GLAST X

- What are gamma rays? Why study them? Why this energy range? Why do we need a satellite?
- What are some of the fundamental questions GLAST is meant to address? A few examples of science topics (very brief overview).
- How do gamma-ray detectors work? Why does the GLAST Instrument look as it does?

ASK QUESTIONS!
Why study $\gamma$’s?

Gamma rays carry a wealth of information:

- $\gamma$ 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 $\gamma$ rays: can probe cosmological volumes. Any opacity is energy-dependent (light interacts with light!).

- conversely, $\gamma$ rays readily interact in detectors, with a clear signature.

- $\gamma$ rays are neutral: no complications due to magnetic fields. Point directly back to sources, etc.
Why this energy range? (20 MeV - > 300 GeV)

The Flux of Diffuse Extra-Galactic Photons

The Grand Unified Photon Spectrum (GUPS) c.a. 1990, Ressell and Turner

Note:
1 MeV=10^6 eV
1 GeV=10^9 eV
1 TeV=10^{12} eV
1 eV=1.6x10^{-19}J
Measurement techniques

Atmosphere:

For $E_\gamma \sim O(100)\ GeV$, must detect above atmosphere (balloons, satellites)

For $E_\gamma > O(100)\ GeV$, information from showers penetrates to the ground (Cerenkov)

Energy loss mechanisms:

$E=mc^2$. If $2\times$ the rest energy of an electron ($\sim 0.5\ MeV$) is available (i.e., if the photon energy is large enough), in the presence of matter the photon can convert to an electron-positron pair:

Fig. 2: Photon cross-section $\sigma$ in lead as a function of photon energy. The intensity of photons can be expressed as $I = I_0 \exp(-\alpha x)$, where $x$ is the path length in radiation lengths. (Review of Particle Properties, April 1980 edition).
GLAST and the next generation of ground-based experiments are well-matched.

(Note: updated figure in foldout A of the proposal)
GLAST will do fundamental science, with a very broad menu that includes:

- Systems with supermassive black holes
- Gamma-ray bursts (GRBs)
- Dark Matter
- Solar physics
- Probing the era of galaxy formation

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

The high energy gamma ray detector on the Compton Gamma Ray Observatory (20 MeV - ~20 GeV)
The success of EGRET: probing new territory

History:
- SAS-2, COSB (1970’s-1980’s) exploration phase: established galactic diffuse flux

EGRET (1990’s) established field:
- increased number of ID’d sources by large factor;
- broadband measurements covering energy range ~20 MeV - ~20 GeV;
- discovered many yet-unidentified sources;
- discovered surprisingly large number of Active Galactic Nuclei (AGN);
- discovered multi-GeV emissions from gamma-ray bursts (GRBs);
- discovered GeV emissions from the sun

GLAST will explore the unexplored energy range above EGRET’s reach, filling in the present gap in the photon spectrum, and will cover the very broad energy range ~ 20 MeV - 300 GeV (→ 1 TeV) with superior acceptance and resolution. Historically, opening new energy regimes has led to the discovery of totally unexpected new phenomena.
Features of the gamma-ray sky

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

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

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

galactic sources (pulsars, un-ID’d)

**An essential characteristic:** **VARIABILITY** in time!

Combined, the improvements in GLAST provide a ~ two order of magnitude increase in sensitivity over EGRET.

The wide field of view, large effective area, highly efficient duty cycle, and ability to localize sources in this energy range will make GLAST an important fast trigger for other detectors to study transient phenomena.
Diffuse Extra-galactic Background Radiation

Is it really isotropic (e.g., produced at an early epoch in intergalactic space) or an integrated flux from a large number of yet unresolved sources? GLAST has higher sensitivity to weak sources, with better angular resolution.

GLAST will bring alive the gamma-ray sky!

The origin of the diffuse extragalactic gamma-ray flux is a mystery. Either sources are there for GLAST to resolve (and study!), OR there is a truly diffuse flux from the very early universe.
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 $\gamma$-rays emitted within a few degrees of jet axis. Mechanisms are speculative; $\gamma$-rays offer a direct probe.
Prior to EGRET, the only known extra-galactic point source was 3C273; however, when EGRET launched, 3C279 was flaring and was the brightest object in the gamma-ray sky!

