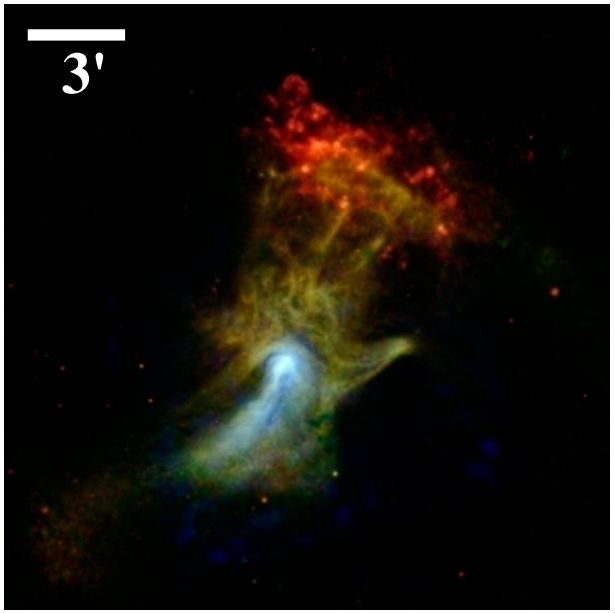
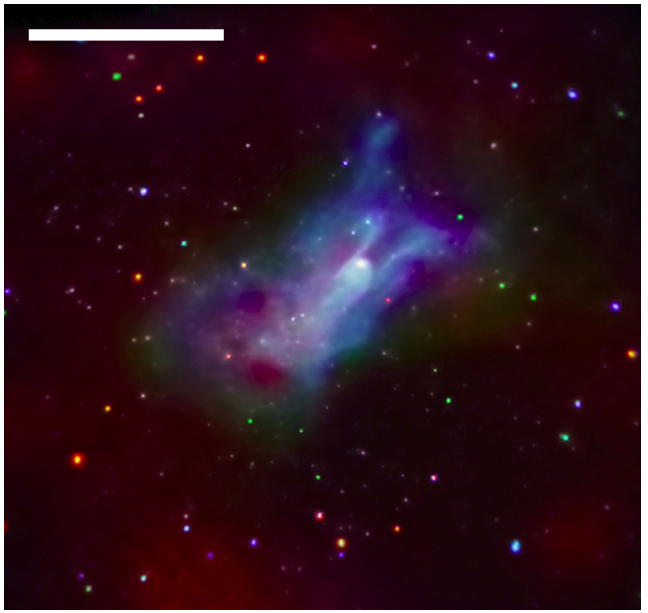
X-Ray Emission from Pulsar Wind Nebulae

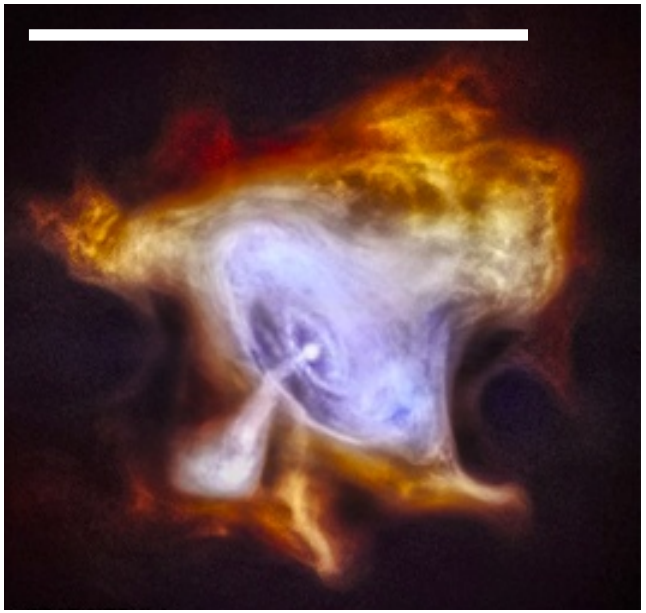
Matthieu Renaud

LUPM, CNRS/IN2P3 – University of Montpellier, France

OCEVU Workshop « The physics of relativistic outflows »
Toulouse, 22-24 March 2016







Gamma-Ray Emission from Pulsar Wind Nebulae

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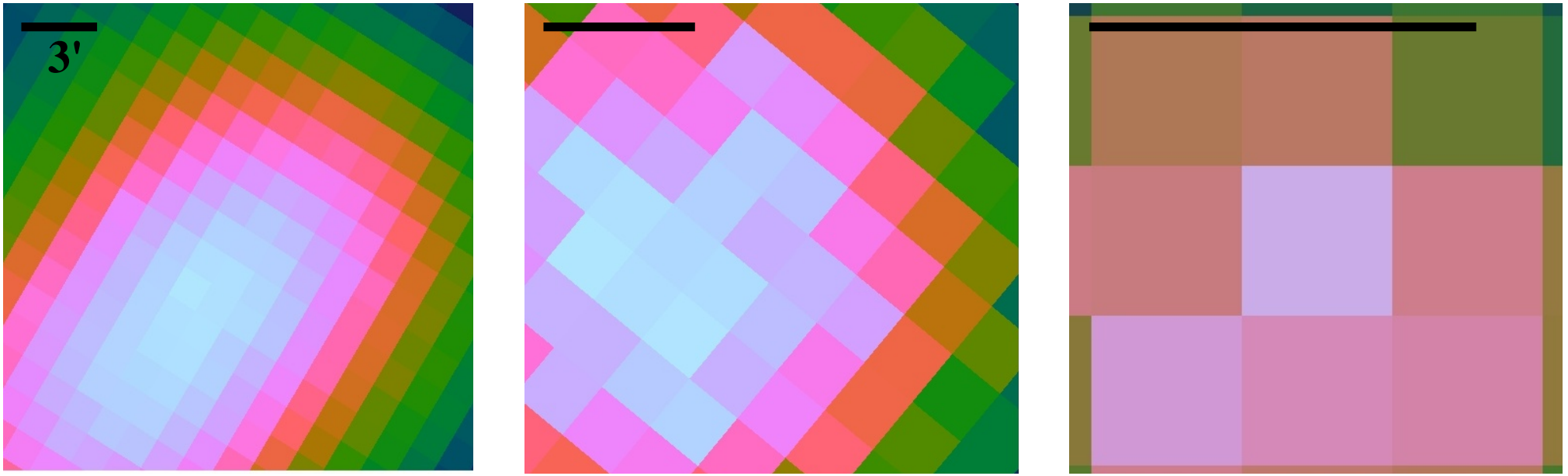
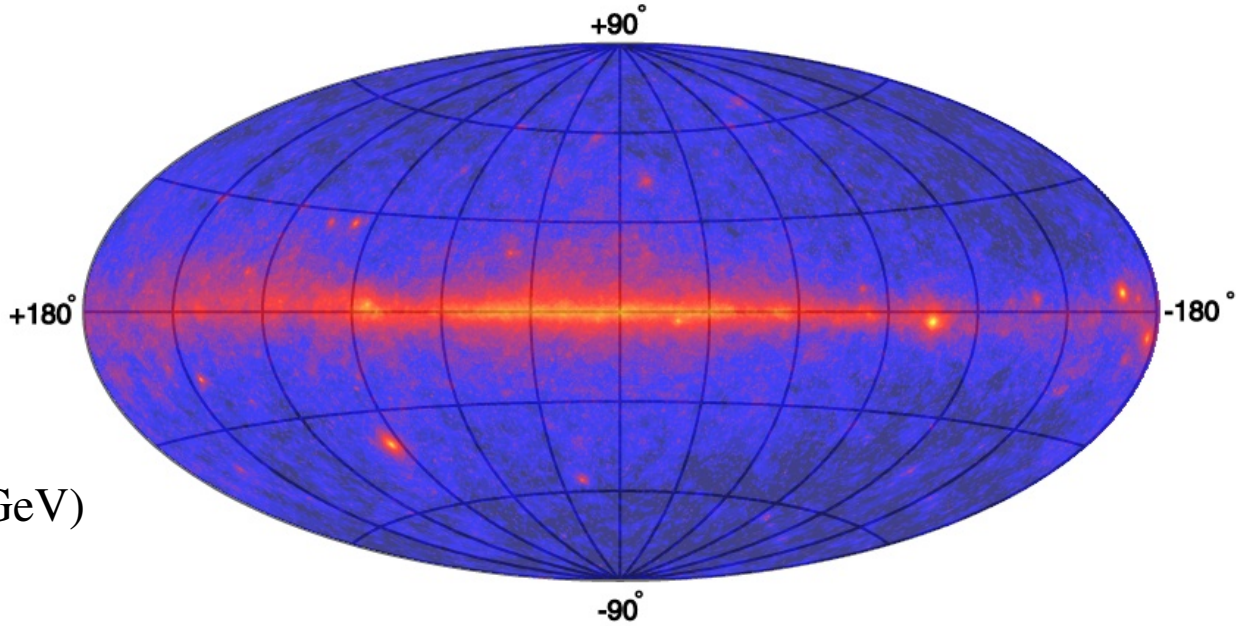


GeV-TeV or HE/VHE γ-ray astronomy

HE: 0.1-100 GeV
(*Fermi*-LAT, *AGILE*)



FoV ~ 2.4 sr, $PSF_{68\%}$ ~ 5-0.8-0.1° (0.1-1-20 GeV)

> 3000 3FGL (Fermi-LAT) sources

360 2FHL sources (E > 50 GeV)

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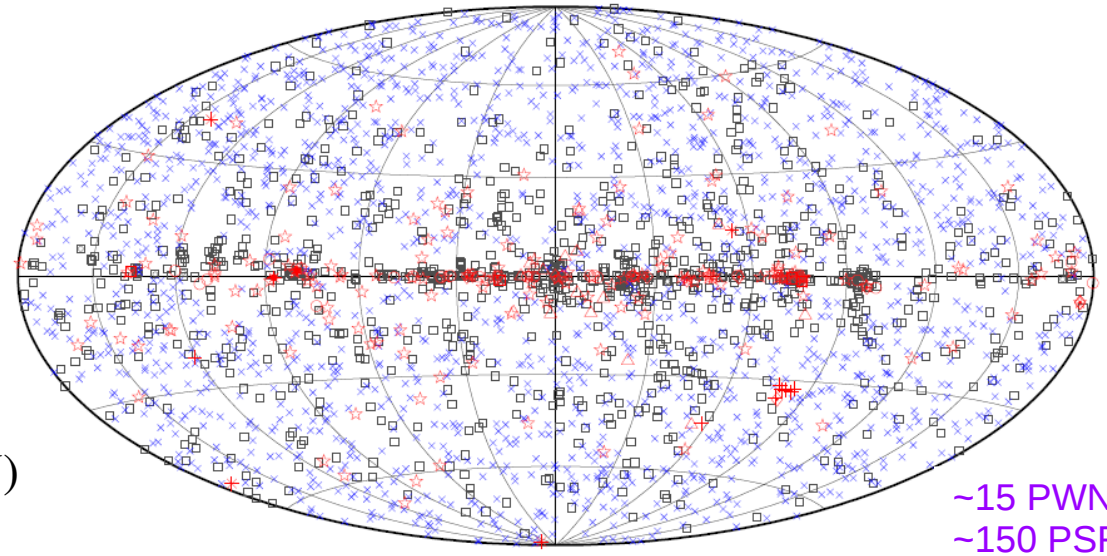

(Acero et al., Ackermann et al. 2015)

~15 PWNe
~150 PSRs
~1000 UNId
~30 SNRs
~1700 AGNs

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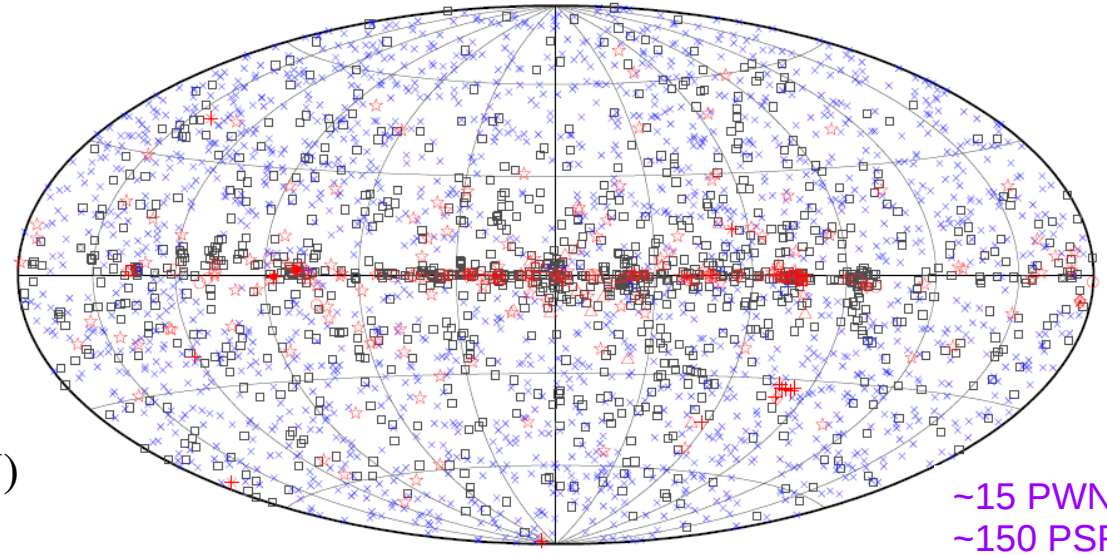

(Acero et al., Ackermann et al. 2015)

~15 PWNe
~150 PSRs
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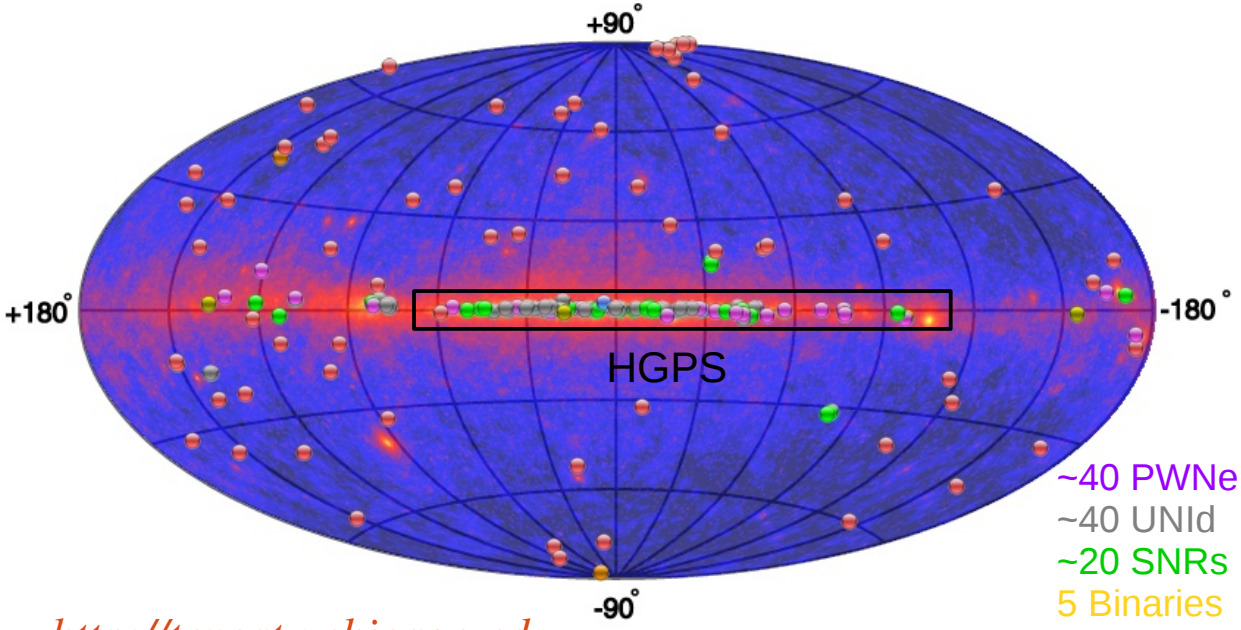
~1700 AGNs

VHE: 0.1-100 TeV
(IACTs & EAS arrays)

FoV ~ 5°, $PSF_{68\%}$ ~ 0.05° (E > 1 TeV)
~170 VHE sources (2/3 Galactic)



http://tevcat.uchicago.edu

~40 PWNe
~40 UNId
~20 SNRs
5 Binaries
~65 AGNs

GeV-TeV or HE/VHE γ-ray astronomy

HE: 0.1-100 GeV
(*Fermi*-LAT, *AGILE*)

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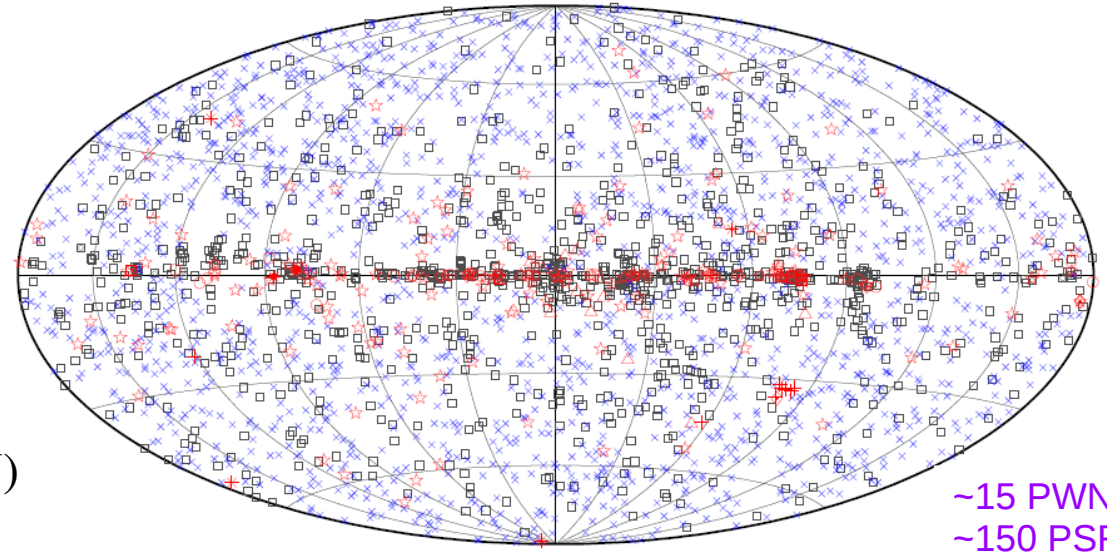

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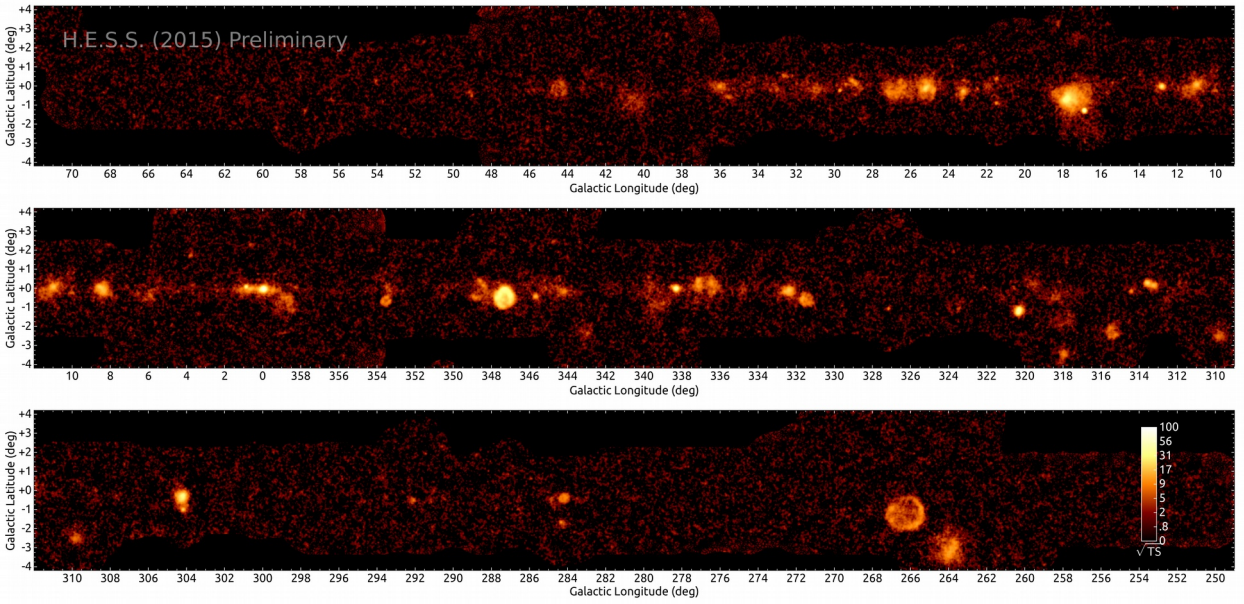
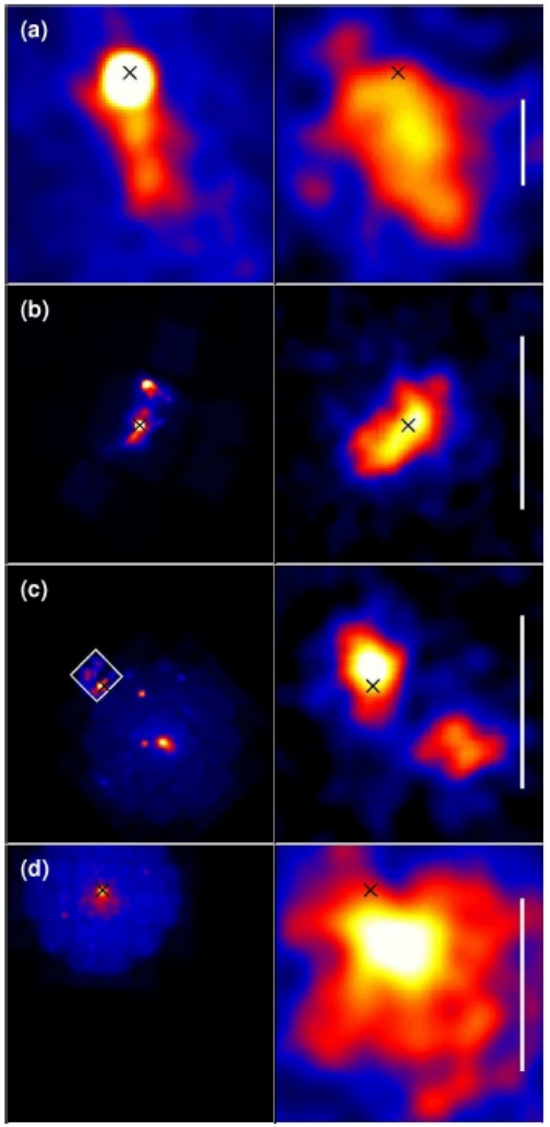
~170 VHE sources (2/3 Galactic)
77 H.E.S.S. Galactic Plane Survey sources

(HGPS, Deil et al. 2015, H.E.S.S. Collab. in prep.)



Gamma-Ray PWNe in a nutshell

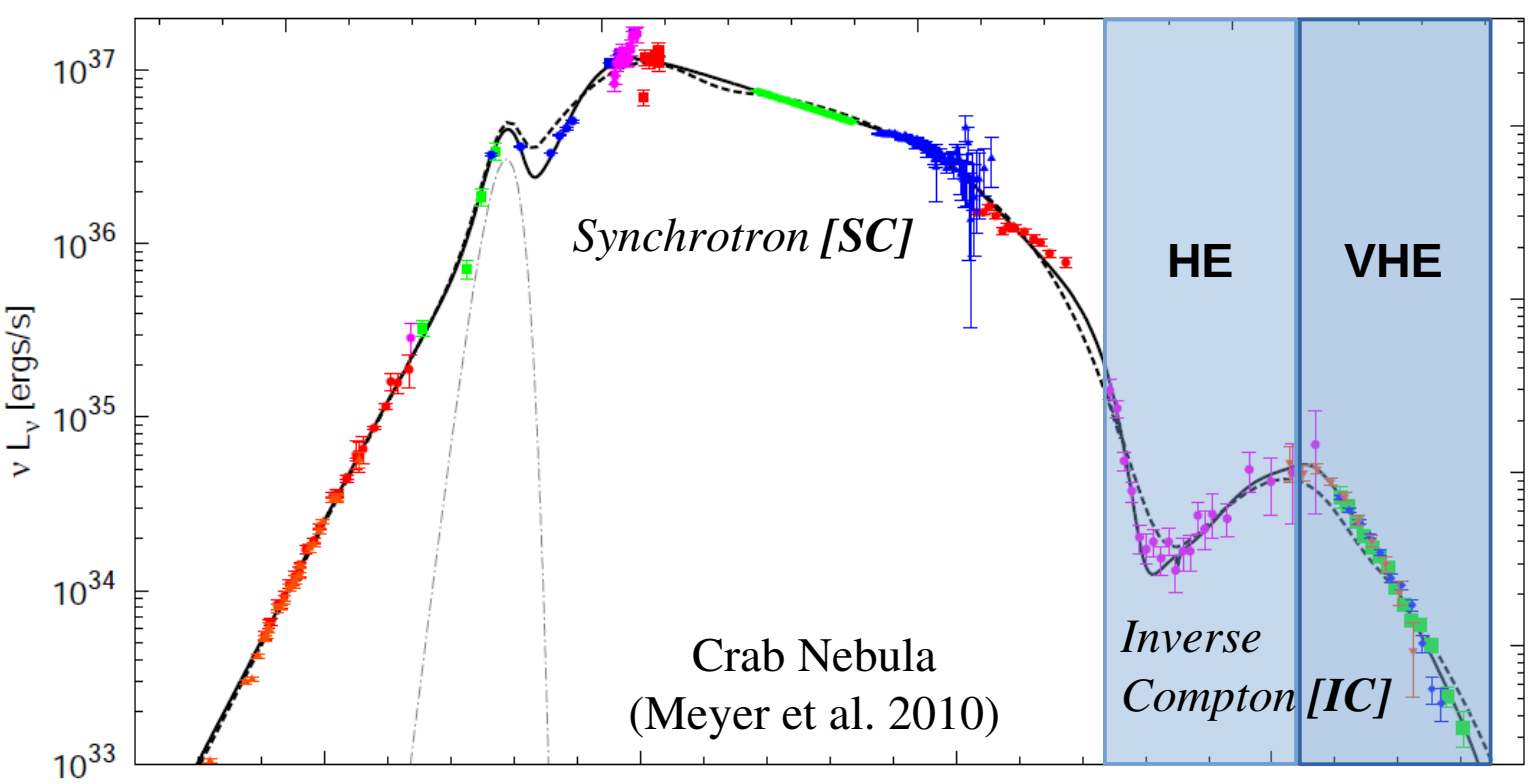
(Hinton & Hofmann 2009)



~keV **~TeV**

HE: 0.1-100 GeV
(*Fermi*-LAT, *AGILE*)

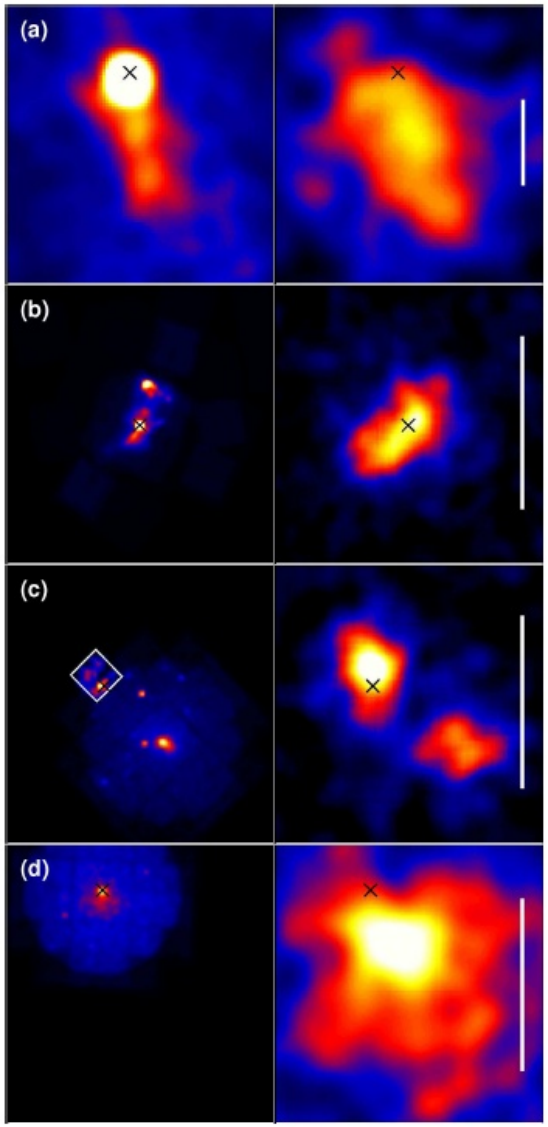
VHE: 0.1-100 TeV
(IACTs & EAS arrays)



(N.B. : hadronic emission from p-p interactions could also contribute...)

