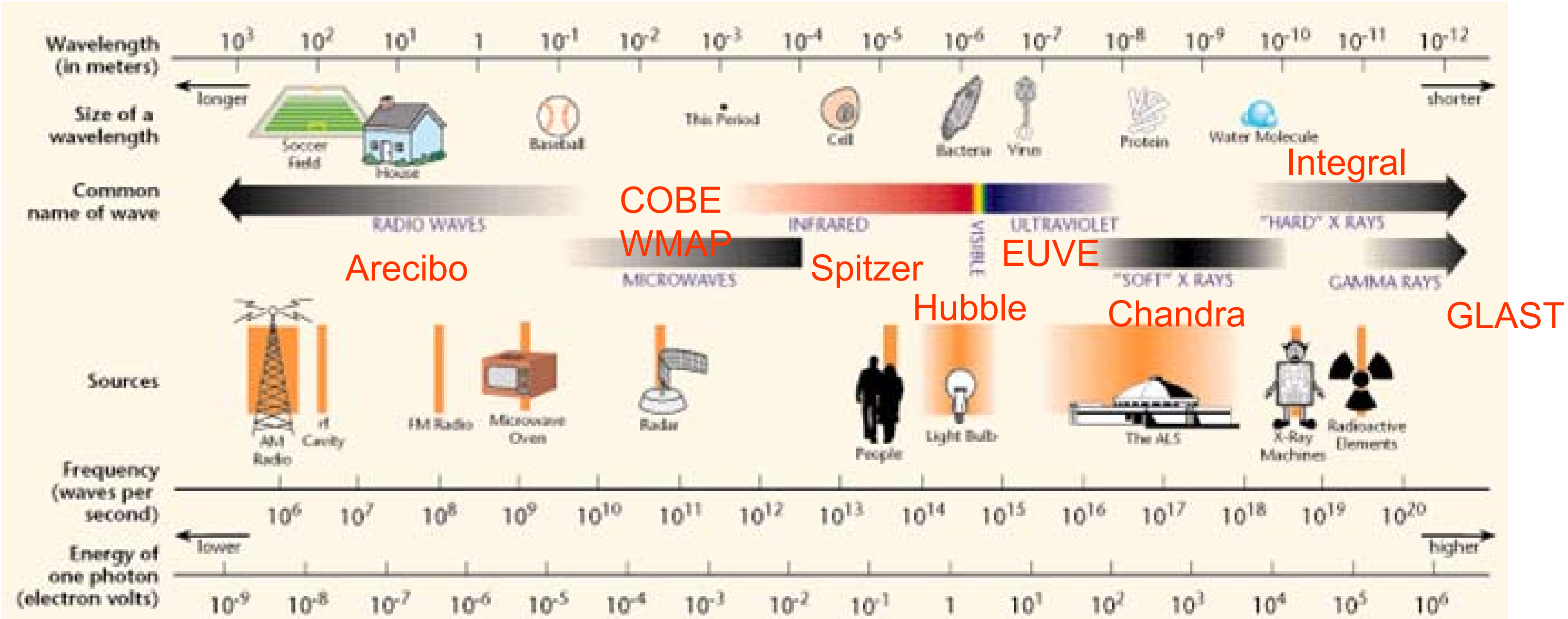
Gamma-ray Large Area Space Telescope

Physics 10 Lecture

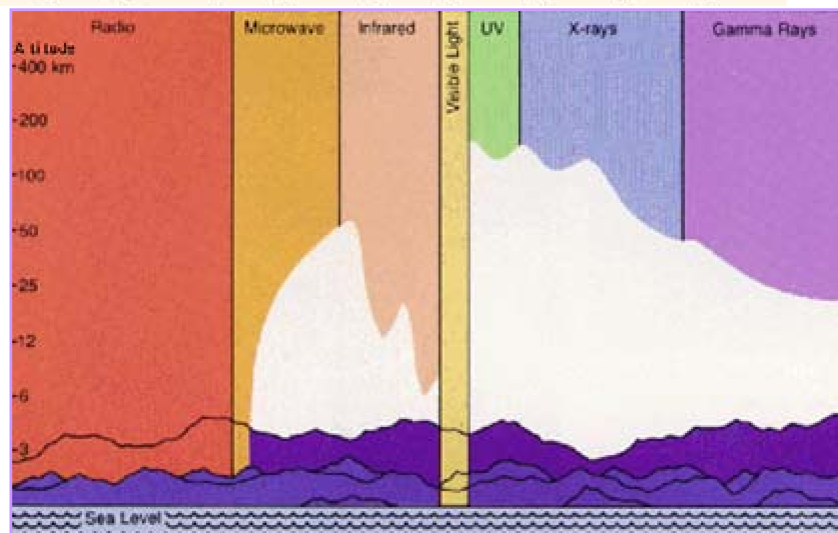
Robert Johnson, William Atwood

November 21, 2006

Why a Gamma-Ray Telescope in Space?



- Extend our astronomical coverage of the E/M spectrum ***five decades*** beyond the chart shown above.
- Our atmosphere is opaque to photons in the gamma energy range, requiring an orbiting observatory.



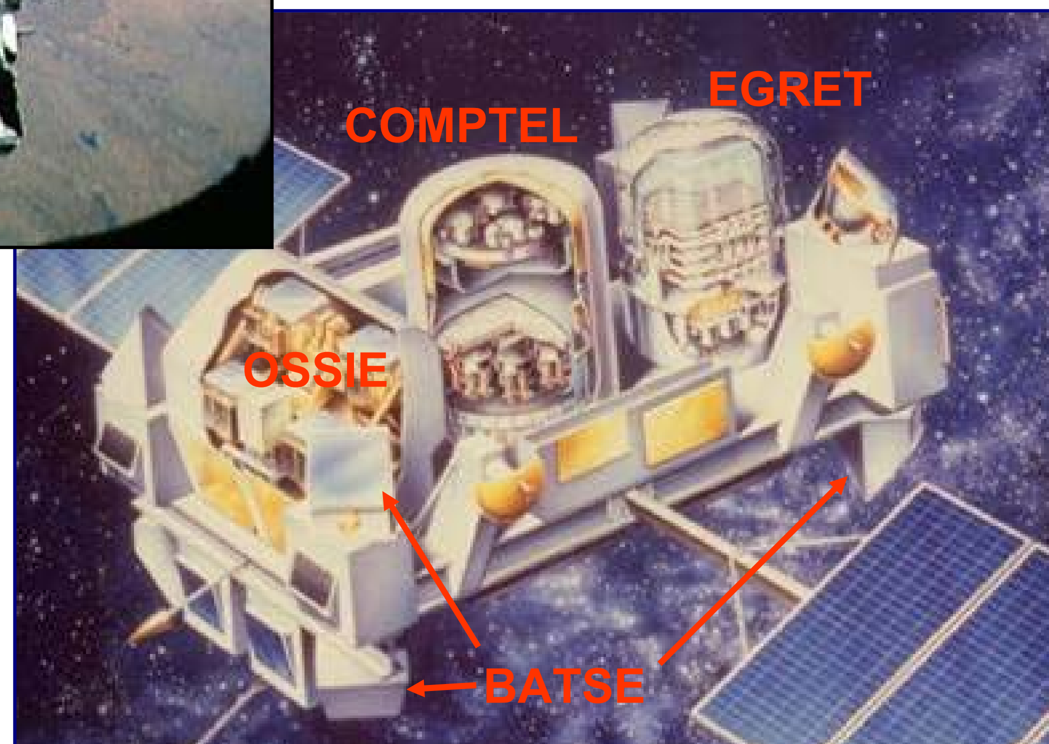
Scientific Heritage: CGRO-EGRET


Deployment from Atlantis, 1991

NASA's gamma-ray "Great Observatory"

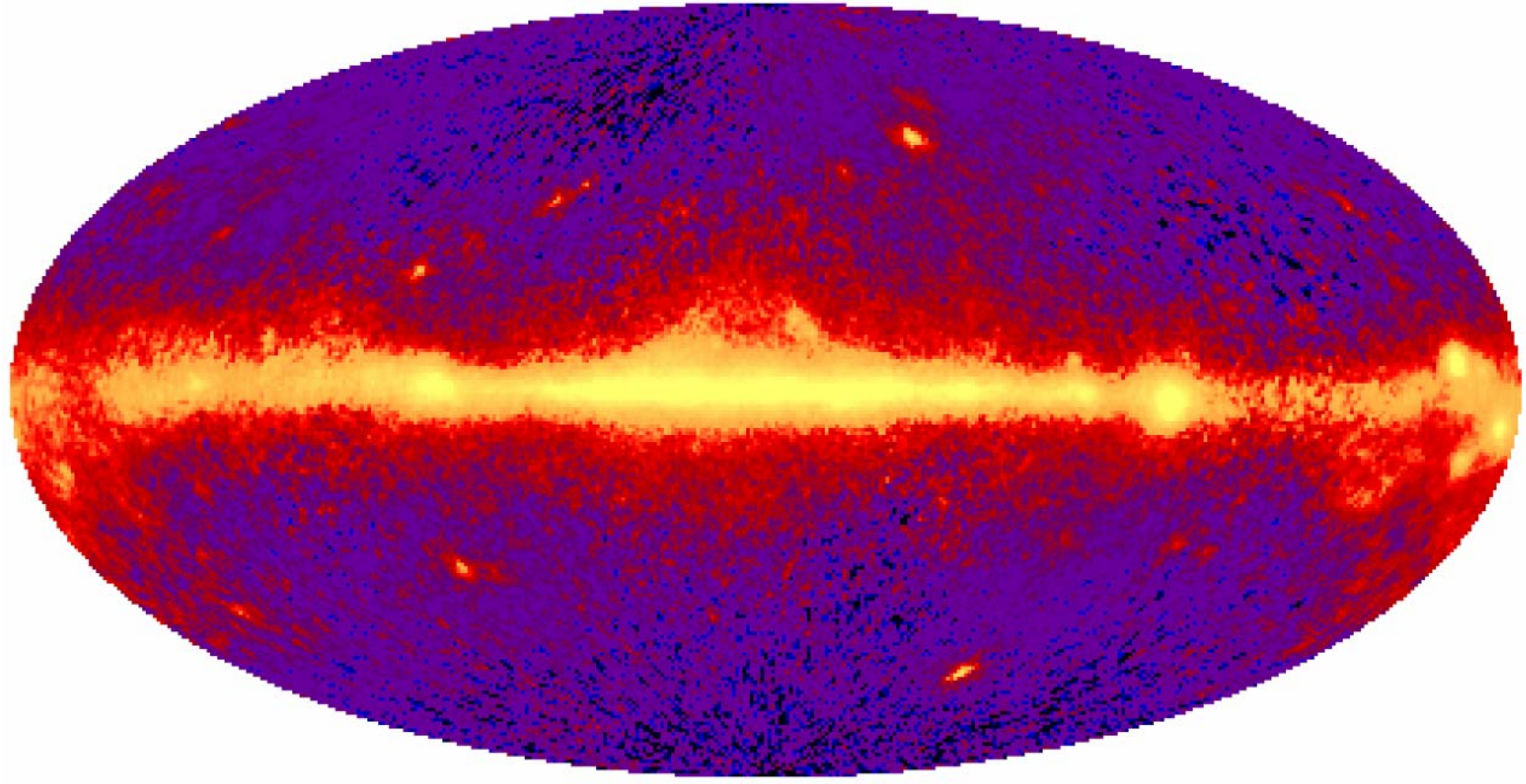
Deployed: April 1991

Reentry: June 2000



- EGRET: high-energy (>20 MeV), pair-conversion telescope
- COMPTEL: Compton-scattering telescope (1 MeV to 30 MeV)
- OSSIE: 50 keV to 10 MeV spectrometer
- BATSE: bursts and transients, 20 keV to 1 MeV (8 modules)

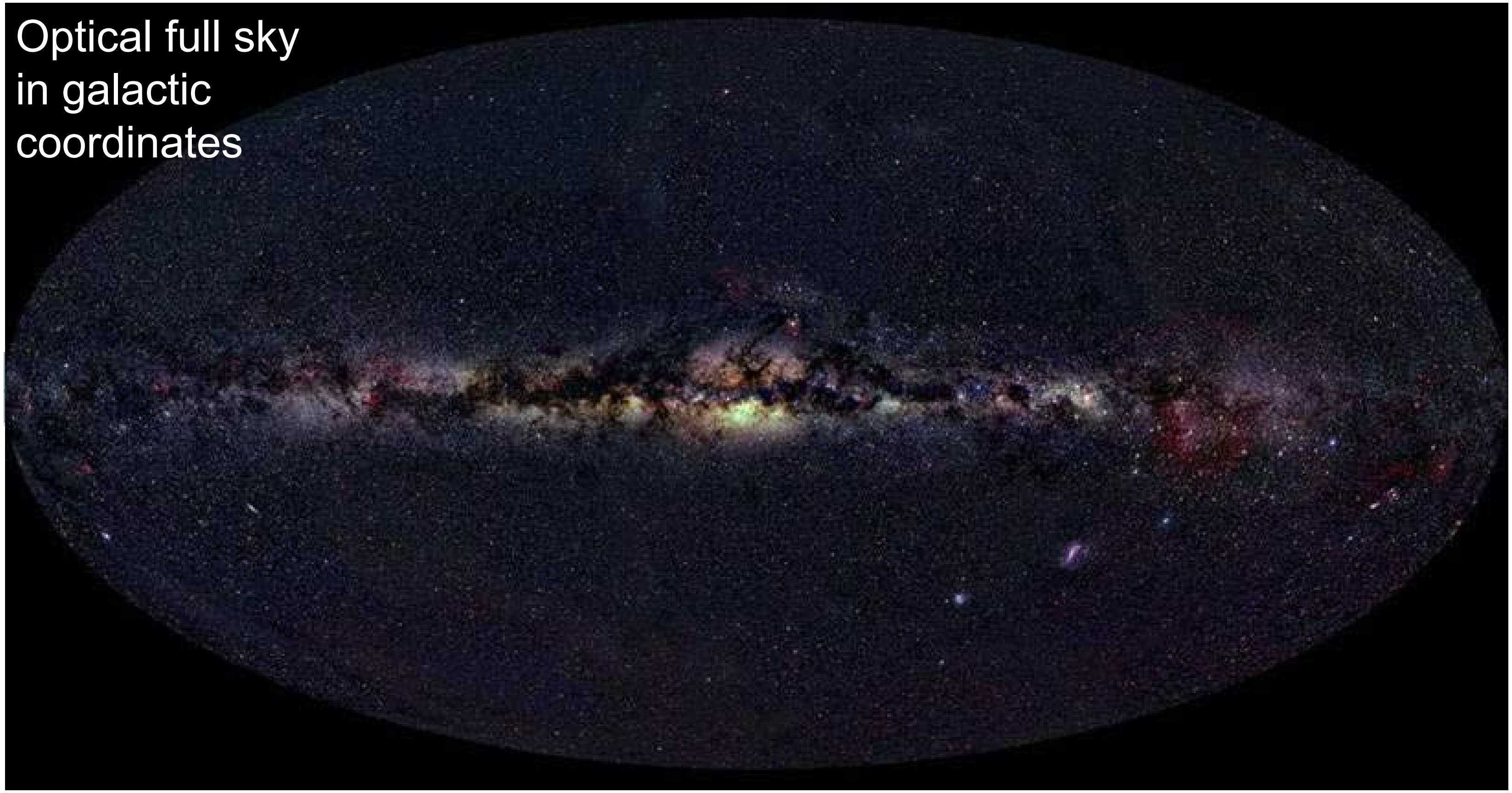
EGRET All-Sky Map for E>100 MeV



Aitoff Projection

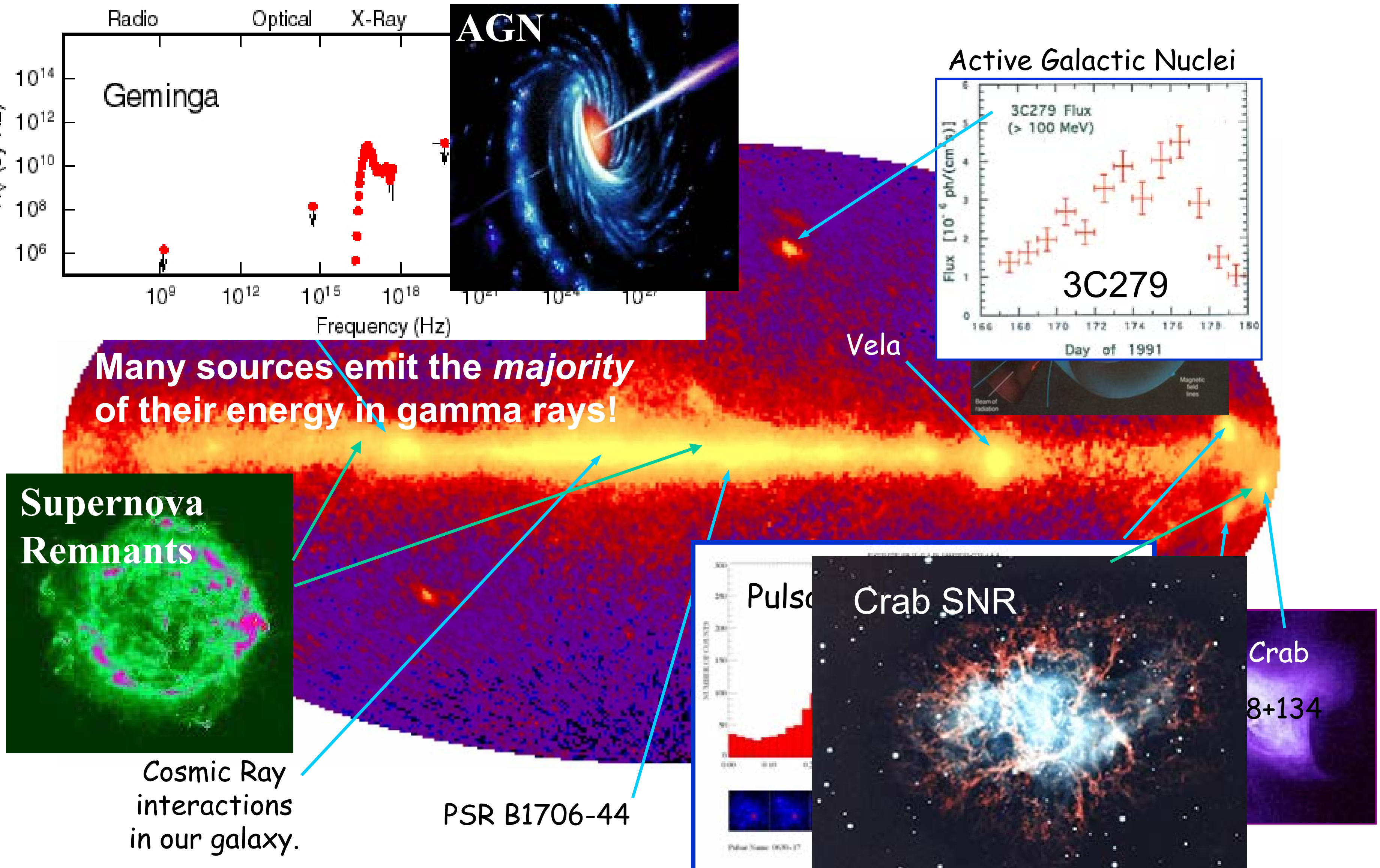
David Aitoff, 1889

(Neither conformal (preserving angles) nor equivalent (preserving area ratios))

