Using the Fermi-LAT to Search for Indirect Signals from Dark Matter Annihilation

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Representing the Fermi-LAT Collaboration

with acknowledgements to:
Brandon Anderson, Elliott Bloom, Alessandro Cuoco, Jennifer Siegal-Gaskins, Gabrijela Zaharijas, and others whose work/slides compose the majority of this talk

Dark Matter Signatures in the Gamma-Ray Sky -- May 7, 2012

Background

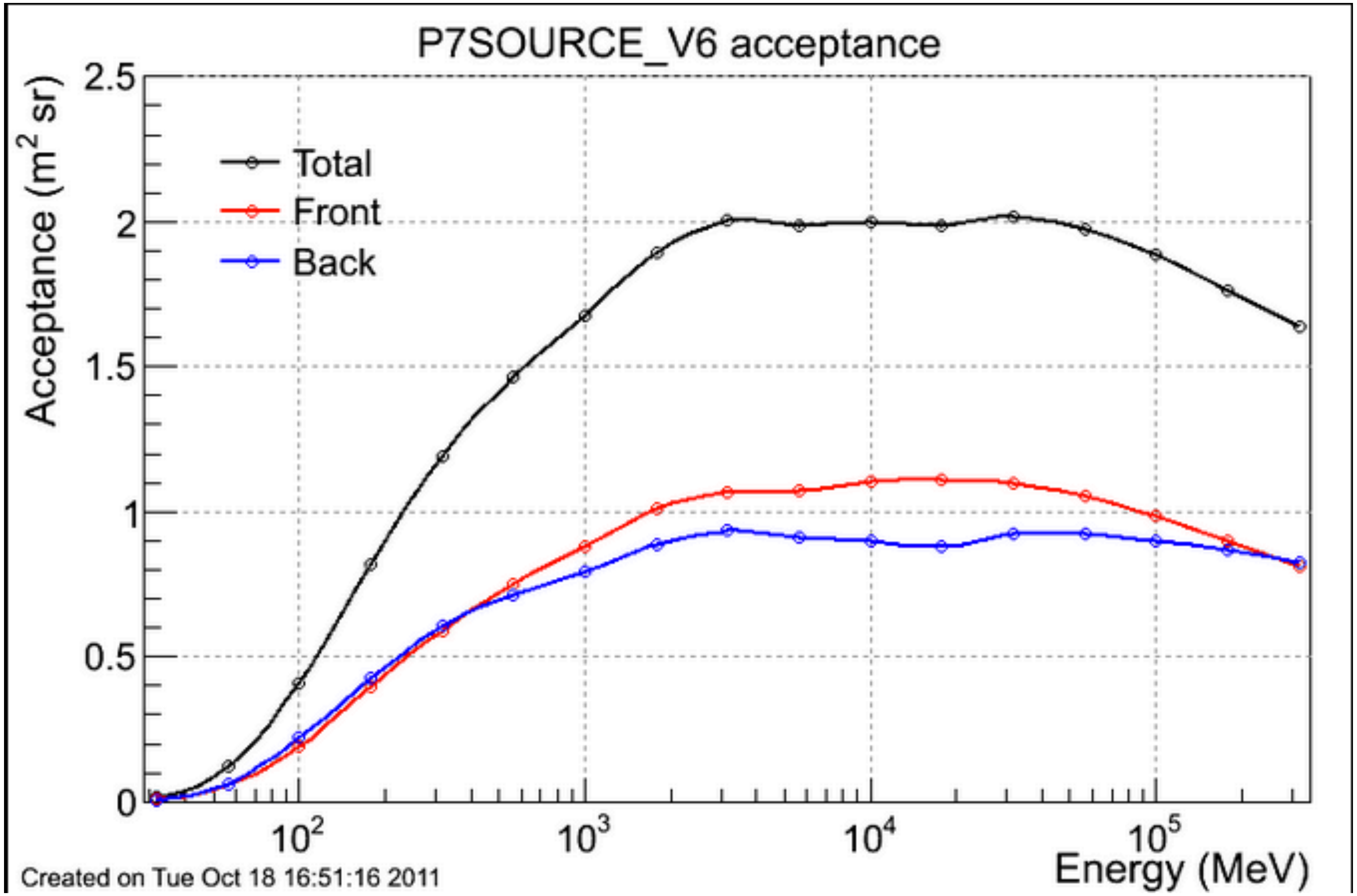
- 1.) The Fermi-LAT Telescope as a black box
- 2.) Techniques for the detection of dark matter
- 3.) Analysis of the Milky Way Halo
- 4.) Gamma-Ray Line Search
- 5.) Gamma Rays from Clusters

Observational Capabilities of the Fermi-LAT

- Energy Range: 20 MeV - 300 GeV (statistics limited)
- Effective Area: ~8000 cm^2
- Field Of View: 2.4 sr

- Angular Resolution: Highly Energy Dependent
  - 3.5° at 100 MeV (68% radius)
  - 0.15° at 10 GeV (68% radius)
- Energy Resolution: ~10%

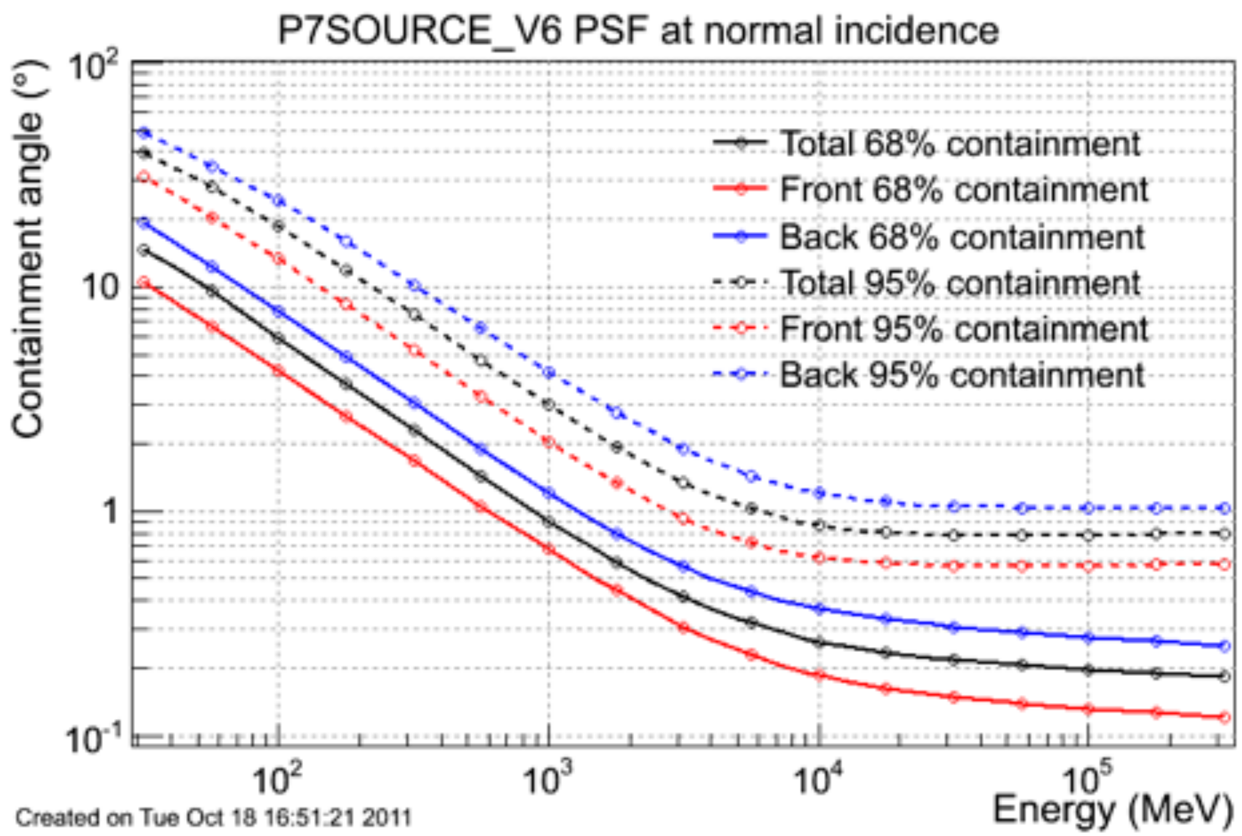
Acceptance of the Fermi-LAT vs. Energy



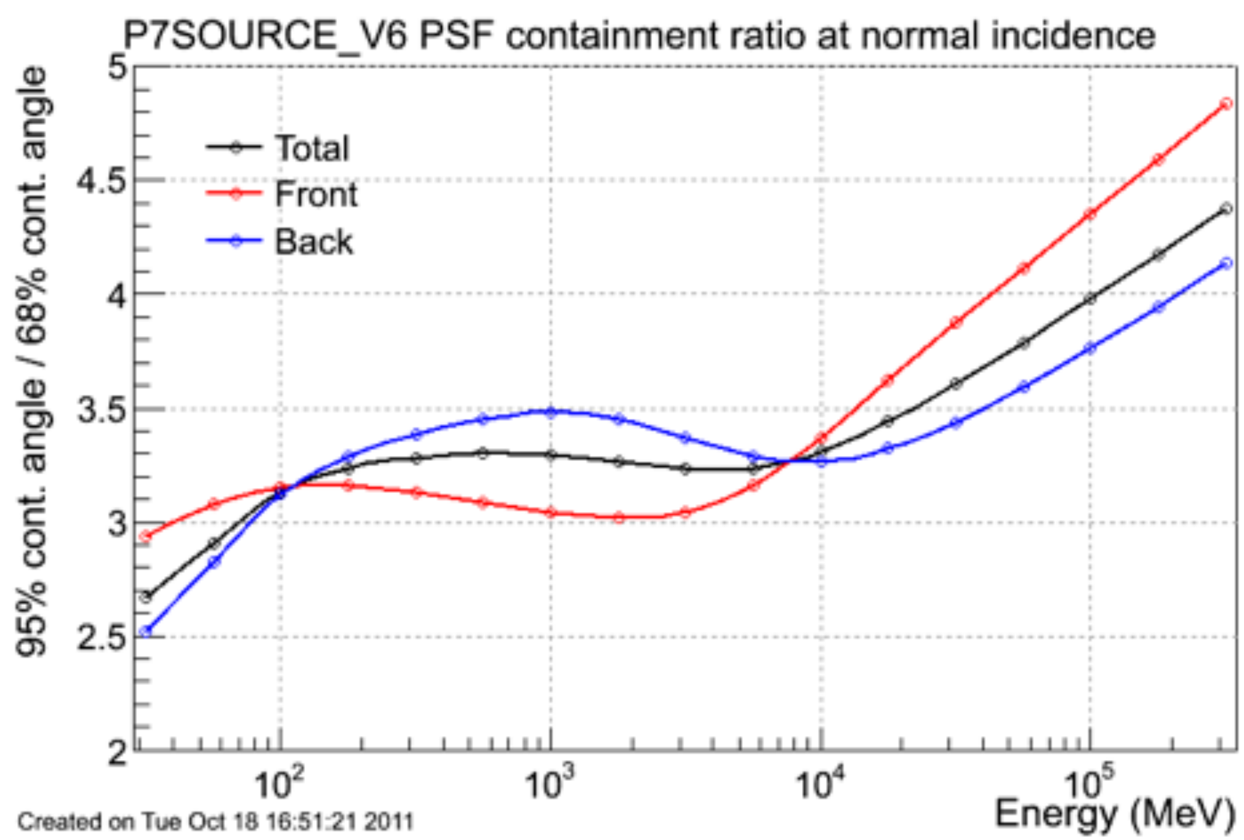
- Acceptance of the Fermi-LAT peaks at approximately 10 GeV, FRONT and BACK acceptance are relatively equivalent

Angular Resolution of the Fermi-LAT

- Angular resolution degrades
quickly at low energy, but levels off above ~10 GeV

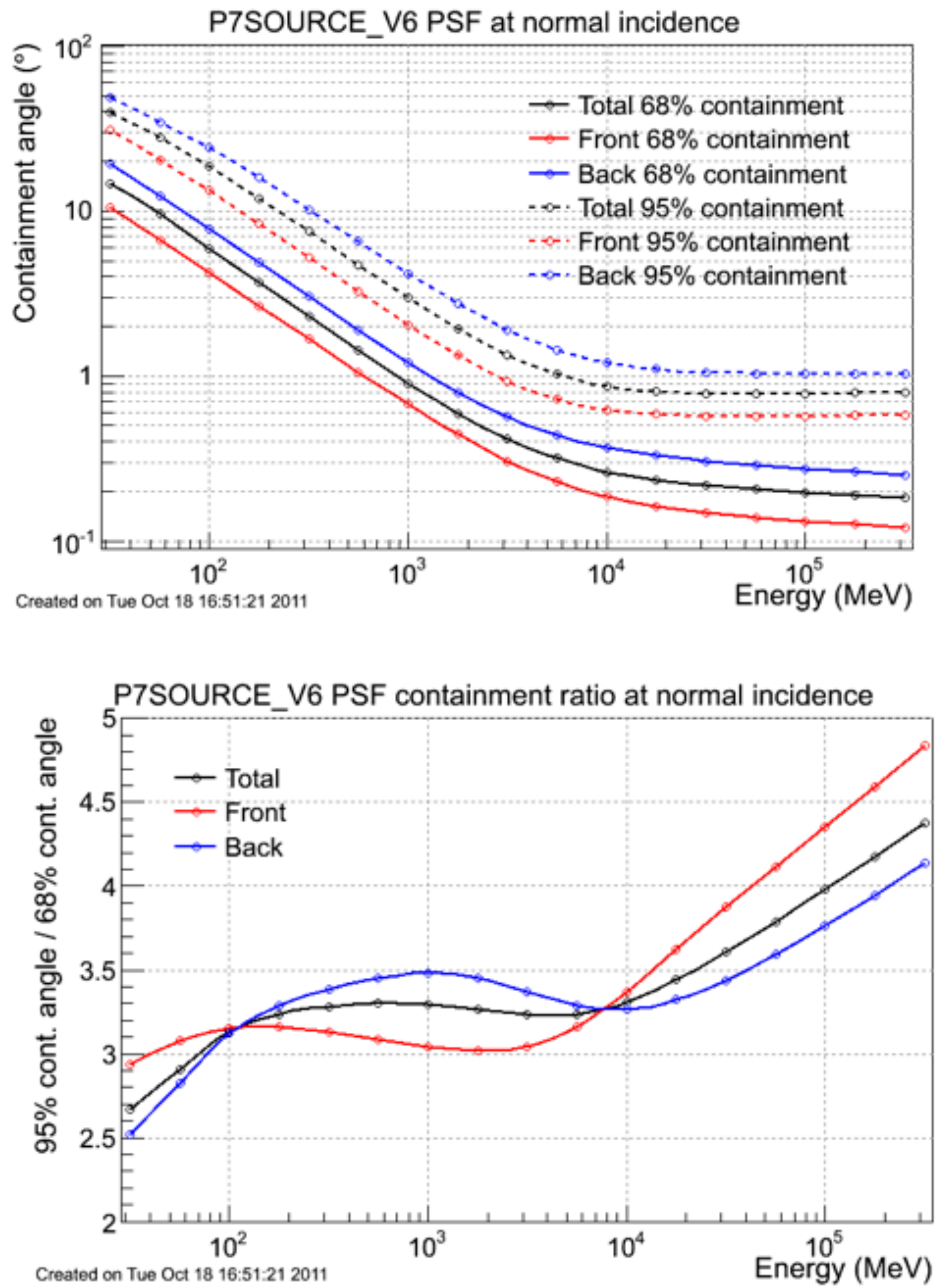


- <u>Not</u> a gaussian distribution - ratio of 95% to 68% containment angle is wider than gaussian, and is energy dependent



