A Search For Spectral Lines From WIMP Annihilation in the Milky Way Using the Fermi Large Area Telescope

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Representing the Fermi LAT Collaboration

3rd Fermi Symposium
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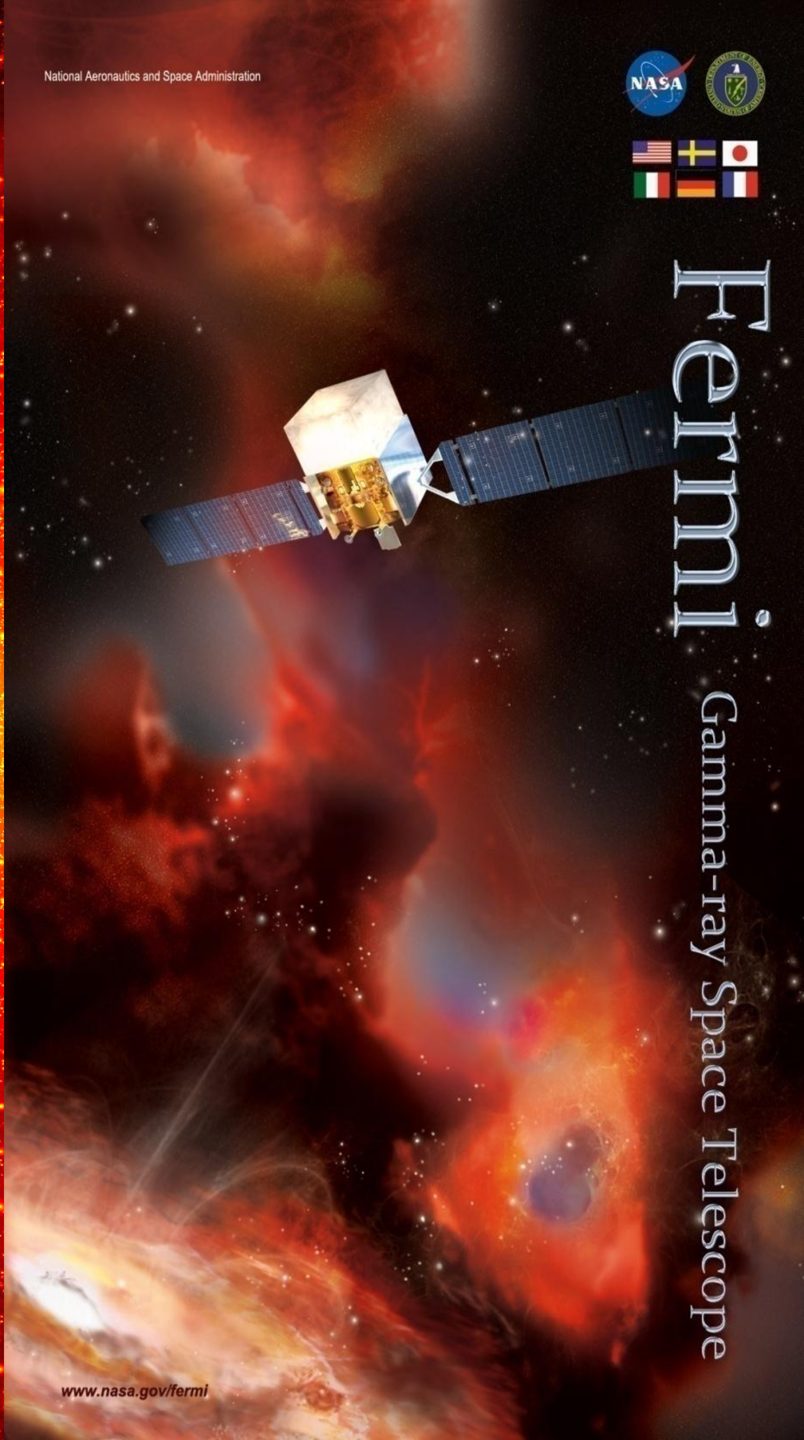
Via Lactea II



Photon Line Search Region of the Sky and Data Selection

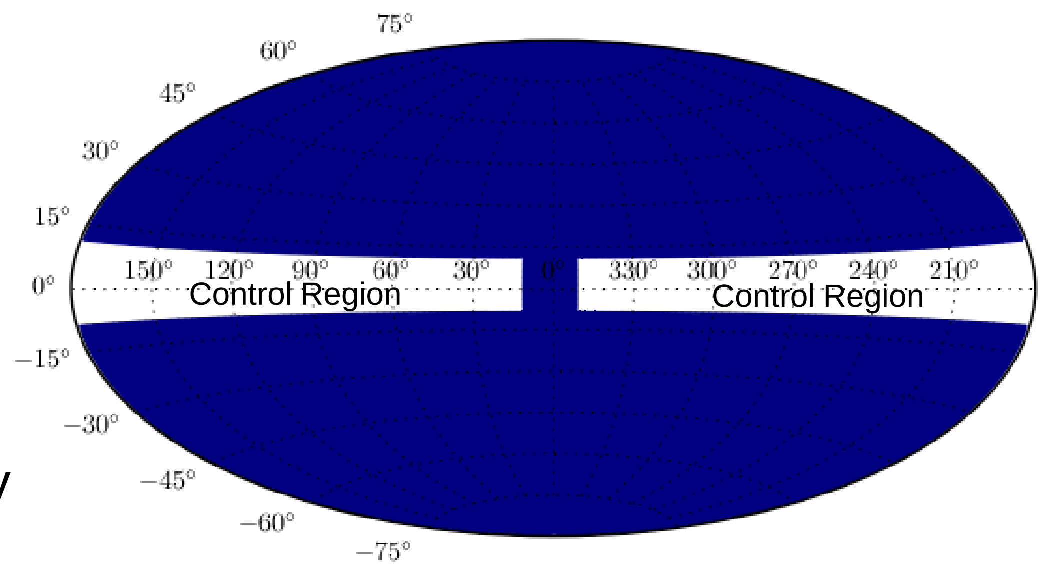
- August 7, 2008 - June 30, 2010 – ~23 months of data
- Remove Galactic Plane except for GC: includes (|B|>10°) | (|L|<10°)
- LAT Profile Energy (fit shower profile assuming cylindrical symmetry) in range [4.8, 264] GeV (the profile energy is not public at this time).
  - Best results for line analysis, not so important for standard astrophysics analyses. Pass 7 coming this year solves the energy measurement issue.
- P6V3 Data Clean Cuts (now public) && (LAT frame theta) < 65º && (Earth zenith angle) <105º && abs(LAT Rocking angle) < 52º
- Removed 1087 point sources, using 1FGL Catalog (1451 sources total).

  ✓ Cut Radius @ PSF 68% containment

  ✓ 6 point sources within a 1 deg by 1 deg square at the GC are not removed.

  ✓ Removes ~10% of photons

Region of the Sky Used in Analysis



- This work is largely based on the thesis of Y. Edmonds of SLAC, Stanford University. She successfully defended her Thesis on March 3rd.

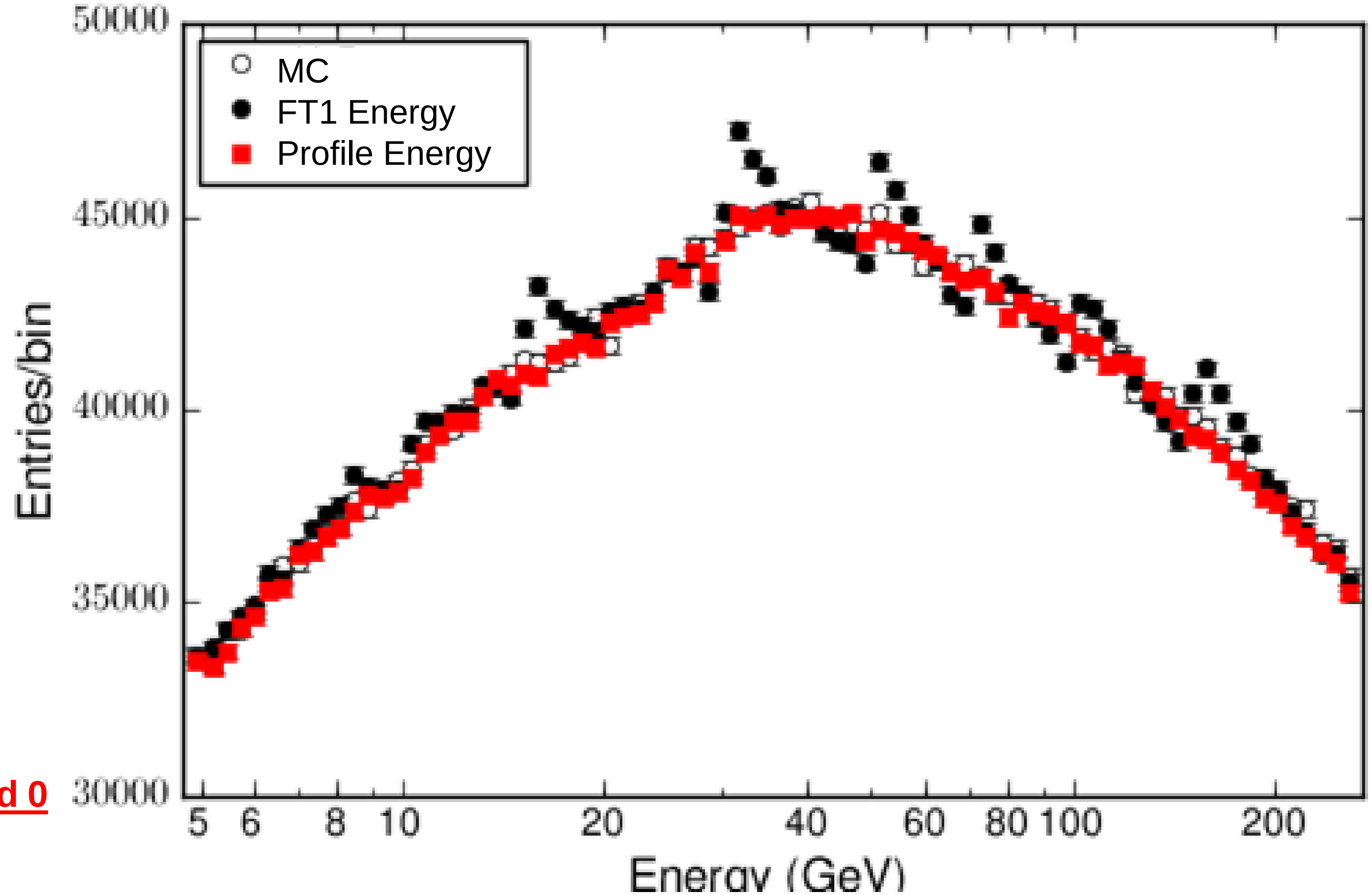
Why Use The Profile Energy for the LAT Line Search?

• P6V3 FT1 energy is not well suited to perform a line search.

✓ FT1 energy has a number of structures at the few percent level that could be mistaken for photon lines from 5 GeV – 300 GeV. Impacts ULs.

•These structures don't affect typical astrophysical analyses.

• The Energy measurement problem is corrected in Pass7, which will be released this year (2011).



