Seven years of gamma-ray astrophysics with the Fermi LAT

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on behalf of the Fermi LAT Collaboration
The Fermi Gamma-Ray Space Telescope is an International Science Mission exploring the gamma-ray sky by means of its two main instruments:

- **GLAST Burst Monitor (GBM):** 8 keV → 40 MeV
- **Large Area Telescope (LAT):** 20 MeV → > 300 GeV

Huge energy range: including largely unexplored band for a total of >7 energy decades!
The Fermi LAT

**Precision Si-strip Tracker (TKR)**
- Measures incident $\gamma$-ray direction
- 18 XY tracking planes: 228 $\mu$m strip pitch
- High efficiency. Good position resolution
- 12x 0.03 $X_0$ front end $\rightarrow$ reduce multiple scattering
- 4x0.18$X_0$ back-end $\rightarrow$ increase sensitivity $\geq 1$ GeV

**Anticoincidence Detector (ACD)**
- 89 scintillator tiles
- First step in the reduction of large charged cosmic ray background
- Segmentation reduces self-veto at high energy

**Hodoscopic CsI Calorimeter**
- Segmented array of 1536 CsI(Tl) crystals
- 8.6 $X_0$: shower max contained
  - $\sim 200$ GeV normal ($1.5X_0$ from TKR included)
  - $\sim 1$ TeV @ 40° (CAL-only)
- Measures the incident $\gamma$-ray energy
- Rejects cosmic-ray background

**Electronics system**
- Includes flexible, highly efficient, multi-level trigger

The LAT is also an excellent electron detector! See the presentation by Carmelo Sgrò.
Fermi observation strategy

- Mostly ~uniform sky survey
  - Dec 2013 – Dec 2014, transitioned to galactic center biased survey for 1 year
- Target of opportunity observations generally between 1 day – few weeks in duration:
  - flaring AGN, Novae, Sun, Crab, Binary systems, etc
- 2.5 hour autonomously commanded pointed observations following detection of bright hard-spectrum GRB
- The wide field of view and survey mode operation allows Fermi to explore the high energy gamma-ray sky on timescales from milliseconds to years
An overview of the Fermi LAT Science

- Dark Matter searches
- Terrestrial gamma-ray flashes
- GRBs
- Blazars
- Radio Galaxies
- Starburst Galaxies
- Globular Clusters
- SNRs & PWN
- Gamma-ray Binaries
- Pulsars: isolated, binaries, & MSPs
- Sun: flares & CR interactions
- Unidentified Sources
- Terrestrial gamma-ray flashes

Galactic

Local

Extragalactic
The gamma-ray sky above 1 GeV

1.25 days
### The LAT Catalogs

<table>
<thead>
<tr>
<th>Catalog</th>
<th>Energy Range (GeV)</th>
<th>Data Interval (months)</th>
<th>Sources</th>
<th>Event Selection</th>
<th>Release Date</th>
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<tr>
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<td>0.2-100</td>
<td>3</td>
<td>205</td>
<td>P6V1 DIFFUSE</td>
<td>Feb. 2009</td>
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<td>1451</td>
<td>P6V3 DIFFUSE</td>
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<td>24</td>
<td>1873</td>
<td>P7V6 SOURCE</td>
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<td>1FHL</td>
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<td>36</td>
<td>511</td>
<td>P7V6 CLEAN</td>
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<td>3FGL</td>
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<td>48</td>
<td>3033</td>
<td>P7V15 SOURCE</td>
<td>Jan. 2015</td>
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<td>50-2000</td>
<td>80</td>
<td>360</td>
<td>P8_SOURCE</td>
<td>In press</td>
</tr>
</tbody>
</table>

- There are also class-specific LAT source catalogs
  - AGN, Pulsars, GRBs, SNRs, transients…
The Fermi LAT 3rd Source Catalog (3FGL)

- 4-years data sample with P7 reprocessed data
- 3033 sources detected with $>4\sigma$ significance
The 3FGL gamma-ray sources

- Normal Galaxies
- Globular Clusters
- Pulsar Wind Nebulae
- Supernova Remnants
- High Mass Binaries
- Galactic Associations
- Unassociated (low latitude)
- Unassociated (high latitude)
- BL Lacs
- Flat Spectrum Radio Quasars
- Unclassified Blazars
- Other AGN

- Pulsars 6%
- Unclassified Blazars 19%
- BL Lacs 21%
- Flat Spectrum Radio Quasars 16%
- Unassociated (low latitude) 11%
- Unassociated (high latitude) 22%
At present the LAT has detected 161 gamma-ray pulsars

- Half of the gamma-ray pulsars were not known before Fermi
The Fermi LAT pulsars: main discoveries

- Before Fermi only 7 gamma-ray pulsars were detected → now 161!
  - Discover of gamma-ray MSPs
- Emission region: outer gap model preferred wrt polar cap model
- Pulsars considered to be stable gamma-ray sources were discovered to be variable!

