Fermi

Gamma-ray Space Telescope (formerly GLAST)

Searches for Dark Matter

Dave Thompson
NASA GSFC
on behalf of the Fermi Mission Team

Special thanks to Elliott Bloom, KIPAC-SLAC, Stanford University

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.
- Start of a new era in gamma-ray astrophysics.

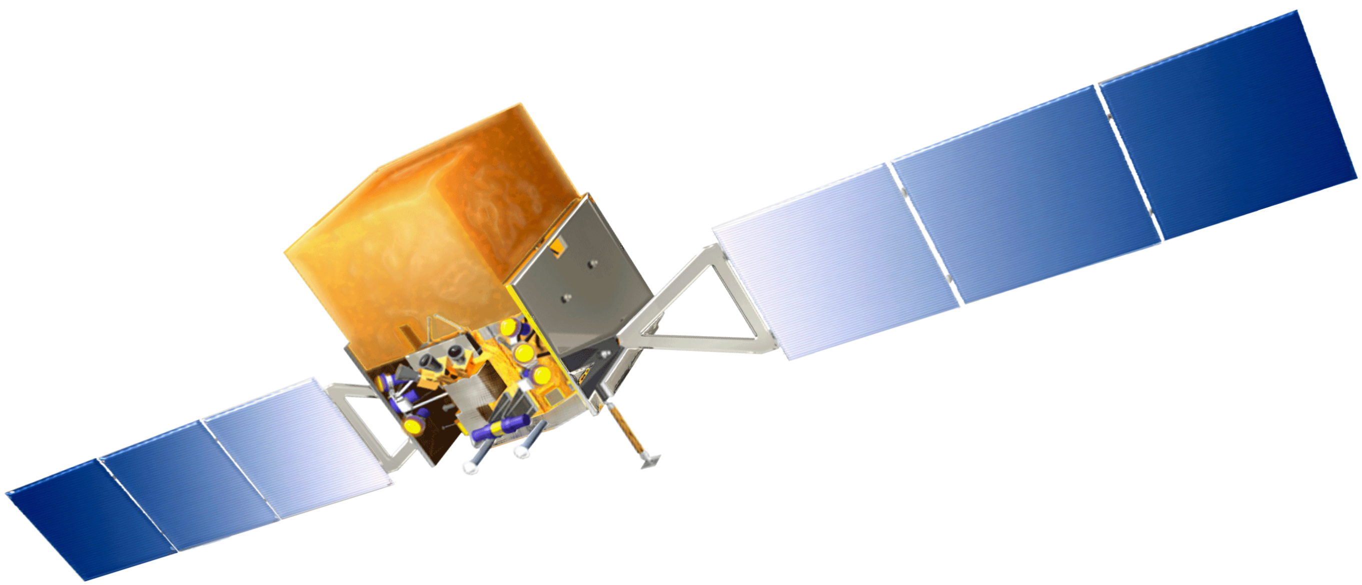
Outline

- 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
- Fermi LAT Searches for Evidence of Dark Matter
  - Approaches and challenges
- Current Status

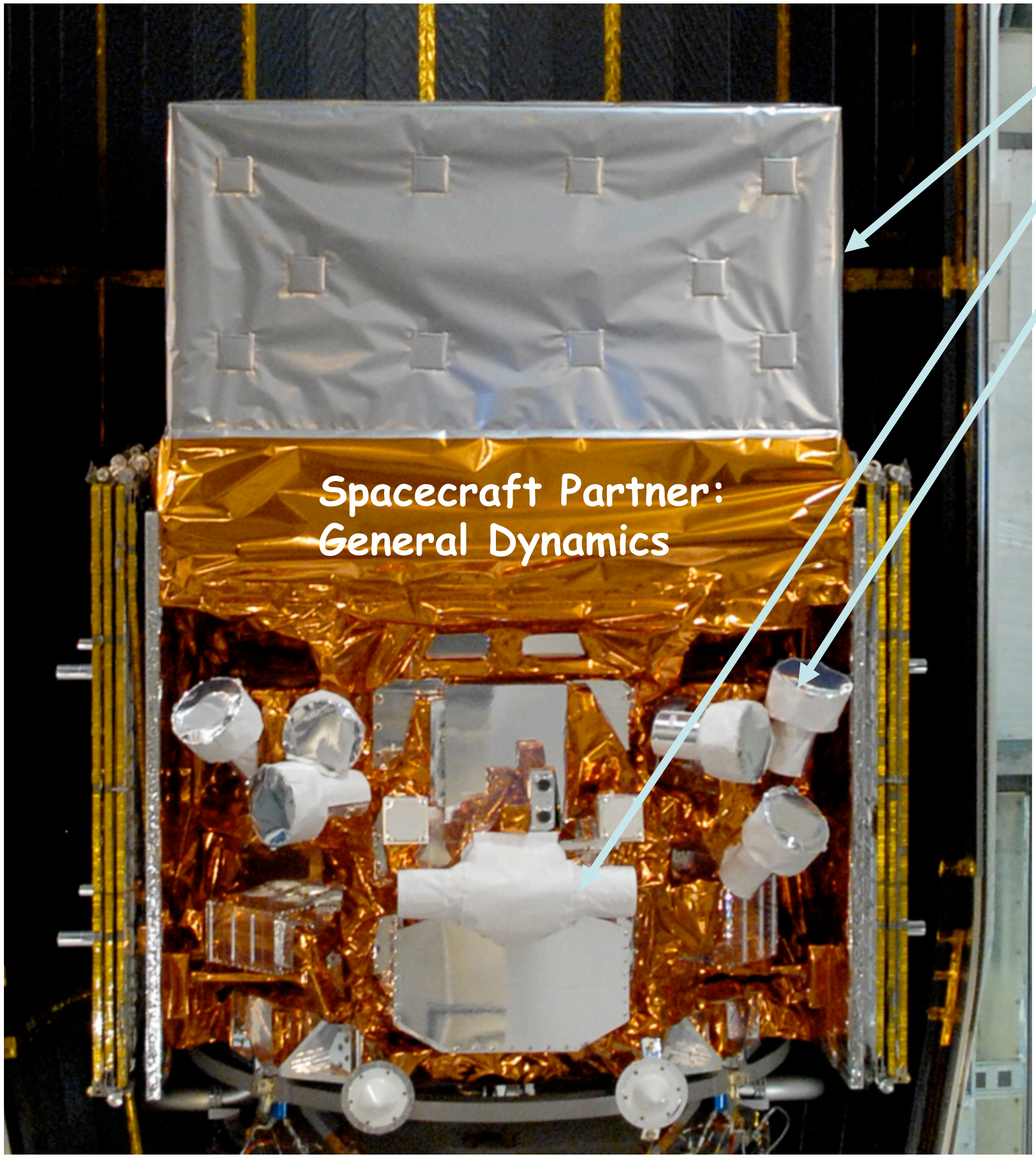
The Fermi Gamma-ray Space Telescope

Why study > 100 MeV γ's?

- γ rays offer a direct view into Nature's largest accelerators.
  - Past missions have shown that the γ-ray sky is dynamic, revealing information about powerful objects like pulsars, blazars, and supernovae.
- the Universe is mainly transparent to γ rays with < 20 GeV that can probe cosmological volumes (z~700). Any opacity is energy-dependent for higher energy.
- Most particle relics of the early universe produce γ rays when they annihilate or decay.



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

GBM Collaboration

National Space Science & Technology Center

University of Alabama
in Huntsville

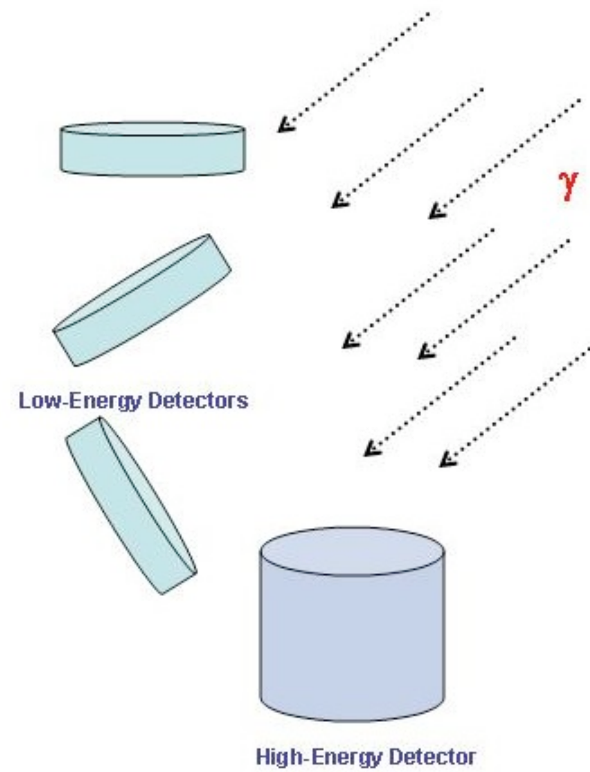
NASA
Marshall Space Flight Center

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.



GLAST LAT Collaboration

- France
  - IN2P3, CEA / Saclay
- Italy
  - INAF, INFN, ASI
- Japan
  - Hiroshima University
  - ISAS, RIKEN
- Sweden
  - Kalmar University
  - Royal Institute of Technology (KTH)
  - Stockholm University
- 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

Principal Investigator:
Peter Michelson (Stanford University)

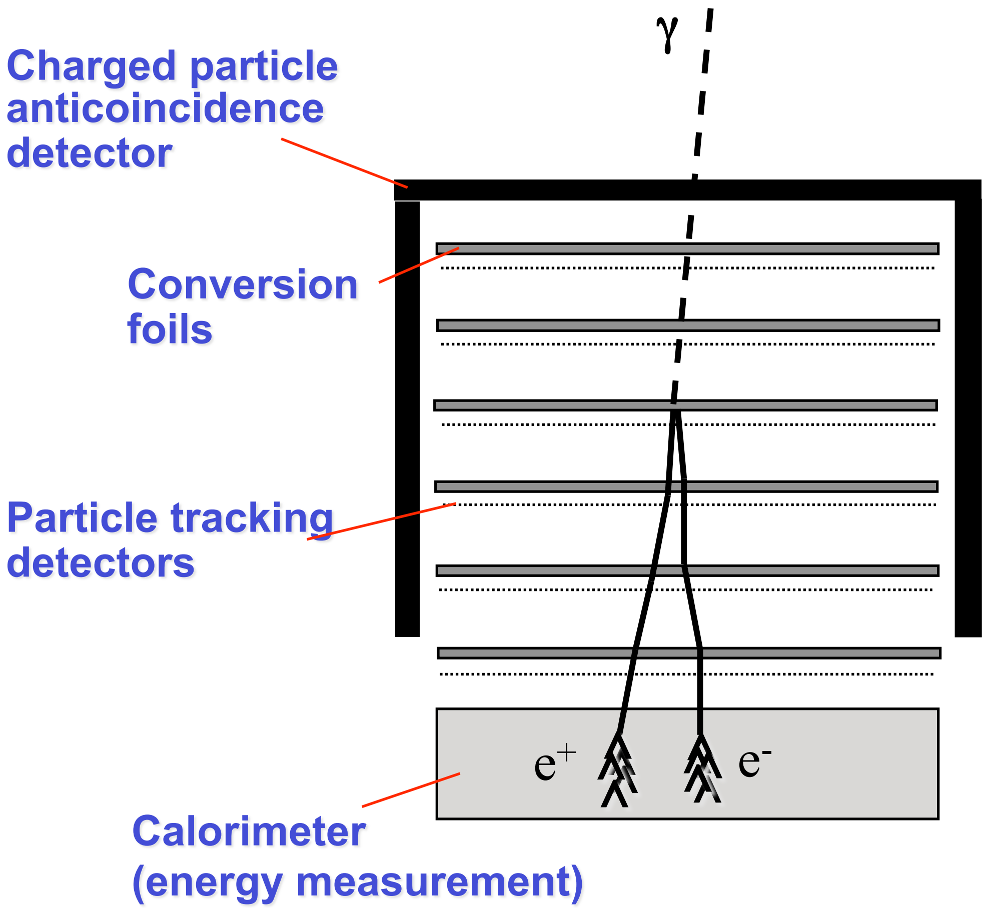
~270 Members and Affiliates
(includes ~90 Affiliated Scientists, 37 Postdocs, and 48 Graduate Students)

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

LAT Project Managed at SLAC National Accelerator Laboratory, Stanford University.

