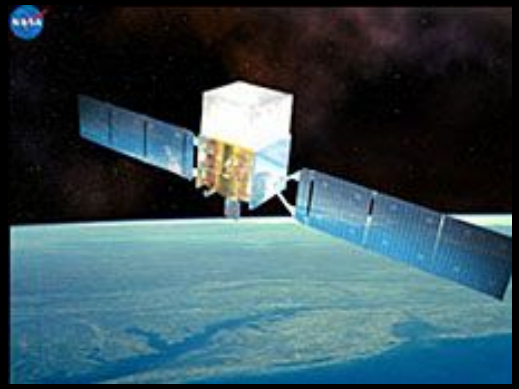


Fermi Observations of Pulsars and Pulsar Wind Nebulae

Marianne Lemoine-Goumard
CENBG (Bordeaux, France)

on behalf of the
Fermi-LAT Collaboration
& the Pulsar Timing Consortium

– Searching for the sources of Galactic Cosmic rays,
Paris, France, 14 December 2012 –

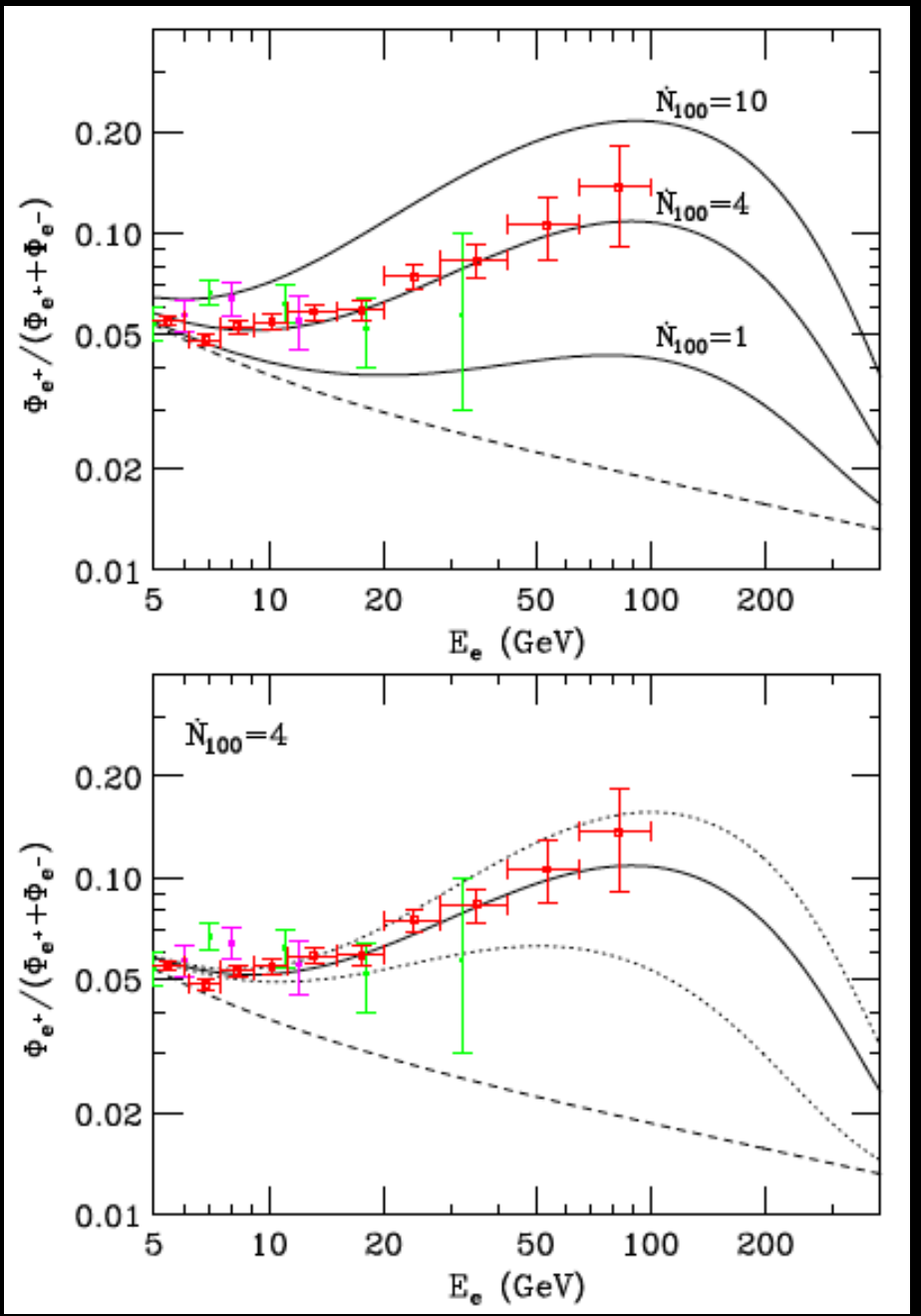
A direct link between Pulsars and PWNe and Cosmic-Rays

Rotation powered neutron stars produce e+e- pairs injected in ISM when out of Pulsar Wind Nebula

Pulsars are excellent antimatter factories !

PAMELA excess can be explained if average escape from SNR takes place 10^4-10^5 years after SN

Hooper D., Blasi P., Serpico P., JCAP01(2009)025



Three ways to detect Pulsars with Fermi-LAT

1- Folding gamma-ray photons according to a known pulsar timing model, from radio or X-rays

All 6 EGRET pulsars were detected this way (but Geminga, Crab and Vela **could** have been discovered in blind searches; Ziegler 2008, Chandler et al. 2001)

LAT photons are now folded for 762 Pulsars thanks to the Fermi Pulsar Timing Consortium !

2- Blind searches for pulsations directly in the gamma-ray data

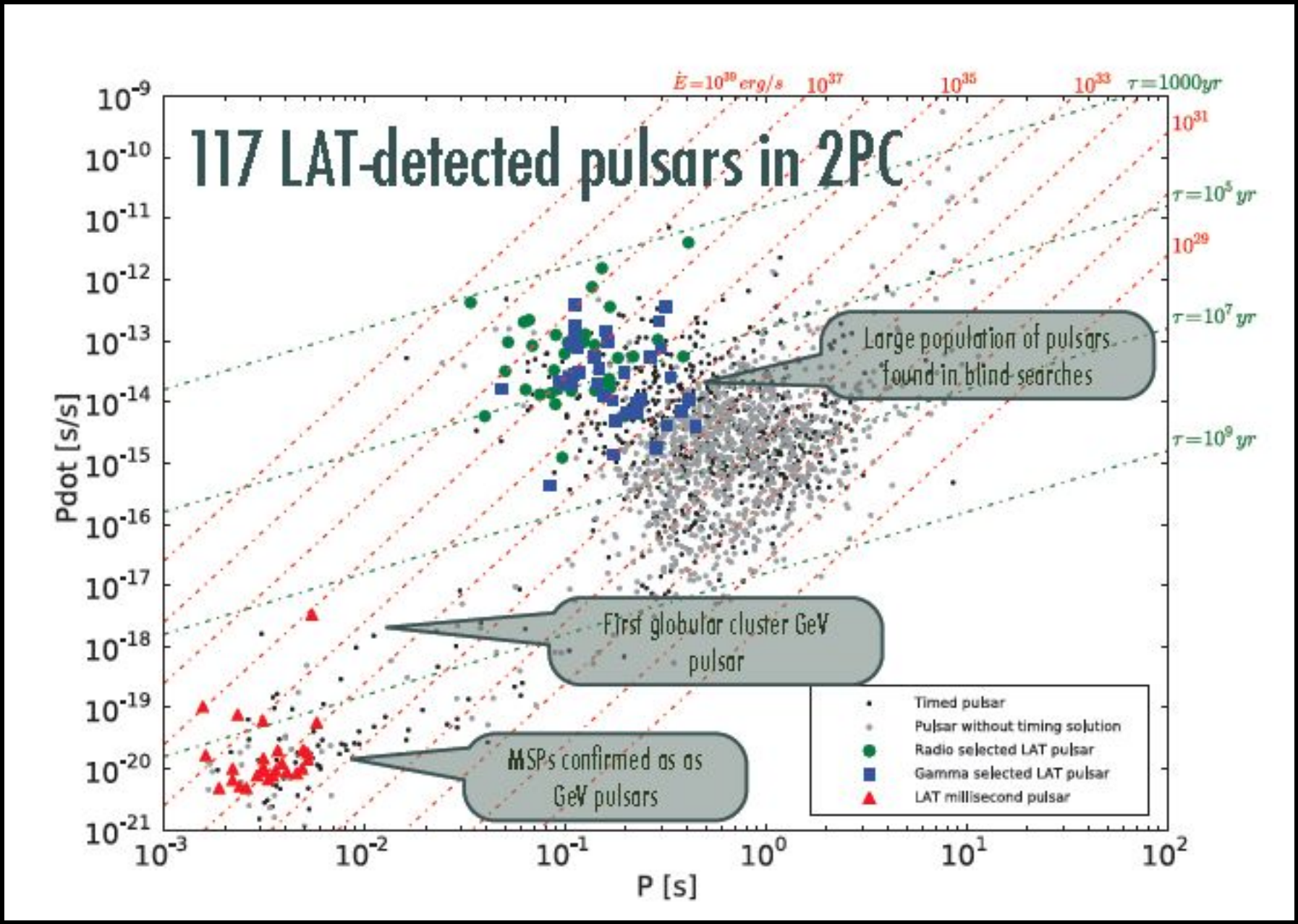
Spectacularly successful for young pulsars

Really hard for MSPs!

3- Radio pulsar searches of LAT unidentified sources

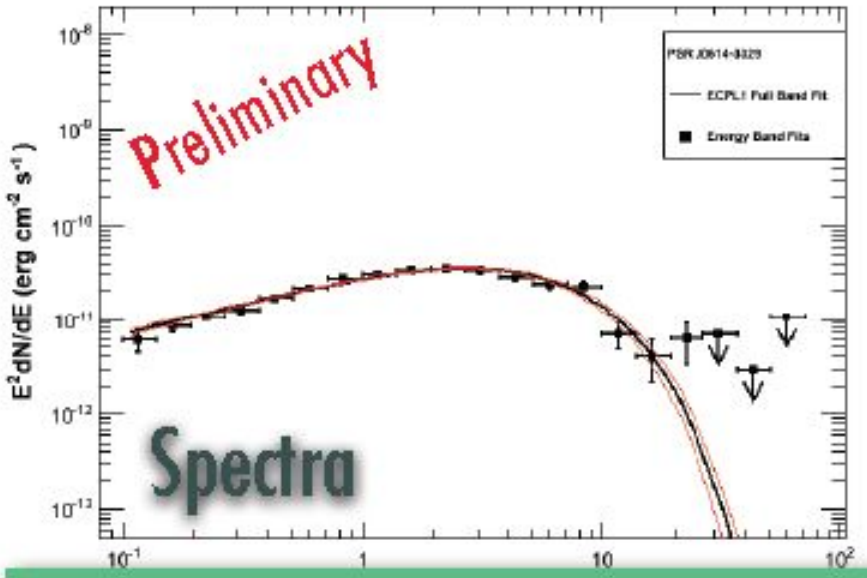
Sensitivity to MSPs, binaries, very noisy pulsars

