Dark Matter Properties from the Faintest Galaxies

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Fermilab Astrophysics Seminar
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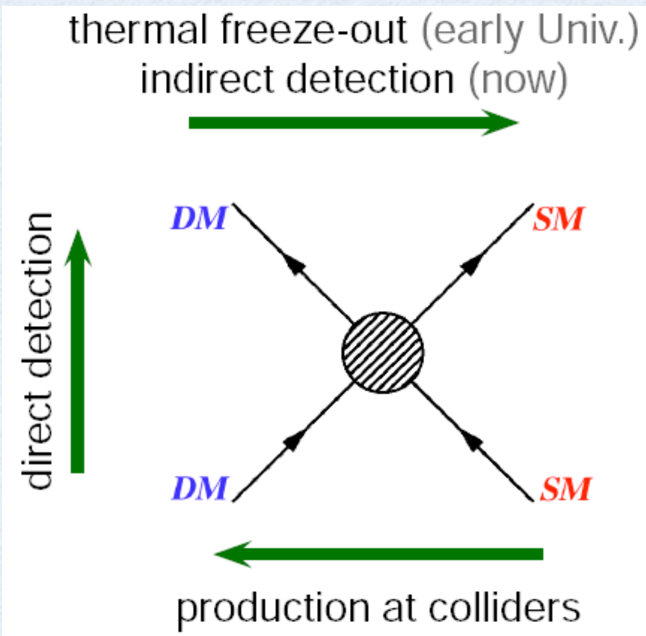
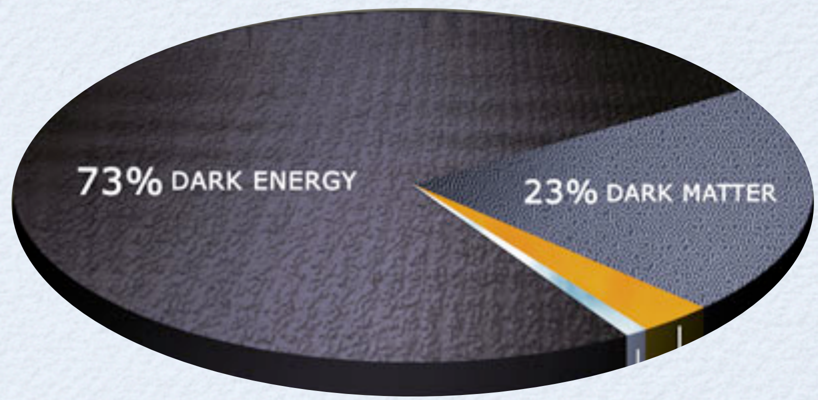
Particle Dark Matter

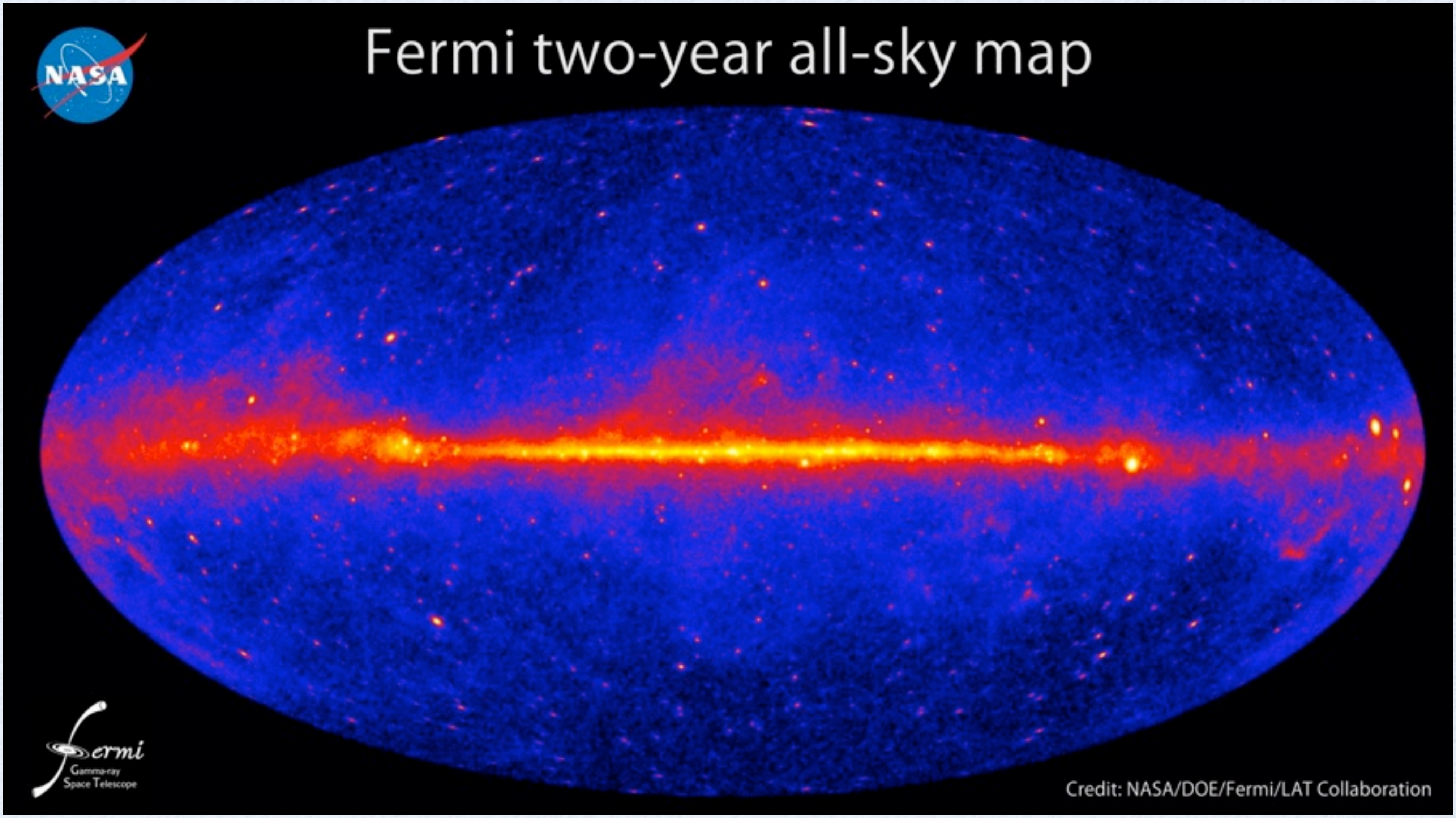
Weakly Interacting Massive Particles (WIMPs) in equilibrium in early Universe, may freeze-out with significant relic abundance

$$\sigma v \sim 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$



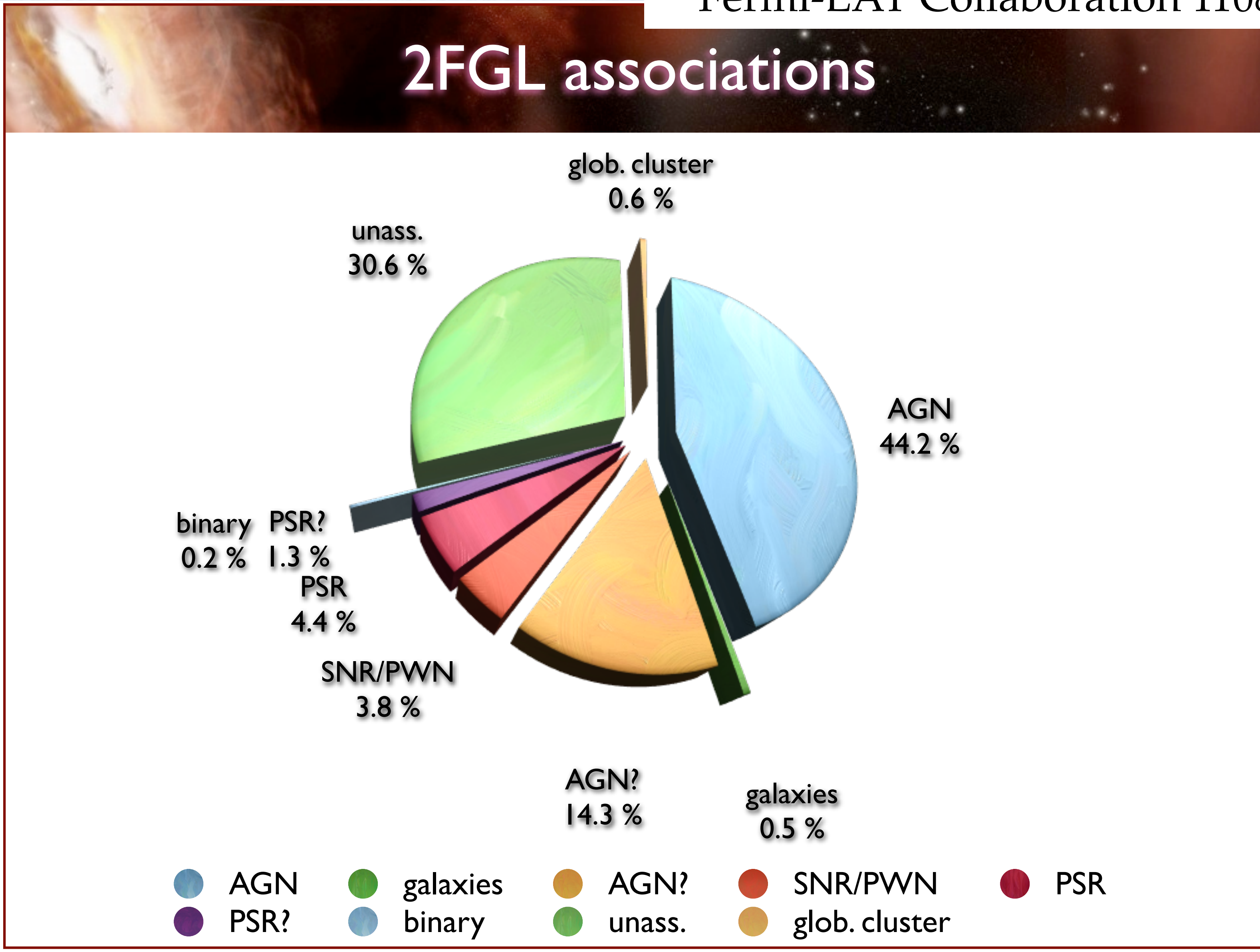


$$\sigma v = a + b v^2 = [\sigma v]_0 \left(1 + \frac{b}{a} v^2\right)$$


Fermi two-year all-sky map
NASA
fermi
Gamma-ray
Space Telescope
Credit: NASA/DOE/Fermi/LAT Collaboration

Point Sources in Fermi

Fermi-LAT Collaboration 1108.1435



Notable non-Fermi sources (yet)

- Galaxy clusters [Pinzke, Pfrommer, Bergstrom 2011; Gao et al. 2012; Ando & Nagai 2012; Han et al. 2012]
- Dwarf spheroidals (dSphs) [Tyler 2002; Evans, Ferrer, Sarkar 2004; Strigari et al. 2007, 2008]
- (Optically) dark subhalos [Tasitsiomi & Olinto 2002; Koushiappas et al. 2004; Pieri et al. 2008; Baltz et al. 2008; Springel et al. 2008; Anderson et al. 2010; Baxter et al. 2011; Buckley & Hooper 2011; Belikov et al. 2011]

If they are dark matter sources, then:

$$\left\{ \int_{E_{\rm th}}^{M_\chi} \sum_i \frac{dN_{\gamma,i}}{dE} \frac{\langle \sigma v \rangle_i}{M_\chi^2} \, dE \right\} \left\{ \int_0^{\Delta\Omega} \left\{ \int_{\rm LOS} \rho^2[r(\theta, \mathcal{D}, s)] \, ds \right\} d\Omega \right\}$$

