Overview of Galactic Searches for Dark Matter

Louis E. Strigari
Indiana University
Gamma ray sky workshop
University of Minnesota
Oct 11, 2013

Predictions of the standard *Cold Dark Matter* model

1. Density profiles rise towards the centers of galaxies

Universal for all halo masses

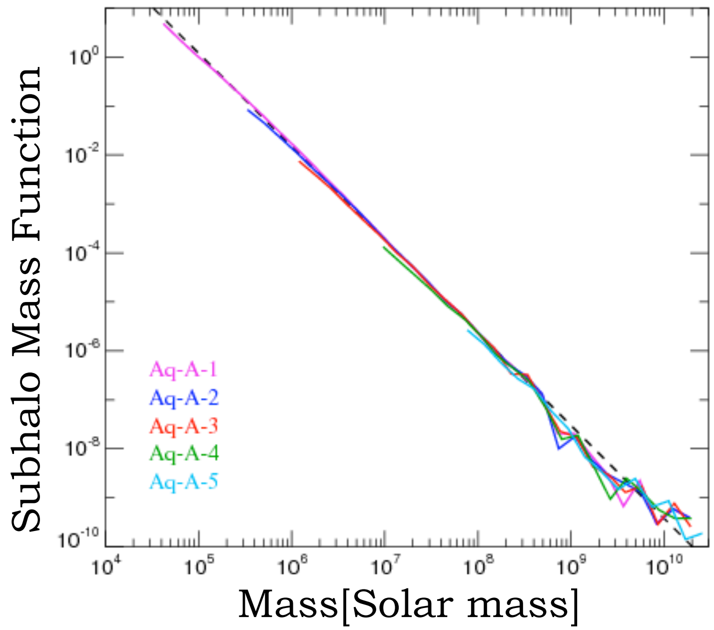
Navarro-Frenk-White (NFW) model

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

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 that predicted in simulations

General arguments: Kleyna et al. MNRAS 2003, 2004; Goerdt et al. APJ2006; 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

Earilest papers:
Kauffmann et al. 1993; Klypin et al. 1999; Moore et al. 1999

Milky Way satellite galaxies (dwarf spheroidals)

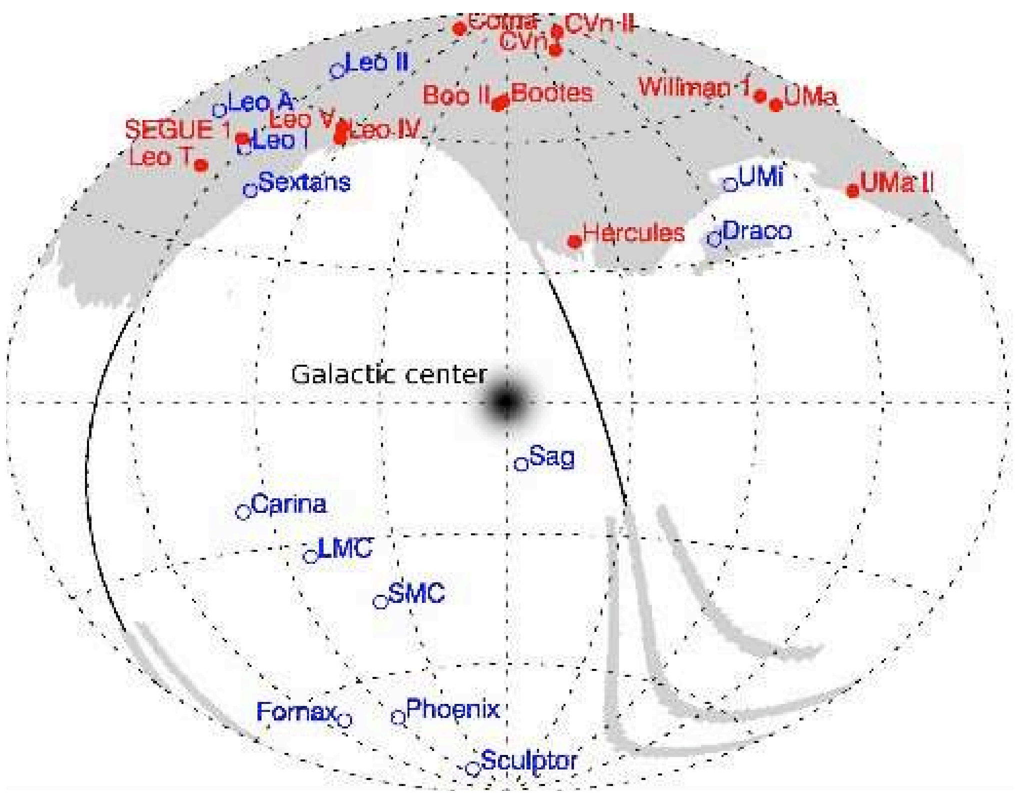
Properties

✦ Dark matter masses from motions of individual stars

✦ Most dark matter-dominated galaxies known

✦ Luminosities from hundreds to millions Solar luminosities

✦ No high energy gamma-rays from astrophysical sources



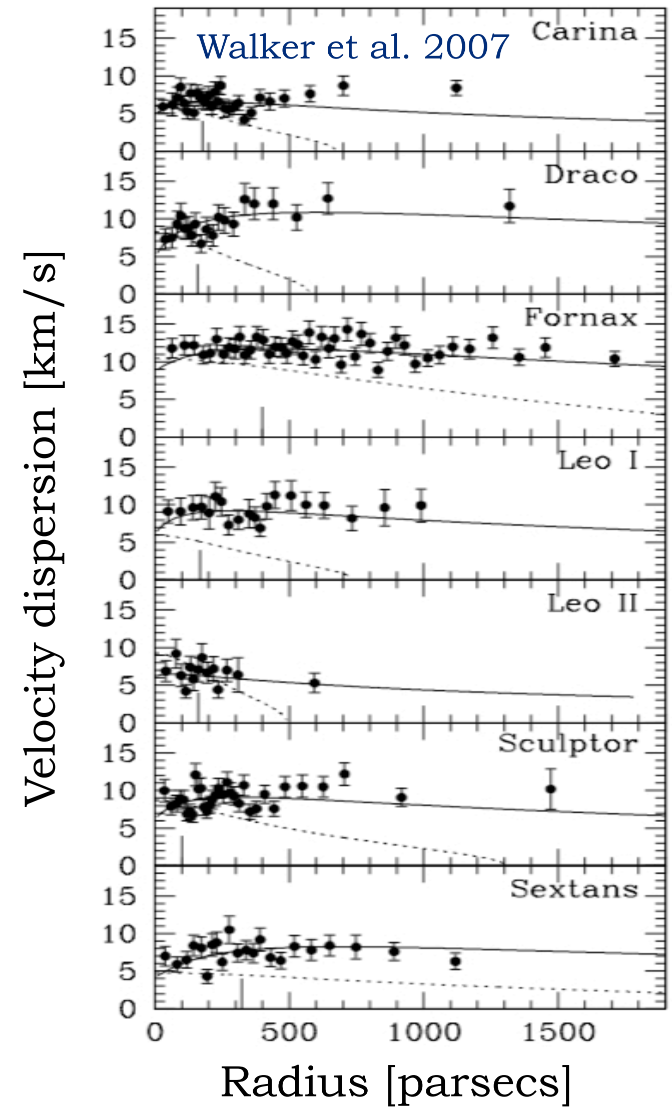
Dark matter in satellite galaxies (dwarf spheroidals)

- 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]

