New Results from Fermi

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PHENO 2009 Symposium
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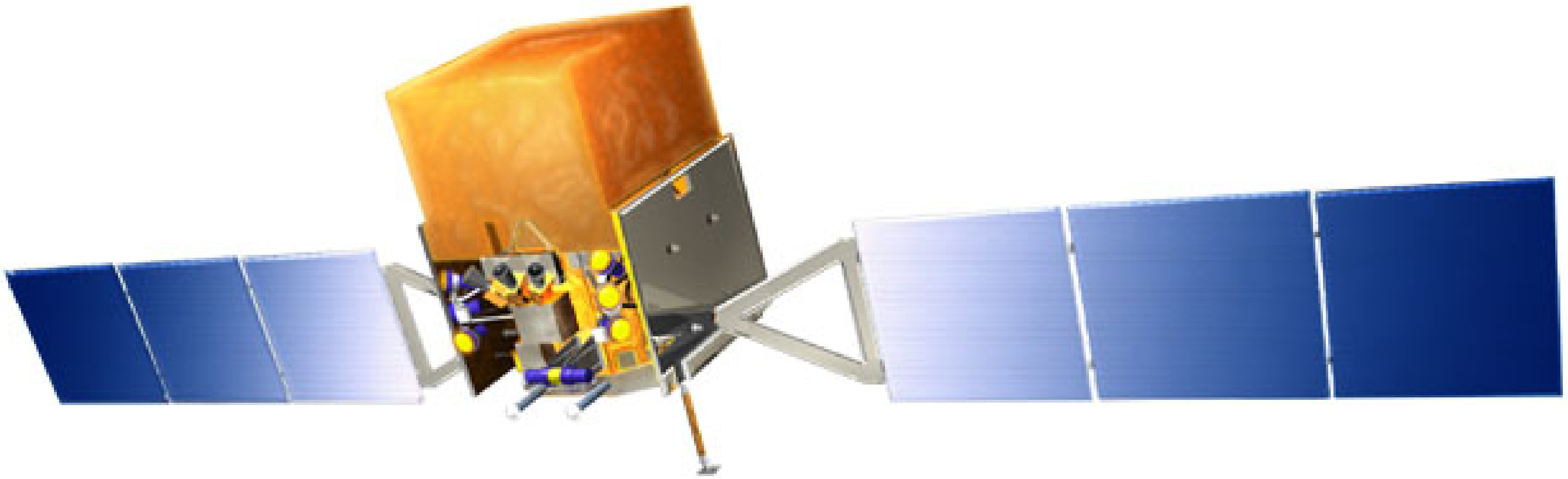
Outline

- The Fermi mission
- The Fermi gamma-ray sky
- Dark matter and new physics searches with Fermi: preliminary results
- Measurement of the high energy electron +positron spectrum
- Conclusions

The Observatory

- Observe the gamma ray sky in the 20 MeV to >300 GeV (LAT) energy range with unprecedented sensitivity
- Two instruments:



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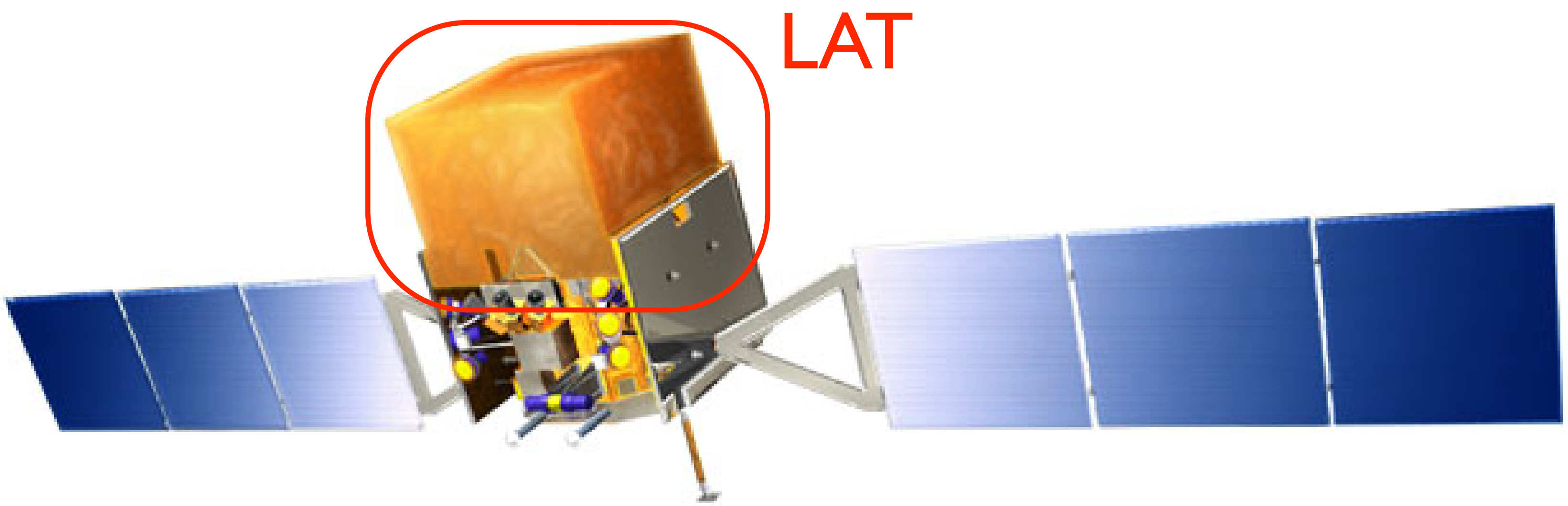
Large Area Telescope (LAT):
20 MeV - 300 GeV

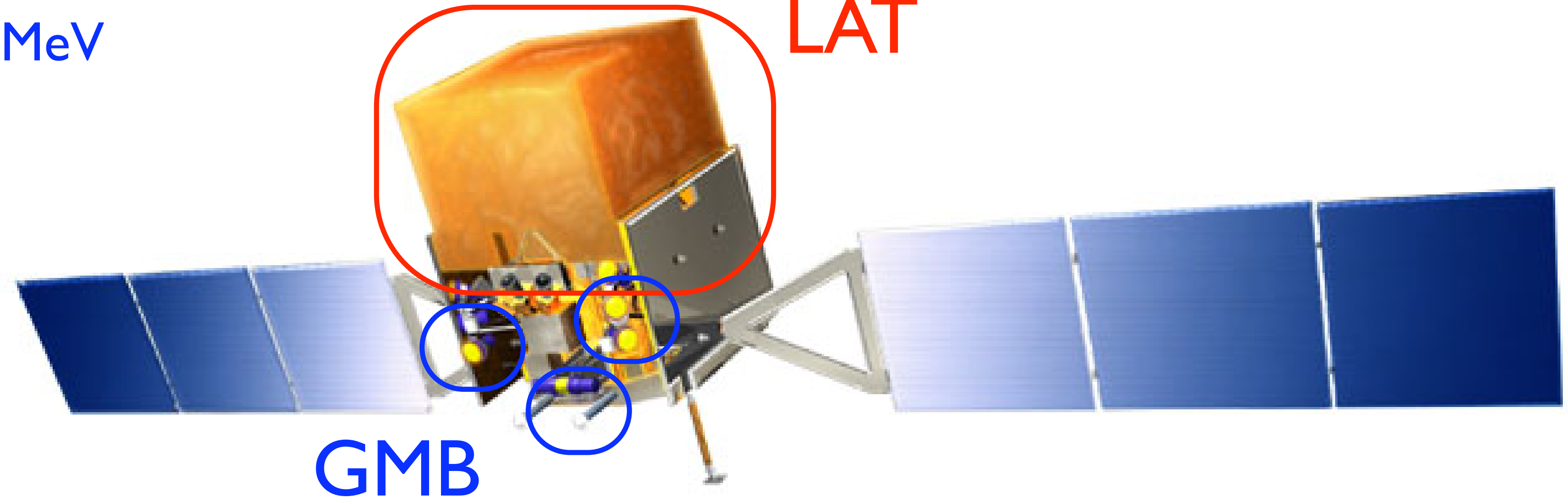


The Observatory

- Observe the gamma ray sky in the 20 MeV to >300 GeV (LAT) energy range with unprecedented sensitivity
- Two instruments:

Large Area Telescope (LAT):
20 MeV - 300 GeV

GLAST Burst Monitor (GBM):
8 keV - 40 MeV



The LAT

arXiv:0902.1089 [astro-ph.IM]

Pair conversion telescope

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:

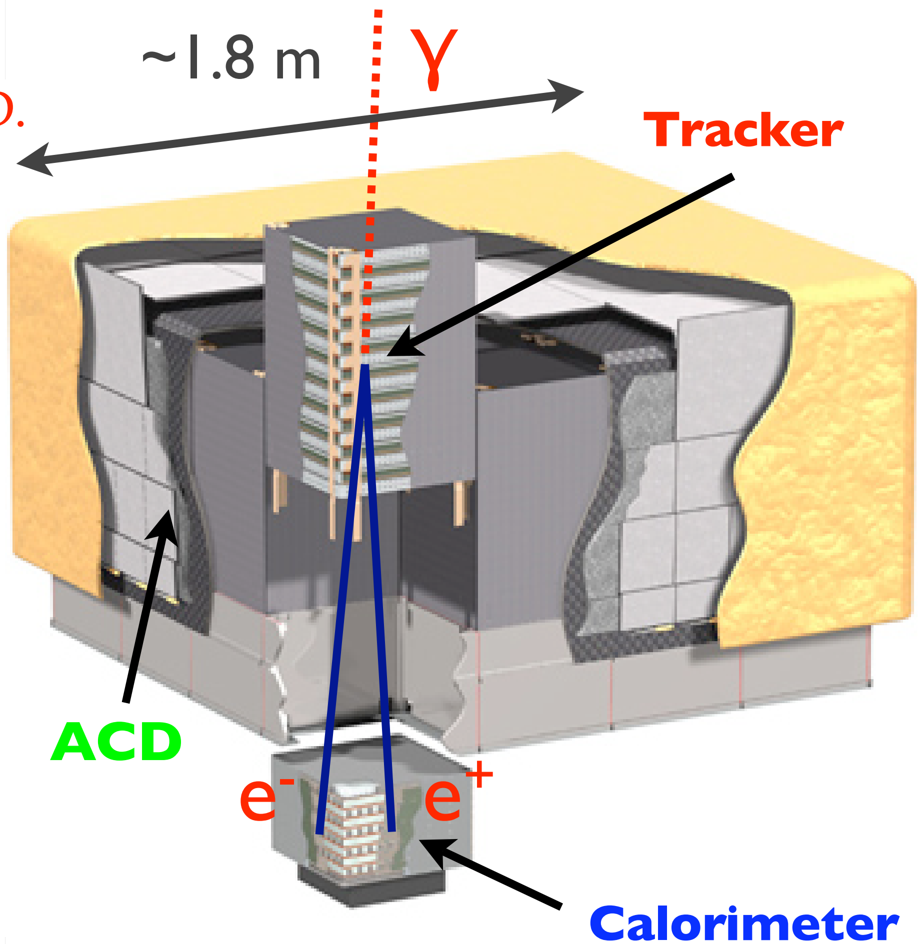
measurement of photon energy, shower imaging.

Array of 1536 CsI(Tl) crystals in 8 layers. 8.6 radiation lengths on-axis.

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.



Fermi
Gamma-ray Space Telescope

The Launch

- Fermi was launched by NASA on June 11, 2008 from Cape Canaveral
- Launch vehicle: Delta II heavy launch vehicle
- Orbit: 565 km, 25.6^{o} inclination, circular orbit
- The LAT observes the entire sky every ~3 hrs (2 orbits)
- Design life: 5 year (min)

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The Collaboration

- **France**
  - IN2P3, CEA/Saclay
- **Italy**
  - INFN, ASI, INAF
- **Japan**
  - Hiroshima University
  - ISAS/JAXA
  - RIKEN
  - Tokyo Institute of Technology
- **Sweden**
  - Royal Institute of Technology (KTH)
  - Stockholm University
- **United States**
  - Stanford University (SLAC, KIPAC, and HEPL/Physics)
  - University of California at Santa Cruz - Santa Cruz Institute for Particle Physics
  - Goddard Space Flight Center
  - Naval Research Laboratory
  - Sonoma State University
  - Ohio State University
  - University of Washington

~390 Members
(~95 Affiliated Scientists, 68 Postdocs, and 105 Graduate Students)

construction managed by Stanford Linear Accelerator Center (SLAC), Stanford University

also members from Australia, Germany, Great Britain, Spain

Fermi Science

- How do super massive black holes in Active Galactic Nuclei create powerful jets of material moving at nearly light speed? What are the jets made of?
- What are the mechanisms that produce Gamma-Ray Burst (GRB) explosions? What is the energy budget?
- How does the Sun generate high-energy gamma-rays in flares?
- How has the amount of starlight in the Universe changed over cosmic time? (Probe EBL in the 10 GeV to 100 GeV range)
- What are the unidentified gamma-ray sources found by EGRET?
- How do pulsars work and what is their gamma ray and $e^- + e^+$ spectrum?

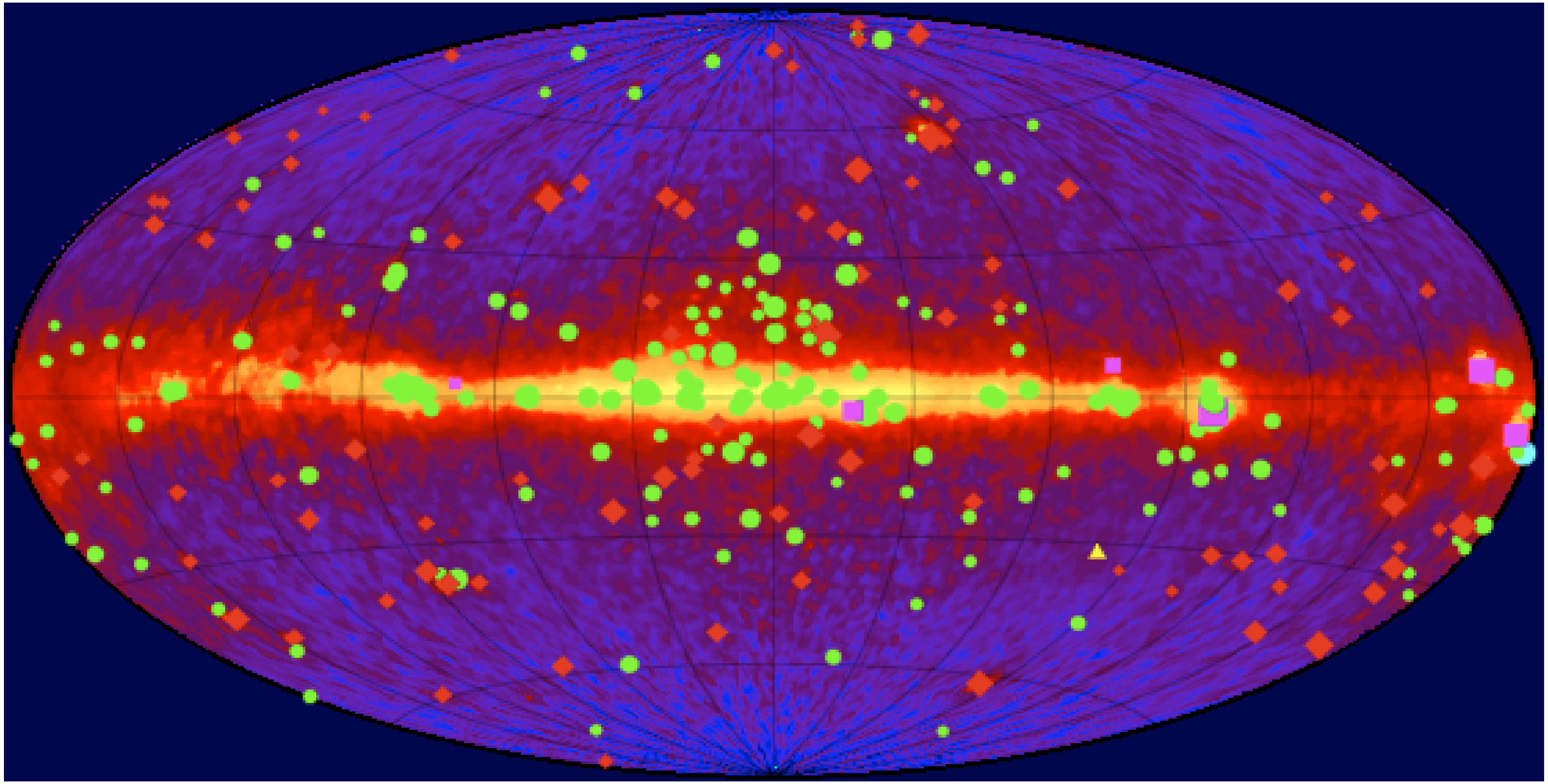
➡ What is the origin of cosmic rays that pervade the galaxy?

