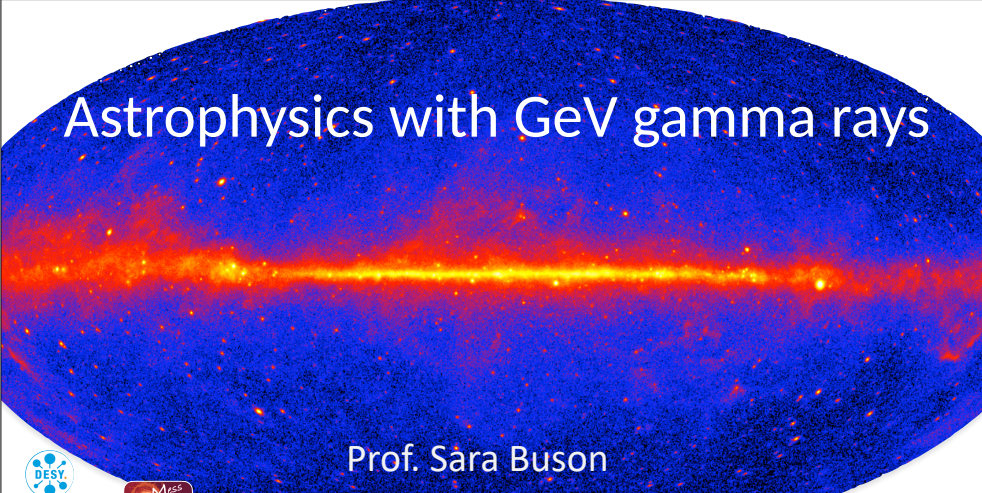


Astrophysics with GeV gamma rays



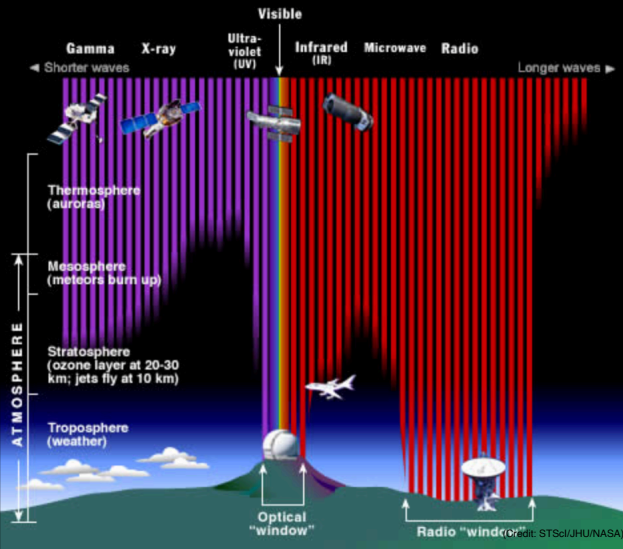
Prof. Sara Buson

DESY Astroparticle Division
Universität Würzburg

6th Hel.A.S. Astrophysics Summer School
24 August 2026



Why do we fly telescopes in Space?




High-energy $\rightarrow$ high luminosities
LCH accelerator should have circumference of Mercury's orbit to reach 10^{20} eV!

Brief Overview of γ -ray Astrophysics

2008	Fermi (GLAST): first all-sky monitoring of MeV-GeV sky, every 3 hrs with sensitivity a factor of >10 better than EGRET
2007	AGILE: Similar technology and capabilities as EGRET, intended to bridge the gap between CGRO/EGRET and Fermi (GLAST)
2004	Neil Gherels Swift Observatory: Dedicated g-ray burst mission, prompt X-ray/optical/UV follow up, arcsec localization of GRBs
2002	INTEGRAL: Major advances in high-resolution imaging and spectroscopy of Galactic g-ray sources
1999	XMM-NEWTON: narrow- and broad-range spectroscopy; performing the first simultaneous imaging of objects in both X-ray and optical band
1999	Chandra: high angular resolution, 0.5arcsec; first imaging of astrophysical jets at high-energy
1997	BeppoSAX: First high-precision localization of γ -ray bursts; established cosmological origin of g-ray bursts
1991	CGRO: First all-sky survey at γ -rays; many major discoveries in all areas of γ -ray astronomy; γ -ray astronomy becomes an integral part of astronomy
1989	SIGMA: First high-resolution images (13') in hard X-rays / soft γ -rays
1987	Whipple (Ground-based ACT): First credible detection of a TeV source (Crab Nebula)
1981	SMM: Studies of solar flare g-ray emission; ^{60}Co lines from SN 1987A
1979	HEAO-3: Discovery of radioactive ^{26}Al emission in the Milky Way
1975	COS-B: First detailed g-ray map of the Milky Way with 24 point-sources
1972	SAS-2: First high-energy g-ray images; discovery of Geminga pulsar
1968	OSO-3: Discovery of >100 MeV emission from the Milky Way
1967	VELA satellites: Discovery of γ -ray bursts (not published until 1973)
1961	EPLORER-II: First detection of high-energy γ rays from space

first Earth-orbiting explorers, surveys

rocket experiments
(not complete)



Brief Overview of γ -ray Astrophysics

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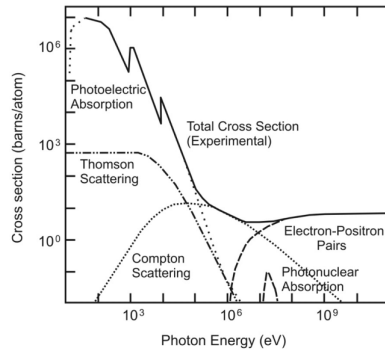
rocket experiments
(not complete)

Note: no sharp delimitation between energy ranges, generally speaking:

- "X-rays" in the $\sim\text{keV}$ energy band up to $\sim\text{MeV}$ s
- " γ rays" from $\sim\text{MeV}$ s to higher energies



