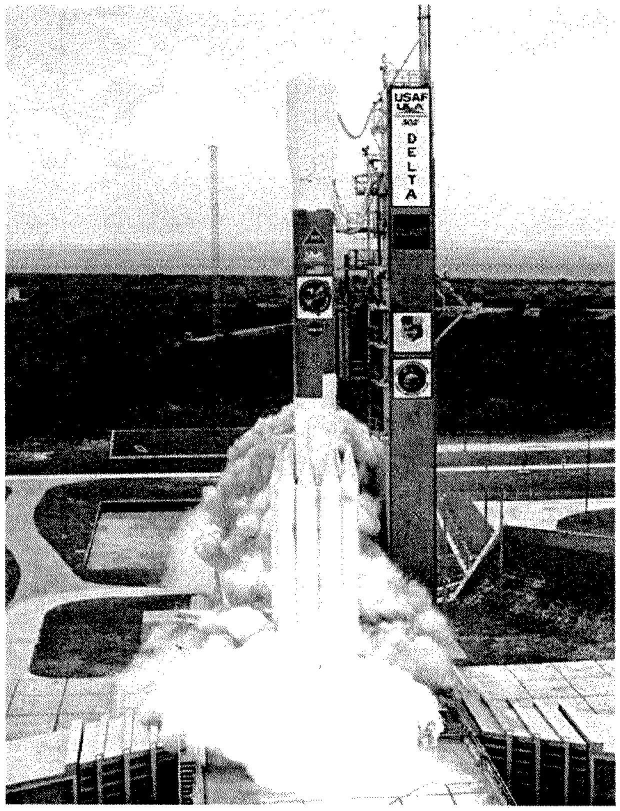
Fermi Gamma-ray Space Telescope



Fermi Gamma-ray Space Telescope – science highlights for the first two years on orbit

Alexander Moiseev

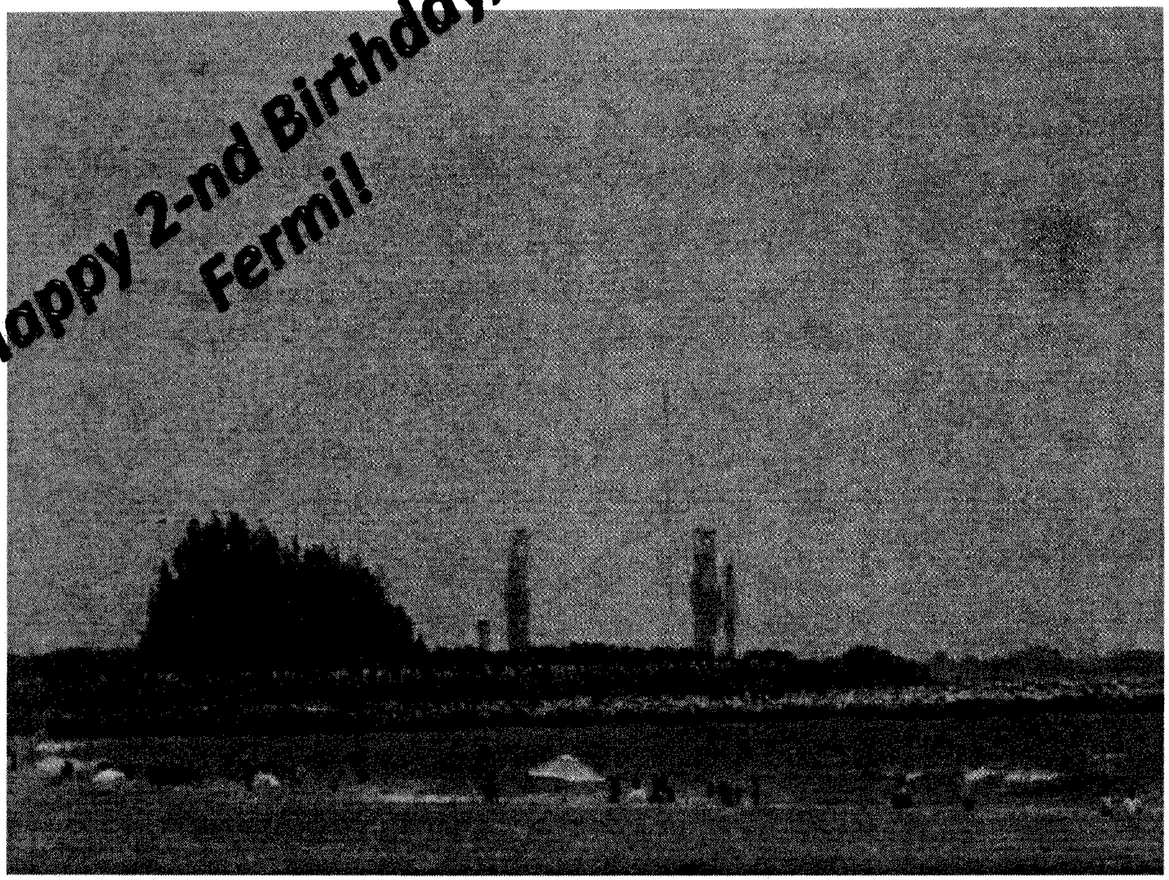
NASA Goddard Space Flight Center and University of Maryland

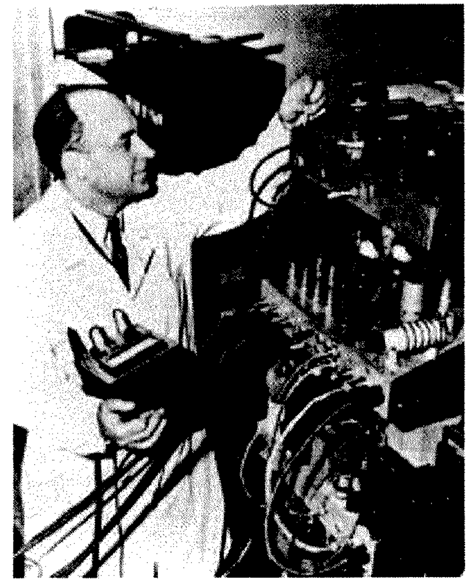
for the Fermi LAT Collaboration

Fermi Gamma-ray Space Telescope

Fermi Gamma-ray Space Telescope was launched on June 11, 2008

Happy 2-nd Birthday, Fermi!





1901 – 1954

...

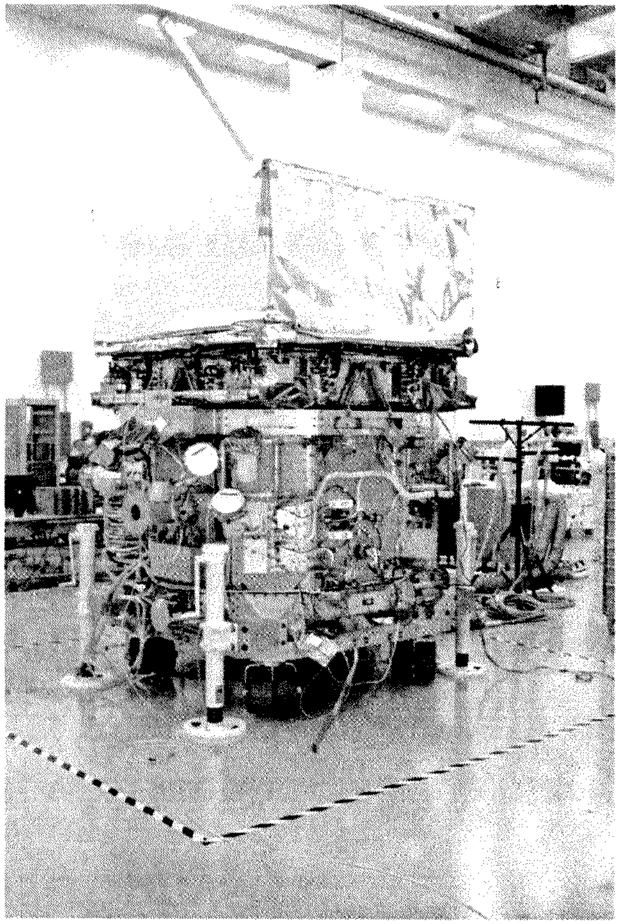
...

2008 - ......

"There are two possible outcomes: If the result confirms the hypothesis, then you've made a measurement. If the result is contrary to the hypothesis, then you've made a discovery. " Enrico Fermi

Alexander Moiseev *March 21, 2011* *SINP / MSU, Moscow*

The Fermi LAT Collaboration



Spacecraft with LAT and GBM before shipping to KSC

LAT collaboration

France
- IN2P3/LLR Ecole Polytechnique
- IN2P3/CENBG Bordeaux
- IN2P3/LPTA Montpellier
- CEA/Saclay
- CESR Toulouse

Germany
- MPI fuer extraterrestr. Physik, Garching

Italy
- INFN Bari, Padova, Perugia, Pisa, Rome, Trieste, Udine
- ASI
- INAF-IASF

Japan
- Hiroshima University
- ISAS/JAXA
- Tokyo Institute of Technology

Spain
- IEEC-CISC, Barcelona

Sweden
- Royal Institute of Technology (KTH)
- Stockholm University

United States
- Stanford University (HEPL/Physics, SLAC, KIPAC)
- UC Santa Cruz
- Goddard Space Flight Center
- Naval Research Laboratory
- Sonoma State University
- Ohio State University
- University of Washington
- University of Denver
- Purdue University – Calumet

