Searches for Dark Matter with the Fermi-LAT

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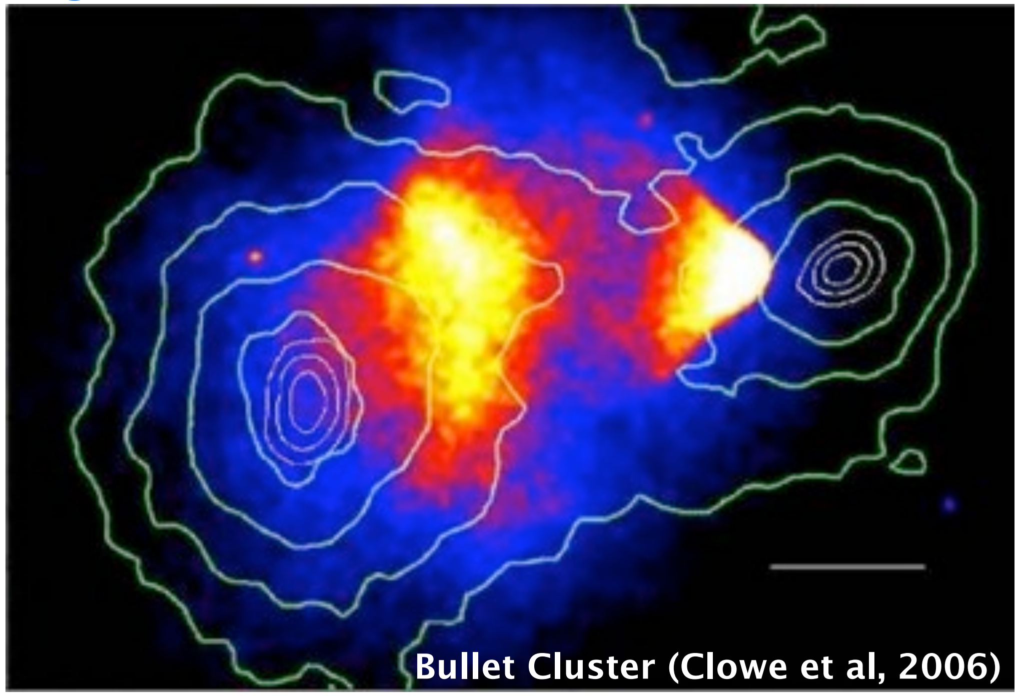
on behalf of the LAT Collaboration
SLAC-KIPAC-Stanford University

SLAC Summer Institute
August 1, 2011

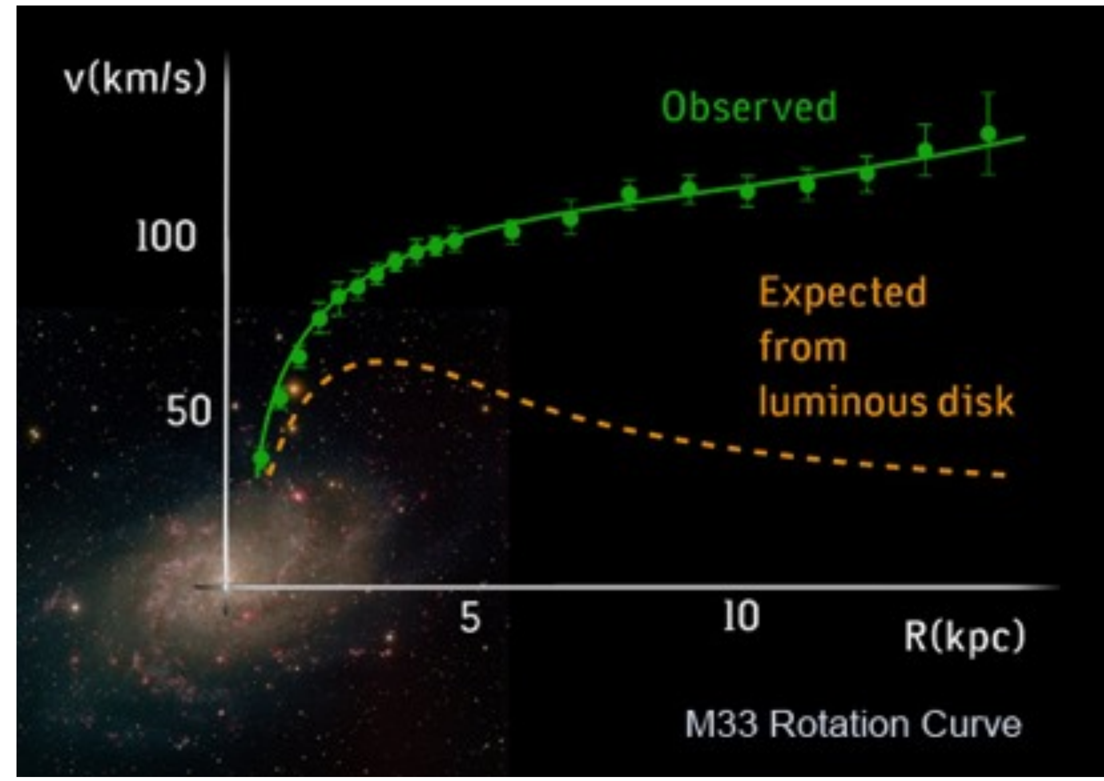
Evidence for Dark Matter

Galaxy Cluster Mass Distribution

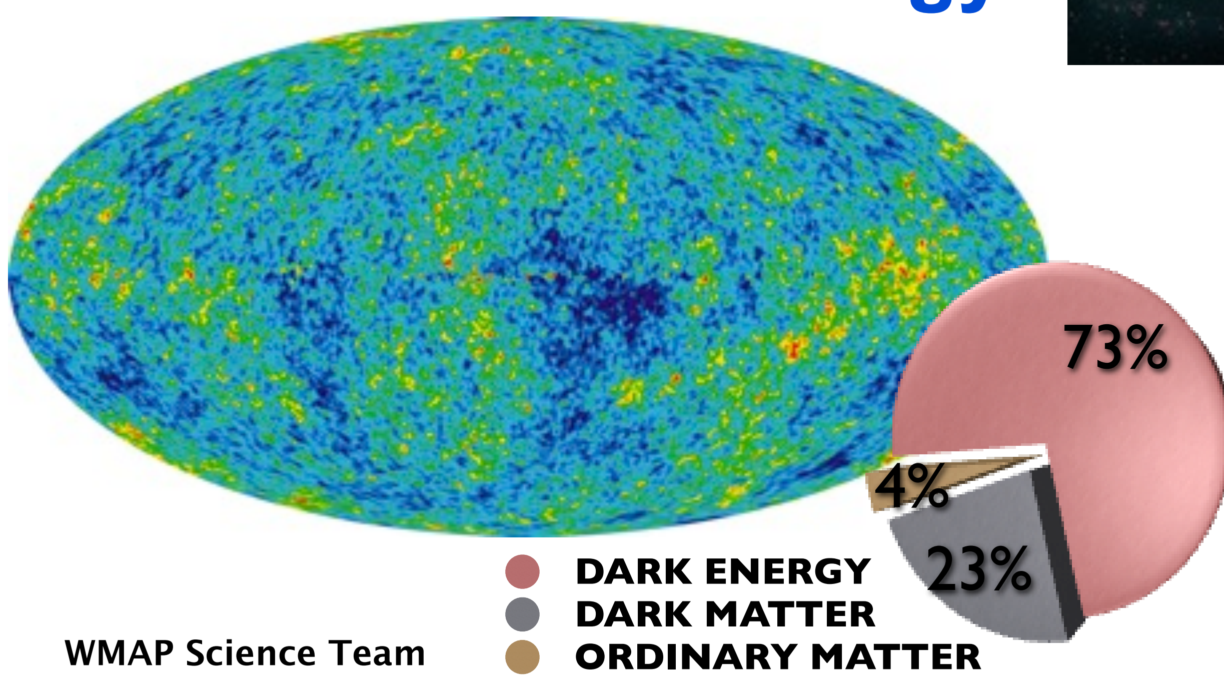


Bullet Cluster (Clowe et al, 2006)

