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

Alexander Moiseev

NASA GSFC and University of Maryland

for the Fermi LAT Collaboration

Launch from Cape Canaveral, June 11, 2008

Fermi LAT Collaboration

United States (NASA and DOE)

- *California State University at Sonoma*
- *Goddard Space Flight Center*
- *Naval Research Laboratory*
- *Ohio State University*
- *Stanford University (HEPL, KIPAC and SLAC)*
- *University of California at Santa Cruz – SCIPP*
- *University of Denver*
- *University of Washington*

France

- *CEA/Saclay*
- *IN2P3*

Italy

- *ASI*
- *INFN (Bari, Padova, Perugia, Pisa, Roma2, Trieste, Udine)*
- *INAF*

Japan

- *Hiroshima University*
- *Institute for Space and Astronautical Science / JAXA*
- *RIKEN*
- *Tokyo Institute of Technology*

Sweden

- *Royal Institute of Technology (KTH)*
- *Stockholm University*

122 full members

95 affiliated scientists

38 management, engineering and technical members

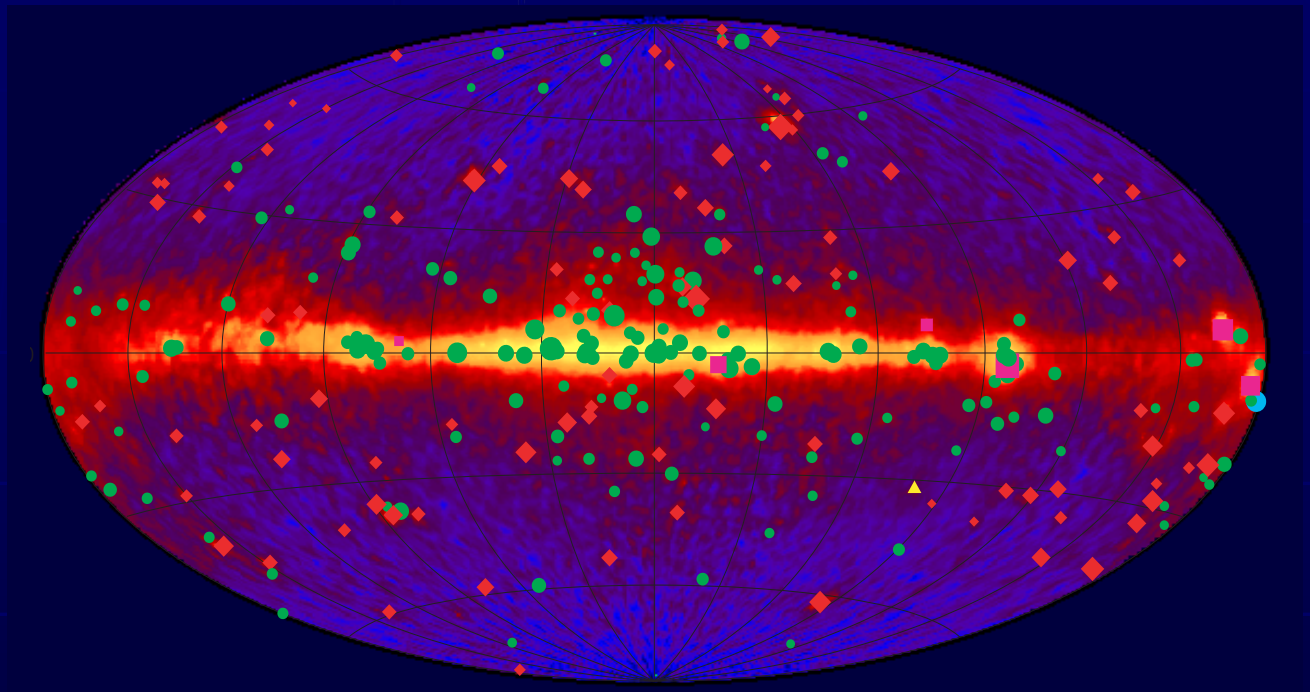
68 post-doctoral members

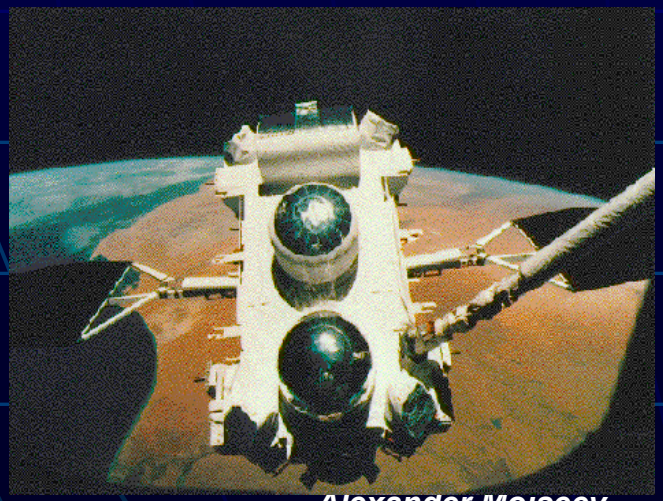
105 graduate students

EGRET Legacy. April 5,1991 – June 4, 2000

3rd EGRET catalog

- AGN - blazars
- unidentified
- pulsars
- LMC





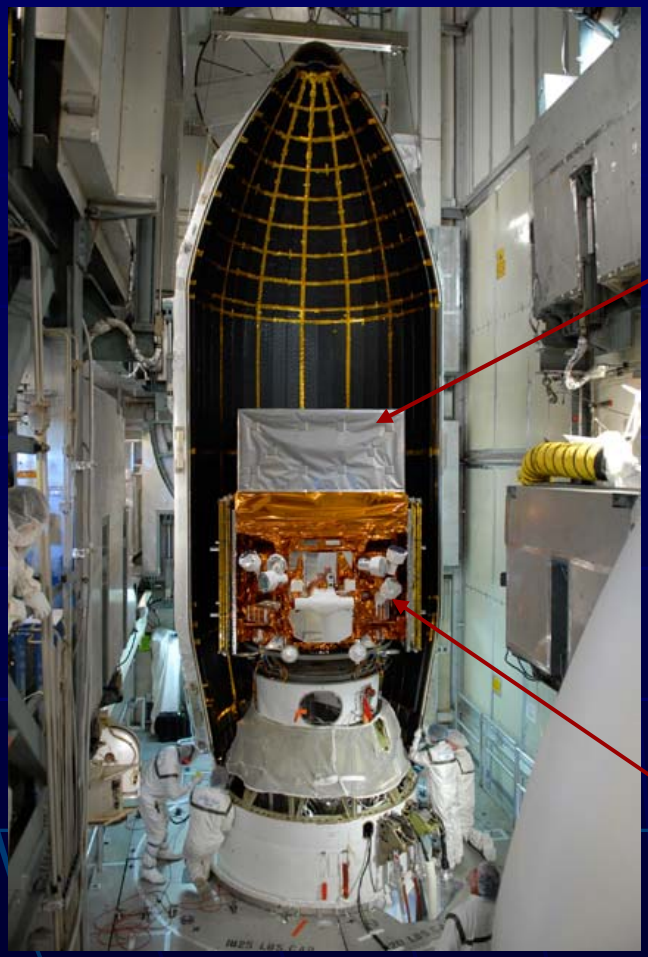
Fermi Science Questions

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 and how different are they?*
- *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 Gamma-ray Space Telescope



Two instruments onboard Fermi:

- ✓ **Large Area Telescope LAT**
  - main instrument, gamma-ray telescope, 20 MeV - >300 GeV energy range
  - scanning (main) mode - 20% of the sky all the time; all parts of sky for ~30 min. every 3 hours
  - ~ 2.4 sr field of view, 8000 cm^2 effective area above 1 GeV
  - good energy (5-10%) and angular (~3^0 at 100 MeV and <0.1^0 at 1 GeV) resolution
- ✓ **GLAST Burst Monitor GBM**

5-year mission (10-year goal), 565 km circular orbit, 25.6^0 inclination

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 of ~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 angular 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

The LAT Instrument Overview

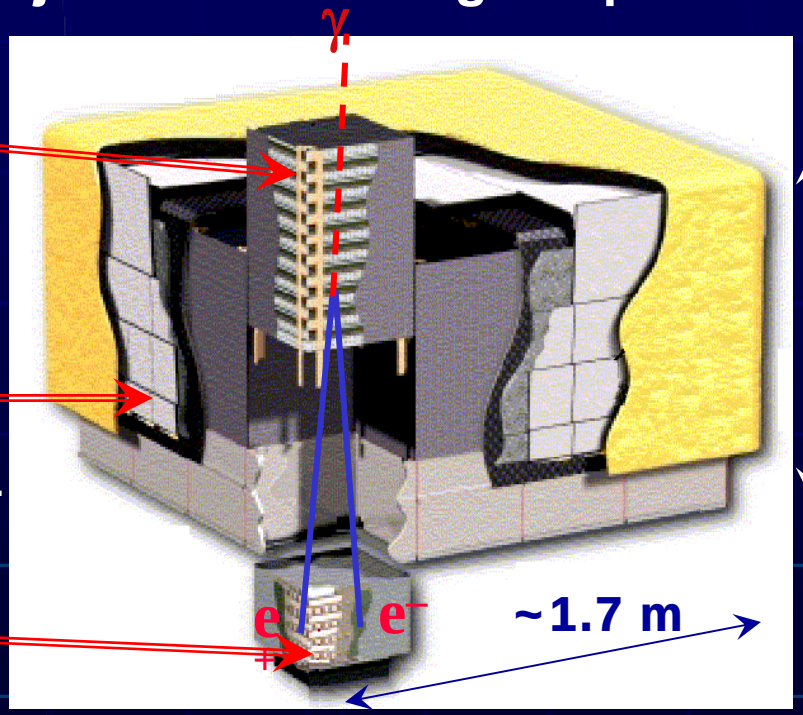
Pair-conversion gamma-ray telescope: 16 identical "towers" providing conversion of γ into e^+e^- pair and determination of its arrival direction (Tracker) and energy (Calorimeter). Covered by segmented AntiCoincidence Detector which rejects the charged particles background

Silicon-strip tracker: 18 double-plane single-side (x and y) interleaved with 3.5% X_0 thick (first 12) and 18% X_0 thick (next 4) tungsten converters. Strip pitch is 228 μm; total 8.8×10^5 readout channels

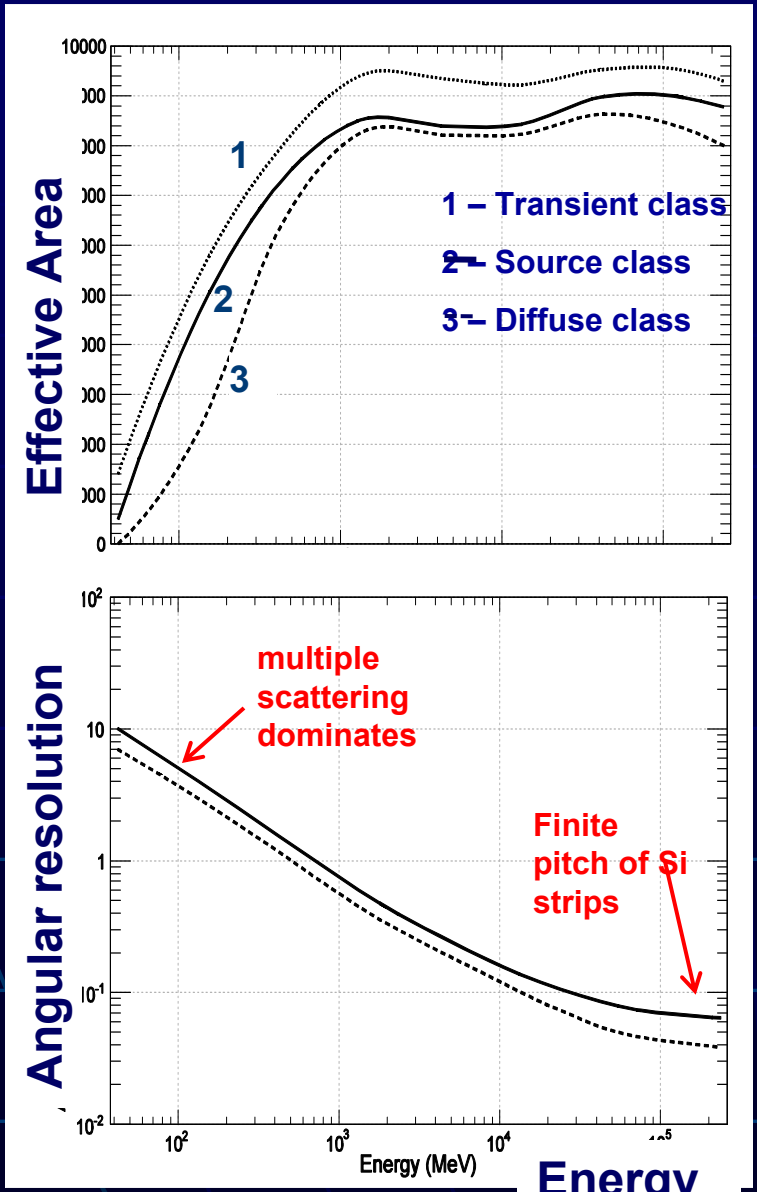
Segmented Anticoincidence Detector: 89 plastic scintillator tiles and 8 flexible scintillator ribbons. Segmentation reduces self-veto effect at high energy.

