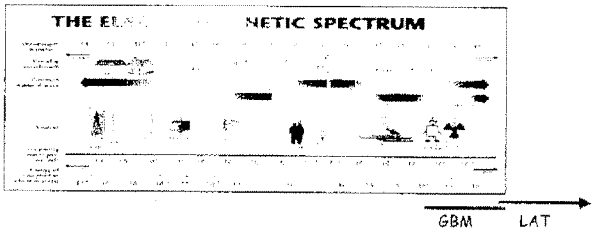
A new view of the high energy gamma-ray sky with the Fermi Gamma-Ray Space Telescope

Julie McEnery
NASA/GSFC

see *http://fermi.gsfc.nasa.gov/* and links therein

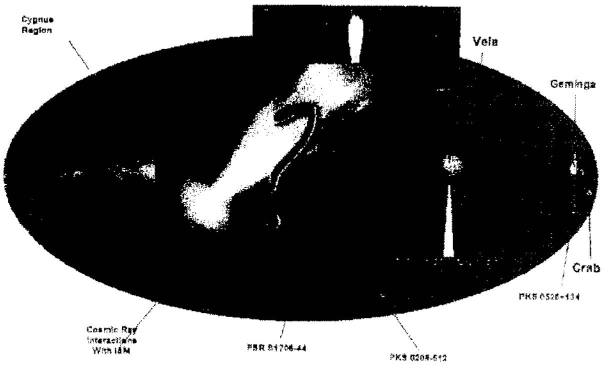
Gamma-Ray Astrophysics



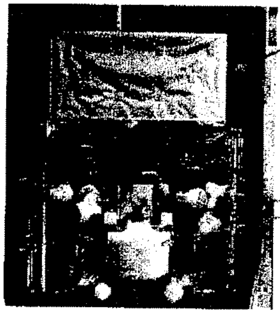
- The Fermi energy range falls at the energetic end of this scale!
- Very energetic photons require even more energetic particles to produce them – HE gamma-ray astrophysics does not probe quiet parts of the Universe.
- High energy gamma-rays explore nature's accelerators - "Where the energetic things are"
  - natural connections to UHE cosmic-ray and neutrino astrophysics

---

The EGRET Gamma-Ray Sky



Fermi instruments



Large Area Telescope (LAT):

- 20 MeV - >300 GeV (including unexplored region 10-100 GeV)
- 2.4 sr FoV (scans entire sky every ~3hrs)

Gamma-ray Burst Monitor (GBM)

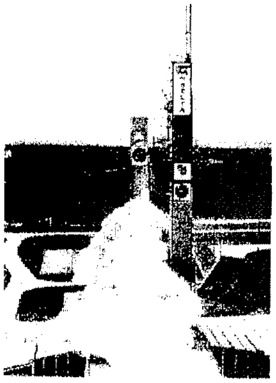
- 8 keV - 40 MeV
- views entire unocculted sky

Launched June 11, 2008!

- Large leap in all key capabilities, transforming our knowledge of the gamma-ray universe. Great discovery potential.

Launch!

- **Launch from Cape Canaveral Air Station 11 June 2008 at 12:05PM EDT**
- **Circular orbit, 565 km altitude (96 min period), 25.6 deg inclination.**



LAT Collaboration

- France
  - CNRS/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 and HEPL/Physics)
  - University of California, Santa Cruz - Santa Cruz Institute for Particle Physics
  - Goddard Space Flight Center
  - Naval Research Laboratory
  - Sonoma State University
  - The Ohio State University
  - University of Washington

PI: Peter Michelson
(Stanford)

~400 Scientific Members (including 96 Affiliated Scientists, plus 68 Postdocs and 105 Students)

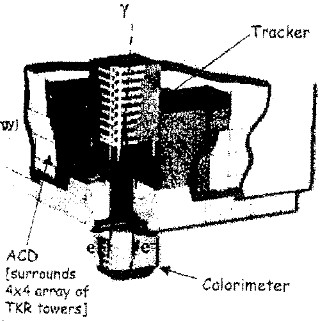
Cooperation between NASA and DOE, with key international contributions from France, Italy, Japan and Sweden.

Project managed at SLAC.

The Fermi Large Area Telescope

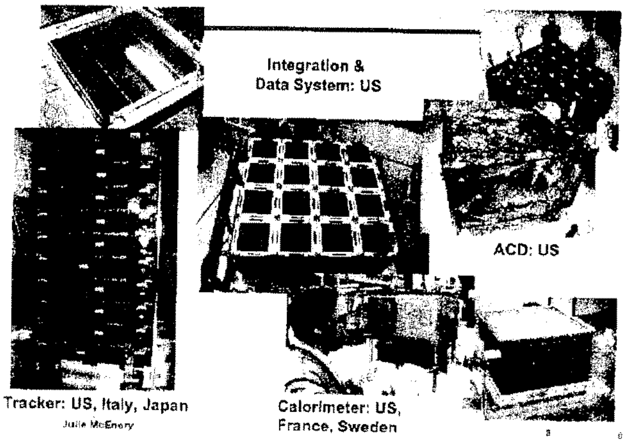
Overall LAT Design:
- 4x4 array of identical towers
- 3000 kg, 650 W (allocation)
- 1.8 m × 1.8 m × 1.0 m

