Highlights from the Fermi Large Area Telescope after 5 years of operations

Carmelo Sgrò
INFN–Pisa
carmelo.sgro@pi.infn.it

on behalf of the Fermi LAT collaboration

HSTD9 - September 5, 2013

The Fermi observatory

http://fermi.gsfc.nasa.gov/

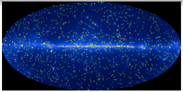
- Launched by NASA on 2008 June 11, from Cape Canaveral, Florida
- Launch vehicle: Delta II Heavy
- Almost circular orbit, at 565 km altitude and 25.6° inclination

Large Area Telescope (LAT)

- Pair conversion telescope
- Energy range: 20 MeV – >300 GeV
- Field of view: ~ 2.4 sr (at 1 GeV)
- Effective area: $\sim 6500\ \mathrm{cm}^2$ on axis (at > 1 GeV)

FERMI SCIENCE TARGET

THE γ-RAY SKY ABOVE ~ 20 MEV



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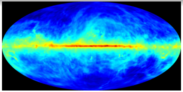

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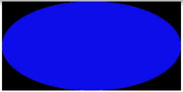

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Resolved sources:

- point-like vs. extended
- stable vs. variable
- bright vs. faint

Galactic diffuse:

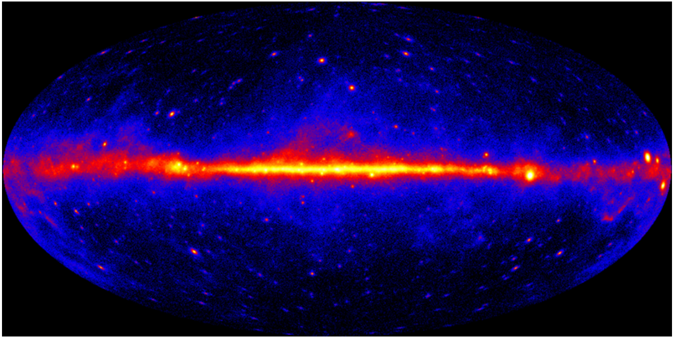
Cosmic-ray interactions with the interstellar medium

Isotropic diffuse

- Unresolved sources
- Truly diffuse emission
- Residual cosmic-rays

+ Local sources:

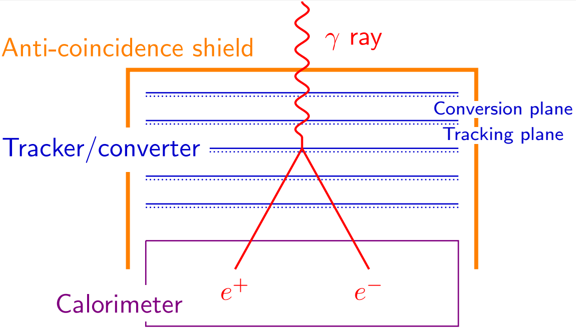
- Sun
- Earth
- Moon



+ New Physics (DM search)

▶ Cosmic-ray $e^- + e^+$: spectra & anisotropy

Detection principle

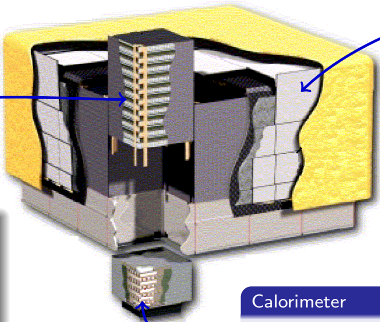


- Standard technique for high-energy γ-ray astrophysics
  - Dominant interaction mechanism for $E >\sim 20MeV$
  - Used by past experiment like COS-B and EGRET
- γ-ray converts in the middle of Tracker/Converter $\rightarrow$ γ-ray direction
- Calorimeter absorb part of the e.m. shower $\rightarrow$ γ-ray energy
- No signal in the Anti-coincidence shield $\rightarrow$ charged particle discrimination

The Large Area Telescope
Atwood, W. B. et al. 2009, ApJ, 697, 1071

Large Area telescope

- Overall modular design
- 4×4 array of identical towers (each one including a tracker and a calorimeter module)
- Tracker surrounded by an Anti-Coincidence Detector (ACD)



Anti-Coincidence Detector

- Segmented (89 tiles) as to minimize self-veto at high energy
- 0.9997 average detection efficiency

