The Fermi Large Area Telescope at L+4

Luca Baldini
Università di Pisa and INFN–Pisa
luca.baldini@pi.infn.it

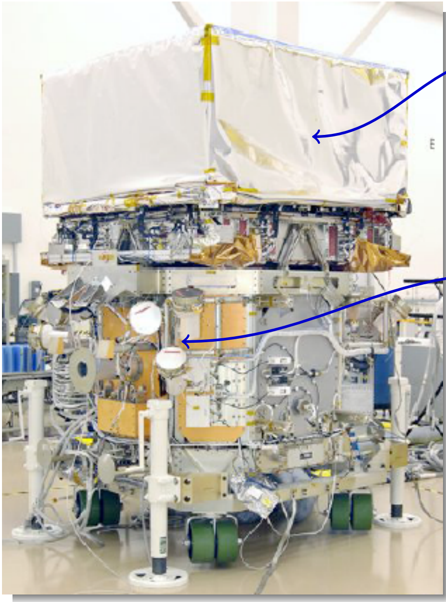
on behalf of the Fermi LAT collaboration

HERD meeting, Beijing, October 17 2012

Outline

- Not a *standard* Fermi overview talk.
- Focus on what might be useful in planning a future high-energy space detector.
- Basic design drivers. . .
  - . . . and how they tie to the science requirements.
- Instrument implementation.
- Some selected science highlights:
  - i.e., how it all worked out in practice. . .
  - . . . and what still needs to be done.

The Fermi Observatory

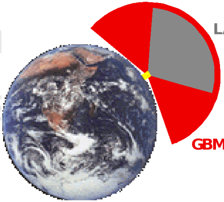


Large Area Telescope (LAT)

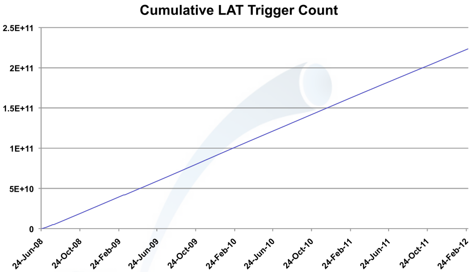
- Pair conversion telescope.
- Energy range: 20 MeV–300 GeV.

Gamma-ray Burst Monitor (GBM)

- 12 NaI and 2 BGO detectors.
- Energy range: 8 keV–30 MeV.

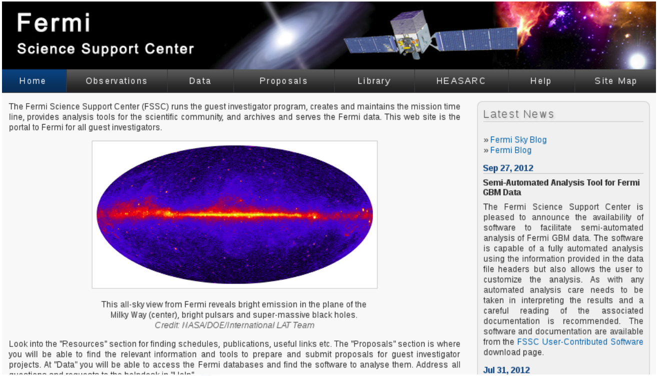


Status of the Observatory at L+4

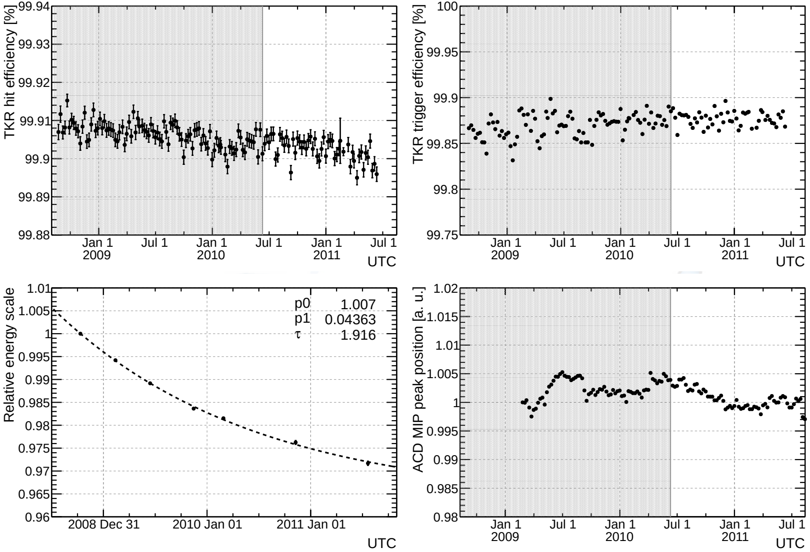


- Data taking trivia:
  - $>$ 250 B LAT readouts in orbit;
  - $>$ 50 B events down-linked to ground;
  - $>$ 700 M γ-ray candidates made public.
- All subsystem working properly, no performance degradation.
- More than 99% up-time collecting science data (out of the SAA).
  - Including detector calibrations/hardware issues.
- Prime phase of the mission (5 years) ending in mid 2013.
  - First senior review successfully passed in January 2012;
  - The baseline is to operate through 2016 (TBR in 2014).

