I. Do we need alternatives to *Cold Dark Matter*?

and

II. Halo models & Direct Detection

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Opening statements

- Motivated by astrophysical issues there has been recent renewed interest in going beyond collision-less *CDM* models

- Non-WIMP dark matter models have been developed that predict/explain deviations from standard *CDM: self-interacting (e.f. Feng, et al. 2010; Loeb & Weiner 2011; van den Aarssen 2012; Tulin, Yu, Zurek 2013)*, *or warm DM*

- Are the astrophysical issues due to new dark matter physics, incomplete *CDM* theory, or limits of modern observations?

Predictions of the standard *Cold Dark Matter* model

1. Density profiles rise towards the centers of galaxies

Universal for all halo masses

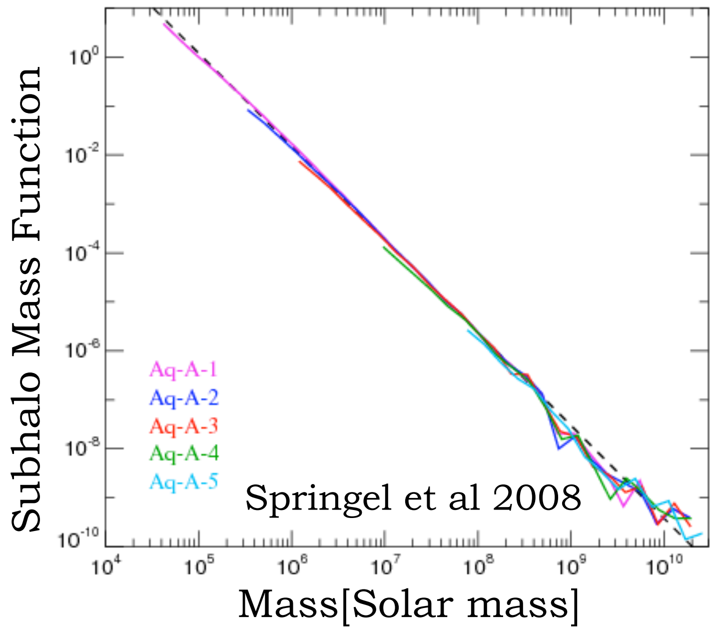
Navarro-Frenk-White (NFW), Einasto model

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

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. APJ2006; de Blok et al. AJ 2008, Oh et al. ApJ 2011
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

Earilest papers: 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
   [Wadepuhl & Springel MNRAS 2011; Parry et al. MRNAS 2011; Pontzen & Governato MRNAS 2012; Brooks et al. ApJ 2012]
   ii) Cosmology/dark matter is wrong

2. ***The data is wrong (or interpretation incomplete)***
   i) Measuring dark matter density profiles of galaxies is difficult
   ii) Counting satellites
      a) Many more faint satellites around the Milky Way
      b) Milky Way is an outlier
      [Liu et al. 2010, Tollerud et al. 2011, Guo et al. 2011, Strigari & Wechsler ApJ 2012]

Basic expectations

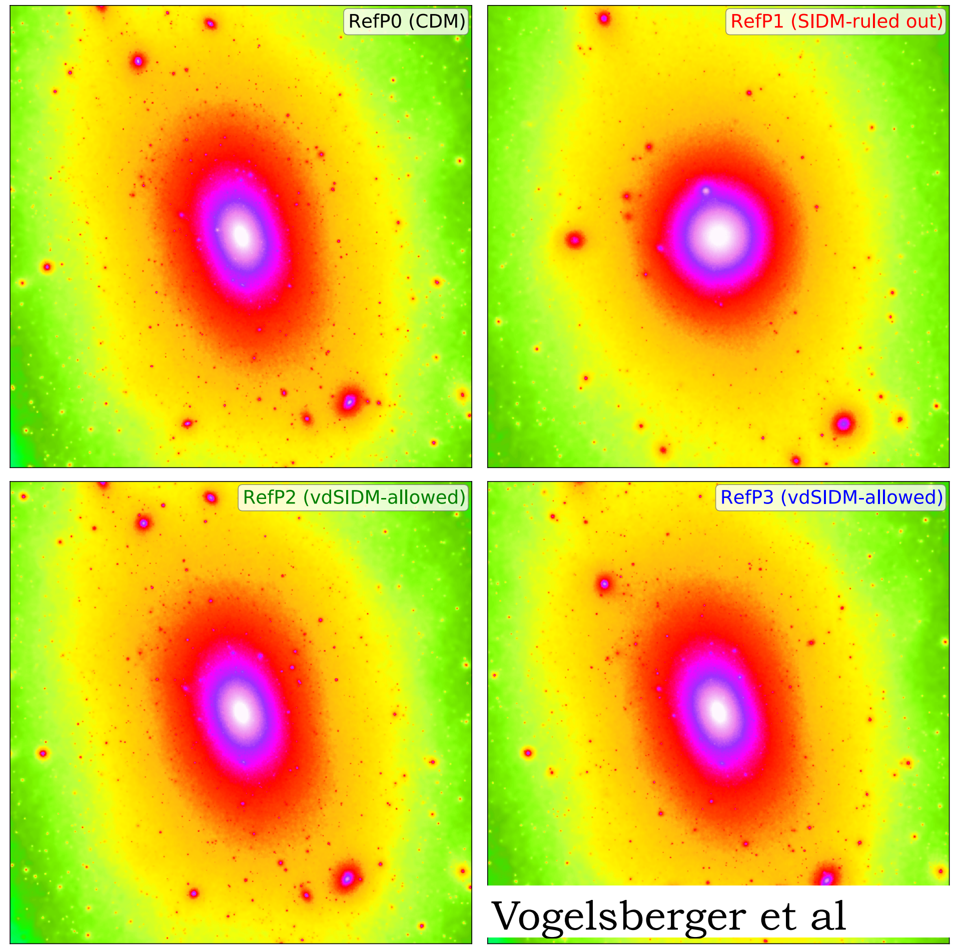
- *CDM*, and *non-CDM* models going a way towards providing more robust, testable predictions