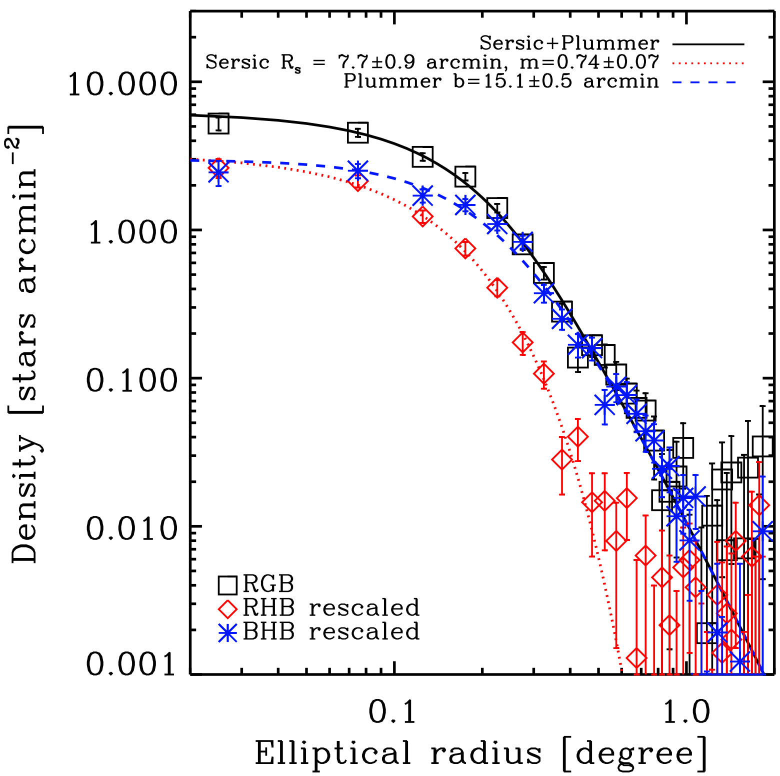
- New orbit-based approaches [Breddels et al 2012, Jardel and Gebhardt 2012, 2013]

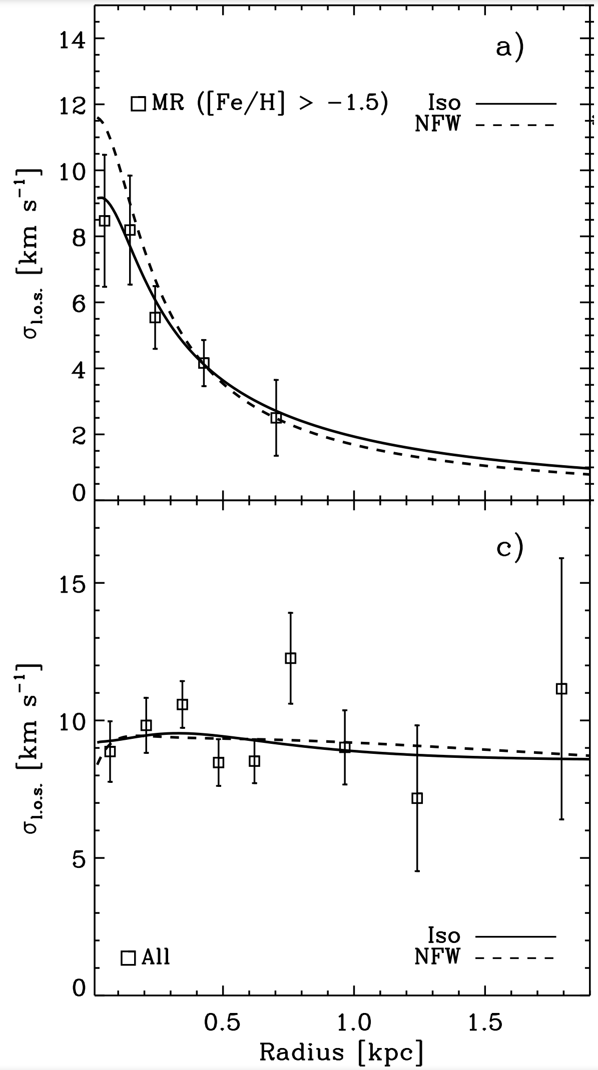


Multiple populations in Sculptor dwarf spheroidal

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

[Battaglia et al 2008]