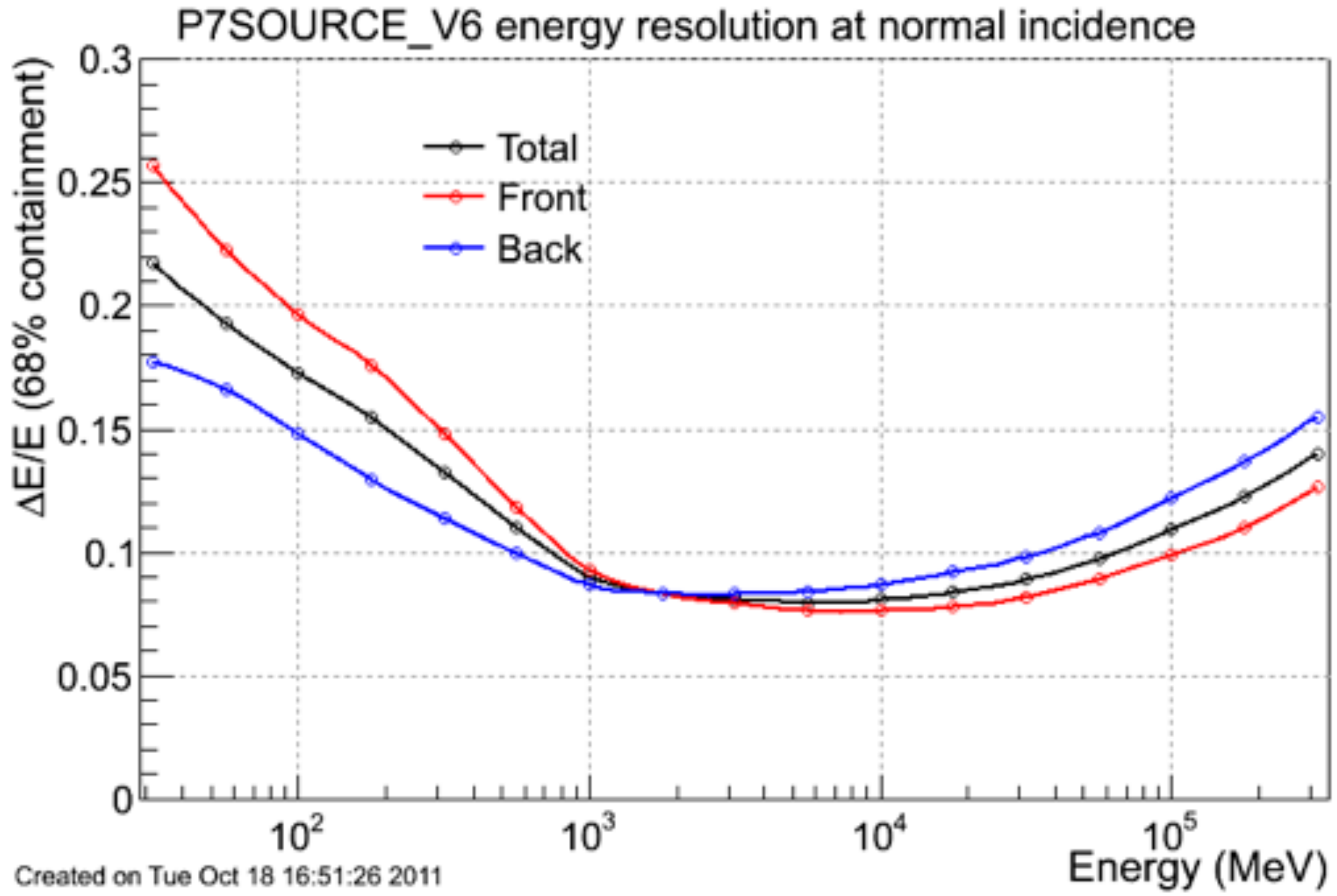
Angular Resolution of the Fermi-LAT

- In the P7_V6 response function, the PSF has a completely negligible dependence on the angle of incidence

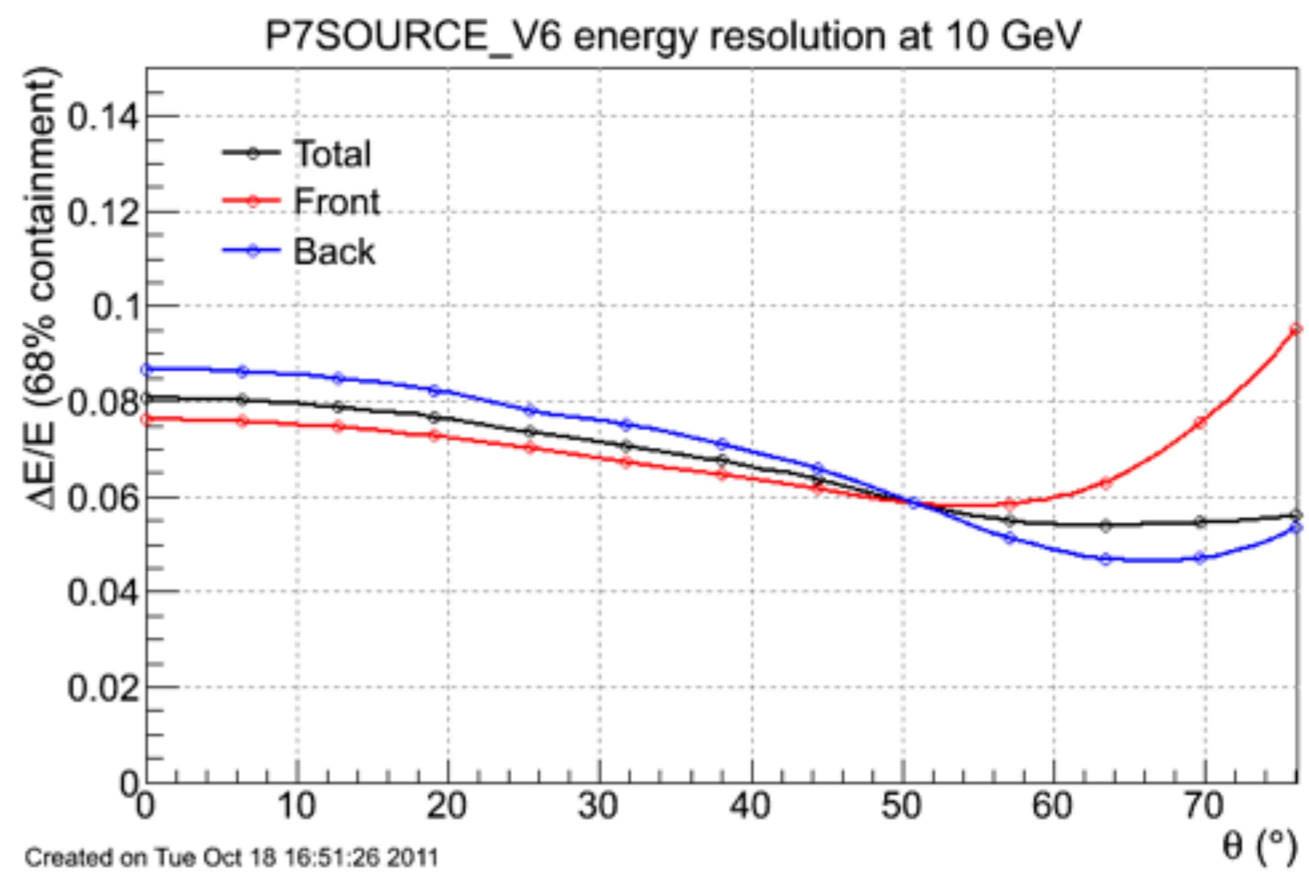


Energy Resolution of the Fermi-LAT

- Energy resolution of the Fermi-LAT also peaks in the range ~10 GeV - but stays consistently below 20% above 100 MeV

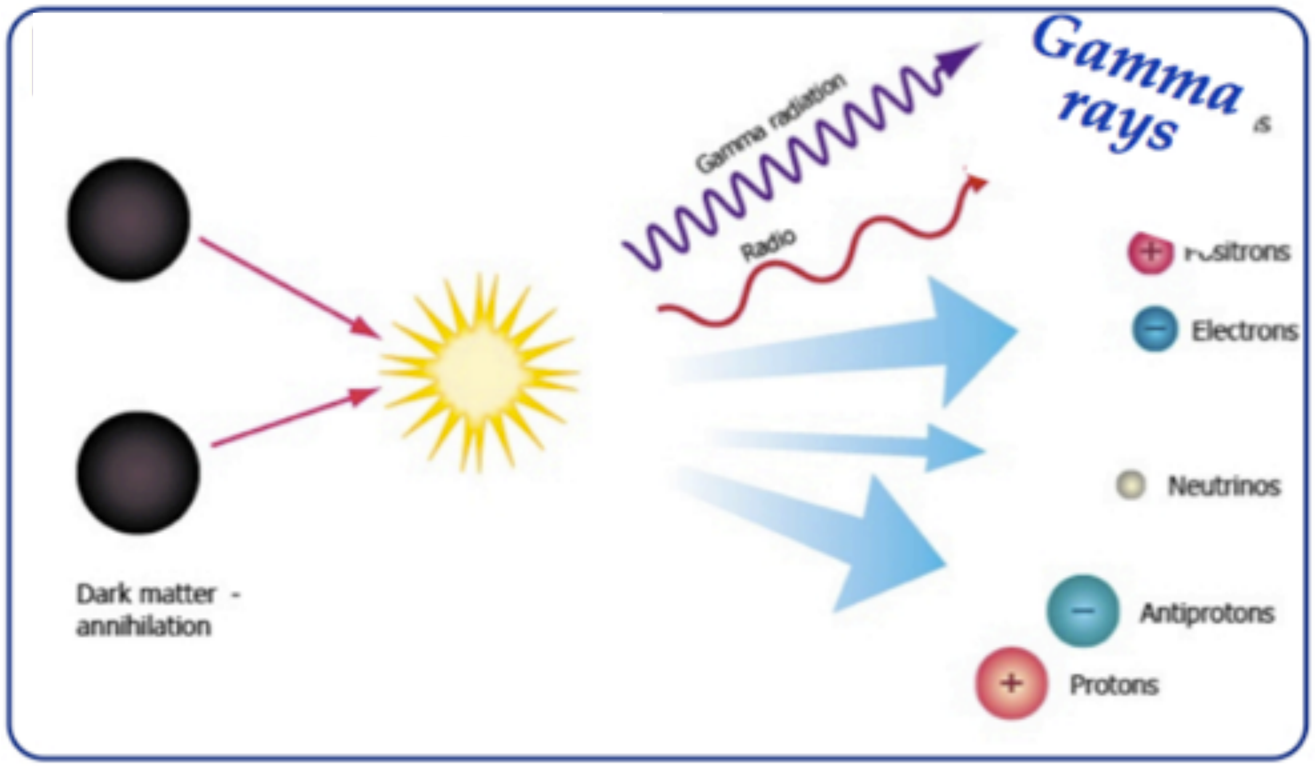


- The energy resolution depends only mildly on the angle of incidence



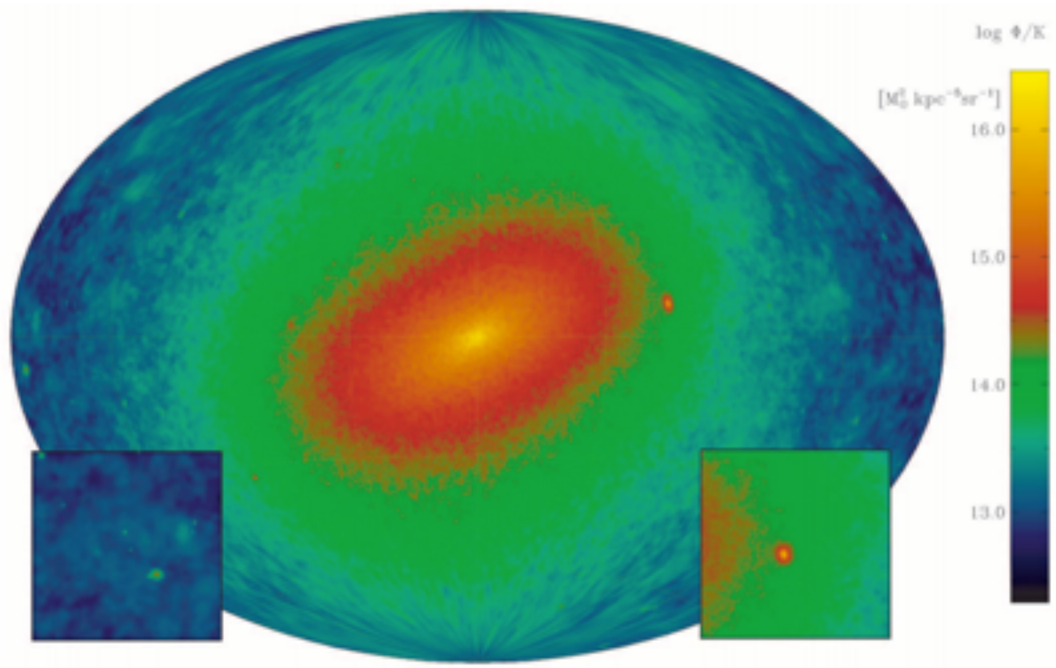
Dark Matter Indirect Detection

Particle Physics

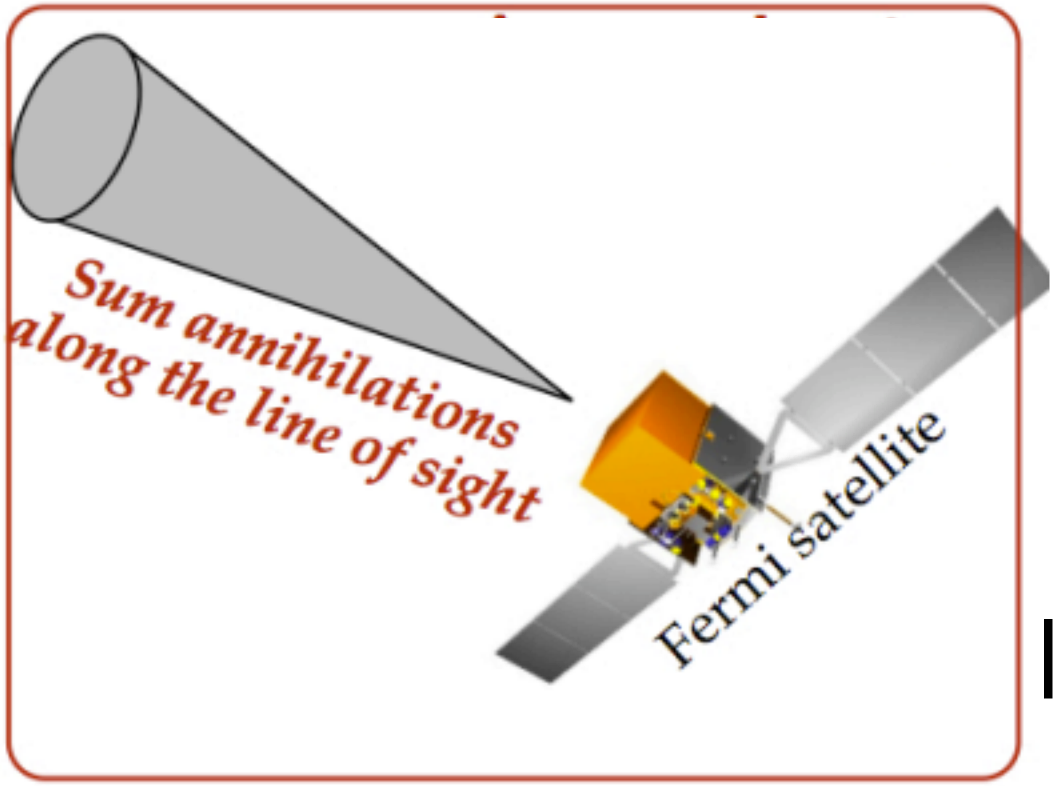


Slides Courtesy of G. Zaharijas

Astrophysics



Diemand et al. 2008



Instrumental Response

Techniques for the Detection of Dark Matter

- Morphological Differentiation
    - Galactic Center Search (see talk by Simona)
    - Milky Way Halo Analysis (this talk)
    - *Dwarf Spheroidal Search (see talk by Louis)*
    - Anisotropy Power Spectrum (see talk by Jennifer)
    - Gamma-Rays from Galaxy Clusters (this talk)
    - *Cosmic Ray Electrons/Gammas from the Sun*

Relatively background free

Astrophysical backgrounds critical

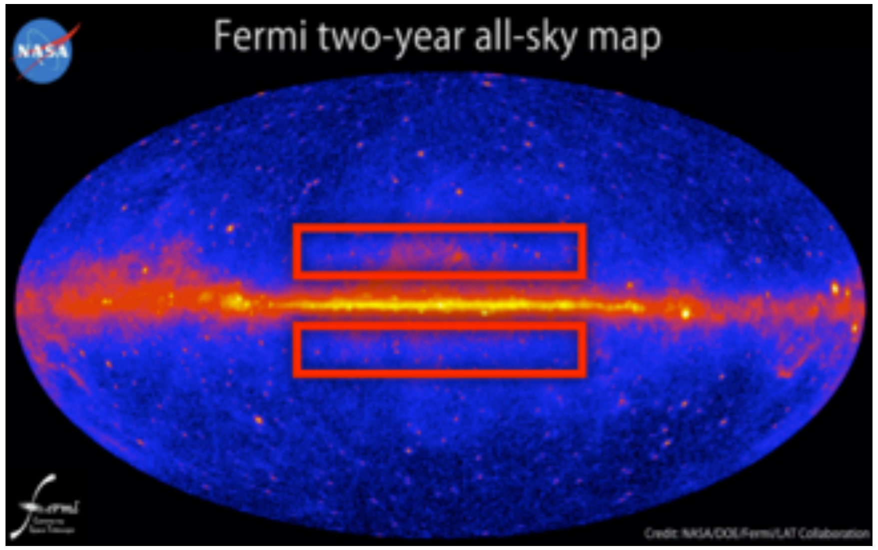
- Spectral Differentiation
    - *Gamma-Ray Line Search (this talk)*
    - e^+e^- ratio and Electron + Positron Spectrum

