Alexander von Humboldt
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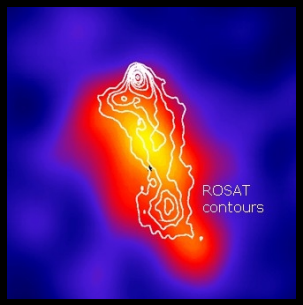
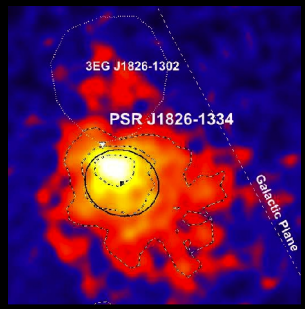
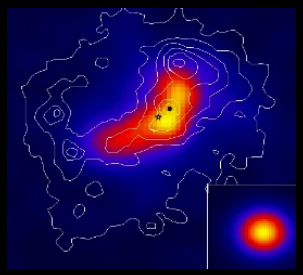
Pulsar Wind Nebulae in γ-rays : from GeV to TeV energies

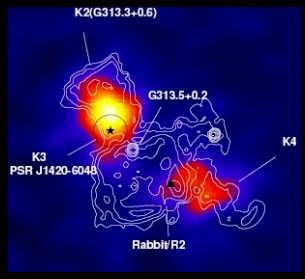
Marie-Hélène Grondin
MPIK (Heidelberg, Germany)

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









– SciNeGHE 2012, Lecce, Italy –
– 20 June 2012 –

Outline

1. Brief introduction to :

- Pulsar Wind Nebulae (PWNe)

- Scientific context : history, instruments, etc.

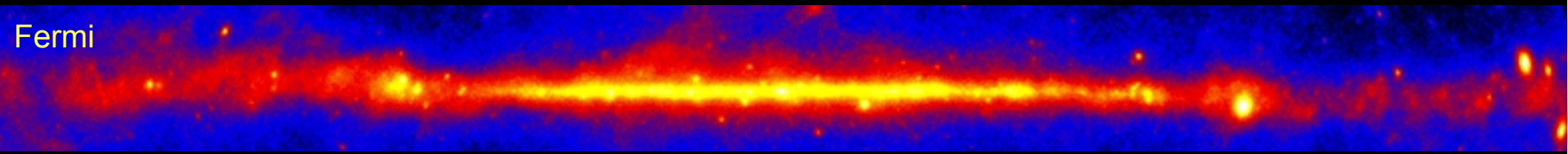
2. GeV & TeV Pulsar Wind Nebulae :

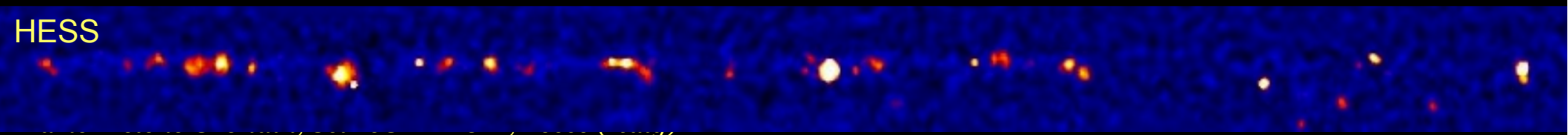
- Young PWNe

- Offset/middle-aged PWNe

- PWN candidates

3. Summary

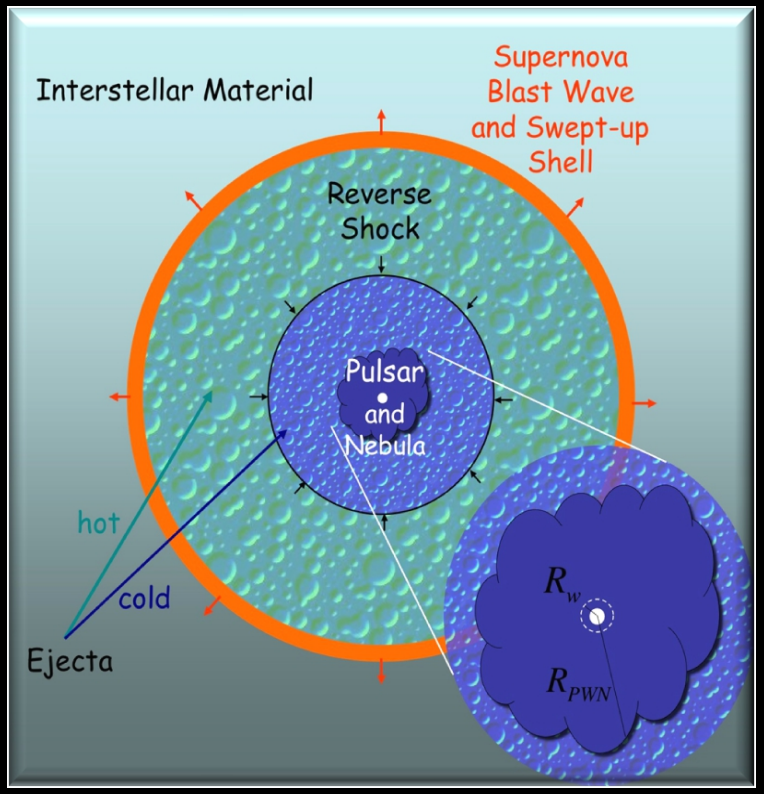




Introduction

Pulsar Wind Nebulae (PWNe)

- *Relativistic particles* ($e^{\pm}$) *injected by the 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*



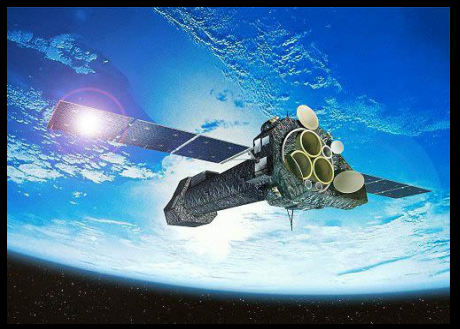
(Gaensler & Slane, 2006, ARA&A, 44, 17)

GeV/TeV emission mechanisms

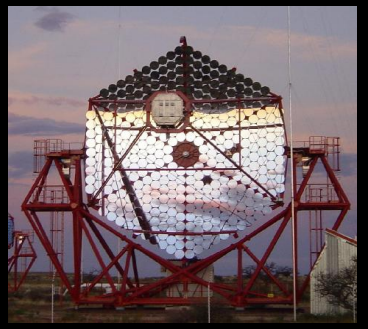
- *Non-thermal photon emission of leptonic or hadronic origin*
  - *Observations in the GeV/TeV range → disentangle between the radiation processes*
  - *Multiwavelength observations → constrain the physical properties of the sources*

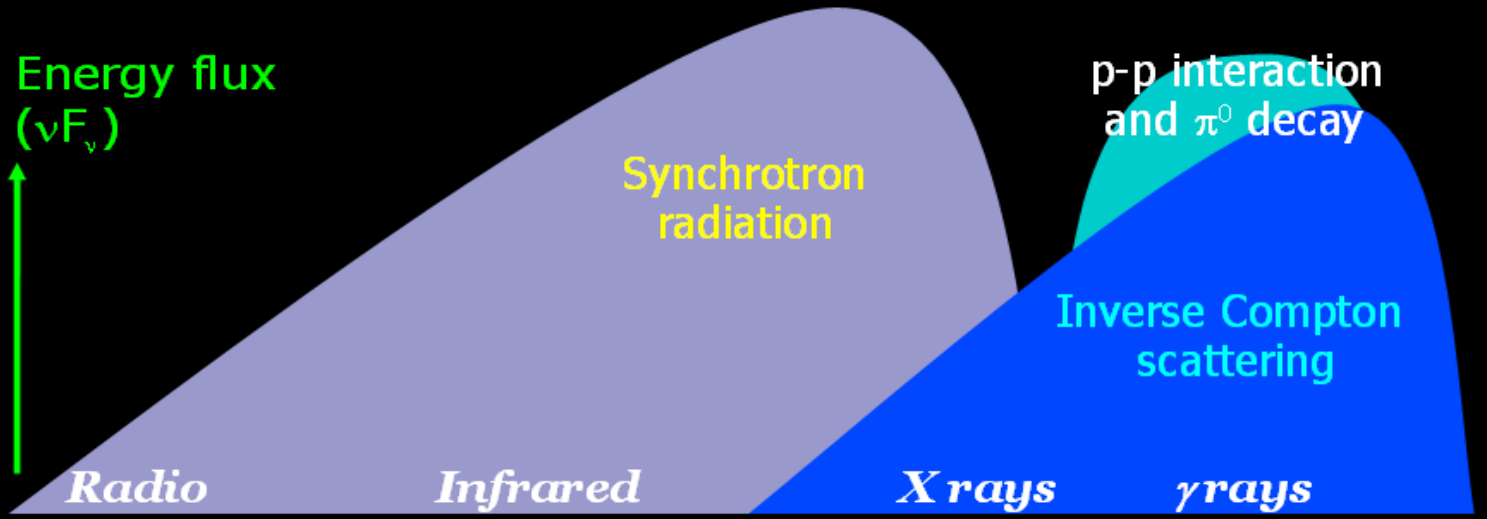
Radio telescopes

Satellites



Cherenkov Telescopes

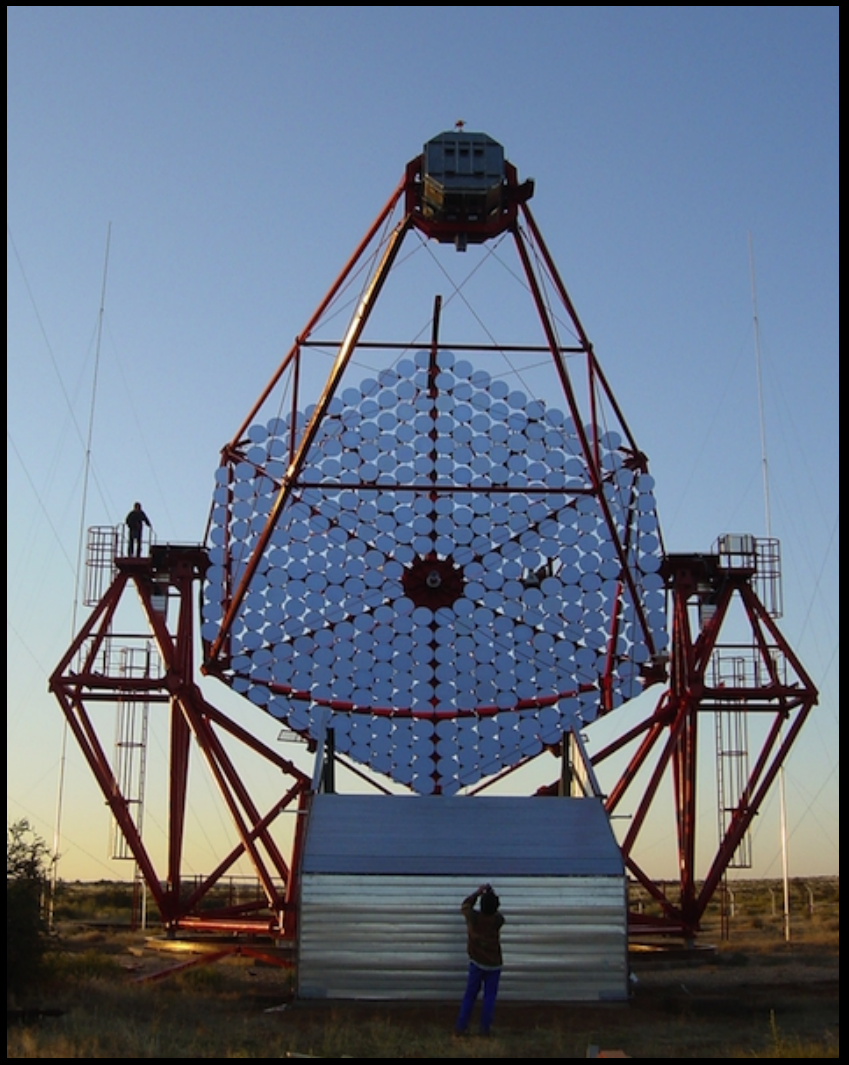




Credits : J. Hinton

Gamma-ray astronomy : two strategies

Fermi
(LAT : 20 MeV – 300 GeV)