Generic Pair Conversion Telescope

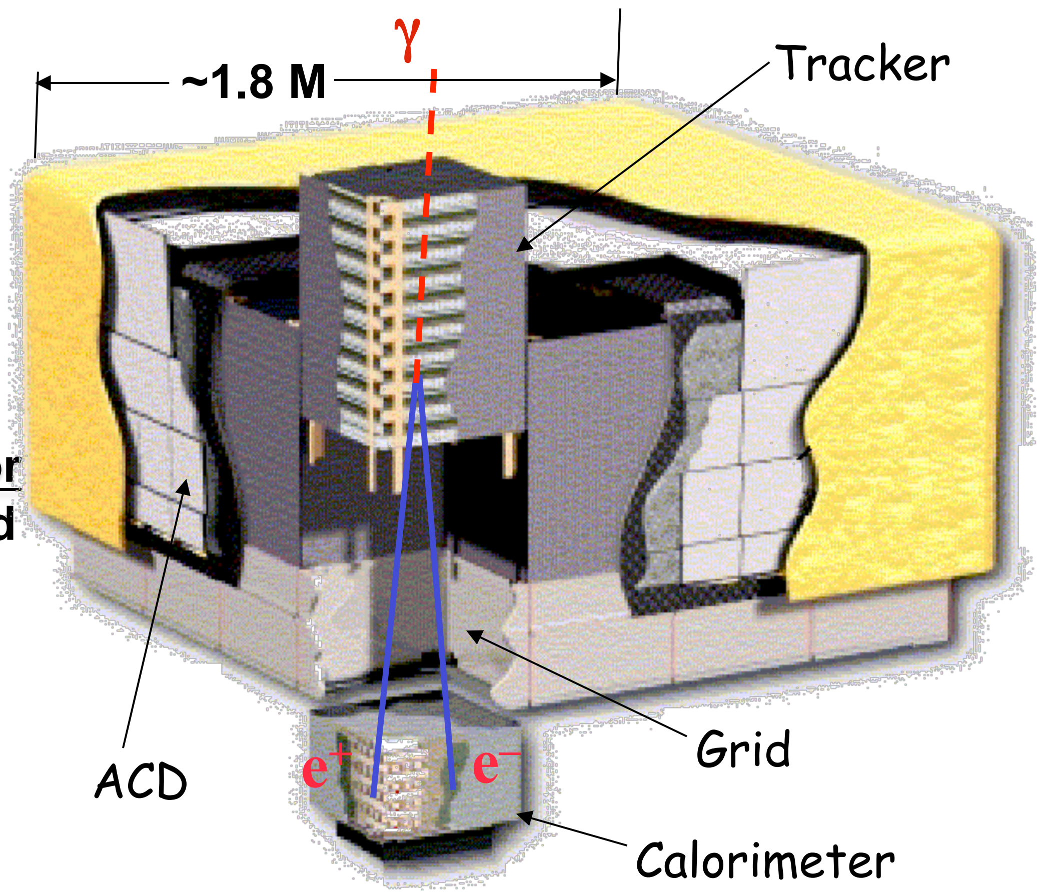
Principle of Operation



Overview of LAT

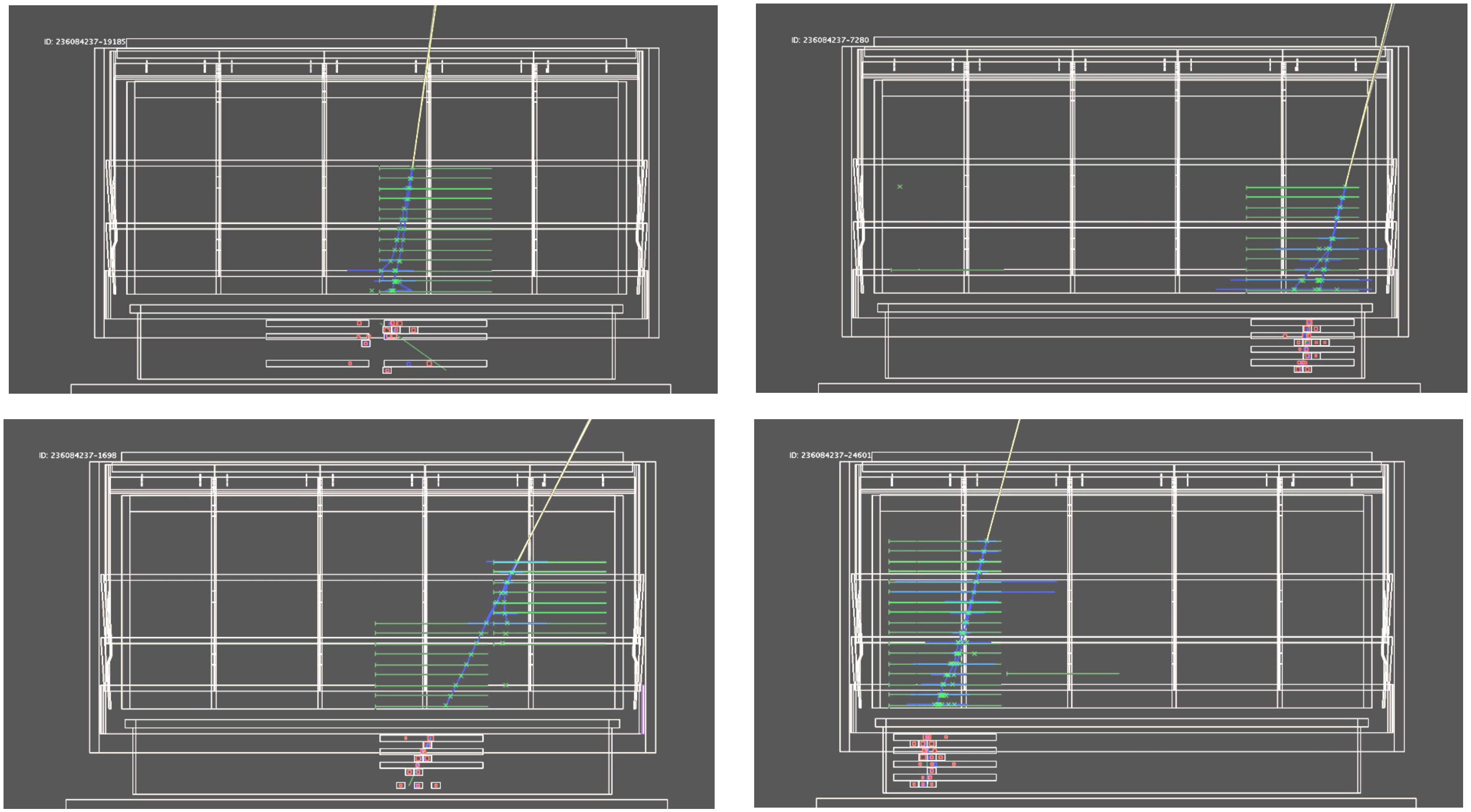
- <u>Precision Si-strip Tracker (TKR)</u> 73 m^2 Si, 18 XY tracking planes. Single-sided silicon strip detectors (228 μm pitch) Measure the photon direction; gamma ID. 1.5 RL W in thin foils.
- <u>Hodoscopic CsI Calorimeter(CAL)</u> Array of 1536 CsI(Tl) crystals in 8 layers. Measure the photon energy; image the shower. 8.5 RL CsI(Tl)
- <u>Segmented Anticoincidence Detector (ACD)</u> 89 plastic scintillator tiles and 8 ribbons. Reject background of charged cosmic rays; segmentation removes self-veto effects at high energy. Rejection of CP is 0.9997
- <u>Electronics System</u> Includes flexible DAC, robust hardware trigger, and software filters in flight software.

16 towers-TKR+CAL+DAQ



<u>Systems work together to identify and measure the flux of cosmic gamma rays with energy 20 MeV - >300 GeV.</u>

LAT Gamma Candidate Events



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.

Fermi LAT Capabilities (MC + Beam Tests)

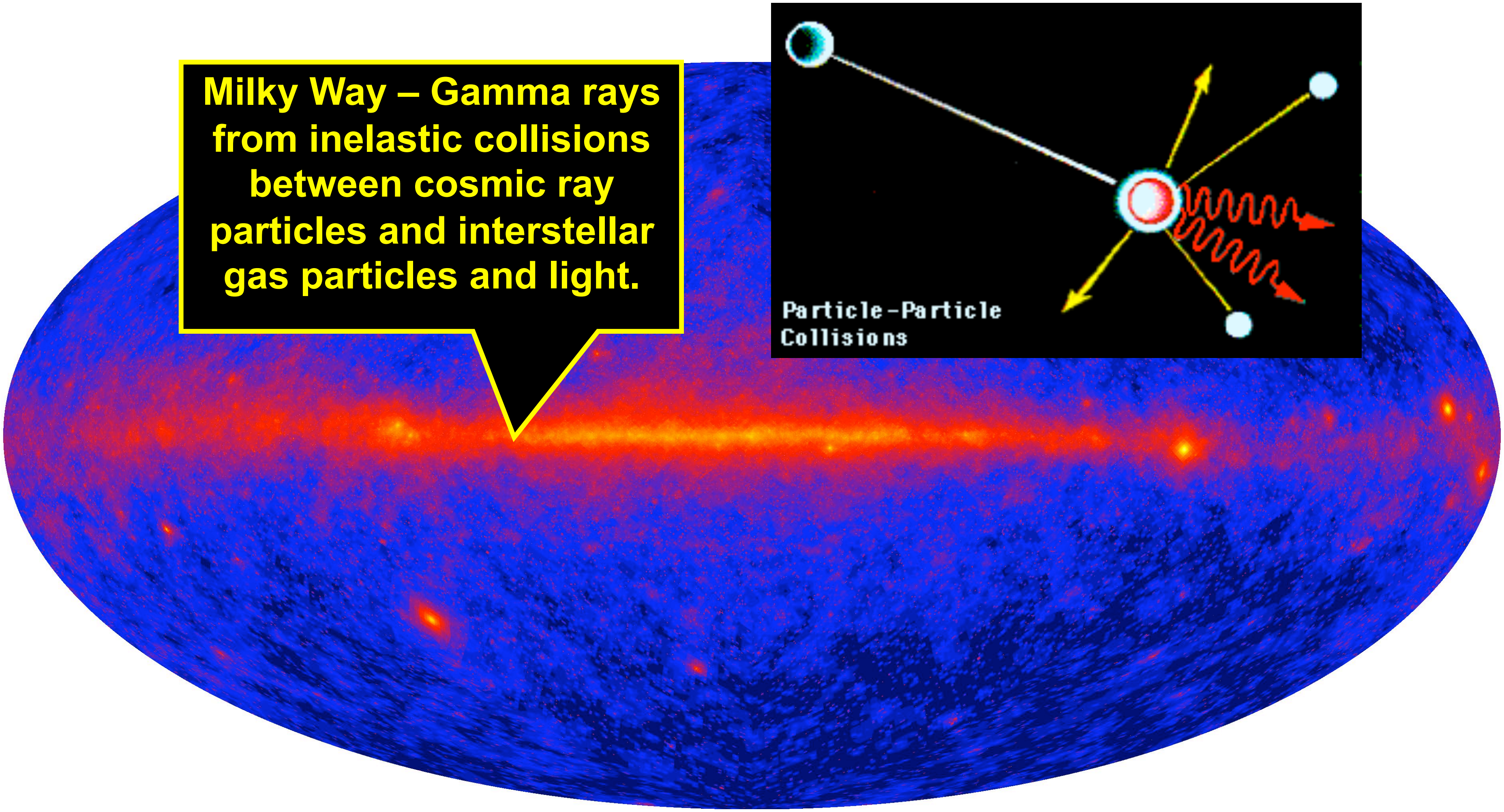
- Very large Field of View (FOV) (~20% of sky).
- Large effective area (factor > 5 bigger than EGRET).
- Broadband - 4 decades in energy.
- Photon energy resolution ~10% @ normal incidence, <~ 6% for photons incident at larger angles (>60 degrees to normal to front face of LAT).
- Point Spread function (PSF) for gamma rays a factor > 3 better than EGRET for E>1 GeV.
- Results in factor > 30 improvement in sensitivity to EGRET below 10 GeV, and >100 improvement at higher energies.
- No expendables → long mission without degradation - 5 year requirement , 10 year goal.

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 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 entire sky every three hours!

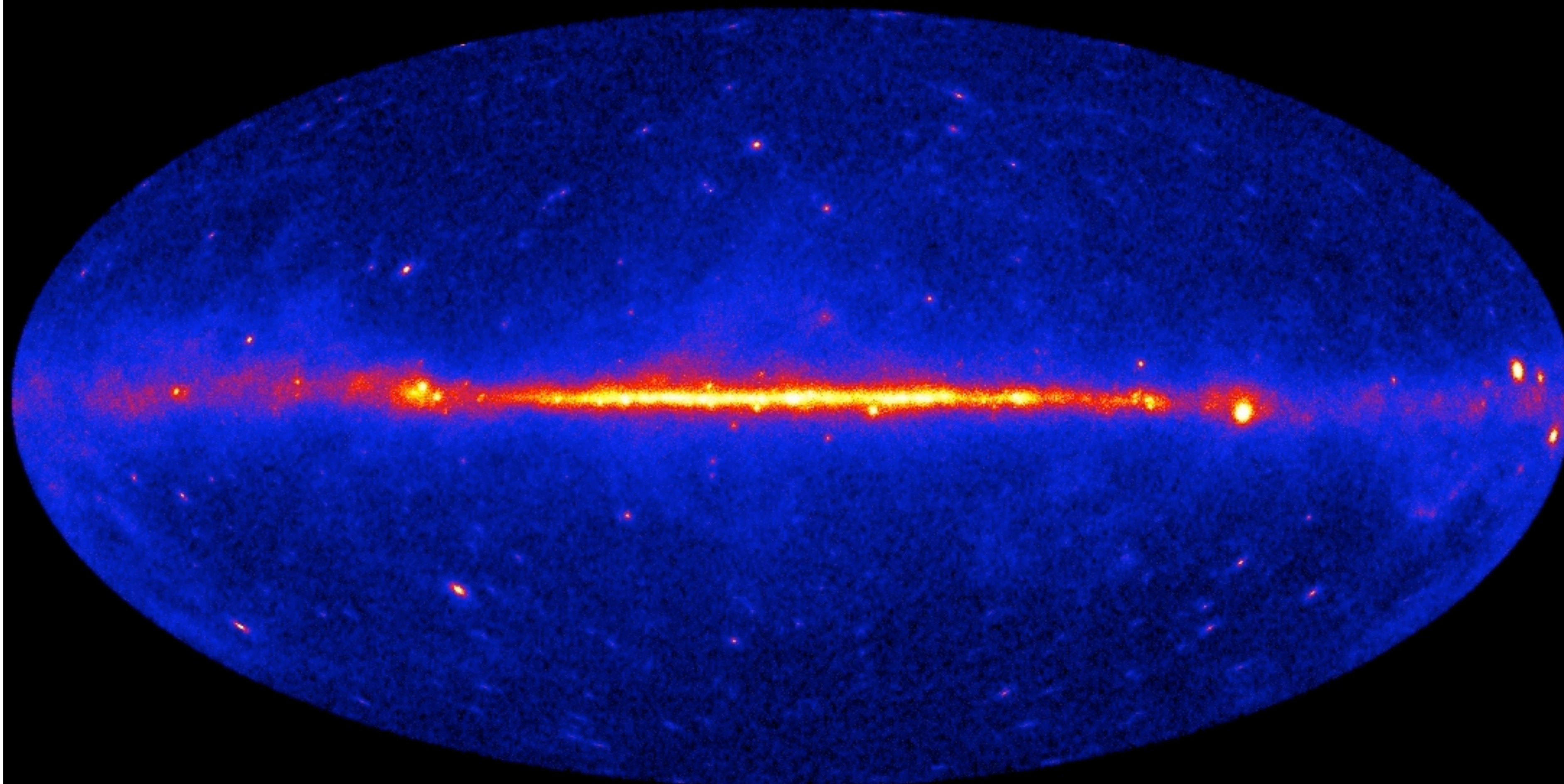
Quick Overview of the Gamma-ray Sky

Large Area Telescope First Light!