γ -ray Astrophysics Photon Cross Section, Detection Principle

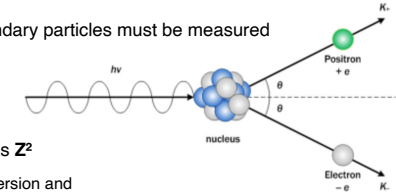


Although a large number of possible interactions are known, there are three key interaction mechanisms with matter:

- Photoelectric effect
 - Compton scattering
 - Pair production
- **Pair production** is the dominant process above the MeV/GeV range

γ -ray detection: efficiency vs. angular resolution

- At energies above a few **10 MeV**, **pair production in the nuclear field** is the dominant photon-matter interaction
- **Photons cannot be directly detected** → their secondary particles must be measured



- Pair-production cross section scales approximately as Z^2
 - **High-Z, dense materials** provide efficient photon conversion and energy containment
 - But they also increase **multiple scattering** of the secondary particles

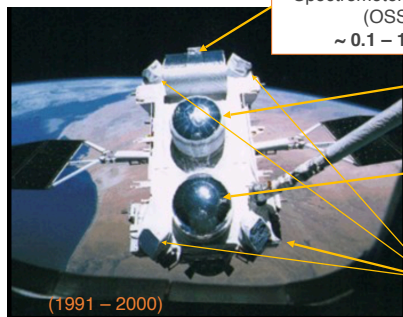
A fundamental trade-off

Detection efficiency & energy resolution ↔ Angular resolution

- **Secondary particles can be detected and tracked**
- Their trajectories allow us to **reconstruct the original γ -ray direction**

6

The Compton Gamma Ray Observatory (CGRO)



Oriented Scintillation-Spectrometer Experiment (OSSE):
~ 0.1 – 10 MeV

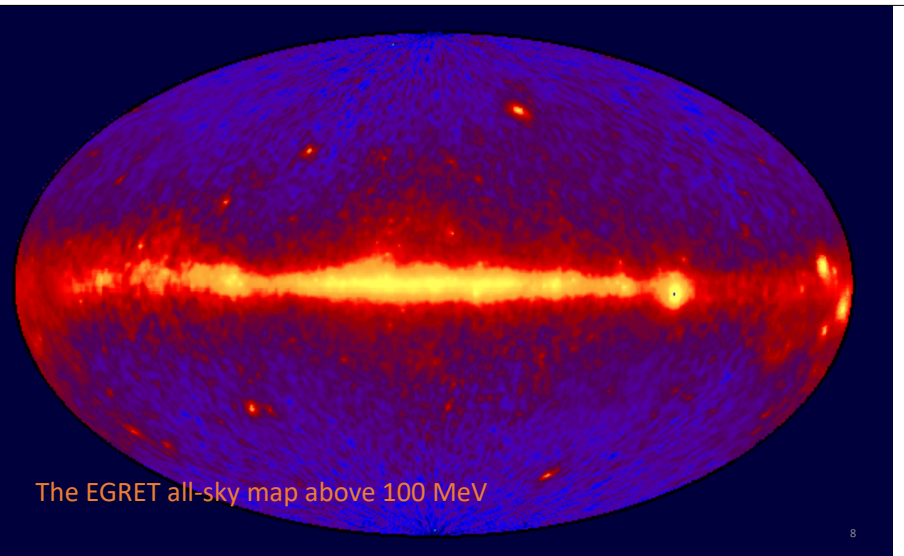
Compton Telescope (COMPTEL):
~ 1 – 30 MeV

Energetic Gamma-Ray Experiment Telescope (EGRET): pair conversion telescope,
~ 20 MeV – 30 GeV

Burst and Transient Source Experiment (BATSE):
~ 0.015 – 110 MeV

EGRET used high-voltage, **gas-filled spark chambers** to convert incoming high-energy gamma rays into electron-positron pairs, tracking their paths to find direction, paired with a sodium iodide (NaI) crystal calorimeter underneath to measure their total energy.

7



The EGRET all-sky map above 100 MeV

8

The present: the silicon era in gamma-ray Astrophysics

- A new era in gamma-ray astronomy was enabled by the introduction of silicon-strip detectors as the core of a “solid-state” spark chamber, replacing the gas-filled, wire-readout chambers used in SAS-2, COS-B, and EGRET. These detectors track photons and distinguish them from the much more numerous charged particles.
- **Silicon trackers** are **self-triggering devices**, reducing dead time to nearly zero and improving timing, count-rate, spectral, and spatial performance. Their compact design also **enables steradian-scale Fields of View (FoV)**, allowing much larger portions of the sky to be observed simultaneously.

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AGILE (Astro-rivelatore Gamma a Immagini LEggero)



Similar technology and capabilities as EGRET, intended to bridge the gap between EGRET and Fermi (LAT)
Italian gamma-ray satellite mission; launched on April 23, 2007

Two instruments:

- Gamma-Ray Imaging Detector (GRID):
 - 30 MeV – 50 GeV
- SuperAGILE: 18 – 60 keV

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The *Fermi* Gamma-Ray Space Telescope (formerly: Gamma Ray Large Area Space Telescope, GLAST)

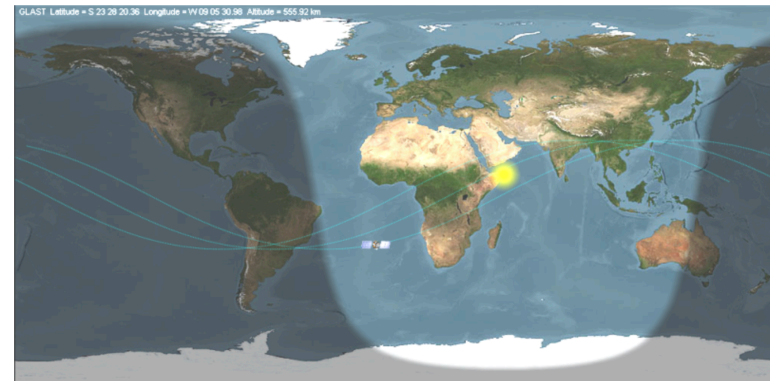


Launched June 11, 2008. Similar concept as EGRET (pair conversion), but much improved sensitivity, large field of view ($\sim \pi$ sr), and slightly extended energy range ($\sim 20\text{MeV}$ – 2000GeV).