➡ What is the nature of dark matter?

The EGRET Sky

April 5, 1991 – June 4, 2000

3rd EGRET catalog, 271 sources



◆ AGN - blazars ● unidentified ■ pulsars ▲ LMC

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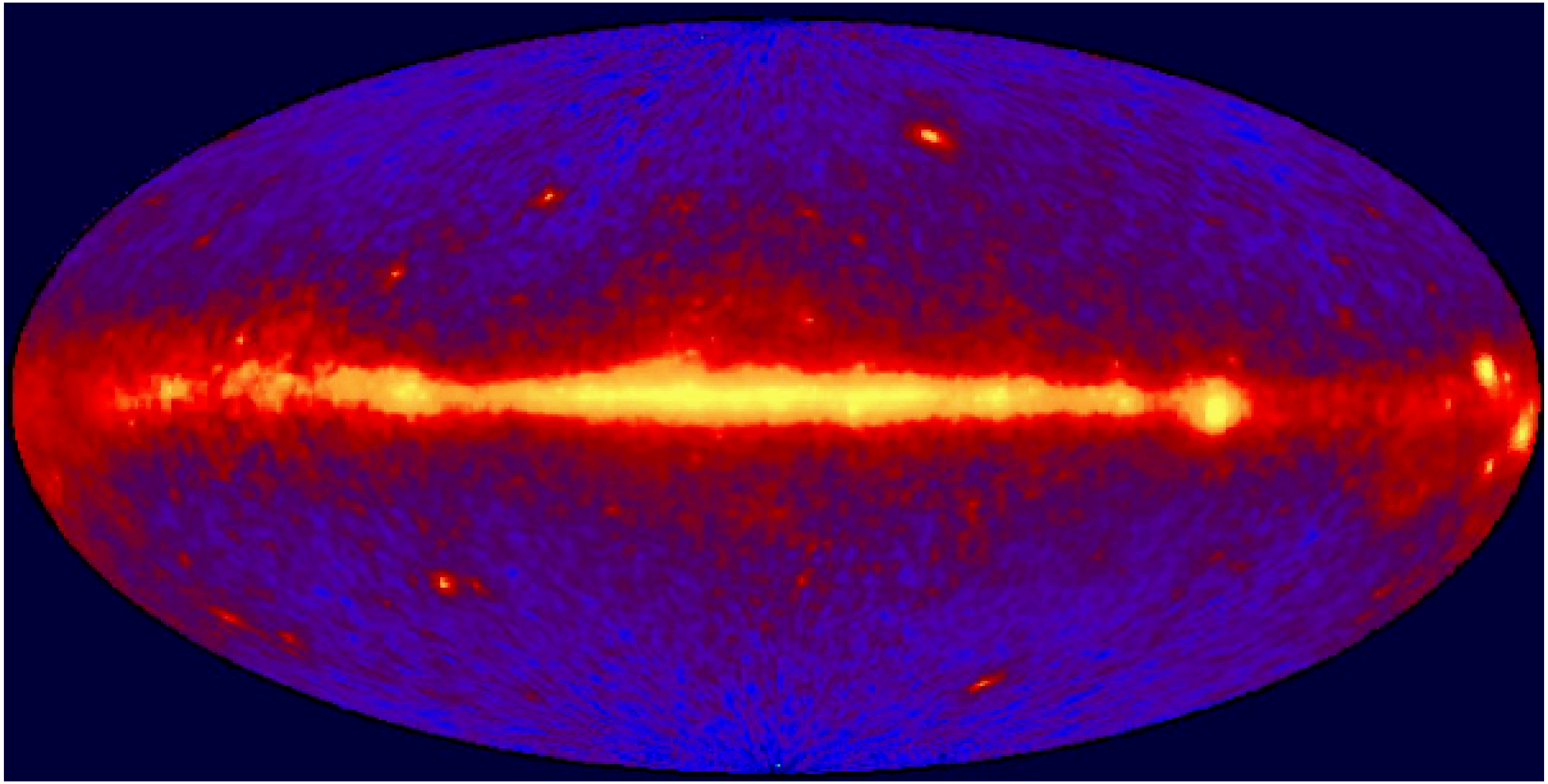
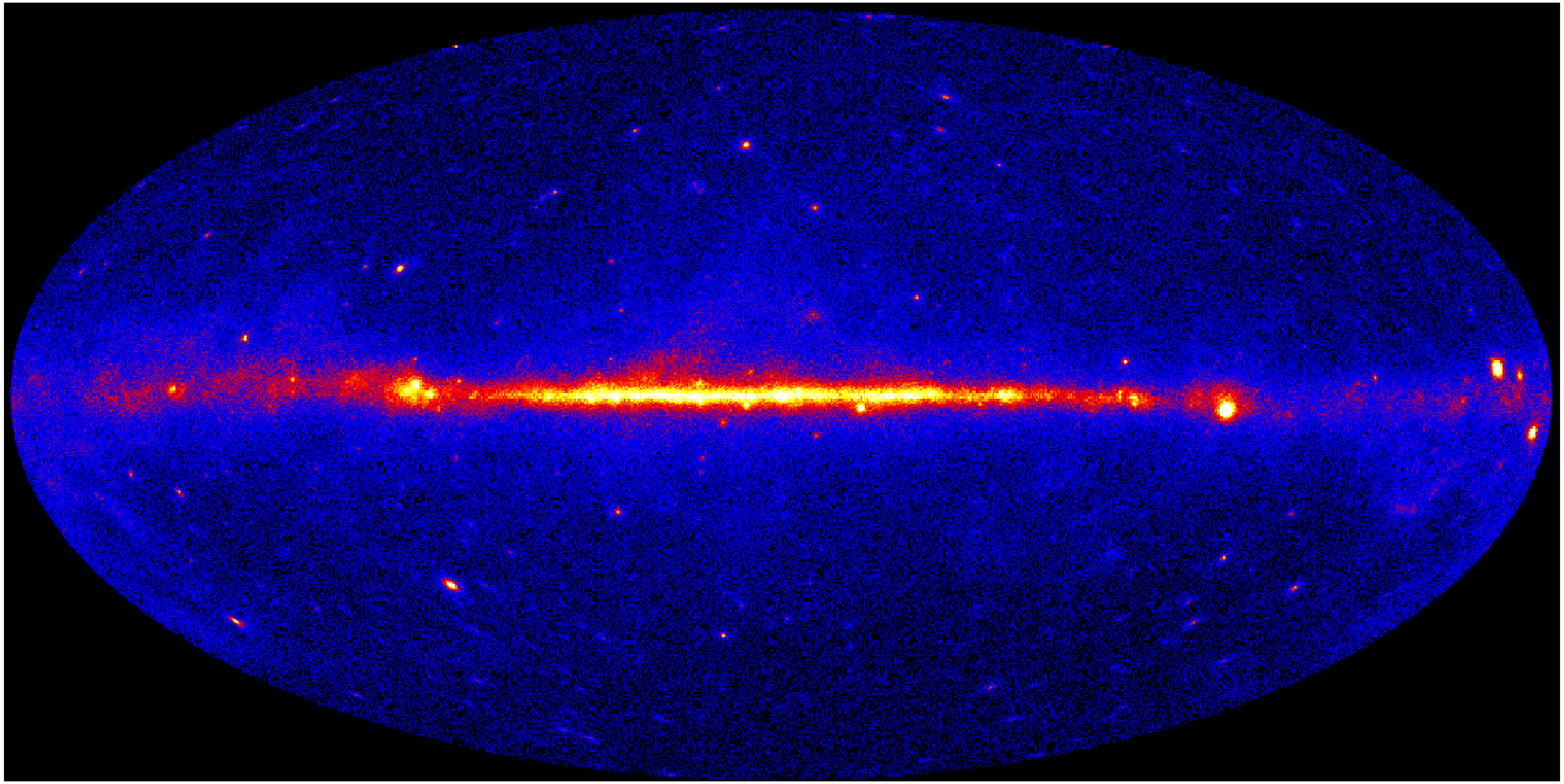


◆ **AGN - blazars** ● **unidentified** ■ **pulsars** ▲ **LMC**

The 3-month Fermi Sky

arXiv:0902.1340 [astro-ph.HE]

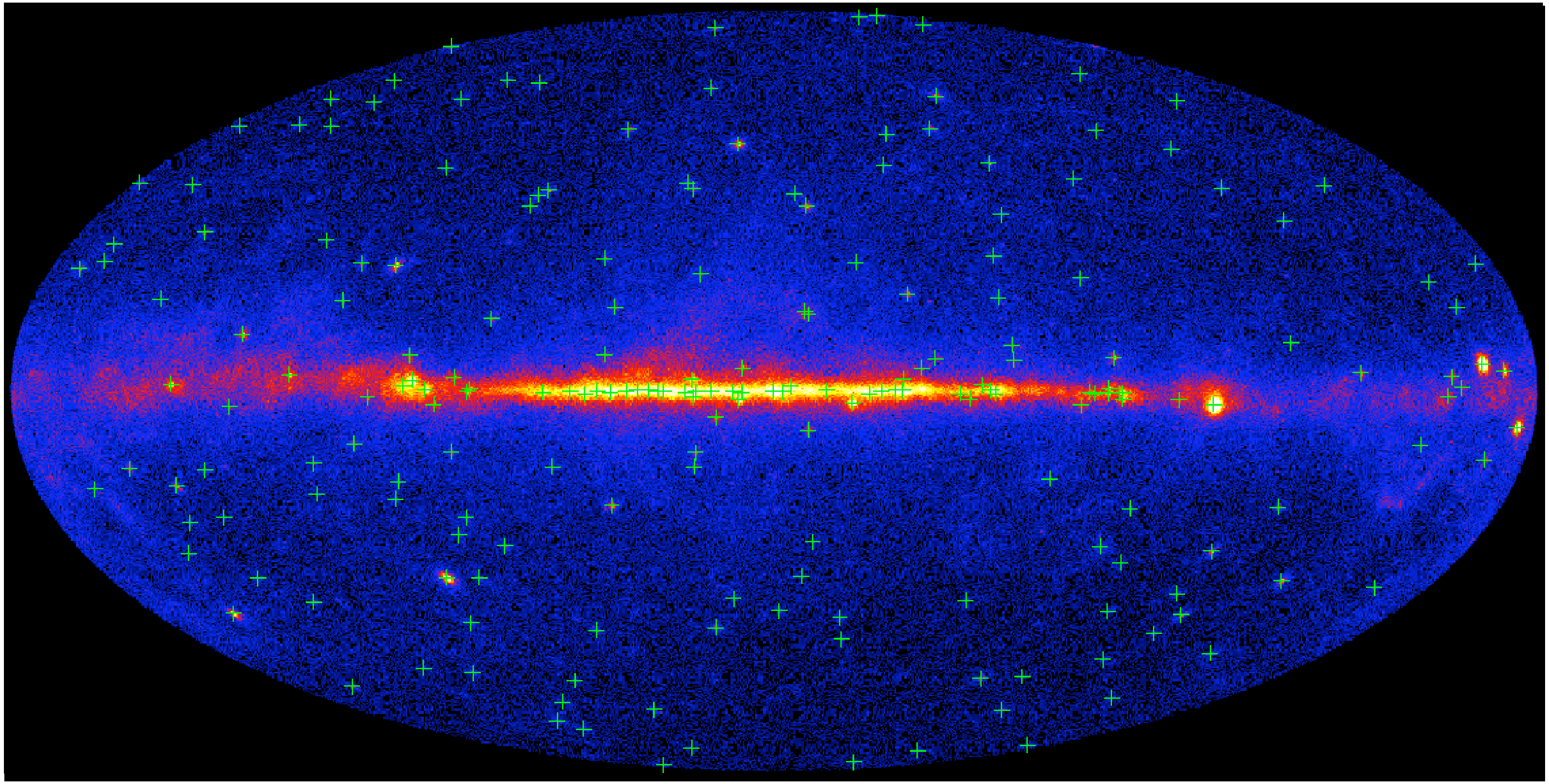


Galactic coordinates, Aitoff projection

The 3-month Fermi Sky

arXiv:0902.1340 [astro-ph.HE]

205 bright sources (significance > 10σ; EGRET found fewer than 30)
Crosses mark source locations, in Galactic coordinates. 1/3 at |b| < 10°.
Only 60 clearly associated with 3EG EGRET catalog. The sky changes!



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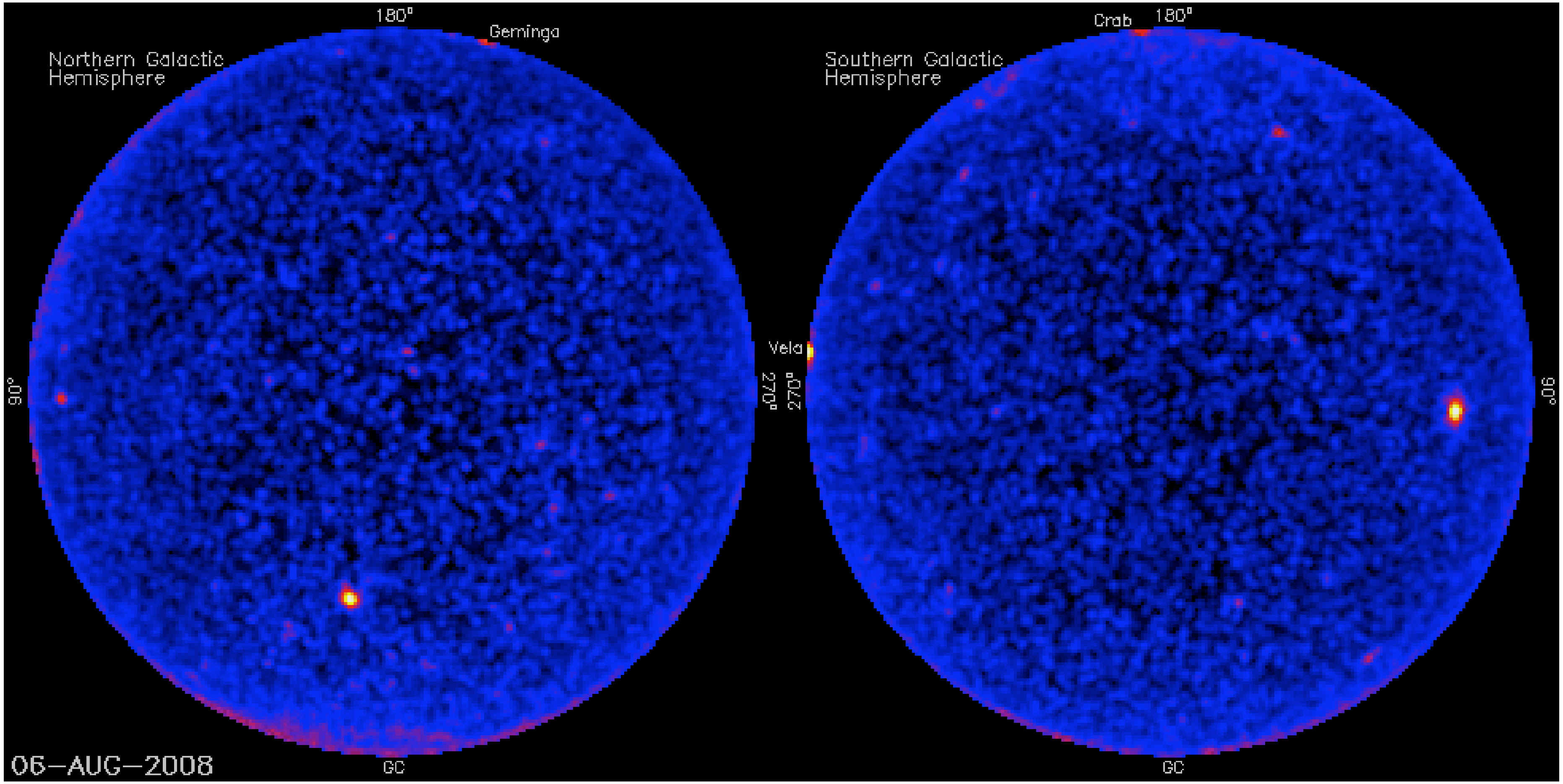


