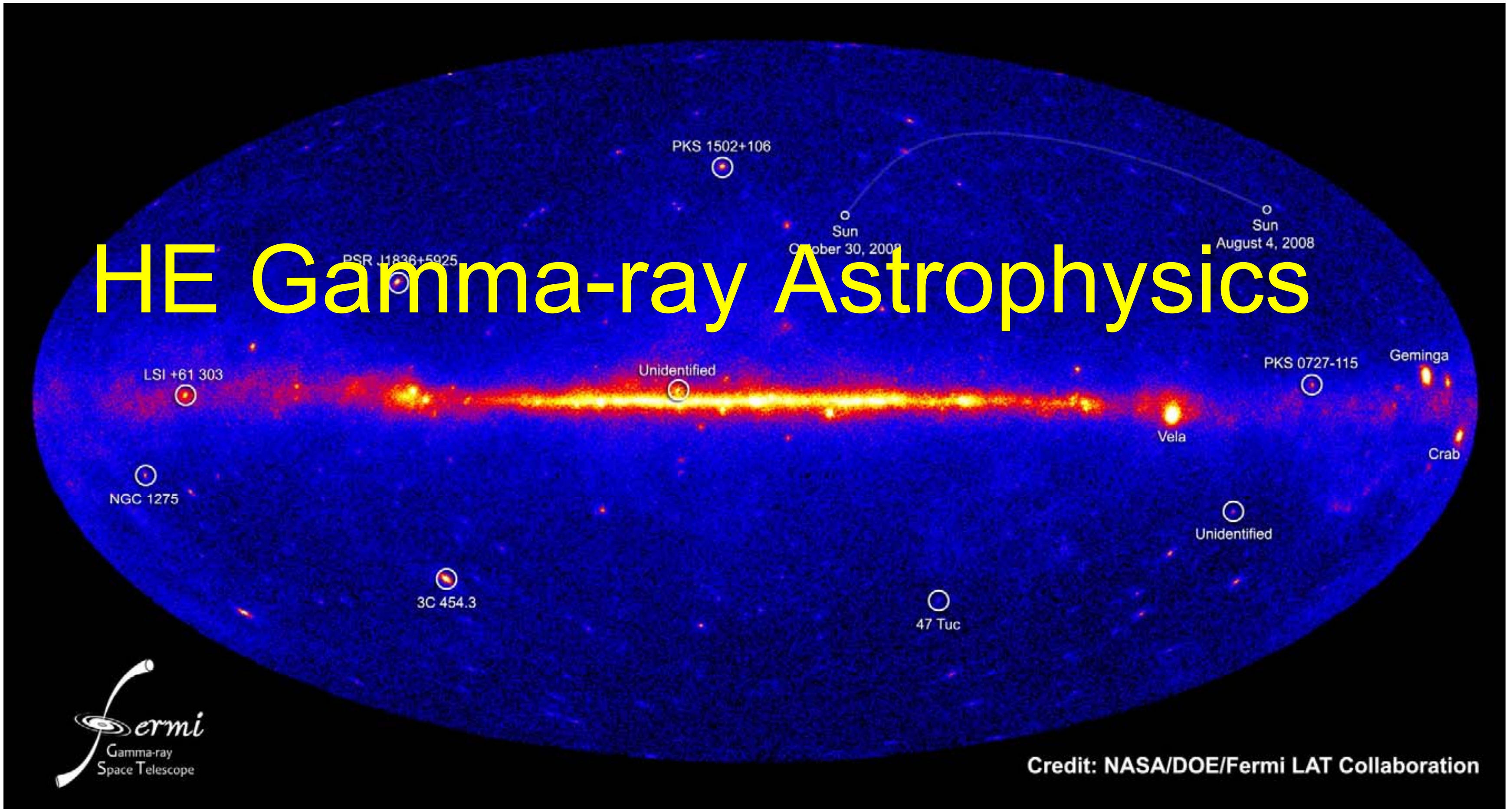
# HE Gamma-ray Astrophysics




**Francesco Longo**

**Department of Physics, University of Trieste and INFNTrieste**

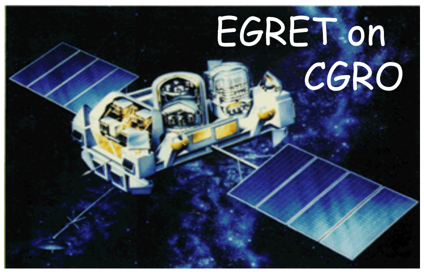
**credits to the Fermi - LAT collaboration**

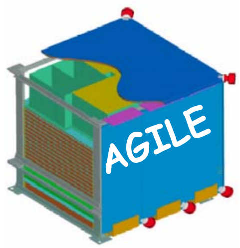
# Summary

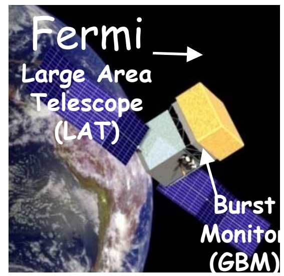
- Brief Introduction to Gamma-ray Astrophysics
  - The Main Questions
- HE Gamma-ray astrophysics
  - From EGRET to (AGILE) / Fermi - LAT
- Introduction to Fermi LAT data analysis
  - Documentation

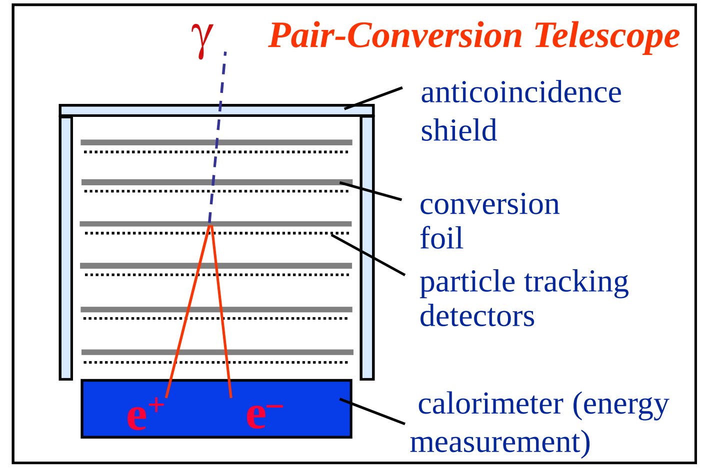
# Gamma-ray Experiment Techniques

- Space-based:
  - use pair-conversion technique



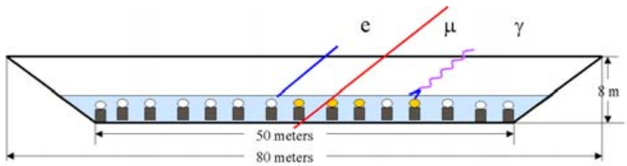




- Ground-based (VHE shower info reaches gnd):
  - Airshower Cerenkov Telescopes (ACTs)

    image the Cerenkov light from showers induced in the atmosphere. Examples: Whipple, STACEE, CELESTE, VERITAS, MAGIC, HESS

  - Extensive Air Shower Arrays (EAS)



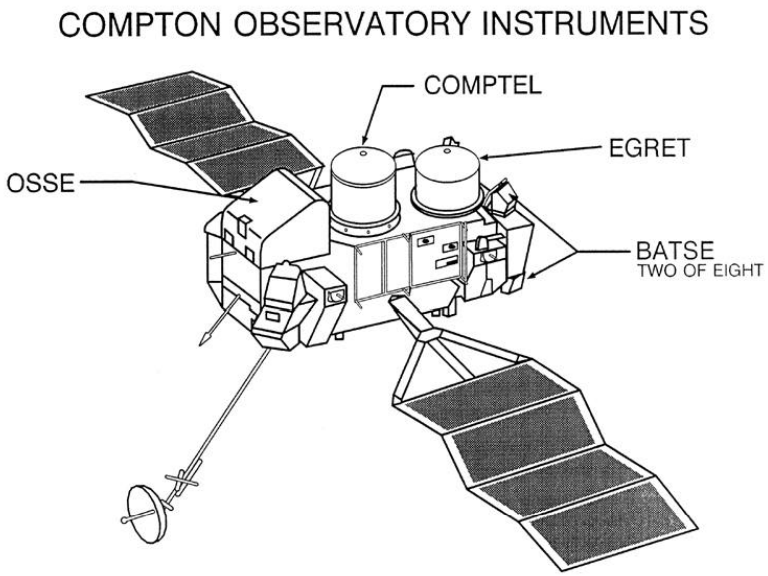

Directly detect particles from the showers induced in the atmosphere. Examples: MILAGRO, ARGO,

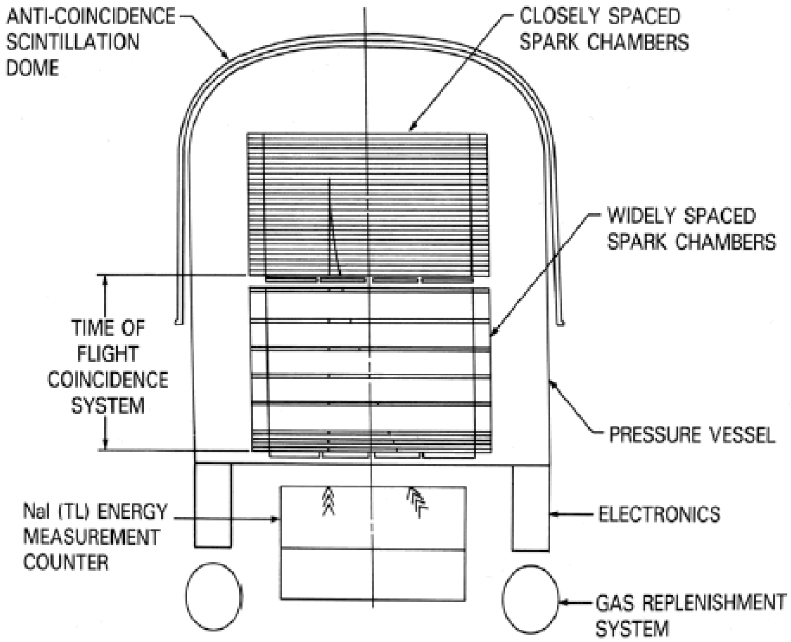
# Some key questions for Gamma-Astrophysics

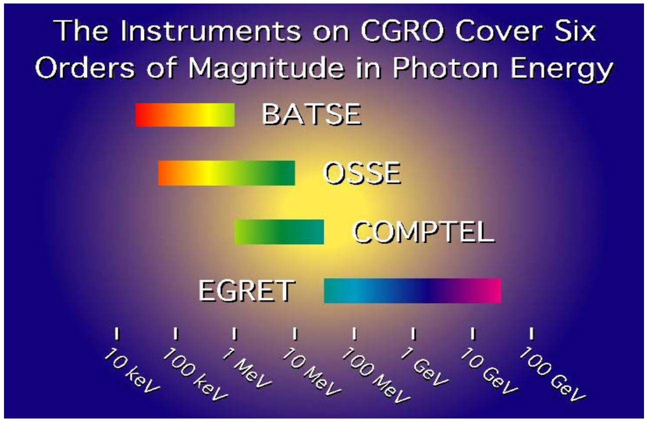
- Black Holes
  - Supermassive BH – AGN
  - Stellar BH – Galactic Gamma-ray binaries
  - Stellar BH – Gamma Ray Bursts
- Compact objects
  - Electromagnetic fields in strong Gravitational fields
- The origin of cosmic-rays
  - Particle acceleration – the Fermi mechanism
- The Nature of Dark Matter
- Photon propagation over cosmological distances