“Observatory” = “Data are public”

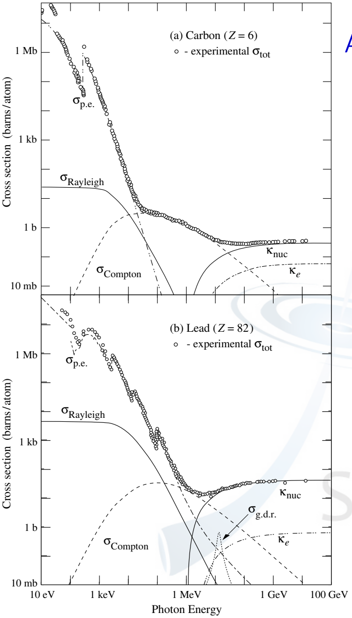


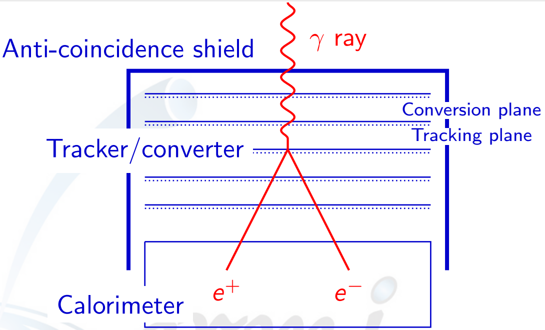
- All LAT photon data go public *immediately*.
  - Data access at `http://fermi.gsfc.nasa.gov/ssc/`
- The LAT collaboration also maintains and distributes the necessary analysis elements (IRFs, diffuse models).
- Significant effort to make all the analysis improvements available to the community at large as soon as possible.



- All subsystems working nominally (well above specifications).
  - No sign of performance degradation after 4+ years in orbit.

Detection principle





- Pair production is the dominant interaction process for photons in the LAT energy range;
- e^+e^- pair provides the information about the γ-ray direction/energy;
- e^+e^- pair provides a clear signature for background rejection (really?).

Science design drivers

- Effective area and Point Spread Function:
  - thickness and layout of conversion layers;
  - PSF also drives the design of the sensors, the spacing of the detection planes and the overall TKR design.
- Energy range and resolution:
  - thickness and design of the calorimeter;
- Field of view:
  - determined by the aspect ratio of the instrument;
- Charged particle background rejection:
  - mainly drives the ACD design;
  - also impacts the TKR and CAL design (which are needed for the background rejection).
  - need for a flexible triggering and event filtering system.

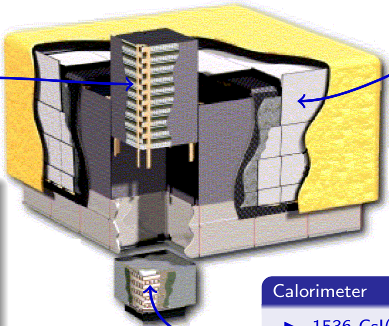
Mission design drivers

- Launcher type and allocated space:
  - maximum possible lateral dimensions of the instruments (i.e. geometric area);
  - about $\sim 1.8 \times 1.8$ m^2 for Fermi (the LAT footprint is actually $\sim 1.5 \times 1.5$ m^2).
- Power budget:
  - number of electronics readout channels in the tracker (i.e strip pitch, number of layers);
  - about 650 W overall for Fermi;
- Mass budget:
  - essentially limits the total depth of the calorimeter (once the footprint is fixed);
  - 3000 kg for Fermi.
- Telemetry bandwidth:
  - need onboard filtering.
- Launch and operation in space:
  - sustain the vibrational loads during the launch;
  - operate in vacuum, sustain thermal gradients.

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 and Anti-Coincidence Detector (ACD)



Tracker

- Silicon strip detectors, W conversion foils; 1.5 radiation lengths on-axis.
- 10k sensors, 80 m^2 of silicon active area, 1M readout channels.
- High-precision tracking, short dead time.

