Olaf Reimer Leopold-Franzens-Universität Innsbruck & KIPAC Stanford

FERMIS FIRST YEAR IN ORBIT

Fermi LAT Collaboration

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

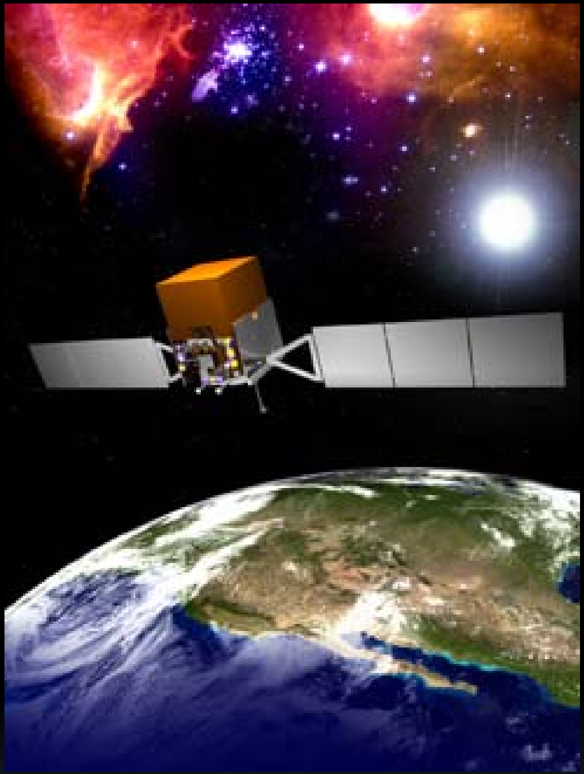
~390 Members
(112 Full Members, 95 Affiliated Scientists, 68 Postdocs, and 105 Graduate Students)

Fermi LAT science objectives

Thousands of AGN
blazars and radiogal = f(θ,z)
evolution $z < 5$
Sag A*

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

γ-ray binaries
Pulsar winds
μ-quasar jets



Possibilities
starburst galaxies
galaxy clusters
measure EBL
unIDs

Dark Matter
neutralino lines
sub-halo clumps;
$e^+ + e^-$ spectrum

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

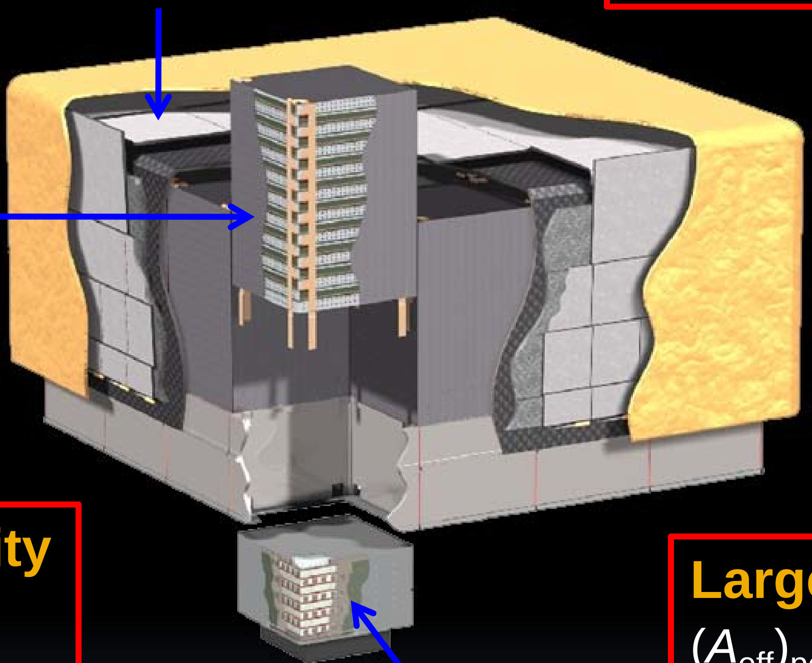
Pulsars
emission from radio and X-ray pulsars
blind searches for new Gemingas
magnetospheric physics
pulsar wind nebulae

Fermi LAT technichal realization

Single Photon Angular Resolution
3.5° @ 100 MeV
0.15° @ 10 GeV

Anticoincidence Detector

Converter/Tracker



Hodoscopic Calorimeter

Wide Energy Range
20 MeV … ~300 GeV

Wide FoV
(~ 2.4 sr)

Low dead time
< 100 μs/event

Large Effective Area
$(A_{eff})_{peak}$ > 8,000 cm^2

Point Source Sensitivity
< 3 x 10^{-9} ph $cm^{-2}s^{-1}$

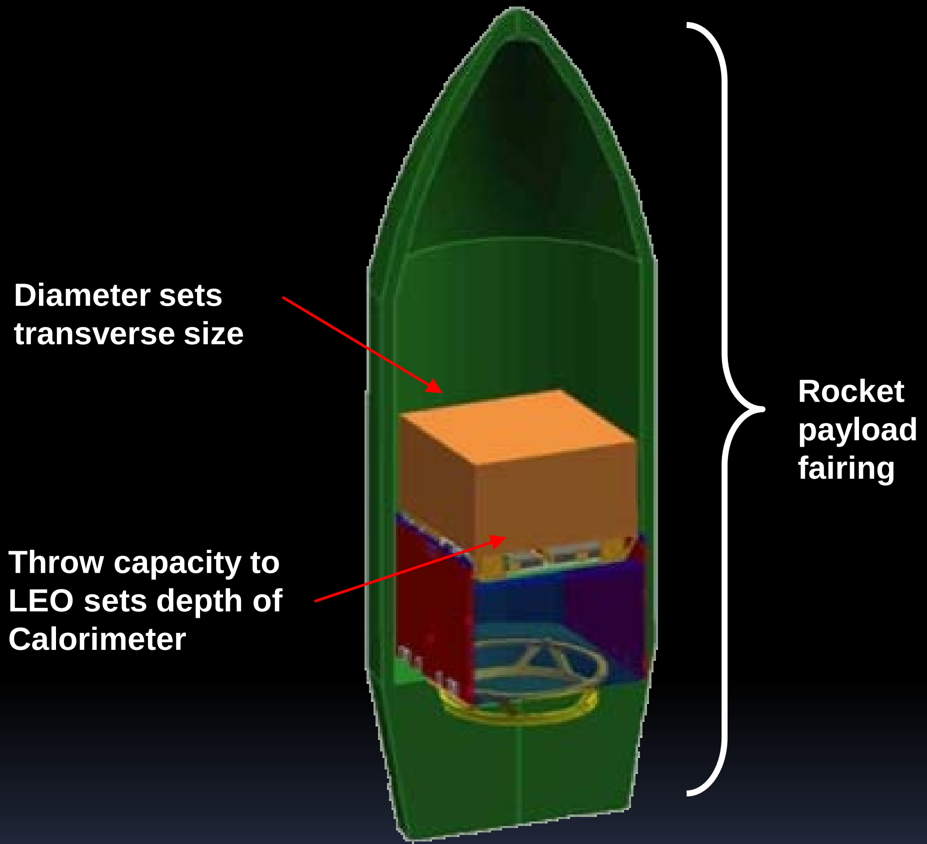
Source Localization
0.3' – 1'

Good Energy Resolution
$\Delta E/E$ ~ 10%; 100 MeV – 10 GeV
< 20%; 10 GeV – 300 GeV

Fermi Large Area Telescope

A pair conversion telescope

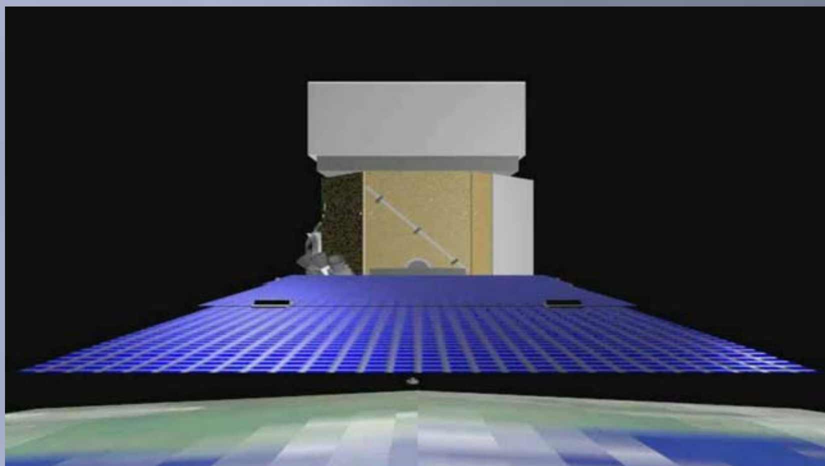
When Fermi LAT was still GLAST…



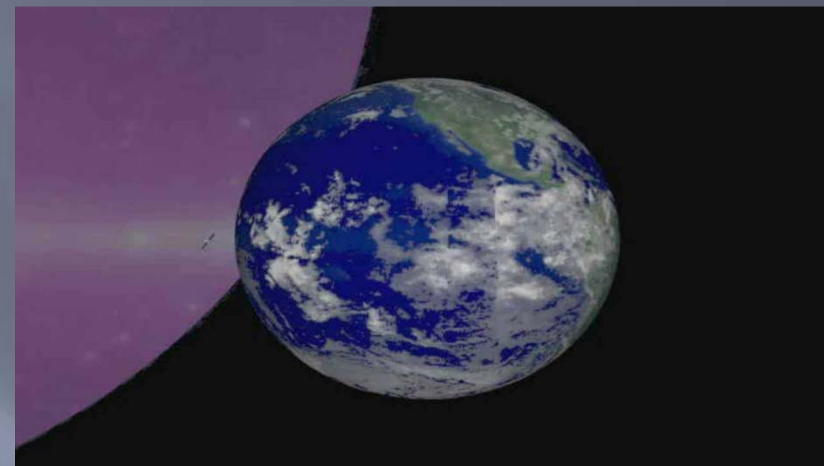
Fermi Gamma-Ray Space Telescope

June 11, 2008 12:05 PM EDT;
Cape Canaveral , FL

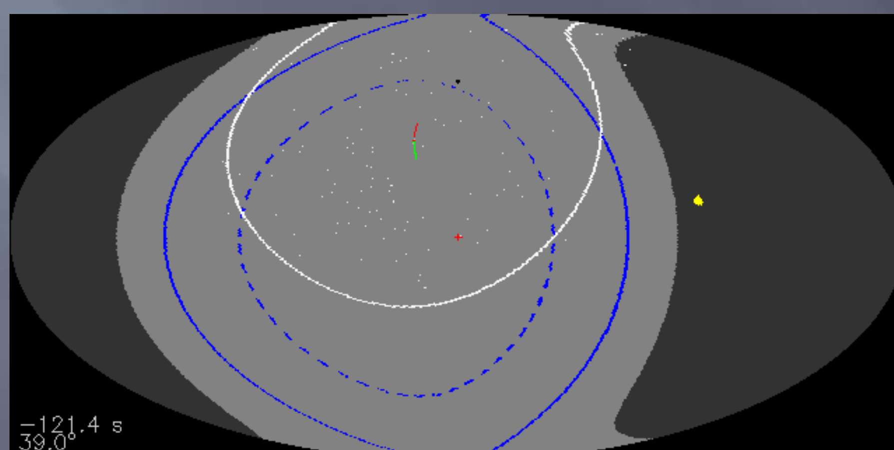
- Rocking mode



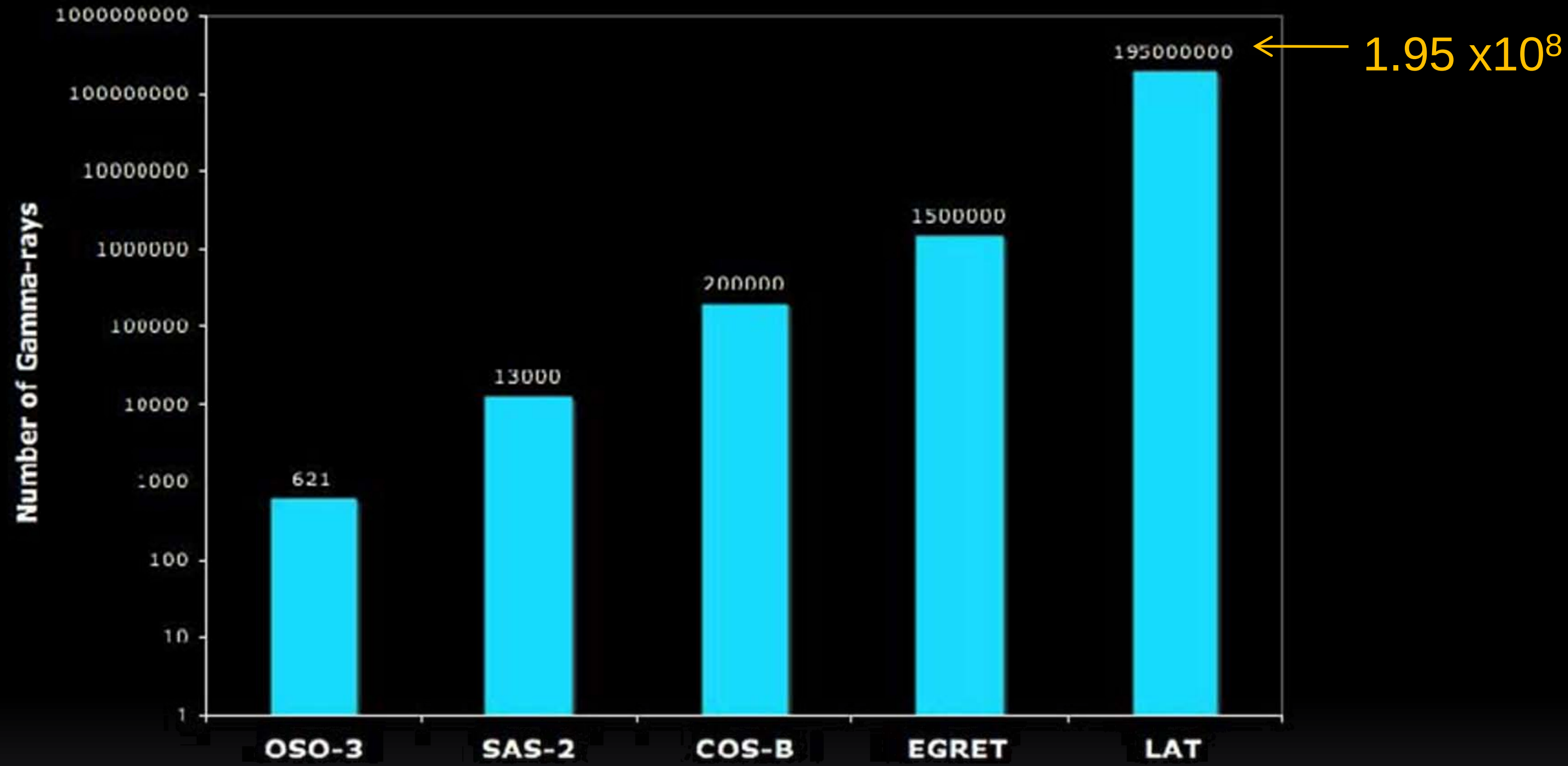
- Scanning mode



- Autonomous repointing

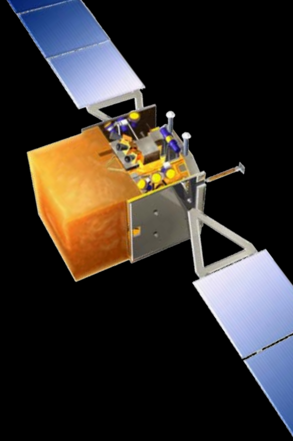


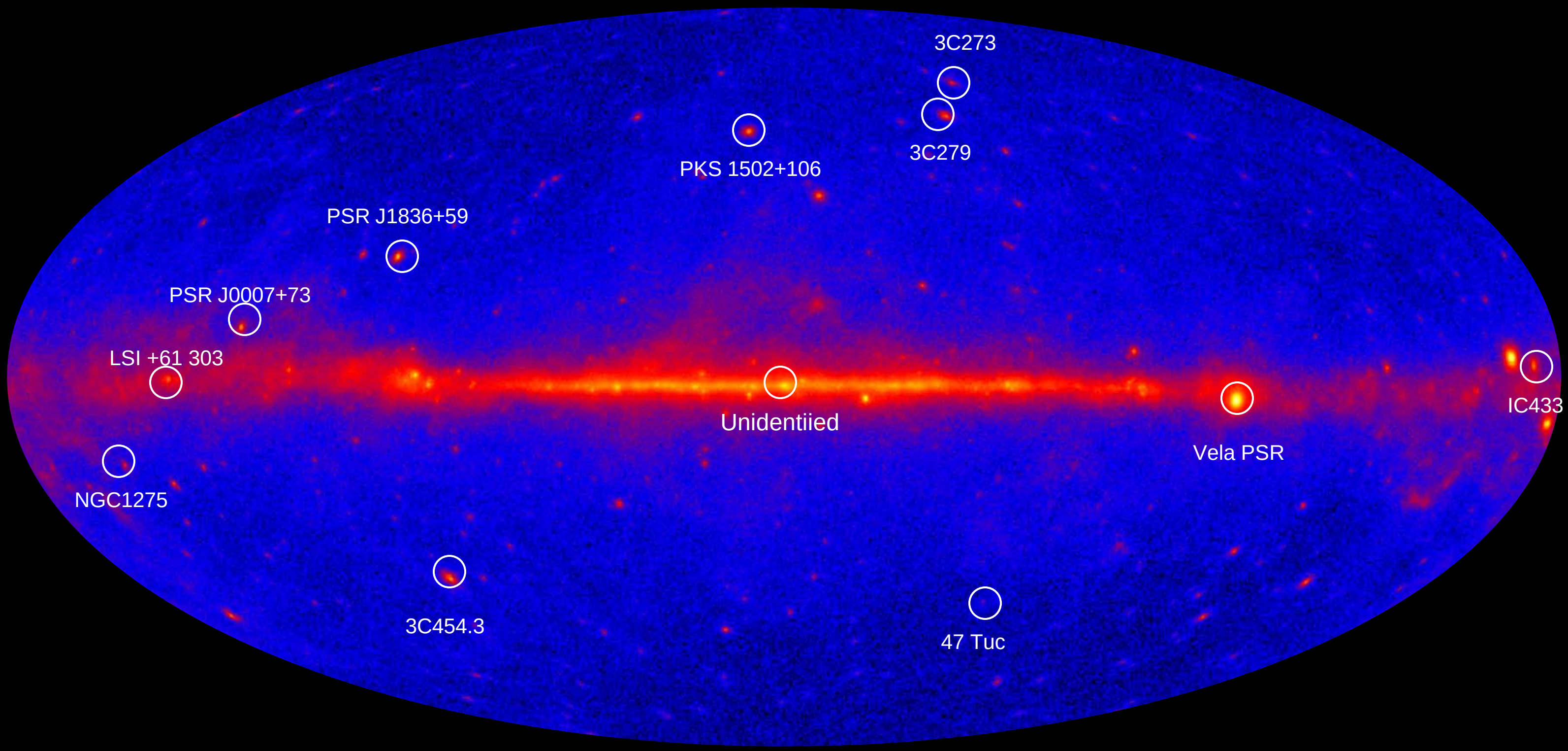
My only slide on the history of satellite-based high-energy γ-ray astronomy



- By now, Fermi has outperformed any previous (COS-B, EGRET), or operating (AGILE) GeV γ-ray telescope
- This statement relates to simple exposure and number of recorded γ-ray events but independently valid for instrument characteristics like psf, dE/E, A_{eff} , τ_d, Δcalib

