Fermi
Gamma-ray Space Telescope

Indirect Searches for Dark Matter with the Fermi LAT

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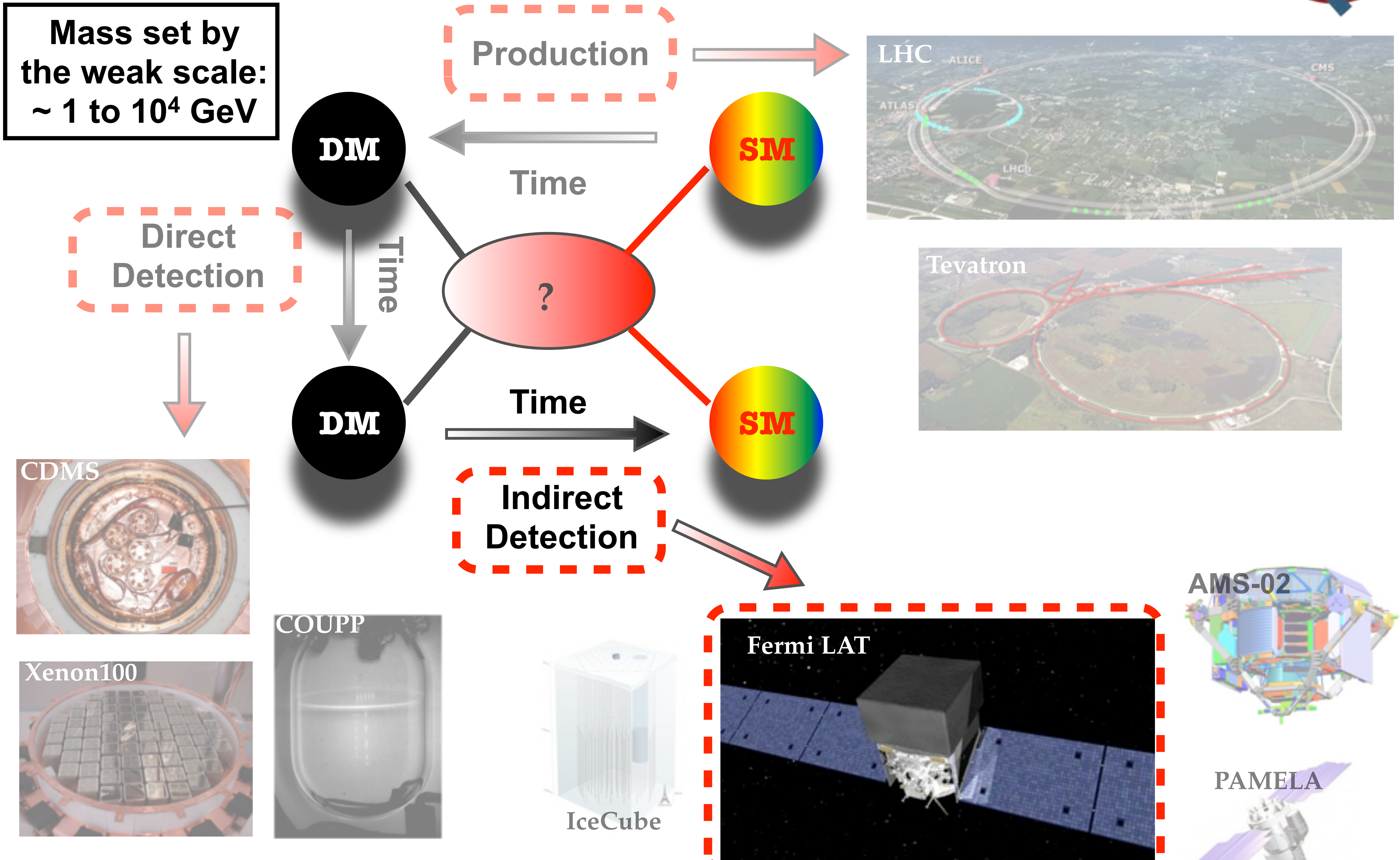
on behalf of the
Fermi-LAT Collaboration

Aspen 2013 - Closing in on Dark Matter

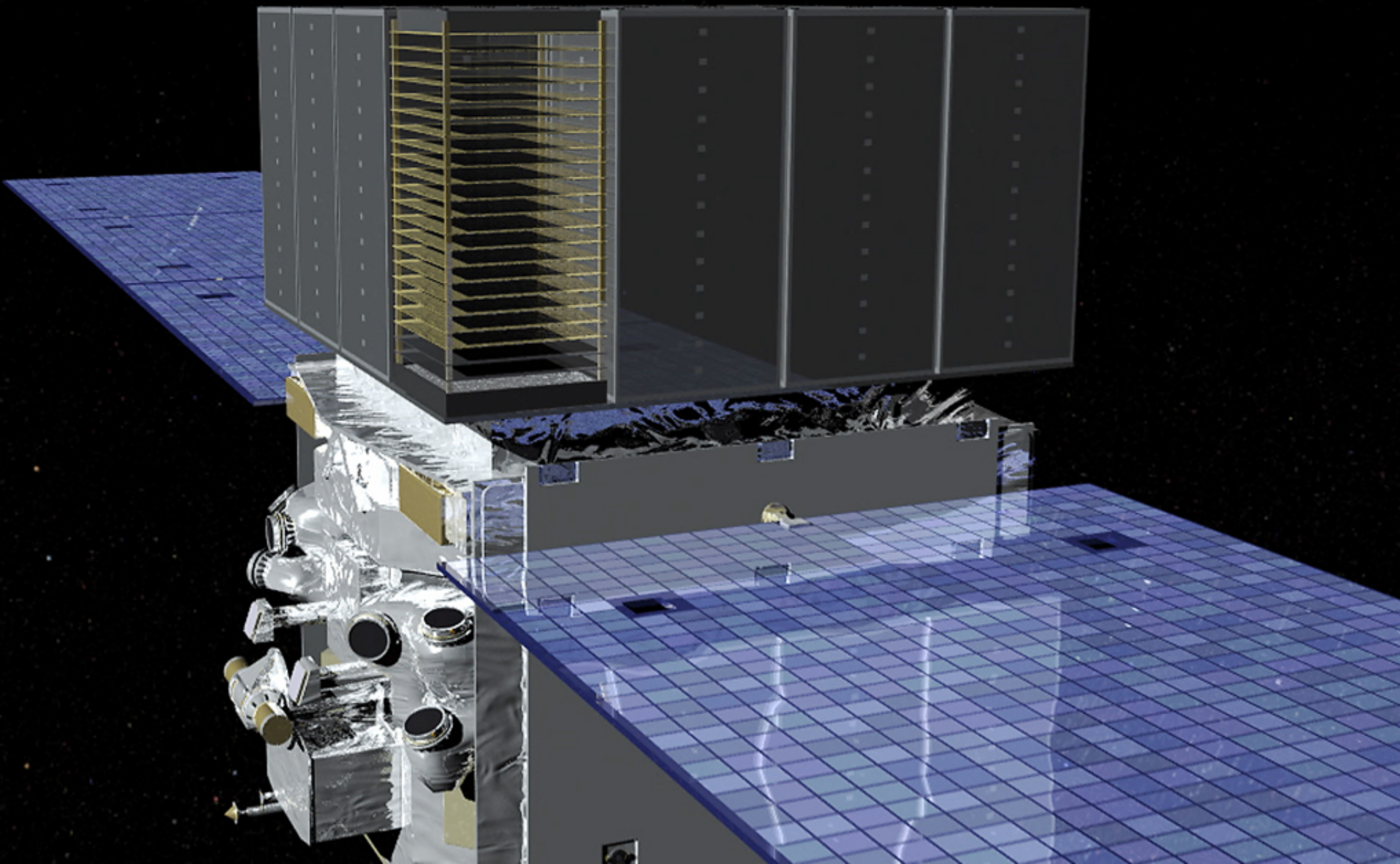
SLAC KIPAC STANFORD UNIVERSITY

Particle Dark Matter

Mass set by the weak scale: ~ 1 to 10^4 GeV



The Fermi Large Area Telescope (LAT)

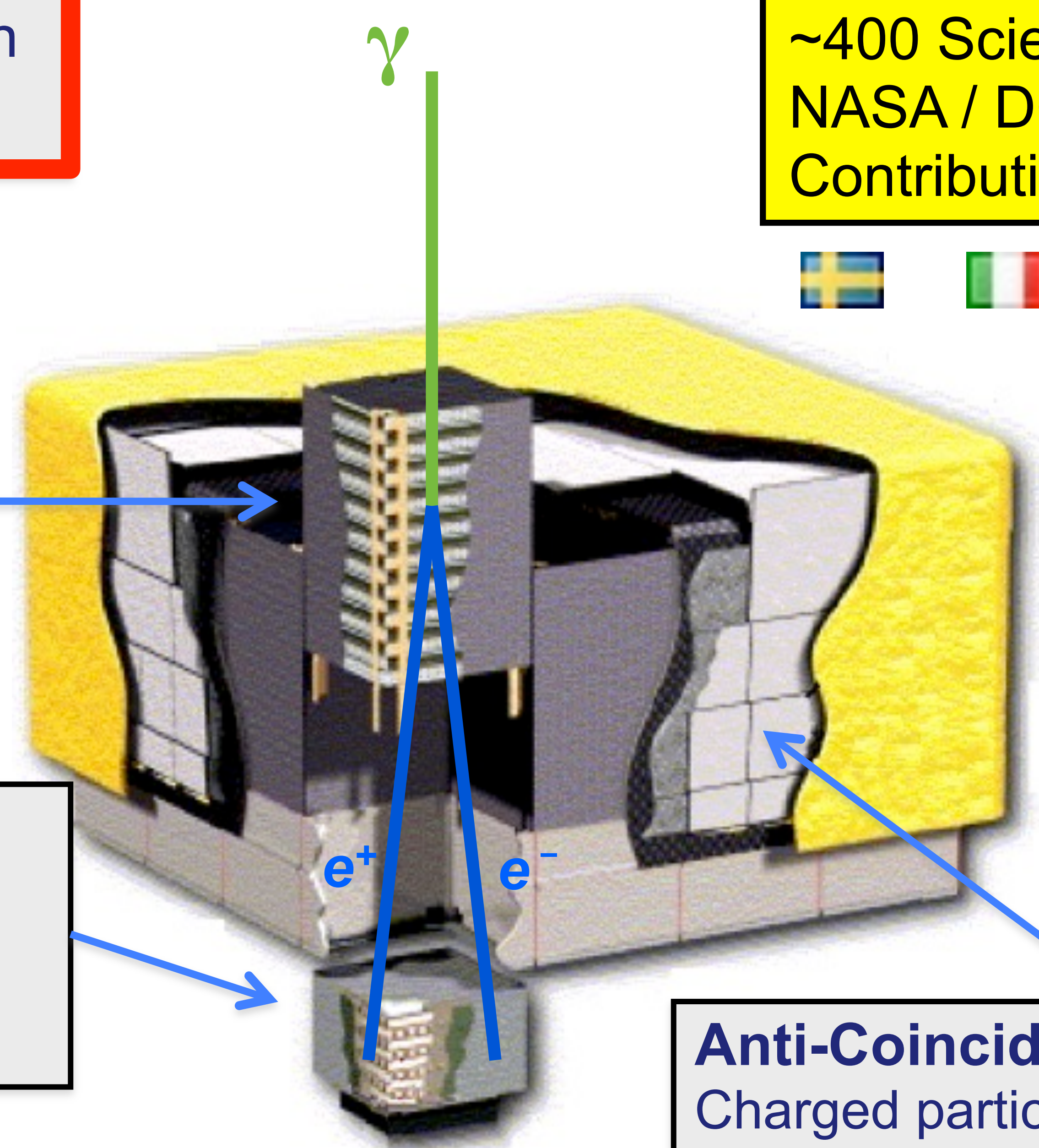


The Fermi Large Area Telescope

Public Data Release:
All γ-ray data made public within 24 hours (usually less)

Fermi LAT Collaboration:
~400 Scientific Members, NASA / DOE & International Contributions

Si-Strip Tracker:
convert $\gamma \to e^+e^-$
reconstruct γ direction
EM vs. hadron separation



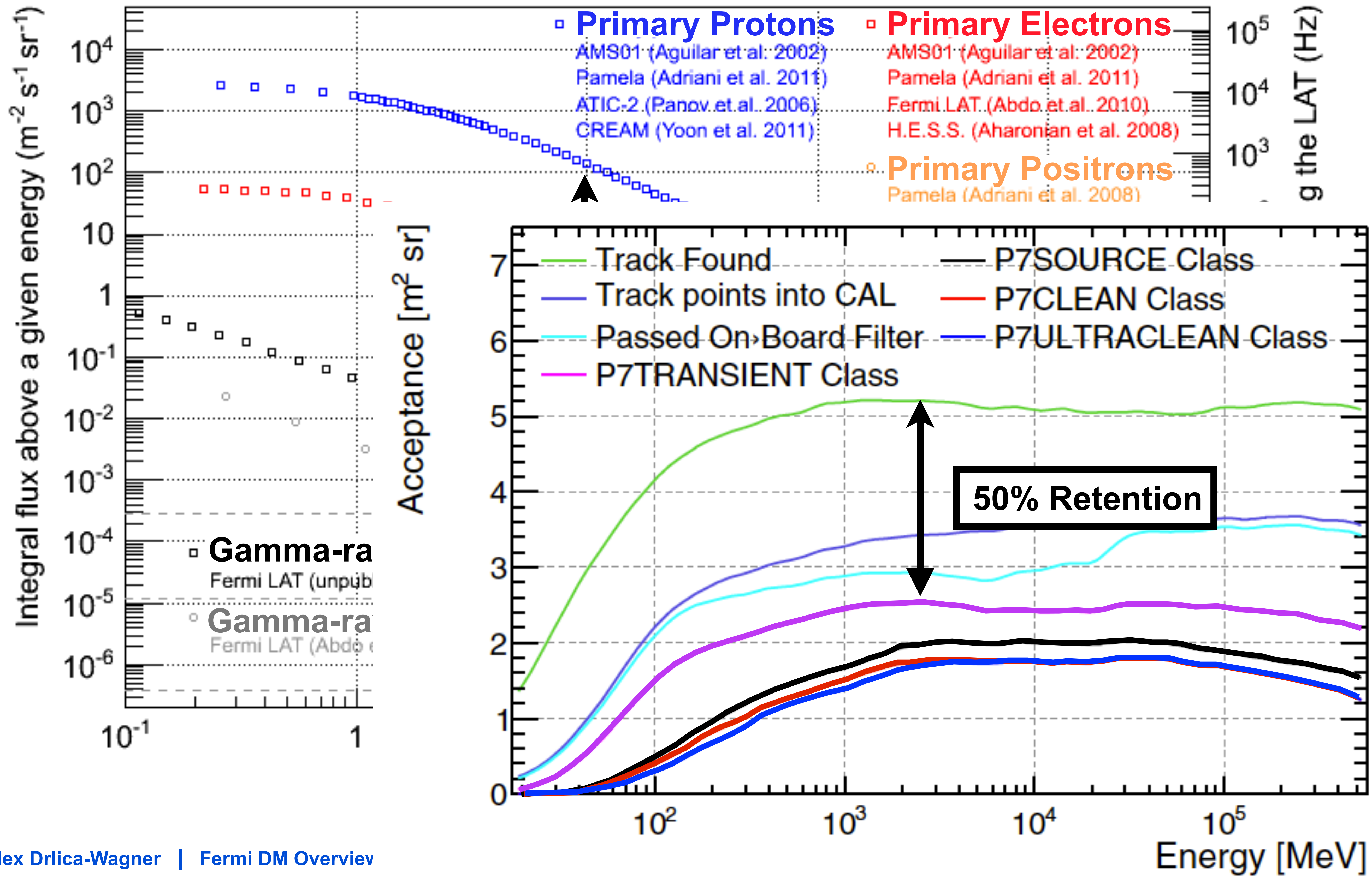
Hodoscopic CsI Calorimeter:
measure γ energy
image EM shower
EM v. hadron separation

Anti-Coincidence Detector:
Charged particle separation

Sky Survey:
The LAT observes the whole sky every 3 hours (2.5 sr FOV)

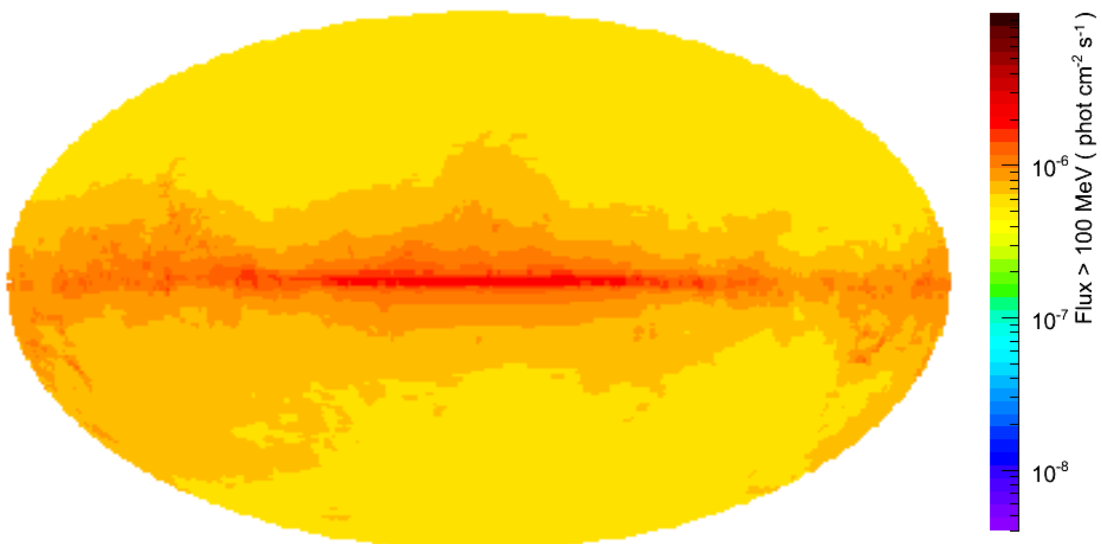
Trigger and Filter:
Reduce data rate from ~10kHz to 300-500 Hz