EGRET discovery image of gamma-ray blazar 3C279 (z=0.54) E>100 MeV (June 1991)

VARIABILITY: EGRET has seen only the tip of the iceberg.
AGN shine brightly in GLAST energy range

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

Estimated luminosity of 3C 279:
\[ \sim 10^{45} \text{ erg/s} \]
corresponds to \( 10^{11} \) times total solar luminosity
just in \( \gamma \)-rays!! Large variability within days.

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 \( \gamma \) rays from a very small volume!
A surprise from EGRET: detection of dozens of AGN shining brightly in $\gamma$-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 $\gamma$-rays at cosmological distances. The Universe is largely transparent to $\gamma$-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. How do AGN work?
• Large acceptance and field of view allow relatively fast monitoring for variability over time -- correlate with other detectors at other wavelengths.
• 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.
Some AGN shine brightly in the TeV range, but are barely detectable in the EGRET range. GLAST will allow quantitative investigations of the double-hump luminosity distributions, and may detect low-state emission:

EGRET 3rd Catalog: 271 sources
GLAST 1st Catalog: >9000 sources?
+ new source classes also anticipated
IF AGN spectra can be understood well enough, they may provide a means to probe the era of galaxy formation:

(Stecker, De Jager & Salamon; Madau & Phinney; Macminn & Primack)

If $\gamma \gamma$ c.m. energy $> 2m_e$, pair creation will attenuate flux. For a flux of $\gamma$-rays with energy, $E$, this cross-section is maximized when the partner, $\epsilon$, is

$$\epsilon \approx \frac{1}{3} \left( \frac{1\,TeV}{E} \right) eV$$

For 10 GeV- TeV $\gamma$ - rays, this corresponds to a partner photon energy in the optical - UV range. Density is sensitive to time of galaxy formation.
Roll-offs in the observed $\gamma$-ray spectra from AGN at large $z$ probe the EBL.

Opacity (Salamon & Stecker, 1998)

No significant attenuation below $\sim$10 GeV. EBL over cosmological distances probed by gammas in the 10-100 GeV range. In contrast, the TeV-IR attenuation is more local.

Macminn & Primack (1995)

EGRET

Mrk 421

(z=0.031)

Whipple

A dominant factor in EBL models is the era of galaxy formation: AGN roll-offs may thus help distinguish models of galaxy formation.
GLAST Probes the Optical-UV EBL

(1) thousands of blazars - instead of peculiarities of individual sources, look for systematic effects vs redshift. Favorable aspect ratio important here.

(2) key energy range for cosmological distances (TeV-IR attenuation more local due to opacity).

Effect is model-dependent **(this is good):**

- How many blazars have intrinsic roll-offs in this energy range (10-100 GeV)? (An important question by itself for GLAST!) Again, power of statistics is the key.
- What if there is conspiratorial evolution in the intrinsic roll-off vs redshift? More difficult, however there may also be independent constraints (e.g., direct observation of integrated EBL).
- Most difficult: **must measure the redshifts for a large sample of these blazars!**
- Intrinsic roll-offs also for pulsar studies.

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

EGRET source position error circles are \(~0.5^\circ\), resulting in counterpart confusion.

GLAST will provide much more accurate positions, with \(~30\) arcsec - \(~5\) arcmin localizations, depending on brightness.
Supernova remnants as accelerators

What is the origin of cosmic rays? What are the acceleration mechanisms?

Seminal work: Fermi (1949)

Current ideas: shock acceleration from supernovae (< 30% of released energy sufficient to produce all cosmics up to $\sim 10^{14}$ eV)

expect: interaction of CR’s with gas swept up by blast should produce $\pi^0 \rightarrow \gamma \gamma$. Flux $O(10^{-7}$ ph/cm$^2$/s) at 1kpc.

Many shell remnants resolvable in other bands. Subtended angle typ. $O(1^\circ)$.

GLAST can resolve SNRs spatially and spectrally:

(S. Digel et al, simulation of $\gamma$-Cygni)
Overlap with ground-based experiments

- GLAST will help confirm the calibration of ground-based experiments such as VERITAS.
- GLAST will provide measurements of the Crab unpulsed flux from below 100 MeV to ~1 TeV.
Pulsars

- Can distinguish acceleration models by observing high-energy roll-offs

- Models also predict very different statistics:

<table>
<thead>
<tr>
<th>Pulsar type</th>
<th>EGRET</th>
<th>LAT/Polar Cap</th>
<th>LAT/Outer Gap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio</td>
<td>7</td>
<td>150</td>
<td>50</td>
</tr>
<tr>
<td>Millisecond</td>
<td>1</td>
<td>20</td>
<td>-</td>
</tr>
<tr>
<td>Radio quiet</td>
<td>1</td>
<td>&lt;10</td>
<td>600</td>
</tr>
</tbody>
</table>

(Zhang & Harding, 1999)  (Romani, 1999)
During the all-sky survey, GLAST will have sufficient sensitivity after one day to detect (5σ) the weakest EGRET sources.
Gamma Ray Bursts (GRB)

GRBs discovered in 1960’s accidentally by the Vela military satellites, searching for gamma-ray transients (guess why!) The question persists: What are they??