- *Self-interacting dark matter*

  - Halos expected to be more spherical, cored central density

- *Warm dark matter*

  - Halos form at later epochs in the Universe
  - Simulations show Einasto like profiles, with reduced concentrations (Lovell et al. 2011)



Vogelsberger et al

See also Rocha et al 2013

Kinematics of dwarf spheroidals

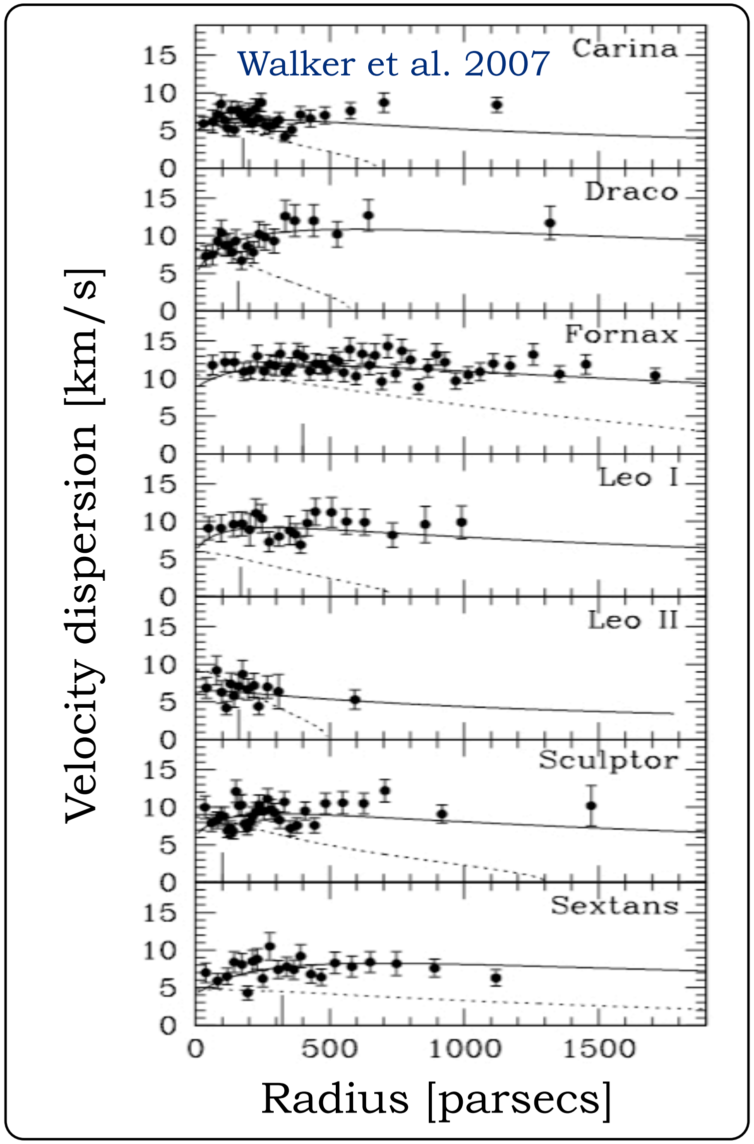
Dark matter in satellite galaxies (dwarf spheroidals)

- Modeled as single stellar population, range of dark matter density profiles allowed

- Standard modeling assumes spherical symmetry but not isotropy [e.g. Strigari et al 2008, Lokas 2009, Walker et al 2009]

- Some corrections for non-spherical potentials [Hayashi, Chiba 2012, Kowalczyk et al. 2013]

- New orbit-based approaches [Breddels et al 2012, Jardel and Gebhardt 2012, 2013]