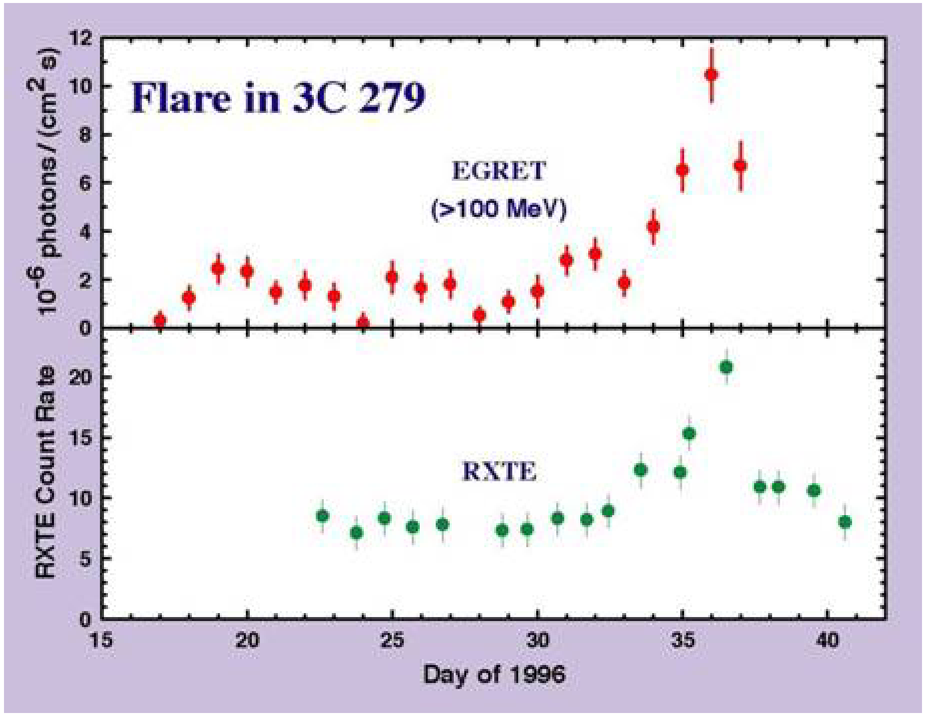


This coordinate system is tilted by 62.6° w.r.t. celestial coordinates (Earth's equator)

Gamma Ray Sources



AGN and Blazars

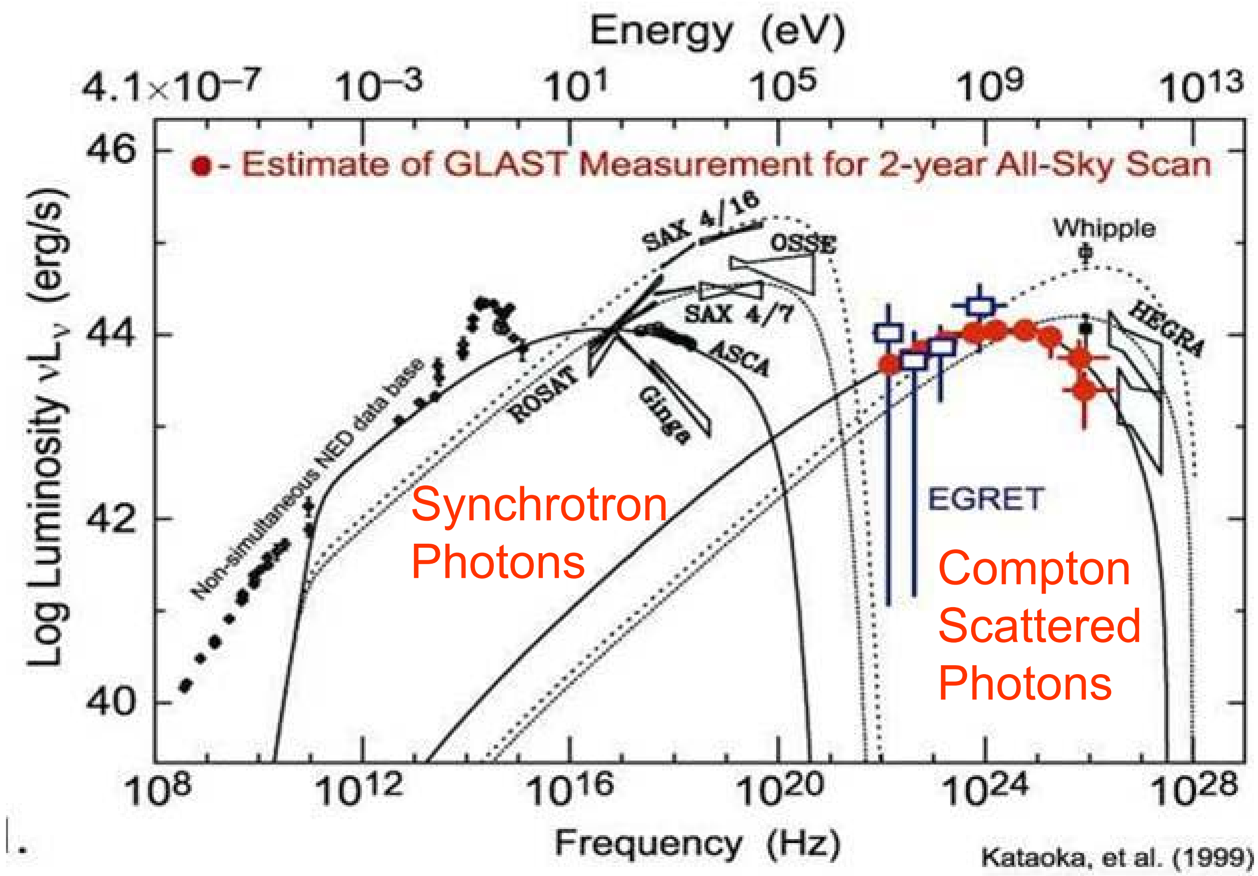


A quasar ~4 billion light years distant

- Active galaxies are believed to have supermassive black holes at their cores, which are rapidly ingesting matter and emitting jets of energetic particles and radiation.
- If we are looking down the “barrel” of the jet, then we see a “blazar”, an active galaxy dominated by high-energy gamma radiation.
- The high-energy emission is surprisingly variable, changing by factors of 10 in a few days.

Distant galaxies, far from the Milky Way.

Measurement of AGN Spectra

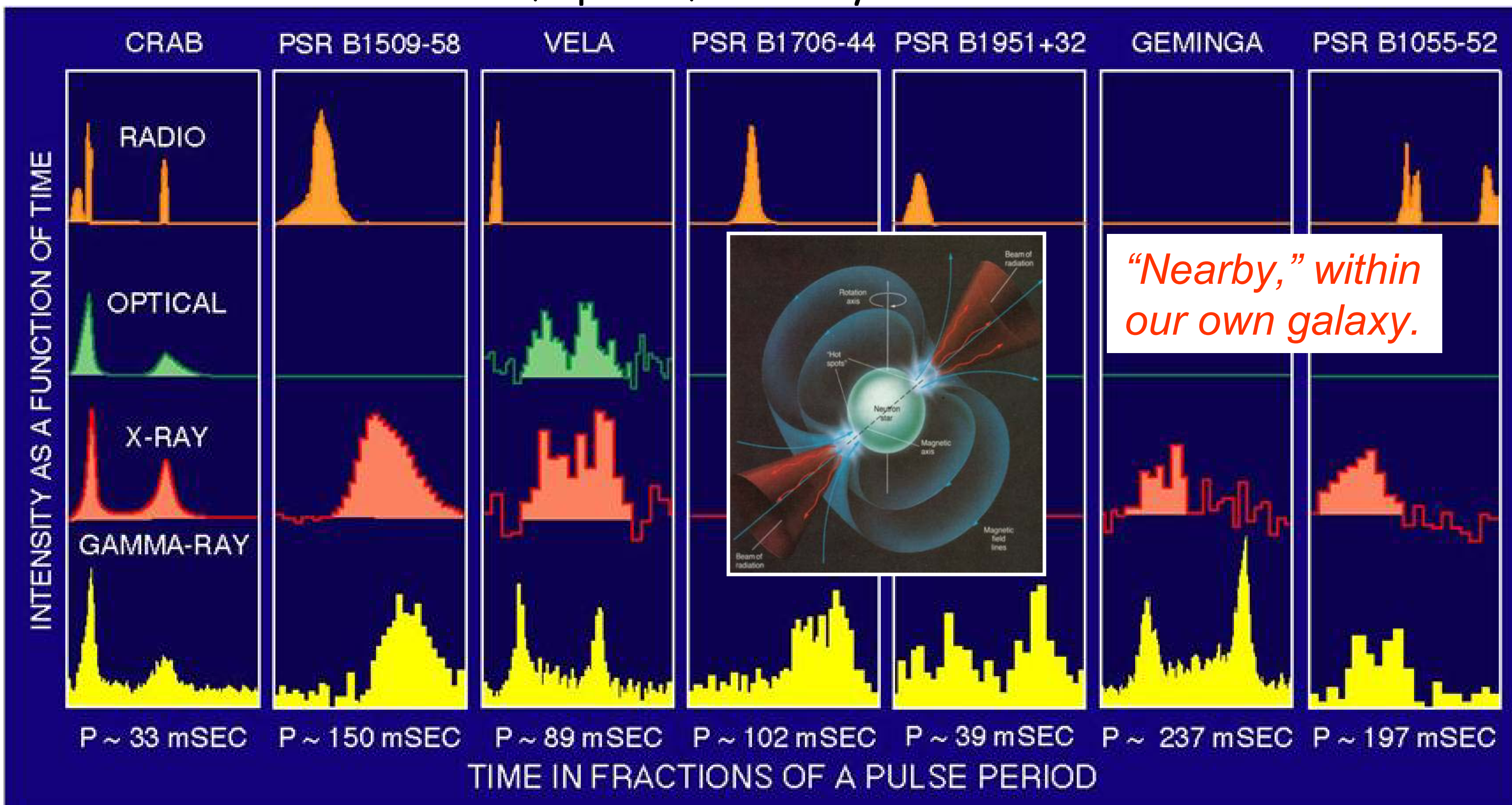


Mrk 501

- Gamma rays are believed to be produced by particles accelerated in relativistic shocks moving along the jets. Details are poorly understood.
- GLAST will be our eye into the high-energy, presumably synchrotron self-Compton, part of the AGN “blazar” spectrum.
- We will want to observe how the spectrum changes as the AGN flares.

Gamma-Ray Pulsars

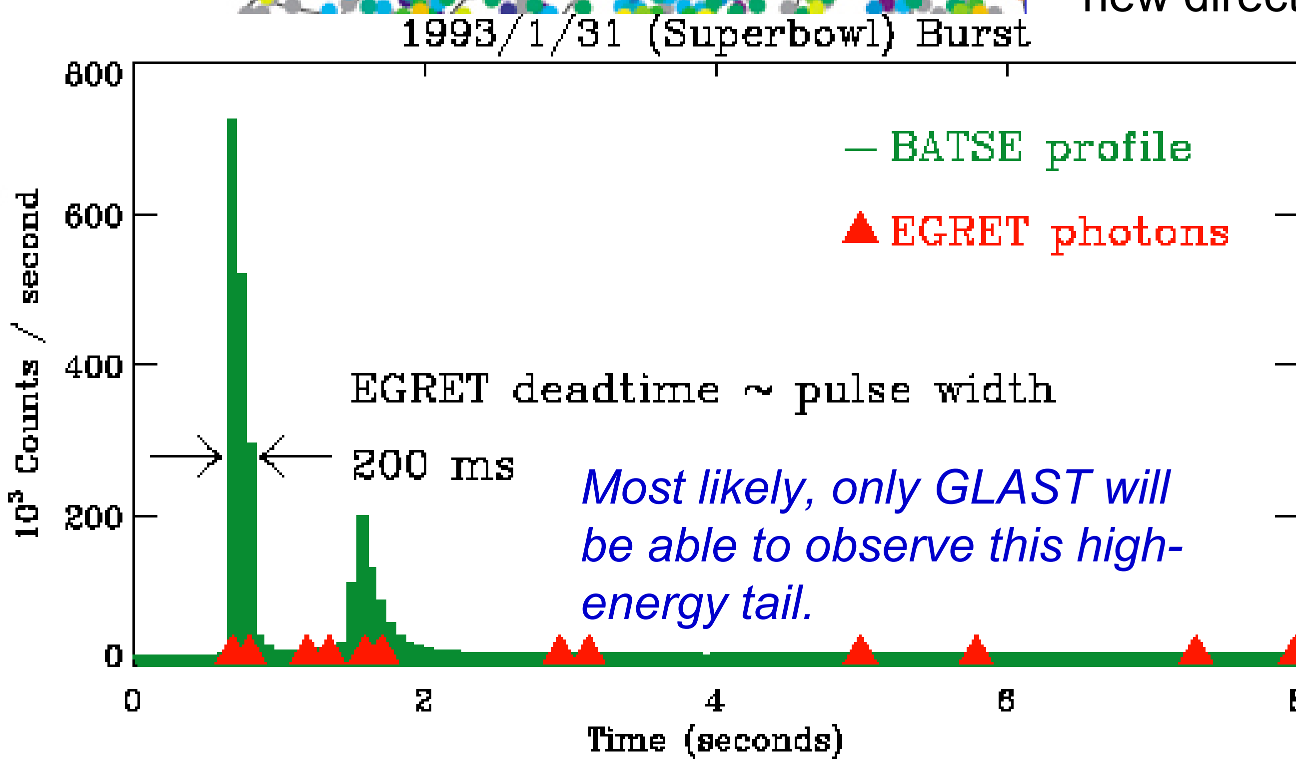
- Only 7 pulsars have been shown so far to have pulsed gamma-ray emission. GLAST should increase this by at least a factor of 10.
- Our SCIPP group is working on techniques to detect pulsars that have not been seen in radio, optical, or x-ray.



"Nearby," within our own galaxy.

Gamma Ray Bursts (GRB)

- Approximately one burst each day
- Each burst arrives from a new direction
- stribution on the
sts *extragalactic*
onfirmed in the
rs by observation
counterparts)

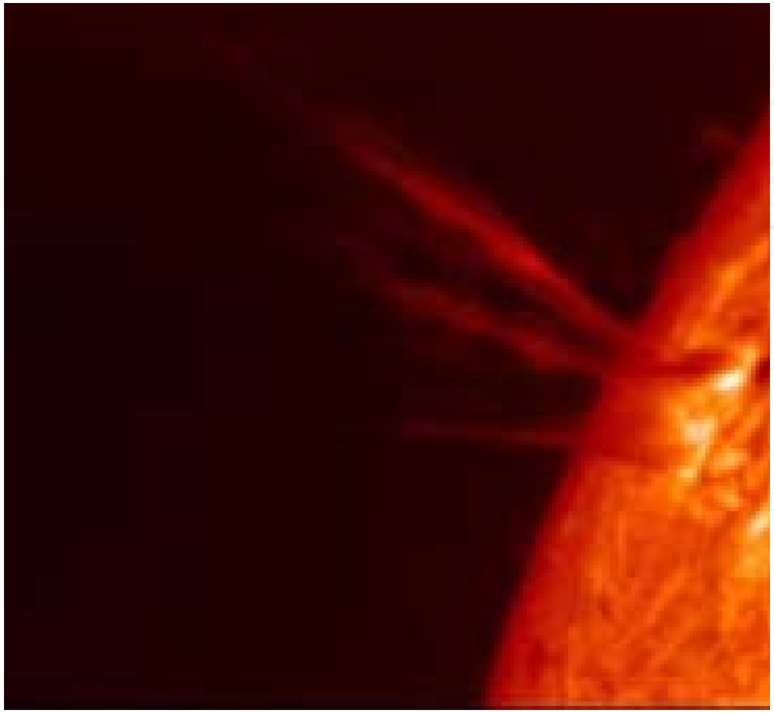


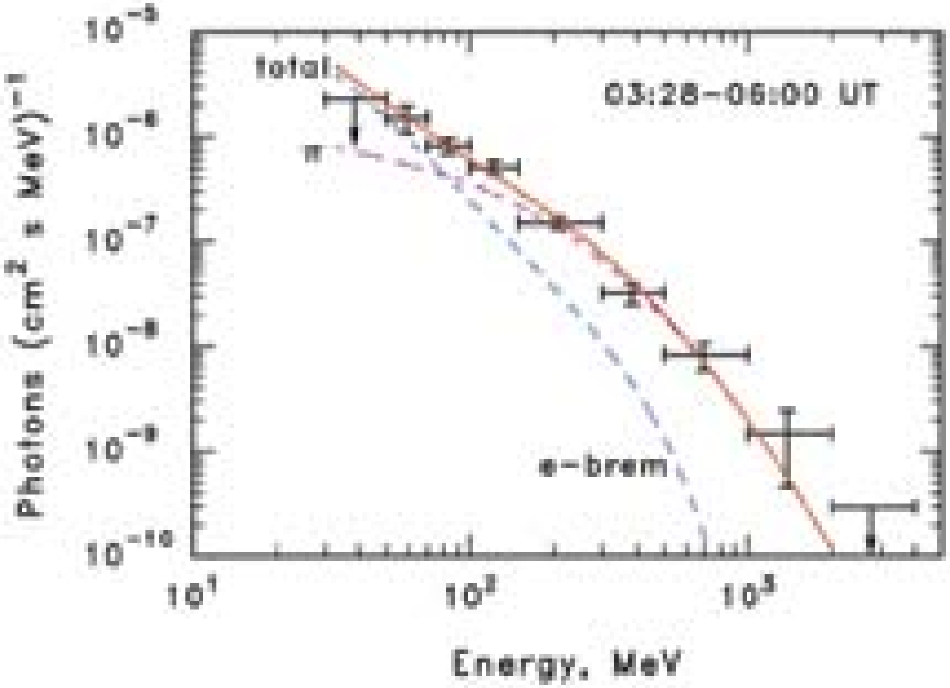
Most likely, only GLAST will be able to observe this high-energy tail.