EGRET has detected very high energy emission associated with bursts, including an 18 GeV photon ~75 minutes after the start of a burst:

GLAST will provide definitive and unique information about the high energy behavior of bursts. How many have delayed, high energy activity??
GRBs and Deadtime

Distribution for the 20th brightest burst in a year

No. Intervals

Log (ΔT s)

Time between consecutive arriving photons

E > 10 MeV

GLAST opens a wide window on the study of the high energy behavior of bursts!
The theory of strings, which attributes the infinite variety of the cosmos to the harmonies of subatomic membranes, has emerged over the past two decades as the leading contender for the "theory of everything." It would explain the four forces of nature—gravity, electromagnetism, and the weak and strong nuclear forces—as a single force with different manifestations. But how could such a theory ever be proved? The last time the four forces acted as one was at the big bang: to recreate those conditions, physicists would need a particle accelerator larger than the solar system, which Congress might be reluctant to fund. Despairing of the task, some scientists call theories of everything an exercise in theology.

"For the first time since the Dark Ages," physicist Paul Ginsparg and Sheldon L. Glashow wrote 12 years ago, "we can show how our noble search may diverge with faith replacing science once again." That proclamation now seems premature. Researchers have devised the first astronomical probe of theories of everything and have also discovered that the four forces may unite under conditions short of the big bang. "Unification, the theory of everything, might actually be accessible experimentally," says Nima Arkani-Hamed of the Stanford Linear Accelerator Center.

The probe was conceived by Giovanni Amelino-Camelia of the University of Oxford and the Institute of Physics in Newton, Switzerland, and his colleague. They propose that gamma ray bursts could focus the speed of light in a vacuum depends on its wavelength. According to special relativity, the speed of light is the same in a vacuum regardless of wavelength. Therefore, the detection of a wavelength-dependent speed would imply the existence of a kind of physical law more fundamental than relativity.

Dimensions in the speed of light are familiar to anyone who has looked at a prism. Because glass, water and other substrates allow red light to go faster than blue, the prism splits light into a rainbow.

Energy, space, too, is a substance of sorts. By the laws of quantum mechanics, particles bubble in and out of existence as the world fluctuates around creaseless eras. In quantum theory, which incorporates special relativity but not gravity, time that those fluctuations affect wavelengths of light equally. Theories of everything allow fluctuations in gravity, which might be a substance made of light. Longer the wavelength of light, the more it might induce such leaping action to occur.

Although the retardation is predicted to be small, it might show up in gamma-ray bursts. Whatever the mysterious these ultrafast flashes made of light and flicker randomly, the blinding glare would handle out any distortion at a distant observer. A flicker would appear as a flicker moment after it appears at longer wavelengths. Across a typical range of gamma-ray burst parameters, a flicker would be around 10 microsecond—or much longer if the radiation has traveled for 10 billion years. But it may be too large for current instruments to detect. And the Gamma-ray Large Area Space Telescope, scheduled to begin operation in 2004, will certainly have the requisite resolution.

\[
V = c \left(1 - \xi \cdot \frac{E}{E_{OG}} + \ldots\right)
\]

Amelino-Camelia et al, Ellis, Mavromatos, Nanopoulos

Effects could be O(100) ms or larger, using GLAST data alone. But ?? effects intrinsic to bursts?? Representative of window opened by such old photons.
New Source Classes?

- Unidentified EGRET sources are fertile ground. Example: mid-latitude sources separate population (Gehrels et al., Nature, 23 March 2000)

- Radio (non-blazar) galaxies. EGRET detection of Cen A (Sreekumar et al., 1999)

- “Gamma-ray clusters”: emission from dynamically forming galaxy clusters (Totani and Kitayama, 2000)

- Various hypotheses for origin of the extragalactic diffuse, if not from unresolved blazars.

