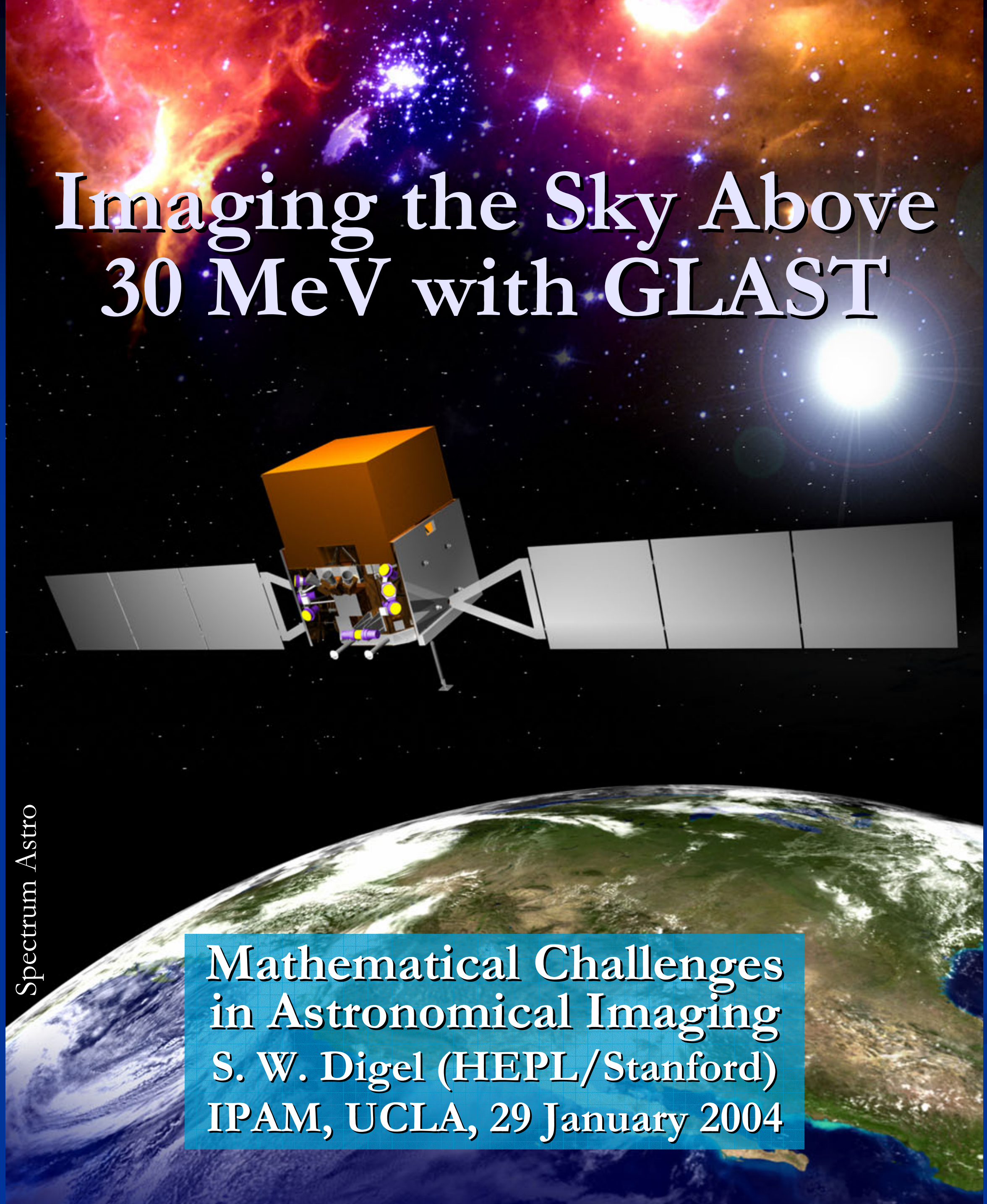

Imaging the Sky Above
30 MeV with GLAST
Spectrum Astro
Mathematical Challenges
in Astronomical Imaging
S. W. Digel (HEPL/Stanford)
IPAM, UCLA, 29 January 2004

Outline

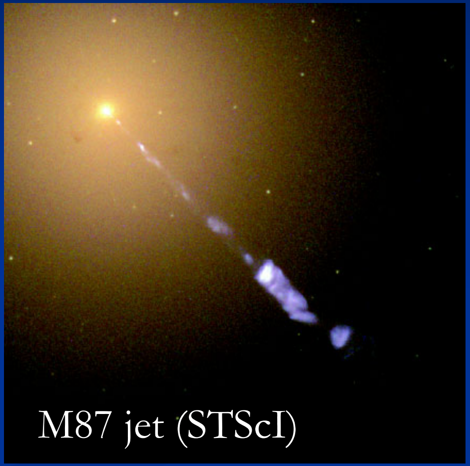
- Introduction
  - Why bother? Celestial high-energy gamma rays
  - Detecting gamma rays in space
- GLAST* mission
  - LAT** instrument design
  - Nature of the data and performance of the LAT
- Analysis from low to high level
- Imaging the sky
  - Approaches for source detection & characterization

*Gamma-ray Large Area Space Telescope

**Large Area Telescope, the principal instrument on GLAST

Motivation: Wealth of Astro- and Astroparticle Physics

- Extragalactic
  - Blazars – most of their luminosity is in gamma rays
  - Other active galaxies – Centaurus A
  - Normal galaxies – Large Magellanic Cloud + starburst
  - Galaxy clusters
  - Isotropic emission
  - Gamma-ray bursts
- In the Milky Way
  - Pulsars, binary pulsars, millisecond pulsars, plerions
  - Supernova remnants, OB/WR associations, black holes?
  - Microquasars, microblazars?
  - Diffuse – cosmic rays interacting with interstellar gas and photons
  - WIMP annihilation?
- Solar flares
- Moon…

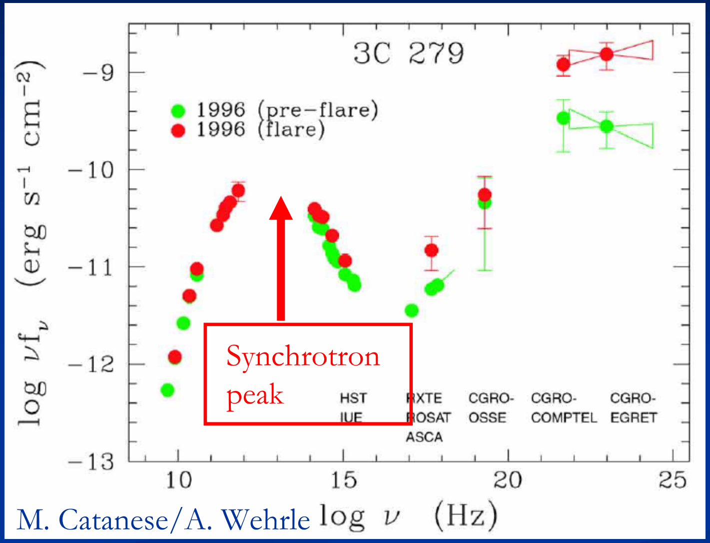

M87 jet (STScI)


Crab pulsar & nebula (CXC)

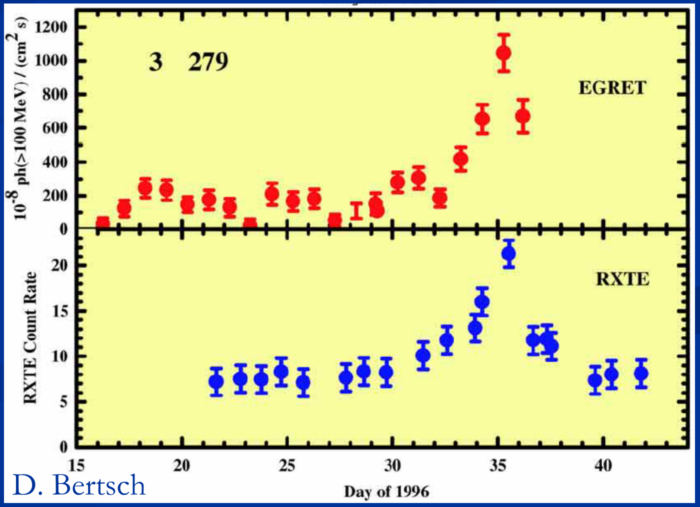
Common theme (except for WIMPS): Nonthermal emission, particle acceleration (e.g., in jets and shocks); γ-ray emission from Bremsstrahlung, inverse Compton, pion decay, curvature radiation