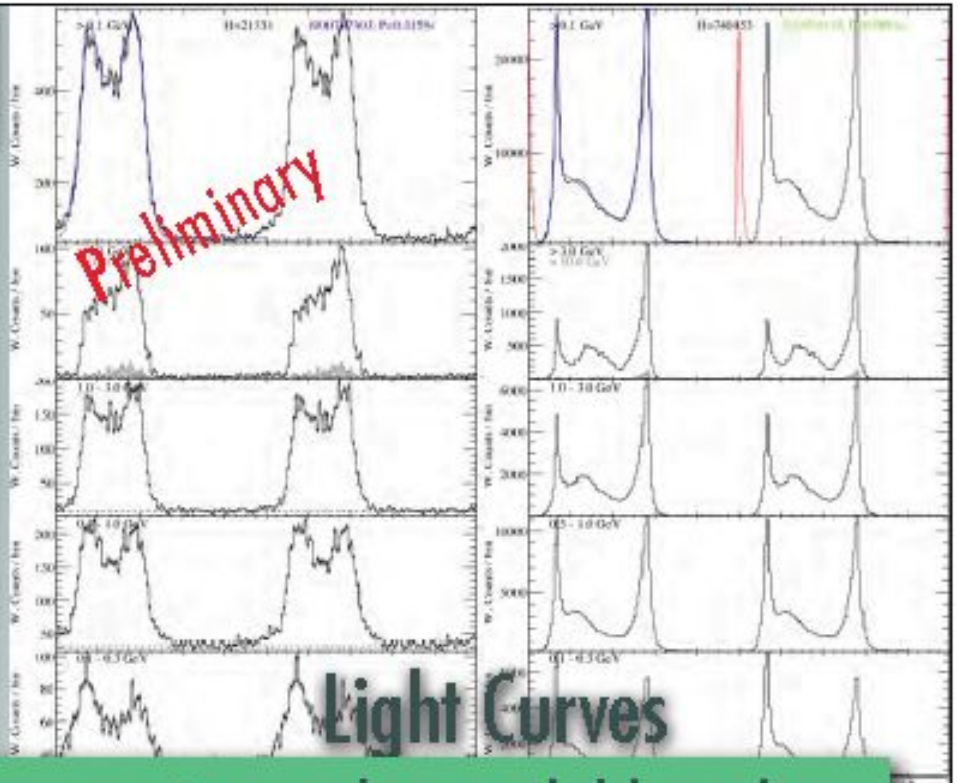
A growing population of LAT Pulsars



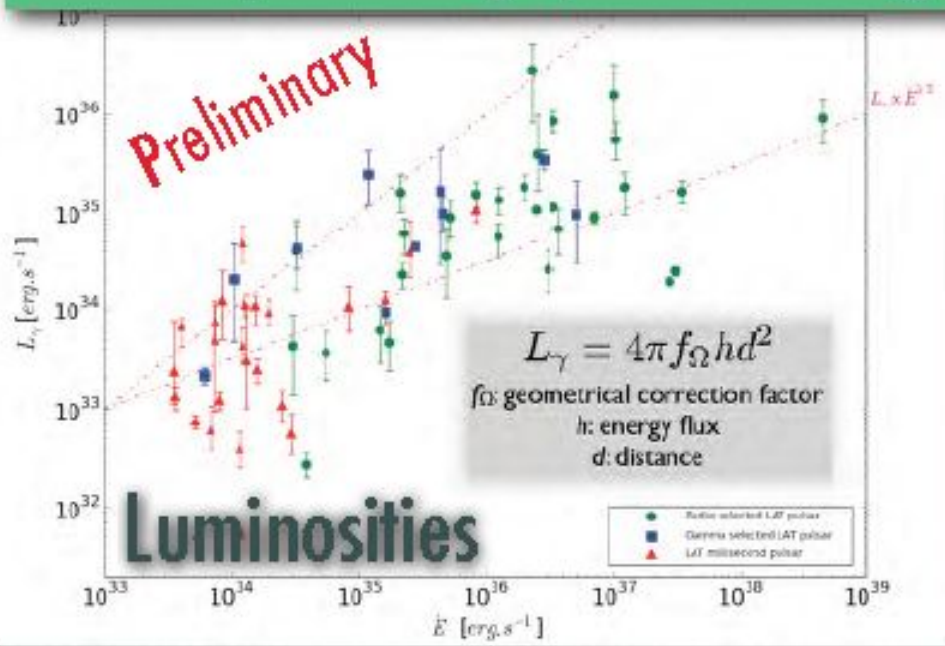
Credit: Paul Ray (Fermi Symposium)

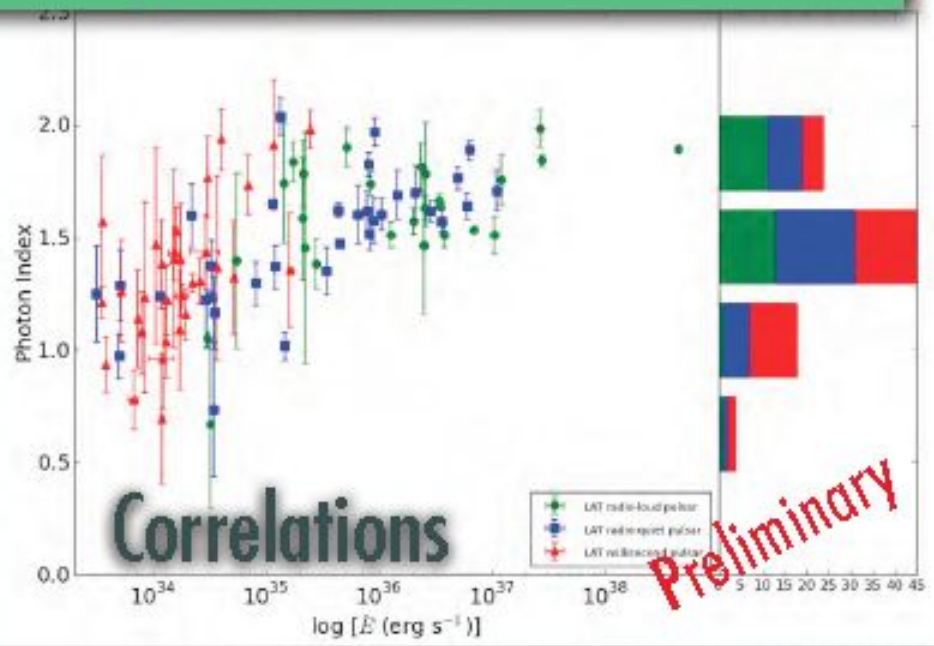
Fermi Second Pulsar Catalog (2PC)



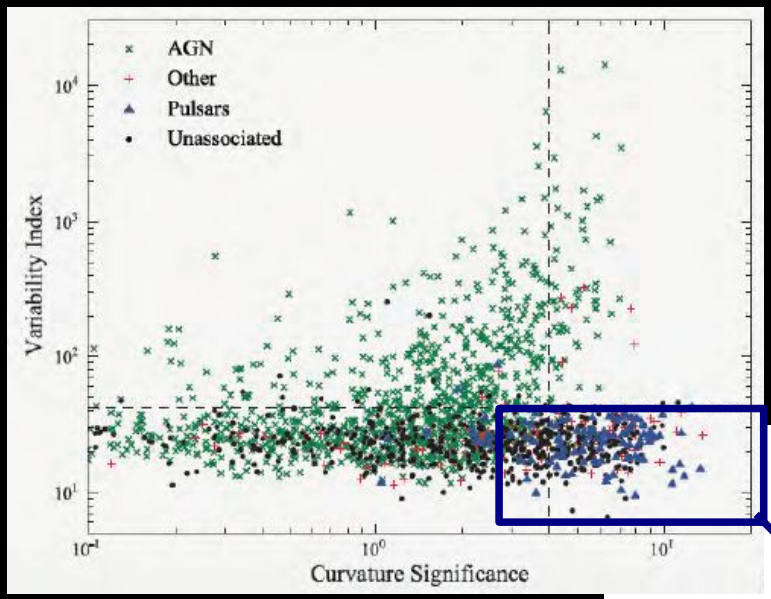


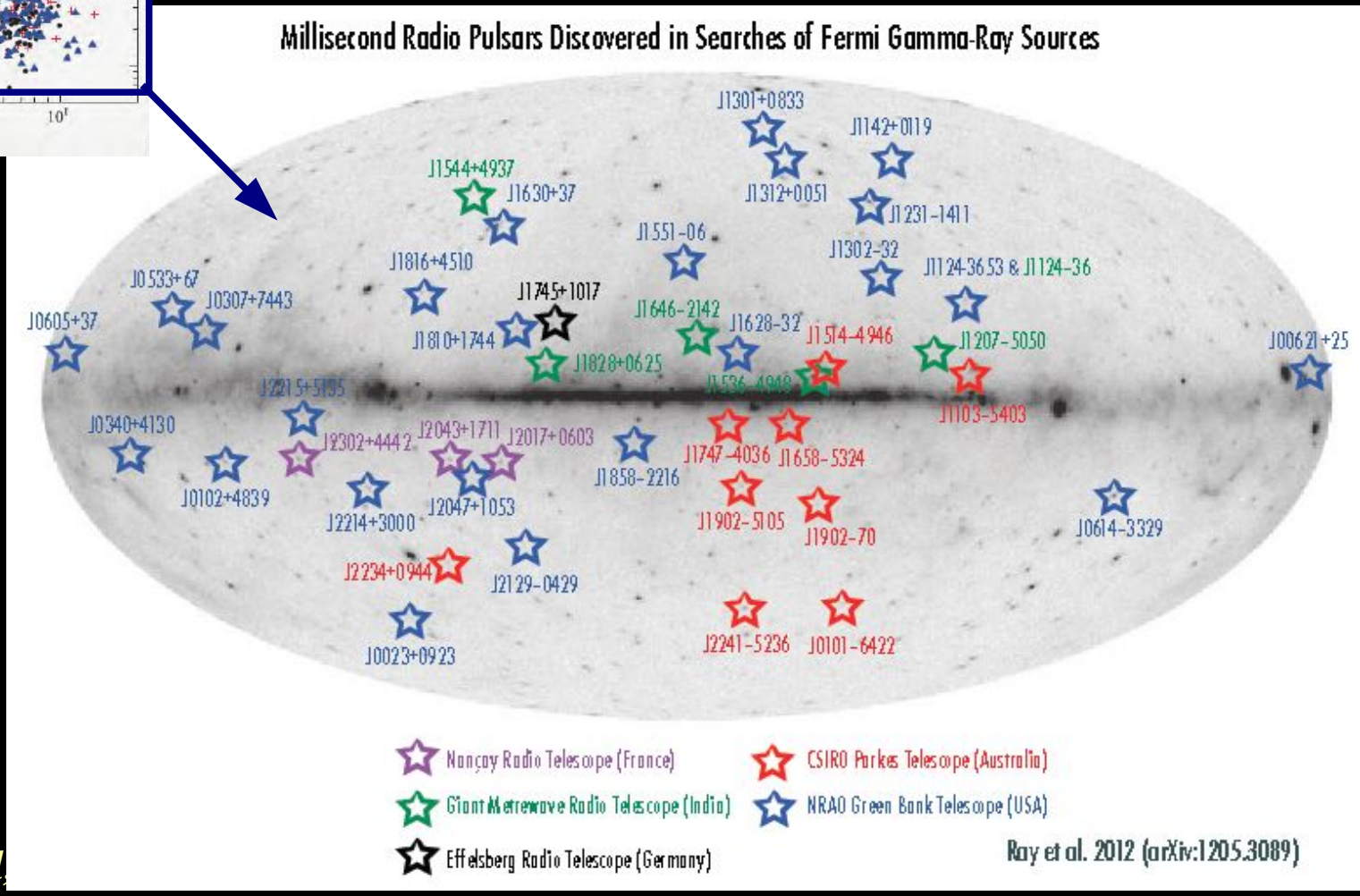
All data, including spectral and light curve points to be available online





40 MSPs included in 2PC : Success !



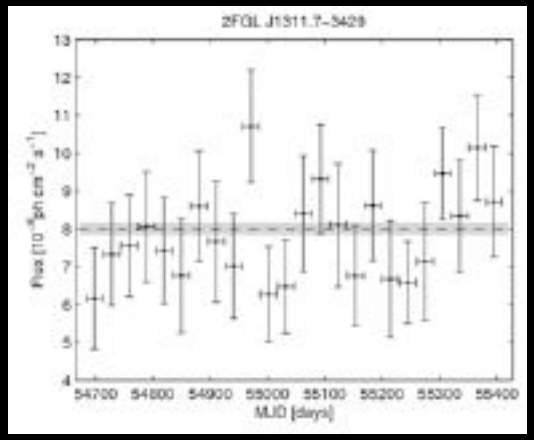


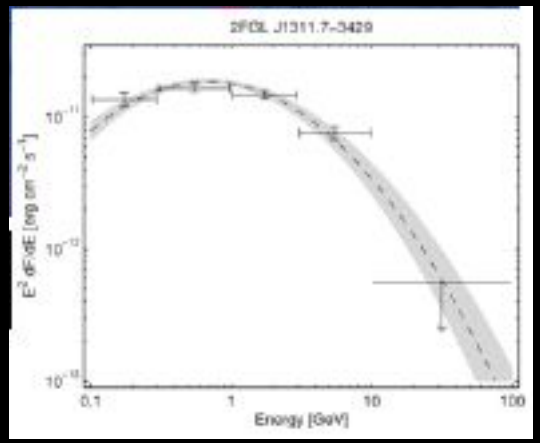
NEW (not in 2PC): a blind search MSP !

