Gamma-ray Astrophysics: An Introduction

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Outline

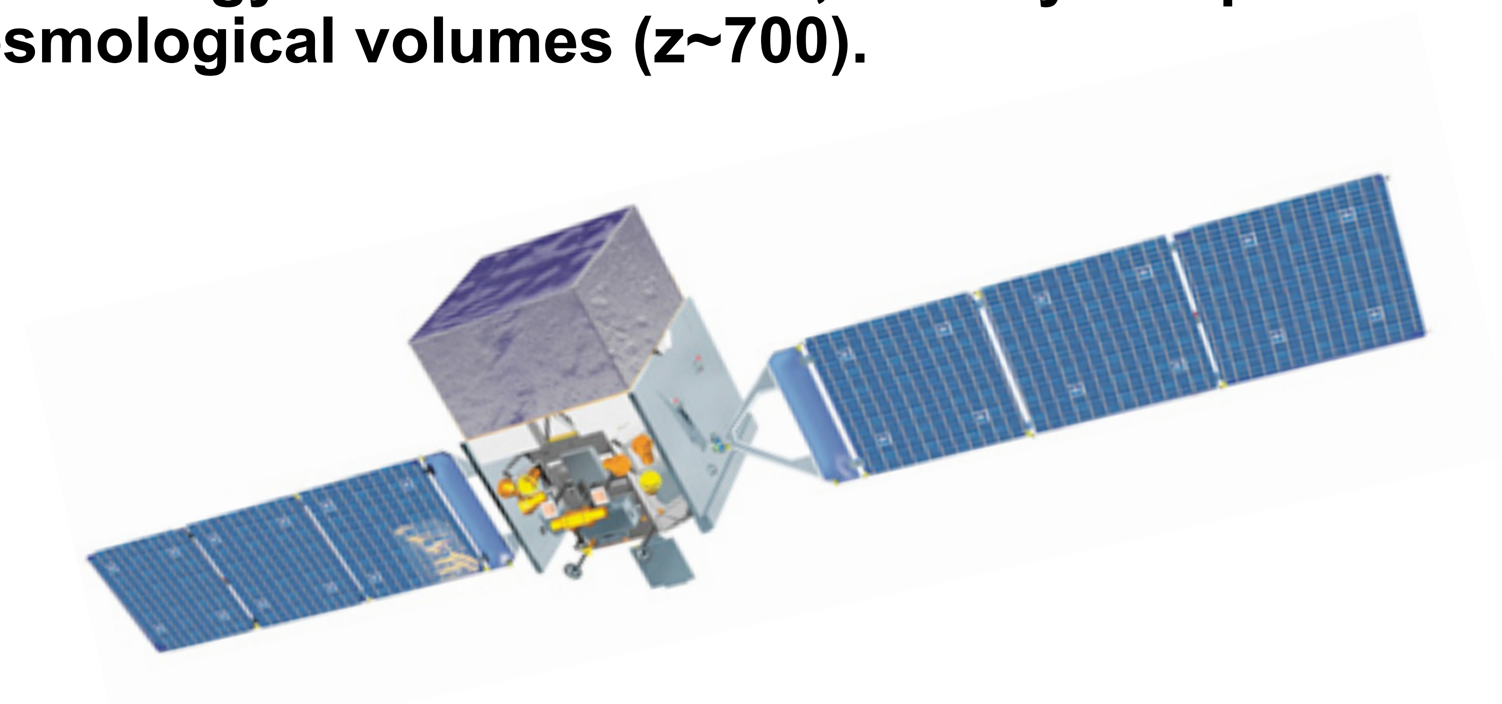
- Introduction - Gamma rays in space
- The Fermi Gamma-ray Space Telescope
  - Gamma-ray Burst Monitor (GBM)
  - Large Area Telescope (LAT)
- The High-Energy Gamma-ray Sky
  - Bursts, blazars, pulsars, and more
- Current Status and Future Plans

Astrophysics - Some Reminders

- The basic questions of astrophysics are twofold:
  - What is out there in the Universe?
  - How do those things work?
- For anything beyond our Solar System, we learn about the Universe by what comes to us - light and particles
- Different types of light (wavelength, frequency, photon energy) carry information about different objects and different physical processes.

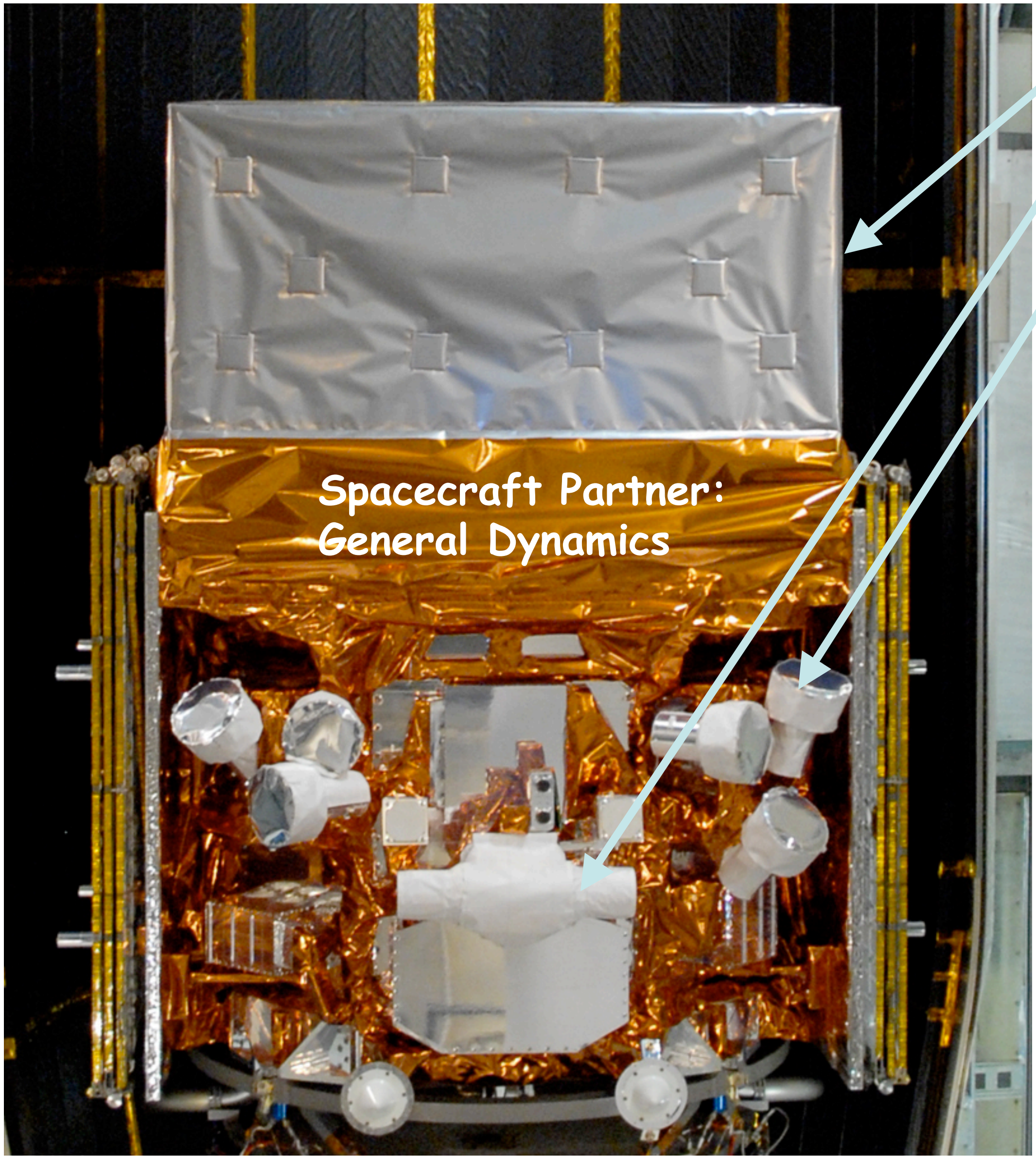
Why Study Gamma rays?

- Gamma rays offer a direct view into Nature's most powerful accelerators.
  - Past missions have shown that the γ-ray sky is dynamic, revealing information about extreme objects like pulsars, blazars, and supernovae.
- The Universe is mainly transparent to gamma rays with energy less than 20 GeV, so they can probe cosmological volumes (z~700).



The Fermi Gamma-ray Space Telescope

The Observatory



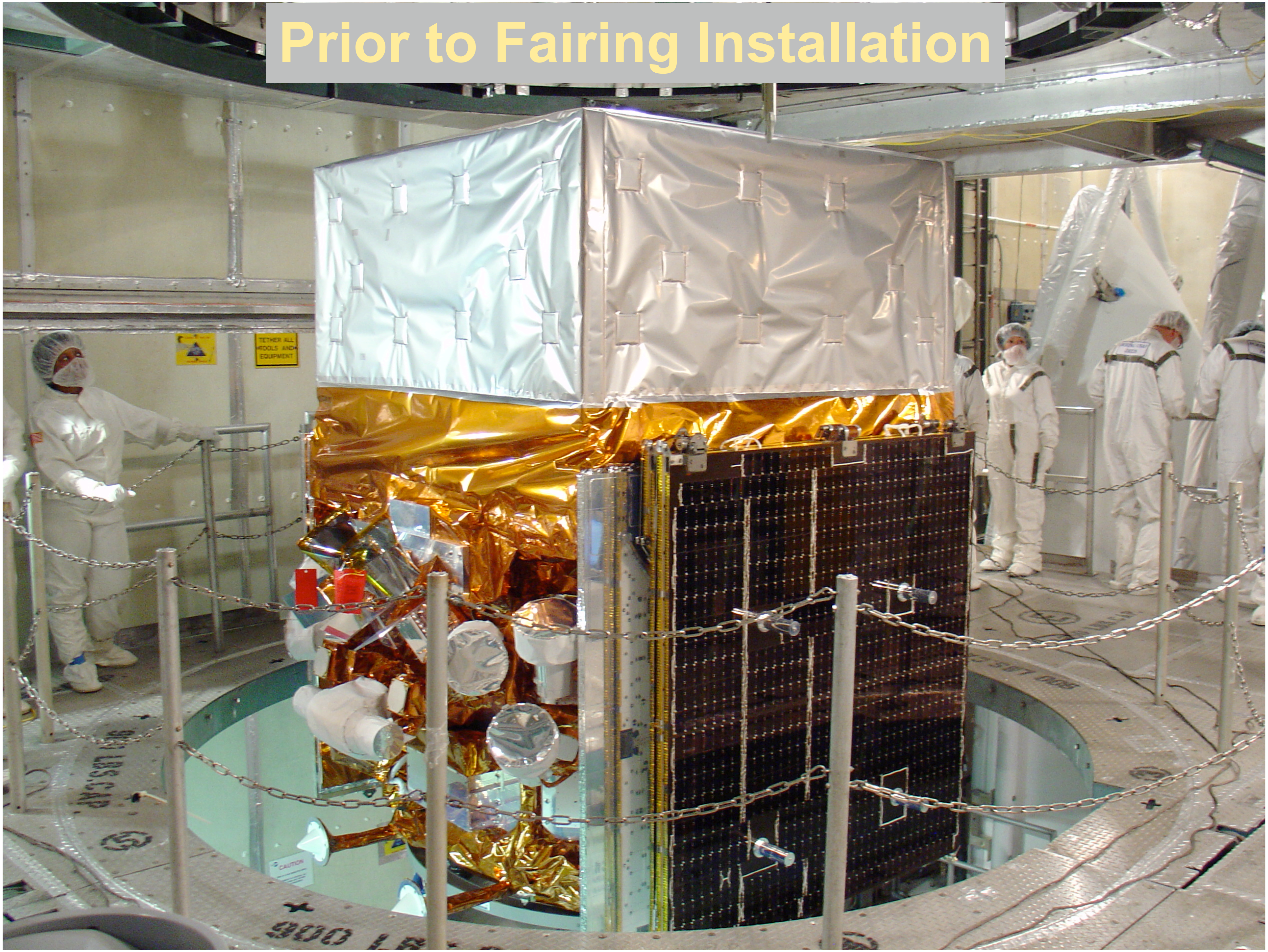
Large AreaTelescope (LAT)
20 MeV - >300 GeV

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

KEY FEATURES

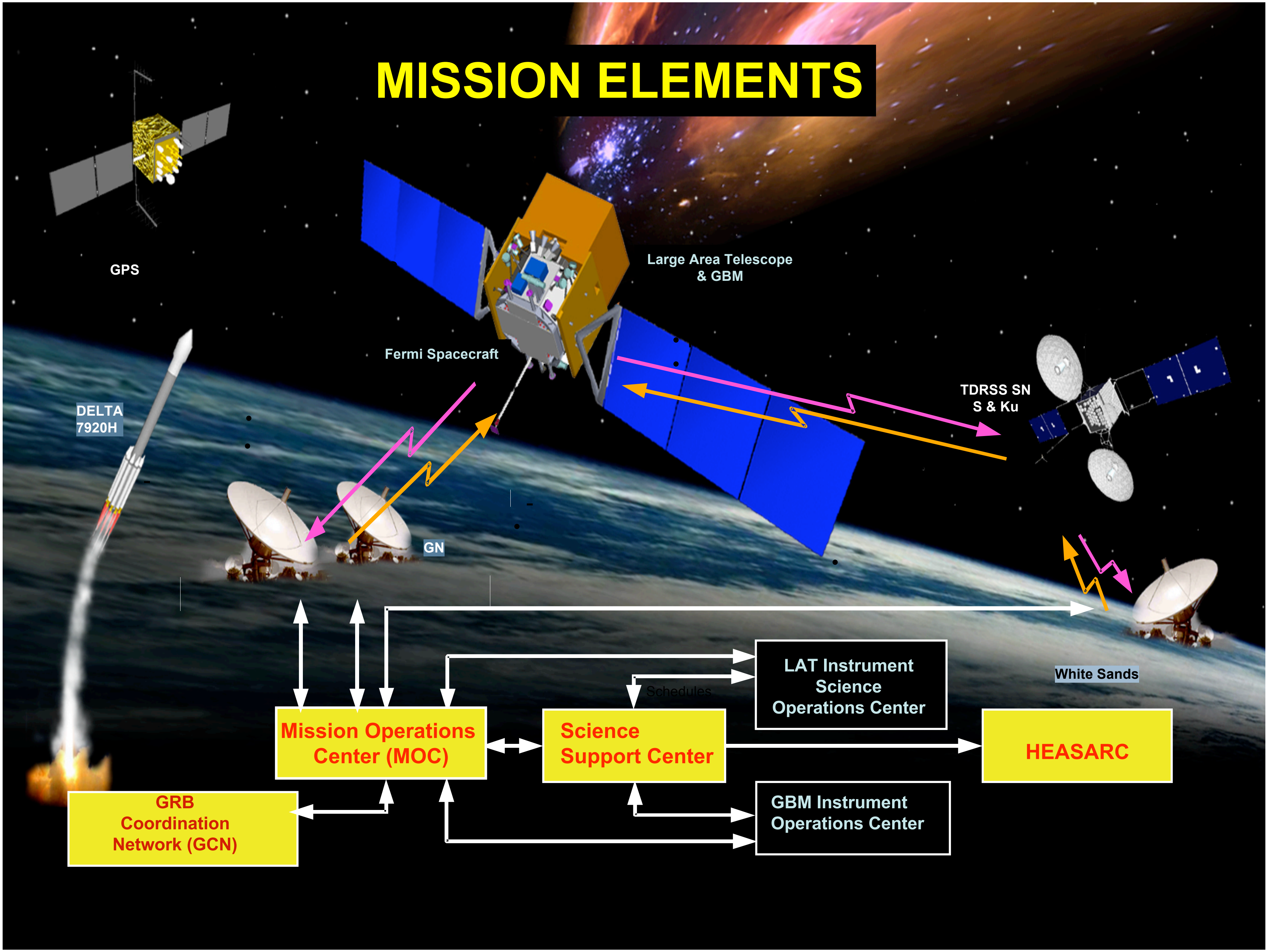
- Huge field of view
  - LAT: 20% of the sky at any instant; in sky survey mode, expose all parts of sky for ~30 minutes every 3 hours. GBM: whole unocculted sky at any time.
- Huge energy range, including largely unexplored band 10 GeV - 100 GeV. Total of >7 energy decades!
- Large leap in all key capabilities. Great discovery potential.

Prior to Fairing Installation



Launch!

- Launch from Cape Canaveral Air Station 11 June 2008 at 12:05PM EDT
- Circular orbit, 565 km altitude (96 min period), 25.6 deg inclination.