Galaxy Rotation Curves

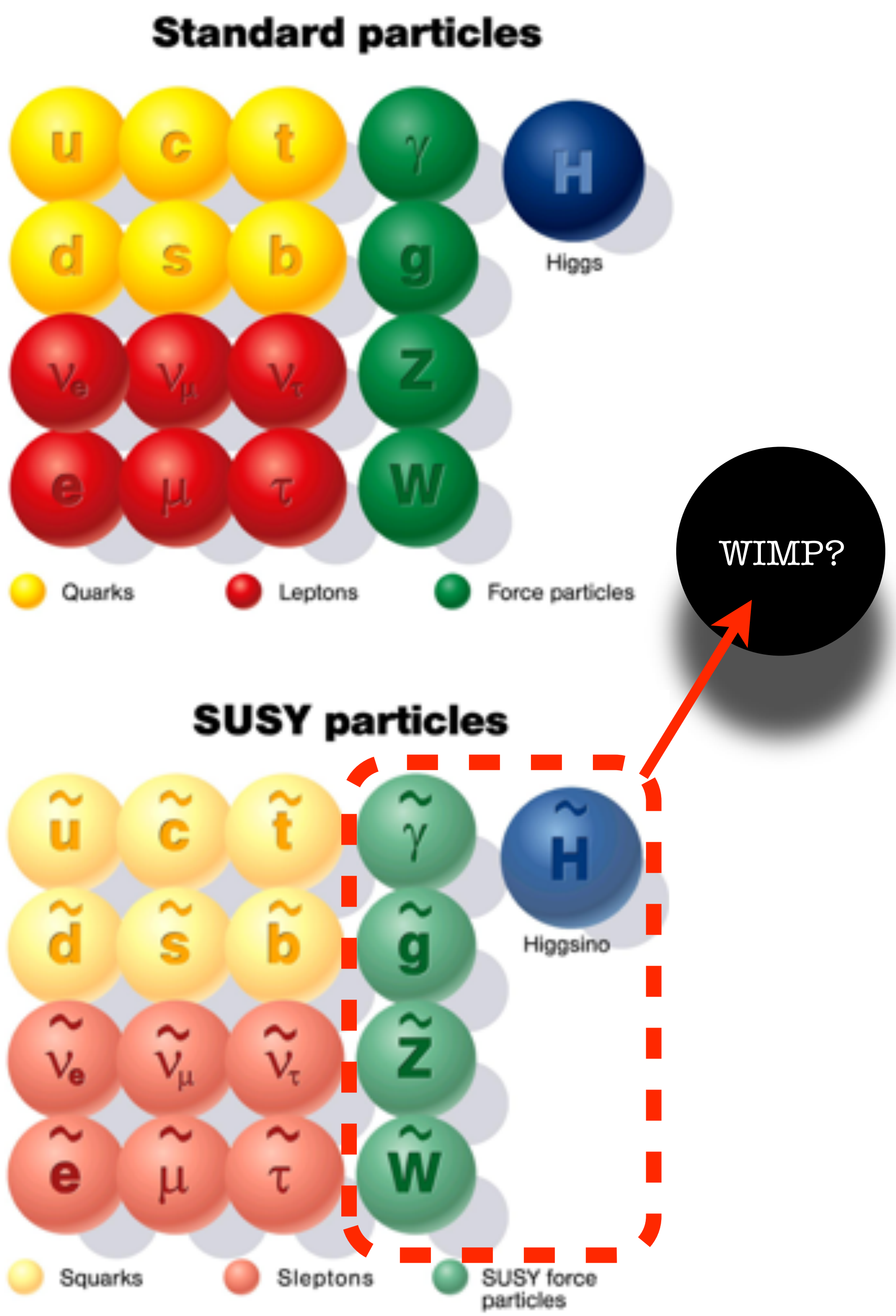


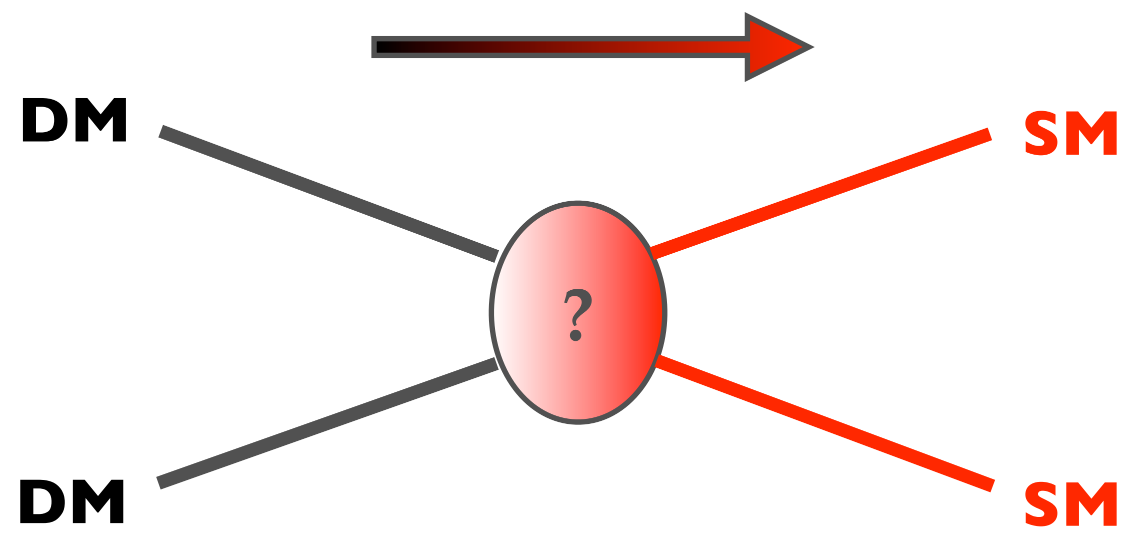
Precision Cosmology



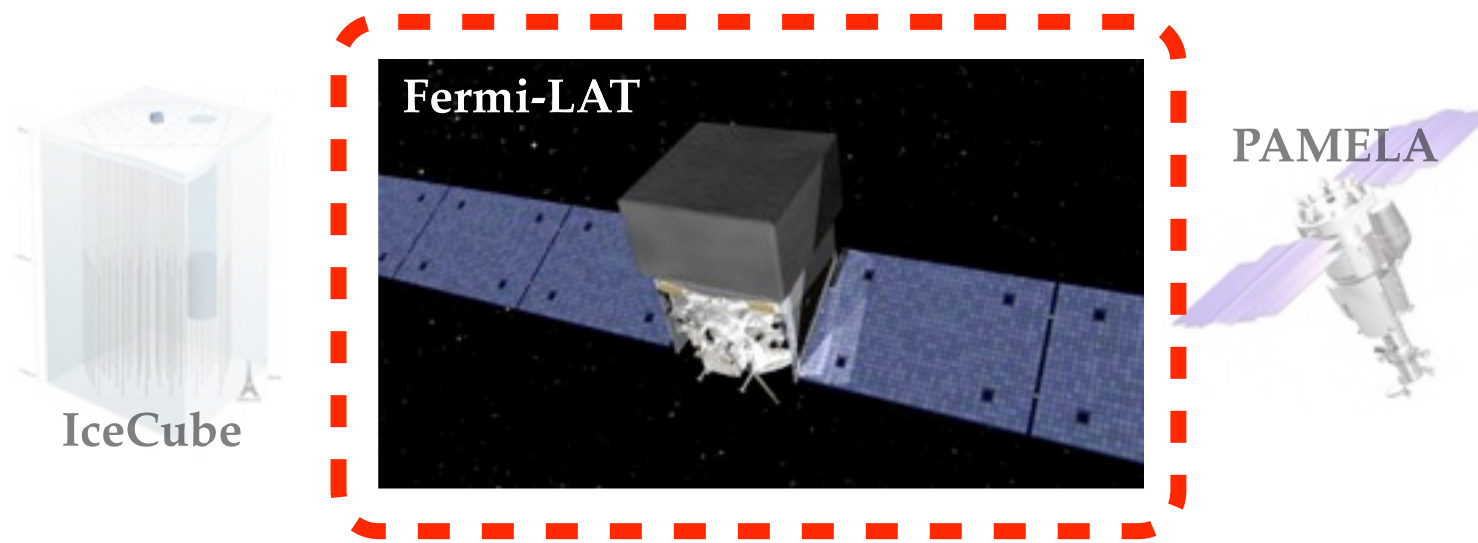
WMAP Science Team

Particle Dark Matter





INDIRECT SEARCHES



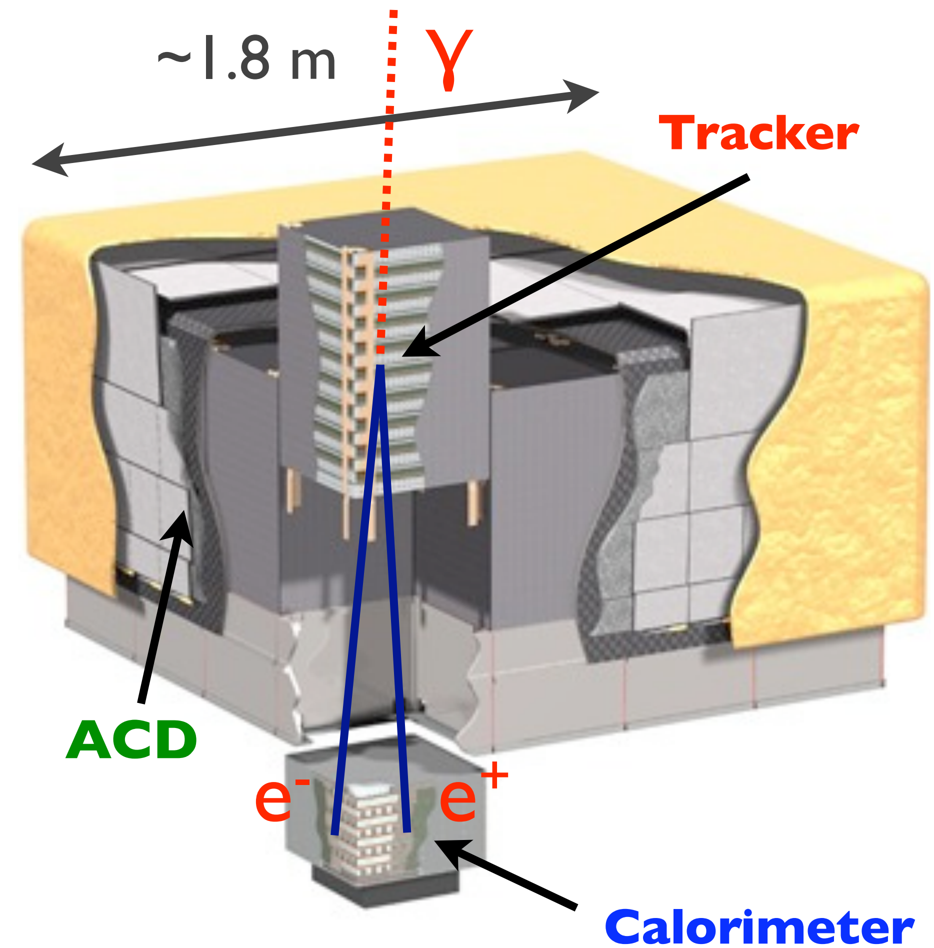
The Fermi Large Area Telescope (LAT)

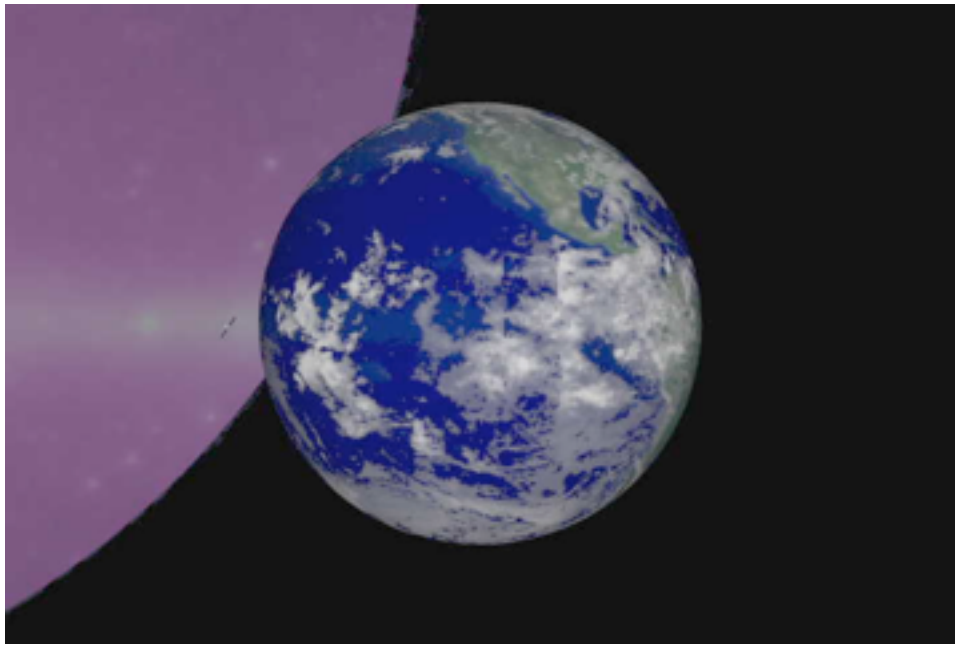
Pair conversion telescope

Segmented Anti-Coincidence Detector (ACD): charged particle veto (0.9997 average detection efficiency). Segmented design reduces self-veto at high energy.
89 plastic scintillator tiles and 8 ribbons.

Precision Si-strip Tracker:
precise measurement of photon direction, photon ID.
Si strip detectors, W conversion foils; 80 m^2 of Si active area. 1.5 radiation lengths on-axis.

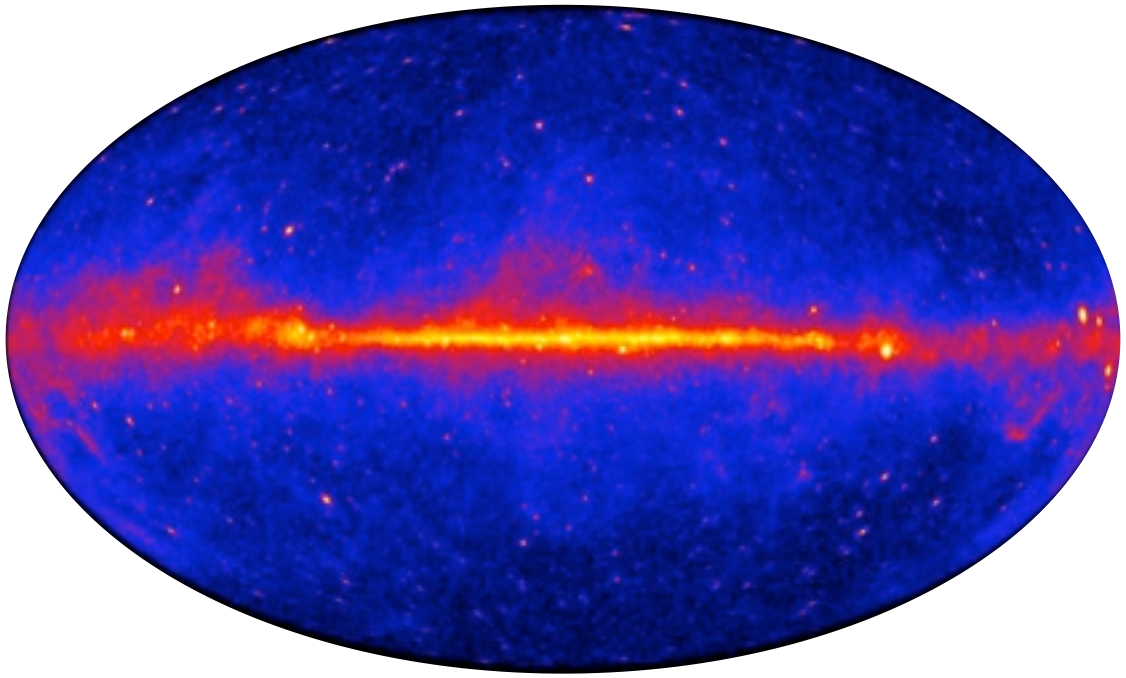
Hodoscopic CsI Calorimeter:
measurement of photon energy, shower imaging.
Array of 1536 CsI(Tl) crystals in 8 layers. 8.6 radiation lengths on-axis.





The Gamma-ray Sky

Fermi-LAT 2 year sky map



Fermi-LAT Likelihood Analysis

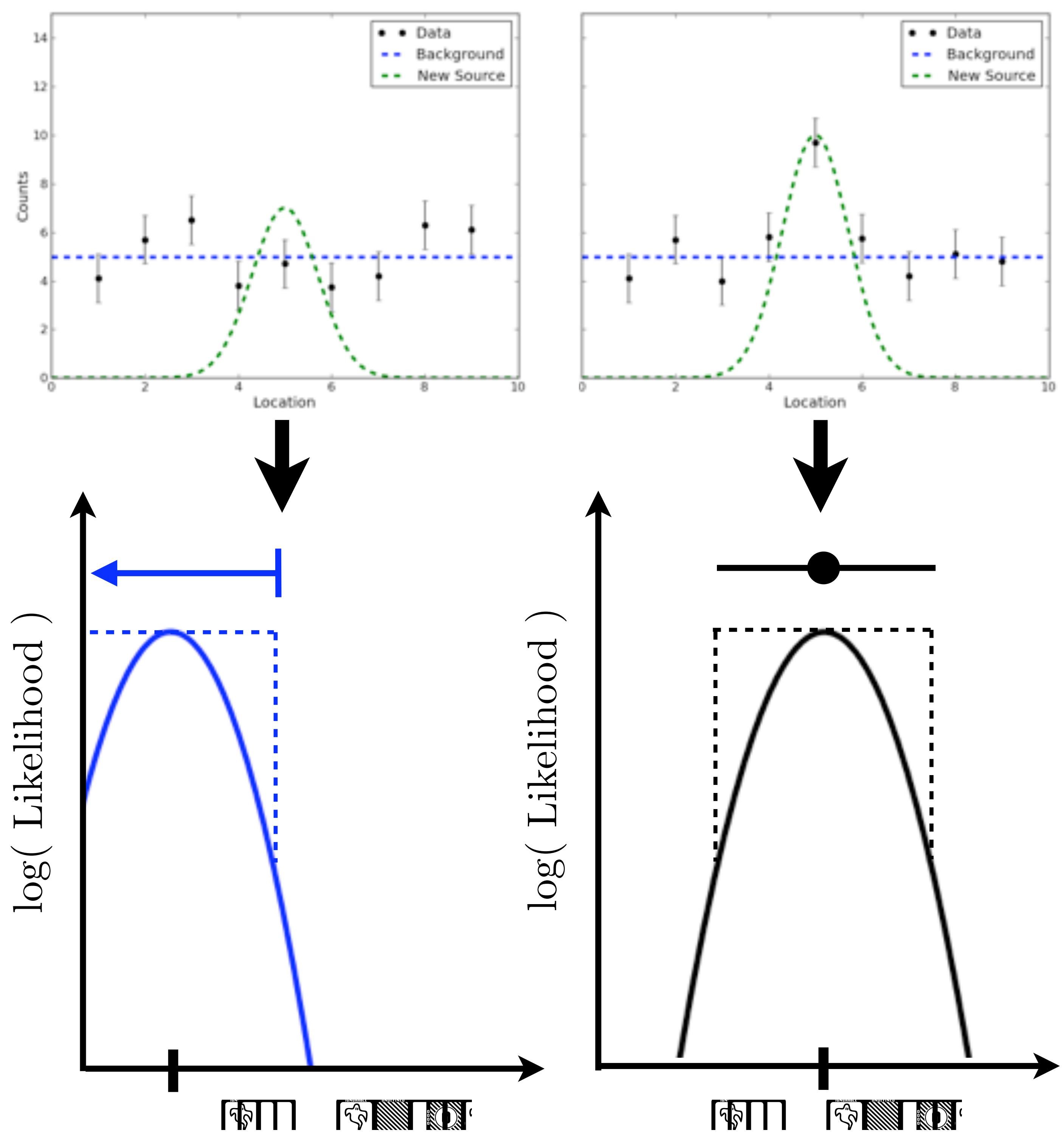
- **We like to ask the question:**
  - **Is there a new source of gamma rays?**
  - **How confident are we that this new source exists/does not exist?**
- **The LAT instrument response changes by orders of magnitude: events are not equal!**
- **Likelihood Analysis:**
  - **Probability of getting the observed data given a model.**

Data → **Likelihood** ← **Model**

$$\mathcal{L} = \prod_i \frac{m_i^{n_i} e^{m_i}}{n_i!}$$

  - **Maximize the value of the likelihood function with respect to free parameters of interest (i.e., flux of new source).**
  - **Assess significance by changing parameter of interest around maximum.**

