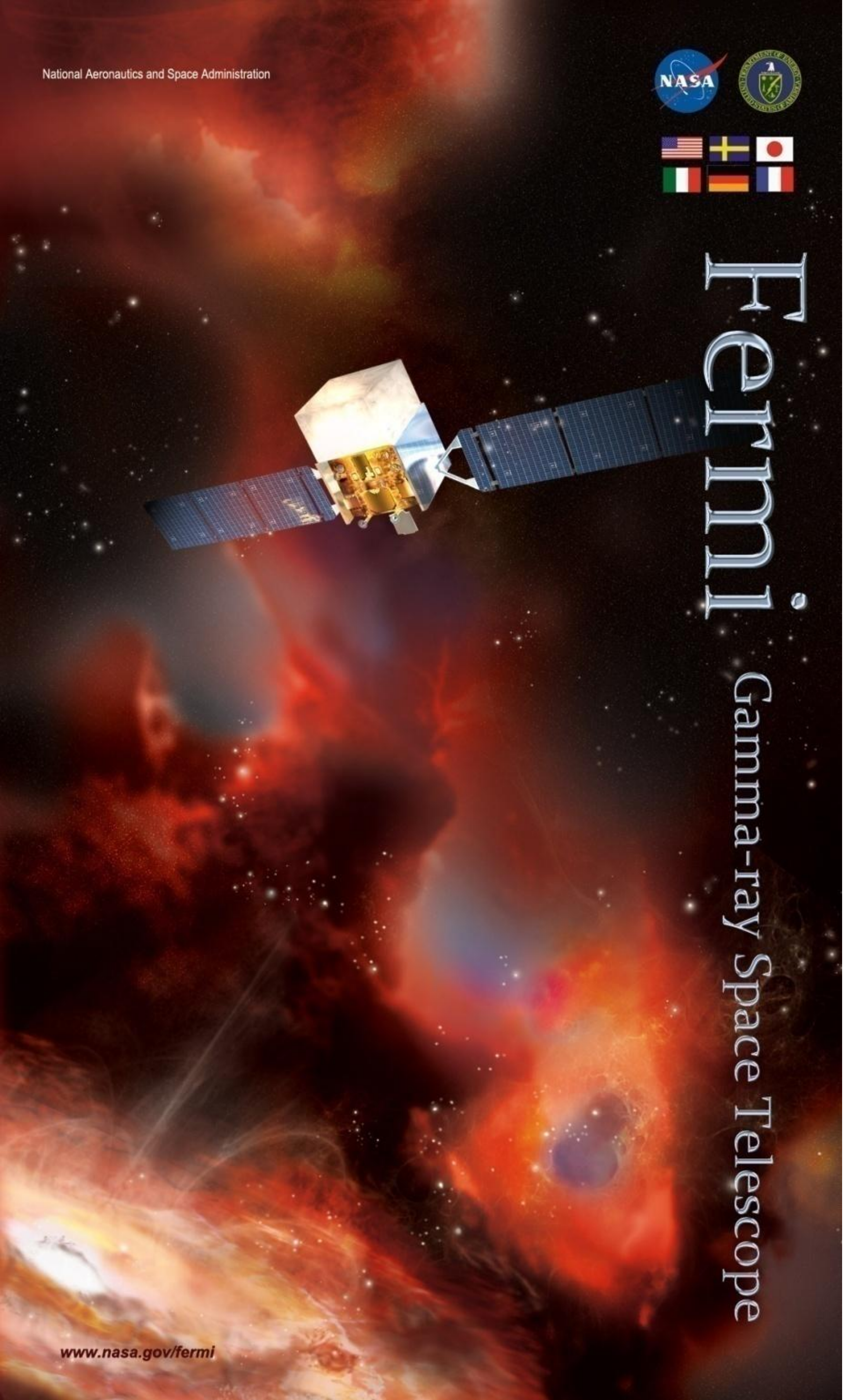
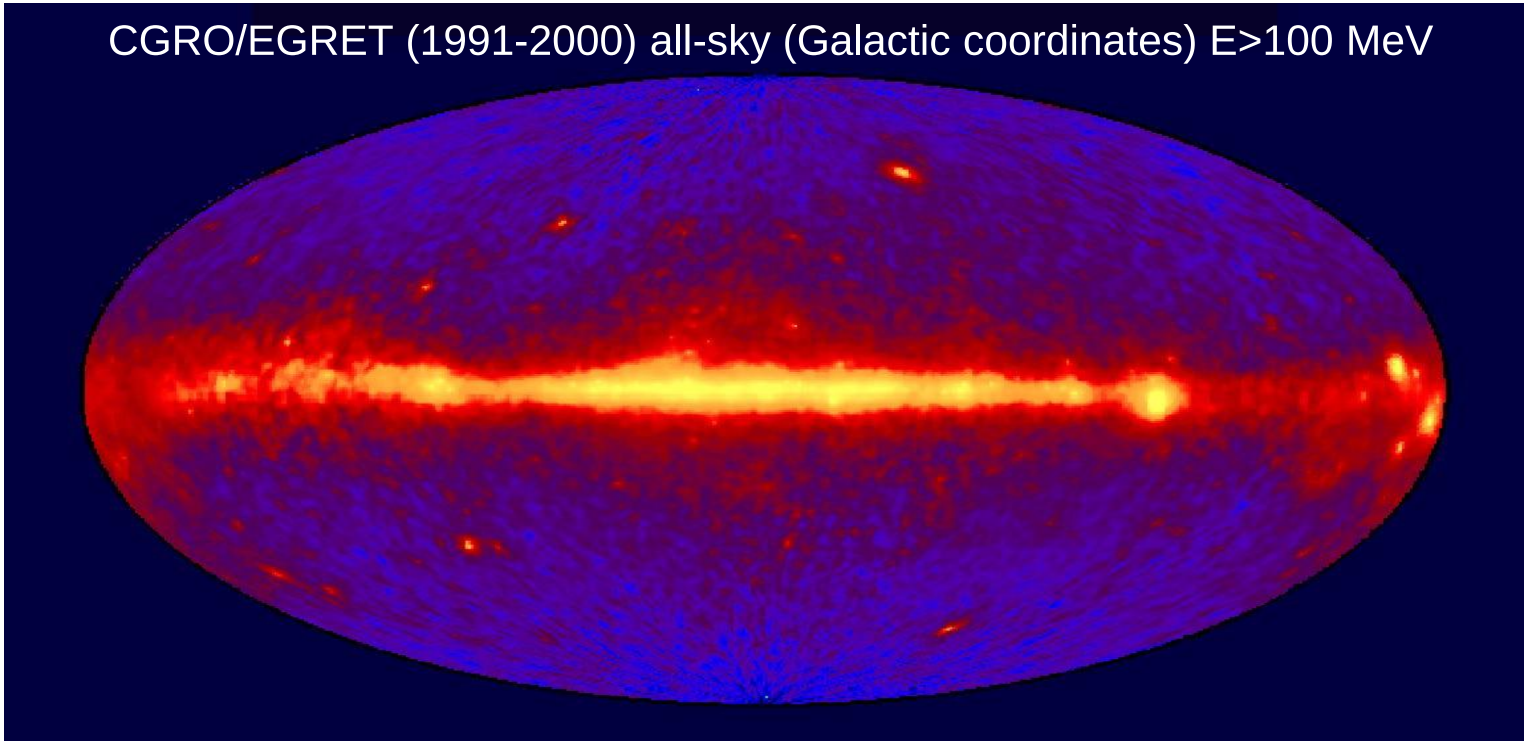


The γ-ray sky after one year of the *Fermi* satellite

Jean Ballet
(AIM, CEA/DSM/IRFU/SAp)
on behalf of the Fermi LAT Collaboration

LPNHE February 18, 2010

Features of the EGRET gamma-ray sky



diffuse extra-galactic background (flux ~ 1.5×10^{-5} $cm^{-2}s^{-1}sr^{-1}$)

Galactic diffuse (flux ~30 times larger)

high latitude (extra-galactic) point sources (typical flux from EGRET sources O(10^{-7} - 10^{-6}) $cm^{-2}s^{-1}$)

Galactic sources (pulsars, un-ID'd)

An essential characteristic: VARIABILITY in time!

Field of view important for study of transients

GLAST LAT science objectives

> 2000 AGNs
blazars and radiogal = f(θ,z)
evolution z < 5
Sgr A*

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

γ-ray binaries
Pulsar winds
μ-quasar jets

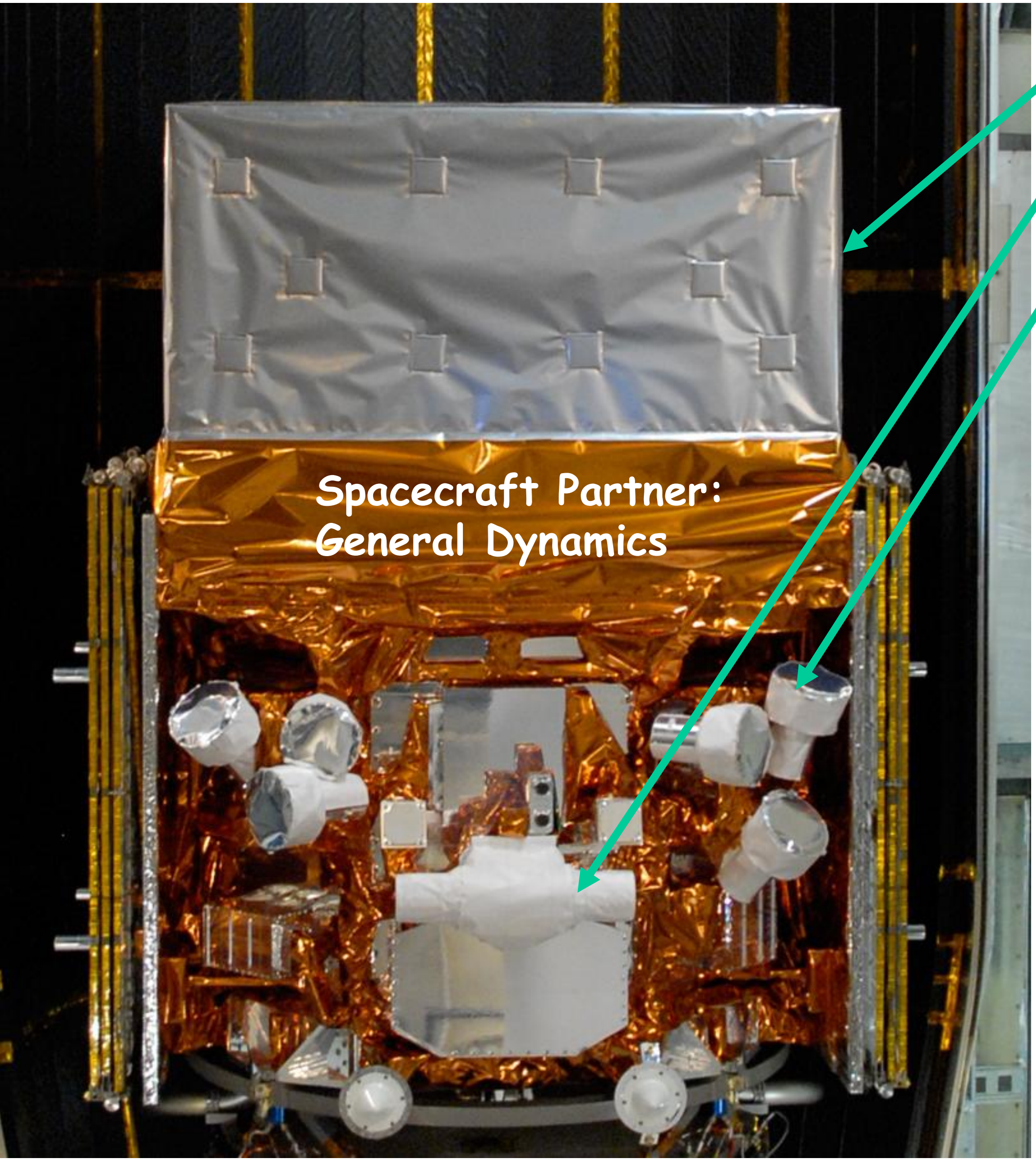
Possibilities
starburst galaxies
galaxy clusters
measure EBL
unIDs

Dark Matter
neutralino lines
sub-halo clumps

Cosmic rays and 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

The GLAST Observatory



Large AreaTelescope (LAT)
20 MeV - >300 GeV

Gamma-ray Burst Monitor (GBM)
NaI and BGO Detectors
8 keV - 40 MeV

KEY FEATURES

- Huge field of view
  - LAT: 19% 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.

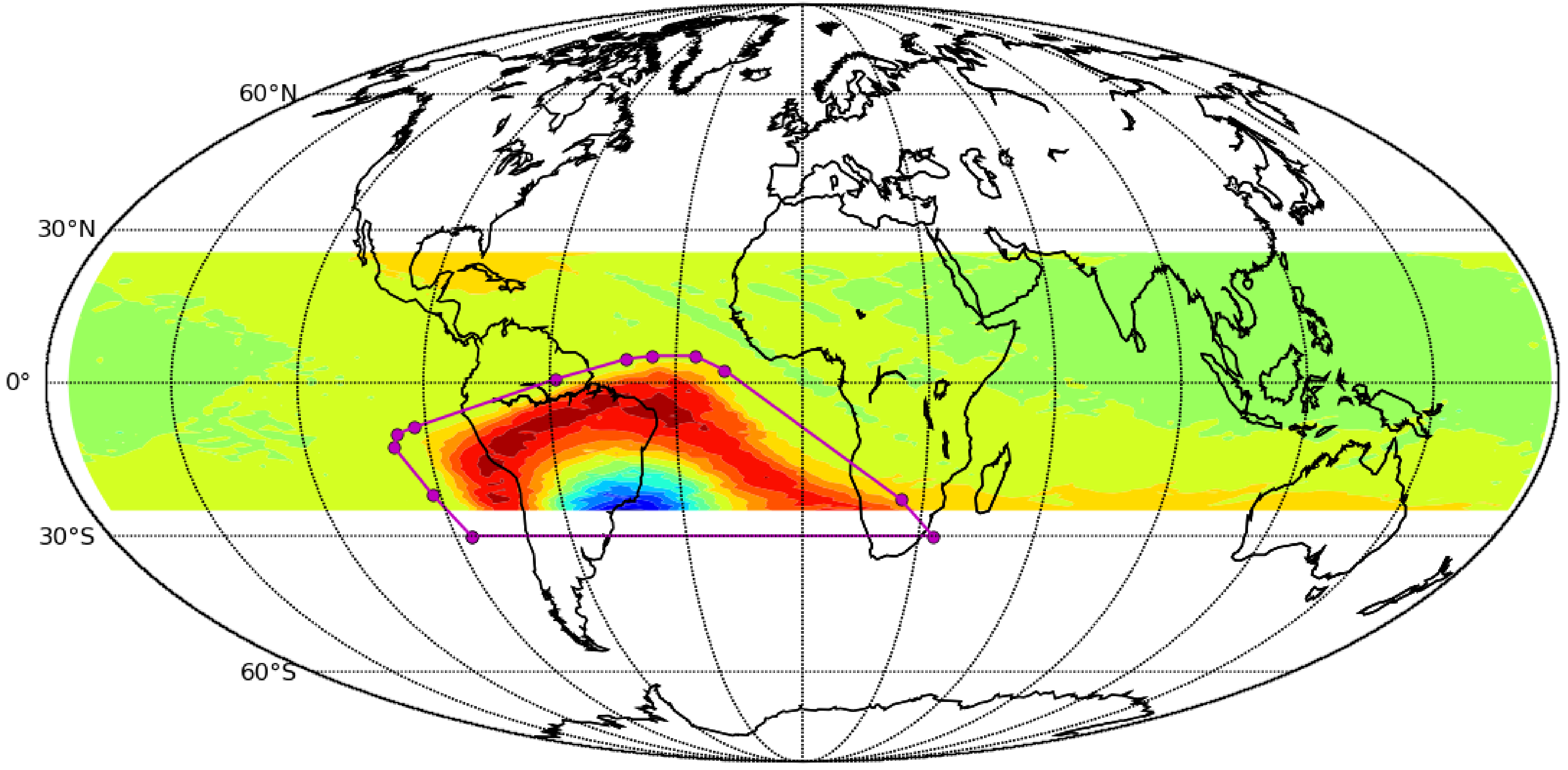
Launch!

Cape Canaveral

11 June 2008 at 12:05PM EDT

26 August 2008
NASA renames GLAST to Fermi

Fermi in orbit



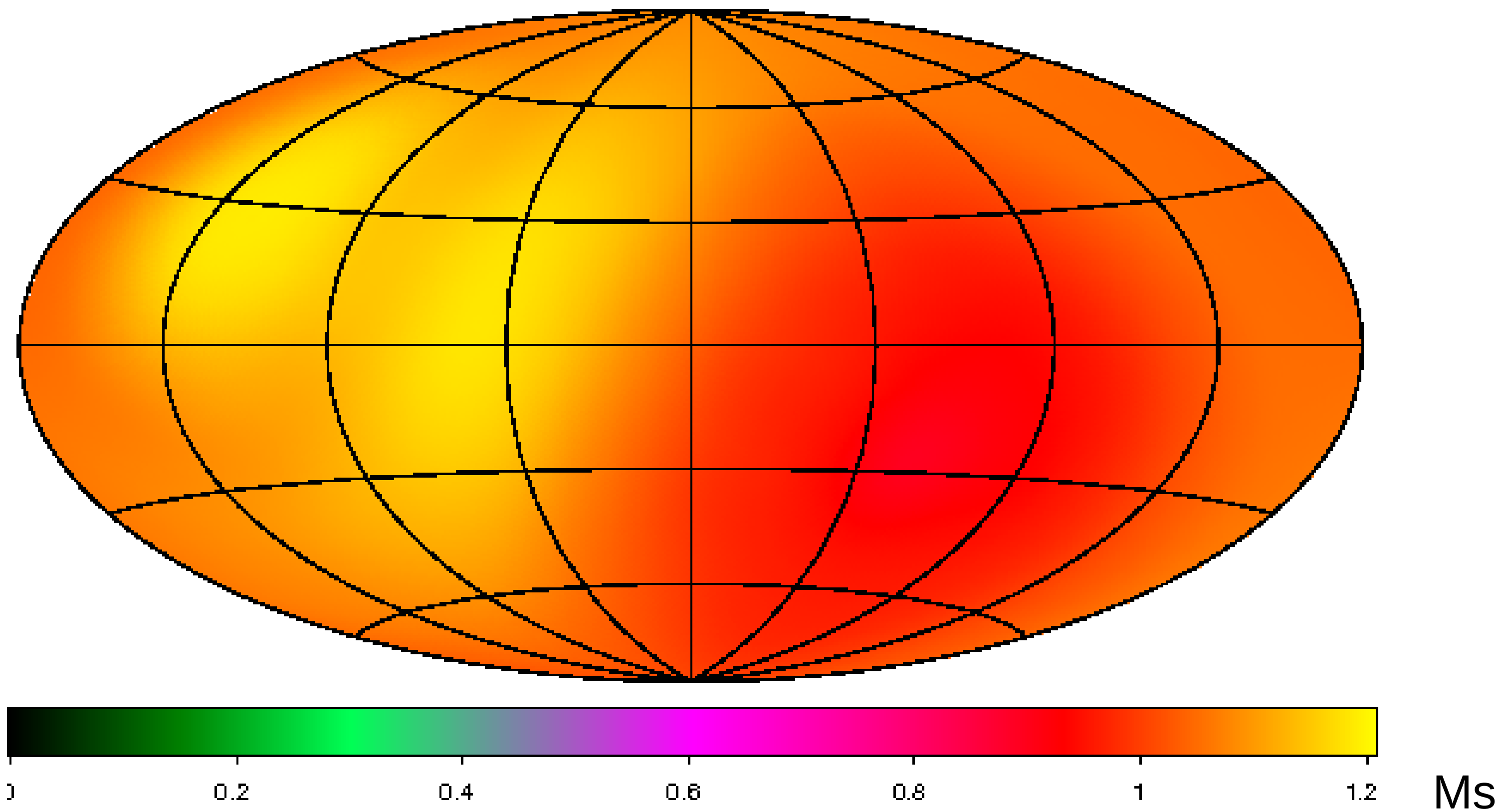
Circular orbit, 565 km altitude (96 min period), 25.6 degrees inclination

Does not operate inside South Atlantic Anomaly

Inclined at 35° from zenith, on alternate sides at each orbit

Exposure map

- Data used are the first three months of all-sky scanning data, Aug. - Oct. 2008. Total live time is 7.53 Ms
- Scanning scheme makes exposure map very uniform (South Atlantic Anomaly creates 25% North-South asymmetry)



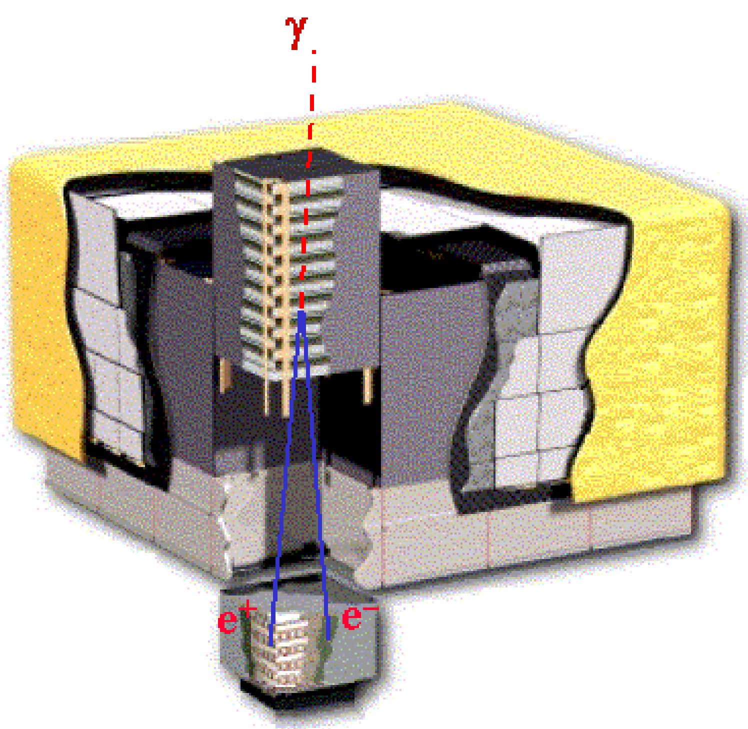
Equivalent on-axis observing time, Galactic coordinates, Aitoff projection

LAT Collaboration – an AP-HEP partnership

France

- **CNRS/IN2P3 (LLR, CENBG, LPTA)**
- **CEA/Saclay, CNRS/INSU (CESR)**

Pair conversion telescope
Tracker + calorimeter + anticoincidence



PI: Peter Michelson
(Stanford)

~390 Scientific Members (including 96 Affiliated Scientists, plus 68 Postdocs and 105 Students)

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

Managed at SLAC.

1 year private data
All data public since 25 August 2009
5 years operations (+ 5 years)

Data distributed by Fermi Science Support Center at Goddard
http://fermi.gsfc.nasa.gov/ssc/data/access/

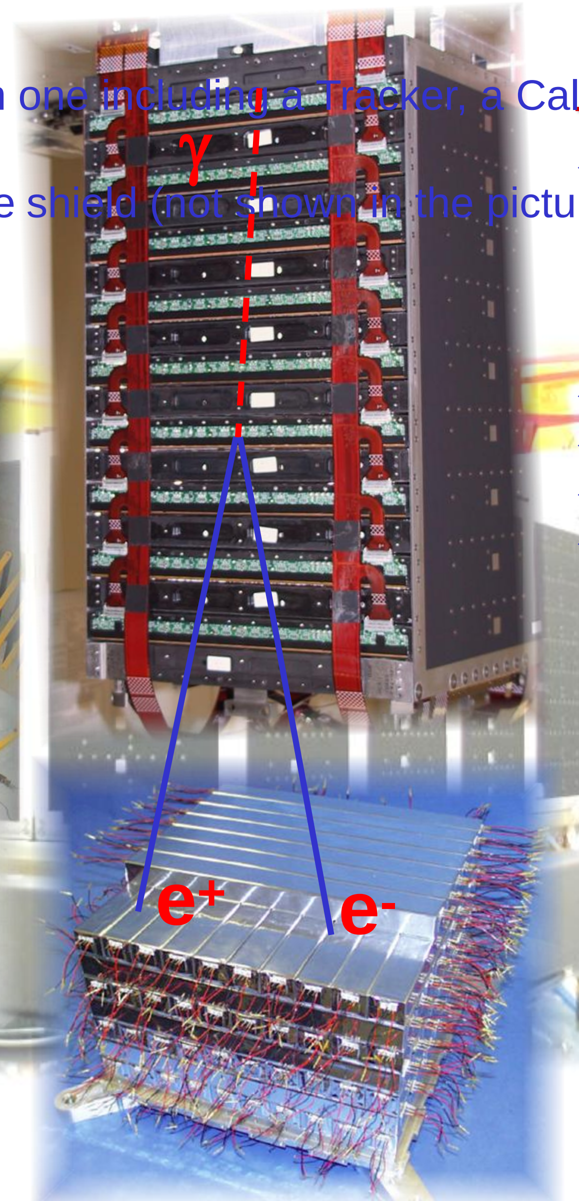
Overview of the Large Area Telescope

Overall modular design:

- ✓ 4x4 array of identical towers - each one including a Tracker, a Calorimeter and an Electronics Module
- ✓ Surrounded by an Anti-Coincidence shield (not shown in the picture)
- ✓ 3 ton – 650 W

Anti-Coincidence (ACD):

- ✓ Segmented (89 tiles).
- ✓ Self-veto @ high energy limited.
- ✓ 0.9997 detection efficiency (overall).