Anti-Coincidence Detector

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

Calorimeter

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

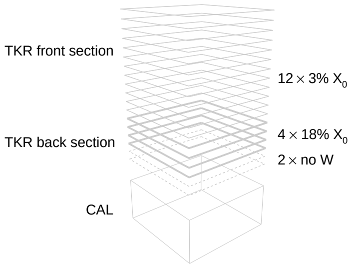
Silicon Tracker/Converter (1/2)

Atwood, W. B. et al. 2007, Astropart. Phys., 28, 422–434

- Primary roles:
  - convert γ rays into electron/positron pairs;
  - main event trigger (more on this later);
  - direction reconstruction.
- Also important for:
  - background rejection (SSD veto, hit counting);
  - energy measurement at low energy (i.e., below a few hundred MeV).
- Use of Silicon Strip Detector (SSD) technology:
  - precise tracking with $\sim$ no detector-induced deadtime;
  - self-triggering.
- Key features:
  - ~ 73 m^2 of single-sided SSDs (400 μm thickness, 228 μm pitch);
  - 884,736 independent readout channels (~ 200 μW per channel);
  - digital readout (plus layer OR time over threshold);
  - $\sim 10^{-6}$ noise occupancy at the nominal 1/4 of a MIP threshold (providing $\sim 100\%$ detection efficiency).
  - Running at < 500 (i.e. $\sim 5 \times 10^{-4}$) masked strips after 4+ years of operation in space.

Silicon Tracker/Converter (2/2)

Atwood, W. B. et al. 2007, Astropart. Phys., 28, 422–434

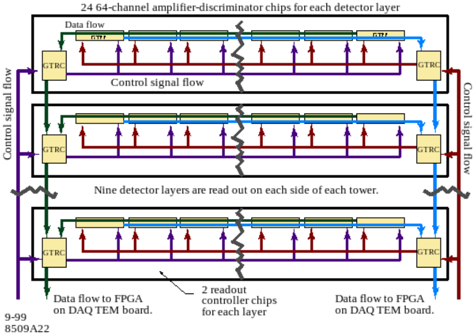


- Trade-offs in the design of the tracker converter:
  - overall thickness of the converter foils: conversion efficiency vs. multiple scattering (limiting the angular resolution at low energy);
  - number and spacing of the planes: energy dependence of the PSF;
  - strip pitch: hit resolution vs. power consumption.
- 18 paired x–y layers ($\sim$ 36 cm on a side, spaced by $\sim$ 3.5 cm) in two distinct sections:
  - front has better PSF and lower background contamination;
  - 1.5 X_0 on axis—that's a lot for a tracker!

The Tracker Electronic System

Baldini, L. et al. 2006, IEEE Trans. on Nucl. Sci., 53, 466–473

- Basic design
  - 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 takes place 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
  - On board zero suppression

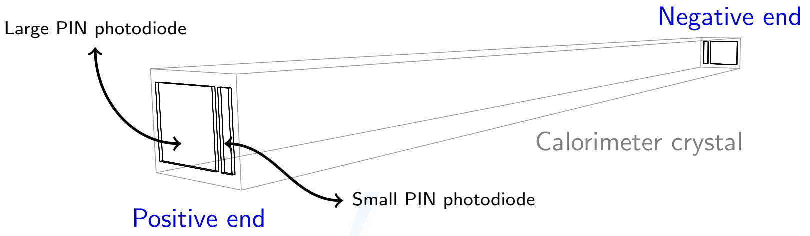
Electromagnetic Calorimeter (1/2)

Grove, J. E. and Johnson, W. N. 2010, Proc. of SPIE, 7732, 77320J-1

- Primary roles:
  - energy reconstruction;
  - contribution to the event trigger (more on this later);
- Also important for:
  - background rejection (shower shape);
  - seeding the tracker reconstruction.
- Crystal detector elements:
  - 8 layers of 12 CsI(Tl) crystals ($27 \times 20 \times 326$ mm^3) per tower;
  - hodoscopic stacking (alternating orthogonal layers);
  - 8.6 X_0 on-axis.
- Readout electronics:
  - dual PIN photodiode on each crystal end;
  - each one processes by two electronics chains ($\times 1$, $\times 8$);
  - four readout ranges, dynamic range 2 MeV–70 GeV per crystal.