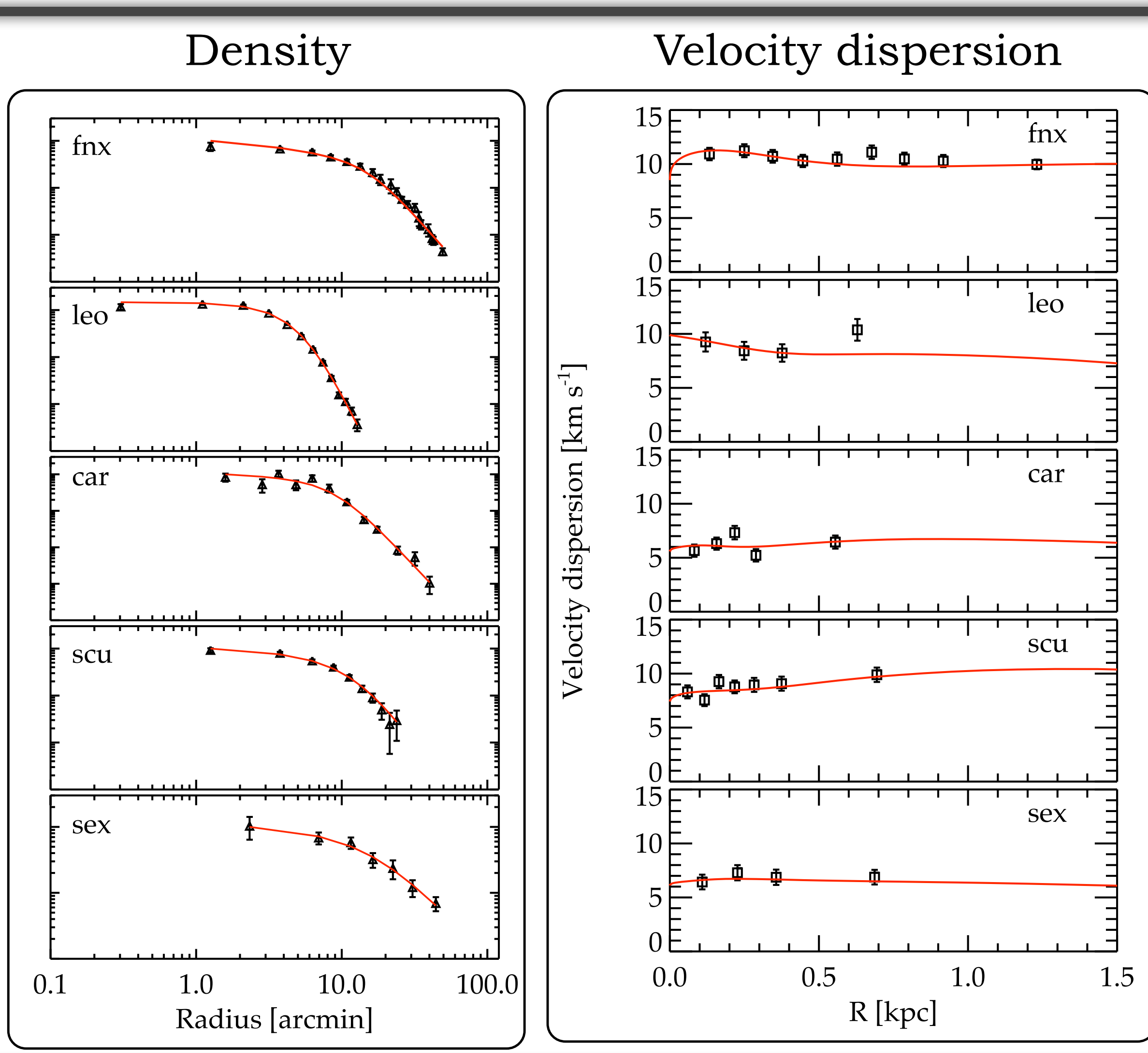
CDM-based models of dwarf spheroidals

✦ Combine jeans-based modeling with method of isotropic distribution functions [Strigari, Frenk, White MNRAS 2010]

✦ Full photometric and kinematic parameter space is very degenerate.

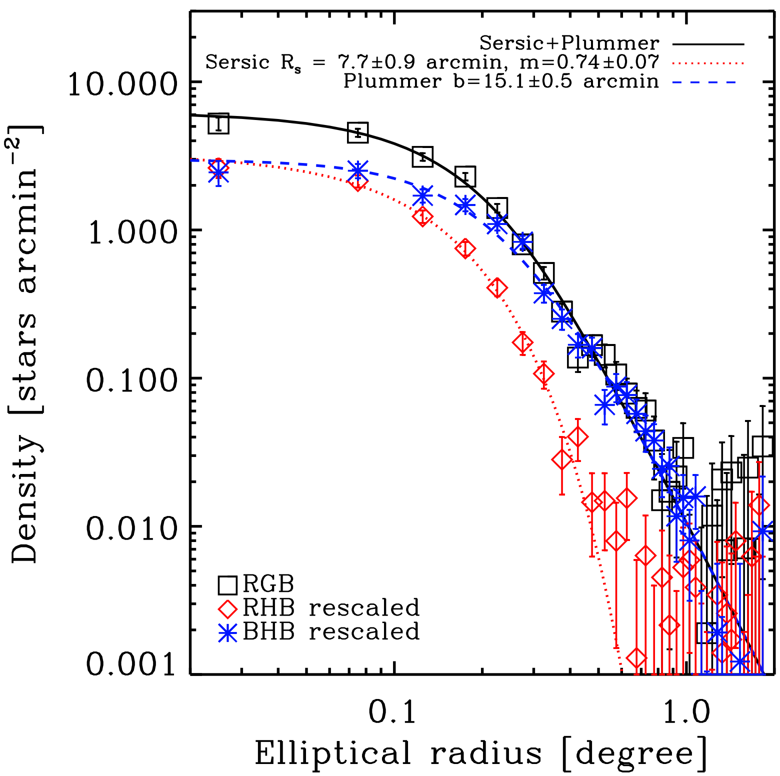
✦ CDM-based NFW models fit all dwarf spheroidals

