The Galaxy in a new light: GeV-TeV connection on SNR/PWN/Pulsars

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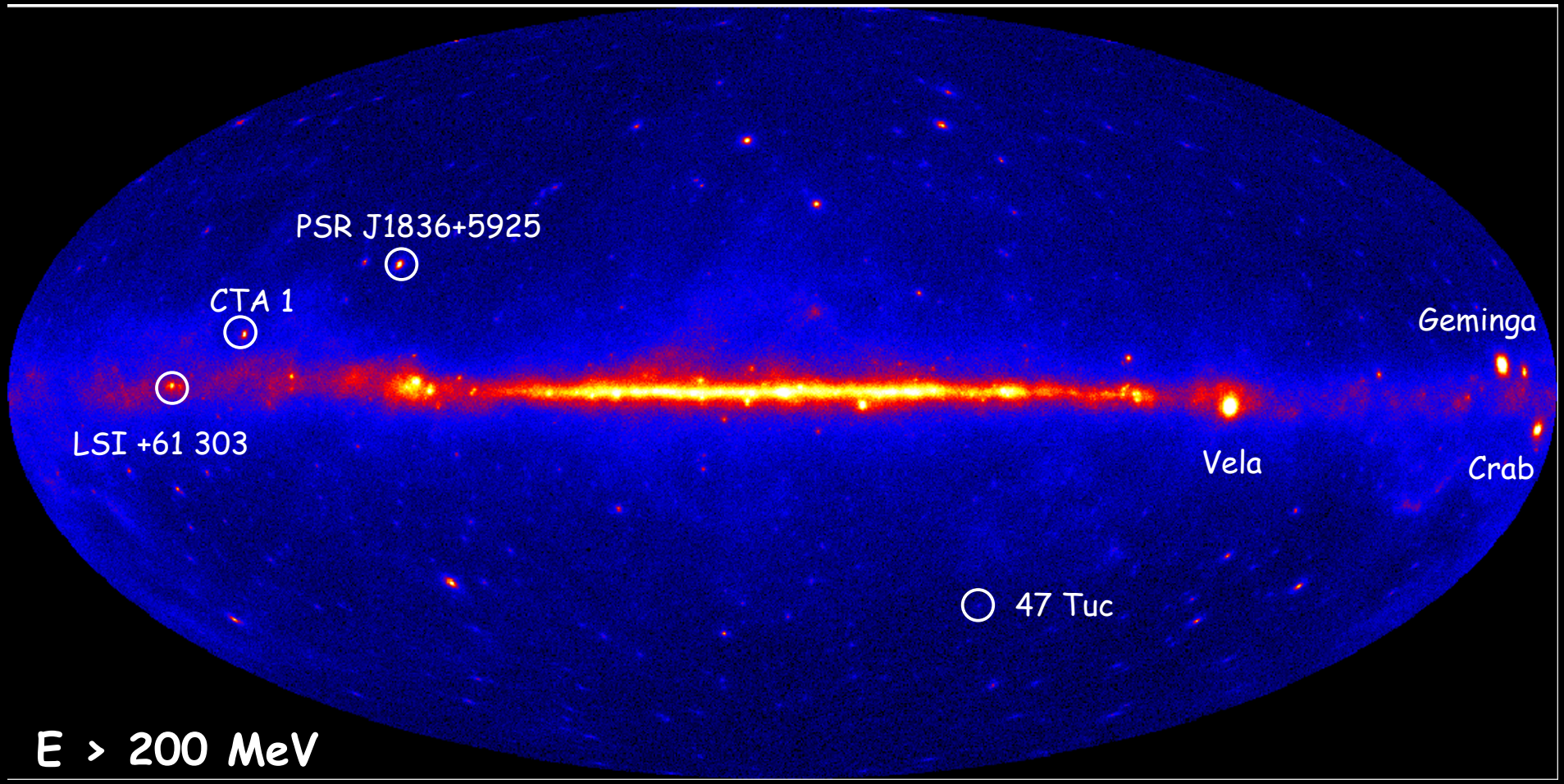
for the Fermi-LAT Collaboration

9-month all-sky survey

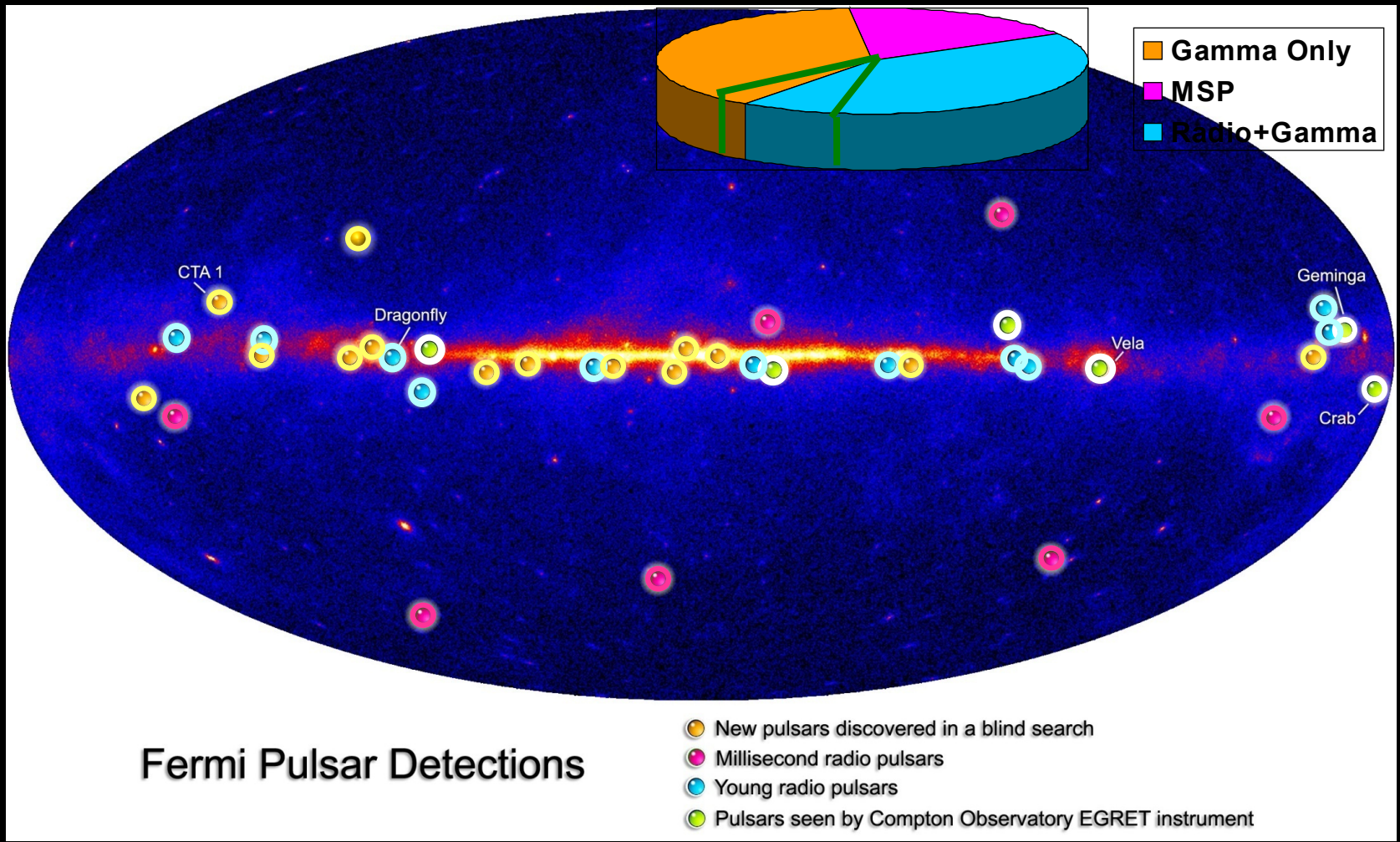
Fermi-LAT reveals best ever view of the gamma-ray sky !



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).



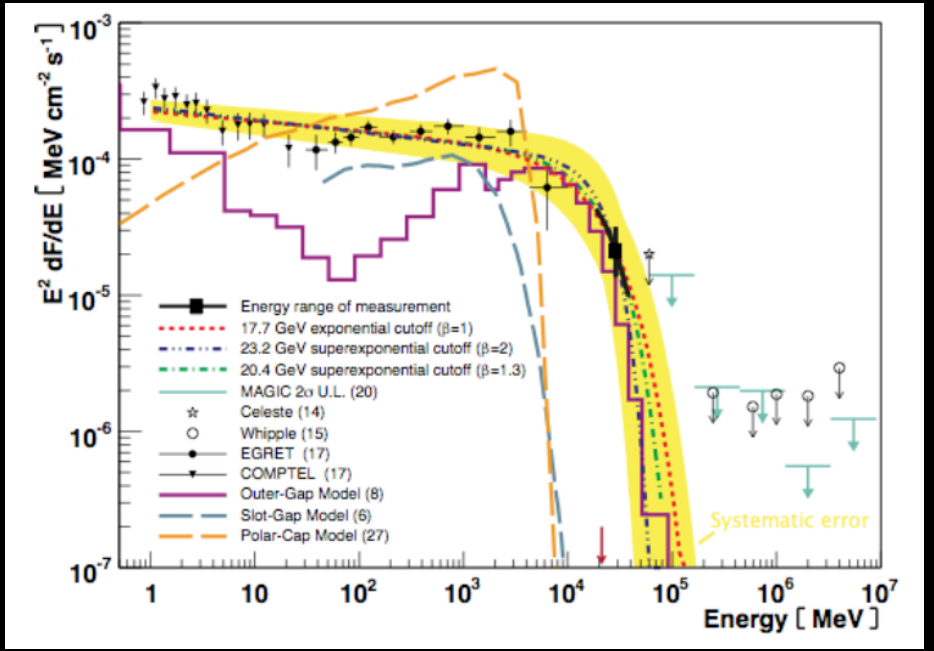
Earlier γ-ray observations of the Crab Pulsar

EGRET observations (*Nolan et al., ApJ 409:697, 1993; Fierro et al., ApJ 494:734, 1998; Kuiper et al., A&A 378:9*

- Large uncertainties on the spectrum at high energy
- No cut-off detected in the EGRET energy band
- Study of the pulsar spectroscopy