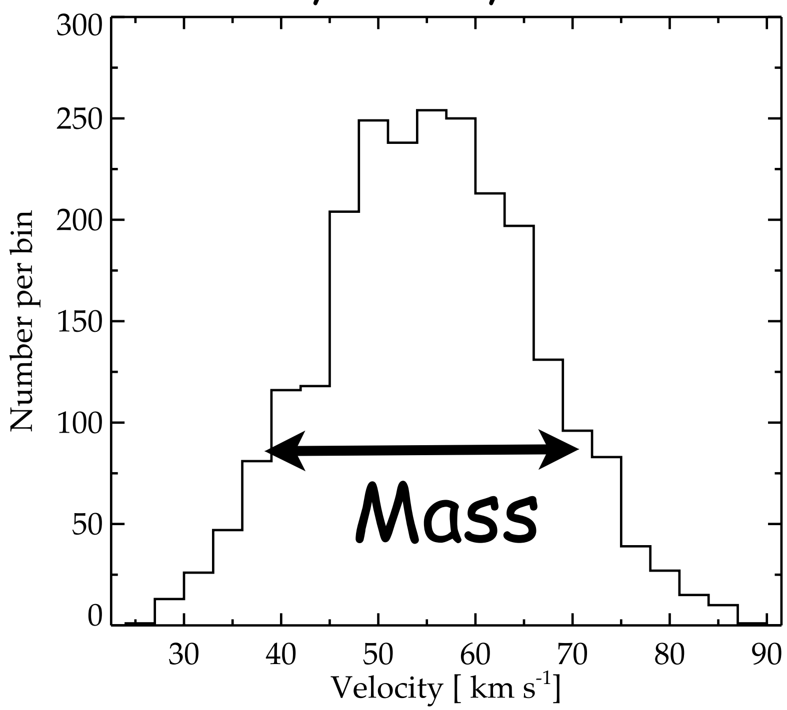
J value

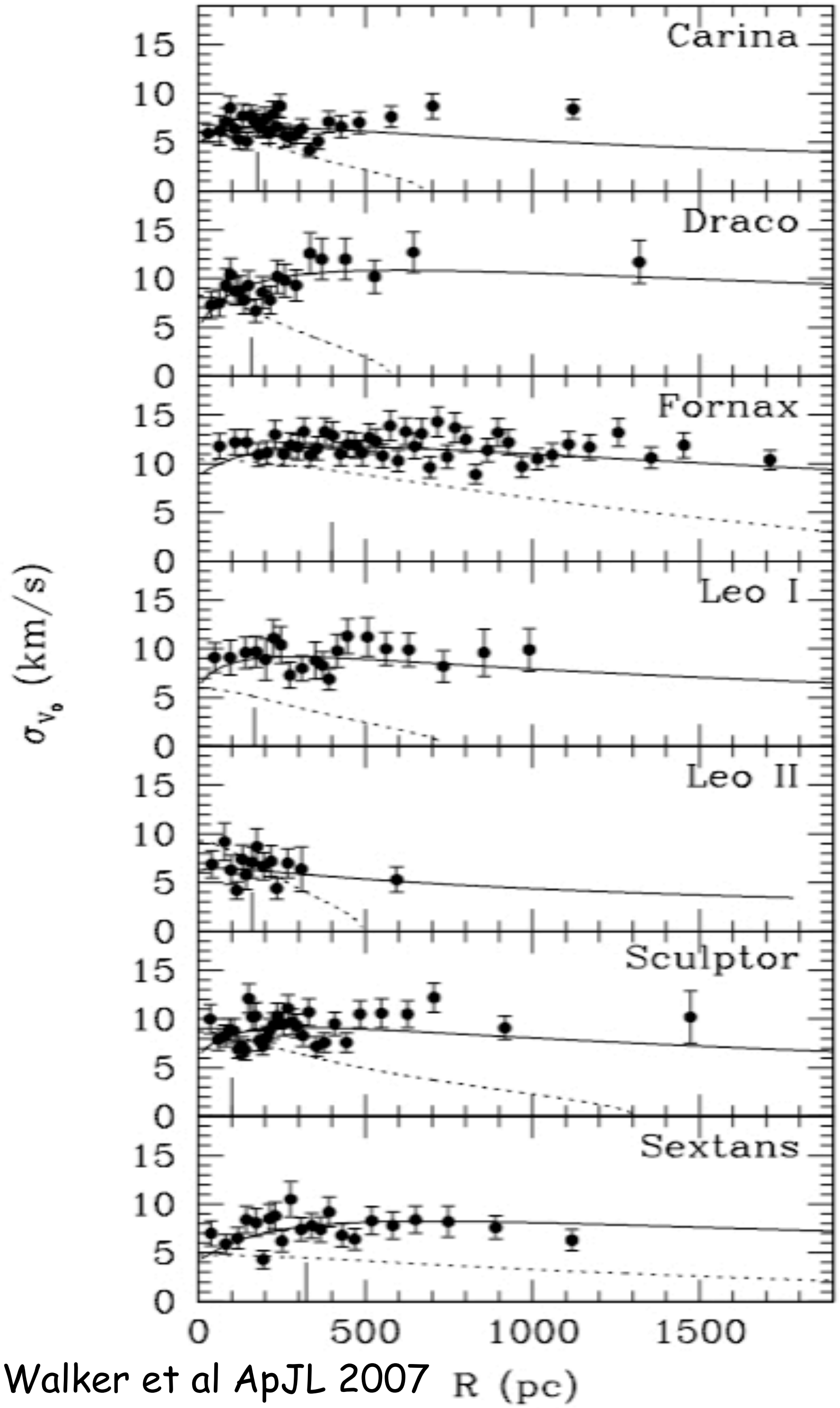
Search for dark matter from dSphs

- Well understood dark matter distributions
- Nearby, may be modeled as point sources
- No sources of gamma-rays from cosmic rays or star formation

Large Dark-to-Luminous mass ratios

Walker, Mateo, et al. 2009





Walker et al ApJL 2007

Outstanding questions

- How precise can the masses be determined? (Strigari et al. ApJ 2007; Lokas et al. MNRAS 2009; Walker et al ApJ 2009; Wolf et al. MNRAS 2009)
- Do CDM-based NFW profiles provide best model? Core/cusp issue? (e.g. Gilmore et al. ApJ 2007; Walker & Penarrubia ApJ 2011)
- Degeneracy with kinematics variables (e.g. light profile, anisotropy of stars) (Strigari, Kaplinghat, Bullock, 2007 ApJL; Evans and An MRNAS 2008)?
- Are the kinematic solutions self-consistent?

Standard dSph Kinematics Cookbook

$$\sigma^2_{los}(R) = \frac{2}{I_\star(R)} \int_R^\infty \left(1 - \beta\frac{R^2}{r^2}\right) \frac{\nu_\star \sigma_r^2 r dr}{\sqrt{r^2 - R^2}}$$

- Model both the stellar and the dark matter distribution
- Statistics of stellar orbits (velocity anisotropy)
- Assume hydrostatic equilibrium, determine mass
- Warning!: acceptable solutions don't guarantee consistent distribution function

$$\mathcal{L}(\mathscr{A}) \equiv P(\{v_i\}|\mathscr{A}) = \prod_{i=1}^{n} \frac{1}{\sqrt{2\pi(\sigma^2_{los,i} + \sigma^2_{m,i})}} \exp\left[-\frac{1}{2}\frac{(v_i - u)^2}{\sigma^2_{los,i} + \sigma^2_{m,i}}\right]$$

Testing for self-consistency

- Assuming Isotropic Orbits:

$$f(\mathcal{E}) = \frac{1}{\sqrt{8}\pi^2}\left[\int_0^{\mathcal{E}} \frac{\mathrm{d}^2\rho}{\mathrm{d}\Psi^2}\frac{\mathrm{d}\Psi}{\sqrt{\mathcal{E}-\Psi}} + \frac{1}{\mathcal{E}^{1/2}}\left(\frac{\mathrm{d}\rho}{\mathrm{d}\Psi}\right)_{\Psi=0}\right]$$

- Simplest constant anisotropy models:

$$f(E,L) = L^{-2\beta} f_E(E)$$

- Simplest radially-varying anisotropy models [Osipkov-Merritt]

$$\beta = 1 - \frac{\sigma_\theta^2 + \sigma_\phi^2}{2\sigma_r^2} \quad = \quad \frac{1}{1+(r_a/r)^2}$$

Testing LCDM with subhalo kinematics

- Consider a subhalo in simulation
- Imagine a galaxy with the stellar density profile lives there
- Predict velocity dispersion (assuming isotropy)
- Compare with observed velocity dispersion
- Test goodness-of-fit

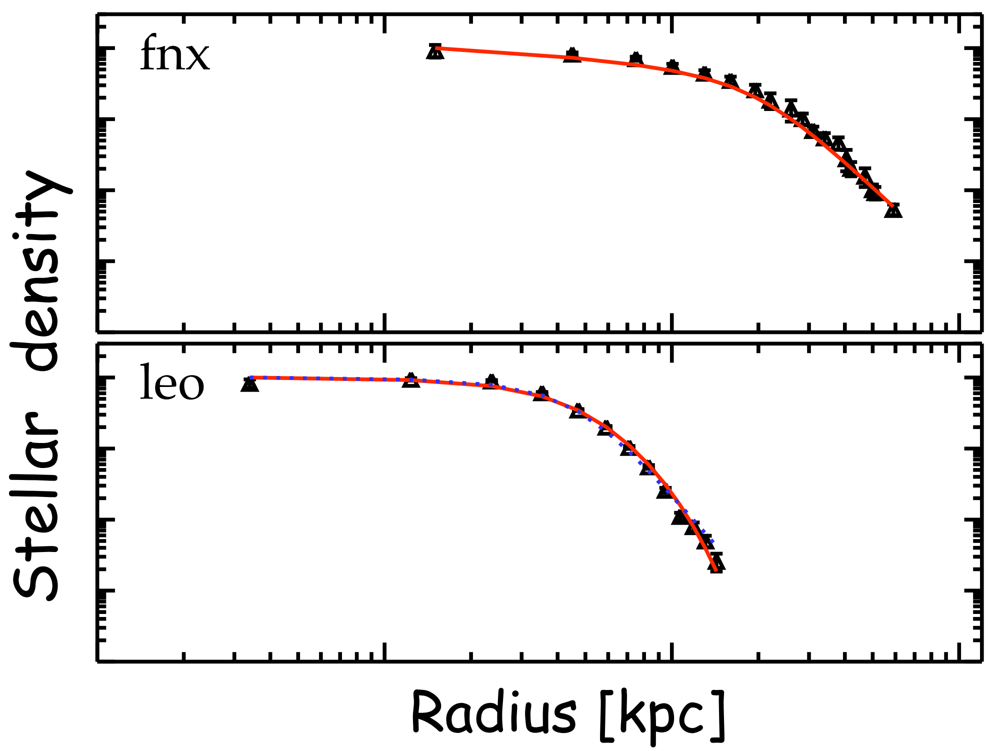
dSph Photometric profiles

Core in 3D

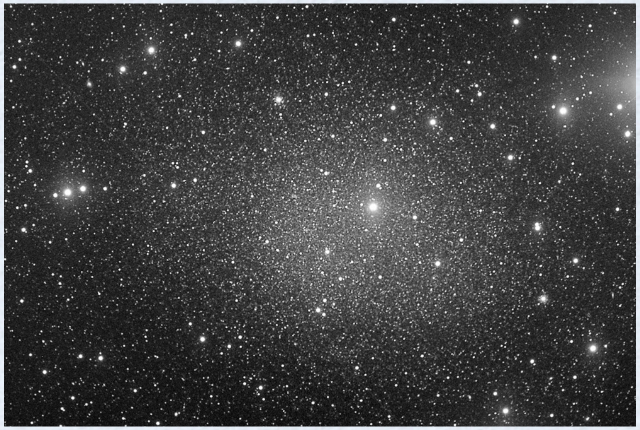
$$\rho_{\rm pl}(r) = \frac{\rho_0}{[1 + (r/r_{\rm pl})^2]^{5/2}}$$