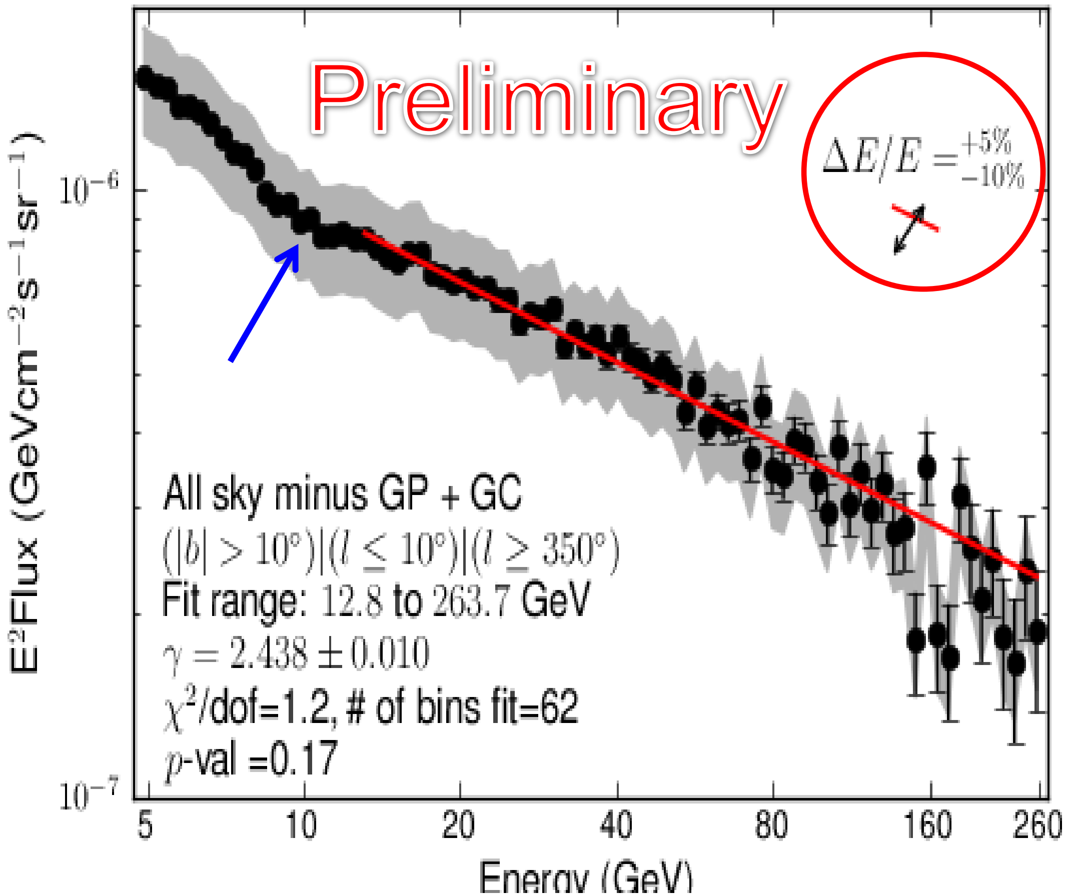
Suppressed 0

Fermi LAT Inclusive Photon Spectrum from ROI 4.8 – 264 GeV

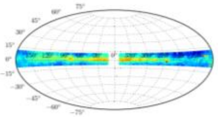
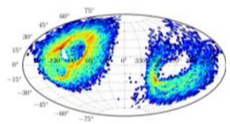
- Inclusive Photon Spectrum is featureless power-law, index ~2.44 (13 < E < 264 GeV)
- Estimate background from charged particles to be < 5% for E > 100 GeV based on results from LAT Extragalactic Background results (Abdo et al. 2010), and MC of CR background spectrum yielding index ~ 2.6 after cuts (compared to our measured index of 2.44 for γs). No additional CR subtraction is made based on this estimate at this time.

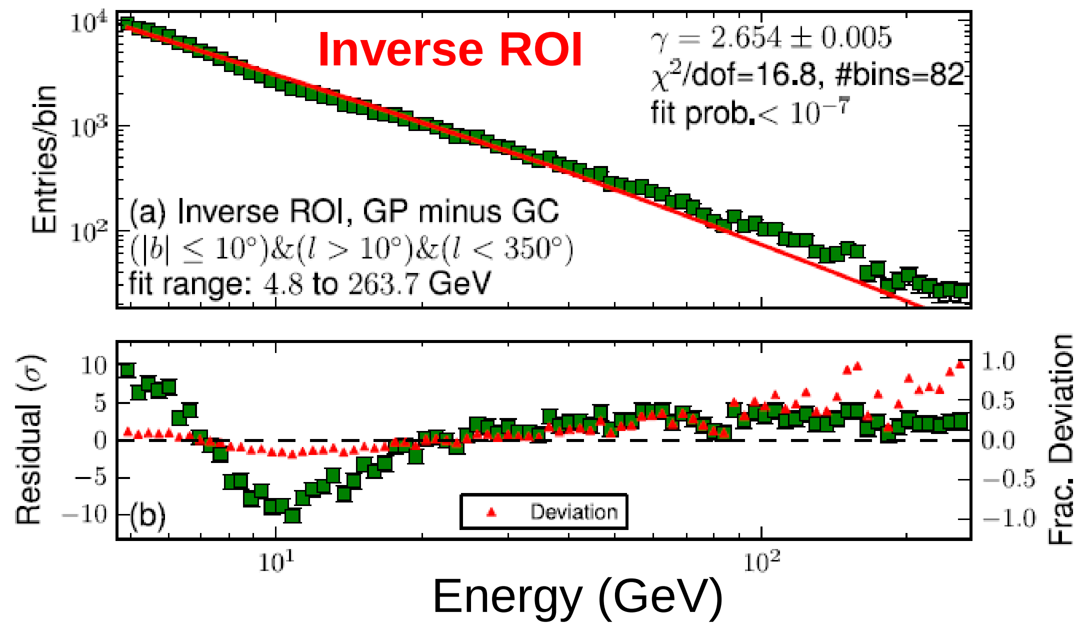
E^2 x flux [GeVcm^{-2}s^{-1}sr^{-1}]
P6V3 dataclean class

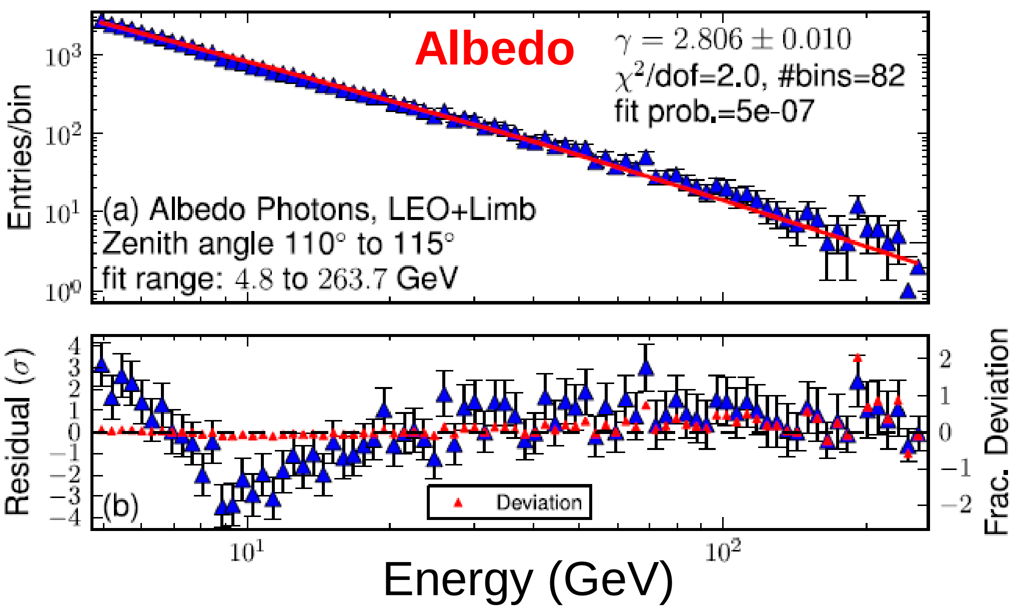
± 20 % Systematic error on effective area



Control datasets spectral fitting

- Inverse RO 
  - Structure is more significant
  - 5 GeV bump ~10σ, 10 GeV dip ~12σ
- Albedo 
  - Structure is present





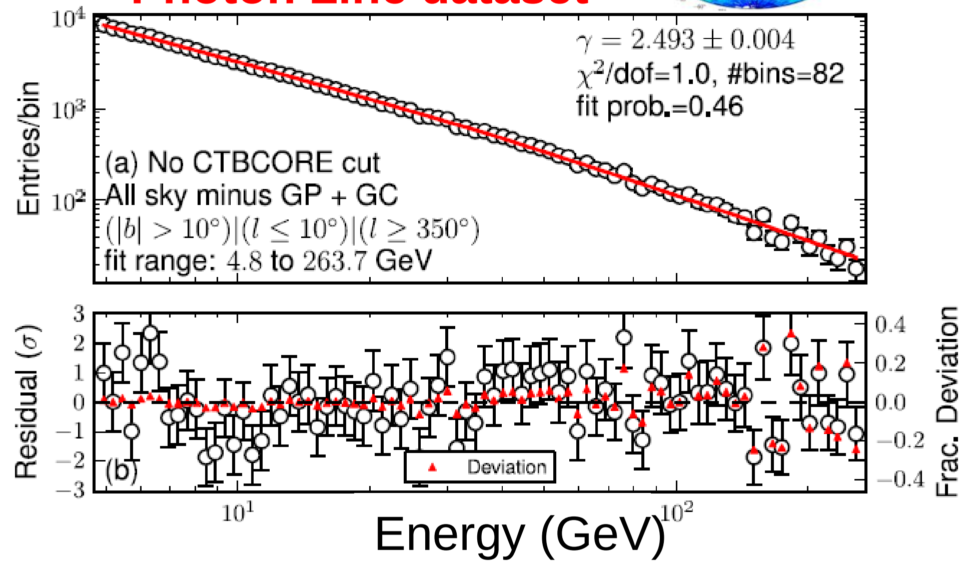
- Structure at ~5 and ~10 GeV must be systematic effects!
- Possibility of causing false detection in the line search
- Published line analysis we used events above 20 GeV, no issues.

Removing the CTBCORE Cut

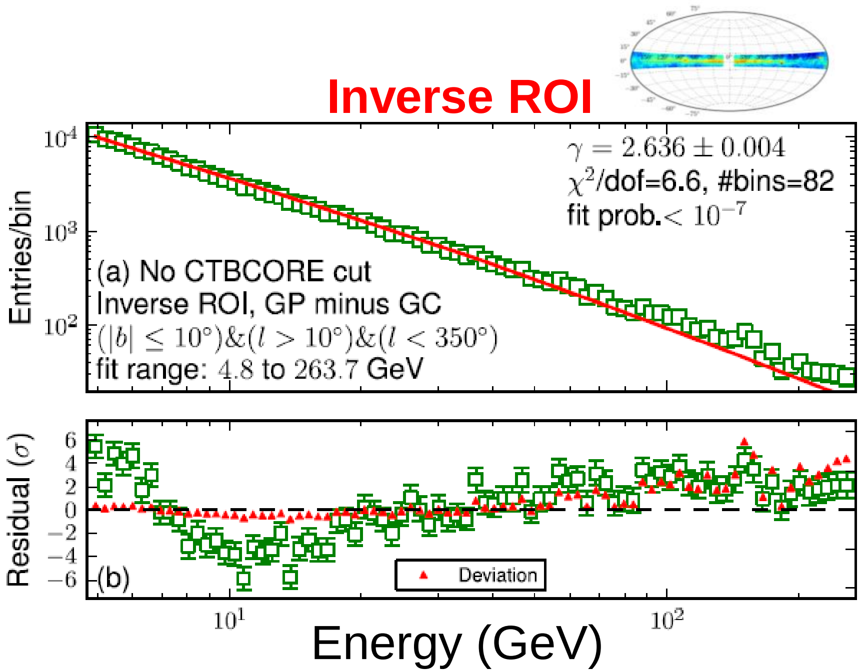
CTBCORE is used to improve γ PSF.

