Early Results

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Kavli Institute for Particle Astrophysics and Cosmology

(on behalf of the LAT Collaboration)

Brookhaven National Laboratory Seminar
February 19, 2008

Outline

- Introduction
- LAT Operations
- Early Science Results
  - First publication
  - Preliminary results
- Summary

Launch
June 11, 2008

Lunch Vehicle
Delta 2920H-10

Launch Site
Kennedy Space Center

Orbit
565 km, circular

Inclination
25.6°

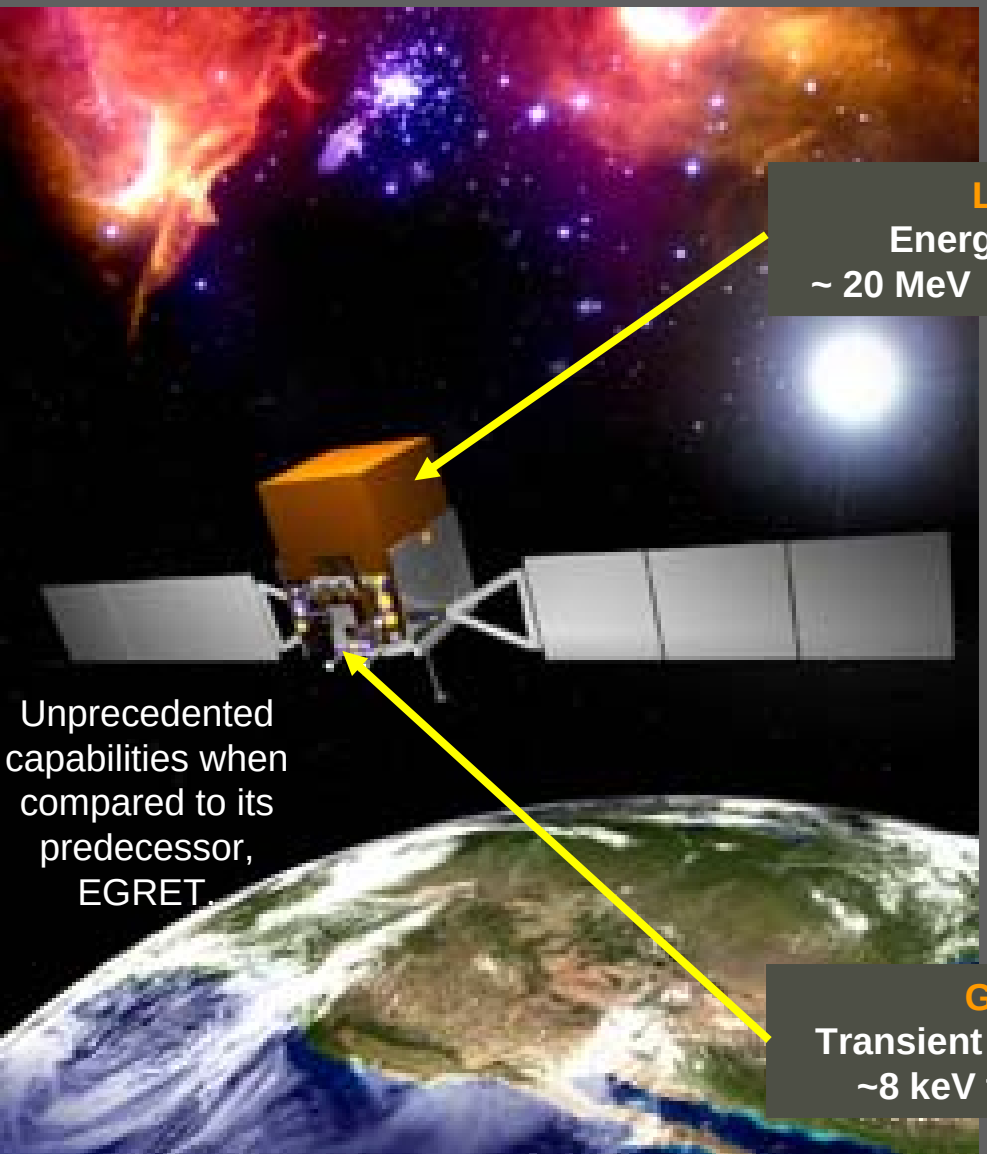
Lifetime
5 years (min)

Fermi Gamma ray Space Telescope

Fermi measures direction, energy, flux and arrival time of γ

GBM Principal Investigator: Charles Meegan

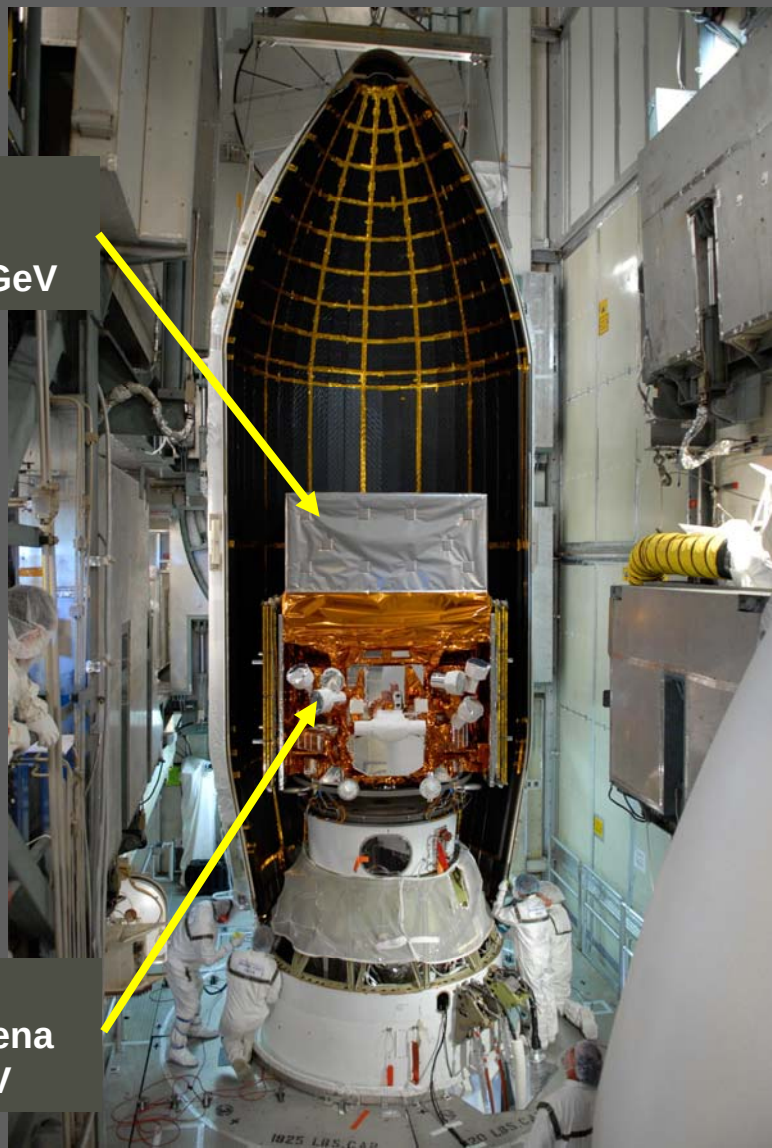
LAT Principal Investigator: Peter Michelson



LAT
Energy range
~ 20 MeV to >300 GeV

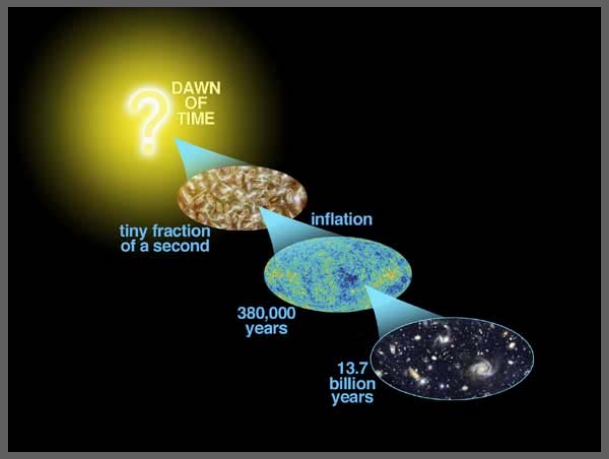
Unprecedented capabilities when compared to its predecessor, EGRET.

GBM
Transient phenomena
~8 keV to 40 MeV



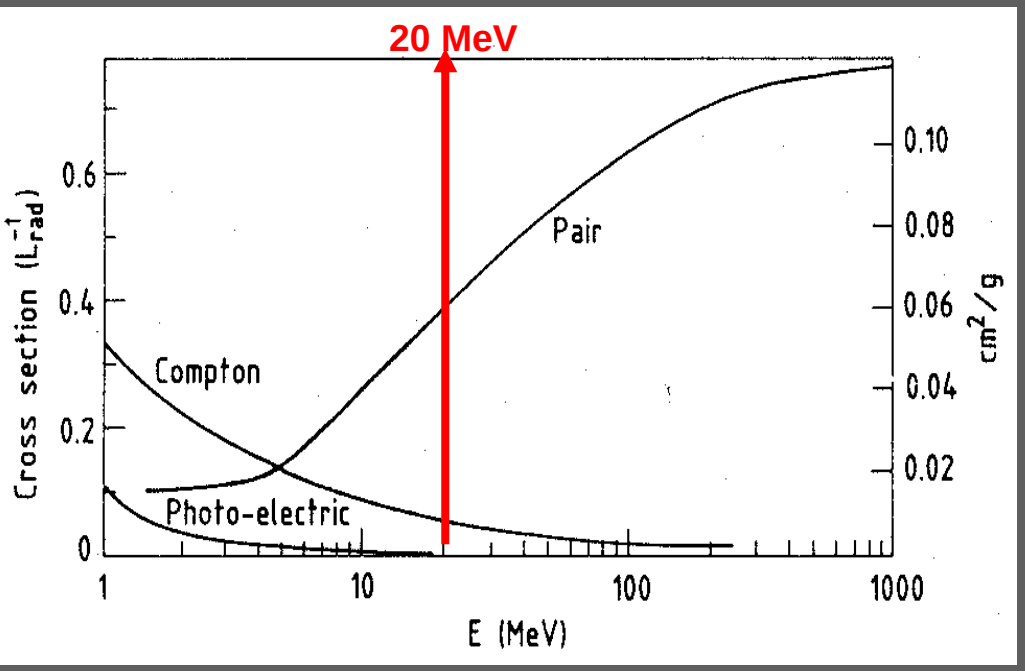
Characteristics of γ rays

- Most violent processes in the Universe
  - Extreme conditions in Nature
- Non thermal emission
  - Acceleration on several distance and time scales
- Direct information from the source
  - Neutral particles
- Universe is transparent to gamma rays
  - Opacity is energy dependent

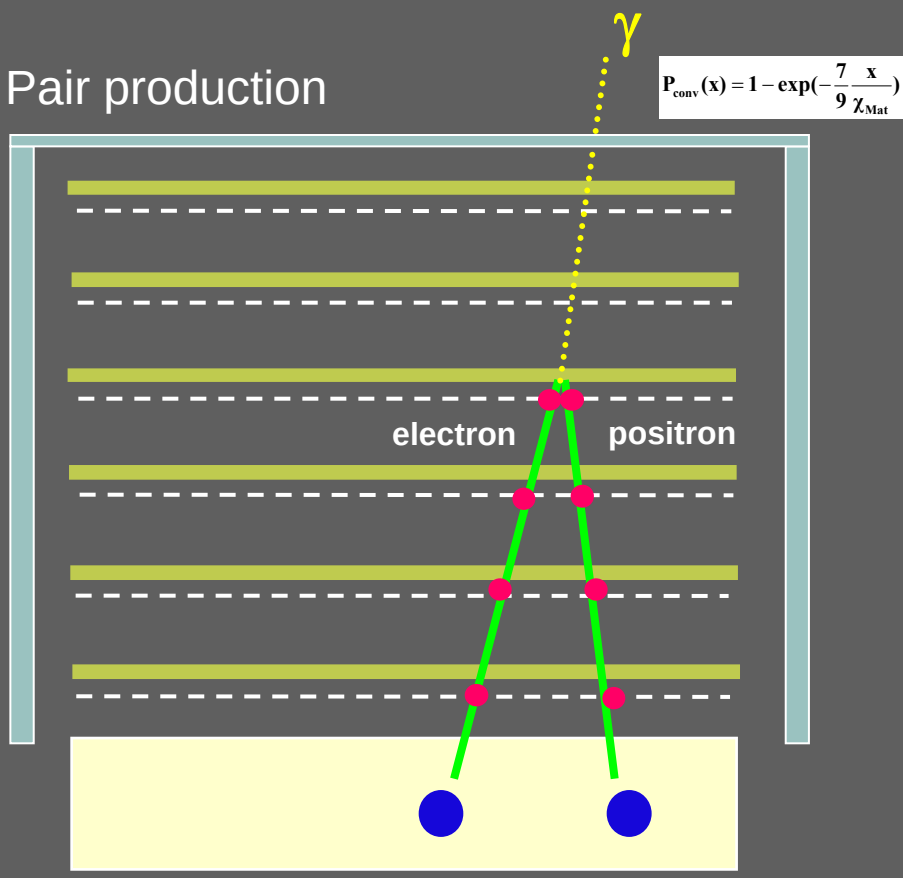


Gamma Ray Space Telescopes

- **Short wavelength**
  - **Radiation cannot be focused**
- **Cross section increases ~ 20 MeV**
  - **Pair production dominates**

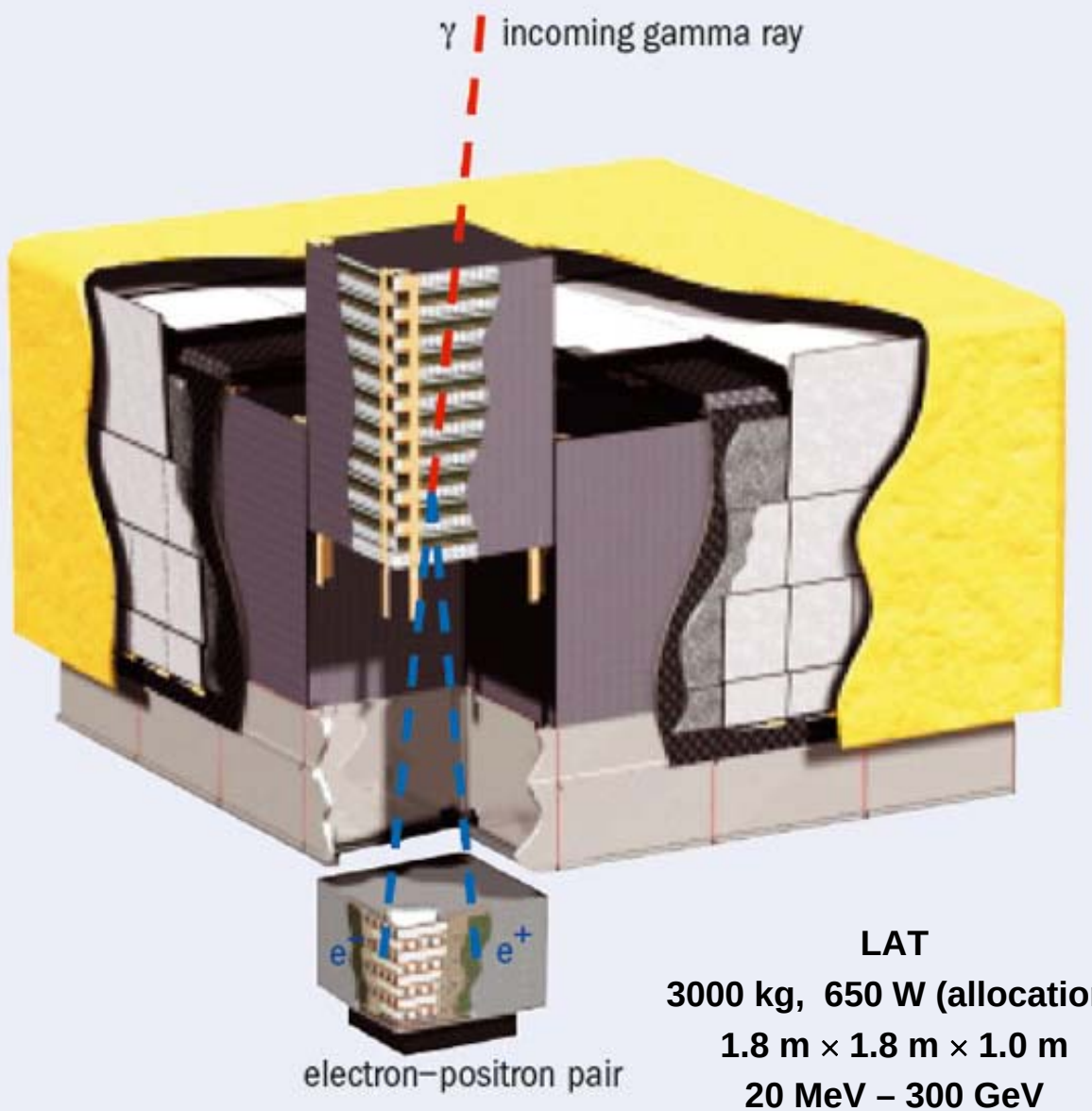


Pair production



$$A_{eff} \cong A_{Geo} \cdot P_{conv} \cdot \varepsilon_{Ana}$$

Large Area Telescope



LAT

3000 kg, 650 W (allocation)

1.8 m × 1.8 m × 1.0 m

20 MeV – 300 GeV

Tracker

γ direction and identification

Calorimeter

γ energy

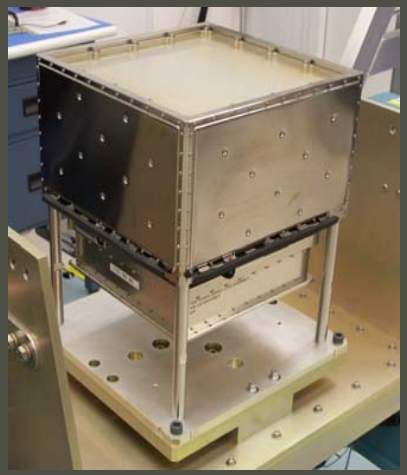
image particle showers

Anti-coincidence detector

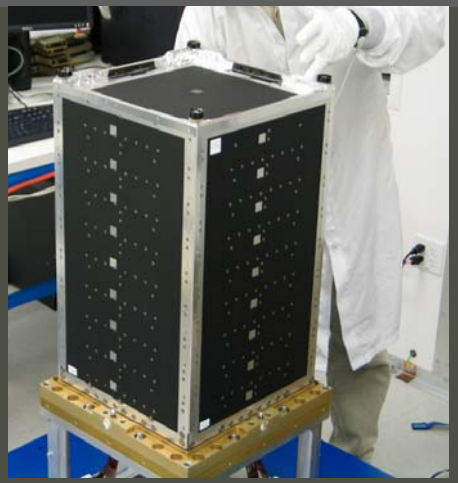
Background rejection

segmentation reduces self-veto at high energies

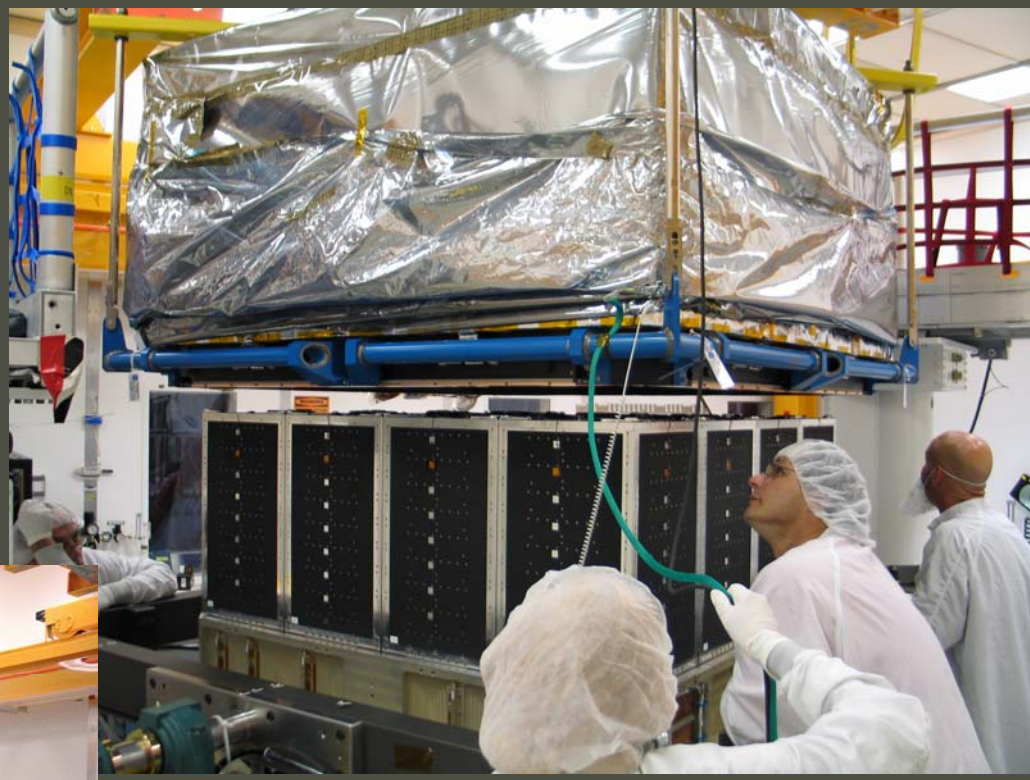
LAT Integration and Tests at SLAC



Calorimeter



Tracker



Integration of anti-coincidence detector with 16 towers

Fermi LAT Collaboration

- **France**
  - IN2P3, CEA/Saclay
- **Italy**
  - INFN, ASI, INAF
- **Japan**
  - Hiroshima University
  - ISAS/JAXA
  - RIKEN
  - Tokyo Institute of Technology
- **United States**
  - Stanford University (SLAC, KIPAC and HEPL)
  - Goddard Space Flight Center – Laboratory for High Energy Astrophysics
  - Naval Research Laboratory
  - Ohio State University
  - Sonoma State University
  - University of California at Santa Cruz - Santa Cruz Institute for Particle Physics
  - University of Washington
- **Sweden**
  - Royal Institute of Technology (KTH)
  - Stockholm University

Principal Investigator:
Peter Michelson (Stanford & SLAC)

~270 Members
(includes ~90 Affiliated Scientists, 37 Postdocs, and 48 Graduate Students)

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

LAT Instrument construction managed at SLAC National Accelerator Laboratory

LAT Instrument Science Operations Center

- LAT Operations
  - Mission Planning
  - Flight Software
  - Science Data Processing
  - Science Data Monitoring
- Analysis products to end users
  - Export final products to Fermi Science Support Center at GFSC
- Automated analyses with rapid turn-around
  - Flaring sources
  - Refinement of and blind search for Gamma-ray bursts
  - Light curves for pre-selected list of sources
    - Some are already released to the general public!