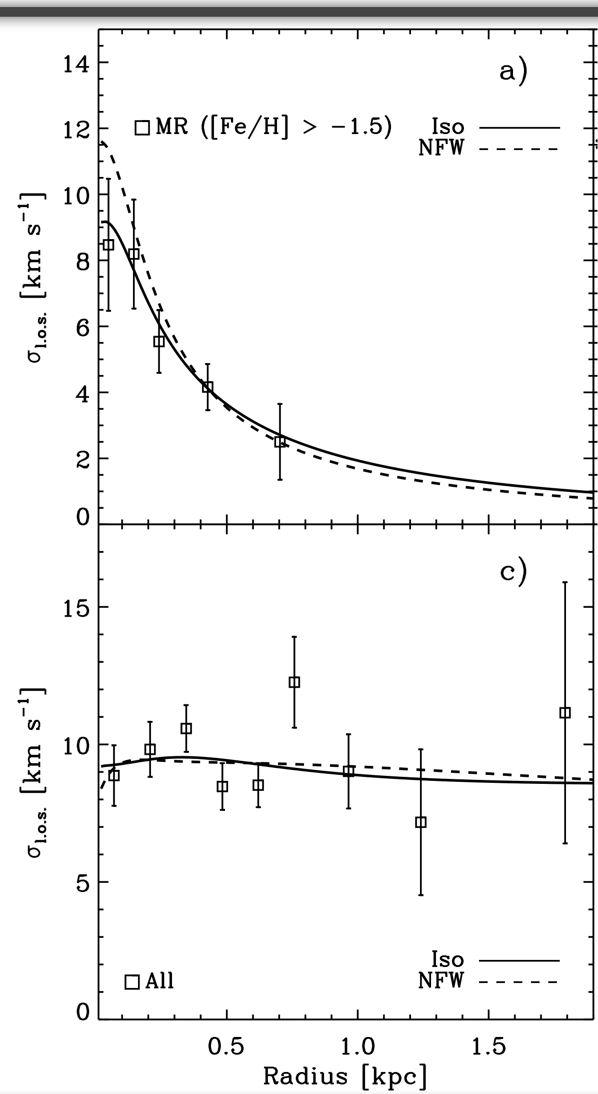
✦ Are the issues with CDM now solved?



Multiple populations in Sculptor dwarf spheroidal

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



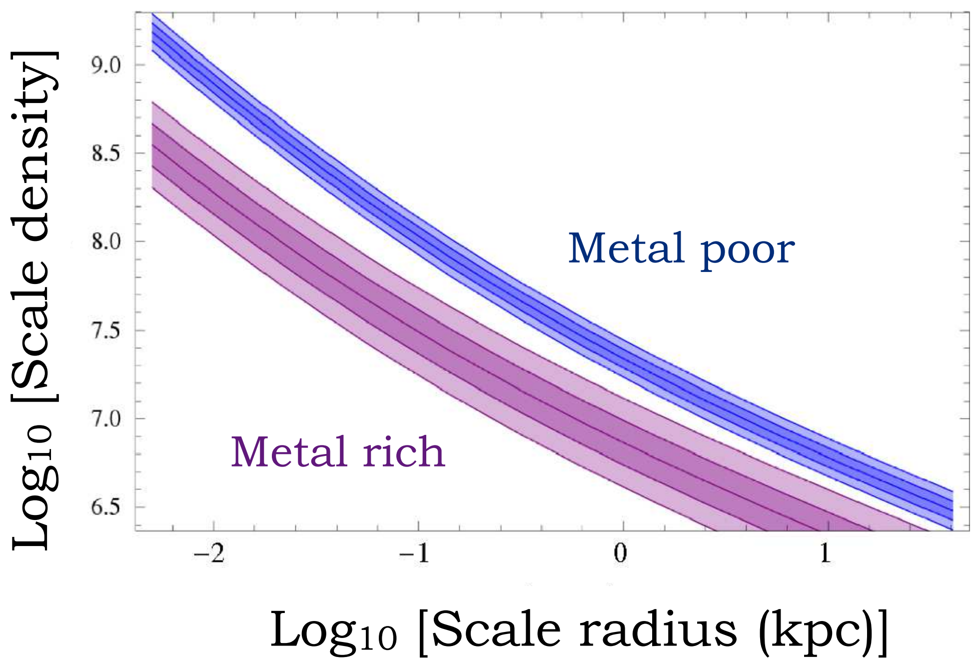


Multiple populations in Sculptor dwarf spheroidal

Mass estimators may be used to determine dark matter masses within half-light radii of galaxies [Walker et al. 2009, Wolf et al. 2009]