<https://fermi.gsfc.nasa.gov>

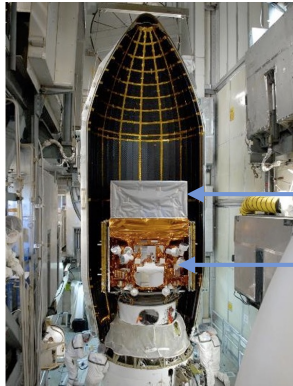
Orbit:

circular 565km altitude, 25.5° inclination (96min period)



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The *Fermi* Observatory

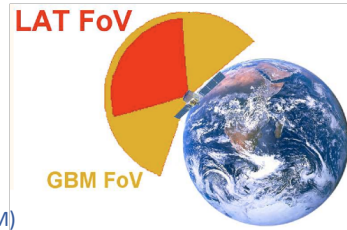


Operations

Primary mode: constant slewing to survey sky; scan entire sky every 3 hours

Large Area Telescope (LAT)
[20 MeV — 2 TeV]

Gamma Burst Monitor (GBM)
[8 KeV — 40 MeV]



LAT sees 1/5 of the sky at any time
GBM sees entire un-occulted sky

13

Salient Features of the LAT



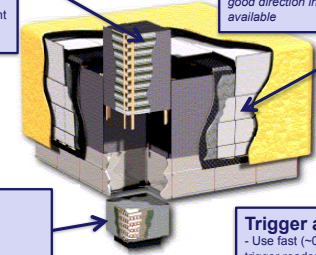
Tracker (TKR):

18 Si bi-layers
Front- 12 layers (~60% X_0)
Back- 6 layers (~80% X_0)

Angular resolution ~2x better for front
Many EM showers start in TKR

Anti-Coincidence Detector (ACD):

$\epsilon = 0.9997$ for MIPs
Segmented: less self-veto when good direction information is available



Calorimeter (CAL):

8 layers (8.6 X_0 on axis)

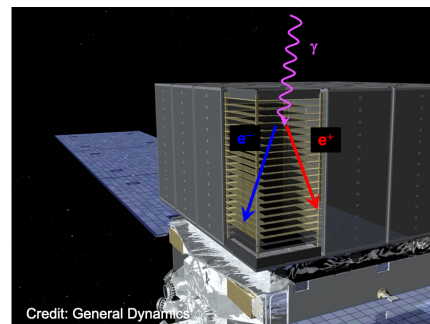
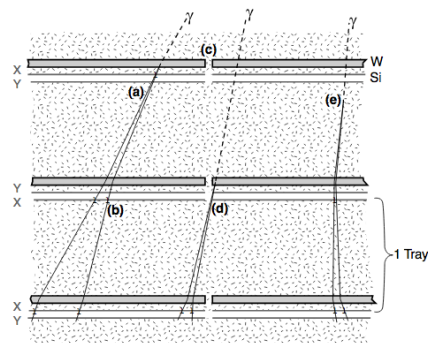
$\Delta E/E \sim 5-20\%$
Hodoscopic, shower profile and direction reconstruction above ~200MeV

Trigger and Filter

- Use fast (~0.5 μ s) signals to trigger readout and reject cosmic ray (CR) backgrounds
- Reduce data rate from ~10kHz to 300-500 Hz.

650W electric power; data rate reduced from ~10kHz to 300-500Hz

Tracker detection principle



Credit: General Dynamics

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Tracker: Conversion foils

Material: W
Aim: ~1 r.l.

properties	Si	W
Z	14	74
D (g/cm ³)	2.33	19.3
r.l. (cm)	9.37	0.35

12 layers with
0.03 r.l. of W
(0.01 of Si)



We try to have a good compromise
Significantly increase conversion prob. without causing too much MS

4 layers with
0.1 r.l. of W



We are getting desperate
Give up a bit on the resolution, really try to cause a p-p conversion

2 layers with no W



We give up
(actually see later)

Tracker assembly at INFN Pisa

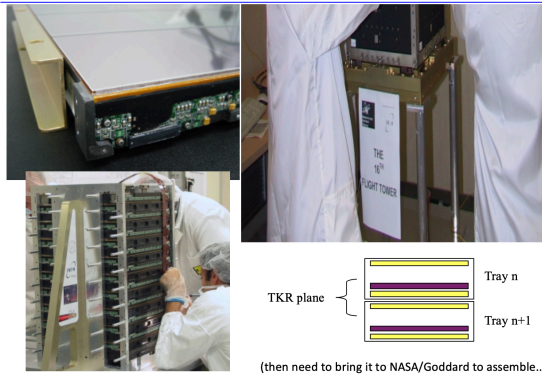


- Wafers glued and wired-bonded in 4 x 1 ladders
- Four ladders integrated into a ~ 36 x 36 cm² detection plane
- Composite trays providing the mechanical structure

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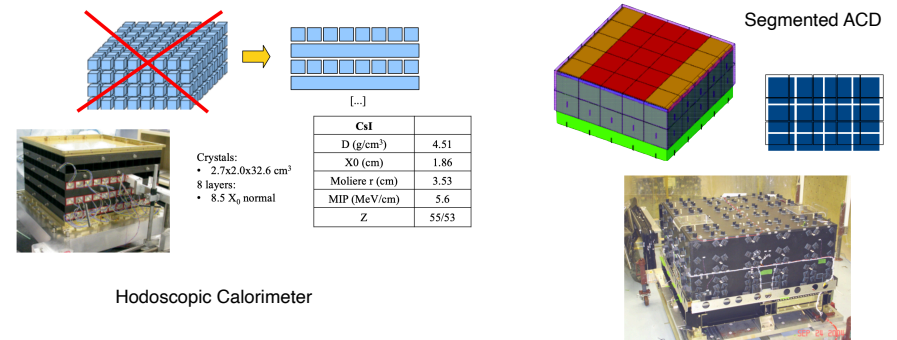
Tracker: basics