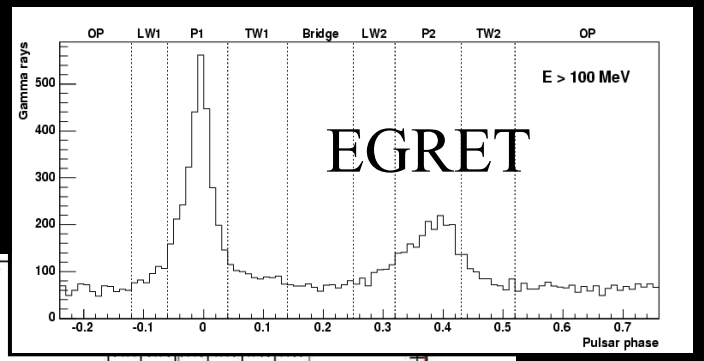
MAGIC observations above 25 GeV (*MAGIC collaboration, Science 322:1221, 2008*):

- Pulsations observed above 25 GeV
- Estimation of the cut-off energy, assuming the EGRET spectrum (spectral index of 2.022) and a simple exponential cut-off (b=1) scenario: Ec = (17.7 ± 2.8 ±5.0) GeV
- Emitting region located well above the neutron star (NS) surface



High energy spectral energy distribution of the Crab Pulsar (MAGIC collaboration, Science 322:1221, 2008)

The Crab pulsar



>100 MeV (*Fermi*)

1.4 GHz radio
(Nançay & Jodrell Bank)

Abdo et al., ApJ, submitted

PRELIMINARY

Counts

Phase

Unprecedented timing accuracy and statistics

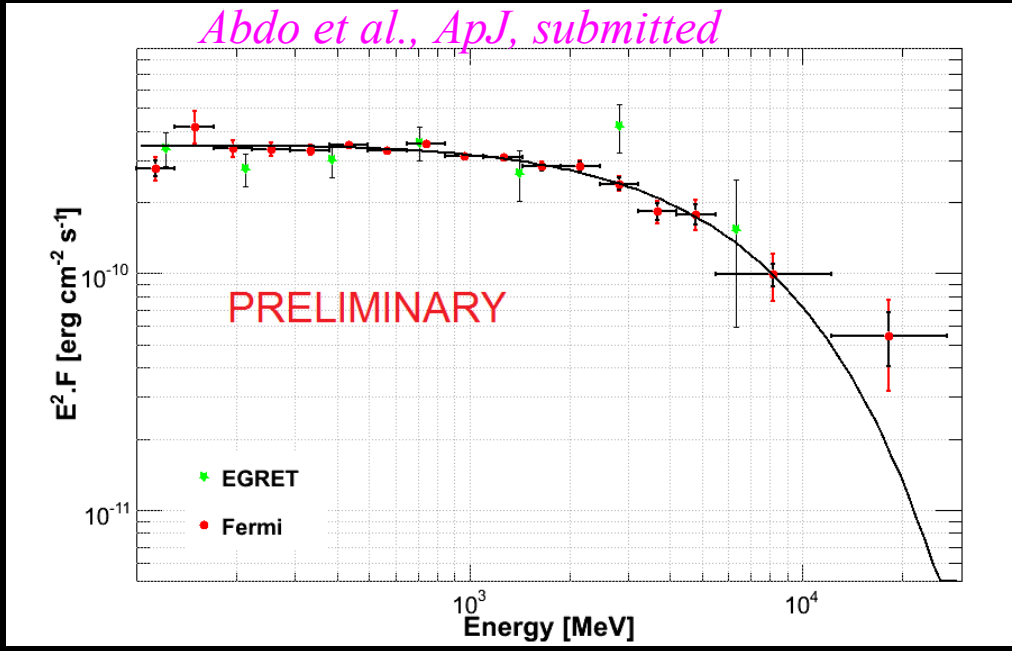
Spectral analysis of the Crab Pulsar

Analysis in the whole phase interval

Best fit above 100 MeV obtained with a power-law with an exponential cut-off

An hyper exponential cut-off (b=2) spectrum is excluded at ~ 5σ

Crab Pulsar spectral parameters:



Spectral energy distribution of the Crab Pulsar

Spectral Index ~ (1.97 ± 0.02 ± 0.06)

Cut-off energy ~ (5.8 ± 0.5 ± 1.2) GeV

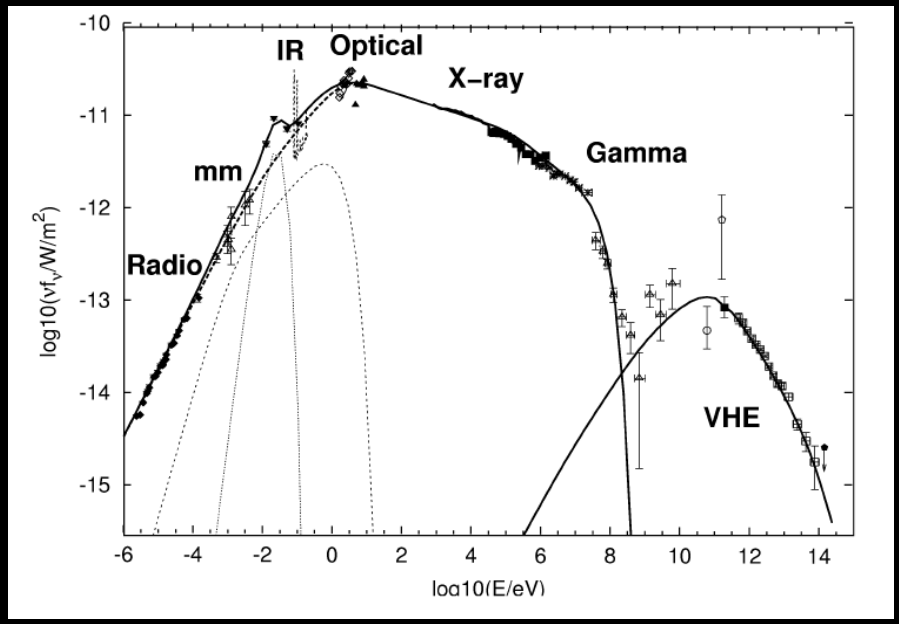
Flux above 100 MeV ~ (2.09 ± 0.03 ± 0.18)x10^{-6} cm^{-2} s^{-1}

Pulsed photons observed up to ~20 GeV

→ Consistent with an emitting region well above the NS surface, as reported by the MAGIC collaboration

Earlier γ-ray observations of the Crab Nebula

- EGRET observations of the synchrotron/Inverse Compton spectrum in the 70 MeV – 30 GeV energy band (*De Jager et al., ApJ 457:253, 1996*):
  - Large uncertainties on the spectrum shapes for both components
  - Variability observed (on year time scales) at 3.1σ level below 150 MeV, no variability for the Inverse Compton component
  - no cut-off detected for the Inverse-Compton component
- Tcherenkov
  - Inverse Compton peak energy estimated at (77 ± 35) GeV (MAGIC observations above 60 GeV (*Albert et al, ApJ 674:1037, 2008*))



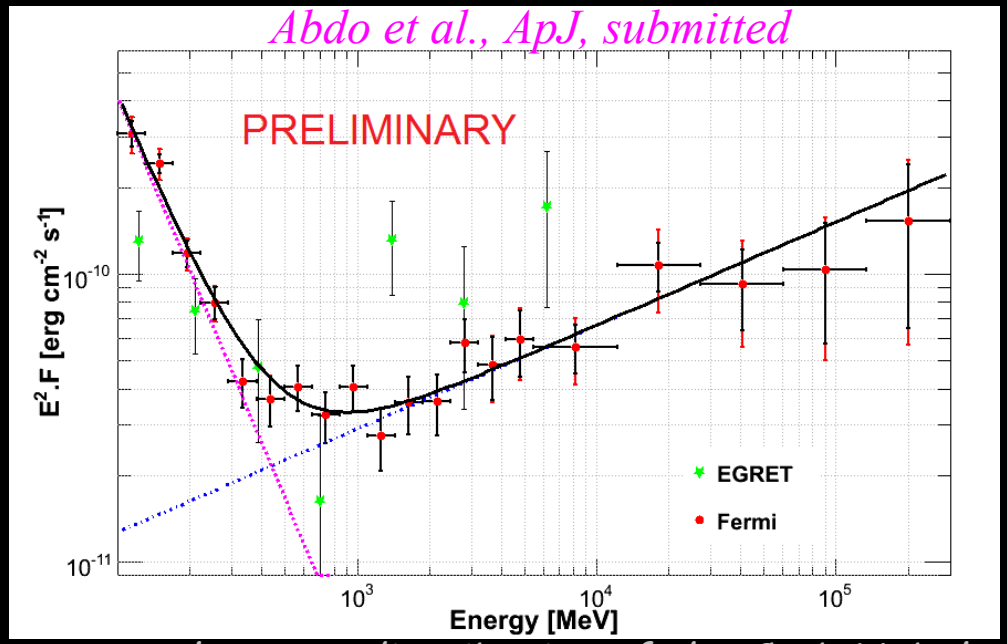
Spectral energy distribution of the Crab Nebula (Horns & Aharonian, ESAPS 552:439, 2004)

Spectral analysis of the Crab Nebula

Analysis in the off-pulse window

Synchrotron and inverse Compton (IC) components are resolved

Crab Nebula spectral parameters (renormalized to the total phase):



Spectral energy distribution of the Crab Nebula

- Spectral index (synchrotron) ~ (3.99 ± 0.12 ± 0.08)
- Spectral index (IC) ~ (1.64 ± 0.05 ± 0.07)
- Flux above 100 MeV ~ (9.8 ± 0.7 ± 1.0)x10^{-7} cm^{-2} s^{-1}

No significant cut-off and variability can be observed, neither for the synchrotron nor for the IC component

The spectral parameters for the IC component are consistent with EGRET *(De Jager et al, ApJ 457:253, 1996)*