MISSION ELEMENTS
GPS
Large Area Telescope
& GBM
Fermi Spacecraft
DELTA
7920H
TDRSS SN
S & Ku
GN
White Sands
Schedules
LAT Instrument
Science
Operations Center
Mission Operations
Center (MOC)
Science
Support Center
HEASARC
GRB
Coordination
Network (GCN)
GBM Instrument
Operations Center

GBM Collaboration

National Space Science & Technology Center

University of Alabama
in Huntsville

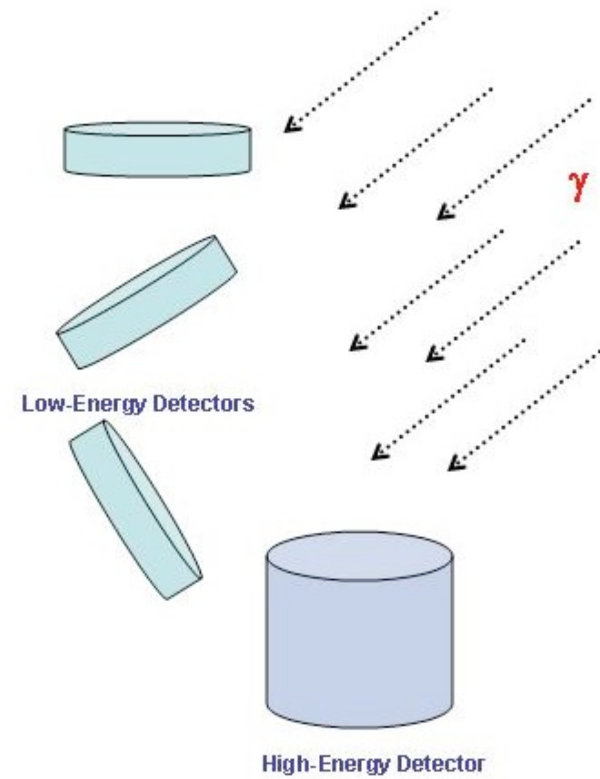
NASA
Marshall Space Flight Center

Max-Planck-Institut für
extraterrestrische Physik

Los Alamos
NATIONAL LABORATORY

William Paciesis (PI)
Jochen Greiner (Co-PI)

Principle of Operation: relative size of signals in the large flat NaI detectors provides directional information. Energies are measured in two energy bands with the NaI and BGO detectors.



Fermi LAT Collaboration

- France
- Italy
- Japan
- Sweden
- United States
  - California State University at Sonoma
  - University of California at Santa Cruz - Santa Cruz Institute of Particle Physics
  - Goddard Space Flight Center – Laboratory for High Energy Astrophysics
  - Naval Research Laboratory
  - Ohio State University
  - Stanford University (KIPAC - Physics - SLAC)
  - University of Washington
  - Washington University, St. Louis

Sponsoring Agencies

Department of Energy
National Aeronautics and Space Administration

CEA/Saclay	**ASI**
IN2P3/CNRS	**INFN**
MEXT	**K. A. Wallenberg Foundation**
KEK	**Swedish Research Council**
JAXA	**Swedish National Space Board**

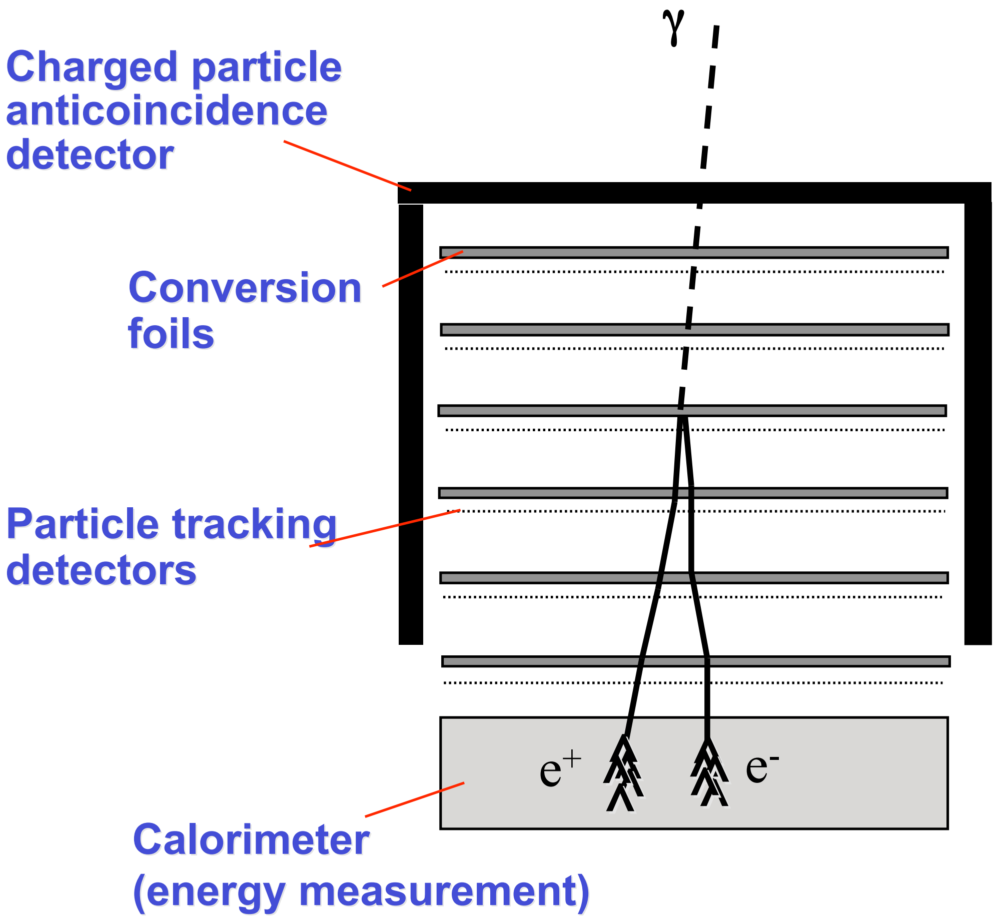
Principal Investigator:
Peter Michelson (Stanford University)
~390 Members
(~95 Affiliated Scientists, 68 Postdocs, and 105 Graduate Students)

construction managed by SLAC National Accelerator Laboratory, Stanford University

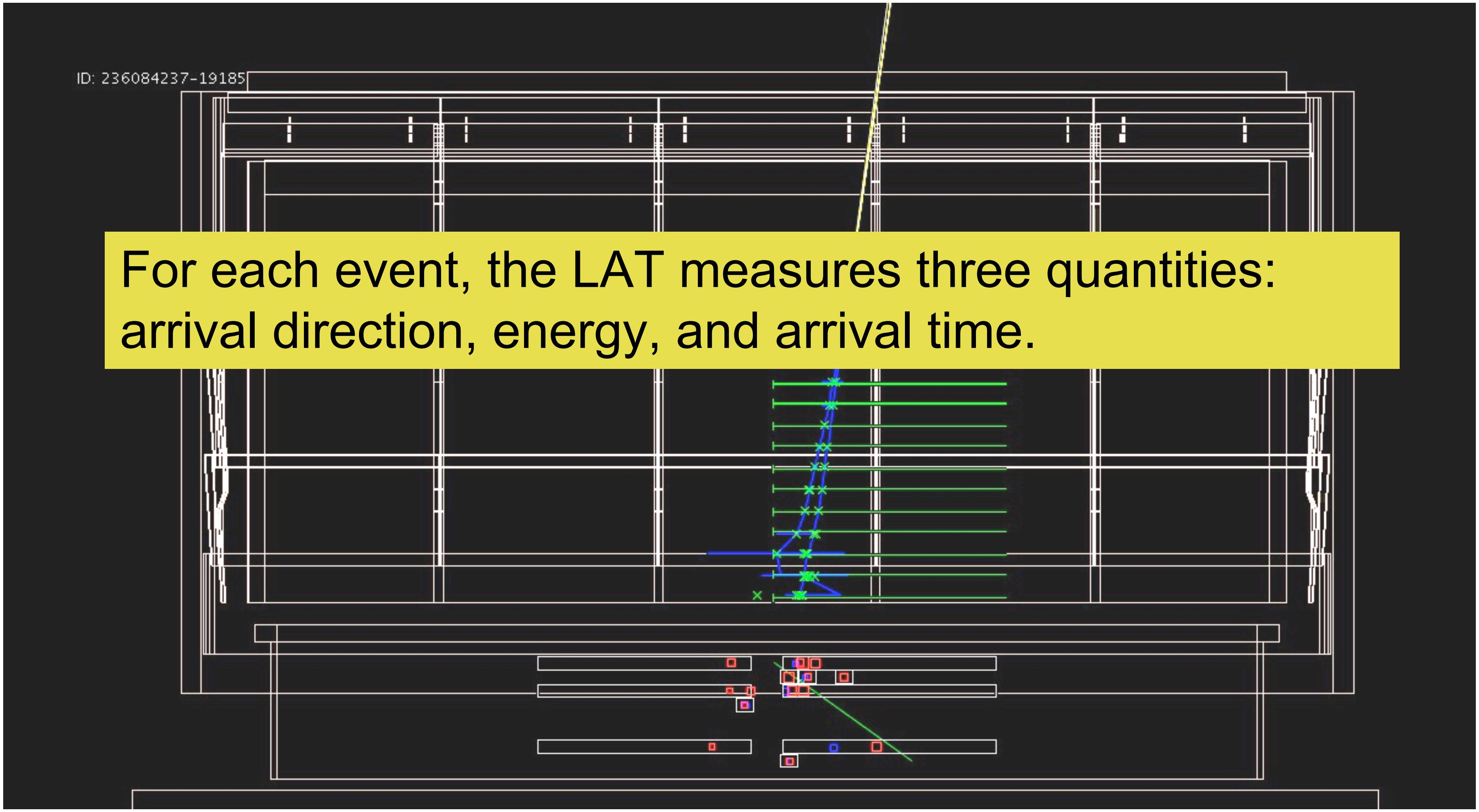
LAT: A Pair Production Telescope

Energies high enough that $E = mc^2$ is important

Principle of Operation



LAT Gamma Candidate Event



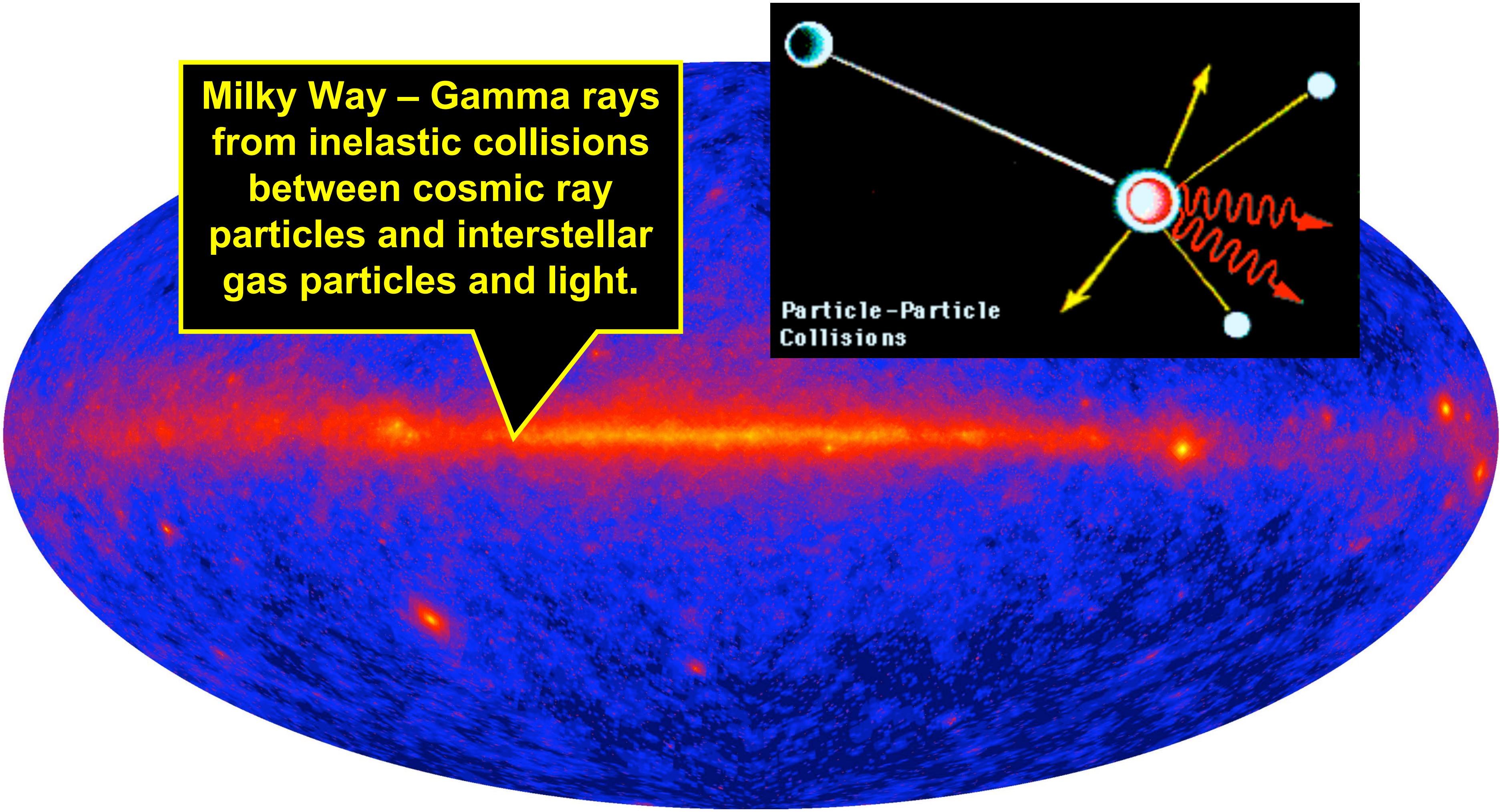
The green crosses show the detected positions of the charged particles, the blue lines show the reconstructed track trajectories, and the yellow line shows the candidate gamma-ray estimated direction. The red crosses show the detected energy depositions in the calorimeter.

What is *Fermi* seeing?

- A key point - because gamma rays are detected one at a time like particles, the *Fermi* telescopes do not have high angular resolution like radio, optical or X-ray telescopes. No pretty pictures of individual objects.
- Instead, *Fermi* trades resolution for field of view. The LAT field of view is 2.4 steradians (about 20% of the sky), and the GBM field of view is over 8 steradians.
- The *Fermi* satellite is usually operated in a scanning mode, always looking away from the Earth.
- **The combination of huge field of view and scanning means that the LAT and GBM view the <u>entire sky</u> every three hours!**

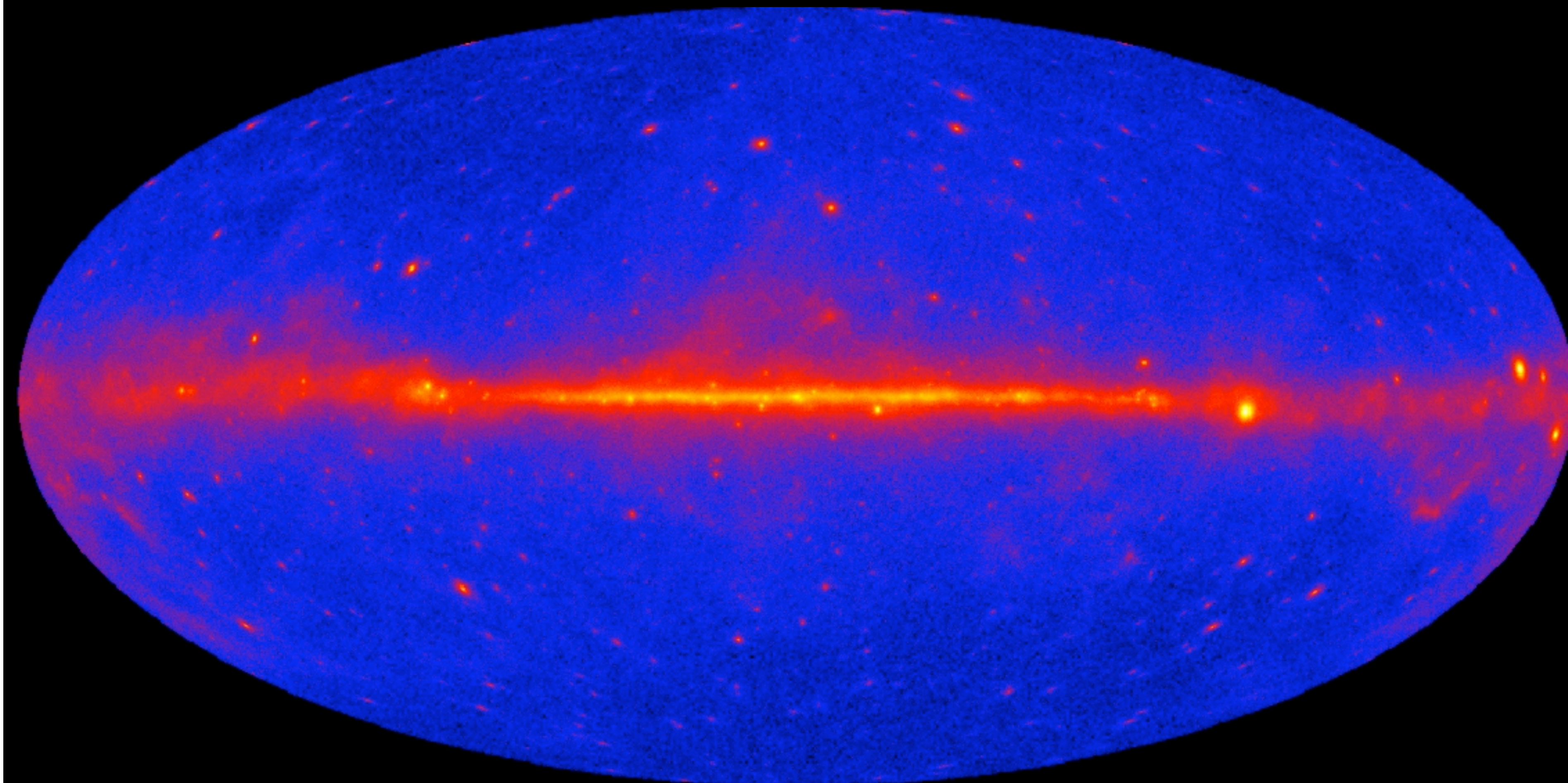
Overview of the Gamma-ray Sky

Large Area Telescope First Light!