Assembly at INFN Pisa



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Calorimeter / Anti-Coincidence Detector



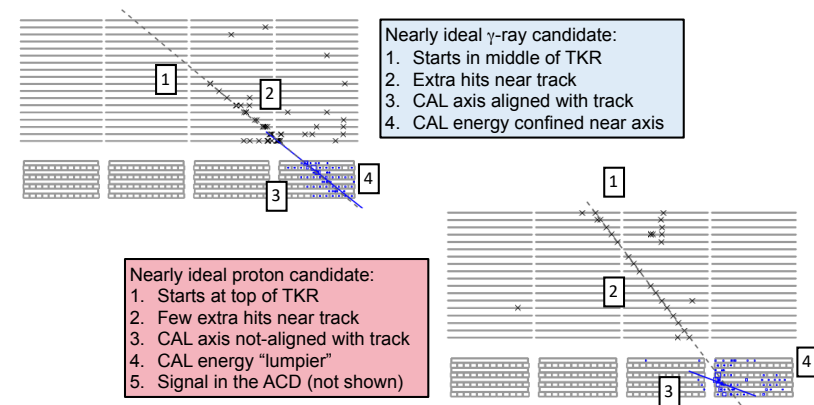
18

On the spacecraft



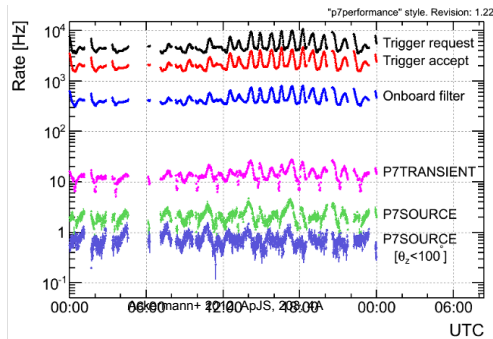
19

LAT detects individual γ rays (and Cosmic Rays)



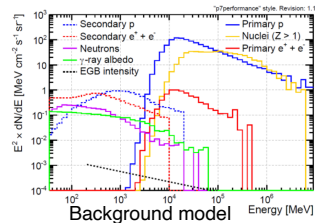
20

Particle Background Rate Reduction



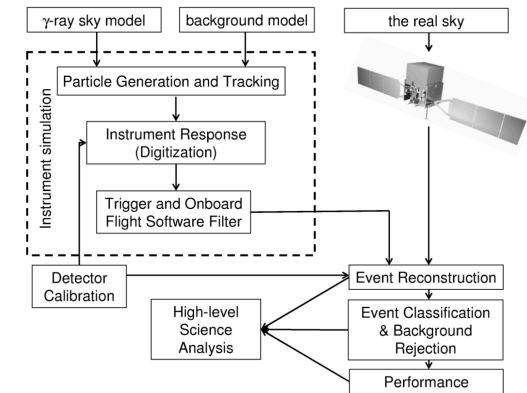
Factor of $> 10^5$ in bkg. reduction is achieved in several stages

About 50% g-ray efficiency inside fiducial volume from 1-100 GeV



21

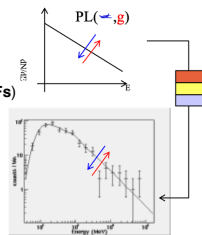
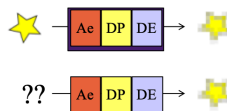
Instrument simulation, calibration, data analysis



22

From detected events to source properties

- We measure a set of events with:
 - Arrival time
 - Reconstructed sky position
 - Reconstructed energy
- We want to infer the **source properties**:
 - Position, spectrum, flux, etc.



Forward-folding & likelihood analysis

- Direct **unfolding** is challenging in the presence of significant background
- Instead, we **forward-fold** source models through the instrument response functions (IRFs)
- Maximum likelihood** then determines the best-fit parameters of the source model

Key advantages & limitations

- Model-dependent**, but uses essentially all available information
- Likelihood can be **unbinned**, even when IRFs are tabulated in bins
- Provides a natural framework for **systematic uncertainty studies**
- Caution**: standard likelihood-ratio tests cannot directly compare **non-nested models**

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Instrument Response Functions

- The IRFs are factored into three terms:
- efficiency in terms of the detector's **effective area**,
 - angular resolution as given by the **point-spread function (PSF)**,
 - energy resolution given by the **energy dispersion**.

$$R(E', \hat{v}'; E, \hat{v}) = A_{eff}(E, \hat{v}) P(\hat{v}'; E, \hat{v}) D(E'; E, \hat{v})$$

Measured Energy & Direction

Effective Area

Energy Dispersion

Point-spread Function

True Energy & Direction

Expected Count Rate

Source Flux

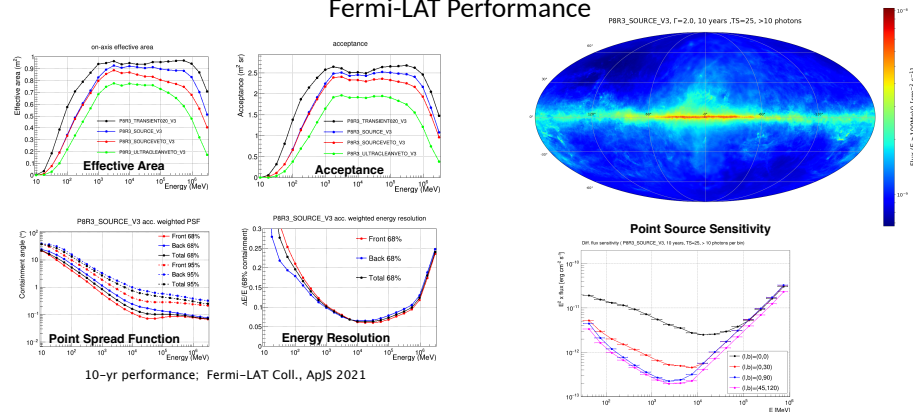
$$\frac{dM(E', \hat{v}')}{dt} = \int \int R(E', \hat{v}'; E, \hat{v}) F(E, \hat{v}) d\hat{v} dE$$

