Understanding the gamma-ray sky: 3 years of Fermi data
Fermi MISSION ELEMENTS

Mission Operations Center (MOC)

Fermi Science Support Center

GRB Coordinates Network

LAT Instrument Science Operations Center (SLAC)

GBM Instrument Operations Center

TElemetry 1 kbps

TDRSS SN S & Ku

GPS

Fermi Spacecraft

DELTA 7920H

White Sands

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Observation modes

Pointing (traditional telescope)
- Continuous stare, if not obscured
- Otherwise:
  - Follow Earth limb (CGRO strategy)
  - Slew to a secondary point
  - Survey mode
- Recent targets
  - Nadir, to detect TGF events
  - Crab, during flare
  - GC: MW campaign

Survey mode – our standard
- Look away from Earth, but rock toward poles to equalize north/south
- Full sky coverage every 3 hours.

2FGL survey mode exposure

Maximum deviation 30%
Note that south pole is less due to South Atlantic Anomaly
Fermi-LAT collaboration

United States
• California State University at Sonoma
• University of California at Santa Cruz - Santa Cruz Institute of Particle Physics
• Goddard Space Flight Center – Laboratory for High Energy Astrophysics
• Naval Research Laboratory
• Ohio State University
• Stanford University (SLAC and HEPL/Physics)
• University of Washington

France
• IN2P3, CEA/Saclay

Italy
• INFN, ASI

Japanese GLAST Collaboration
• Hiroshima University
• ISAS/JAXA, RIKEN
• Tokyo Inst of Technology

Spain
• ICREA and Inst de Ciencies de l’Espi

Swedish GLAST Collaboration
• Kalmar University
• Royal Institute of Technology (KTH)
• Stockholm University

PI: Peter Michelson (Stanford & SLAC)
~270 Members (including ~90 Affiliated Scientists, plus 37 Postdocs, and 48 Graduate Students)
Cooperation between NASA and DOE, with key international contributions from France, Italy, Japan and Sweden.
Managed at Stanford Linear Accelerator Center (SLAC).
2-years of LAT data
A pause from gamma rays: Fermi can measure electrons and positrons too! (but cannot distinguish them)

(these data are also not public)
ATIC: “A Whisper, Perhaps, From the Universe's Dark Side”*

*NY Times headline  Nov 25, 2008

\[ E_{e}^{30}dN/dE_{e} \left( \text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{sr}^{-1}\cdot\text{GeV}^{-1} \right) \]

- ATIC 1+2,  \( \bullet \) Alpha Magnetic Spectrometer,
- \( \triangle \) HEAT magnetic spectrometer,  \( \bigcirc \) BETS,
- \( \times \) PPB-BETS,  \( \Diamond \) Emulsion chambers

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Fermi can measure electrons, too!

Our paper “Measurement of the Cosmic Ray $e^+e^-$ Spectrum from 20 GeV to 1 TeV with the Fermi Large Area Telescope” (05/2009) has 266 citations.
New result: positron asymmetry!

Use Earth’s magnetic field

arXiv:1109.0521
Asymmetry confirms PAMELA
Detecting gamma-rays: Pair conversion detector design & requirements

- **Anticoincidence shield:**
  - Required by very high flux of cosmic rays relative to gammas (~10^4)
  - Must be very efficient
  - Segmented to reduce self-veto

- **Conversion foil (W):**
  - High Z
  - Thick for efficiency
  - *But:* thin for good PSF, due to multiple scattering

- **Tracking (Si strips in Fermi):**
  - Good efficiency, coverage
  - Small pitch

- **Calorimeter (CsI in Fermi):**
  - Thick to contain shower
  - *But:* Thin to reduce mass for launch
  - Segmented for shower pattern recognition

**Also:**
- **Trigger system**
- **Data acquisition**
- **Onboard analysis**

**Spacecraft:**
- **Power**
- **Communication**
- **Orientation, control, info**
- **Downlink**

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Overview of the LAT

- **Precision Si-strip Tracker (TKR)**
  18 XY tracking planes. Single-sided silicon strip detectors (228 μm pitch) Measure the photon direction; gamma ID.