Milky Way Halo Analysis

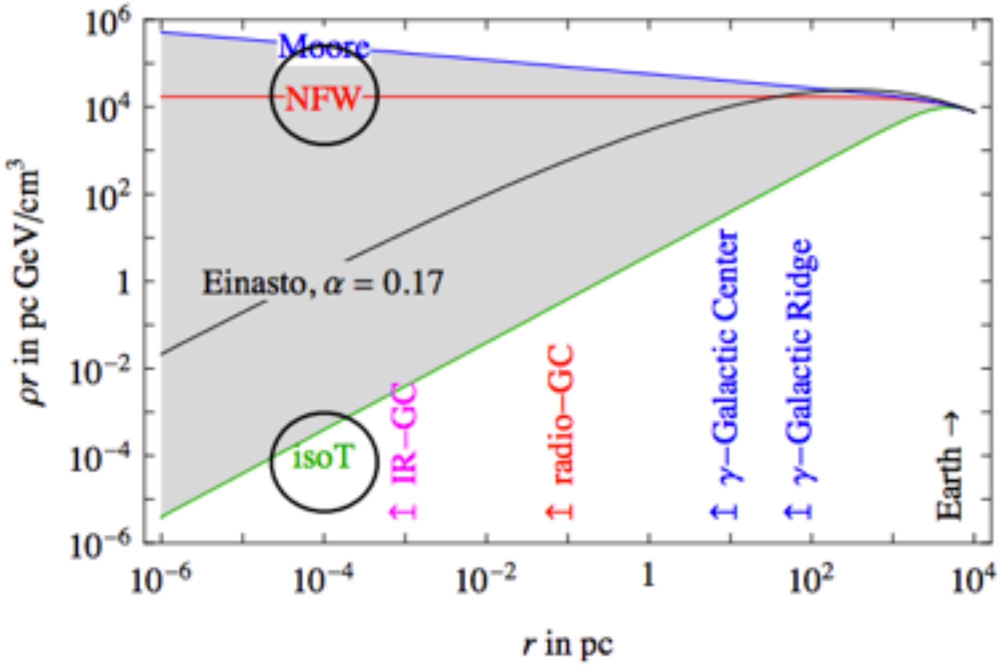
- GOAL: Search for a signal from Dark Matter annihilation by examining gamma-rays in the galactic halo.
- Targets: Any annihilating or decaying dark matter particle which produces relativistic standard model particles
- Benefits: Large flux of dark matter expected from the Milky Way Dark Matter Halo. Observations above the galactic plane help to reduce background.
- Difficulties: Many astrophysical backgrounds to consider (e.g. ROI largely overlaps Fermi Bubbles) . Unknown diffusion parameters play a confounding role.

Milky Way Halo Analysis: Dark Matter Models

- Region of Interest: 5° < |b| < 15° and |l| < 80°



- Assume a dark matter density following either an isothermal or NFW profile



- Examine both annihilating and decaying DM, with a mass range of 5 GeV - 10 TeV, and annihilating into either bb-bar, $\mu^+\mu^-$ or $\tau^+\tau^-$

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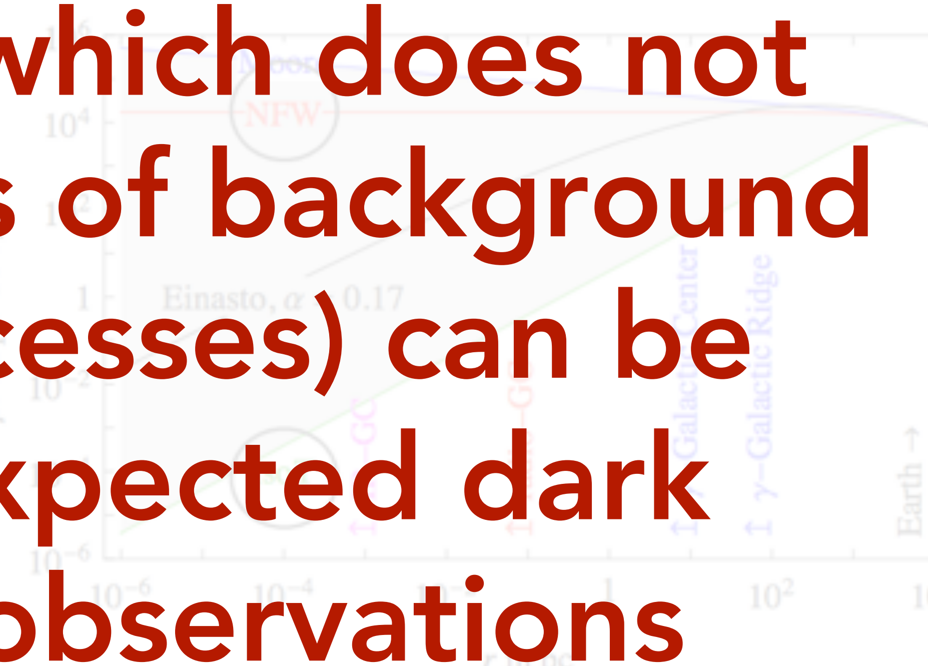
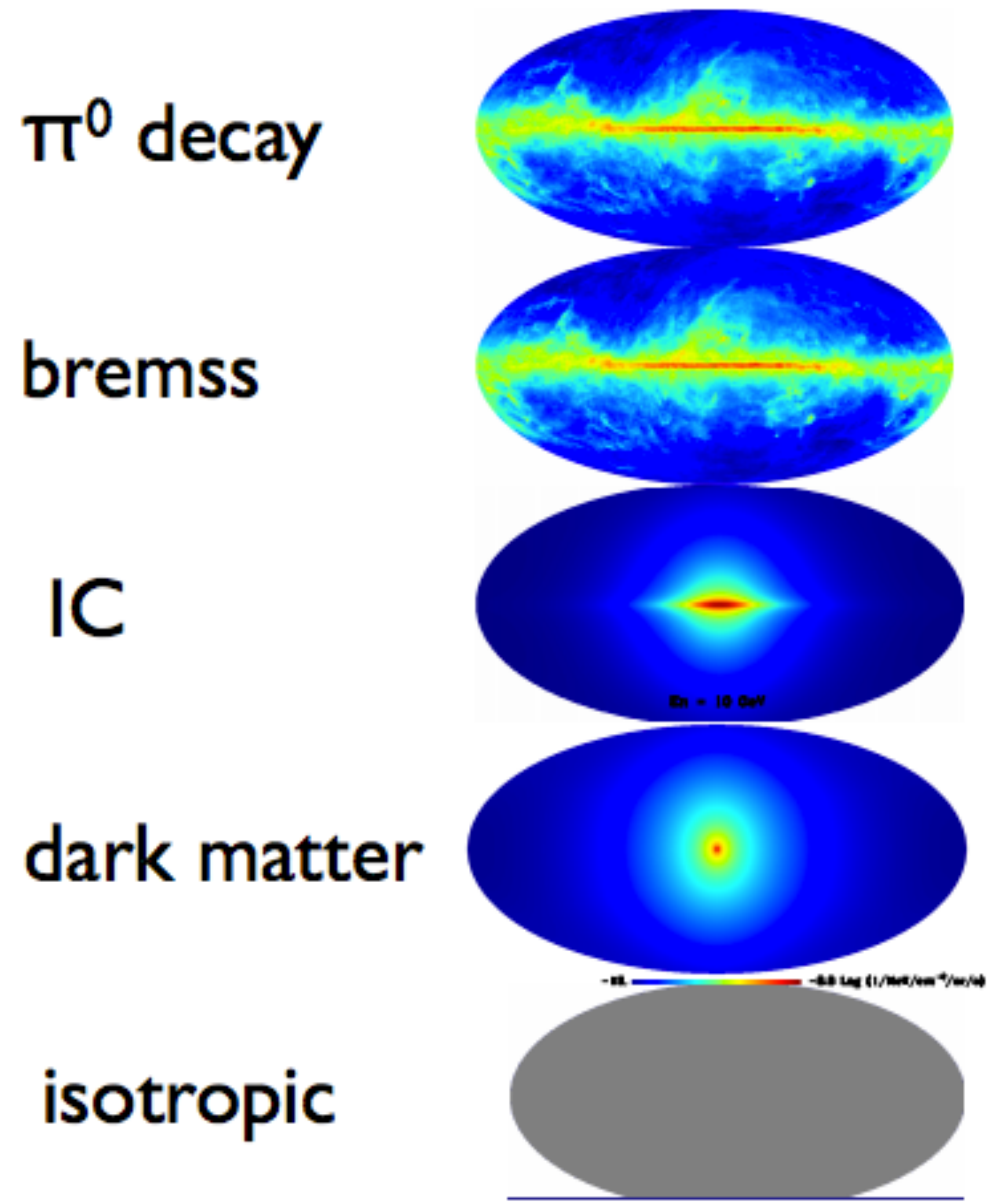


- Examine both annihilating and decaying DM, with a mass range of 5 GeV - 10 TeV, annihilating into either bb-bar, $\mu^+\mu^-$ or $\tau^+\tau^-$

Note: A conservative limit (which does not depend on the characteristics of background astrophysical emission processes) can be made by comparing the expected dark matter flux to Fermi-LAT observations

Milky Way Halo Analysis: Astrophysical Backgrounds

- Diffuse background includes π^0 emission, bremsstrahlung, inverse-Compton scattering etc.
- Models are derived from the Fermi-LAT diffuse gamma-ray study (Ackermann et al. 2012) and then first order variations are allowed
- However, in this analysis the cosmic-ray source density for electrons and protons is allowed to float independently between radial bins - but forced to 0 within r=3 kpc (to provide more conservative limits)



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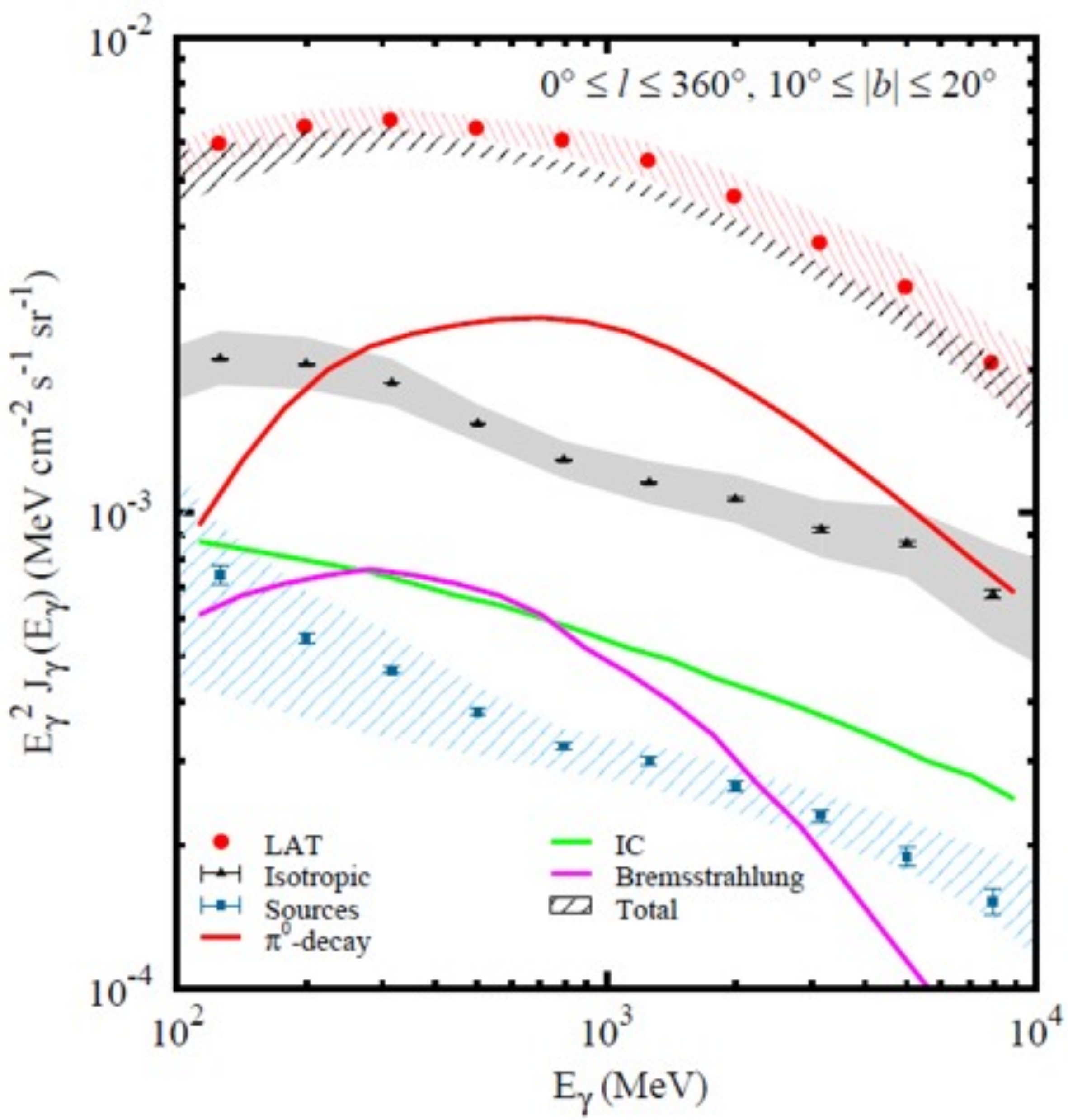

Abdo et al. (2009)

Milky Way Halo Analysis: Astrophysical Backgrounds

Parameter	Value					
Halo Height z_h(kpc)	2	4	6	8	10	15
Diffusion Coefficient D_0 (cm^2s^{-1})	2.7×10^{28}	5.3×10^{28}	7.1×10^{28}	8.3×10^{28}	9.4×10^{28}	1.0×10^{29}
Diffusion Index δ	0.33	0.33	0.33	0.33	0.33	0.33
Alfven Velocity v_A (km s^{-1})	35.0	33.5	31.1	29.5	28.6	26.3
Nucleon Injection Index (Low) $\gamma_{p,1}$	1.86	1.88	1.90	1.92	1.94	1.96
Nucleon Injection Index (High) $\gamma_{p,2}$	2.39	2.39	2.39	2.39	2.39	2.39
Nucleon break rigidity $\rho_{br,p}$(GV)	11.5	11.5	11.5	11.5	11.5	11.5