# The EGRET Legacy

# EGRET



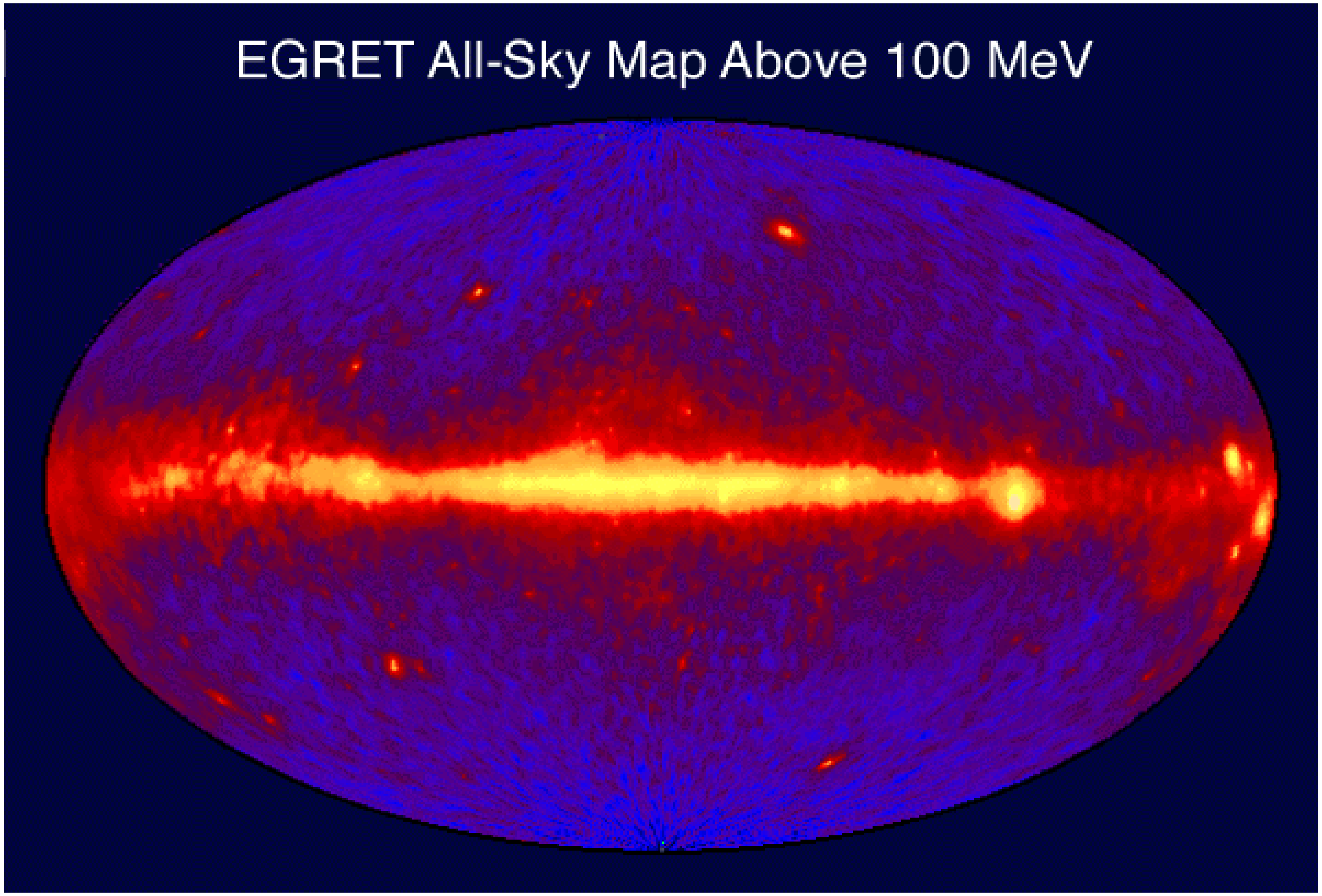



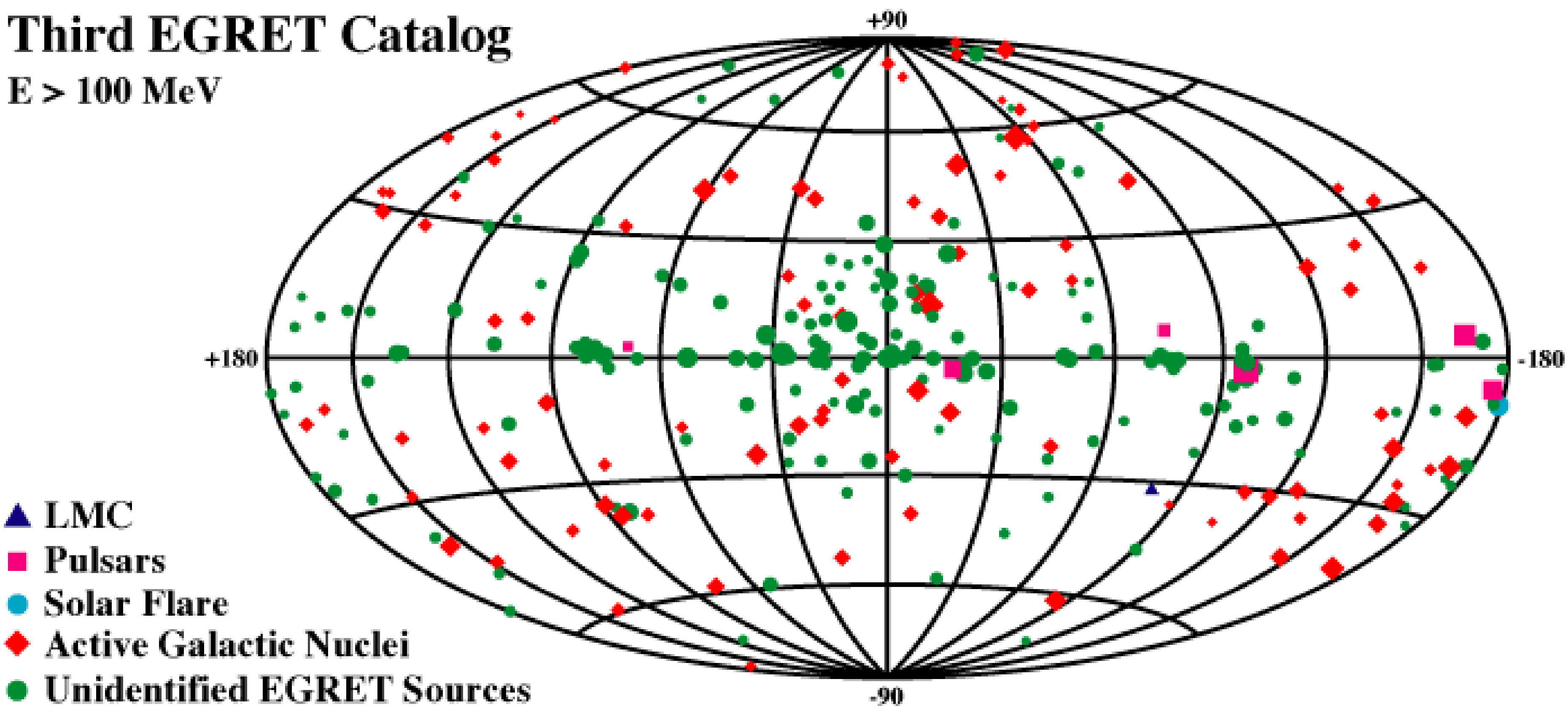

## EGRET

- 1991-2000
- 30 MeV - 30 GeV
- AGN, GRB, Unidentified Sources, Diffuse Bkg

# The Legacy from EGRET

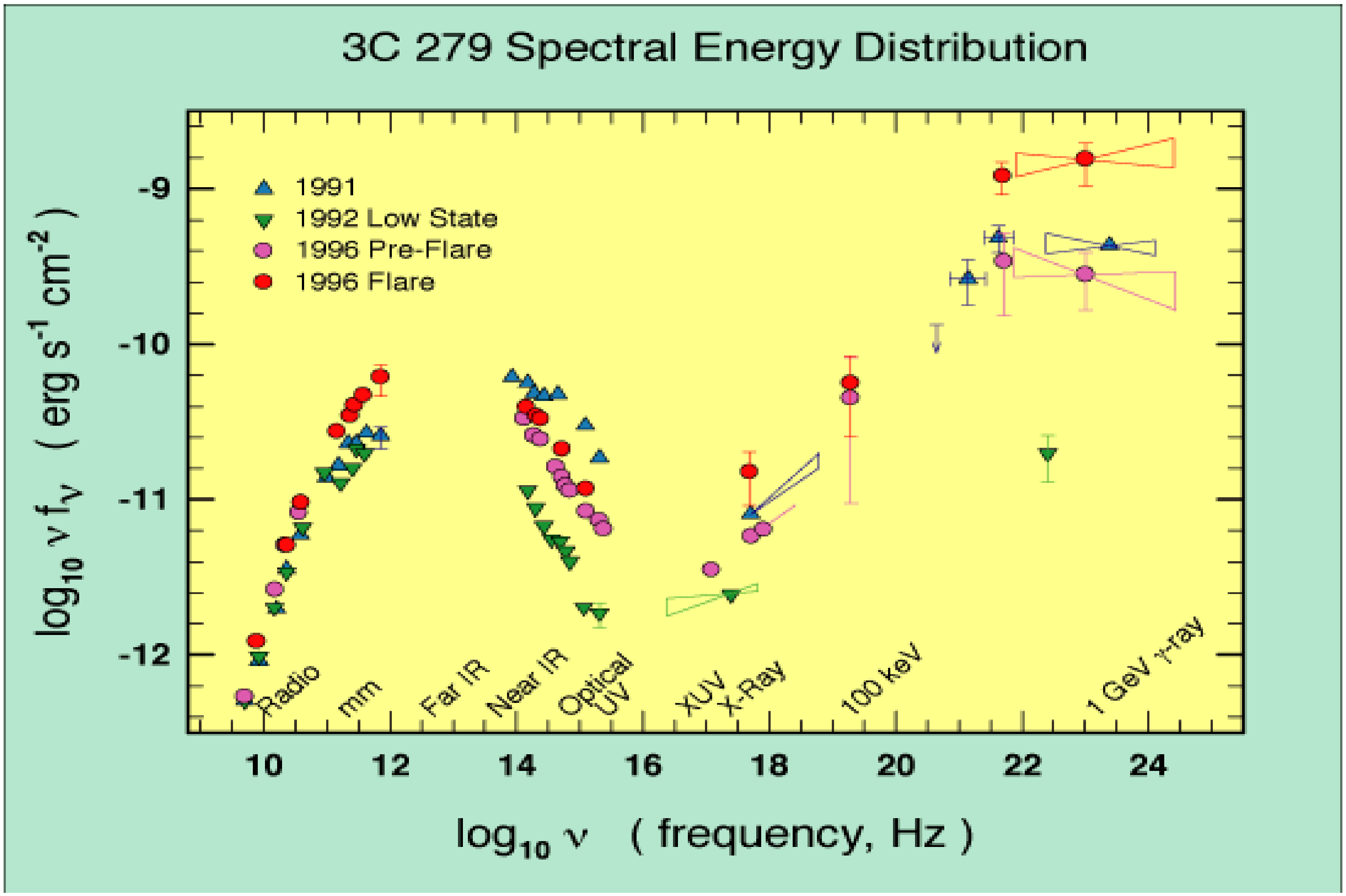


# EGRET Gamma-ray Sources



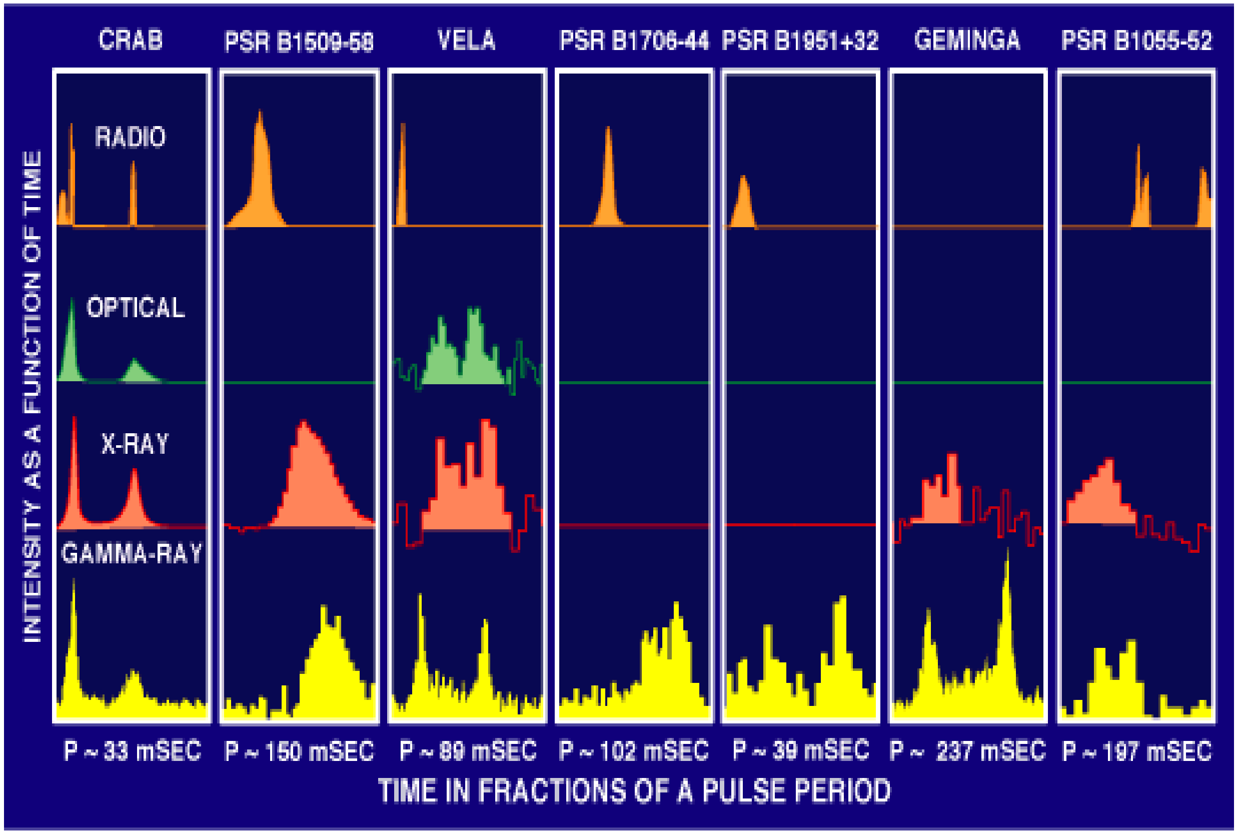
# Challenge # 1

- Need simultaneous multiwavelength data to study variability and emission processes



# Challenge # 2

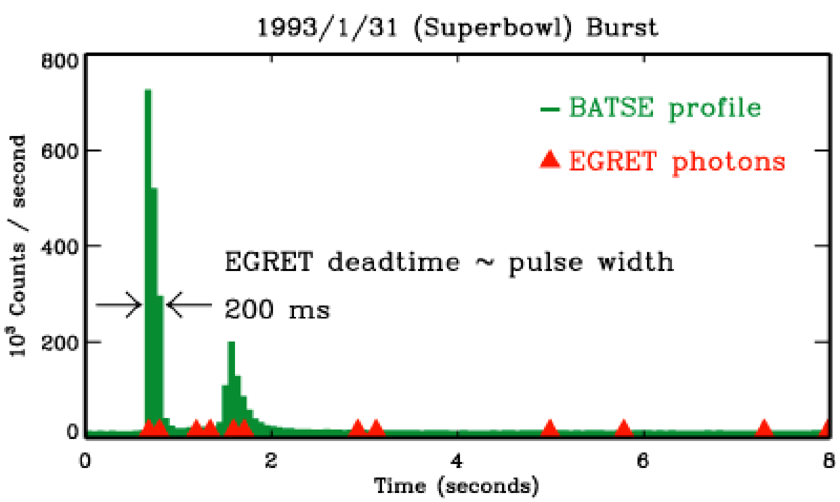
- Need more exposure and optimal timing (and radio monitoring) to discover more gamma-ray PSRs.