One-sided Limit | **Two-sided Limit**

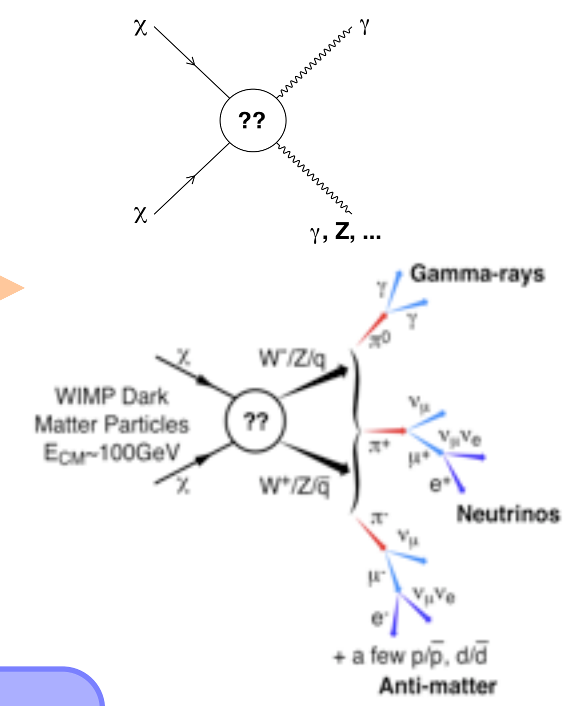


Dark Matter Annihilation

Gamma Ray Flux
(measured by Fermi)

Particle Physics
(photons per annihilation)

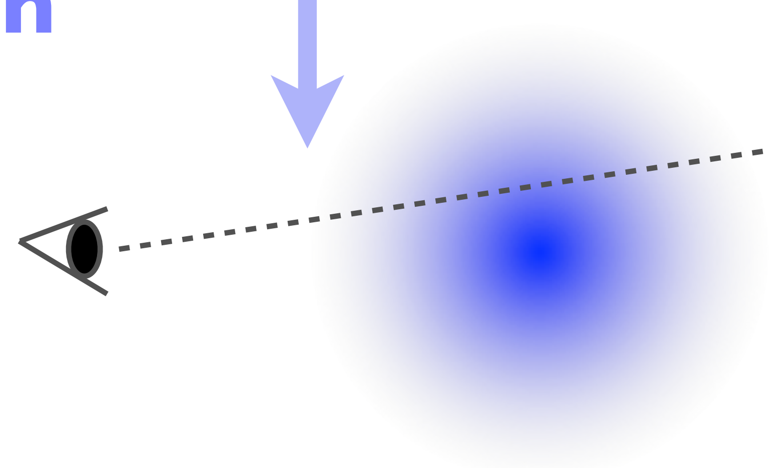
$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f$$



$$\times$$

$$\int_{\Delta\Omega(\phi,\theta)} d\Omega \int_{los} \rho^2(r(l,\phi))dl(r,\phi)$$

DM Distribution
(line of sight integral)

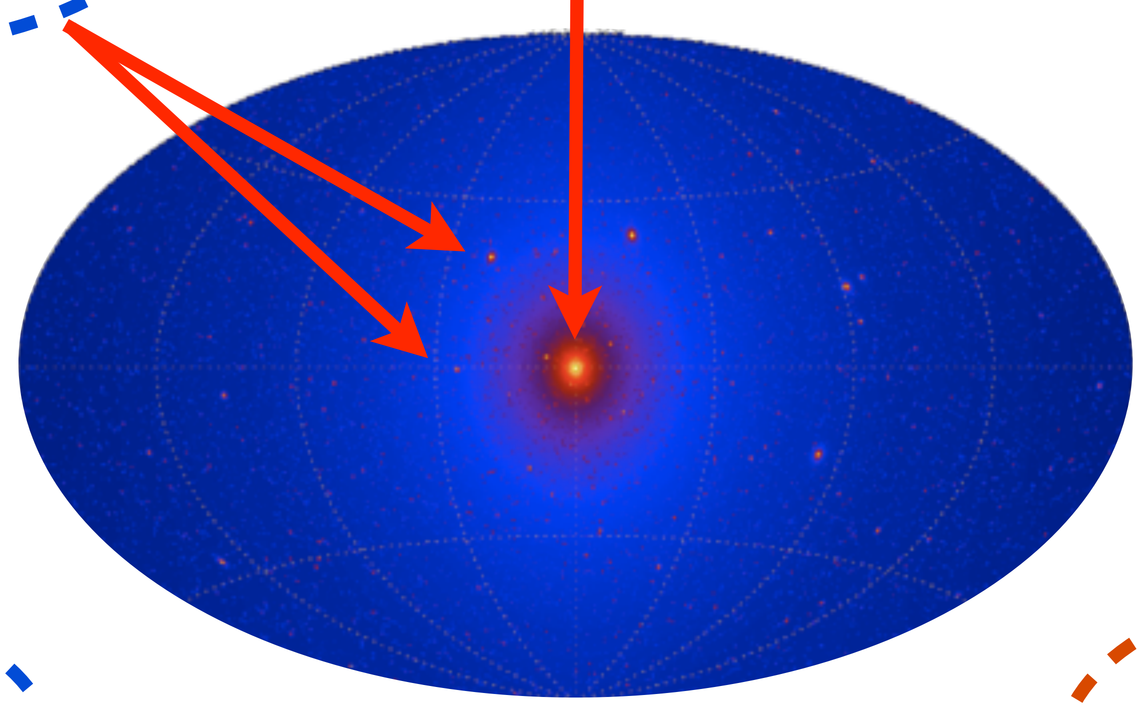


LAT Searches for Dark Matter

Galactic center:
Good statistics but source confusion/diffuse background

Satellites:
Low background and good source ID, but low statistics

Milky Way halo:
Large statistics but diffuse background



Electrons and Positrons!

Spectral lines:
No astrophysical uncertainties, good source ID, but low statistics

Galaxy clusters:
Low background but low statistics

Extragalactic:
Large statistics, but astrophysics, Galactic diffuse background

Pre-launch sensitivities published in Baltz et al., 2008, JCAP 0807:013 [astro-ph/0806.2911]

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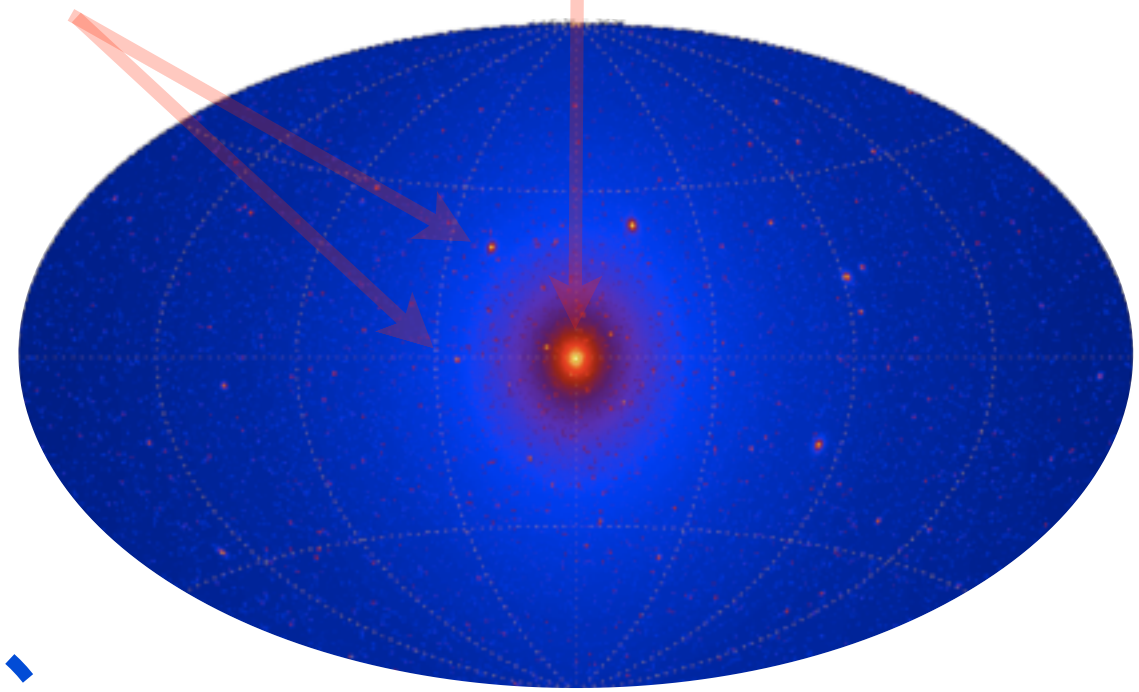

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Y. Edmonds, E. Bloom et al.

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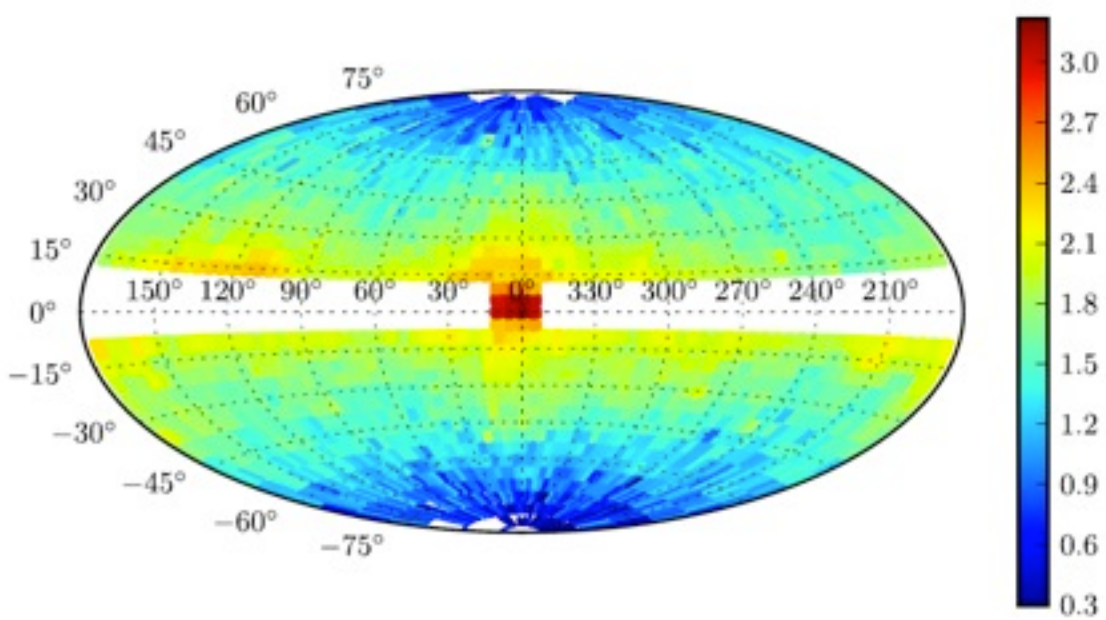
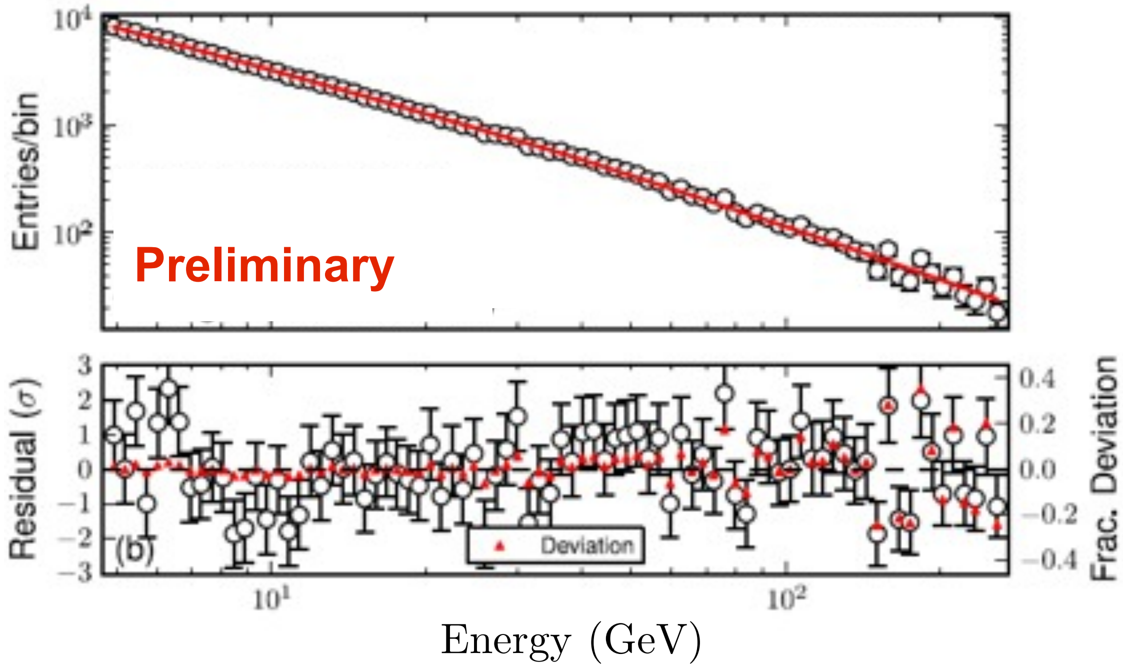
Spectral Lines

