Fermi
Gamma-ray Space Telescope

New results from Fermi-LAT and their implications for the nature of dark matter and the origin of cosmic rays

Alexander Moiseev

CRESST/NASA GSFC and University of Maryland

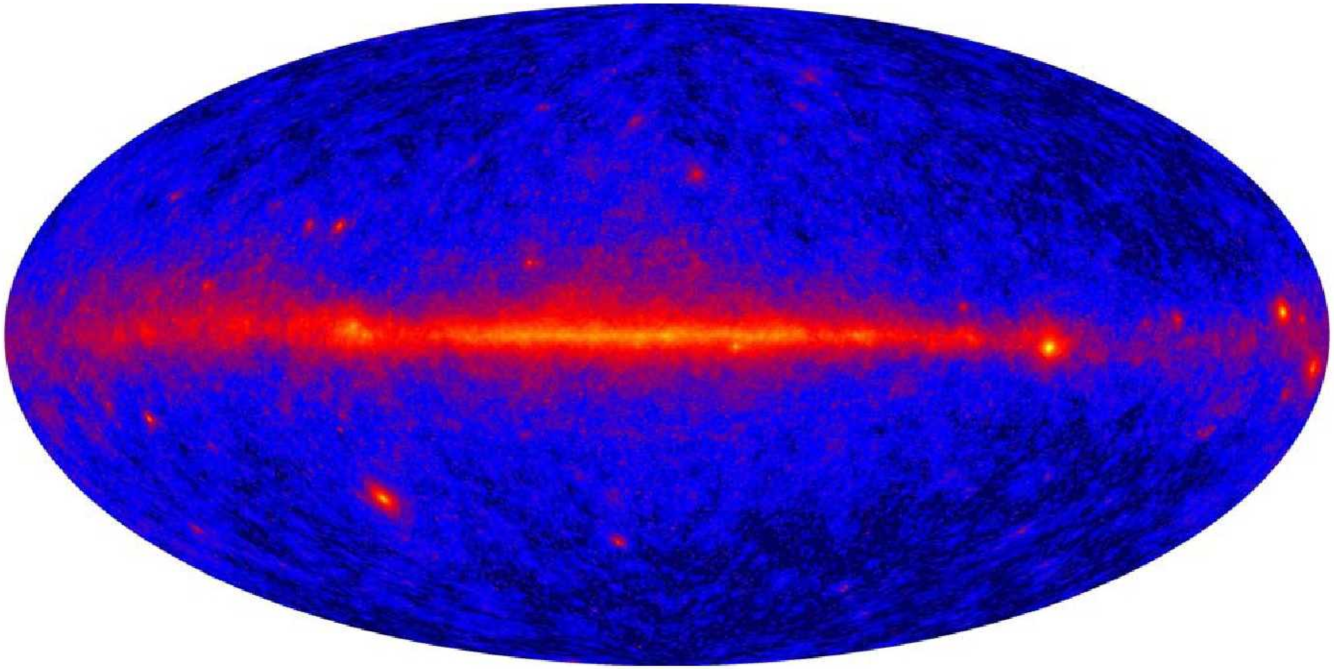
for the Fermi LAT Collaboration

Fermi Gamma-ray Space Telescope

Launch from Cape Canaveral, June 11, 2008

First Light – 4 days, 133K photons

- GLAST launch – June 11, 2008
- 13 days after launch: LAT and GBM activation – June 24. Start of on-orbit calibration



- 20 days after launch: LAT First light – July 1-4 !
- 23 days after launch (!): Start of nominal science observations – August 4
- Renamed to Fermi – August 28

Fermi Science Questions

Fermi science objectives cover probably everything in high energy astrophysics:

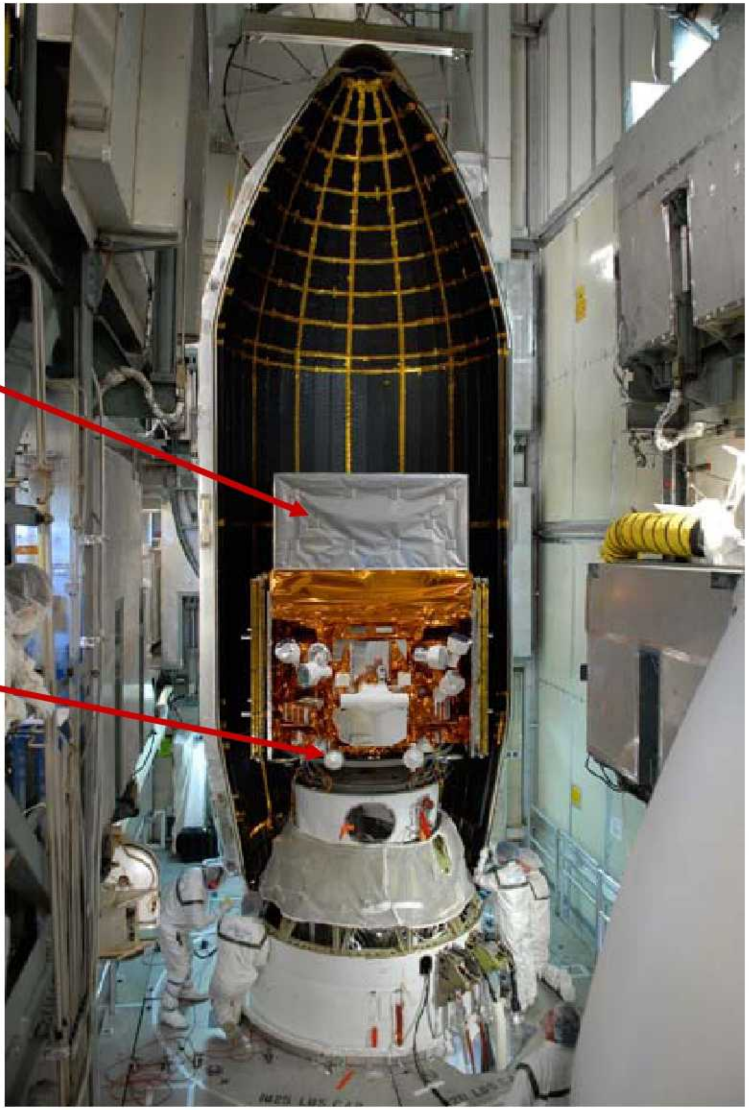
- *How do super massive black holes in Active Galactic Nuclei create powerful jets of material moving at nearly light speed? What are the jets made of?*
- *What are the mechanisms that produce Gamma-Ray Burst (GRB) explosions? What is the energy budget?*
- *How does the Sun generate high-energy γ-rays in flares?*
- *How do the pulsars operate? How many of them are around ?*
- *What are the unidentified γ-ray sources found by EGRET?*
- *What is the origin of the cosmic rays that pervade the Galaxy?*
- *What is the nature of dark matter?*

Multiwavelength observations in cooperation with gamma-ray, X-ray, radio, and optical telescopes

Fermi Observatory

Two instruments onboard:

- **Large Area Telescope LAT**
  - main instrument, gamma-ray telescope, 20 MeV - >300 GeV
  - scanning (main) mode - 20% of the sky all the time; all parts of sky for ~30 min. every 3 hours
- **GLAST Burst Monitor GBM**
  - 8 KeV – 40 MeV
  - observes whole unocculted sky all the time, searching for gamma-ray bursts



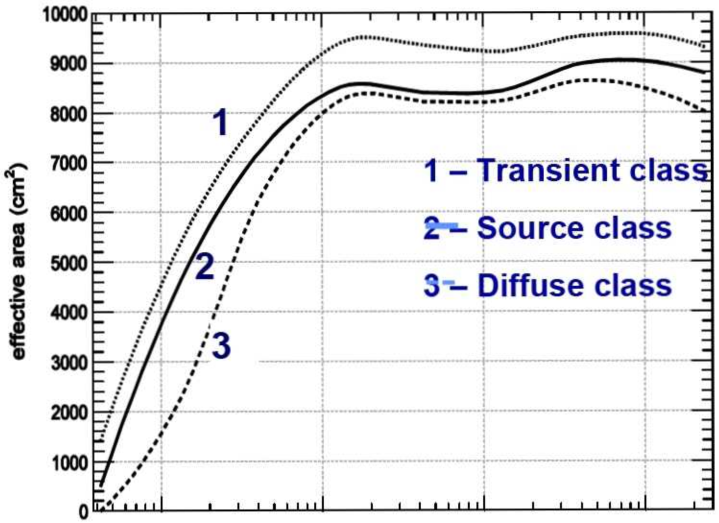
Large Area Telescope LAT

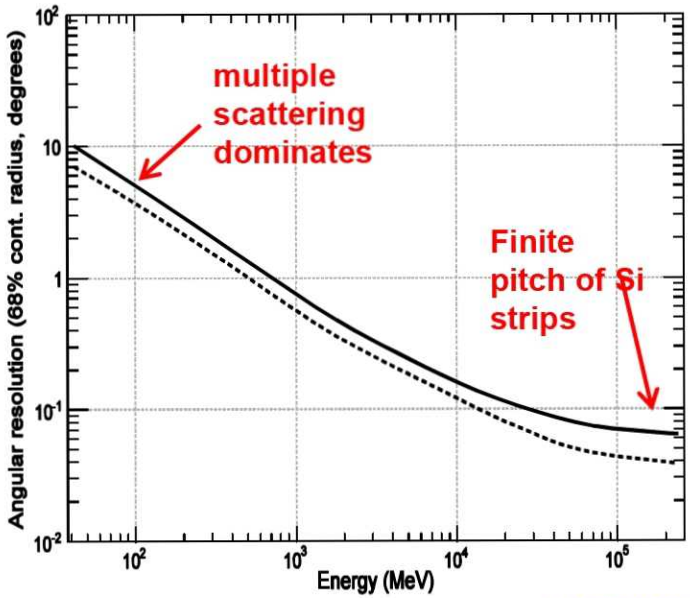
Heritage from OSO-III, SAS-II, COS-B, and EGRET, but:

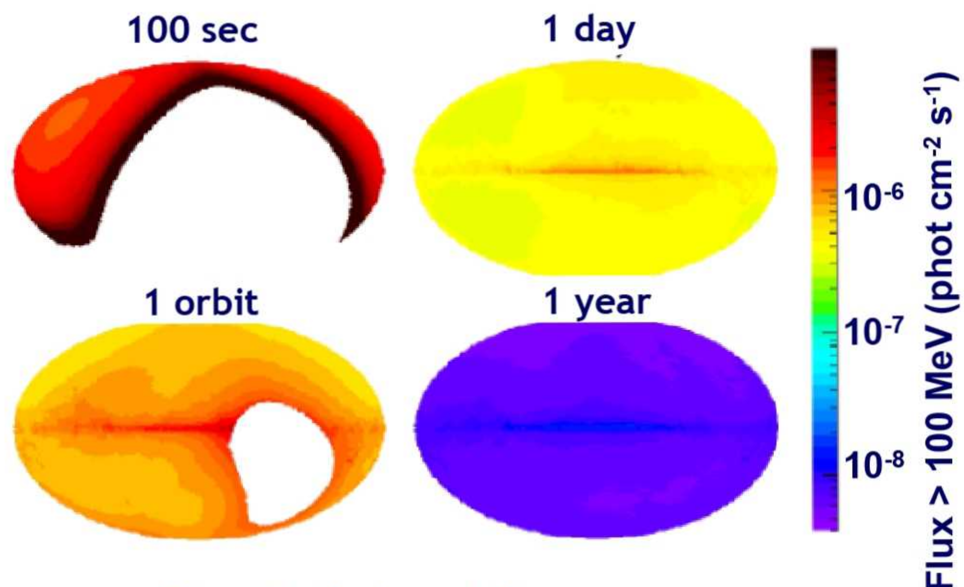
- large field of view (2.4 sr at 1 GeV, 4 times greater than EGRET) and large effective area (~8000 cm^2 on axis at 1 GeV)
- large energy range, overlapping with EGRET under 10 GeV and with HESS, MAGIC, CANGAROO and VERITAS above 100 GeV, including poorly-explored 10 GeV – 100 GeV range.
- Good energy (<15% at E>100 MeV) and spatial resolution
  - Unprecedented PSF for gamma-rays, >3 times better than EGRET for E>1GeV
- Small dead time (<30 μs, factor of ~4,000 better than EGRET) – GRB time structure!
- Excellent timing to study transient sources
- No consumables – chance for longer mission!