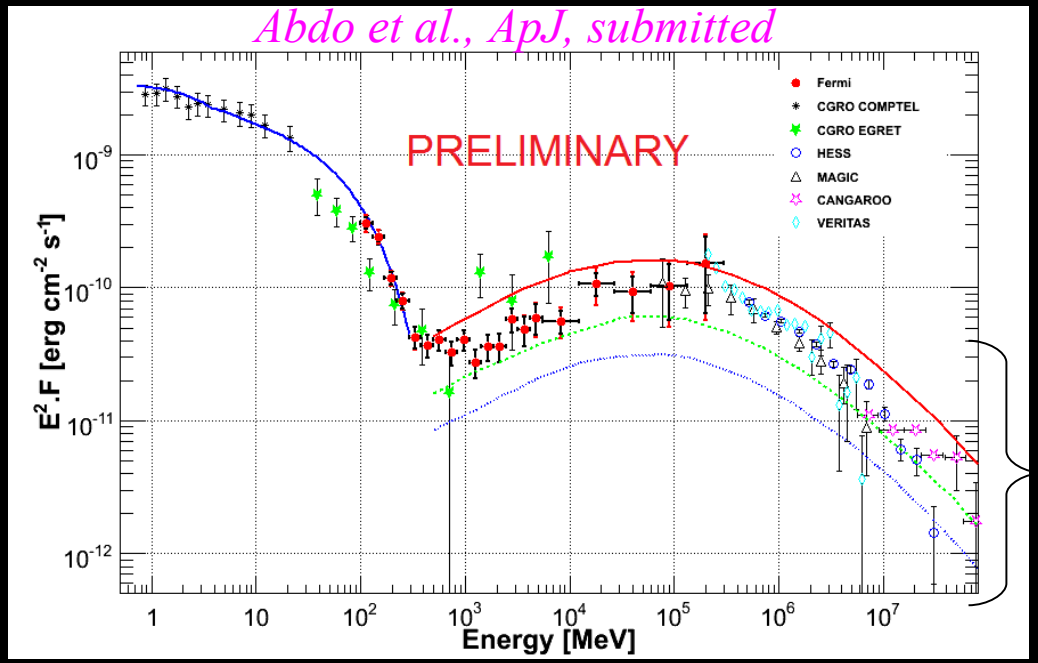
GeV-TeV connection on the Crab Nebula

- No cut-off seen with LAT only
- The LAT spectrum links up satisfactorily to the Cherenkov results.
- A joint fit (using Cherenkov and LAT results) could be performed:

→ Estimation of the cut-off or break energy

→ Cross-calibration of ground-based telescopes *(Bastieri et al., 2005)*

- The IC spectrum (LAT and Cherenkov) is consistent with a mean magnetic field 100 μG < B < 200 μG



Predictions of Atoyan & Aharonian, MNRAS 1996

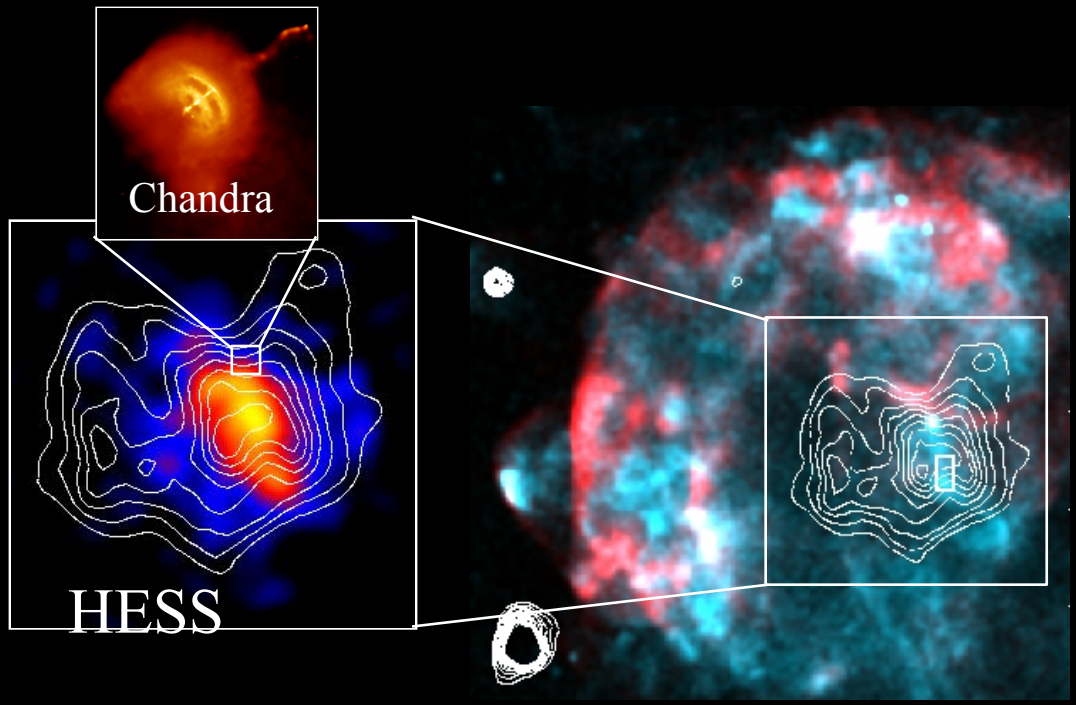
100 μG

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)*



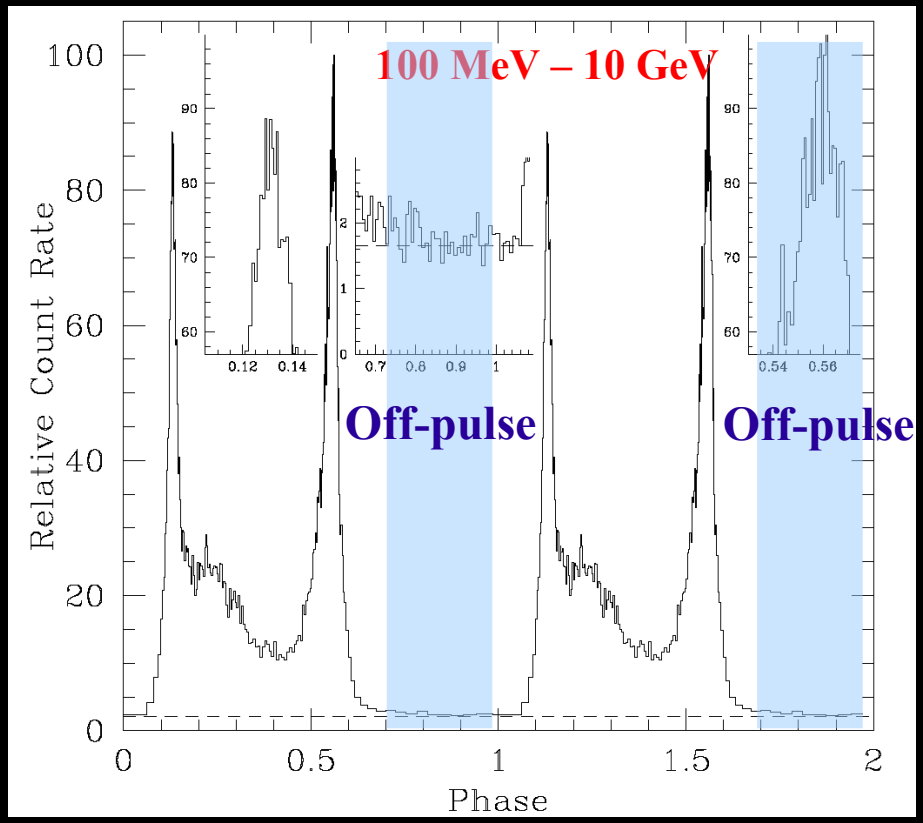
The Vela pulsar: very bright in γ-rays !

100 MeV < E < 10 GeV: ~32000 pulsed photons with 75 days of data !

Selection of a very restricted off-region to avoid the contamination of pulsed events: 0.7-1.0

Vela pulsar phase histogram (2 cycles are shown)

(Abdo et al.,2009, ApJ, 696, 1084)



Detection of a source in the Vela X region

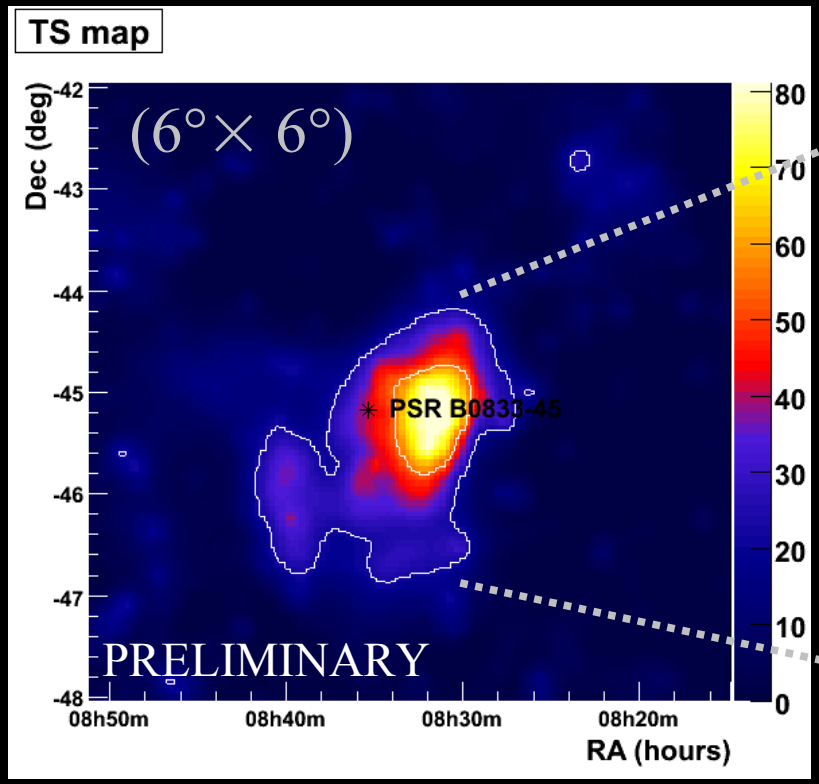
Using 9 months of survey data with Fermi-LAT and the off-pulse events:

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

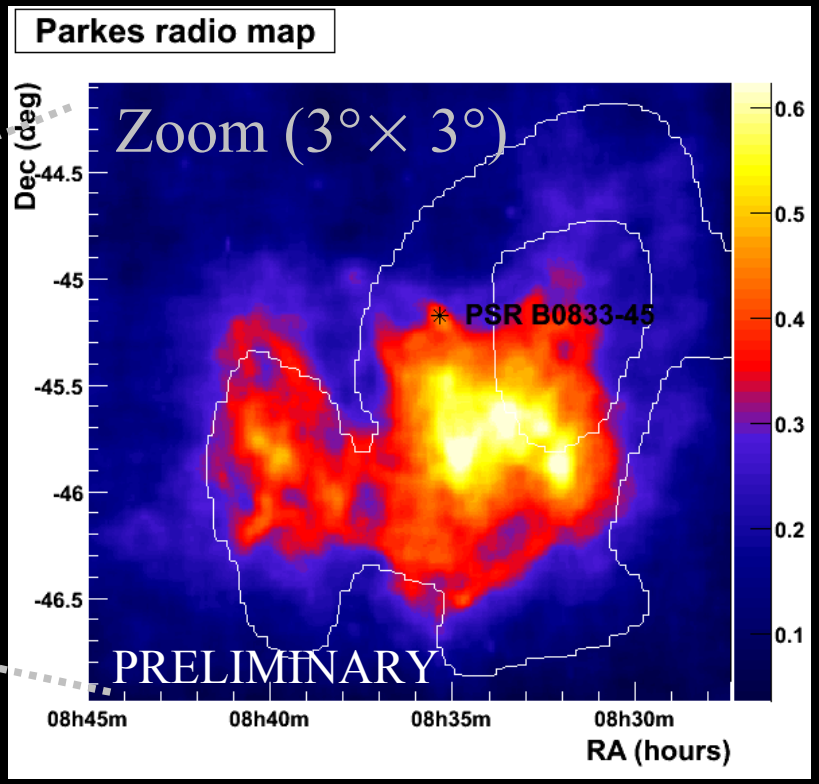
Fermi-LAT TS map (E > 800 MeV)

