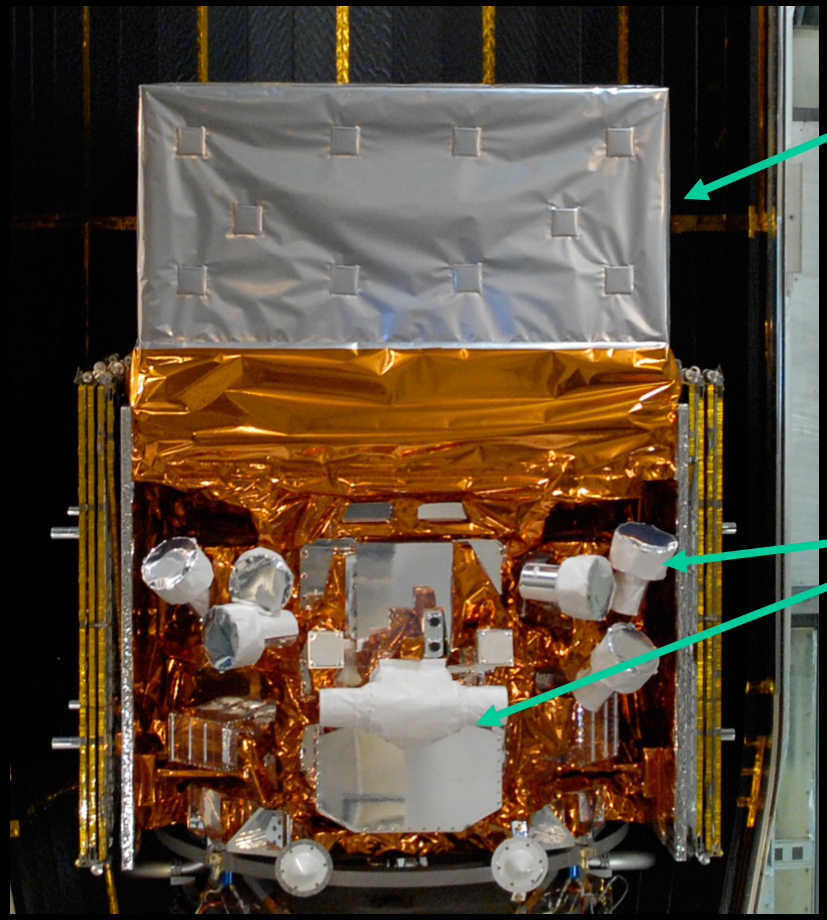
The Galaxy in a new light: Observations of the Fermi-LAT

Marianne Lemoine-Goumard
CEN Bordeaux-Gradignan

for the Fermi-LAT Collaboration

What is Fermi?



Large Area Telescope (LAT):

20 MeV - >300 GeV (including unexplored region 10-100 GeV)

2.4 sr FoV (scans entire sky every ~3hrs)

Gamma-ray Burst Monitor (GBM)

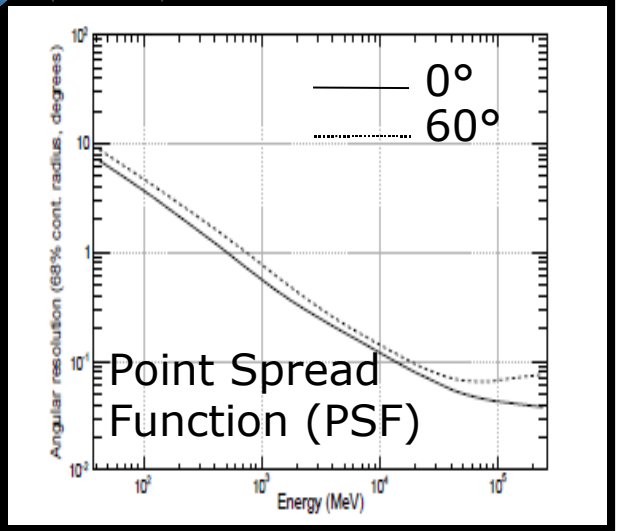
8 keV - 40 MeV

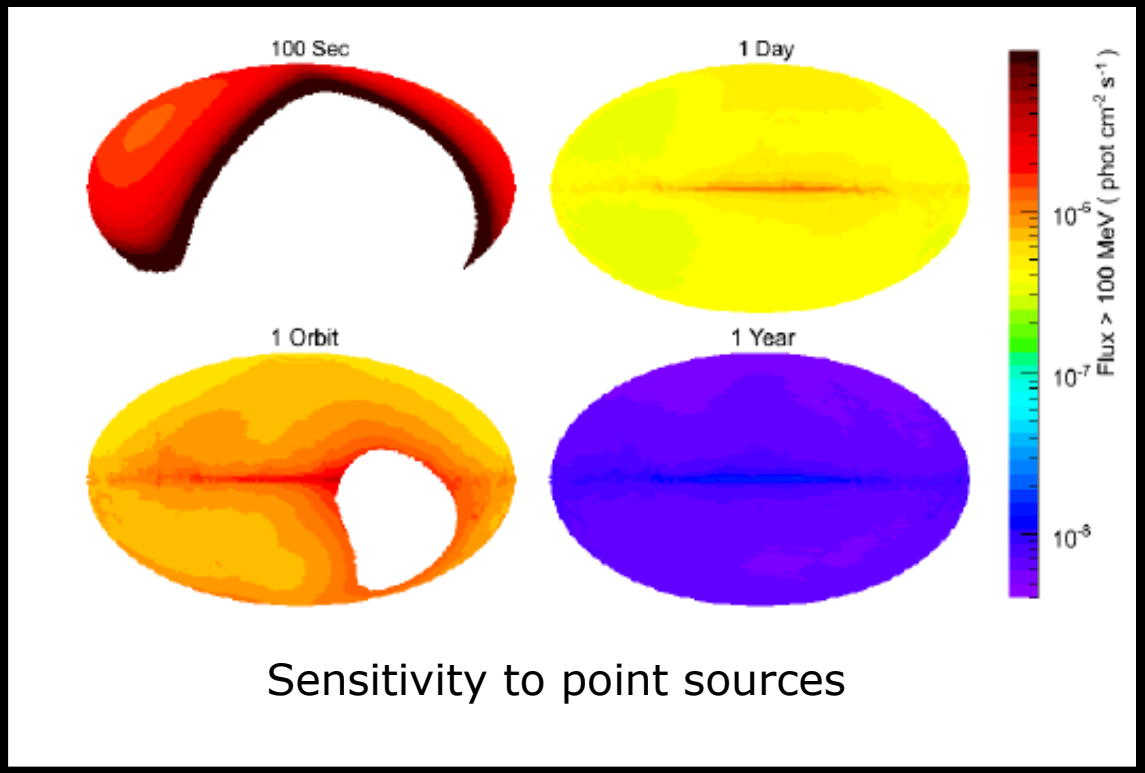
views entire unocculted sky

Launch June 2008!

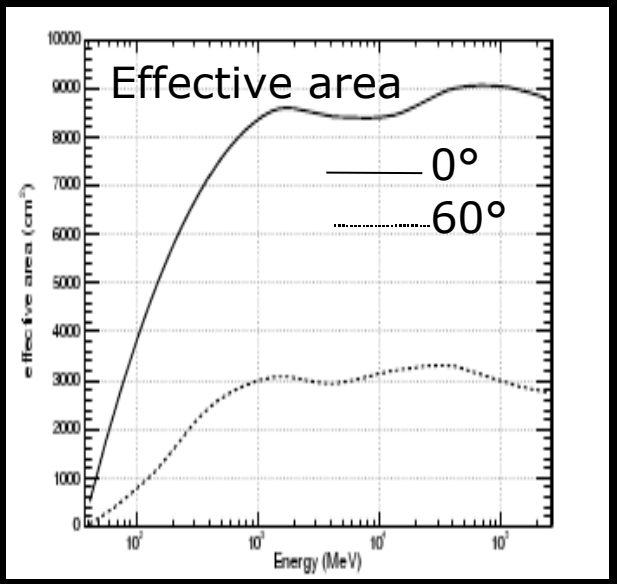
Large leap in all key capabilities, transforming our knowledge of the gamma-ray universe. Great discovery potential.

Observatory Performance





Sensitivity to point sources



Energy Resolution: ~10%
PSF (68%) at 100 MeV: ~ 3.5° (front)
PSF (68%) at 10 GeV: ~ 0.1°
Field Of View: 2.4 sr
Point Source sens(>100 MeV): 3x10^{-9} cm^{-2}s^{-1}

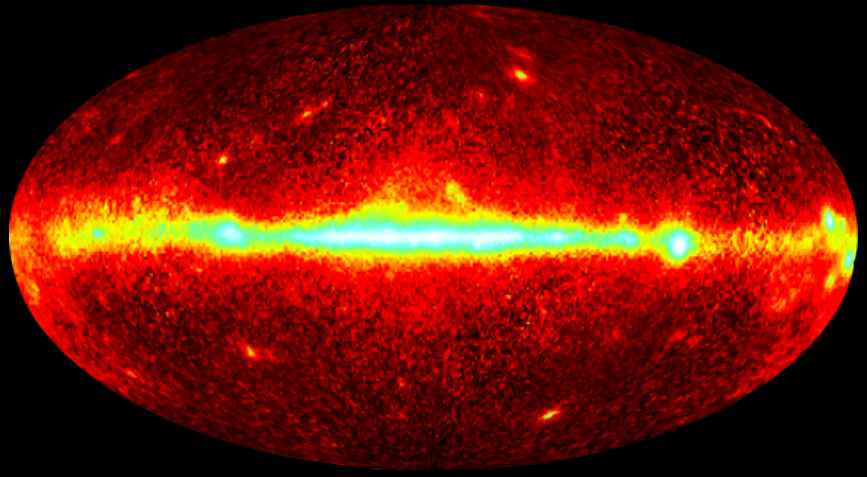
(1-year survey, assuming dN/dE~E^{-2})

LAT Galactic Scientific Program

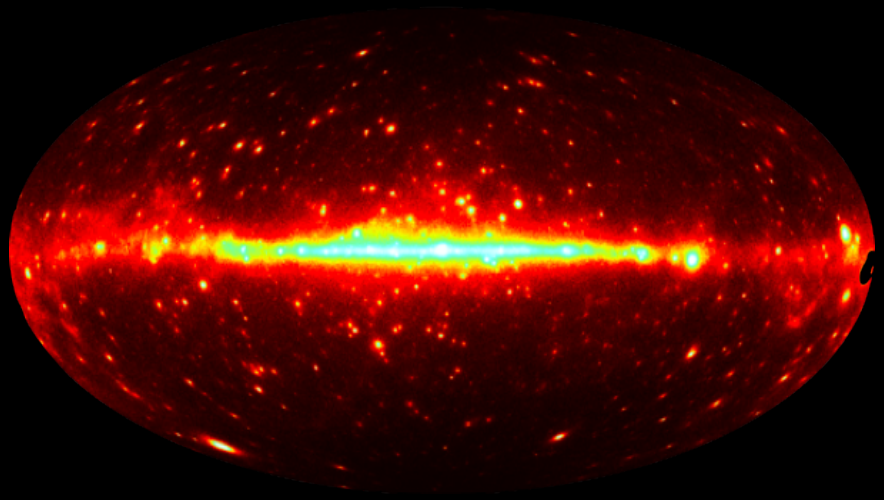
- Pulsars
- Supernova remnants/pulsar wind nebulae
- X-ray binaries
- Cosmic-ray acceleration and propagation
- Diffuse gamma-ray emission (Galactic and extragalactic)
- Solar system objects *(see talk by N. Giglietto)*
- Unidentified sources/new populations
- Dark matter *(see talk by S. Murgia)*

....

Gamma-ray sky from 5 years of EGRET

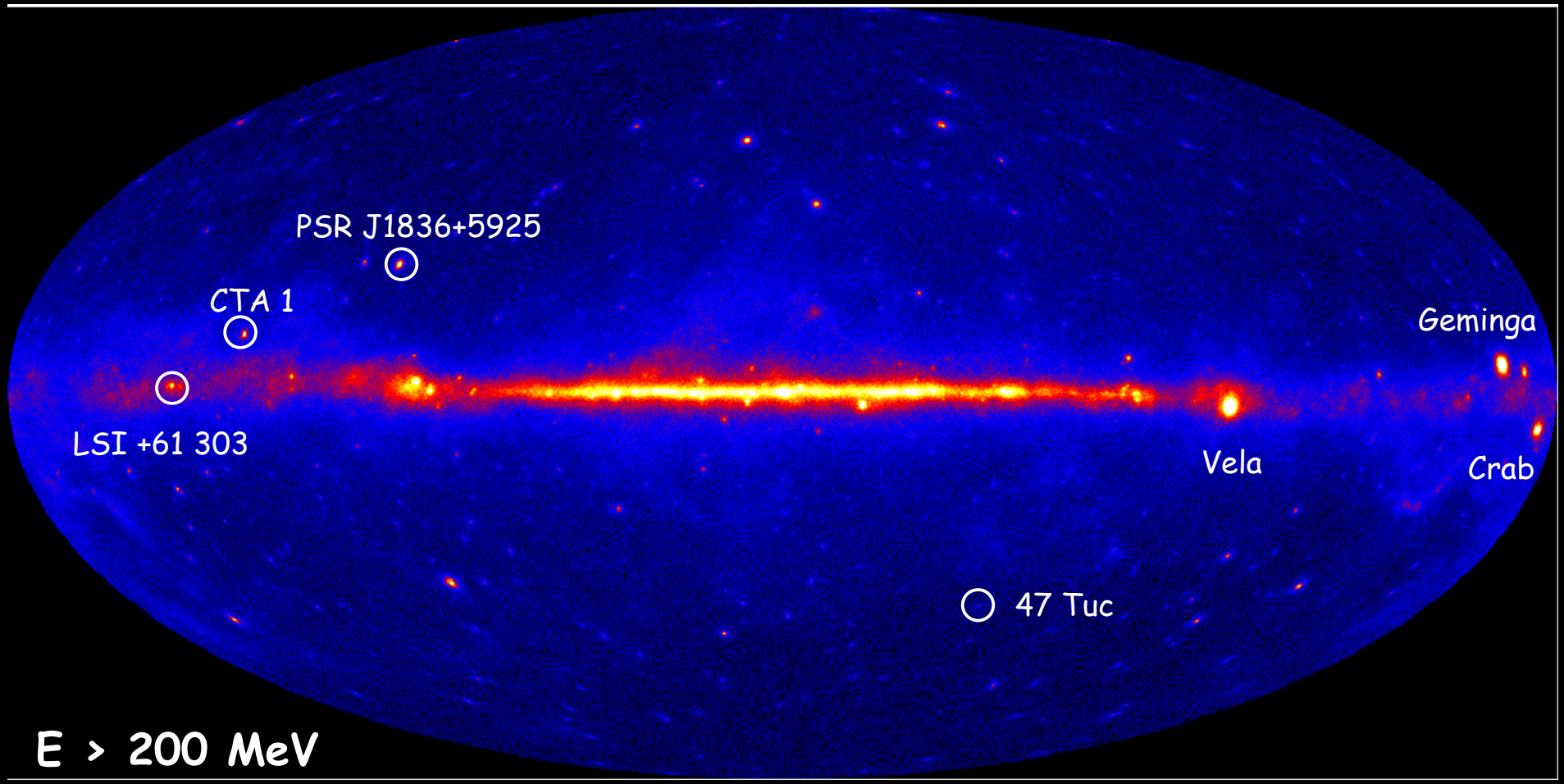


1 year simulation of Fermi LAT



9-month all-sky survey

Fermi-LAT reveals best ever view of the gamma-ray sky !



