Key Features of Fermi-LAT

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for the

***Fermi* LAT collaboration**

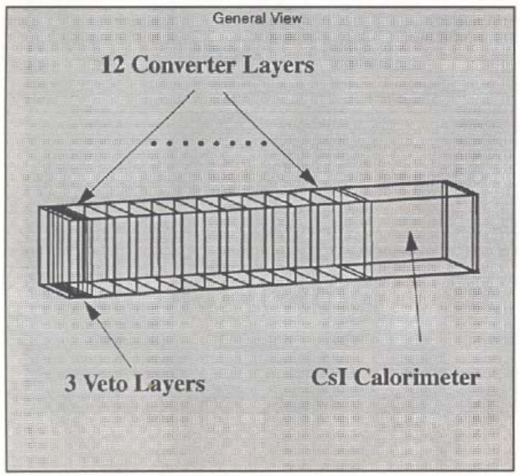
Key to success: a good Monte Carlo

- **From the start of GLAST (now *Fermi*-LAT) we had a Monte Carlo model of the instrument**
- **Contemporary instruments too complex to use simple metrics to characterize their performance**
- **The Monte Carlo model captures our best and most complete understanding of the instrument**
- **The MC model is the instruments calibration –or- "yard stick"**
- **The LAT was designed optimized and "debugged" using the MC model**
- **All of the reconstruction software was crafted using the MC model as well as directly using the MC model and ray tracing to propagate trajectories through the 3D geometry**
- **The event analysis was designed and developed using the MC model**

The First GLAST MC

Within one day of the first GLAST concept, a MC was put together to explore the design idea

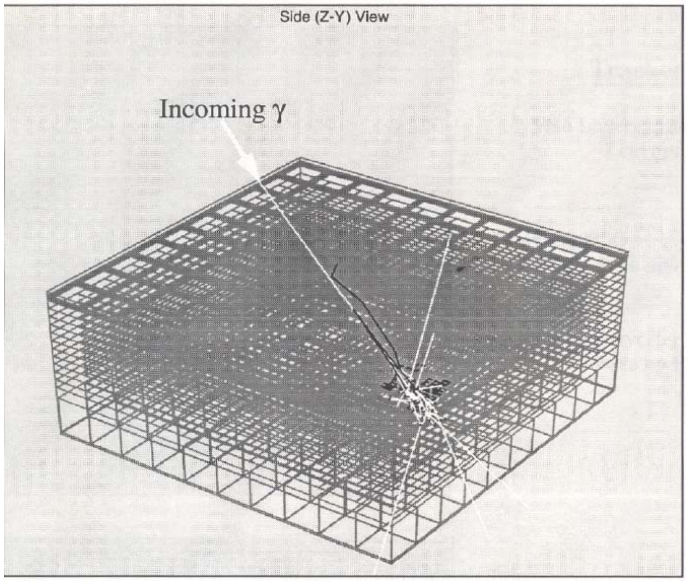
A Single GLAST Tower Module



The 3 Veto Layers and 12 Converter Layers form the GLAST Tracker Module

A GLAST Tracker plus the CsI Calorimeter form a GLAST Tower Module

Contents of the GLAST Simulation



- **The 3-layer SSD x-ray front end ACD was replaced with more conventional scintillator tile.**
- **The number of towers was gradually reduced as the achievable noise performance of the SSD front end electrons proved to be better then initially thought.**
- **The Calorimeter was first simulate as a pixelated device (easier to do), but was intended from the start to be Per Carlson's crossed hodoscopic design.**

Debugging the Design

Many aspects of LAT were optimized using the MC
Key to doing Astronomy is Image Resolution (characterized by the PSF).

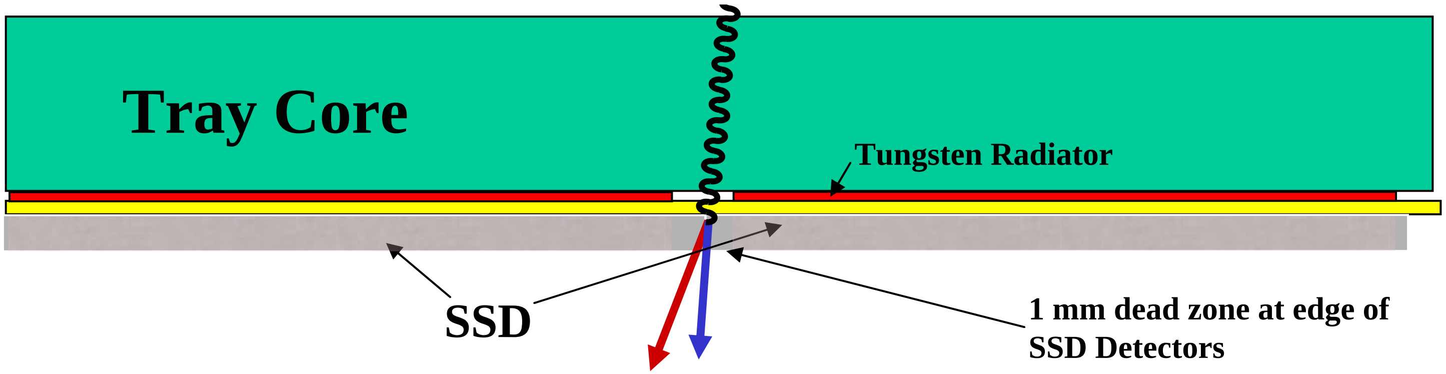
- **PSF-Core – Localization & Identification**
- **PSF-Tails – General light pollution & obscuration of near-by faint sources**

Example: **Limiting Tungsten Radiators to cover only the active area of each SSD**

Issue: **The SSD's are not sensitive all the way to their edges: there is a ~ 1mm dead region.**
Hence the SSDs only cover (87.5/89.5)2 = 95.6%