- **Hodoscopic CsI Calorimeter (CAL)**
  1536 CsI(Tl) crystals in 8 layers. Measure the photon energy; image the shower.

- **Segmented Anticoincidence Detector (ACD)**
  89 plastic scintillator tiles. Reject background of charged cosmic rays; segmentation removes self-veto effects at high energy.

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

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

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Real events can be messy!

Analysis goals:
• measure incoming direction and energy
• Identify particle
Real events can be messy!

Actually, two detectors: ‘Front’ and ‘Back’
Our angular resolution, or PSF

Dashed line is a measurement using the data. Current public representation is wrong by x2 at high energies. This misunderstanding played a role in at least two external “discoveries”
The Gamma-ray data set is (partly) public
Many independent analyses
Did Hooper and Goodenough discover DM in our data?

"When I look at this data, it lines up perfectly," he says. "It quacks like a duck."
And did Ando and Kusenko discover "primordial magnetic fields" by detecting halos around AGN’s that we missed?
Our Nearest Non-blazar AGN

Fermi data reveal giant gamma-ray bubbles

Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.
Our Nearest Non-blazar AGN
Goal: account for every photon

• Steady Sources of photons
  – Point sources
    • Pulsars, including binaries
    • Galaxies, mostly AGN
      – AGN probes B, photons
    • Unknown
  – Galactic diffuse
  – Isotropic diffuse
    • Unresolved point sources
    • Proton background
    • Unknown

• Transients
  – GRB
  – Nova
Making the 2FGL catalog
Understanding the sky: extract a list of sources for the 2FGL catalog

Data: 28 M
Exposure: 52 Ms

Two years (excluding 3 GRBs) “Pass7 processing”

[1FGL: 11 months]

1873 entries
[1FGL: 1451]

Light curves, SED plots, associations

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Bright sources at high latitudes are easy

MRK 421

3C 273
3C 279
PSR J1231-1411
Strong source high latitude example: SED plots

Circles are 3°, 100 MeV PSF (‘front’ section) (varies by a factor of 30 with energy!)

Use log parabola if better fit

Pulsars fit with exponential cutoff

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Measuring point source properties: maximize likelihood

- Model of the sky must account for all photons
  - PSF
  - Aeff
  - Galactic, isotropic diffuse including CR
  - 1/8 degree grid, pixels centered on plane
  - Earth limb
- An important issue: how to measure significance?
  Test Statistic: $\text{TS} = -2\log(L_{\text{fit}}/L_{\text{null}})$

  - We conservatively choose only sources with $\text{TS}>25$. 

$\text{TS}=14$  
$\text{TS}=32$  
$\text{TS}=1000$

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Extended source templates

- W51C
- W44
- CenA Lobes
- MSH 15-52
- Vela X
- IC 443
- LMC
- Cygnus Loop
- HESS J1825-137
- W30
- W28
- SMC

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Details about the sky model

- Tessellate sky using HEALPix: 1728 regions
  - Each ~5° square pixel defines:
    - Center of circular regions for:
      - data (5 deg)
      - sources (10 deg)
    - sources inside are varied; those outside fixed to results of previous iteration
    - Note ~x3 overlap of data: not independent
- Diffuse component normalizations free
- Iteration procedure:
  - Each region fit (full likelihood maximized) independently
  - Each fit remeasures point source positions: Apply updates between cycles.
  - Check changes in log(L): iterate until none changes by more than 10 (8-10 iterations required)
Localization

Basic principle: the likelihood function, as a function of the position of a source, is an estimator of the position, with the curvature defining the resolution.

Demo with 3C 273.

Error ellipse defined by 95% contour (2.45σ). Plot shows contours, and results of fit to quadratic surface.
Stage I Summary

Consistency mostly good

Contributions for all energies, full sky

Example consistency check:
all photons in 5° radius circle
(Approx. 12 d.o.f.)

Free parameters

<table>
<thead>
<tr>
<th>Type</th>
<th>Number</th>
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<tbody>
<tr>
<td>Spectra</td>
<td>7603</td>
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<tr>
<td>Diffuse normalization</td>
<td>3456</td>
</tr>
<tr>
<td>Location (2 per TS&gt;16 source)</td>
<td>5096</td>
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</tbody>
</table>

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It is not all so rosy...