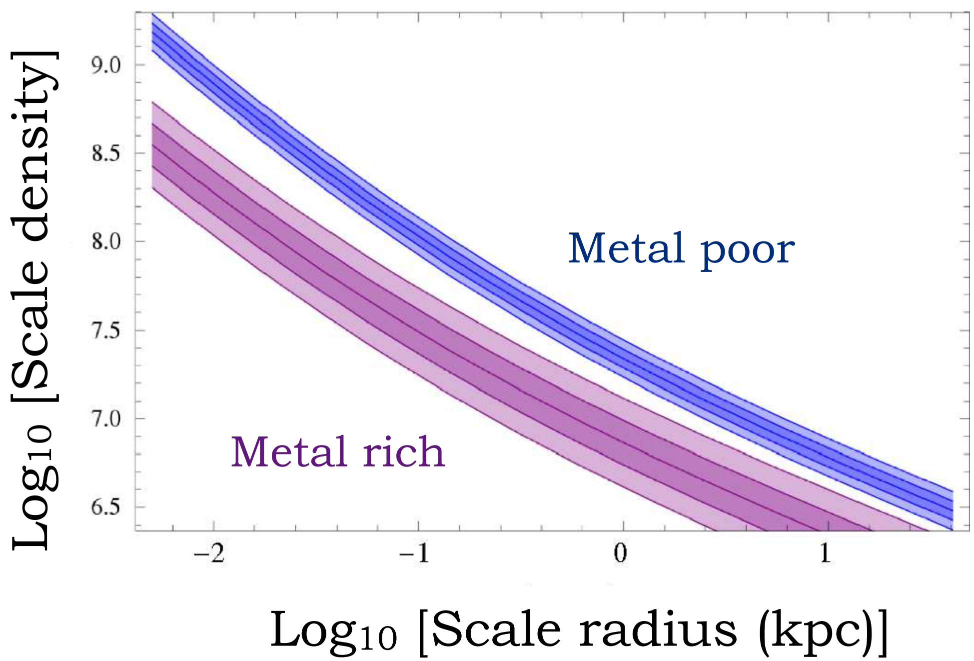


Multiple populations in Sculptor dwarf spheroidal

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

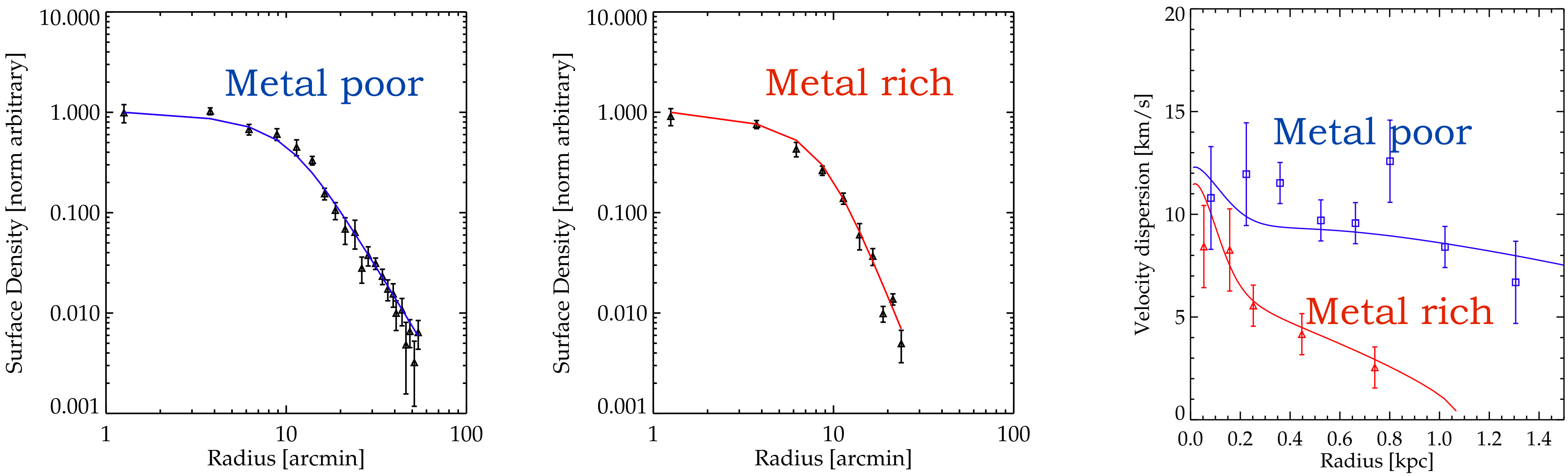
- Walker & Penarrubia (ApJ 2011) find that multiple populations are inconsistent with an NFW profile

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



Multiple populations in Sculptor dwarf spheroidal

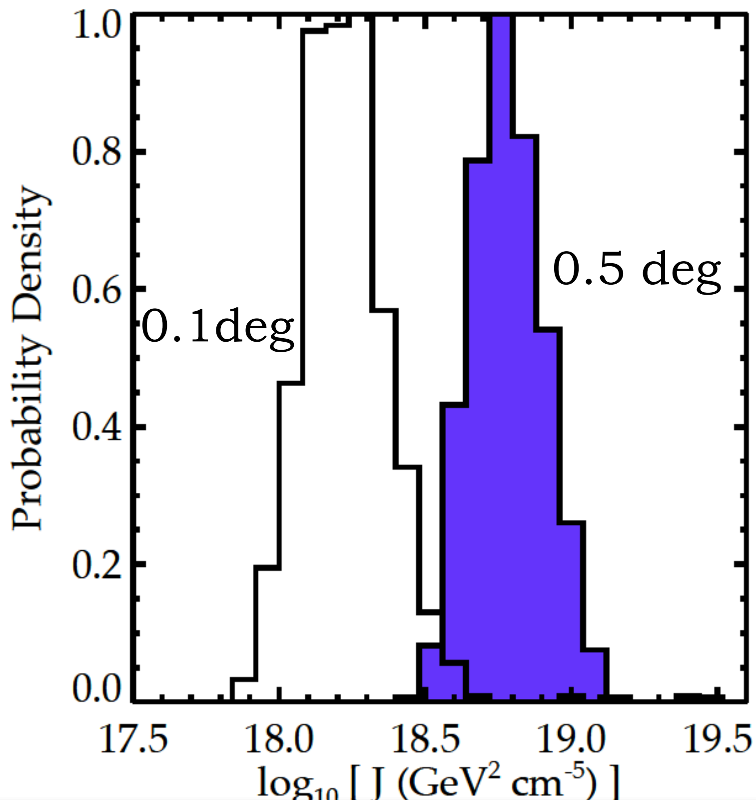
Apparent systematic in previous analyses. NFW models not ruled out by dwarf spheroidals (in prep)



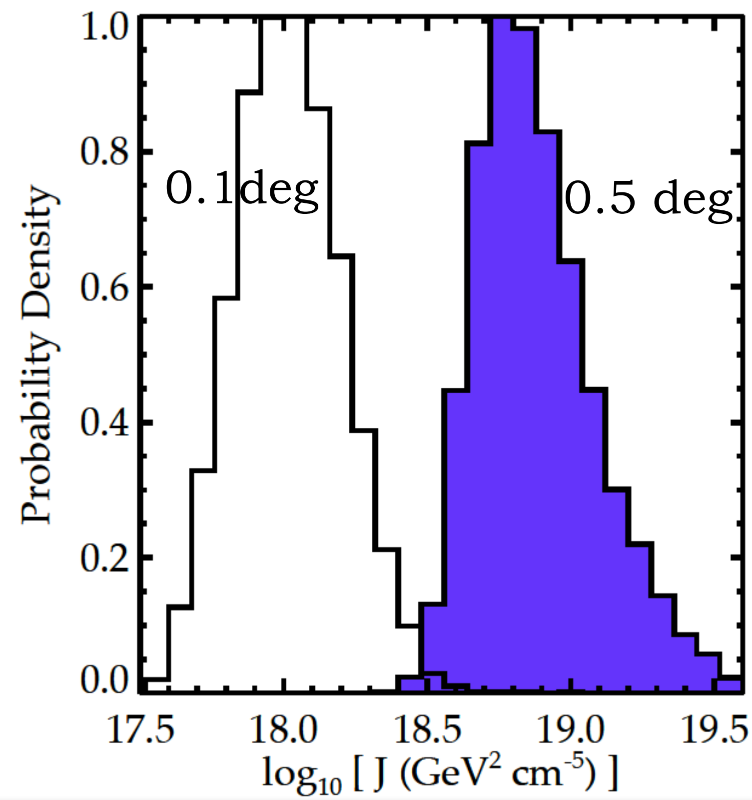
Connection to gamma-rays

$$N_\gamma \frac{1}{2}\frac{\langle\sigma_{\rm ann}v\rangle}{M_{dm}^2}\frac{1}{4\pi}\int_{\ell_-}^{\ell_+}\rho^2[r(\ell)]d\ell$$

