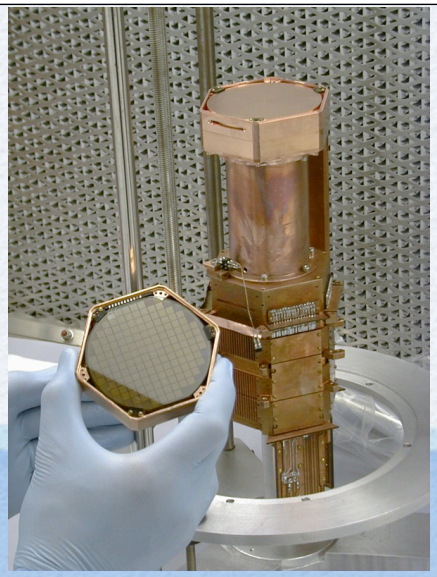
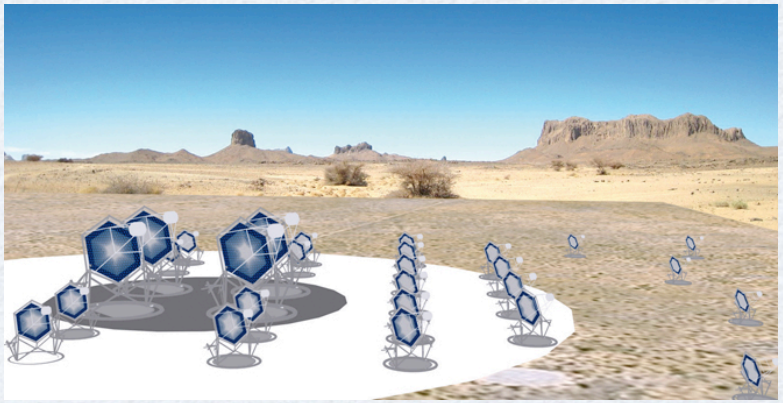




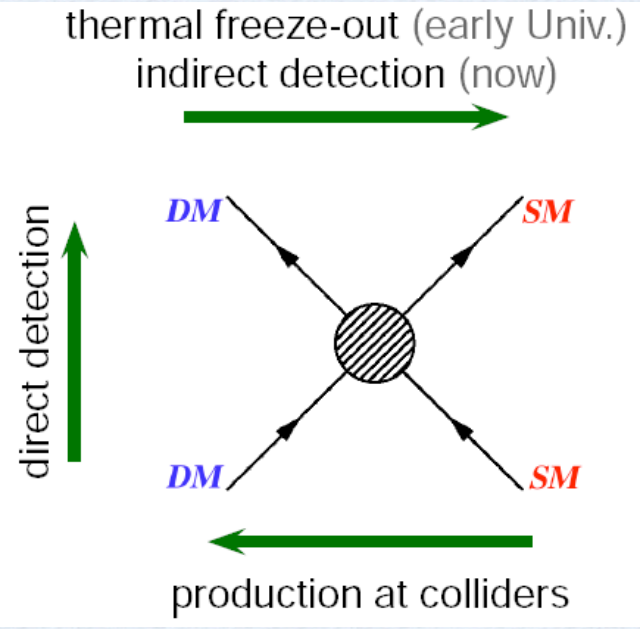
Latest Results in Dark Matter Detection

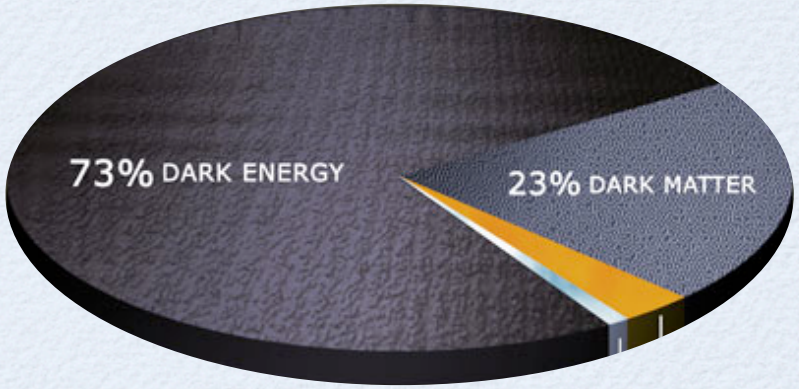
Louis E. Strigari
Stanford University/KIPAC
KITP Faint Dwarfs Conference
2/17/2012

WIMP Dark Matter

WIMPs in equilibrium in early Universe, may freeze-out with significant relic abundance

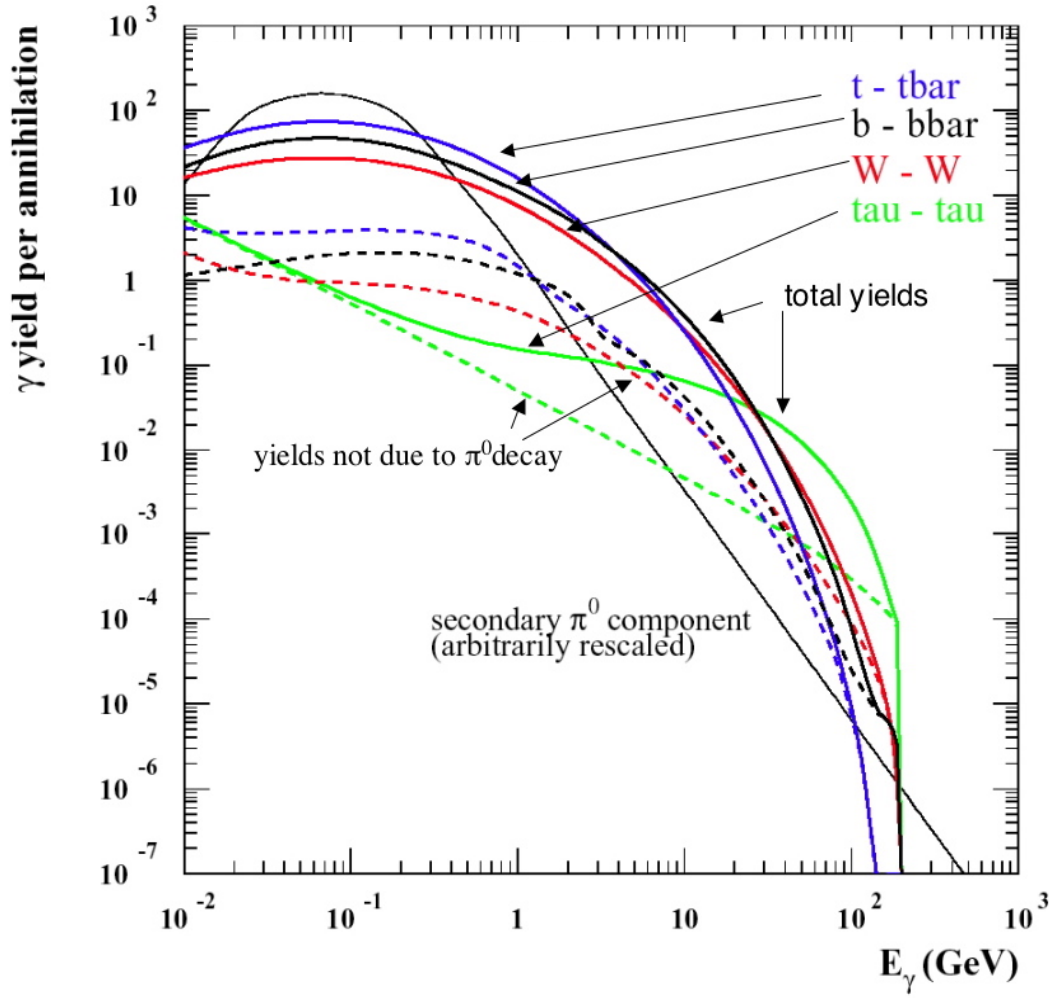
$$\sigma v \sim 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$





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

How to find the dark matter



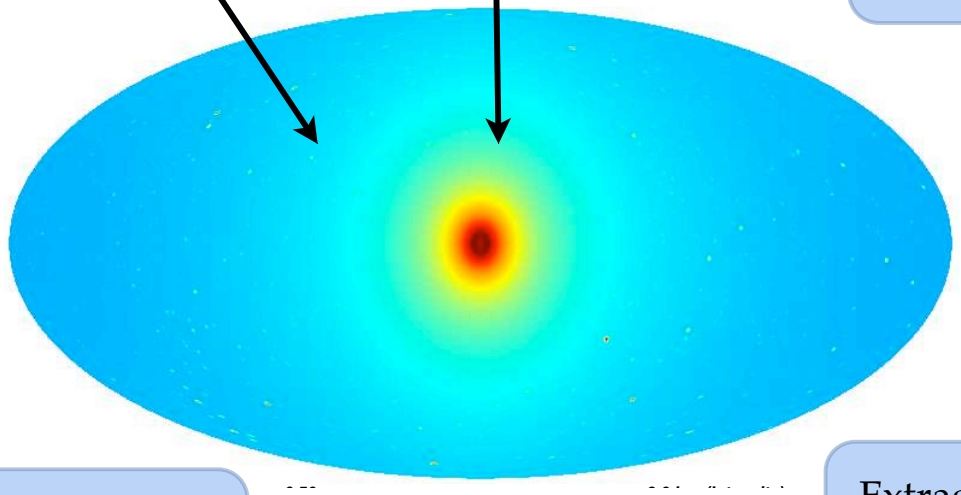
- Typical photon energy about 1/10 of the WIMP mass
- ~ few to hundreds of photons many be produced