- **Precision Si-strip Tracker (TKR)**
  18 XY tracking planes. 228 μm pitch).
  High efficiency.
  Good position resolution (ang. resolution at high energy)
  12 x 0.03 X_0 front end => reduce multiple scattering.
  4 x 0.18 X_0 back-end => increase sensitivity >1GeV
- **CsI Calorimeter(CAL)**
  Array of 1536 CsI(Tl) crystals in 8 layers.
  Hodoscopic => Cosmic ray rejection, shower leakage correction.
  8.5 X_0 => Shower max contained <100 GeV
- **Anticoincidence Detector (ACD)**
  Segmented (89 plastic scintillator tiles)
  => minimize self veto

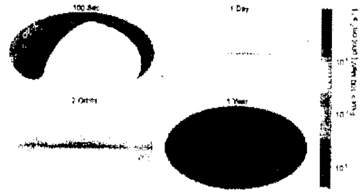


Systems work together to identify and measure the flux of cosmic gamma rays with energy 20 MeV - >300 GeV.

Lat Construction: An international effort

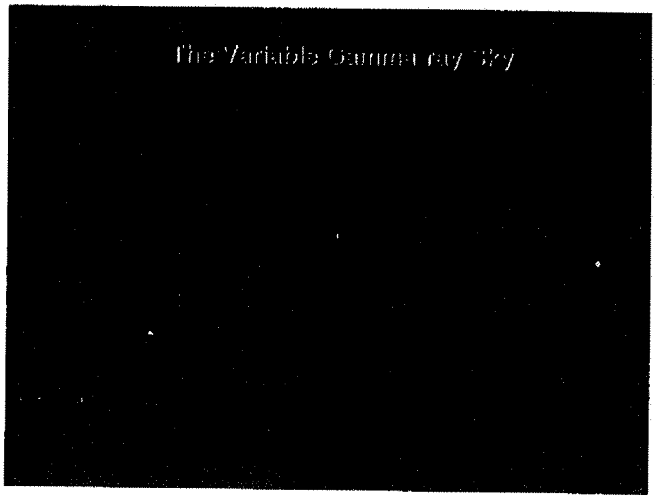


Operations and observing modes



LAT sensitivity on 4 different timescales: 100 s, 1 orbit (96 mins), 1 day and 1 year

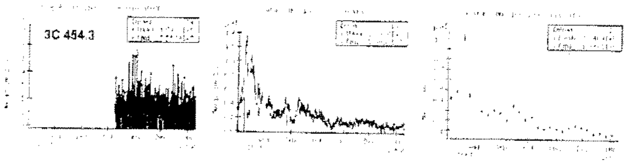
- Almost all observations in survey mode - the LAT observes the entire sky every two orbits (~3 hours), each point on the sky receives ~30 mins exposure during this time.
- 25 ARRs
  - 5 hour pointed mode observations in response to bright GBM detected GRB
- Calibrations (13 hours), Engineering (5 days)
  - Very high uptime!



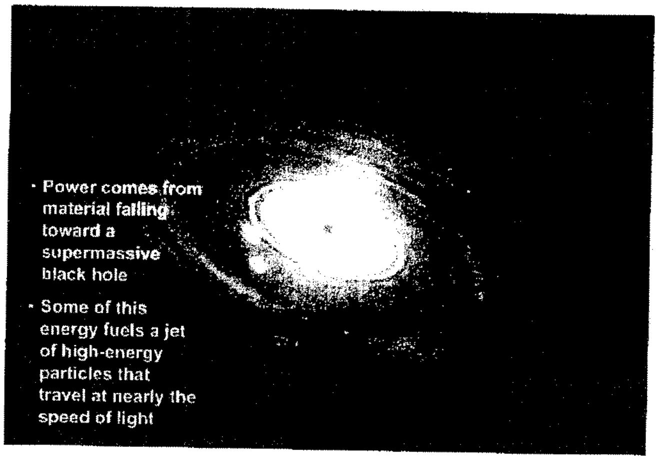
The Variable Gamma-ray Sky

Monitoring the sky

- Automated Science Processing (ASP)
  - Transient detection: Uses source detection algorithm to find candidate point sources in data from each epoch (6hr, day, week)
  - Follow-up Source Characterization: Runs full likelihood analysis on list from source detection step + "Data Release Plan" (DRP) sources (to produce fluxes and spectra)
- Flare Advocates:
  - LAT scientists examine output from ASP pipeline and perform follow-up analyses, produce ATels, and propose ToOs