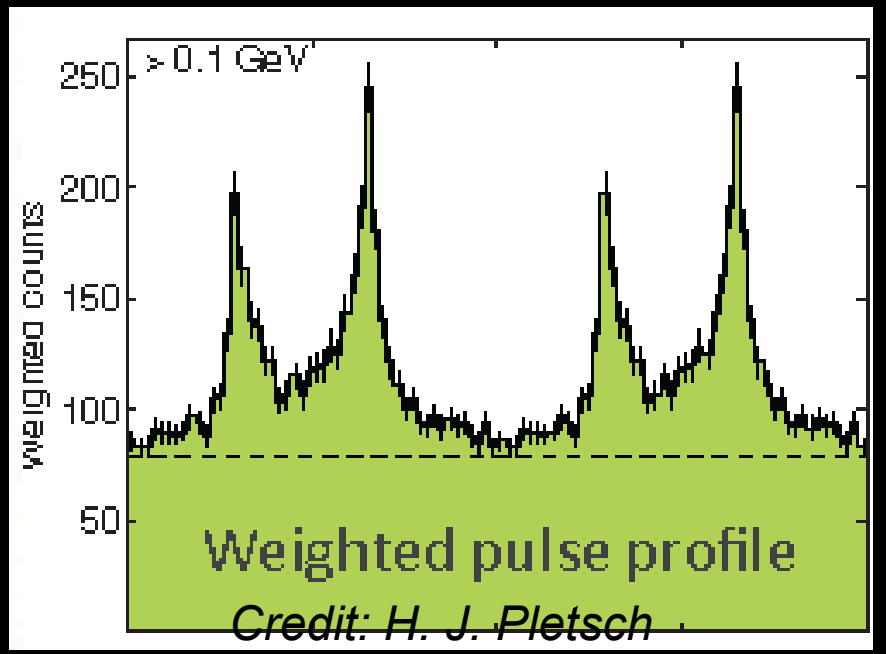
Blind Search for MSPs extremely difficult: Pulsar parameters unkown + unkown orbital parameters (for binary system) => increase computational complexity by orders of magnitude

Initial target source: 2FGL J1311.7-3429, brightest unidentified steady source seen by LAT with very curved spectrum & in search for optical counterparts Romani (2012) observed quasi sinusoidal optical flux modulation => conjecture: black widow pulsar binary

Sucessful detection of pulsed emission using a total of 10^{17} grid points (10^8 in f, 10^2 in fdot, 10^7 in orb.) !







And some of these pulsars even emit gamma-rays above 10 GeV !

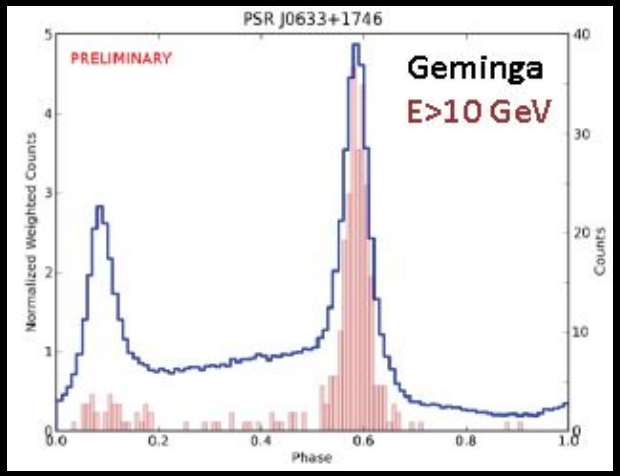
Fermi LAT Catalog above 10 GeV: nearly 3 years, 514 sources detected

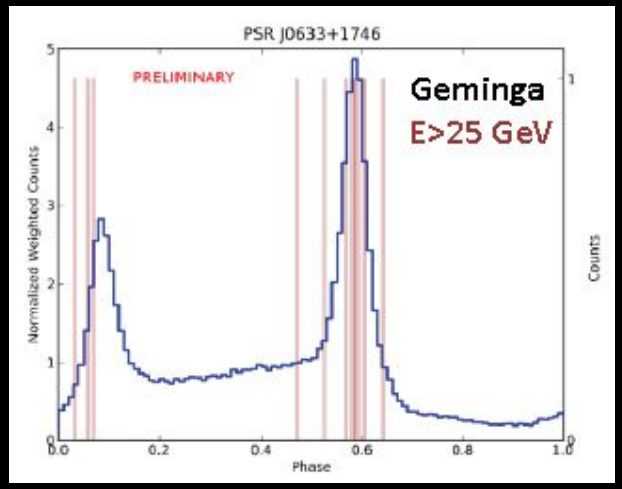
Among them 27 pulsars are detected

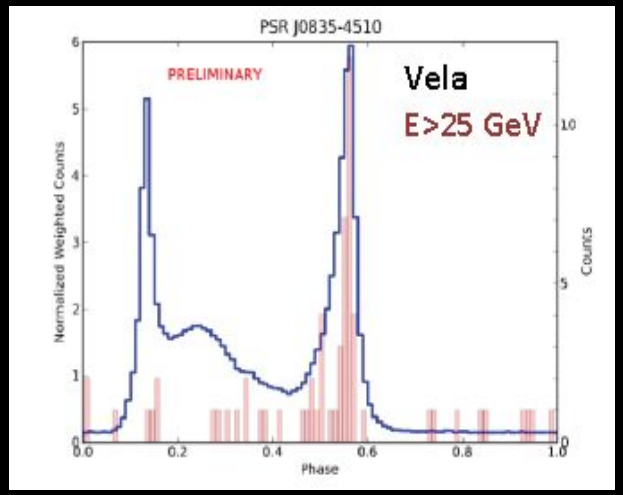
Pulsations observed above 10 GeV for 11 (out of 27):

J0007+730 (CTA1), J0534+2200 (Crab), J0614-3329, J0633+174 (Geminga), J0835-4510 (Vela), J1028-5819, J1048-5832, J1709-4429, J1808-2332, J2021+3651 (Dragonfly), J2032+4127

Normalized weighted light curve (100 bins) in the 0.3-10 GeV range (blue) and unweighted light curve above 10 GeV (pink): *Credit: D. Paneque (Fermi Symposium 2012)*

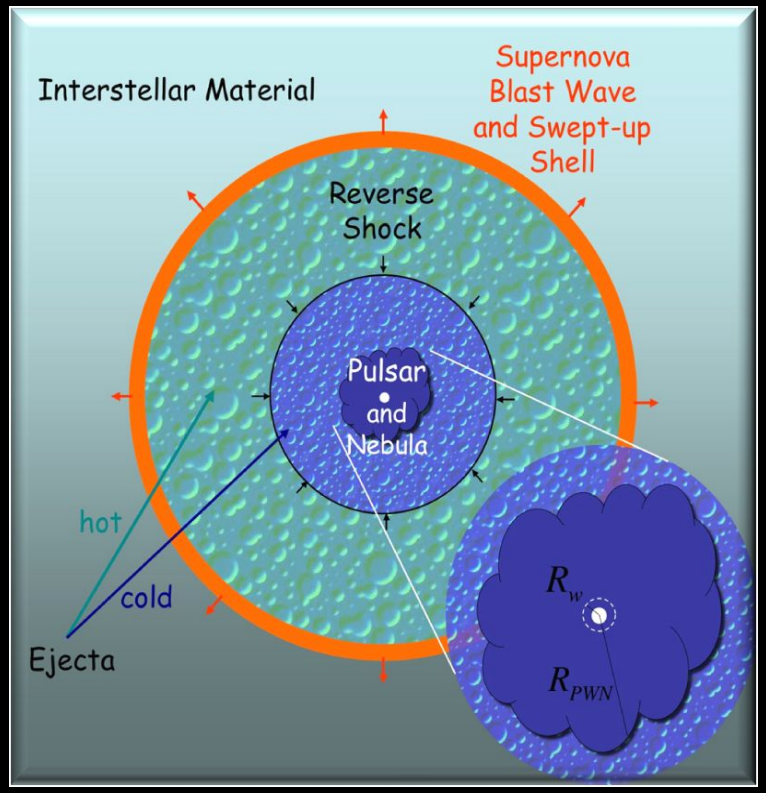




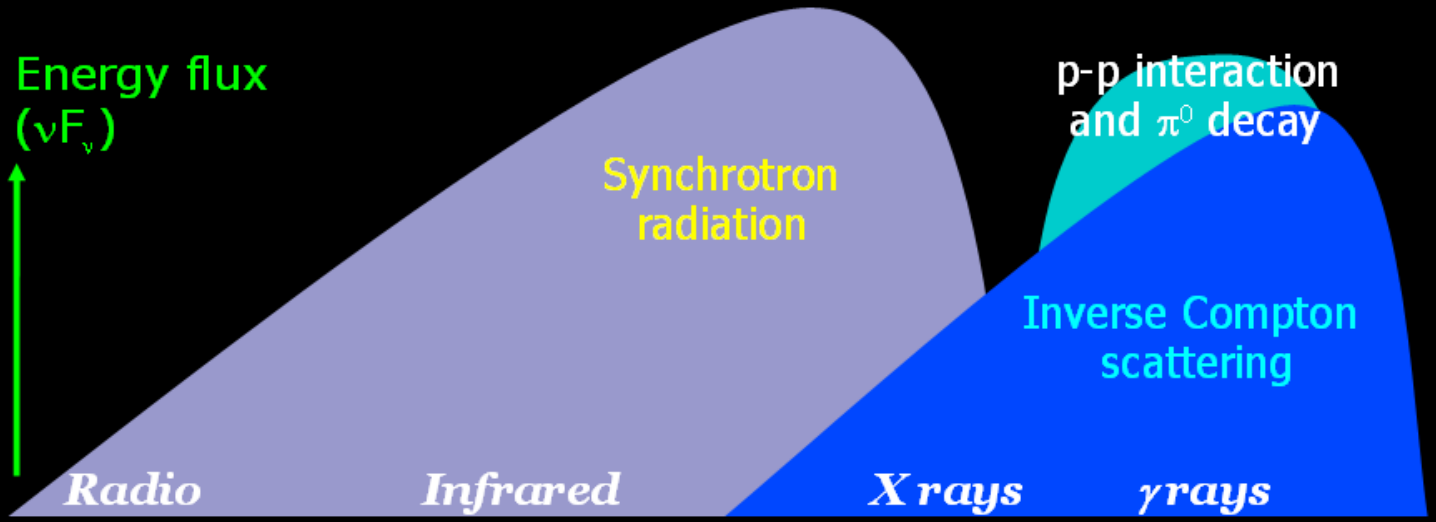


Pulsar Wind Nebulae

- Relativistic particles injected by the central pulsar
- Ejecta of the supernova swept up
- Flow decelerated by the shock
- Particles are accelerated at the shock (Diffusive Shock Acceleration, Resonant cyclotron absorption, etc.) and radiate



(Gaensler & Slane, 2006, ARA&A, 44, 17)



Credits : J. Hinton

A growing population detected by the LAT

1- Young PWNe :

- Crab Nebula (Abdo et al, 2010, 708, 1254)
- MSH 15-52 (Abdo et al., 2010, ApJ, 714, 927)

2- Middle aged PWNe :

- Vela X (Abdo et al, 2010, ApJ, 713, 146)
- HESS J1825-137 (Grondin et al, ApJ, 2011, 738, 42)

3- PWNe candidates:

- SNR CTA1 (Abdo, A. A. et al. 2012, ApJ, 744, 146)
- HESS J1837-069 (Lande et al, 2012, ApJ, 756, 5) — **Likely**
- HESS J1857+026 (Rousseau et al., A&A, 2012, 544, A3)

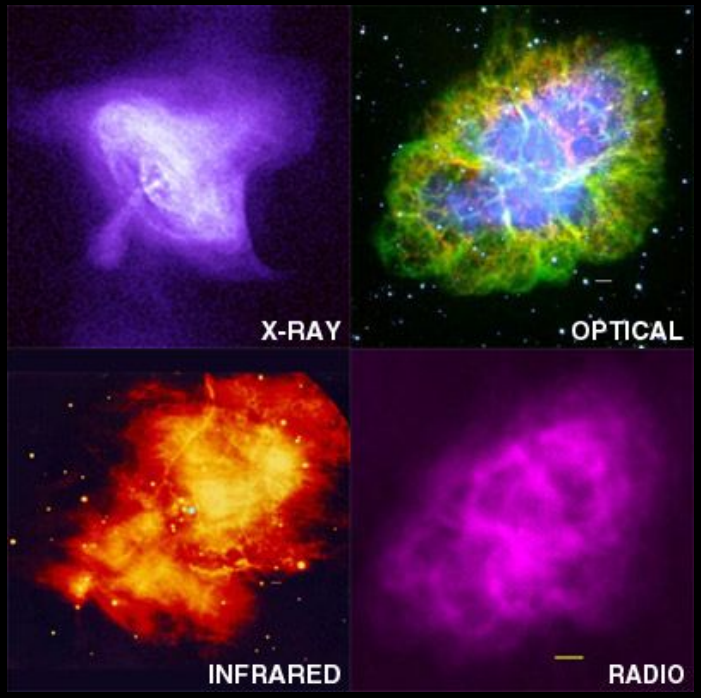
- HESS J1023-575 (Ackermann et al, 2011, 726, 35) — **Less likely**

- HESS J1640-465 (Slane et al, 2010, ApJ, 720, 266)
- MSH 11-62 (Slane et al, 2012, ApJ, 749, 131) — **Even less likely**