More About Classes of Sources: **Blazars**

- Active galaxies with beamed jets associated with accreting massive BHs in active galaxies
- EGRET discovery: Tremendous γ-ray luminosities (beamed) 10^{48-49} erg s^{-1}
  - Bulk Lorentz factors Γ ~>5-10
- Strongly variable, timescale of <hours
- ~70 strong IDs from EGRET, ~30 suspected
- z ~ 0 - 2.5
  - Potential probe of extragalactic background light



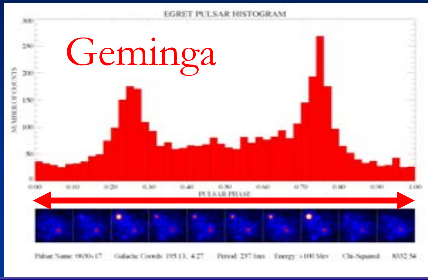
M. Catanese/A. Wehrle



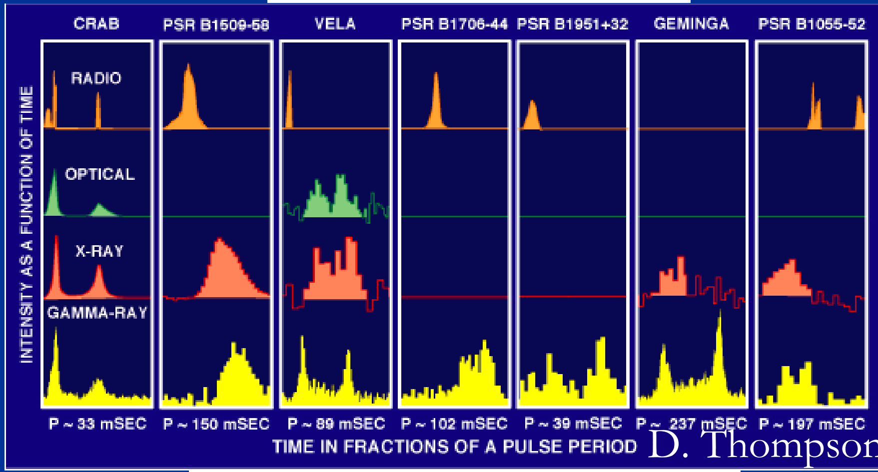
D. Bertsch

More: Rotation-Powered Pulsars

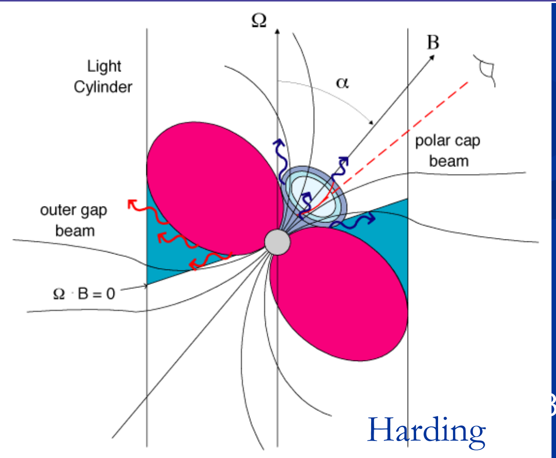
- Rapidly rotating magnetized neutron stars (and ***B* not parallel to *Ω***)
- ~8 detected pulsating by EGRET
  - Steady (averaged over a period) sources, and not necessarily seen pulsating at other wavelengths
- Acceleration mechanisms are well understood (Polar Cap and Outer Gap models)
- ~$10^{35\text{-}36}$ erg s^{-1} luminosities means can see them for a few kpc



0.24 s



D. Thompson

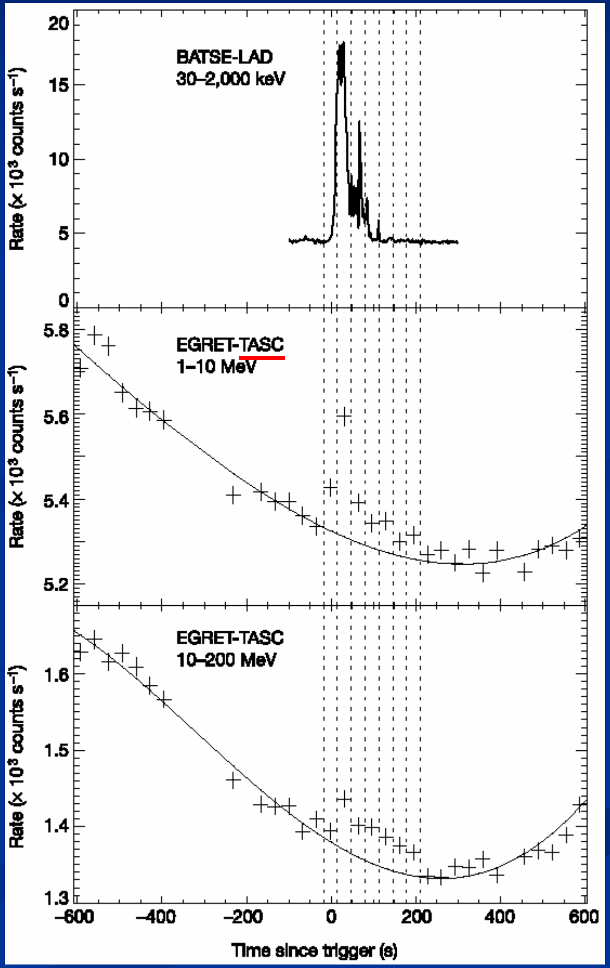


Harding

More: Gamma-ray bursts

- Something bad (hypernova?) happens at cosmological distances
  - Internal shocks and external shocks → pulses and afterglows
- Primarily hard X-ray, although several have been seen at high energies (~100 MeV) with EGRET
  - Recent result shows high-energy component may trace a different particle population, or indicate a proton component

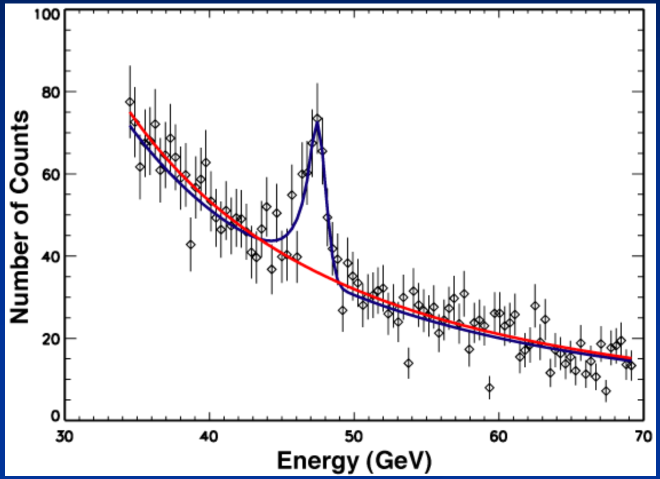
GRB940217

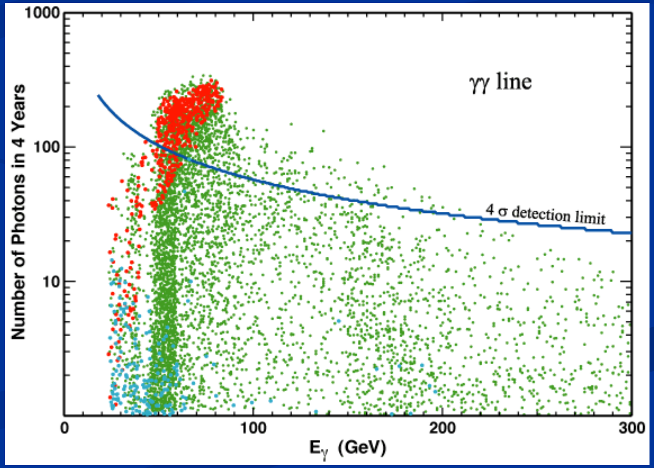


González et al. (2003)

More: Particle Dark Matter

- Some N-body simulations of dark matter in the halo of the Milky Way predict a very cuspy distribution (e.g., Navarro et al. 1996)
- If the dark matter is the Lightest Supersymmetric Particle, χ, the mass range currently allowed is 30 GeV-10 TeV.
- Annihilation processes $\chi\chi \rightarrow \gamma\gamma$ and $\chi\chi \rightarrow \gamma Z$ are potentially detectable by GLAST (e.g., Bergström & Ullio 1998)
  - LAT observations can apparently cover an interesting range of the 7-dimensional parameter space for MSSM.
- EGRET apparently didn't see a source coincident with the Galactic center, but also is not very sensitive in the >10 GeV range