Instrument Response

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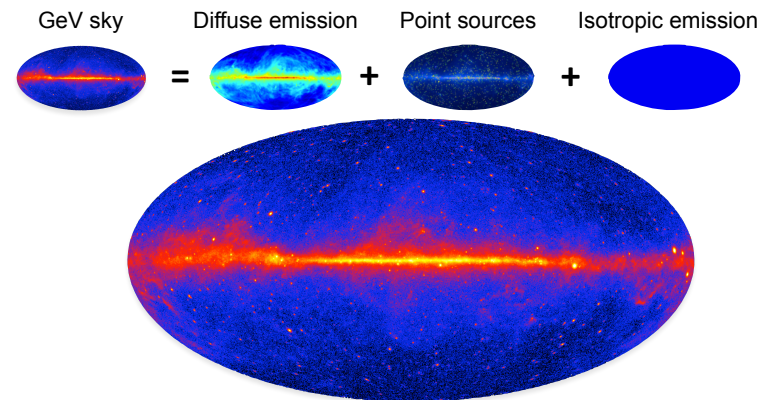
Instrument Response Functions

Fermi-LAT Performance



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Decomposing the GeV Sky



26

Fermipy: community-driven development

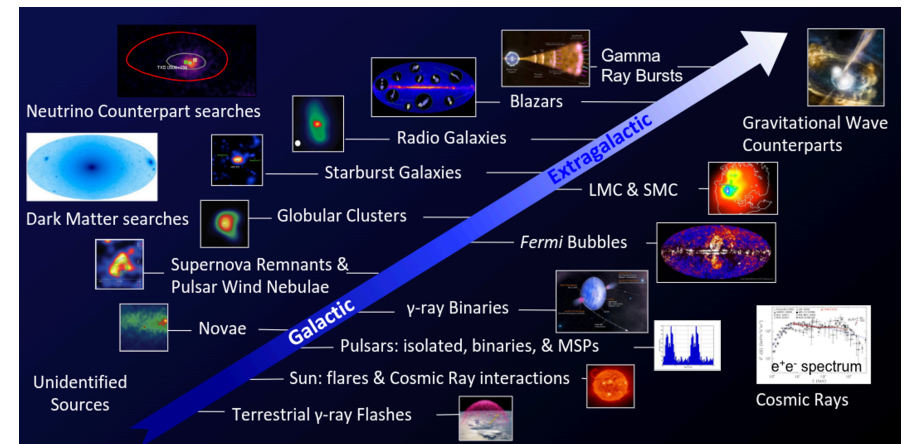
*Fermi-LAT data available publicly within a few hours;
Fermi analysis tools public*



- Fermipy** is a Python package aimed to facilitate **Fermi-LAT data analysis** using the Fermi Science Tools
 - LAT collaboration members lead **maintenance, development, and community support**
 - GitHub** provides issue tracking and a platform for community contributions
- Continuous developments**
 - Improvements based on Collaboration and community inputs (e.g. psmmap, Bruehl 2021)
 - Updates documentation for **latest catalogs and data products**
 - Jupyter notebook tutorials**
- Fermipy** Git-repo, via pip / conda at : <https://fermipy.readthedocs.io/>

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Fermi-LAT Science Covers Huge Phase-Space

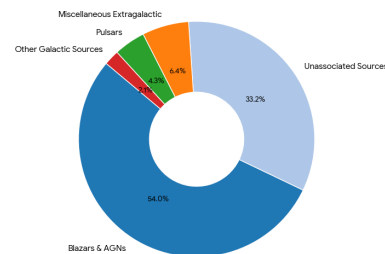


Fermi-LAT: 18 years of continuous survey

- 18 years of uninterrupted monitoring of the gamma-ray sky, from 50 MeV to 1 TeV
- Incremental catalog updates every ~2 years
- FL16Y released in February 2026; analysis methodology based on 4FGL(-xx)

16-year list (FL16Y) of 7220 sources

- Prior to *Fermi*-LAT only 271 gamma-ray sources were known
 - More than 30% of the sources had no counterpart
- 7220 sources cataloged and regularly monitored
 - Fraction of sources with no counterpart essentially the same
- Dedicated efforts on unassociated sources and improvements on diffuse gamma-ray background model

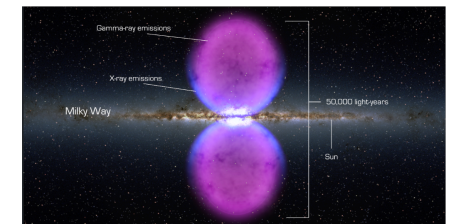
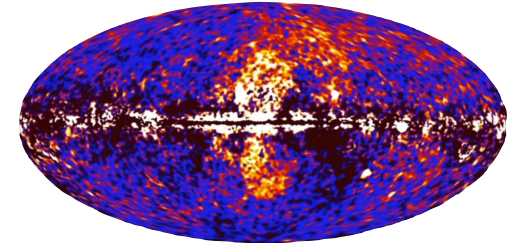


