Physics and Astrophysics of cosmic rays

VIth CNRS thematic school of Astroparticle physics, OHP, November 2019

Justine Devin

Centre d'Études Nucléaires de Bordeaux Gradignan - CNRS/IN2P3

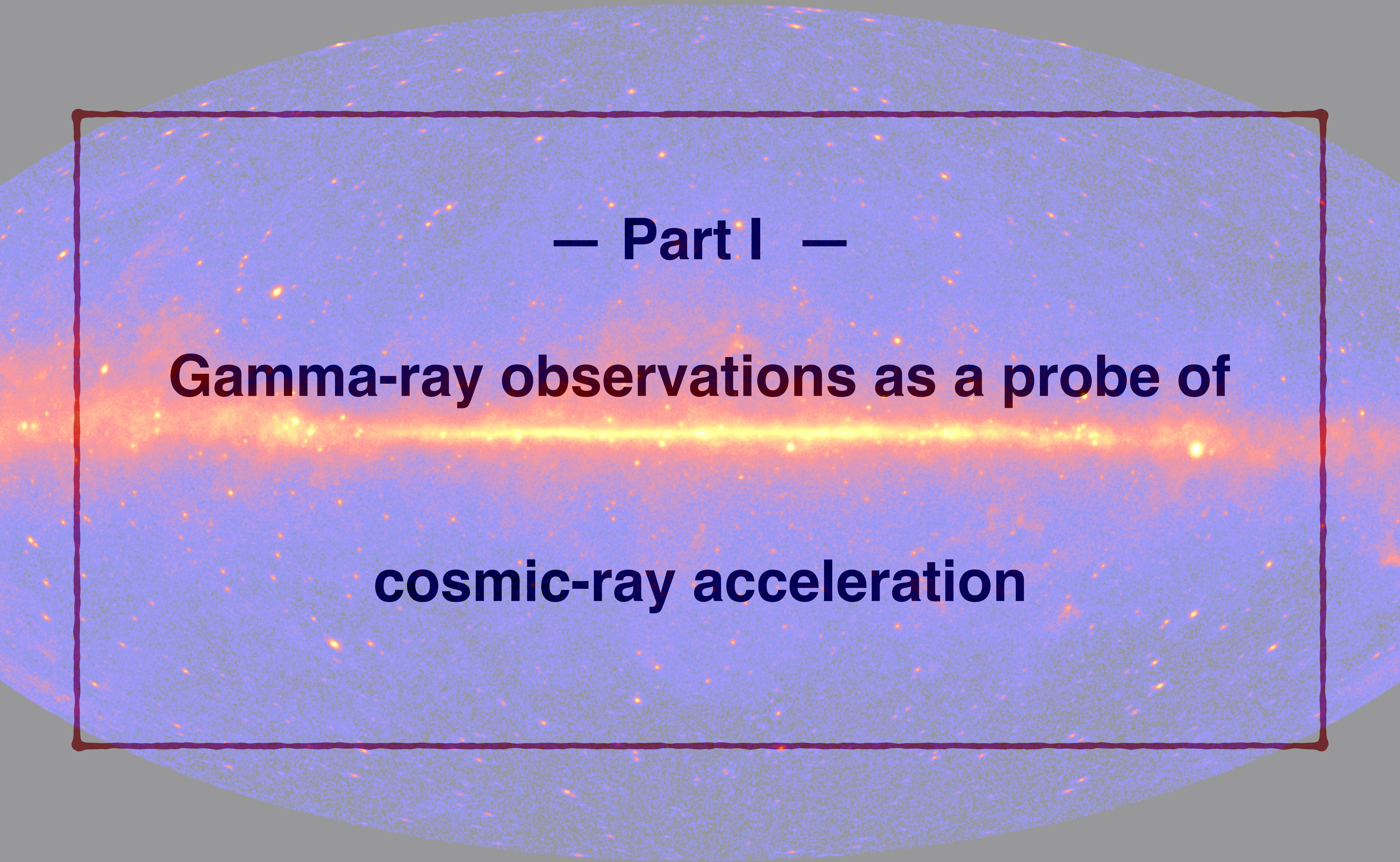
CHASING GALACTIC COSMIC-RAY SOURCES WITH GAMMA RAYS

I. **Gamma-ray observations as a probe of cosmic-ray acceleration**

II. **Identification of gamma-ray sources**
   1. **Methods**
   2. **Difficulties**

III. **Identification and analysis of the gamma-ray emission from a composite supernova remnant**

IV. **Searching for PeVatrons in the Galaxy**



— Part I —

Gamma-ray observations as a probe of

cosmic-ray acceleration

Gamma-ray astronomy: a recent field

Space-based gamma-ray astronomy

- First gamma-ray detection: 1958 (Peterson & Winckler)
- 22 events detected with *Explorer 11* (Kraushaark & Clark 1962)

(~ 50 MeV—500 GeV)

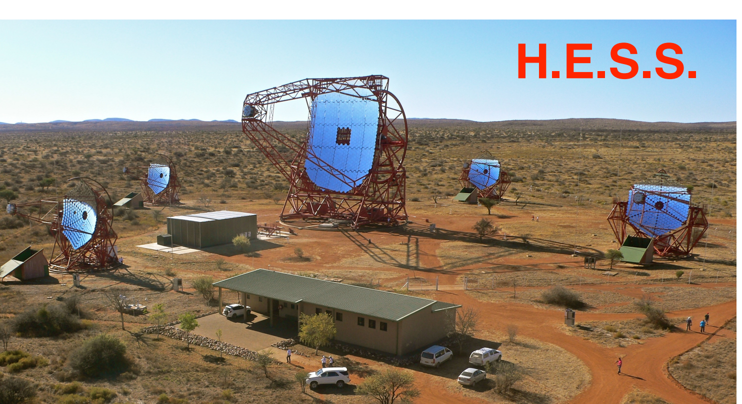
Ground-based gamma-ray astronomy

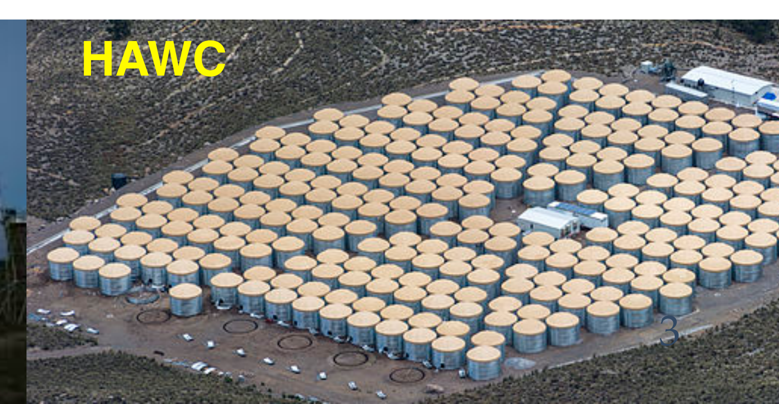
(~ 50 GeV—100 TeV)

- 1968: Whipple - first detection of the Crab pulsar at these enegies (Weekes et al 1989)