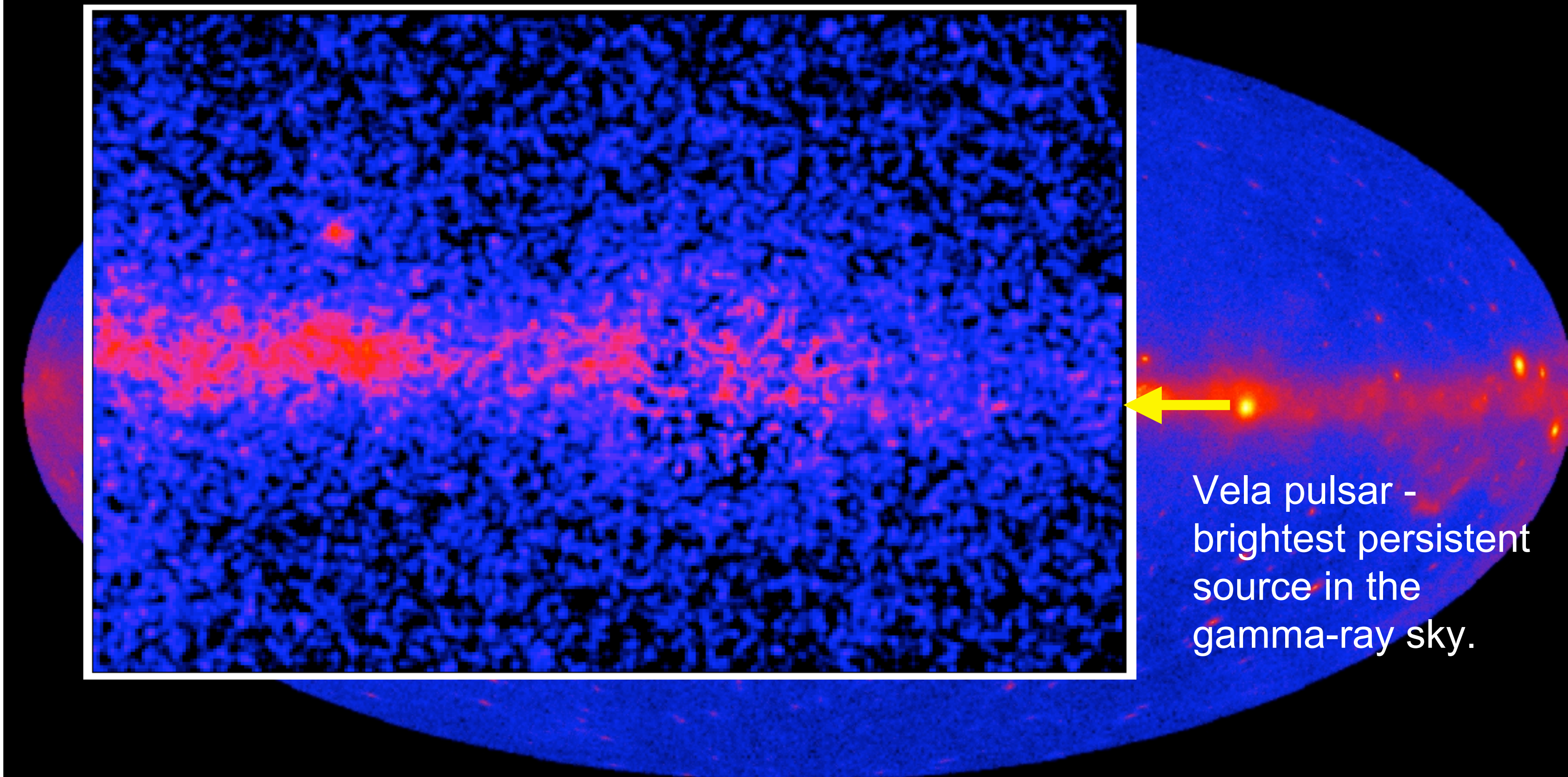


This image represents just four days of observations.

One year of LAT scanning data



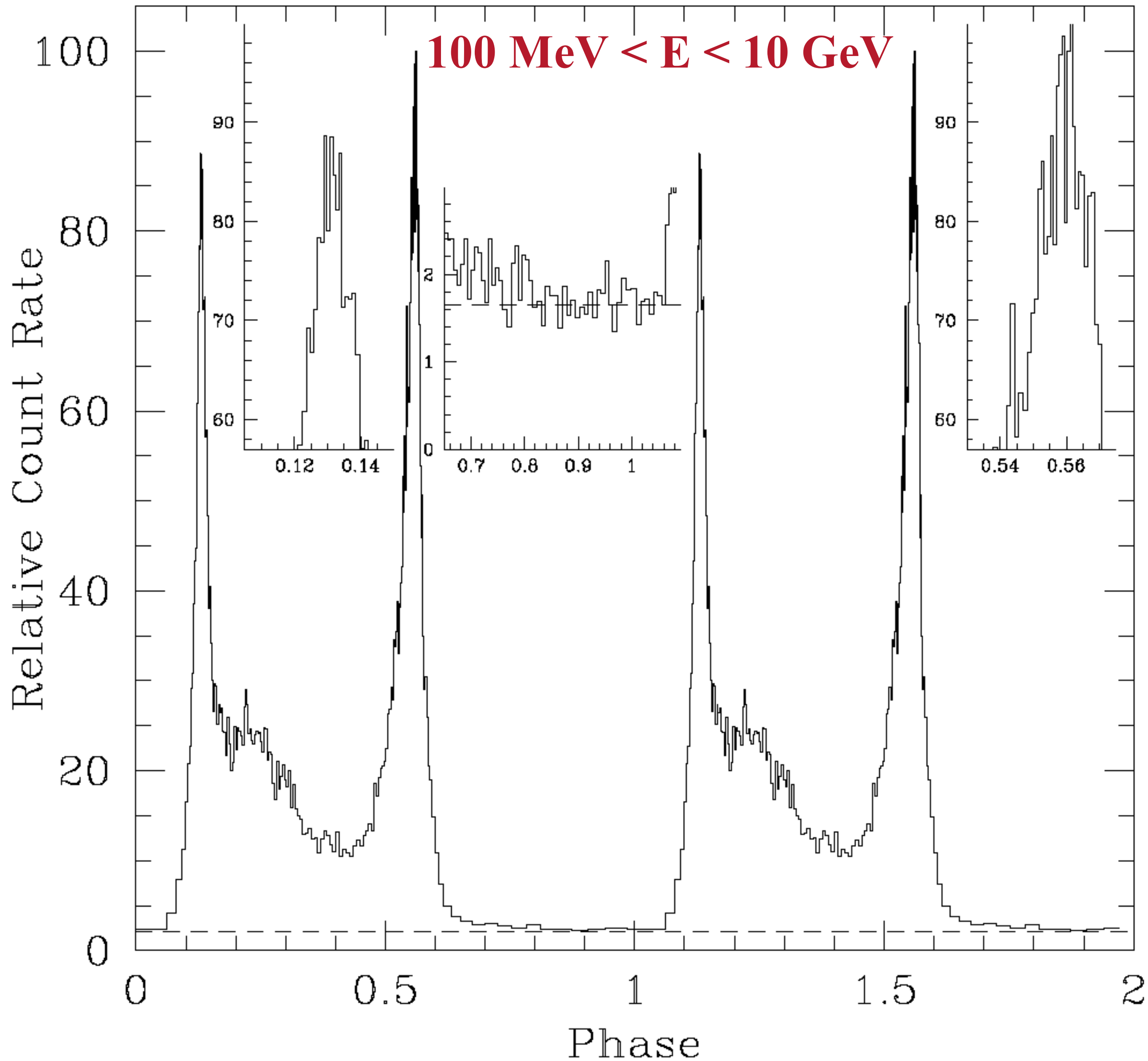
Pulsars - rapidly rotating neutron stars



Vela pulsar - brightest persistent source in the gamma-ray sky.

The actual rotation of the star takes less than 1/10 second.

First *Fermi* view of the Vela Pulsar



Remarkably sharp peaks; features to ~0.3ms.

Turns nearly completely off between the double pulses.

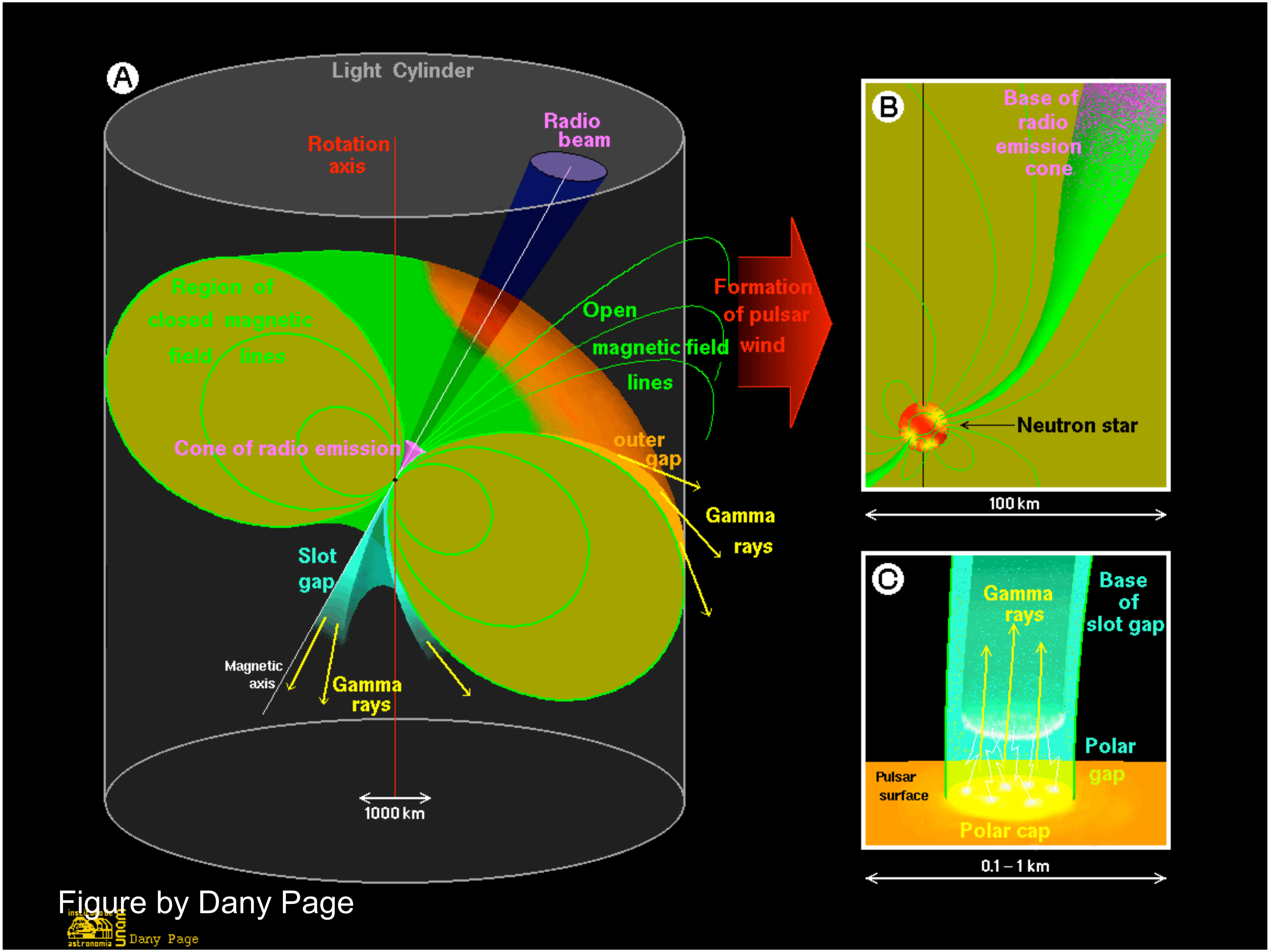
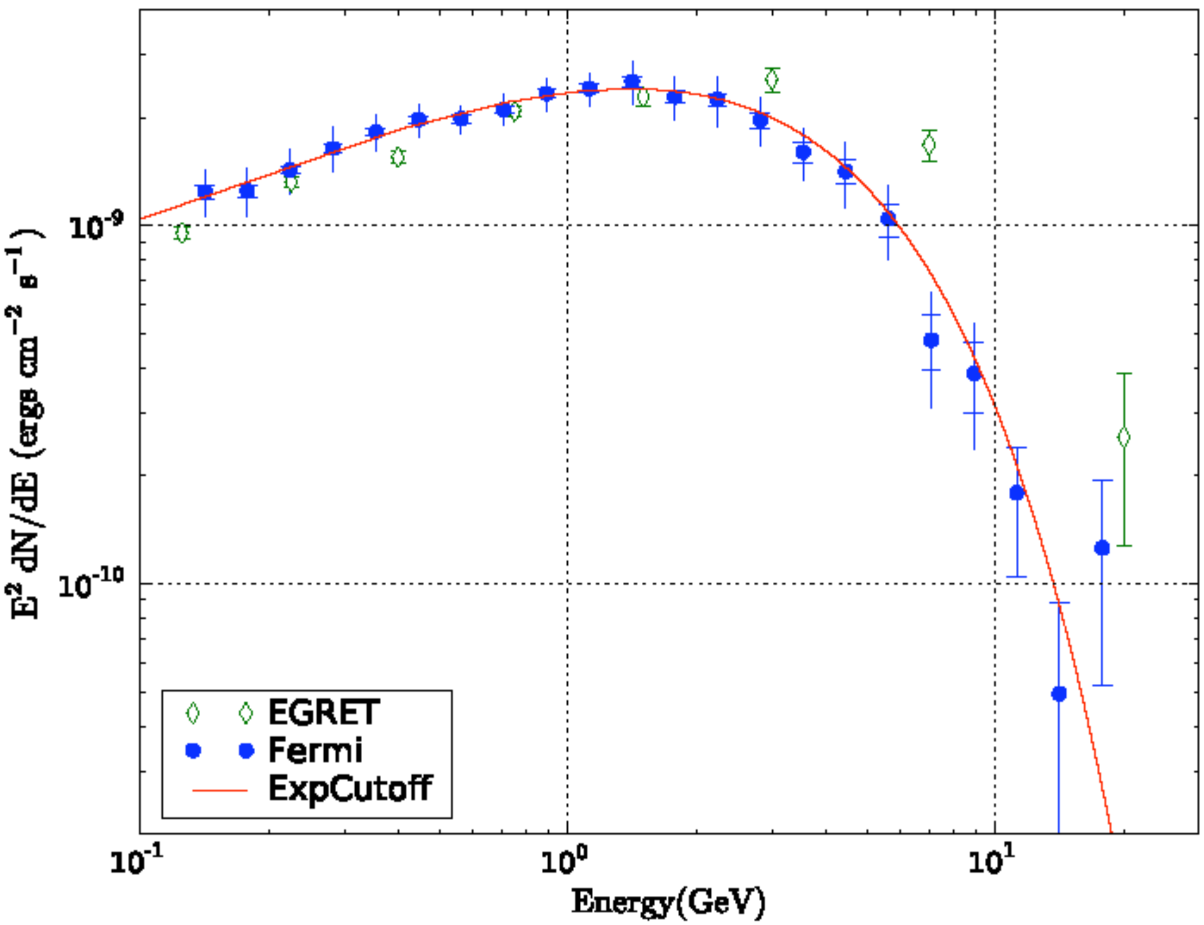