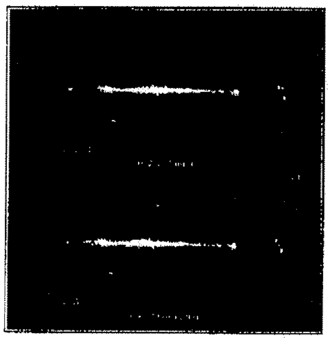


Active galaxies



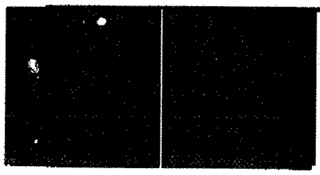
- Power comes from material falling toward a supermassive black hole
- Some of this energy fuels a jet of high-energy particles that travel at nearly the speed of light

The flaring and variable sky

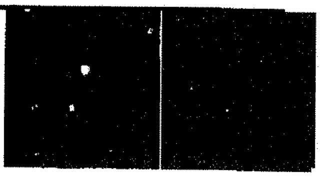


- >40 Astronomers telegrams
  - Discovery of new gamma-ray blazars PKS 1502+106, PKS 1454-354...
  - Flares from known gamma-ray blazars: 3C454.3, PKS 1510-089,3C273, AO 0235+164, PSK 0208-512, 3C66A, PKS 0537-441
  - Galactic plane transients: J0910-5041, 3EG J0903-3531, J1057-6027

Multiwavelength Observations of LAT Transients in the Galactic Plane



3EG J0903-3531 (October 5, 2009)
- Brightened over 3 days
- 5x above 3EG flux

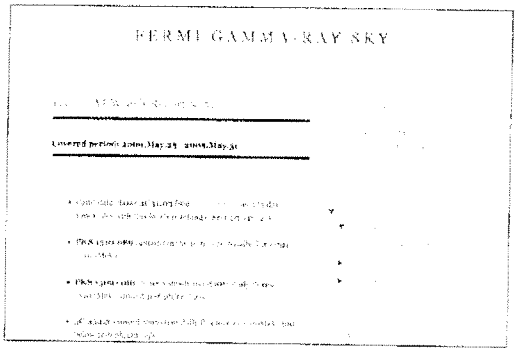


Fermi J0910-5041
(October 15, 2009)
- Brightened over 2 days
- XRT source plus SUMMS and AT20G candidate counterpart

Fermi J1057-6027 (June 11, 2009)
- Brightened over 1 day
- Coincident with known LAT source
-10x above LAT flux

---

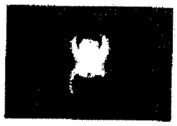
http://fermisky.blogspot.com/



FERMI GAMMA-RAY SKY

Gamma-ray bursts come in at least three flavors

Collapsars: A rapidly spinning stellar core collapses and produces a supernova, along with relativistic jets that can produce long GRBs

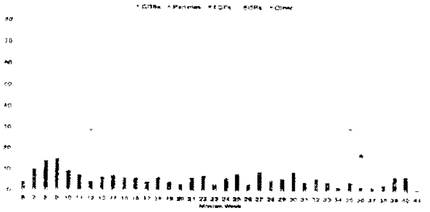


Compact Mergers: Two neutron stars, or a neutron star and a black hole, collide and merge, producing a jet that gives rise to a short GRB

In both these cases, the burst probably produces a black hole.

Magnetars: Neutron stars in our Galaxy or nearby galaxies with extremely strong magnetic fields can give off powerful bursts that resemble short GRBs

Gamma-ray Burst Monitor



USA (MSFC, UAH, LANL) and Germany (MPE)

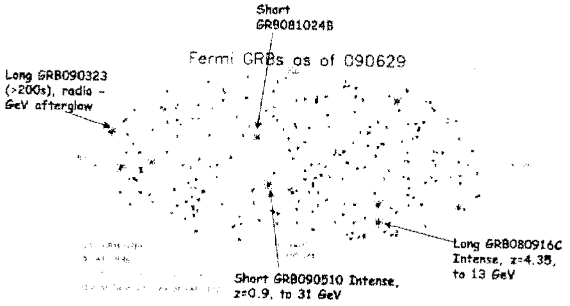
PI- Bill Paciesas (UAH)

Co-PI- Jochen Greiner (MPE)

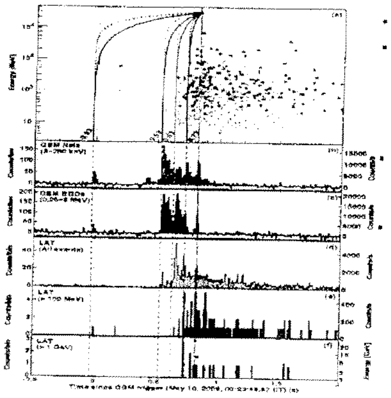
- Since July 2008, GBM has detected over 260 GRB (250/year c.f. 200/year predicted)
  - Benefited from flexible onboard triggering algorithms
- Also has seen three SGRs (SGR 0501+4516, SGR 1806-20 and SGR 1E1547.0-5408), >10 TGFs and a solar flare.

Gamma-ray bursts

- 10 long and 2 short bursts detected by LAT at GeV energies
  - Both types of GRB show similar phenomenology at high energies
  - Swift XRT has detected X-ray afterglows from the 7 brightest LAT bursts resulting in the determination of the burst redshift/distance.