Targets

Satellites: Low bkgd, good source id, low statistics

Galactic center: Good statistics, source confusion/ diffuse backgrounds

Halo: Good statistics but diffuse backgrounds



Spectral lines: Good source id, low statistics

Extragalactic: Good statistics, diffuse bkgds and astrophysics

Galaxy clusters: Low backgrounds but low statistics

Dwarf Spheroidals

- Well understood dark matter distributions
- Nearby, may be modeled as point sources
- No sources of gamma-rays from cosmic rays or star formation [Grcevich & Putman ApJ 2010]

J value

The gamma-ray flux is:

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

Particle Model

Dark Matter Halo Model

Kinematics: More detailed look

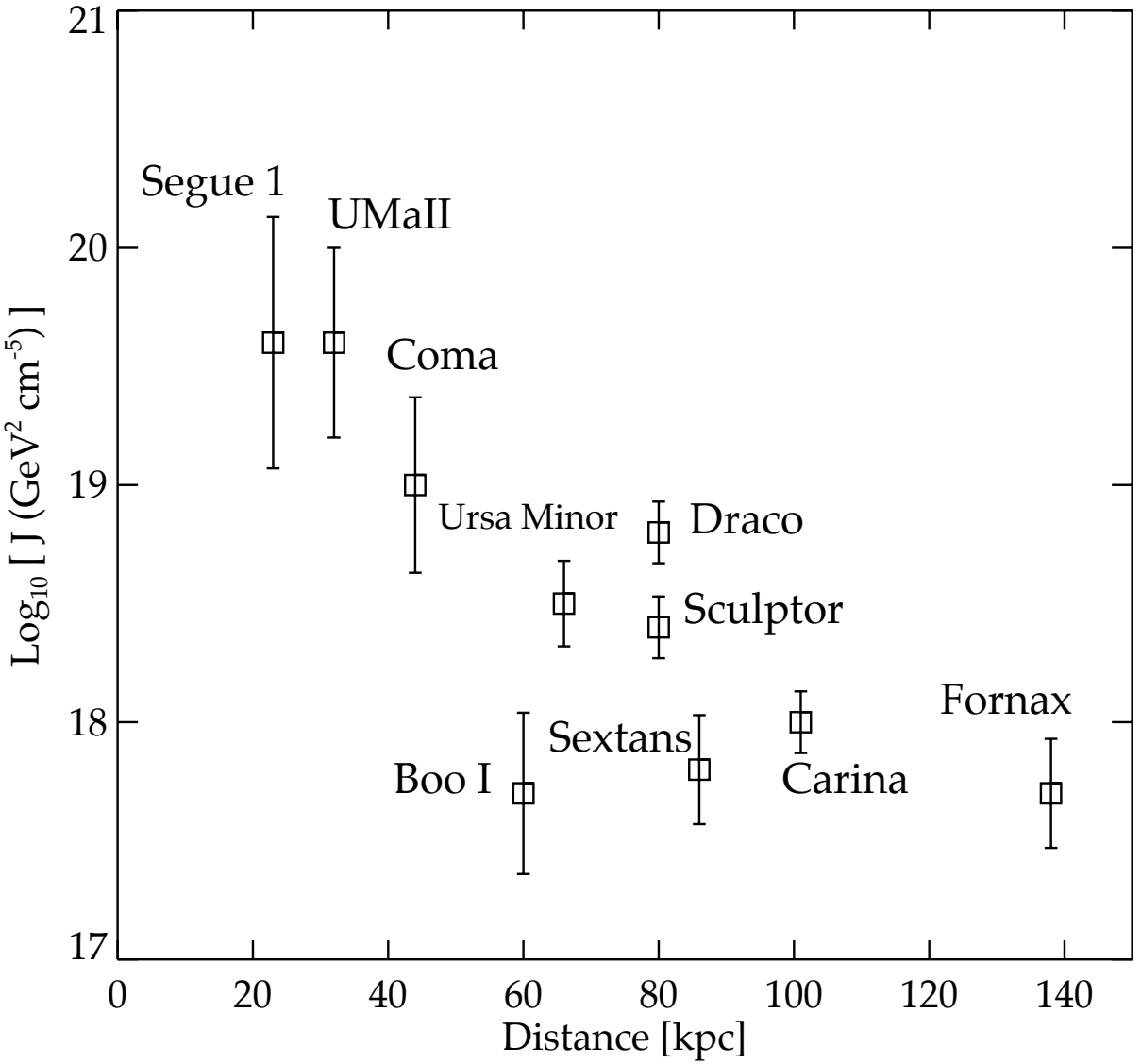
- Mass within approximate half-light radius well-determined [Strigari et al. APJL 2007, PRD 2007, APJ 2008; Walker et al. 2009; Wolf et al. 2009]
- Corresponds to ~ 0.5 deg for dSph distance
- Insensitive to dark matter core/cusp