About 6h-8h after we have taken the data in space the end users have the final analysis products on their laptops!

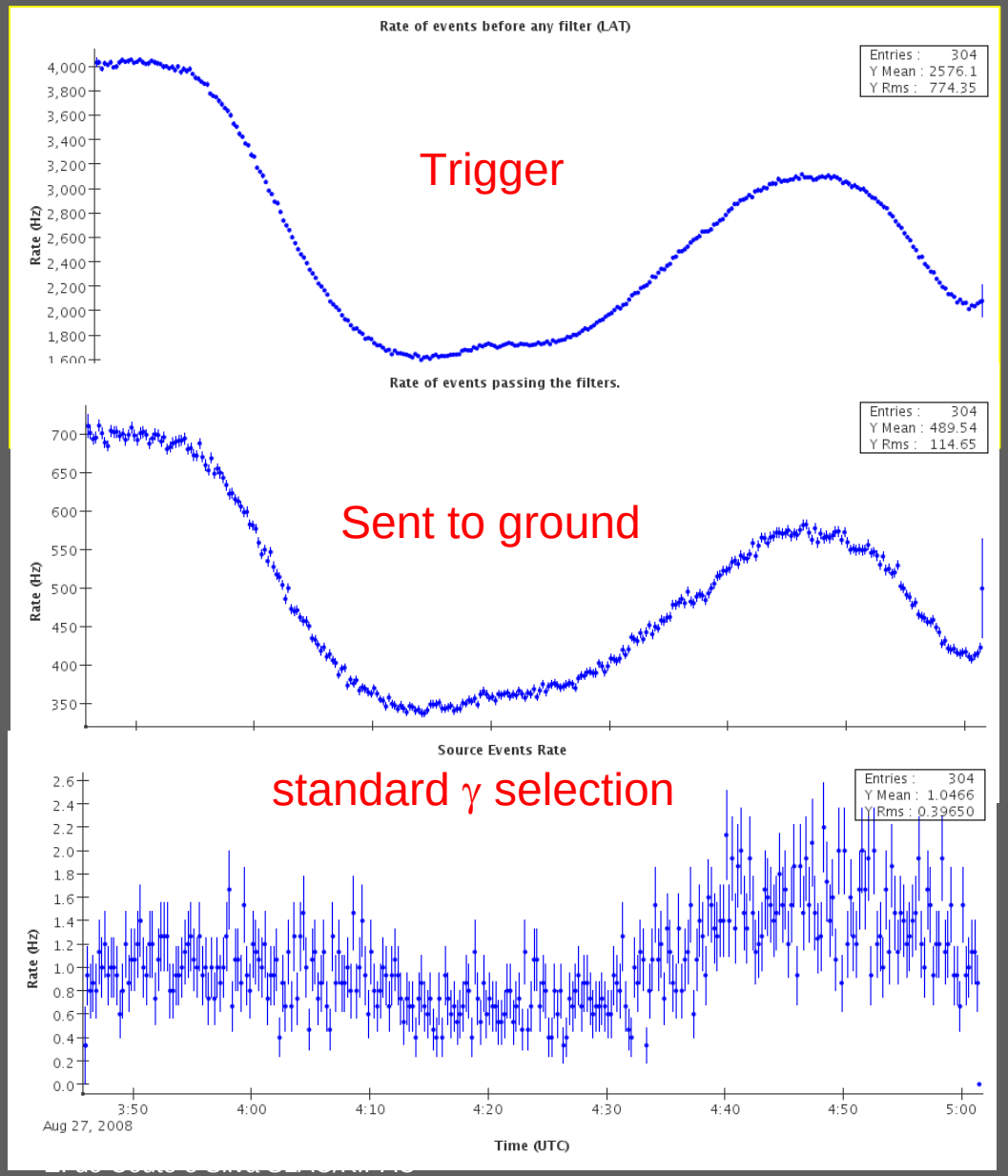
On-orbit Detector Performance

- **Fermi turned on very smoothly**
  - **Reached nominal configurations quickly**
  - **No major problem was identified**
- **Conservative thresholds were barely used**
  - **Backgrounds matched expectations**
- **Stable post launch calibrations**
  - **Minor changes with respect to pre-launch**
- **Optimized time for science observations**
  - **SAA boundary update**
  - **2.5 h of engineering runs every 3 months**

It was not only luck…

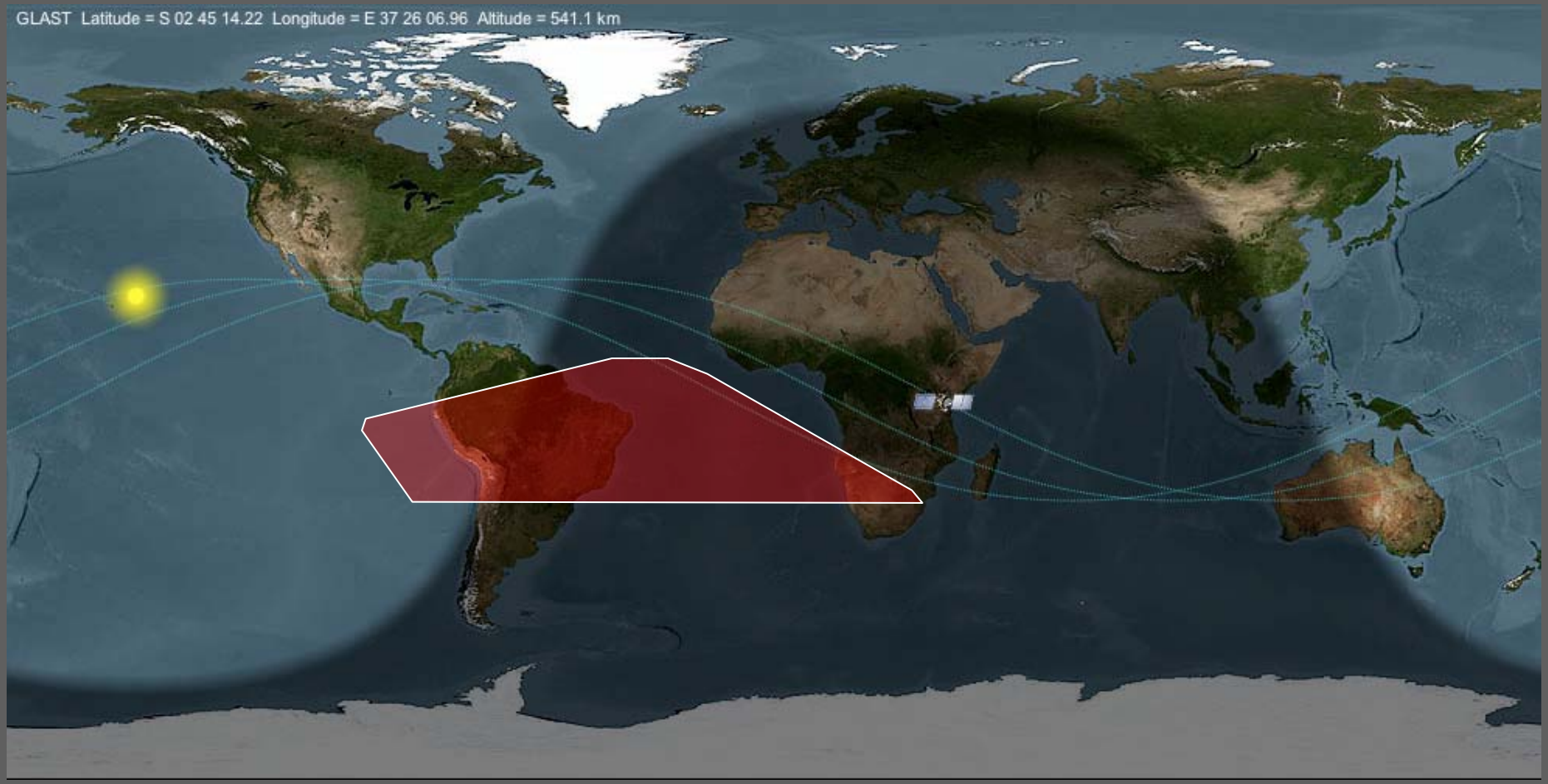
Robust HEP detector
Comprehensive NASA testing
(including additional tests self-imposed by the Fermi-LAT collaboration)

Rates during science operations



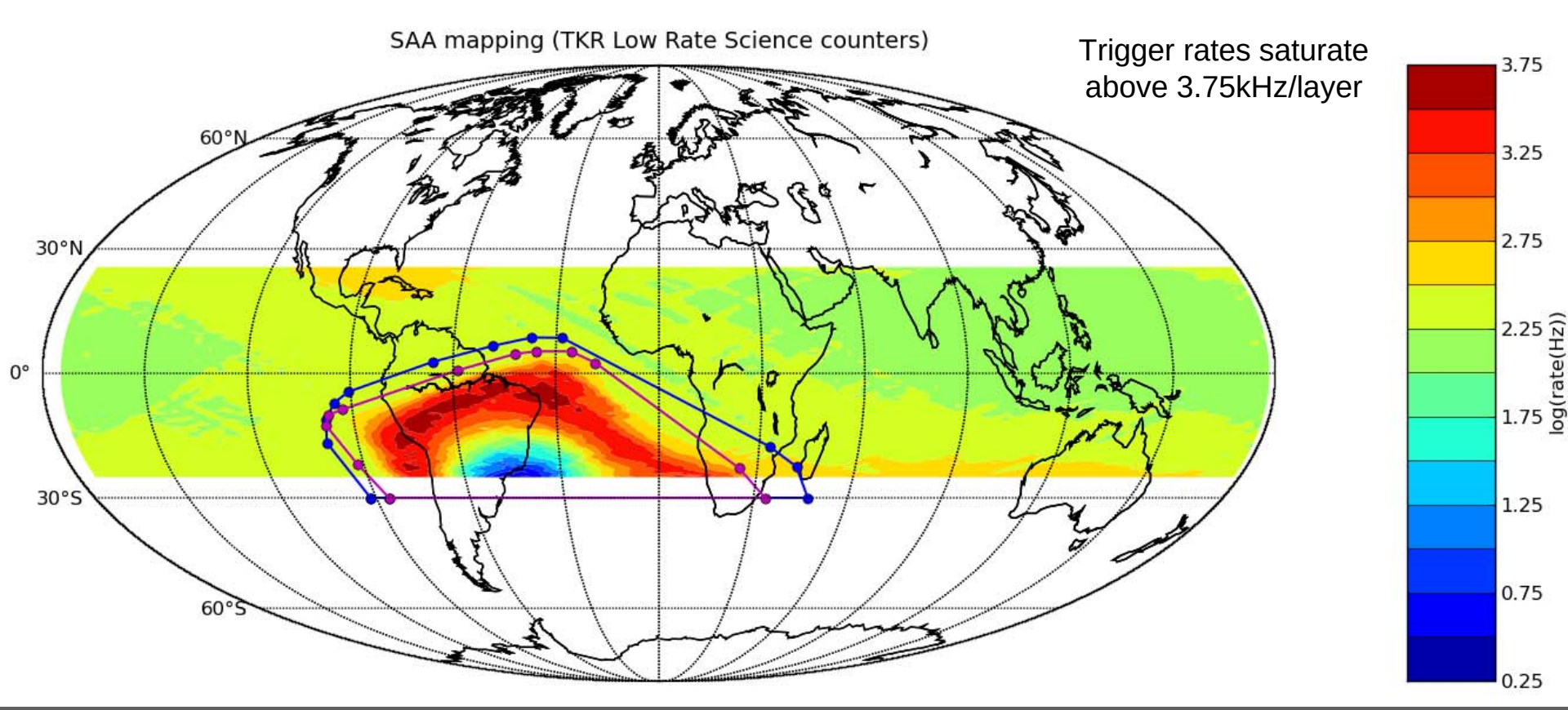
- **Average input rate**
  - **~ 2500 Hz**
- **Donwlink rate (sent to ground)**
  - **~ 450 Hz**
- **γ rates (after event selection)**
  - **~ 2 Hz**
- **Large fraction of events sent to ground consists of background**
  - **Ground processing reduces background by factor 100**

South Atlantic Anomaly (SAA)



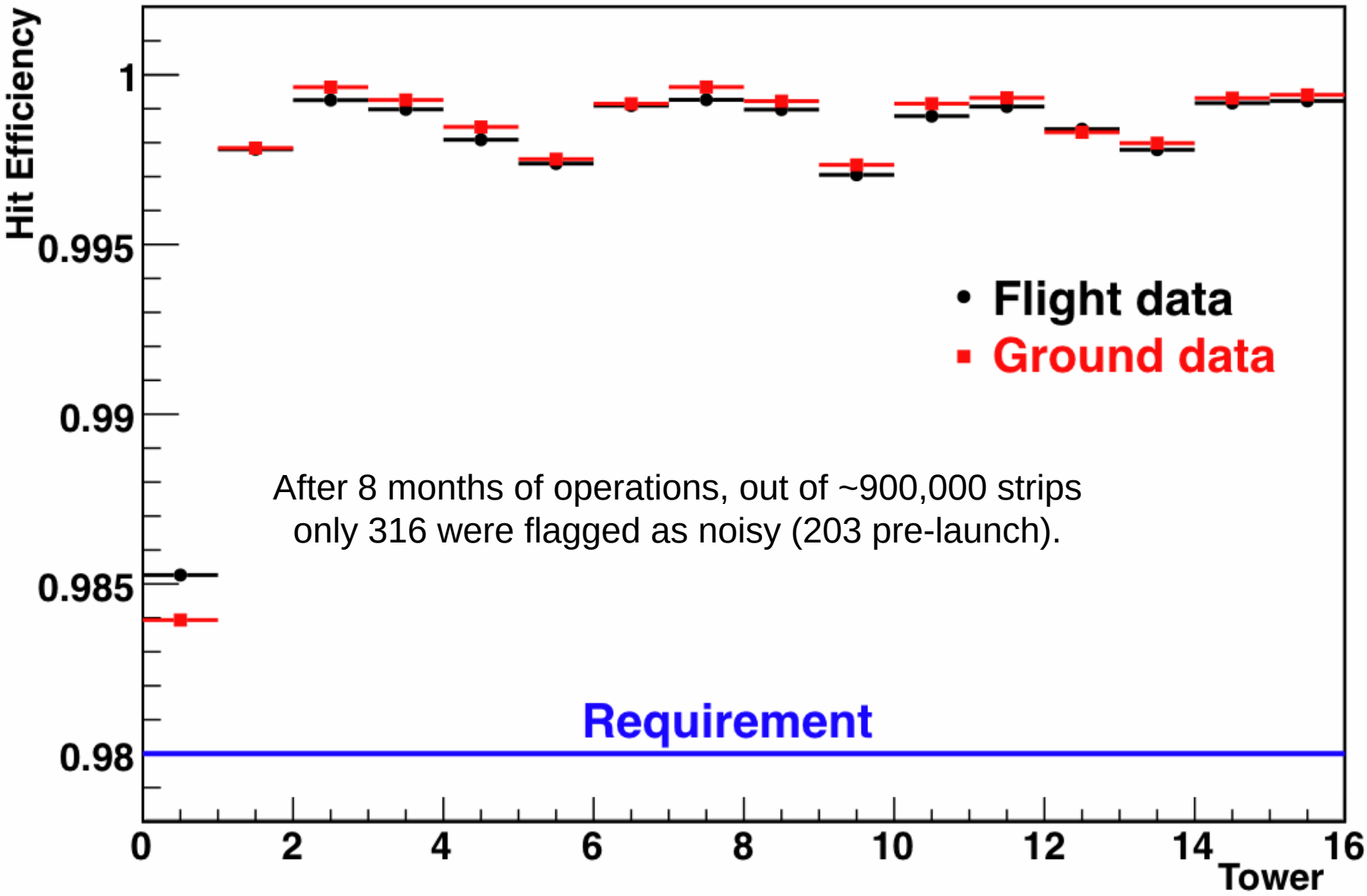
The SAA is a region with large particle background (mostly low energy protons). Science data are not collected during SAA passages

Update of SAA polygon



- **The LAT was turned on with a conservative definition of the SAA boundary**
  - **During commissioning we reduced time lost in SAA from 17% to 13%**

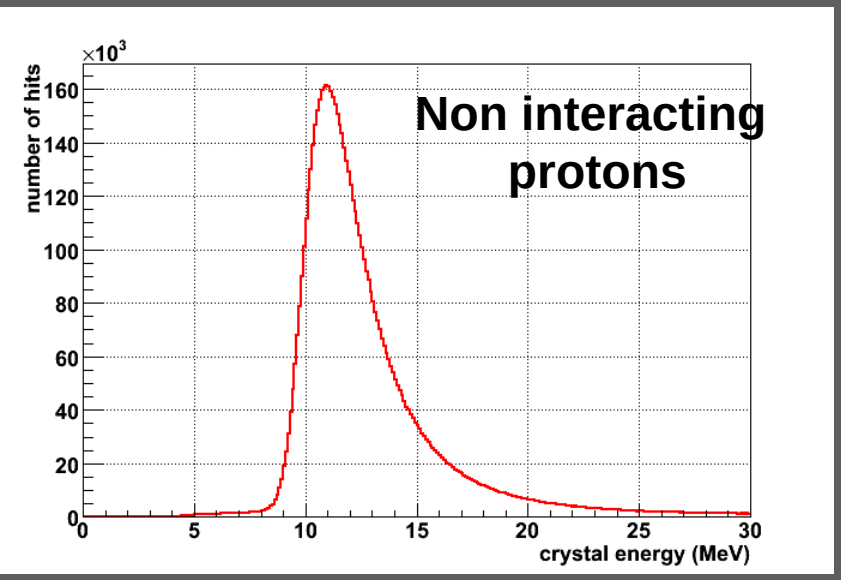
Hit Efficiency in the Tracker

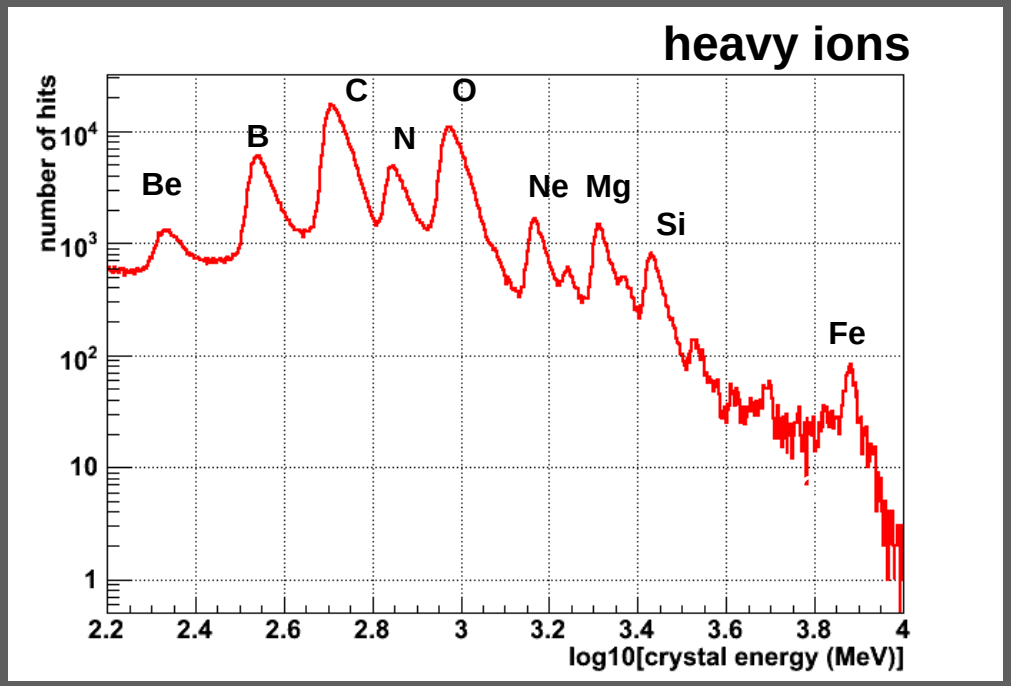


After 8 months of operations, out of ~900,000 strips only 316 were flagged as noisy (203 pre-launch).