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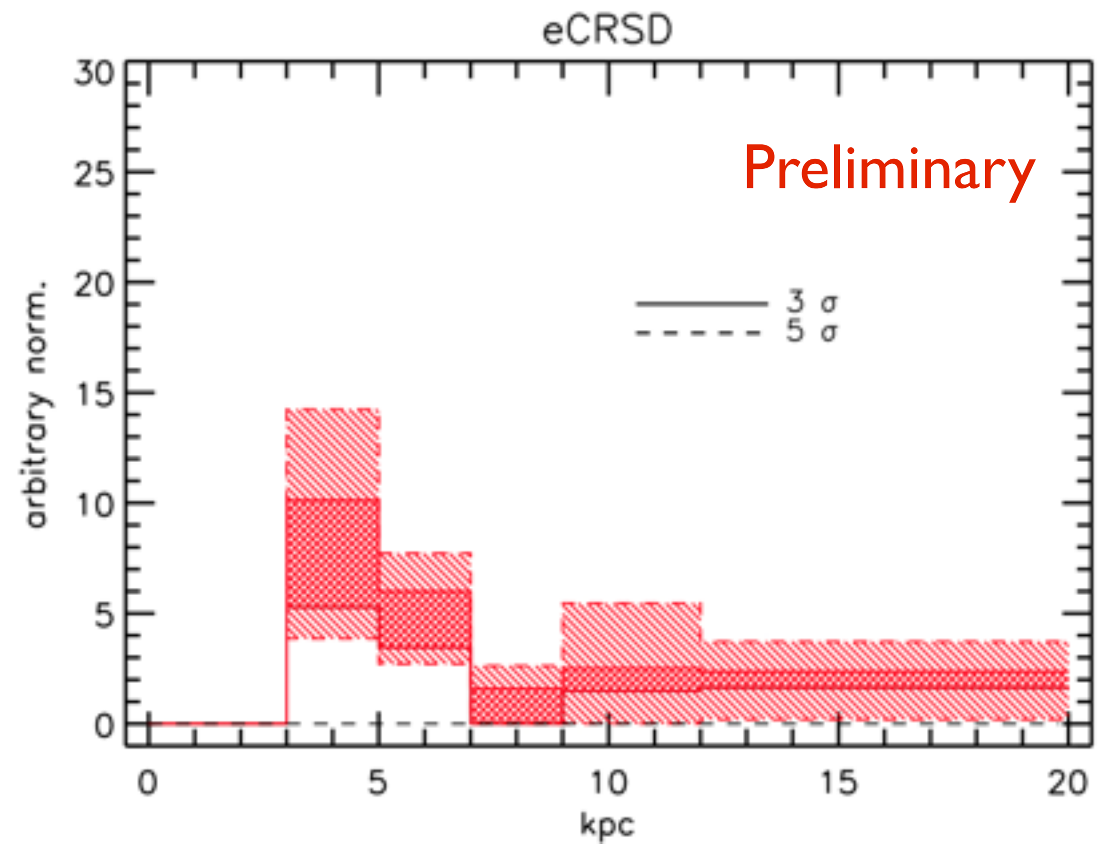
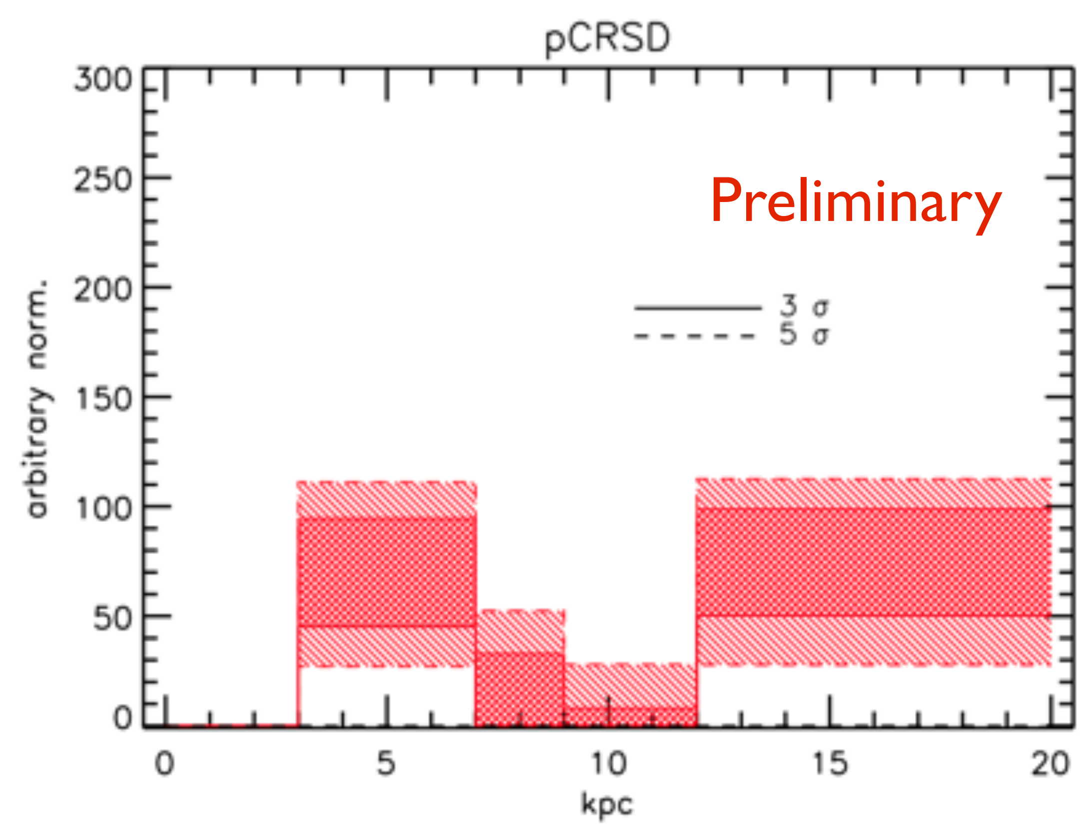


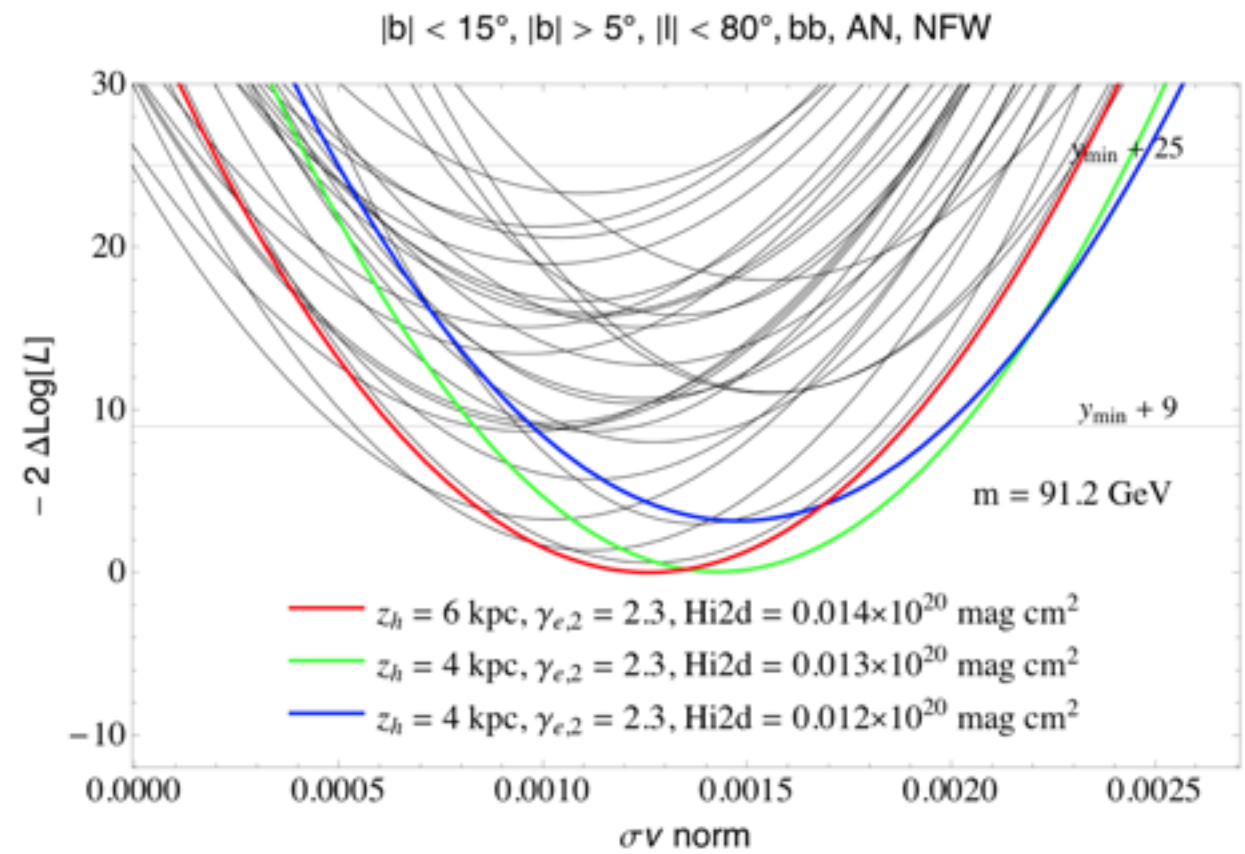


Milky Way Halo Analysis: Astrophysical Backgrounds

- For a given dark matter model, the best fit to the Fermi data is obtained for all cosmic-ray models, then a log-likelihood is computed

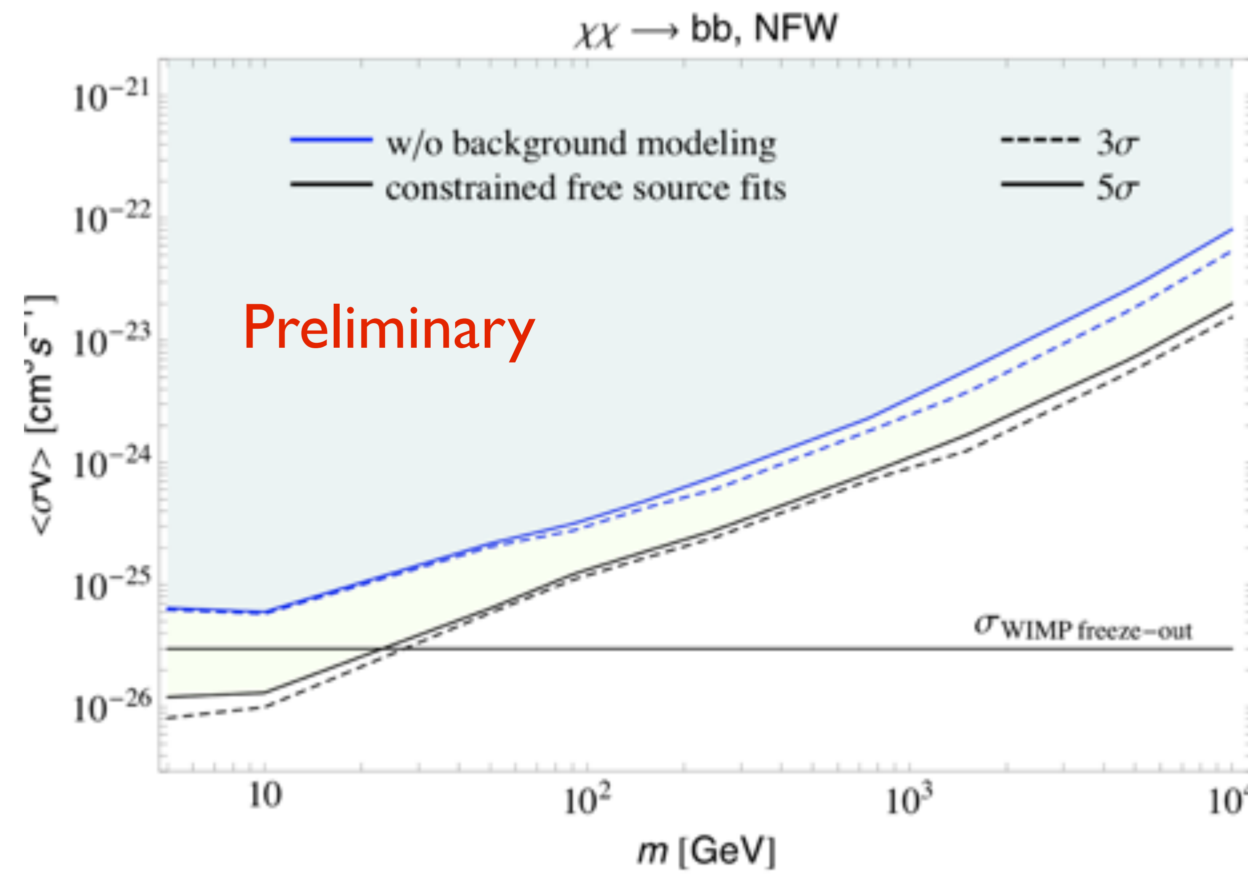
- This provides the maximum dark matter cross-section to within a given confidence level

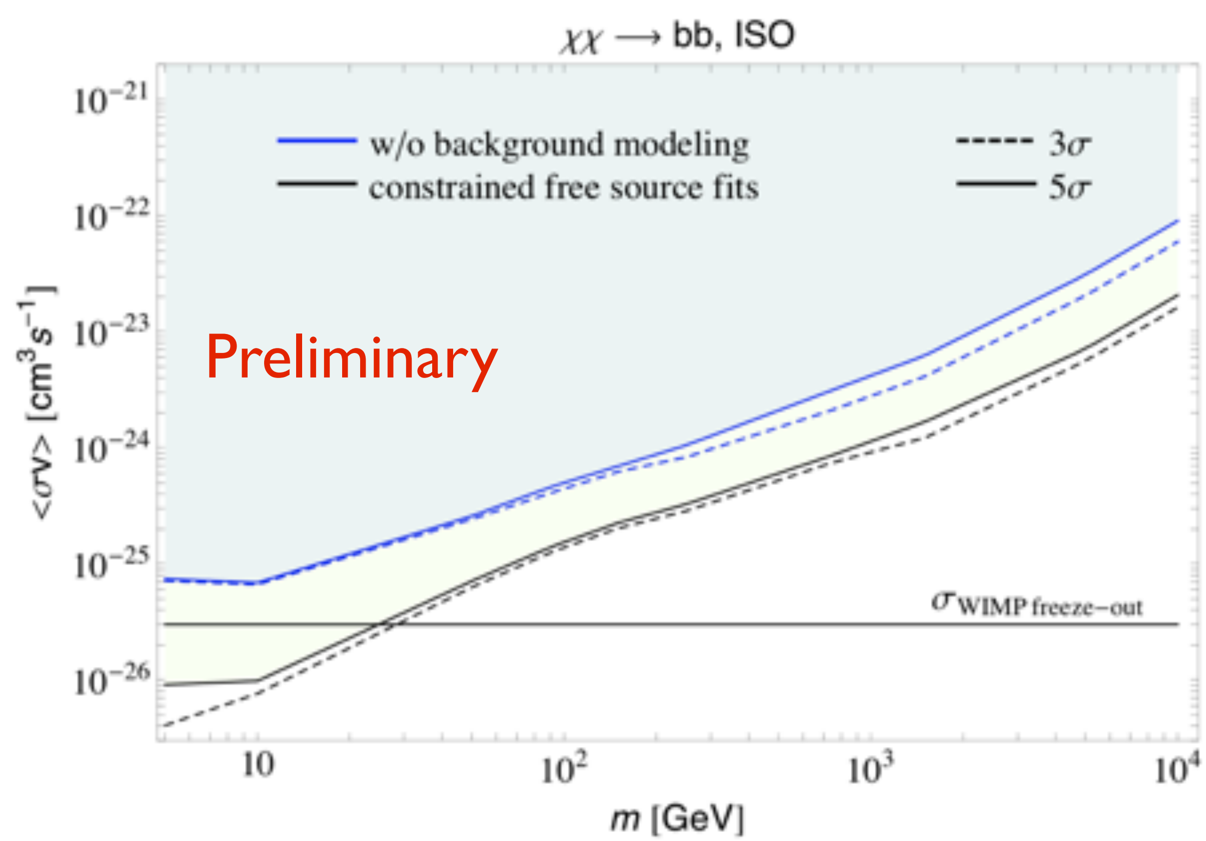
Preliminary



Milky Way Halo Analysis: Dark Matter Limits

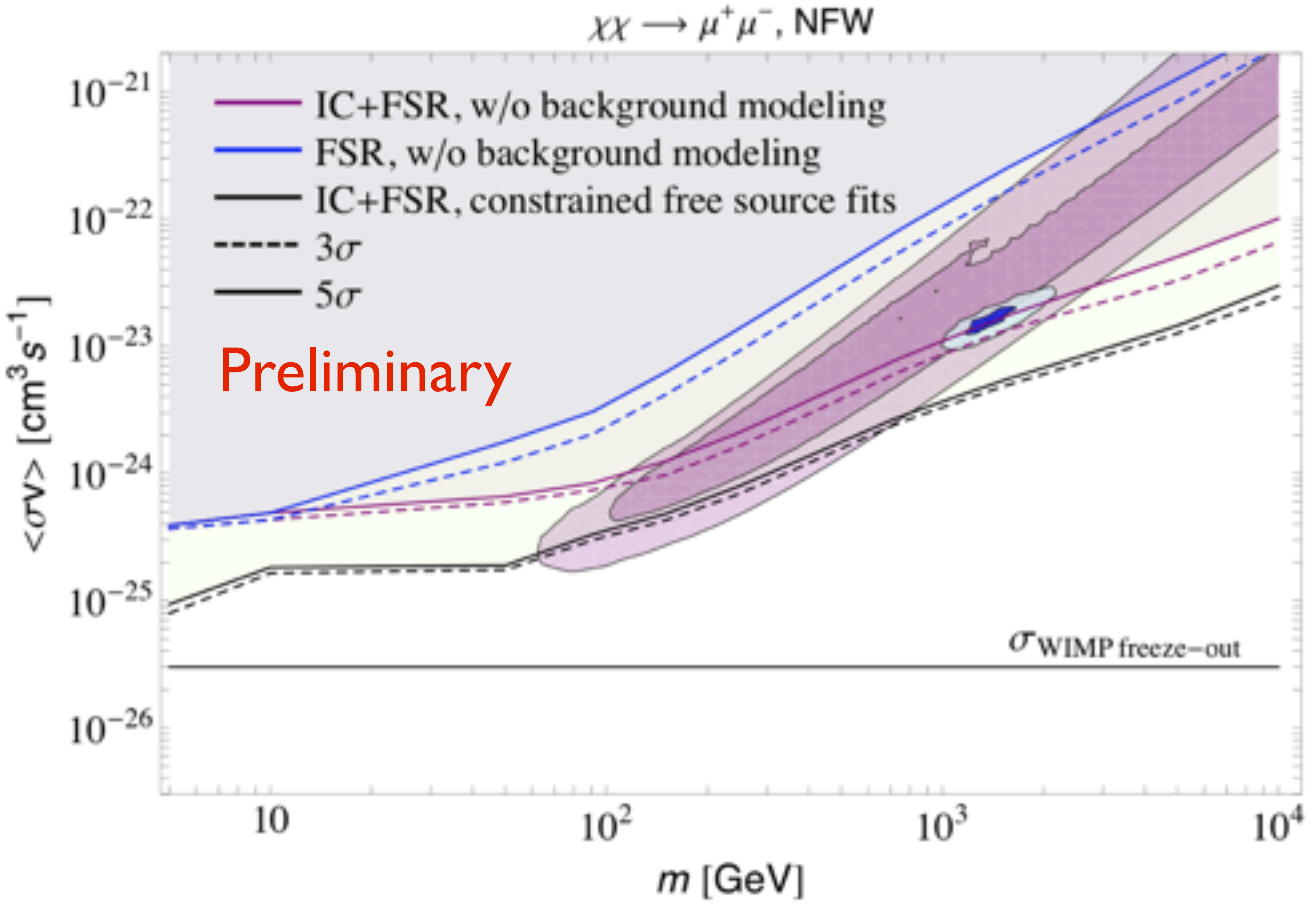
- Dark Matter limits are competitive with other methods (e.g. dwarf analysis, Galactic center)
- Have reached the thermal cross-section at 3σ below ~30 GeV
- Relatively profile independent