Time profile can be complex, with delayed arrival of high energy photons.

Solar Gamma Rays

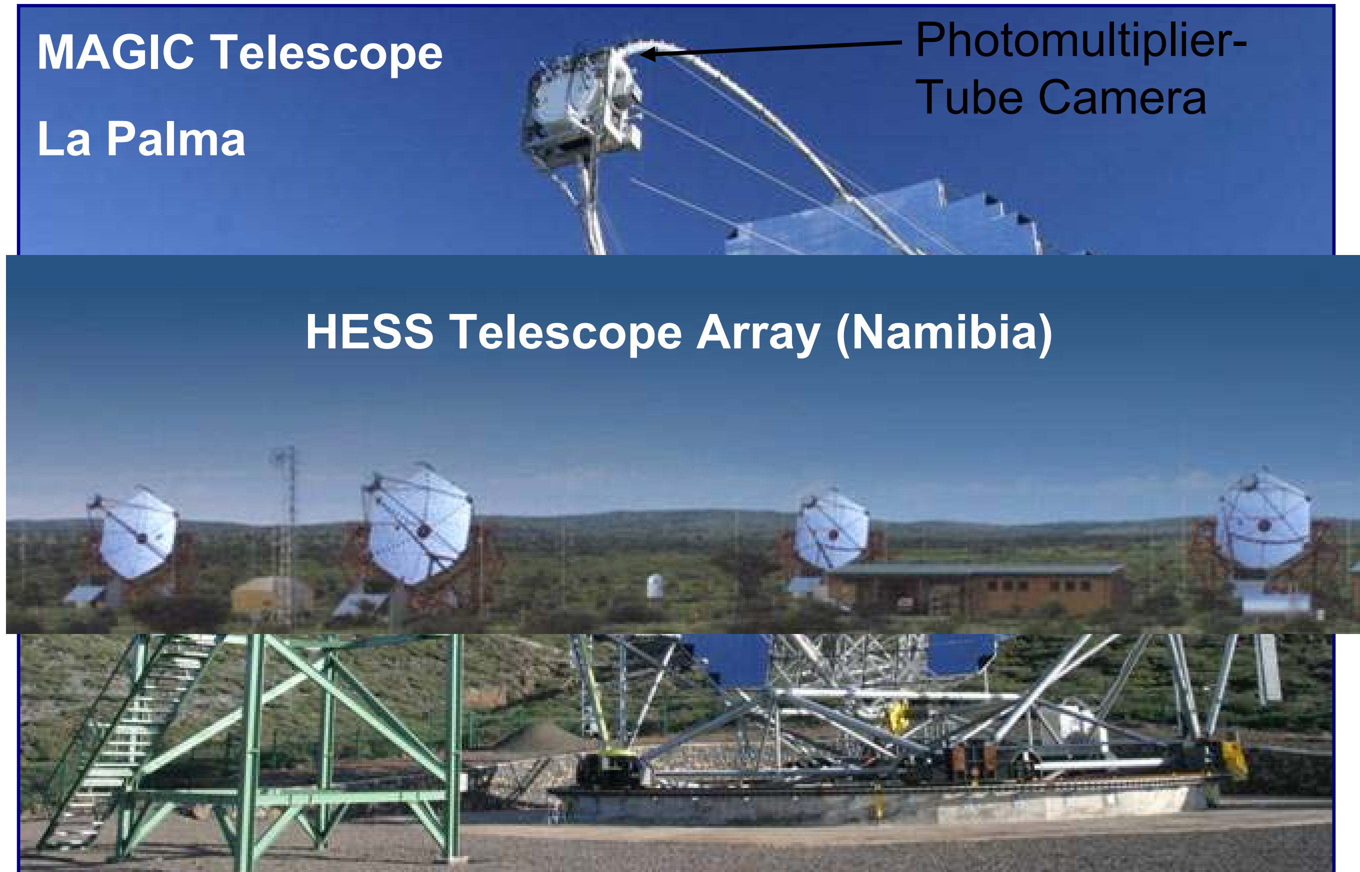
- Ordinary stars are not visible in the gamma-ray sky. Their gamma emission is too weak, and they are too far away, except…
- High-energy gamma rays have been observed from the nearest star, our sun, during extraordinary solar flares.
- Photons as energetic as 1000 MeV were observed by EGRET in a 1991 flare. Such photons cannot be from thermal emission—their presence indicates particle accelerators at work in the vicinity of the flare.



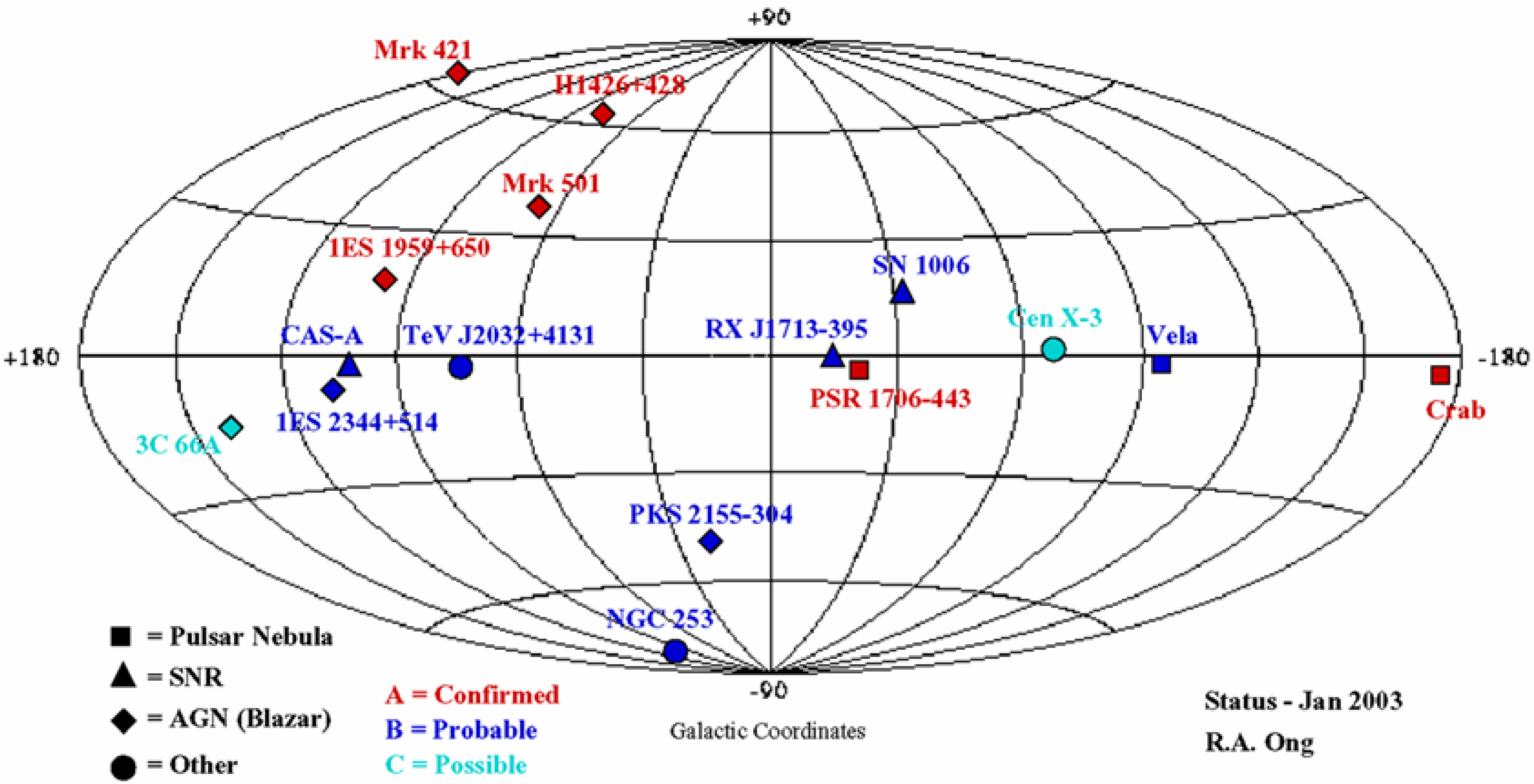


Ground-Based Gamma-Ray Telescopes

- Very High Energy (VHE) gamma rays (E>100 GeV) can be detected by viewing from the ground the electromagnetic showers that they produce high in the upper atmosphere.
- At least 4 new projects (Hess, Kangaroo, Magic, Veritas) are pursuing this approach, following the initial success of the Whipple observatory.
- Images of the EM showers are made by focusing the Cherekov light with large reflectors
- Cameras pixelated with PMTs detect the very faint, fast signals.



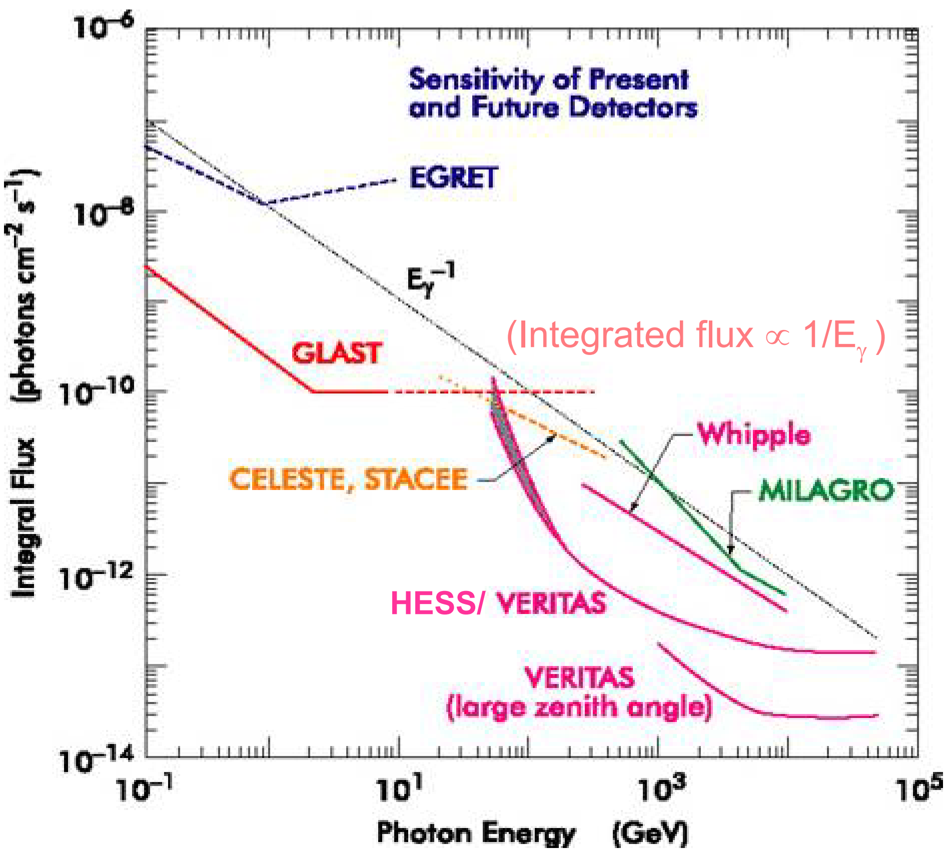
VHE Gamma-Ray Sources, Pre-MAGIC/HESS



- These gamma-rays have TeV and greater energies!
- The list is rapidly growing now, from MAGIC & HESS data.
- *Note that Prof. Williams works on this type of telescope.*

Covering the Gamma-Ray Spectrum

- Broad spectral coverage is crucial for studying and understanding most astrophysical sources.
- GLAST and ground-based Very-High-Energy (VHE) gamma-ray telescopes cover complimentary energy ranges.
- The improved sensitivity of GLAST is necessary for matching the sensitivity of the next generation of ground-based detectors.
- GLAST goes a long ways toward filling in the energy gap between space-based and ground-based detectors—there will be overlap for the brighter sources.
- Only GLAST has a wide field of view, to scan the sky each day.



Predicted sensitivities to a point source. EGRET, GLAST, and Milagro: 1-yr survey. Cherenkov telescopes: 50 hours on source. (Weekes et al., 1996, with GLAST added)

Some Scientific Goals

- Extreme Astrophysics
  - Probe high-energy, non-thermal astrophysics environments
  - Searches for new sources of high-energy radiation
- Understanding acceleration of high energy particles in astrophysics
  - Shock acceleration in AGN jets
  - Acceleration in ultra-intense fields around pulsars
  - Investigating the origin of galactic cosmic rays
- Cosmology
  - Extinction of gamma rays from distant AGN by interactions with the extragalactic photon flux
  - Search for a diffuse extra-galactic gamma-ray flux
- Fundamental Physics
  - Searches for neutralino annihilation (dark matter)
  - Investigation of hypothesized gamma-ray dispersion by the intergalactic vacuum (quantum gravity)

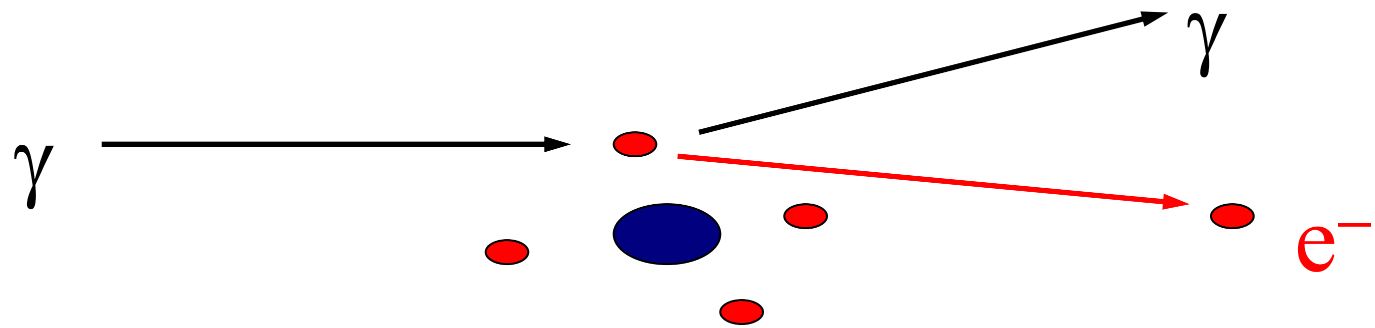
How to Image a Gamma-Ray Source

- Lenses are useless: at this energy there is no refraction. The gamma-ray either goes straight through the glass or else gets absorbed.
- Mirrors are useless: the gamma-rays will penetrate into the mirror. They will not reflect.
- However, gamma-ray photons have enough energy that they can readily be detected one at a time! We only need to measure each gamma-ray's direction of travel in order to image the source.
- GLAST does more: we measure both
  - Photon direction $\rightarrow$ spatial image
  - Photon energy $\rightarrow$ spectrograph
- Only one more possible piece of information: photon polarization. This is very difficult to measure for a gamma ray.