Dark Matter and New Physics with Fermi

Solving the Dark Matter Puzzle

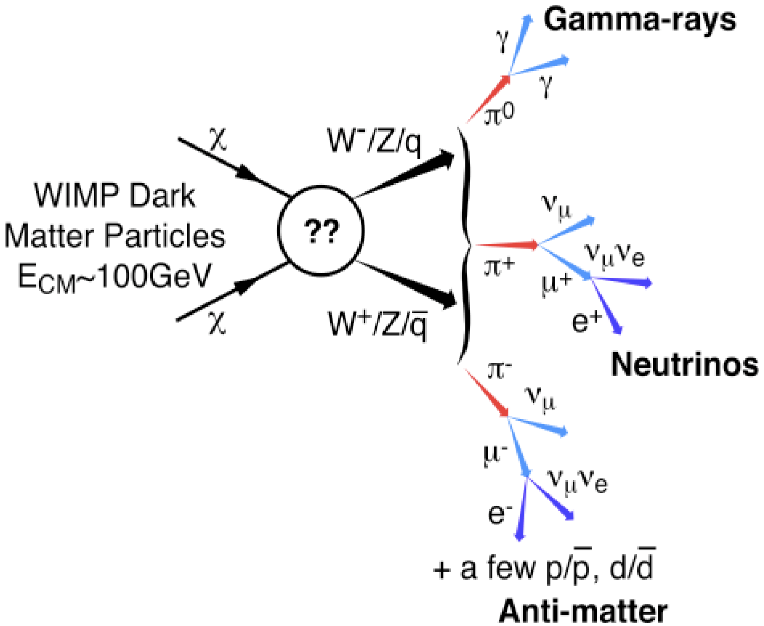
- Fermi has a unique perspective and it will investigate the existence of WIMPS indirectly through their annihilation or decay into photons and into electrons
- Indirect detection of a dark matter signal would be complementary to direct detection and collider searches and it would provide invaluable information on the distribution of dark matter in space
- Not an easy task! Large uncertainties in the signal (DM distribution, underlying particle physics model) and in the background (particle background, photons from diffuse emission, and point sources)

WIMP Signal

Continuum spectrum with cutoff at M_W

- E. g. photons (or e^+e^-) from annihilation of neutralinos, KK dark matter

Neutralino annihilation into γ



Spectral line at M_W

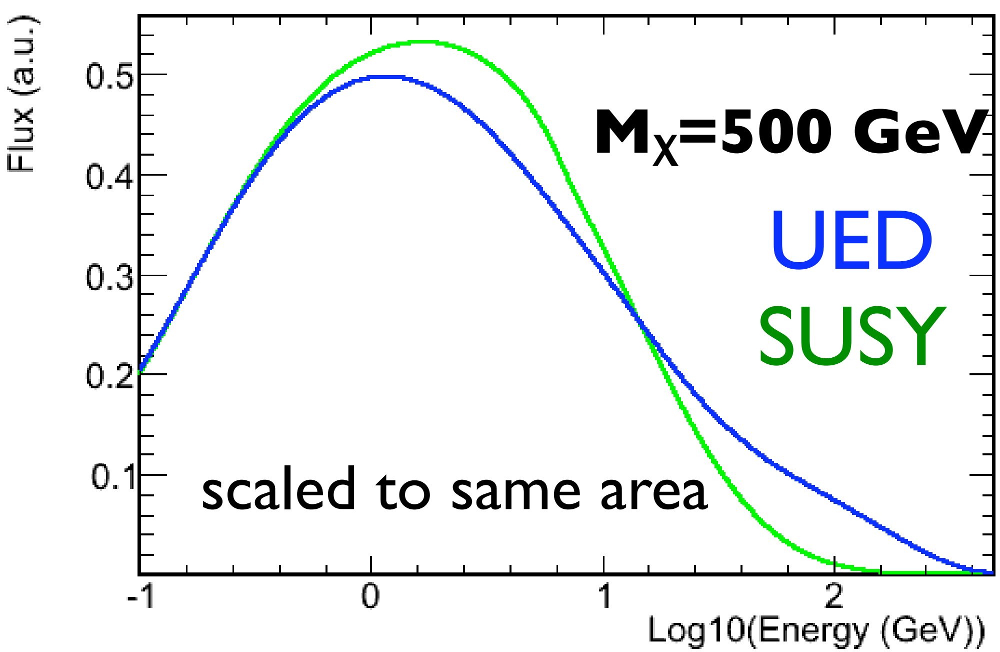
- Detection of prompt annihilation or decay into photons (or e^+e^-) would provide a smoking gun for dark matter annihilation

- Requires best energy resolution

- Line signal can be strongly suppressed but enhancements are predicted in some models (e.g. gravitino decay, leptophilic models)

UED vs SUSY

- Consider the photon spectrum from 500 GeV WIMP annihilation in SUSY and in UED (*):
  - UED: photons mostly from lepton bremsstrahlung
  - SUSY: photons mostly from b quark hadronization and then decay, energy spread through many final states lower photon energy. p-wave dominated cross-section yields lower photon fluxes for equal masses



➡Spectra can look very different in these scenarios

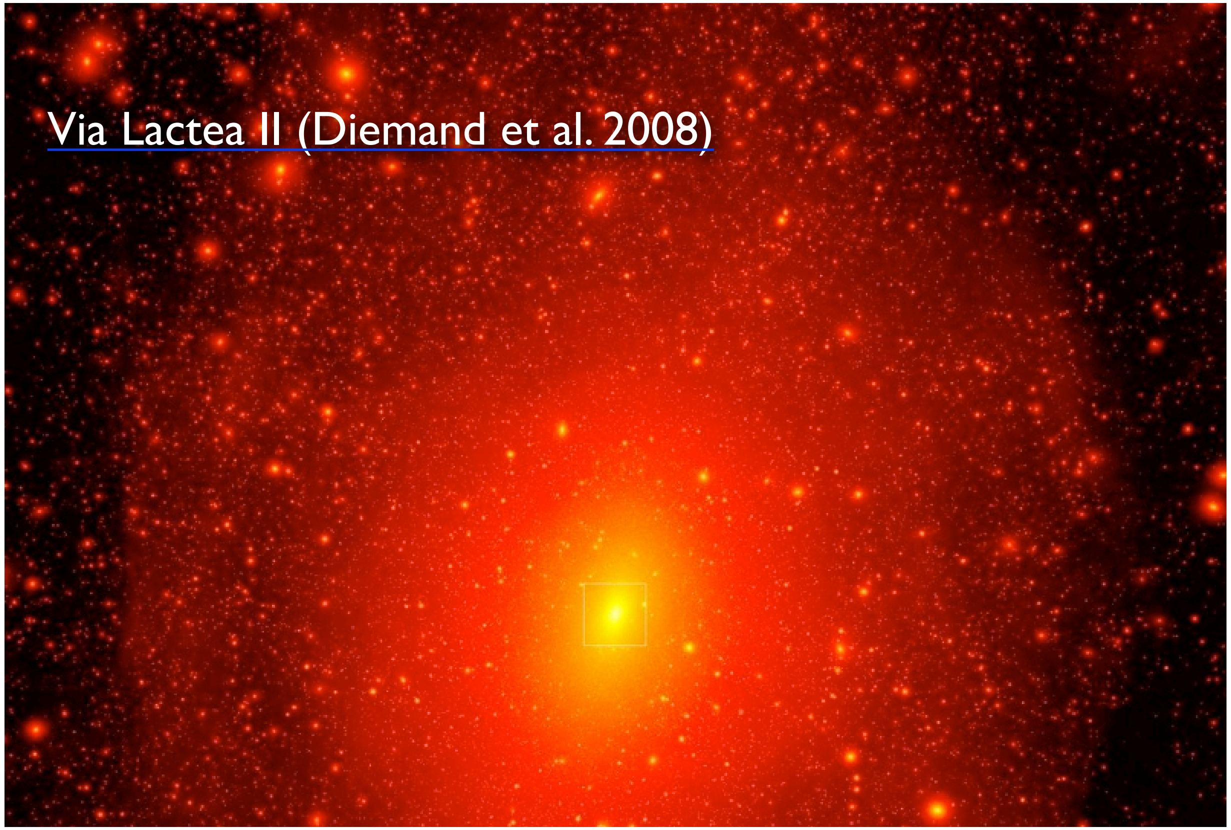
mSUGRA parameters:

$$\begin{aligned} m_0 &= 500 \text{ GeV} \\ m_{1/2} &= 1160 \text{ GeV} \\ A_0 &= 0, \quad \tan\beta = 10 \end{aligned}$$

(*) G. Bélanger, F. Boudjema, A. Pukhov and A. Semenov, Comput. Phys. Commun. 174 (2006) 577; hep-ph/0405253
G. Bélanger, F. Boudjema, A. Pukhov and A. Semenov, Comput. Phys. Commun. 149 (2002) 103; hep-ph/0112278

Dark Matter Distribution

- The dark matter annihilation (or decay) signal strongly depends on the dark matter distribution.
- Cuspier profiles and clumpiness of the dark matter halo can provide large boost factors



NFW profile

$$\rho(r) = \rho_0 \frac{r_0}{r} \frac{1 + (r_0/a_0)^2}{1 + (r/a_0)^2}$$

$$\rho_0 = 0.3 \text{ GeV/cm}^3$$

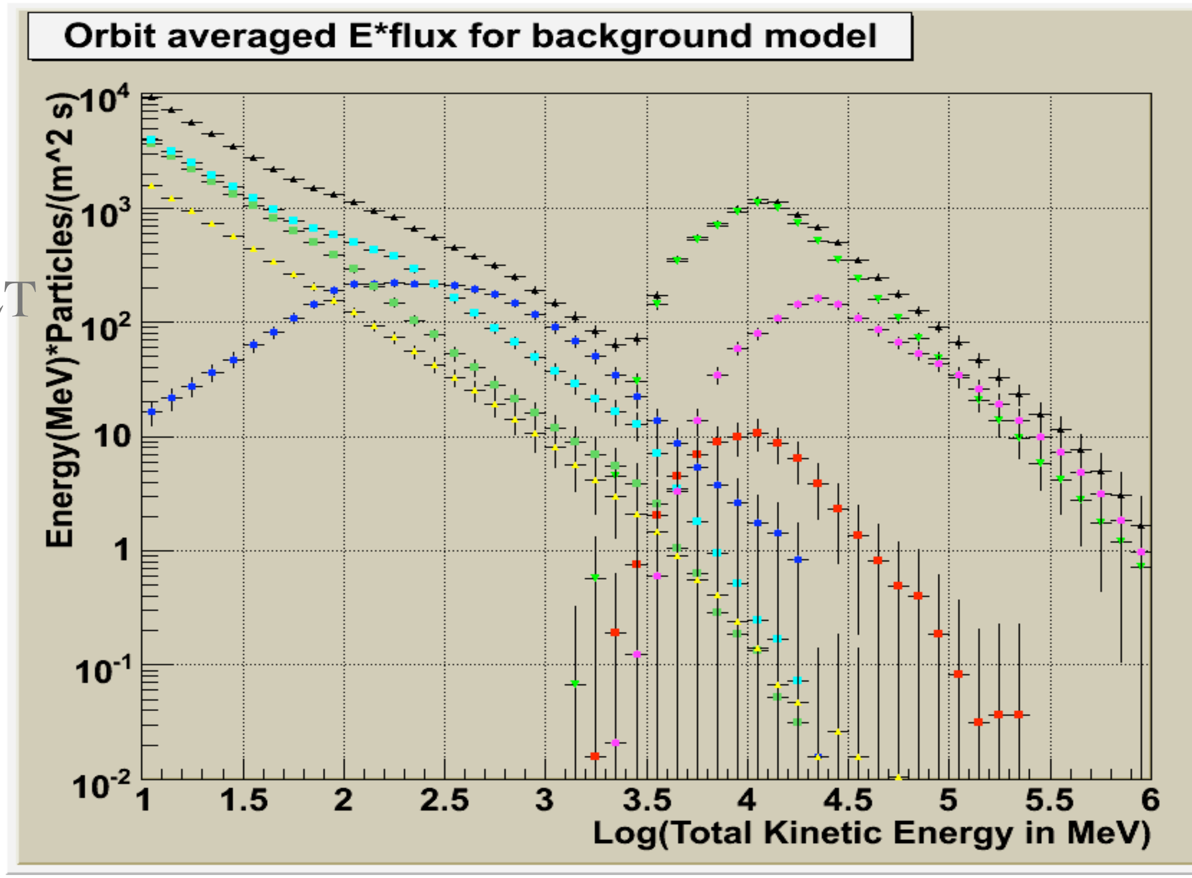
$$a_0 = 20 \text{ kpc}, \ r_0 = 8.5 \text{ kpc}$$

$$\text{cut radius} = 10^{-5} \text{ kpc}$$

Via Lactea II predicts a cuspier profile, $\rho(r) \propto r^{-1.24}$

Backgrounds

- Photons from galactic diffuse emission (due to CR particles interactions - IC, π^0 decay, bremsstrahlung - with gas in the ISM and low energy photons in the IRF), photons from extra-galactic diffuse emission
- Charged particles (protons, electrons, positrons), some neutrons, Earth albedo photons. They dominate the flux of cosmic photons
- Less than 1 in 10^5 survive the photon selection
- Above a few GeV, background contamination is required to be less than10% of EGB γ measured by EGRET



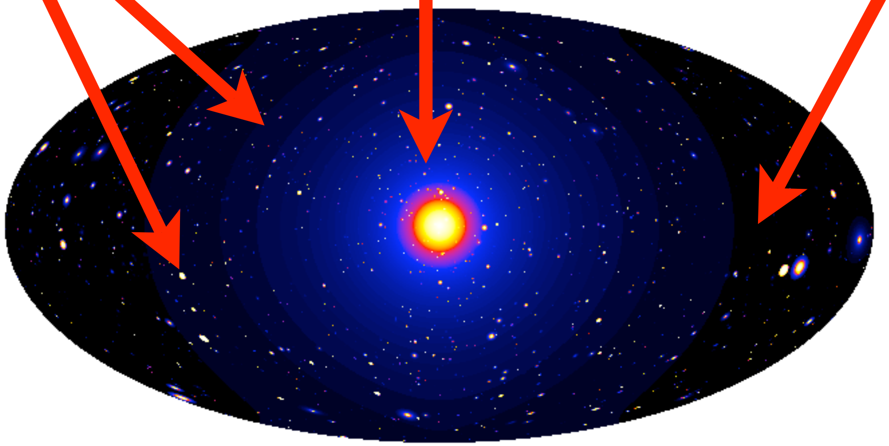
Total flux
CR protons
CR e^-, e^+
Albedo p, pbar
Albedo e^-
Albedo e^+
Albedo γ
Heavy nuclei

Search Strategies

Galactic center:
Good Statistics but source confusion/diffuse background

Satellites:
Low background and good source id, but low statistics, astrophysical background

Milky Way halo:
Large statistics but diffuse background



All-sky map of DM gamma ray emission (Baltz 2006)

And electrons!