see for details Atwood, W. B. et al. 2009, ApJ arXiv:0902.1089v1

LAT Performance







Sensitivity to point sources

LAT is all-sky monitor, unlike EGRET and AGILE

Main results for the first 8 months

- *Pulsars*
- *Active Galactic Nuclei (AGN)*
- *Gamma-Ray Bursts (GRB)*
- *Diffuse radiation*
- *Electron + positron spectrum*

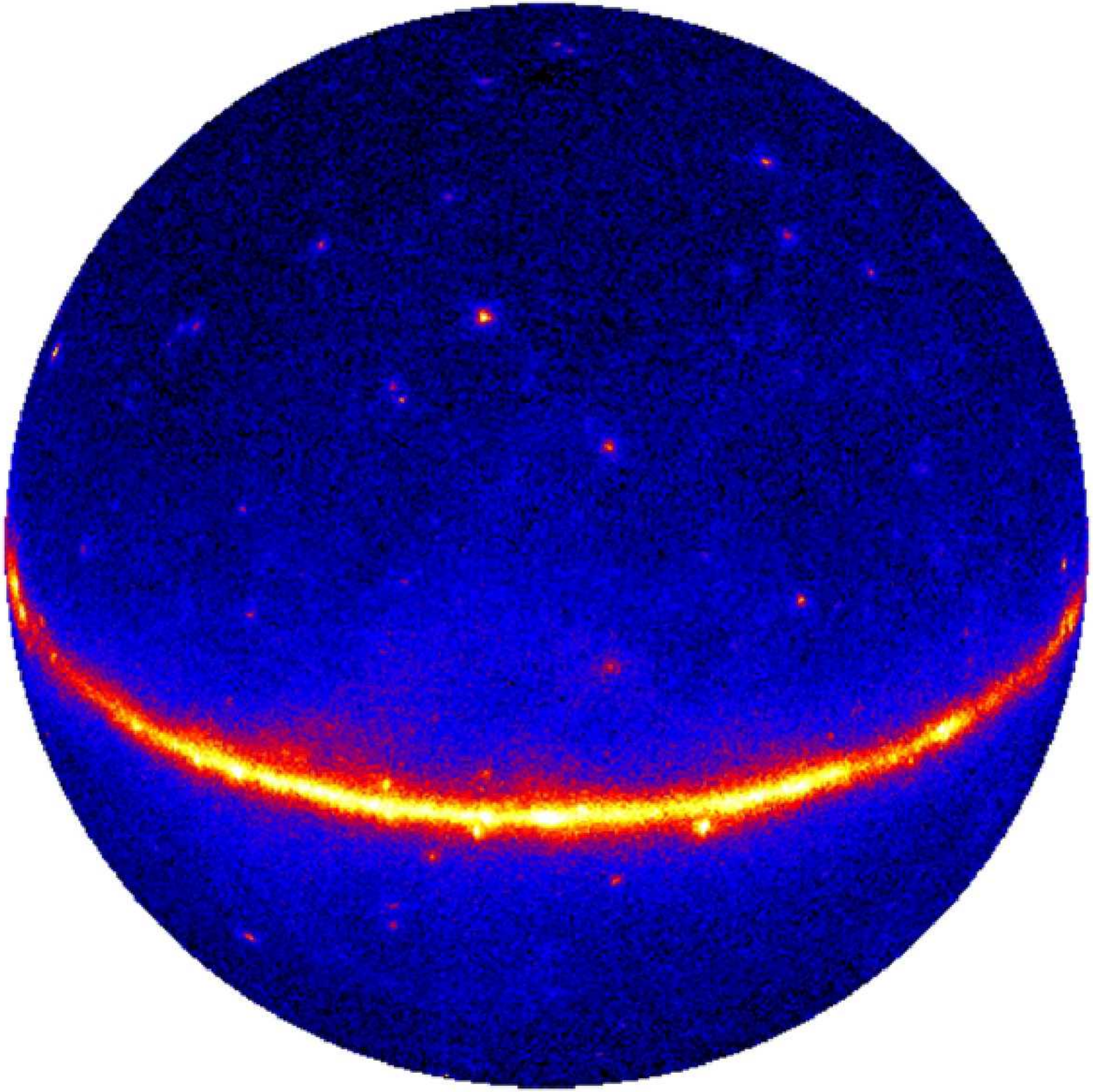
13 papers in refereed journals (7 published, 6 accepted)

– *Science, Astrophysical Journal, Astrophysical Journal Letters, Astrophysical Journal Supplements, Physical Review Letters*

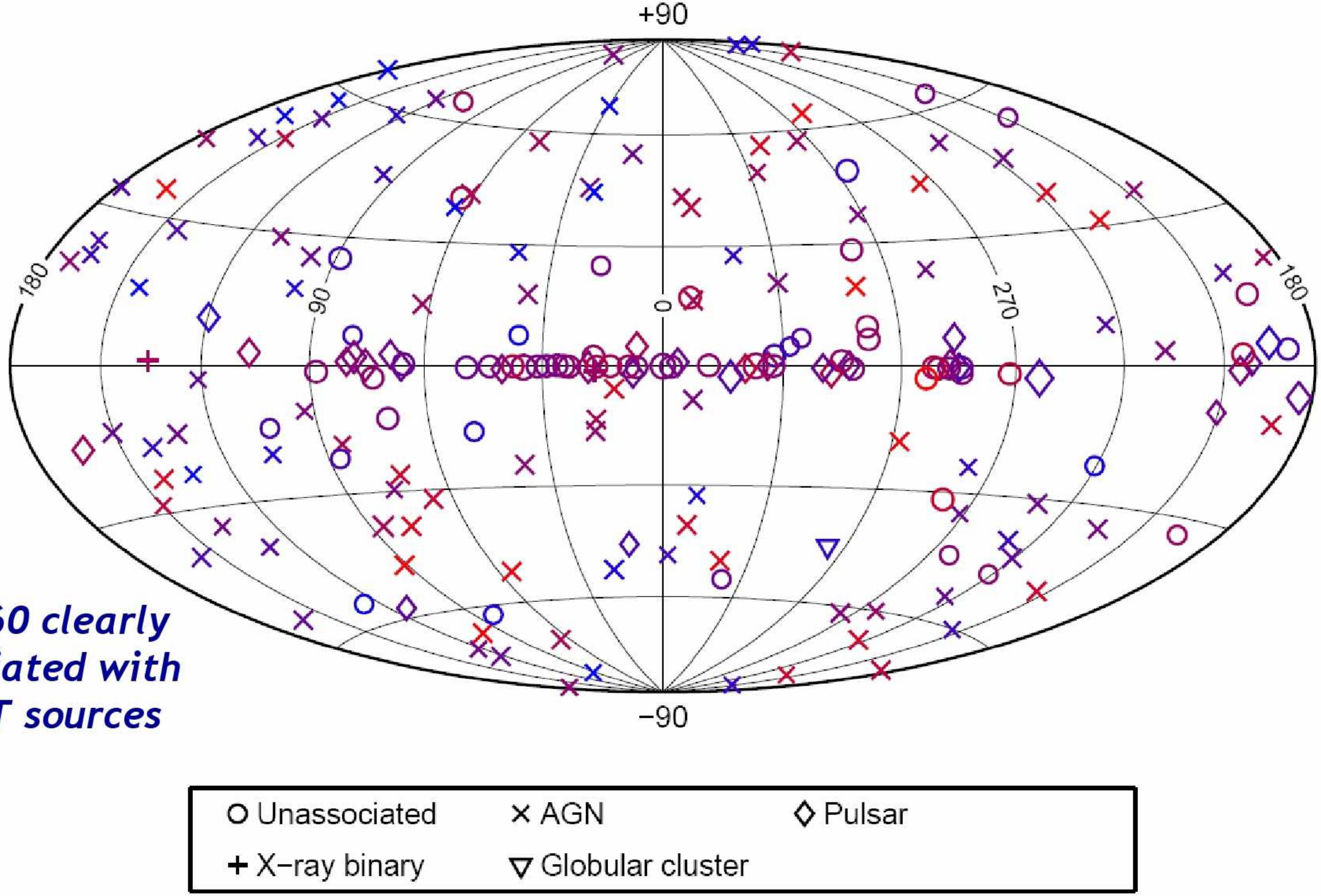
- *9 papers ready (5 submitted, 4 ready to submit)*
- *38 rapid publications*

– *29 Astronomer's telegrams (ATEL), 9 Gamma-ray burst coordination network (GCN) circulars*

LAT 3 month sky map : 205 high confidence bright sources (> 10 σ)



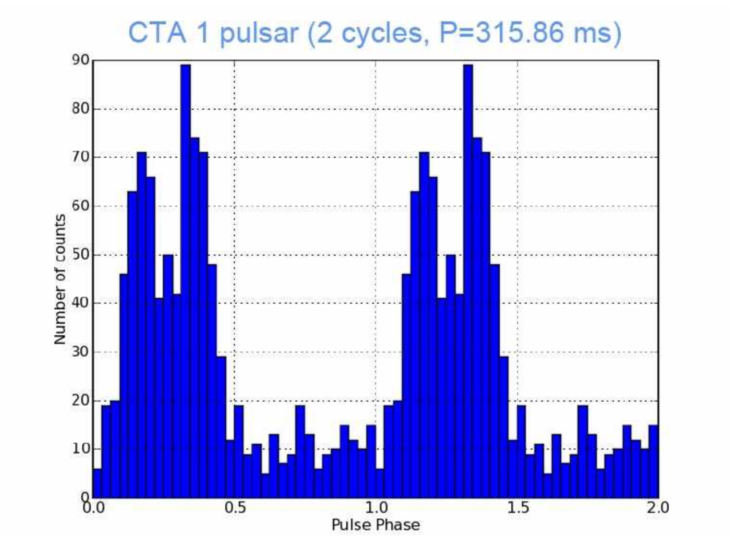
arXiv:0902.1340v1 [astro-ph.HE] 8 Feb 2009