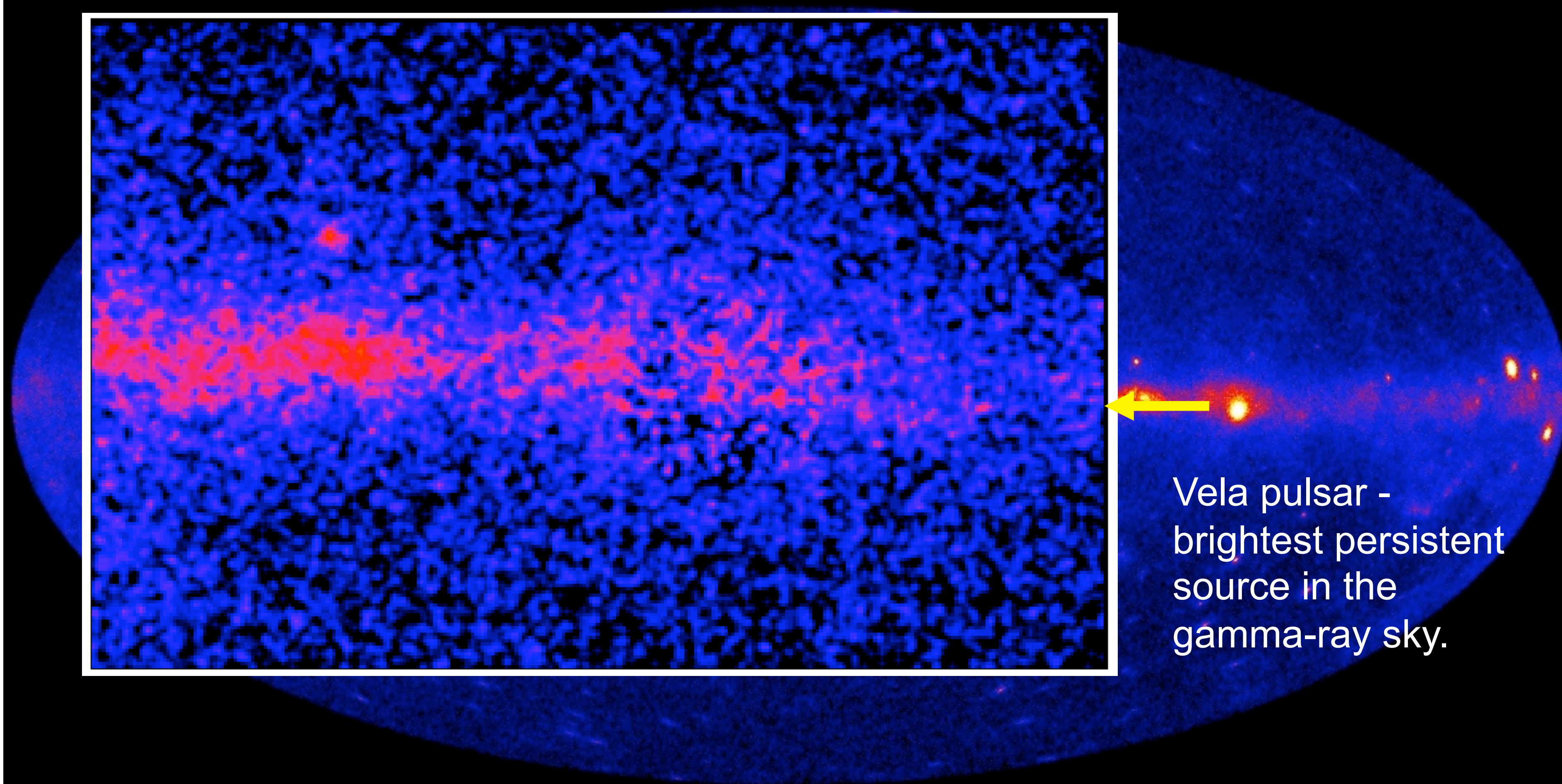


The Fermi Large Area Telescope sees the whole gamma-ray sky every three hours. This image represents just four days of observations.

Three months of LAT scanning data



Pulsars - rapidly rotating neutron stars



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

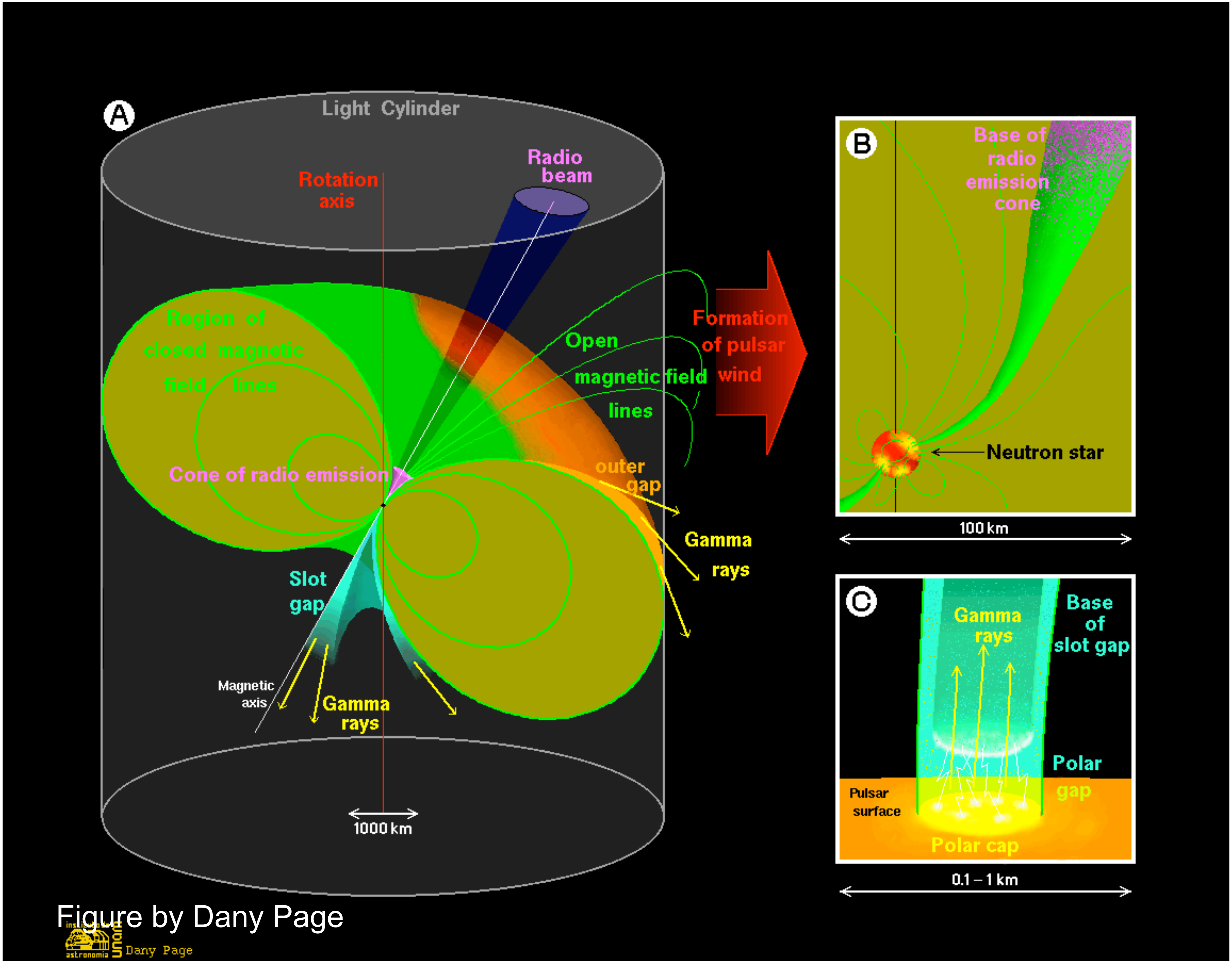
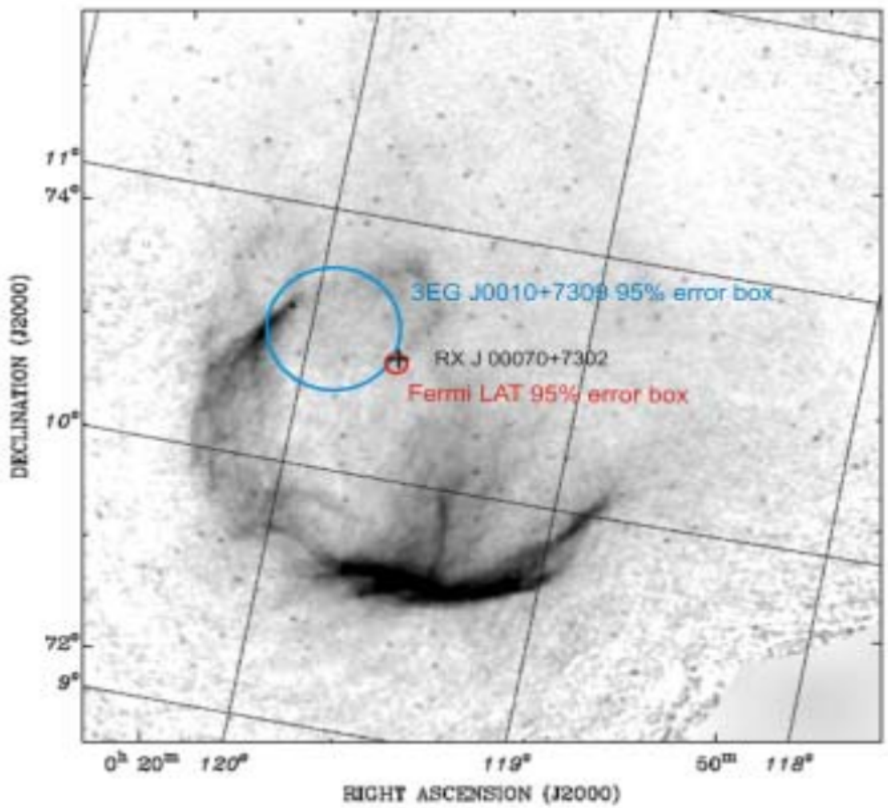


Figure by Dany Page

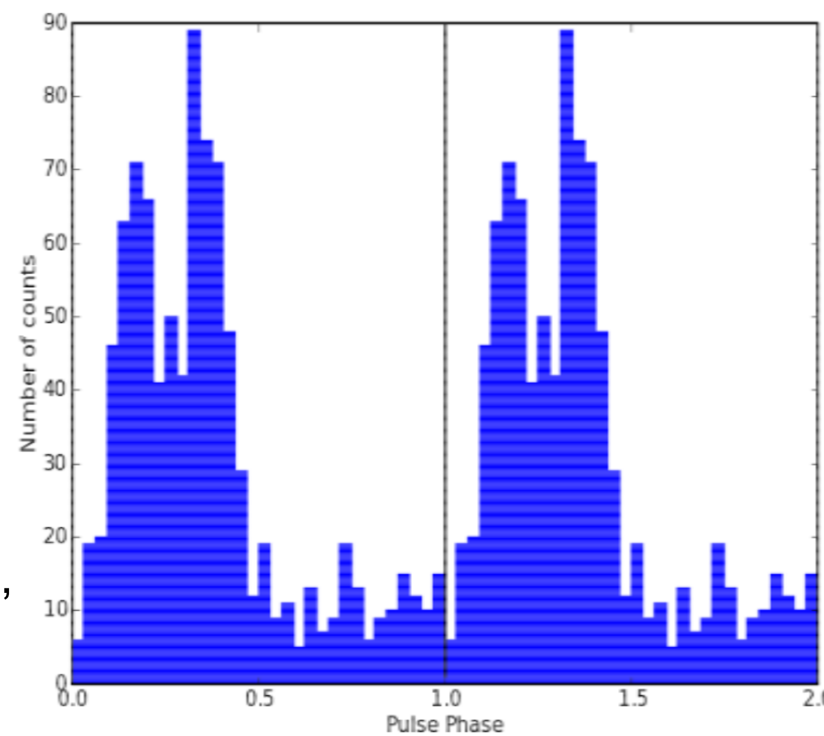
LAT discovers a radio-quiet pulsar!