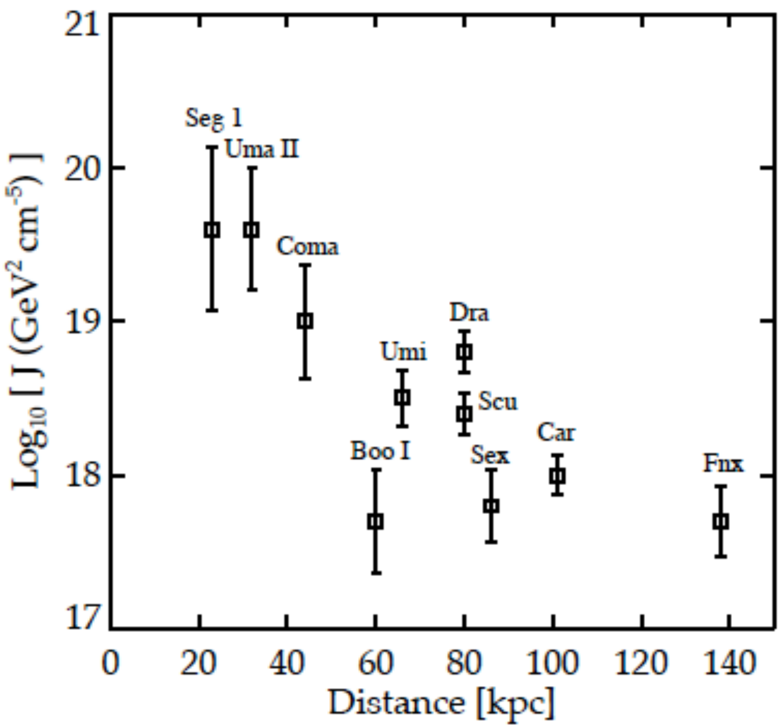
Fixed NFW

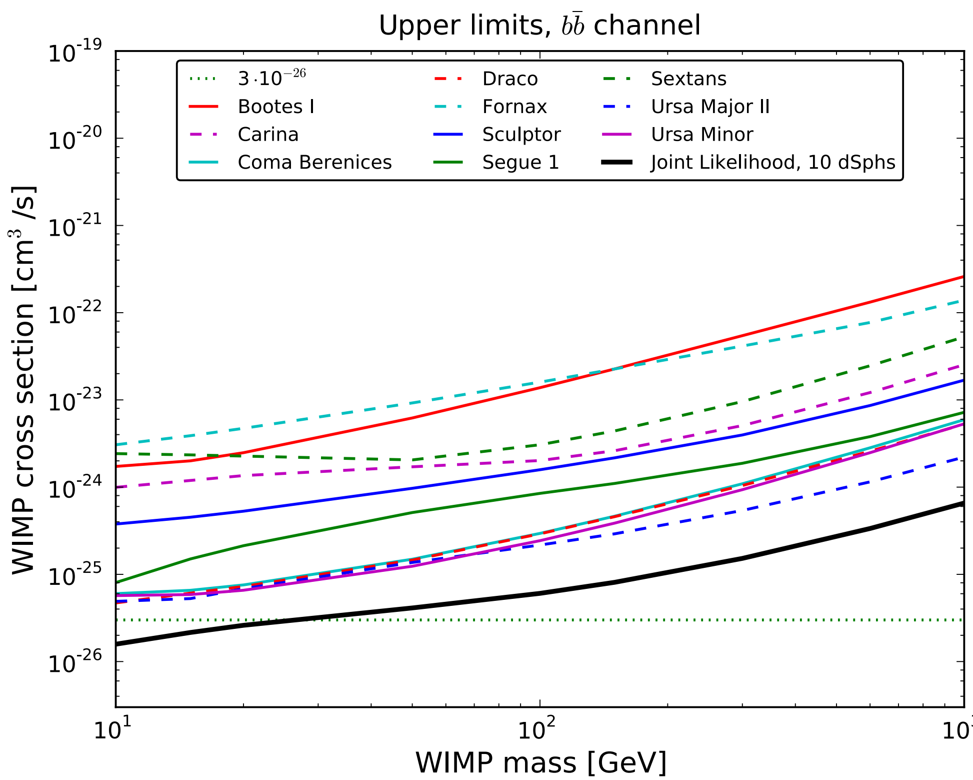


Core allowed



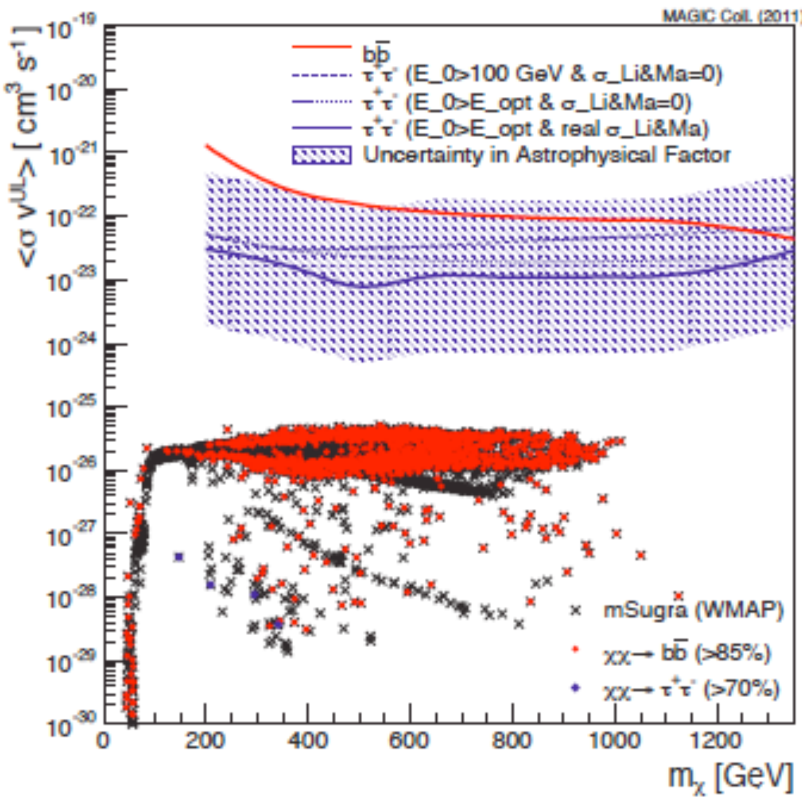
Dark matter bounds from Fermi-LAT



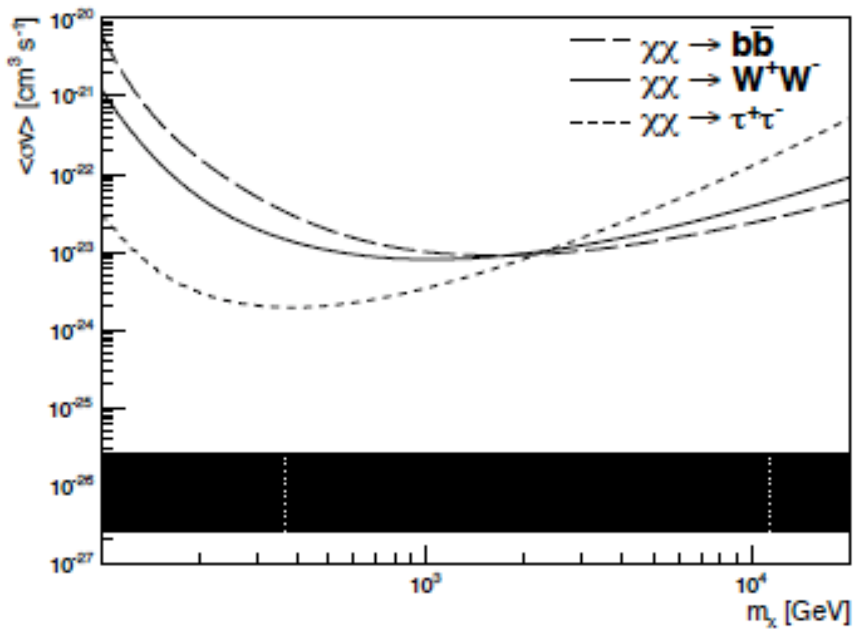


Fermi-LAT Collaboration PRL 2011

Dark matter bounds from ACTs



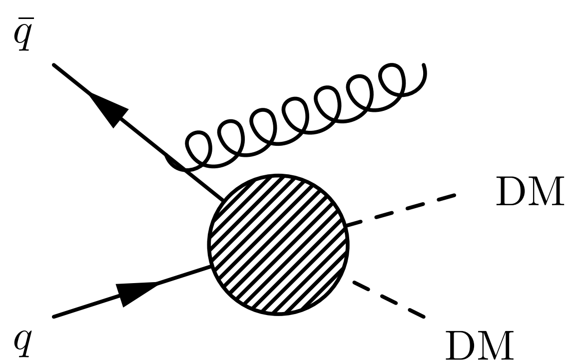
MAGIC

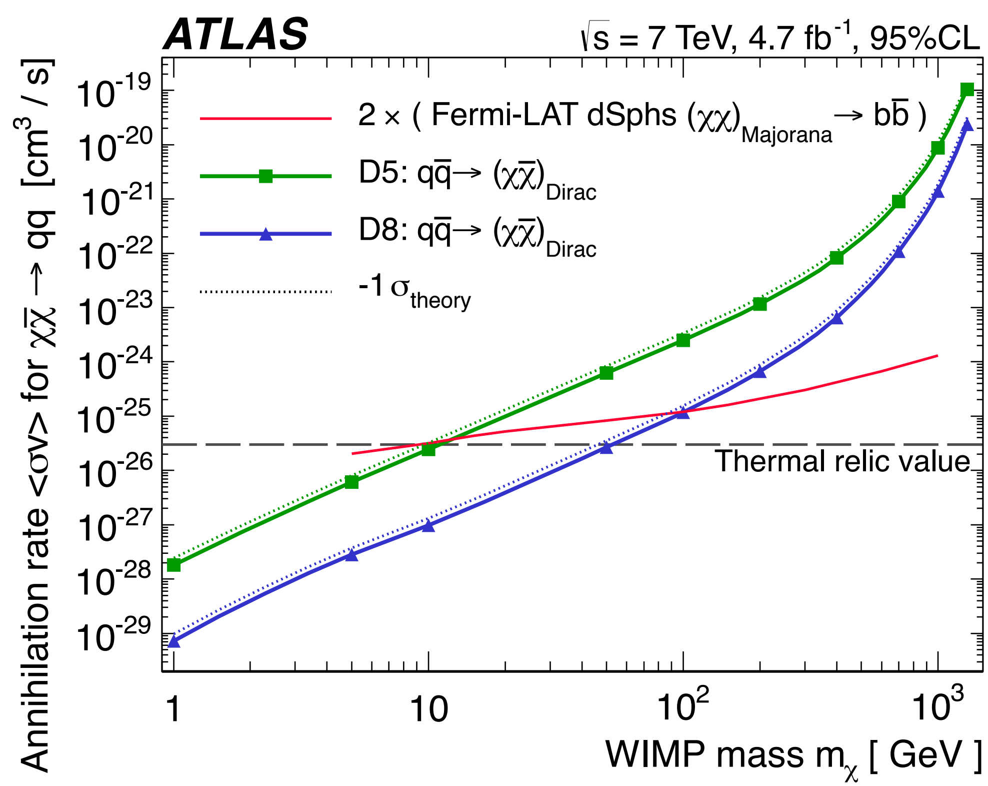


VERITAS

Connection between indirect and collider searches

- WIMP a Dirac Fermion with vector, axial-vector interactions
- No excess of monojet events





Galaxy clusters

- Masses of galaxy clusters determined from temperature profile of x-ray spectra, and electron gas density profile from the X-ray luminosity

- Assumption of hydrostatic equilibrium gives the mass within a fixed physics radius, M(r)

- Nearby clusters Fornax, Coma, and Virgo are some of the most interesting sources (Pinzke et al PRD 2011; Ando & Komatsu JCAP 2012)

