GLAST Large Area Telescope:

Science Goals and Instrument Design

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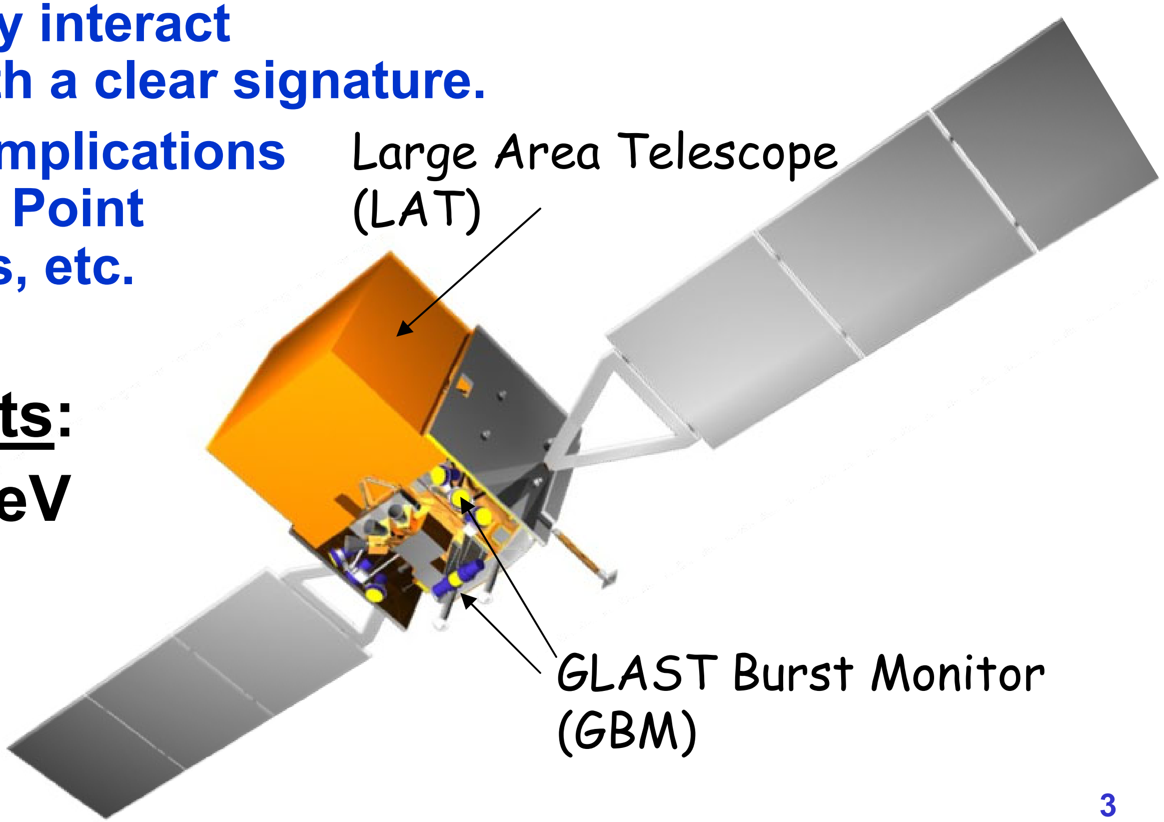
Outline

- Why γ's? Why this energy range?
- A few science topics highlights
- LAT instrument design overview
- Data challenges
- Summary

Why study γ's?

Gamma rays carry a wealth of information:

- γ rays do not interact much at their source: they offer a direct view into Nature's largest accelerators.
- similarly, the Universe is mainly transparent to γ rays: can probe cosmological volumes. Any opacity is energy-dependent.
- conversely, γ rays readily interact in detectors, with a clear signature.
- γ rays are neutral: no complications due to magnetic fields. Point directly back to sources, etc.



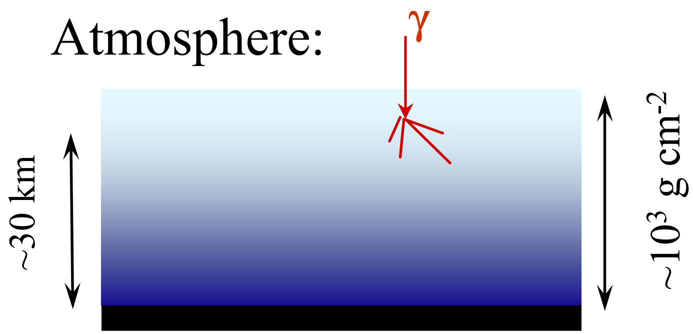
<u>Two GLAST instruments</u>:

LAT: 20 MeV – >300 GeV

GBM: 10 keV – 25 MeV

Cosmic γ-ray Measurement Techniques

Atmosphere:



For E_γ < ~ 100 GeV, must detect above atmosphere (balloons, satellites)

For E_γ > ~100 GeV, information from showers penetrates to the ground (Cerenkov, air showers)

Photon interaction mechanisms:

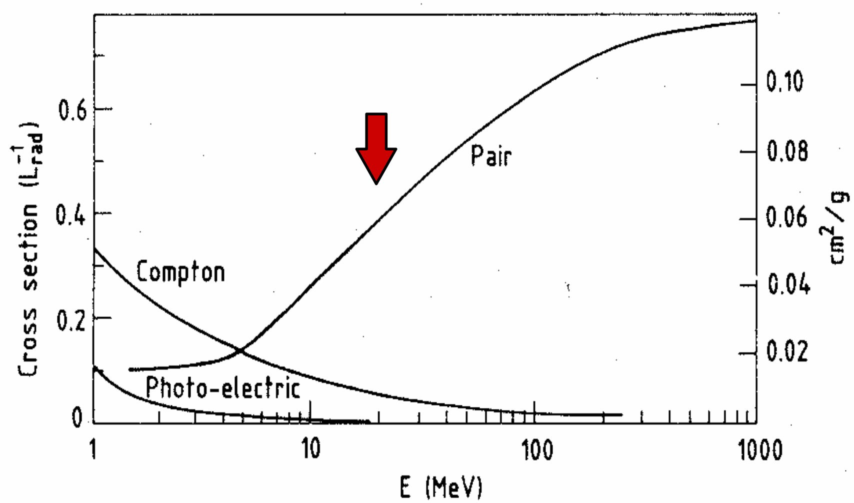
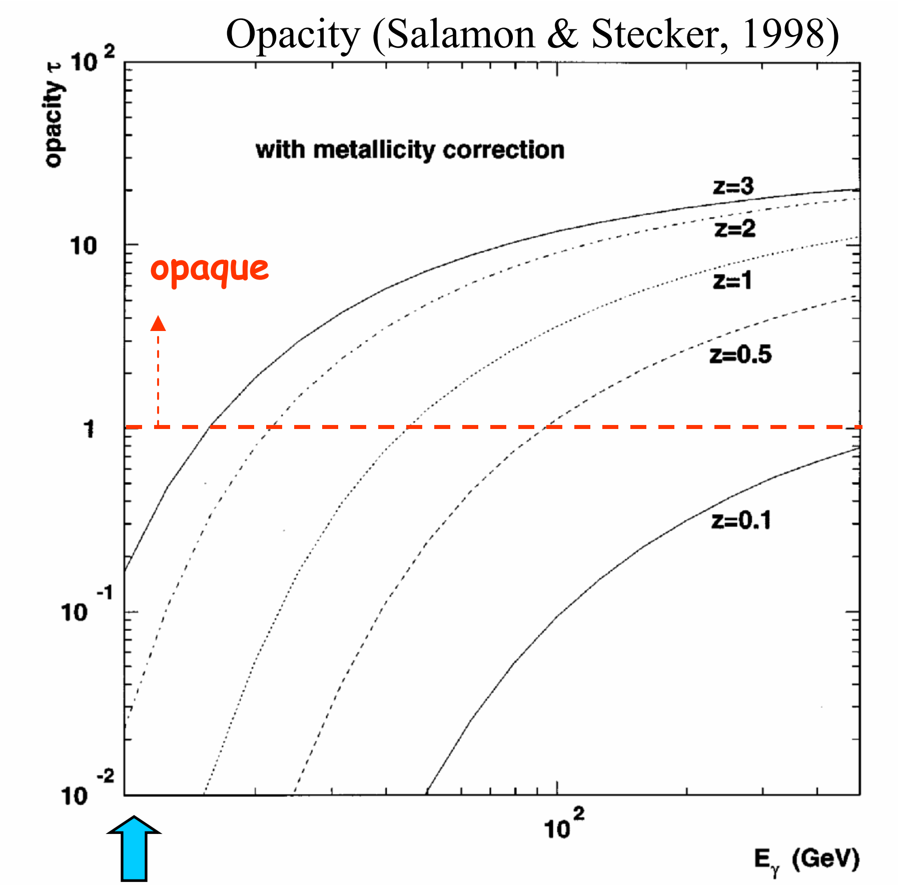


Fig. 2: Photon cross-section σ in lead as a function of photon energy. The intensity of photons can be expressed as $I = I_0 \exp(-\sigma x)$, where x is the path length in radiation lengths. (Review of Particle Properties, April 1980 edition).

An Important Energy Band for Cosmology

Photons with E>10 GeV are attenuated by the diffuse field of UV-Optical-IR extragalactic background light (EBL)



No significant attenuation below ~10 GeV.

only $e^{-\tau}$ of the original source flux reaches us

EBL over cosmological distances is probed by gammas in the 10-100 GeV range. Important science for GLAST!

In contrast, the TeV-IR attenuation results in a flux that may be limited to more local (or much brighter) sources.

A dominant factor in EBL models is the time of galaxy formation -- attenuation measurements can help distinguish models.

