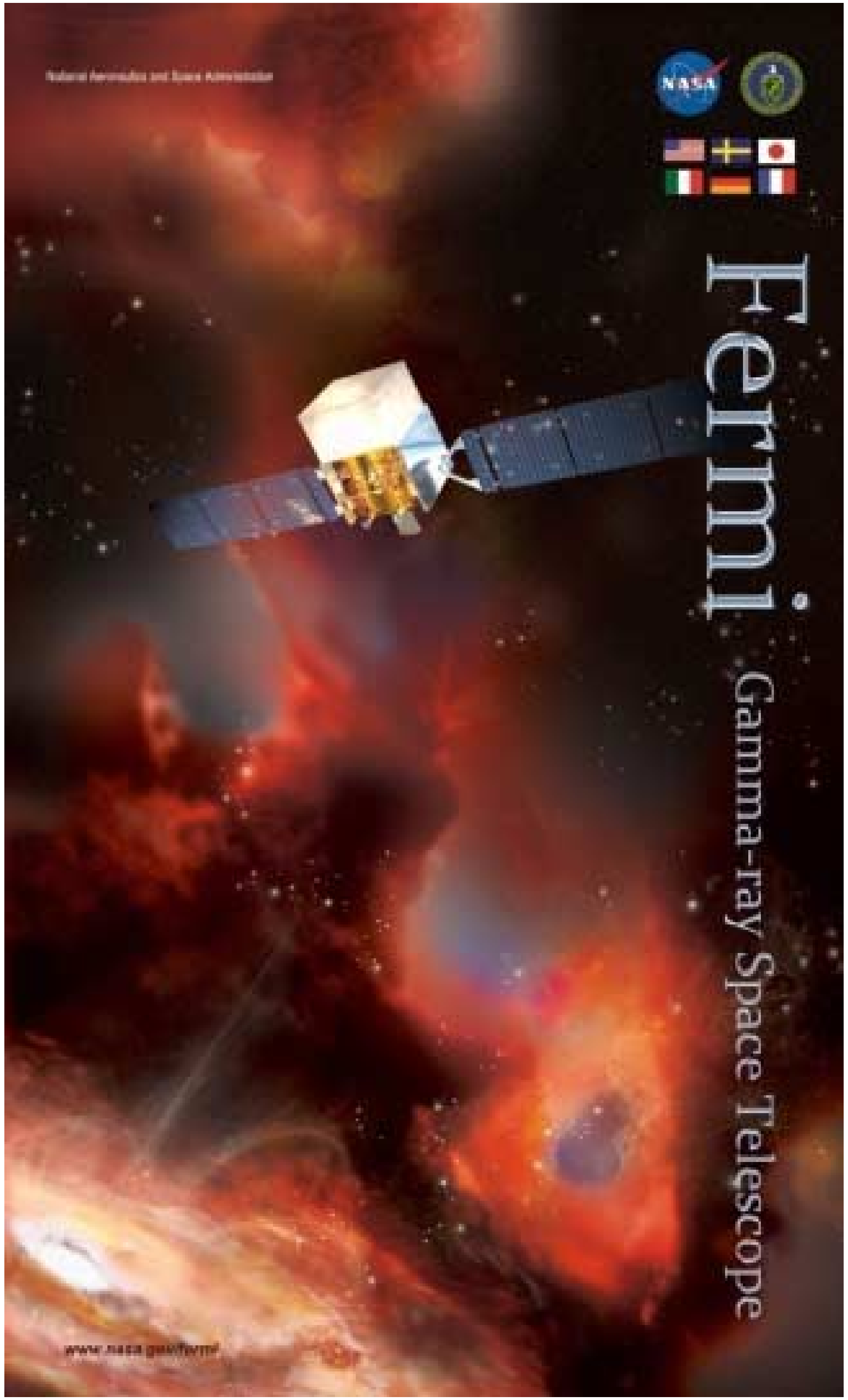


The FERMI Large Area Telescope in orbit

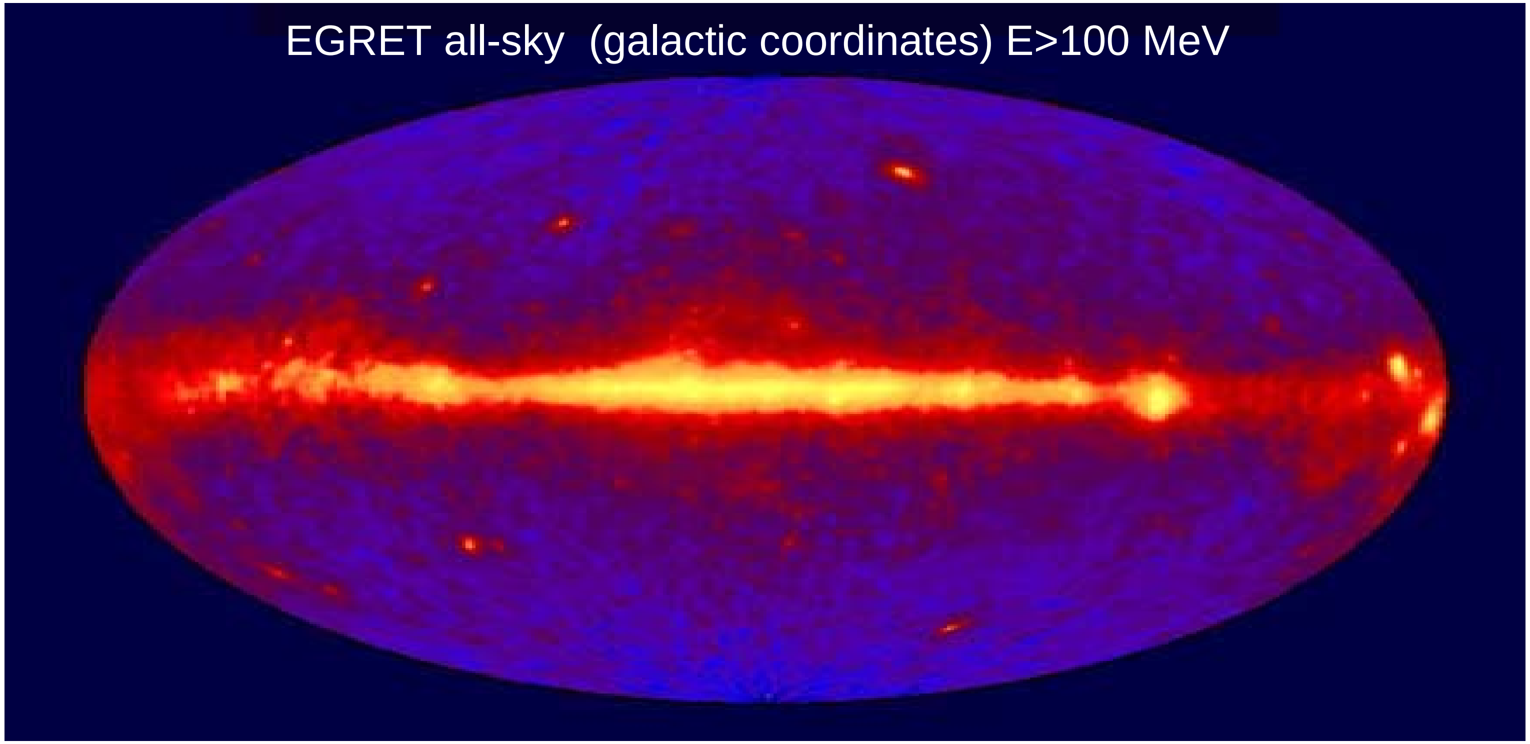
Jean Ballet **(CEA/DSM/IRFU/SAp)**

on behalf of the Fermi LAT Collaboration

Service de Physique des Particules

March 30, 2009

Features of the EGRET gamma-ray sky



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

galactic diffuse (flux ~30 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 important for study of transients

Fermi LAT science objectives

> 2000 AGNs
blazars and radiogal = f(θ,z)
evolution z < 5
Sgr A*

10-50 GRB/year
GeV afterglow
spectra to high energy

γ-ray binaries
Pulsar winds
μ-quasar jets

Possibilities
starburst galaxies
galaxy clusters
measure EBL
unIDs

Dark Matter
neutralino lines
sub-halo clumps

Cosmic rays and clouds
acceleration in Supernova remnants
OB associations
propagation (Milky Way, M31, LMC, SMC)
Interstellar mass tracers in galaxies

Pulsars
emission from radio and X-ray pulsars
blind searches for new Gemingas
magnetospheric physics
pulsar wind nebulae

The Observatory

Large AreaTelescope (LAT)
20 MeV - >300 GeV

Gamma-ray Burst Monitor (GBM)
NaI and BGO Detectors
8 keV - 30 MeV

KEY FEATURES

- **Huge field of view**
  - **–LAT: 20% of the sky at any instant; in sky survey mode, expose all parts of sky for ~30 minutes every 3 hours. GBM: whole unocculted sky at any time.**
- **Huge energy range, including largely unexplored band 10 GeV - 100 GeV.**

Total of >7 energy decades!

- **Large leap in all key capabilities. Great discovery potential.**

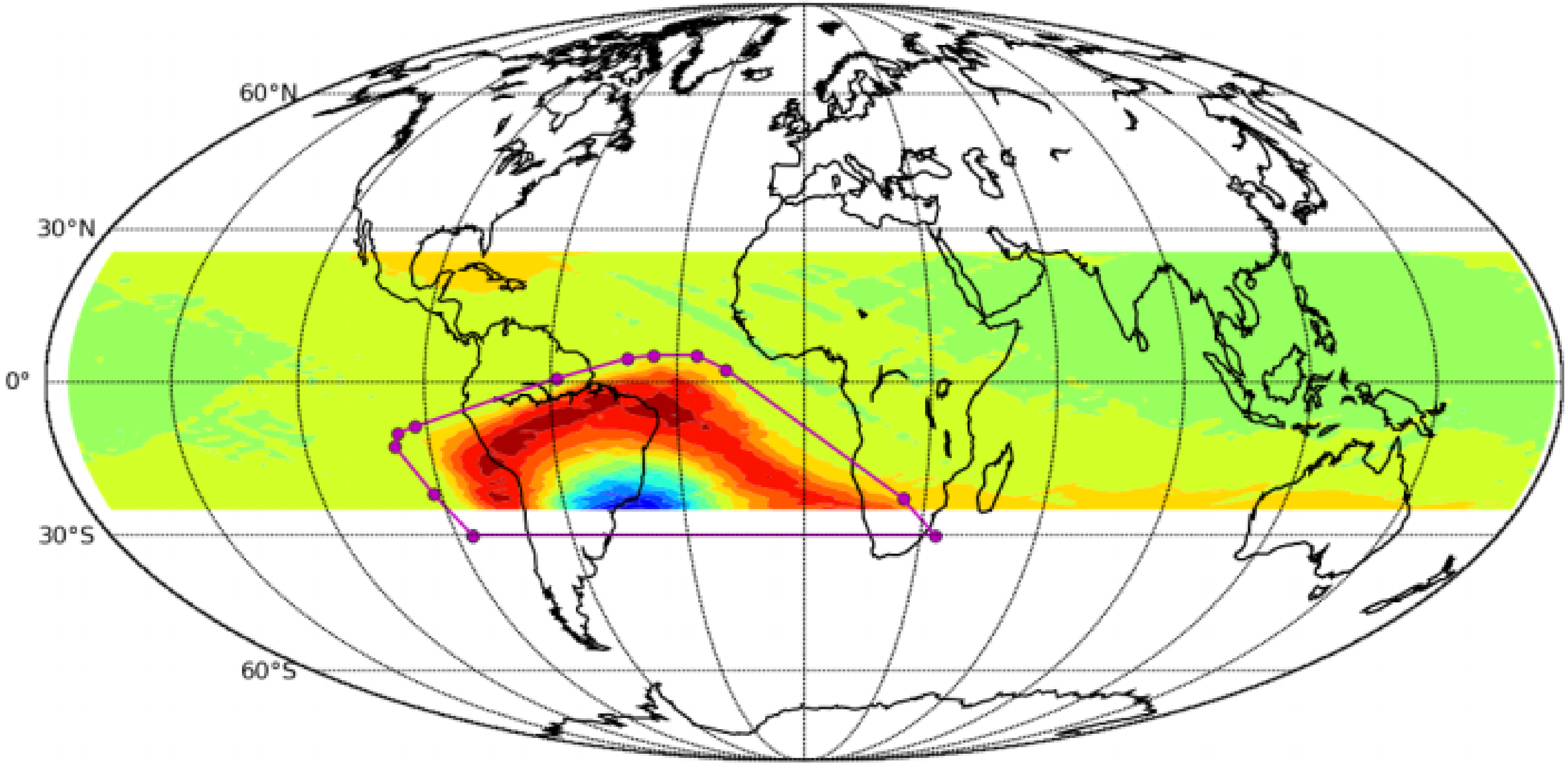
Launch!

Cape Canaveral

11 June 2008 at 12:05PM EDT

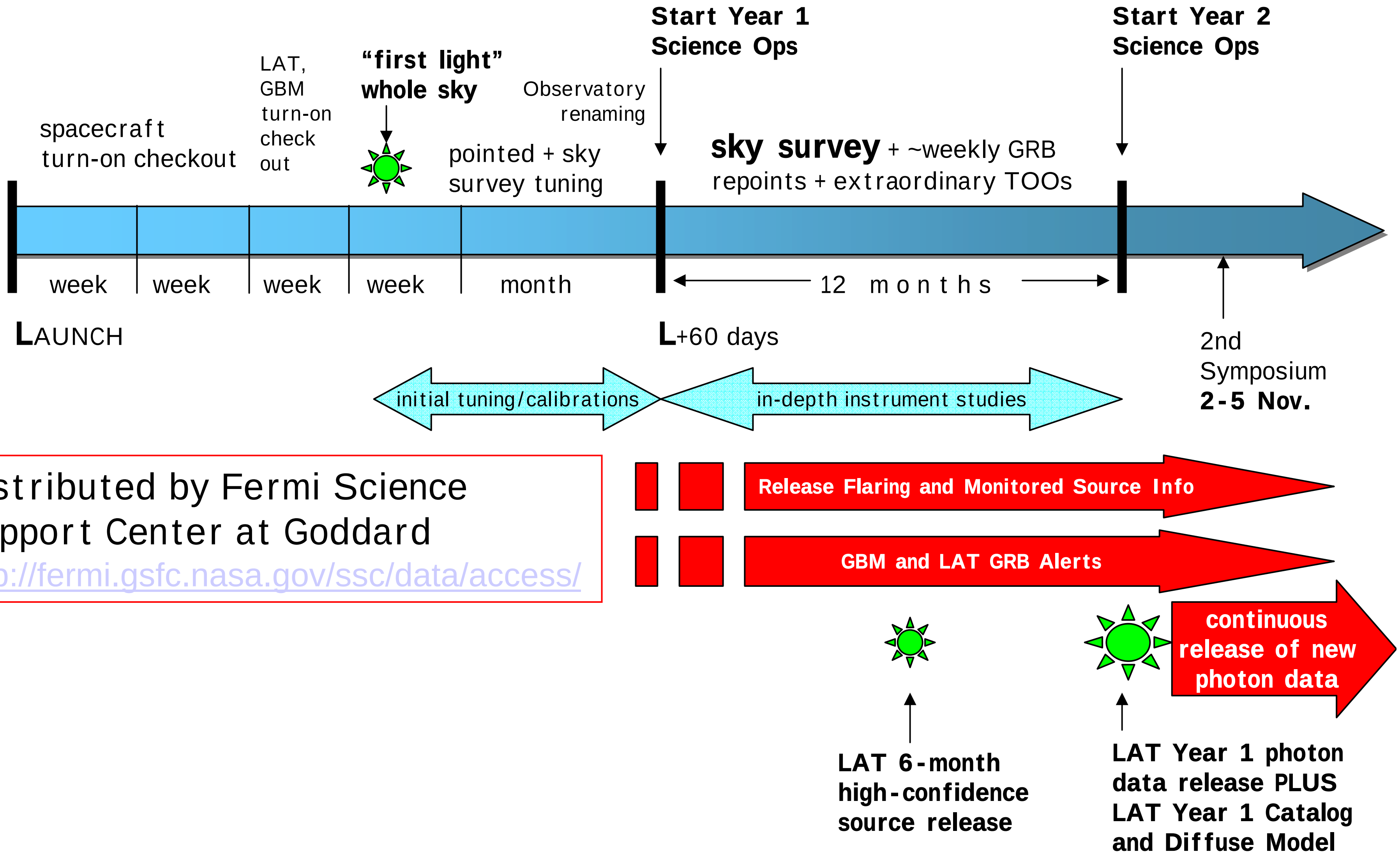
August 26 2008
NASA renames GLAST to Fermi

Fermi in orbit



Circular orbit, 565 km altitude (96 min period), 25.6 degrees inclination
Does not operate inside South Atlantic Anomaly
Inclined at 35° from zenith, on alternate sides at each orbit

Year 1 Science Operations Timeline



Distributed by Fermi Science Support Center at Goddard
http://fermi.gsfc.nasa.gov/ssc/data/access/

LAT Collaboration – an AP-HEP partnership

- France
  - CNRS/IN2P3 (LLR, CENBG, LPTA)
  - CEA/Saclay
- Italy
  - INFN, ASI, INAF
- Japan
  - Hiroshima University
  - ISAS/JAXA
  - RIKEN
  - Tokyo Institute of Technology
- Sweden
  - Royal Institute of Technology (KTH)
  - Stockholm University
- United States
  - Stanford University (SLAC and HEPL/Physics)
  - University of California, Santa Cruz - Santa Cruz Inst. for Particle Physics
  - Goddard Space Flight Center
  - Naval Research Laboratory
  - Sonoma State University
  - The Ohio State University
  - University of Washington

PI: Peter Michelson
(Stanford)

~390 Scientific Members (including 96 Affiliated Scientists, plus 68 Postdocs and 105 Students)

Cooperation between NASA and DOE, with key international contributions from France, Italy, Japan and Sweden.