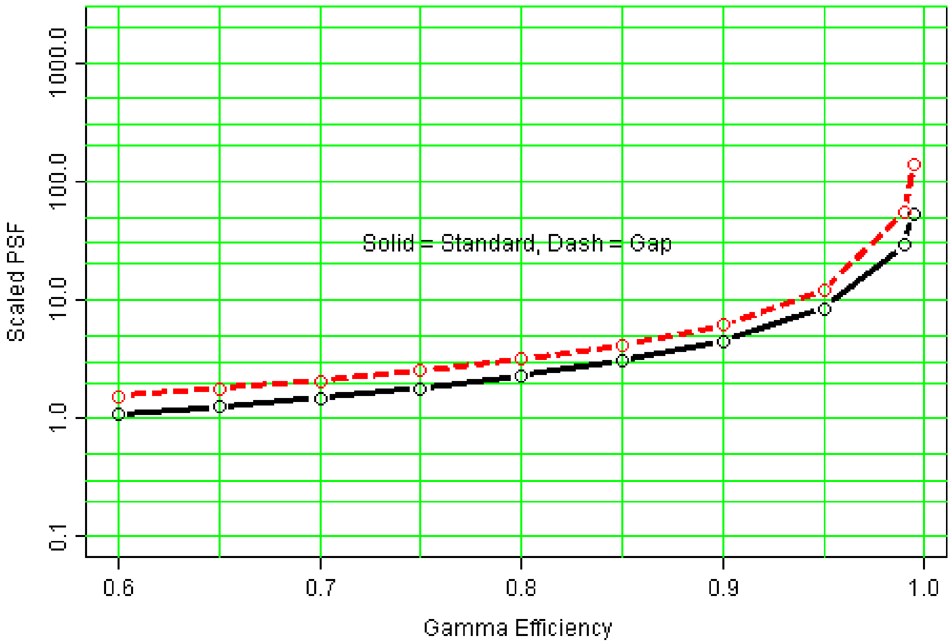
Conversions which happen in the dead zone between SSDs have a much degraded PSF.

Example of a Gap Conversion

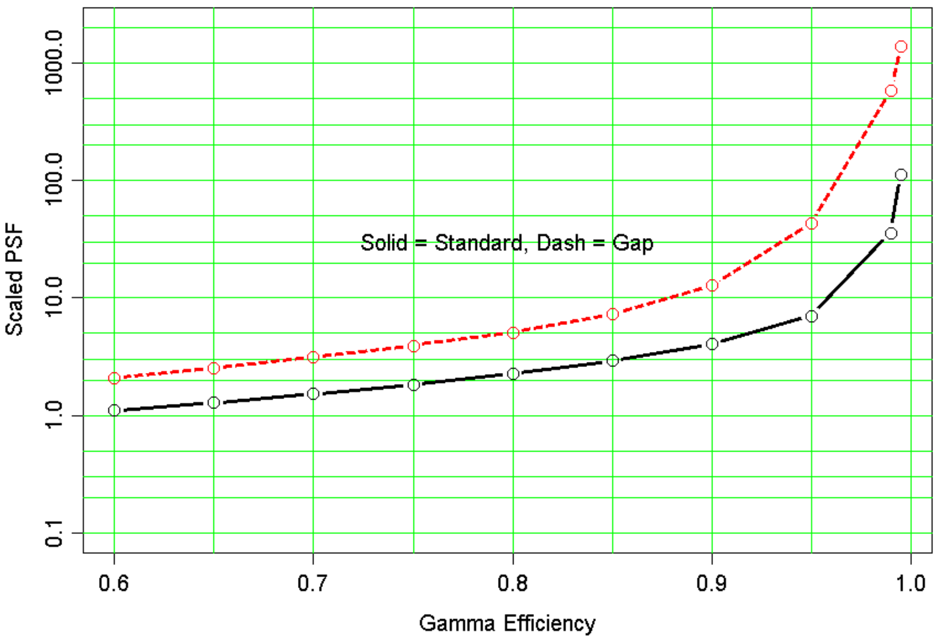


By limiting radiators to cover just SSD active area we eliminate 66% (92%) of these poorly measured conversions

Scaled PSF vs Gamma Eff. for Thin Radiators



Scaled PSF vs Gamma Eff. for Thick Radiators



Recon Software Development

The detailed track fitting was extensively tested using MC muons

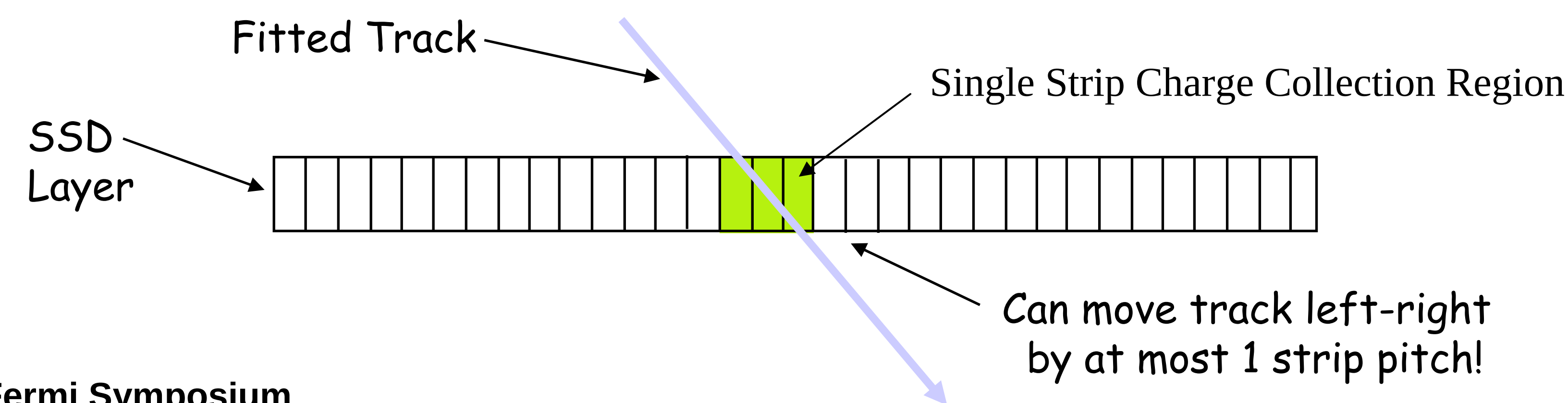
The Monte Carlo revealed issues as to how to properly assign errors to SSD clusters

The position error on a "square" distribution: $\frac{Width}{\sqrt{12}}$

Naively expect the error on a Cluster to be $\frac{ClusterWidth}{\sqrt{12}}$

But… Consider a track going through an SSD –
The cluster edges determine the centroid
AND they are ~ 100% Correlated.