Tracker

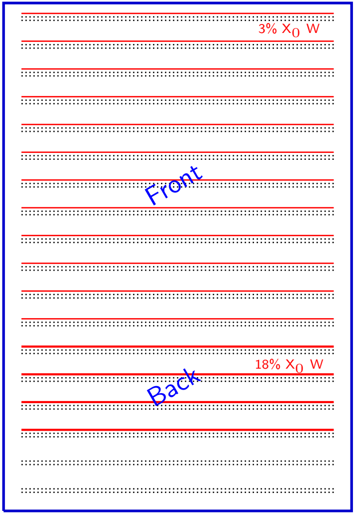
- Silicon strip detectors, W conversion foils; 1.5 radiation lengths on-axis
- 10k sensors, 73 m^2 of silicon active area, 1M readout channels
- High-precision tracking, short dead time

Calorimeter

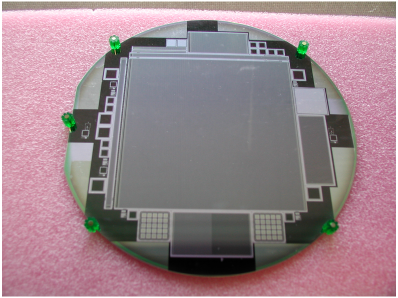
- 1536 CsI(Tl) crystals; 8.6 radiation lengths on-axis
- Hodoscopic, 3D shower profile reconstruction for leakage correction

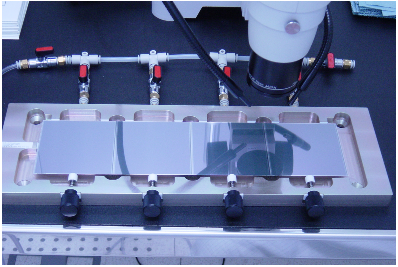
The Tracker/Converter Design

Atwood, W. B. et al. 2007, Astropart. Phys., 28, 422434



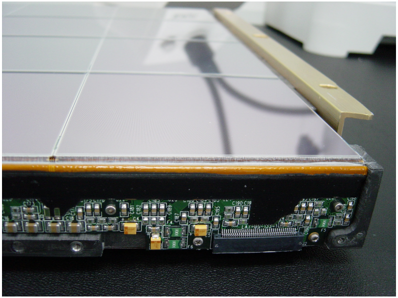
- 18 x–y detection planes
  - Single sided SSDs, below the W foils
- 19 trays in a tower
  - Basic mechanical structure
- Front: 12 planes with 0.03 X_0 converter
  - Best angular resolution
- Back: 4 planes with 0.18 X_0 converter
  - Increase the conversion efficiency
- Bottom: 2 planes with no converter
  - Tracker trigger needs at least 3 x -y layers
- Total depth: 1.5 X_0 on axis



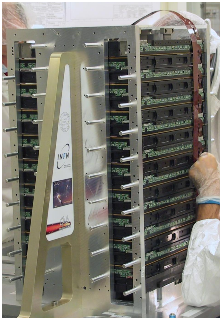


- The Single-sided Silicon Strip Detector
  - AC-coupled
  - Outer size 8.95×8.95 cm^2
  - Strip pitch 228 μm
  - Thickness 400 μm
  - Depletion voltage $<$ 120 V
  - Leakage current 1 nA/cm^2 @ 150 V
  - Fabricated at HPK
- The ladder
  - 4 SSD glued and bonded together
  - To form a ~ 36 cm long strip detector

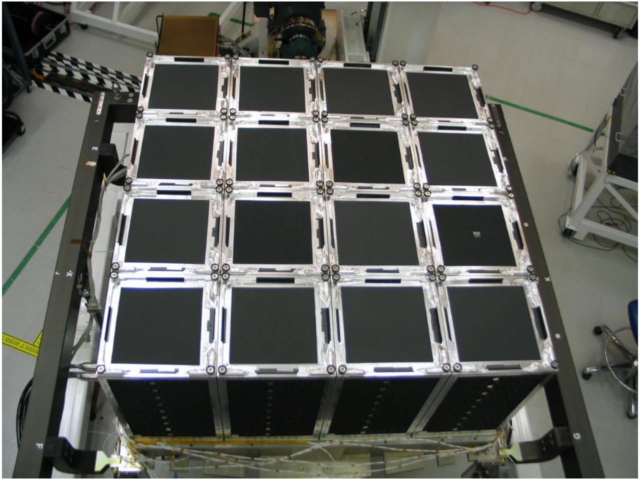
The Tracker Structure



- Tray Structure
  - Detectors are glued on both surfaces
  - W converter on bottom face
  - Electronic board on the side
    - 90° pitch adapters
    - readout via flat cables
- Tower assembly
  - Each tray is rotated 90° wrt the next one