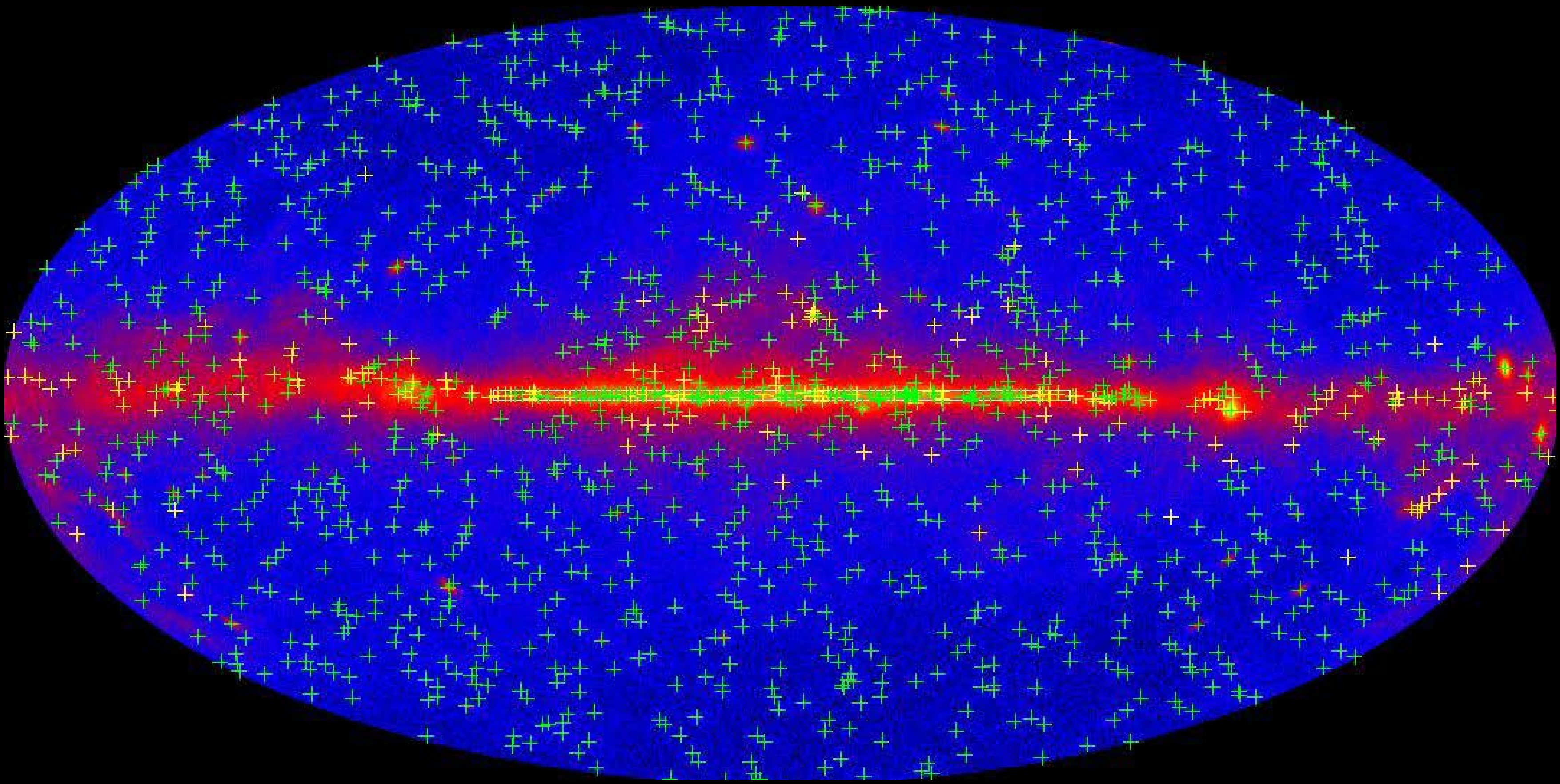
The Fermi sky after 1 year





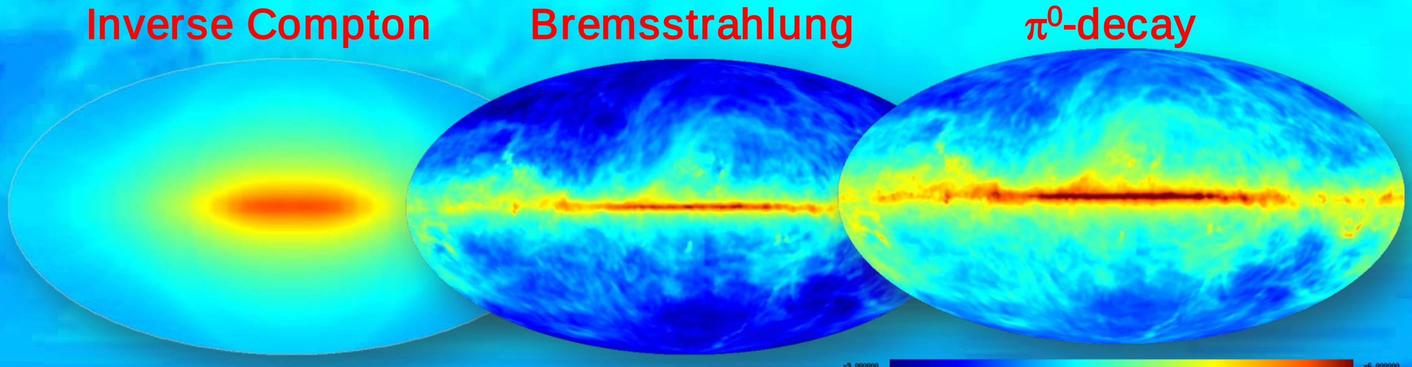
Dec 2009: 1st year source catalog takes shape

> 1000 sources after Fermi 1st year operations

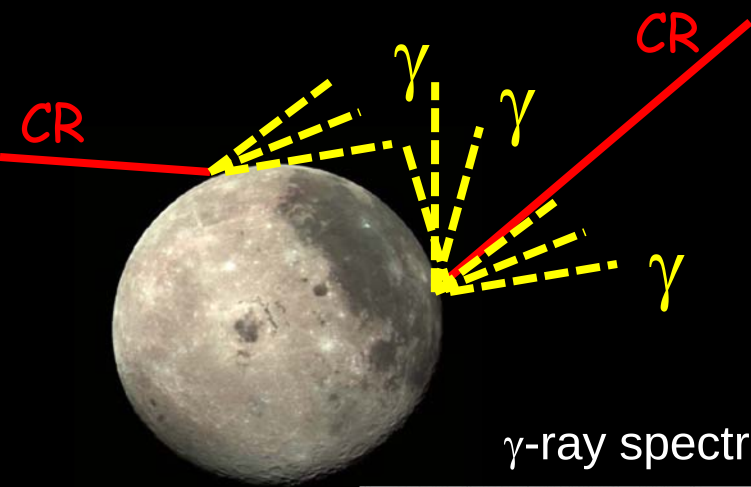


Diffuse Continuum Gamma Radiation

- Cosmic Rays present throughout our Galaxy
- Magnetic fields (synchrotron radio maps)
- Interstellar radiation fields (CMB, IR, OPT/UV)

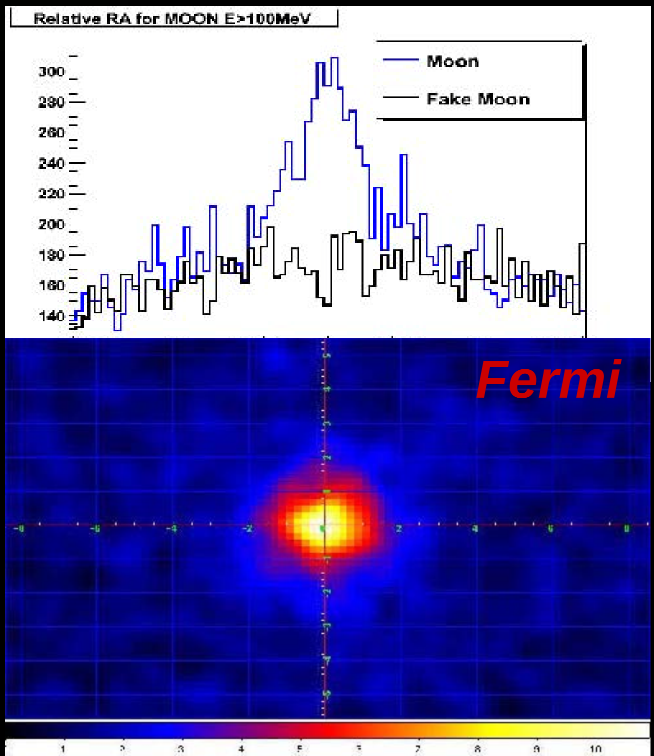


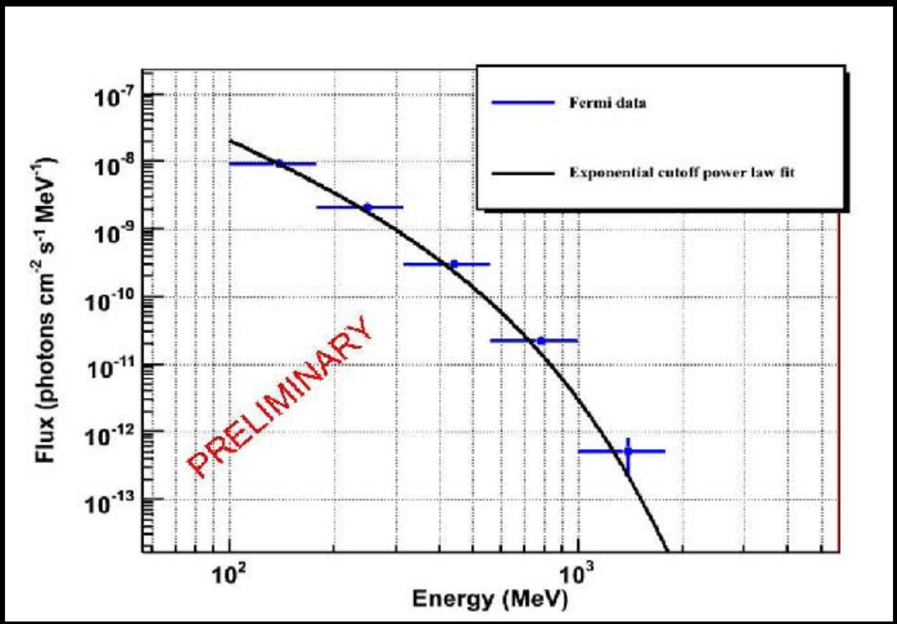
Cosmic Ray Interactions with the Moon surface



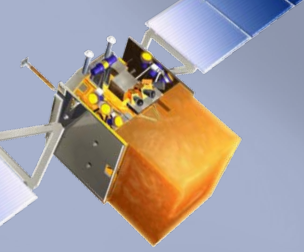
γ-ray spectrum characteristic for *moon limb or center interactions*

E > 100 MeV
0.2º/bin



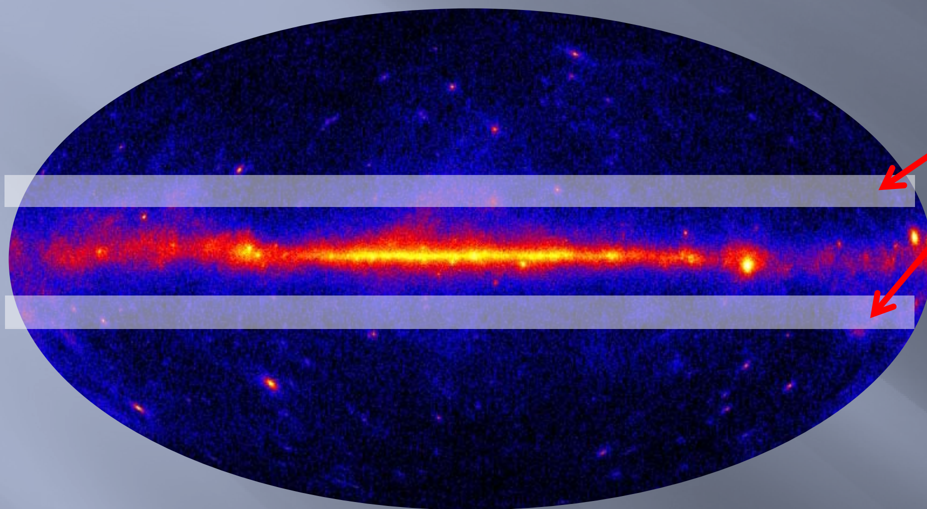


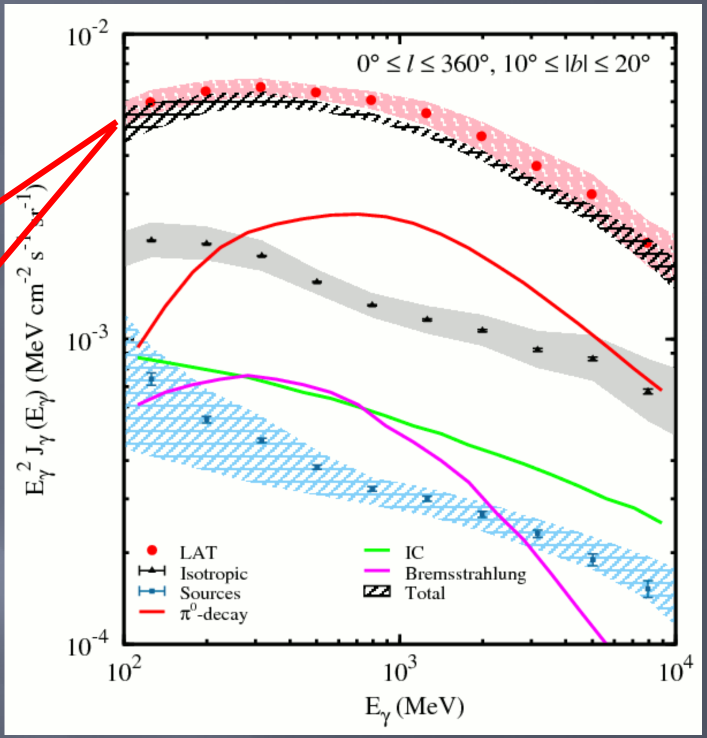
$f_{>100\ MeV} = (1.06 \quad 0.2)\ \mathrm{x}10^{-6}$ ph cm^{-2}s^{-1}



Galactic diffuse emission

100 MeV – 10 GeV





EGRET GeV excess is not seen in 10º ≤ |b| ≤ 20º, thus not an universal feature at the gamma-ray sky

→ standard CR interaction models adequate (which do justice to locally measured CR abundances, CR sec/prim ratios, long/lat distr.)

→ Fermi/LAT errors are systematics dominated, estimated to ~10%

So we‘re back to common <u>CR particle interaction physics</u>!

1. ~~Hard *nucleon* injection spectrum~~

2. ~~Hard *electron* injection spectrum~~

3. Atypical local ~~p and~~ e spectra
   affects diffuse g-ray sky only mildly

4. ~~Imperfect knowledge of $\sigma(pp \rightarrow \pi^0)$~~

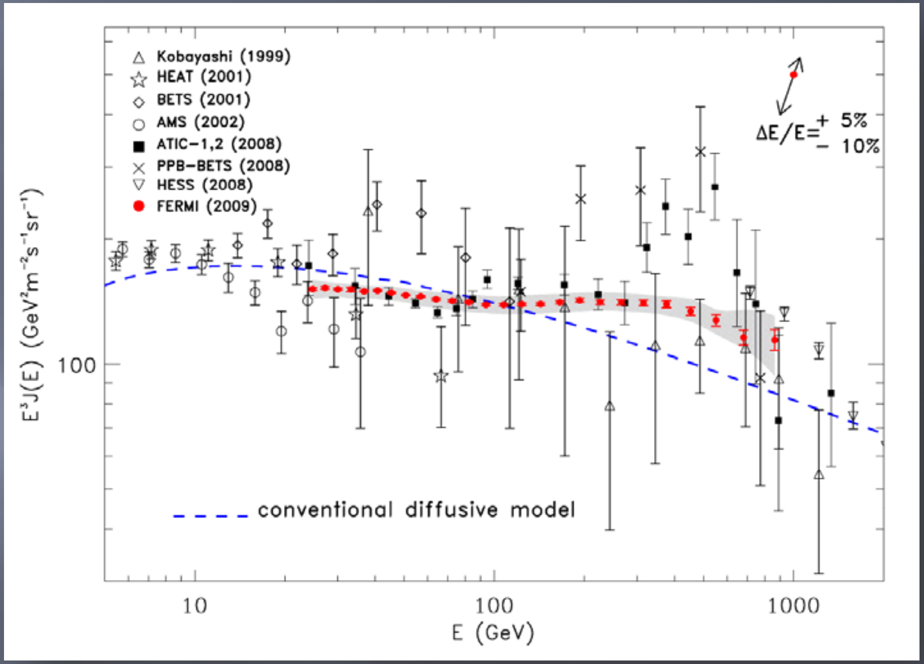
5. Unresolved GeV γ - ray sources

6. Instrumental effect
   charged particle background f(E)
   self-veto due to monolithic cal $\rightarrow A_{eff}$

7. ~~Manifestation of dark matter~~

Gamma-ray instruments hunting in CR territory: the *Fermi* $e^+ + e^-$ spectrum

- 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



No prominent spectral features between 20 GeV and 1 TeV…

… but Fermi and *PAMELA* data might require a new high-energy positron source

- *Nearby conventional astrophysical sources* (e.g. pulsars) injecting required amounts of e^+ and e^-, injected spectrum & efficiency are very uncertain
- even standard *TeV electron propagation* can have many stochastic realizations
- *Dark matter?* (annihilation → boost factors?; decay → prominent feature at m_χ?)

Gamma-ray instruments hunting in CR territory: the H.E.S.S. $e^{+}+e^{-}$ spectrum

H.E.S.S. has measured cosmic-ray electrons between 340 GeV and 5 TeV

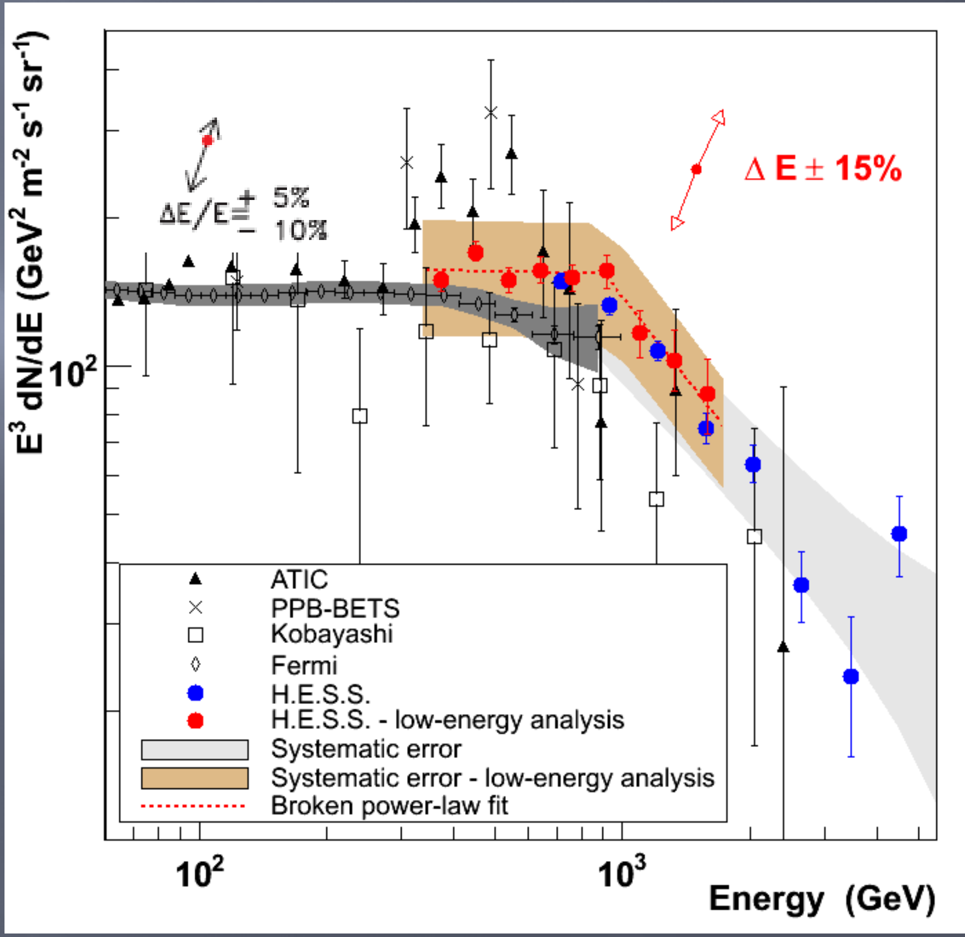
Systematic uncertainties include atmospheric variations, uncertainties in hadronic interaction models and H.E.S.S. energy scale uncertainty

FERMI: $\Gamma \sim 3.05$

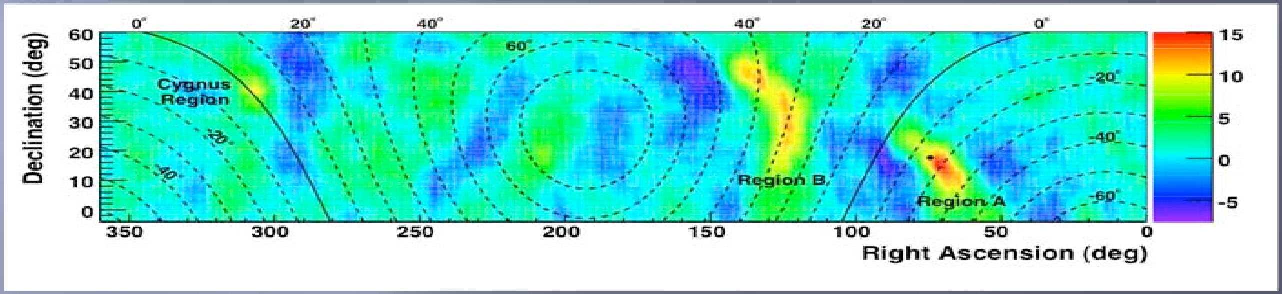
H.E.S.S.: Smooth spectrum that steepens at 0.9 TeV

$\Gamma_1 = 3.0 \quad 0.1_{stat.} \quad 0.3_{syst.}$

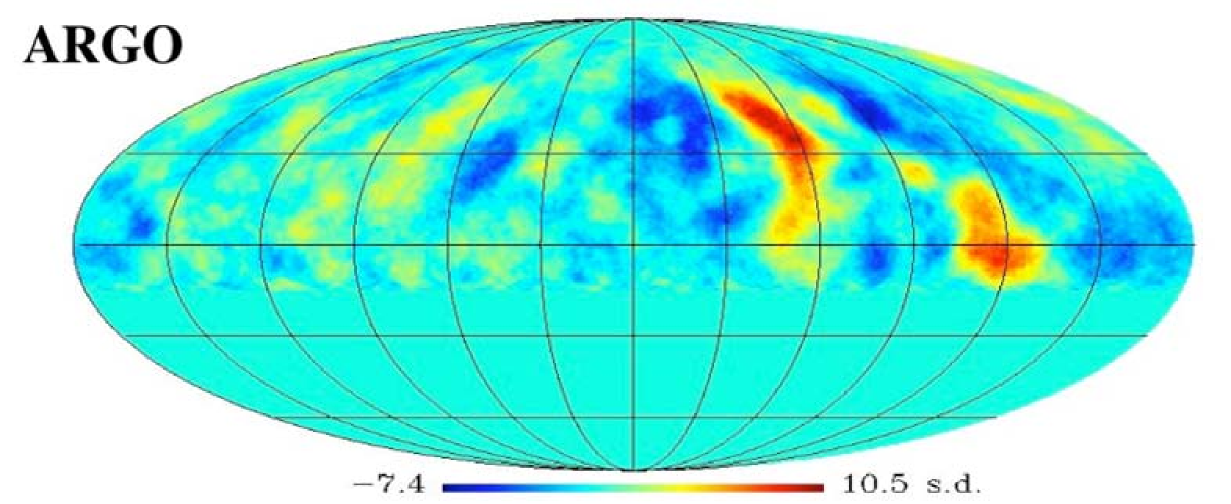
$\Gamma_2 = 4.1 \quad 0.3_{stat.} \quad 0.3_{syst.}$



Milagro & Argo: A TeV Cosmic Ray Anisotropy ?