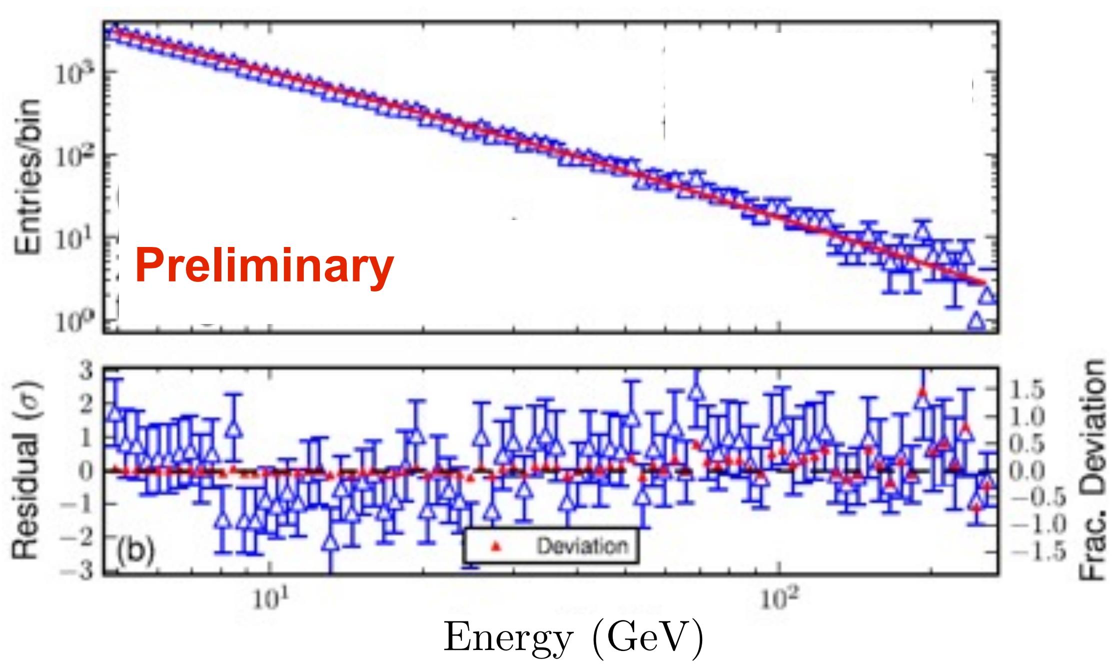
- **WIMP annihilation into mono-energetic photons is the "smoking gun" signal.**
- **Analyze 2 years of data from high galactic latitude and the galactic center (increased statistics).**
- **Inclusive photon spectrum from 4.8 - 264 GeV (remove photons from point sources).**



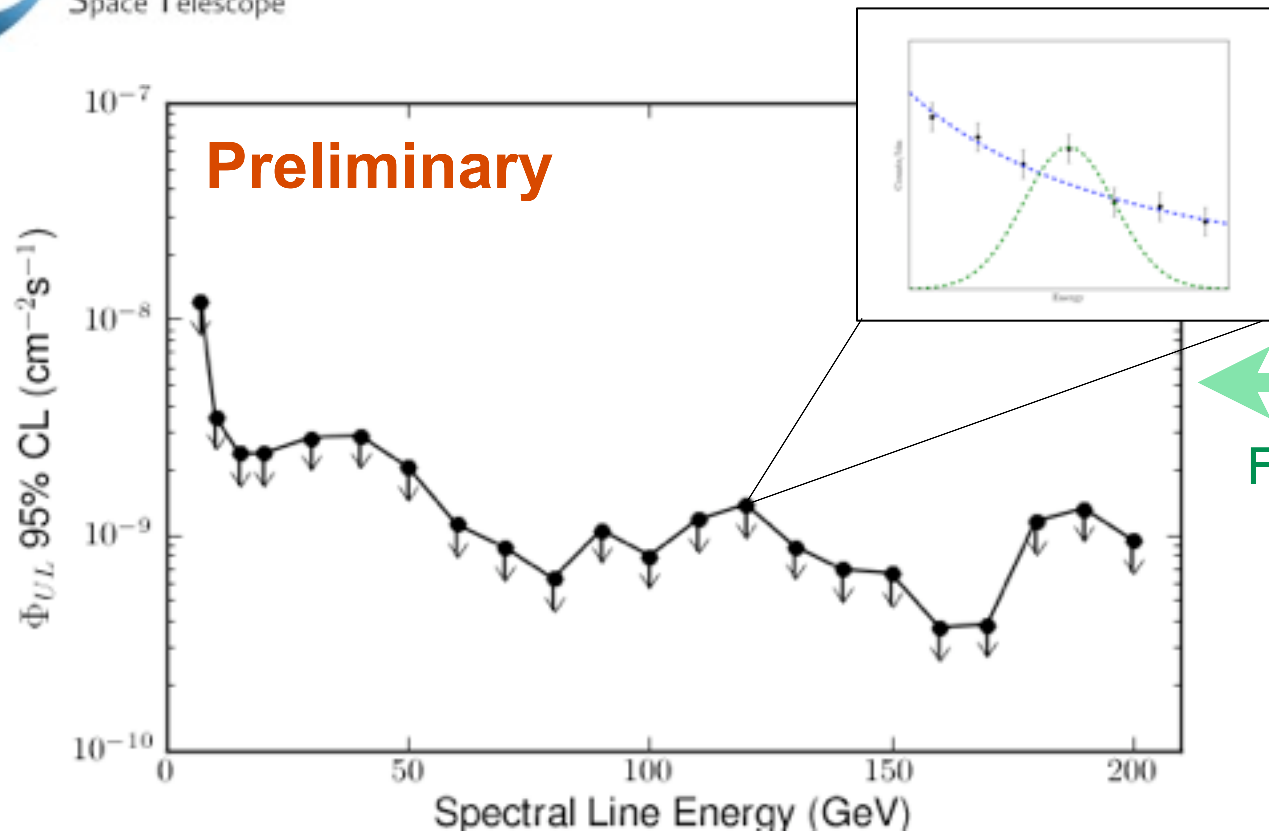
Inclusive Photon Set

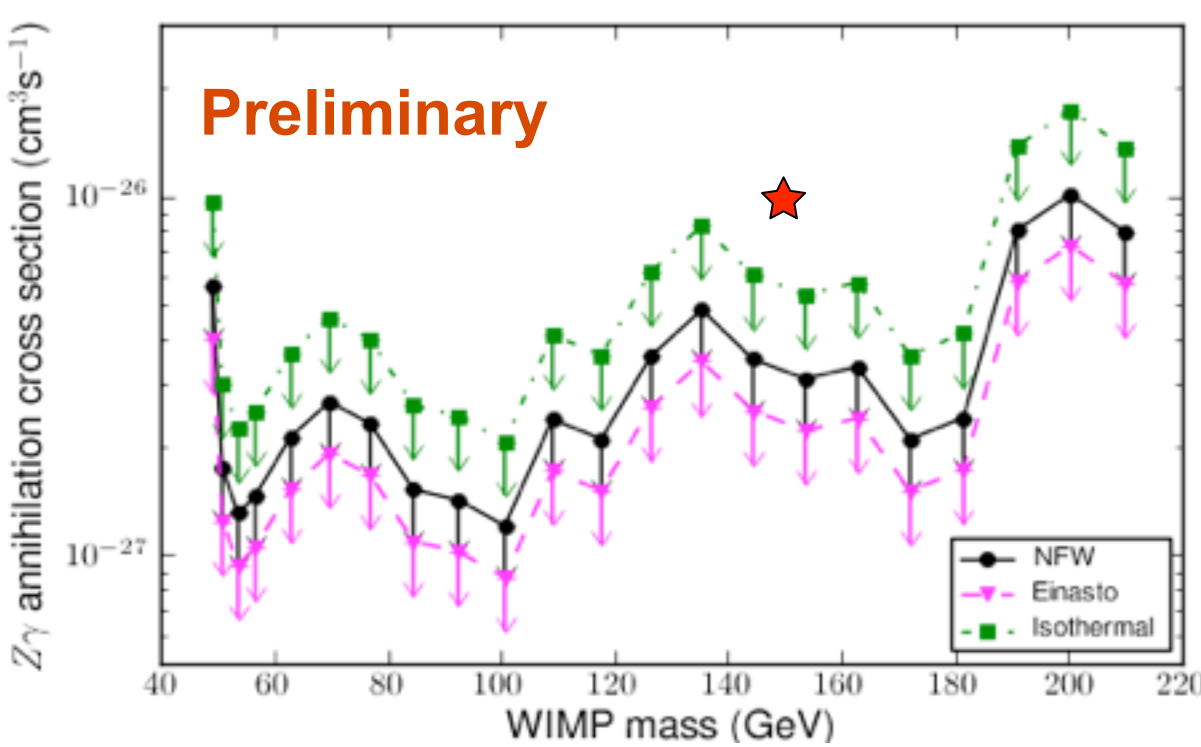


Earth Limb Photon Set



Spectral Lines





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

Flux Limits

Annihilation Channel and Yield

Dark Matter Distribution

- **Flux limits depend only on the data and the instrumental resolution.**
- **Cross section limits require choice of annihilation channel and dark matter distribution**
- **Rule out some models proposed to explain positron excess (Acharya, Kane, et al., 2011)**

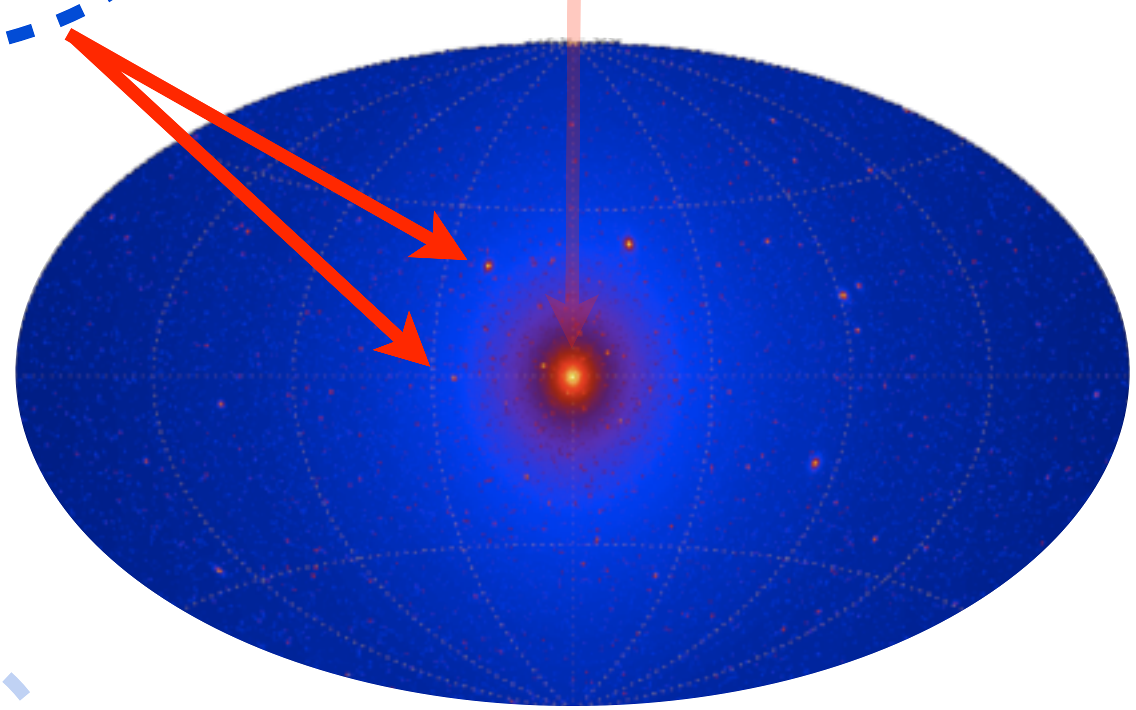
Satellite Galaxies

Satellites:
Low background and good source ID, but low statistics

M. Llena Garde, et al.

Galactic center:
Good statistics but source confusion/diffuse background

Milky Way halo:
Large statistics but diffuse background



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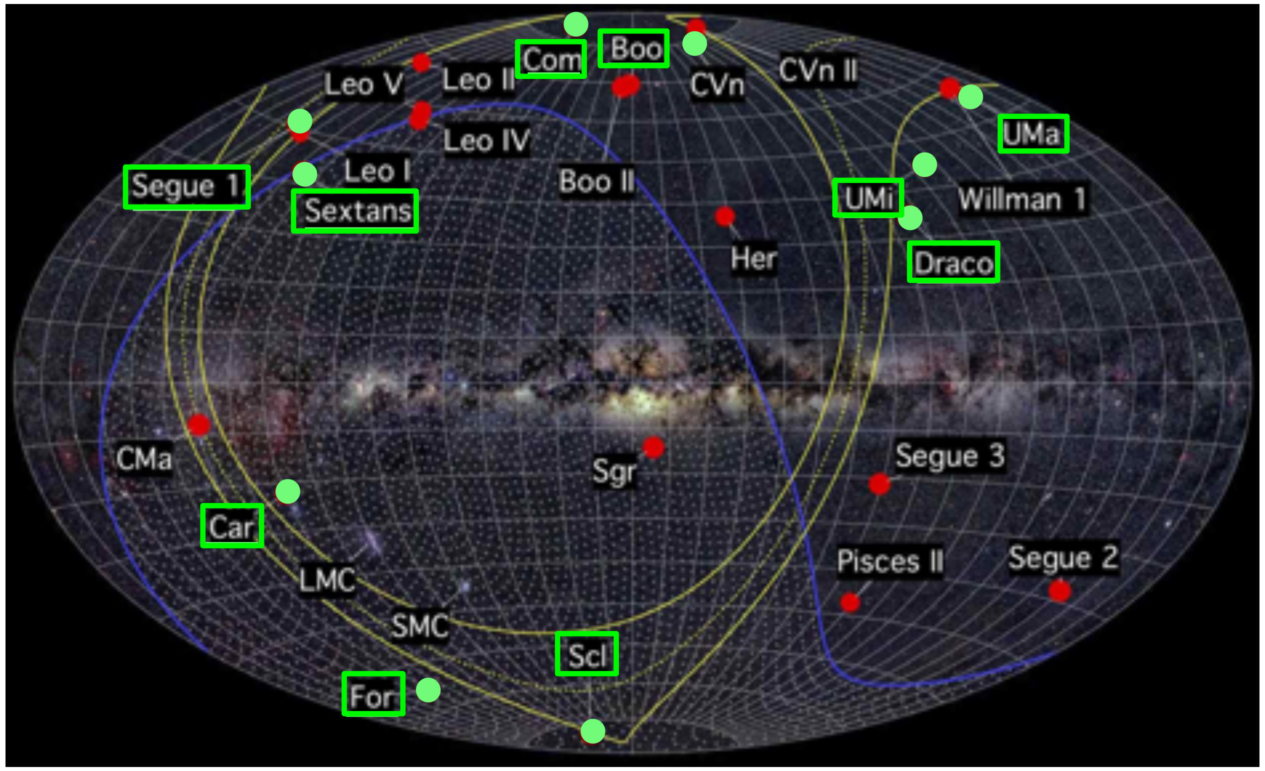
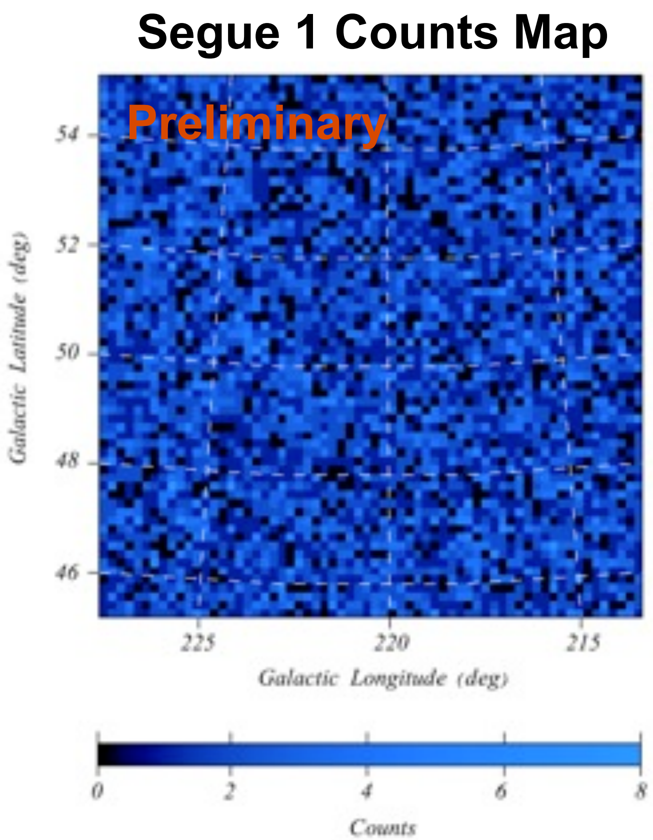
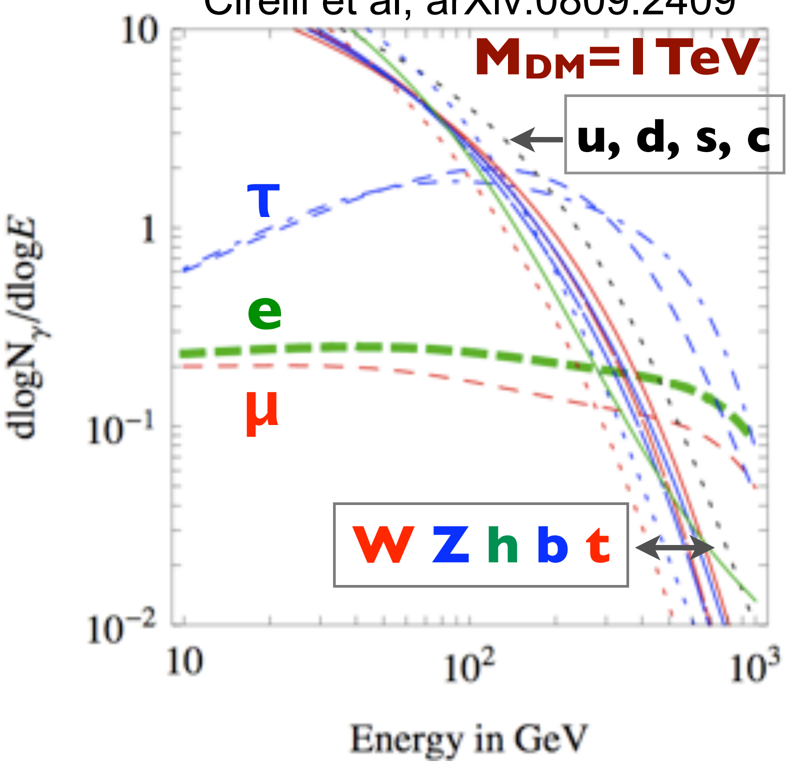