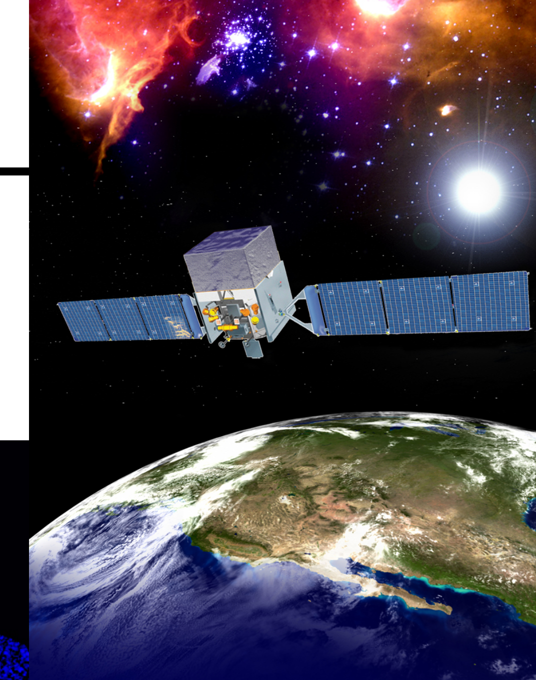
Southern sky

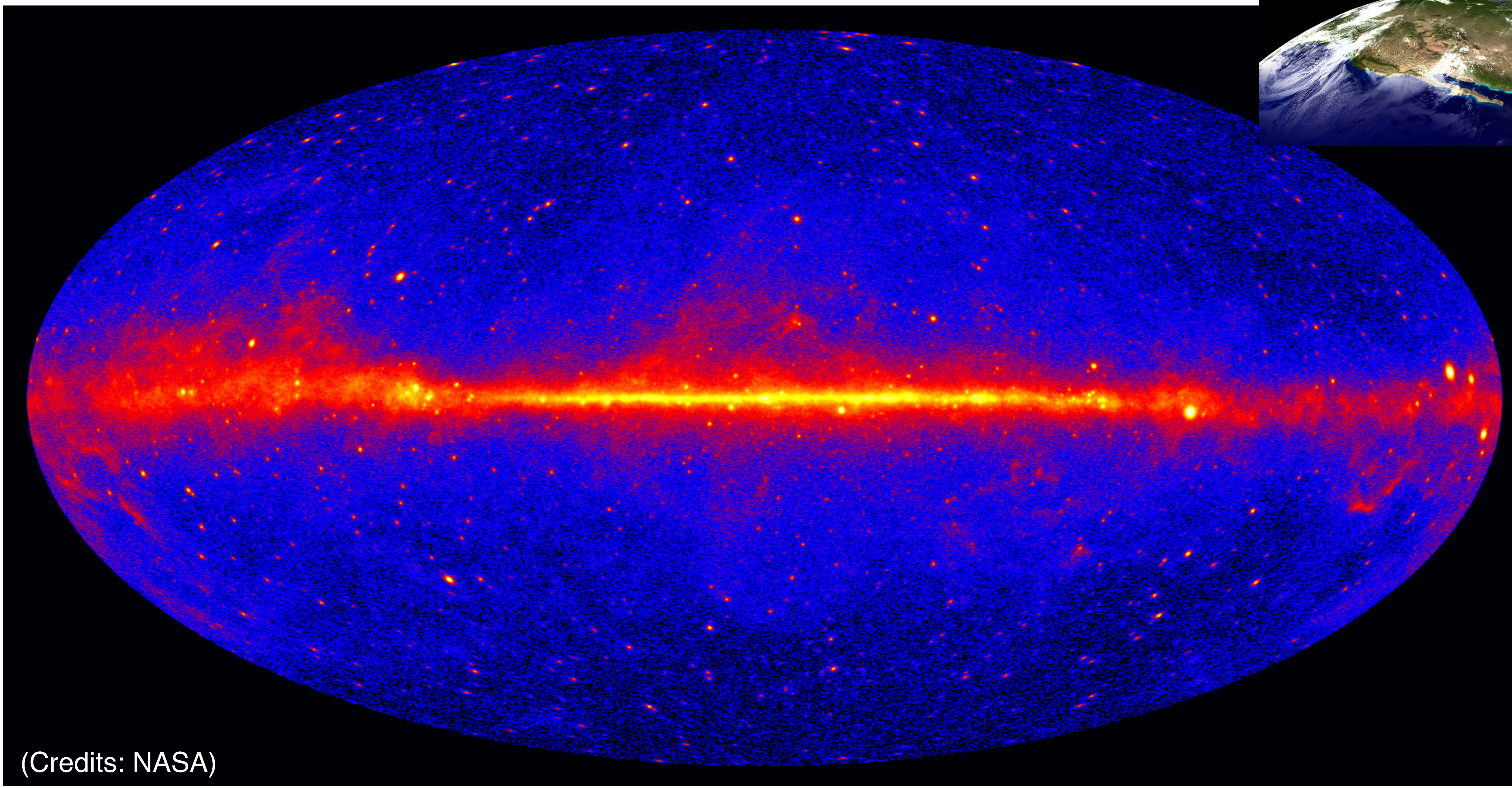
Northern sky





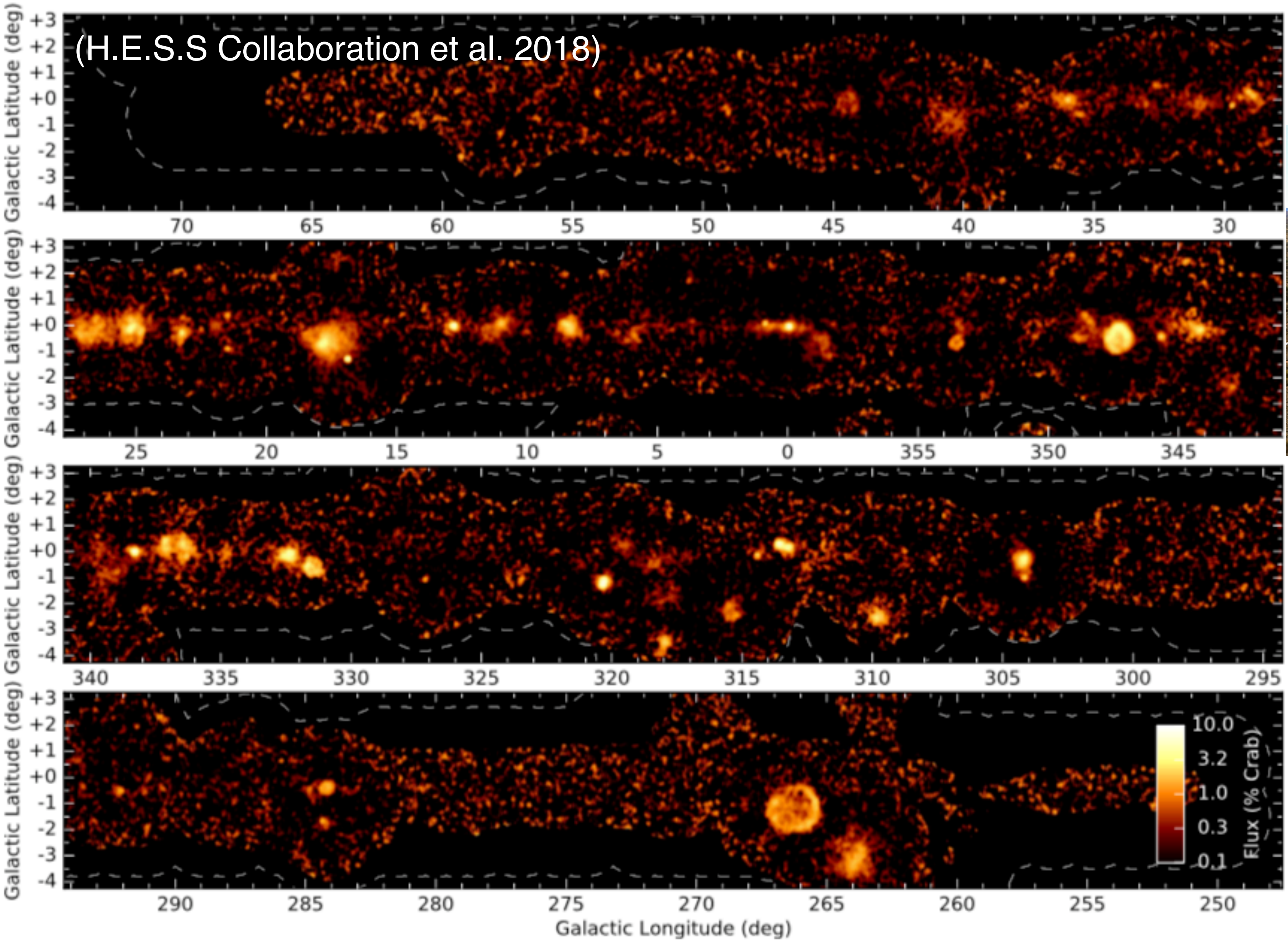
The GeV sky as seen with the Fermi-LAT

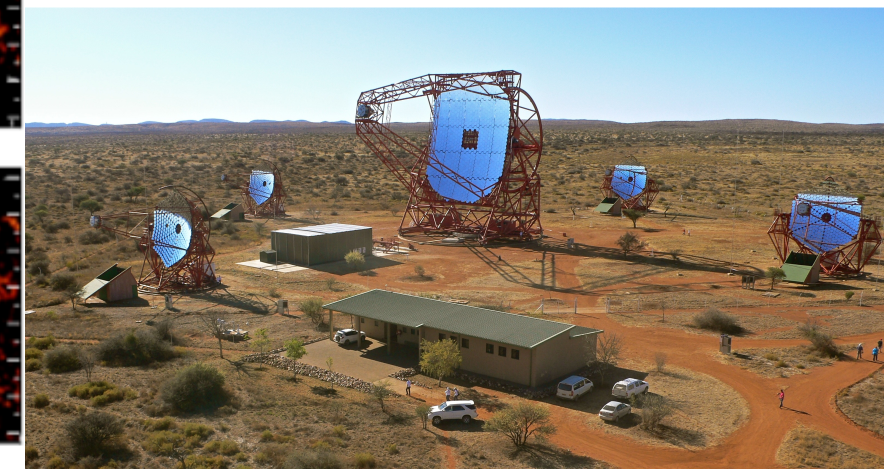




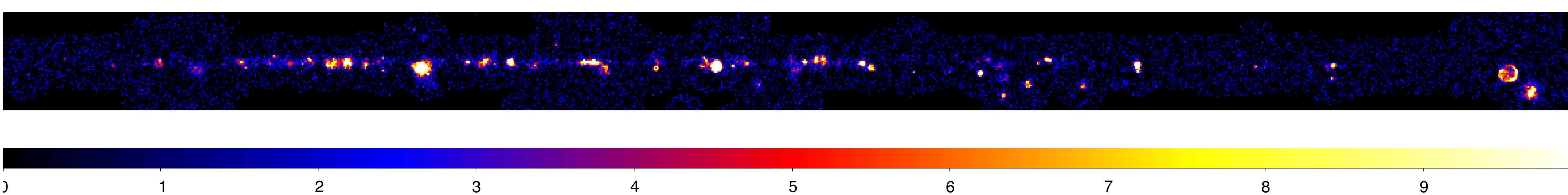
Count map for E > 1 GeV (5 years of Fermi-LAT data)