Fermi needs timing measurements

Gamma-ray photons from pulsars are not frequent (1 over 1330 rotations is received from the Crab Pulsar !!!)

Fermi observations are long (several months) => billions of rotations of the pulsar

High precision needed for the phase calculation (i.e fraction of rotation)

2 possibilities:

Blind search for Geminga-like pulsars (using Fast Fourier Transform or Time Differencing Technique that reduces the computational time)

Using known ephemeris at other wavelengths (radio or X-rays) but ATNF gives ~1800 pulsars known ! Difficult to have timing ephemerides for all

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

Who's involved ?

Jodrell Bank (England) : 102 pulsars

Parkes (Australia) : 205 pulsars

RXTE (space) : 4 pulsars

Nançay : 156 pulsars

Green Bank (USA) : 6 pulsars

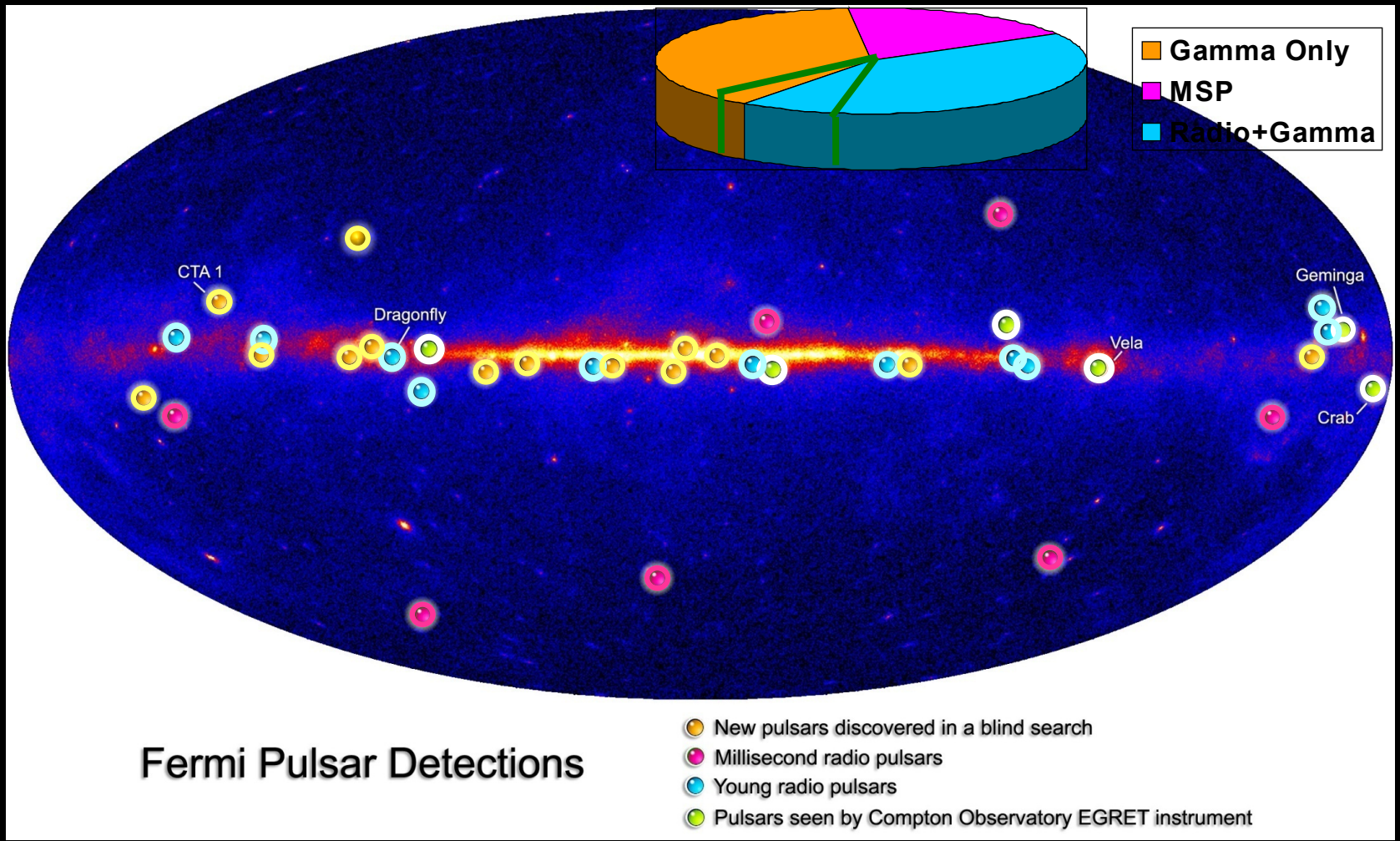
+ other contributions.

Arecibo (Puerto Rico) : 1 pulsar,
Urumqi (China) : 36 pulsars

Fermi detects slew of new pulsars !

46 gamma-ray pulsars !!! 6 before Fermi

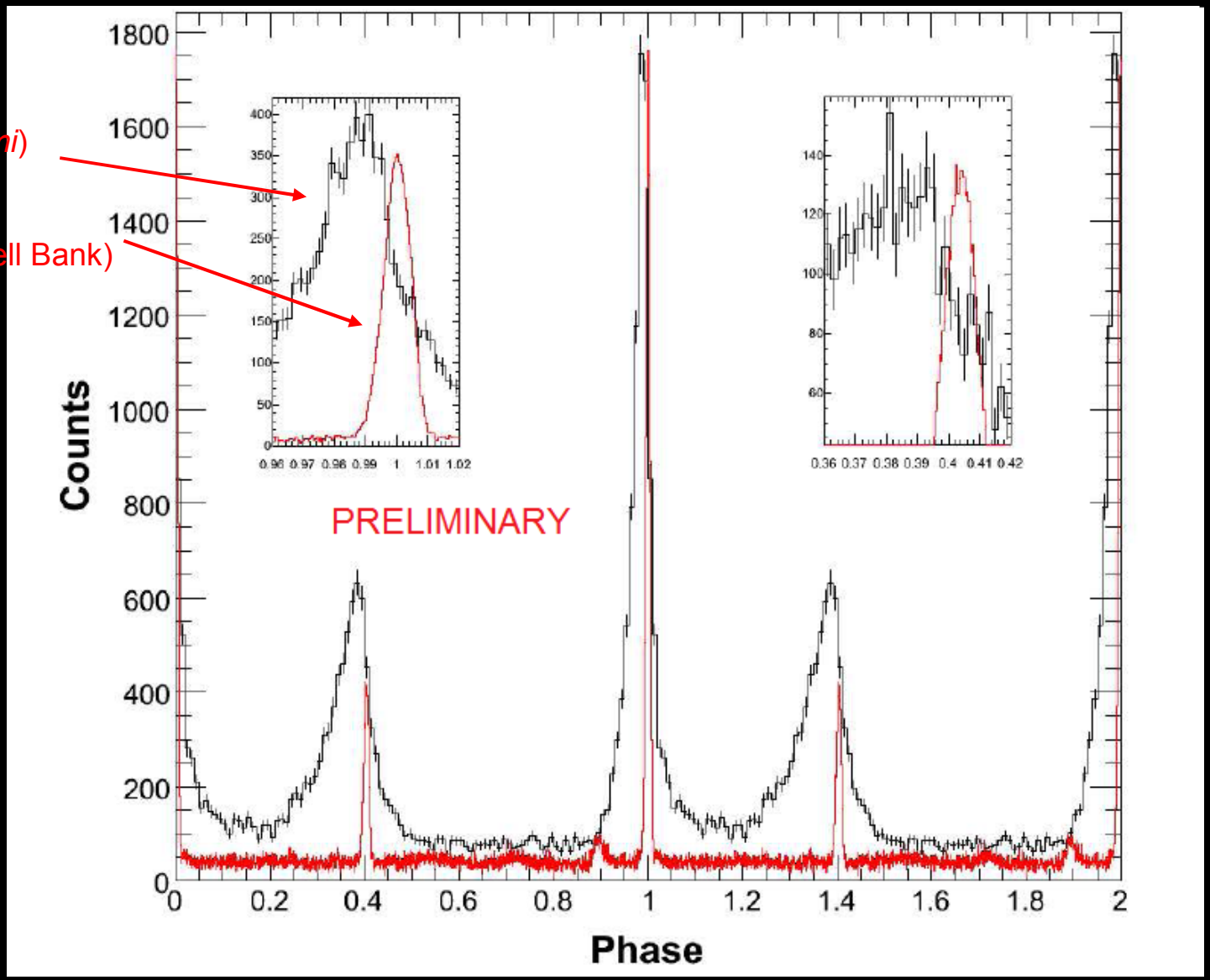
16 previously unknown pulsars (orange). Gamma-ray emissions from known radio pulsars (magenta, cyan) and from known or suspected gamma-ray pulsars (green).



The Crab pulsar

>100 MeV (*Fermi*)

1.4 GHz radio
(Nançay & Jodrell Bank)



Unprecedented timing accuracy

Solving EGRET UNIDs Example: Pulsar J1028-5819

COS-B source

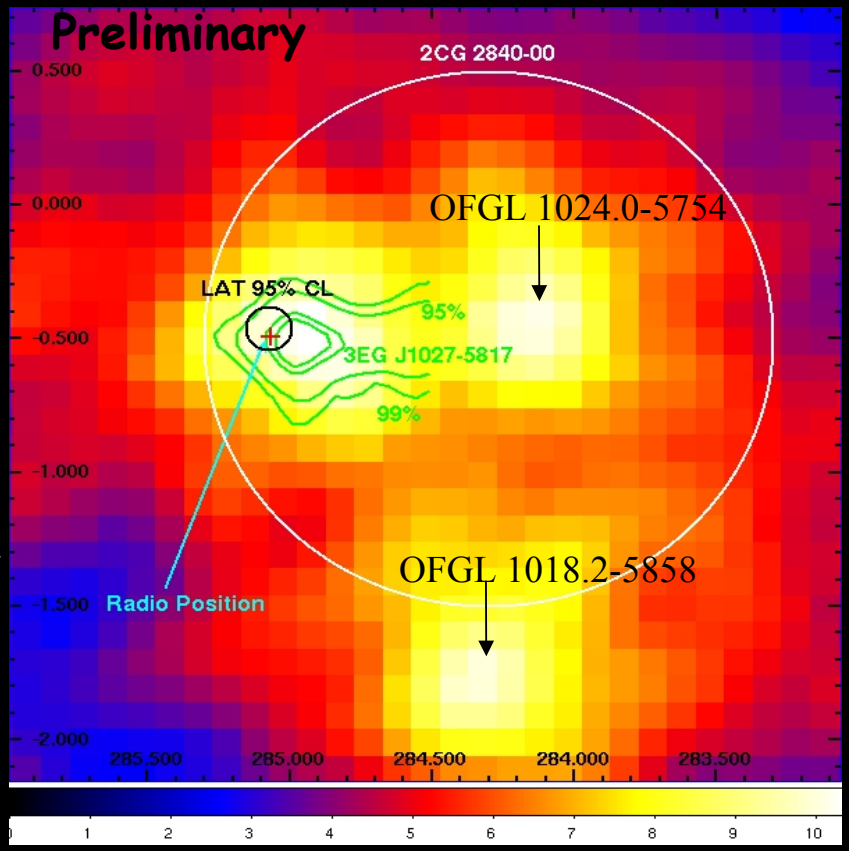
Partially Resolved by EGRET

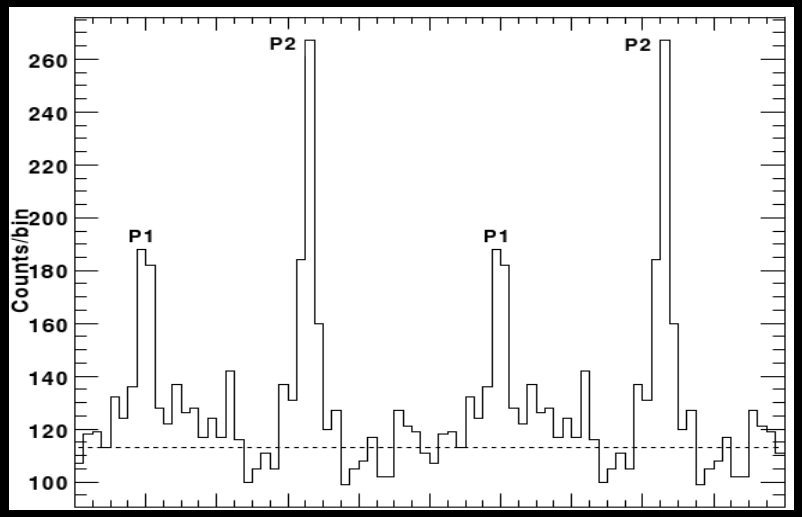
LAT point source

- (l,b)=(285.074°,-0.459°)
- 95% CL radius of 0.079°

Power law with exponential cut-off

- Cutoff ~ 2-3 GeV, index ~1.2
- Flux (0.1-30 GeV): 1.62±0.27±0.32e-07 cm^{-2} s^{-1}