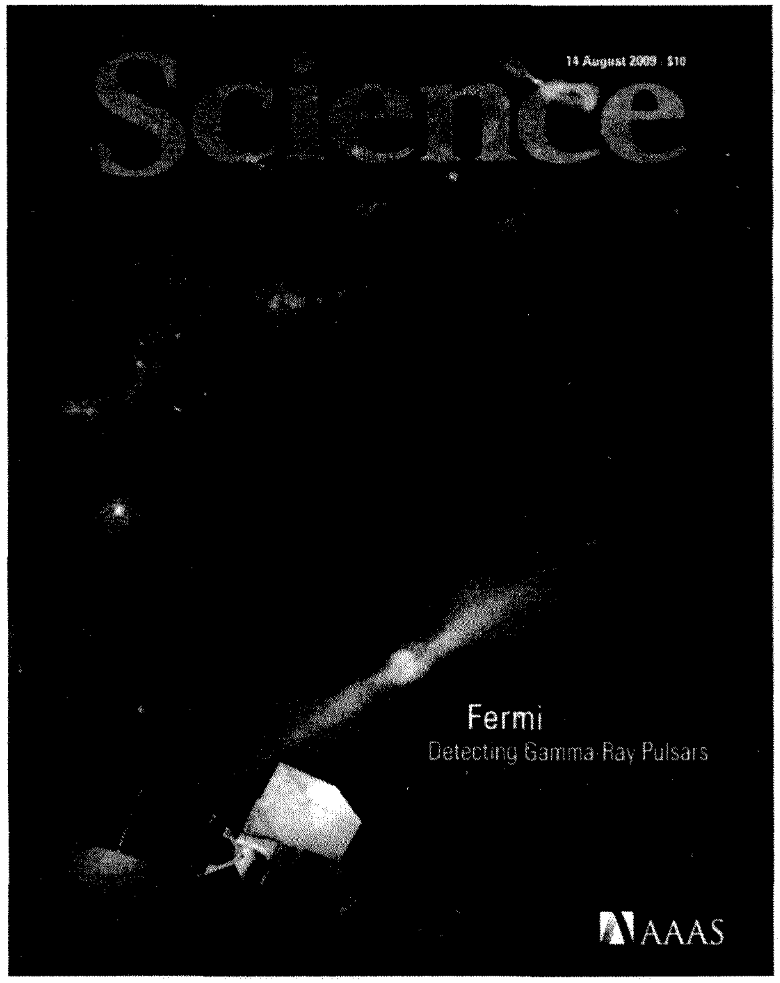
Fermi Science Questions

Fermi science objectives cover probably everything in high energy astrophysics:

- **How do super massive black holes in Active Galactic Nuclei create powerful jets of material moving at nearly light speed? What are the jets made of?**
- **What are the mechanisms that produce Gamma-Ray Burst (GRB) explosions? What is the energy budget?**
- **How does the Sun generate high-energy γ-rays in flares?**
- **How do the pulsars operate? How many of them are around and how different are they?**
- **What are the unidentified γ-ray sources found by EGRET?**
- **What is the origin of the cosmic rays that pervade the Galaxy?**
- **What is the nature of dark matter?**

Multiwavelength observations in cooperation with gamma-ray, X-ray, radio, and optical telescopes

Fermi results recognized as one of the top 10 science breakthroughs of 2009 (Science, December 2009)



Many discoveries in different topics. Fermi LAT Collaboration just has published its 100-th paper (~ 2,500 citations to date)

Each of these paper is a complete high-level analysis covering one of the topics listed above.

It is impossible to address all of them in one talk!
I will briefly go through the main results. Please do not hesitate to ask me for the details off line

Some Highlights

Fermi LAT successfully operates on the orbit for more than 2 years and demonstrates excellent performance, which is continuously monitored and calibrated. LAT collected > 100 billion on-orbit triggers

- **Discovery and study of >70 gamma-ray pulsars, 24 of which are found in "blind" search. 16 are millisecond (or "recycled" pulsars)**
  - **20 new millisecond radio-pulsars discovered thanks to LAT data (more are being found almost every week)!**
- **Remarkable high-energy emission from gamma-ray bursts**
- **Very high statistics measurement of the cosmic ray e^+e^- flux to 1 TeV**
- **Nailing down the diffuse galactic GeV emission**

Some Highlights (cont.)

- First Fermi determination of the isotropic (extragalactic) diffuse flux
- Early searches for Dark Matter signatures in different kinds of sources
- Many new results on supermassive black hole systems (AGN), including sources never seen in the GeV range
- More cosmic accelerators: Galactic X-ray binaries and supernova remnants. Probing the cosmic ray distributions in other galaxies: LMC and SMC
- Extragalactic Background Light constraints
- Year-one source catalog: 1451 sources
- High energy gamma-ray flares of Crab nebula detected

Fermi Large Area Telescope (LAT)

Fermi Gamma-ray Space Telescope

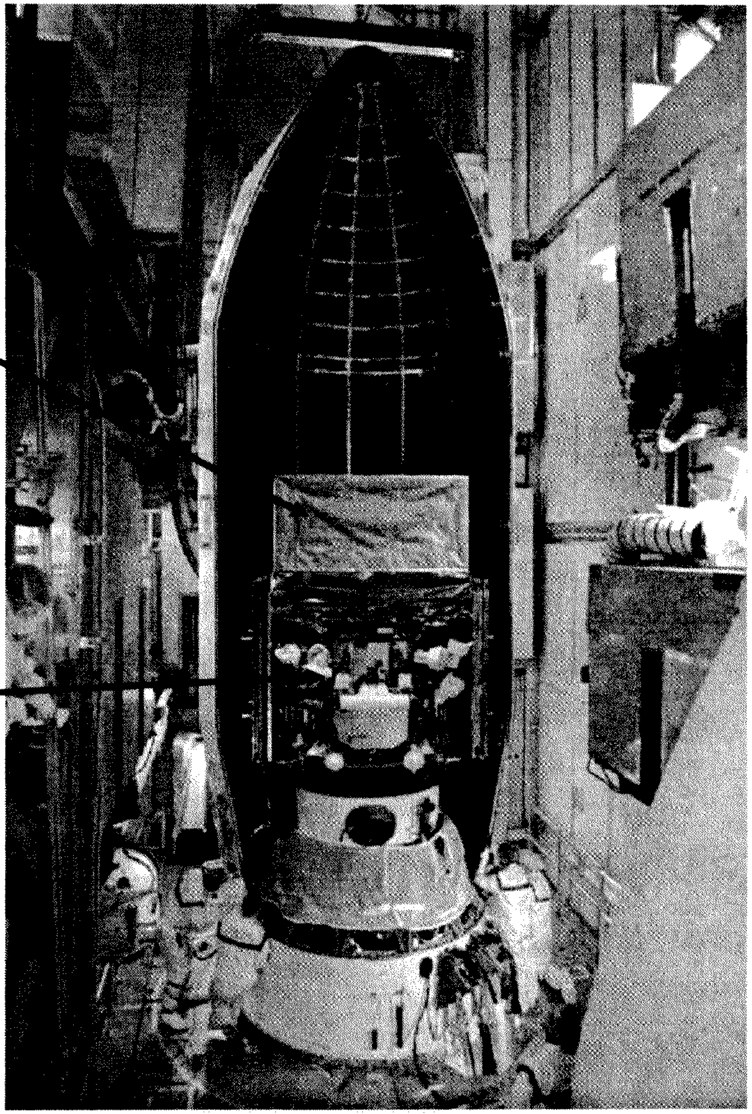
Two instruments onboard:

✓ **Large Area Telescope LAT**

- **main instrument, gamma-ray telescope, 20 MeV - >300 GeV**
- **scanning (main) mode - 20% of the sky all the time; all parts of sky for ~30 min. every 3 hours**

✓ **GLAST Burst Monitor GBM**

- **8 KeV – 40 MeV**
- **observes whole unocculted sky all the time, searching for gamma-ray bursts**



Large Area Telescope LAT

Heritage from OSO-III, SAS-II, COS-B, and EGRET, but:

- large field of view (2.4 sr at 1 GeV, 4 times greater than EGRET) and large effective area (~8000 cm^2 on axis at 1 GeV)
- large energy range, overlapping with EGRET under 10 GeV and with HESS, MAGIC, CANGAROO and VERITAS above 100 GeV, including poorly-explored 10 GeV – 100 GeV range.
- Good energy (<15% at E>100 MeV) and spatial resolution
  - Unprecedented PSF for gamma-rays, >3 times better than EGRET for E>1GeV
- Small dead time (<30 μs, factor of ~4,000 better than EGRET) – GRB time structure!
- Excellent timing to study transient sources
- No consumables – chance for longer mission!

The LAT Instrument Overview

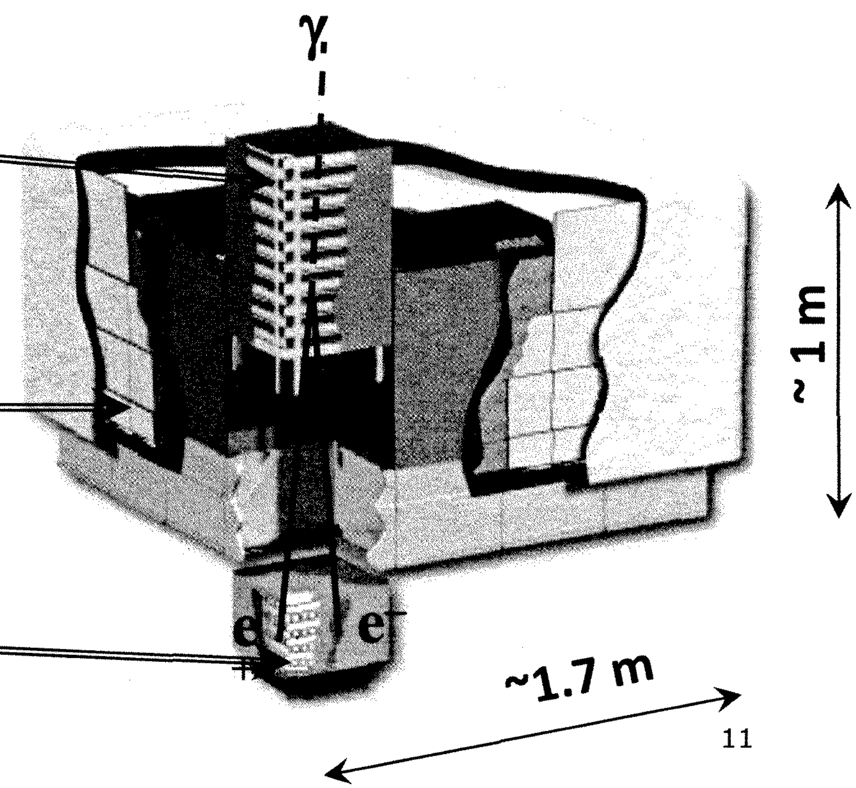
<u>Pair-conversion gamma-ray telescope:</u> 16 identical "towers" providing conversion of γ into e^+e^- pair and determination of its arrival direction (Tracker) and energy (Calorimeter). Covered by segmented AntiCoincidence Detector which rejects the charged particles background

<u>Silicon-strip tracker:</u> 18 double-plane single-side (x and y) interleaved with 3.5% X_0 thick (first 12) and 18% X_0 thick (next 4) tungsten converters. Strip pitch is 228 μm; total 8.8×10^5 readout channels

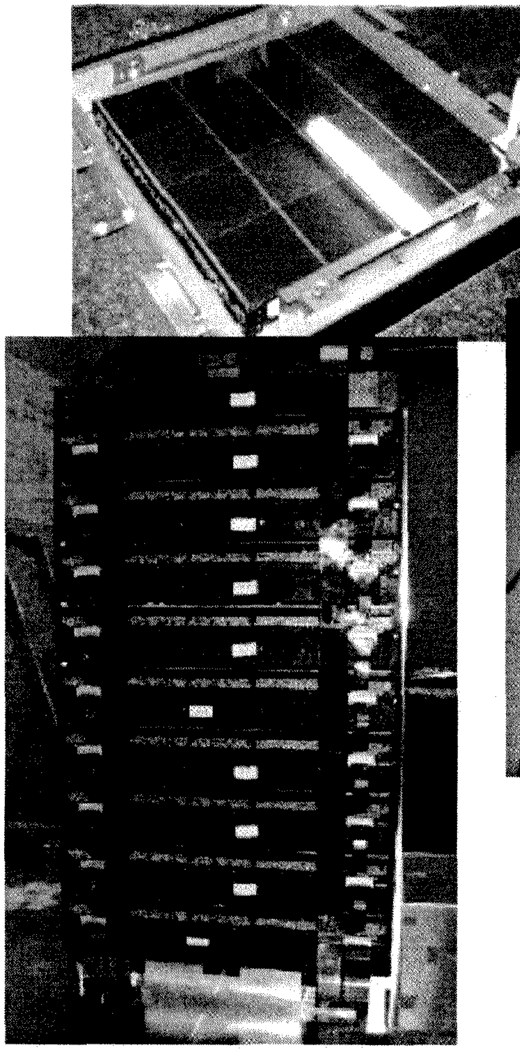
<u>Segmented Anticoincidence Detector:</u> 89 plastic scintillator tiles and 8 flexible scintillator ribbons. Segmentation reduces self-veto effect at high energy.