The Galactic TeV sky as seen with H.E.S.S





Integral flux (E > 1 TeV) in units of % Crab



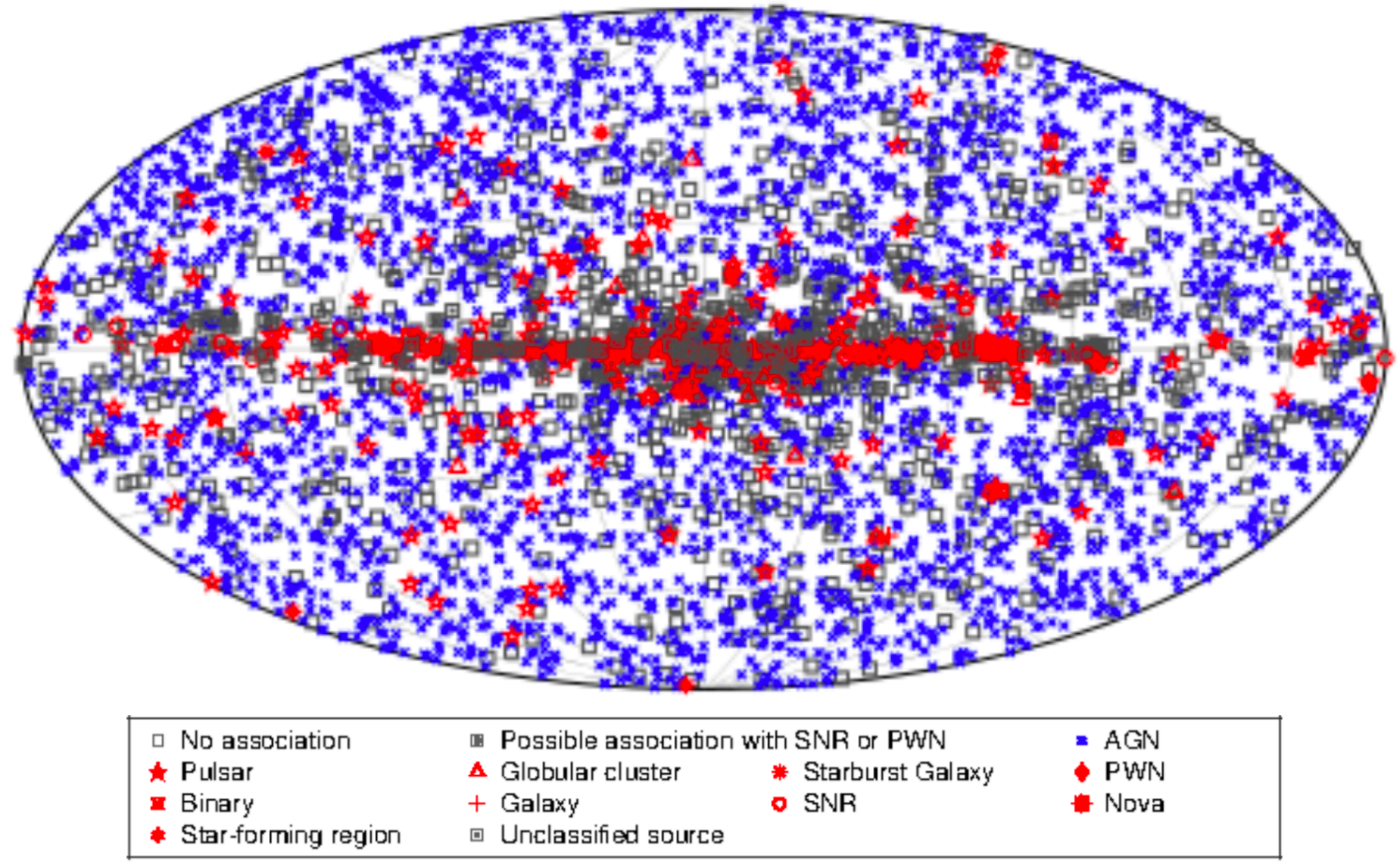
Significance (0 — 10)

The gamma-ray sky

The GeV catalog (High energy, HE)

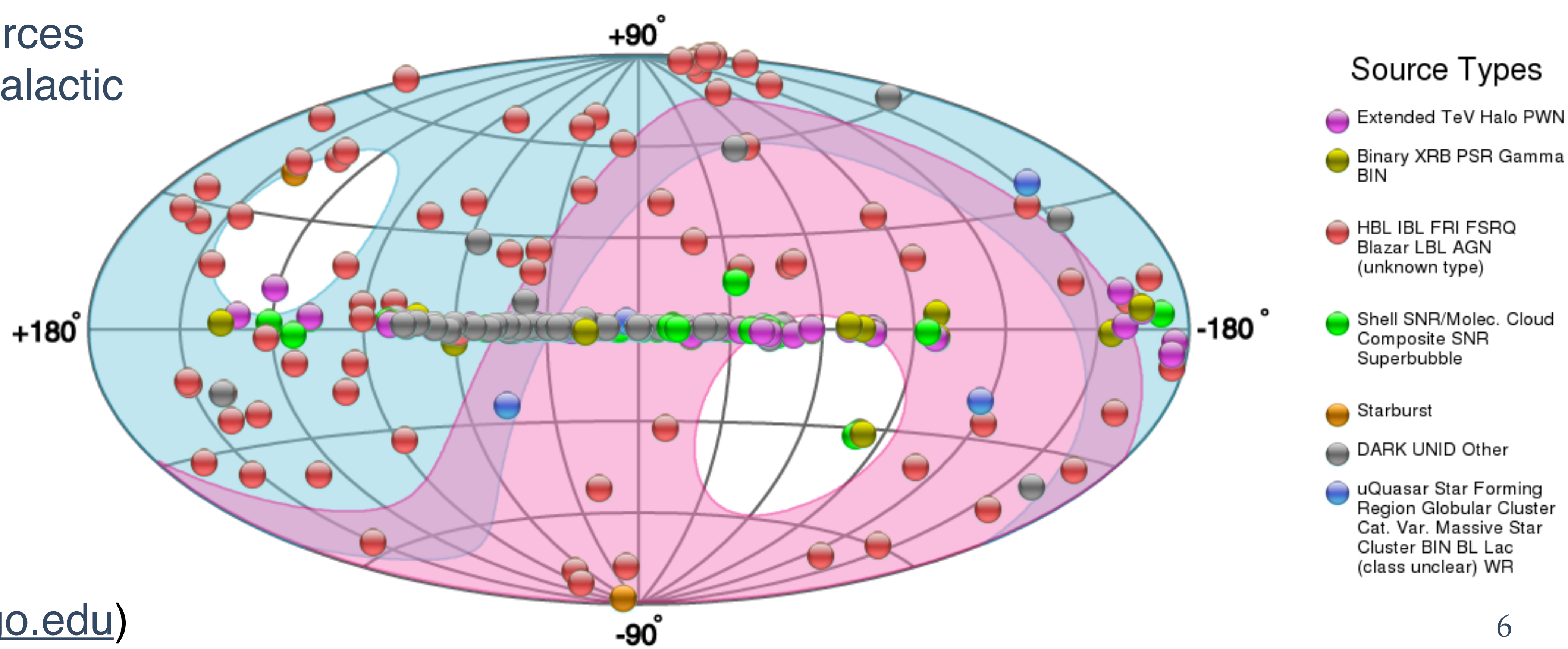
- 5065 sources
- 75 extended sources
- 1337 with no counterparts
- more than 3130 blazars
- 239 pulsars

(Fermi-LAT collaboration, 2019)



The TeV catalog (Very high energy, VHE)

- More than 200 sources
- Majority are extragalactic
- 39 2HWC sources
- 78 HGPS sources



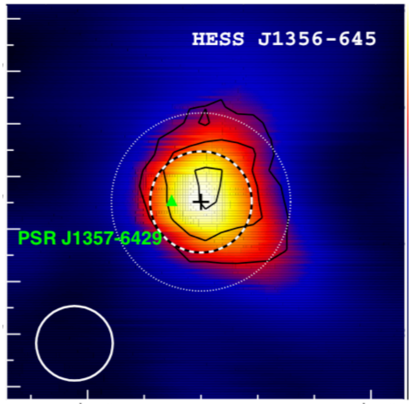
(http://tevcat2.uchicago.edu)

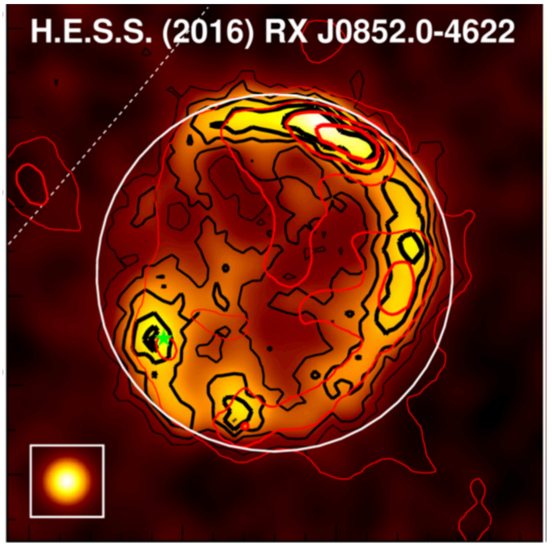
Gamma-ray emitting sources in the Galaxy

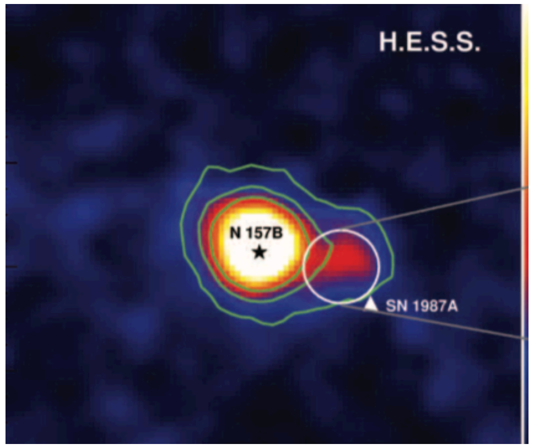
- Supernova remnants (SNRs)
- Pulsars and their nebulae (PSRs, PWNe)

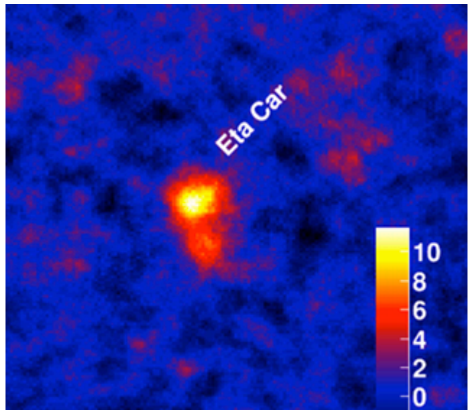
→ Particular focus on these sources; Best candidates to accelerate Galactic cosmic rays (up to ~ 3 x 10^{15} eV)

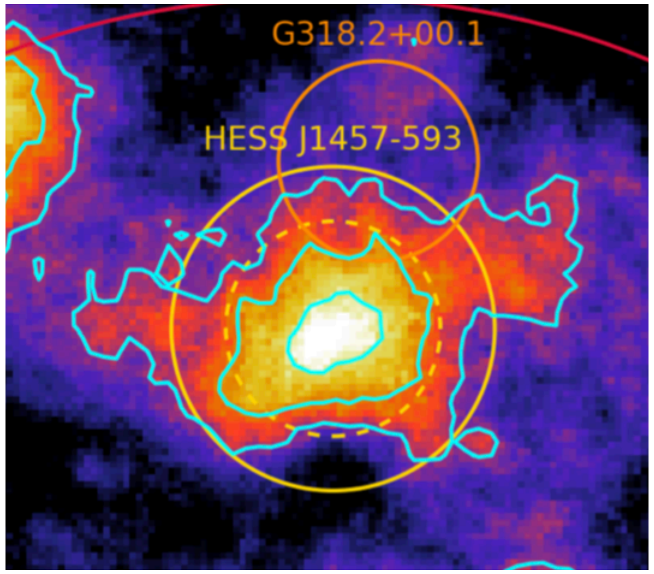
- Star forming regions and Superbubbles
- Binaries
- Diffuse emission