D. Engovatov

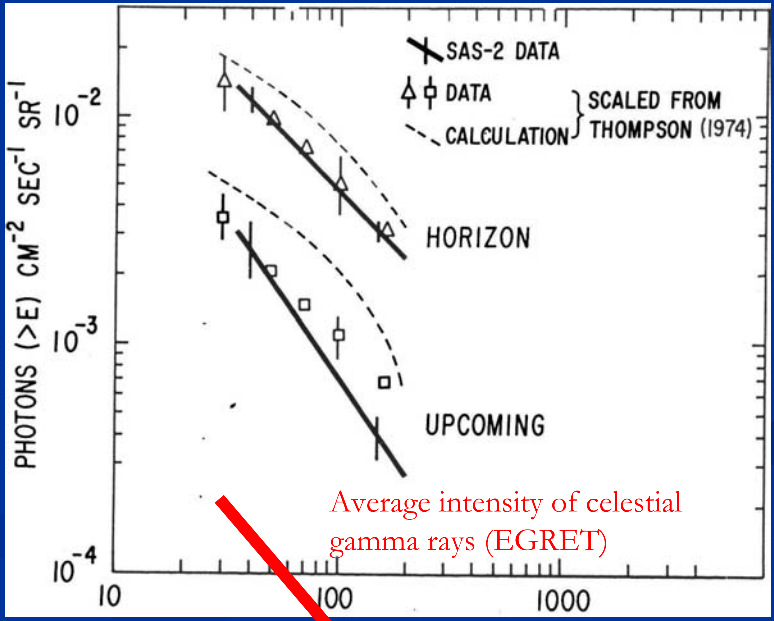
Important Points About Detecting High-Energy Gamma Rays

- In the range up to ~50 GeV, the detector must be in space
- Charged-particle background is intense
  - Background rejection is vital
- Earth's limb and the nadir are an intense source of albedo gamma rays
  - So albedo suppression is important, too

Trigger rates in LAT

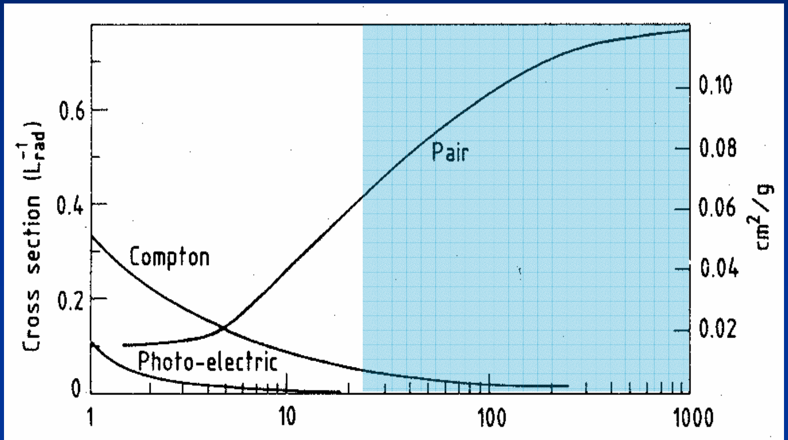
Bright γ pt. src.	1/minute
Avg. γ, entire FOV	2 Hz
Cosmic Rays	~3 kHz
Albedo γ rate*	~100 Hz

* If pointed at the horizon



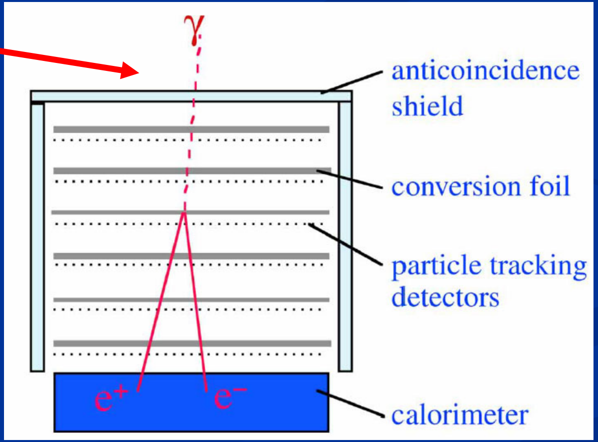
Important points (2)

- Above ~few MeV pair conversion is the dominant interaction process with matter
  - Can't focus these γ-rays



from Rev. Particle Prop.

- Schematic pair conversion 'telescope'
  - PSF is poor
  - FOV is enormous



PSF

Chandra	~1"
LAT (100 MeV)	**12000"**
LAT (10 GeV)	**360"**

FOV

Chandra	**10^{-4} sr**
LAT	**2.2 sr**

Important points (3)

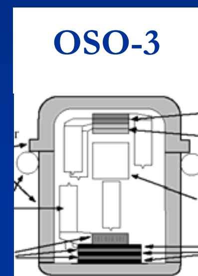
- Celestial fluxes are low (except for GRBs, which are impulsive)
  - Photon number fluxes typically ~E^{-2}
- The Milky Way is a *relatively* bright, structured, foreground
  - ~10% of flux at low latitudes is from point sources

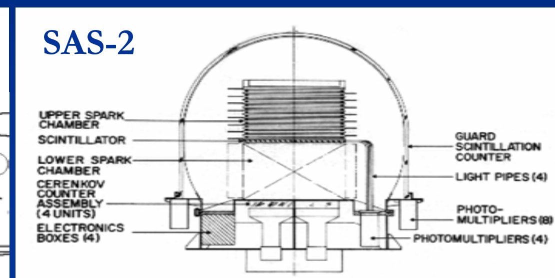
γ-ray rates in LAT

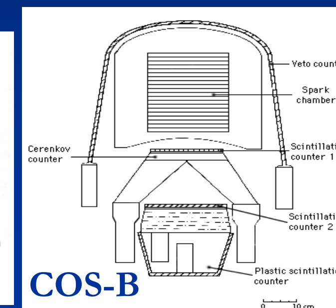
Bright pt. src.	**1/minute**
Avg., entire FOV	**2 Hz**

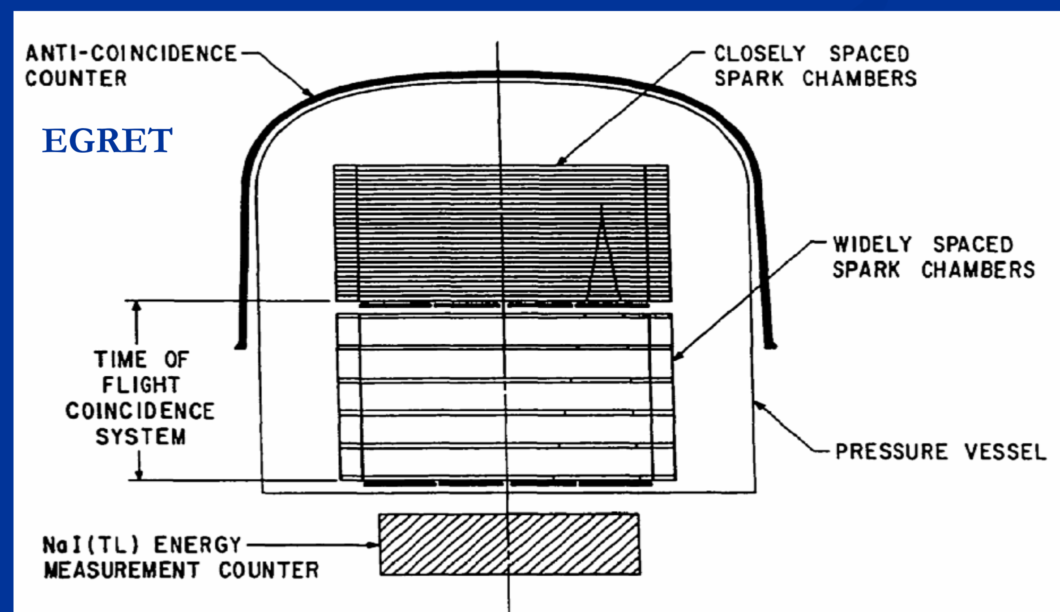
Brief History of Detectors

- 1967-1968, OSO-3 detected Milky Way as an extended γ-ray source
- 1972-1973, SAS-2, isotropic extragalactic emission
- 1975-1982, COS-B, ~25 point sources, 1st extragalactic point source.
- 1991-2000, EGRET, large effective area, good PSF, long mission life, excellent background rejection, ~300 point sources