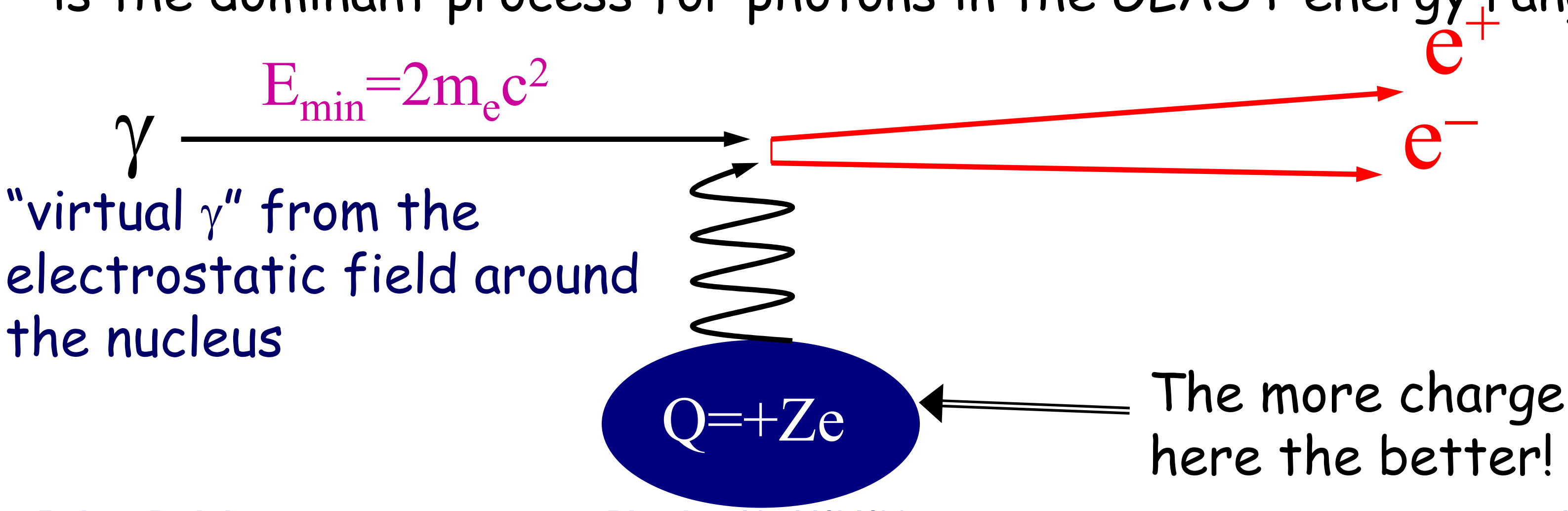
Interaction of Gamma Rays with Matter

2 dominant processes:

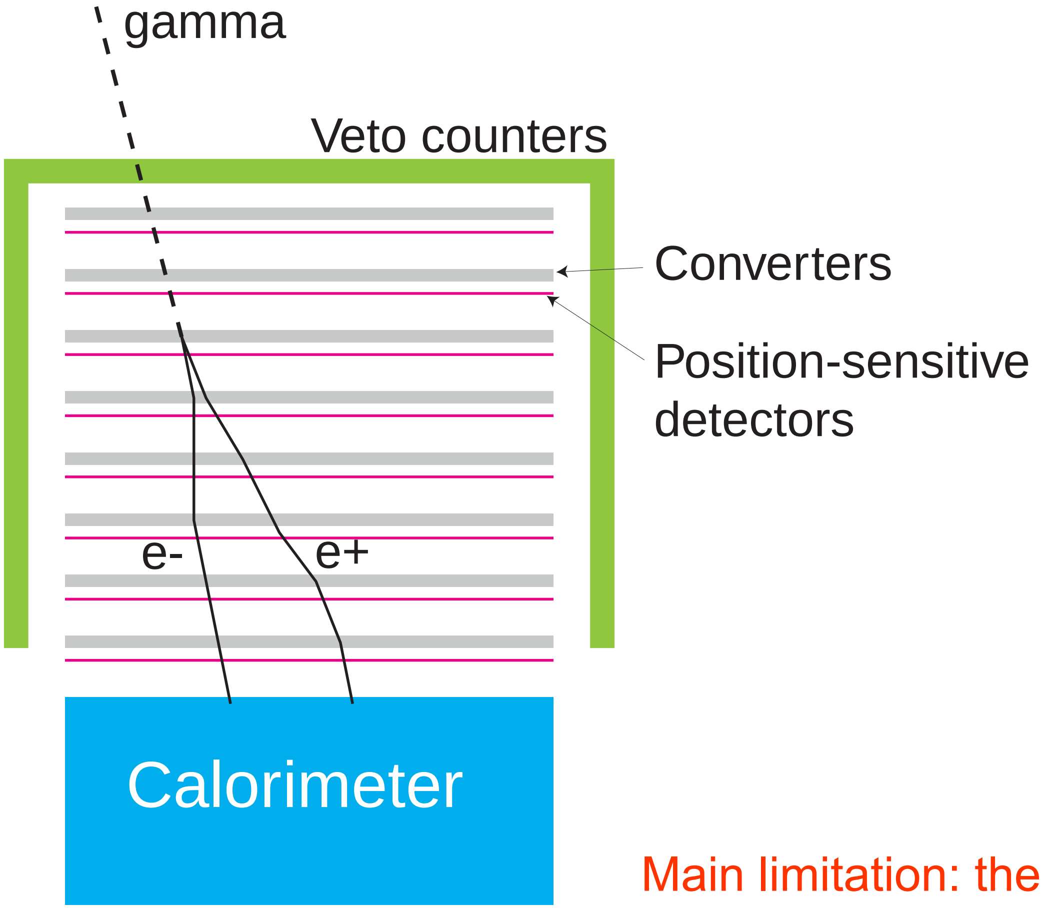
- Compton Scattering. (Collision with an atomic electron.)



- Pair Conversion. (Glancing collision with the atomic nucleus.) This is the dominant process for photons in the GLAST energy range.



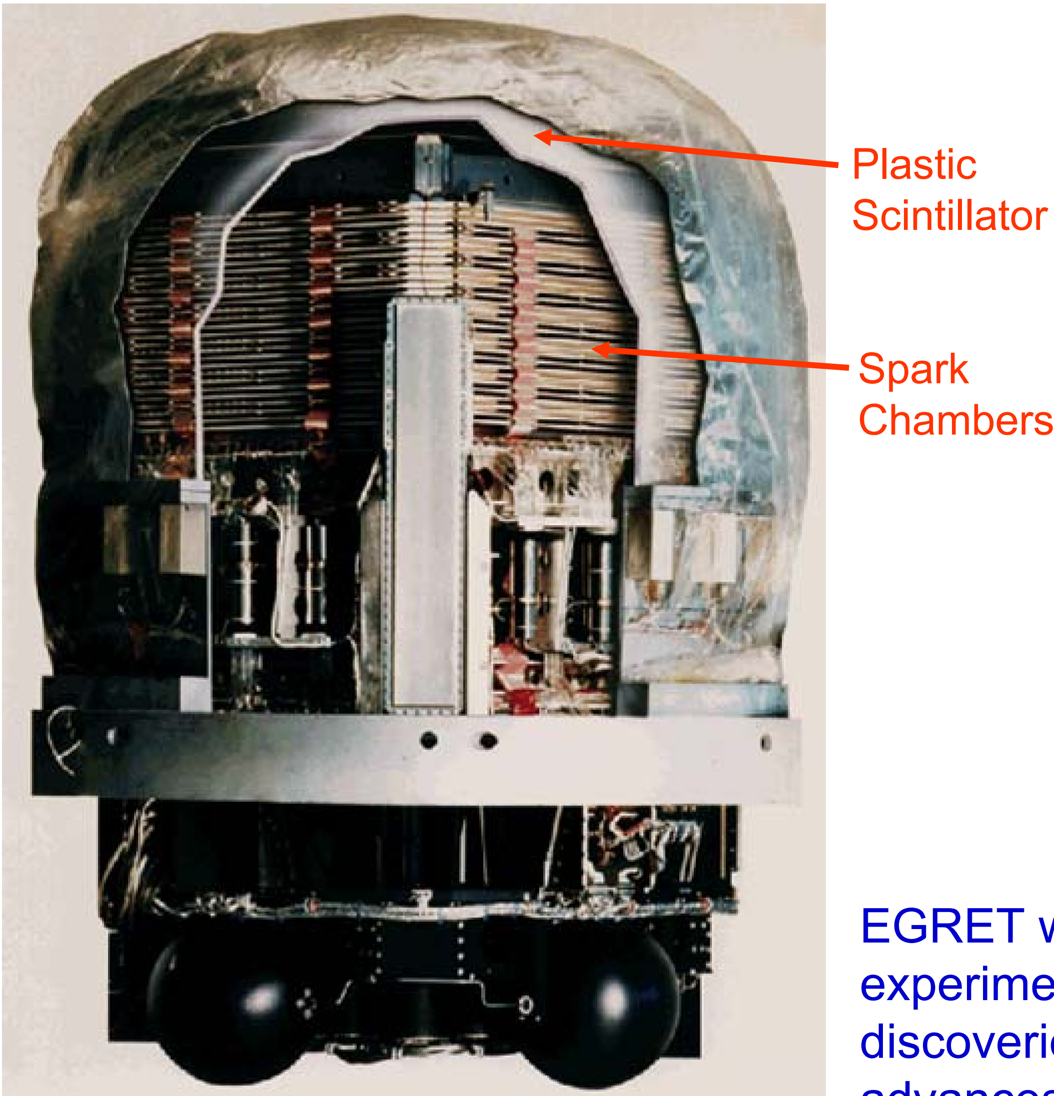
Pair-Conversion Telescope Principle



- Tracker/Converter: heavy metal converts the photon to a positron-electron pair. The measured tracks point back to the astronomical source.
- Calorimeter: measures the photon energy
- Veto counters: a signal indicates presence of a charge cosmic ray, instead of a photon.

Main limitation: the electron and positron scatter in the converter and detector material, limiting the angular resolution to the order of 0.1 to 1 degree!

EGRET Pair-Conversion Telescope



- Tracking based on wire spark chambers
  - 1960s technology
  - Slow (ms deadtime)
  - Each spark consumes some of the gas
- Time-of-flight system needed for triggering and additional background rejection
  - Constricts the field of view

EGRET was a highly successful experiment, credited with many discoveries, but 30 years of technological advances allow us to improve upon it.

GLAST LAT Overview: Design

Si Tracker

8.8×10⁵ channels

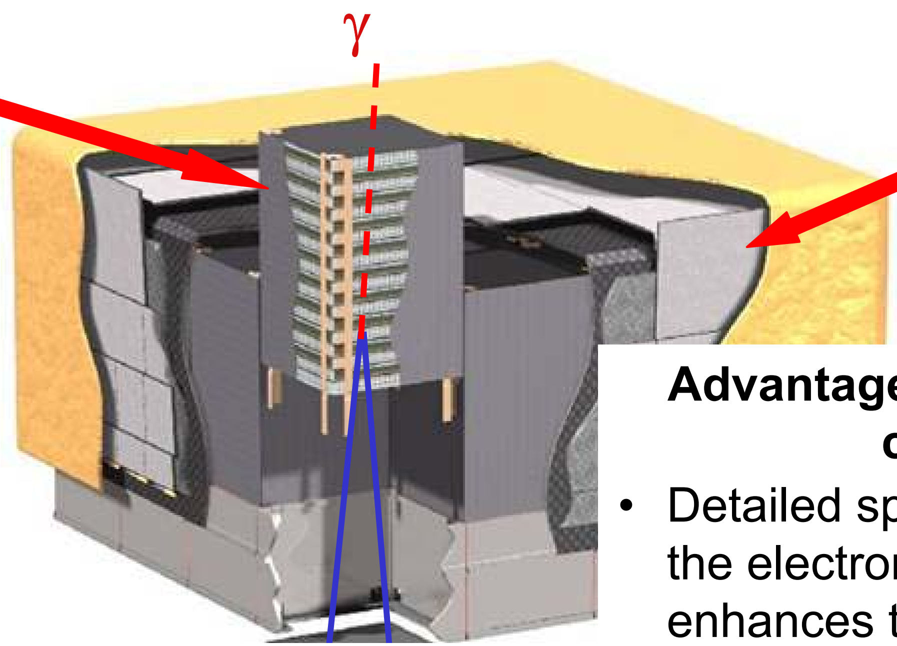
<160 Watts

16 tungsten layers

36 SSD layers

Strip pitch = 228 µm

Self triggering



ACD

Segmented scintillator tiles

0.9997 efficiency

Minimal self veto

Advantages of a hodoscopic calorimeter:

- Detailed spatial reconstruction of the electromagnetic shower enhances the rejection of

Advantage of a segmented veto shield:

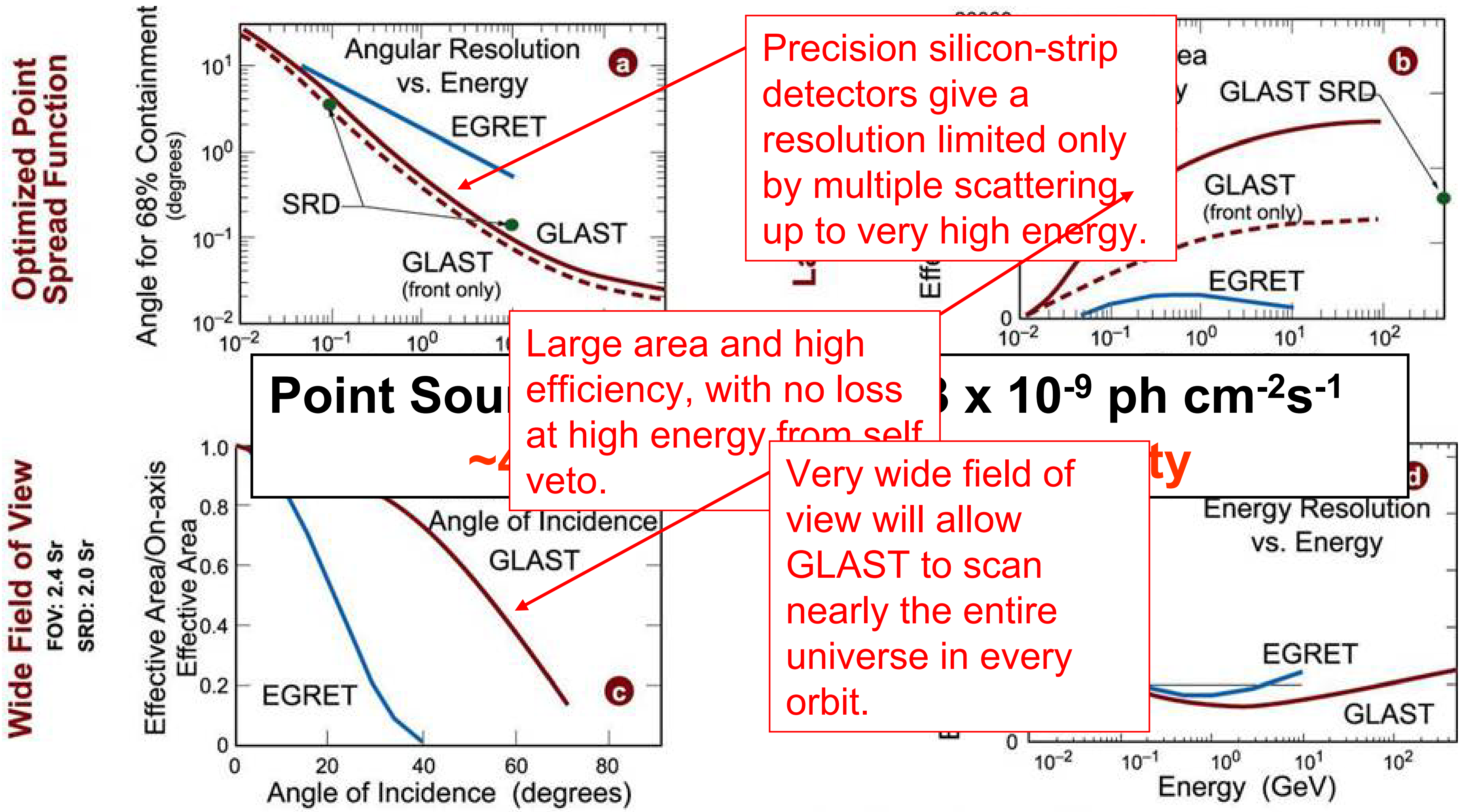
- Reduces the incidence of self-veto, allowing the instrument to trigger efficiently at very high energies.
- The EGRET effective area dropped rapidly above 10 GeV because x-ray albedo from the calorimeter showers tended to fire the veto shield.
- In GLAST the veto is based only upon the ACD tile to which the tracks project.

acquisition

high-energy showers

LAT Instrument Performance

Including all Background & Track Quality Cuts



Precision silicon-strip detectors give a resolution limited only by multiple scattering up to very high energy.

Large area and high efficiency, with no loss at high energy from self veto.

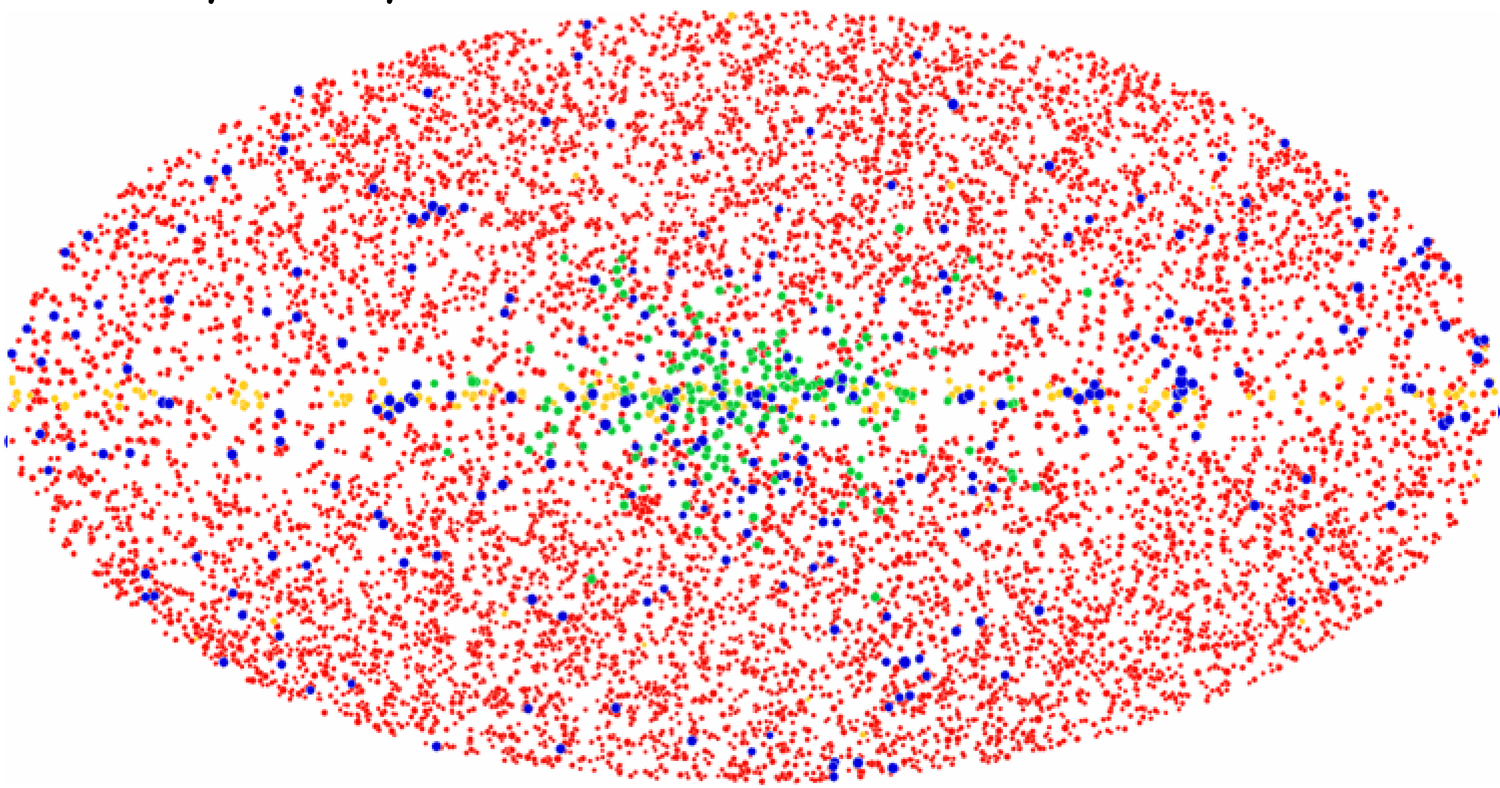
Very wide field of view will allow GLAST to scan nearly the entire universe in every orbit.