Figure by Dany Page

Vela Pulsar – Phase-averaged Spectral Energy Distribution

$$N(E) = N_0 E^{\Gamma} e^{-(E/E_c)^b}$$



Consistent with b=1 (simple exponential)

$$\Gamma = -1.51 \begin{matrix} +0.05 \\ -0.04 \end{matrix}$$

$$E_c = 2.9 \pm 0.1 \text{ GeV}$$

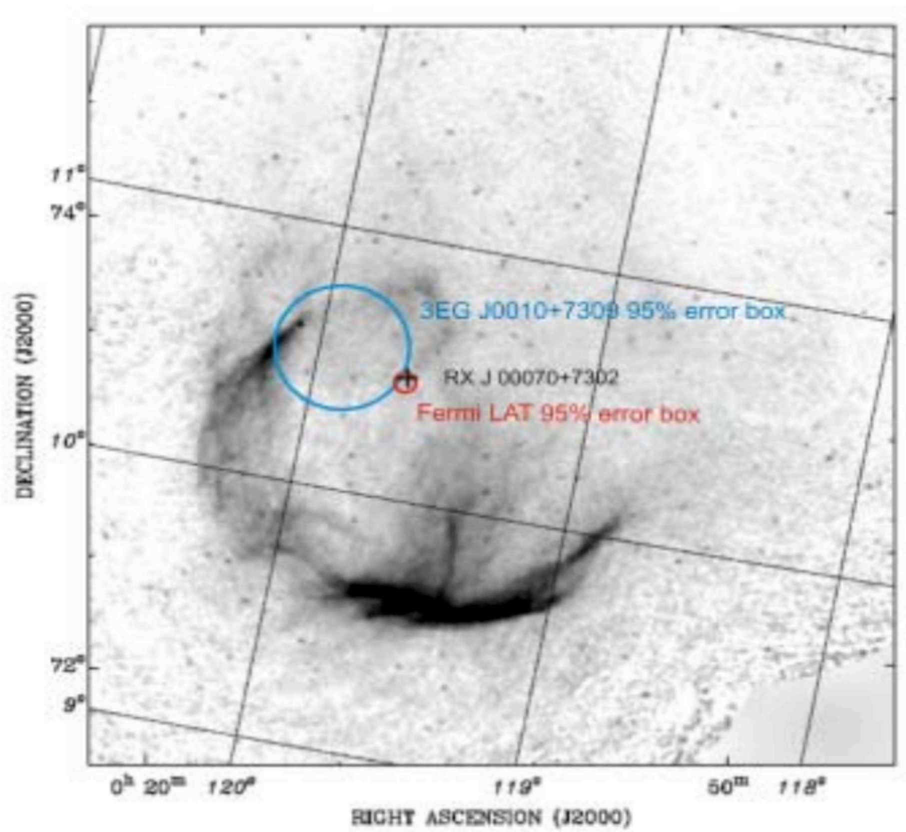
b=2 (super-exponential) rejected at 16.5σ

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

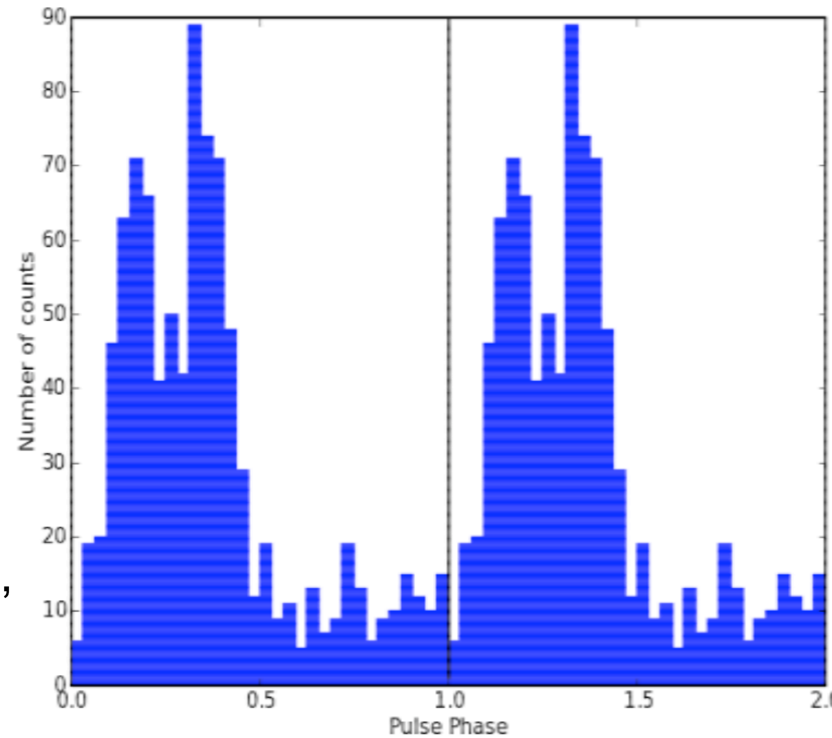
LAT discovers a radio-quiet pulsar!

24 pulsars have now been found in blind searches of LAT data.

P ~ 317 ms
Pdot ~ 3.6E-13
Characteristic age ~ 10,000 yrs



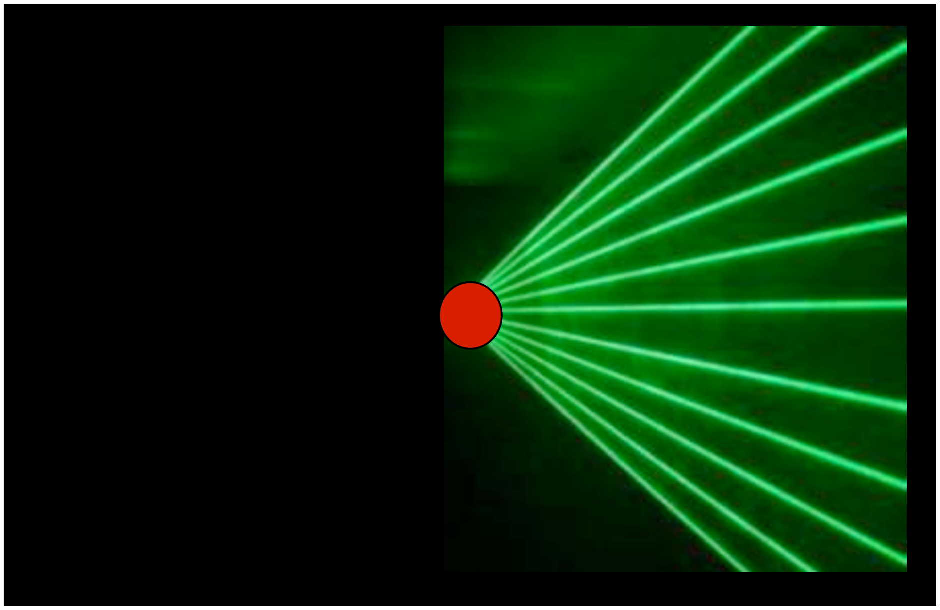
Location of EGRET source 3EG J0010+7309, the Fermi-LAT source, and the central X-ray source RX J0007.0+7303



Gamma-only Pulsars: Beamshape

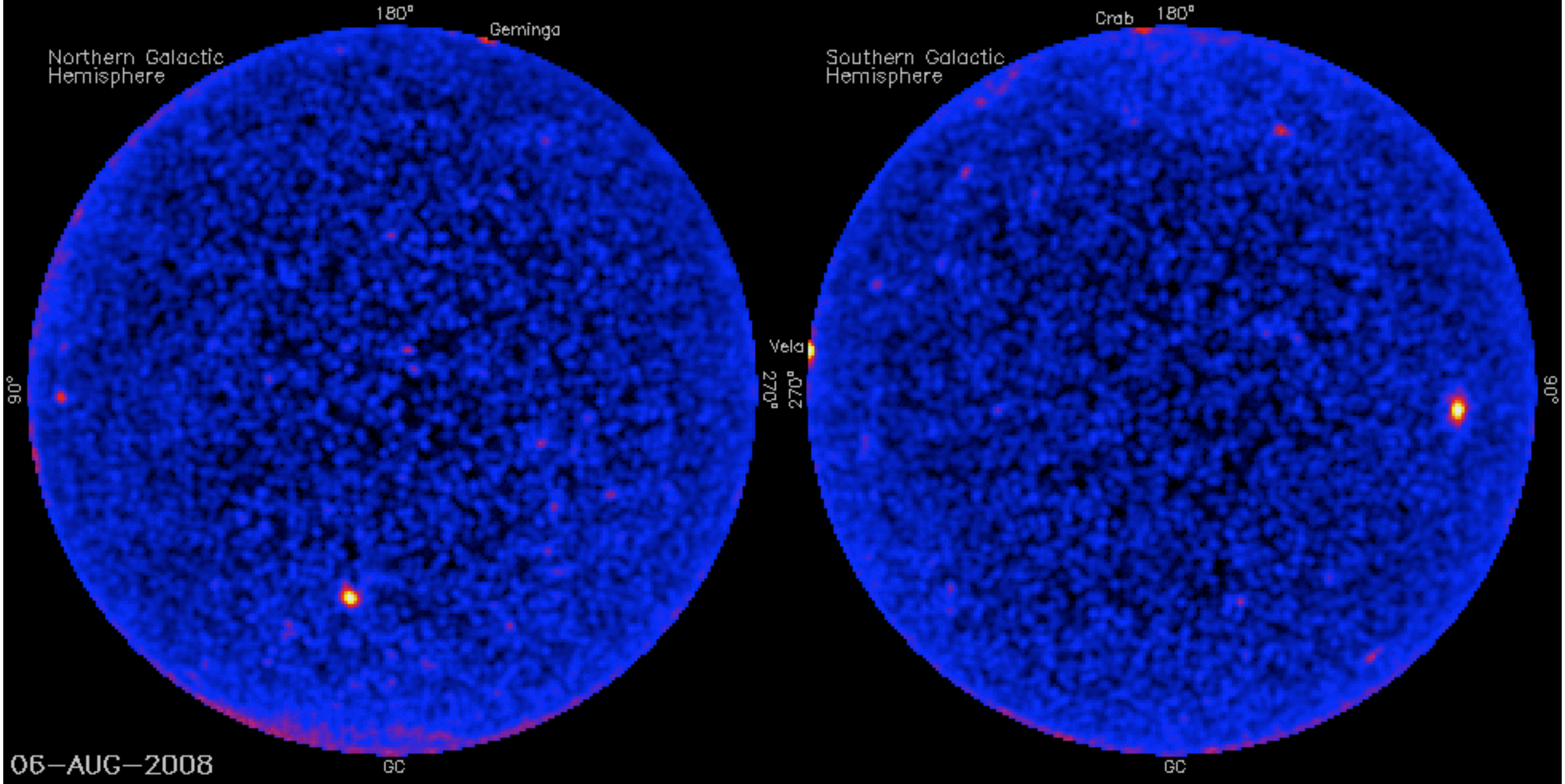
Traditional ‘Lighthouse’ Beam

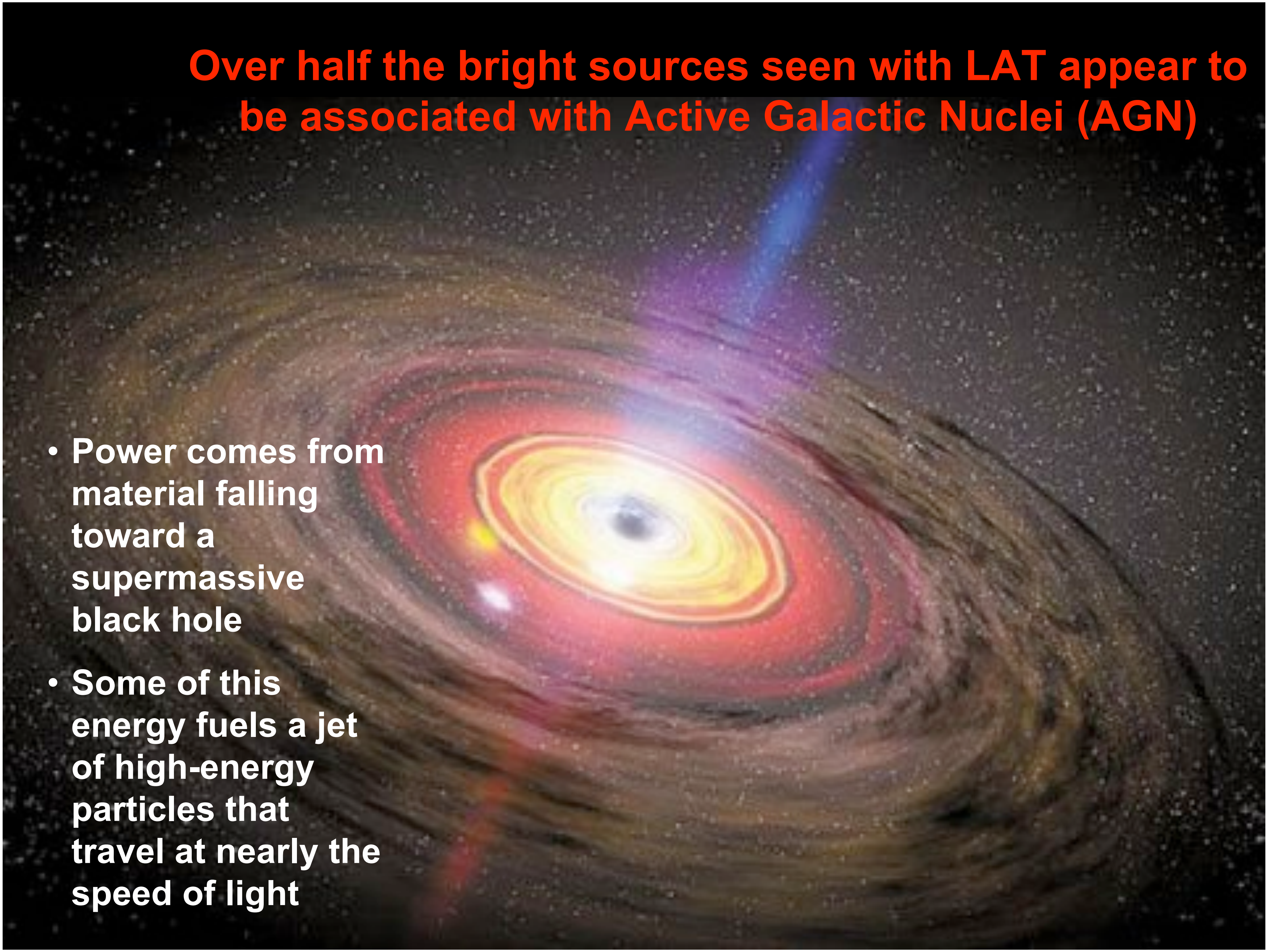
Wide ‘Fan beam’



Gamma-ray-only pulsars open a new window on these exotic and powerful objects, helping us learn how they work and how they influence our Galaxy.