Background Rejection



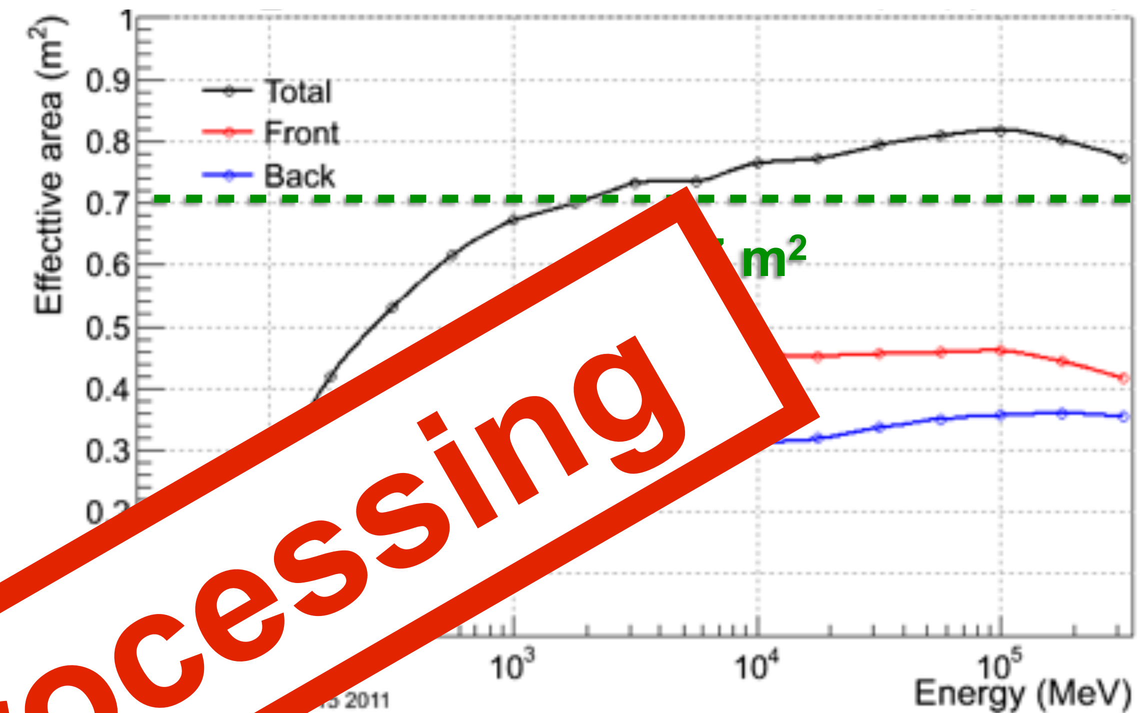
Fermi-LAT Performance

All-Sky Coverage



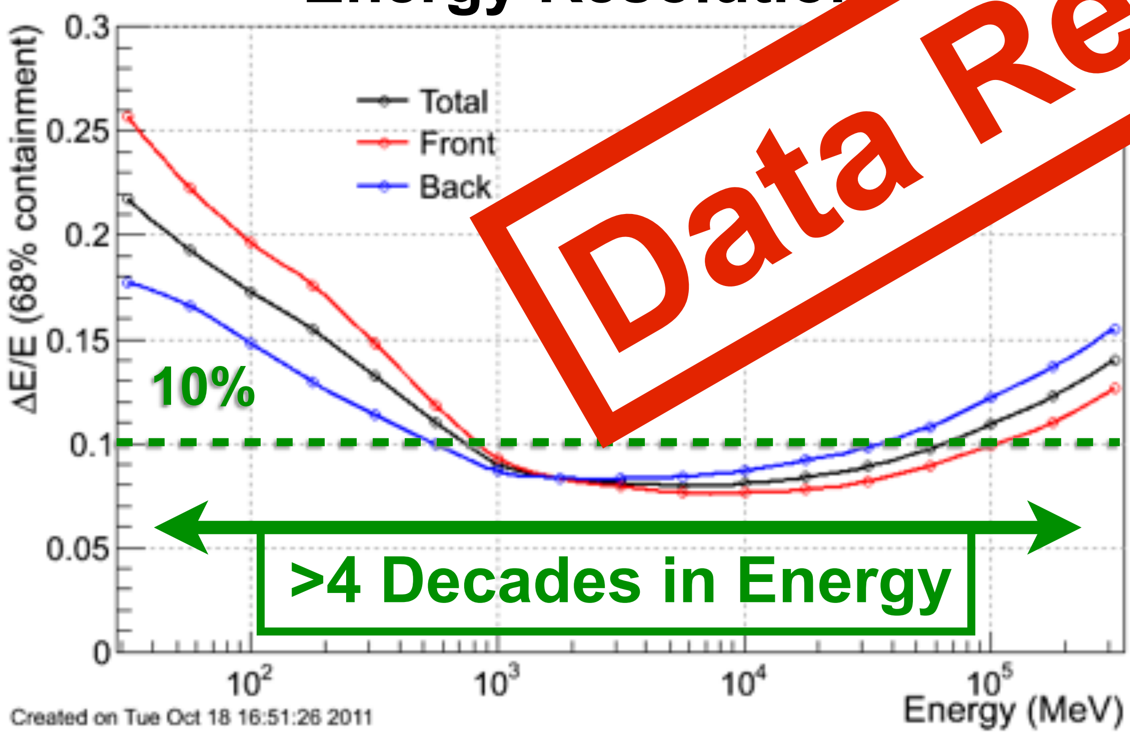
Every ~3 Hours

Effective Area

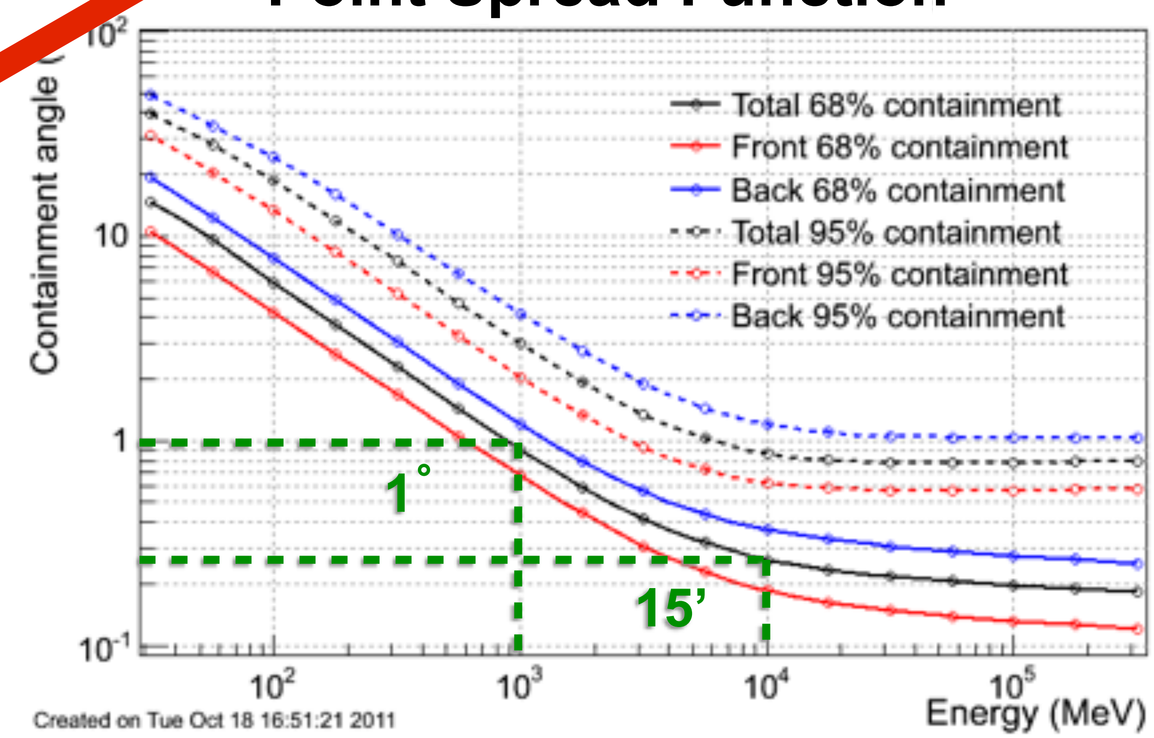


Data Reprocessing

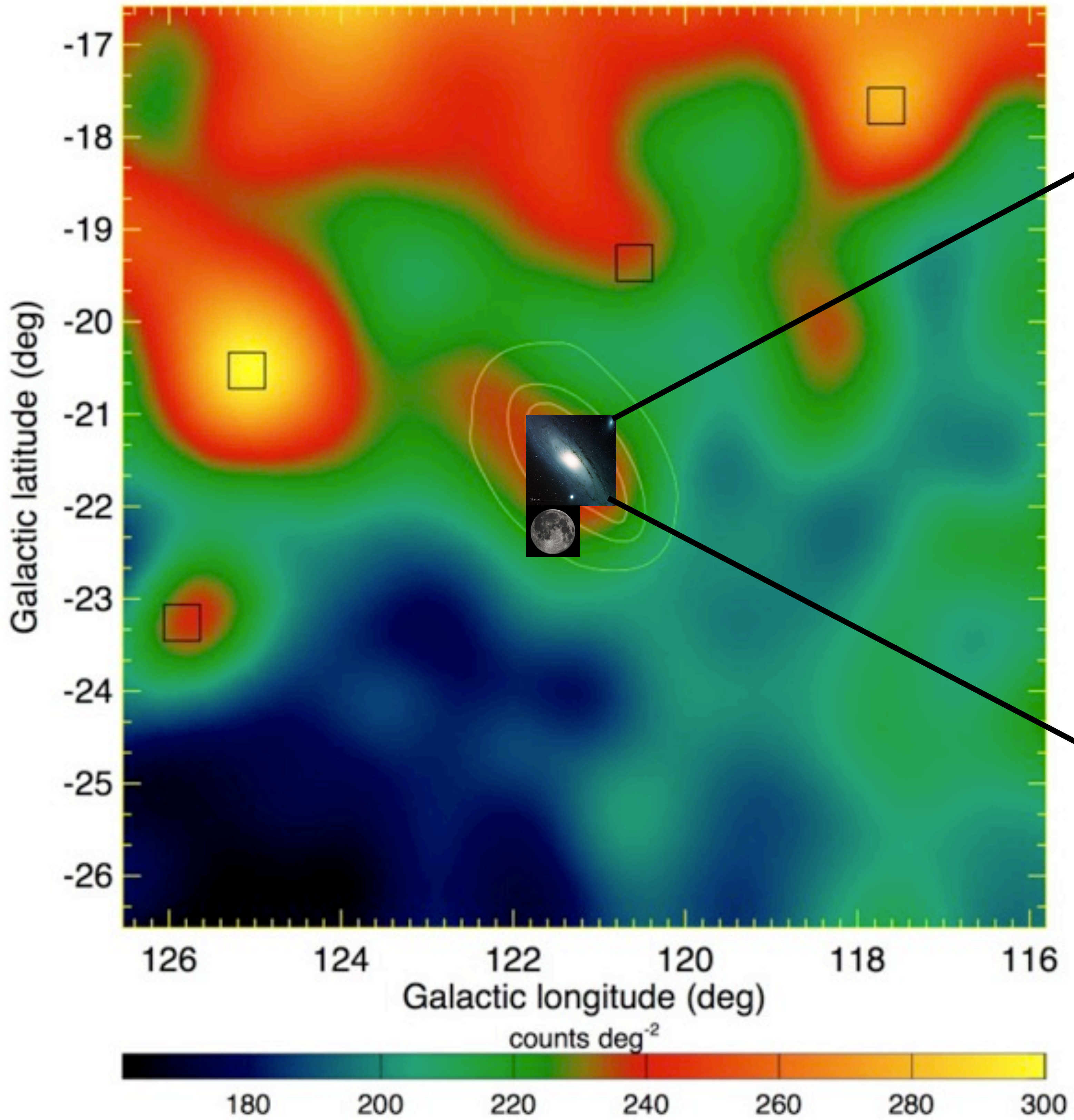
Energy Resolution



Point Spread Function

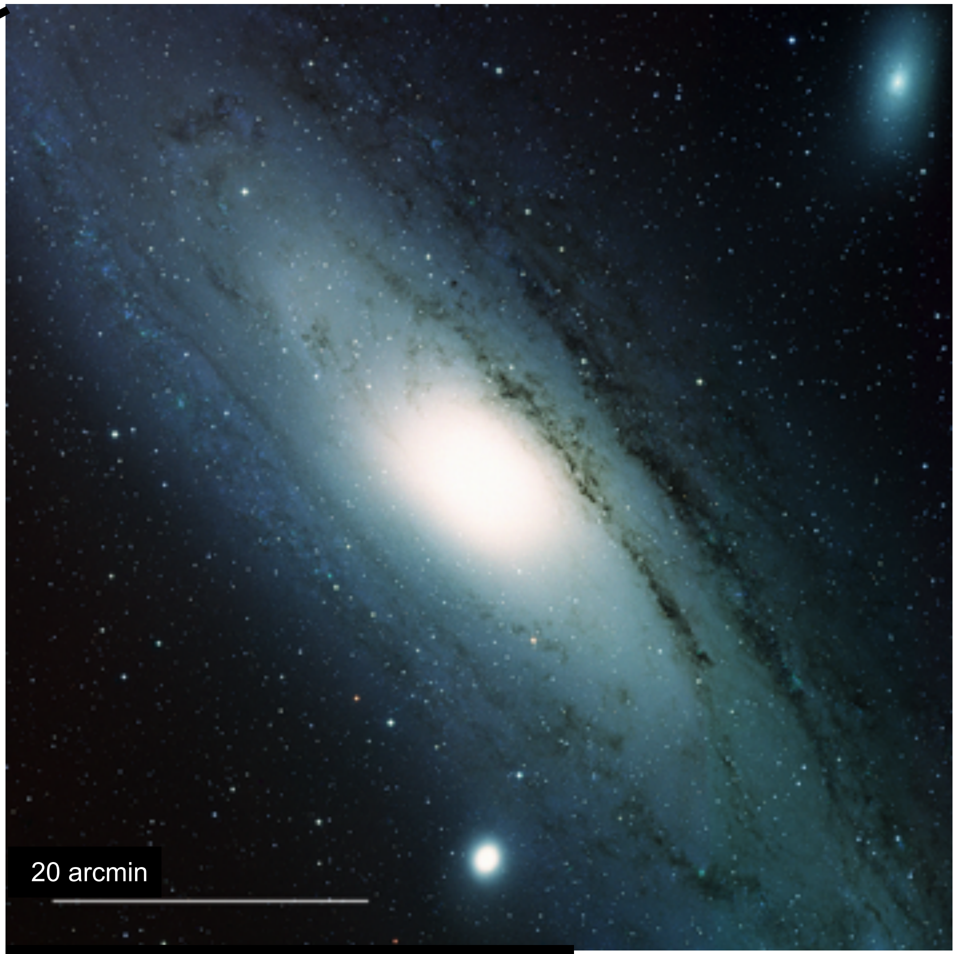


Fermi-LAT Performance



Andromeda (M31)

Optical DSS Image



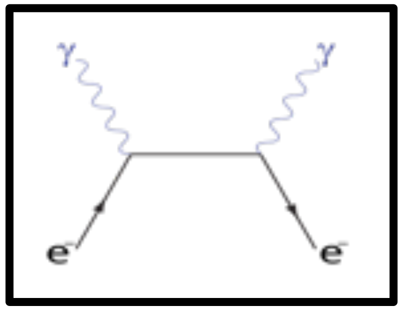
Gamma-ray Source Identification

Energy Source
Explosion
Rotation
Accretion

+

Accelerator
Shocks
Magnetic reconnection
etc.

+



Target Material
Gas & Dust
Photon Fields
etc.

=

Gamma-rays!

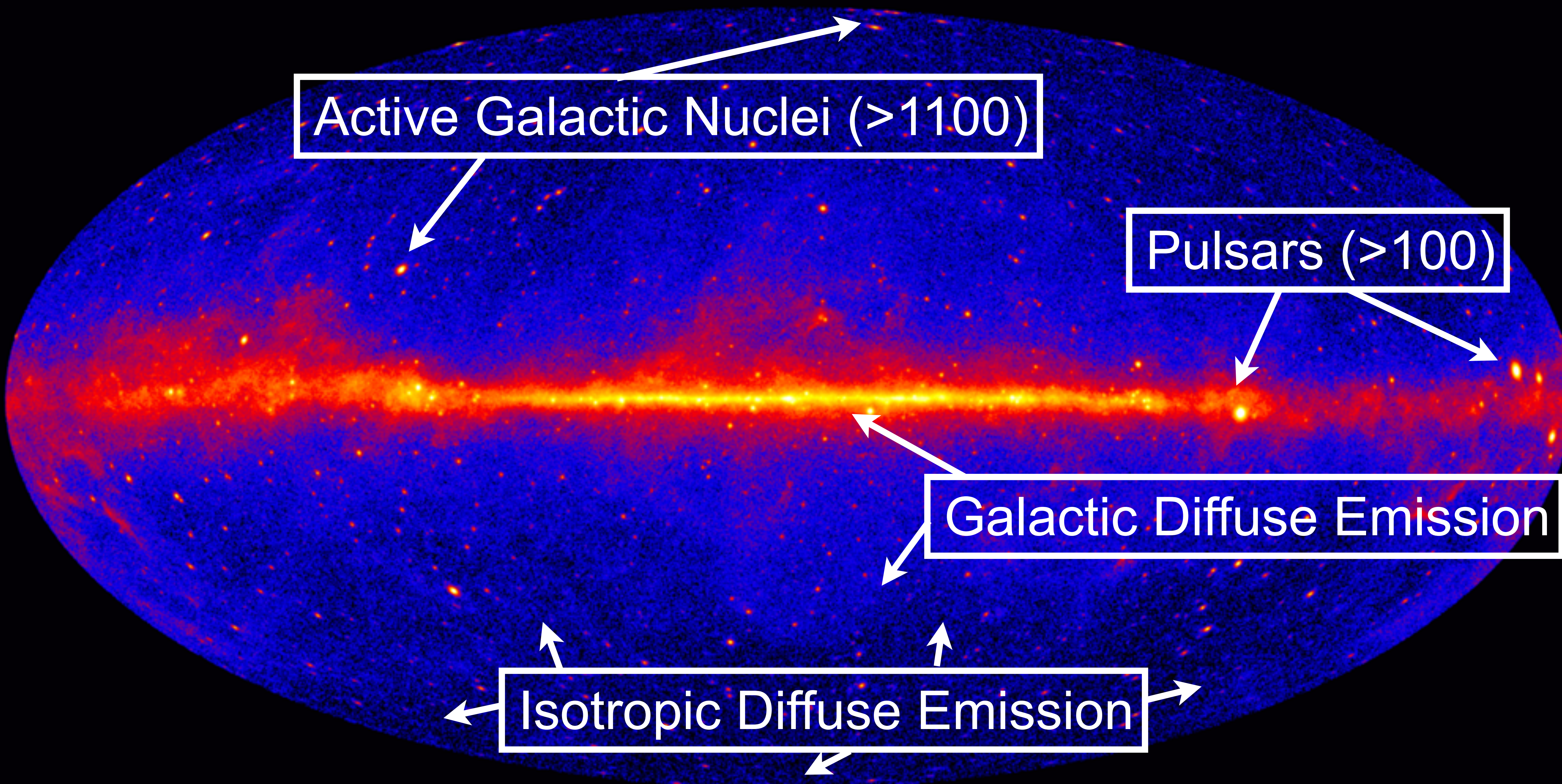
The gamma-ray sky is a crowded and exciting place

Non-thermal emission often leaves tracers at other wavelengths

- Correlated Variability: Coincident flux variations across wavelengths
- Timing: Periodicity of pulsars
- Spatial Morphology: Spatially extended sources
- Spatial Coincidence: Source localization
- Spectral Continuity: Look at bounding energy regimes

Combination of data across multiple instruments is essential

Fermi-LAT 4-Year All-Sky Map (>1GeV)



+ Pulsar Wind Nebulae + Supernova Remnants + Globular Clusters + Starburst Galaxies + Unassociated Sources + ...

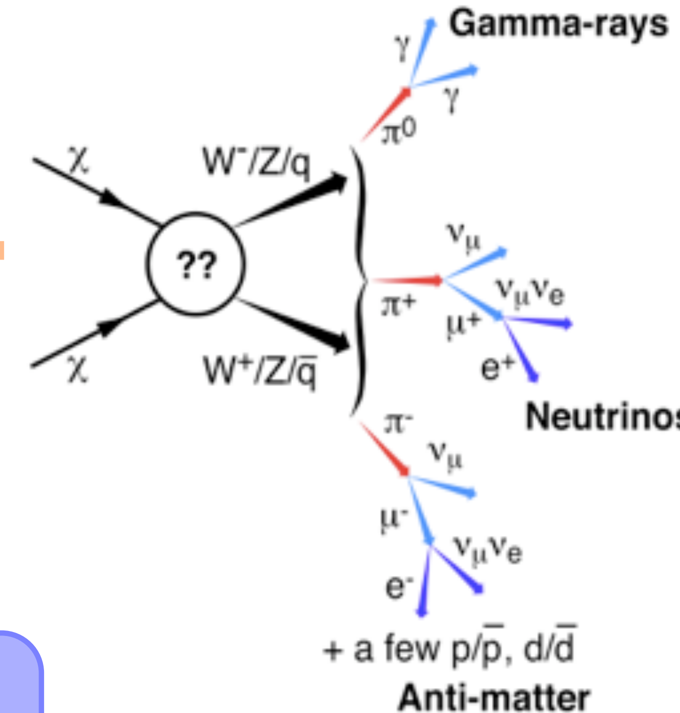
... and Dark Matter?