The error on WHERE the tracks enters the SSD is just $\frac{\sigma_P}{\sqrt{12}}$



10 GeV Muons - ϕ Dependence

Cluster Size Error Dependence

Upper Plots:

Error ~ $\frac{Cl.Width \bullet Pitch}{\sqrt{12}}$

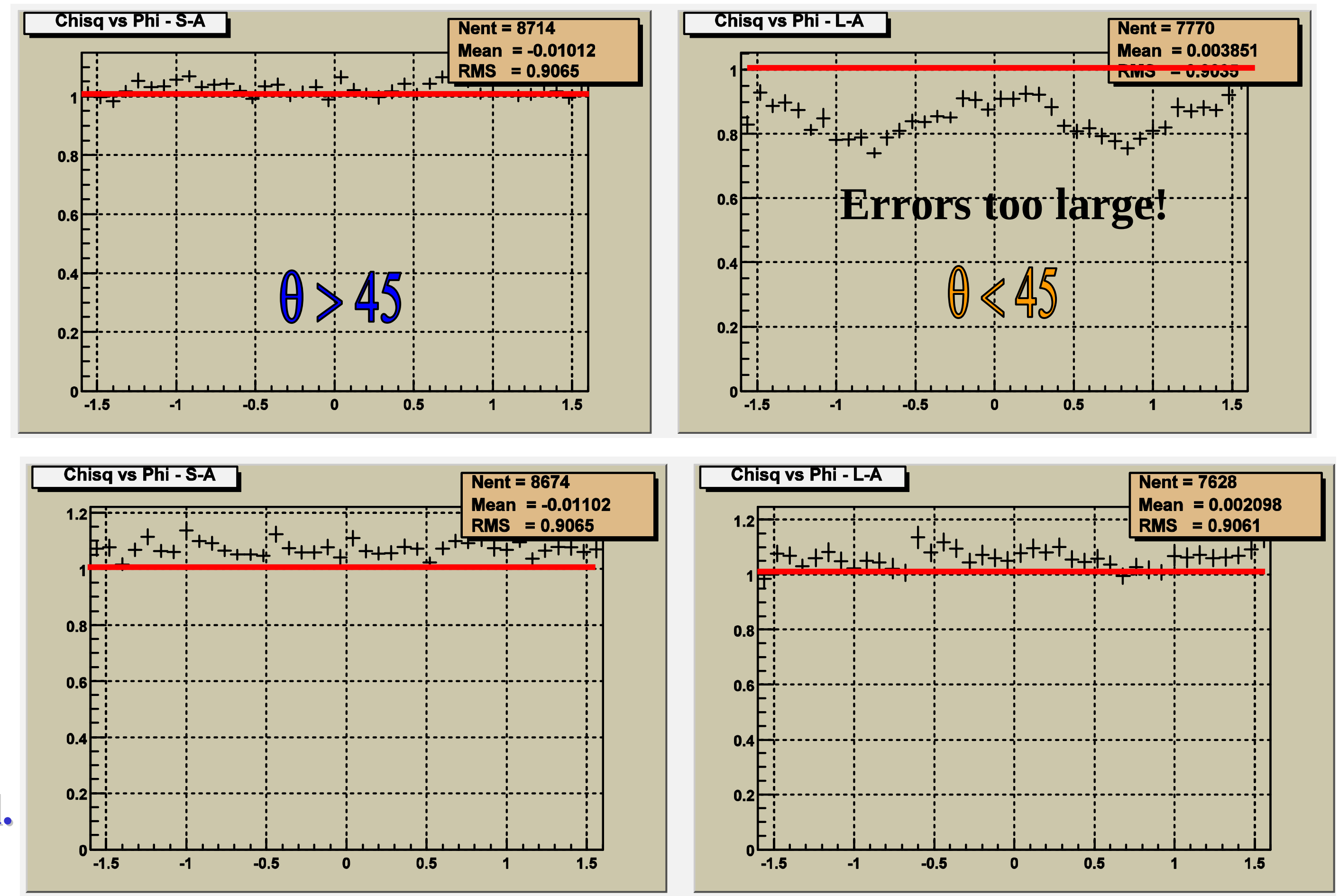
Resolution: Meas. Errors

Lower Plots:

Error ~ $\frac{Pitch}{\sqrt{12}}$

But now errors seem a bit too small.

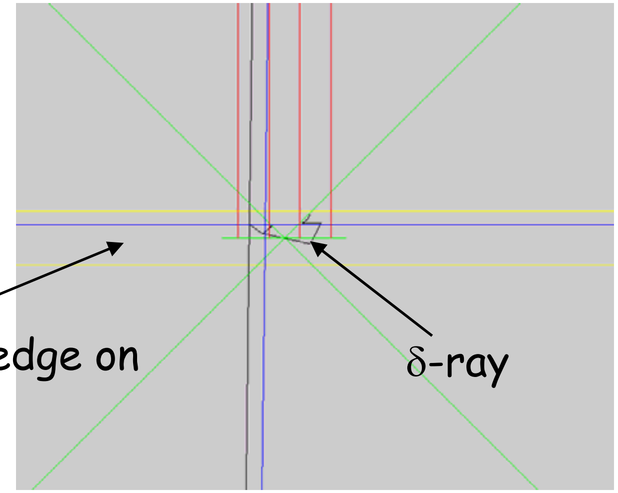
RED Line at $\langle\chi^2\rangle = 1$



Strip & Cluster Meas. Errors

Could δ-rays be the source?

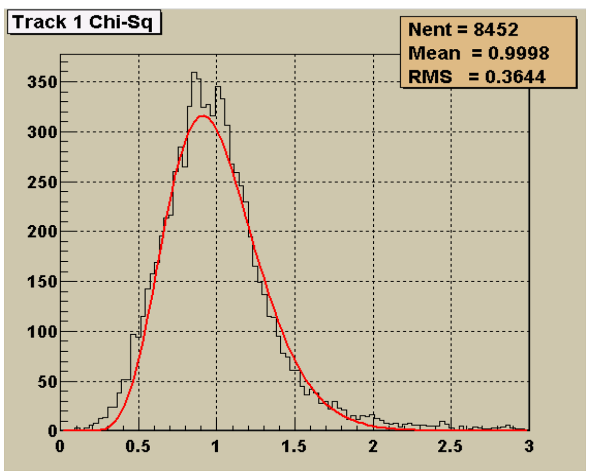
$$\text{Error} \sim \frac{(\text{Cl.Width} - \text{Pred.Cl.Width} + 1) \bullet Pitch}{\sqrt{12}}$$



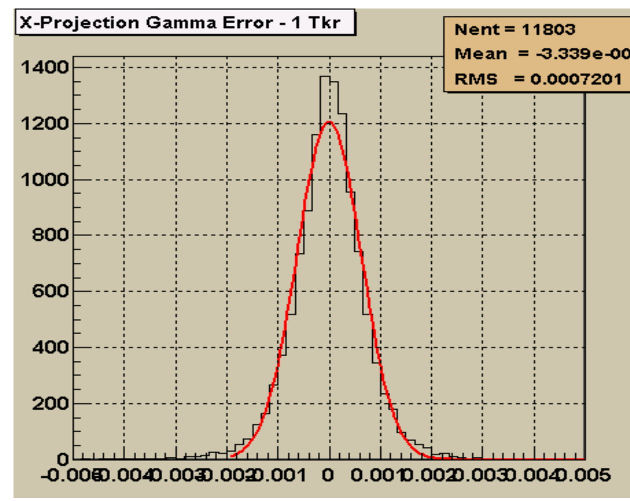
Finally arrive at:

$\langle N_{hits} \rangle = 24$

$\langle \chi^2 \rangle = 1.0$

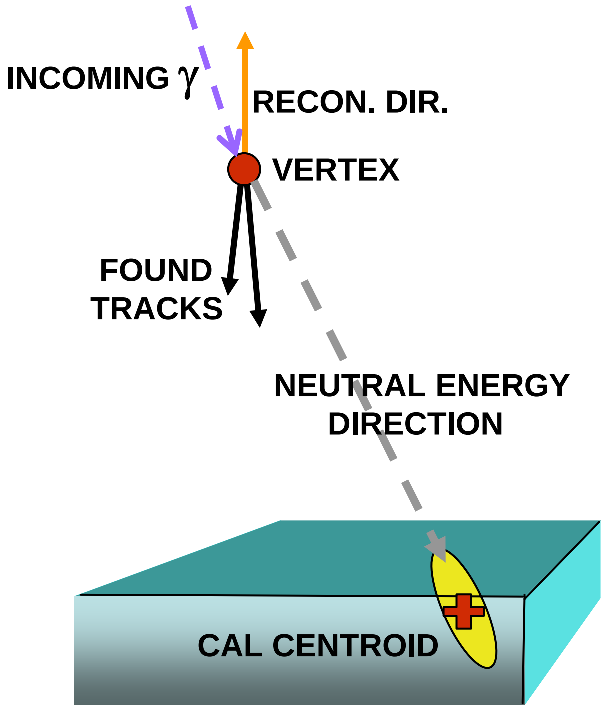


$\langle \sigma_{FIT} \rangle$ = .63 mrad



Another Example:

Neutral Energy Concept



Sometimes at the start of the shower the charge pair does not well reflect the direction of the incoming photon.

Bremstrahlung can cause much (most) of the energy to windup in photons.

The Calorimeter Centroid is a measure of where these photons impact the calorimeter.

A "Neutral Energy" direction can be inferred by connecting the found **Vertex** with the **Cal. Centroid**.

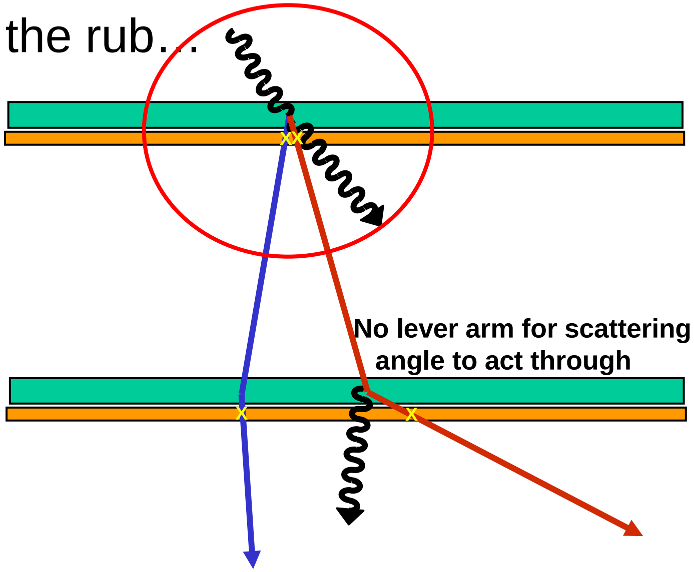
One can determine the covariant error matrix for this inferred direction by using the errors on the centroid location.

By having an imaging calorimeter, GLAST-LAT is the first Gamma Ray instrument able to do this!

Where does the charged solution go wrong?

At energies < 1 GeV only the first 2 Tracker Hits determine the direction

Here's the rub...



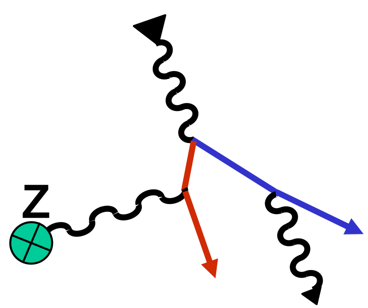
Internal and ***External***
Brems. distort direction
This is addition to multiple scattering

Expect effect to be more
sever in 18% radiators
(Thick - 18%, Thin - 3%)

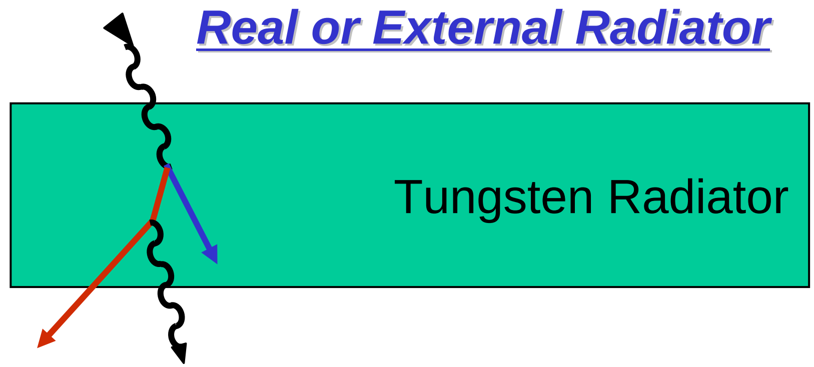
Brems. In 2nd and lower
decks doesn't effect direction

Due to ***Internal*** Brems.
ratio of effected events
(Thin : Thick Decks)
will be < ratio of rad. lens.