Most sources apparently associated with diffuse structures probably result from inadequate representation of the diffuse

Galactic center is complicated!

Orion molecular cloud:

Sources: TS>10 seeds for 2FGL
Sources: did we miss any?

TS residual map, threshold=10, $\sim 3\sigma$
(catalog: 25)
Variability analysis

**variability index** is based on 24 ~monthly flux measurements.

likelihood ratio of observed values to the null, constant hypothesis

A total of 458 sources were found to be variable with high confidence.
2FGL Associations

Red symbols: Identified sources

Blue symbols: Associated sources

- No association
- AGN
- Starburst Gal
- Galaxy

- Possible association with SNR or PWN
- Pulsar
- PWN
- SNR

- Globular cluster
- HMB
- Nova
## Classifications

<table>
<thead>
<tr>
<th>CLASS</th>
<th>Identified</th>
<th>Associated</th>
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</thead>
<tbody>
<tr>
<td>Pulsar, identified by pulsations</td>
<td>83</td>
<td>-</td>
</tr>
<tr>
<td>Pulsar, no pulsations seen in LAT yet</td>
<td>-</td>
<td>25</td>
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<tr>
<td>Pulsar wind nebula</td>
<td>3</td>
<td>0</td>
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<tr>
<td>Supernova remnant</td>
<td>6</td>
<td>4</td>
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<tr>
<td>Supernova remnant / Pulsar wind nebula</td>
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<td>58</td>
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<tr>
<td>Globular cluster</td>
<td>0</td>
<td>11</td>
</tr>
<tr>
<td>High-mass binary</td>
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<td>0</td>
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<tr>
<td>Nova</td>
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<td>0</td>
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<td>BL Lac type of blazar</td>
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<tr>
<td>Non-blazar active galaxy</td>
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<td>10</td>
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<tr>
<td>Radio galaxy</td>
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<td>10</td>
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<tr>
<td>Seyfert galaxy</td>
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<td>5</td>
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<tr>
<td>Active galaxy of uncertain type</td>
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<td>257</td>
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<tr>
<td>Normal galaxy (or part)</td>
<td>2</td>
<td>4</td>
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<tr>
<td>Starburst galaxy</td>
<td>0</td>
<td>4</td>
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<tr>
<td>Class uncertain</td>
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<td>1</td>
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<tr>
<td><strong>Unassociated</strong></td>
<td>-</td>
<td><strong>576</strong></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>127</strong></td>
<td><strong>1746</strong></td>
</tr>
</tbody>
</table>
Properties of the unassociated
Additional details

- Why are so many 1FGL sources (352 out of 1499) not included in 2FGL??

Detailed analysis, ~10 pages, 8 figures focusing on different procedures narrows down to 89 ‘non-confirmed’
Some potential sources that we don’t find are important!

- Milky Way satellite analysis
WIMP annihilation from Dwarf spherioidals

\[ \phi_{WIMP}(E, \psi) = J(\psi) \times \Phi^{PP}(E) \]

**Particle physics:**

\[ \Phi^{PP}(E) = \frac{1}{2} \frac{\langle \sigma_{\text{ann}} v \rangle}{4 \pi m_{\text{WIMP}}^2} \sum_f \frac{dN_f}{dE} B_f \]

**Astrophysics:**

\[ J(\psi) = \int_{l.o.s.} dl(\psi) \rho^2 (l(\psi)) \]

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**Dwarf Spheriodal satellite J-factors**

Uncertainties matter!
The result

Upper limits, $\bar{b}b$ channel

Hint of an exclusion

WIMP mass [GeV]

WIMP cross section $[\text{cm}^3/\text{s}]$
No time to cover

• Pulsars – up to 100 now, many MSPs, breakthroughs in blind detection
• AGNS
• GRBs
• The nova
• Diffuse analysis: do unresolved sources account for it?
Summary

• Many discoveries
• But: After three years, we are still trying to understand both the performance of the detector, and subtleties in the sky!
• Dark matter still the holy grail 😊