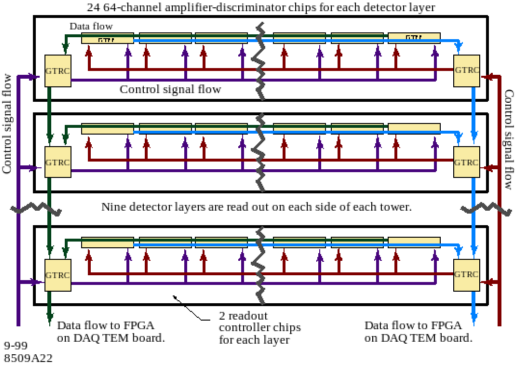
The LAT Tracker



18 LAT TKR modules (16 + 2 spares) were integrated, tested and qualified for space use in 9 months

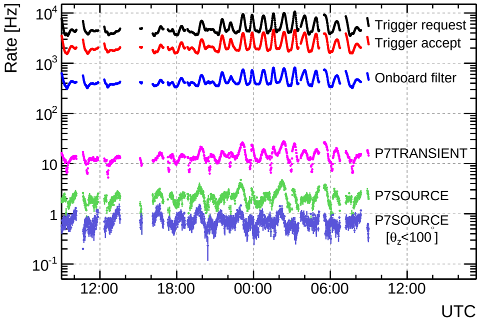
- $\sim$ 2 mm spacing between silicon layers
- $\sim$ 2 mm separation between towers
- $\sim$ 73 m^2 of silicon detectors
- 884,736 readout channels

- Basic design
  - Digital readout
  - 24 front-end chips and 2 controllers handle one Si layer
  - Data can shift left/right to either of the controllers (can bypass a dead chip)
  - Zero suppression in the controllers (hit strips + layer OR TOT in the data stream)
  - Two flat cables complete the redundancy



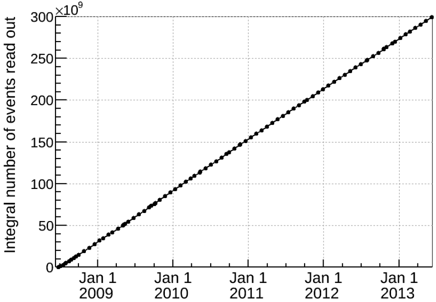
- Key features
  - Low power consumption (≈ 200 μW/channel)
  - Low noise occupancy (≈ 1 noise hit per event in the full LAT)
  - Self-triggering (three x–y planes in a row, i.e. sixfold coincidence)
  - Redundancy, Si planes may be read out from the right or from the left controller chip

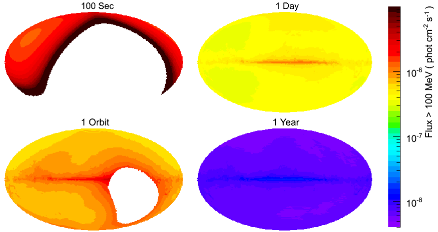
Trigger



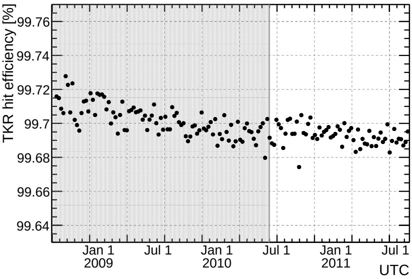
- Triggering on (almost) all the charged particle that crosses the LAT (∼2 kHz)
- Programmable on-board filter to fit the data volume into the allocated bandwidth (∼1.5 Mb/s average).
- Most of the ∼400 Hz of events passing the gamma filter and downlinked to ground are actually charged-particle background