- Satellite galaxies of the Milky Way are hosted in large dark matter clumps.
- Not expected to produce gamma-rays through astrophysical processes
- No significant detections of gamma-ray sources at these locations.
- Likelihood analysis dependent on spectral shape

Cirelli et al, arXiv:0809.2409



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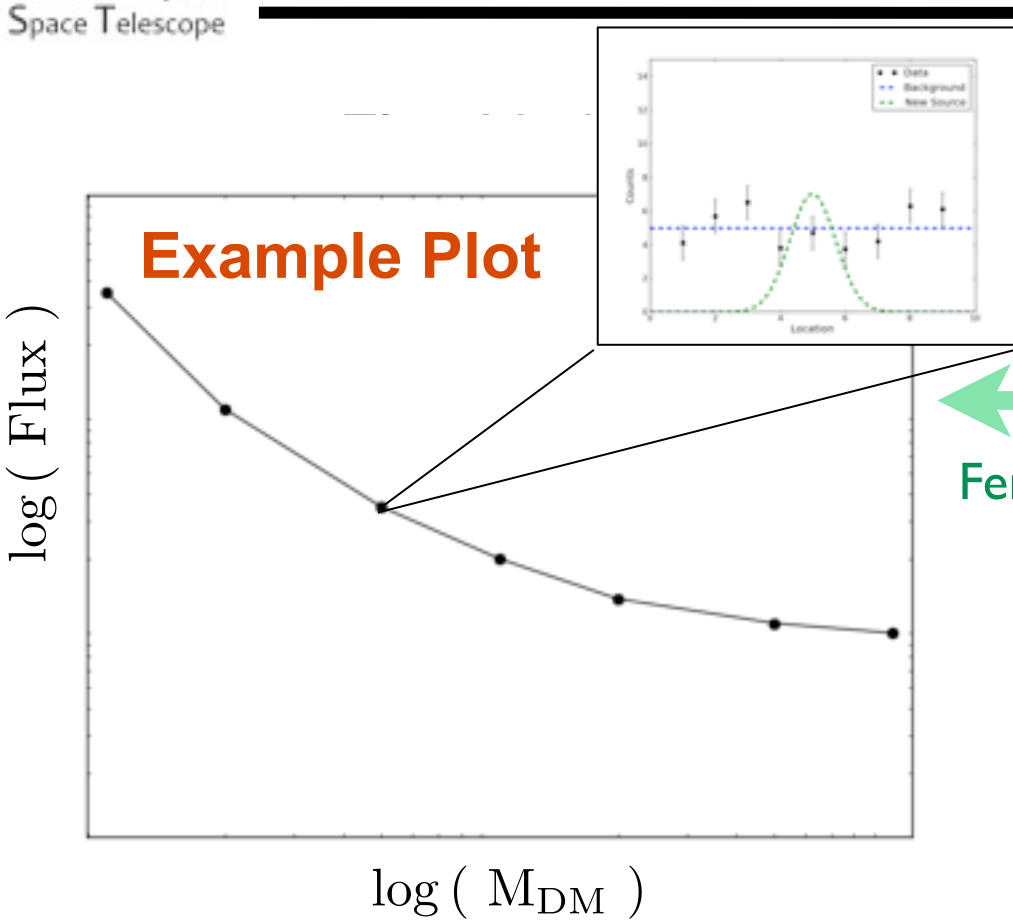
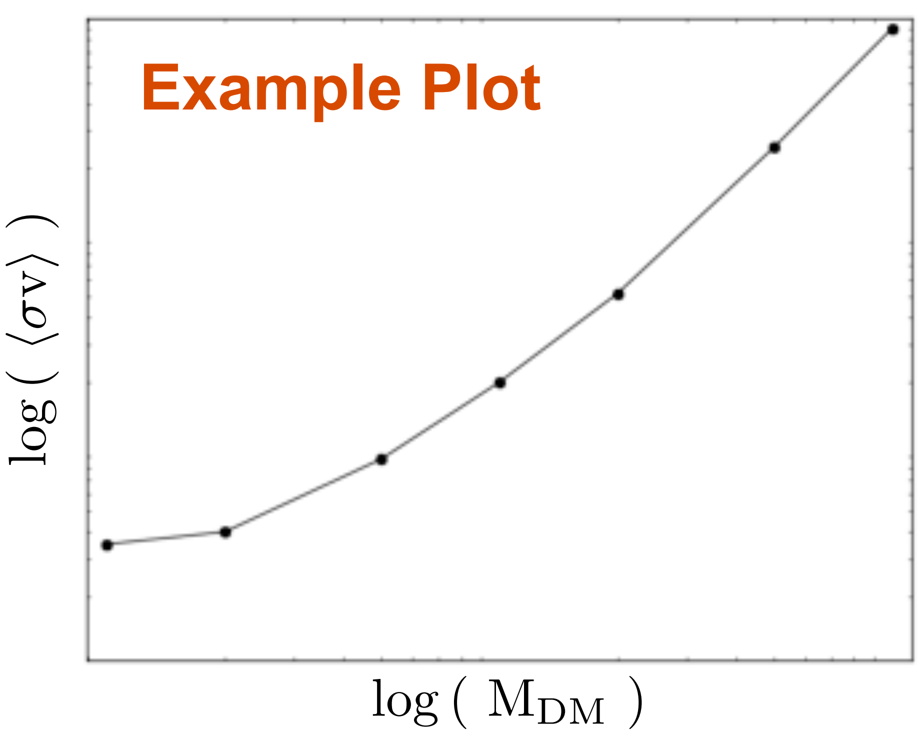




Dark Matter Spectrum

Fermi Data

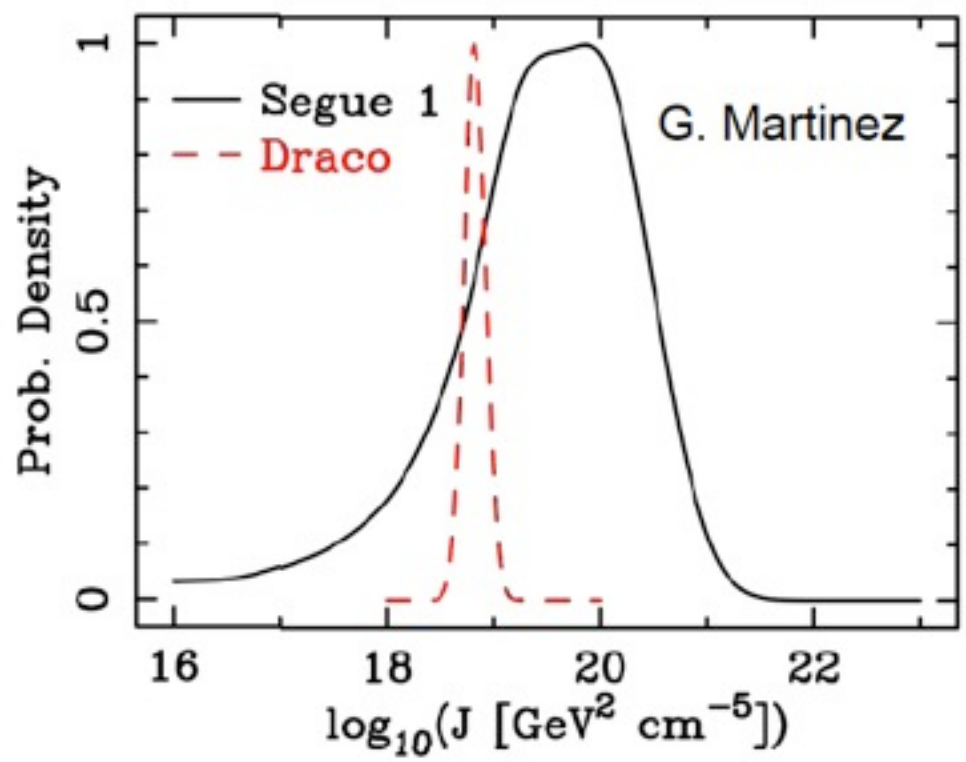
$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f \times \int_{\Delta\Omega(\phi,\theta)} d\Omega \int_{los} \rho^2(r(l,\phi))dl(r,\phi)$$

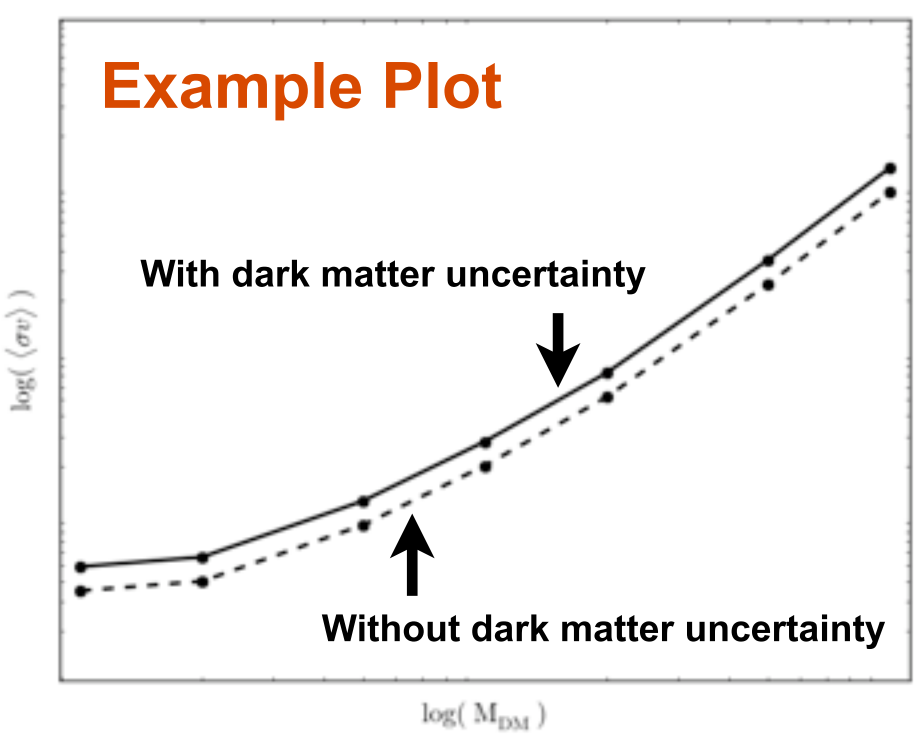
Factor of Mass^2

Dark Matter Distribution

- **Flux limits are highest for low mass models (more background at low energy).**
- **However, factor of mass^2 dominates when calculating the velocity-averaged cross section.**
- **Normalization will depend on the dark matter distribution.**

Satellite Galaxies





- The dark matter content of satellites come from the analysis of stellar dynamics.
- The dark matter content for each dwarf galaxy is uncertain.
- Some satellites with large dark matter content also have the large uncertainties
- Treat this uncertainty as a nuisance parameter in the likelihood
- Raises the upper limits on cross section