Tracker/Converter (TKR):

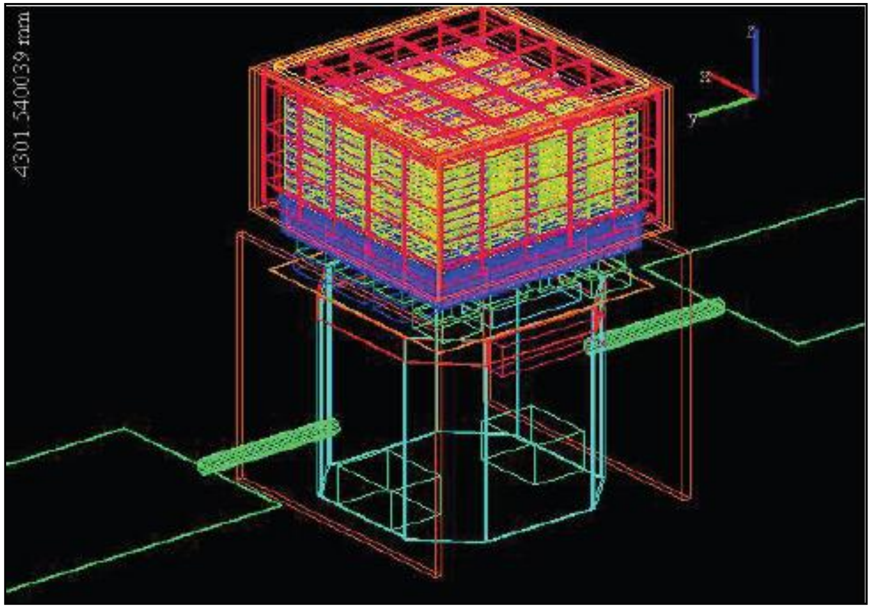
- ✓ Silicon strip detectors (single sided, each layer is rotated by 90 degrees with respect to the previous one).
- ✓ W conversion foils.
- ✓ ~80 m^2 of silicon (total).
- ✓ ~10^6 electronics chans.
- ✓ High precision tracking, small dead time.

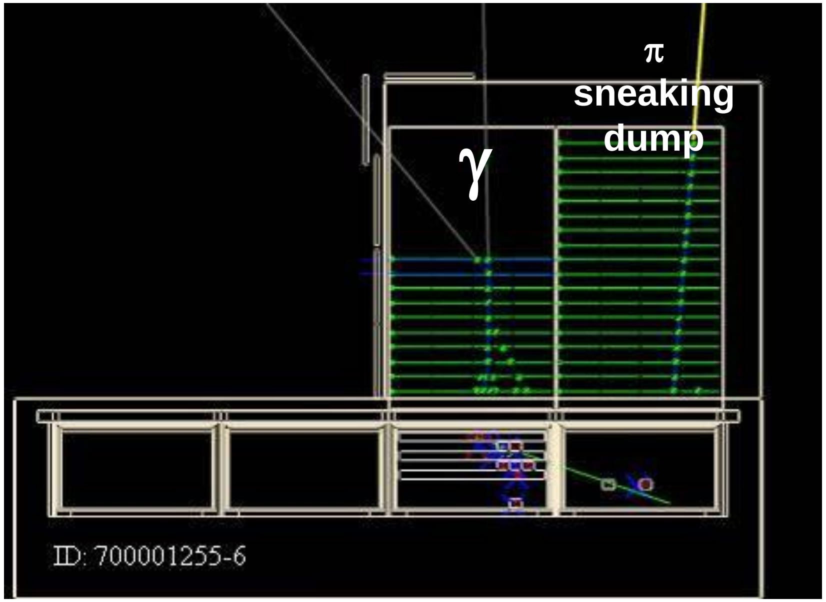
Calorimeter (CAL):

- ✓ 1536 CsI crystals.
- ✓ 8.5 radiation lengths.
- ✓ Hodoscopic.
- ✓ Shower profile reconstruction (leakage correction)

From simulation to reconstruction

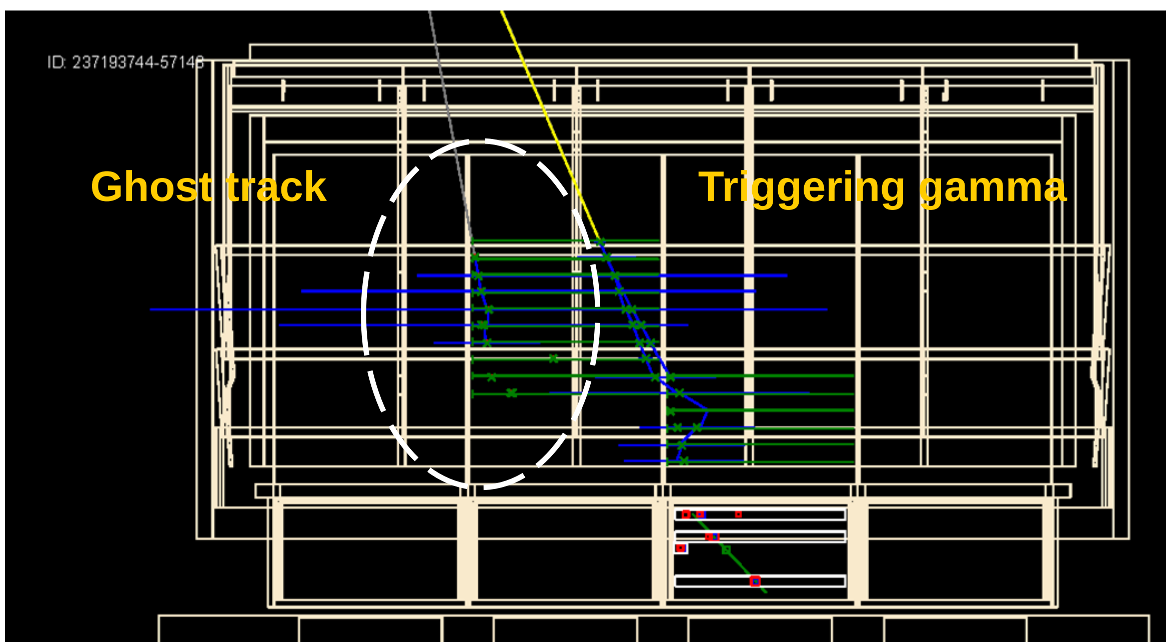
- ❑ **Accurate detector model**
  - – **>45k volumes**
- ❑ **Physical interactions modeled with Geant4**
- ❑ **MC validation**
  - – **ground test with CR muons on the full LAT**
  - – **beam test on a calibration unit**
    - – **100M evts of γ, e, p, e+, C, Xe between 50MeV and 300GeV collected at CERN and GSI in 2006**





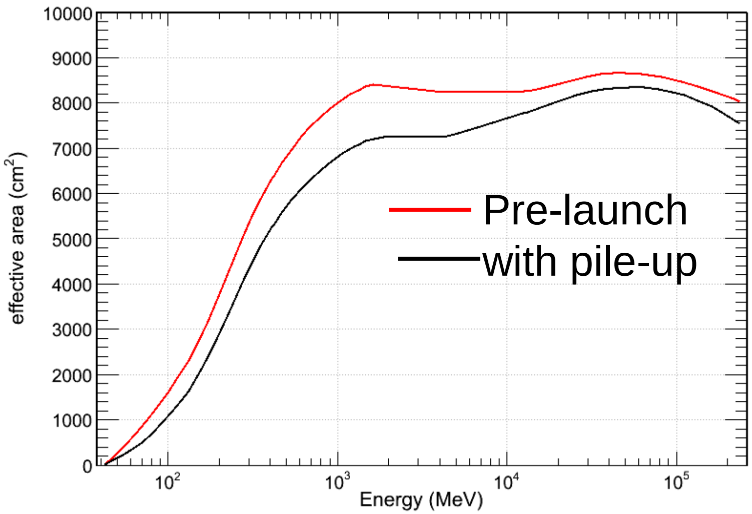
In flight response - pileup events

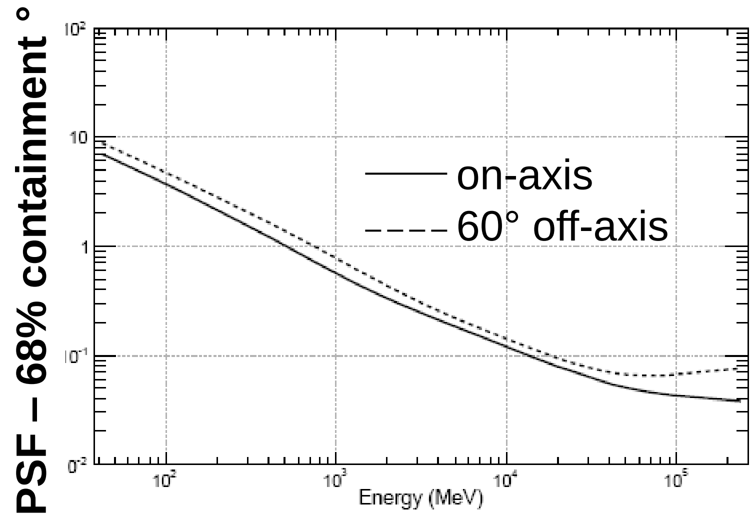
- CR rate is a steep function of earth magnetic field
- Fraction of off-time particles in the detector which leave ghost signal in coincidence with gammas
  - Between 2% and 15% depending on magnetic latitude
- Ghost effect
  - confuse/slow tracking and pattern recognition (→ CAL-seeded track recon)
  - Alter event topology and fake bkg rejection topological cuts

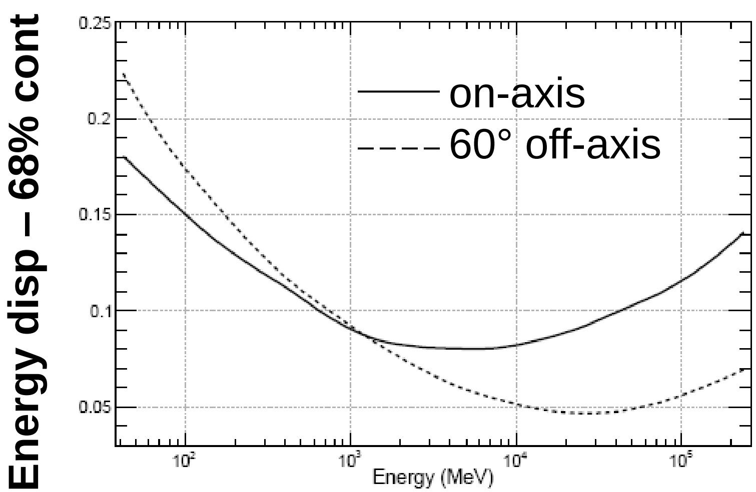


Instrument Response Functions

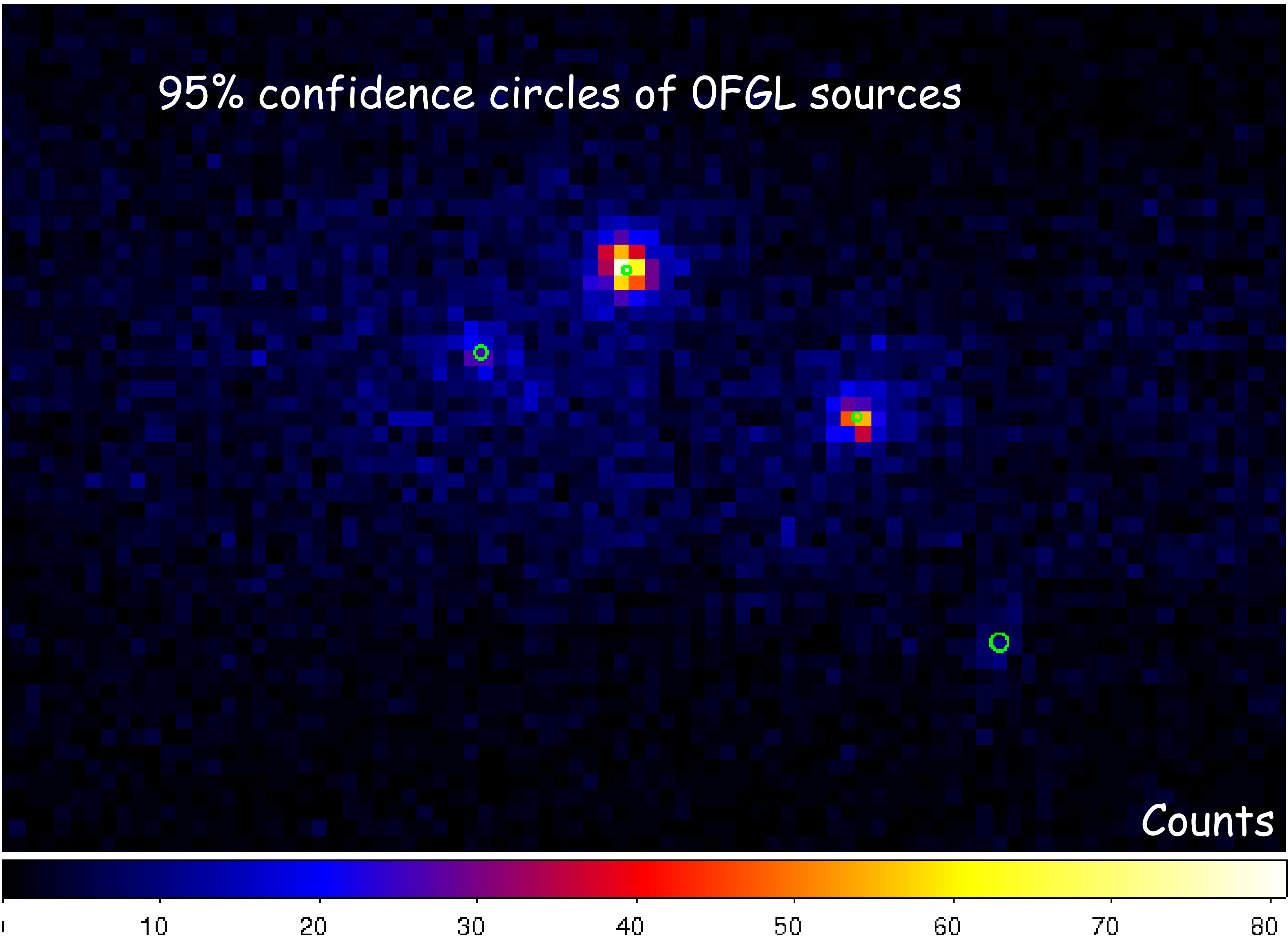
Google lat performance → http://www-glast.slac.stanford.edu/software/IS/glast_lat_performance.htm



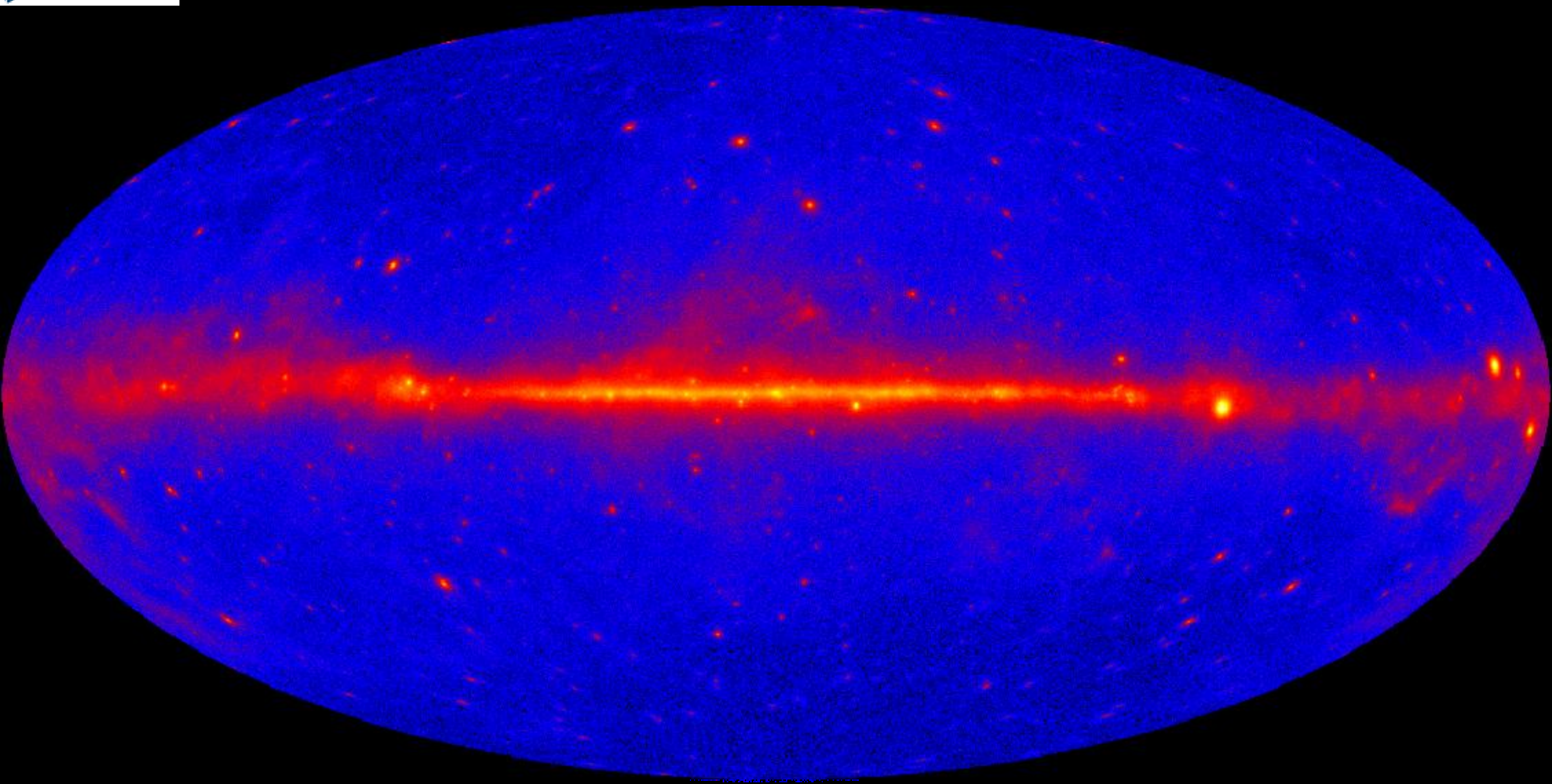




- Instrument response mapped into analytical functions or simple tables
- General simulation for all-purpose analysis vs specific analysis MC sim
- Serve large community of users
- Systematics from response representation choice and MC fidelity


95% confidence circles of 0FGL sources
Counts
10
20
30
40
50
60
70
80

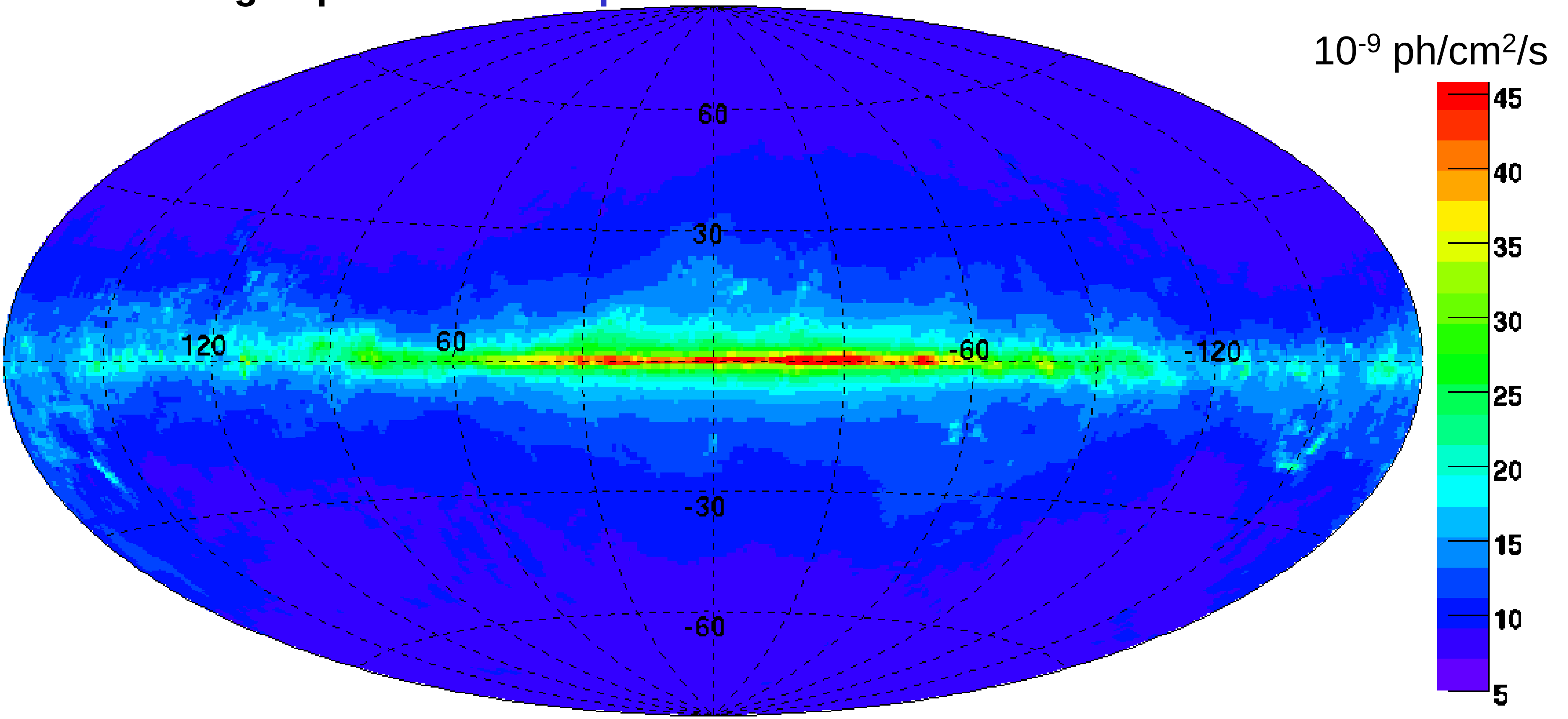
1451 LAT sources (11 months)



- Front > 200 MeV, Back > 400 MeV, log color scale
- Galactic coordinates, Aitoff projection

Sensitivity map

- **Structure is mostly that of the interstellar medium**
- **Below 10^{-8} ph/cm^2/s outside the Galaxy (|b| > 30°)**
- **Strong dependence on spectral index**