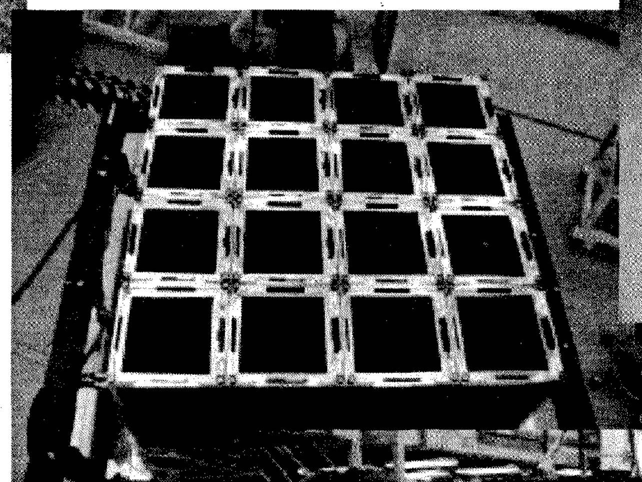
<u>Hodoscopic CsI Calorimeter</u> Array of 1536 CsI(Tl) crystals in 8 layers.

<u>Electronics System</u> Includes flexible, robust hardware trigger and software filters.



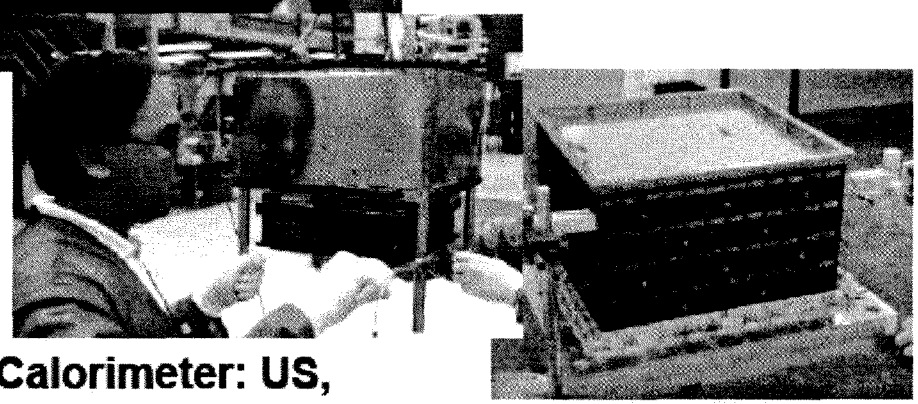
LAT Construction: An international effort





Integration & Data System: US

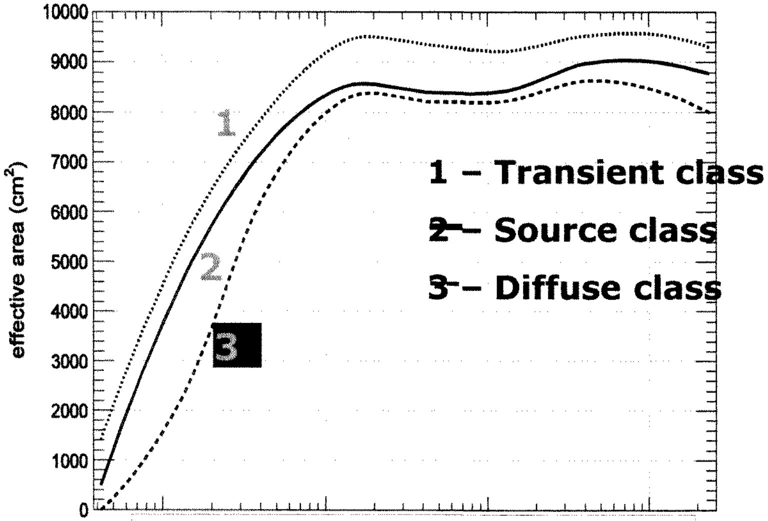
ACD: US

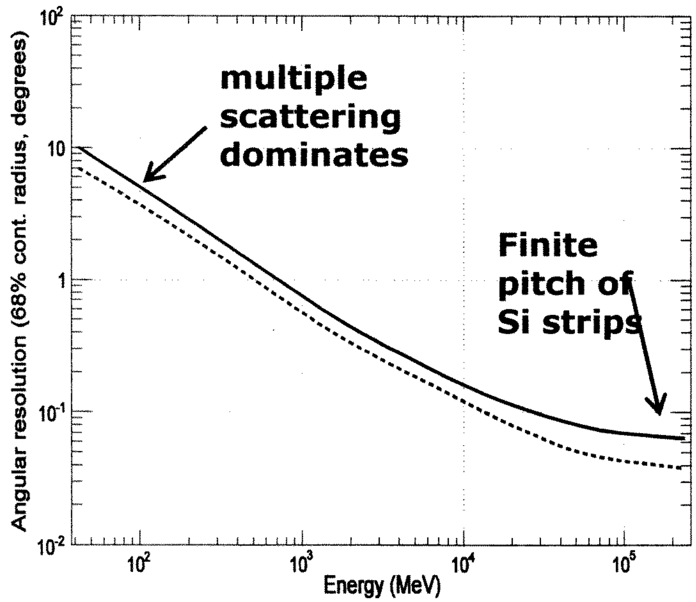


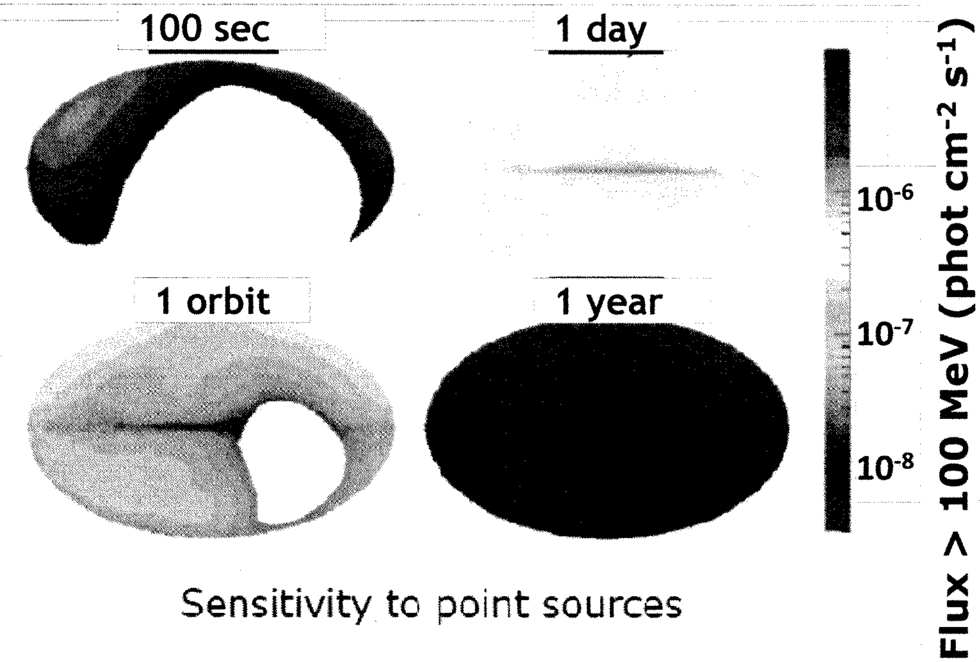
Tracker: US, Italy, Japan

Calorimeter: US, France, Sweden

LAT Performance







Sensitivity to point sources

One of the main features: **most of the time the LAT is operating in the sky-scanning mode, making it all-sky monitor, unlike EGRET and AGILE, and especially ground-based ACTs**

Gamma-Ray Sources

What we measure?