- Residual structure is highly muted
- Fit probability improved

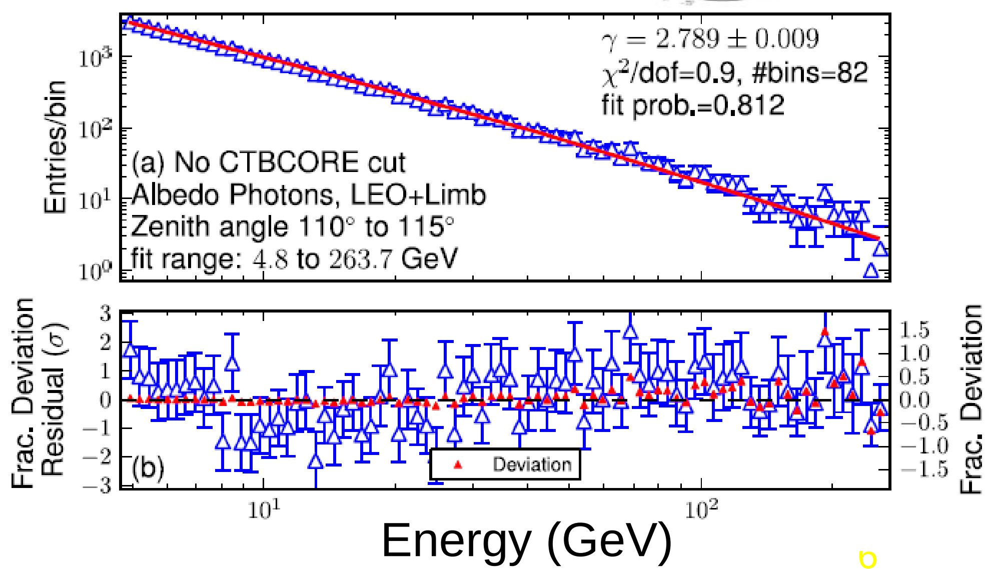
Photon Line dataset



Inverse ROI

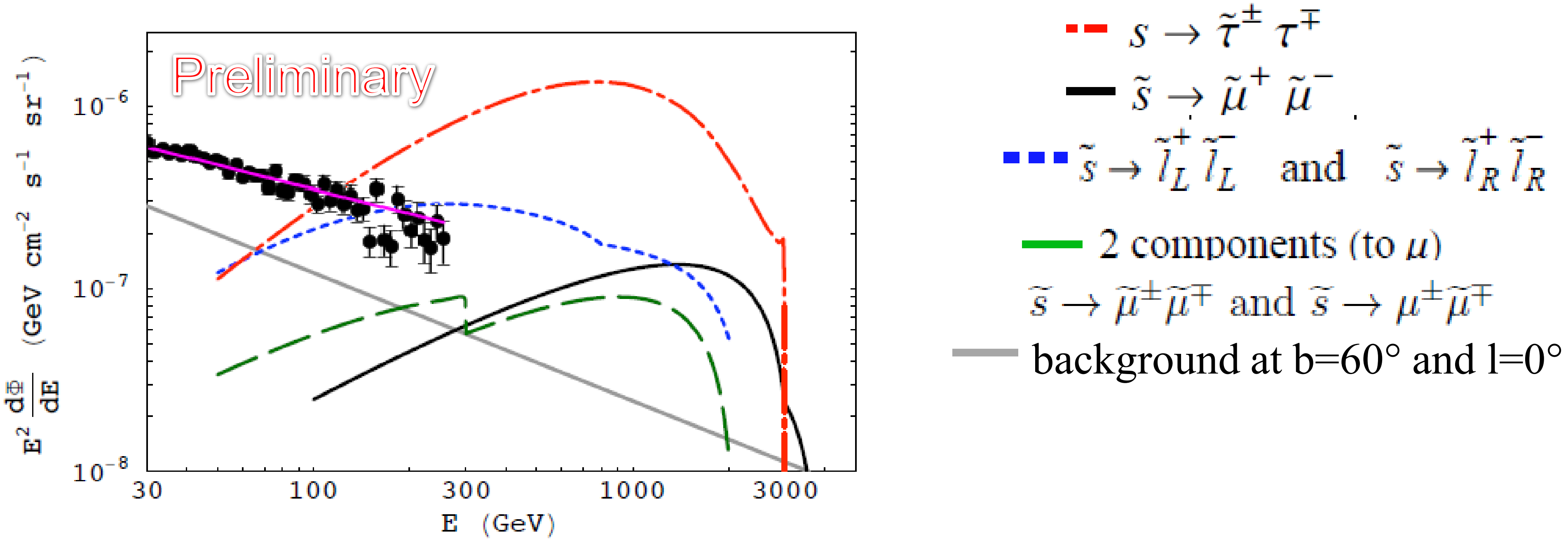


Albedo



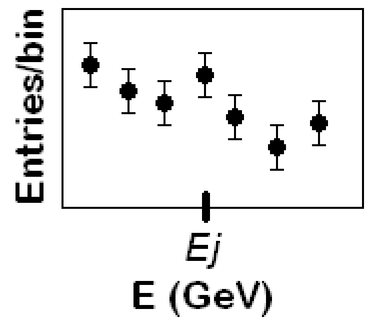
Dark Matter Implications

- Featureless spectrum has implications for DM models with final state radiation
  - Line search not optimized for such broad features
- Figure from Arvanitaki et al. arXiv:0904.2789v2 [hep-ph]
  - Plot of gamma-rays from final state radiation and τ decay for 4 models with decaying TeV DM
  - b=60º, l=0º
  - Should be nearly isotropic



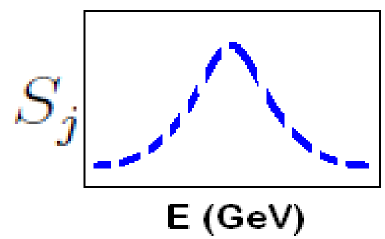
Method for Line Search

- Search for spectral line on energy grid E_j *(7-200 GeV)*

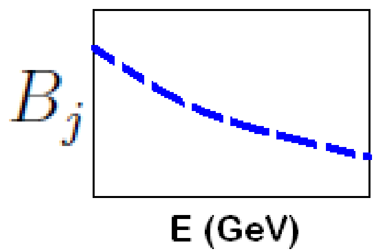


Fitting ranges in search are ± $4\sigma_E$ wide. Unbinned fit over this range.

- Counts spectrum
- Two components
  - Signal distribution

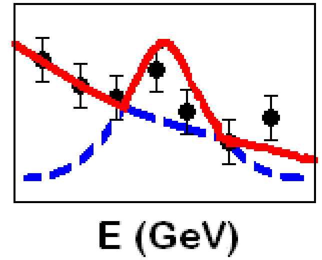


  - Background distribution



- Composite unbinned likelihood fit for fraction of events from signal PDF, f_j

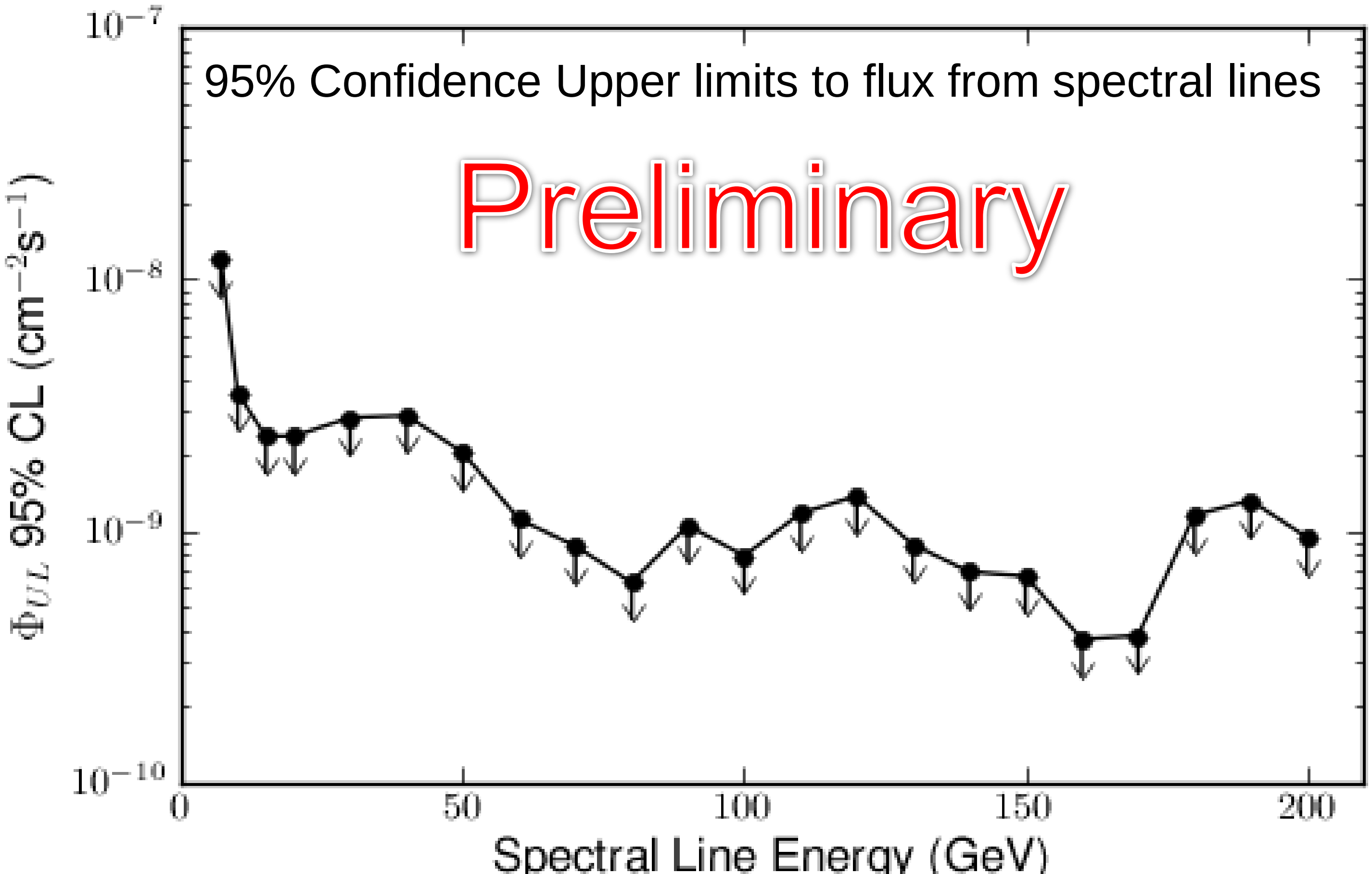
$$\mathscr{L}_j\left(f_j,\Gamma_j\right)=\prod_{i=1}^{N_j} f_j S_i(E_i)+(1-f_j)B(E_i,\Gamma_j),$$
$$-1<f_j<1$$