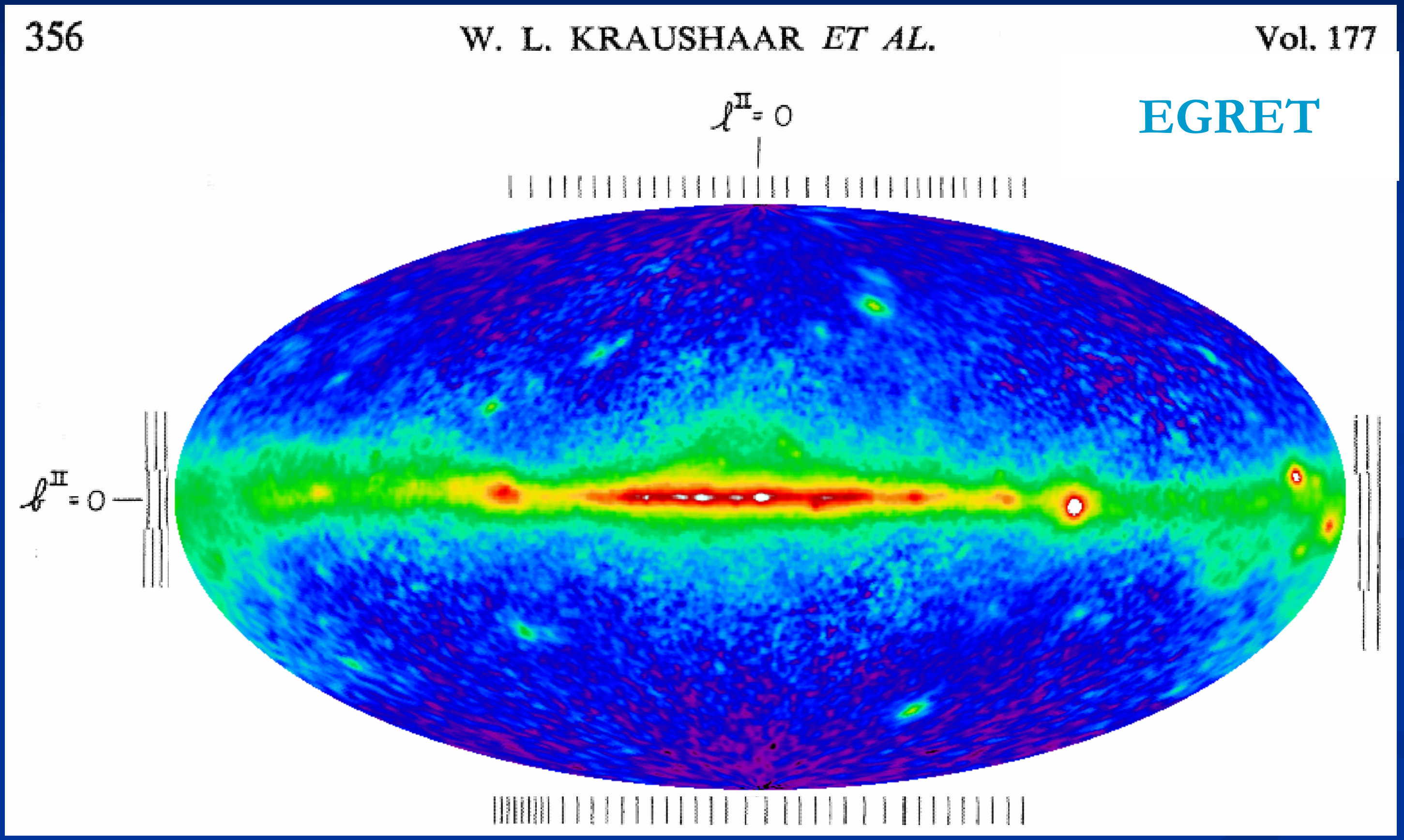






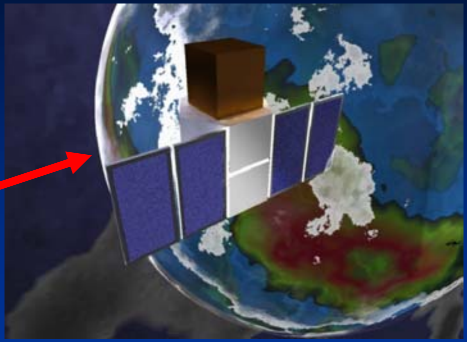


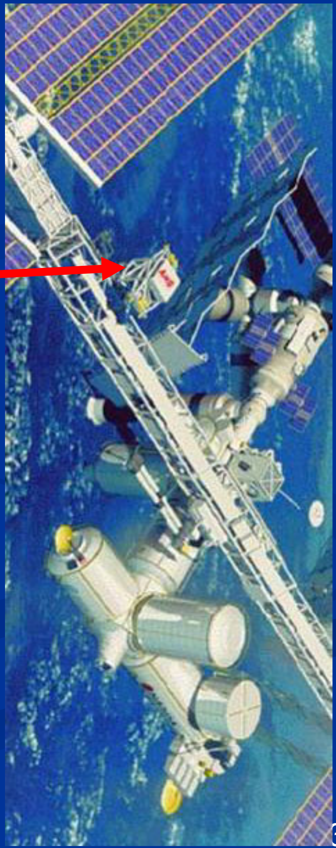
History cont.



- ~1.4 Mγ, ~60% interstellar emission from the MW
- ~10% are cataloged (3EG) point sources

Future Missions

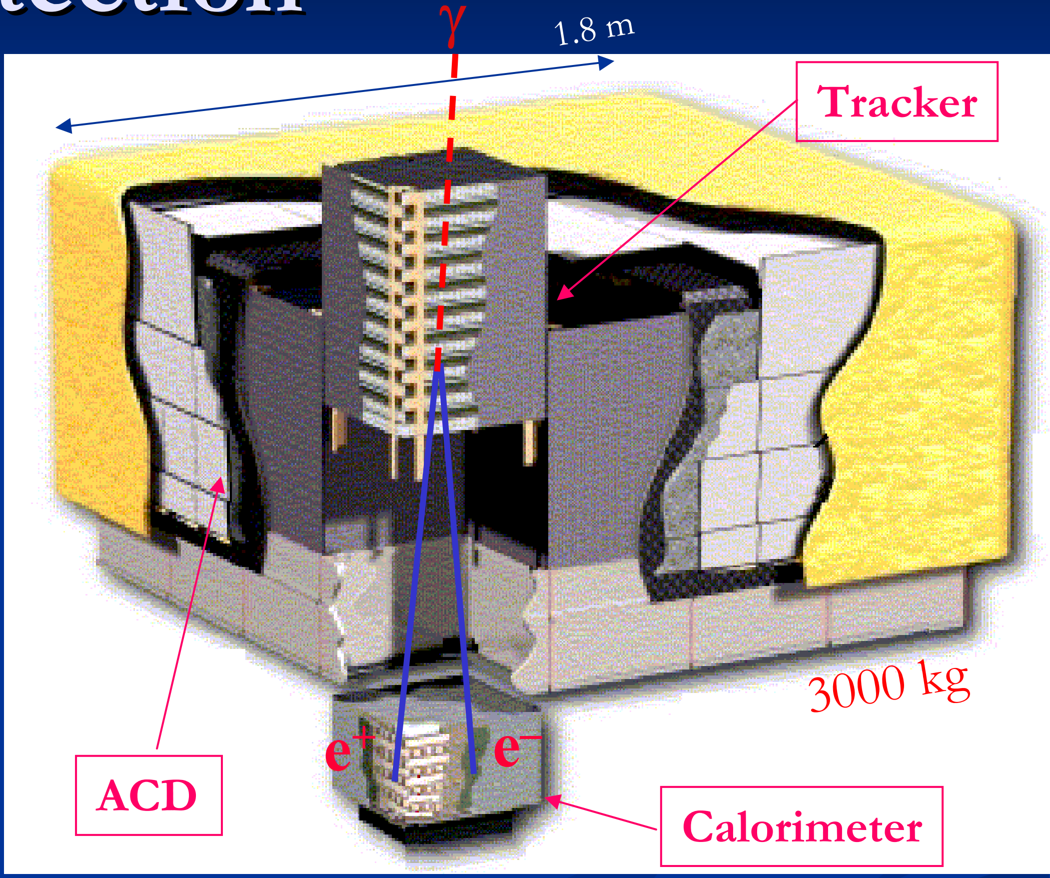




- AGILE (Astro-rivelatore Gamma a Immagini LEggero)
  - ASI small mission, mid 2005 launch, good PSF, large FOV, short deadtime, very limited energy resolution
- AMS (Alpha Magnetic Spectrometer)
  - International, cosmic-ray experiment for ISS, will have sensitivity to >1 GeV gamma rays, scheduled for 16th shuttle launch once launches resume
- GLAST…

Design of the LAT for gamma-ray detection

- **Tracker** 18 XY tracking planes with interleaved W conversion foils. Single-sided silicon strip detectors (228 μm pitch). Measure the photon direction; gamma ID.
  - 12 'Front' (3.5% RL), 4 'Back' (25% RL)
- **Calorimeter** 1536 CsI(Tl) crystals in 8 layers (8.5 RL); PIN photodiode readouts. Image the shower to measure the photon energy.
- **Anticoincidence Detector (ACD)** 89 plastic scintillator tiles. Signals passage of cosmic rays; segmentation limits self-veto at high energy.