Internal Radiator

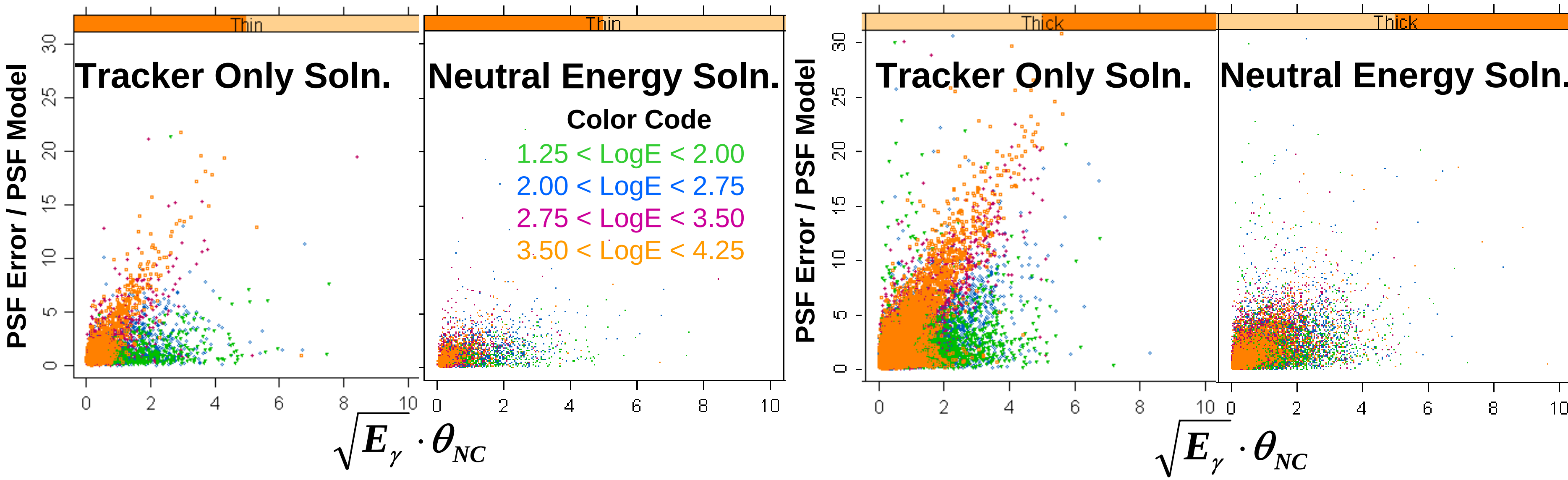


Real or External Radiator



All Gamma Results

Events Using Neutral Energy Solution



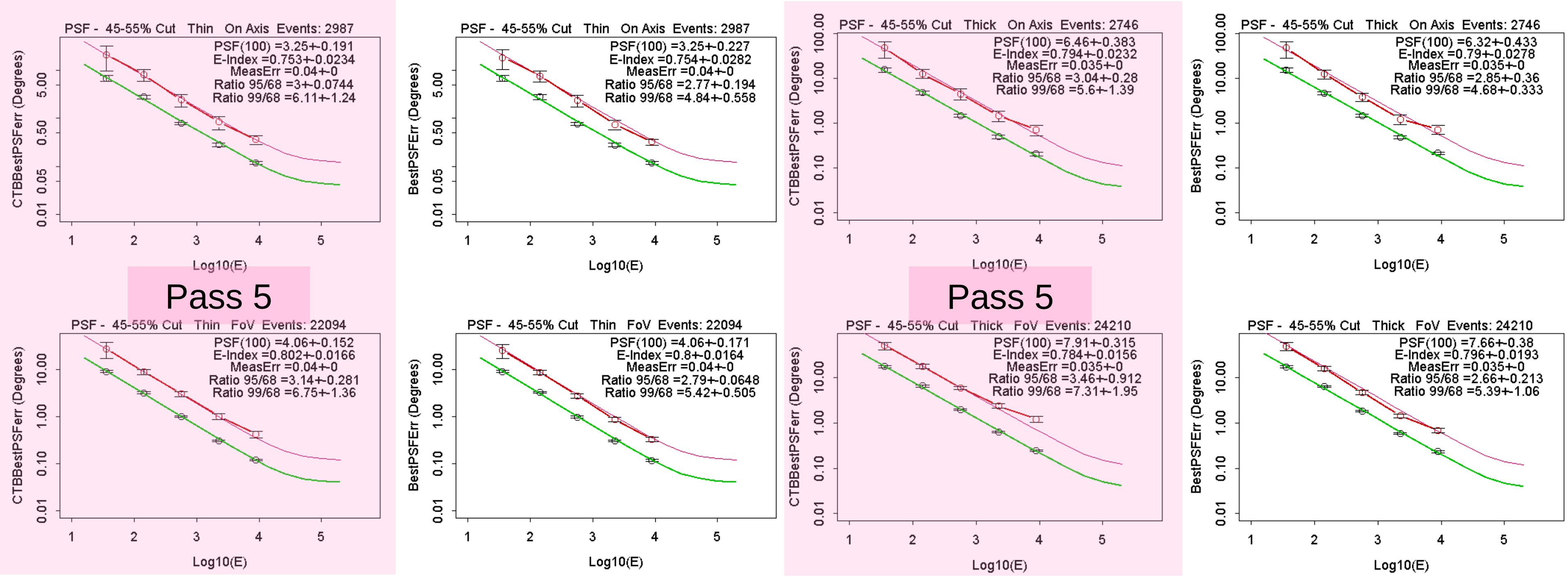
$\sqrt{E_\gamma} \cdot \theta_{NC}$ **is the energy-scaled angle between the neutral energy direction and the charged solution**

Comments

- 44% events use the Neutral Energy Solution
- The effectiveness of using Neutral Energy increases with increasing energy
- The far tails on the PSF are reigned in

Quantitative PSF Results

Thin Radiators **Thick Radiators**



- **Every aspect of the Pass 5 PSFs are improved with the inclusion of the Neutral Energy Solution**
- **The far tails show the greatest improvement**

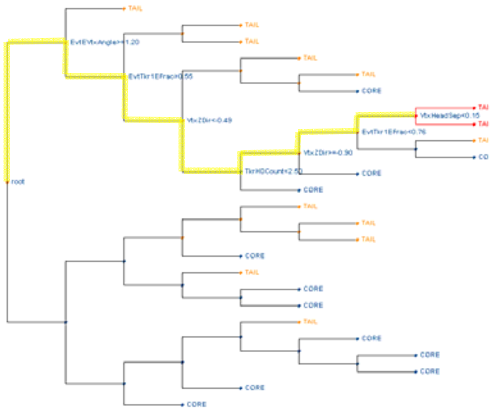
Event Analysis

The Monte Carlo allowed a detailed and modern statistical approach to refining the PSF