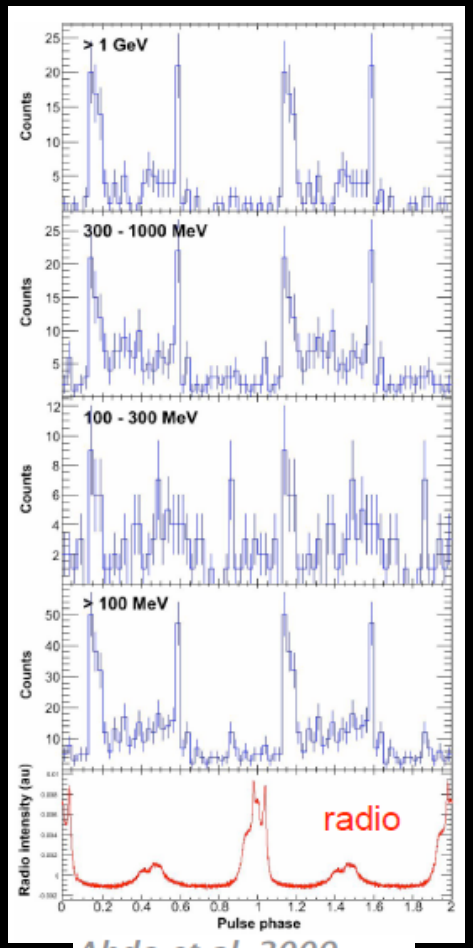




New source classes: Millisecond pulsars

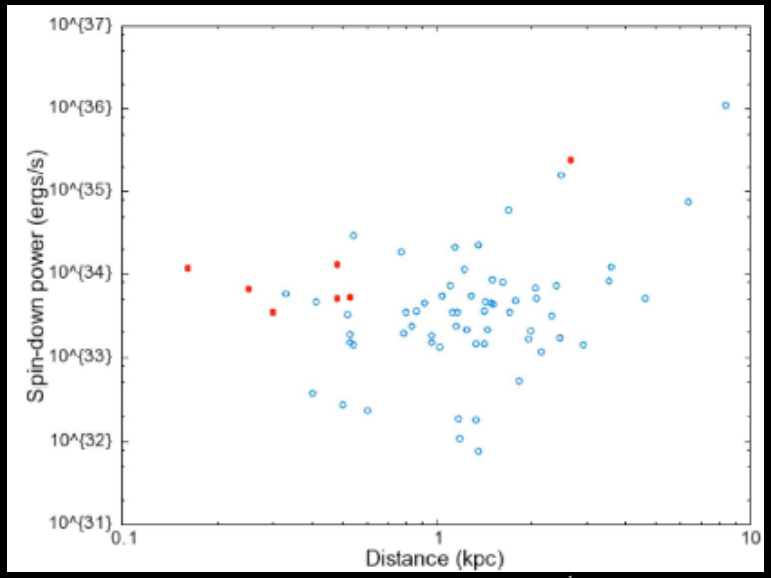
MSP: much lower surface magnetic field than normal pulsars (10^8 G vs 10^{12} G) but comparable spin-down power

J0030+0451: Fermi first MSP



Abdo et al. 2009
astro-ph/0904.4377

Detection of 8 Galactic MSPs



Abdo et al., Science Express, 2nd July 2009

So far we see the bright nearby ones

Properties (pulse profiles and spectra) reminiscent to that of normal pulsars

=> basic emission mechanism similar for MSPs and young pulsars

Millisecond pulsars in 47 Tucanae

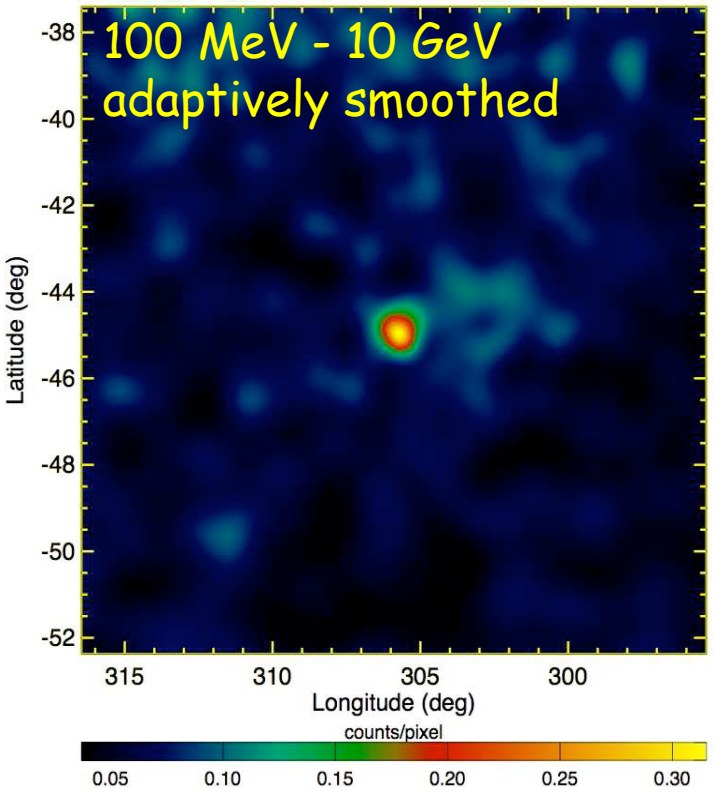
(distance ~ 4 kpc, 190+days continuous obs.)

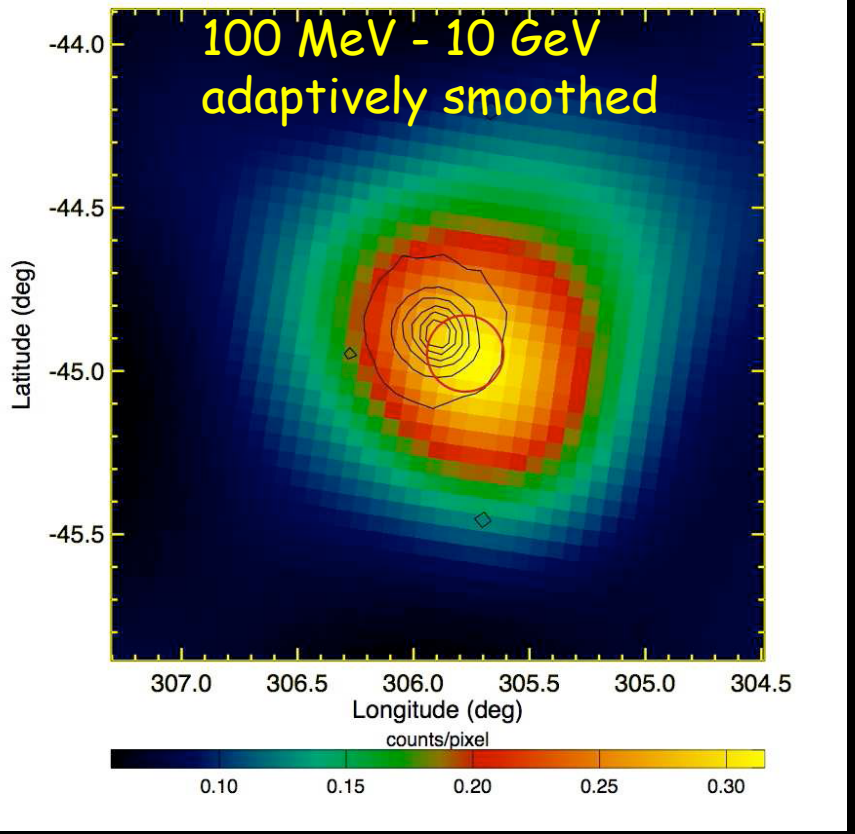
Long awaited detection of a globular cluster

Spectral shape similar to average of galactic fields MSPs

Luminosity suggests < 40 MSPs in 47 Tuc (radio/X-rays: 30-60)

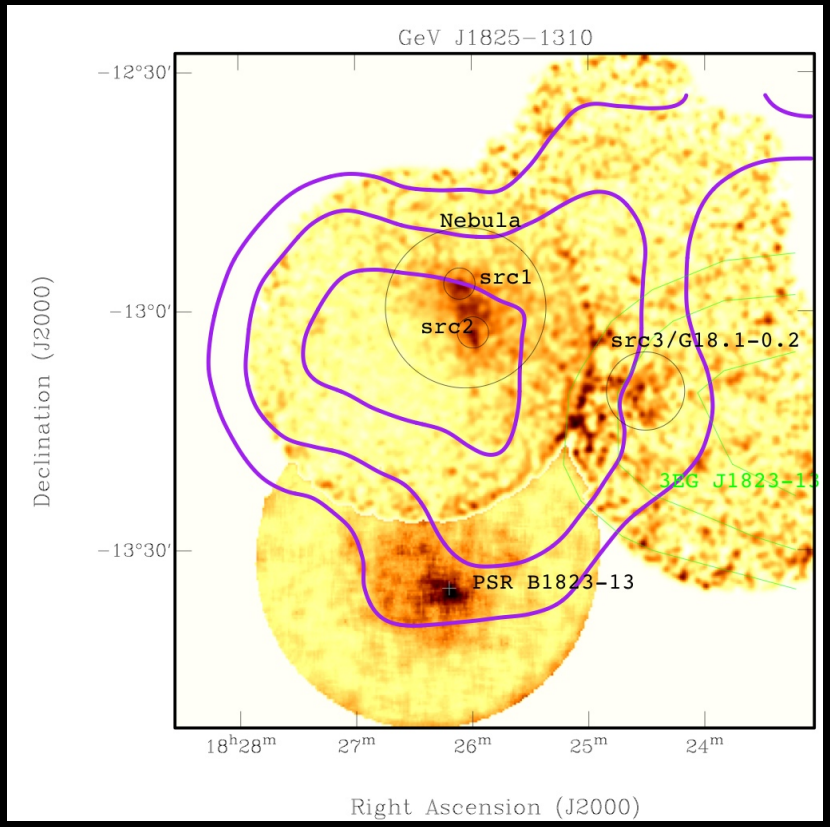
See presentation by M. Kerr



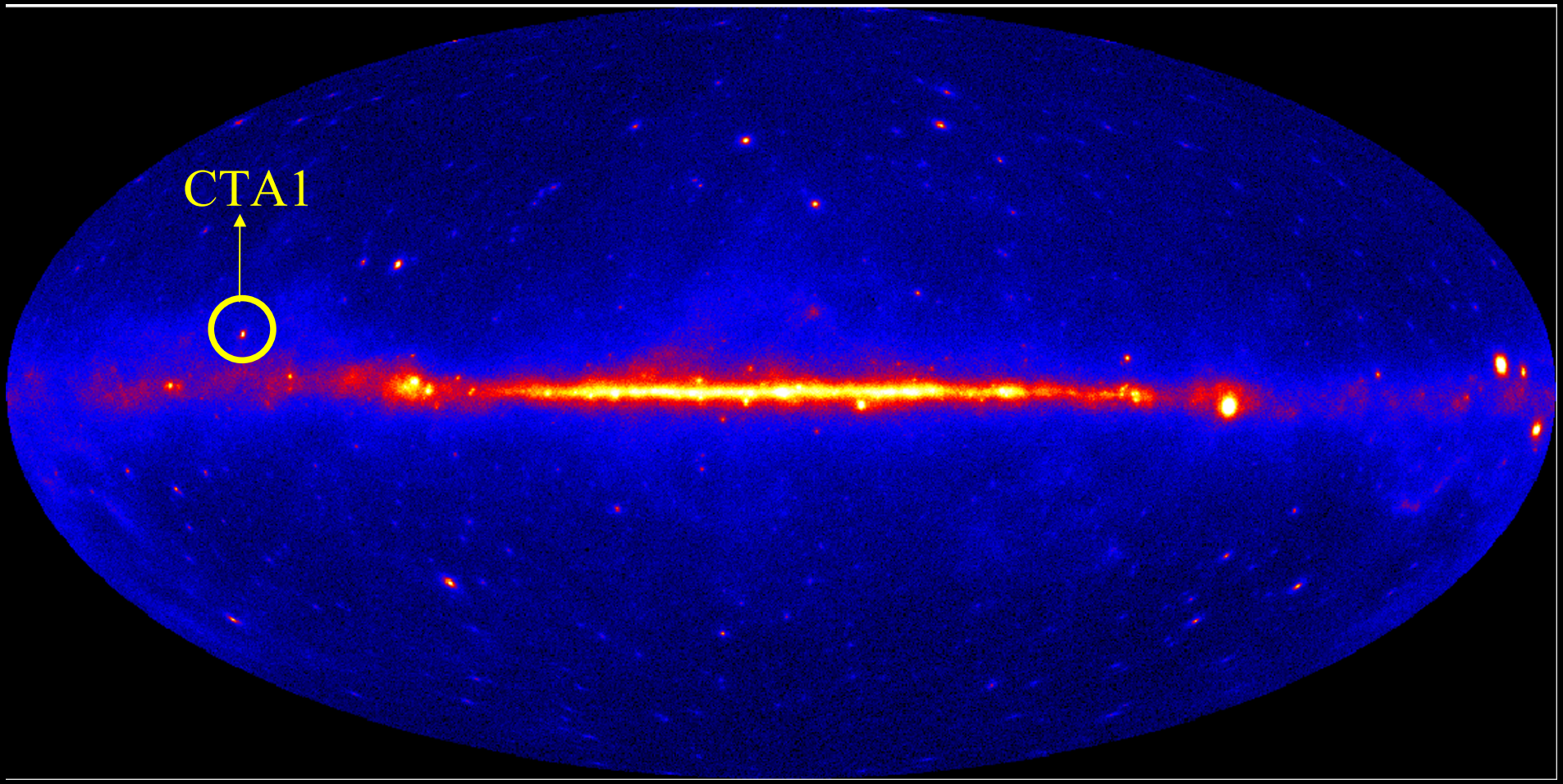


The LAT "blind" search for pulsars

- Search is "blind" in terms of timing parameters
- Where do we look?
  - ~100 "interesting" locations in the sky
  - ~200 LAT unidentified sources
- How do we search?
  - Time-differencing technique (Atwood et al. 2006, Ziegler et al. 2008)
  - Once a good candidate is found, standard pulsar tools are used: e.g. PRESTO, tempo2



