Dark matter in the Milky Way and satellites: Implications for CDM and direct detection

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Two parts of the talk

1. Extracting constraints on dark matter from dwarf spheroidals

2. Galactic halo models and low mass WIMPs

Opening statements

- Motivated by astrophysical issues and particle theory there has been renewed interest in going beyond collisionless *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, Fan et al. 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

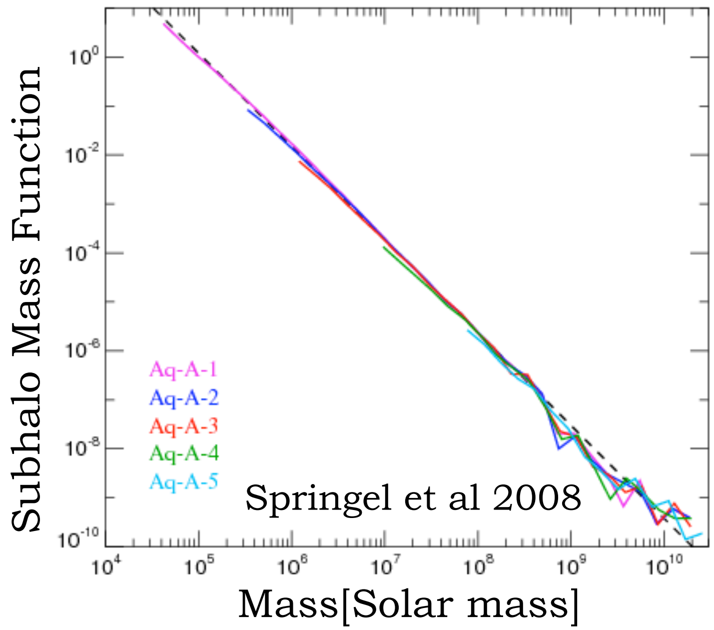
Navarro-Frenk-White (NFW), Einasto model

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

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

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
   [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

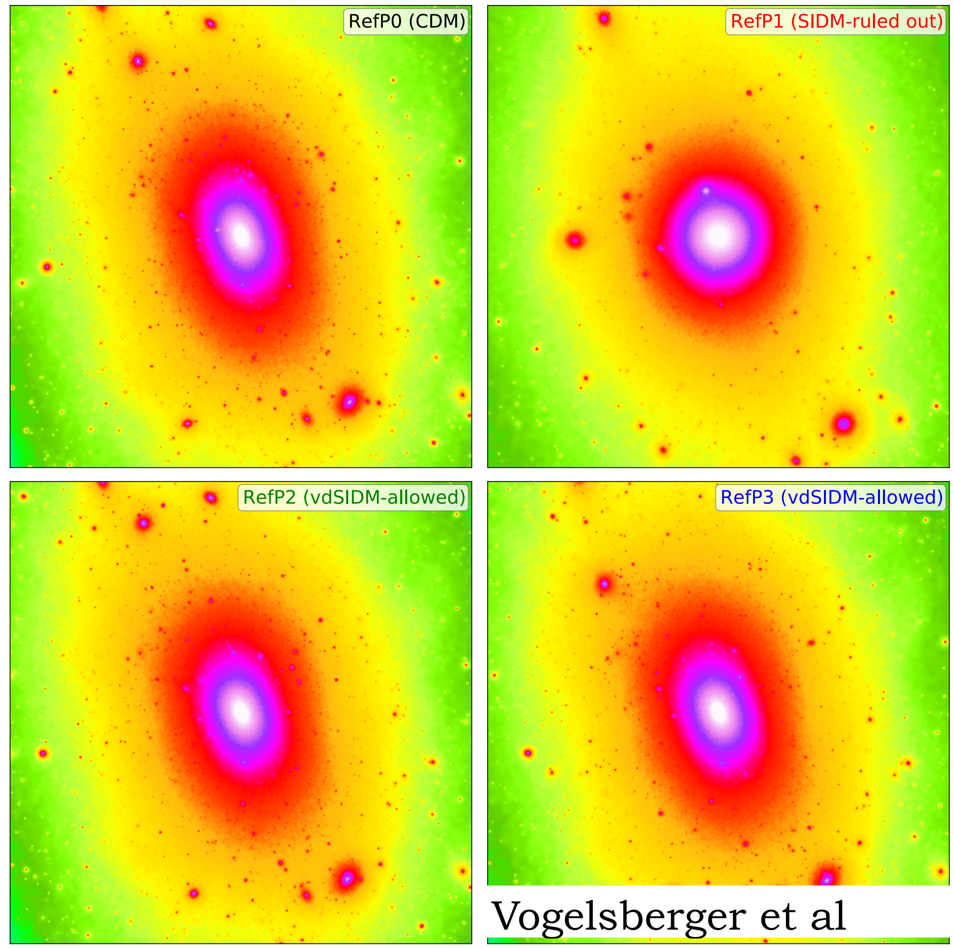
- *CDM*, and *non-CDM* models going a way towards providing more robust, testable predictions

- *Self-interacting dark matter*

  - Halos expected to be more spherical, cored central density

- *Warm dark matter*

  - Halos form at later epochs in the Universe
  - Subhalos have reduced concentrations (Lovell et al. 2011)



Vogelsberger et al

See also Rocha et al 2013, Talks by A. Peter, H. Yu, W. Dawson

Modify theory or scrutinize observations?