- Localized anisotropy on 5-10º size scale with a fractional excess up to 7×10^{-4} above the cosmic ray background (15 σ)
- Excess is *not* gamma rays, but hadronic cosmic rays (7 σ)
- Different spectrum than cosmic rays (4 σ) that is harder up to ~10 TeV
- Gyroradius of a 10 TeV proton in a 1 mG field is 0.01 pc (2000 AU)
- Cosmic Ray Propagation and/or nearby source?



Active Galactic Nuclei (AGN)

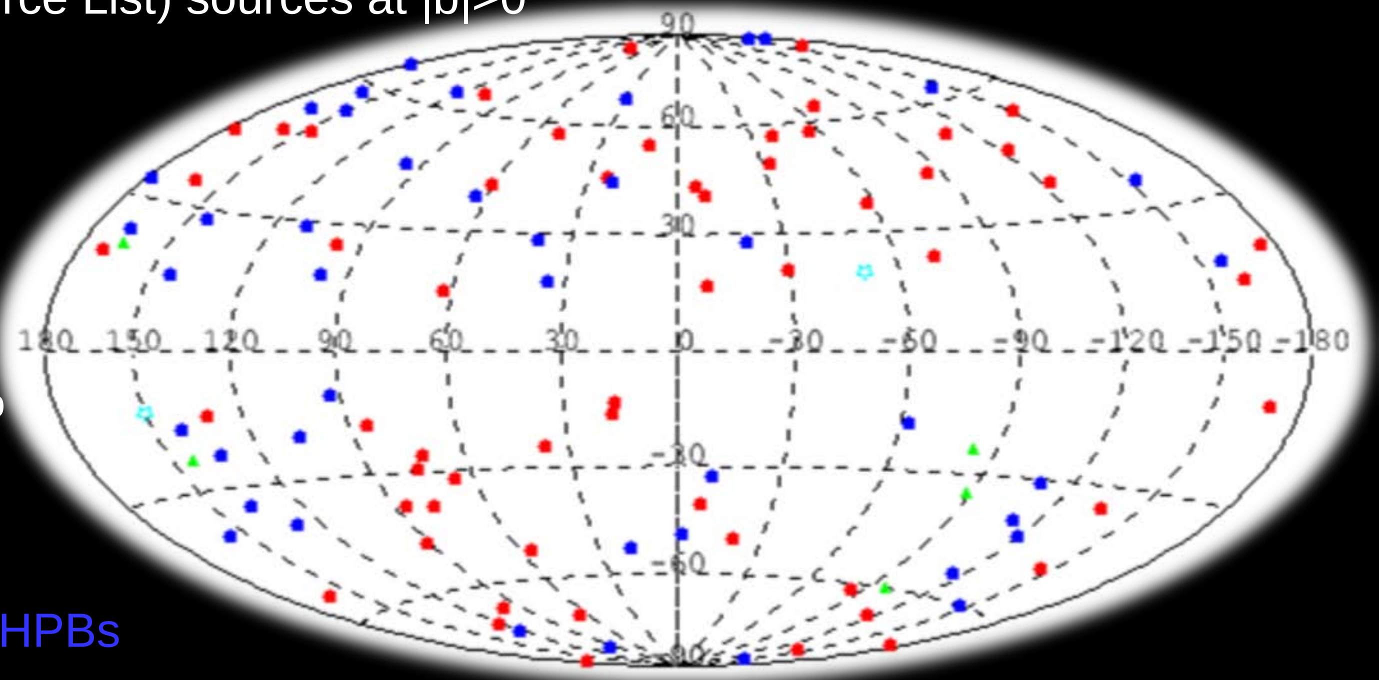
Fermi's dominant source class, but

- Emission mechanisms (particularly for high energy component)
  - Leptonic (IC of synchrotron or external photons) or
  - hadronic ($\pi_0 \rightarrow \gamma\gamma$, proton synchrotron)
- Emission location
  - Single zone for all wavebands (completely constraining for simplest leptonic models)
  - Opacity effects and energy-dependent photospheres
- Particle acceleration mechanisms
- Jet composition
  - Poynting flux, leptonic, ions
- Jet confinement
  - External pressure, magnetic stresses
- Accretion disk—black hole—jet connection
- Effect of blazar emission on host galaxies and galaxy clusters

The LAT Bright AGN Sample (LBAS)

• 3-month dataset, TS>100

• 132 0FGL (Bright Source List) sources at |b|>0



• 106 AGNs associated
- CGRaBS-CRATES (Healey+ 08)
- BZCat (Massaro+ 08)

• EGRET sources :30%

• 58 FSRQs

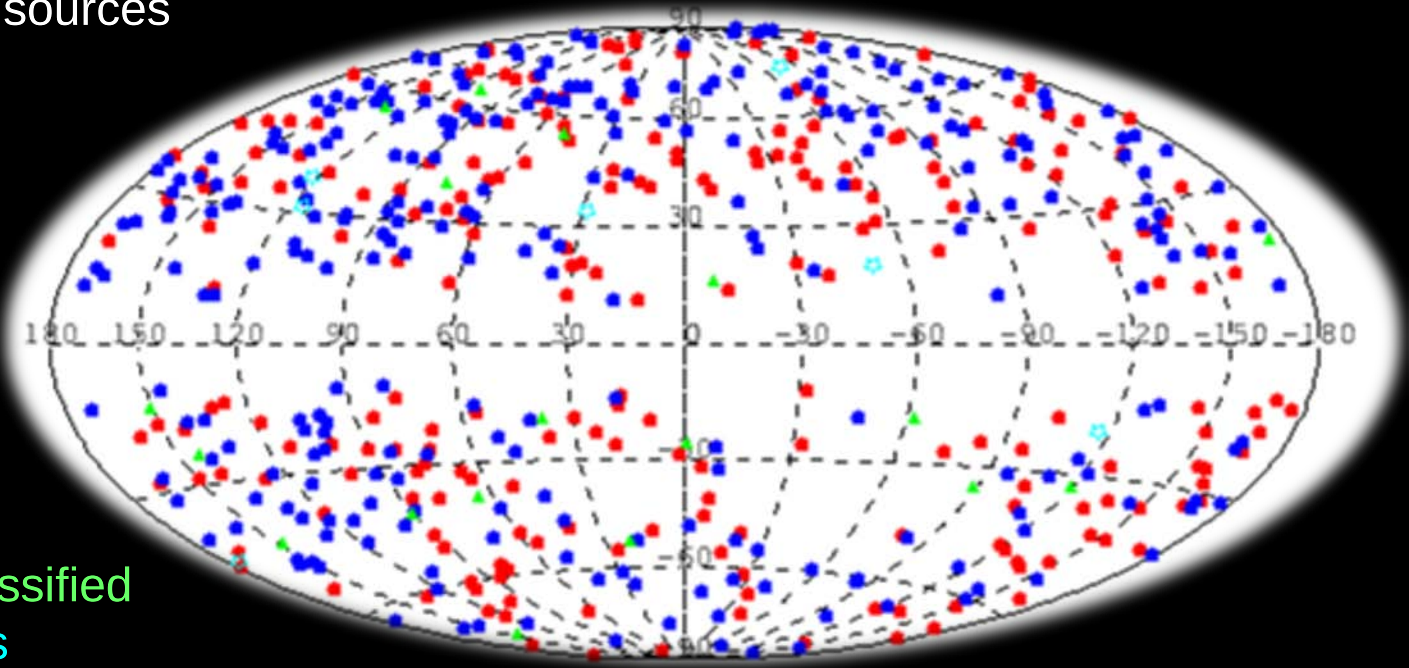
• 42 BLLacs (40%), 10 HPBs

• 2 Radio Galaxies: Cen A, NGC1275

• 4 AGN yet to be classified

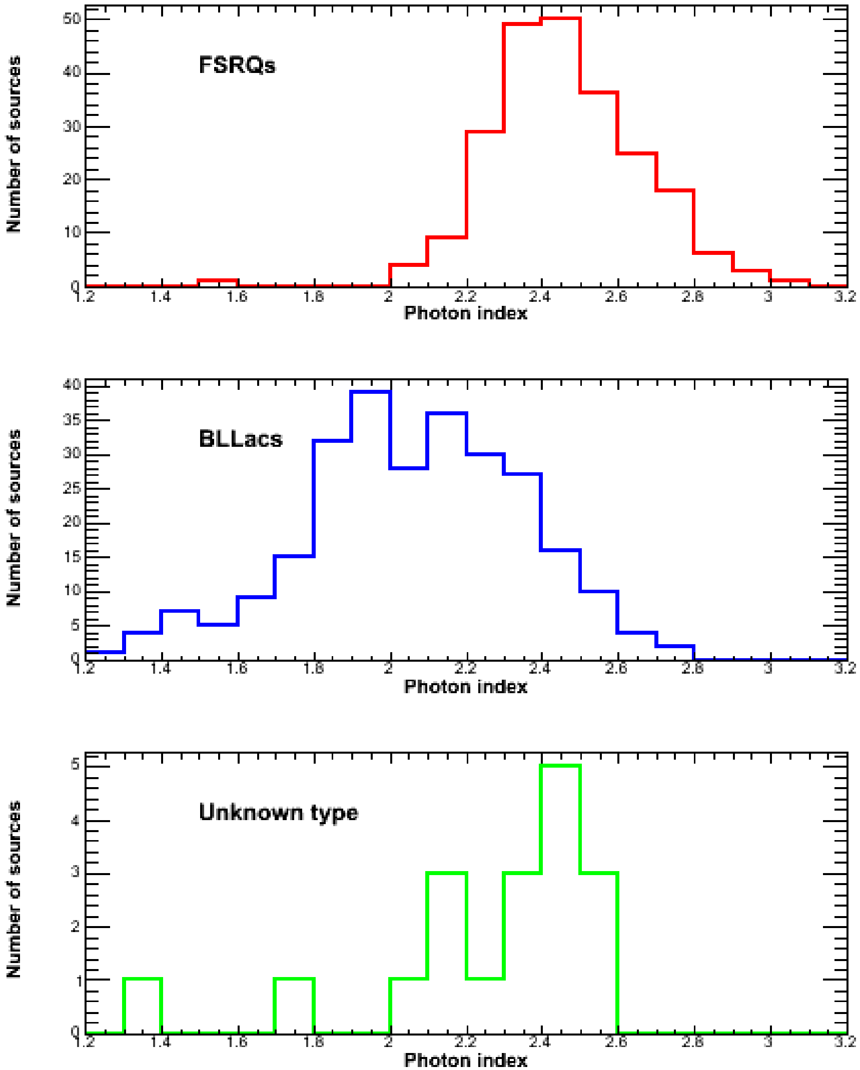
The First LAT AGN catalog

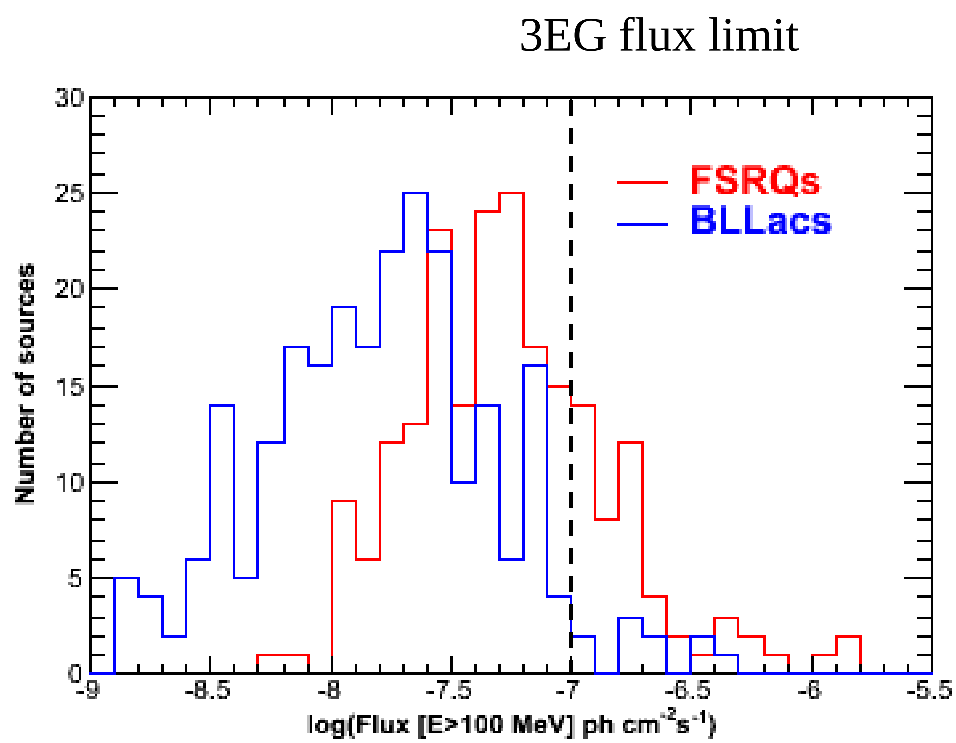
- 11 month data set
- 1079 TS>25, |b|>0 sources
- 700 AGNs
- 120 candidates (CRATES)
- Census:
  - 228 FSRQs
  - 256 BLLacs
  - 40 left to be classified
  - 6 radio-galaxies



Differences between Northern Hemisphere and Southern one (FSRQs: 7%, BLLACs: 25 %)