Fermi-LAT TS contours superimposed (white)



Parkes radio map at 8.4 GHz

Fermi-LAT contours superimposed (white)

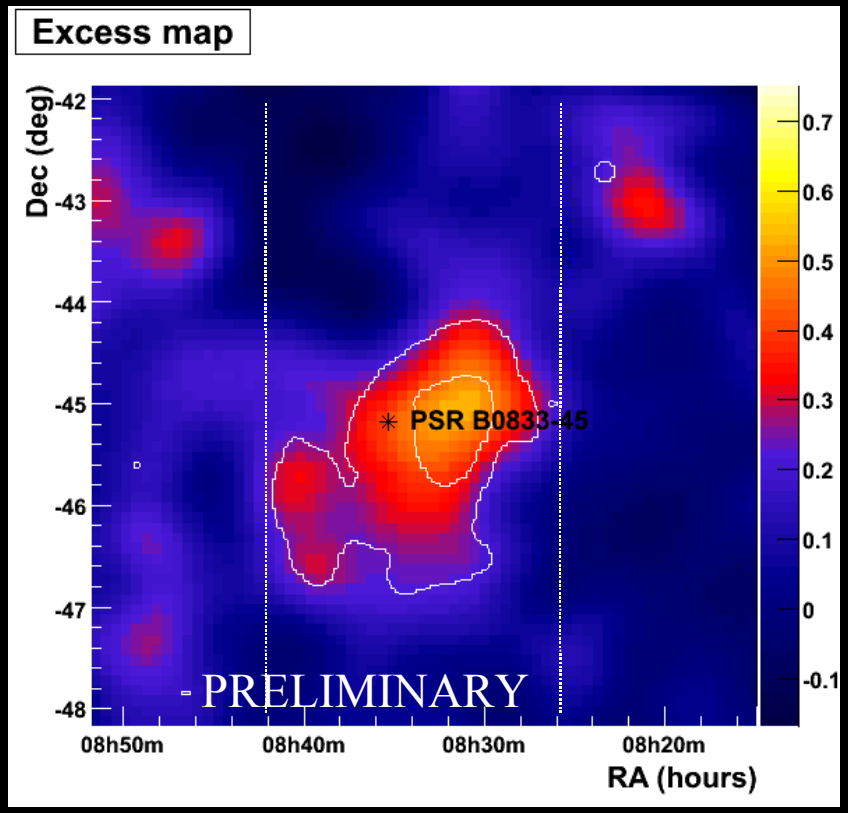


M-H Grondin, M Lemoine-Goumard, ICRC 2009

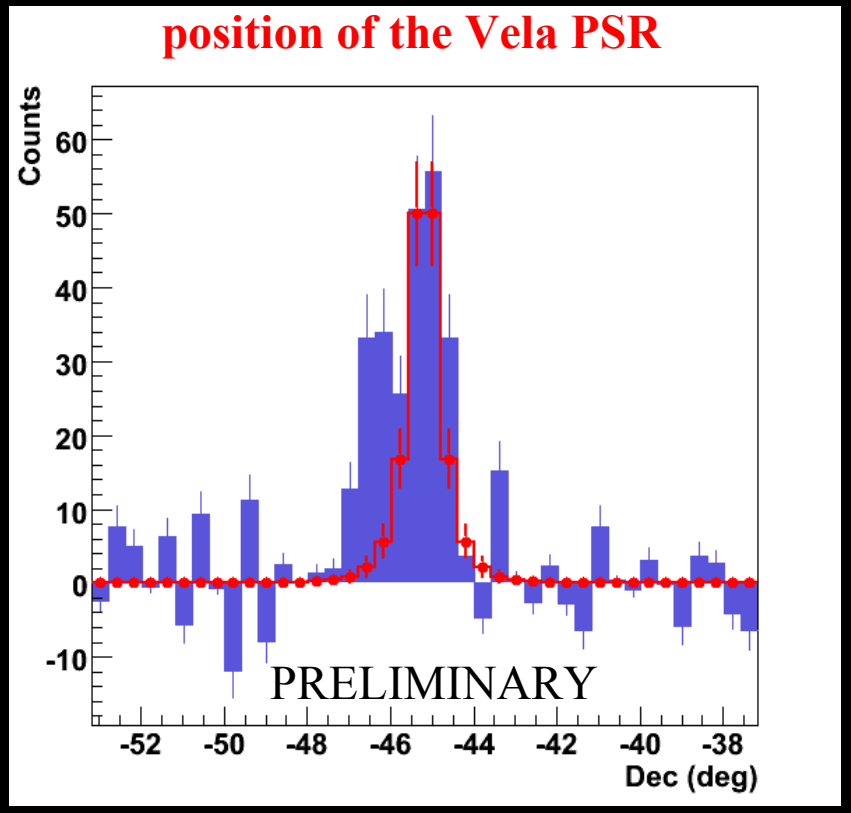
An extended source

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

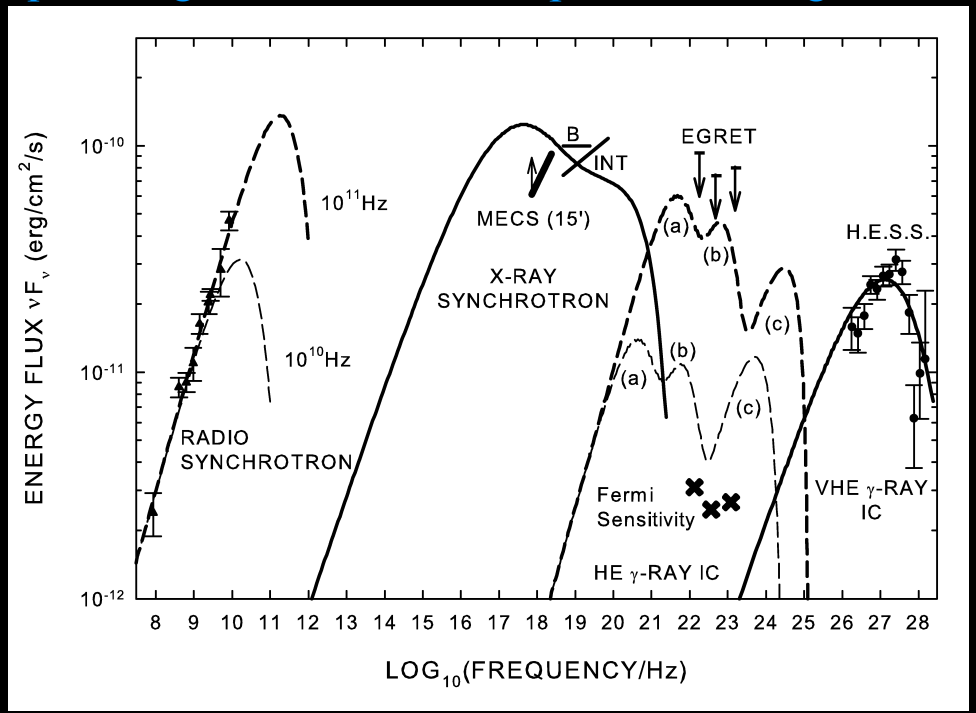


M.-H. Grondin & M. Lemoine-Goumard, ICRC, 2009

Vela X: perspectives

- Radio, VHE spectrum and Fermi-LAT data for entire PWN suggests presence of two distinct electron populations
  - radio-emitting particles may be relic population; higher energy electrons injected by pulsar

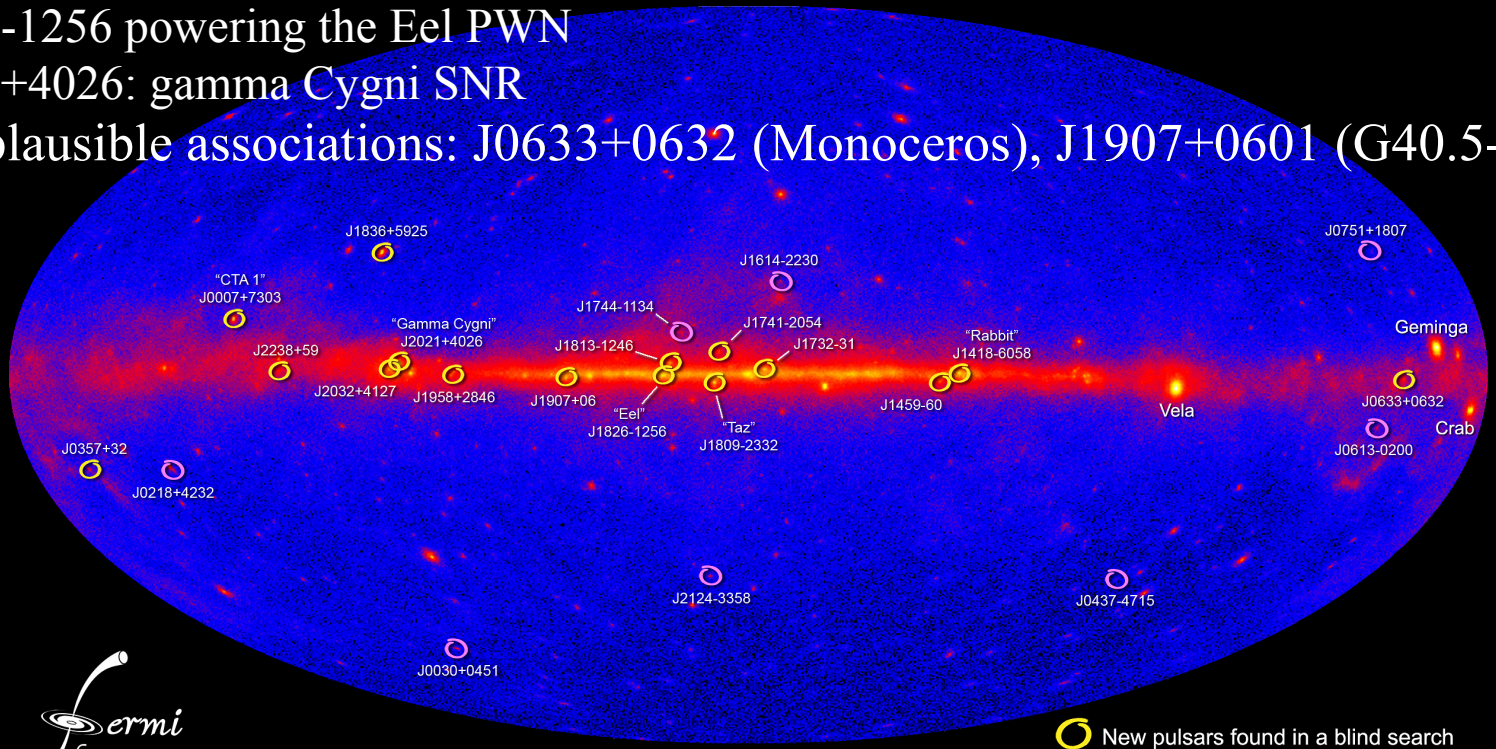
- Maximum energy of radio-emitting electrons not well-constrained
  - this population generates IC emission in GLAST band (consistent with positional agreement and extension)
  - upcoming observations will provide strong constraints on this electron population