GRB090510



- Z=0.9
- Emission of 31 GeV photon implies Γ_{min}>1220 (implying that short bursts are at least as relativistic as long ones)
- Extended (in time) emission at higher energies
- High energy emission in LAT starts later than the lower energy in GBM.

Testing Einstein's Theory of Special Relativity

- The Principle of Invariant Light Speed – *Light in vacuum propagates with the speed c (a fixed constant) in terms of any system of inertial coordinates, regardless of the state of motion of the light source.*

- Consider a race between two photons traveling a very large distance at slightly different speeds. The slower photon will arrive later.
  - To do this we need
    - Distant object
    - Very bright
    - Well defined start time

- To make it interesting, we want to make this test at the highest possible photon energies.
  - Some models of quantum gravity predict that space itself might be distorted by effects of quantum gravity.

Limits on Lorentz Invariance Violation

- **Heuristic modification of the photon dispersion relation :**
  - $c^2 P^2 = E^2 (1+ f(E/E_{QG}))$ E_{QG} *: effective LIV energy scale*
  - For $E << E_{QG}$: $c^2 P^2 = E^2 (1+ \alpha(E/E_{QG})^n + O(E/E_{QG})^{n+1}) \Longrightarrow$ $v = \delta E/\delta P \sim c (1+ \alpha(E/E_{QG})^n)$
    - n=1 or 2 in current studies
    - α is just a constant (can disappear in E_{QG})
      - $\alpha<0$: subluminal regime (high energy photons arrive later)
      - $\alpha>0$: superluminal regime (high energy photons arrive earlier)
- **Simple case : n=1, $\alpha<0$:**
  - Consider a photon of energy E observed at t.
  - If it belongs to the GRB, at the very least it has been emitted *after* the trigger t0.
  - Thus the maximal time delay due to LIV is t-t0 : $\delta t<t-t0$
  - With a distance estimate, this results in a "conservative" lower limit on E_{QG}
    - Independent of intrinsic time lags in GRBs

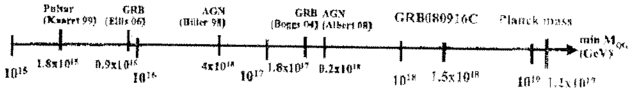
Limits on Lorentz Invariance Violation

- **Lorentz Invariance:**
  - GRB080916C
  - Highest energy, ≈ 13.2 GeV photon, detected 16.5 sec after GBM trigger
  - Conservative lower limit on the quantum gravity mass (assuming linear energy scaling and high energy photons emitted after GRB trigger):

$$M_{QG} > 1.50 \times 10^{18}\ \mathrm{GeV}/c^2$$

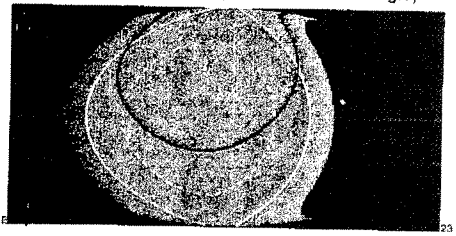
  - GRB090510
  - Highest Energy, ~31 GeV photon detected 858 ms after onset of GBM emission

$M_{QG} > 1.42 \times 10^{19}\ \mathrm{GeV}/c^2$ ($>1.19\ M_{Planck}$!) - rules out many n=1 scenarios

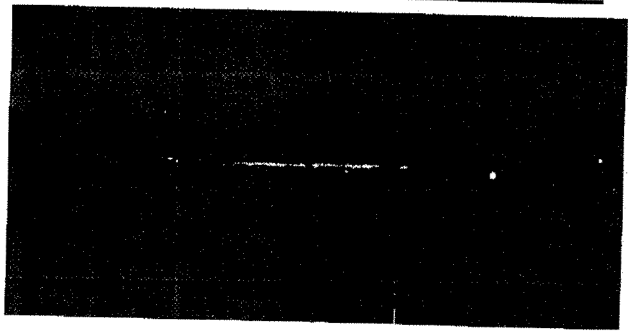


GRB090902B - Autonomous repoint

- LAT pointing in celestial coordinates from -120 s to 2000 s
  - Red cross = GRB 090902B
  - Dark region = occulted by Earth (qz>113°)
  - Blue line = LAT FoV (±66°)
  - White lines = 20° (Earth avoidance angle) / 50° above horizon
  - White points = LAT events (no cut on zenith angle)



One year Fermi-LAT Sky



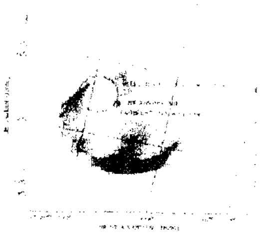
Over 1000 new high-energy gamma-ray sources!