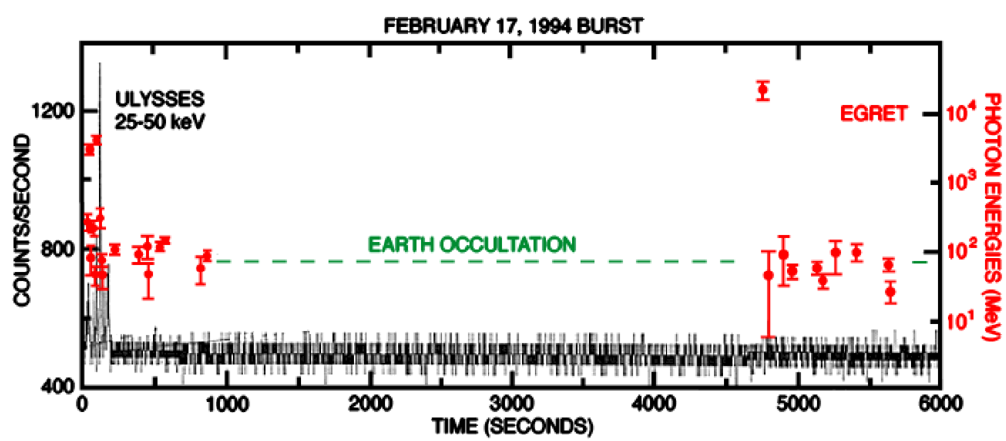
# Challenge # 3

- Need fast timing for gamma-ray detection (improving EGRET deadtime, 100 msec → 100 microsec or less).

Prompt Emission (GRB 930131)

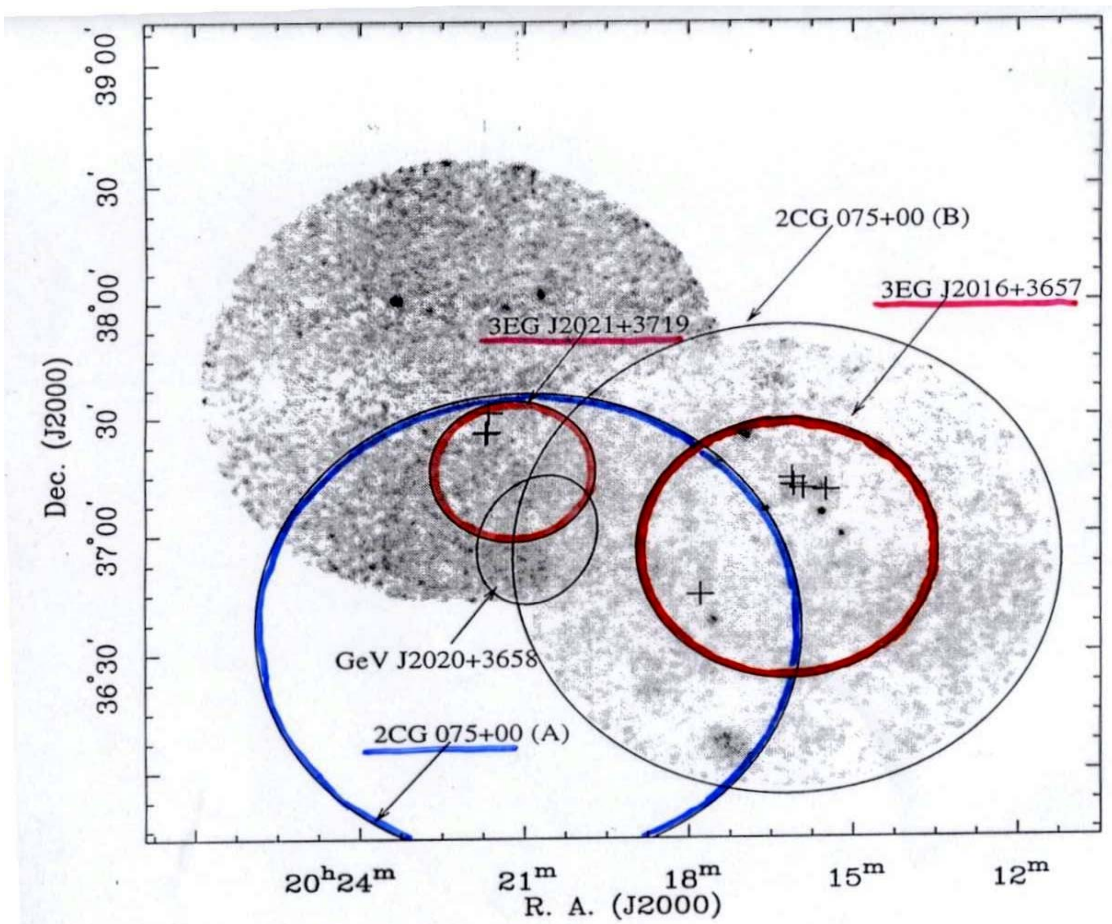



Delayed Emission (GRB 940217)

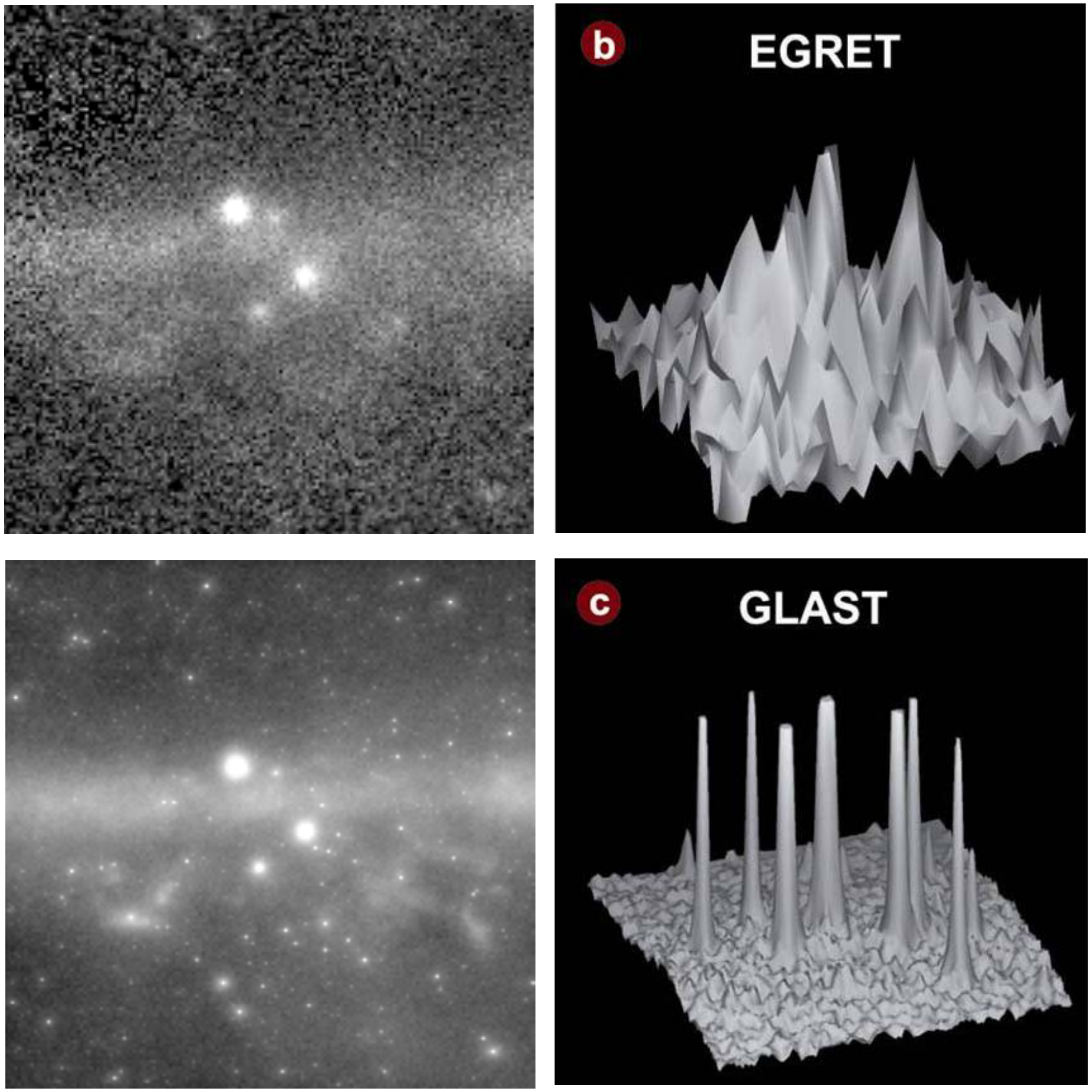


# Challenge # 4

- Need arcminute positioning of gamma-ray sources (improving EGRET error box radii by a factor of 2-10).



# Technology impact -- PSF




*Cygnus region ($15^0$ x $15^0$), $E\gamma$ > 1 GeV*

**EGRET**
**(1991-2000)**
Phases 1-5

**Spark chamber**

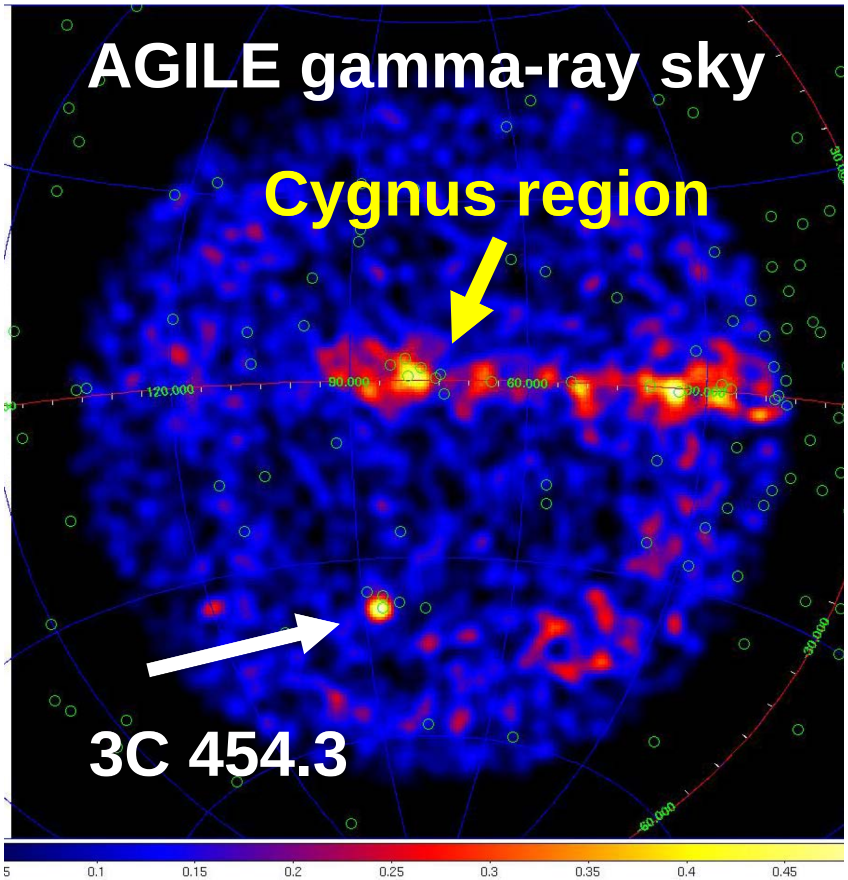
- **sense electrode spacing ~mm**
- **sensitive layer depth ~cm**
  - ***up to 28 hit over >1m***