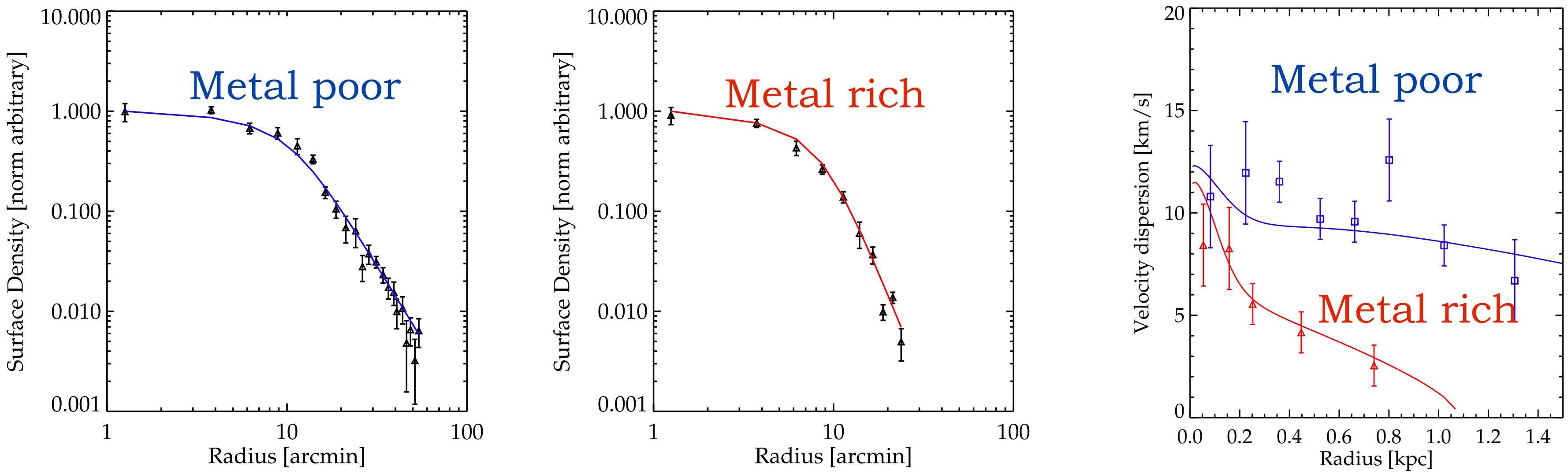
- Walker & Penarrubia (ApJ 2011) find that multiple populations are inconsistent with an NFW profile

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



Multiple populations in Sculptor dwarf spheroidal

- Construct generalized model of photometry and kinematics of dSphs
- NFW profiles *are consistent* with the multiple populations



Strigari, Frenk, White 2013 in prep

Testable predictions

- Radial orbits in the outer region of the metal rich population
- Mild cusp in the three-dimensional stellar density profile
- Forthcoming HST observations provide astrometry $<$ 10 km/s (almost the projected SIM sensitivity, e.g. Strigari et al. 2007)
- Does this analysis translate to measurements of low surface brightness galaxies? [Simon et al. 2005, Kuzio de Naray et al. 2008, Oh et al. 2011]

Counting satellites

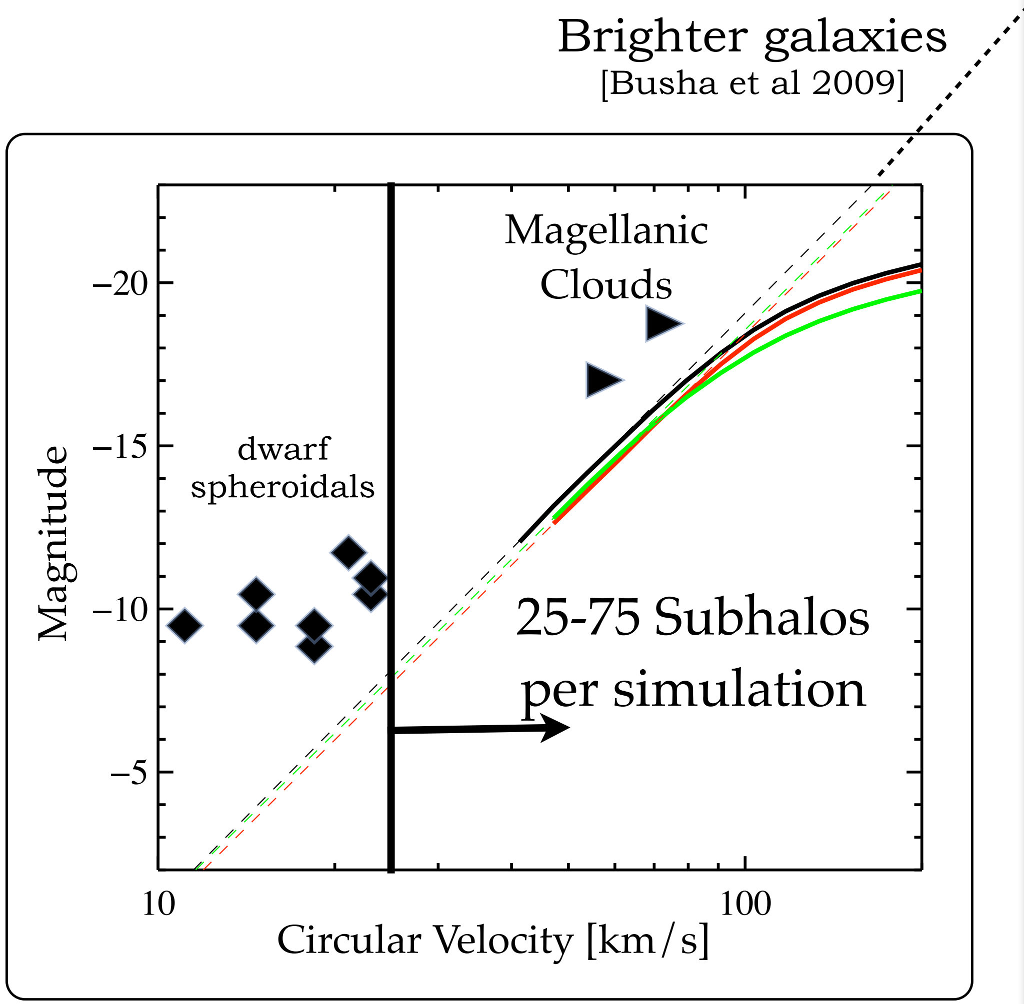
Where are the massive dark subhalos?

- *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?