HESS
(~100 GeV – ~100 TeV)

Status in the GeV range

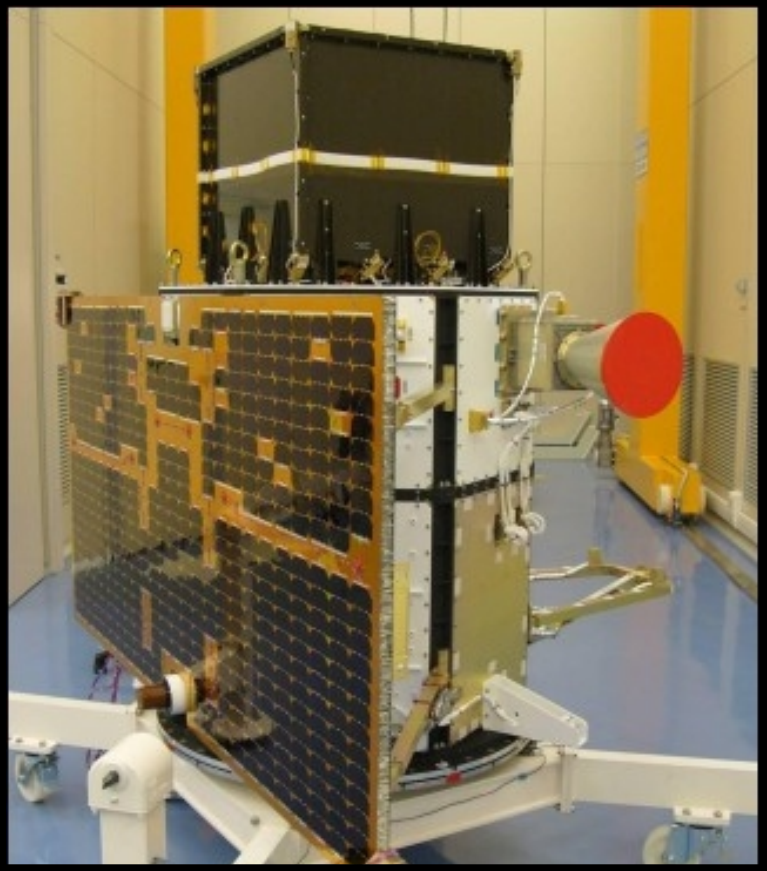
Recent launches of the gamma-ray satellites AGILE (2007) and Fermi (2008)

→ detection of ~1900 GeV sources (2FGL Catalog, Nolan et al, 2012, ApJS 199, 31)

→ ~30% unidentified sources

→ ~50% sources close to the Galactic plane

Fermi

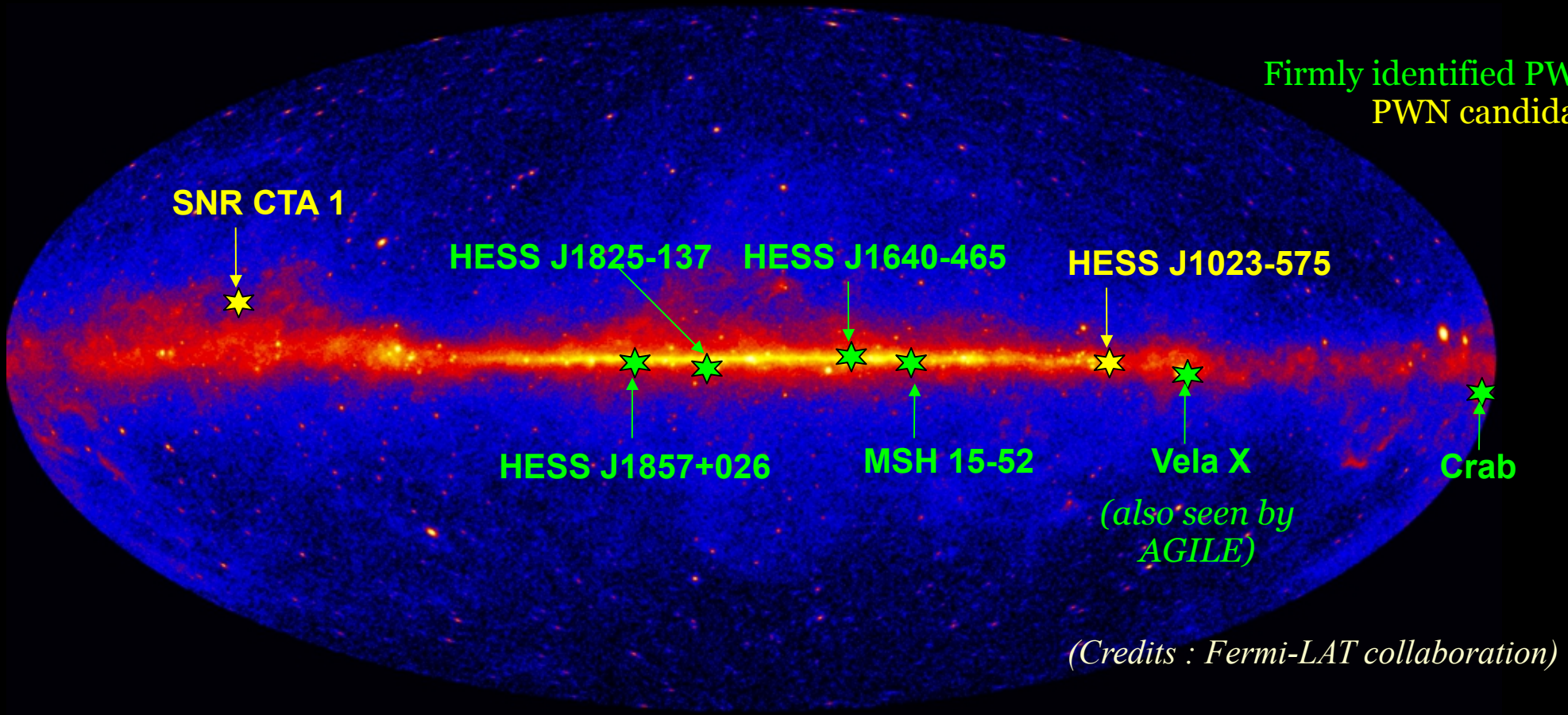


AGILE
(30 MeV – 50 GeV)

Fermi-LAT
(20 MeV – 300 GeV)

The GeV γ-ray sky

Already 6 PWNe firmly identified, 2 PWN candidates + *>100 pulsars*



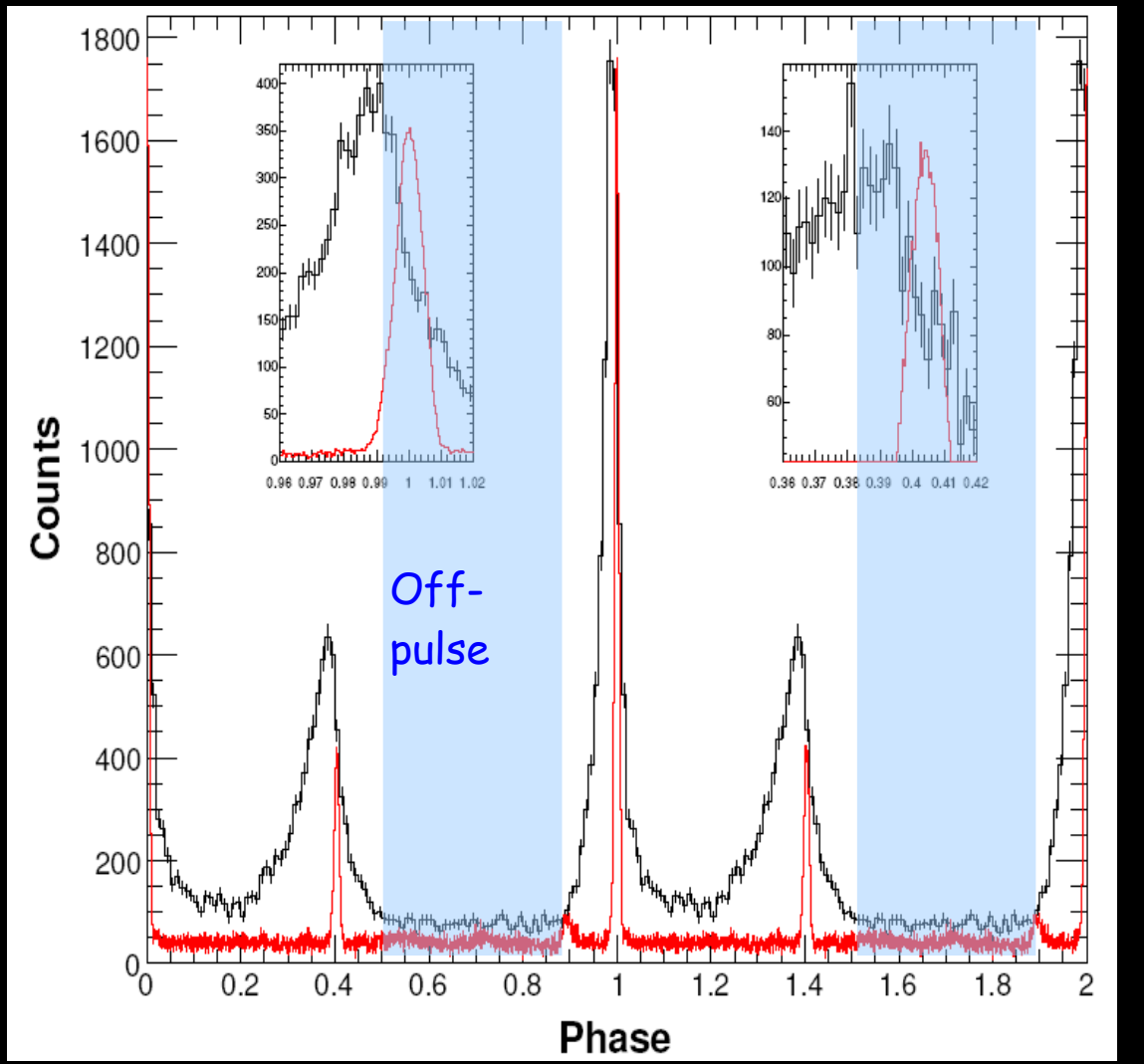
36-month image of the gamma-ray sky above 1 GeV

Why do we detect so few GeV PWNe ?

Their study (detection, morphological & spectral analyses) requires :

- A preliminary temporal analysis of the powering pulsar

→ substraction of the pulsed component → – 60 to 80% of the statistics



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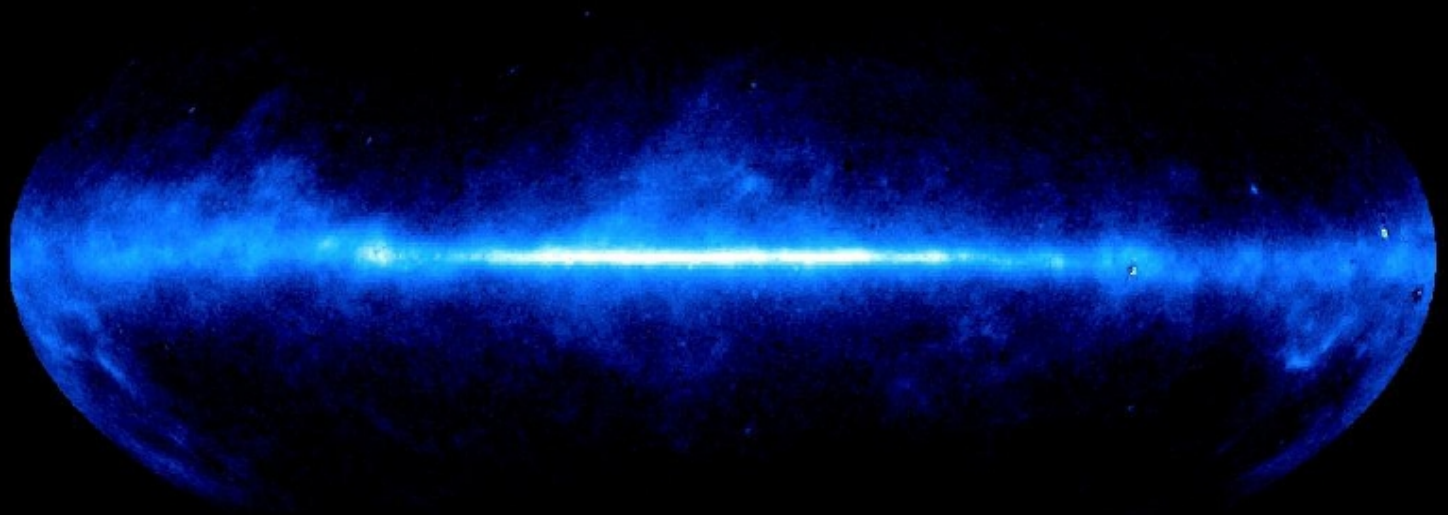
→ *substraction of the pulsed component*

- A good knowledge of :

- The diffuse background (spatial and spectral structures in the galactic diffuse emission)



Why do we detect so few GeV PWNe ?

