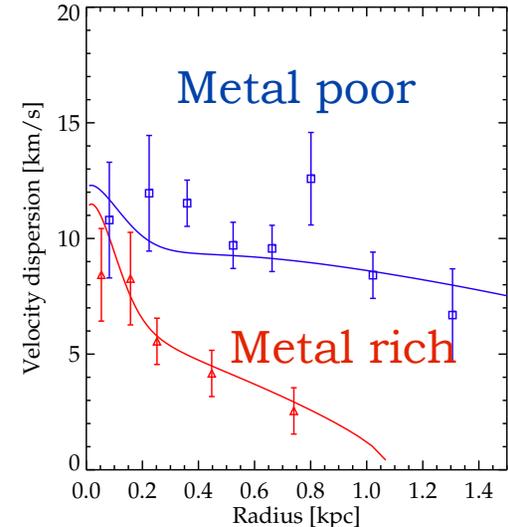
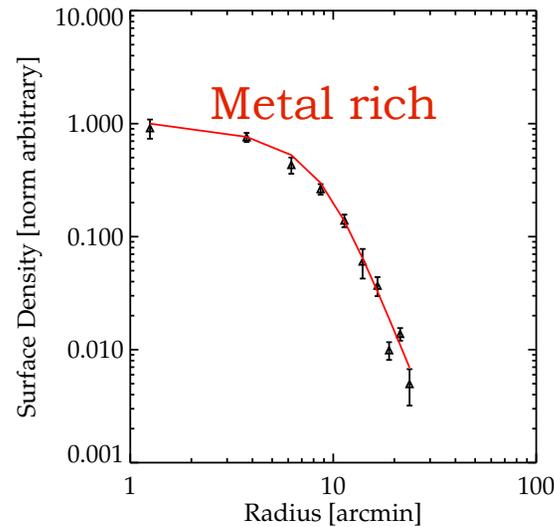
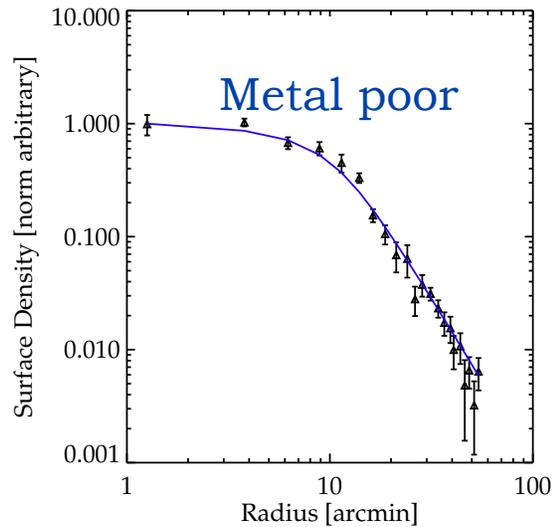
- Walker & Penarrubia (ApJ 2011) state that multiple populations are inconsistent with an NFW profile

- Agnello & Evans (ApJ 2012) use virial theorem to rule out NFW profile



Multiple populations in Sculptor dwarf spheroidal

- WP11 and AE12 modeling turn out to be not general enough
- Construct generalized model of photometry and kinematics of dSphs
- Maximum likelihood analysis (Strigari, Frenk, White 2013 in prep)