Managed at SLAC.

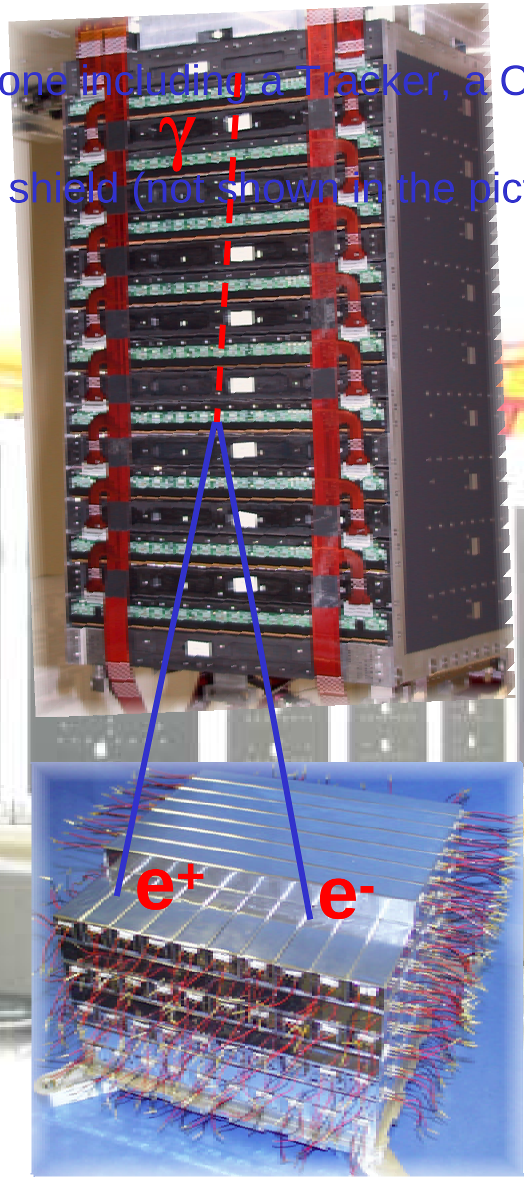
Overview of the Large Area Telescope

Overall modular design:

- ✓ 4x4 array of identical towers - each one including a Tracker, a Calorimeter and an Electronics Module
- ✓ Surrounded by an Anti-Coincidence shield (not shown in the picture)
- ✓ 3 ton – 650 W

Anti-Coincidence (ACD):

- ✓ Segmented (89 tiles).
- ✓ Self-veto @ high energy limited.
- ✓ 0.9997 detection efficiency (overall).



Tracker/Converter (TKR):

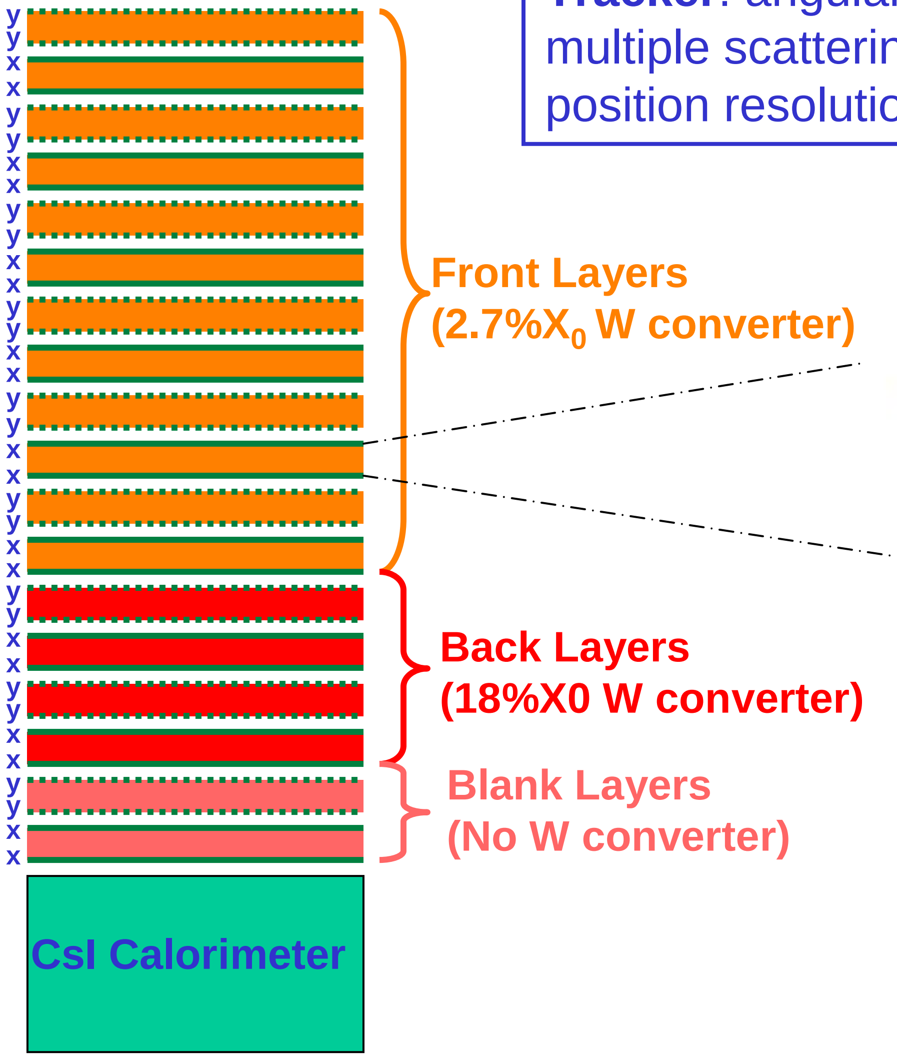
- ✓ Silicon strip detectors (single sided, each layer is rotated by 90 degrees with respect to the previous one).
- ✓ W conversion foils.
- ✓ ~80 m^2 of silicon (total).
- ✓ ~10^6 electronics chans.
- ✓ High precision tracking, small dead time.

Calorimeter (CAL):

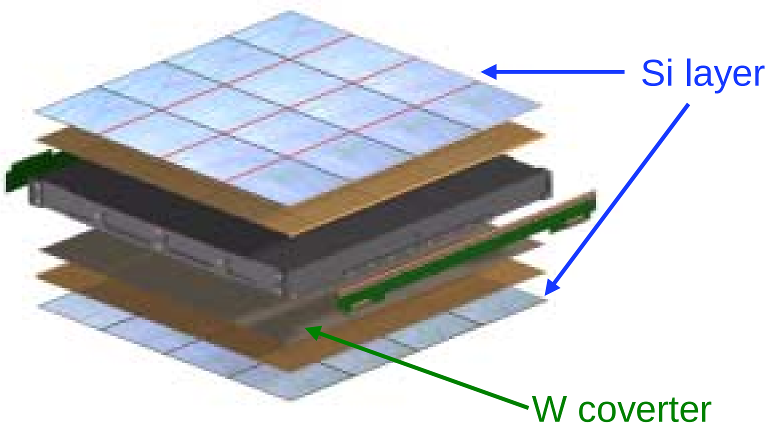
- ✓ 1536 CsI crystals.
- ✓ 8.5 radiation lengths.
- ✓ Hodoscopic.
- ✓ Shower profile reconstruction (leakage correction)

Tracker Details

Tracker Tower



Tracker: angular resolution is determined by:
multiple scattering (at low energies) => Many thin layers
position resolution (at high energies) => fine pitch detectors

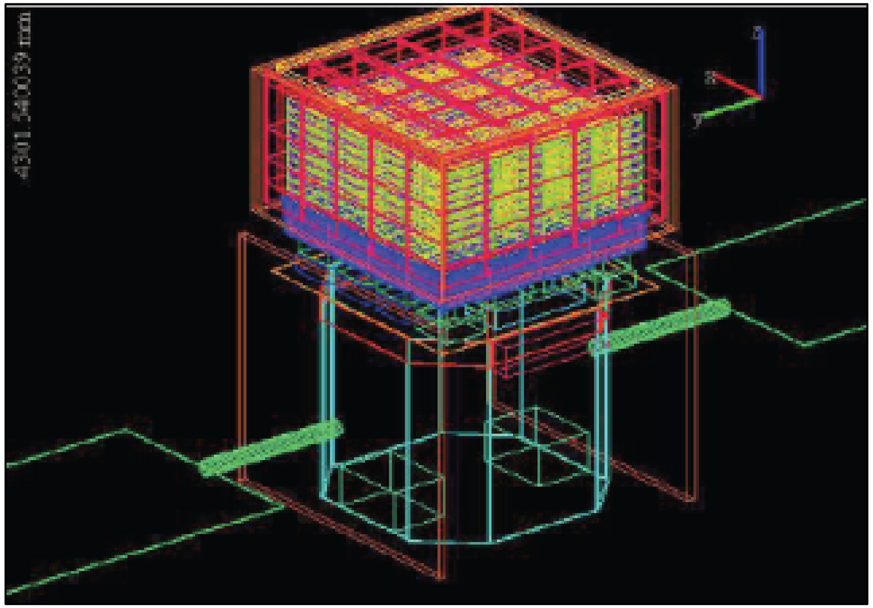


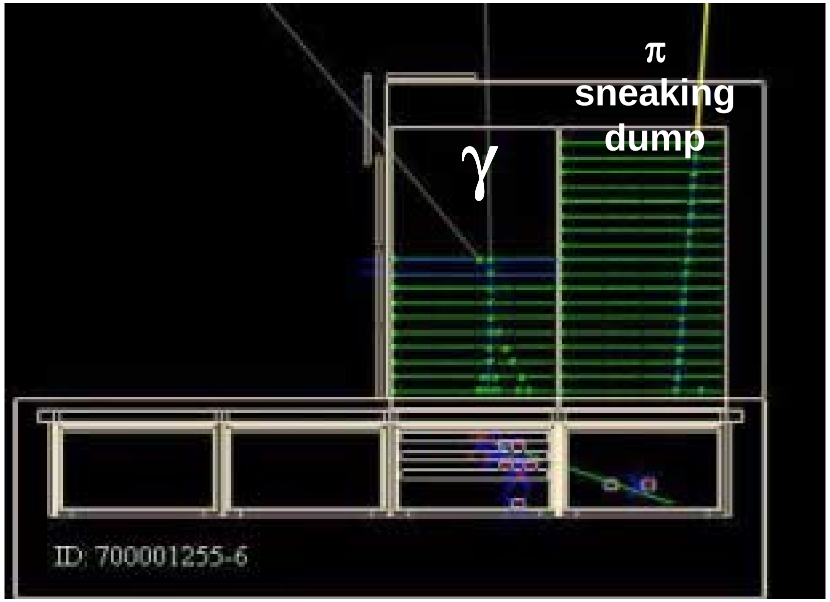
- ❑ **Front** (thin) conversion layers to have small multiple scattering errors at low energies
- ❑ **Back** (thick) layers to increase conversion probability

See Atwood *et al.* 2007, Astropart.Phys.28:422-434

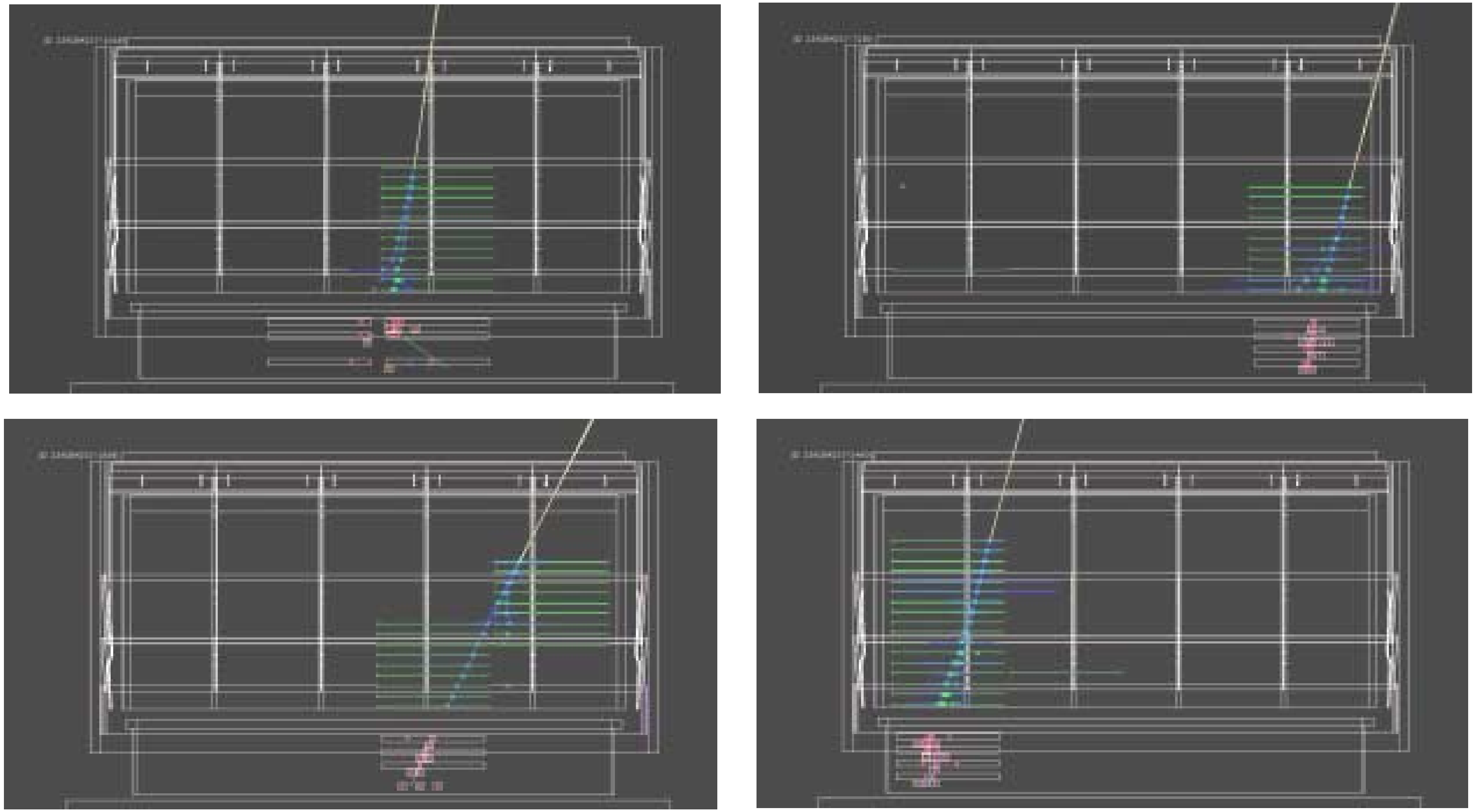
From simulation to reconstruction

- Accurate detector model
  - >45k volumes
- Physical interactions modeled with Geant4
- MC validation
  - ground test with CR muons on the full LAT
  - beam test on a calibration unit
    - 100M evts of γ, e, p, e+, C, Xe between 50MeV and 300GeV collected at CERN and GSI in 2006