Heavy ions used to calibrated the calorimeter

~100 h of data

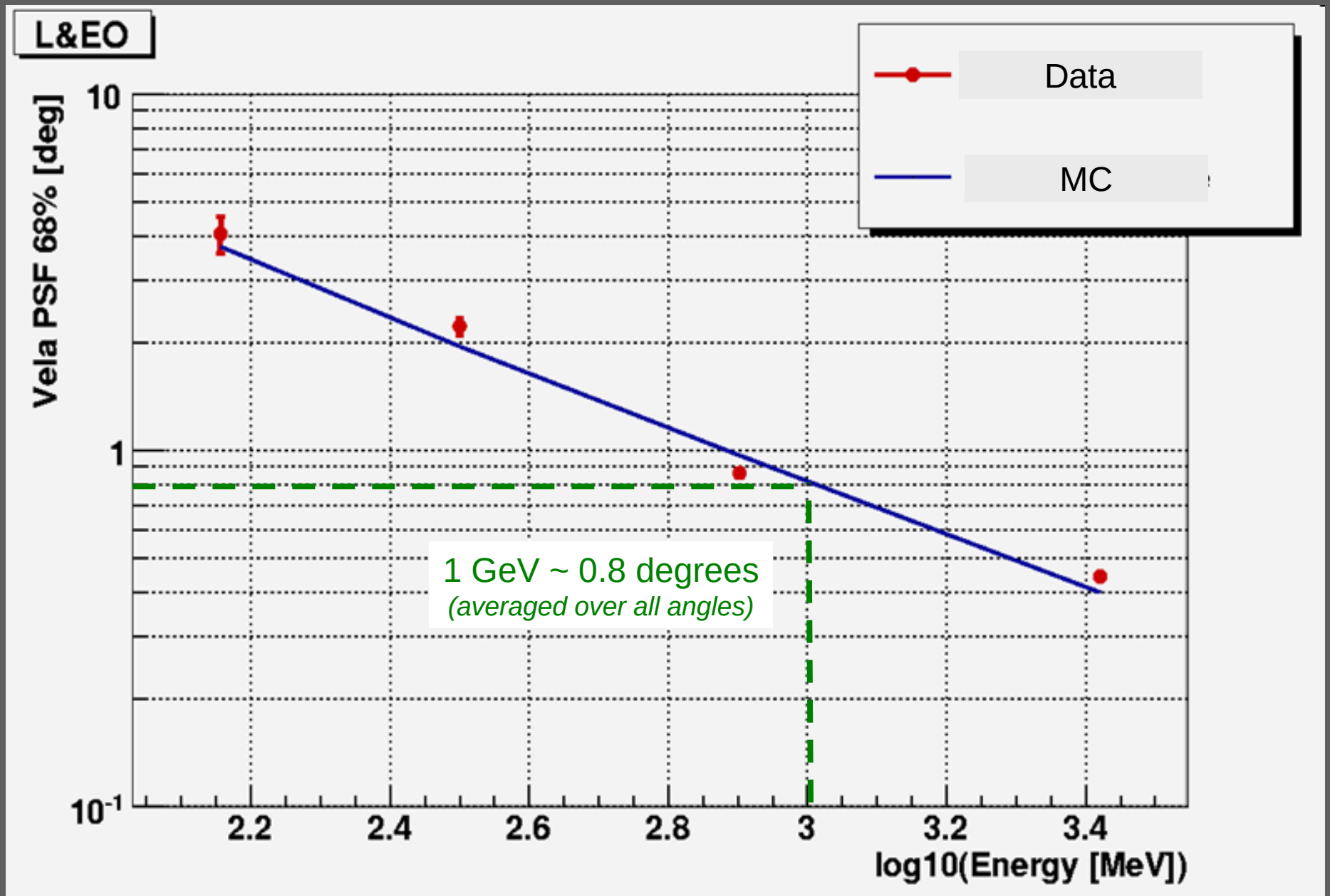




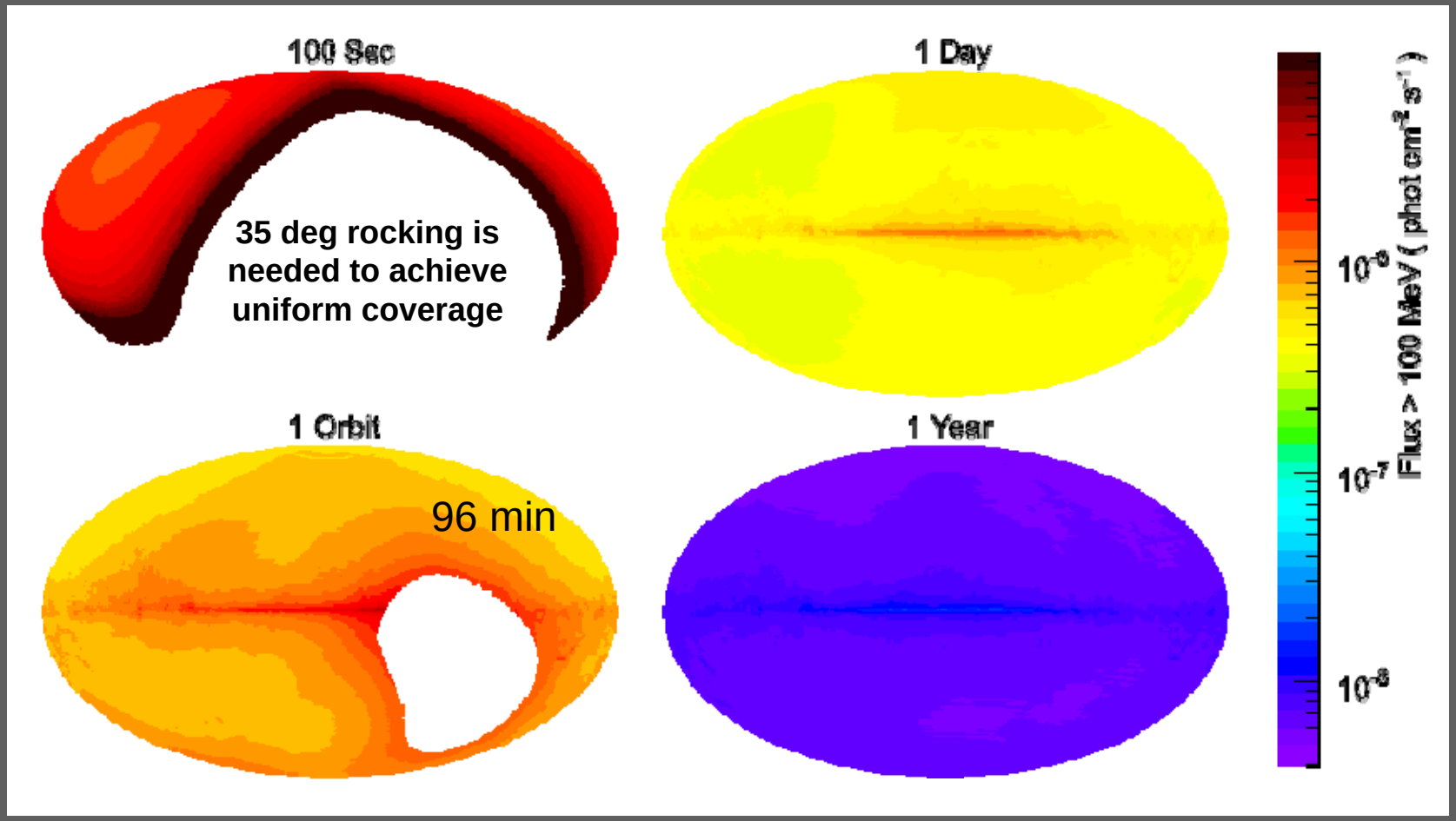
Heavy ions are used to calibrate the high energy scales

Peak positions were stable within 1% (since launch)

Point Spread Function – Vela Pulsar



Expected LAT Sensitivity



Huge field of view

Observes 20% of the sky at any instant (sky survey)

exposes all parts of sky for ~30 minutes every 3 hours.

Science with Fermi

- **Cosmic Ray Acceleration**
  - Gamma ray Emission from hadronic interactions
  - Shock physics
- **Dark Matter, New Physics and Early Universe**
  - Extragalactic Background Light and galaxy formation
  - Searches for Dark Matter and Extra Dimensions
  - Tests of Lorentz Invariance
- **Relativistic Outflows**
  - Physics of jets and Particle Acceleration
  - Radiation Processes
  - High energy behaviour of transients
- **High Energy Sky Survey**
  - Unidentified EGRET sources and GLAST Source Catalog
  - Population Studies
  - Diffuse Gamma ray emission
  - New classes of Astrophysical Objects

LAT strengths:

All-sky monitoring

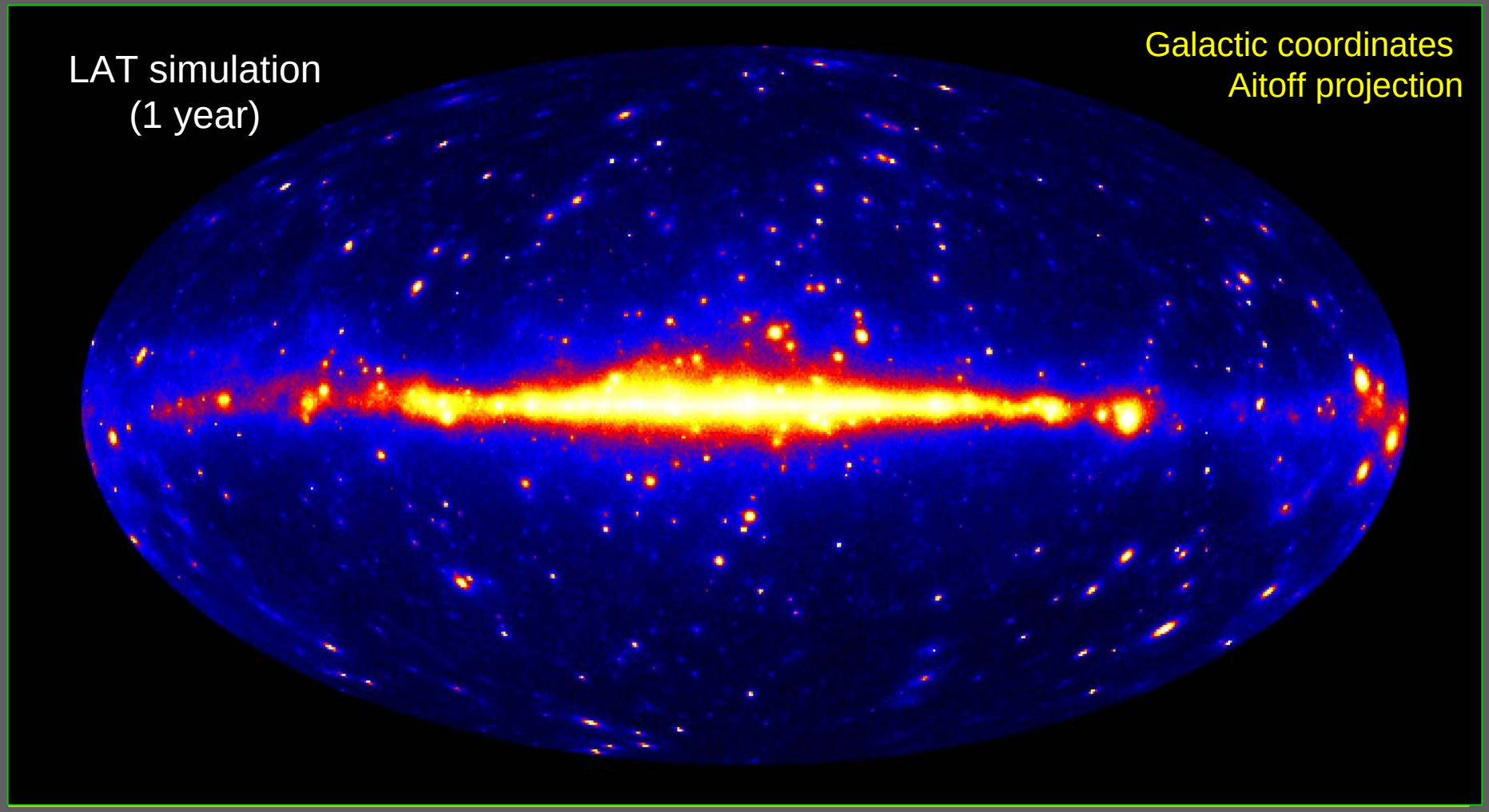
Broad range of time scales

Several decades in energy

Discovery Window E>10 GeV

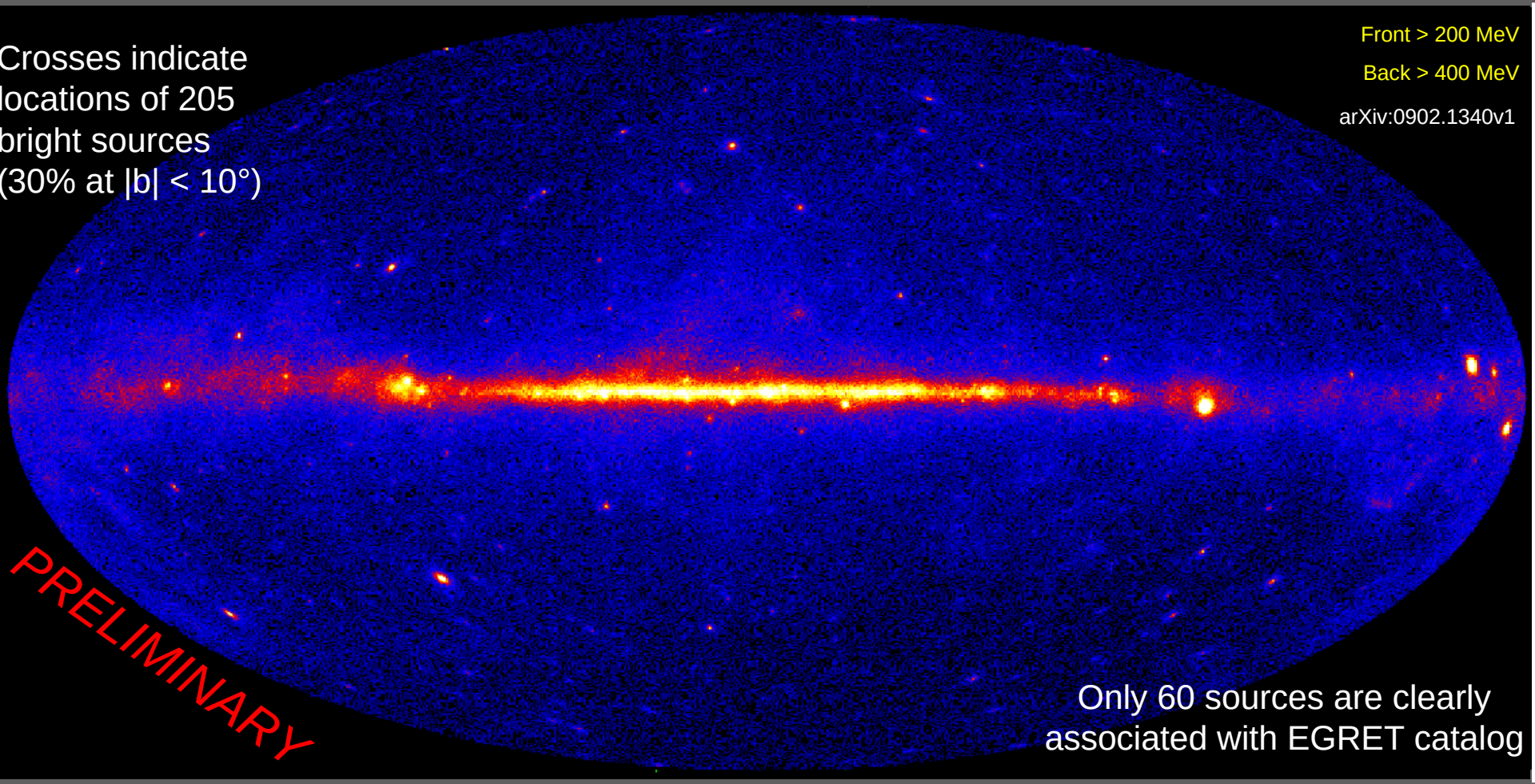
and much more…

All Sky Survey in gamma rays



The diffuse emission is a tracer of interstellar gas, provides information about cosmic ray spectra and intensities and may contain signatures of new physics

Bright LAT Sources after 3 months



The release of these data provides opportunities for multiwavelength studies and facilitate proposals for the second cycle of Fermi Guest Investigator proposals (Mar 6)

CTA1: about 10deg above the plane of the MW and 1.4 kpc away

EGRET gamma ray source

(3EG J0010 +7309)

95% error circle (0.24°)

Radio

- High resolution shell image
- Low density medium
- No pulsations

γ rays (EGRET)

- No ID
- No variability
- No pulsation

X ray source

(RX J0007.0+7302)

X rays

- Faint thermal (outside)
- Nonthermal emission (center)
- Offset from center

Fermi gamma ray source

95% error circle (0.038°)

γ rays (Fermi)

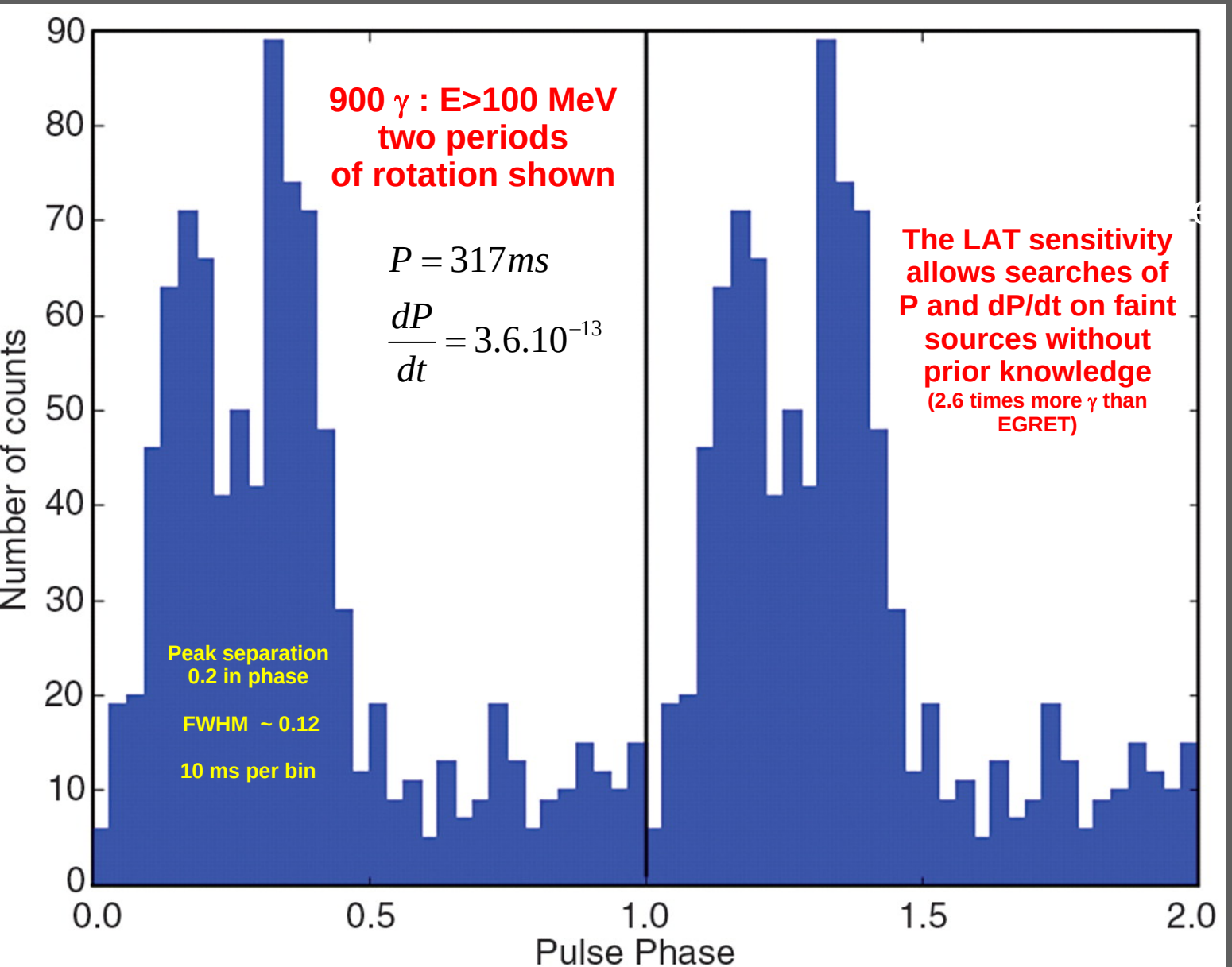
- High resolution imaging
- Good timing properties

This is a typical SNR: incomplete shell filaments and extended emission

What is powering it?