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

Extra-galactic:
Large statistics, but astrophysics, galactic diffuse background

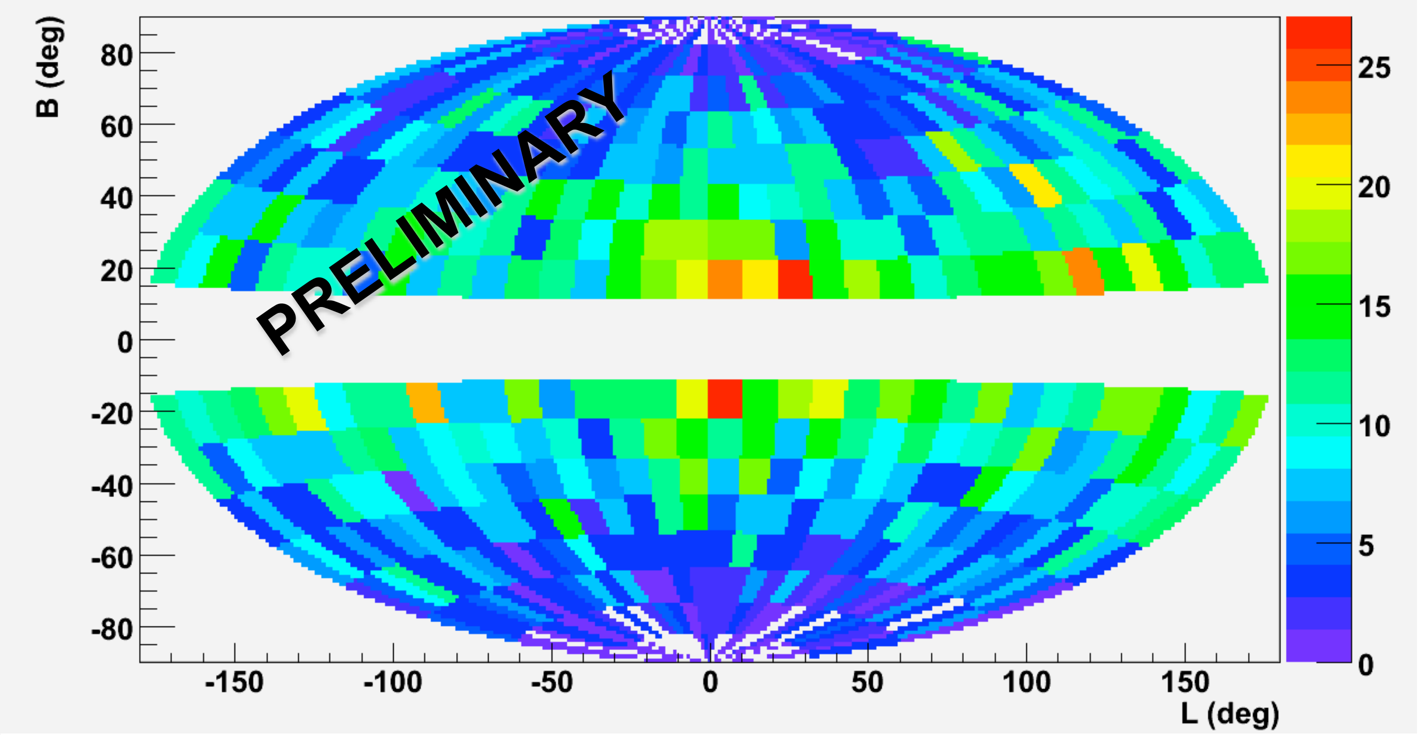
➡ Uncertainties in the underlying particle physics model and DM distribution affect all analyses

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

DM Line

- Search for lines in the first 3 months of Fermi data (Aug 8, 2008 + 90 days). Test of analysis method for 1-year blind search)
- To reduce background contamination, remove galactic disk (|b|>10°)
- Consider 20-300 GeV energy range
- Exclude point sources (remove 0.2° radius around the source)

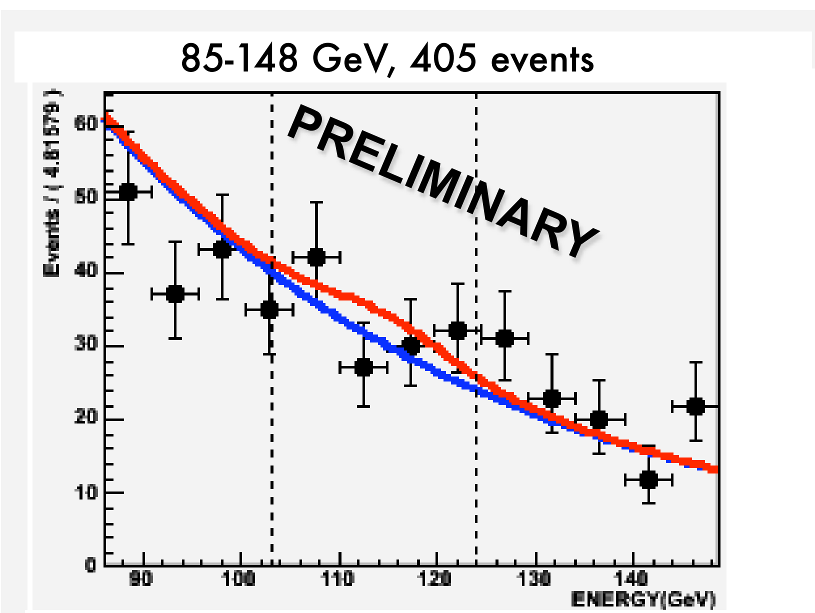
➡ Optimal energy resolution and calibration very important for this analysis

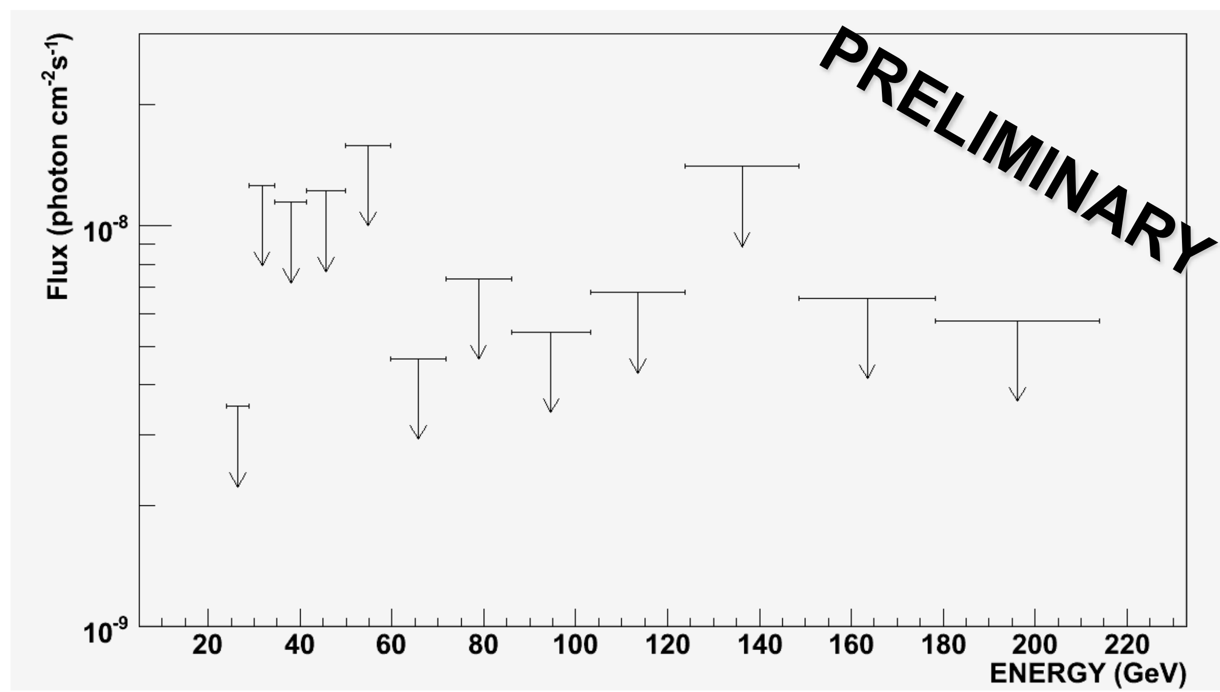


95% C.L. Upper Limits

- Perform an unbinned maximum likelihood fit to the data. The signal is the detector resolution (well described by two gaussians) and the background is approximated by an exponential: $N_b B(E) + N_s S(E)$ where: $B(E) = e^{-\alpha E}$

- Data are binned as $\Delta E/E = 20\%$ (resolution ~10% @ 100 GeV)
- The background is fixed by fitting the side bins. The only free parameter is the number of signal events (constrained to be >0)





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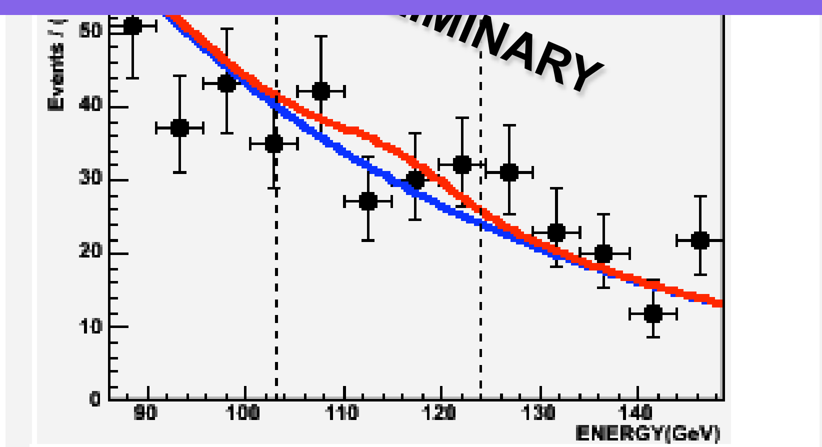
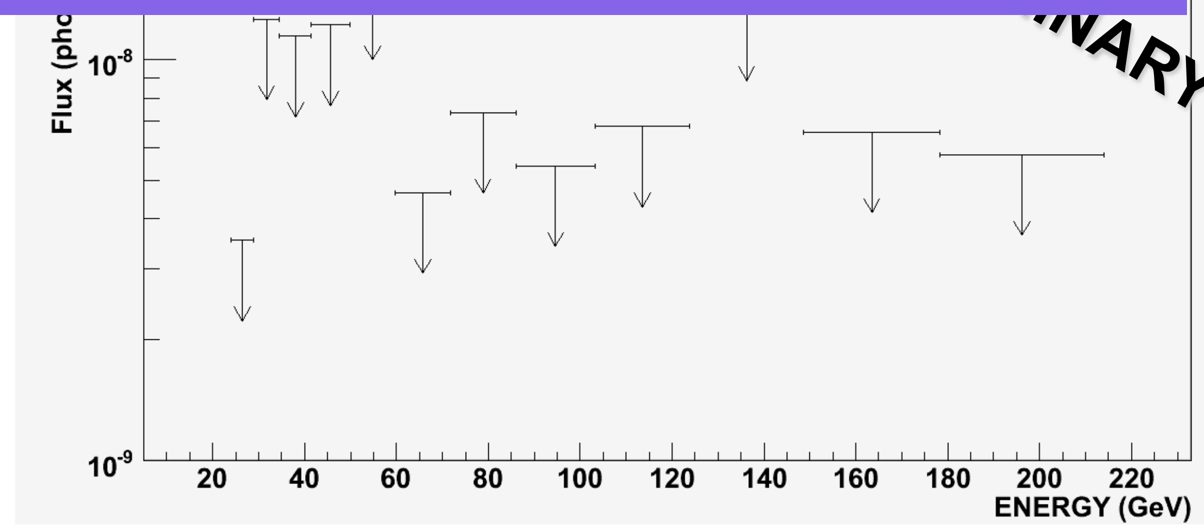
Analyses are underway which include alternative statistical methods.

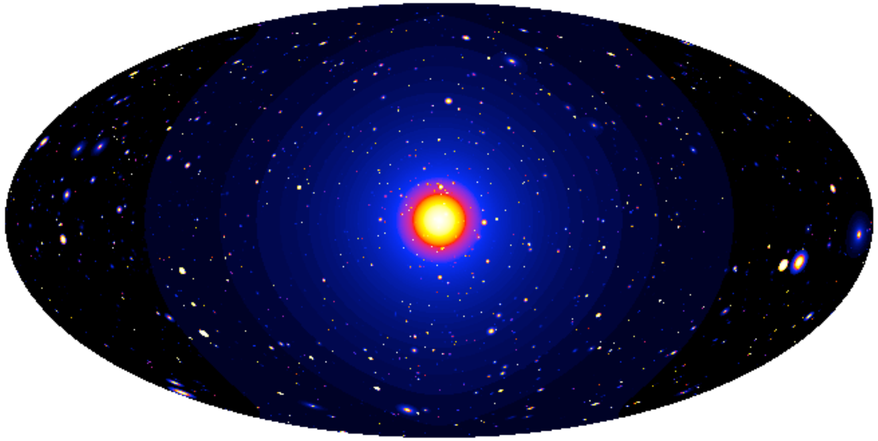
Updated results will cover approximately 1 year of data.





DM Satellites

- Expect isotropic distribution of subhalos in the galactic halo
- Search for DM subhalos:
  - ★ No appreciable counterpart at other wavelengths
  - ★ Emission constant in time
  - ★ Spatially extended (~1^{o} average radial extension for nearby, detectable clumps)
  - ★ Spectrum determined by DM, very different from power law
- Search for sources (>5σ significance) passing these criteria in the first 3 months of Fermi data (Aug 7 to Nov 7, 2008)
- 200 MeV - 60 GeV energy range



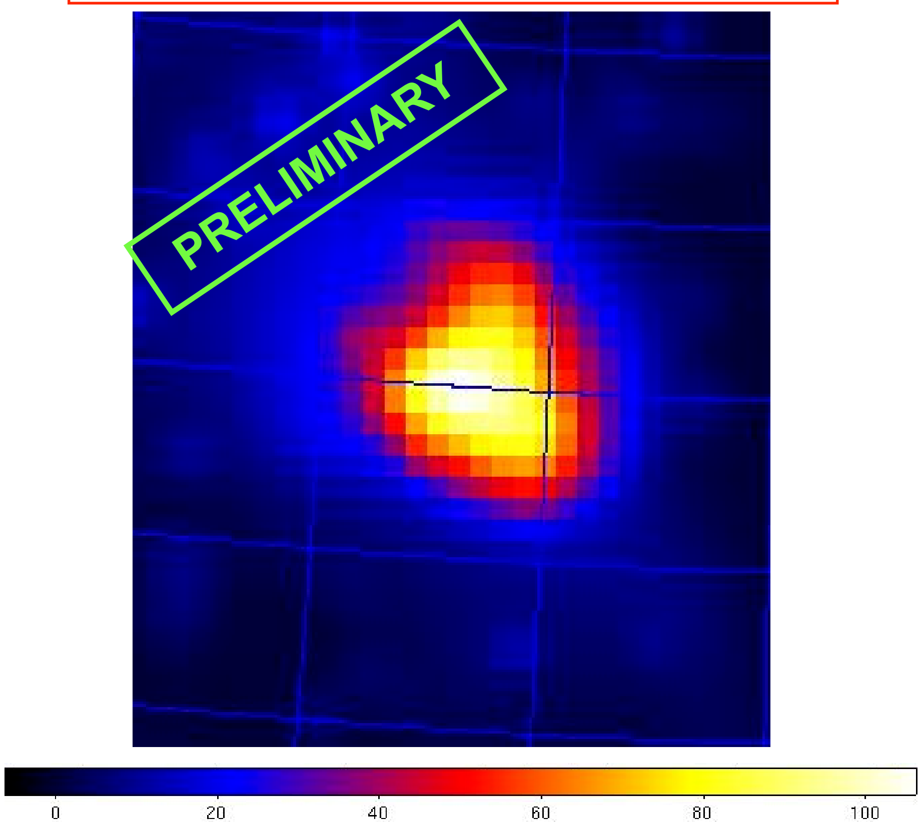
DM Satellite Candidate

- One source is found in the first 3 months of data which is:
  - Possibly extended (test NFW vs point-like hypothesis)
  - Possibly non-power law (test power-law vs WIMP b-bar spectrum)
  - Not variable (based on 1-week interval light curve)
  - No dSph counterpart
  - No molecular cloud counterpart