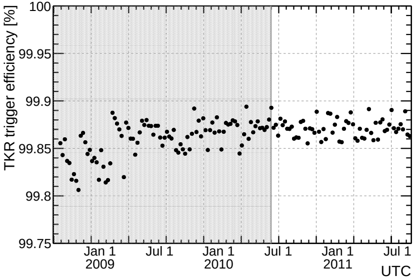
- All subsystems contribute to the L1 hardware trigger:
  - `TKR`: three consecutive TKR x-y planes hit in a row
  - `CAL LO`: single CAL log with more than 100 MeV (adjustable)
  - `CAL HI`: single CAL log with more than 1 GeV (adjustable)
  - `ROI`: MIP signal in the ACD tiles close to the triggering TKR tower
  - `CNO`: signal in one of the ACD tiles compatible with a heavy





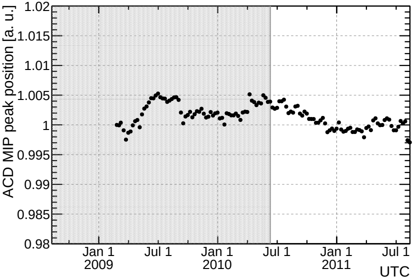
- More than 99% up-time collecting science data (out of the SAA)
  - Including detector calibrations/hardware issues
  - Fraction of time in side SAA is $\sim 13\%$
- Primary mode: sky survey
  - Scan entire sky every 3 hours
  - 1 orbit rock north, 1 orbit rock south
  - LAT boresight stays away from the Earth
- Autonomous Repoint Request
- Target of Opportunity

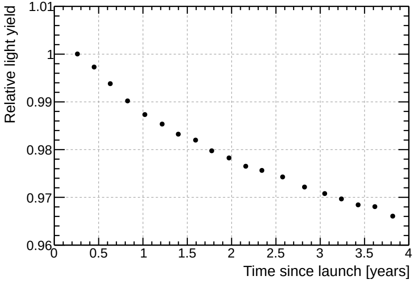




Ackermann, M. et al. 2012, Phys. Rev. Lett. 108, 011103

- No significant degradation in time
  - Small trend in efficiency
  - Consistent with number of masked TKR strips

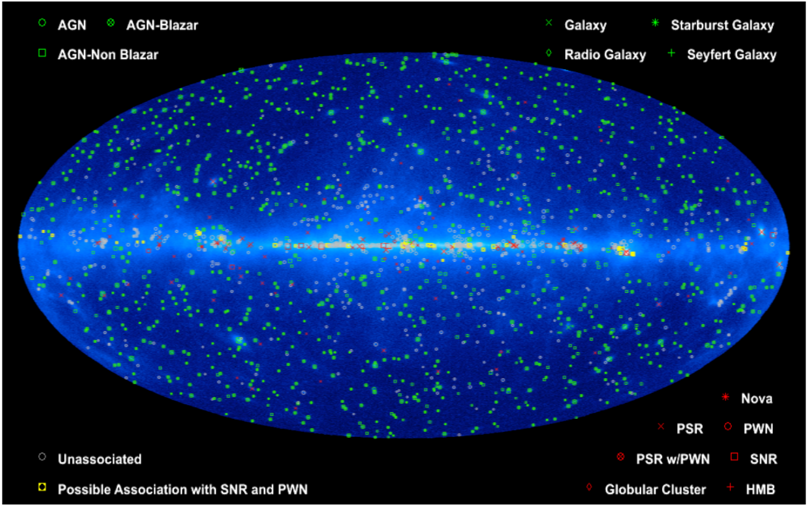




- No significant degradation in time
  - CAL crystal light yield attenuation due to radiation damage ($\sim 1\%$/year as expected)

The Second Fermi Catalog (2FGL)

Nolan, P. L. et al. 2012, ApJS, 199, 31,
http://fermi.gsfc.nasa.gov/ssc/data/access/lat/2yr_catalog/



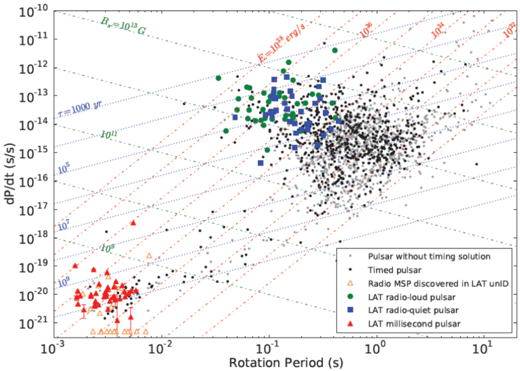
- Dataset: 24 months of data (100 MeV–100 GeV), 35.7 M events
- 1873 sources (the deepest catalog ever in this energy range)