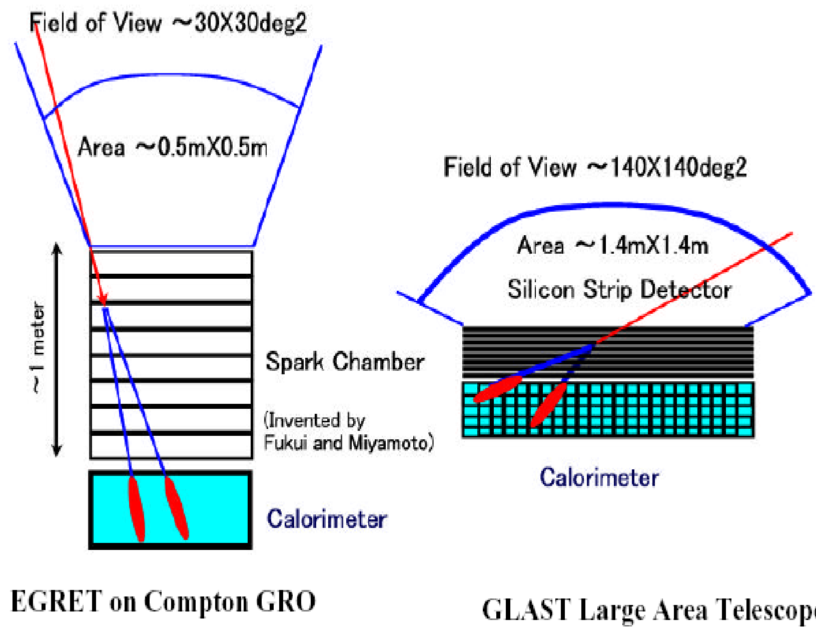
**LAT**
**(2008- >2013)**
1-yr simulation

**Si-strip detectors**

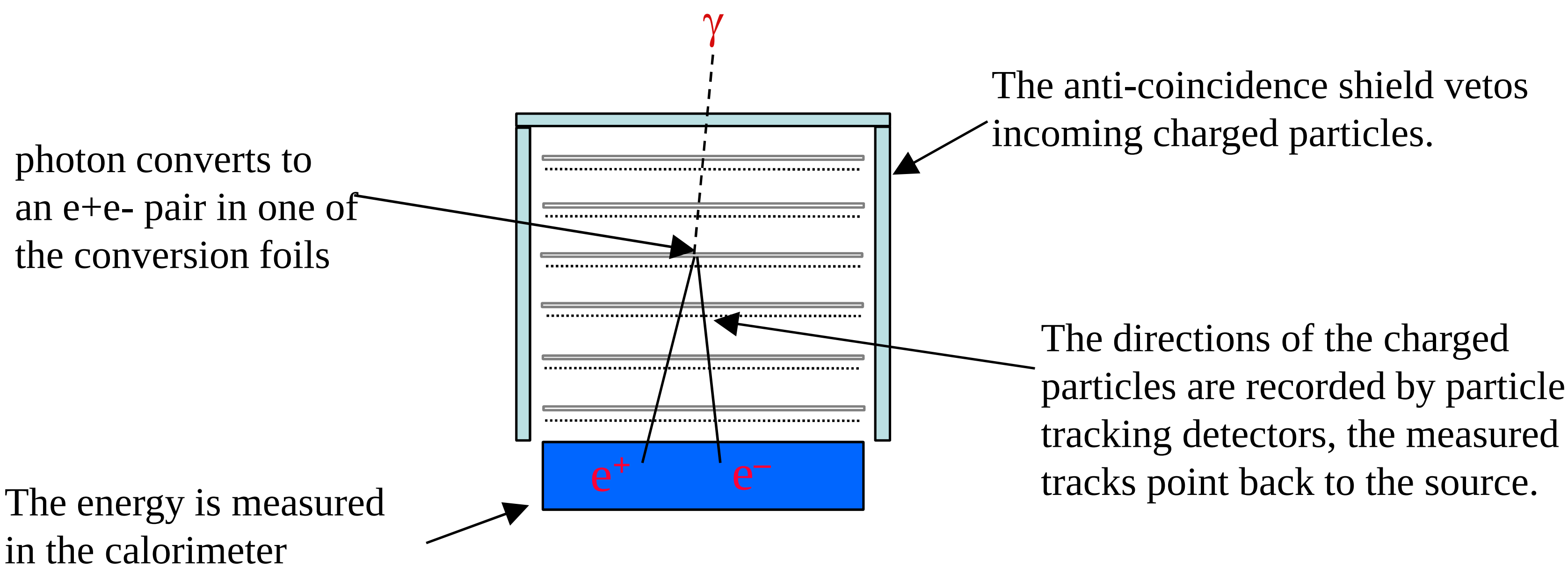
- **sense electrode spacing ~0.2mm**
  - ***better single hit resolution***
- **sensitive layer depth ~0.4mm**
  - ***converter proximity to minimize MCS***

# Technology impact - FoV



# Pair Conversion Technique




**Tracker**: angular resolution is determined by:
multiple scattering (at low energies) => Many thin layers
position resolution (at high energies) => fine pitch detectors

**Calorimeter**:
Enough $X_0$ to contain shower, shower leakage correction.

**Anti-coincidence detector**:
Must have high efficiency for rejecting charged particles, but not veto gamma-rays

# AGILE

# AGILE

agenzia spaziale italiana

INAF

INFN

Carlo Gavazzi Space SpA

OERLIKON CONTRAVES

ALCATEL ALENIA SPACE
An Alcatel/Finmeccanica company

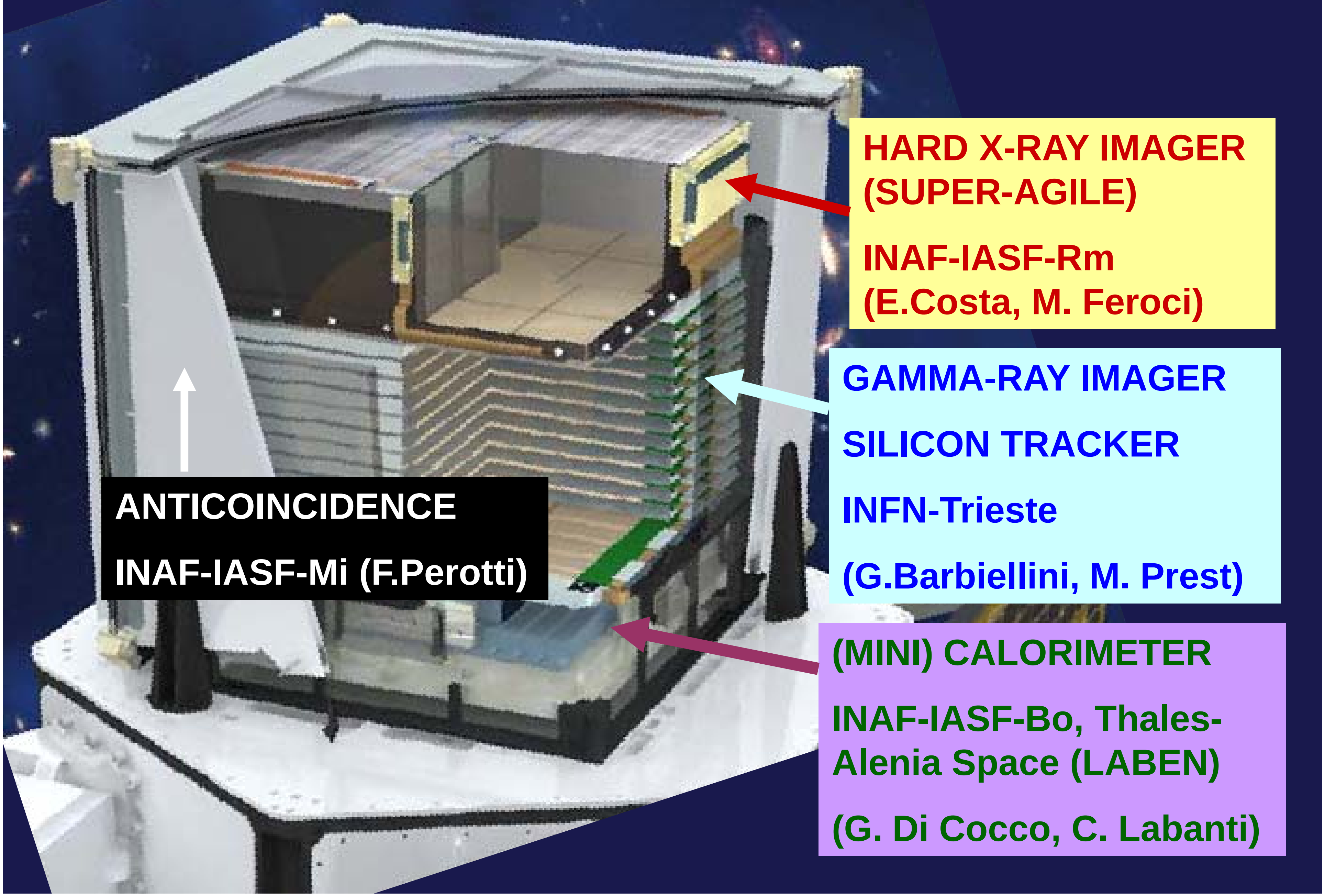
telespazio
A Finmeccanica/Alcatel company

Galileo Avionica

MIPOT

ENEA

# AGILE: inside the cube…



# Fermi LAT

# The Gamma-ray Observatory


Large AreaTelescope (LAT)
20 MeV - >300 GeV

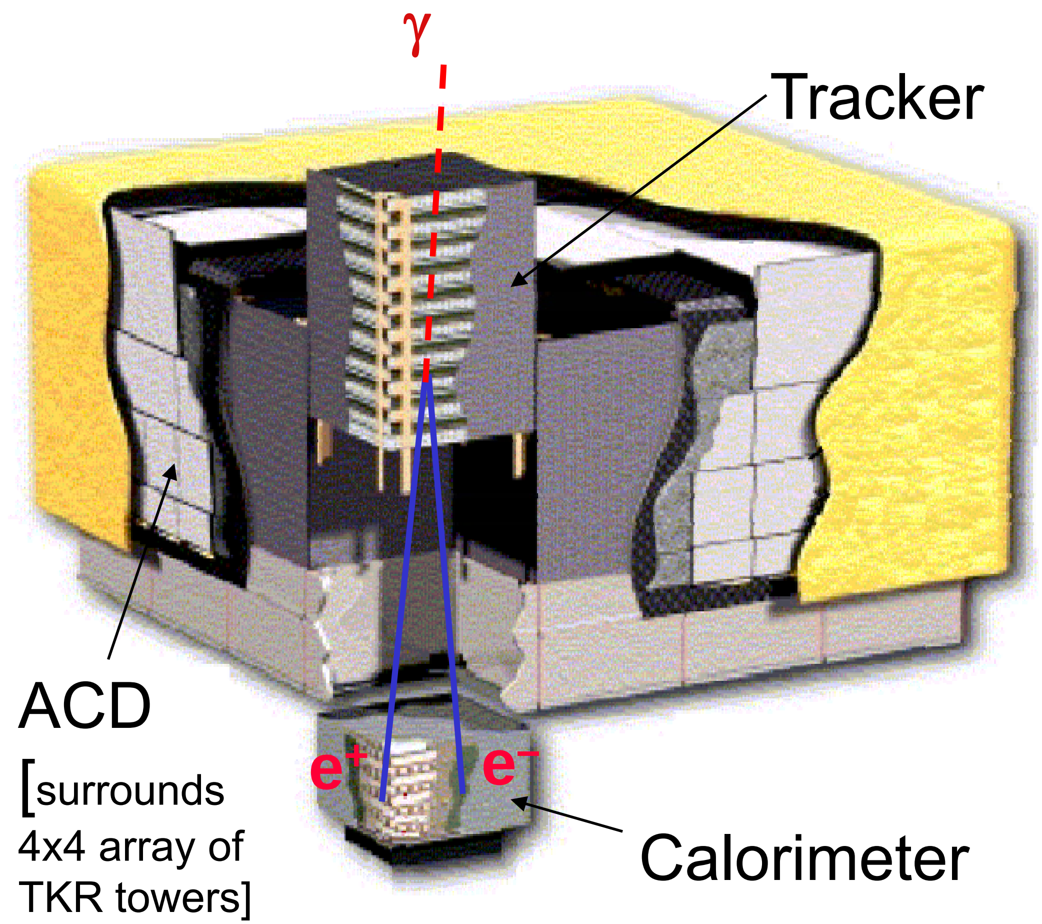
Gamma-ray Burst Monitor (GBM)
NaI and BGO Detectors
8 keV - 40 MeV

## KEY FEATURES

- Huge field of view
  - LAT: 20% of the sky at any instant; in sky survey mode, expose all parts of sky for ~30 minutes every 3 hours
  - GBM: whole unocculted sky at any time.
- Huge energy range, >7 decades!
  - including largely unexplored band 10-100 GeV
- Very small deadtime, <1us absolute timing accuracy
- Large leap in all key capabilities
- Great discovery potential

# Overview of 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)
  Array of 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.