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- A preliminary temporal analysis of the powering pulsar

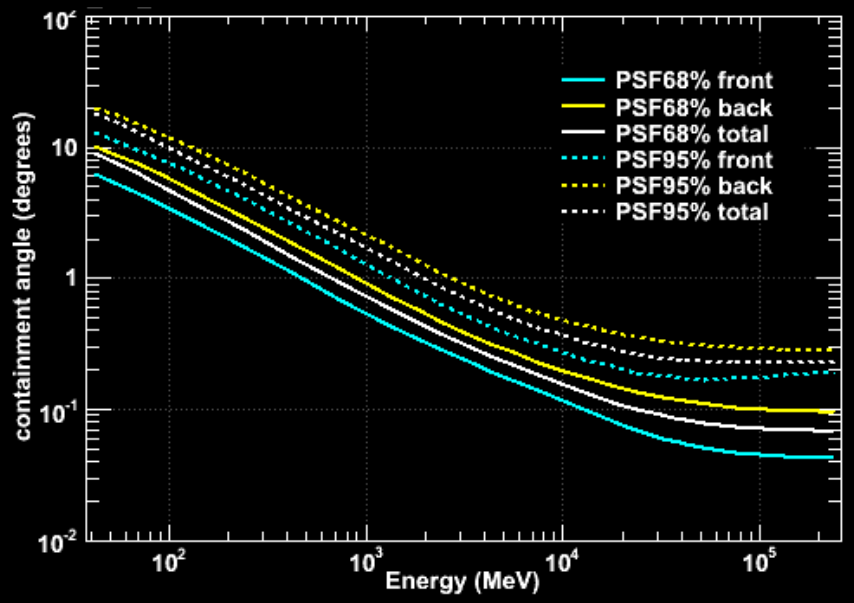
→ substraction of the pulsed component

- A good knowledge of :

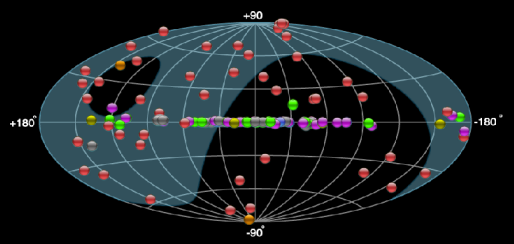
- The diffuse background (spatial and spectral structures in the galactic diffuse emission)

- The instrumental point spread function (PSF) varying over the LAT range :

~5° at 100 MeV → ~0.6° at 1 GeV → <0.15° at 10 GeV



Imaging Atmospheric Cherenkov Telescopes



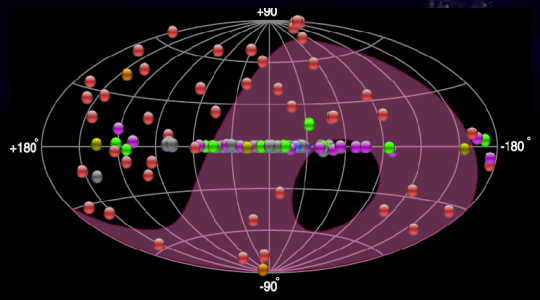
Energy range : few tens of GeV - 80 TeV
Area > 10^4 m^2
Background Rejection > 99%
Angular Resolution ~0.05°

MAGIC

VERITAS

HESS

CANGAROO III



The VHE sky

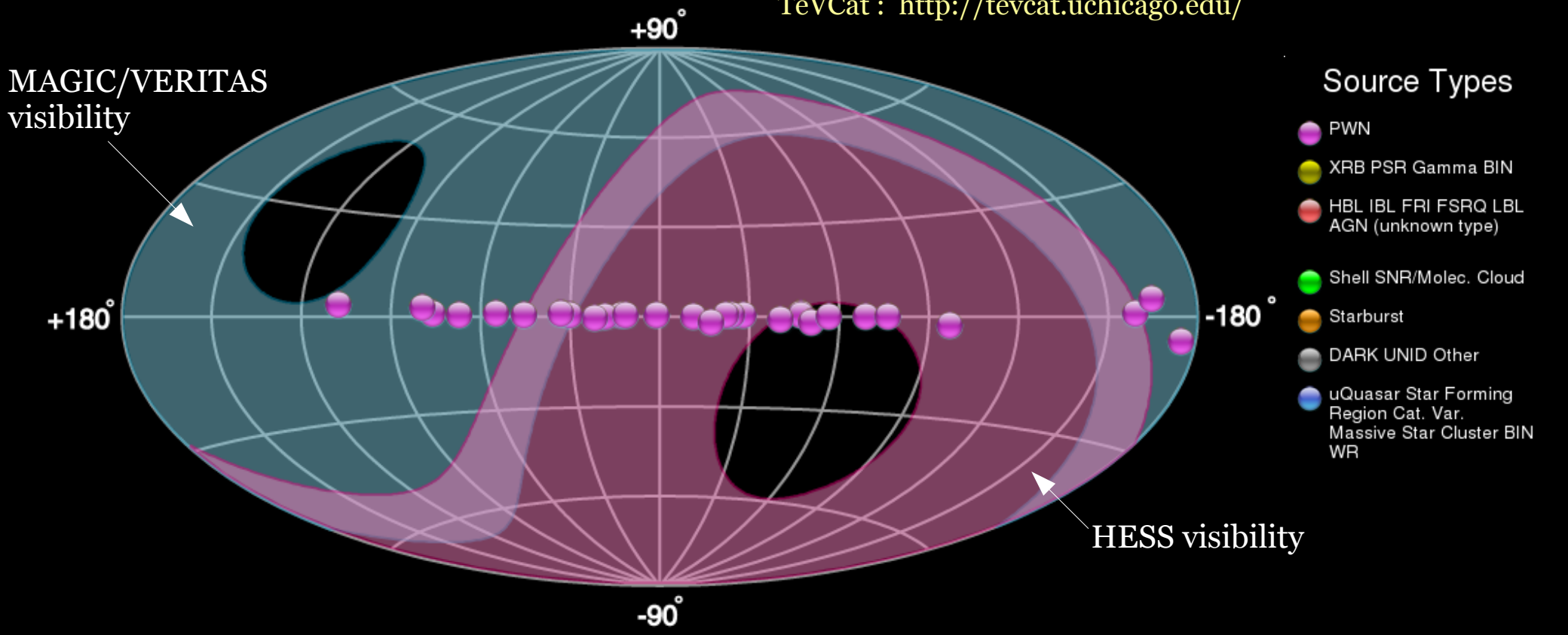
Improved sensitivity of current generation of Imaging Atmospheric Cherenkov Telescopes (IACTs)

→ *detection of >100 VHE sources*

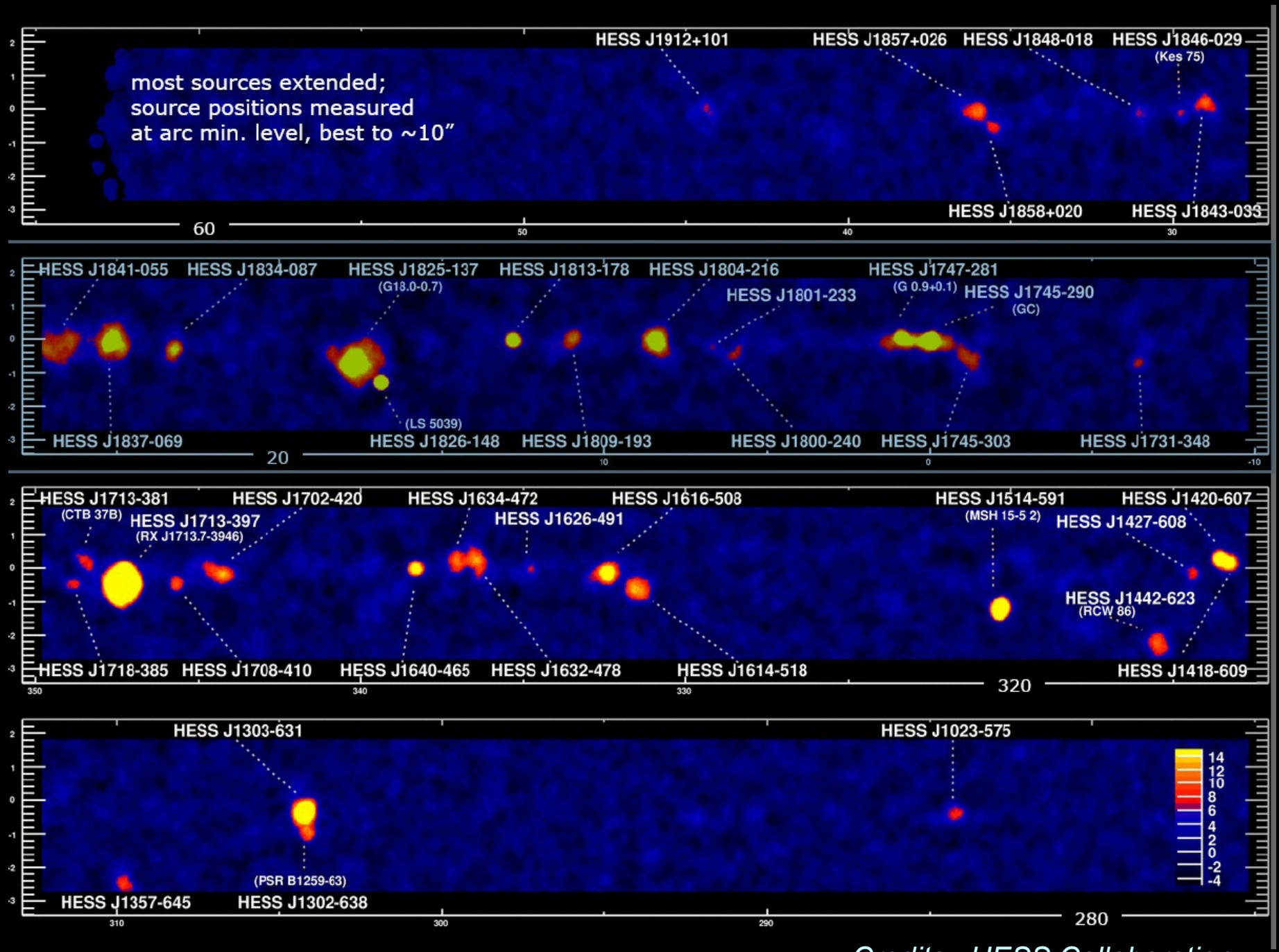
→ *~60 Galactic VHE sources known*

→ *~34 are identified as PWNe, >12 candidates*

TeVCat : http://tevcat.uchicago.edu/



HESS & the Galactic Plane Survey



Credits : HESS Collaboration

Observational results

1. Young PWNe

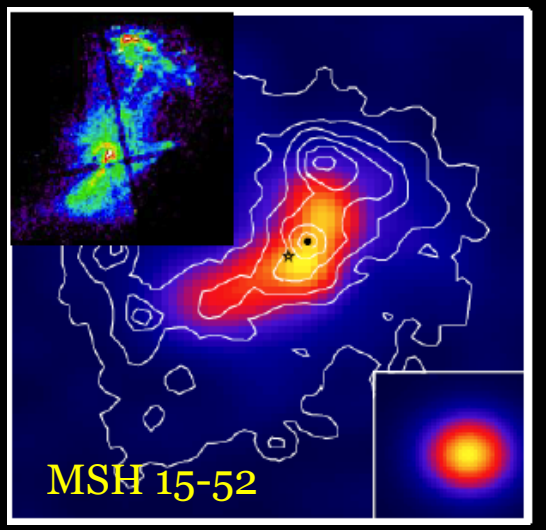
Detection in the GeV-TeV range :