GLAST Science

GLAST will have a very broad menu that includes:

- Systems with supermassive black holes
- Gamma-ray bursts (GRBs)
- Pulsars
- Solar physics
- Origin of Cosmic Rays
- Probing the era of galaxy formation
- Solving the mystery of the high-energy unidentified sources
- Discovery! Particle Dark Matter? Other relics from the Big Bang? Testing Lorentz invariance. New source classes.

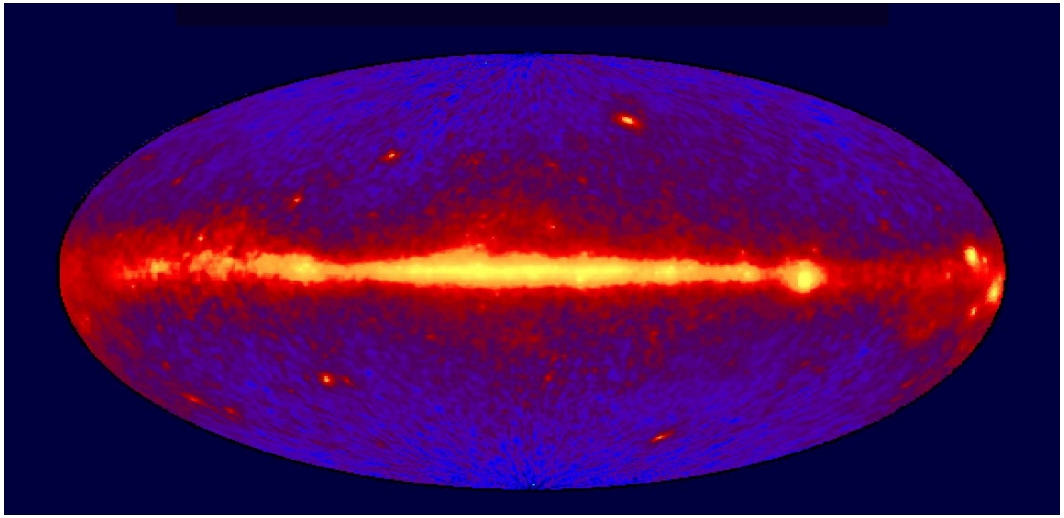
Huge increment in capabilities.

GLAST draws the interest of both the the High Energy Particle Physics and High Energy Astrophysics communities.

GLAST LAT High Energy Capabilities

- *Huge FOV (~20% of sky)*
- *Broadband (4 decades in energy, including unexplored region > 10 GeV)*
- *Unprecedented PSF for gamma rays (factor > 3 better than EGRET for E>1 GeV)*
- *Large effective area (factor > 4 better than EGRET)*
- ***Results in factor > 30-100 improvement in sensitivity***
- *No expendables → long mission without degradation*

Features of the gamma-ray sky



EGRET all-sky survey (galactic coordinates) E>100 MeV

diffuse extra-galactic background (flux ~ 1.5×10^{-5} $cm^{-2}s^{-1}sr^{-1}$)

galactic diffuse (flux ~O(100) times larger)

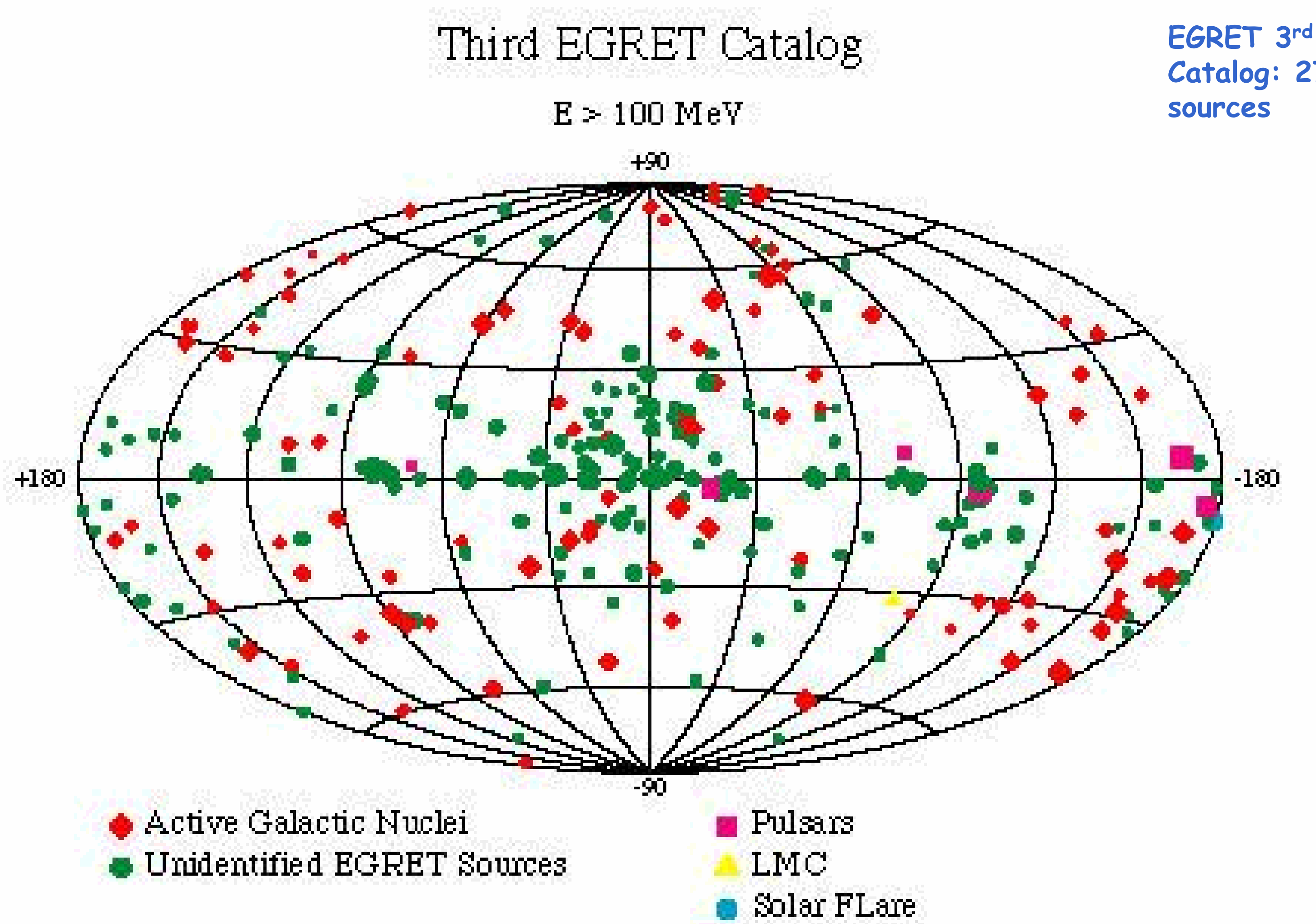
high latitude (extra-galactic) point sources (typical flux from EGRET sources O(10^{-7} - 10^{-6}) $cm^{-2}s^{-1}$

galactic sources (pulsars, un-ID'd)

An essential characteristic: VARIABILITY in time!

Field of view, and the ability to repoint, important for study of transients.