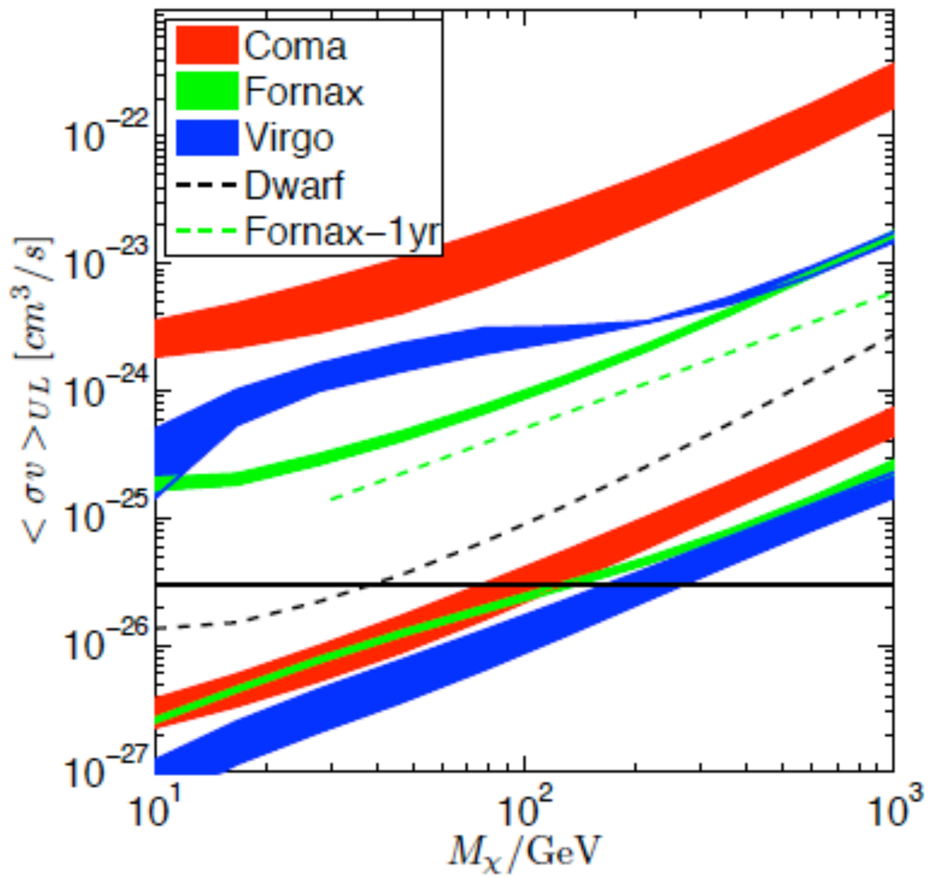
- Significant contribution to the flux expected from substructure in the clusters (e.g. Gao et al. MNRAS 2012)

Galaxy clusters

No detection of any galaxy clusters by Fermi-LAT yet (Ackerman et al. JCAP 2012)

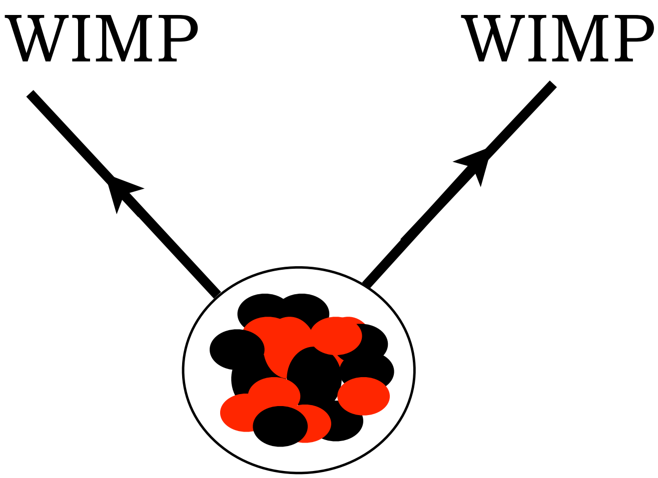
Limits on annihilation cross section strongly depend on assumption for cluster substructure (Han et al. MRNAS 2012, Ando & Nagai JCAP 2012)

HESS bounds from Fornax cluster above 1 TeV (Abramowski et al. ApJ 2012)



Han et al. MNRAS 427 2012

Direct dark matter searches



- Recoil energy of nucleus ~10 keV

Two types of interactions

- *Spin-Independent:*
  - Cross section scales as the mass number of nucleus.
  - Enhancement from coherent scattering
- *Spin-dependent:*
  - Cross section depends on angular momentum
  - No coherent enhancement