Gamma-Ray PWNe in a nutshell

(Hinton & Hofmann 2009)



~keV **~TeV**

HE: 0.1-100 GeV
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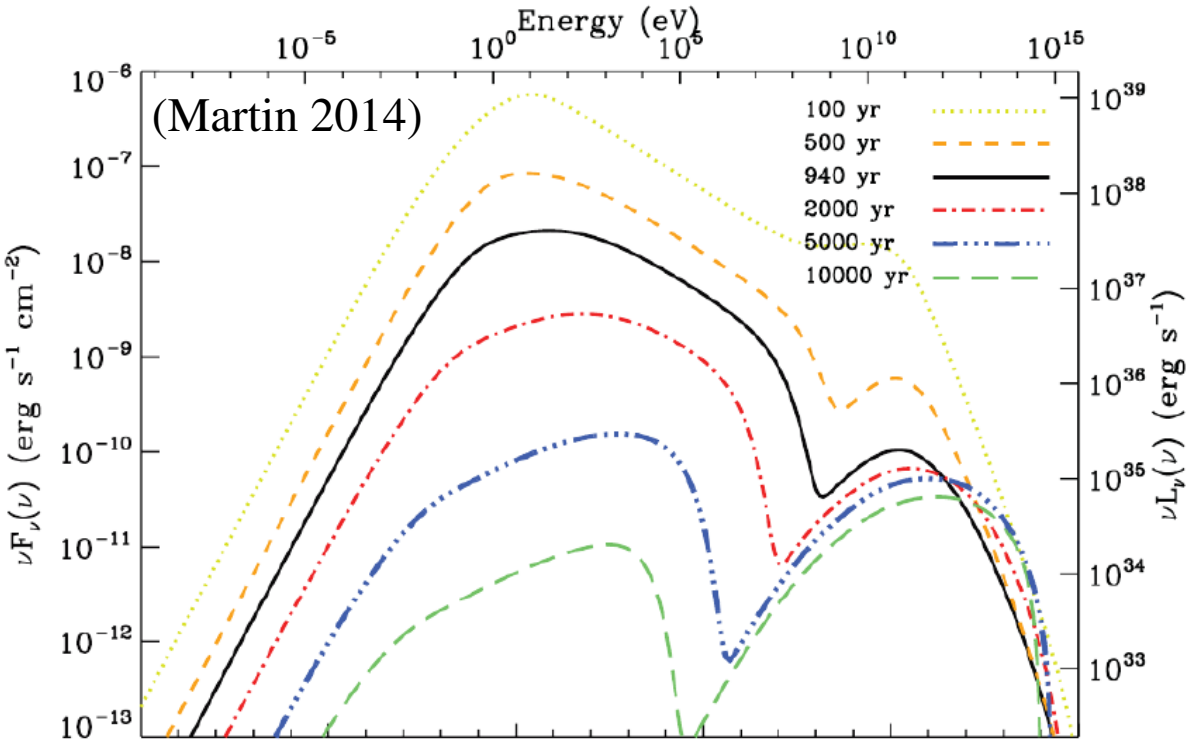
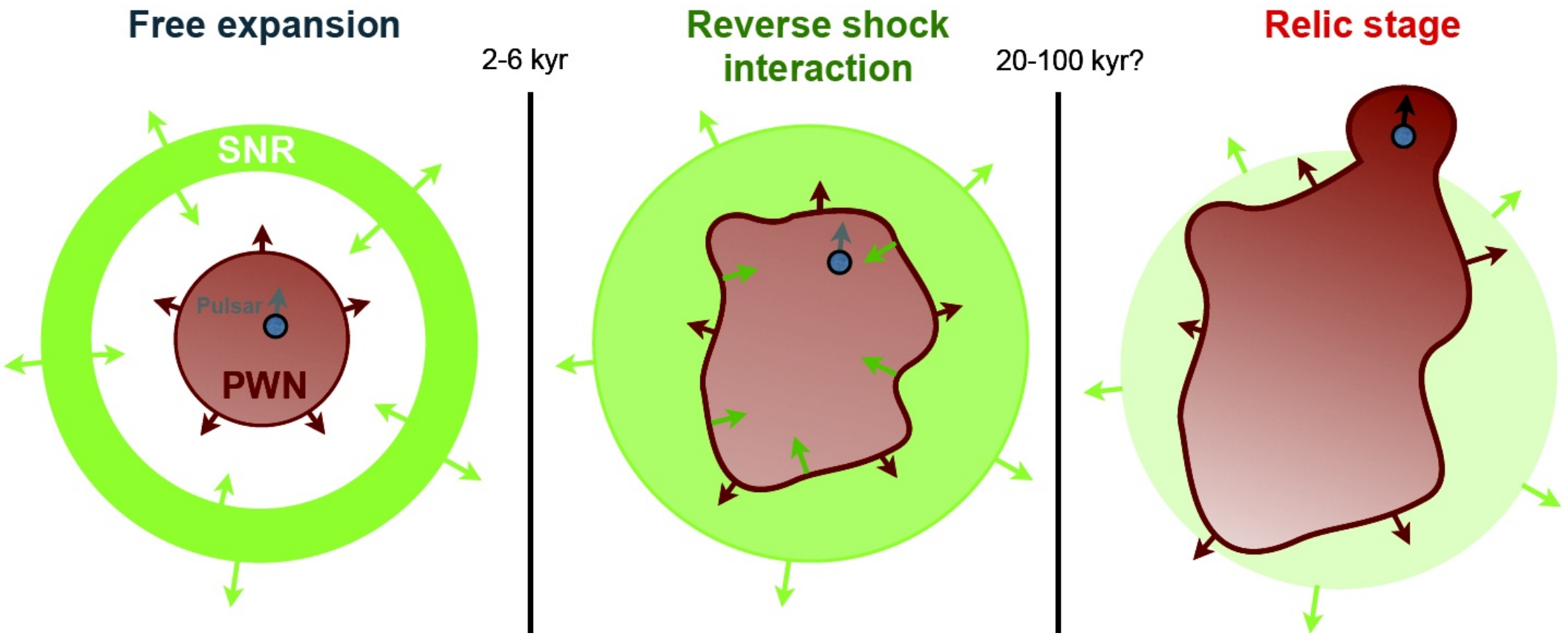
(IACTs & EAS arrays)

$e^{+/-}$ spectrum (Γ, E_{tot}, E_{max}), B-field when combined with X-ray data



PWN evolution

(Klepser et al. 2013)



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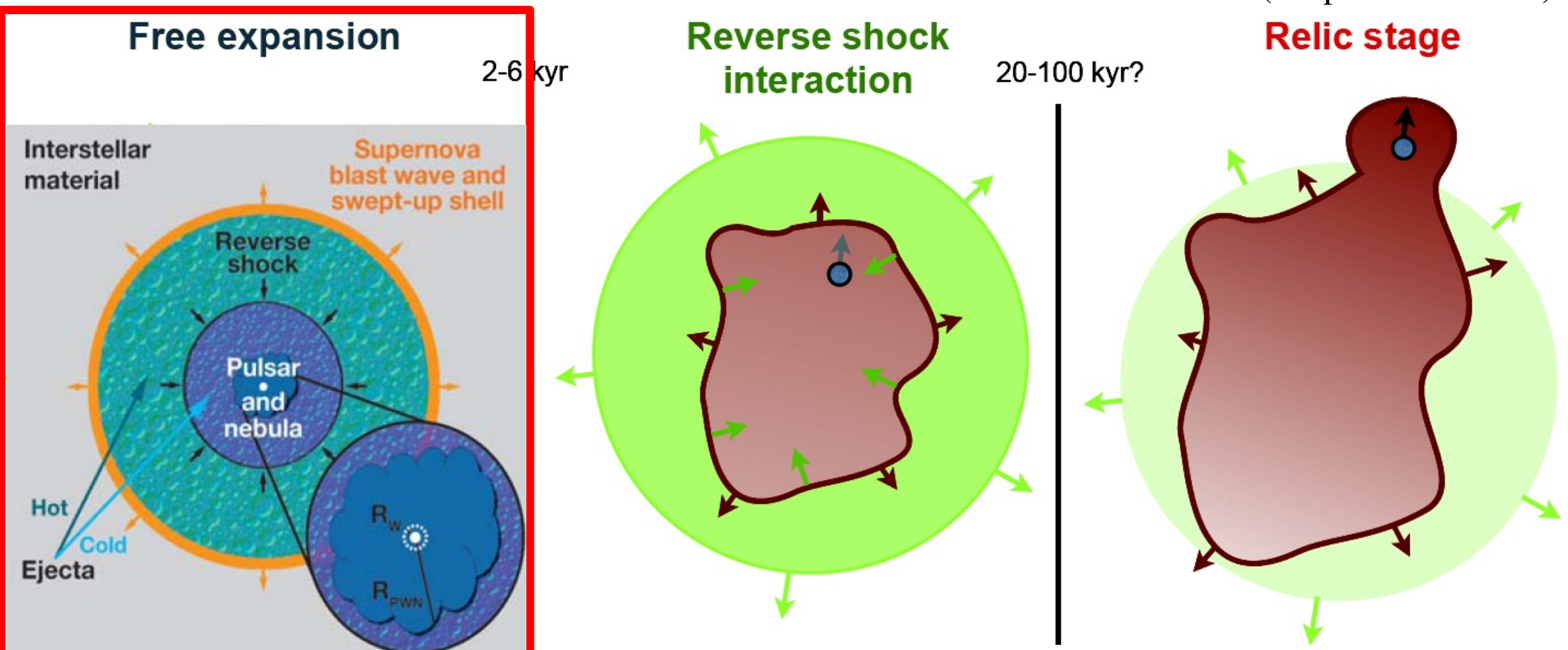
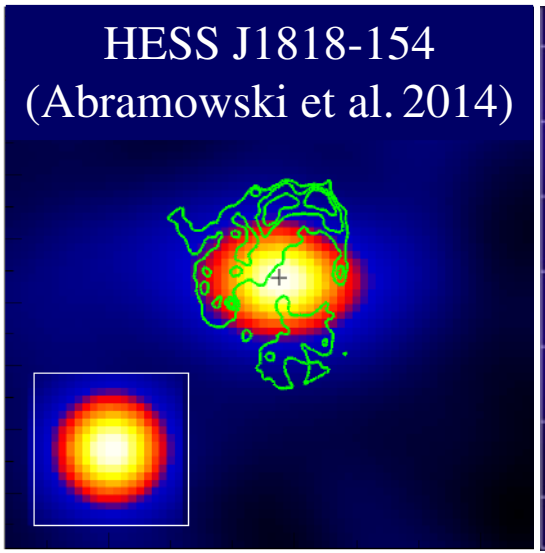
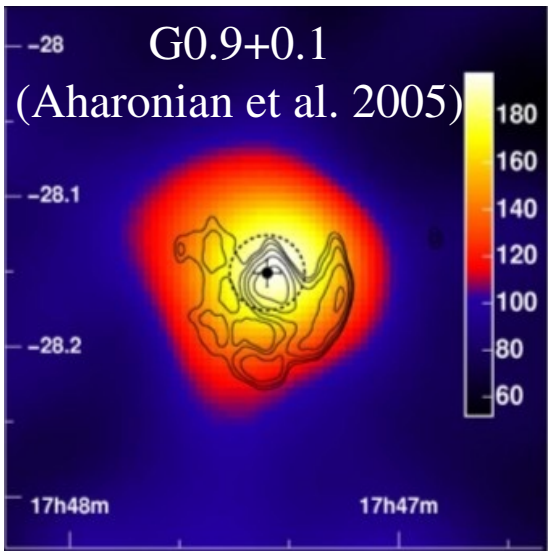


GeV-TeV : Crab Nebula, 3C 58, MSH 15-52
N 157B

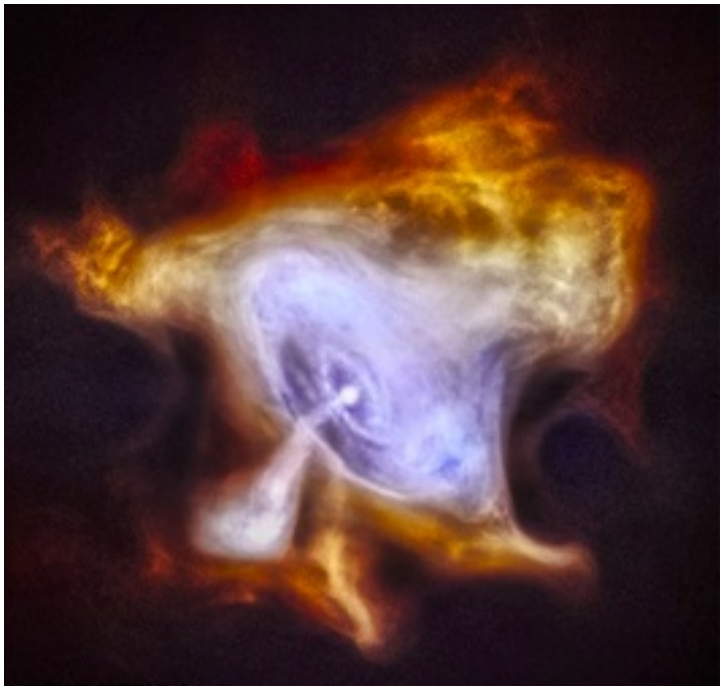
TeV-only : G0.9+0.1, G21.5-0.9, Kes 75,
HESS J1813-178, G54.1+0.3,
HESS J1818-154, HESS J1849-000

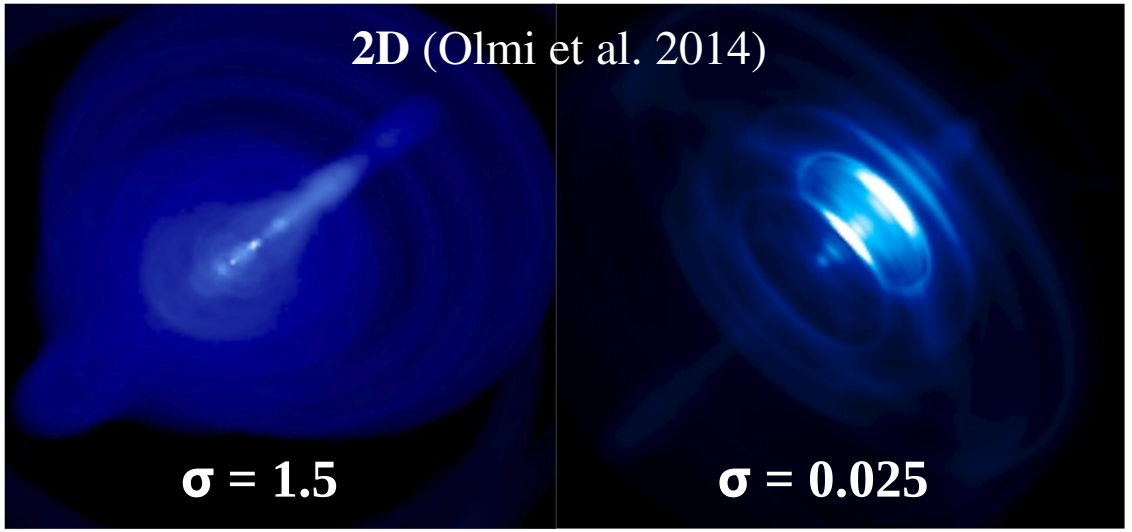


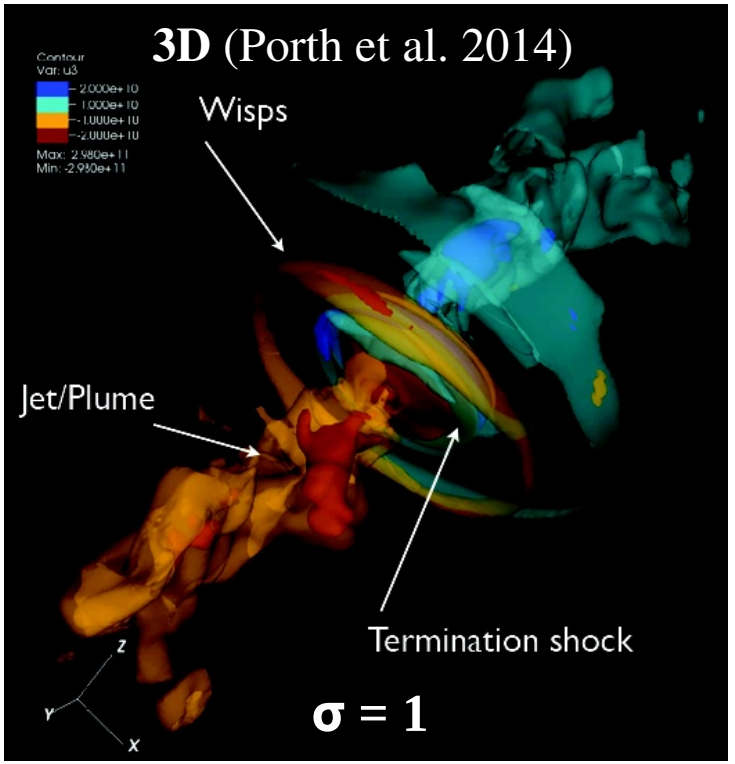


Crab Nebula

- Far from being isotropic…!

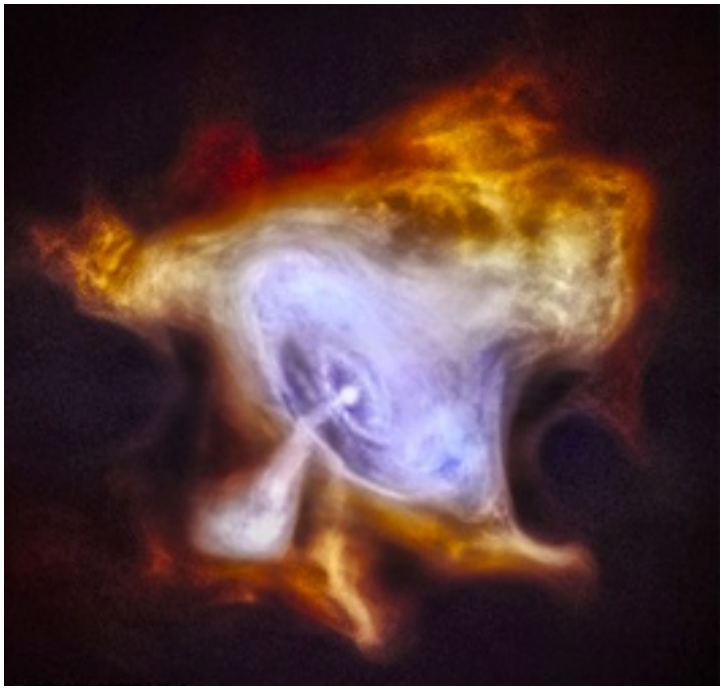


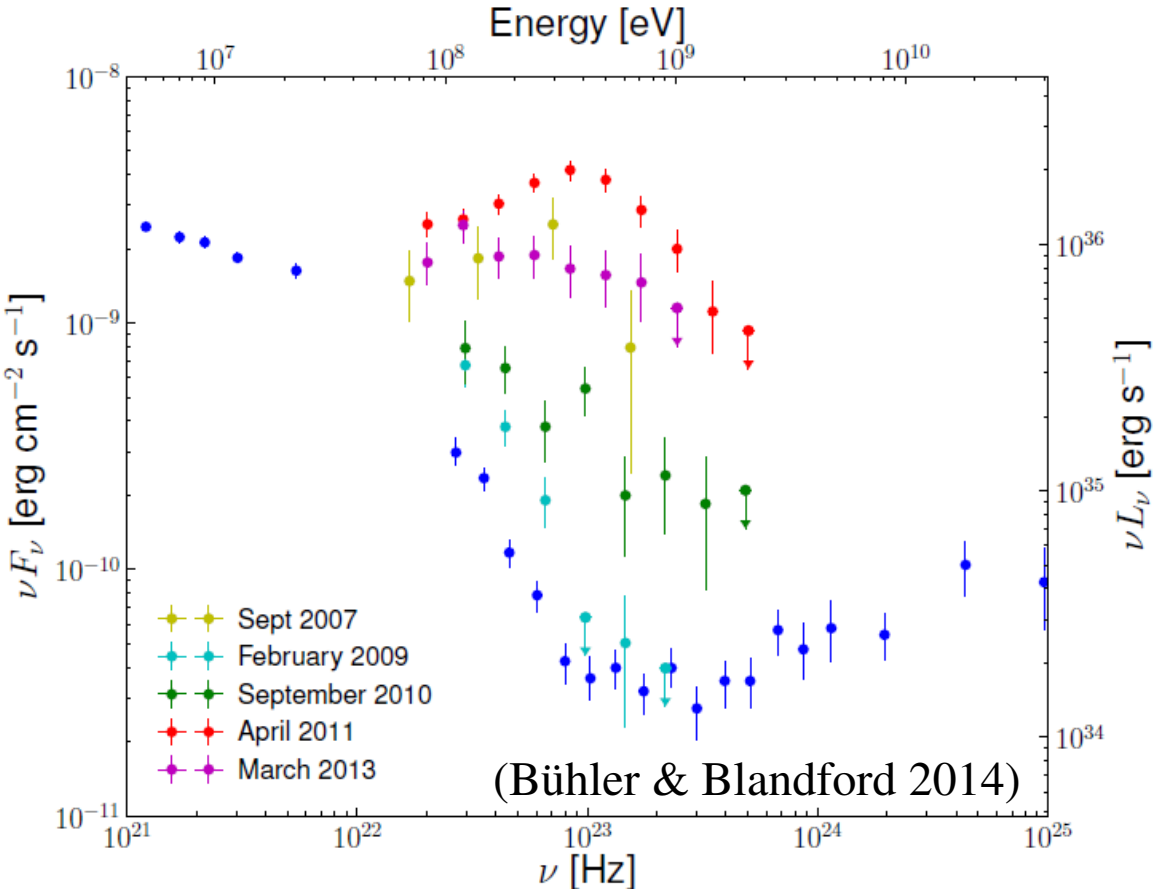


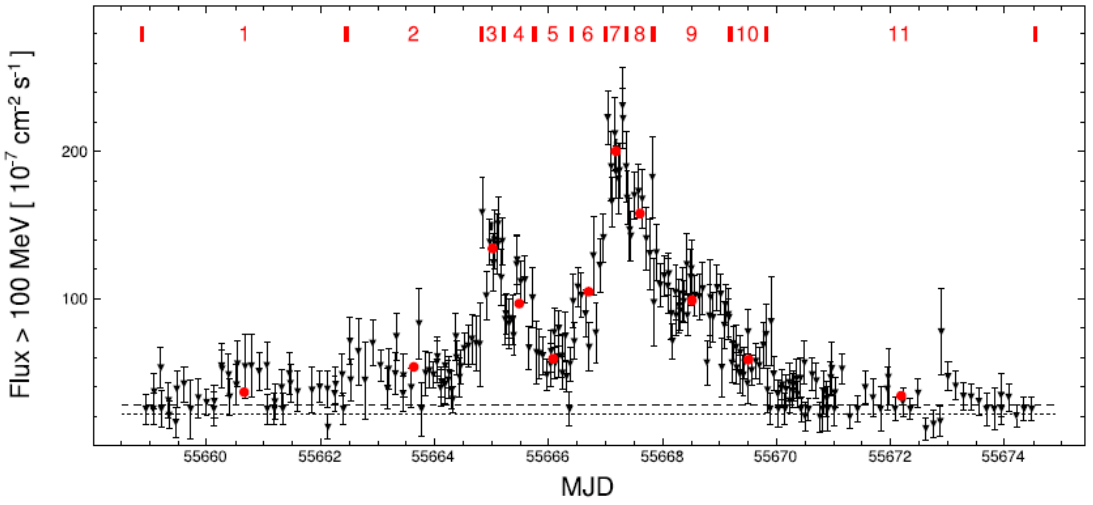


Crab Nebula

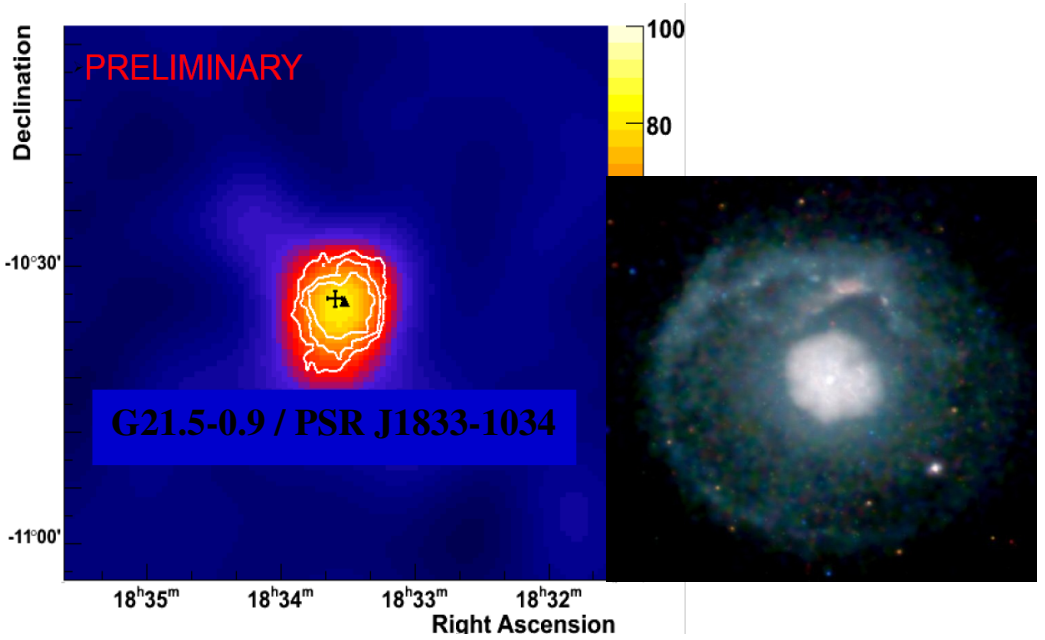
- Far from being isotropic…!
- Not anymore a candle…!



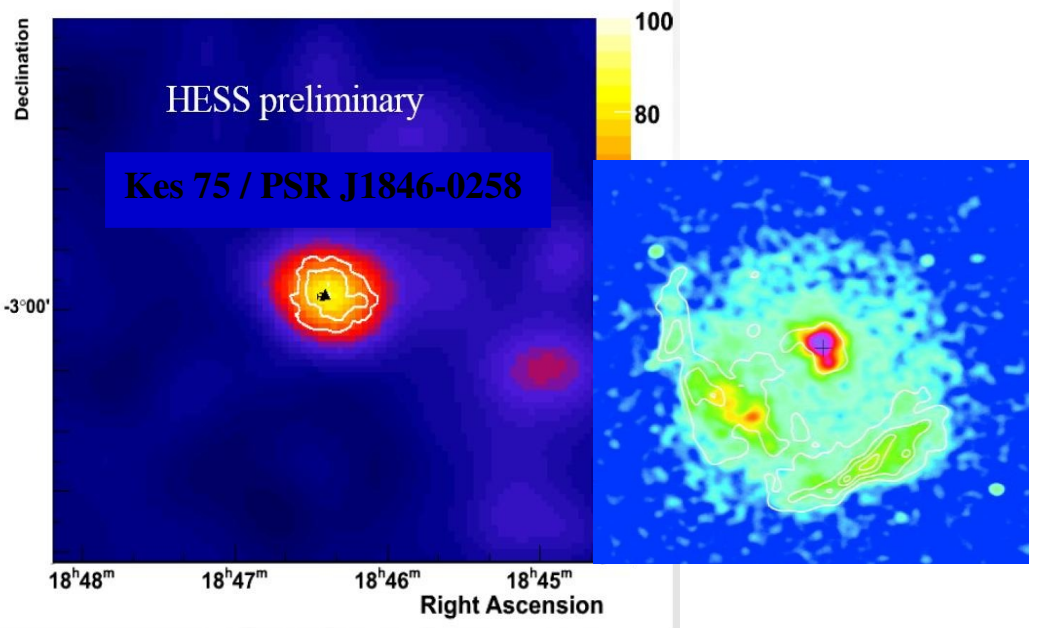




Young Gamma-Ray PWNe



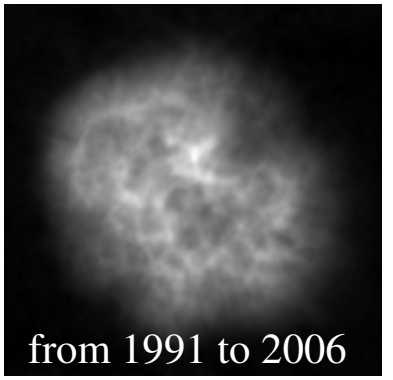
(Djannati-Ataï et al., Terrier et al. 2008)



PSR J1833-1034 (Camilo et al. 2006)

τ_c = 4.7 kyr, $\dot{E}_{36}$ = 33, d = 4.7 ± 0.4 kpc

age = 870^{+200}_{-150} yr (Bietenholz & Bartel 2008)



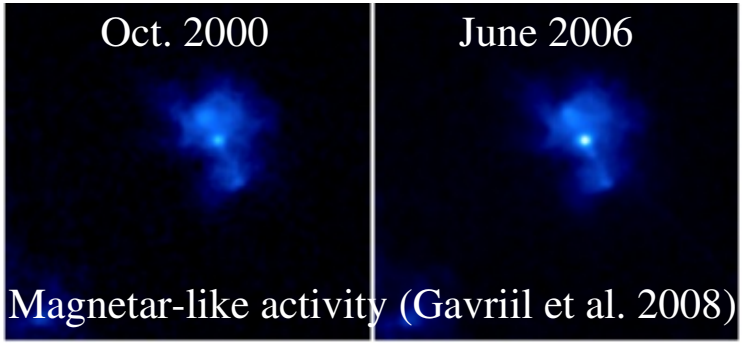
PSR J1848-0258 (Gotthelf 2000)

τ_c ~ 723 yr, $\dot{E}_{36}$ = 8.3, d = 5.1-7.5 kpc

age ~ τ_c (Leahy & Tian 2008)

n = 2.65 ± 0.01 → n = 2.19 ± 0.03

(Livingston et al. 2006, Archibald et al. 2015)