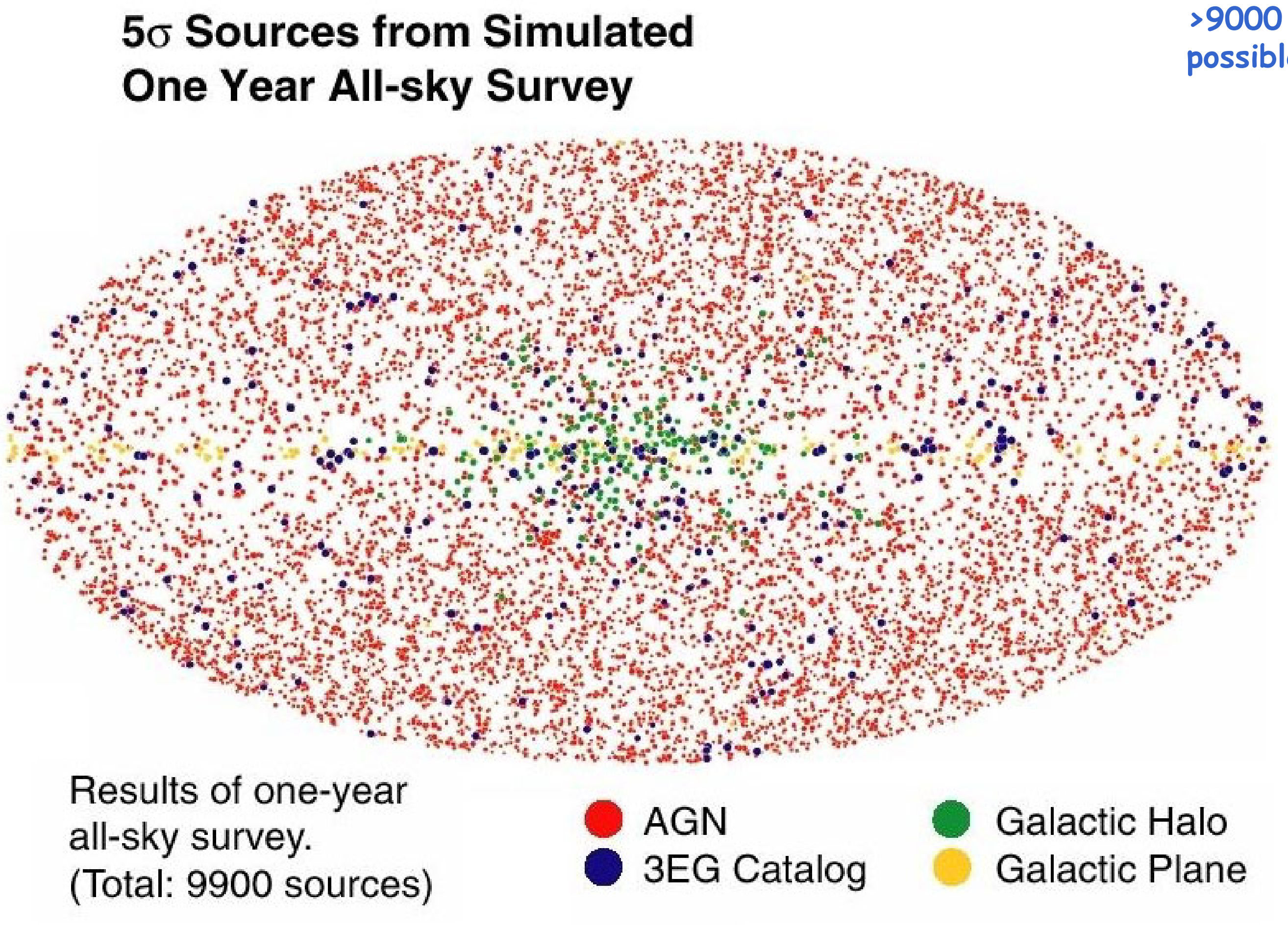
Sources



EGRET 3rd Catalog: 271 sources

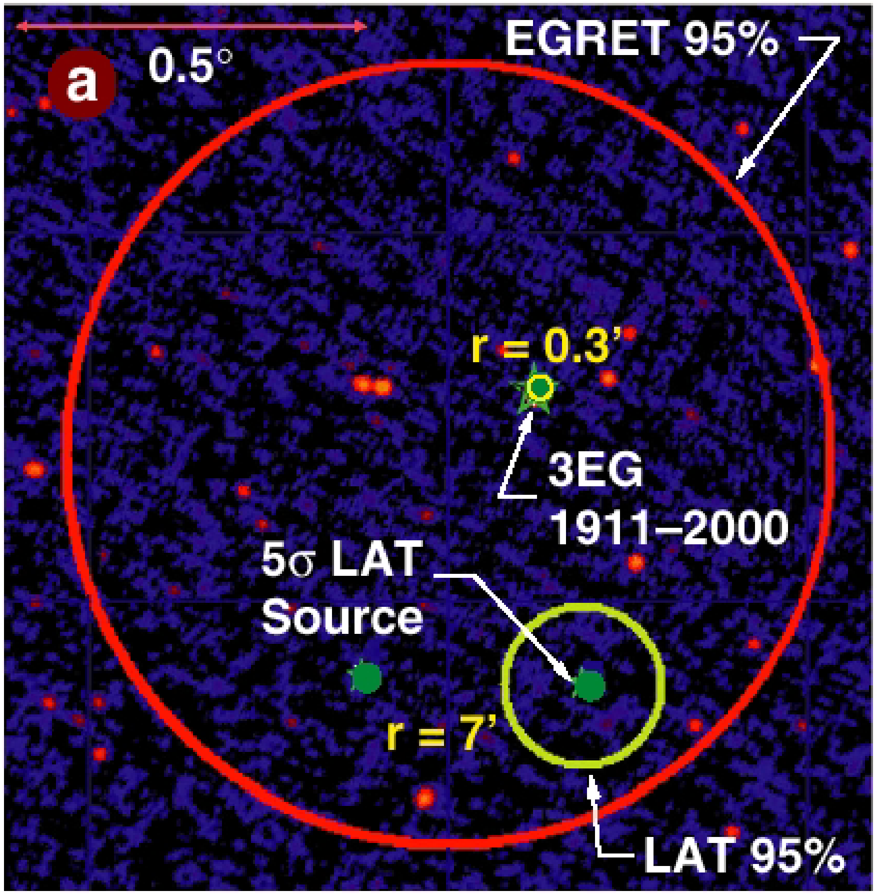
Sources

LAT 1st Catalog:
>9000 sources
possible



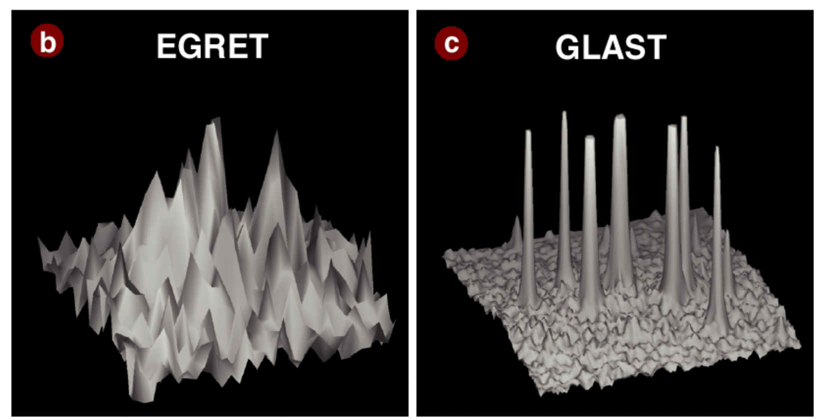
Unidentified Sources

172 of the 271 sources in the EGRET 3rd catalog are “unidentified”



- Rosat or Einstein X-ray Source
- 1.4 GHz VLA Radio Source

EGRET source position error circles are ~0.5°, resulting in counterpart confusion.
GLAST will provide much more accurate positions, with ~30 arcsec - ~5 arcmin localizations, depending on brightness.



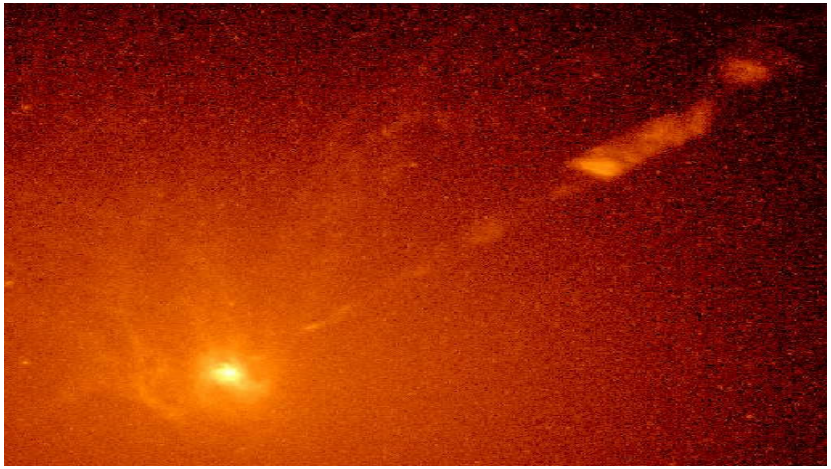
Cygnus region (15x15 deg)

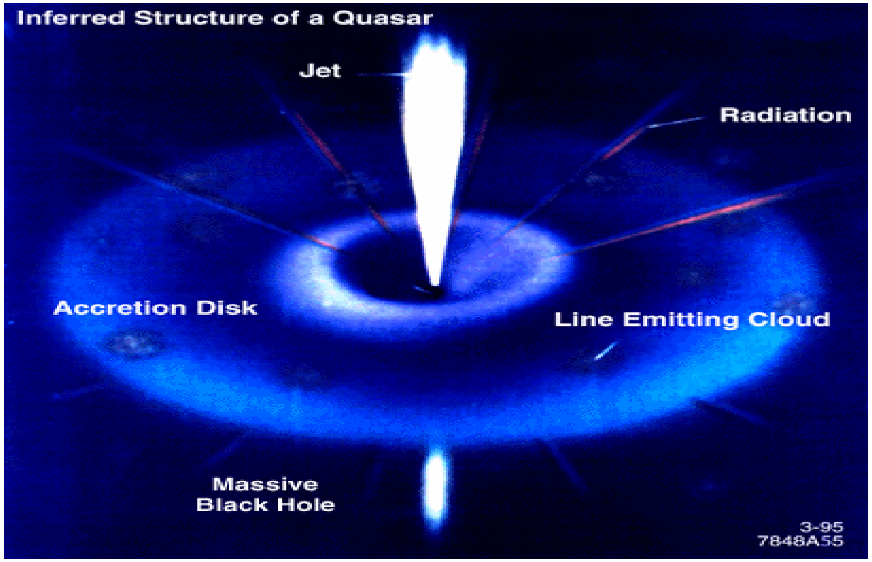
Active Galactic Nuclei (AGN)

Active galaxies produce vast amounts of energy from a very compact central volume.

Prevailing idea: powered by accretion onto super-massive black holes (10^6 - 10^{10} solar masses). Different phenomenology primarily due to the orientation with respect to us.