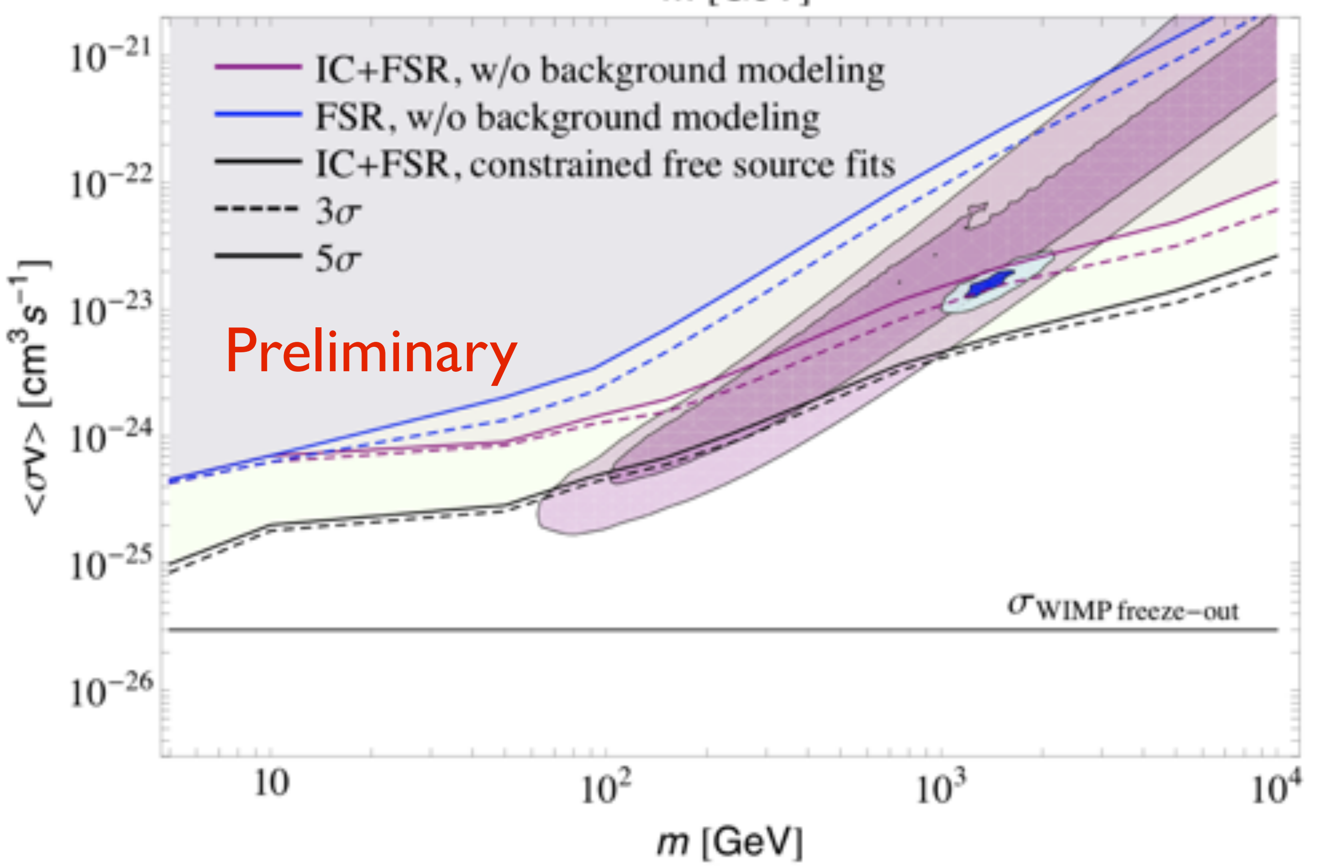




Milky Way Halo Analysis: Dark Matter Limits

- Dark Matter limits are competitive with other methods (e.g. dwarf analysis, galactic center)
- Have reached the thermal cross-section with 3σ upper-limit below ~30 GeV
- Relatively profile independent
- Rules out majority of parameter space which fits PAMELA excess!





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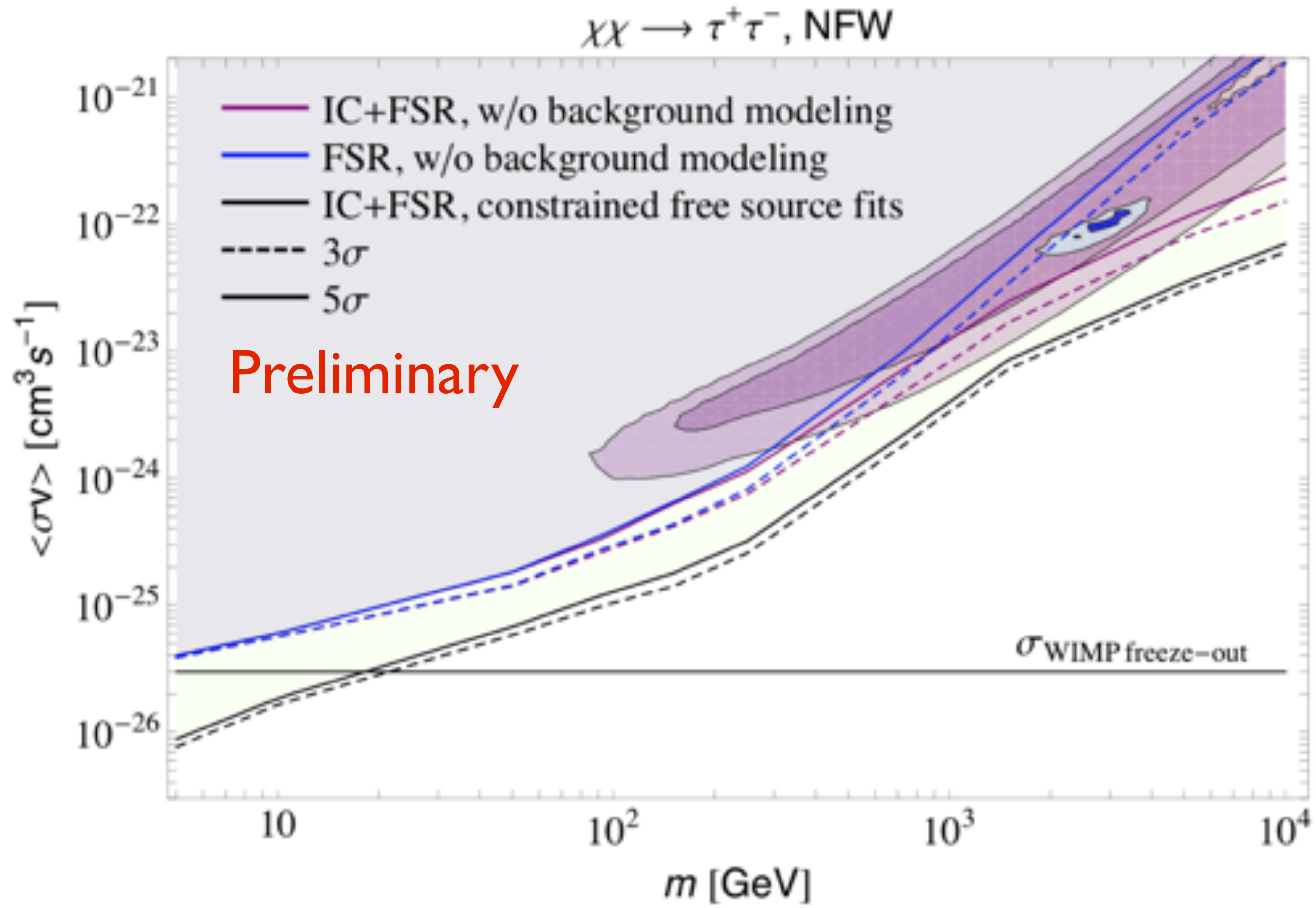
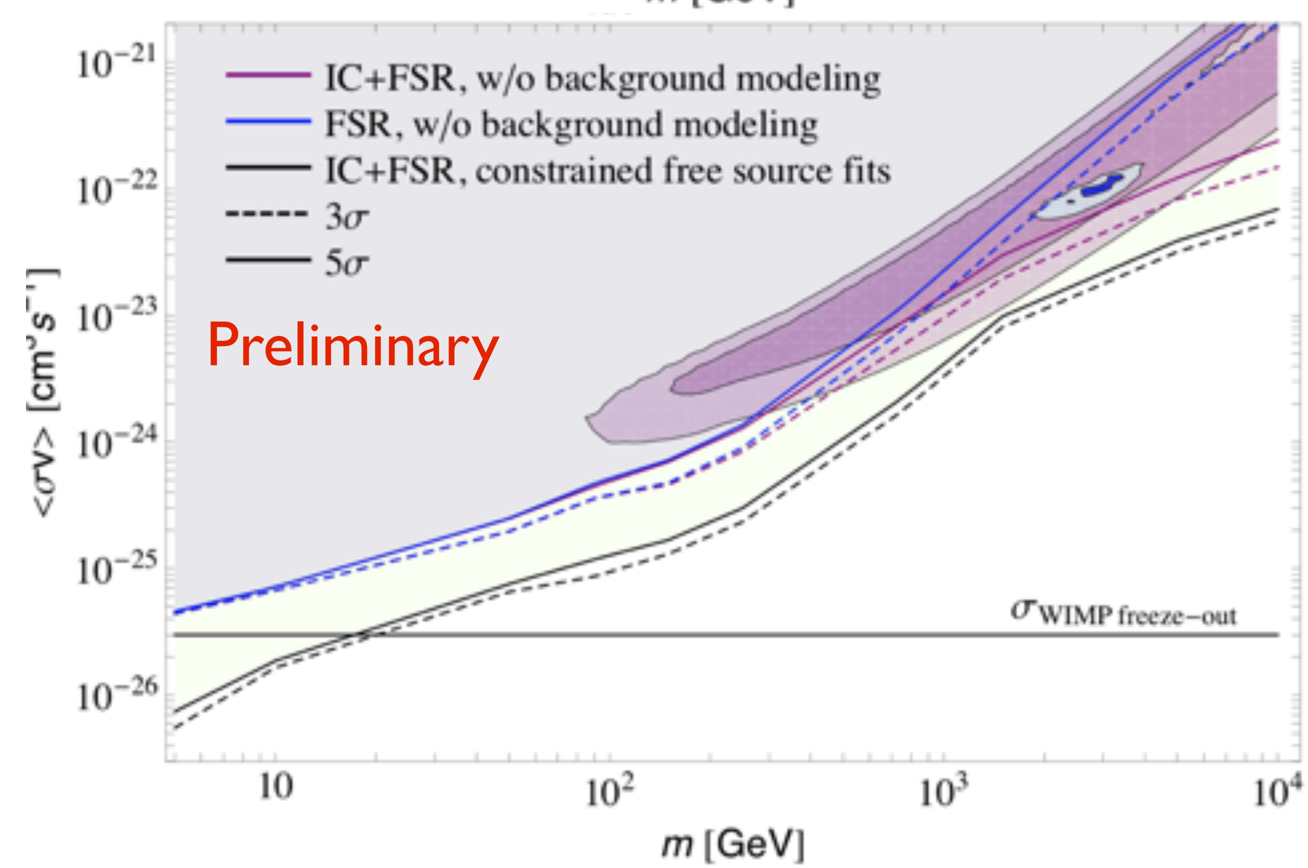




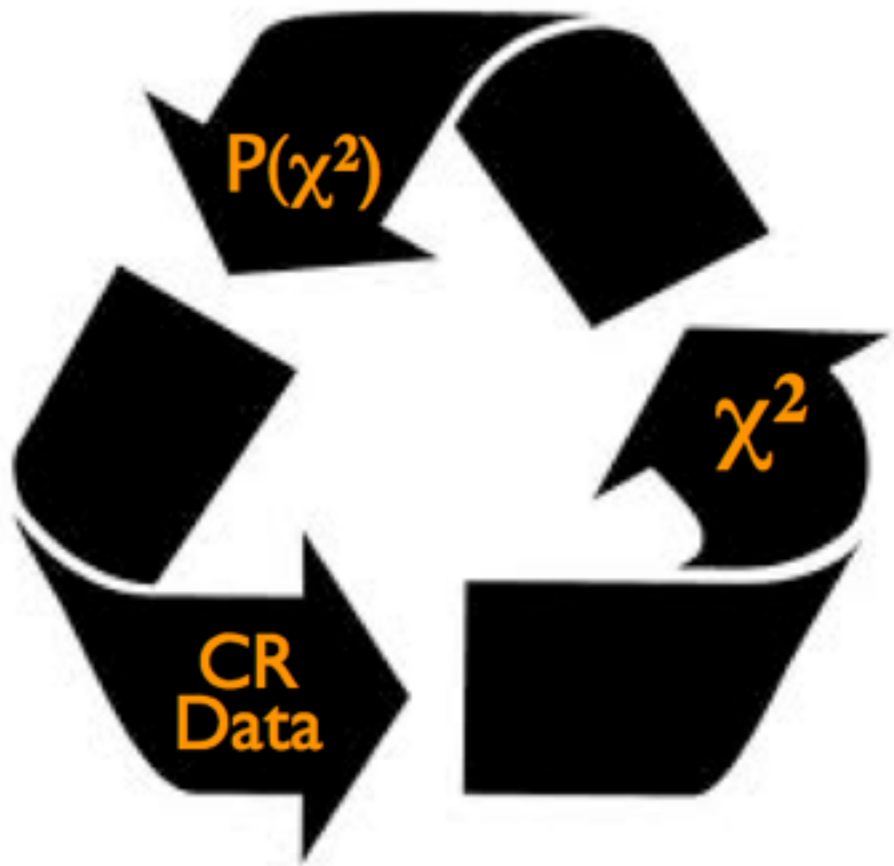
Milky Way Halo Analysis: Classification Tree

- Instead of considering first-order changes in the diffusion parameters, we can consider the large-dimensional parameter space of diffusion parameter choices, normalizing each to the observed cosmic-ray abundance.