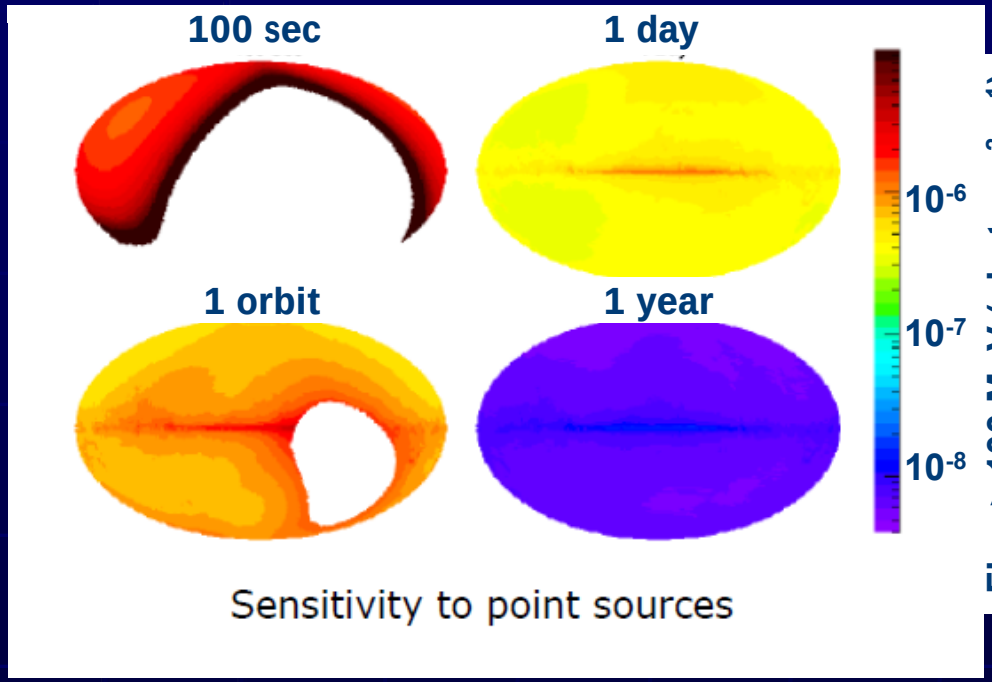
Hodoscopic CsI Calorimeter Array of 1536 CsI(Tl) crystals in 8 layers.

Electronics System Includes flexible, robust hardware trigger and software filters.



LAT Performance

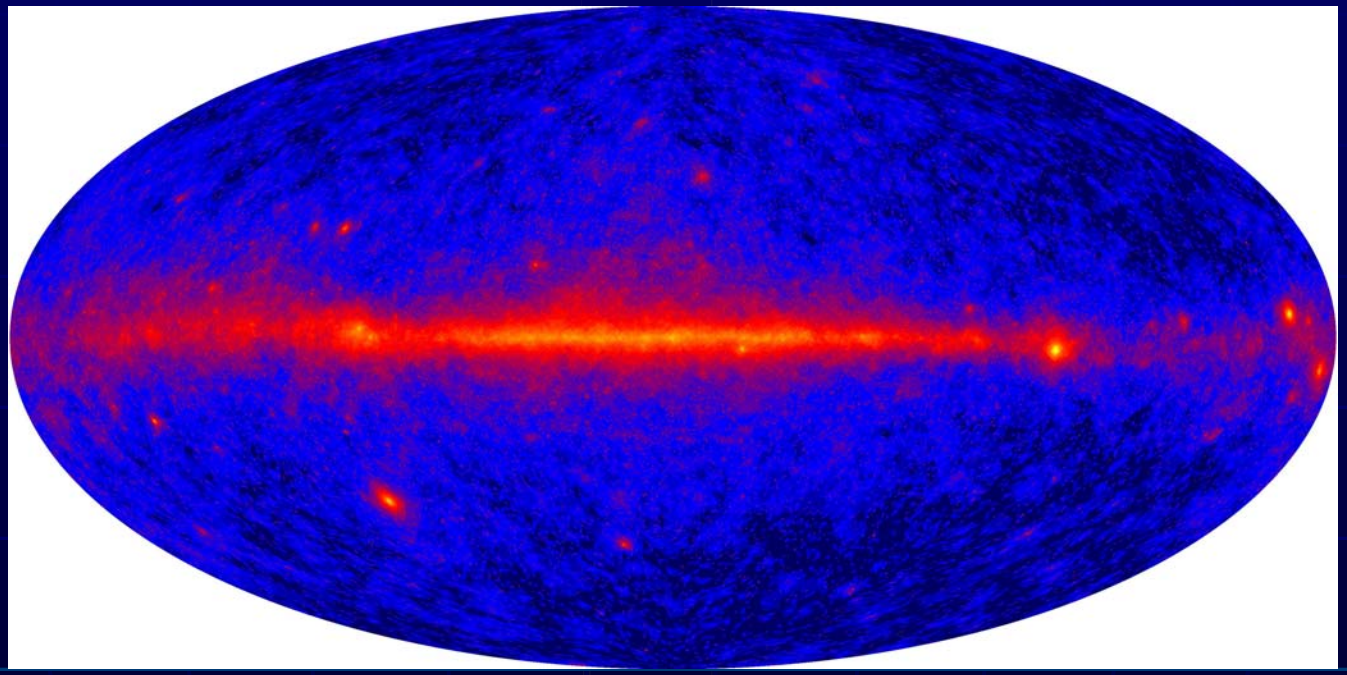




LAT is all-sky monitor, unlike EGRET and AGILE

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 !
- 53 days after launch (!): Start of nominal science observations – August 4
- Renamed to Fermi – August 26

Main results for the first year:

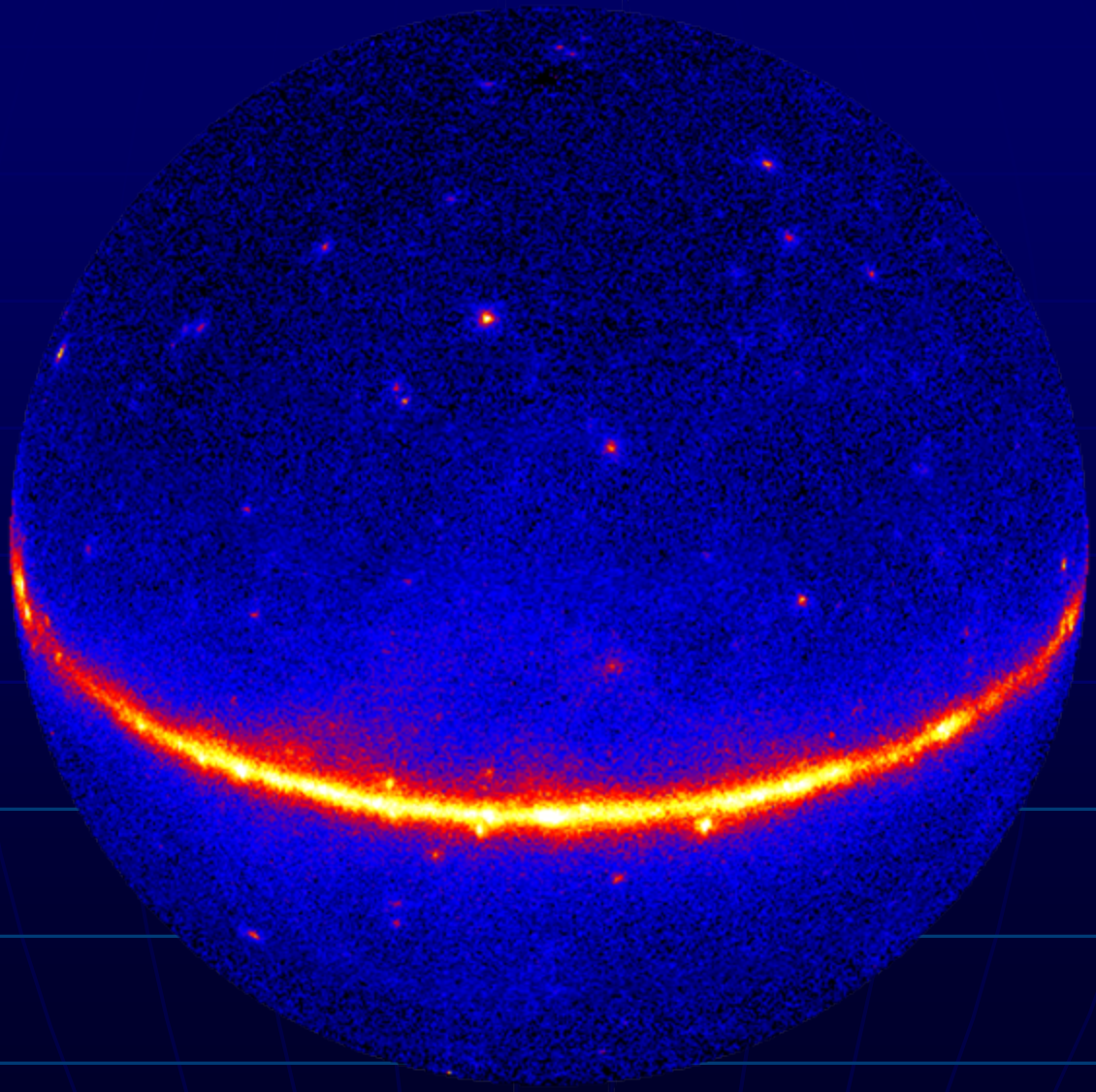
- *Pulsars*
- *Active Galactic Nuclei (AGN)*
- *Gamma-Ray Bursts (GRB)*
- *Diffuse radiation*
- *Electron + positron spectrum*

Plus: 6 papers submitted, 3 ready for submission, Astronomers' telegrams: 37

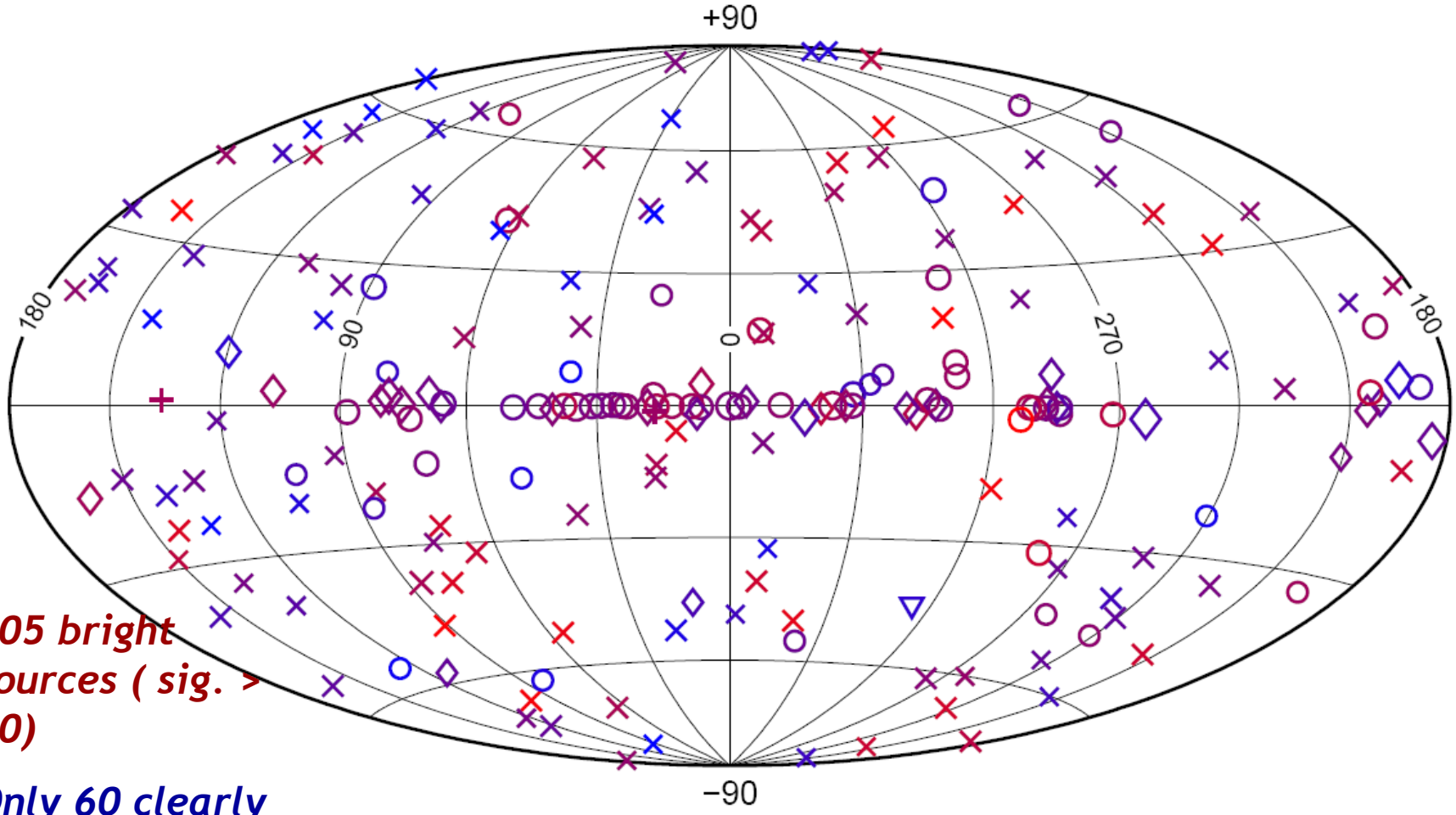
PAPERS

Journal	Published	Accepted	Total
Astronomy and Astrophysics	1	-	1
Astroparticle Physics	-	2	2
Astrophysical Journal	7	3	10
Astrophysical Journal Letters	3	-	3
Astrophysical Journal Supplement	1	-	1
Journal of Cosmology and Astroparticle Physics	1	-	1
Physical Review Letters	1	-	1
Science	4	-	4
Total	18	5	23

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



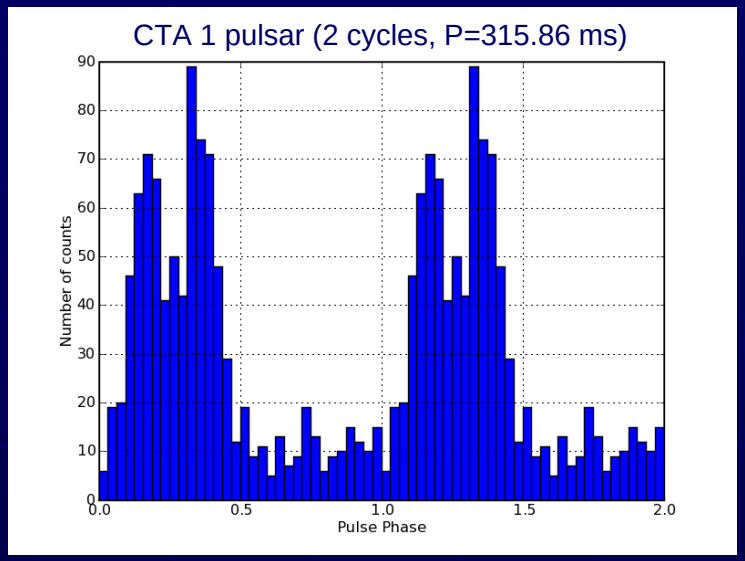
arXiv:0902.1340v1 [astro-ph.HE] 8 Feb 2009