Indirect Detection

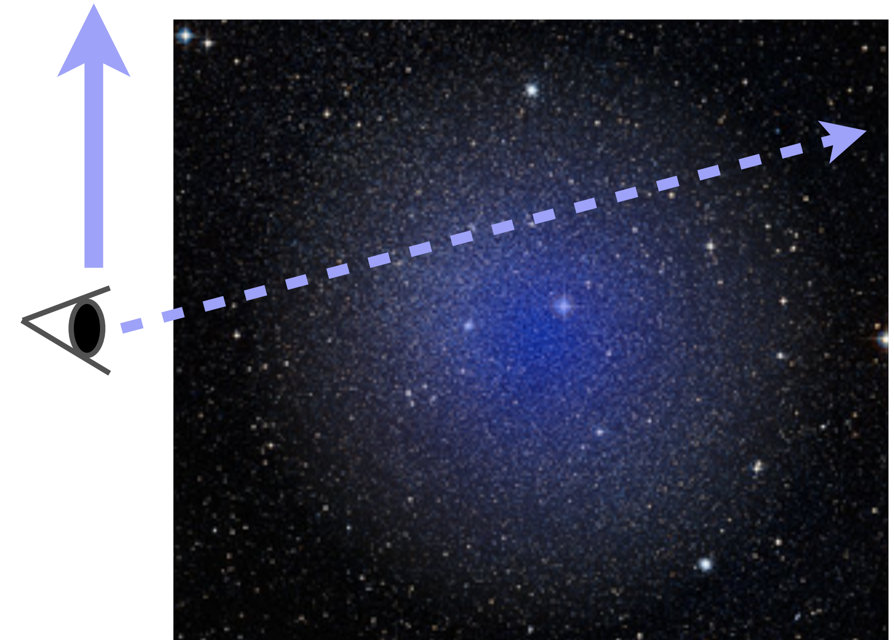
Gamma-ray Flux
(signal in data)

Particle Physics
(photons per annihilation)

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \phi, \theta) = \frac{1}{4\pi}\frac{<\sigma_{ann} v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f \times \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$



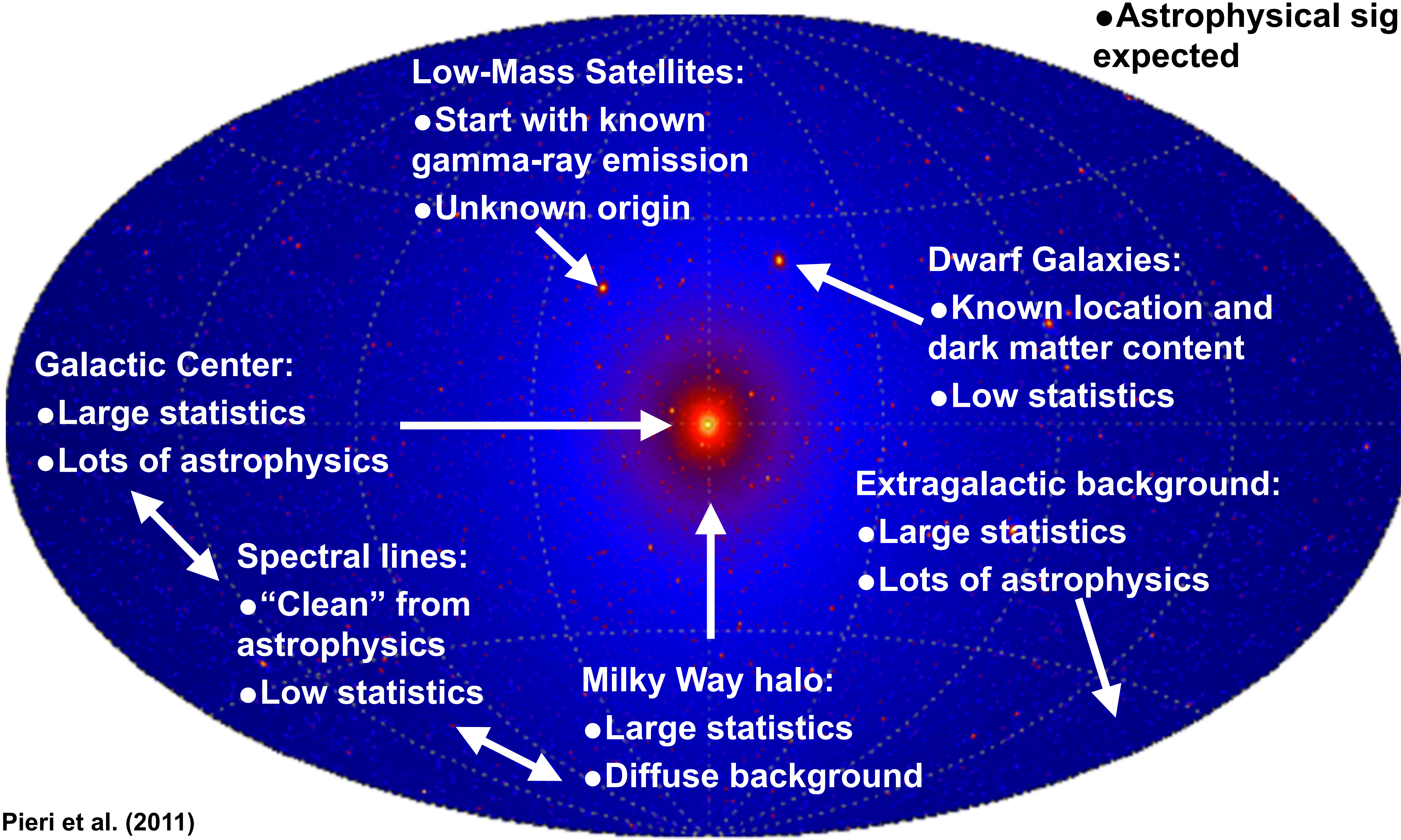
Dark Matter Distribution
(line-of-sight integral)



Dark Matter in the Milky Way Halo

Galaxy clusters:
- Possibly large statistics
- Astrophysical signal expected

Electrons and Positrons!



Pieri et al. (2011)

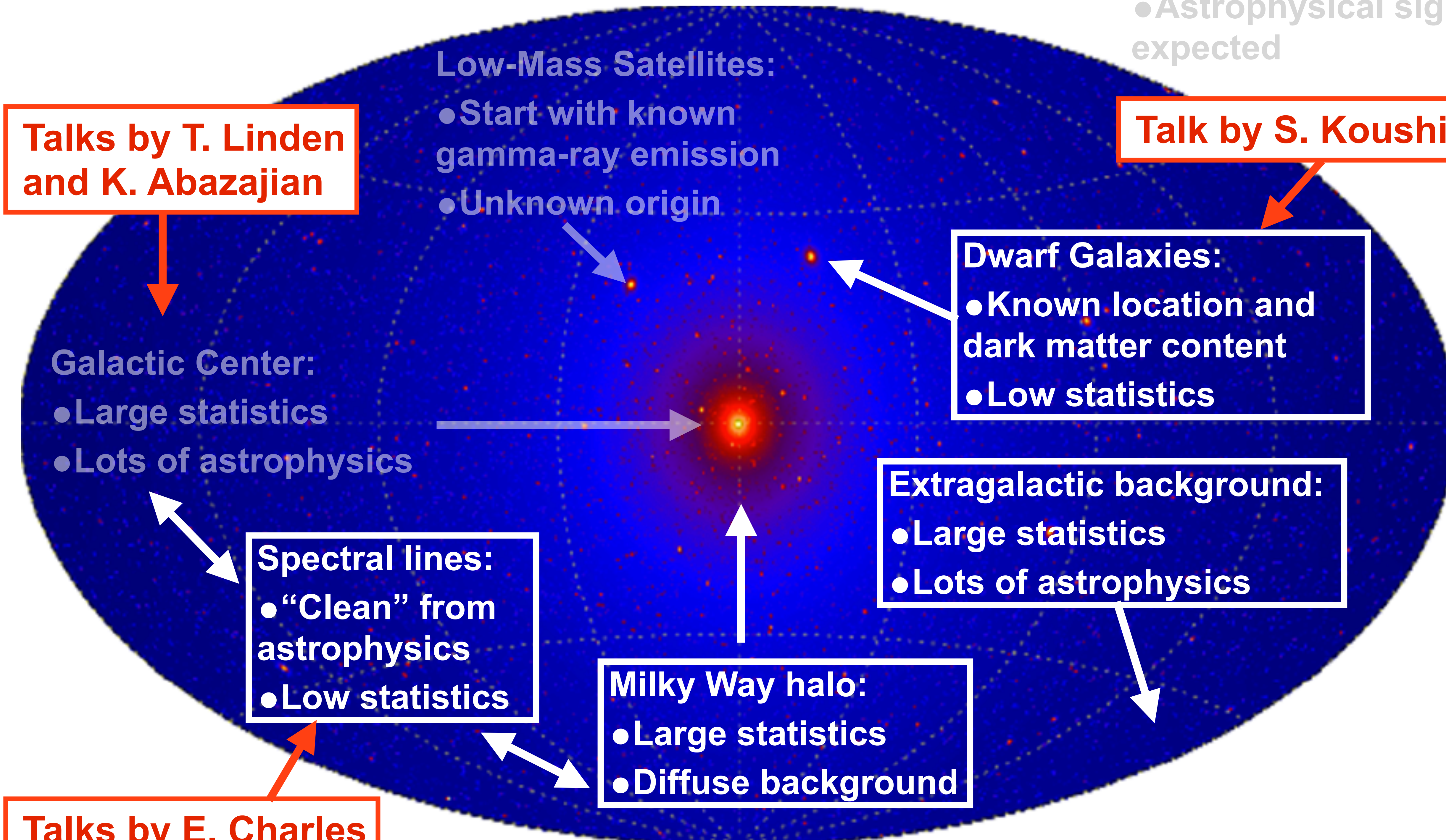
Dark Matter in the Milky Way Halo

Galaxy clusters:
- Possibly large statistics
- Astrophysical signal expected

Electrons and Positrons!

Talks by T. Linden and K. Abazajian

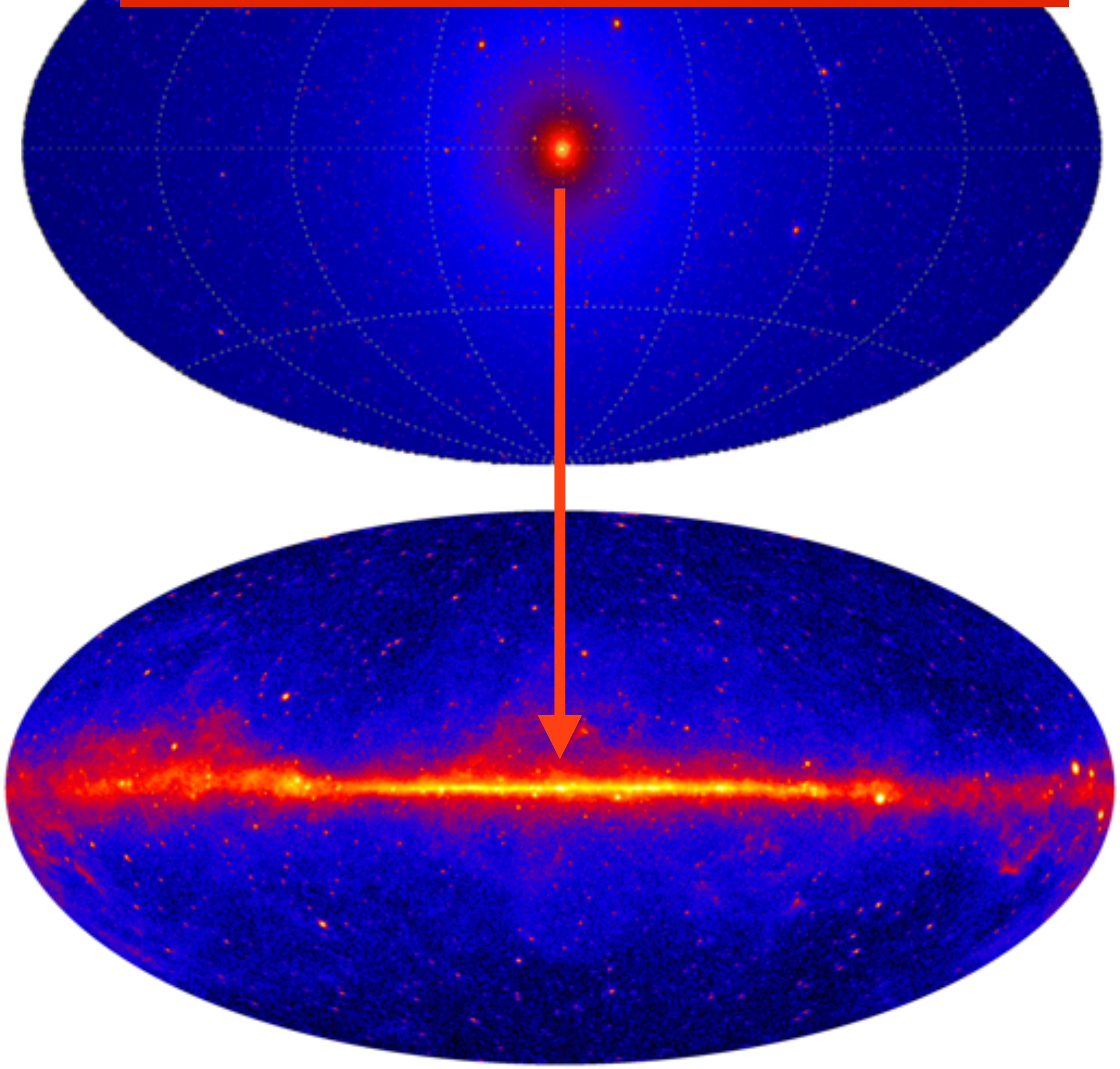
Talk by S. Koushiappas



Talks by E. Charles and D. Whiteson

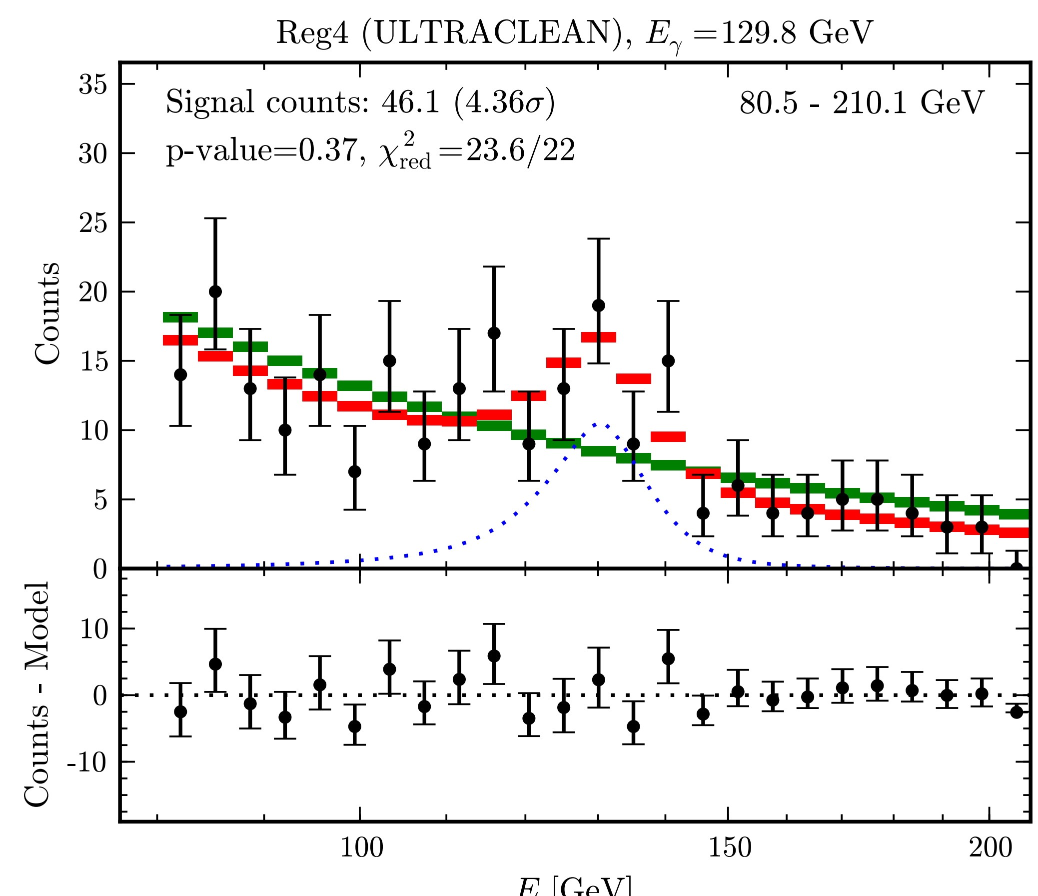
Spectral Lines

Talks by E. Charles & D. Whiteson on Thurs.

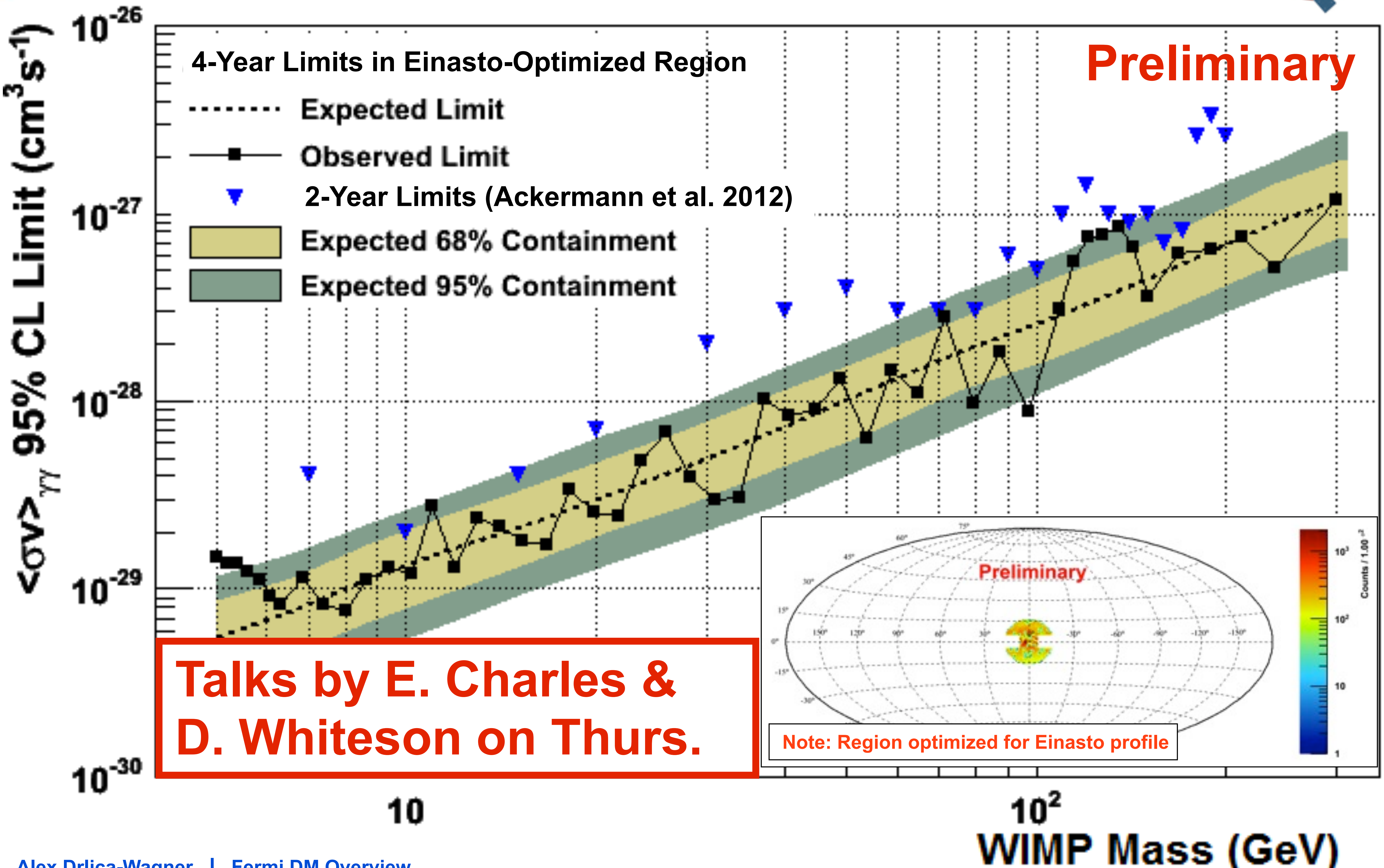


Weniger, arXiv:1209.4562
Ackermann et al., arXiv:1205.2739
Su et al. arXiv:1206.1616

- **The Galactic center seems like an obvious place to search**
  - **Deep gravitational potential**
  - **Relatively nearby**
- **Extremely complicated region**
  - **Diffuse emission from cosmic-ray interactions with Galactic gas and dust**
  - **Densely populated by astrophysical sources (e.g., pulsars, SNR)**
- **Degeneracy may be broken by a sharp spectral feature (i.e., a line)**