Electromagnetic Calorimeter (2/2)

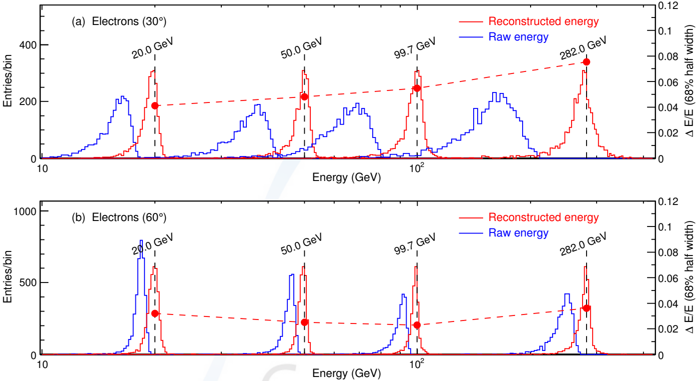
Grove, J. E. and Johnson, W. N. 2010, Proc. of SPIE, 7732, 77320J-1



- CAL xtals with readout at each end:
  - measure longitudinal position of the energy deposition from light asymmetry;
  - provide a full 3-dimensional image of the EM shower;
- CAL imaging capabilities are crucial for both background rejection and energy reconstruction at high energy:
  - remember, the LAT is $\sim 10\ X_0$ on axis, so there is a significant shower leakage out the back of the CAL.

Energy resolution at high energy

Ackermann, M. et al. 2010, Review D, 82, 92004



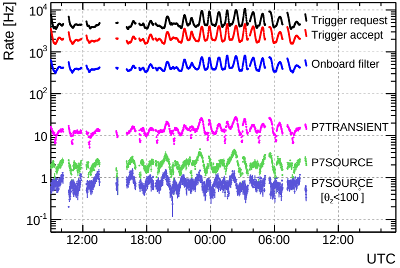
- Shower leakage becomes the main limiting factor above $\sim$ 10 GeV.
  - The LAT is $1.5 + 8.6 = 10.1\ X_0$ thick on axis—but the acceptance in the FoV peaks at around $\sim 40^\circ$.
- Energy reconstruction through a 3D fit of the shower profile:
  - $<$ 10% energy resolution at $\sim$ 300 GeV demonstrated at beam tests;
  - Simulations indicate a decent energy resolution up to at least 1 TeV.

The Anticoincidence Detector

Moiseev A. et al. 2007, Astropart. Phys. 27, 339–358

- Primary roles:
  - event triggering and onboard filter (more on this later);
  - background rejection.
- Also important for:
  - identifying heavy ions for CAL calibration purposes.
- One important lesson learned from the previous mission:
  - backsplash from the CAL in high-energy event can hit the ACD;
  - can cause *self-veto*, especially for monolithic shields.
- The LAT ACD is segmented:
  - 89 tiles (overlapping in one dimension) plus 8 *ribbons* (covering the gaps in the other);
  - can extrapolate tracks to specific tiles;
  - this also makes complete hermeticity more difficult to achieve.

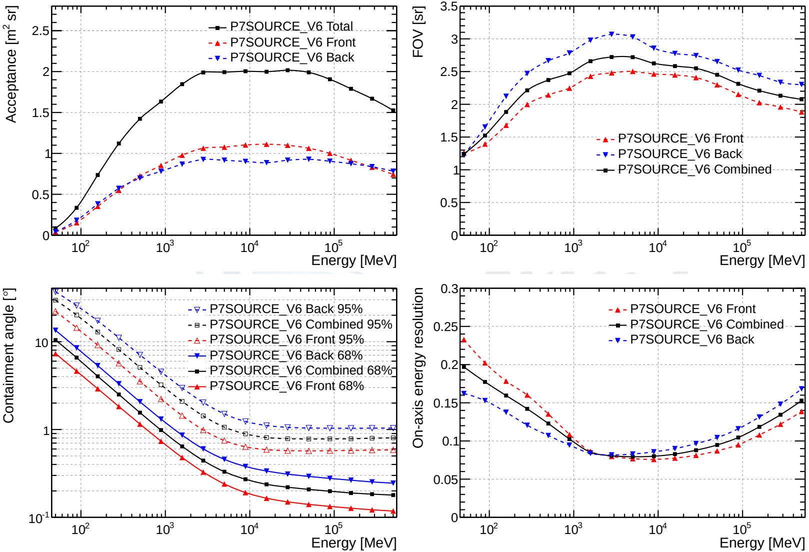
Trigger and On-Board Filter



- All subsystems contribute to the L1 hardware trigger ($\sim$ 2.2 kHz):
  - `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.
- Adjustable hardware prescales to limit the deadtime fraction:
- Programmable on-board filter to fit the data volume into the allocated bandwidth ($\sim$ 1.5 Mb/s average).
  - Most of the $\sim$ 400 Hz of events passing the gamma filter and downlinked to ground are actually charged-particle background.