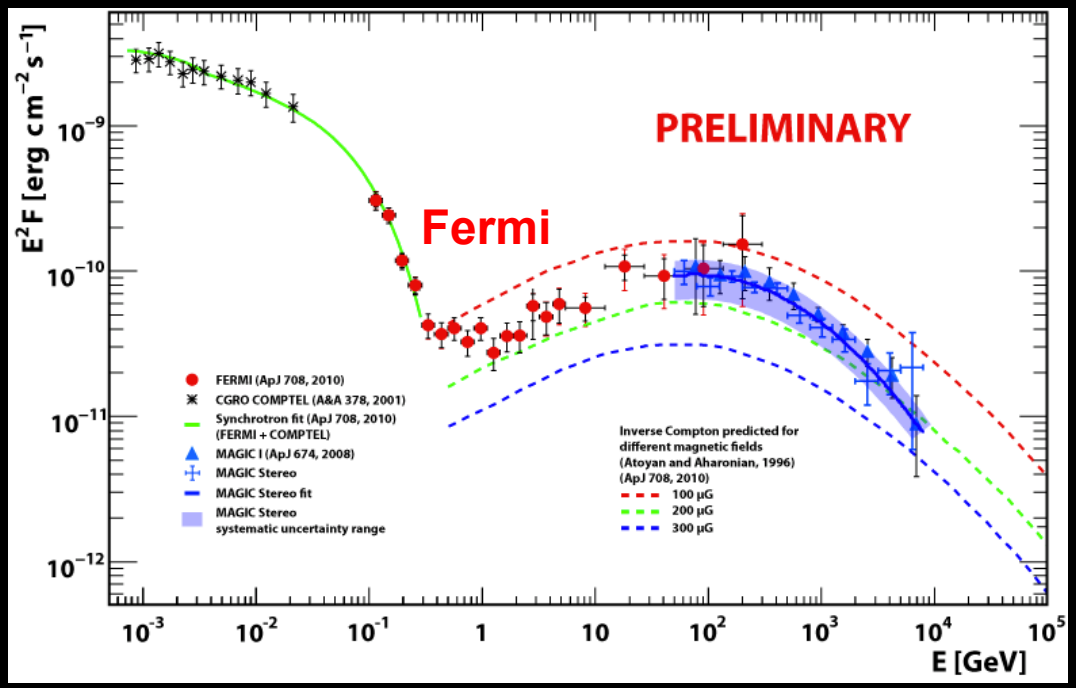
The Crab Nebula, the brightest VHE source...

The brightest VHE galactic «steady» source, observed by every Cherenkov experiment & Fermi (Abdo et al, 2010, 708, 1254):

- γ-ray emission below 500 MeV due to synchrotron emission
  - → electrons accelerated up to ~1 PeV
- high energy component due to IC (mainly on synchrotron photons)
  - → fit of the IC peak at ~60 GeV (using Fermi and IACT results)
  - → magnetic field constraint in the 100 – 200 μG range



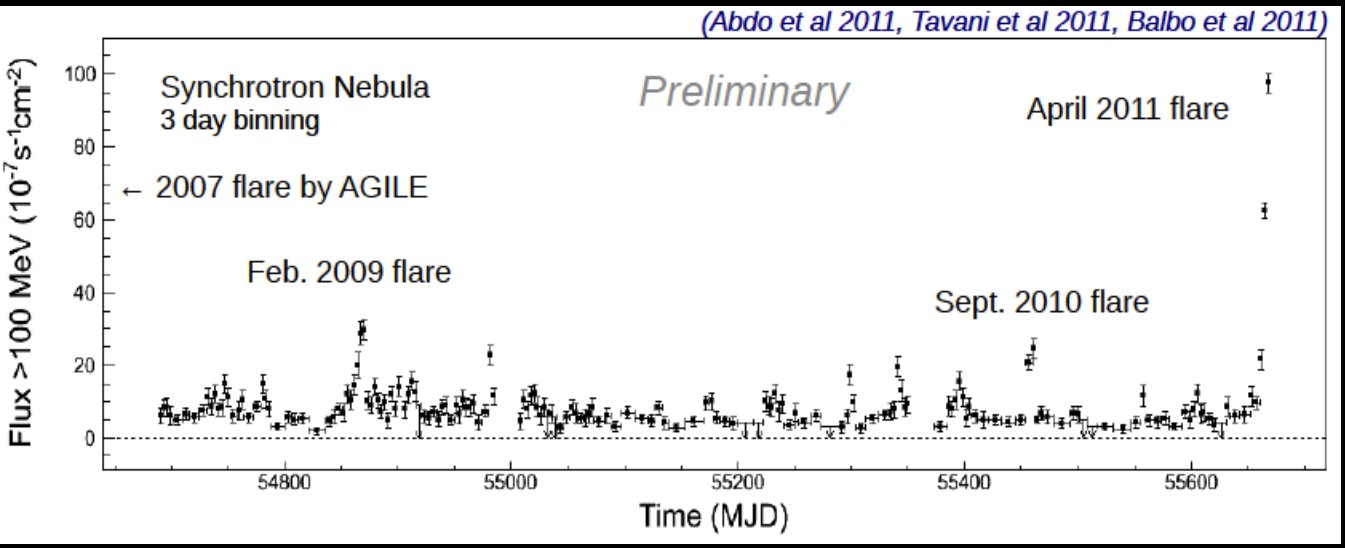
E. de Cea del Pozo, ICRC 2011

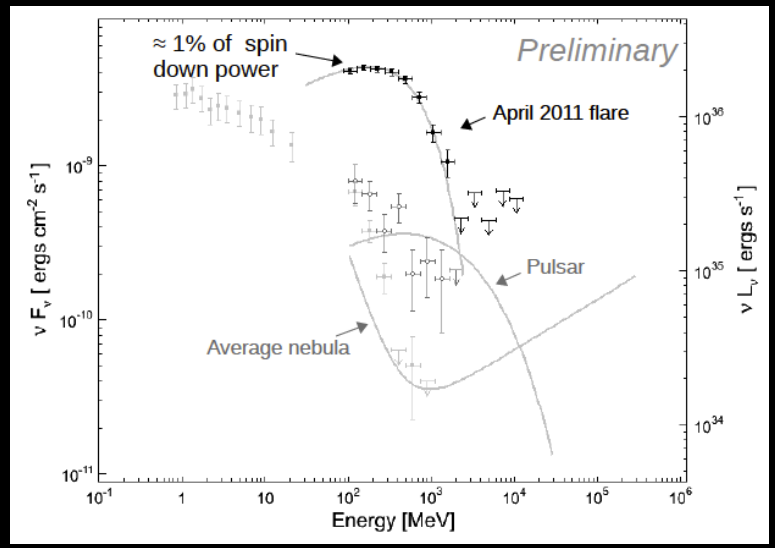


… but no more a standard candle

Recent flares of the synchrotron component (Oct. 2007, Feb. 2009, Sept. 2010, Apr. 2011) :

R. Buehler, Fermi Symposium 2011





Three day Crab synchrotron curve

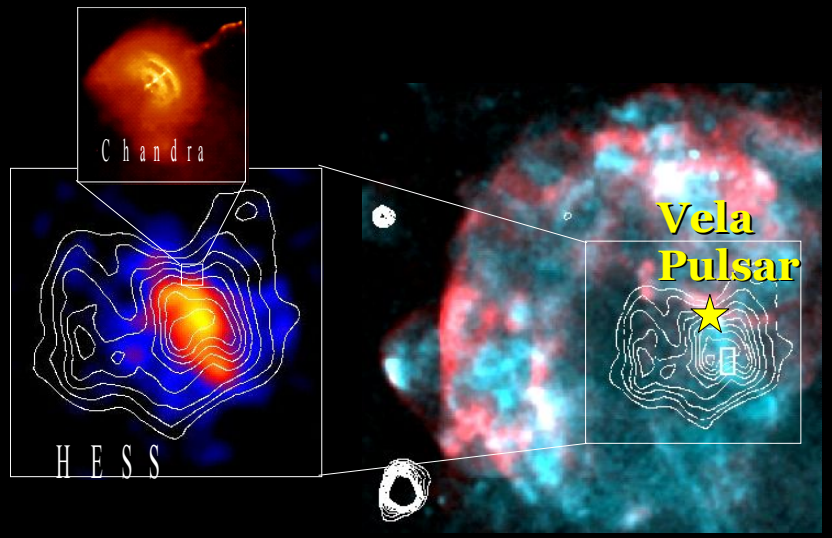
- Average flux ~6e-7 ph/cm2/s above 100 MeV, whith three flares as extremes of persistent variability

- Flux increase by ~5 during 2009 and 2010 flares, by ~30 during 2011 flare !

- - *Compact emission region < 0.0004 pc ~ 0.04" (for D<4)* → *Emission from the inner nebula*

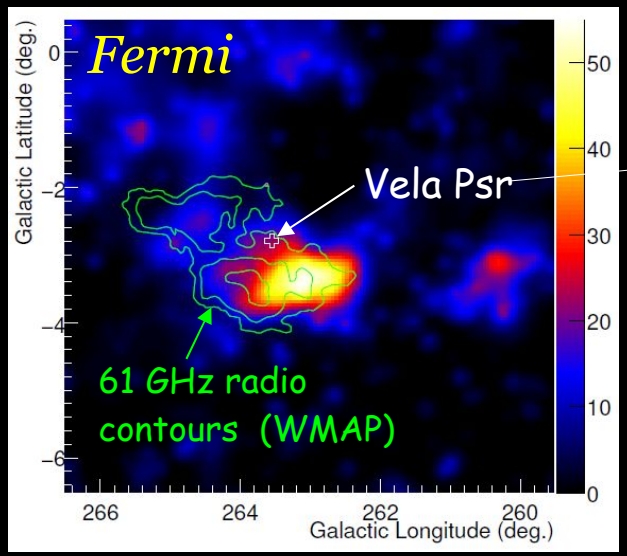
The puzzling Vela X PWN

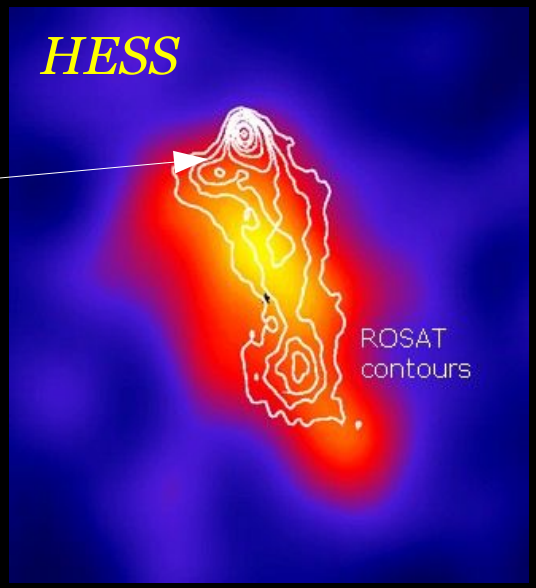
- Associated with the Vela Pulsar (d = 290 pc)
- Located south of the pulsar



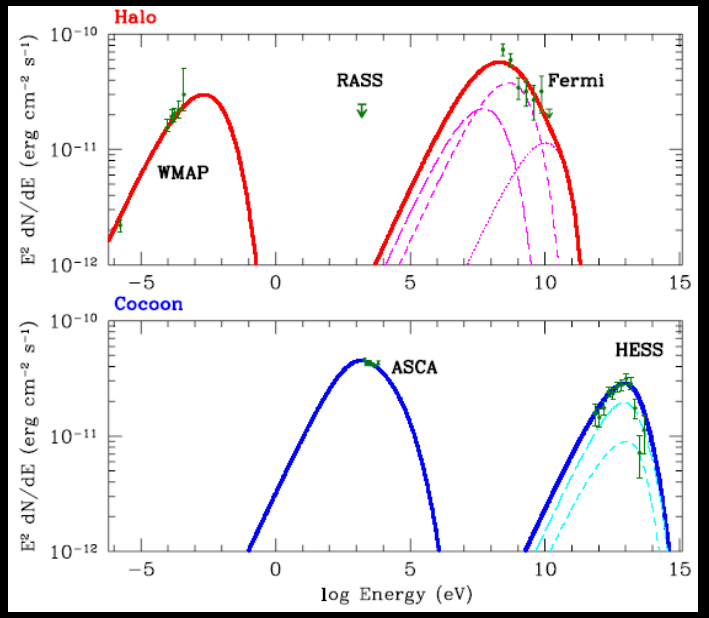
- Morphology :
  - Radio & HE gamma-rays : Halo (2° x 3°)
  - X-rays & VHE : Cocoon (length < 1°)

- Multiwavelength spectrum :
  - strongly favors a two-component leptonic model (suggested by de Jager et al., 2008, ApJ, 689, L125) : one young population for the X-ray/VHE-peak cocoon & a relic one for the radio/MeV-peak halo.





Abdo et al, 2010, ApJ, 713, 146



Multi-wavelength spectrum of Vela X

...and even more puzzling !