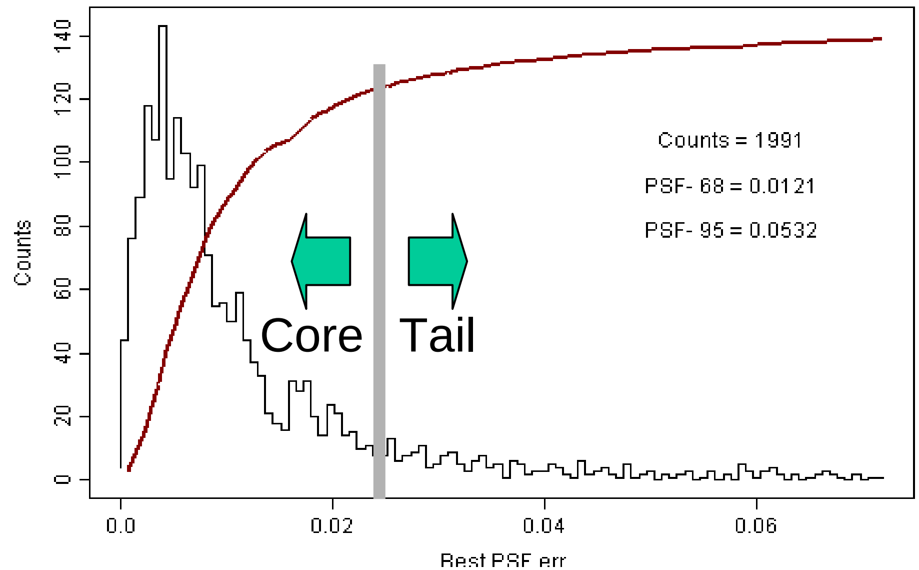
Classification Trees

- An efficient use of **All** the Information
- Automatic generation procedure
- Statistically **robust** if averaged over several "Trees"
- Objective- independent of analyst biases

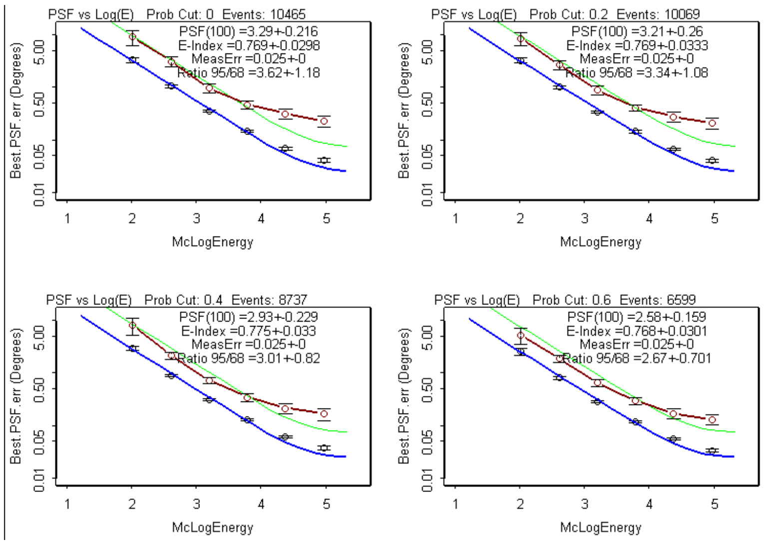
Tree
with one path illustrated



PSF Classes for CT training

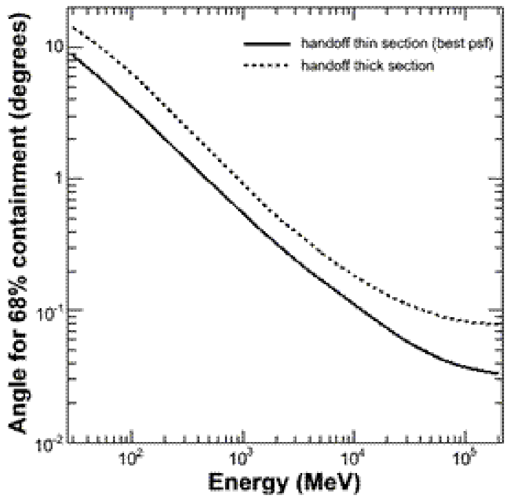


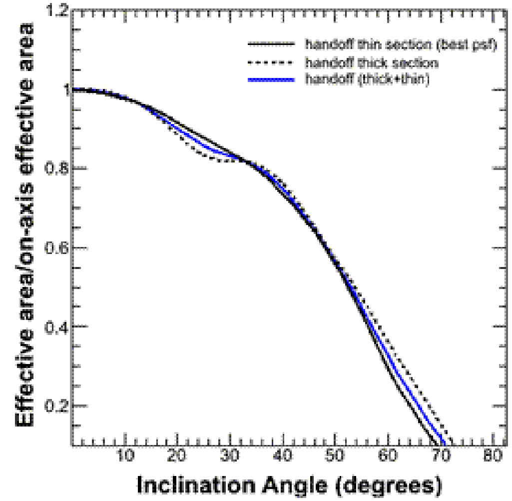
Near On-Axis PSF (cos(θ) < -.9)

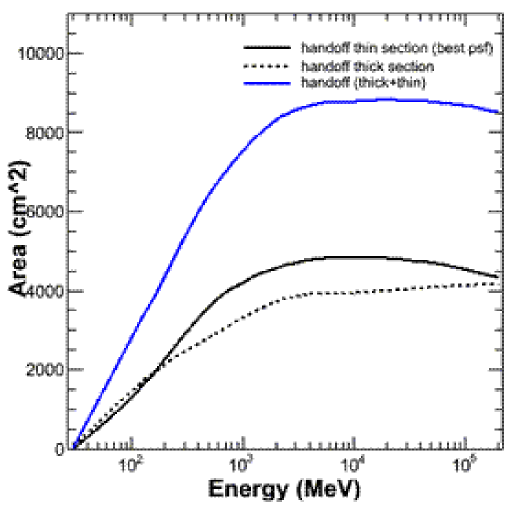


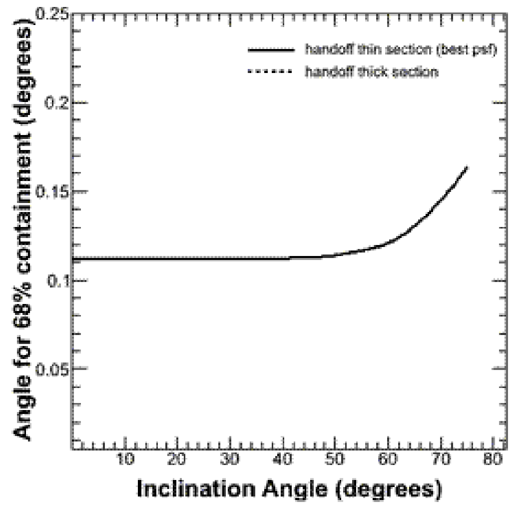
Instrument Characterization

The Monte Carlo + Instrument Model is the yard-stick by which the LAT characteristics are determined