Spin-Independent direct dark matter searches

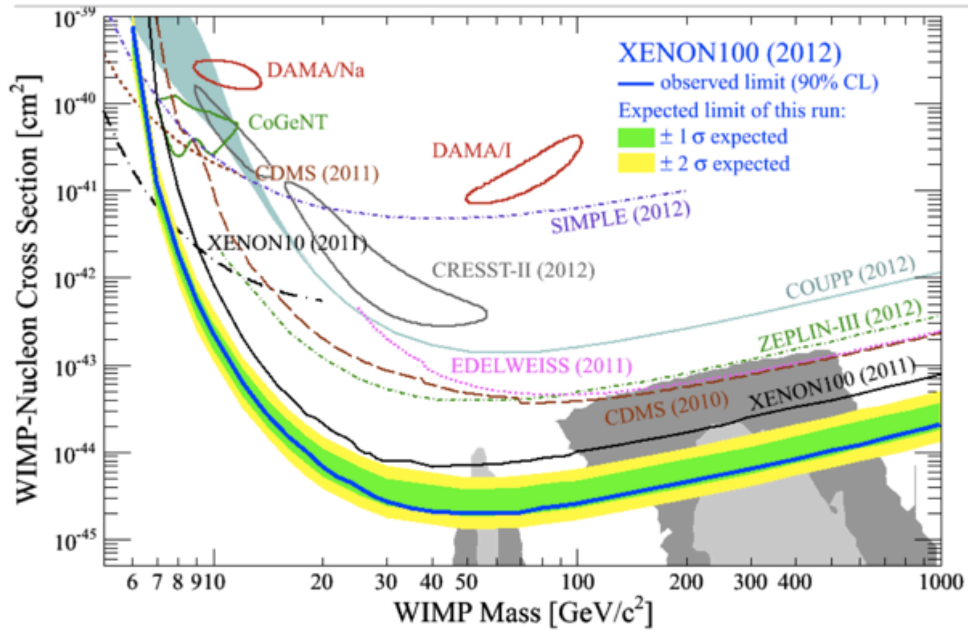
Event rate

$$\frac{dR}{dE_r} = N_T \frac{\rho_\odot}{M_{dm}} \int_{v_{min}}^{v_{esc}} \frac{d\sigma(E_r, v)}{dE_r} v f(\vec{v}, \vec{v}_E) d^3\vec{v}$$

Cross section

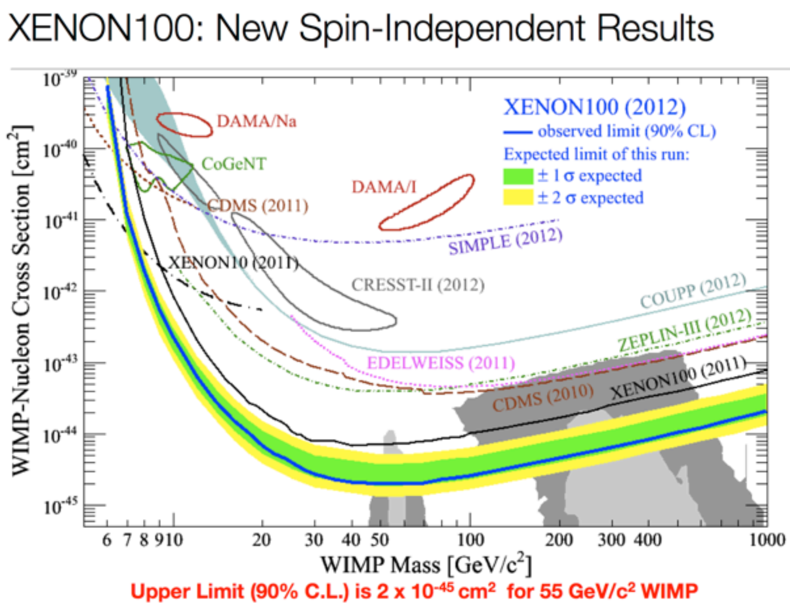
$$\frac{d\sigma}{dE_R} = \frac{\mu_A^2}{M_*^4} [f_p Z + f_n(A - Z)]^2 \left[\frac{m_A}{2\mu_A^2 v^2} F^2(E_R)\right]$$

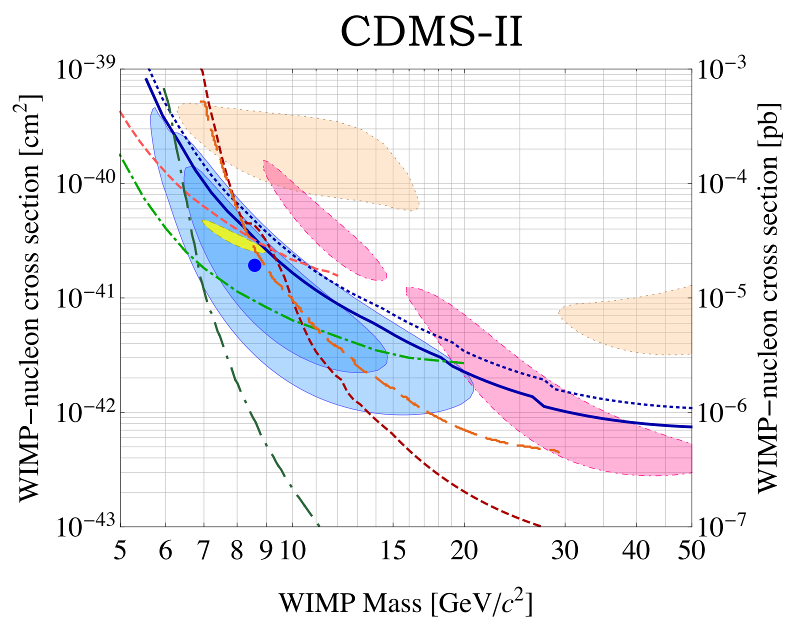
XENON100: New Spin-Independent Results



Upper Limit (90% C.L.) is 2 x 10^{-45} cm^2 for 55 GeV/c^2 WIMP

Are these results consistent?



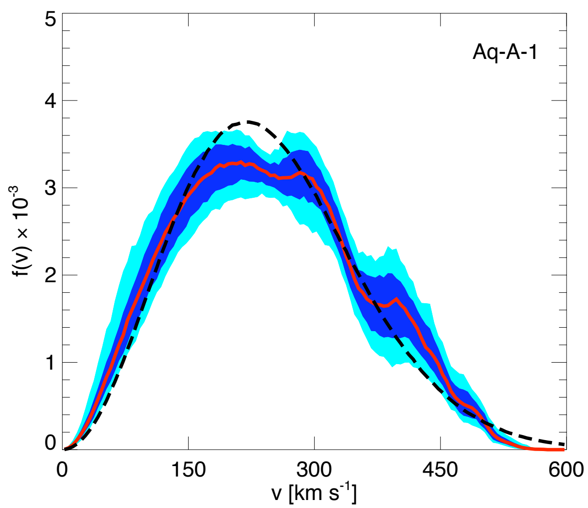


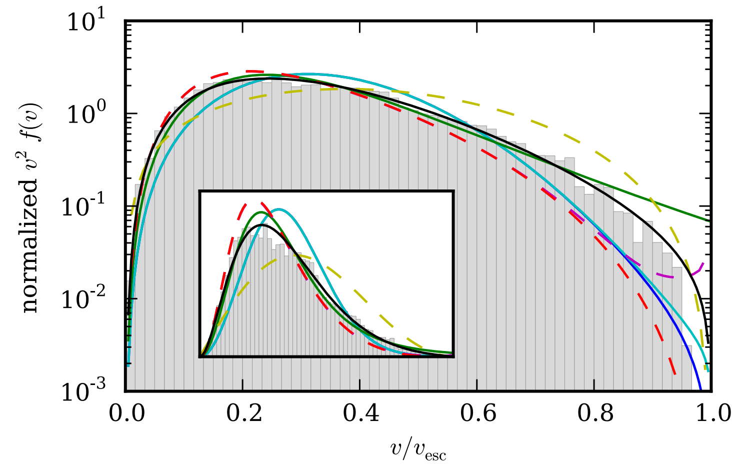
- DAMA, CoGENT, and CDMS-II report events not accounted for by known backgrounds