- Larger dataset
  - Double the exposure time: 4 years from August 2008 to July 2012
  - Energy range from 100 MeV to 300 GeV
- Higher data quality → Reprocessed data
  - Improved LAT calibration
  - Better high-energy Point Spread Function
  - Better source localization
- Upgraded interstellar emission model
- Significantly deeper than 2FGL, some 2500 sources
- Association rate similar to 2FGL

- In preparation, will be available soon...

The Fermi-LAT Catalog of γ-ray pulsars

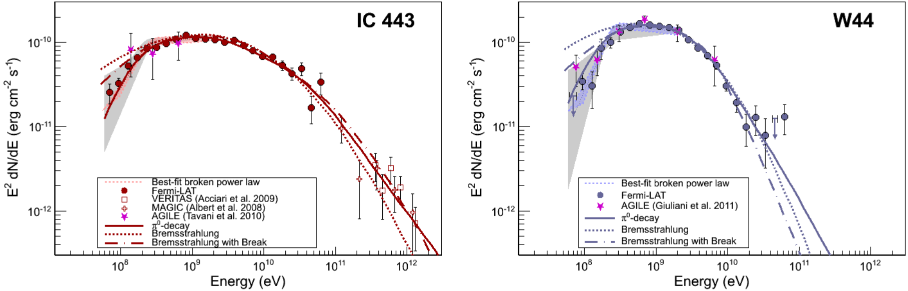
arXiv 1305.4385, accepted by ApJS



- Huge increase in number of known γ-ray pulsars
  - From ~ 6 pre-Fermi-LAT to 117 now
- Large fraction ($\sim 1/2$) of young γ-ray pulsars are radio-quiet
  - γ-ray beam is wider than radio beam
- Radio searches on LAT sources discovered > 40 MSPs
  - Potential for nHz, kilo-parsec scale gravitational wave detection array

Proton acceleration signature in Supernova Remnant

Ackermann et al. Science 2013, 339, 807 2013

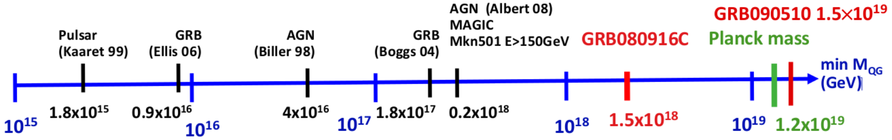


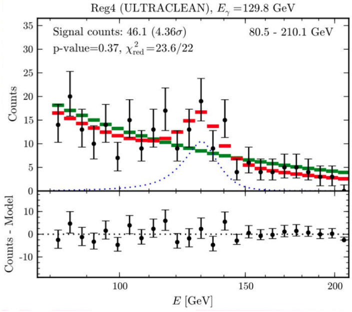
- Clear indication of low-energy "turnover"
  - The pion-decay "Bump"
- Gray systematic error band dominated by uncertainties on the diffuse emission
- Leptonic models (Bremsstrahlung or Inverse Compton) disfavored
- Most of the γ-ray emission must be of hadronic origin

Limits on Lorentz Invariance Violation

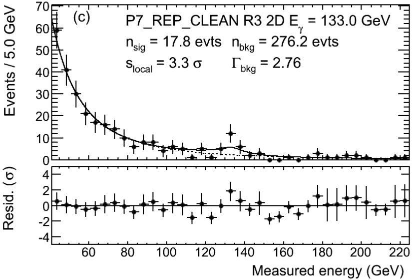
Abdo A.A. 2009 Nature 462 331-334

- Quantum gravity predicts Lorentz Invariance Violation (LIV) near Planck scale (10^{19} GeV)
- GRB emits short light pulse at great distance: can probe variation in arrival time (light speed) as function of energy
- *GRB 090510* (z=0.9): we see a 31 GeV photon less than 1 second after the first X-ray photons, after traveling >7 billion light years
- This requires the quantum–gravity mass scale to be at least 1.2 times the Planck mass
- Assuming dispersion: $\nu = \delta E/\delta P \sim c(1 - (E/E_{QG})^n)$ with $n = 1$
- Assuming that the GeV photons are not emitted *before* the X-ray burst