Instrument Response Functions

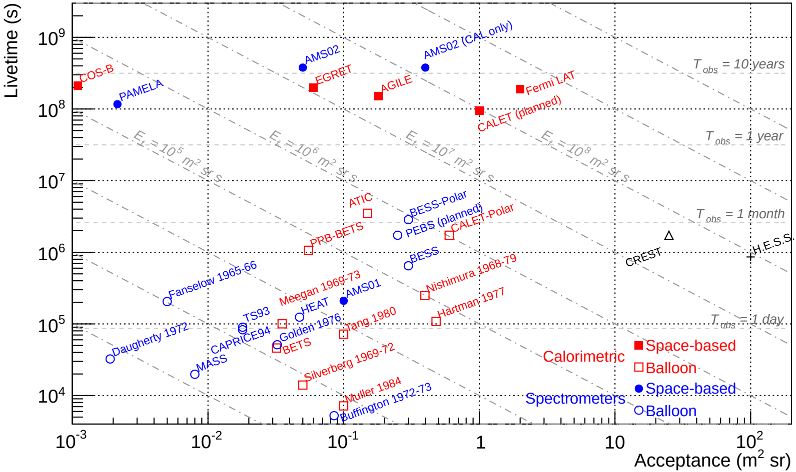
http://arxiv.org/abs/1206.1896, accepted for publication on ApJS



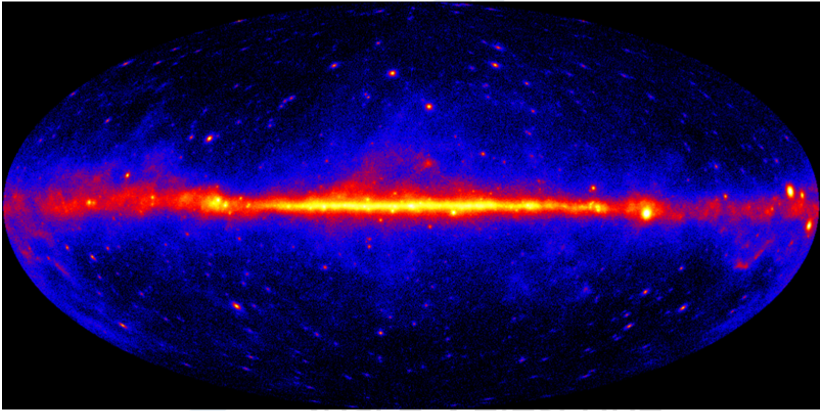
- ~ 2 m^2 sr acceptance, ~ 2.5 sr FoV, 10–15% $\Delta E/E$.

The Fermi-LAT in Context

Thompson, D. J., Baldini, L., Uchiyama, Y. 2011, Astropart. Phys., in press

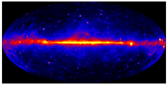


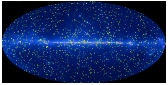
- Fermi and AMS-02 are good examples of complementary design concepts:
  - acceptance (Fermi) vs. energy resolution and particle ID (AMS-02).

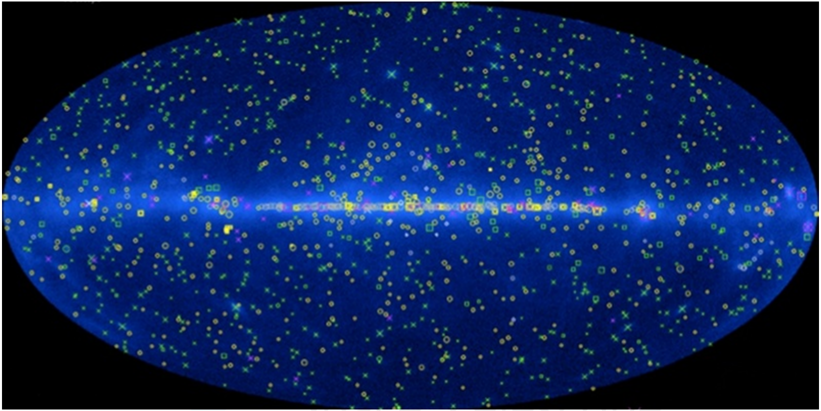


- The γ-ray sky
  - Rate map (exposure corrected) of γ-candidates above 200 MeV collected during the first year of data taking.