A gamma-ray source in the young supernova remnant CTA1



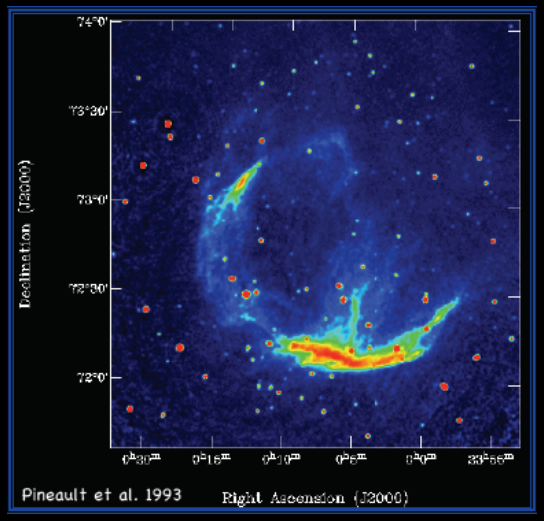
G119.5+10.2: CTA 1

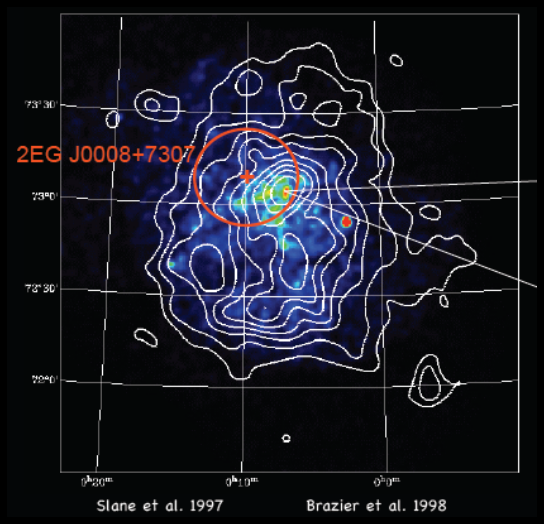
- Large diameter SNR (~90') with a partial shell morphology

  D= 1.4 ± 0.3 kpc; Age ~ 5000-15000 yrs => young SNR in the Sedov phase

  CTA1 contains a faint X-ray source RXJ0007.0+7303 at a center of a PWN

- Chandra observations: jet structure from compact source
  - Definitely a pulsar though no sign of periodicity found
- High energy emission from EGRET source 3EG J0010+7309 matches RX J0007.0+7303 though EGRET position uncertainty is very large
  - Is the EGRET source associated with the Pulsar ? The PWN ?





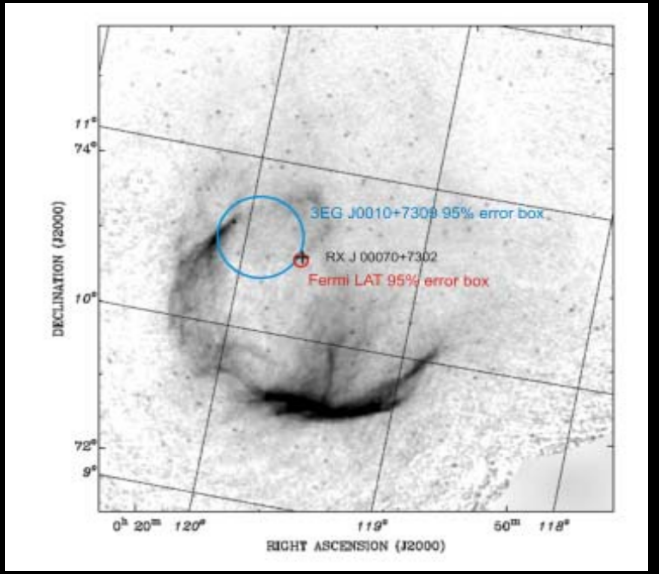
LAT discovers a radio-quiet pulsar !

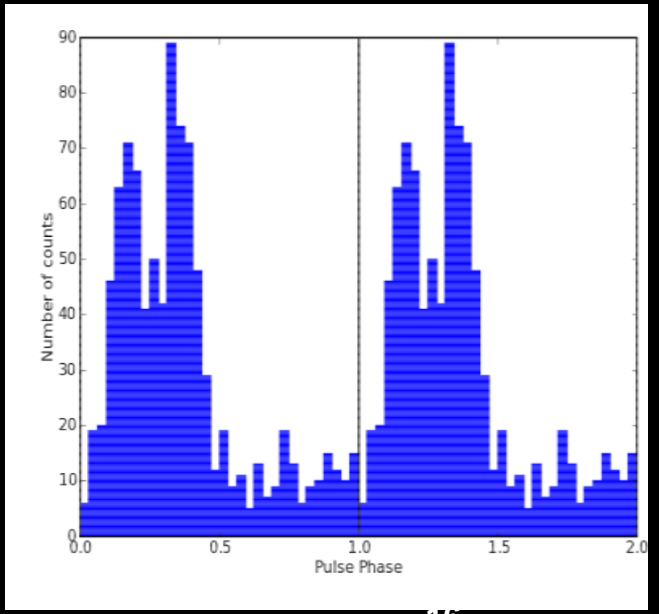
> 900 photons (E >100 MeV) detected by the LAT
Flux = (3.8 ± 0.2)E-7 ph cm^{-2} s^{-1}

Selection of γ-rays (E > 100 MeV) within a radius of 1°
Arrival time of LAT photons corrected to the solar-system barycenter using the Chandra position
Application of a blind search technique based on photon arrival time differencing

- Significant pulsations
- P ~ 316 ms
- Pdot ~ 3.6E-13
- Characteristic age ~ 14 000 yrs
- Spin down power ~ 4.5E35 erg s^{-1}

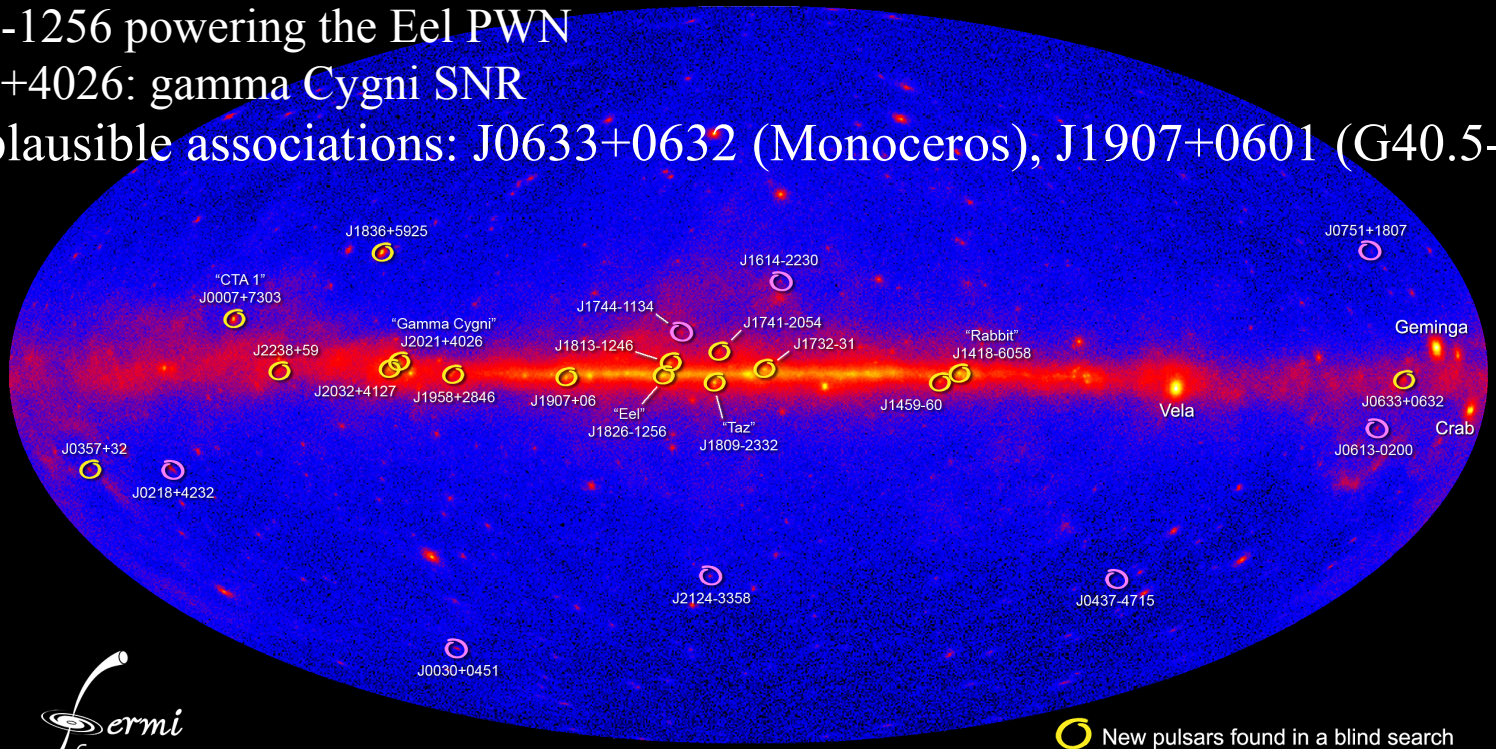
More details in:
The Fermi Gamma Ray Space Telescope discovers the Pulsar in the Young Galactic Supernova-Remnant CTA 1, Science Express, 16th October 2008 (astro-ph 0810.3562)





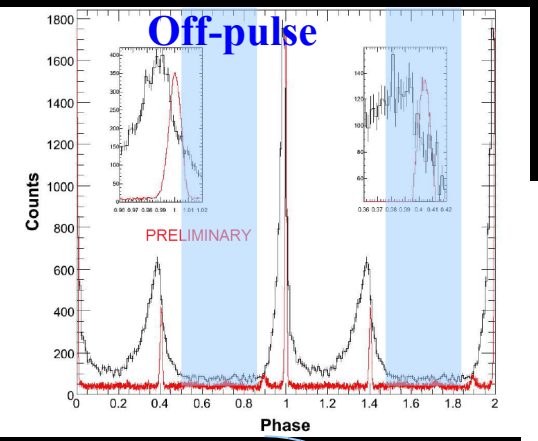
Fermi blind search pulsars: the link to SNRs and PWNe

- Detection of 16 new gamma-ray pulsars through blind frequency search: Abdo et al. , Science Express, 2nd July 2009
- 5 pulsars likely associated with PWN/SNR:
  - J0007+7303: CTA1
  - J1418-6058 (Kookaburra complex): G313.3+0.1, the Rabbit
  - J1809-2332 (Taz PWN): mixed-morphology type SNR G7.5-1.7
  - J1826-1256 powering the Eel PWN
  - J2021+4026: gamma Cygni SNR
- 2 more plausible associations: J0633+0632 (Monoceros), J1907+0601 (G40.5-0.5)

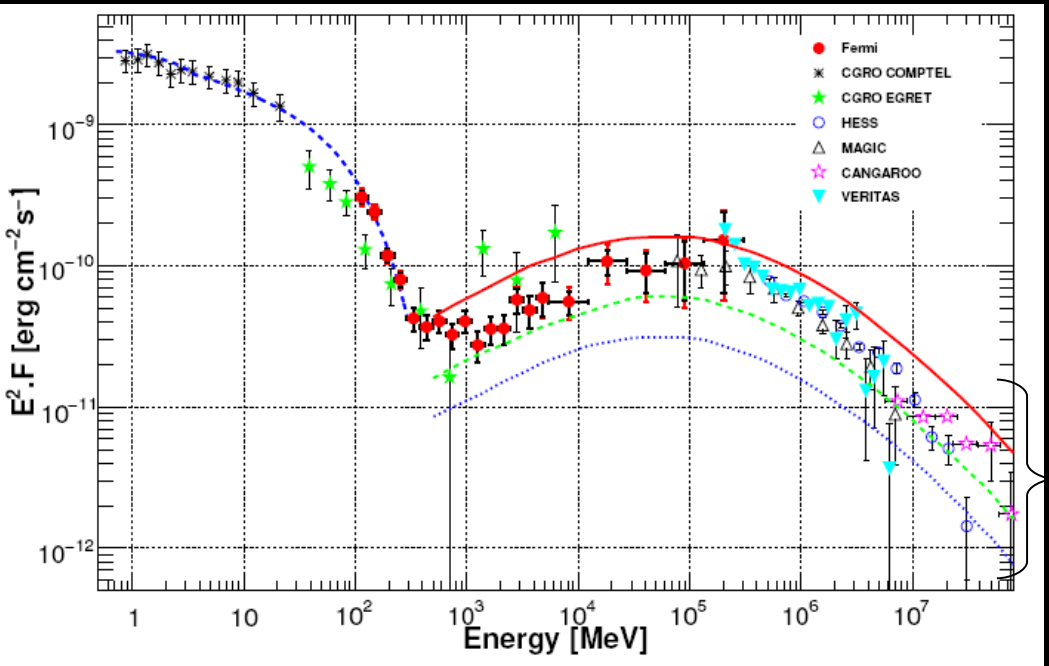


Fermi view of the Crab Nebula

- Synchrotron component fit with COMPTEL + LAT => cut-off at ~100 MeV
- No cut-off seen with LAT data only for the IC component
- LAT high energy and Cherenkov spectra link up naturally
- Overlaying predictions of *Atoyan, A.M. and Aharonian, F.A., 1996, MNRAS, 278, 525* for different nebular mean magnetic fields, the results obtained by the LAT and ground based telescopes are consistent with 100 μG < B < 200 μG, indicating a magnetic field well beyond the equipartition field in the Crab nebula (300 μG)