HST Image of M87 (1994)



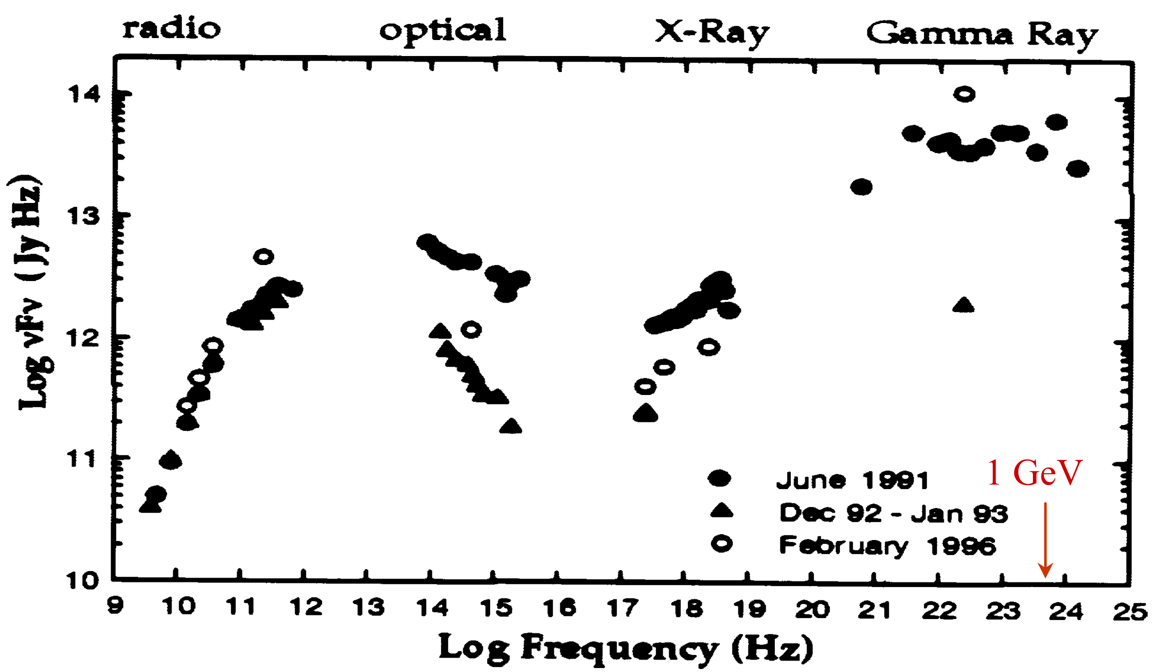


Models include energetic (multi-TeV), highly-collimated, relativistic particle jets. High energy γ-rays emitted within a few degrees of jet axis. Mechanisms are speculative; γ-rays offer a direct probe.

AGN Shine Brightly in Gammas

Power output of AGN is remarkable. Multi-GeV component can be dominant.

Estimated luminosity of 3C 279:
~ 10^{45} erg/s
corresponds to 10^{11} times total solar luminosity
just in γ-rays. Large variability within days.



Multiwavelength Spectrum of 3C 279

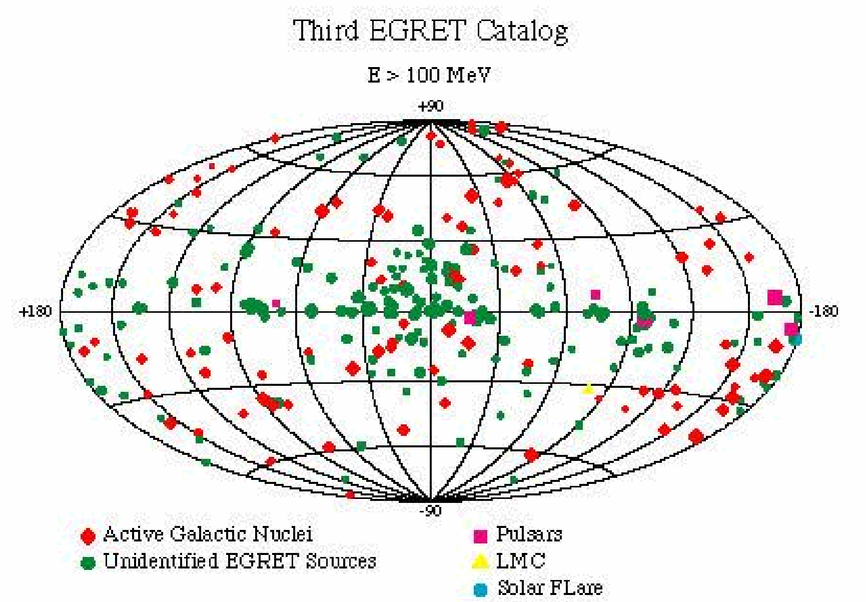
Sum all the power over the whole electromagnetic spectrum from all the stars of a typical galaxy: an AGN emits this amount of power in JUST γ rays from a very small volume!

A surprise from EGRET:

detection of >70 AGN

shining brightly in

γ-rays -- Blazars

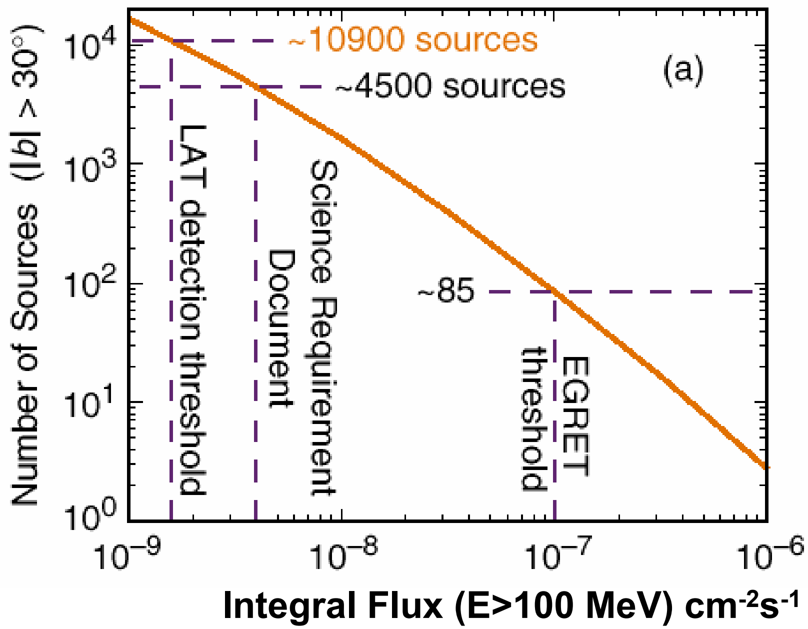


- a key to solving the longstanding puzzle of the extragalactic diffuse gamma flux -- is this integrated emission from a large number of unresolved sources?
- blazars provide a source of high energy γ-rays at cosmological distances. The Universe is largely transparent to γ-rays (any opacity is energy-dependent), so they probe cosmological volumes.

AGN: What GLAST will do

EGRET has detected ~ 70 AGN.
Extrapolating, GLAST should expect to see dramatically more – many thousands:

- Allows a statistically accurate calculation of AGN contribution to the high energy diffuse extra-galactic background.
- Constrain acceleration and emission models. Correlate with other wavelength facilities. How do AGN work?

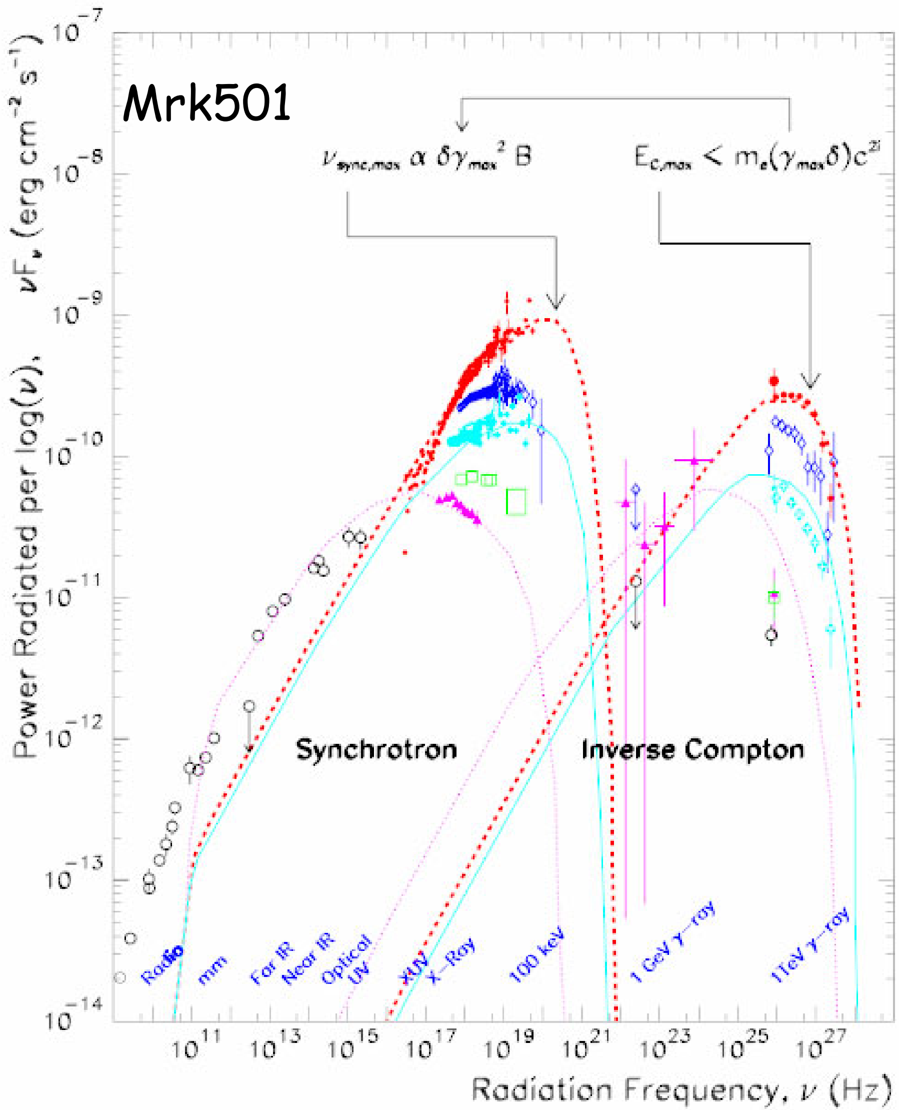


- Probe energy roll-offs with distance (light-light attenuation): info on era of galaxy formation.
- Long mission life to see weak sources and transients.

Joining the unique capabilities of GLAST with other detectors will provide a powerful tool.