Gamma-ray flares from the Crab Nebula, Science 331(2011), 739

1st Fermi LAT SNR Catalog

- 3 years Pass7 data, 279 ROIs studied, 102 detections
  - population studies, spectral and morphology studies
- Paper submitted to ApJ
Correlations between radio and GeV spectra

- If radio and GeV emissions originate from the same particle population the spectral indices should be correlated
- Data challenge model assumptions
  - Underlying particle populations may have different indices
  - Emitting particle populations may not follow power law: breaks?
  - Multiple emission zones?

π^0 decay or e^+/− bremsstrahlung
Inverse Compton with cooling
Inverse Compton without cooling
The gamma-ray sky above 50 GeV: 2FHL catalog

- Energy range from 50 GeV to 2 TeV
- 80 months of data
- 360 sources detected:
  - 78 detected by IACTs (TeVCat)
  - 230 detected in 1FHL
  - 303 detected in 3FGL
  - 57 brand new sources (not 1FHL/3FGL)
Comparison with HESS GP survey

HESS Significance Map (Aharonian et al. 2006, Carrigan et al. 2013)

- H.E.S.S. detected 69 sources reaching a sensitivity of ~2% of the >1 TeV Crab Nebula flux
- The LAT detects 36 sources with an average sensitivity of 3-4% of the Crab Nebula flux
- The LAT detects an equal number of PWNe/SNRs while for H.E.S.S they are in a 1.5:1 ratio
Dark Matter

• Astrophysical evidence for missing mass
  – Galaxy rotation curves
  – Colliding clusters
  – Cosmological probes ($\Omega_{dm} h^2 \approx 0.1$)

• Observational evidence indicates:
  – Non-baryonic
  – (Almost totally) neutral
  – (Almost totally) collisionless

• Theoretical candidates:
  – Axions, sterile neutrinos, etc.
  – Modifications to gravity
  – Weakly Interacting Massive Particles (WIMPS)
WIMPs as DM candidates

- A WIMP in chemical equilibrium in the early universe naturally has the right density to be Cold Dark Matter
  - At early times, WIMPs are produced in $\ell^+\ell^-$, ..., collisions in the hot primordial soup (thermal production)
  - WIMP production ceases when the production rate becomes smaller than the Hubble expansion rate (freeze-out)
  - After freeze-out, the number of WIMPs per photon is constant

- Standard relic density calculation yields for nonrelativistic relics:
  - $\Omega_{dm}h^2 \approx \frac{3 \times 10^{-27} \text{cm}^3 \text{s}^{-1}}{\langle \sigma v \rangle} \approx 0.1$

- Electroweak cross-sections are in correct range:
  - $\sigma v \sim 10^{-26} \text{cm}^3 \text{s}^{-1}$

Freeze-out:
$\Gamma_{\text{ann}} = n \langle \sigma v \rangle \sim H$

$\langle \sigma v \rangle_{\text{ann}} \sim 3 \times 10^{-26} \text{cm}^3/\text{s}$ for thermal relic
Indirect searches for dark matter in the GeV gamma-ray sky

GeV Sky = Galactic + Point Sources + Isotropic

WIMP Dark Matter Particles $E_{CM} \sim 100\text{GeV}$

Neutrinos $\nu_{\mu}, \nu_{\tau}, \nu_{e}$

Anti-matter $p/\bar{p}, d/\bar{d}$

Gamma-rays $\gamma$, $Z$, $H^0$, ...

???
Dark matter signatures in gamma-rays

Annihilation

\[ \phi(E, \Delta \Omega) = \frac{1}{4\pi^2 m^2} \sum_f dN_f/dE B_f \int_{\Delta \Omega} d\Omega \int_{l.o.s.} dl \rho^2(l(\Omega)) \]

Decay

J-factor – DM distribution (line-of-sight integral)

\[ <\sigma v>_{\text{ann}} \sim 3 \times 10^{-26} \text{cm}^3/\text{s} \] for thermal relic

Intrinsic Particle Properties

Continuum Signal

Monochromatic Signal

Gustafsson et al. PRL 99.041301
Dark matter search targets

Satellites
Low background and good source id, but low statistics

Galactic Center
Good Statistics, but source confusion/diffuse background

Milky Way Halo
Large statistics, but diffuse background

Dwarf Galaxies
Known location and DM content
Low statistics

Spectral Lines
Little or no astrophysical uncertainties, good source id, but low sensitivity because of expected small branching ratio