Satellite Galaxies

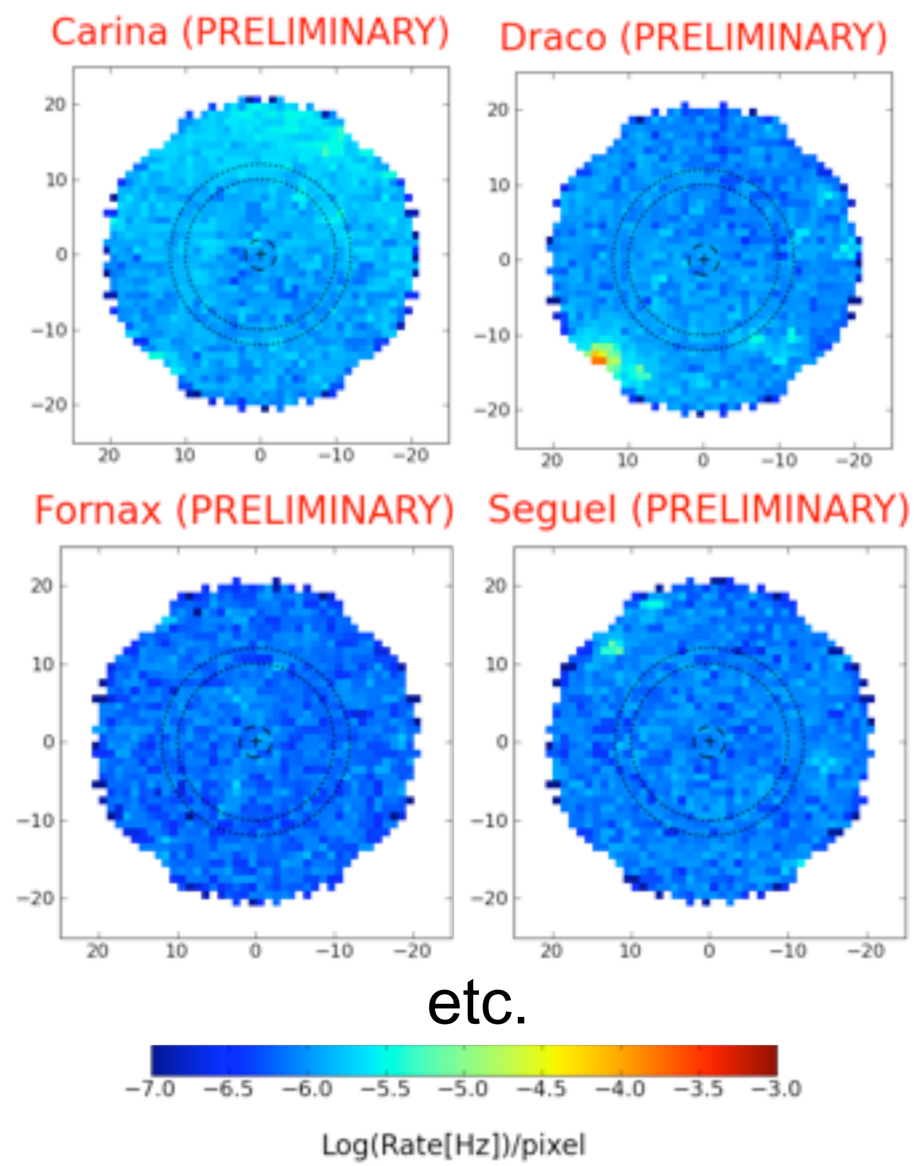
- **Combine results from multiple satellite galaxies:**
  - **Dark matter particle characteristics are shared across the satellites.**
  - **Background models and dark matter distributions are different for each satellite.**

- **Create a combined likelihood:**

$$\mathcal{L}(\langle\sigma v\rangle, m_{\rm WIMP}; \vec{\Theta}) = \prod_{i=1}^{N} \mathcal{L}_i(\langle\sigma v\rangle, m_{\rm WIMP}, b_i; \vec{\Theta}_i)$$

Same for all satellites

Fit for each satellite



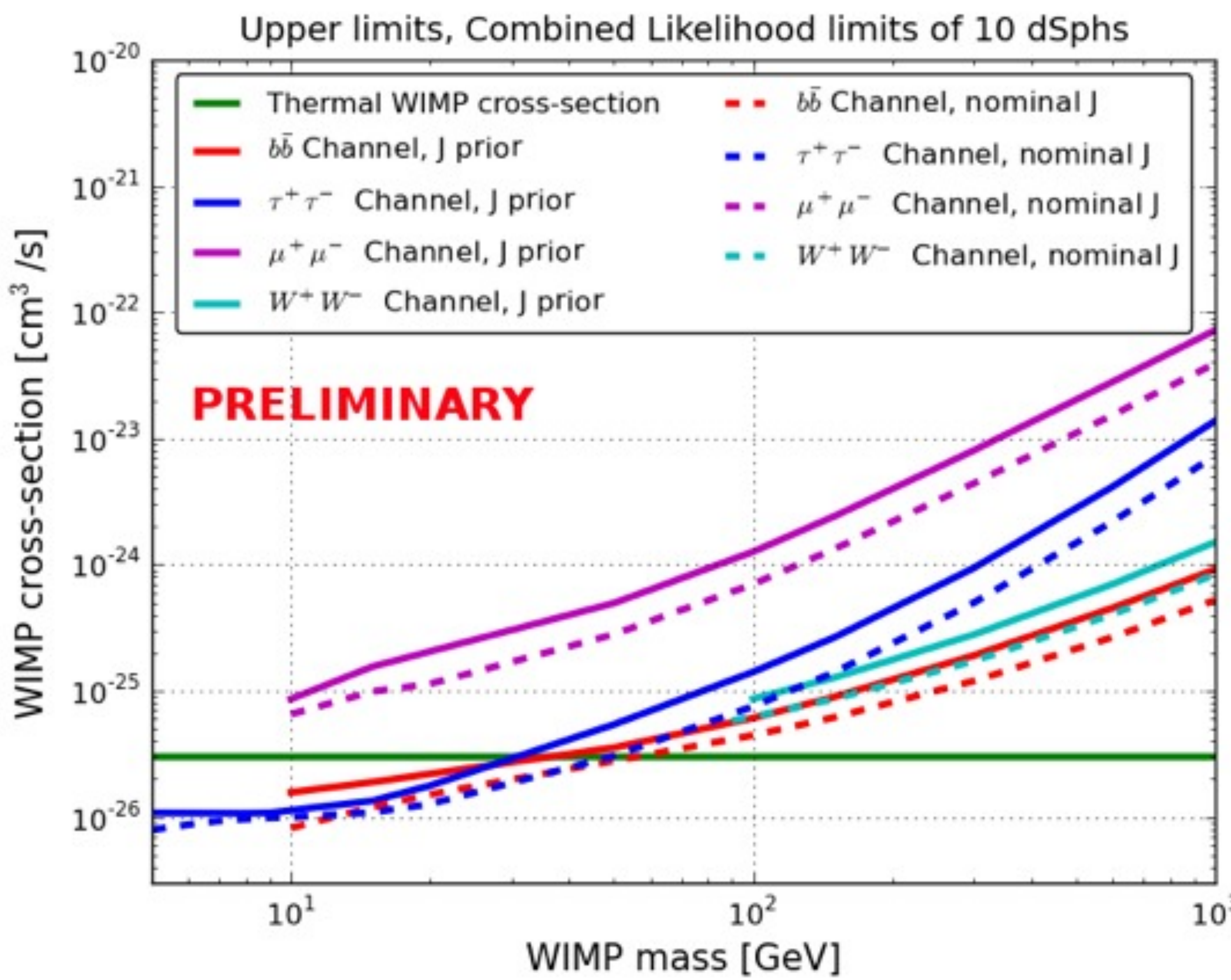
- **Akin to combining data from various time periods (thus, increasing the observing time)**

Satellite Galaxies

- **Put everything together with 10 satellites, 2 years of data, and testing 4 annihilation channels:**

$$b\bar{b} \quad \mu^+\mu^- \quad \tau^+\tau^- \quad W^+W^-$$

- **Begin to cut into the conventional cross section for a thermal WIMP.**
- **Very interesting in the low-mass regime (i.e., CoGeNT results)**
- **Potential for improvement:**
  - **More integration time**
  - **Improved instrument performance**
  - **More satellites.**



Extragalactic Background

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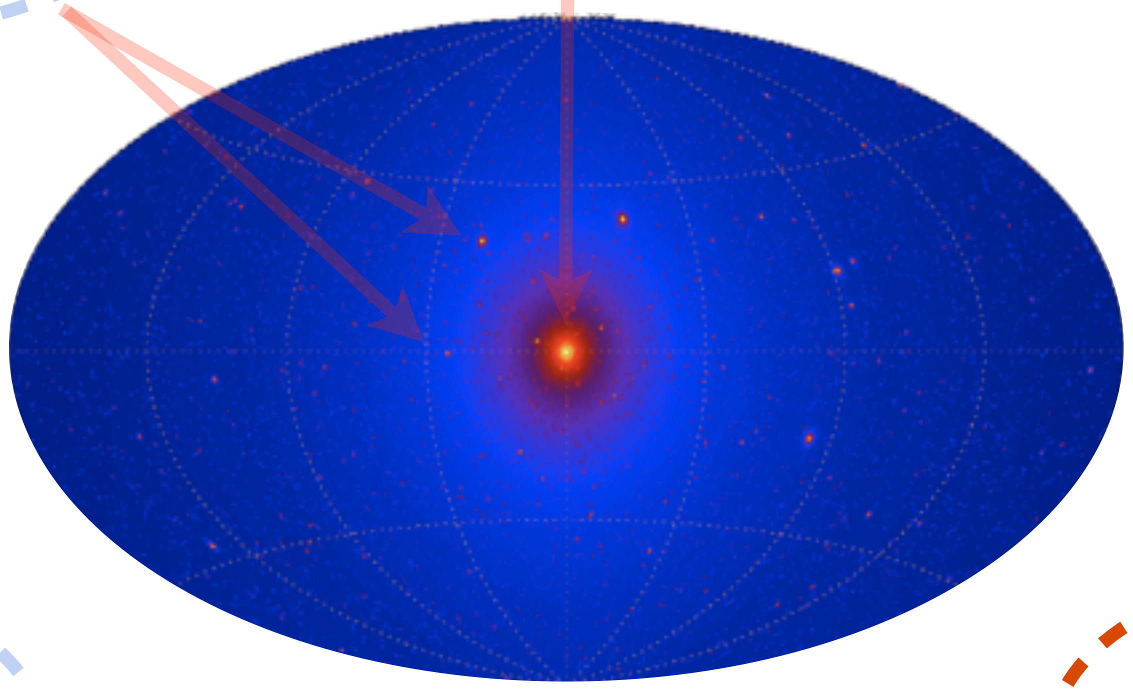

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M. Ajello, K. Bechtol, et al.

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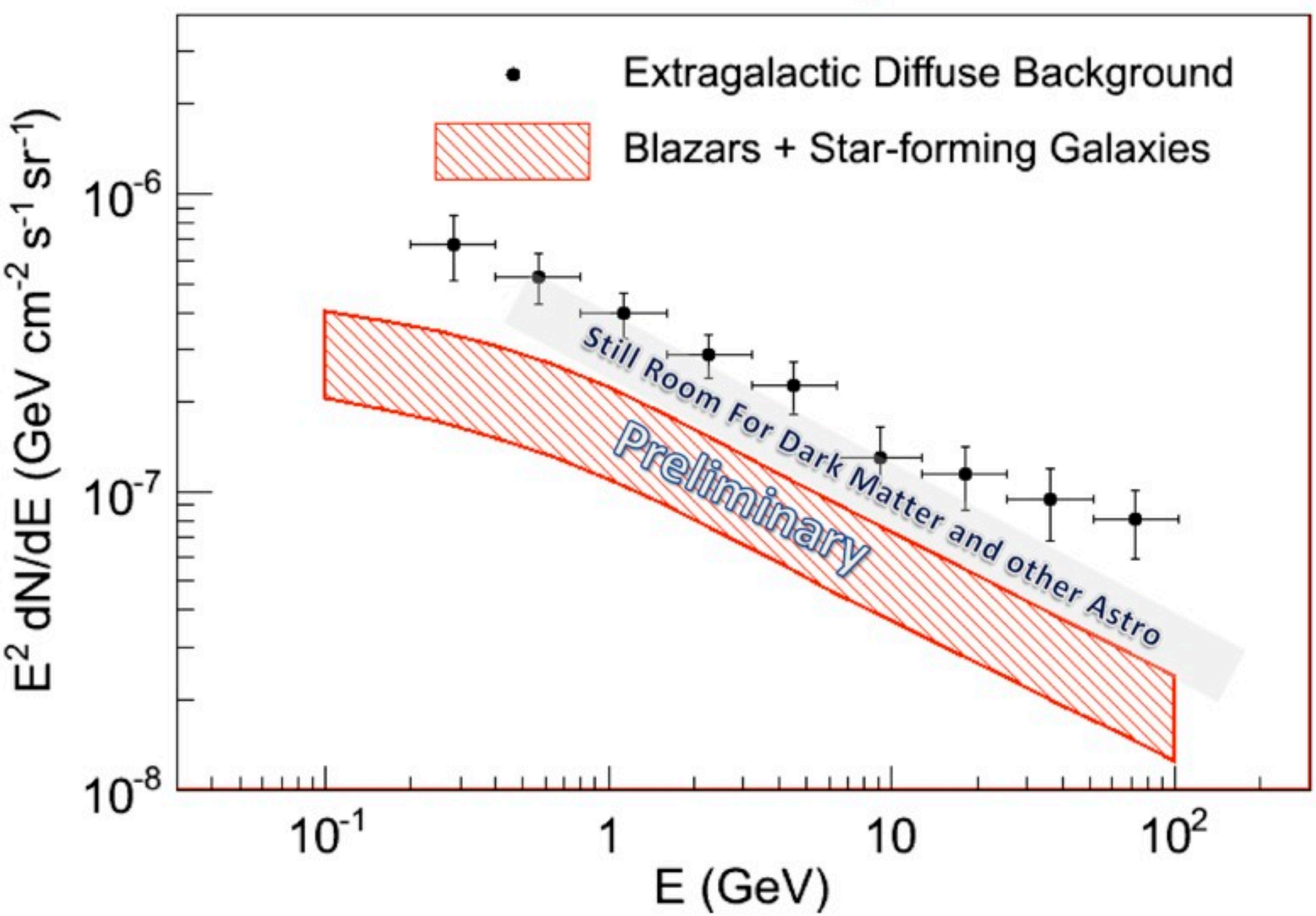