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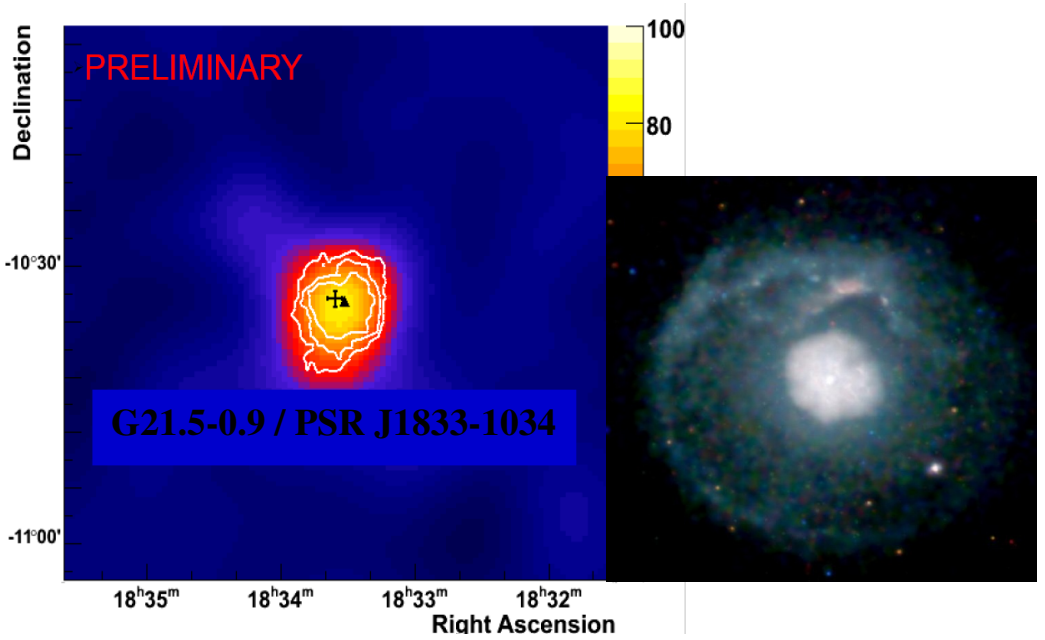

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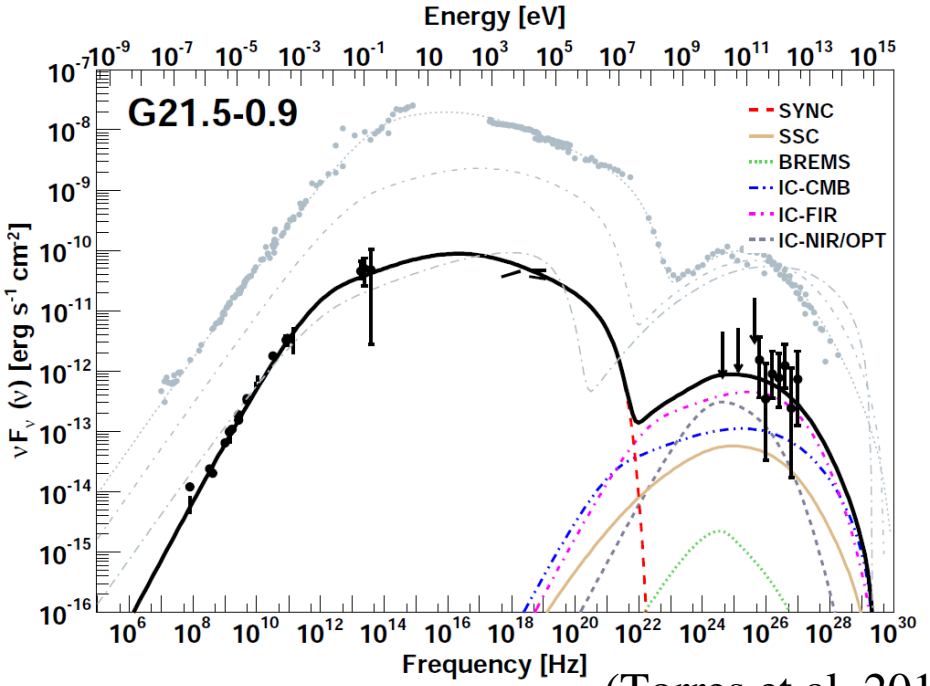
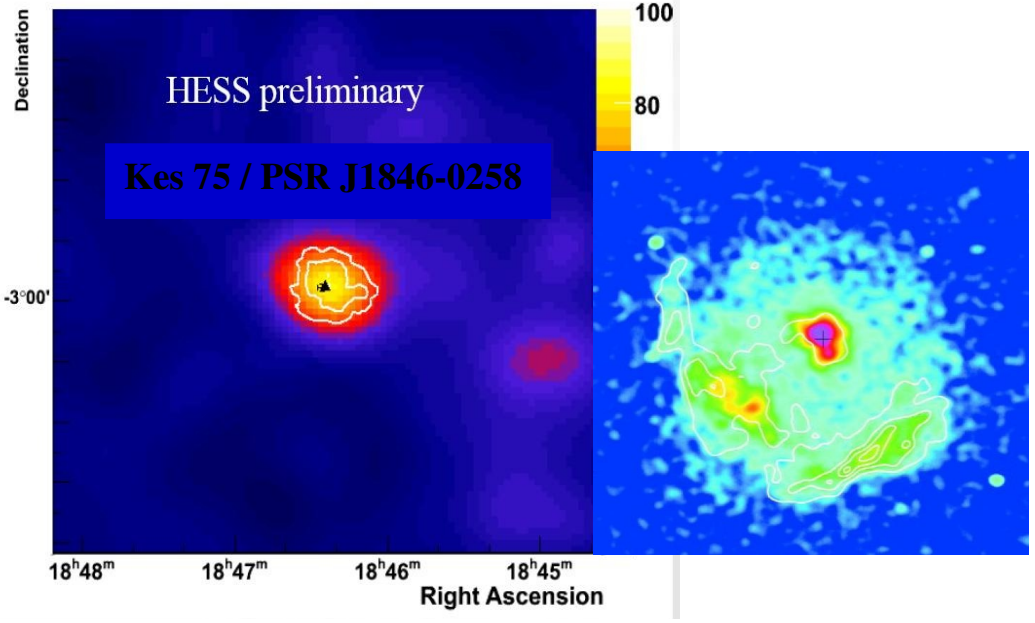
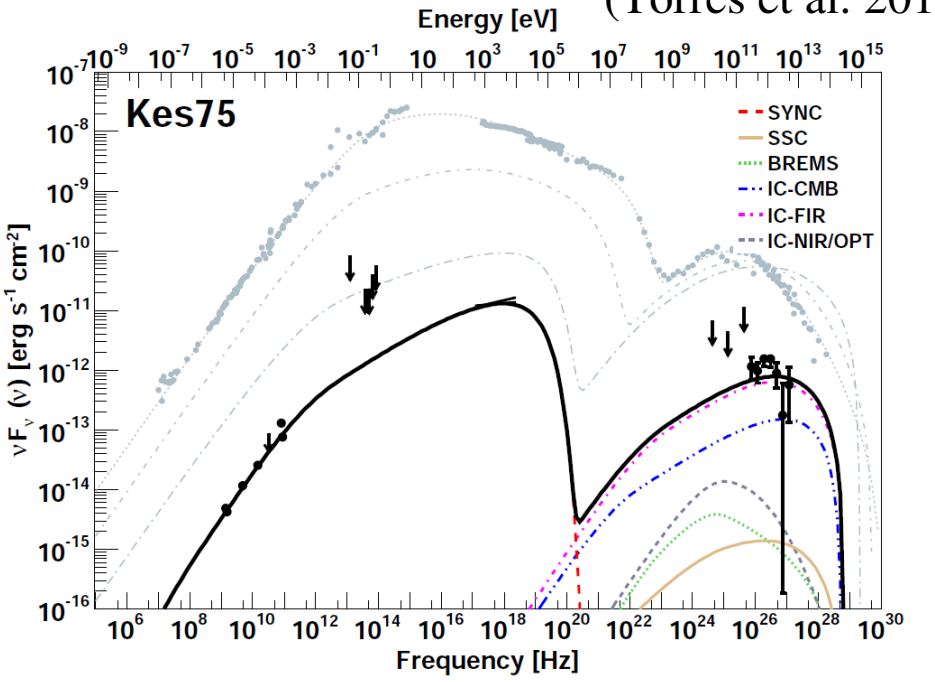


(Torres et al. 2014)





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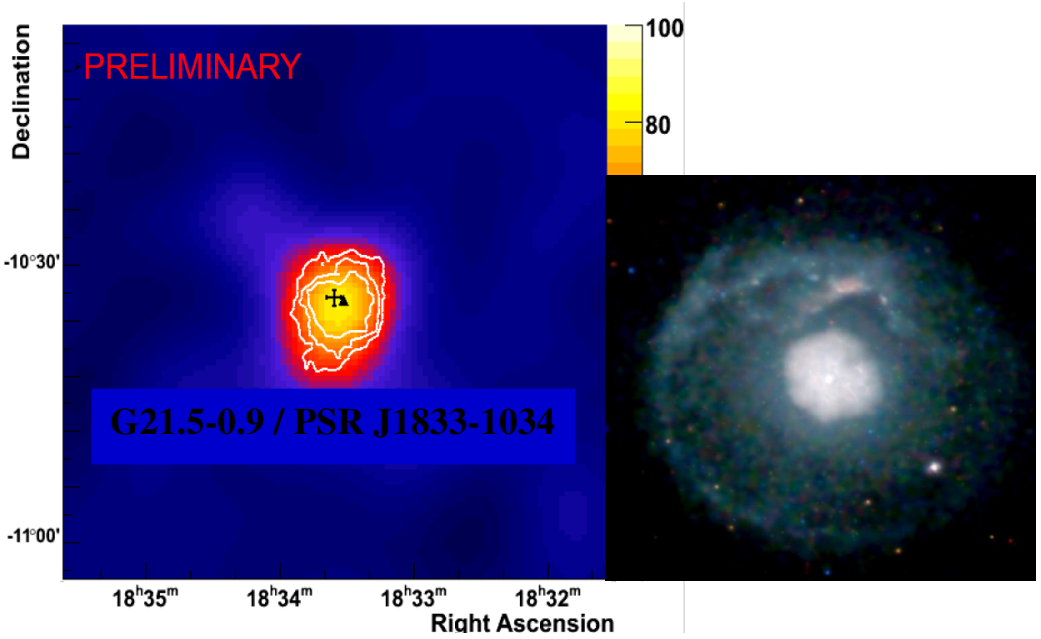

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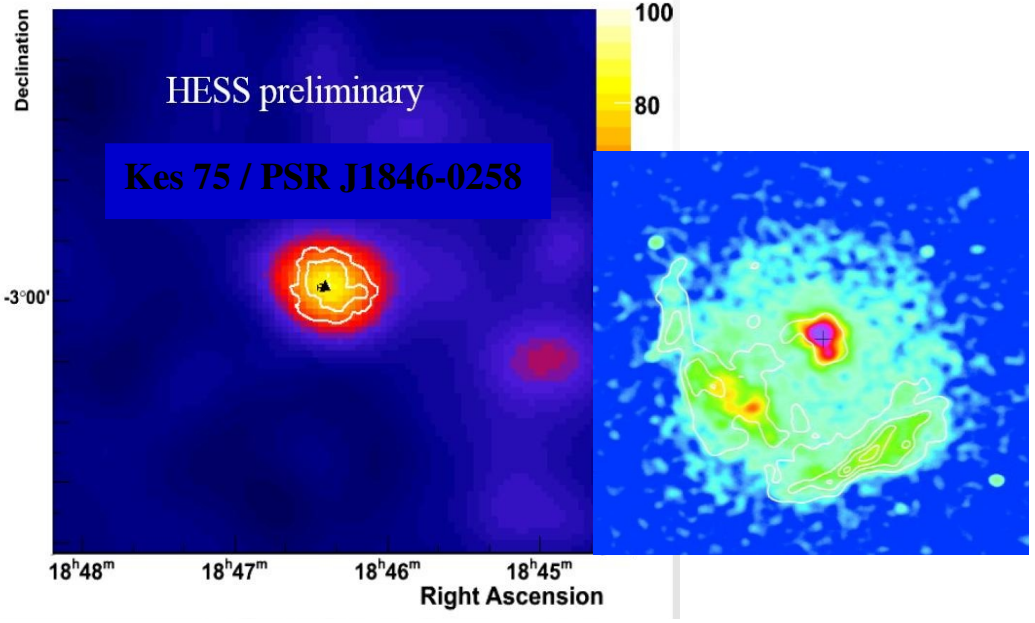
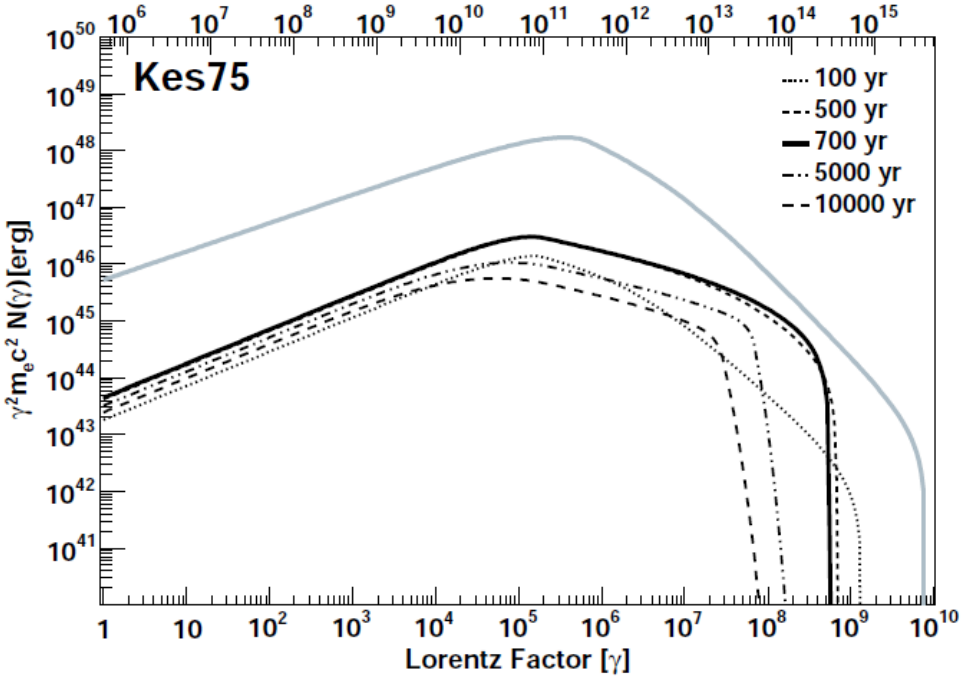


Time-dependent dynam./spectral evolution models
(Gelfand et al. 2009-14, Tanaka & Takahara 2010-13, Bucciantini et al. 2011, Martin et al. 2012-15)

→ 1-zone modeling

→ Injection: broken power-law ($E_b = 10^5$-$10^6\ m_{\pm}c^2$)



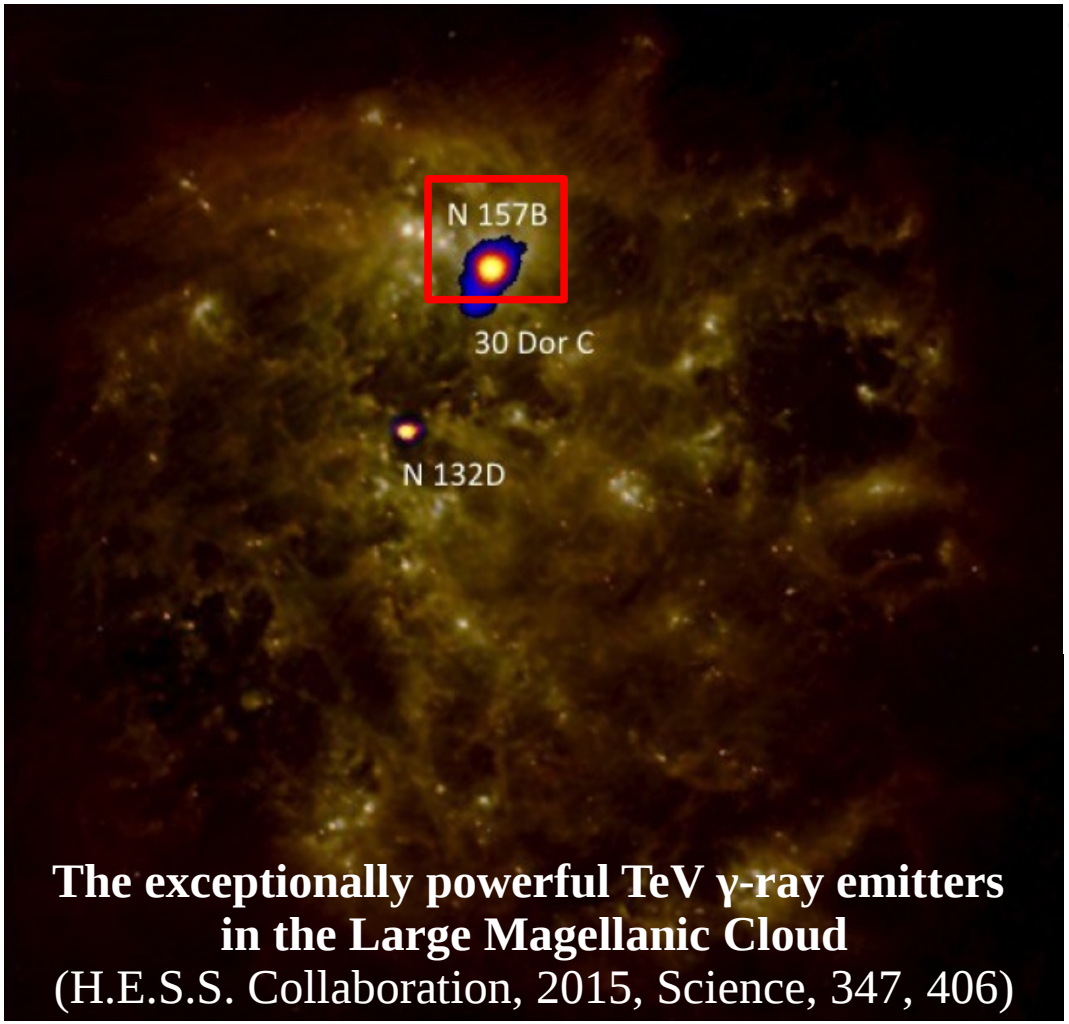
Particle-dominated nebulae ($B_{PWN} < B_{eq}$)

→ Origin of TeV emission?

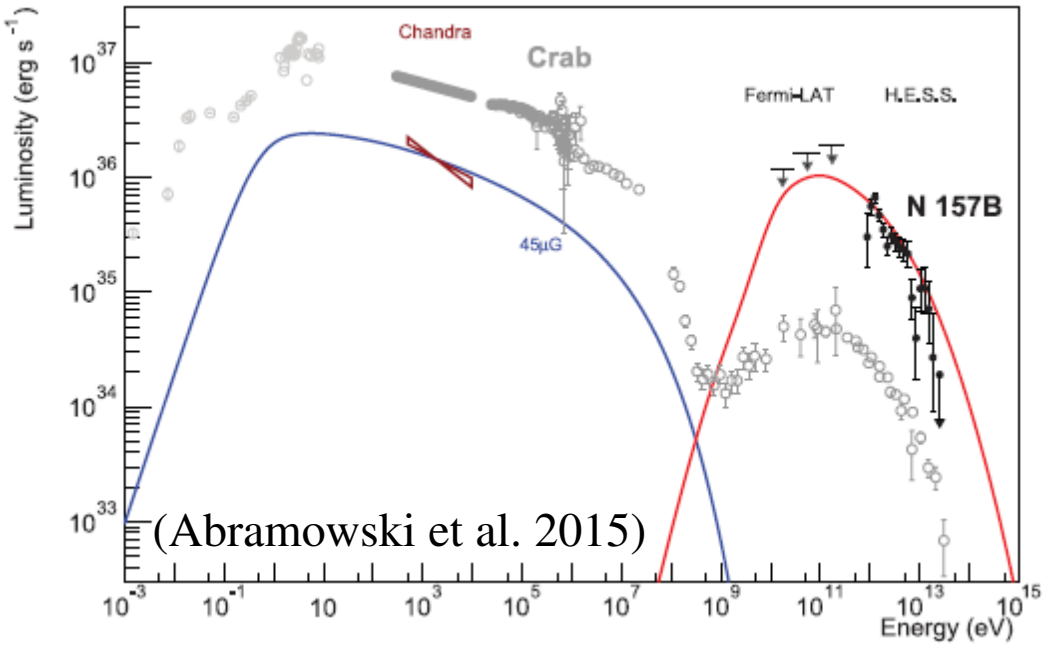
→ Seed photon fields poorly constrained

→ Two-component spectrum? (Vorster et al. 2013)

Young Gamma-Ray PWNe



The exceptionally powerful TeV γ-ray emitters in the Large Magellanic Cloud
(H.E.S.S. Collaboration, 2015, Science, 347, 406)

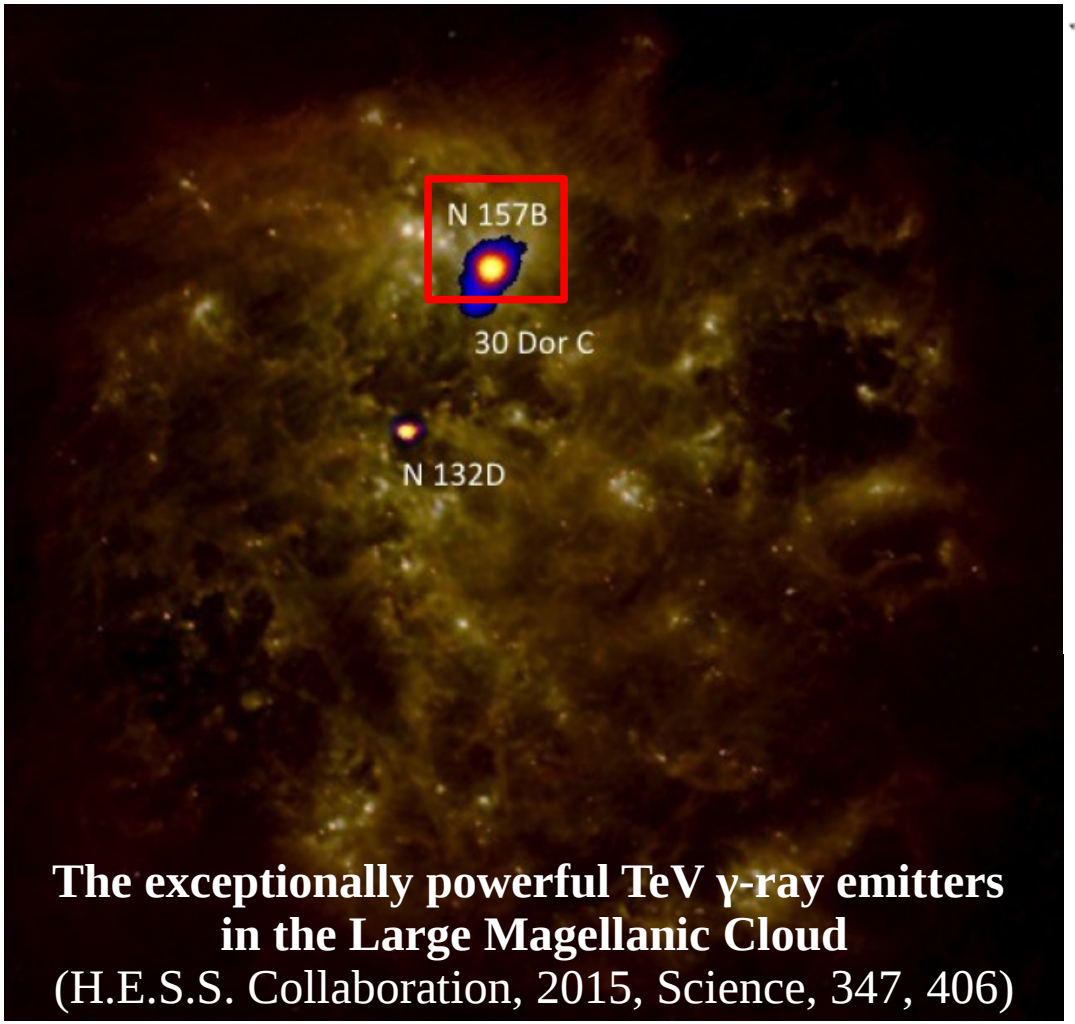


(Abramowski et al. 2015)

N 157B: Crab twin pulsar PSR J0537-6910, but...

B-field and acceleration efficiency ~3 and ~5 smaller explained by particular environment (LH 99 cluster)

Young Gamma-Ray PWNe



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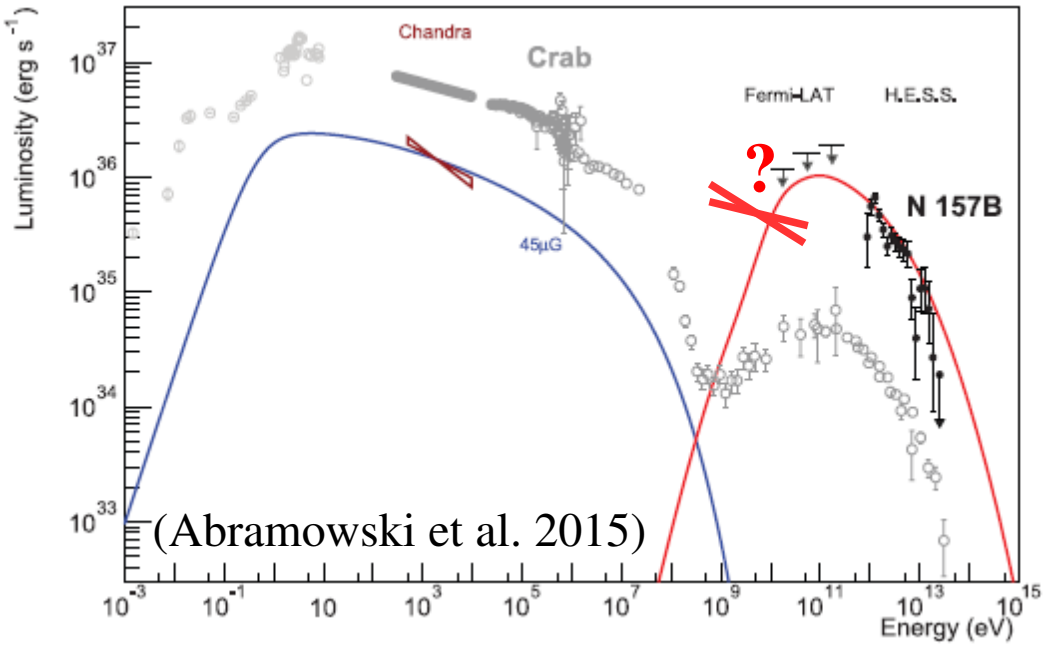
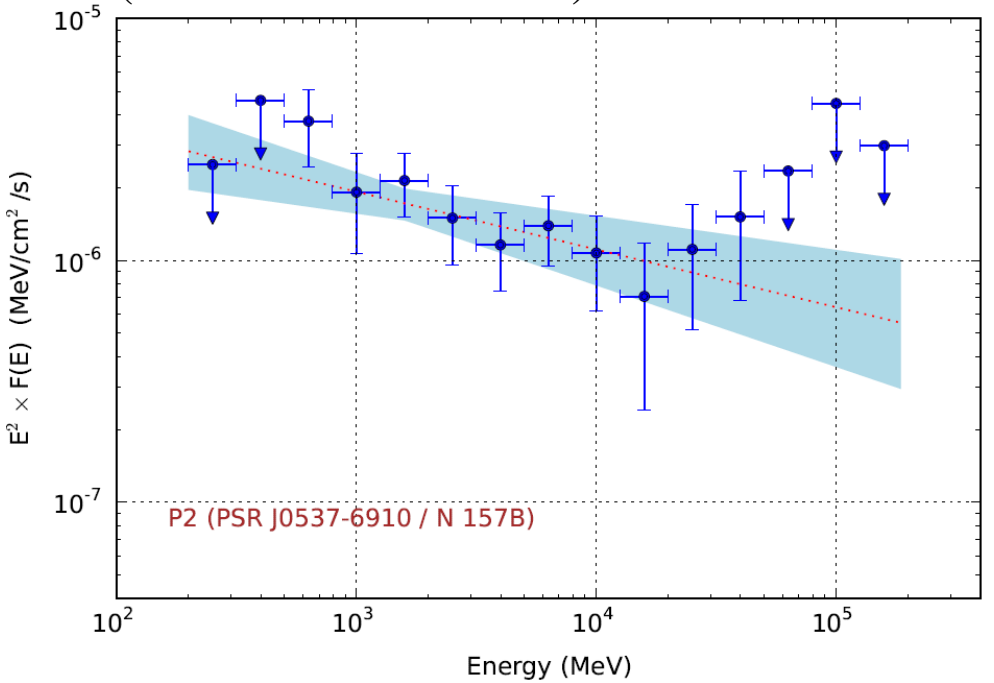


(Abramowski et al. 2015)

(Ackermann et al. 2015)

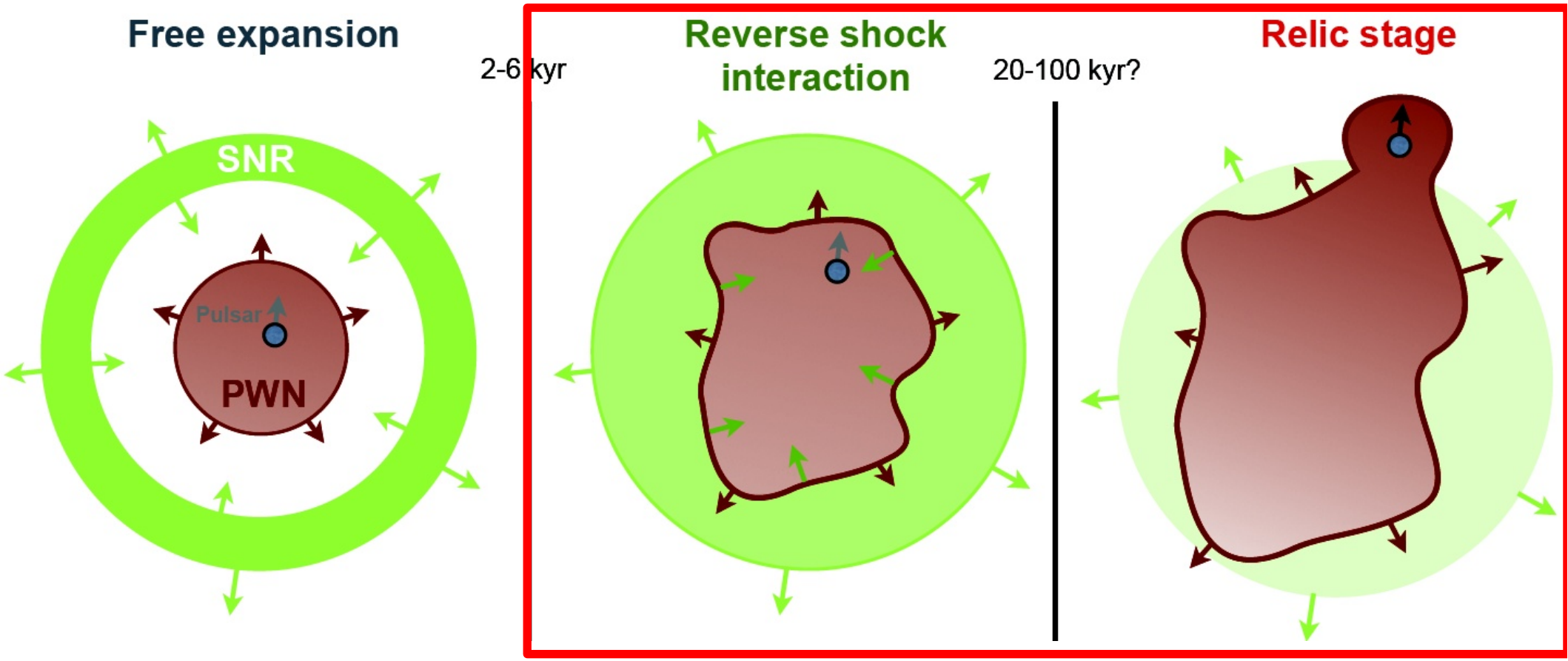


N 157B: Crab twin pulsar PSR J0537-6910, but...