The Variable Gamma-ray Sky

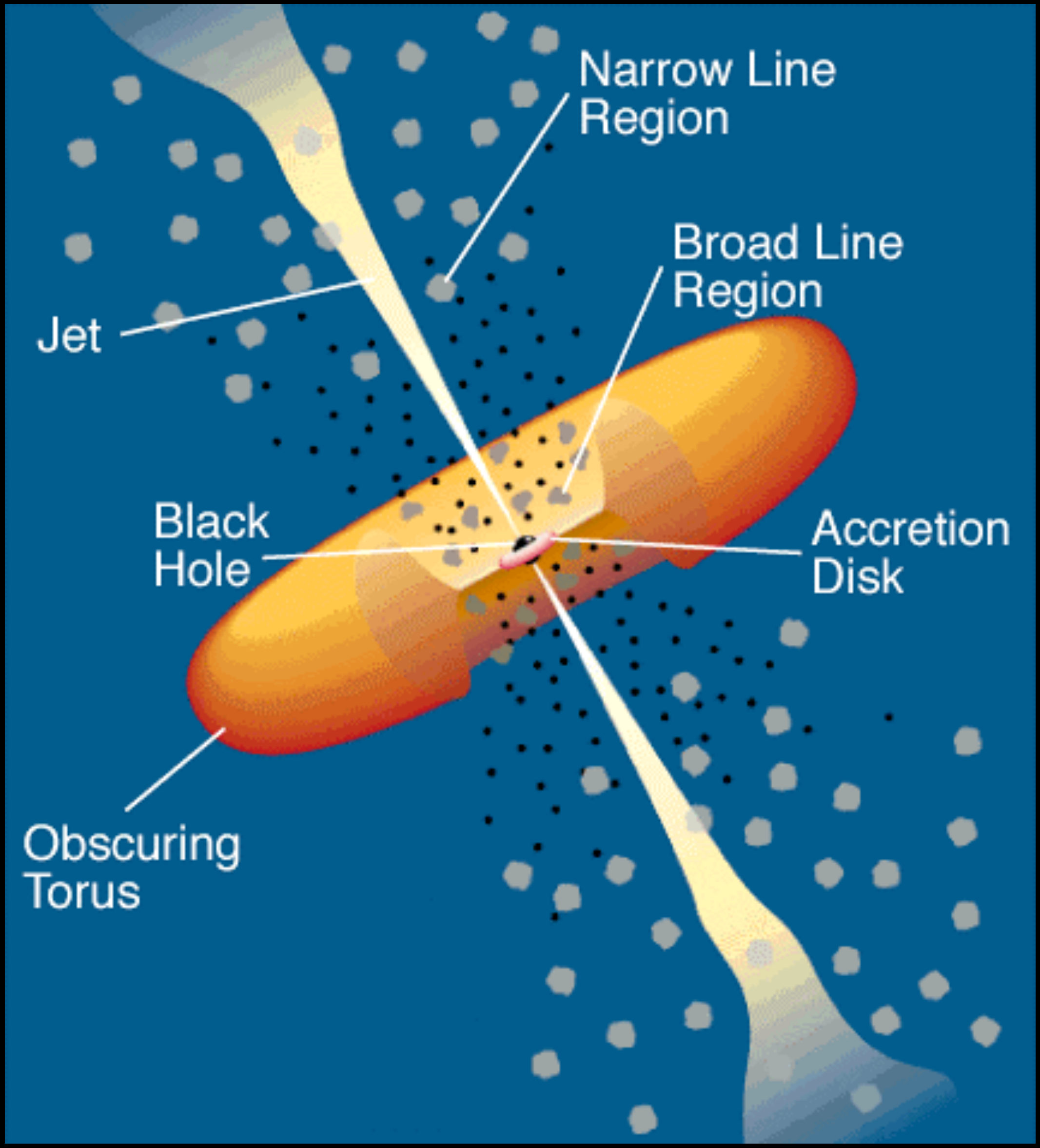




Over half the bright sources seen with LAT appear to be associated with Active Galactic Nuclei (AGN)

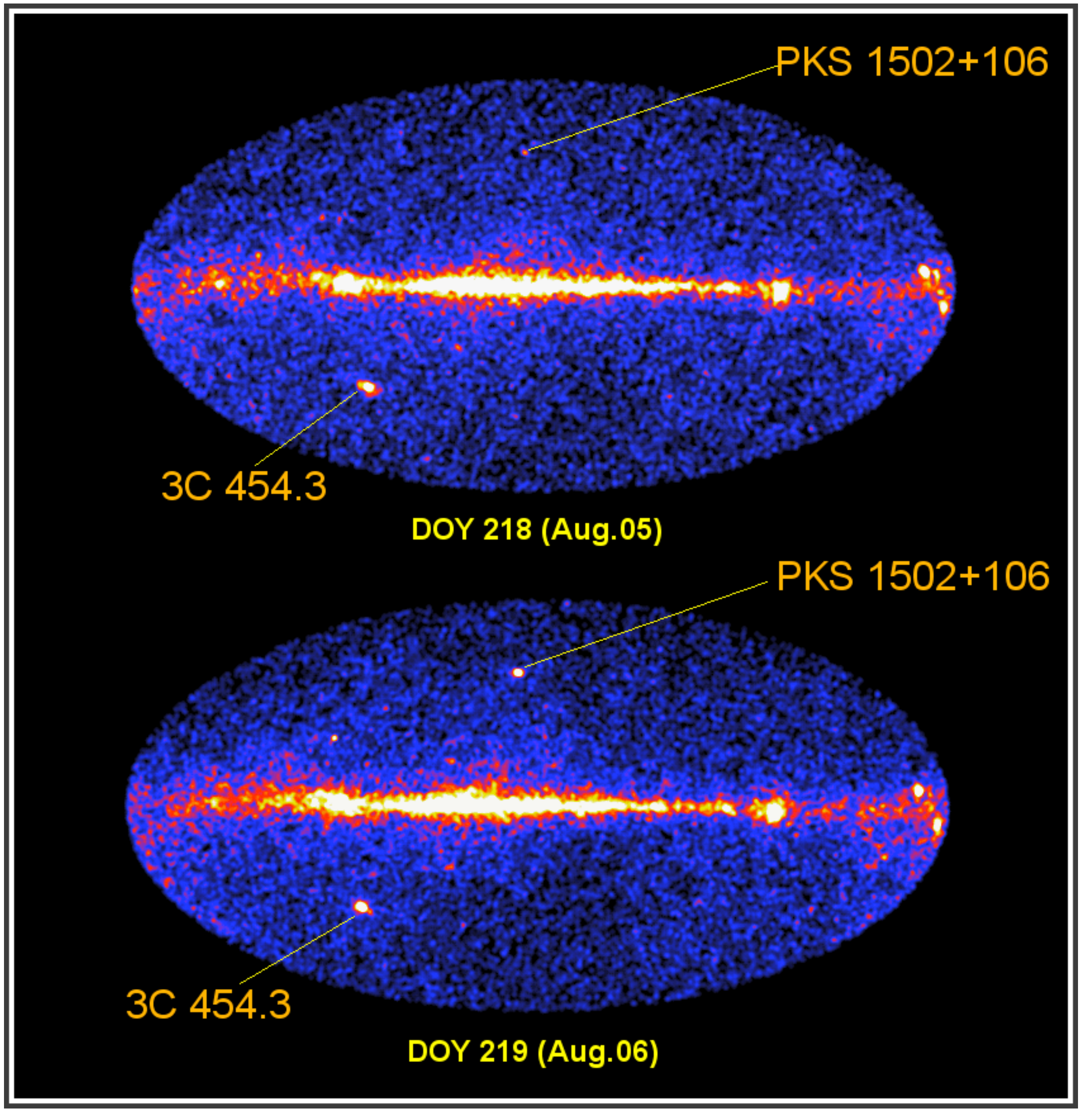
- Power comes from material falling toward a supermassive black hole
- Some of this energy fuels a jet of high-energy particles that travel at nearly the speed of light

AGN



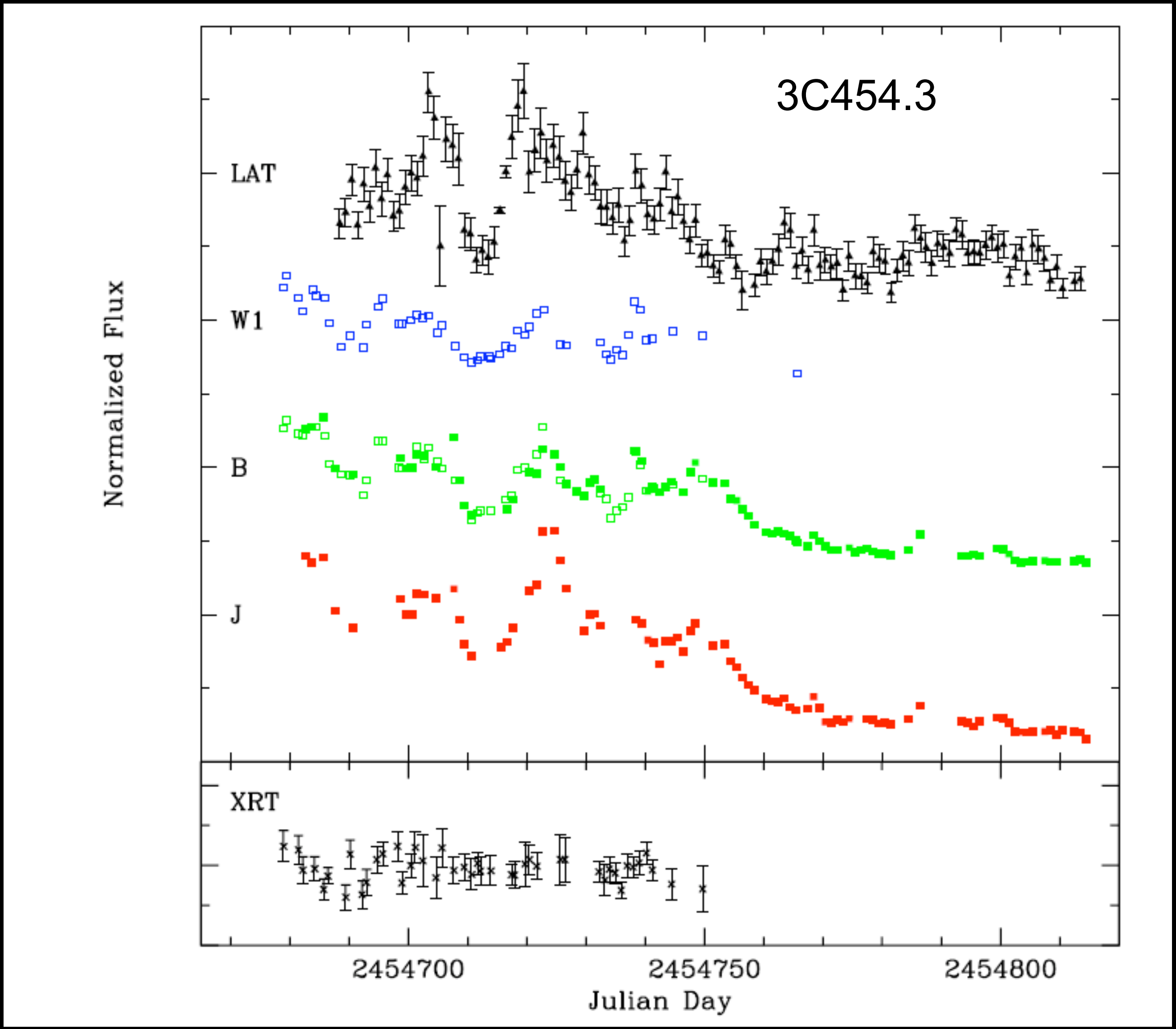
- **Unified models of AGN suggest that different types of AGN are really defined by how we see them.**
- **When such jets are pointed at Earth, we see what is called a *blazar***
- **Gamma rays are an important way to learn how these jets operate**

Flaring sources



- Automated search for flaring sources on 6 hour, 1 day and 1 week timescales.
- > 40 Astronomers Telegrams (ATels)
  - Discovery of new gamma-ray blazars PKS 1502+106, PKS 1454-354
  - Flares from known gamma-ray blazars: 3C454.3, PKS 1510-089,3C273, AO 0235+164, PSK 0208-512, 3C66A, PKS 0537-441, 3C279
  - Galactic plane transients: J0910-5041, 3EG J0903-3531

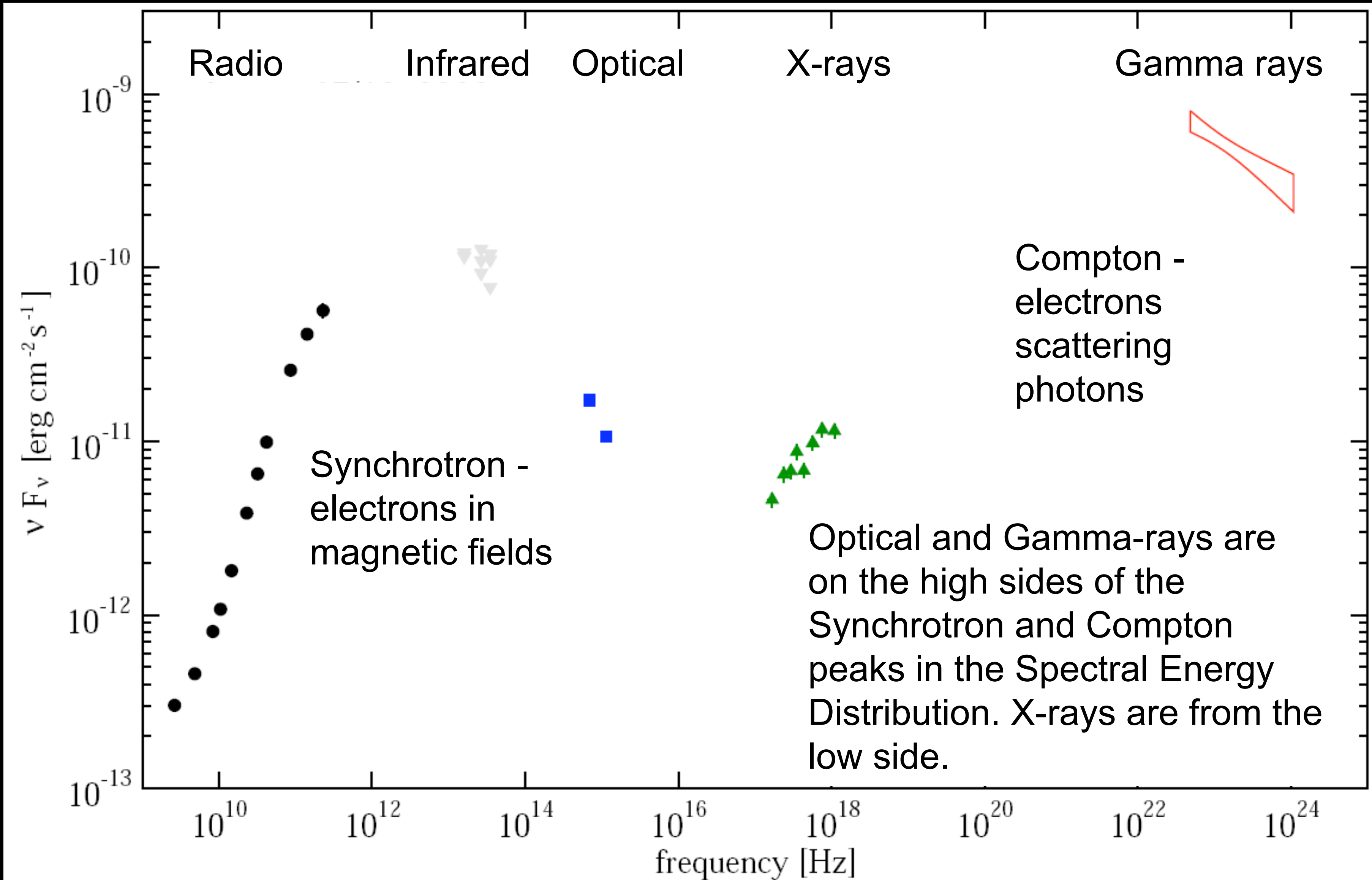
How to learn about jets? Variability



Bonning et al. 2008

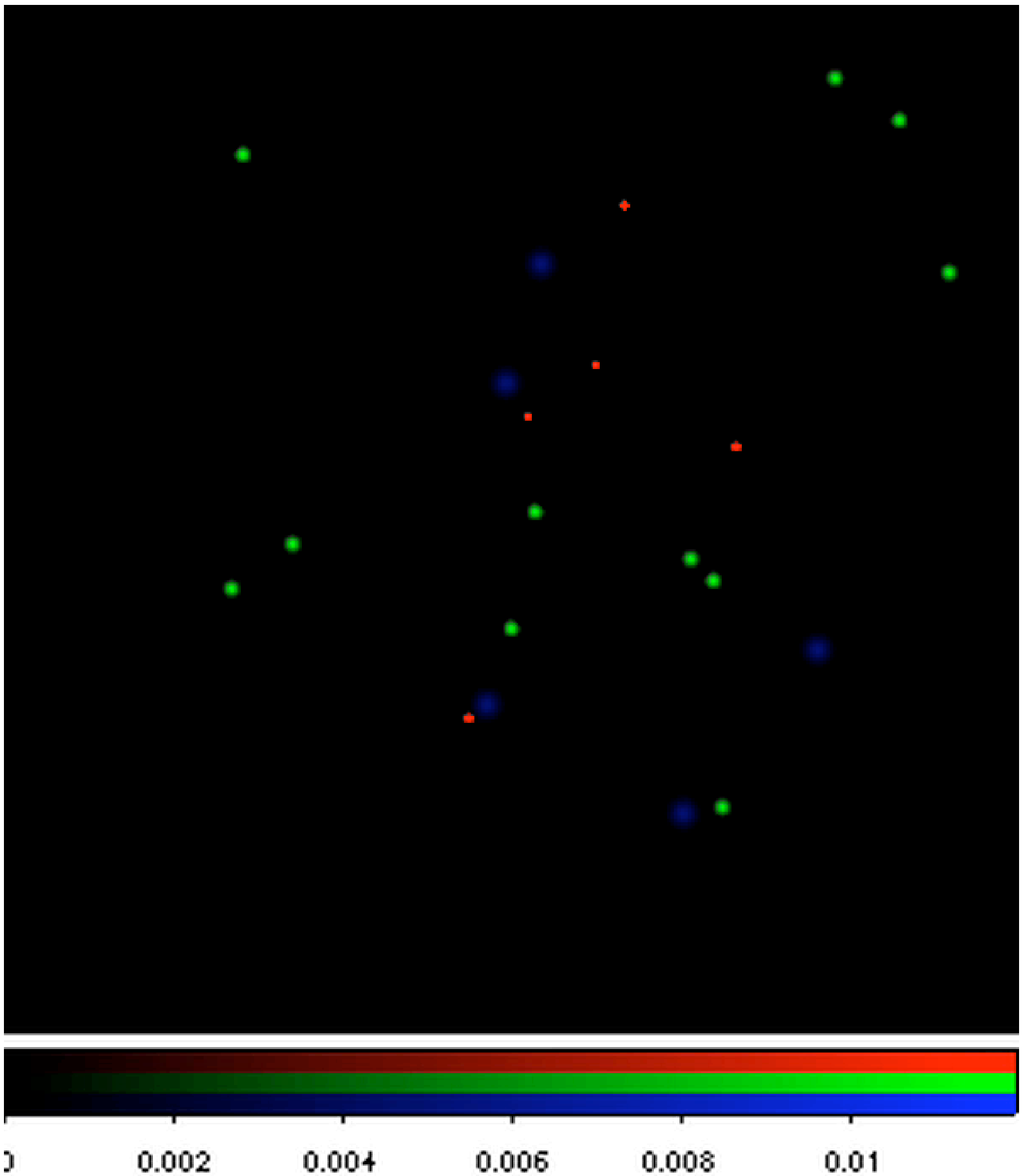
Correlated variability helps us learn how jets work.