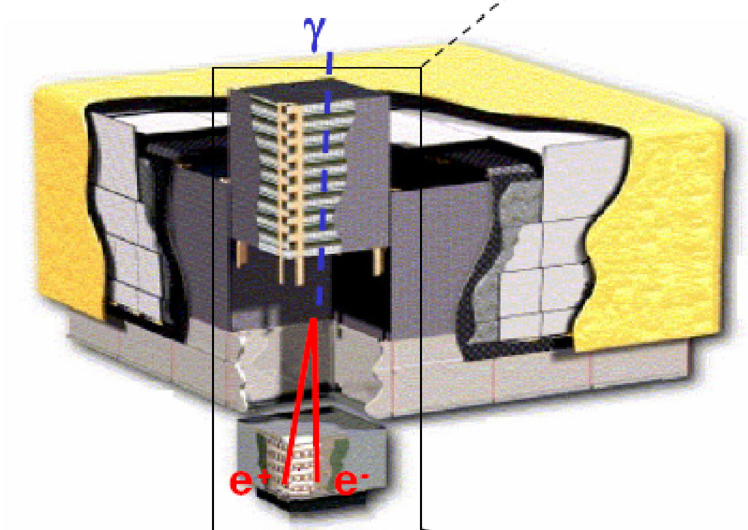



**Systems work together to identify and measure the flux of cosmic gamma rays with energy 20 MeV - >300 GeV.**

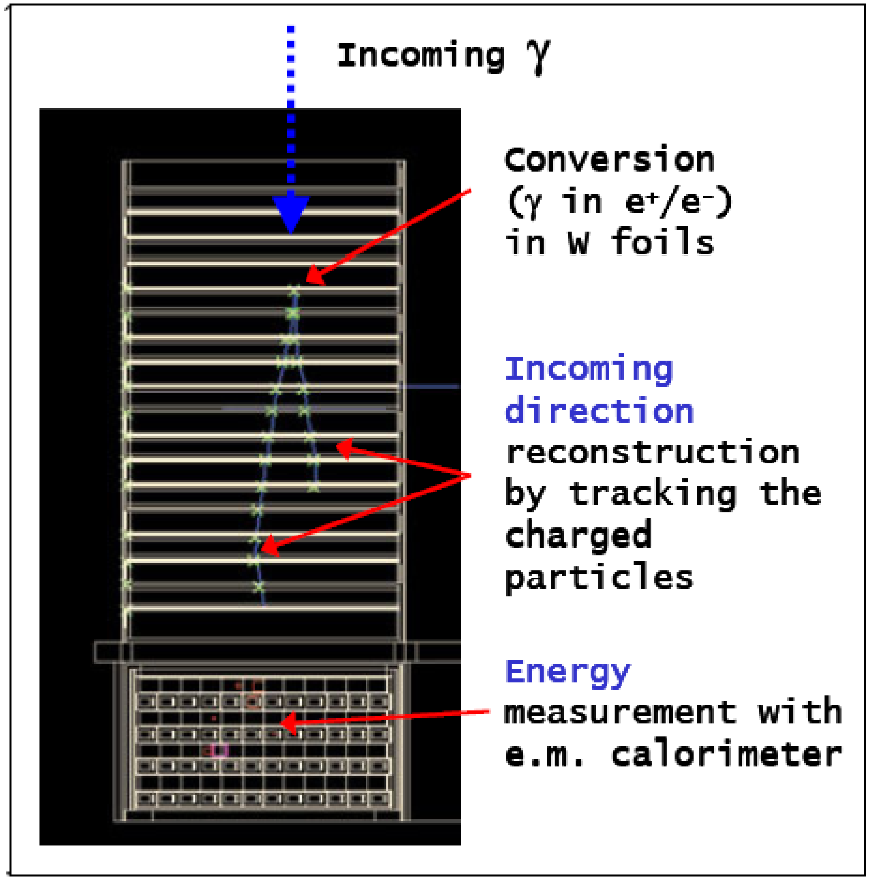
# LAT as Gamma-ray detector

4 x 4 array of identical towers with:

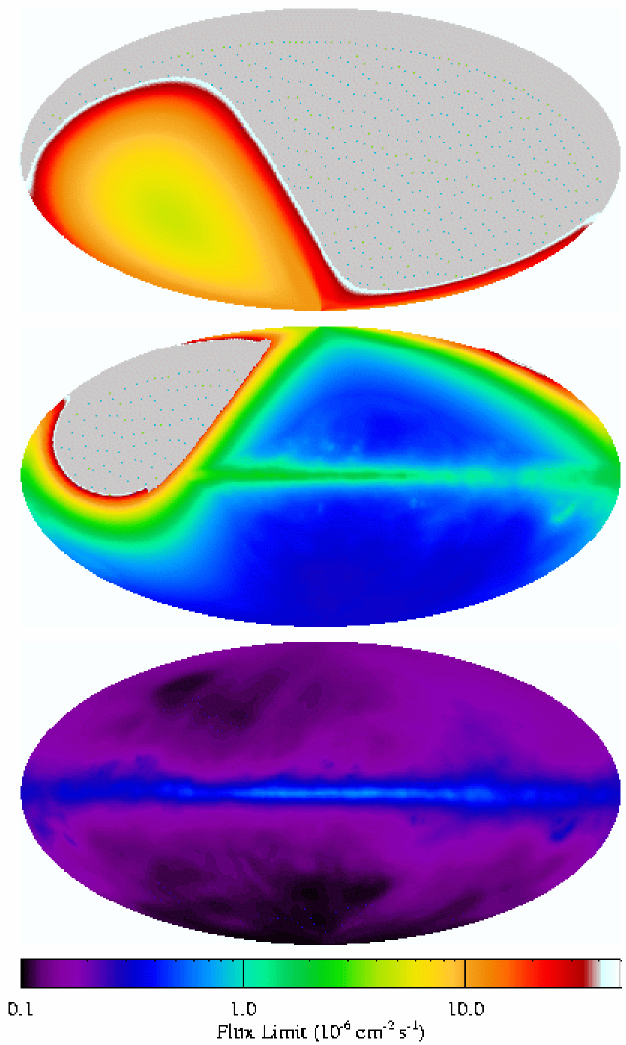
- Precision Si-strip tracker (TKR)
  - With W converter foils
- Hodoscopic CsI calorimeter (CAL)
- DAQ and Power supply box




An anticoincidence detector around the telescope distinguishes gamma-rays from charged particles



# Observation Mode

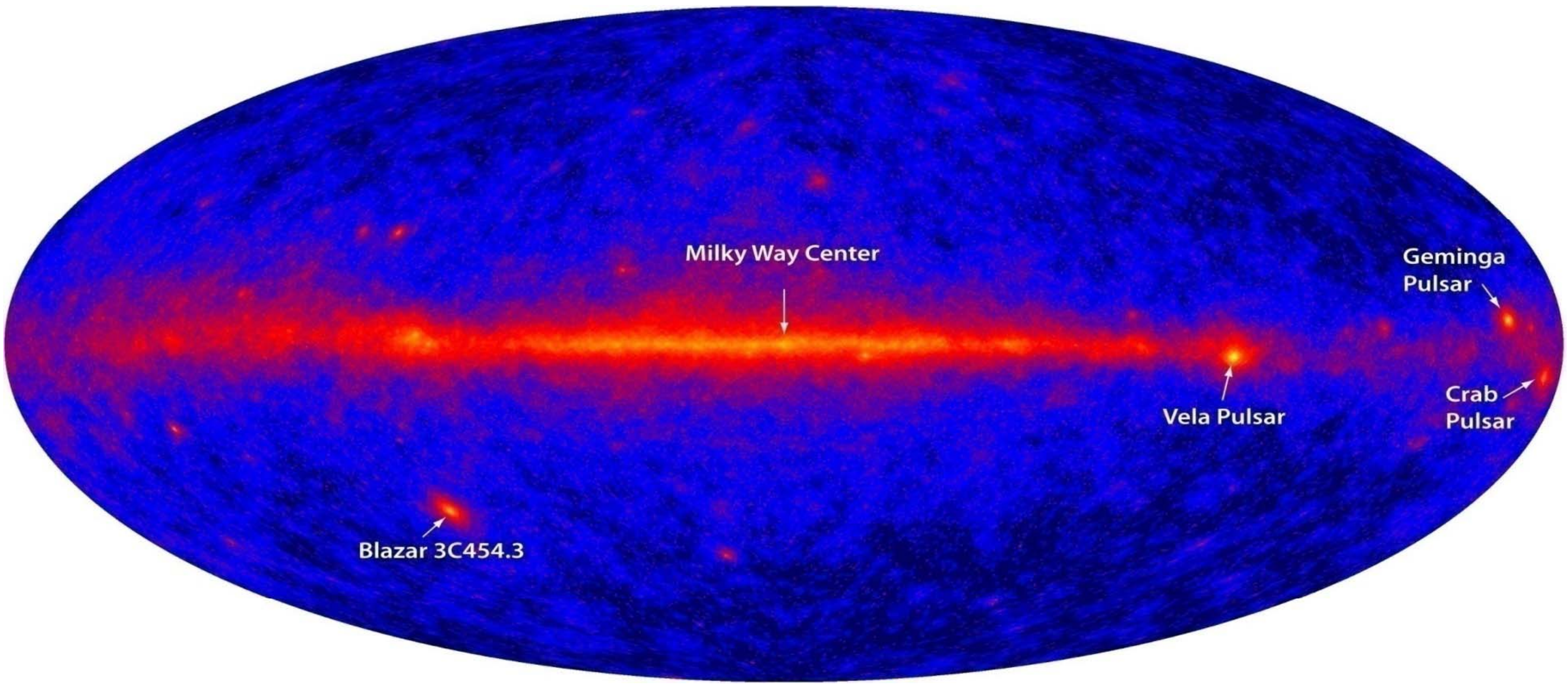



The field of view of the LAT is huge > 20% of the sky.

Rocking mode provides an efficient way of observing the entire sky with reasonably uniform exposure on timescales of hours.

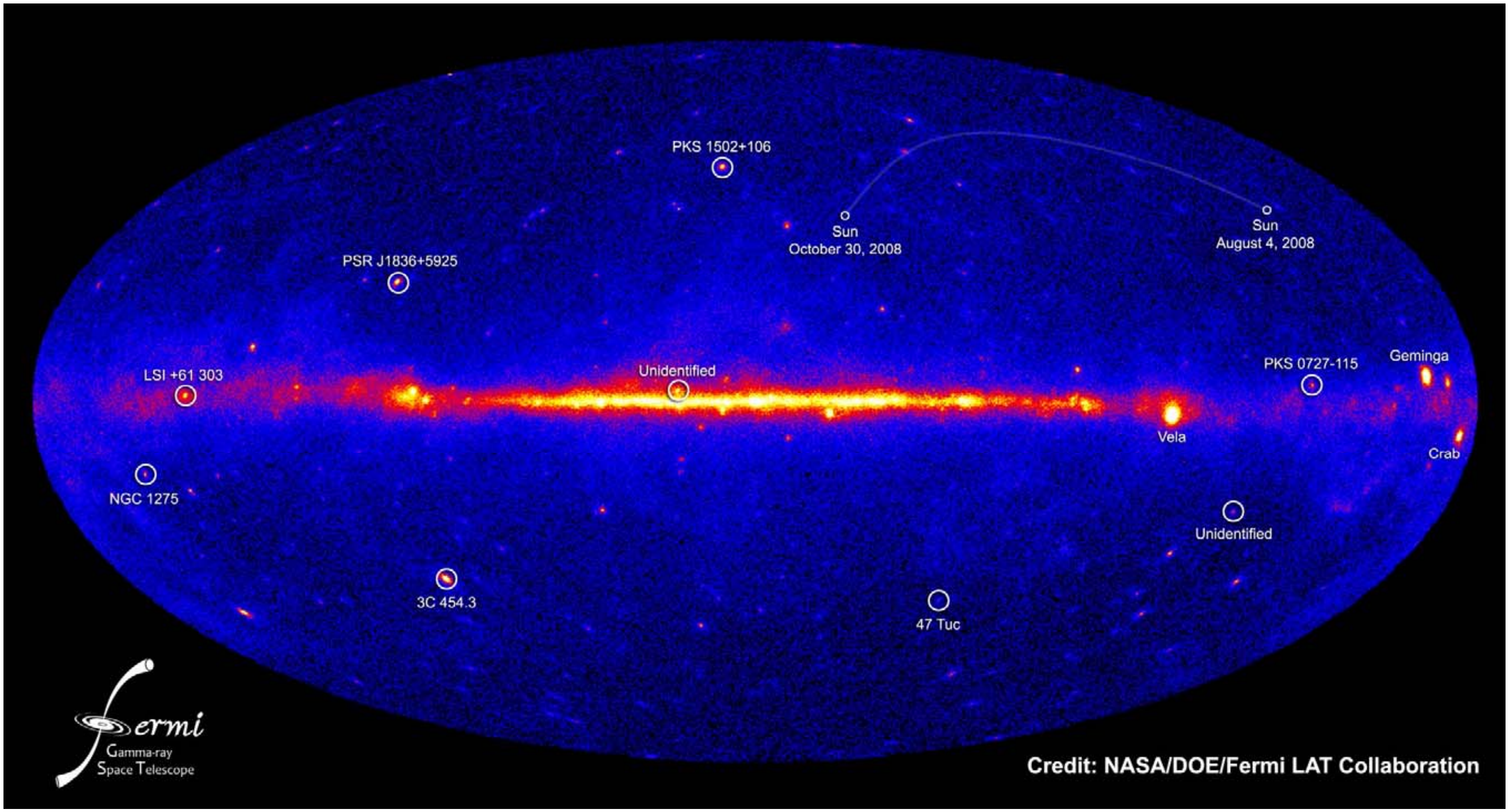
more exposure → greater sensitivity
more coverage → excellent for monitoring the sky on timescales from hours to years

# Fermi LAT First Light




Four days of all-sky survey engineering data.