First discovery paper: a radio-quiet pulsar

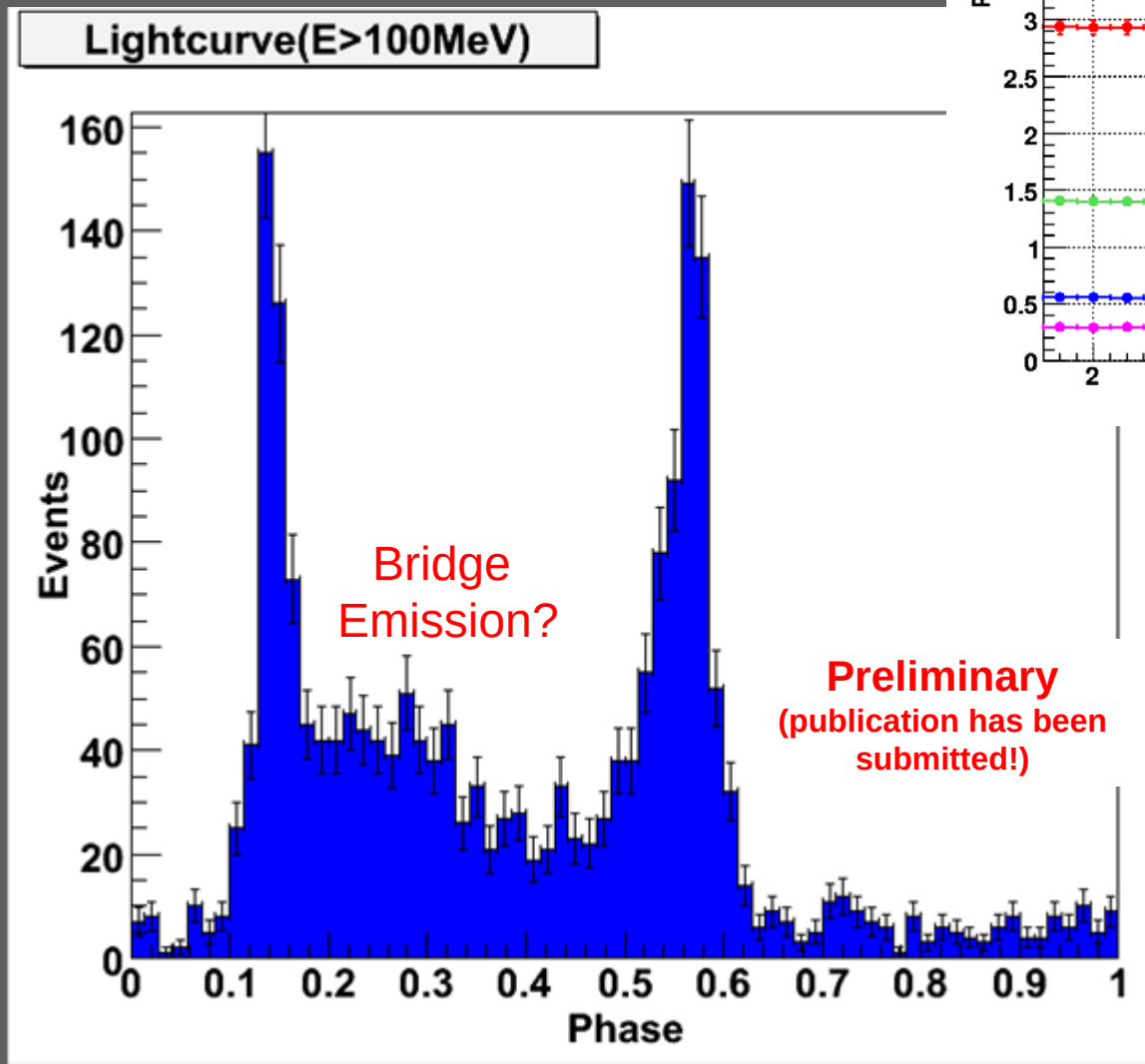
Abdo, A., et al Science 322, 1218 (Oct 16, 2008)

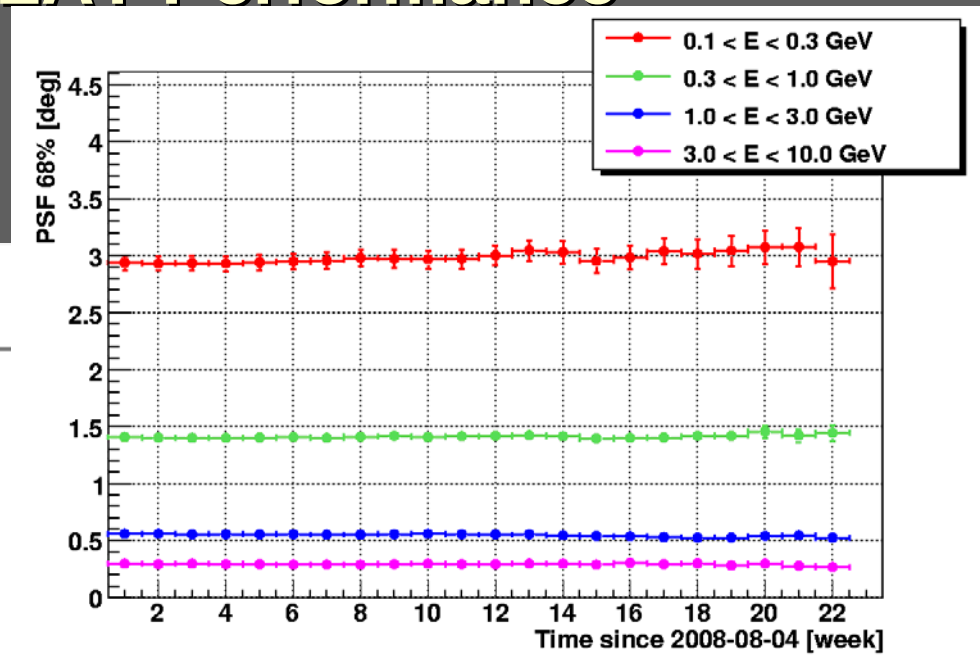


Blind search algorithms look for gamma ray sources (low flux) over a large parameter space in frequency and its time derivative

Vela Pulsar and LAT Performance

Brightest source in the gamma ray sky
(but weak in other wavelengths)



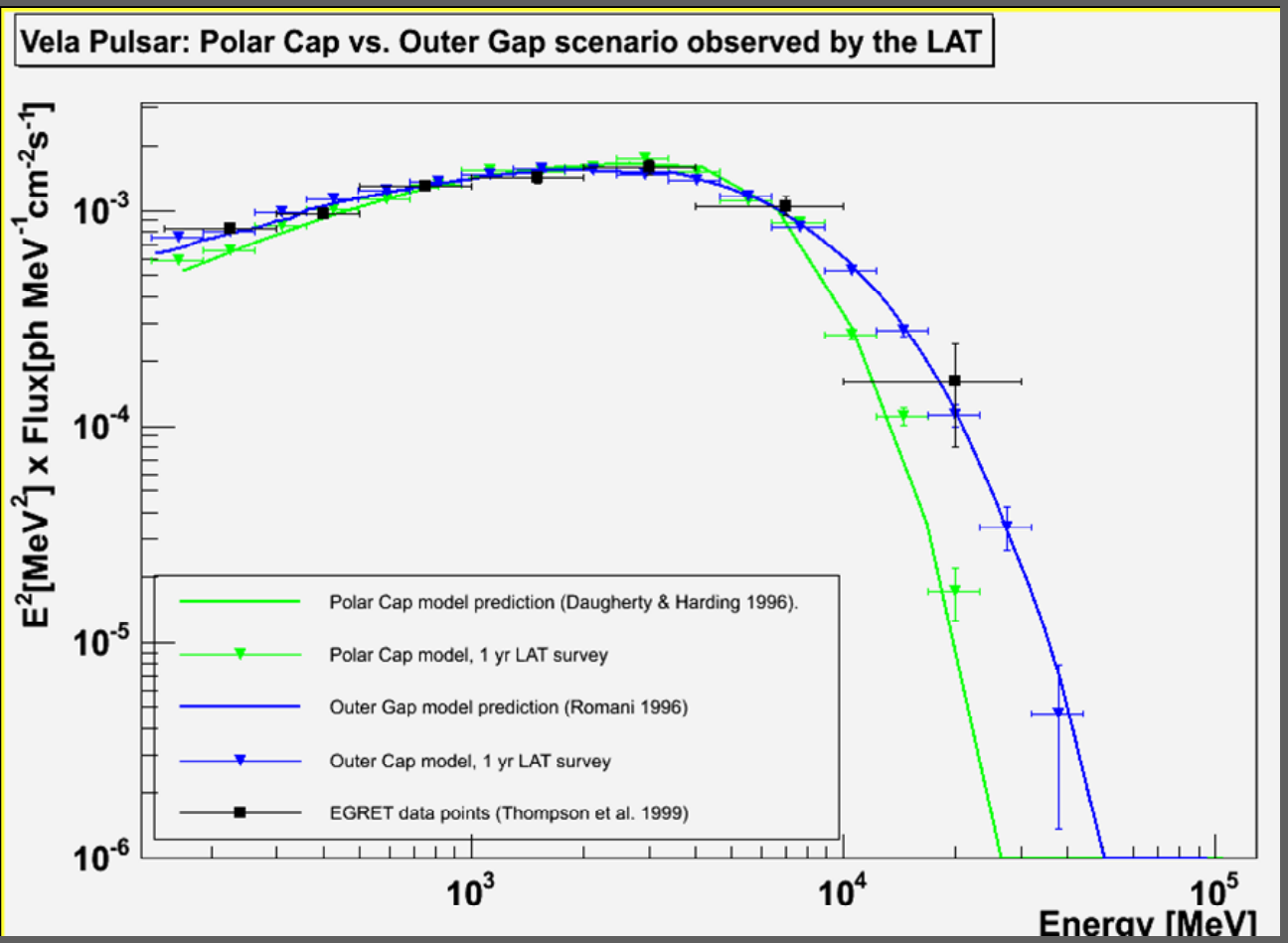


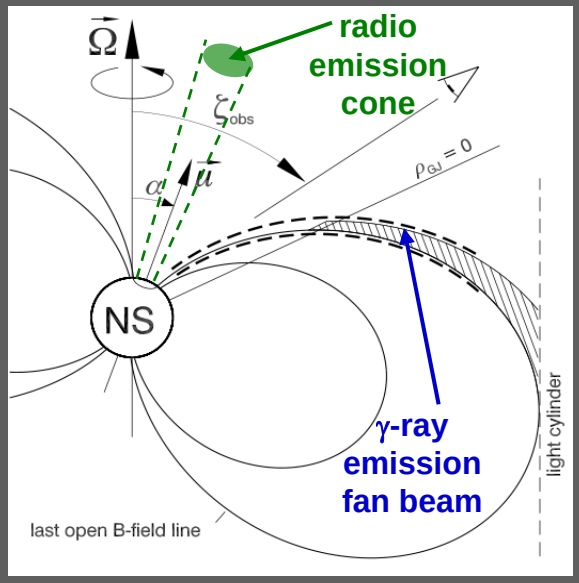
- Vela pulsar used to provide instrumental checks
  - PSF
  - Absolute timing

Vela Pulsar Simulations with LAT

- **Acceleration in Magnetosphere**
  - **Outer magnetosphere** $\gamma\gamma \rightarrow e^+e^-$
  - **Near the NS surface** $\gamma + \vec{B} \rightarrow e^+ + e^-$

Measure spectral cut-off



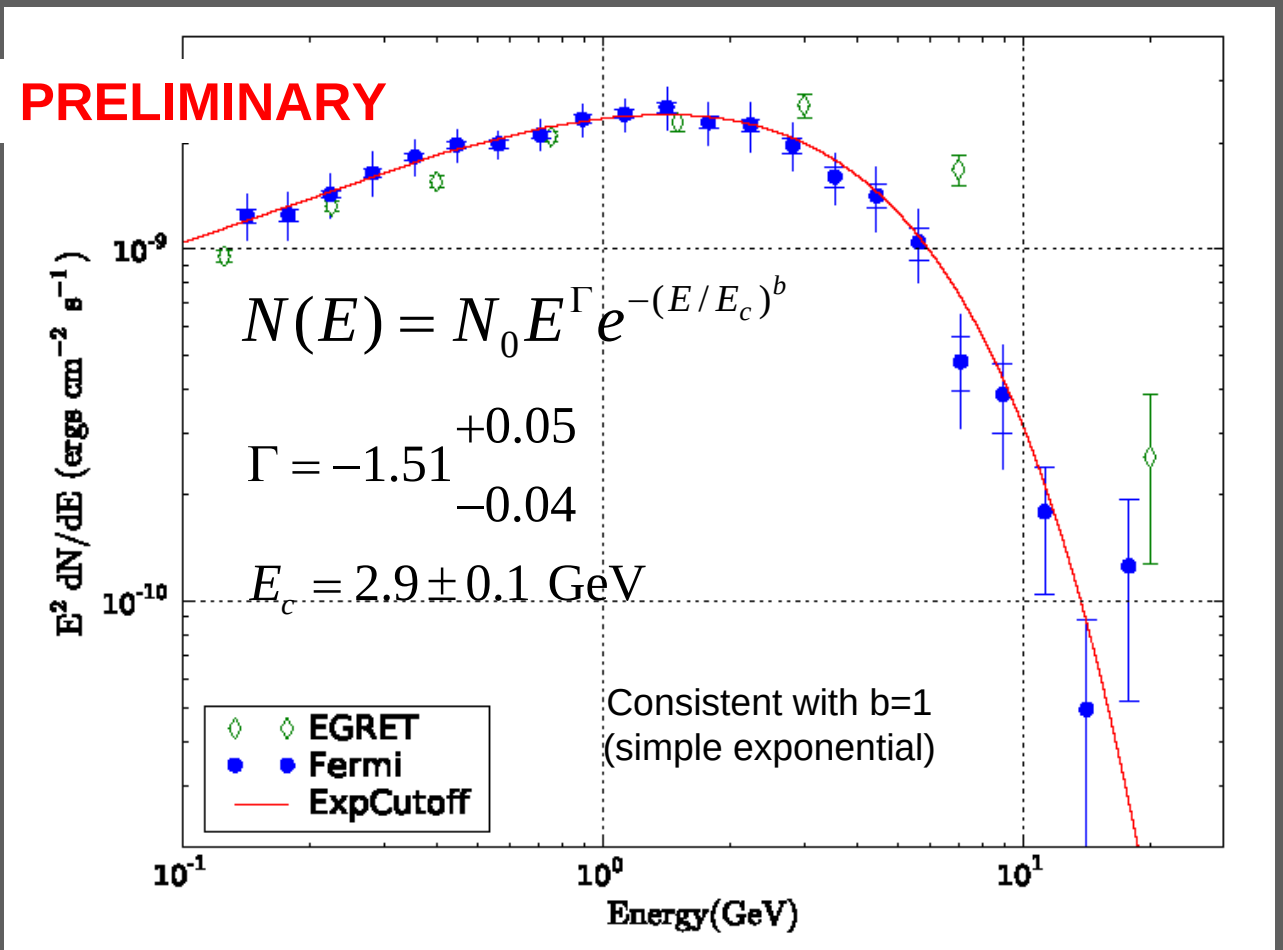


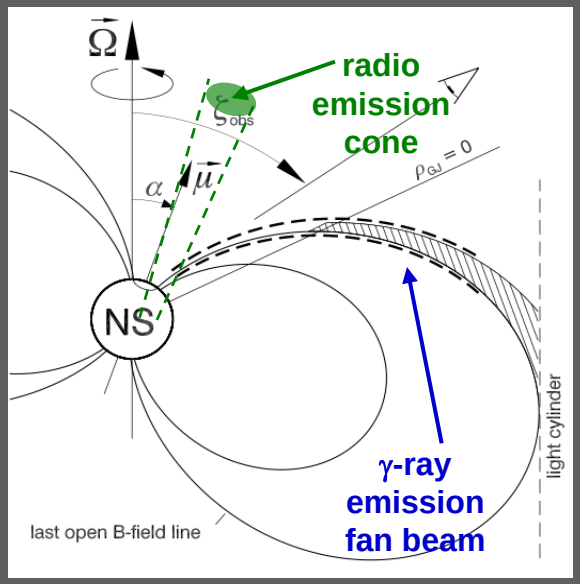
Early spectrum results submitted to *Nature*

Location of Emission in Vela Pulsar

In press *Astrophysical Journal*

- **Acceleration in Magnetosphere**
  - **Outer magnetosphere** $\gamma\gamma \rightarrow e^+e^-$
  - **Near the NS surface** $\gamma + \vec{B} \rightarrow e^+ + e^-$

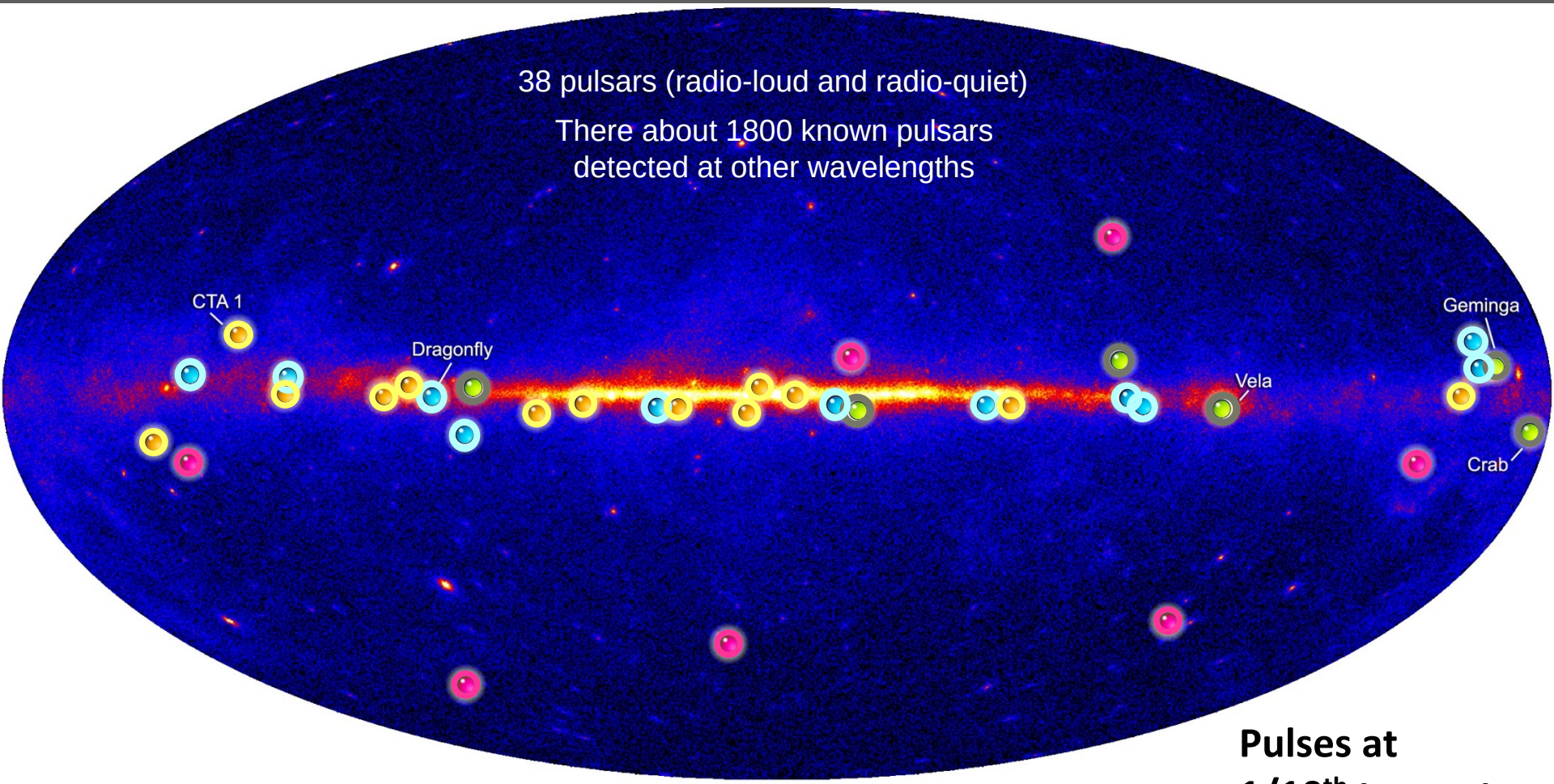




No evidence for magnetic pair attenuation
Near-surface emission ruled out

Fermi γ Ray Pulsars

identified pulsars constitute ~40% of bright sources at low latitude



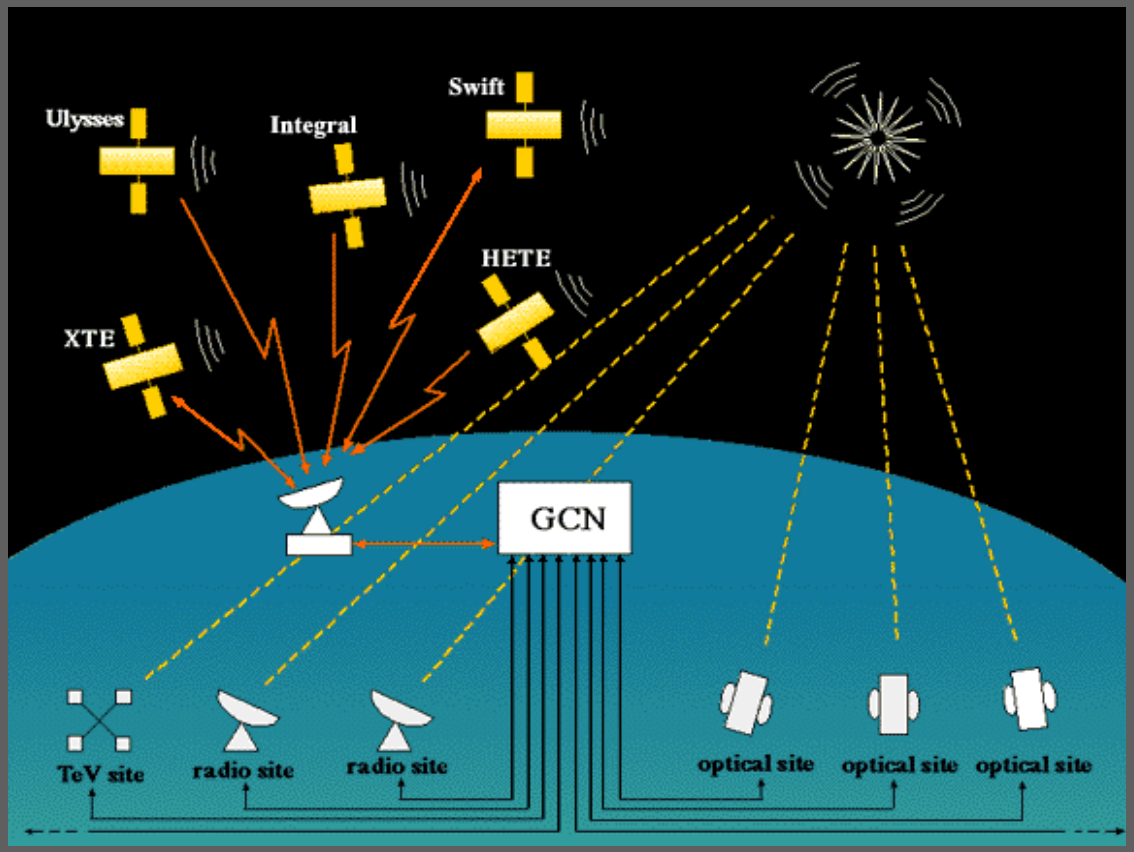
Pulses at 1/10th true rate

Fermi Pulsar Detections

12 New pulsars discovered in a blind search
7 Millisecond radio pulsars
13 Young radio pulsars
6 Pulsars seen by Compton Observatory EGRET instrument