How to learn about jets? Variability



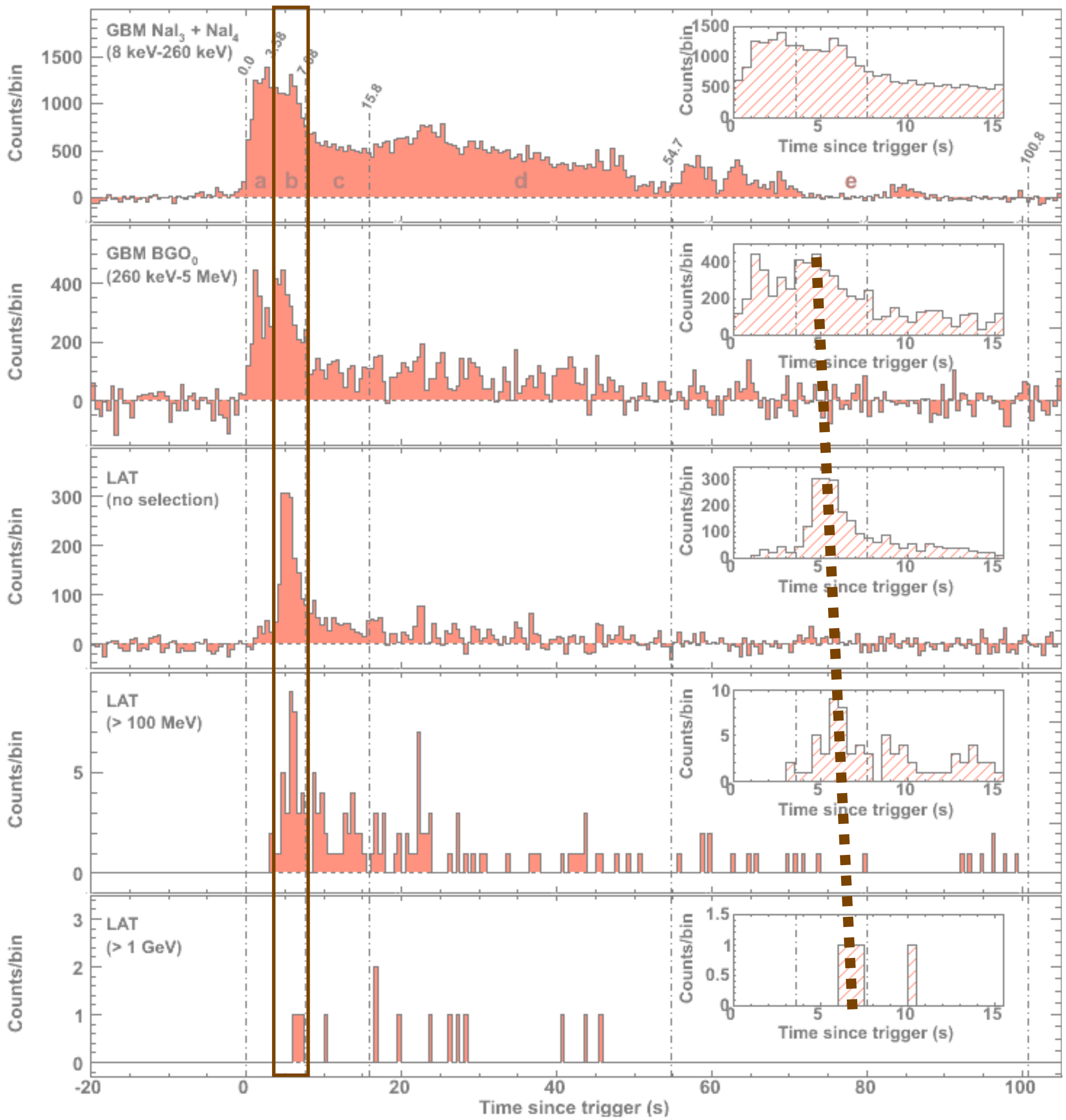
Abdo et al. 2009

Gamma-Ray Bursts (GRBs): the most powerful explosions since the Big Bang



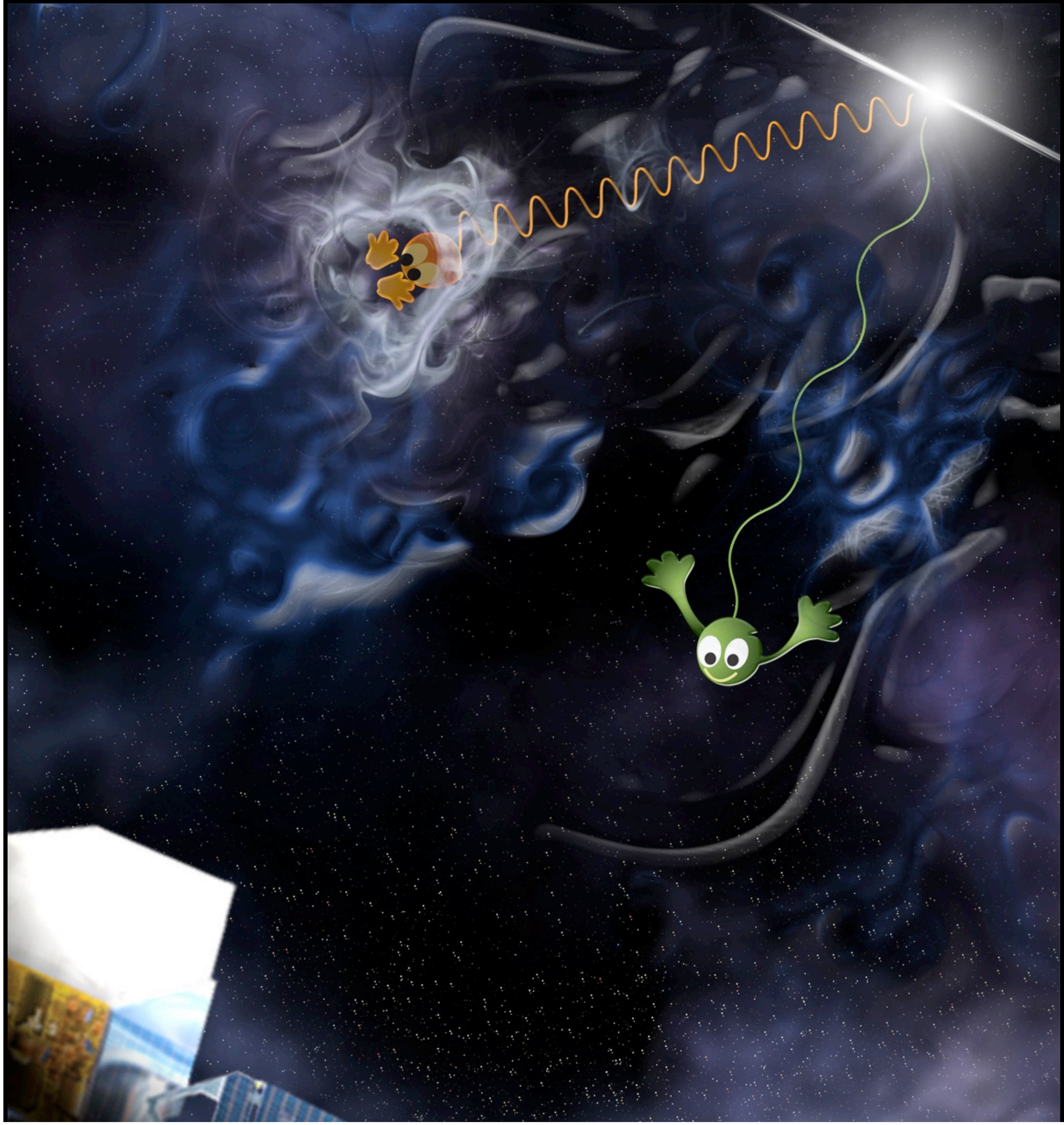
- Originally discovered by military satellites, GRBs are flashes of gamma rays lasting a fraction of a second to a few minutes.
- Optical afterglows reveal that many of these are at cosmological distances
- The GBM and LAT extend the energy range for studies of gamma-ray bursts to higher energies, complementing Swift and other telescopes.
- Fermi is helping learn how these tremendous explosions work.

Multiple detector light curve - GRB 080916C



- The bulk of the emission of the 2nd peak is moving toward later times as the energy increases
- Clear signature of spectral evolution
- Redshift of 4.35 implies 10^{55} ergs if isotropic.
- The high-energy emission seems to start later than the low-energy emission

Quantum Gravity and Lorentz Invariance Violation?

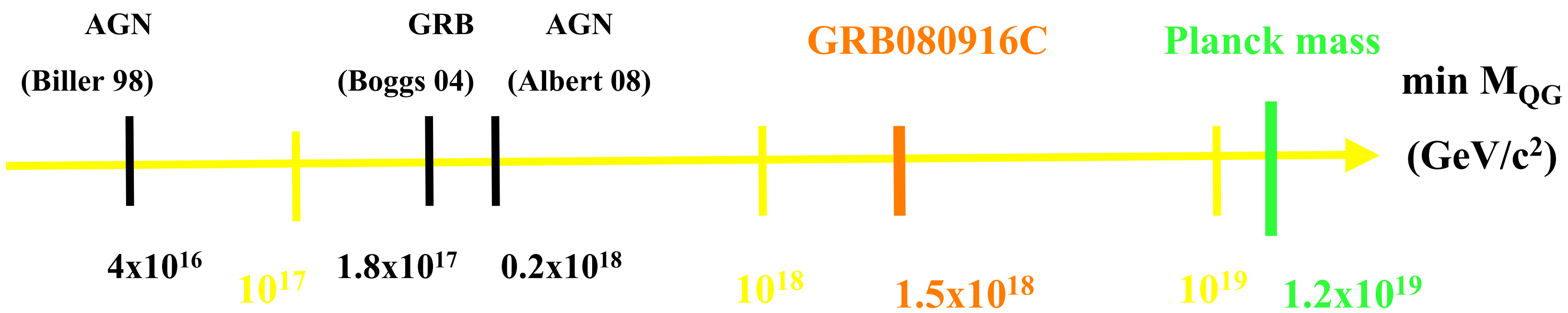


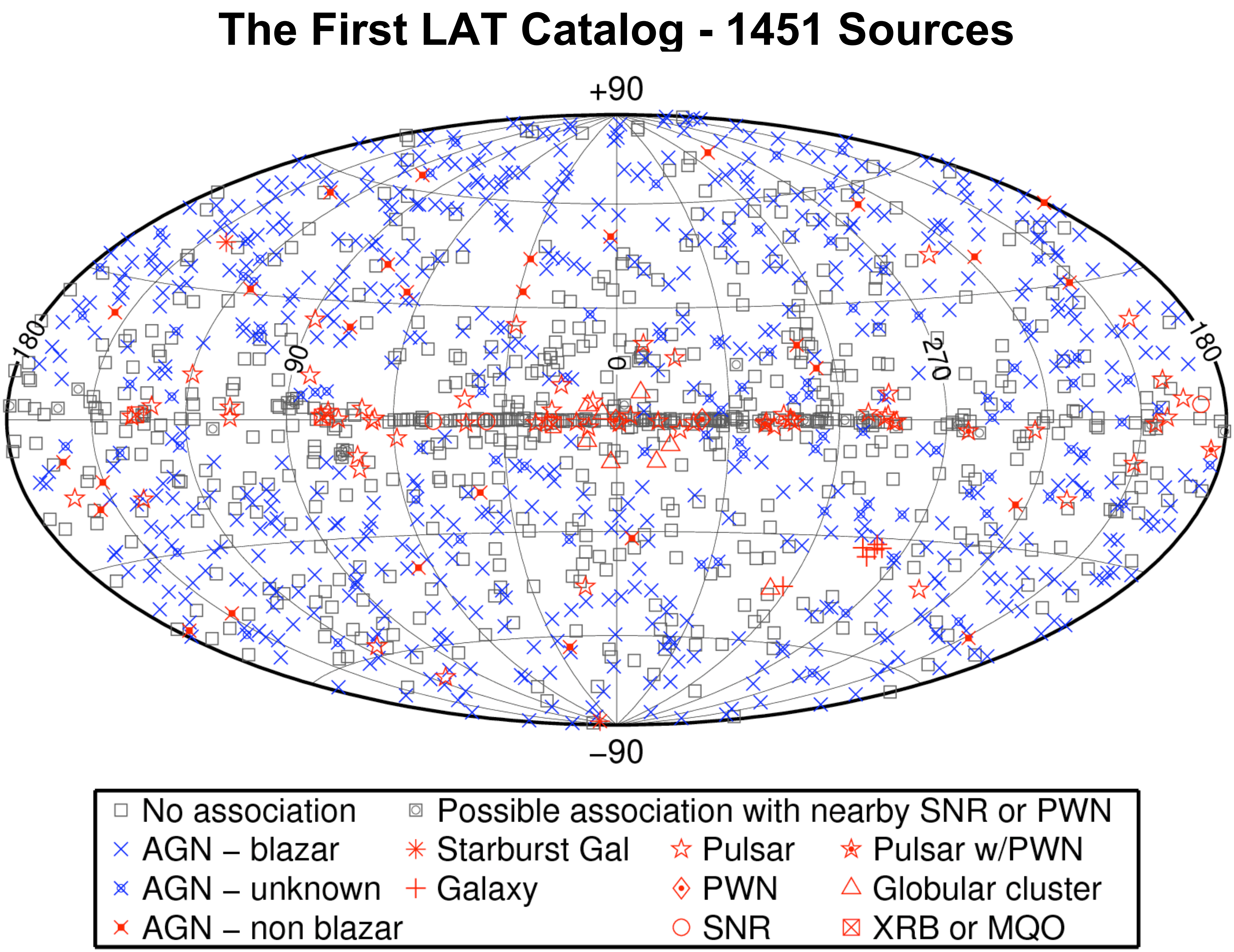
At the smallest size scale, space itself may be distorted by effects of quantum gravity. These effects could cause the speed of light to differ from its constant value, depending on its wavelength. Distant gamma-ray bursts seen over the huge energy range of Fermi set strong limits on possible variation of c with energy.

Quantum Gravity and Lorentz Invariance Violation?