- Crab Nebula

- MSH 15-52

- SNR CTA1

- HESS J1640−465



PWNe detected at TeV energies :

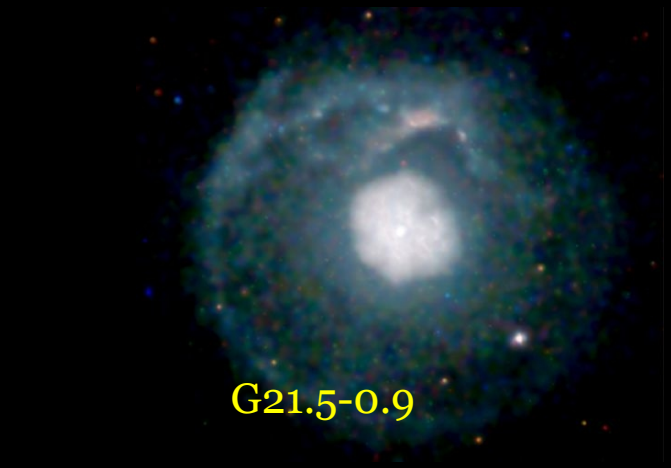
- SNR G0.9+0.1

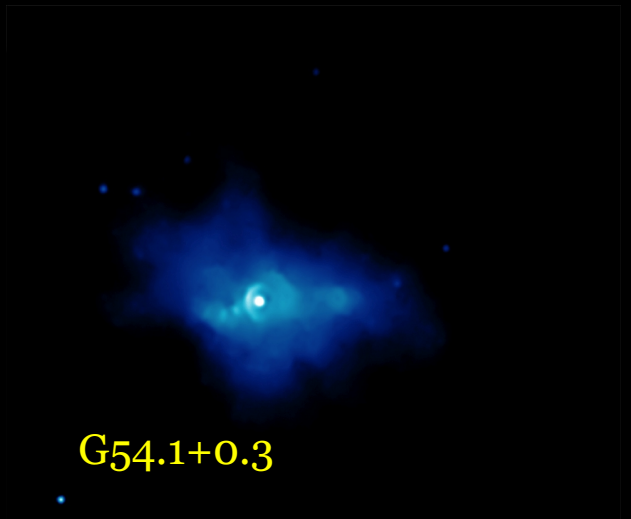
- SNR G21.5−0.9 & Kes 75

- HESS J1813−178

- SNR G54.1+0.3 (associated to PSR J1930+1852)

- HESS J1834−087 (Candidate associated to W41)





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

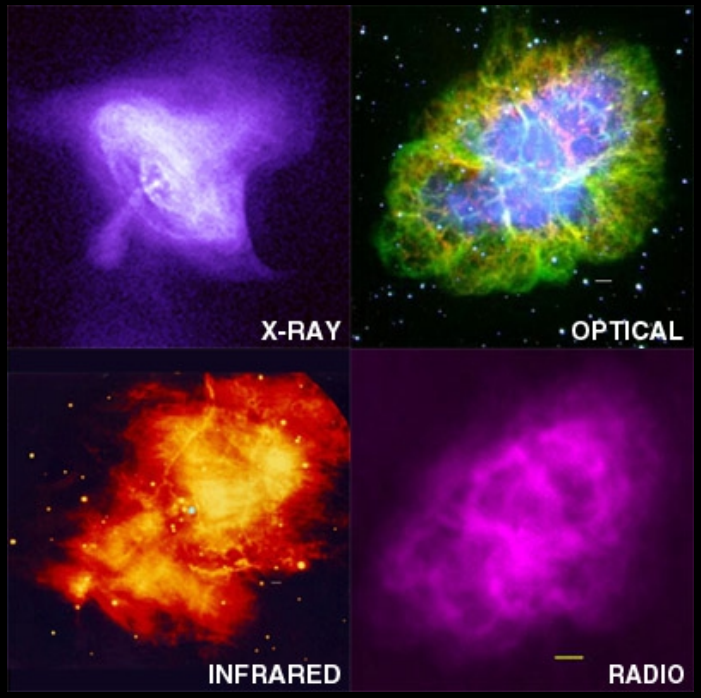
→ electrons accelerated up to ~1 PeV

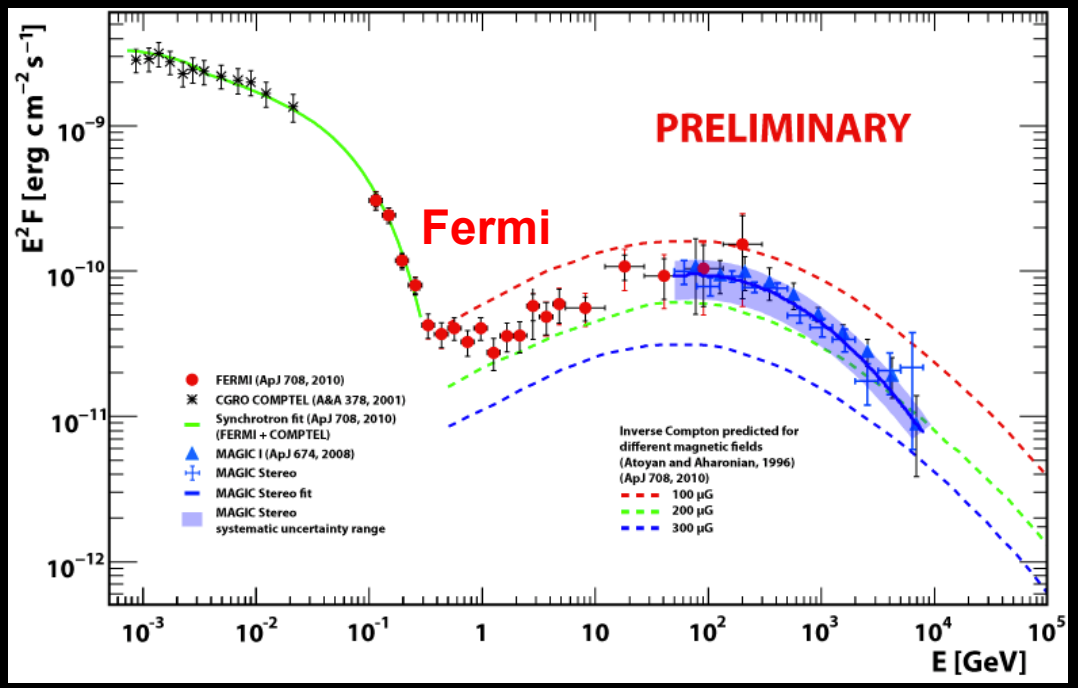
- high energy component due to IC (mainly on synchrotron photons)

→ fit of the IC peak at ~60 GeV (using Fermi and IACT results)

→ magnetic field constraint in the 100 – 200 μG range (Abdo et al, 2010, ApJ, 708, 1254)

E. de Cea del Pozo, ICRC 2011

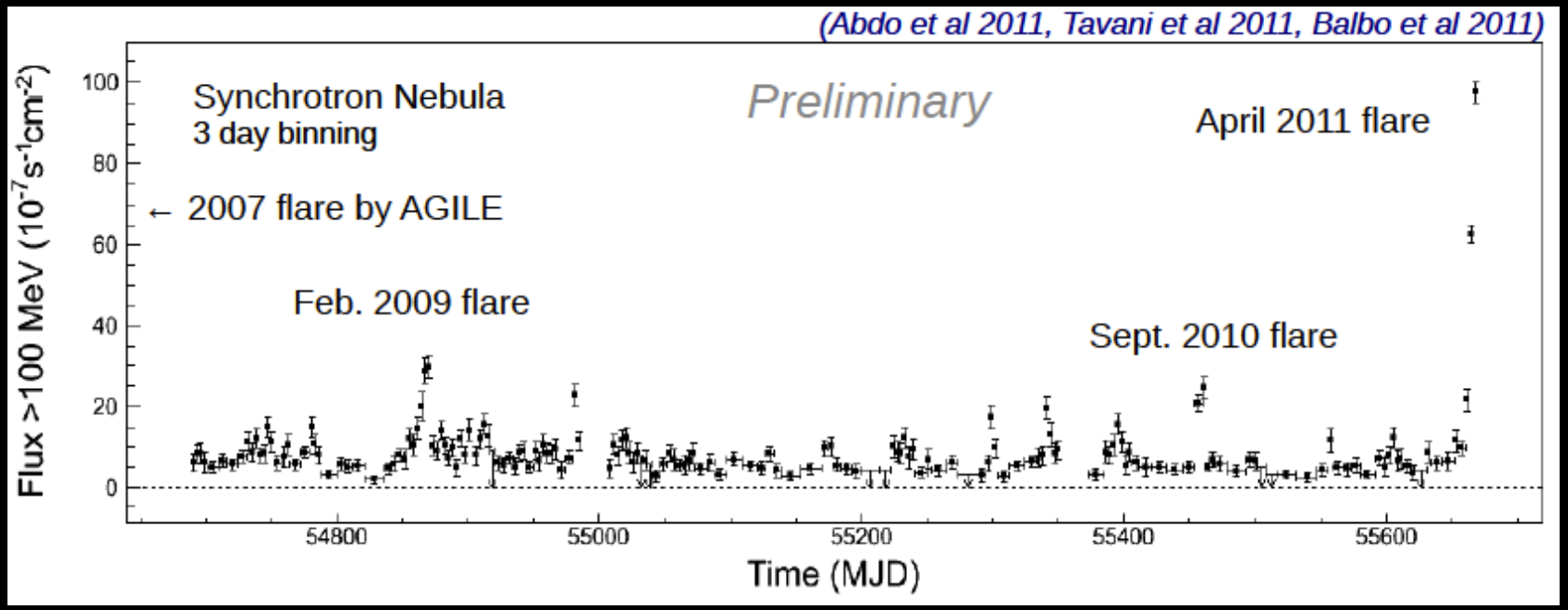




… but no more a standard candle

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 !