Blazars: Photon index – Flux distributions





Photon index vs ν_{syn}

- All (but one) FSRQs are LPBs

- Most BLLacs are HPBs

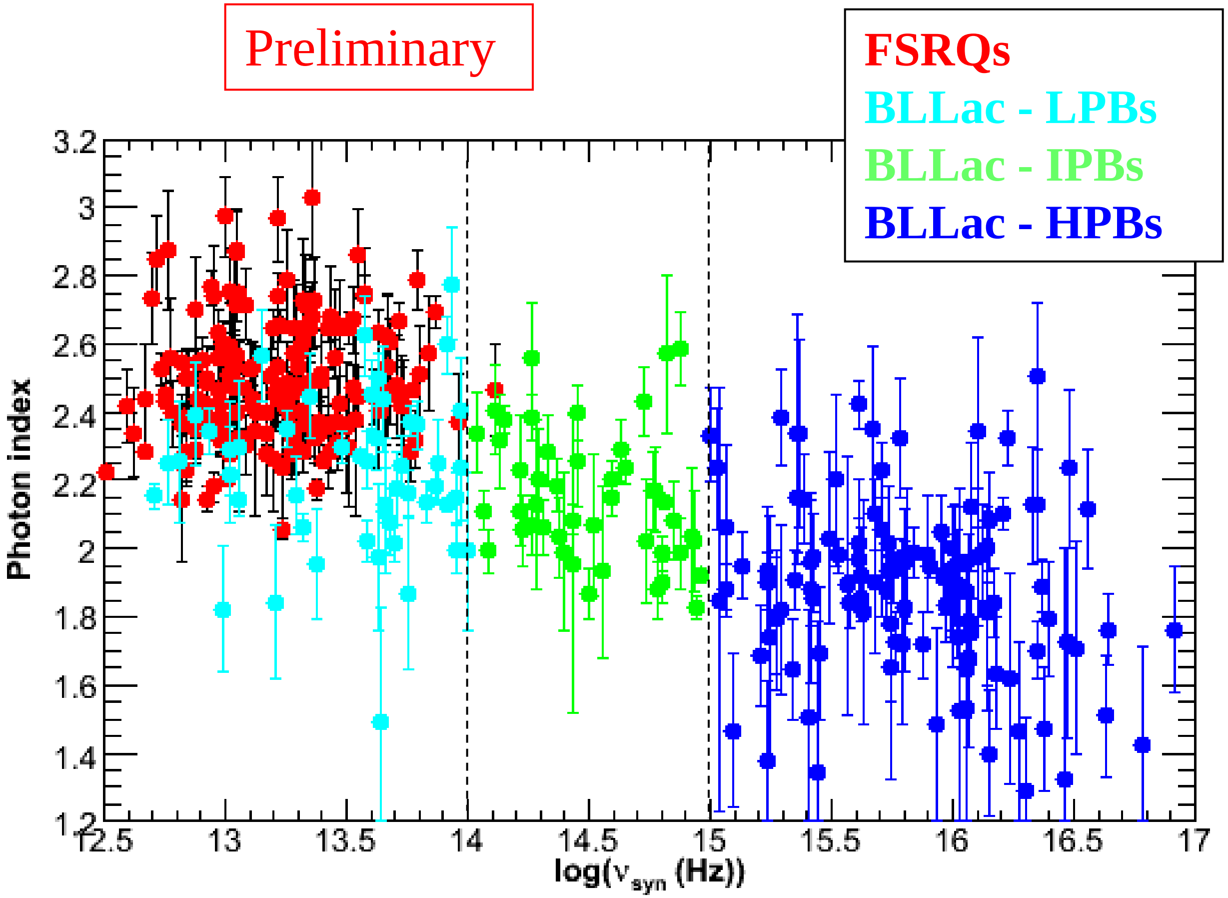
BLLac- LPBs: 49

BLLac- IPBs: 46

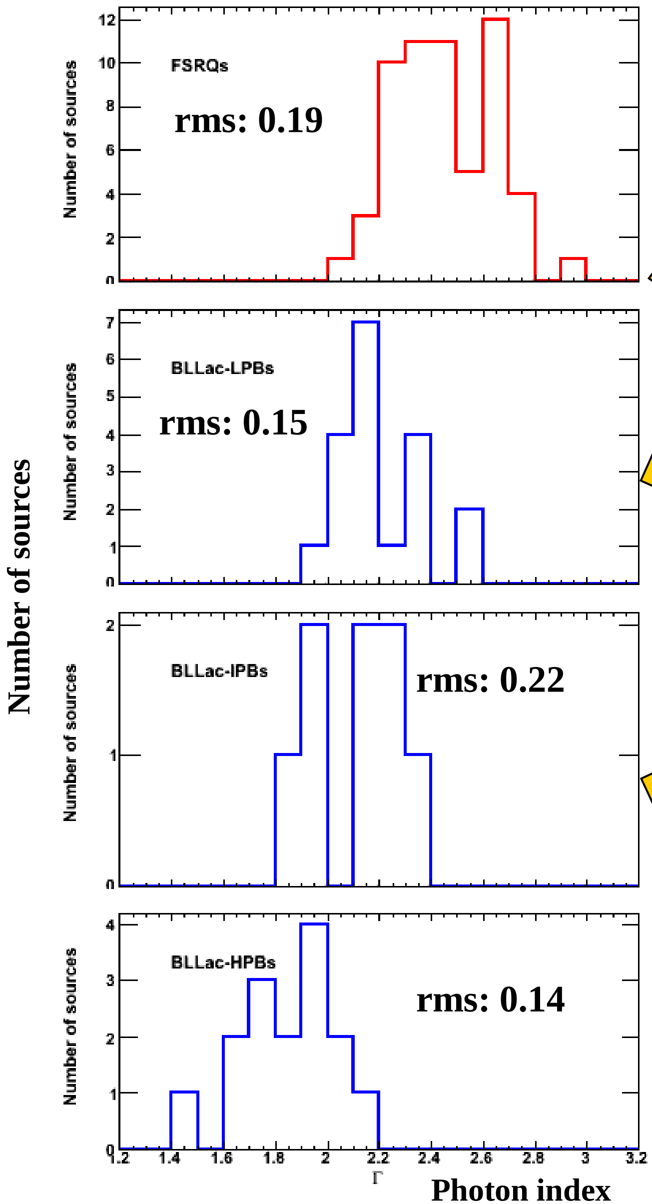
BLLac- HPBs: 117

- Fairly strong correlation between γ-ray photon index and ν_{syn}

- in LBAS, even stronger correlation observed

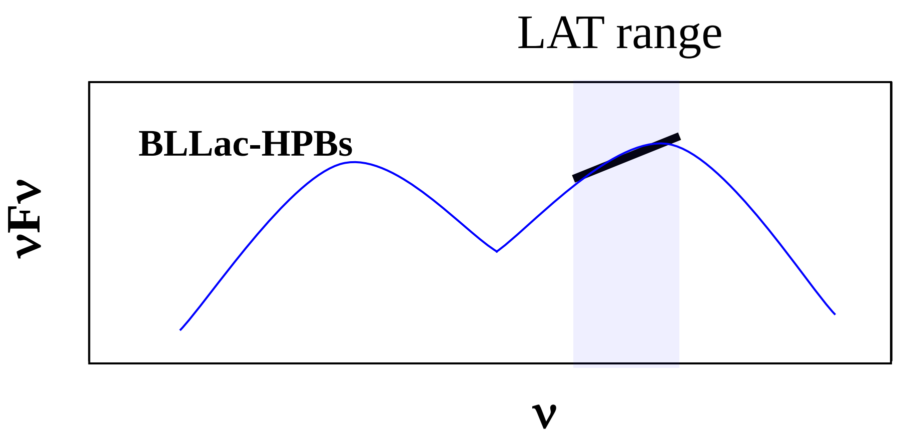


Photon index distributions in LBAS



Preliminary

Photon index determined with a 6-month data set

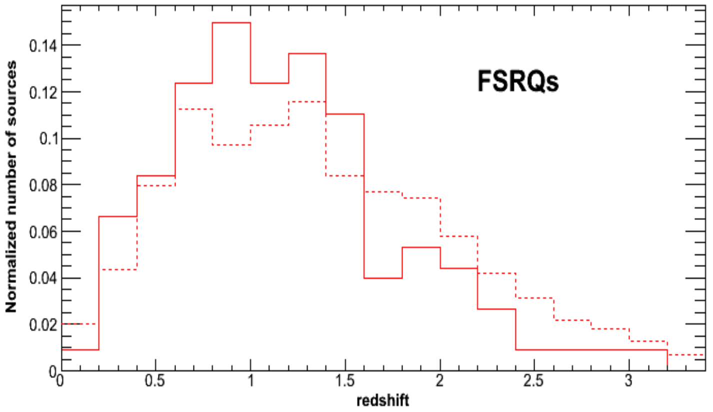


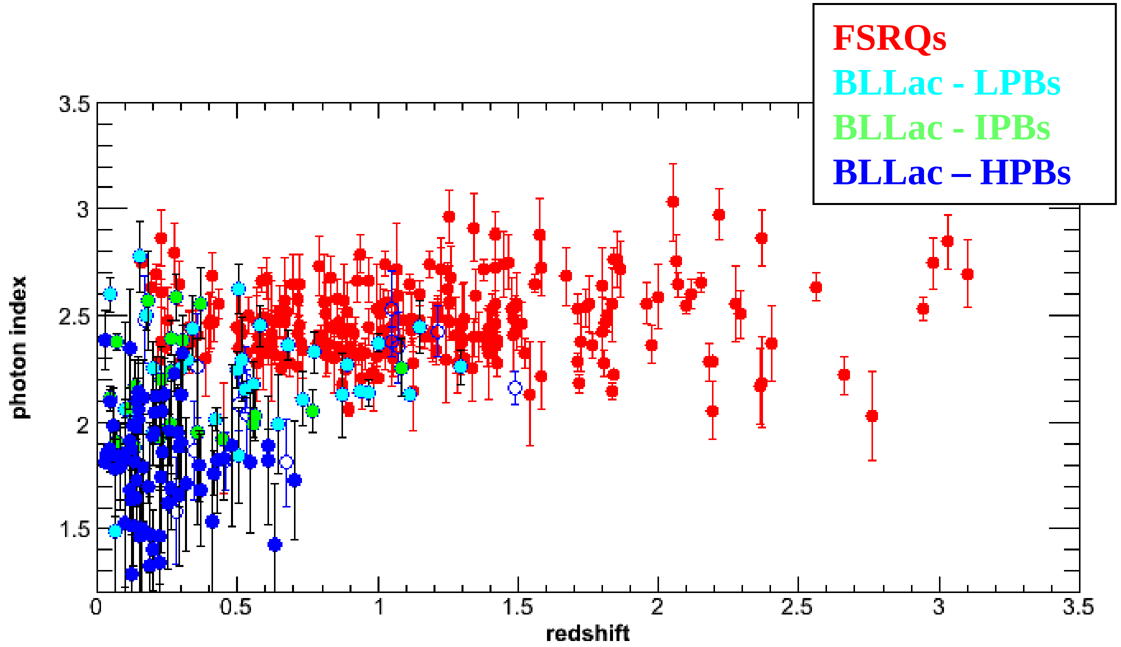
Distribution narrowness points to a small numbers of parameters driving the SEDs of blazars

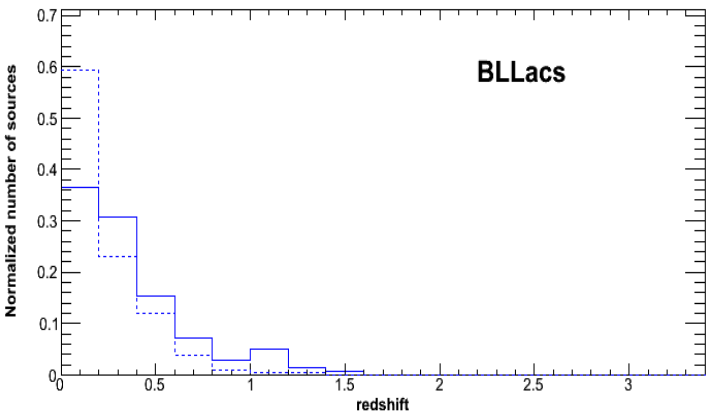
Blazars: Redshift distribution

Similar to parent populations but:

- FSRQs
  - no change of Γ with z
- BLLACs
  - notable evolution of Γ with z



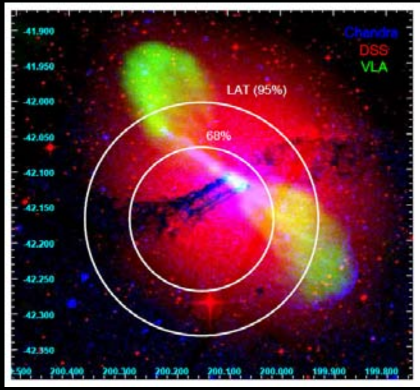




Radio (non-blazar) Galaxies

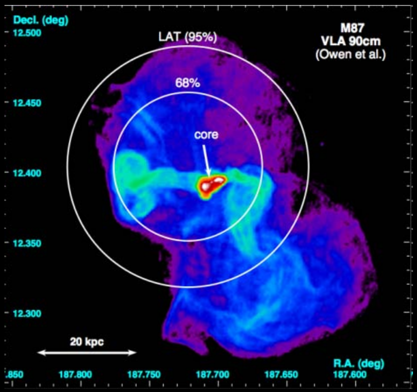
Cen A

- nearest radio galaxy, FRI, D=3.7 Mpc, seen by EGRET and HESS
- Fermi-LAT detection. G: 2.71 0.09, TS=318
- two-zone SSC model required to reproduce whole SED



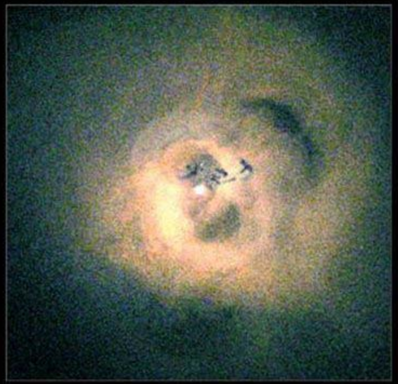
M 87

- giant radio galaxy, FR1, D=16Mpc
- detected by HESS, VERITAS
- G : 2.26 0.13, $F_{8:}$ 2.45 0.6, TS=108
- No indication of variability over 11 months
- good fit of SED with one-zone SSC (e from sub-pc core)



NGC 1275

- “cooling core” cluster
- detected by COSB, not by EGRET
- LAT flux 8 x larger than EGRET upper limit



CHANDRA X-RAY [3-COLOR]

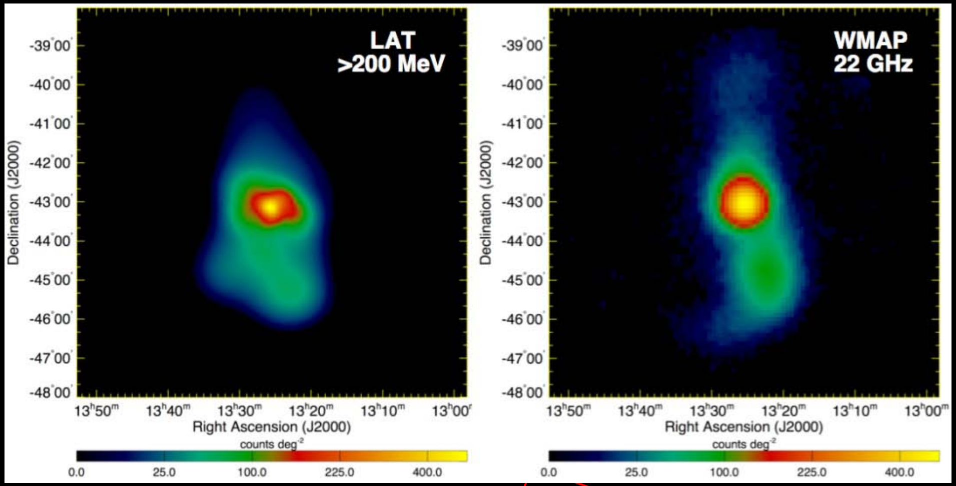
Further AGN-classes or ambiguity in classification?

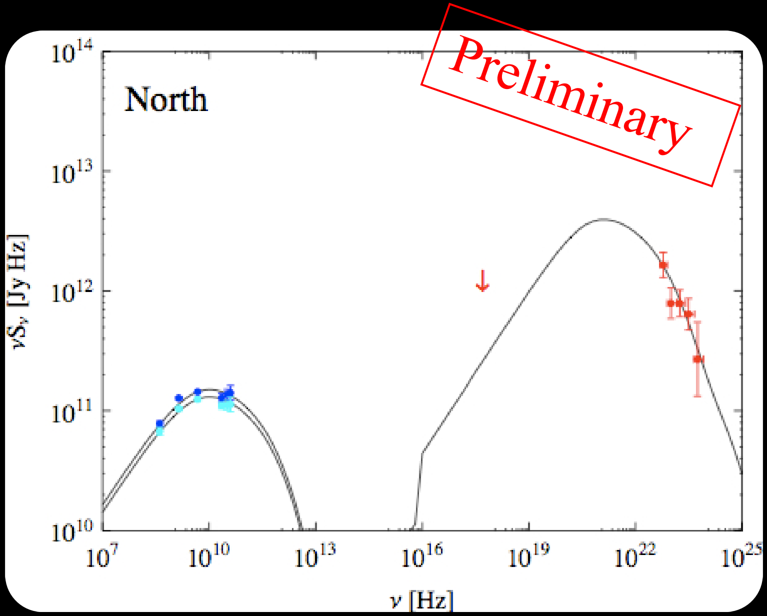
PMN J0948+0022, Narrow-line, radio loud Sy1

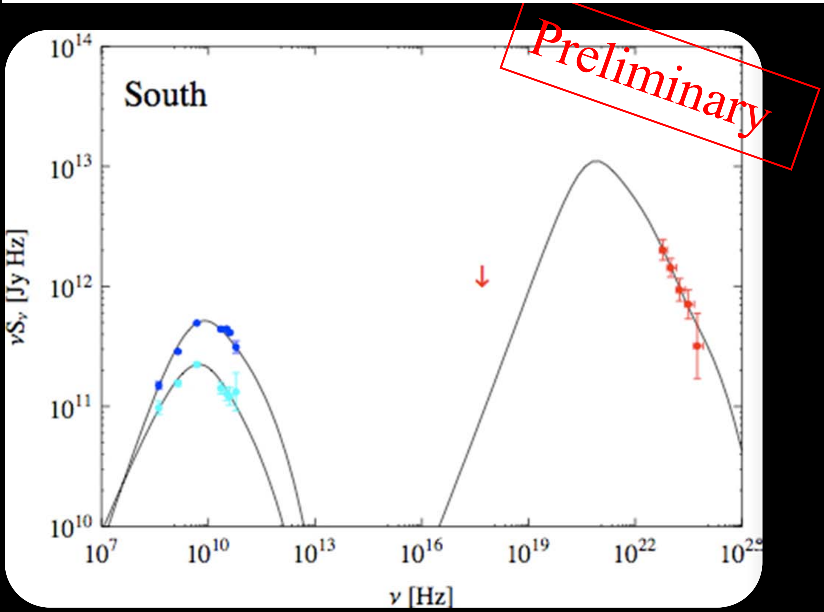
- SED similar to FSRQ, less powerful
- Radio emission is strongly variable and with flat spectrum → suggests Doppler boosting, now confirmed by LAT
- 3 similar other sources detected

Cen A: The Giant Radio Lobes

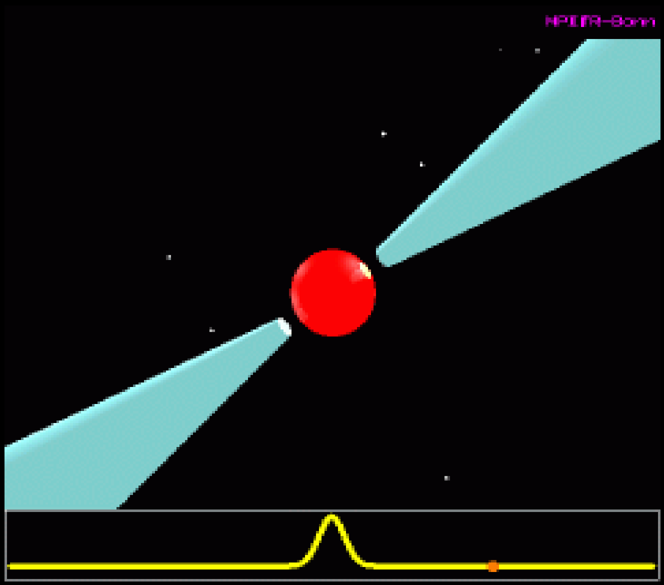
- Radio source extent ~10°, at d=3.7 Mpc, 600 kpc
- Spectra of ambient photons as seen by lobes
  - CMB dominant at low-E
  - EBL (opt+IR) contributes at high-E
  - Host galaxy and dust negligible
- B close to equipartition
- electrons must be accelerated in situ

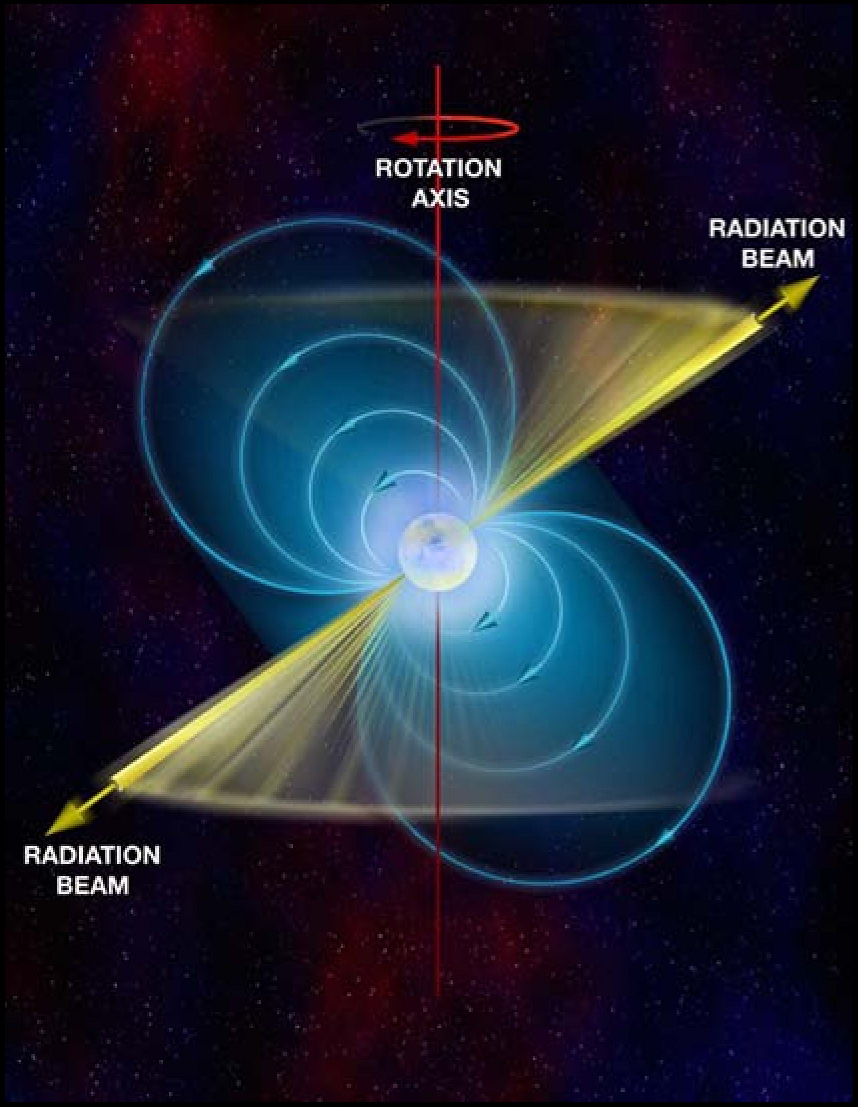






Isolated Neutron Stars / Pulsars





γ-ray photons from PSRs are not frequent
(1 over 1330 rotations in case of Crab pulsar)

Fermi observations are long: billions of rotations

→ high precision needed for phase calculation!