Point Sou… 3 x 10^{-9} ph $cm^{-2}s^{-1}$

~4… ty

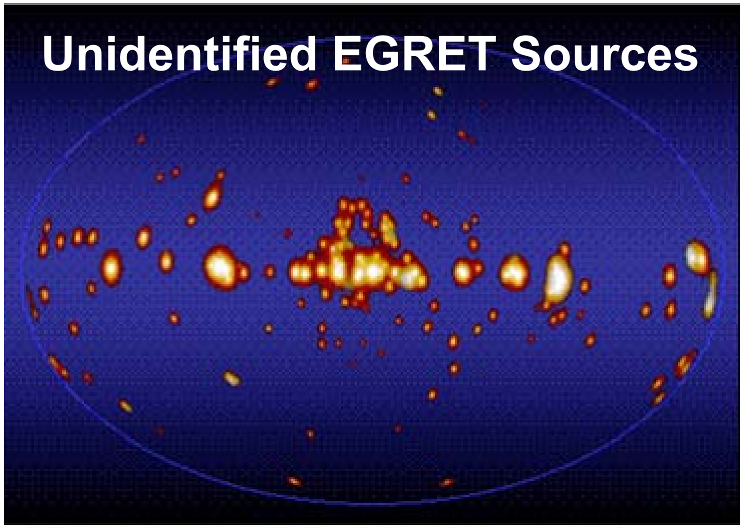
GLAST Survey: ~10,000 sources (2 years)

5σ sources from a simulated
1-year all-sky survey.



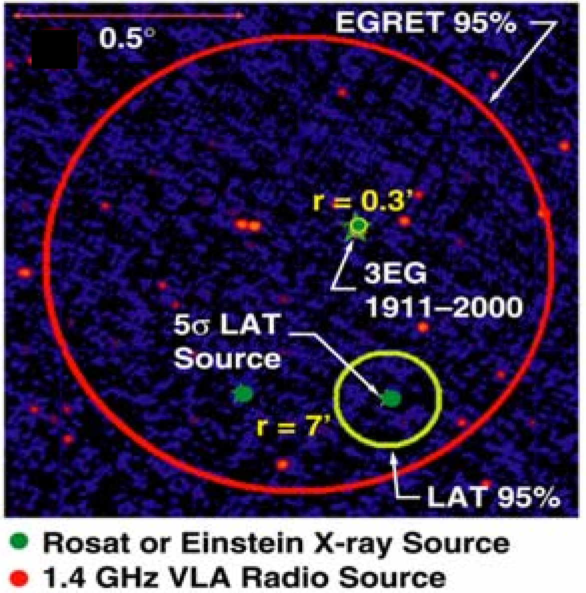
GRB, AGN, 3EG + Gal. plane & halo sources

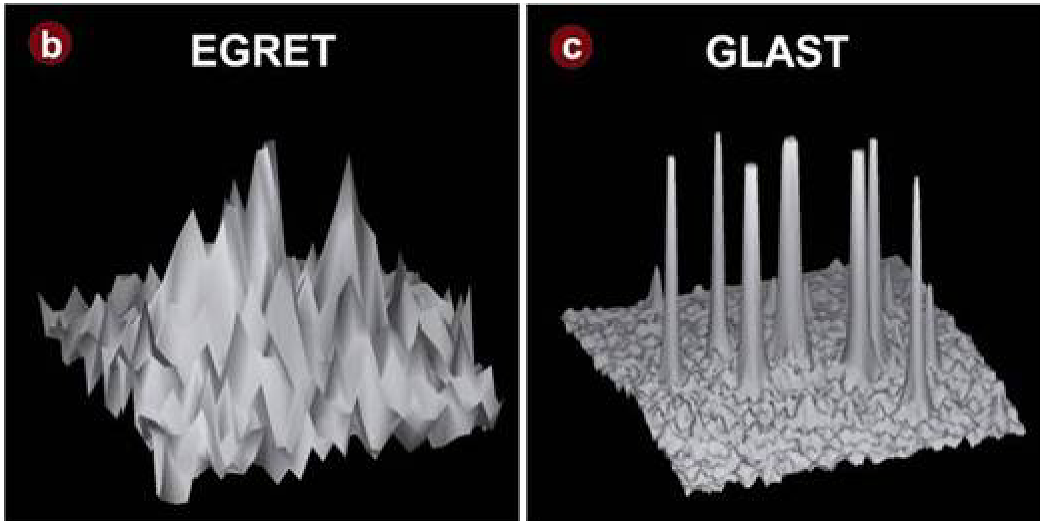
LAT Science Capabilities - Resolution



Greatly improved source localization and continuous monitoring of transient behavior will aid in the search for counterparts and the identification of sources.

These capabilities will be especially important for identification of sources in the crowded galactic plane, as illustrated in the simulation below.

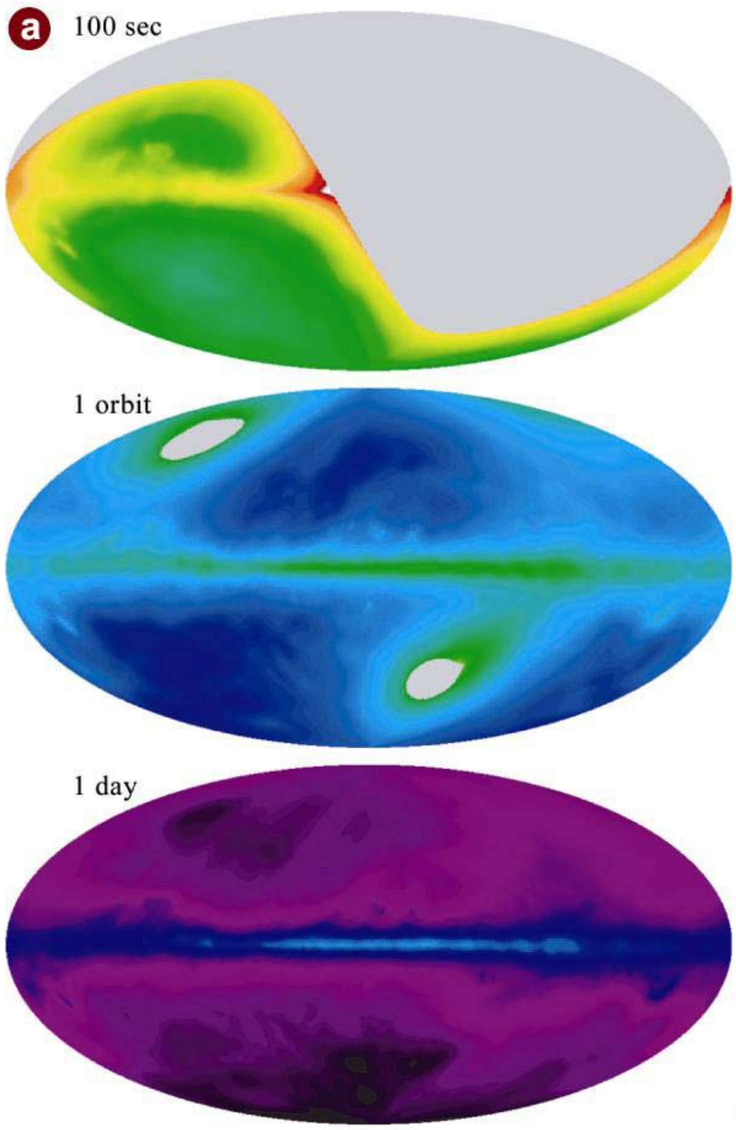


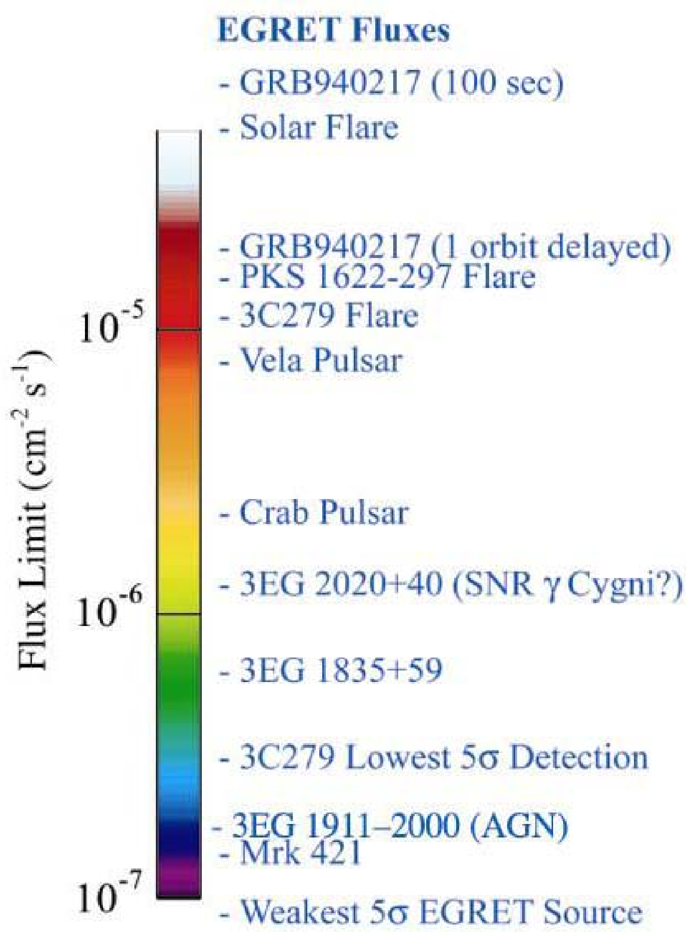


Cygnus region (15^0 x 15^0), $E\gamma > 1$ GeV

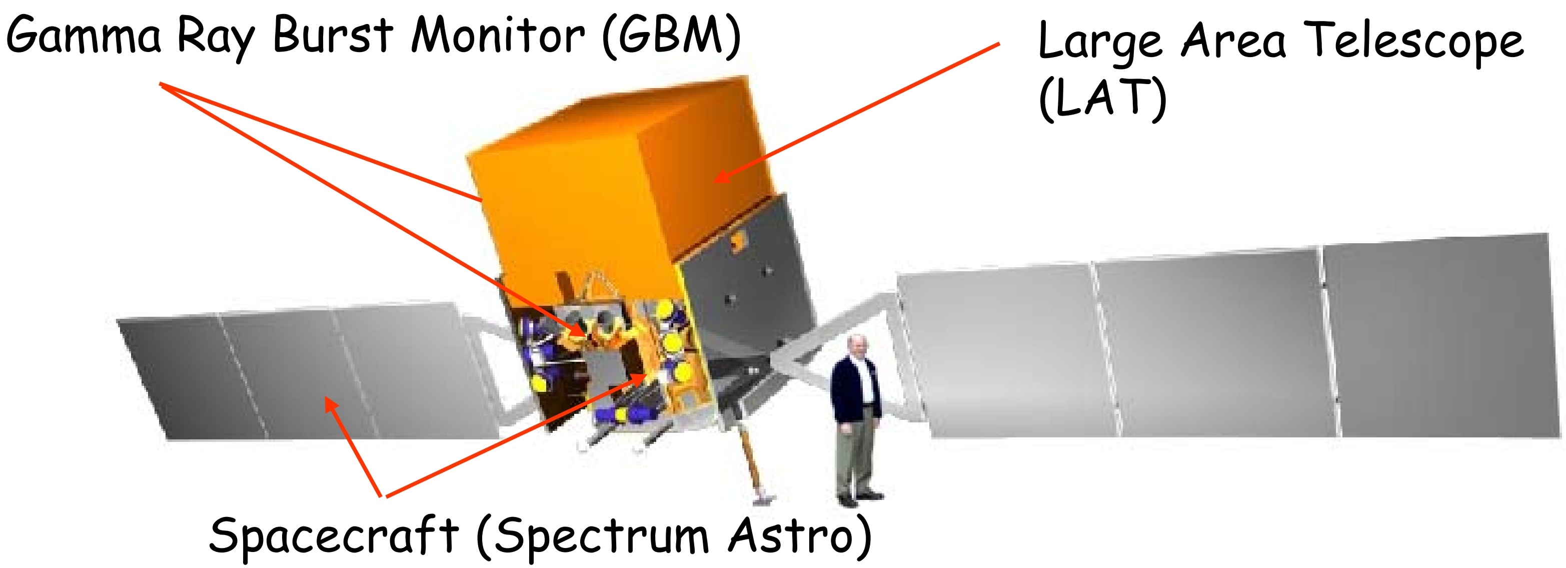
Detection of Transients

In scanning mode, GLAST will achieve in one day a sufficient sensitivity to detect (5σ) the weakest EGRET sources.





GLAST Observatory

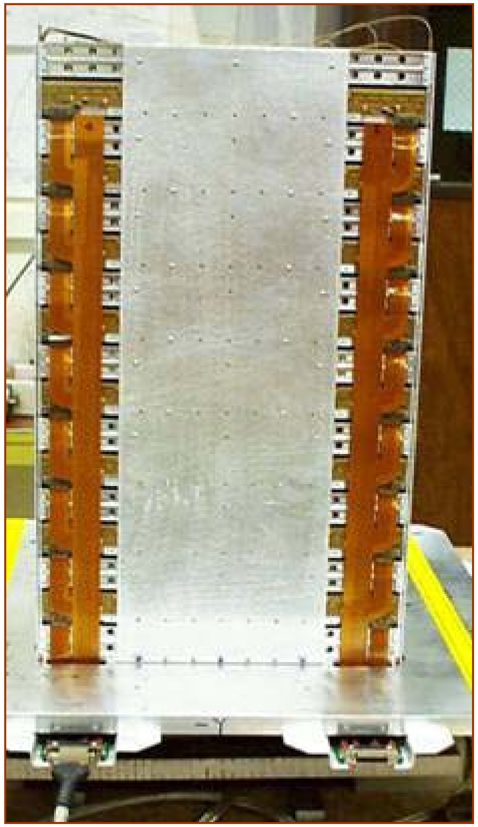


Launch Vehicle	Delta II – 2920-10H
Launch Location	Kennedy Space Center
Orbit Altitude	575 Km
Orbit Inclination	28.5 degrees
Orbit Period	95 Minutes
Orientation	+X to the Sun
Launch Date	October 7, 2007

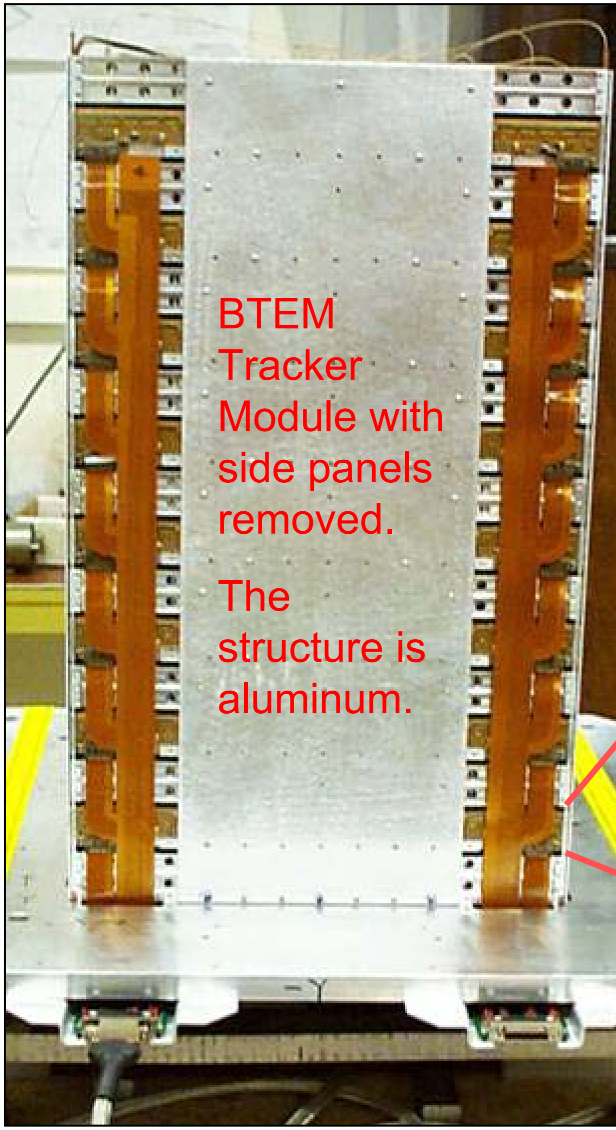
UCSC Contributions to LAT Instrument

- Original conceptual design of GLAST (Bill Atwood) from 1992
  - Monte-Carlo simulations of the instrument
  - Reconstruction of simulated data (tracks, energy, photon direction)
  - Background elimination studies and methods
    - Work continues on this to this day!
- Tracker design and development, starting in 1994 (R. Johnson)
  - Beam tests in 1997 and 1999 with prototype trackers built at UCSC
  - Balloon flight of a prototype tower in 2001
- Lead flight tracker design, engineering, fabrication and test, starting in 2000; completion in 2005.
  - R. Johnson: tracker subsystem manager
- Tracker electronics design and fabrication

Beam-test & Balloon-flight prototype



Beam-Test Engineering Model Tracker



The BTEM Tracker Module

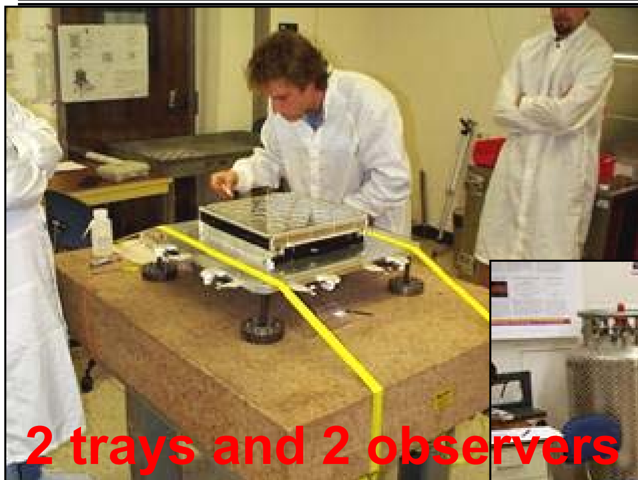
- 2.7m^2 silicon, ~500 detectors, 42k channels.
- Designed and built at UCSC

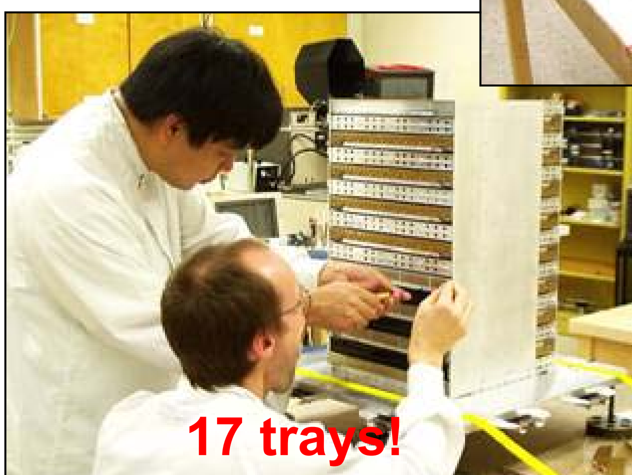
End of one readout hybrid module.