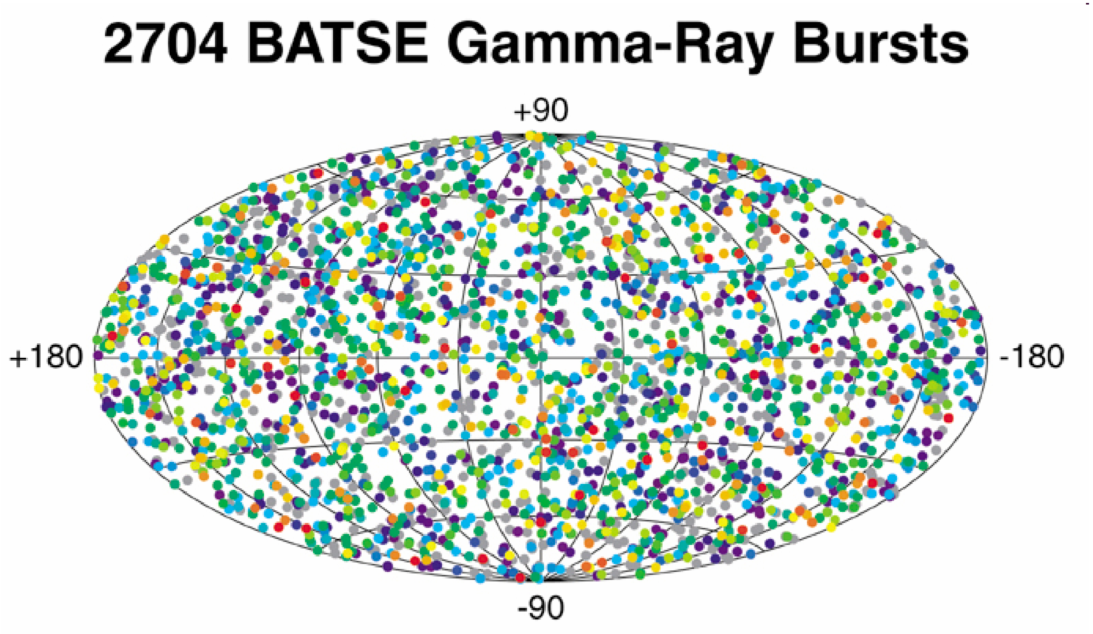
AGN: Future Prospects

- **Multiwavelength studies will continue to be the key to understanding how the engines work**
- **Models: same population of HE electrons produces both components**



Gamma Ray Bursts

Bursts are isotropic and non-repeating (as far as we can tell):

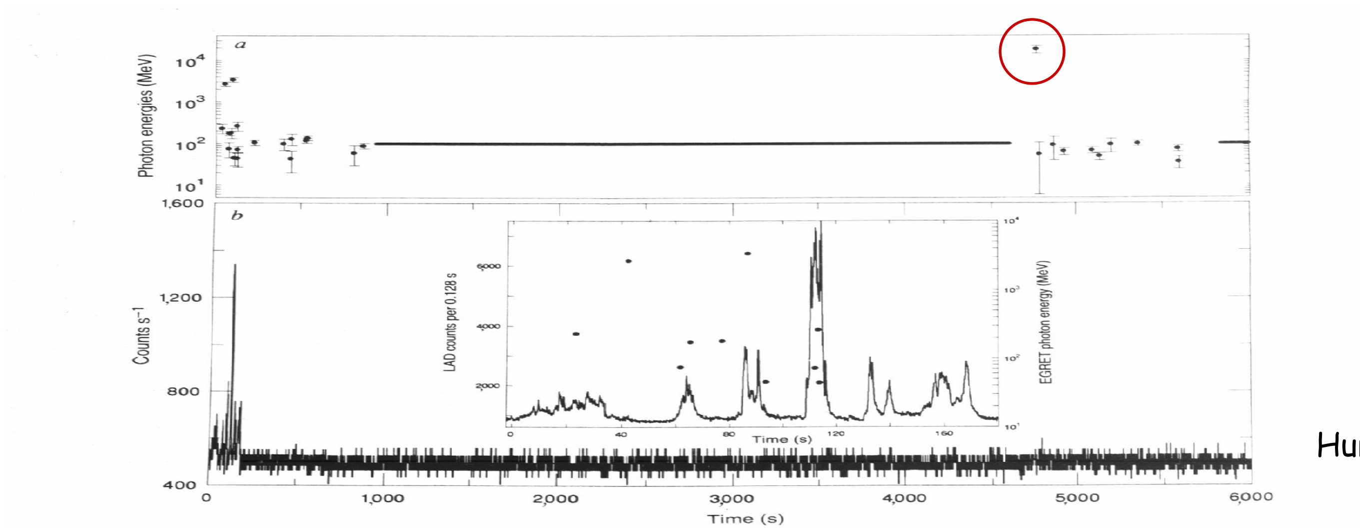


=> important to view as much of the sky as possible

Gamma Ray Bursts

GRBs are now confirmed to be at cosmological distances (since Beppo-Sax). The question persists : What are they??

EGRET has detected very high energy emission associated with bursts, including a 20 GeV photon ~75 minutes after the start of a burst:

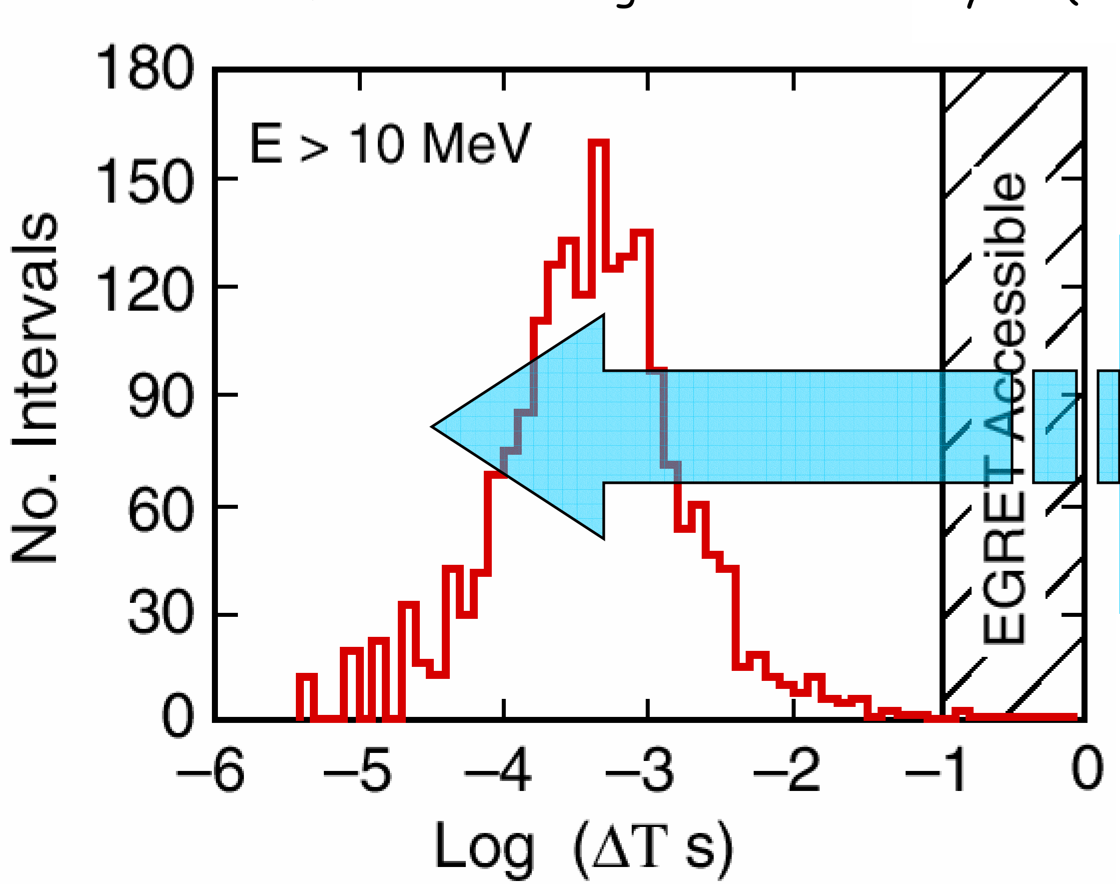


Hurley et al., 1994

Future Prospects: GLAST will provide definitive information about the high energy behavior of bursts: LAT and GBM together will measure emission over >7 decades of energy.

GRBs and Instrument Deadtime

Distribution for the 20th brightest burst in a year (Norris et al)

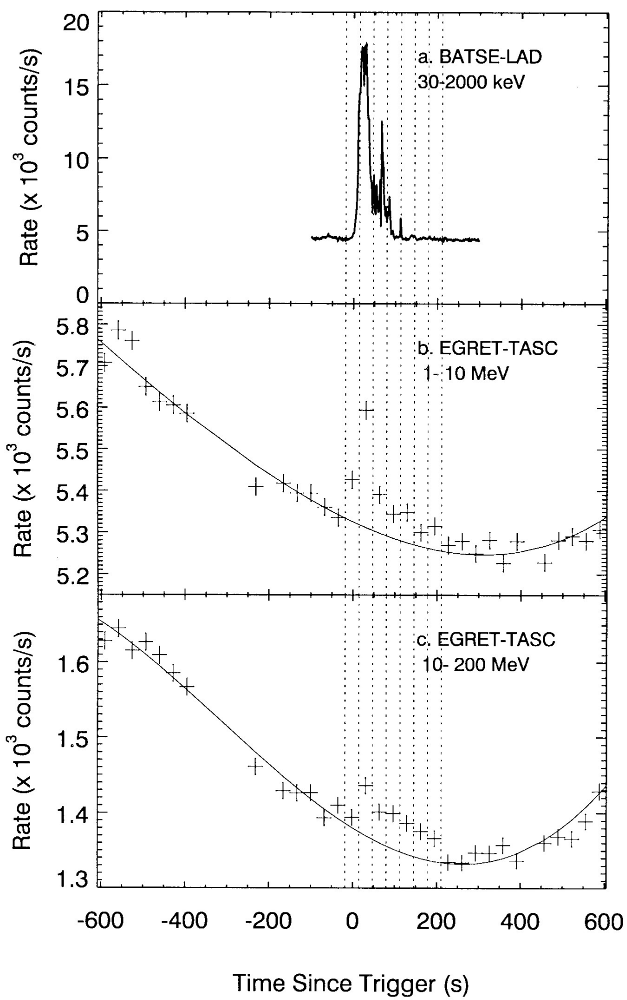


Time between consecutive arriving photons

LAT will open a wide window on the study of the high energy behavior of bursts.