Spectral energy distribution of Vela X assuming an extension for the nebula
(De Jager et al, ApJ 689:L125, 2008)

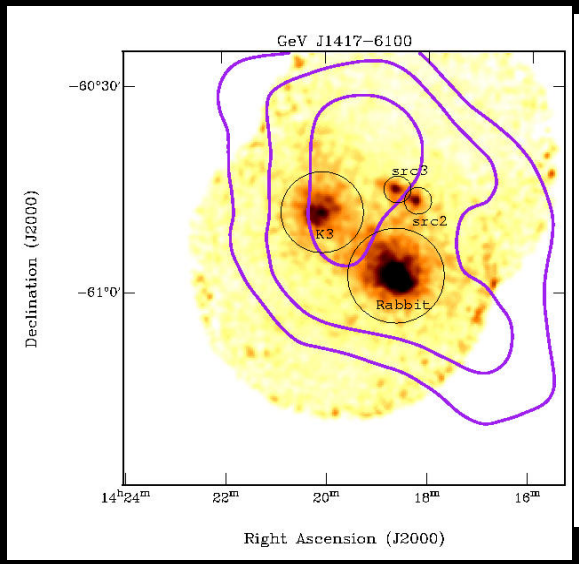
Fermi blind search pulsars: the link to SNRs and PWNe

- 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)

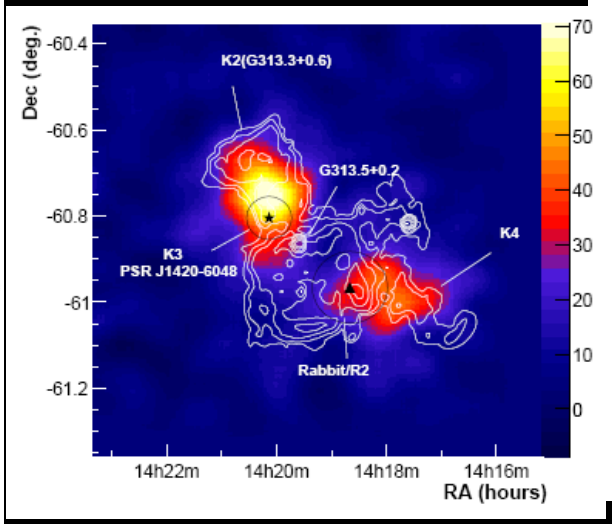


A famous example: the Kookaburra complex

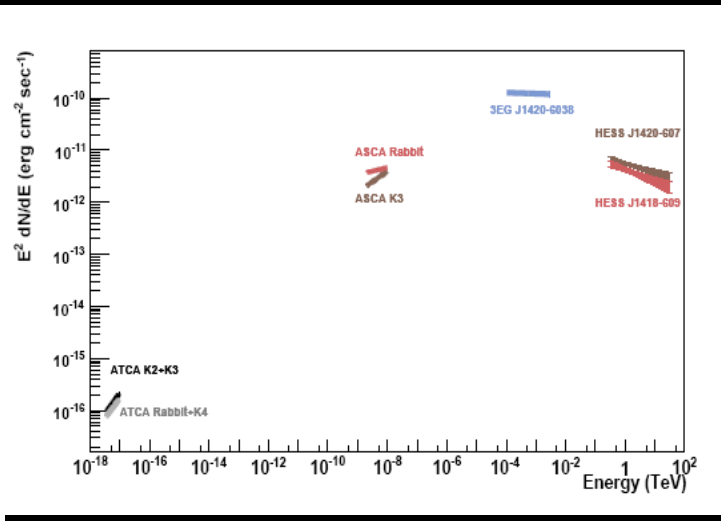
- EGRET : GeV J1417–6100/3EG J1420–6038
  - Confused source : the two PWN lie within its 95%-CL uncertainty region
  - Evidence of variability significant contribution from a pulsar wind nebula
  - Re-analysis of the EGRET data (*Reimer & Funk, astro-ph/0611653, 2006*) :
    - GeV emission essentially due to K3 and PSR J1420-6048 (no periodicity observed)
- H.E.S.S. :
  - Two sources detected *(Aharonian et al, A&A 456:245, 2006)* that match K3 and the Rabbit nebula



X-ray emission (yellow) and EGRET contours (violet)



H.E.S.S. excess map. X-ray (black) and radio (white) contours are superposed

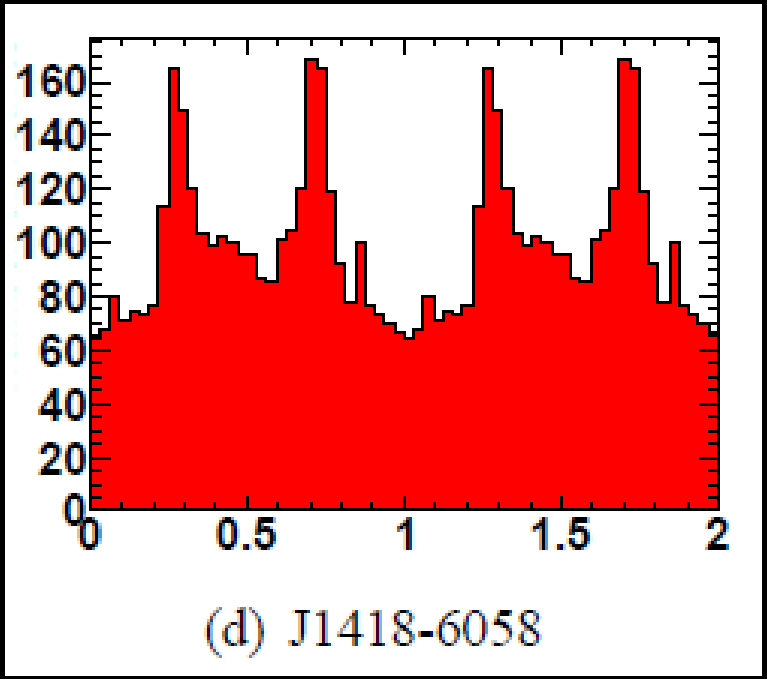


Spectral energy distribution for HESS J1420−607/K3/K2 and HESS J1418−609/Rabbit/K4

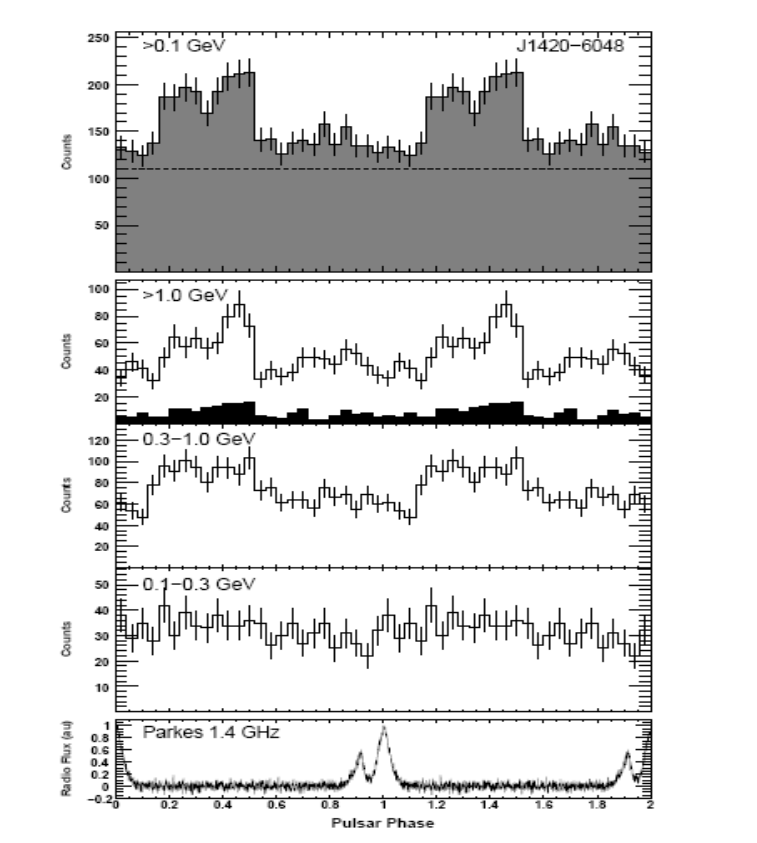
Fermi detections in this region

- Blind searches (Time Differencing Technique) performed on LAT catalog sources

  → Pulsed emission observed in the Rabbit nebula, with period P~110 ms (catalog source SEP0113)
- Looking at the off-pulse, significant emission => detection of the Pulsar PSR J1420-6048 using Parkes timing solution
- Most of the signal observed by EGRET might be pulsed emission