Abdollahi et al. 2022; Ballet et al. 2026

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The Fermi bubbles

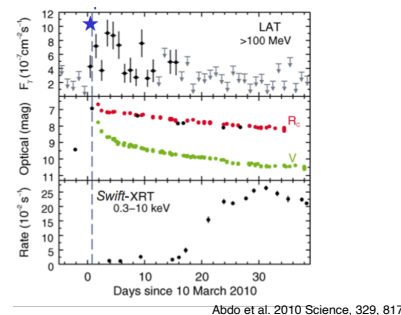
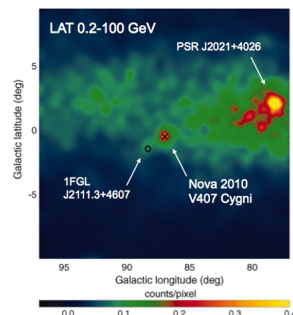
- **Giant gamma-ray-emitting lobes** extending above and below the center of the Milky Way
- **Origin remains unknown**
- **Possible explanations include:**
 - Remnants of a **massive burst of star formation**
 - Relics of an **eruption from the supermassive black hole** at the Galactic center



Su et al. 2012

30

Fermi LAT as Novae Finder – the First



Abdo et al. 2010 Science, 329, 817

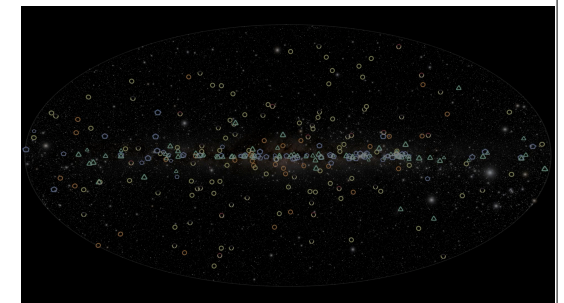
- Initial LAT detection 2010 March 10, same day as nova V407 Cyg optical discovery: γ -ray identification via spatial ($r_{95}=3.7'$) & temporal coincidence with a symbiotic recurrent nova

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The 3rd Fermi LAT pulsar catalog

Gamma-ray pulsars: a rapidly growing population

- **11 $\rightarrow$ ~340** known gamma-ray pulsars with Fermi-LAT
- **~10%** of pulsars detected at other wavelengths are also detected in gamma-rays
- **First gamma-ray pulsar discovered in another galaxy**
- **>100 millisecond pulsars**, with exceptionally stable rotational periods
- **Gamma-Ray Pulsar Timing Array:** probing the **stochastic gravitational-wave background**

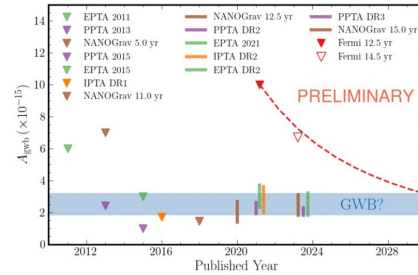


Smith et al. ApJ 2023

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Gamma-ray Pulsar Timing Array

- **Supermassive black hole binaries** are expected to generate a **stochastic gravitational-wave background (GWB)** as their orbits decay
- The GWB induces **correlated timing residuals** in pulsar arrival times, with a characteristic power-law spectrum ($\Gamma = 13/3$)
- **Pulsar Timing Arrays (PTAs)** use precise pulsar timing to detect and characterize these GW-induced delays
- **Fermi-LAT is the first Gamma-Ray PTA**
 - Gamma rays are **unaffected by the interstellar medium**, reducing propagation-related noise compared with radio observations
- Provides an **independent probe of the GWB** and an important **cross-check of radio noise models**



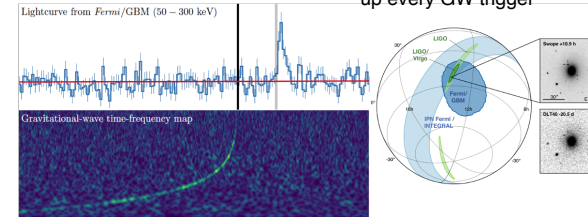
Fermi Collaboration Science 2022; Kerr et al. 2024, Valtolina S. et al PRD 2026

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Multimessenger astrophysics

Fermi-LAT monitors sky regions of GW events searching for electromagnetic counterparts

- The continuous monitoring of the gamma-ray sky has also allowed Fermi to have a leading role in the multimessenger astrophysics field
- Discovery of the simultaneous emission of a gravitational wave and gamma-rays from a binary system of coalescing neutron stars
- Fully automated analysis pipelines following up every GW trigger

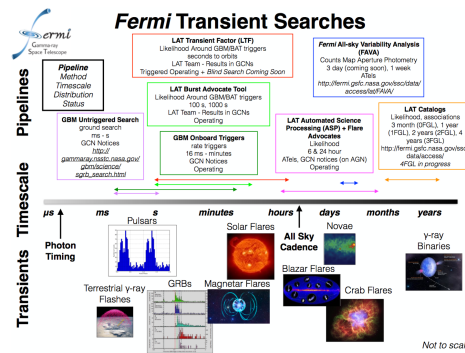


LAT follow up analyses publicly available at <http://fermigb.stanford.edu/GWTable/>