205 bright sources (sig. > 10)

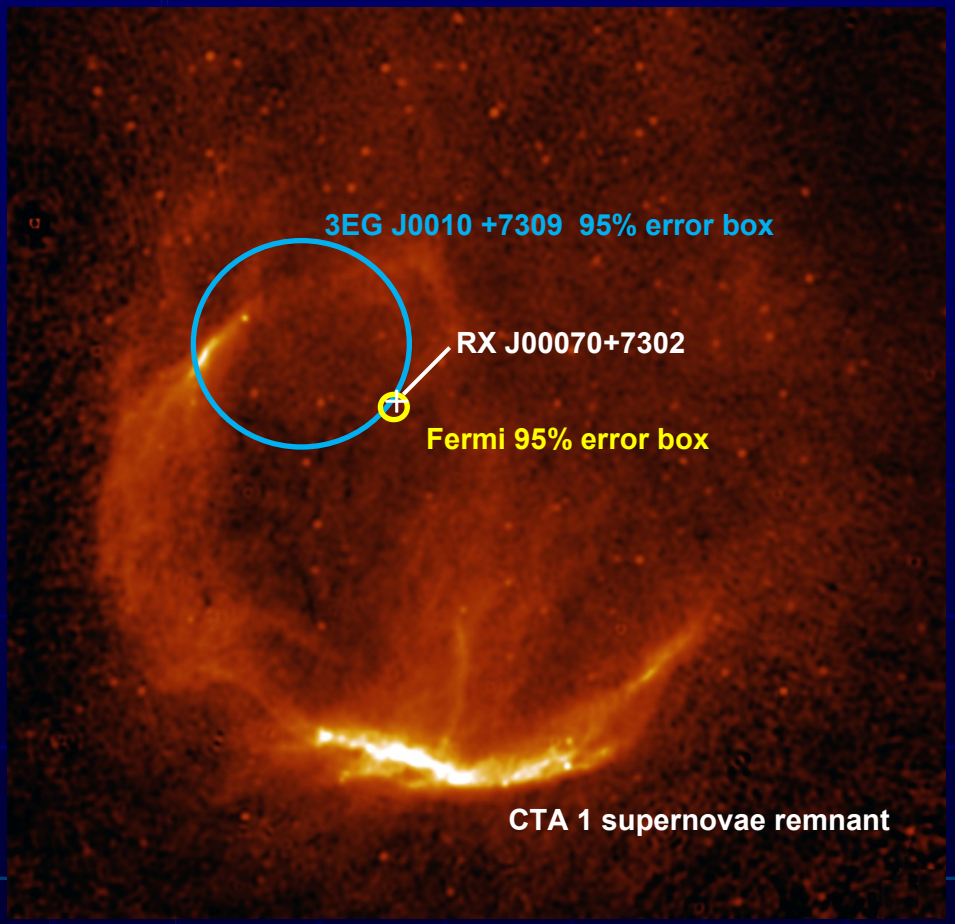
Only 60 clearly associated with EGRET sources

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



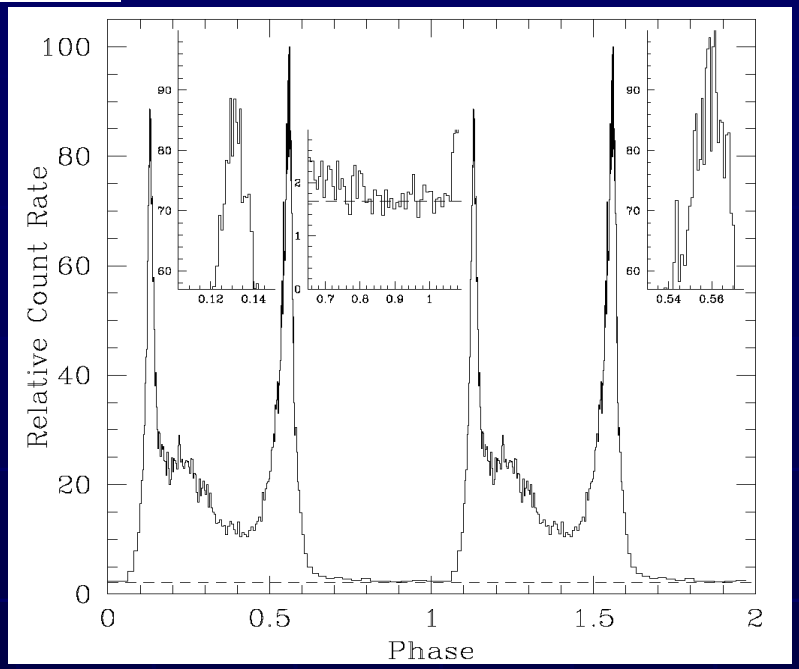
Exhibits all characteristics of a young high-energy pulsar (characteristic age ~1.4 x 10^4 yr), which powers a synchrotron pulsar wind nebula embedded in a larger SNR.

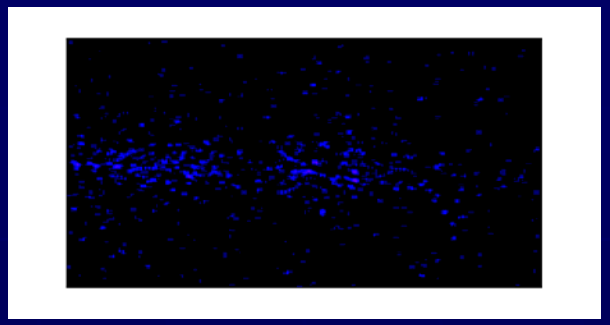
This source was a very bright AND well positioned unidentified EGRET source. This source was deliberately targeted during LAT checkout

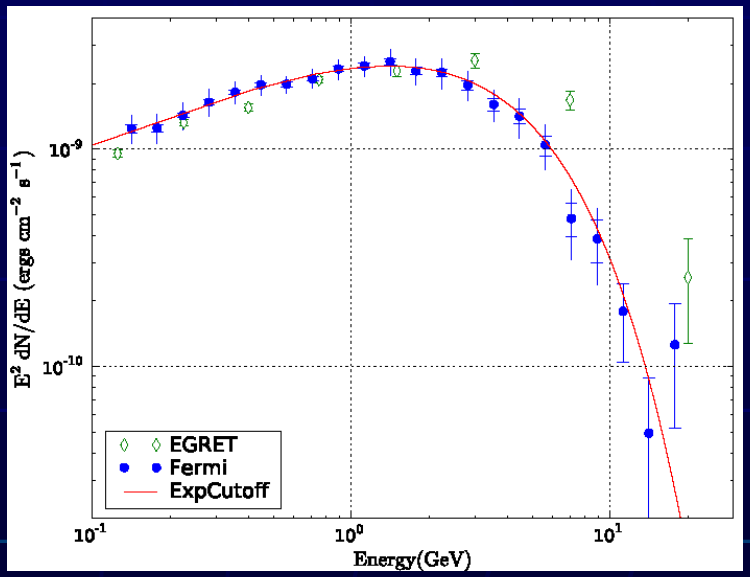


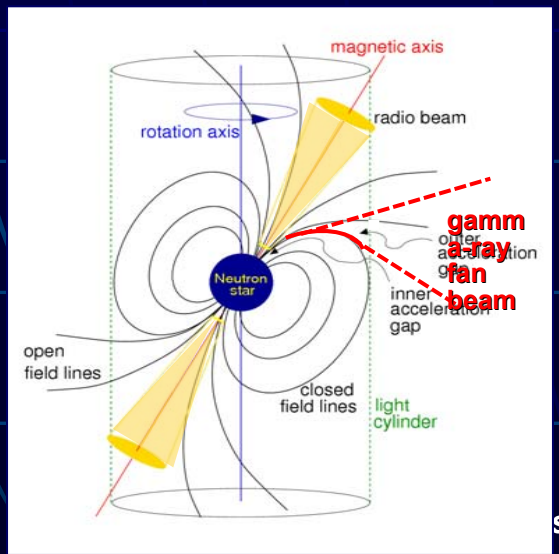
γ-ray source at l,b = 119.652, 10.468; 95% error circle radius =0.038° contains the X-ray source RX J00070+7302

Vela Pulsar









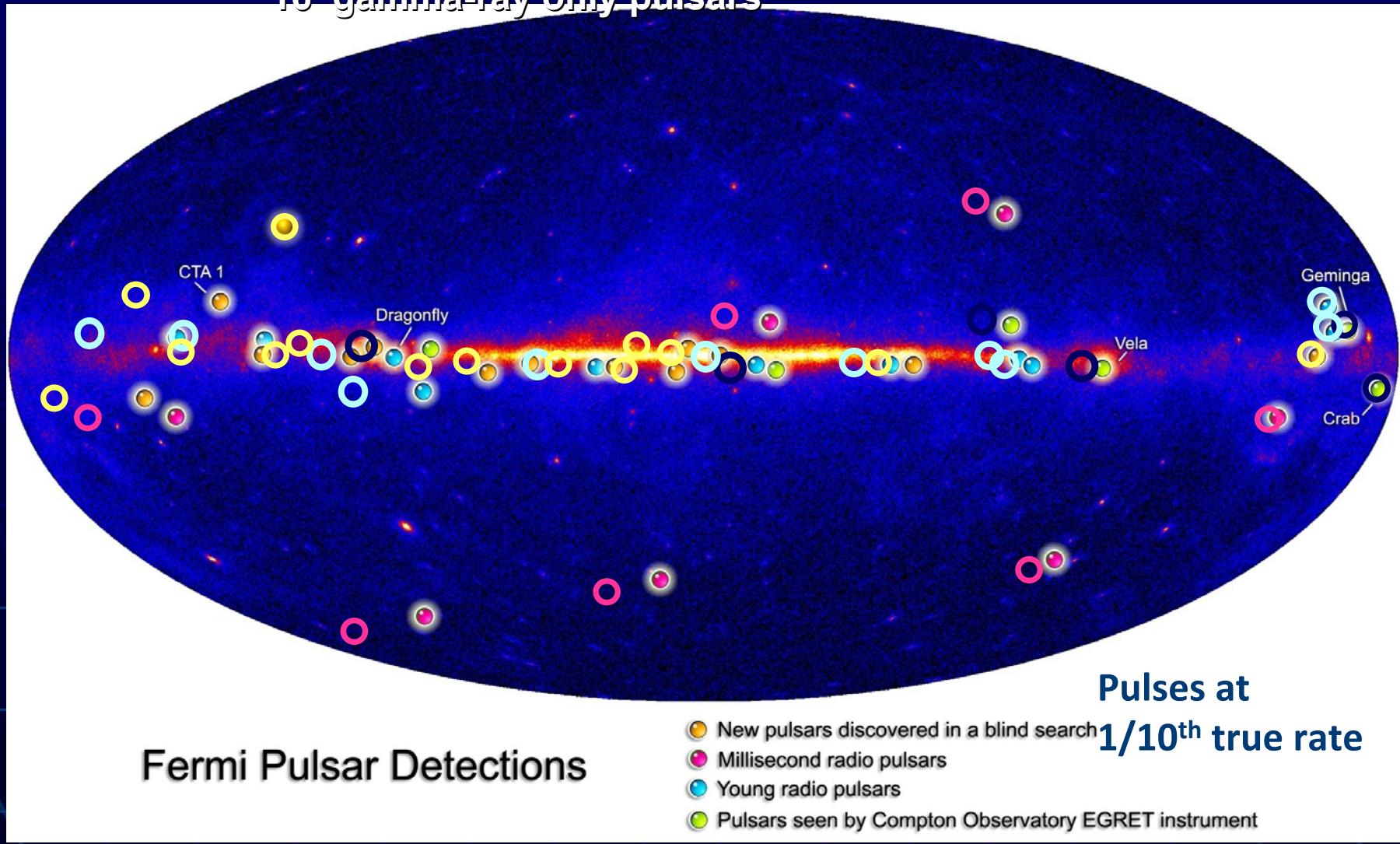
- *Acceleration in Magnetosphere*
  - *Outer magnetosphere*
  - *Near the NS surface*
- *LAT data consistent with simple exponential cut-off*
  - *favors outer-gap model*

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

The Pulsing γ-ray Sky

31 gamma-ray and radio pulsars (including 8 ms pulsars)