Parameter	Range
Diffusion Coefficient	$1\times10^{27} \to 4\times10^{29}$
Halo Height	$1 \to 11$ kpc
Diffusion Index	0.33, 0.50
Alfven Velocity	$0 \to 50$ km s^{-1}
Electron Injection Index	$1.8 \to 2.5$
Nucleon Injection Index (Low)	$1.7 \to 2.6$
Nucleon Injection Index (High)	2.26, 2.43
Source Distribution	Parameterized, SNR, Pulsars

- A classification tree must be employed to weed through this parameter space (quickly reject models which will not fit the data without running full Galprop simulations for each)

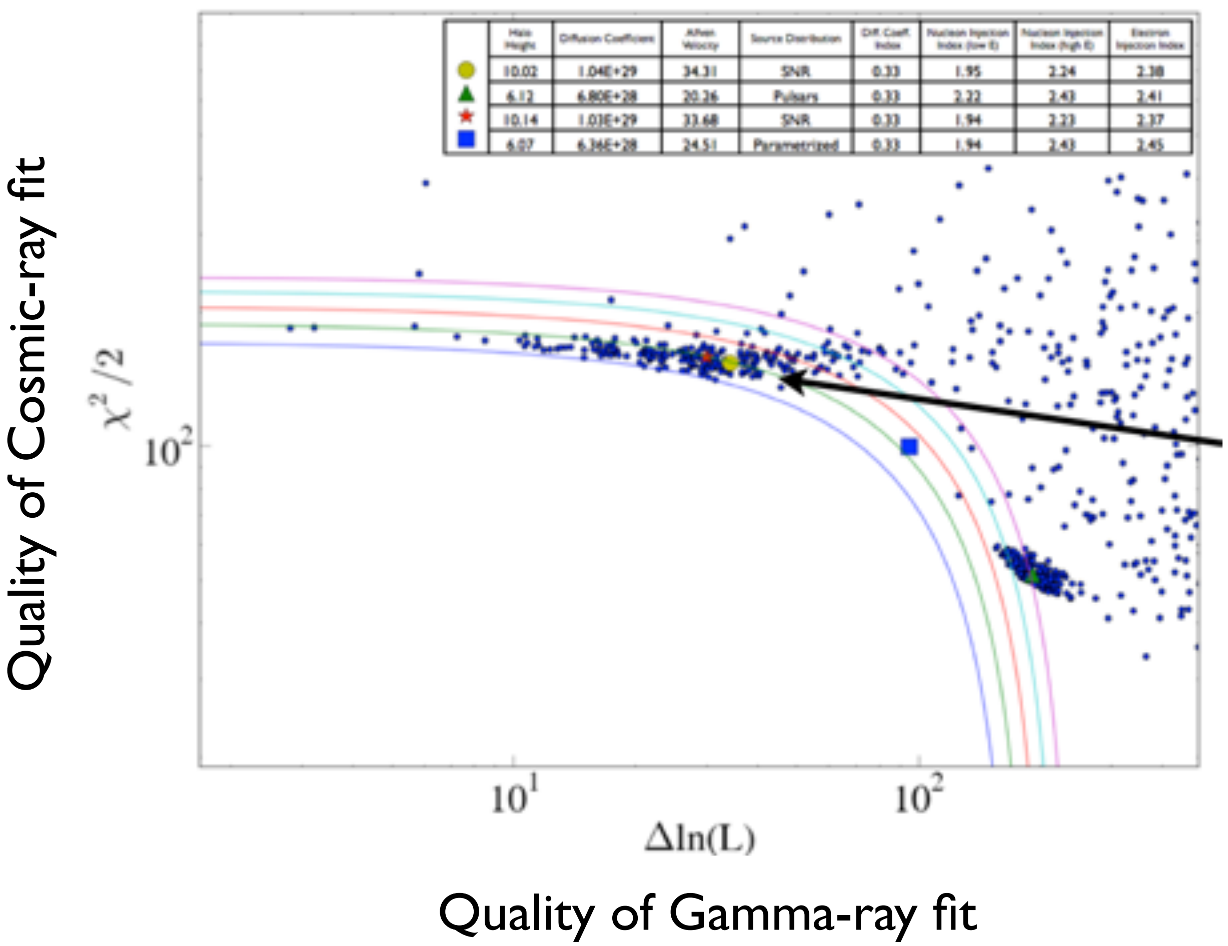
Milky Way Halo Analysis: Classification Tree



- The classification tree yields a set of diffusion parameter and cosmic ray injection spectra which yield a best fit to the local cosmic-ray density
- For these best fit parameters, Galprop then computes the expected gamma-ray spectrum and intensity

- Dark matter models are then added to this gamma-ray spectrum, and fitting this model to the Fermi data generates a log(likelihood) for the dark matter cross-section for each dark matter model

Milky Way Halo Analysis: Classification Tree



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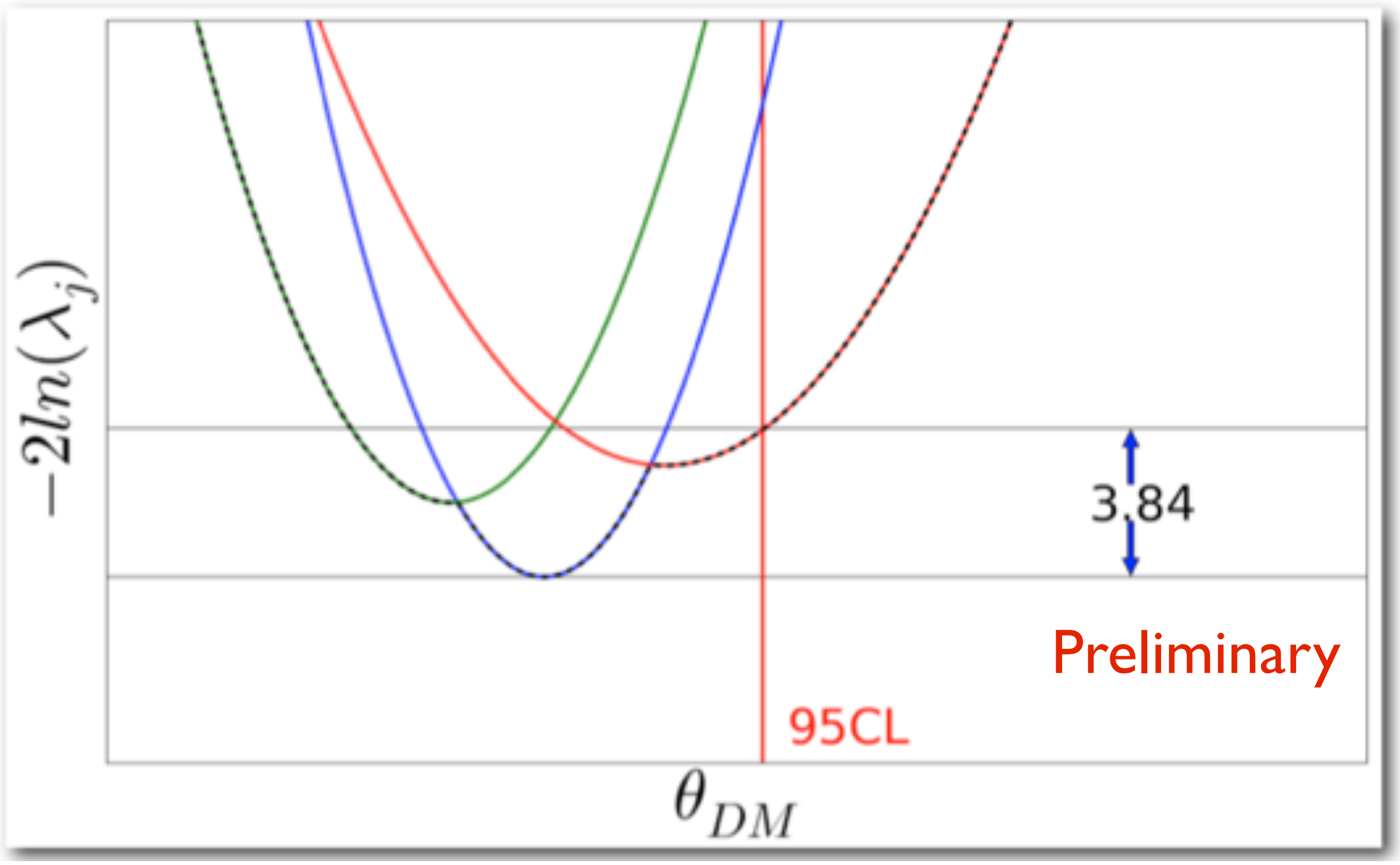
Milky Way Halo Analysis: Classification Tree

- For various models a best fit is obtained using dark matter with a given cross section to minimize the log(likelihood). The maximum cross-section within 95% confidence is obtained.



Courtesy of B. Anderson

- For a given dark matter mass and annihilation pathway -- the limit is obtained from the model for the Galactic diffuse which allows for the highest dark matter cross-section

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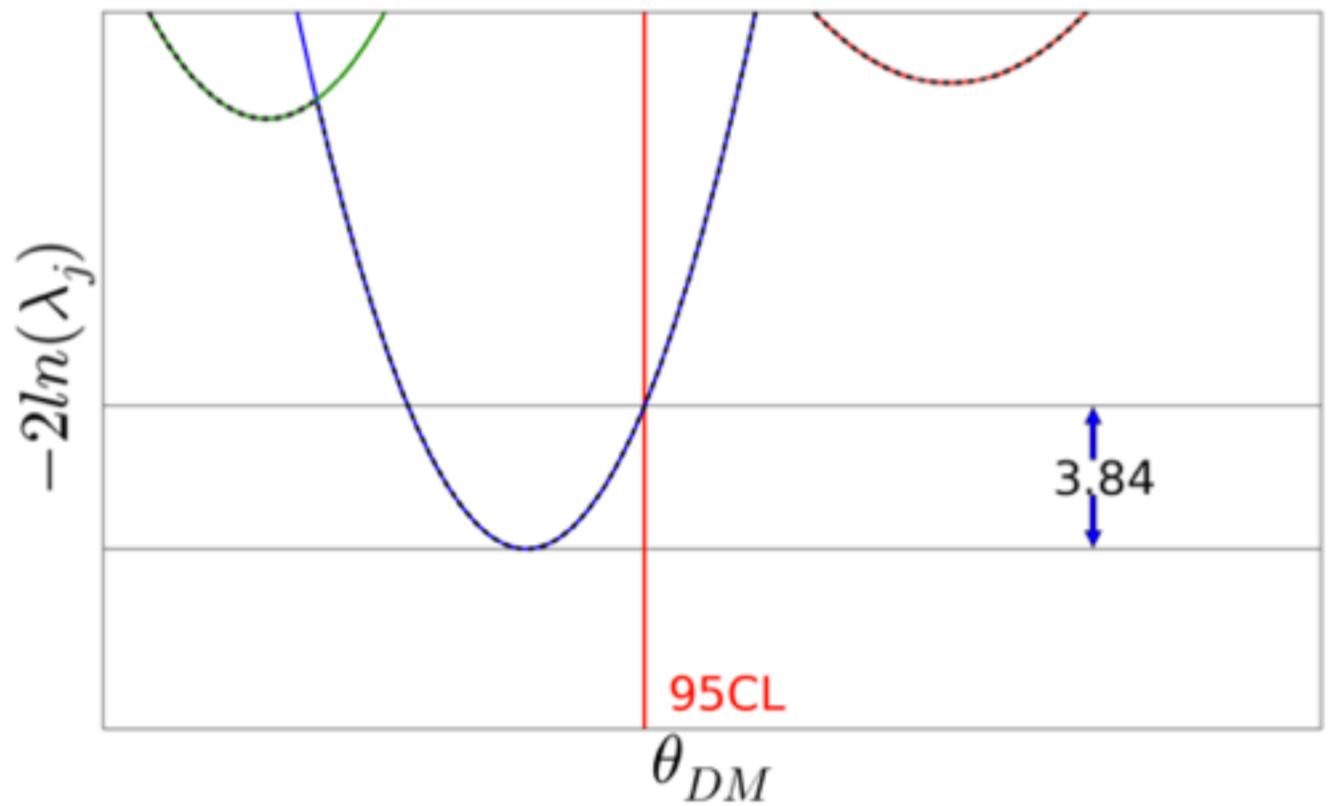
Undersampled



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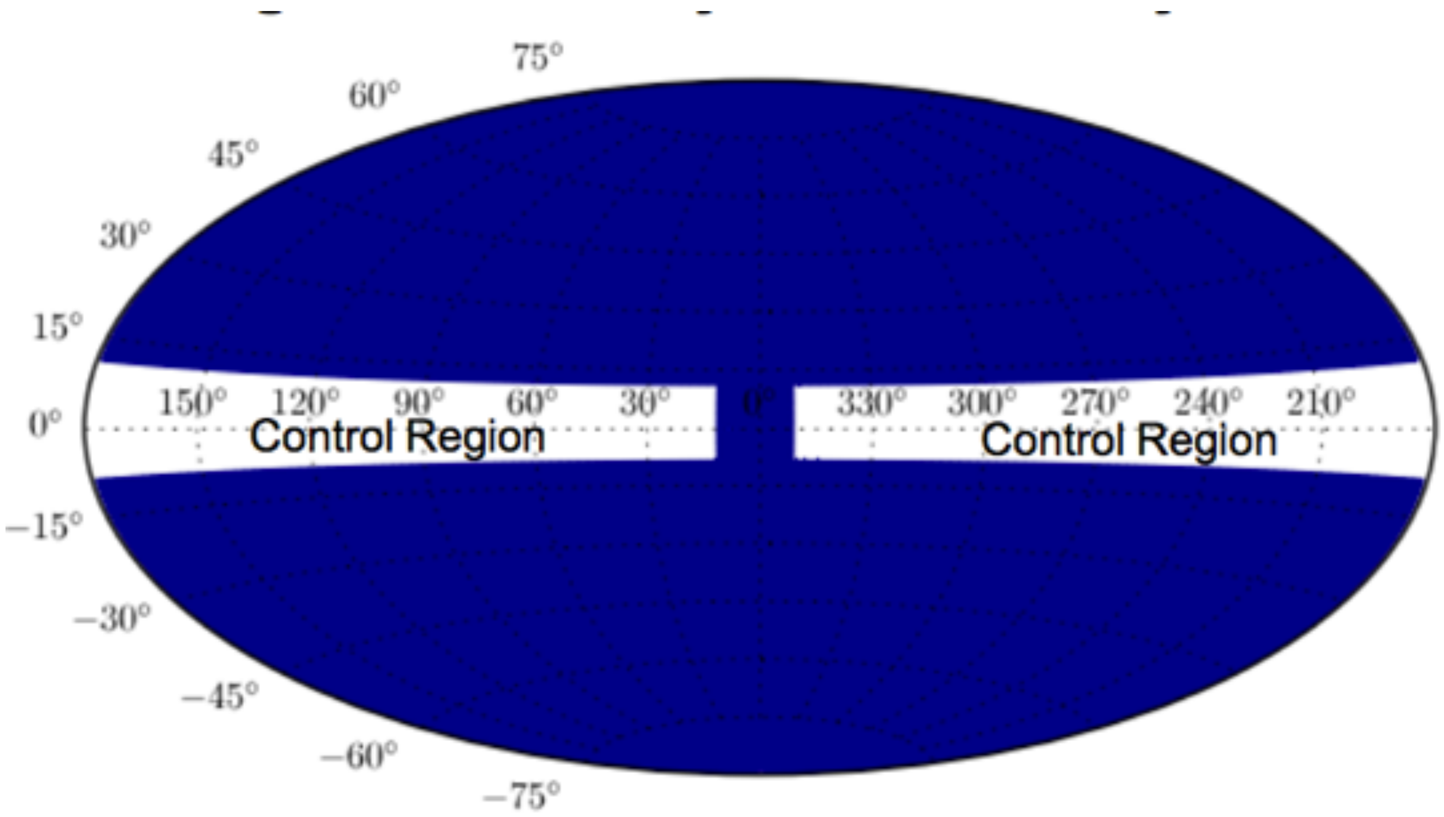
Milky Way Halo Analysis: Conclusions

- Obtain a strong limit on dark matter annihilation through the use of conservative assumptions:
  - ROI which eliminates the Galactic plane, galactic center, and much of the Fermi bubbles region
  - Allow the cosmic ray source density to vary freely in each radial bin
- Two rigorous analysis pathways have been developed which can be easily improved with both further Fermi-LAT data, as well as upcoming results from AMS.

Gamma-Ray Line Survey

- GOAL: Search for a spectral signal from an annihilation (or decay) of dark matter directly into $\gamma\gamma$
- Targets: Any annihilating or decaying dark matter particle which produces photons directly -- or possibly produces a very hard spectrum of single photons through internal bremsstrahlung
- Benefits: No astrophysical process is expect to produce a gamma-ray line. Resulting constraints can fall far below thermal cross-section
- Difficulties: Direct production of $\gamma\gamma$ is not a generic prediction of dark matter annihilation or decay. Spectral modeling of backgrounds can be complicated.