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

- For remainder of talk, put aside theoretical models

- Understand *observational* systematics

  1. Kinematics of dwarf spheroidals (dSphs)
  2. Counting satellites

Kinematics of dwarf spheroidals

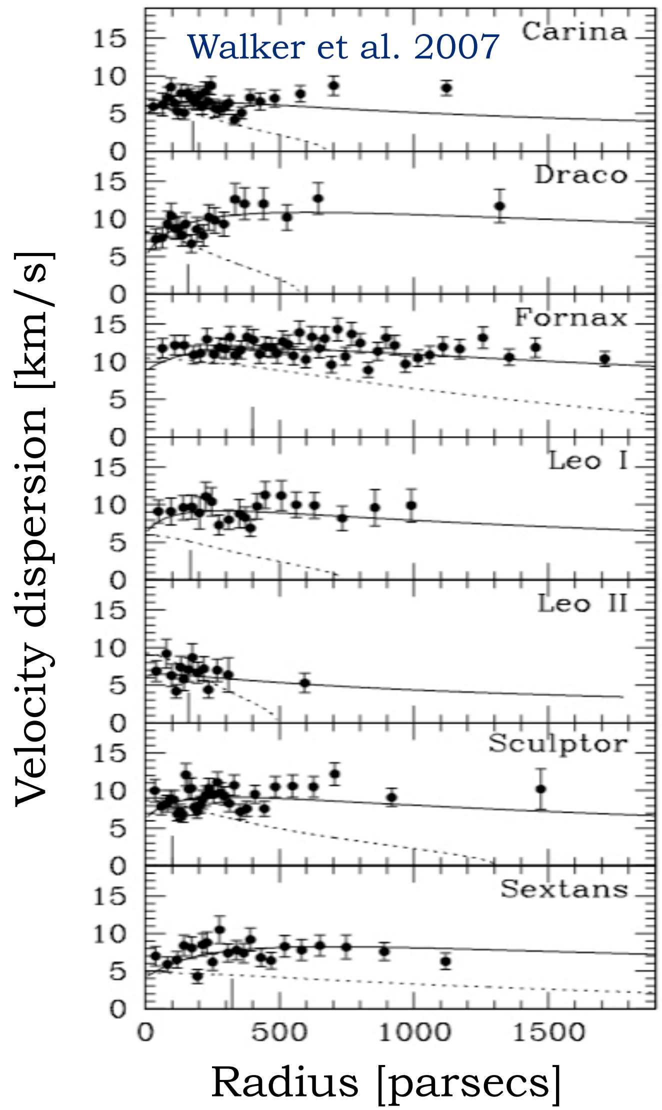
Dark matter in satellite galaxies (dwarf spheroidals)

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

- Standard modeling assumes hydrostatic equilibrium, spherical symmetry, but not isotropy [e.g. Strigari et al 2008, Lokas 2009, Walker et al 2009, Richardson & Fairbairn 2013]

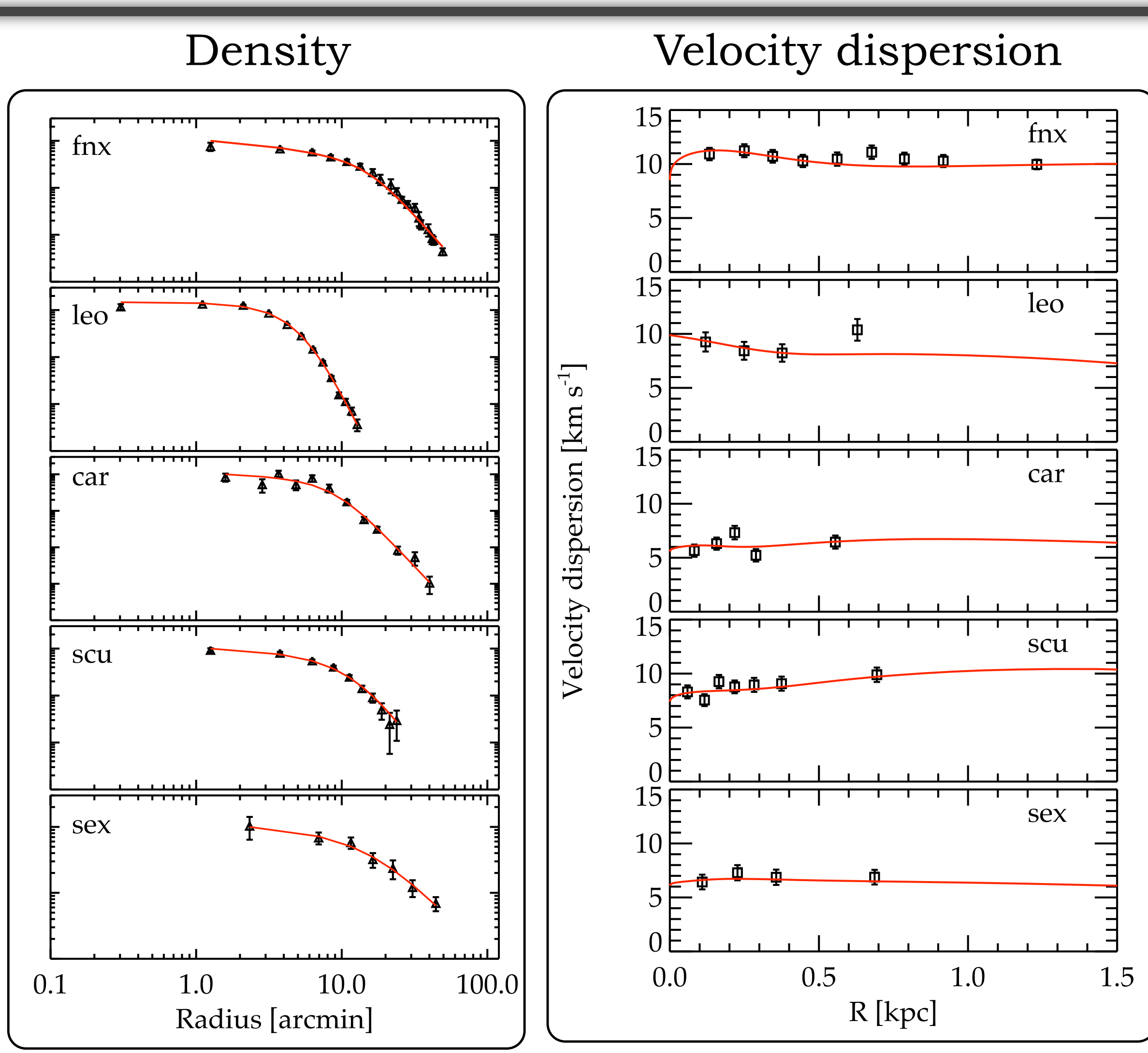
- Some corrections for non-spherical potentials [Hayashi, Chiba 2012, Kowalczyk et al. 2013]