- NFW profiles *are consistent* with the multiple populations

Multiple populations in Sculptor dwarf spheroidal

Testable predictions

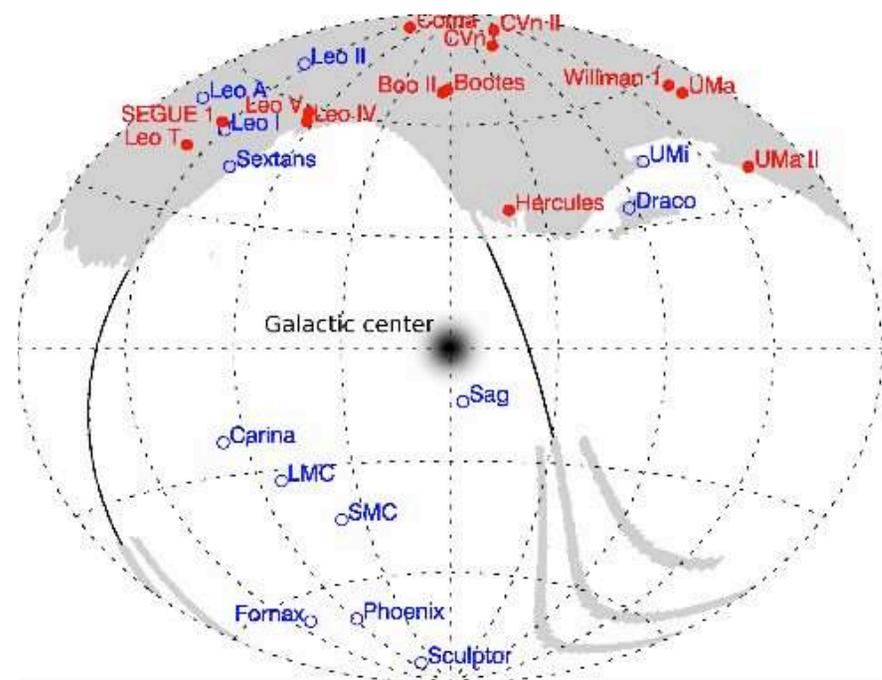
- Orbits of the inner, metal rich population are radial
- Cusp in the stellar density profile
- Forthcoming HST observations provide astrometry < 10 km/s (almost the the projected SIM sensitivity)

Counting satellites

How rare is the Milky Way Galaxy?