Pulsars

- **Extremely dense stars, huge magnetic fields, rapidly rotating**

New Pulsar in CTA 1

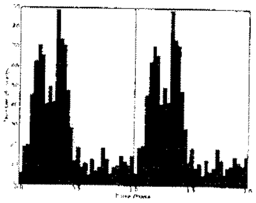
Science Express October 16
Abdo et al., 2008, Science



LAT 95% error radius = 0.038 deg
EGRET 95% error radius = 0.24 deg

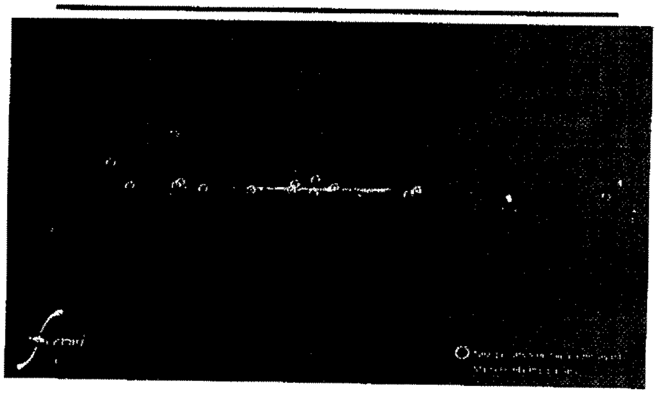
P ~ 316 ms
Pdot ~ 3.6×10^{-13}
Characteristic age ~ 10 kyr
Flux (>100MeV) = $3.8 \pm 0.2 \times 10^{-7}$ ph cm-2 s-1

Pulse undetected in radio/X-ray



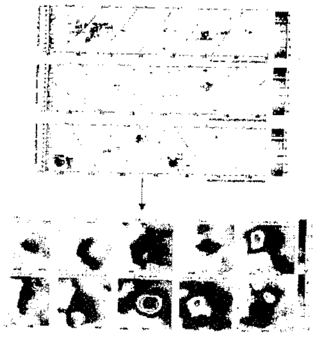
Unidentified EGRET sources - many are pulsars!

New Populations of Pulsars



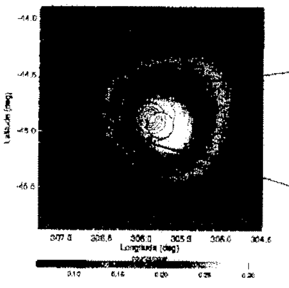
Connection with Higher Energy Gammas

- Milagro (TeV) observations (14/34 Galactic BSL sources with 3 sigma Milagro excess.
- 9/14 are gamma-ray pulsars
- All 6 previously known Milagro sources now associated with Fermi Pulsars.)

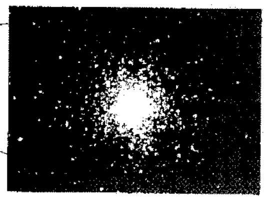


Abdo et al 2009

Fermi detection of 47 Tucanae



Globular star cluster containing 23 known radio ms pulsars



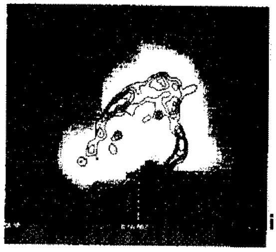
Consistent with Fermi PSF for point source

Fermi likely to be detecting the combined emission from these ms pulsars assuming average γ-ray efficiency of ~ 10 %
- Search for pulsations from individual pulsars is ongoing

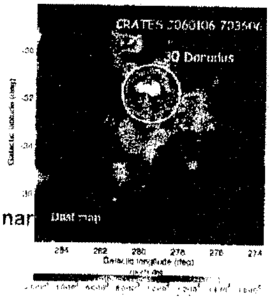
Extended Sources

- LAT is resolving the MeV-GeV gamma-ray emission from extended sources.

W44

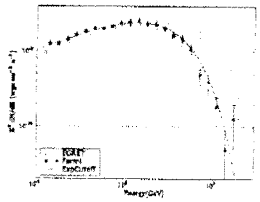


LMC

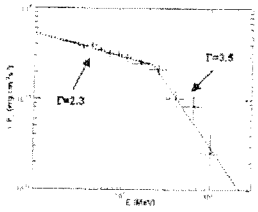


High Energy Gamma-ray spectra

- LAT sensitivity and wide bandpass allows the measurement of many non power-law spectra



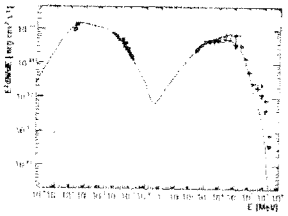
Phase averaged Vela Pulsar spectrum (power-law with exponential cutoff)



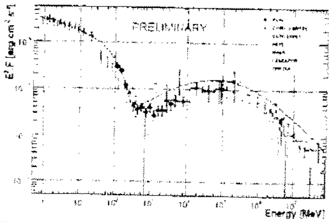
3C454.3: Broken power-law

LAT Energy Range

PKS 2155-304



High energy Crab Nebula Spectrum

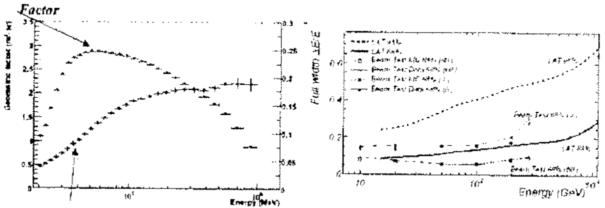


- Joint fits between LAT (MeV-GeV) and IACTs (GeV-TeV)
- Peak sensitivity at a few GeV for typical spectra