… but no more a standard candle

Flare of April 2011 :

Buehler et al, 2012, ApJ, 749, 26

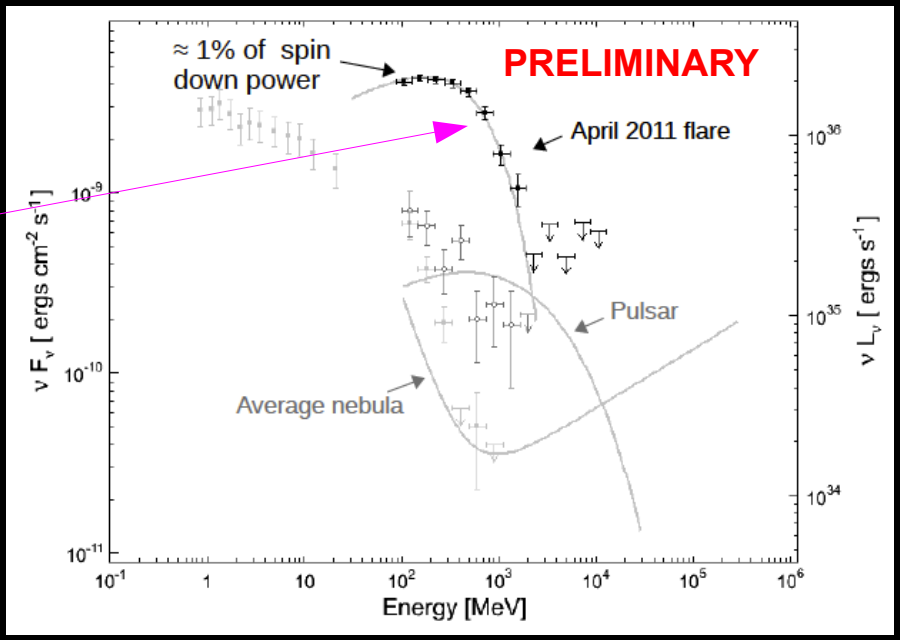
- *New spectral component : power law with an exponential cutoff (pulsar-like, but no sign of pulsation in flare photons)*

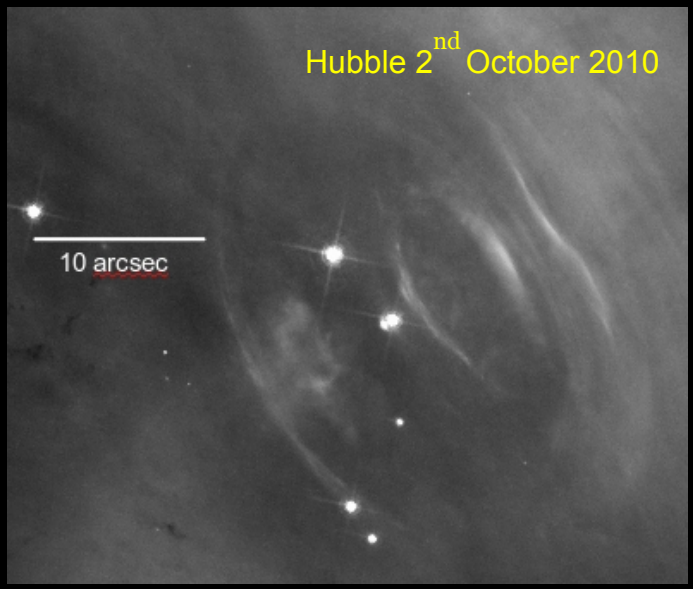
- *No correlation with any waveband is observed*

- *Significant synchrotron emission > 1 GeV and fast acceleration very difficult for shock acceleration*

- *Compact emission region < 0.0004 pc ~ 0.04" (for D<4)*

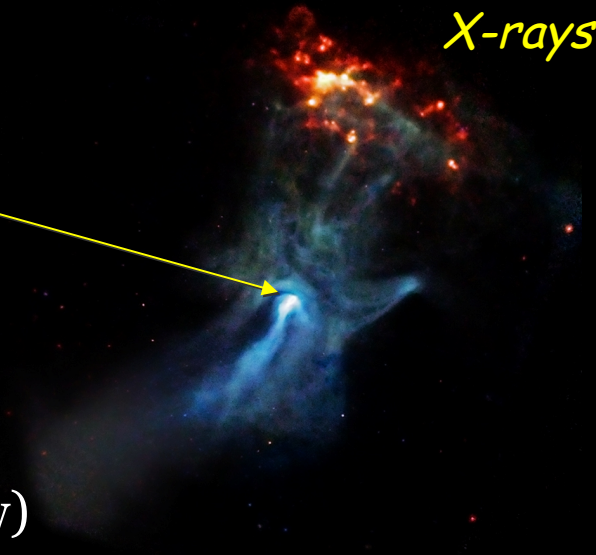
→ *Emission from the inner nebula*



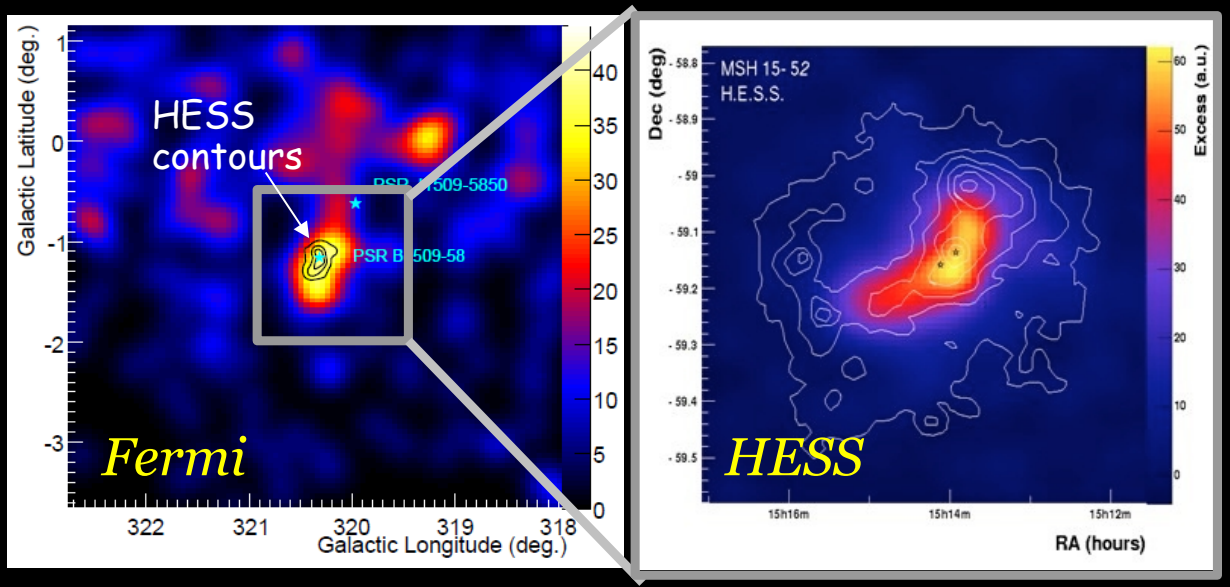


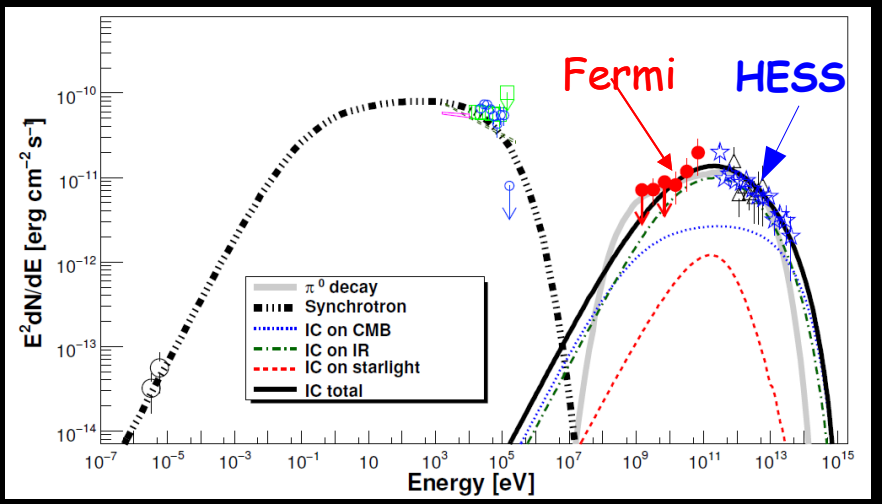
MSH 15-52

- *Young composite supernova remnant*
- *Bright X-ray PWN powered by PSR B1509-58*
- *PWN seen by Fermi, HESS and CANGAROO : matches the X-ray morphology*



- Multiwavelength modeling :
  - hadronic scenario is disfavored (energetic point of view)
  - high energy emission explained by Inverse Compton scattering (FIR field)





Abdo et al., 2010, ApJ, 714, 927

Aharonian et al, A&A 435 , L17, 2005

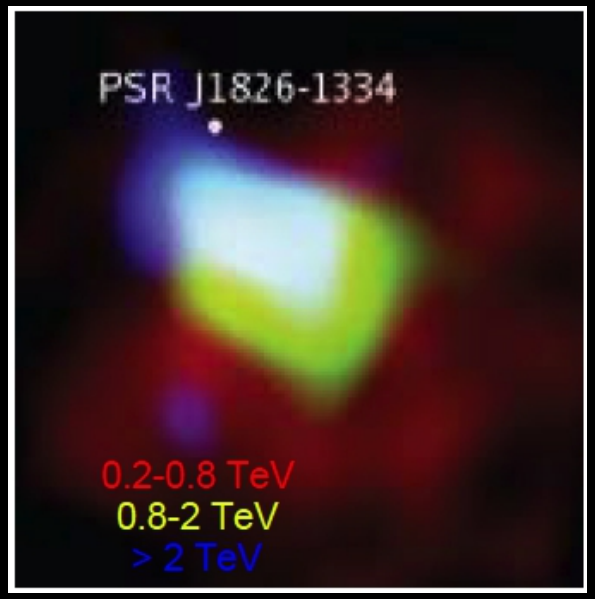
Spectral energy distribution of the MSH 15-52

2. Middle-aged & Offset PWNe

Detection in the GeV-TeV range :

- Vela X

- HESS J1825-137



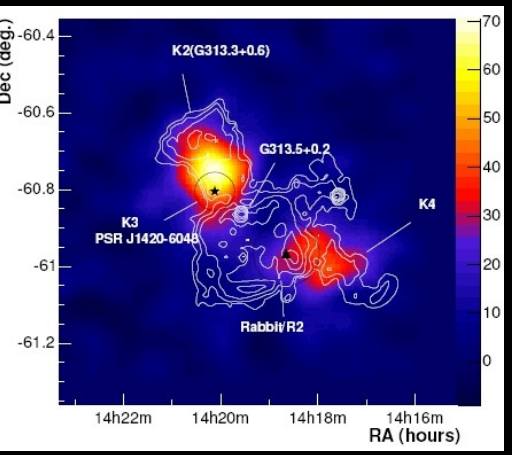
Detected at TeV energies :

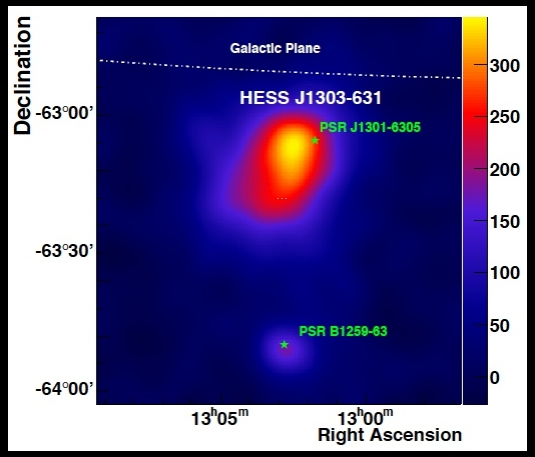
- Kookaburra (radio/γ-ray psr) & Rabbit (γ-ray psr)

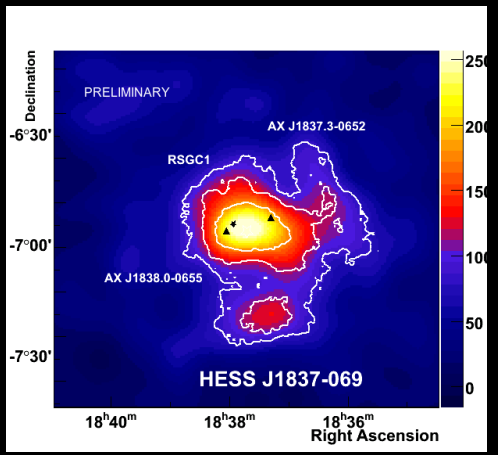
- HESS J1303-631 (radio psr)

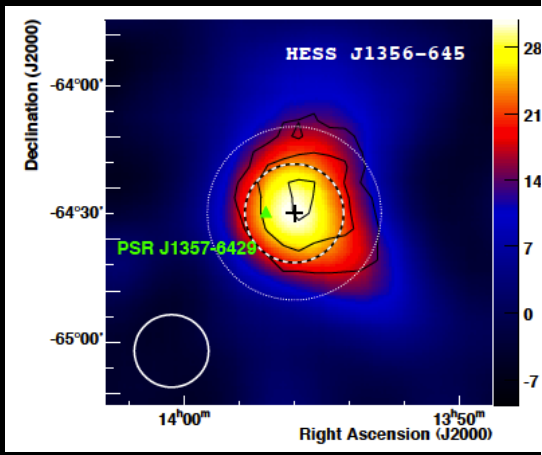
- HESS J1837-069 (X-ray psr)