16 gamma-ray only pulsars



Pulses at 1/10th true rate

Unified Picture of AGNs

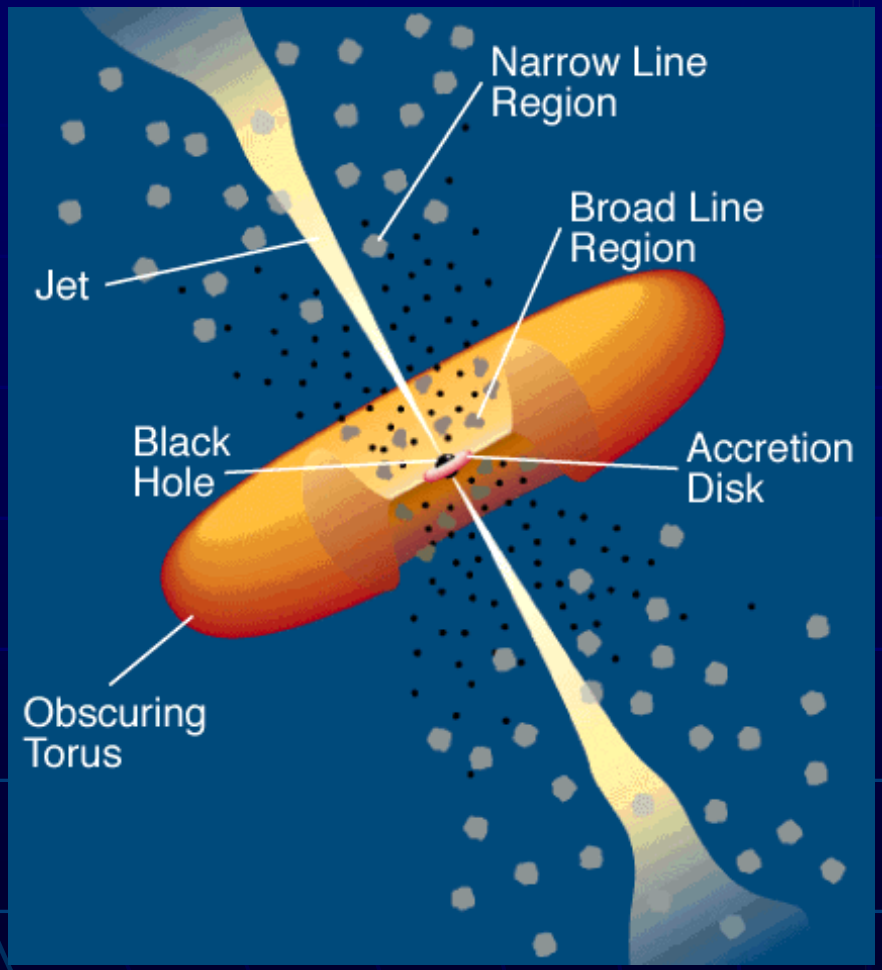
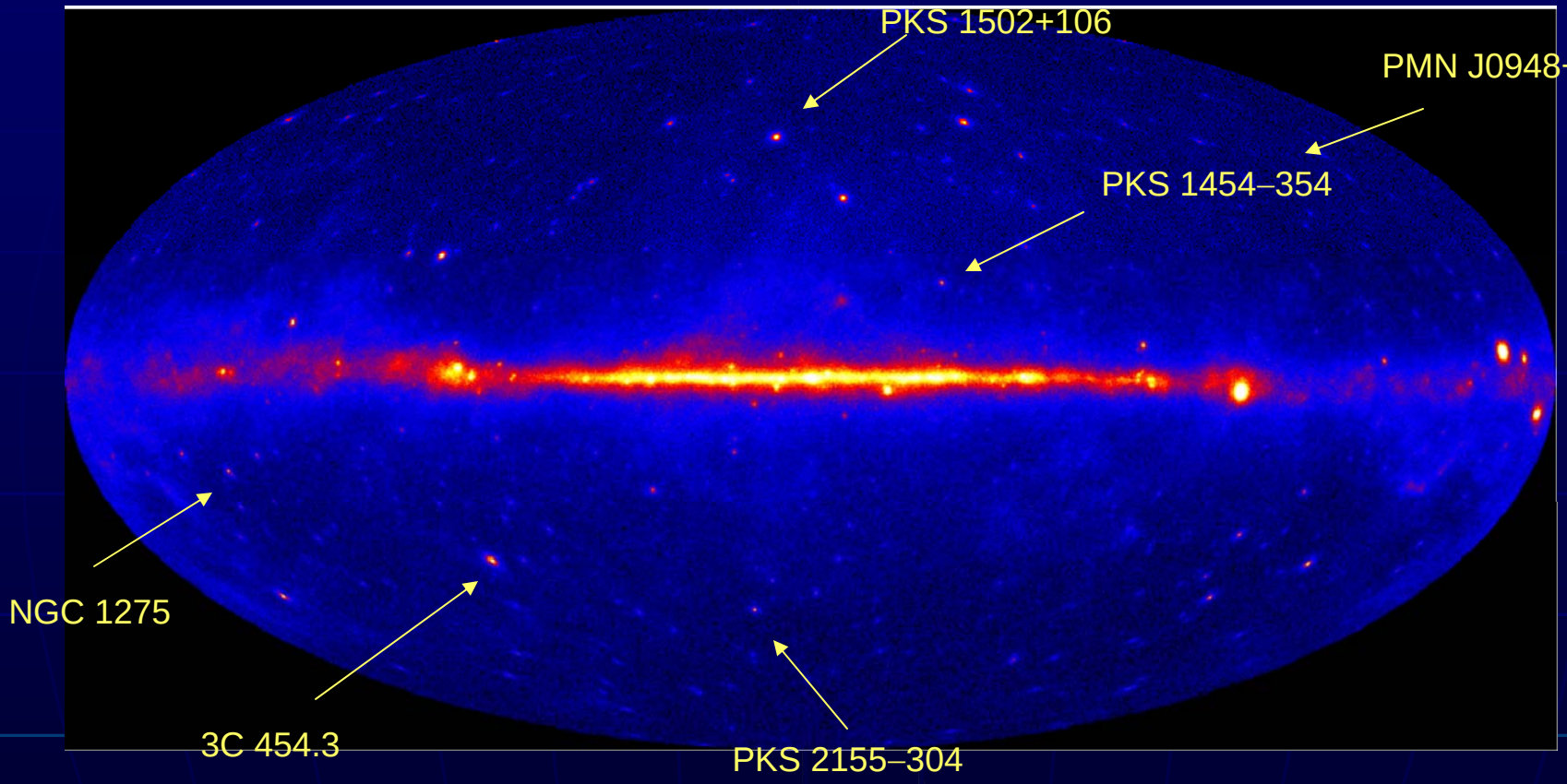


Image Credit: C.M.Urry & P. Padovani

- *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 for 9 months



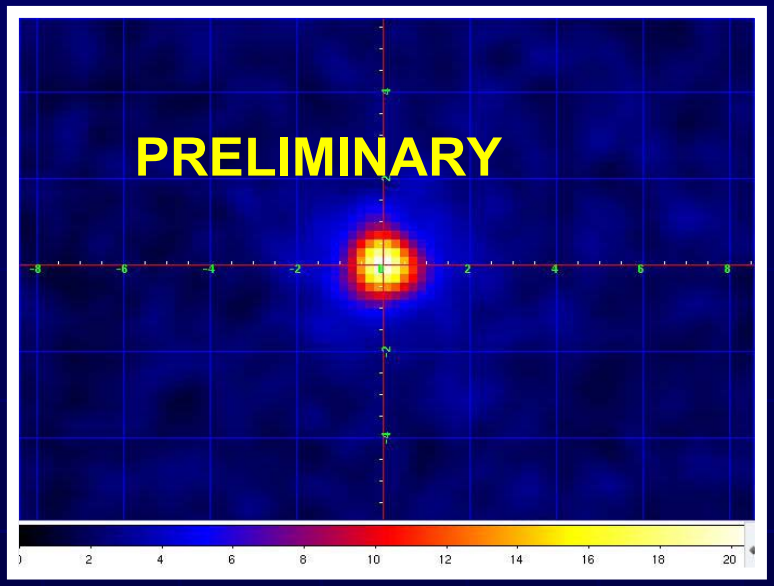
- *58 FRSQs, 42 BL Lacs, 4 Unc., 2 radio galaxies (numbers as of May 10)*
- *Automated Science Processing (ASP) with 1 × 10^{-6} ph cm^{-2} s^{-1} trigger threshold (daily)*
- *Flare Advocates*

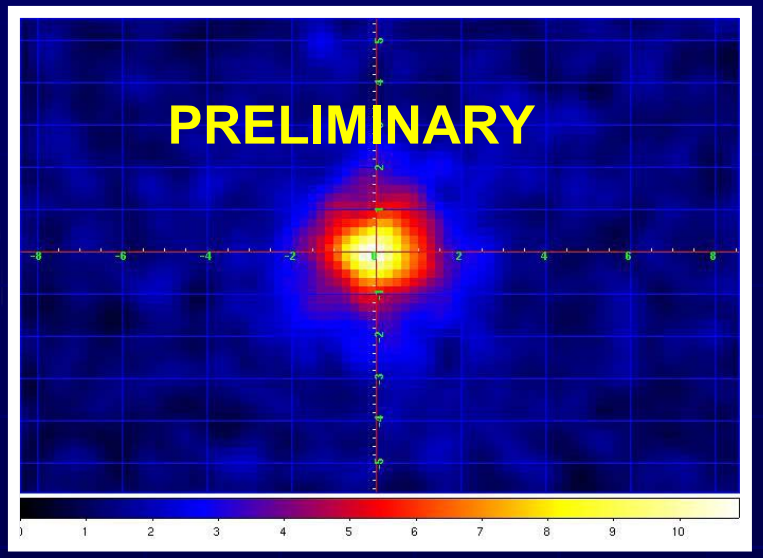
Some Multiwavelength Campaigns

- *3C 454.3: Jul-Oct; radio, opt, UV, Swift*
- *BL Lac: 15 Aug-5 Sep; opt, UV, X-ray*
- *PKS 2155-304: 25 Aug-6 Sep; radio, opt, UV, X-ray, TeV (HESS)*
- *1ES 1959+650: Sep-Nov*
- *PKS 0528+134: 27 Sep-Oct; radio, IR, opt, UV, X-ray*
- *3C 273: 31 Oct-7 Feb; radio, opt, X-ray*
- *3C 279: Aug—Mar; radio, opt, X-ray, TeV*
- *Mrk 421: Jan-May; radio, opt, X-ray, TeV (VERITAS, MAGIC)*