Gamma-ray sources, galactic and extragalactic:

- **Persistent sources. They should be detected against a diffuse background. This background allegedly comes from interactions of CR with ISM**
  - **The "background" includes unresolved sources and possibly some contribution from "new physics" phenomena**
  - **Source identification requires as high as possible angular resolution and as good as possible knowledge of background in order to determine statistical significance of the source**
- **Variable sources. Long (month-year scale) and short (day-hour-min etc) flare-like variability. Periodical variation (pulsars)**

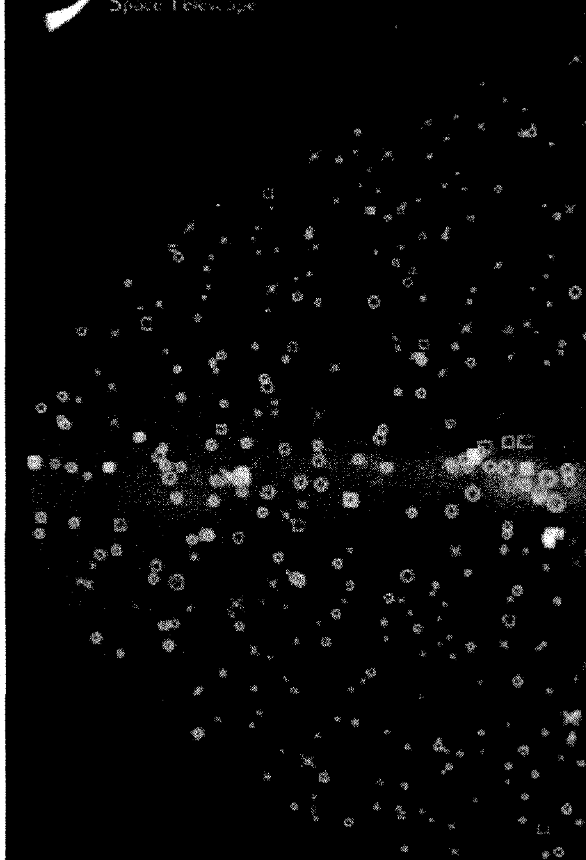
Diffuse gamma-ray radiation (background). **Accuracy depends on accounting for as many as possible discrete sources (whose contribution should be subtracted) , reliable modelling of CR interaction with ISM and IC scattering of CR electrons with CMB**

- **Galactic**
- **Extragalactic (high latitude)**

The Fermi LAT 1FGL Source Catalog

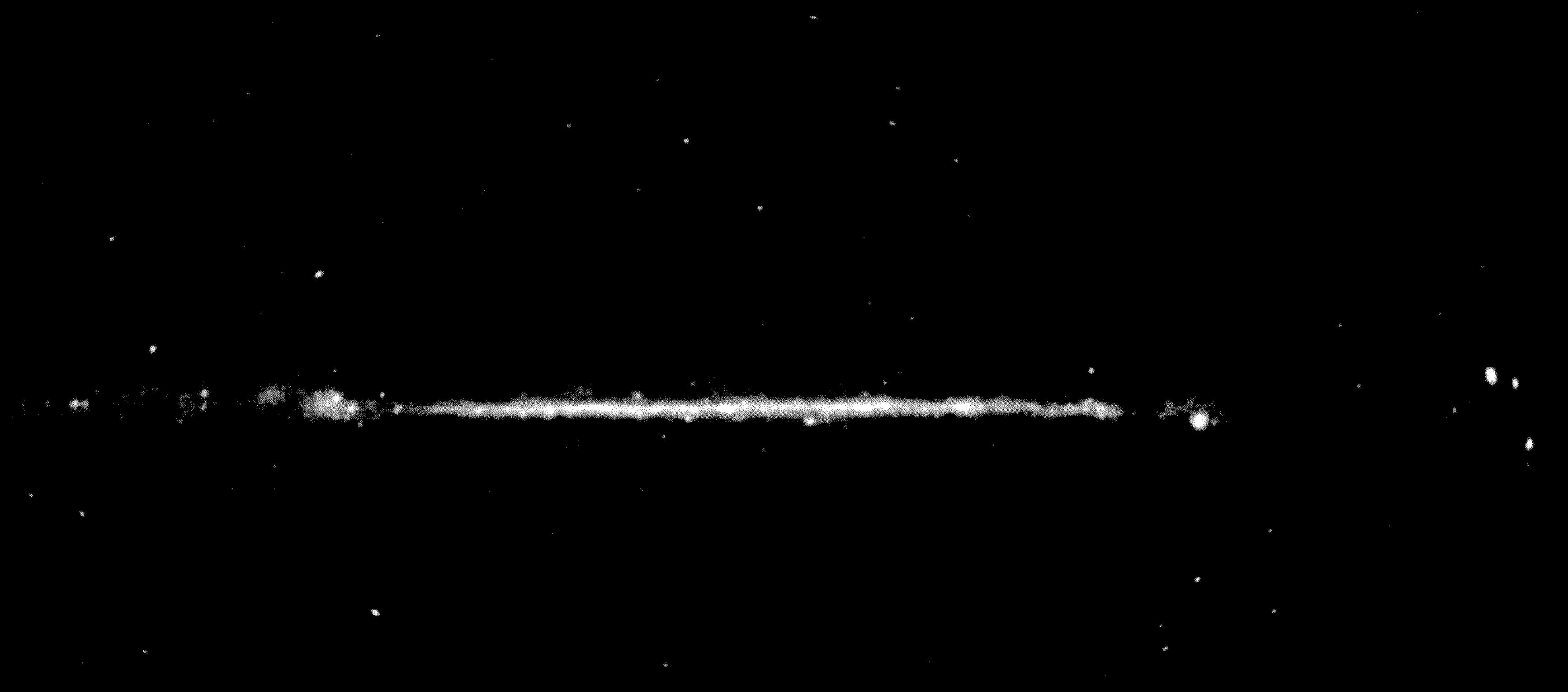
fermi
Gamma-ray Space Telescope

Description	Designator	Number Assoc. (ID)
Pulsar, X-ray or radio, identified by pulsations	psr (PSR)	7 (56)
Pulsar, radio quiet (LAT PSR, *subset of above*)	PSR	24
Pulsar wind nebula	pwn (PWN)	2 (3)
Supernova remnant	† (SNR)	41 (3)
Globular Cluster	glc (GLC)	8 (0)
Micro-quasar object: X-ray binary (black hole or neutron star) with radio jet	mqo (MQO)	0 (1)
Other X-ray binary	hxb (HXB)	0 (2)
BL Lac type of blazar	bzb (BZB)	295 (0)
FSRQ type of blazar	bzq (BZQ)	274 (4)
Non-blazar active galaxy	agn (AGN)	28 (0)
Active galaxy of uncertain type	agu (AGU)	92 (0)
Normal galaxy	gal (GAL)	6 (0)
Starburst galaxy	sbg (SBG)	2 (0)
Unassociated		630



Credit: *Fermi* Large Area Telescope Collaboration

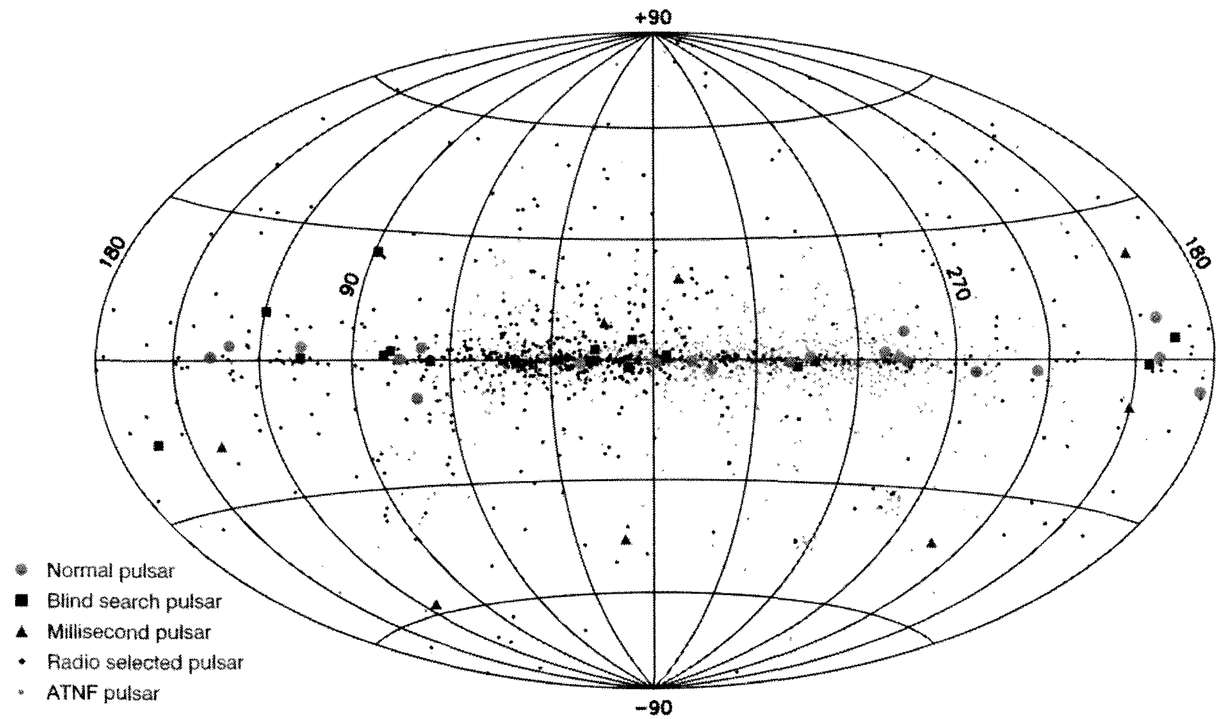
Fermi two-year all-sky map



Credit: NASA/DOE/Fermi/LAT Collaboration

Pulsars in 1FGL: LAT Pulsar Catalog

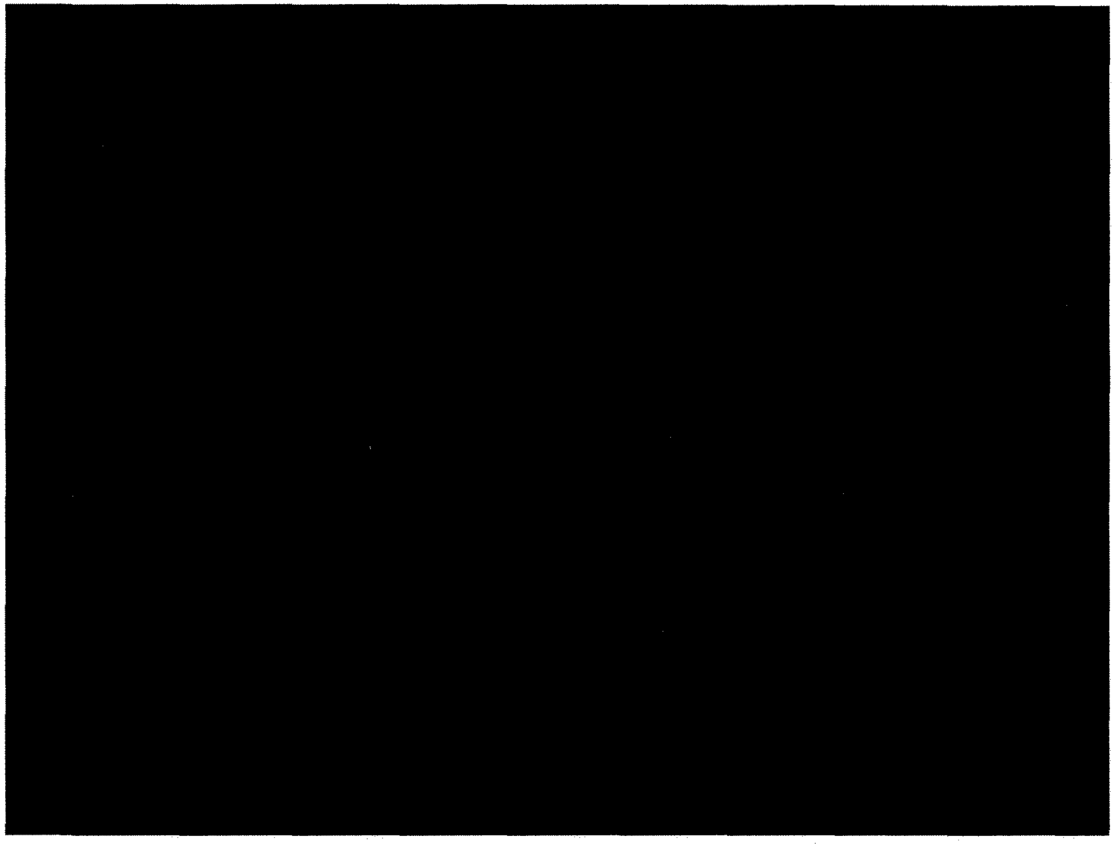
- Comprehensive, uniform presentation of 46 pulsars detected by the LAT using the first 6 months of LAT data (now >60 LAT-detected pulsars)
- Of the 46, 16 resulted from blind searches, and 24 were discovered using ephemerides from radio monitoring*, including 8 MSPs



- Light curves (with tabulated peak phases), spectral fits, log N-log S

* Consortium of radio & X-ray astronomers; Smith et al. (2008)

The Pulsing gamma-ray Sky. More than 60 gamma-ray pulsars are now known.