- 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



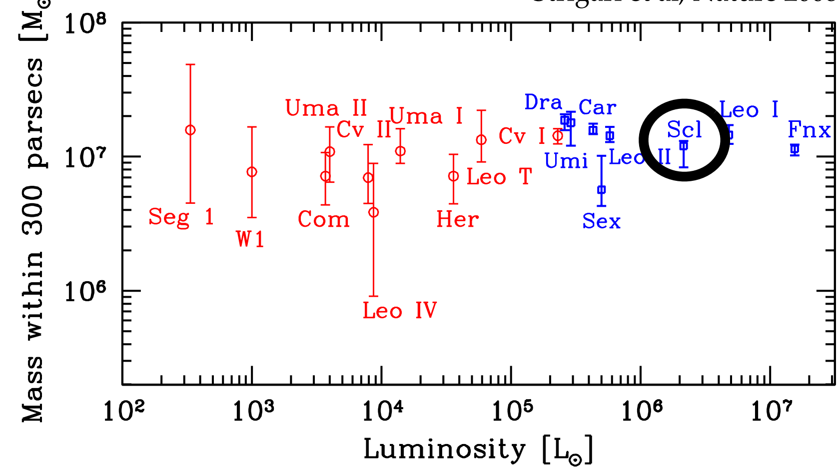
Some particular dSphs

- Ursa Minor (66 kpc)
  - Kinematically cold sub-population of stars (Kleyna et al. 2003, Sanchez-Salcedo & Lora, 2007; Lora et al. 2012 Pace et al. 2012)

- Fornax (140 kpc):
  - Five globular clusters
  - Separate sub-populations based on metallicity (Walker & Penarrubia ApJ 2011)

- Sculptor (80 kpc)
  - Population of X-ray binaries (Maccarone et al 2005)
  - Separate sub-populations based on metallicity (Battaglia et al. 2008)

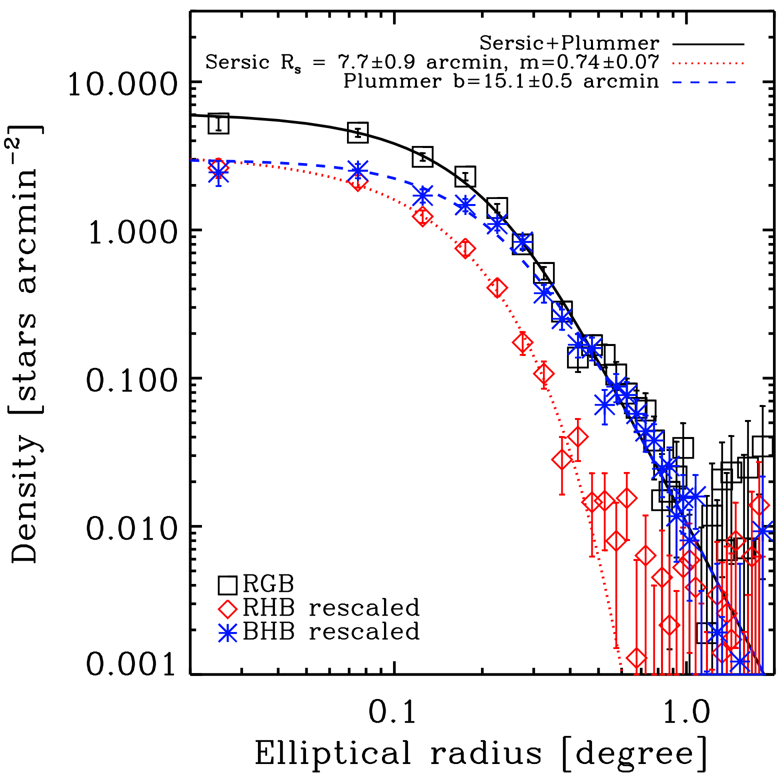
Strigari et al, Nature 2008

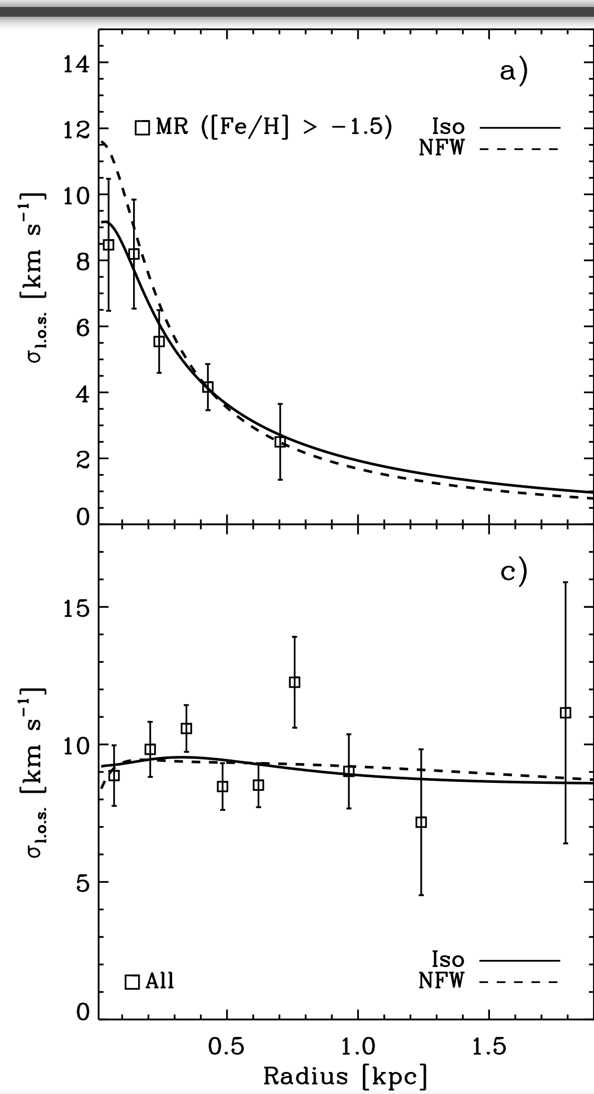


Multiple populations in Sculptor dwarf spheroidal

Metal Rich (MR) and Metal Poor (MP) population

[Battaglia et al 2008]