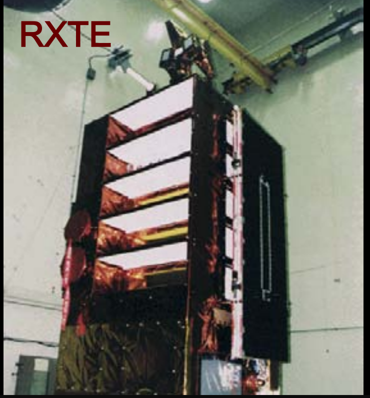
There are two options:

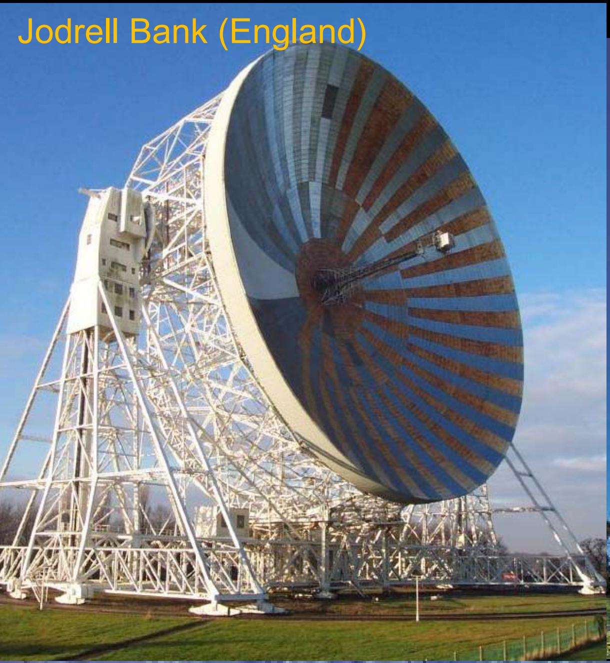
- **Blind search** in γ-ray data
  Problems: manifold search window, trials, timing noise…

- Forward folding with **known ephemerides**
  Problems: ~ 2000 PSRs known, impossible to get contemporary timing solutions for all along LAT obs

The known γ-ray pulsars have $\dot{E} > 3.10^{34}$ erg/s. Pulsars may not be detectable below this value.
We decided to focus on pulsars with:
$\dot{E} > 10^{34}$ erg/s
↓
224 γ-ray pulsar candidates

Pulsar timing consortium

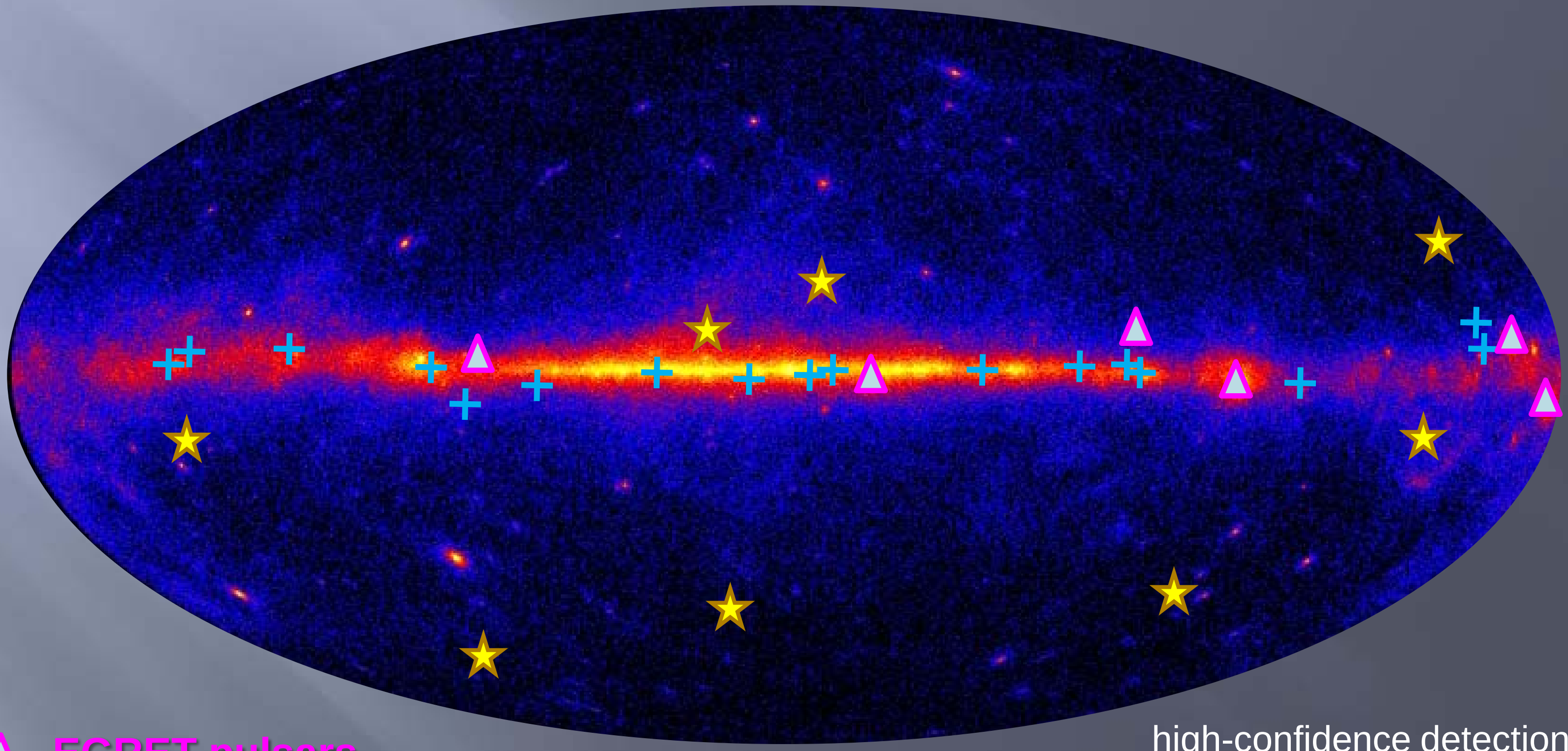




Prime Galactic Populations: Pulsars

31 gamma-ray and radio pulsars (including 8 msPSRs)

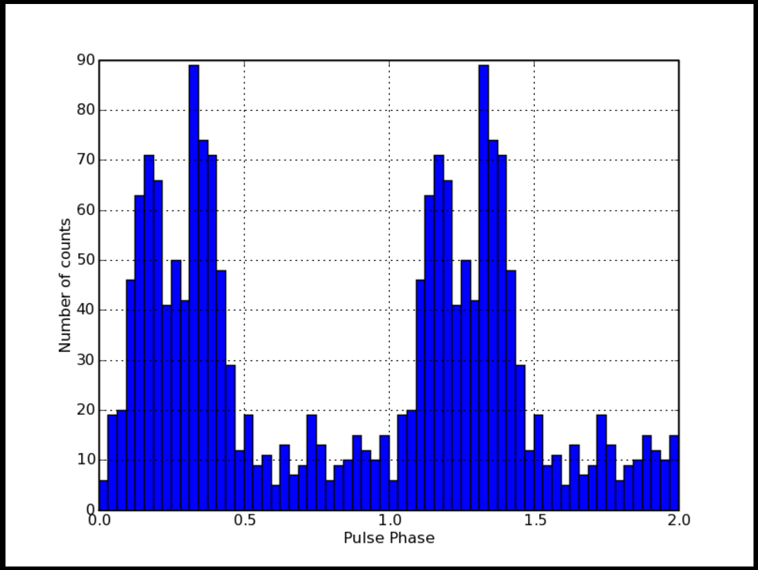
Pulses at ~1/10th real rate



high-confidence detections from 1st six month Fermi operations

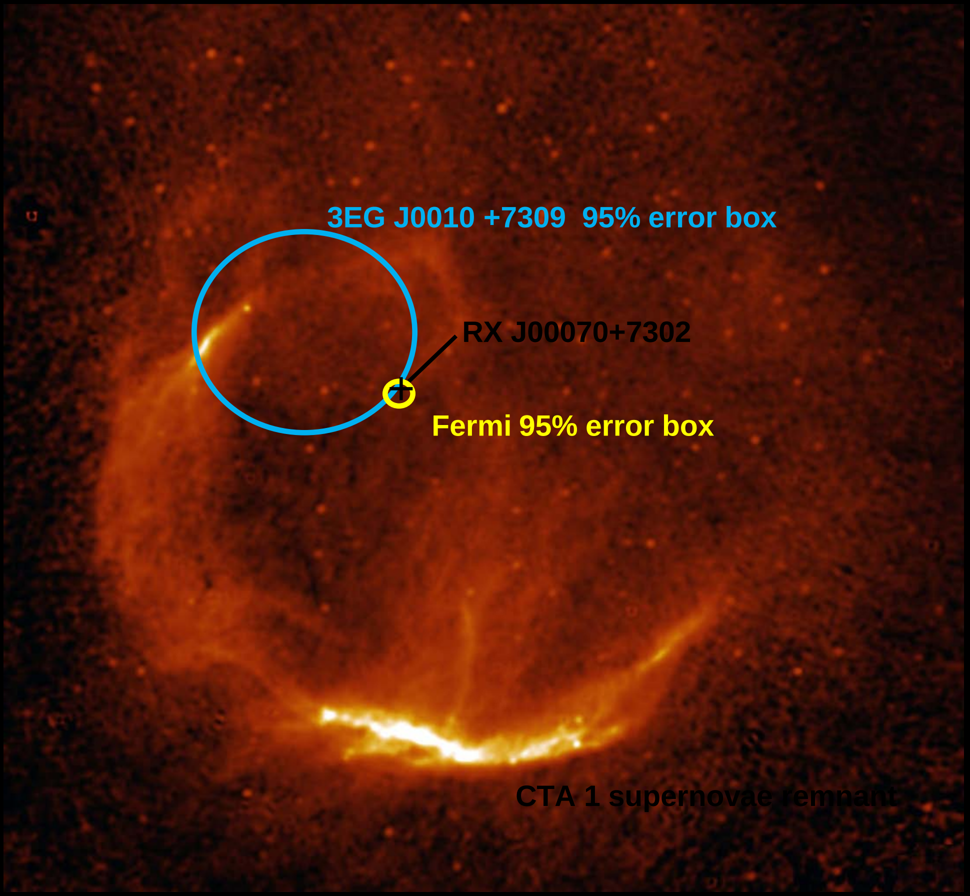
- △ EGRET pulsars
- + young pulsars discovered using radio ephemeris
- ★ millisecond pulsars discovered using radio ephemeris

Pulsar in CTA 1



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

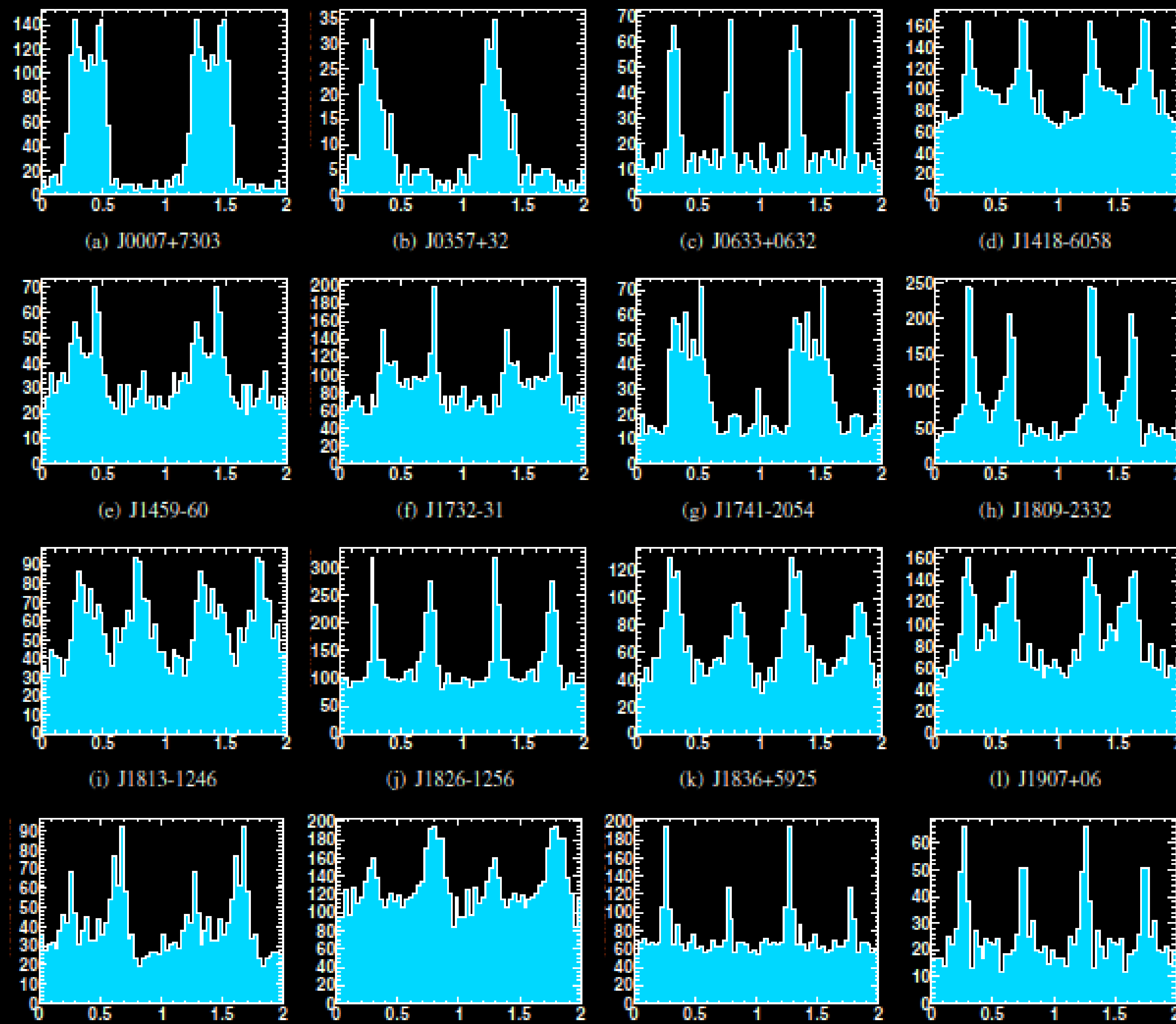
- spin-down luminosity ~10^{36} erg s^{-1}, sufficient to supply the PWN with magnetic fields and energetic electrons.



- γ-ray source at *l,b* = 119.652, 10.468; 95% error circle radius =0.038° contains the X-ray source RX J00070+7302, central to the PWN superimposed on the radio map at 1420 MHz.

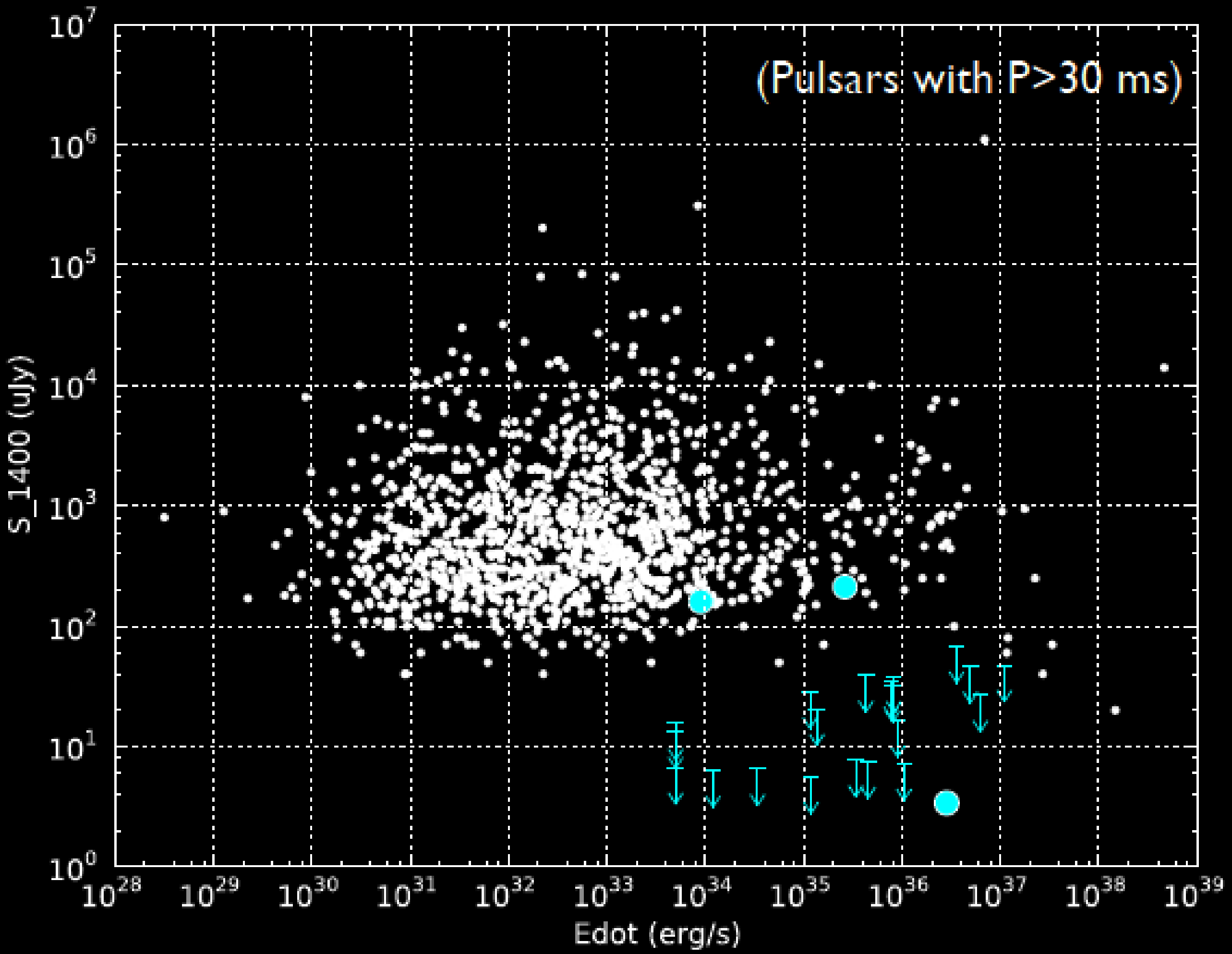
- pulsar off-set from center of radio SNR; rough estimate of the lateral speed of the pulsar is ~450 km/s

Blind-searched Fermi PSRs



(a) J0007+7303 (b) J0357+32 (c) J0633+0632 (d) J1418-6058
(e) J1459-60 (f) J1732-31 (g) J1741-2054 (h) J1809-2332
(i) J1813-1246 (j) J1826-1256 (k) J1836+5925 (l) J1907+06
(m) J1958+2846 (n) J2021+4026 (o) J2032+4127 (p) J2238+59

What means "radio-quiet"?

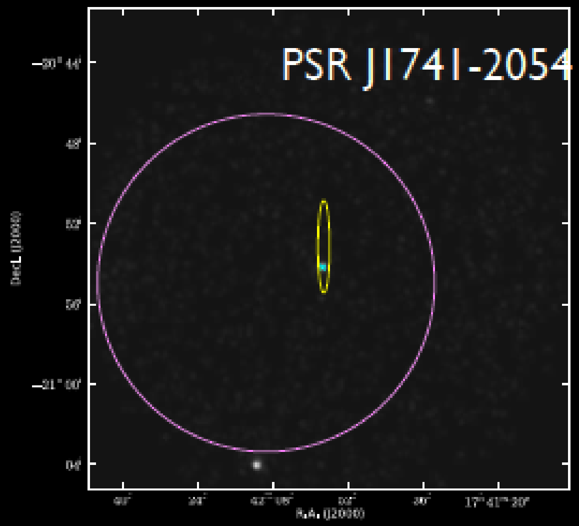


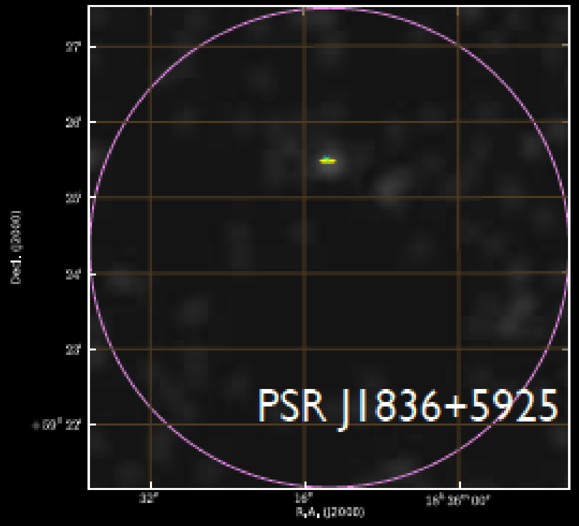
- 25 gamma-ray selected pulsars

➡ 3 detected, 21 upper limits (all <70 μJy), 1 left to observe

The power of timing

- Improved rotational parameters
- Study timing noise and glitches (free from any radio propagation effects)
  - Glitch detected in CTA1 pulsar on 2009 May 1
- **Precise positions**, which enable multiwavelength follow up!
  - Sub-ms residuals lead to arcsec position accuracy



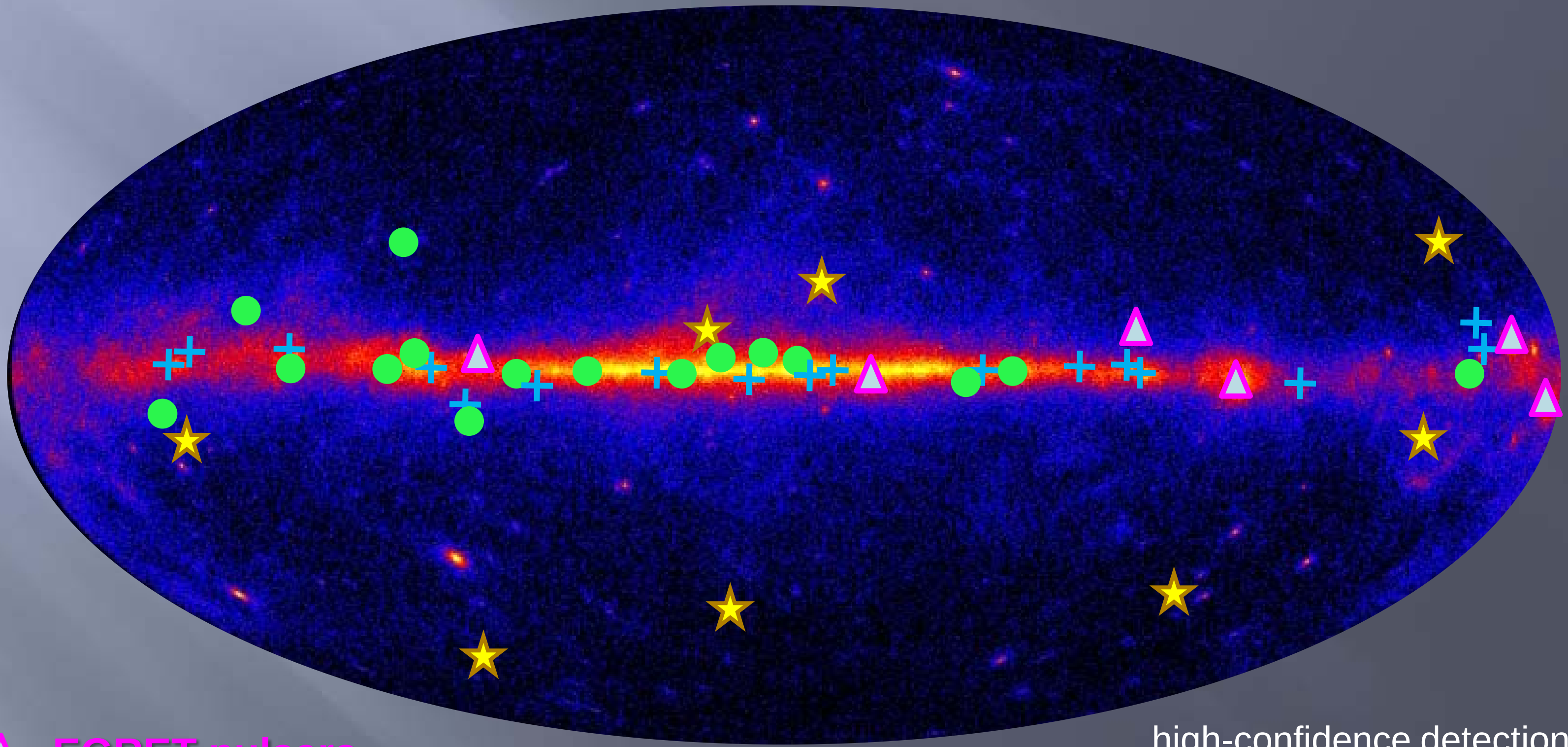


Prime Galactic Population: Pulsars

31 gamma-ray and radio pulsars (including 8 msPSRs)