- **SURPRISES!** (most important)
Instrument must measure the **direction**, **energy**, and **arrival time** 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

**Energy loss mechanisms:**

- instrument must detect γ-rays with high efficiency and reject the much higher flux (x \(\sim\) 10^4) of background cosmic-rays, etc.;

- energy resolution requires calorimeter of sufficient depth to measure buildup of the EM shower. Segmentation useful.
Primary Design Impacts of Science Requirements

Effective area and PSF requirements drive the converter thicknesses and layout. PSF requirements also drive the design of the mechanical support.

Energy range and energy resolution requirements set thickness of calorimeter.

On-board transient detection requirements, and on-board background rejection to meet telemetry requirements, drive the electronics, processing, flight software, and trigger design.

Background rejection requirements drive the ACD design (and influence the calorimeter and tracker layouts).

Field of view sets the aspect ratio (height/width).

Time accuracy provided by electronics and intrinsic resolution of the sensors.

Instrument life has an impact on detector technology choices. Derived requirements (source location determination and point source sensitivity) drive the overall system performance.
Aside: some definitions

**Effective area**
(total geometric acceptance) • (conversion probability) • (all detector and reconstruction efficiencies). Real rate of detecting a signal is (flux) • $A_{\text{eff}}$ (neglecting deadtime and exposure effects).

**Point Spread Function (PSF)**
Angular resolution of instrument, after all detector and reconstruction algorithm effects. The 2-dimensional 68% containment is the equivalent of ~1.5$\sigma$ (1-dimensional error) if purely Gaussian response. The non-Gaussian tail is characterized by the 95% containment, which would be 1.6 times the 68% containment for a perfect Gaussian response.

**Hit efficiency**
Probability that a tracking sensor will record the passage of a charged particle through its active volume.
LAT Instrument Basics

- **4x4 array of identical towers**
  Advantages of modular design.

- **Precision Si-strip Tracker (TKR)**
  Detectors and converters arranged in 18 XY tracking planes. Measure the photon direction.

- **Hodoscopic CsI Calorimeter (CAL)**
  Segmented array of CsI(Tl) crystals. Measure the photon energy.

- **Segmented Anticoincidence Detector (ACD)**
  First step in reducing the large background of charged cosmic rays. Segmentation removes self-veto effects at high energy.

- **Central Electronics System**
  Includes flexible, highly-efficient, multi-level trigger.

**Systems work together to identify and measure the flux of cosmic gamma rays with energy 20 MeV - >300 GeV.**
Results of hard work by many people.
Technical foundation: Bill Atwood
Silicon Strip Detector Principle

VLSI
Low-noise, Low-power Amplifier/Discriminator
(S/N typically > 20)

n⁻ Bulk ~5kΩ–cm

p⁺ Implant Strips at Ground

Electrons

Holes

n⁺ Implant

200 μm

400 μm

Al Strip Electrodes

Coupling Cap

Depletion region Charged particle produces ~32,000 electron/hole pairs.

Al Backplane at ~+90V
Calorimeter

- **Concept**
  - Modular design matches GLAST Tower Concept
  - Hodoscopic Imaging of EM Showers
  - CsI(Tl) Detectors with long space history
  - PIN photodiode readout for reliability and compact design

- **Hodoscopic Design**
  - 8 layers of 12 CsI blocks in each tower
  - Custom dual-PIN photodiode on each end
  - low-power front end electronics supporting large dynamic range (~$10^5$)

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**Position Measurement**

Position = $0.5 + \frac{f^* (A - B)}{(A + B)}$
ACD Design Approach

- Segmented plastic scintillator (Bicron-408) with wave-shifting fibers (BCF-91MC) + photomultiplier (Hamamatsu R1635, R5900) readout; each segment (tile) has a separate light-tight housing.

- Separate tile housings provide resistance to accidental puncture by micrometeoroids.

- Wave-shifting fiber readout provides the best light collection uniformity within the space constraints and minimizes the inert material.

- ACD “hat” covers the top and the sides of the tracker down to the calorimeter, covering the gap between tracker and calorimeter where the grid is located.
Benefits of Modularity

- Construction and Test more manageable, reduce costs and schedule risk.
- Early prototyping and performance tests done on detectors that are full-scale relevant to flight.
- Aids pattern recognition and background rejection.
- Good match for triggering large-area detector with relatively localized event signatures.

Must demonstrate that internal dead areas associated with support material and gaps between towers are not a problem.
The GLAST baseline instrument design is based on detailed Monte Carlo simulations.