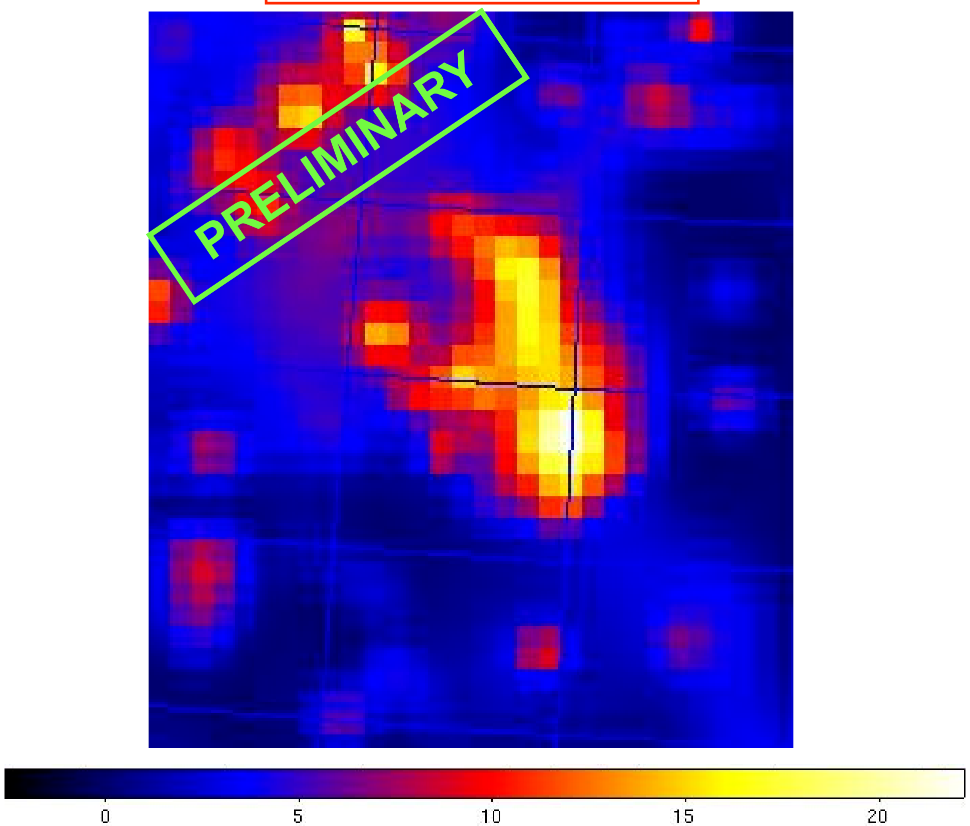
TS Maps: 200 MeV-60 GeV

- Pixel size: 0.125°
- Grid size: 2°x1°

TS Map: source with NFW profile



Residual TS Map



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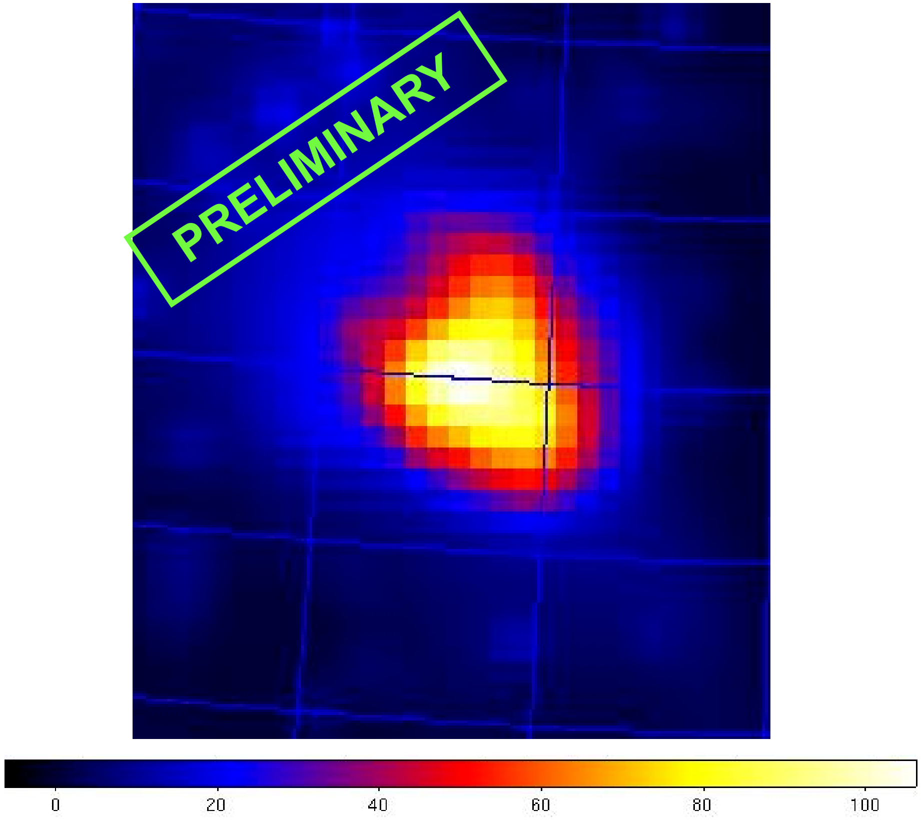
Another source?

TS Map: source with NFW profile



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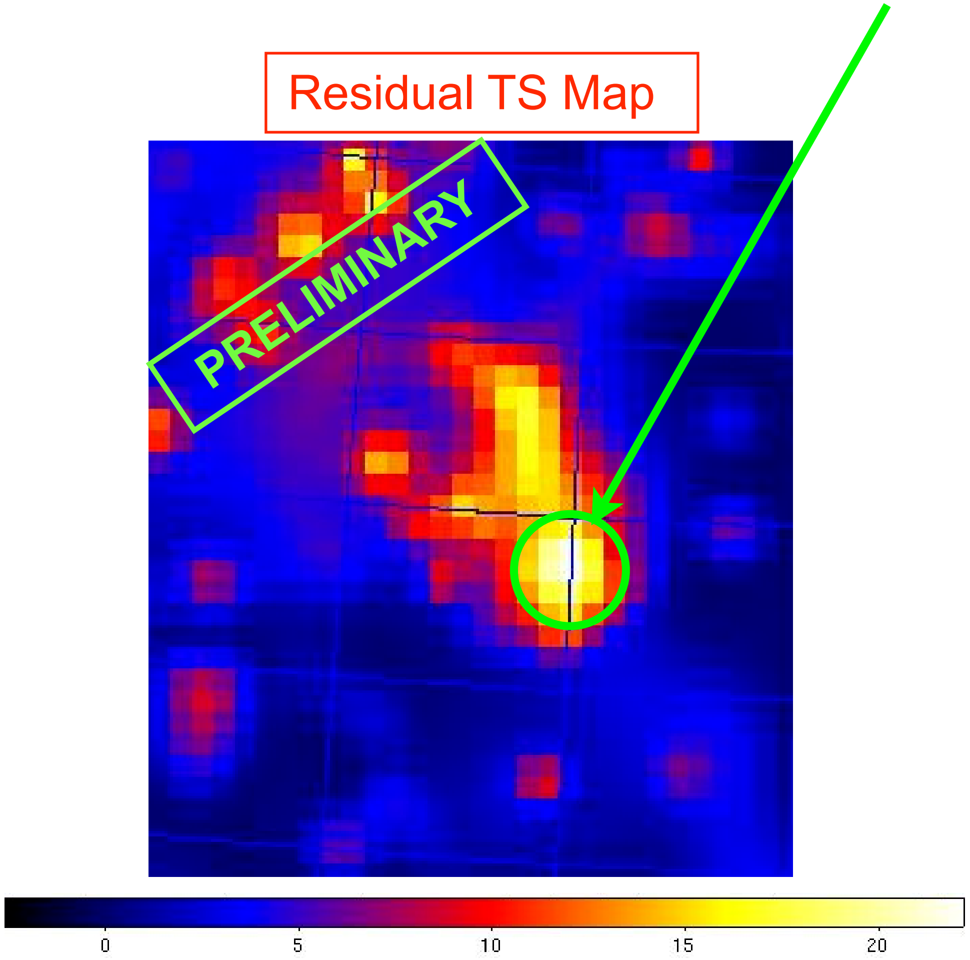

TS Maps: 3.2 GeV-6.4 GeV

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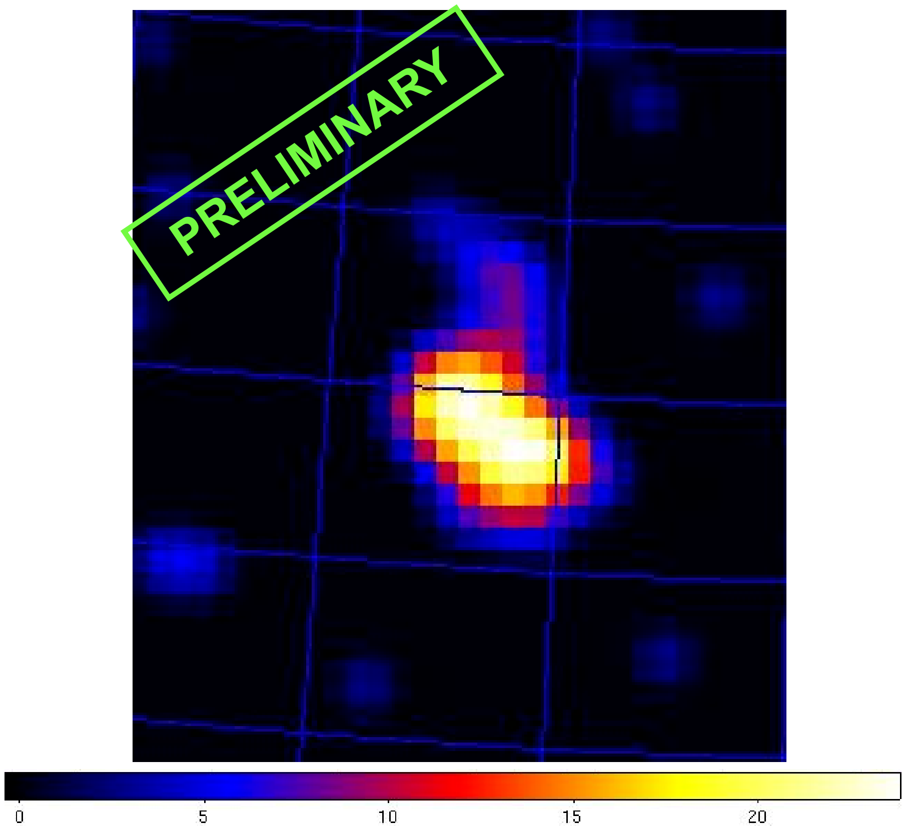
Another source?

TS Map: source with NFW profile



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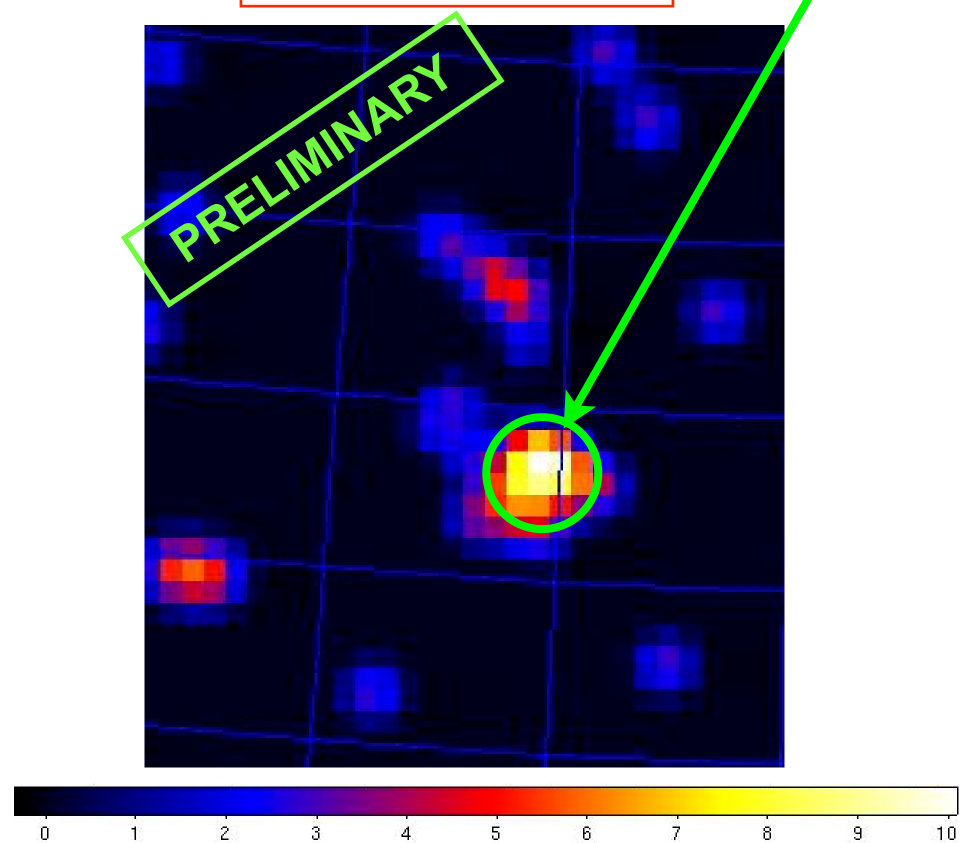

Counts Map: 3.2GeV-6.4GeV

- Pixel size: 0.125º
- Grid size: 2ºx1º

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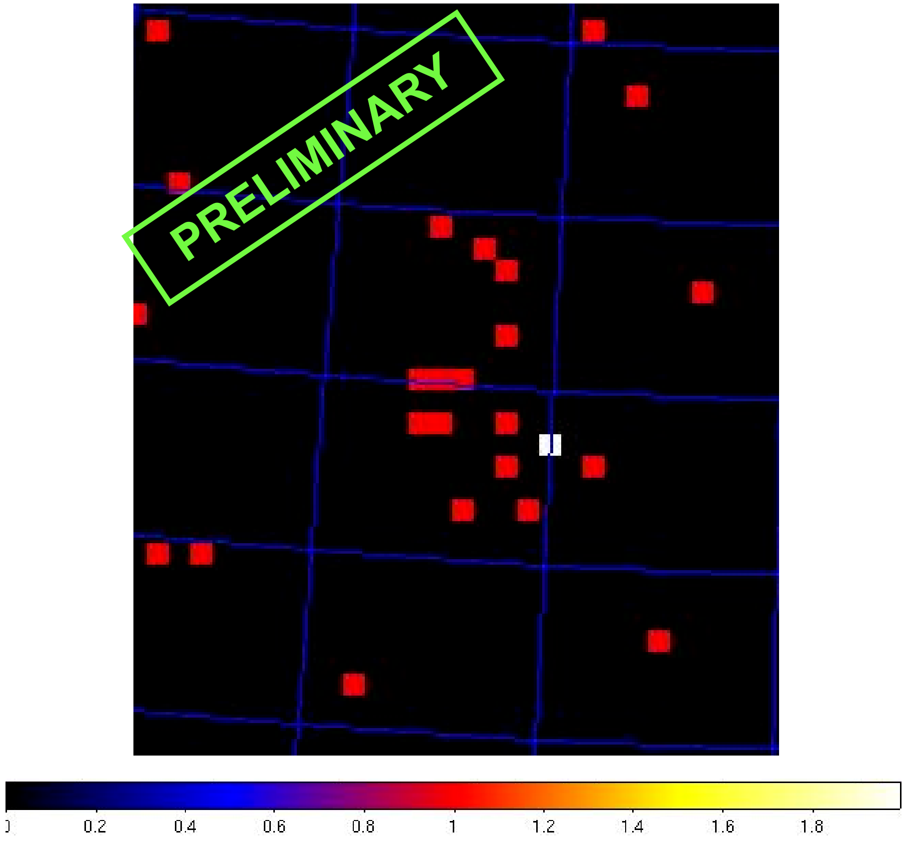
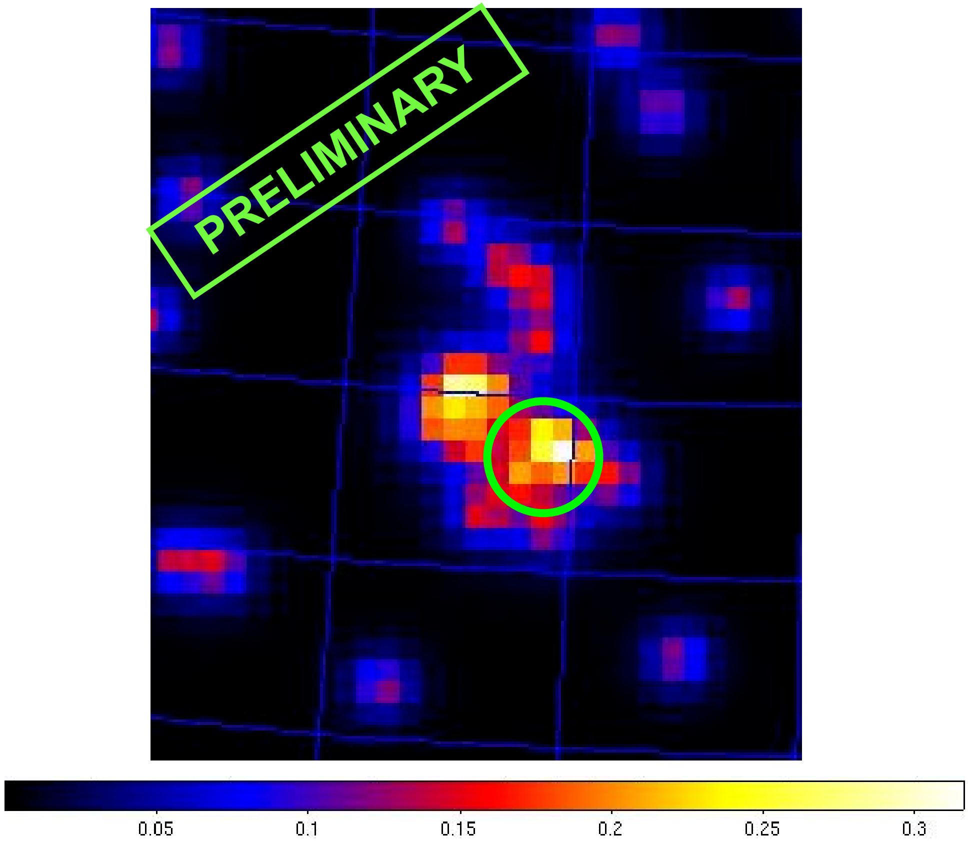