Some Experimental Facts about GRBs

- Typical fluences
  - $10^{-4 \text{ to } -7}$ ergs cm^{-2}
- Cosmological distances
  - z ~ 1-2
- Rate
  - 1 /Myrs/galaxy
- Non-thermal emission
  - up to γ rays
  - E_{peak} ~ few hundred keV
- Temporal properties
  - Rapid flux variations
  - miliseconds
- Burst durations
  - From seconds to hours

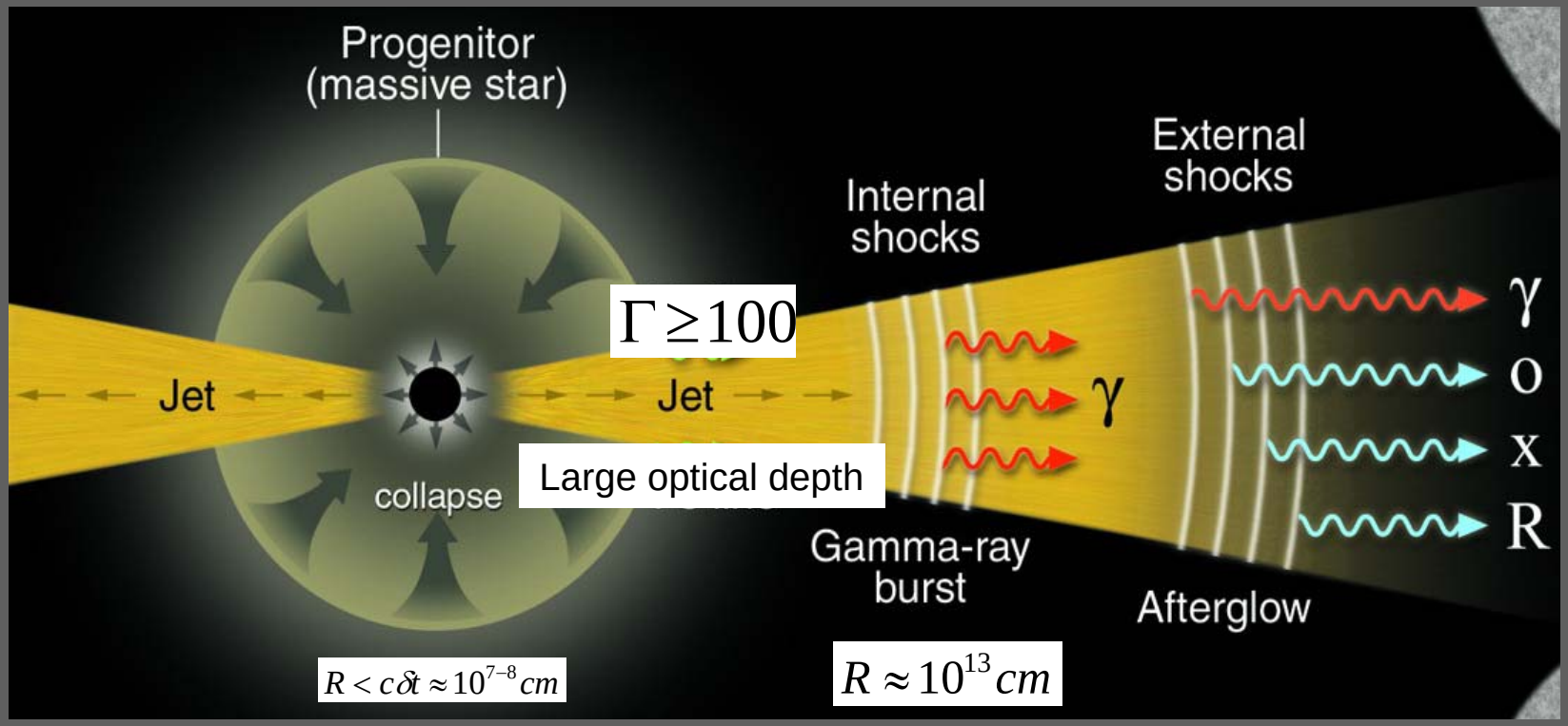


Transient phenomena are hard to catch!

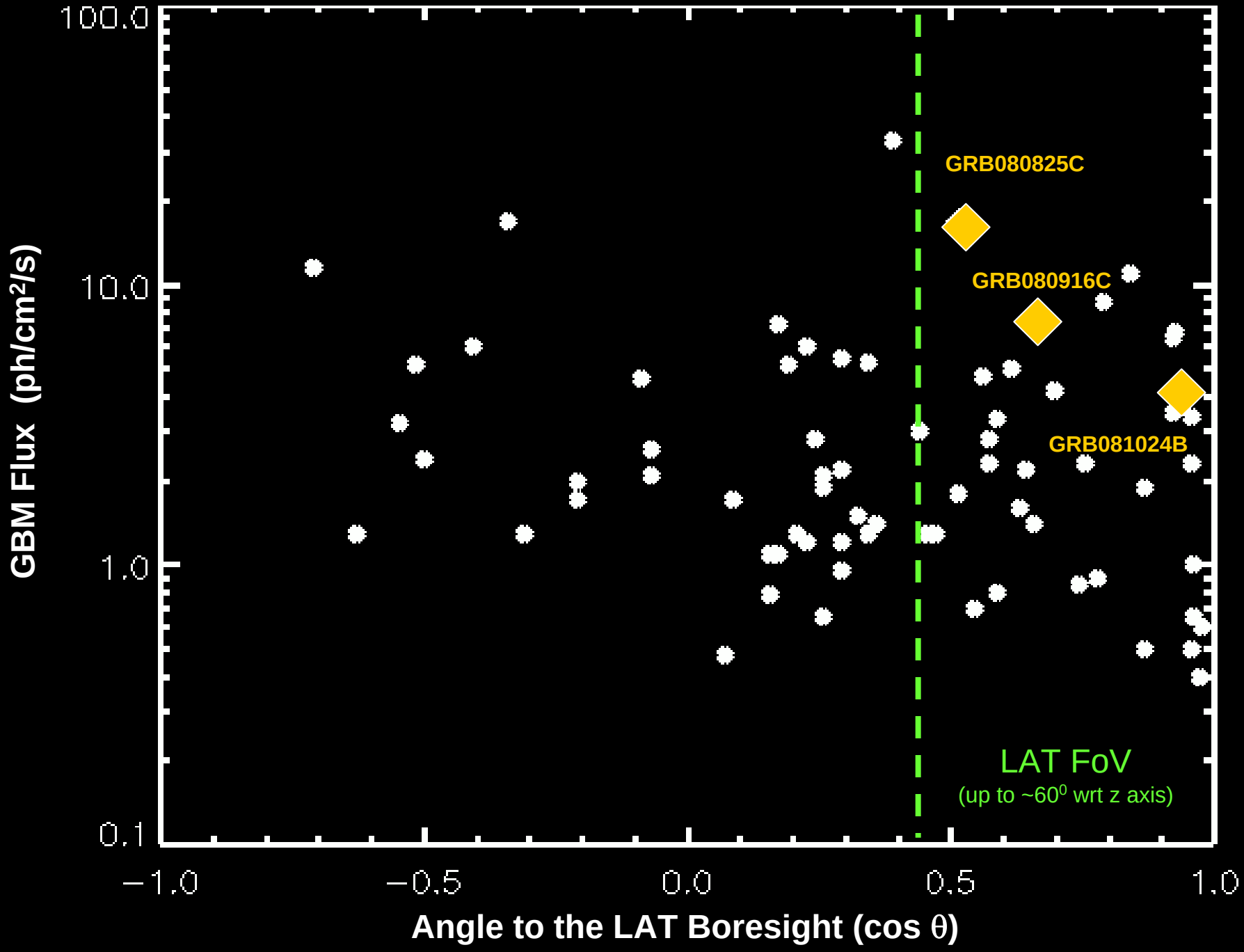
GRB: Nature's most luminous objects

- Time resolved spectra (Fermi)
  - Type of emission and dominance of components
- Energy dependent temporal correlations (Fermi)
  - Location of emission in GRB
- Redshift (other telescopes,rely on Fermi images)
  - Constrain Lorentz factor and estimate GRB power

Fermi data probe the prompt GRB phase with unprecedented capabilities



Peak GBM Flux (50-300 keV) versus LAT boresight angle



LAT : The Beginning of a New Era for GRBs

Measured time delays between high and low energy photons

GRB 080825C: Fermi-LAT observations — Bouvier et al. GCN 8183

SOURCE: GCN
TITLE: GCN CIRCULAR
NUMBER: 8183
SUBJECT: GRB 080825C: Fermi-LAT observations
DATE: 08/09/05 17:45:46 GMT
FROM: Aurelien Bouvier at Stanford <bouvier@stanford.edu>

Aug 25

> 10 events with E > 100 MeV
Long duration ~ 50 s
Warmed us up …

GRB 080916C: Fermi LAT observation — Tajima et al. GCN 8246

SOURCE: GCN
TITLE: GCN CIRCULAR
NUMBER: 8246
SUBJECT: GRB 080916C: Fermi LAT observation
DATE: 08/09/16 18:25:23 GMT
FROM: Nicola Omodei at INFN(Pisa)/GLAST <nicola.omodei@pi.infn.it>

Sep 16

> 100 events with E > 100 MeV
> 10 events with E > 1 GeV
Long Duration ~ 100 s
Extraordinary event

Abdo, A., et al Science, Feb 19, 2009

Fermi-LAT observation of GRB 081024B — Omodei GCN 8407

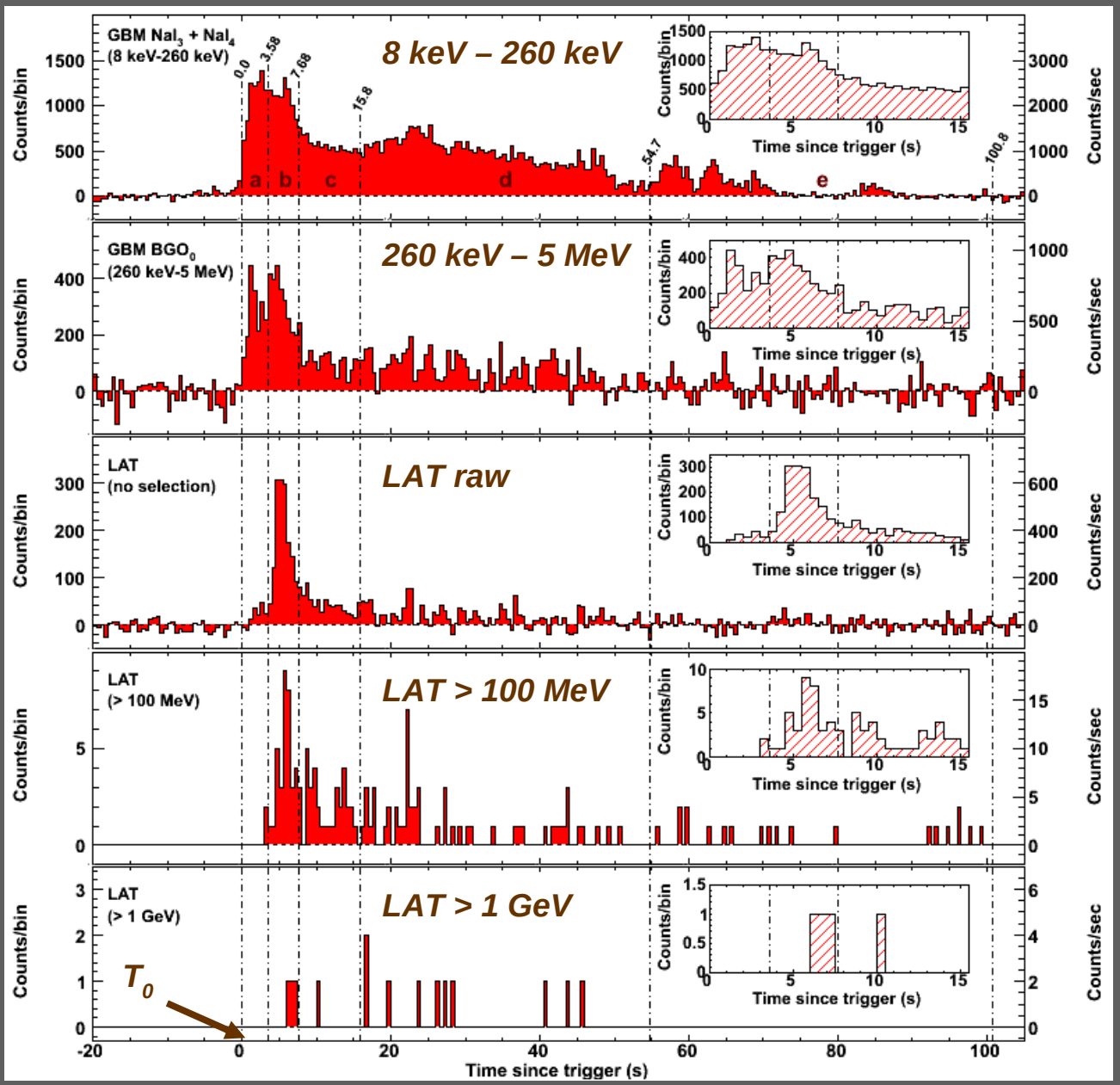
SOURCE: GCN
TITLE: GCN CIRCULAR
NUMBER: 8407
SUBJECT: Fermi-LAT observation of GRB 081024B
DATE: 08/10/25 14:07:58 GMT
FROM: Nicola Omodei at INFN(Pisa)/GLAST <nicola.omodei@pi.infn.it>

Oct 24

> 10 events with E > 1 GeV
Short duration ~ 3 s
For the first time ever

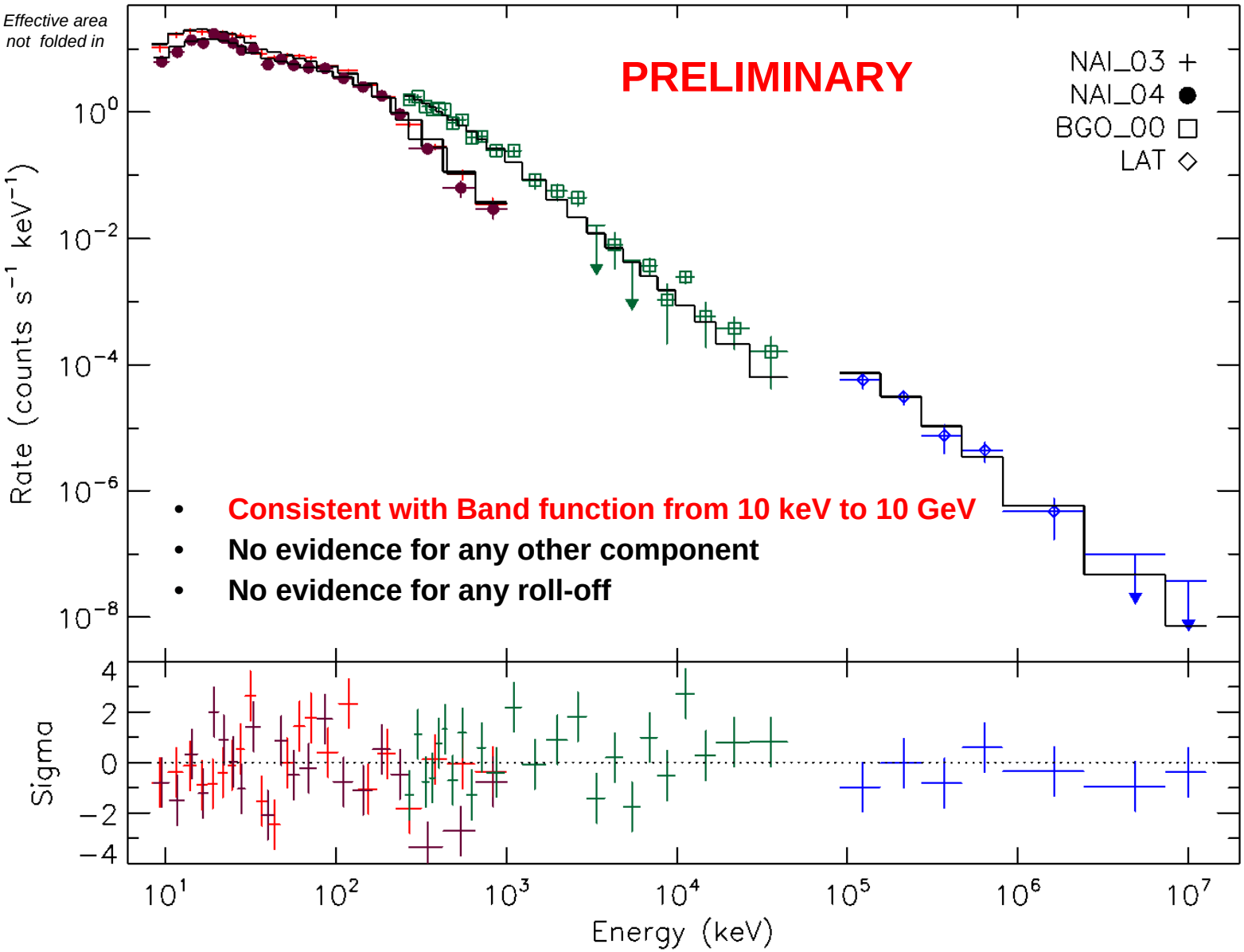
PRELIMINARY

GRB 080916C Light Curves



- First 3 light curves are background subtracted
- The LAT can be used as a counter to maximize the rate and to study time structures above tens of MeV
  - The first low-energy peak is not observed at LAT energies
- Spectroscopy requires LAT event selection (>100 MeV)
  - 5 intervals for time-resolved spectral analysis