Lower energy threshold (300 MeV, front events)

- Morphological analysis in different energy bands

→ unveils an energy-dependent morphology

- 300 MeV – 1 GeV (red) :

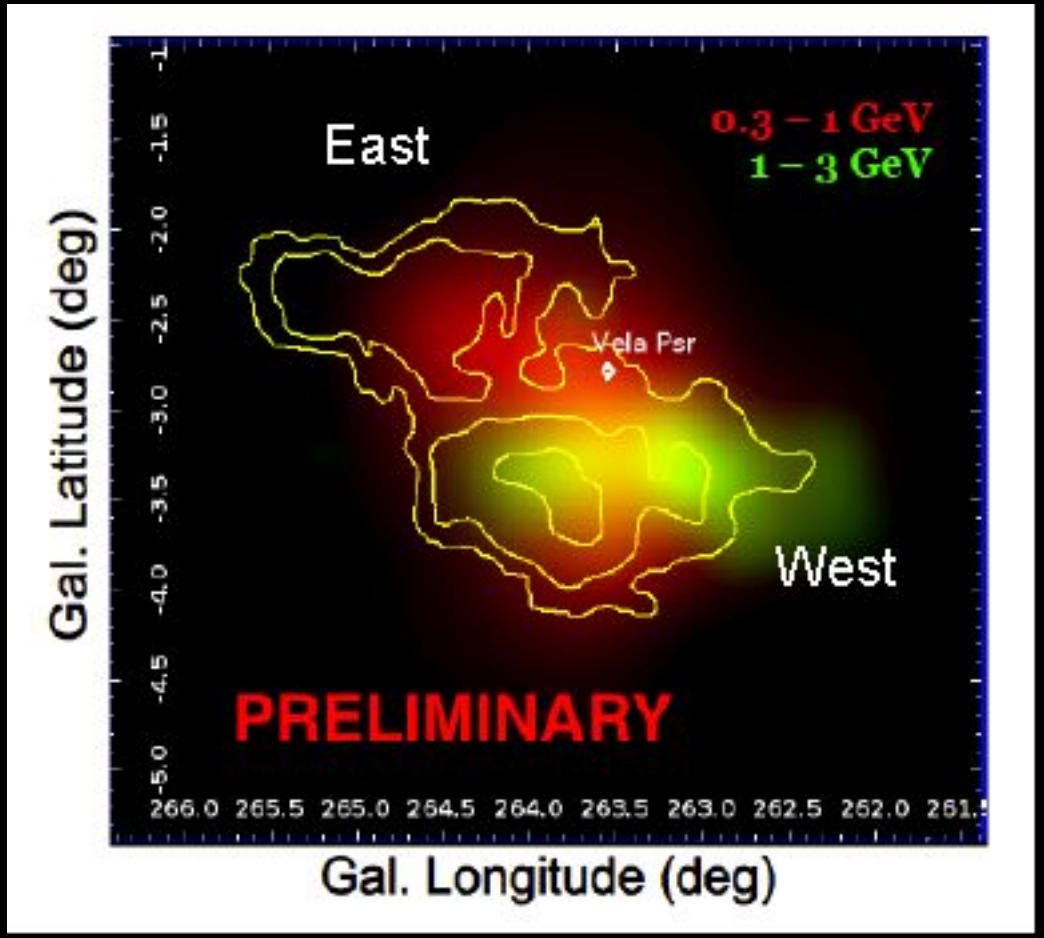
HE emission matches the radio halo (yellow contours)

- Above 1 GeV (green) :

correlates only with the « Western » wing of the radio emission

(as reported in the 1st Fermi paper)

Grondin et al., to be submitted



Fermi-LAT TS map of the Vela-X region
Red: 300 MeV – 1 GeV
Green : 1 – 3 GeV

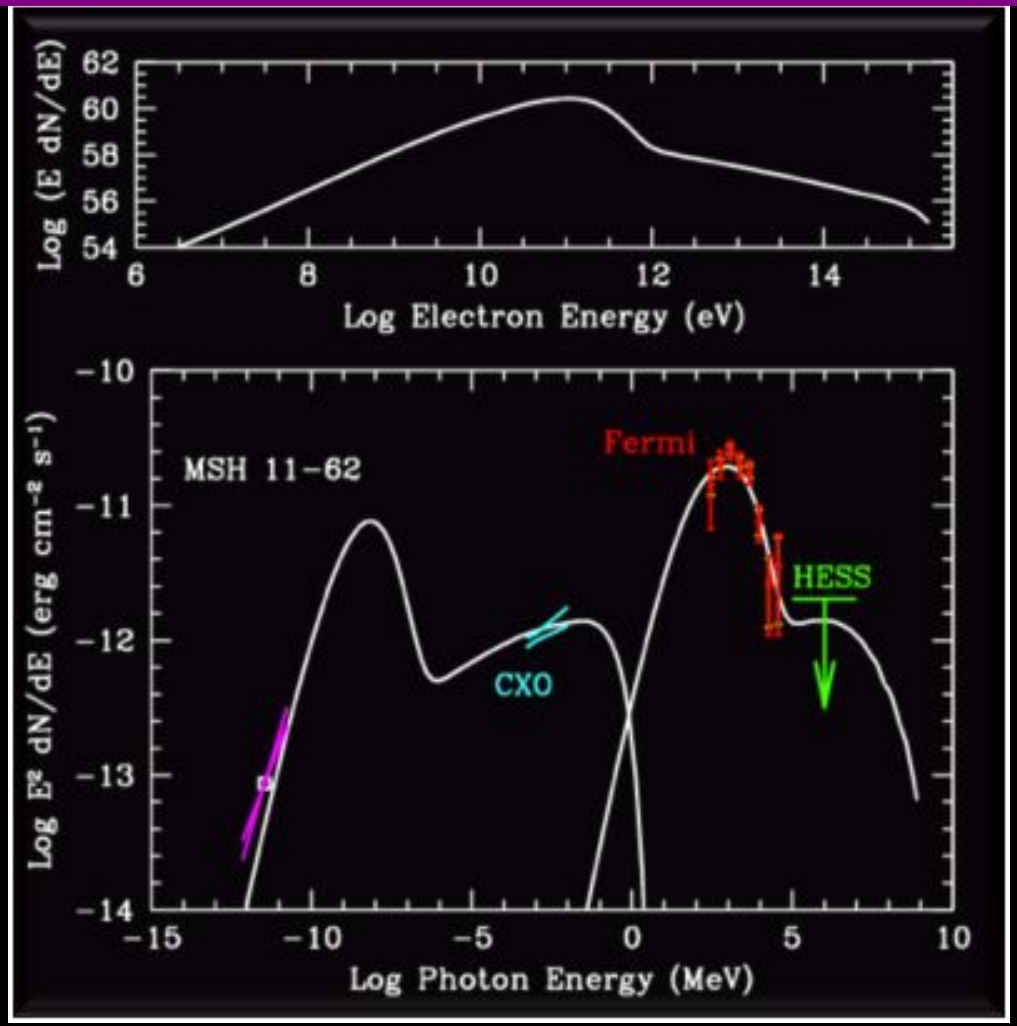
A PSR-like PWN candidate ! MSH 11-62

1FGL J1112.1-6041 is spatially associated with MSH 11-62

- Radio observations reveal shell with bright nebula in center
  - no pulsar known, but surely a PWN
- X-ray studies show thermal shell with a central PWN:
  - pulsar candidate seen at the center of the PWN (offset from radio center)

- if the GeV emission is produced by the PWN, broadband modeling appears to provide additional support for presence of Maxwellian electron component

Fermi observations of MSH 11-62 are consistent with emission arising from an evolved PWN, but pulsar hypothesis cannot be ruled out
=> timing is extremely important



Marianne Lemoine-Goumard, 2012, APC (Paris)

Going further: Search for TeV PWNe in the GeV range

Second search for PWNe and PWNe candidates using *Fermi*-LAT data :
- Search in the off pulse
- Search at high energy around TeV sources

Why ?
PWNe are the most populous class of Galactic sources in the TeV energy range
~1/3 of TeV Galactic sources are UNID → potential PWNe
→ TeV information on the position and extension could improve sensitivity.

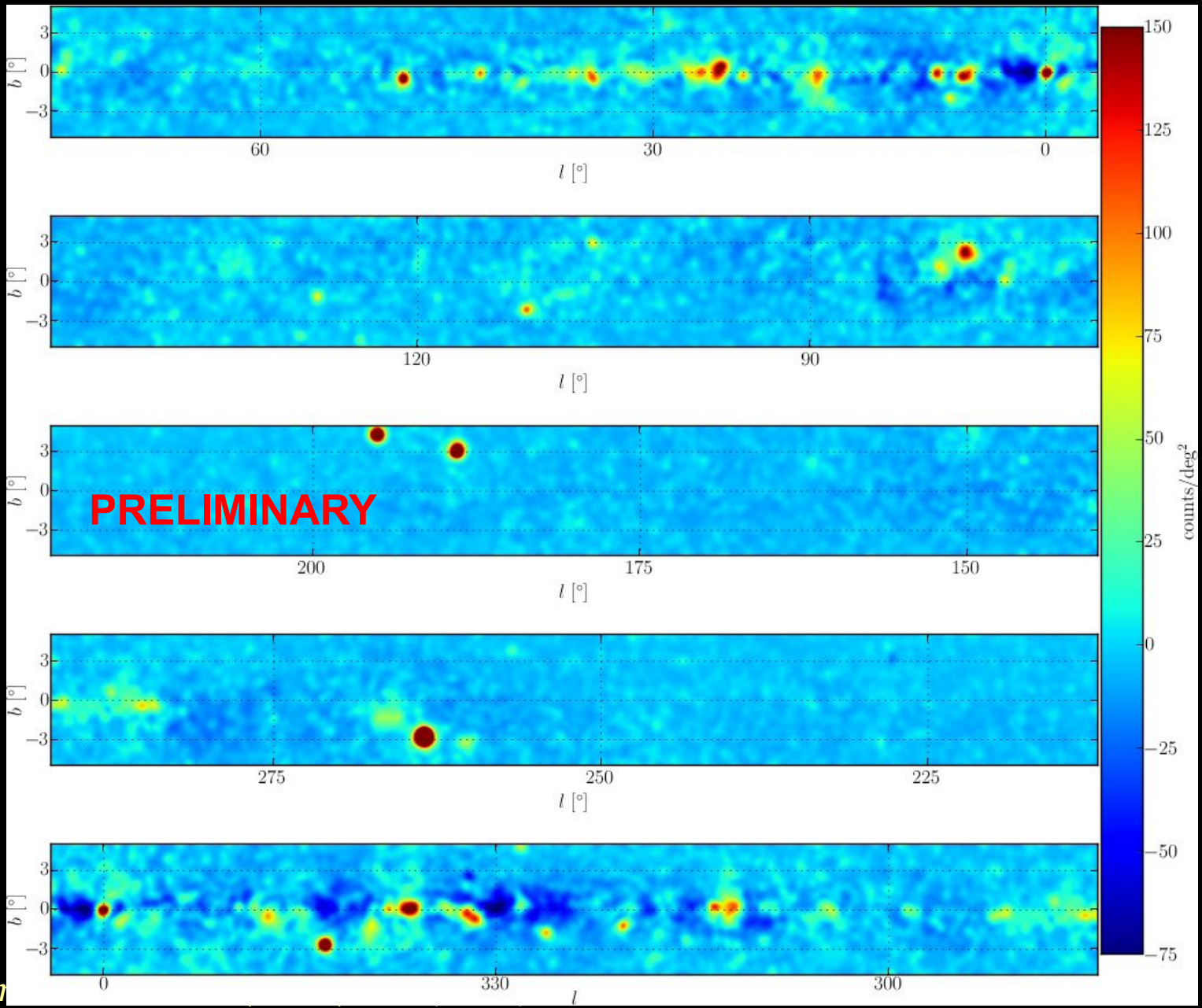
What are we looking for ?
- New GeV detections
- Study the morphology
- Constraints on the SED models

Which candidates ?
- Select only Galactic sources (latitude of +/- 5°) which are not identified as SNRs
- Remove the Galactic center for reliability and Vela X

=> 58 sources to analyze above 10 GeV (good PSF, reduce Galactic bckg)