Gamma-Ray Line Survey

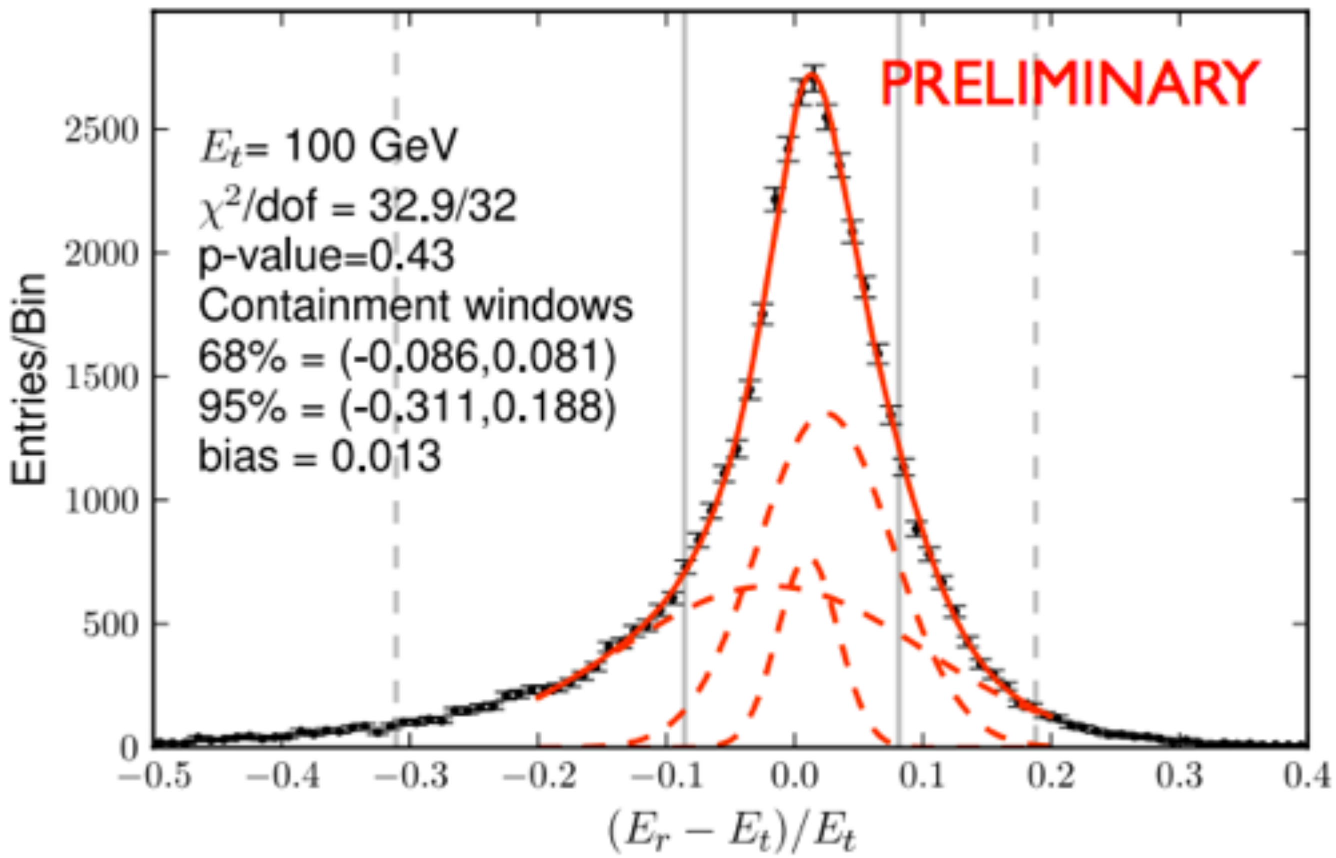


- ROI includes nearly the full sky, to maximize statistics
- However, the region of the Galactic plane away from the Galactic center is excluded, as the expected Signal/Noise is lowest here
- Additionally, 1087 point sources from 1FGL catalog are removed -- by introducing an energy dependent mask at the 68% containment radius

Avoids statistical uncertainty in trials if we are selecting best-fit ROIs

Gamma-Ray Line Survey

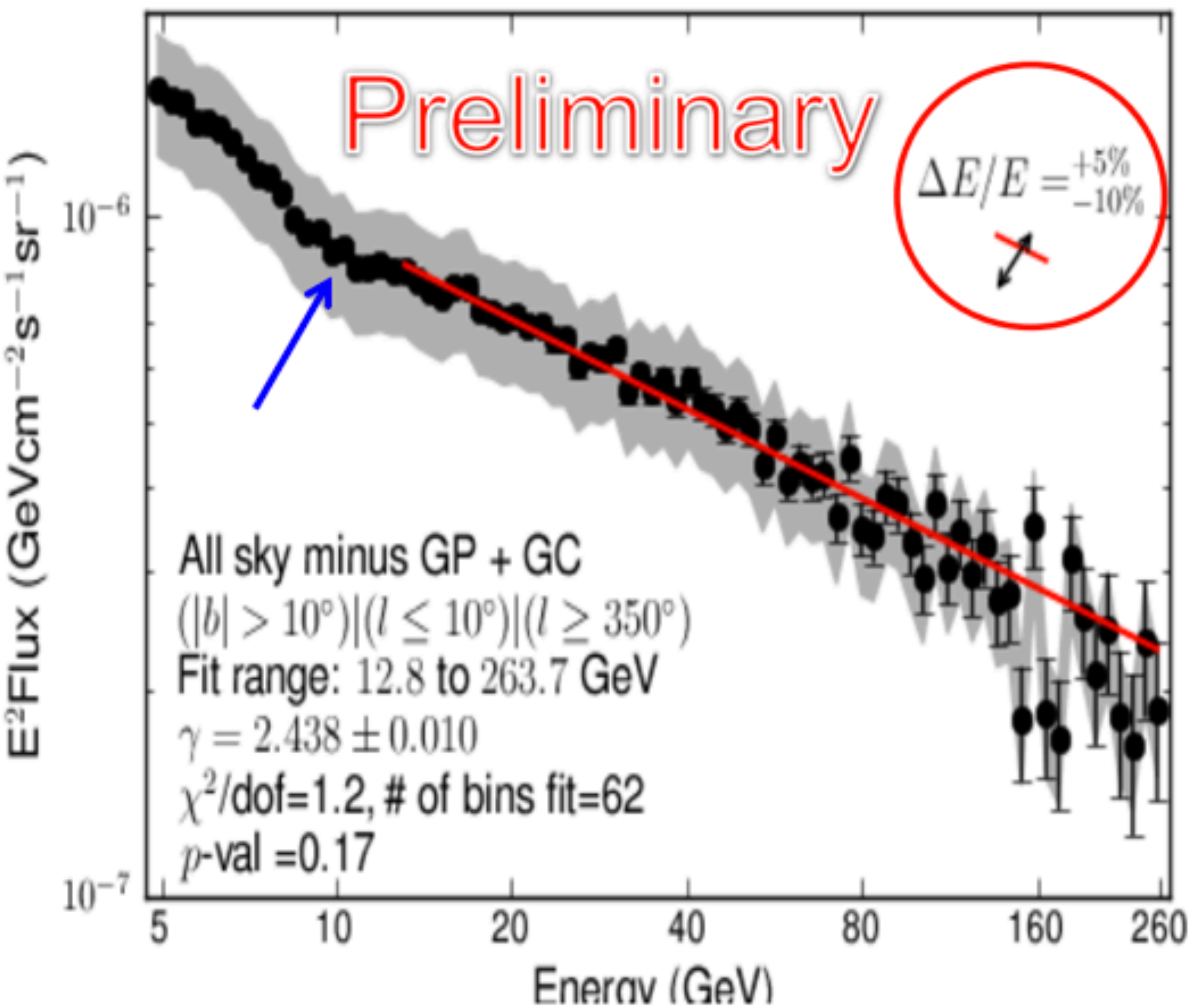
Simulated 100 GeV line



- Gamma-ray line is also smeared by instrumental effects

- However, the LATs ~10% energy resolution allows differentiation from most astrophysical processes

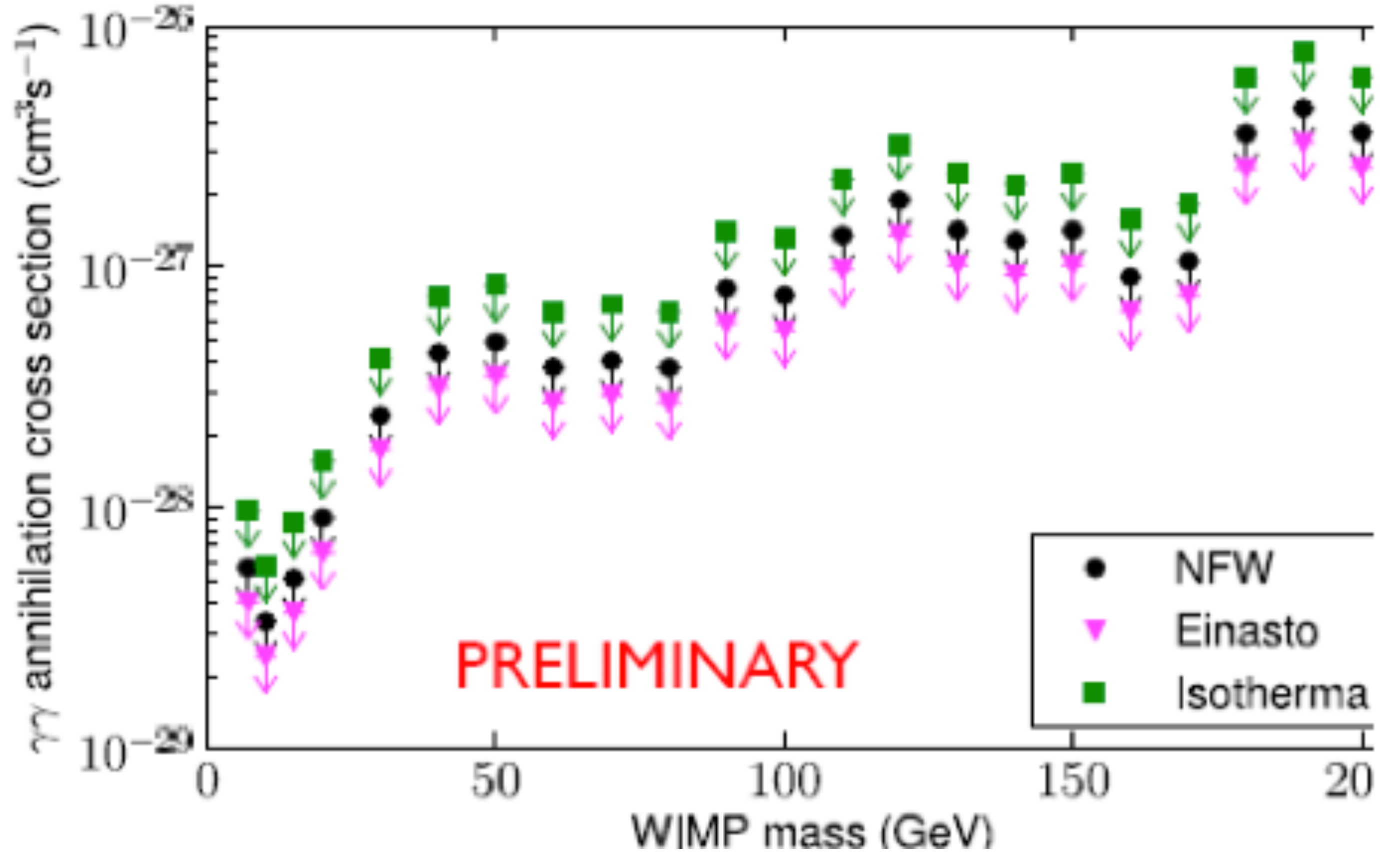
Gamma-Ray Line Survey: Results



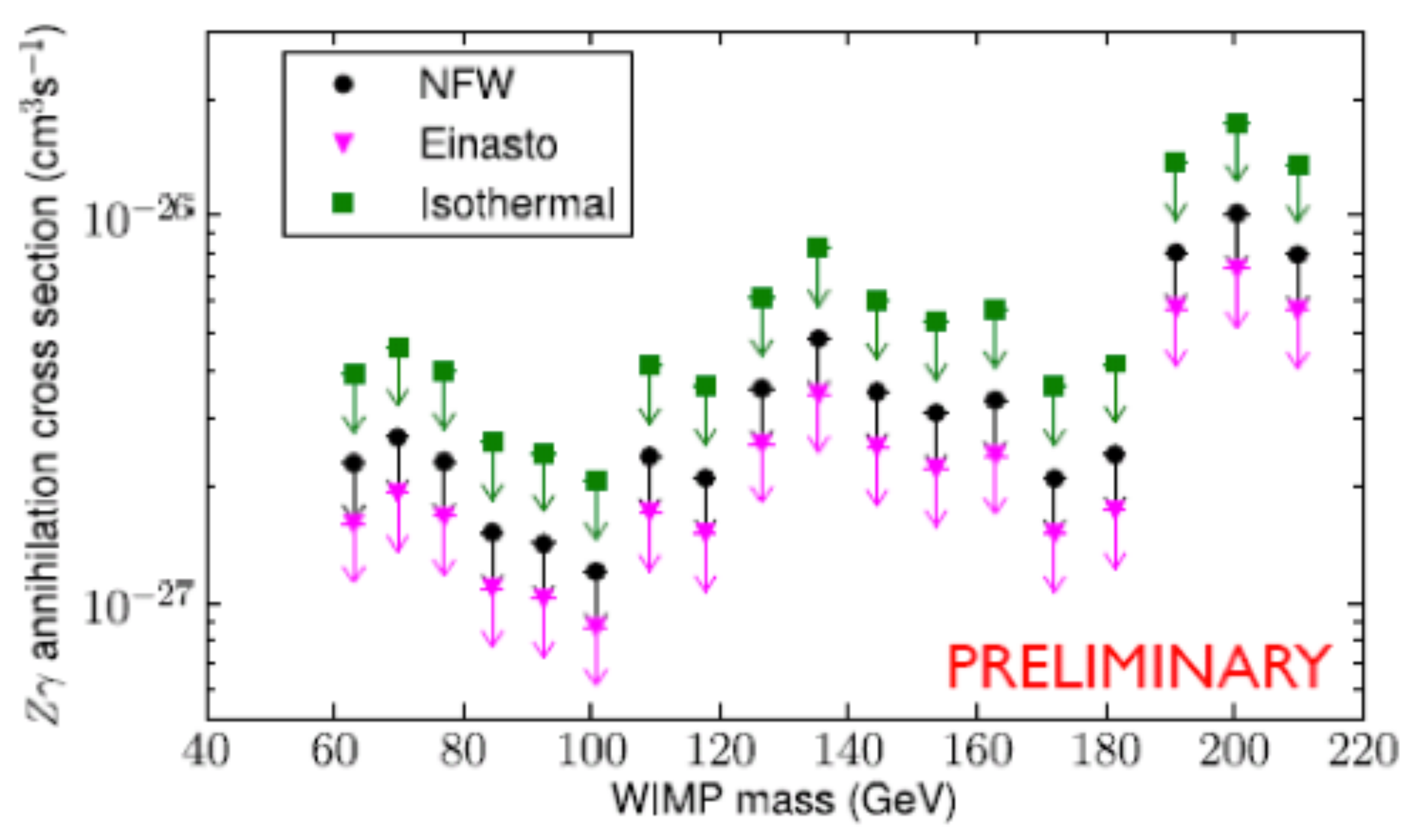
- Background is well fit by a power law (χ^2/dof = 1.2)
- Index 2.438 +/- 0.010

Gamma-Ray Line Survey: Results

- These place strong limits on the cross-section for annihilation directly into γγ



- Limits are in some contention with the recent results of Weniger (2012), who reports a signal at 130 GeV with a 3σ post-trial significance