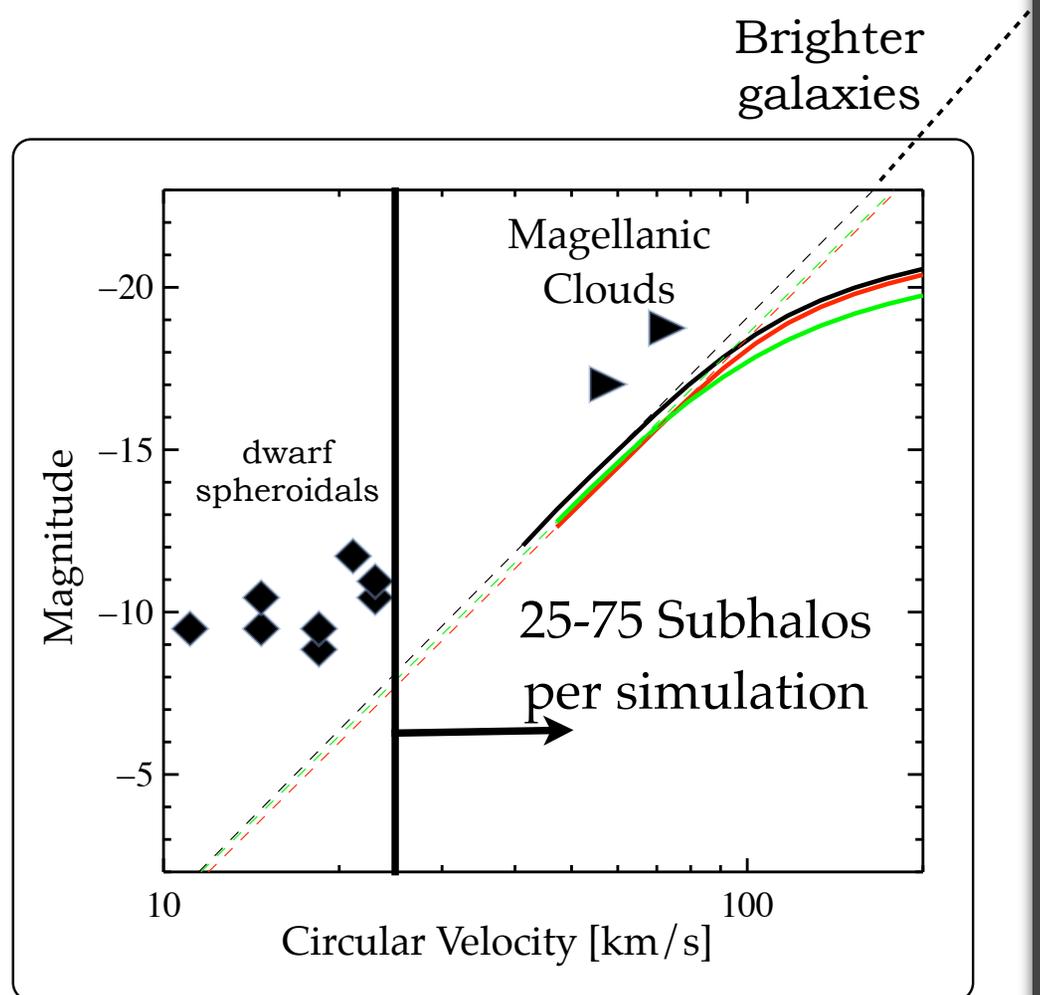
List of Milky Way satellites

Satellite	M_V	$L_V [L_\odot]$	$d_{\text{sun}} [\text{kpc}]$
Large Magellanic Cloud	-18.5	2.15×10^9	49
Small Magellanic Cloud	-17.1	5.92×10^8	63
Sagittarius	-15.0	8.55×10^7	28
Fornax	-13.1	1.49×10^7	138
Leo I	-11.9	4.92×10^6	270
Leo II	-10.1	9.38×10^5	205
Sculptor	-9.8	7.11×10^5	88
Sextans	-9.5	5.40×10^5	86
Carina	-9.4	4.92×10^5	94
Draco	-9.4	4.92×10^5	79
Ursa Minor	-8.9	1.49×10^5	69
Canes Venatici I	-8.6	2.36×10^5	224
Leo T	-8.0	5.92×10^4	417
Hercules	-6.6	3.73×10^4	138
Boötes I	-6.3	2.83×10^4	60
Ursa Major I	-5.5	1.36×10^4	106
Leo IV	-5.0	8.55×10^3	158
Canes Venatici II	-4.9	7.80×10^3	151
Ursa Major II	-4.2	4.09×10^3	32
Coma	-4.1	3.7×10^3	44
Boötes II	-2.7	1.03×10^3	43
Willman 1	-2.7	1.03×10^3	38
Segue 1	-1.5	3.40×10^2	23



A population of missing massive satellites?

- ♦ *Cold dark matter* predicts dozens of 'dark' satellites more massive than the dwarf spheroidals (*'Too big to fail problem'* Boylan-Kolchin et al. 2011)
- ♦ Not enough 'bright' Milky Way satellites
- ♦ Theoretical solutions
 - Baryons
 - Alternative dark matter
- ♦ Observational systematics
 - Is the Milky Way an oddball?



Magellanic Clouds around other 'Milky Ways'