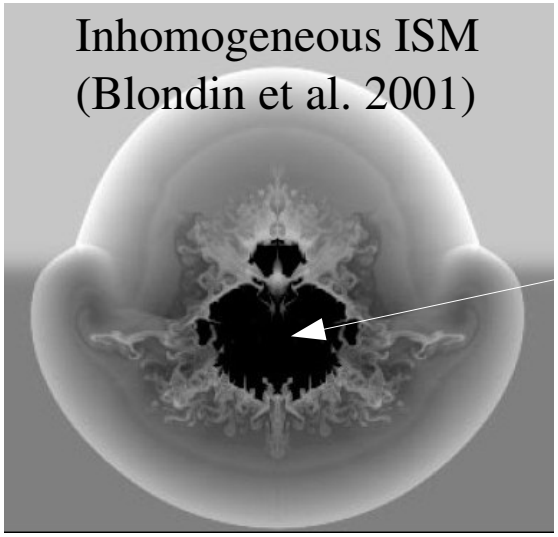
B-field and acceleration efficiency ~3 and ~5 smaller explained by particular environment (LH 99 cluster)

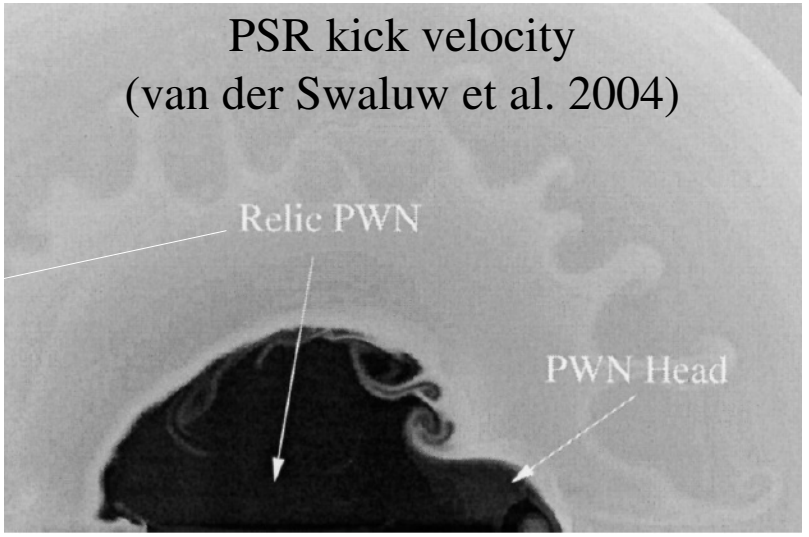
→ GeV emission ? PSR+PWN ? Two-component ?

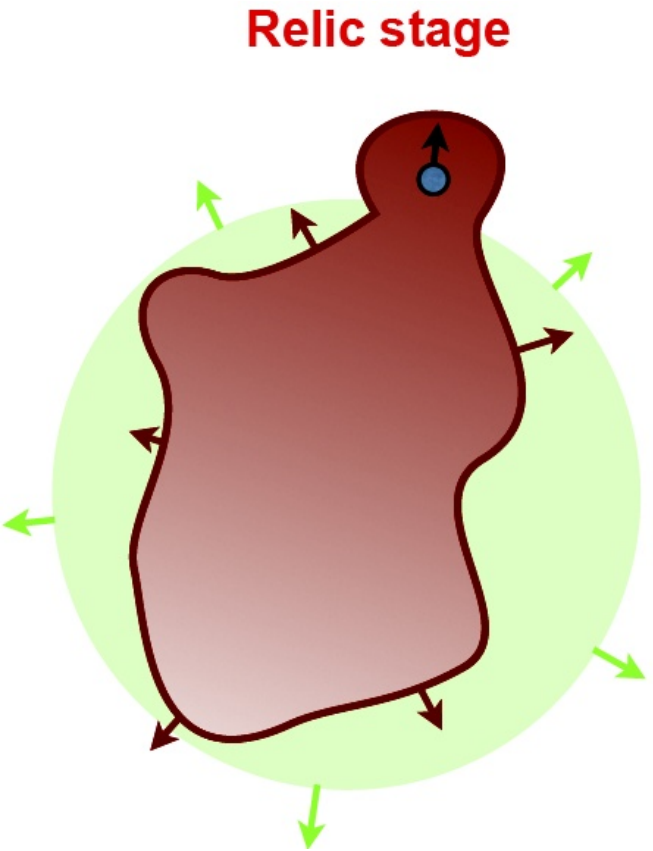
Middle-aged Gamma-Ray PWNe



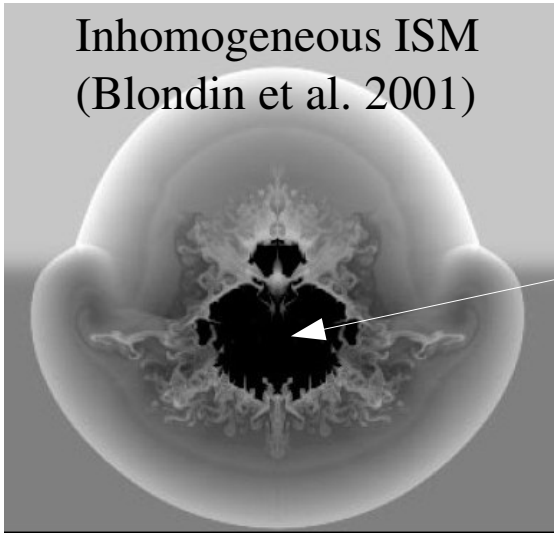
Middle-aged Gamma-Ray PWNe

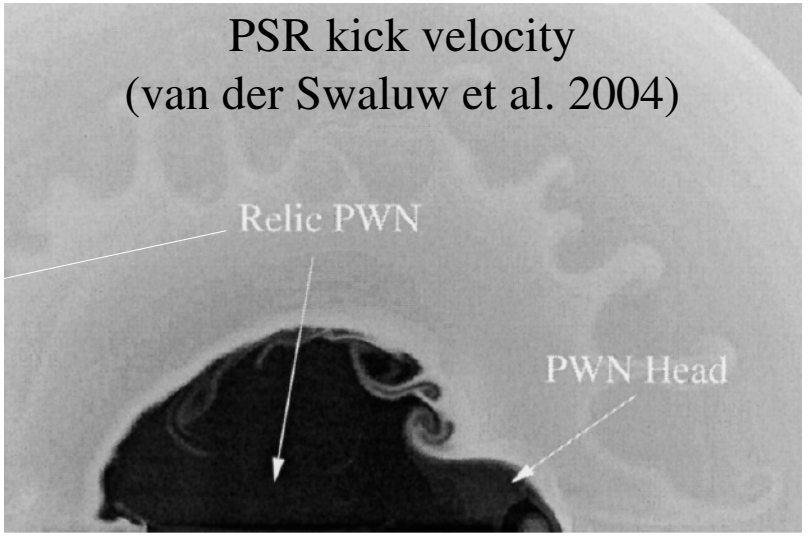


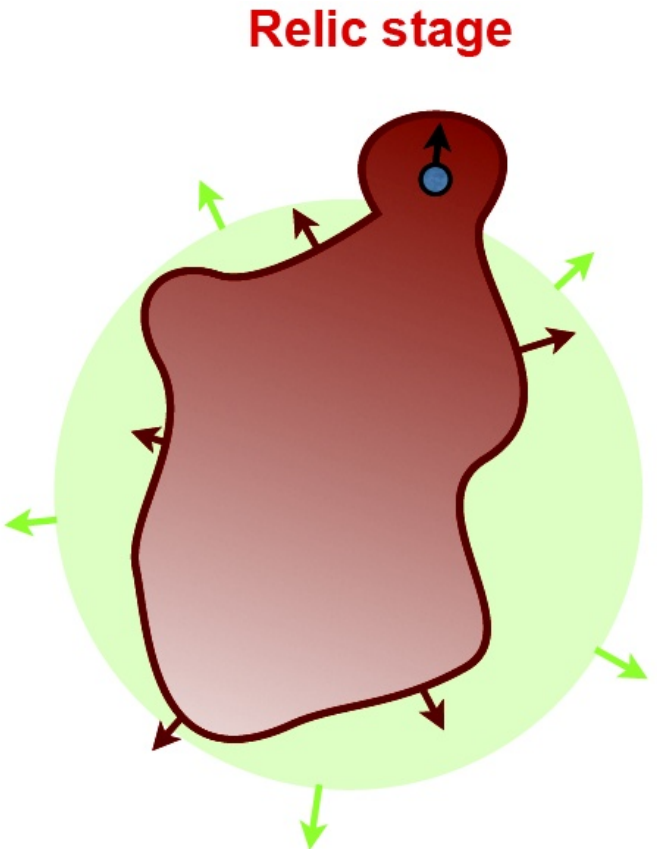


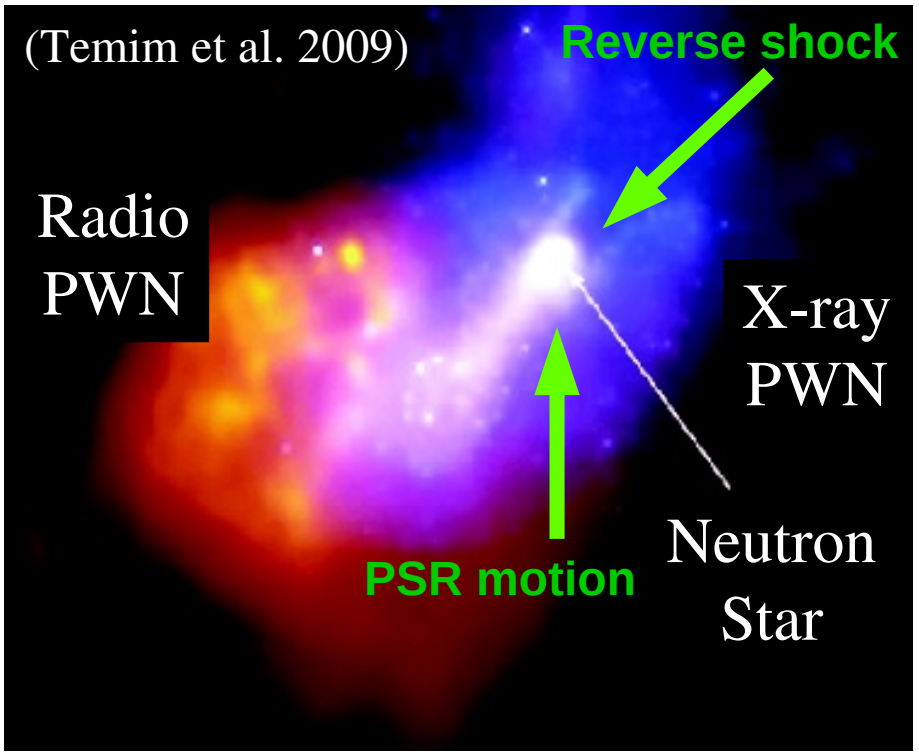


Middle-aged Gamma-Ray PWNe

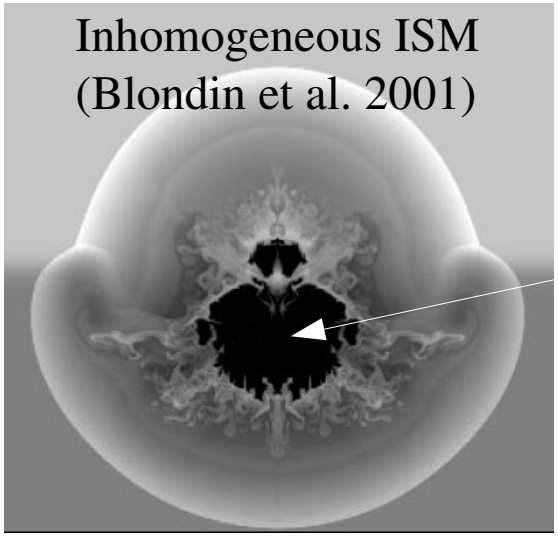


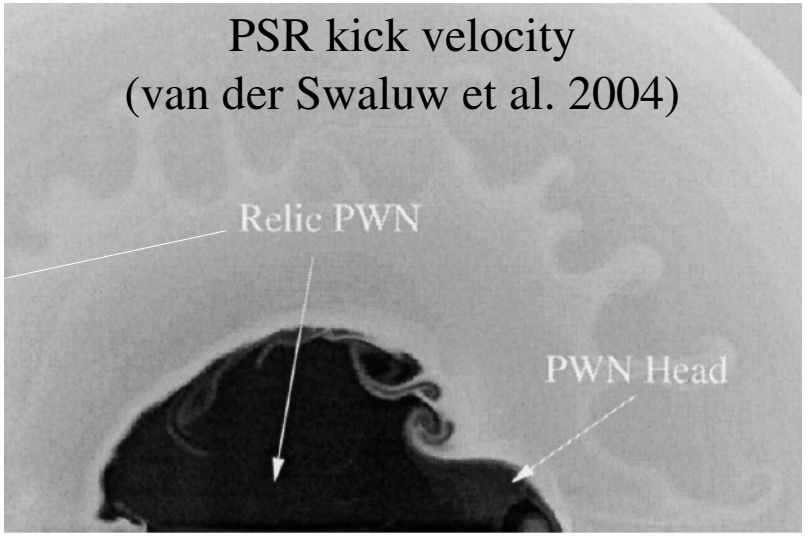




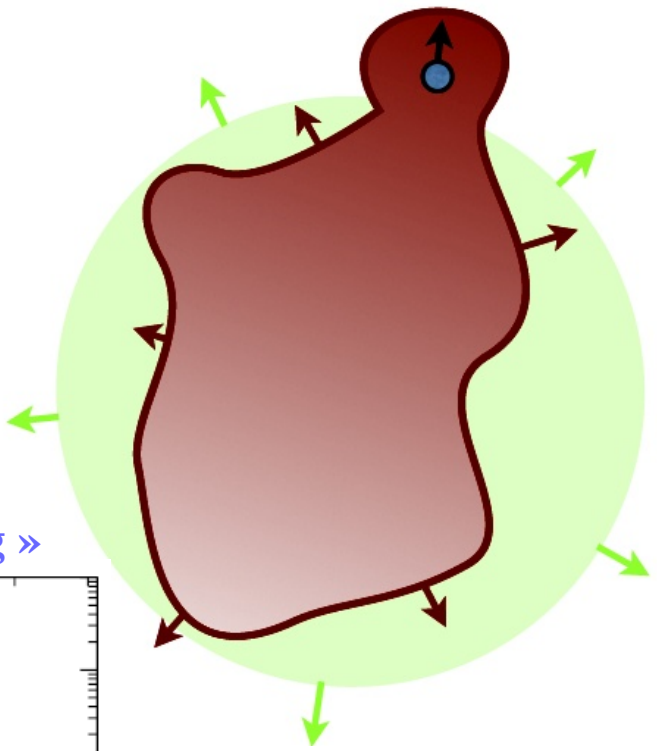


Middle-aged Gamma-Ray PWNe

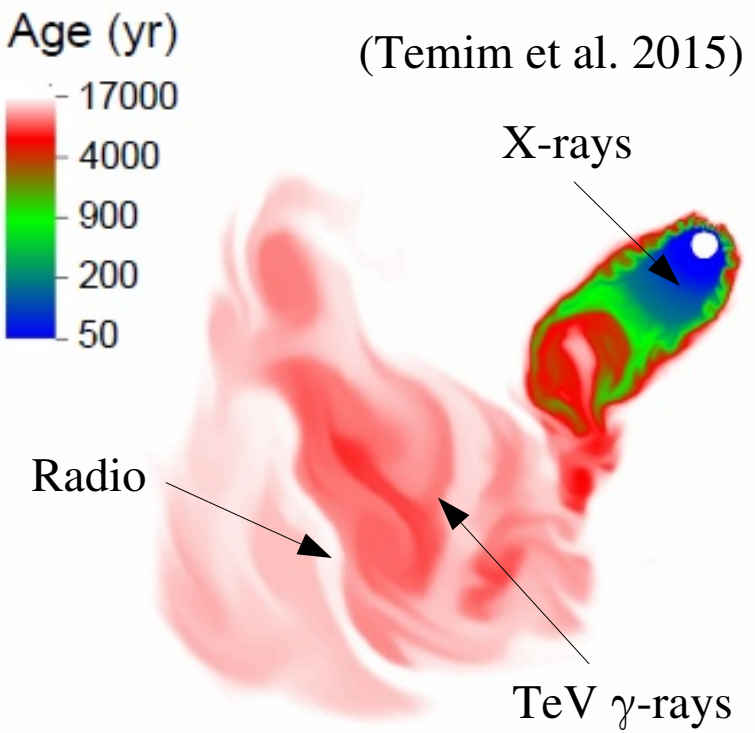


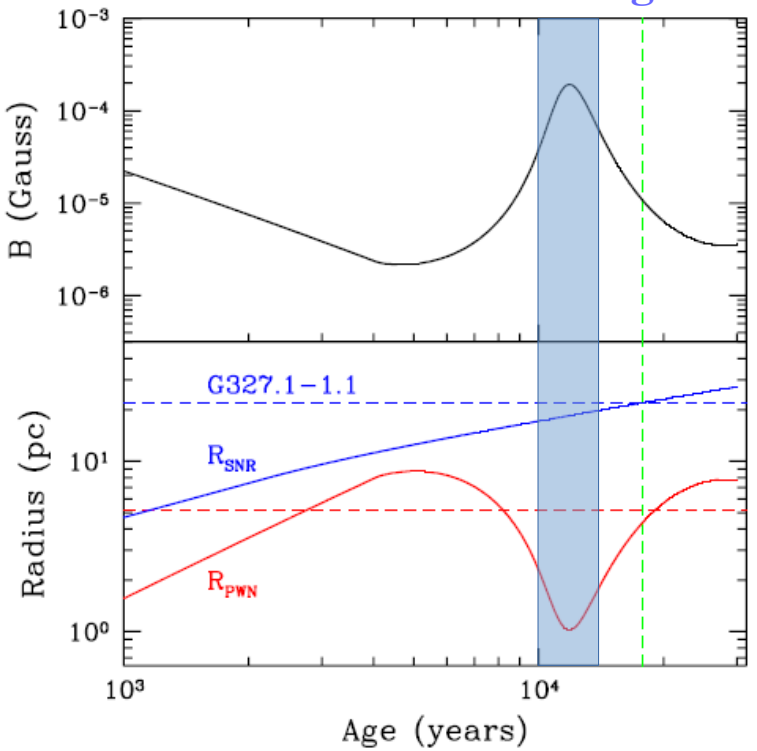


Relic stage

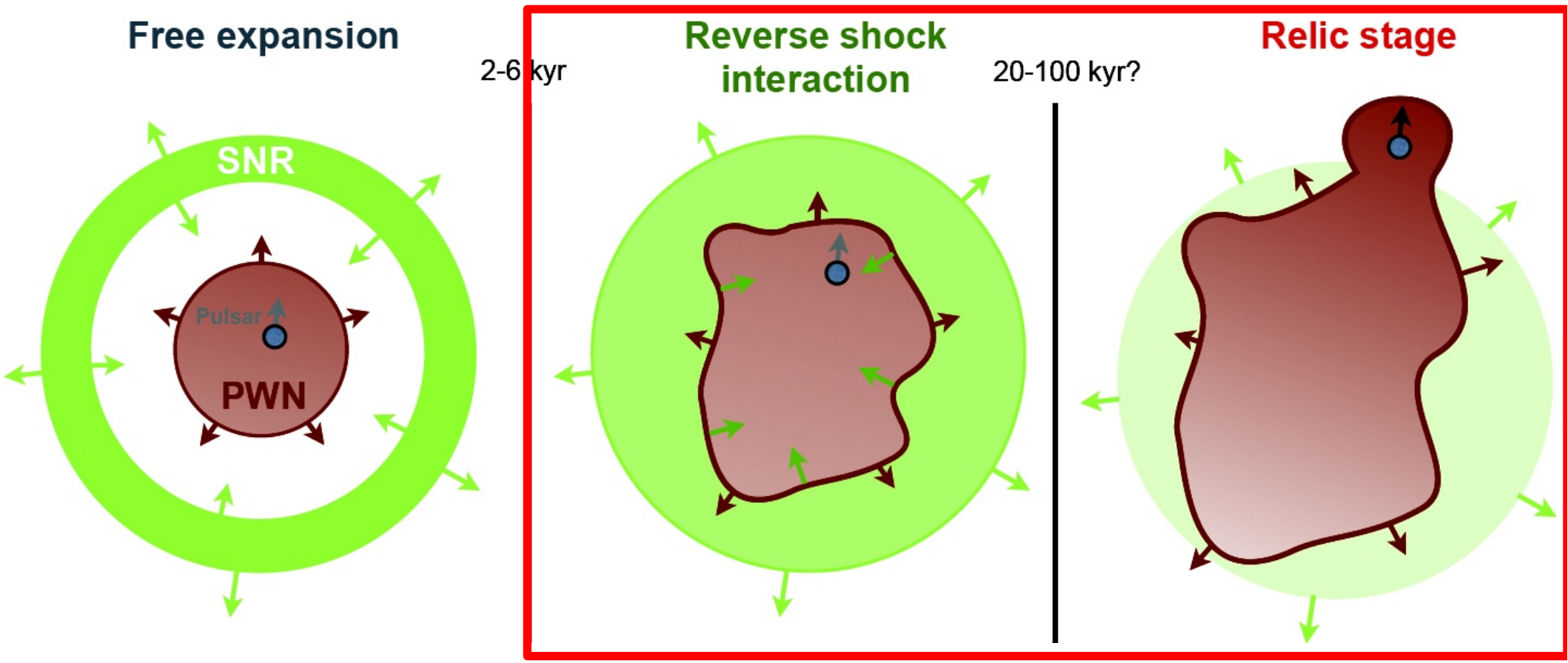


« crushing »





Middle-aged Gamma-Ray PWNe



The Expected Flux of TeV Photons from Plerions

O.C. de Jager[1], A.K. Harding[2], M.G. Baring[2], A. Mastichiadis[3]
[1] *Space Research Unit, PU vir CHO, Potchestroom 2520, South Africa*
[2] *LHEA, NASA/GSFC, Greenbelt, MD 20771, USA*
[3] *Max Planck Institut für Kernphysik, Heidelberg, Germany*

Implications of HESS Observations of Pulsar Wind Nebulae

Ocker C. de Jager and Arache Djannati-Ataï

Unidentified Gamma-Ray Sources as Ancient Pulsar Wind Nebulae

O.C. de Jager*, S.E.S. Ferreira*, A. Djannati-Ataï†, M. Dalton‡, C. Deil§, K. Kosack¶, M. Renaud†, U. Schwanke‡ and O. Tibolla§

$\tau_{keV} \sim 1.2\ \mathrm{kyr}\ (B/10\mu G)^{-3/2}$
$\tau_{TeV} \sim 6.5\ \mathrm{kyr}\ (B/10\mu G)^{-2}$

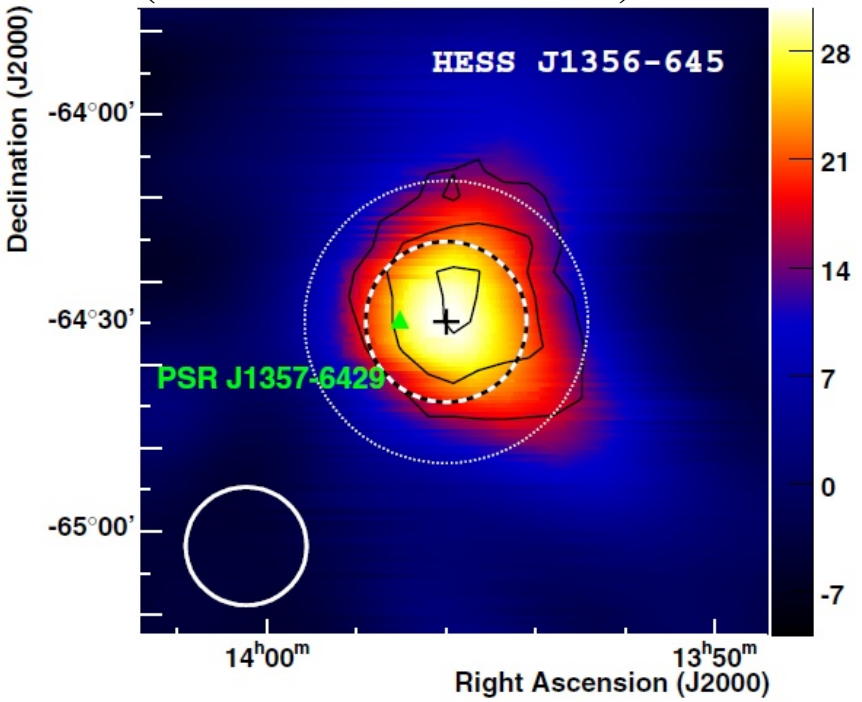
Particle-dominated expanding long-lived-$e^{+/-}$-«filled bags»

→ Gamma-ray bright & X-ray faint
→ Large & offset from pulsar

} **How to identify them?**

1. Multi-wavelength observations

(Abramowski et al. 2011)



PSR J1357-6429: $d \sim 2.5$ kpc, $\tau_c = 7.3$ kyr, $\dot{E}_{36} = 3.1$

$\rightarrow L_{1\text{-}10\text{TeV}}/\dot{E} \sim \mathbf{10^{-3}}\ d_{2.5}$, $\sigma \sim \mathbf{9}\ d_{2.5}^2$ pc , offset $\sim \mathbf{5}\ d_{2.5}$ pc

$\rightarrow$ Required transverse velocity ~ $\mathbf{680}\ d_{2.5}\ \tau_{7.3}^{-1}$ km/s

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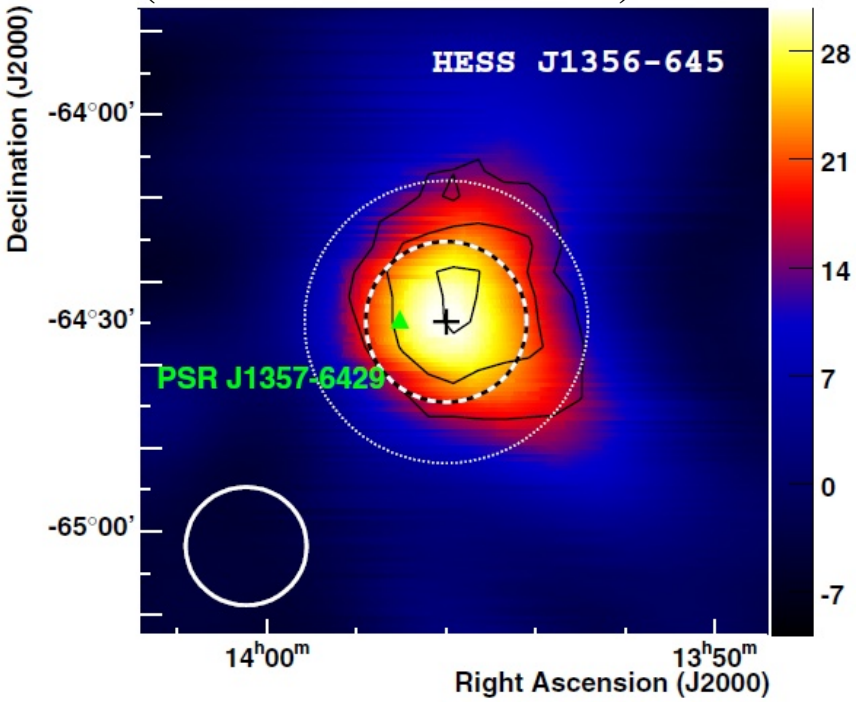