Operated in test particle beams at SLAC in 1999 and 2000.

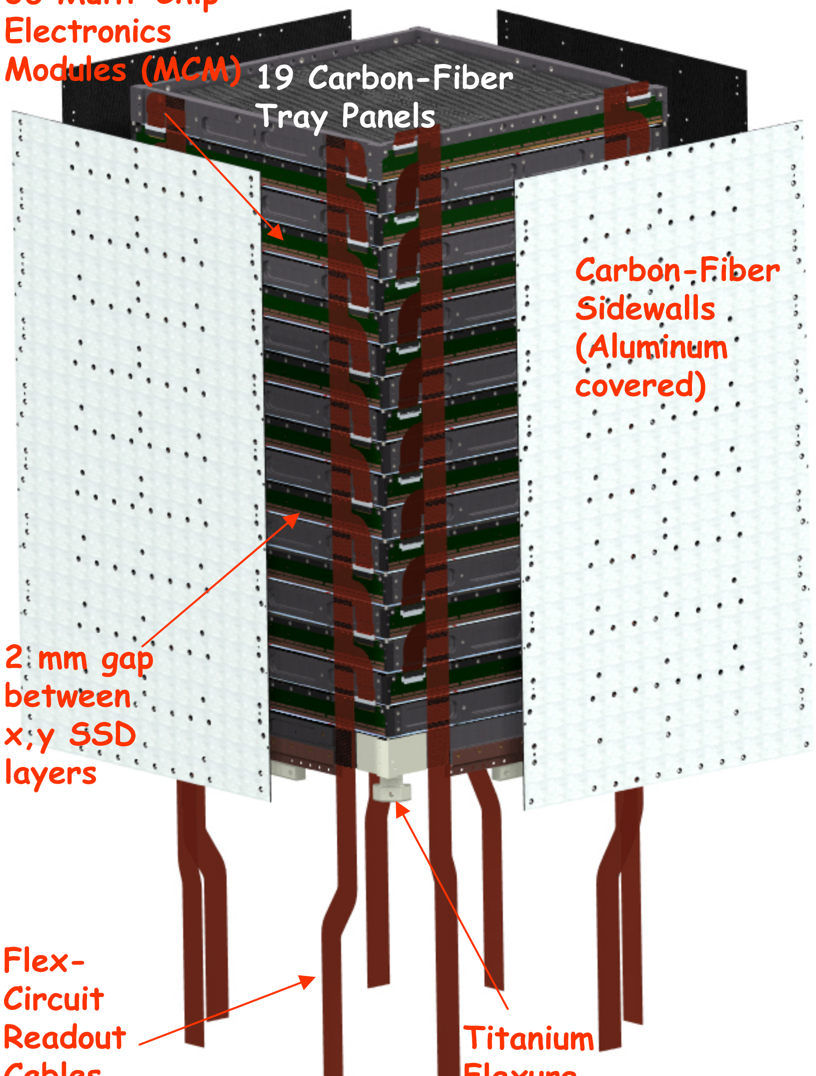
Flew at 120,000 feet over Texas in a balloon in the summer of 2001.

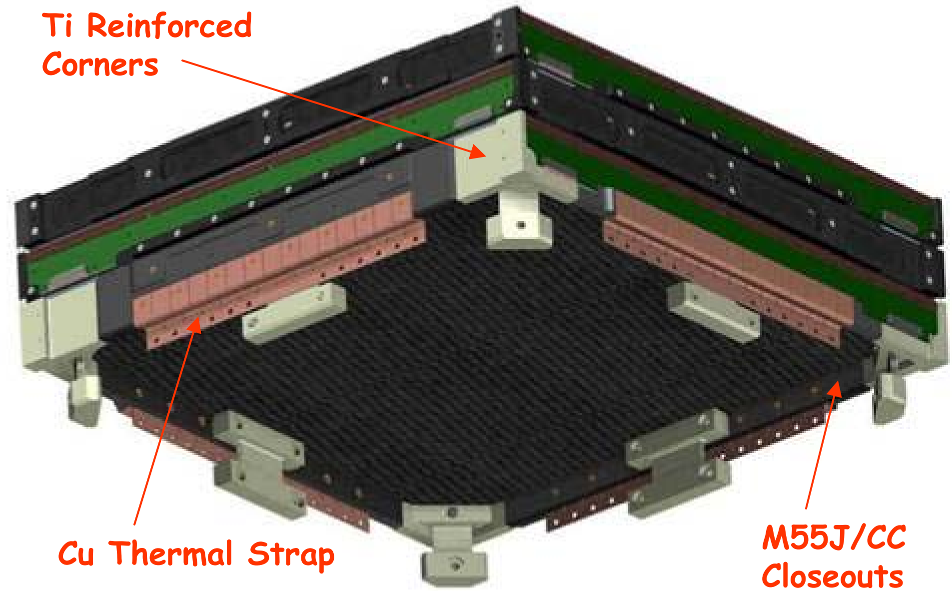
Assembly of the BTEM Tracker at SCIPP





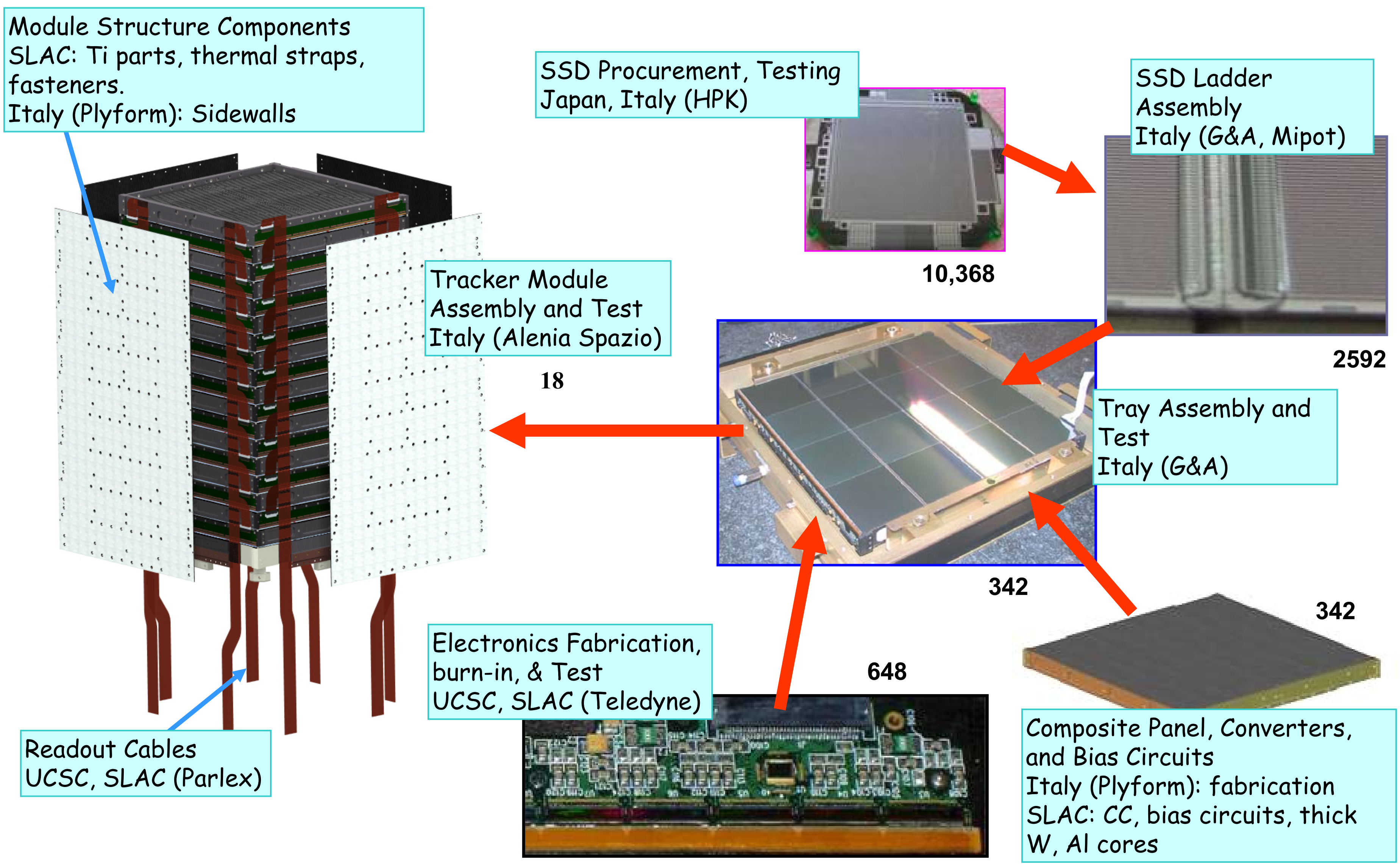
Silicon-Strip Tracker/Converter





- 19 stiff composite panels support 18 *x* and 18 *y* layers of silicon-strip detectors and 16 layers of tungsten converter foils.
- 36 custom readout electronics boards, each with 1536 amplifier channels, mount on the sides of the panels to minimize inter-tower dead space.

Tracker Production Overview

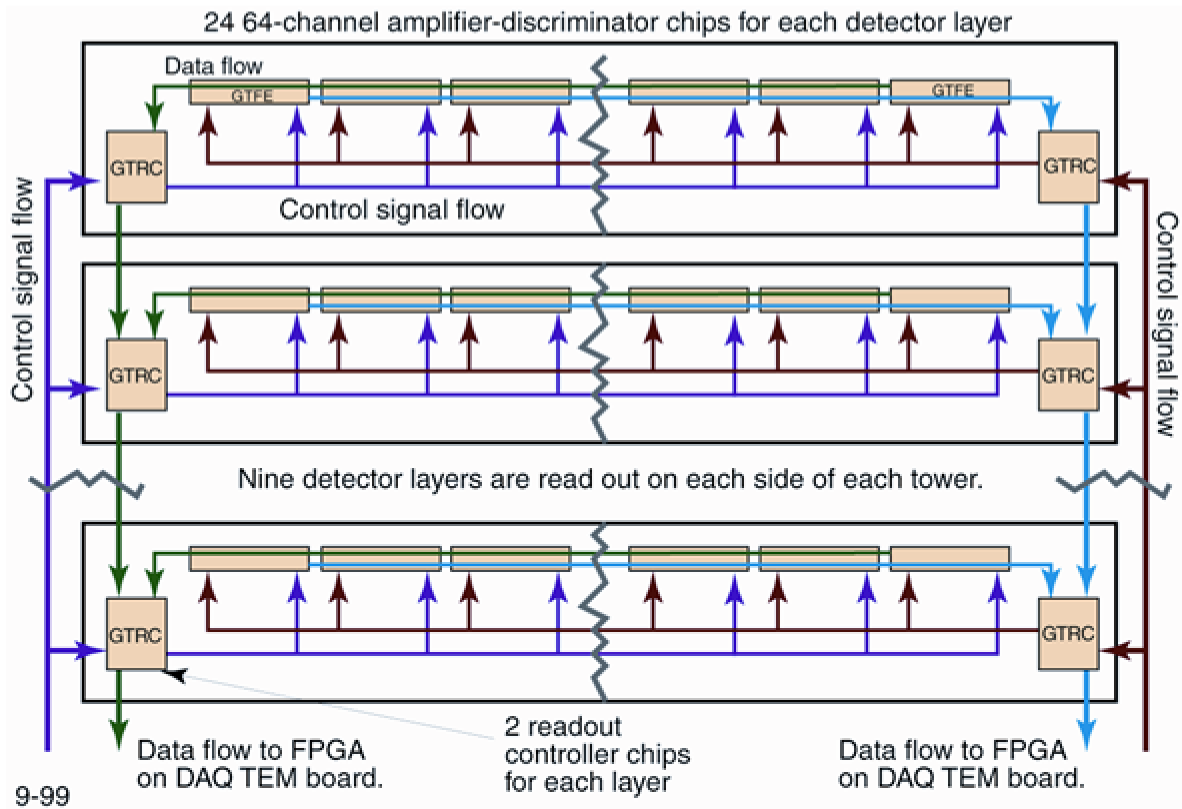


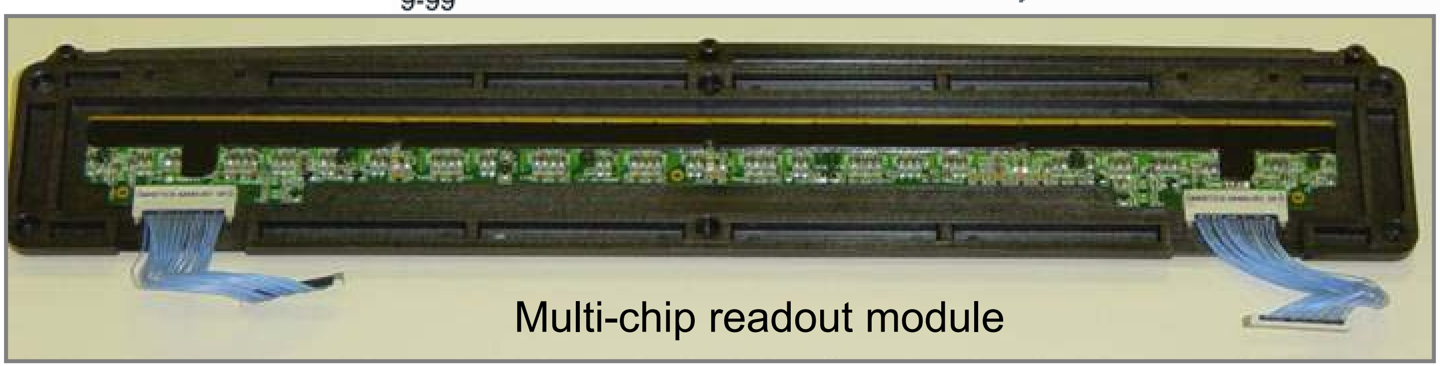
GLAST Tracker Electronics

ASIC based, for minimum power (180 μW/ch).

Redundant 20 MHz serial control and readout paths:

Each chip can be controlled or read by either of two paths.

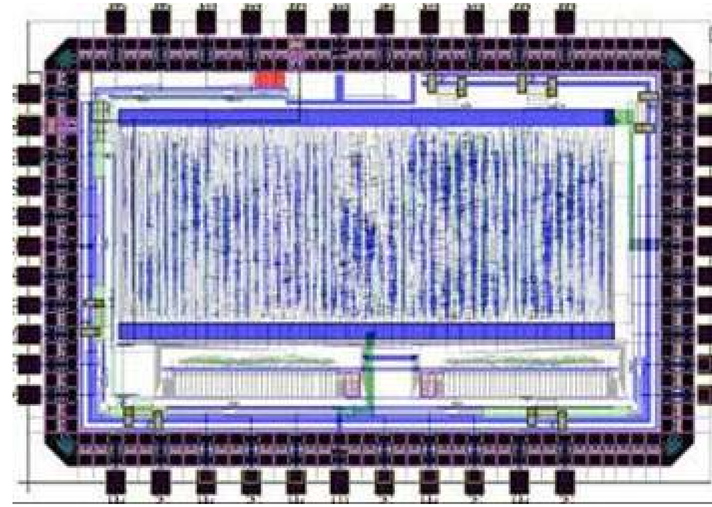




Multi-chip readout module

Tracker ASICs

- Custom designed integrated circuits are extensively used in all of the detector subsystems and the data acquisition
- Two such ASICs were developed at SCIPP for the Tracker:
  - Digital readout controller chip
  - 64-channel amplifier/discriminator chip



Trigger and Data mask registers
Standard-cell auto route

Control logic, command decoders
Standard-cell auto route

4-deep event memory (addressed by TEM)
Custom layout

Calibration mask and capacitors

2 custom DACs

64 amplifier-discriminator channels.