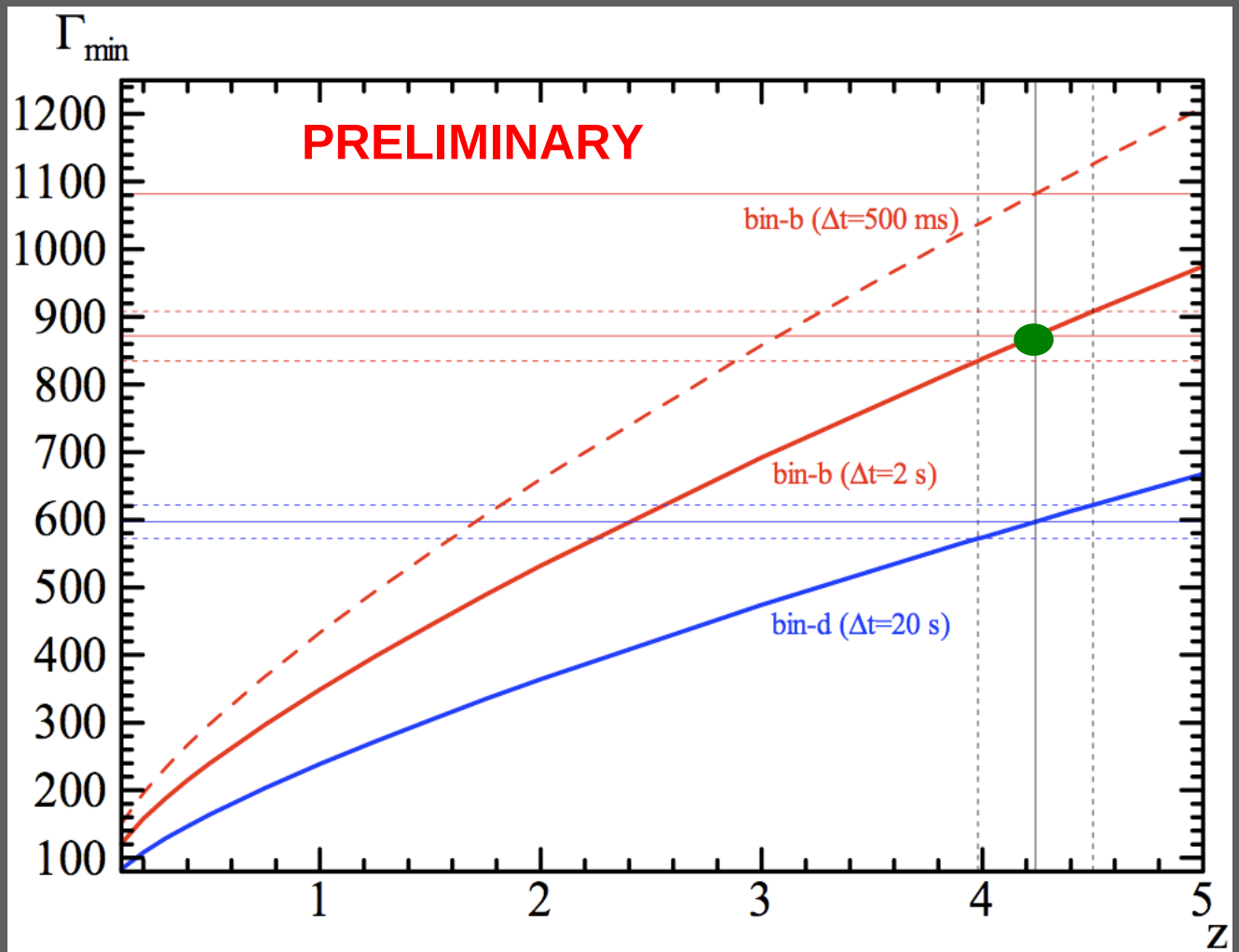
Spectroscopy of the Main LAT Peak



- **Consistent with Band function from 10 keV to 10 GeV**
- **No evidence for any other component**
- **No evidence for any roll-off**

Opacity and High Lorentz Factor

- No intrinsic absorption
  - Did not observe expected time and spectral signatures
- No extrinsic absorption
  - Did not measure spectral cut-off



- Extraordinary event
  - Top 1% of all GRBs
- Fluence (10 keV - 10 GeV)
  - ~ 2.4 x 10^{-4} ergs/cm2
- Redshift (GROND)
  - 4.2 ± 0.3
- Eiso
  - ~ 8.3 x 10^{54} ergs

$$\Gamma_{min} \sim 860 \pm {}^{40}_{50}$$

Searching for Broken Lorentz Invariance

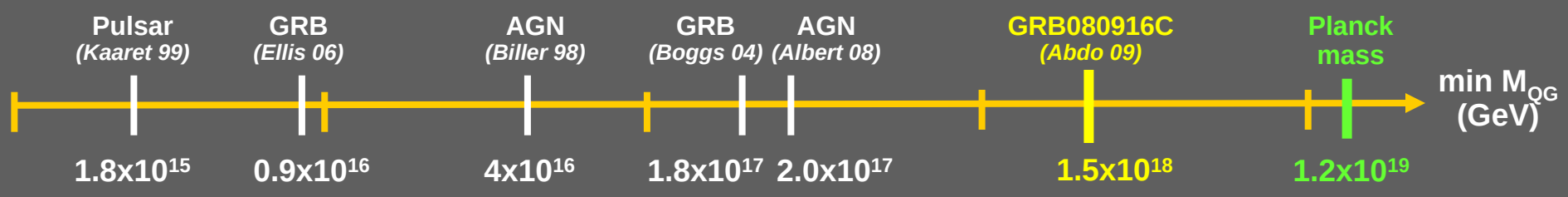
broken Lorentz symmetry will lead to a dispersion relation for photon propagation with leading-order in the Planck length

- **16.5 s delay between GBM trigger and LAT 13 GeV γ**

- **Lower limit on the quantum gravity scale**
  - **conservative**
  - **assumes linear energy scaling**
  - **one order of magnitude higher than the previous best estimate**

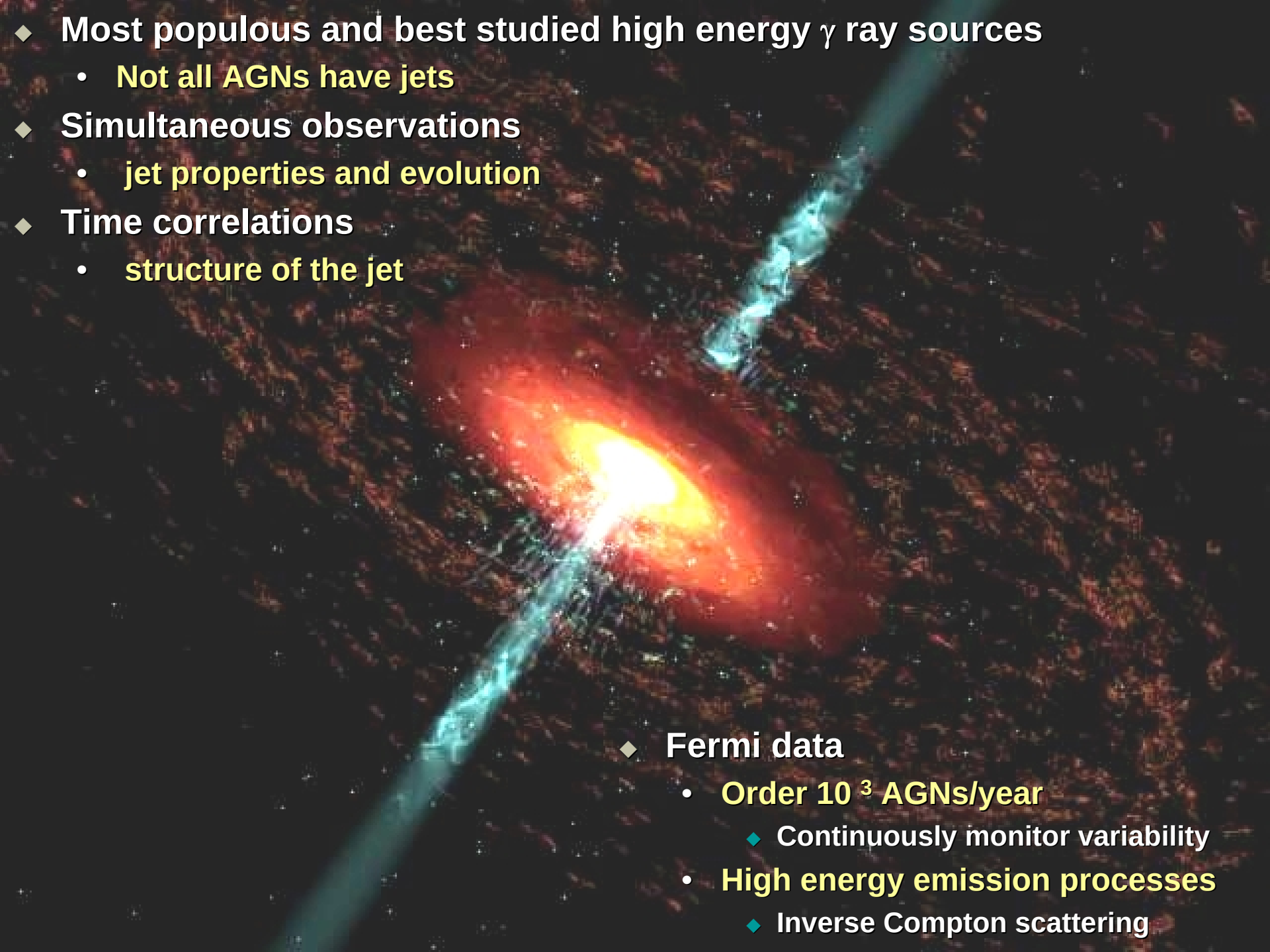
PRELIMINARY

$$E_{QG} = \frac{L.\Delta E}{\eta c.\Delta t} = (1.50 \pm 0.20).10^{18} GeV / c^2$$



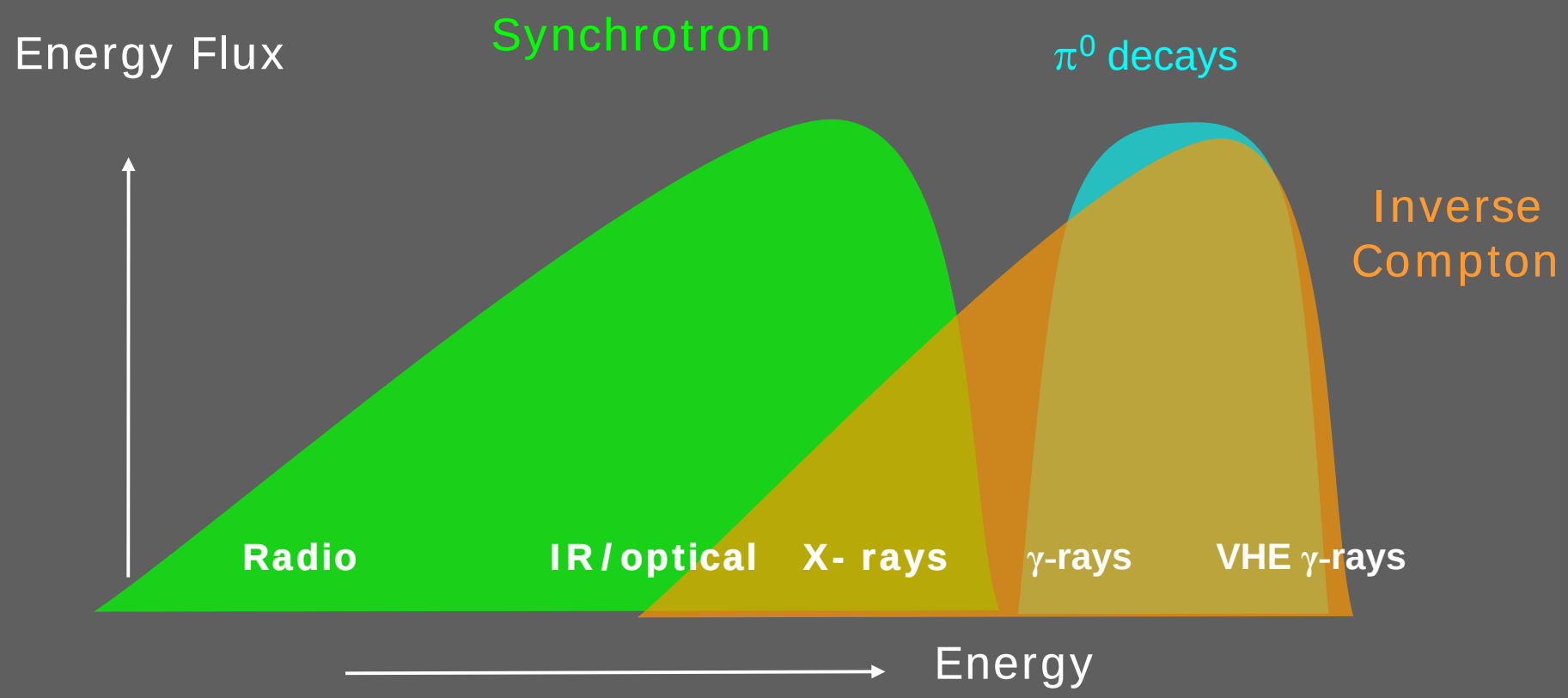
A. Abdo et al
Soience Feb 19,2009

- Most populous and best studied high energy γ ray sources
  - Not all AGNs have jets
- Simultaneous observations
  - jet properties and evolution
- Time correlations
  - structure of the jet



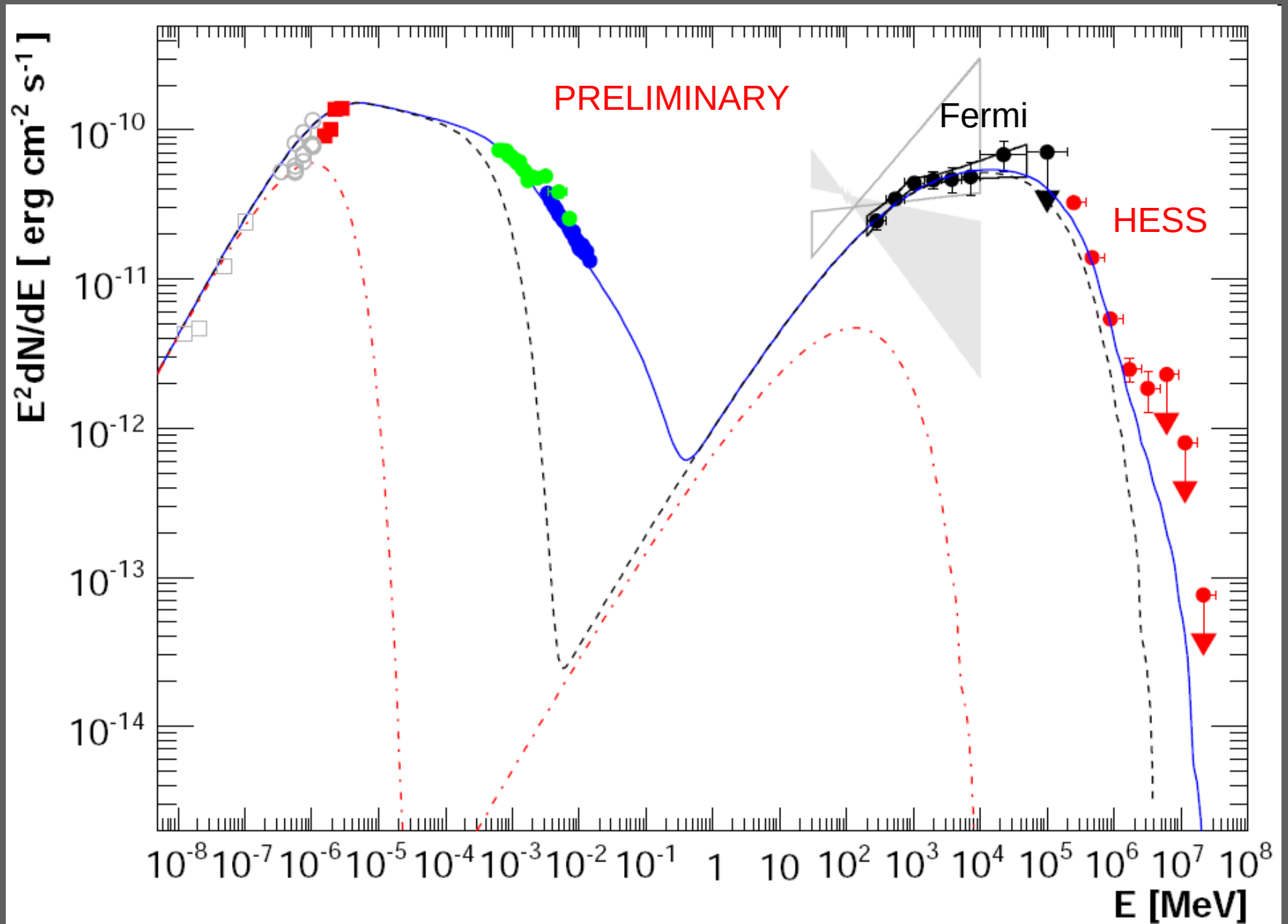
- Fermi data
  - Order 10^3 AGNs/year
    - Continuously monitor variability
  - High energy emission processes
    - Inverse Compton scattering