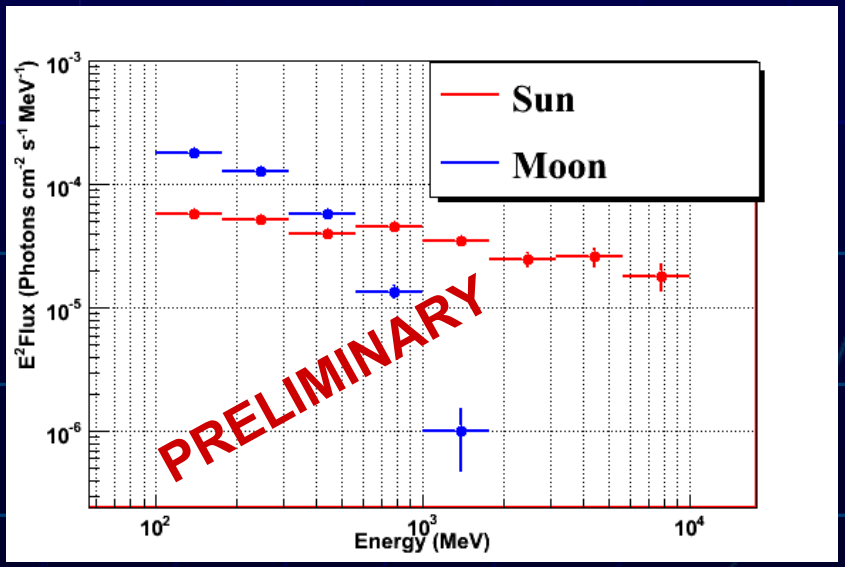
Fermi also detects

the Sun and the Moon

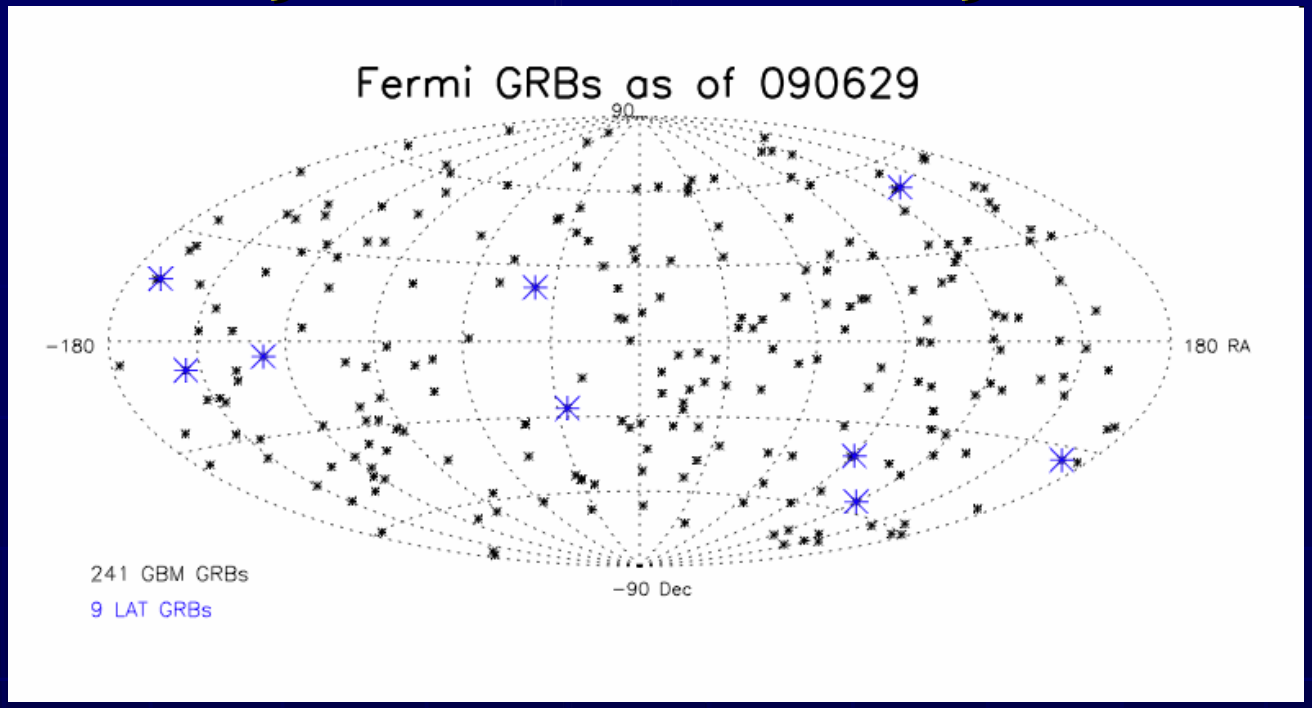


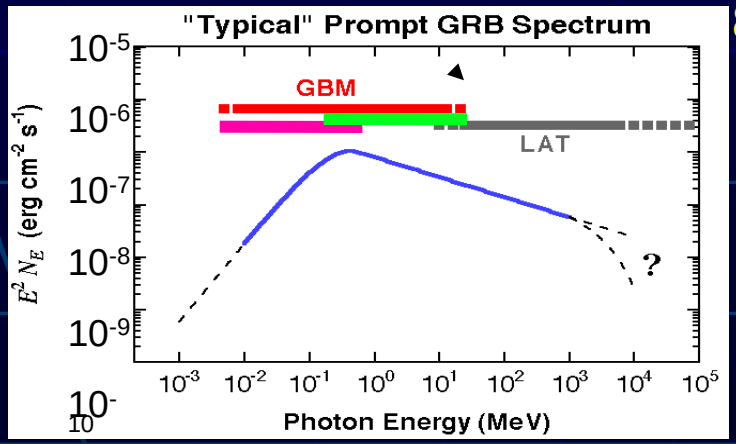


and their spectra



Gamma-ray Bursts Detected by GBM and LAT

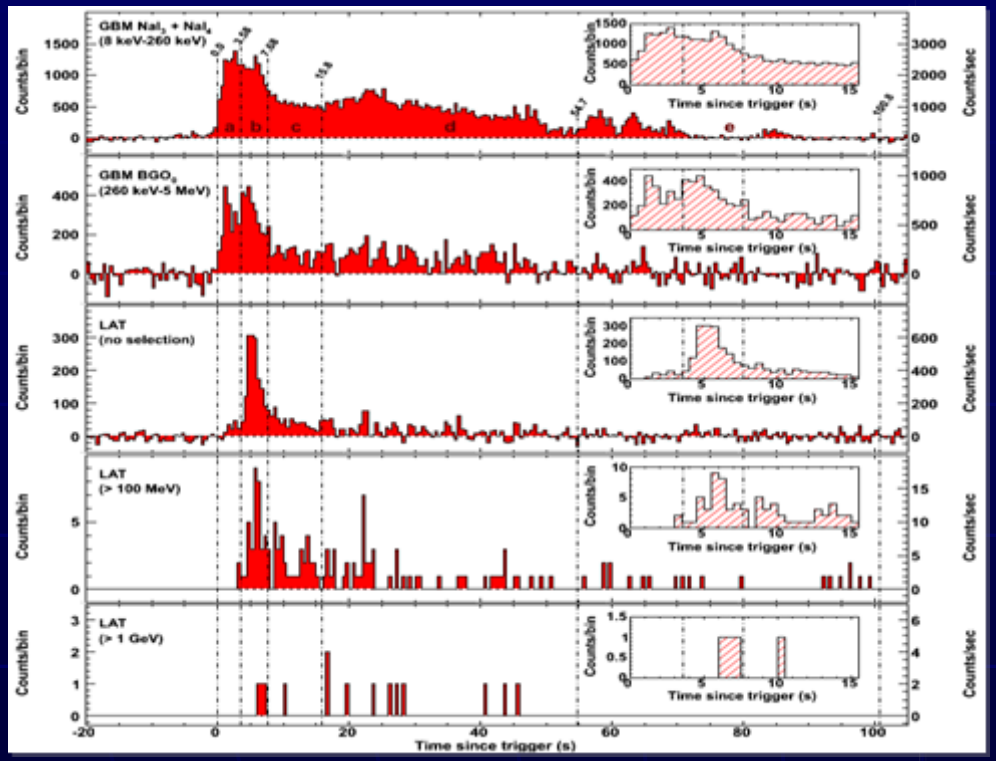


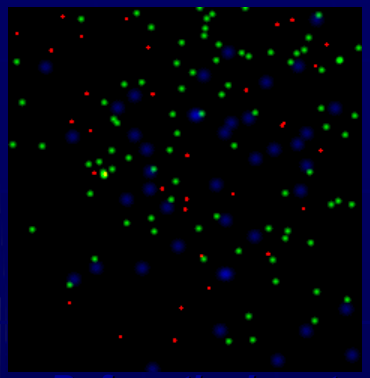


8 LAT-detected high-energy bursts

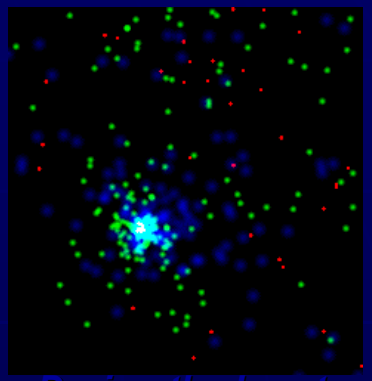
GRB 080825C
GRB 080916C z = 4.35 +/-0.15 (GROND/photometric)
GRB 081024B short-duration burst
GRB 081215A
GRB 090217
GRB 090323 z = 3.6 (Gemini/spectroscopic)
GRB 090328 z = 0.736 (Gemini/spectroscopic)
GRB 090510 short-duration burst z = 0.9 (VLT)

GRB 080916C – Strongest ever seen

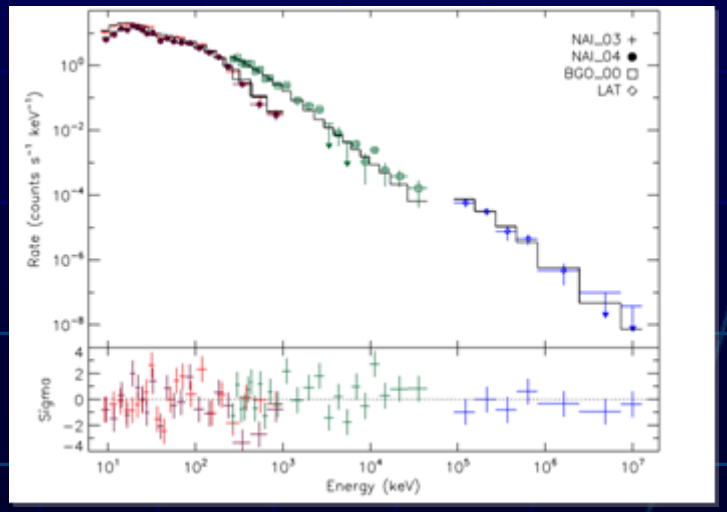




Before the burst
(T_0-100 s to T_0)



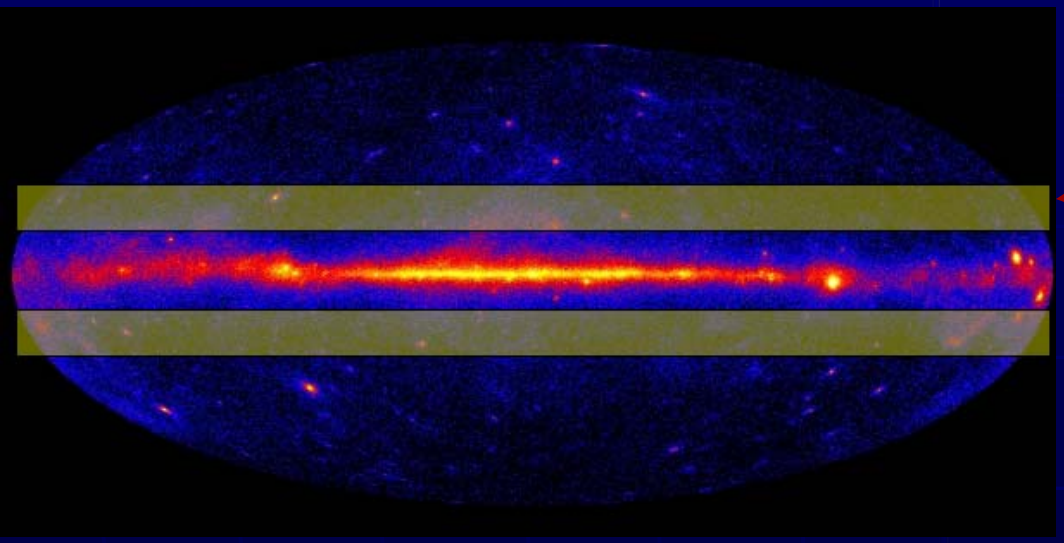
During the burst
(T_0 to T_0+100 s)

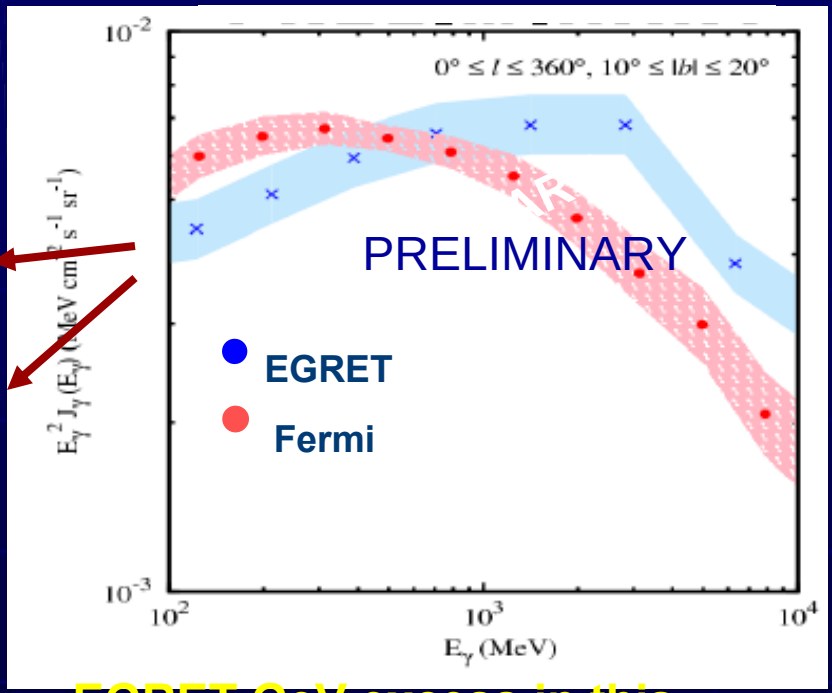


- *Redshift = 4.35 → E_{iso} = ~10^{55} ergs*
- *Evolving Band function fits well*
- *Delay of High-E photons of ~5 s*
- *Max photon energy of 13 GeV*

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 <u>not</u> confirmed
- Sources are a minor component
- LAT errors are systematic dominated and estimated ~10%
- Work to analyze and understand diffuse emission over the entire sky and broader energy range is in progress

Search for Dark Matter

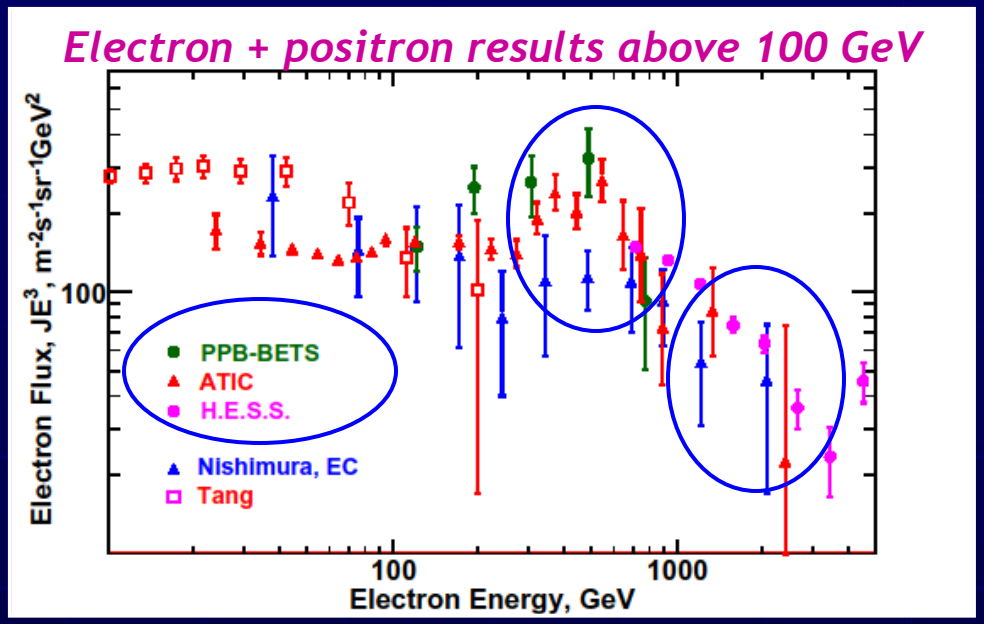
- *Line searches: 3 months of Fermi-LAT data has been analysed for the full sky minus |b|<10° and minus point sources in energy range from 20 MeV to 300 GeV. No detection at 5σ confidence level*

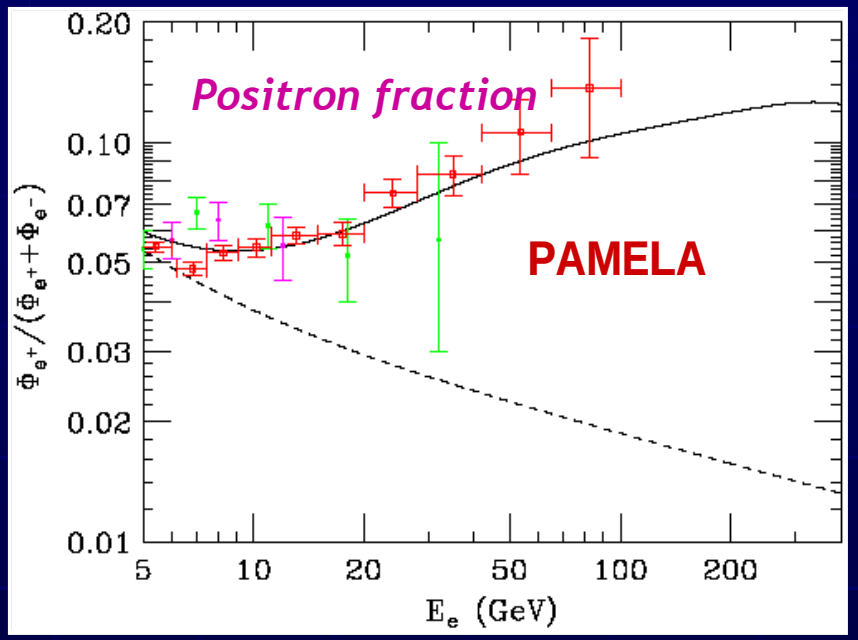
- *Dwarf spheroidal galaxies, the largest DM clumps predicted from the Nbody simulations are excellent targets as they should be almost background free. Unfortunately, no significant gamma-ray emission from dSph galaxies detected so far, checking 10 best candidates, high latitude dSph galaxies at distance < 150 kpc, -30 > b > 30 degrees*

- *Galactic Center - very promising region, but the analysis is very complicated due to bright diffuse background and many bright sources.*

- *Mid-latitude diffuse radiation - EGRET excess at a few GeV is not confirmed*

High energy cosmic ray electrons: Year of 2008: New results (before Fermi)





Cosmic Ray sources or something else ?