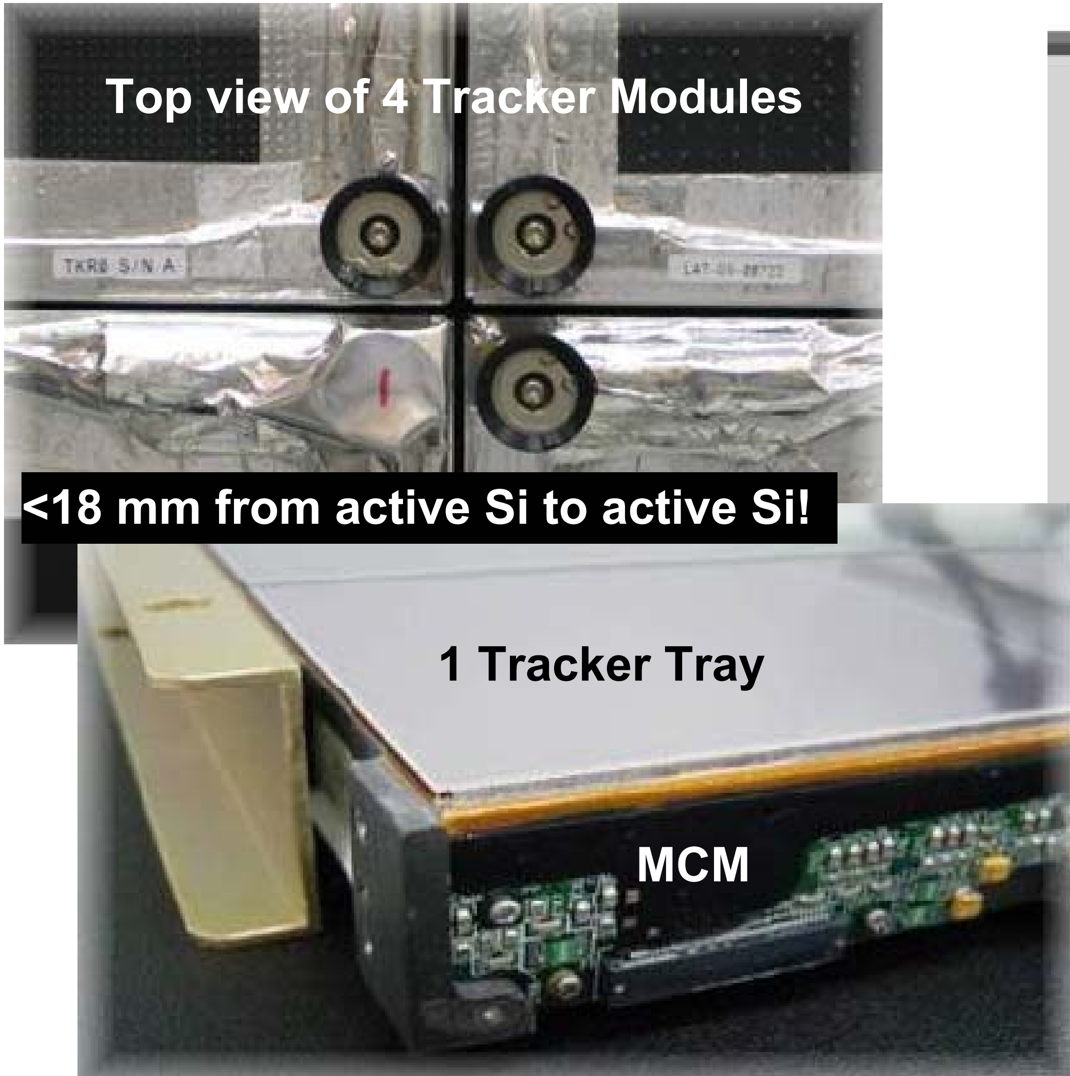
I/O pads and protection structures

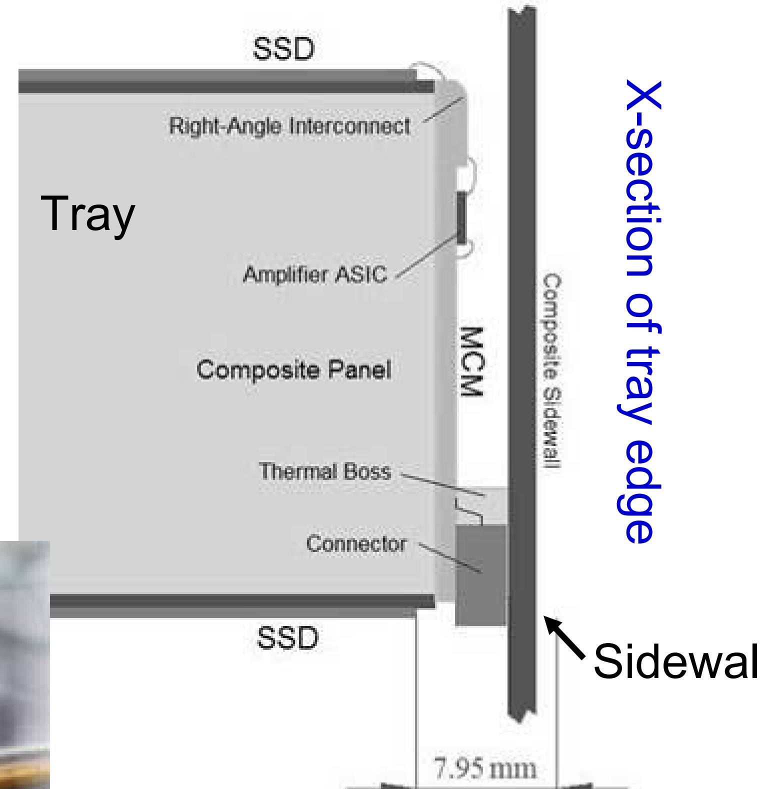
The First Tracker Tower

Upside down, with 1 wall removed.

Assembly Complete

Tracker Mechanical Fabrication Challenges





X-section of tray edge

Right-angle interconnect

Very tight space for electronics

High precision carbon-composite structure to maintain 2.5 mm gaps between modules

GLAST Tracker Status

16+2 towers completed.

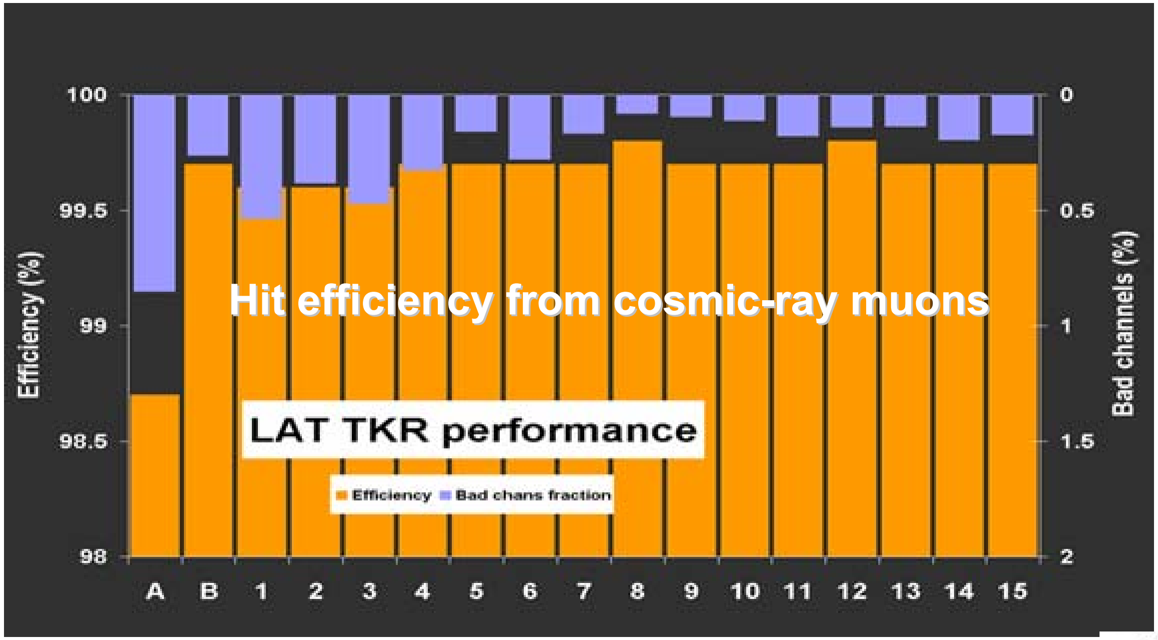
Flight array fully integrated in completed LAT.

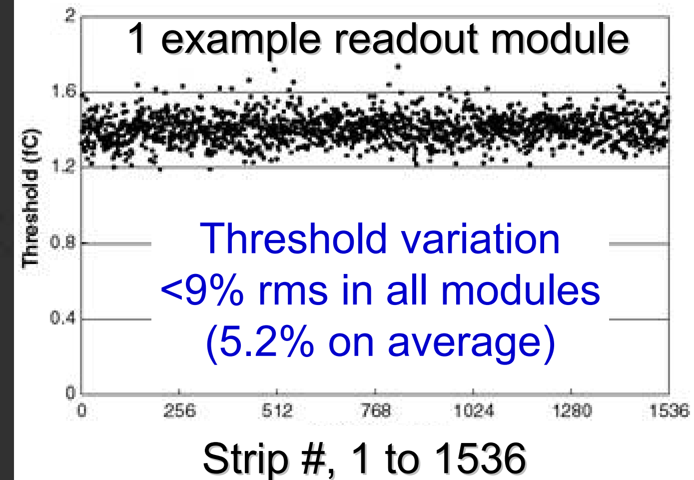
Environmental testing completed at NRL.

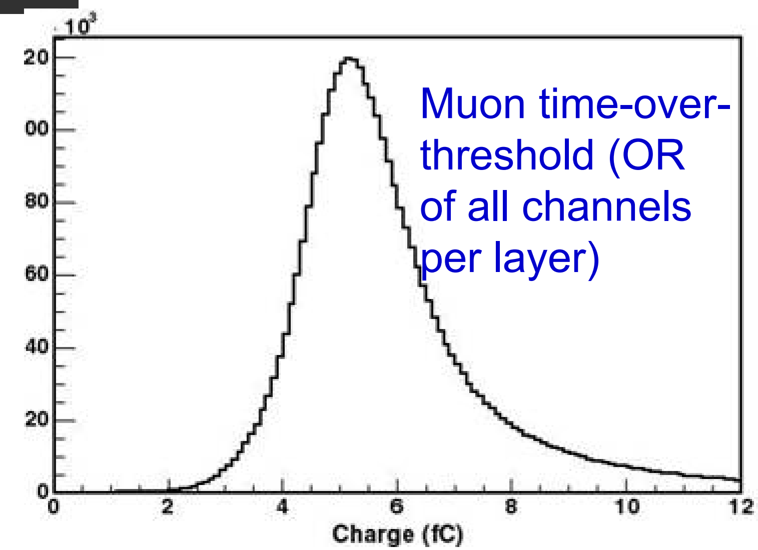
Delivered to General Dynamics last month.

Two spare towers completed beam testing at CERN in September.

GLAST Tracker Performance

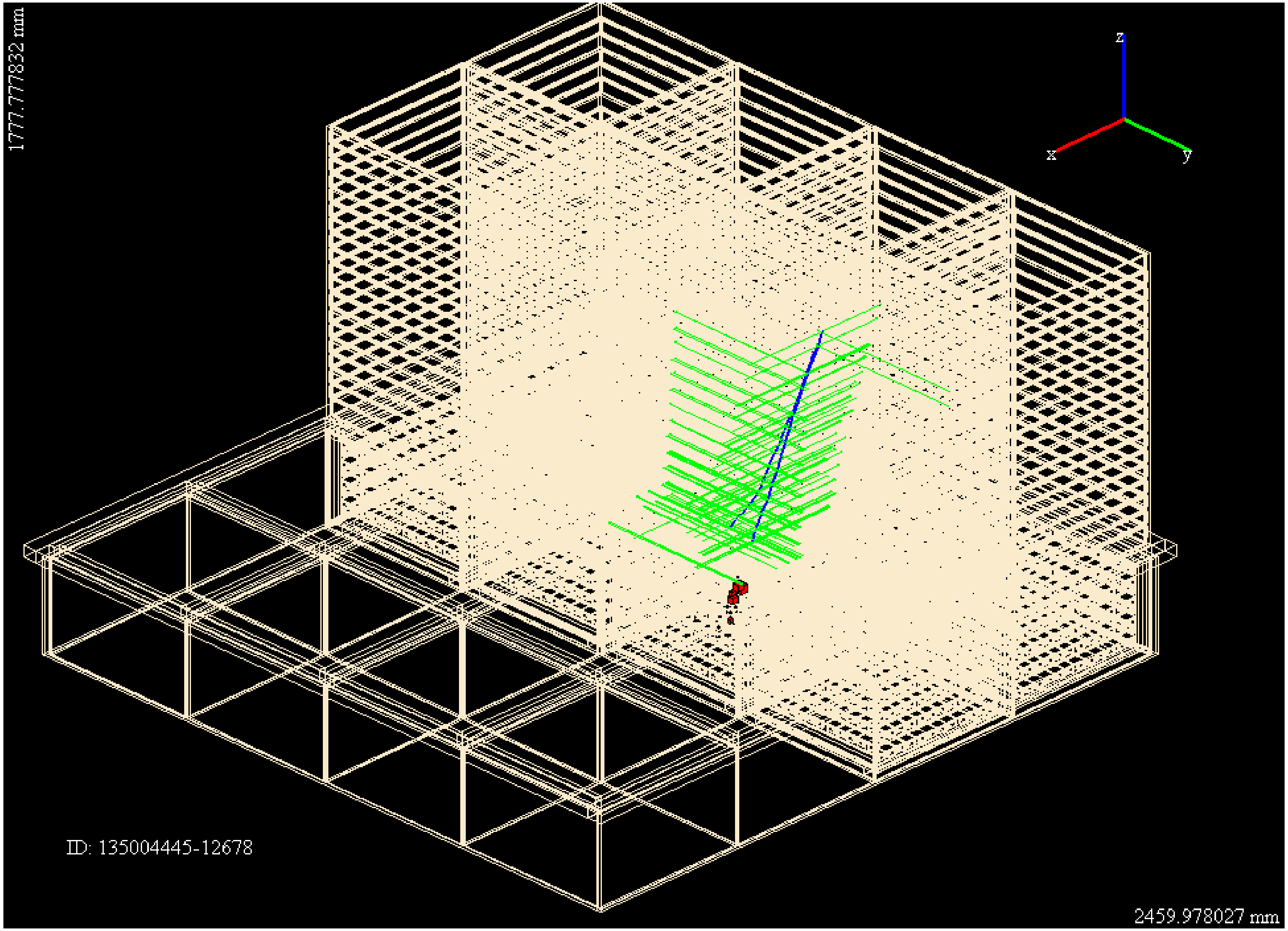






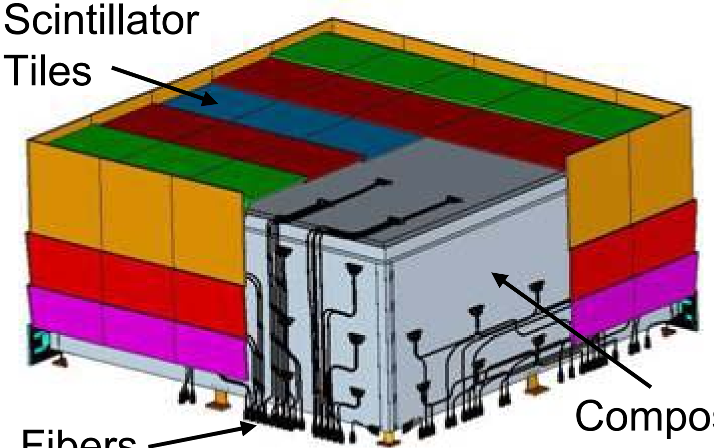
- Hit efficiency (in active area) >99.4%
- Overall Tracker active area fraction: 89.4%
- Noise occupancy $<5\times10^{-7}$
  - (with small number of noisy channels masked)
- Power consumption 158 W (178 μW/ch)
- Time-over-threshold 43% FWHM

Cosmic-Ray Gamma Conversions in 8 Towers



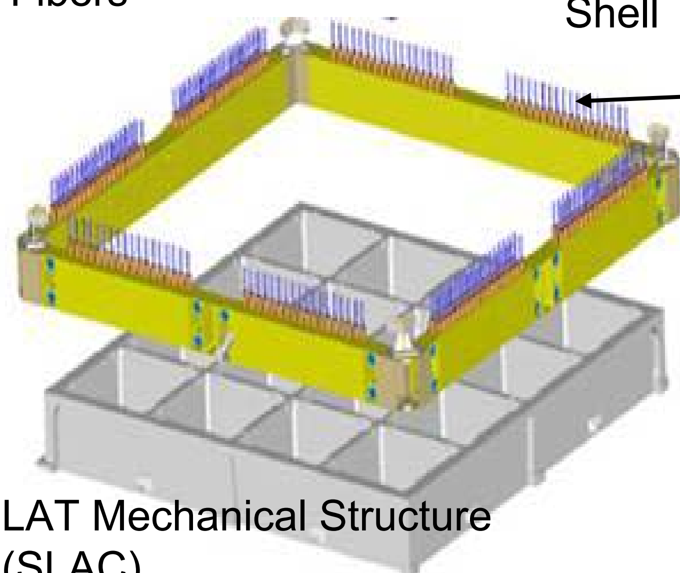
Anti-Coincidence Detector (NASA GSFC)

Scintillator Tiles



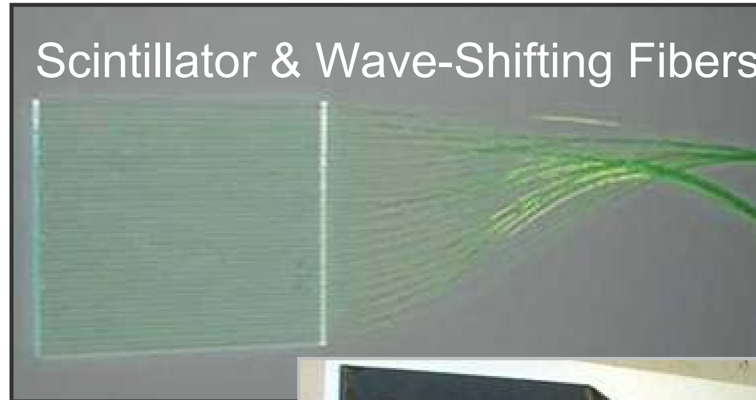
Fibers

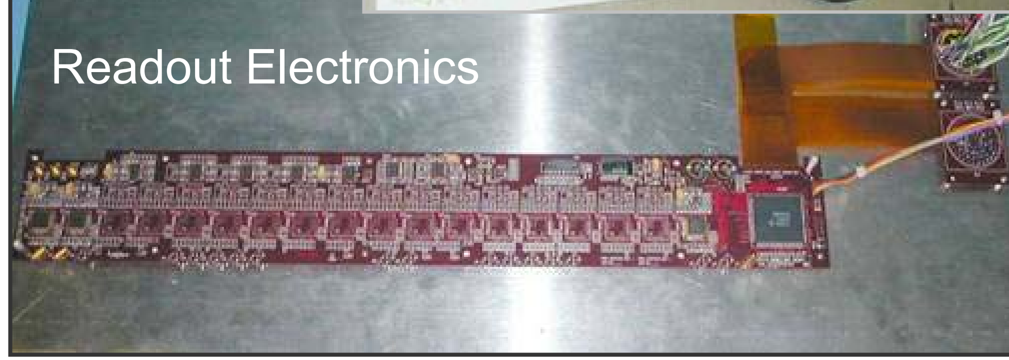
Composite Shell



Photomultiplier Tubes & Electronics

LAT Mechanical Structure (SLAC)





Anti-Coincidence Detector

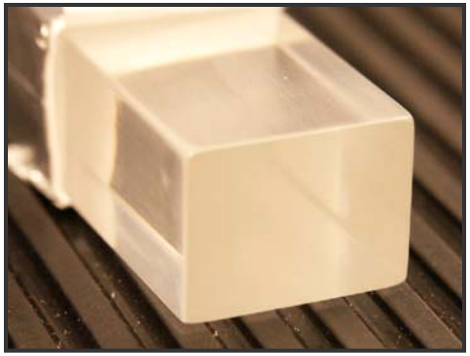
ACD during assembly. Only the lowest layer of tiles needs to be added.