High Energy Emission Mechanisms

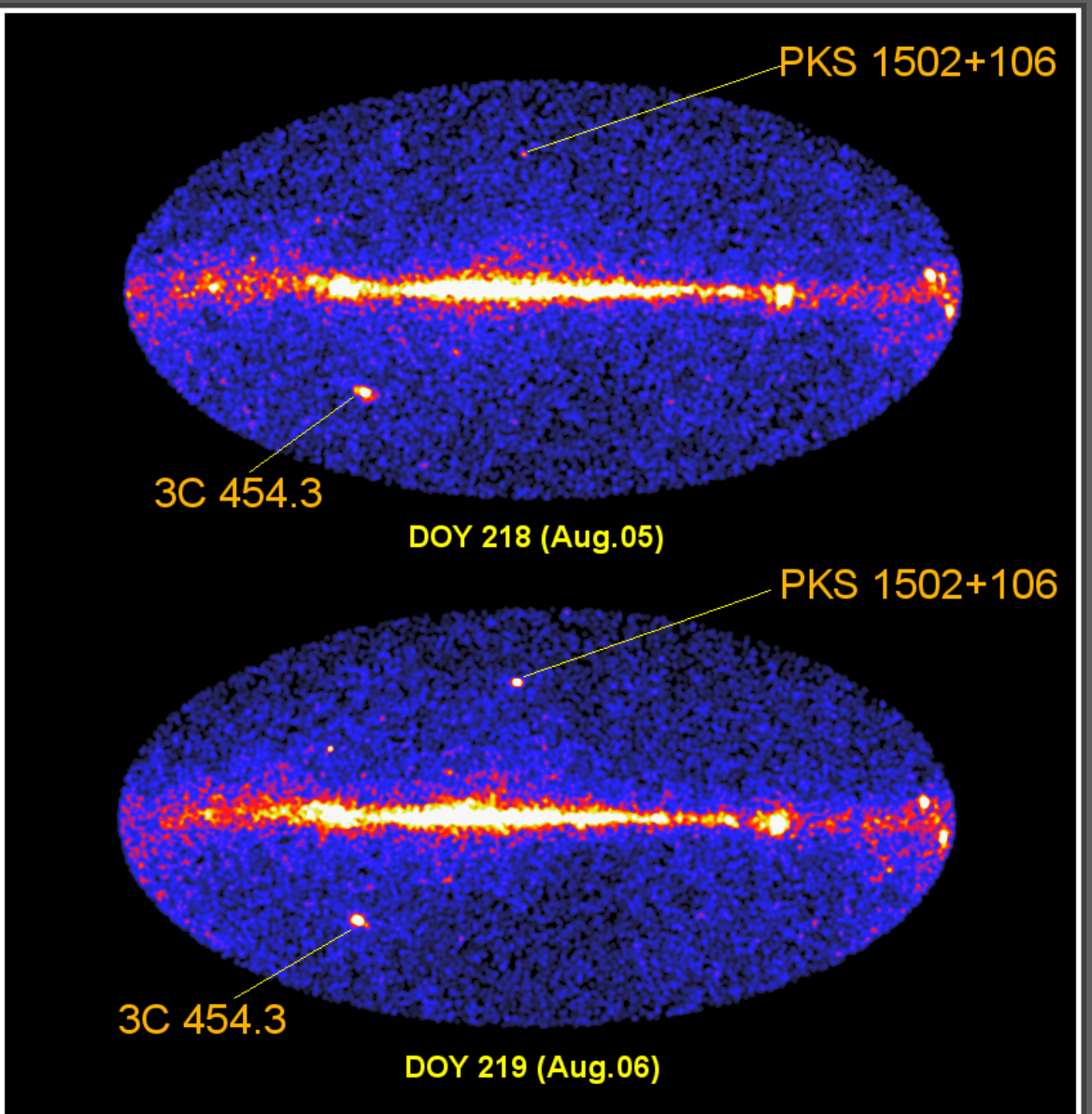


Inverse Compton Scattering (IC)
Hadronic Emissions

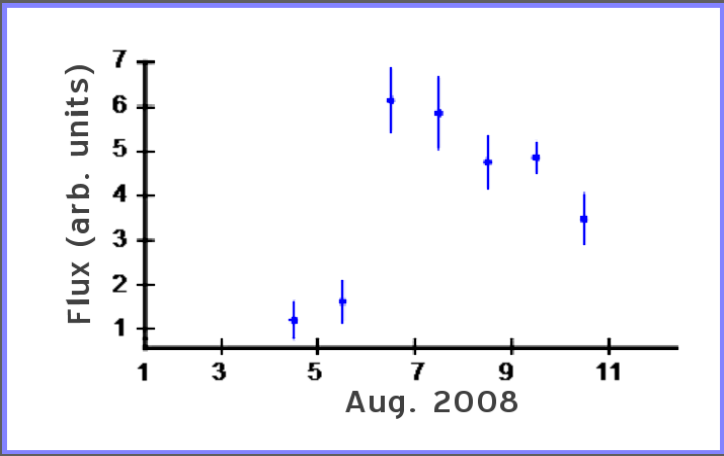
Fermi – HESS Campaign PKS 2155-304



First Flares from Active Galactic Nuclei

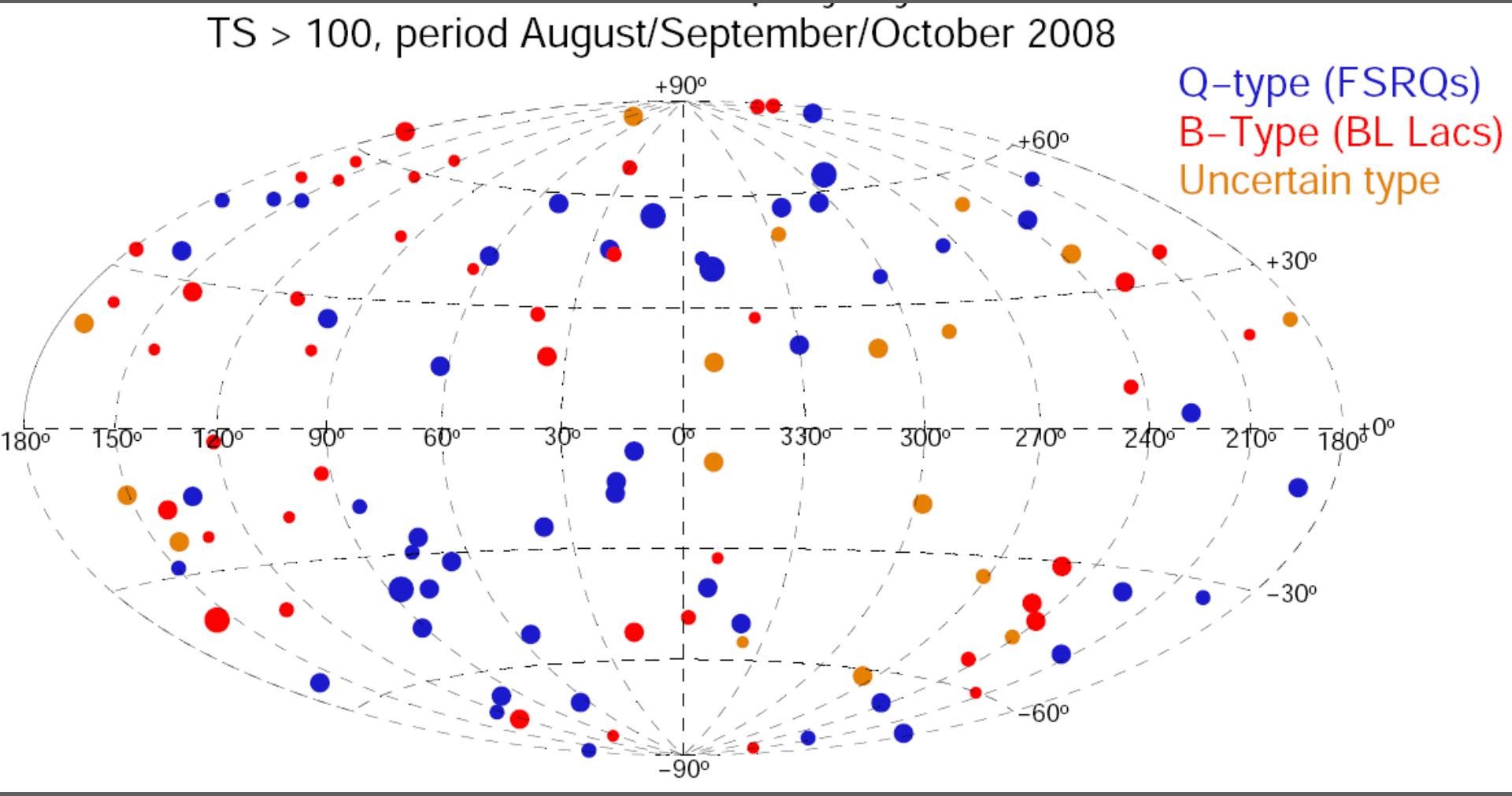


- Fermi is studying variability in gamma rays over different time scales.
  - 3C 454.3
  - PKS 1502-106
    - Not seen by EGRET!



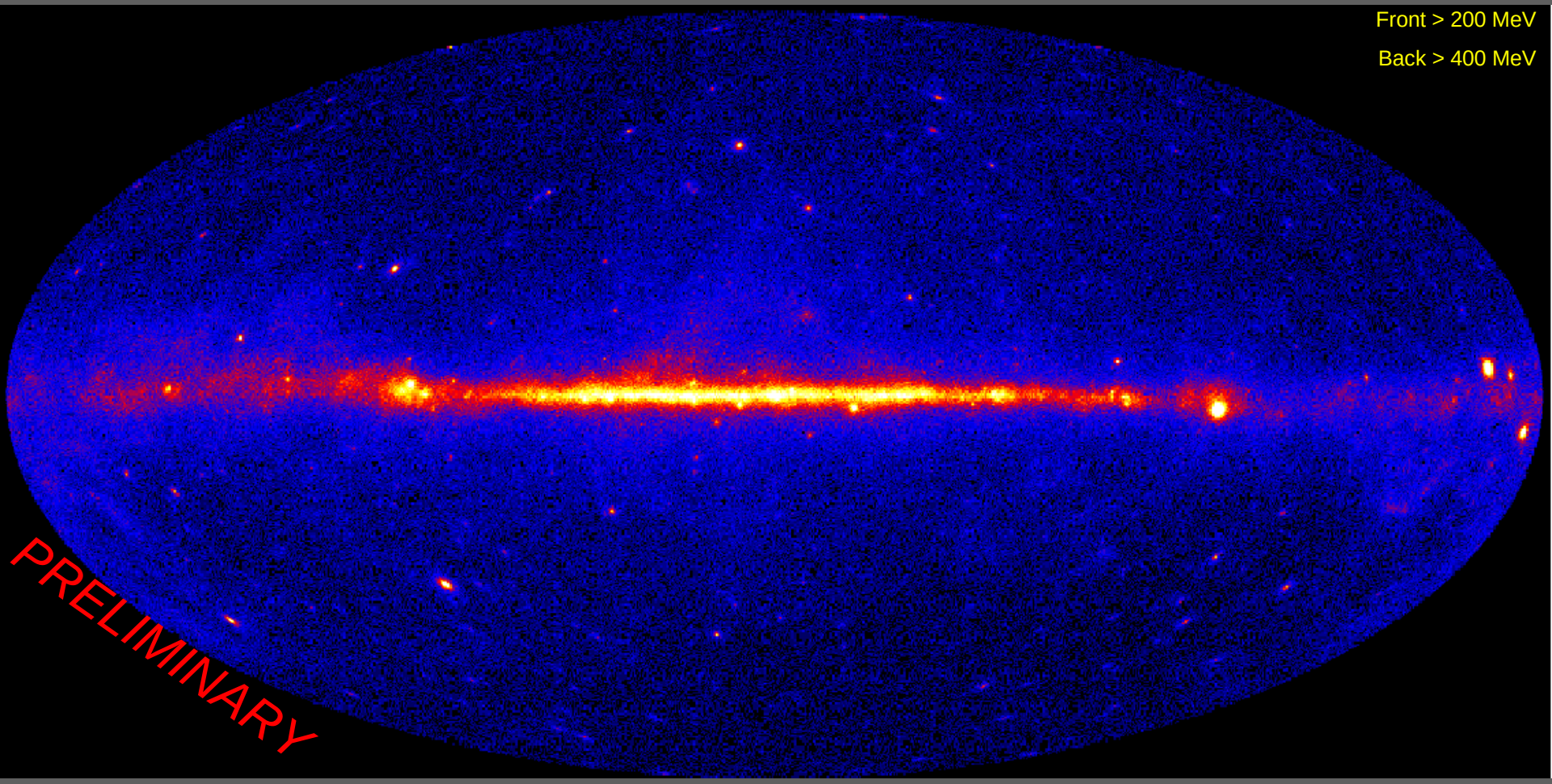
The LAT Blazar γ ray sky

Fermi data will improve our understanding of supermassive black holes



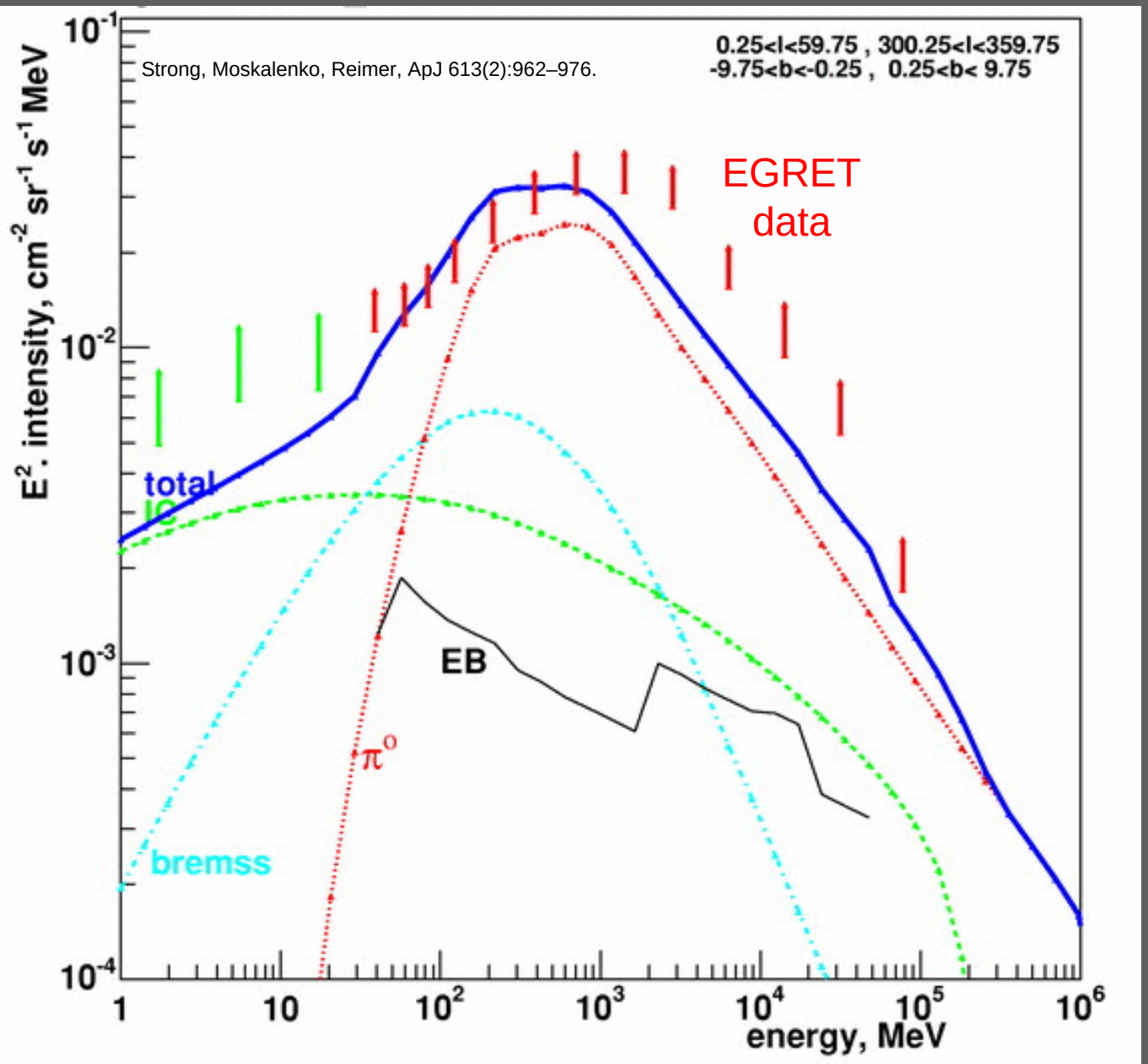
90% are radio bright and only 30% were detected by EGRET
(due to low duty cycle and source variability)

All Sky Survey in gamma rays



The diffuse emission is a tracer of interstellar gas, provides information about cosmic ray spectra and intensities and may contain signatures of new physics

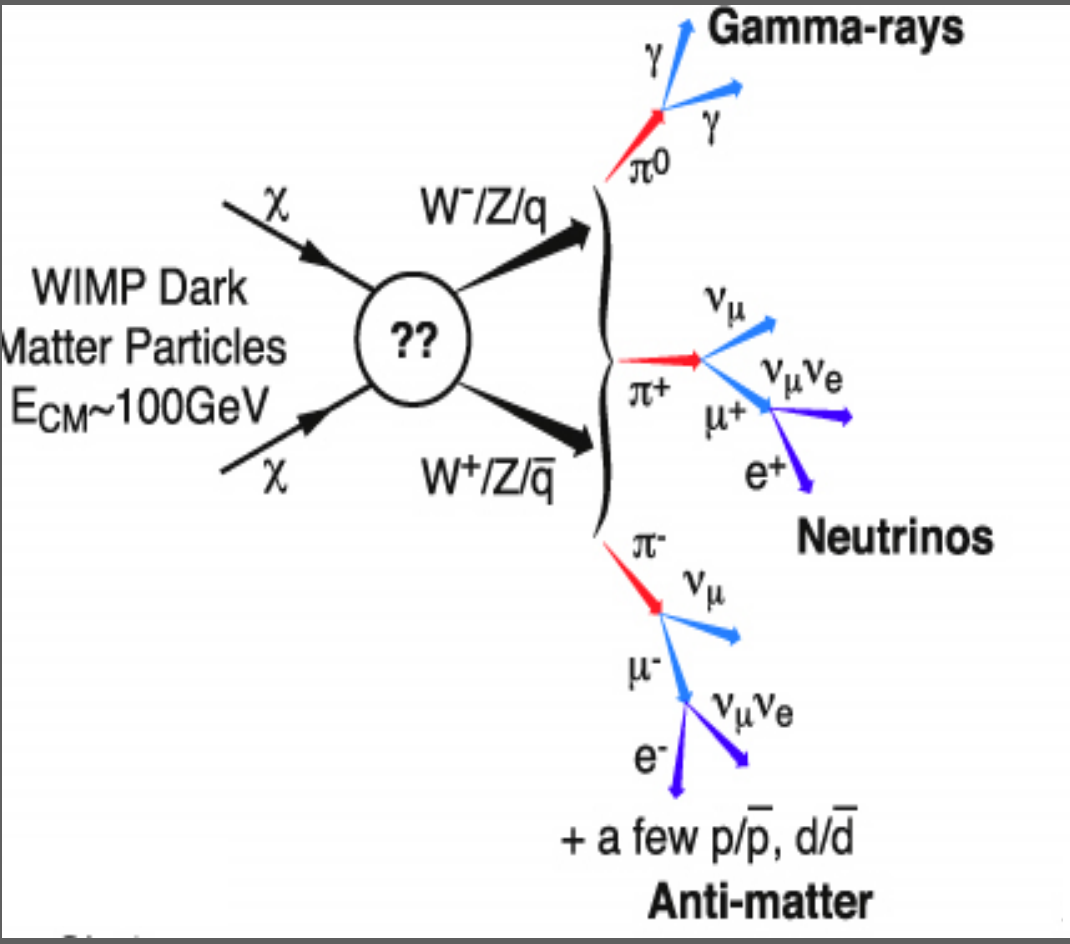
EGRET GeV Excess for E>1 GeV

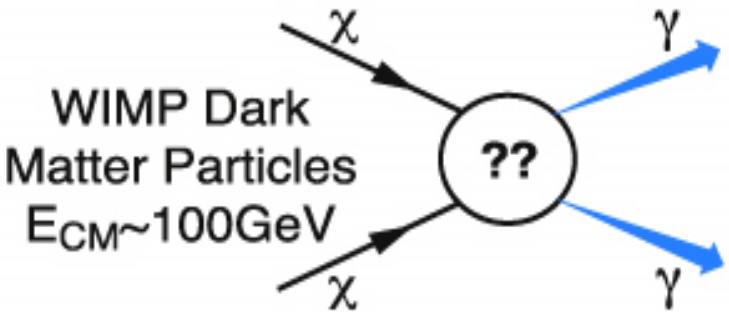


Excess in the diffuse flux is present all directions of the sky
(here we show the Galactic center)

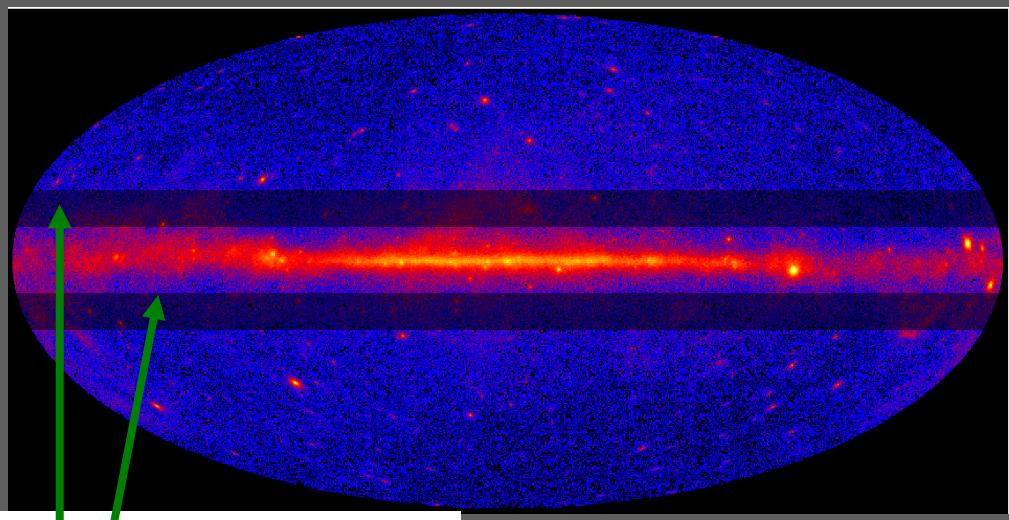
New Physics?

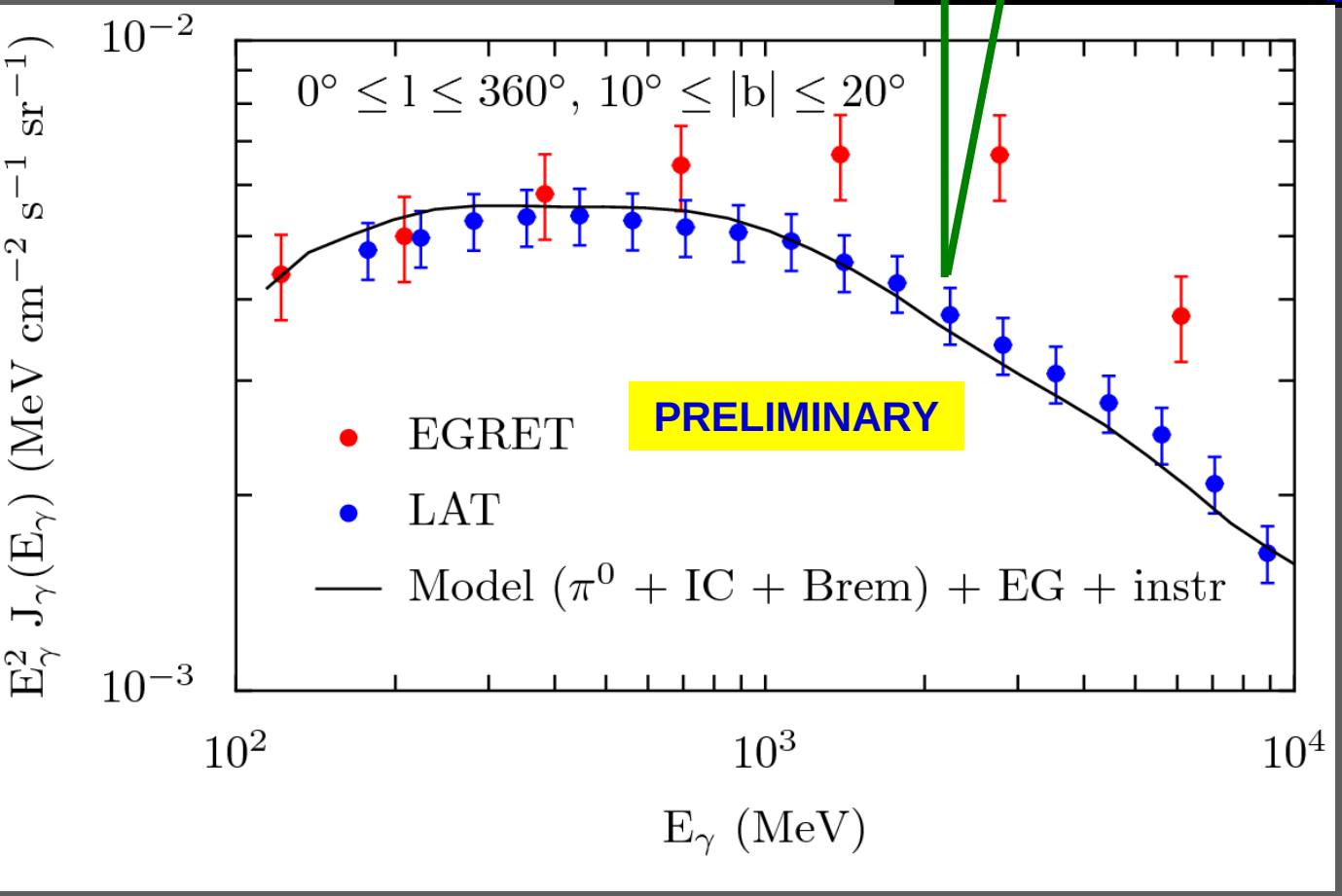
Physics Beyond the Standard Model?