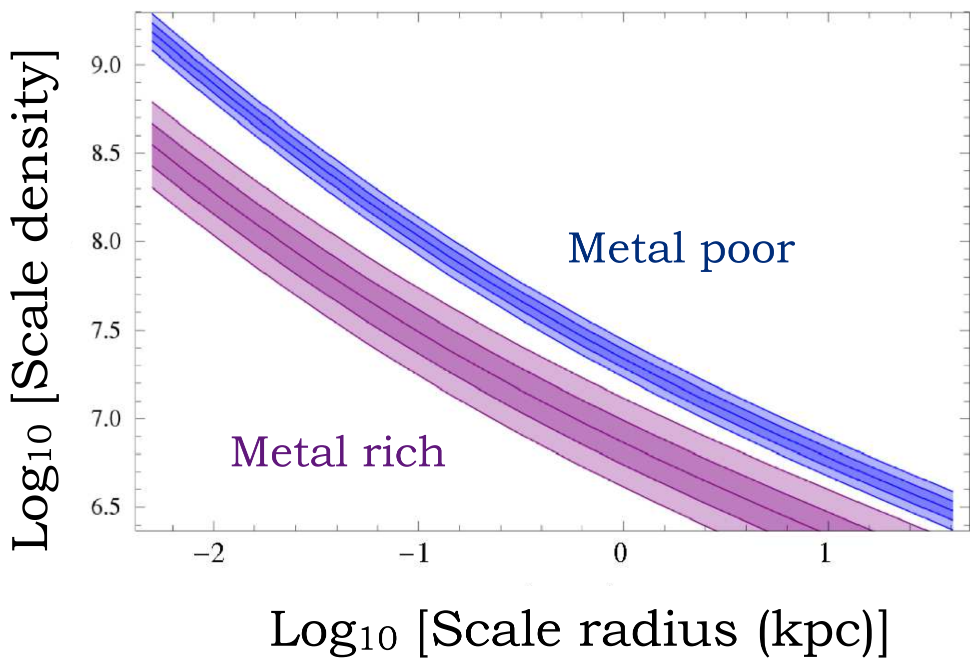


Multiple populations in Sculptor dwarf spheroidal

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

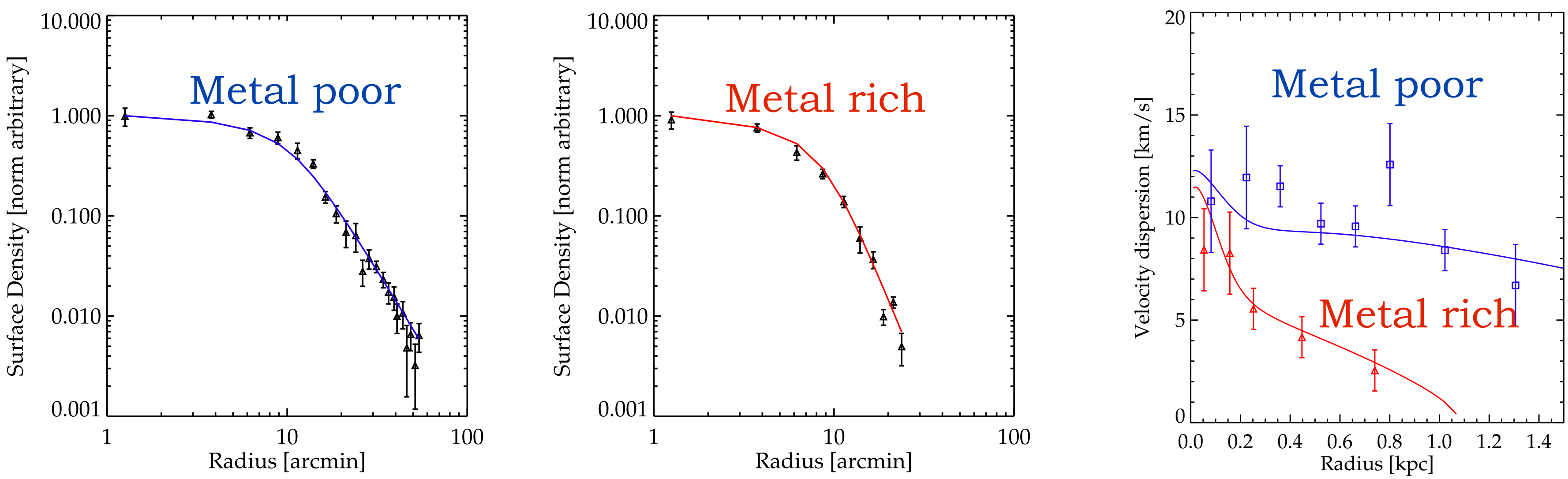
- Walker & Penarrubia (ApJ 2011) find that multiple populations are inconsistent with an NFW profile

- 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



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

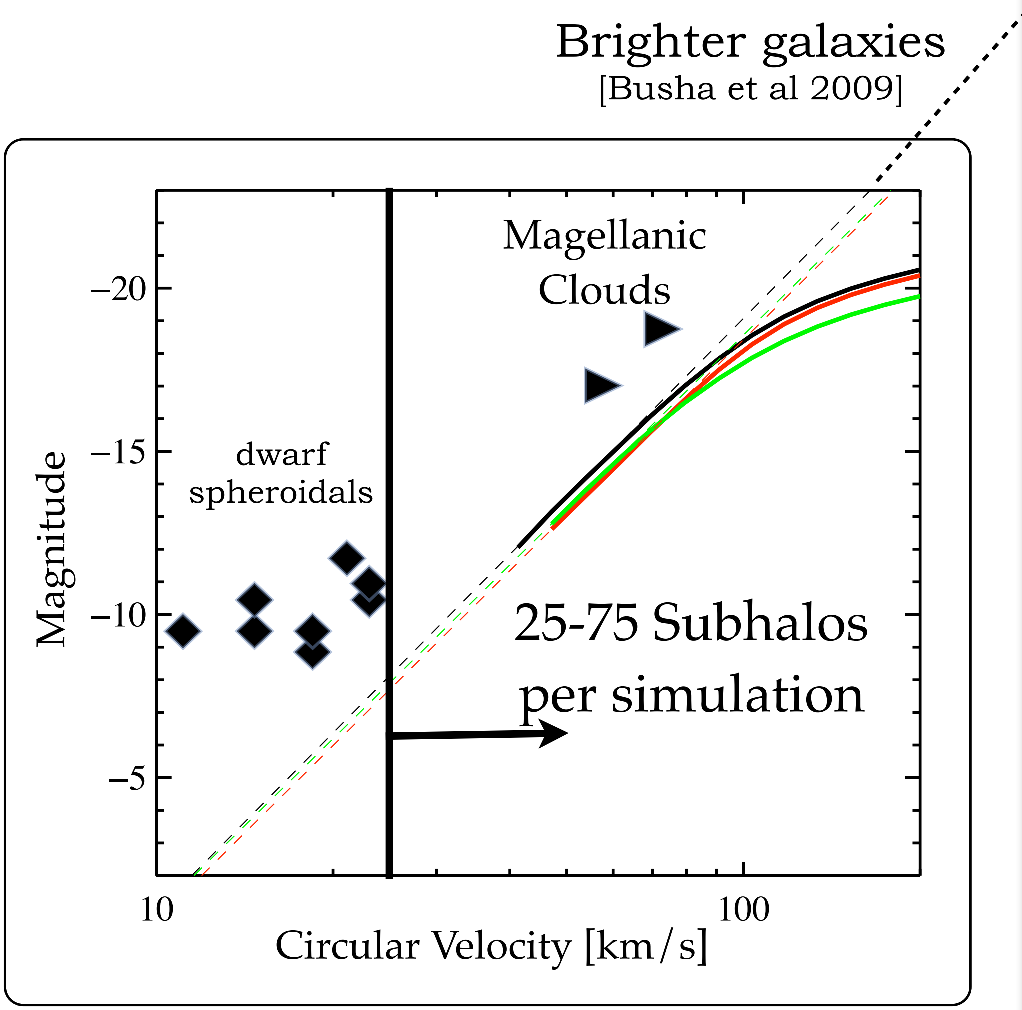
Are we missing massive dark subhalos?