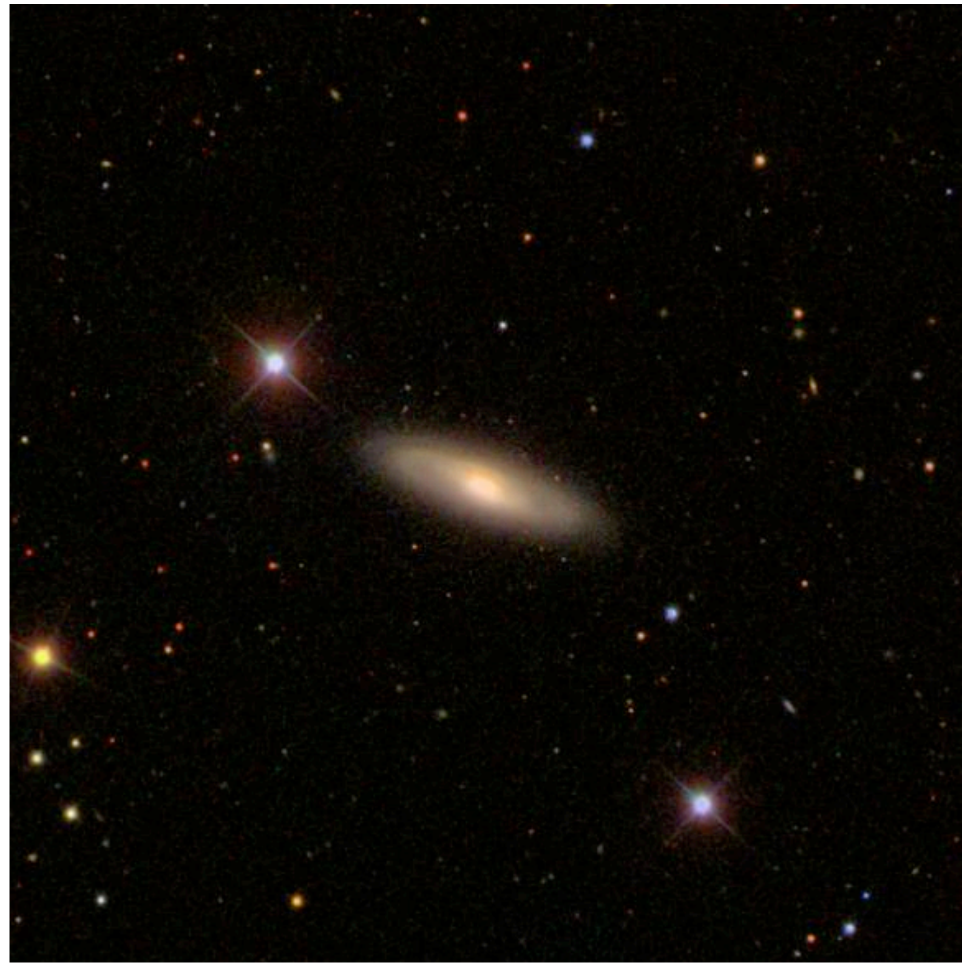
Dwarf spheroidals around other 'Milky Ways'

- 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; Robotham et al. 2012]

- 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'

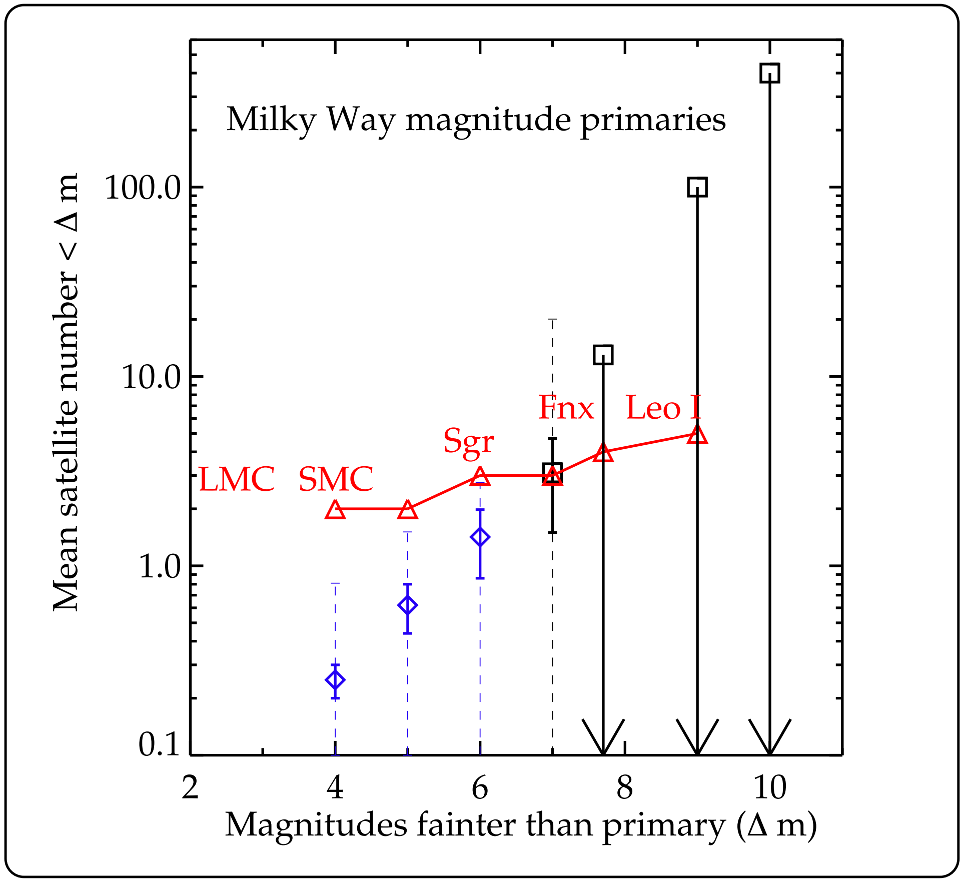


Satellites of other 'Milky Ways'

- Down to limits of modern surveys, <u>Milky Way is 'normal'</u> [Strigari & Wechsler ApJ 2012]

- Is the solution to satellites issue likely due to incomplete theory?