# Fermi LAT 3 months image

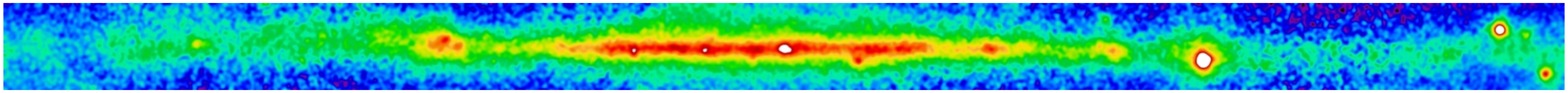


# HE astrophysics

- The “golden age”?
- Extragalactic sky
  - Population studies
  - High redshift GRB
  - Multiwavelenght studies
- Galactic sky
  - Pulsars
  - Identifications of source classes
- Search for DM in progress

# Basics of HE data analysis

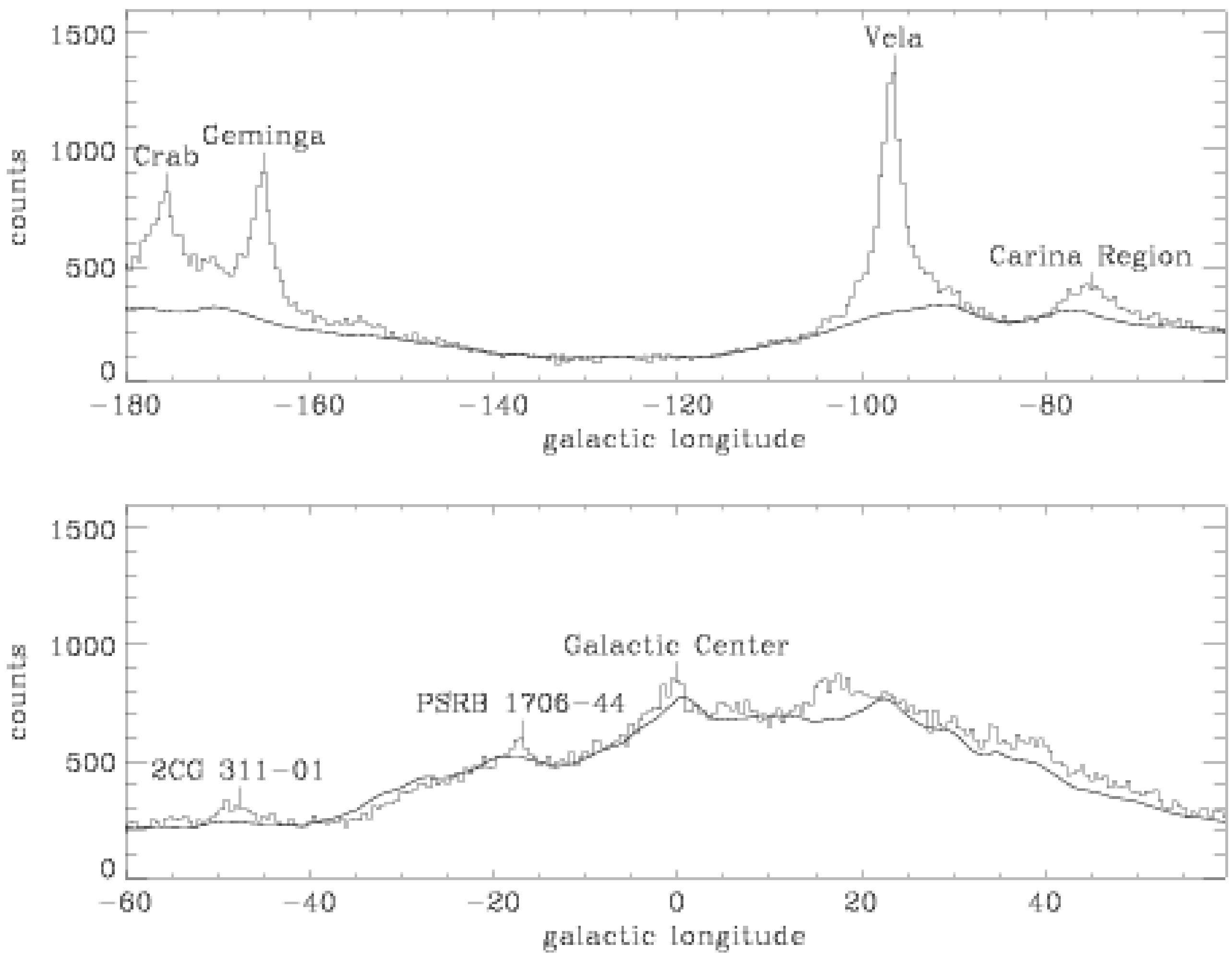
# Analysis Topics



EGRET >300 MeV

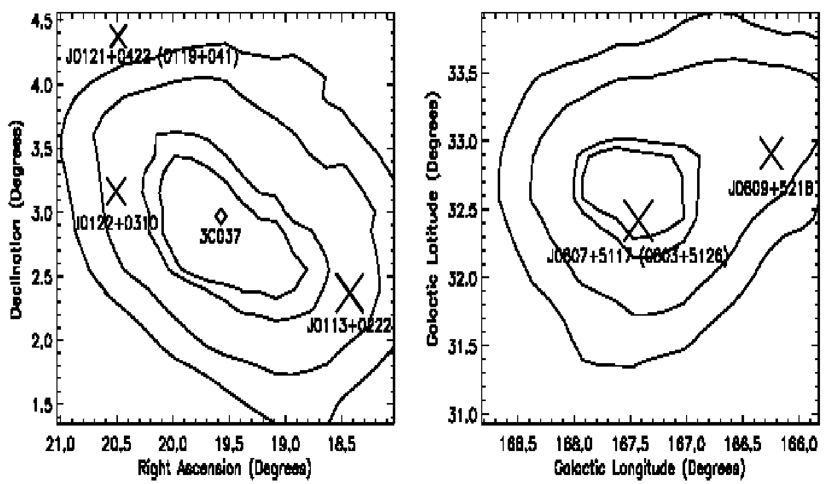
- First a word about interstellar gamma-ray emission:
- Brightest at low latitudes, but detectable over the whole sky
- >60% of EGRET celestial gamma rays
- It fundamentally affects the approach to the analysis

# Data Analysis



# Analysis Topics: Source detection

- Source detection means at least 2 things:
  - Recognizing that you've detected a point source that you didn't know about (and defining its statistical significance and location on the sky)




Source location contours for two 3EG sources (Hartman et al. 1999). Potential (additional) counterparts, unresolved by EGRET, are indicated

  - Determining the significance of the detection of (or measuring an upper limit for) an already-known source

Sowards-Emmerd, Romani, & Michelson (2003, ApJ, 590, 109)

# Analysis Topics: Spectral analysis

- Well, this means measuring spectra
  - Mostly power laws resulting from shock acceleration, which is scale free
  - Spectral breaks occur for physics reasons and measuring them is diagnostic of the sources.
- For EGRET, the analysis of source spectra was a 2-step process
  - Fluxes were derived for fairly broad ranges of energy independently
  - Then a spectral model was fit
- The complication was that the exposure for a broad energy range depends on the source spectrum, so the fitting process was iterative.

$$F_\gamma = (2.01 \pm 0.12) \times 10^{-6} (E/0.214\ \mathrm{GeV})^{-2.18 \pm 0.08}\ \text{photon}\ (\mathrm{cm}^2\ \mathrm{s\ GeV})^{-1}\ .$$

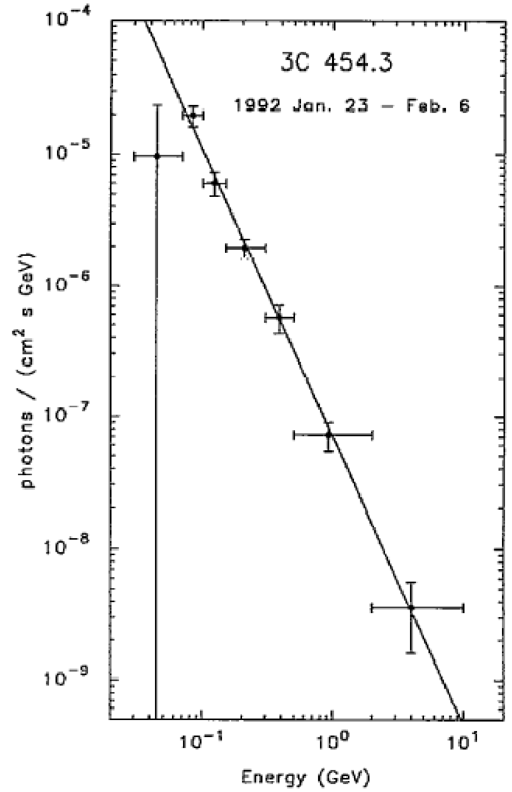



FIG. 3.—High-energy gamma ray spectrum of 3C 454.3 during the time interval 1992 January 23 to February 6. See text for comments on the 30–70 MeV point.

Hartman et al. 1993 (ApJ, 407,L41),

# A useful reference

- EGRET: Mattox et al. (1996) Astrophysical Journal v.461, p.396



THE ASTROPHYSICAL JOURNAL, 461:396–407, 1996 April 10


## THE LIKELIHOOD ANALYSIS OF EGRET DATA

J. R. MATTOX,[1,2,3,4] D. L. BERTSCH,[1] J. CHIANG,[5] B. L. DINGUS,[1,3] S. W. DIGEL,[1,6] J. A. ESPOSITO,[1,3]
J. M. FIERRO,[7] R. C. HARTMAN,[1] S. D. HUNTER,[1] G. KANBACH,[8] D. A. KNIFFEN,[9] Y. C. LIN,[7]
D. J. MACOMB,[2,3] H. A. MAYER-HASSELWANDER,[8] P. F. MICHELSON,[7] C. VON MONTIGNY,[1,10]
R. MUKHERJEE,[1,3] P. L. NOLAN,[7] P. V. RAMANAMURTHY,[1,10] E. SCHNEID,[11]
P. SREEKUMAR,[1,3] D. J. THOMPSON,[1] AND T. D. WILLIS[7]
*Received 1994 March 22; accepted 1995 October 13*

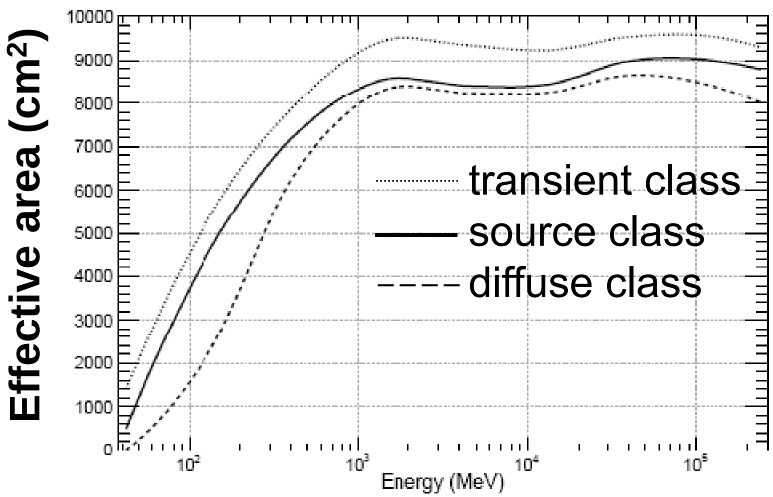
### ABSTRACT

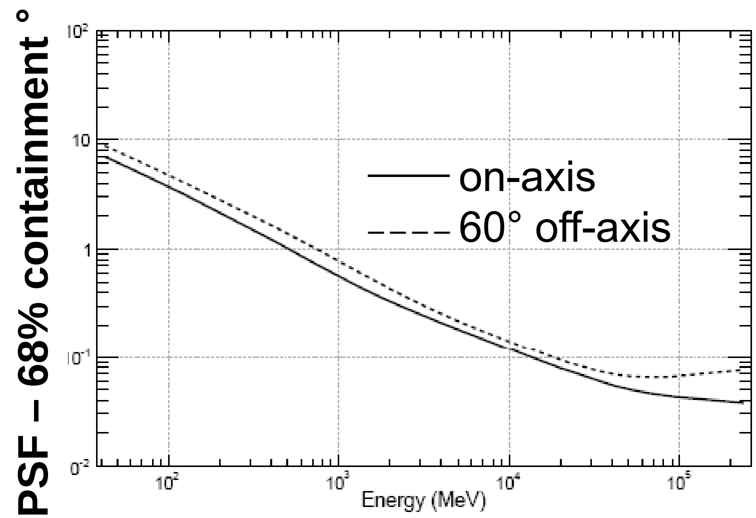
The use of likelihood for the analysis of high-energy $\gamma$-ray data from the EGRET instrument aboard the *Compton Gamma-Ray Observatory* is described. Maximum likelihood is used to estimate point-source flux densities, source locations, and background model parameters. The likelihood ratio test is used to determine the significance of point sources. Monte Carlo simulations have been done to confirm the validity of these techniques.