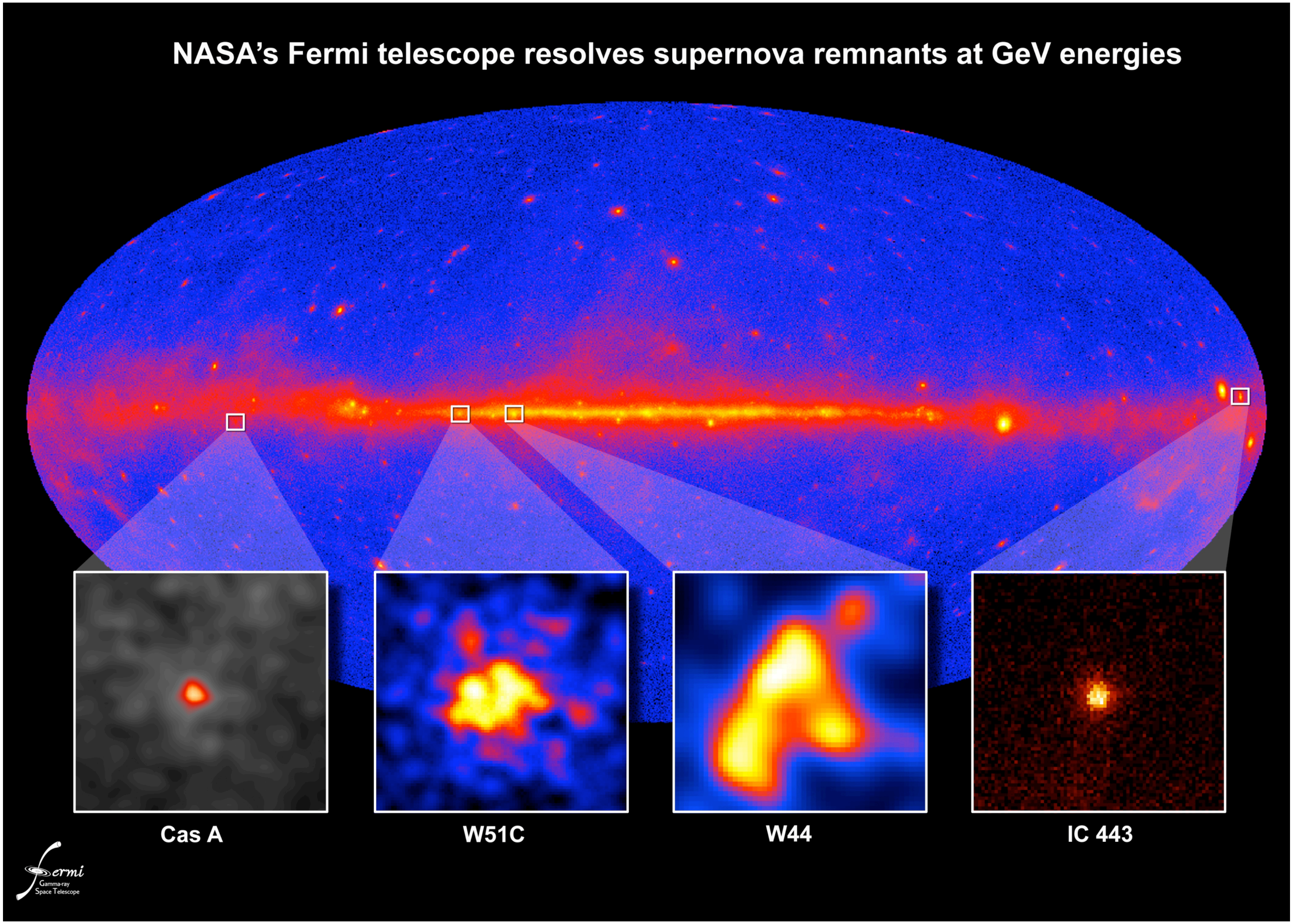
$\Delta t = \pm(\Delta E/M_{QG,1}c^2)D/c$ is the expected difference in arrival times for photons with difference in energy of ΔE at a distance D, for the linear case of quantum gravity with this mass scale.

Gamma-ray bursts seen over a broad energy range (keV to > 10 GeV) at large distances (10^{28} cm or more) set limits on the QG scale.




The First LAT Catalog - 1451 Sources
+90
–90
180
90
0
270
180
No association
Possible association with nearby SNR or PWN
AGN – blazar
Starburst Gal
Pulsar
Pulsar w/PWN
AGN – unknown
Galaxy
PWN
Globular cluster
AGN – non blazar
SNR
XRB or MQO

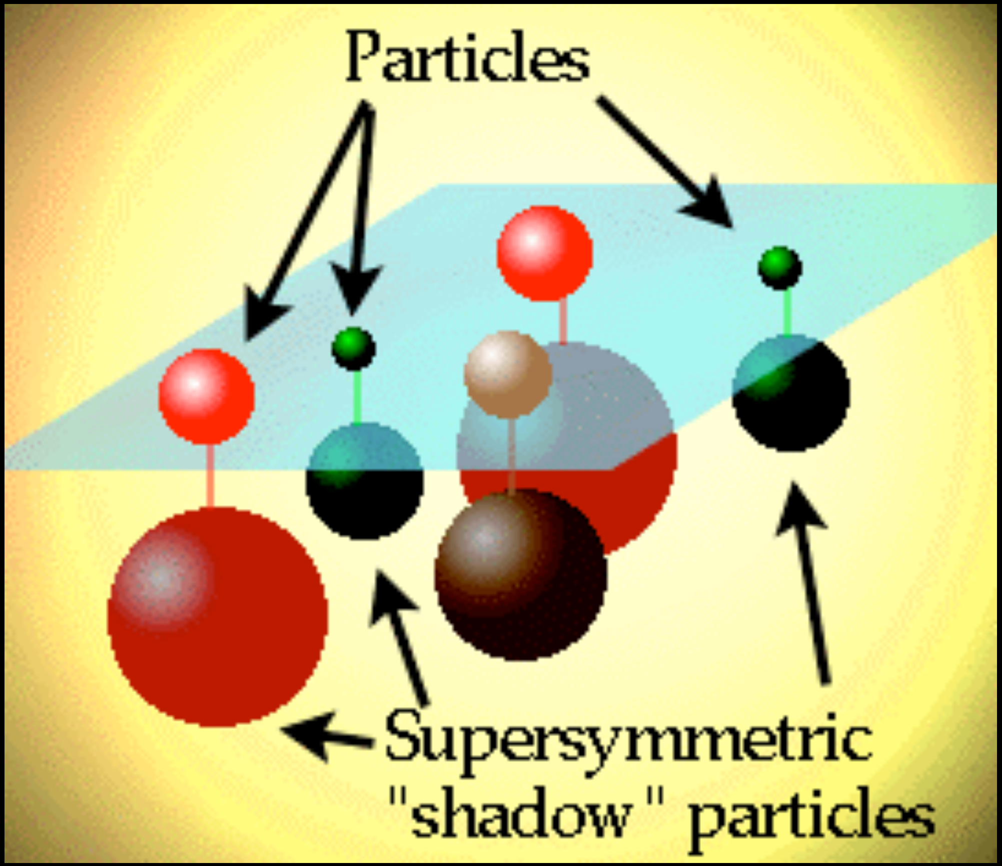
Supernova Remnants - Spatially Resolved

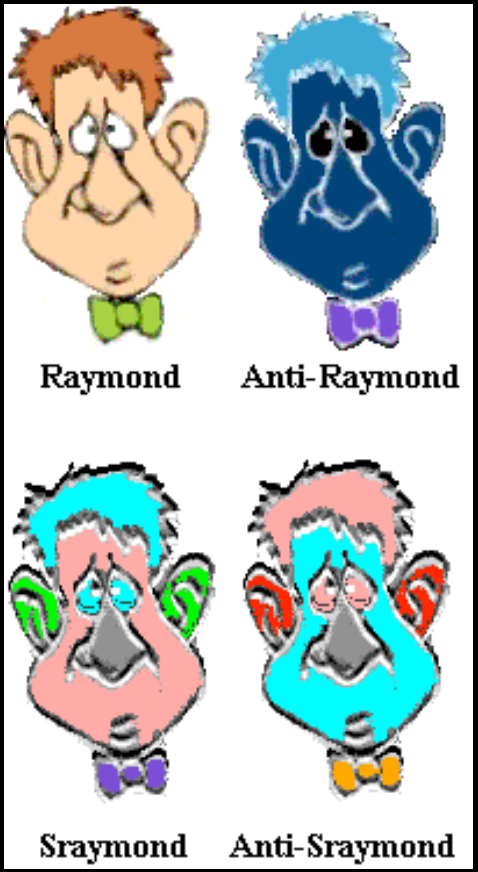


What Next for Fermi?

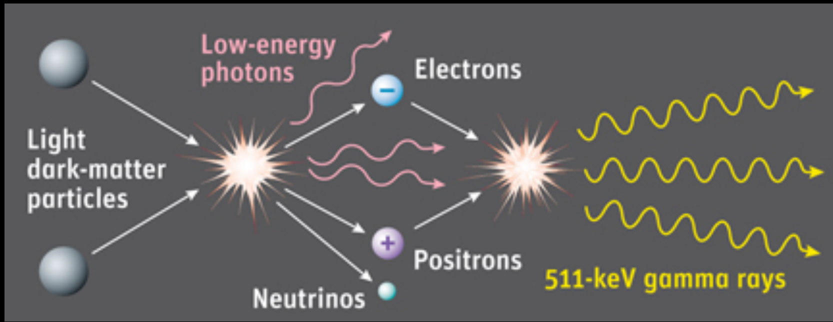
- We have only scratched the surface of what the Fermi Gamma-ray Space Telescope can do.
  - The gamma-ray sky is changing every day, so there is always something new to learn about the extreme Universe.
- Beyond pulsars, blazars, X-ray binaries, SNR, and gamma-ray bursts, other sources remain mysteries. Over 40% of the sources in the First LAT Catalog do not seem to have obvious counterparts at other wavelengths.
  - Multiwavelength studies will be critical for learning the nature of such sources.
- A major milestone came in August, when the LAT data became public). The Fermi Science Support Center, at http://fermi.gsfc.nasa.gov/ssc/ is the access center for these data.

A leading candidate for dark matter: Supersymmetry particles a.k.a. "WIMPs" (weakly interacting massive particles)

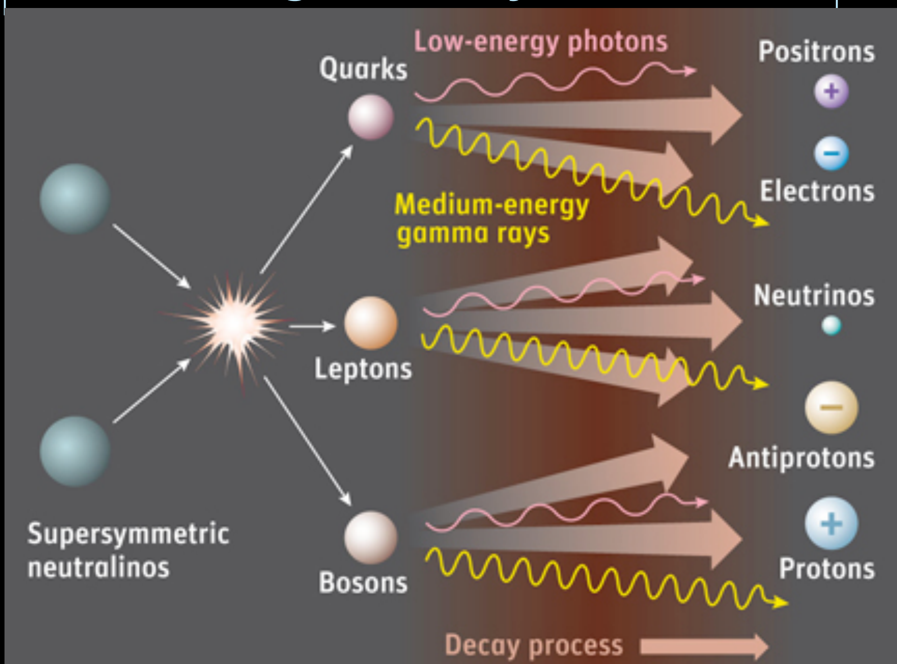




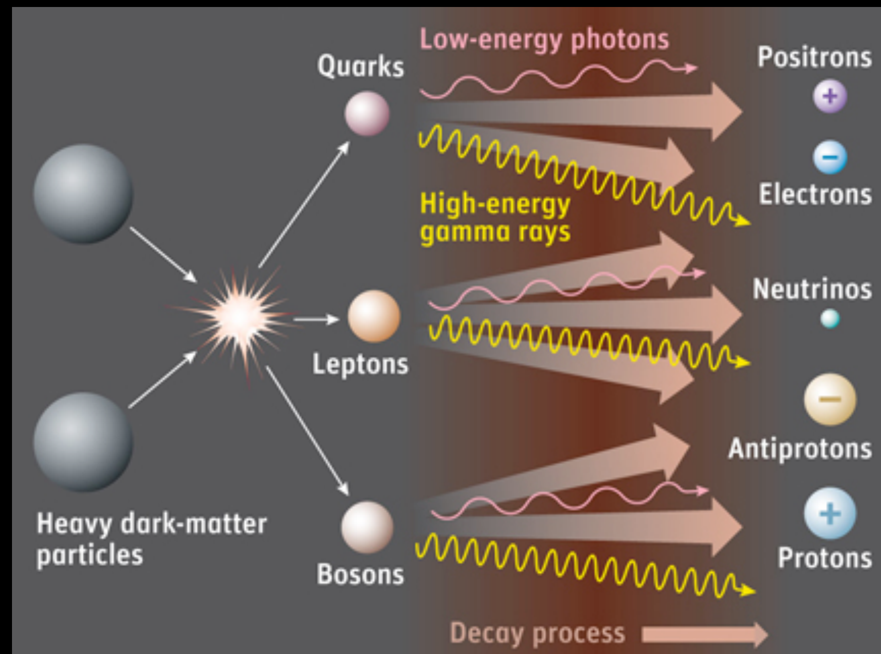
Dark-matter particles annihilate with one another, leading to gamma rays



Light dark-matter particles produce 511 keV (low-energy) gamma rays



WIMP dark-matter particles (neutralinos) produce 30 MeV to 10 GeV (medium-energy) gamma rays



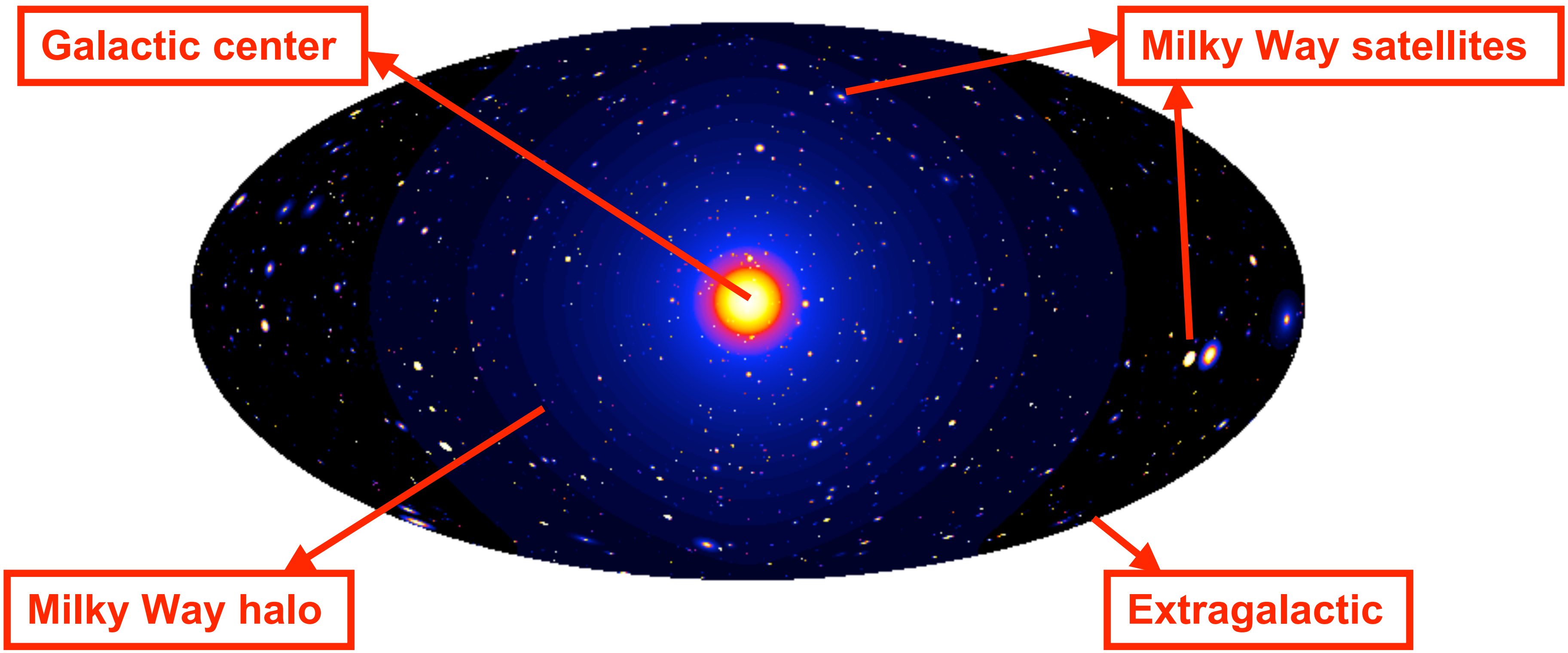
Heavy dark-matter particles produce 300 to 600 GeV (high-energy) gamma rays