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

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

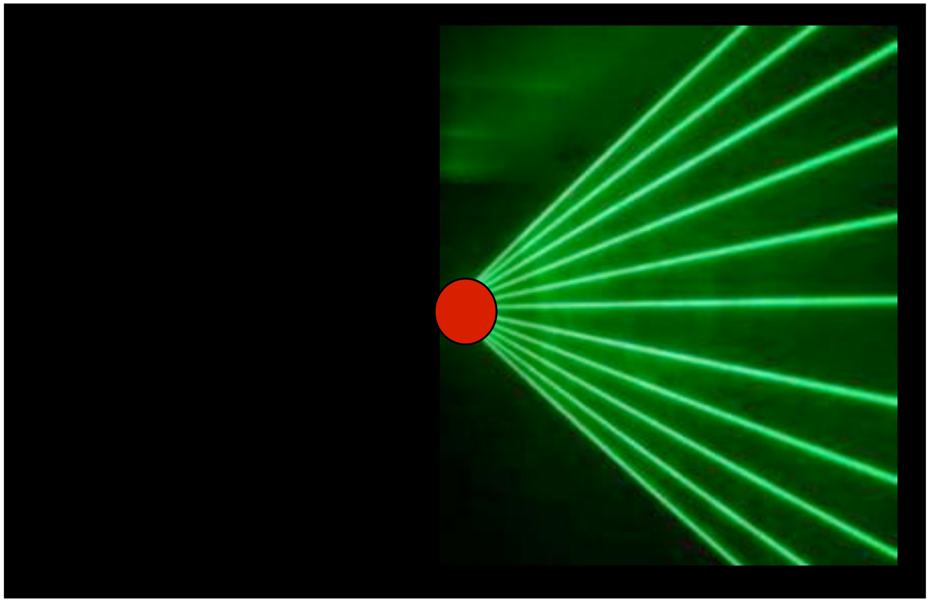
P ~ 317 ms
Pdot ~ 3.6E-13
Characteristic age ~ 10,000 yrs



Gamma-only Pulsars: Beamshape

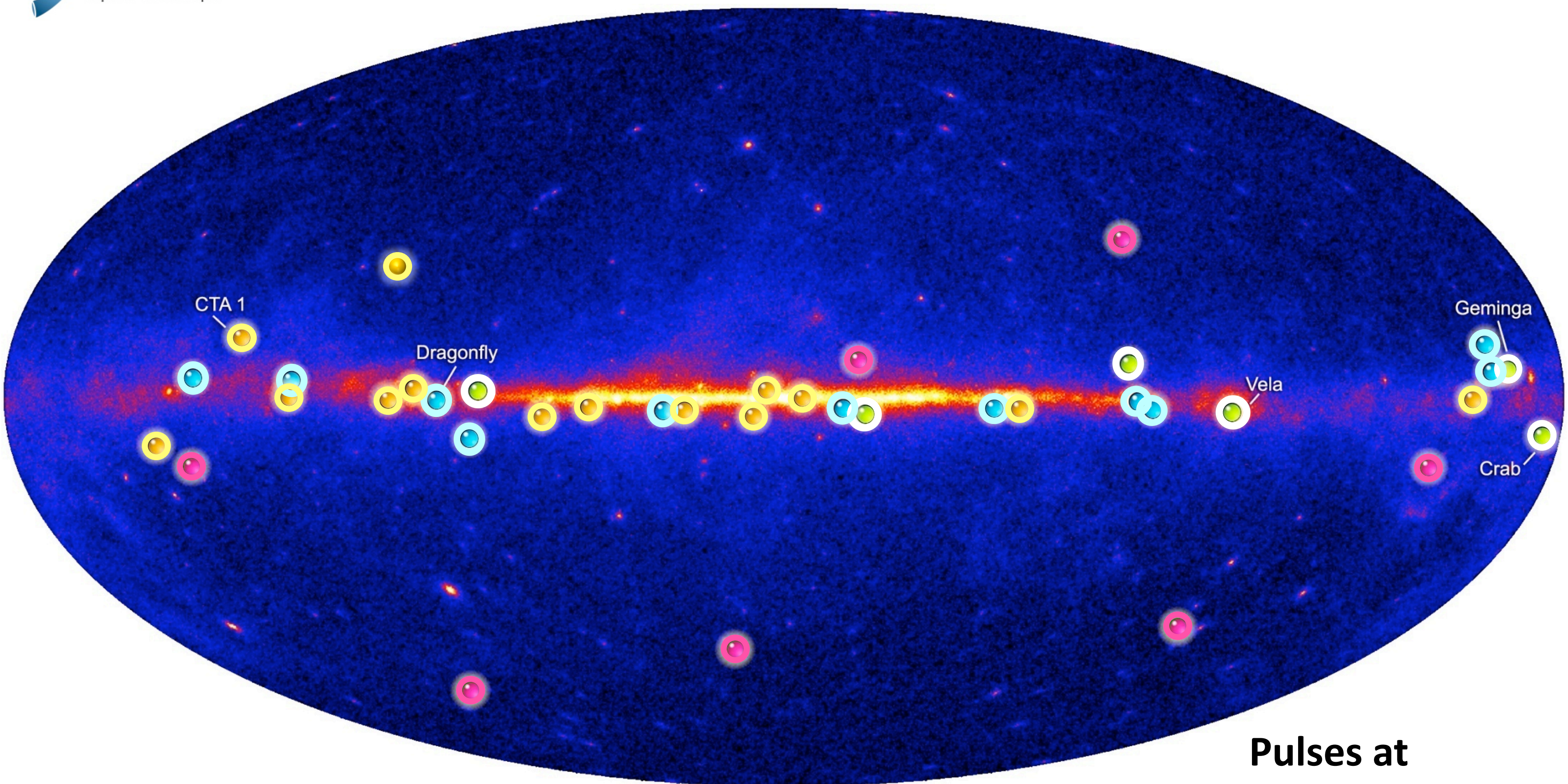
Traditional 'Lighthouse' Beam

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 Pulsing γ-ray Sky



Pulses at 1/10th true rate

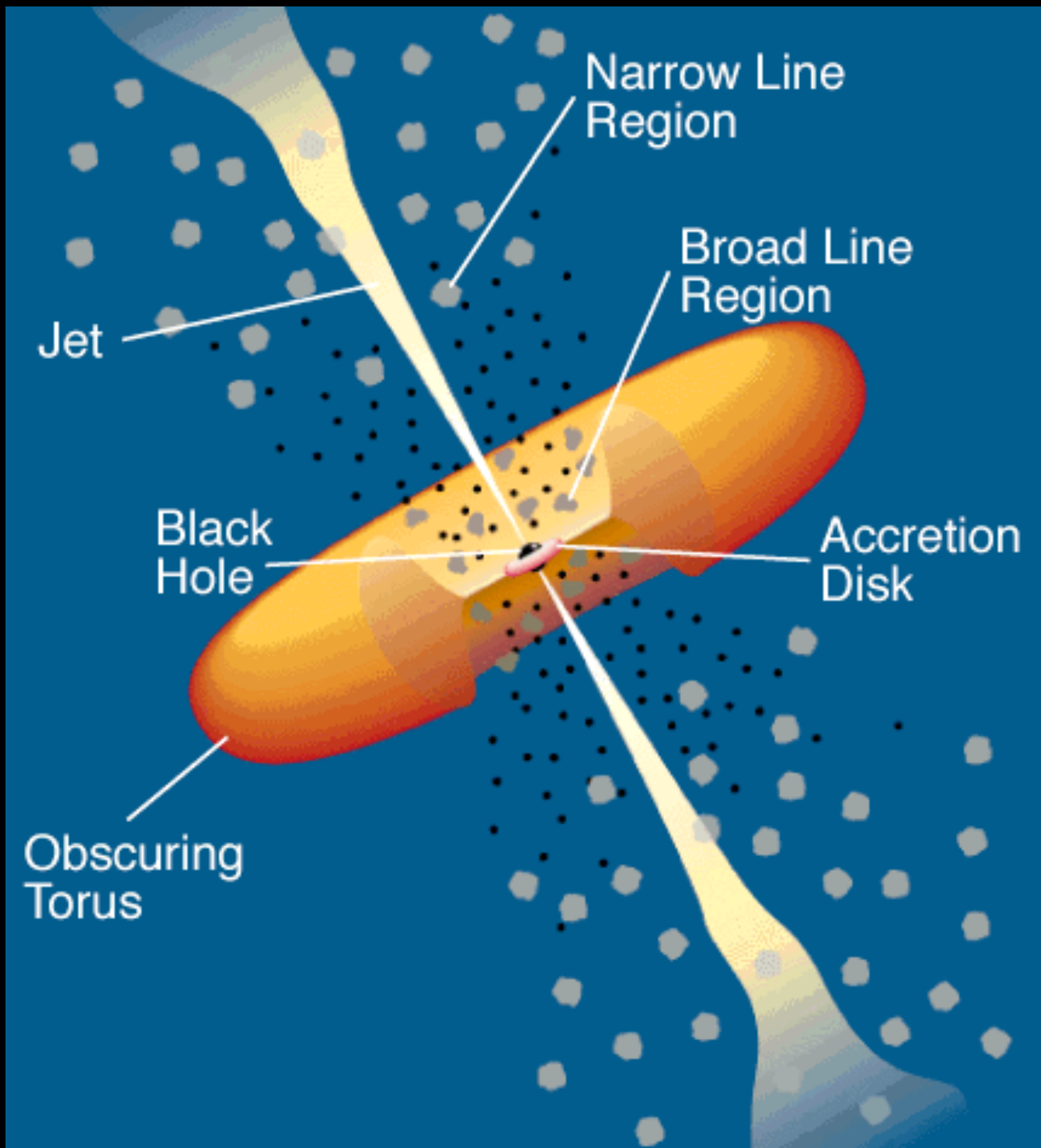
Fermi Pulsar Detections

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

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

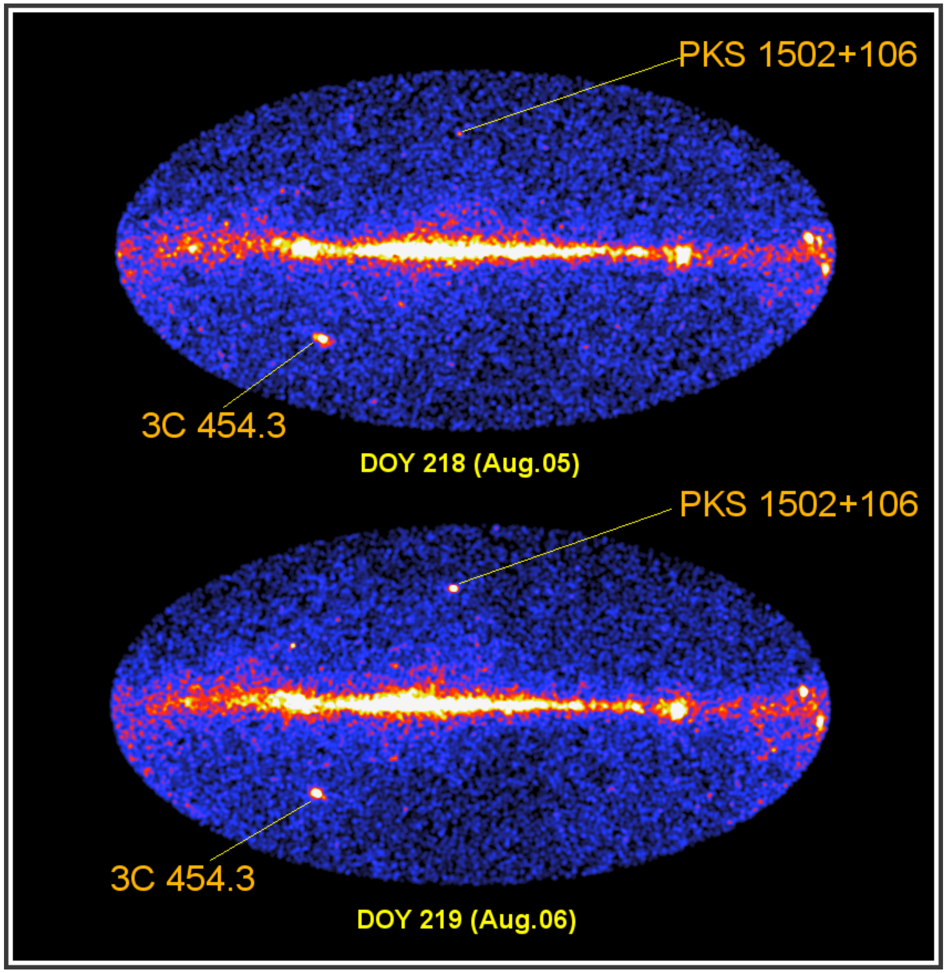
- Power comes from material falling toward a supermassive black hole
- Some of this energy fuels a jet of high-energy particles that travel at nearly the speed of light