16 gamma-ray only pulsars

Pulses at ~1/10th real rate

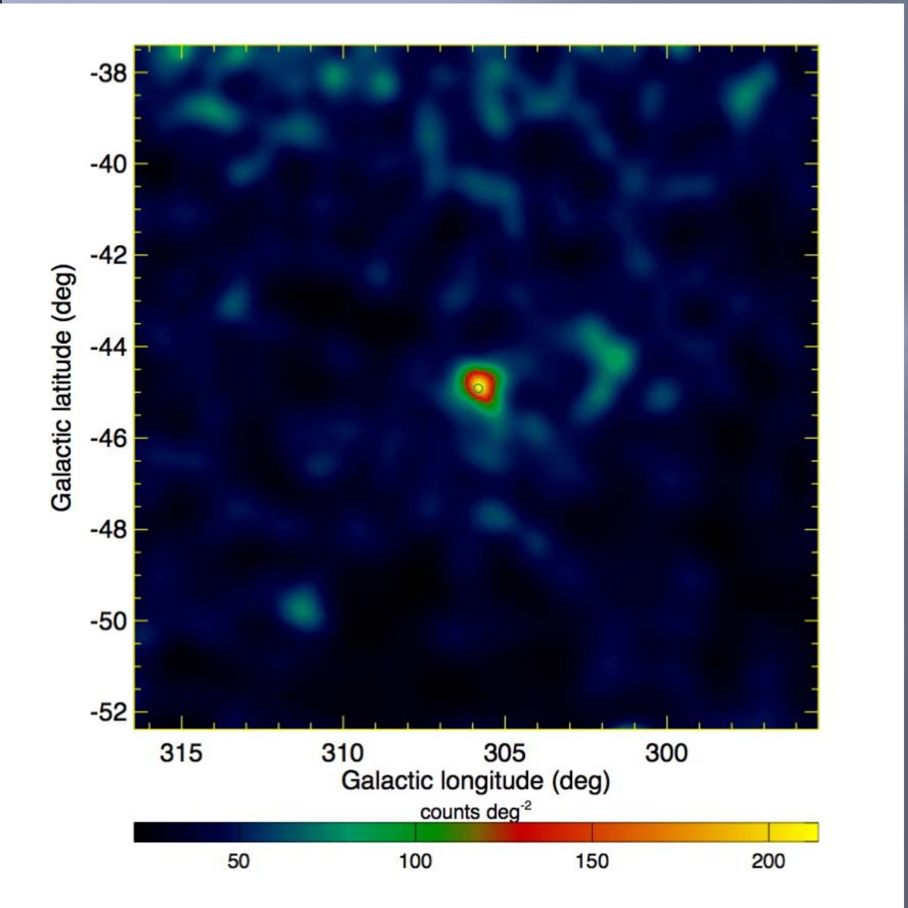


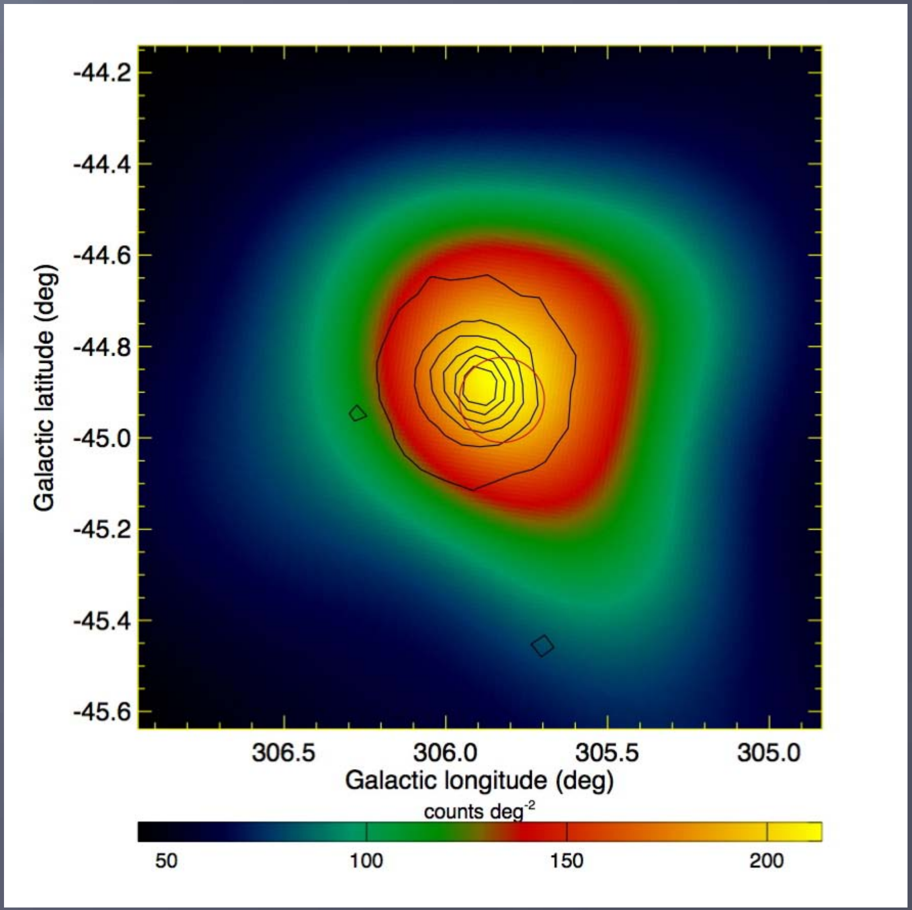
high-confidence detections from 1st six month Fermi operations

- △ EGRET pulsars
- \+ young pulsars discovered using radio ephemeris
- ★ millisecond pulsars discovered using radio ephemeris
- ● pulsars discovered in blind search

Globular clusters known to host sizeable number of msPSRs: 47Tuc detected as a (steady) GeV gamma-ray source

Adaptively smoothed counts maps (200 MeV - 10 GeV, s.n.r = 5)





Large area

The source lies in an isolated sky region

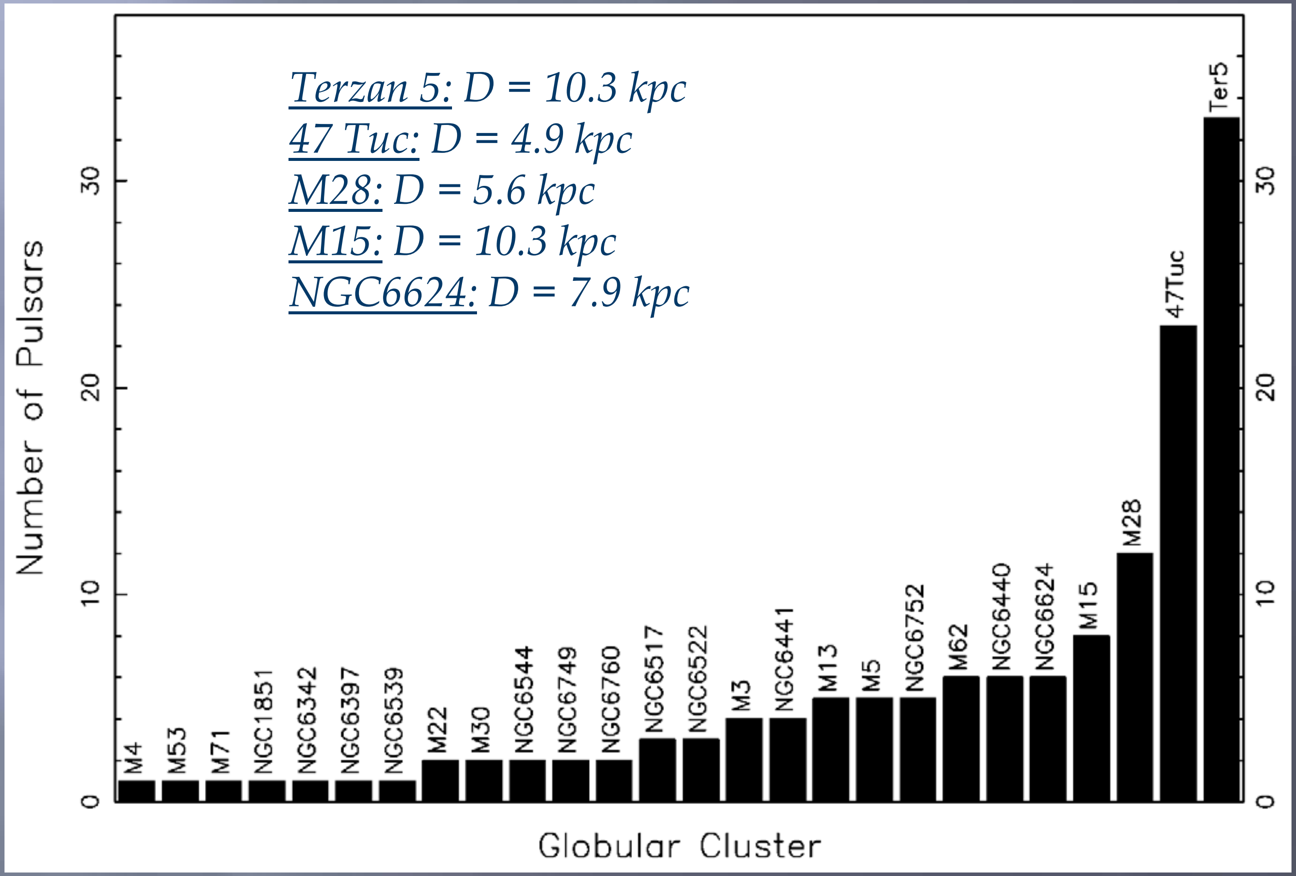
Zoom

Location of LAT source relative to 47 Tuc

red circle: LAT 95% error radius

contours: DSS2 stellar distribution (arbitrary units)

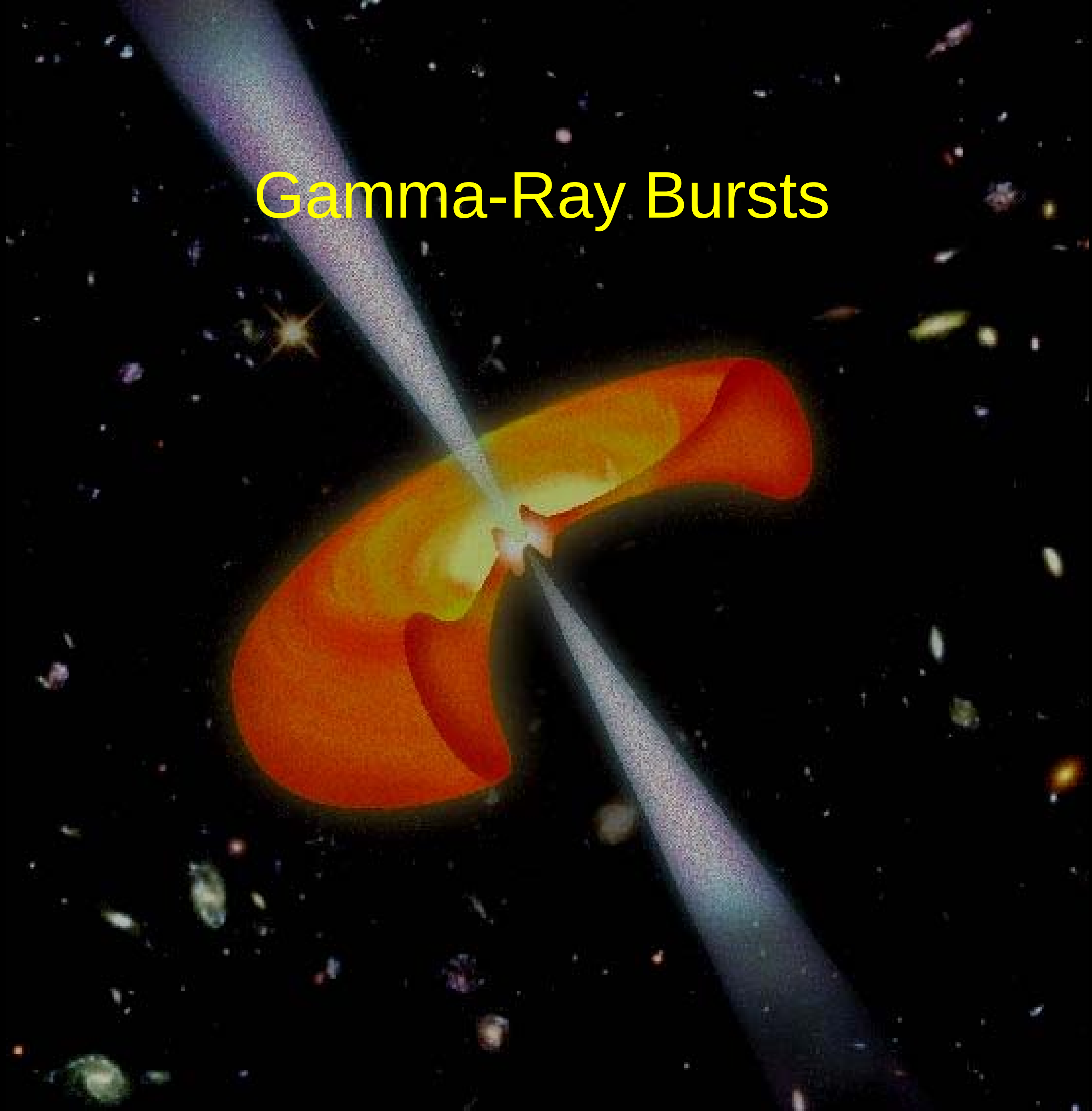
Other Globular Clusters ?



There are ~ 100 MSPs in 26 GCs.

Promising sources of collective emission. Some more individuals might be detectable.
Search for pulsations ongoing.

Gamma-Ray Bursts



GRBs: We have come a long way since…

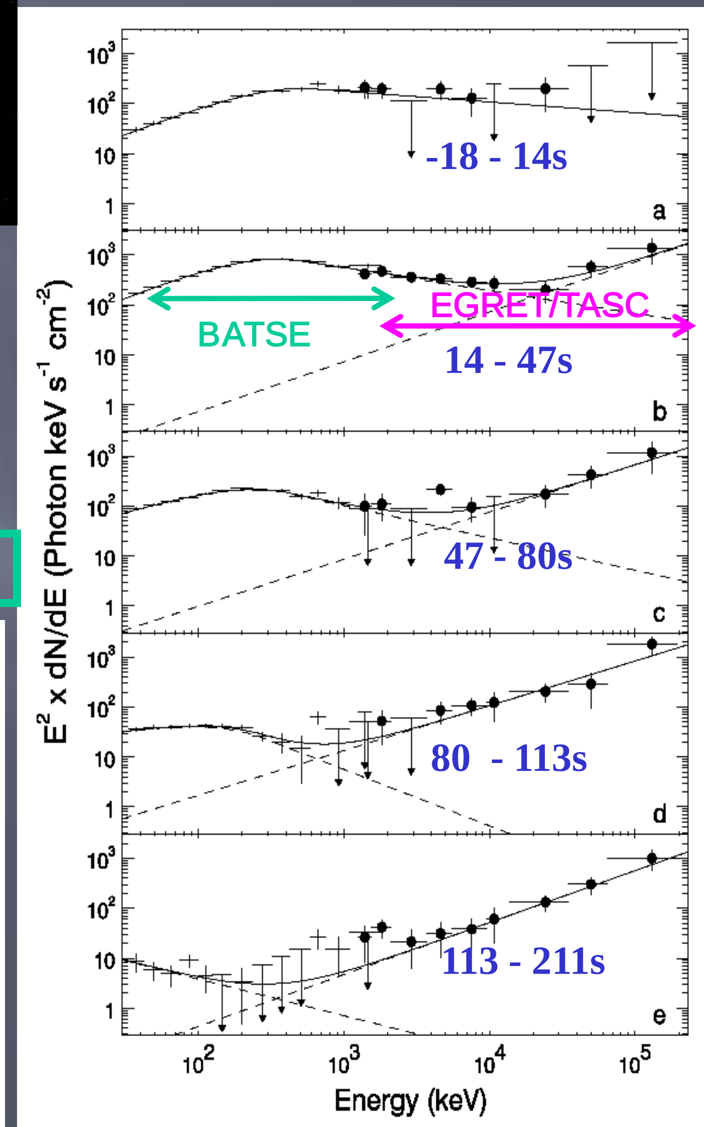
Brightest explosions in Universe
(10^{51} erg in few x 10 sec flash)
standard candles?

Black hole birth
progenitors?
sub-classes?

Ultra-relativistic outflows (Γ ~ 100)
particles vs pointing flux?
internal vs external shocks?

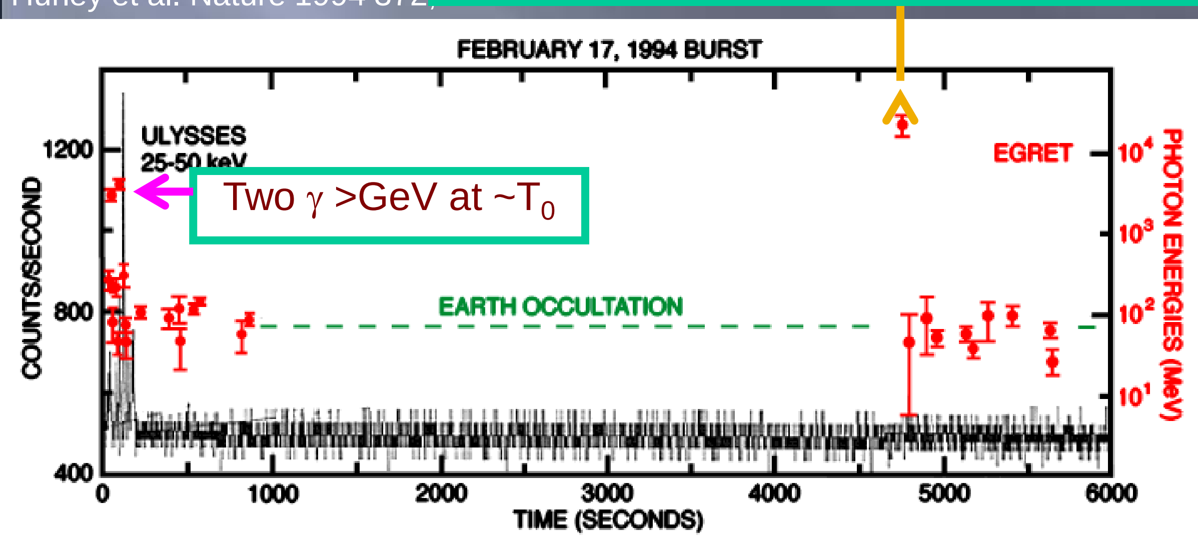
Early universe probes
GRBs from Pop III stars?
metalicity effects?
usable for cosmology?