Only 60 clearly associated with EGRET sources

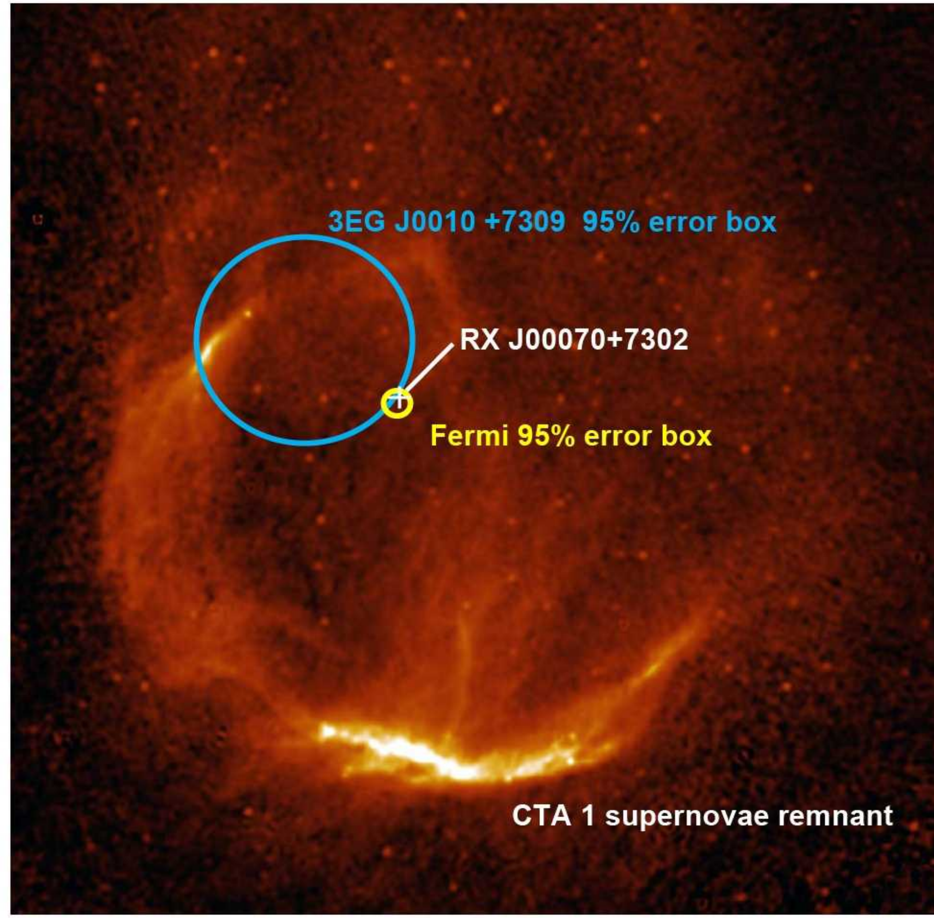
Fermi Gamma-ray Space Telescope

CTA 1 – First gamma-ray pulsar discovered by Fermi in blind search



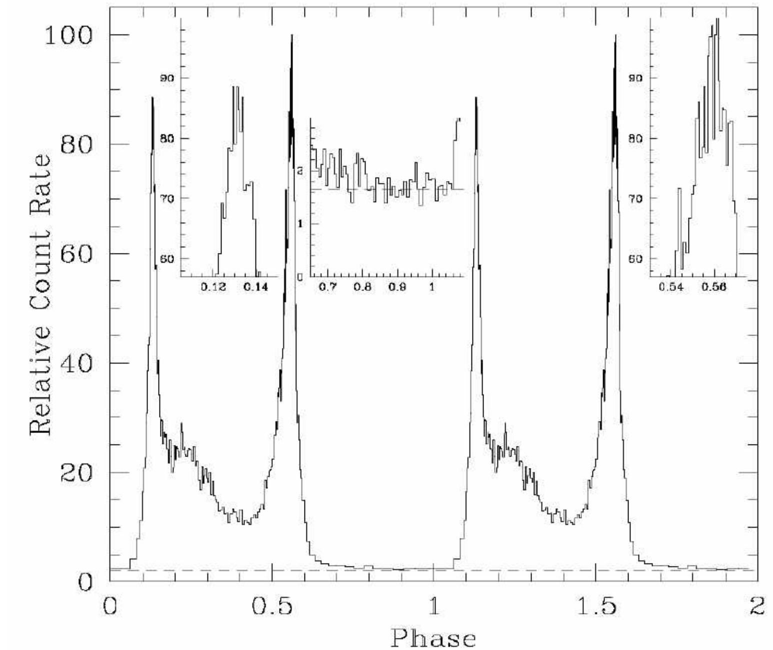
Exhibits all characteristics of a young high-energy pulsar (characteristic age ~1.4 x 10 yr), which powers a synchrotron pulsar wind nebula embedded in a larger SNR.

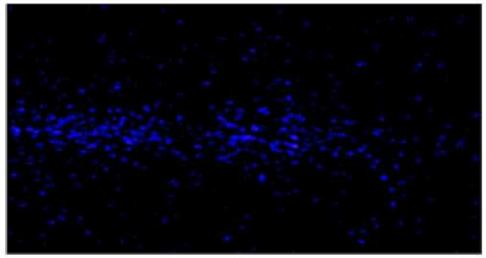
This source was a very bright AND well positioned unidentified EGRET source. This source was deliberately targeted during LAT checkout

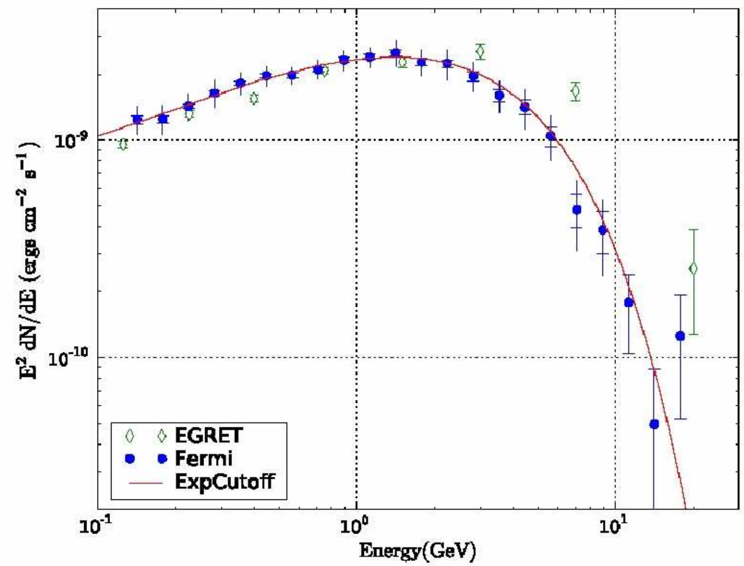


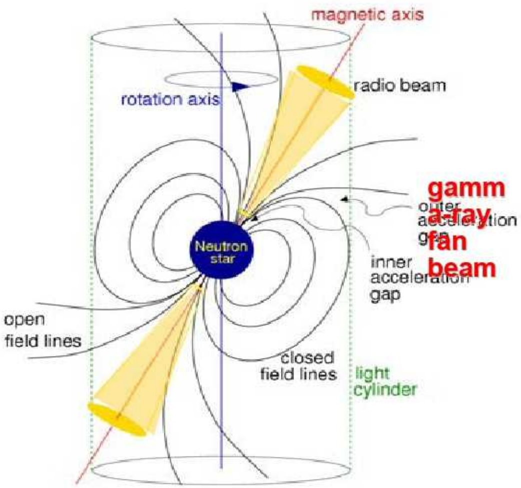
γ-ray source at l,b = 119.652, 10.468; 95% error circle radius =0.038° contains the X-ray source RX J00070+7302

Vela Pulsar





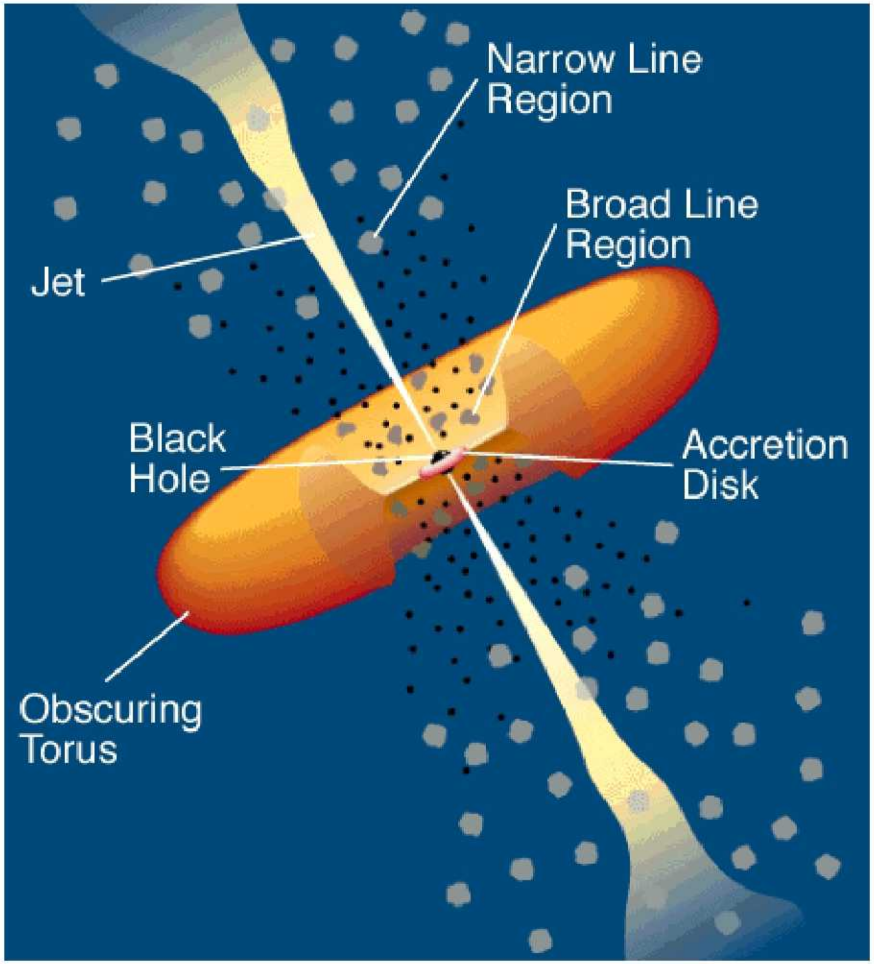




- ***Acceleration in Magnetosphere***
  - ***Outer magnetosphere***
  - ***Near the NS surface***
- ***LAT data consistent with simple exponential cut-off***
  - ***favors outer-gap model***

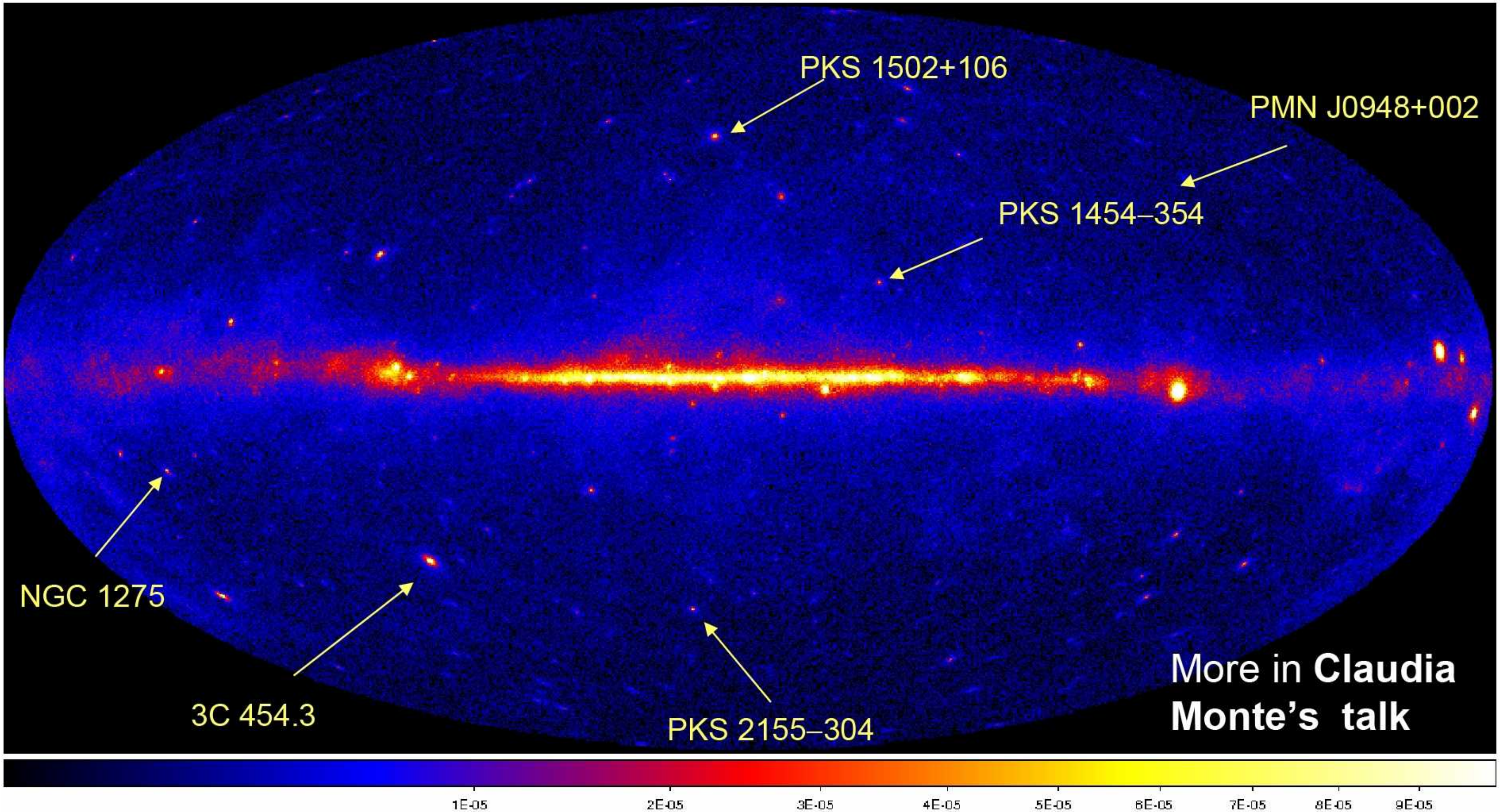
$$N(E) = N_0 E^{\Gamma} e^{-(E/E_c)^b}$$
$$\Gamma = -1.5^{+0.05}_{-0.04}$$
$$E_c = 2.9 \pm 0.1 \text{ GeV}$$