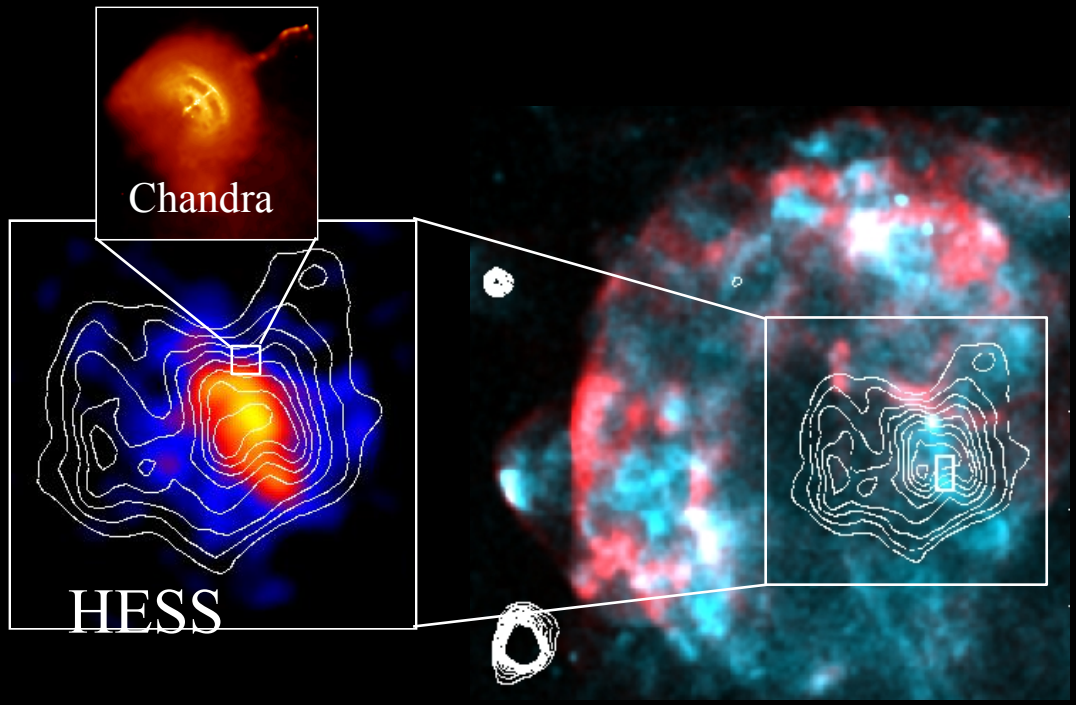
See presentation by M. Lemoine-Goumard



Predictions of Atoyan & Aharonian, MNRAS 1996,
100 μG
200 μG
300 μG

Vela X multi-wavelength observations

Elongated "cocoon-like" hard X-ray structure extends southward of pulsar
- clearly identified by HESS as an extended VHE structure
- this is not the pulsar jet (which is known to be directed to NW); presumably the result of reverse shock interaction
- an upper limit, assuming a point source at the position of Vela PSR, was reported using the first 75 days of Fermi data: **F(>100 MeV) < 4.5e-7 photons/cm^2/s** *(Abdo et al.,2009, ApJ, 696, 1084)*



Detection of a source in the Vela X region

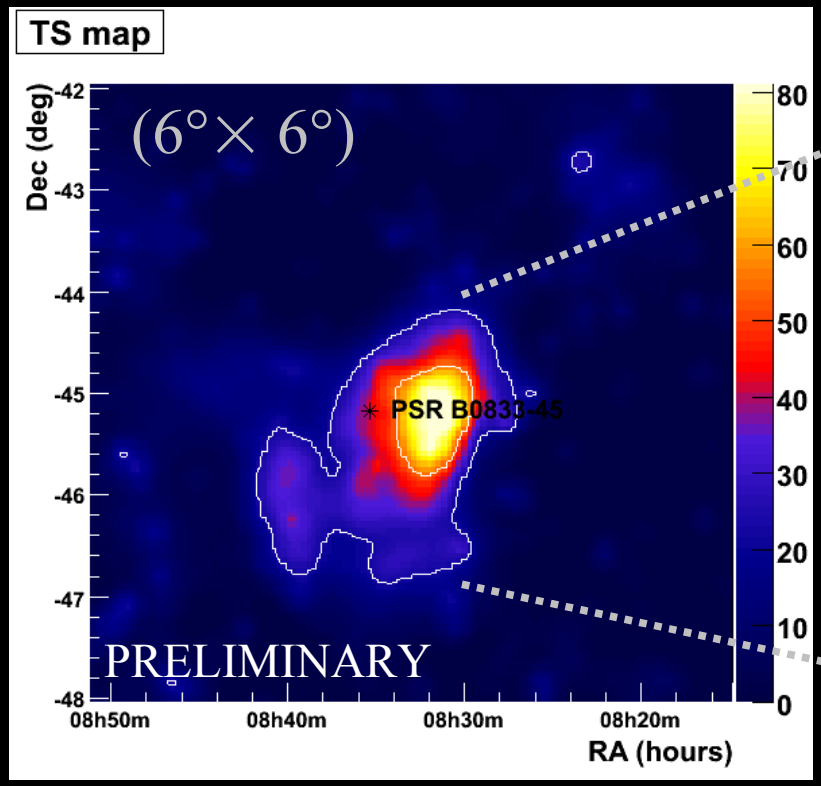
Using 9 months of survey data with Fermi-LAT and the off-pulse events:

TS ~80 (i.e ~9σ) for E > 800 MeV: significant detection

Good positional agreement with Vela X as seen with 8.4 GHz Parkes radio data

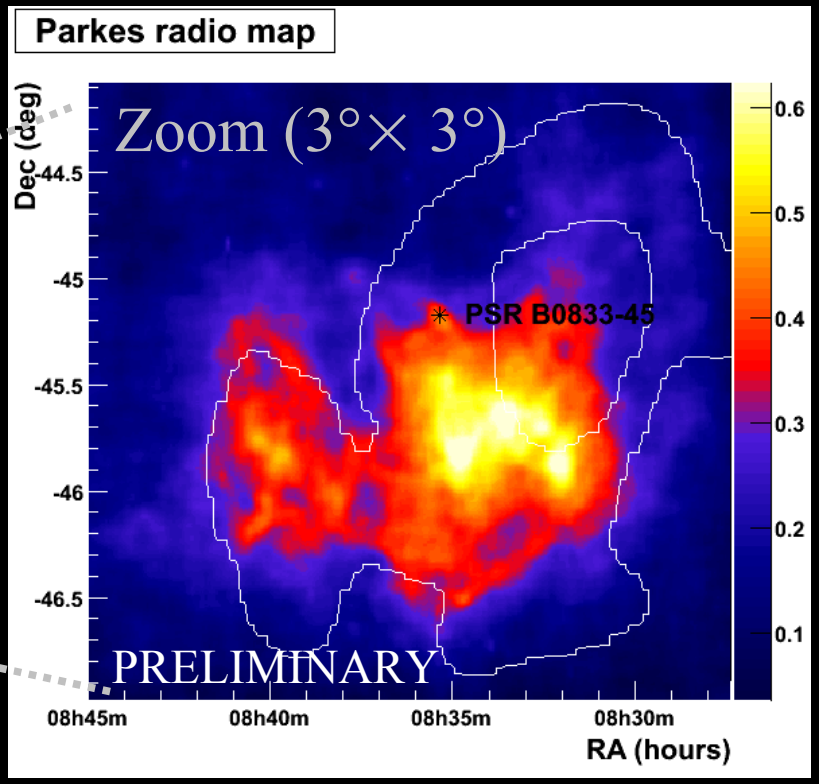
Fermi-LAT TS map (E > 800 MeV)

Fermi-LAT TS contours superimposed (white)



Parkes radio map at 8.4 GHz

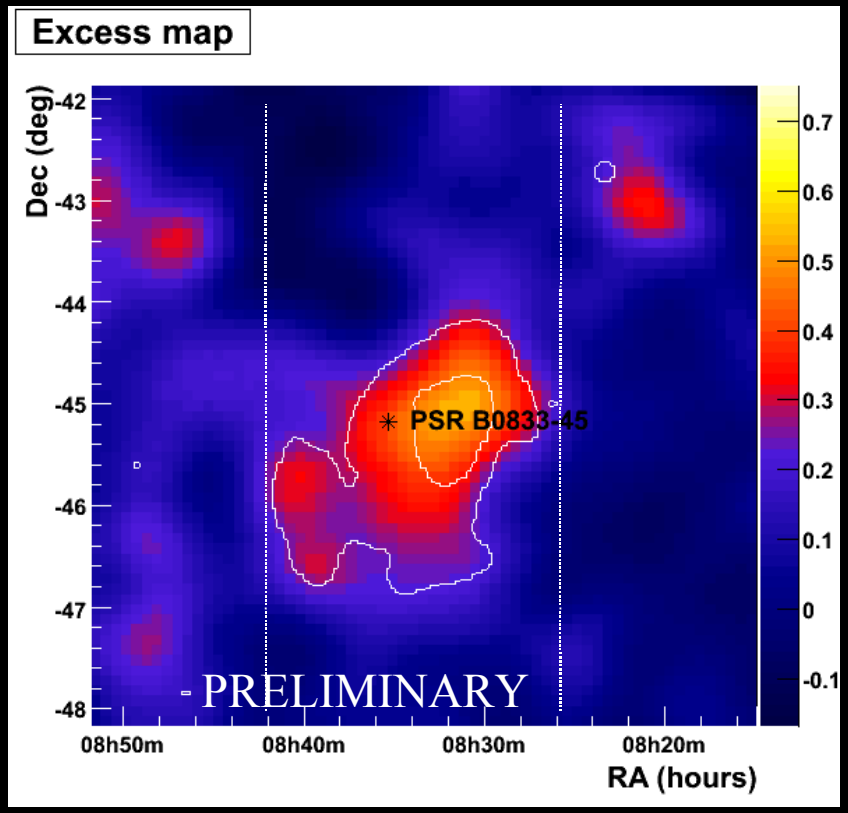
Fermi-LAT contours superimposed (white)



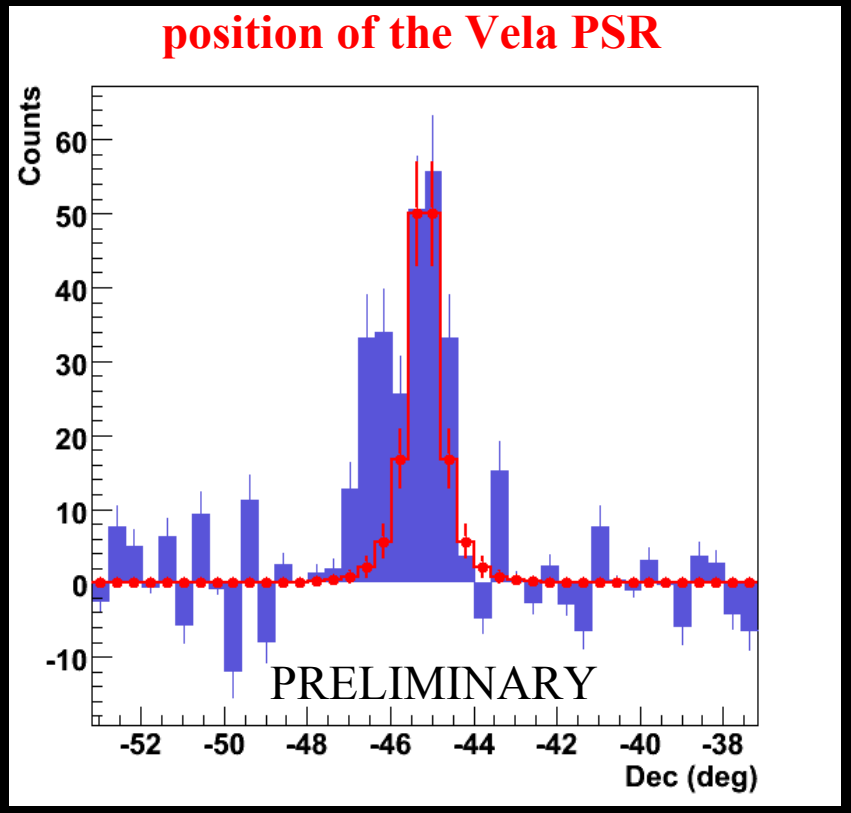
An extended source

Spatially extended !