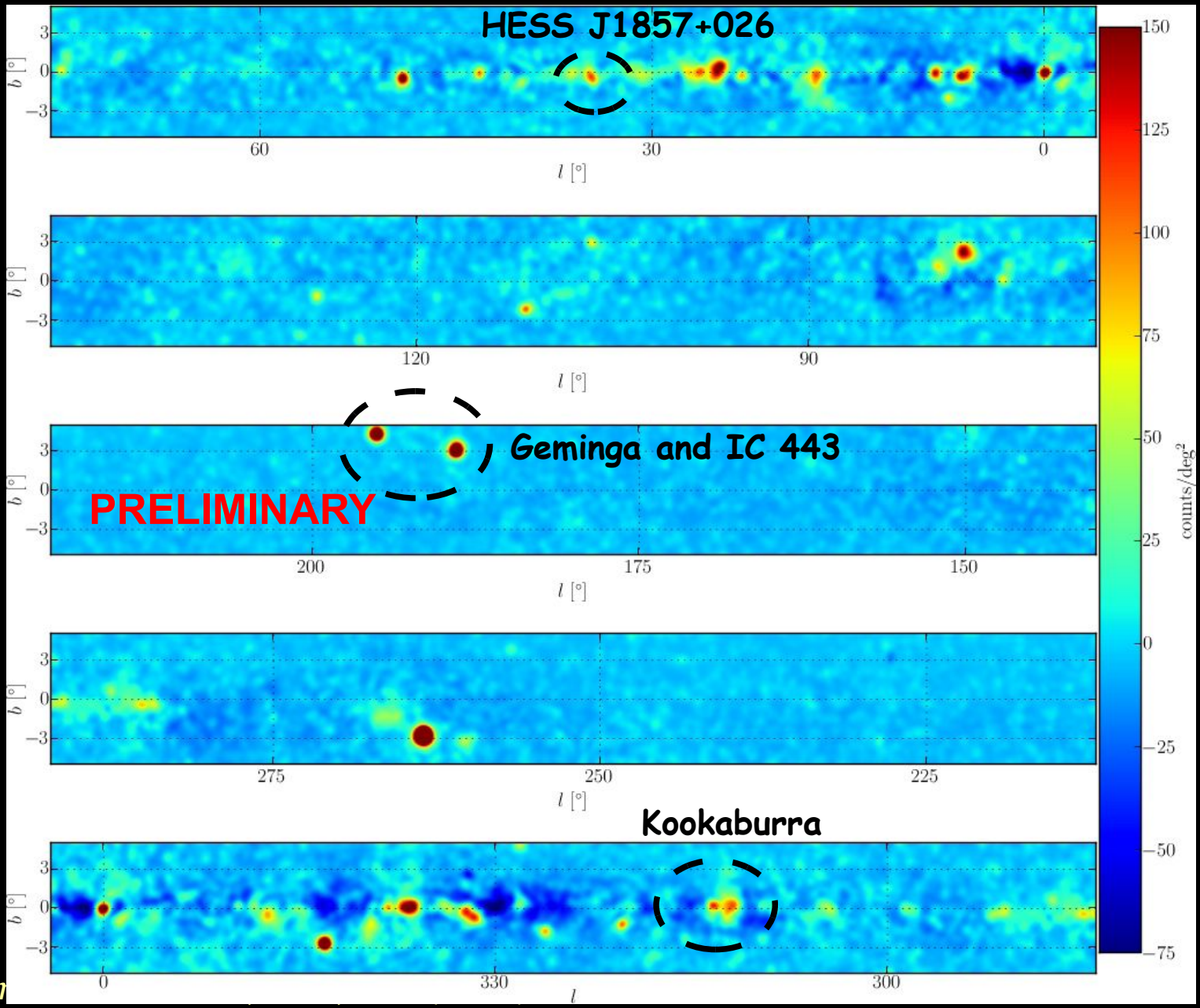
The Galactic Plane as seen by the LAT

Background subtracted counts map smoothed with a Gaussian of 0.27°



The Galactic Plane as seen by the LAT

Background subtracted counts map smoothed with a Gaussian of 0.27°



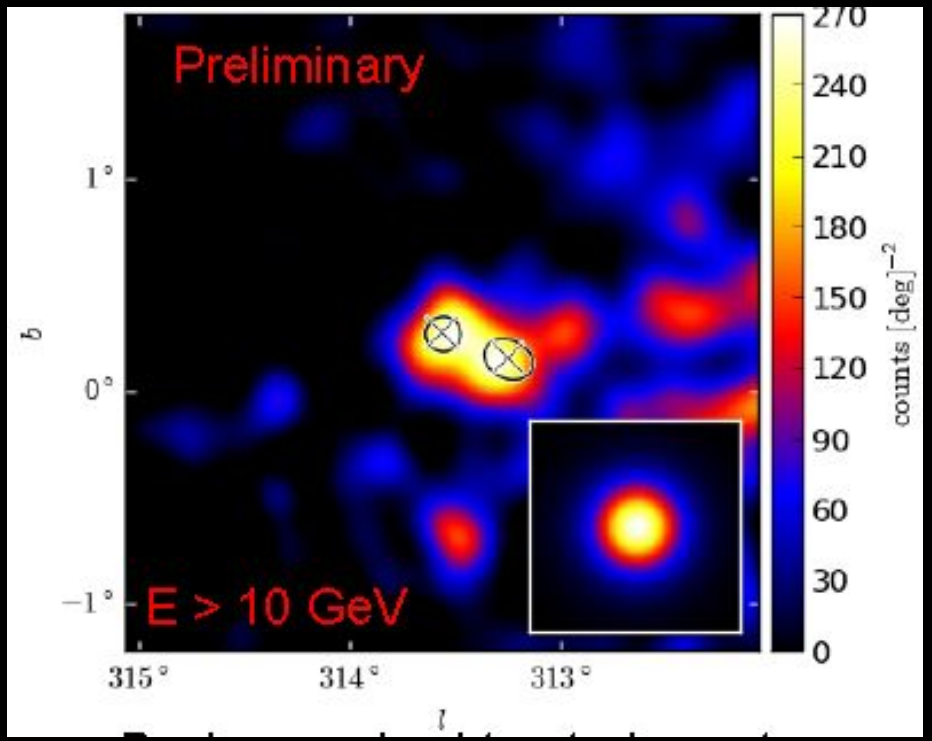
Another GeV PWN: K3

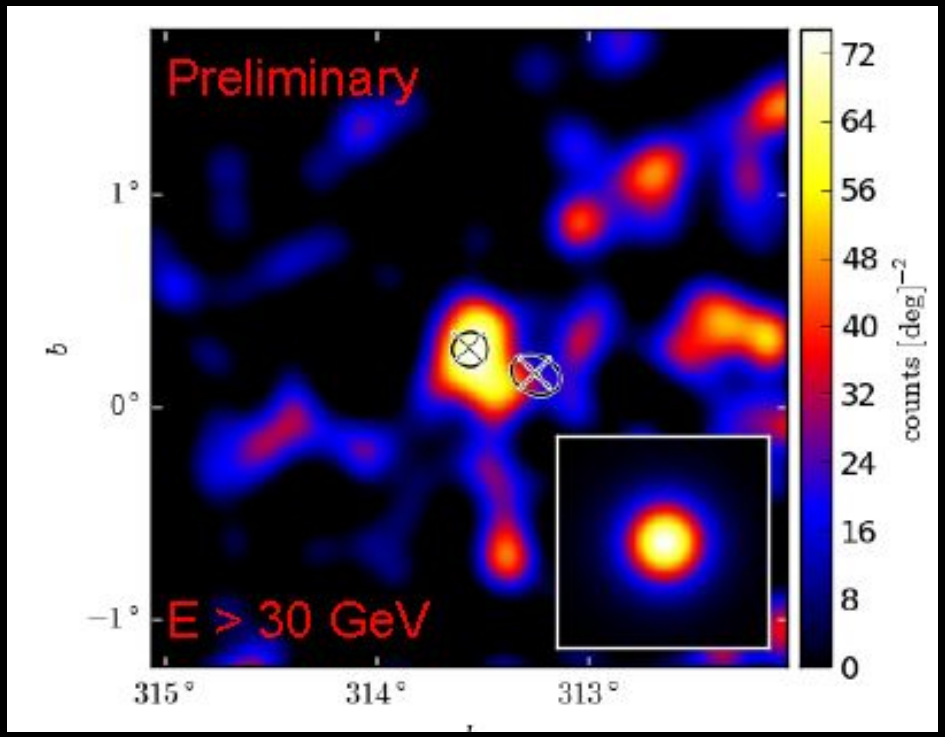
The complex of compact and extended radio/X-ray sources, called Kookaburra (Roberts et al. 1999), spans over one square degree along the Galactic plane

It contains 2 PWNe detected at TeV: HESS J1420-607 and HESS J1418-609

LAT GeV emission on HESS J1418 vanishes above 30 GeV; but still bright signal coming from HESS J1420: indicates a potential PWN detection by the LAT

Detected also at E>100 GeV by Neronov and Semikoz (2012; arXiv1201.1660)

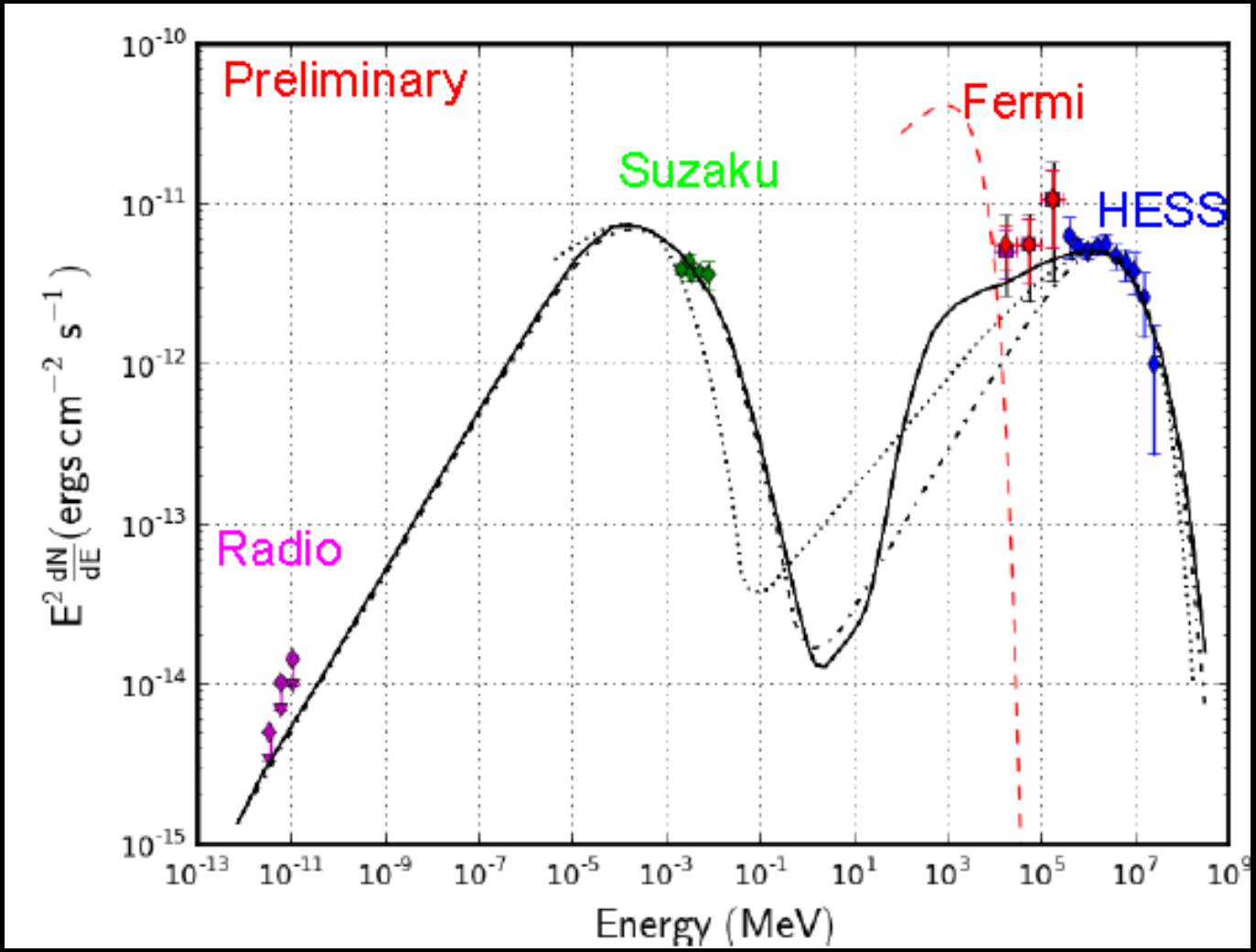




Background subtracted counts map smoothed with a Gaussian of 0.27°

HESS J1420-607 and the GeV-TeV connection

Models point towards an association of the GeV emission with the TeV PWN HESS J1420-607



PSR J1420-6048

Hadronic + leptonic model Van Etten & Romani (2010)

Leptonic model Van Etten & Romani (2010)

Leptonic model Kishishita (2012)

At low energy (10-30 GeV) the SED of HESS J1420-607 might be contaminated
Excellent GeV-TeV connection

Marianne Lemoine-Goumard, 2012, APC (Paris)