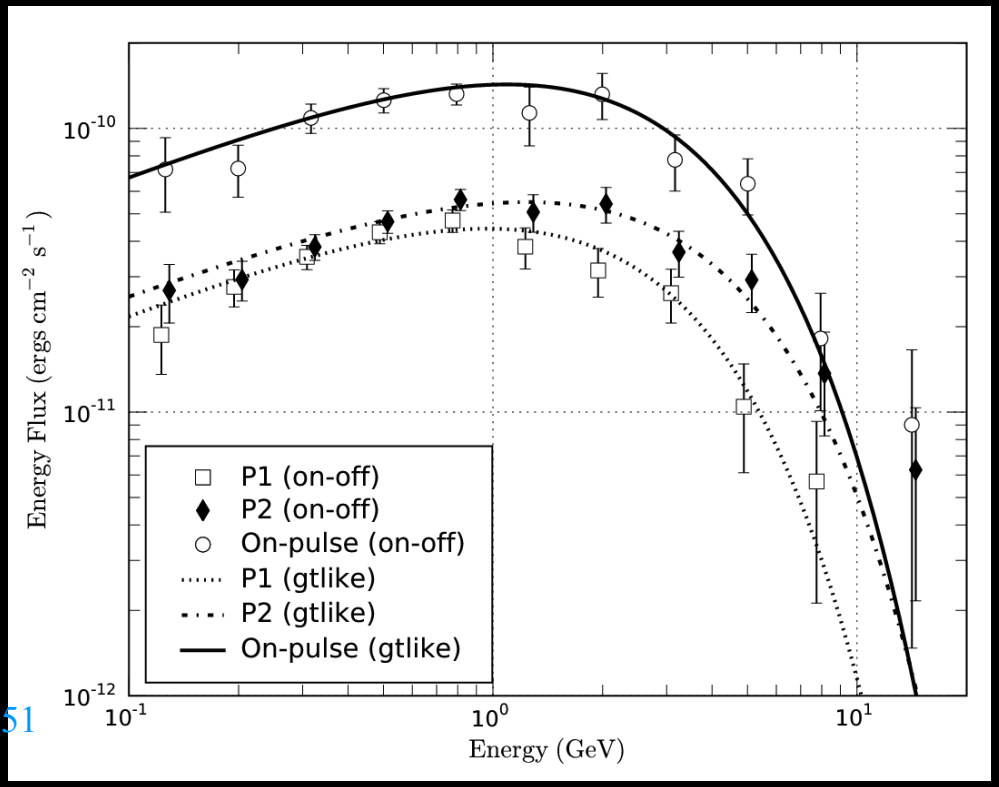
Abdo et al., Science Express, 2nd July 2009



A last word about LAT pulsars

- Generally (but not always), two peaks separated by ½ rotations.
- Generally (but not always), gamma peak offset from radio.
- Exponential cut-offs at ~1 to ~3 GeV.
- Favors outer magnetospheric emission.
- MSPs resemble young pulsars.

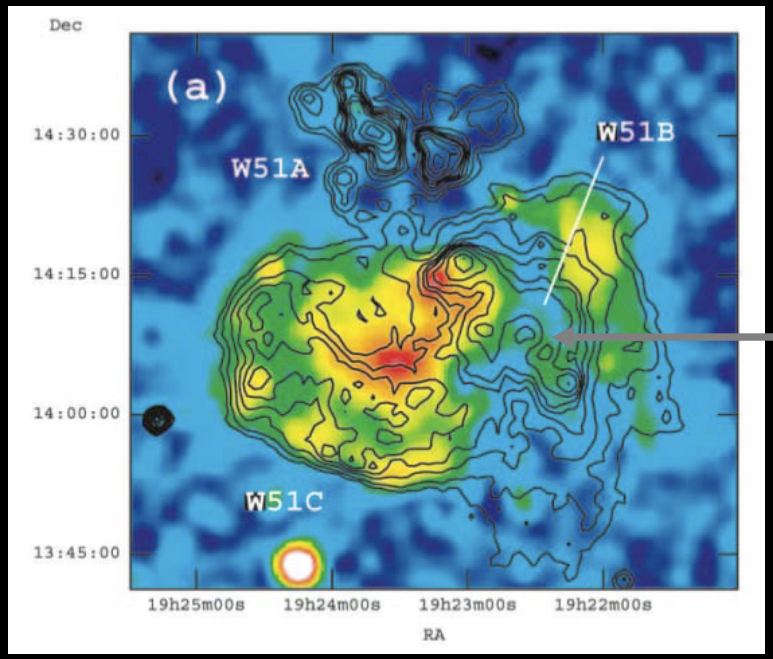
Do not favour observations using Tcherenkov telescopes...



LAT spectrum for PSR J2021+3651

SNR W51C

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



- D ~ 6 kpc, Age ~ 20000 yrs
- Molecular cloud interactions
- SNR diameter ~ 30 arcmin

... may be extended for LAT at high energies

- very large: 90 pc x 70 pc

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

Very recent HESS detection:
extended source compared to HESS PSF
3% Crab flux above 1 TeV
Sevral possible associations: PWN, star forming region, shocked molecular cloud

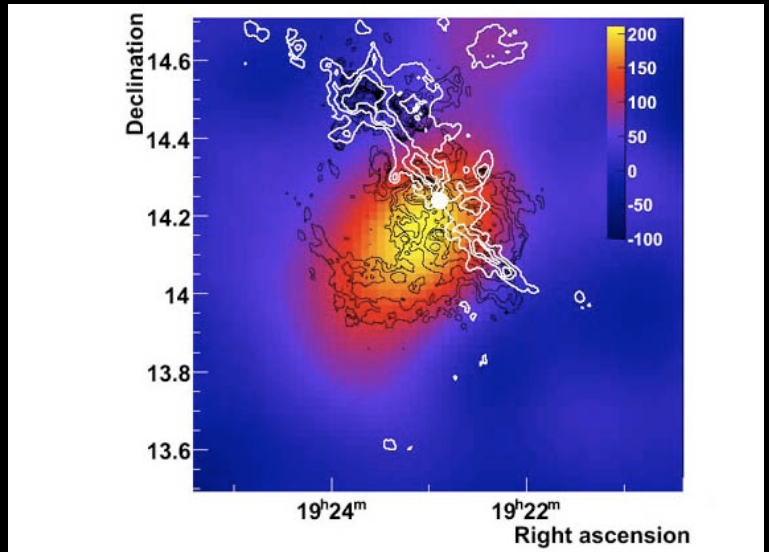


Fig. 2: VHE gamma ray image, with the 11 cm radio contours superimposed in black (from Moon & Koo 1994), and 13CO radio emission contours tracing molecular clouds superimposed in white (from Jackson et al. 2006). The filled white circle shows the location of OH maser emission (Green et al. 1997).

A Fermi-LAT extended source in the W51C region

Y. Uchiyama, ICRC 2009

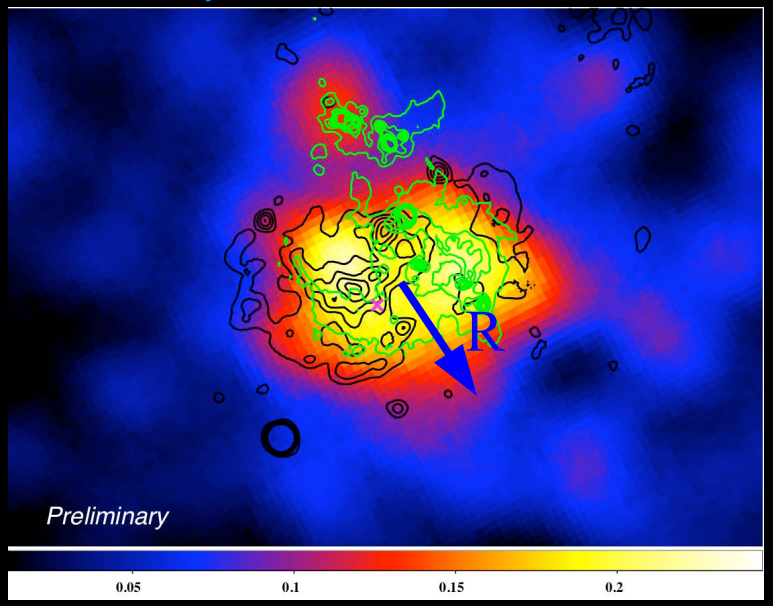
X-ray:
- Thermal emission by shock-heated plasma (kT=0.2 keV)
- Central region due to cloud evaporation?

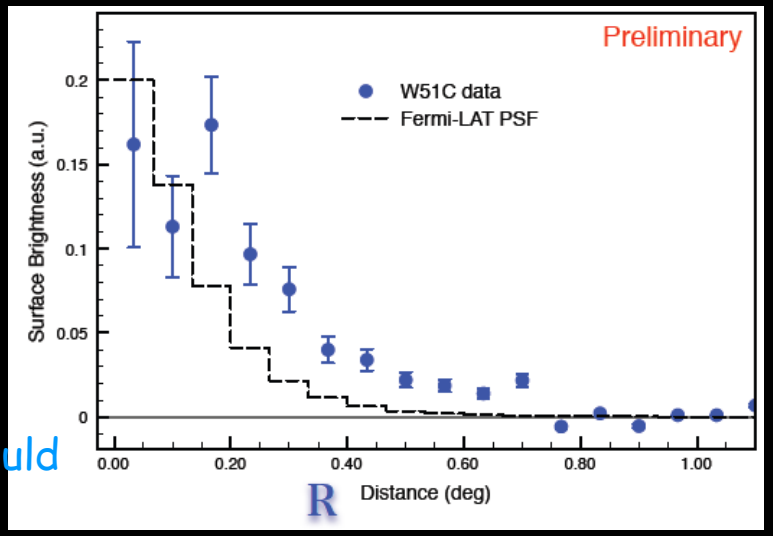
Radio:
- Peaks are HII regions
- Synchrotron radiation of SNR W51C is well matched with thermal X-ray emission

X□ : CXOJ192318.5+140305 (a neutron star?)