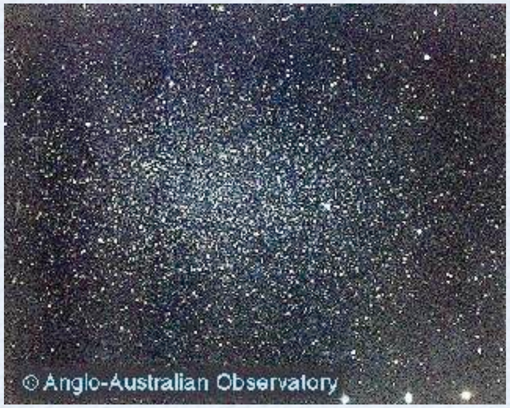
Cusp in 3D

$$\rho_\star(r) \propto \frac{1}{x^a(1 + x^b)^{(c-a)/b}}$$

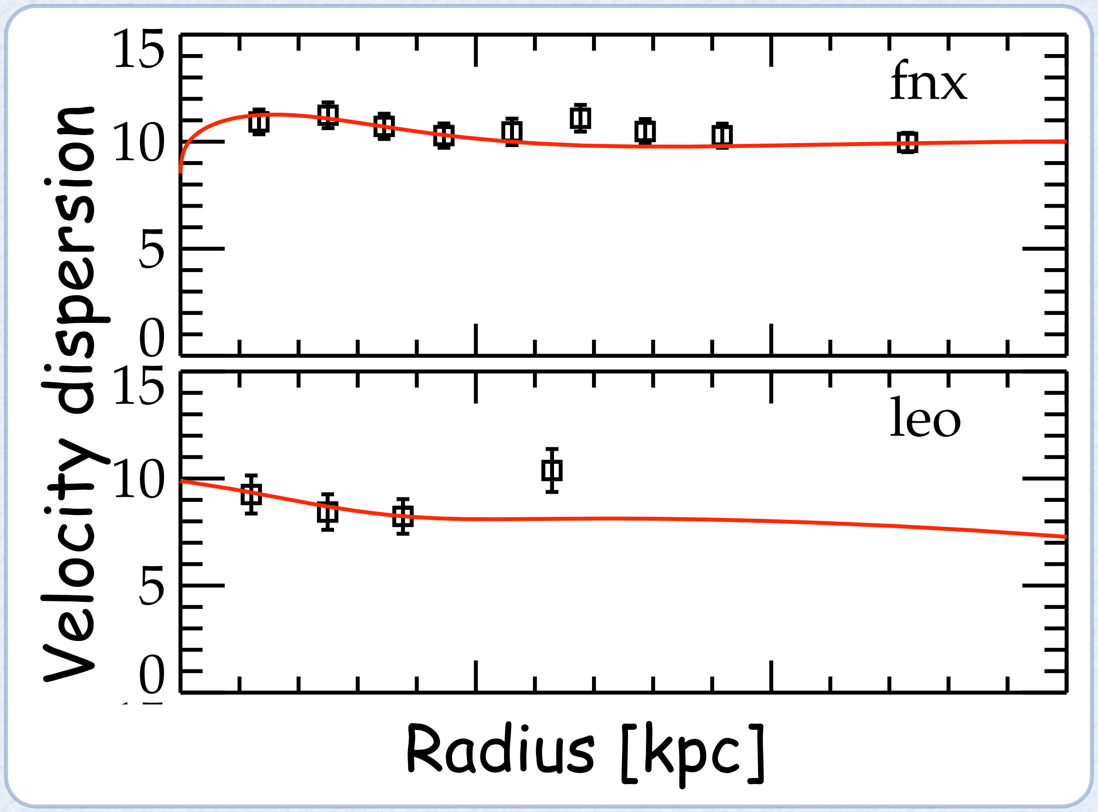


Strigari, Frenk, White MNRAS 2010

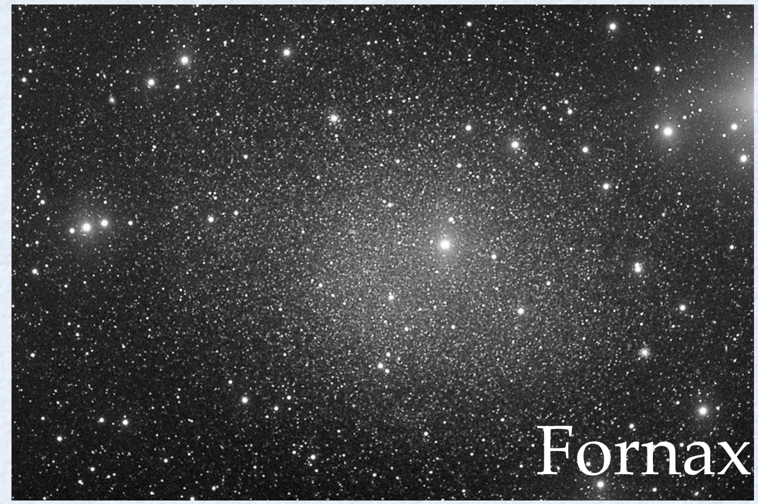


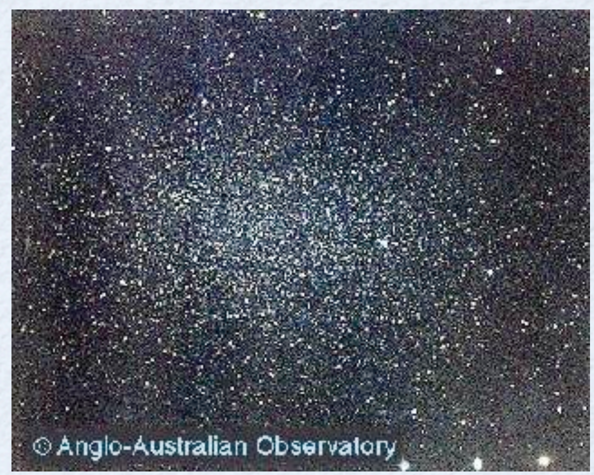


Matching 2nd moment of distribution

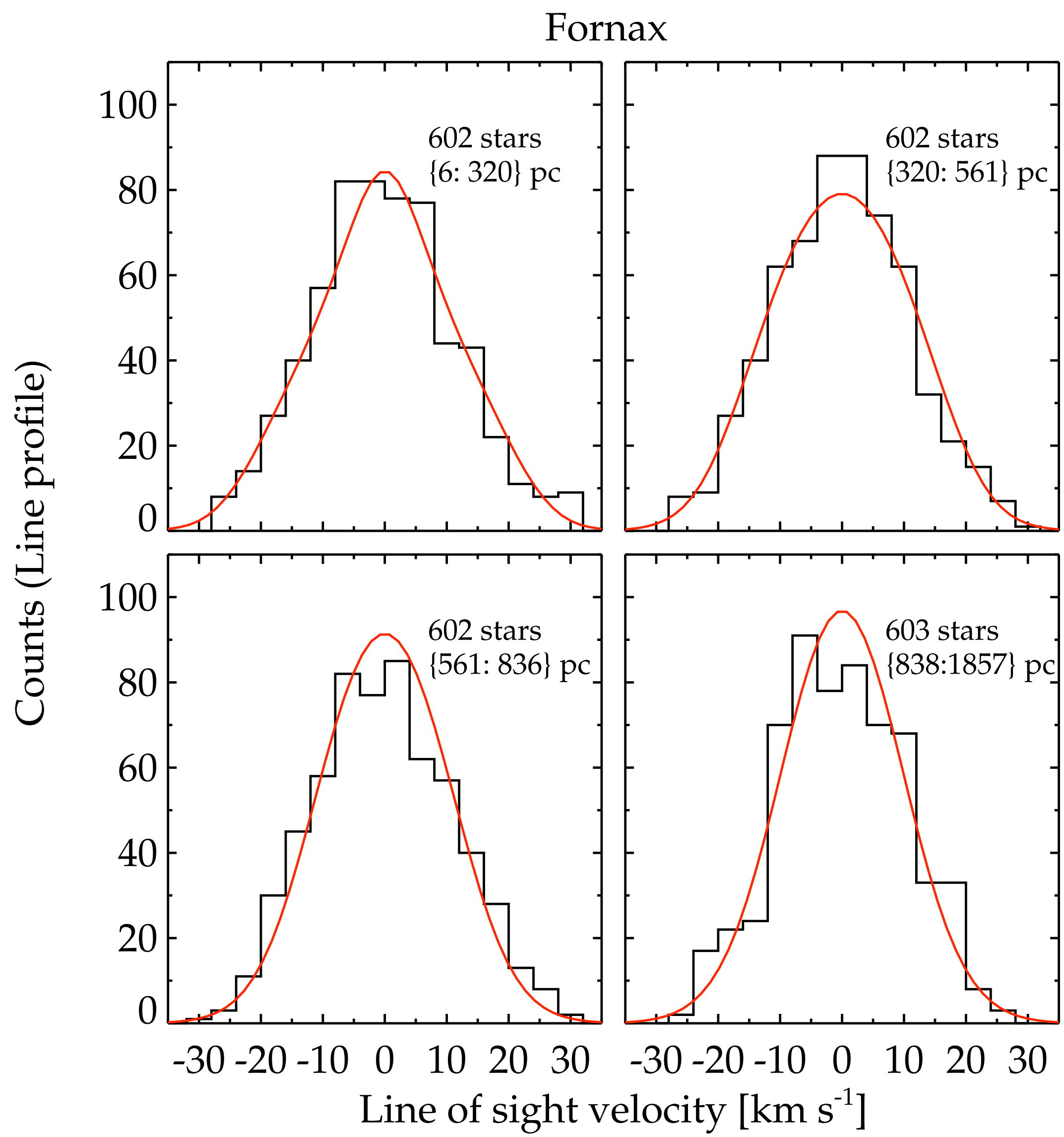


Strigari, Frenk, White MNRAS 2010





Higher order moments



Strigari, Frenk, White MNRAS 2010

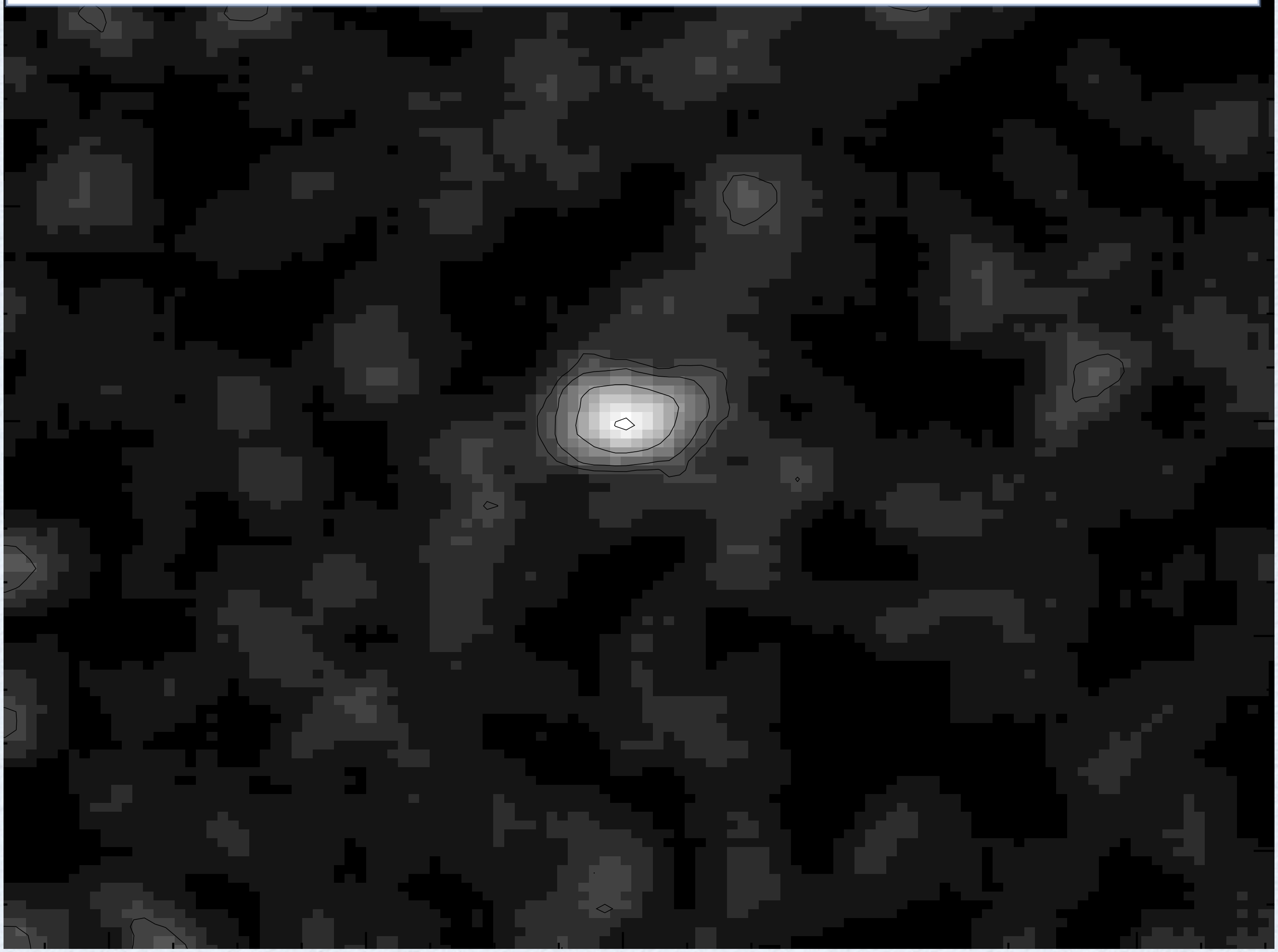
Kinematics: Implications

- Isotropic, NFW models are consistent with data
- No core/cusp issue for bright dwarf spheroidals
- Further testing for anisotropic, non-spherical models [Breddels et al. 2011; Jardel & Gebhardt ApJ 2012; Baghramian, Afshordi, LS]
- Circular velocities range 10-25 km/s

Stellar systems of a *really* new kind

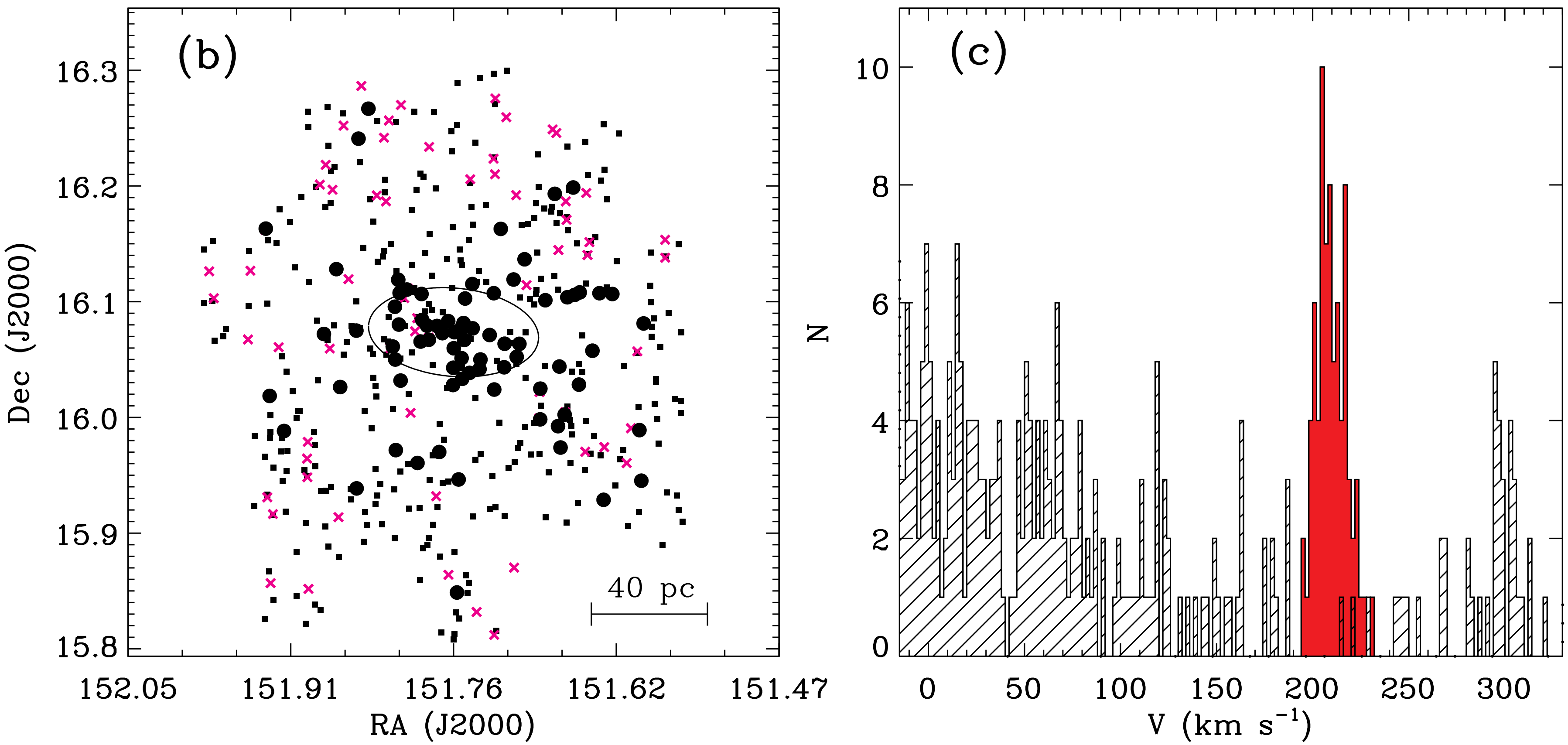
A NEW MILKY WAY COMPANION: UNUSUAL GLOBULAR CLUSTER OR EXTREME DWARF SATELLITE?

Beth Willman[1], Michael R. Blanton[1], Andrew A. West[2], Julianne J. Dalcanton[2,3], David W. Hogg[1], Donald P. Schneider[4], Nicholas Wherry[1], Brian Yanny[5], Jon Brinkmann[6]



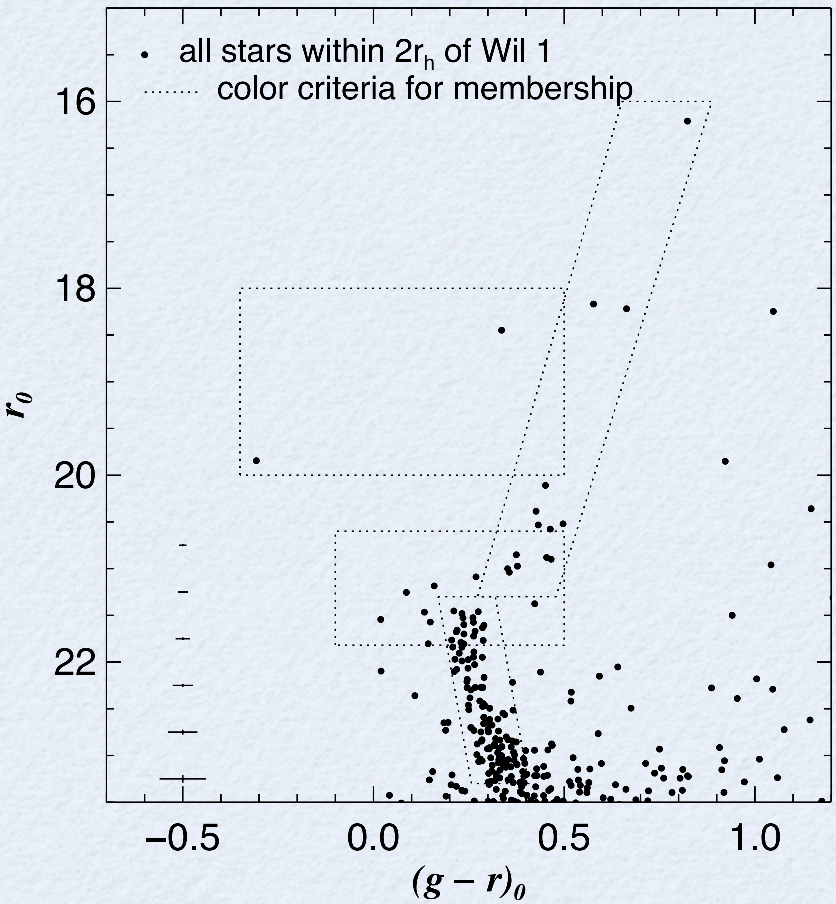
A COMPLETE SPECTROSCOPIC SURVEY OF THE MILKY WAY SATELLITE SEGUE 1: THE DARKEST GALAXY*