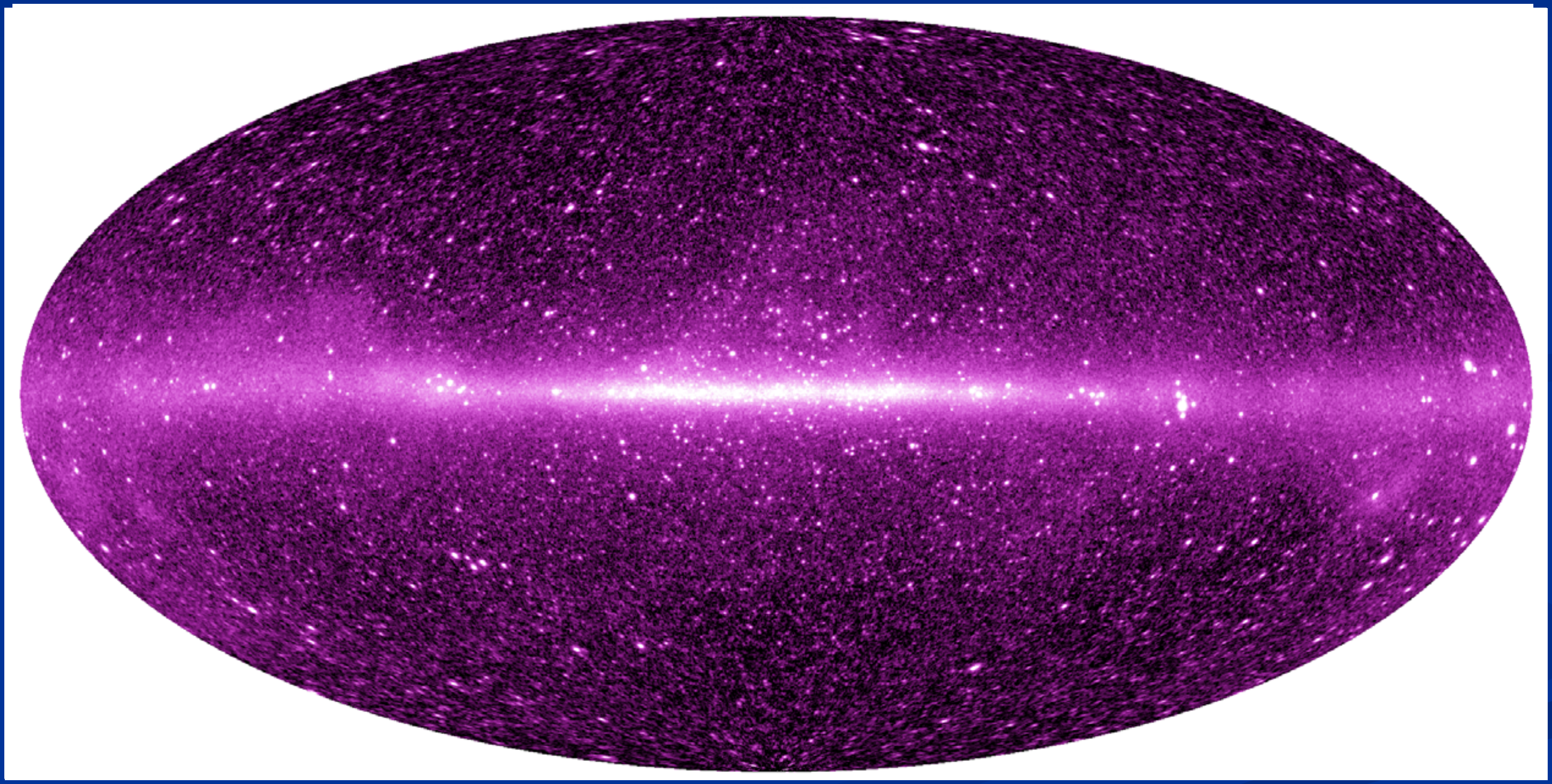
- **Electronics System** Includes flexible, robust hardware trigger and software filters. ~800k channels, 600 W

LAT in perspective

- Within its first few weeks, the LAT will double the number of celestial gamma rays ever detected

Instrument	Years	Ang. Res. (100 MeV)	Ang. Res. (10 GeV)	Energy Range (GeV)	$A_{eff}\Omega$ (cm^2 sr)	# Gamma Rays
OSO-3	1967–68	18°	–	>0.05	1.9	621
SAS-2	1972–73	7	–	0.03–10	40	~10,000
COS-B	1975–82	7	–	0.03–10	40	$\sim 2 \times 10^5$
EGRET	1991–00	5.8	0.5°	0.03–10	750	1.4×10^6
AGILE	2005–	4.7	0.2	0.03–50	1500	4×10^6/yr
AMS	2005+–	–	0.1	1–300	500	$\sim 2 \times 10^5$/yr
GLAST LAT	**2007–**	**3.5**	**0.1**	**0.02–300**	**25,000**	**1×10^8/yr**

The Gamma-Ray Sky



Simulated LAT (>1 GeV, 1 yr)

Maximizing Return

- GLAST is the last large high-energy gamma-ray telescope that can be expected for a decade or more, depending on what it discovers
- Even for GLAST, the cost per celestial gamma ray will remain fairly high, ~40 ¢ each

Analysis Levels

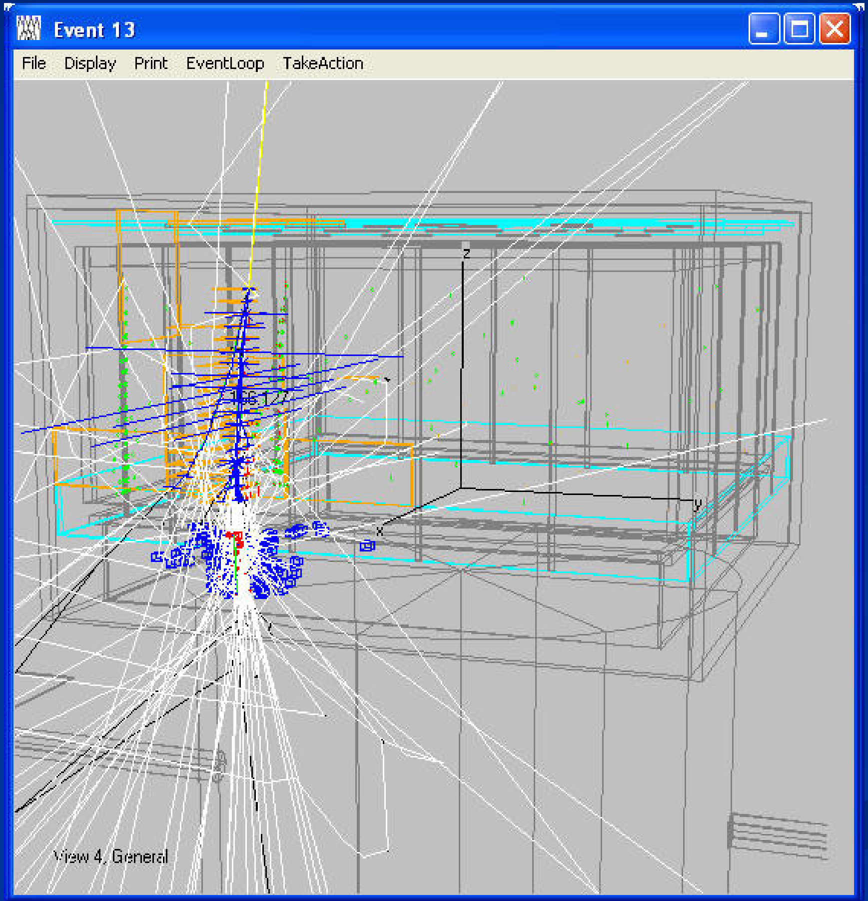
- Reconstruction and classification of events
  - Charged particles vs. gamma-rays
  - Quality of reconstruction of energy, direction
- Detection and characterization of celestial sources of gamma rays
  - Locations, spectra, variability & transient alerts, angular extents
- Identification of sources & population studies
  - Counterparts and correlations