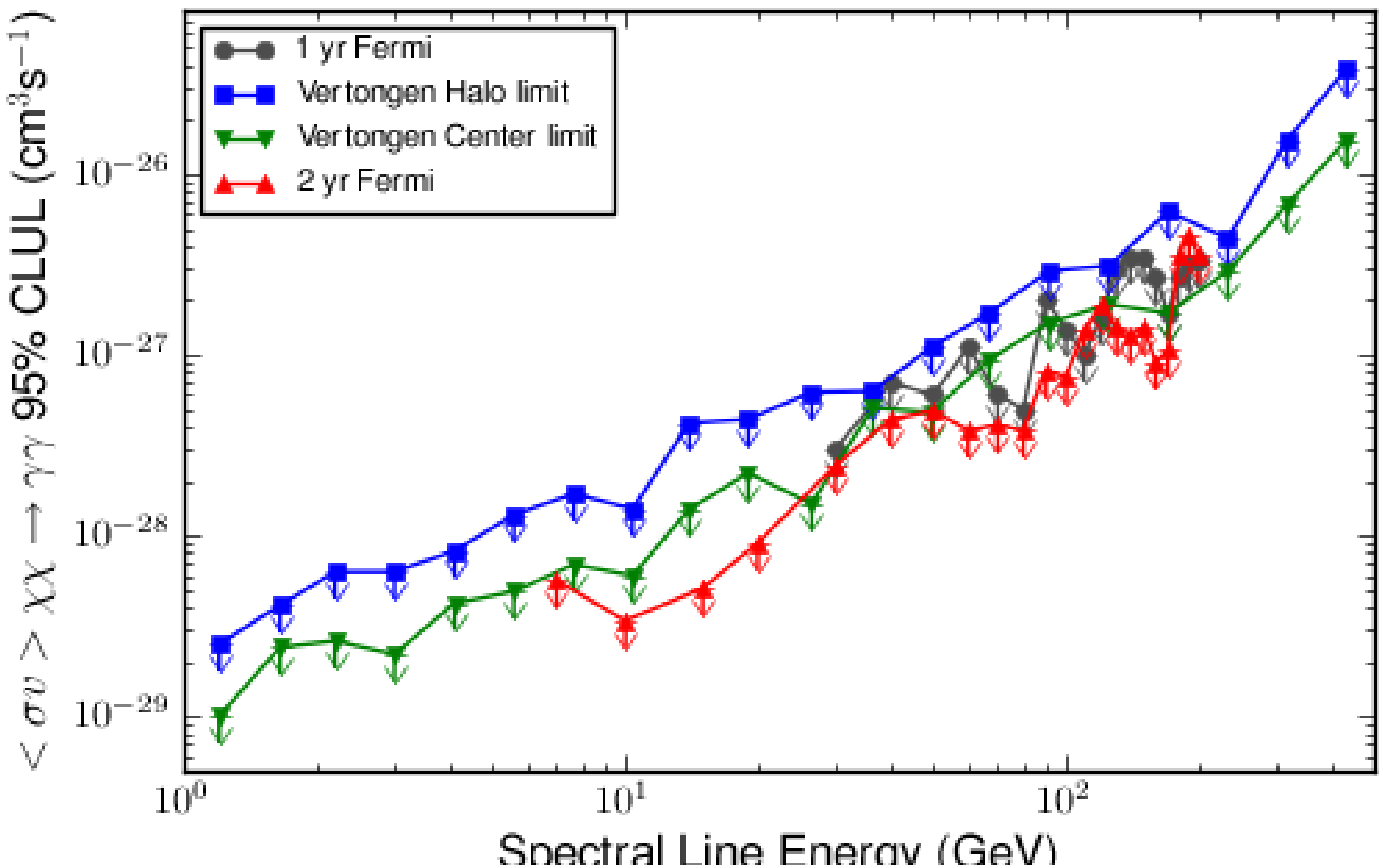
Free parameters:
- Signal fraction
- Spectral index

Fermi LAT 23 Month Line search results
Flux Upper Limits, 7 GeV – 200 GeV

- ± 20 % overall scale systematic error (+20 % systematic for UL).
- Additional systematic on spectral structures with LAT resolution for E < 13.2 GeV of s/bg ~ 1%. **7 and 10 GeV bins use a modified event selection to reduce the systematic uncertainty associated with public IRFs**.
- For E > 12 GeV no indication of a spectral structure systematic effect is seen.

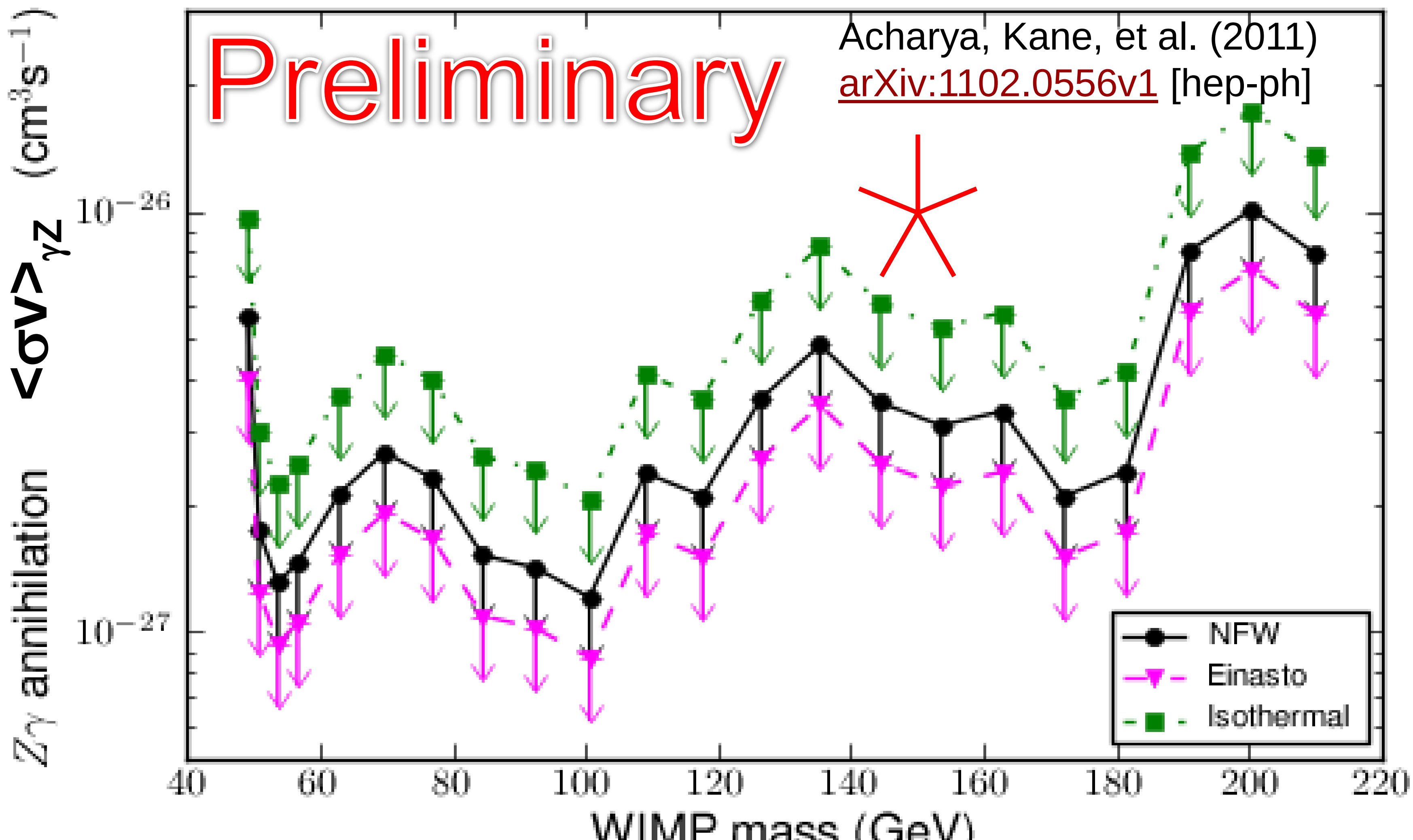


Comparison of LAT Collaboration Analysis to Non-LAT-Collaboration Analysis, Vertongen and Weniger, arXiv:1101.2610v1, for γγ Cross Section Limits.



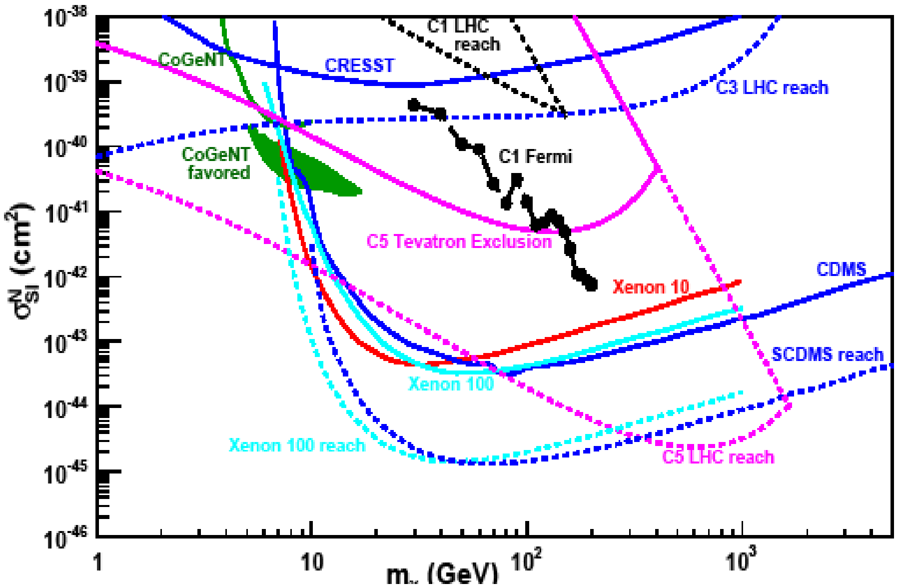
Fermi LAT 23 Month
γZ-Cross-section limits
7 GeV – 200 GeV

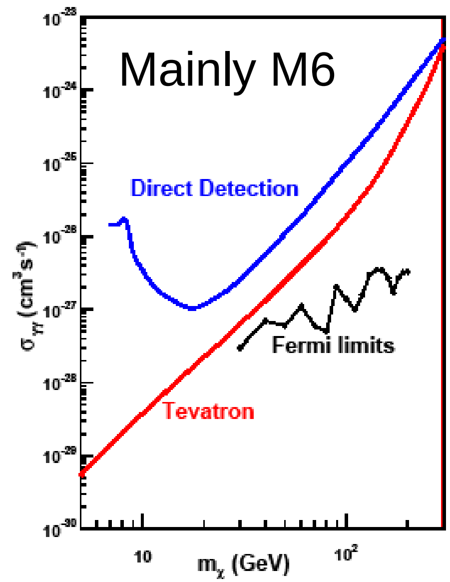
- +20 % overall scale systematic error (UL)
- Additional systematic on structure with LAT resolution for E < 13 GeV of s/bg ~ 1%.
- For E > 12 GeV no indication of a structure systematic effect is seen.

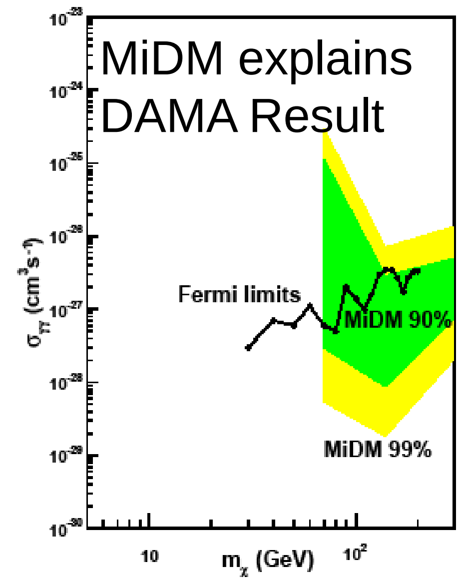


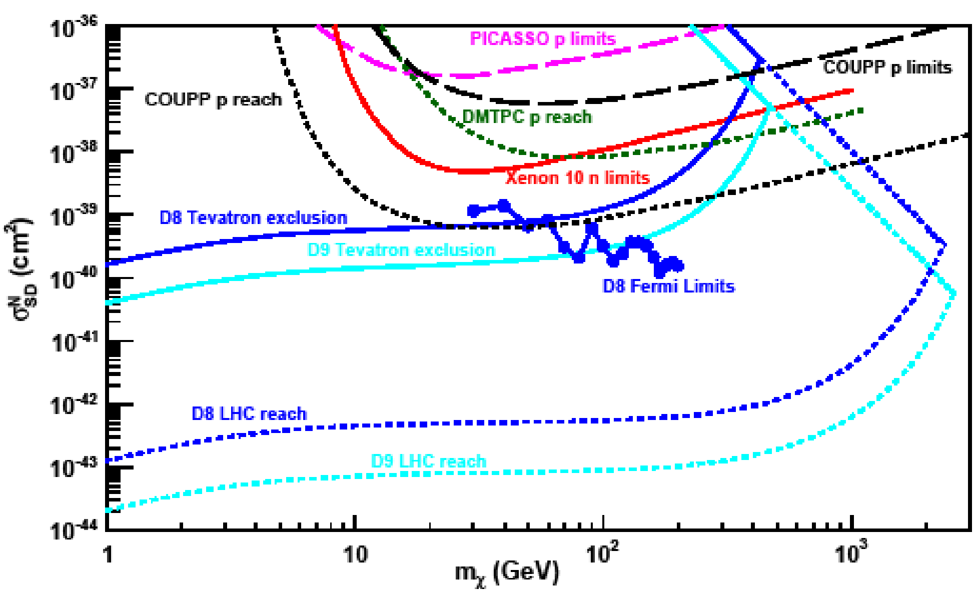
Gamma Ray Line Constraints on Effective Theories of Dark Matter