Data

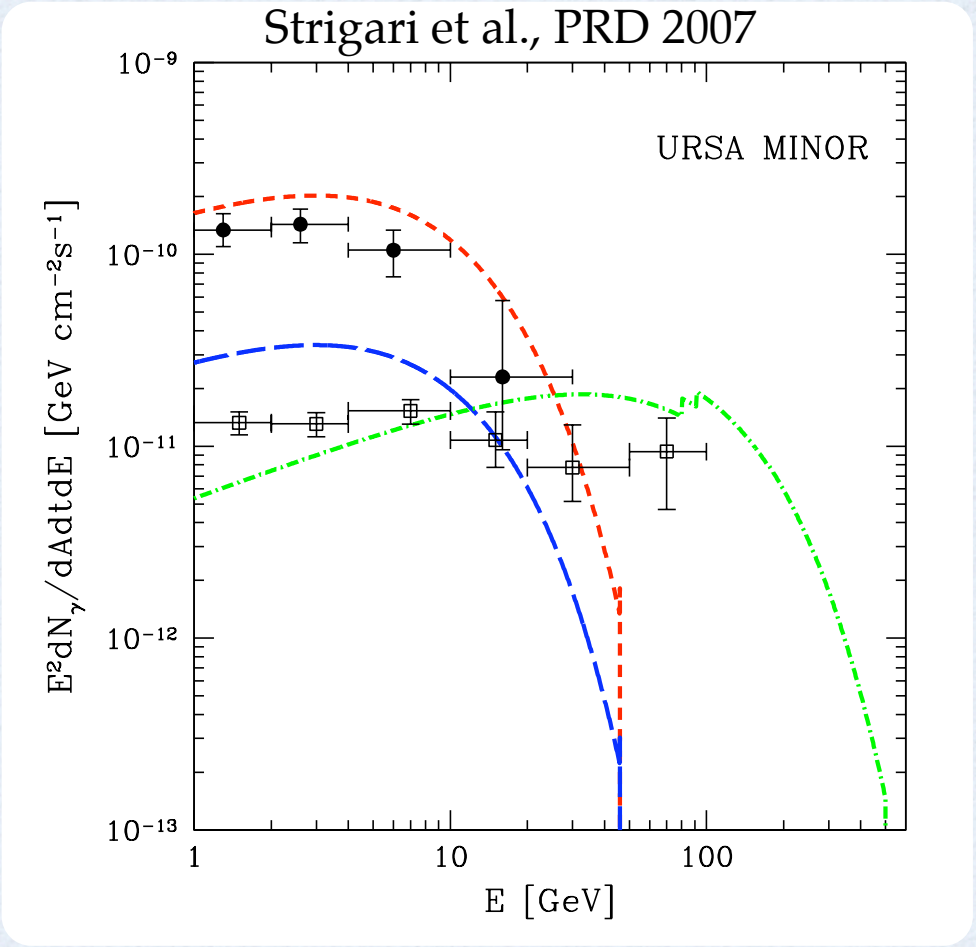
Model parameters

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

Dark matter distributions

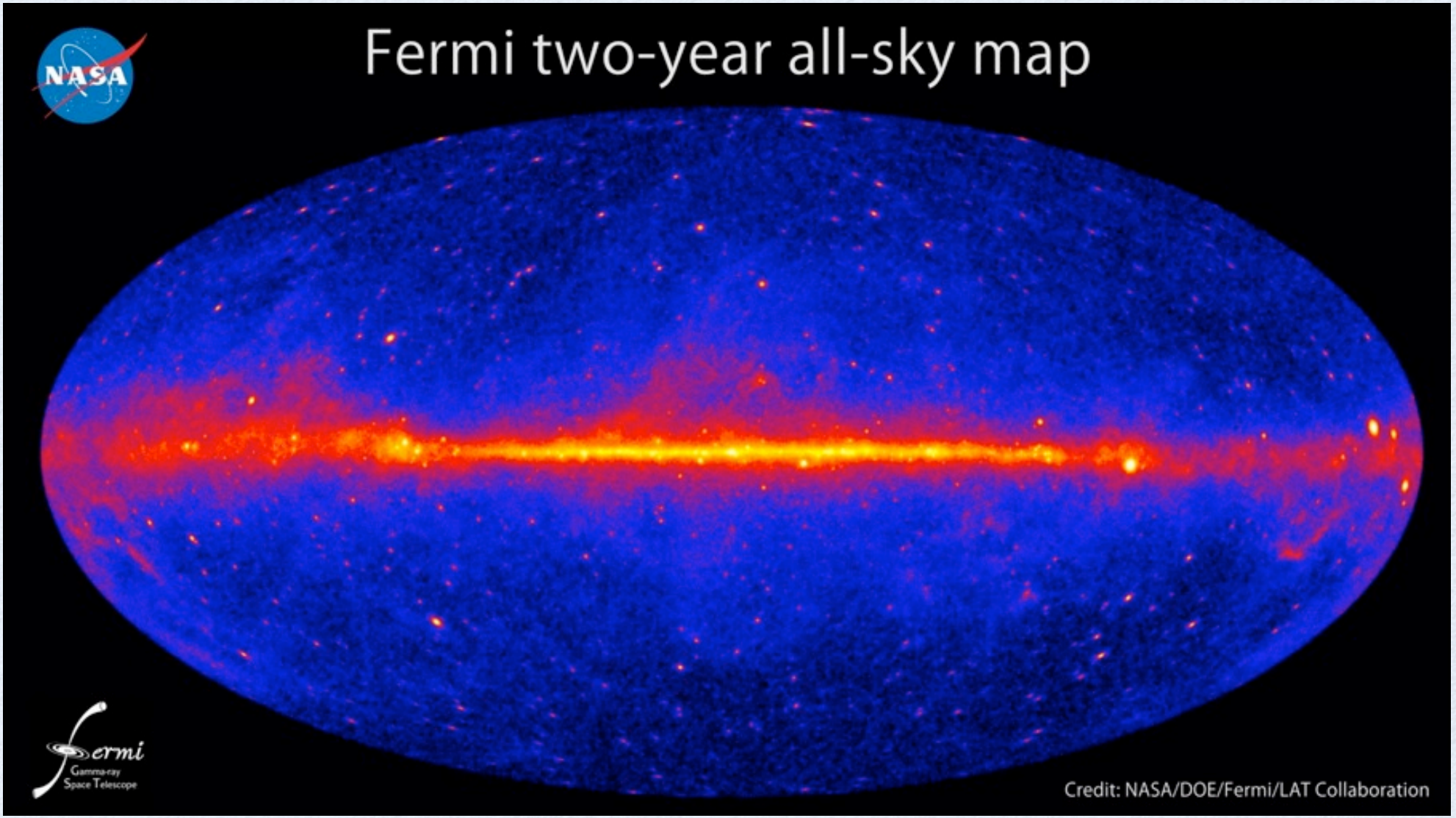


Pre-Fermi Predictions

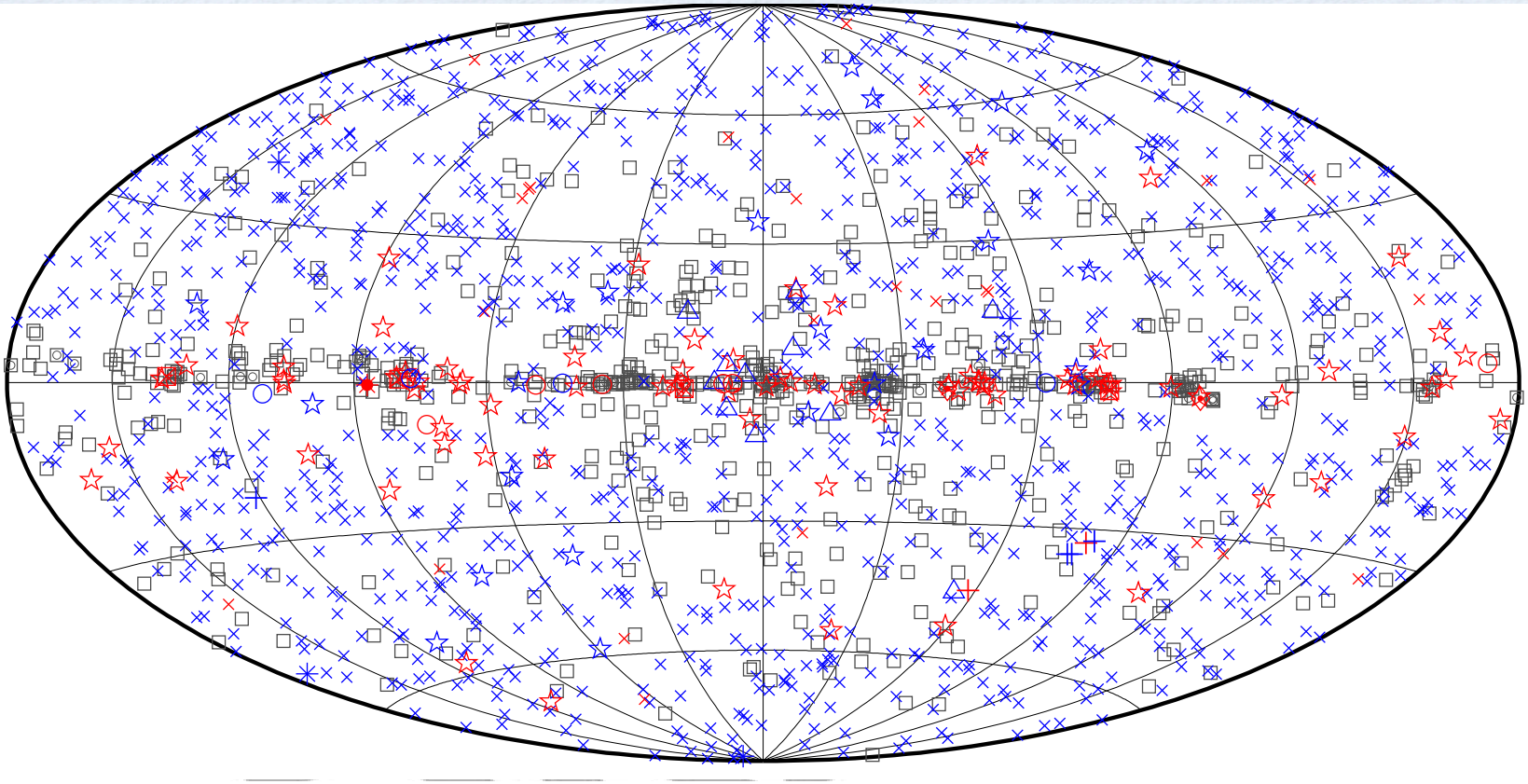


- Data: EGRET galactic and extragalactic backgrounds
- Theoretical models for 50 and 500 GeV WIMPs
- Best constraints come from Ursa Minor (66 kpc) and Draco (80 kpc)

Tyler PRD 2002, Evans et al. 2004, Strigari et al. PRD 2007, APJ 2008


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

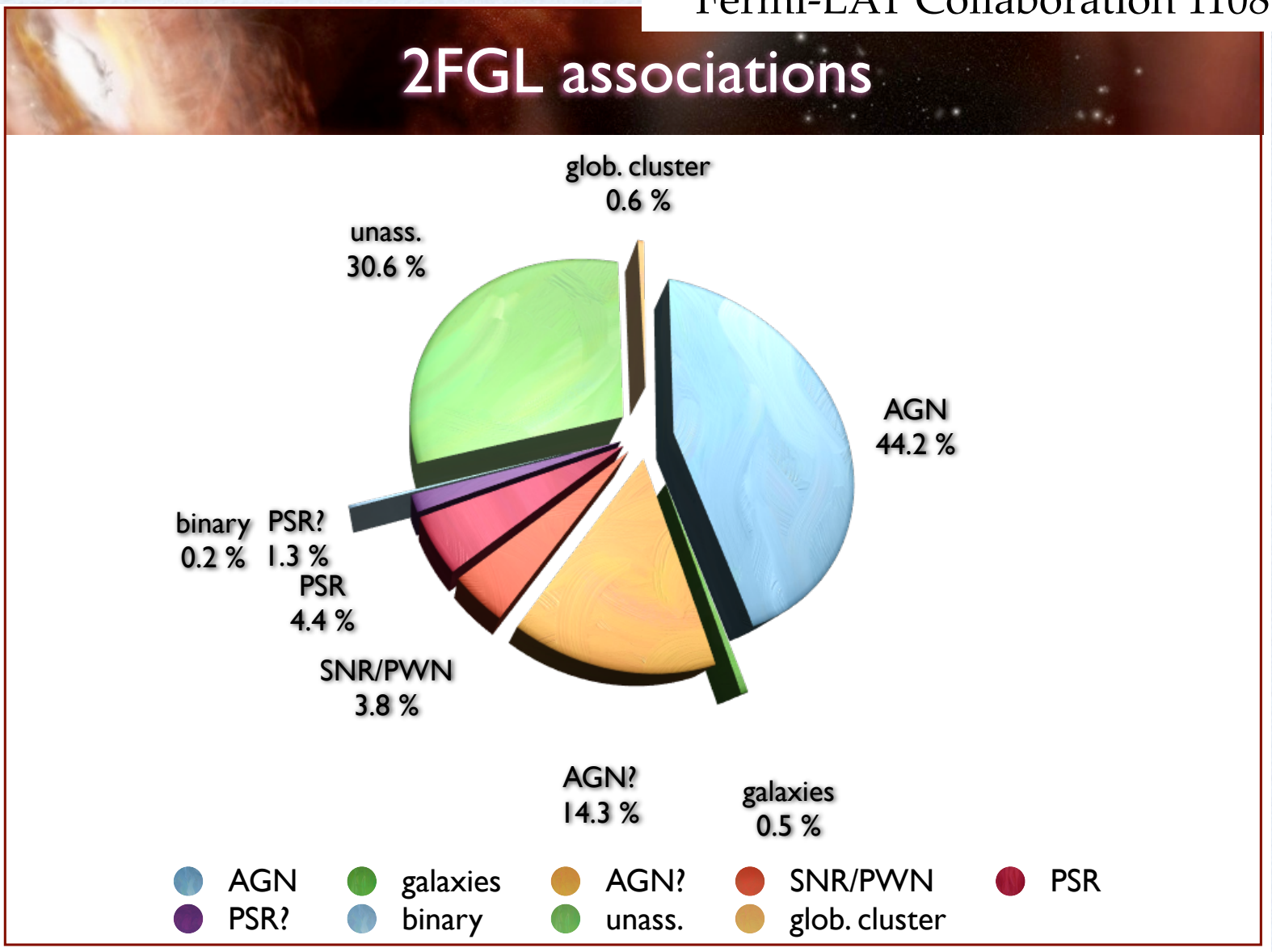
2 year source catalog



□ No association	⊡ Possible association with SNR or PWN	
× AGN	☆ Pulsar	△ Globular cluster
✳ Starburst Gal	⧫ PWN	⊠ HMB
+ Galaxy	○ SNR	✷ Nova