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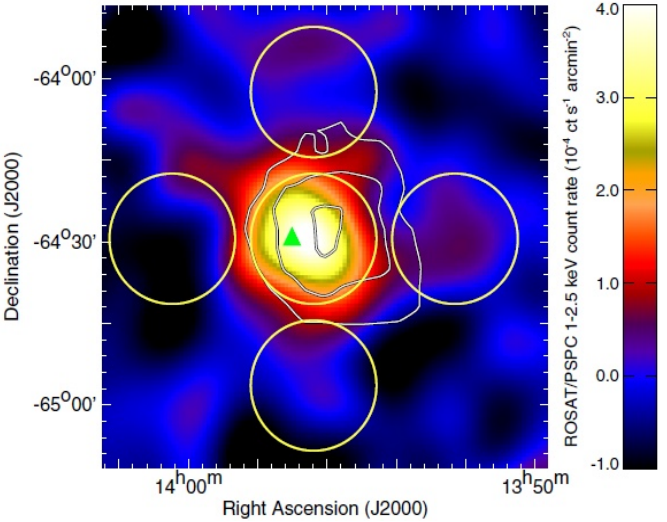
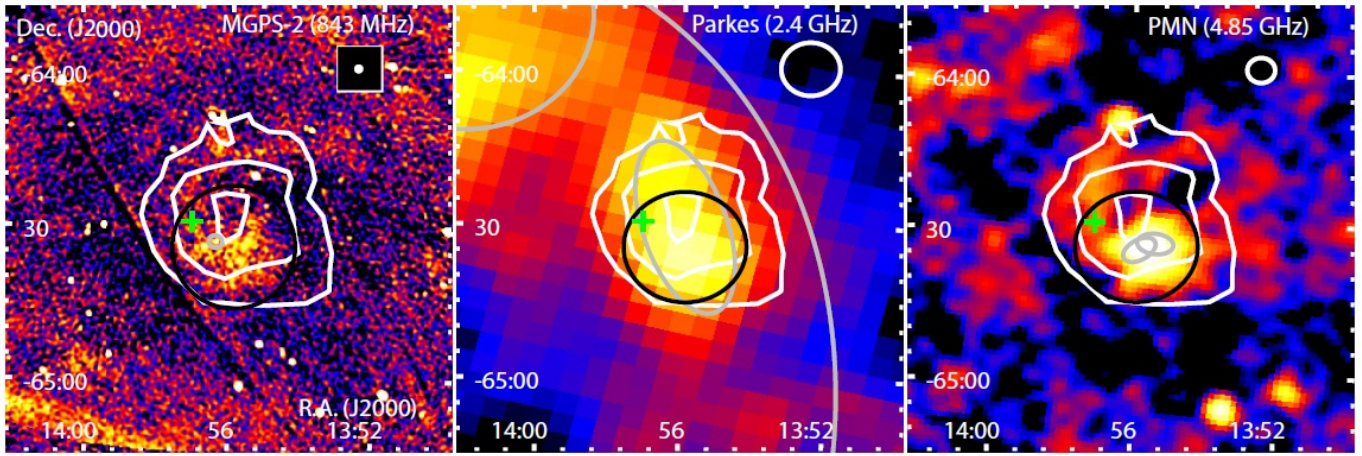
ROSAT/PSPC 1-2.5 keV

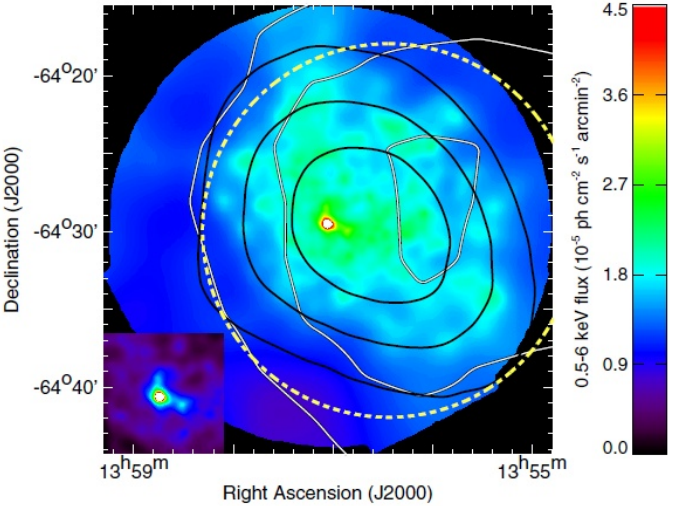


Radio and X-ray counterparts

(see also Chang et al. 2012, Izawa et al. 2015)



XMM-Newton/MOS 0.5-6 keV



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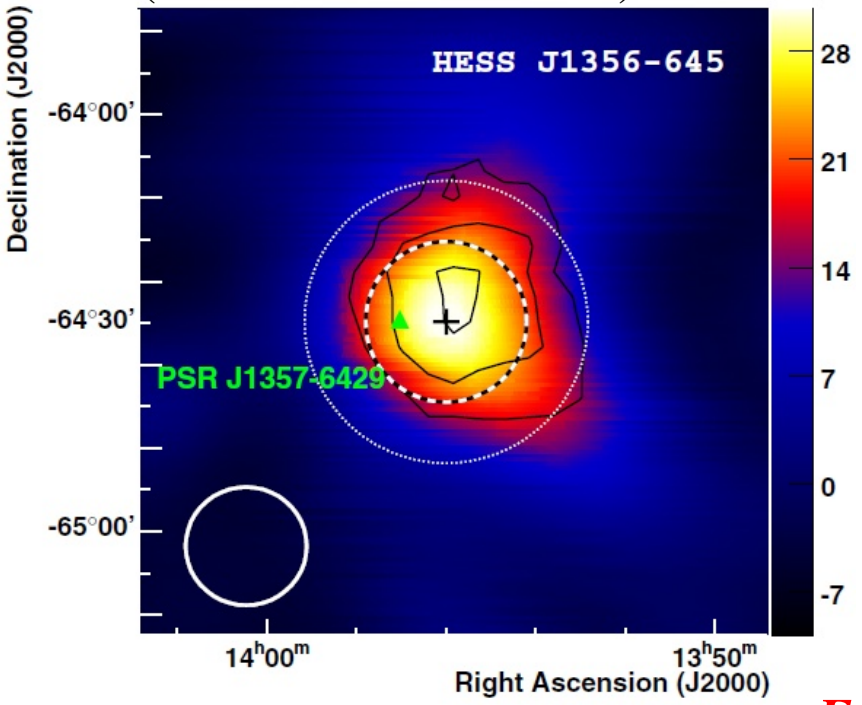

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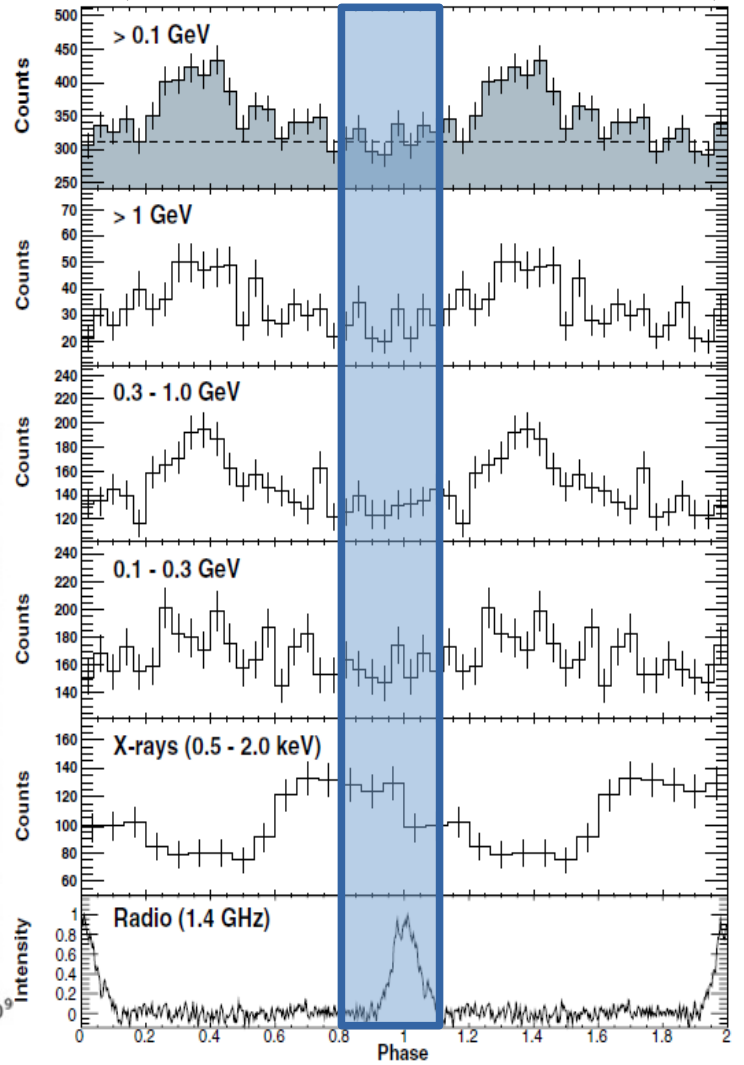
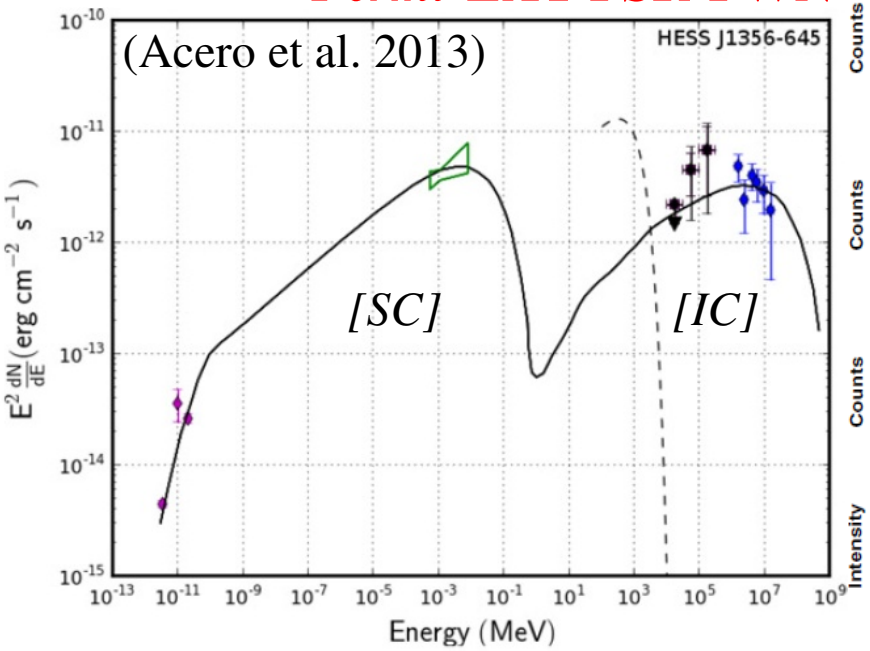
$\rightarrow$ Required transverse velocity ~ $\mathbf{680}\ d_{2.5}\ \tau_{7.3}^{-1}$ km/s

(Lemoine-Goumard et al. 2011)



Fermi-LAT PSR-PWN

(Acero et al. 2013)



Simple 1-zone modeling

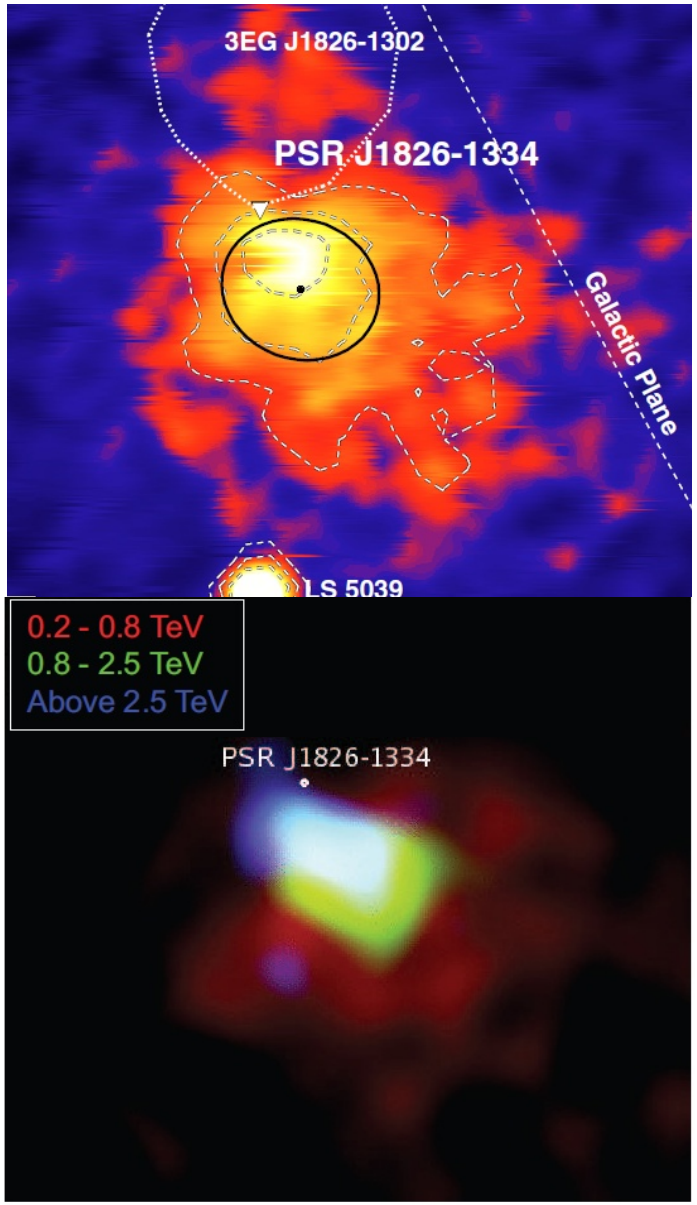
B ~ 3–5 μG

$E_{tot} \sim 5 \times 10^{47}$ erg

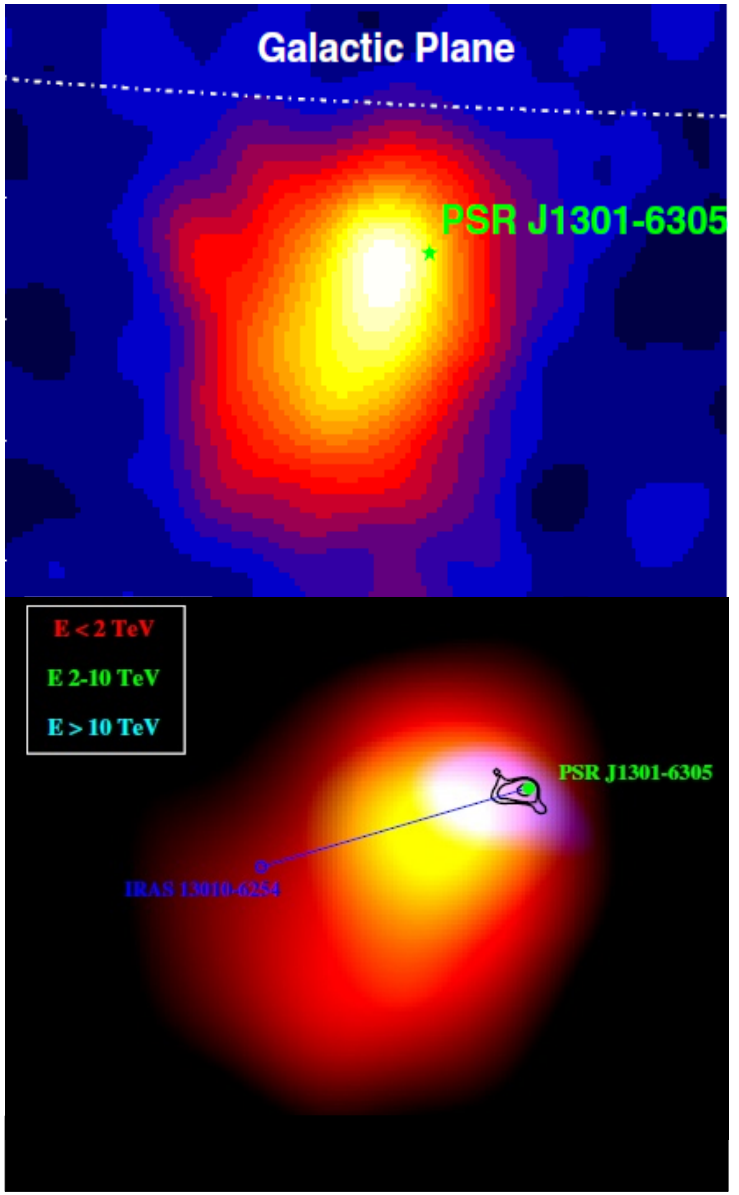
$\eta \leq 0.1$ for $P_0 \leq 70$ ms

2. Energy-dependent morphology

HESS J1825-137 (Aharonian et al. 2006)



HESS J1303-631 (Abramowski et al. 2012)



PSR B1823-13: $d \sim 4$ kpc, $\tau_c = 21$ kyr, $\dot{E}_{36} = 2.8$

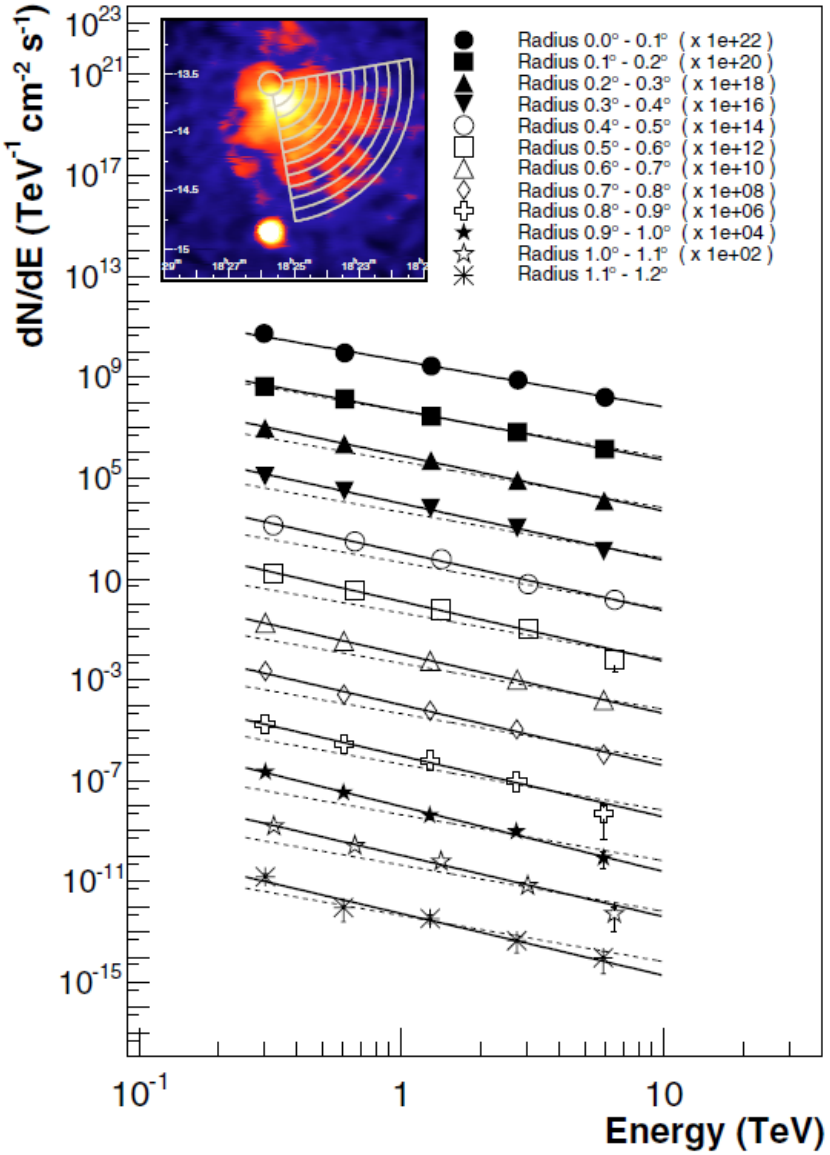
$L_{>0.2TeV}/\dot{E} \sim \mathbf{10^{-1}}\, d_4$, $\sigma \sim \mathbf{16}\, d_4$ pc , offset $\sim \mathbf{11}\, d_4$ pc

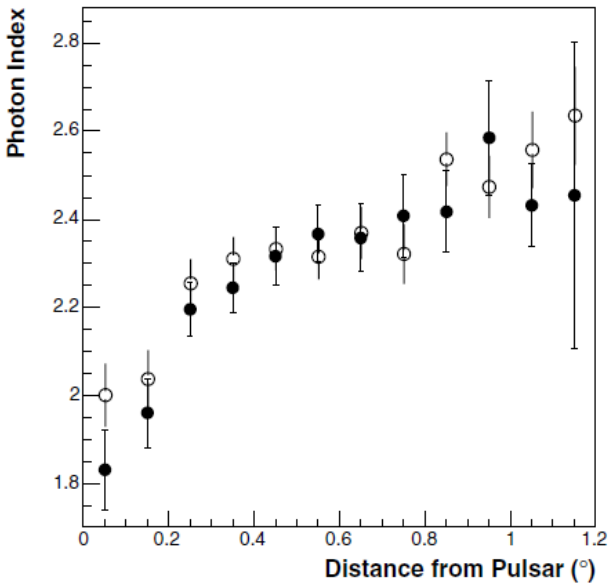
PSR J1301-6305: $d \sim 6.6$ kpc, $\tau_c = 11$ kyr, $\dot{E}_{36} = 1.7$

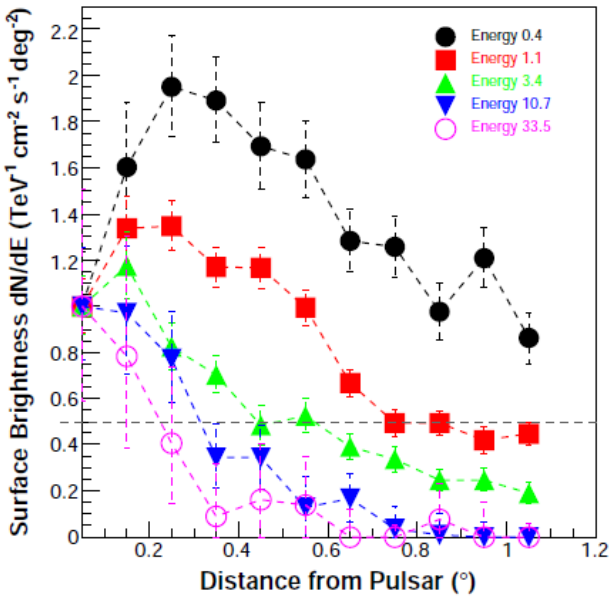
$L_{1\text{-}30TeV}/\dot{E} \sim \mathbf{0.04}\, d_{6.6}$, $\sigma \sim \mathbf{20}\, d_{6.6}$ pc , offset $\sim \mathbf{10}\, d_{6.6}$ pc

2. Energy-dependent morphology

HESS J1825-137 (Aharonian et al. 2006)







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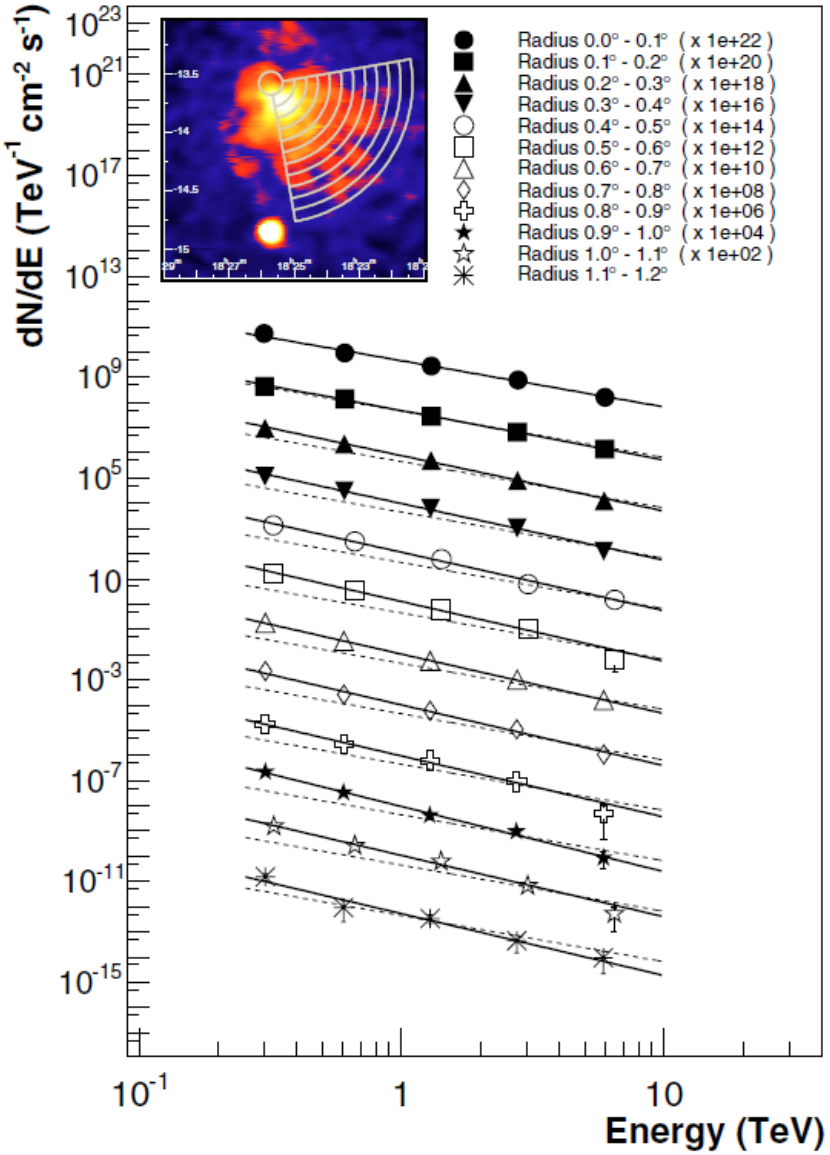
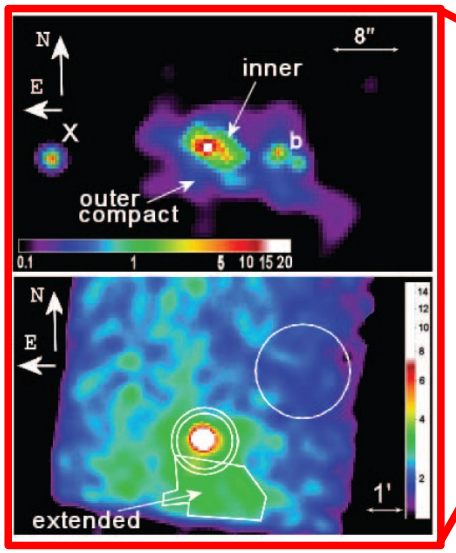
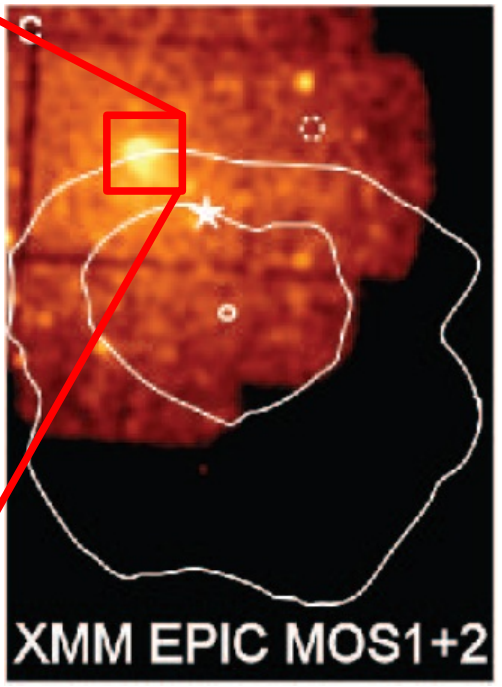
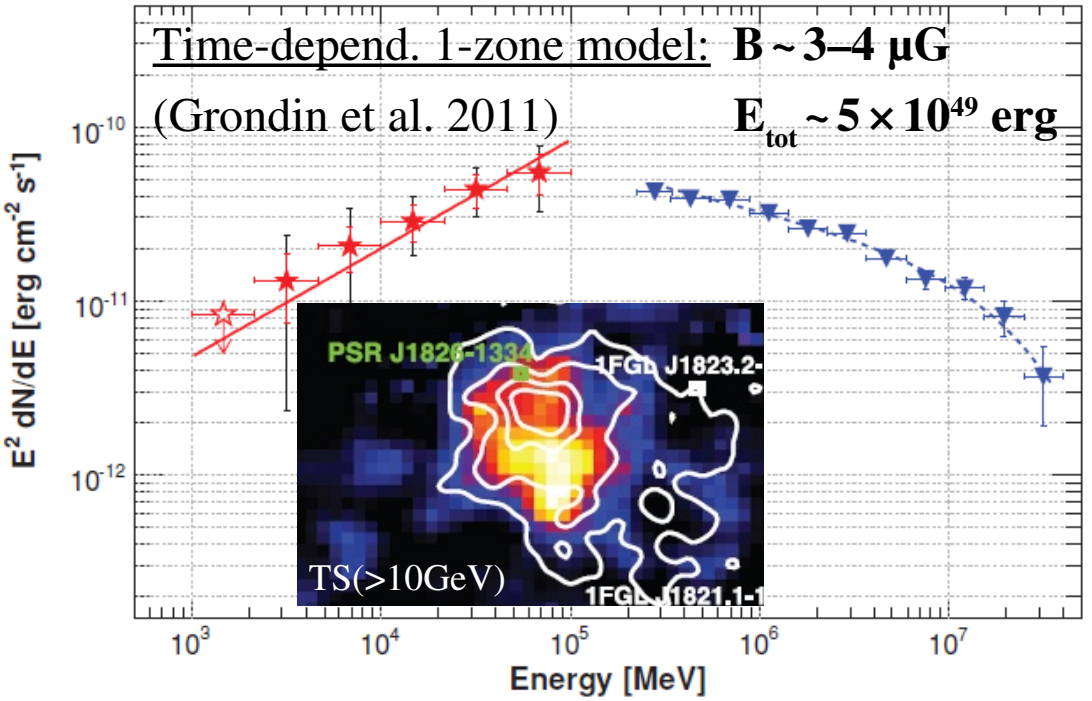