Smoothed excess map (σ = 0.3°)
E > 800 MeV
Fermi-LAT TS contours (white)



Profile along the Declination axis
Blue: observed counts
Red: Point source simulated at the position of the Vela PSR

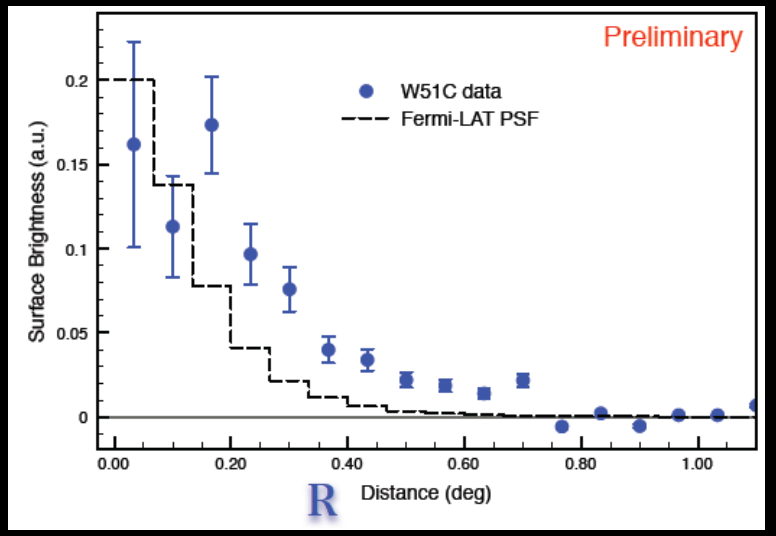


M.-H. Grondin & M. Lemoine-Goumard, ICRC, 2009

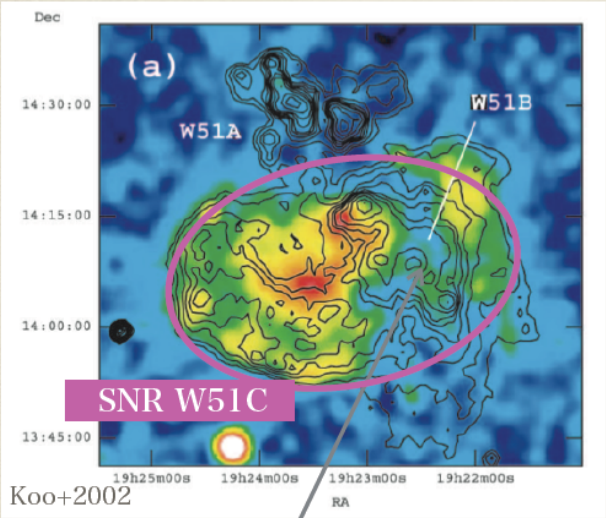
An extended source in the W51C region

See presentation by Y. Uchiyama

- D ~ 6kpc, Age ~20000 yrs
- Molecular cloud interactions
- SNR diameter ~30 arcmin
- Very recent HESS detection
- **Detection with Fermi-LAT ! Extended emission beyond the LAT PSF; very large luminosity using 6kpc (~4×10^{35} erg/s)**

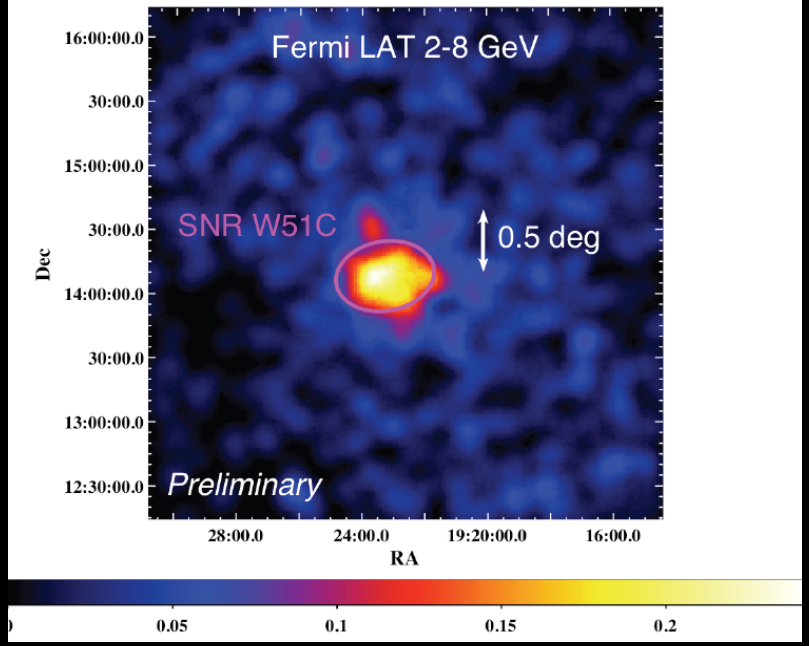


ROSAT X-ray (color), VLA (contours)



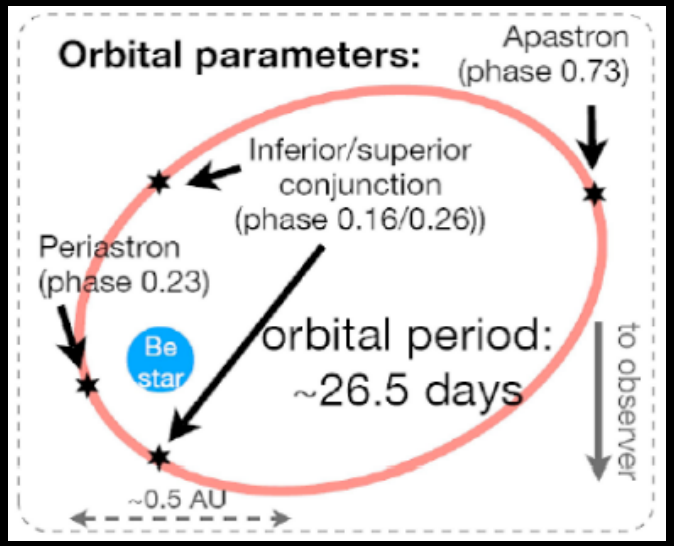
Star-forming region W51B overlaps with SNR W51C
(W51B is likely interacting with SNR W51C)

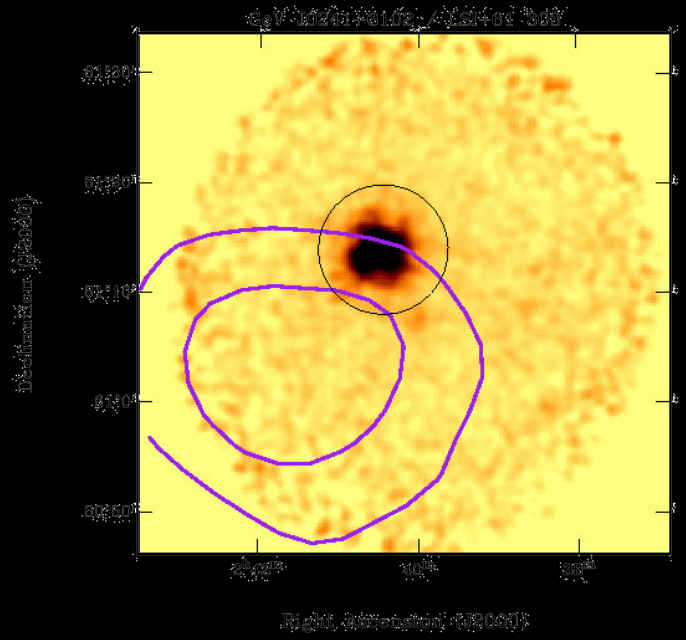
Fermi LAT counts map: very bright (>40 σ) gamma-ray source



LSI +61 303: short introduction

High mass X-ray binary at a distance of 2 kpc
Optical companion is a B0 Ve star of 10.7 mag with a circumstellar disk
Compact object probably a neutron star
High eccentricity of the orbit; Orbital period of 26.5 days
EGRET source 3EG J0241+6103 has been associated with LSI +61 303 but position is uncertain
Detection by MAGIC and VERITAS

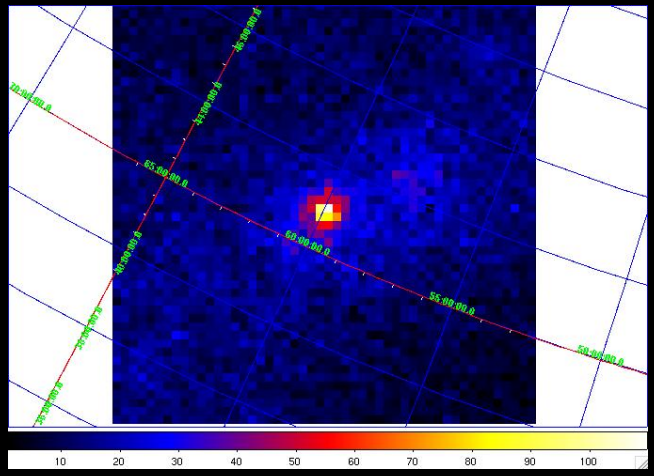


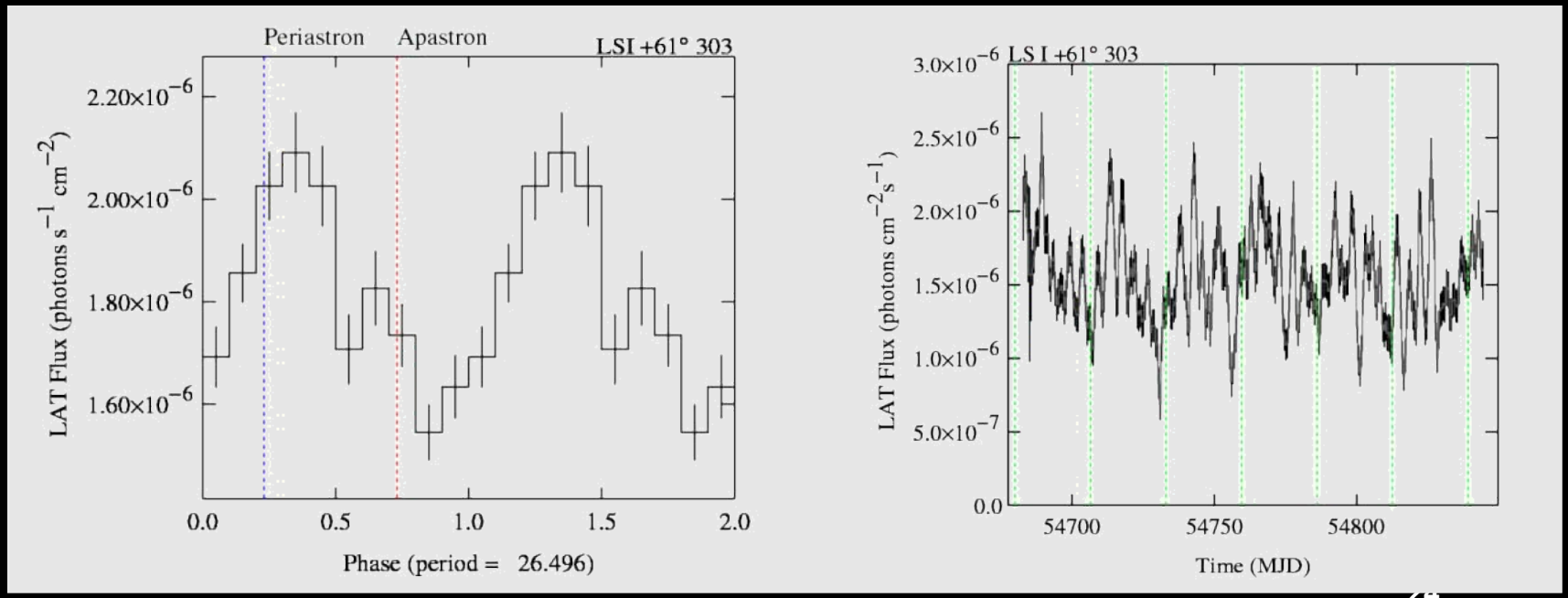


LSI +61 303: the first HE gamma-ray binary

- LS I +61°303 fitted to R.A.=40.076, Dec.=61.233 with 95% error radius of 1.8' → consistent with the known position of the optical counterpart
- Flux variability clearly evident
- Periodicity in the LS I +61°303 light curve at 26.4±0.5 days

  Folded light curve indicates peaks of emission around periastron.





LAT Transients in the Galactic Plane

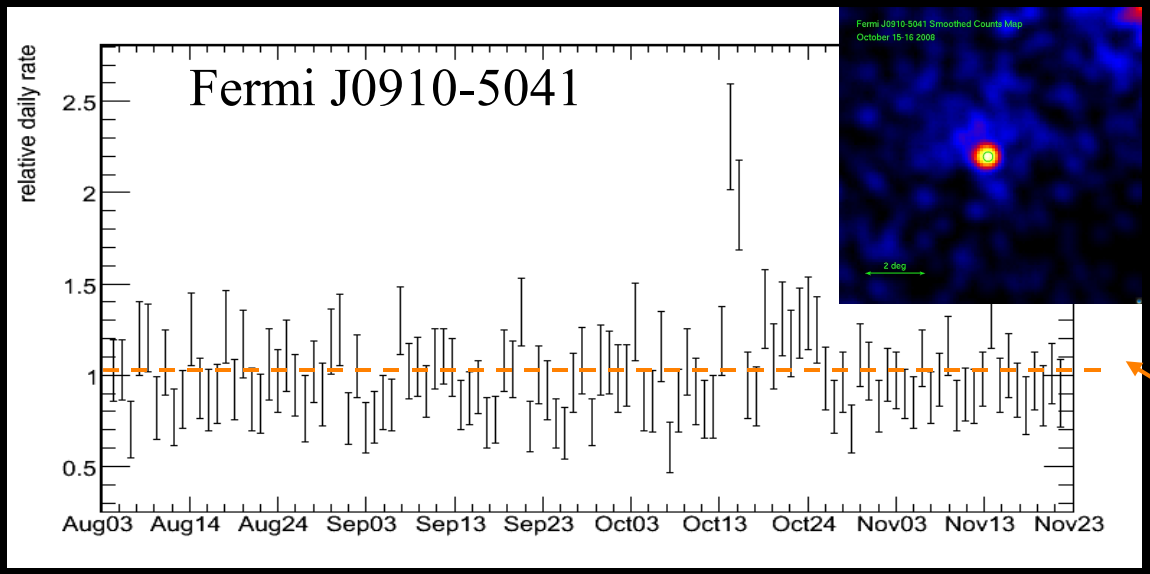
ASP flare monitoring
All sky search every 6 hours, 1 day, 1 week

- 3 unidentified transients detected near the Galactic Plane as of July 2009
- ATel #1771
  - Spatially coincident with 3EG J0903-3531
    - ~5 x brighter than EGRET
  - 68% error radius 0.11 deg
- ATel #1788
  - New GeV source, Fermi J0910-5041
  - 68% error radius 0.07 deg
- New transient on 11 June Fermi J1057-6027, gamma-ray increase within 1 day (Atel #2081)