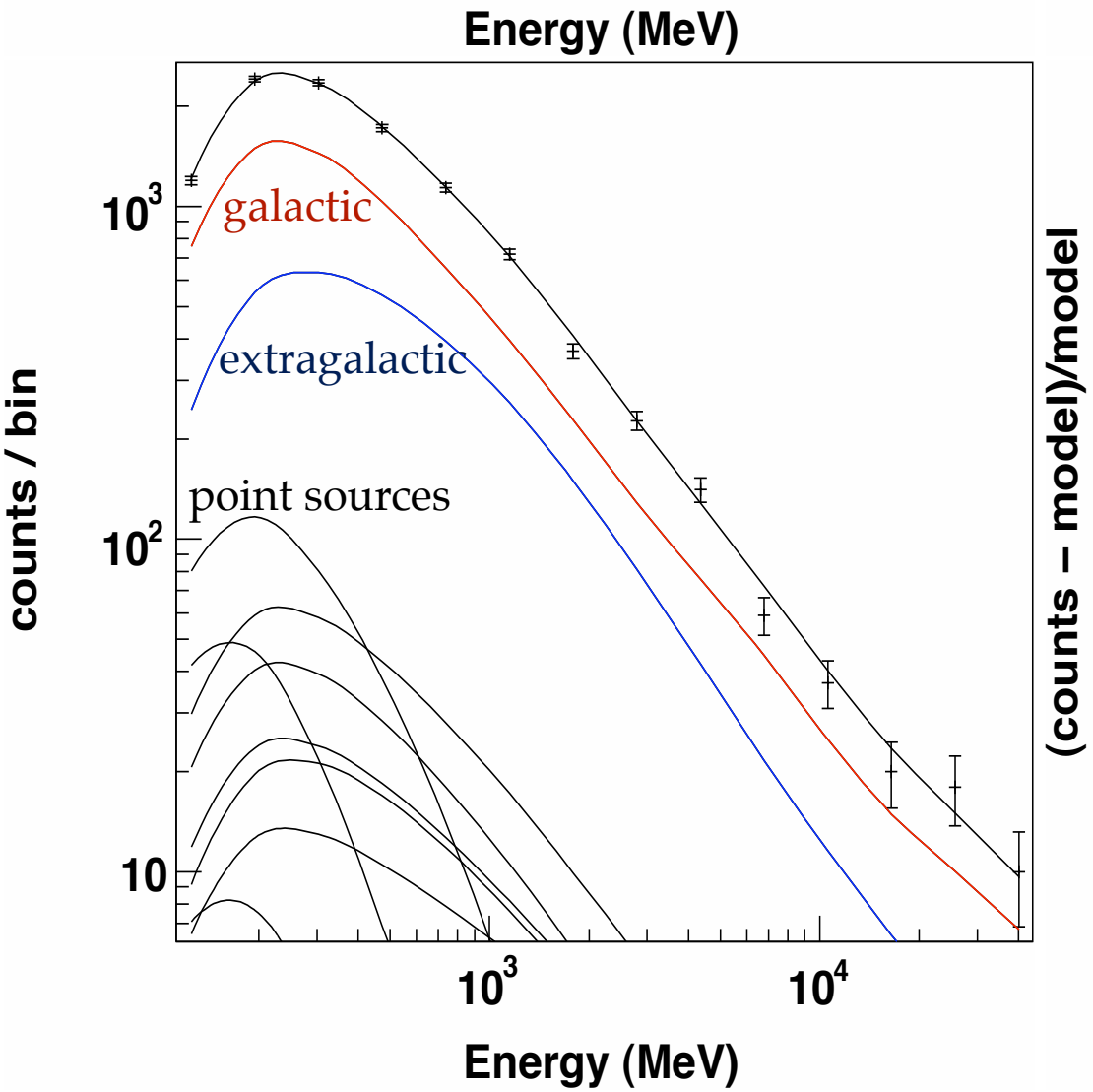
Point Sources in Fermi

Fermi-LAT Collaboration 1108.1435

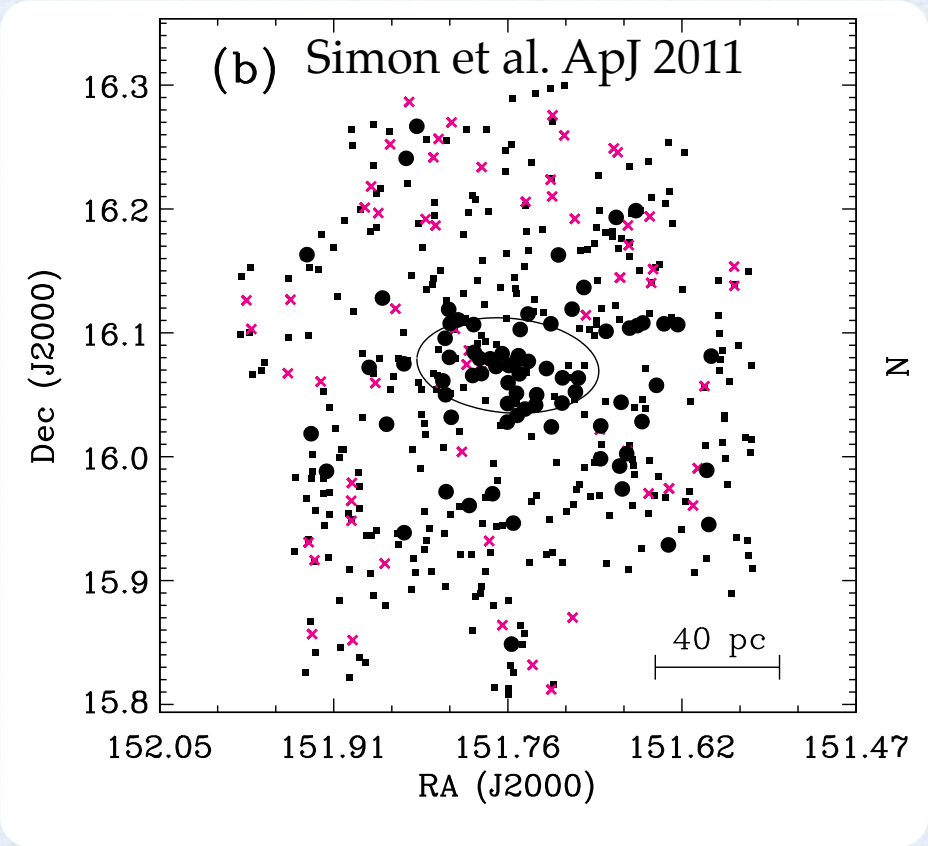


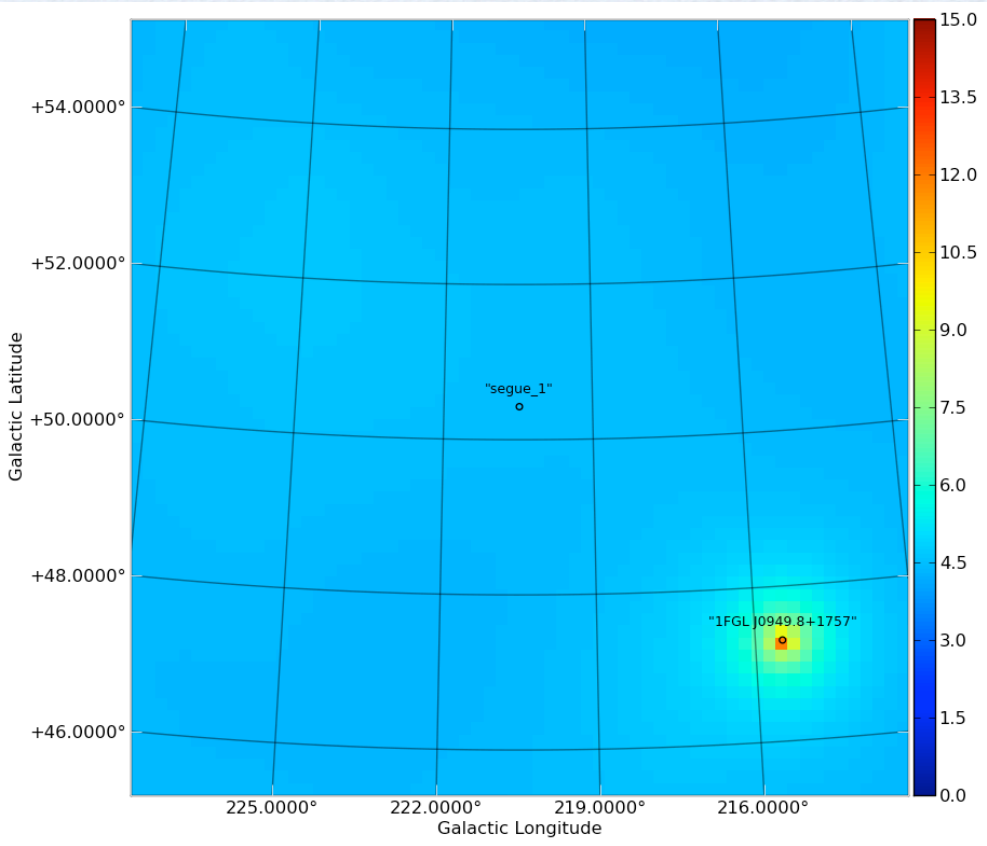
Search for emission from satellites

Fermi-LAT Collaboration, ApJ 2010



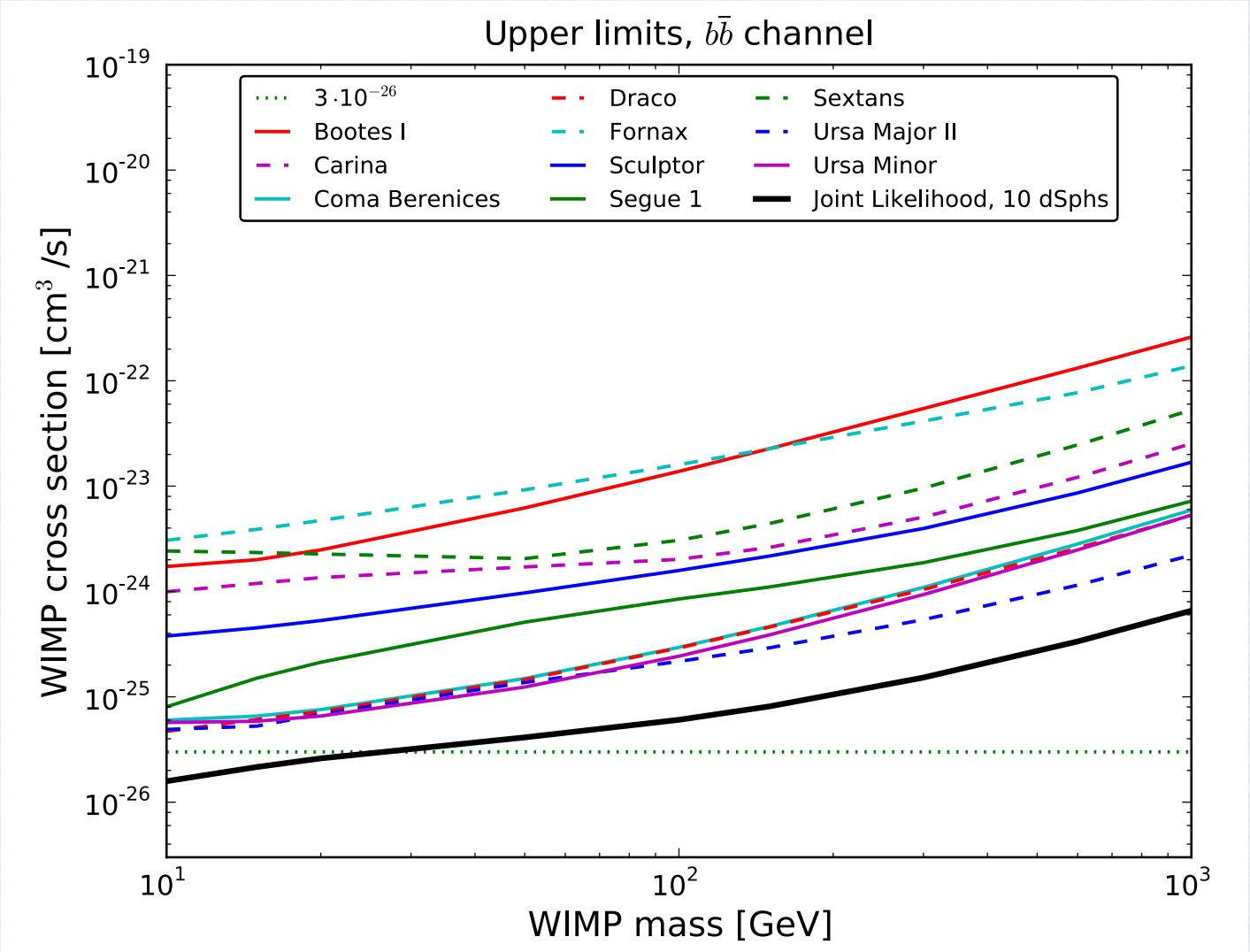
Search for emission from satellites





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

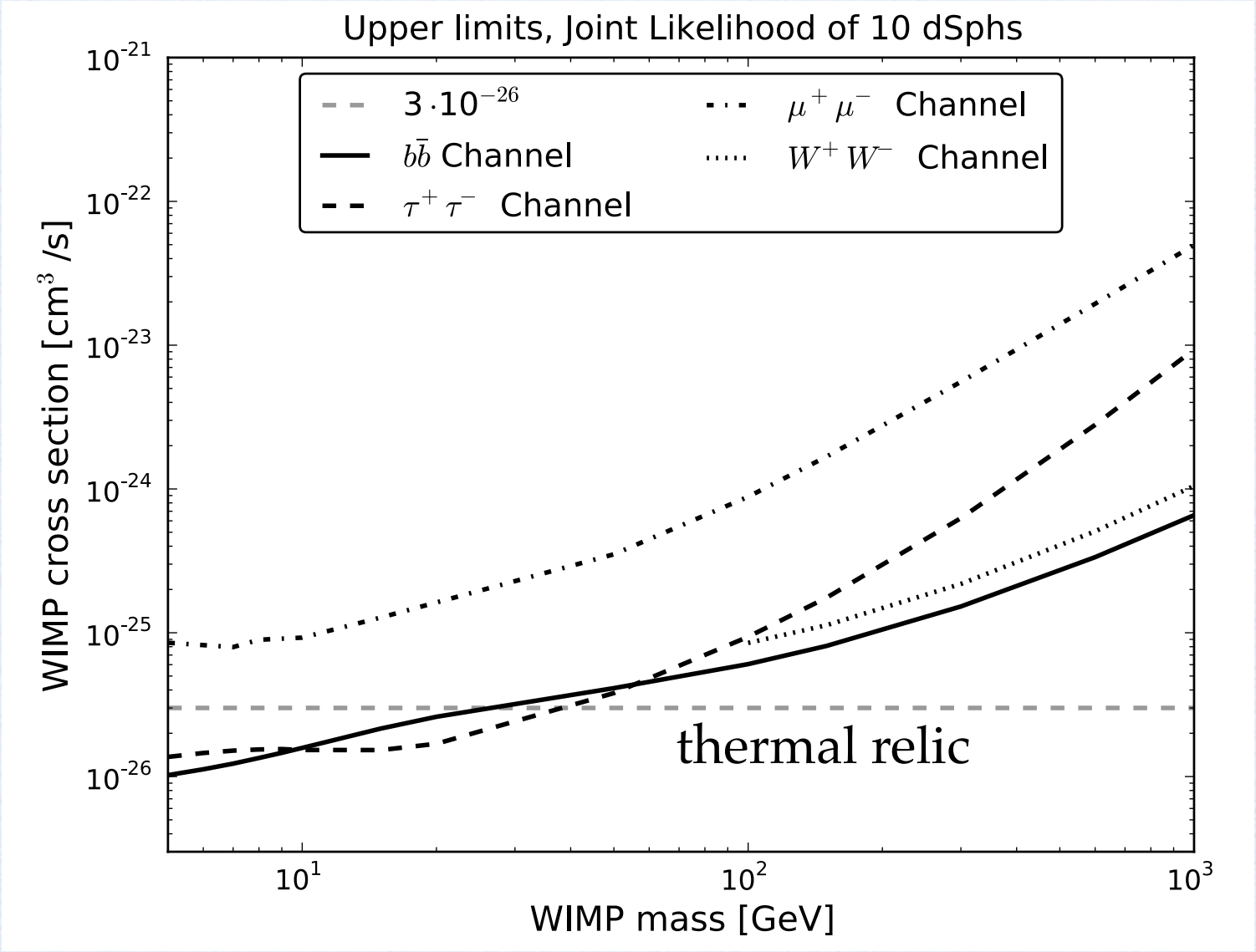
Fermi-LAT Collaboration, PRL 2012



Also: Geringer-Sameth & Koushiappas 2012