Smoothed Counts Map



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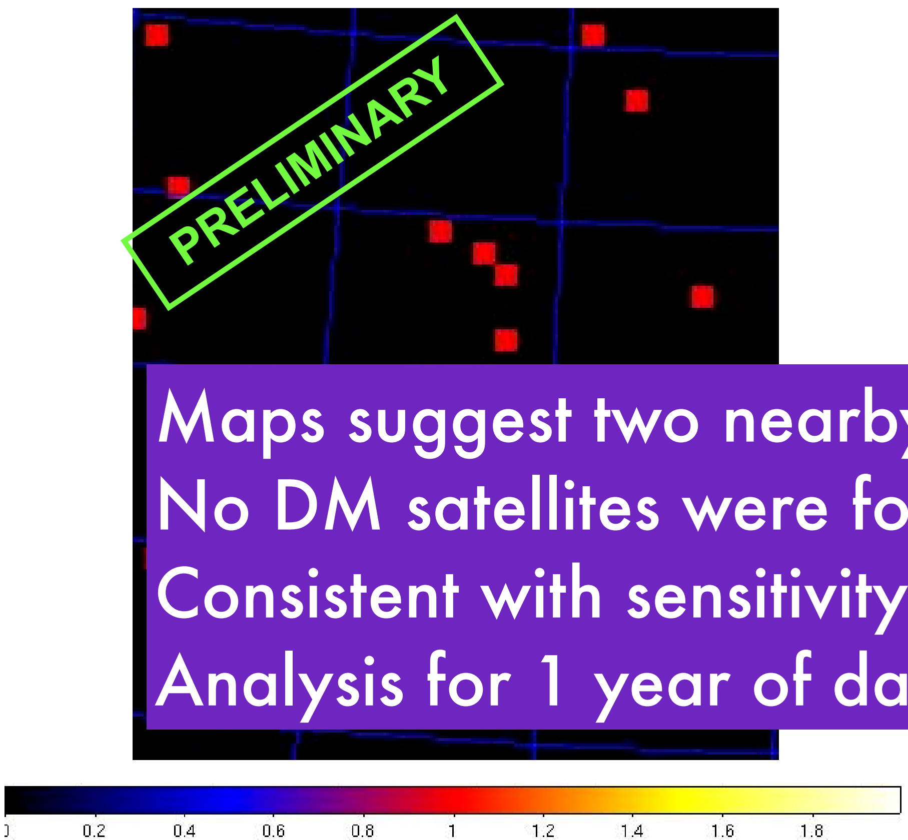

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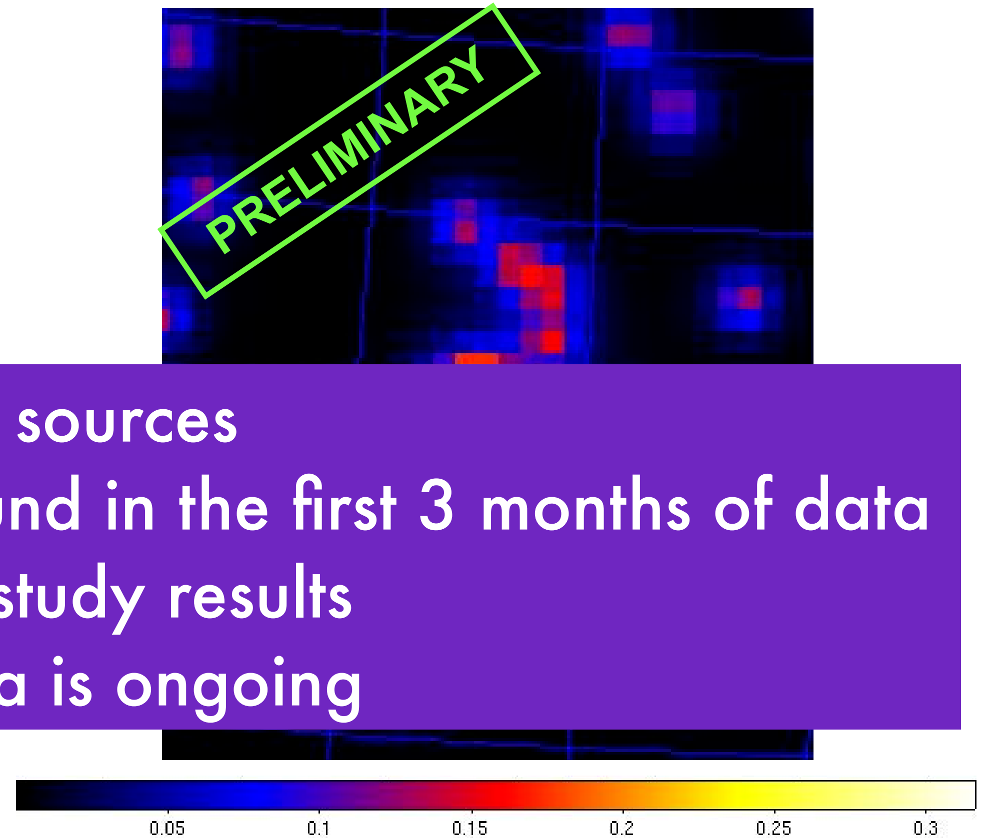


Maps suggest two nearby sources
No DM satellites were found in the first 3 months of data
Consistent with sensitivity study results
Analysis for 1 year of data is ongoing

The Gamma-ray Diffuse Emission

The Fermi Measurement

- EGRET observed an all sky excess in the GeV range compared to predictions from cosmic ray propagation and γ ray production models consistent with local cosmic-ray nuclei and electron spectra

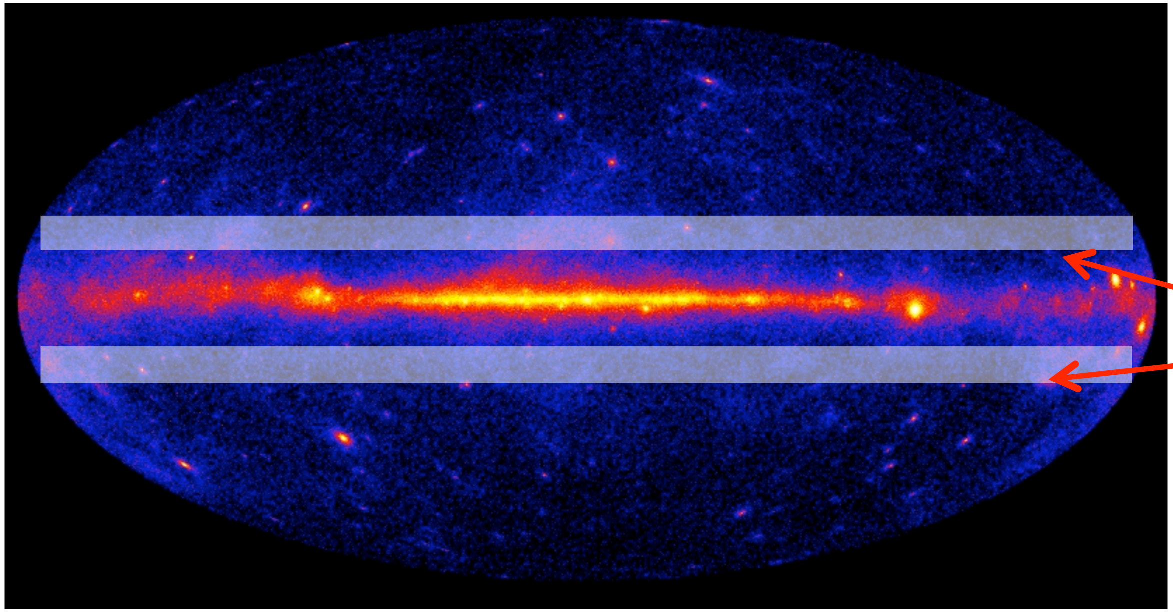
➡ The data collected by the LAT from mid-August to end of December does not confirm the excess at intermediate latitudes

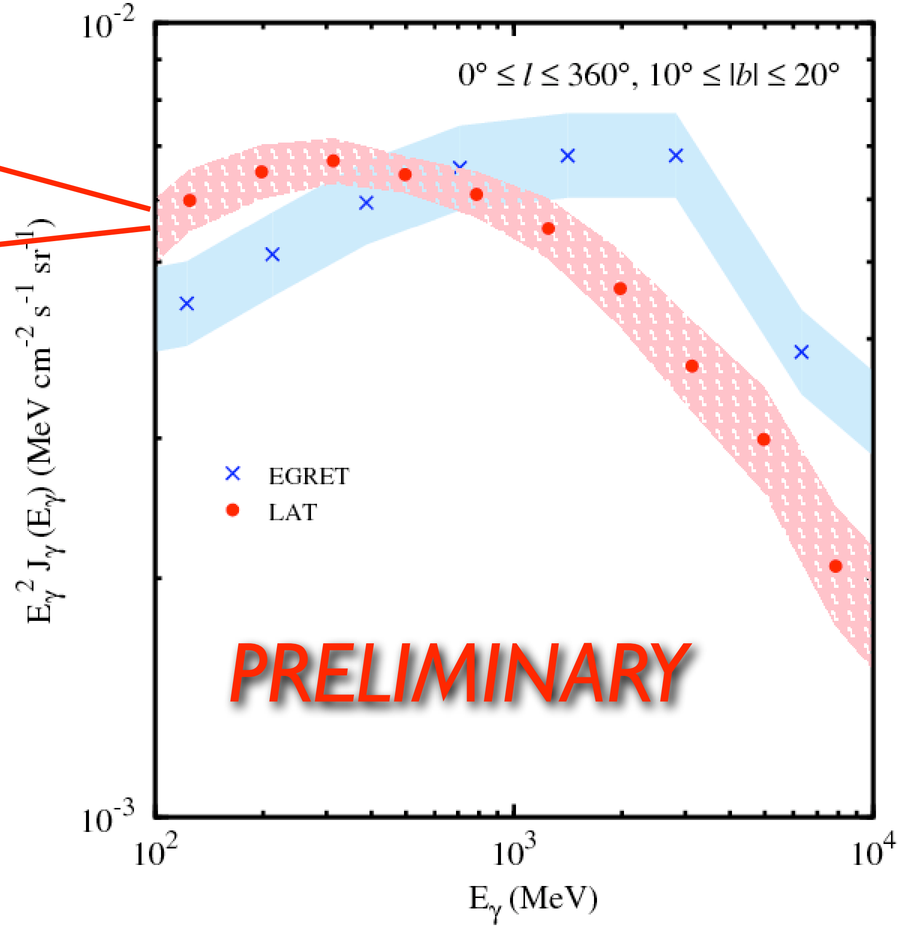
- Sources are not subtracted, but they are a minor component. LAT error is systematic dominated (~10%, preliminary)

- Strongly constrains DM interpretations

The Fermi Measurement

100 MeV – 10 GeV





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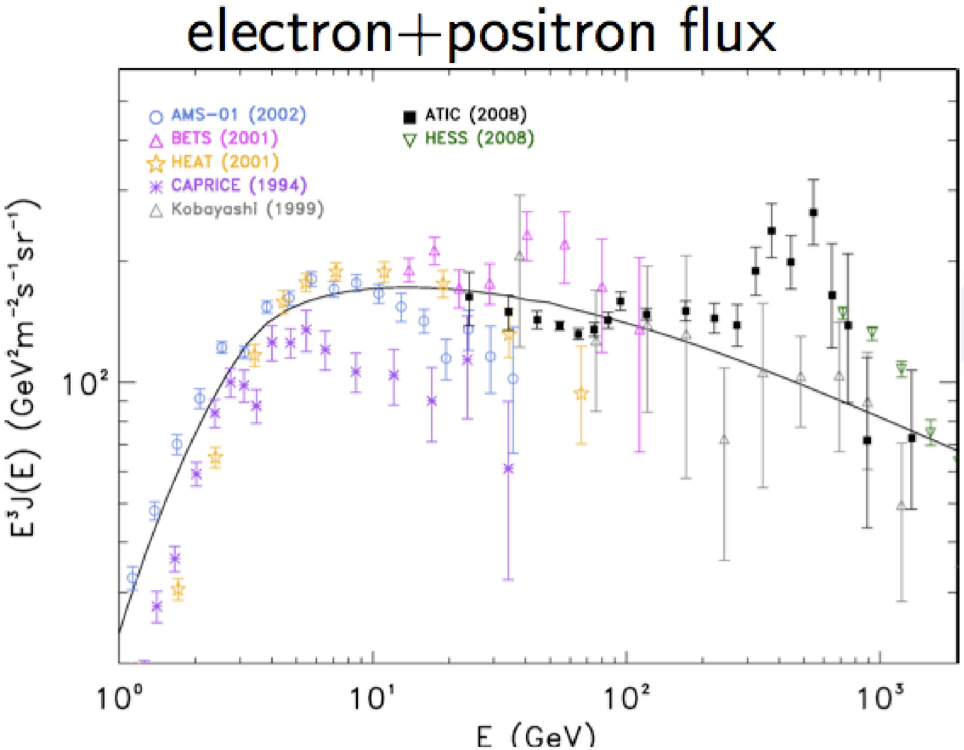
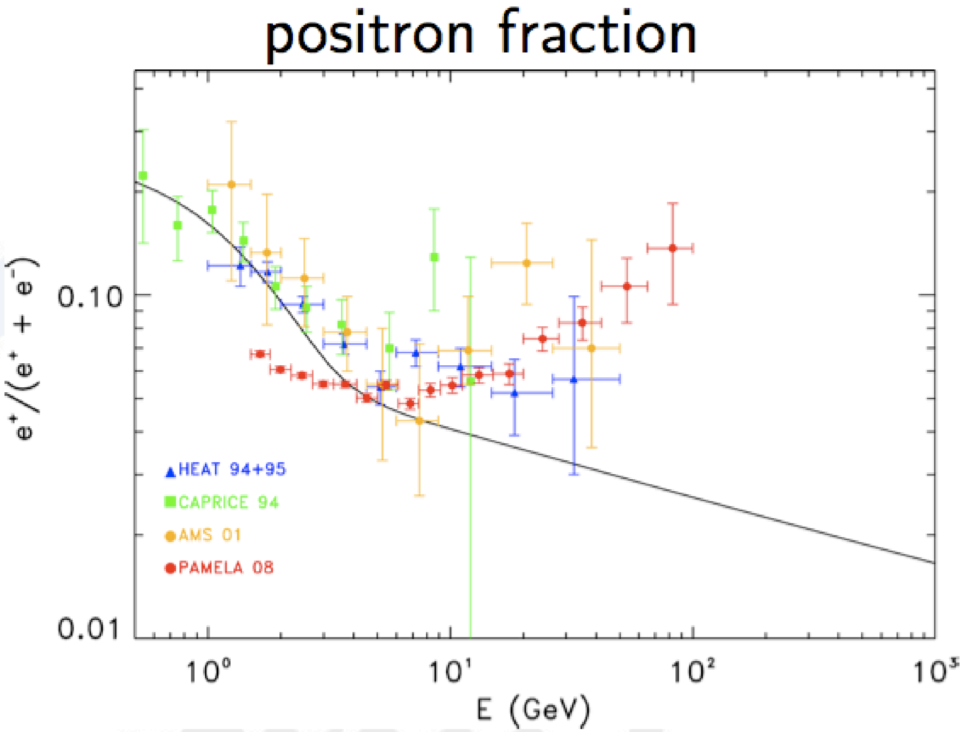
The High Energy Cosmic Ray e^+e^- Spectrum