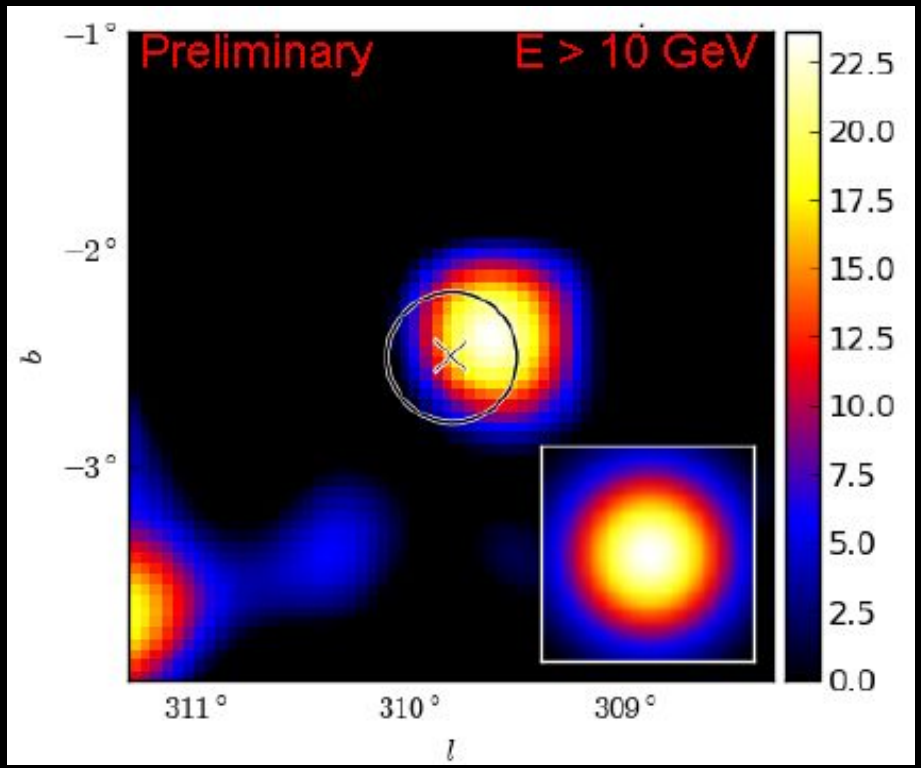
A new GeV PWN: HESS J1356-645

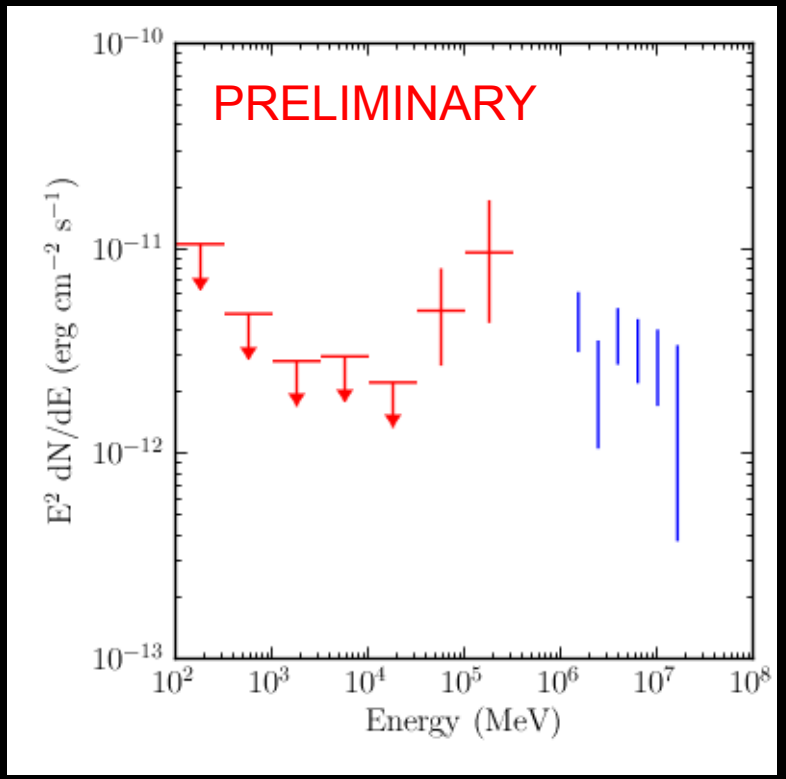
HESS J1356-645 is an extended source detected in the TeV energy range by H.E.S.S. during the Galactic Plane Survey.

Its high spin-down power of 3.1×10^{36} erg s^{-1} makes it a good PWN candidate.

Significant detection with Fermi and very hard spectrum matching the TeV flux (both detected in the off-pulse search and the TeV search)

=> point towards an association of the GeV and TeV sources



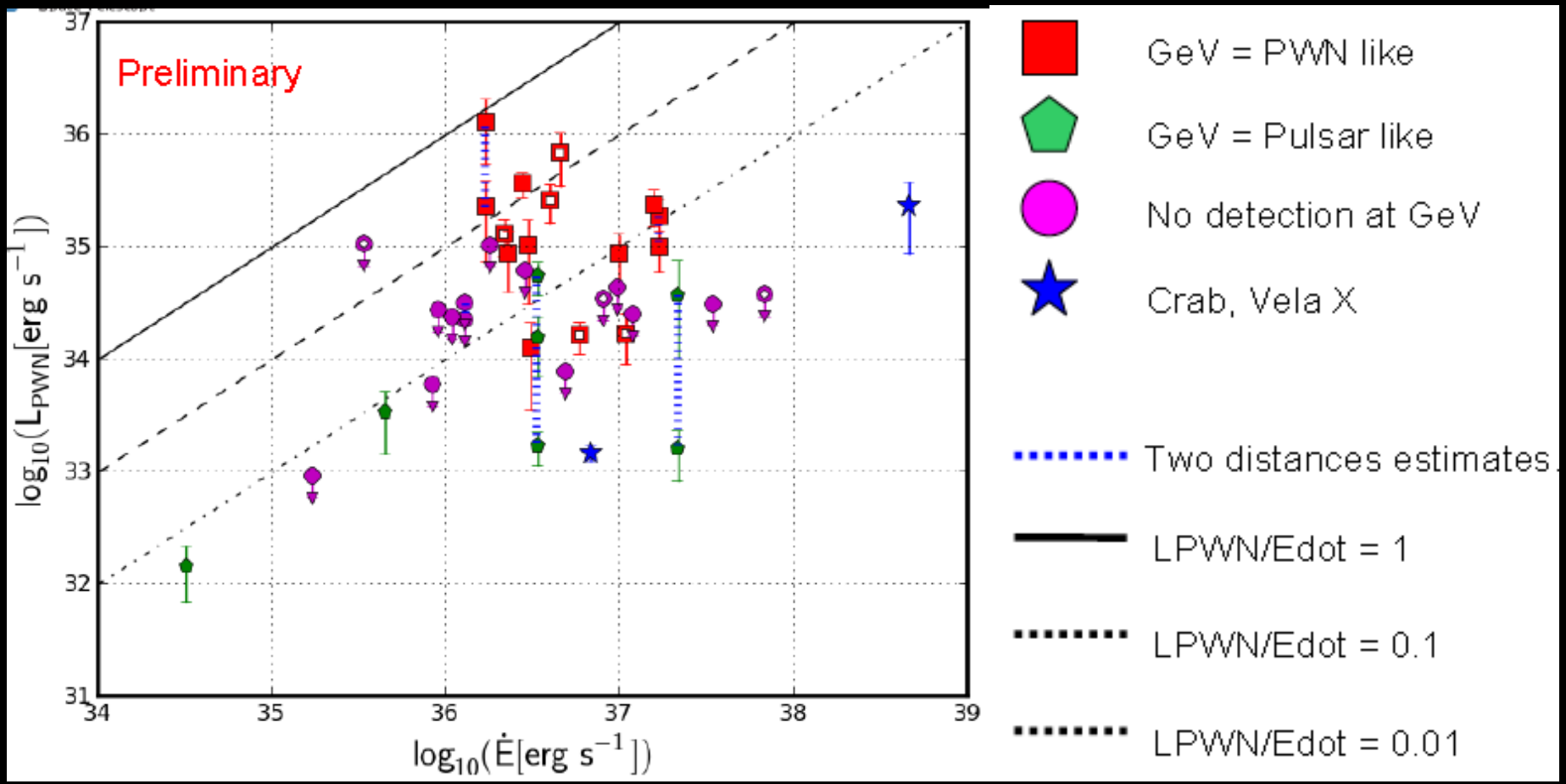


PWNe in the GeV range : towards a real population

Already 6 PWNe clearly identified + several PWNe candidates

→ So far, Fermi detects PWNe powered by bright (energetic) and young Pulsars

→ Efficiency < 10% of the spin-down power of the powering pulsar is required to explain the gamma-ray luminosity above 100 MeV

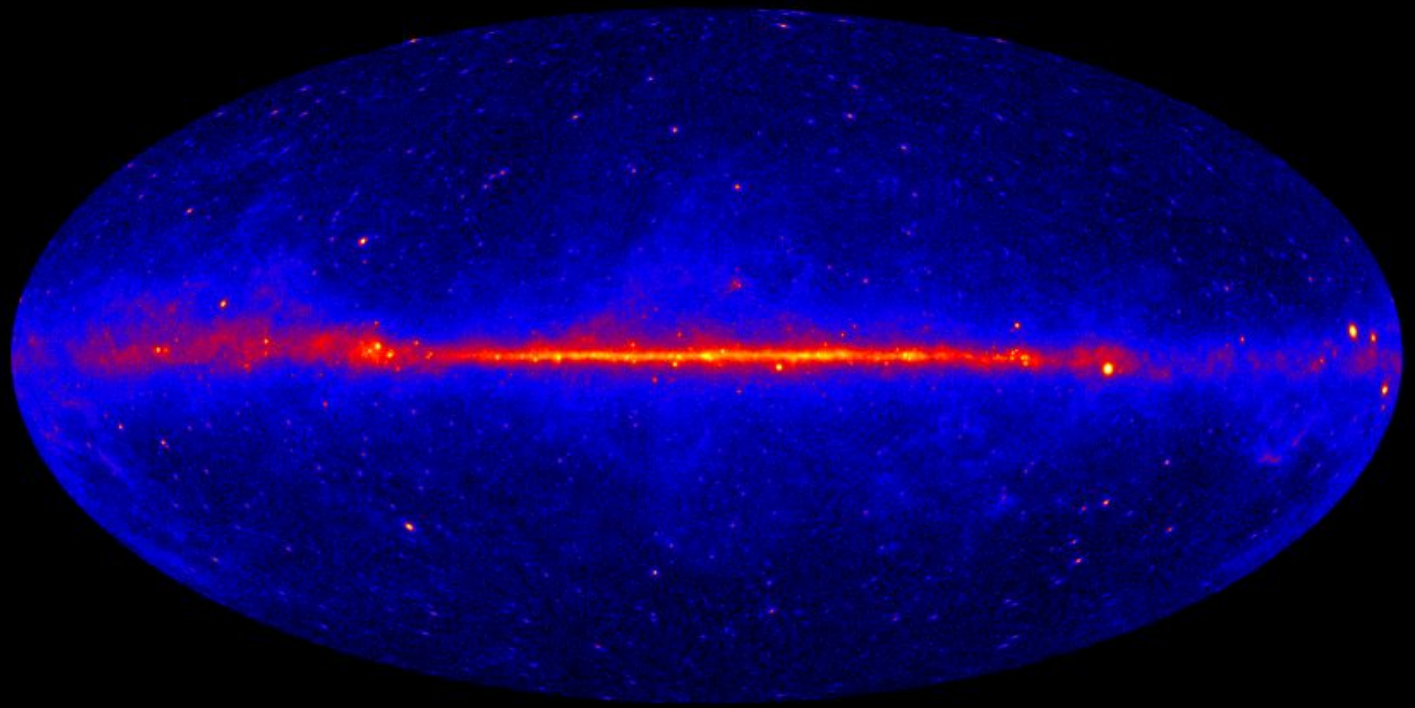


GeV observations : summary

- Already 117 Pulsars detected by Fermi-LAT: 77 young or middle aged PSR + 40 MSPs
  - Superb sensitivity has enabled phase-resolved spectroscopy and detailed light curve studies of many pulsars
- 1 New MSP detected by blind frequency searches: very good prospect for the future !
- 6 identified PWNe and a dozen of good candidates associated to TeV PWNe
  - 2 young PWNe: Crab and MSH 15-52
  - 4 middle aged PWNe: Vela X, HESS J1825, HESS J1356, HESS J1420
  - Some constraining ULs help to constrain the origin of the gamma-ray emission
- Potential sources of CR electrons => see talk by D. Grasso