- Possible ways to make results consistent:
  1) Experimental issues
  2) Particle model (e.g. Isospin-violating DM, e.g. Feng & Kumar 2008)
  3) Galactic halo model

- Can compare experiments independent of ``astrophysics" (Fox et al. JCAP 2011, Frandsen et al. 2013 1304.6066, Del Nobile et al. 2013 1304.6183)

``Cosmological” velocity distribution

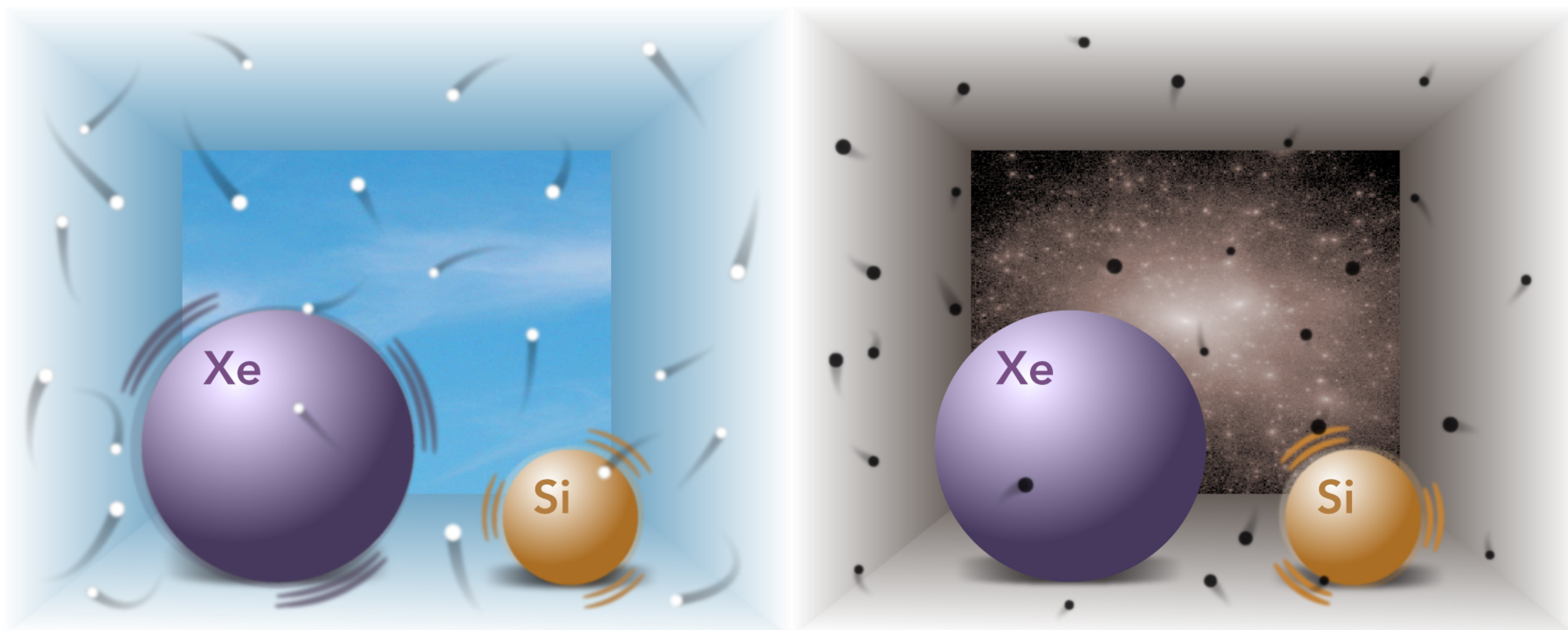




- Experiments and interpretations use the ``standard halo model” (Lewin & Smith 1996)

- ``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)

Dark matter halos



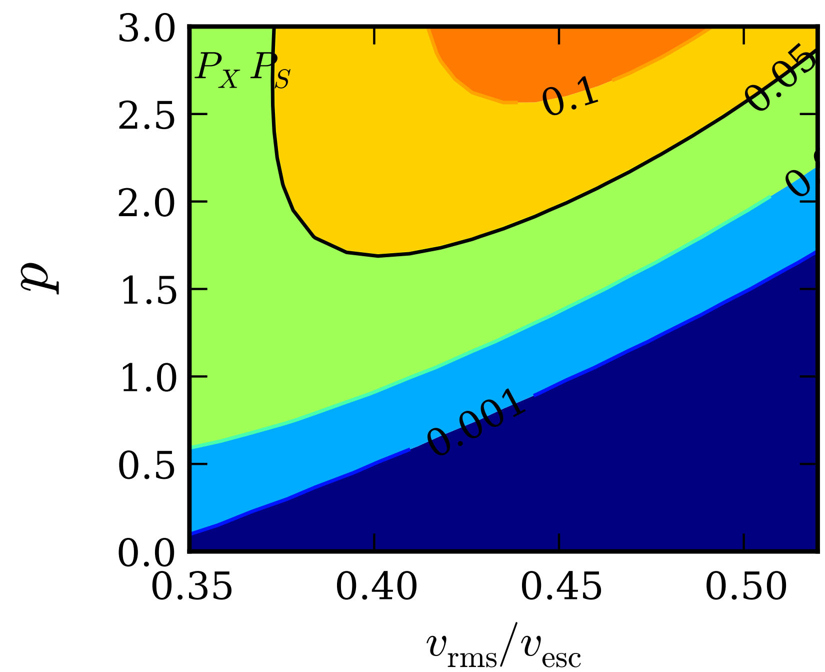
Credit: Greg Stewart/SLAC National Accelerator Laboratory at Stanford

- Important implications for detectors with heavy nuclei targets and ~ 10 GeV mass WIMPs

``Cosmological" velocity distribution: Implications

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

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



- 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. Within reach for LUX

Local Inventory of Dark Matter

- Local mass density in Galactic disk is ~ 0.1 Msun/pc^3 (Holmberg & Flynn 2000, 2004)

- Stars, molecular gas, cold/warm/hot components

- Surface mass density out to 1.1 kpc is 74 +- 6 Msun/pc^2. 56 +- 6 Msun/pc^2 from disk.