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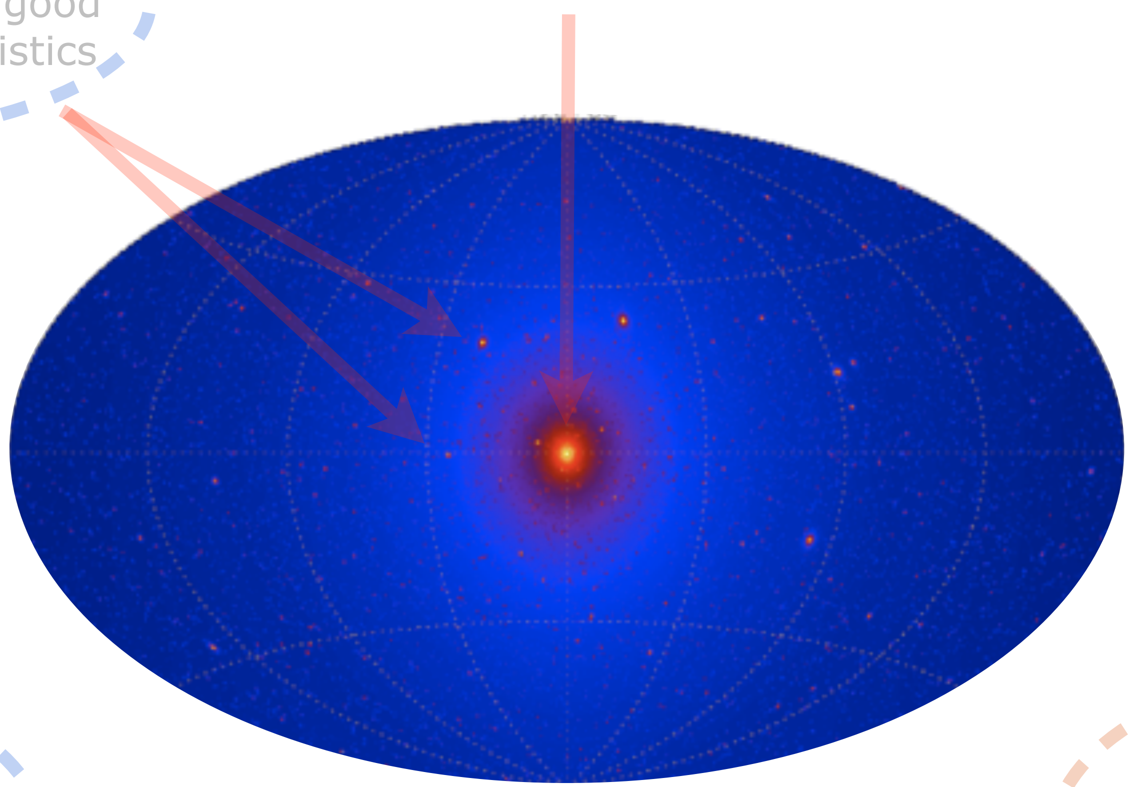

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W. Mitthumsiri, C. Sgro, et al.

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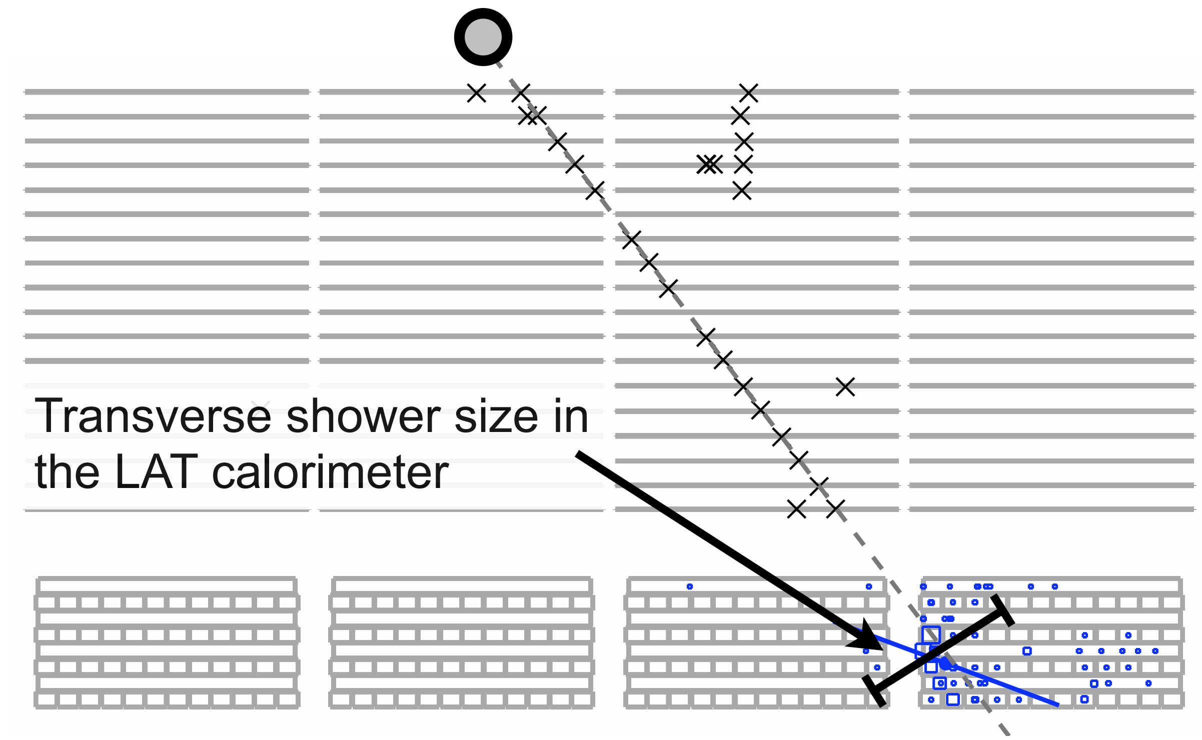
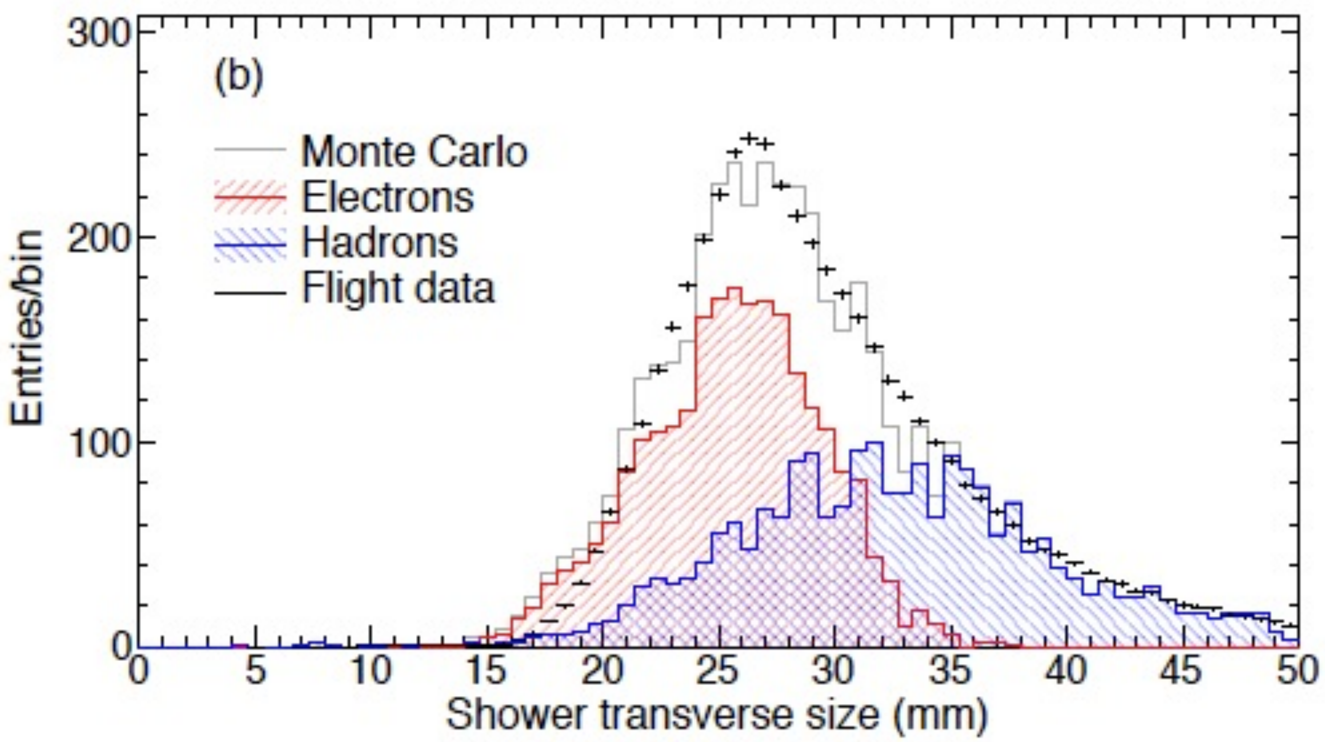
Electrons and Positrons

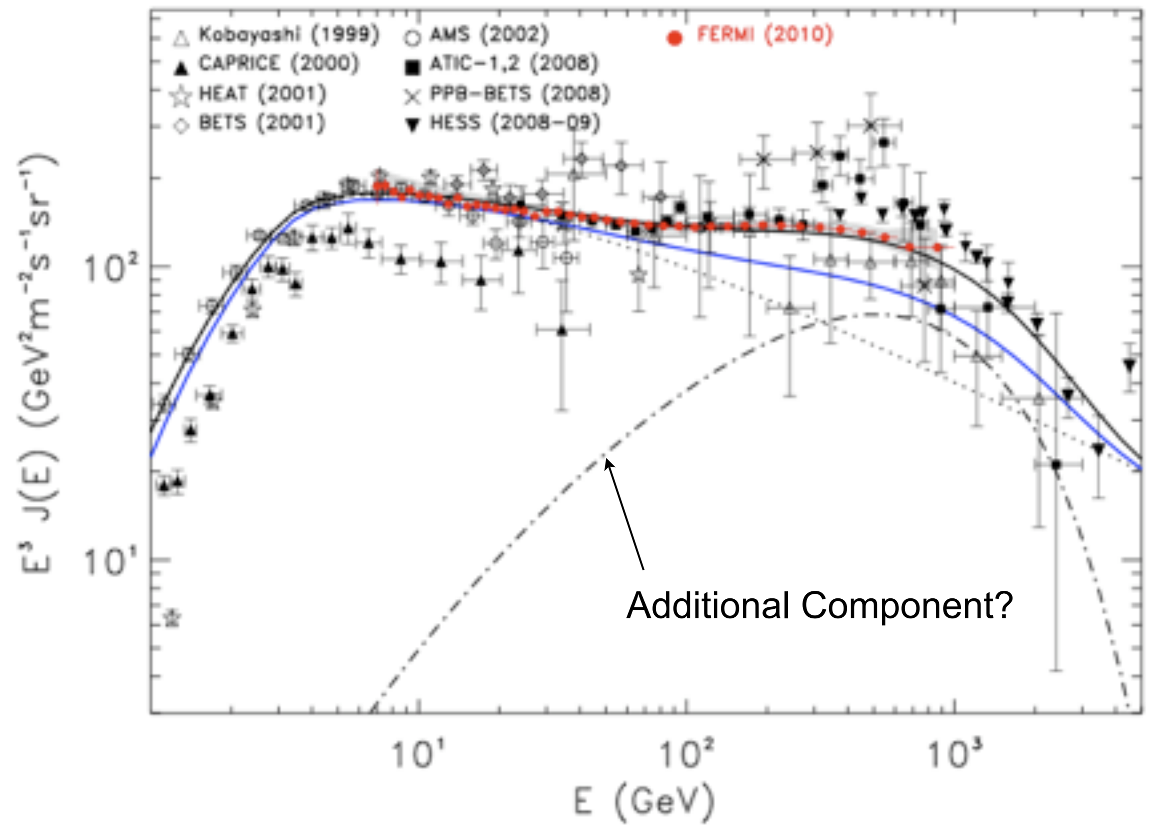
- **Recent measurements from other experiments (i.e., PAMELA) have shown an unexpected excess of high energy electrons and positrons.**
- **It is difficult for these particles to travel large distance (due to energy loss).**
- **While most LAT analyses are interested in gamma-ray events, the LAT is first and foremost an instrument for measuring electromagnetic showers.**
  - **Reverse the charged particle cut to remove photons**
  - **Analyze shower characteristics to distinguish electromagnetic showers from hadronic showers**

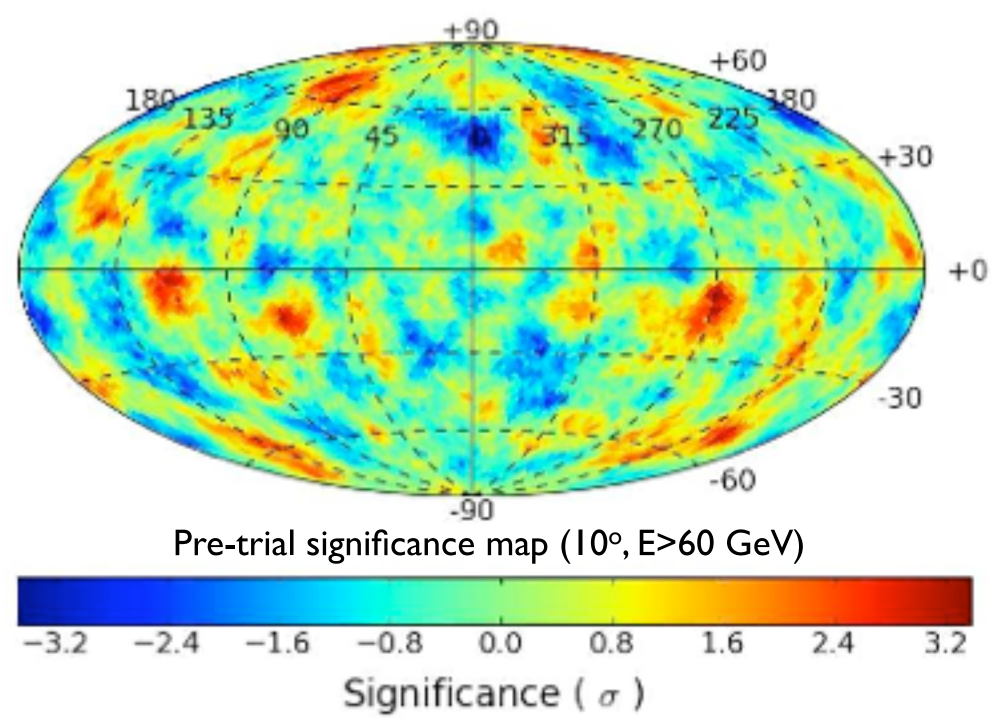




Electrons and Positrons

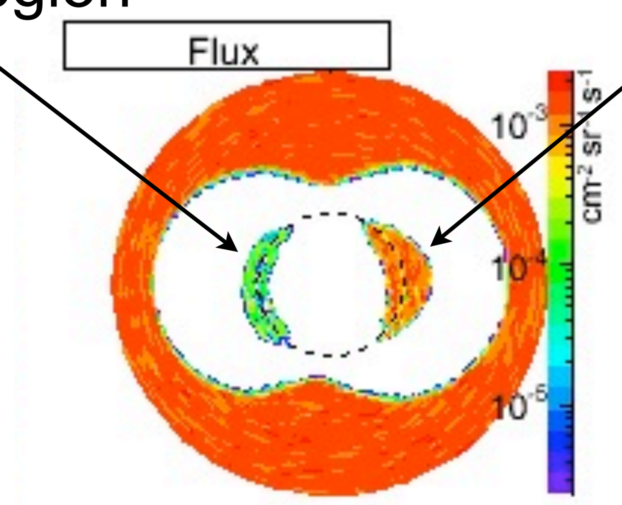
- Measure the cosmic-ray e⁻ + e⁺ spectrum from 7 GeV to 2 TeV
- Significant excess over predictions at higher energies (100s of GeV)
- Local source of electrons and positrons:
  - Pulsars?
  - Dark matter annihilation?
- No significant anisotropy found for e⁻ + e⁺ (which might have been expected from a local source)