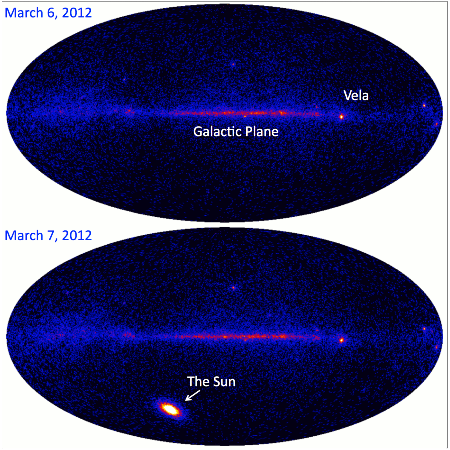


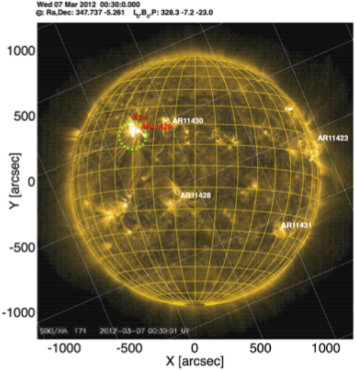
Bringmann+ [arXiv:1203.1312], Weniger [arXiv:1204.2797]



A. Alberts at TeVPA 2013

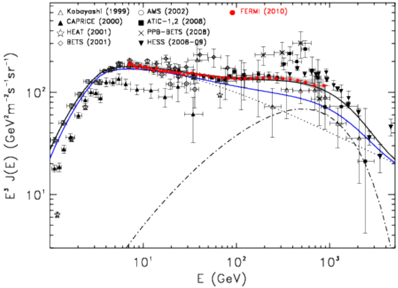
- Line emission from dark matter annihilation or decay ($\gamma\gamma$ and $Z\gamma$ channels)
- No significant detection in the Region of Interest searched
- A line at ~ 130 GeV from the Galactic Center?
  - Recent claims triggered a huge interest
  - Comprehensive Fermi LAT team analysis ongoing
    - 3.3σ (local) significance with ~ 4 years of data
    - Line-like feature observed also in Earth Limb
    - Paper submitted (http://arxiv.org/abs/1305.5597)





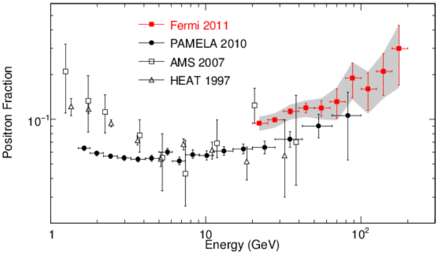
- We are close to maximum of the Sun cycle
  - ~ 20 flares seen by the LAT up to now
- A very bright Solar Flare was detected on March 7, exceeding 1000 times the γ-ray flux of the steady Sun and 100 times the flux of Vela
  - High energy emission ($>$100 MeV, up to 4 GeV) lasted for ~ 20 hours

Not only γ-rays: Cosmic Ray Electrons



Abdo, A. A. et al. 2009 PRL 102, 181101

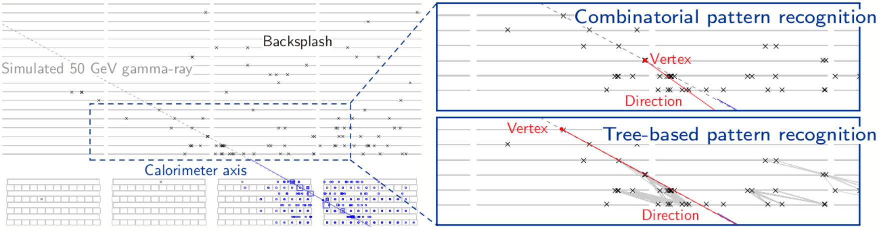
Ackermann, M. et al. 2010 PRD 82, 092004



Ackermann, M. et al. 2012, Phys. Rev. Lett. 108, 011103

- Systematics limited spectrum from 7 GeV to 1 TeV
  - Standard γ-ray reconstruction
  - Dedicated event selection
- Separate electron and positron spectra and fraction
  - Using the Earths magnetic field as charge discriminator
  - Limited by statistics at high-energy, as we need special data-taking runs (*looking down* for this analysis)