- *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?



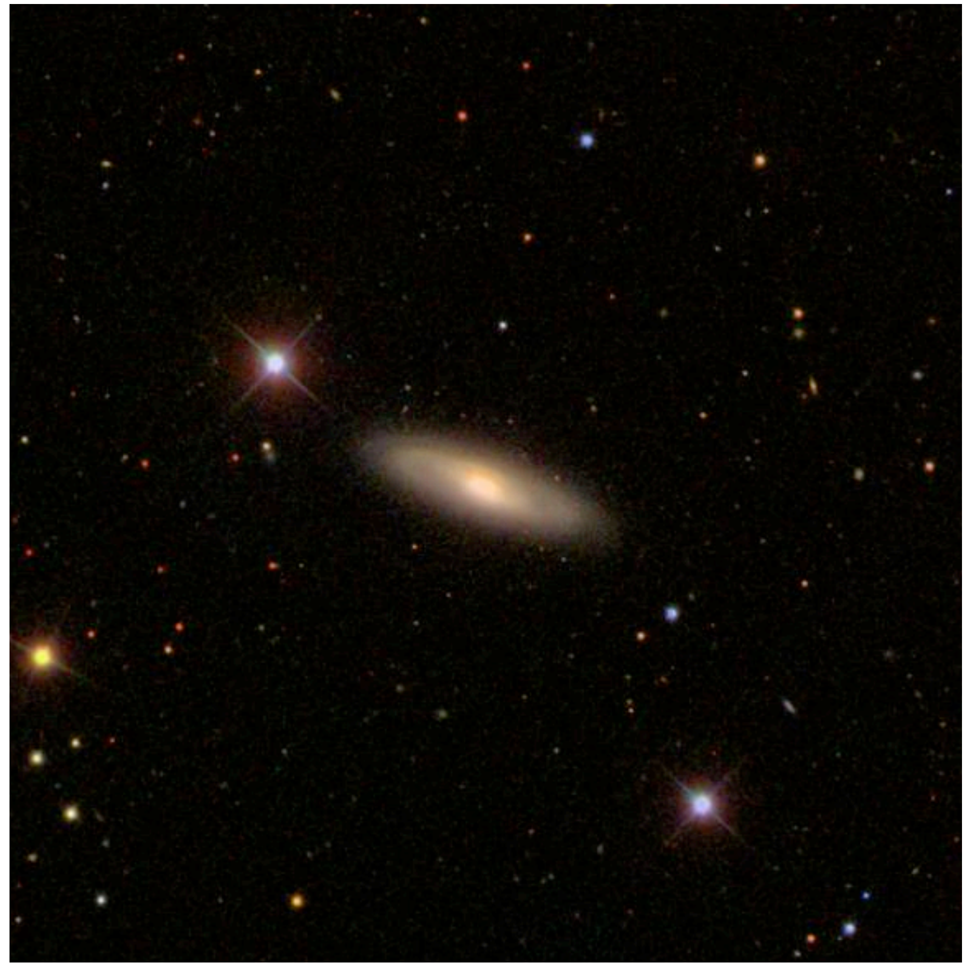
Dwarf spheroidals around other ‘Milky Ways’

- 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’