LAT Gamma Candidate Events – Flight Data



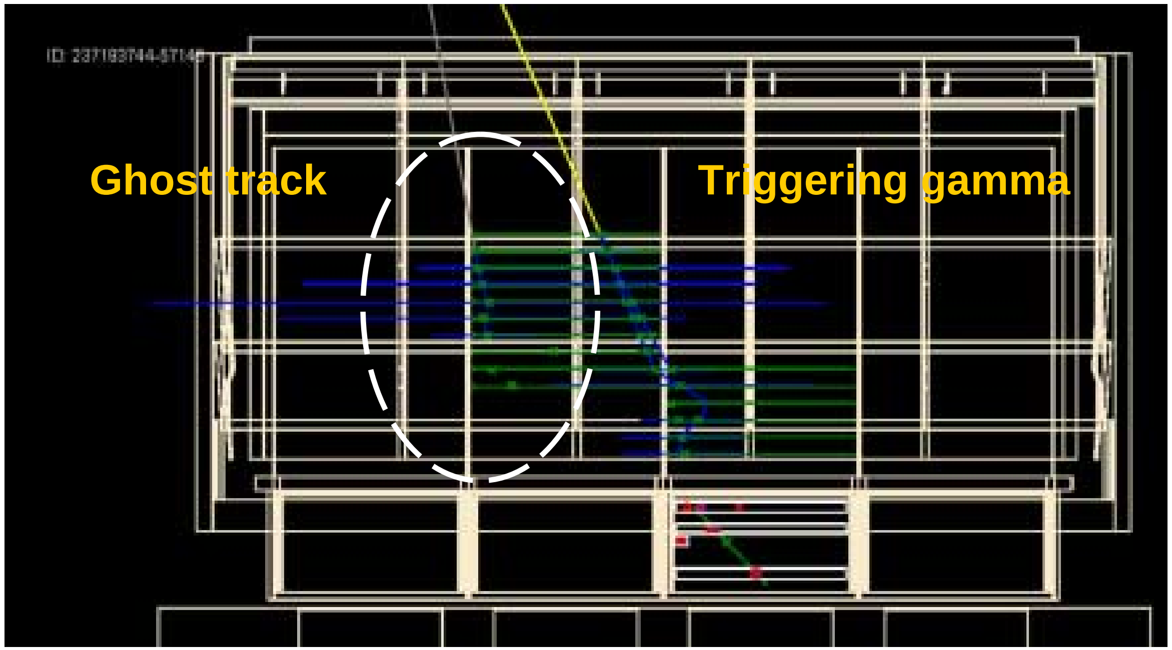
The green crosses show the detected positions of the charged particles, the blue lines show the reconstructed track trajectories, and the yellow line shows the candidate gamma-ray estimated direction. The red crosses show the detected energy depositions in the calorimeter.

Event and rejection analysis

- Full subsystems reconstruction (clusters, tracks, energy)
- Quality knobs on event direction and energy reconstruction
- Subsystem specific vetoes for background events + classification trees to optimize selection and provide probabilities for the event to be a photon
  - **ACD:** hermeticity, veto tiles struck by tracks, veto large pulse height from heavies, veto low PH in corners
  - **TKR:** dE/dx (layer-or), preshower image (distribution of clusters around tracks)
  - **CAL:** shower shape (EM vs had), veto back and side entering evts
- Event classes definition based on overall background rate
- Major on-going developments
  - **Charged particles branch:** ACD vetoed events go to a particleID analysis branch to tag candidate e, p, heavies by means of shower shape (TKR+CAL)
  - TKR-only events to enhance response to transients (GRB)
  - CAL-only events considered to enhance photon acceptance

In flight response - pileup events

- CR rate is a steep function of earth magnetic field
- Fraction of off-time particles in the detector which leave ghost signal in coincidence with gammas
  - Between 2% and 15% depending on magnetic latitude
- Ghost effect
  - confuse/slow tracking and pattern recognition (→ CAL-seeded track recon)
  - Alter event topology and fake bkg rejection topological cuts



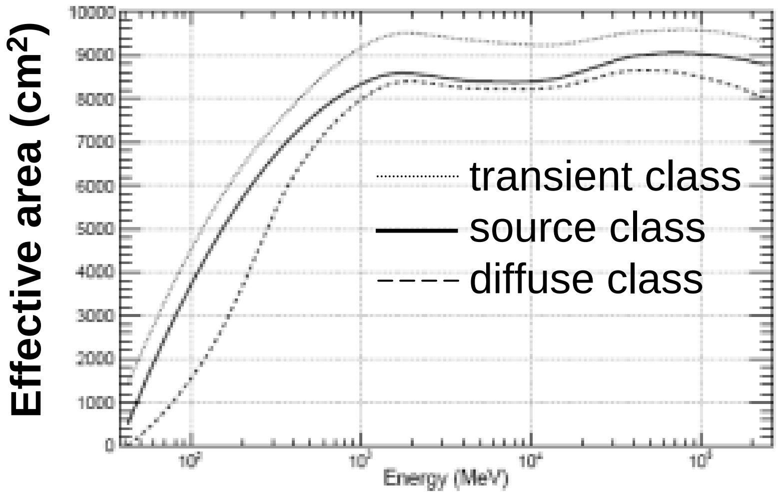
Assessment of pile-up effects

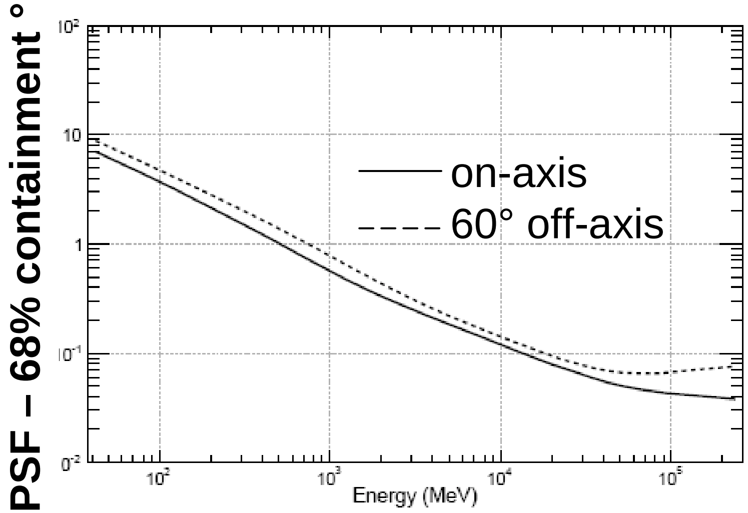
PRELIMINARY

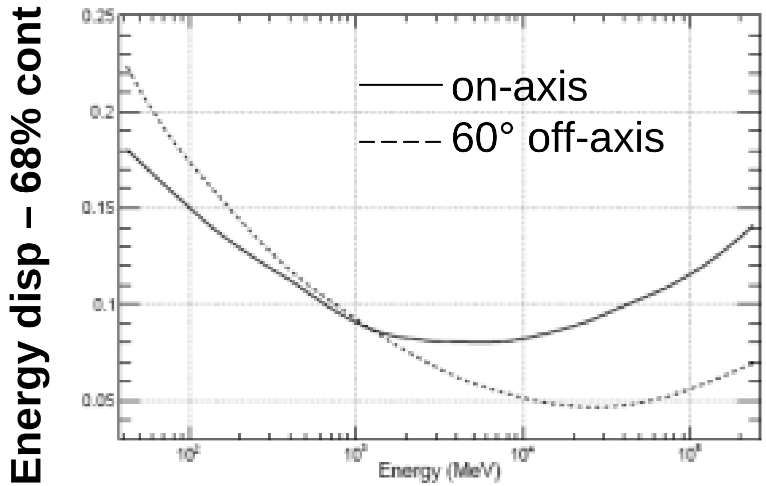
- Simulations enriched with ghosts from real periodic trigger events indicate
  - Larger effect at low energies
  - Maximum of 40% lower efficiency at 100MeV on-axis wrt pre-launch simulations
  - Rapidly decreasing with energy - negligible above 10GeV
  - Maximum effect on flux (over all spectrum) → 30% bias
  - Maximum effect on spectral parameters (for E^{-2} power law) → 0.1 bias
- Very close to early papers assessment of systematics
  - Much reduced systematics when corrected for!
- On-going work for corrections
  - Correct IRFs for difference using simulations with ghosts
  - Filter ghost events before recon
  - Retrain event selection after addition of ghost in simulation + recon-filtering → release post-launch IRFs for public data

Instrument Response Functions

Google: lat performance → http://www-glast.slac.stanford.edu/software/IS/glast_lat_performance.htm





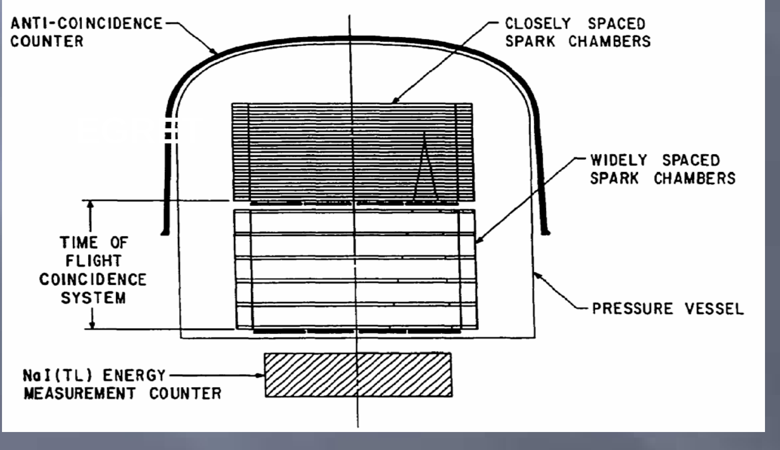


- ❑ Instrument response mapped into analytical functions or simple tables
- ❑ General simulation for all-purpose analysis vs specific analysis MC sim
- ❑ Serve large community of users
- ❑ Systematics from response representation choice and MC fidelity

LAT as a telescope

	Years	Ang. Res. (100 MeV)	Ang. Res. (10 GeV)	Eng. Rng. (GeV)	$A_{eff}\,\Omega$ (cm^2 sr)	# γ-rays
EGRET	**1991–00**	**5.8°**	**0.5°**	**0.03–10**	**750**	**1.4×10^6/yr**
AGILE	**2007–**	**4.7°**	**0.2°**	**0.03–50**	**1,500**	**4×10^6/yr**
***Fermi* LAT**	**2008–**	**3.5°**	**0.1°**	**0.02–300**	**25,000**	**1×10^8/yr**

- After 3 months LAT has surpassed EGRET and AGILE celestial γ-ray totals
- Unlike EGRET and AGILE, LAT is an effective All-Sky Monitor
  whole sky every ~3 hours



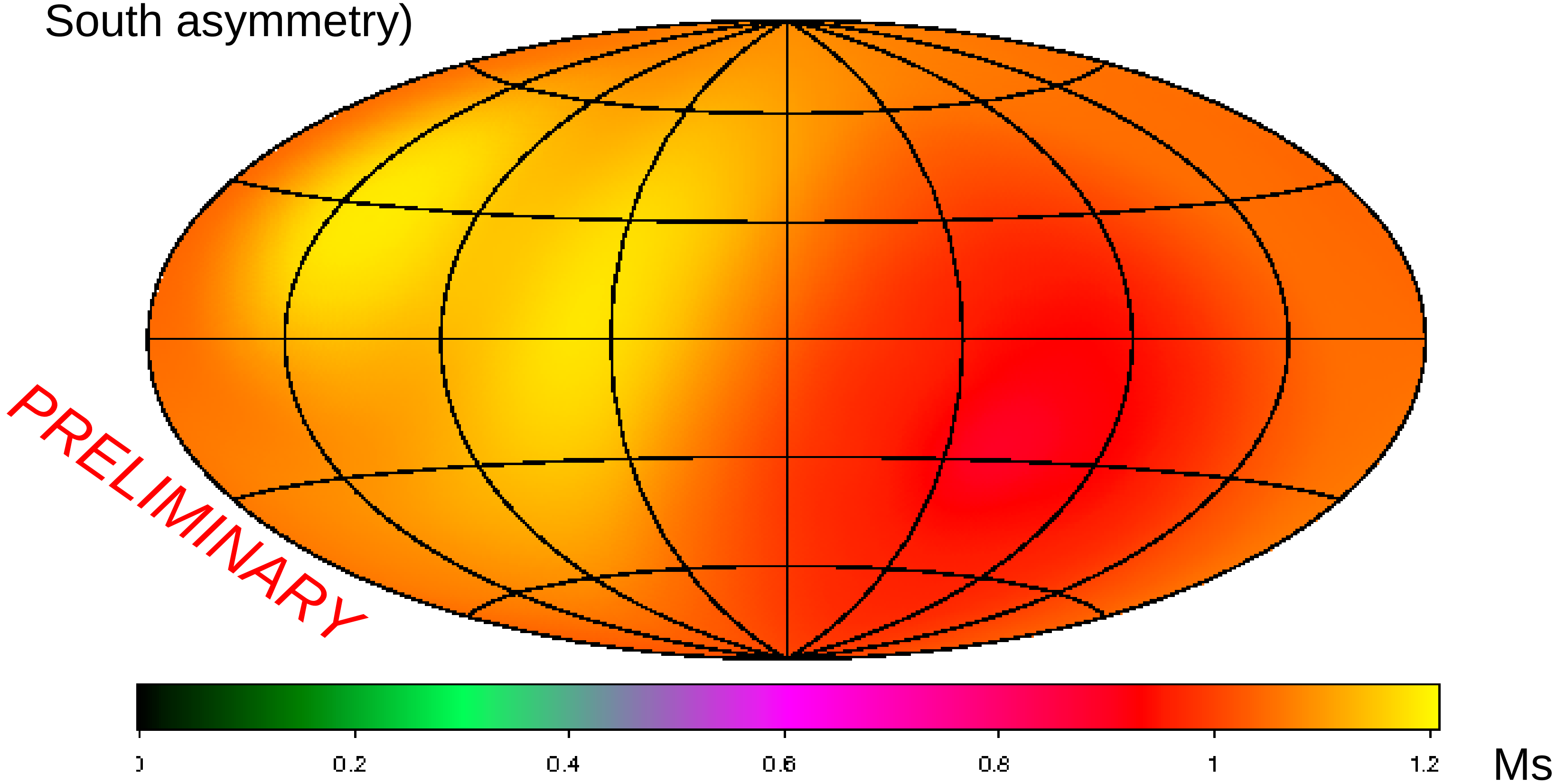
CGRO EGRET

AGILE (ASI)

Fermi / LAT

Exposure map

- Data used are the first three months of all-sky scanning data, Aug. - Oct. 2008. Total live time is 7.53 Ms
- Scanning scheme makes exposure map very uniform (SAA creates 25% North-South asymmetry)