CR Electron Measurements





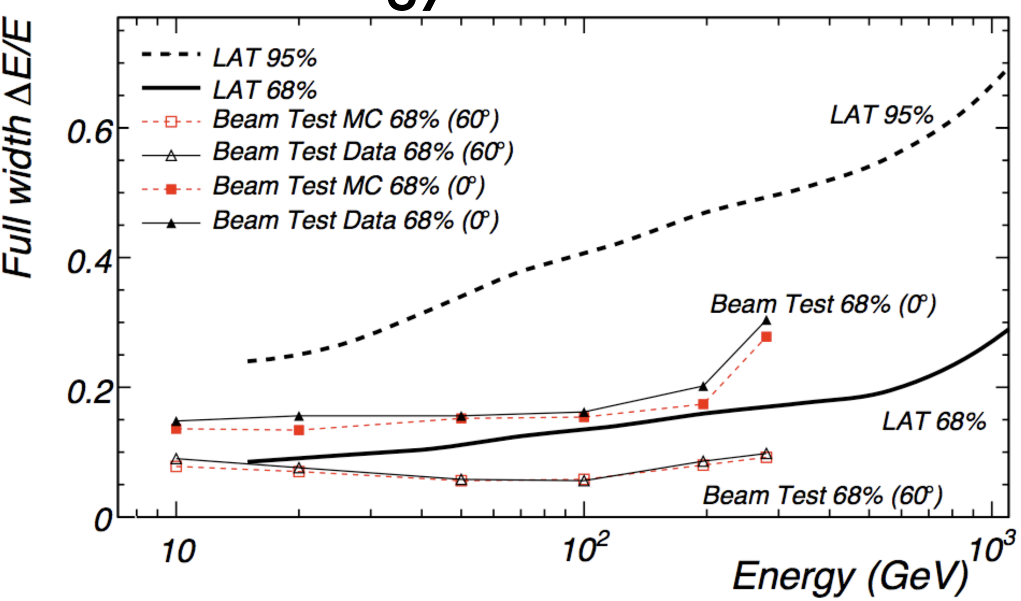
- Tantalizing hints from space:
  - ATIC observes an excess in the 300-800 GeV range with a steepening at high energy confirmed by HESS
  - PAMELA measures an increase in the positron fraction at high energy in disagreement with theoretical predictions for secondary positron production
- Primary positron source (e.g. pulsar(s) or dark matter clump)?

Fermi CRE Analysis

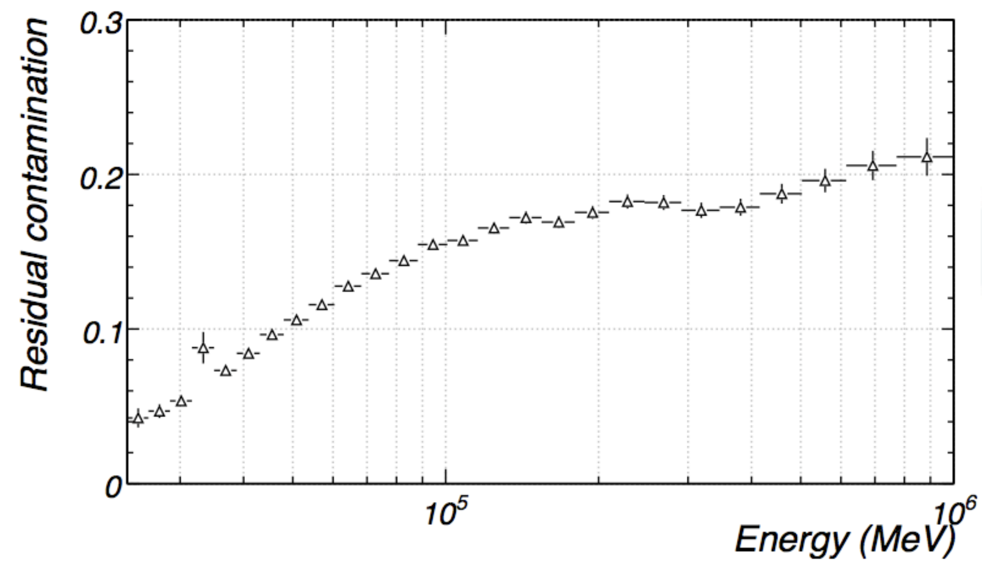
Phys. Rev. Lett. 102, 181101 (2009)

➡ Fermi is an excellent electron+positron detector (but it can't discriminate charge)

Energy resolution



Residual hadronic contamination



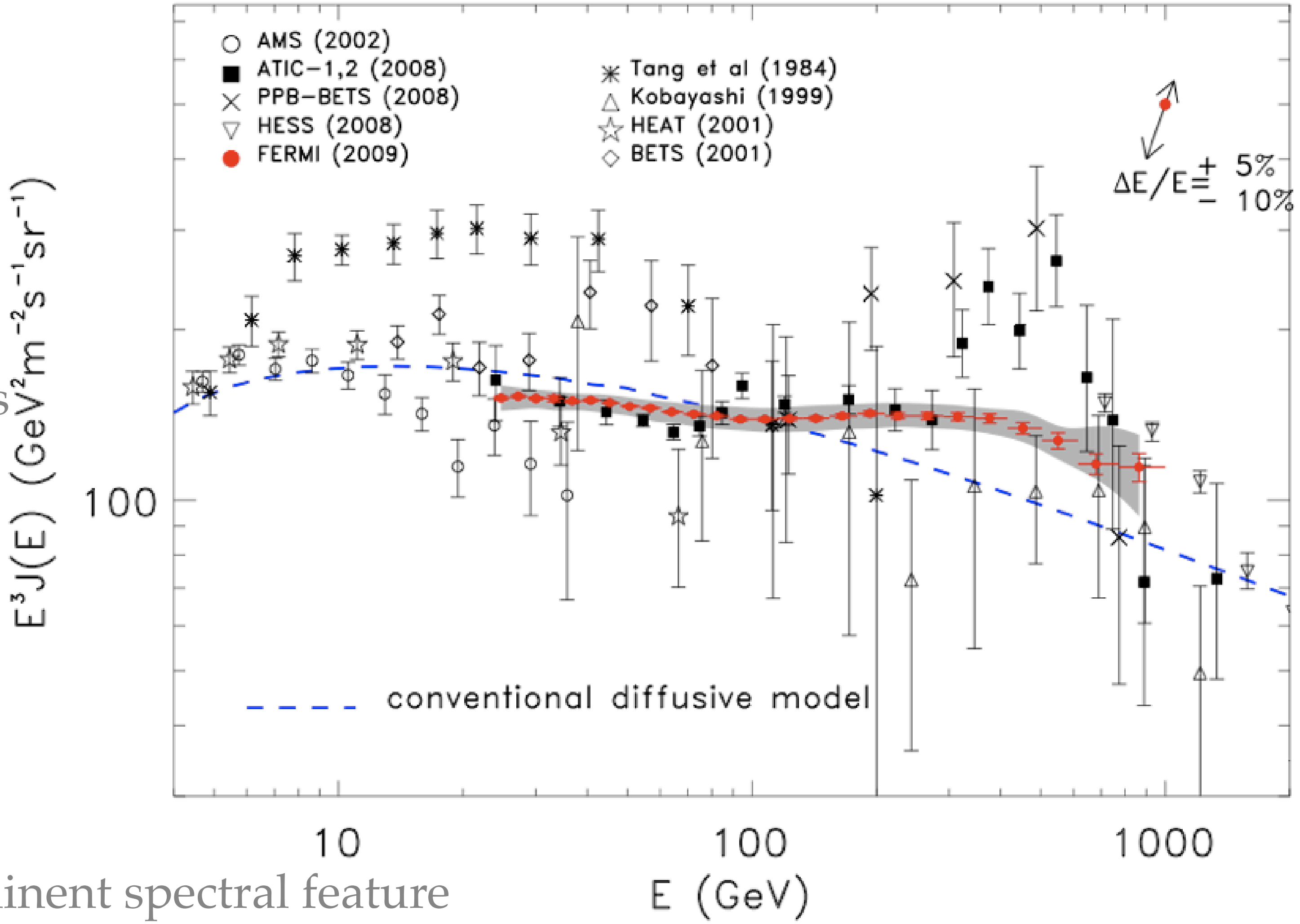
- Validated with the calibration unit beam test up to 282 GeV
  - Excellent agreement over the whole phase space
  - Reasonable to trust MC up to 1 TeV

- Hadronic contamination rises from few % to ~20% over the whole energy range.
  - Estimated from a large MC simulation
  - Subtracted from candidate electrons
- γ contamination is less than 2% in the highest energy bin

Fermi CRE Spectrum

Phys. Rev. Lett. 102, 181101 (2009)

- High statistics: ~4.5M events in 6 months
  - errors dominated by systematic uncertainties
- Not compatible with the pre-Fermi data diffusive model ($E^{-3.3}$ whereas we measured $E^{-3.0}$)

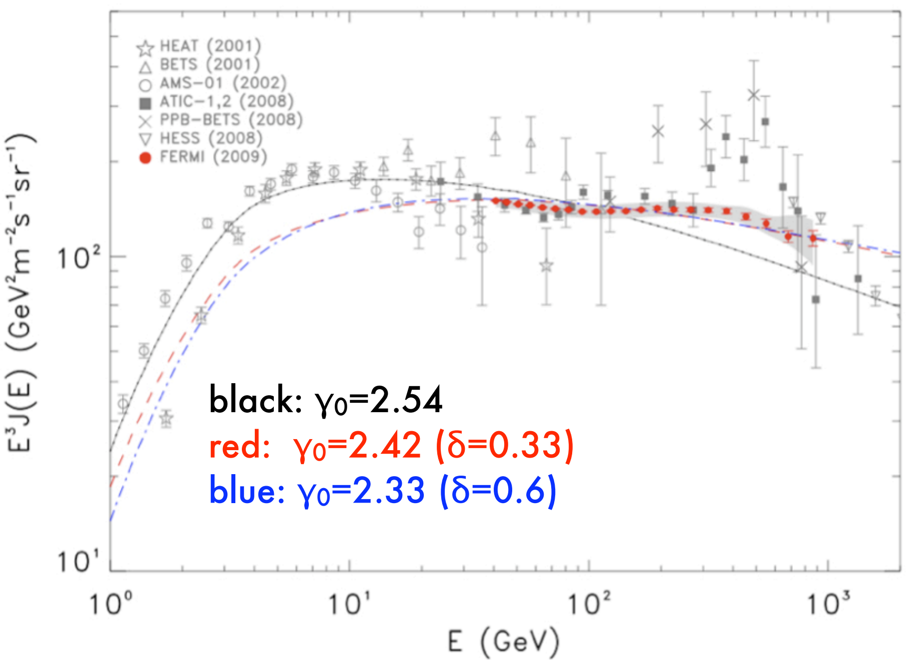


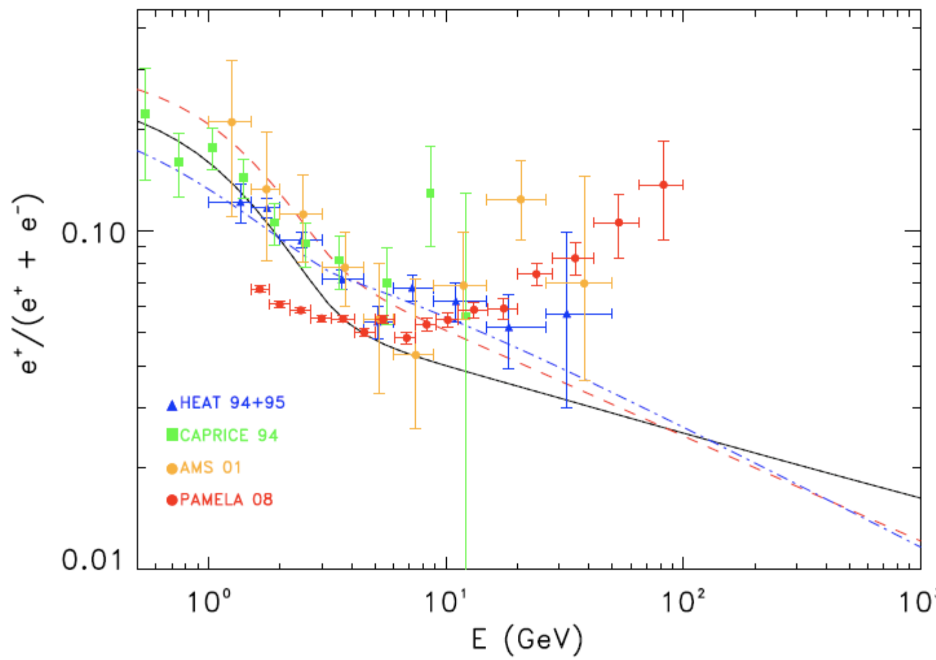
- No evidence of a prominent spectral feature
  - ATIC excess: 70 electrons between 300 and 800 GeV
  - ➡ we would have seen an excess of 7000 electrons

Conventional GCRE

arXiv:0905.0636 [astro-ph.HE]

- Conventional diffusive CR model (based on GALPROP code): e^+e^- originate from sources averaged over the galaxy (SNRs, pulsars) with model parameters adjusted to fit a large amount of *pre-Fermi* CR data:
  - universal e^- injection spectral index=2.54 above 4 GeV; diffusion coefficient ~$E^{1/3}$; synchrotron & IC energy losses; e^+ secondaries from CR hadrons interacting in the ISM
  - ➡ <u>reasonable agreement with Fermi data if injection spectrum is harder (2.42), but not consistent with PAMELA positron fraction</u>

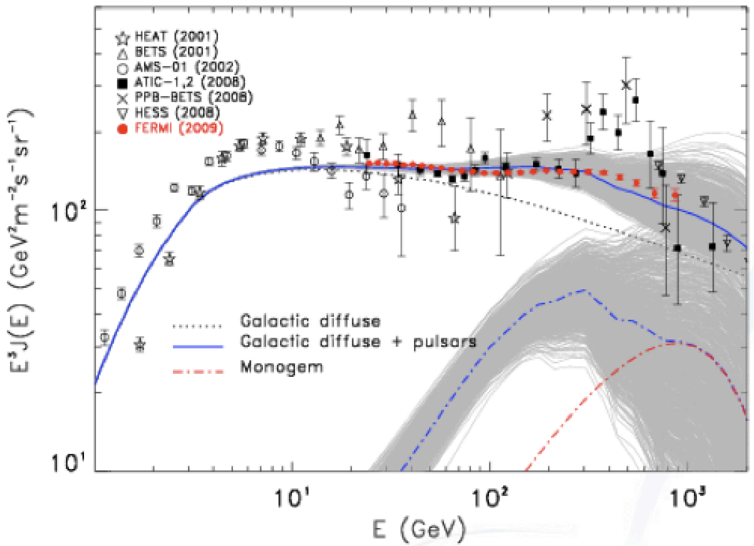


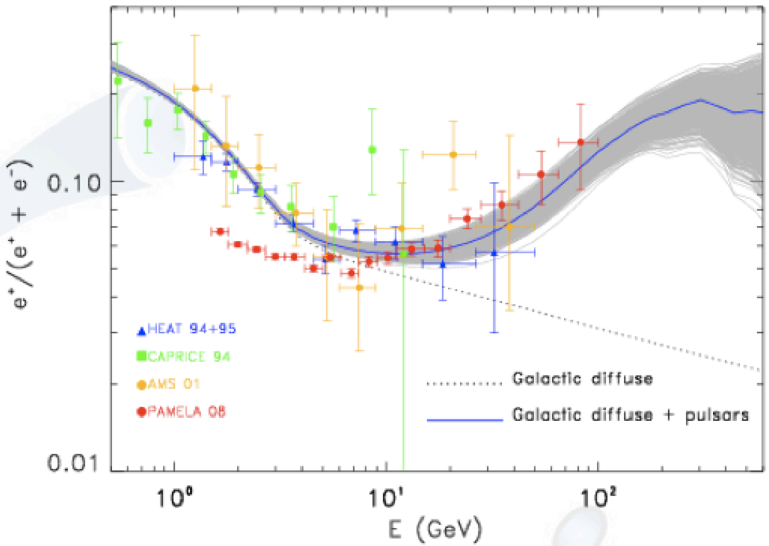


Nearby Pulsars

arXiv:0905.0636 [astro-ph.HE]