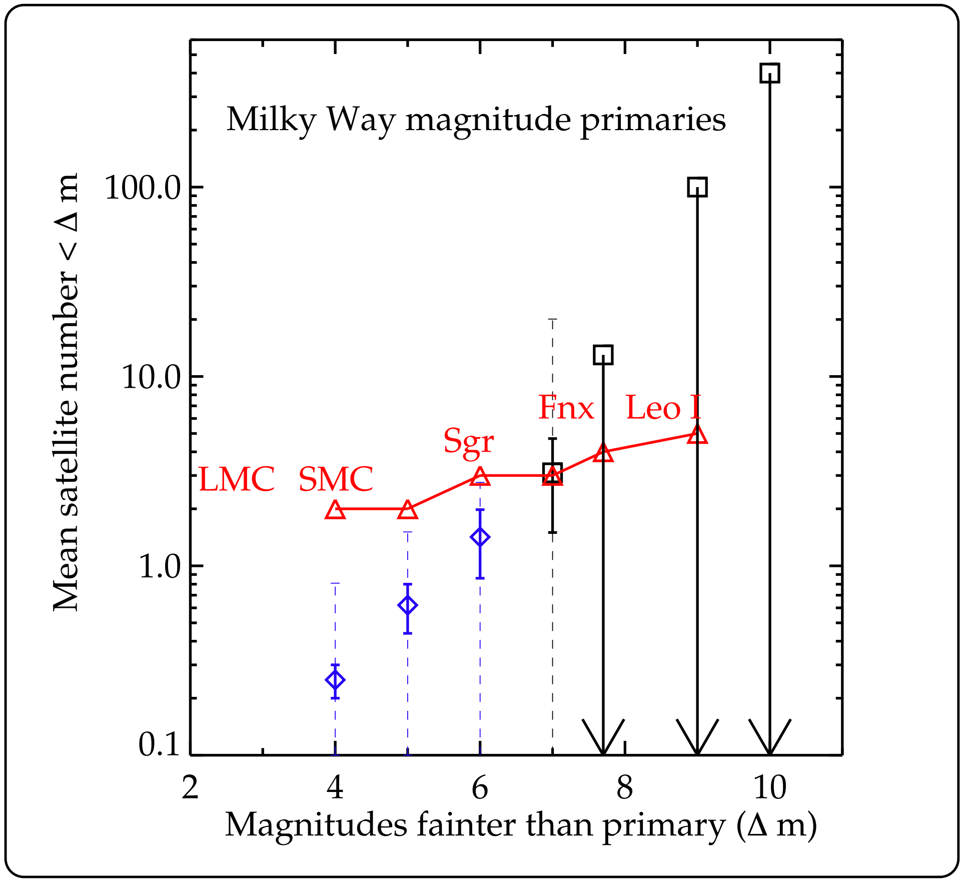


Satellites of other 'Milky Ways'

- Down to limits of modern surveys, Milky Way is 'normal' [Guo et al. MNRAS 2012; 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

Final thoughts on Satellites/TBTF Issue

- Possibly significant variation in subhalo properties for Milky Way mass hosts (Purcell & Zentner JCAP 2012)

- Given uncertain kinematics dSphs are may still be consistent with subhalos with Vmax > 30 km/s

- Mass of the Milky Way? (Wang et al. 2012; Sohn et al. 2013; Last year's KITP dwarf workshop)

- New theoretical ideas (Brooks et al 2013)

- Are we *too* worried about one galaxy?

2. Galactic halo models and low mass WIMPs

On the WIMP Velocity distribution

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

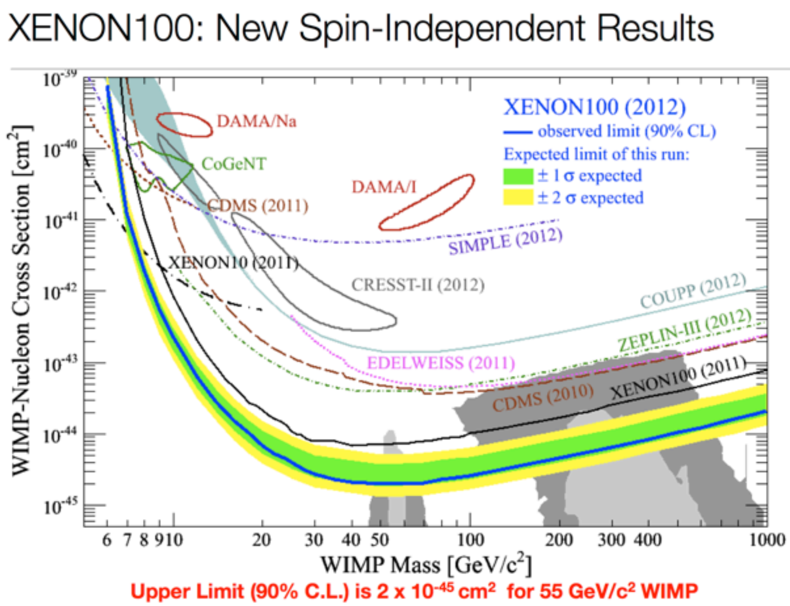
- Two issues with this assumption:

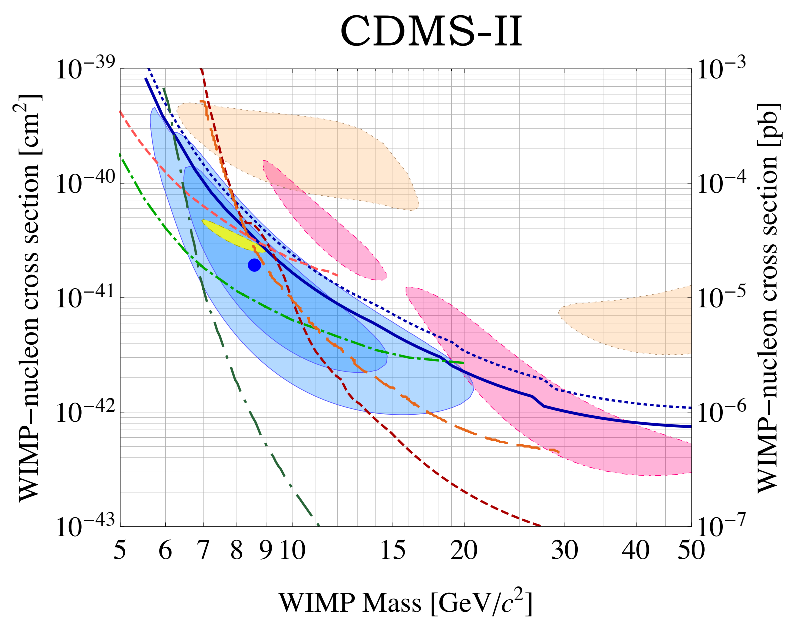
    1. Does not analytically correspond to an NFW/Einsto profile

    2. Several dark matter-only simulations find different distributions

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

Are these results consistent?