- New pulsars discovered in a blind search
- Millisecond radio pulsars
- Young radio pulsars
- Pulsars seen by EGRET

Fermi Pulsar Detection

Pulses at 1/10th true rate

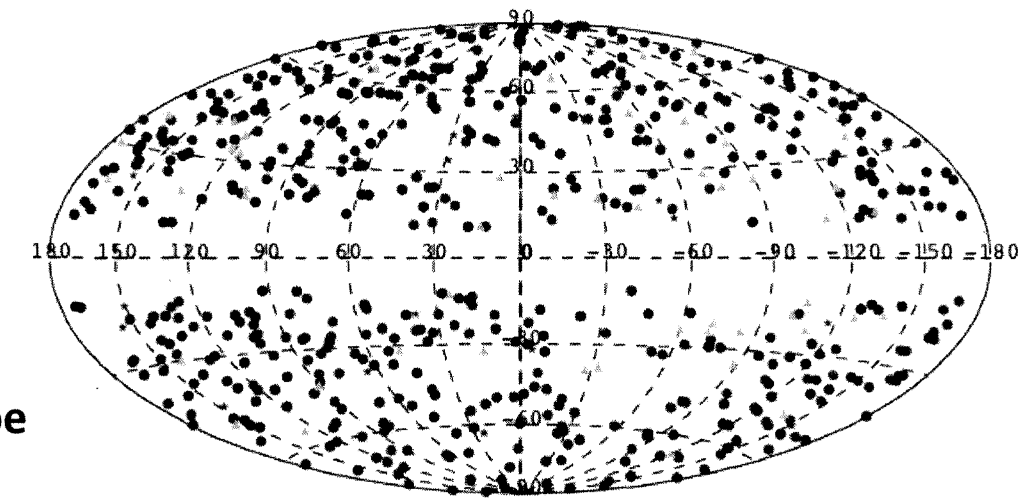
Fermi
Gamma ray
Space Telescope

AGNs in 1FGL: First LAT AGN Catalog (1LAC)

Based on 1FGL sources associated with AGN, but for $|b| > 10^{\circ}$ & includes lower-confidence associations (down to $P = 0.5$)

- 671 1FGL sources: 300 BL Lacs, 296 FSRQs, 41 AGNs of other types, 72 of unknown type (some multiple associations)

FSRQ
BL Lacs
Radio galaxies
AGNs unknown type



1LAC paper also lists 51 low-latitude associations and 104 high-latitude 'affiliations' (plausible associations for which quantitative probabilities could not be defined)

AGNs – most numerous sources (about half of 1FGL) detected by Fermi LAT

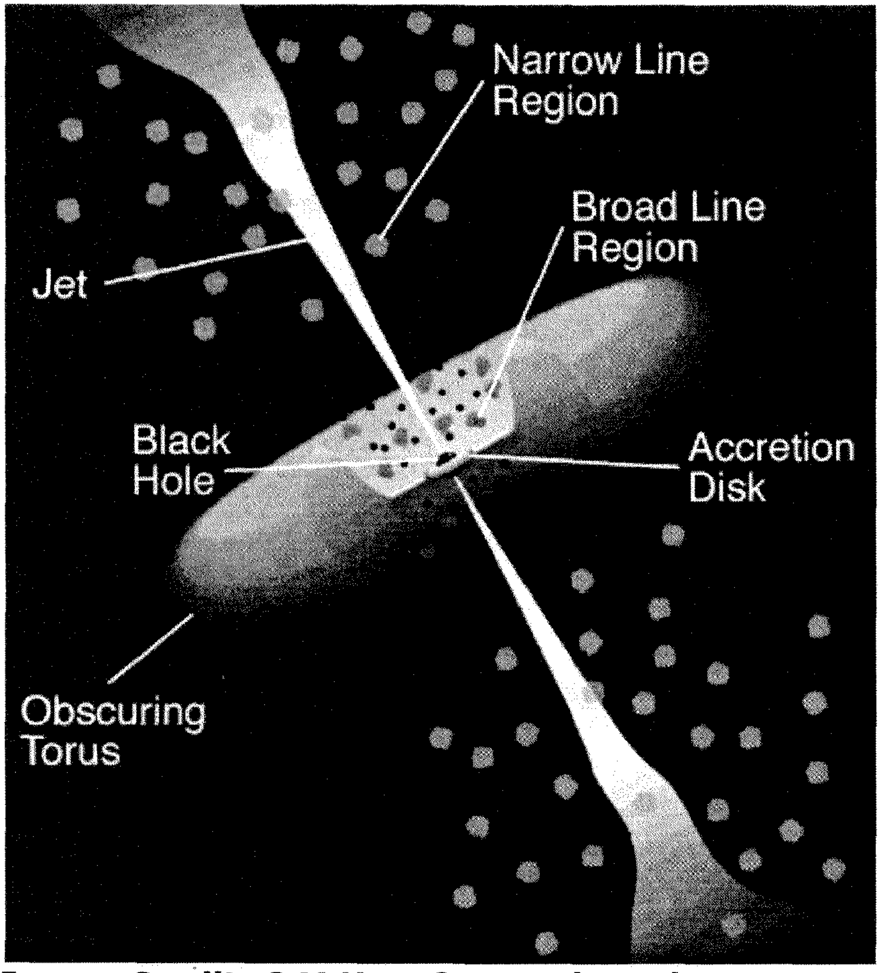
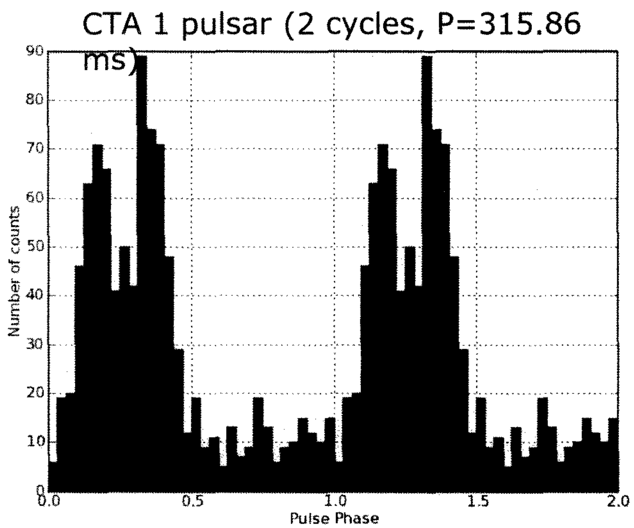


Image Credit: C.M.Urry & P. Padovani

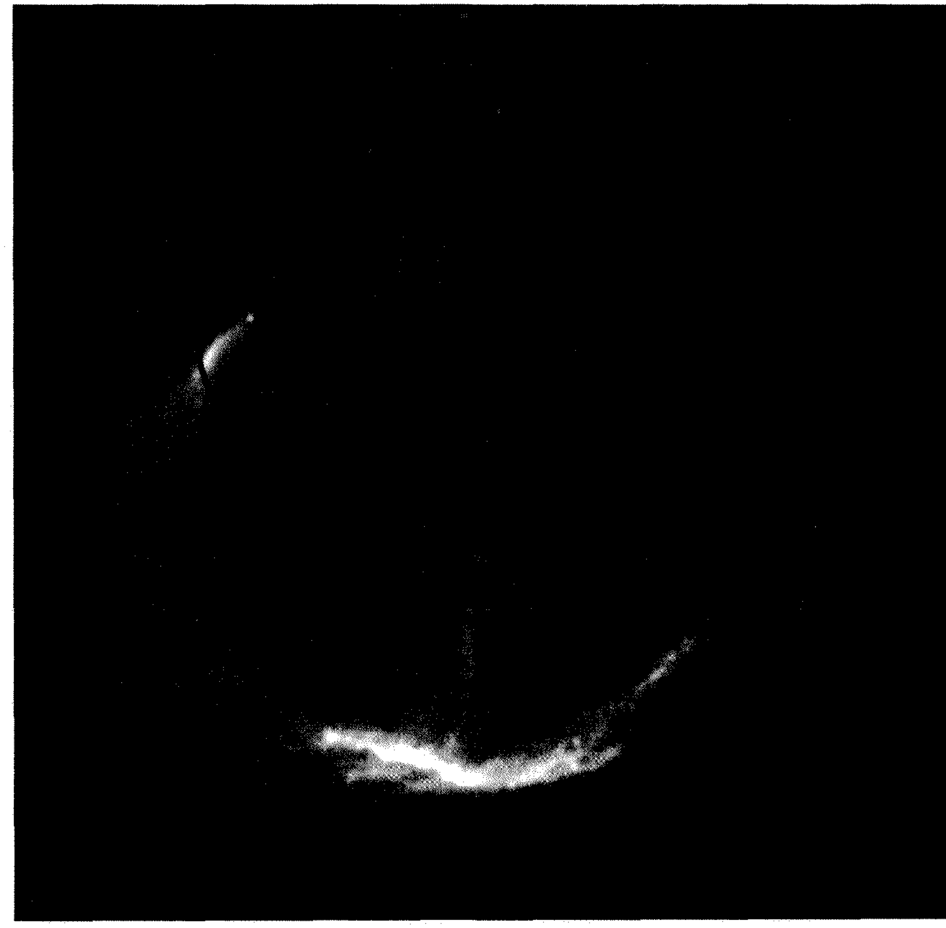
- *Powered by accretion onto a central, supermassive black hole*
- *Accretion disks produce optical/UV/X-ray emission via various thermal processes*
- *Jets: highly collimated outflows with Γ~10*
  - *Large brightness temps, superluminal motion, rapid variability in γ-rays*
- *Unified Model: observer line-of-sight determines source properties, e.g., radio galaxy vs blazar*
- *Other factors: accretion rate, BH mass and spin, host galaxy*