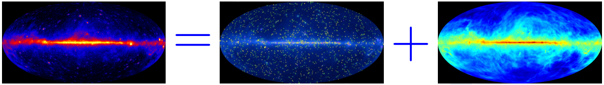
Dissecting the gamma-ray sky

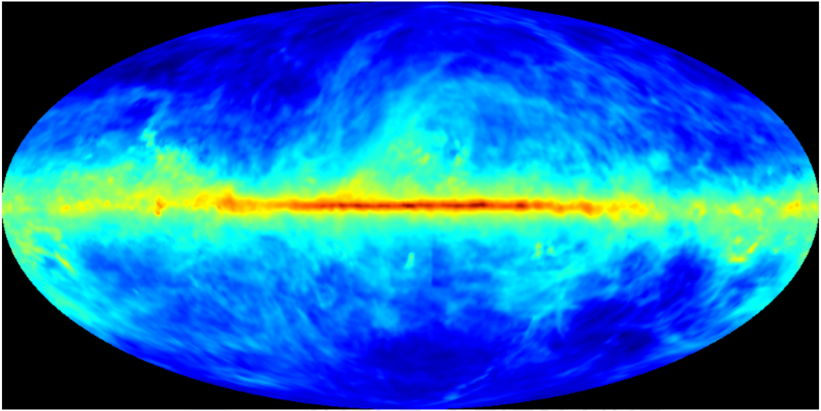






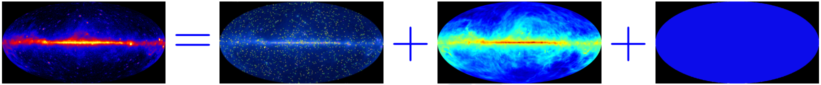
- Resolved point sources
  - The catalogs are among the most important collaboration science products (more about this in the following)

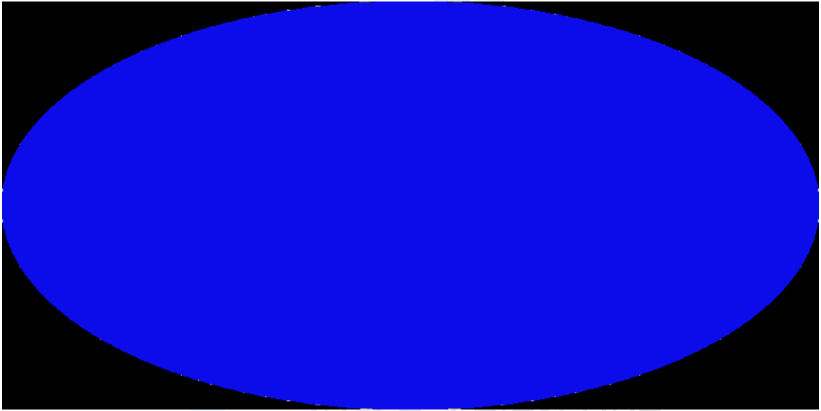




- Galactic diffuse radiation (accounts for the vast majority of photons)
  - Cosmic-ray interactions with the interstellar medium (Synchrotron, Inverse Compton, π^0 decay, Bremsstrahlung).