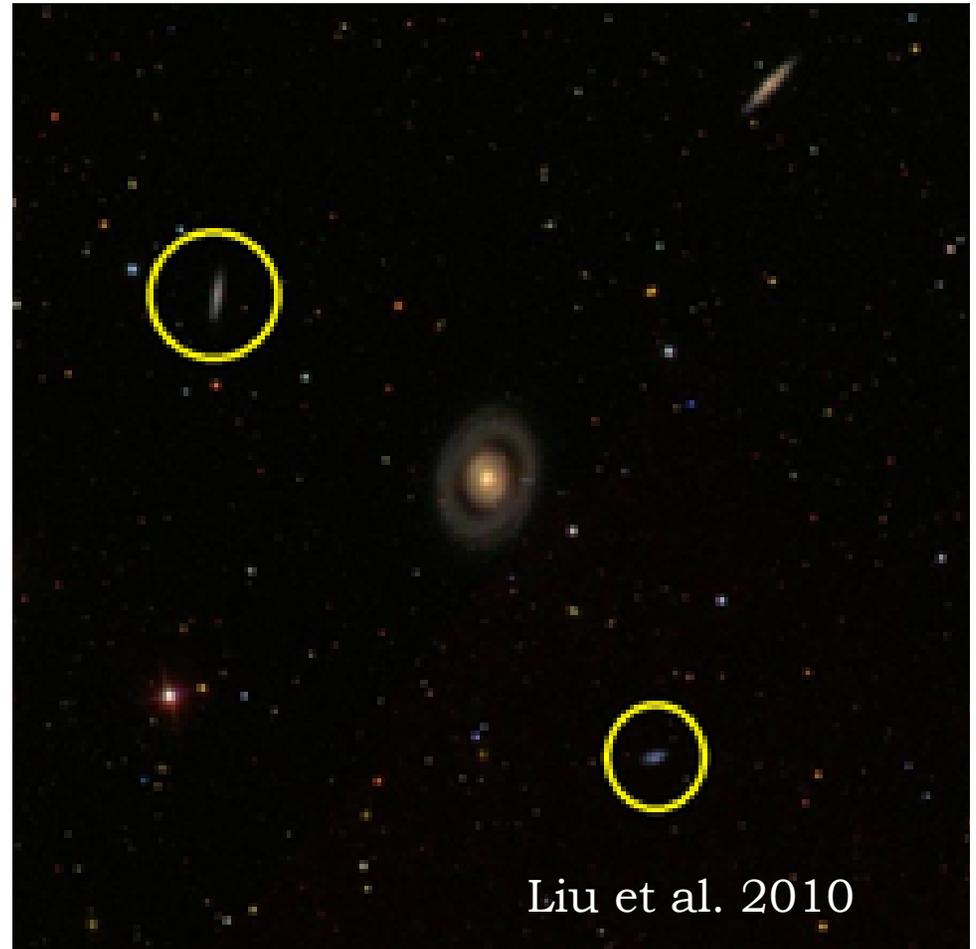


From cosmological surveys:

- About 5% of 'Milky Ways' have 'Magellanic Clouds' [Liu et al. 2010, Lares et al. 2011; James & Ivory 2011; Tollerud et al. 2011, Guo et al. 2011]

From simulations:

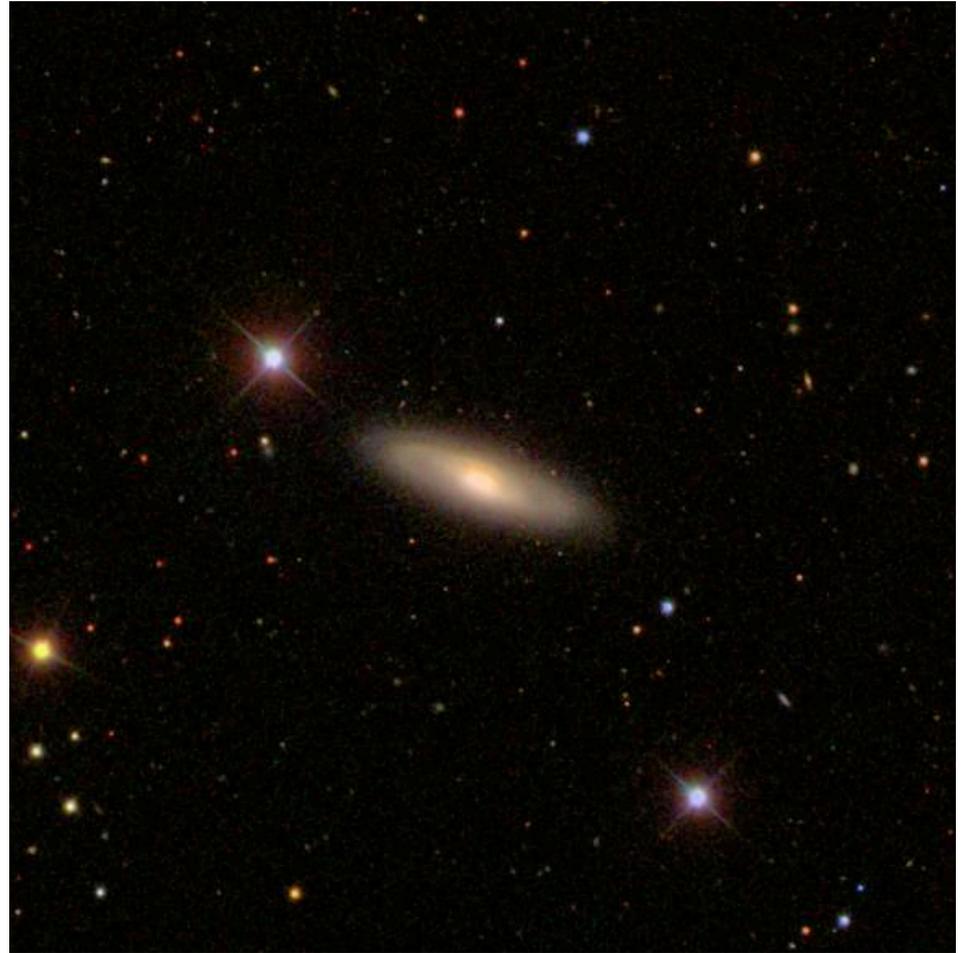
- 5-10% of 'Milky Ways' have 'Magellanic Clouds' [Boylan-Kolchin et al. 2009; Busha et al. 2010]