- *Spectral feature at ~ 620 GeV reported by ATIC and PPB-BETS suggests a nearby source (astrophysical or exotic)*
- *Pamela : increase of positron fraction above 10 GeV also suggests a presence of a source or new production process at high energy*
- *H.E.S.S. detects spectrum steepening (or cut-off) above ~1 TeV : local source? Weaker re-acceleration?*
- *More than 100 papers mentioning these results within a few months*

FERMI FLIGHT DATA ANALYSIS FOR ELECTRONS

Main challenges:

- ✓ Energy reconstruction:
  - optimized for photon energy < 300 GeV; we extended it up to 1 TeV
- ✓ Electron-hadron separation
  - achieved needed 10^3 - 10^4 rejection against hadrons
- ✓ Validation of Monte Carlo with the beam tests and flight data
- ✓ Assessment of systematic errors

Our strong points:

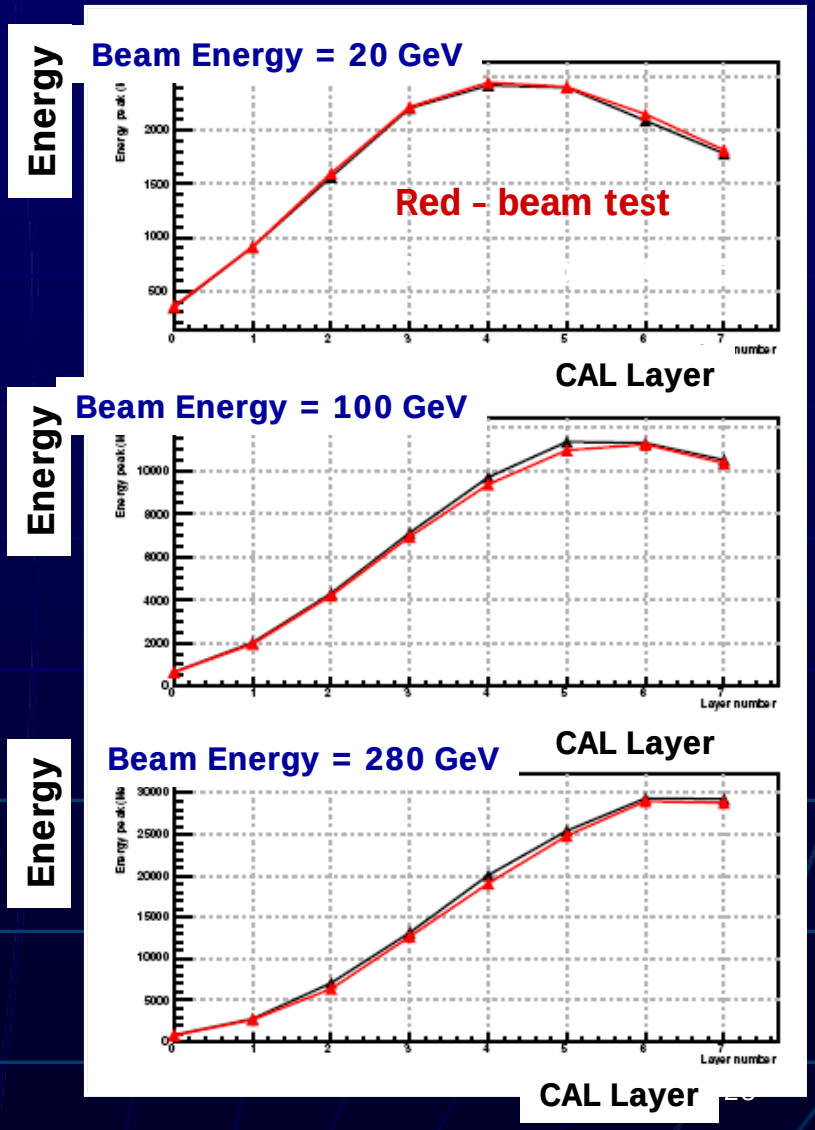
- ✓ Extensive MC simulations
- ✓ High precision 1.5 X_0 thick tracker:
  - powerful in event topology recognition
  - serves as a pre-shower detector
- ✓ Segmented calorimeter with imaging capability
- ✓ Segmented ACD:
  - removes gammas and contributes to event pattern recognition
- ✓ Extensive beam tests:
  - SLAC, DESY, GSI, CERN, GANIL
- ✓ High flight statistics:
  - Expecting ~10 M electrons above 20 GeV a year

Energy reconstruction

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 the LAT Calibration Unit

Very good agreement between shower profile in beam test data (red) and Monte Carlo (black)

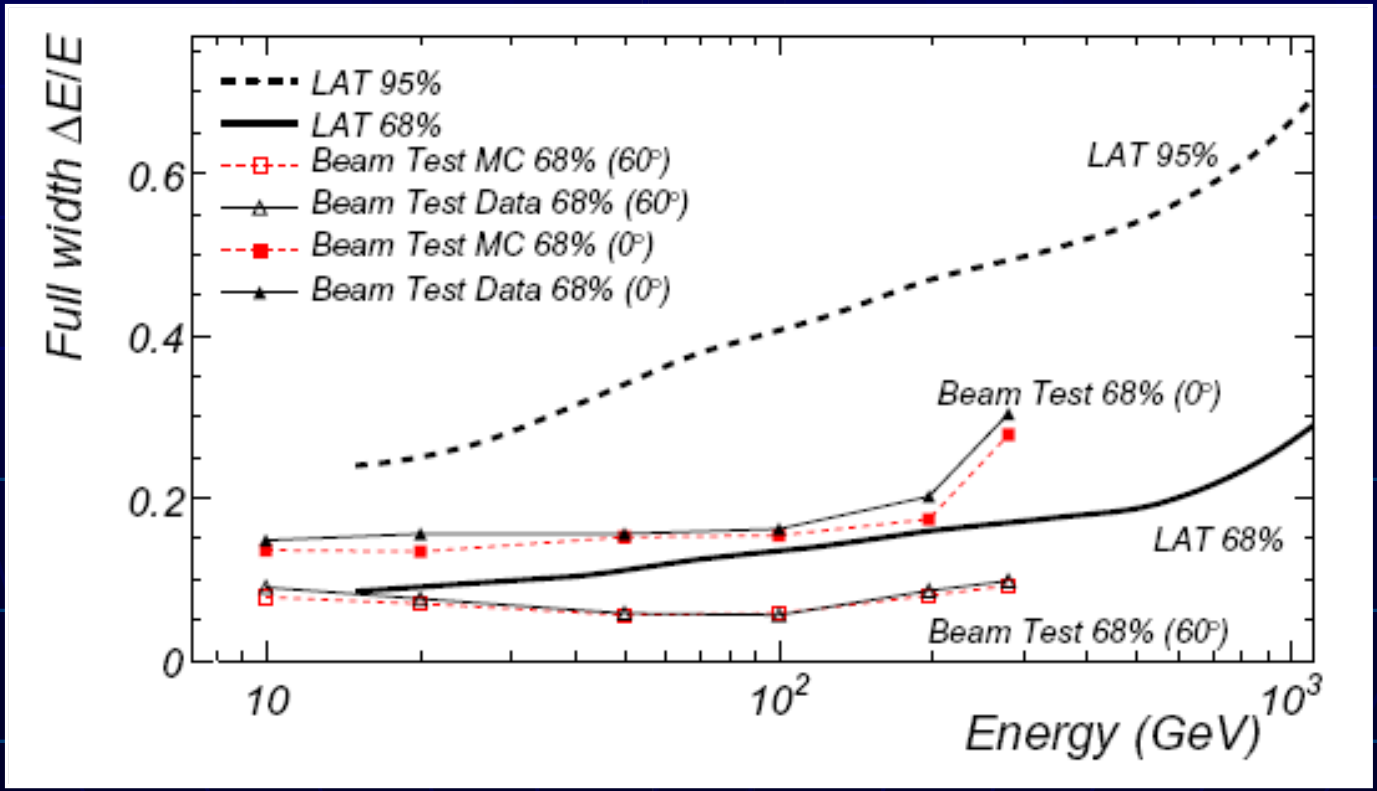


Energy resolution

Agreement between MC and beam test within a few percent up to 280 GeV

→ *we can be confident in MC* →

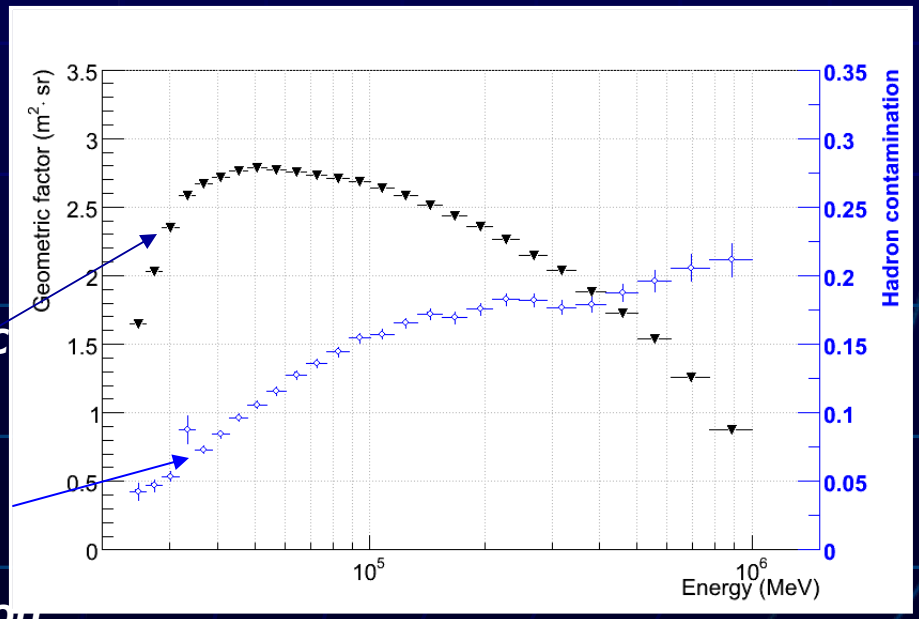
we have reasonable grounds to extend the energy range to 1 TeV relying on Monte Carlo simulations



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 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

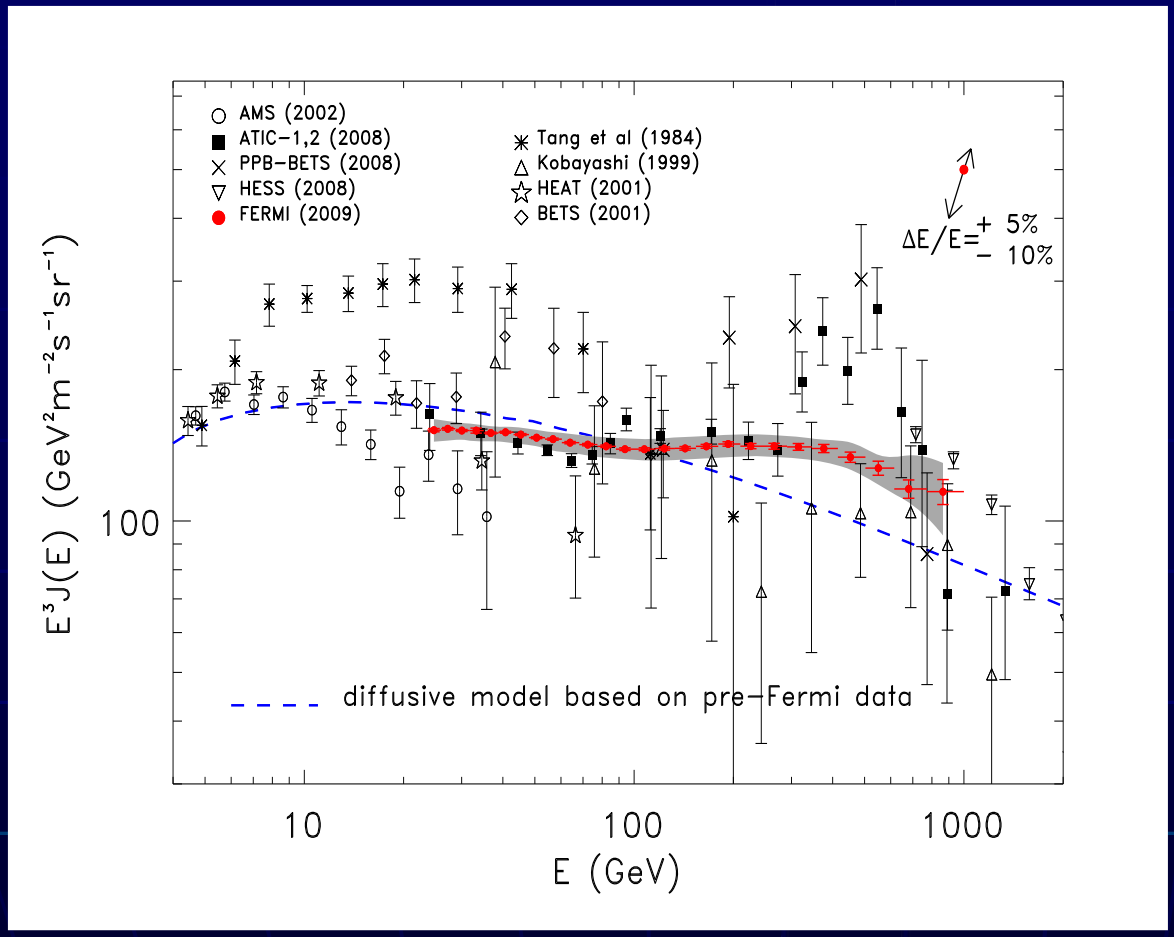
Key issue: *good knowledge and confidence in Instrument Response Function*