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

Fermi-LAT Collaboration, PRL 2012



Implications

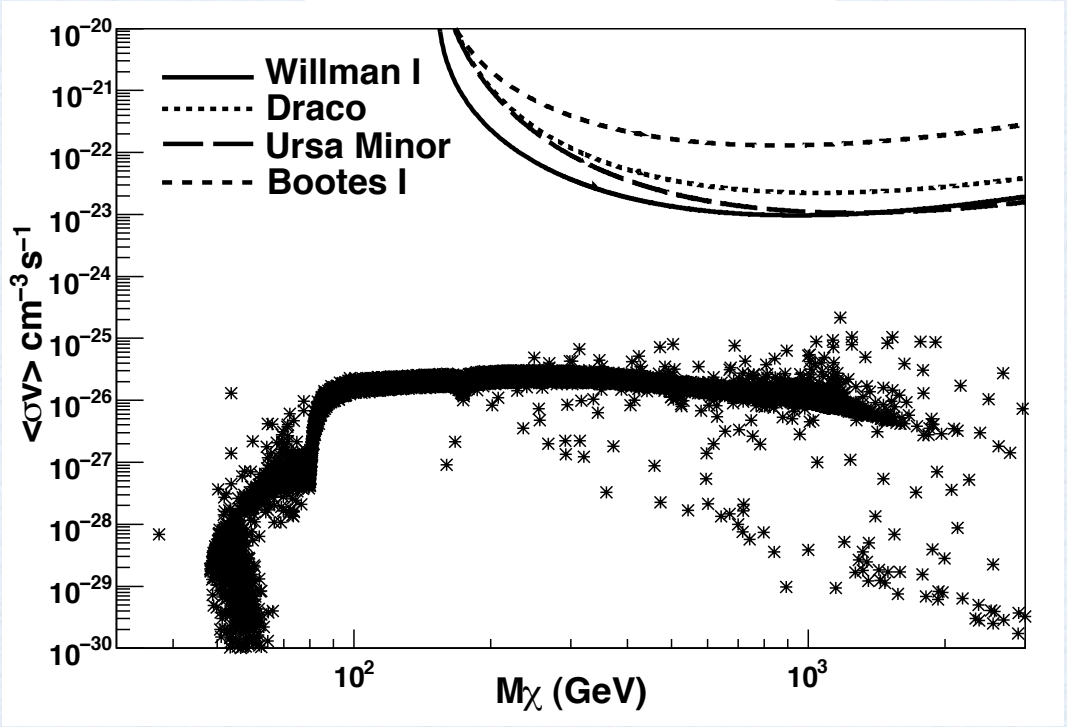
- Dark matter in the mass range 10-25 GeV that dominantly annihilate to b-quarks and tau leptons ruled out
  - For pure s-wave interactions, this constrains WIMP production in the early Universe
- For the first time we are probing thermal relic WIMP dark matter
- Very little ambiguity due to dark matter substructure [Kuhlen et al. ApJ 2008; Springel et al. MNRAS 2008; Martinez et al. JCAP 2009]