Anti-Coincidence Detector

Completed ACD

Calorimeter

1728



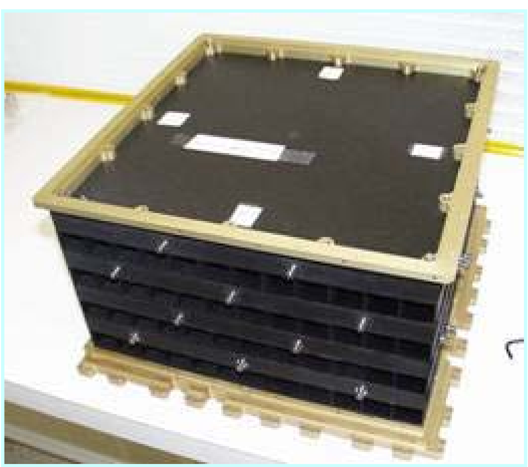
CsI Crystals (Sweden)

Photo-Diodes (HPK)

1728

Detector Assembly (NRL/Swales)

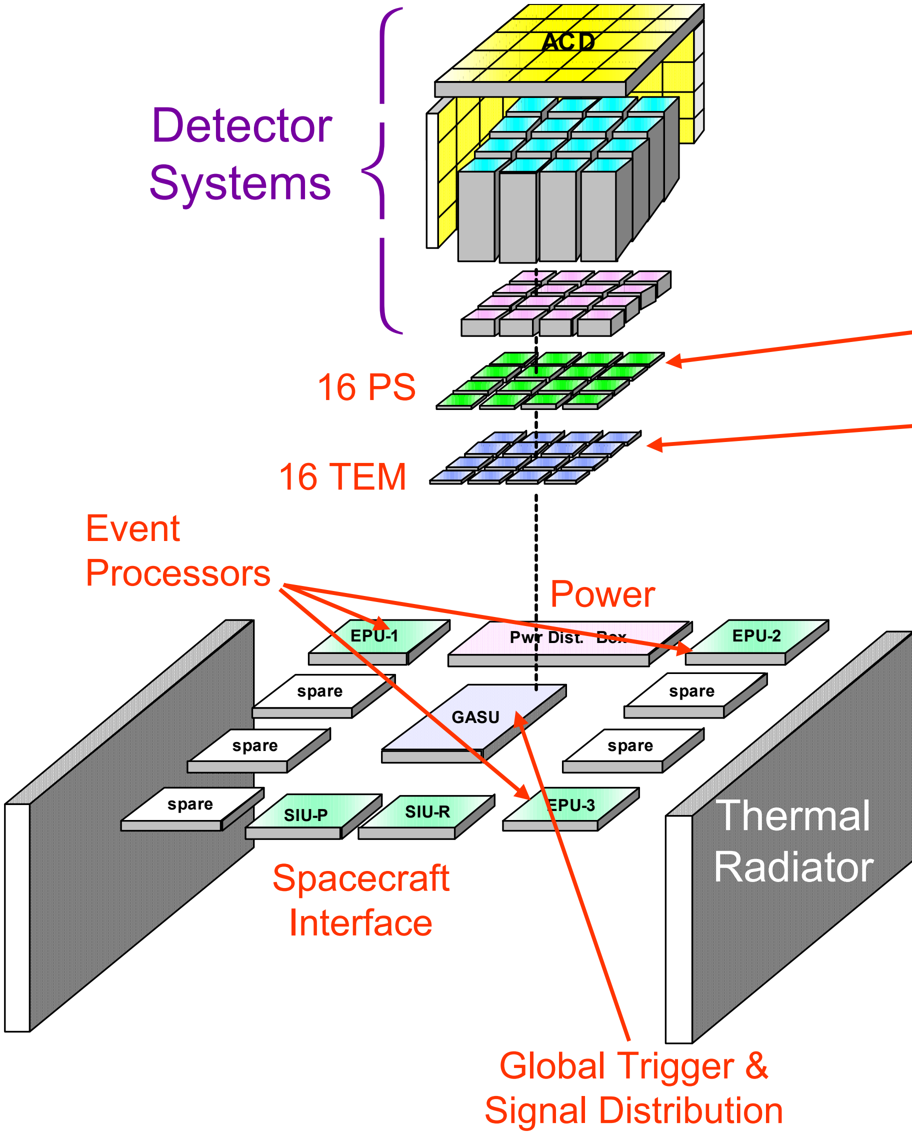
18



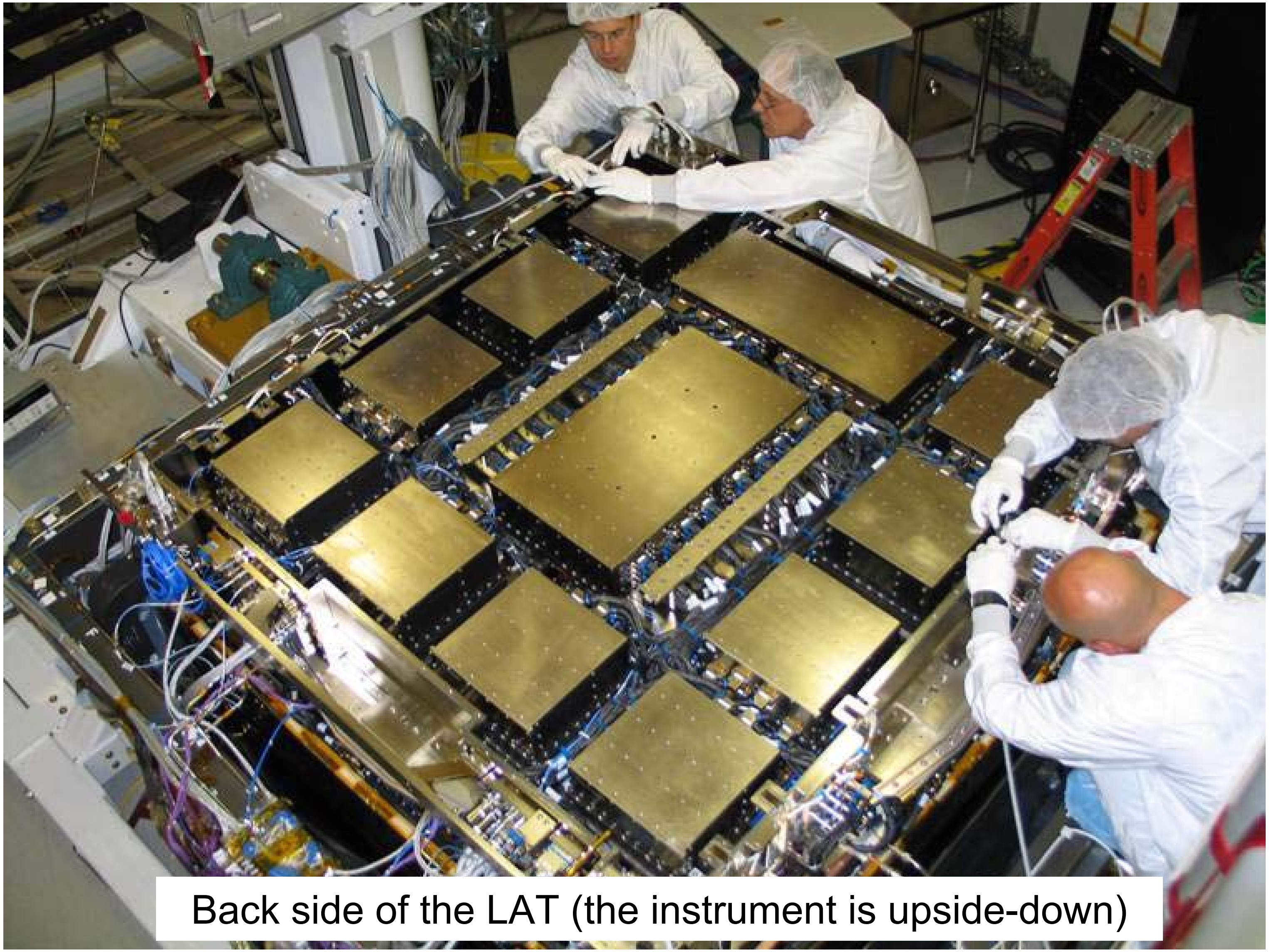
C-Composite Structure (France)

Electronics & Assembly (NRL)

Data Acquisition Electronics (SLAC)

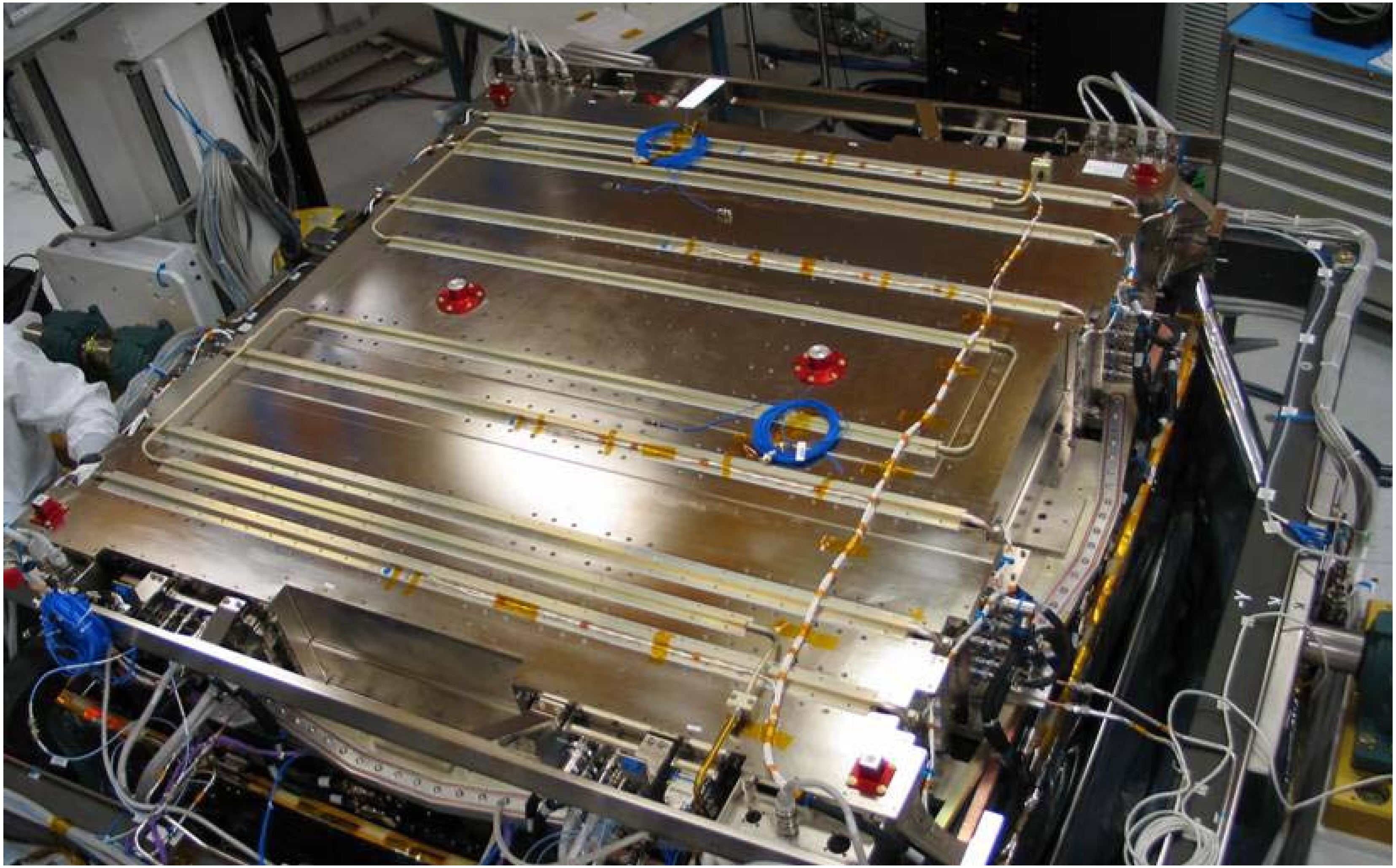


Electronics Modules and Wiring Harness



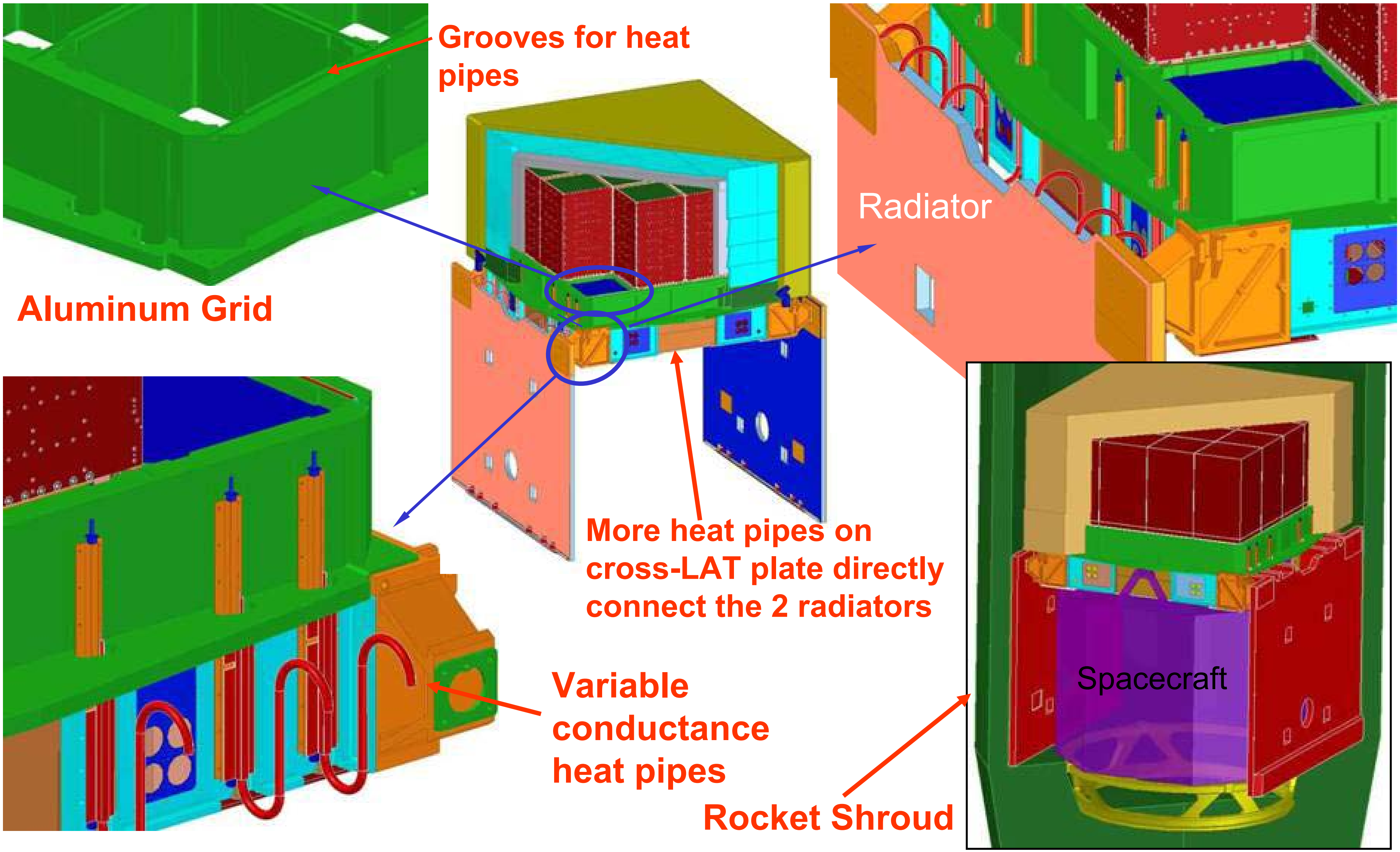
Back side of the LAT (the instrument is upside-down)

Cross-LAT Plate



Back side of the LAT. The electronics modules are covered by an aluminum plate outfitted with heat pipes.

LAT Structural/Thermal Design



The LAT, Ready for Delivery to NASA

Conclusion

- After >13 years of work, we are excited to be so close to launch and DATA!
- Our group continues working on several fronts:
  - Support of the Tracker hardware during integration and test.
  - Software/analysis preparation, especially for background rejection.
  - Science analysis preparation
    - Diffuse photons
    - Pulsars
    - AGN