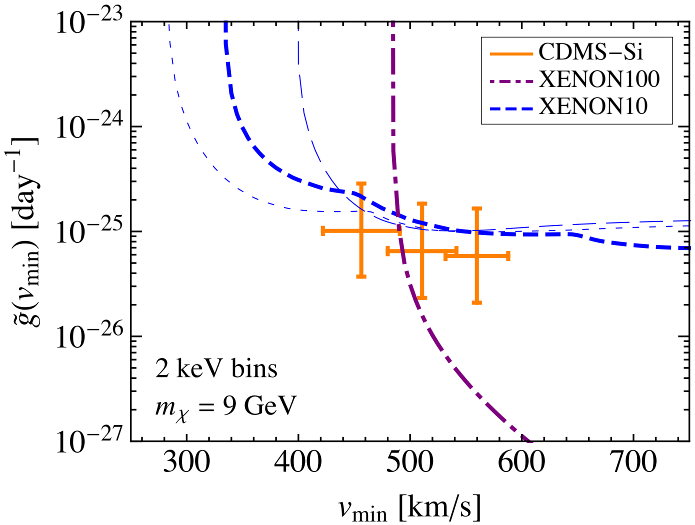




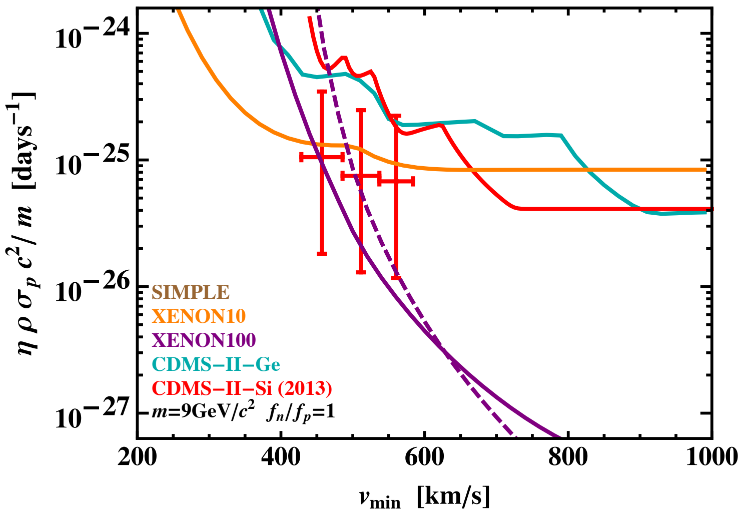
- Depends on the Vmin parameter space that is probed [Talk by P. Fox]

- Ways to make results consistent:
  1) Experimental details (R. Lang talk)
  2) Particle model (e.g. Isospin-violating DM, e.g. Feng & Kumar 2008)
  3) Galactic halo model (A. Green talk)

Applications to ``vmin” technique to CDMS, XENON100



Frandsen et al. 2013 1304.6066

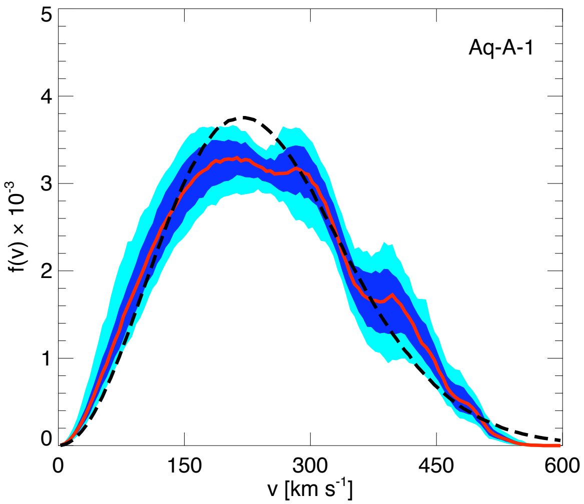


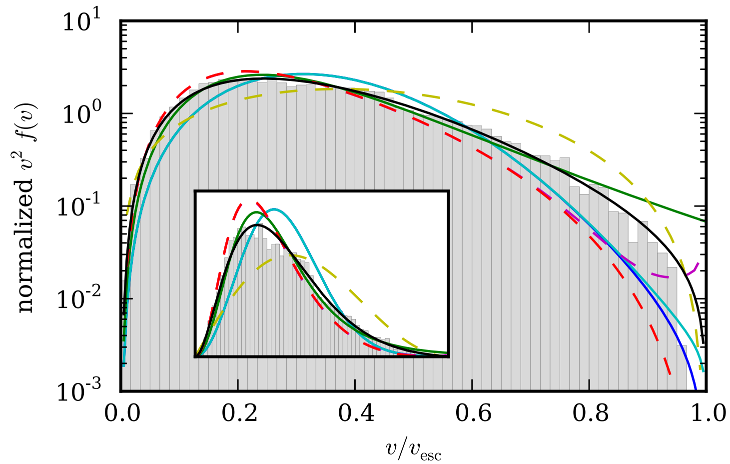
Del Nobile et al. 2013 1304.6183

- Small number of CDMS-II events, threshold, and energy resolution, complicate interpretation of overlap

- Simply assume the thresholds reported by CDMS-II, Xenon100

``Cosmological" velocity distribution





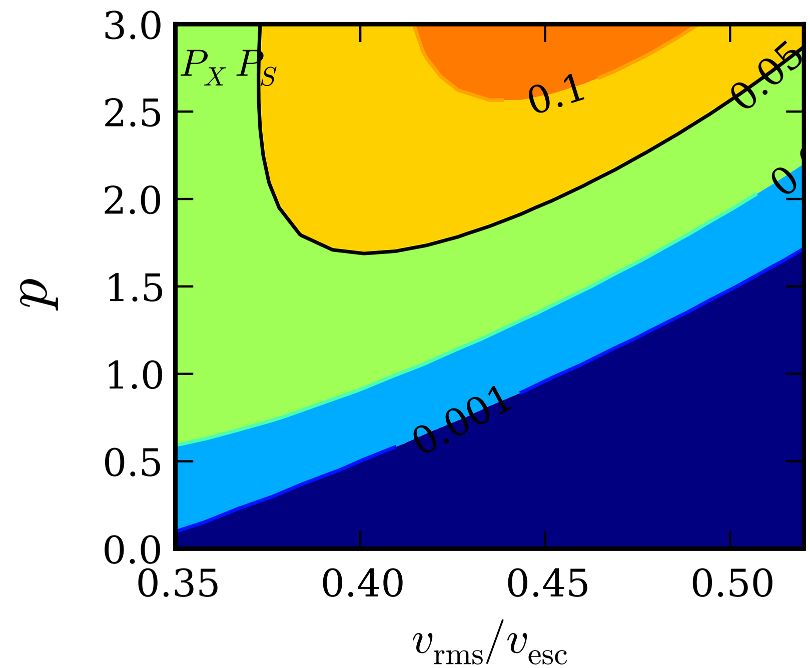
- ``Cosmological" VDF: fewer particles in the tail of the distribution, smooth fall-off to the escape velocity (e.g. Vogelsberger et al. 2009; Ling et al. 2009; Kuhlen et al. 2010; Lisanti, LS, Wacker, Wechsler 2011; Mao et al ApJ 2013; Mao et al 2013)