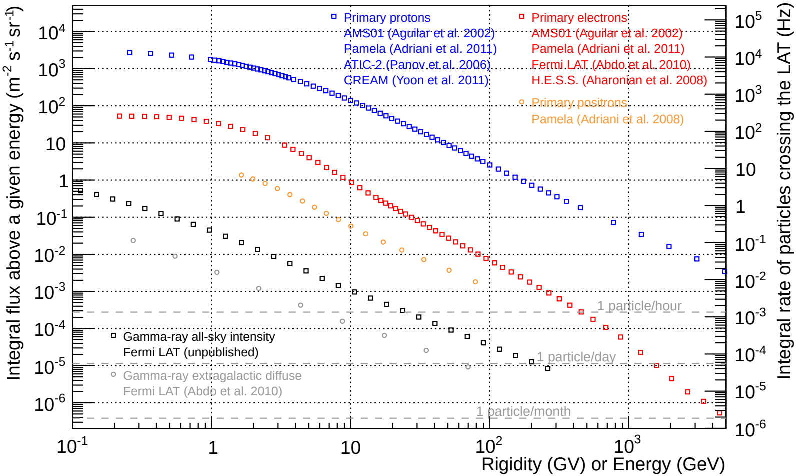
Dissecting the gamma-ray sky





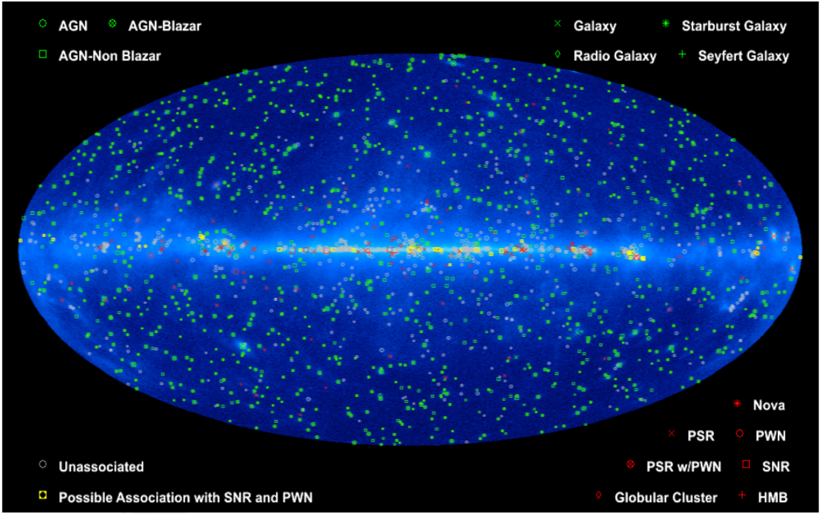
- Isotropic diffuse
  - Unresolved sources and truly diffuse (extragalactic) emission.
  - Residual cosmic-rays surviving background rejection filters.

Statistics is the culprit at high energy



- Both for point source and diffuse studies
  - (e.g., $\sim$ 1 EGB γ-ray per week above 100 GeV)

The Second Fermi Catalog (2FGL)
Nolan, P. L. et al. 2012, ApJS, 199, 31

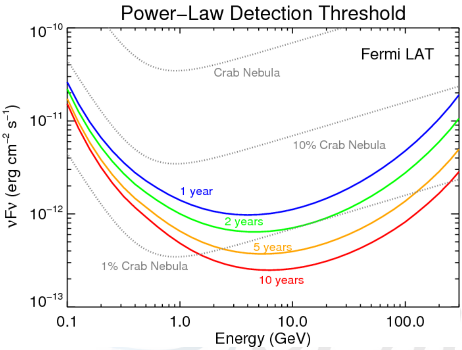


- Dataset: 24 months of data (100 MeV–100 GeV), 35.7 M events.
- 1873 sources (the deepest catalog ever in this energy range).

—Low energy

Bkg. dominated

$\propto \sqrt{t}$



—High energy

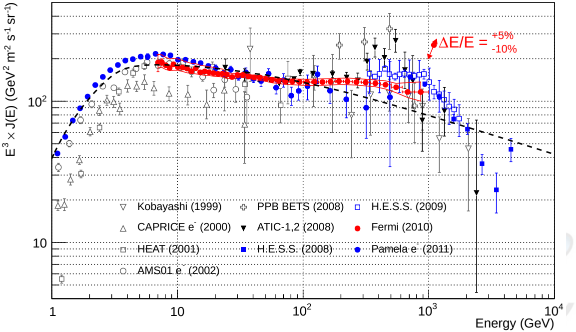
Photon counting

$\propto t$

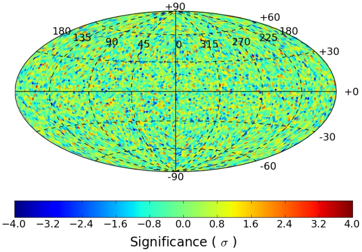
- Envelope of the minimum detectable power-law spectra over the full band, varying the spectral index (not a *differential sensitivity plot*).
  - Accounts for uncertainties in the background and source density
- High-energy limiting sensitivity comes from photon counting statistics (rather than the background)
  - Fermi sensitivity increasing linearly with time;
  - Note: a better background rejection or PSF won't help much.
  - (And more: complementarity with ground-based telescopes).

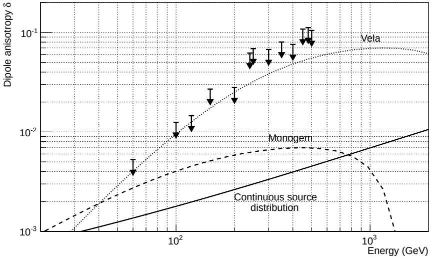
Cosmic-Ray Electron Spectrum

Ackermann, M. et al. 2010 Phys. Rev. D 82, 092004



- First systematic-limited measurement of the CRE spectrum between 7 GeV and 1 TeV.
- Significant work put toward improving the energy reconstruction at very high energy (a few TeV is the goal).
  - Calorimeter crystal saturation currently limiting the energy reach.
  - See http://arxiv.org/abs/1210.2558 for the state of the art.
- Confirming the cutoff measured by H.E.S.S. would clearly be of great interest.