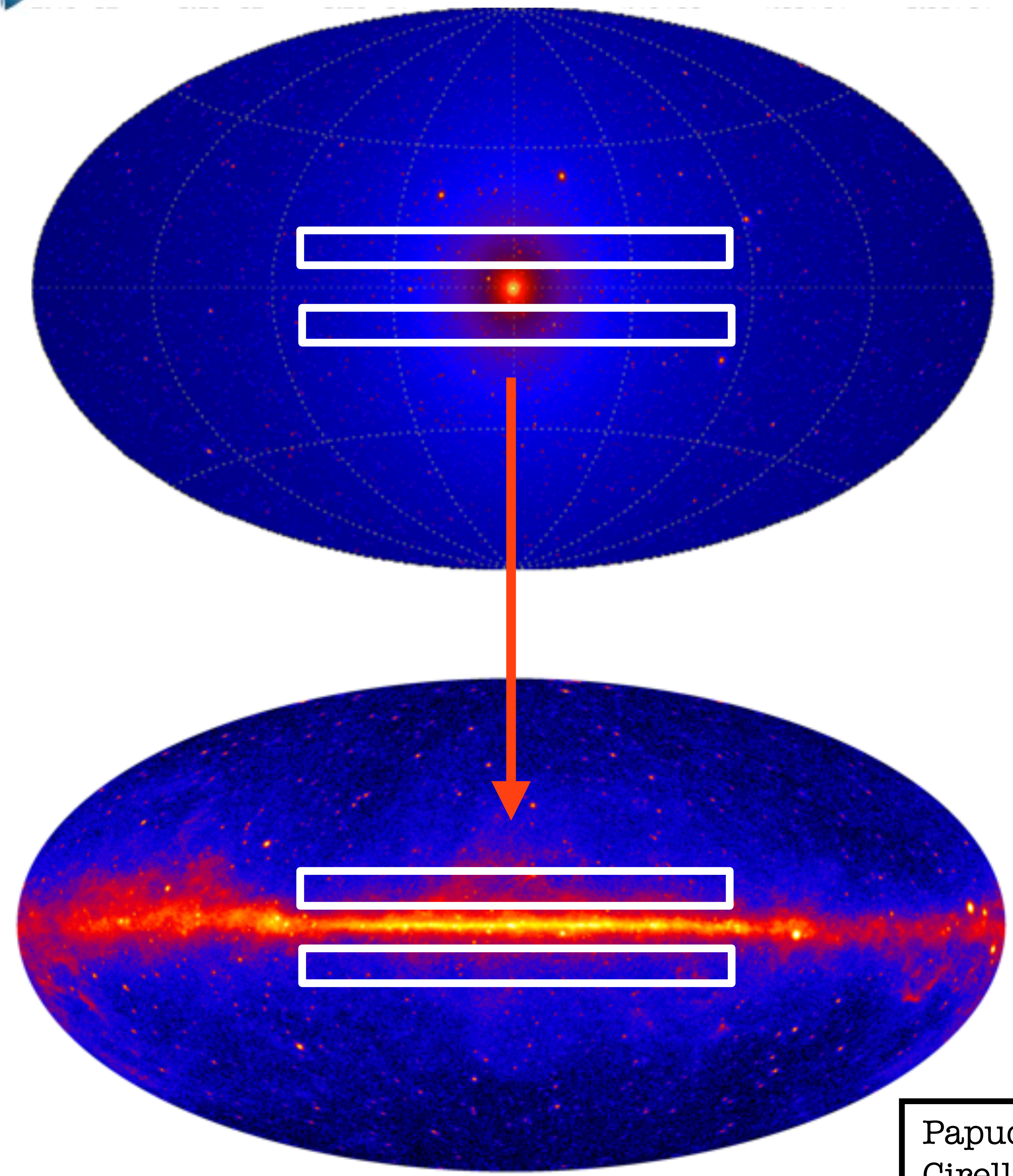


95% CL $\langle\sigma v\rangle_{\gamma\gamma}$ Limits



Talks by E. Charles & D. Whiteson on Thurs.

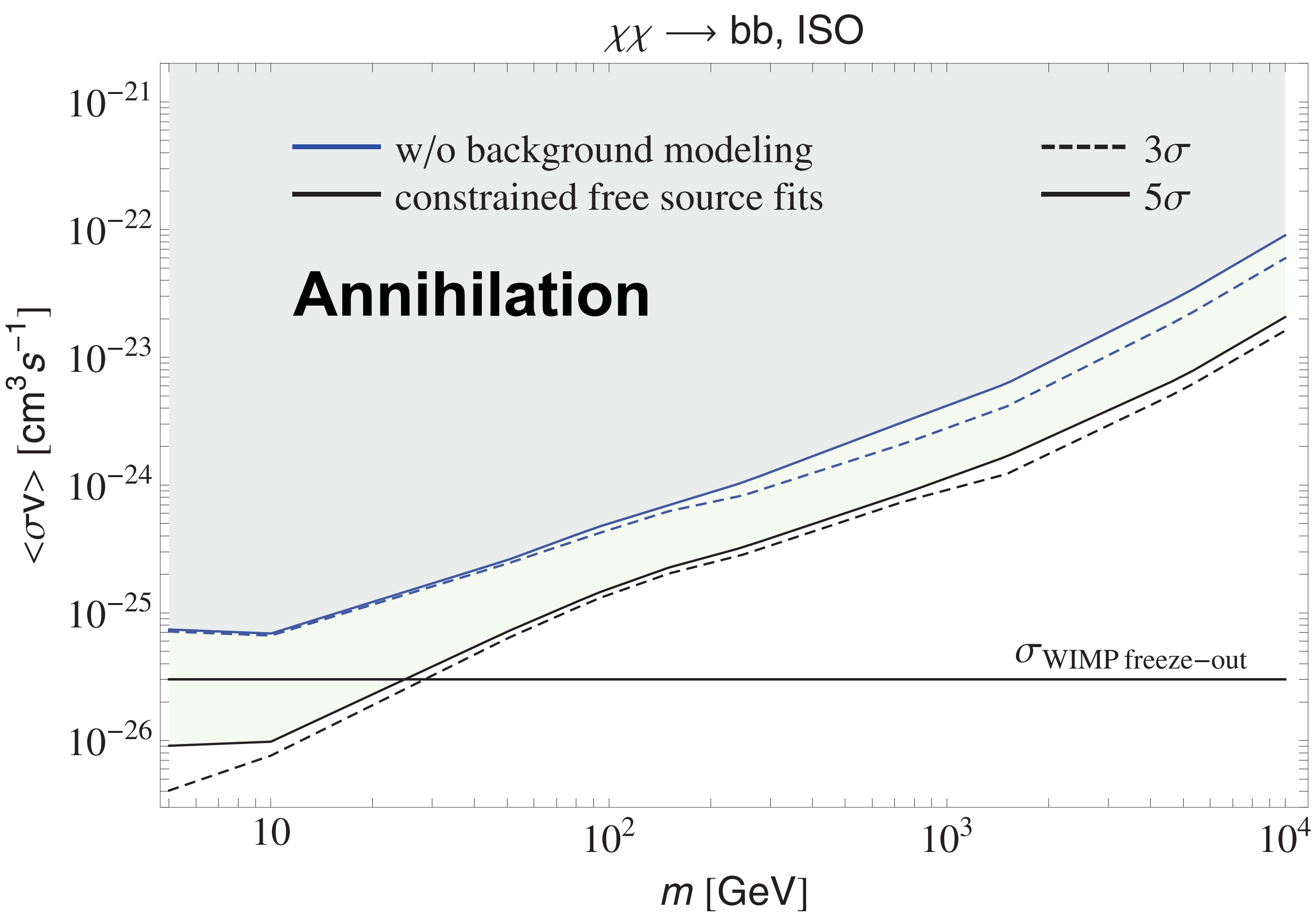
Galactic Halo

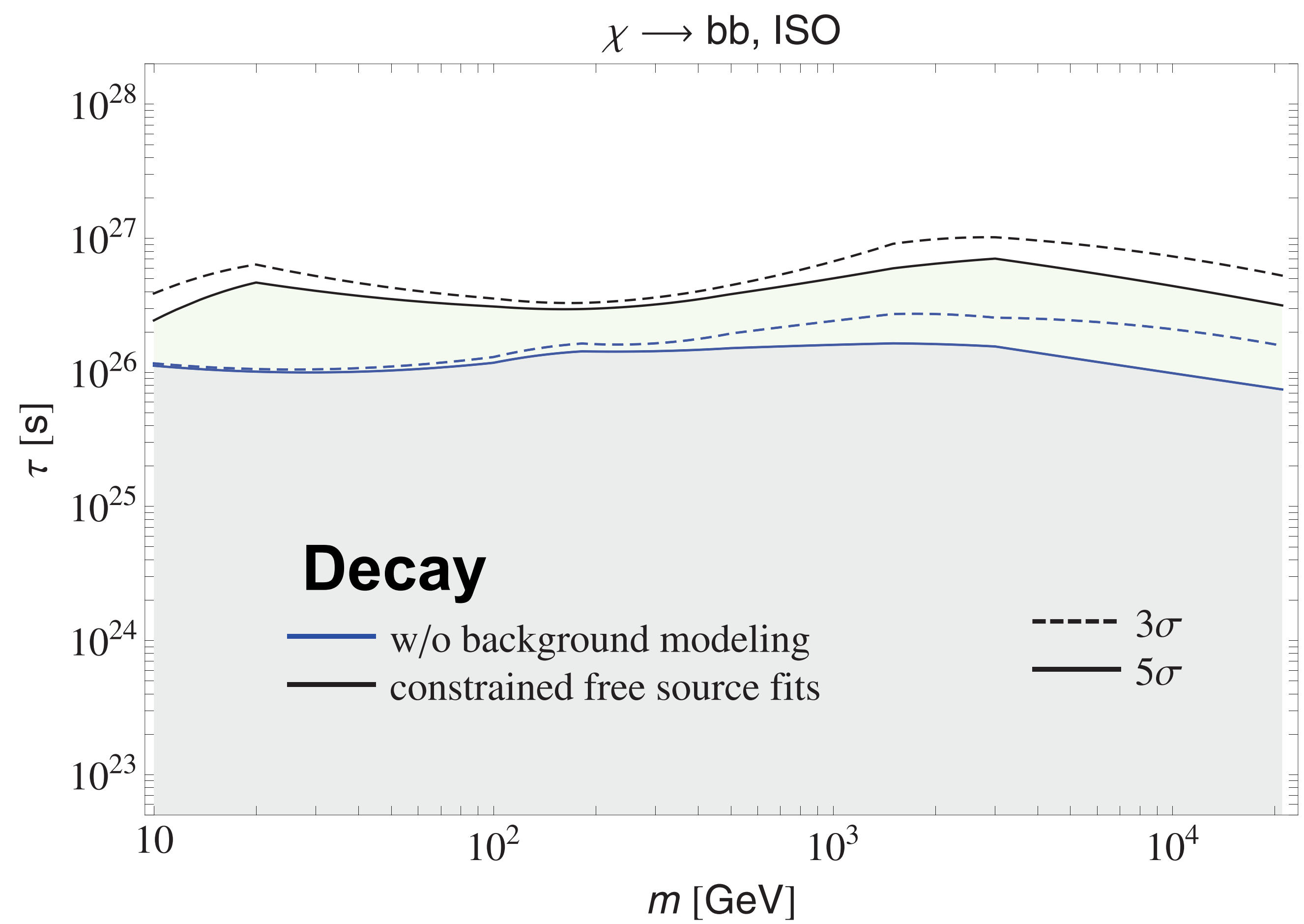


- Search for continuum emission from dark matter annihilation or decay in the smooth Galactic dark matter halo.
- Analyze bands 5˚ off the plane
  - Decreases astrophysical background
  - Mitigate uncertainty from the inner slope of the dark matter density profile
- Two approaches:
  - More conservative - Assume all emission from dark matter (no astrophysical model)
  - More accurate - Fit dark matter source and astrophysical emission simultaneously

Papucci et al., arXiv:0912.0742
Cirelli et al., arXiv:0912.0663
Ackermann et al., arXiv:1205.6474

Galactic Halo



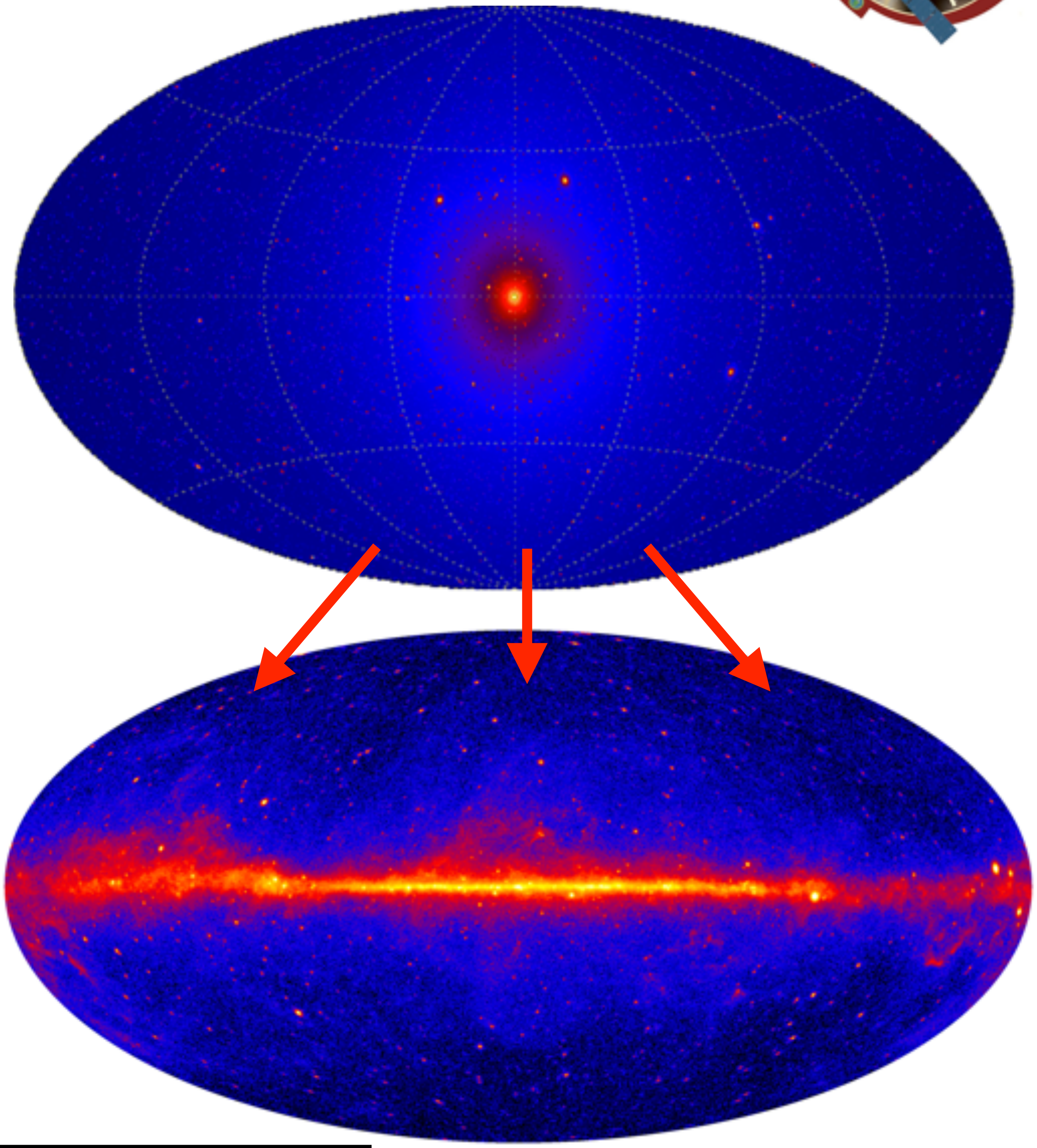


- **Modeling of the astrophysical emission improves dark matter constraints by a factor of ~5.**
- **When astrophysics is modeled, it is possible to constrain the thermal relic cross section for WIMPs with mass < 30 GeV (b-bbar & tau+tau- channels).**

Ackermann et al., arXiv:1205.6474

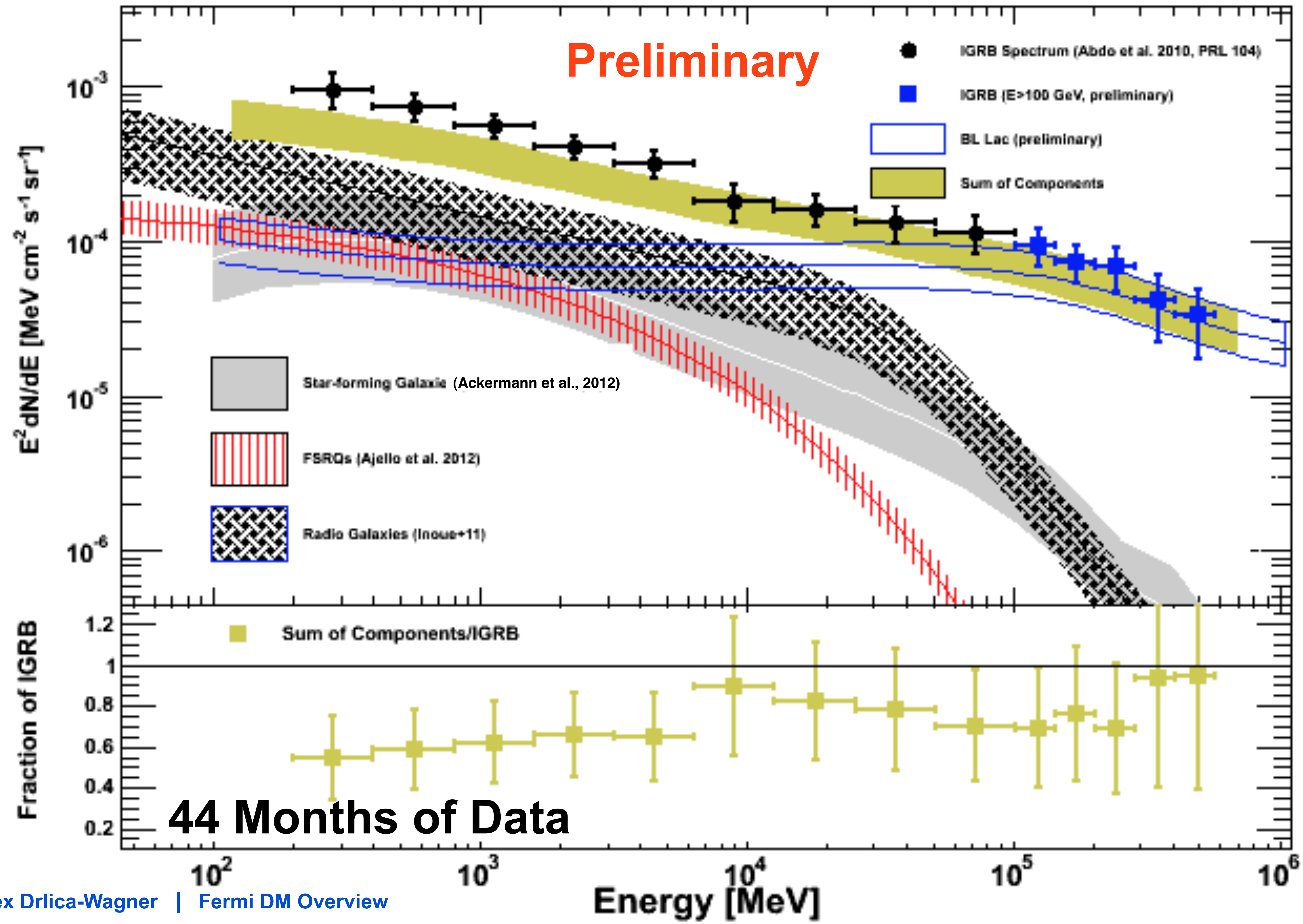
Isotropic Gamma-ray Background

- **WIMP annihilation or decay can manifest itself in the extragalactic background**
- **Contributions from many source classes**
  - **Normal galaxies (radio and star-forming)**
  - **Active galactic nuclei (FSRQ & BL LACs)**
  - **Dark matter?**
- **A contribution from unresolved sources can manifest itself in the angular power spectrum of the isotropic background**