- Issues with halo sampling, baryons (talks by C. Frenk, R. Wechsler)

``Cosmological” velocity distribution

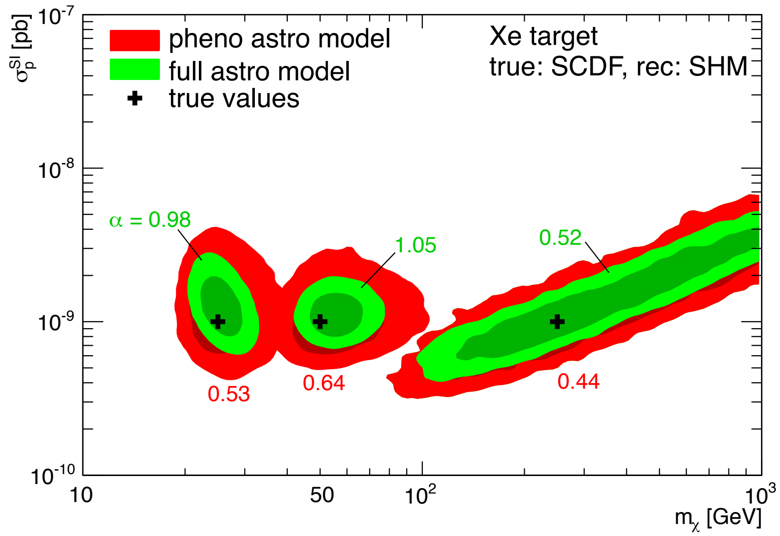
$$f(|\mathbf{v}|) = \begin{cases} A\exp(-|\mathbf{v}|/v_0)\left(v_{\rm esc}^2 - |\mathbf{v}|^2\right)^p, & 0 \le |\mathbf{v}| \le v_{\rm esc} \\ 0, & \text{otherwise,} \end{cases}$$

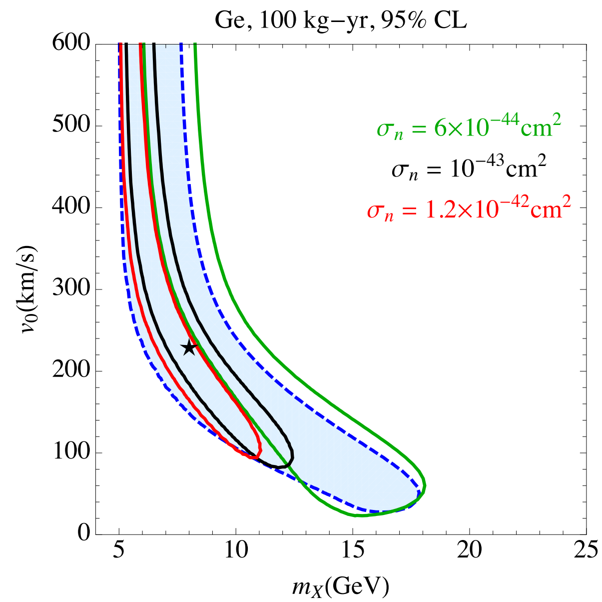
$$v_{\rm rms} \equiv \left[4\pi \int_0^{v_{\rm esc}} dv\, v^4 f(v)\right]^{1/2}$$



- For reported thresholds, Xenon 100 and CDMS-II Si results are compatible with 8.6 GeV WIMP (Mao et al 2013, 1304.6401)
- Xenon threshold at about 5.25 keV would fully test scenario

Reconstructing WIMP properties





- For ``reasonable” halo models, bias can be made to be minimal (e.g. Pato, LS, Trotta, Bertone 2013)
- Low-mass dark matter constraints strongly depend on fiducial model (e.g. Shoemaker & Friedland 2013)
- More ``model independent” approaches (e.g. Peter 2011; Kavanagh & Green 2013)

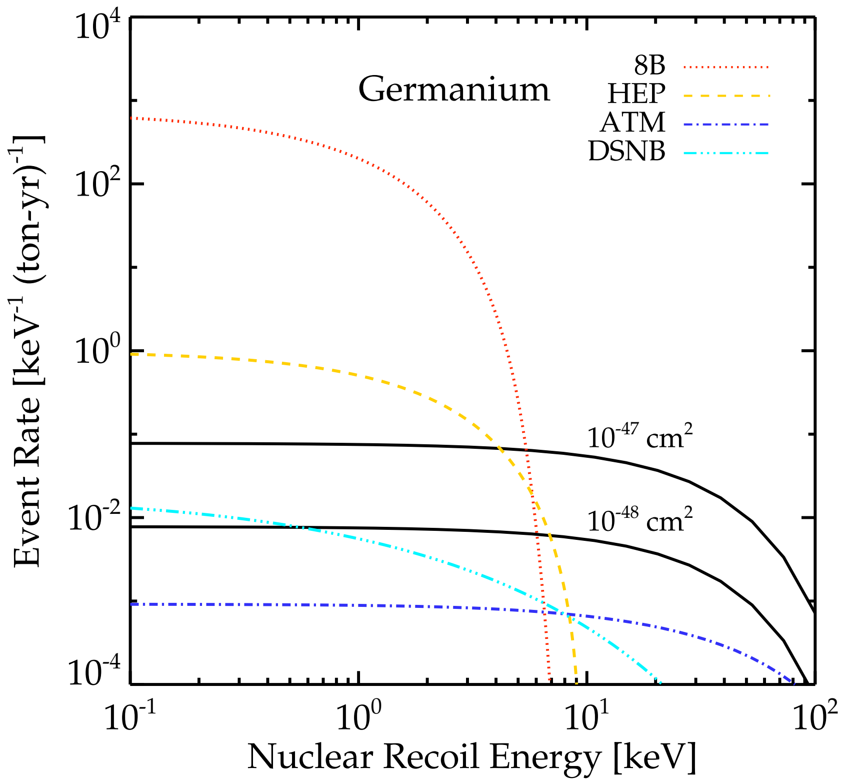
Neutrinos revisited

- 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)

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



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 continue to clarify in the next few years...

Halo models & Direct Detection

- (Carefully) interpret results in the context of non-standard velocity dark matter distributions
- We need a new CDM inspired standard *(non-standard)* halo model