- Extensive review of all the reconstruction algorithms
- Based on the experience with flight data
- CAL Recon: multiple clusters, improved shower profile fit
- TKR Recon: new tree-based pattern recognition
- Performance improvement:
  - Larger acceptance
  - Better PSF at high energy
  - Wider energy range
  - Better control of systematic uncertainlty



Summary

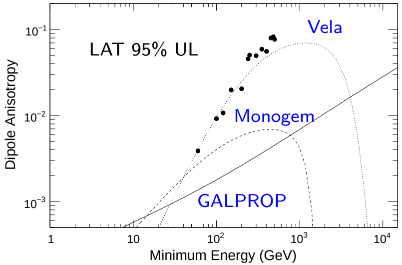
- The Fermi Large Area Telescope has proven to be an excellent telescope for gamma rays above ~20 MeV
- Extended operations began June 2013
- LAT operations extremely stable
  - All subsystem working properly, no performance degradation
- New Pass8 gamma-ray analysis will enhance acceptance and resolution starting late 2013

- Remember, Fermi data are publicly available
  - Get data and analysis software at Fermi Science Support Center
    - http://fermi.gsfc.nasa.gov/ssc/

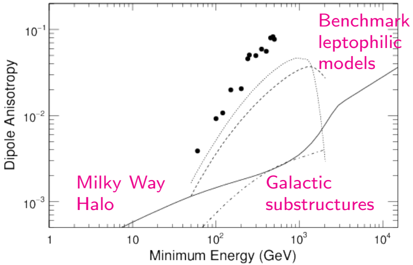
EXTRA

- Fermi offers a unique opportunity for the measurement of possible anisotropies
  - Large exposure and complete sky coverage
- Current results based on one year of data, more than 1.6 M CRE candidate above 60 GeV
- Limits on dipole anisotropy is a valuable tool to constrain models
  - Dominance of a single, very bright nearby source is disfavored
  - Dark Matter models predict a smaller effect

Astrophysical sources

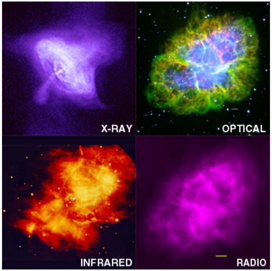


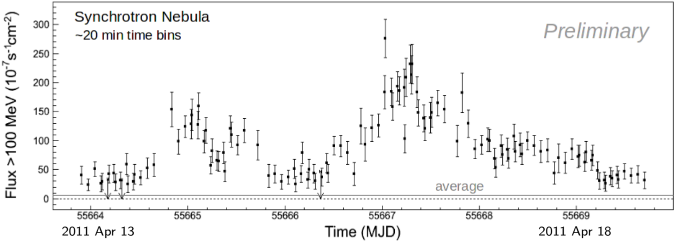
Dark Matter models



Variability: the Crab flare case
Standard Candle no more

- Many of the point sources show temporal variability...
- ...but the flare of the Crab nebula was a surprise
  - 5 episodes from 2007 up to now
- The wind emanating from a rotating neutron star (Crab Nebula) produces strong γ-ray flux
- Those γ rays are produced by energetic (PeV) electrons (via synchrotron), but not clear how to accelerate them
- Rapid variability ($\sim$hours) constrains the size of electron acceleration region





Tavani et al. 2012
Science 331 736-739
(AGILE)