CTA 1 – First gamma-ray pulsar discovered by Fermi in blind search



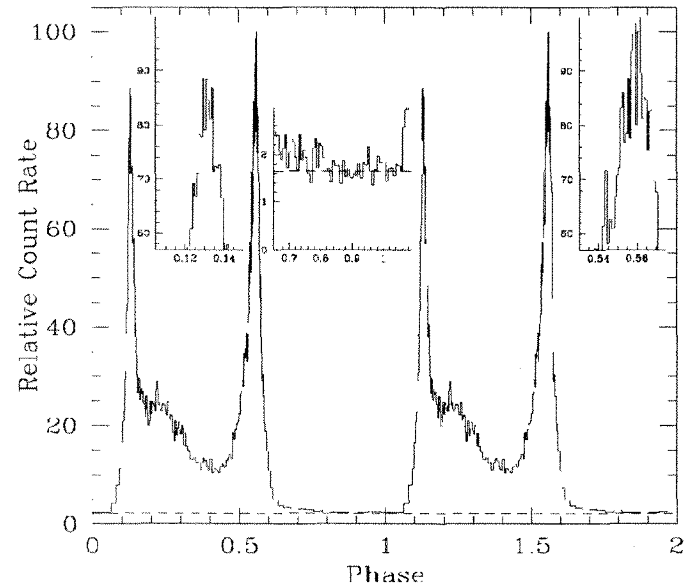
Exhibits all characteristics of a young high-energy pulsar (characteristic age ~1.4 x 10^4 yr), which powers a synchrotron pulsar wind nebula embedded in a larger SNR.

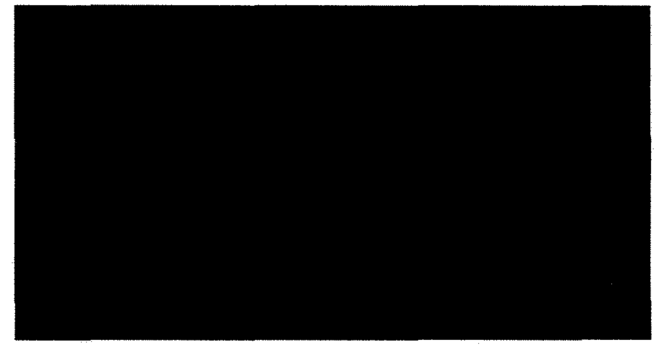
This source was a very bright AND well positioned unidentified EGRET source. This source was deliberately targeted during LAT checkout

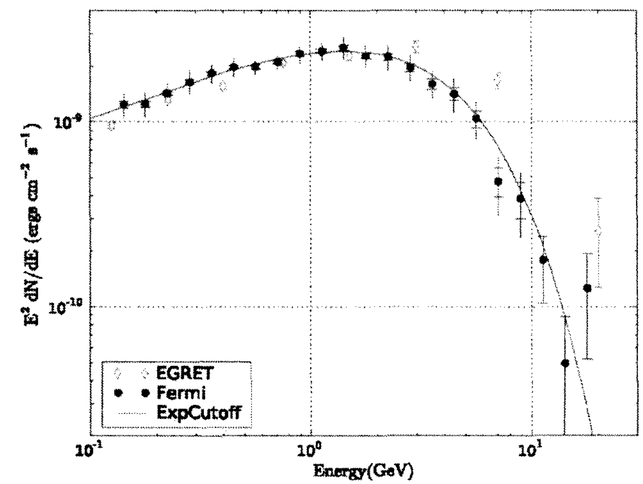


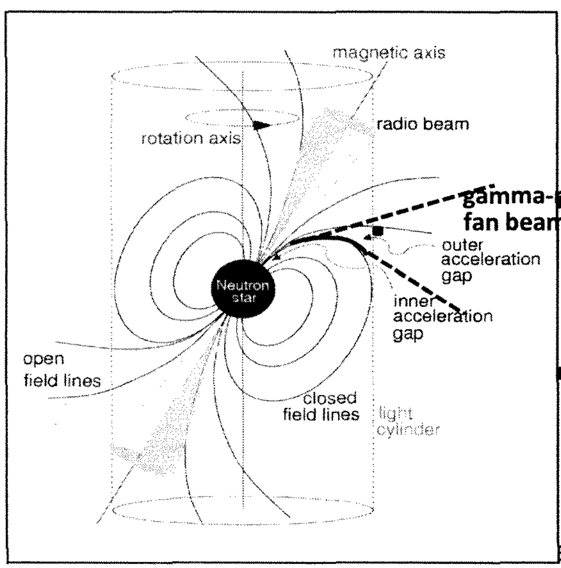
Gamma-ray source at l,b = 119.652, 10.468; 95% error circle radius =0.038° contains the X-ray source RX J00070+7302

Vela Pulsar – very first target for Fermi, used for calibration







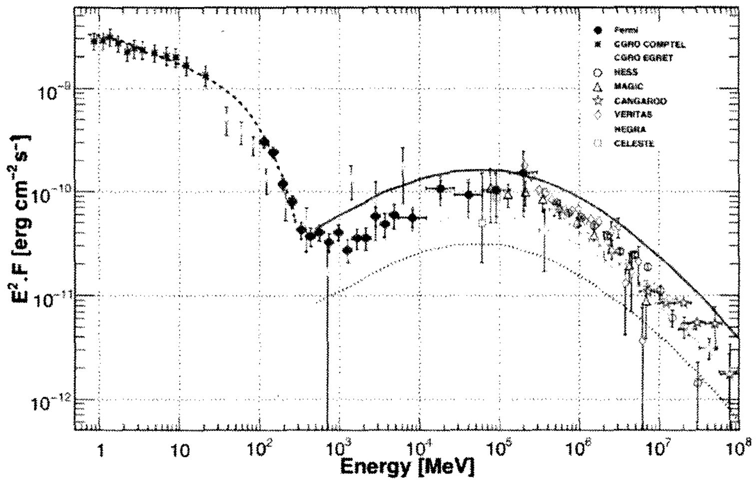


- **Acceleration in Magnetosphere**
  - **Outer magnetosphere**
  - **Near the NS surface**
- **LAT data consistent with simple exponential cut-off**
  - **favors outer-gap model**

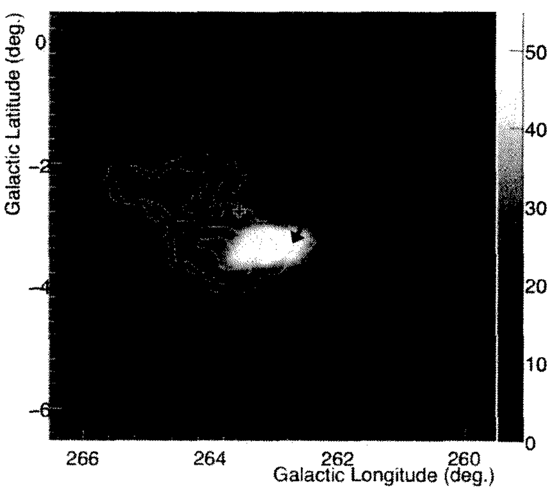
$$N(E) = N_0 E^{\Gamma} e^{-(E/E_c)^b}$$
$$\Gamma = -1.5^{+0.05}_{-0.04}$$
$$E_c = 2.9 \pm 0.1 \text{ GeV}$$

Pulsar Wind Nebulae - Powerful Particle Accelerators

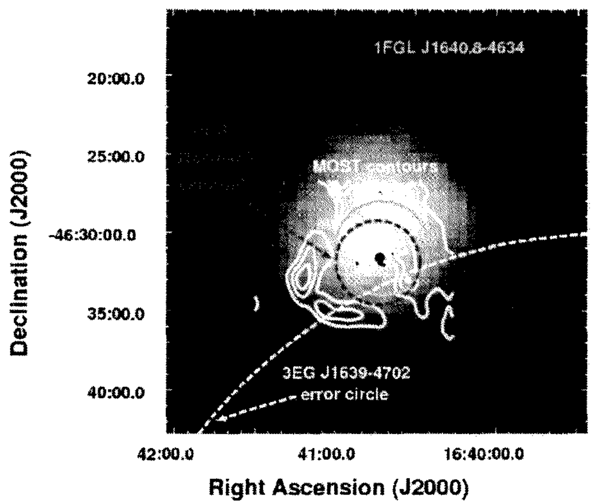
Fermi Gamma-ray Space Telescope



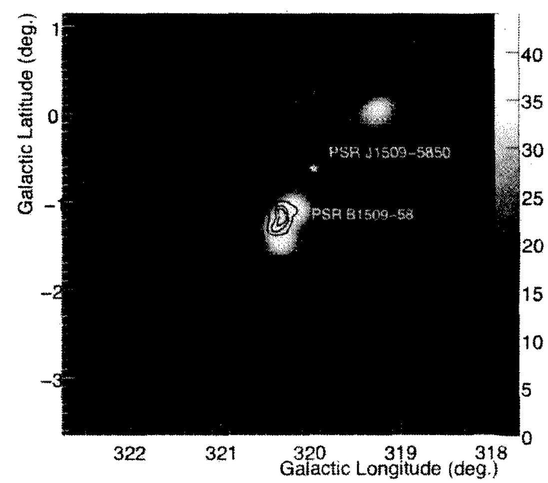
Crab Nebula Spectral Energy Distribution. Red points are Fermi LAT data, showing transition from synchrotron to Compton components.