Illustrations by Gregg Dinderman/*Sky & Telescope*

DM (only) in the gamma ray sky

Milky Way Halo simulated by Taylor & Babul (2005)

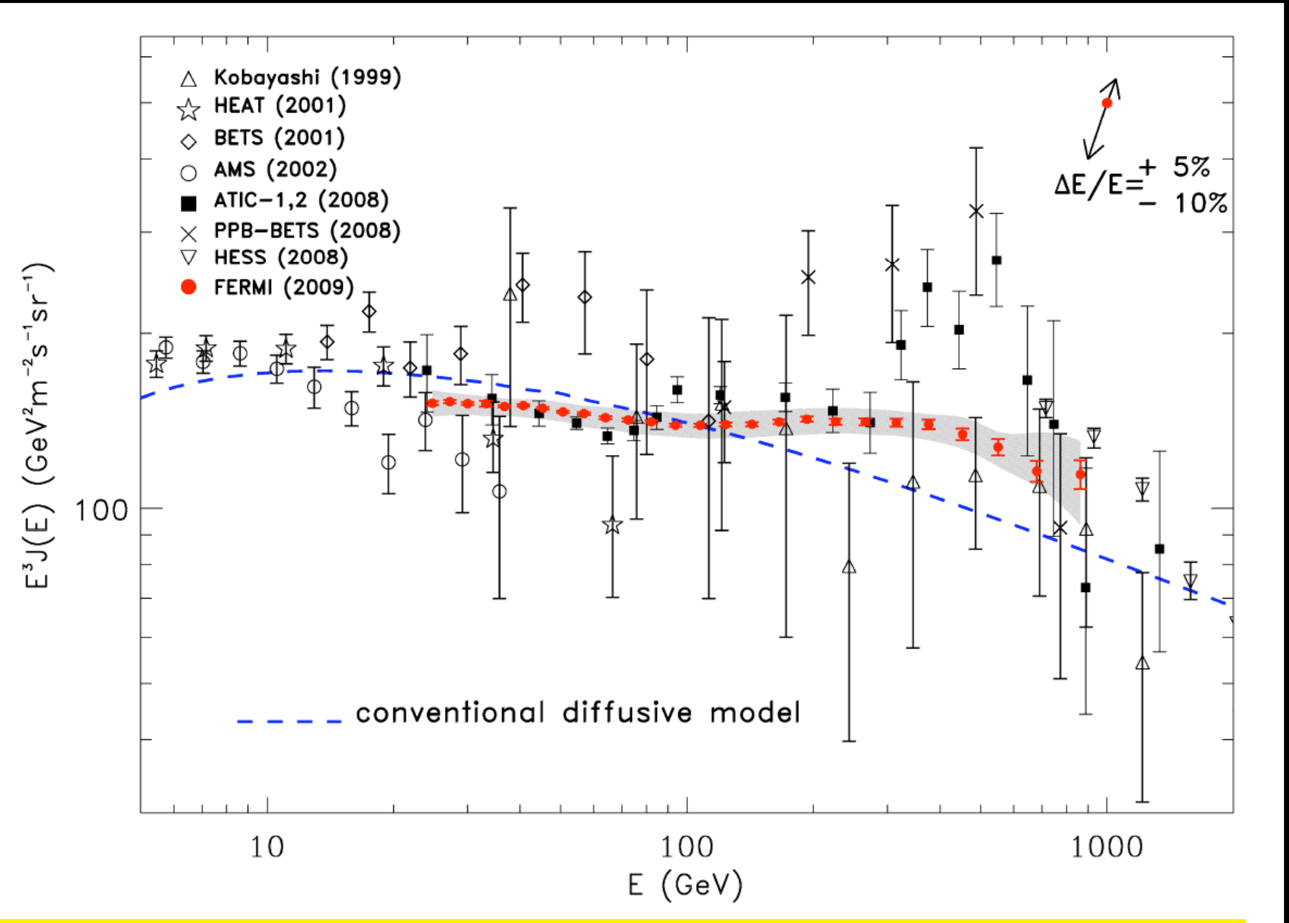
All-sky map of DM gamma ray emission (Baltz 2006)



Fermi LAT: $e^{+}+e^{-}$ spectrum

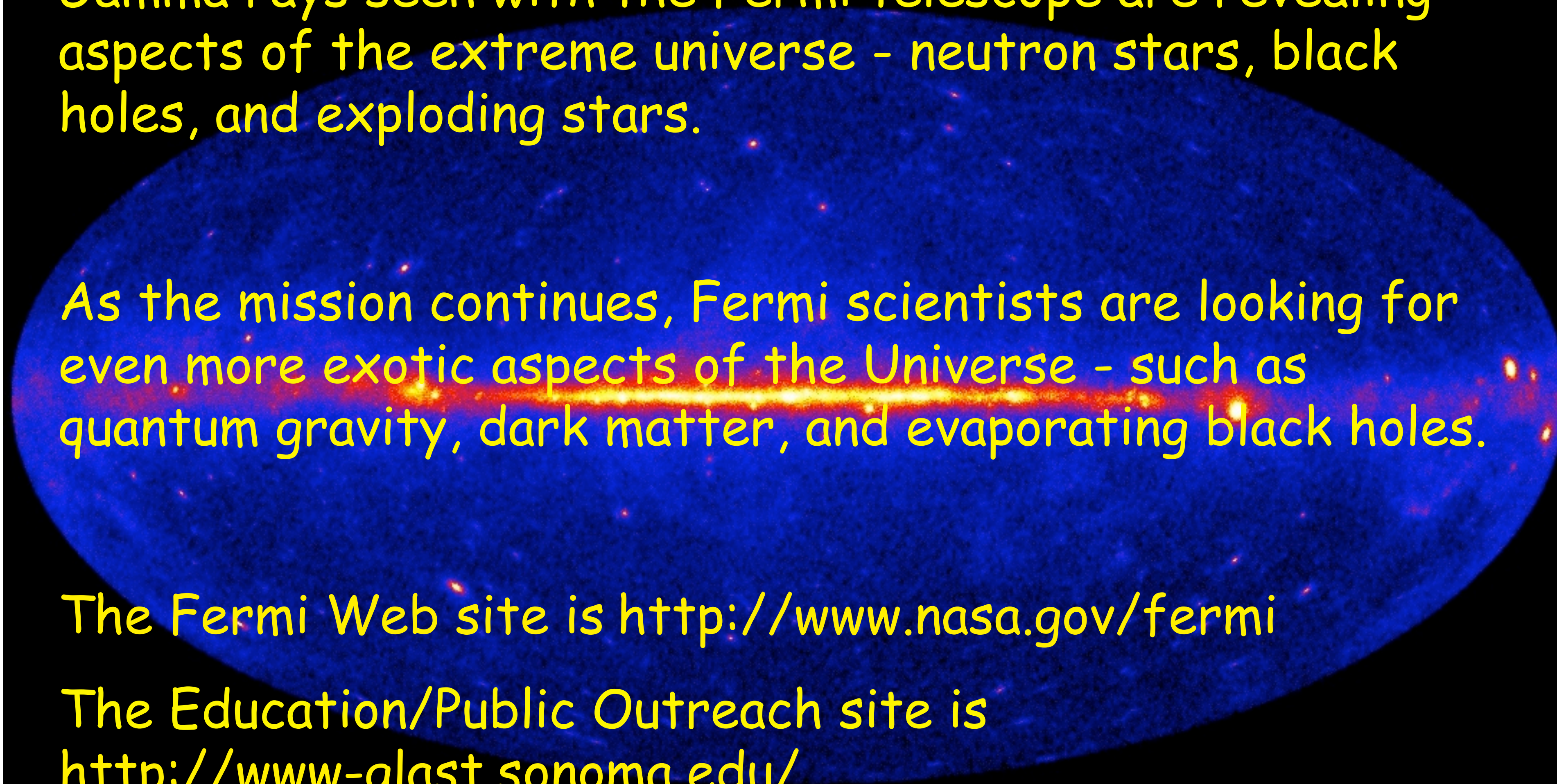
- no prominent spectral features between 20 GeV and 1 TeV; significantly harder spectrum than inferred from previous measurements
  Abdo et al. 2009, Phys. Rev. Lett. 102, 181101

- events for e^{+} e^{-} analysis required to fail ACD vetoes for selecting γ events; resulting γ contamination < 1%
- further cuts distinguish EM and hadron events; rejection 1:10^{3} up to 200 GeV; ~1:10^{4} at 1 TeV
- energy reconstruction aided by shower imaging capability of calorimeter
- more than 4x10^{6} e^{-} e^{+} events in selected sample



The excess above the conventional model suggests a local source, but what?

Summary - just the beginning



Gamma rays seen with the Fermi telescope are revealing aspects of the extreme universe - neutron stars, black holes, and exploding stars.

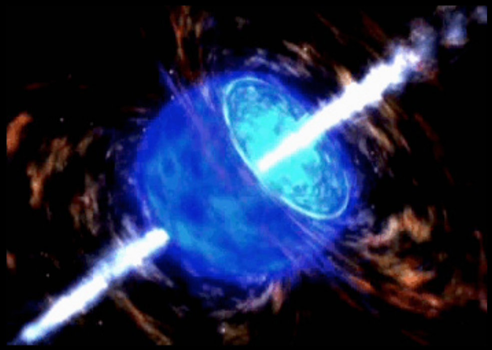
As the mission continues, Fermi scientists are looking for even more exotic aspects of the Universe - such as quantum gravity, dark matter, and evaporating black holes.

The Fermi Web site is http://www.nasa.gov/fermi

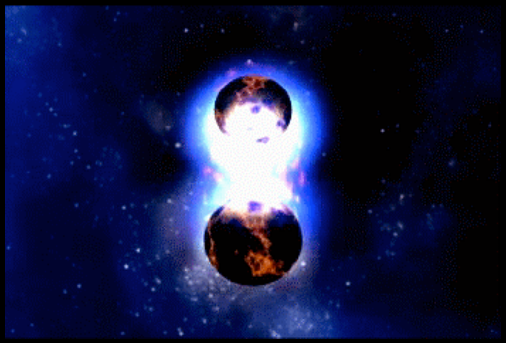
The Education/Public Outreach site is http://www-glast.sonoma.edu/

All the Fermi data are public. Join the fun!

Gamma-ray bursts come in at least three flavors

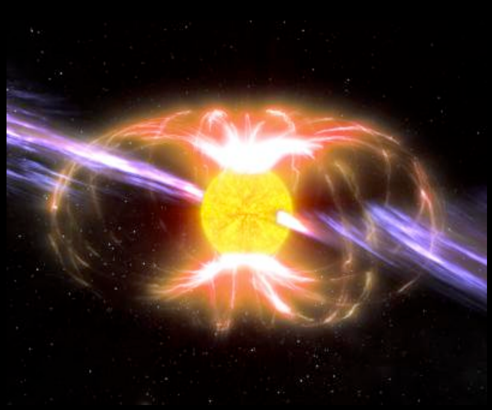


Collapsars: A rapidly spinning stellar core collapses and produces a supernova, along with relativistic jets that can produce long GRBs



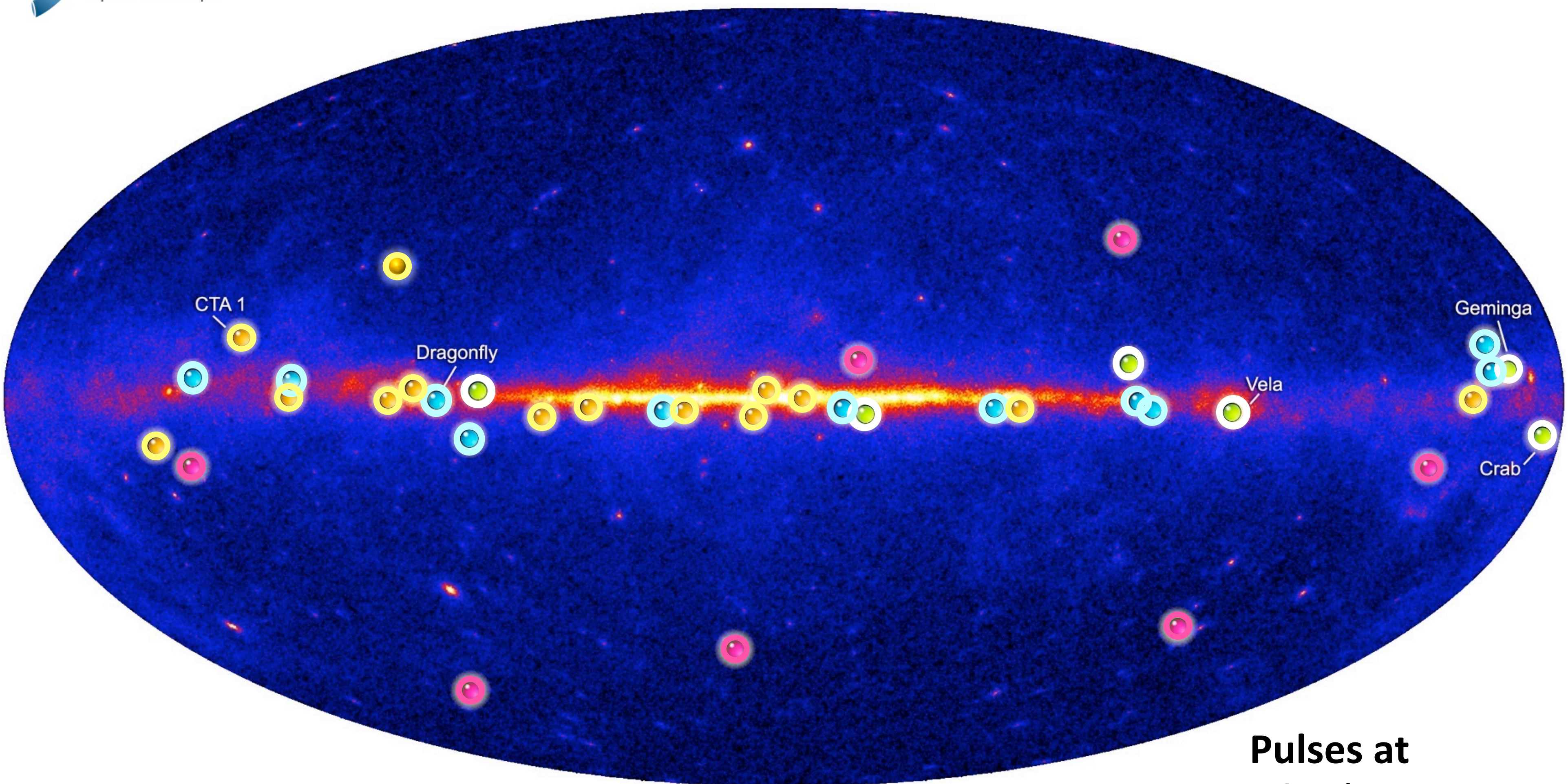
Compact Mergers: Two neutron stars, or a neutron star and a black hole, collide and merge, producing a jet that gives rise to a short GRB

In both these cases, the burst probably produces a black hole.



Magnetars: Neutron stars in our Galaxy or nearby galaxies with extremely strong magnetic fields can give off powerful bursts that resemble short GRBs

The Pulsing γ-ray Sky



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

Fermi Pulsar Detections

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

Complementary Indirect Searches I (Using Photons)

Focus of Search	Advantages	Challenges	Experiments
Galactic Center Region - WIMP	Good Statistics	Source Confusion, Gastrophysical background	ACTs, Fermi, WMAP (Haze), Integral, X-ray, radio
DM Galactic Satellites/Dwarfs/ BH Mini Spikes- WIMP	Low Background	Low Statistics, Follow –up Multi-wavelength Observations, Gastrophysical Uncertainties	ACTs (guided by Fermi), Fermi
Milky Way Halo- WIMP	High Statistics	Galactic Diffuse Modeling	Fermi
Spectral Lines- WIMP	No Gastrophysical Backgrounds	Low statistics in many models.	Fermi, ACTs (GC)
Extra Galactic Background- WIMP	High Statistics	Galactic Diffuse Modeling, Instrumental backgrounds	Fermi

Complementary Indirect Searches II
(Using Photons Unless Otherwise Indicated)

Focus of Search	Advantages	Challenges	Experiments
High latitude Neutron stars – KK graviton	Low Background	Gastrophysical Uncertainties, Instrument response ~ 100 MeV	Fermi
$e^+ + e^-$, or e^+/e^-	Very High Statistics	Charged Particle Propagation in galaxy, Gastrophysical Uncertainties	Fermi, PAMELA, ATIC, AMS
Antiproton/Proton	"	"	PAMELA, AMS
AGN Jet Spectra - Axions	Many point sources, good statistics	Understanding details of AGN Jet physics and spectra.	ACTs, Fermi, X-ray, radio (Multi-wavelength).