Liu et al. 2010

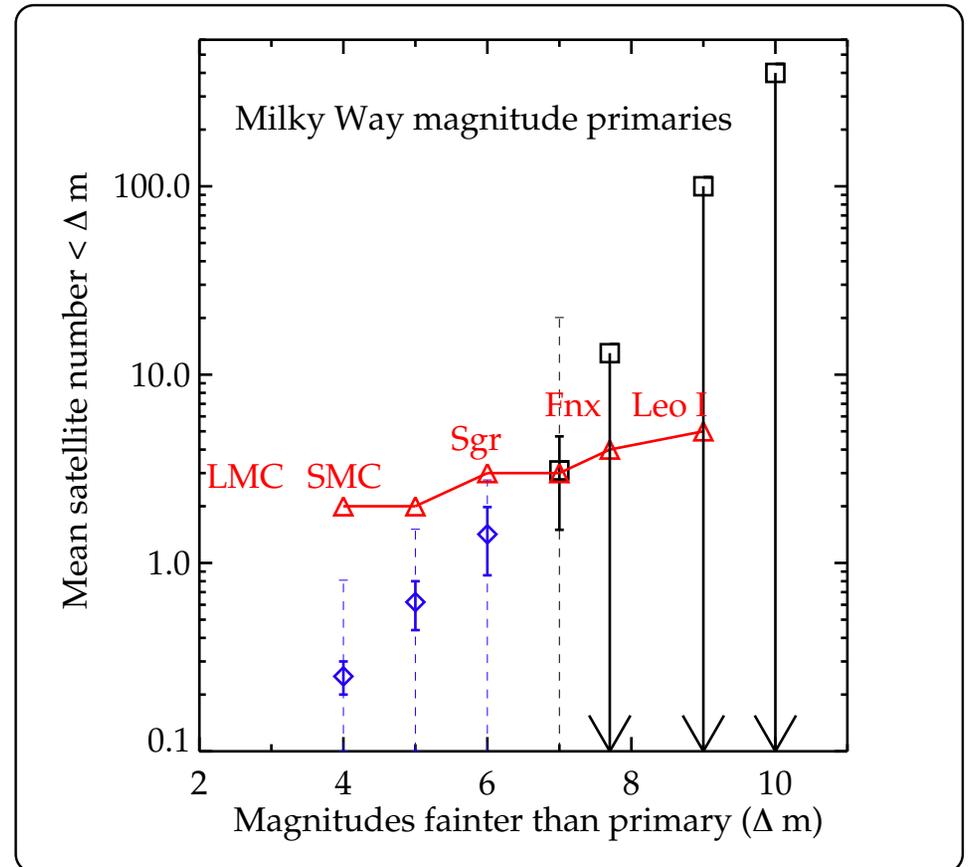
Dwarf spheroidals around other 'Milky Ways'

- ✦ Going fainter difficult because unreliable distances to satellites
- ✦ However it is the most important regime for the satellite abundance issue!
- ✦ Can only use bright, nearby 'Milky Ways'



Satellites of other 'Milky Ways'

- Down to limits of modern surveys, Milky Way is 'normal' (Strigari & Wechsler ApJ 2012)
- Is the solution to satellites issue likely due to incomplete theory?
- Significant improvement very soon with new larger scale surveys



Strigari & Wechsler ApJ 2012

Conclusions

- Important to both improve theory and understand observational systematics to get a handle to classic CDM issues
- CDM-based, NFW dark matter profiles are consistent with dwarf spheroidal data (dSph)
- Down to about the luminosity of Fornax, hints that the Milky Way is 'average'
- Picture should be much more clear next few years...