Unified Picture of AGNs



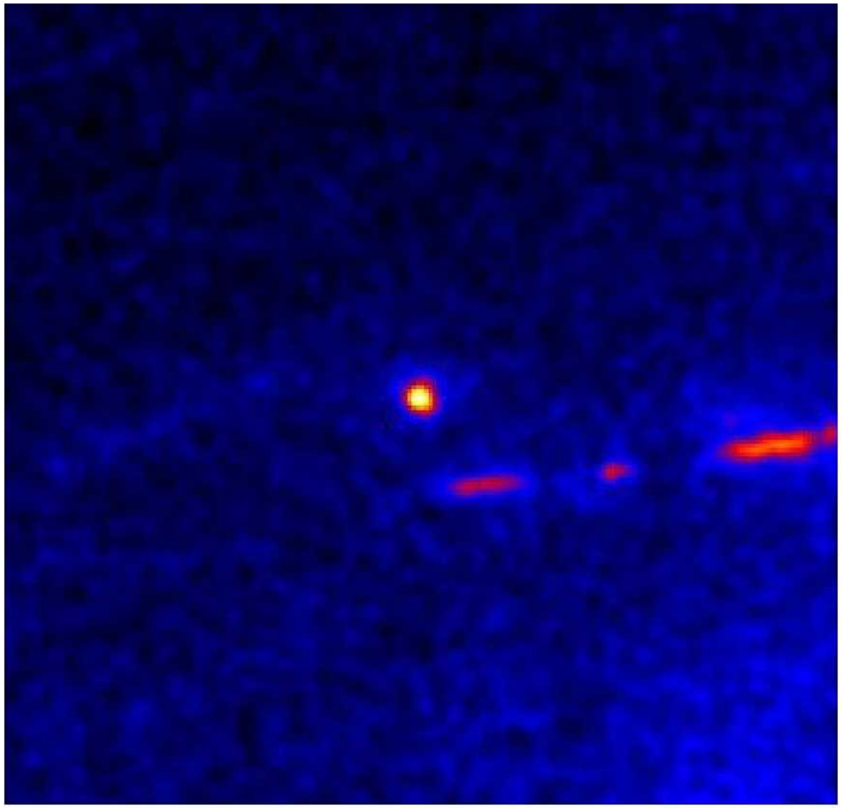
- *Powered by accretion onto a central, supermassive black hole*
- *Accretion disks produce optical/UV/X-ray emission via various thermal processes*
- *Jets: highly collimated outflows with Γ~10*
  - *Large brightness temps, superluminal motion, rapid variability in γ-rays*
- *Unified Model: observer line-of-sight determines source properties, e.g., radio galaxy vs blazar*
- *Other factors: accretion rate, BH mass and spin, host galaxy*

Fermi Results on AGNs

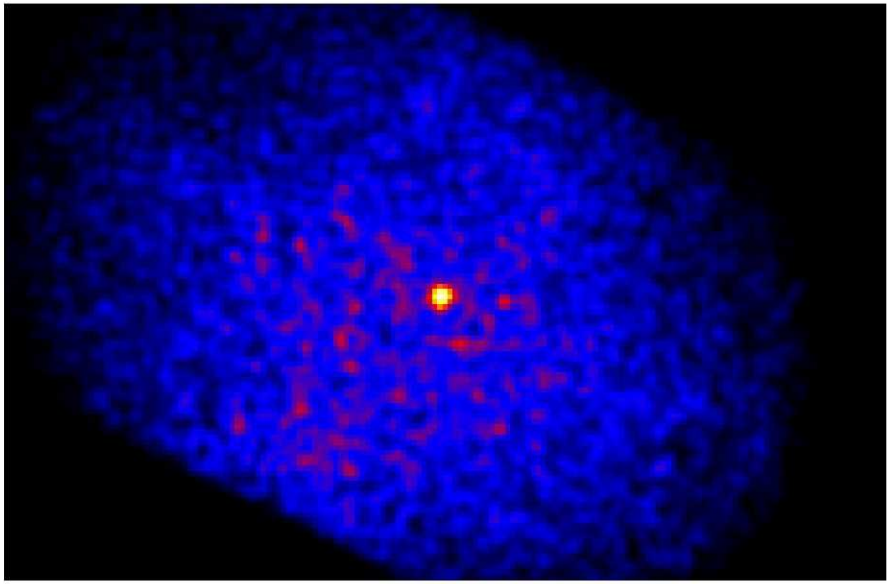


- ***58 FRSQs, 42 BL Lacs, 4 Unc., 2 radio galaxies***
- ***Automated Science Processing (ASP) with 2 × 10^{-6} ph cm^{-2} s^{-1} threshold (daily)***
- ***Flare Advocates***

Fermi detects the Sun and the Moon

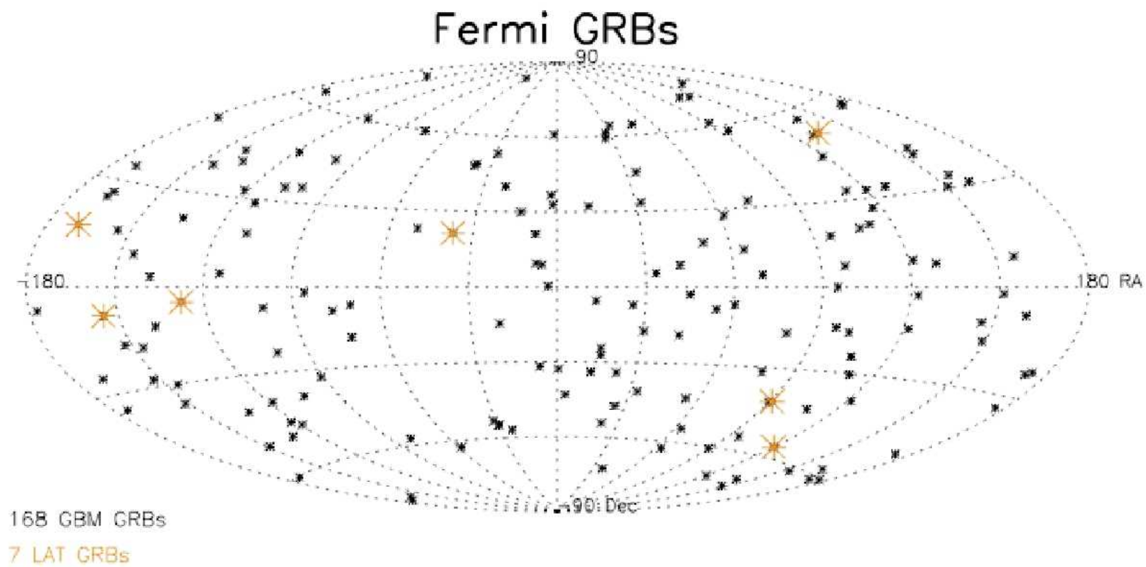


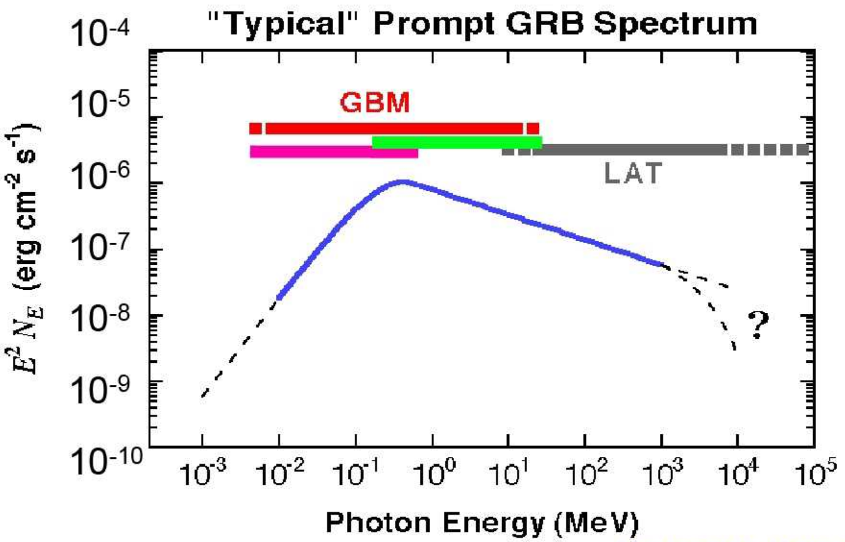
The Sun, July 1 – Sept 24, 2008



The Moon, August 3 – August 7, 2008

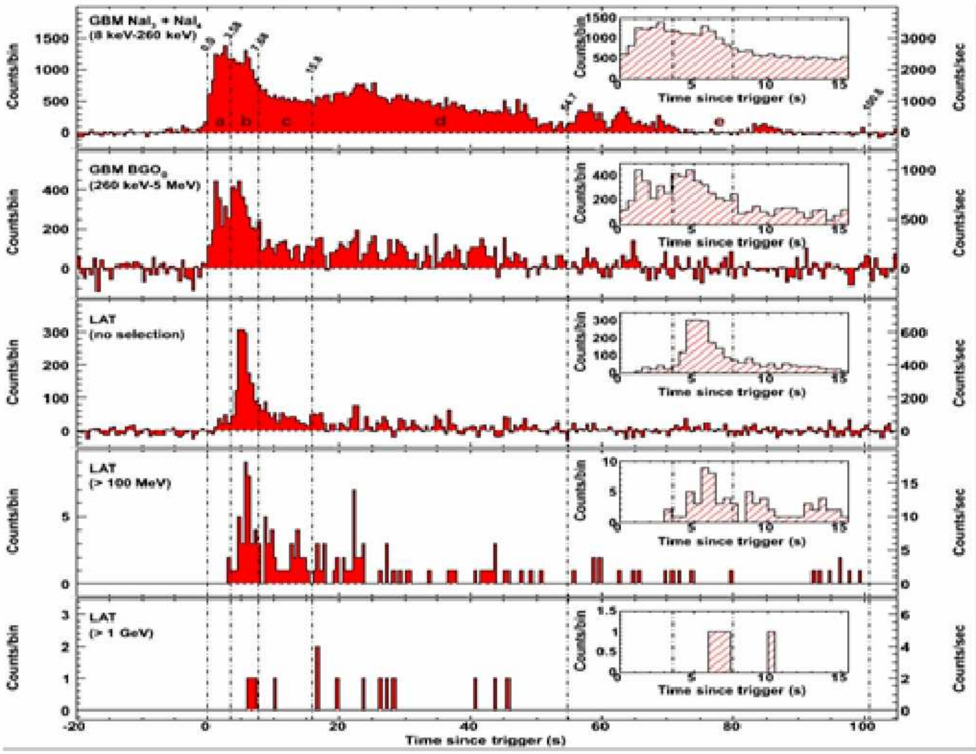
Gamma-ray Bursts Detected by GBM and LAT

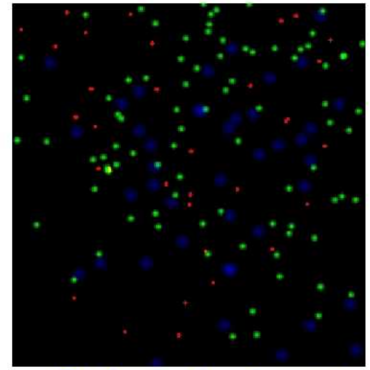




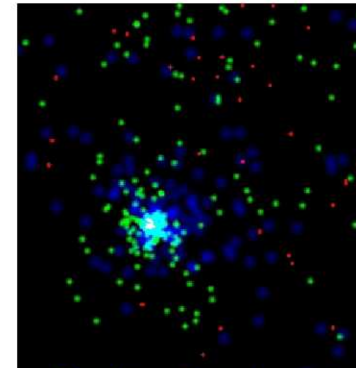
- *GRB 080825C*
- *GRB 080916C – strongest ever seen*
- *GRB 081024B – short*
- *GRB 081215A – LAT rate increase*
- *GRB 090217*
- *GRB 090323 – ARR*
- *GRB 090328 – ARR*