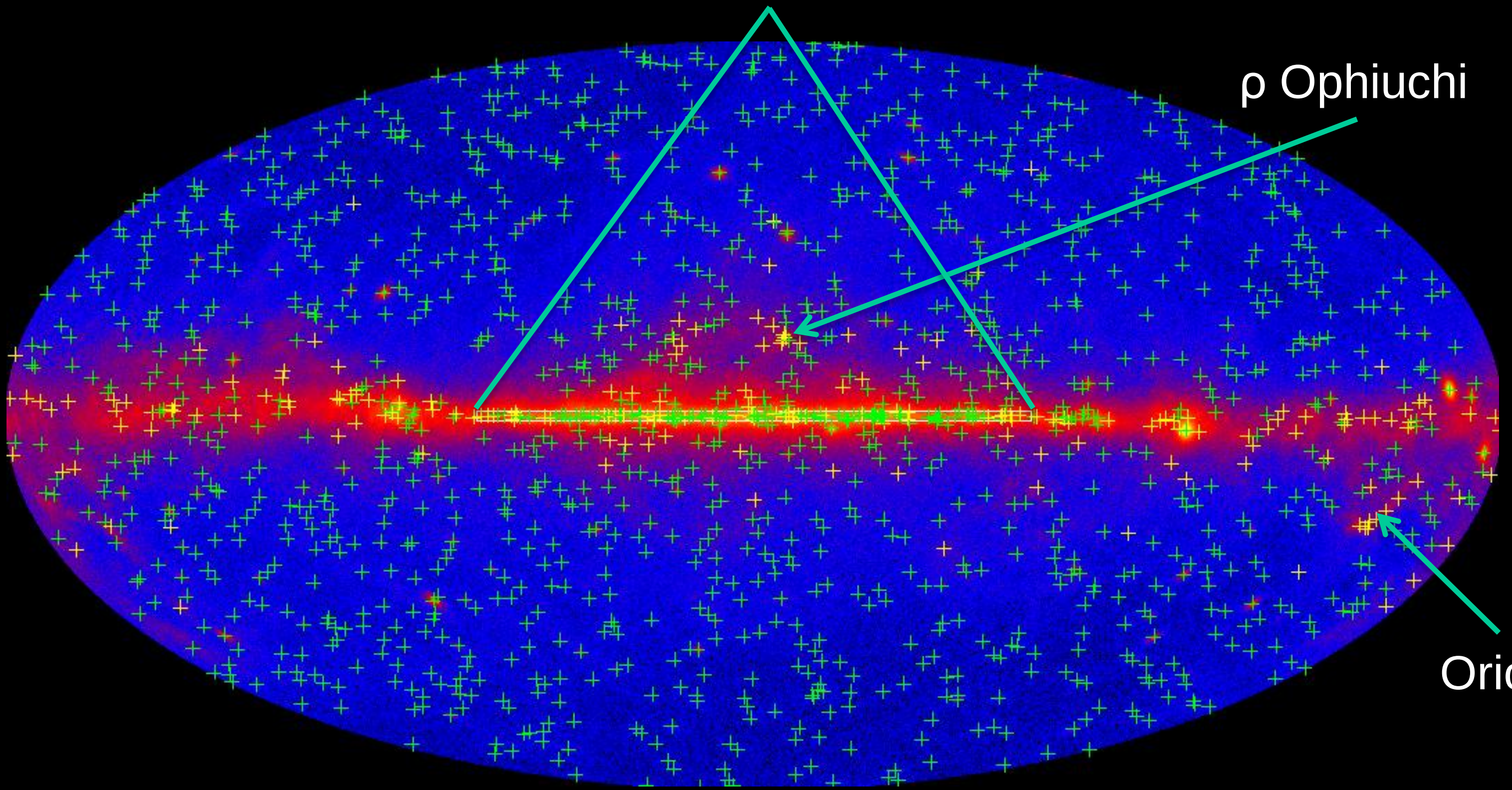


Flux > 100 MeV required to reach TS=25 for average $E^{-2.2}$ spectrum

Galactic coordinates, Aitoff projection

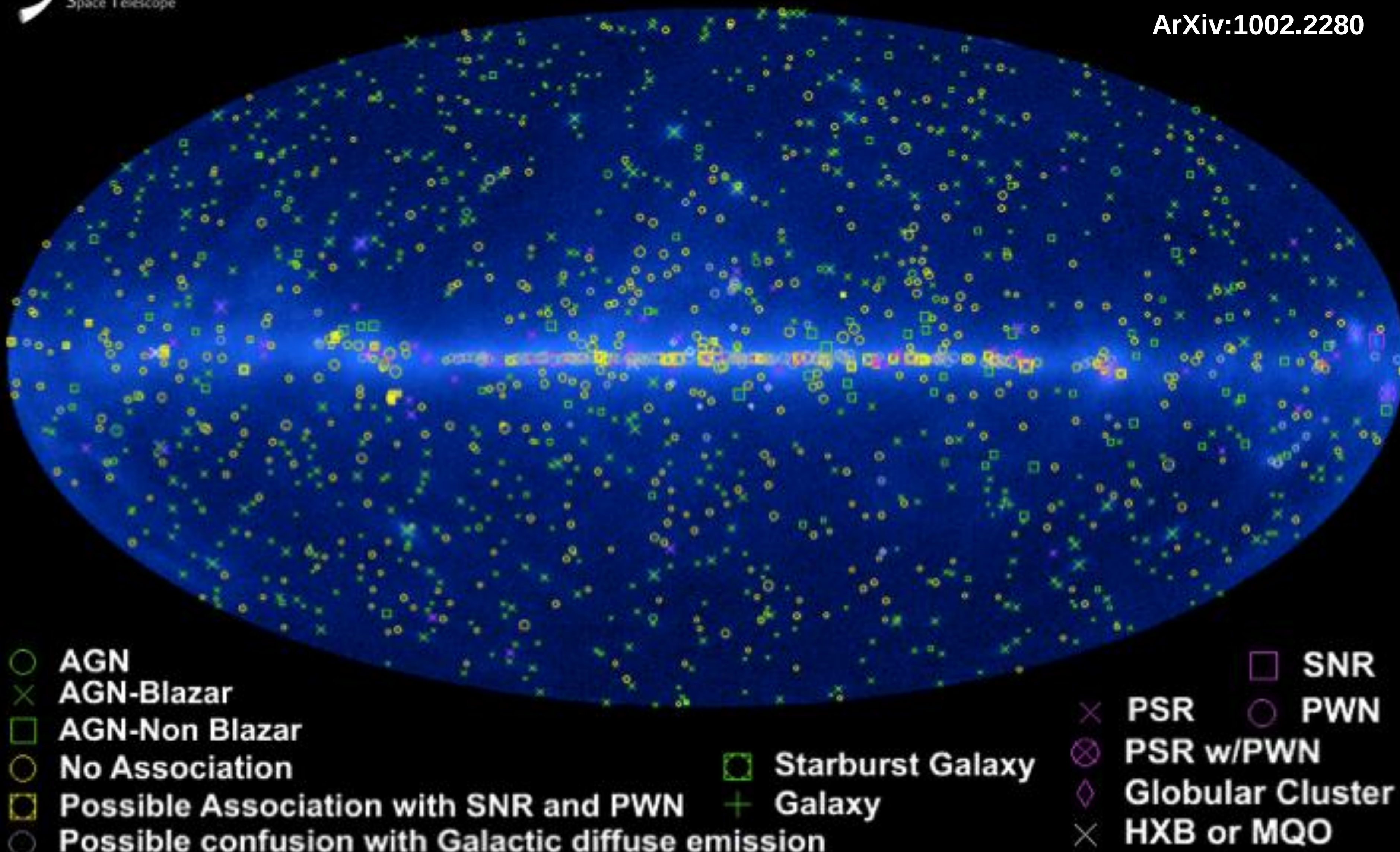
Galactic ridge and dense clouds

- The Galactic ridge (|lat| < 1°, |lon| < 60°) has serious difficulties: sources are close to each other, are not high above the background below 3 GeV, and the Galactic diffuse model is very uncertain there. This even affects sources statistically very significant (TS > 100).
- We set Galactic ridge sources apart entirely (some 120 sources), and warn against using them without detailed analysis. Of course there are still many true sources in there, including pulsars and SNRs.



The Fermi LAT 1FGL Source Catalog

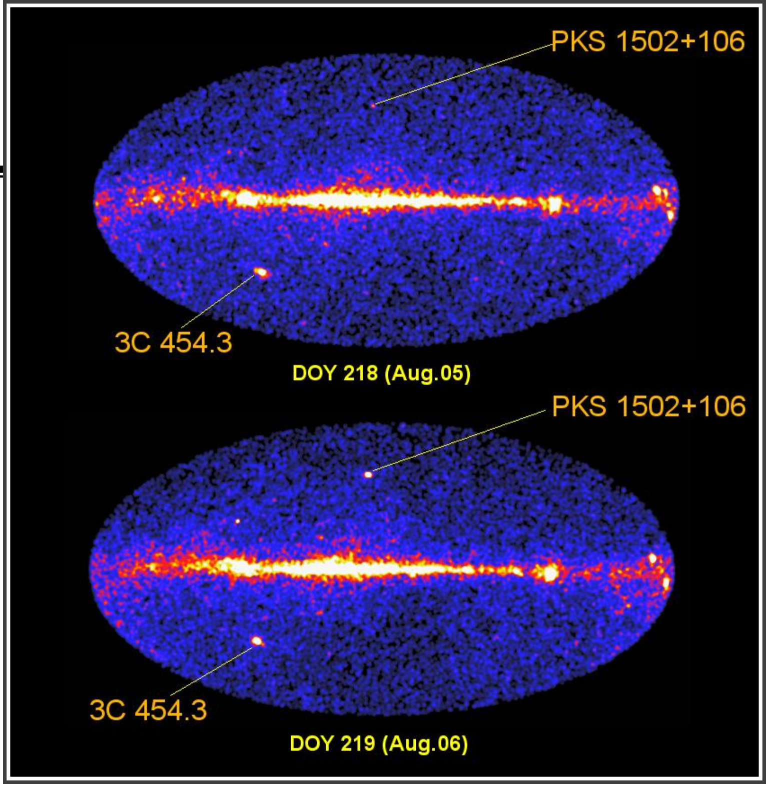
ArXiv:1002.2280

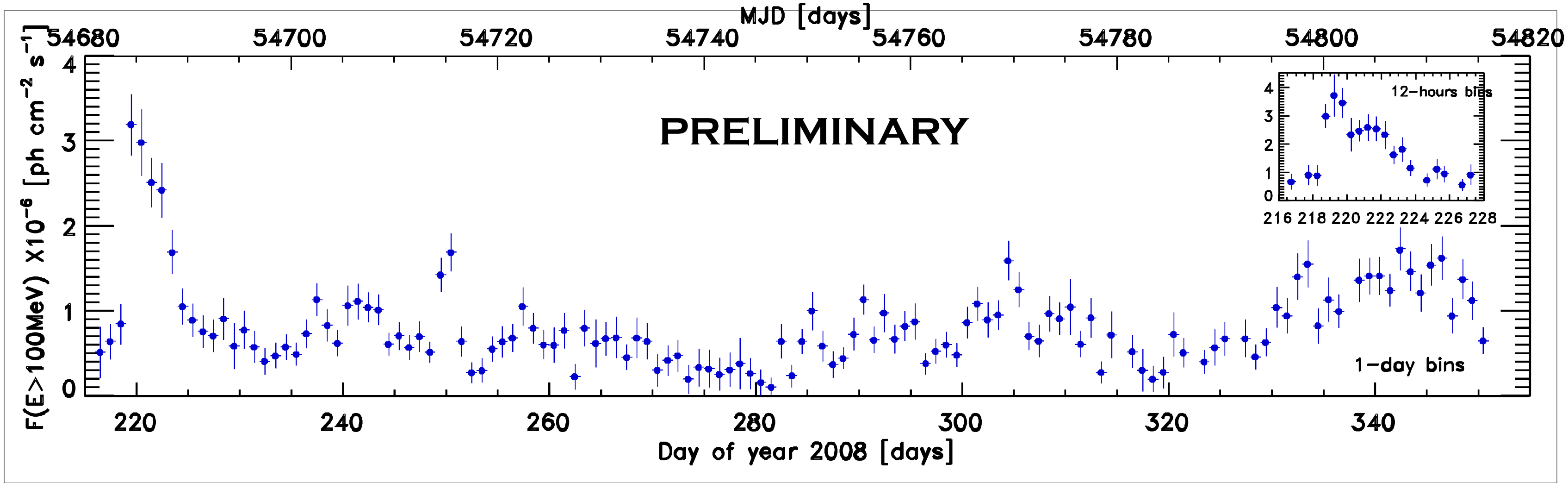


Credit: *Fermi* Large Area Telescope Collaboration

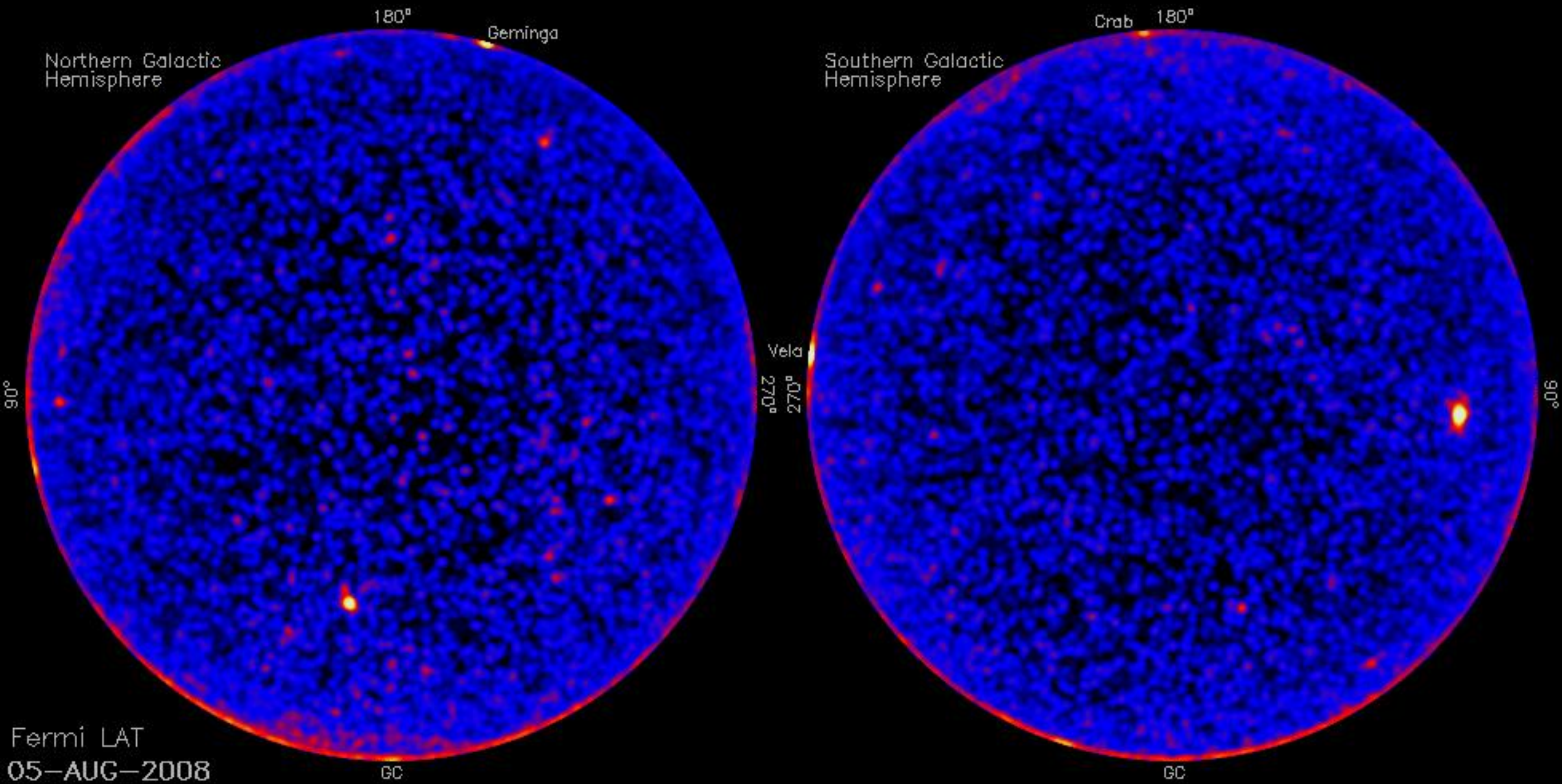
Rapid variability

- PKS 1502+106 (aka OR 103), at z=1.84 (SDSS)
- Extremely rapid flare, possibly the highest ΔL/Δt detected to date in the GeV band (inset in the light curve)
- Flares reported via Atels
- Light curves posted at FSSC





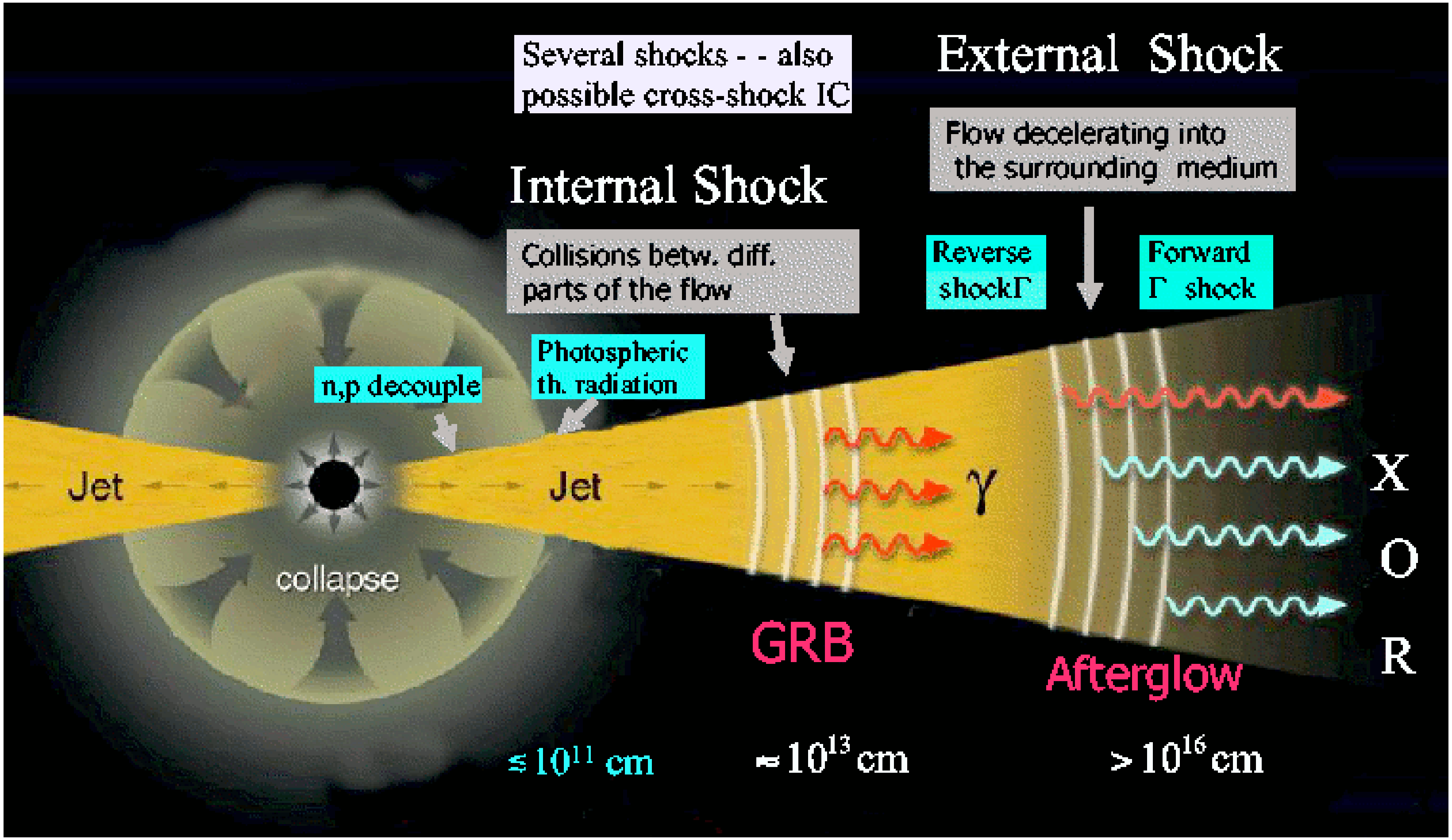
The variable Fermi sky



- **1-day snapshots, > 100 MeV, viewed from the poles (orthographic proj). Red is significant.**
- **The Sun is moving down right of North pole and up right of South pole**

γ-ray bursts: fireball

- Jet accelerated to Γ > 100 while opaque
- **Internal shocks** within ejecta at R~$10^{14\text{-}15}$ cm (prompt emission)
- **External shock** in interstellar medium at R~$10^{16\text{-}17}$ cm (afterglow)



Limits on Lorentz Invariance Violation

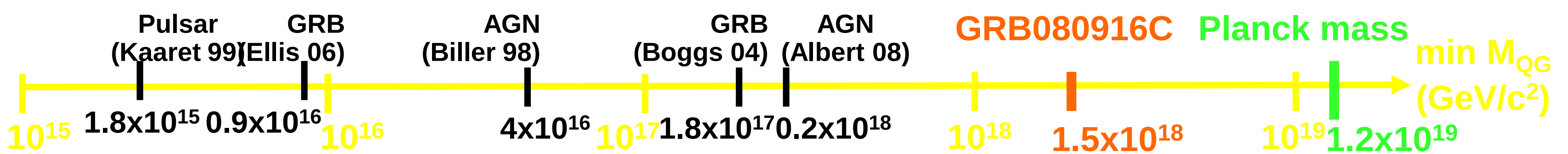
Some quantum gravity models allow violation of Lorentz invariance: $(v_{ph}) \neq c$

$$c^2 p_{ph}^2 = E_{ph}^2 \left[1 + \frac{E_{ph}}{M_{QG,1} c^2} + \left(\frac{E_{ph}}{M_{QG,2} c^2} \right)^2 + \ldots \right] \ , \ v_{ph} = \frac{\partial E_{ph}}{\partial p_{ph}} \approx c \left[1 - \frac{1+n}{2} \left(\frac{E_{ph}}{M_{QG,n} c^2} \right)^n \right]$$

A high-energy photon E_h would arrive after (or possibly before in some models) a low-energy photon E_l emitted together