Improvements in analysis

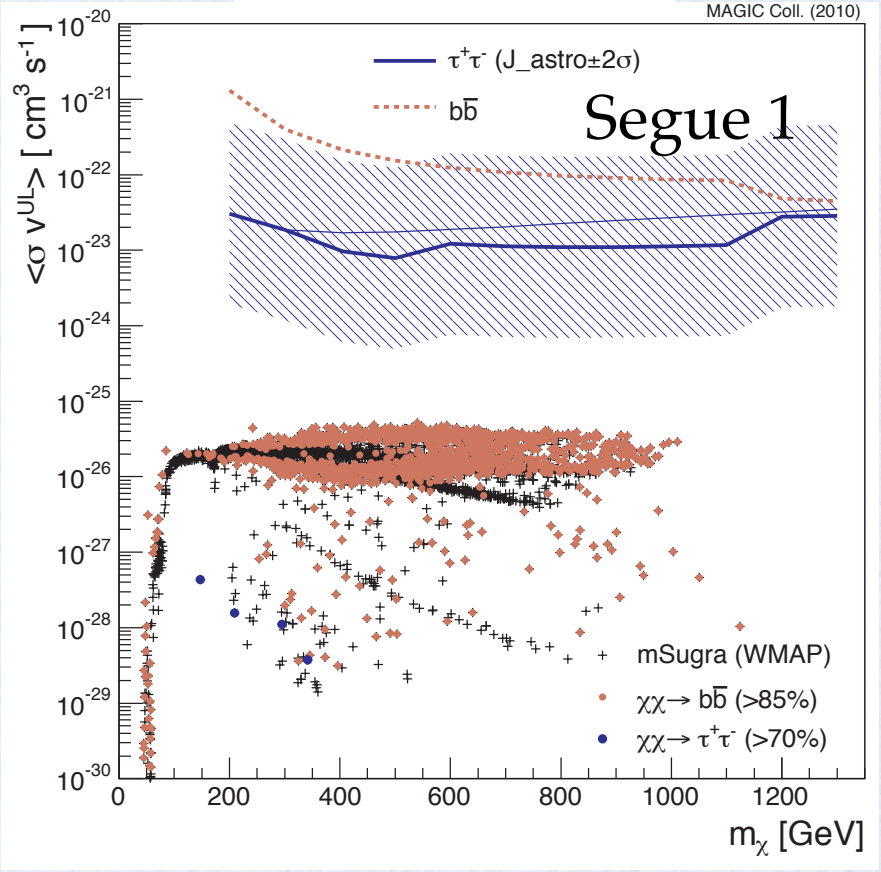
- Only used 2 years of possible 10 years of Fermi data
- Better data on stellar kinematics
  - Improved dynamical models
  - Proper motions
- More MW satellites will be discovered
- Complementarily with ground-based detectors