AGN



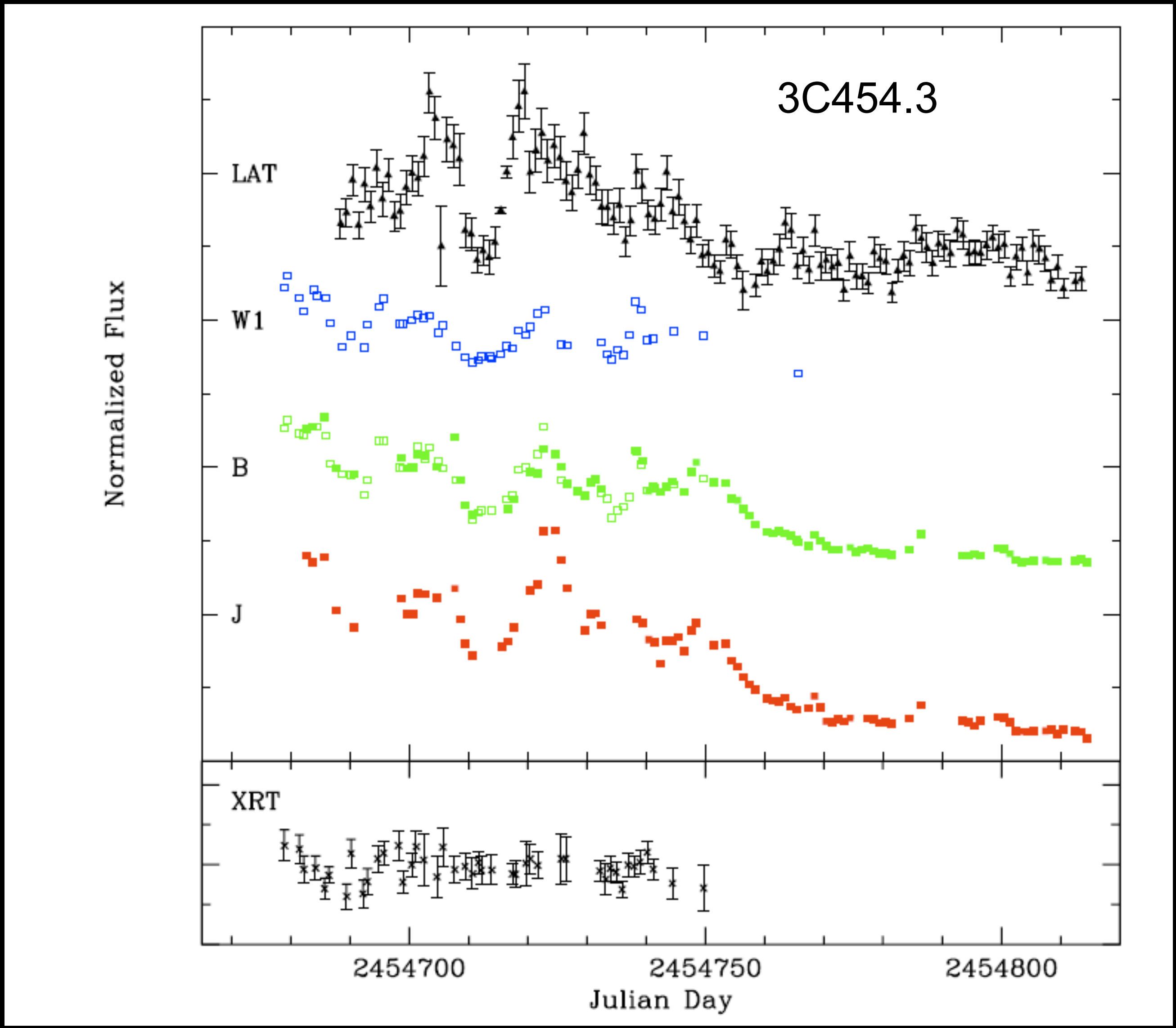
- **Unified models of AGN suggest that different types of AGN are really defined by how we see them.**
- **When such jets are pointed at Earth, we see what is called a *blazar***
- **Gamma rays are an important way to learn how these jets operate**

Flaring sources



- Automated search for flaring sources on 6 hour, 1 day and 1 week timescales.
- 23 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

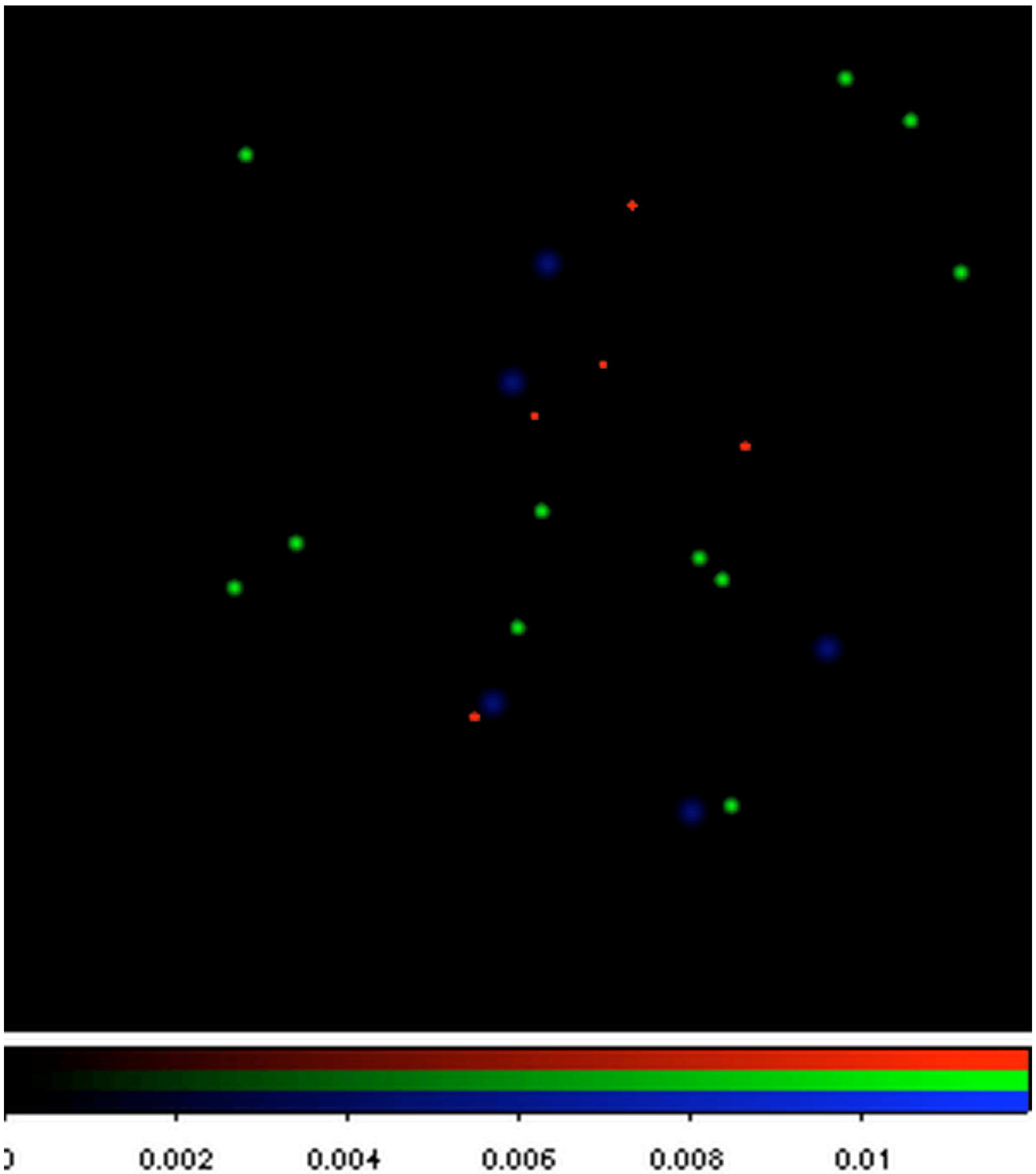
How to learn about jets? Variability



Bonning et al. 2008

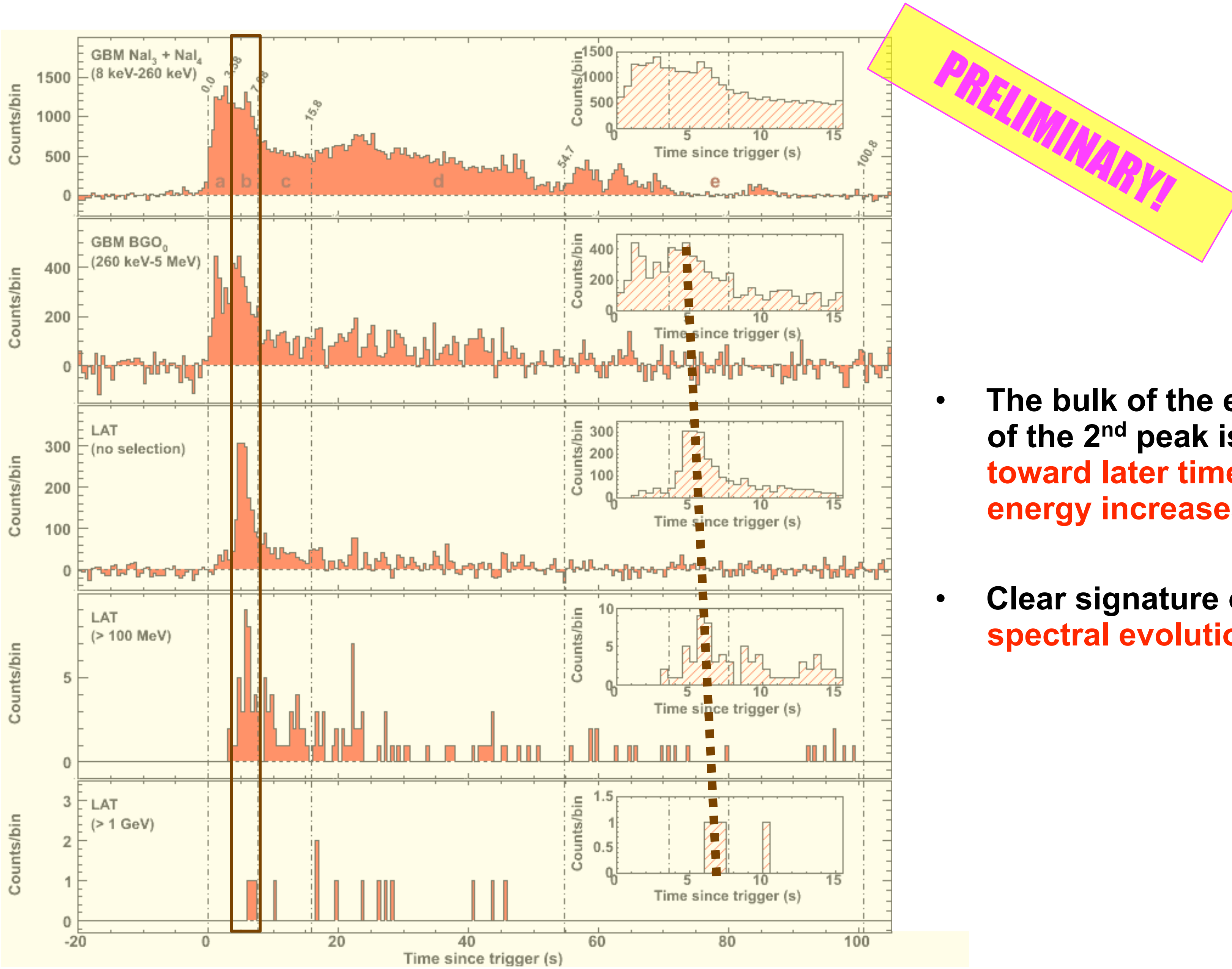
Correlated variability helps us learn how jets work.

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**

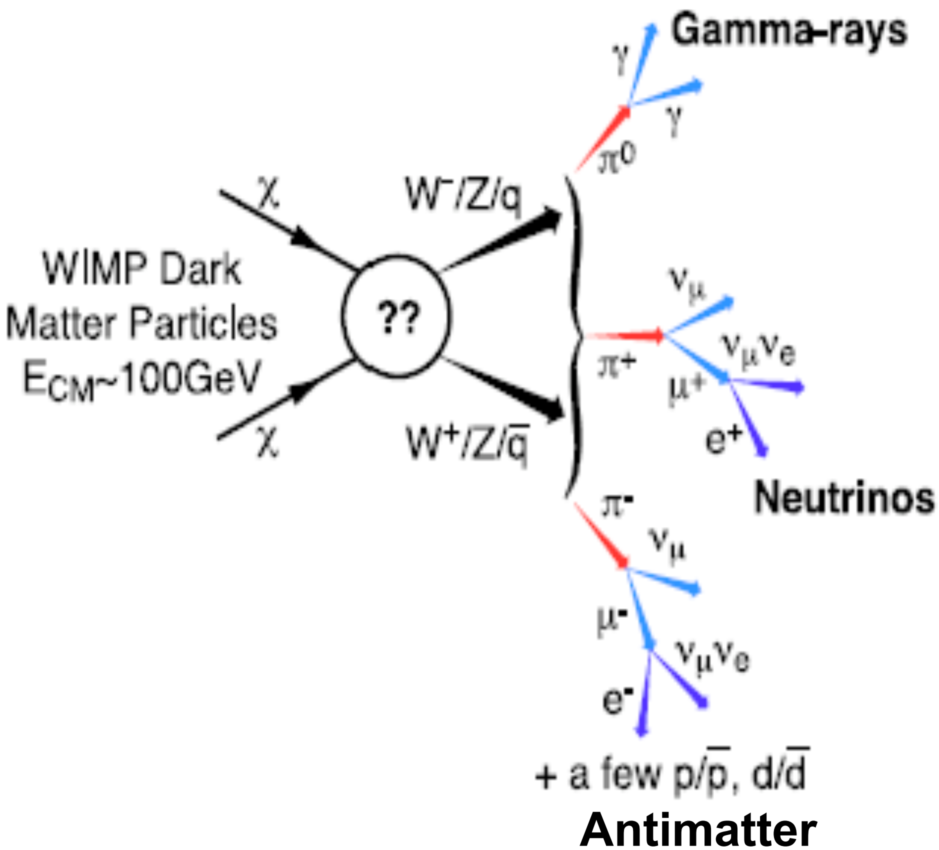
How Can Fermi LAT Search for Signs of Dark Matter?