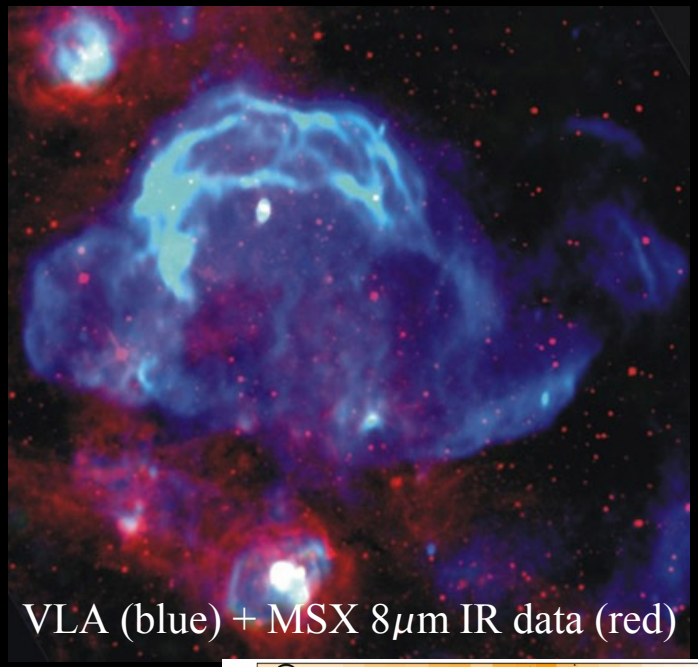
GeV Gamma-ray:
- Origin?
- Extended emission
- Very large luminosity (~ 4×10^{35} erg/s) using 6 kpc

=> Large extension compared to PWN (CXO) and Unrealistically large energy content in electrons would Favour the scenario of molecular cloud interaction





The field of view of W28 (G6.4-1.0)



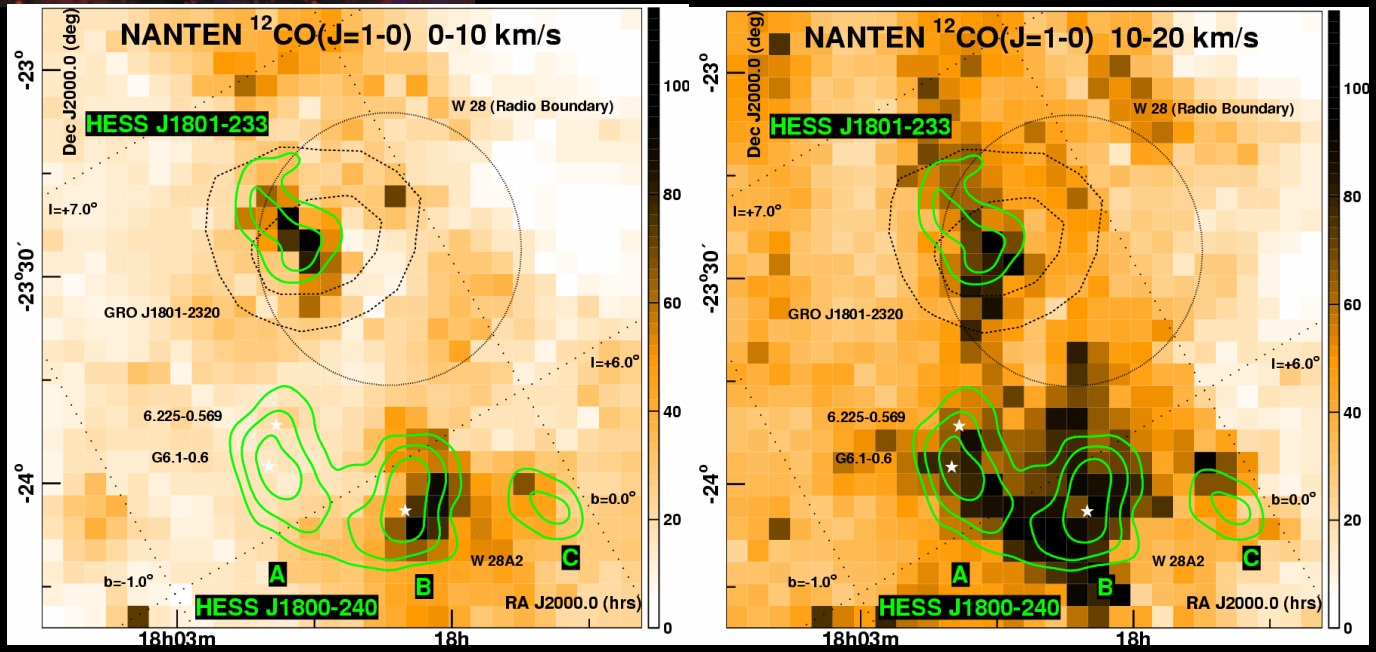
Mixed morphology SNR

Old age ~35000-150000 yrs

Distance 1.8 – 3.3 kpc

Interaction of the remnant with molecular clouds seen in NANTEN CO (J=1-0); presence of OH masers

HII regions and dense molecular clouds in the South



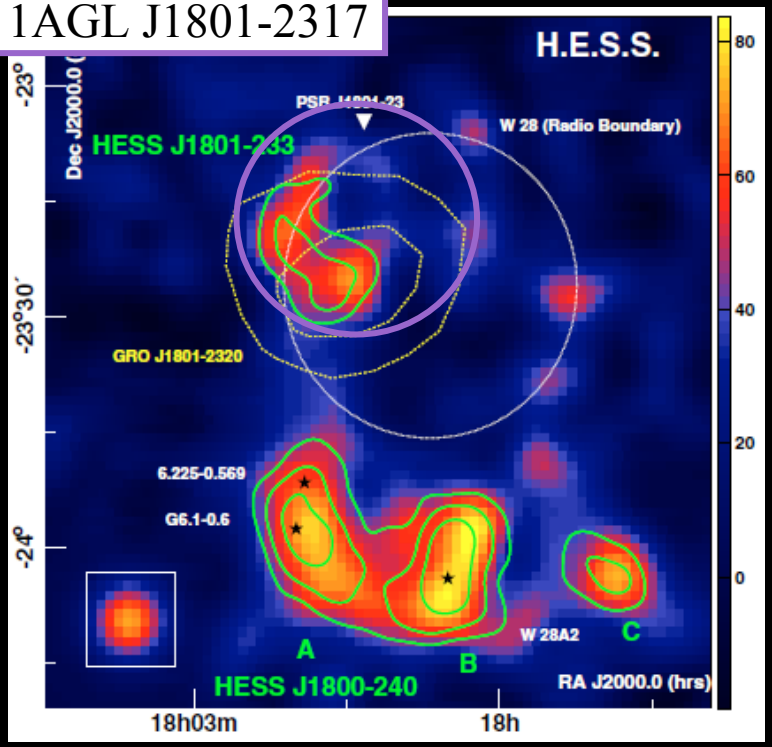
Gamma-ray observations of W28

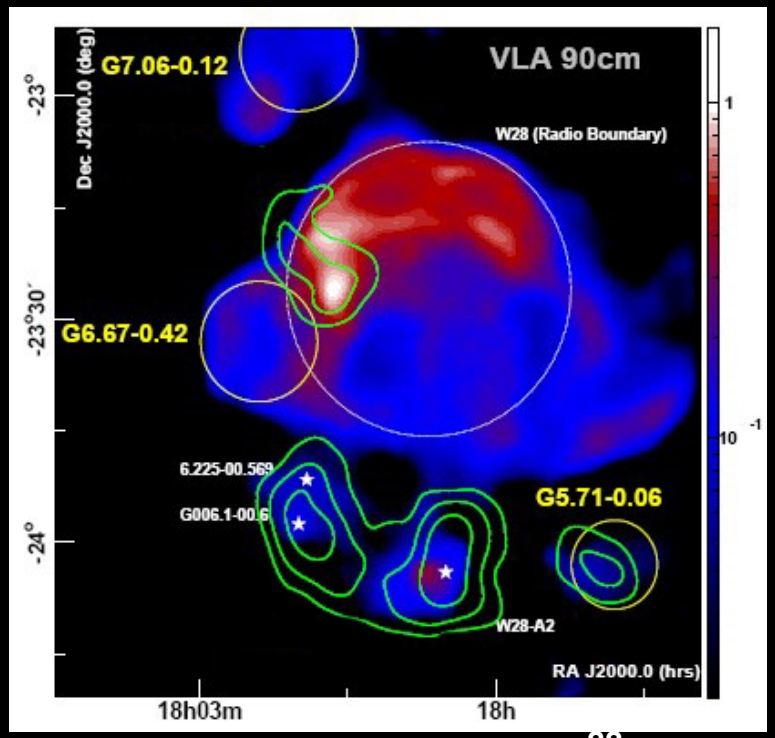
COS-B detection above 300 MeV(Pollock 1985) & EGRET detection above 100 MeV (Esposito et al. 1996)

HESS detections: HESS J1801-233 & HESS J1800-240 which splits into 3 different sources A, B, C; Photon index 2.5 – 2.7