Pointed observations at higher energy

VERITAS

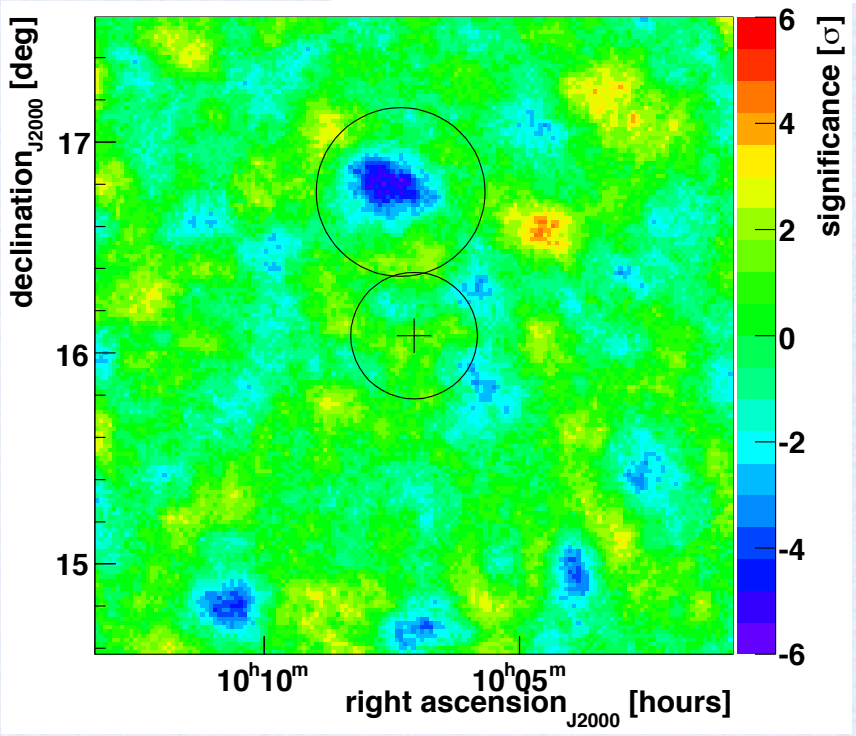


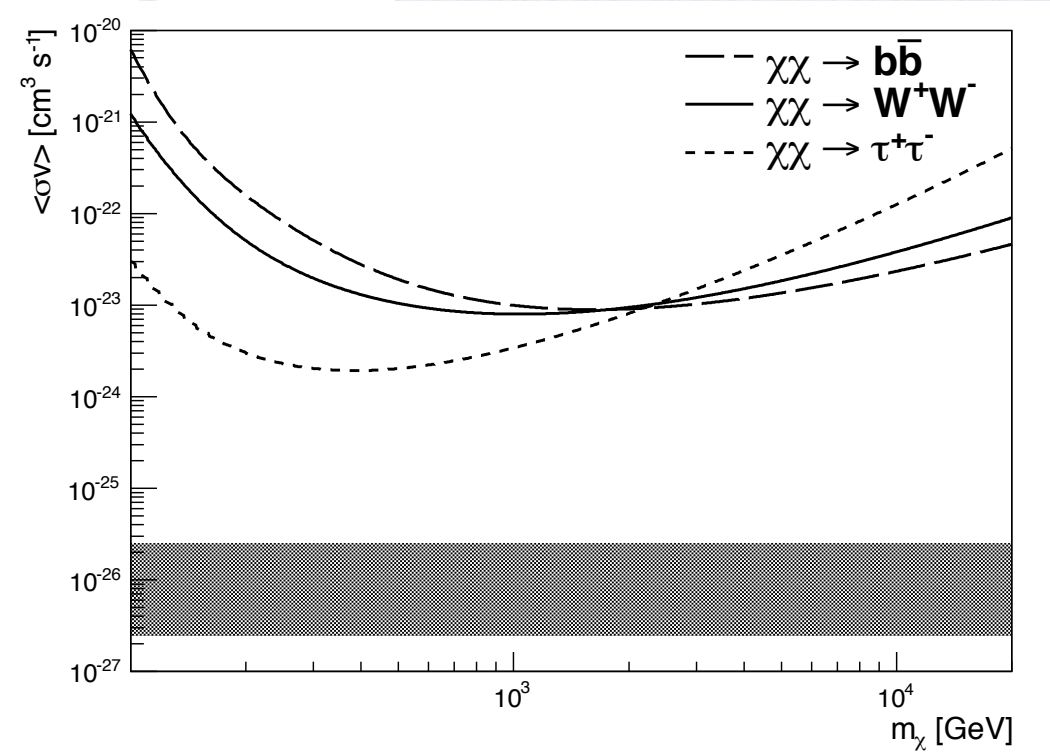
MAGIC



Pointed observations at higher energy

Veritas, arXiv:1202.2144 Segue 1



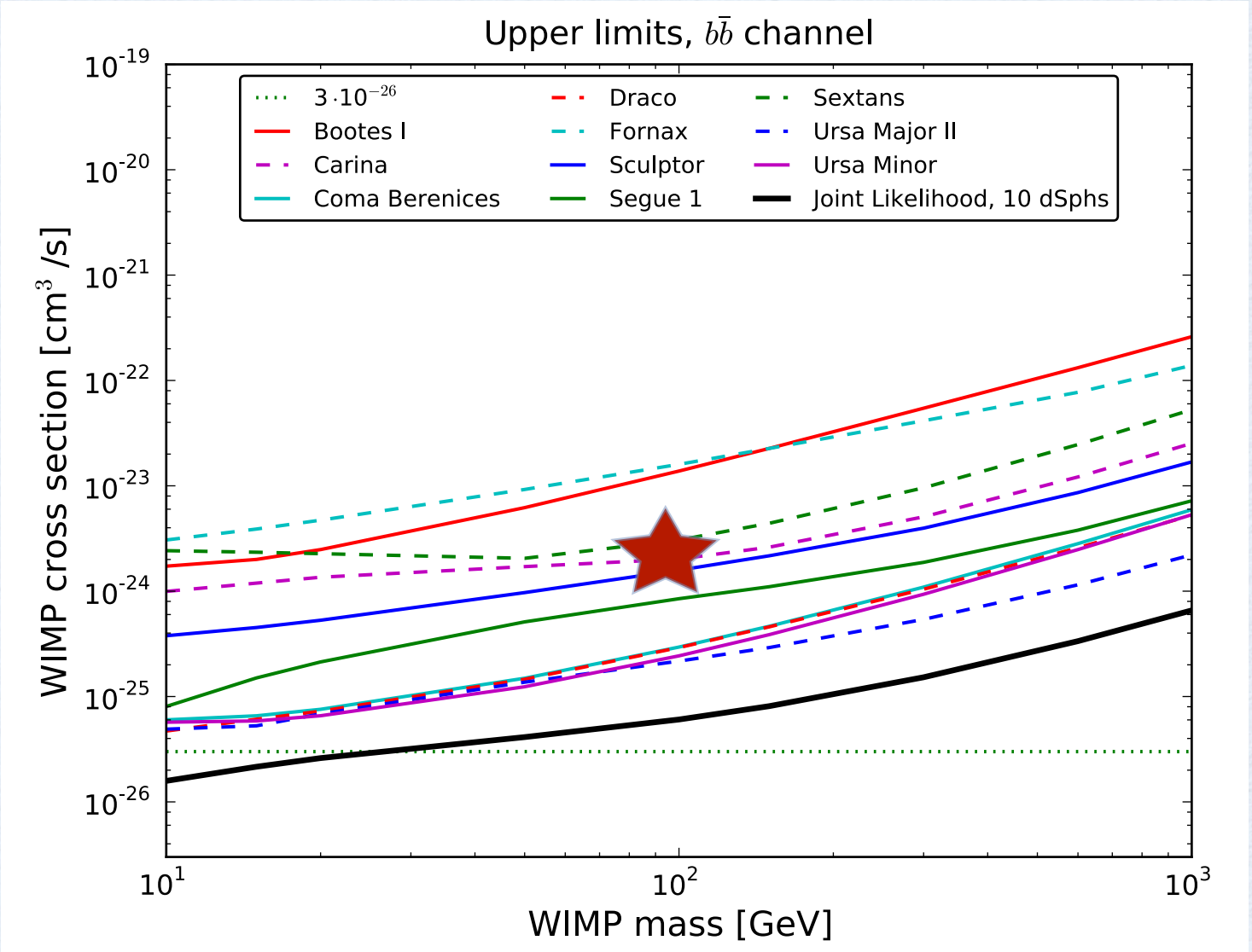


Search for Dark Subhalos

Early calculations: Lake, Nature 1990; Stebbins & Silk, ApJ 1993

- Search for objects that only shine because of dark matter annihilation
- Some satellites could be within a few kpc of the Sun, and their extension may be resolved by the LAT
- Search criteria:
  - More than 20 degrees from Galactic plane
  - No counterpart at other wavelengths
  - Emission constant in time
  - Spatially extended: 1 degree radial extension

Search for Dark Subhalos



Results from other sources

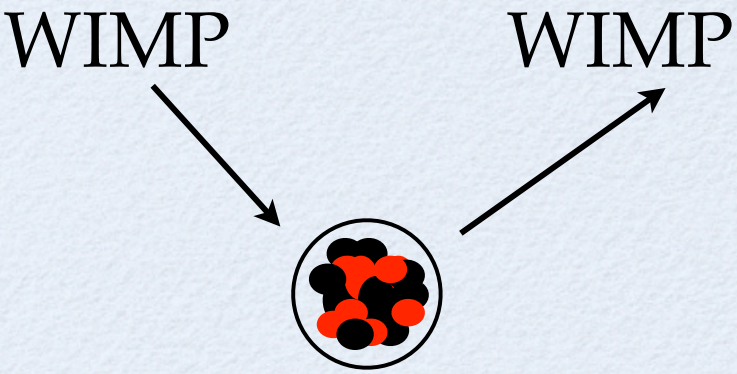
- Galactic center [e.g. Hooper & Linden 2011, Hooper 2012 arXiv:1201.1303]
  - 10 GeV WIMP to electron, muons, taus; also explains direct searches
  - Uncertain diffuse model
- Galaxy clusters [Han et al. 2012, Ando & Nagai 2012]
  - Uncertain substructure boost factor
- Extragalactic [Abdo, A., et al. 2010, JCAP, arXiv:1002.4415]
- M31 [Abdo et al. A&A 523 L2, arXiv:1012.1952]
  - Consistent with Cosmic ray predictions

Direct Detection Implications

Weak Scale Interactions

Spin-Independent: cross section ~ A^2

Spin-Dependent: cross section ~ J(J+1)



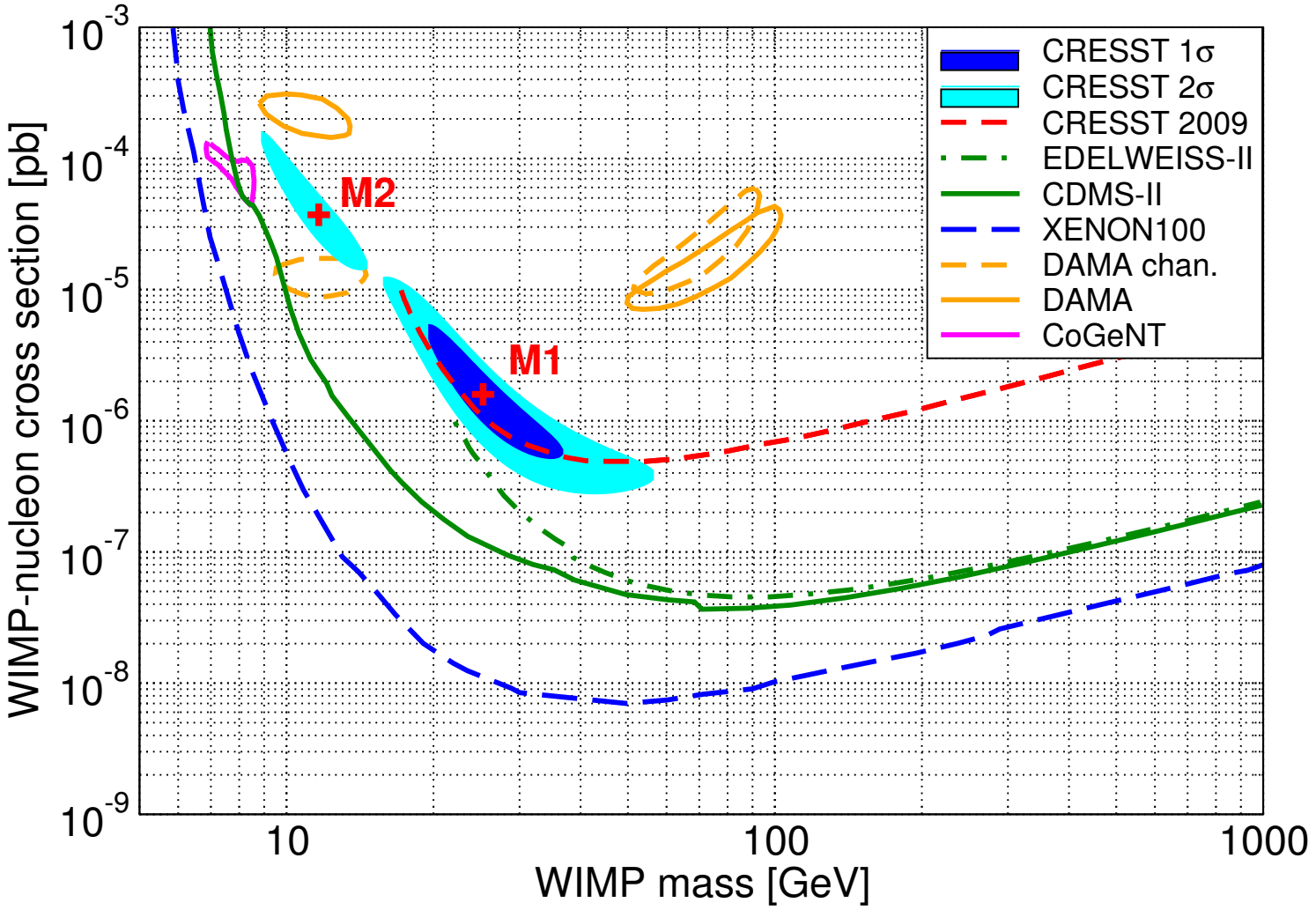
- Annihilation and Elastic Scattering Cross Sections are related, but highly model-dependent

The rate in a detector is:

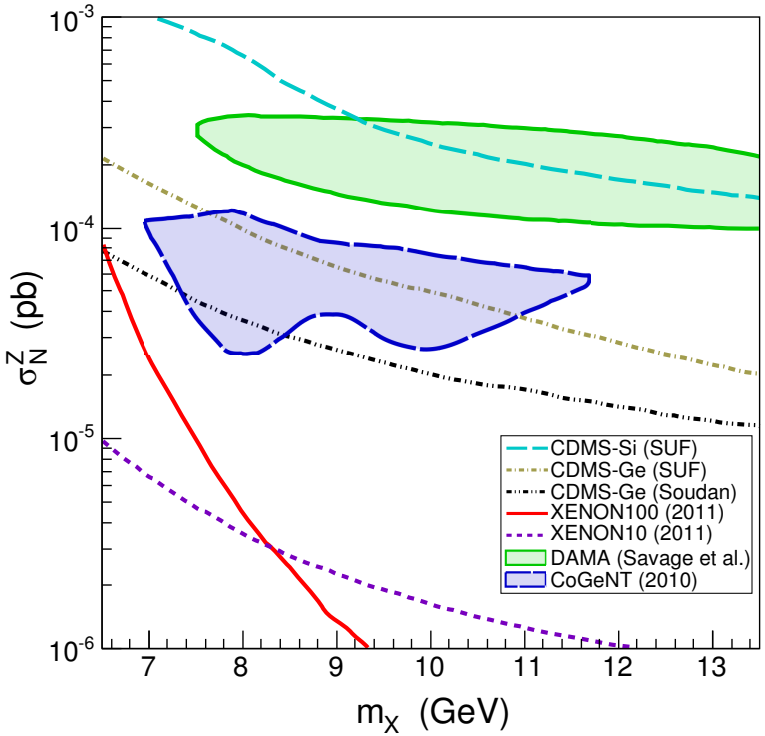
$$\frac{\mu_A^2}{M_*^4}\left[f_p Z + f_n(A-Z)\right]^2 \quad \text{x} \quad N_T n_X \int dE_R \int_{v_{\min}}^{v_{\max}} d^3v\, f(v) \frac{m_A}{2v\mu_A^2} F_A^2(E_R)$$

Particle model — Dark Matter Distribution

Modern WIMP limits

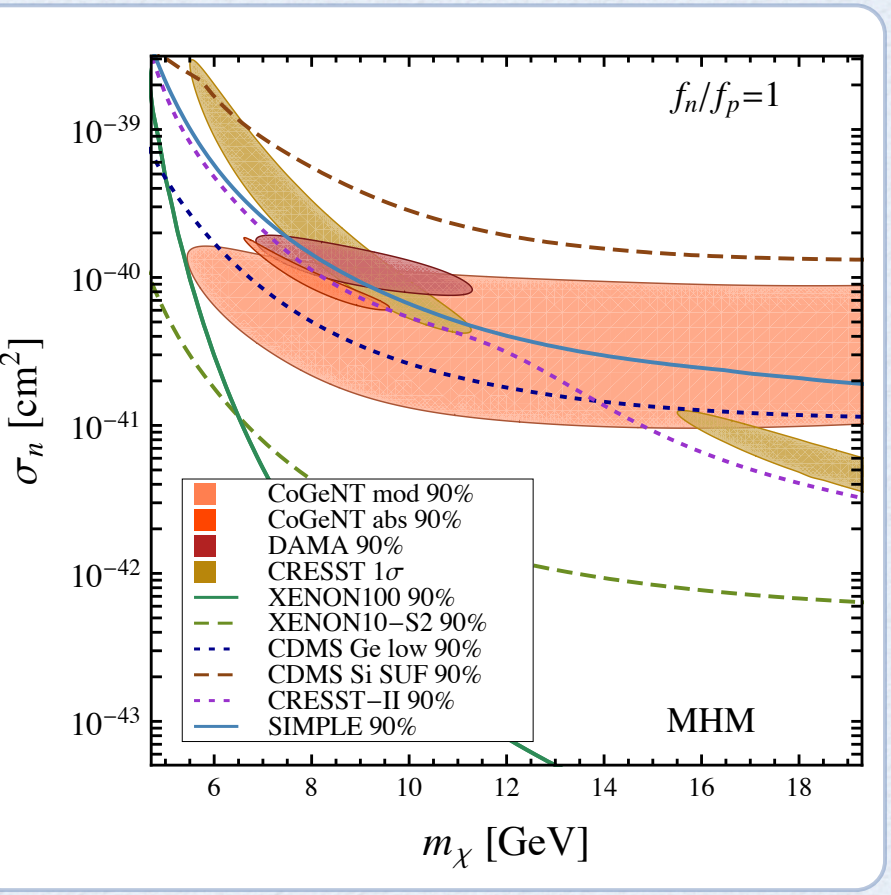


Altering particle model



- Results may be brought into agreement for different WIMP coupling from proton to neutron [Giuliani PRD 2005; Feng, Kumar, Marfatia, Sanford PLB 2010]
- Many model now ruled out by Fermi-LAT dSph result [Kumar, Sanford, Strigari, PRD 2012]

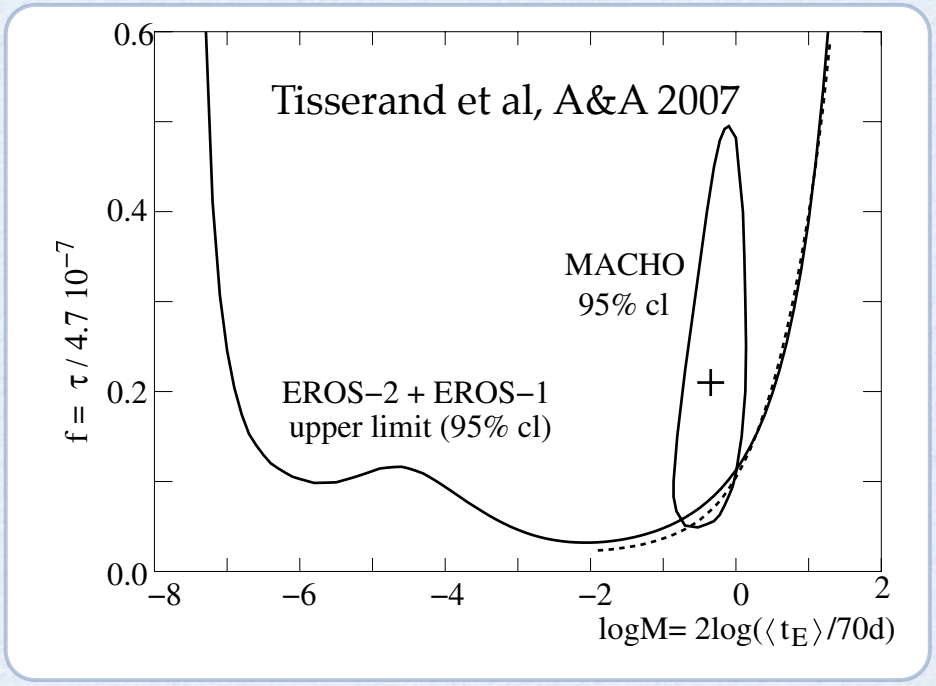
Effect of Galactic halo modeling



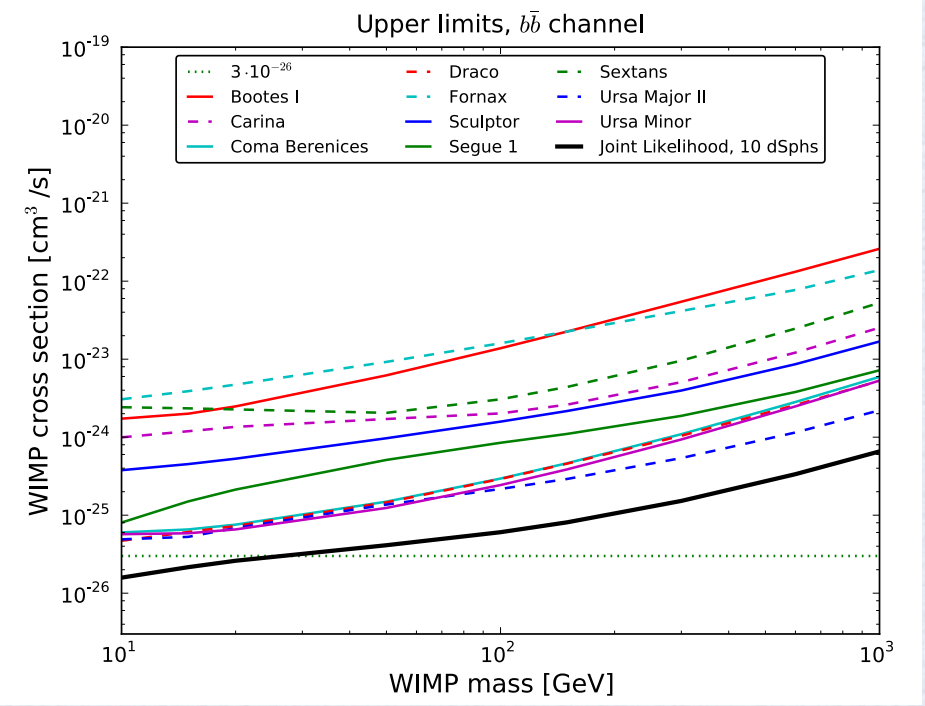
- Smooth dark matter distribution [e.g. Catena & Ullio JCAP 2010; Garbari, Read, Lake, MNRAS 2011]
- Substructure in the DM distribution [e.g. Koushiappas & Kamionkowski 2008, Vogelsberger et al 2008, Kuhlen et al 2009]
- Velocity distribution of Isotropic NFW [Lisanti, Strigari, Wacker, Wechsler PRD 2011, Catena & Ullio 2012, Frandsen et al. JCAP 2012, Kuhlen et al. 2012]

What have we learned?

MACHOs



WIMPs



Progress in Dark Matter Detection

"In a spiral galaxy, the ratio of dark-to-light matter is about a factor of ten. That's probably a good number for the ratio of our ignorance-to-knowledge. We're out of kindergarten, but only in about ~~third grade~~." Middle School?

—Vera Rubin, in Bright Galaxies Dark Matters