- Significant improvement very soon with new larger scale surveys (GAMA, DES, LSST...)



Strigari & Wechsler ApJ 2012

Galactic halo models and low mass WIMPs

About WIMP Velocity distribution

- Experiments and interpretations used the ``standard halo model" (Lewin & Smith, etc)

- Two issues with this assumption:

  1. Does not analytically correspond to an NFW/Einsto profile

  2. Several dark matter-only simulations find different distributions

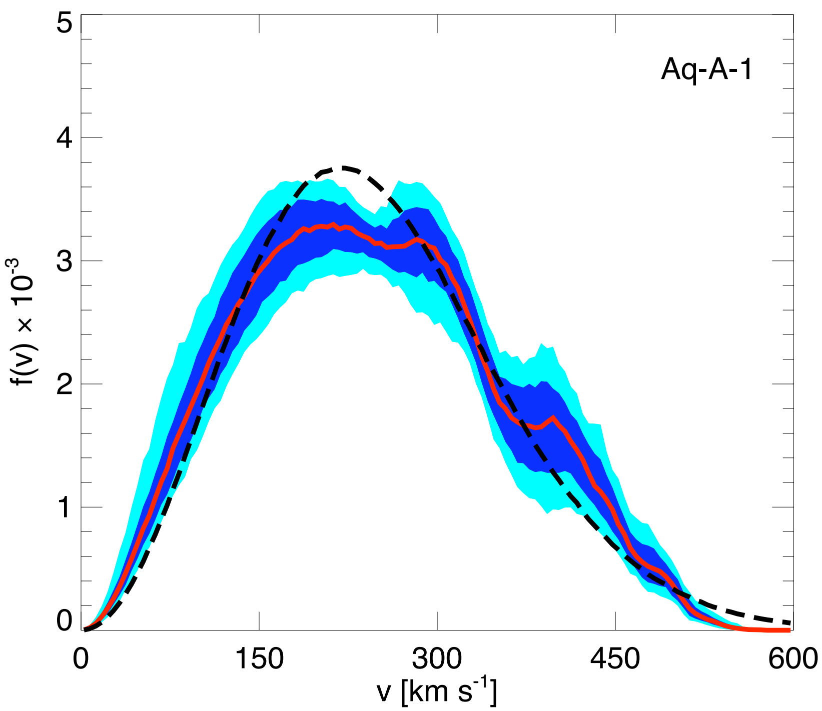
- Differences are very significant for interpretation of low mass WIMP results

- To extract mass and cross section, must propertly marginalize over Galactic halo model parameters (e.g. Pato, LS, Trotta, Bertone 2013)

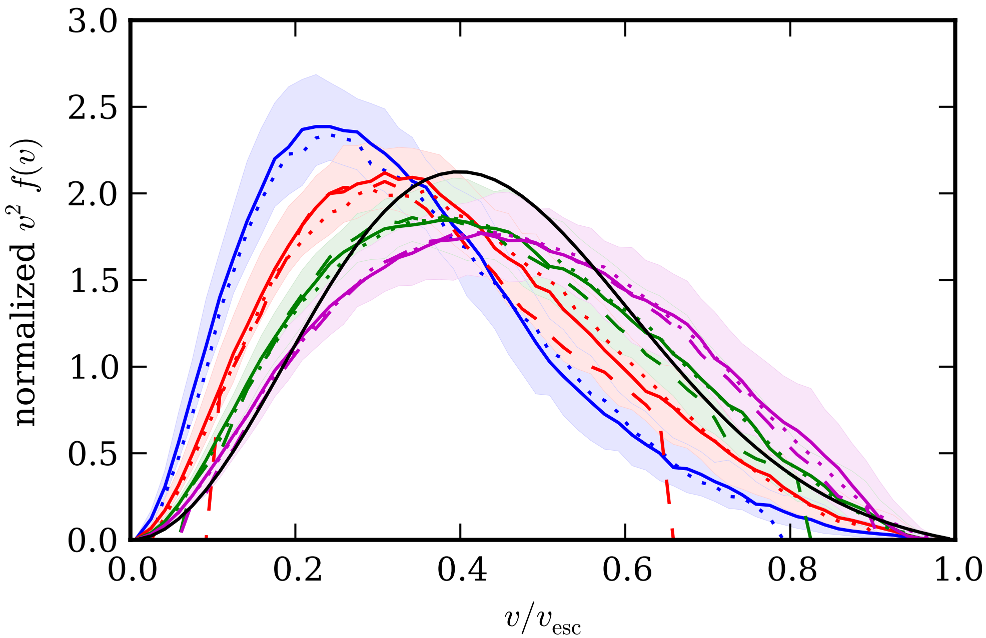
Simulation perspective

- Simulate small number of halos with very high resolution: 1 billion particles per MW halo (Vogelsberger et al 2009, Kuhlen et al. 2010)
  - Scatter in VDF at the Solar radius measurable
  - Limited halo-to-halo variance
- 'Stack' larger number of halos with lower resolution: ~10,000 particles per halo (Mao et al. ApJ 2013)
  - Better estimate of halo-to-halo variance
  - Difficult to determine scatter within halo
- Attempt to model baryonic + dark matter physics (Ling et al. JCAP 2009)