- HESS J1356-645 (radio, X- & γ-ray psr)



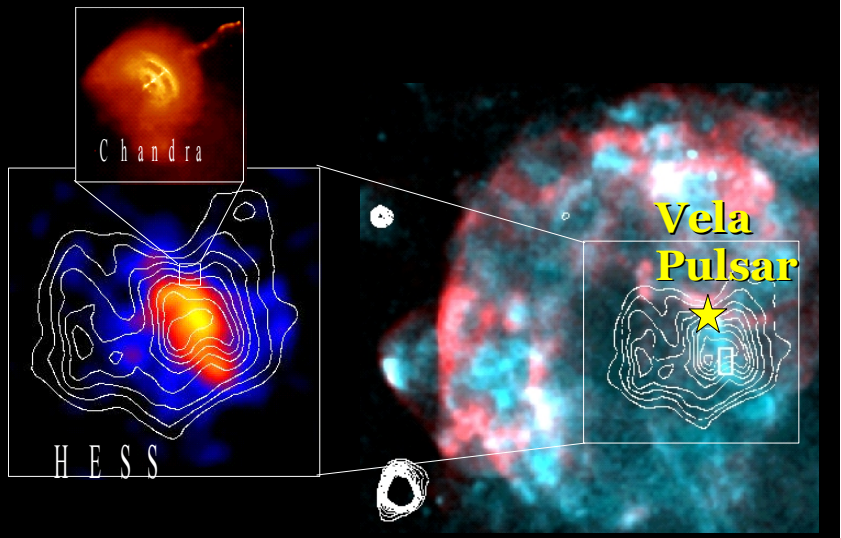






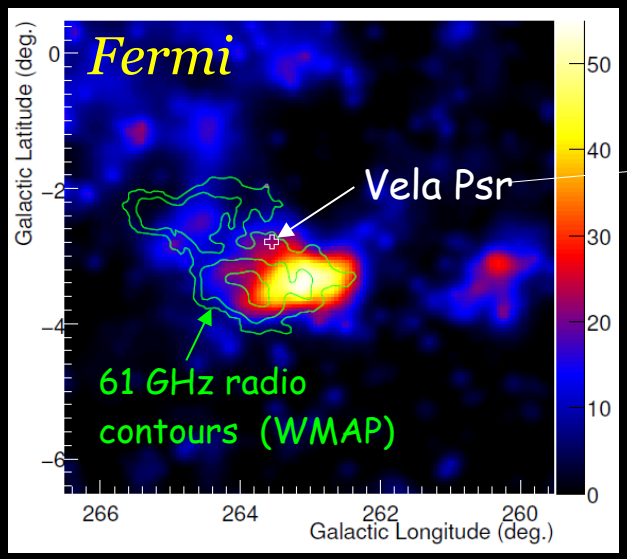
Vela X

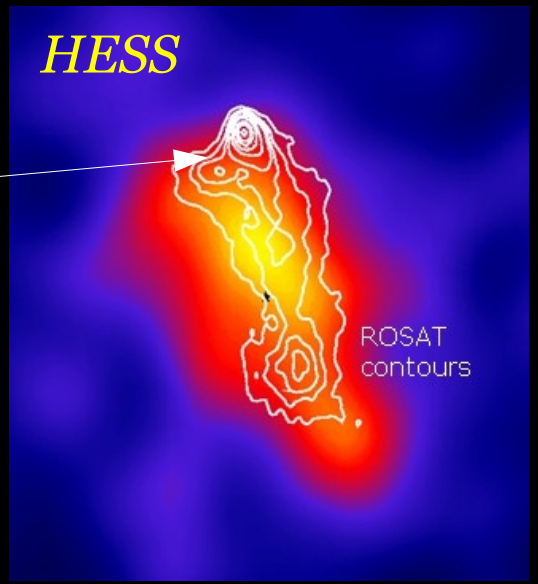
- *Associated with the Vela Pulsar (d = 290 pc)*
- *Located south of the pulsar*

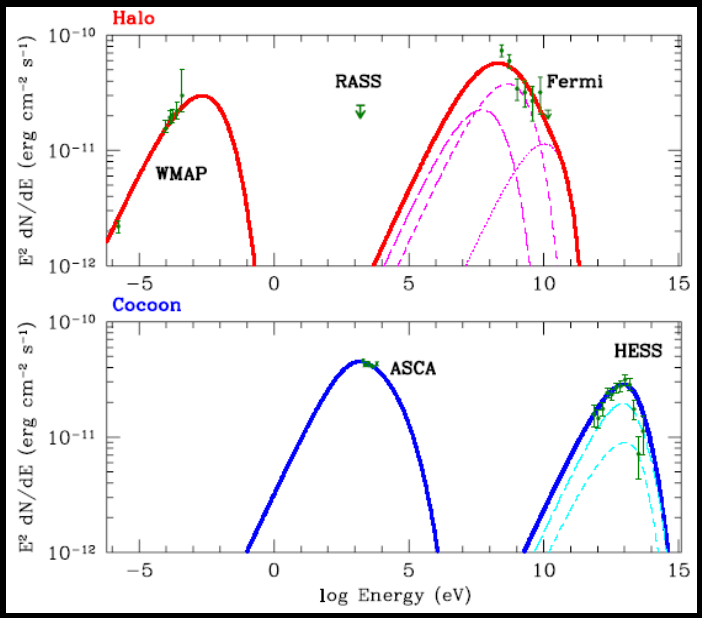


- *Morphology :*
  - *Radio & HE gamma-rays : Halo (2° x 3°)*
  - *X-rays & VHE : Cocoon (length < 1°)*

- *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

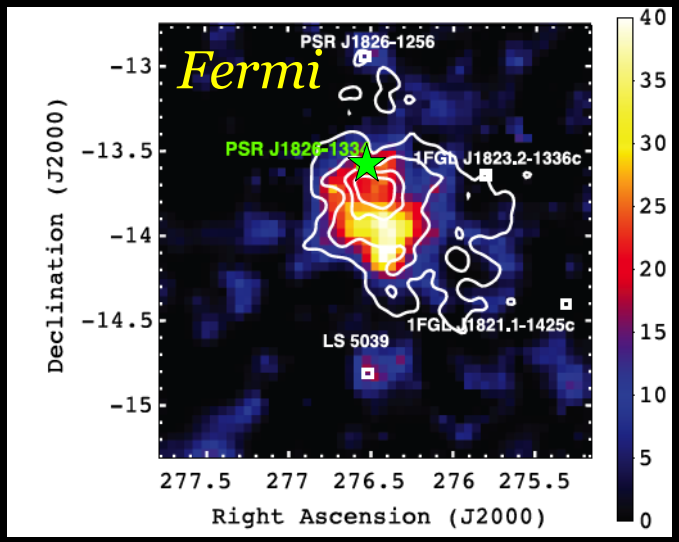
HESS J1825-137

- *Discovered during the H.E.S.S. Galactic Plane Survey*
- *Associated to the radio pulsar PSR J1826-1334*

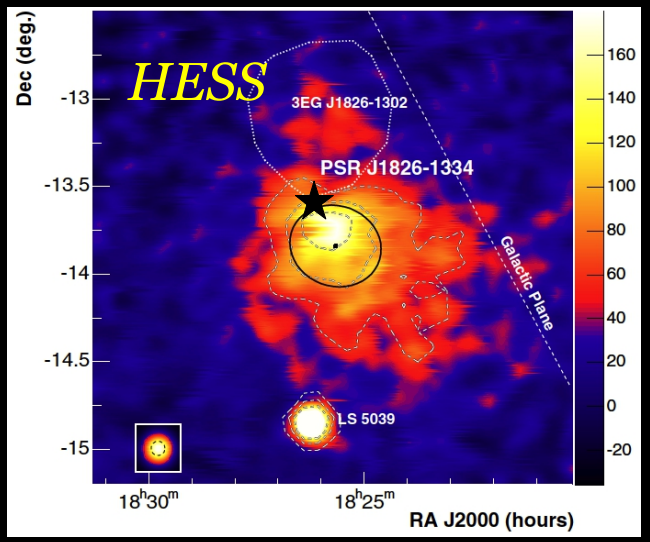
- *Energy-dependent morphology at VHE due to cooling mechanisms*
- *TeV spectral steepening with distance from pulsar consistent with radiative losses*
- *Fermi-LAT detection of an extended source coincident with the TeV PWN*

- *Multiwavelength spectrum :*

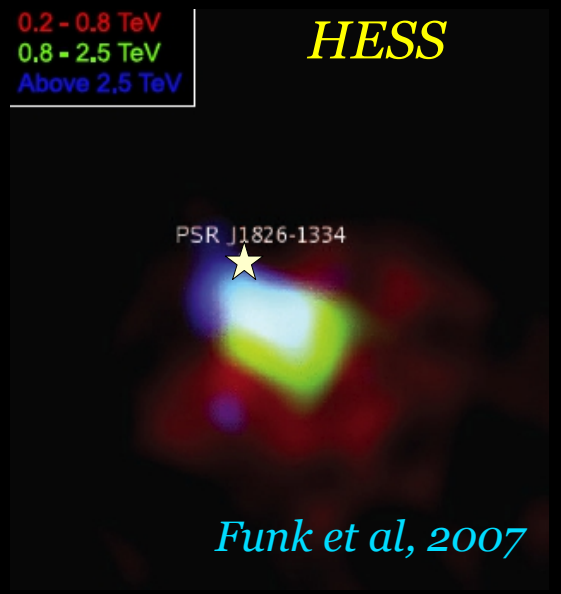
→ *favors a leptonic injection & implies a low magnetic field (3-4 μG)*



Grondin et al, ApJ, 2011, 738, 42



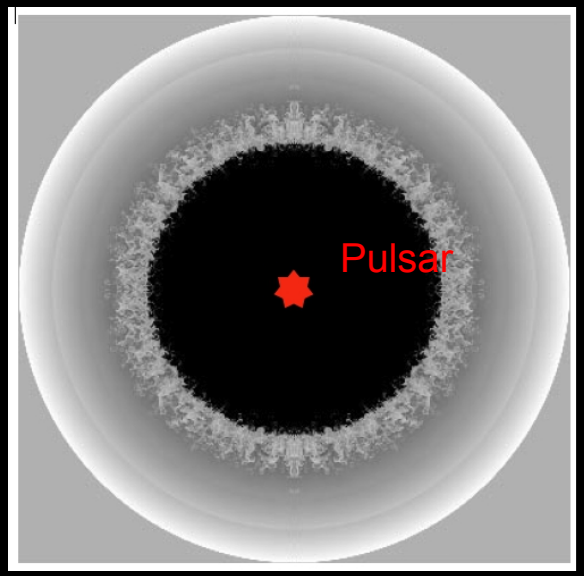
Aharonian et al, 2006, A&A 460, 365

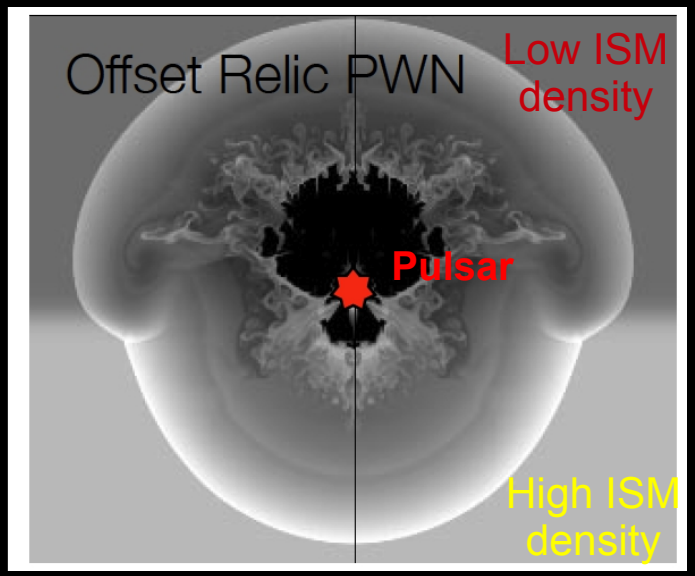


Funk et al, 2007

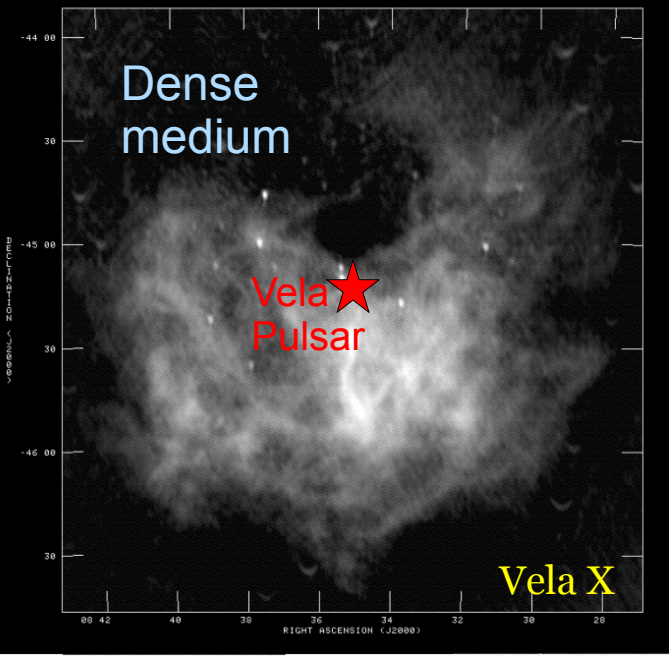
Why are these PWNe offset ?