GRB 080916C : the tightest upper limit so far (Abdo et al. 09),

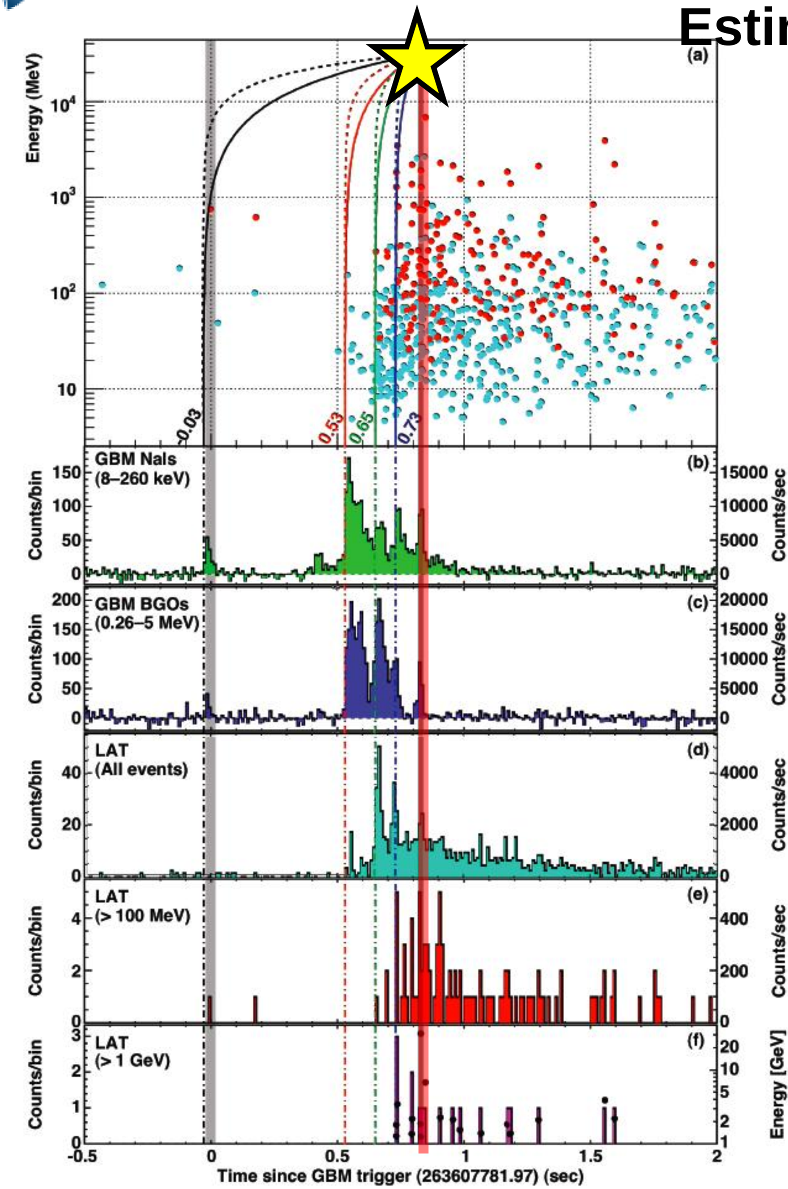
$$M_{QG,1} > (1.50 \pm 0.20) \times 10^{18}\ \mathrm{GeV}/c^2$$



$$\Delta t = \frac{(1+n)}{2H_0} \frac{E_h^n - E_l^n}{(M_{QG,n} c^2)^n} \int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}} dz'$$

n = 1,2 for linear and quadratic Lorentz invariance violation, respectively

GRB090510 : first time M_{QG}>M_{planck}



Estimate lower limit of $M_{QG,1}$ for various ⊿t, ⊿E

◆ **Most conservative case :**

31GeV photon starts from any <1MeV emission ⊿t < 859 ms,

$M_{QG,1}/M_{plank}$ > 1.19

◆ **Least conservative case:**

31 GeV photon associates with < 1 MeV spike ⊿t < 10ms,

$M_{QG,1}/M_{plank}$ > 102

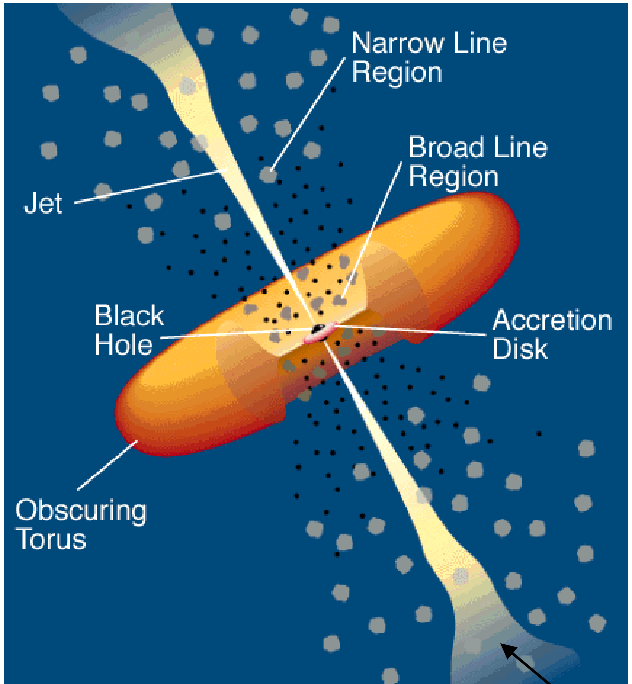
Our new limit : $M_{QG,1}/M_{plank}$> several is much stronger than the previous result ($M_{QG,1}/M_{plank}$ > 0.1 : GRB080916C ;Abdo+09)

Greatly constrain the quantum gravity model (n=1)

z = 0.9, short GRB

Abdo et al. 2009, Nature 462, 331

Blazars



Almost all galaxies contain a massive black hole
-99% of them are (almost) silent (e.g. our Galaxy)

-1% per cent is active (mostly radio-quiet AGNs): BH+disk: most of the emission in the UV-X-ray band

0.1% is radio loud: jets mostly visible in the radio

M_{BH} of $10^7 – 10^9$ M_o

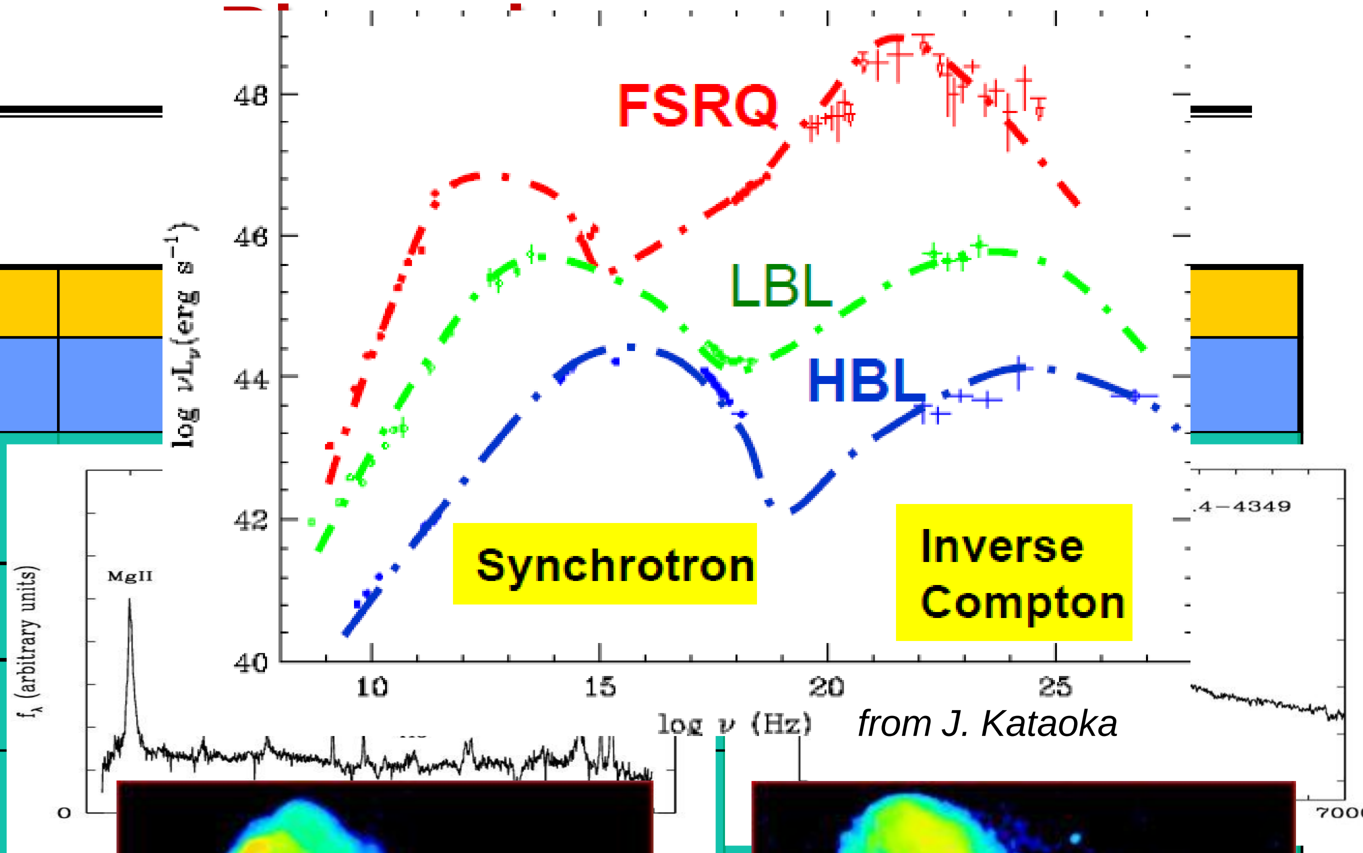
Blazar characteristics

- Compact radio core, flat or inverted spectrum
- Extreme variability (amplitude and t) at all frequencies
- High optical and radio polarization

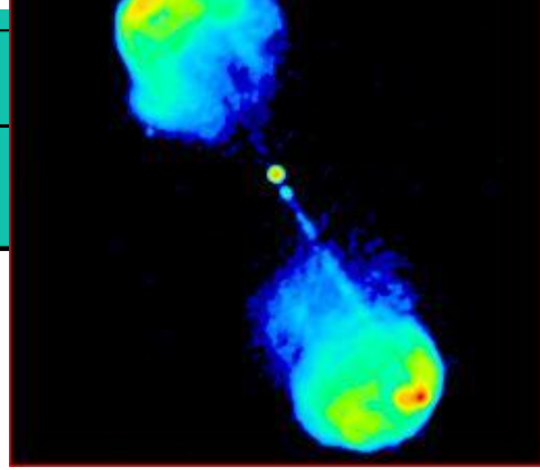
FSRQs: bright broad (1000-10000 km/s) emission lines often evidences for the “blue bump” (acc. disc)

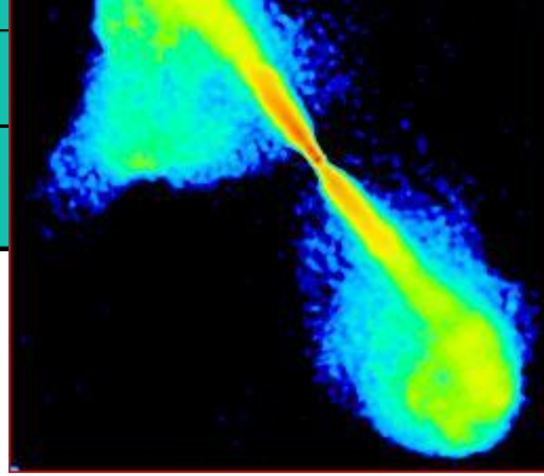
BL Lac: weak (EW<5 Å) emission lines no signatures of accretion

class
defining property
environment
Power
Parent population
Synchrotron hump in SED
EGRET-detected
Redshift of EGRET sources



from J. Kataoka

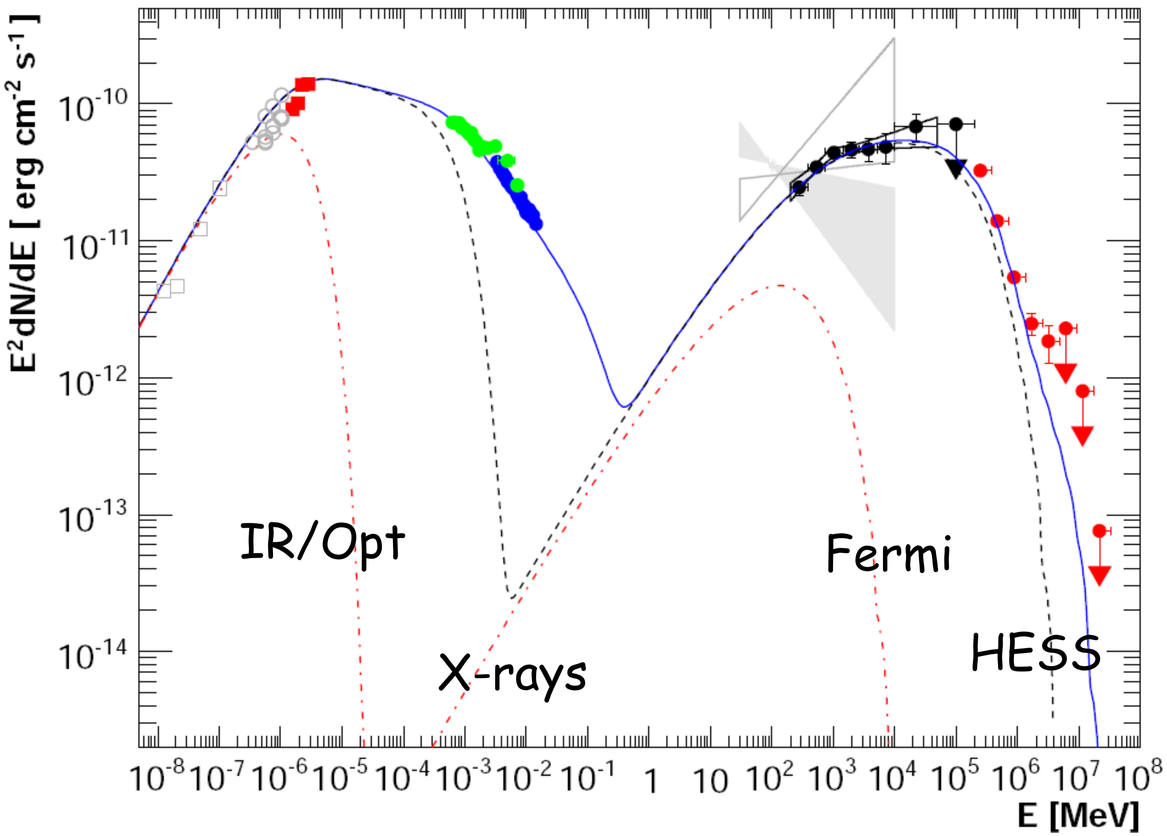




Spectral coverage

LAT energy range is very broad (20 MeV - 300 GeV), includes the largely unexplored range between 10 and 100 GeV

Allows ground-based TeV data to be combined with the space-based GeV data. Multi-wavelength campaigns are regularly organized.



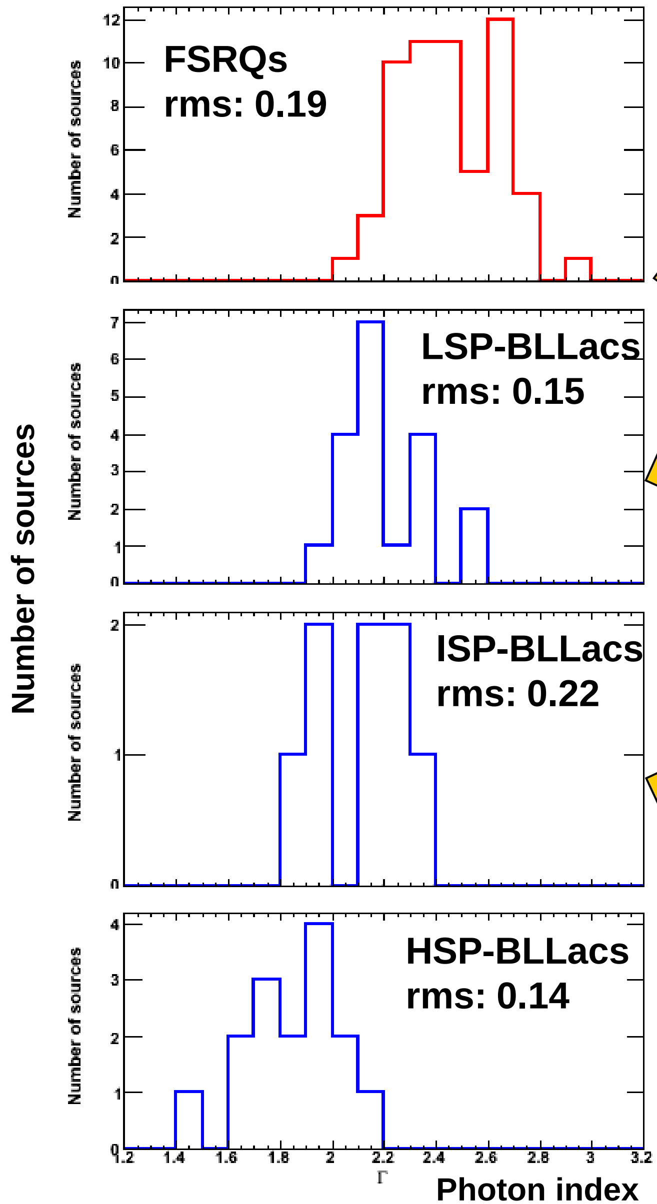
SED for PKS 2155-304

HSP-BLLac, z=0.116 nonflaring, low / quiescent state

Spectral break in the LAT range

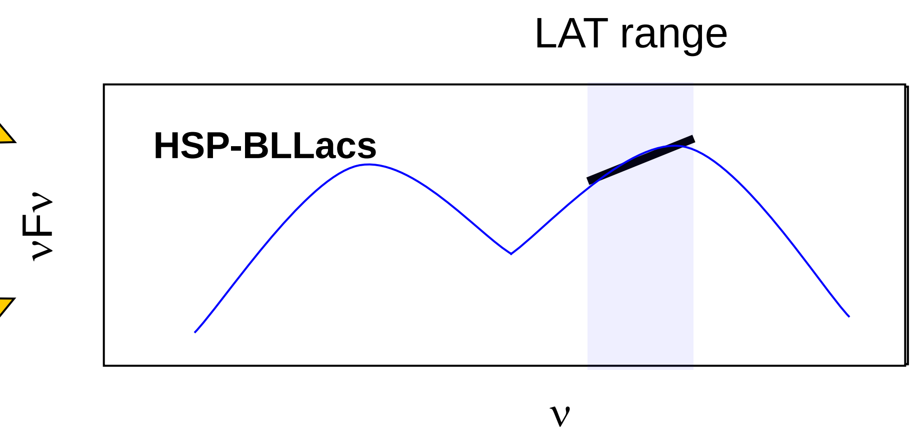
Abdo et al. 2009 ApJ 696, L150

Photon index distributions in LBAS



Abdo et al. 2010
ApJ 710, 1271

Photon index determined with the first 6-month data set



- Strong correlation between photon index and blazar class
- Narrow distributions point to a small numbers of parameters driving the blazar SEDs

The GeV-TeV connection

21/28 TeV AGNs detected by Fermi-LAT (5.5 months of data), now 25/30

- **mostly BLLacs, mostly HSPs**
- **2 RGs: Centaurus A, M87**

Abdo et al. 2009
ApJ 707, 1310

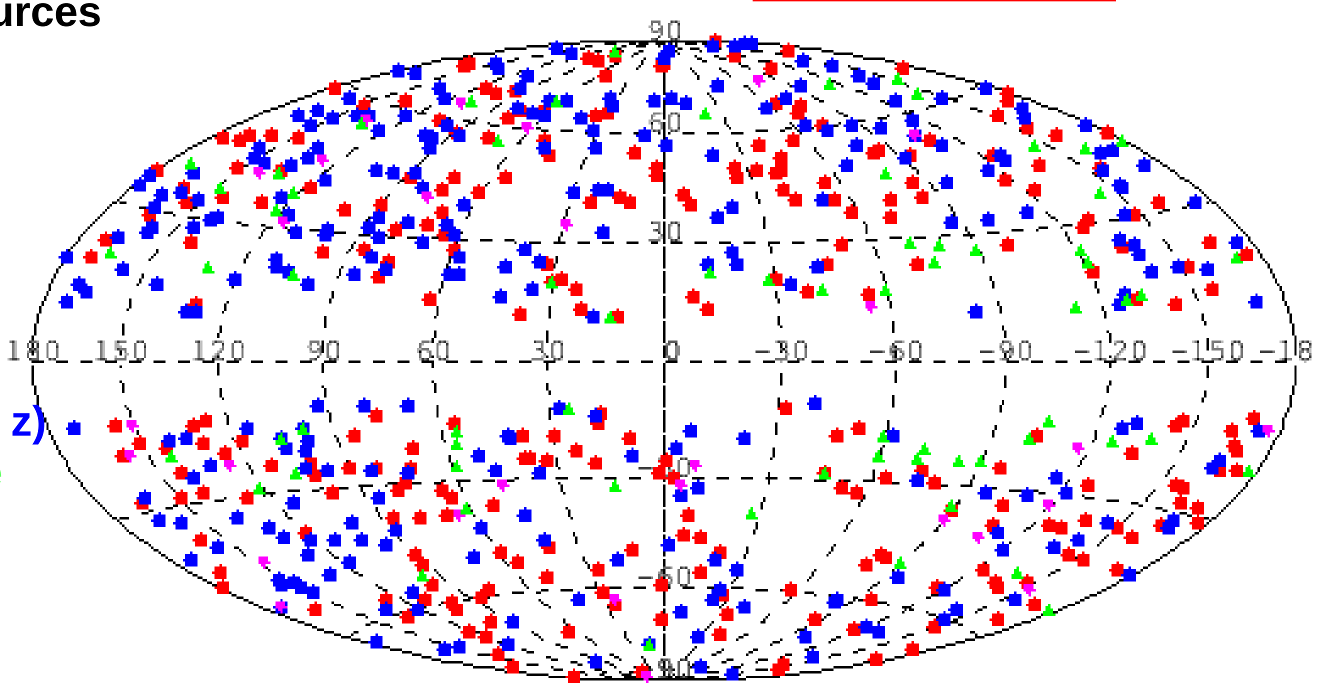
Name	TS	Parameters of fitted power-law spectrum: Flux (>200 MeV) $F \pm \Delta F_{\rm stat} \pm \Delta F_{\rm sys}$ [10^{-9}cm^{-2}s^{-1}]	Photon Index $\Gamma \pm \Delta\Gamma_{\rm stat} \pm \Delta\Gamma_{\rm sys}$ [1]	Decorr. energy [GeV]	Highest energy photons: $1^{\rm st}$ [GeV]	$5^{\rm th}$ [GeV]	Probability of constant flux: 10 day [1]	28 day [1]
	[1]							
3C 66A	2221	$96.7 \pm 5.82 \pm 3.39$	$1.93 \pm 0.04 \pm 0.04$	1.54	111[a]	54	< 0.01	< 0.01
RGB J0710+591	42	$0.087 \pm 0.049 \pm 0.076$	$1.21 \pm 0.25 \pm 0.02$	15.29	74	4	0.98	0.94
S5 0716+714	1668	$79.9 \pm 4.17 \pm 2.84$	$2.16 \pm 0.04 \pm 0.05$	0.82	63	9	< 0.01	< 0.01
1ES 0806+524	102	$2.07 \pm 0.38 \pm 0.71$	$2.04 \pm 0.14 \pm 0.03$	1.54	30	4	0.05	< 0.01
1ES 1011+496	889	$32.0 \pm 0.27 \pm 0.29$	$1.82 \pm 0.05 \pm 0.03$	1.50	168	32	0.54	0.50
Markarian 421	3980	$94.3 \pm 3.88 \pm 2.60$	$1.78 \pm 0.03 \pm 0.04$	1.35	801	155	0.06	0.02
Markarian 180	50	$5.41 \pm 1.69 \pm 0.91$	$1.91 \pm 0.18 \pm 0.09$	1.95	14	2	0.98	0.54
1ES 1218+304	147	$7.56 \pm 2.16 \pm 0.67$	$1.63 \pm 0.12 \pm 0.04$	5.17	356	31	0.53	0.06
W Comae	754	$41.7 \pm 3.40 \pm 2.46$	$2.02 \pm 0.06 \pm 0.05$	1.13	26	18	0.01	< 0.01
3C 279	6865	$287 \pm 7.13 \pm 10.2$	$2.34 \pm 0.03 \pm 0.04$	0.59	28	21	< 0.01	< 0.01
PKS 1424+240	800	$34.35 \pm 2.60 \pm 1.37$	$1.85 \pm 0.05 \pm 0.04$	1.50	137	30	< 0.01	0.16
H 1426+428	38	$1.56 \pm 1.05 \pm 0.29$	$1.47 \pm 0.30 \pm 0.11$	8.33	19	3	0.83	0.39
PG 1553+113	2009	$54.8 \pm 3.63 \pm 0.85$	$1.69 \pm 0.04 \pm 0.04$	2.32	157	76	0.40	0.54
Markarian 501	649	$22.4 \pm 2.52 \pm 0.13$	$1.73 \pm 0.06 \pm 0.04$	2.22	127	50	0.57	0.18
1ES 1959+650	306	$25.1 \pm 3.49 \pm 2.83$	$1.99 \pm 0.09 \pm 0.07$	1.60	75	21	0.91	0.29
PKS 2005-489	246	$22.3 \pm 3.09 \pm 2.14$	$1.91 \pm 0.09 \pm 0.08$	1.01	71	8	0.86	0.97
PKS 2155-304	3354	$109 \pm 4.45 \pm 3.18$	$1.87 \pm 0.03 \pm 0.04$	1.13	299	46	< 0.01	< 0.01
BL Lacertae	310	$51.6 \pm 5.81 \pm 12.2$	$2.43 \pm 0.10 \pm 0.08$	0.85	70	4	0.61	0.23
1ES 2344+514	37	$3.67 \pm 2.35 \pm 1.62$	$1.76 \pm 0.27 \pm 0.23$	5.28	53	3	0.76	0.46
M 87	31	$7.56 \pm 2.70 \pm 2.24$	$2.30 \pm 0.26 \pm 0.14$	1.11	8	1	0.43	0.57
Centaurus A	308	$70.8 \pm 5.97 \pm 5.80$	$2.90 \pm 0.11 \pm 0.07$	0.47	6	4	0.38	0.97

Most of the bright TeV blazars have been in low states since Fermi was launched.
Low variability in the GeV range.
Search for new TeV emitters