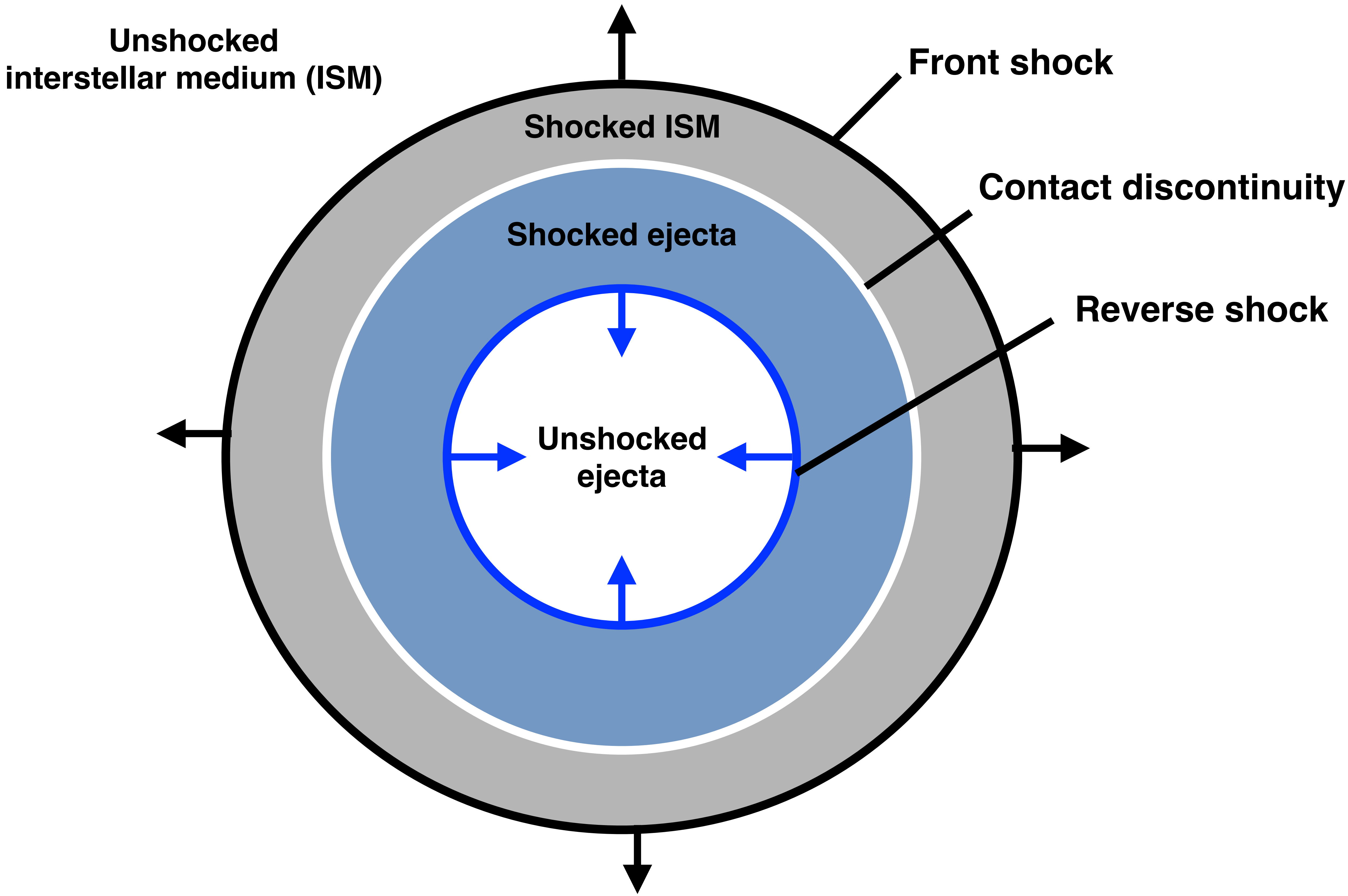






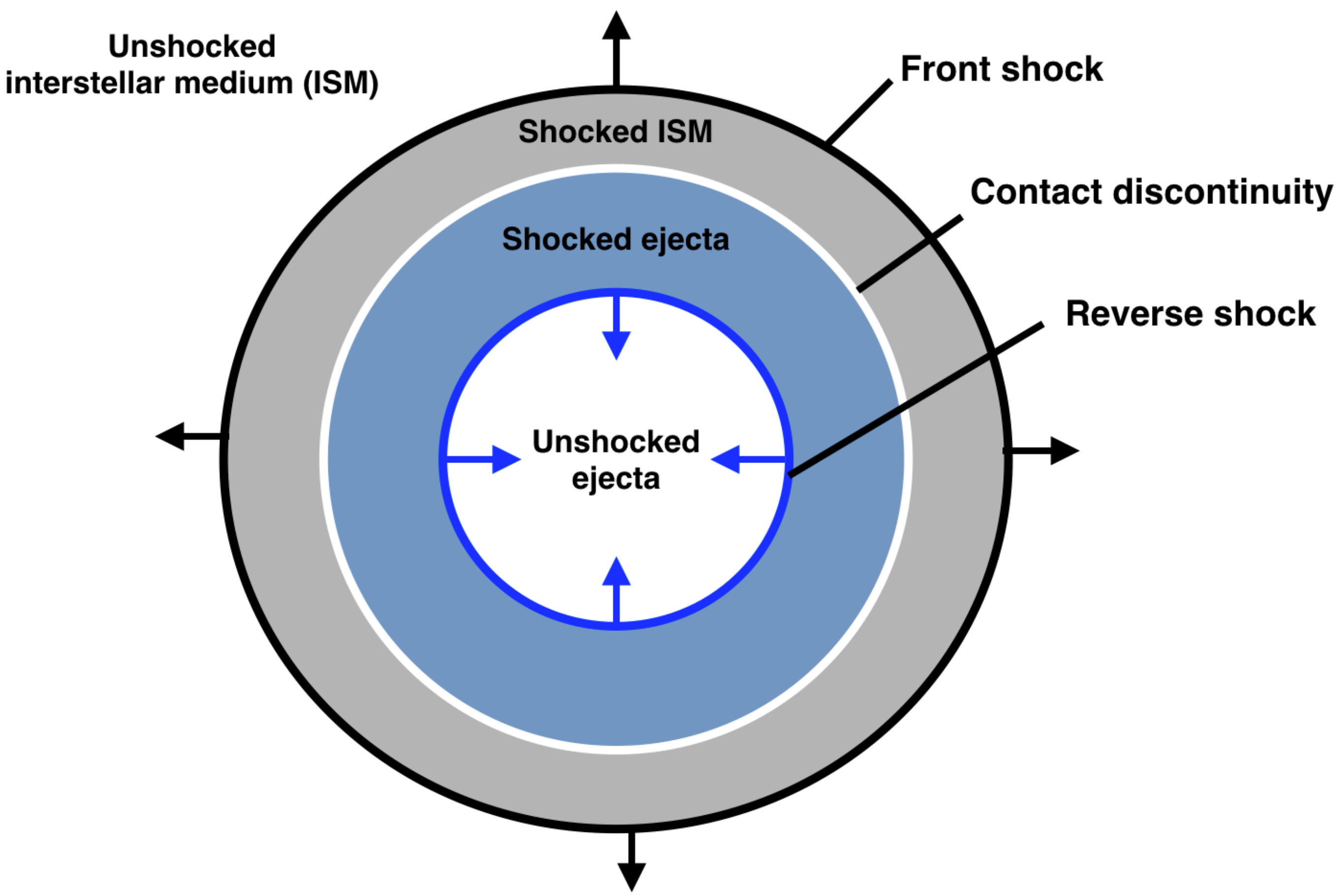
- Large amount of unidentified gamma-ray sources: new types of sources?

Supernova remnants



Particle acceleration (diffusive shock acceleration mechanism) at the shock front

Supernova remnants



- **Free expansion phase/ejecta-dominated phase**
- **Sedov-Taylor phase**

$$R_s = 1.15 \left(\frac{E}{\rho_0} \right)^{\frac{1}{5}} t^{\frac{2}{5}}$$

- **Radiative phase**

T ~ 10^4 K, recombination of the ionized gas with electrons => Dense and cold shell Radio/GeV/Optical line emission

Evolutionary stage of a supernova remnant (SNR) depends on M_{ej}, E_{sn} and n_0