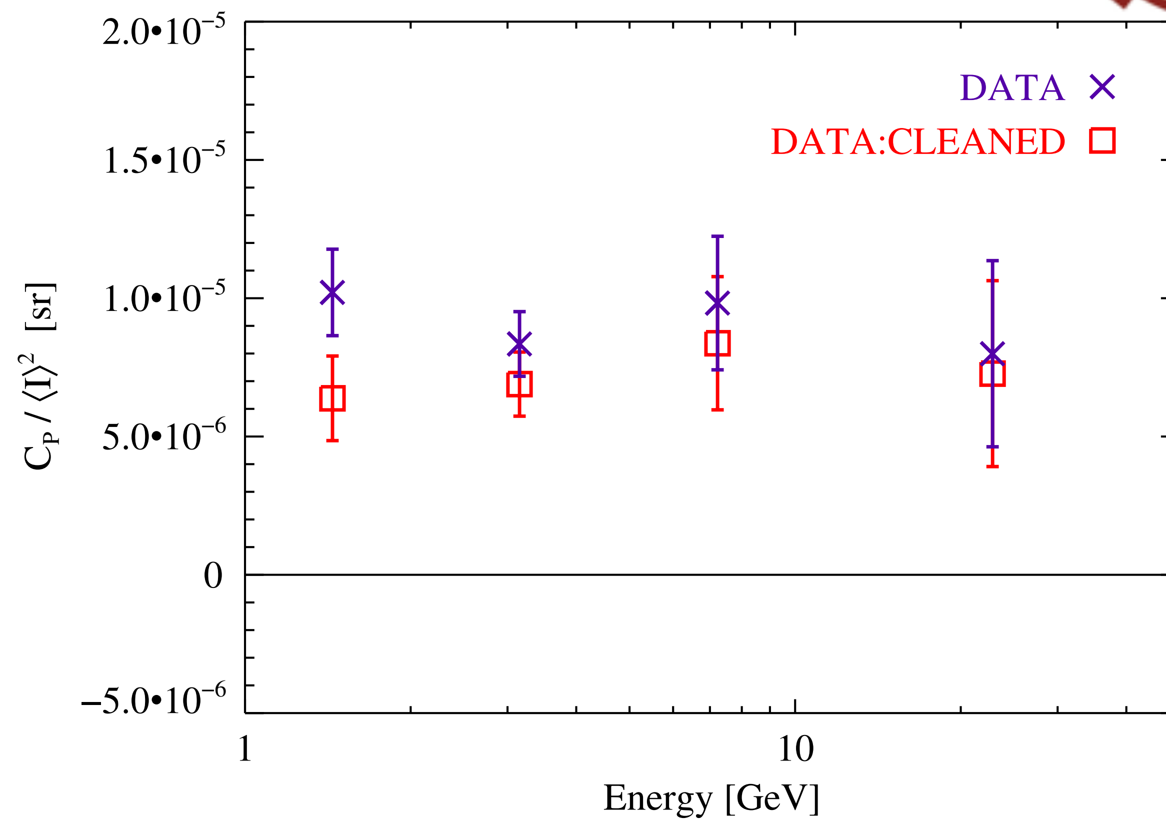


Abdo et al., arXiv:1002.3603
Ackermann et al., arXiv:1202.2856

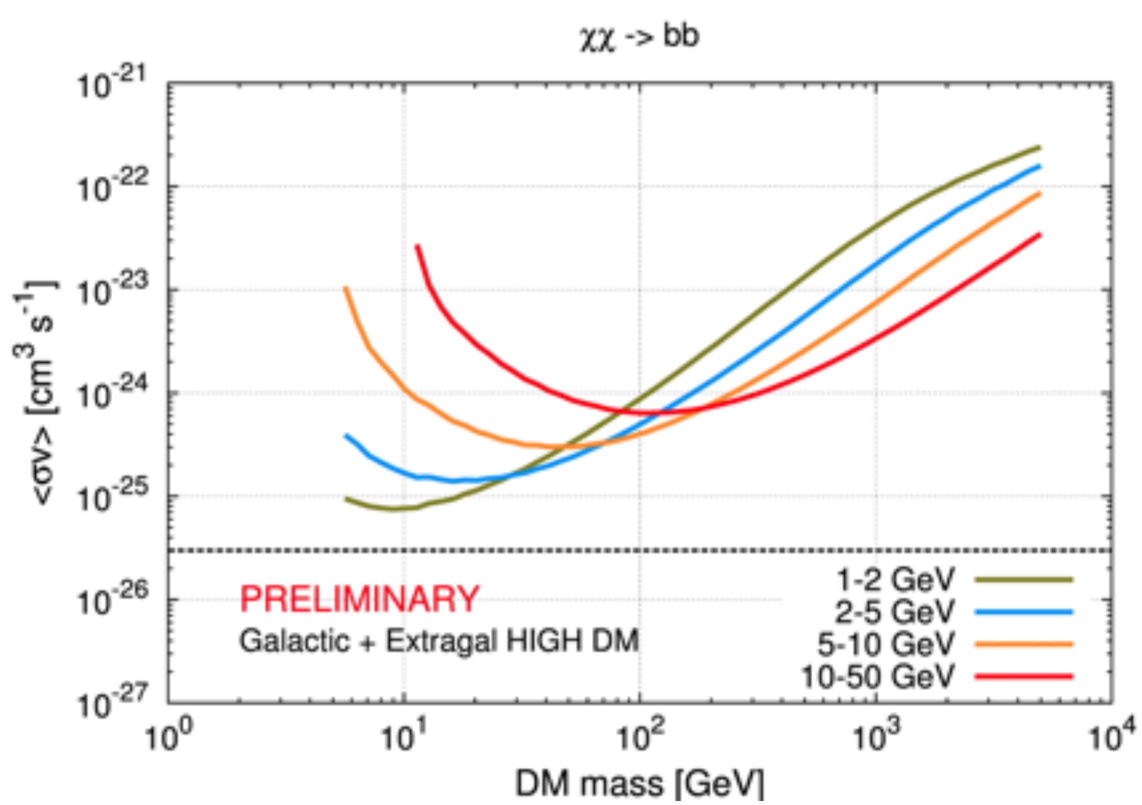
Isotropic Gamma-ray Background



Isotropic Gamma-ray Background



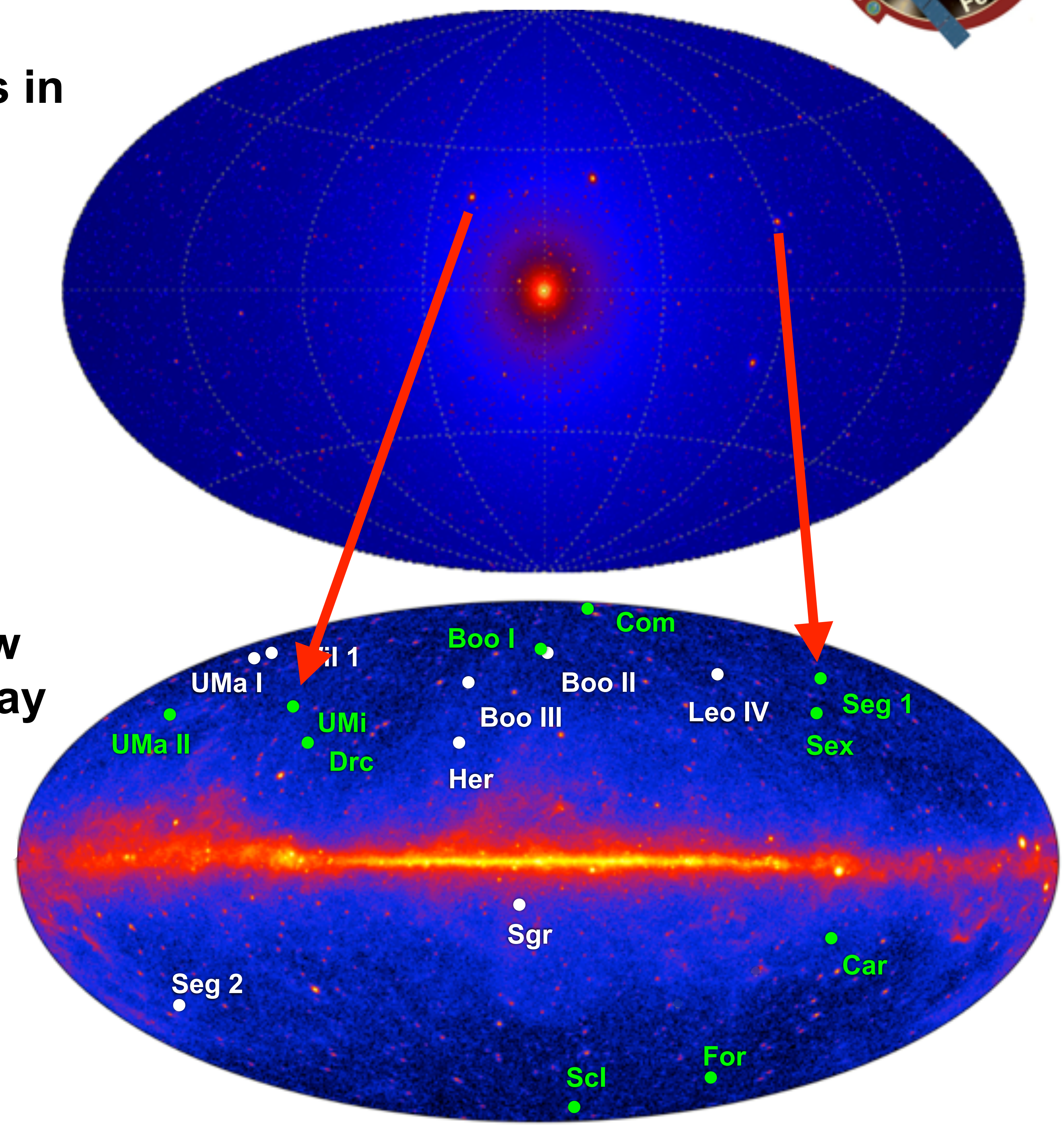
- **Significant (>3σ) detection of angular power between 1-10 GeV (decreased significance between 10-50 GeV)**
- **Consistent with constant value in the four energy bins from 1-50 GeV.**
- **Consistent with the contribution from unresolved source populations (e.g. blazars and star-forming galaxies)**
- **Constrain the contribution of dark matter to the isotropic gamma-ray background**



Ackermann et al., arXiv:1202.2856

Dwarf Spheroidal Galaxies

- **Most dark-matter dominated objects in the universe (100 - 1000 times more dark matter than visible matter)**
- **Relatively nearby (25 - 150 kpc)**
- **High Galactic latitudes (minimize astrophysical foregrounds)**
- **Multi-wavelength observations show no basis for astrophysical gamma-ray production**
  - **No active star formation (no energy injection)**
  - **No appreciable magnetic fields (no acceleration)**
  - **No gas or dust (no target material)**

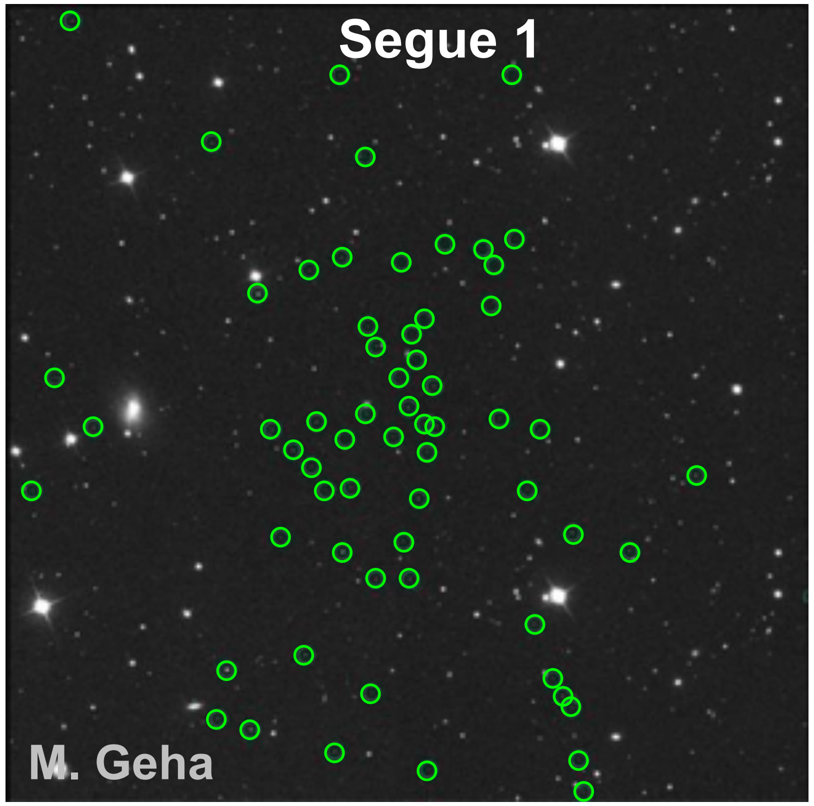


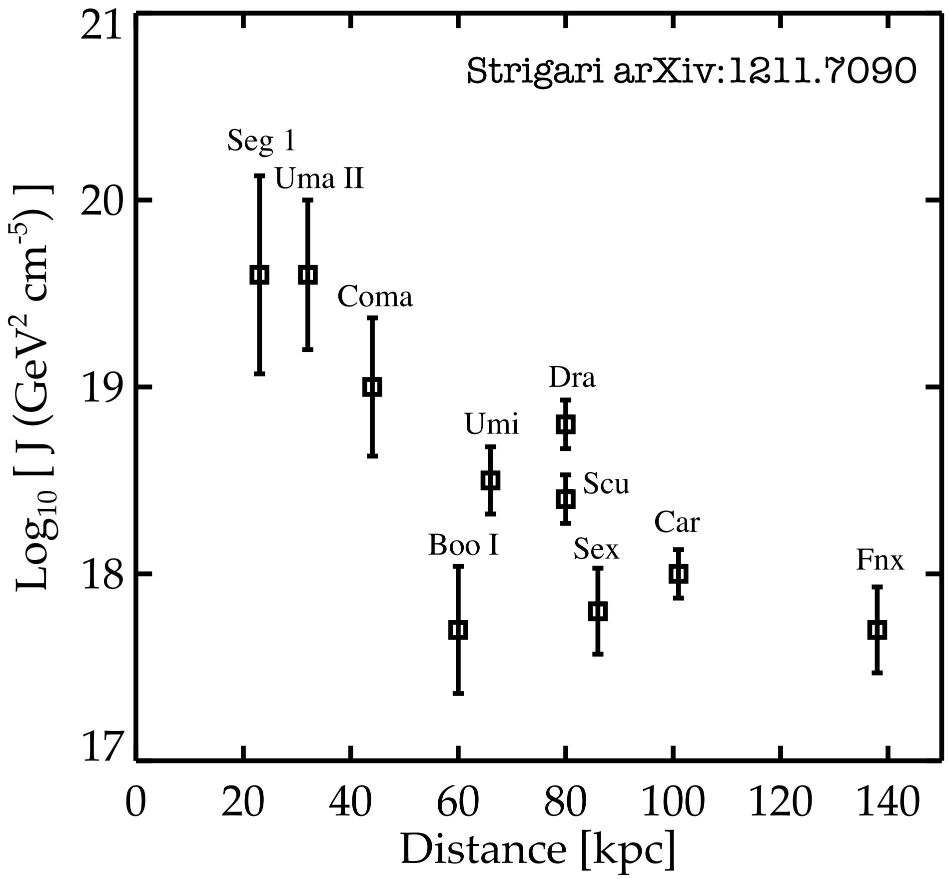
Ackermann et al., arXiv:1108.3546
Geringer-Sameth et al., arXiv:1108.2914
Mazziotta et al., arXiv:1203.6731

Talk from S. Koushiappas

Dark Matter Content

- **Dark matter content determined from stellar velocity dispersion**
  - **Classical dwarfs: spectra for several thousand stars**
  - **Ultra-faint dwarfs: spectra for fewer than 100 stars**
- **Fit stellar velocity distribution of each dwarf (assuming an NFW profile)**
- **Calculate the J-factor by integrating out to a radius of 0.5 deg.**
  - **Comparable to the half-light radius of many dwarfs**
  - **Minimizes the uncertainty in the J-factor**
  - **Large enough to be insensitive to the inner profile behavior (core vs. cusp)**
- **Include the J-factor uncertainty as a nuisance parameter in the joint likelihood**





Joint Likelihood Analysis

- Assume same dark matter particle in all dwarf spheroidal galaxies
- Perform a combined likelihood analysis of multiple dwarfs
  - Predicted flux for each dwarf will depend on individual dark matter content (J-factor)
  - Include statistical uncertainties from stellar kinematic data.
  - Fit backgrounds independently for each dwarf
- Joint likelihood function:

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f \times \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

$$L(D\,|\,\mathbf{p_m},\{\mathbf{p_k}\}) = \prod_k L_k^{\mathrm{LAT}}(D_k\,|\,\mathbf{p_m},\mathbf{p_k}) \times \frac{1}{\ln(10)J_k\sqrt{2\pi}\sigma_k} e^{-(\log_{10}(J_k)-\overline{\log_{10}(J_k)})^2/2\sigma_k^2}$$

Shared by all dwarfs (dark matter particle parameters)

Fit for each dwarf (background sources)

Uncertainty in J-factor

Ackermann et al., arXiv:1108.3546

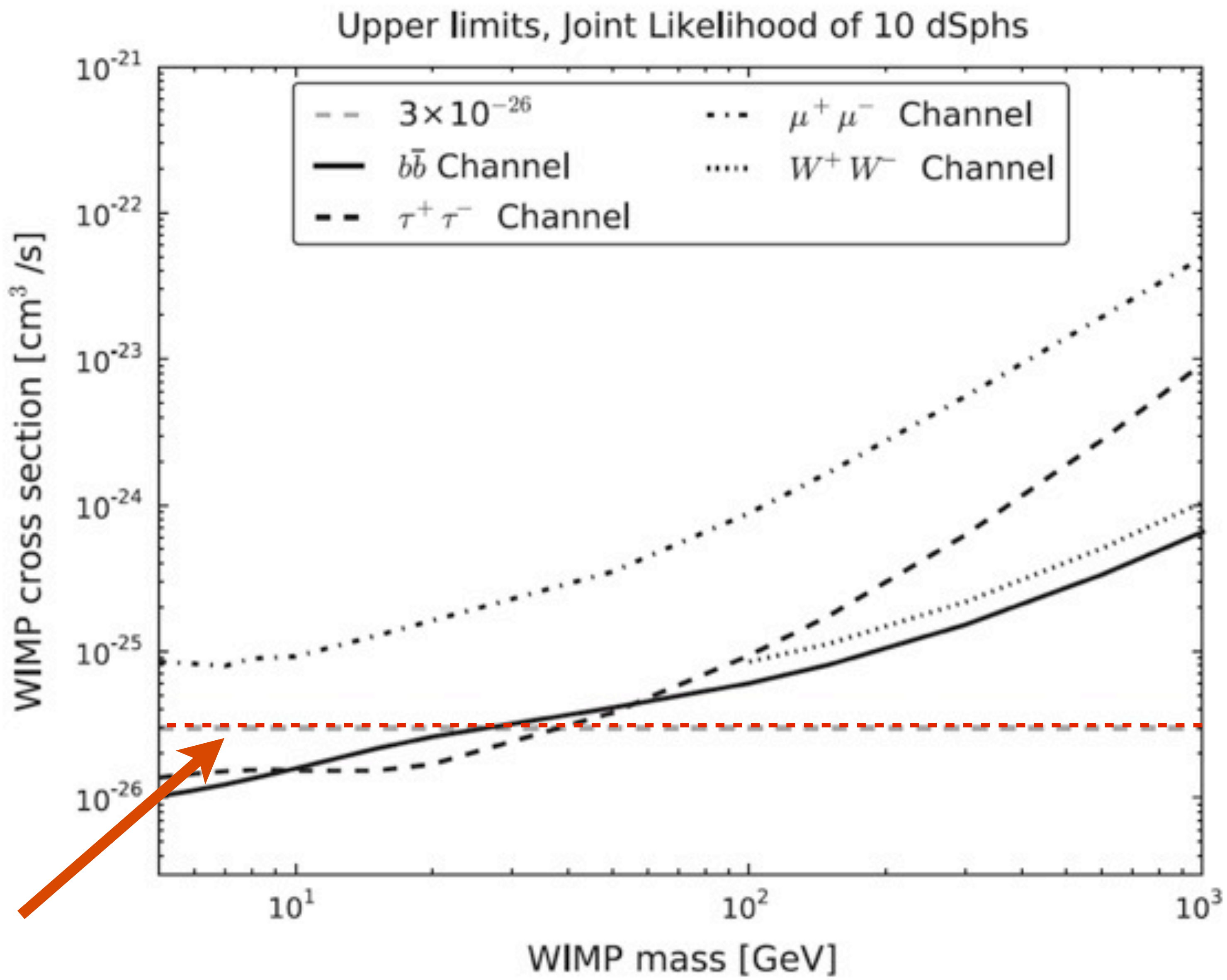
2-Year Pass 6 Analysis

- **Constraints from a joint likelihood analysis of:**
  - **10 dwarf galaxies**
  - **200 MeV - 100 GeV gamma rays**
  - **2 years of P6_V3_DIFFUSE data and IRFs (derived from Monte Carlo)**

- **Astrophysical model:**
  - **Point-like source from the 1FGL**
  - **Diffuse backgrounds from 1 year Galactic and Isotropic models**