« … asymmetries in the surrounding interstellar medium give rise to asymmetries in the position of the PWN relative to the pulsar and explosion site…. »





Blondin et al, 2001, ApJ, 563, 806



Frail et al, 1996

3. PWN candidates

Detected in the GeV-TeV range

- HESS J1857+026 (radio psr PSR J1856+0245)

- SNR CTA1 (γ-ray psr PSR J0007+7303)

- HESS J1640-465

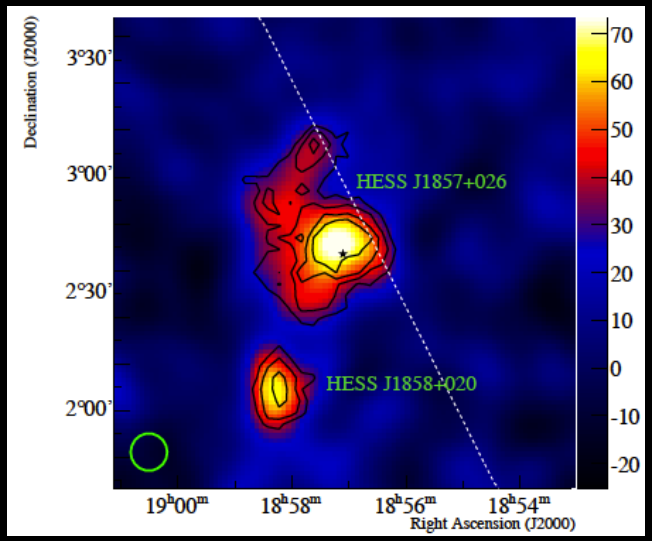
- HESS J1023-575 (γ-ray psr PSR J1023-5746, close to Westerlund 2)

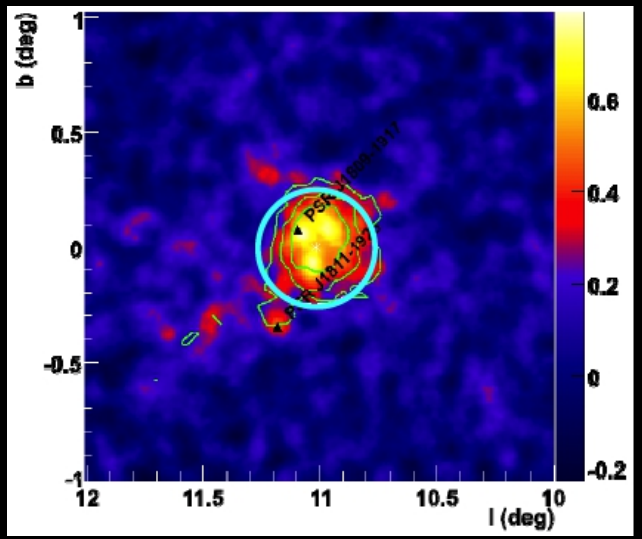
VHE sources associated to pulsars recently discovered in radio, γ-rays :

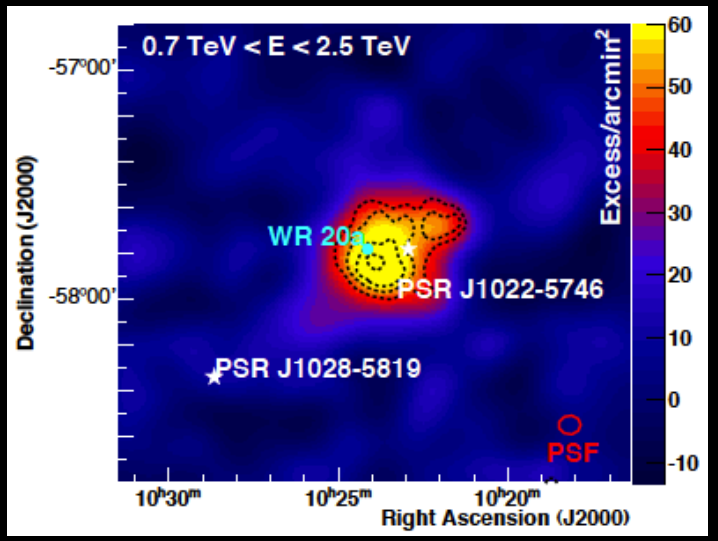
- HESS J1809-193/PSR J1809-1917

- HESS J1718-385 /PSR J1718-3825

…

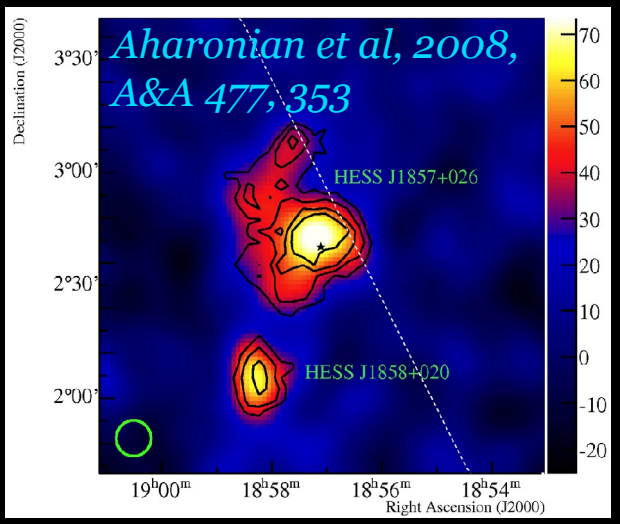






HESS J1857+026 : a relic nebula ?

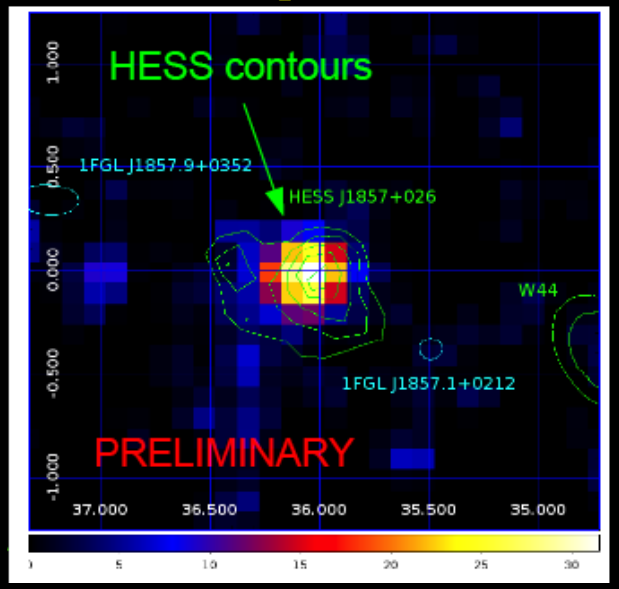
HESS excess map



- *Discovered during the H.E.S.S. Galactic Plane Survey*
  - *slightly extended (0.08° x 0.11°)*
  - *soft spectrum ($\Gamma \sim 2.4$)*

- *Associated to the energetic radio-loud pulsar PSR J1856+0246*

Fermi TS map above 10 GeV



- *Detected by Fermi (Rousseau et al, 2012, A&A, arXiv:1206.3324)*
  - *excellent correlation with the TeV source but no significant extension*
  - *hard spectrum ($\Gamma \sim 1.5$)*

- *Multiwavelength data (no X-ray detection) :*

→ *favors a leptonic injection of a relic population & implies a low magnetic field (2-3 μG)*

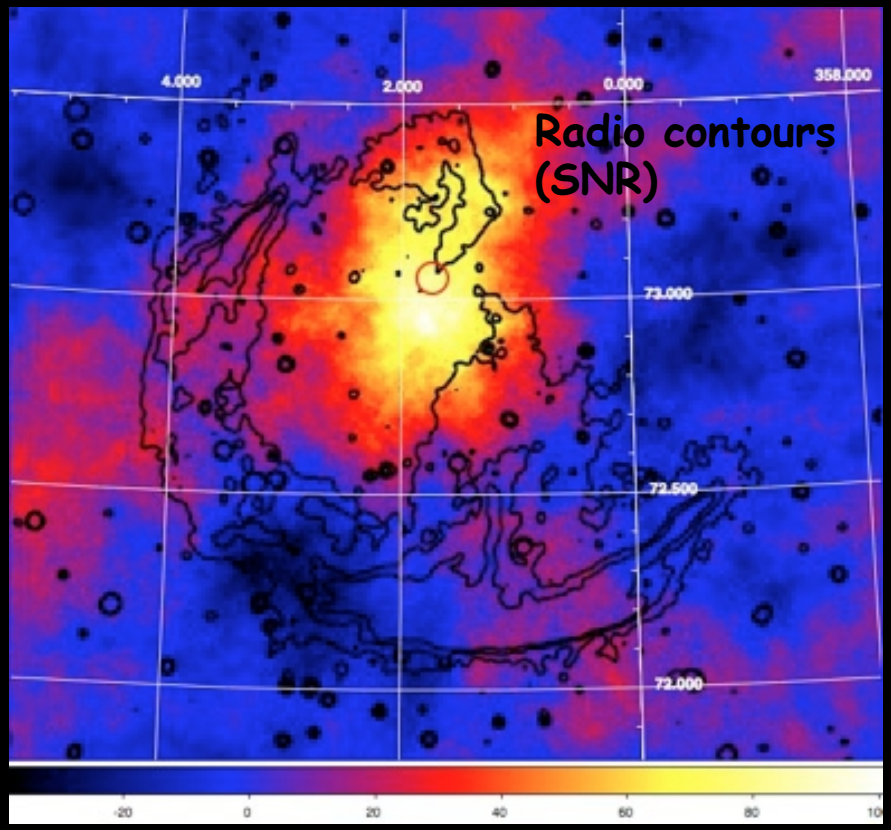
SNR CTA1 & HESS J1640-465

SNR CTA1 :