(Pavlov et al. 2008, Uchiyama et al. 2009)



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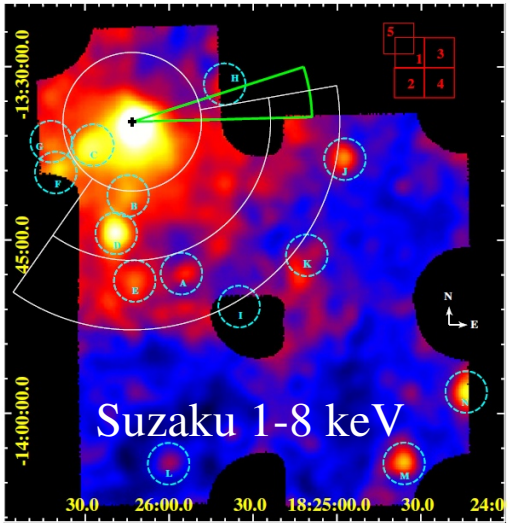
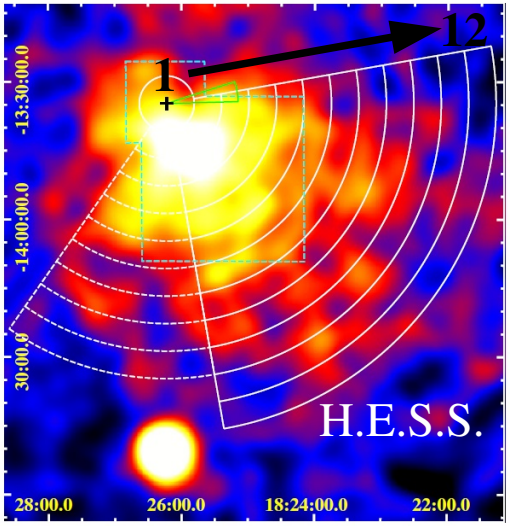
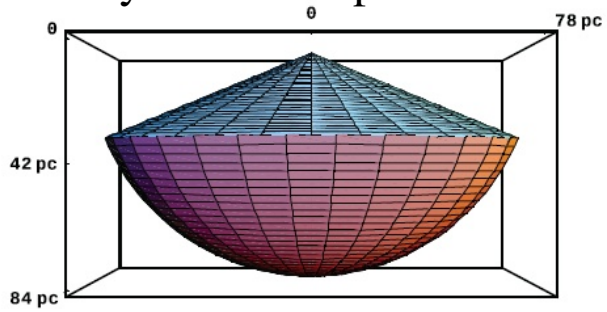
2. Energy-dependent morphology

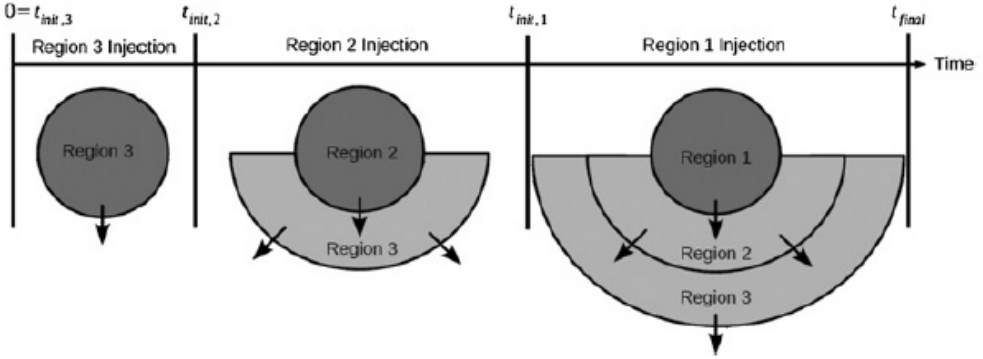
HESS J1825-137 (Van Etten & Romani 2011)





3D multi-zone time-dependent modeling with radial velocity & B-field profiles and diffusion





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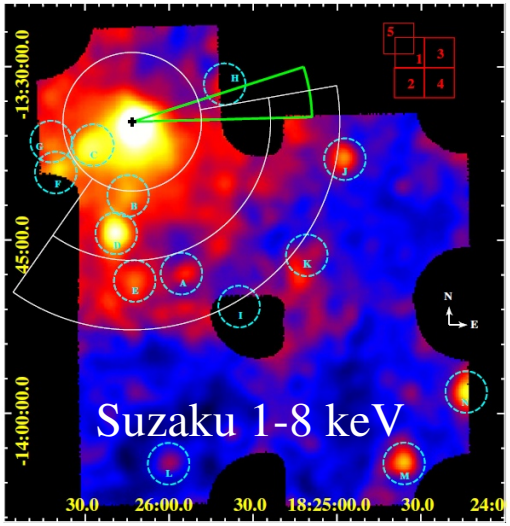

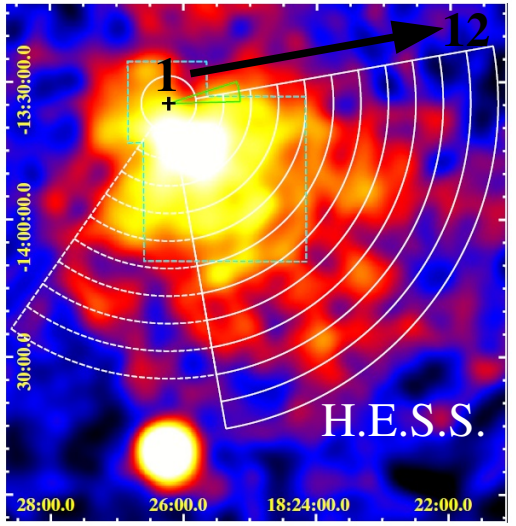

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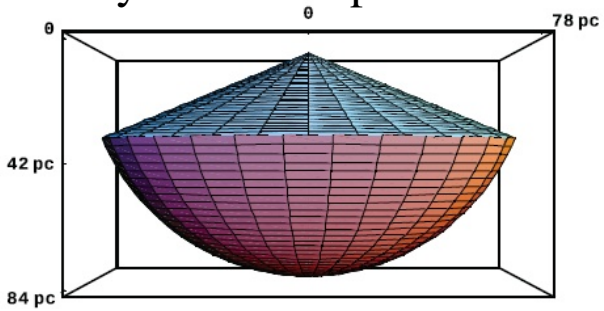
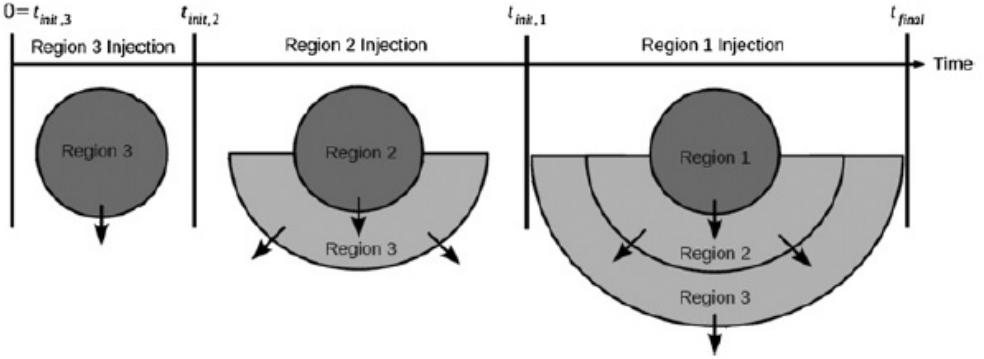
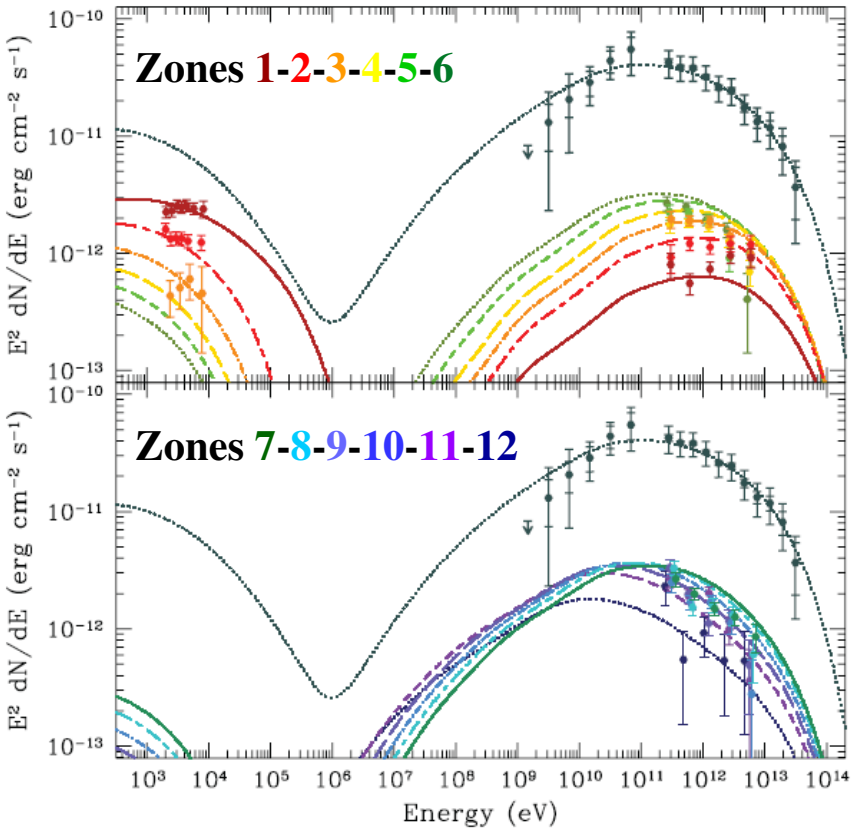
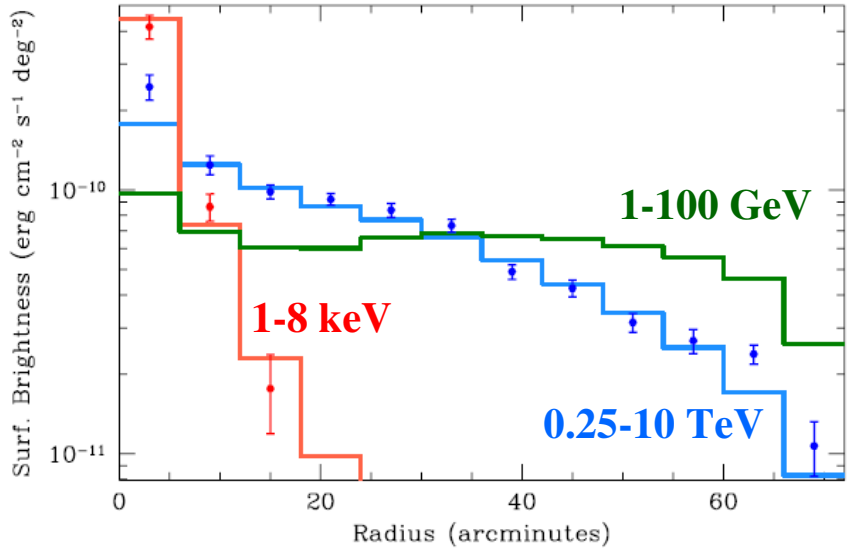


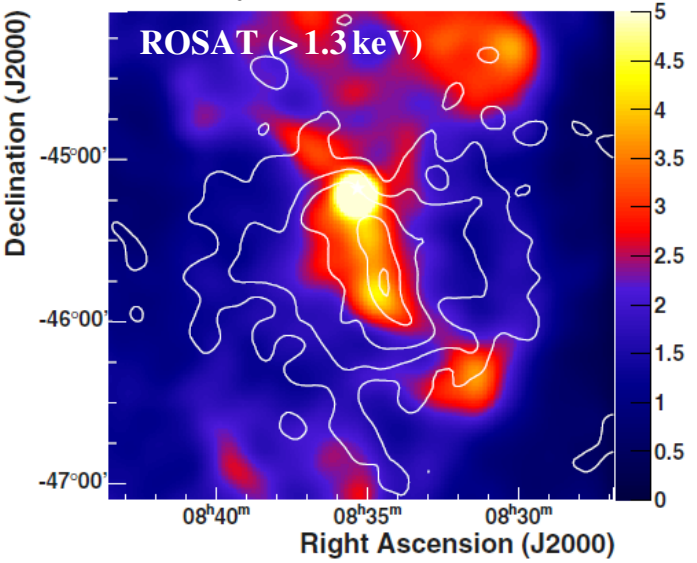




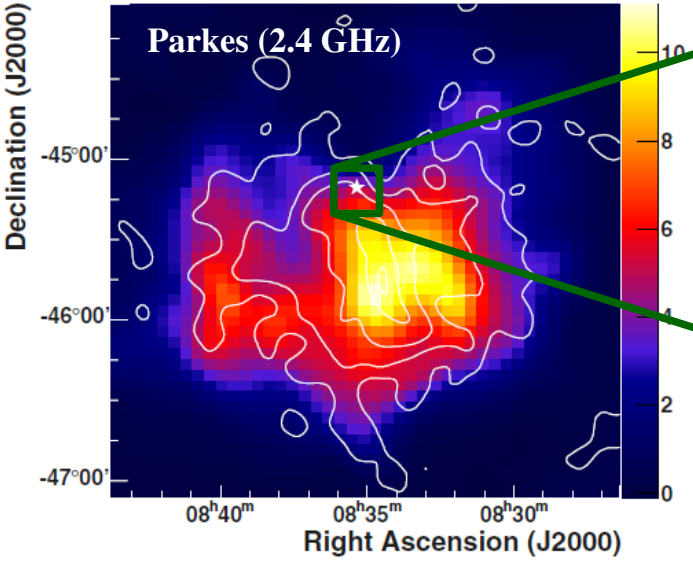


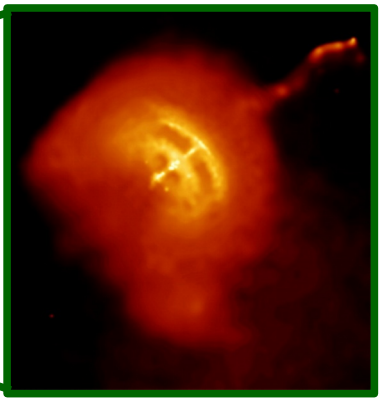
Vela PSR and its wind nebula components

X-ray/TeV « cocoon »



Radio/GeV « halo »

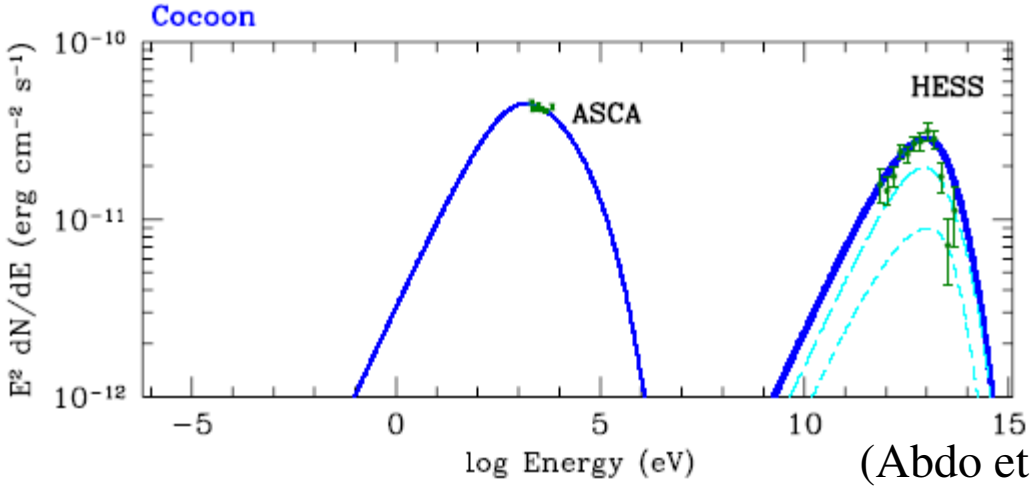


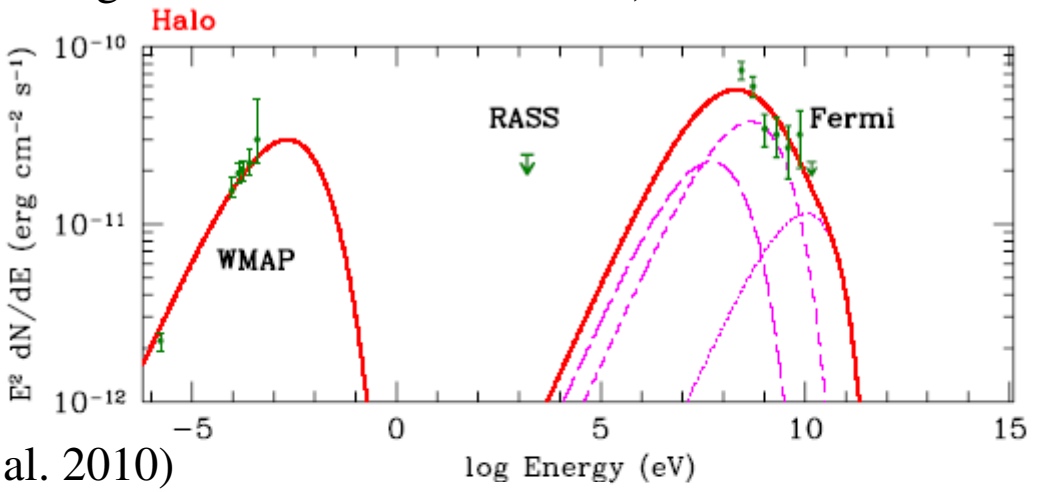


PSR B0833-45

d~290 pc, $\tau_c = 11$ kyr, $\dot{E}_{36} = 7$

Two-component leptonic model (de Jager, Slane & LaMassa 2008)



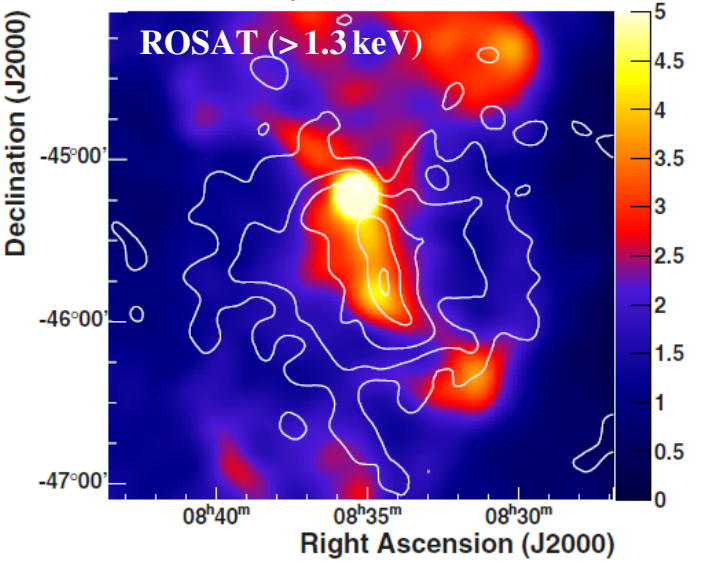


(Abdo et al. 2010)

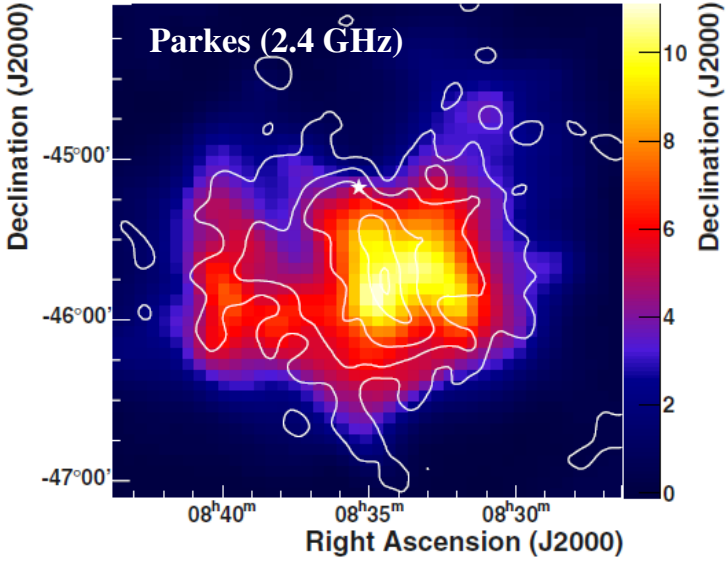
Component	B (μG)	E_c (eV)	Γ	$E_{\rm tot}$ (erg)	χ^2/dof
Halo	$3.93^{+0.46}_{-0.38}$	$1.01^{+0.07}_{-0.13} \times 10^{11}$	$1.97^{+0.02}_{-0.02}$	$5.05^{+0.45}_{-0.56} \times 10^{48}$	10.7/9
Cocoon	$3.80^{+0.10}_{-0.08}$	$5.69^{+0.16}_{-0.33} \times 10^{14}$	$1.998^{+0.003}_{-0.001}$	$1.50^{+0.01}_{-0.05} \times 10^{46}$	57.7/15

Vela PSR and its wind nebula components

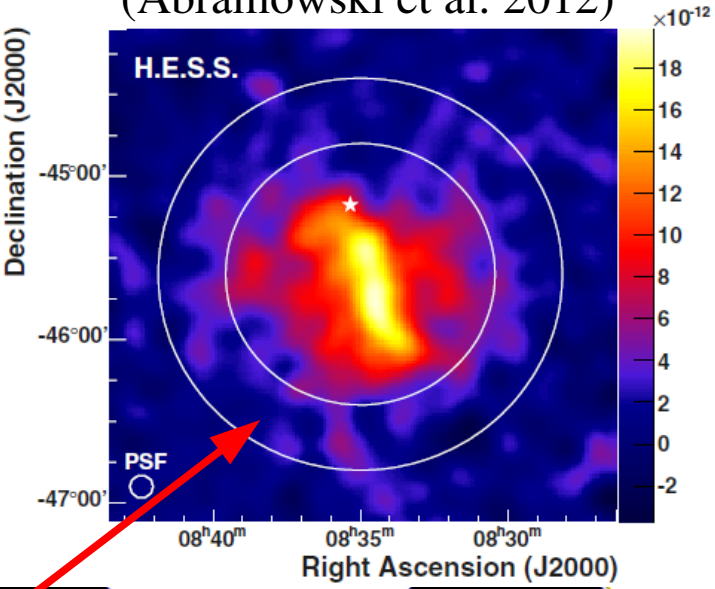
X-ray « cocoon »

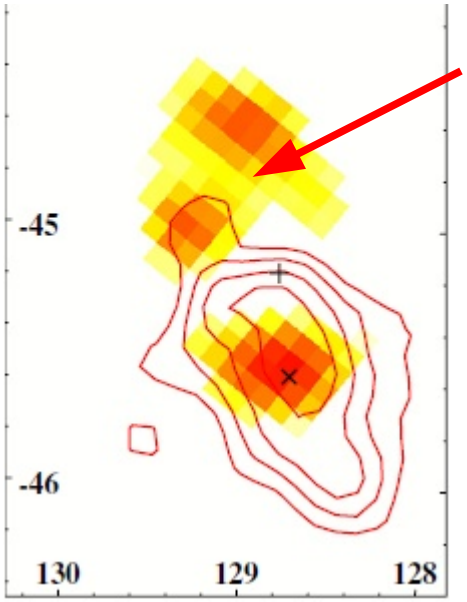


Radio « halo » (Vela X)



(Abramowski et al. 2012)

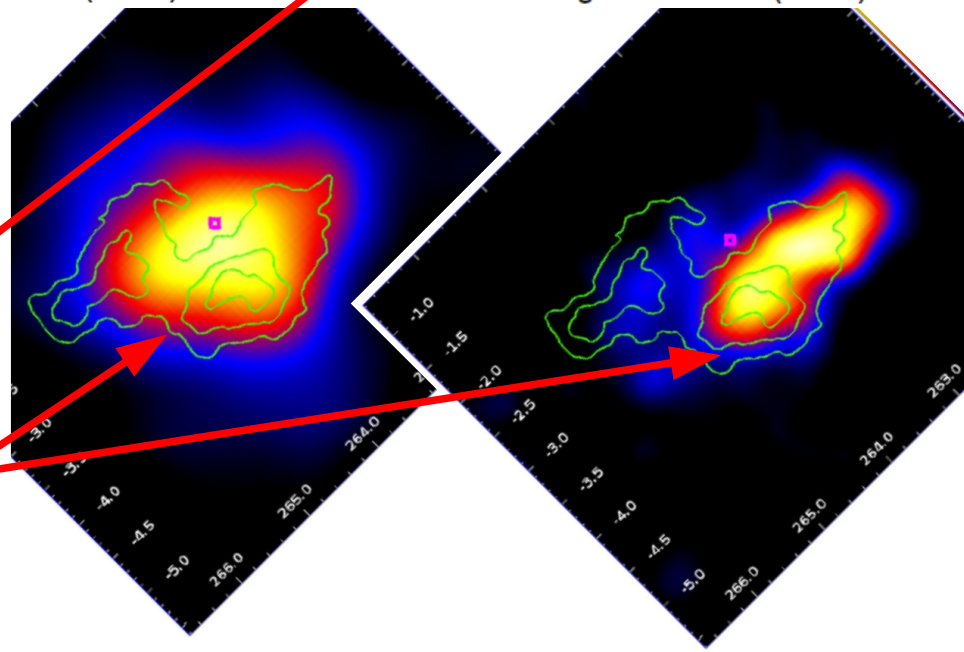




Freshly injected particles after RS passage?

VHE emission from halo with the same spectrum?

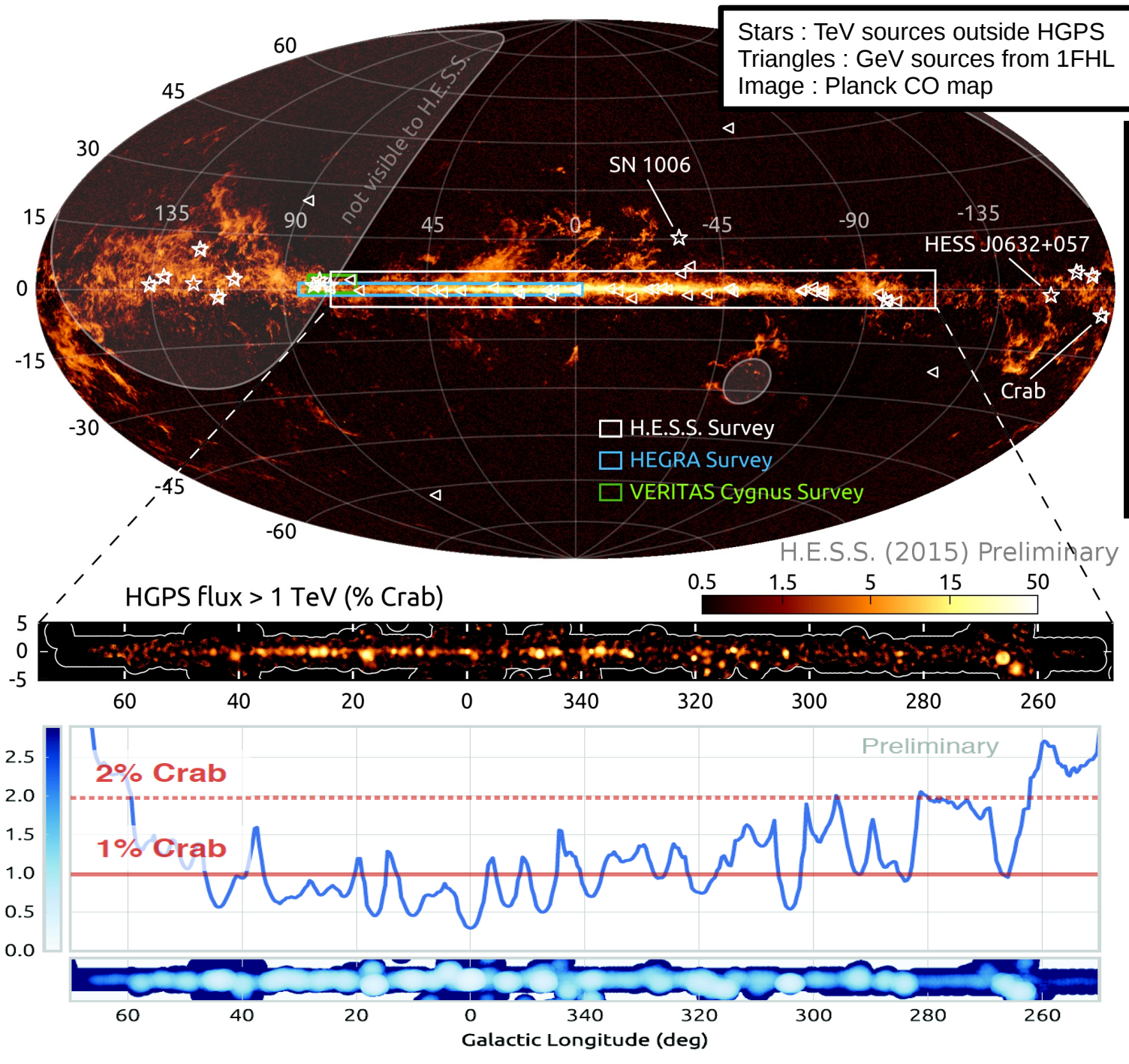
HE morphology changing with energy?