The First LAT AGN catalog (1LAC)

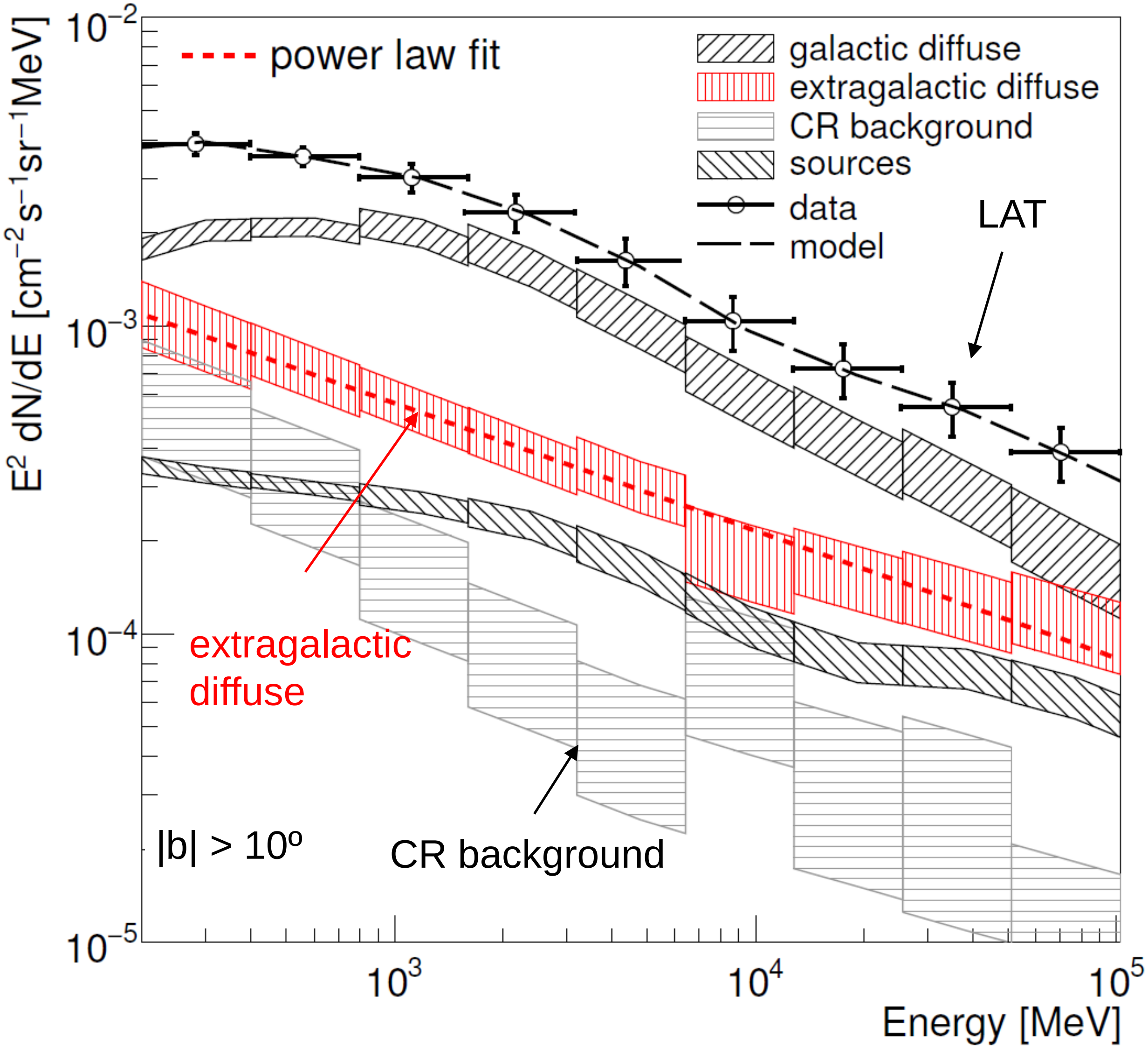
- **11 month data set**
- **1079 TS>25, |b|>10° sources**
- **668 AGNs (P_{assoc}>80%)**
+186 candidates
- **Census:**
  - **286 FSRQs**
  - **284 BLLacs**
    (141 with measured z)
  - **69 of unknown type**
  - **~10 Radio galaxies**

Preliminary



ArXiv:1002.0150

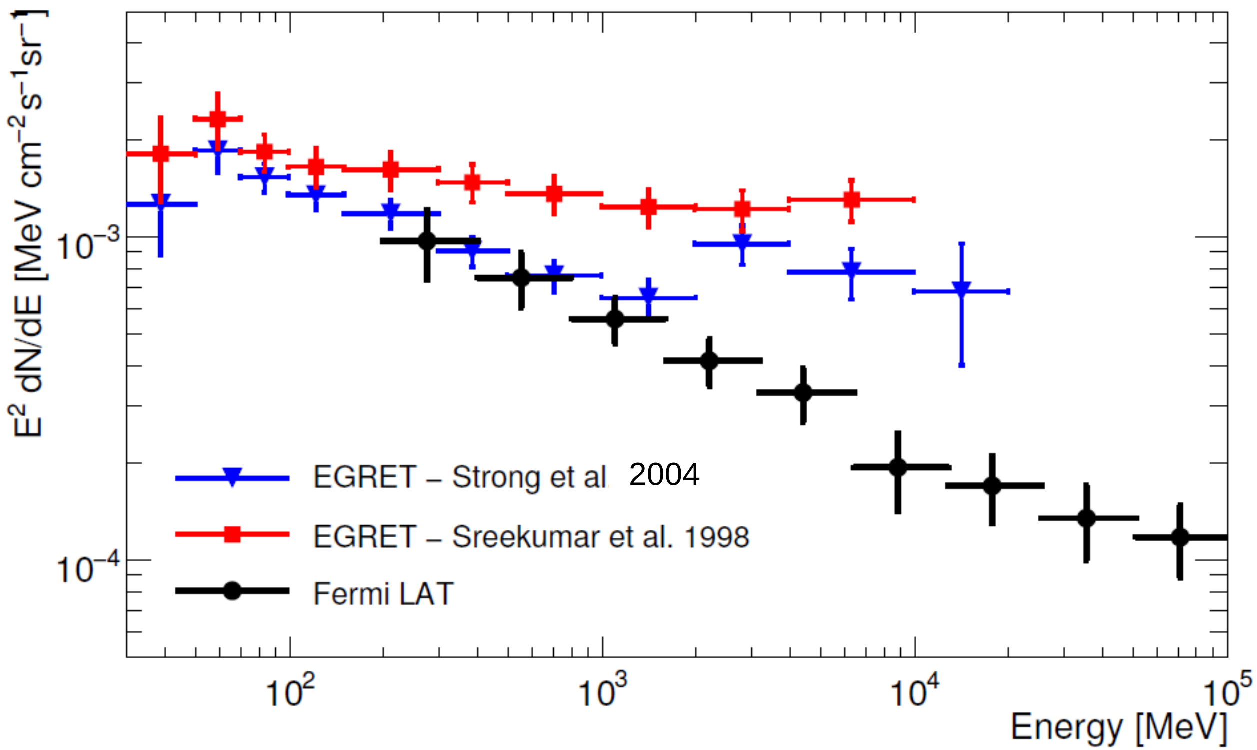
The LAT isotropic diffuse flux



error bars / bands: statistical error + LAT effective area uncertainty + residual background contamination uncertainty

- **Spectrum can be fitted by power law:** $\gamma = 2.41 +/- 0.05$
- **Flux above 100 MeV:** $F_{100} = 1.03 +/- 0.17 \times 10^{-5}\ cm^{-2}\ s^{-1}\ sr^{-1}$
- **Foreground modeling uncertainty not included in error bands**

Comparison with EGRET results



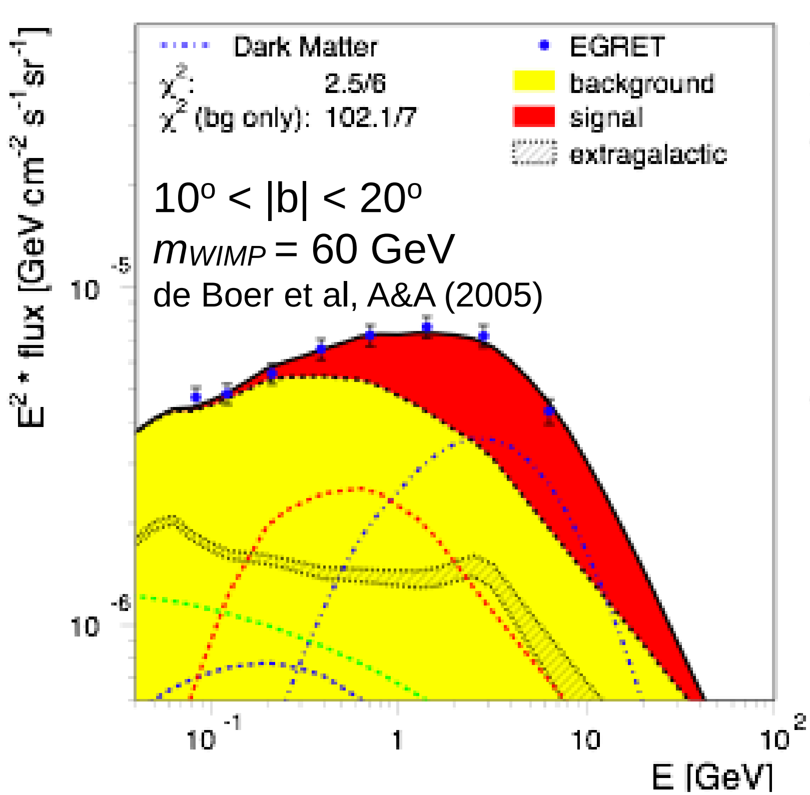
- **Considerably steeper than the EGRET spectrum by Sreekumar et al.**
- **No spectral features around a few GeV seen in re-analysis by Strong et al.**

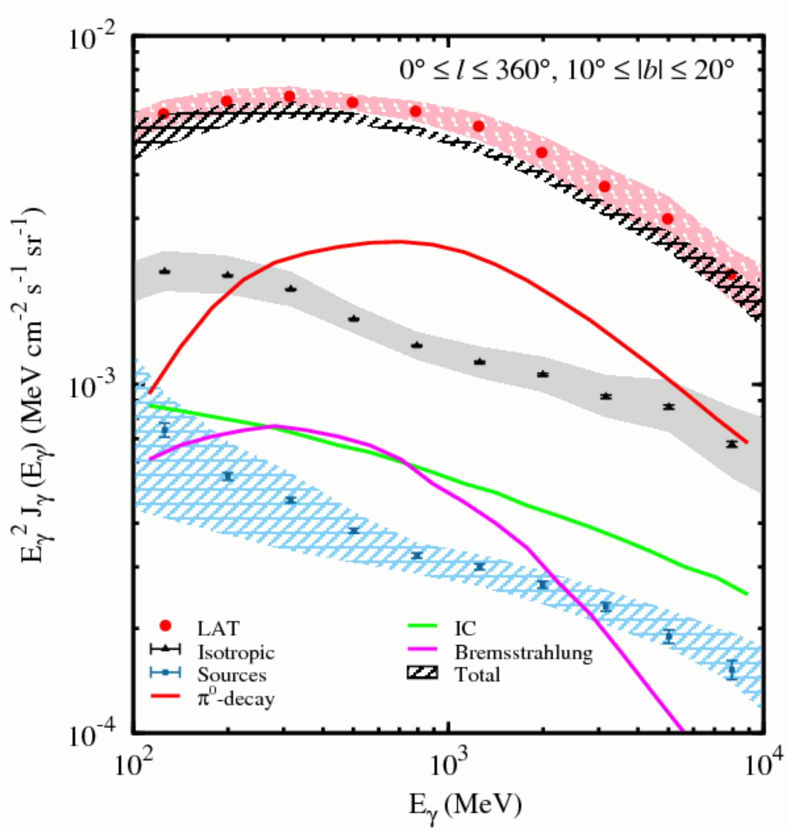
	Flux, E>100 MeV	spectral index
LAT (this analysis)	**1.03 +/- 0.17**	**2.41 +/- 0.05**
EGRET (Sreekumar et al., 1998)	1.45 +/- 0.05	2.13 +/- 0.03
EGRET (Strong et al. 2004)	1.11 +/- 0.10	
LAT + resolved sources below EGRET sensitivity	1.19 +/- 0.18	2.37 +/- 0.05
	x 10^{-5} cm^{-2} s^{-1} sr^{-1}	

EGRET GeV excess

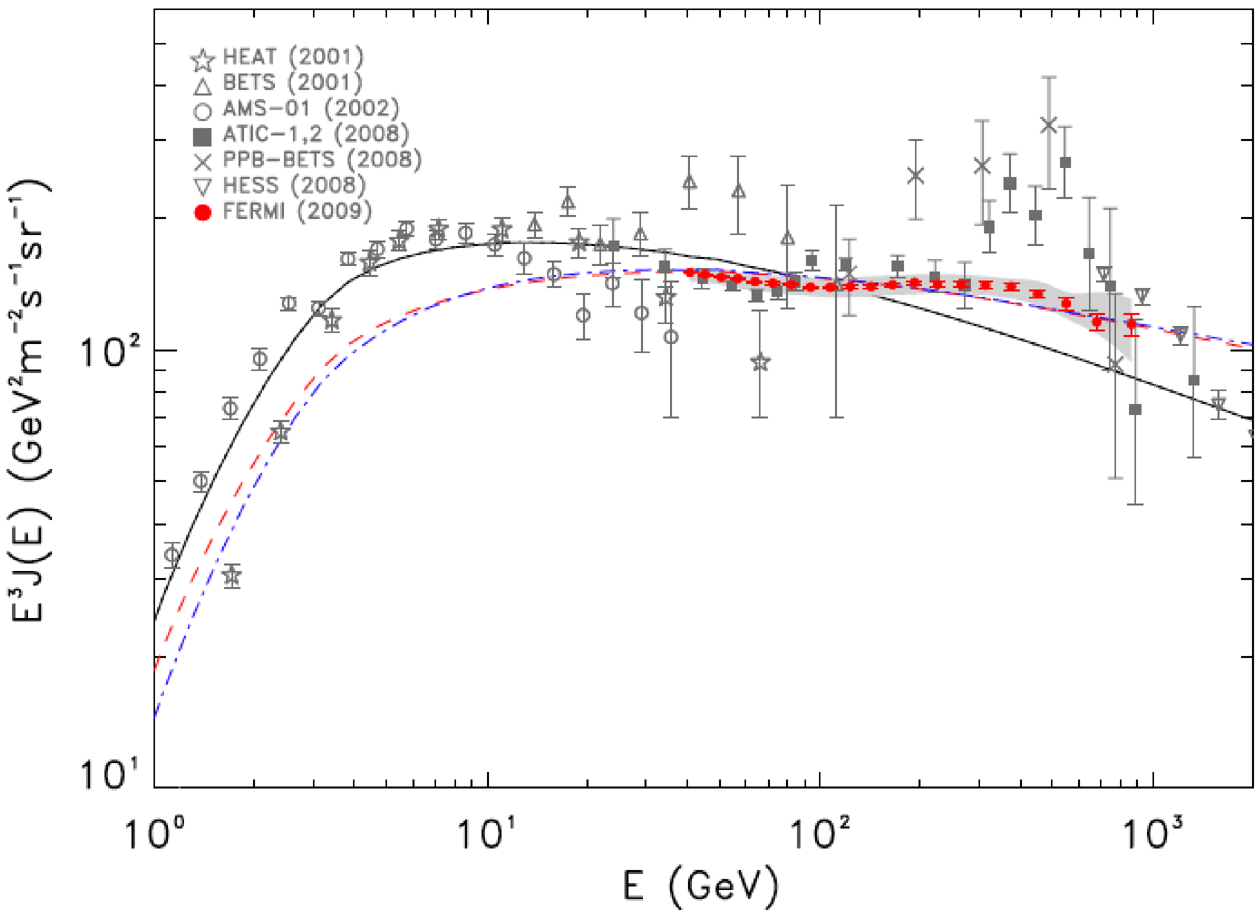
EGRET observed an all sky excess in the GeV range compared to predictions from cosmic-ray propagation and γ-ray production models which could be attributed to dark matter annihilation

The data collected by the Fermi LAT during the first 5 months of operation does not confirm the excess at intermediate latitudes and strongly constrains dark matter interpretations
Abdo et al. 2009, PRL 103, 251101





Fermi-LAT electron-positron spectrum



Harder spectrum than conventional cosmic-ray model (GALPROP) but no very large peak below 1 TeV

Abdo et al. 2009
PRL 102, 181101

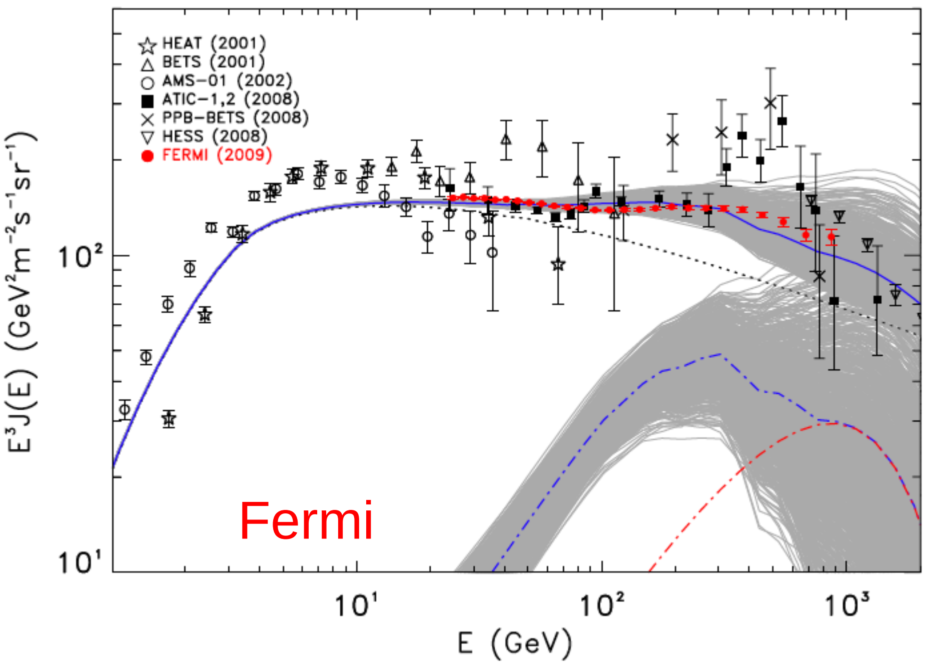
Total statistics collected for 6 months of Fermi LAT observations

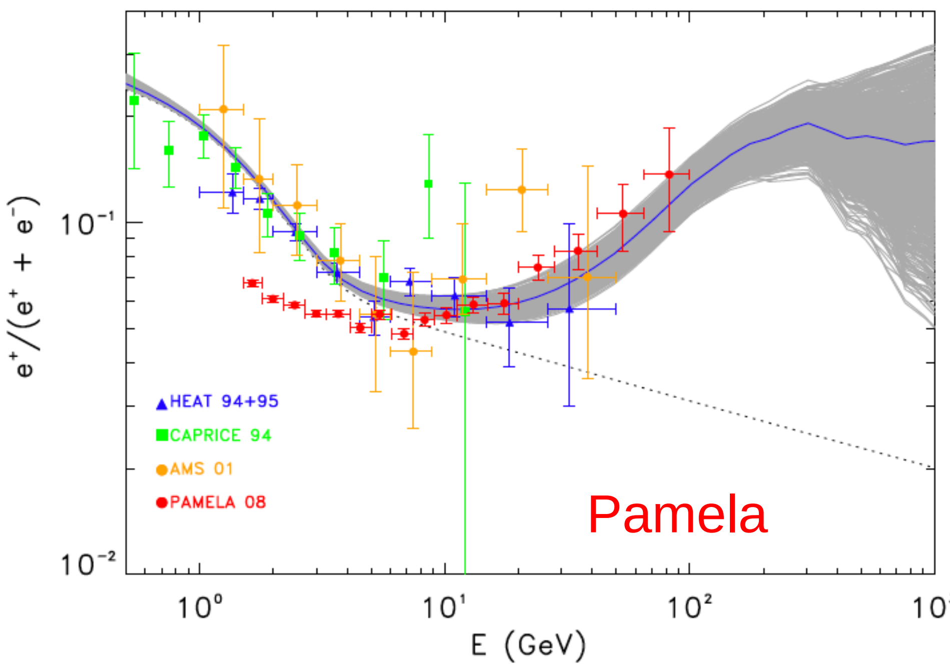
- **~4.5 million candidate electrons above 20 GeV**
- **544 candidate electrons in last energy bin (770-1000 GeV)**

Pulsar origin of the bump?