Geometric Factor

Residual hadron contamination

Fermi-LAT electron spectrum from 20 GeV to 1 TeV



Phys. Rev. Letters 102, 181101 (2009)

- ✓ ***Cited 38 times within a month***
- ✓ ***APS Viewpoint***

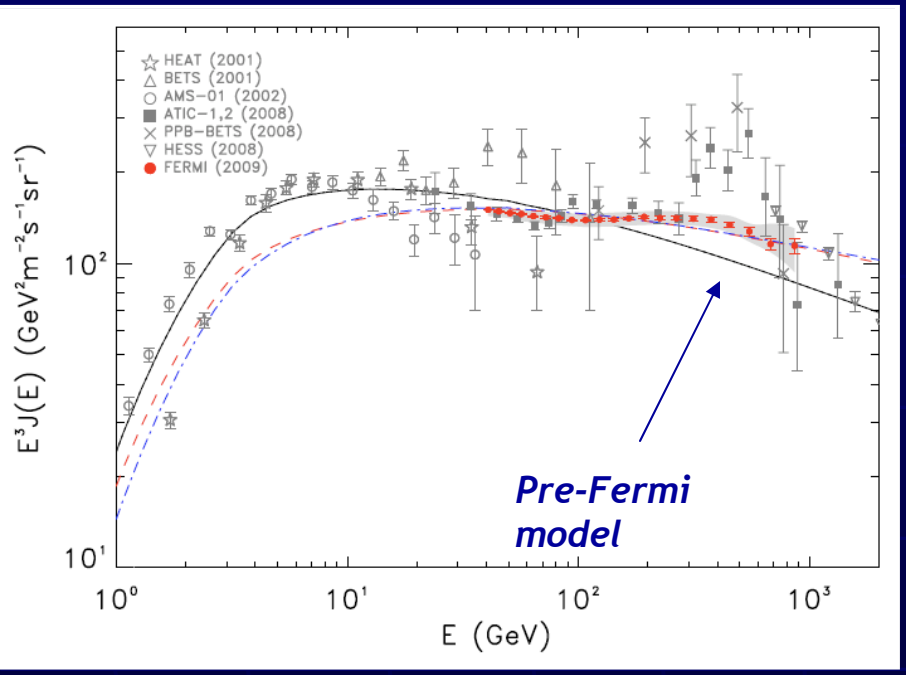
Total statistics collected for 6 months of Fermi LAT observations:

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

Some interpretations…

Can our result be fitted with pre-Fermi model?

Based on our interpretation paper: D.Grasso et al., astro-ph 0905.0636 (May 4, 2009); accepted by Astroparticle Physics



Pre-Fermi Diffuse Galactic Cosmic-Ray Source Model: electrons accelerated by continuously distributed astrophysical sources, likely SNR

Spectrum can be fitted by model with harder injection spectral index (-2.42) than in pre-Fermi model (-2.54). *All that within our current uncertainties, both statistical and systematic*

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

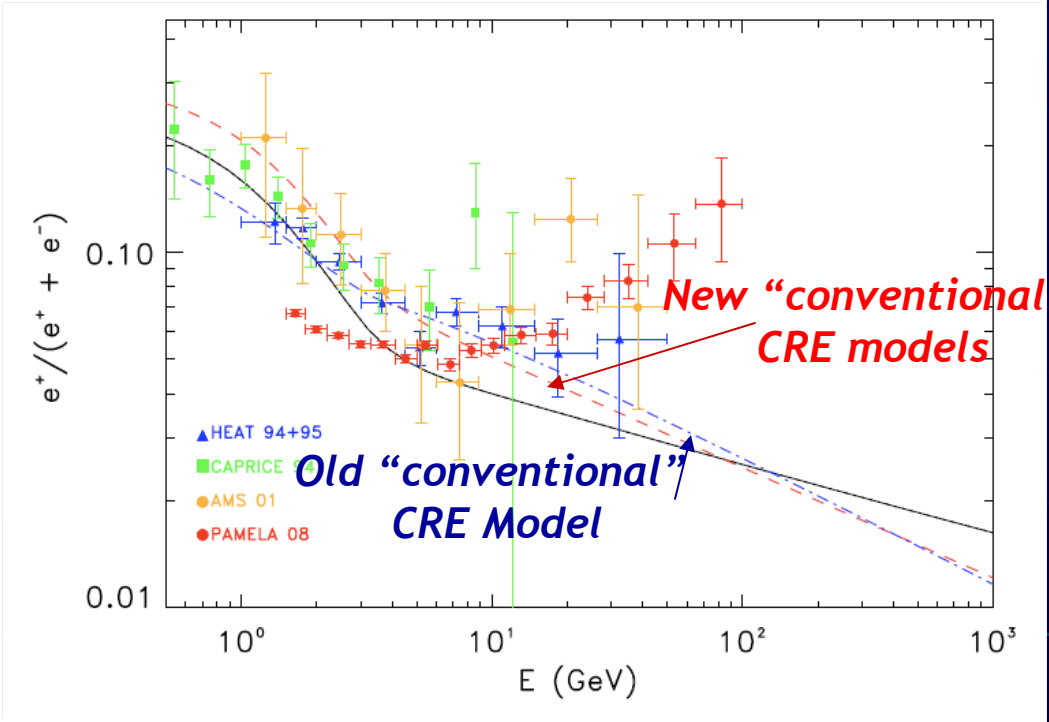
I deeply apologize for missing references to numerous interpretation papers that appeared during the last 1-2 months

Remark: if we subtract the e^+ fraction of the flux, using Pamela data, the e^- spectrum becomes softer by ~0.1 and consequently requires softer injection spectrum

Now include recent Pamela result on positron fraction:

Qualitative approach: the harder primary CRE spectrum is, the steeper secondary-to-primary e+/e- ratio should be.

Pamela shows the opposite

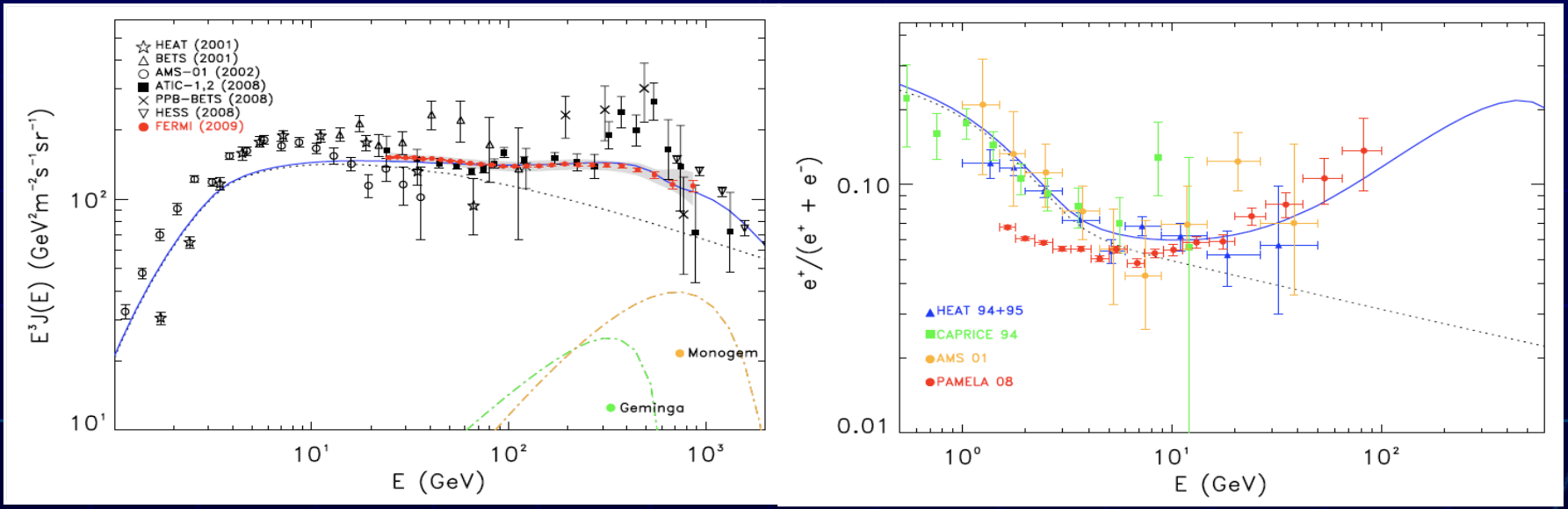


Precise Fermi measurement of the hard *e+e-* spectrum increases the discrepancy between a purely secondary origin for positrons and the positron fraction measured by Pamela

It is becoming clear that we are dealing with at least three distinct origins of high energy electrons and positrons

- One is uniformly distributed "distant" sources, likely SNR
- Another is unavoidable e^+e^- production in CR interactions with ISM

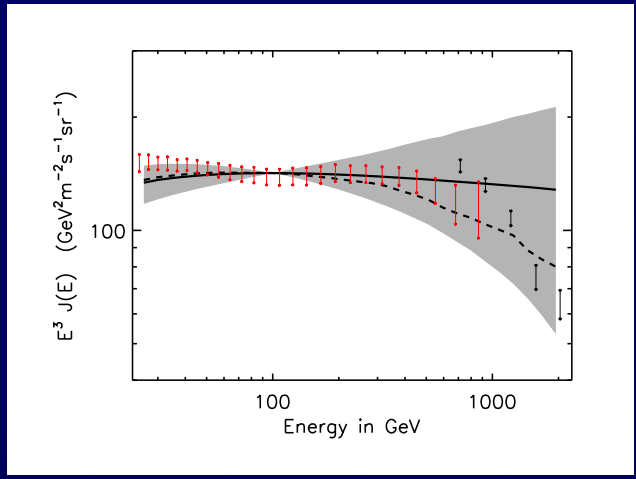
What creates positron excess at high energy? Nearby ($d < 1$ kpc) and Mature ($10^4 < T/yr < 10^6$) pulsars ?

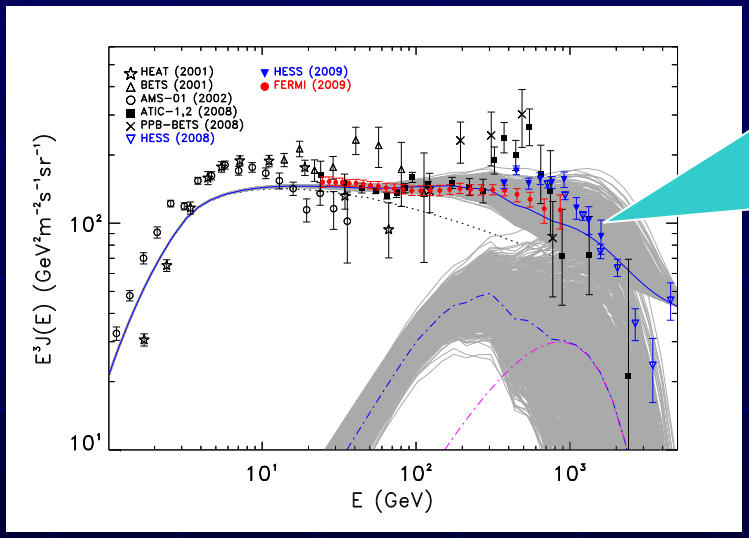


Example of fit to both Fermi and Pamela data with Monogem and Geminga pulsars and with a single, nominal choice for the e+/e- injection parameter – works better

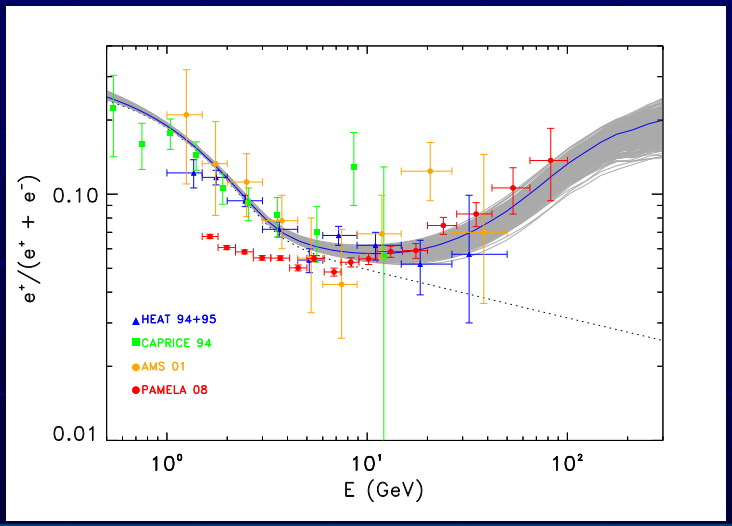
What if we randomly vary the pulsar parameters,

relevant for e+e- production (*injection spectrum, e+e- production efficiency, PWN "trapping" time*), and include more contributing pulsars stochastically?