Galaxy Clusters
Low background, but low statistics

Isotropic contributions
Large statistics, but astrophysics, galactic diffuse background
Dwarf spheroidal galaxies (dSphs) are dark and highly DM-dominated systems. Most are found at high latitude where astrophysical foregrounds are low. Low backgrounds make these a very clean target for indirect DM searches.
Dark Matter content of dSph Galaxies

- Gamma-ray signal from each dwarf is proportional to its J-factor:
  \[ J = \int_{\Delta\Omega(\phi, \theta)} d\Omega' \int_{l.o.s.} \rho^2(r(l, \phi')) dl(r, \phi') \]
- Dwarf J-factors are determined spectroscopically from stellar velocity dispersions
  - Classical dwarfs: spectra for several thousand stars
  - Ultra-faint dwarfs: spectra for fewer than 100 stars
- Using the LOS velocity dispersion and an assumed DM density profile (NFW) we can calculate a J-factor for each dwarf (Martinez, 2013)
- Statistical uncertainty in the J-factor is folded into the gamma-ray analysis
• 15 dwarfs used for composite analysis (UMaI, CVn1, and Leo1 excluded due to ROI overlap).
Upper limits on DM annihilation cross section from dSph analysis

- 6 years of Fermi-LAT Pass8 data from 15 dwarf spheroidal galaxies constrain the thermal relic cross section for low mass dark matter
- DM Limits from the LAT Dwarf stacking analysis are highly competitive with those provided by ground-based gamma-ray observatories (HESS, MAGIC)
- LAT Dwarf limits are more constraining for WIMP models with mass below 1 TeV
- Currently, statistically limited (especially at high masses)
- Paper accepted by PRL (arXiv 1503.02641)
Search for gamma-ray lines

- WIMP annihilations in the Universe may produce gamma rays detectable by the LAT
  - $\chi\chi \rightarrow \gamma\gamma$, $\gamma Z^0$, $\gamma H^0$ would produce a narrow feature
  - Sharp, distinct spectral feature ("smoking gun")
    - Likely a small branching fraction
    - Signal predicted to be small (b.f. typically $\sim 10^{-2}$ to $10^{-4}$)
- Most recent line search from the LAT Collaboration:
  - 5.8 years Pass 8 data sample
    - Improved energy reconstruction
    - Increased effective area
  - Energy interval from 200 MeV to 500 GeV
  - Improved understanding of systematics
ROI optimization

- **ROIs for line search:**
  - R3 (circle with 3° radius centered on the GC), R16 (Einasto Optimized), R41 (NFW Optimized), R90 (Isothermal Optimized), R180 (Decay Optimized)

- **Control regions:**
  - 31 boxes 10° × 10° along the GP
  - Same line search algorithms as in signal ROIs
  - Allow to evaluate systematics
Upper limits on the WIMP mass from line searches

No evidence of spectral lines found!
The line feature at 133 GeV

- A potential signal was reported in the 3.7yrs data sample for a small ROI containing the GC
  - Bringmann+, JCAP 07 (2012), 054
  - Weniger+, JCAP 08 (2012), 007
- The LAT detected the feature, although with low global significance
- Newest LAT data analysis:
  - Increased data set (5.8 yrs)
  - Use of Pass 8 event classification
    - Improved energy reconstruction
    - Greater exposure towards the GC
  - Modified observing strategy from Dec 2013 to Dec 2014
- The excess in the 3.7 yrs data is of 2σ (3.3σ with Pass 7 data) and decreases using the full 5.8 yrs data set
• Likely the brightest dark matter source in the gamma-ray sky, but it is embedded in large and complicated backgrounds:
  – resolved sources
  – unresolved sources
  – diffuse emission
• Several independent studies find GeV excesses above the expected diffuse background
• The excess at the Galactic center could be due to:
  – dark matter
  – unresolved sources (e.g. MSPs)
  – ...
• Paper submitted to ApJ
LAT analysis upgrade: Pass 8

- A major upgrade of the LAT (aka Pass 8) was released in 2015
  - Complete revamp of LAT event reconstruction algorithms
  - More than double acceptance below 100 MeV
  - Retroactively updated entire Fermi-LAT data archive
Conclusions and perspectives

• Fermi has opened a window on the extreme high-energy Universe
• Exciting results in all fields of gamma-ray astrophysics
  – Many discoveries, many new source classes, many surprises
    • Many results not shown here!
  – The LAT gamma-ray data improved our understanding of CR accelerations processes and allowed to set more constrained limits on new physics than previously done
• The LAT has been monitoring the gamma-ray sky for 7 years and is still in good health
• Significant improvements of the LAT performance
  – Updated event reconstruction with Pass 8
  – Updated diffuse model coming soon
• Extended long term operations will provide a unique opportunity for time domain astrophysics and multi-wavelength observations