GRB941017

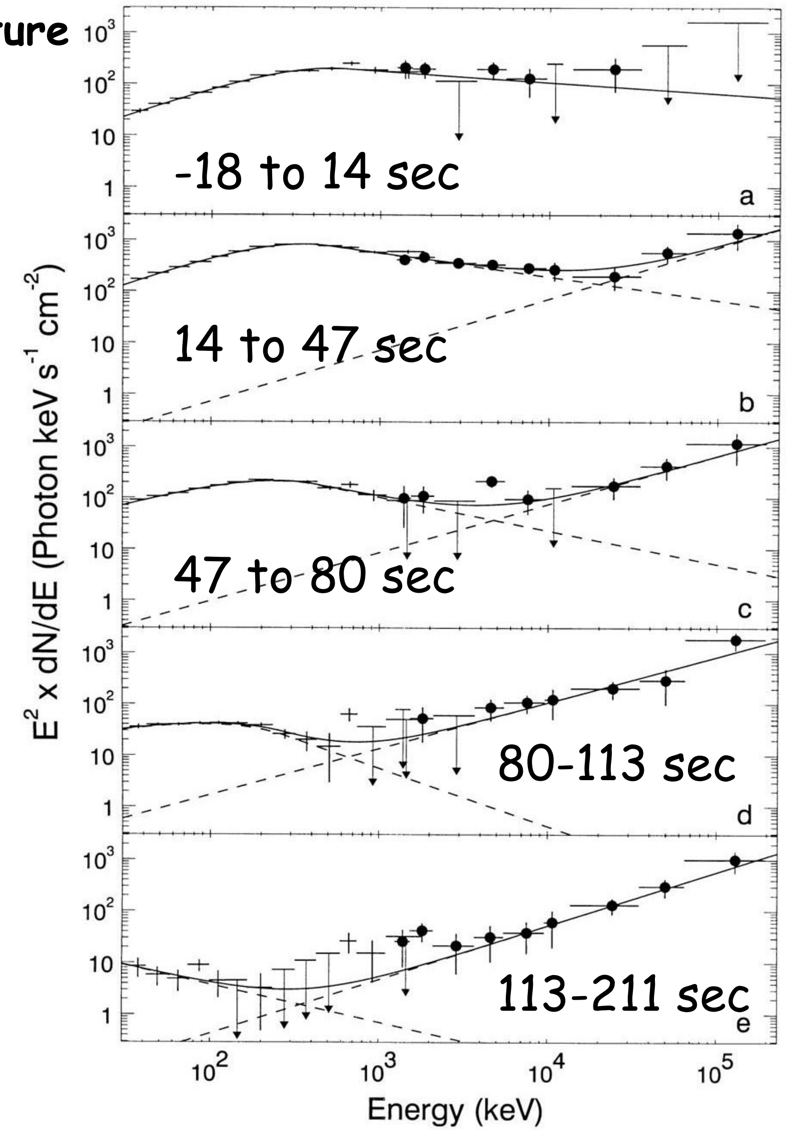
Recent analysis by Gonzalez et al., published in Nature



Compare data from EGRET and BATSE: Distinct high-energy component has different time behavior!

What is the high-energy break and total luminosity?

Need GLAST data!



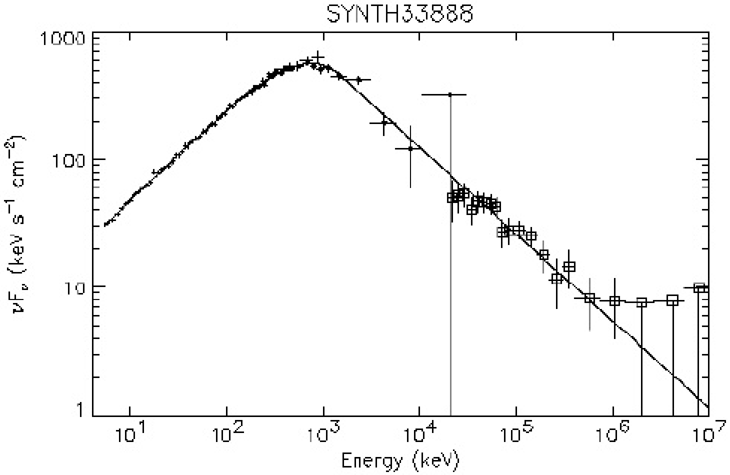
Roles of the GBM

- provides spectra for bursts from 10 keV to 30 MeV, connecting frontier LAT high-energy measurements with more familiar energy domain;

Simulated GBM and LAT response to time-integrated flux from bright GRB 940217

Spectral model parameters from CGRO wide-band fit

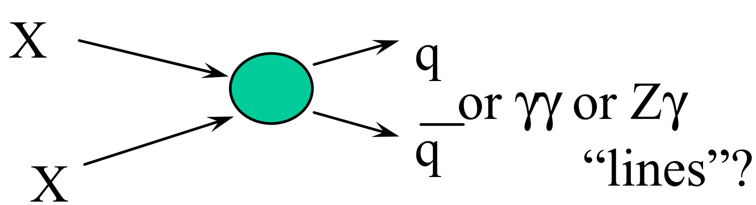
1 NaI (14 º) and 1 BGO (30 º)

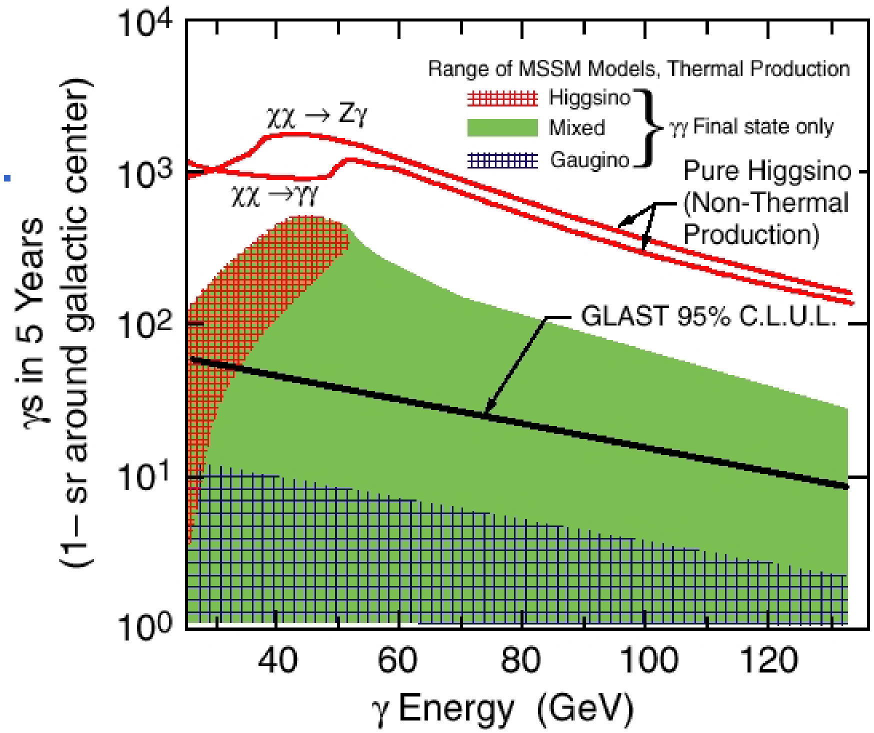


- provides wide sky coverage (8 sr) -- enables autonomous repoint requests for exceptionally bright bursts that occur outside LAT FOV for high-energy afterglow studies (an important question from EGRET);
- provides burst alerts to the ground.

Particle Dark Matter

Some important models in particle physics could also solve the dark matter problem in astrophysics. If correct, these new particle interactions could produce an anomalous flux of gamma rays.



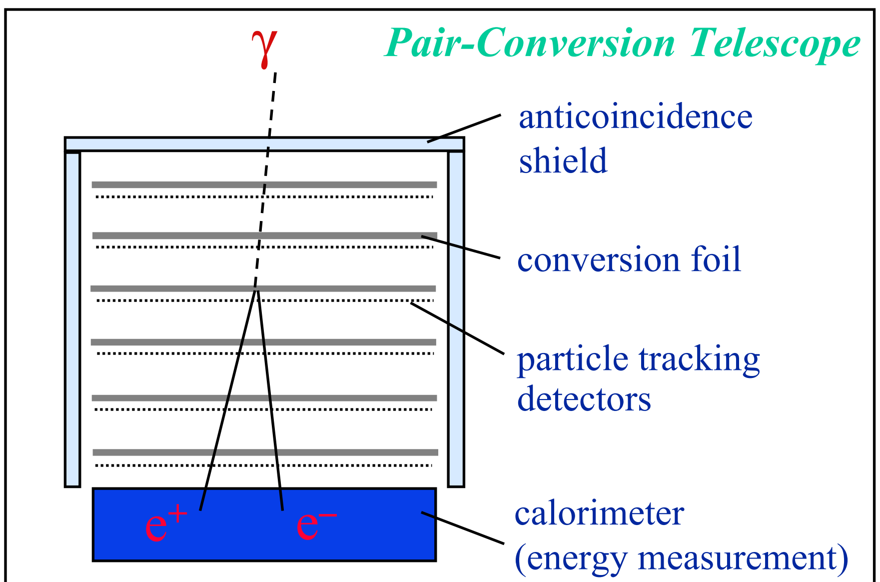


Just an example of what might be waiting for us to find!