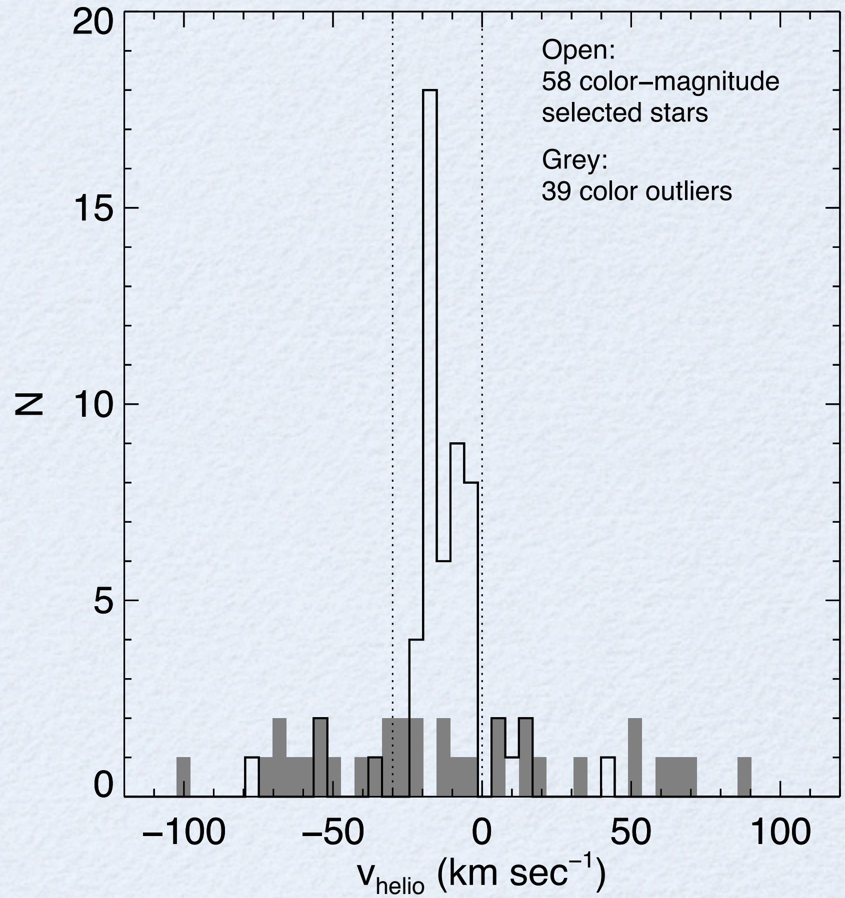
Joshua D. Simon[1], Marla Geha[2], Quinn E. Minor[3], Gregory D. Martinez[3], Evan N. Kirby[4,5], James S. Bullock[3], Manoj Kaplinghat[3], Louis E. Strigari[6,5], Beth Willman[7], Philip I. Choi[8], Erik J. Tollerud[3], and Joe Wolf[3]



WILLMAN 1 - A PROBABLE DWARF GALAXY WITH AN IRREGULAR KINEMATIC DISTRIBUTION

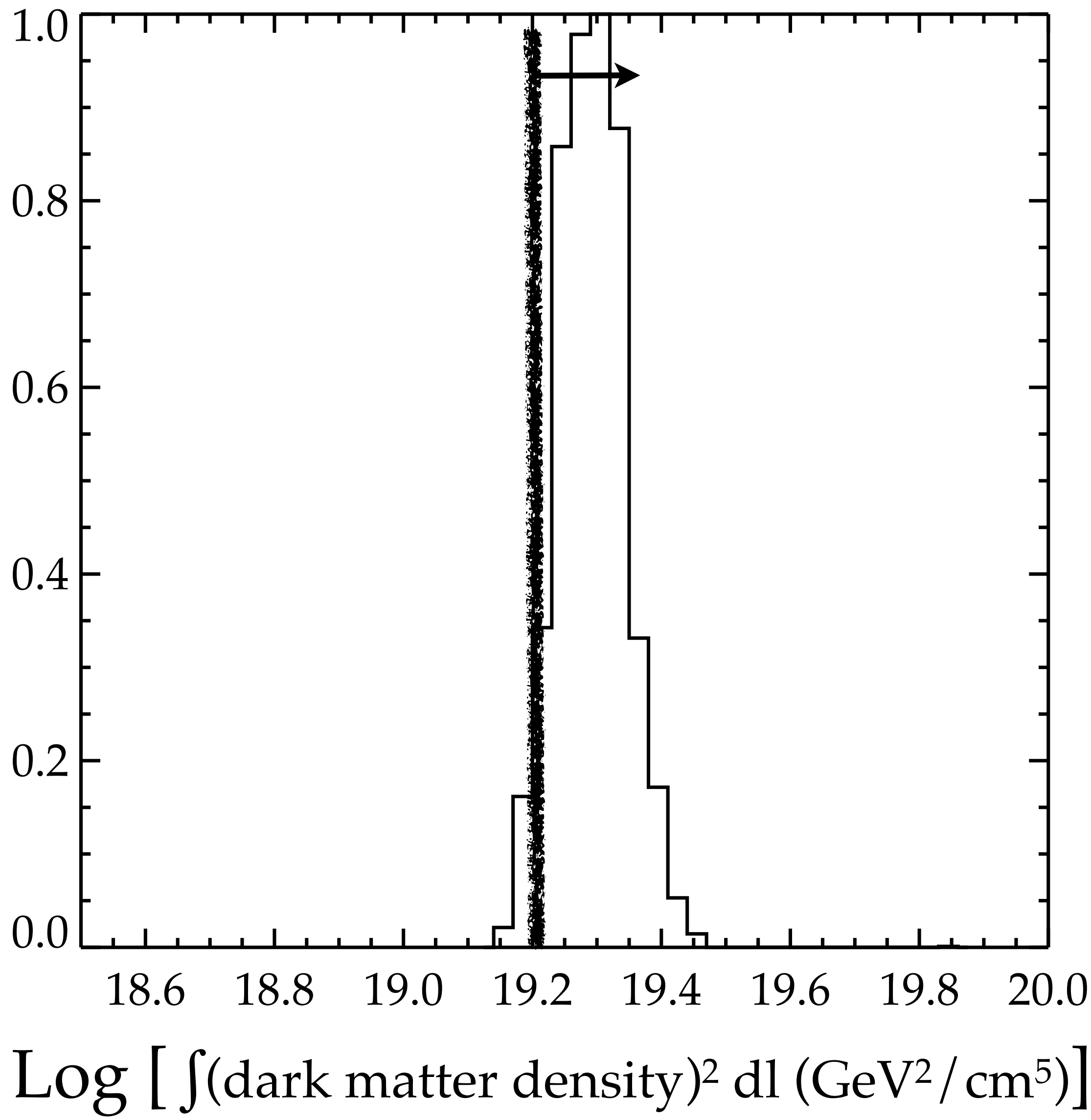
Beth Willman[1], Marla Geha[2], Jay Strader[3,4], Louis E. Strigari[5], Joshua D. Simon[6], Evan Kirby[7,8], Nhung Ho[2], Alex Warres[1]



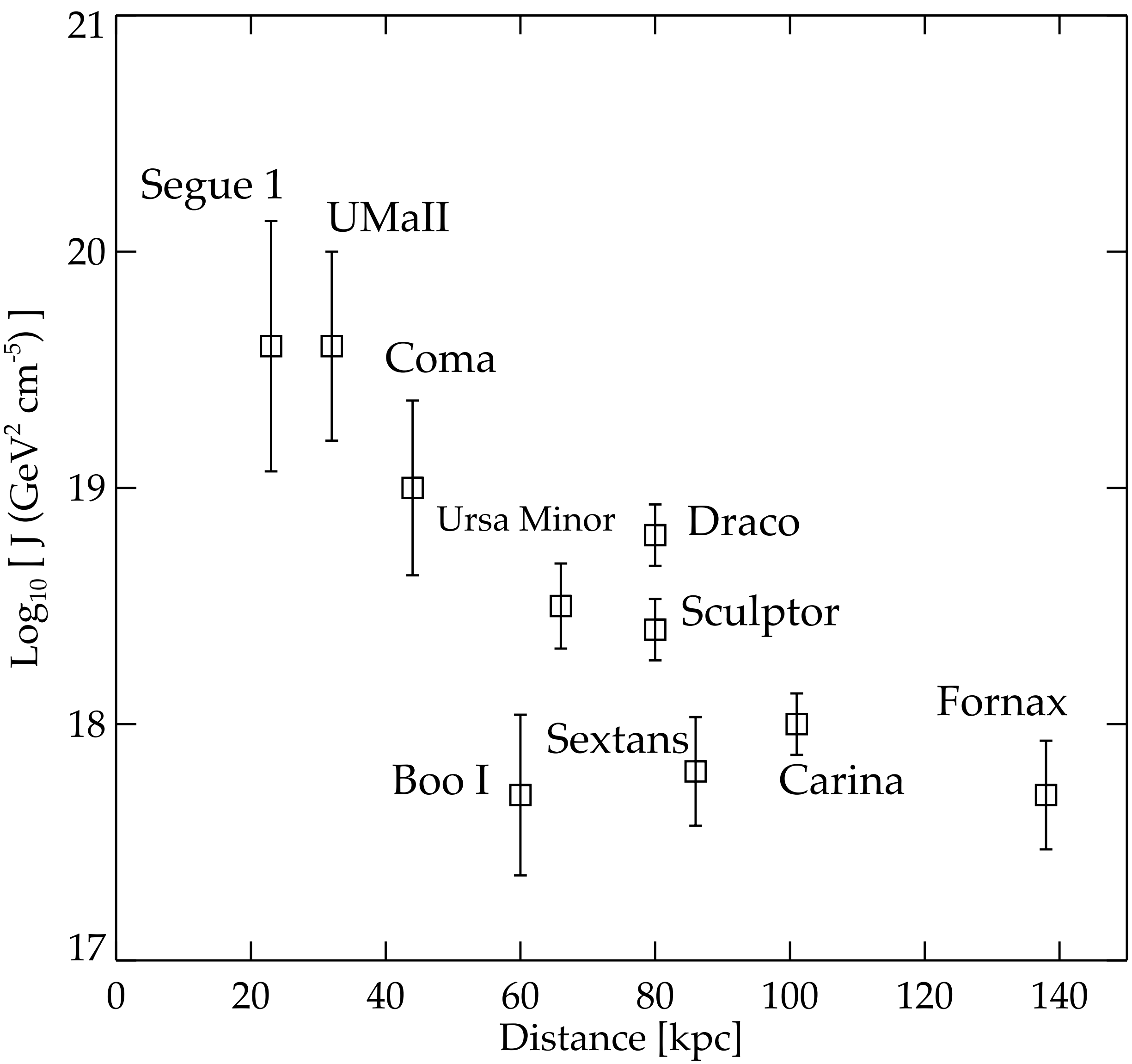


Willman et al., 2010

$$\mathcal{L}(\mathscr{A}) \equiv P(\{v_i\}|\mathscr{A}) = \prod_{i=1}^{n} \frac{1}{\sqrt{2\pi(\sigma^2_{los,i} + \sigma^2_{m,i})}} \exp\left[-\frac{1}{2}\frac{(v_i - u)^2}{\sigma^2_{los,i} + \sigma^2_{m,i}}\right]$$