Jessica Goodman, et al. arXiv:1009.0008v2 [hep-ph] 18 Dec 2010 Fermi data points from **PRL 11 months of data.**





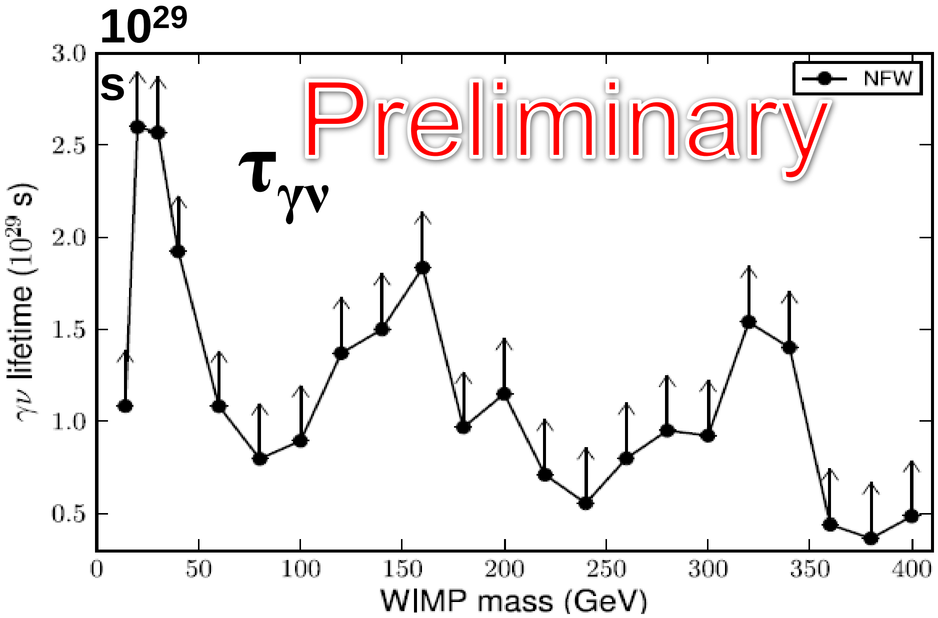




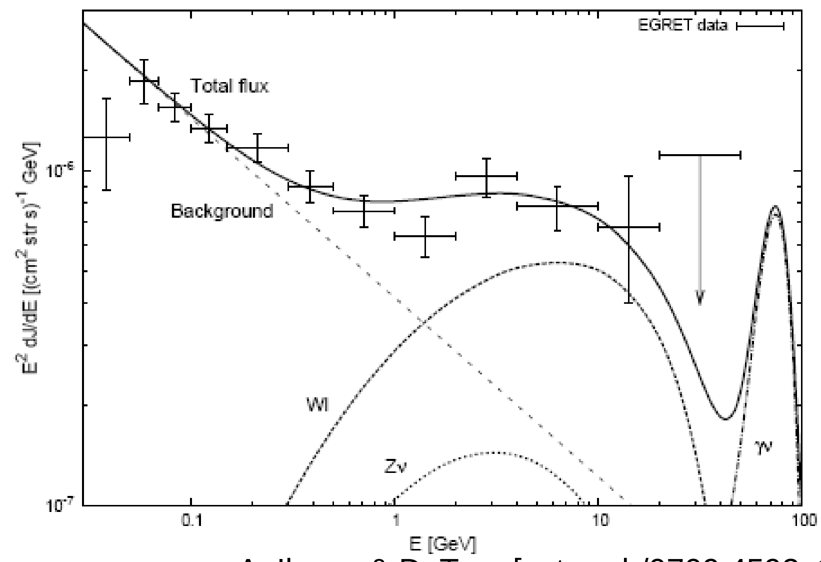
Plots for the PRL line search (1-year of data), mapped into direct detection parameter space assuming an NFW profile. The two plots on left are for a scalar WIMP. The top right indirect detection plots are for a Majorana WIMP. (T. Tait Private communication)

Decay lifetime lower limits

- Limits similar for all 3 DM density profiles due to linear dependence of flux on ρ
- Disfavors lifetimes smaller than 10^{29} s



Gravitino Decay
m_χ = 150 GeV
τ = 2 x 10^{26} s



A. Ibarra & D. Tran [astro-ph/0709.4593v1]

Summary and Conclusions

- Only limits on DM so far, but they are improving as the LAT looks deeper, we improve the instrument analysis, and we better understand the astrophysical and instrumental backgrounds.
  - An example of better understanding shown in this talk is our study the CTBCORE cut impact on the LAT acceptance, and how to fix it. Much better in Pass 7.
- Current Fermi LAT Collaboration DM limits are challenging interesting parts of the theoretical phase space.
  - This is particularly the case for DM models that were invented to explain the ATIC, Pamela, and Fermi electron and positron results.
  - The photon line limits have a broader significance beyond specific models using an effective field theory formalism. Easy comparison with direct detection and accelerator DM results (J. Goodman, et al. arXiv:1009.008v2 [hep-ph], 18 Dec 2010).
- Pass 7 will be a significant improvement and will be released this year. The energy measure and acceptance systematics are highly muted over Pass 6. Pass 8 is in the works!

Extra Slides

Photons from WIMP Annihilation

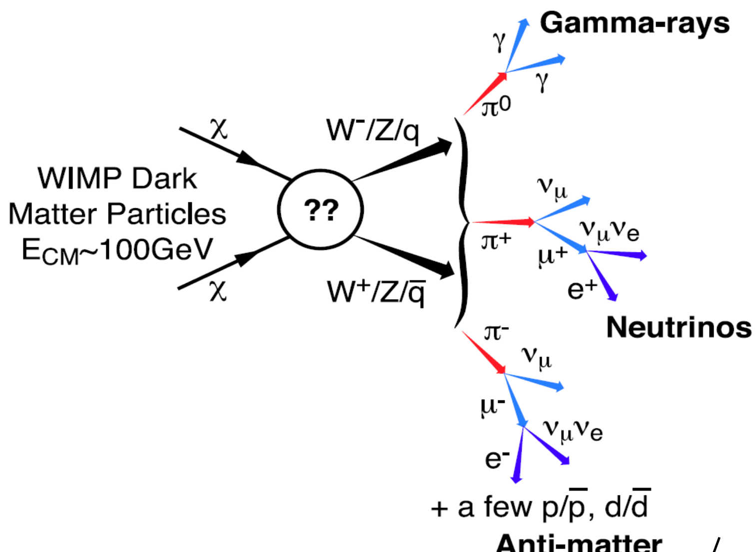
$$\frac{d\Phi_\gamma}{dE_\gamma}\left(E_\gamma,\phi,\theta\right) = \frac{1}{4\pi}\boxed{\frac{\langle\sigma_{ann}v\rangle}{2m_\chi^2}\sum_f \frac{dN_\gamma^f}{dE_\gamma}B_f}$$

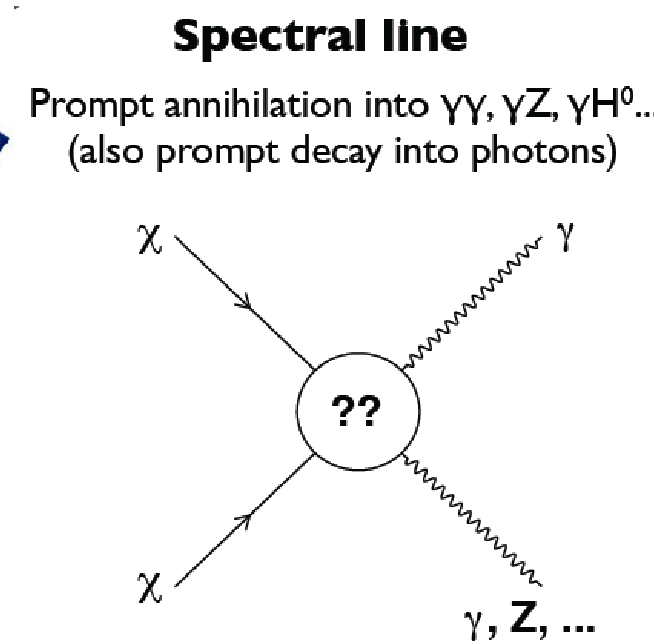
$$\times \boxed{\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los}\rho^2\left(\vec{r}\left(l,\theta',\phi'\right)\right)dl}$$

Particle Physics

J ≡ DM Distribution

- Charged particles are more complicated (need to include propagation, energy losses)





Note: For a decaying DM particle $\frac{\langle\sigma v\rangle}{2m^2}\rho^2 \rightarrow \frac{1}{m\tau}\rho$

Search For Spectral Lines

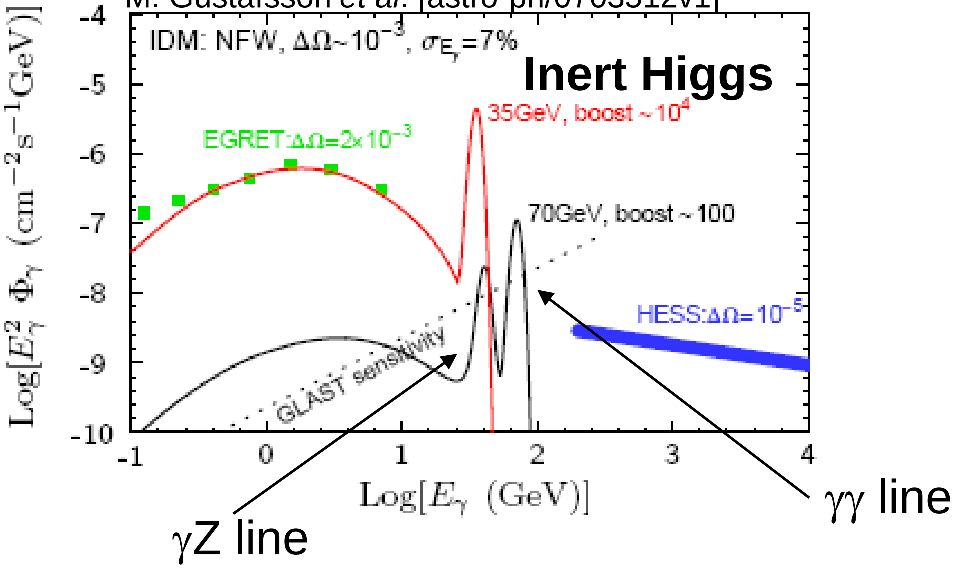
- Clean signal of dark matter with no astrophysical uncertainties!
- **WIMP** Annihilations (Decay) $\rightarrow$ $\gamma\nu$, $\gamma\gamma$, γZ, γH^0, …

- The photon line signal is suppressed in SUSY as internal loops are needed in that case. However, the signal is enhanced in other models such as Inert Higgs, and gravitino decays.