- Consider contribution from suitable pulsar populations (from the ATNF catalog): nearby (within 3 kpc), mature but not too old (5×10^4 to 10^7 yr)
- Vary parameters (injection index, cutoff energy, $e^{\pm}$ conversion efficiency, delay between pulsar birth and electron release) and create different possible summed contributions of all pulsars
- Provides reasonable interpretation for Fermi, PAMELA and HESS data

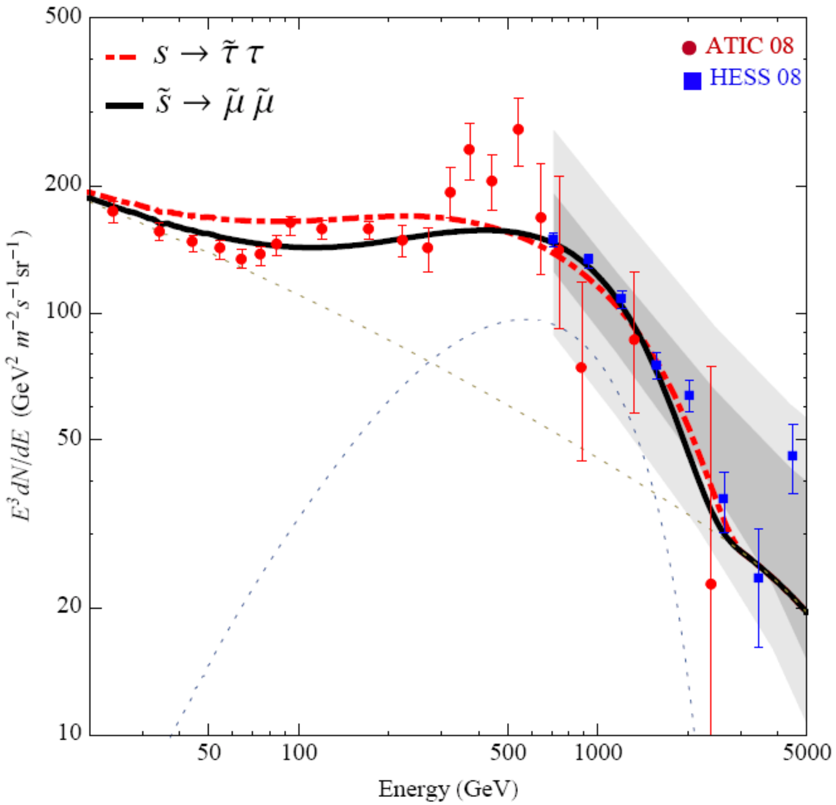


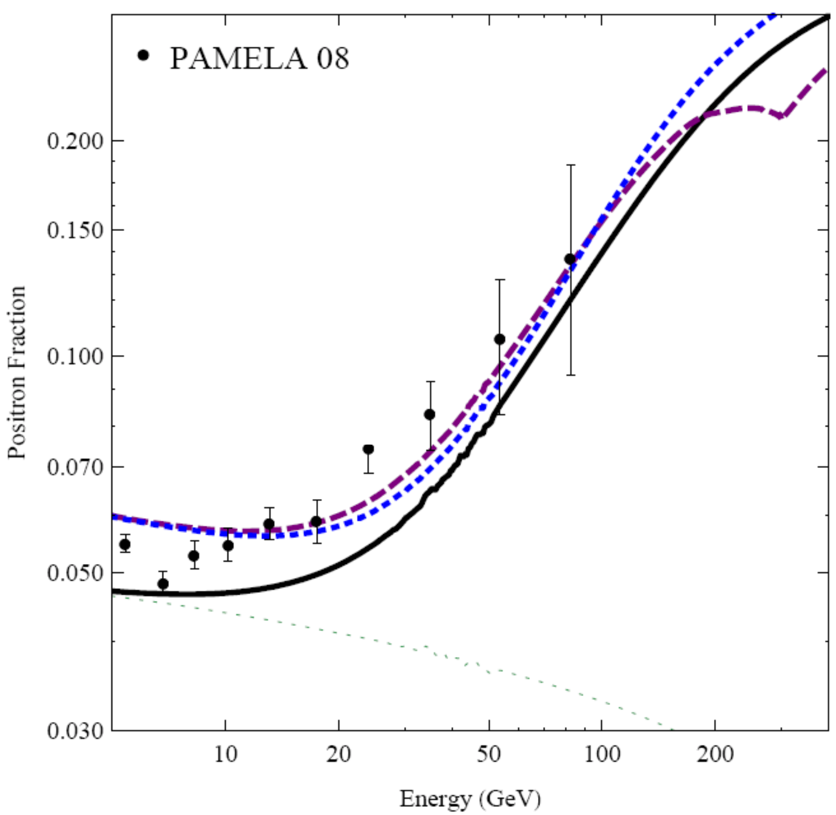


Possible DM Interpretation

arXiv:0904.2789 [hep-ph]

- In supersymmetric unified theories, the electroweak mass DM particle can decay with a lifetime of ~10^{26} sec (Arvanitaki, et al. 2009)
- PAMELA positron excess and lack of excess in antiprotons favor direct decay into leptons in this scenario





Possible DM Interpretation

arXiv:0904.2789 [hep-ph]

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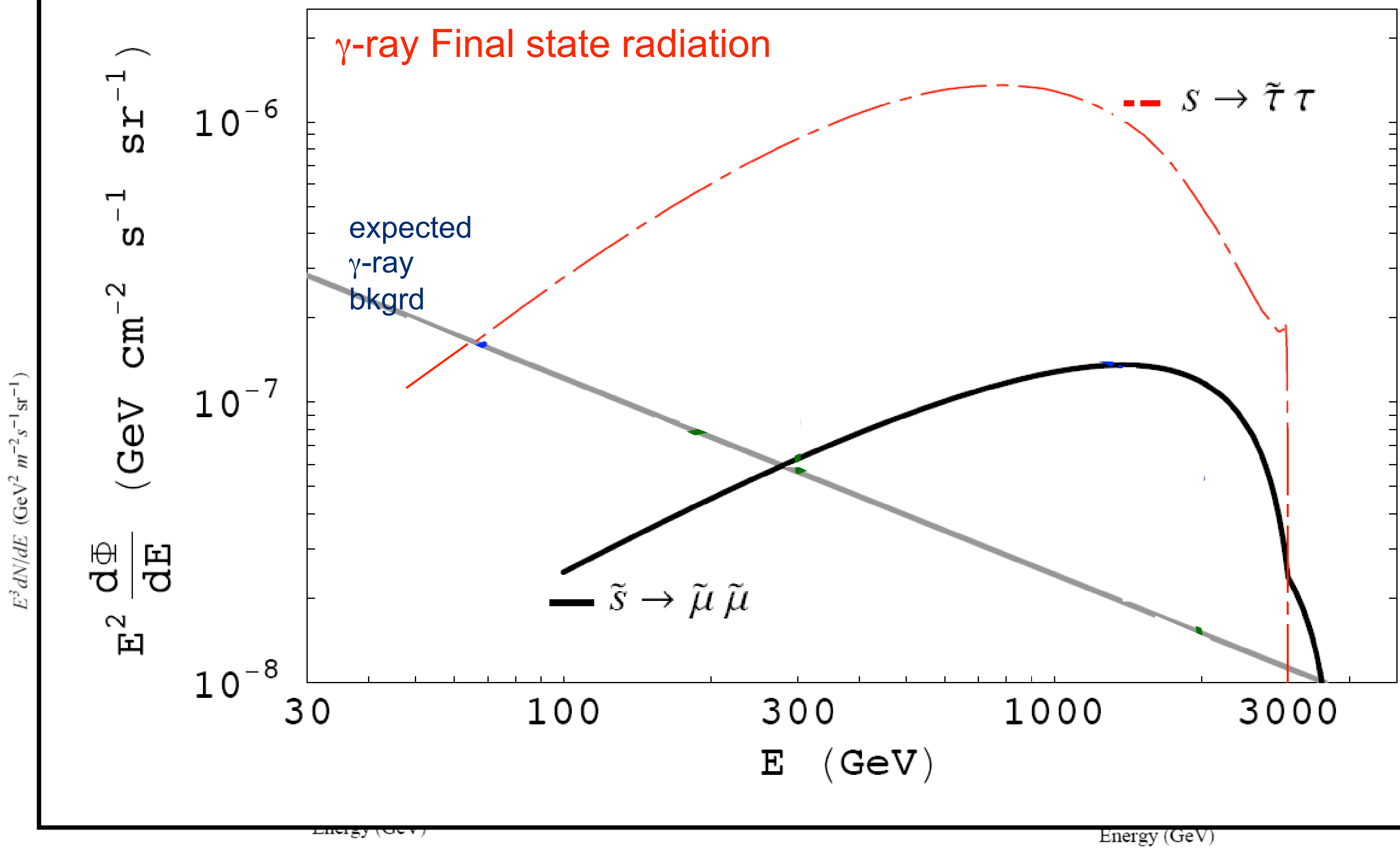
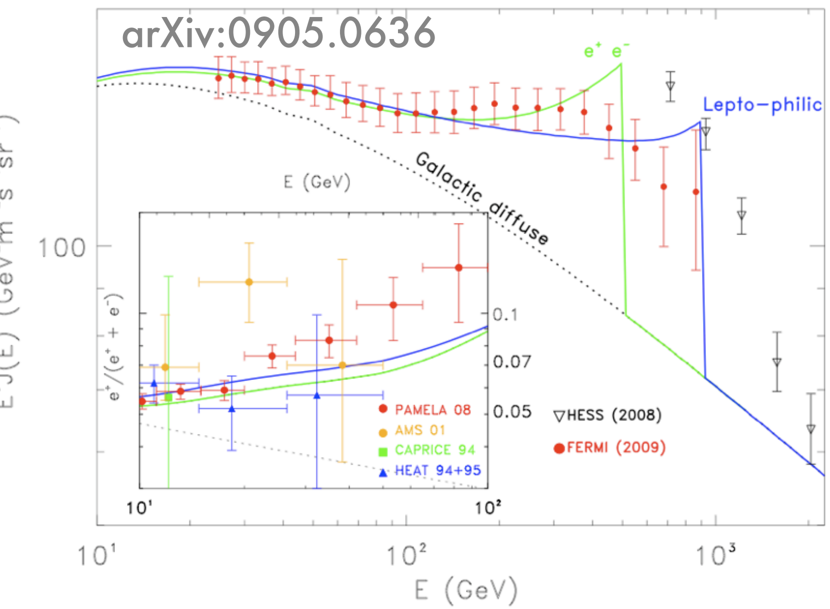
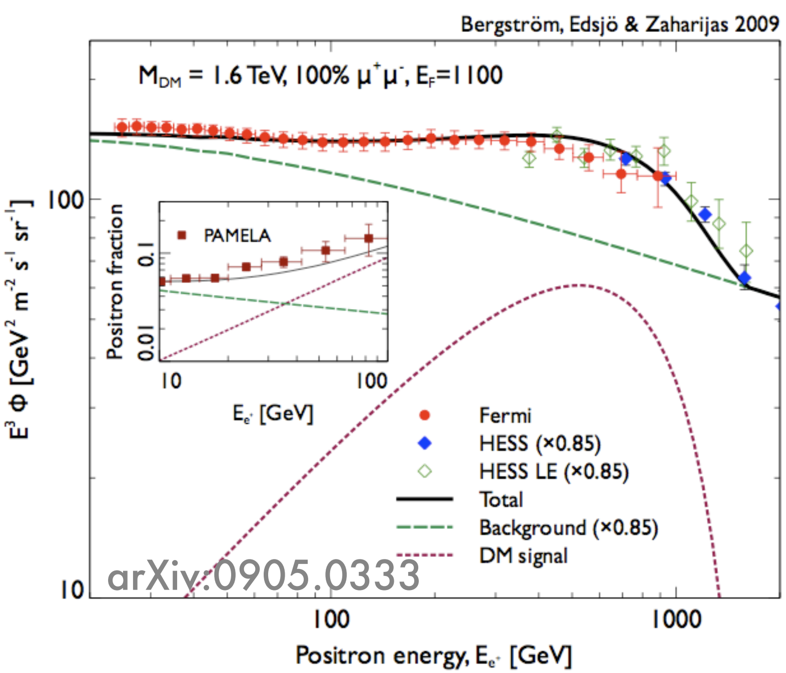
Possible DM “smoking gun” if FSR detected in γ-rays (~isotropically)



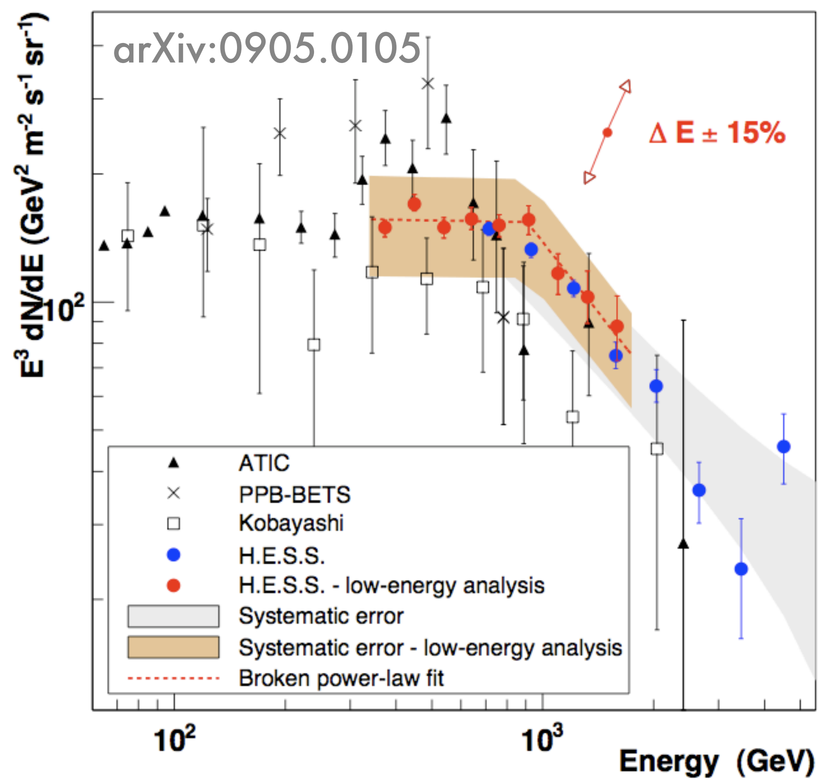
Example DM Fits





New HESS Result

- HESS measures power law spectrum (with spectral index 3) with steepening at 1 TeV



Conclusions

- Many exciting results from Fermi-LAT after just a few months of all-sky survey observations

- With the measurement of the galactic diffuse emission at intermediate latitudes and of the CR electron+positron spectrum, the data coming from the LAT have already made significant impact in the dark matter interpretation of potential signals from other experiments

- Some preliminary results on DM searches based on 3 months of data have been presented. Results for ~1 year of data for all analyses will be released in the upcoming months!