'Imaging'

Increasing level

Nature of the LAT Data

- Events are readouts of TKR hits, TOT, ACD tiles, and CAL crystal energy depositions, along with time, position, and orientation of the LAT
- Limited bandwidth for telemetry → data are extremely filtered
  - ~3 kHz trigger rate
    ~100 Hz filtered event rate,
    ~10 Gbyte/day raw data,
    ~2 × 10^5 γ-rays/day
- Reconstruction finds tracks and energies; classification distinguishes γ-rays from cosmic rays – all before the astronomy

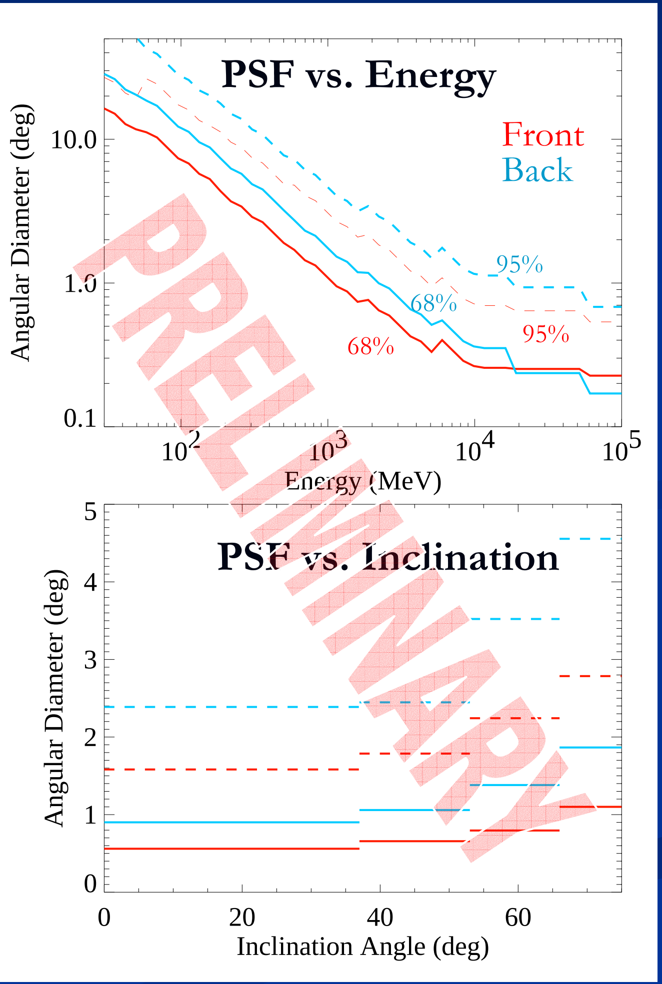


T. Usher

LAT Response Functions

- LAT response functions depend on incident direction, energy, plane of conversion, ‘quality’, etc.
  - Derived from detailed instrument simulation supported by beam tests
- PSF
  - 95%/68% containment ratio ~2.5-3 (vs. 1.6 for Gaussian)

PRELIMINARY

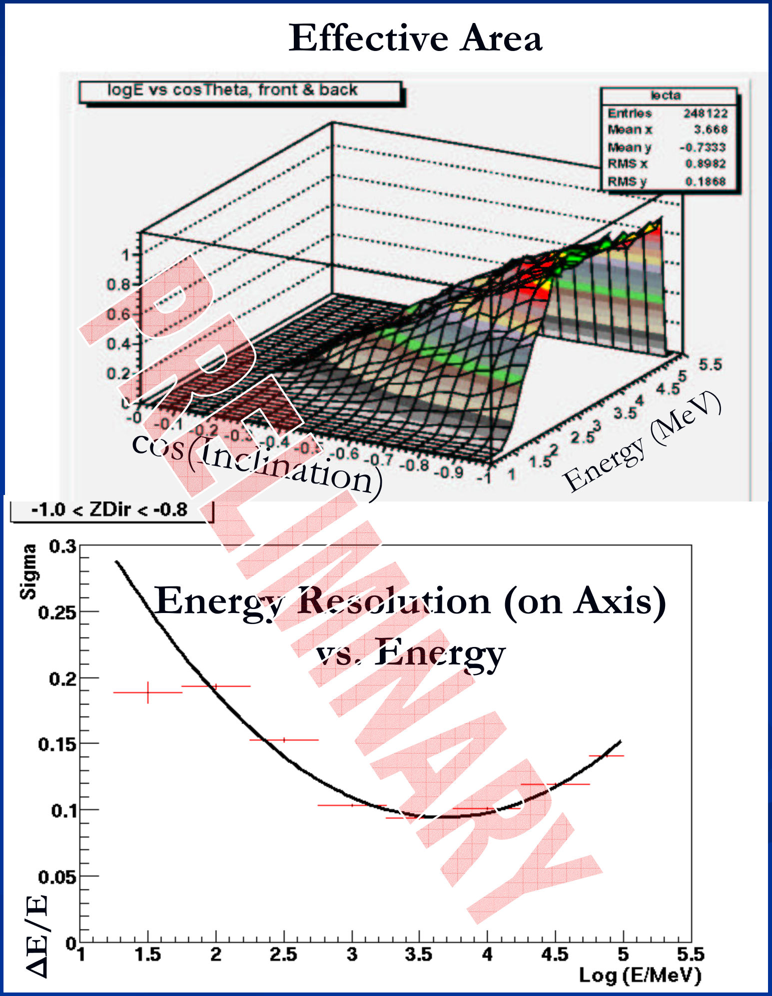


PRELIMINARY

LAT Response Functions (2)

- Effective Area
  - Front + Back shown combined here
  - Rolloff at low energies
- Energy resolution
  - Adequate
  - Actually improves at large inclinations

PRELIMINARY



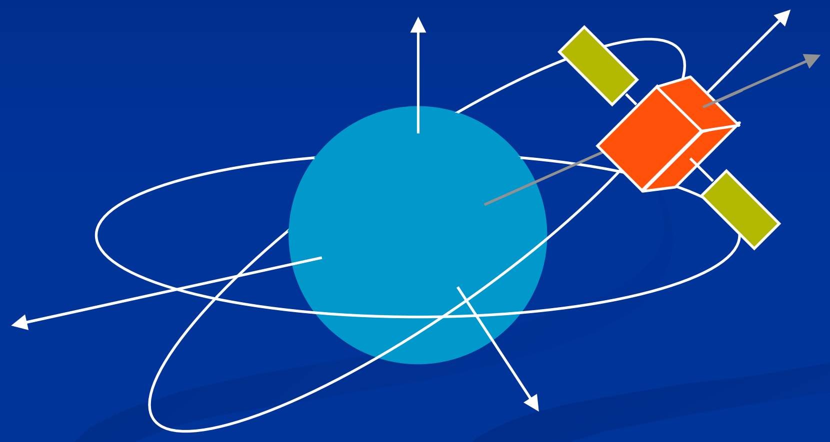
PRELIMINARY

Summing up the Analysis Issues

- So we want to do astronomy with
  - Low celestial fluxes, intense backgrounds from cosmic-ray and albedo γ-rays
  - Bright celestial foreground emission from Milky Way
  - Broad PSFs and overlapping PSFs of many sources in even a small field
  - Response functions that vary strongly across the FOV, and several event classes
  - Continuous scanning and rocking as the standard observing mode
  - Extra credit: Lunar and solar cuts, sky is not flat, …