AGILE detection

1AGL J1801-2317

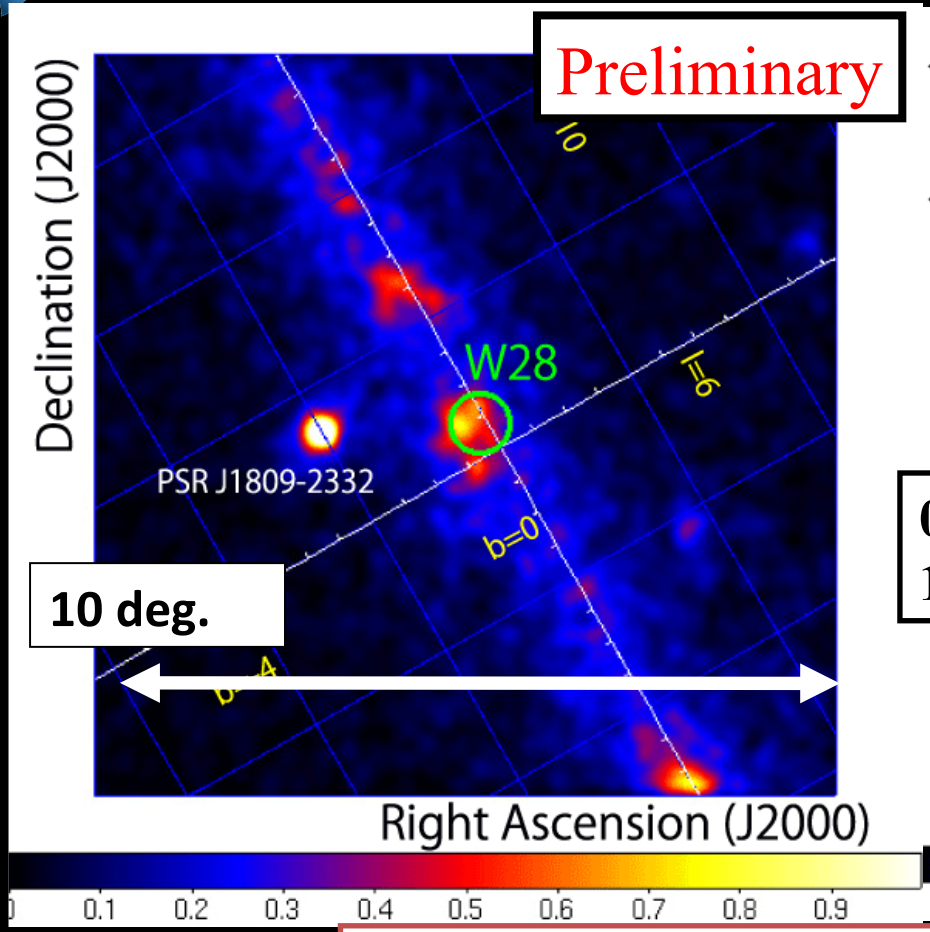


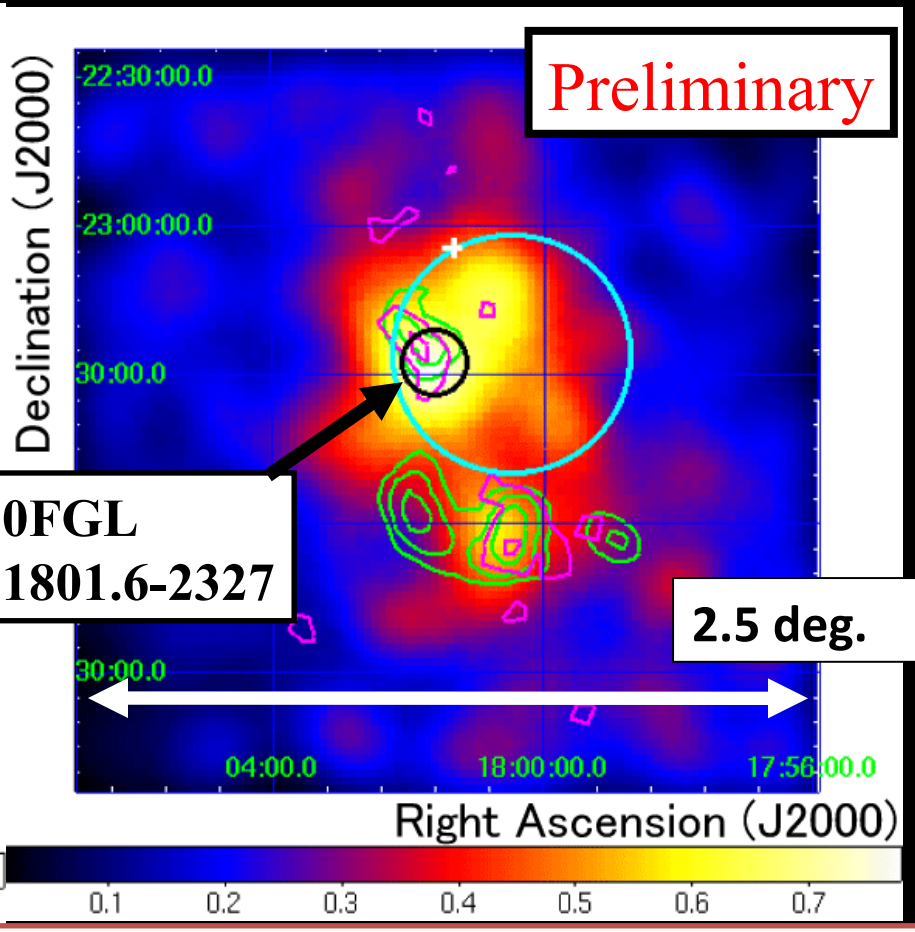


Fermi-LAT Count maps of the W28 region

2-10GeV

H. Katagiri, PASJ, 2009



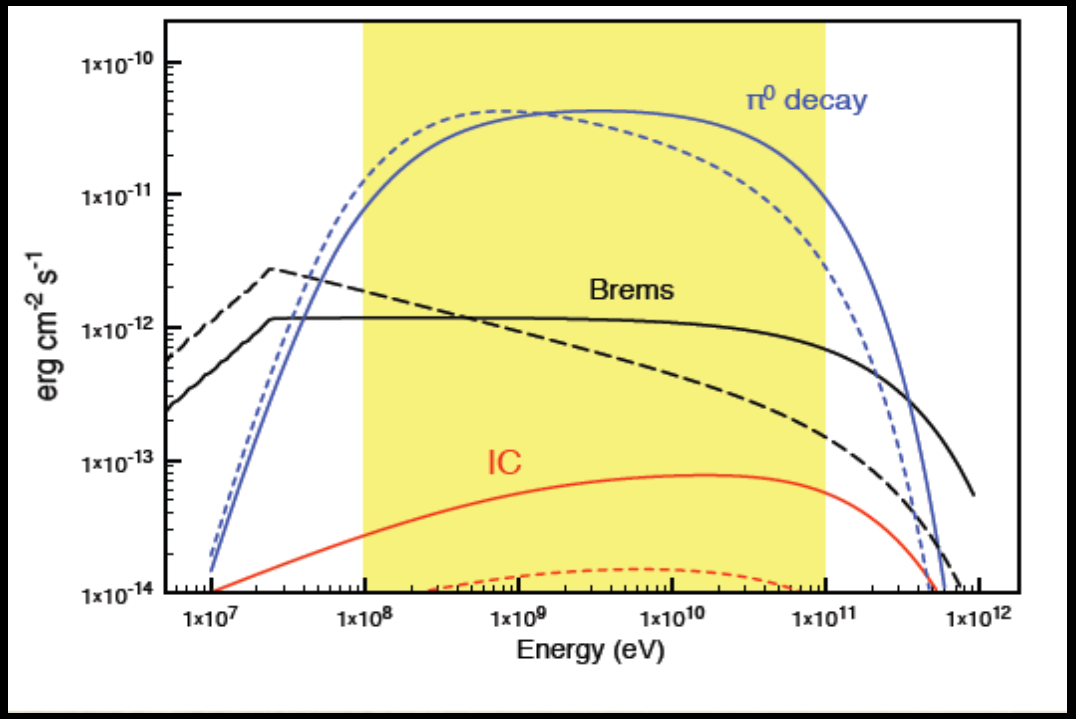


- Green contours: TeV significance 4,5,6 sigma
- Magenta contours: NANTEN (CO J=1-0) v=0-10km/s
- Mosaic: FERMI(1pixel=0.025deg. Smoothing Gaussian kernel=0.2deg.)
- Cross: PSR J1801-23
- Black circles : Bright source catalog 95% confidence region (Abdo et al. 2009)

Hadronic or leptonic ???

D=3kpc & constant injection over 10 000 yrs

- $n = 100\ cm^{-3}$
- $W_p = 10^{49}$ erg
- $W_e = 10^{47}$ erg
- $E_{p,max} = E_{e,\,max} = 0.5$ TeV
- Particle index = 2.0 (solid)
- Particle index = 2.3 (dashed)



Y. Uchiyama, TeVPA 2009

More on GeV-TeV connection: MILAGRO

34 sources in the BSL within the MILAGRO fov are not related to extragalactic sources

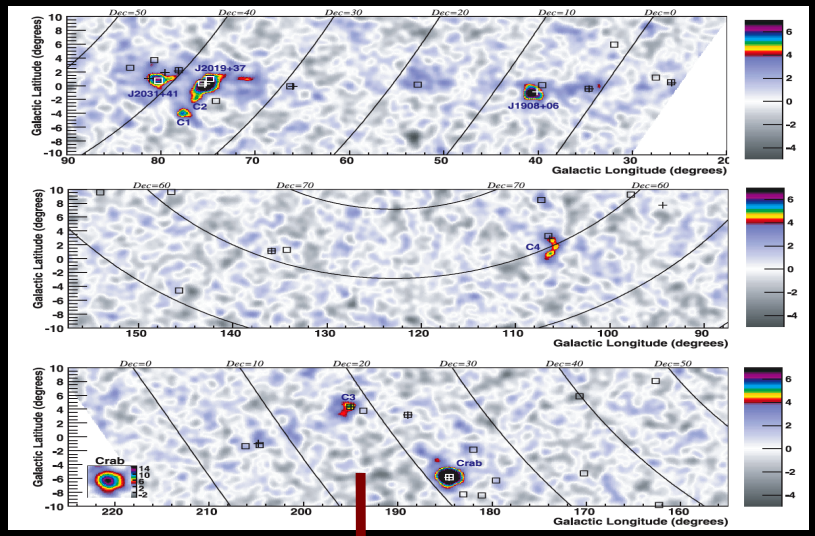
14 over these 34 sources have a significance greater than 3σ:

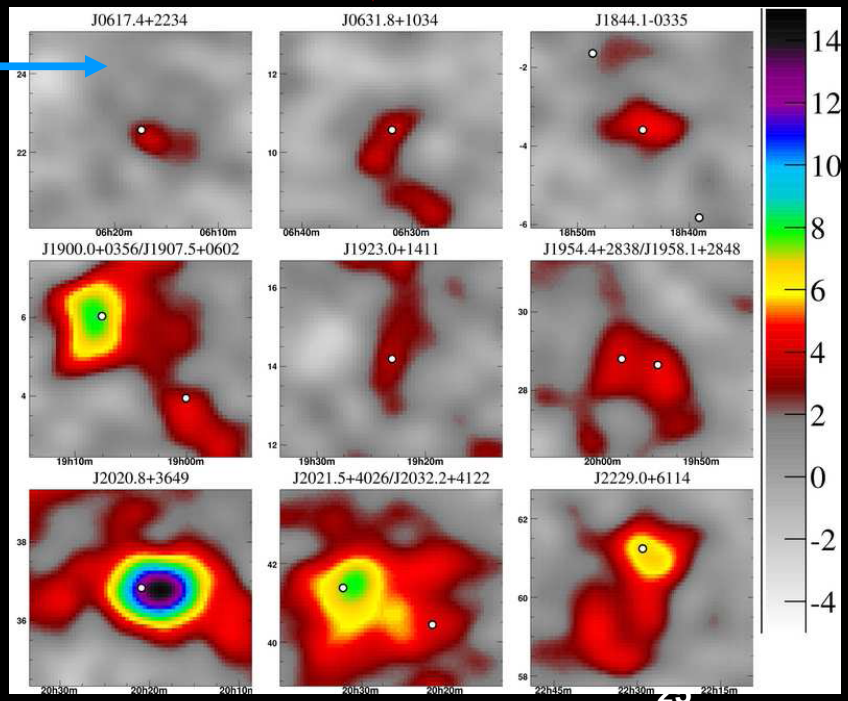
9 related to Pulsars

3 related to SNR: IC443, W51C, SNR G65.1+0.6

2 to unidentified sources: 0FGL J1900.0+0356 & 0FGL J1844.1-0335

Suggest that most of MILAGRO sources are multi-TeV PWN





Summary

Fermi LAT nominal science operations mode for ~1 year

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

TeV Connection

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

Lots of Galactic sources are common or complementary in the two energy bands; a generalized picture show that many TeV sources are PWN associated to a GeV Pulsar or molecular cloud interactions observed in both energy bands

Since late summer 2009 the data are 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…