Experimental Technique

- Instrument must measure the <u>direction</u>, <u>energy</u>, and <u>arrival time</u> of high energy photons (from approximately 20 MeV to greater than 300 GeV):

  - photon interactions with matter in GLAST energy range dominated by pair conversion:
    - ➡ determine photon direction
    - ➡ clear signature for background rejection
  - limitations on angular resolution (PSF)
    - **low E: multiple scattering => many thin layers**
    - **high E: hit precision & lever arm**



<u>Energy loss mechanisms:</u>

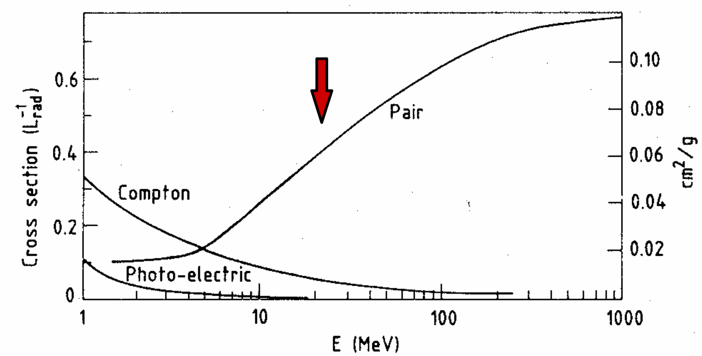
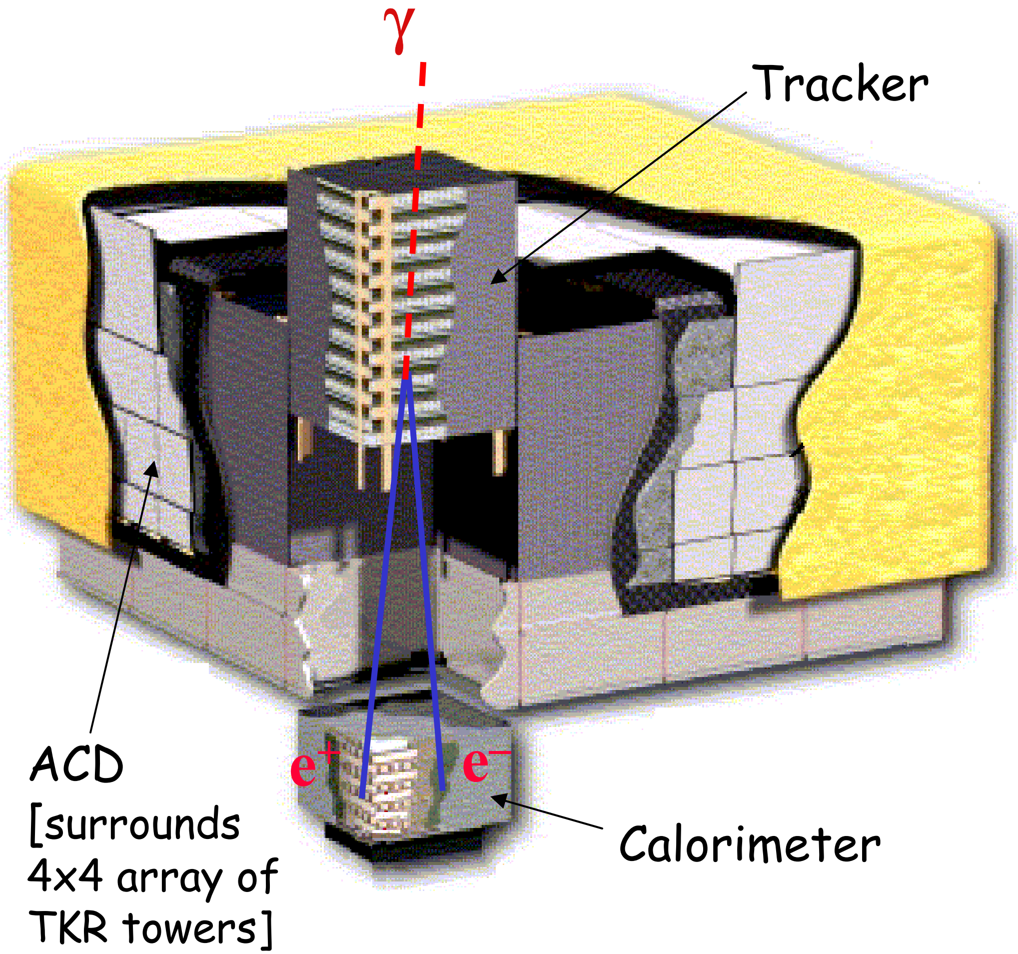


Fig. 2: Photon cross-section σ in lead as a function of photon energy. The intensity of photons can be expressed as $I = I_0 \exp(-\sigma x)$, where x is the path length in radiation lengths. (Review of Particle Properties, April 1980 edition).

- must detect γ-rays with high efficiency and reject the much larger ($\sim 10^4$:1) flux of background cosmic-rays, etc.;
- energy resolution requires calorimeter of sufficient depth to measure buildup of the EM shower. Segmentation useful for resolution and background rejection.

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.

Design Performance Validation: LAT Monte-Carlo Model

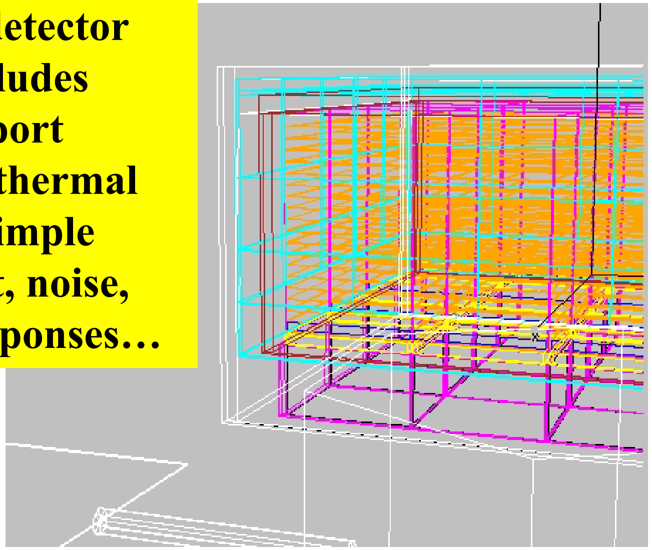
LAT design based on detailed Monte Carlo simulations.

Integral part of the project from the start.

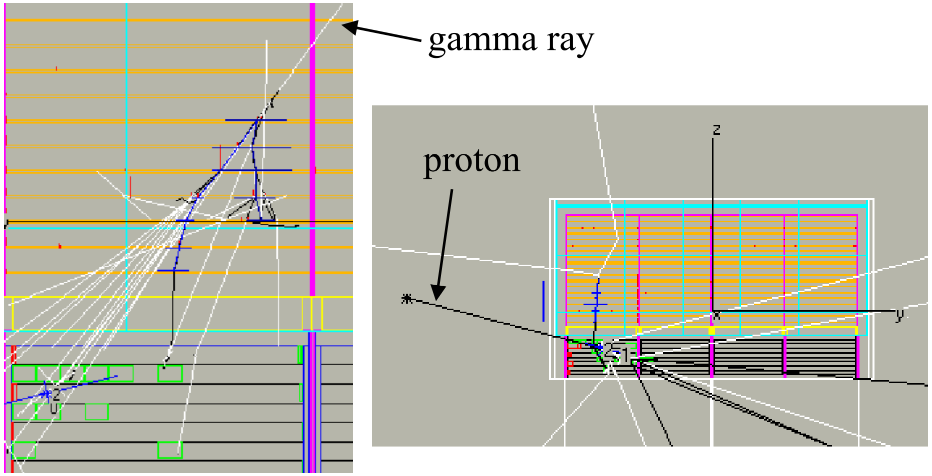
- **Background rejection**
- **Effective area and resolutions**
- **Trigger design**
- **Overall design optimization**

Simulations and analyses are all C++, based on standard HEP packages.

Detailed detector model includes gaps, support material, thermal blanket, simple spacecraft, noise, sensor responses…

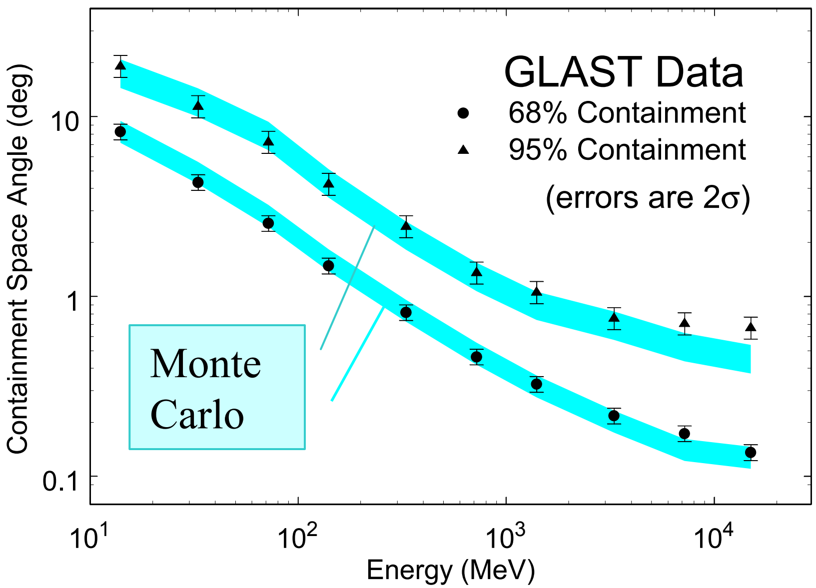


Instrument naturally distinguishes gammas from backgrounds, but details matter.