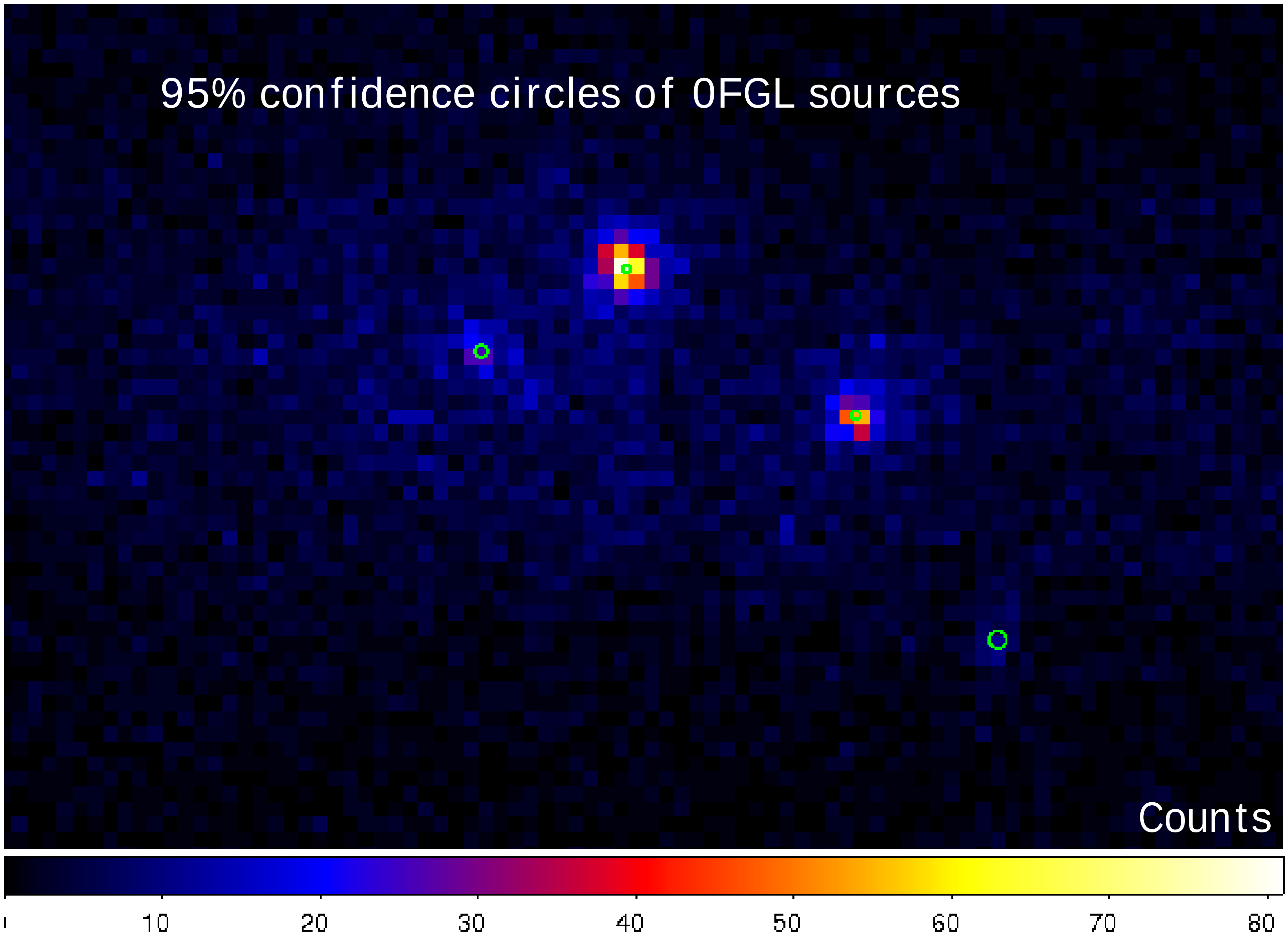


Equivalent on-axis observing time, Galactic coordinates, Aitoff projection

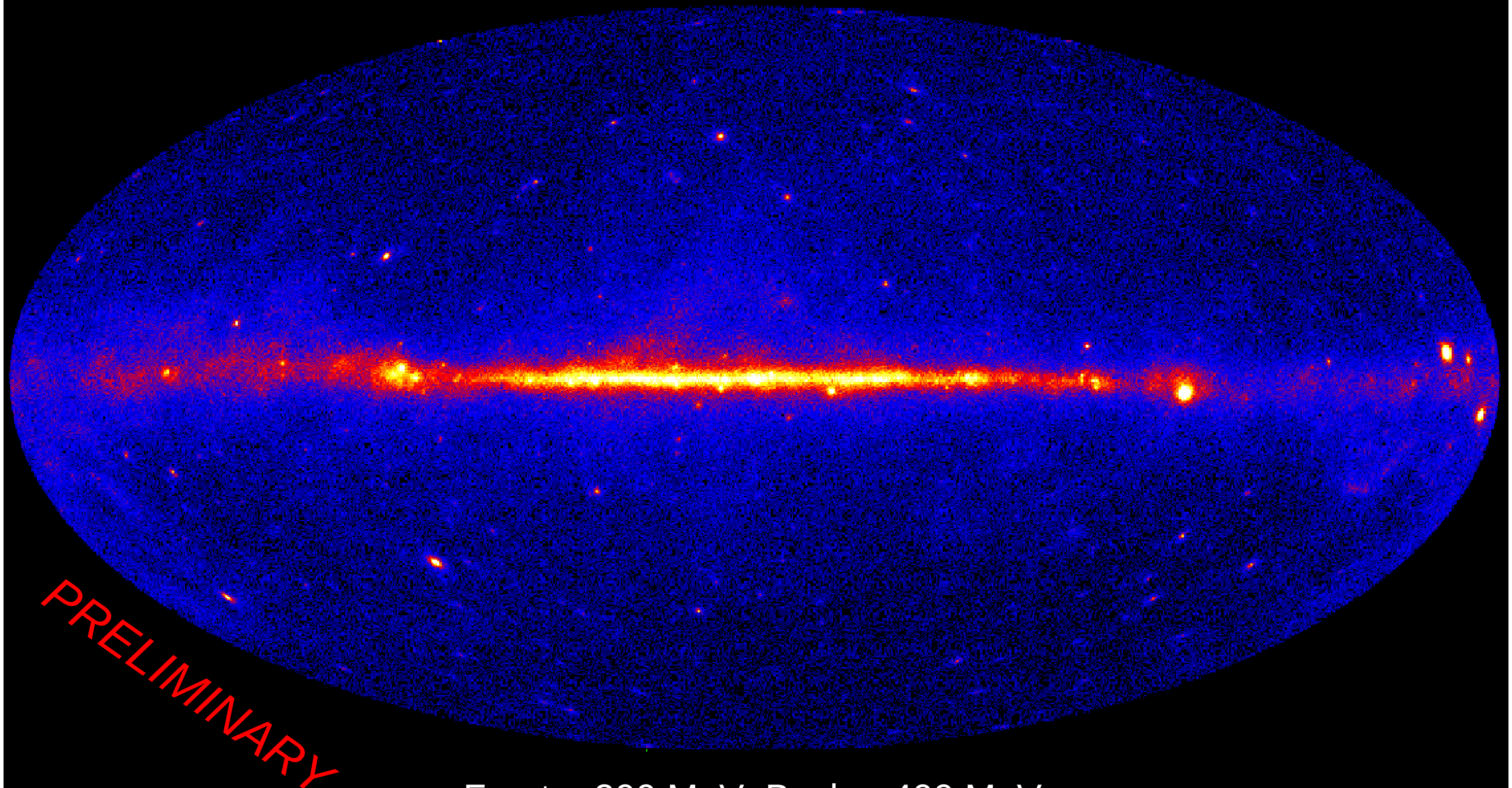
The LAT Bright Source List (0FGL)

- 1.8 M events above 200 MeV with current cuts
- Wavelet analysis (peak detection) for source detection
  1. Front events > 200 MeV + Back events > 400 MeV
  2. Front events > 1 GeV + Back events > 2 GeV
- Large overlap at low energy ➔ Maximum likelihood analysis for locations, source significance, fluxes below and above 1 GeV, and variability information.
- Confidence level greater than **10 σ** over 3 months. Not uniform - sources near the Galactic plane must be brighter because of the strong diffuse background
- Associations with known sources

The Point Spread Function is key to source detection and identification


95% confidence circles of 0FGL sources
Counts
10
20
30
40
50
60
70
80

205 LAT Bright Sources

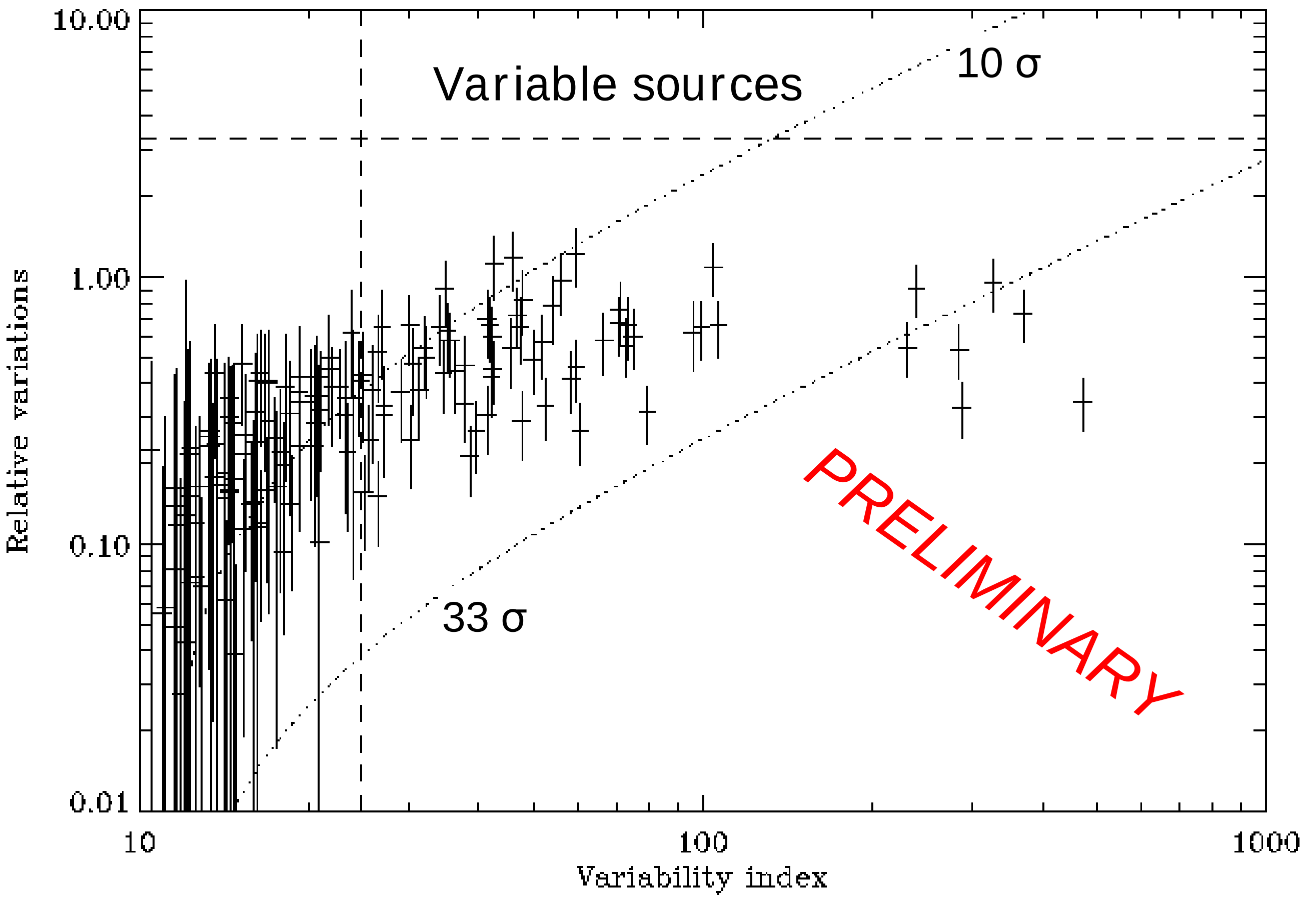


Front > 200 MeV, Back > 400 MeV

Crosses mark source locations, in Galactic coordinates. 1/3 at |b| < 10°.
Only 60 clearly associated with 3EG EGRET catalog. The sky changes!

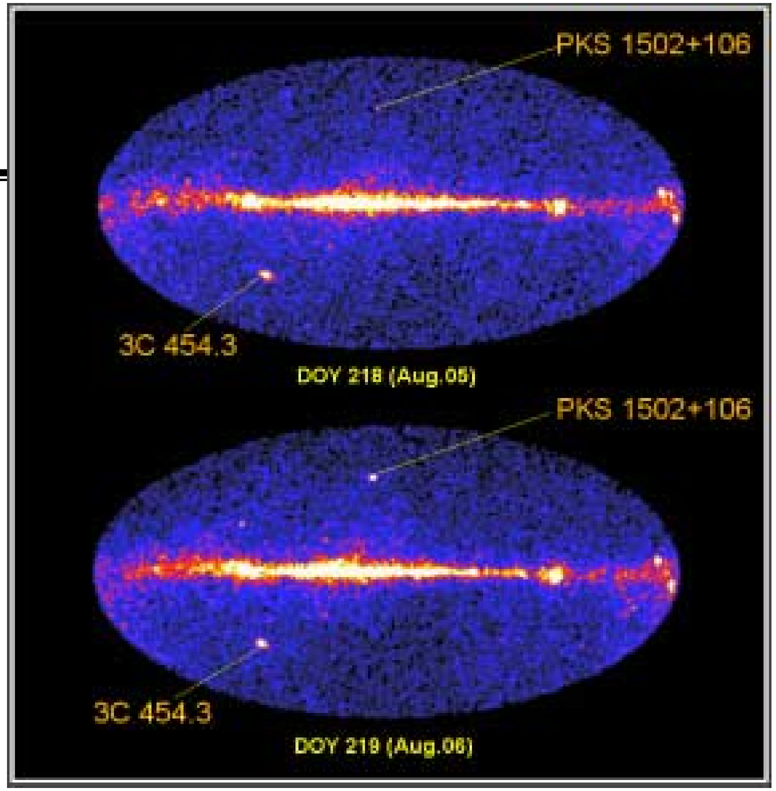
Source variability

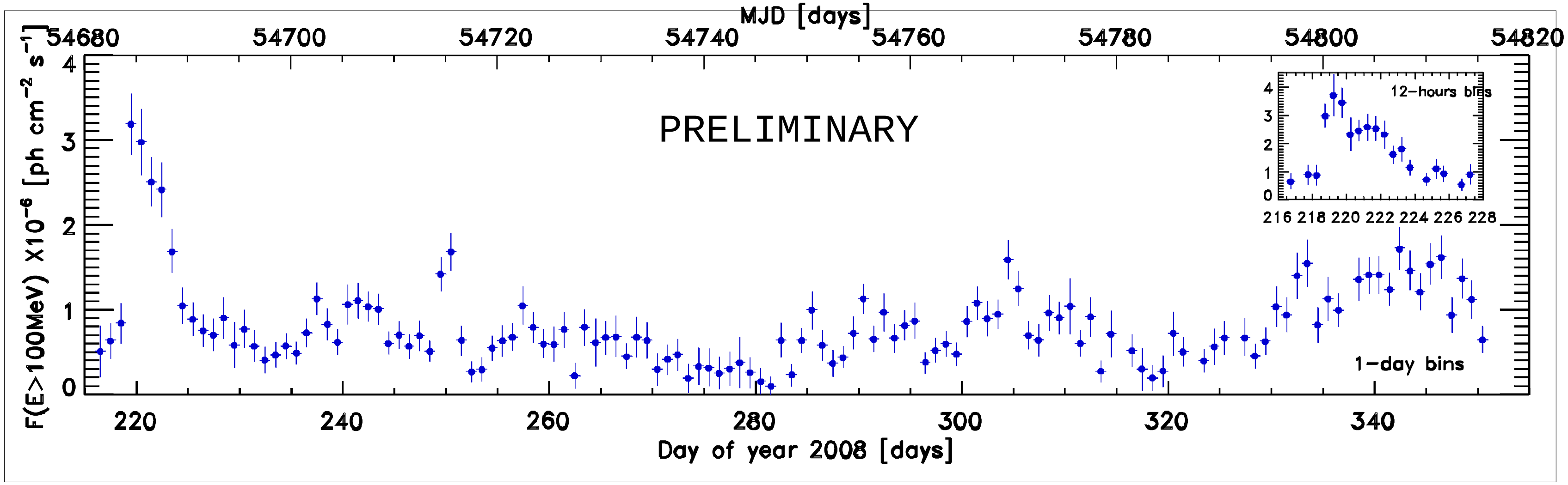
- Flag as variable for probability < 1%
- 1/3 sources flagged as variable
- Not very large fractional variability