★ Unidentified transients

○ Low latitude blazars from the bright source list

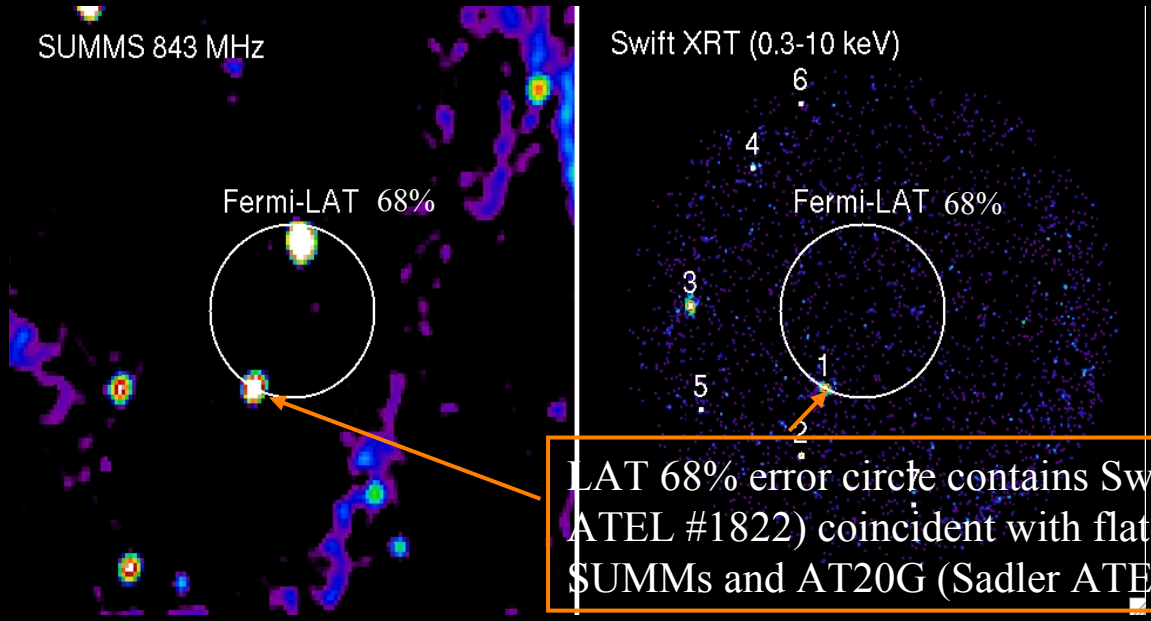
A Galactic transient detailed study: Fermi J0910-5041



Counts per day (E>200 MeV)

- 2 deg radius
- exposure corrected
- scaled to average background rate

Average background rate

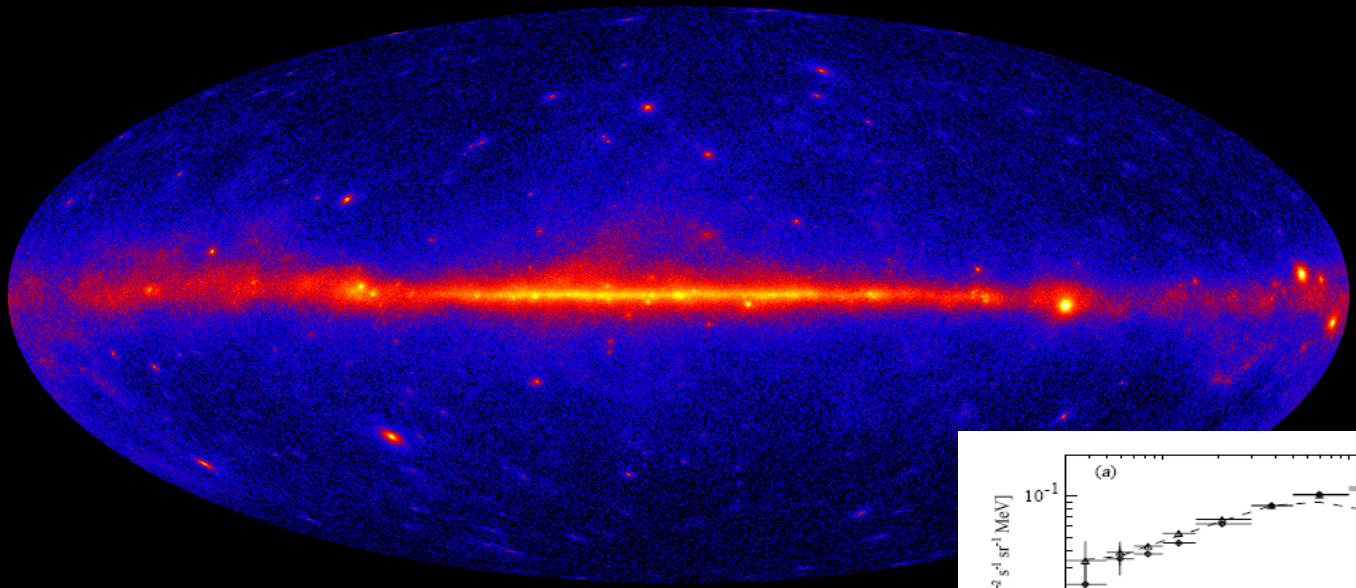


Fermi J0910-5041 (ATEL #1788)

- October 15, 2008, γ-ray increase over 2 days
- 10x above average γ-ray flux
- Swift XRT TOO within 1 day

LAT 68% error circle contains Swift XRT source (Landi et al. ATEL #1822) coincident with flat-spectrum radio source from SUMMs and AT20G (Sadler ATEL #1843)

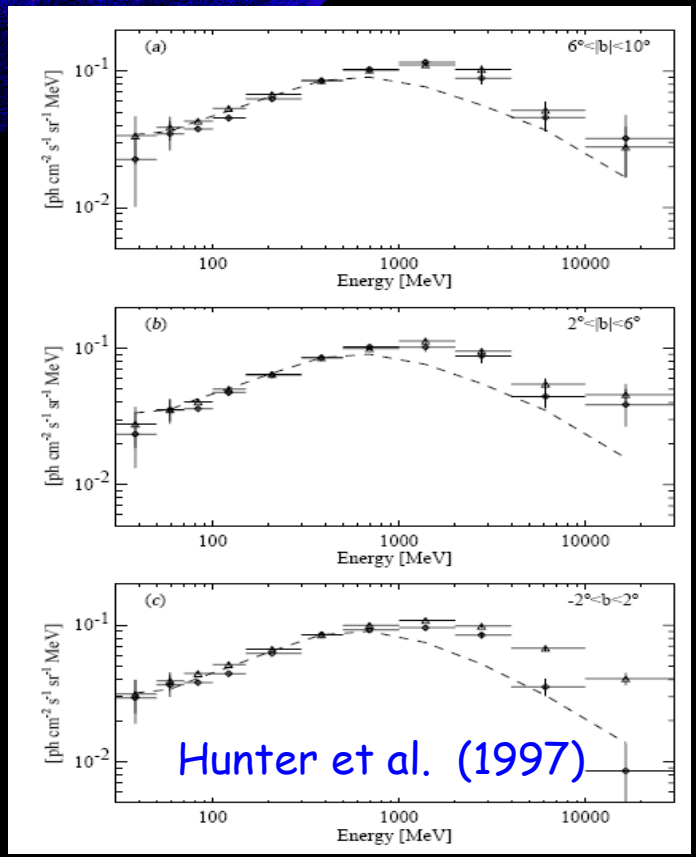
Galactic Diffuse Emission



EGRET observations showed excess emission > 1 GeV when compared with conventional model consistent with local cosmic-ray nuclei and electron spectra

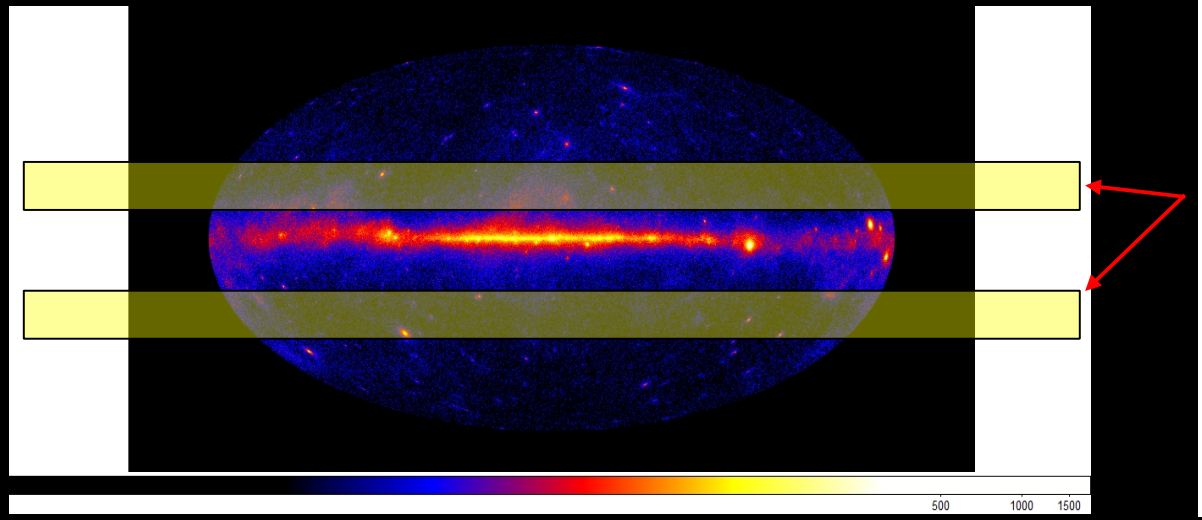
Potential explanations

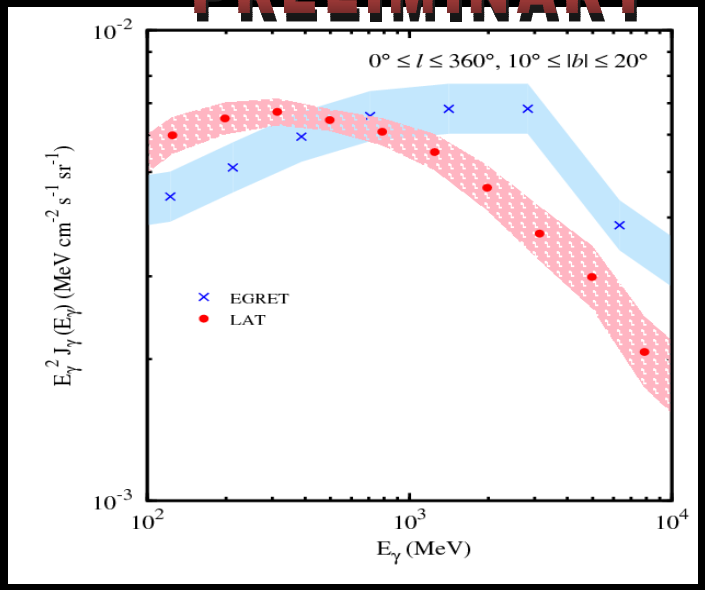
- Variations in cosmic-ray spectra over Galaxy
- Unresolved sources (pulsars, SNRs, …)
- Dark matter
- Instrumental



EGRET vs. LAT mid-latitude region: GeV excess gone !

PRELIMINARY





Data from mid-August to end of December for $10° \le |b| \le 20°$

EGRET data retrieved from GSSC (counts, exposure), processed, spectrum extracted for same region

No source subtraction (minor component)

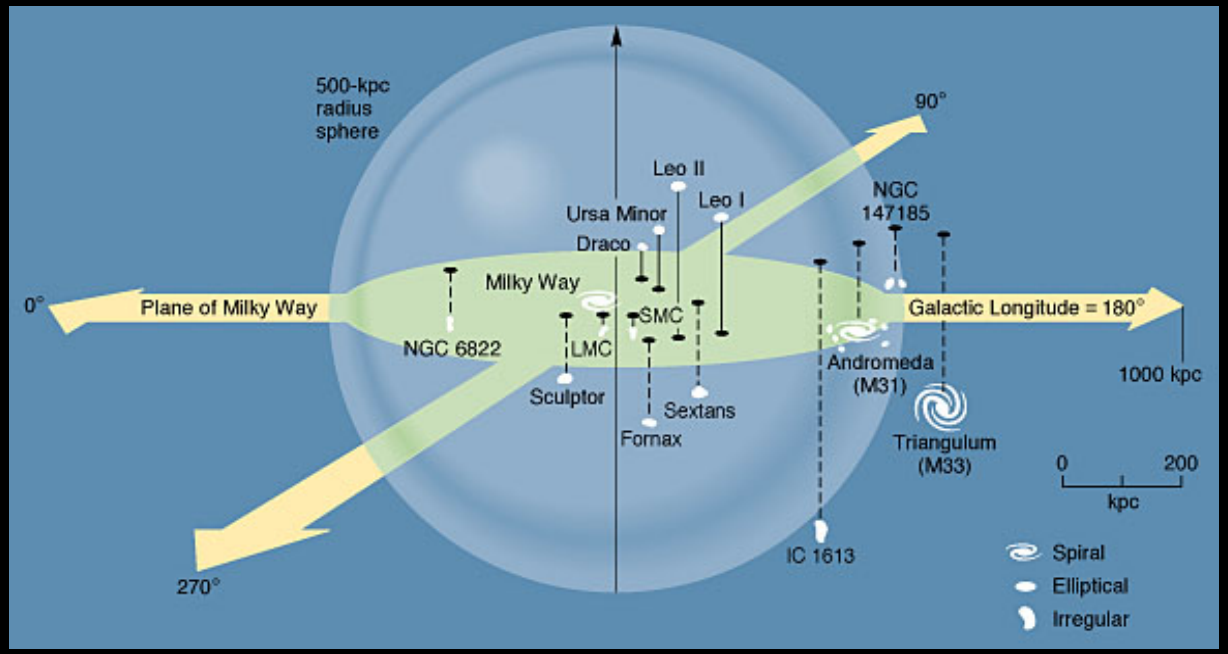
LAT spectrum is significantly softer than EGRET → we do <u>not</u> confirm the EGRET GeV excess

See presentation by T. Porter

Local Group Galaxies

- SMC non-detection by EGRET: CR density is smaller than in the MW (otherwise it would have flux ~2×10^{-7} cm^{-2} s^{-1} > 100 MeV)
- First direct evidence:

  CRs are galactic and not universal !
- LMC detection by EGRET: CR density is similar to MW