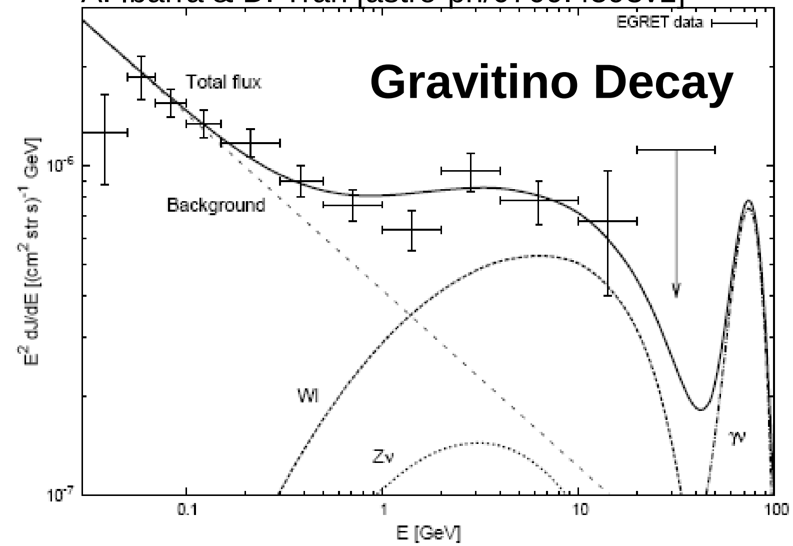
Particle	Branching Ratios
Neutralino	10^{-3} to 10^{-5}
Inert Higgs Gustafsson, Lundstrom, Bergstrom, Edsjo. March 2007	0.36 to 10^{-4}
Gravitino Ibarra, Tran. Sept 2007	0.66 (85 GeV) 0.05 (150 GeV)

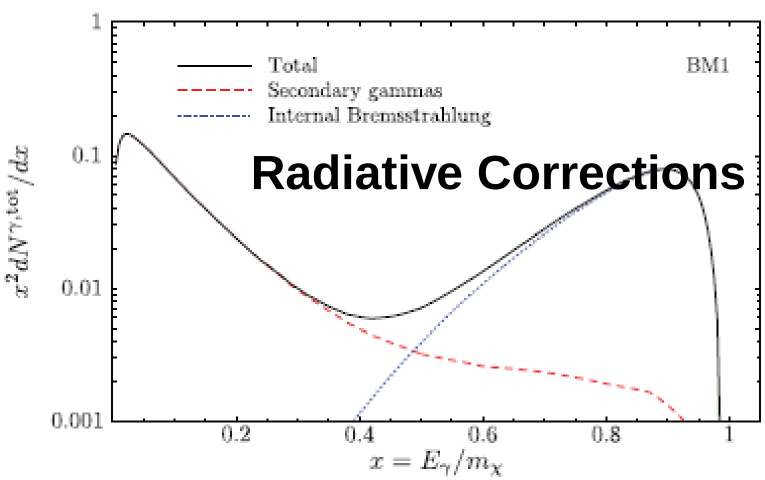
Theories with Enhanced Lines

M. Gustafsson *et al*. [astro-ph/0703512v1]



A. Ibarra & D. Tran [astro-ph/0709.4593v1]





T. Bringmann *et al*. [hep-ph/0710.3169v2]

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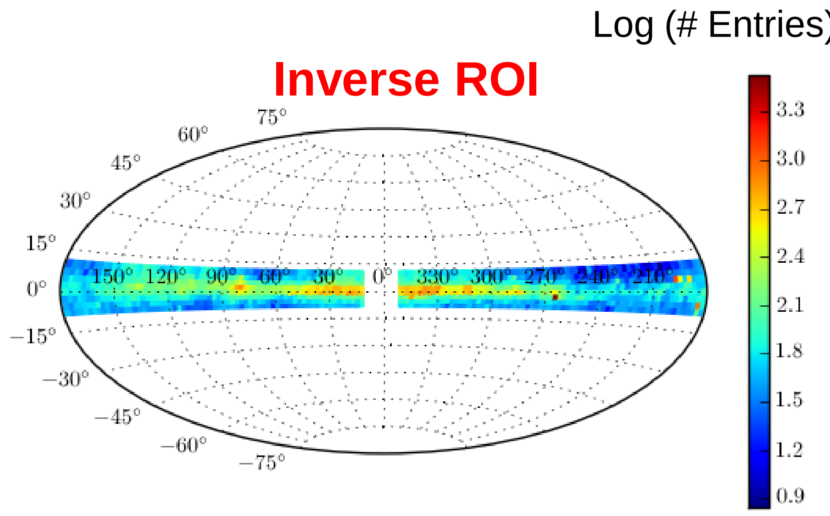
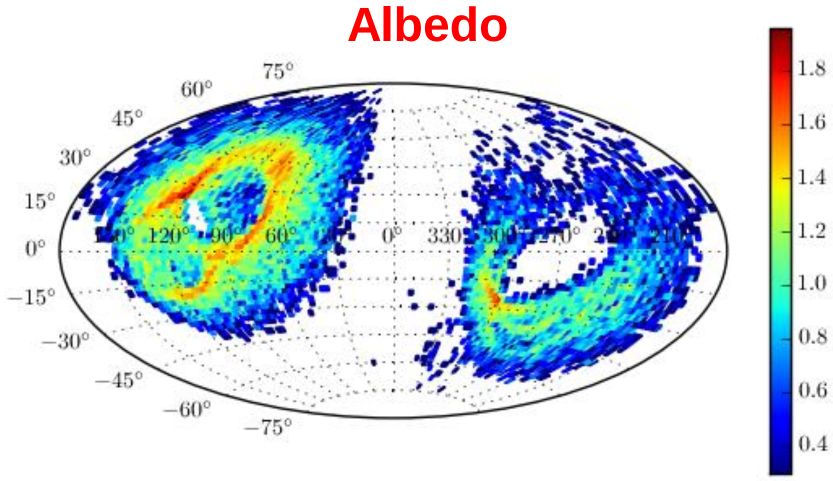
Control datasets

- Inverse ROI
  - Galactic plane excluding Galactic center
    - Point sources included
    - Bright diffuse emission
    - No DM density enhancements expected from DM profiles
  - Number of events (122,000) larger than line dataset
- Albedo photons
  - Gamma-rays from interaction of cosmic rays with Earth atmosphere
    - No signs of DM or sources
  - LAT albedo paper: arXiv:0912.1868v1 [astro-ph.HE]
    - ~60 days of observation time
  - Significantly fewer events (34,000)

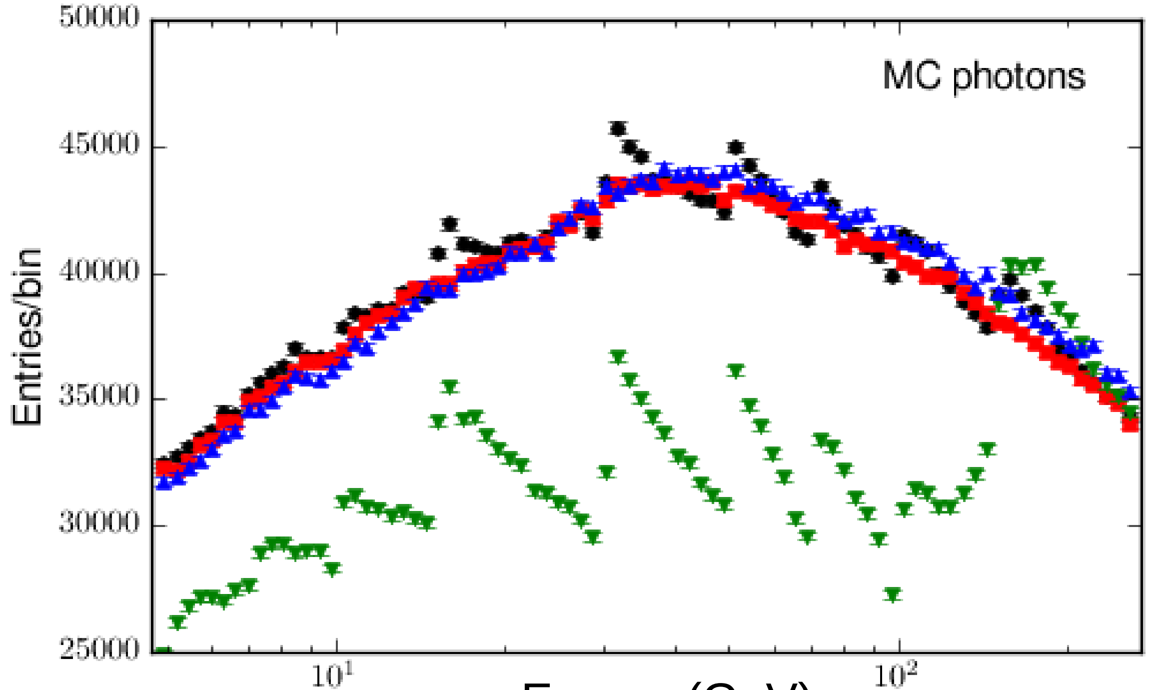




P6V3 Energy Reconstruction Method Selection

- 3 LAT energy reconstruction methods:
  - ■ Shower Profile
  - ▼ Likelihood
  - ▲ Parametric Correction
  - ● CTBBestEnergy
    - Selected from available energies
    - publicly available