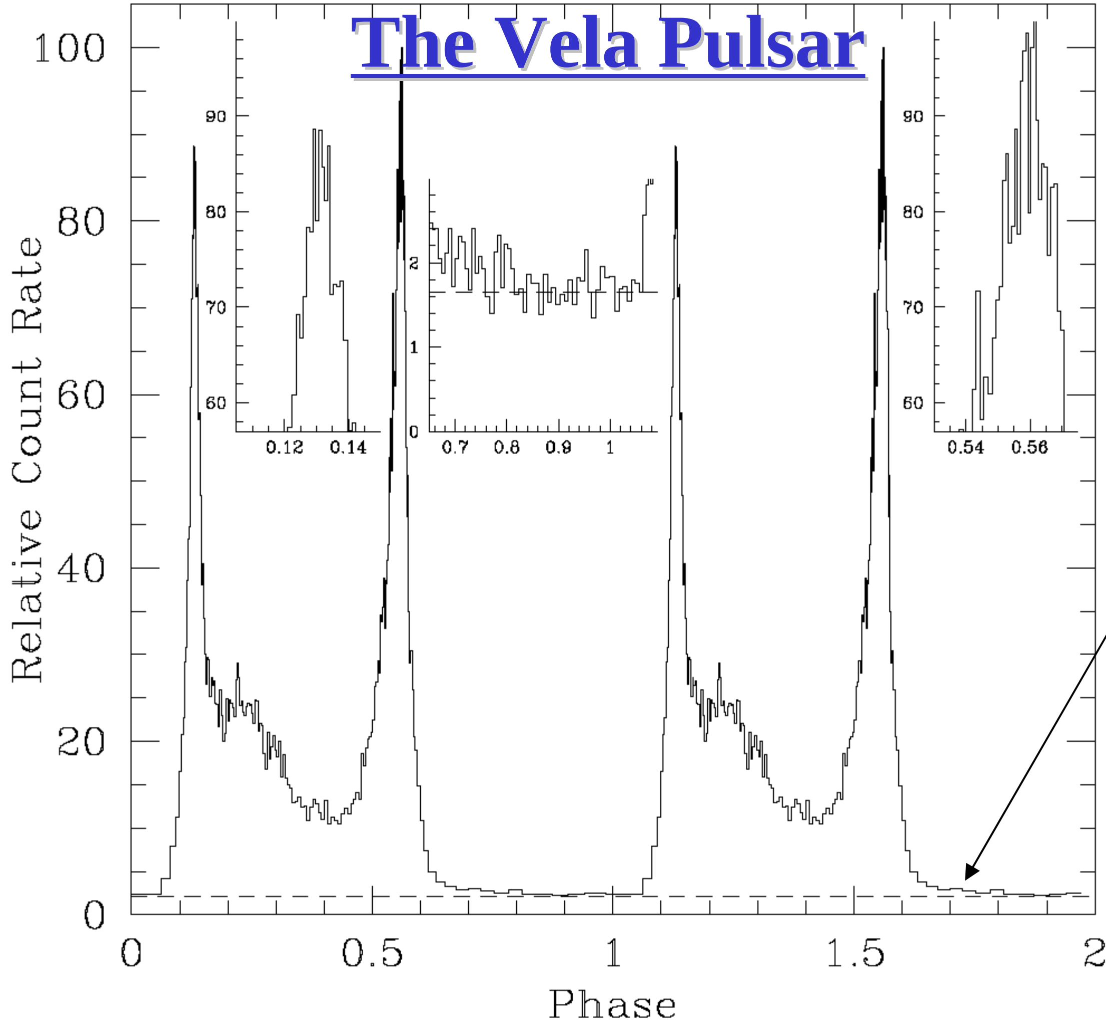






Results

Reduced tails on the PSF results in cleaner sources.
Light pollution is reduced!