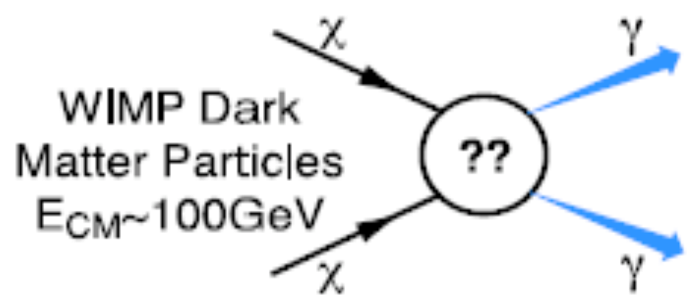
Pre-launch Estimates for GLAST Sensitivity to Dark Matter Annihilation Signals, Baltz, et al., Journal of Cosmology and Astroparticle Physics, Issue 07, pp. 013 (2008)

What is the Nature of Dark Matter

- There is no end of “natural” particle candidates for non-baryonic dark matter from particle physics.
  - Axions
  - Sterile Neutrinos
  - Large Extra Dimensions ~ 100 MeV particle
  - WIMP (in annihilation) (For observed relic density, M_W~100 GeV, $<\sigma_{annihilation}*v> \sim 3\times10^{-26}$ cm^3/sec, works well)
    - SUSY
      - Neutralino
      - Gravitino (decay)
    - Universal Extra Dimensions (UED)
    - Little Higgs
    - XDM
    - …
  - WIMPZilla
  - …

WIMP Annihilation





WIMP Spectral Shape and Flux Magnitude

γ-ray flux factors

$\int(\sum_i dN/dE\ B_i)dE$
x
$4\pi \int\rho^2(r)r^2dr\ /\ M^2_{WIMP}$
x
$<\sigma v>/2$
x
$1/4\pi d^2$

Energy spectrum
(depends upon particle mass, branching fractions)

x

number density²
(depends upon dark matter clustering)

x

annihilation cross-section
(depends upon underlying particle physics, inflation…)

x

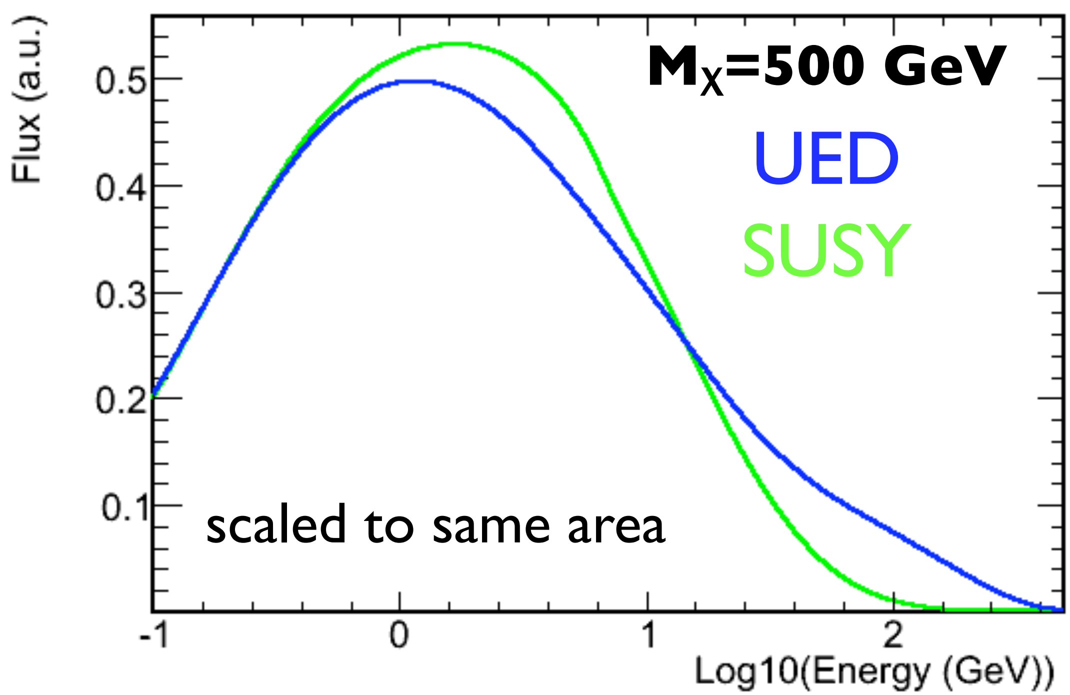
distance⁻²
(depends upon dark matter clustering)

Spectral shape: Universal ?

***Flux magnitude:* Factors difficult to disentangle for single point source**

UED vs. SUSY

- Consider 500 GeV WIMP in SUSY and in UED (use micromegas* code to generate γ spectrum):
  - UED: γs mostly from lepton bremsstrahlung
  - SUSY: γs 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 flux for equal masses



mSUGRA parameters:

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

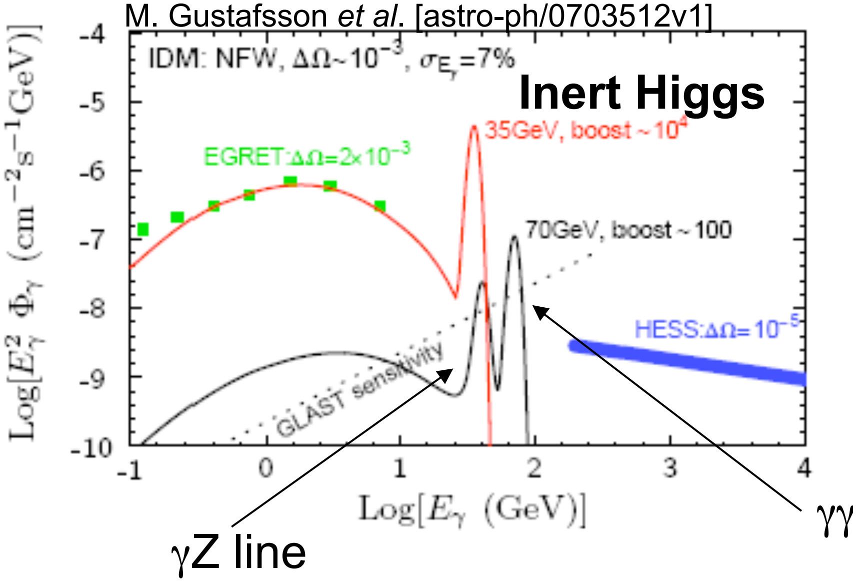
➡Spectra can look different in these scenarios

* G. Bélanger, F. Boudjema, A. Pukhov and A. Semenov, Comput. Phys. Commun. 174 (2006) 577; hep-ph/0405253
G. Bélanger, F. Boudjema, A. Pukhov and A. Semenov, Comput. Phys. Commun. 149 (2002) 103; hep-ph/0112278

Speculations on WIMP Spectral Lines

Galactic Center

M. Gustafsson *et al*. [astro-ph/0703512v1]



Extra-Galactic Background

A. Ibarra & D. Tran [astro-ph/0709.4593v1]

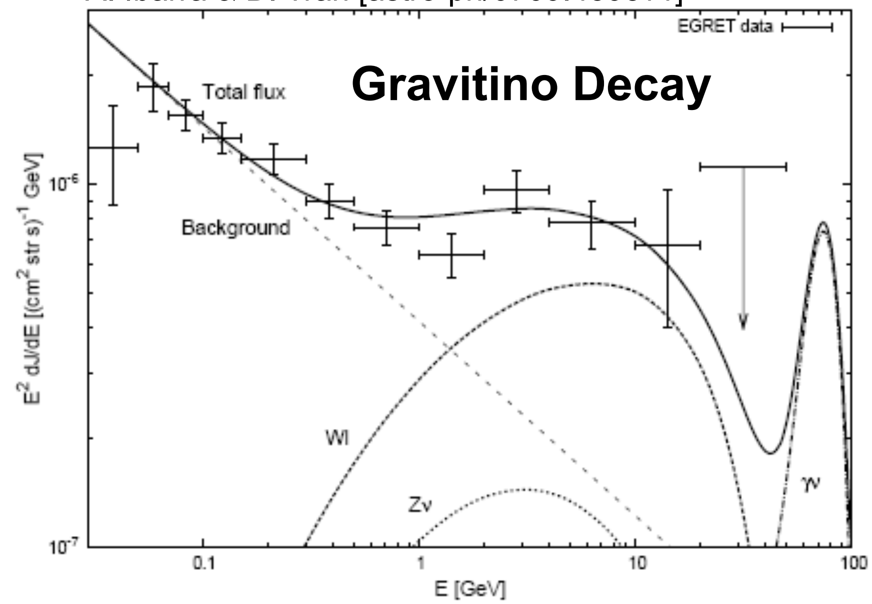


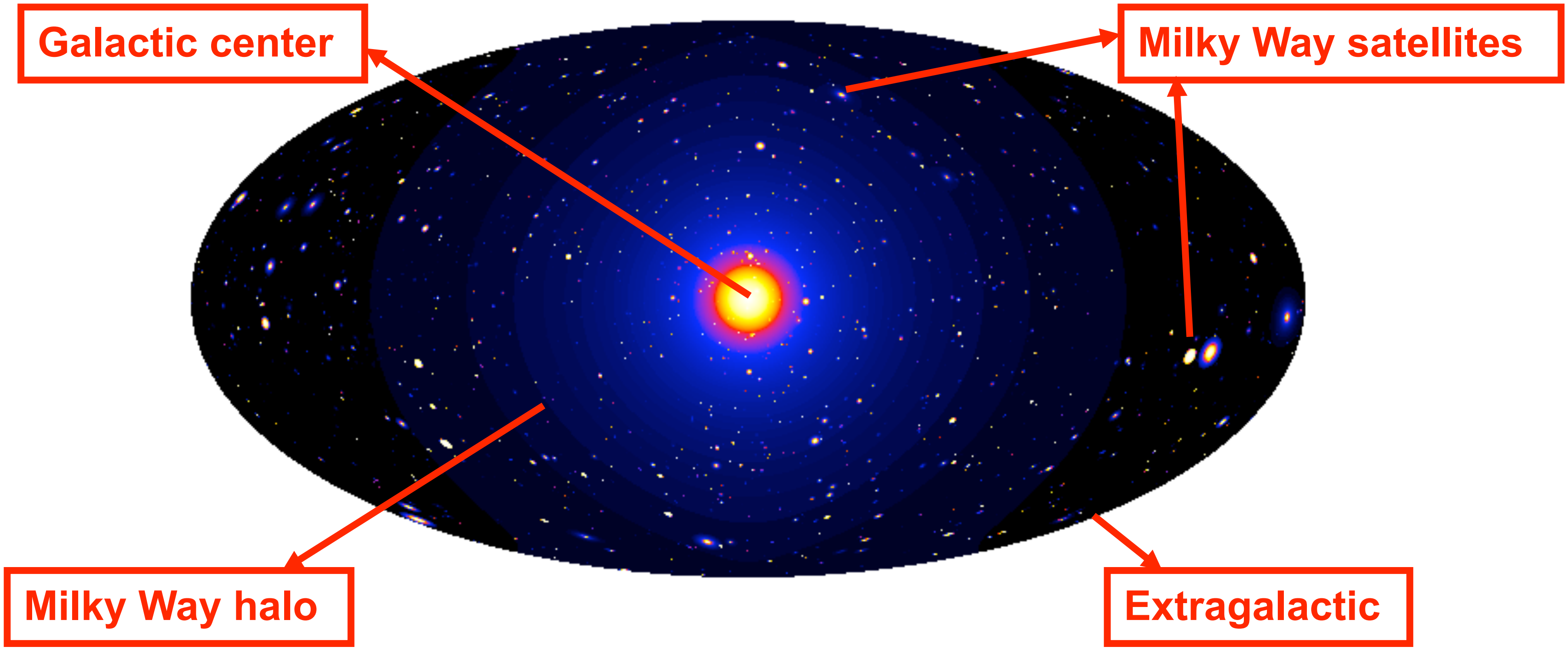
TABLE I: Branching ratios for gravitino decay in different R-parity violating channels for different gravitino masses.

$m_{3/2}$	$\mathrm{BR}(\psi_{3/2} \to \gamma\nu)$	$\mathrm{BR}(\psi_{3/2} \to W\ell)$	$\mathrm{BR}(\psi_{3/2} \to Z^0\nu)$
10 GeV	1	0	0
85 GeV	0.66	0.34	0
100 GeV	0.16	0.76	0.08
150 GeV	0.05	0.71	0.24
250 GeV	0.03	0.69	0.28

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)



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).

Current Status - Guided by Two Principles

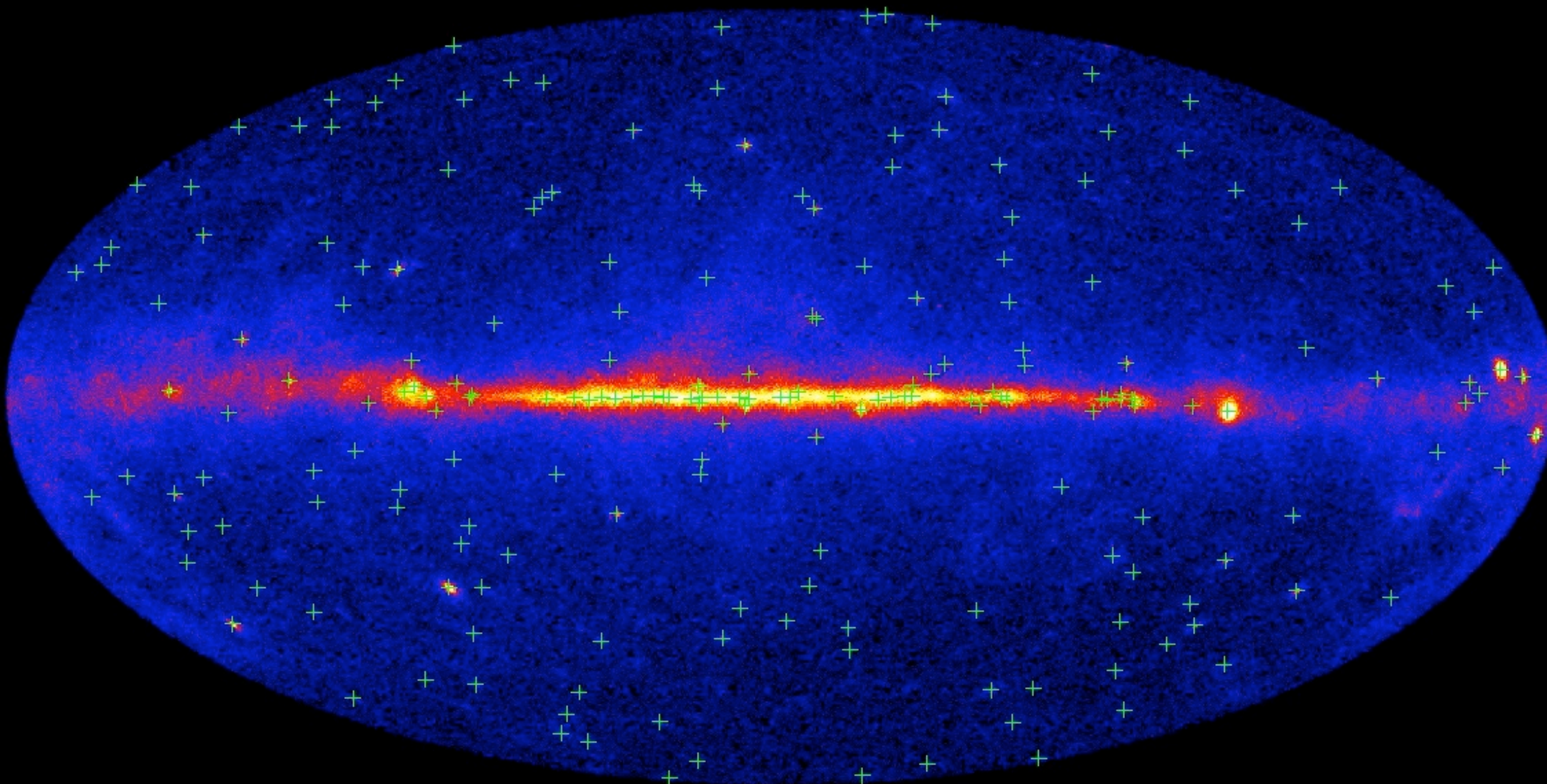
"The weight of evidence for an extraordinary claim must be proportioned to its strangeness."