Gonzalez, Nature 2003 424, 749



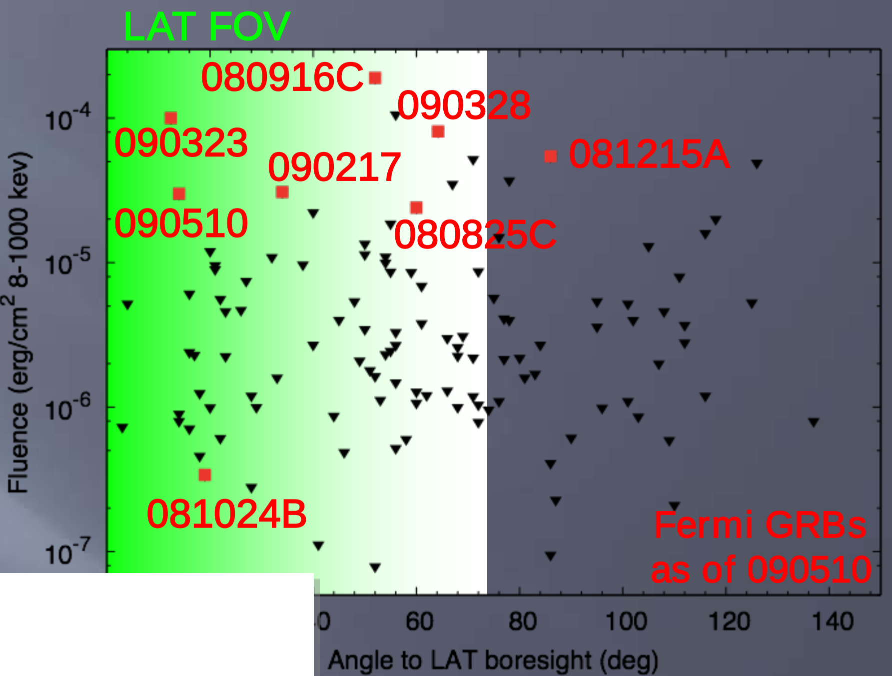
The One 18 GeV photon at ~T$_0$+75 min

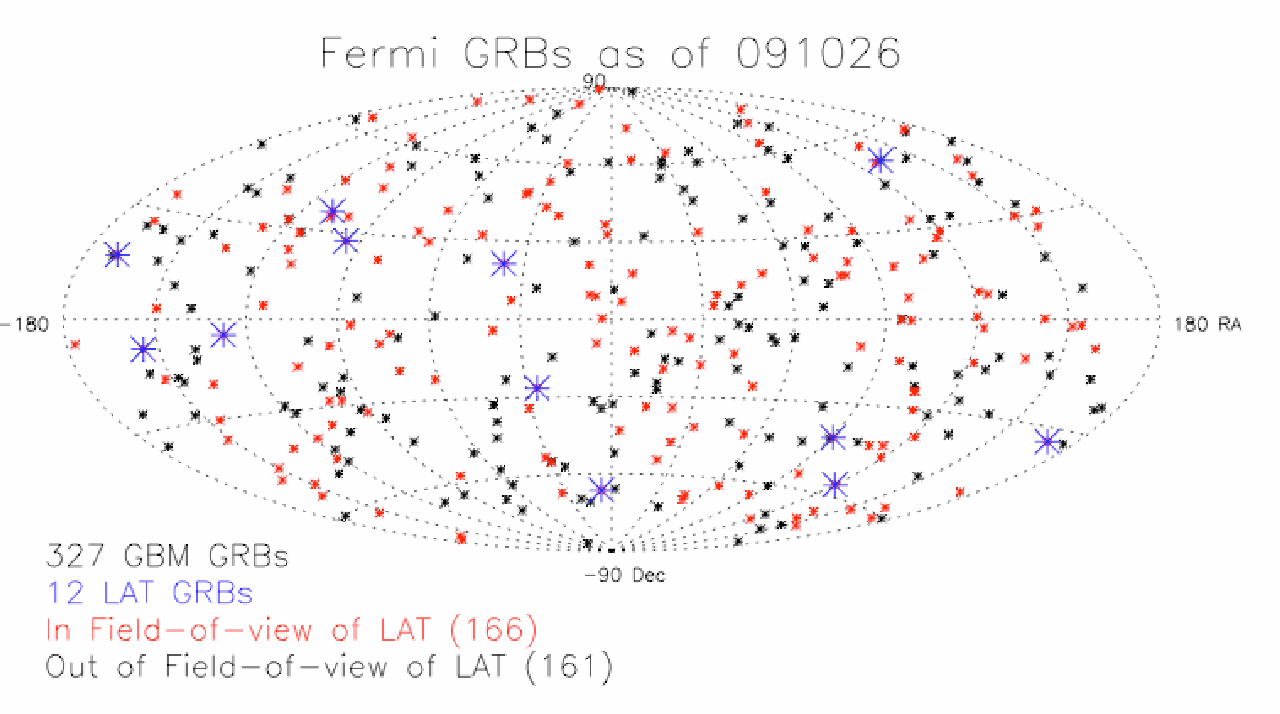
Hurley et al. Nature 1994 372, 652



Fermi Detection of GRBs

- 327 GBM detection since 09/10/2009
- 12 LAT detections (out of 166 in FOV)





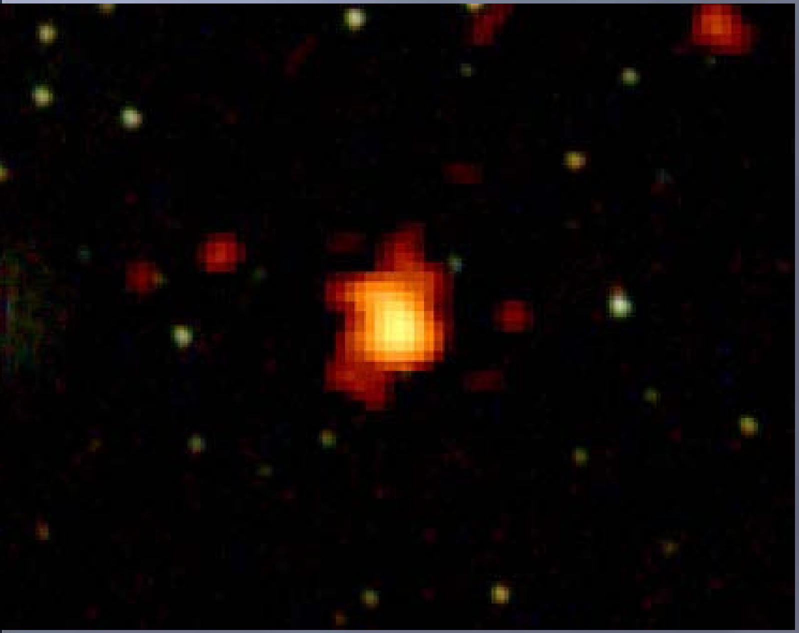
The LAT Bursts so far …

GRB	duration	# of events > 100 MeV	# of events > 1 GeV	delayed HE onset	Long-lived HE emission	Extra Component	Highest Energy	Redshift
080825C	long	~10	0	?	✔	x	~600 MeV	
080916C	long	>100	>10	✔	✔	?	~ 13.2 GeV	4.35
081024B	short	~10	2	✔	✔	?	3 GeV	
081215A	long	—	—	—	—	--	—	
090217	long	~10	0	x	x	x	~1 GeV	
090323	long	~20	>0	?	✔	?	?	3.57
090328	long	~20	>0	?	✔	?	?	0.736
090510	short	>150	>20	✔	✔	✔	~31 GeV	0.903
090626	long	~20	>0	?	✔	?	?	
090902B	long	>200	>30	✔	✔	✔	~ 33 GeV	1.822
090926	long	>150	>50	✔	✔	✔	~20 GeV	2.1062

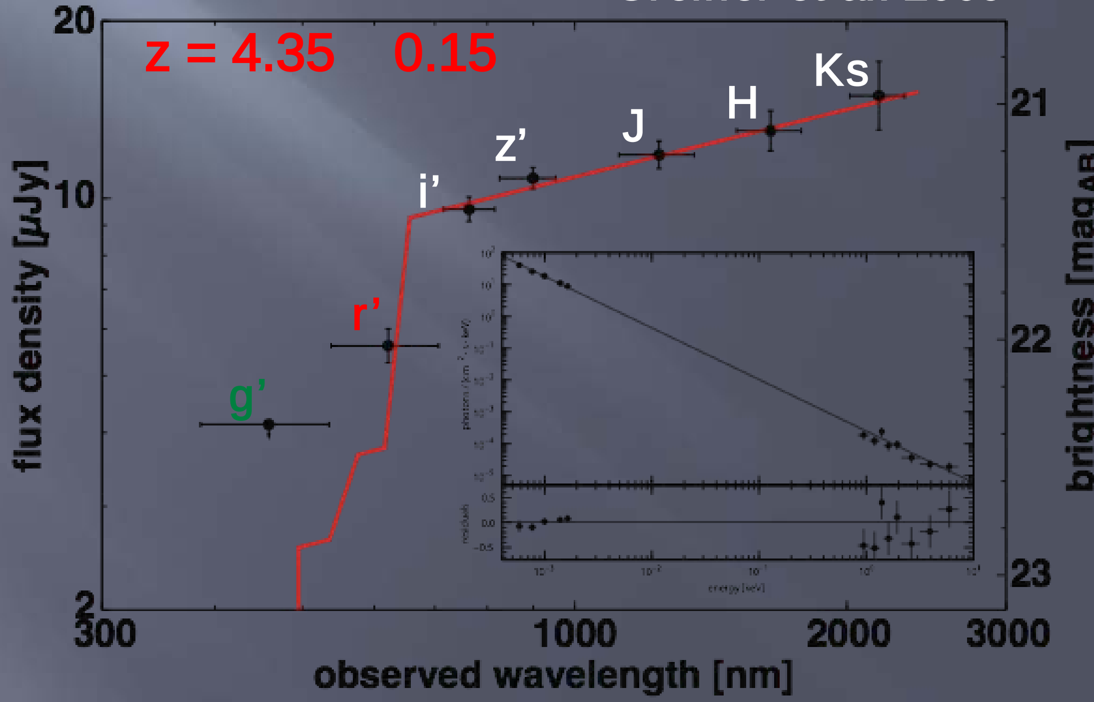
Redshift Determination

- GROND (at the ESO 2.2 m) measured redshift at z=4.35±0.15 using Lyα break by simultaneous 7-filter observation

Swift XRT image of afterglow
NASA/Swift/Stefan Immler



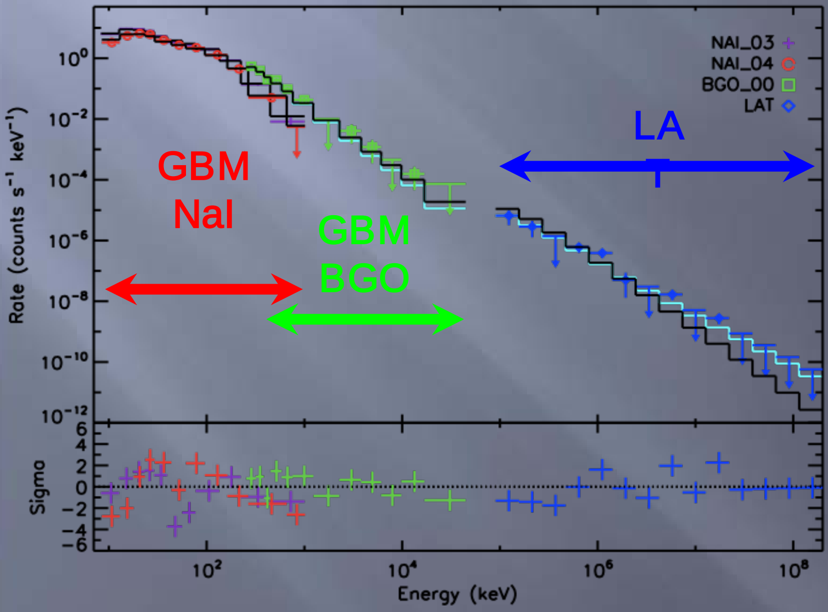
Greiner et al. 2009

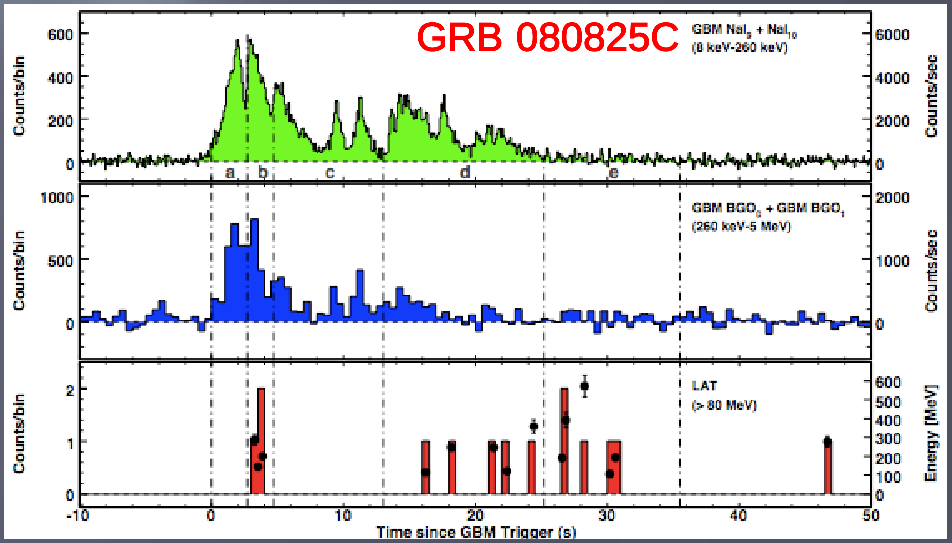


The Long-Lived HE Emission

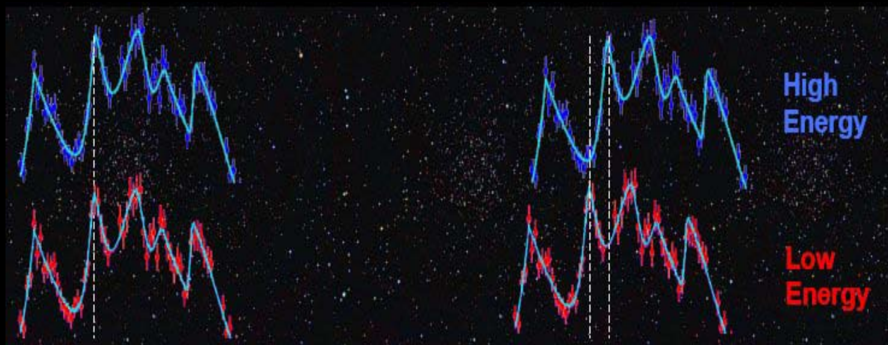
- HE (>100 MeV) emission shows different temporal behavior
- Temporal break in LE emission while no break in HE emission
  - Indication of cascades induced by ultra-relativistic ions?
  - or angle-dependent scattering effects?

  - Separate emission mechanisms between keV and GeV photons?



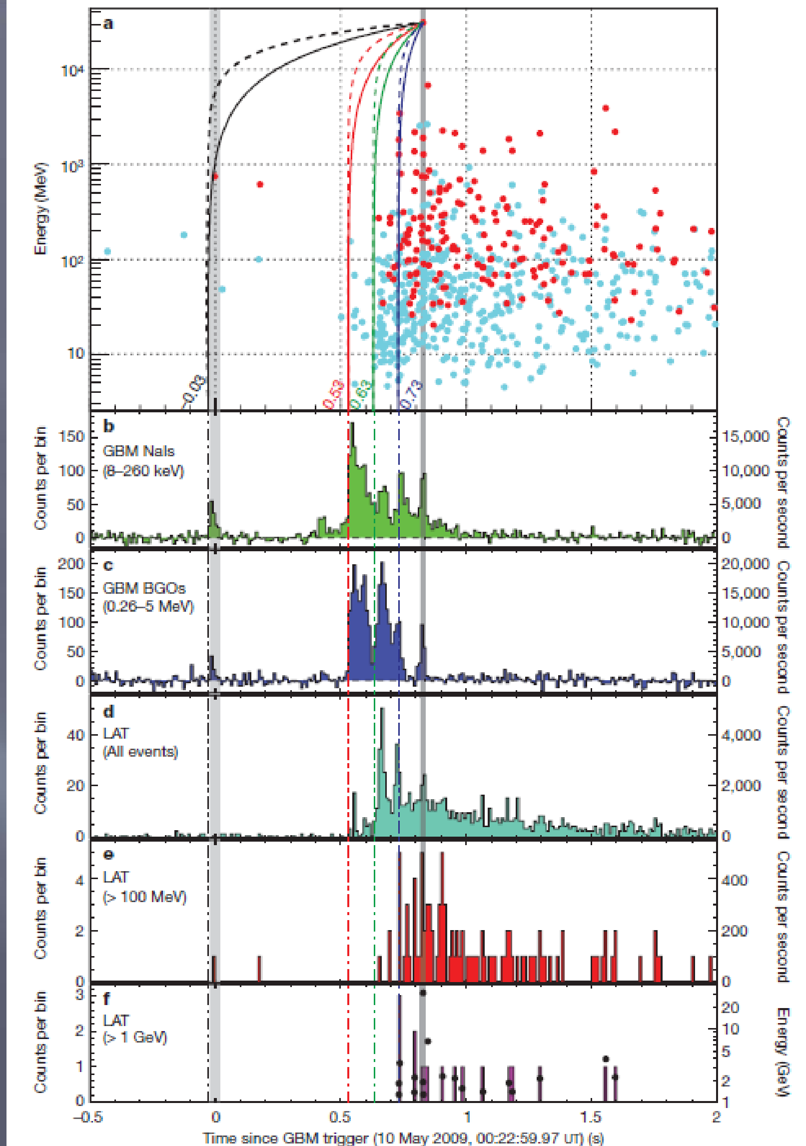


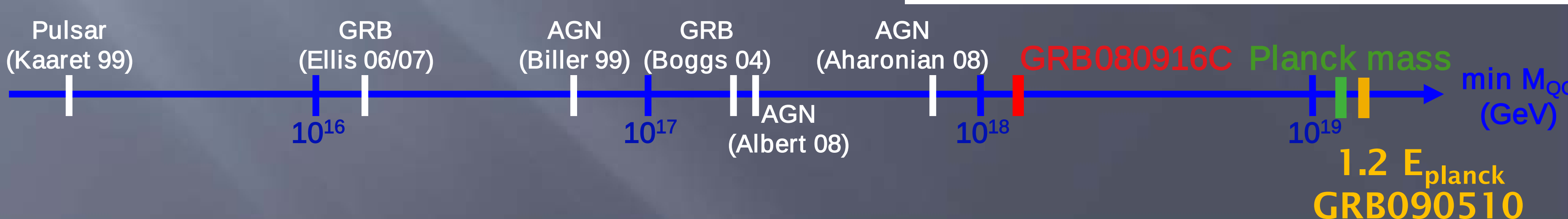
Implications



Quantum Gravitiy models predicted energy dependence of the speed of light

$$c' = c\left(1 \pm \xi\frac{E}{E_{\rm P}} \pm \zeta^2\frac{E^2}{E_{\rm P}^2}\right)$$

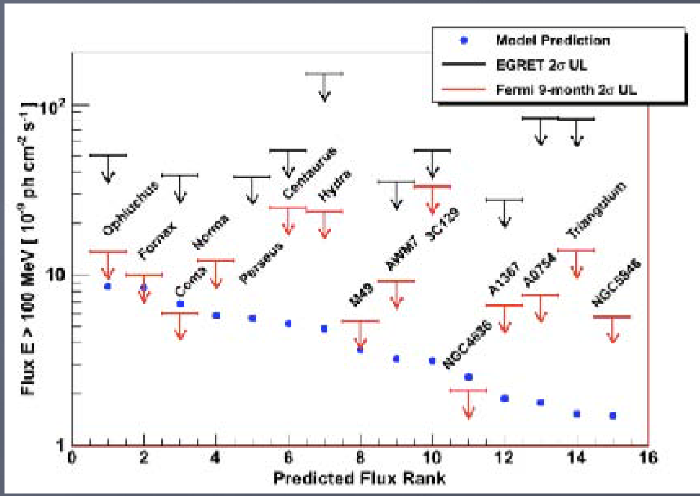




Galaxy clusters - CR calorimeter?

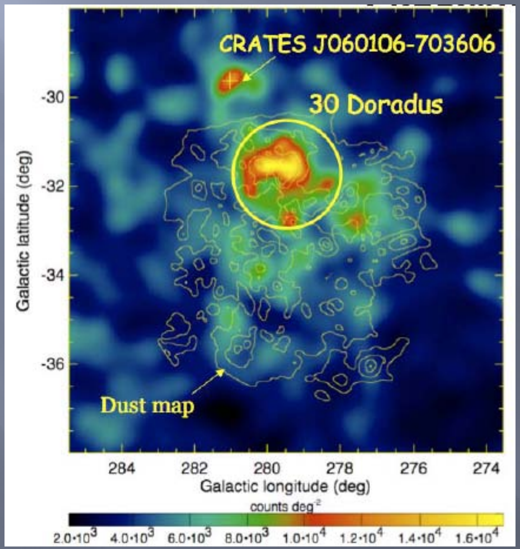
- CR storage over cosmological time scales
- CRs, AGN feedback, DM annihilation

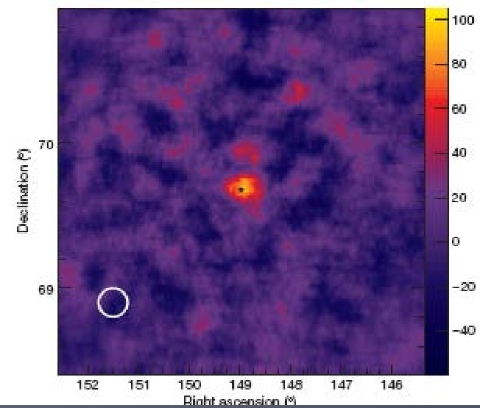
No easy pick for gamma-ray astronomy,
…still upper limits:



Starformation & Cosmic Rays – YES!