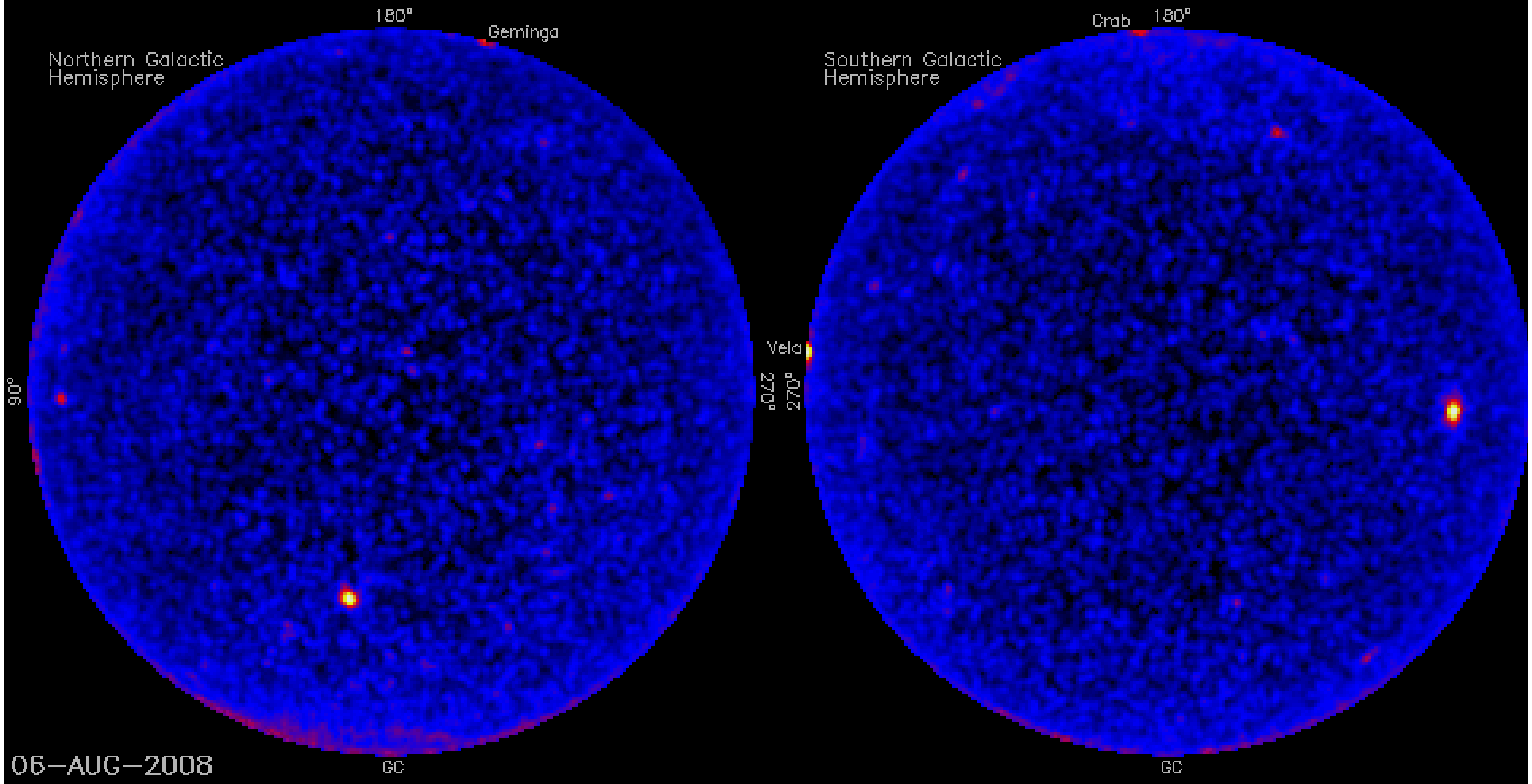
Rapid variability

- PKS 1502+106 (aka OR 103), at z=1.84 (SDSS)
- **Extremely rapid flare, possibly the highest ΔL/Δt detected to date in the GeV band** (insert in the light curve)





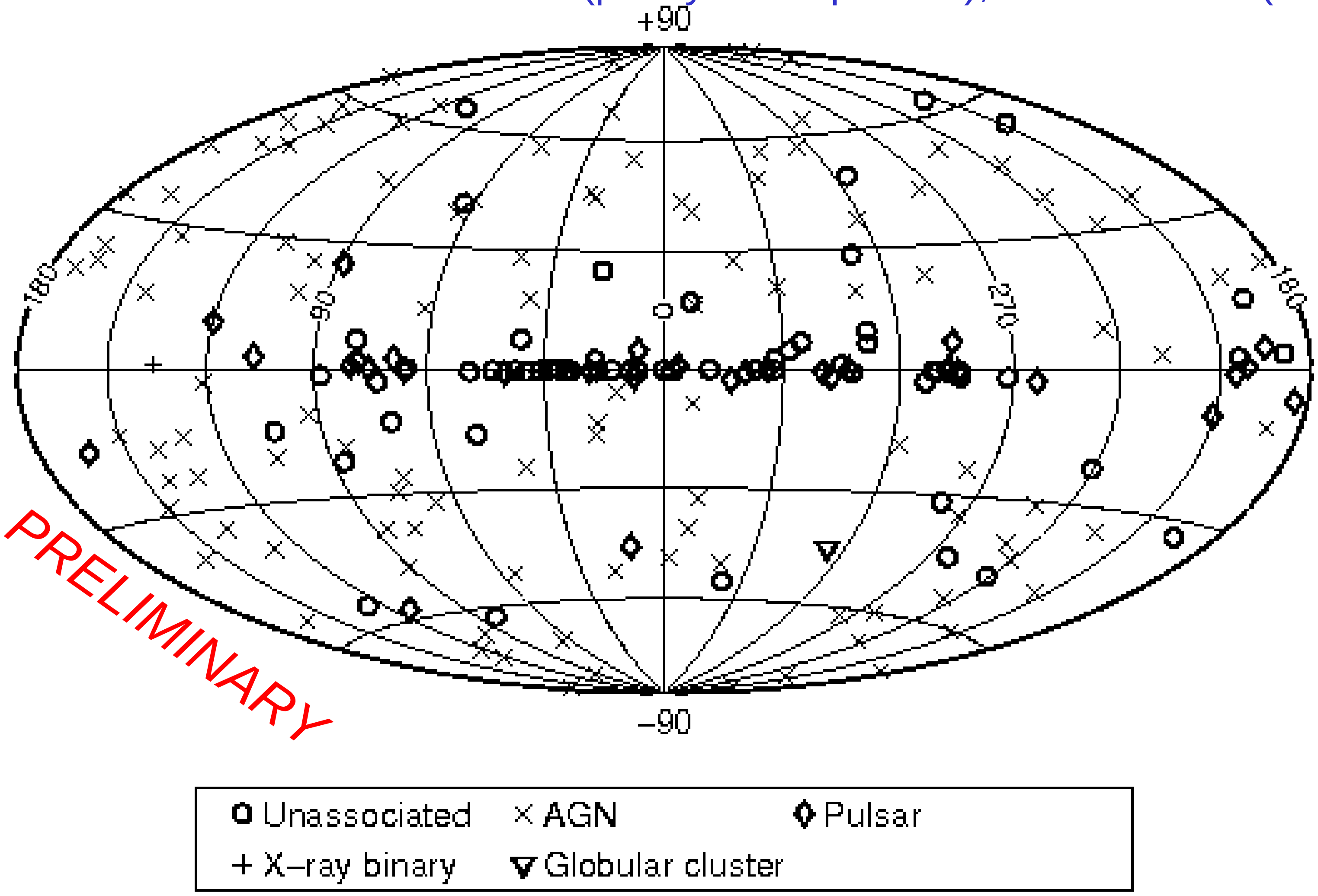
The variable Fermi sky



1-day snapshots, > 100 MeV, viewed from the poles (orthographic proj).
Red is significant.
The Sun is clearly visible moving downwards right of the North pole

Source association

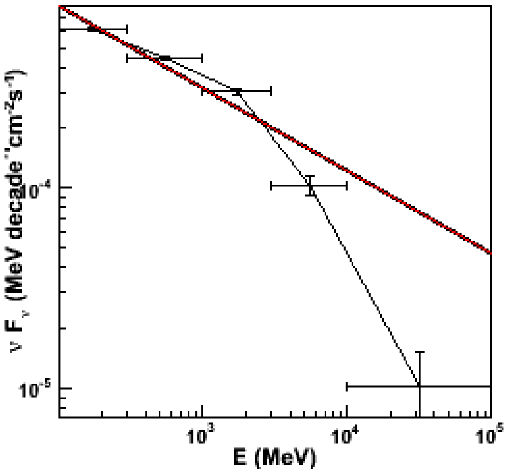
- 2/3 of the sources at |b|>10°, mostly AGN
- Not that many unassociated outside the plane
- Globular cluster 47 Tuc (plenty of ms pulsars), LMC / 30 Dor (diffuse)



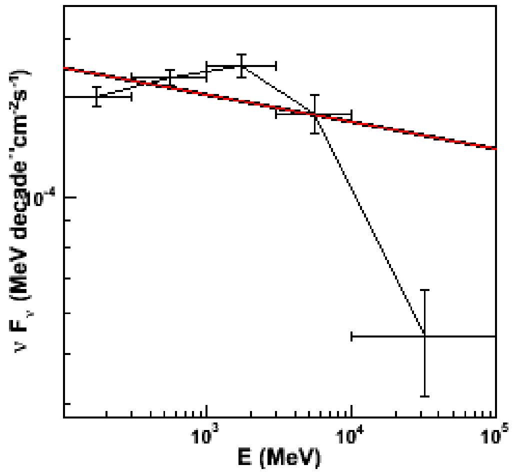
SED at LAT energies

Preliminary

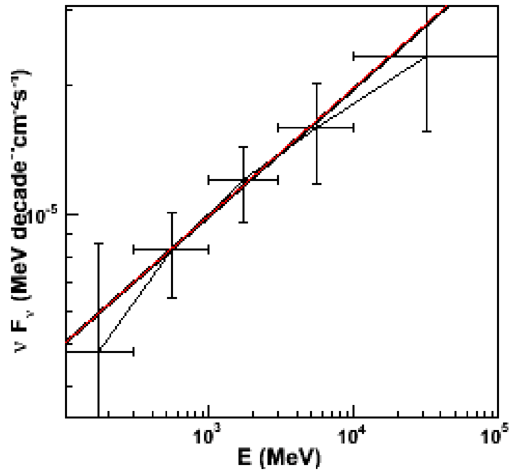
3C454.3 (FSRQ)



AO 0235+165 (Int. BL)



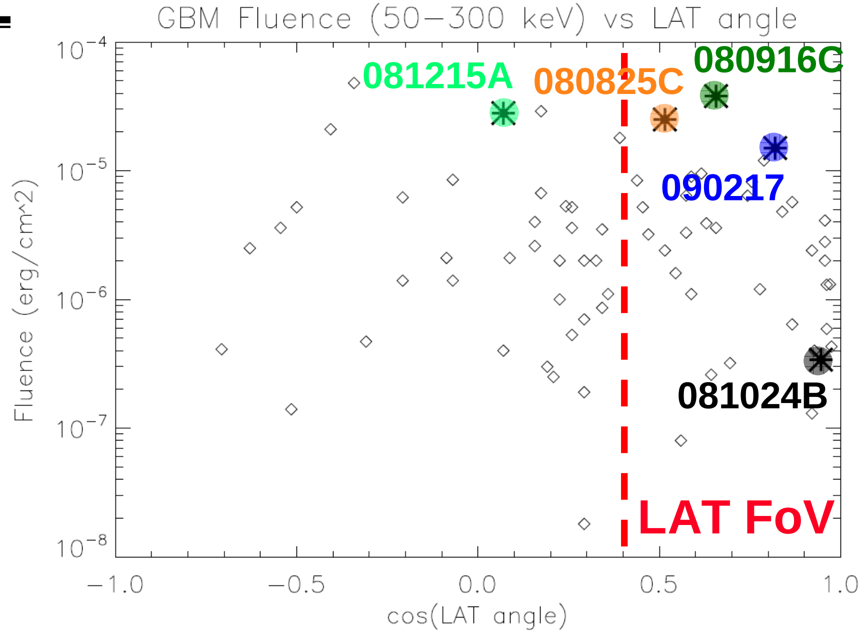
Mkn501 (HBL)

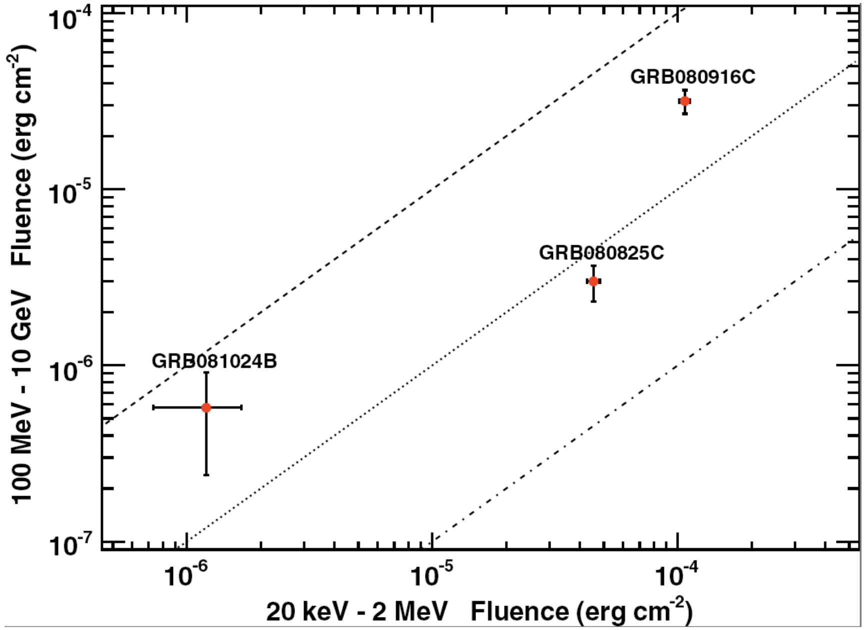


Significant departures from pure power-law distributions for bright blazars
Not always as nicely curved as the models