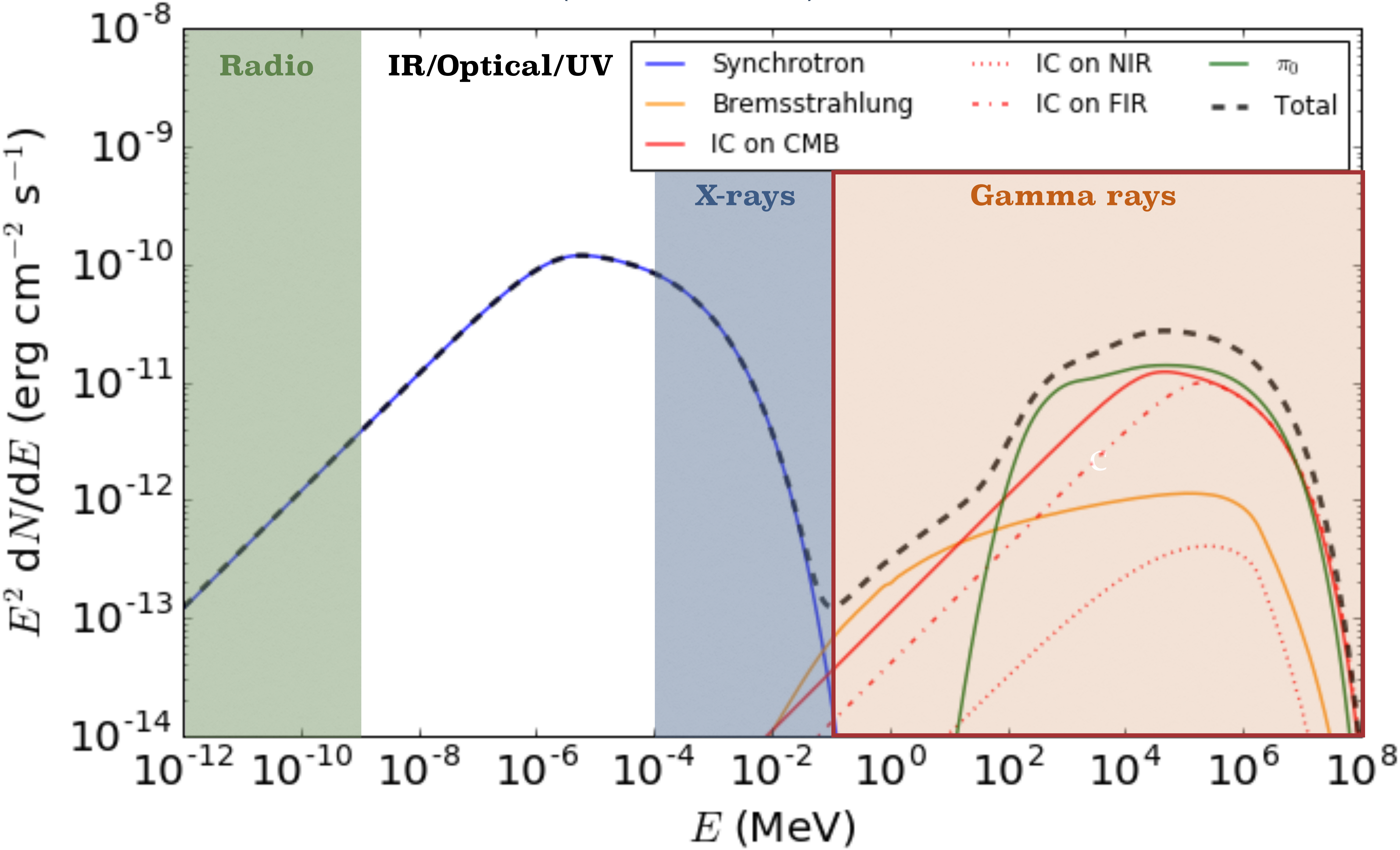
- Particle **spectrum** described by a **power law with an exponential cut off**

$$\frac{dN}{dE} \propto E^{-s} \exp\left(- \frac{E}{E_{\rm cut}} \right)$$

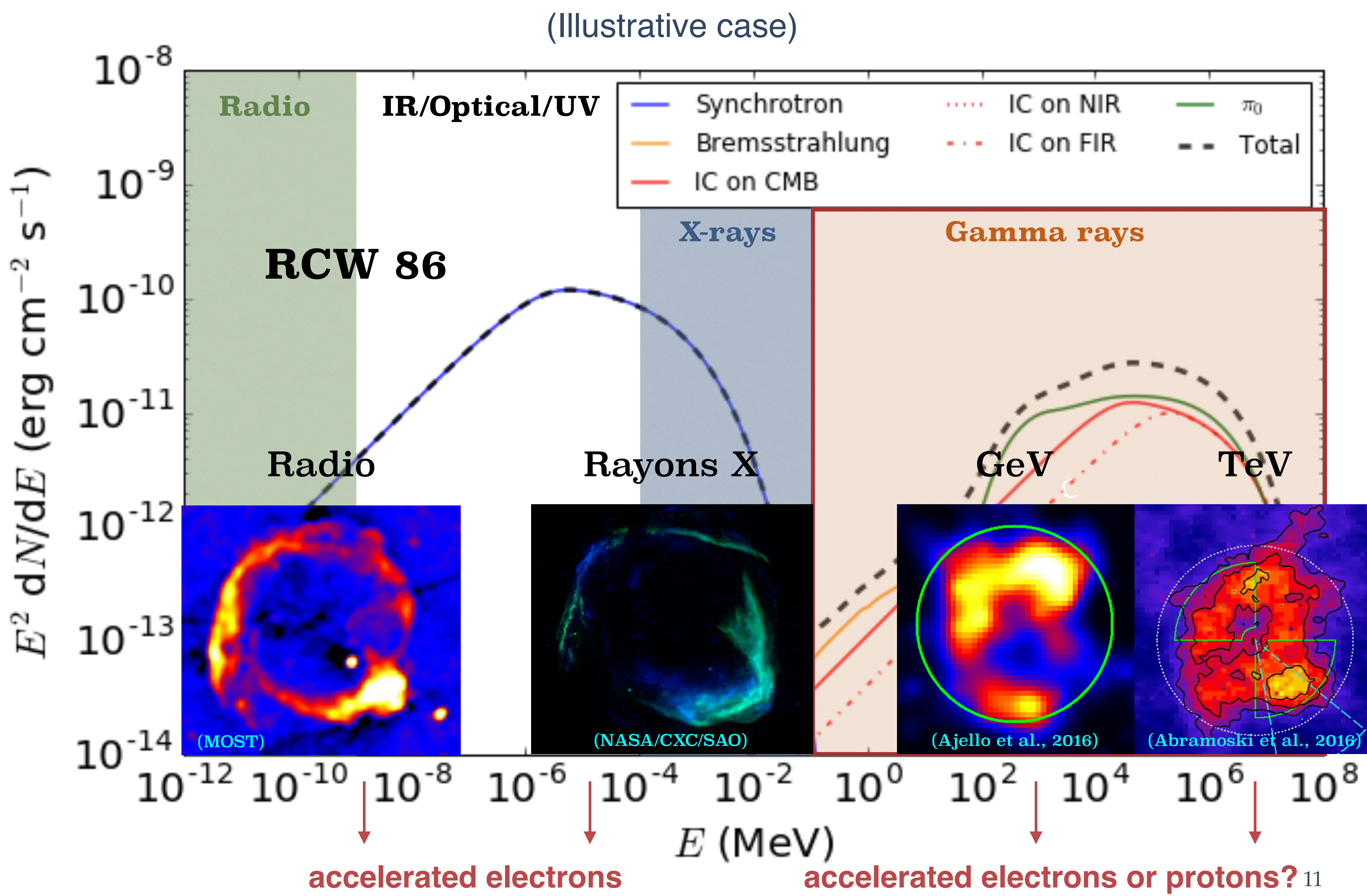
- Break in the electron spectrum due to **synchrotron cooling** ($s_{e,2} = s_{e,1} + 1$)

Broadband nonthermal emission from SNRs

(Illustrative case)