Two years of work was put into this **before** any significant investment was made in hardware development.

- Cosmic-ray rejection of $>10^5:1$ with 80% gamma ray efficiency.
- Solid predictions for effective area and resolutions (computer models now verified by beam tests).
- Current reconstruction algorithms are existence proofs -- many further improvements are possible.
- Practical scheme for triggering.
- Design optimization.

Simulations and analyses are all OO (C++), based on GISMO toolkit.

**Zoom in on a corner of the instrument**

- scintillators
- front scintillators
- module walls
- First TKR module plane

**The instrument naturally distinguishes most cosmics from gammas, but the details are essential. A full analysis is important.**

- gamma ray
- proton
Simulations validated in detailed beam tests

Experimental setup in ESA for tagged photons:

X Projected Angle
3-cm spacing, 4% foils, 100-200 MeV

GLAST Data
- 68% Containment
- 95% Containment
(errors are 2σ)

Monte Carlo

Data

Monte Carlo

GLAST
The good agreement between simulation and data held for all tracker configurations tested.

Substantial improvement introduced for beam test tracker analysis: **Kalman filter** Highly effective track reconstruction algorithm when both measurement error and multiple scattering effects are important.
Derived performance parameter: high-latitude point source sensitivity ($E>100$ MeV), 2 year all-sky survey: $1.6 \times 10^{-9}$ cm$^{-2}$ s$^{-1}$, a factor $>50$ better than EGRET’s ($\sim 1 \times 10^{-7}$ cm$^{-2}$s$^{-1}$).
Tracker/Converter Issues

Some lessons learned from simulations

Expanded view of converter-tracker:

At low energy, measurements at first two layers completely dominate due to multiple scattering—MUST have all these hits, or suffer factor \( \sim 2 \) PSF degradation. If eff = 90%, already only keep \((.9)^4 = 66\%\) of potentially good photons. => want \( >99\% \) efficiency.

Low energy PSF completely dominated by multiple scattering effects: \( \theta_0 \sim 2.9 \text{ mrad} / E[\text{GeV}] \) (scales as \((x_0)^{1/2}\))

High energy PSF set by hit resolution/plane spacing: \( \theta_D \sim 1.8 \text{ mrad} \)

At higher energies, more planes contribute information:

<table>
<thead>
<tr>
<th>Energy</th>
<th># significant planes</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 MeV</td>
<td>2</td>
</tr>
<tr>
<td>1 GeV</td>
<td>~5</td>
</tr>
<tr>
<td>10 GeV</td>
<td>&gt;10</td>
</tr>
</tbody>
</table>

All detectors have some dead area: if isolated, can trim converter to cover only active area; if distributed, conversions above or near dead region contribute tails to PSF unless detailed and efficient algorithms can ID and remove such events.

S. Ritz
95%/68% containment, 2D Gaussians

prob of being at a particular point in XY is:

$$\frac{1}{2\pi \sigma^2} \cdot \exp \left(-\frac{(x^2 + y^2)}{2\sigma^2}\right)$$

for sigma=1:

$$\text{probab}(r) := \frac{1}{2\pi} \cdot \exp \left(\frac{-r^2}{2}\right)$$

$$\text{intprob}(r) := \int_0^r 2\pi \cdot r \cdot \text{probab}(r) \, dr$$

$$\text{root}(\text{intprob}(b) - 0.68, b) = 1.51$$

$$\text{root}(\text{intprob}(b) - 0.95, b) = 2.445$$

$$\frac{\text{root}(\text{intprob}(b) - 0.95, b)}{\text{root}(\text{intprob}(b) - 0.68, b)} = 1.62$$
For energy measurement and background rejection, want events to pass through the calorimeter. The aspect ratio (Area/Height) then governs the main field of view of the tracker:

EGRET had a relatively small aspect ratio
GLAST has a large aspect ratio

*note: “peripheral vision” events useful at low energy, but are not included in performance calculations.
Summary

- GLAST will address many important questions:
  - What is going on around black holes? How do Nature’s most powerful accelerators work? (are these engines really black holes?)
  - What are the unidentified sources found by EGRET?
  - What is the origin of the diffuse background?
  - What is the high energy behavior of gamma ray bursts?
  - What else out there is shining gamma rays? Are there further surprises in the poorly measured energy region?
  - When did galaxies form?

- Large menu of “bread and butter” science
- **Large discovery potential**

Expect the community of investigators interested in gamma-ray data to grow enormously during the GLAST era!