Random variations of the **pulsar parameters** relevant for **e+e- production**

[*injection spectrum, e+e- production efficiency, PWN “trapping” time*]





Electron/positron **emission** from **pulsars** offers a **viable interpretation** of **Fermi** CRE data also **consistent** with the **HESS** and **Pamela** results

But not the only one

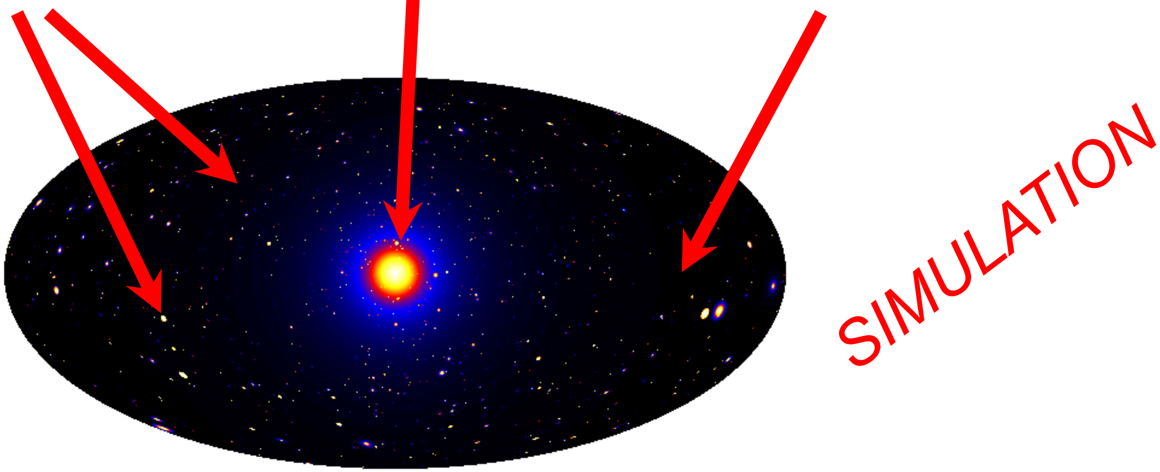
Grasso et al. 2009
Astropart. Phys. 32, 140

Dark matter: search strategies

Galactic center:
Good Statistics but source confusion/diffuse background

Satellites:
Low background and good source id, but low statistics, astrophysical background

Milky Way halo:
Large statistics but diffuse background



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

Spectral lines:
No astrophysical uncertainties, good source id, but low statistics

Extra-galactic:
Large statistics, but astrophysics, galactic diffuse background

Uncertainties in the underlying particle physics model and DM distribution affect all analyses

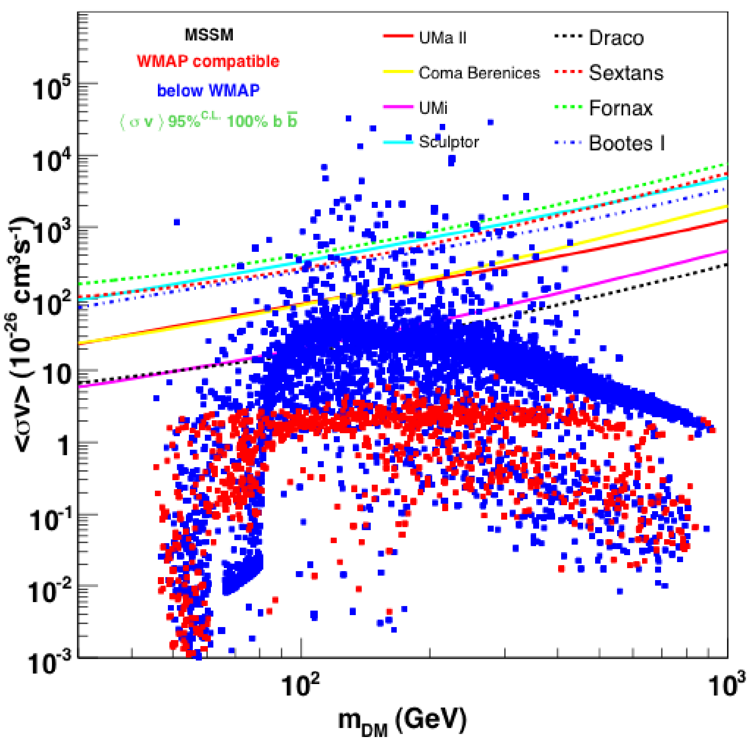
Pre-launch sensitivities published in Baltz et al., 2008, JCAP 0807:013 [astro-ph/0806.2911]

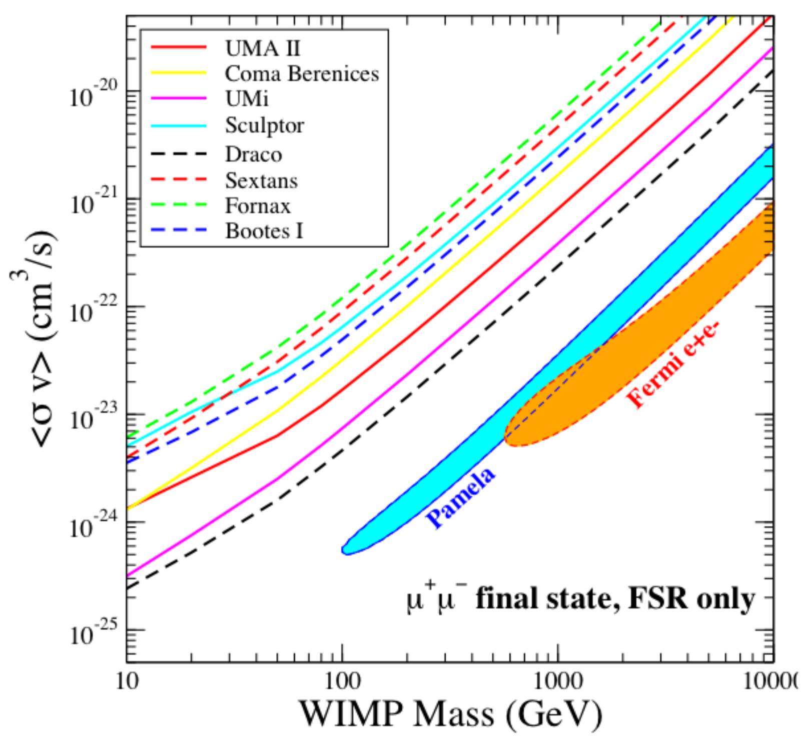
Search for DM in dwarf Spheroidals

Accepted for publication, ApJ
arXiv preprint: 1001.4531

Exclusion regions cutting into interesting parameter space for some WIMP models

WIMPs with large annihilation cross-sections into leptonic final states have been invoked to partially explain cosmic-ray data as the by-product of dark matter annihilation





Pulsar emission model

In the simplest model, the emission should depend on 4 parameters: spin period, magnetic field, magnetic dipole inclination, and viewing angle

- luminosity derived from rotational energy

  $E_{rot} = \frac{1}{2} I \Omega^2$

  $\dot{E} = - B^2 R^6 \Omega^4 / c^3$

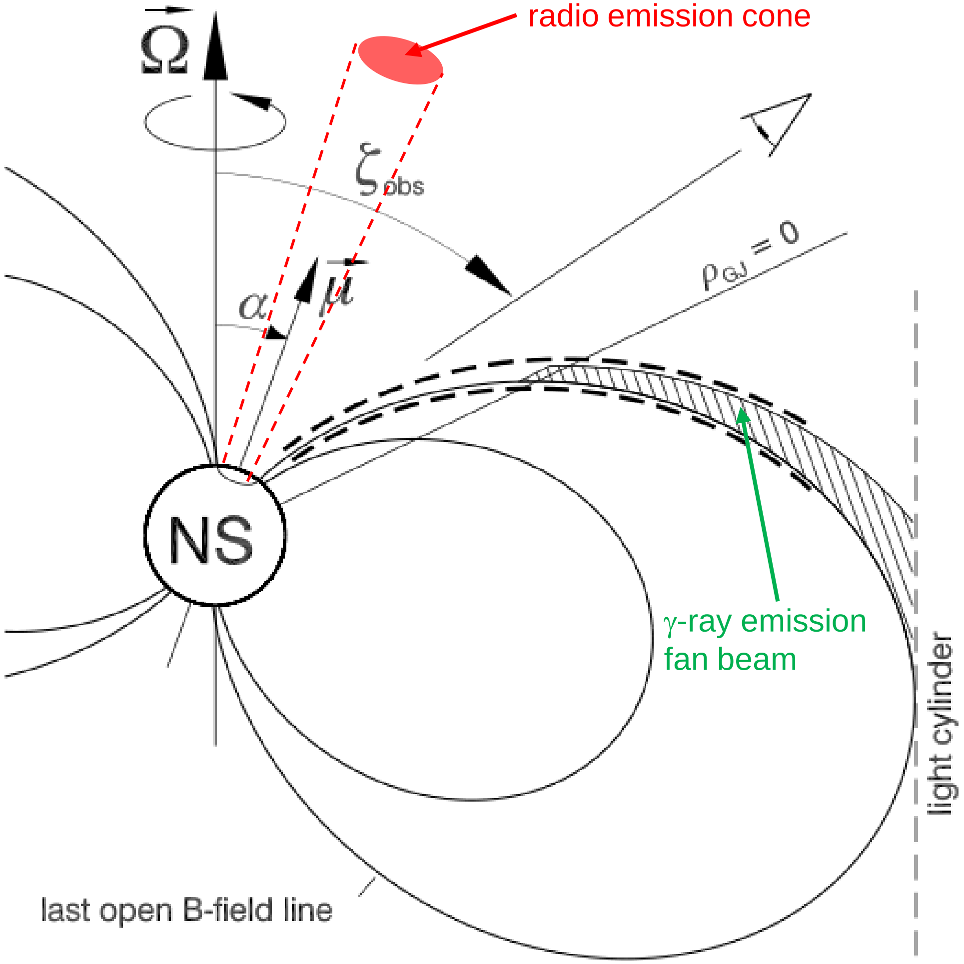
- derived parameters:

  rotational age : $\tau = \Omega / 2\dot{\Omega}$

  B field: $B = 3.2\times10^{19} (P\dot{P})^{1/2}$ G

  spin-down power: $L = I\Omega\dot{\Omega}$

  Young pulsars
  $P \approx 0.1$ s
  $B \approx 10^{12}$ G

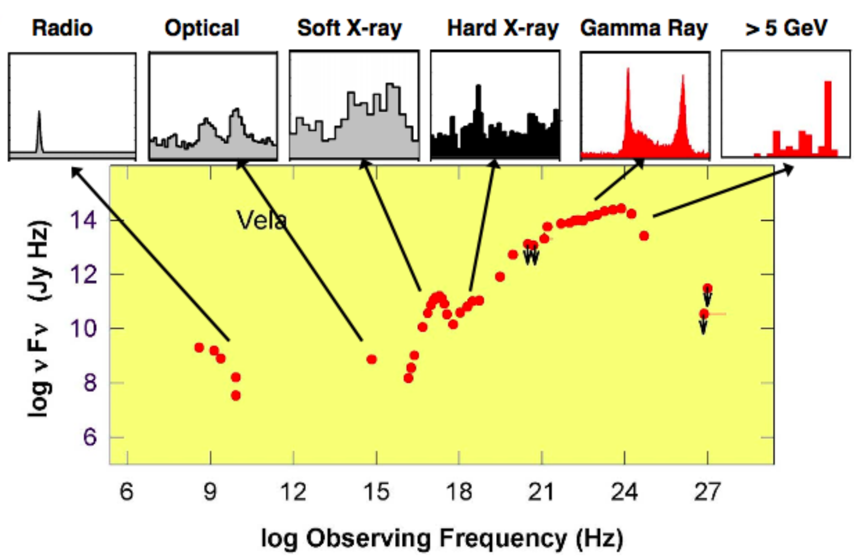


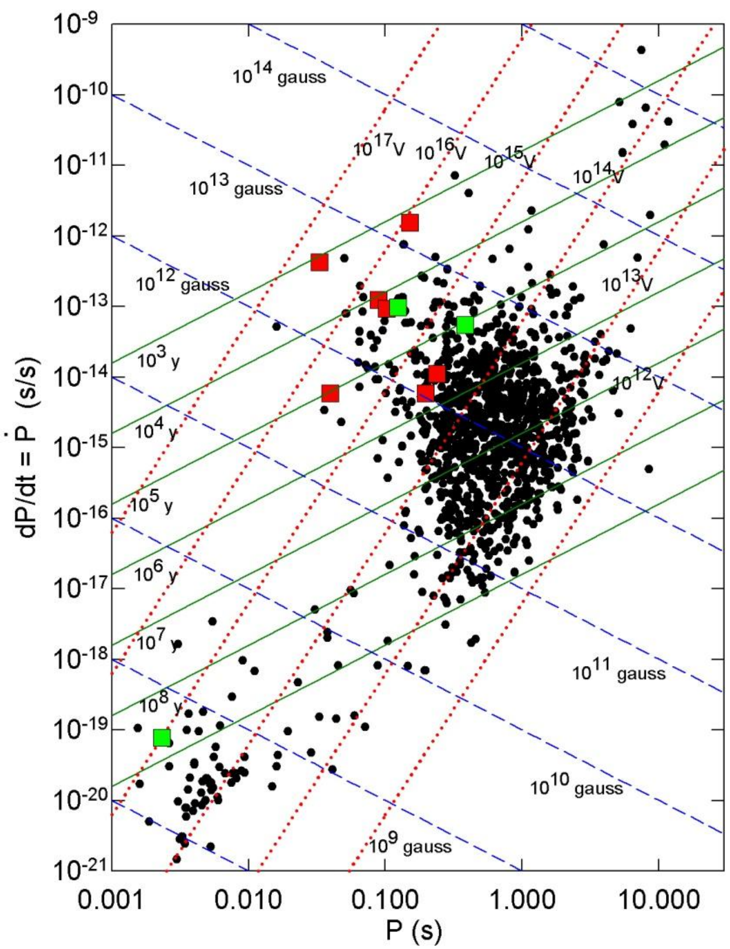
Gamma-ray pulsars before Fermi

Before Fermi and AGILE: 6 detections by EGRET, 1 by COMPTEL (all normal energetic pulsars),

+ a few marginal detections.

Gamma-ray emission: important part of the total energy budget.





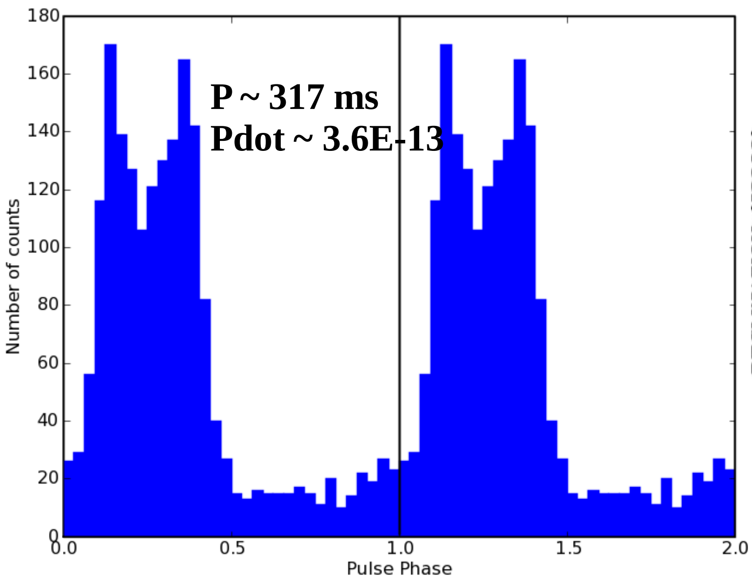
Above: slowdown – period diagram.

Left: emitted power vs. frequency for the Vela pulsar.

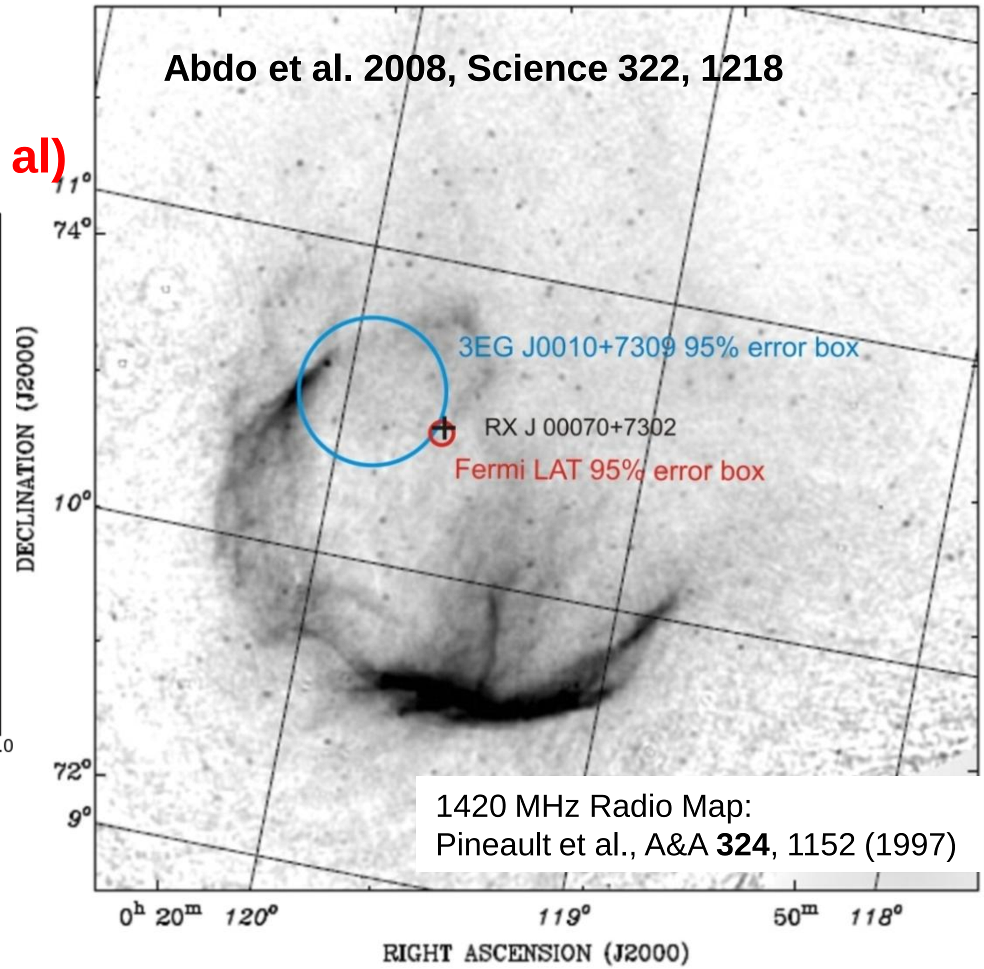
Discovery of First Gamma-ray-only Pulsar

A radio-quiet, gamma-ray only pulsar, in Supernova Remnant CTA1

Quick discovery enabled by
- **large leap in key capabilities**
- **new analysis technique (Atwood et al)**



- Spin-down luminosity ~10^{36} erg s^{-1}, sufficient to supply the PWN with magnetic fields and energetic electrons.
- The γ-ray flux from the CTA 1 pulsar corresponds to about 1-10% of E_{rot} (depending on beam geometry)

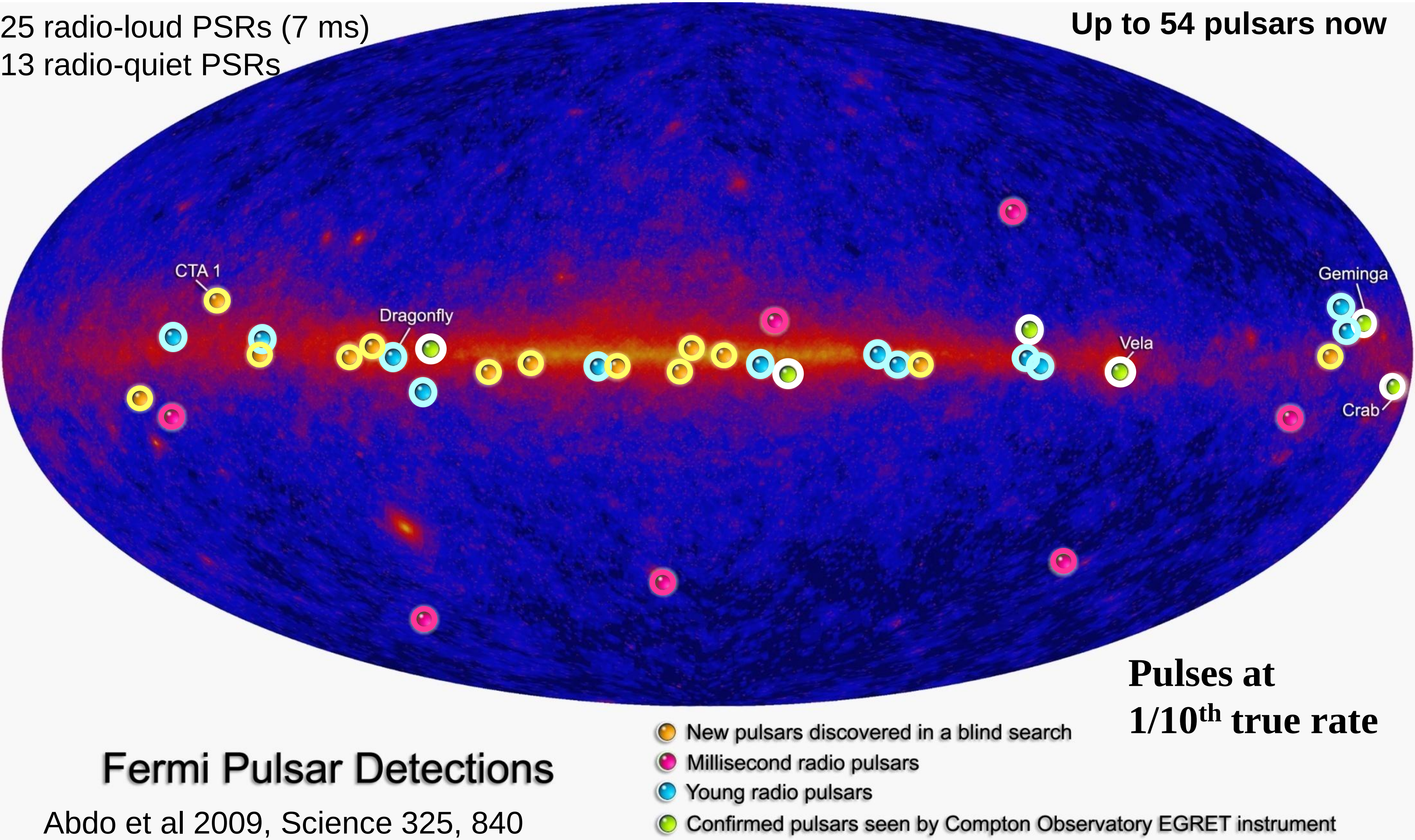


Age ~(0.5 – 1)x10^4 years
Distance ~ 1.4 kpc
Diameter ~ 1.5°

The Pulsing Sky

25 radio-loud PSRs (7 ms)
13 radio-quiet PSRs

Up to 54 pulsars now



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

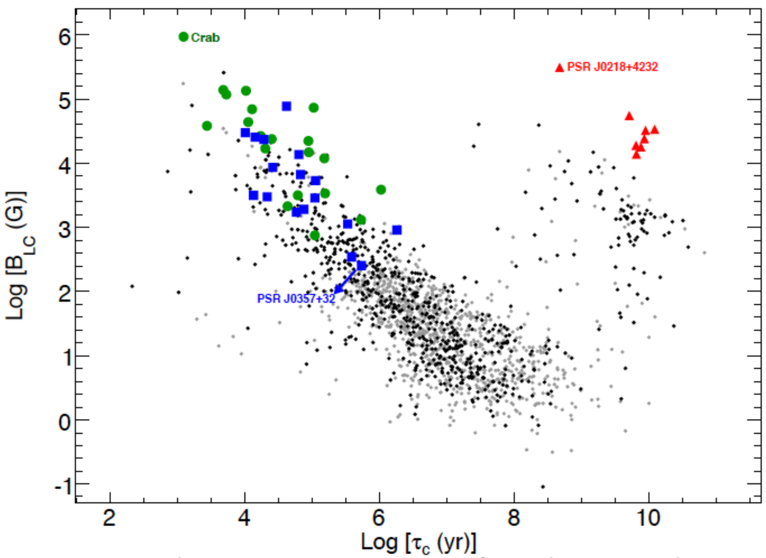
Abdo et al 2009, Science 325, 840
Abdo et al 2009, Science 325, 848

What do we learn ?

As for EGRET, the detected pulsars are relatively close and highly energetic.

The detected pulsars also have the highest values of magnetic field at the light cylinder, B_{LC}.

Both detected normal PSRs and MSPs have comparable B_{LC} values. Similar emission mechanisms operating?