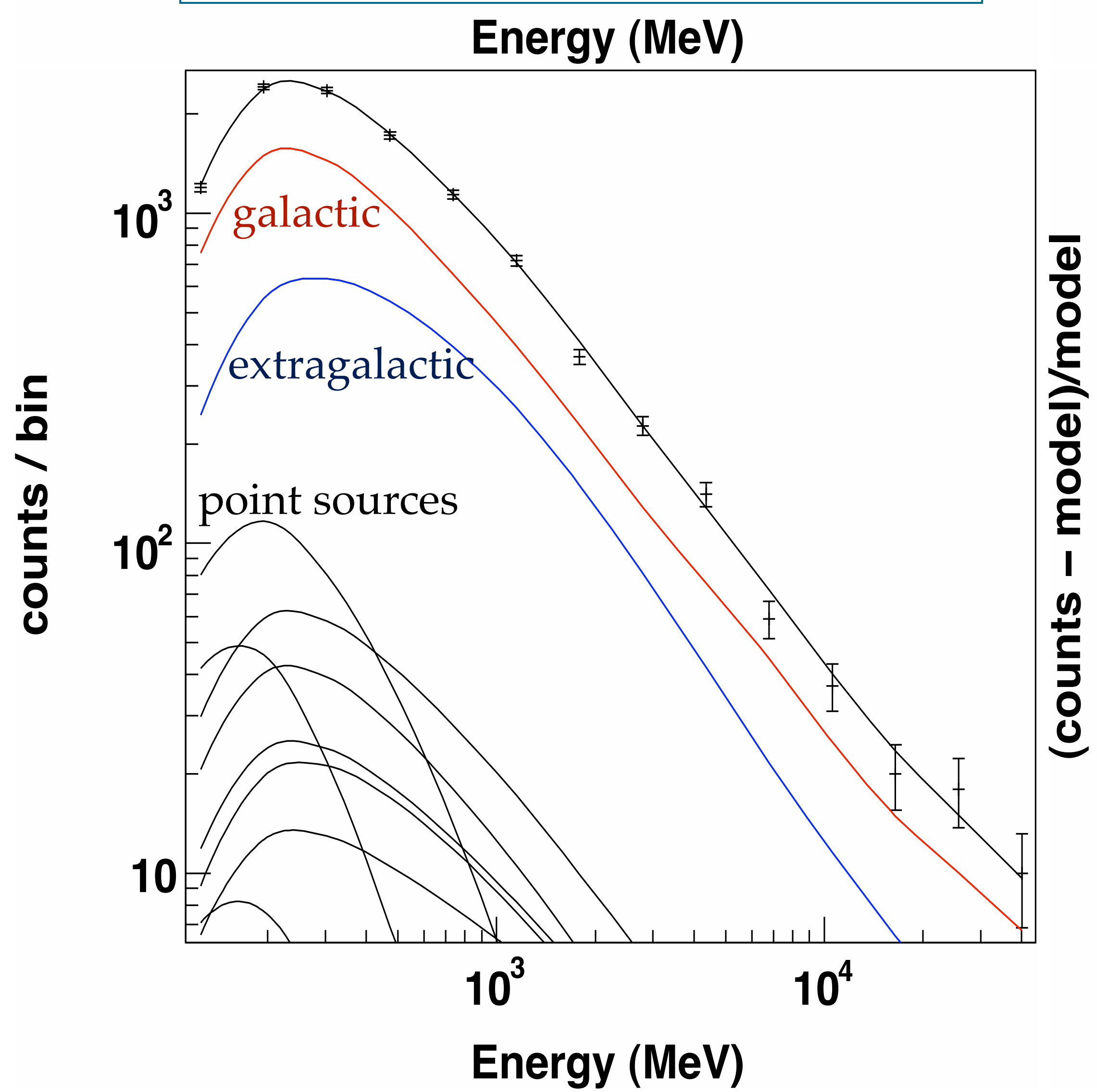


Dark matter distributions



Search for emission from satellites

Fermi-LAT Collaboration, ApJ 2010



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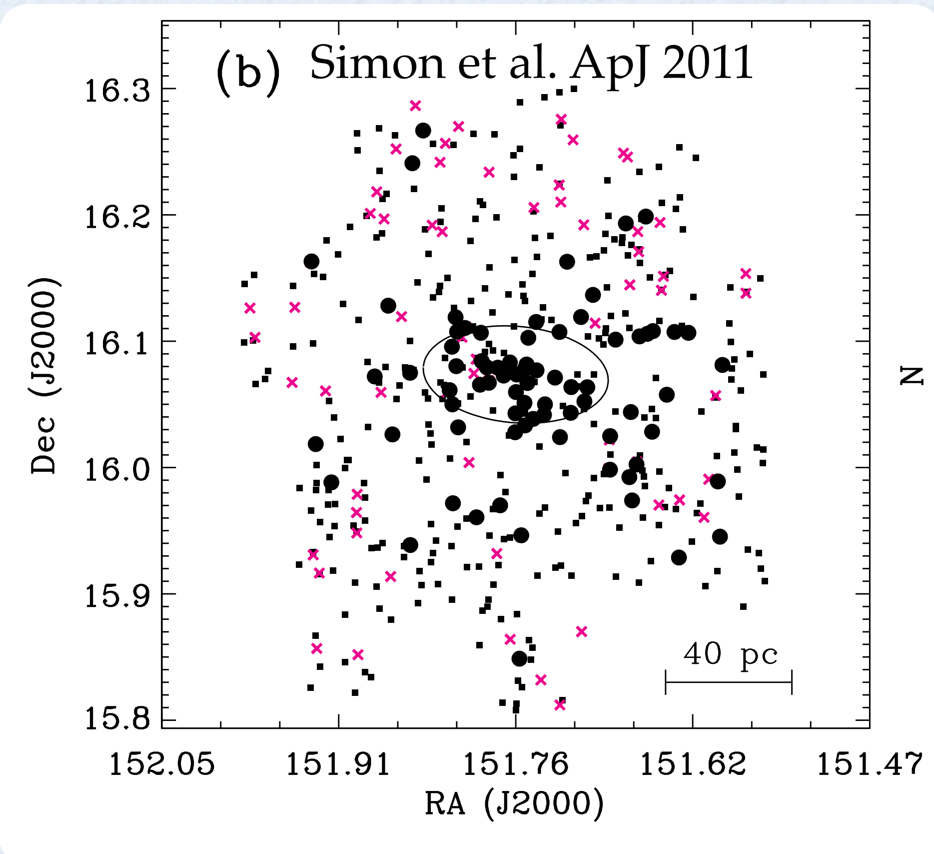
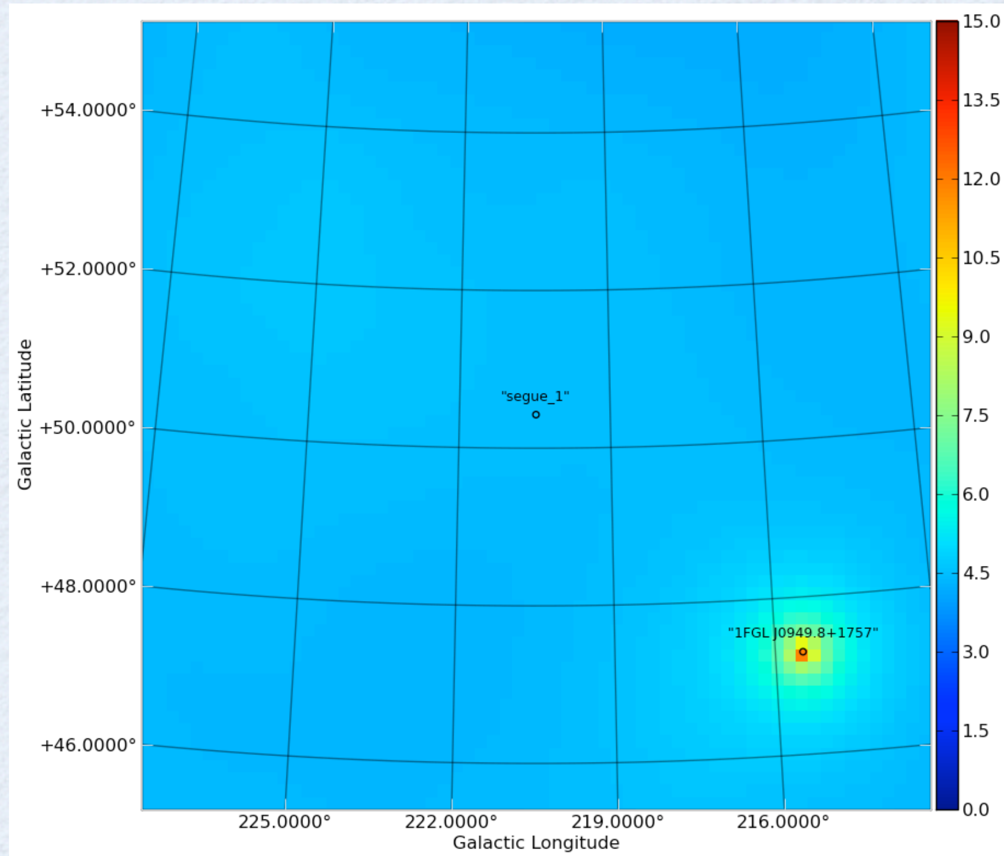
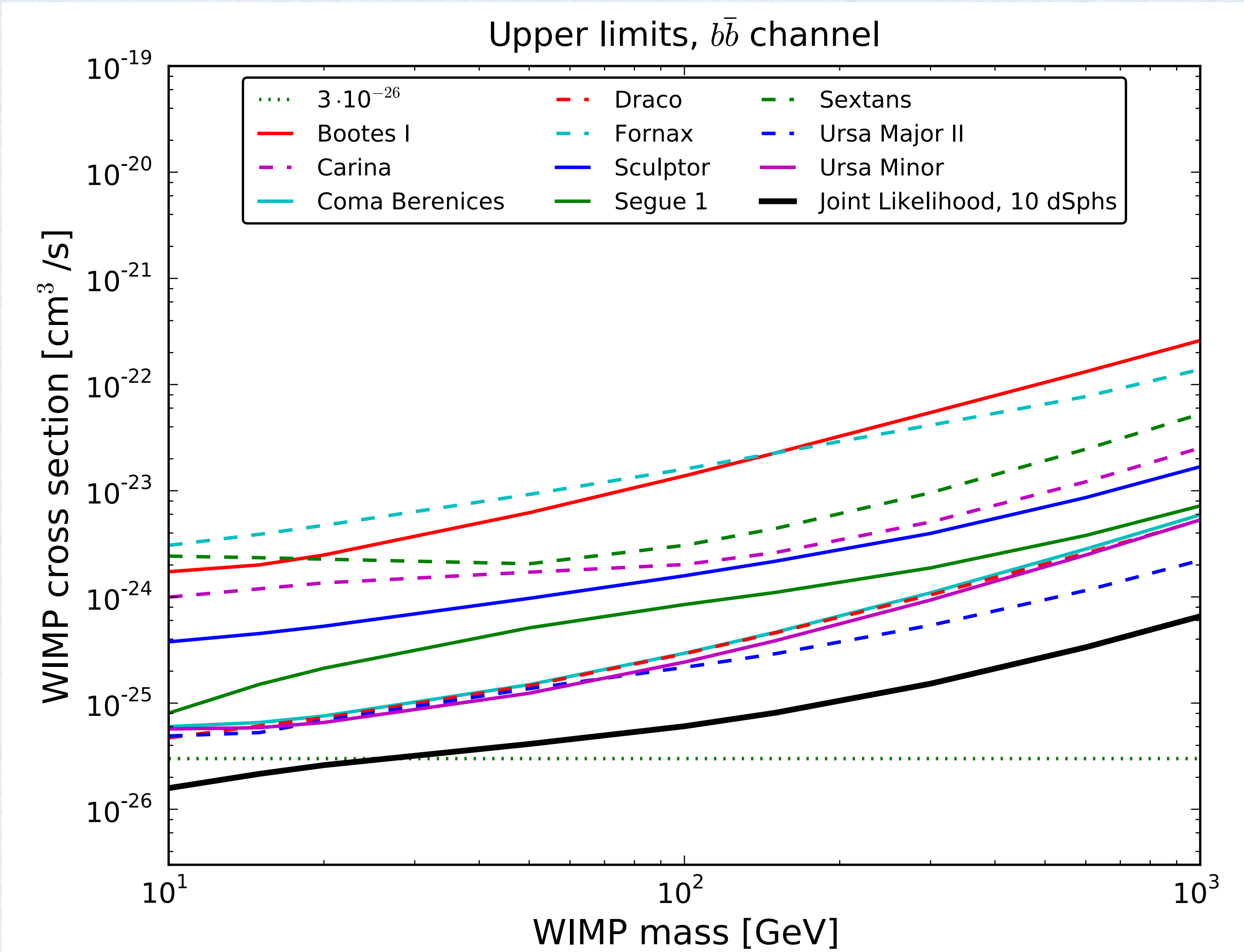




Constraining Dark Matter Models from a Combined Analysis of Milky Way Satellites with the Fermi Large Area Telescope

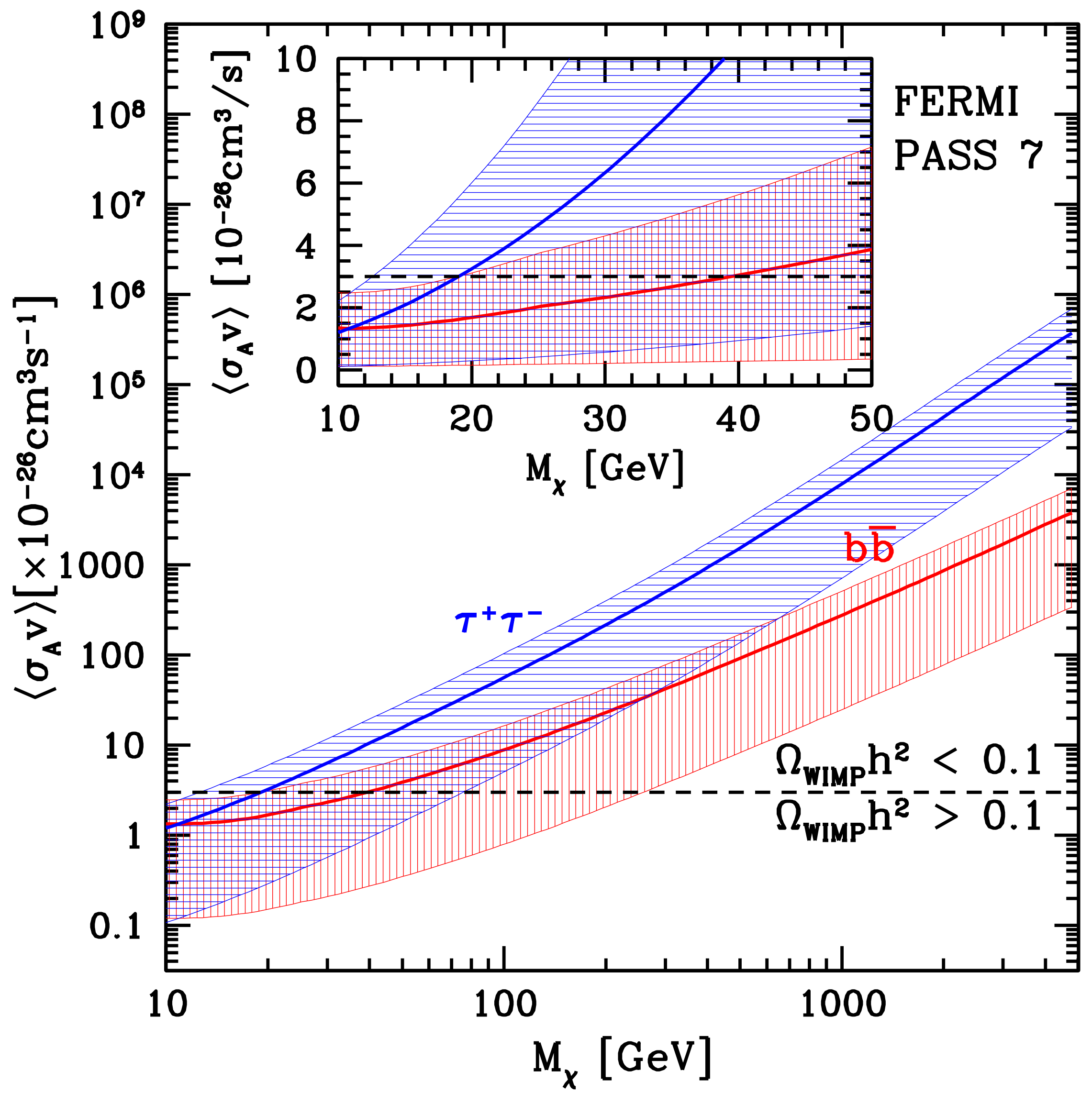
Fermi-LAT Collaboration, PRL 2011

$$L(D|\mathbf{pw},\{\mathbf{p}\}_i) = \prod_i L_i^{\rm LAT}(D|\mathbf{pw},\mathbf{p}_i) \times \frac{1}{\ln(10)\, J_i\sqrt{2\pi}\sigma_i} e^{-\left[\log_{10}(J_i)-\overline{\log_{10}(J_i)}\right]^2/2\sigma_i^2}$$