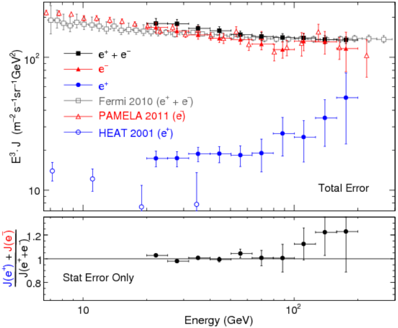


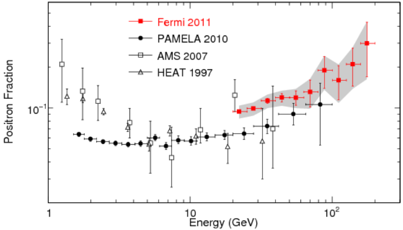


- Fermi offers a unique opportunity for the measurement of possible CRE anisotropies
  - Key factors: large exposure factor and large field of view
- Most stringent upper limits to date based on one year of data
  - More than 1.6 M CRE candidate above 60 GeV
- Limits are comparable to the level of anisotropy expected in realistic models
  - Can potentially expect to detect a signal in 8–10 years
- Again: need a (even) larger exposure if you want to do better!

Separate CR Electron and Positron Spectra

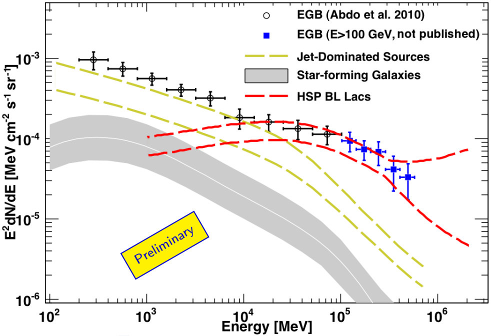
M. Ackermann et al. 2012, PRL 108, 011103





- First measurement of separate electron and positron spectra in this energy range.
  - Limited by statistics at high-energy, as we need special data-taking runs *looking down* for this analysis).
- Positron fraction increasing with energy (consistent with Pamela).
- This will likely be AMS' playground in the near future.

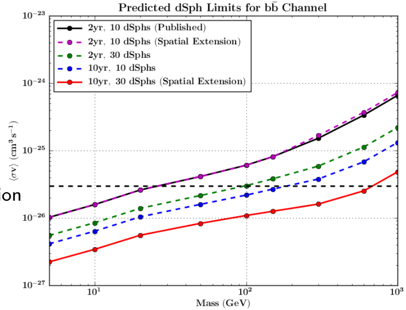
Isotropic Gamma-Ray Background
Abdo A. A. et al. 2010, Phys. Rev. Lett., 104, 101101



- Tremendous scientific interest in pushing this measurement to the highest possible energies.
- Statistics and, to a lesser extent, background rejection are the limiting factor.
- Work ongoing in extending the spectrum to ~ 1 TeV.
  - New energy reconstruction (http://arxiv.org/abs/1210.2558), better event selection.

Prospects for indirect Dark Matter searches

Thermal relic cross section



- dSph are the cleanest target for DM searches w/ Fermi
- Current limits on WIMP annihilation cross-section using dSph are the most constraining; they'll improve with improved statistics
  - as $1/\sqrt{t}$ in the bkg-dominated region, as $\sim 1/t$ at high energy
- Optical surveys will discover more dSphs
  - Current dSphs come from SDSS covering about 1/4 of the sky
  - DES and PanSTARRS are ramping up
- Potential for stringent constraints on WIMP models

A Gamma-Ray Line at 130 GeV?

- (The Fermi LAT collaboration normally does not comment on analyses done by the scientific community using the publicly available LAT data...)
- A recent claim of a feature at ~ 130 GeV in gamma rays triggered a huge interest in the community.
- Really a handful of events!
  - Very hard to tell whether the feature is real, or just a statistical fluctuation or an instrument artifact.
- In prospect: a good example of a science topic in which a better energy resolution would be beneficial.
- But not if you have to trade too much acceptance for that!
  - (And is there any other easy way to do that?)

Conclusions

- Fermi is approaching the end of its prime phase (5 years, ending in August 2013).
  - The observatory performed extremely well, both from the operational and the scientific standpoint.
  - The basic design choices really proved to be rewarding.
  - Good example of a HEA/HEP joint venture.
- Exciting perspectives for a successful extended phase of the mission.
  - Benefits well beyond the expectations from just a deeper exposure.
- Many interesting questions at high energy related to the Fermi science menu.
  - They will likely evolve in the next few years.
- For most of them the statistics (rather than the energy resolution or the particle identification) is the main issue: need a big instrument!