- No significant DM disk component (Moni Bidin et al. ApJ 2010)

Measurements of local density

``Local" measurements

Authors	Total (visible) surface mass density ($M_\odot$ pc^{-2})	Dark matter density ($M_\odot$ pc^{-3})	Method
Kuijken and Gilmore [94]	71 ± 6 (48 ± 8)	–	DF
Holmberg and Flynn [104]	$74 \pm 6\,(56)$	–	M
Bienayme et al. [109]	$64 \pm 5\,(53)$	–	DF
Holmberg and Flynn [105] [a]	–	0.007	DF
Garbari et al. [103]	–	$0.022^{+0.015}_{-0.013}$ (90%)	M
Bovy and Tremaine [99]	–	$0.008^{+0.003}_{-0.003}$	M
Catena and Ullio [110]	–	$0.011^{+0.0010}_{-0.0010}$	–
Weber and de Boer [111]	–	[0.005 – 0.010]	–
Salucci et al. [112]	–	$0.012^{+0.003}_{-0.003}$	–
McMillan [113]	–	$0.011^{+0.0011}_{-0.0011}$	–

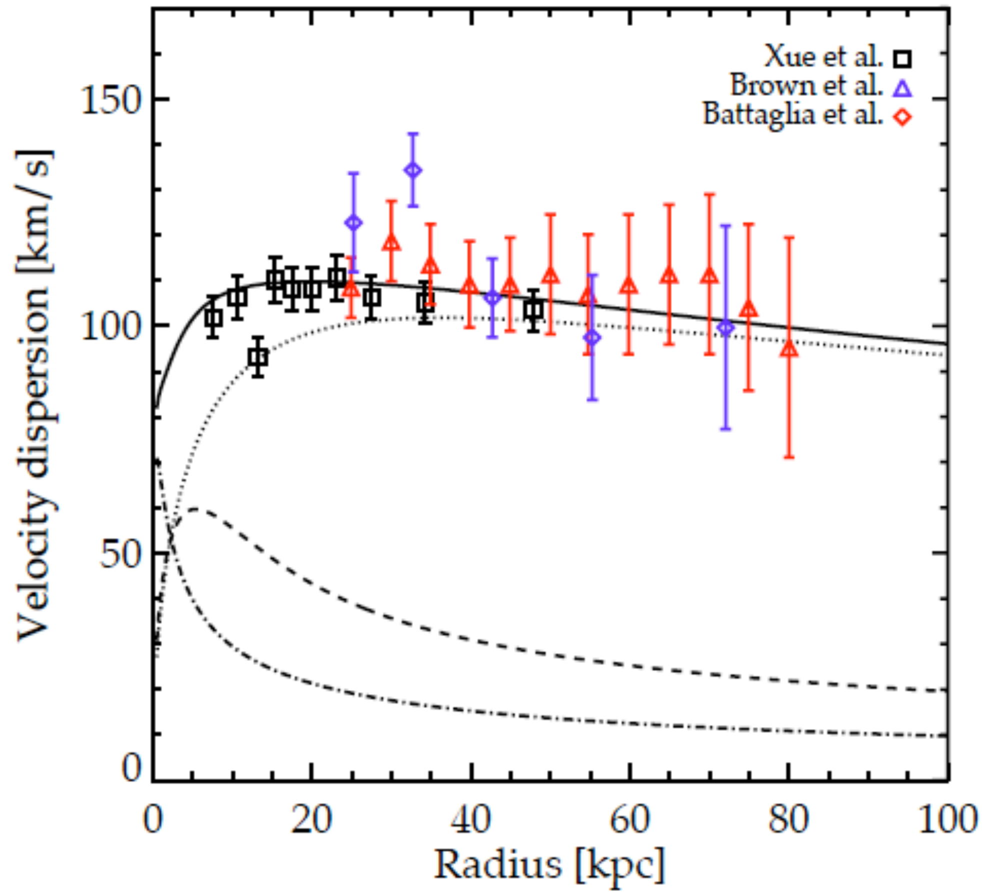
``Global" MW mass measurements

Strigari Phys. Rep 2013

Measurements of MW mass

$$r\frac{d(\rho_s \sigma_r^2)}{dr} + 2\beta(r)\rho_s\sigma_r^2 = \rho_s(r)\frac{GM(r)}{r},$$

from jeans equation



Authors	R (kpc)	Mass ($< R$) (10^{11} $M_\odot$)	Total Mass (10^{12} $M_\odot$)	Tracers	Orbits	Method
Wilkinson and Evans [118]	50	$5.4^{+0.2}_{-3.6}$	$1.9^{+3.6}_{-1.7}$	GC,dSph	R	DF
Sakamoto et al. [119]	50	$5.3^{+0.1}_{-0.4}$	–	S	C	DF
Xue et al. [122]	60	$4.0^{+0.7}_{-0.7}$	$1.0^{+0.3}_{-0.2}$	S	I	M
Gnedin et al. [128]	80	$6.9^{+3.0}_{-1.2}$	–	S	R	M
Watkins et al. [120]	100	$3.3^{+1.1}_{-1.1}$	$0.9^{+0.3}_{-0.3}$	S,GC,dSph	I	M
Deason et al. [121]	50	$4.2^{+0.4}_{-0.4}$	–	S	R	M
Battaglia et al. [127] [a]	–	–	$0.50^{+0.25}_{-0.17}$	S	R	M
Dehnen et al. [125] [a]	–	–	1.5	S	R	M
Li and White [129]	–	–	$2.43^{+0.66}_{-0.65}$	–	–	
Busha et al. [130]	–	–	$1.2^{+1.0}_{-0.7}$	–	–	

Strigari Phys. Rep 2013

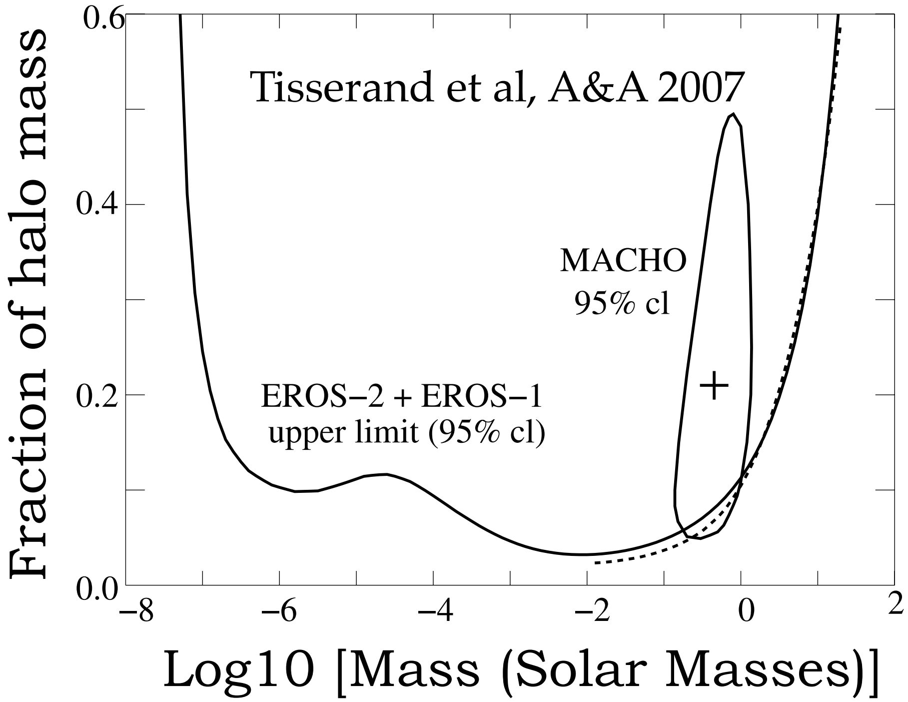
Milky Way Streams

Prominent stellar streams in the Milky Way halo that may be associated with tidally-disrupted dwarf galaxies.

Name	Distance [kpc]	Reference
Magellanic Stream	–	Mathewson [213]
Sagittarius	–	Ibata et al. [151]
Orphan Stream	–	Belokurov et al. [217]
Styx	45	Grillmair [219]
Bootes III	45	Grillmair [219], Carlin et al. [222]

Summary: Progress in dark matter detection

Compact objects



Particles