Fermi-LAT capabilities for electrons

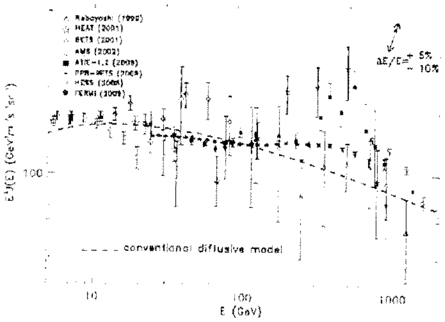
- 100% acceptance above 20 GeV (onboard filtering is disabled)
- Use ACD to veto against gamma-rays (<2% contamination)
- Transverse shower-shape in TKR and Calorimeter to distinguish electromagnetic from hadron events

Geometric Factor



Residual hadron contamination

Fermi-LAT electron observations



Fermi sees more electrons at high energies than expected which suggests a local source, but what?

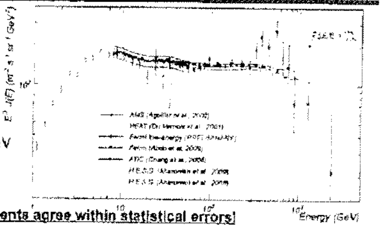
Update: Add the Low Energy Measurement

LAT has two Trigger Modes which can used to measure electrons:

- High Energy By-Pass Trigger
- Tracker 3-in-a-row Diagnostic Trigger

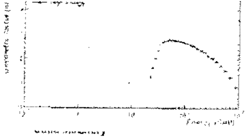
Two independent analyses start from these hardware triggers.

- Low Energy: 100 MeV – 50 GeV
- **High Energy: 20 GeV – 1 TeV**

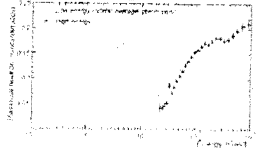


Both measurements agree within statistical errors!

Geometric Factors *(Acceptance)*

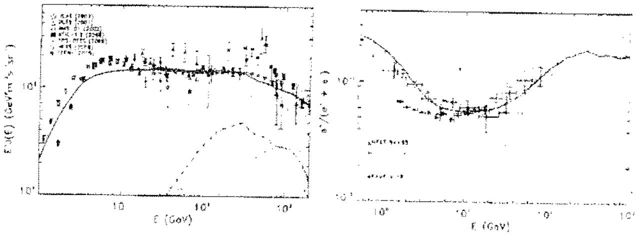


Residual Background Fractions



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

[injection spectrum, e+e- production efficiency, PWN "trapping



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

Want to know more?

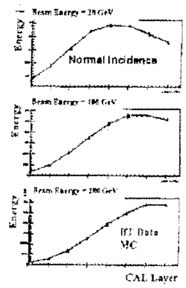
- Fermi symposium
  - Washington DC, Nov 2-5
- http://fermi.gsfc.nasa.gov/ssc/resources/newsletter/
  - General news
  - Multiwavelength
  - Data/software
- LAT data became public on Aug 25
  - http://fermi.gsfc.nasa.gov/ssc

Conclusions

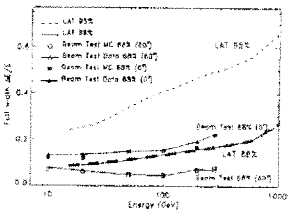
- The LAT and GBM are both working well
- First LAT GeV catalog (currently being validated/checked) contains over 1000 new gamma-ray sources!
  - New classes of gamma-ray sources (millisecond pulsars, gamma-ray binaries, globular clusters, starburst galaxies...)
    - field of gamma-ray astrophysics is rapidly expanding
- GBM is detecting many kinds of MeV transients
  - >250 GRB/year, three SGRs (SGR 0501+4516, SGR 1806-20 and SGR 1E1547.0-5408), >10 TGFs and a solar flare.
- Science returns in solar system studies, Galactic astrophysics, extragalactic astrophysics, cosmic-ray physics and fundamental physics.
- The full data release was last month, software to assist with data analysis is also available.
  - http://fermi.gsfc.nasa.gov/ssc
- Lots more science to come...

CERN Beam Test Compared to Monte Carlo

Longitudinal Shower Profiles



Energy Resolution: Full Width @ 68% Cont.