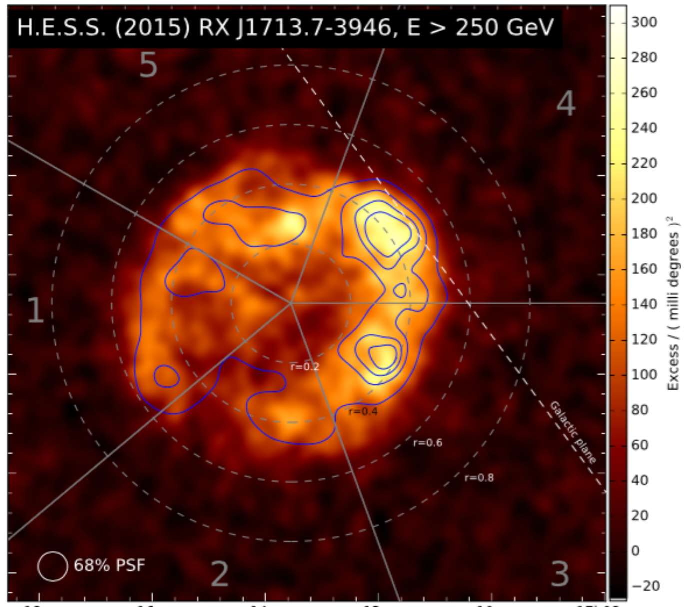
Broadband nonthermal emission from SNRs



Gamma-ray emitting supernova remnants

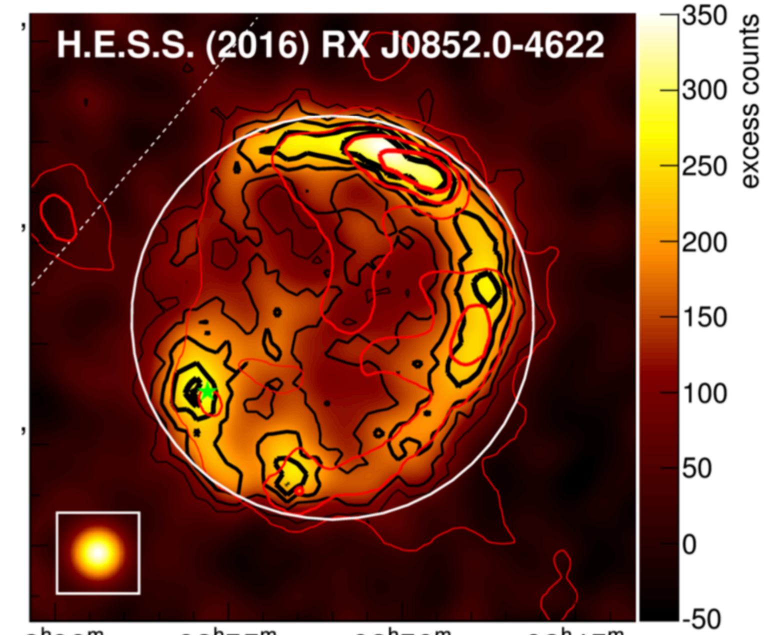
RX J1317-3946

t = 1 – 2 kyr



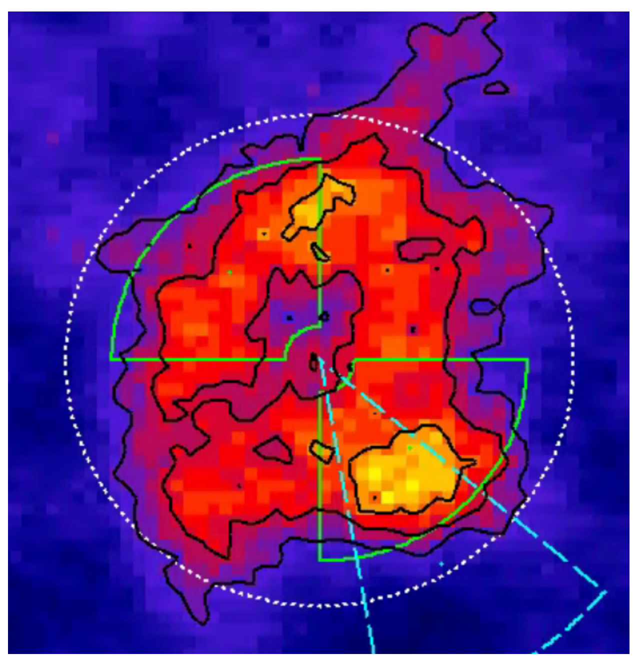
Vela Junior

t = 2 – 4 kyr



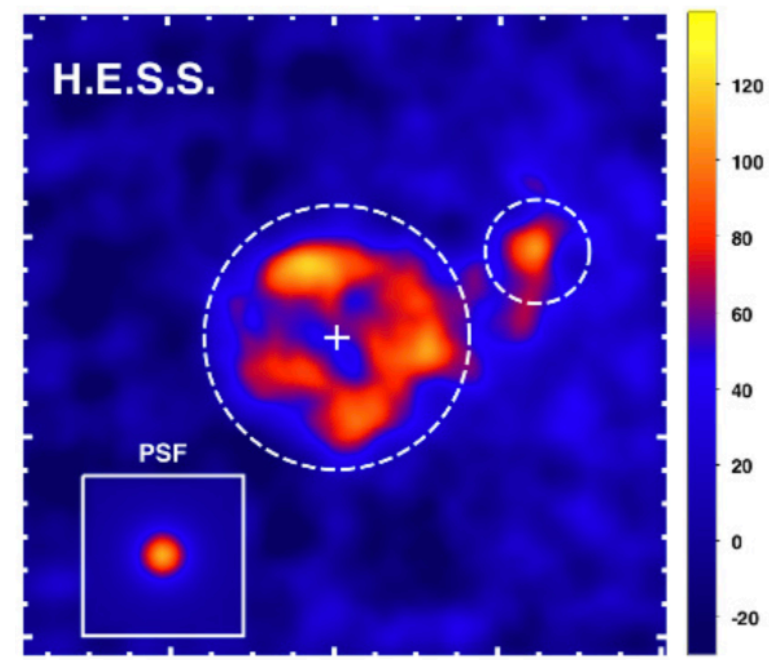
RCW 86

t ~ 1.8 kyr
(historical SNR)



HESS J1731-347

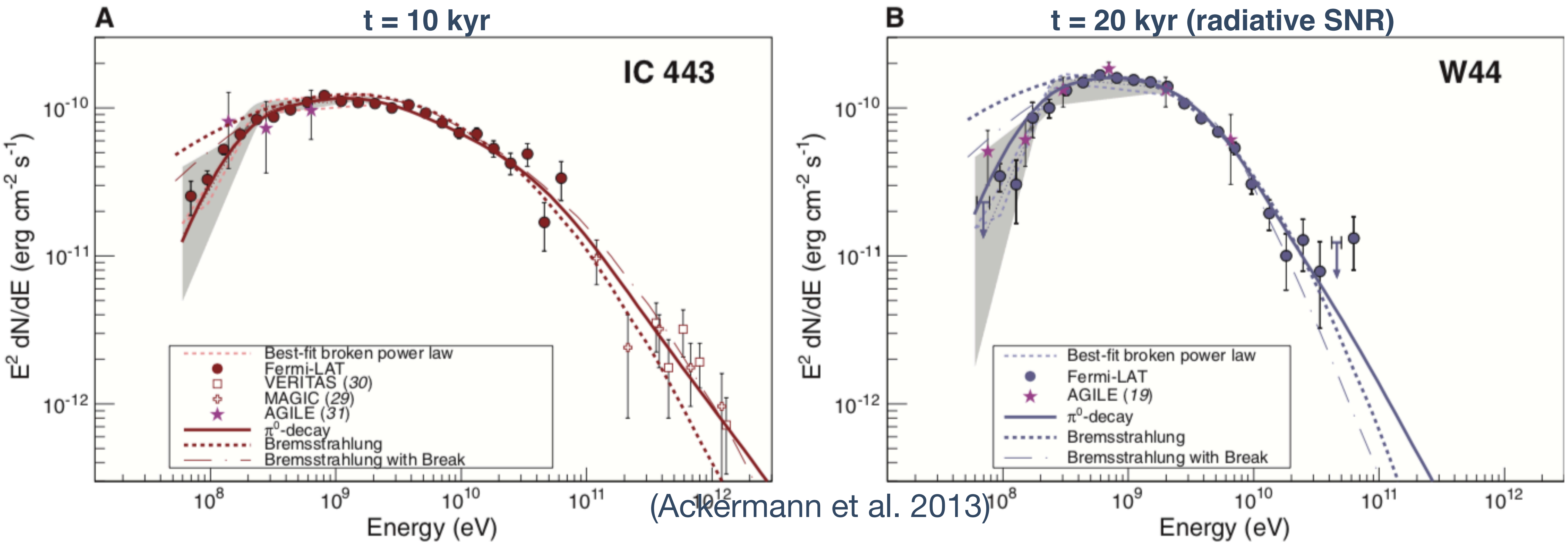
t ~ 2.5 kyr



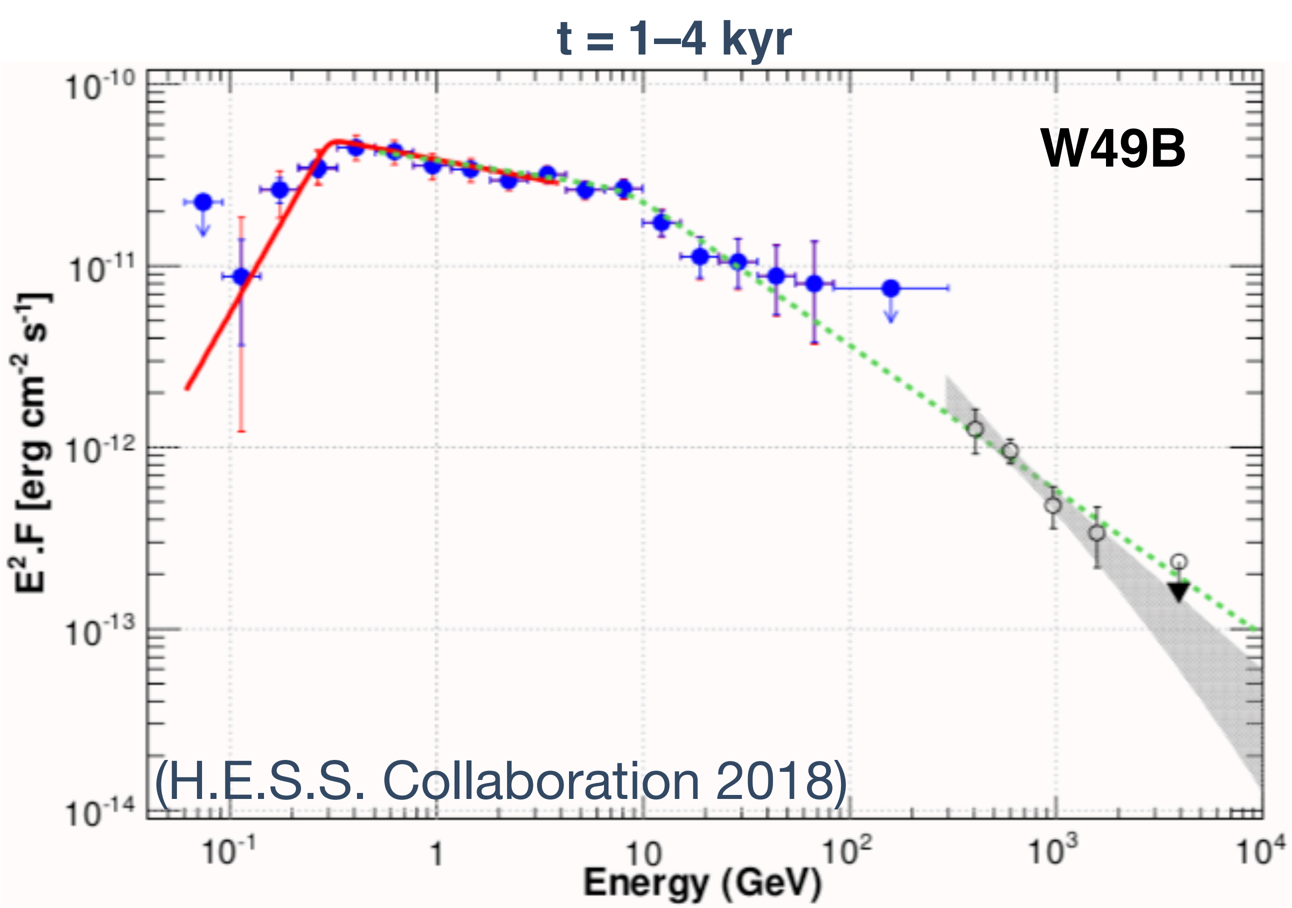
~ 30 likely GeV SNRs + 14 candidates (Fermi-LAT SNR catalog, 2016)
~ 30 TeV SNRs (**or composite SNRs, emission may arise from the PWN**)

Origin of the emission (leptonic or hadronic) still under debate for most of them