E>800 MeV Test Statistic (significance) map. PWN Vela X

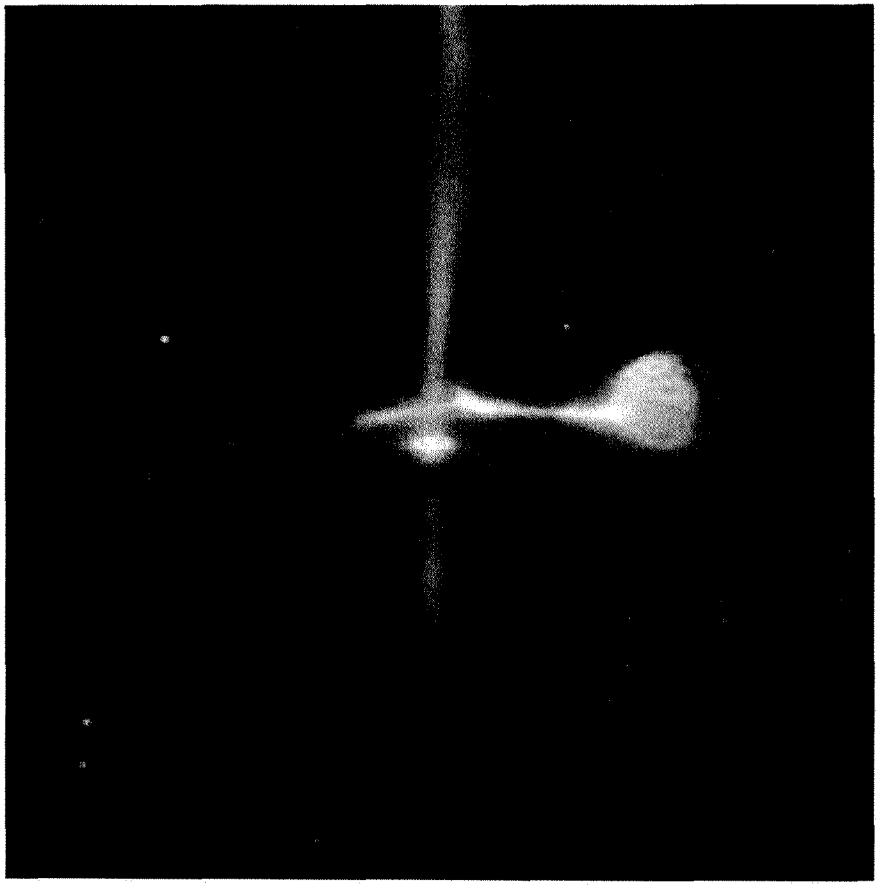


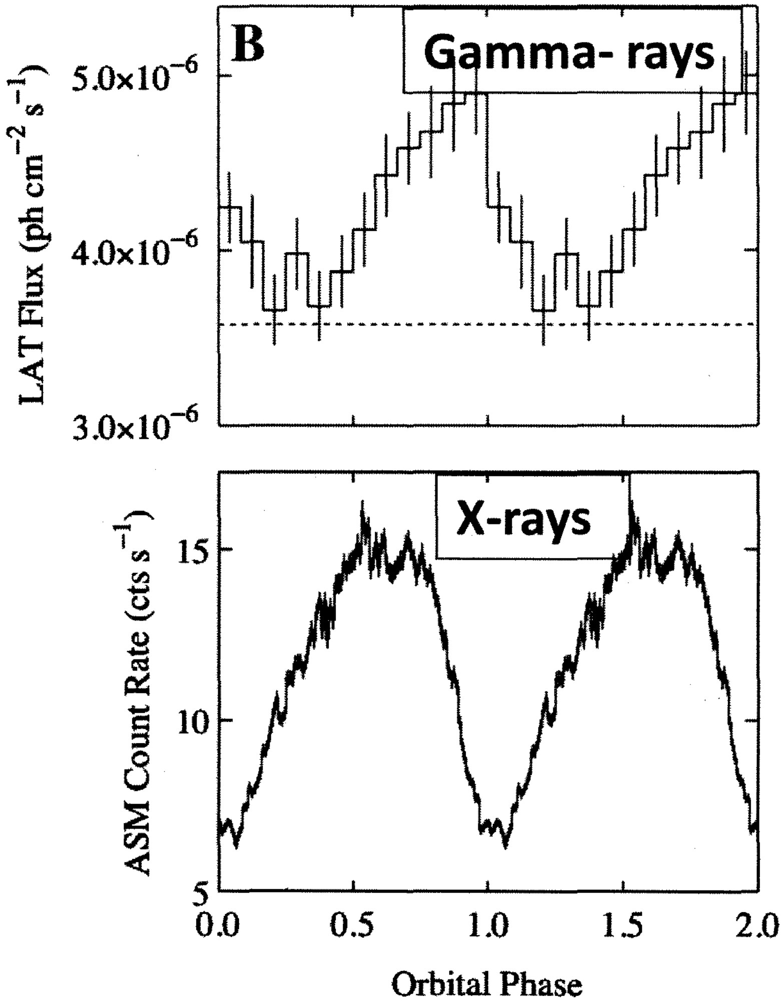
E>2 GeV counts map. PWN HESS J1640-465



E>10 GeV counts map. PWN MSH 15-52

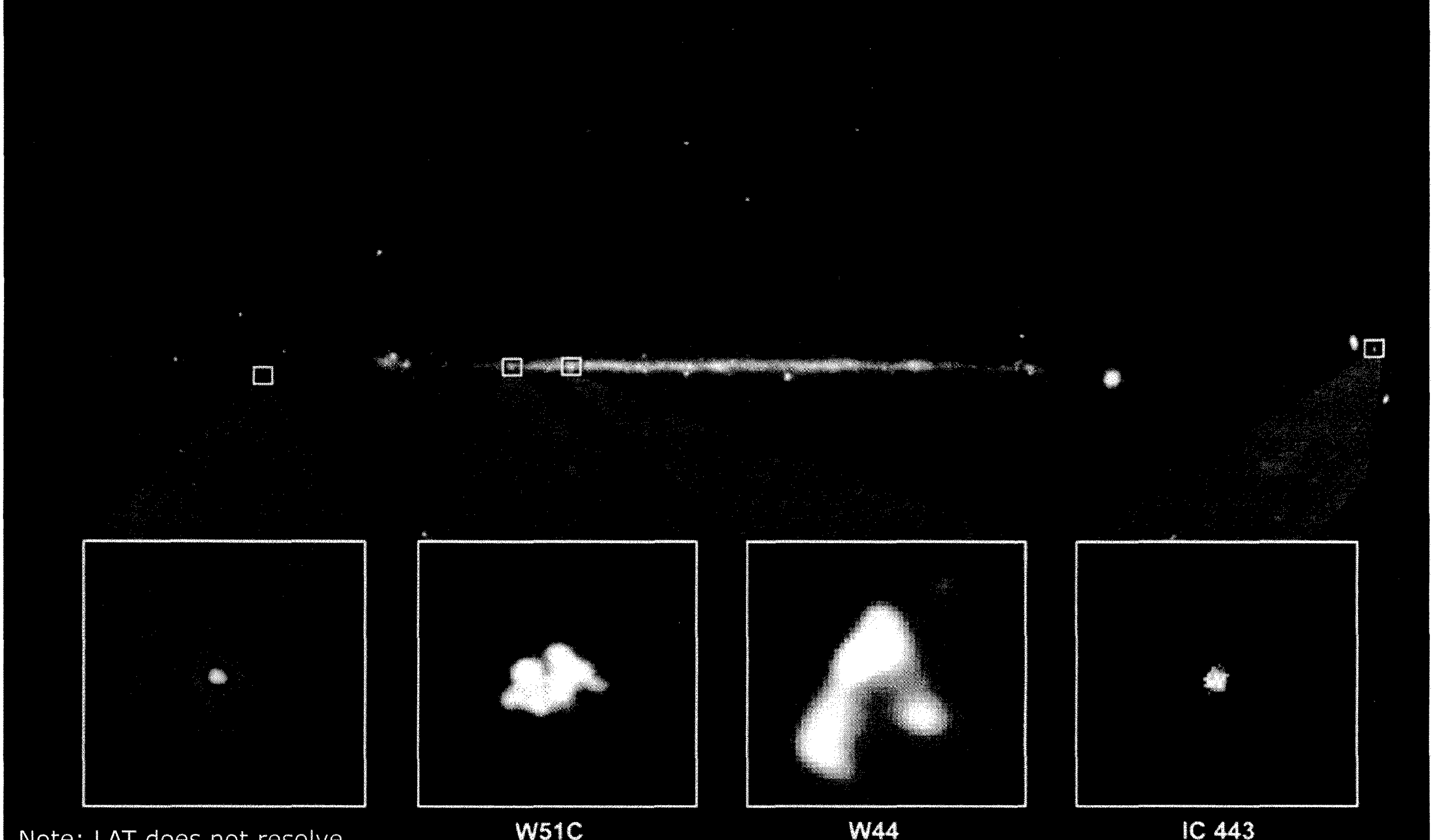
Cygnus X-3 - Binary System - 4.8 Hour Period





Neutron star or black hole binary system, accelerating particles to high energies. The system remains largely a mystery.