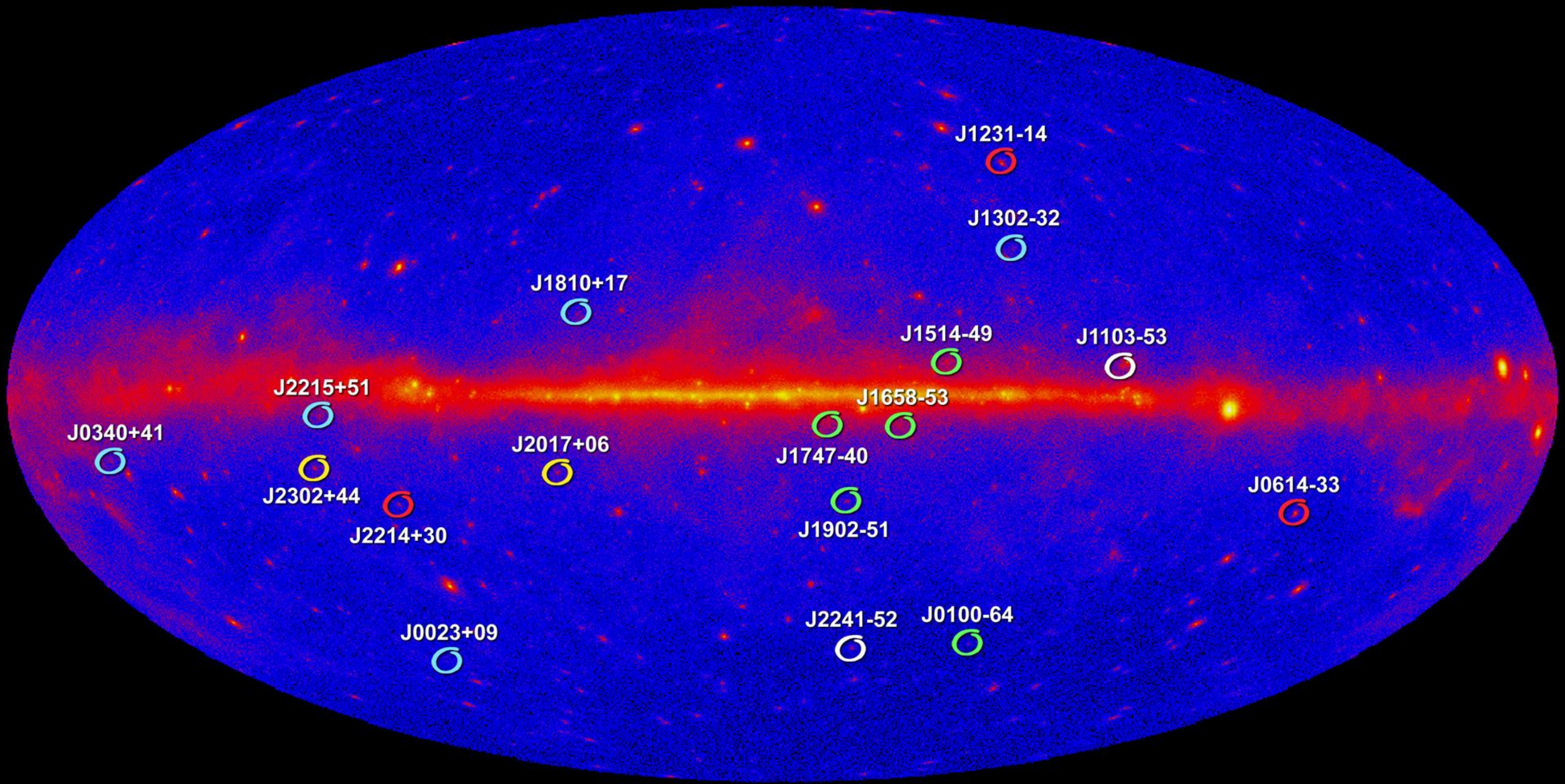


B_{LC} vs. characteristic age for the catalog PSRs

Pulsar catalog: arXiv:0910.1608

17 new MSPs (5 January 2010)

New Millisecond Radio Pulsars Found in Fermi LAT Unidentified Sources



Led by Fernando Camilo (Columbia Univ.) using Australia's CSIRO Parkes Observatory

Led by Mallory Roberts (Eureka Scientific/GMU/NRL) using the NRAO's Green Bank Telescope

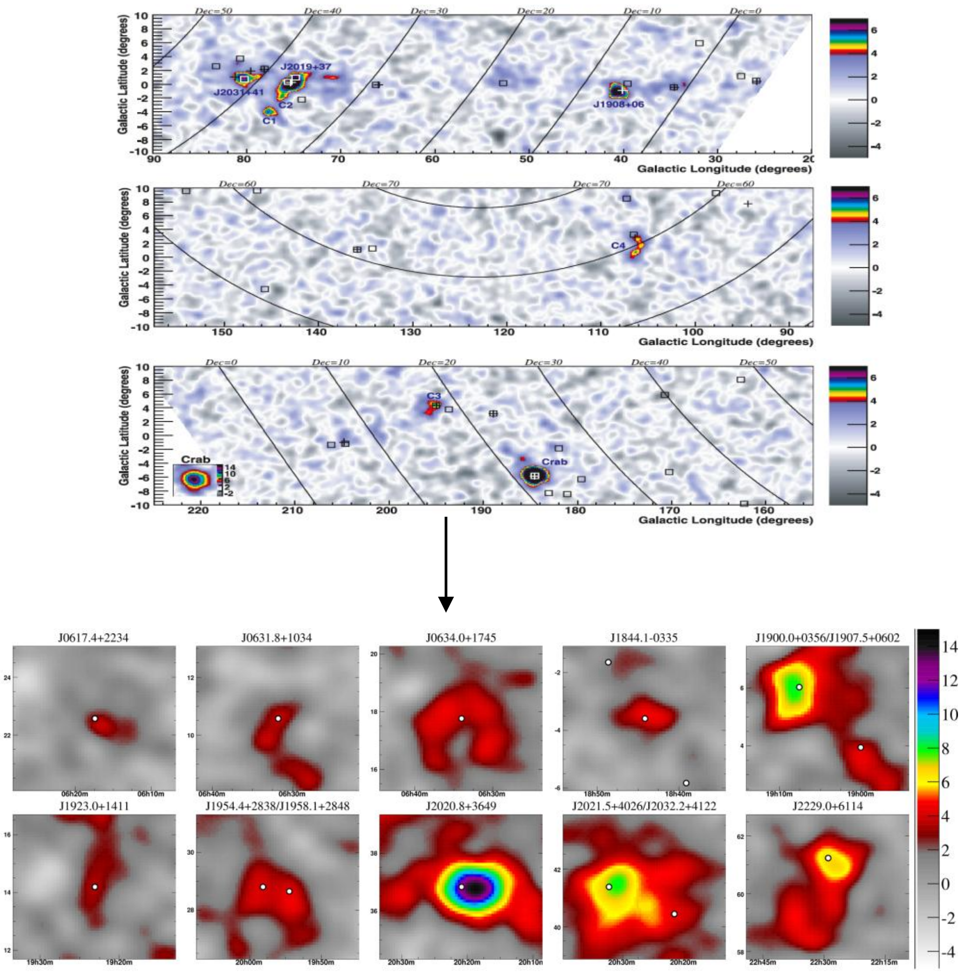
Led by Scott Ransom (NRAO) using the Green Bank Telescope

Led by Ismael Cognard (CNRS) using France's Nançay Radio Telescope

Led by Mike Keith (ATNF) using Parkes Observatory

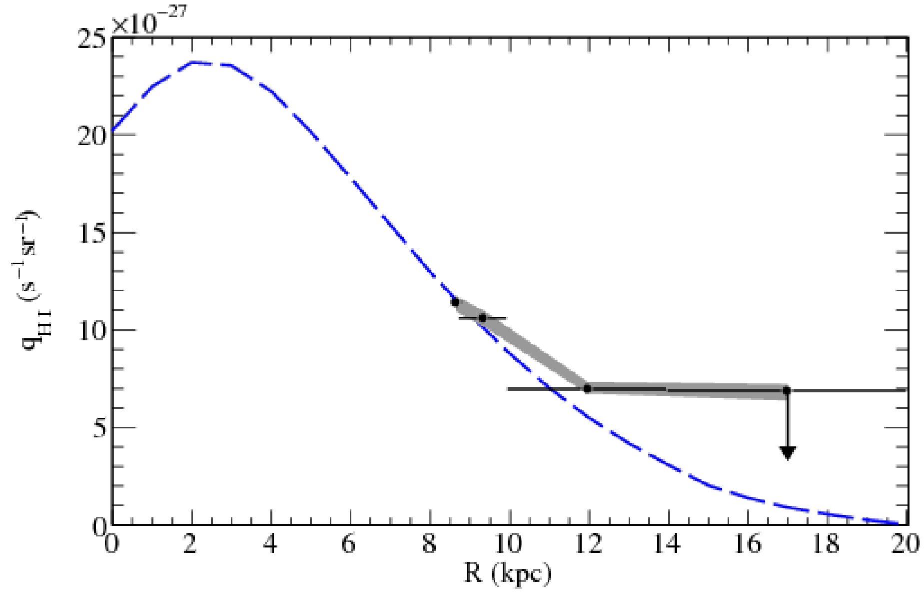
More on TeV connections

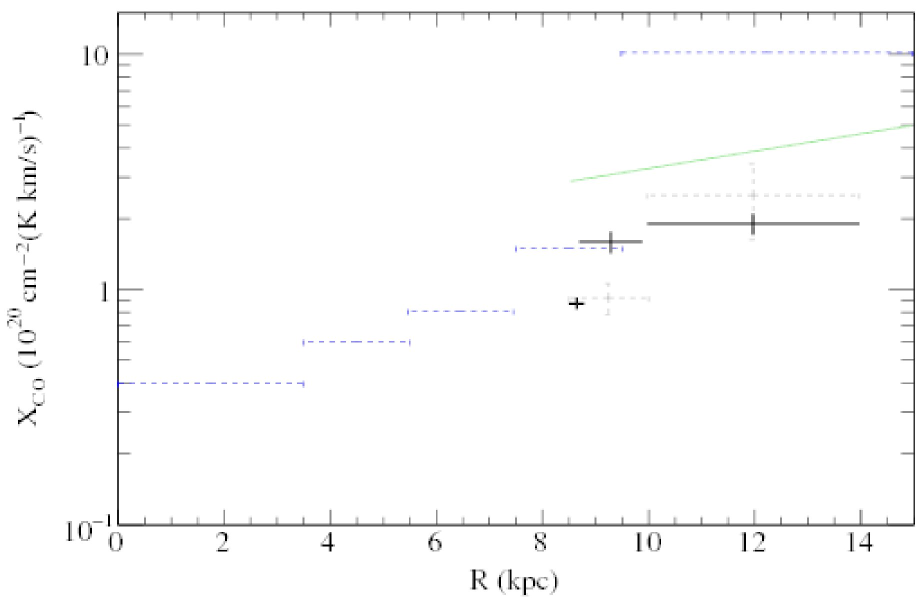
- Milagro (TeV) observations: 14/34 Galactic BSL sources with 3 sigma Milagro excess.
- 9/14 are gamma-ray pulsars
- All 6 previously known Milagro sources associated with Fermi Pulsars.



Galactic diffuse emission

- Local study of the diffuse emission toward Cassiopeia-Cepheus.
- Well known and well resolved interstellar clouds.
- Gould Belt (small cross) consistent with local CR spectrum.
- Trend toward the local arm and Perseus arm (larger crosses).
- Conversion from CO to mass increases outwards.
- CR density decreases outwards, but not as much as in scaled GALPROP model (blue dashes) which uses pulsars for source distribution



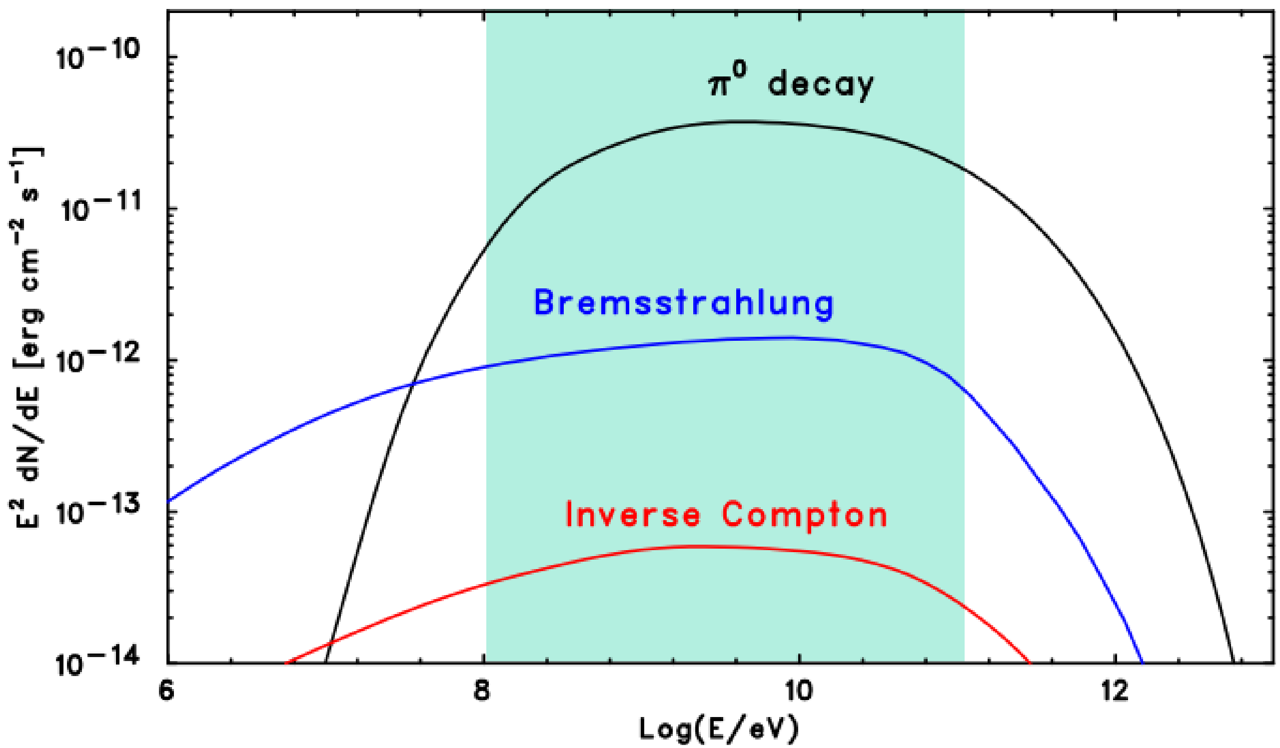


Abdo et al. 2010, ApJ 710, 133

SuperNova Remnants

- Key issues to be addressed by **Fermi LAT**:
  - Searching for **π^0-decay** signatures,
  - Measuring total **CR energy content** per SNR,
  - Measuring **CR spectrum**,
  - Learning how CRs are **released** into ISM.

Typical Gamma-ray Spectrum



- D = 3 kpc
- n = 100 cm^{-3}
- $W_p = 10^{49}$ erg
- $W_e = 10^{47}$ erg
- $E_{p,max} = E_{e,max}$ = 2 TeV
- Particle index = 2.0
- Constant injection over 1.0×10^4 yr

Interaction with molecular cloud enhances Pion-decay/Bremsstrahlung

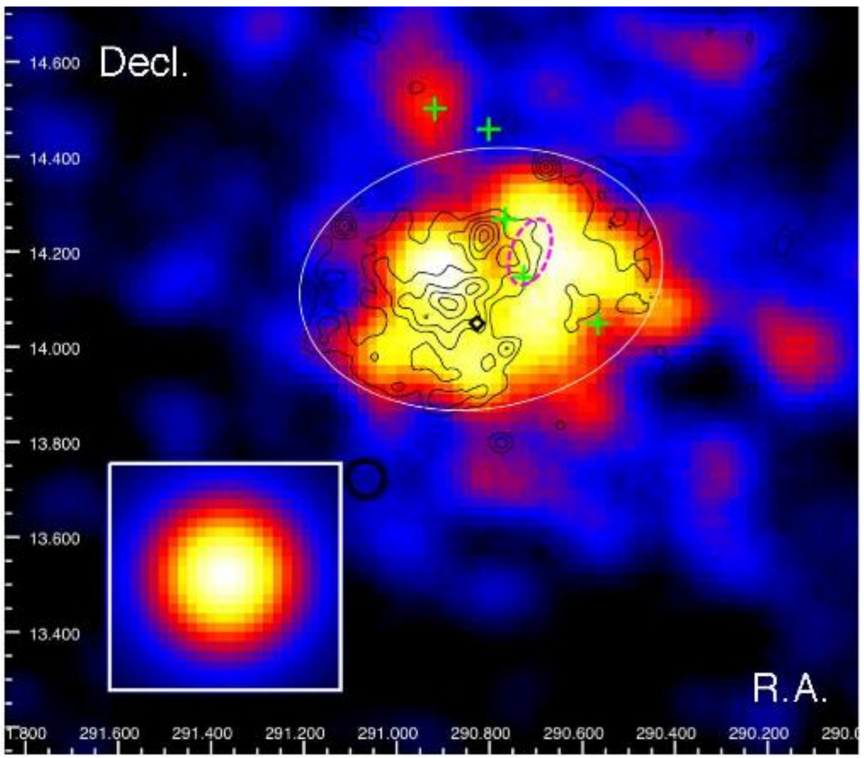
SNR W51C

Fermi-LAT SNR interacting with molecular clouds

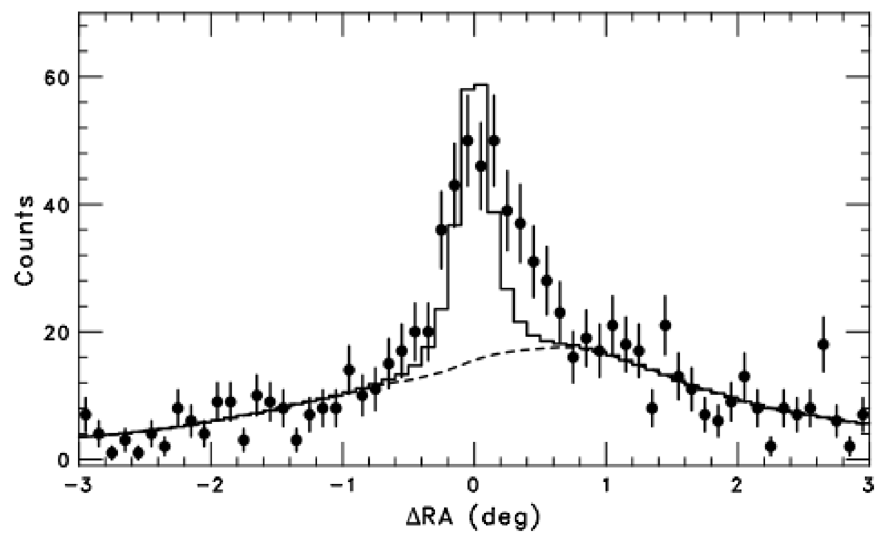
Middle age (30000 yr), Distance 6 kpc, 0FGL J1923.0+1411: **3 months** data yield **23σ**

Smoothed Count Map
(2–10 GeV; front)

Abdo et al 2009, ApJ 706, L1



One-dimensional profile



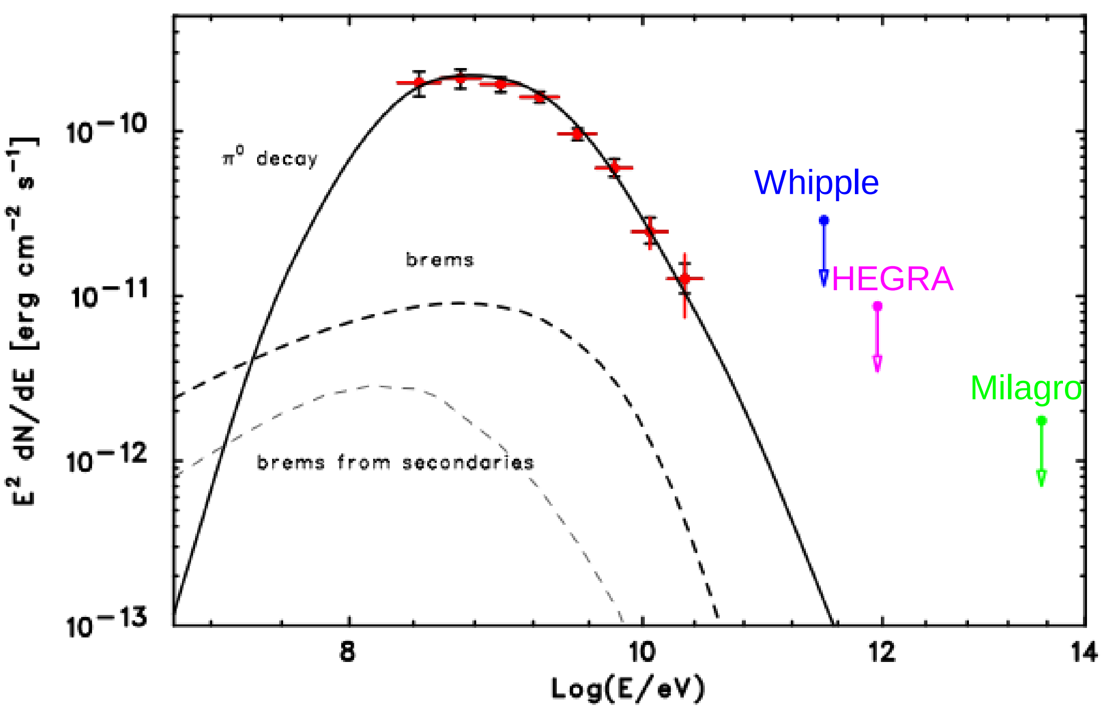
Dash: diffuse backgrounds
Solid: Sum of a point source and the backgrounds

Contours: ROSAT X-ray (Koo et al. 1995)
Dashed magenta ellipse: shocked CO clumps (Koo & Moon 1997)
Green crossed: HII regions (Carpenter & Sanders 1998)
Diamond: CXO J192318.5+143035 (PWN?) (Koo et al. 2005)

Spatially Extended!!

W44 spectrum

π^0-decay dominant case



Similar to W51C:
W44 (0FGL J1855.9+0126 at 39σ)
IC443 (0FGL J0617.4+2234 at 51σ)

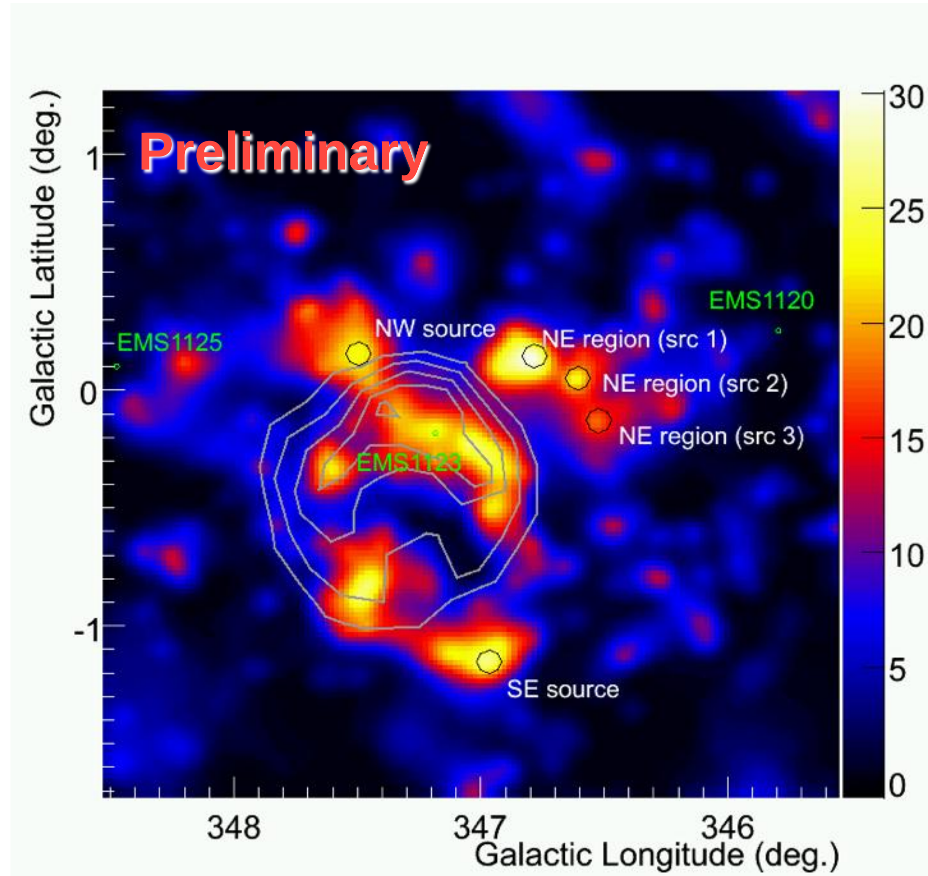
Protons need to have a spectral break at ~ 10 GeV
Possible explanation:
Fast escape of high energy particles with damping of magnetic turbulence due to the dense environment (e.g. Ptuskin & Zirakashvili 2003)

Abdo et al 2010
Science Express 1182787

With Fermi LAT observations, we can study
How particles are released into interstellar space
How SNR shocks are affected by cloud-shell interactions

Fermi LAT view of RX J1713.7-3946

- **Brightest TeV SNR**
- **Faint GeV source in a complicated region**
- **TS Map after subtraction of 11-month catalog sources**
- **Sources to the north coincide with molecular material (CO and HII region)**