Limits robust to background treatments

Geringer-Sameth & Koushiappas PRL 2012



Improvements in analysis

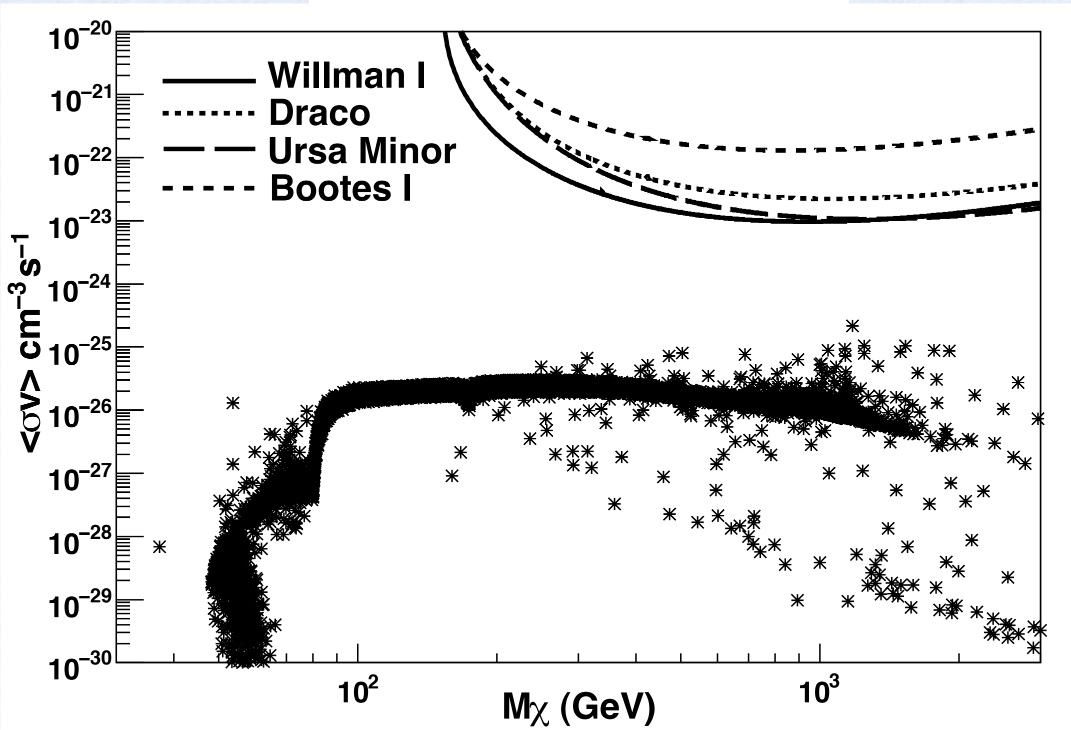
- Better data on stellar kinematics
  - Improved models
  - Proper motions
- More MW satellites will be discovered
- Only used 2 years of possible 10 years of Fermi data
- Complementarily with ground-based detectors

Distribution function modeling

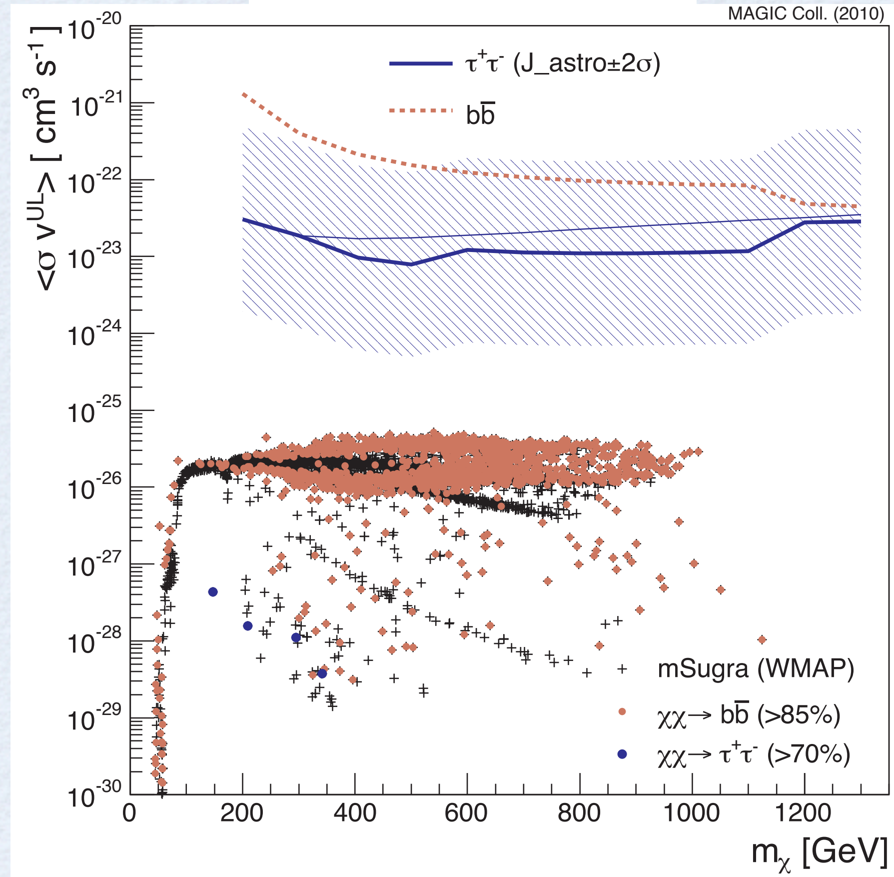
- Discretize the distribution function in (E,L) space [Richstone & Tremaine (1984); Wu & Tremaine (2006); Wu (2007); Magorrian MNRAS (2006)]
- Solve for the weights
- Schwarschild modeling: DF is smooth in phase space and weights are maximized (not marginalized over) [Breddels et al. 2011; Jardel & Gebhardt ApJ 2012]
- Marginalizing over weights via MCMC captures non-smooth features in phase-space
- Implications for J values [Braghmain, Afshordi, LS, to appear]

Pointed observations at higher energy

VERITAS

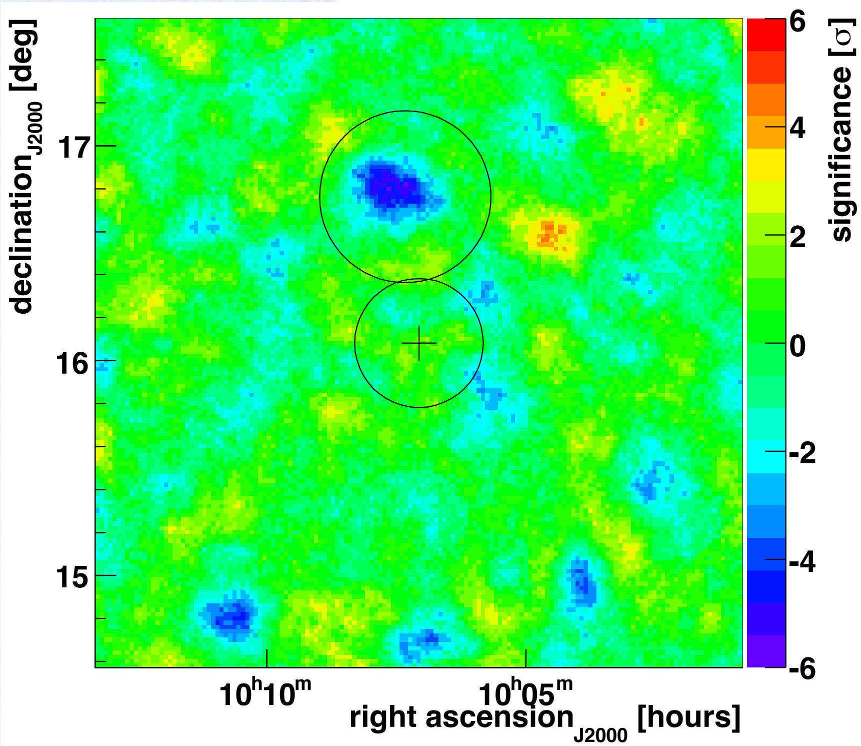


MAGIC

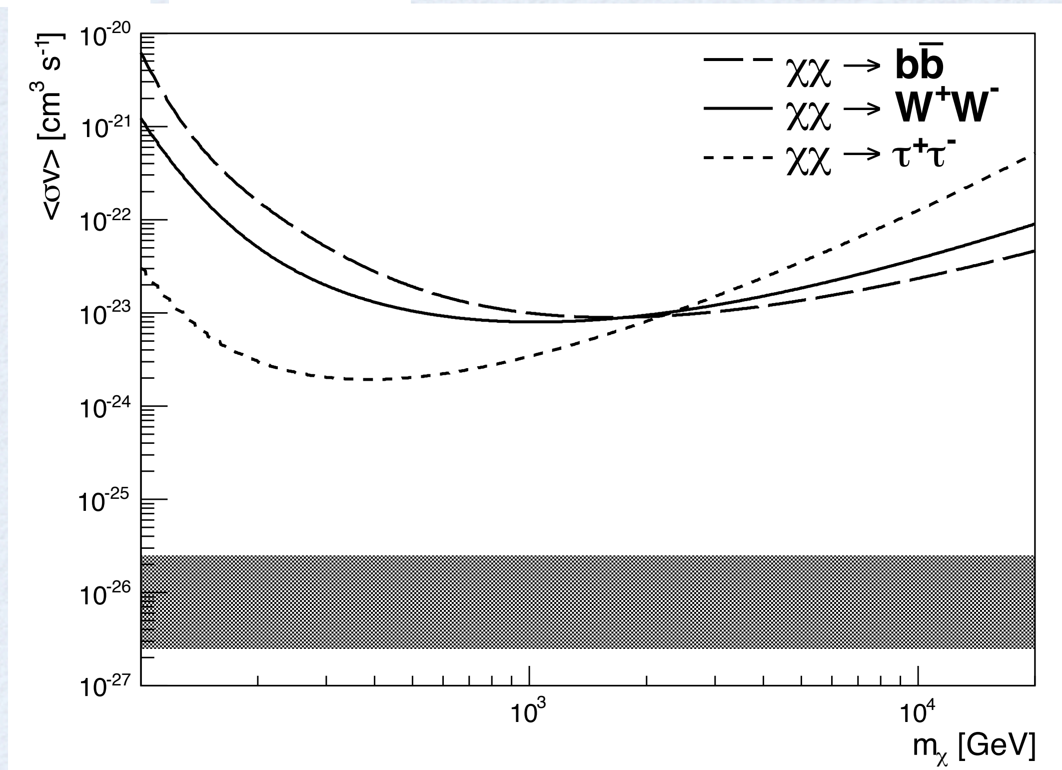


Pointed observations at higher energy

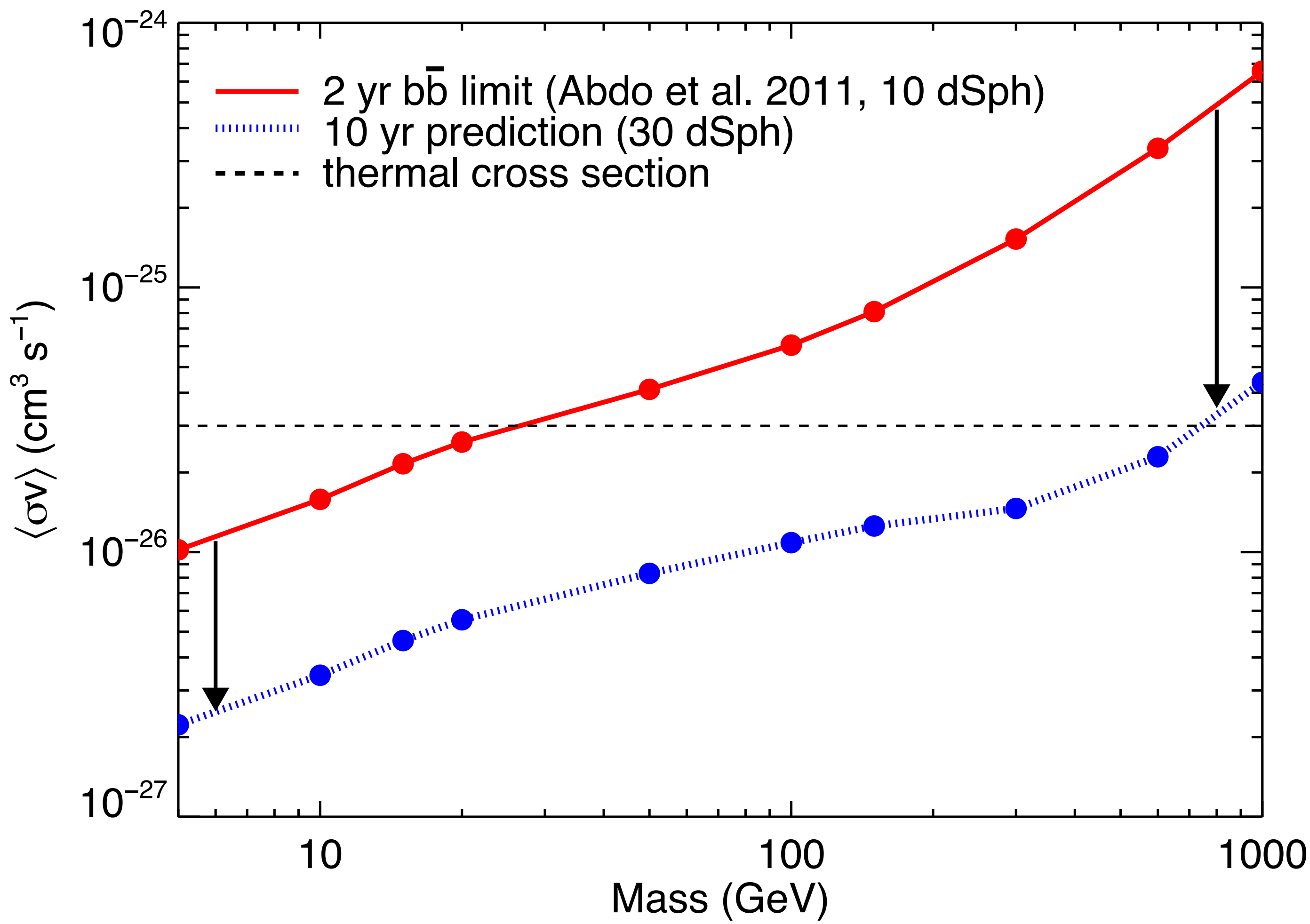
Veritas, arXiv:1202.2144



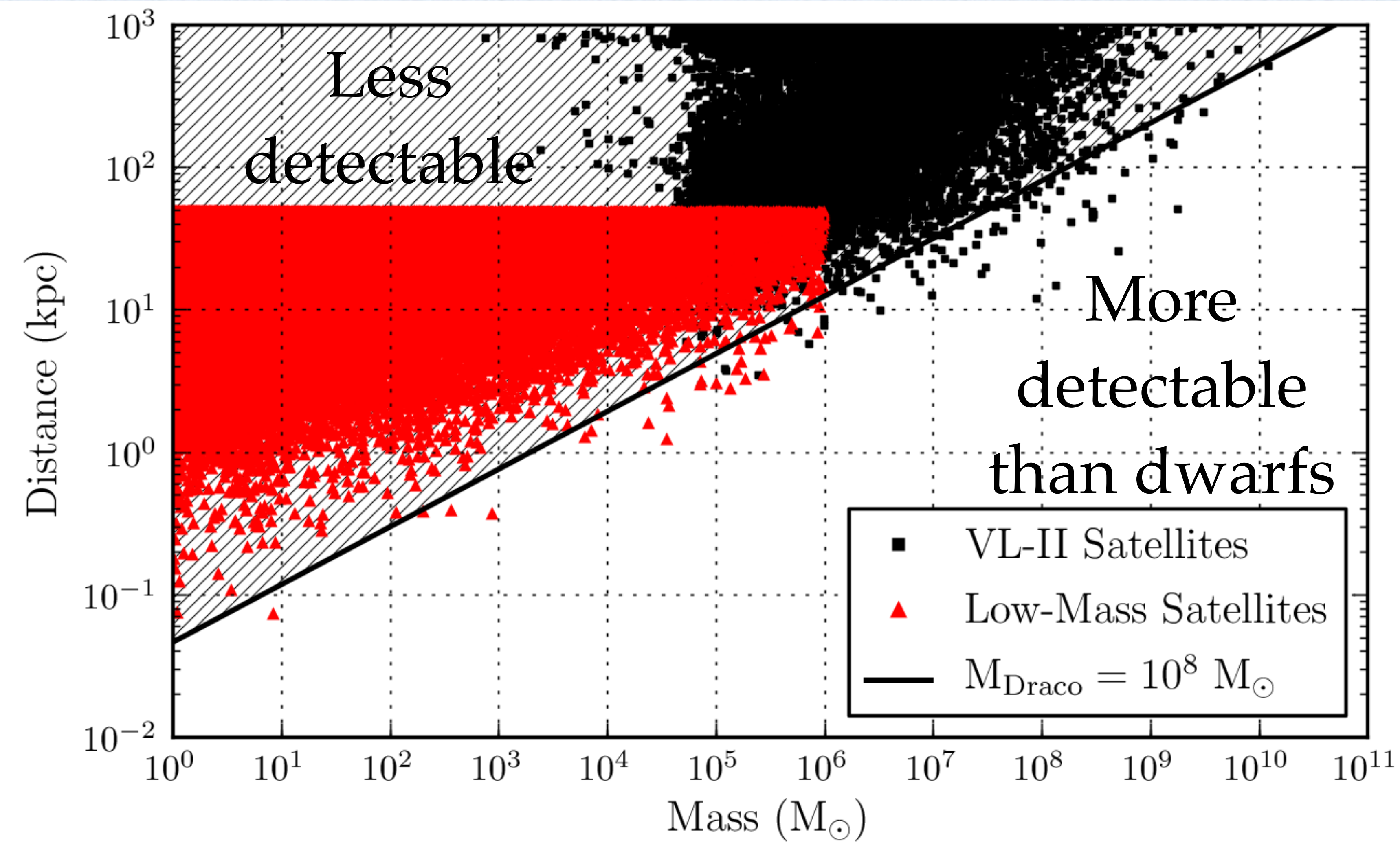
Segue 1



How well will we do?