Fermi Data :
No GeV Excess !
(at mid latitudes)

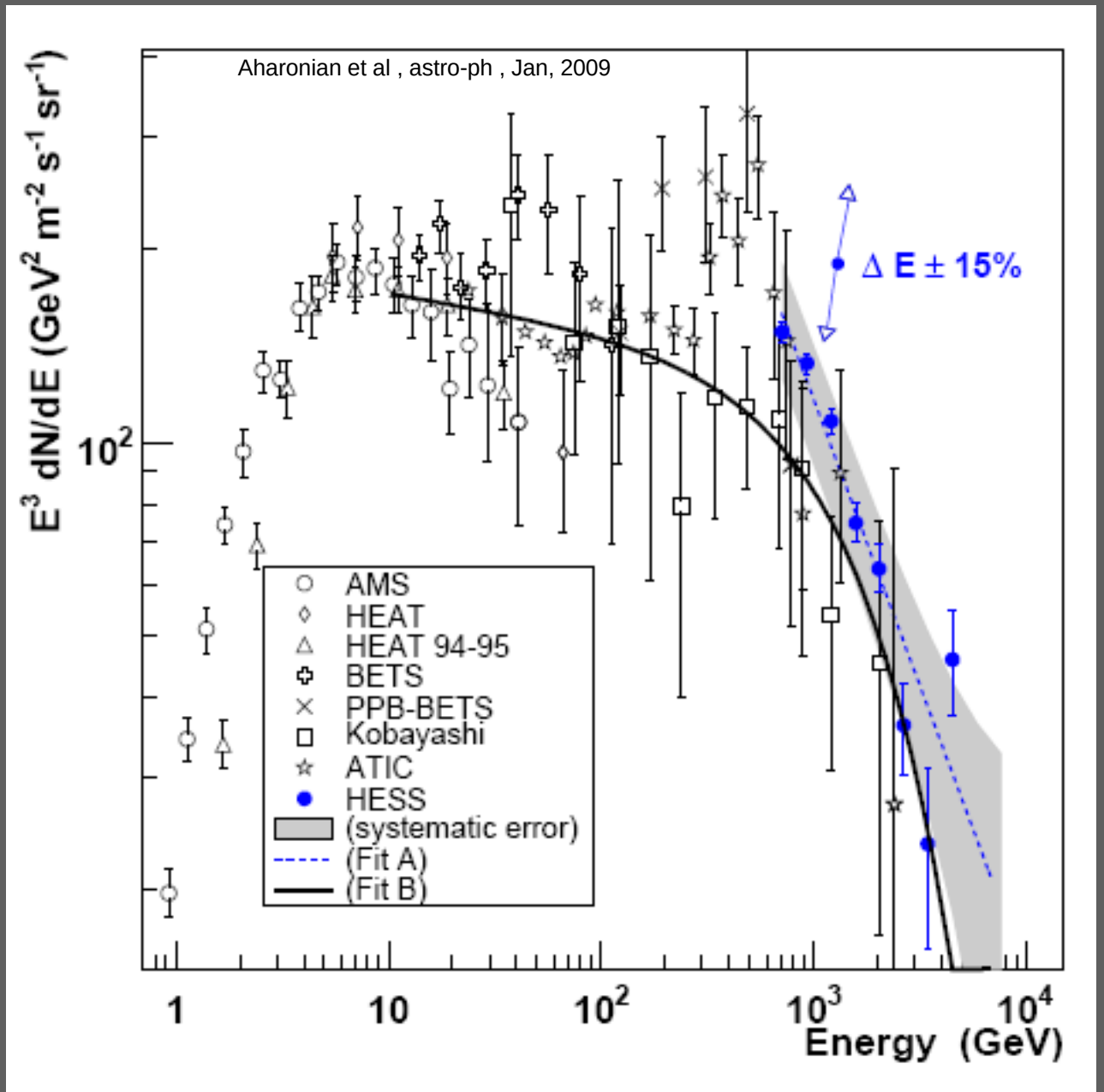




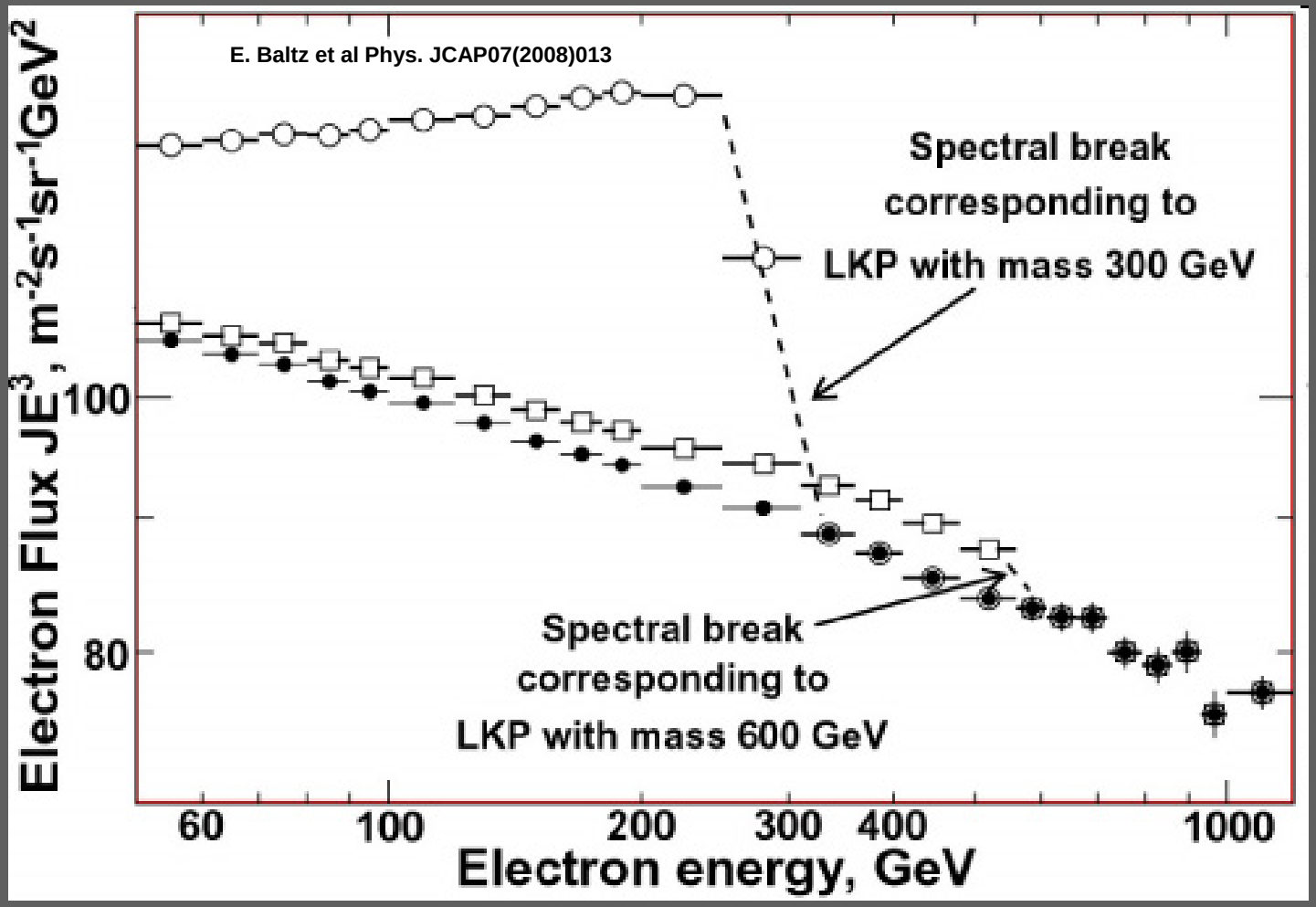
High Energy Electron Positron Spectra

The spectrum is measured below 100 GeV by many balloon and satellite experiments, but there are not so many experiments above >100 GeV

A signature for new physics at hundreds of GeV?



Dark Matter from Extra Dimensions?

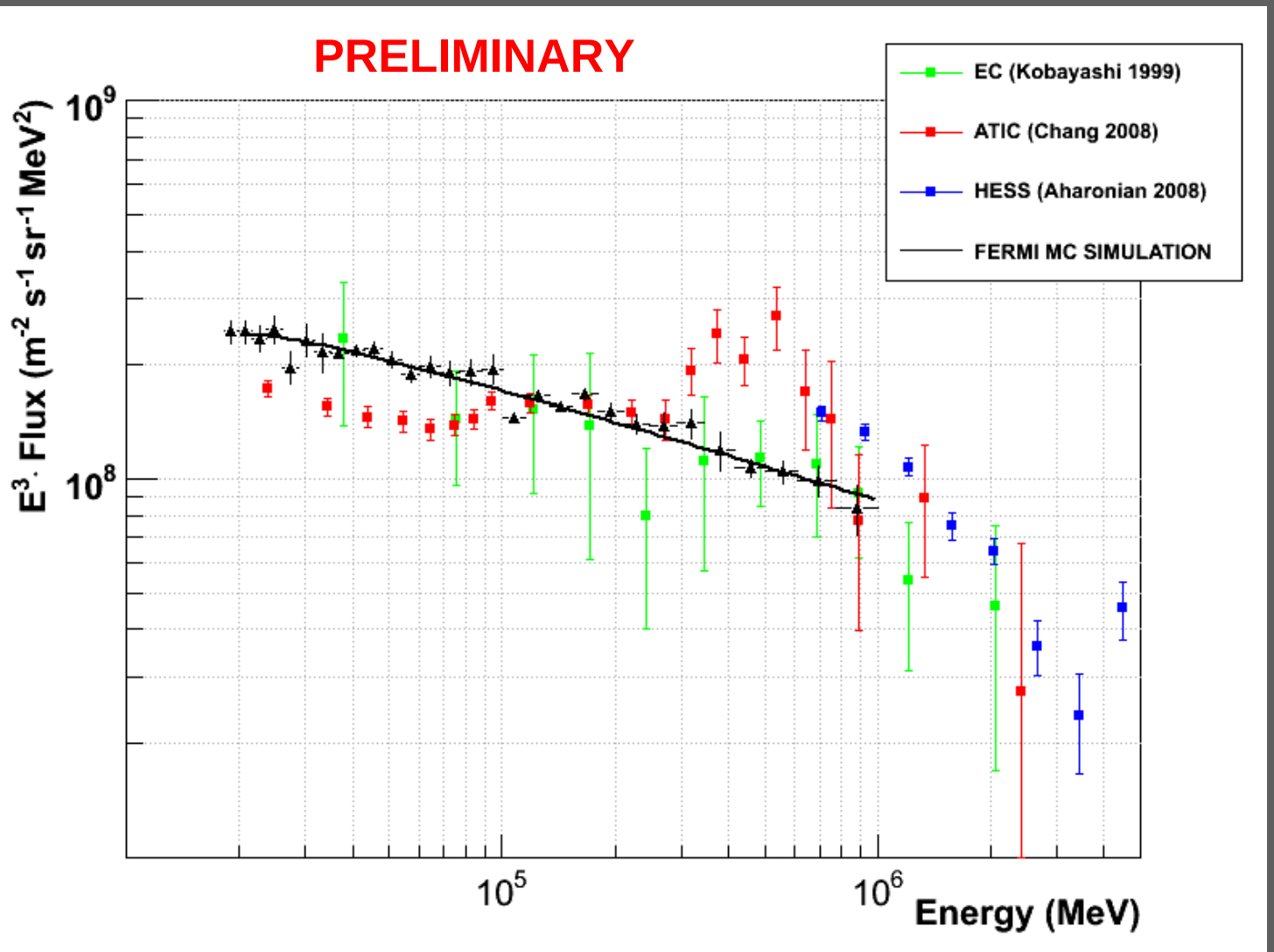


Fermi has more statistics and can distinguish a gradual change in slope

Simulated LKPs with masses of 300 and 600 GeV in the LAT electron spectrum to be collected assuming *five years of operation*.
For this signal, only the nearest clump at a distance of 100 pc is considered.

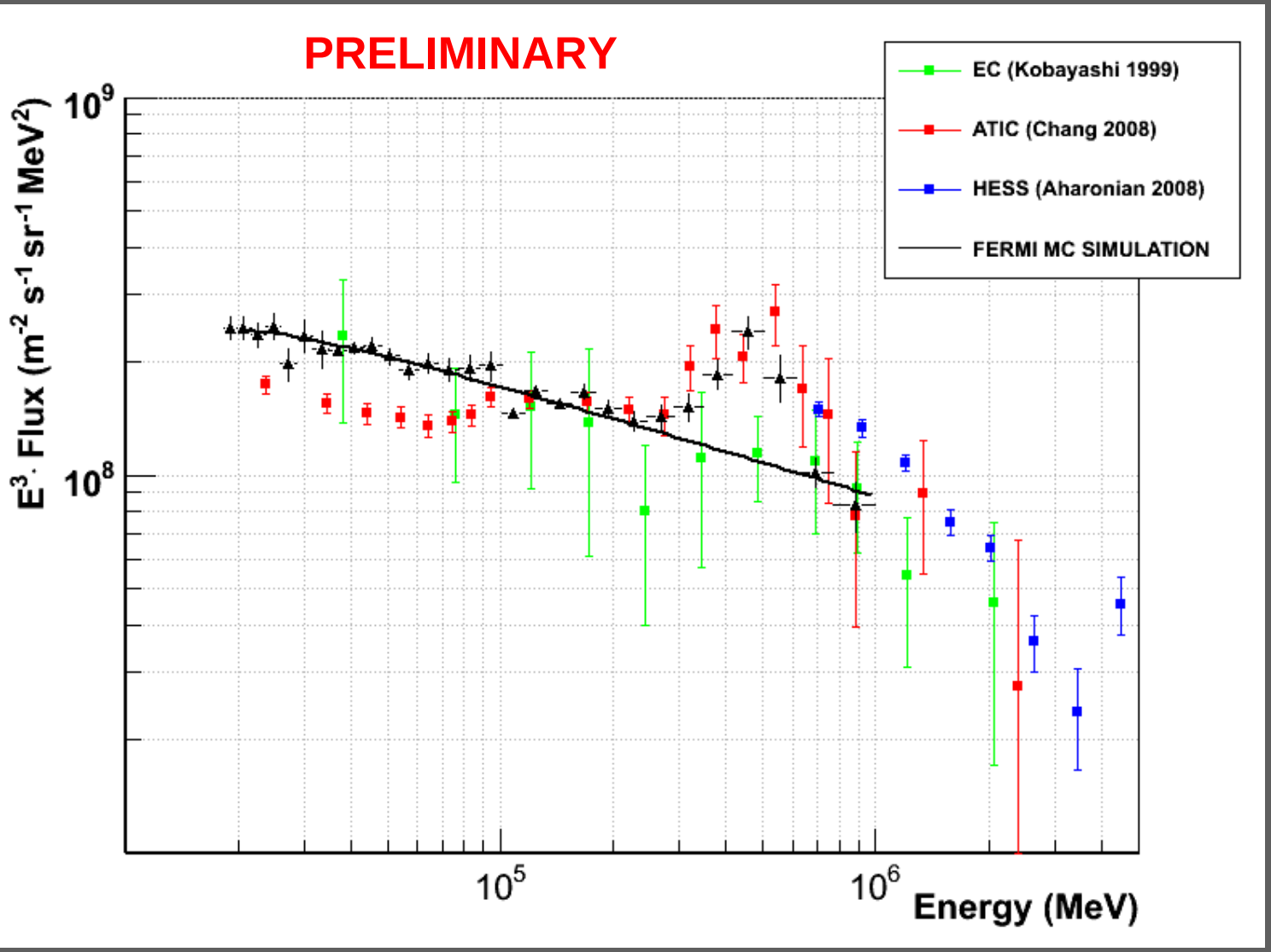
Fermi MC Simulations of CRE spectrum (1)

- Simulation of less than 30 days of on orbit operations
- The solid line is the primary electron model used in the simulation



Spectral index of 3.3 above the geomagnetic cutoff

Fermi MC Simulations of CRE spectrum (2)



We expect to collect in 6 months

>200k events above 100 GeV

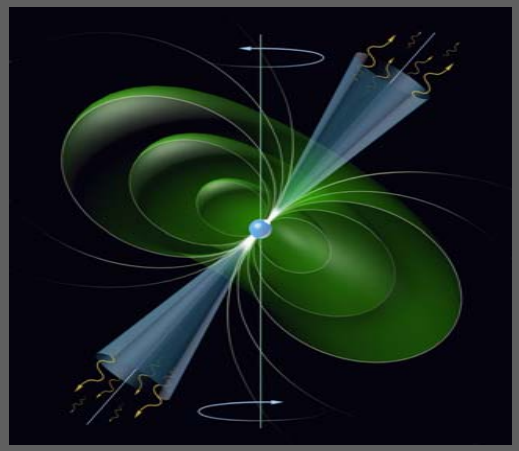
>2.5k events above 500 GeV

Goal: PRL publication by May APS Meeting!

Summary of Early Fermi Results (1)

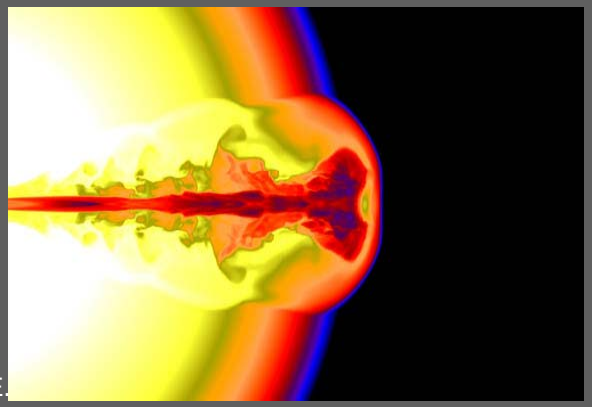
Dark Matter Searches

No evidence of GeV γ-ray excess seen by EGRET
Coming soon: high energy cosmic-ray e+/e- spectrum



Pulsars

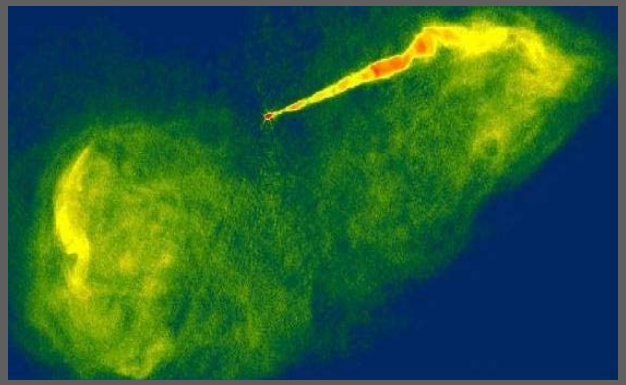
Identified 38 γ-ray pulsars (7 from blind searches)
Discovered new radio-quiet and milisecond pulsars
Determined location of emission in the Vela pulsar



Gamma Ray Bursts

Detected delayed emissions in GRBs (tests of QG)
Begin to probe the GRB prompt phase with unprecedented capabilities (7 decades in energy and time resolved spectra)

Summary of Early Fermi Results (2)



Active Galactic Nuclei

Discovered γ-ray flares from several AGN

Detected about hundred γ-ray blazars

Started a new era for multiwavelength campaigns

12 papers submitted since Aug 2008

15 papers in preparation

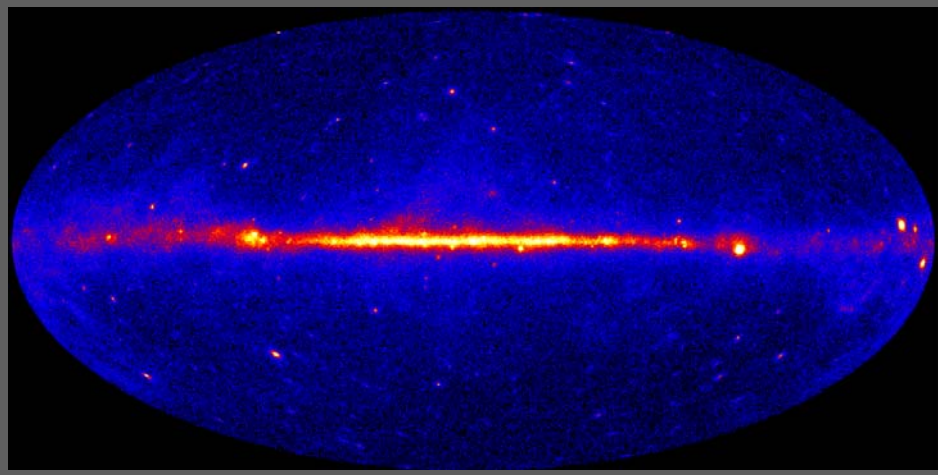
General

Mapping and measuring the entire sky at unprecedented angular and energy resolution and statistical accuracy

Mapping the diffuse Galactic emission and measuring its spectrum

Detected a few hundred sources

First catalogue of bright high-significance sources released



and more that I did not talk about…