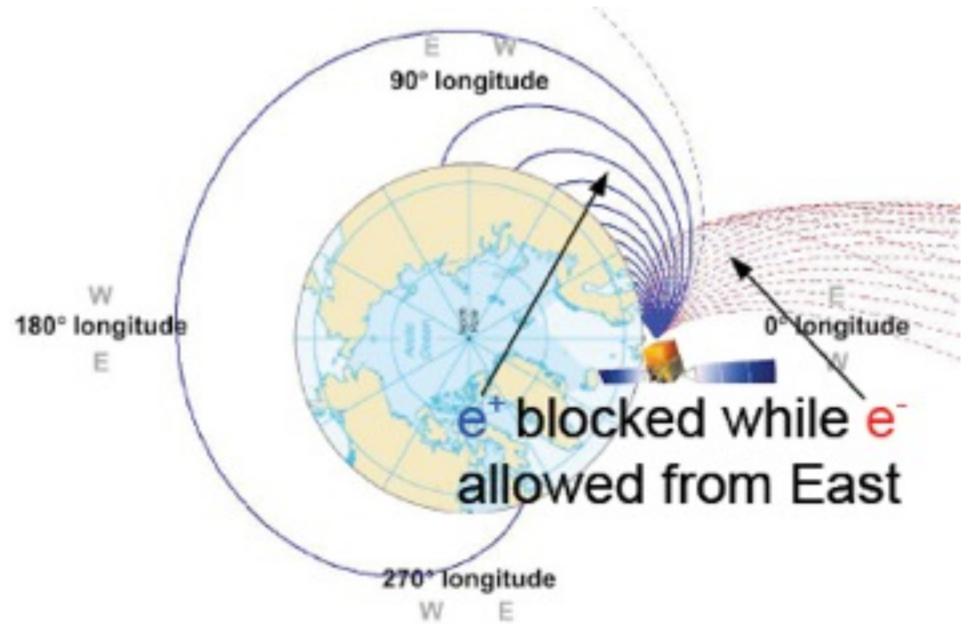


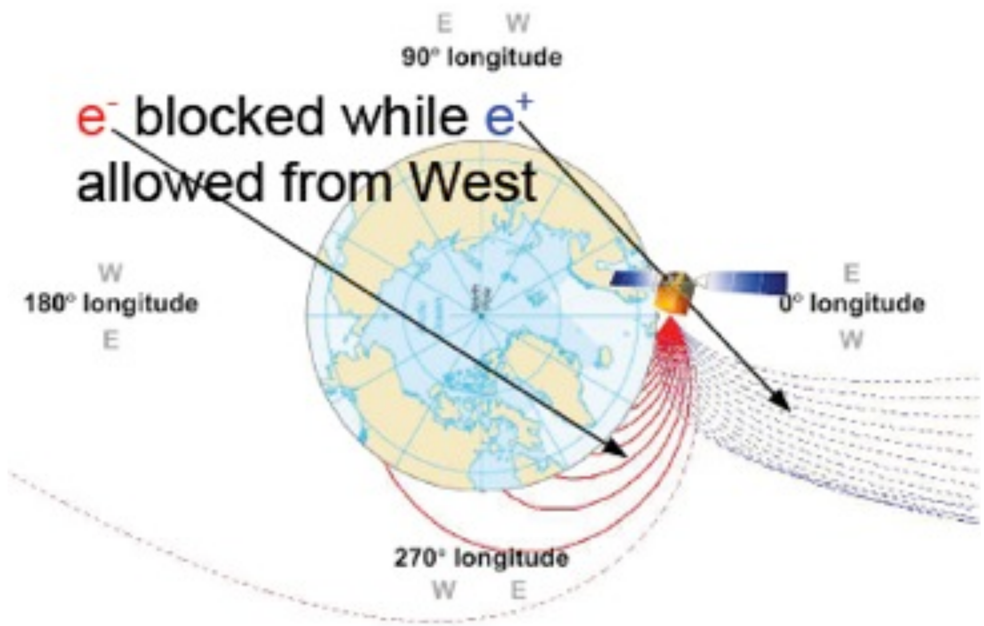


Positron Fraction

- **The LAT cannot distinguish the charge of an incoming event (no magnet).**
- **Earth's magnetic field provides an exciting opportunity...**
  - **Windows near the limb of the Earth where electrons/positrons are excluded**
  - **Windows are energy dependent**
- **Low statistics in high energy positron windows; important to understand proton contamination**

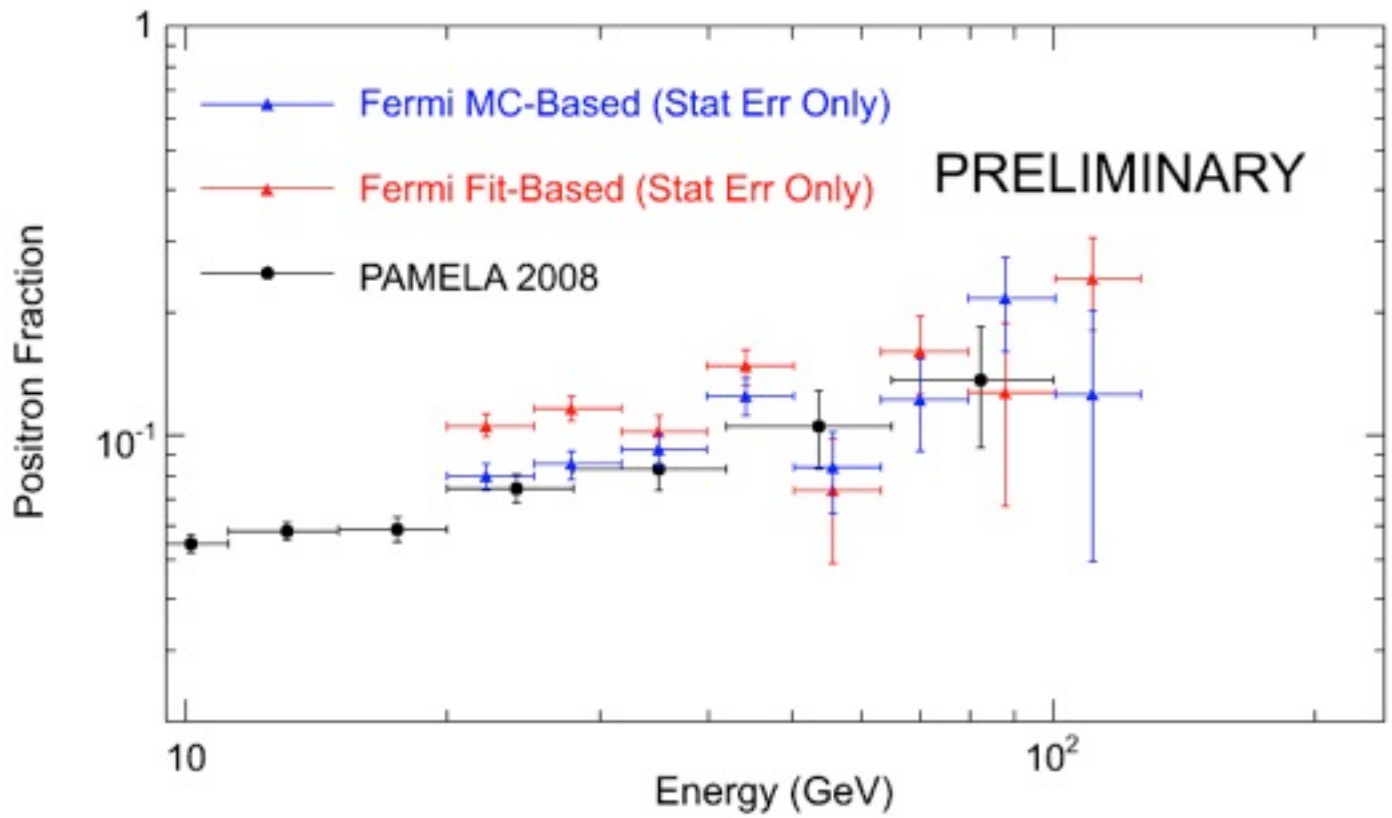






Positron Fraction

- **Two independent LAT analyses are in good agreement with each other and with PAMELA.**
- **Positron fraction, $e^+/(e^- + e^+)$, appears to rise with energy.**
- **Again, this could suggest a local source of leptons.**
- **New results should be coming soon from AMS-02...**



Conclusions

- There are many more searches that I have not discussed:
  - Cosmological WIMP Annhilation
  - Clusters of Galaxies
  - Galactic Center and Halo
  - and others ...
- So far, no LAT search has turned up a conclusive signal.
- Many interesting mysteries have developed:
  - Extragalactic background
  - Increasing positron fraction
  - and others ...
- The next 10 years will be a crucible for WIMP dark matter.

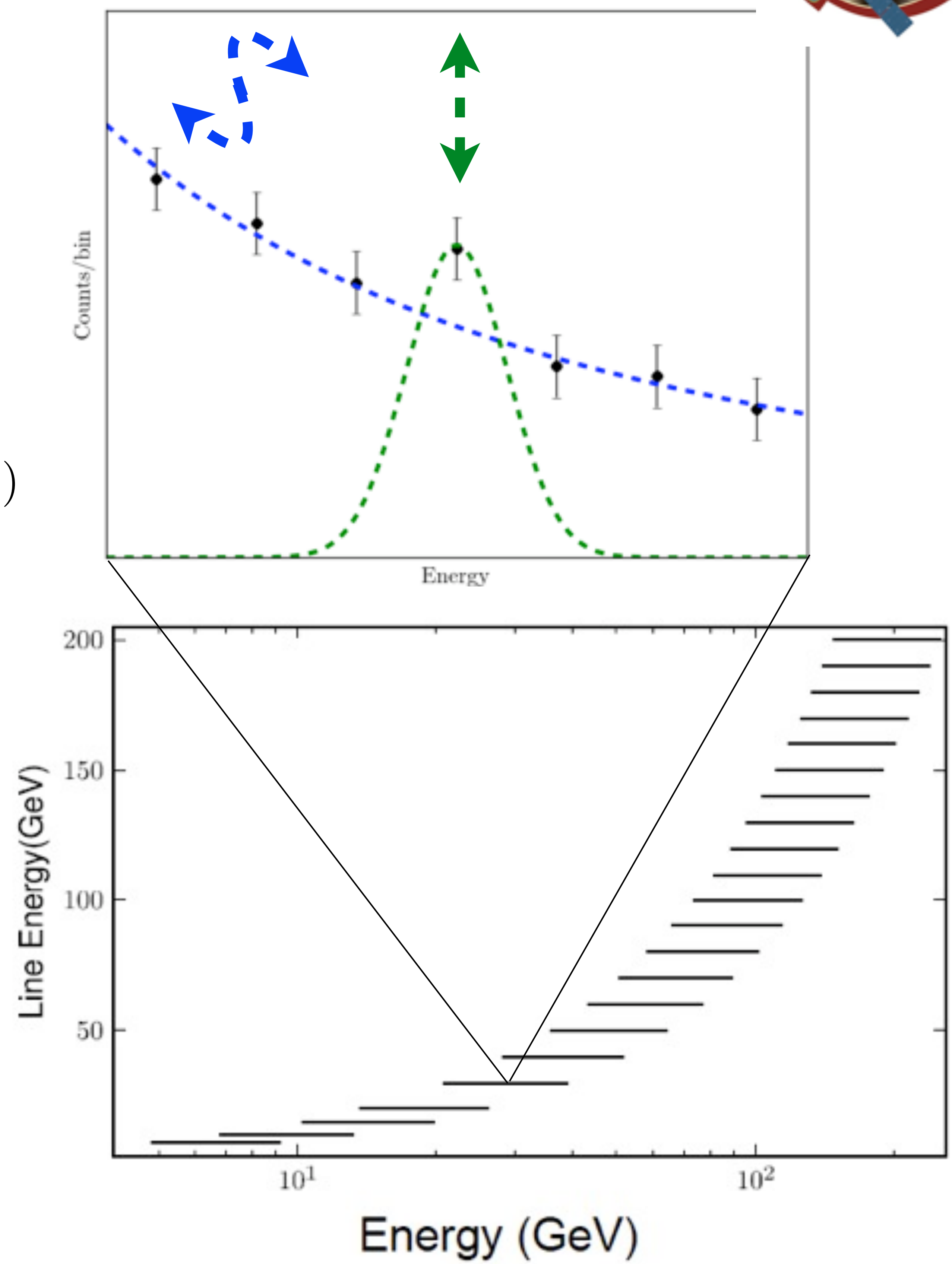
Extra Slides

Spectral Lines

- **Set upper limits on photon lines between 7 - 200 GeV using profile likelihood technique.**
- **Perform an unbinned composite likelihood fit in each bin:**

$$\mathcal{L}_j(f_j, \Gamma_j) = \prod_{i=1}^{N_j} f_j S_i(E_i) + (1 - f_j) B(E_i, \Gamma_j)$$

- **Line energy fixed at bin center**
- **Two free parameters:**
  - **Spectral index of the background**
  - **Normalization of the line signal**



Positron Fraction

Fit-Based Approach

Monte-Carlo-Based Approach