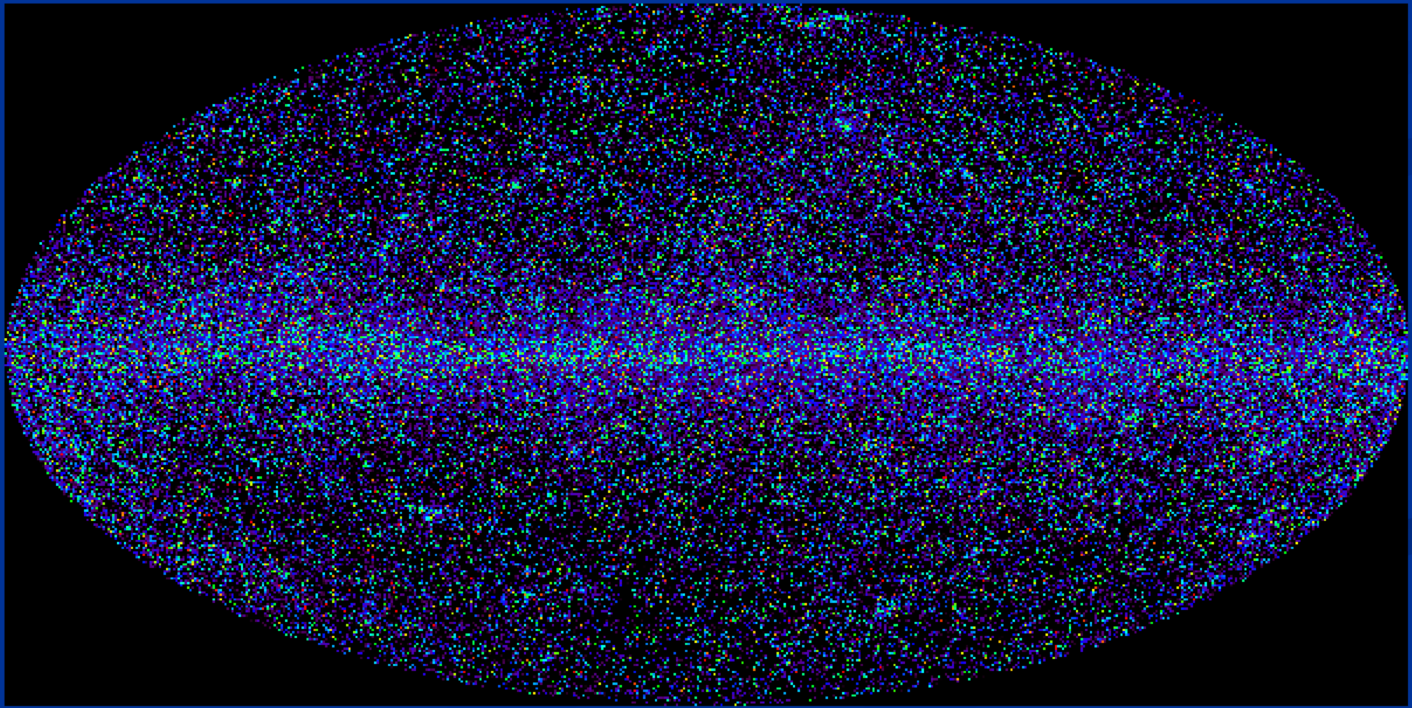
Analysis Issues (2)

- Standard observing mode will be scanning the sky
  - Increases the data taking efficiency vs. inertial pointing
  - Covers the whole sky every 3 hours
  - Keep the earth (and albedo gamma rays) out of the FOV
- High-level data include the pointing & livetime history



Analysis Issues (3)

- We'd also like source detection fast and robust (objective, with understood statistical properties, like upper limits)
- ~4-5 downlinks per day to monitor

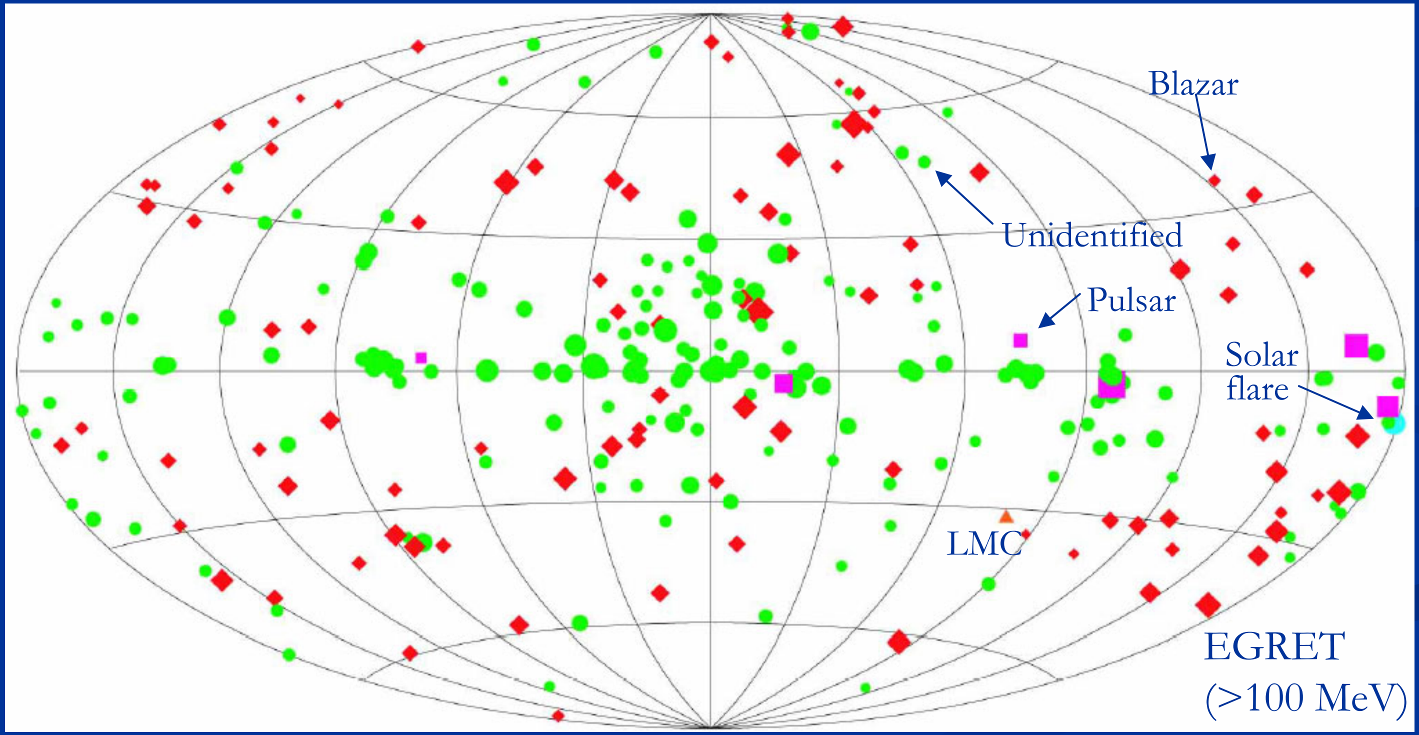


One day's worth of simulated gamma rays, color coded by energy

EGRET: Detection & Characterization

- Many point sources are transient and detected over ~1 week only
- 3EG catalog has 271 sources, almost all of them real (~170 unidentified)

3EG catalog (Hartman et al. 1999)



Strategies for Source Detection

- Do what EGRET did
  - Maximum likelihood analysis – model fitting, first used for COS-B
- Or do what EGRET did, but better
  - Unbinned likelihood analysis, EM
- Nonparametric analyses
  - Wavelets (CWT, DWT), Independent Component Analysis, Bayesian Blocks, Cross Correlation
- Monte Carlo the sky…

J. Scargle's talk

Review of Likelihood Analysis

- Models are straightforward to define – *radiative transfer is simple*

$$I(x,y,E) = I_{MW}(x,y,E) + \sum_i F_i(E)\,\delta(x - x_i, y - y_i)$$

- Data-space version not as simple, of course

$$M(E',\mathbf{p}',t,k) = \int_0^\infty D_k(E';E,\mathbf{p}\cdot\mathbf{z}(t))P_k(|\mathbf{p}'-\mathbf{p}|;E,\mathbf{p}\cdot\mathbf{z}(t))A_k(E,\mathbf{p}\cdot\mathbf{z}(t))\,s(E)\,dE$$

$$\ln\mathcal{L} = \sum_i \ln M(E'_i,\mathbf{p}'_i,t_i,k_i) - N_{\rm pred}$$

$$N_{\rm pred} = \sum_k \iiint M(E',\mathbf{p}',t,k)\,dE'd\mathbf{p}'dt$$

P. Nolan (SU)

- [Extended] Maximum Likelihood analysis is widely used in γ-ray astronomy & we plan to use it for the standard high-level analysis tool for LAT data
  - Introduced by Pollock et al. (1981) for analysis of COS-B data, also used extensively for EGRET analysis.