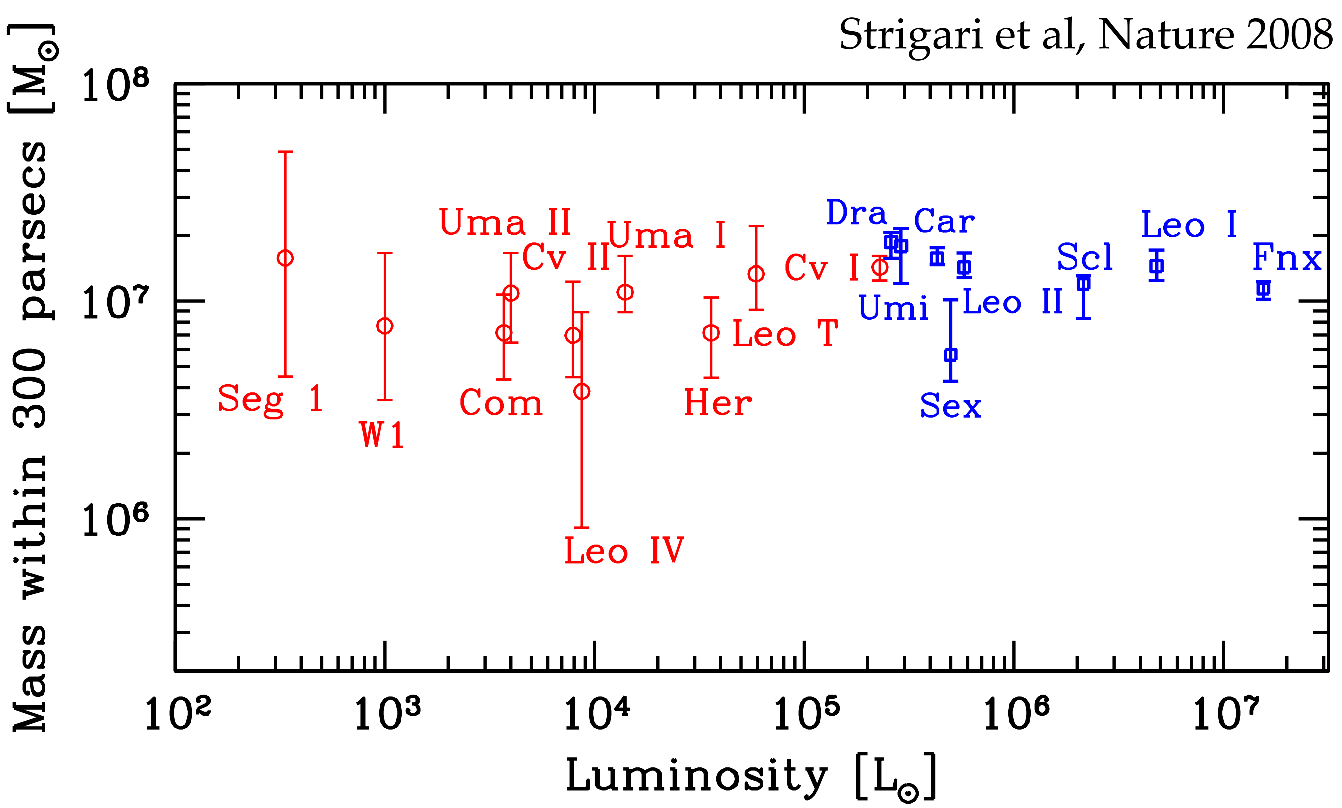
Search for Dark Subhalos



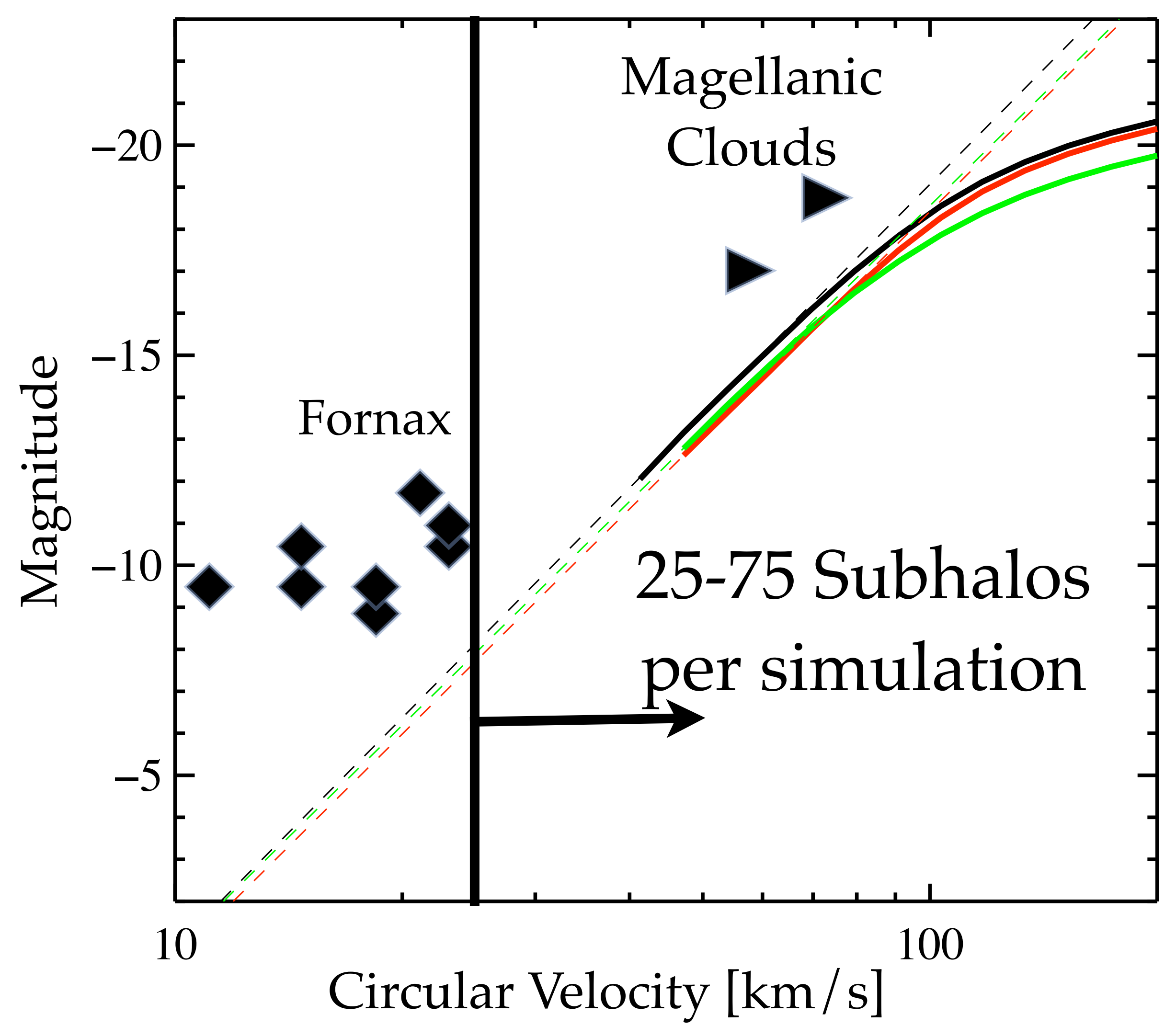
Fermi-LAT Collaboration, ApJ 2012

How rare is our Milky Way Galaxy?

Dark matter in all satellites



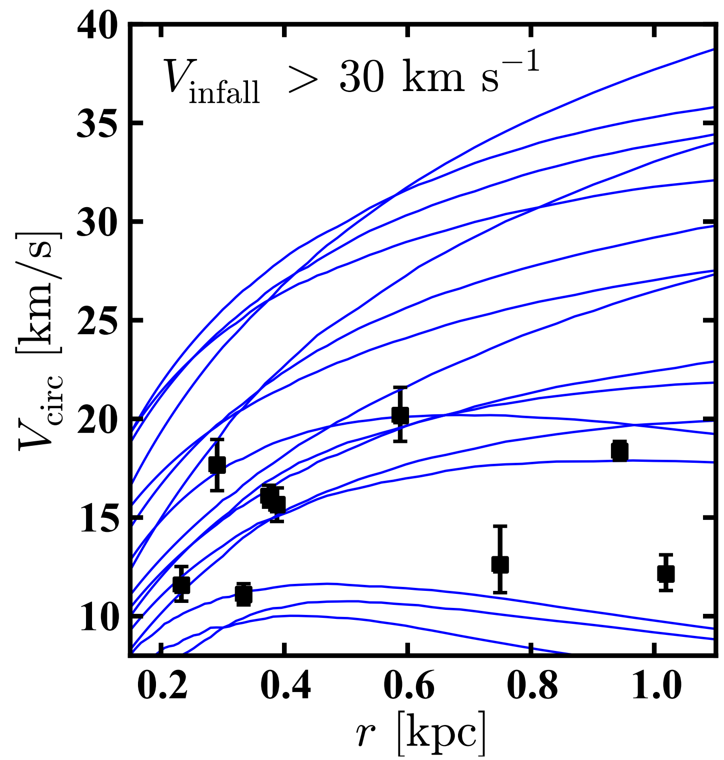
Luminosity-mass mapping



Further Implications

- Semi-analytic models predict more bright satellites than observed [e.g. Cooper et al. MNRAS 2010; Bovill & Ricotti ApJ 2011]

- Does the mapping between circular velocity and luminosity imply a ``massive failure" of LCDM? [e.g. Boylan-Kolchin et al., 2011]



A few ways out

1) Inclusion of Baryons in simulations [Wadepuhl & Springel MNRAS 2011, Parry et al. MNRAS 2012]

2) More fundamental modification simulations

- warm dark matter
- primordial power spectrum

3) Low mass of the Milky Way [Vera-Ciro et al. 2012; Wang et al. 2012]

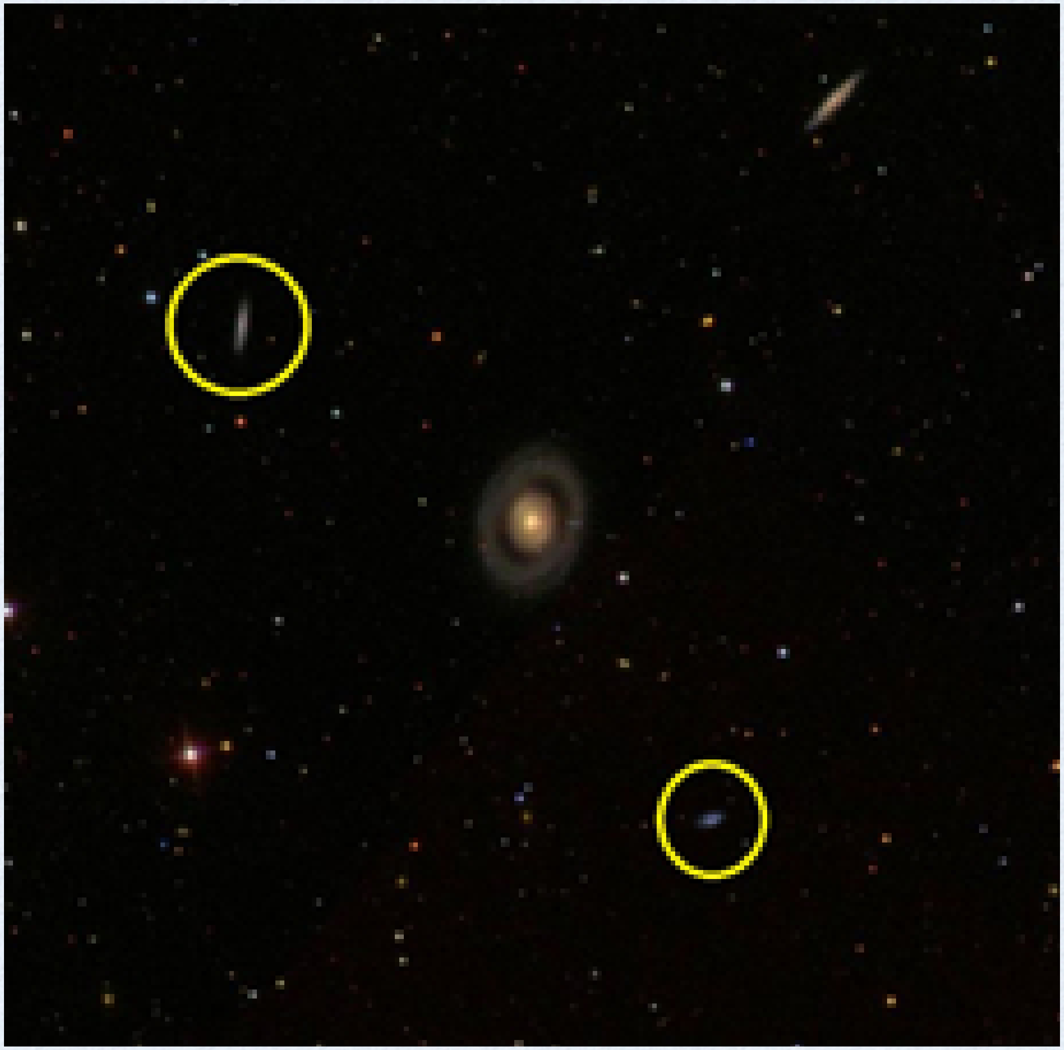
4) The Milky Way is an oddball

Testing the oddball hypothesis

Satellite	M_V	$L_V [L_\odot]$	$d_{\rm sun}$[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