GRB 080916C – Strongest ever seen

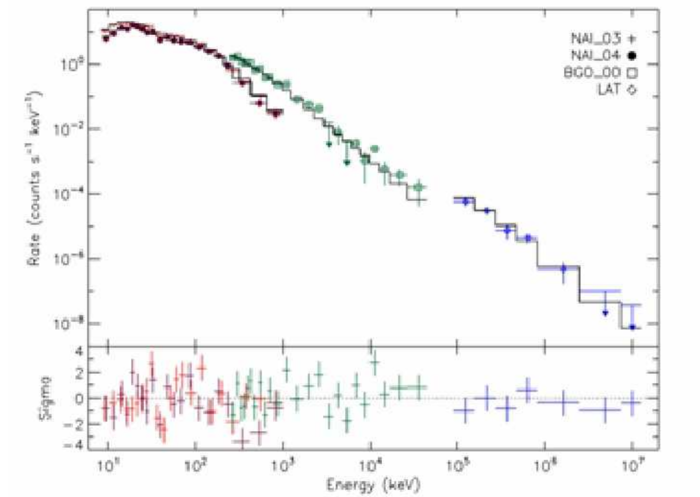




Before the burst
(T_0-100 s to T_0)



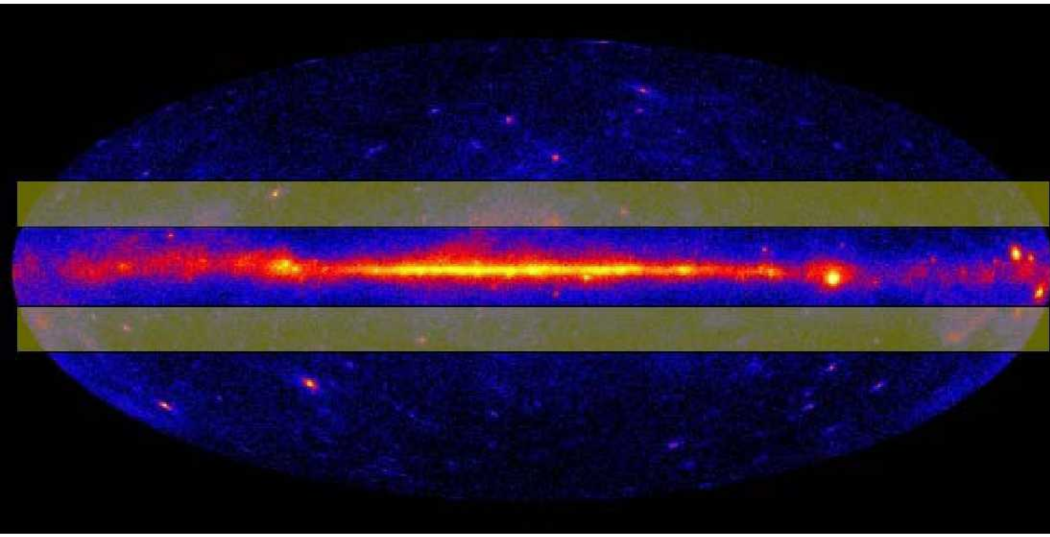
During the burst
(T_0 to T_0+100 s)

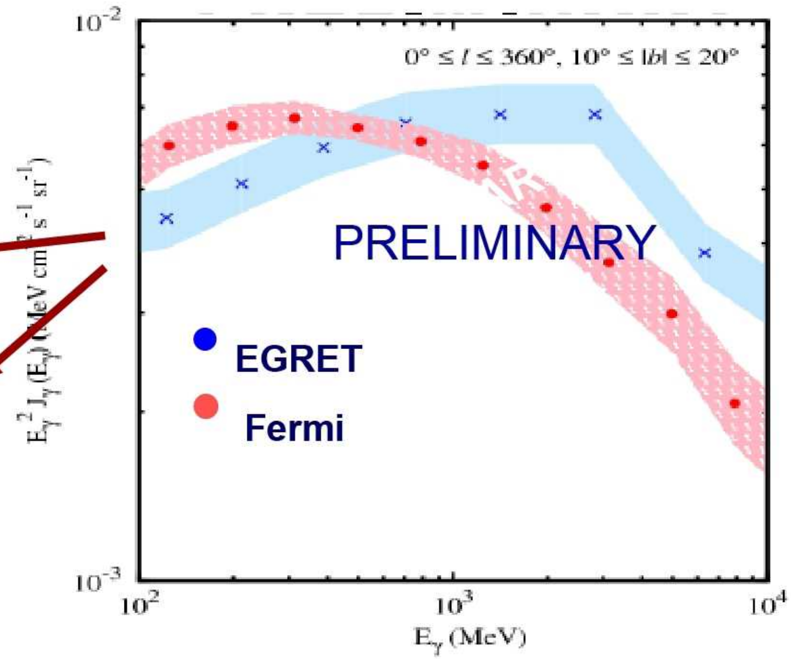


- Redshift = 4.35 → E_{iso} = ~10^{55} ergs
- Evolving Band function fits well
- Delay of High-E photons of ~5 s
- Max photon energy of 13 GeV

Abdo et al. Science (2009) V323 Issue 5922 p 1668

Galactic diffuse radiation, 100 MeV - 10 GeV, mid-latitude region

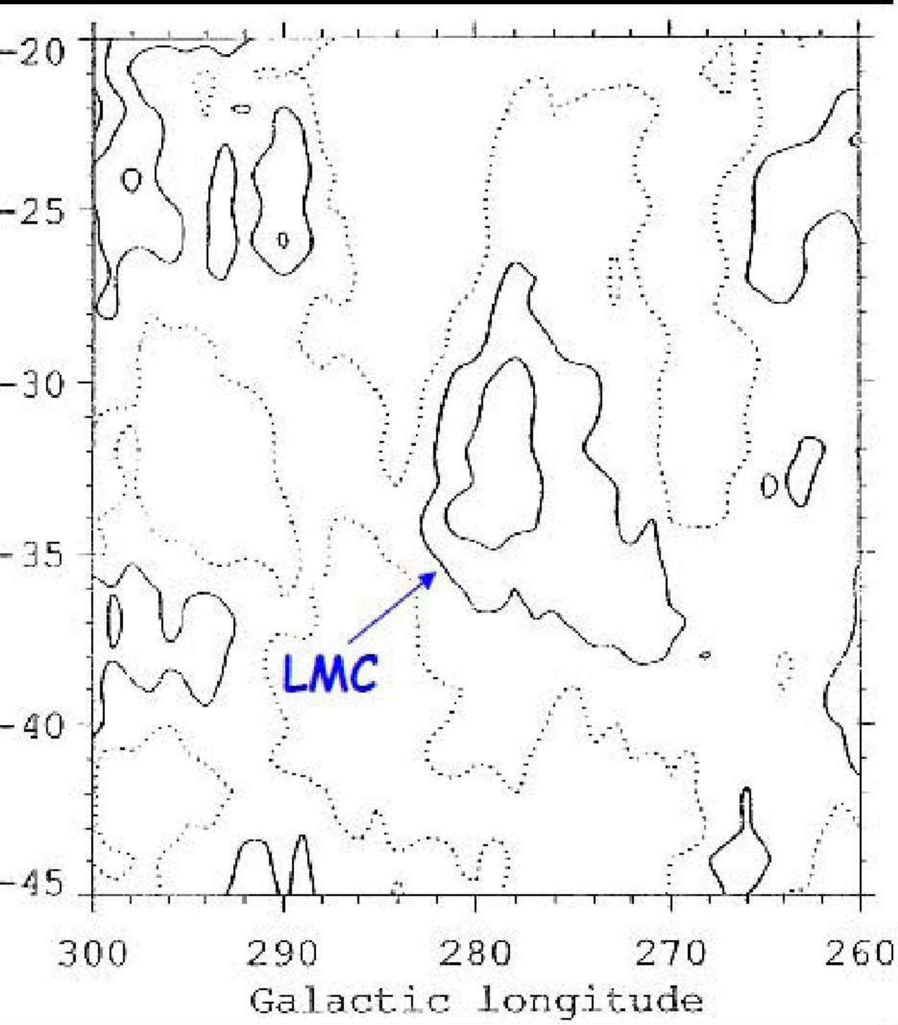


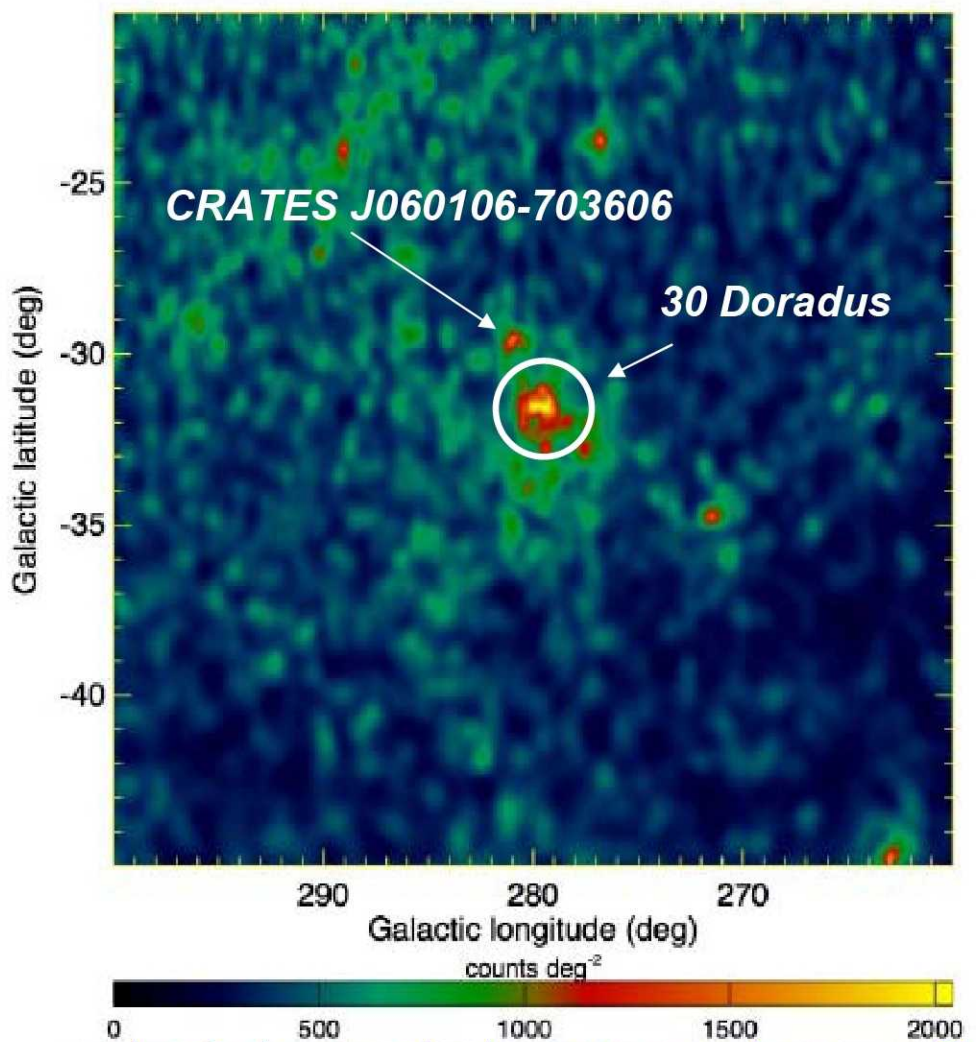


- Spectra shown for mid-latitude range → EGRET GeV excess in this region of the sky is not confirmed
- Sources are a minor component
- LAT errors are systematics dominated and estimated ~10%
- Work to analyze and understand diffuse emission over the entire sky and broader energy range is in progress

EGRET vs. Fermi View of LMC

PRELIMINARY





adaptively smoothed counts map (s.n.r. = 5)

– ***Fermi Gamma-ray Space Telescope* fully operational..**

– **In first few days of sky survey, the LAT corroborated many of the great discoveries of EGRET; now finding new sources as well;**