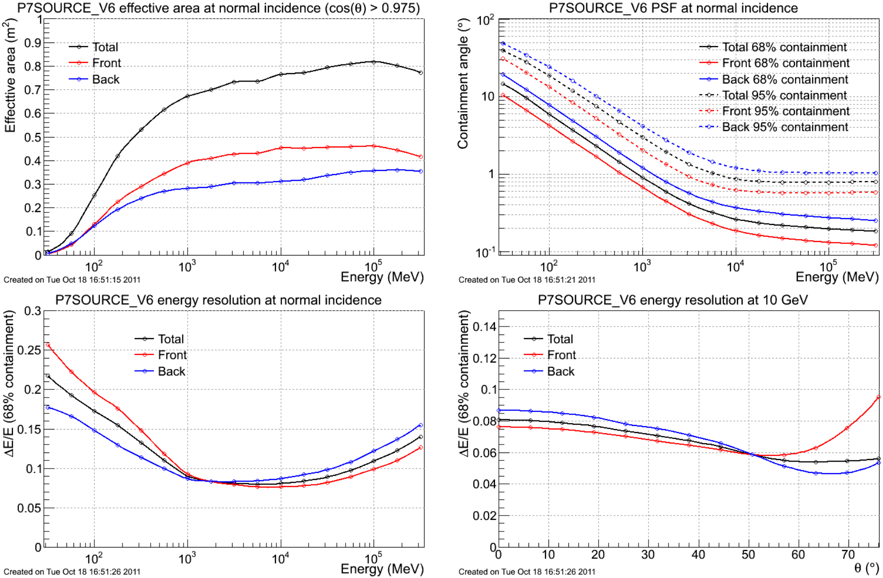
Abdo A.A. et al. 2011
Science 331 739-742

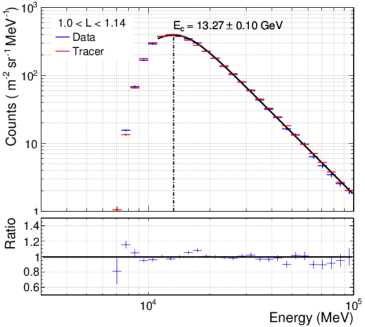
Buehler R. et al. 2012
ApJ 749 26

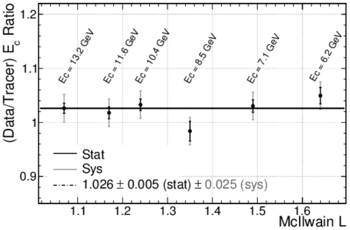
Atel 4239 on 2012 July 4^{th} (to celebrate the "Higgs discovery")

Instrument response function

http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm







- The value for the cutoff rigidity can be predicted using a particle tracing code
  - Using code written by Smart & Shea (Final Report, Grant NAG5-8009, 2000)
  - Cross checks on the fidelity of the geomagnetic field model have been performed using rigidity measurements from other satellites such as SAMPEX and HEAO-3
- Comparison of predicted and measured values provides an opportunity to perform an in-fight verification
- By using different McIlwain L intervals we obtain several calibration points from 6 to 13 GeV
  - The energy scale is known within 5% (in this energy range)

Details in: Astropart. Phys., 35, 346 (2012)

Spectral lines

Phys. Rev. D, 86, 022002 (2012)

Phys. Rev. Lett. 104, 091302 (2010)

The inner galaxy

Dwarf galaxies

Phys. Rev. Lett. 107, 241302 (2011)

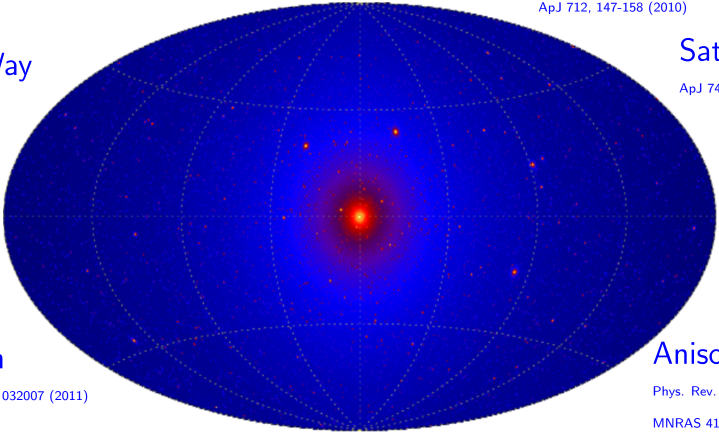
ApJ 712, 147-158 (2010)

Milky Way halo

arXiv:1205.6474

Satellites

ApJ 747, 121 (2012)



The Sun

Phys. Rev. D 84, 032007 (2011)

Anisotropies

Phys. Rev. D,85, 3007 (2012)

MNRAS 414, 2040 (2011)

Isotropic gamma-ray background

JCAP 04 (2010) 014

- Recent AMS-02 results in agrement with Pamela
  - Confirm positron fraction rising above 10 GeV
- AMS-02 is a cosmic-ray detector, with a permanent magnet for charge separation
- Fermi exploits the Earth magnetic field