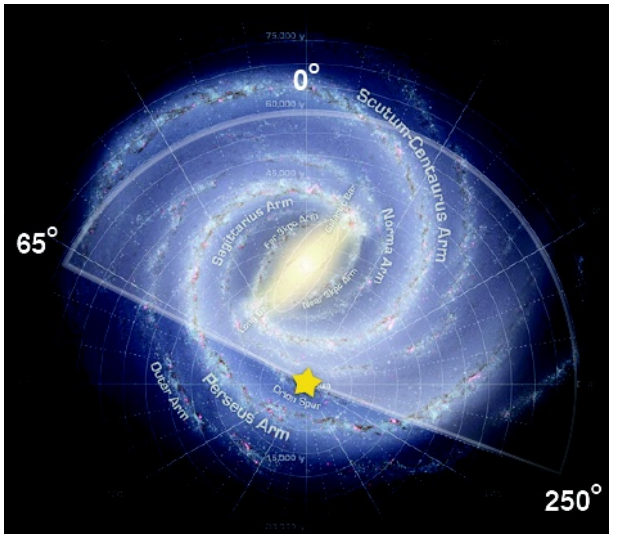


IBIS/ISGRI 18-40 keV PS-substracted image (Mattana et al. 2011, also Katsuda et al. 2011)

Fermi-LAT TS maps: 0.3-1 (left) & 1-100 (right) GeV with *WMAP* 61 GHz contours (Grondin et al. 2013)

H.E.S.S. Galactic Plane Survey (HGPS)

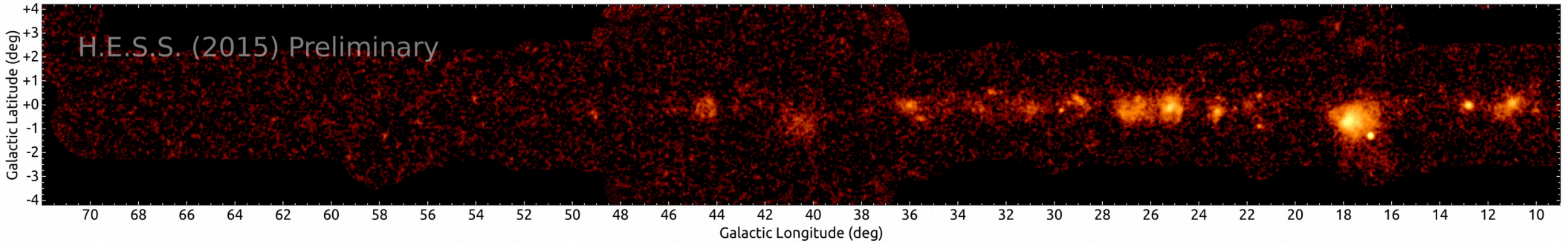


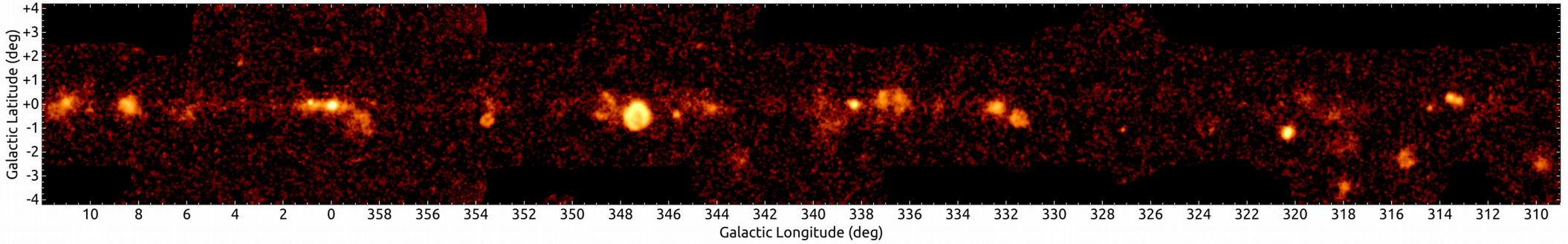


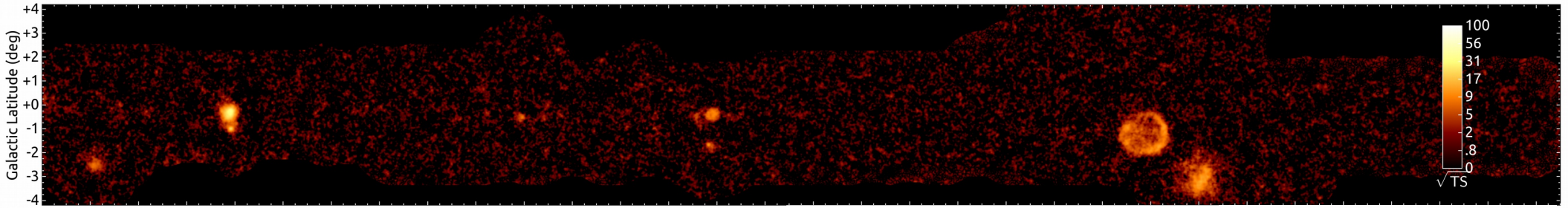
HGPS dataset

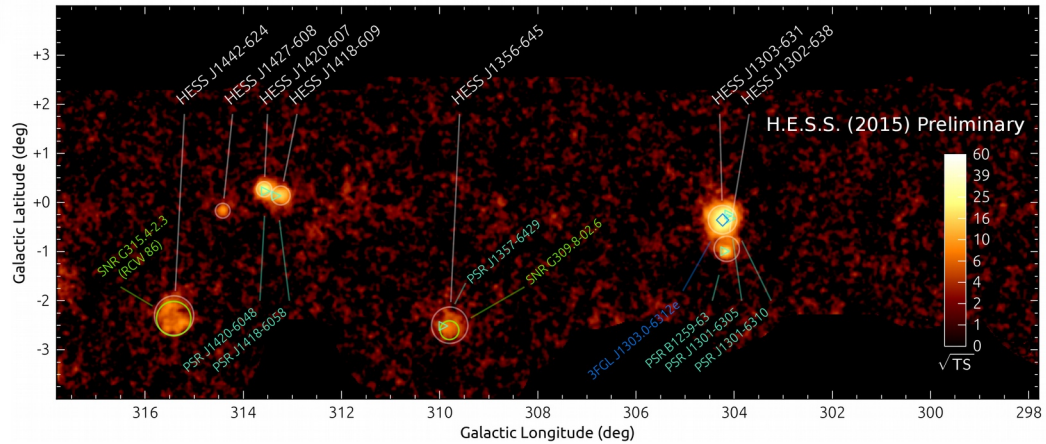
Telescopes	**H.E.S.S. I**
Observations	**2004 to 2013**
Total exposure	**3000 hours**
Sky region	**250° < l < 65°** **-3.5° < b < 3.5°**
Energy range	**0.2 – 100 TeV**
Resolution (R68)	**0.07 deg**

H.E.S.S. Galactic Plane Survey (HGPS)



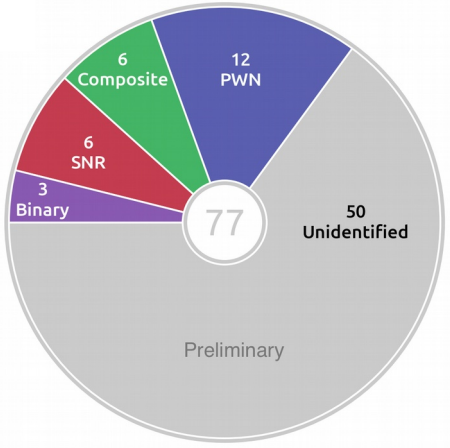




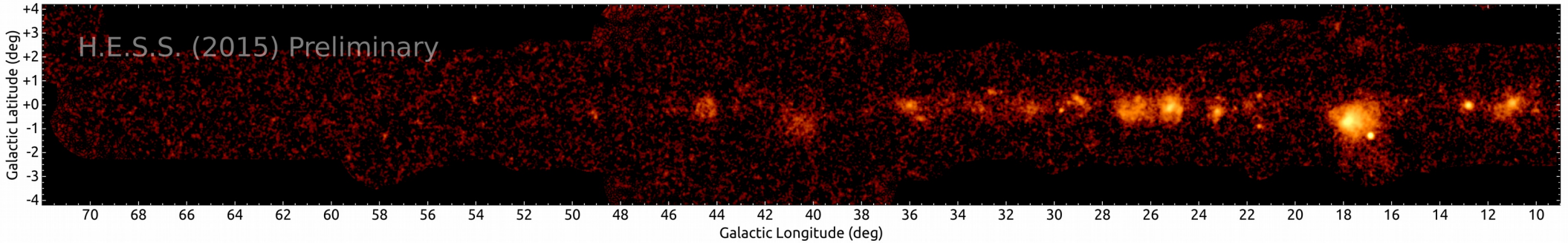


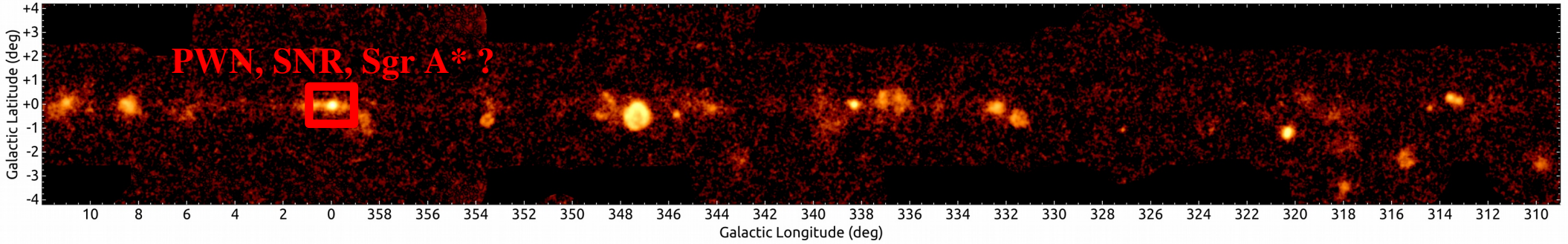
Systematic cross-correlation with PSR, PWN, SNR, GeV

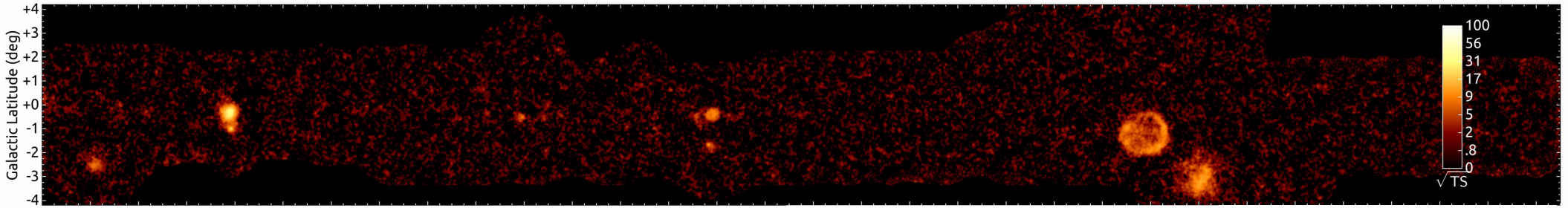
(SNRcat Univ. Manitoba)

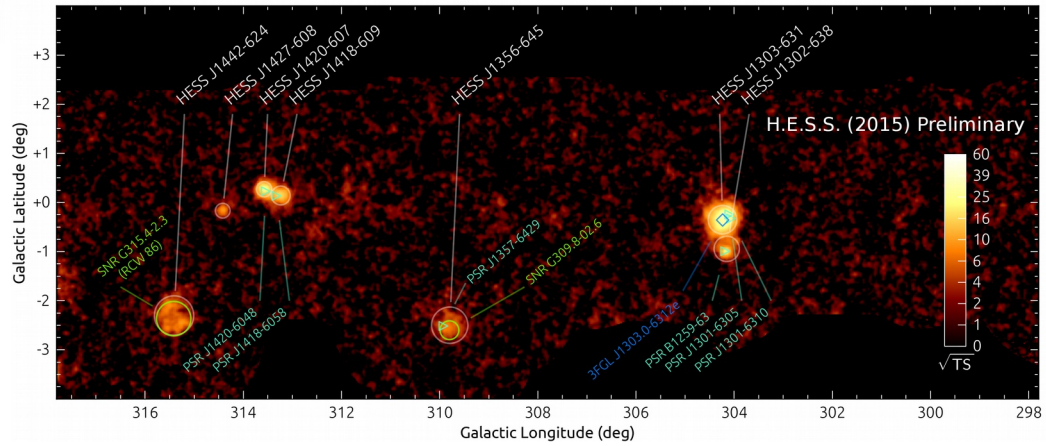


H.E.S.S. Galactic Plane Survey (HGPS)



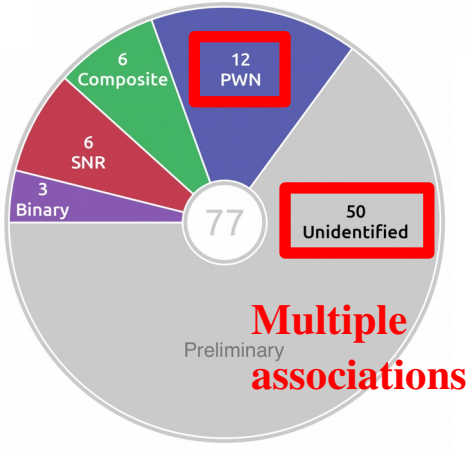




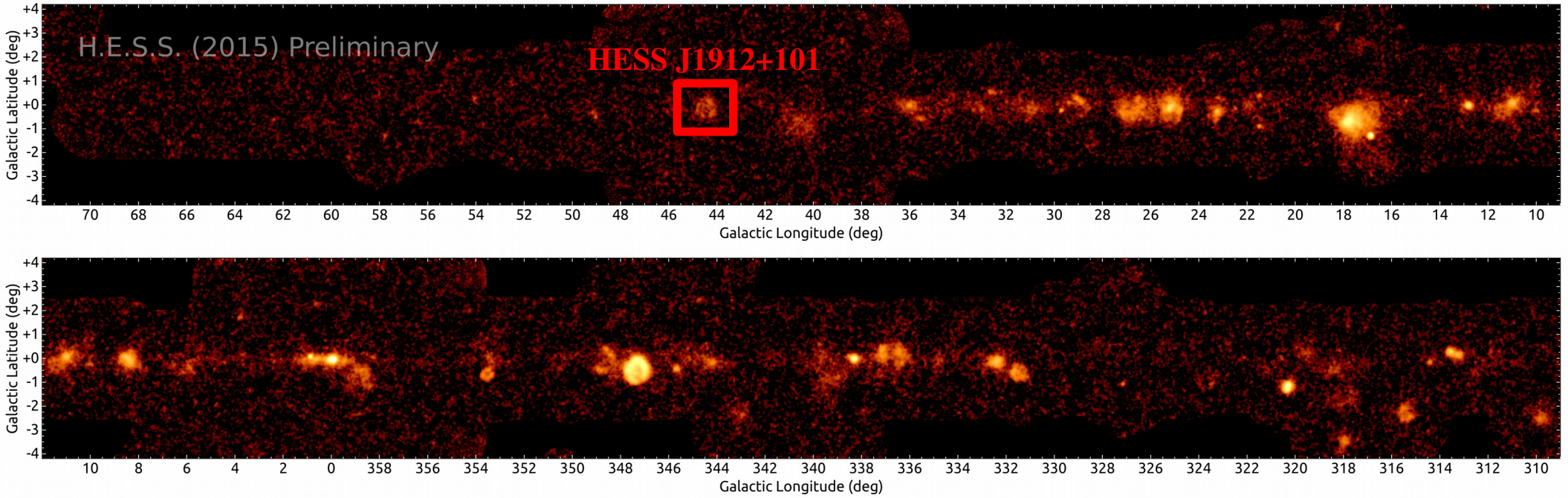


Systematic cross-correlation with PSR, PWN, SNR, GeV

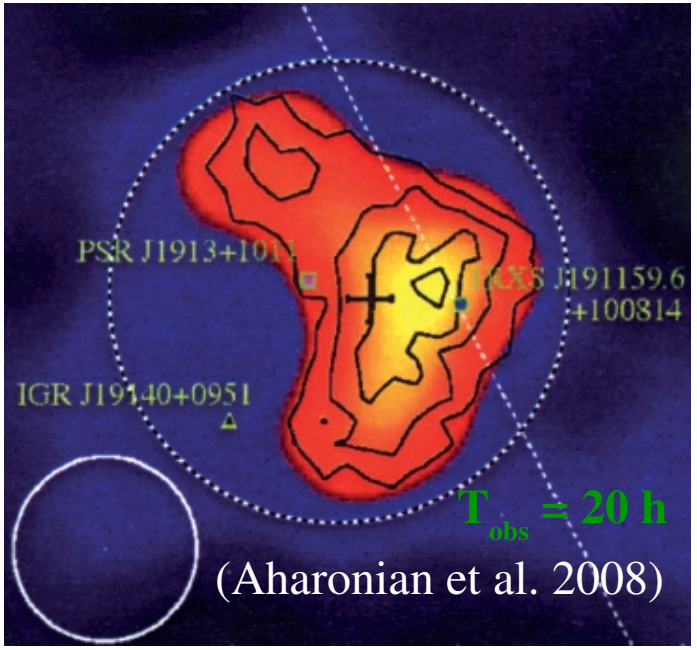
(SNRcat Univ. Manitoba)



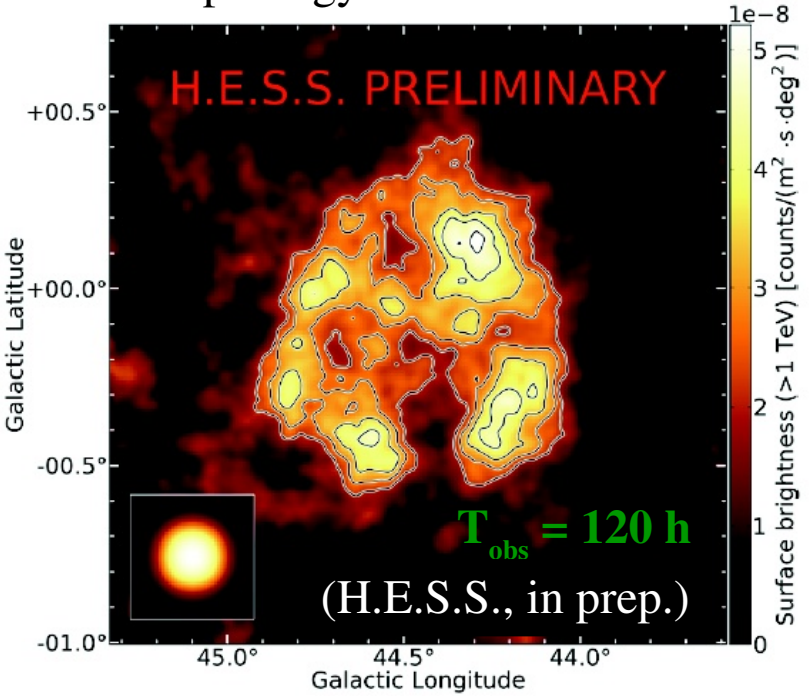
H.E.S.S. Galactic Plane Survey (HGPS)



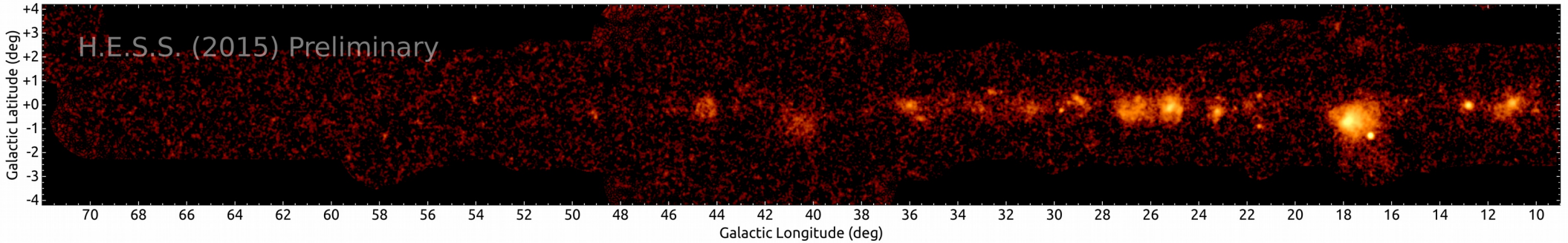
Nebula of PSR J1913+1011 (τ_c=170 kyr, $\dot{E}_{36}$=2.9)?

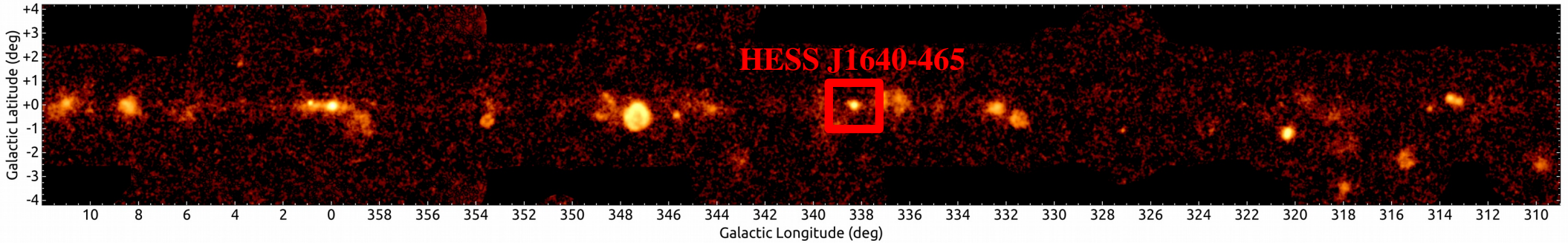


Shell morphology → TeV SNR candidate!

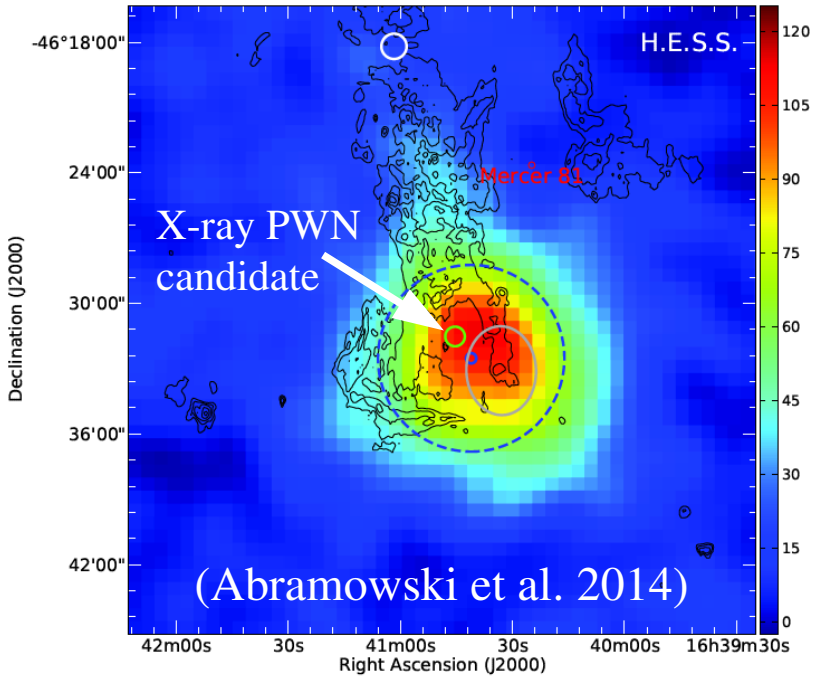


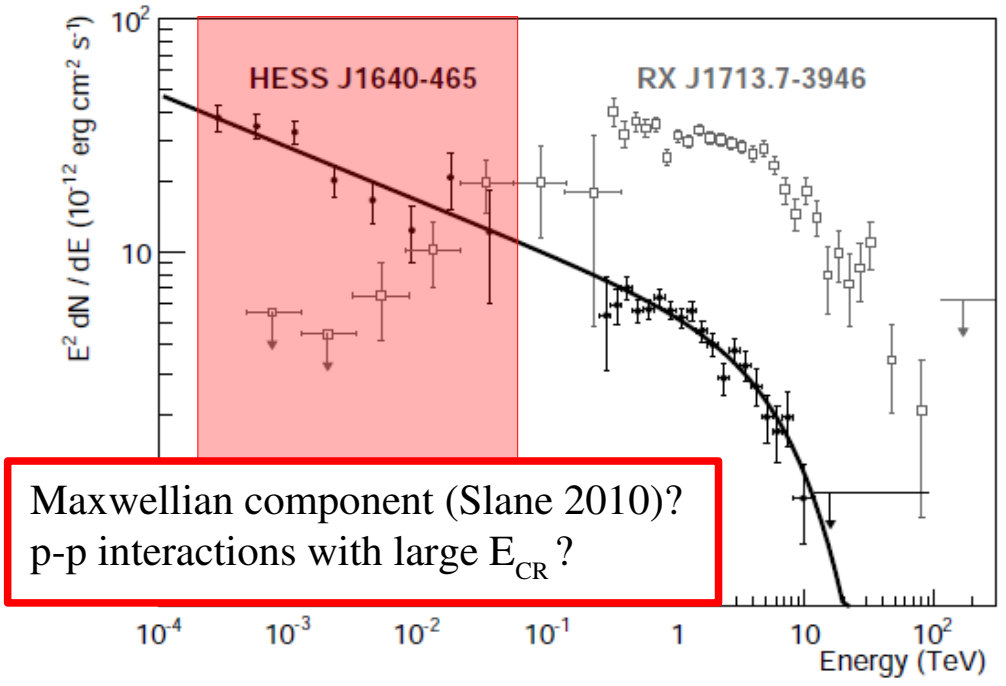
H.E.S.S. Galactic Plane Survey (HGPS)





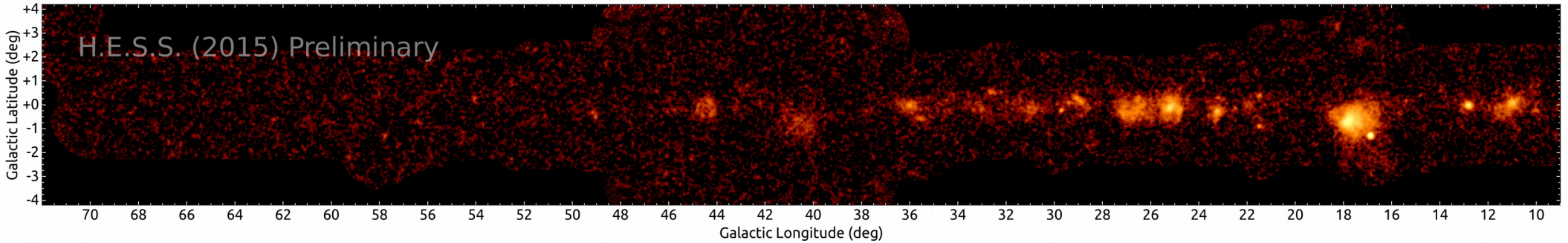
Exceptionally luminous TeV SNR?

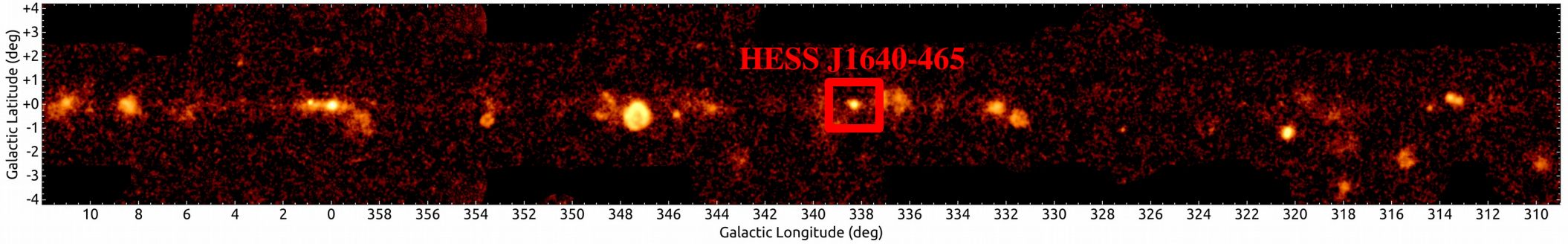




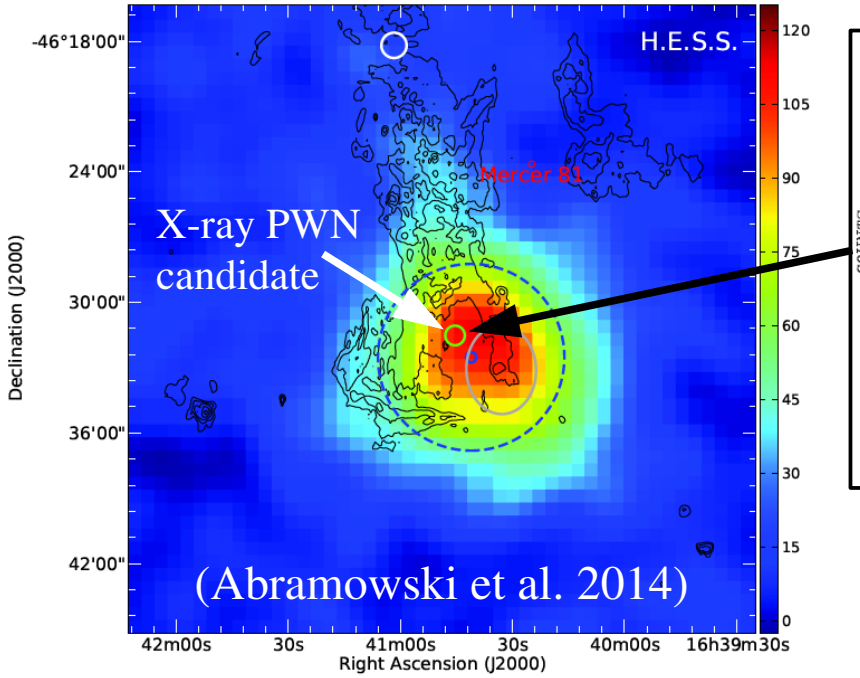
Maxwellian component (Slane 2010)?
p-p interactions with large E_{CR} ?