– **With 6 months of the sky:**
  - **Large number of pulsars detected, many only in γ-rays;**
  - **Many flaring active galaxies observed; about half not seen by EGRET;**
  - **Flaring sources observed along the galactic plane;**
  - **High-energy emission seen from 6 GRBs; first time seen from short-duration burst;**
  - **Quiescent sun detected at high energies;**
  - **Major progress in understanding Galactic diffuse emission**
  - **First precise measurement of high energy electron spectrum**
  - **Extensive search for dark matter signatures**

– **With time, *Fermi* will probe deeper and deeper into the high-energy Universe**

FERMI FLIGHT DATA ANALYSIS FOR ELECTRONS

Main challenges:

Energy reconstruction:
- optimized for energy < 300 GeV; we extended it up to 1 TeV

Electron-hadron separation
- achieved needed 10^3 – 10^4 rejection power against hadrons, with hadron residual contamination < 20%

Validation of Monte Carlo with the flight data:
- carefully compared MC and flight data

Assessment of systematic errors:
- uncertainty in the resulting spectrum is systematic dominated due to very large statistics

Our strong points:

Extensive MC simulations:
- different particles, all energies and angles
- comparison with beam test
- accurate model of CR background

High precision 1.5 X_0 thick tracker:
- powerful in event topology recognition
- serves as a pre-shower detector

Segmented calorimeter with imaging capability:
- fraction of mm to a few mm accuracy position reconstruction depending on energy

Segmented ACD:
- removes gammas and contributes to event pattern recognition

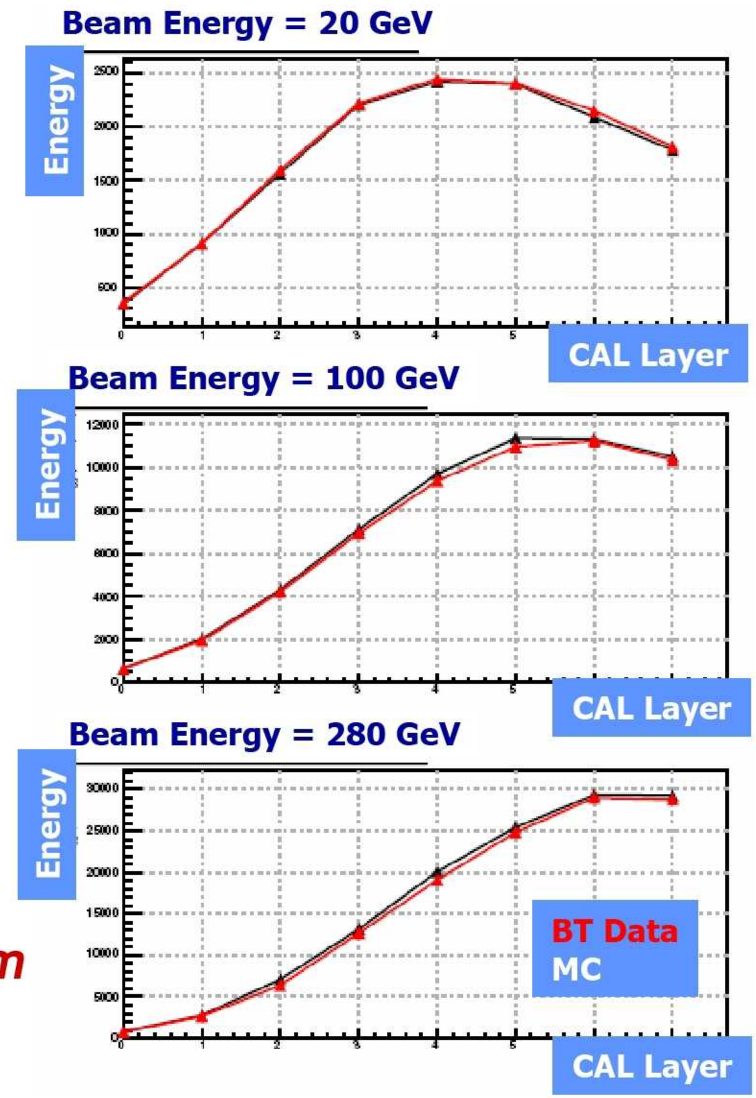
Extensive beam tests:
- SLAC, DESY, GSI, CERN, GANIL

High flight statistics:
- ~10 M electrons above 20 GeV a year

Event energy reconstruction

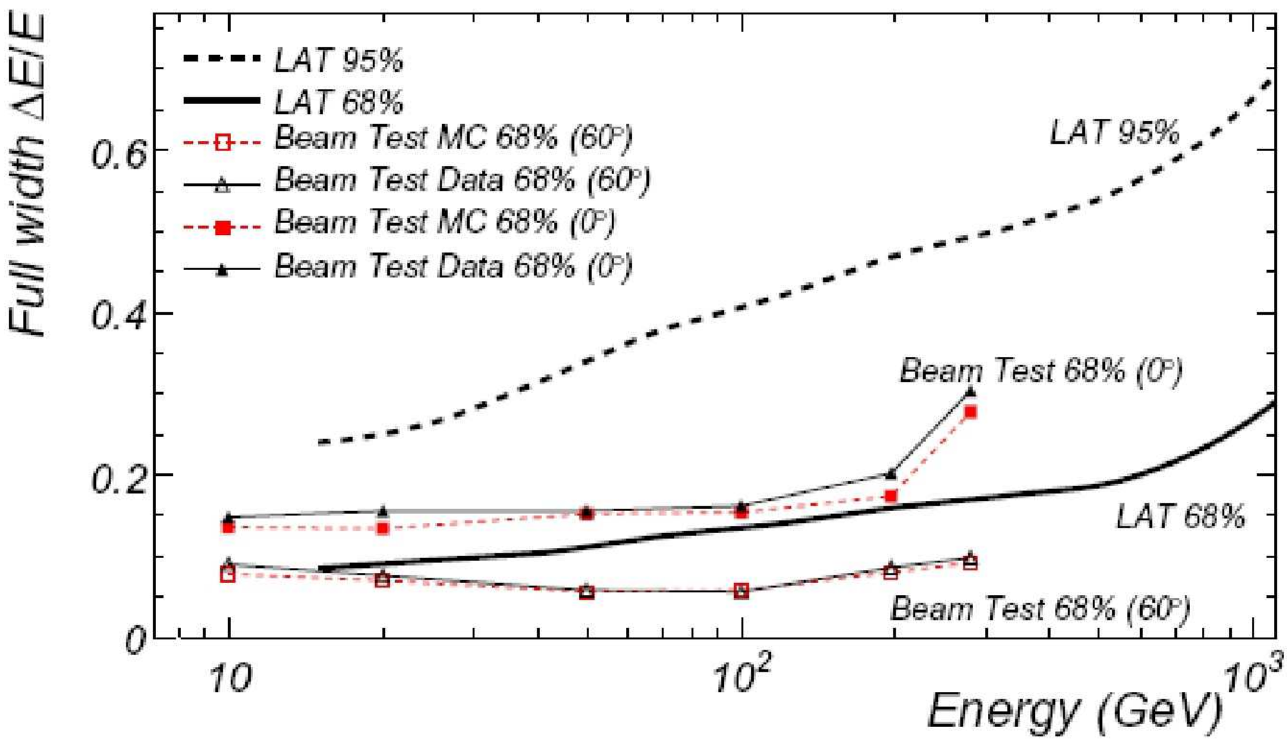
1. Reconstruction of the **most probable value** for the event energy:
   - based on calibration of the response of each of 1536 calorimeter crystals
   - energy reconstruction is optimized for each event
   - **calorimeter imaging capability** is heavily used for fitting shower profile
   - **tested at CERN beams** up to 280 GeV with LAT Calibration Unit

✓ ***Very good agreement between beam test and Monte Carlo***



Energy resolution

Agreement between MC and beam test within a few percent up to 280 GeV → we can be confident in MC → *we have reasonable grounds to extend the energy range to 1 TeV relying on Monte Carlo simulations*



Achieved electron-hadron separation and effective geometric factor

Candidate electrons pass on average **12.5 X_0** (Tracker and Calorimeter added together)

Simulated residual hadron contamination (5-21% increasing with the energy) is deducted from resulting flux of electron candidates

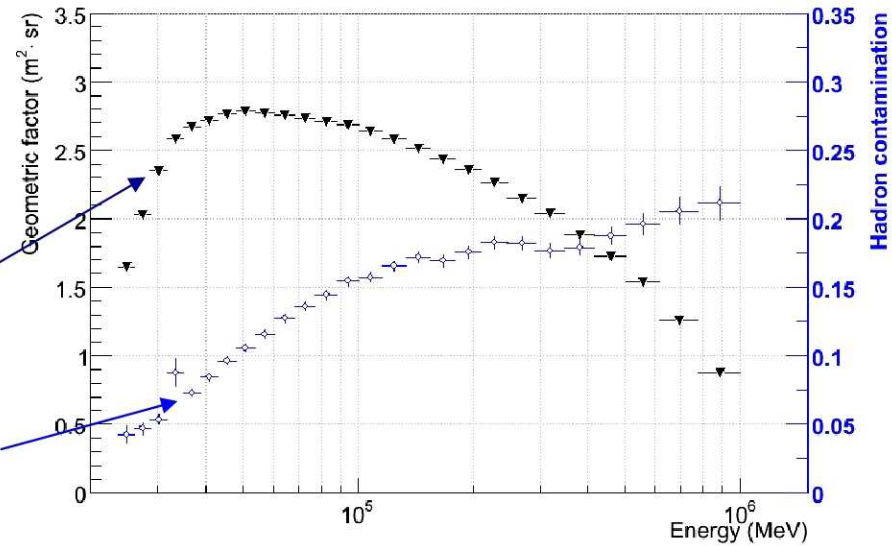
Effective geometric factor exceeds 2.5 m^2sr for 30 GeV to 200 GeV, and decreases to ~1 m^2sr at 1 TeV

Full power of all LAT subsystems is in use: tracker, calorimeter and ACD act together

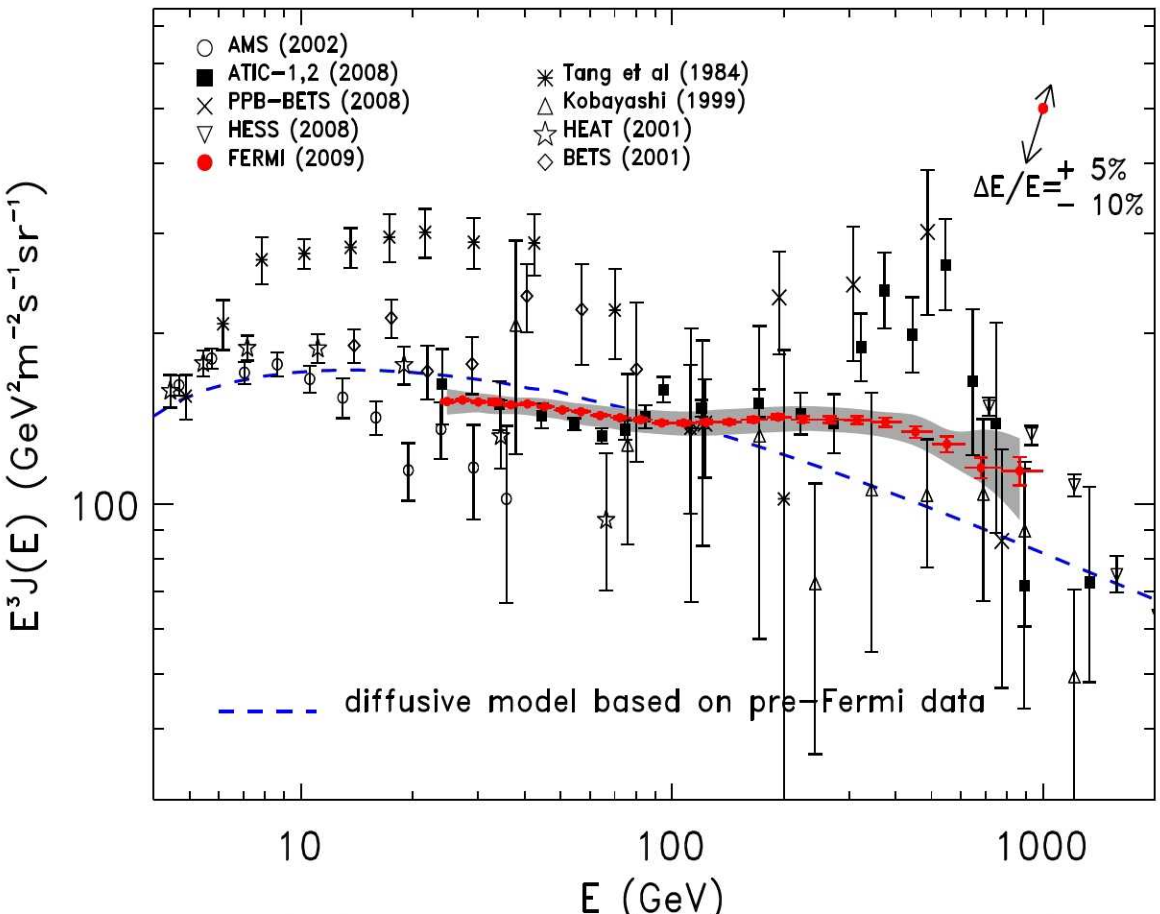
***Key issue:** good knowledge and confidence in Instrument Response Function*