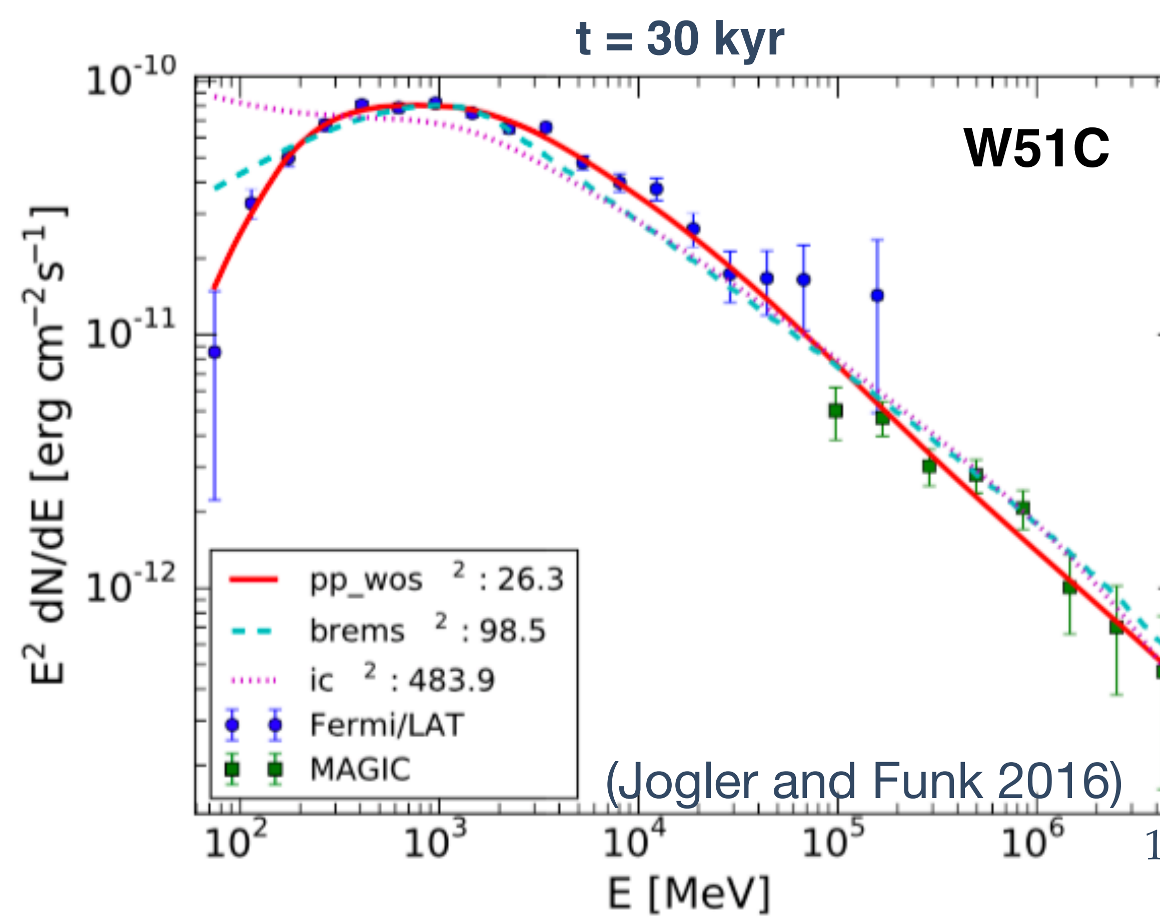
SNRs as cosmic-ray accelerators



(Ackermann et al. 2013)

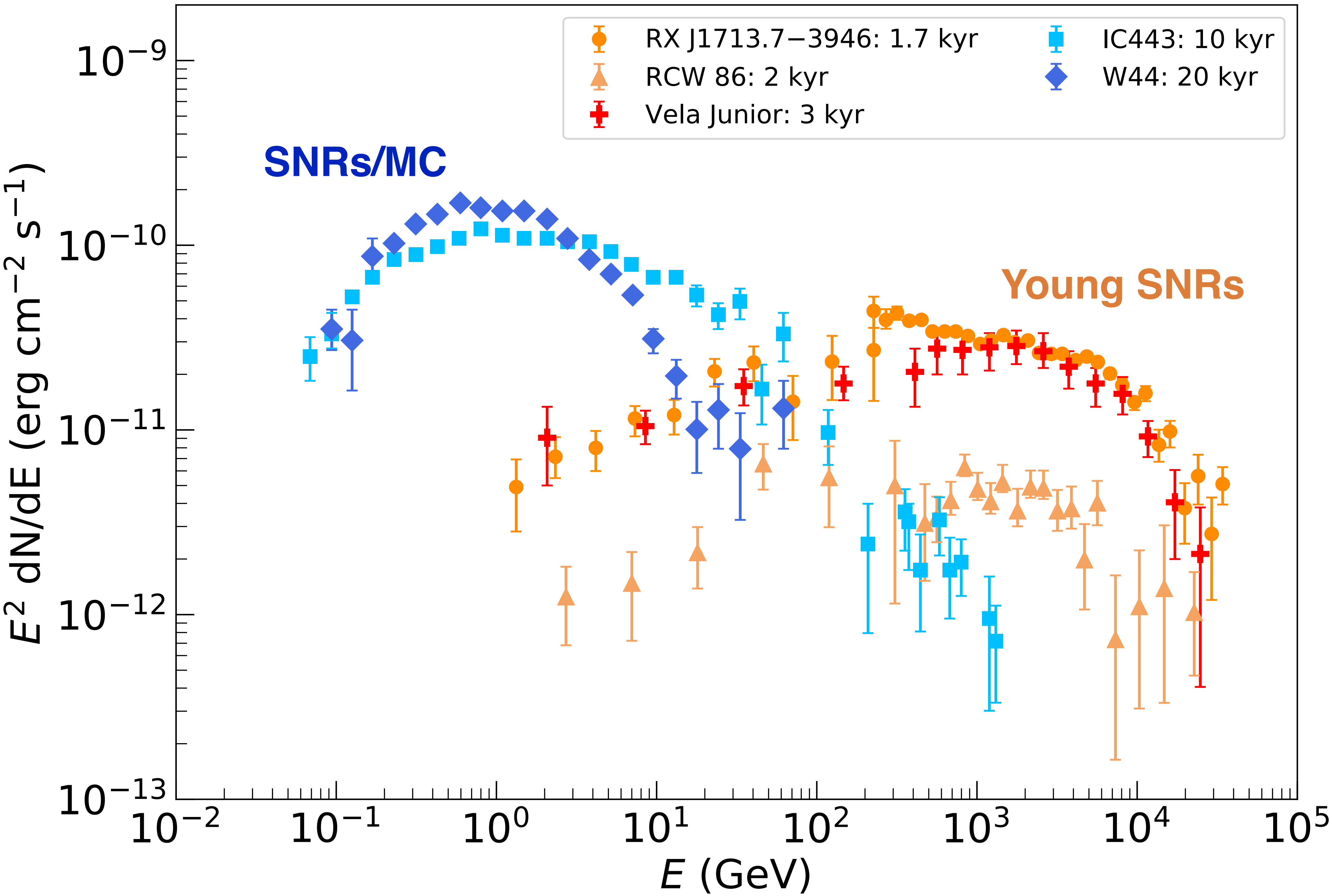


(H.E.S.S. Collaboration 2018)



(Jogler and Funk 2016)