MC photons

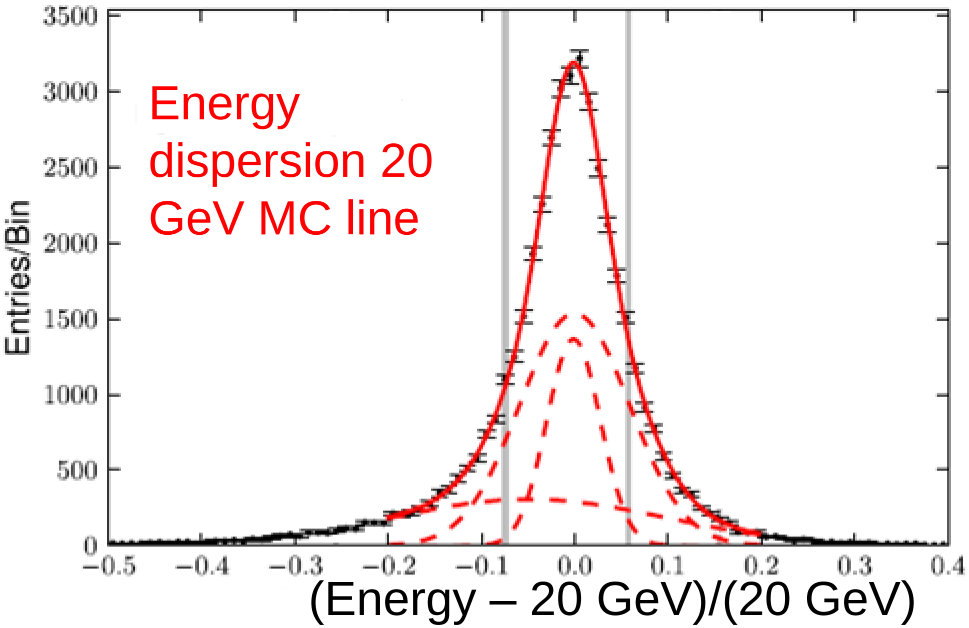


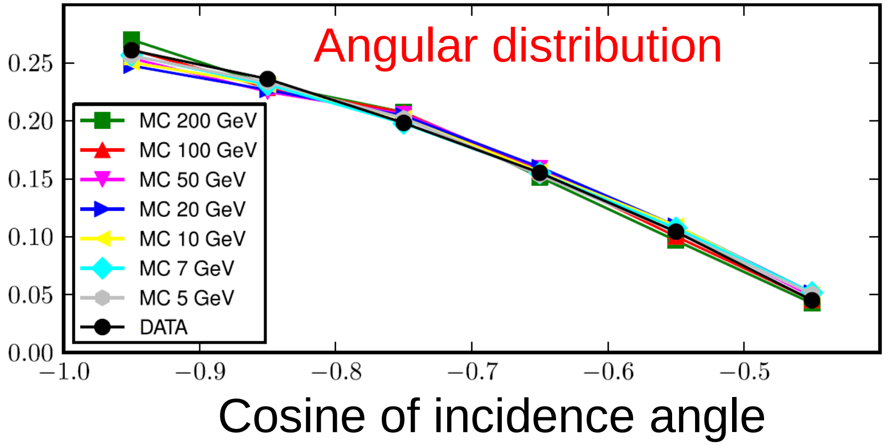
suppressed zero

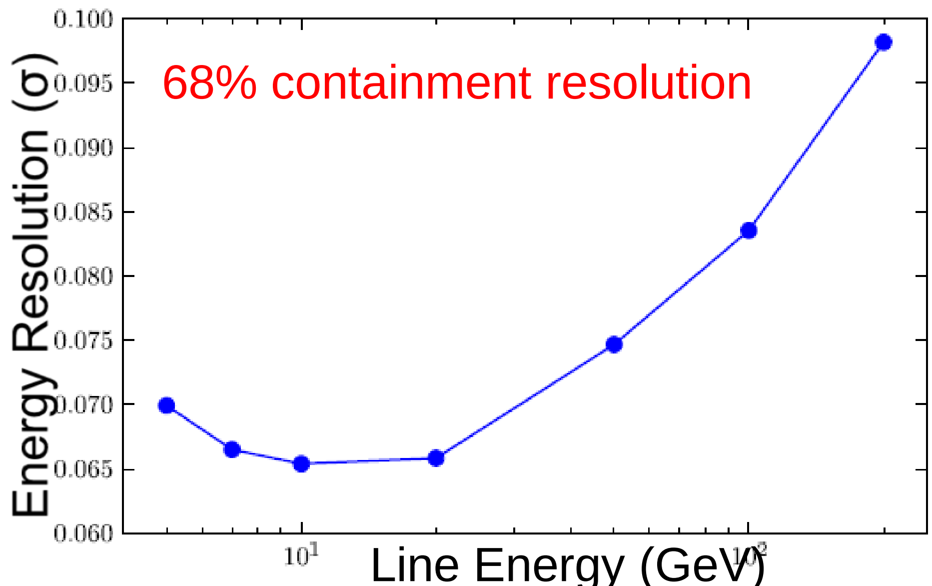
The Energy measurement problem is corrected in Pass7, which will be released this year (2011).

Instrument Response to Lines

- Simulate spectral lines with LAT MC at 5, 7, 10, 20,50, 100, and 200 GeV
- Generated uniformly over LAT face
  - Distribution of incidence angle in MC similar to line dataset
- Fit energy dispersion to sum of 3 Gaussians to get simple parameterization of line shape







Search for Spectral Lines

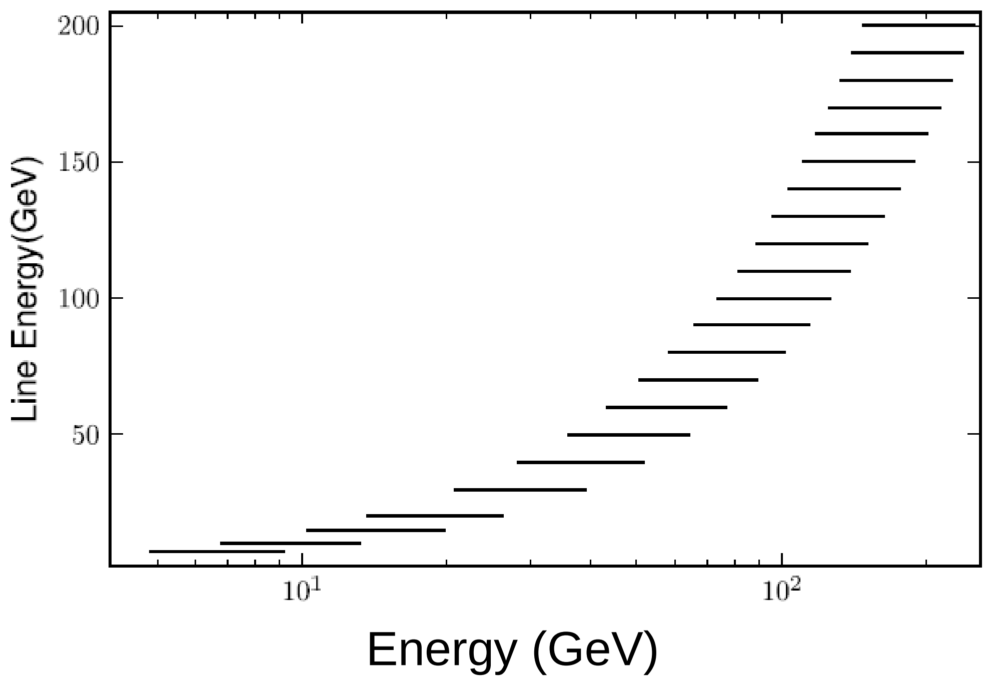
- The shape of the line is determined by the Fermi LAT resolution function for the profile energy determined via MC and checked with beam test results.
  - Resolution (68% containment) = - 8% + 5% @ 7 GeV
  - Resolution (68% containment) = -10% +10% @ 200 GeV
  - Composite likelihood fits signal + background *S(E)* = signal pdf, *B(E)* = background pdf = power law, *f* = signal fraction
  - *f* and Γ free, *f* ≥0 constraint

$$L = \prod_{i=0}^{N} f \cdot S(E_i) + (1 - f) \cdot B(E_i, \Gamma)$$

- Fitting ranges in search are ± 4σ wide on a grid of energies: 7,10,15,20,30,40,50,…,200. (Control "look-elsewhere" effect.)
  - The fitting ranges overlap significantly – leads to correlations in upper limits.
  - LAT team analysis shows a systematic effect that gives an enhanced signal at ~ 7 GeV that is mainly the result of analysis data cut in P6V3 ("CTBCORE"). This is being changed in future releases. Beware the smoking gun in P6V3! Solved with pass 7 to be released this year.
    - "CTBCORE" is a high level cut variable that influences the quality of the γ directional information.
  - The LAT team reports no lines observed, and gives upper limits. No detection at 95% CL.

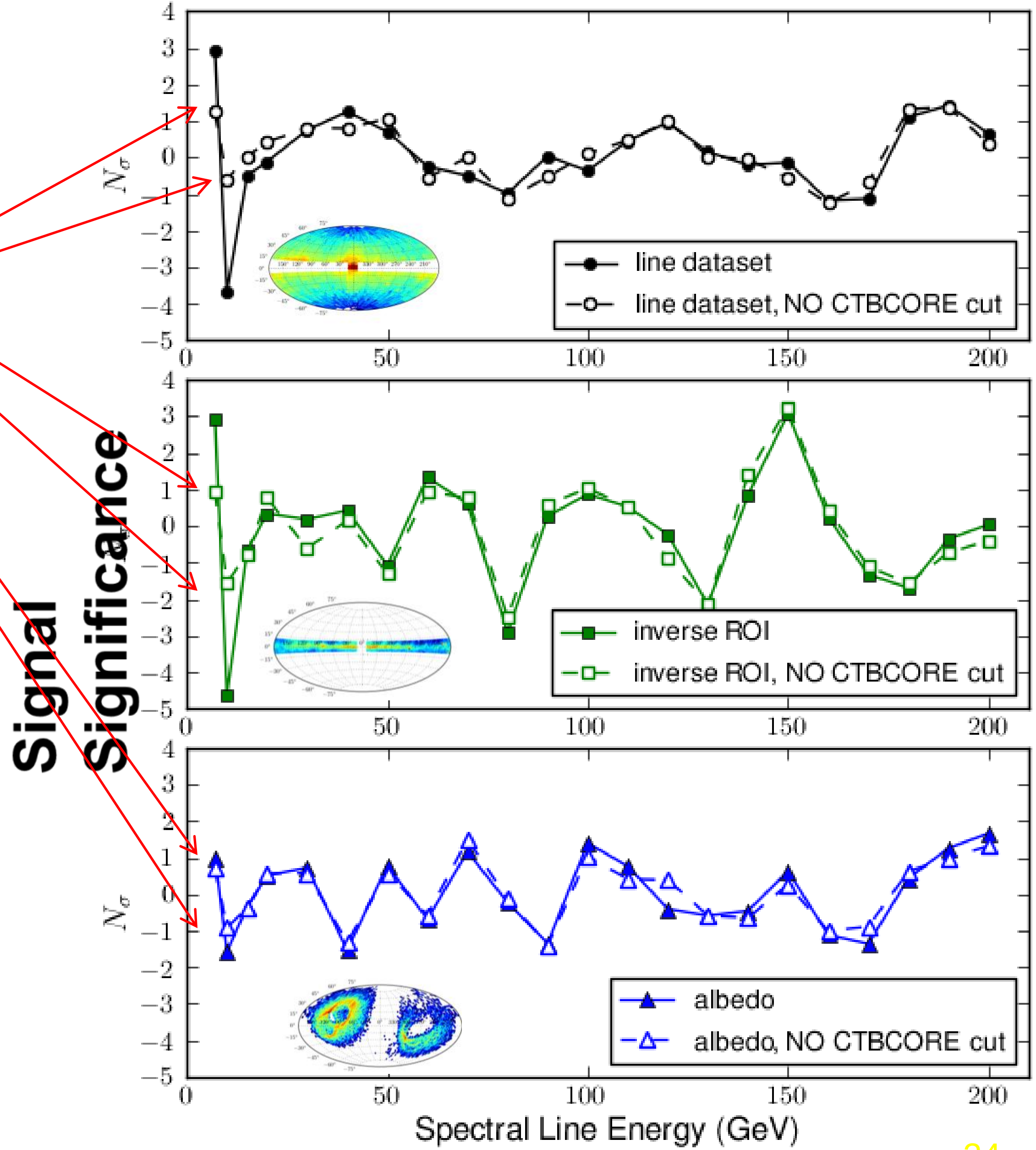
Search energy ranges

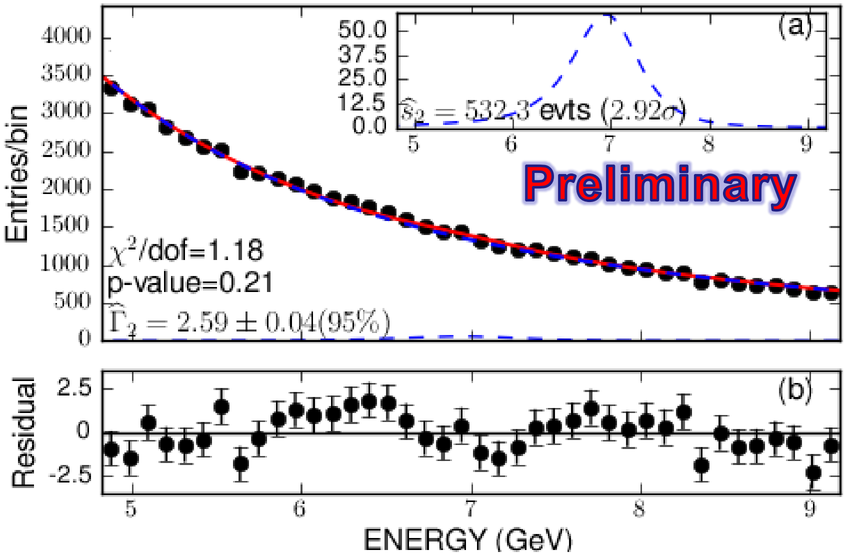
- Fit performed for spectral lines with true energy E_j:
  - 7, 10, 15, and 20 to 200 GeV at 10 GeV increments
- Search energy range is $E_j \pm 4\sigma$
- Search ranges overlap



Systematics of Photon Line Search

- Removing **CTBCORE** cut significantly reduces signal significance for spectral lines <10 GeV
- Photon Line dataset
  - 7 GeV signal goes from 3σ to 1.2σ
  - 6.5 GeV signal goes from 4σ to 2.6σ
- This systematic is highly muted in the Pass7 public data release later this year.