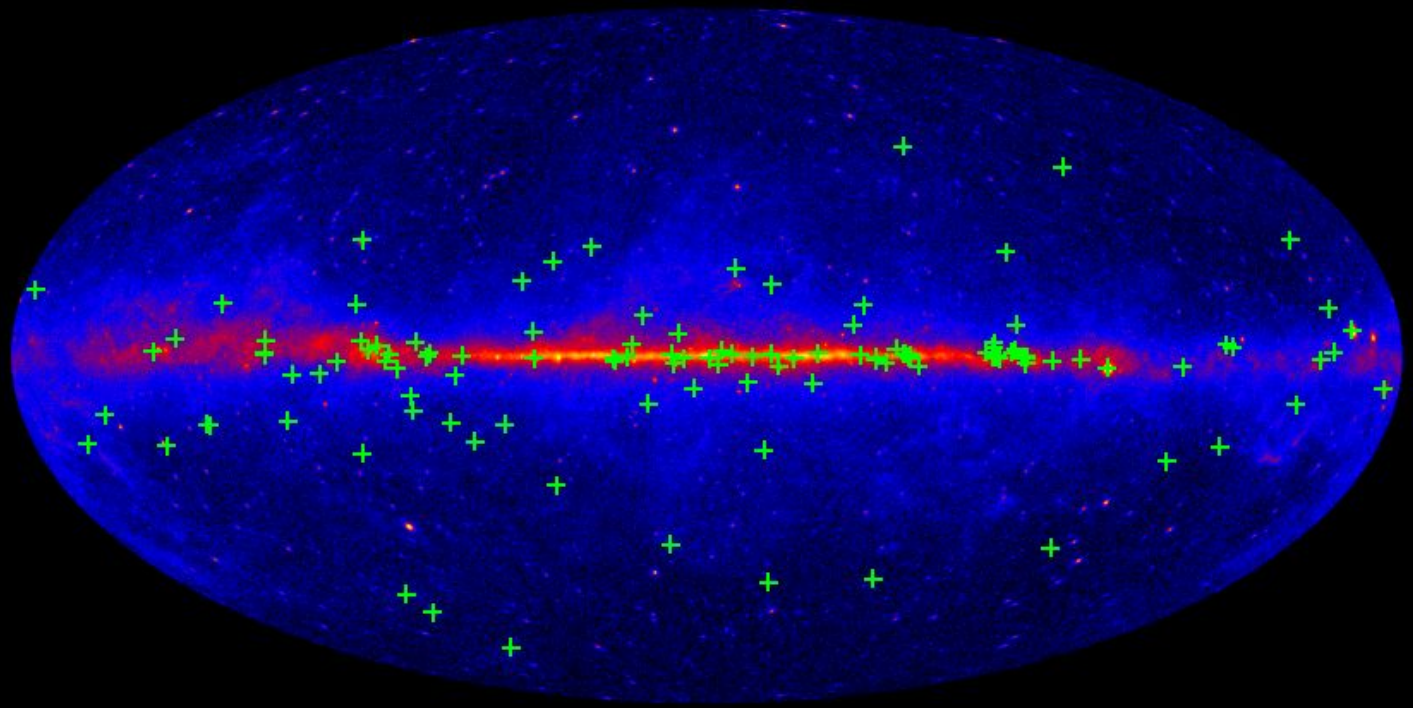
=> A real population of Pulsars and PWNe is being detected by the LAT ! Stay tuned: the 2nd Pulsar Catalog and the PWNe search around TeV Galactic sources will be submitted very soon

Growing and growing…



36-month all-sky image. Pass 7.6 Source class events

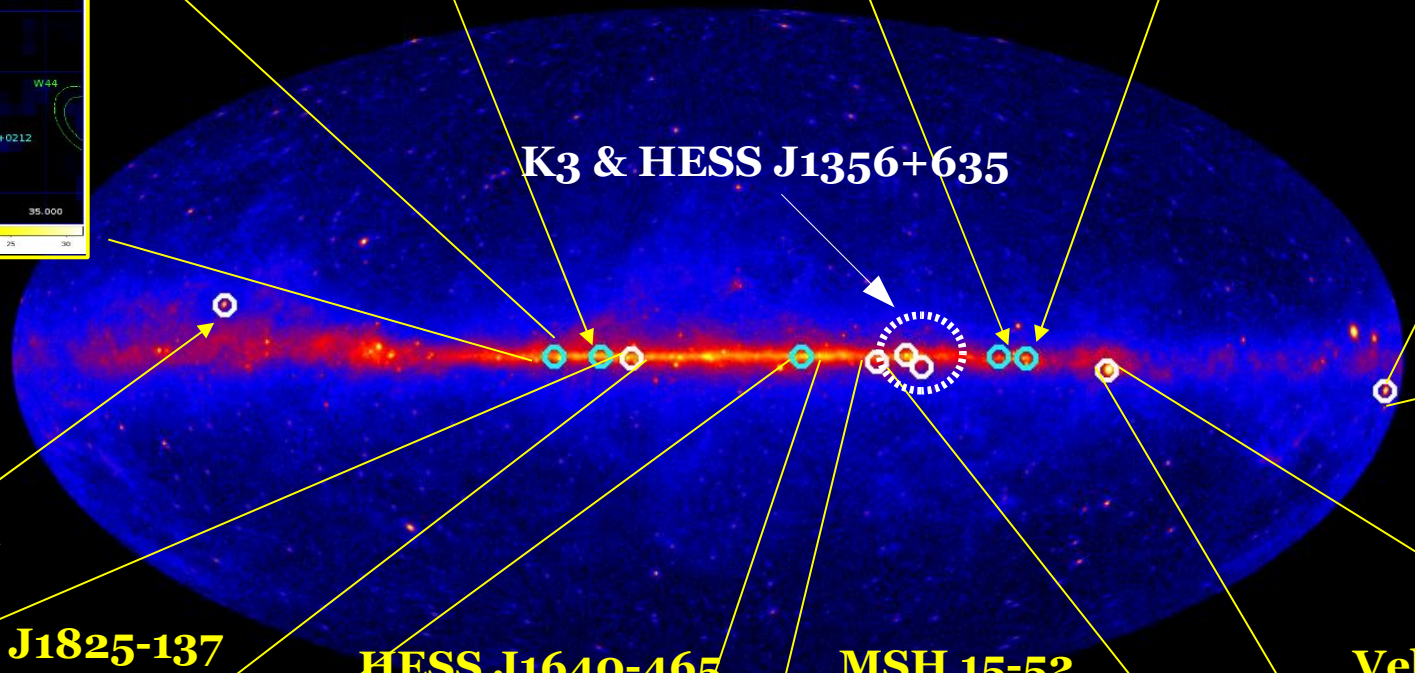
Growing and growing…



+ 2PC Pulsars

Marianne Lemoine-Goumard, 2012, APC (Paris)

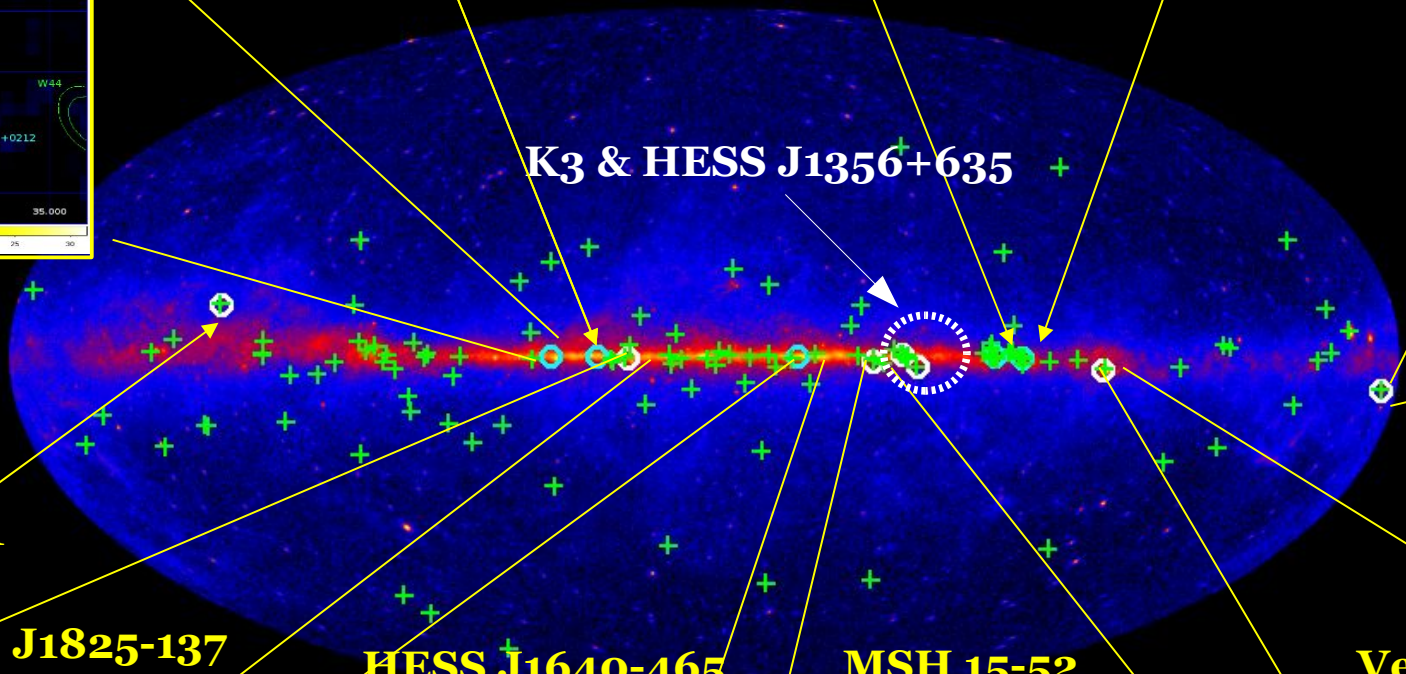
Growing and growing…



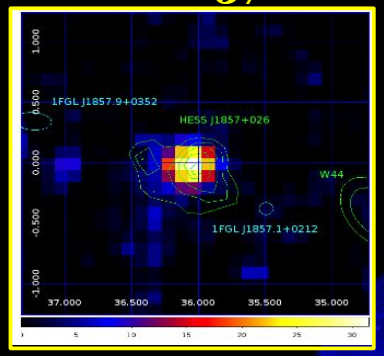
PWNe identified and candidates

Marianne Lemoine-Goumard, 2012, APC (Paris)

And many more to come soon !



HESS J1857+026

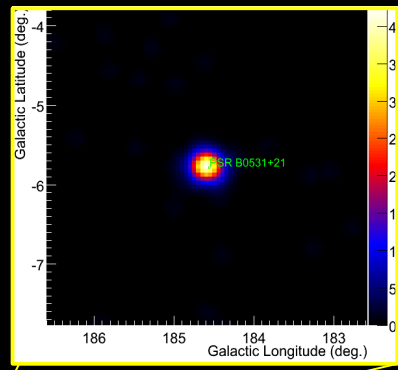


HESS J1837-0657

MSH 11-62

HESS J1023-575

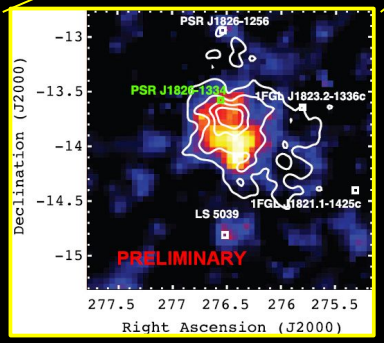
Crab Nebula



K3 & HESS J1356+635

SNR CTA 1

HESS J1825-137



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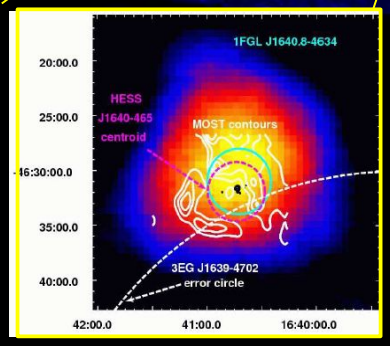
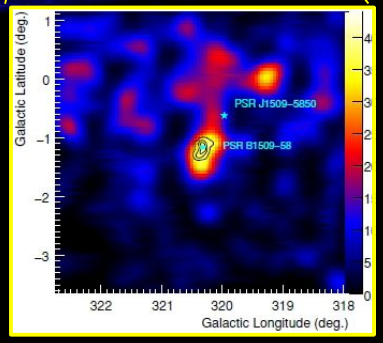
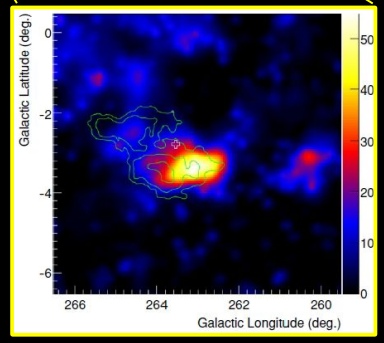


MSH 15-52



Vela X



Marianne Lemoine-Goumard, 2012, APC (Paris)