Attributed to Laplace

"Eliminate all other factors, and the one which remains must be the truth.

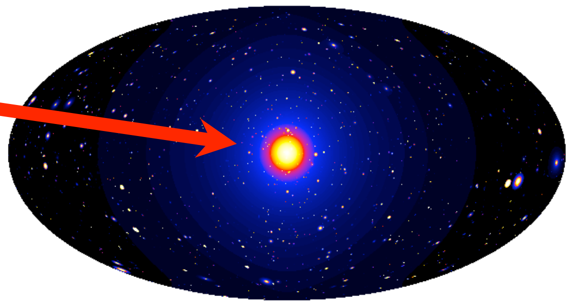
Attributed to Sherlock Holmes

205 LAT Bright Sources

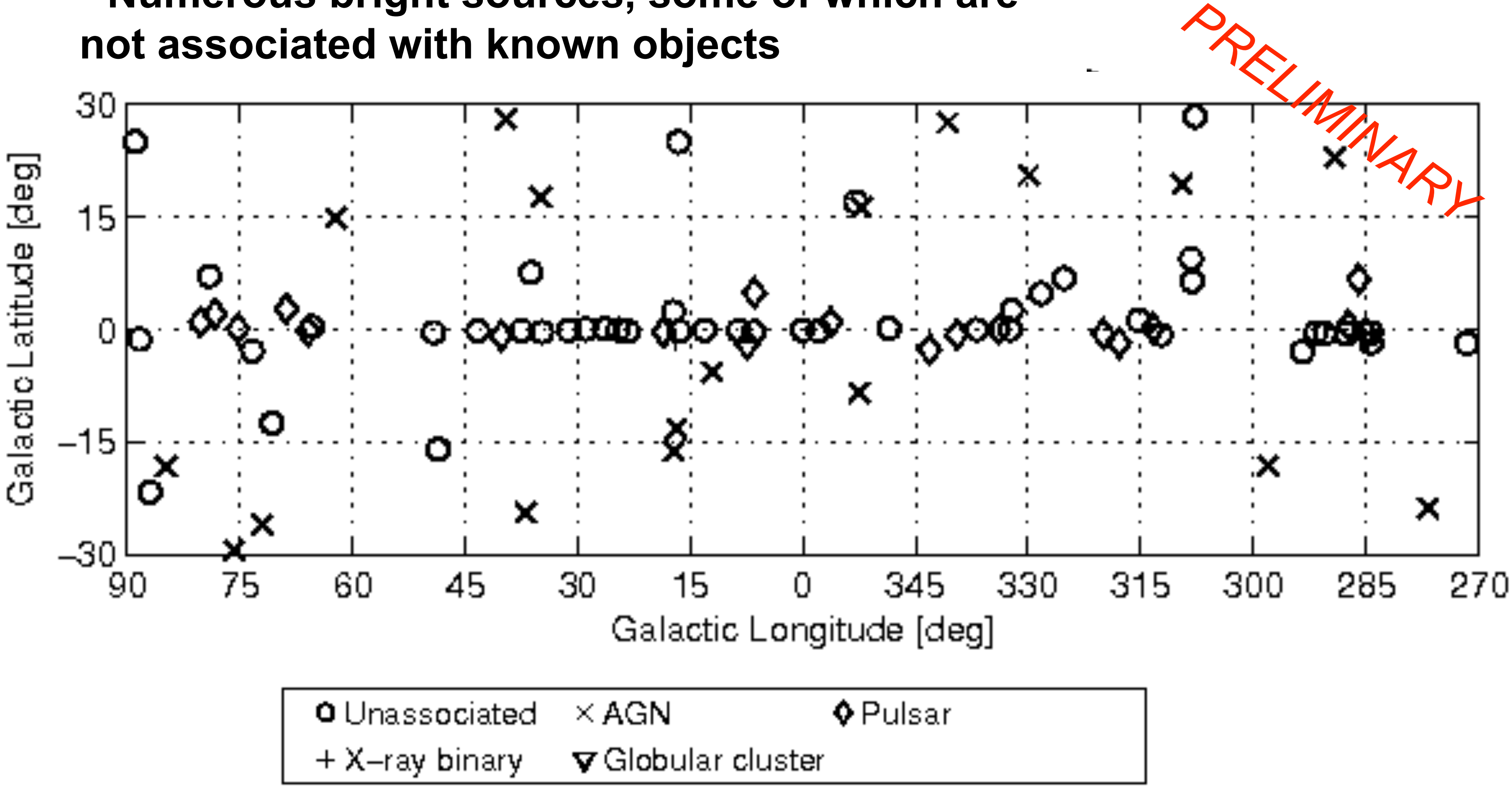


Crosses mark source locations, in Galactic coordinates.
10 σ significance. Three months data.

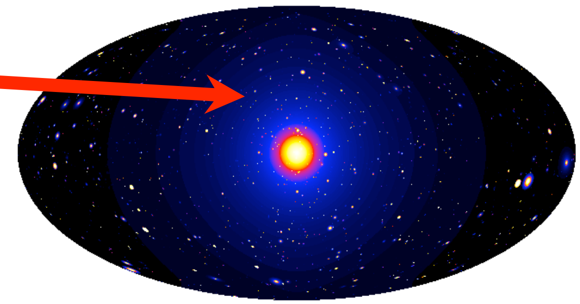
Galactic Center

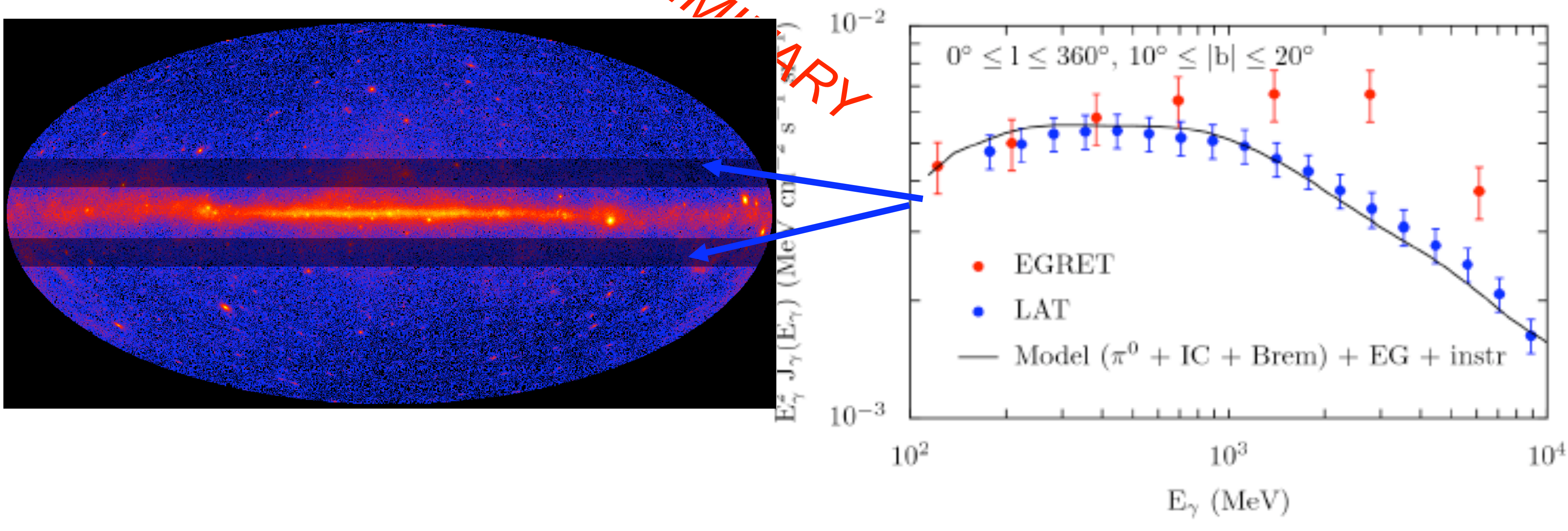


- Substantial diffuse emission, not entirely understood
- Numerous bright sources, some of which are not associated with known objects



Galactic Halo

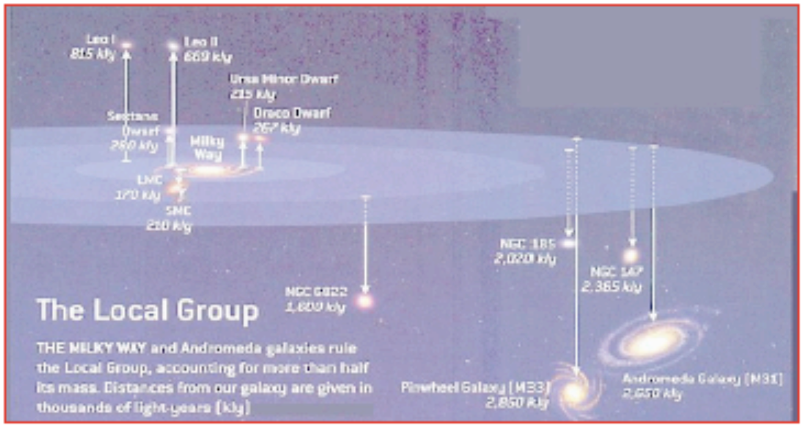


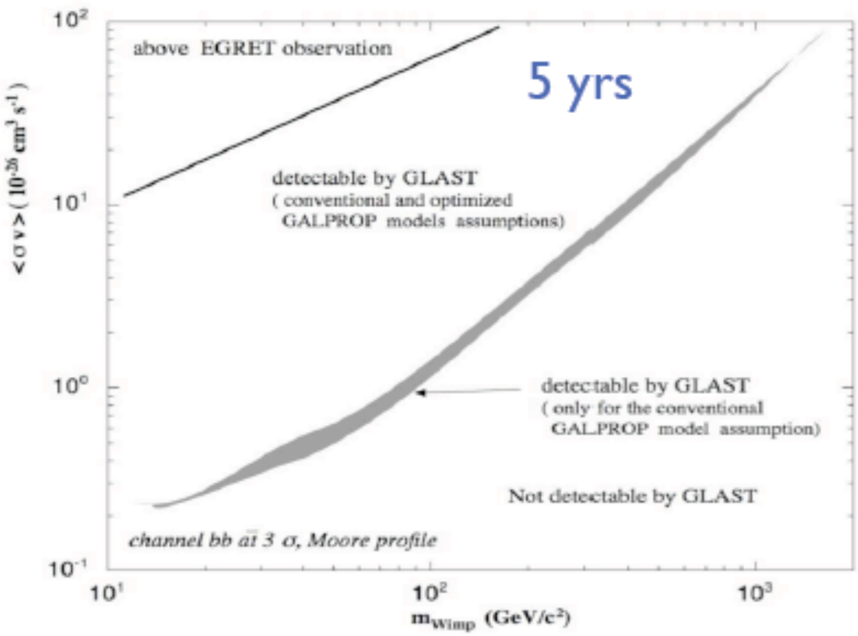


- Spectra shown for mid-latitude range → GeV excess reported by EGRET in this region of the sky is not confirmed. This GeV excess had been interpreted by some as evidence for dark matter.
- Sources are not subtracted but are a minor component.
- LAT errors are dominated by systematic uncertainties and are currently estimated to be ~10% → this is preliminary.