Geometric Factor

Residual hadron contamination



Fermi-LAT electron spectrum from 20 GeV to 1 TeV



Submitted to PRL on March 19, 2009

Accepted April 21

Measurement of the Cosmic Ray e++e- Spectrum from 20 GeV to 1 TeV with the Fermi Large Area Telescope

A. A. Abdo et al. (Fermi LAT Collaboration)

Published 4 May 2009

Physics 2, 37 (2009)

Total statistics collected for 6 months of Fermi LAT observations

- *> 4 million electrons above 20 GeV*
- *> 400 electrons in last energy bin (770-1000 GeV)*

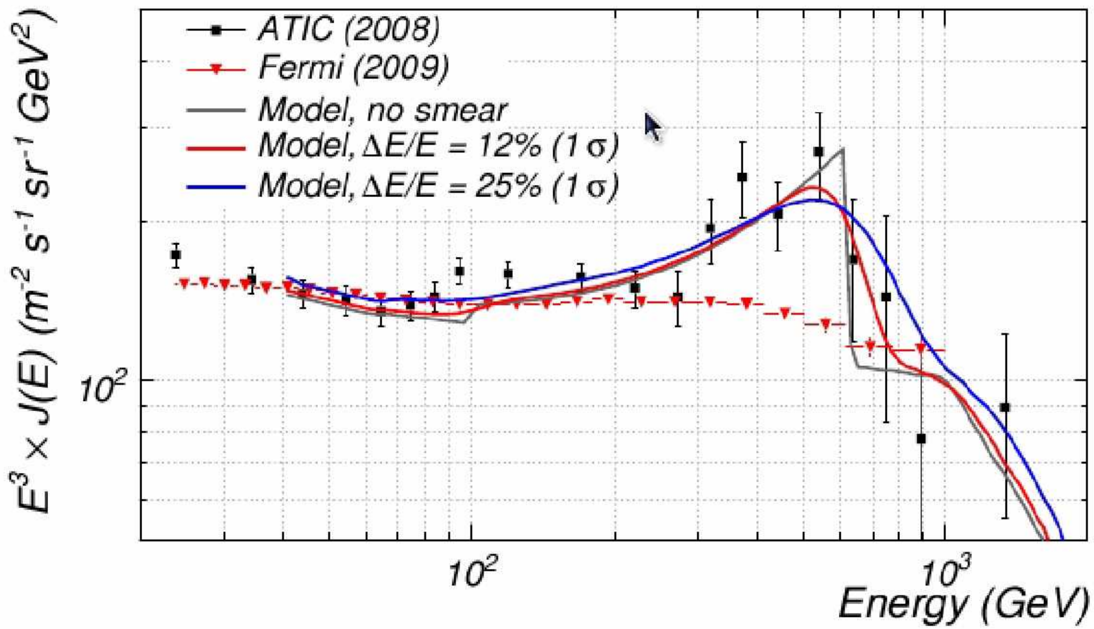
And finally we want to check – could we miss "ATIC-like" spectral feature?

We validated the spectrum reconstruction by:

– *comparing the results for different path length subsets*

– *varying the electron selections*

– *simulating the LAT response to a spectrum with an "ATIC-like" feature:*

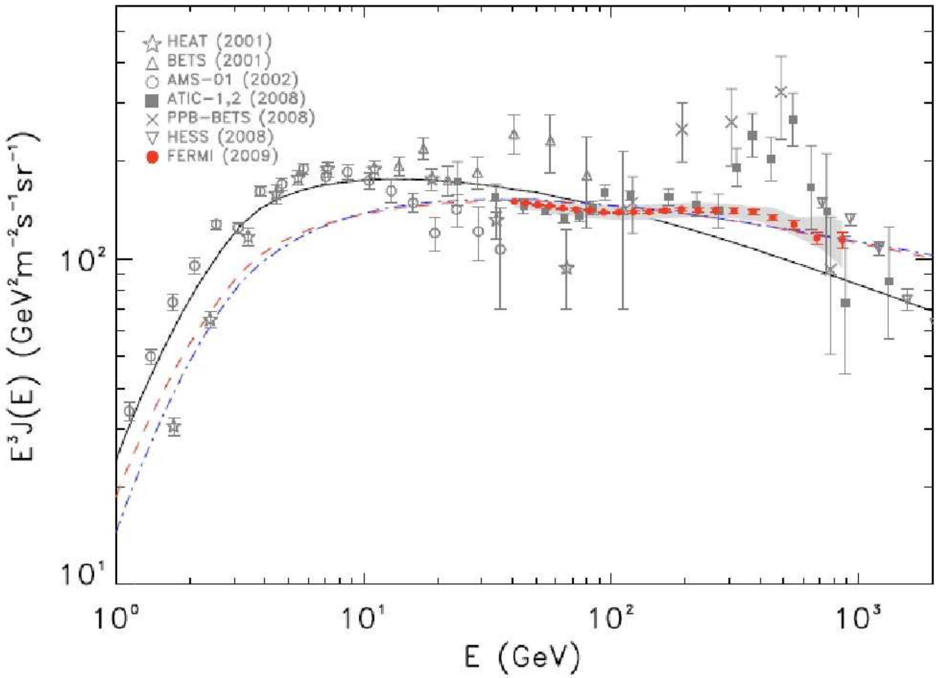


This demonstrates that the Fermi LAT would have been able to reveal "ATIC-like" spectral feature with high confidence if it were there. Energy resolution is not an issue with such a wide feature

Some interpretation…

ON POSSIBLE INTERPRETATIONS OF THE HIGH ENERGY ELECTRON-POSITRON SPECTRUM MEASURED BY THE FERMI LARGE AREA TELESCOPE

D. GRASSO[1 †], S. PROFUMO[2 *], A.W. STRONG[3 #], L. BALDINI[1], R. BELLAZZINI[1], E. D. BLOOM[4], J. BREGEON[1], G. DI BERNARDO[1,5], D. GAGGERO[1,5], N. GIGLIETTO[6,7], T. KAMAE[4], L. LATRONICO[1], F. LONGO[8,9], M.N. MAZZIOTTA[8], A. A. MOISEEV[10,11], A. MORSELLI[12] J.F. ORMES[13], M. PESCE-ROLLINS[1], M. POHL[14], M. RAZZANO[1], C. SGRO[1], G. SPANDRE[1], T. E. STEPHENS[15]



astro-ph 0905. 0636 (May 4, 2009)

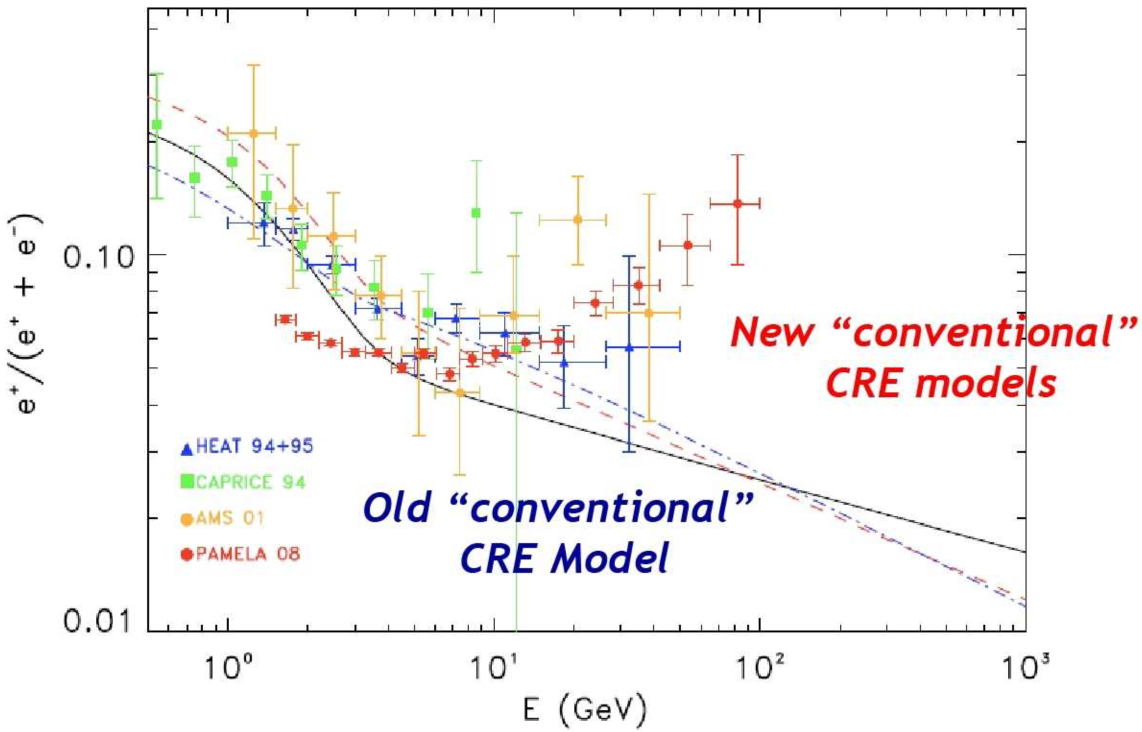
Spectrum can be fit by Diffuse Galactic Cosmic-Ray Source Model (electrons accelerated by continuously distributed astrophysical sources, likely SNR), with harder injection spectral index (-2.42) than in previous CR models (-2.54). All that within our current uncertainties, both statistical and systematic

$$J_{e^\pm} = (175.40 \pm 6.09) \left(\frac{E}{1 \text{ GeV}}\right)^{-(3.045\pm0.008)} \text{GeV}^{-1}\text{m}^{-2}\text{s}^{-1}\text{sr}^{-1}$$

with χ^2 per degree of freedom of 9.7 / 23 ***(χ^2 =9.7, d.o.f 24)***

Now – let's include recent Pamela result on positron fraction:

Harder primary CRE spectrum → steeper secondary-to-primary e+/e- ratio

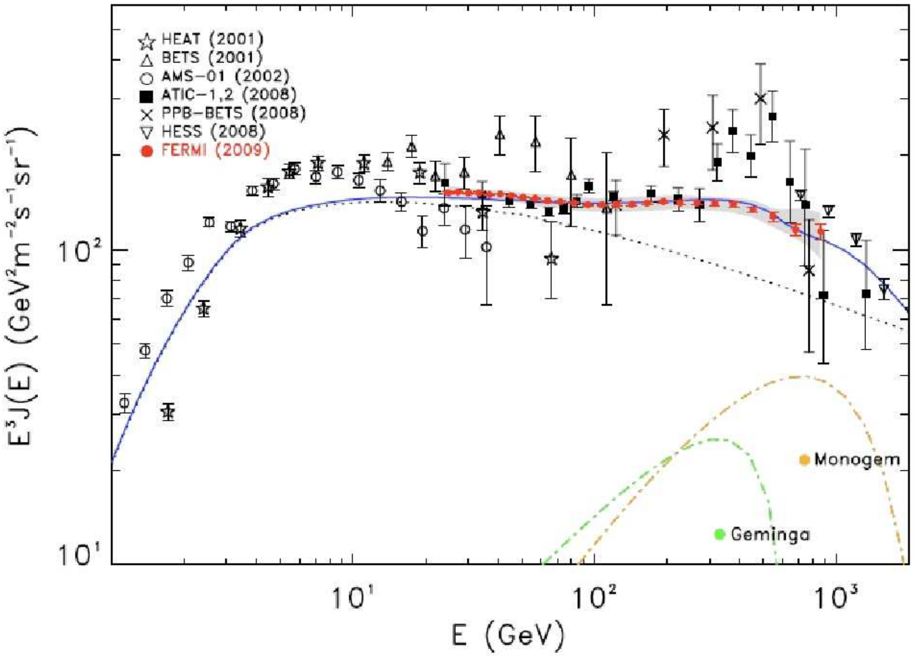


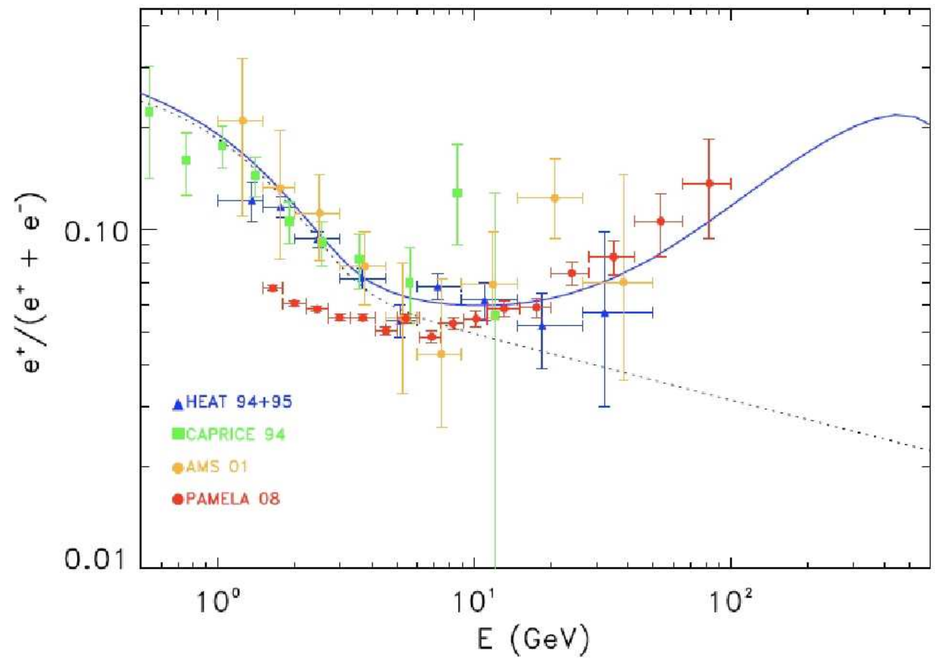
Fermi CRE data exacerbates the discrepancy between a purely secondary diffuse cosmic-ray origin for positrons and the positron fraction measured by Pamela

Need other contributors of electrons:

Pulsars: Most significant contribution to high-energy CRE:

Nearby (d < 1 kpc) and **Mature** ($10^4 < T/yr < 10^6$) Pulsars

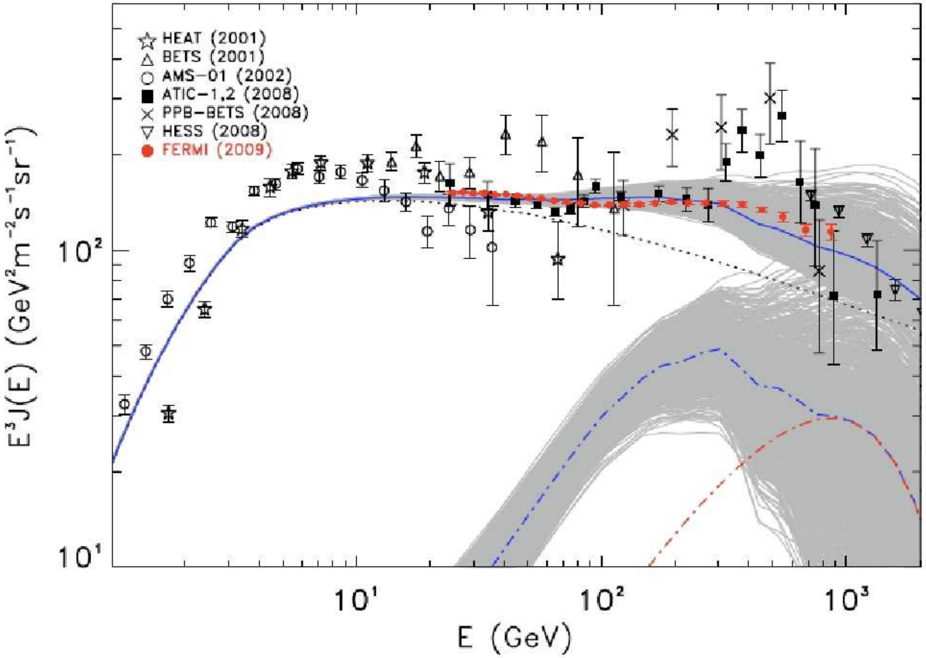


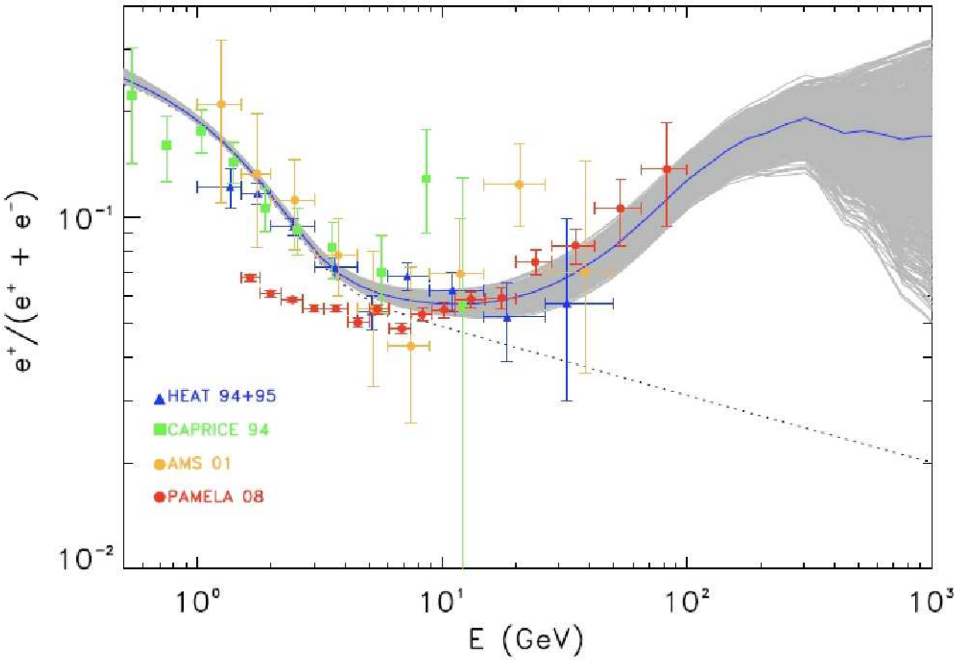


Example of fit to both Fermi and Pamela data with known (ATNF catalogue) nearby, mature pulsars and with a single, nominal choice for the e+/e- injection parameters

What if we randomly vary the pulsar parameters relevant for e+e- production?

(*injection spectrum, e+e- production efficiency, PWN “trapping” time*)



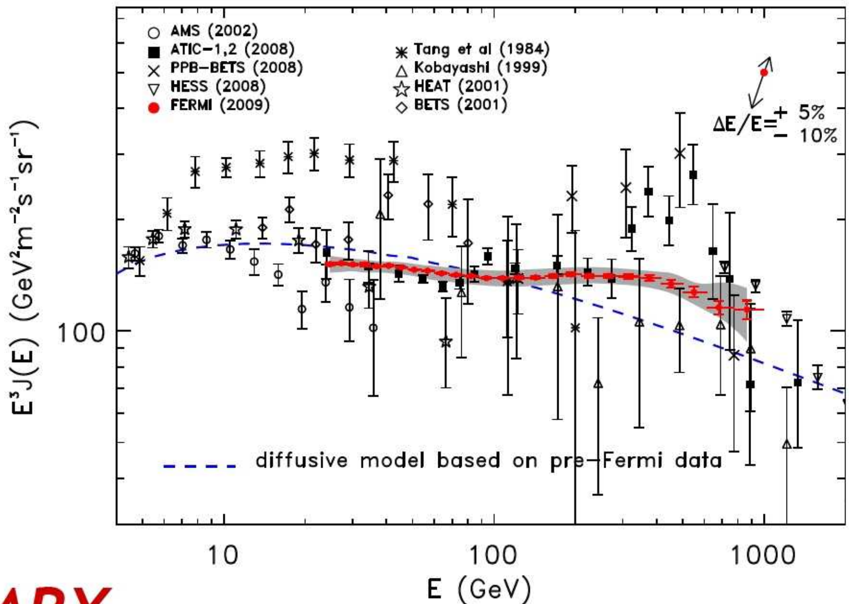


Under reasonable assumptions, electron/positron emission from pulsars offers a viable interpretation of Fermi CRE data which is also consistent with the HESS and Pamela results. Maybe too many degrees of freedom, but the assumption is plausible

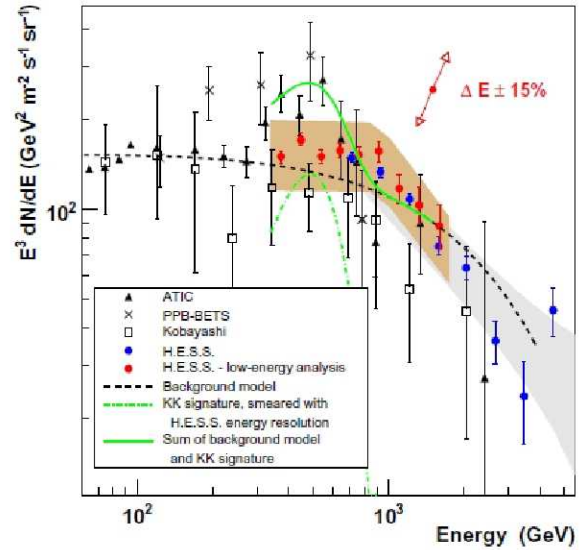
Dark matter: the impact of the new Fermi CRE data

1. *Much weaker rationale to postulate a DM mass in the 0.3-1 TeV range ("ATIC bump") motivated by the CR electron+positron spectrum*
2. *If the Pamela positron excess is from DM annihilation or decay, Fermi CRE data set stringent constraints on such interpretation*
3. *Even neglecting Pamela, Fermi CRE data are useful to put limits on rates for particle DM annihilation or decay*
4. *We find that a DM interpretation to the Pamela positron fraction data consistent with the new Fermi-LAT CRE is a viable possibility. DM origin of CRE is not ruled out*

Origin of the local source is still unclear – astrophysical or "exotic"



H.E.S.S. astro-ph 0905.0105, May 1, 2009 ***NEW***



SUMMARY

- ***The measured spectrum is compatible with a power law within our current systematic errors. The spectral index (-3.04) is harder than expected from previous experiments and simple theoretical considerations***
- ***"Pre-Fermi" diffusive model requires a harder electron injection spectrum (by 0.12) to fit the Fermi data, but inconsistent with positron excess reported by Pamela if it extends to higher energy***
- ***Additional component of electron flux from local source(s) may solve the problem; its origin, astrophysical or exotic, is still unclear***
- ***Valuable contribution to the calculation of IC component of diffuse gamma radiation***

Future plans:

✓ *Search for anisotropy in the electron flux – contributes to the understanding of the "extra" source origin*

✓ *Study systematic errors in energy and instrument response to determine whether or not the observed spectral structure is significant – also critical for understanding of the source origin, as well as models constrains*

✓ *Expand energy range down to ~ 5 GeV (lowest possible for Fermi orbit) and up to ~ 2 TeV, in order to reveal the spectral shape above 1 TeV*

✓ *Increase the statistics at high energy end. Each year Fermi-LAT will collect ~ 400 electrons above 1 TeV with the current selections if the spectral index stays unchanged*

THANK YOU !