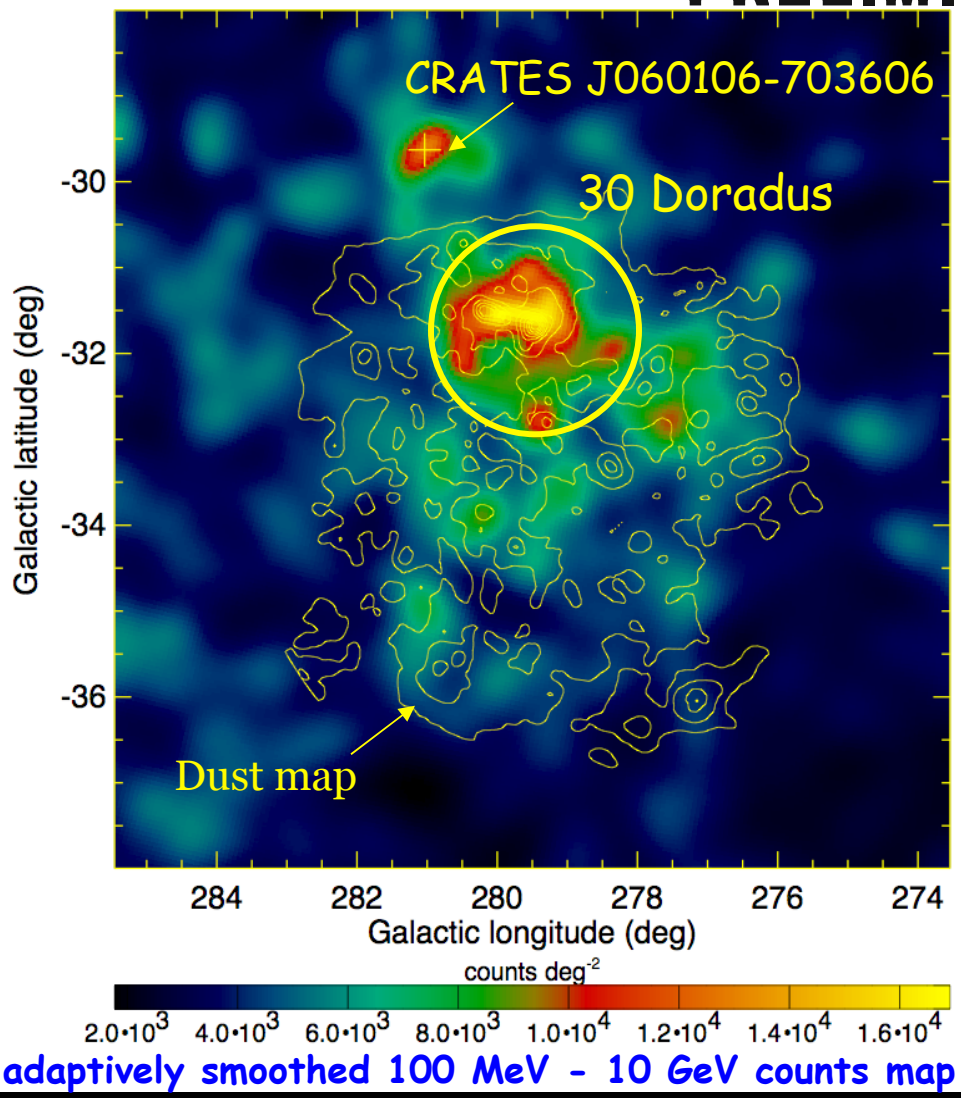


Source	F(>100 MeV), cm^{-2} s^{-1}
LMC	$(1.9\pm0.4)\times10^{-7}$
SMC	$<0.5\times10^{-7}$
M31	$<0.8\times10^{-7}$

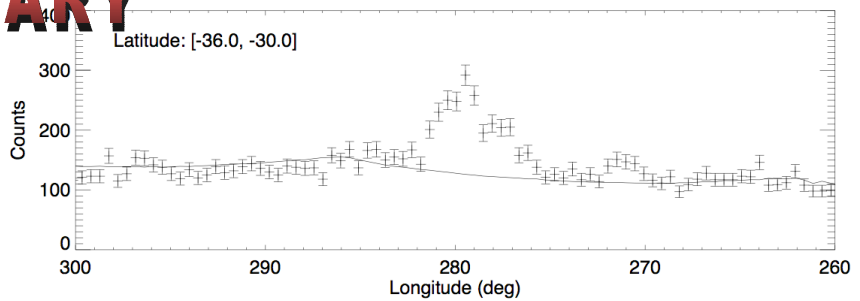
EGRET: Sreekumar et al.(1992-94)

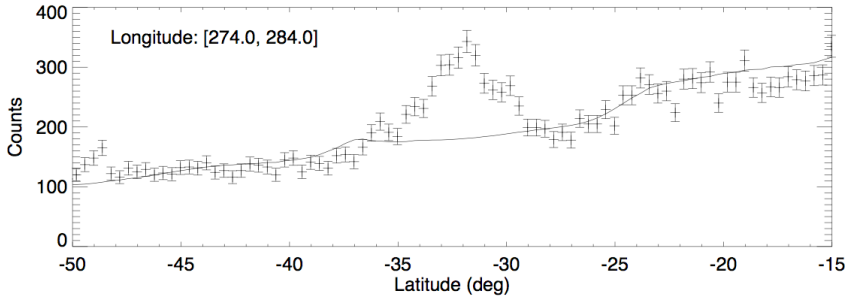
LAT/Fermi image of the LMC

PRELIMINARY



adaptively smoothed 100 MeV - 10 GeV counts map





212 days of survey data
> 2000 events above 100 MeV
Location (assuming point source):
l = 84.6° ± 0.2° (95%)
b = -69.1° ± 0.1° (95%)

Consistent with 30 Doradus / R136 location (l = 84.67°, b =-69.10°)

T. Porter, ICRC 2009

Summary

Fermi LAT nominal science operations mode for ~11 months

response and continuous all sky coverage provide significant advances

Gamma ray sources

46 pulsars detected, 16 only in gamma-rays

Solving puzzles from EGRET era and finding new source classes: globular cluster, millisecond pulsars

3 LAT transients in the Galactic Plane

Galactic diffuse emission

EGRET GeV excess not confirmed at mid-latitudes

Resolving of nearby galaxy (LMC) diffuse emission

TeV Connection

Very large energy range that allows ground-based TeV data to be combined with Fermi

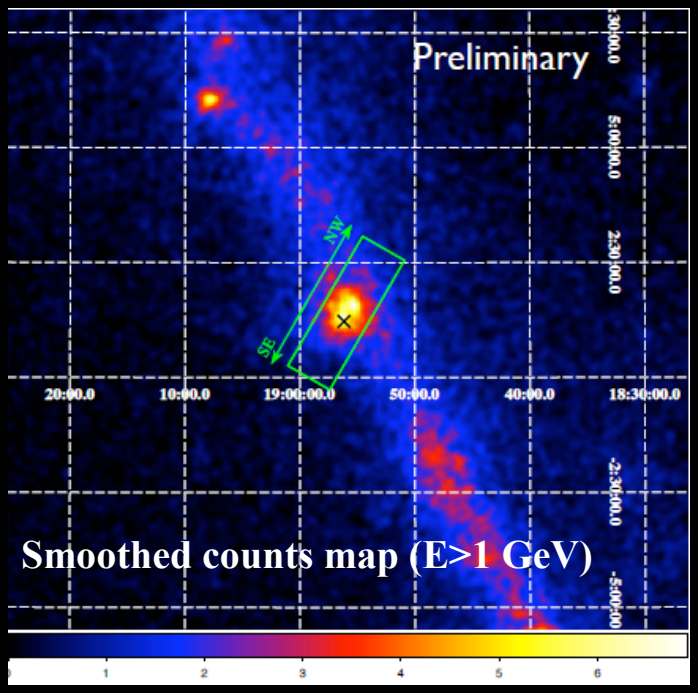
From late summer 2009 the data will become public, software to assist with data analysis is already available - come and join the fun!

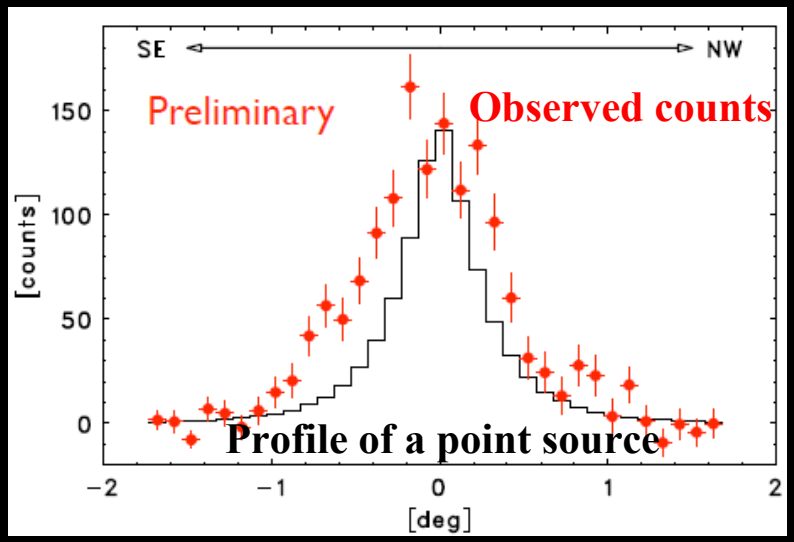
- http://fermi.gsfc.nasa.gov/ssc

Lots more science to come…

BACK-UP

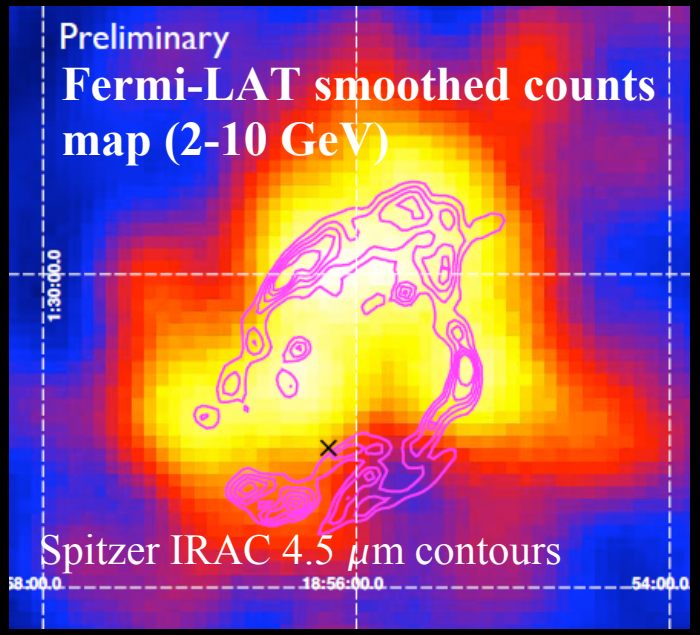
The W44 region as viewed by Fermi-LAT



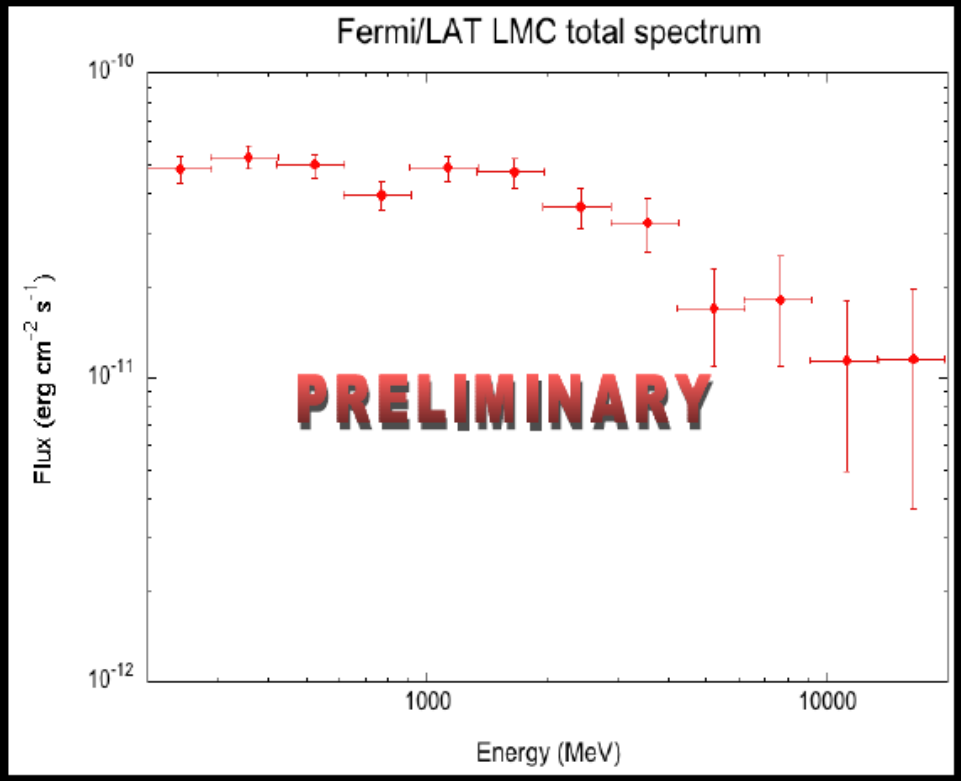


See presentation by Y. Uchiyama

- D ~ 3kpc, Age ~20000 yrs
- Molecular cloud interactions
- Spatial extent ~35 arcmin ×26 arcmin
- Spatially coincident with 3EG J1856+0114 but large error circle
- **Detection with Fermi-LAT ! Extended emission beyond the LAT PSF**



Global LMC spectrum



Derived spectrum via likelihood fitting

Model:
- SFD extinction map as gas template
- CRATES blazar
- GALPROP
- isotropic background

TABLE I: Comparison of maximum likelihood model fitting results

LMC Model	TS	Number of Parameters
Point source	869.1	4
2D Gaussian source	1088.5	5
HI gas map	1173.4	2
CO gas map	932.2	2
HI + CO gas map	1176.1	4
SFD extinction map	1179.6	2
IRIS 100 μm map	1179.1	2

Statistical errors only!