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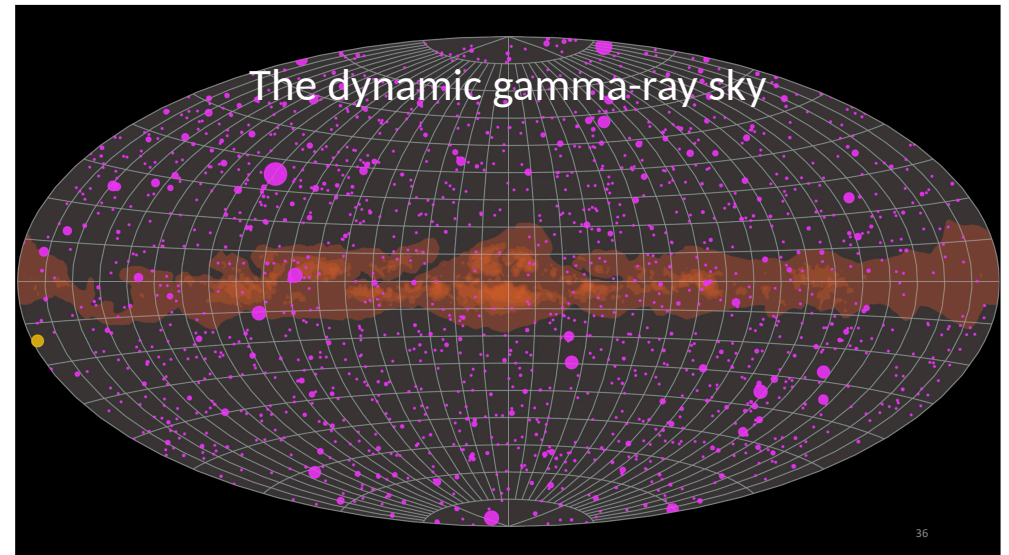
Fermi-LAT: enabling rapid multi-messenger follow-up

- **All-sky survey:** combines **instantaneous access** with a **18-year archive**
 - Real-time or near-real-time coverage of events anywhere on the sky
 - **GBM:** alerts within ~ 1.5 h; **LAT:** within ~ 3 h
 - LAT can cover **$\sim 80\%$** of a GW localization region in $\sim 1,000$ s
- **Broad and unique energy coverage:** 8 keV to 2TeV
 - Enables studies of a wide range of energetic astrophysical phenomena
- **Dedicated science pipelines and community support**
 - **Flare Advocates:** monitor flaring sources and follow up neutrino alerts $\rightarrow$ **ATels/GCNs**
 - **Burst Advocates:** follow up GRBs observed within the LAT FoV $\rightarrow$ **GCNs**
 - Daily/weekly monitoring of **sources of interest**



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The dynamic gamma-ray sky

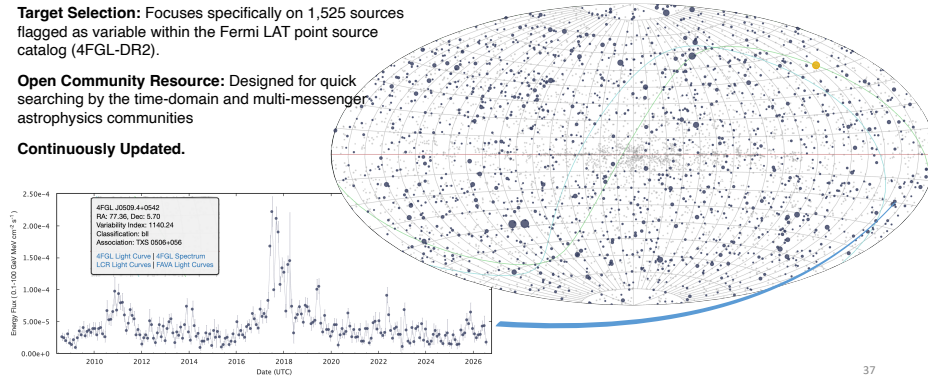


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Fermi-LAT Light Curve Repository

Core Features

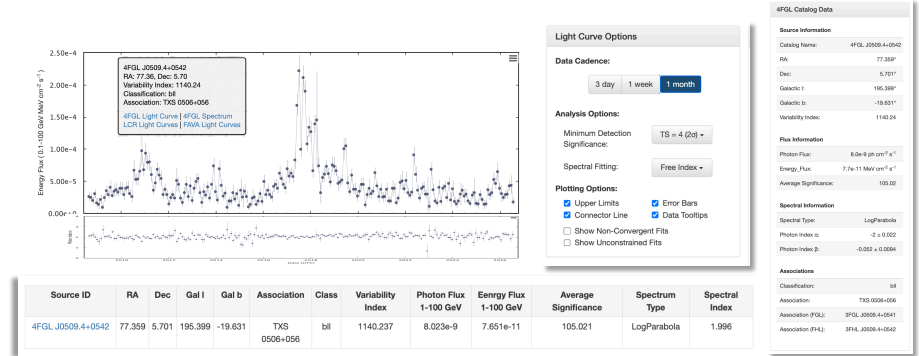
- Multi-Cadence Bins:** Offers data binned at intervals of 3 days, 1 week (7 days), and 1 month (30 days).
- Target Selection:** Focuses specifically on 1,525 sources flagged as variable within the Fermi LAT point source catalog (4FGL-DR2).
- Open Community Resource:** Designed for quick searching by the time-domain and multi-messenger astrophysics communities
- Continuously Updated.**



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Fermi-LAT Light Curve Repository

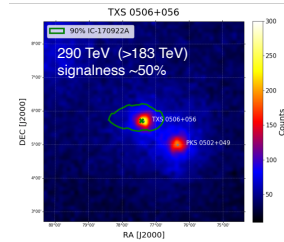
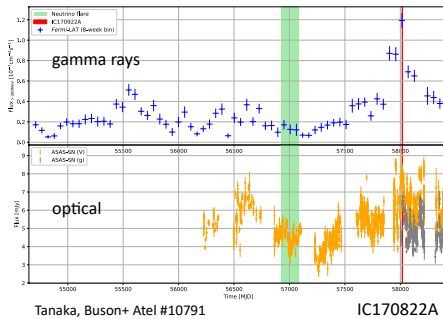
<https://fermi.gsfc.nasa.gov/ssc/data/access/lat/LightCurveRepository/>



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Multimessenger Neutrino Astrophysics