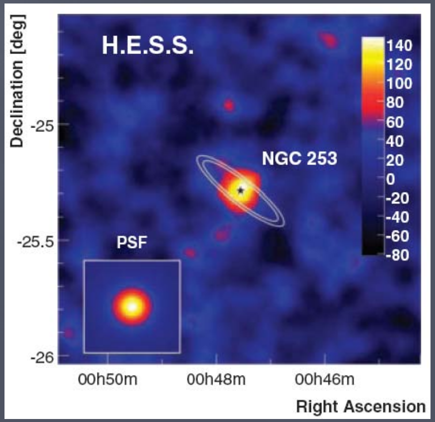
30 Dor in LMC by Fermi



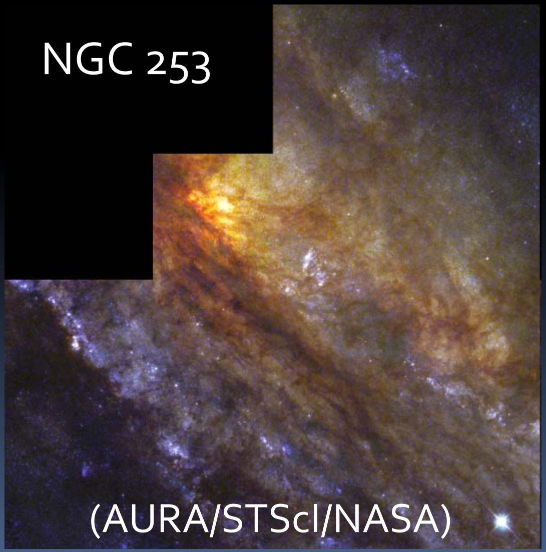


M82 by VERITAS & Fermi

NGC253 by HESS & Fermi

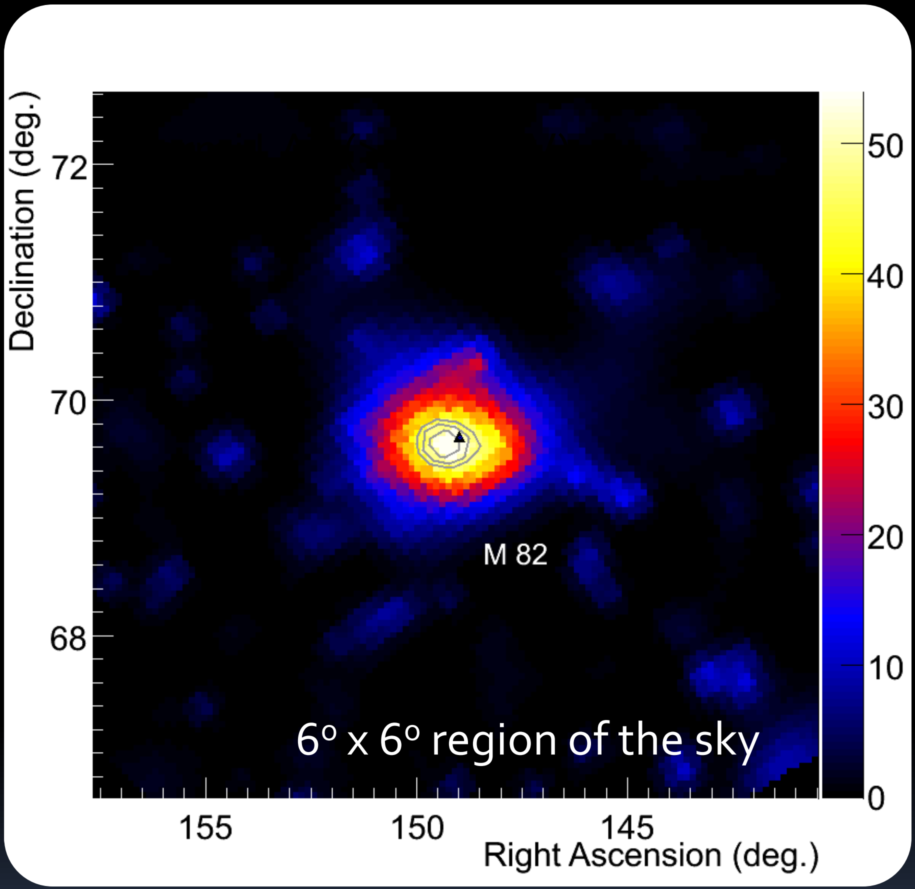


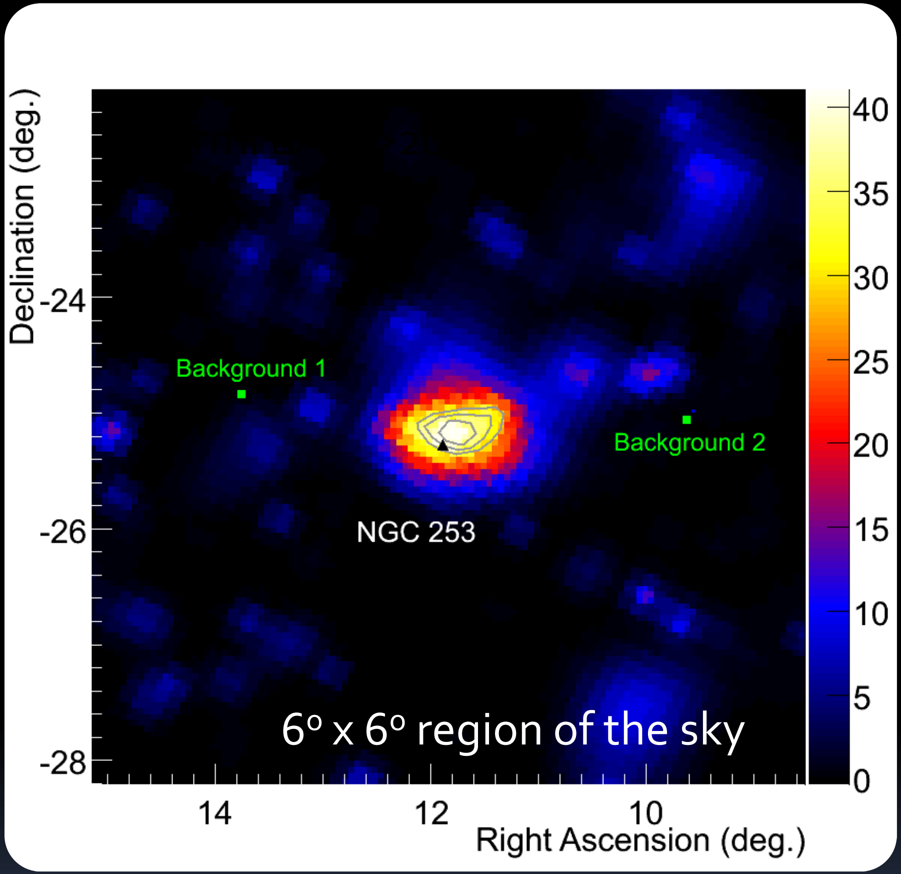
Starburst Galaxies



- **Starburst galaxies distinguished by regions of rapid star formation, 10-1000 × Milky Way rate**
  - Correspondingly high supernovae rates
  - Dense clumps of molecular gas
  - Highly luminous at infrared wavelengths, radio correlation
- **M82 and NGC 253**
  - Two closest starburst galaxies (~3 Mpc)
  - Edge-on viewing angles
  - Small (~100 pc scale) starburst regions
  - Star formation rate ~10 × Milky Way rate
  - Lack active nuclei
  - Extensively studied in multiple wavebands

Fermi Detection Significance Maps



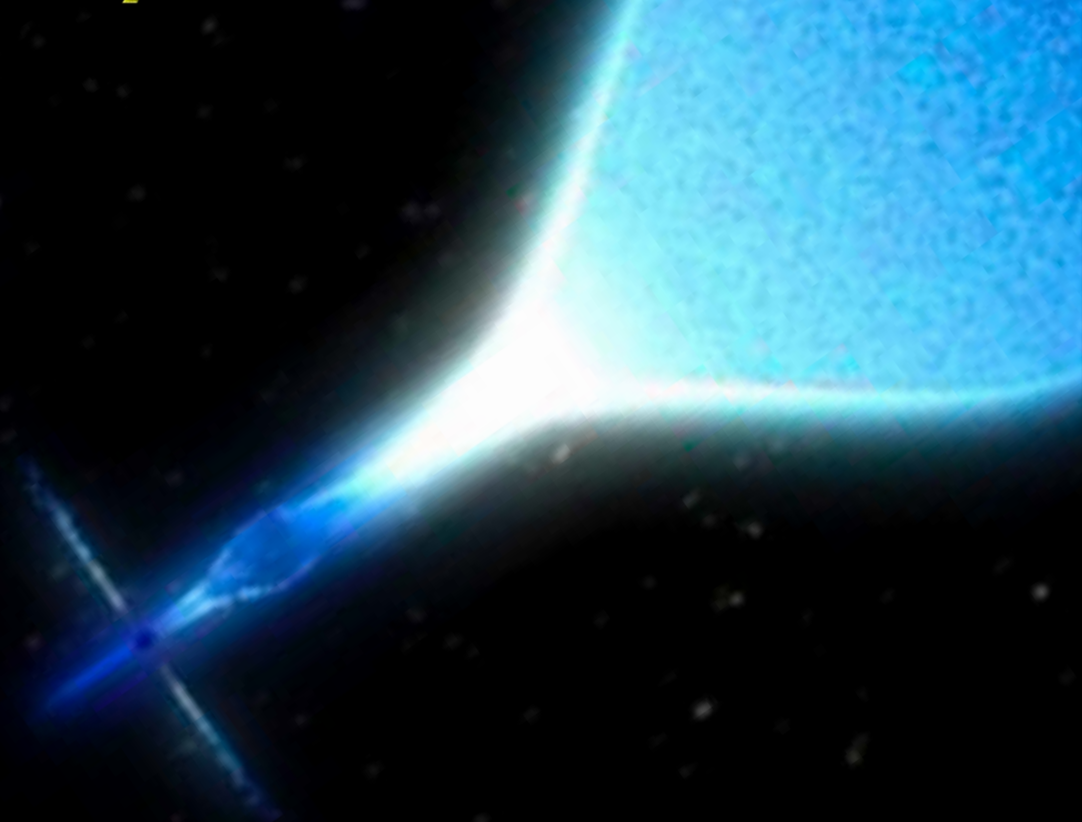


Test Statistic (TS) = -2 log(L_{source} - $L_{no\ source}$)

0.68, 0.95, 0.99 confidence level localization contours

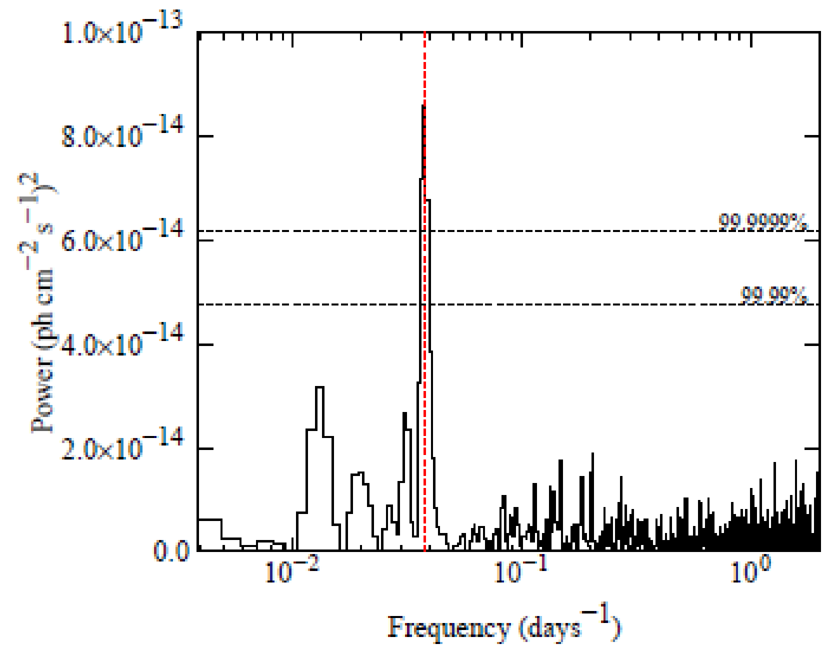
M82 and NGC253 appear for LAT as point sources, starburst regions unresolved.

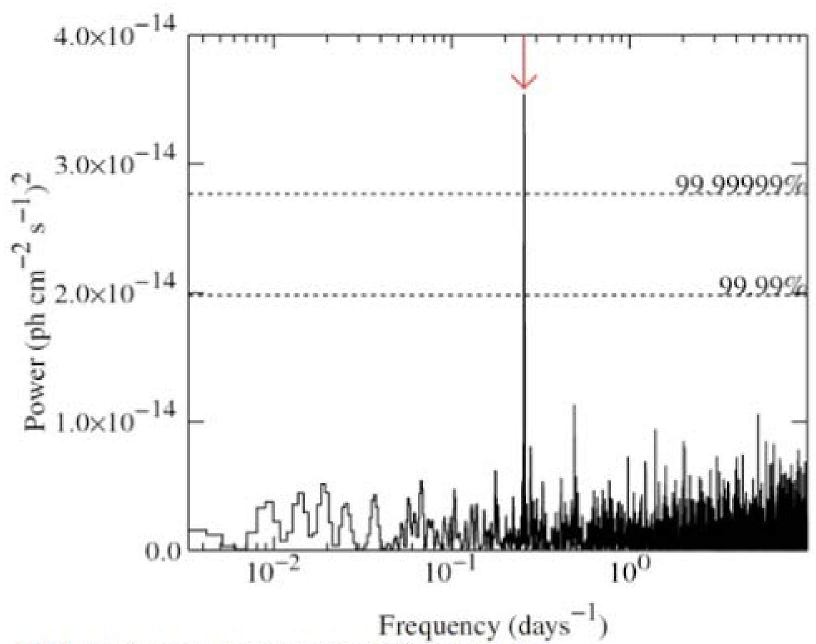
Gamma-Ray Binaries



Binaries:

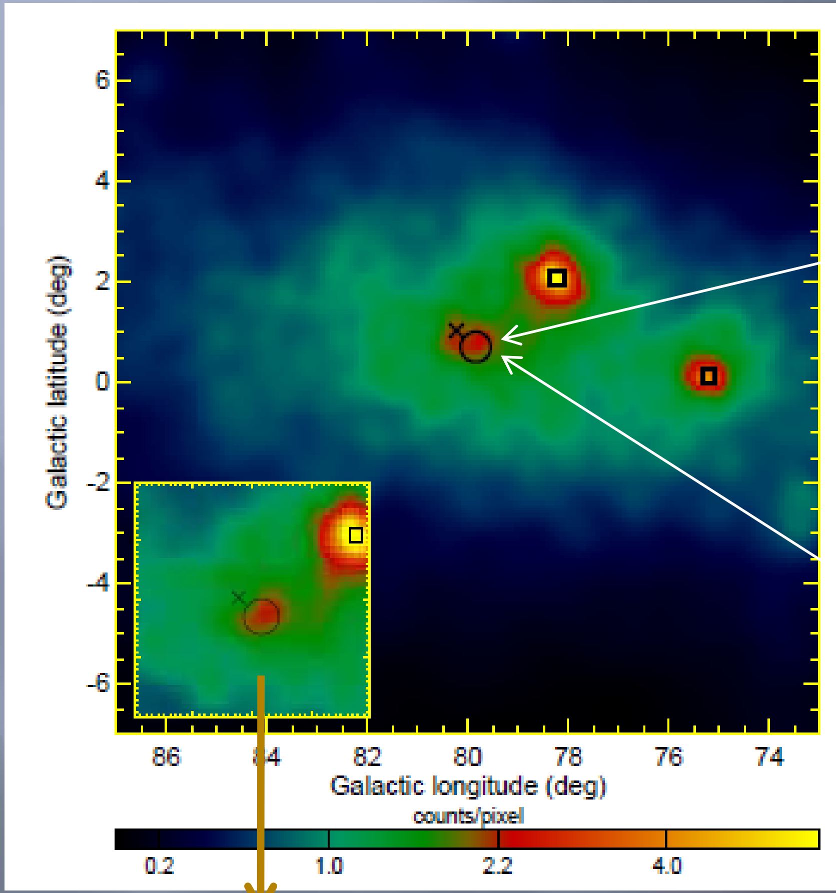
Both LS I 61+303 and LS 5039 have been found as orbital modulated GeV sources, too.





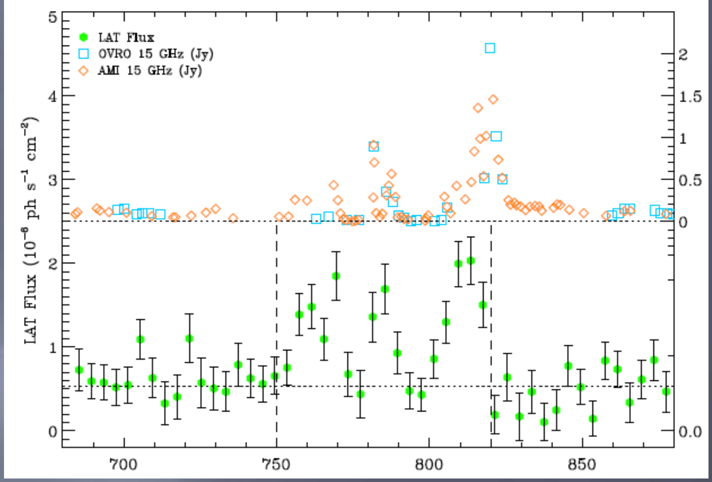
Red arrow shows known orbital period.

Hot from the press: Cyg X-3

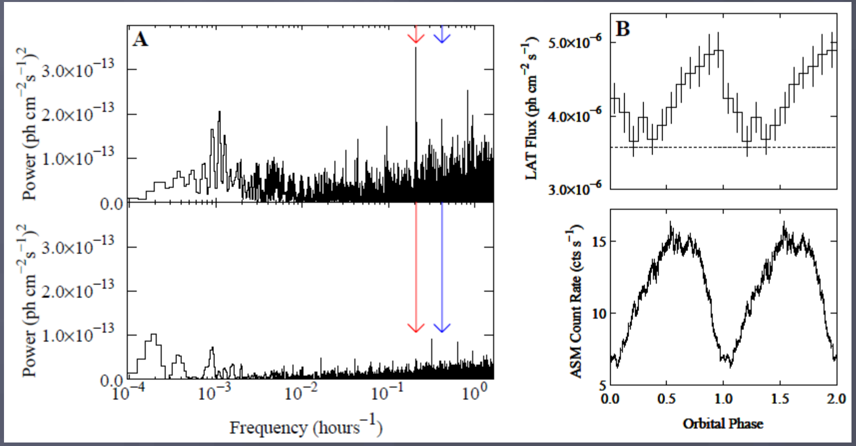


offpulse
PSR J2032+4127

Correlated variability with other wavebands

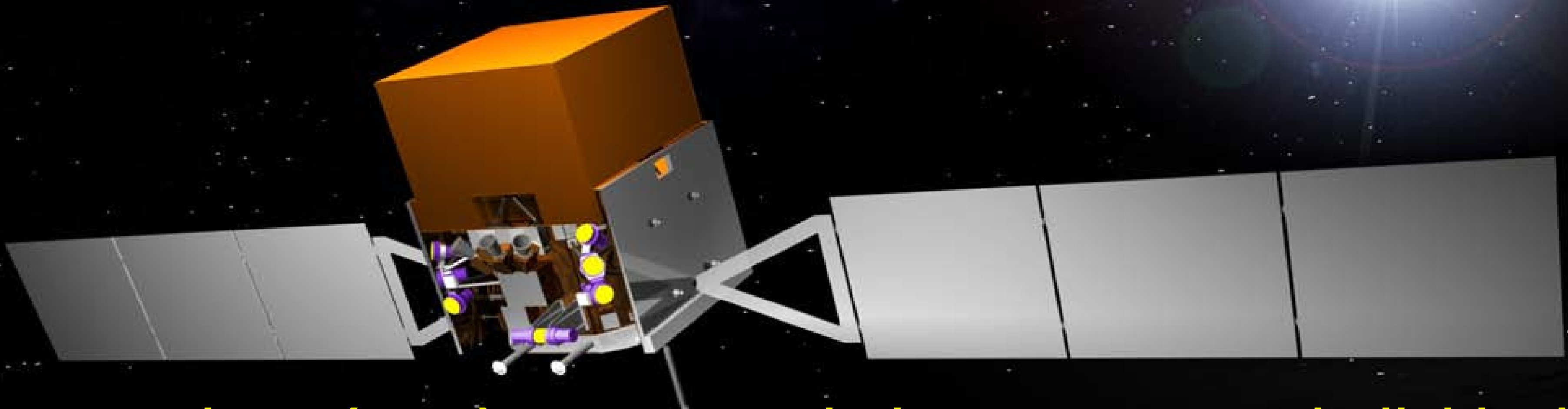


Orbital periodicity (4.8h) identified



Outlook for the photon messenger

→ *Fermi* continues measuring the GeV sky with unprecedented quality



→ resolve O(1000) sources, spiral arm structure, individual molecular clouds, local group galaxies, CR proton spectrum, anisotropy?, & continues indirect DM searches