Supernova Remnants (SNR) - Spatially Resolved

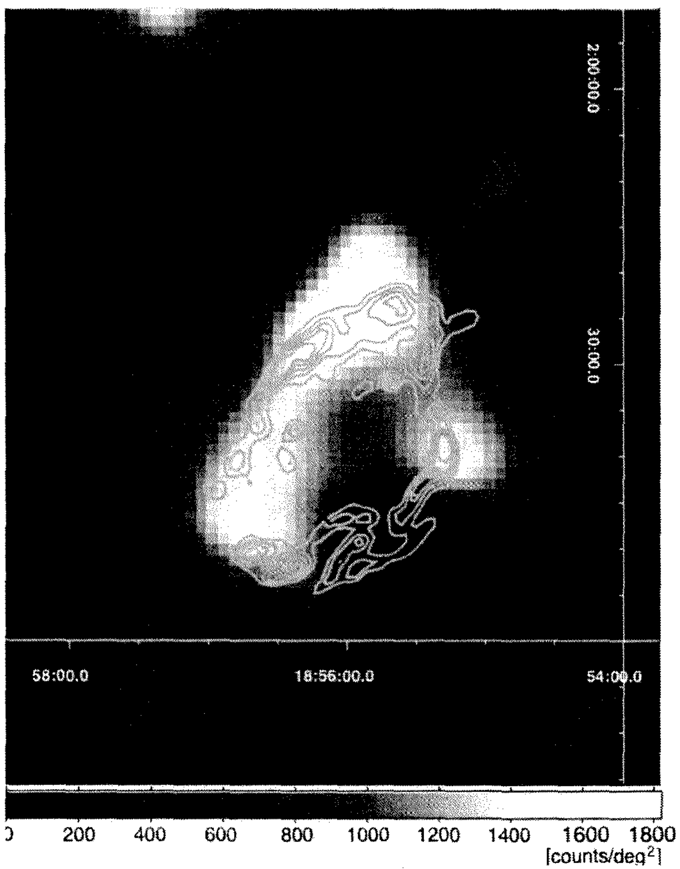


Note: LAT does not resolve
Cas A

Fermi Gamma ray Space Telescope

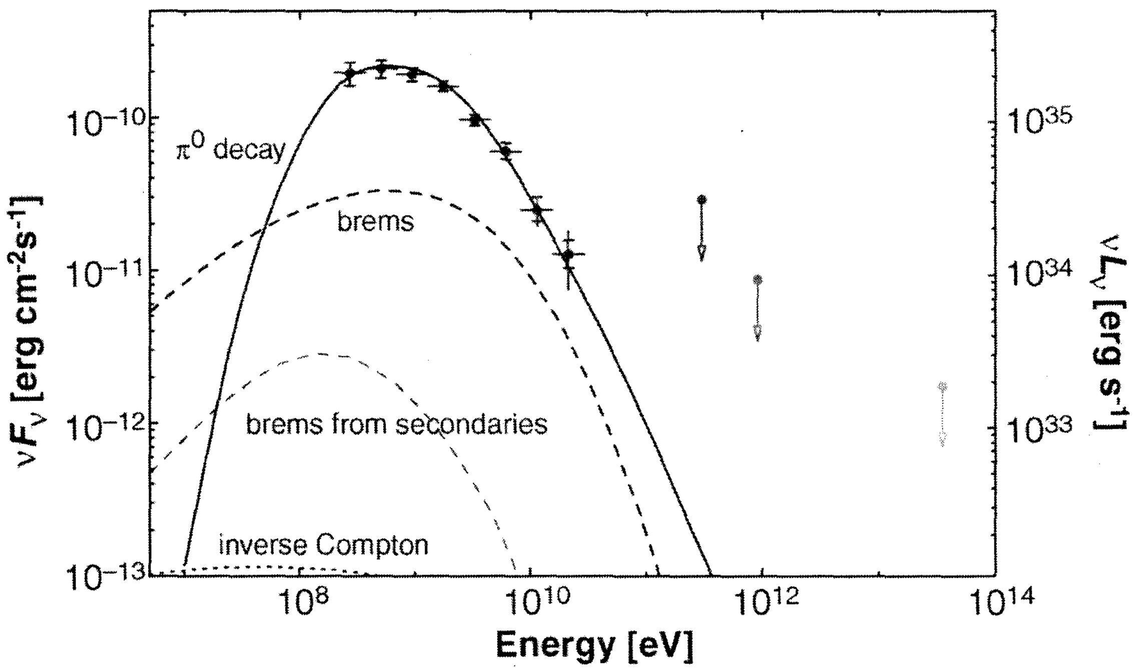
Supernova remnant W44

Well spatially resolved. 2-10 GeV front-converting (high quality) events, deconvolved image.



Green contours are from Spitzer IRAC, shocked H_2

Black cross is PSR B1853+01, not seen as a pulsed

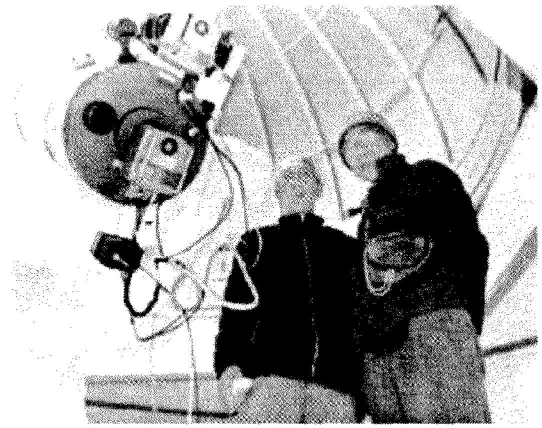


Note: leptonic models are not excluded. Neutrinos could confirm the acceleration of hadrons by SNR. 27

A Surprise - A Gamma-ray Nova

Fermi Gamma-ray Space Telescope

- **In early March, the LAT skywatchers found a new, flaring gamma-ray source in the Cygnus region**
- **To our surprise, we learned that an optical flare of the symbiotic system V407 Cyg (red giant/white dwarf binary) had occurred at about the same time. It was observed by amateur Japanese astronomers Koichi Nishiyama and Fujio Kabashima**



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e-mail: cbat@iau.org; cbatiau@eps.harvard.edu
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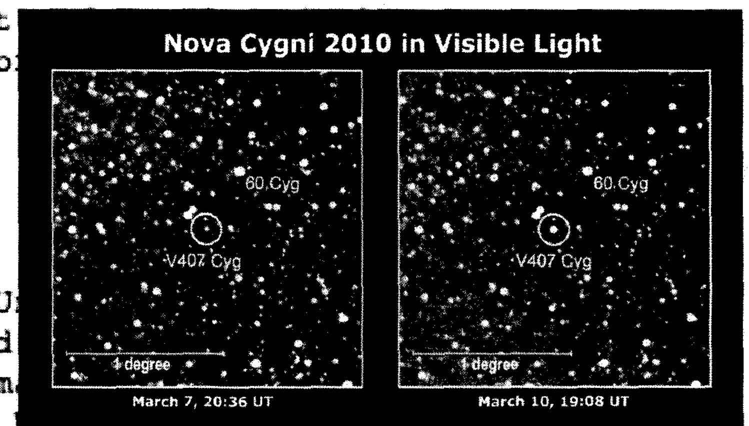
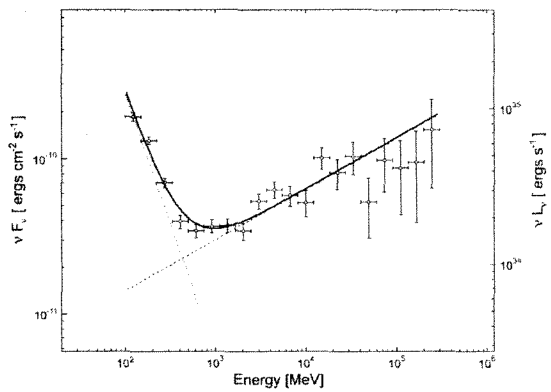
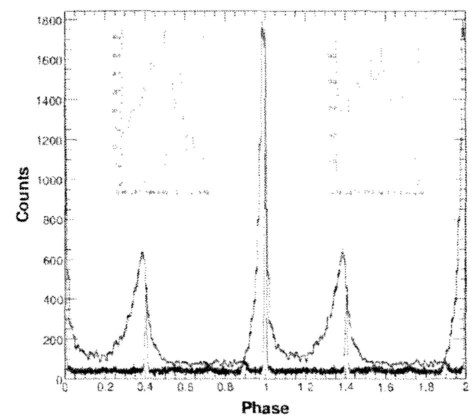


V407 CYGNI
Hiroyuki Maehara, Kwasan Observatory, Kyoto U
discovery by Koichi Nishiyama (Fukuoka, Japan) and
Japan) of an apparent unusually bright outburst (m
star V407 Cyg on an unfiltered CCD image taken on
105-mm camera lens (+ SBIG STL6303E camera). Nishiyama and Kabashima
confirmed the outburst on two unfiltered CCD frames taken on Mar. 10.813 (at
mag 6.8) and 10.814 (mag 6.9) using a 0.40-m reflector (+ SBIG STL1001E

Crab Flares in high energy!

- Remnant from 1054 AD SN at 2 kpc
- Standard candle in X-rays and VHE
- Yearly variable in X-rays ~ 3.5%, 1-150 MeV ~ 40%



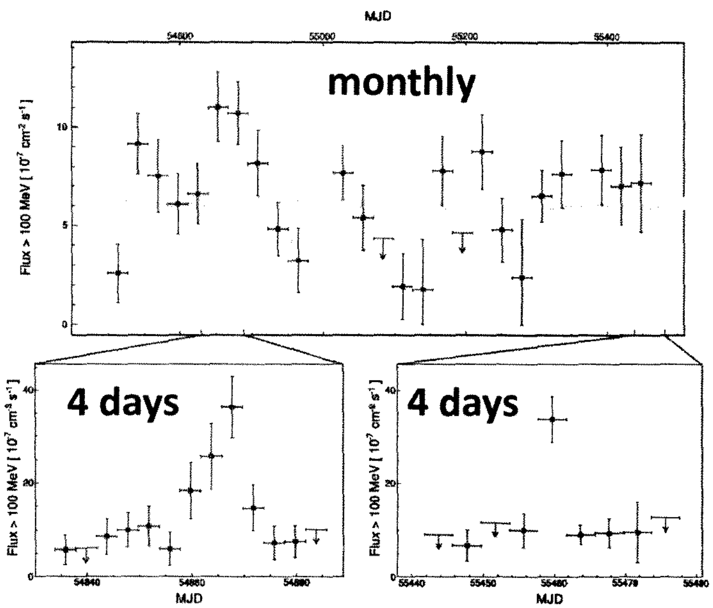


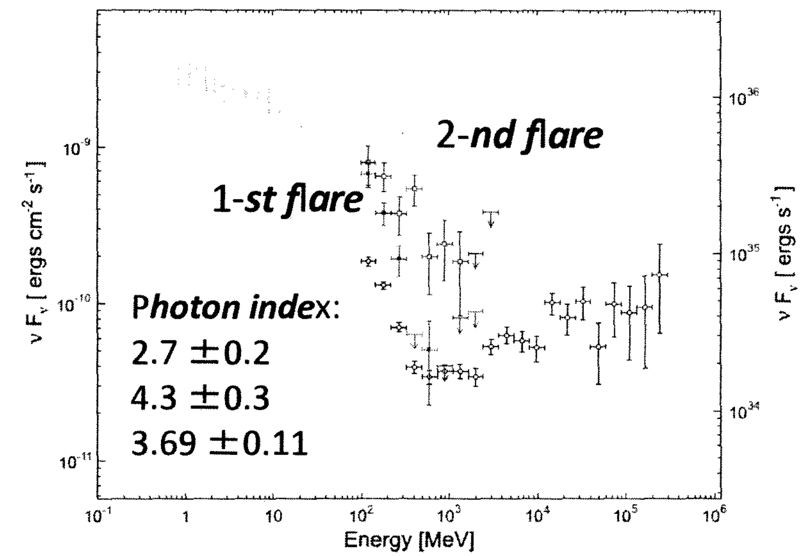
Spectrum between pulses (off-pulse) to remove pulsar contribution

Crab Flares (cont.)

Two flares detected by Fermi LAT:

- **flux increase by a factor ~4 during ~ 16 days (January 26 to February 11, 2009)**
- **Flux increase by a factor of ~6 during ~4 days (September 18-22, 2010). First reported by AGILE**
- **No variation (< 5%) found in pulsed emission and nebula IC component**





- **Second (short) flare has harder spectrum and extends > 1 GeV at >3σ**
- **Energy release small compared to pulsar spin down**

Nothin

PCL XL error
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