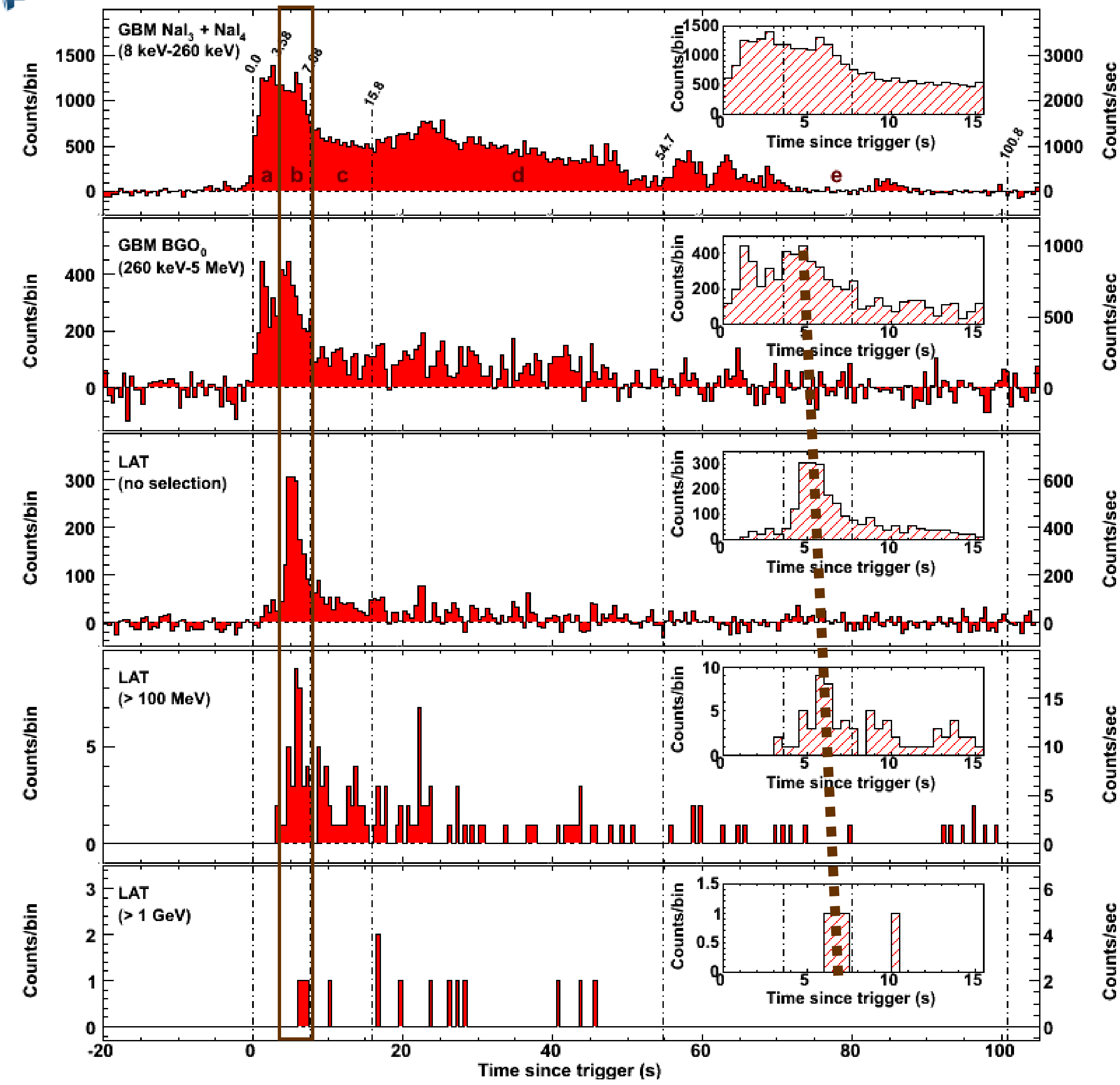
Fermi GRB detections

- **GBM**:
  - 160 GRBs so far (18% are short)
  - Detection rate: ~200-250 GRB/yr
  - A fair fraction are in LAT FoV
  - Automated repoint enabled
- **LAT detections**: (5 in 1st 8 months)
  - GRB080825C:
    >10 events above 100 MeV
  - GRB080916C:
    >10 events above 1 GeV and
    >140 events above 100 MeV
  - GRB081024B: first short GRB with >1 GeV emission
  - 5 + 2 more possible detections





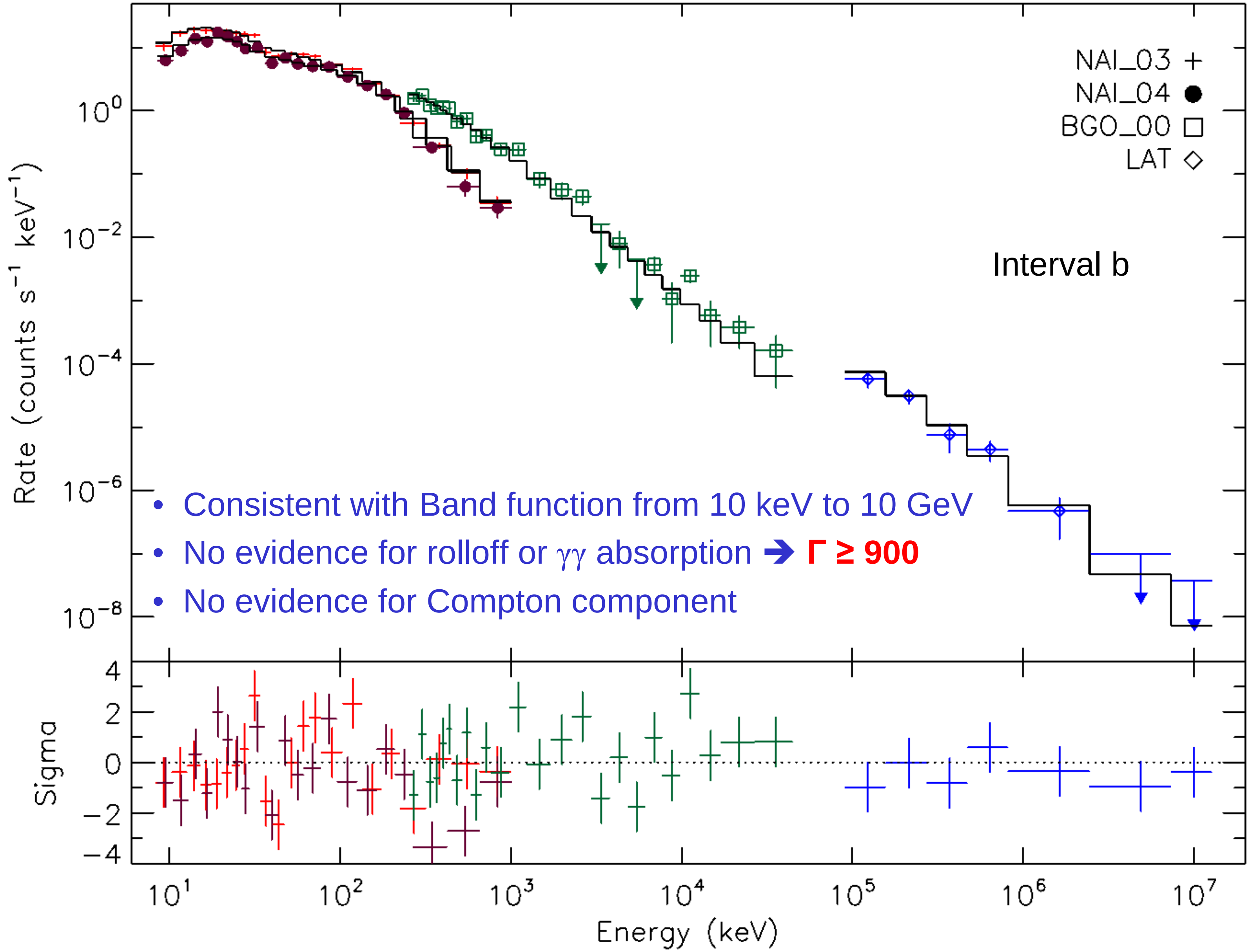
GRB080916C: multi-detector light curve



z = 4.35 (optical)

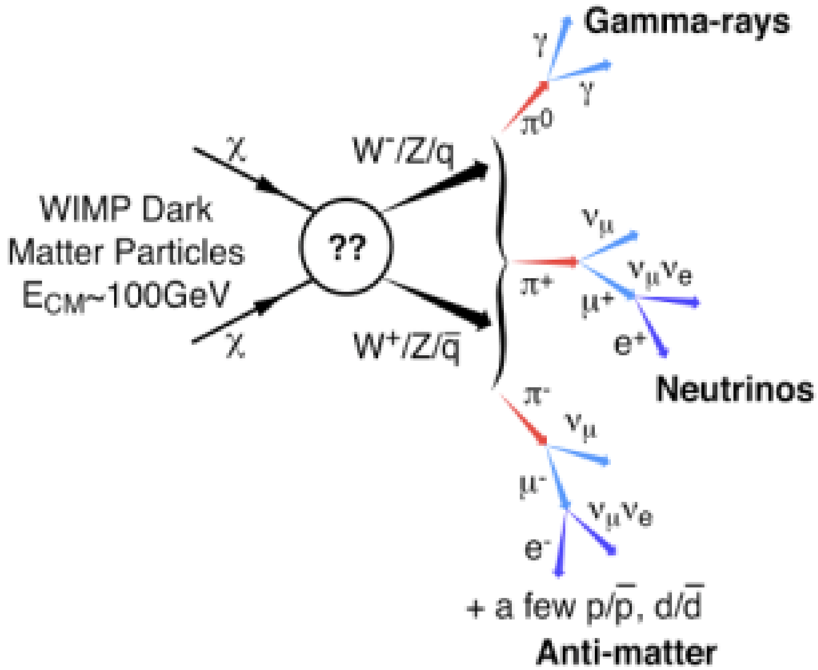
- Most of the emission in the 2nd peak occurs later at higher energies
- This is clear evidence of spectral evolution
- The delay of the HE emission seems to be a common feature of the GRBs observed by the LAT so far
- Highest energy photon (13 GeV) 16.5 s after t_0 Quantum gravity limit **$M_{QG,1} > 1.5\ 10^{18}\ GeV/c^2$**

GRB080916C: spectrum



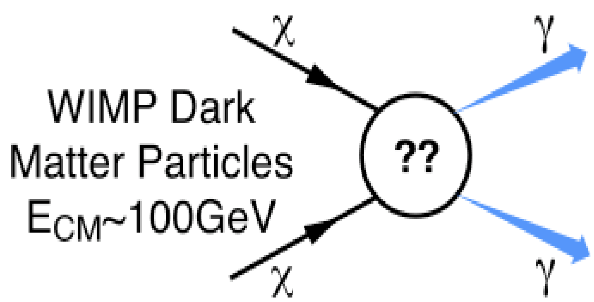
Dark matter: γ from WIMP Annihilation

Continuum spectrum with cutoff at Mχ



Spectral line at Mχ (for γγ)

- ✓ Detection of prompt annihilation into γγ (γZ^0) would provide smoking gun for dark matter annihilation
- ✓ Requires best energy resolution
- ✓ However, annihilation fraction in the range 10^{-3}-10^{-4} (depending on the model)



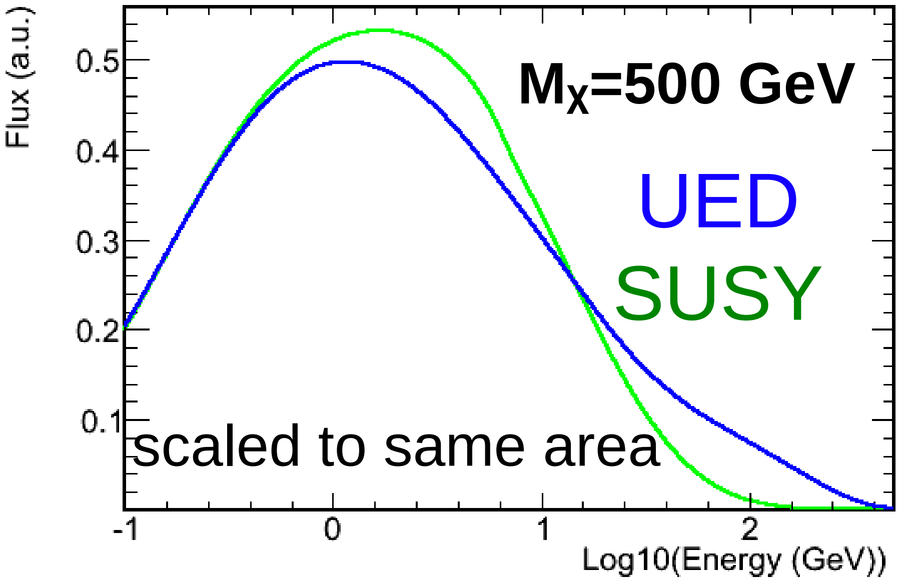
Depends on DM density squared

Two different Scenarios: UED vs SUSY

Consider the photon spectrum from 500 GeV WIMP annihilation in SUSY and in UED:

✓UED: photons mostly from lepton bremsstrahlung

✓SUSY: photons mostly from b quark hadronization and then decay, energy spread through many final states lower photon energy. p-wave dominated cross-section yields lower photon fluxes for equal masses



➡ **Spectra can look very different in these scenarios**

mSUGRA parameters:

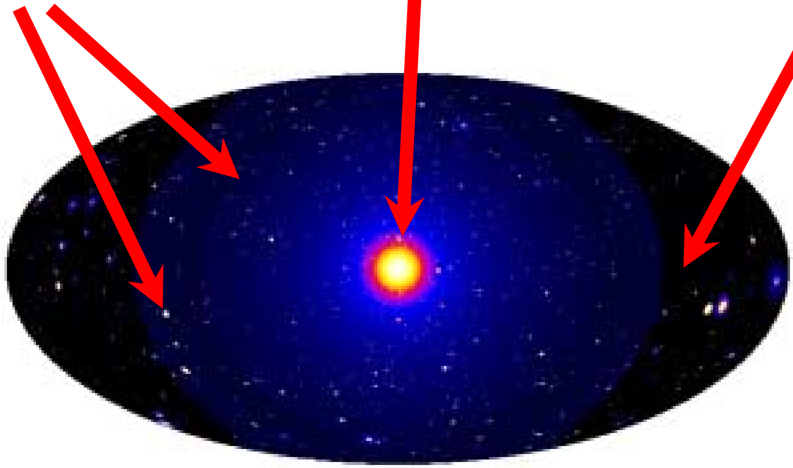
$$m_0 = 500 \text{ GeV}$$
$$m_{1/2} = 1160 \text{ GeV}$$
$$A_0 = 0, \quad \tan\beta = 10$$

Search Strategies

Satellites:
Low background and good source id, but low statistics, astrophysical background

Galactic center:
Good Statistics but source confusion/diffuse background

Milky Way halo:
Large statistics but diffuse background



All-sky map of DM gamma ray emission (Baltz 2006)

Spectral lines:
No astrophysical uncertainties, good source id, but low statistics

Extra-galactic:
Large statistics, but astrophysics, galactic diffuse background

Uncertainties in the underlying particle physics model and DM distribution affect all analyses