Results from simulations



Vogelsberger et al. MNRAS 2009



Colored curves represent different r/r_s

Mao et al. ApJ 2013

Results from simulations

- Over a range of halo mass (10^{12} - 10^{14} Solar mass) VDF is a function of two-parameters (Mao et al. 2013 ApJ)

$$f(|\mathbf{v}|) = \begin{cases} A \exp(-|\mathbf{v}|/v_0) \left(v_{\rm esc}^2 - |\mathbf{v}|^2\right)^p, & 0 \leq |\mathbf{v}| \leq v_{\rm esc} \\ 0, & \text{otherwise,} \end{cases}$$

$$v_0 / v_{\rm esc} = 0.0842 \log(r/r_s) + 0.289$$

- For the MW, $r/r_s \sim 0.3$

Note: r/r_s is equivalent to specifying rms velocity (Mao et al 2013 in prep)

- Note: power law index 'p' is not the asymptotic slope, defined as

$$k = \gamma - \frac{3}{2}$$

Minimizing impact of simulation scatter

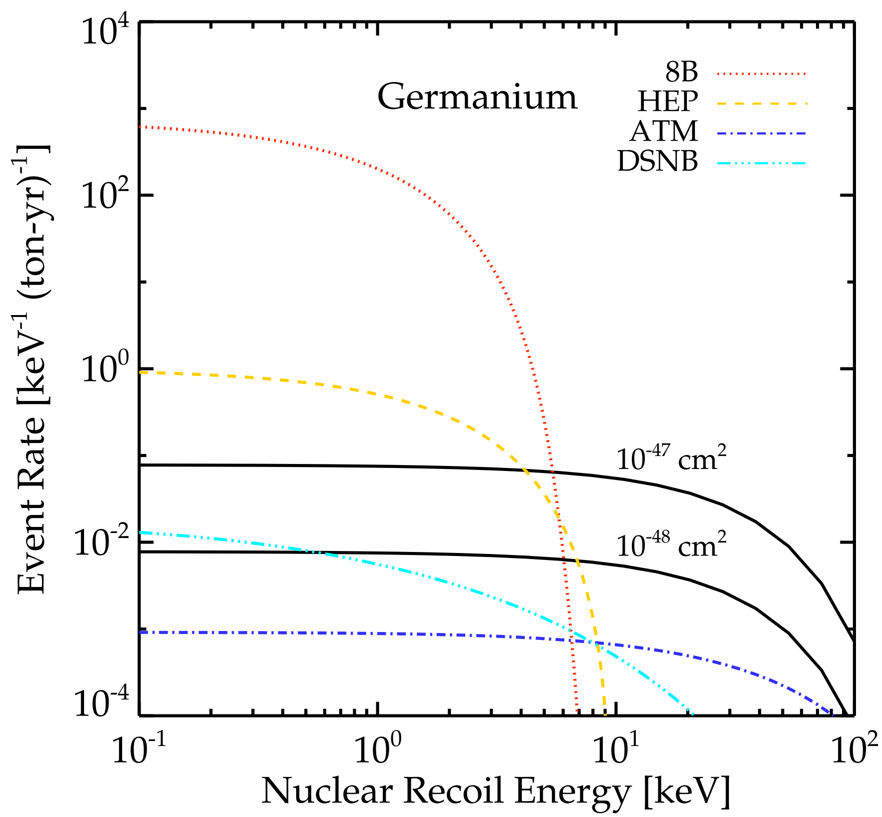
- For a given r/r_s, WIMP mass, and detector, determine the threshold energy at which scatter in the velocity distribution is minimized
    - E.g. for 8 GeV WIMP is Si, corresponding threshold is 4 keV
    - E.g. for 8 GeV WIMP is Xe, corresponding threshold is 1 keV
- Related to previous studies minimizing impact of halo velocity distribution (Fox et al 2011, Gondolo & Gelmini 2012)

Neutrinos revisited

- For low mass WIMPs, must now start to account for Solar neutrinos
- In a detector, 8B Solar neutrino spectrum corresponds to a WIMP mass and cross section
- Likelihood analysis determines how to extract WIMP spectrum from Solar, Atmospheric spectrum (Strigari 2009)

$$\mathcal{L}(N|\sigma) \propto \int_0^\infty dN_b \exp\left[\frac{-(N_b - \bar{N}_b)^2}{2\sigma_b^2}\right] \frac{e^{-\mu}\mu^N}{N!}$$

Talks here by Pradler, Harnik



Strigari, Phys. Reports 2013

Concluding remarks

Do we need alternatives to *Cold Dark Matter*?

- CDM has been challenged many times since it has been developed
- No clear evidence that it needs to be discarded (or totally believed in its current form)
- Picture should become more clear in the next few years...

Halo models & Direct Detection

- (Carefully) interpret results from numerical simulations in the context of direct detection
- Now the time to start thinking about methods to include neutrinos in the analysis