- **Include statistical uncertainties in the solid-angle-integrated J-factor**

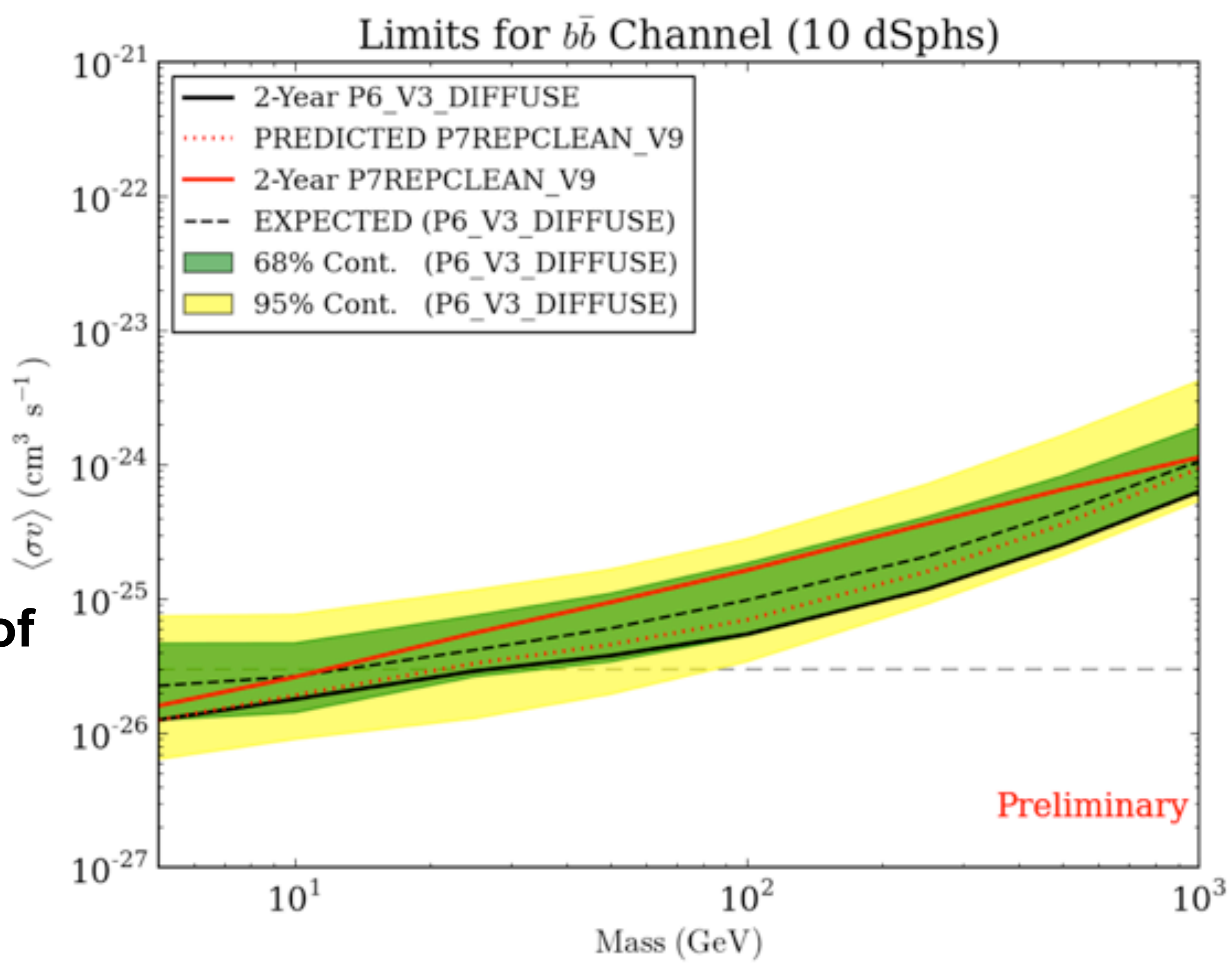
- **Constrain the conventional thermal relic cross section for a WIMP with mass < 30 GeV annihilating to $b\bar{b}$ or $\tau^+\tau^-$**



Ackermann et al., arXiv:1108.3546

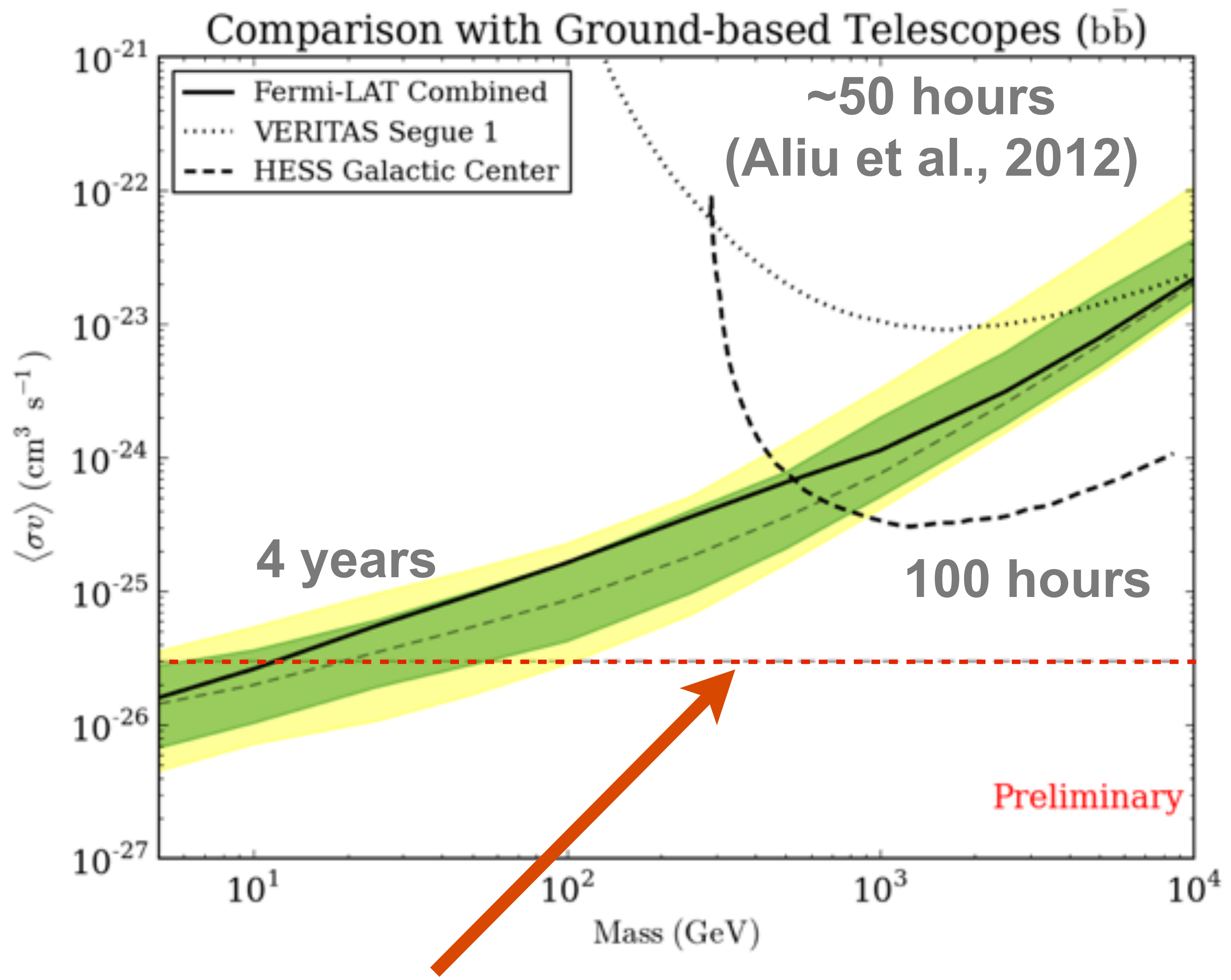
Expected Limits

- **Run full analysis pipeline on realistic sky simulations to calculate expected sensitivity**
- **Statistical scatter is large.**
- **Update analysis with an improved understanding of the instrument (reprocessed Pass 7)**
- **Leads to a statistical reshuffling of gamma-ray-classified events and higher limits.**
- **Both Pass 6 and Pass7 measurements lie within the 68% containment region of a statistical sample.**



Dwarf Spheroidal Summary

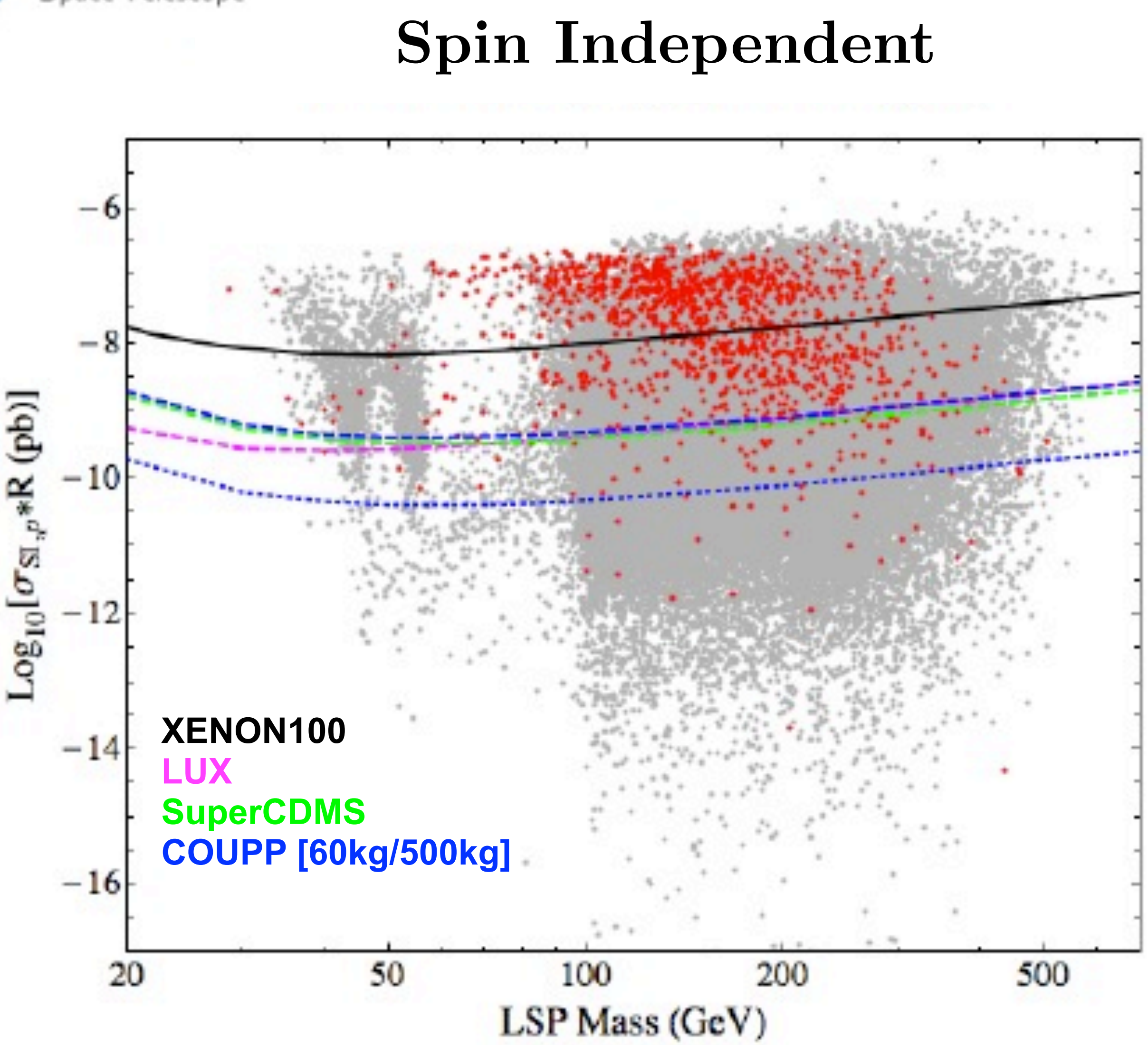
- **4 years of Pass 7 data yields higher limits than 2 years of Pass 6 data; however, the two are statistically consistent with predictions.**
- **Change in the Fermi-LAT dwarf limits are due to statistical fluctuations in the event classification.**
- **Still no evidence for a dark matter signal from these objects.**
- **Immediate improvements are expected from updated diffuse and point source background models.**

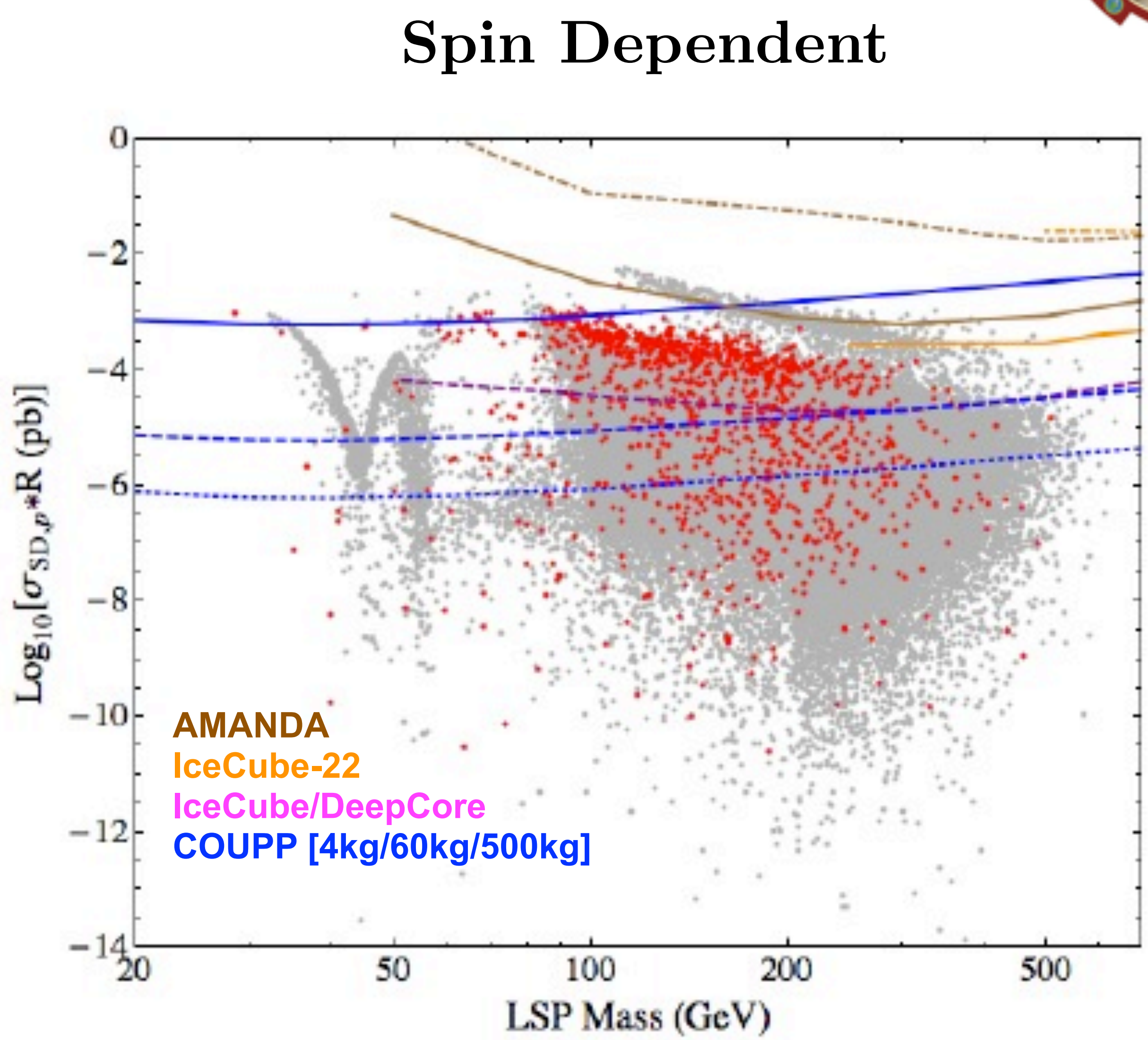


Thermal Relic Cross Section

$$\langle \sigma v \rangle = 3 \times 10^{-26} \mathrm{cm}^3\,\mathrm{s}^{-1}$$

Complementarity: Dwarf Galaxies and the pMSSM



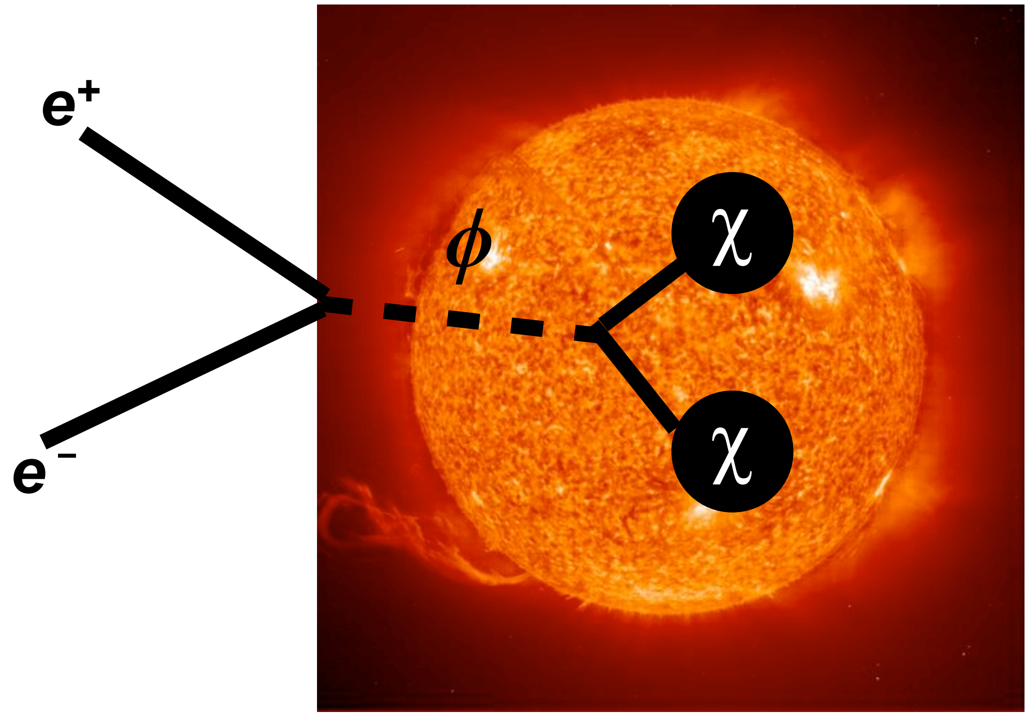


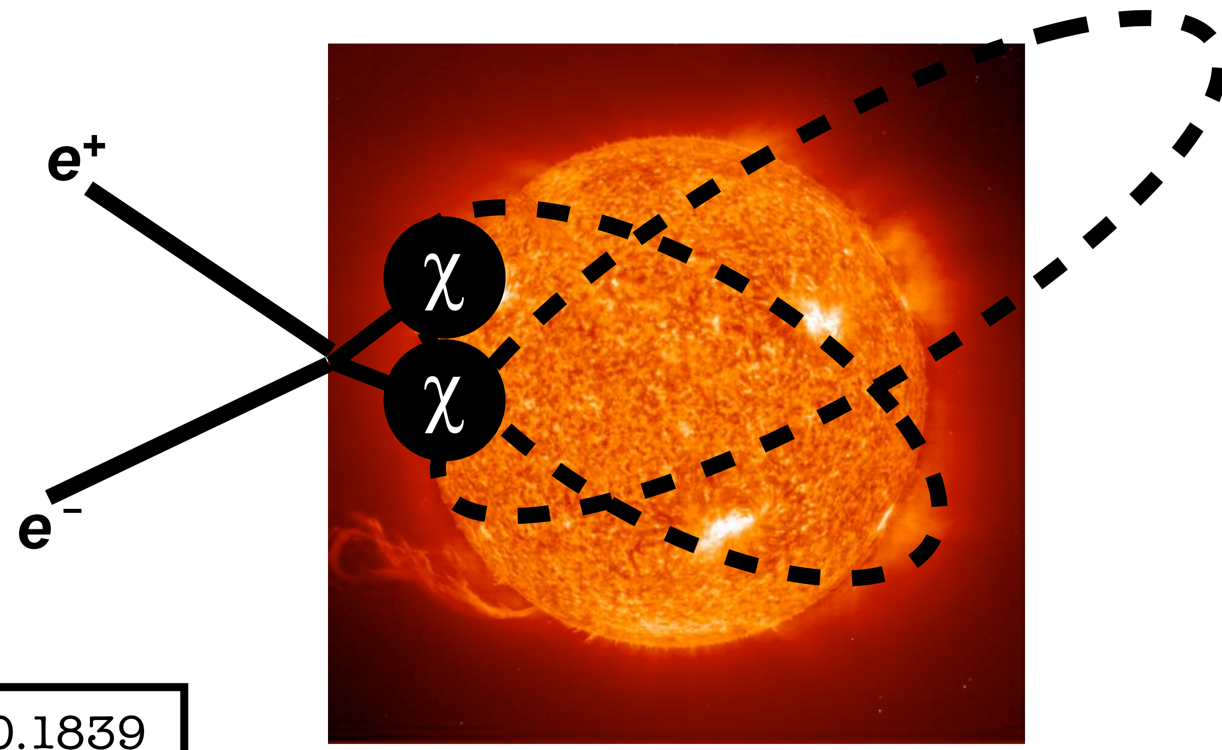
- **Examine complementarity between the LAT and direct detection searches using the pMSSM model scan (19-dimensional scan of the MSSM) shown in gray**
- **Highlight in red models which the LAT may be sensitive to over a 10 year mission**
- **Direct detection generally does better than the LAT with models that don't saturate the WMAP bound low relic density**