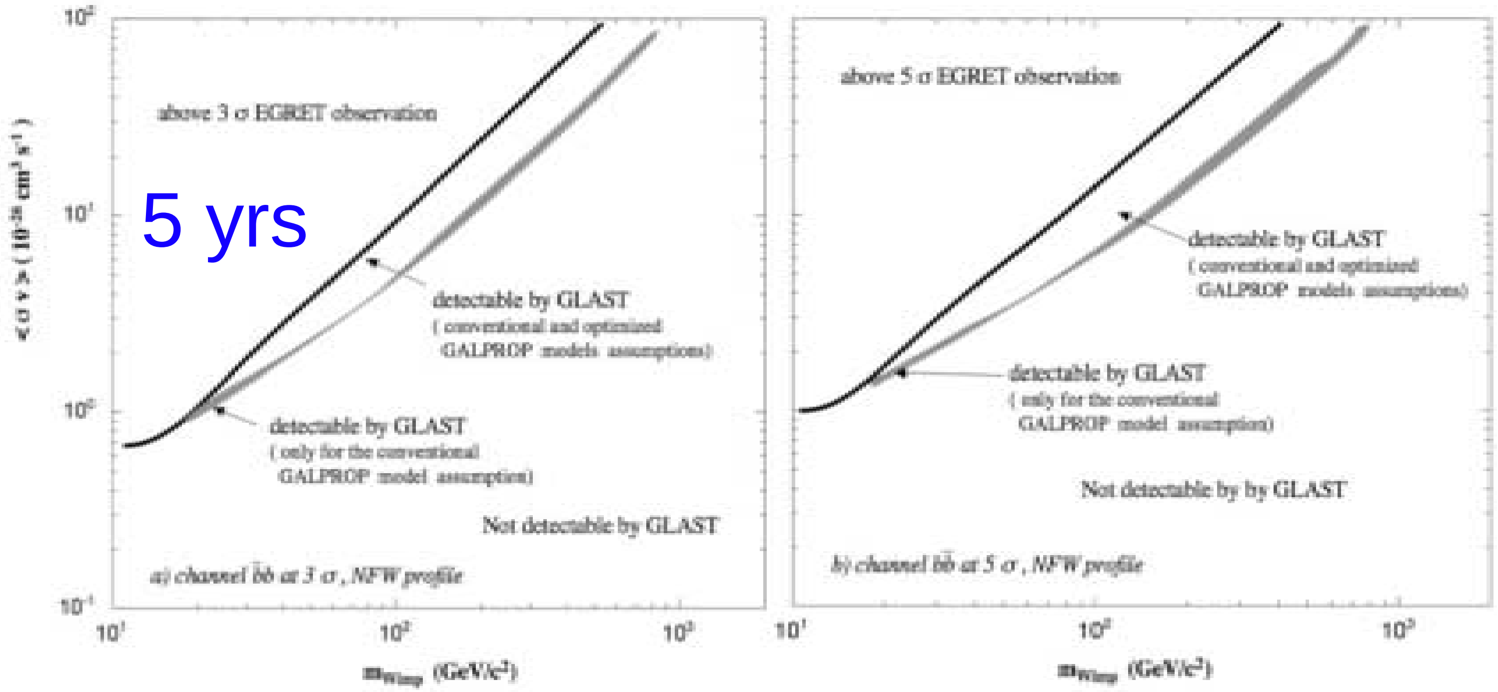
Pre-launch sensitivities published in Baltz et al., 2008, JCAP 0807:013 [astro-ph/0806.2911]

Galactic Center

✓ Select a region of 0.5° around the galactic center, assume NFW profile and consider one WIMP annihilation channel at the time

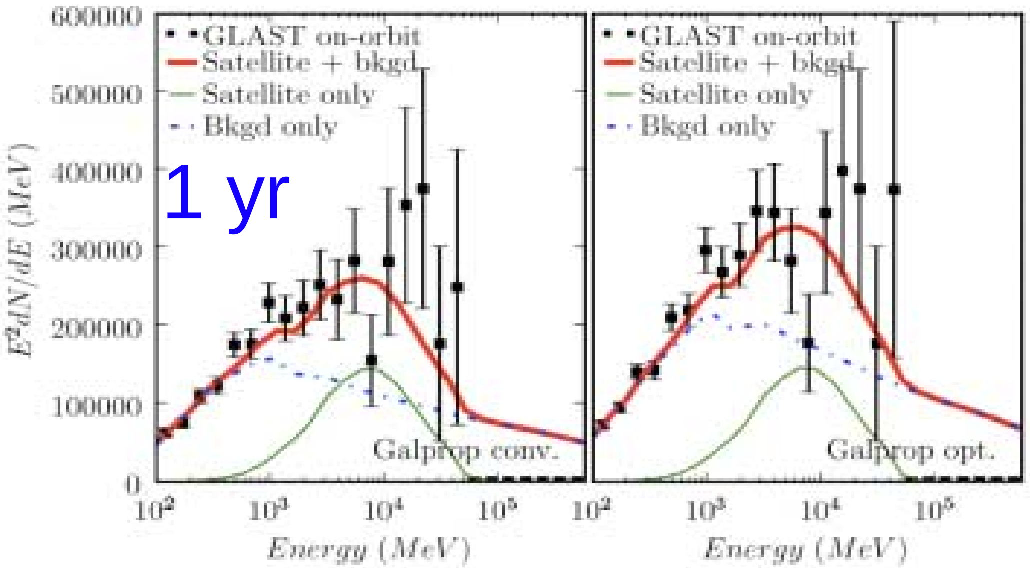
✓ <u>Remove astrophysical sources </u>(based on spectral analysis, multiwavelength observations. Difficult, their behavior at these energies is not known) in the region

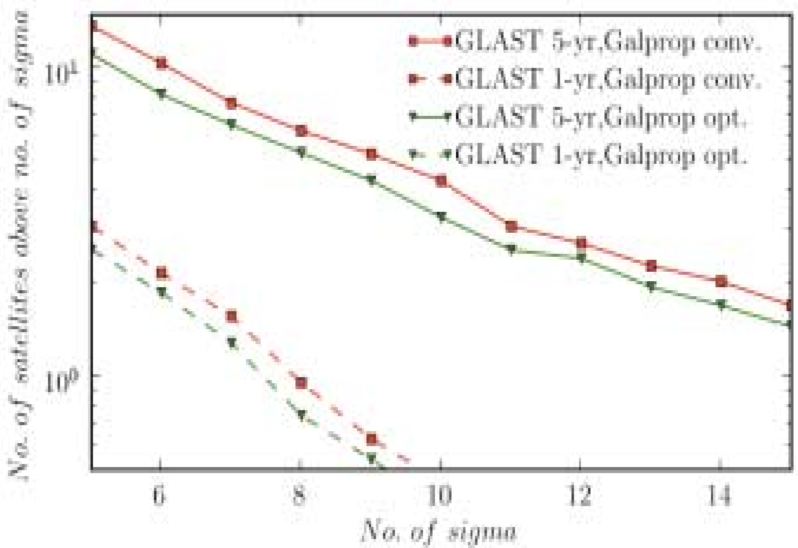
✓ Perform χ^2 test to disentangle dark matter contribution from diffuse background



Dark Matter Satellites

- ✓ Expect isotropic distribution of subhaloes in the galactic halo
- ✓ DM spectrum very different from power law, no appreciable counterpart in radio, optical, X-ray, TeV; emission is expected to be constant in time
- ✓ Assume NFW profile+tidal stripping (satellite distribution by Taylor and Babul, MNRAS 364 (2005) 535-551); 100 GeV WIMP, $<\sigma v> = 2.3 \times 10^{-26}$ cm^3/s annihilating into b-bbar. Background: extra-galactic, galactic emission
- ✓ Generic observable (5 σ, 1 yr) satellite: high galactic latitude, ~ 9 kpc from the Sun, 3×10^7 $M_\odot$, 1° angular size
- ✓ After 4 yrs, EGRET wouldn't have detected any satellites and after 9 yrs, no satellites above 5 σ

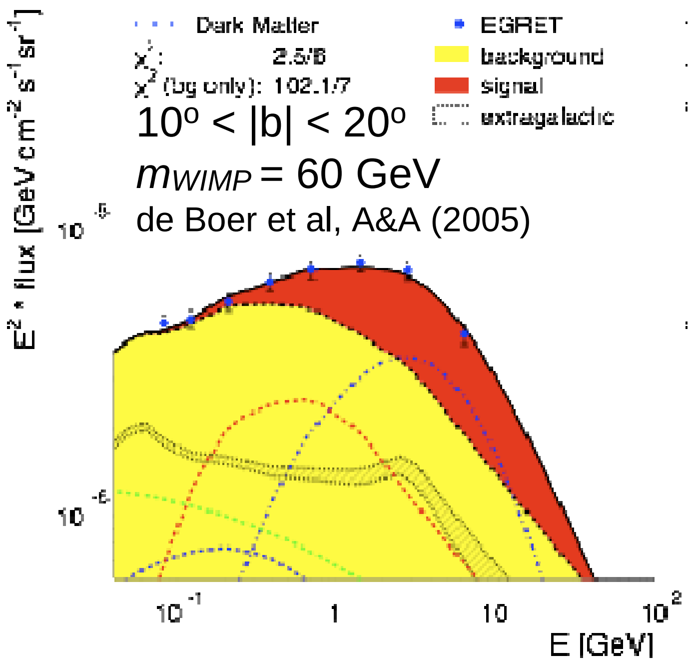


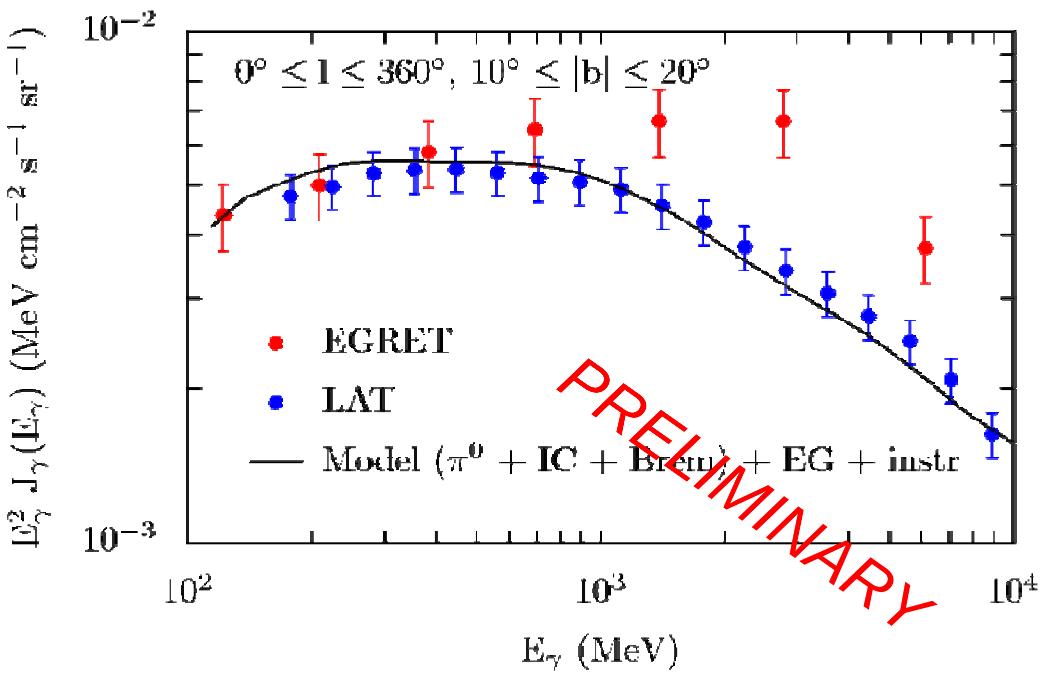


EGRET GeV Excess

EGRET observed an all sky excess in the GeV range compared to predictions from cosmic-ray propagation and γ-ray production models which could be attributed to dark matter annihilation

The data collected by the Fermi LAT during the first 5 months of operation does not confirm the excess at intermediate latitudes and strongly constrains dark matter interpretations



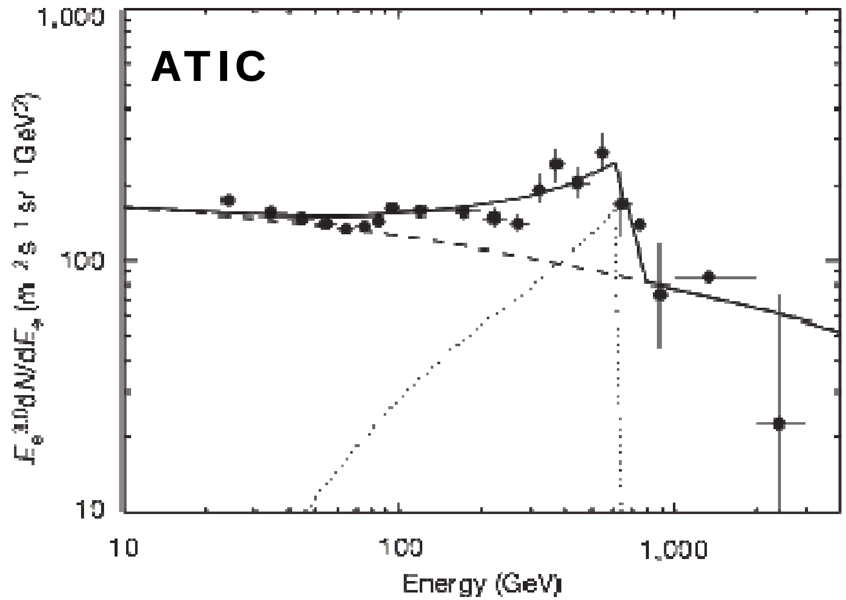


CR e^+e^- Measurements

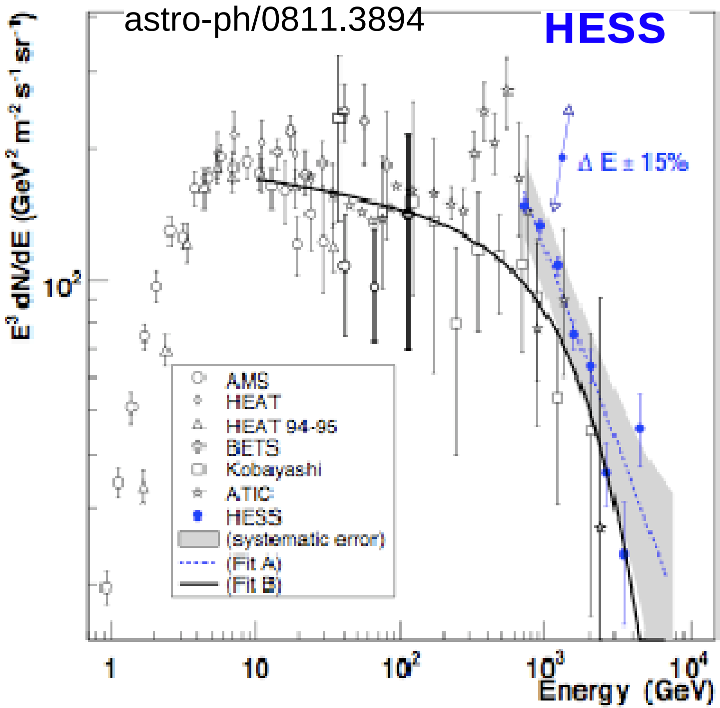
✓ATIC has observed an excess of electrons in the 300-800 GeV range with a steepening at the high energy end also observed by HESS

✓In addition to astrophysical explanations for these measurements (nearby source of high energy electrons), heavy dark matter primarily annihilating into leptons, such as suggested by UED theories, could explain the excess and the high energy downturn

The Fermi LAT is an excellent electron+positron detector (but it can't discriminate charge)
Measures combined CR e+p spectrum (up to energies of ~1 TeV) with very large statistics
Demonstrated background contamination <20% at all energies
Results will be announced early May



Chang et al., Nature **456**, 362-365 (2008)

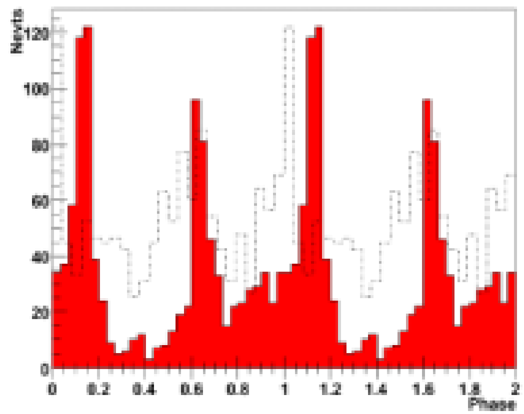


Search for new γ-ray pulsars

6 known γ-ray pulsars from EGRET

One radio quiet (Geminga)

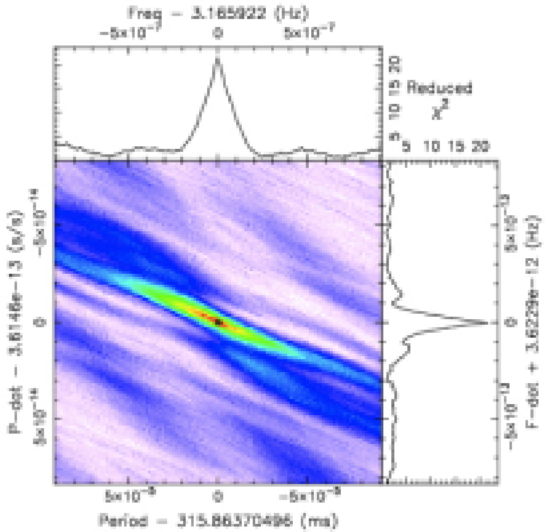
Look for others



1. Radio-quiet gamma-ray sources list generated pre-Launch, with very accurate source locations from other wavelengths.
   a. 3EG J1835+5918 (possibly the "next Geminga")
   b. Compact objects of Pulsar Wind Nebulae (PWNe)
   c. Milagro sources (e.g. MGRO J2019+37)

2. Fermi-LAT sources – a list of gamma-ray sources generated post-Launch with a Fermi localization

The Blind Period Search



The spin parameters (frequency, spin-down) are unknown, so to resolve the phase plot, a search over f, df/dt parameter space has to be implemented to find the timing solution.