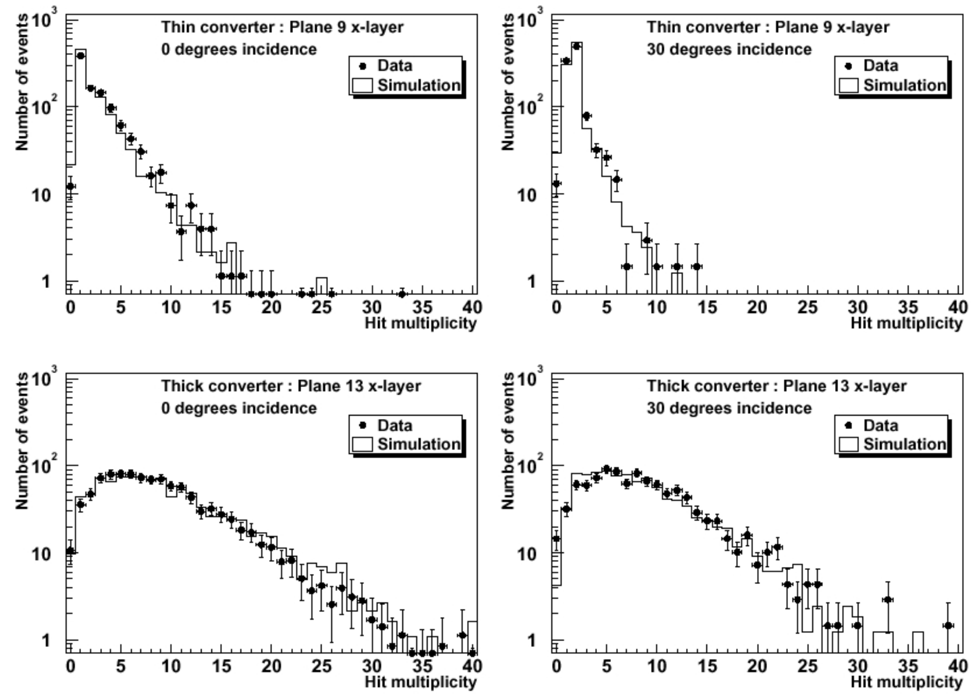
Monte Carlo Modeling Previously Verified in Detailed Beam Tests

High-level performance parameters (e.g., PSF)



1997 SLAC beam test
(photons, positrons)
Demonstrate silicon conversion telescope principle
Published in NIM A446

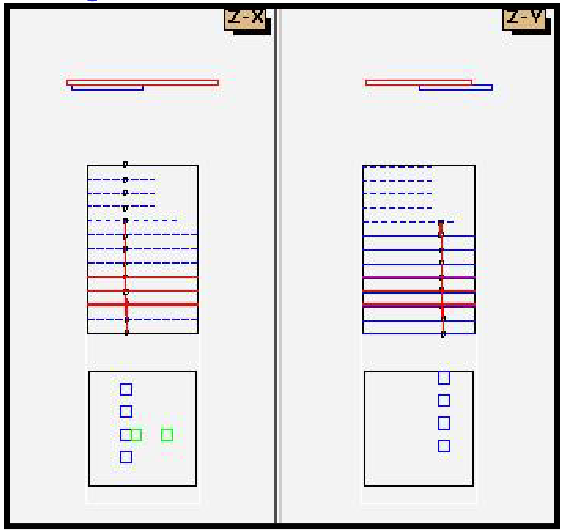
Detailed detector characteristics (e.g., hit multiplicities)



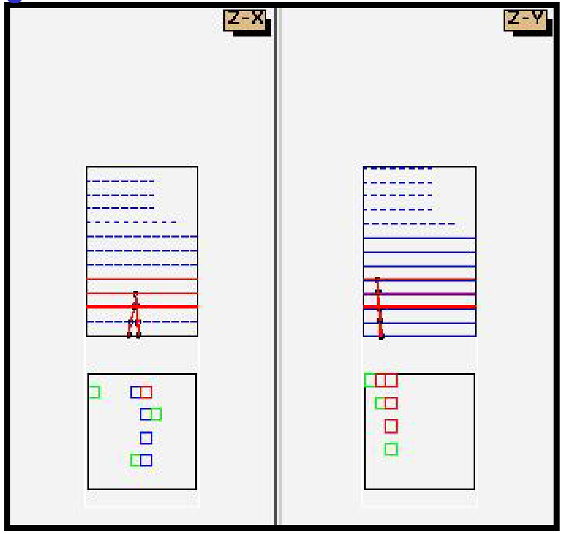
1999-2000 SLAC beam test
(photons, positrons, protons)
flight-scale tower
Published in NIM A474

LAT Balloon Flight

background event candidate:



gamma event candidate:



Purpose of balloon test flight: expose prototype LAT tower module to a charged particle environment similar to space environment and accomplish the following objectives:

- **Help validate the basic LAT design at the single tower level.**
- **Demonstrate the ability to take data in the isotropic background flux of energetic particles in the balloon environment.**
- **Record events for background flux analysis.**

All Objectives met by Balloon Flight on August 4, 2001 (3 hrs at 38 km float)

All subsystems performed properly.

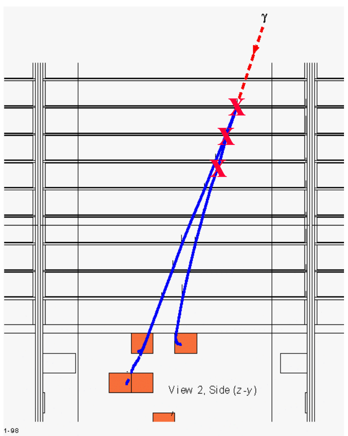
Trigger rate <1.5 kHz, well below BFEM 6 kHz capability.

Instrument Triggering and Onboard Data Flow

Level 1 Trigger

Hardware trigger based on special signals from each tower; initiates readout

Function: • "did anything happen?"
• keep as simple as possible



• **TKR 3 *x•y* pair planes in a row**

workhorse γ trigger

OR

• **CAL:**

LO – independent check on TKR trigger.

HI – indicates high energy event ⟶ disengage use of ACD.

Upon a L1T, all towers are read out within 20μs

Instrument Total L1T Rate: <4 kHz>**

**4 kHz average without throttle (1.3 kHz with throttle); peak L1T rate is approximately 12 kHz without throttle and 3.8 kHz with throttle).

On-board Processing

full instrument information available to processors.

Function: reduce data to fit within downlink

Hierarchical filter process: first make the simple selections that require little CPU and data unpacking.

- **subset of full background rejection analysis, with loose cuts**
- **only use quantities that**
  - **are simple and robust**
  - **do not require application of sensor calibration constants**
- **complete event information**
- **signal/bkgd tunable, depending on analysis cuts:**
  γ:cosmic-rays ~ 1:~few

Total L3T Rate: <25-30 Hz>

(average event size: ~8-10 kbits)

On-board science analysis:
transient detection (AGN flares, bursts)

Spacecraft

Purposes of the Data Challenges

- "End-to-end" testing of analysis software.
- Familiarize team with data content, formats, tools and realistic details of analysis issues (both instrumental and astrophysical).
- Develop additional methods for analyzing GLAST data, encouraging alternatives that fit within the existing framework.
- Provide feedback to the SAS group on what works and what is missing from the data formats and tools.
- Uncover systematic effects in reconstruction and analysis.

Support readiness by launch time to do all first-year science.

Data Challenge Planning Approach

- Walk before running: design a progression of studies.
  - DC1. Modest goals. Contains most essential features of a data challenge (see following slide).
  - DC2. More ambitious science goals. Encourage further development, based on lessons from DC1.
  - DC3. Support for flight science production.

Data Challenge Progression

- DC1
  - modest goals:
    - 1 simulated day all-sky survey simulation (3M bkgd+gamma events to ground, => 400M generated events)
    - find flaring AGN, a GRB
    - single-day point source sensitivity. daily quicklook analysis development.
    - recognize simple hardware problem(s)
    - a few physics surprises
    - exercise:
      - exposure, orbit/attitude handling, data processing pipeline components, analysis tools
    - use existing recon, bkgd rejection and instrument response to show the problem areas that need improvement. secondary goal (not required) is to prototype improvements
  - baseline schedule:
    - Sept-Oct startup problems resolution.
    - Nov-Dec high-level tools beta testing. Finalize instrument response functions.
    - Dec 15 high-level tools release, workshop.
    - mid-January: interim reports (vrvs or face-to-face)
    - Feb 2004 closeout, and plan for DC2 (see following slide).
    - Then, break for flight I&T start. Use the time for fixing problems learned in DC1, software advances, etc.

Bigger Context: “The Universe as a Laboratory”

Address fundamental questions, test limits of physical law using most extreme environments, and study the relics from the Big Bang

- explore black holes: acceleration mechanisms producing high-energy jets; goal to study region around event horizon.
- find origin(s) of the highest energy cosmic rays
- understand gamma-ray bursts
- uncover dark matter
- study CMB
- test Inflation
- search for other Big Bang relics
- detect gravity waves
- confirm and study the ‘Dark Energy’
- Discovery!

GLAST will play a major role in many of these topics.

Summary

- GLAST will address many important questions:
  - What is going on around black holes? How do Nature's most powerful accelerators work?
  - What are the unidentified sources found by EGRET?
  - What is the origin of the diffuse background?
  - What is the origin of cosmic rays?
  - What is the high energy behavior of gamma ray bursts?
  - When did galaxies form?
  - What else out there is shining gamma rays? Are there high-energy relics from the Big Bang? Are there further surprises in the poorly measured energy region?
- Large menu of "bread and butter" science, and large discovery potential.
- GLAST is part of the bigger picture of experiments at the interface between particle physics and astrophysics.

GLAST will provide a wealth of important new data to the science community.