Resolution integrated over all angles

Average material traversed by selected electron events is 12.5X₀ (TKR+CAL sheer thickness + selection effects)

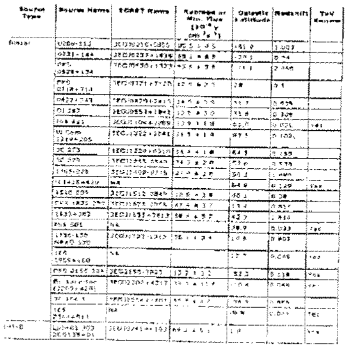
Fitting the longitudinal shower profile event-by-event compensates for fluctuations in leakage

---

LAT High Level data releases

The LAT team releases flux/spectra as a function of time for all sources in a pre-defined list + flaring sources during flares.

- Modified data release after ~6months:
  - Lowered flux threshold to release information on flaring sources by factor of 2.
  - Provided information continuously (not just during flares).
  - started with 23 sources, now have >40



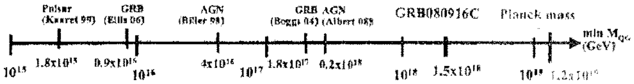
Limits on Lorentz Invariance Violation

- **Heuristic modification of the photon dispersion relation :**
  - $c^2 P^2 = E^2 (1+ f(E/E_{QG}))$ E_{QG}: *effective LIV energy scale*
  - For $E<<E_{QG}$: $c^2 P^2 = E^2 (1+ \alpha(E/E_{QG})^n + O(E/E_{QG})^{n+1})$
    - n=1 or 2 in current studies
    - α is just a constant (can disappear in E_{QG}).

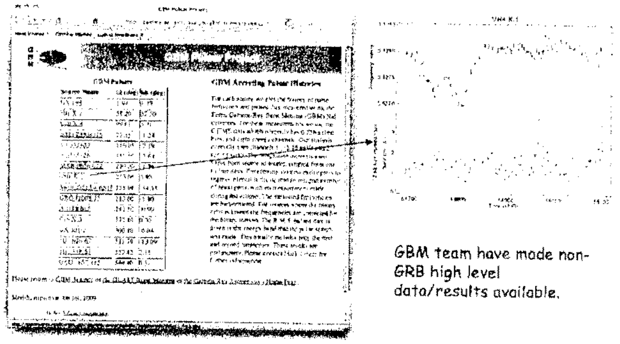
$$\Delta t = \frac{(1+n)}{2H_0}\frac{E_h^n - E_l^n}{(M_{QG,n}c^2)^n}\int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}\,dz'$$

- Highest energy, ≈ 31 GeV photon, detected 859 msec after GBM trigger
- Conservative lower limit on the quantum gravity mass (assuming linear energy scaling and high energy photons emitted after GRB trigger):

$M_{QG} > 1.2\ M_{Planck}$

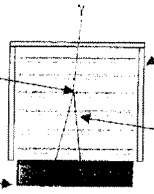


GBM - not just transients



GBM team have made non-GRB high level data/results available.

Pair Conversion Technique



photon converts to an e+e- pair in one of the conversion foils

The anti-coincidence shield vetos incoming charged particles.

The directions of the charged particles are recorded by particle tracking detectors, the measured tracks point back to the source.

The energy is measured in the calorimeter

Tracker: angular resolution is determined by:
multiple scattering (at low energies) => thin conversion foils
position resolution (at high energies) => fine pitch detectors

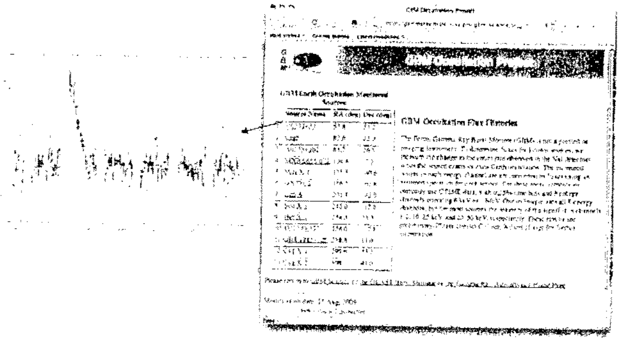
Conversion efficiency -> Thick conversion foils, or many foils

Calorimeter:Enough X_0 to contain shower, shower leakage correction.

Anti-coincidence detector:
Must have high efficiency for rejecting charged particles, but not veto gamma-rays

---

Occultation project



Fermi LAT Papers

Journal	Published	Accepted	Total
Astronomy and Astrophysics	1	-	1
Astroparticle Physics	2	1	3
Astrophysical Journal	10	3	13
Astrophysical Journal Letters	4	1	5
Astrophysical Journal Supplement	1	-	1
Journal of Cosmology and Astroparticle Physics	1	-	1
Physical Review Letters	1	-	1
Science	5	-	5
Total	25	5	30

Another 21 papers are submitted, and many in preparation.