H.E.S.S. Galactic Plane Survey (HGPS)

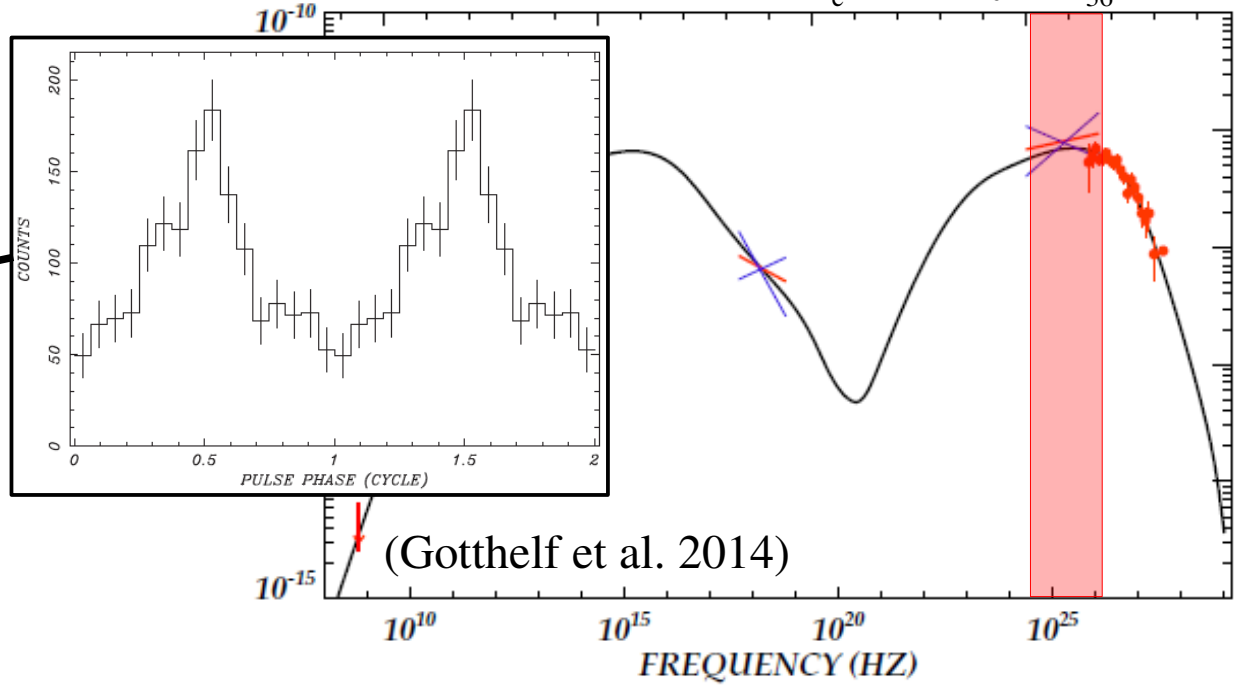




Exceptionally luminous TeV SNR?



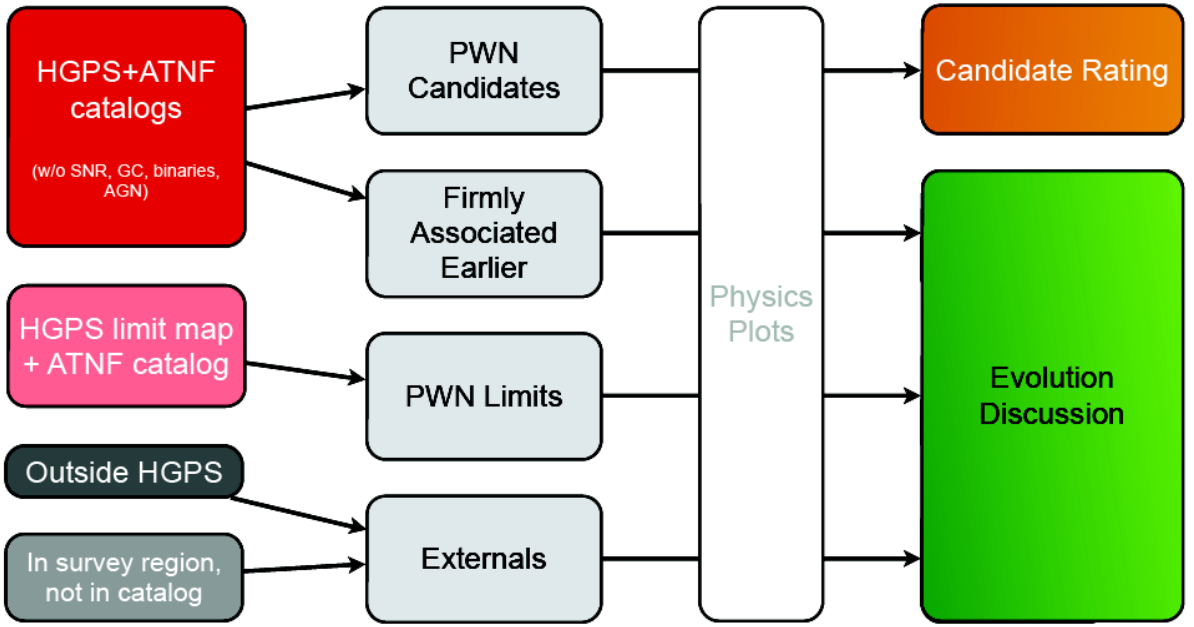
Nebula of PSR J1640-4631 (τ_c=3.35 kyr, $\dot{E}_{36}$=4.4)?

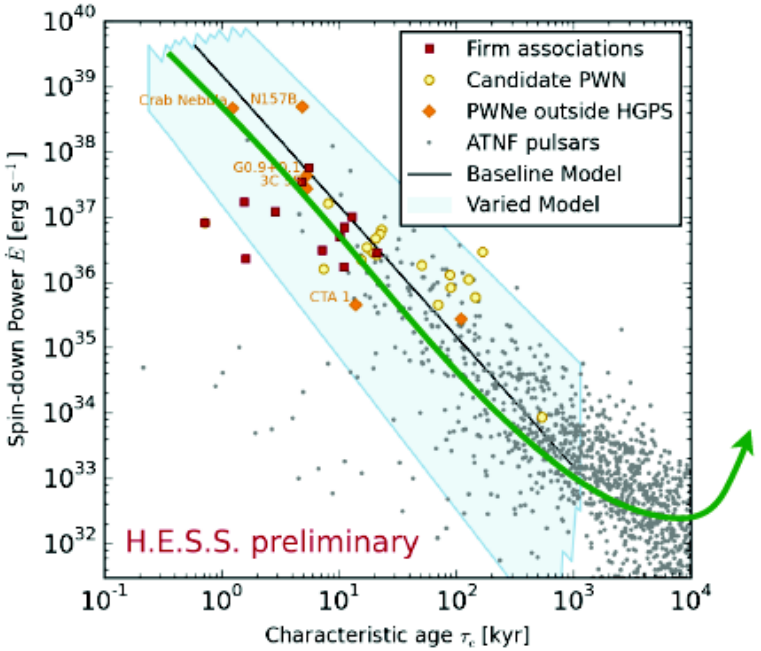


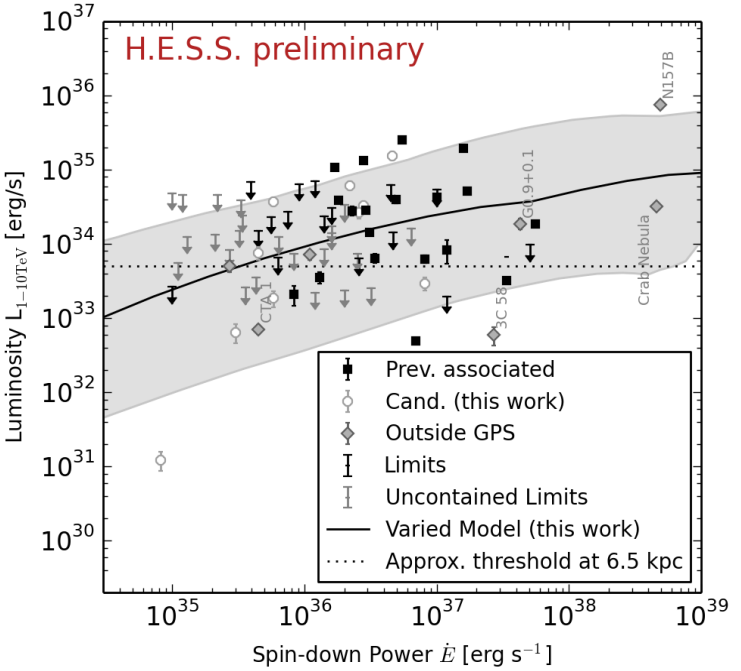
Population of TeV PWNe from the HGPS

Census of all the PWNe detected & upper limits derived in a consistent way

(N.B. : HGPS is not a uniform-exposure survey...)







γ-ray PWNe associated with young/energetic PSRs ($\dot{E}_{35} > 1$)

– GeV: 6 (~10) PWNe (candidates) with $L_{GeV}/\dot{E} < 0.1$

– TeV: ~30 (~10) PWNe (candidates) + UnId "*Dark*" sources

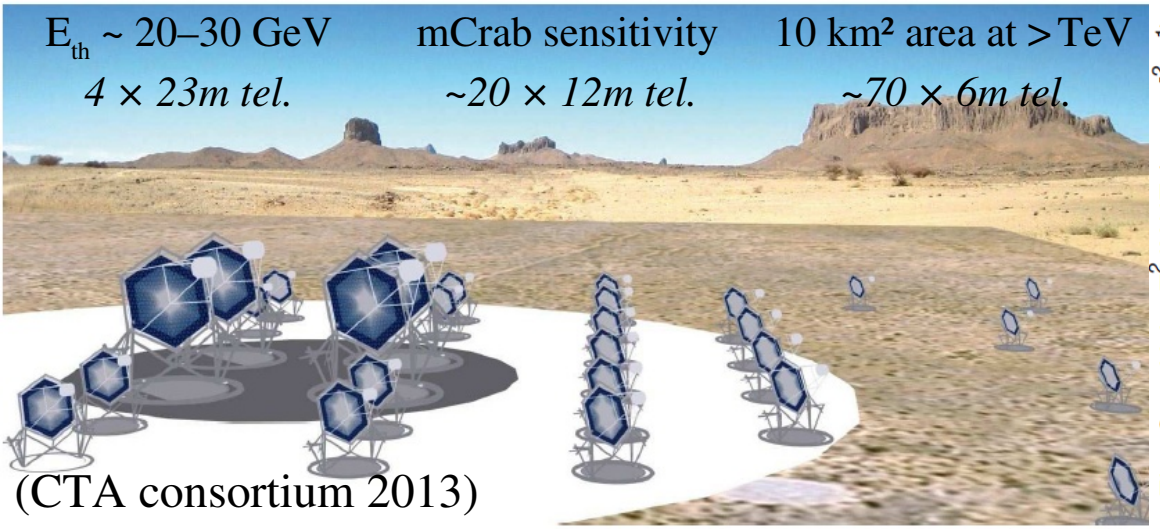
Comparison of TeV and X-ray properties of Galactic PWNe
(see Kargaltsev & Pavlov 2010, Kargaltsev et al. 2012 ; 2013)

Perspectives with CTA

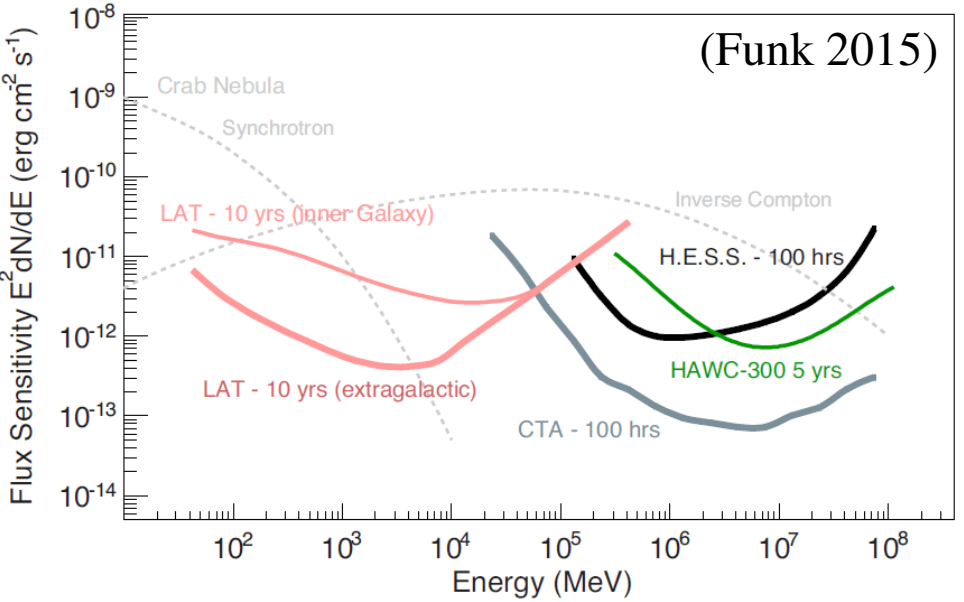
Low-energy | **Medium-energy** | **High-energy**

E_{th} ~ 20–30 GeV | mCrab sensitivity | 10 km² area at >TeV

4 × 23m tel. | *~20 × 12m tel.* | *~70 × 6m tel.*



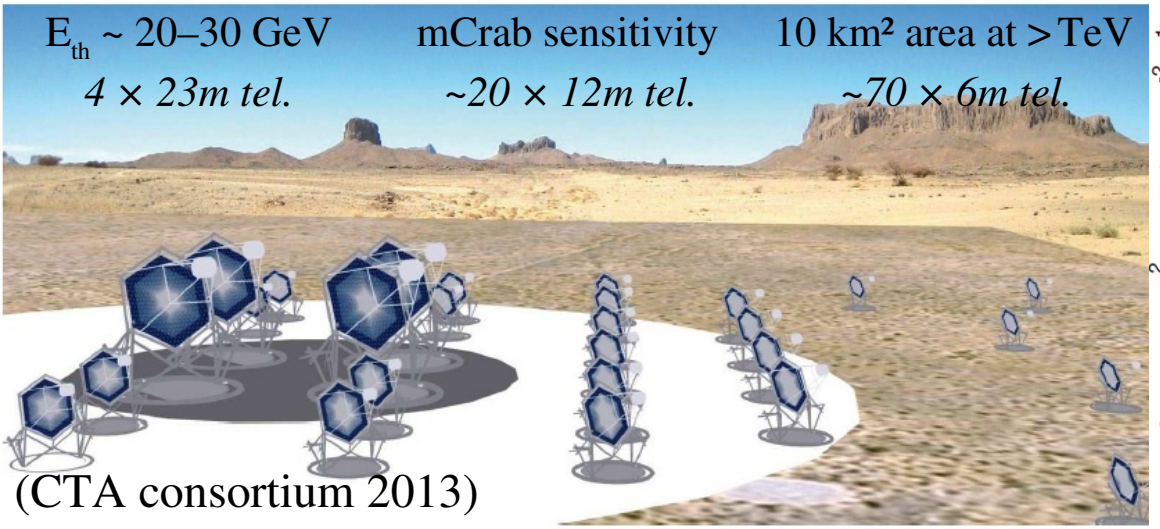
(CTA consortium 2013)



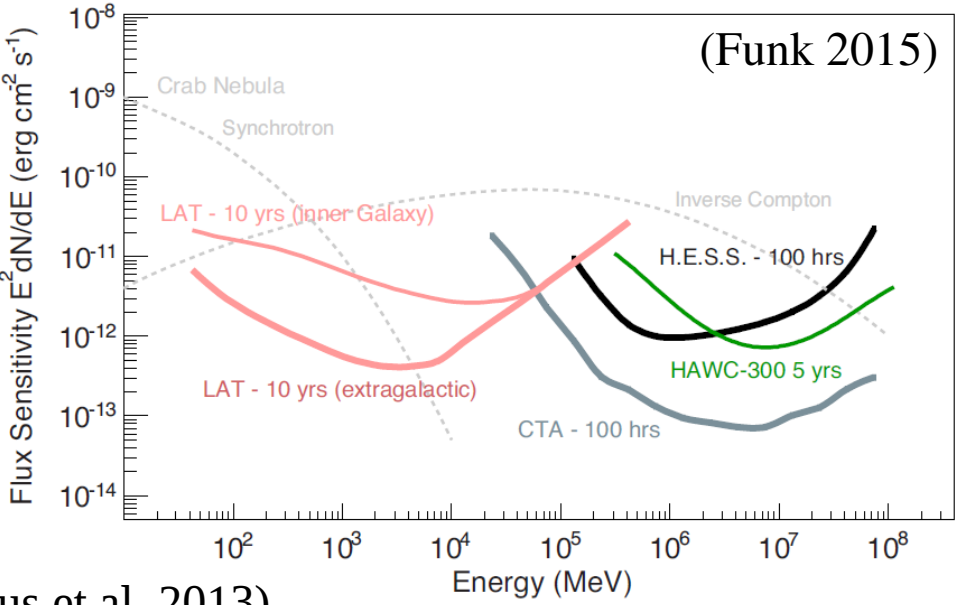
Pre-construction phase → end of 2016
Pre-production phase → 2017-2018
Production phase → 2019-2024

Perspectives with CTA

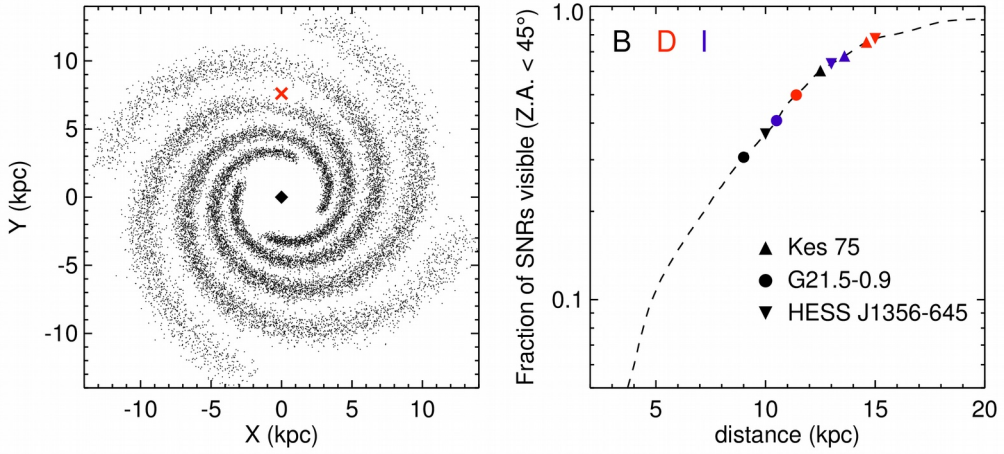
Low-energy | **Medium-energy** | **High-energy**



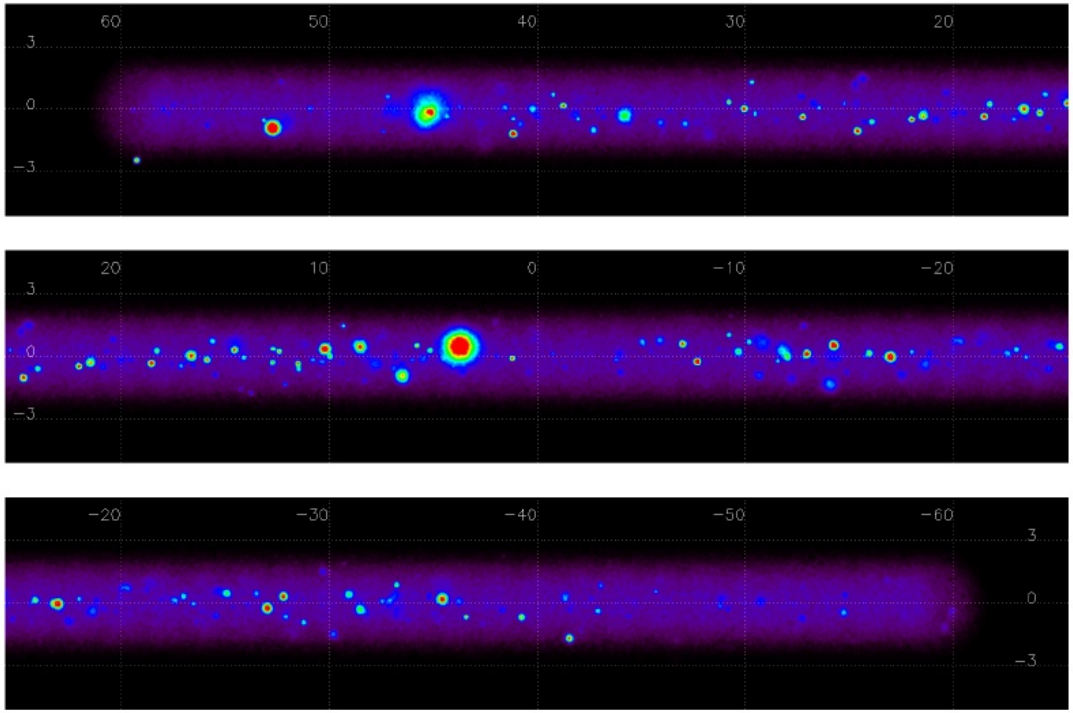
(CTA consortium 2013)



(de Ona-Wilhelmi et al. 2013)



(Dubus et al. 2013)



Faint PWNe detectable to 10 – 15 kpc

τ_{TeV} ~ 40 kyr (B=3 μG) → **~200-400 PWNe!**

→ **source confusion in the inner Galaxy**

→ **E-dependent morphology to identify them**

Concluding remarks

- Importance of PSR/PWN studies:
  - CR positron « excess » measured by PAMELA & AMS-02 (e.g. Blasi & Amato 2010)
  - Wind Nebulae of newly born msec PSRs as sources of UHECRs ? (Lemoine et al. 2015)

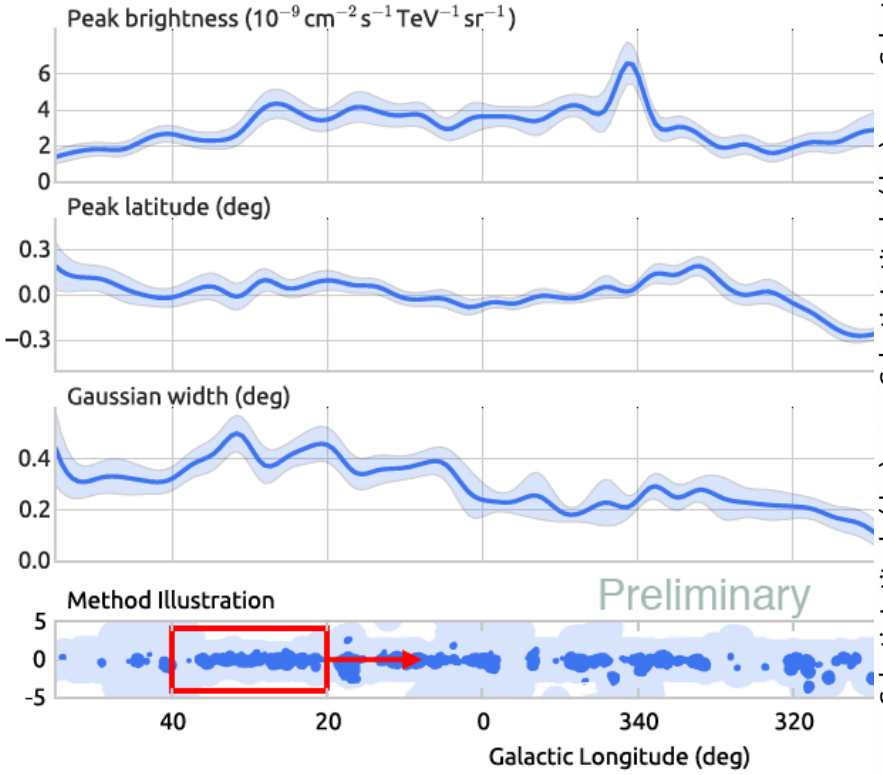
- Modeling :
  - Need for 3D HD/spectral models to be confronted to spectro-morphological measurements
  - How/When can the CR electrons/positrons leave the system?

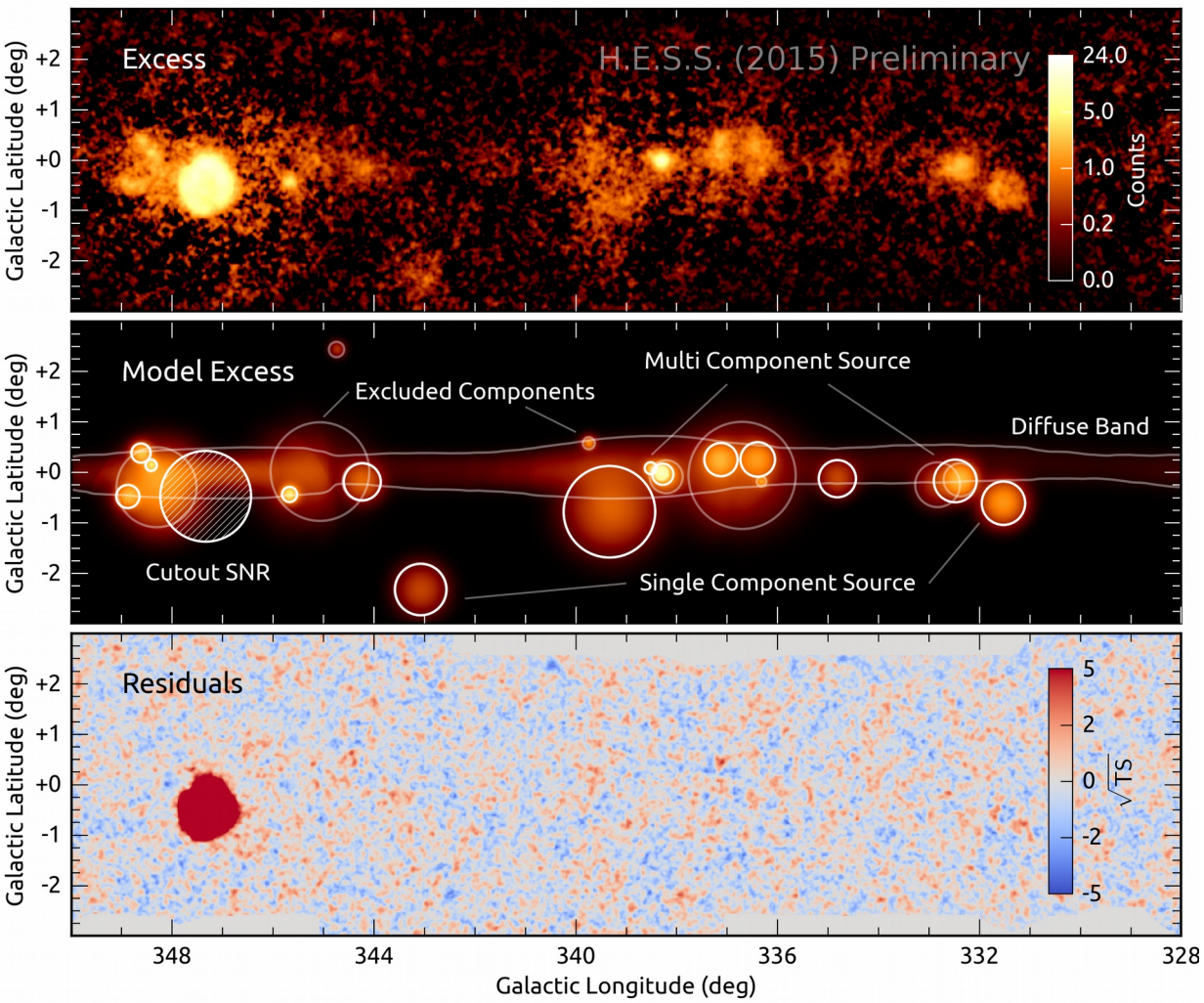
- Observations :
  - Difficulties in the identification of gamma-ray PWNe
  - Puzzling Vela X... and particle escape ? (Hinton et al. 2011, della Torre et al. 2015)
  - Perspectives with CTA : hundreds of PWNe $\rightarrow$ source confusion
  - E-dependent morphology to mitigate this effect & to identify them as PWNe

H.E.S.S. Galactic Plane Survey (HGPS)

New morphology model

– Cut out SNRs and GC (**13** sources)
– Large-scale unresolved Gaussian band model





– 100 Gaussian components (TS > 30)
– **64** sources (re-)analyzed

→ HGPS catalog: 77 sources