Berger et al. arXiv:0812.0980
Cotta et al. arXiv:1111.2604

Complementarity: Electrons from the Sun

- Combination of direct and indirect detection mechanisms
  - WIMP-nucleon scattering leads to WIMP capture by the Sun
  - WIMP-WIMP annihilation leads to the production of cosmic rays
- Dark matter capture and annihilation through an intermediate state
  - WIMP accretion rate determined by scattering cross section
  - Annihilation through an intermediate particle which can travel out of the Sun and decay into cosmic rays
- Inelastic dark matter
  - WIMPs accretion via inelastic scattering (maintain large orbits)
  - Annihilate directly into cosmic-ray electrons in the solar neighborhood

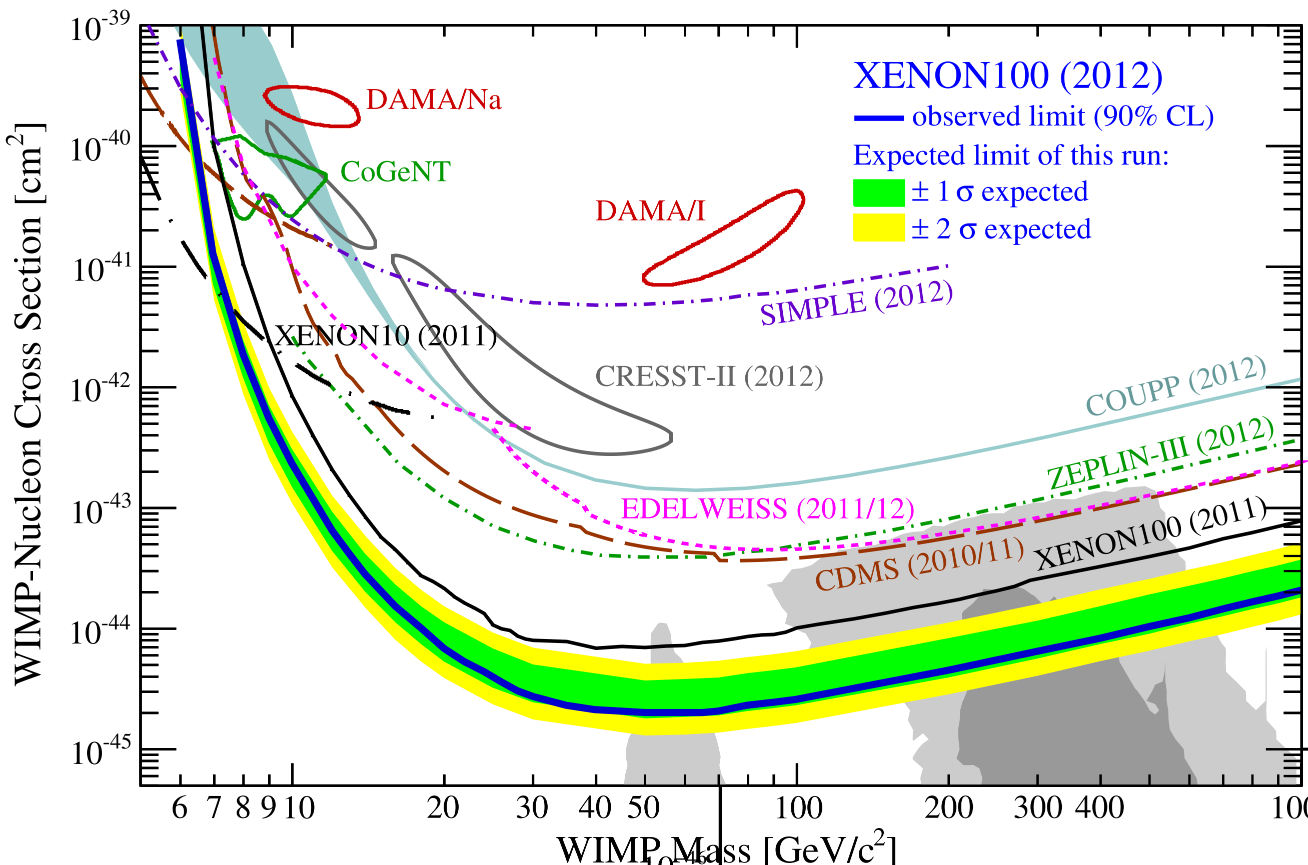


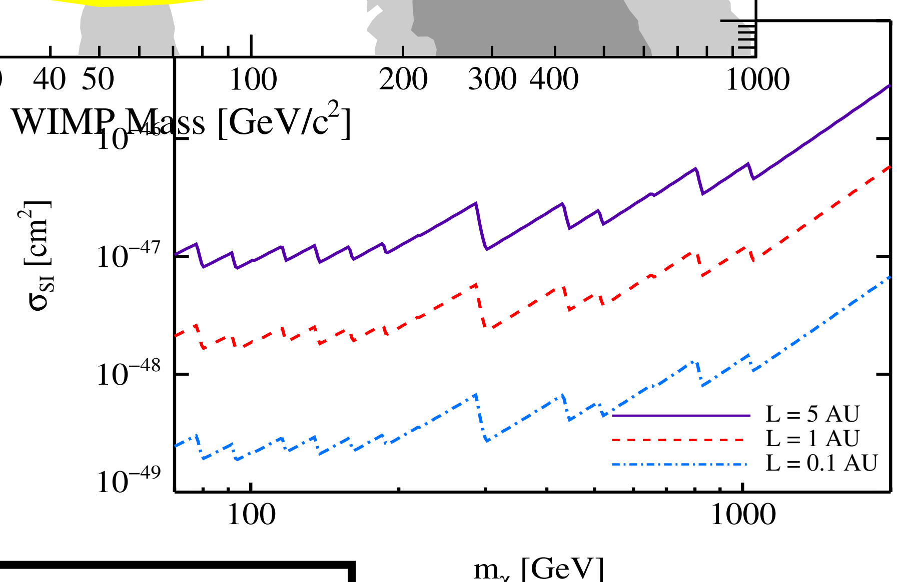


Schuster et al., arXiv:0910.1839
Ajello et al., arXiv:1107.4272

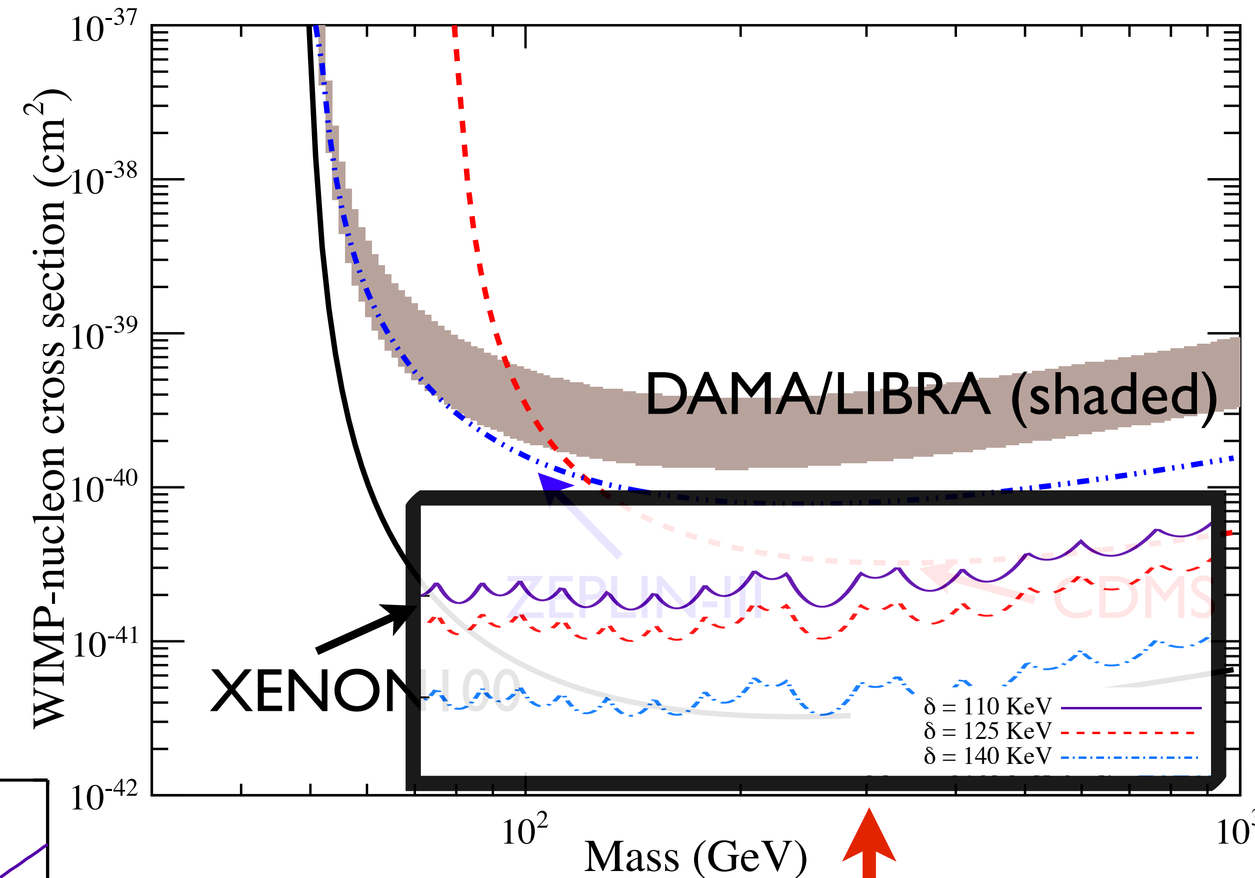
Complementarity: Electrons from the Sun

Spin Independent Constraints





Inelastic Scattering



Assumes WIMP capture through inelastic scattering and annihilation to e+e-

Assumes WIMP annihilation through an intermediate particle to e+e-

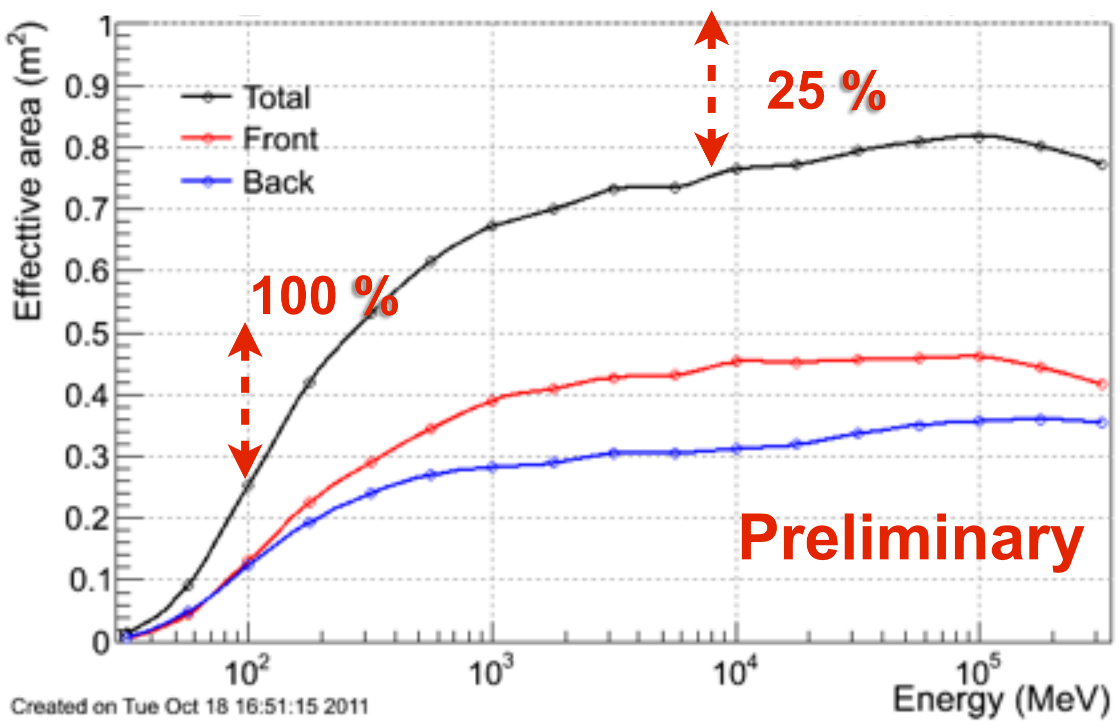
Aprile et al., arXiv:1207.5988
Aprile et al., arXiv:1104.3121
Ajello et al., arXiv:1107.4272

Outlook

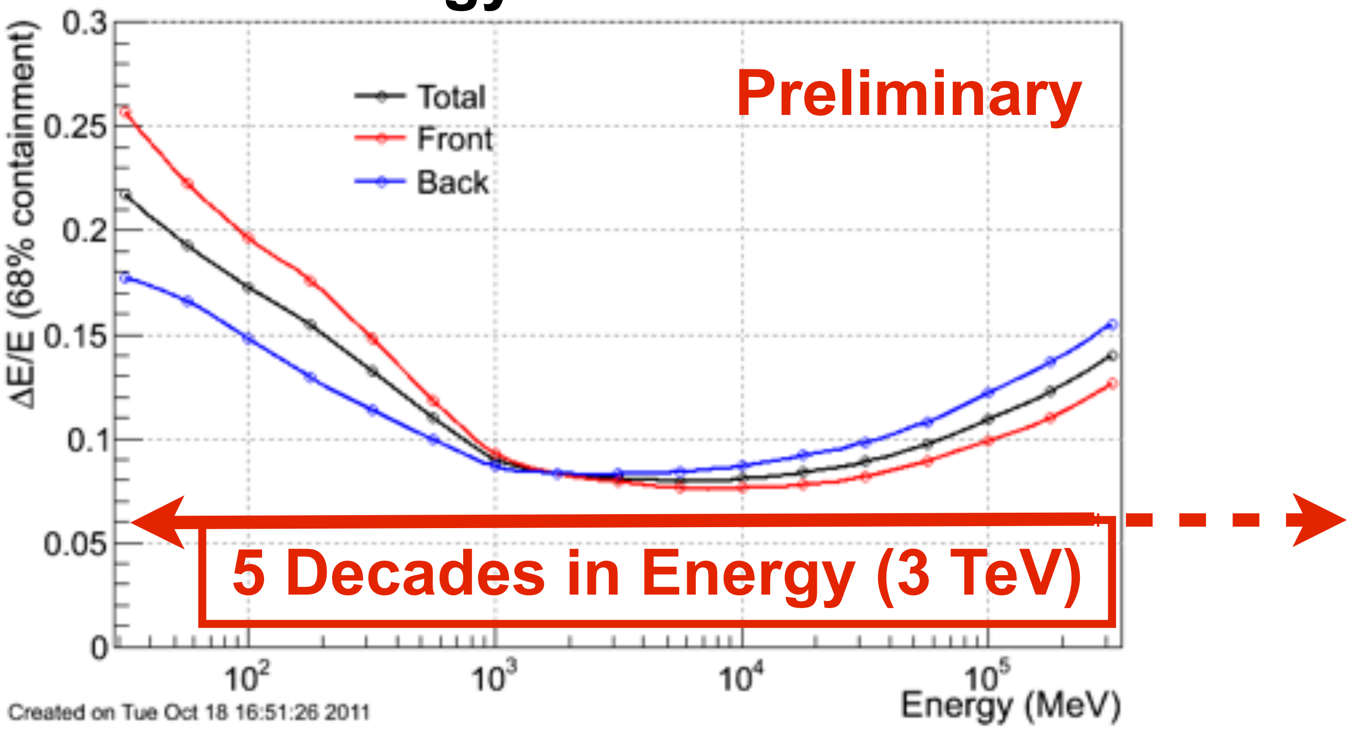
- **Improvements to the LAT instrument performance:**
  - Increased energy range
  - Increased effective area
  - Improved angular resolution
  - Better background rejection
  - New event classes

- **Impacts for dark matter:**
  - Energy Range <==> explore new high-mass parameter space
  - Effective Area <==> increase significance of tentative signals
  - Angular Resolution <==> greater sensitivity to spatially extended subhalos
  - New Event Classes <==> check systematic effects in event selection

Effective Area



Energy Resolution



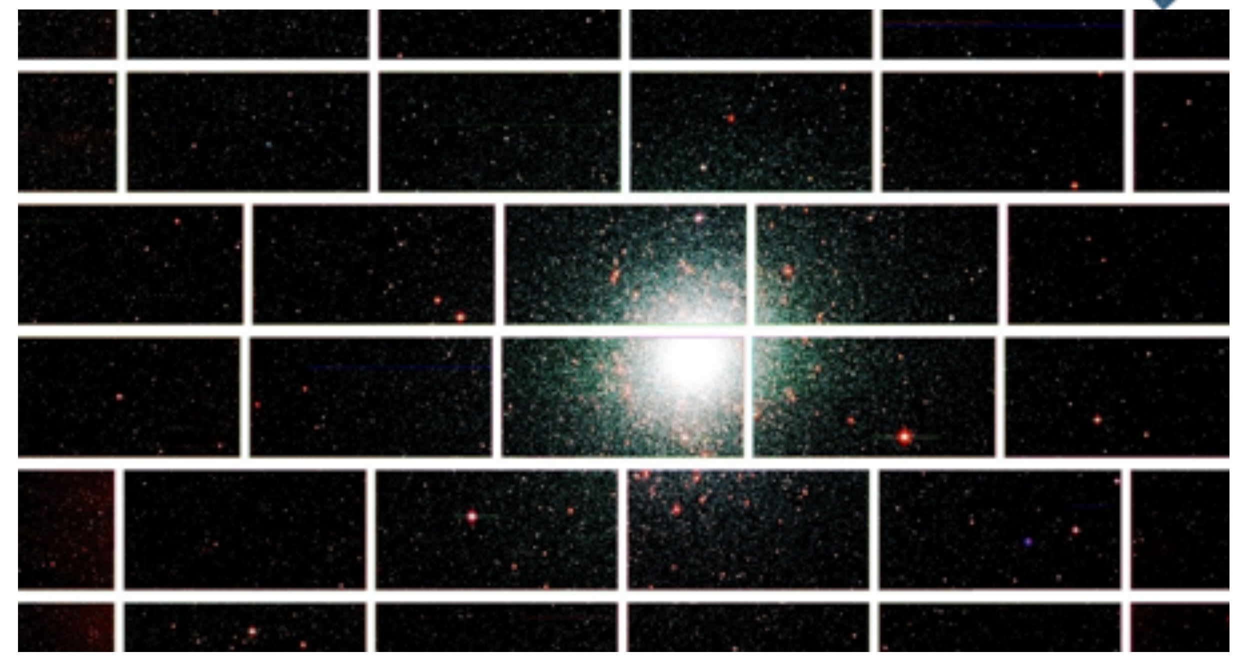
Outlook

- **The Fermi LAT is opening an unprecedented window on the gamma-ray sky**

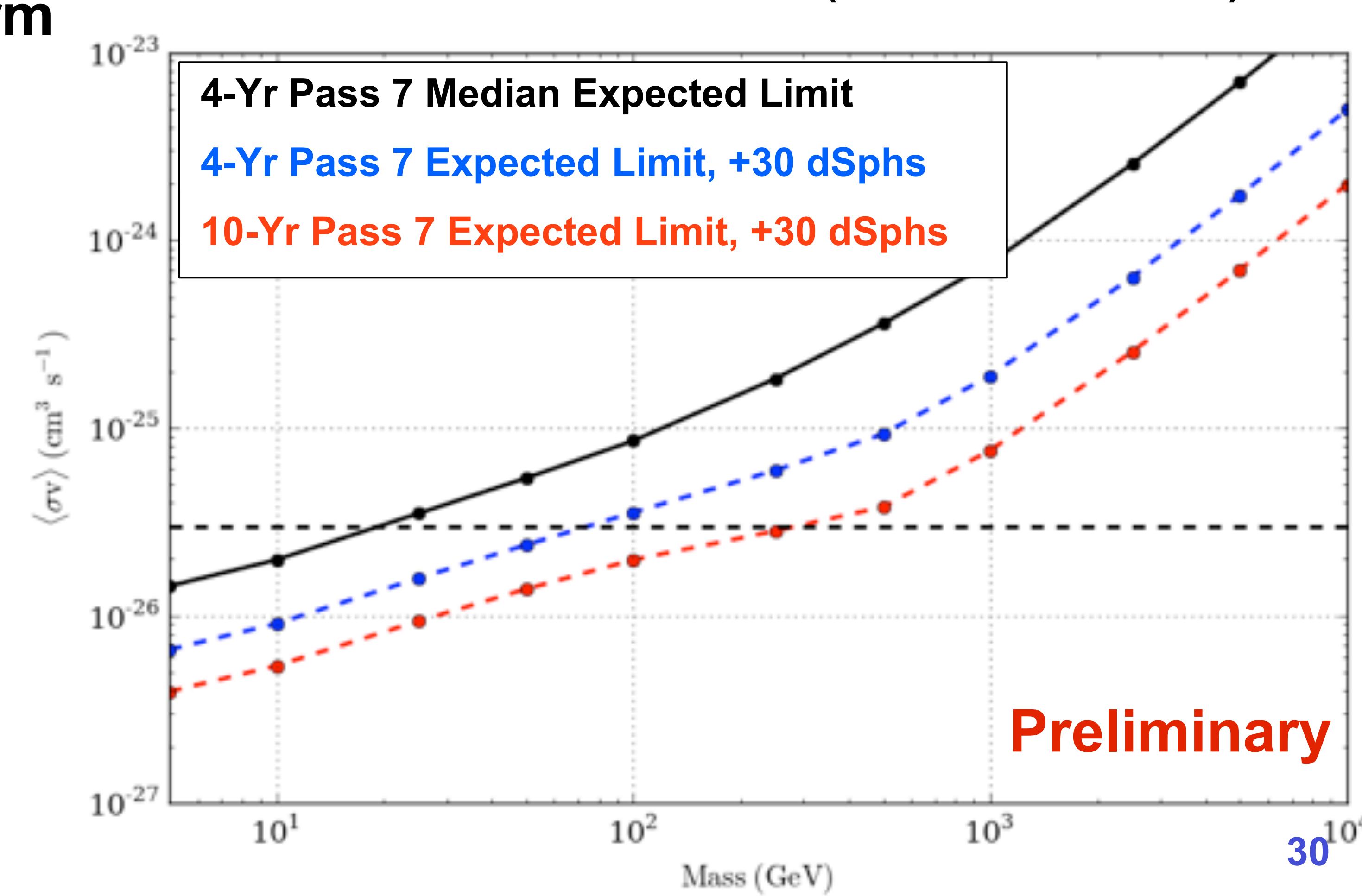
- **The indirect search for dark matter is unavoidably linked to astrophysical and instrumental effects**