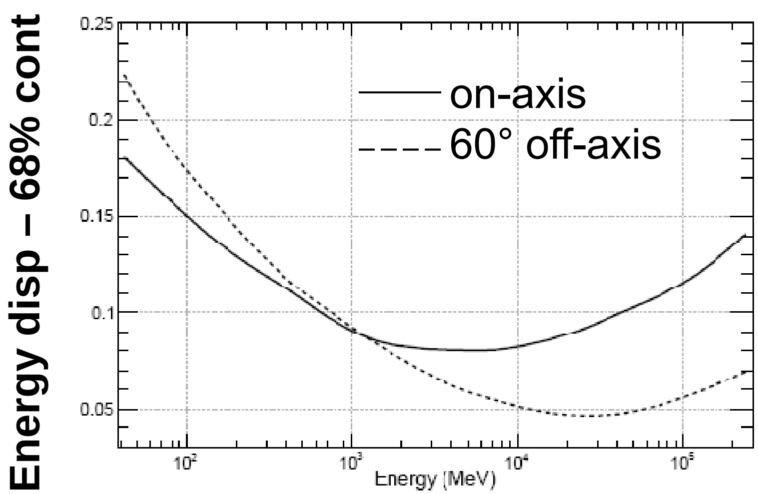
*Subject headings:* gamma rays: observations — methods: data analysis — methods: statistical

# LAT Data Analysis

# Instrument Response Functions



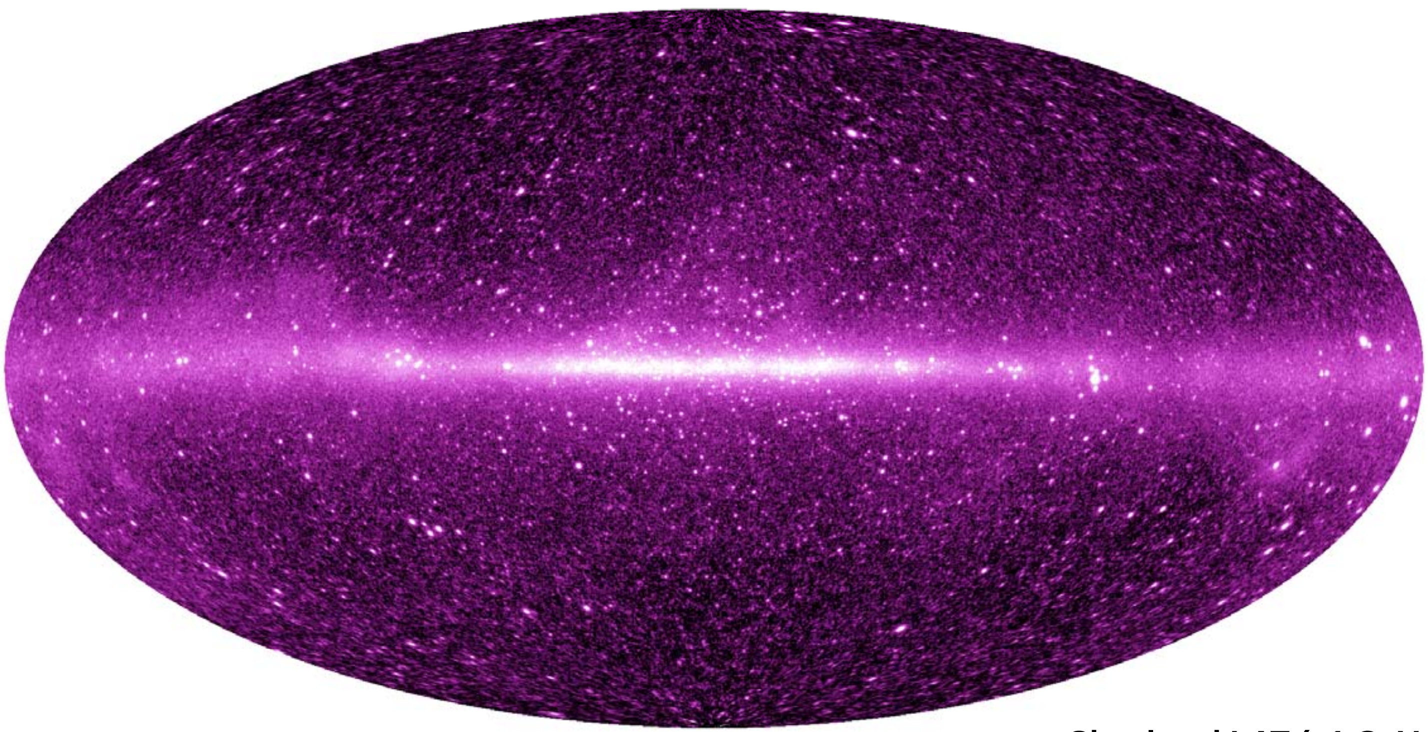

**The Large Area Telescope on the Fermi Gamma-ray Space Telescope**
Atwood, W. B. et al. 2009, ApJ, 697, 1071 doi: 10.1088/0004-637X/697/2/1071

Post-launch performance tuning on-going

➢ IRF update for public data release + future updates

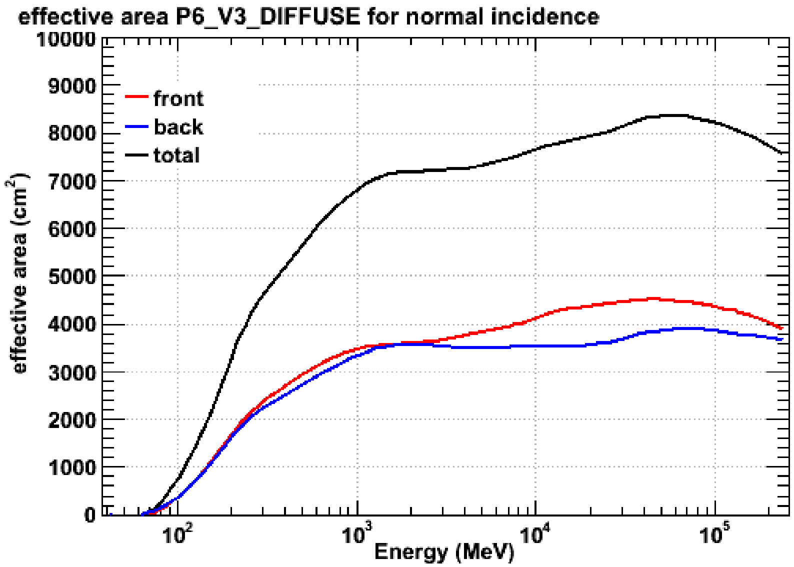
# The Gamma-Ray Sky

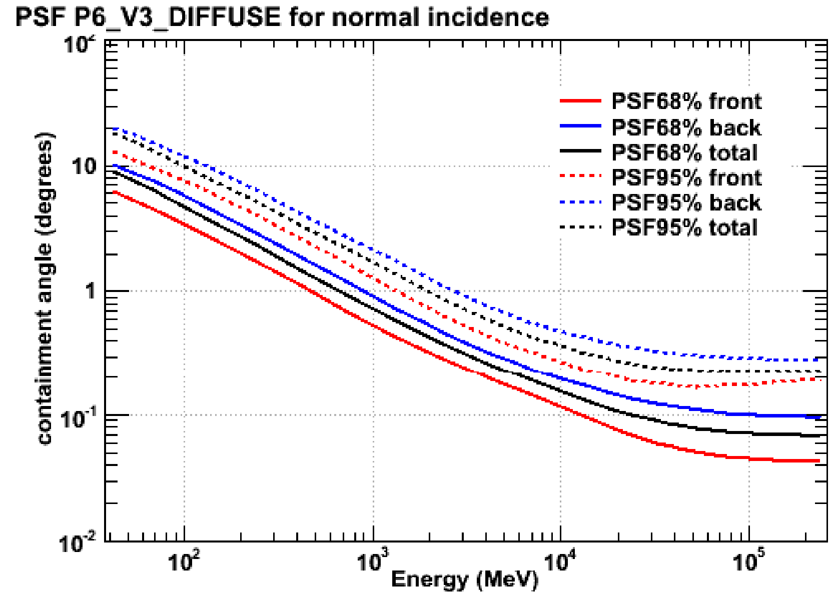
- Comparing EGRET to Fermi LAT:
  - Illustrating the anticipated improvement in our knowledge of the sky

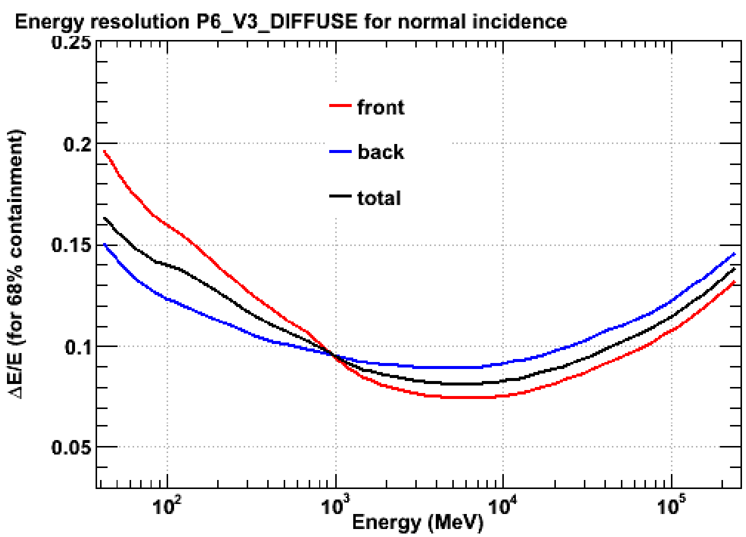


**Simulated LAT (>1 GeV, 1 yr)**

# Instrument Response Functions



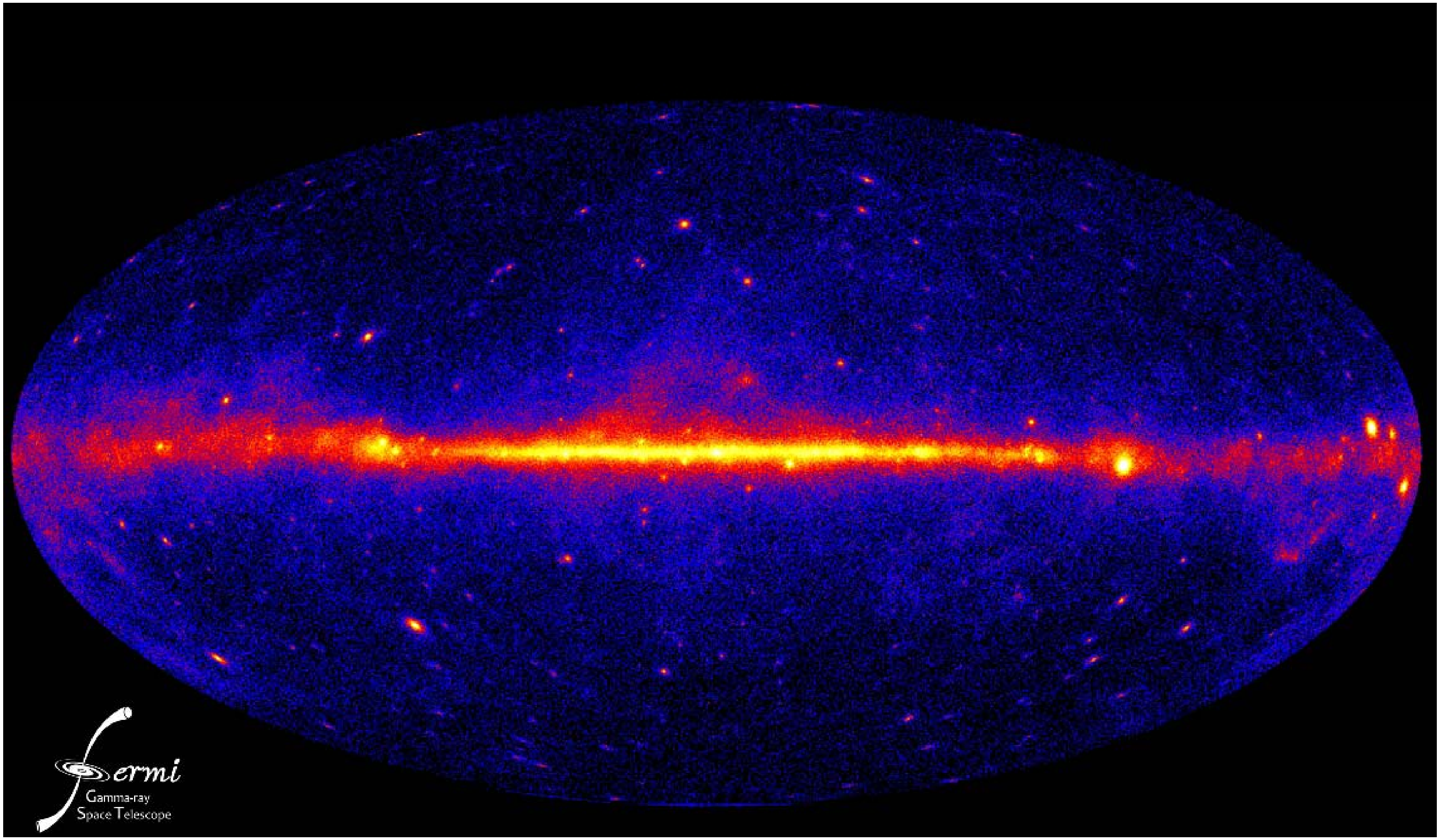




Performance updates are expected soon:

- Mapping the orbital dependence of the pileup effect, which varies with the incoming particle trigger rate.
- Recovering the instrument acceptance after proper correction of the event reconstruction and background rejection analysis based on update simulations

http://www-glast.slac.stanford.edu/software/IS/glast_lat_performance.htm

# The Fermi 1 yr sky



# Data Analysis Issues

- The PSF is large at low energy, small at high energy.
- With the LAT's large effective area, many sources will be detected; their PSFs will merge at low energy.
  - ∴ Analysis is inherently 3D—2 spatial and 1 spectral (& users are interested in temporal!)
- For a typical analysis the source model must include
  - All point sources within a few PSF lengths of the region of interest
  - Diffuse sources (e.g., supernova remnants)
  - Diffuse Galactic emission (modeled)
  - Diffuse extragalactic emission
- Sources are defined by position, spectra, and perhaps time history. Initial values may be extracted from the point source catalog that were compiled by the LAT team.
- The source model will have many parameters. In an analysis some will be fitted, some will be fixed.