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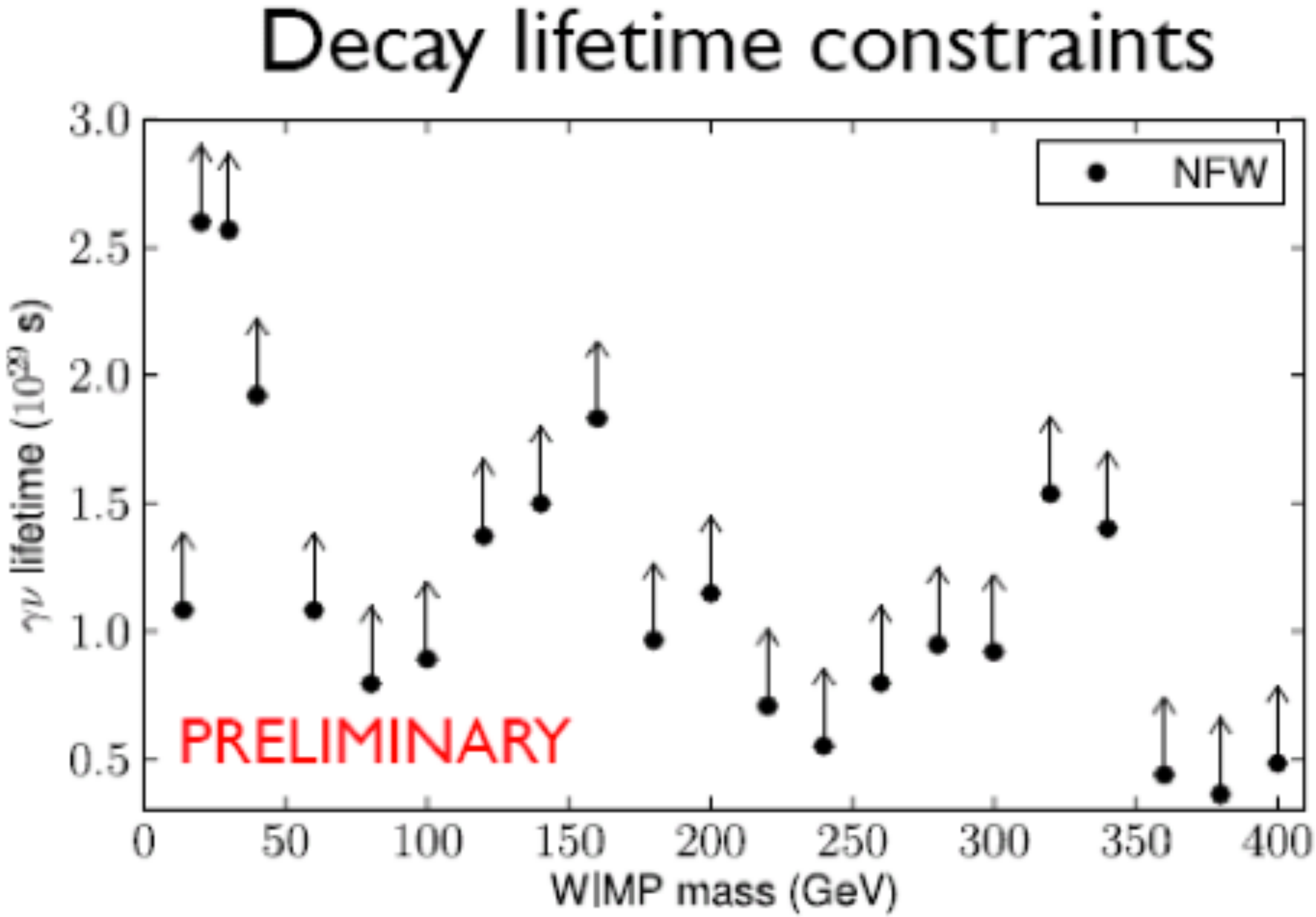
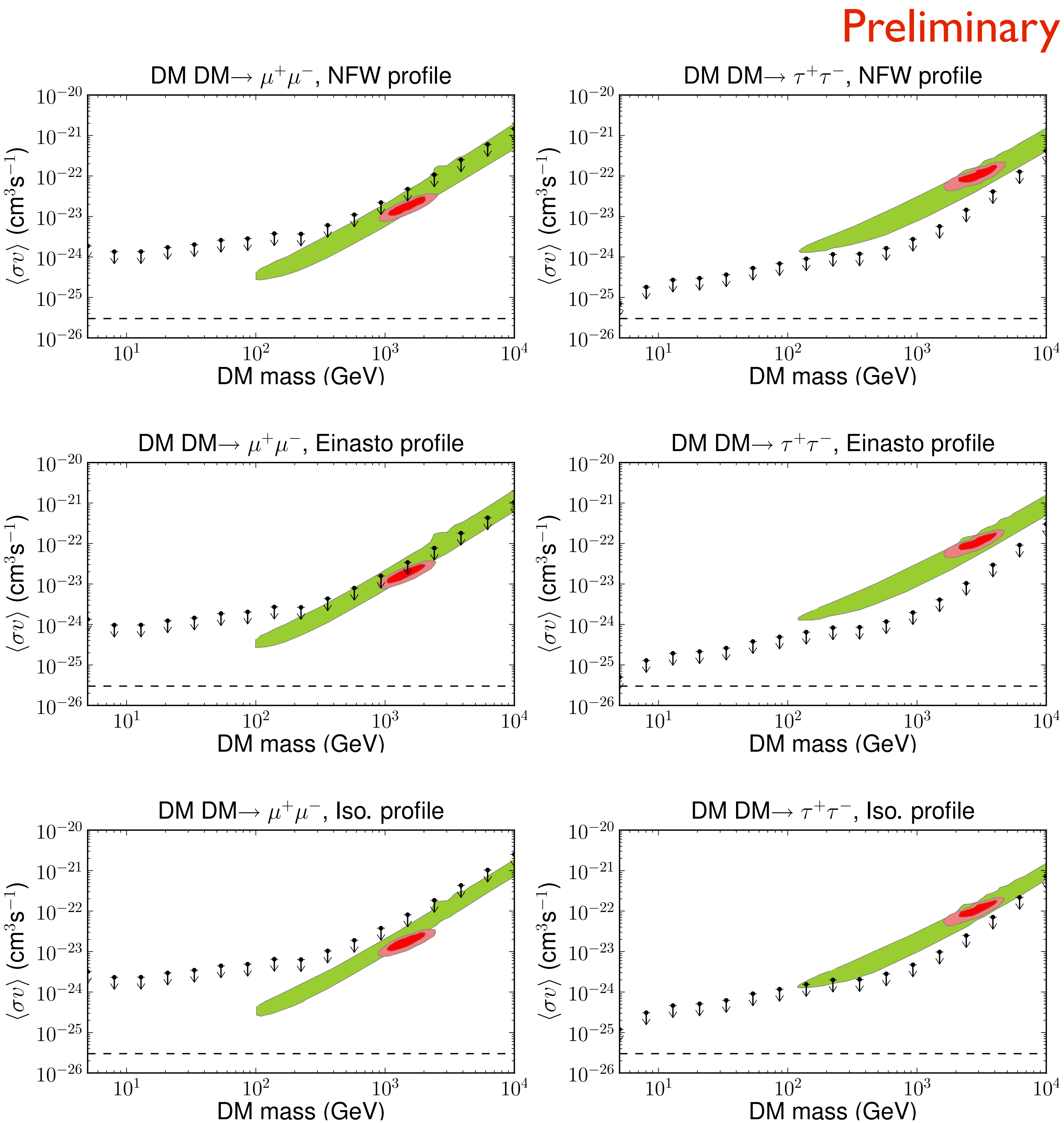


- The model also places extremely strong limits on the decay lifetime (shown for NFW profile)

Gamma-Ray Line Survey: Results

- The line search can also be generalized to a search for hard γ-ray spectra

- This sets stronger constraints than the Halo analysis for several DM channels with hard spectra, such as $\tau^+\tau^-$



Gamma-Ray Line Survey: Conclusions

- The high energy-resolution of the Fermi-LAT has allowed for a systematic study of gamma-ray lines -- limiting the cross-section for direct production of $\gamma\gamma$ to be sub-thermal

- Constraints from spectral information are also applicable to dark matter annihilation pathways with hard spectra

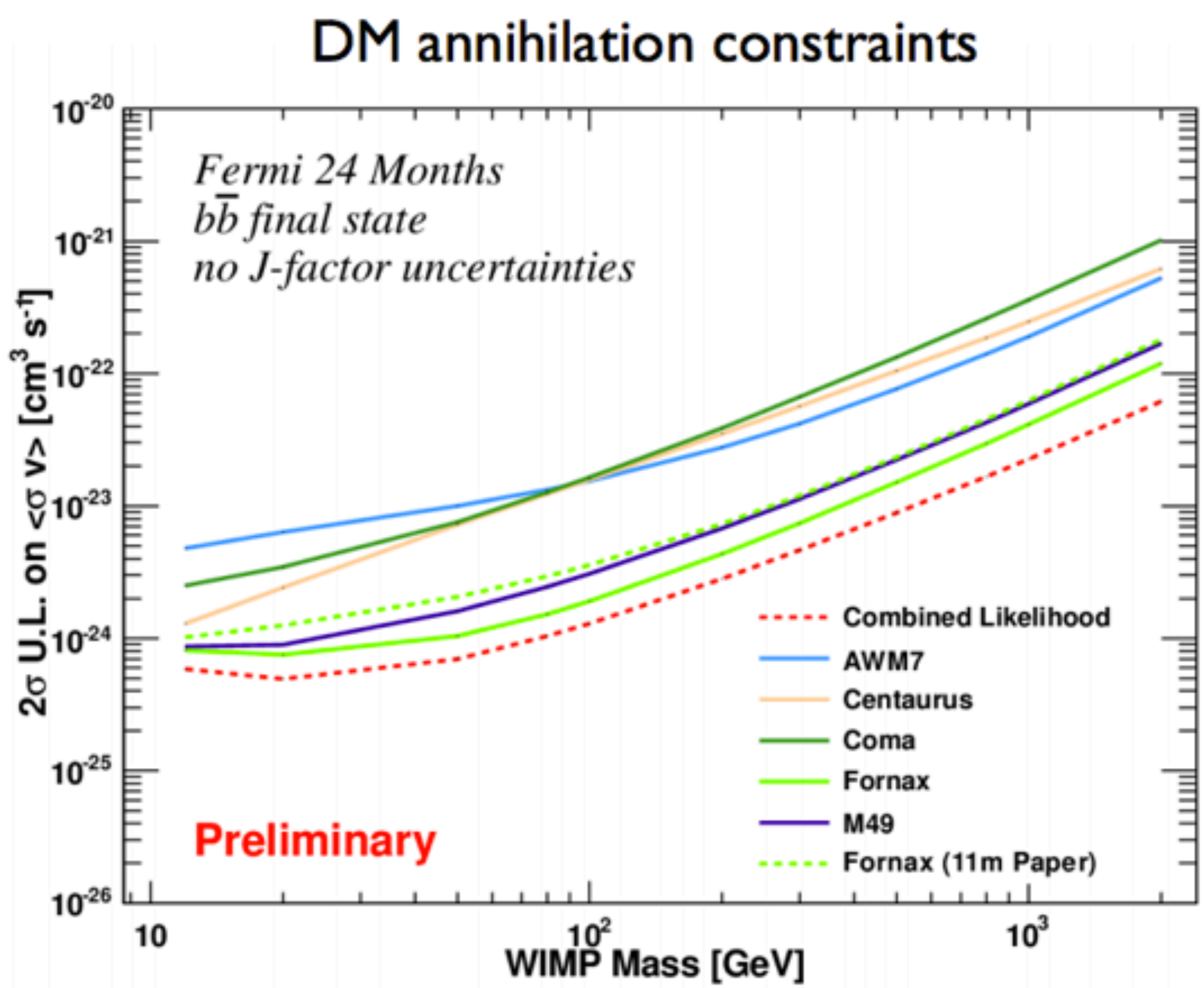
- Currently, an exciting topic of study (see papers by Bringmann et al. 2012, Weniger 2012, Profumo & TL, 2012, Tempel et al. 2012)

Gamma-Rays from Clusters

- GOAL: Search for a spectral signal from an annihilation of dark matter in nearby galaxy clusters
- Targets: Any annihilating or decaying dark matter particle which produces photons directly -- or possibly produces a very hard spectrum of single photons through internal bremsstrahlung
- Benefits: Extremely dense dark matter densities lead to large annihilation cross-section. Can pick clusters lying off the galactic plane.
- Difficulties: Clusters are far away, leading to smaller flux. Many clusters hold AGN and other significant backgrounds.

Gamma Rays from Clusters: Results

- 24 months of data processed with P6_V11
- 10 degree ROI around each cluster
- Clusters modeled as point sources
- Currently no detection of an excess!



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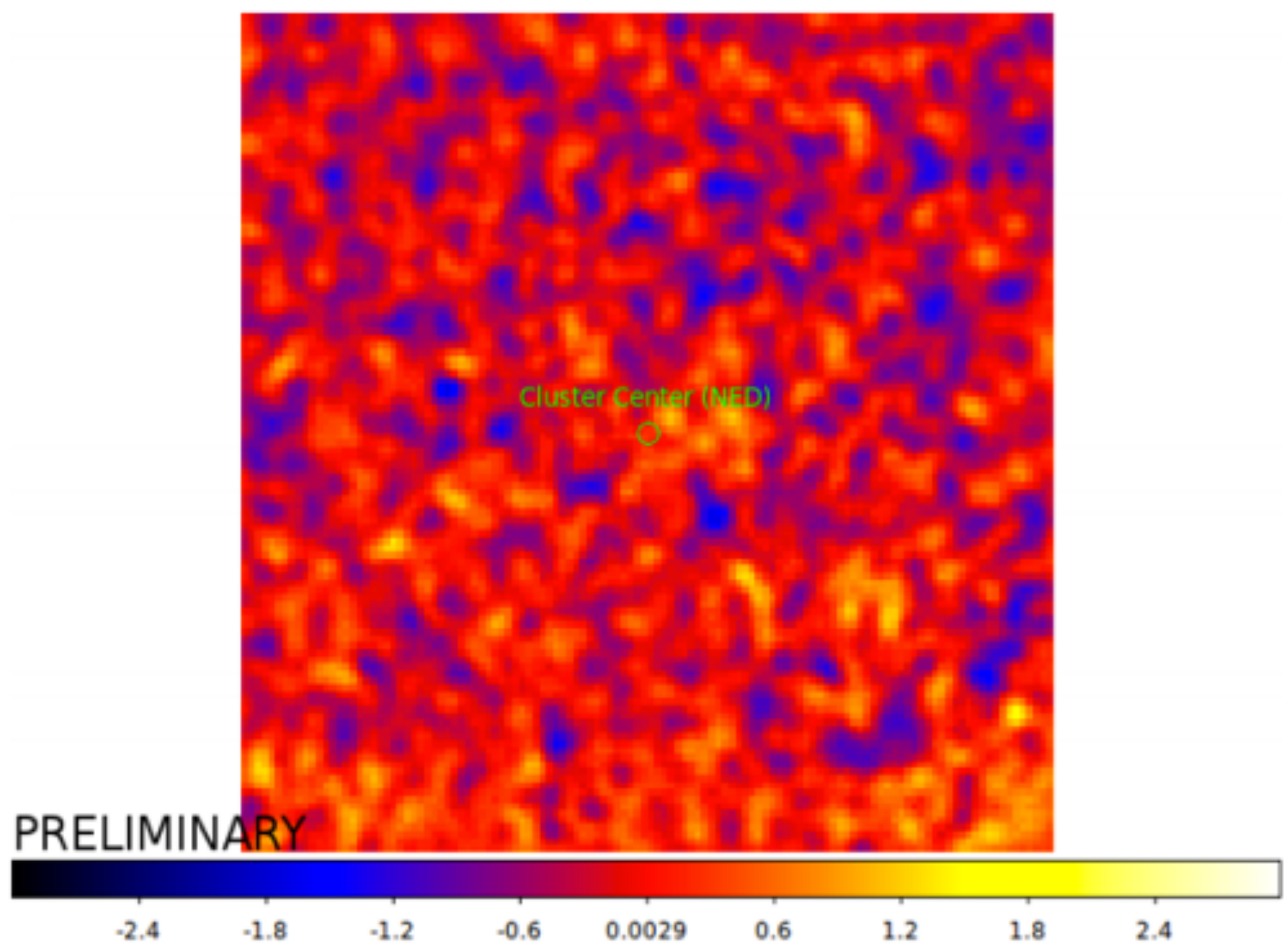
Stacked Residuals



Conclusions

- Investigations by the Fermi-LAT are starting to probe the thermal cross-section for dark matter annihilation
- The Fermi-LAT team has tested the dark matter hypothesis in multiple contexts - due to astrophysical backgrounds and modeling assumptions, this is imperative to establishing strong limits.
- Stay tuned to further talks (today!) on additional dark matter searches with the Fermi-LAT