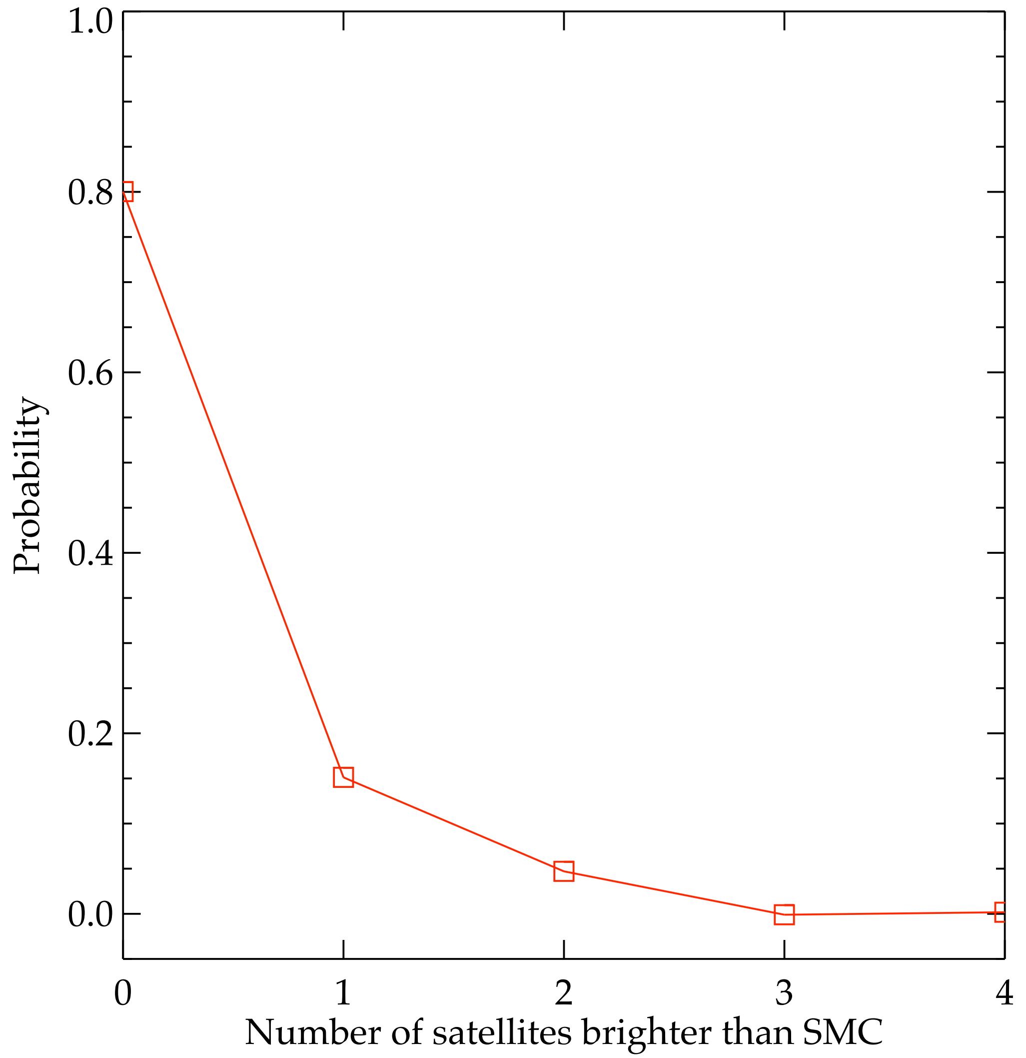
- Search MW-analogs in SDSS for satellite galaxies
- Probabilistic model using background subtraction
- Rely on spectroscopic and photometric redshifts

Magellanic Cloud-like Galaxies



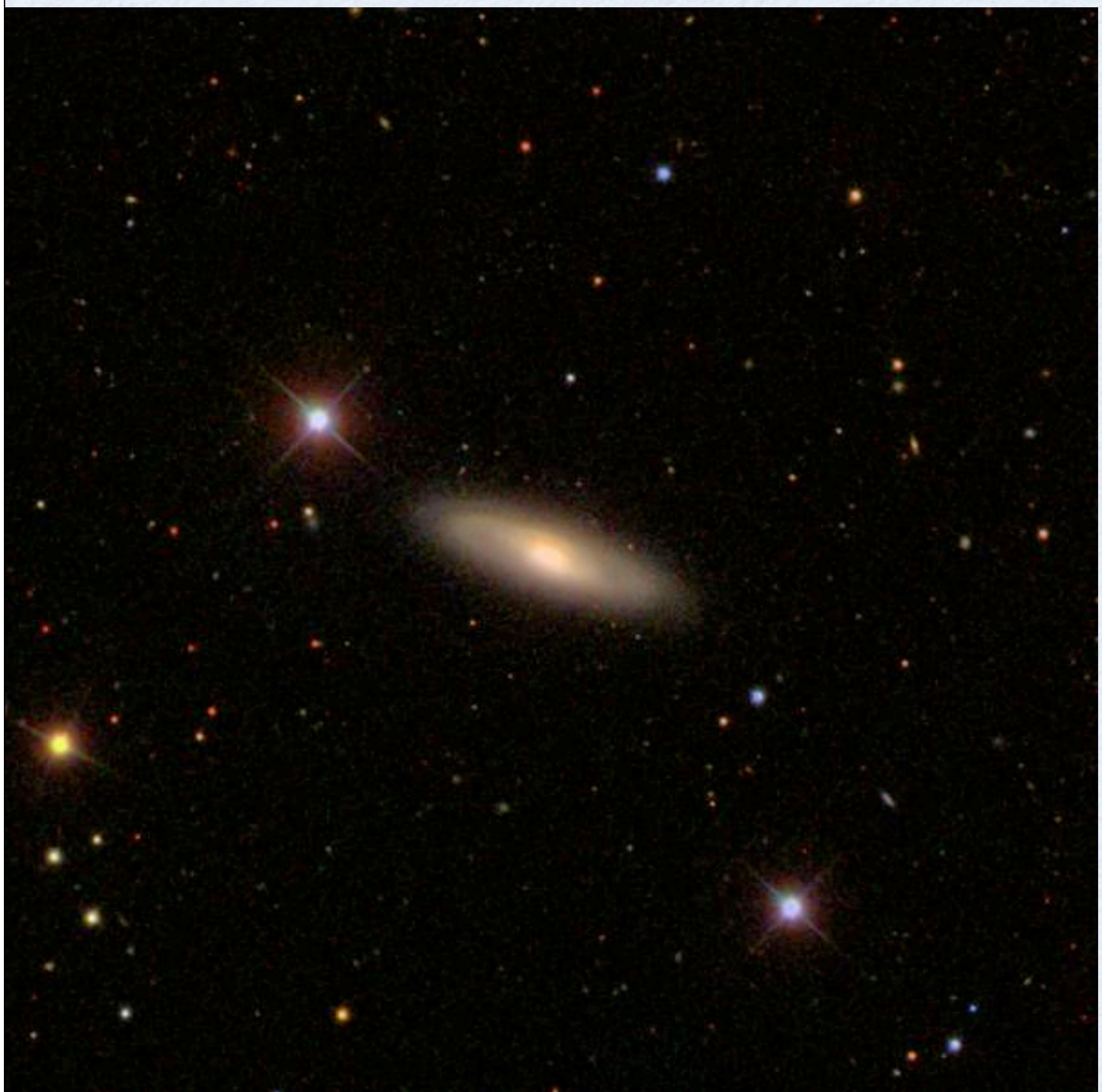
- About 600 systems with spectra on MC-like satellites
- About 10,000 systems with photometric redshifts on MC-like satellites

Probability for Magellanic Clouds



- 5% probability a MW-like system hosts 2 satellites brighter than MCs
- Mean of 0.25 satellites brighter than MCs per MW-like galaxy

Faintest satellites in SDSS

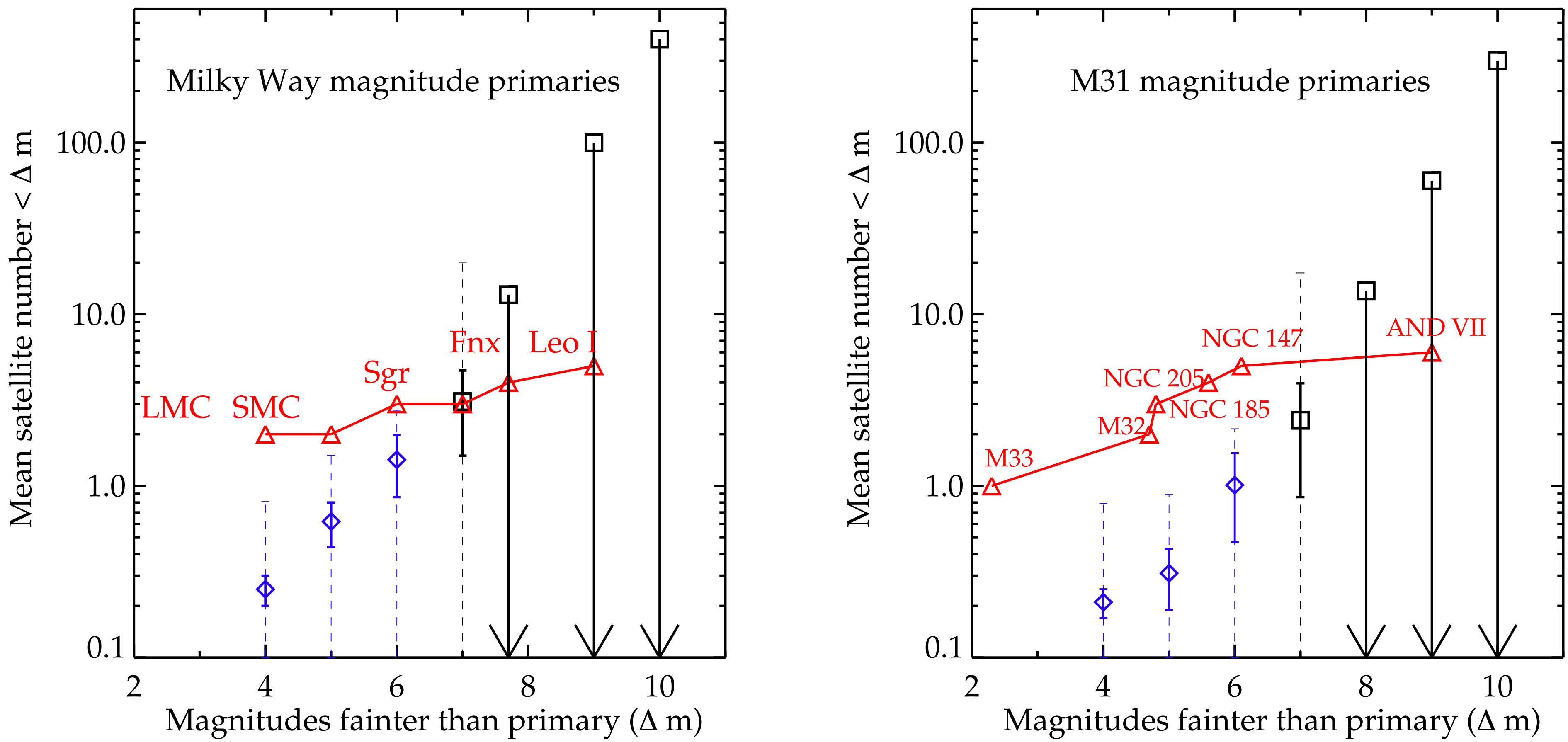


- Very few systems with spectra for Fornax-like satellites

- About 1,000 systems with photometric redshifts for Fornax-like satellites

Cosmic Abundance of Classical Satellites

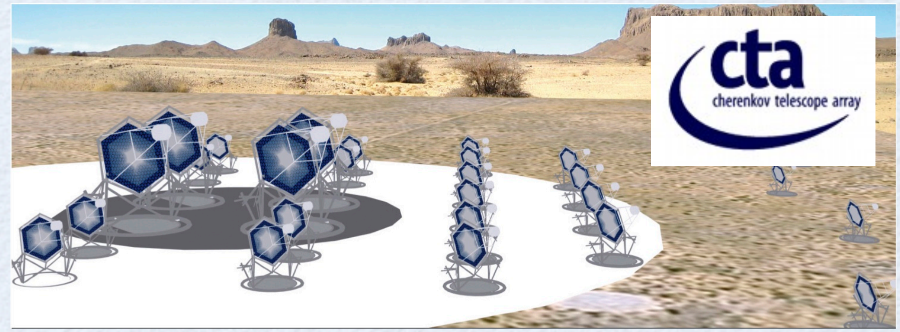
Strigari & Wechsler ApJ 2012

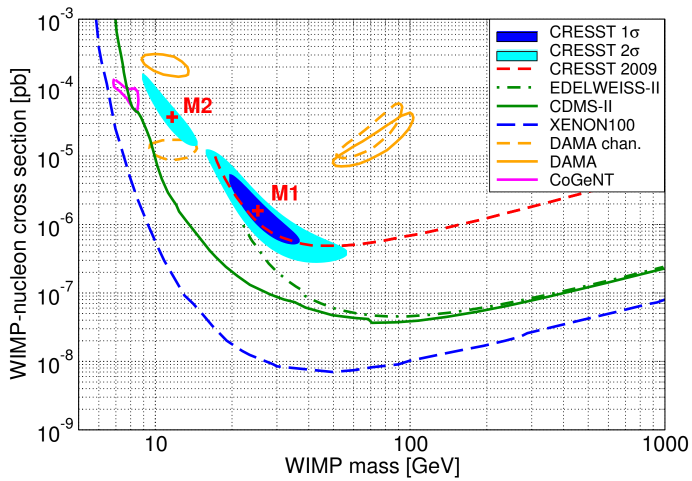


Improvements with Future Surveys

- Dark energy survey will provide at least 4x more MW-like galaxies
- For satellites will reach down to at least two magnitudes fainter than SDSS analysis
- For nearby systems satellites are identified and velocity dispersions can be determined

Going forward





- Fermi-LAT results now rule out thermal relic particle DM in the mass range 10-25 GeV
- More Galactic satellites are out there, and more data is on the way
- Complementarity with direction detection results
- Stay tuned...