# Data Analysis Issues-II

- The instrument response (PSF, effective area, energy resolution) will most likely be a function of energy, angle to the LAT normal, conversion layer (the front or back of the LAT), and the electron-positron vertex angle. The IRF may also depend on the charged particle background resulting from the geomagnetic latitude, Solar cycle phase, etc.
- The LAT will usually survey the sky. Therefore a source will be observed at different instrument orientations.

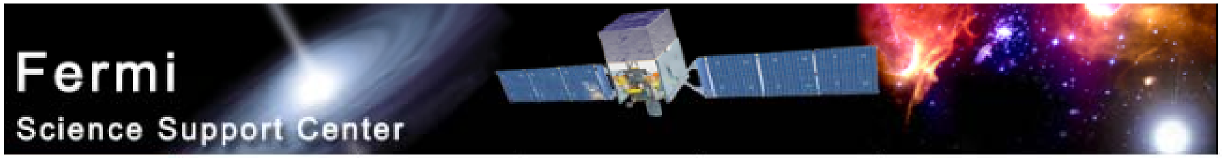
# Observables

- The observables for a photon are:
  - Apparent energy
  - Apparent origin in sky coordinates (2 observables)
  - Apparent origin in instrument coordinates (2 observables)
  - Time
  - Front vs. back of LAT
  - …
- Therefore, a very large data space results. Even with $10^5$ counts, this data space will be sparsely populated.

GODDARD SPACE FLIGHT CENTER

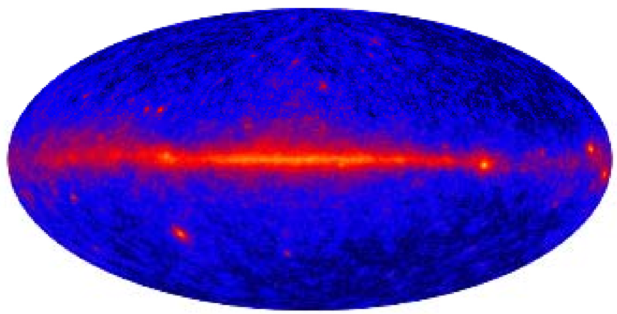
+ NASA Homepage
+ GSFC Homepage
+ Fermi Homepage

SEARCH Fermi: Search + GO




HOME | RESOURCES | PROPOSALS | DATA | HEASARC | HELP | SITE MAP

The Fermi Science Support Center (FSSC) runs the guest investigator program, creates and maintains the mission time line, provides analysis tools for the scientific community, and archives and serves the Fermi data. This web site is the portal to Fermi for all guest investigators.



This all-sky view from Fermi reveals bright emission in the plane of the Milky Way (center), bright pulsars and super-massive black holes.
*Credit: NASA/DOE/International LAT Team*

Look into the "Resources" section for finding schedules, publications, useful links etc. The "Proposals" section is where you will be able to find the relevant information and tools to prepare and submit proposals for guest investigator projects. At "Data" you will be able to access the Fermi databases and find the software to analyse them. Address all questions and requests to the helpdesk in "Help".

## Quicklist

- 2009 Fermi Symposium
- GLAST Fellowship Program
- Fermi Guest Investigator Program
- Fermi Sky Blog
- Multiwavelength Observation Reporting Form
- Fermi User's Group (FUG)

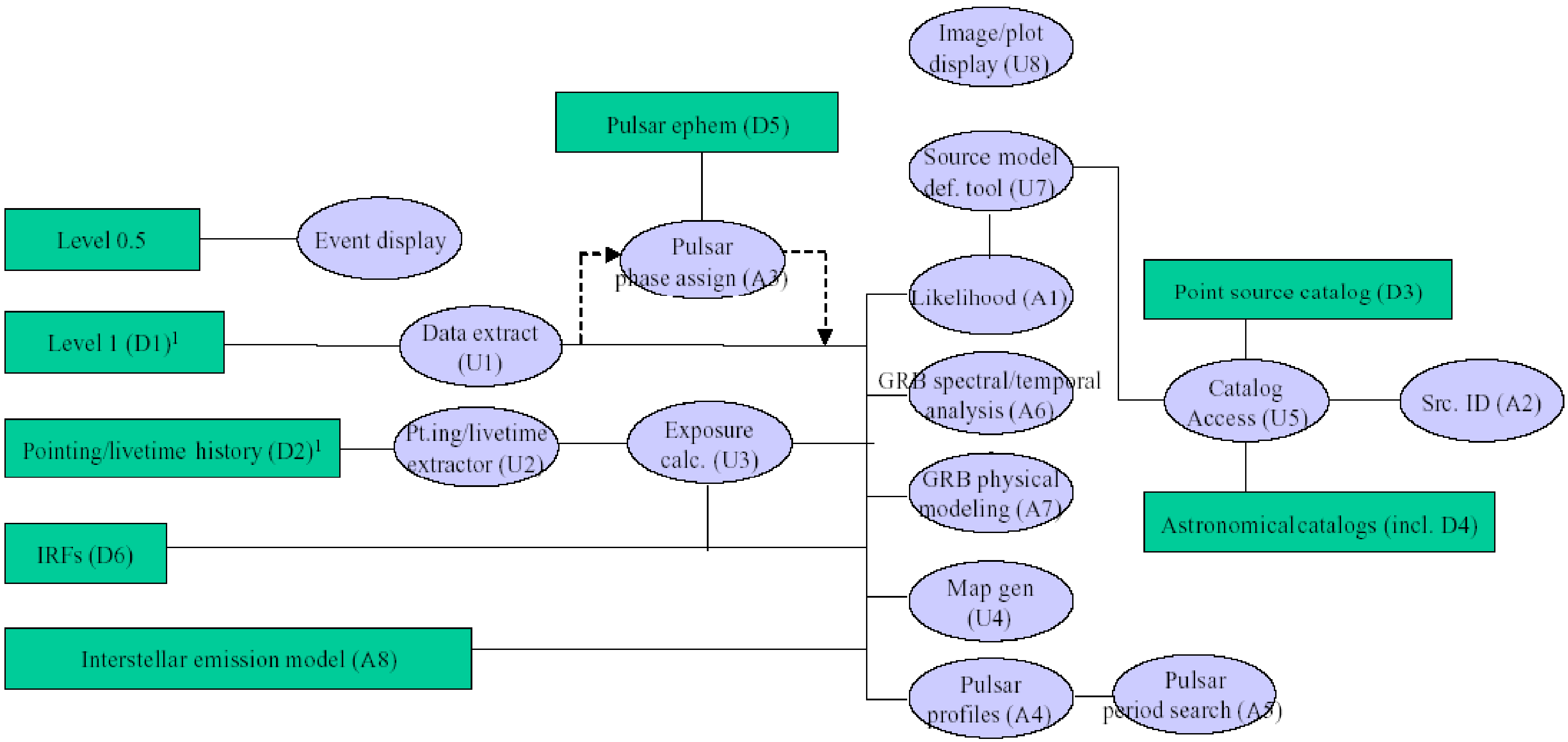
## News

**June 18, 2009**
**Selections for the Cycle-2 Guest Investigator Program**
Selections for the Cycle-2 Guest Investigator Program were announced by NASA HQ on June 18, 2009. A list of these programs can be viewed here.

**April 20, 2009**
**Fermi Symposium**
The 2009 Fermi Symposium is dedicated to results and prospects for scientific exploration of the Universe with the Fermi Gamma-ray Space Telescope and related studies. The symposium will be held shortly after the Fermi data release, offering an opportunity for the astrophysical community to share in the excitement of discoveries being made with the Fermi instruments. Topics will include: blazars and other active galactic nuclei, pulsars, gamma-ray bursts, supernova remnants, diffuse gamma radiation, unidentified gamma-ray sources, and searches for dark matter. The meeting will be held November 2-5, 2009 in downtown Washington, D.C.

fermi.gsfc.nasa.gov/ssc

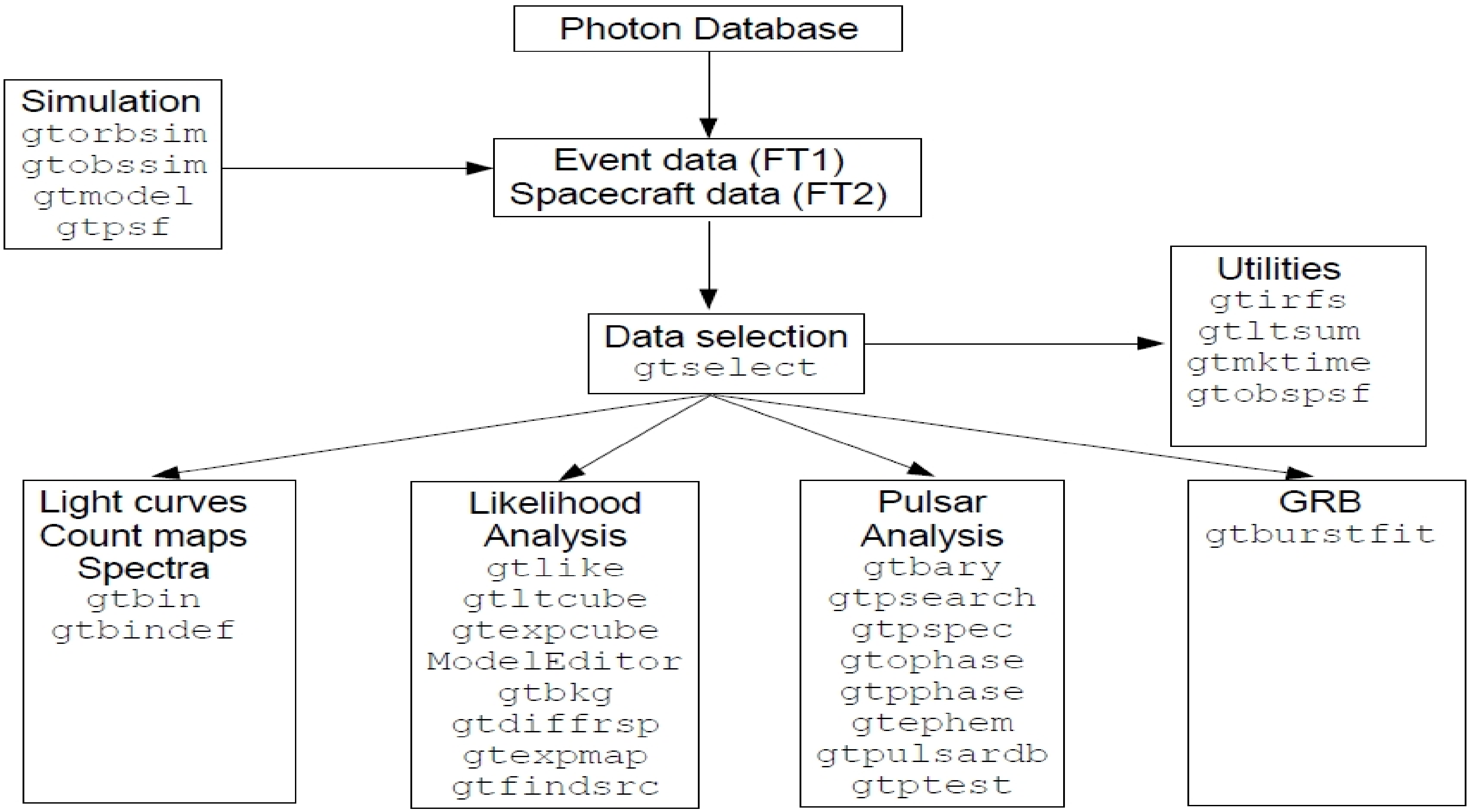
# LAT Science Tools



# Science Analysis Tools

- Overview of capabilities
  - Maximum likelihood tool—spatial-spectral analysis of region (source detection, flux)
    - Includes background models
  - Pulsars—period analysis, blind searches
    - Includes ephemerides DB
  - Event-level observation simulator
    - enables modeling of a large variety of sources: flaring and periodic sources with spectral variability, diffuse sources, etc.
  - GRBs—temporal cuts, spectral analysis: Ftools, XSPEC
- Tools and documentation are released through FSSC website

# Science Tools: Flowchart



# Science Tools: Documentation

- Multi-Tier Documentation
  - Full set accompanies SW release
    - Fermi Mission Technical Handbook
  - Multiple levels:
    - Detailed analysis description (‘Cicerone’)
    - Individual tool descriptions (like fhelp)
    - Analysis threads (cook book examples)
    - Also, ‘Crash Course’ guide