Limitations:

1. Gamma-ray photon data is exceptionally sparse (< 0.5 photons/s).
2. Such long datasets make fully coherent methods like FFTs require large numbers of fdot trials to prevent smearing of the signal. This large number of trials would also greatly reduce the significance of the signal.
3. FFTs of this magnitude require large amounts of memory: 1 month @ 64 Hz = 331 million bins = 5.3 GB of memory!
4. If the pulsar were to glitch (suddenly change its frequency), then the signal power would diminish greatly.

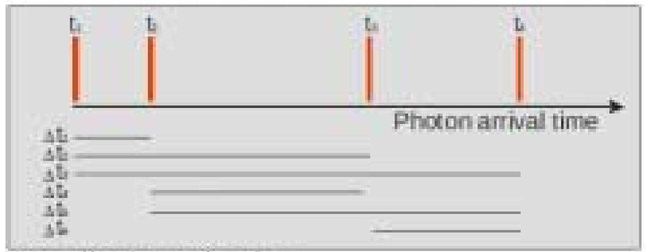
The "Time-Differencing" Technique

Periodicity in photon arrival times will also show up in differences of photon arrival times.

Time differences cancel out long term phase slips and glitches because differencing starts the "clock" over (and over, and over...)

Despite the reduced frequency resolution (and therefore number of bins), the sensitivity is not much reduced because of a compensating reduction in the number of fdot trials

Atwood et. al., **ApJ Lett., 652, 49 (2006)**
Ziegler et. al., **ApJ 680, 620 (2008)**



Credit: M. Ziegler

# of FFT bins = $f * t_{max\_diff} * 2$

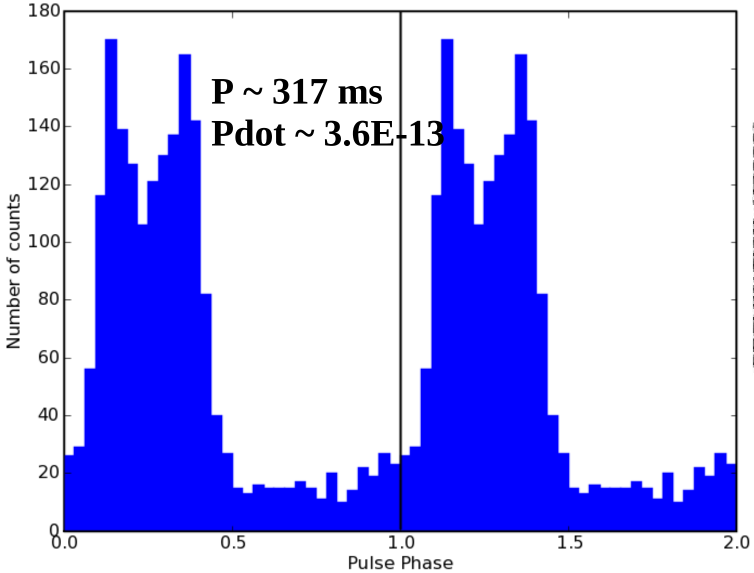
PC with 2GB can handle 33×10^6 bin FFT

Discovery of First Gamma-ray-only Pulsar

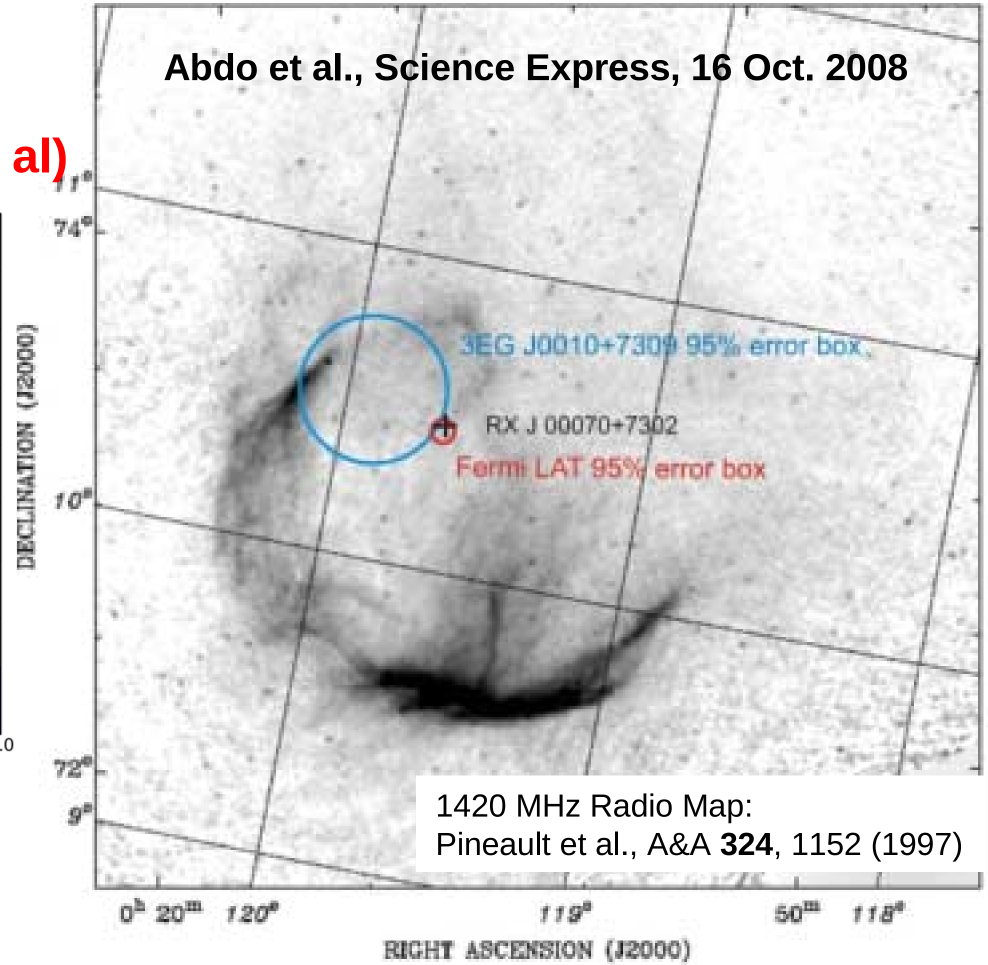
A radio-quiet, gamma-ray only pulsar, in Supernova Remnant CTA1

Quick discovery enabled by

- **large leap in key capabilities**
- **new analysis technique (Atwood et al)**



- Spin-down luminosity ~10^{36} erg s^{-1}, sufficient to supply the PWN with magnetic fields and energetic electrons.
- The γ-ray flux from the CTA 1 pulsar corresponds to about 1-10% of E_{rot} (depending on beam geometry)



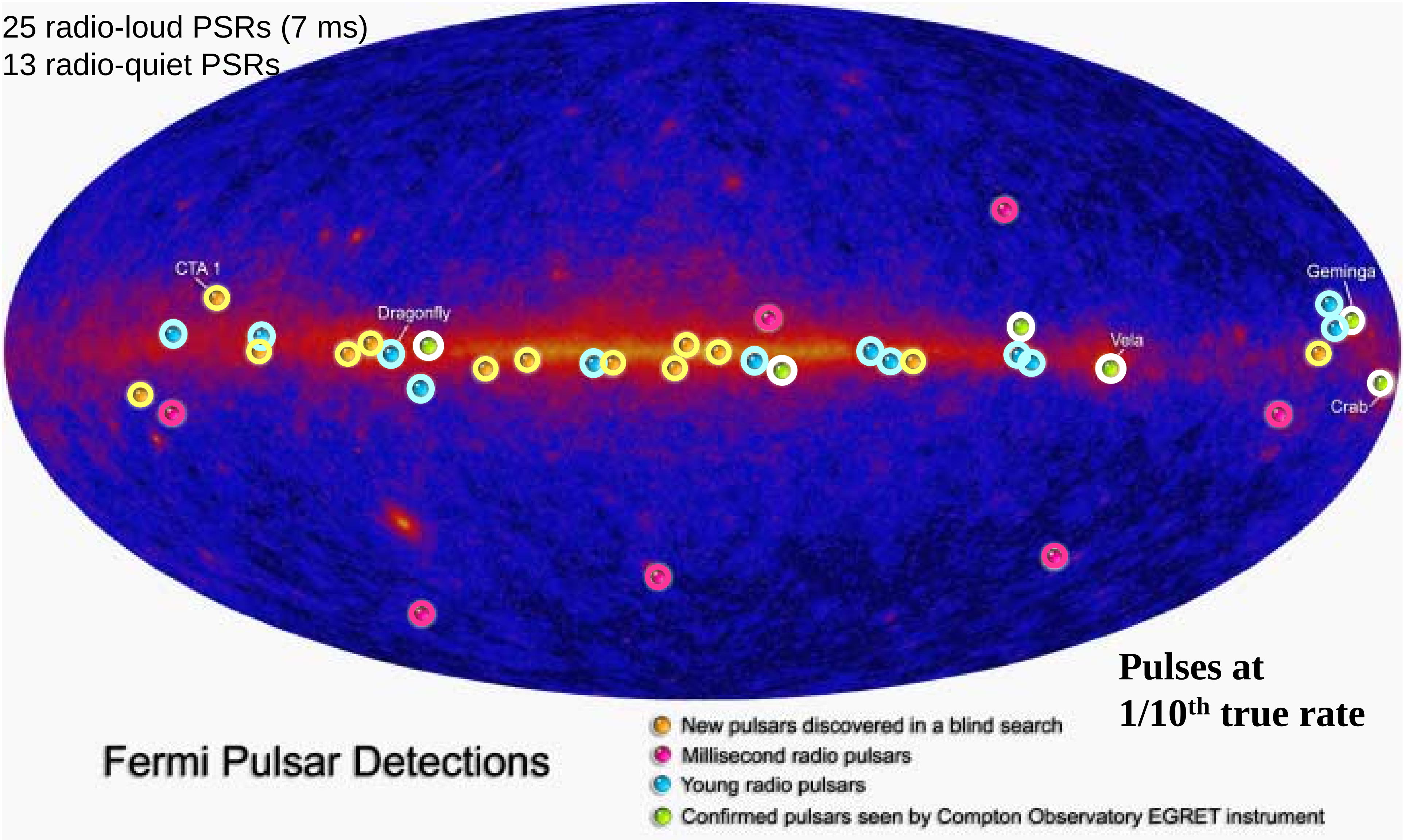
Abdo et al., Science Express, 16 Oct. 2008

1420 MHz Radio Map: Pineault et al., A&A **324**, 1152 (1997)

Age ~(0.5 – 1)x10^4 years
Distance ~ 1.4 kpc
Diameter ~ 1.5°

The Pulsing Sky

25 radio-loud PSRs (7 ms)
13 radio-quiet PSRs



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

Conclusions

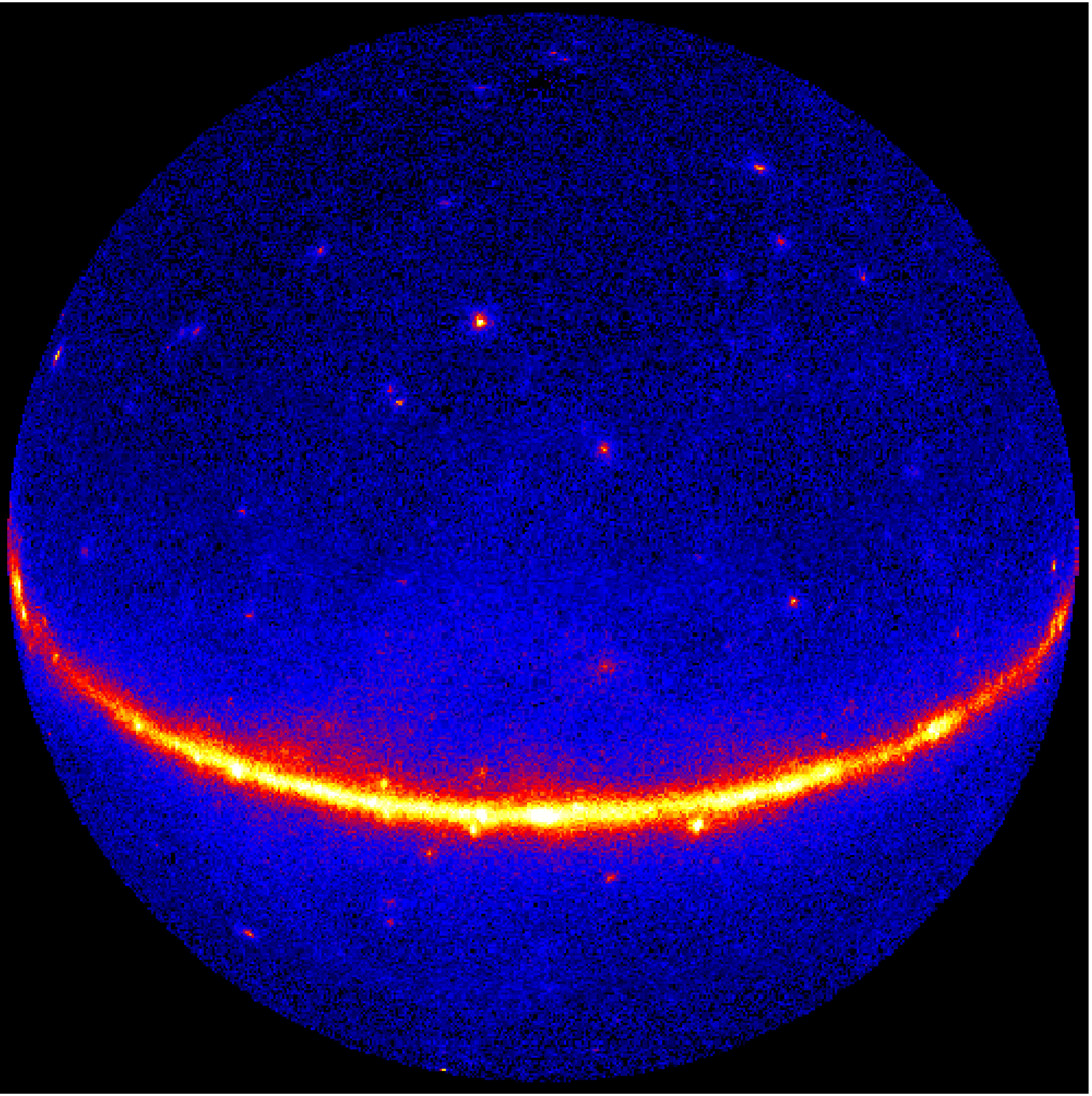
- CGRO/EGRET found only 31 sources above 10 σ in its lifetime, Fermi/LAT found 205 in the first 3 months
- Typical 95% error radius is less than 10 arcmin. For the brightest sources, it is less than 3 arcmin. Improvements are expected.
- About 1/3 of the sources show definite evidence of **variability**.
- 38 **pulsars** are identified by gamma-ray pulsations (up from 6).
- Over half the sources are associated positionally with **blazars** (85% associations outside the plane, up from 60%).
- 37 sources have no obvious associations with known gamma-ray emitting types of astrophysical objects.
- 1 very bright **γ-ray burst**, several fainter ones.
- 2 high-mass **X-ray binaries** (LSI +61 303 and LS 5039)
- Several **TeV sources**, including PWNe and SNR associations (W28, W41, W51, IC443)

Fermi-LAT

3 months

Front > 200 MeV

Back > 400 MeV



Orthographic projection