- **Indirect detection is essential to form *in situ* link to dark matter.**

- **The best is yet to come**
  - **A better understanding of the instrument**
  - **A better understanding of the astrophysics**
  - **New promising new source classes**



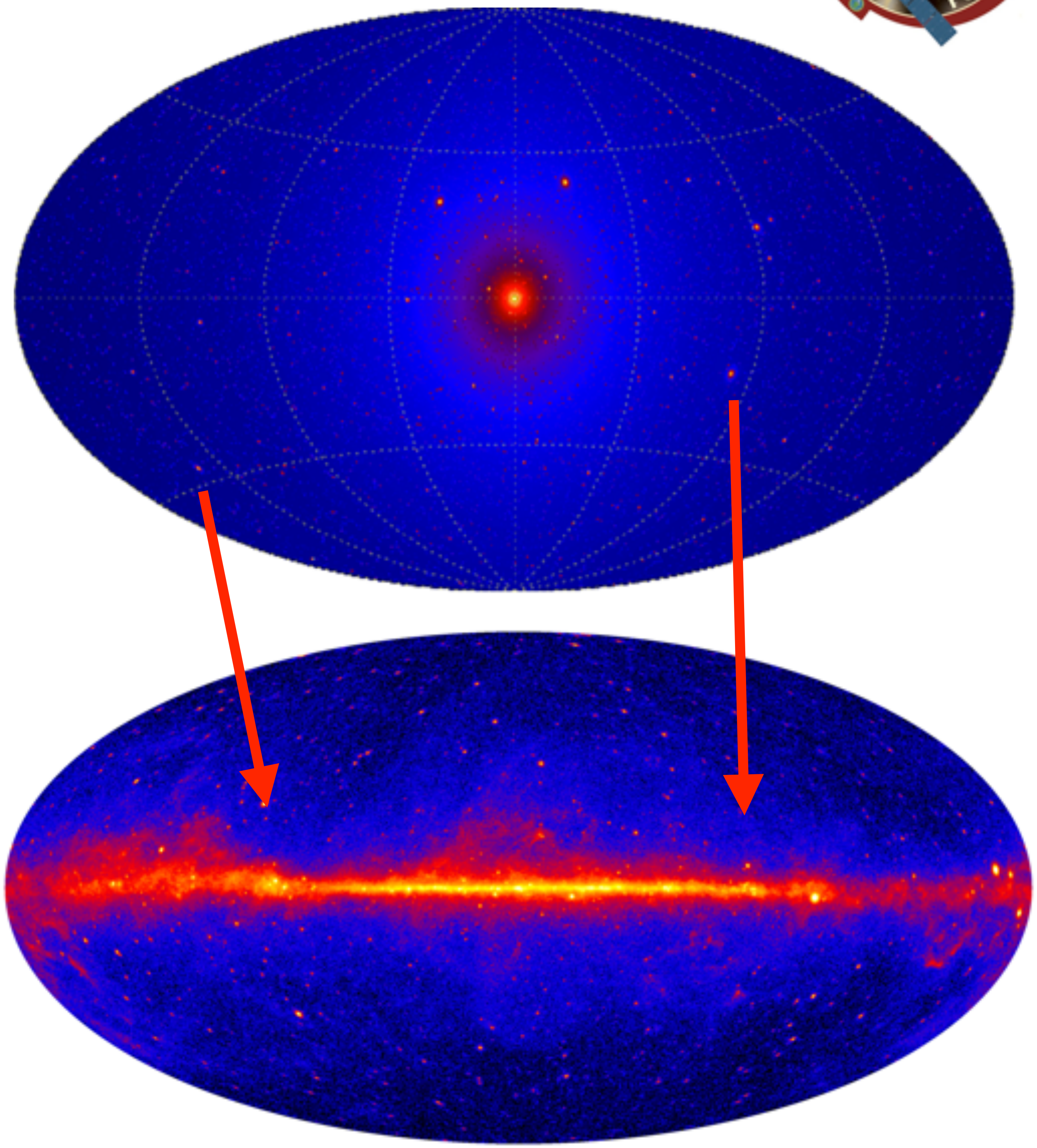
Globular Cluster 47 Tuc (DES Collaboration)



Back Up

Dark Matter Subhalos

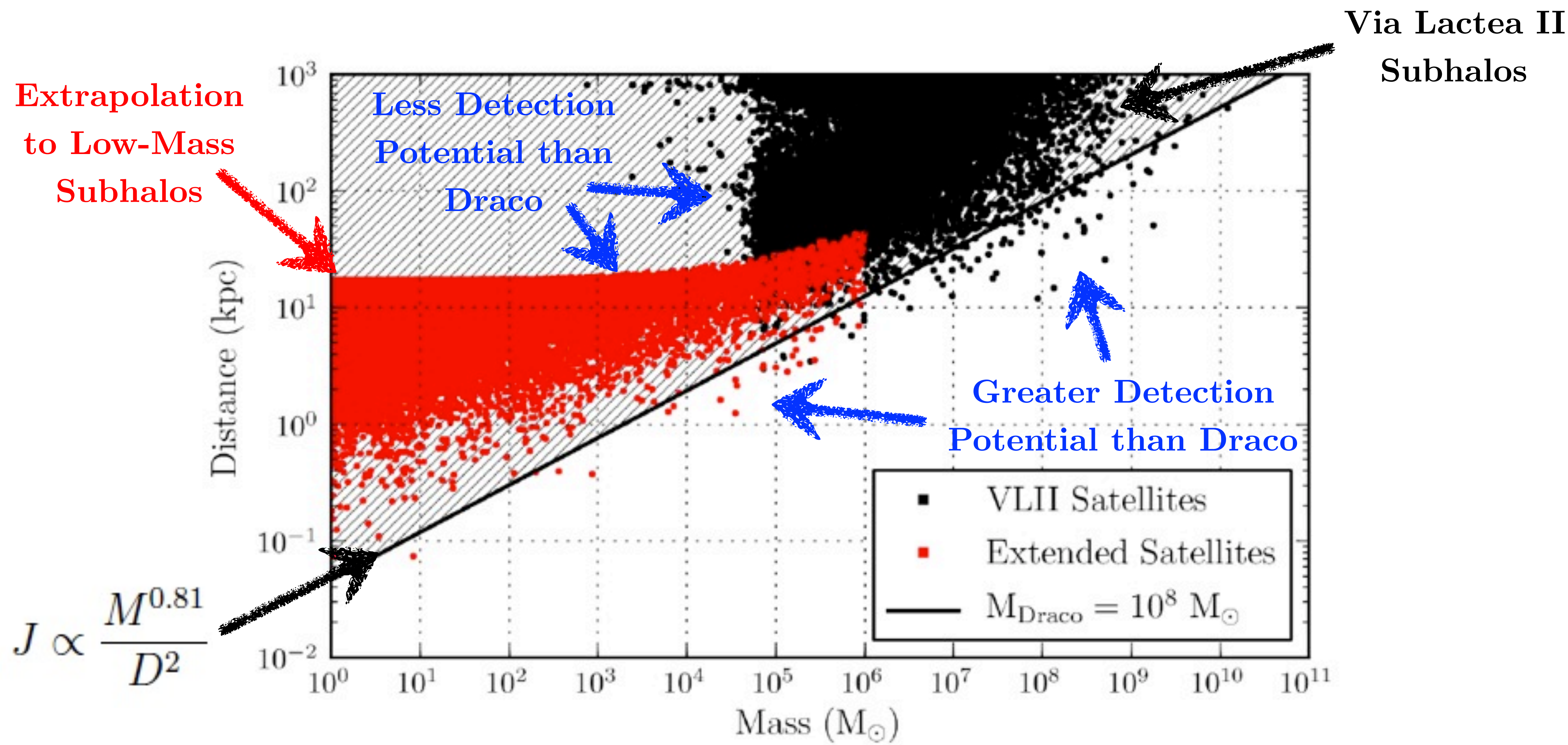
- **Simulations predict that Galactic dark matter halo populated by numerous subhalos**
  - **Largest subhalos contain satellite galaxies**
  - **Smaller subhalos have no tracer in other wavelengths**
- **The brightest of these source would be detected as discrete gamma-ray sources lacking astrophysical associations**
- **Look at unassociated sources:**
  - **~600 unassociated sources in the LAT 2FGL catalog (most near Galactic plane)**
  - **Associations made through:**
    - **Multiwavelength observations**
    - **Searches for periodicity**
    - **Correlated variability**
    - **etc.**



Ackermann et al., arXiv:1201.2691
Hooper et al., arXiv:1208.0828
Zechlin et al., arXiv:1210.3852

Unassociated Subhalos

- **Are dwarf galaxies the best component of substructure for dark matter detection?**
- **Some substructure could be more detectable than the dwarf galaxies…**
- **But we don't know exactly where to look…**

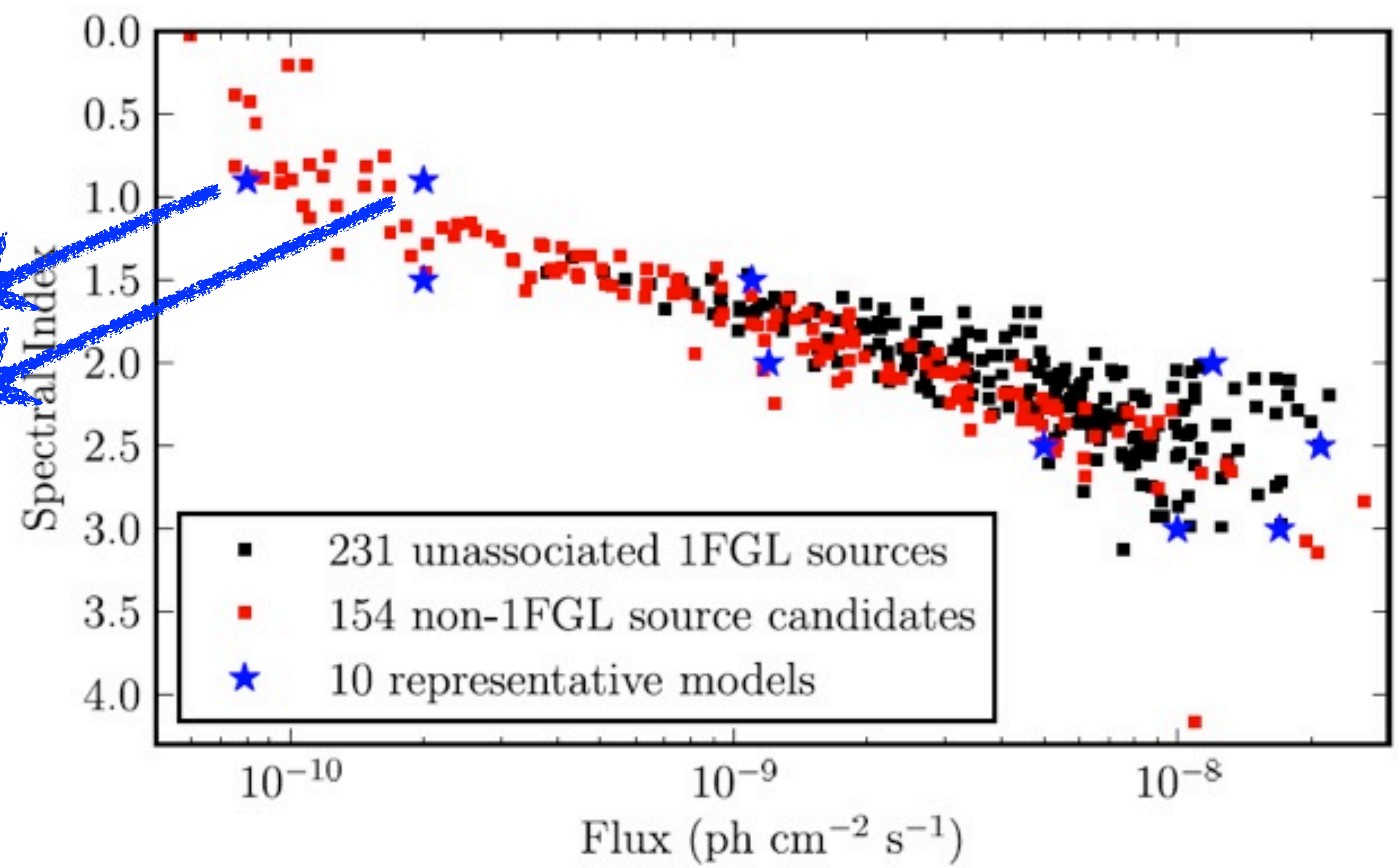


Ackermann et al., arXiv:1201.2691

Unassociated Subhalos

- Examine **unassociated**, high-latitude sources in First LAT Catalog.
- Search for **non-power-law** sources with that may have been missed.
- Test for **spatial extension** and **spectral shape** with 99% confidence.

Spectral Index	Flux $(\mathrm{ph\,cm^{-2}\,s^{-1}})$	TS_{ext}^{99}	TS_{spec}^{99}
0.9	2.0×10^{-10}	6.18	2.38
0.9	8.0×10^{-11}	7.87	2.46
⋮	⋮	⋮	⋮



Ackermann et al., arXiv:1201.2691

Unassociated Subhalos Summary

- **Use N-body simulations to determine the probability of having no subhalos pass selection criteria as a function of $\langle \sigma v \rangle$**

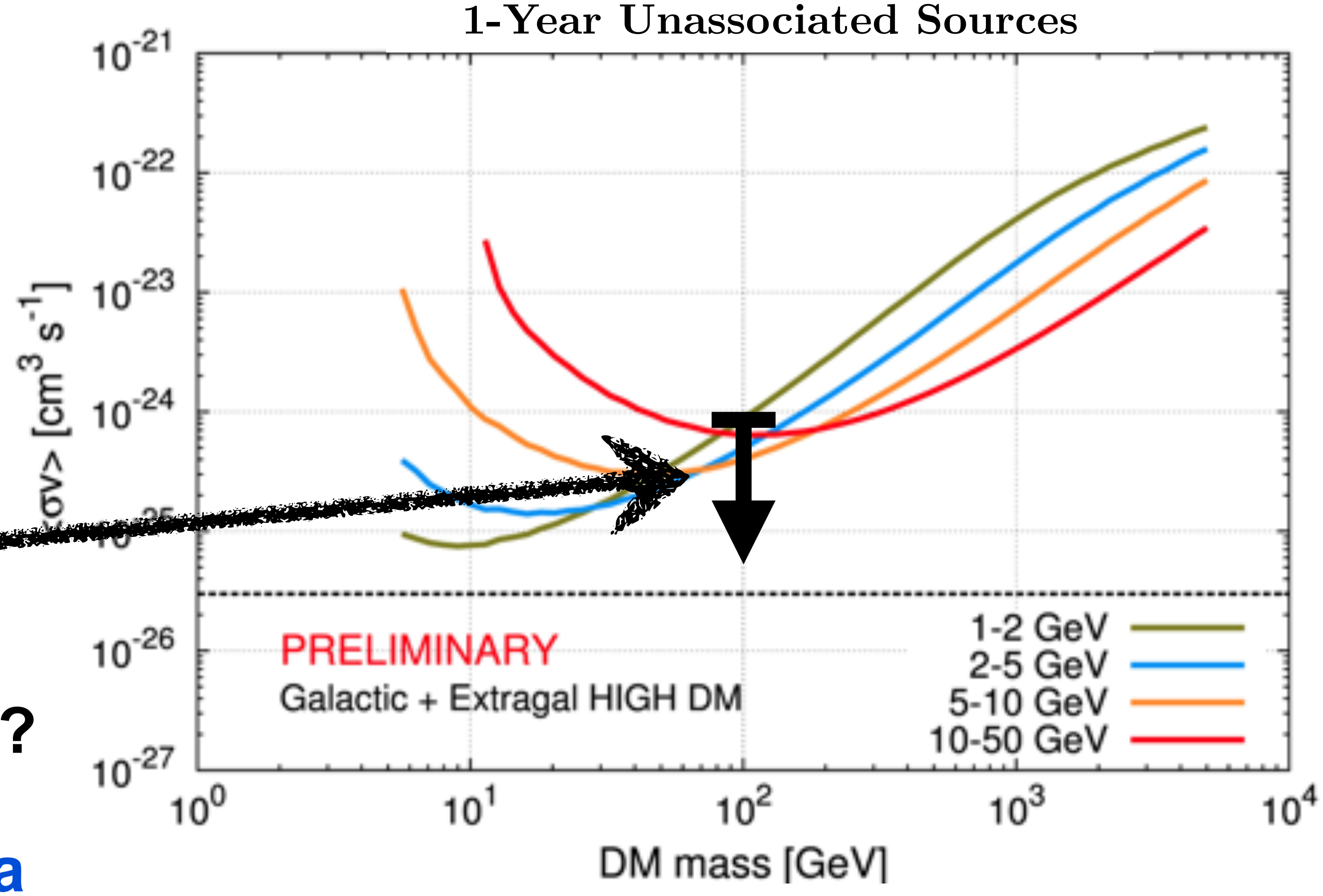
Prob(Don't Detect Simulated Satellite j)

$$P_i(\langle \sigma v \rangle) = \prod_j (1 - \epsilon_{i,j}(\langle \sigma v \rangle))$$

Prob(Don't Detect Any Satellites in Simulation)

$$\langle \sigma v \rangle \sim \mathbf{2 \times 10^{-24}\ cm^3\ s^{-1}}$$

2-Year Anisotropy Analysis
vs.
1-Year Unassociated Sources



- **What would an interesting signal look like?**
  - **Multiple unassociated sources sharing a common hard spectral feature**
  - **Optical follow up of an unusual unassociated source reveals a new ultra-faint dwarf.**

Ackermann et al., arXiv:1201.2691