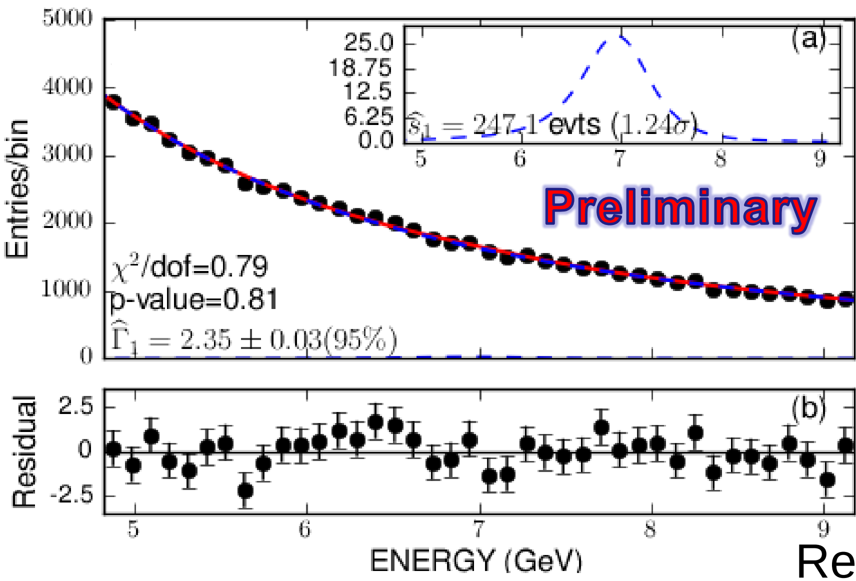




- Using standard event selection we see ~ 3 σ bump at 7 GeV.
- Using standard event selection below 13.2 GeV we estimate a systematic on spectral structures with LAT resolution for E< 13.2 GeV of s/b~3% by not only considering this ROI, but also the control region.

7 GeV signal fitting range (bin center is 7 GeV.)

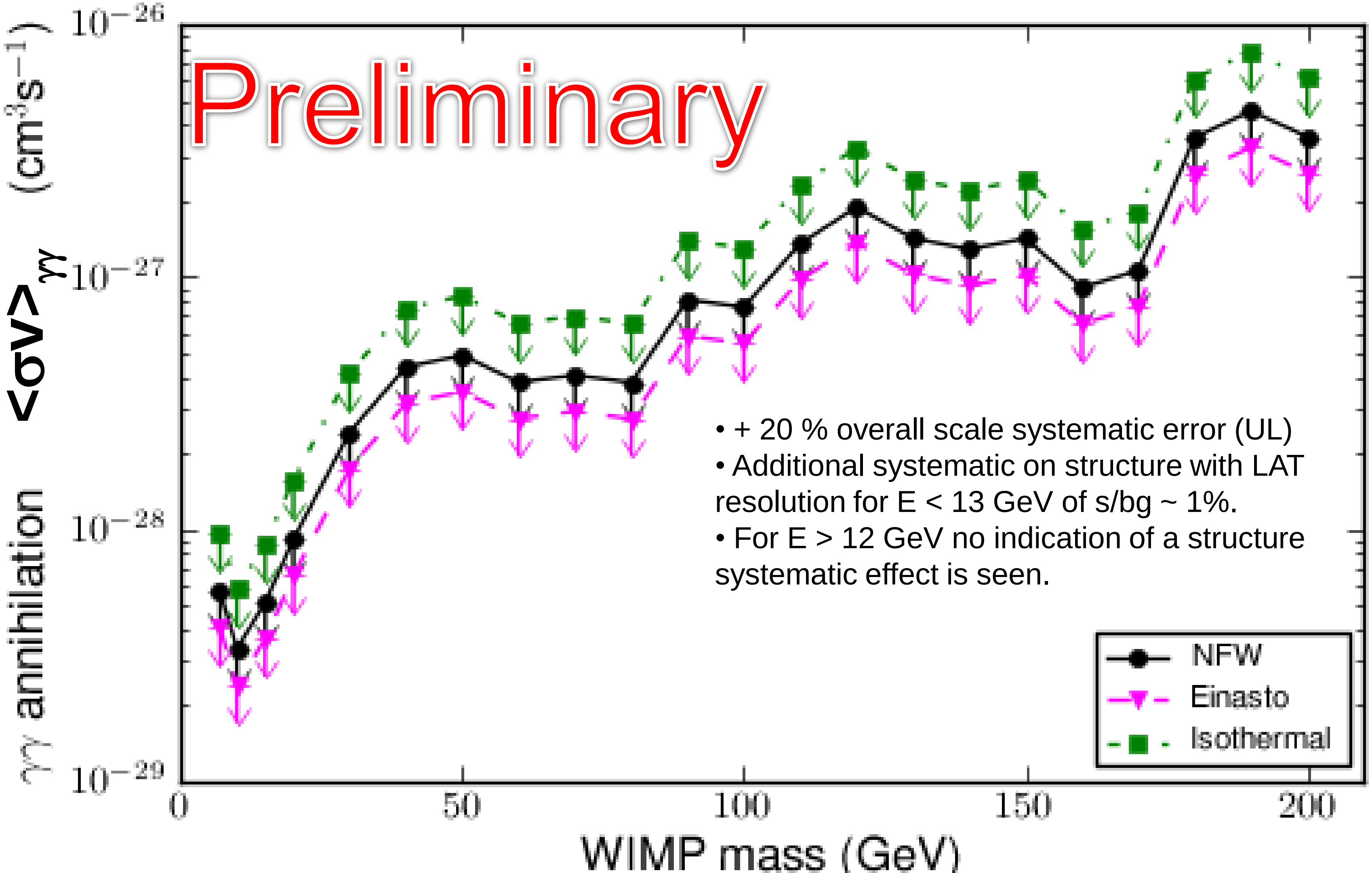
Remove "CTBCORE" Cut below 13.2 GeV, i.e. for 7 GeV (and 10) GeV fits.



- Removing "CTBCORE" cut we see 1.2 σ bump at 7 GeV.
- Removing "CTBCORE" cut below 13.2 GeV we estimate a systematic on spectral structures with LAT resolution for E< 13.2 GeV of s/b~1%.

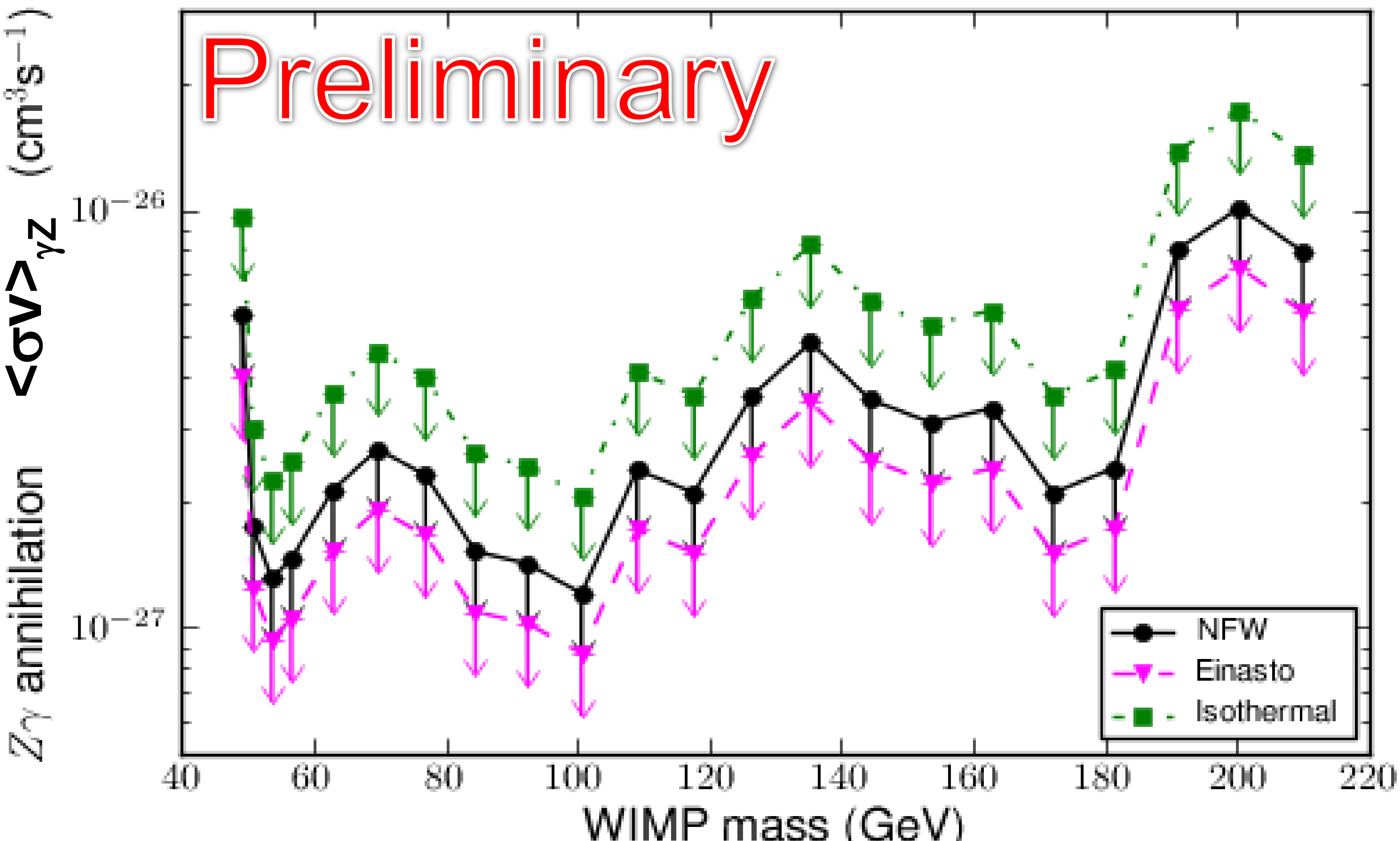
Residual = (#counts – model counts)/ √(#counts)

Fermi LAT 23 Month
γγ-Cross-section upper limits
7 GeV – 200 GeV



Fermi LAT 23 Month γZ-Cross-section limits 7 GeV – 200 GeV

- + 20 % overall scale systematic error (UL)
- Additional systematic on structure with LAT resolution for E < 13 GeV of s/bg ~ 1%.
- For E > 12 GeV no indication of a structure systematic effect is seen.



Gamma Ray Line Constraints on Effective Theories of Dark Matter

Jessica Goodman, et al. arXiv:1009.0008v2 [hep-ph] 18 Dec 2010

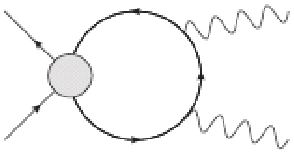


FIG. 1: Representative Feynman diagram for the loop level annihilation of two DM particles χ to a photon and a second vector boson, either another photon or a Z boson, through an operator coupling the DM to SM quarks (represented as the shaded circle).

D for Dirac fermion, M for Majorana, C for complex scalar, and R for real scalar and the number specifies the particular operator belonging to a given WIMP spin. Within each family, the earlier numbers refer to coupling to quark scalar bilinears (D1-4, M1-4, C1-2, and R1-2), the middle numbers to quark vector bilinears (D5-8, M5-6, and C3-4) and quark tensor bilinears (D9-10) and the largest numbers to coupling to gluons (D11-14, M7-10, C5-6, and R3-4). The WIMP electric and magnetic dipole moment operators are labeled D15 and D16.

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu} q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\mu\nu} q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$
D15	$\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$	M
D16	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi F_{\mu\nu}$	D
M1	$\bar{\chi}\chi\bar{q}q$	$m_q/2M_*^3$
M2	$\bar{\chi}\gamma^5\chi\bar{q}q$	$im_q/2M_*^3$

Name	Operator	Coefficient
M3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	$im_q/2M_*^3$
M4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	$m_q/2M_*^3$
M5	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/2M_*^2$
M6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/2M_*^2$
M7	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^3$
M8	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/8M_*^3$
M9	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^3$
M10	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/8M_*^3$
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

TABLE I: Operators coupling WIMPs to SM particles. The operator names beginning with D, M, C, R apply to WIMPs that are Dirac fermions, Majorana fermions, complex scalars or real scalars respectively.