These "wings" are our next target



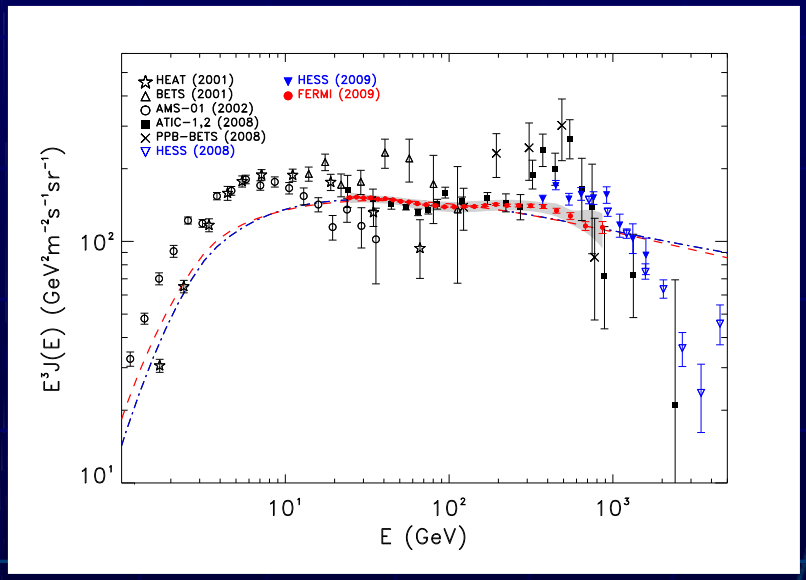
Under reasonable assumptions, electron/positron emission from pulsars offers a viable interpretation of Fermi CRE data which is also consistent with the HESS and Pamela results. Many degrees of freedom, but the assumption is plausible and realistic

Dark matter: the impact of the new Fermi CRE data

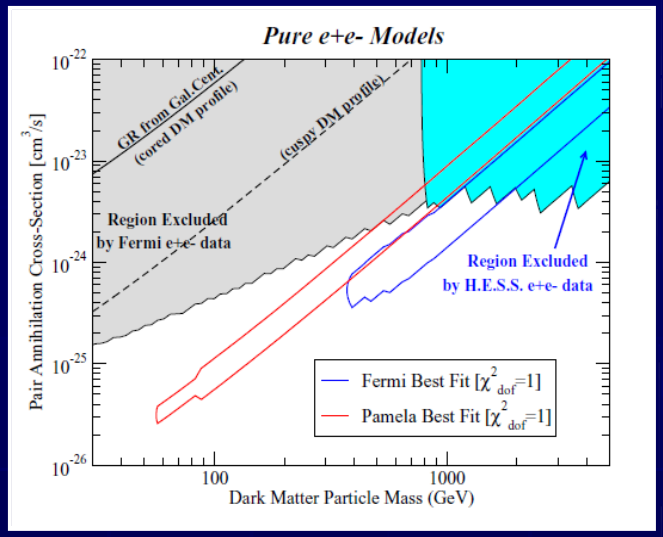
1. *Everything I said about pulsars as sources of e^+e^- is applicable to DM. Dark matter origin of e+e- is not ruled out*

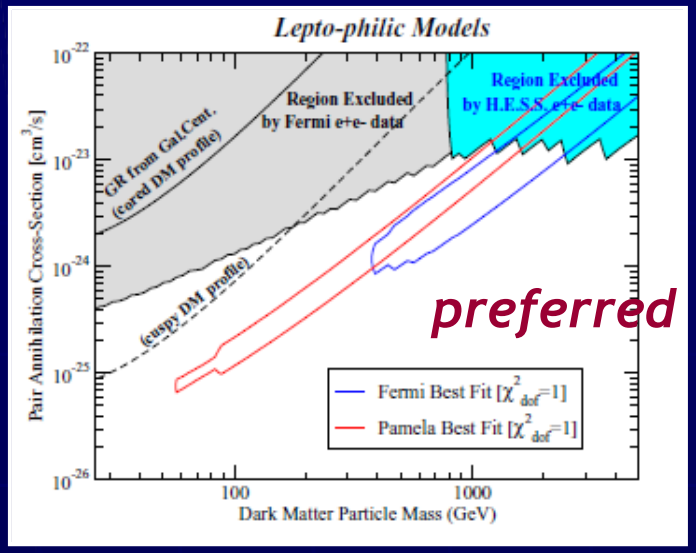
2. *If the Pamela positron excess comes from DM annihilation or decay, the Fermi CRE data set puts constraints on such interpretation (e.g. pair annihilation or decay rate for a given DM mass and diffusion setup)*

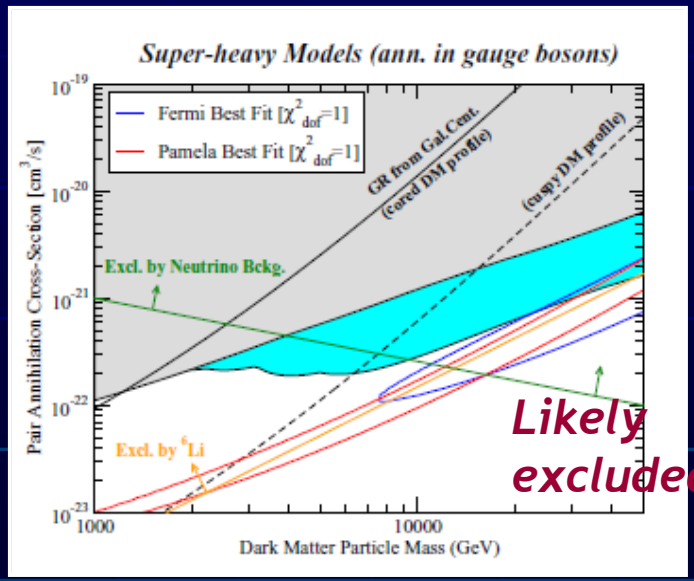
3. *Pamela and Fermi-LAT data tighten the DM constraints, favoring pure $e^{\pm}$, lepto-philic, or super-heavy DM models (Arkani-Hamed et al, Fox and Poppitz, Harnik and Kribs, Cirelli et al, Profumo, Bergstrom et al, Blasi, Balazs et al, and others)*

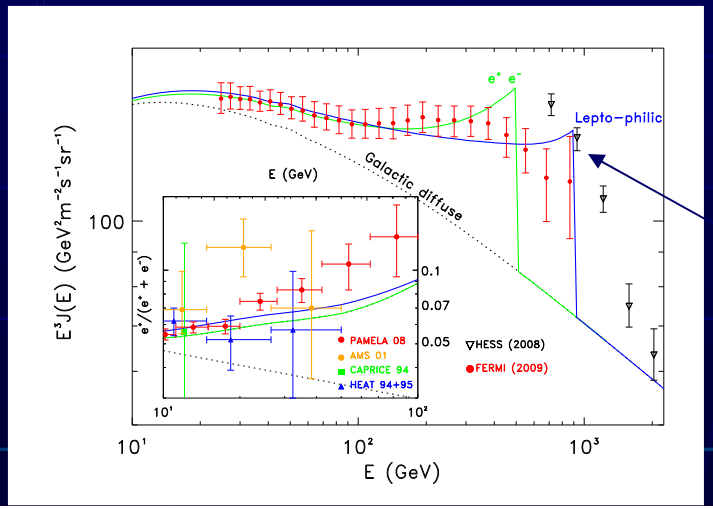


4. *Need precise spectral shape! Irregularities on the falling slope of the spectrum above ~ 1 TeV, if found, may help to determine the origin of high energy electrons, favoring nearby pulsars scenario*





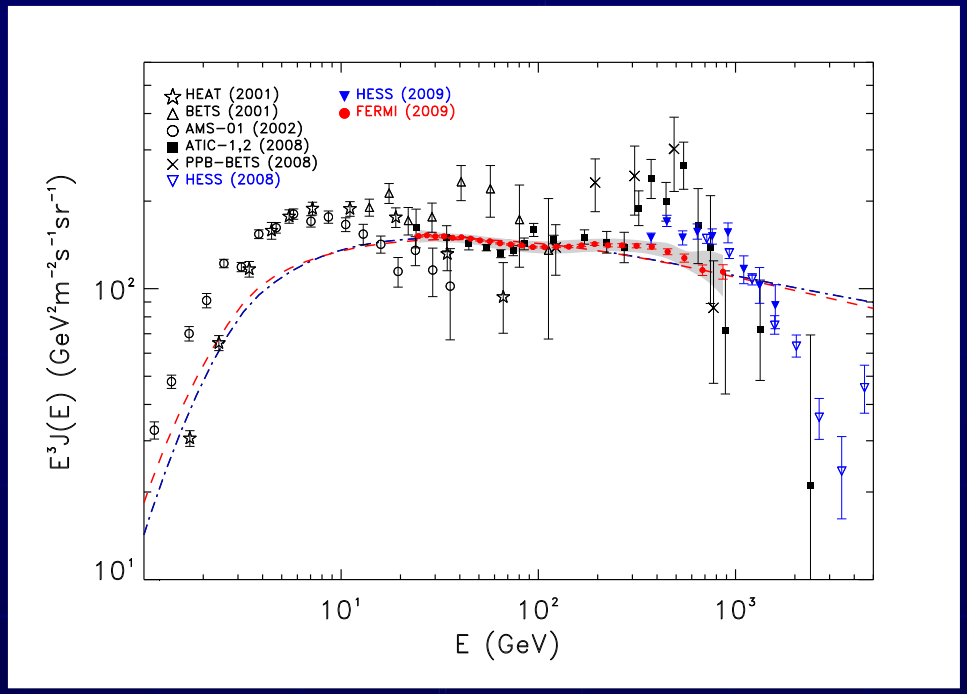




Instrumental energy smearing is not included

Model	Ann. Final State	Mass (GeV)	$\langle\sigma v\rangle$ (cm^3/s)
e^+e^-	e^+e^-	500	9×10^{-25}
Leptophilic	$33\%(e^+e^-)+33\%(\mu^+\mu^-)+33\%(\tau^+\tau^-)$	900	4.3×10^{-24}

Dark matter origin of CRE is not ruled out. *Origin of the local source is still unclear - astrophysical or "exotic"*

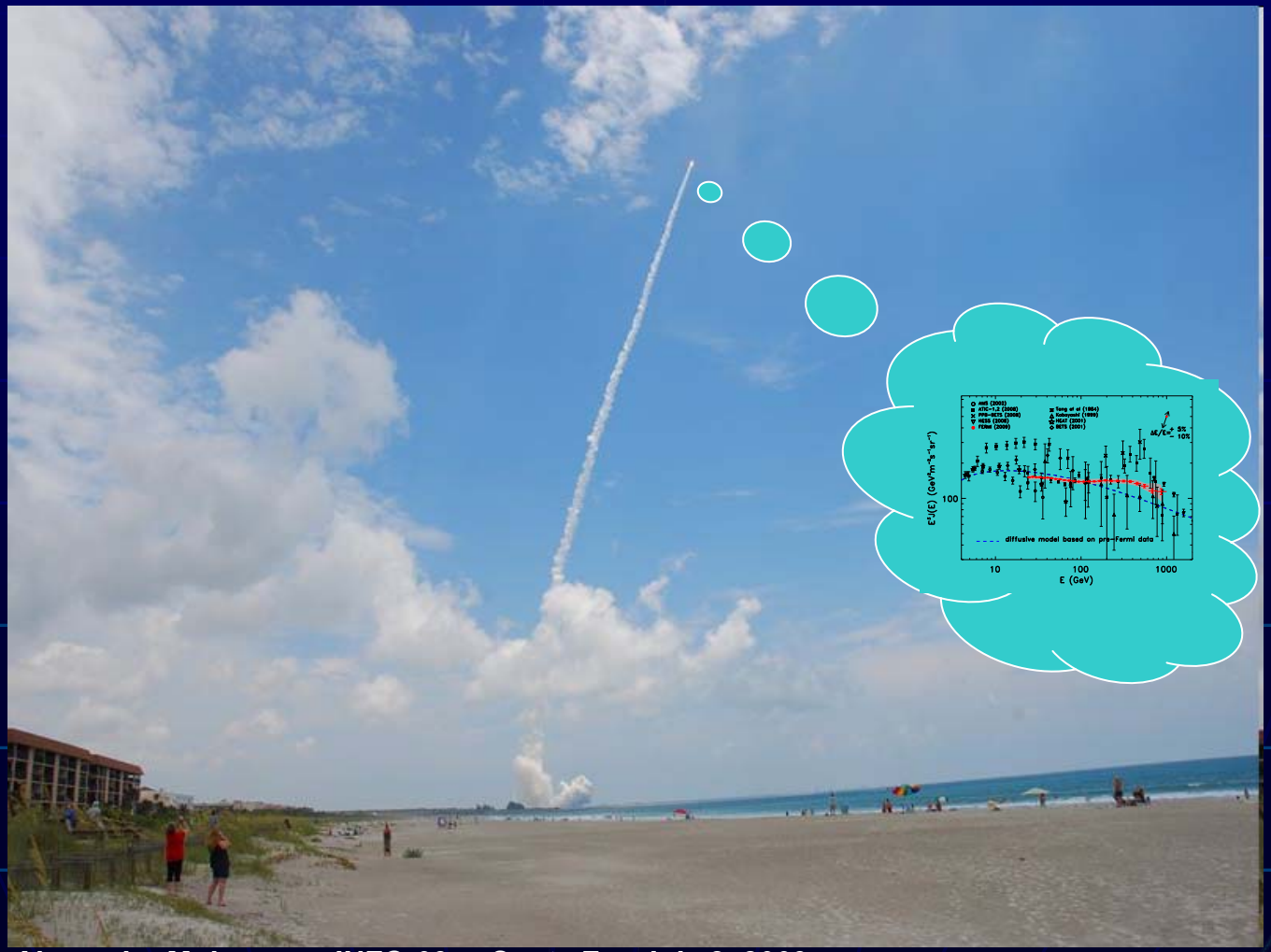


SUMMARY

- *Real breakthrough during last 1-1.5 years in cosmic ray electrons: ATIC, HESS, Pamela, and finally Fermi-LAT. New quality data are available*
- *With the new data more puzzles than was before; need "multiwavelength" campaign: electrons, positrons, gammas, X-ray, radio, neutrino…*
- *We may be coming close to the first direct detection of cosmic ray source*
- *Source nature: astrophysical or exotic – unclear. Possible that other models will be suggested*
- *More results from Fermi-LAT are coming. We are working on extending energy range to 5 GeV – 2 TeV and searching for the CRE anisotropy at a level of ~ 1%*

- ***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 the 1st year all-sky survey:**
  - **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 8 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**
  - **Progress in measuring gamma-radiation from molecular clouds**
- **With time, *Fermi* will probe deeper and deeper into the high-energy Universe**

THANK YOU !


E³J(E) (GeV²m⁻²s⁻¹sr⁻¹)
100
10
100
1000
E (GeV)
diffusive model based on pre-Fermi data