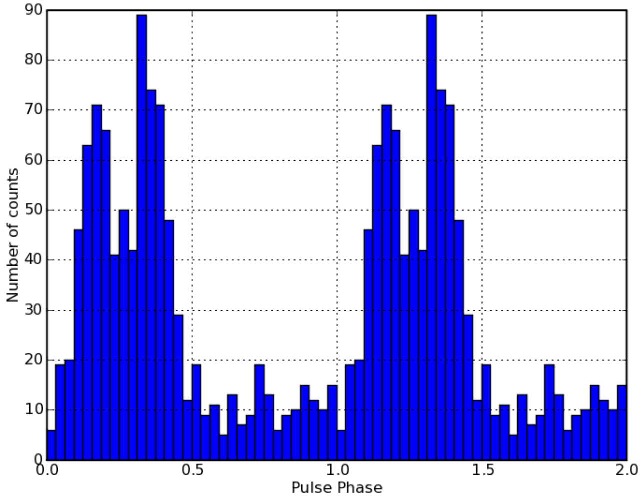


Little “background” in Off-Pulse portion of the Light Curve

Tighter PSF: Better Source Localizations

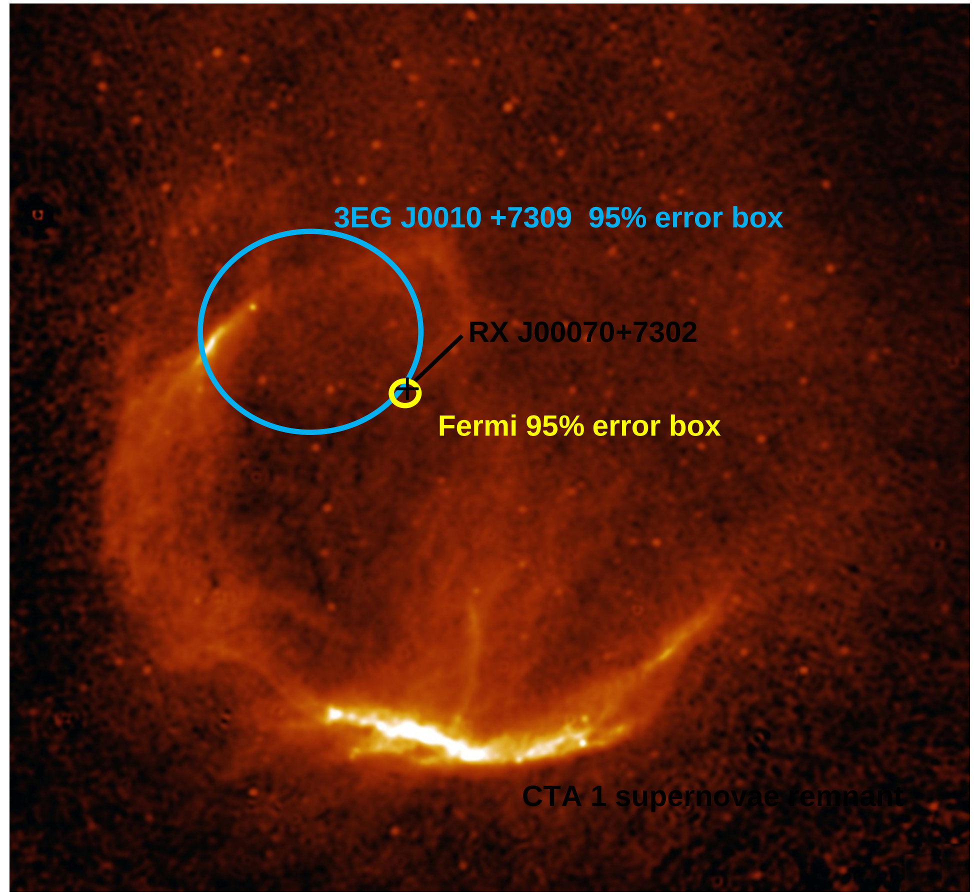
Fermi Gamma-ray Space Telescope

Pulsar in CTA 1



- exhibits all characteristics of a young high-energy pulsar (characteristic age ~1.4 x 10^4 yr), which powers a synchrotron pulsar wind nebula embedded in a larger SNR.

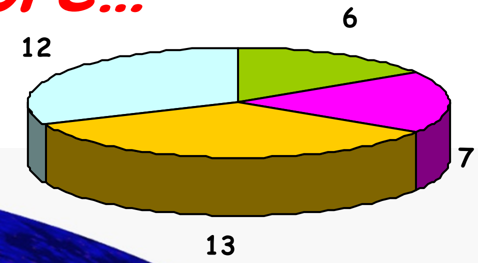
- spin-down luminosity ~10^{36} erg s^{-1}, sufficient to supply the PWN with magnetic fields and energetic electrons.

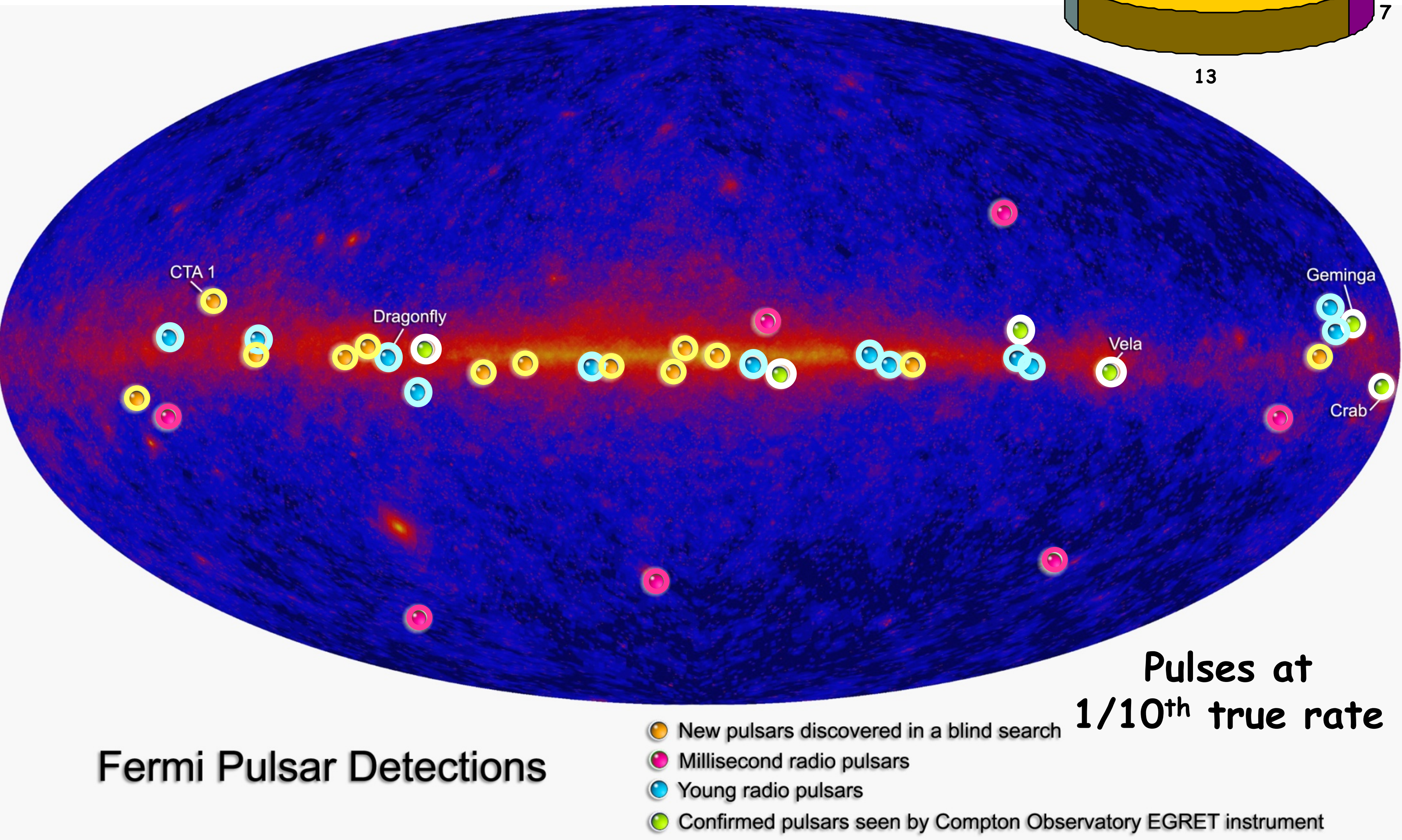


- γ-ray source at l,b = 119.652, 10.468; 95% error circle radius =0.038° contains the X-ray source RX J00070+7302, central to the PWN superimposed on the radio map at 1420 MHz.

- pulsar off-set from center of radio SNR; rough estimate of the lateral speed of the pulsar is ~450 km/s

And more, and more, and more…





Pulses at $1/10^{th}$ true rate

Conclusions

The Monte Carlo and Computer Model of GLAST (now Fermi-LAT) played a critical role from the first day

- **Crucial in developing the design**
- **Guided and unified the Reconstruction with the Simulations**
- **Inspired new analysis methods and ideas**
- **Provided the basis on which to apply modern statistical methods**
- **Is the "yard-stick" by which the instrument is calibrated**