Likelihood Analysis (2)

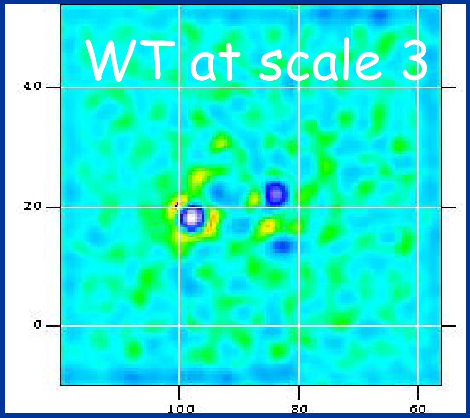
- Why use the EGRET approach?
  - Low fluxes, pervasive structured diffuse emission, & poor angular resolution
- Why *not* use likelihood analysis?
  - Doesn't answer any question that you aren't asking
  - Don't want to bin in inclination angle
  - Not everything we want to study is a point source
  - Requires a good model for the diffuse γ-ray emission of the Milky Way. *Not easy*.
  - Protassov et al. (2002) point out that the principal application, source testing, violates the conditions of Wilks' theorem

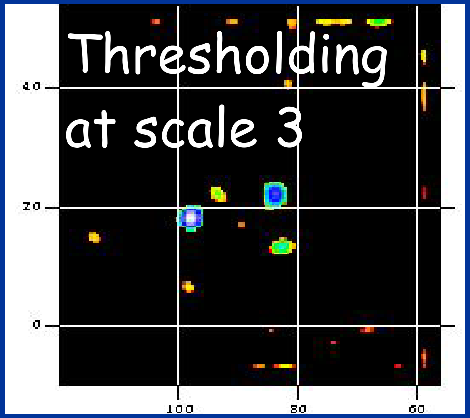
Likelihood Analysis (3)

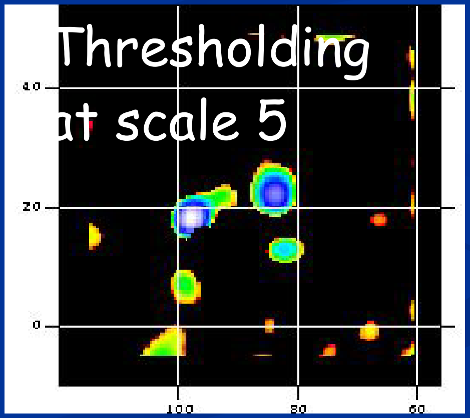
- Why use unbinned likelihood analysis?
  - In principle, uses all of the information in the data
- Why *not* use it? All of the above, plus
  - Computationally tough – multidimensional integration & optimization

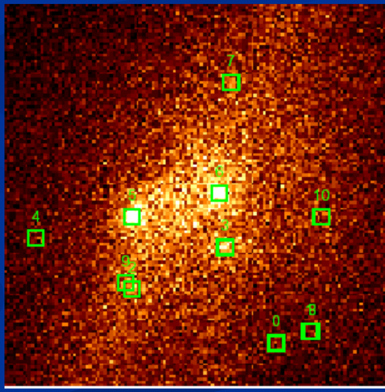
Other Approaches

- Initial investigations underway of alternatives for all or part of the source detection problem
  - WT (Damiani et al. 1997) implemented by F. Marcucci & C. Cecchi (INFN)





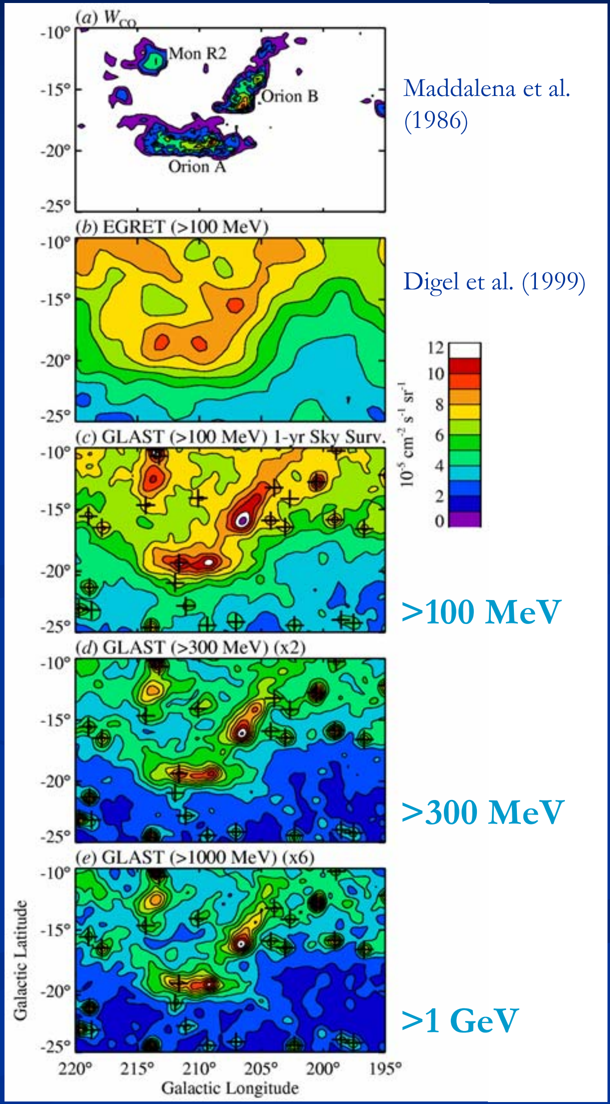




Simulated LAT data in Galactic anticenter

Extended Sources

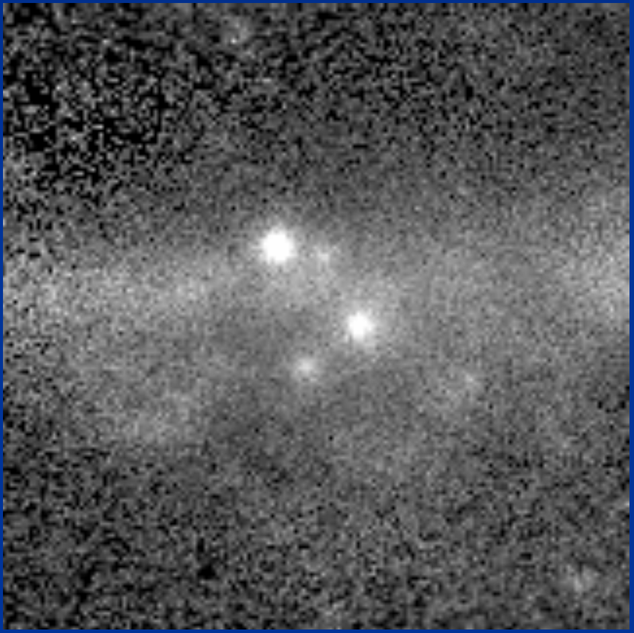
- Orion simulation as an example for LAT resolving extended sources
- Probably ideal case - Nearest giant molecular cloud complex, and have a good template for the emission
- Study of the diffuse emission could permit detailed calibration of molecular content & propagation of cosmic rays & maybe gamma-ray point sources

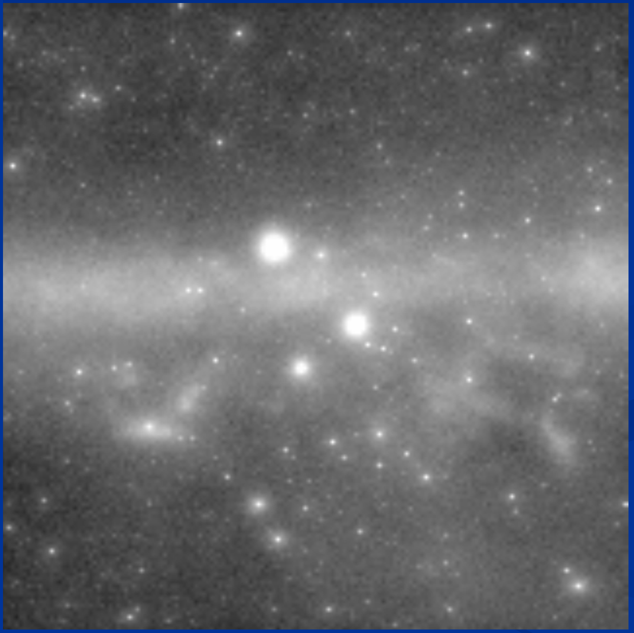


Conclusions

- Gamma-ray sky has diverse source populations
- Exciting science will derive from the great capabilities of the LAT

EGRET
Phases 1-5





LAT

- The challenges for source detection, for maximizing the return are understood and approaches are being investigated
- Look forward to the LAT