Dwarf Galaxies

- Dwarf spheroidal (dSph) galaxies are DM dominated (large mass to light ratio). Promising targets for indirect DM detection
- Sagittarius dwarf is closest to the sun (24 kpc). Assume Moore profile and WIMP annihilation into b-bbar

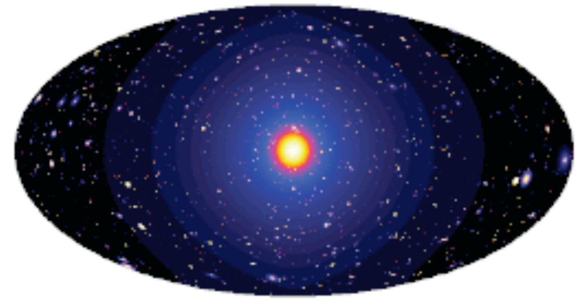




➡10x worse sensitivity if the NFW profile is considered

No dwarf galaxies are found in the LAT Bright source List

Lines

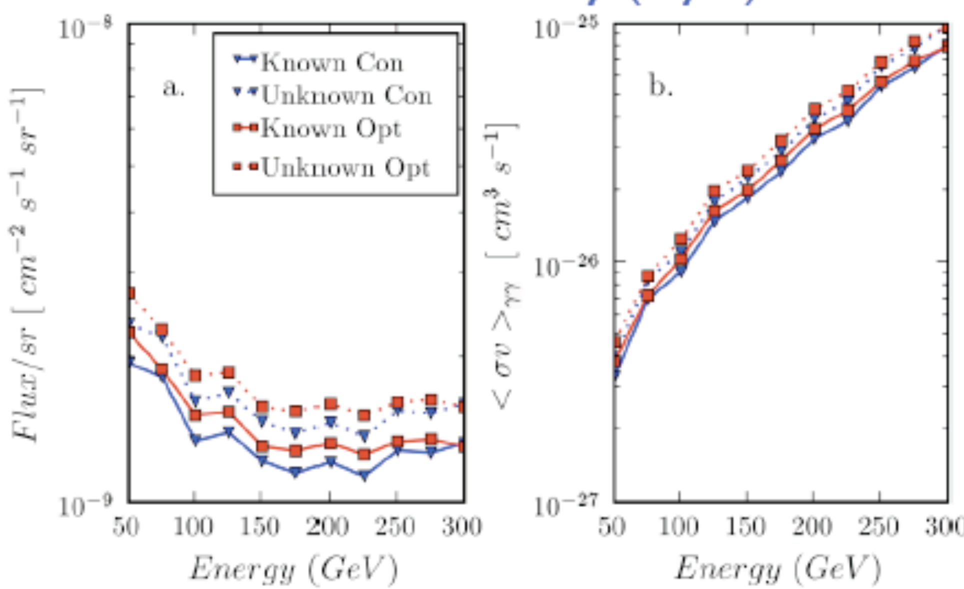


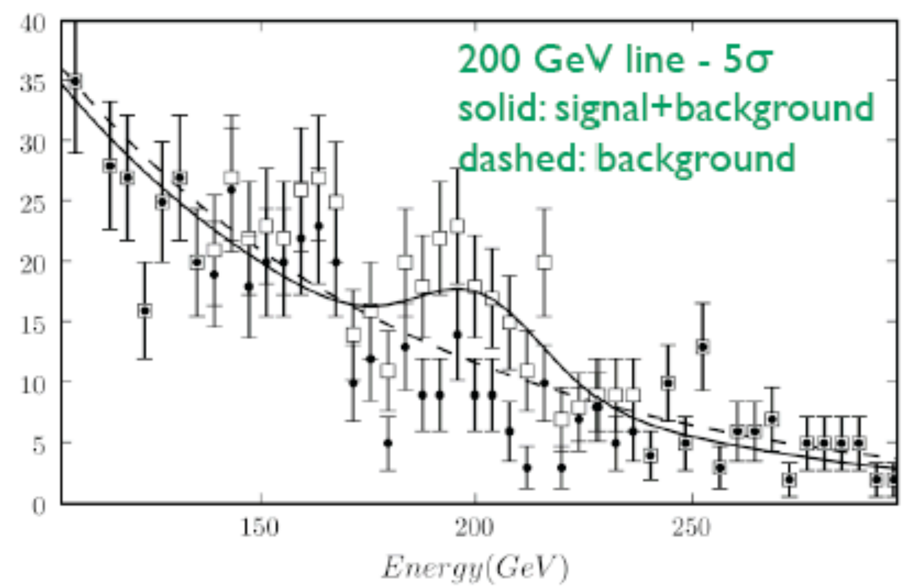
- Search region: annulus between 20º-35º in galactic latitude, removing ±15º band from the galactic disk (signal to background ratio >10x larger than galactic center). Assume NFW profile
- Very distinctive spectral signature
- Generate lines between 50-300 GeV+diffuse background for 5 yrs.
- Better sensitivity is achieved if location of the line is known (discovery at LHC, for example)

No lines have been reported in the LAT data thus far.

➡ For the assumed annulus and profile, boost factors of ~500 are needed to explore interesting MSSM regions

5σ sensitivity (5 yrs)

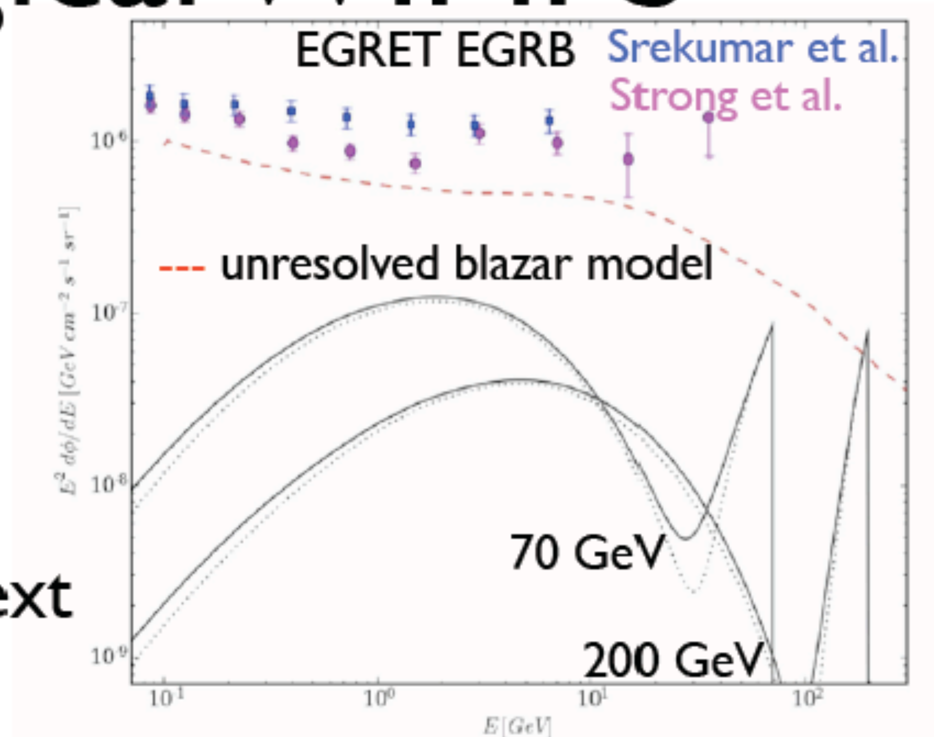


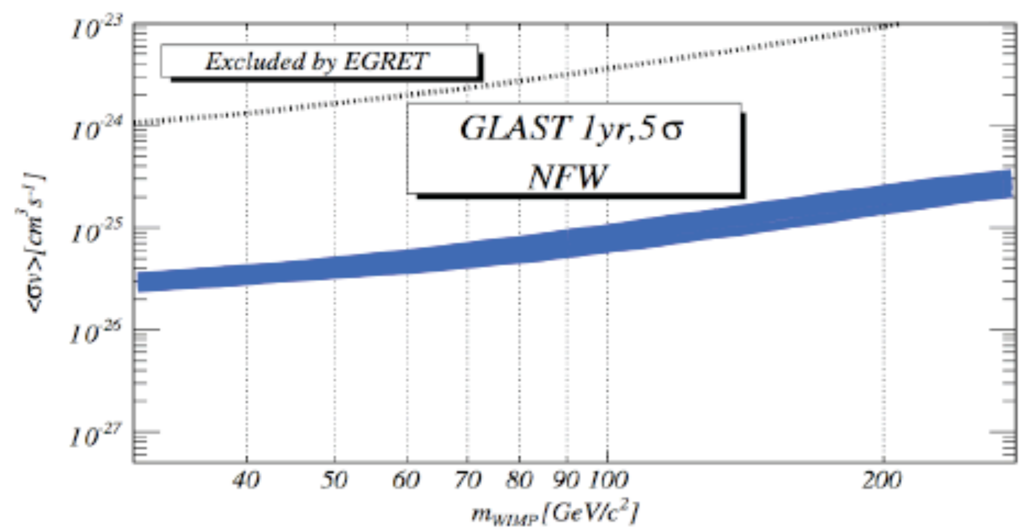


Cosmological WIMPS

- Search for WIMP annihilation signal at all redshift. Spectral distorsion caused by integration over redshift
- Assume generic WIMP (masses 50-250GeV) annihilating into b-bbar, with 5×10^{-4} annihilation fraction into lines
- Uncertainties in DM distribution over cosmological scales (but less sensitive to exact choice of profile) and absorption of high energy γ in the intergalactic medium
- Different assumptions for the background: EGRB measurement by EGRET, unresolved blazar model

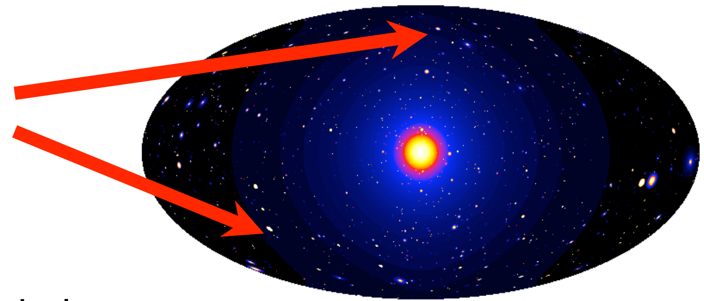
Text





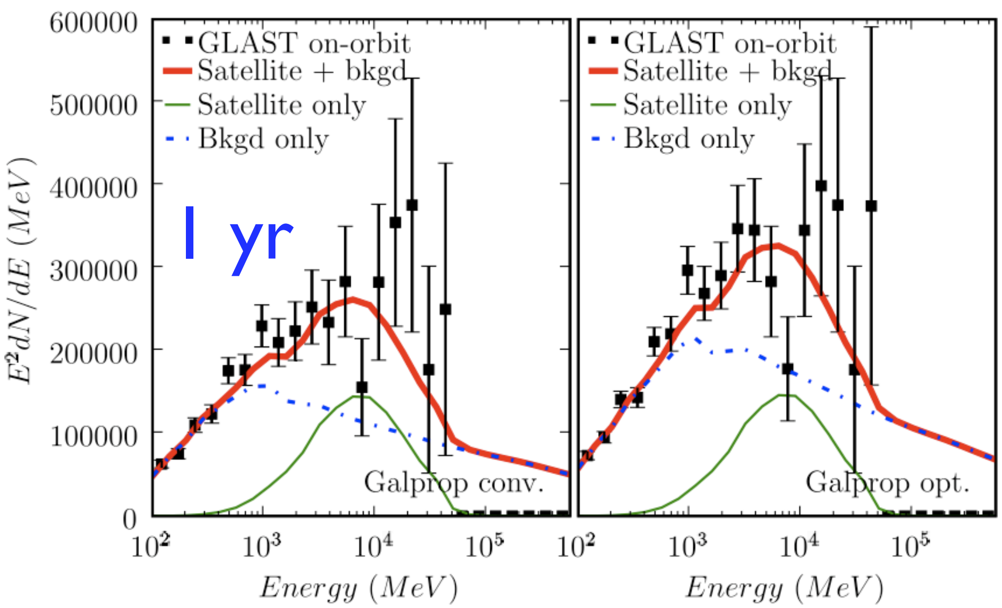
Measurement of the Extragalactic Gamma-ray Background (EGRB) can only be done after all other sources have been accounted for.

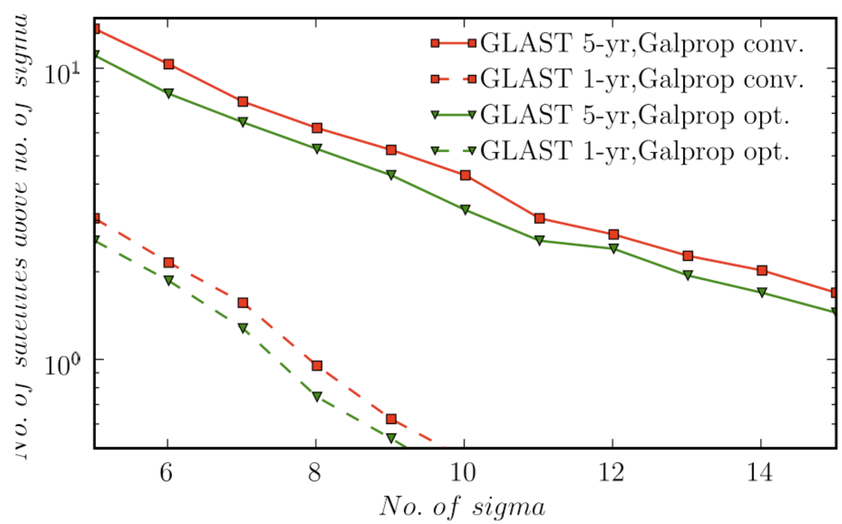
DM Satellites



- 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; the emission is expected to be constant in time
- Consider 100 GeV WIMP, <σv> = 2.3×10^{-26} cm^3/sec annihilating into b-bar. Background: extra galactic, galactic diffuse (including instrumental background doesn't change the sensitivity significantly)
- Generic observable (5σ, 1 yr) satellite: high galactic
- ~9 kpc from the sun, 3×10^7 M , ~1° angular size

37 of the 205 Bright LAT Sources have no association with known astrophysical objects. Study of these is underway.





Summary and Conclusion

- Fermi Gamma-ray Space Telescope is in orbit and working well. Both instruments are performing as expected.
- New results on pulsars, blazars, gamma-ray bursts, diffuse radiation, and gamma-ray sources are emerging.
- These early results show no obvious evidence of Dark Matter signatures - but none was really expected. The Fermi search is a long-term effort.
- Absence of evidence is NOT evidence of absence.
- The search continues. Earliest result is a study of high-energy cosmic-ray electrons, which will be presented at the APS meeting in Denver in early May.
- Stay tuned…..