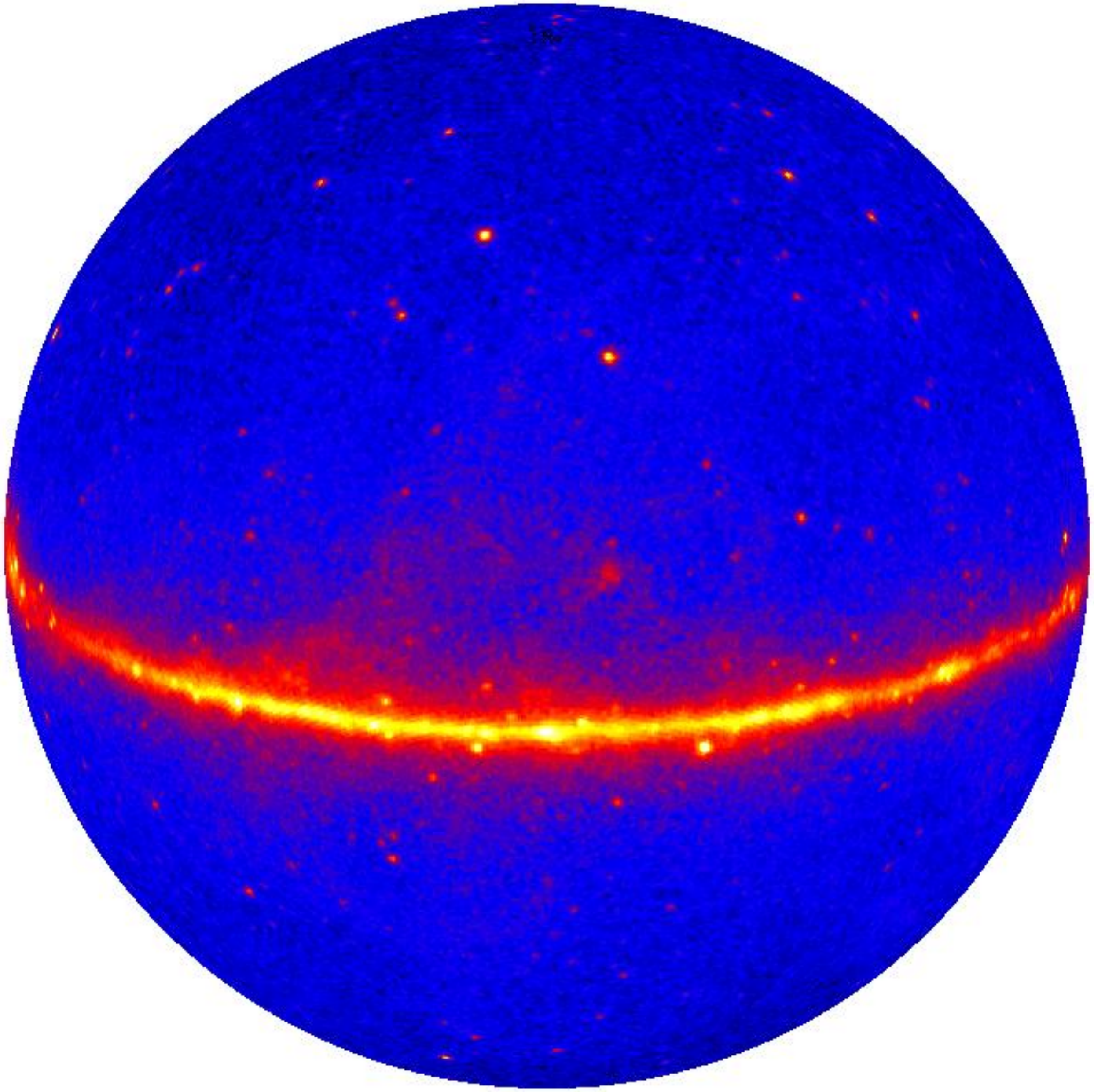
Stefan Funk
Fermi Symposium, Nov. 2009

Conclusions

- 1451 sources in 1FGL catalog
- Typical 95% error radius is less than 10 arcmin
- Over half the sources are associated positionally with a known object, mostly **blazars**
- 55 **pulsars** are identified by gamma-ray pulsations (up from 6), a number of unidentified sources are millisecond pulsars
- 3 very bright **γ-ray bursts**, several fainter ones
- Several **radio galaxies** (Cen A, NGC 1275, M 87)
- 2 **starburst galaxies** (M 82, NGC 253)
- 3 high-mass **X-ray binaries** (LSI +61 303, LS 5039, Cyg X-3)
- Several **PWNe** (Crab, Vela, MSH 15-52) and **SNRs** (W28, W44, W49B, W51C, IC443, Cas A)
- About 40 papers published at February 2010 (2 Nature, 6 Science)

The γ-ray sky viewed from above

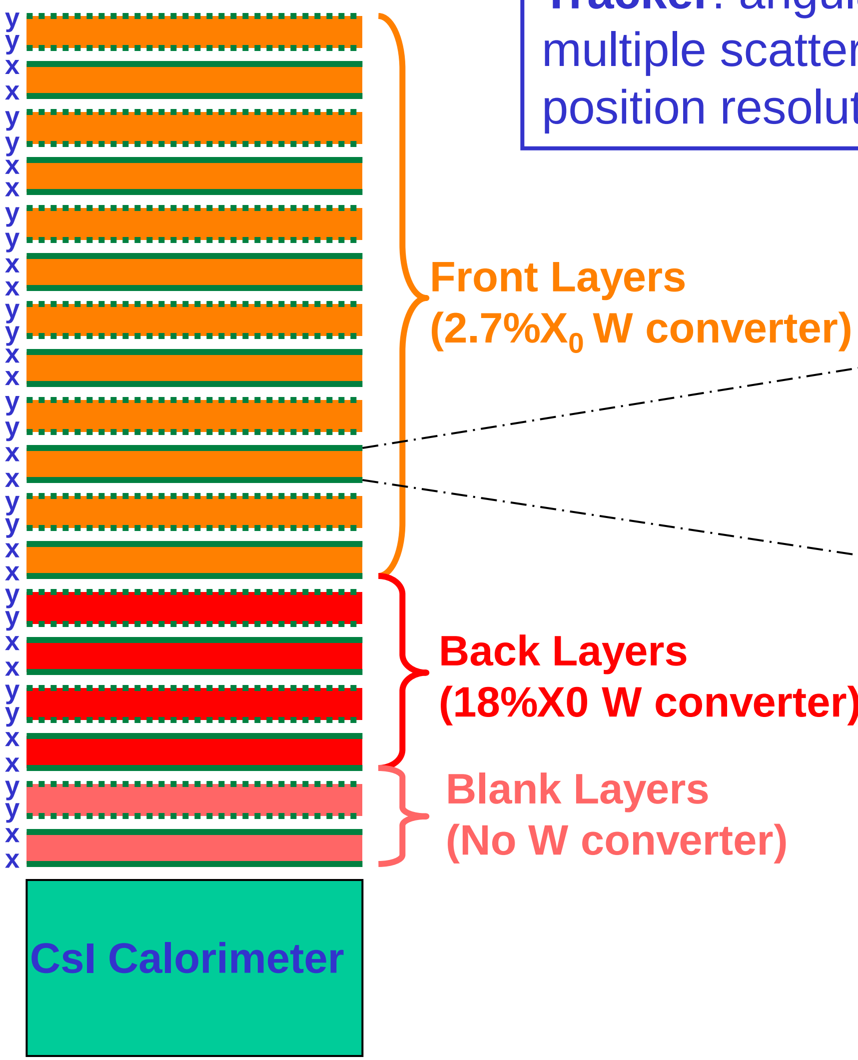
Fermi-LAT
1 year
E > 1 GeV



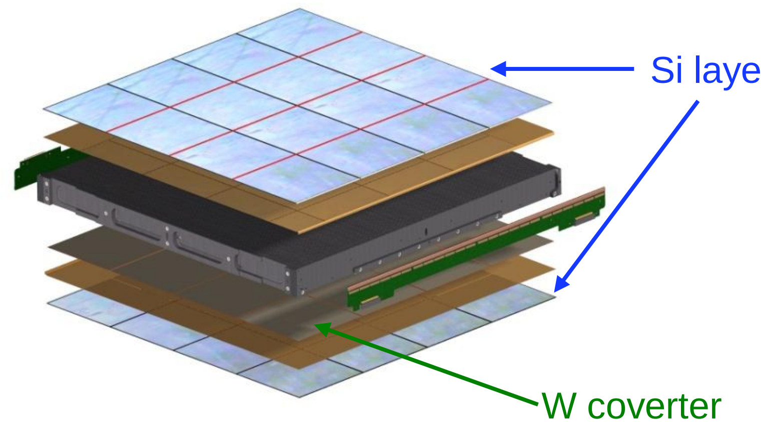
Orthographic projection

Tracker Details

Tracker Tower



Tracker: angular resolution is determined by:
multiple scattering (at low energies) => Many thin layers
position resolution (at high energies) => fine pitch detectors

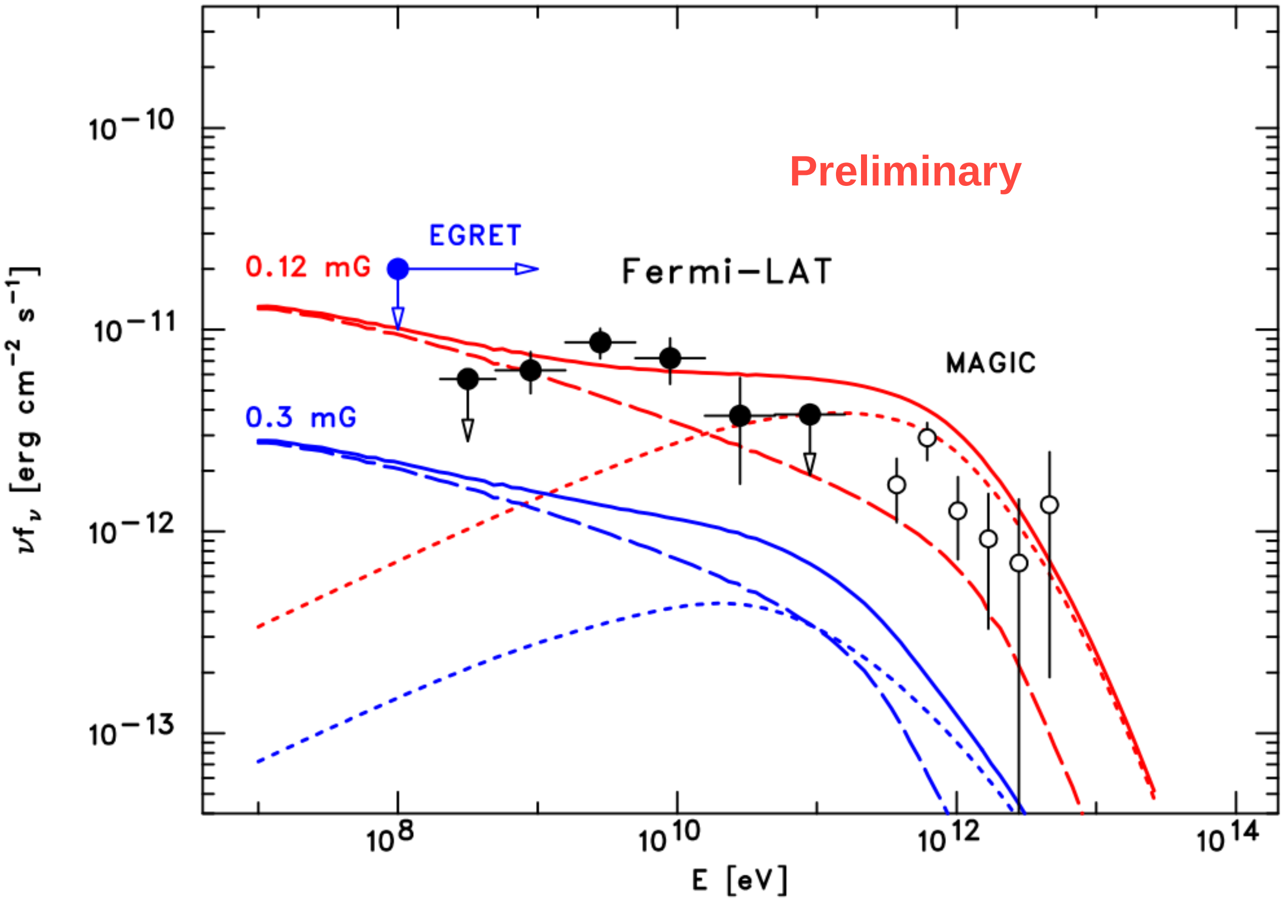


- ❑ **Front** (thin) conversion layers to have small multiple scattering errors at low energies
- ❑ **Back** (thick) layers to increase conversion probability

See Atwood *et al.* 2007, Astropart.Phys.28:422-434

Cas A spectrum

- **Young SNR (330 yrs)**
- **LAT spectrum connects well with MAGIC TeV γ-rays**
- **No sign for a cutoff (as in pulsars)**
- **Bremsstrahlung + Inverse Compton** (Atoyan et al 2000)
- **Can also be fitted by pion decay** (Berezhko et al 2003)



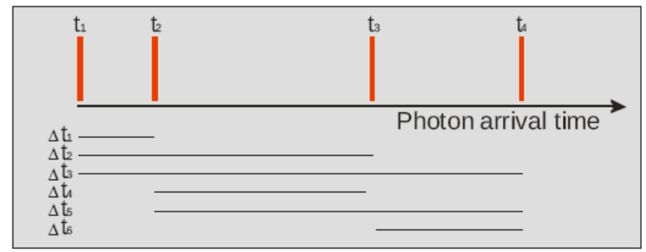
The “Time-Differencing” Technique

Periodicity in photon arrival times will also show up in differences of photon arrival times.

Time differences cancel out long term phase slips and glitches because differencing starts the "clock" over (and over, and over...)

Despite the reduced frequency resolution (and therefore number of bins), the sensitivity is not much reduced because of a compensating reduction in the number of fdot trials

Atwood et. al., **ApJ Lett., 652, 49 (2006)**
Ziegler et. al., **ApJ 680, 620 (2008)**



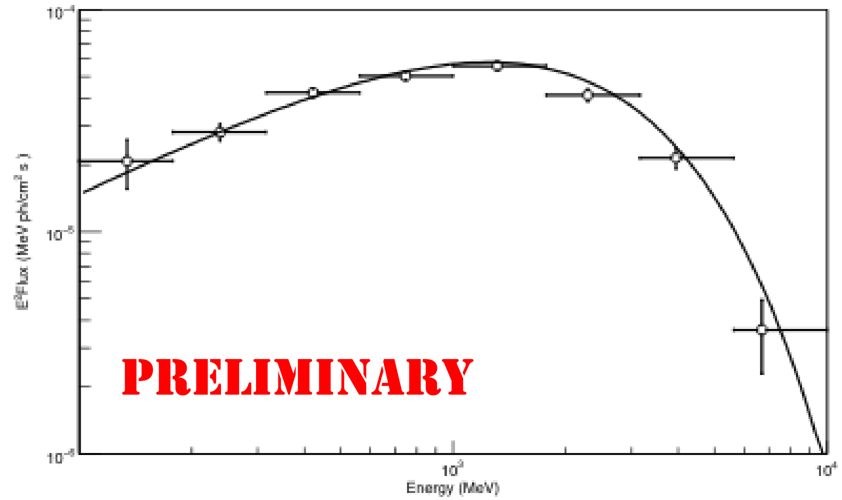
Credit: M. Ziegler

# of FFT bins = f * t_{max_diff} * 2
PC with 2GB can handle 33 x 10^6 bin FFT

EGRET pulsars with Fermi

EGRET pulsars generally are prime targets for spectral analyses with unprecedented details, because of their brightness.

Important variation is seen in spectral properties across the rotation.

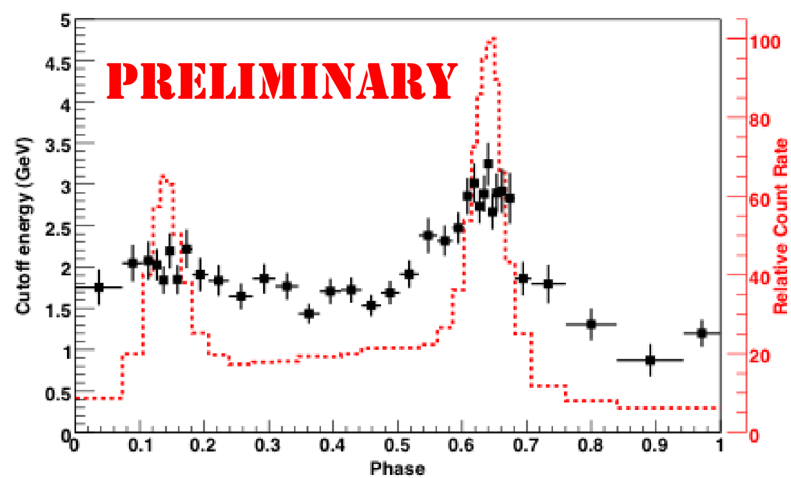


PSR B1055-52 spectrum

Spectral index and cutoff energy variations are thought to be due to emission altitude changes with energy (see e.g. Geminga).

In general, pulsar spectra are consistent with simple-exponential cutoffs, indicative of absence of magnetic pair attenuation.

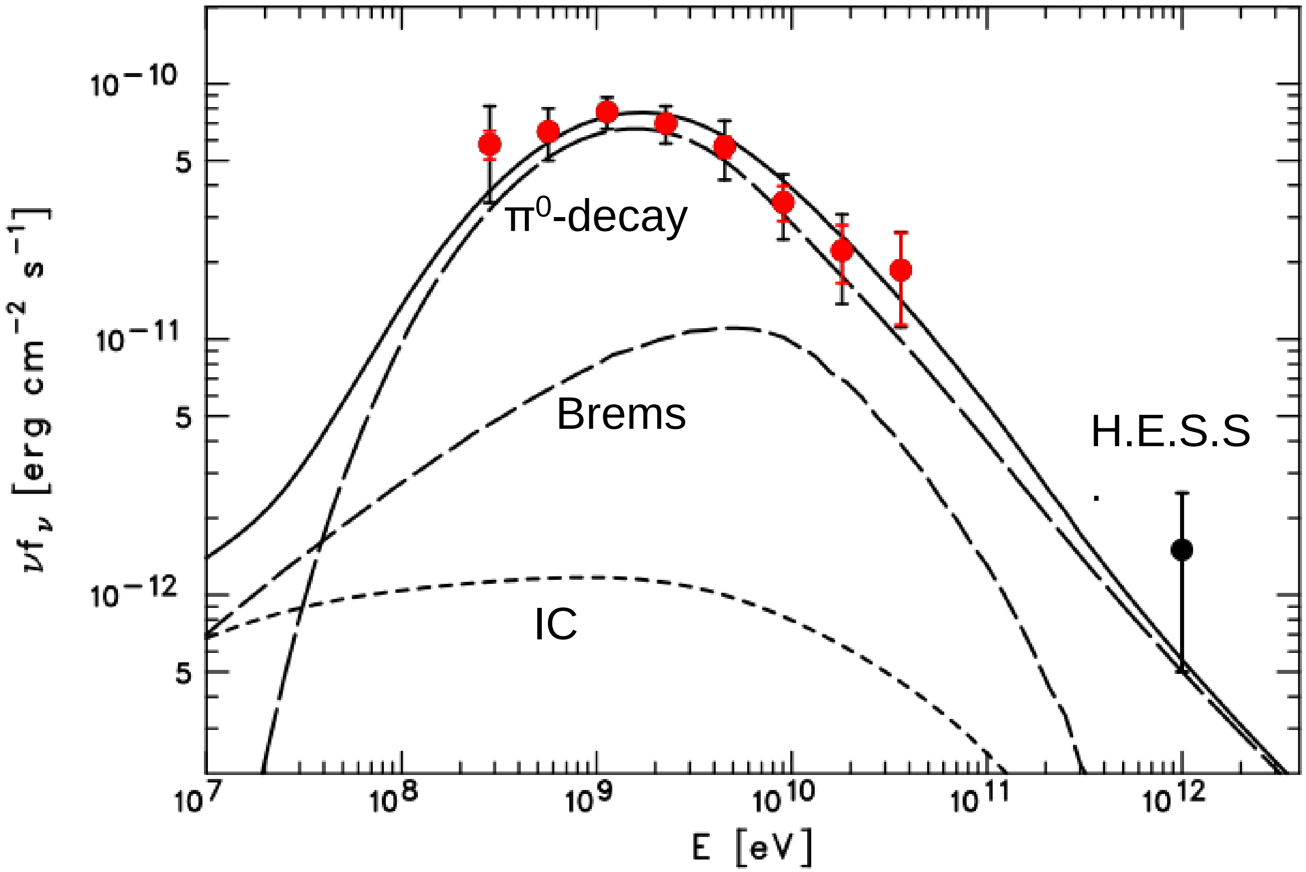
Emission site is not near the polar cap.



Cutoff energy vs. pulse phase, for the Geminga pulsar

W51C spectrum

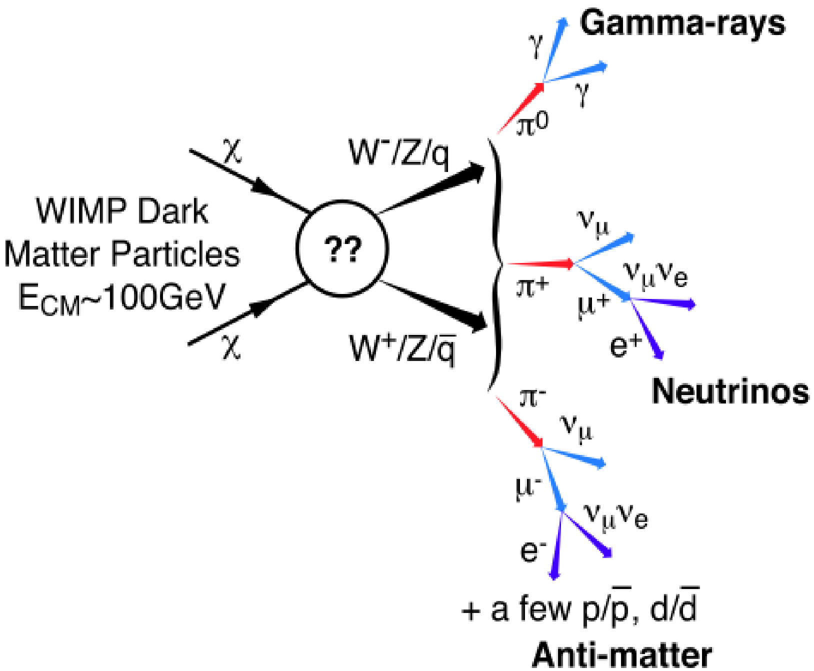
π⁰-decay dominant case



One of the most luminous gamma-ray sources $L = 1 \times 10^{36}$ (D/6 kpc)^2 erg s^{-1}
Spectral steepening in the LAT range
π^0-decay model can reasonably explain the data, requires proton break at ~ 20 GeV
Leptonic scenarios require large amounts of electrons

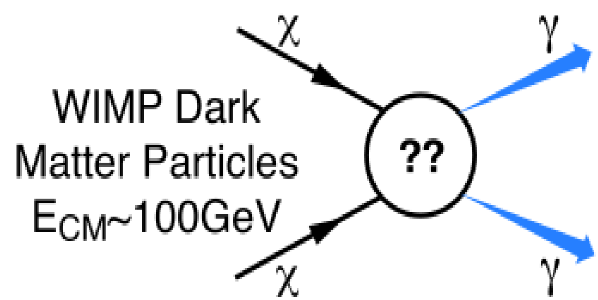
Dark matter: γ from WIMP annihilation

Continuum spectrum with cutoff at Mχ



Spectral line at Mχ (for γγ)

- ✓ Detection of prompt annihilation into γγ (γZ^0) would provide smoking gun for dark matter annihilation
- ✓ Requires best energy resolution
- ✓ However, annihilation fraction in the range 10^{-3}-10^{-4} (depending on the model)



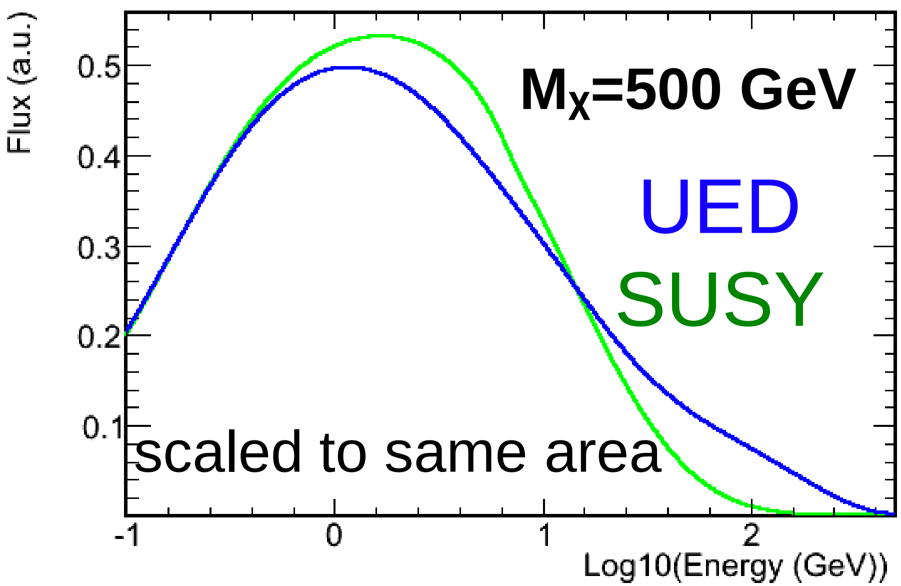
Depends on DM density squared

Two different scenarios: UED vs SUSY

Consider the photon spectrum from 500 GeV WIMP annihilation in SUSY and in UED:

✓UED: photons mostly from lepton bremsstrahlung

✓SUSY: photons 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 fluxes for equal masses



➡ **Spectra can look very different in these scenarios**

mSUGRA parameters:

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