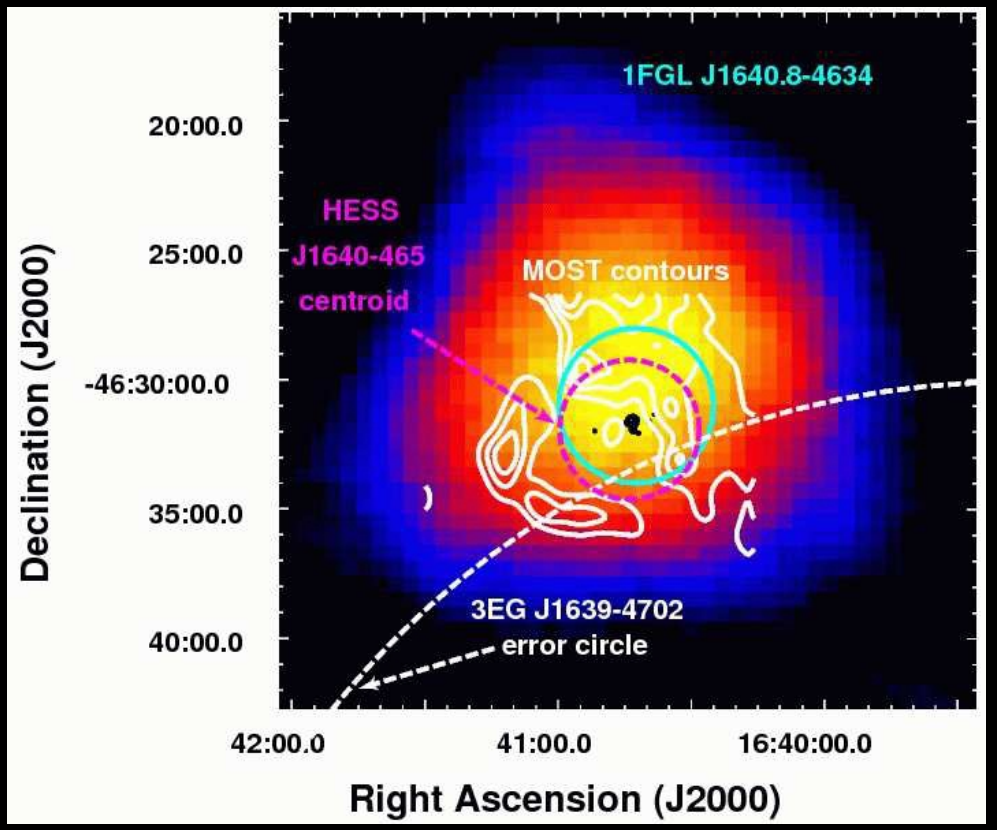
- *PWN candidate detected by VERITAS*
- *Pulsar discovered by Fermi*
  + Off-pulse emission (PWN?)

HESS J1640-465 :

- *PWN candidate detected by HESS*
- *Coincident emission seen by Fermi (but no pulsation detected)*



VERITAS excess map
(McArthur, Fermi Symposium 2011)



Fermi count map
(Slane et al, 2010, ApJ, 720, 266)

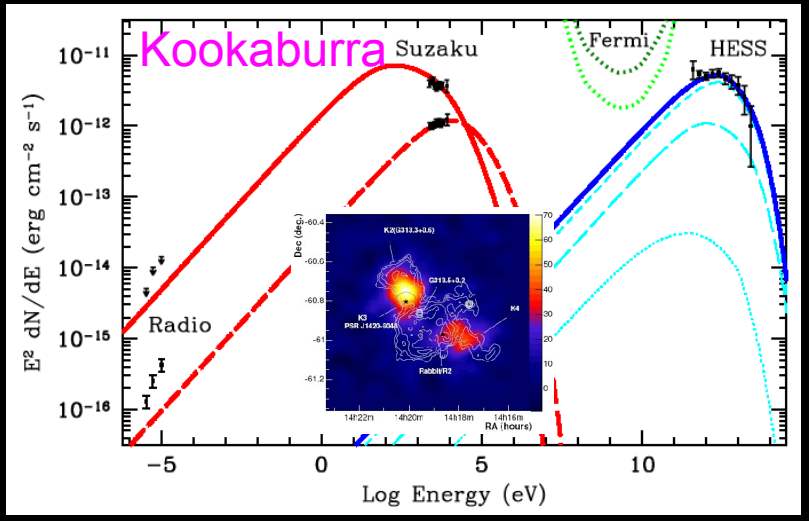
4. Search for TeV PWNe in the GeV range

Some famous candidates searched in the off-pulse window of gamma-ray pulsars:

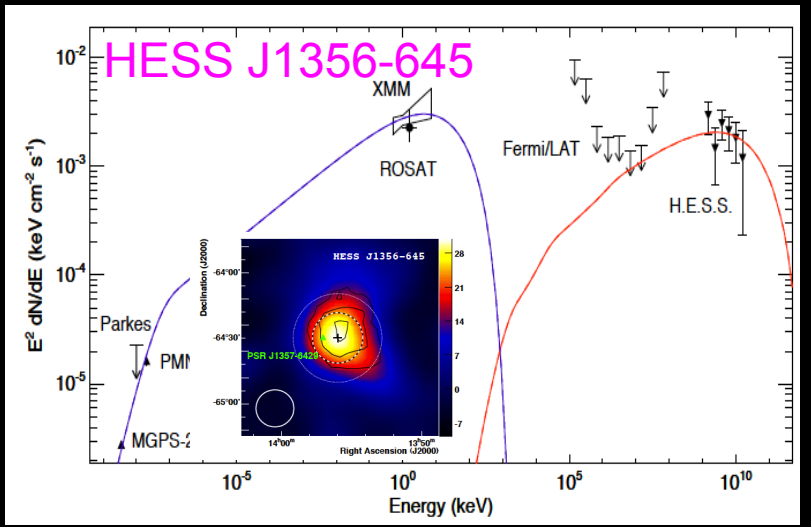
- *Kookaburra & Rabbit*
- *MGRO J1908+06*
- *HESS J1356-465*

+ others (Ackermann et al, 2011, 726, 35)

Van Etten et al, ApJ, 711, 1168



Abramowski et al, 2011 (A&A, 533, A103), Lemoine-Goumard et al, 2011 (A&A, 533, A102)



→ *more data are required to detect any GeV emission from the PWN*

Summary

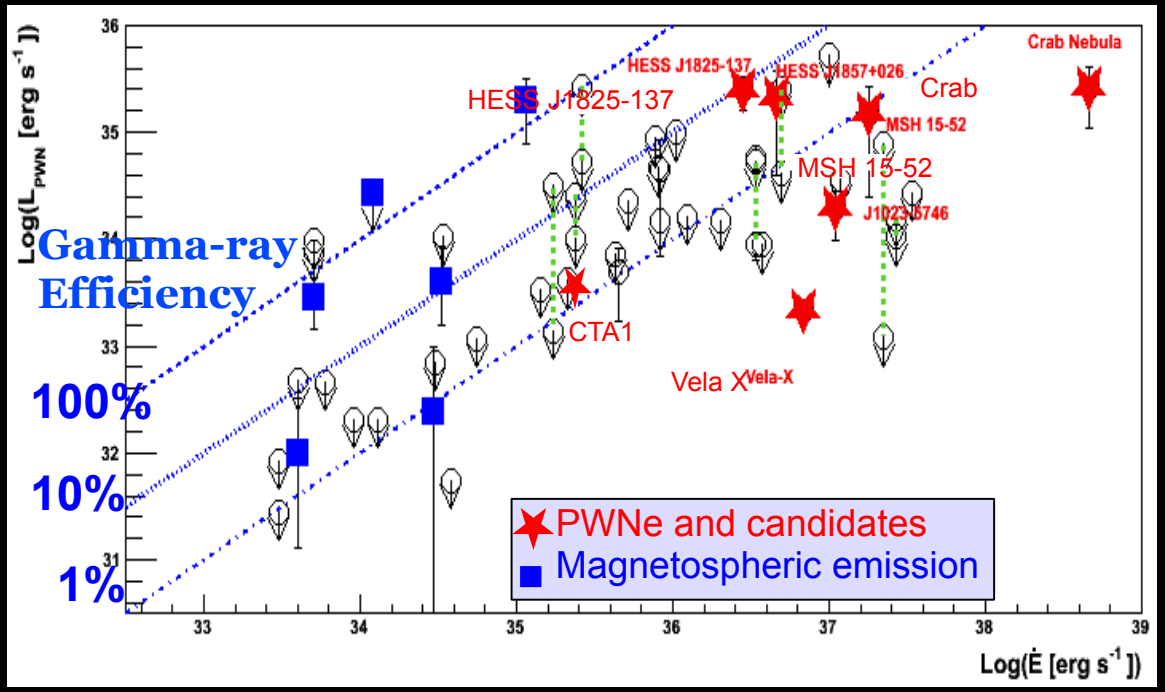
GeV observations of PWNe

- *6 PWNe firmly identified + 2 PWN candidates (PSR J1023-5746 and SNR CTA 1)*
  + other candidates coincident with composite SNRs (MSH 11-62, MSH 15-56)
  - *a leptonic scenario (IC scattering) is favored in each case*
  - *Vela X is the first case suggesting the injection of 2 leptonic populations*

- *Population studies performed in the off-pulse windows of LAT pulsars*

→ *Upper limits on the γ-ray emission of famous TeV PWNe*

→ *Fermi detects PWNe powered by bright (energetic) and young Pulsars*

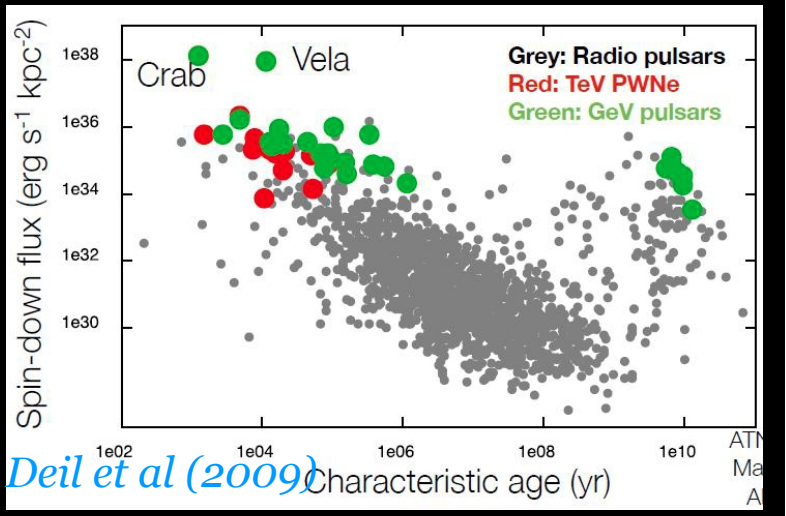


→ Efficiency < 8% of the spin-down power of the powering pulsar required to explain the luminosity above 100 MeV

Ackermann et al, 2011, ApJ, 726, 35

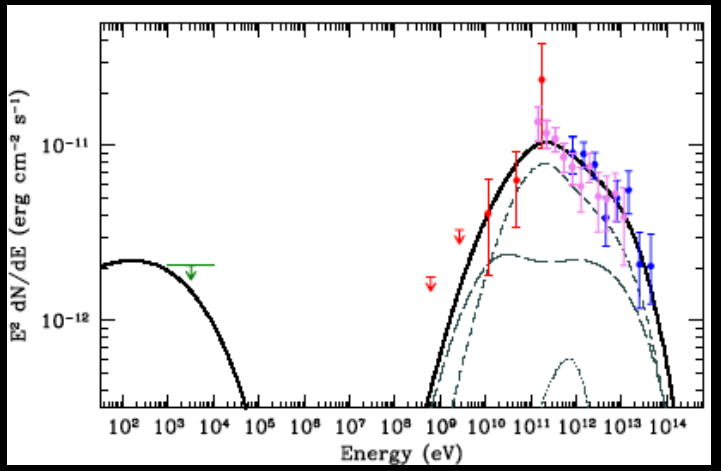
TeV observations of PWNe

- *PWNe : largest population of Galactic TeV sources*
- *Many of the unidentified sources might be PWNe*
- *TeV PWNe preferentially associated to energetic and young pulsars*



Deil et al (2009)

- Dark accelerators (i.e. without multi-wavelength counterparts) :
  - Hadronic accelerators ?
  - So-called relic PWNe, as suggested by de Jager & Djannati-Atai (2008)
    Example : HESS J1857+026
    (Rousseau et al, arXiv :1206.3324)



→ *Multi-wavelength observations may help to identify new PWNe in the TeV domain*