Science impact by citation

"Measurement of the Cosmic Ray $e^{+}+e^{-}$ Spectrum from 20 GeV to 1 TeV with the Fermi Large Area Telescope" (05/2009) – Cited across a broad range - cosmic-ray, astronomy, particle physics (D0, BABAR)	~150
"Fermi/Large Area Telescope Bright Gamma-Ray Source List" (07/2009)	~60
"Fermi Observations of High-Energy Gamma-Ray Emission from GRB 080916C" (03/2009)	~60
"Bright Active Galactic Nuclei Source List from the First Three Months of the Fermi Large Area Telescope All-Sky Survey" (07/2009)	~50
"The Fermi Gamma-Ray Space Telescope Discovers the Pulsar in the Young Galactic Supernova Remnant CTA 1" (11/2008)	~30

GLAST Science Support Center (GSSC)

- Supports guest investigator program
- Provides training workshops
- Provides data, software, documentation, workbooks to community
- Archives to HEASARC
- Joint software development with Instrument Teams, utilizing HEA standards
- Located at Goddard

see http://glast.gsfc.nasa.gov/ssc/

and help desk

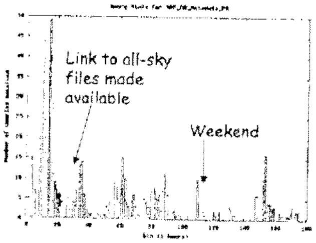
http://glast.gsfc.nasa.gov/ssc/help/

Data Releases

- Beginning of science operations: GBM data + LAT high level data from start of science operations
- Feb 6, 2009: LAT bright source list, first LAT analysis software release
- Aug 25, 2009: low level LAT data, second LAT analysis software release

•~400 queries in first day, many requesting the entire dataset.

•Made link to weekly all-sky files more obvious (so number of queries dropped)



Data analysis workshops

- The FSSC is holding a sequence of regional data analysis workshops
- First workshop on Oct 1 at GSFC
- 1-day, focus on hands-on activities
- ~<25 participants
  - Larger group limits 1-on-1 interactions
- Future workshops
  - Venues chosen based on community feedback
  - May try internet conferencing analysis workshops

GLAST Users Committee Members

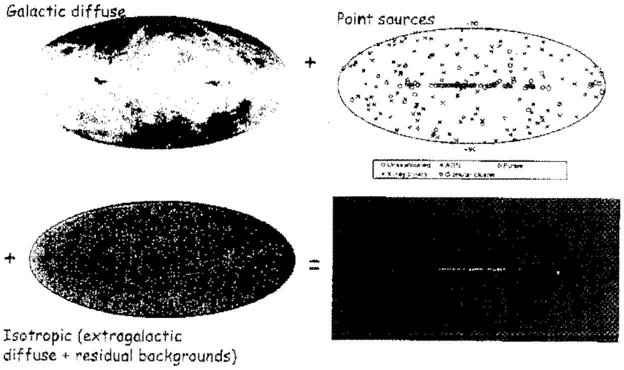
- Alan Marscher (Chair)
- Matthew Baring
- Pat Slane
- Buell Januzzi
- Don Kniffen
- Henric Krawczynski
- Jamie Holder
- Wei Cui
- Scott Ransom
- Jim Ulvestad
- Alicia Soderberg

Plus

- Neil Gehrels
- Ilana Harrus
- Julie McEnery
- Bill Paciesas
- Peter Michelson
- Steve Ritz
- Chris Shrader
- Dave Thompson
- Kathy Turner
- Lynn Cominsky

http://glast.gsfc.nasa.gov/ssc/resources/guc/

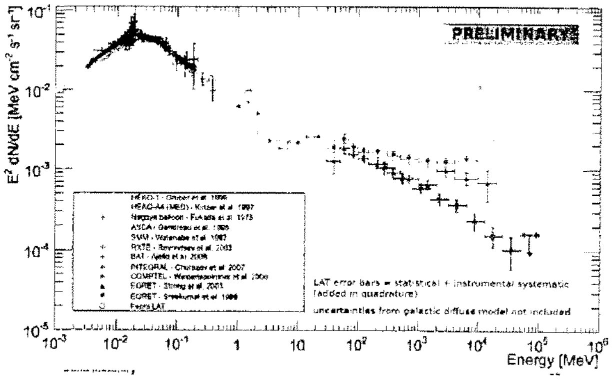
Components of the Gamma-ray sky



Extracting an extragalactic diffuse spectrum

- Start with a very clean data sample (more background rejection compared with the standard classes)
- Pixel-by-pixel max. likelihood fit of |b|>10° sky model components to LAT data:
  - Template γ-ray maps representing different Galactic foreground contributions in independent energy bins (200 MeV - 100 GeV)
  - Spectra of ($>14\sigma$) point sources from LAT catalog are fitted simultaneously with diffuse components (weak source contribution included as a template map).
  - Spectrum of isotropic component
- Subtraction of residual background (derived from Monte Carlo prediction) from isotropic component

SED of the Isotropic diffuse emission (1 keV - 100 GeV



Some Questions Fermi is addressing

- 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?
- What is the origin of the cosmic rays that pervade the galaxy?
- How does the Sun generate high-energy gamma-rays in flares?
- How has the amount of starlight in the Universe changed over cosmic time?
- What are the unidentified gamma-ray sources found by EGRET?
- What is the mysterious dark matter?