IceCube Alert – IC170922A / TXS 0506+056



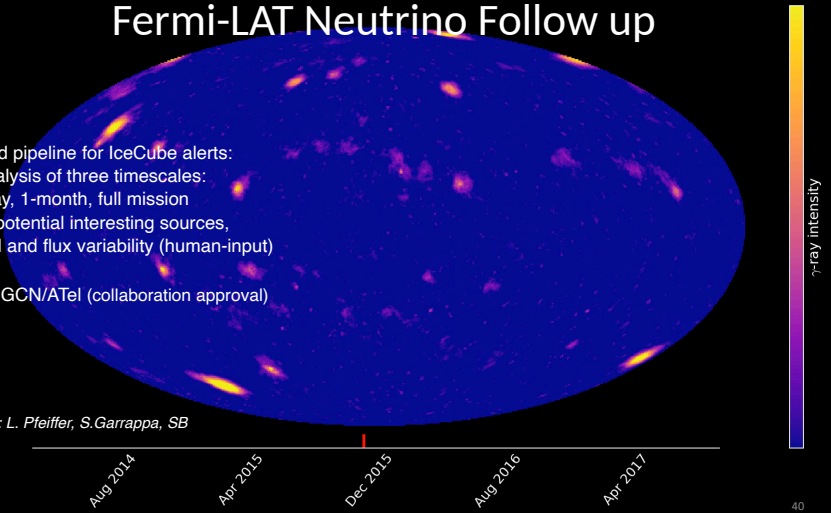
39

Fermi-LAT Neutrino Follow up

Automated pipeline for IceCube alerts:

- LAT analysis of three timescales: 1-day, 1-month, full mission
- Check potential interesting sources, spectral and flux variability (human-input)
- Issuing GCN/ATel (collaboration approval)

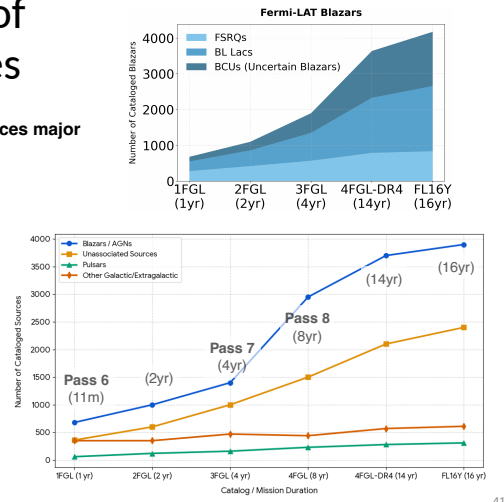
Developers: L. Pfeiffer, S. Garrappa, SB



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Fermi-LAT Census of Gamma-ray sources

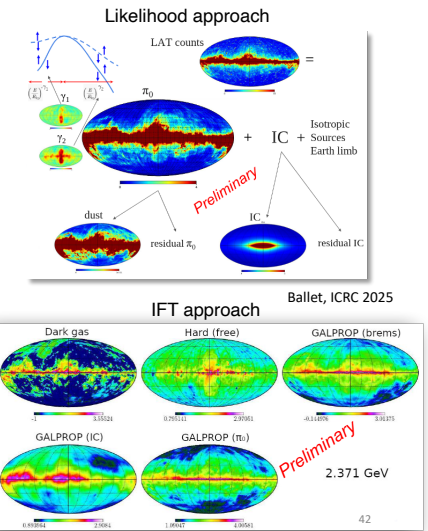
- Each successive source catalog introduces major improvements, including:
 - New event reconstruction
 - Improved diffuse emission models
 - New analysis methods



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5FGL: a new Interstellar Emission Model

- Each successive source catalog introduces major improvements, including:
 - New event reconstruction
 - Improved diffuse emission models
 - New analysis methods
- Next Fermi-LAT source catalog will not be incremental
- 5FGL: a new interstellar emission model (IEM) at work
 - Current IEM residuals are at the ~3% level in large-scale sky maps
- Two complementary approaches are being pursued:
 - Direct likelihood approach based on spectral templates
 - Information Field Theory (IFT) approach



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Fermi-LAT Mission Status

Operationally healthy and scientifically productive, with strong engagement from the scientific community and public

No consumables or rapid component degradation

- Gradual degradation is compensated through calibration

One solar-array drive has stopped rotating

- A modified survey strategy maintains the power margin without compromising observing efficiency

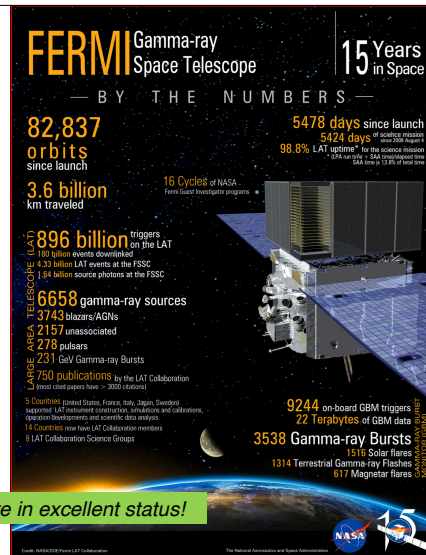
Orbit raise planned to ~563 km

- Higher orbit will reduce the frequency of collision-avoidance maneuvers
- Maneuver planning has increased as the number of tracked objects in the current orbit grows

Mission approved through 2028

- Continuation beyond 2028 will depend on the next Senior Review evaluation

Spacecraft and instrument performance are in excellent status!

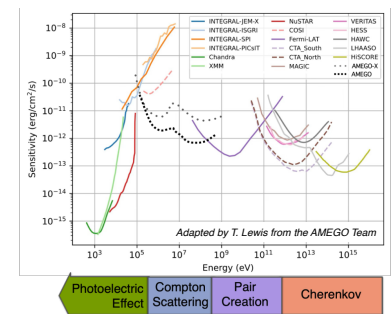


Coming soon: COSI



- The Compton Spectrometer and Imager: NASA SMEX (<120M\$)
- Launch is planned for 2027 on a Falcon 9 rocket from Cape Canaveral

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