Young SNRs and SNRs/MC

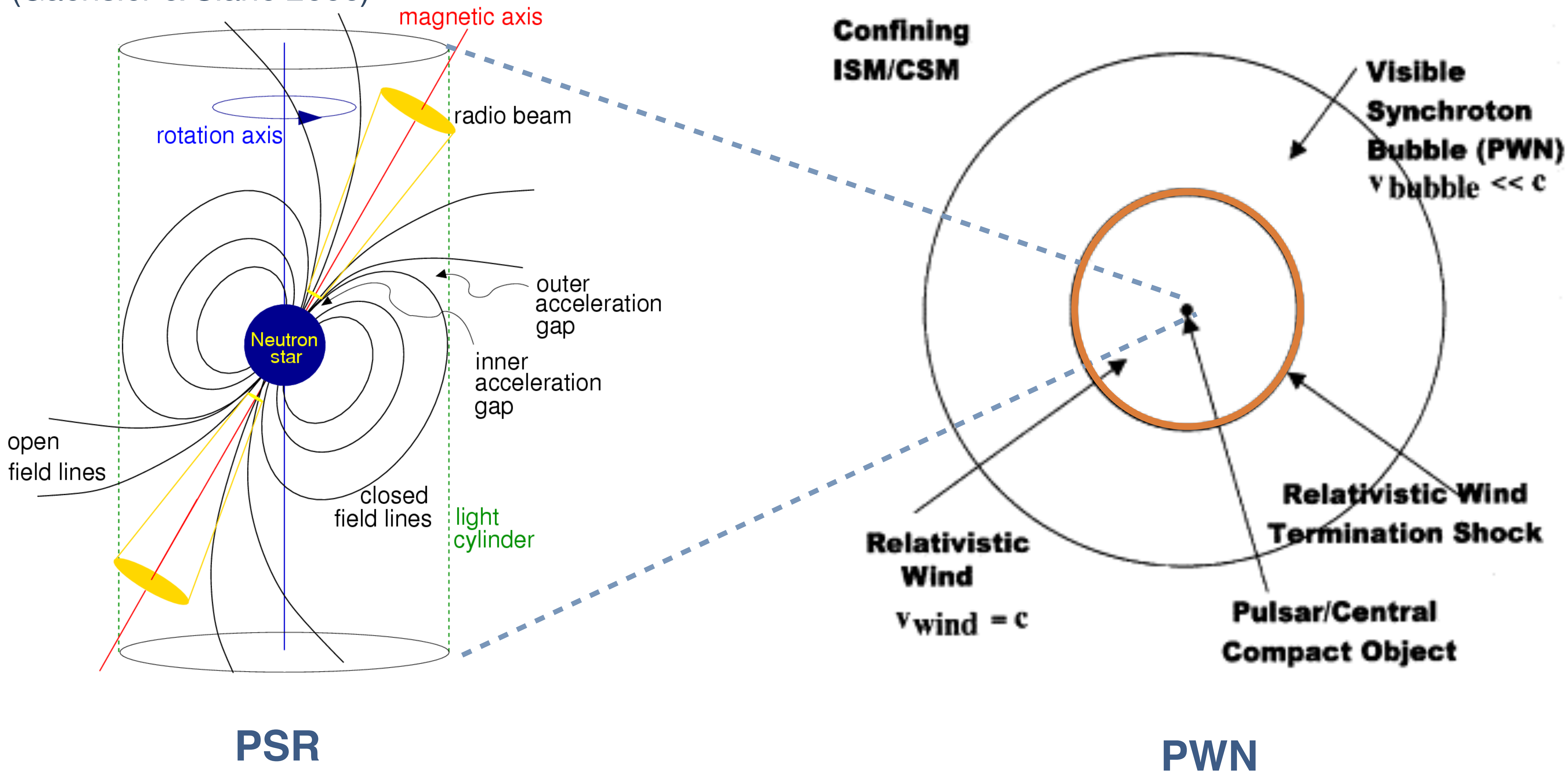


Hard spectrum and brightest at TeV energies

Evidence for proton acceleration and brightest at GeV energies

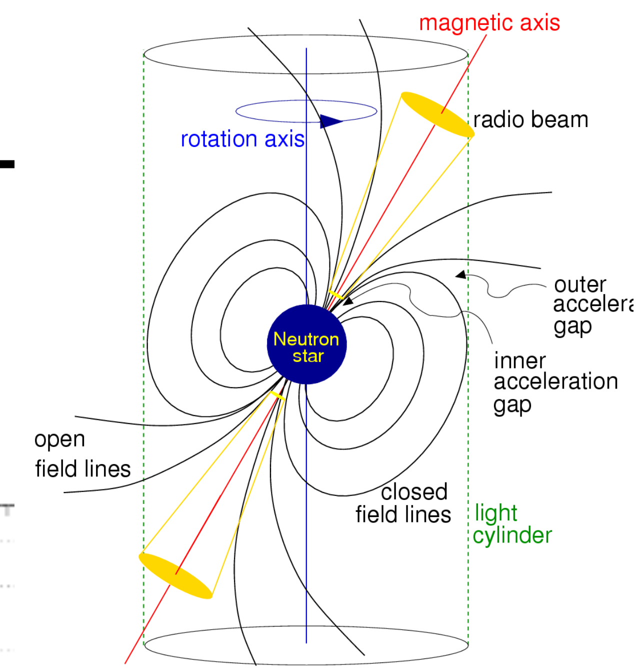
Pulsars and their nebulae

(Gaensler & Slane 2006)

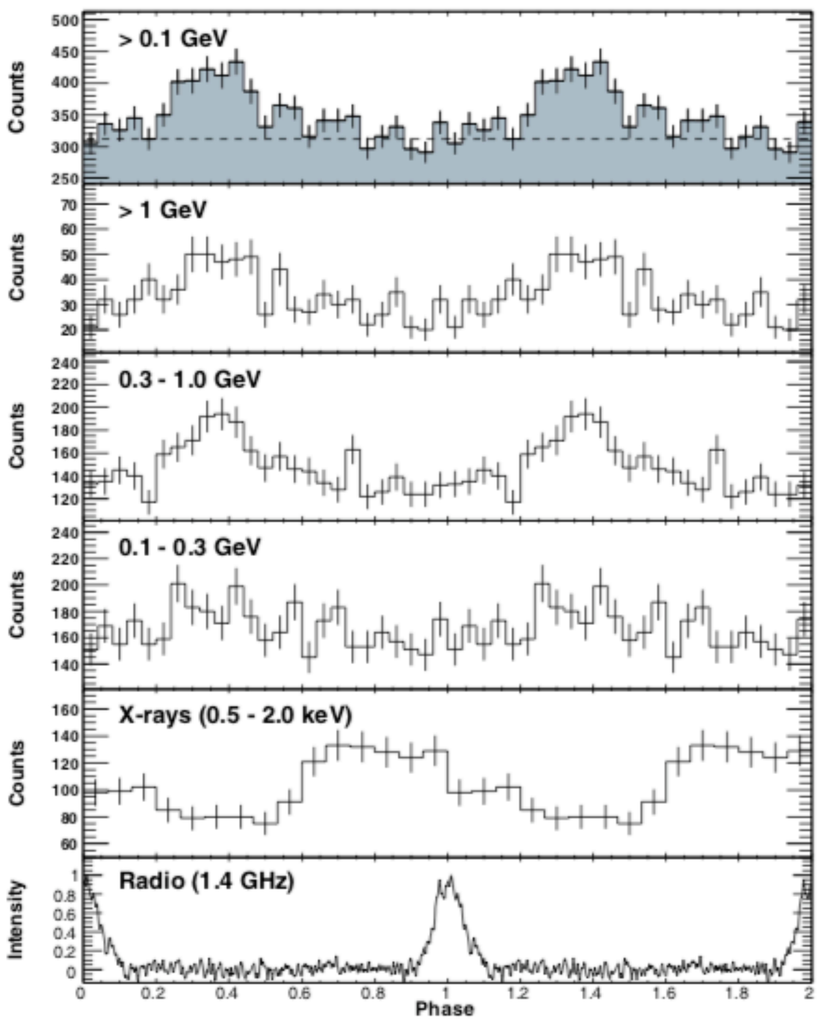


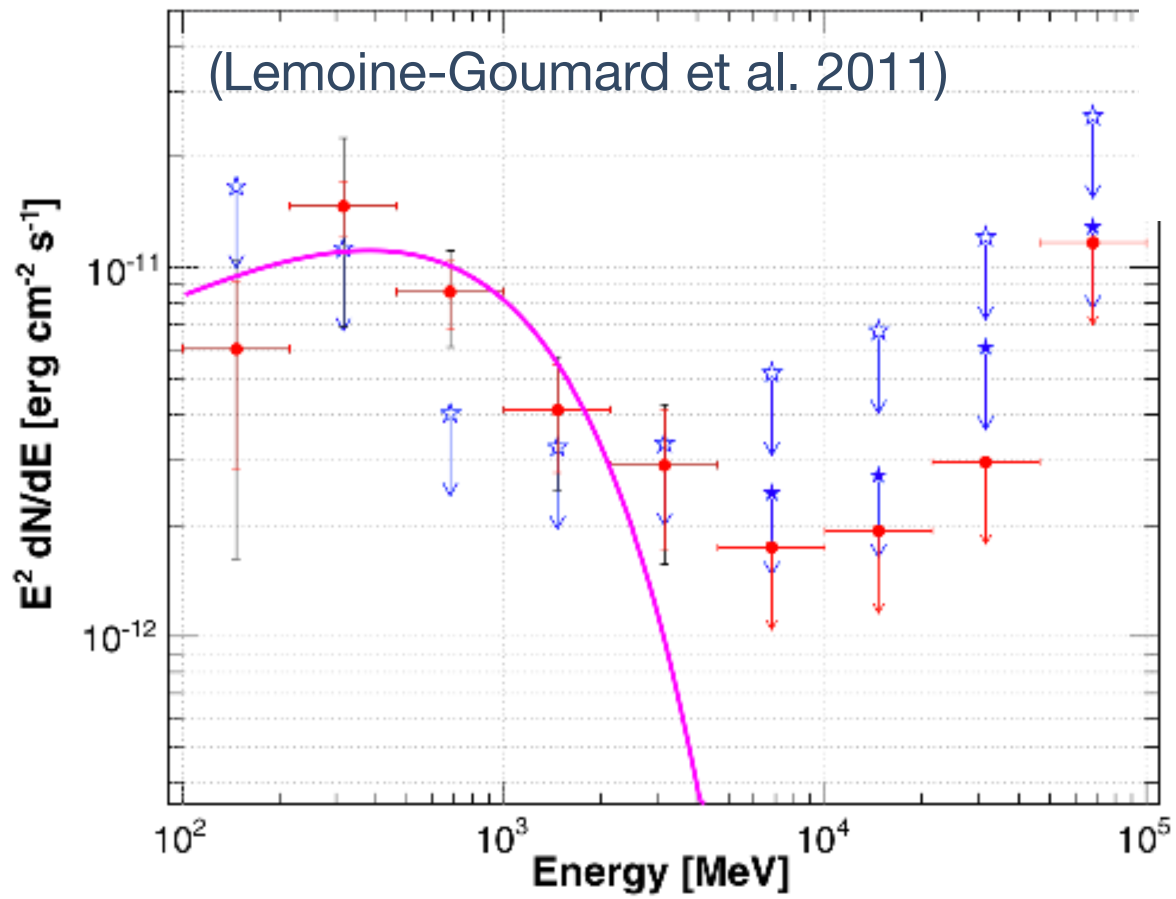
- Electrons extracted from the neutron star
- Photon emission => **e+/e- pair creation**
- e-/e+ diffuse away from the PSR and **are re-accelerated** at the **termination shock** of the PWN

Gamma-ray emission from PSRs



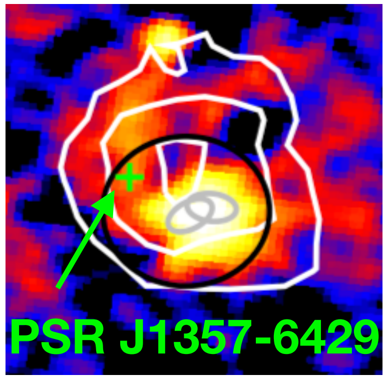
PSR J1357-6429

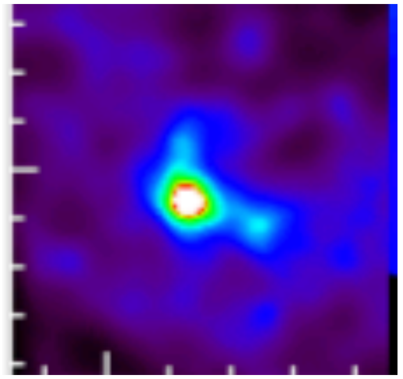


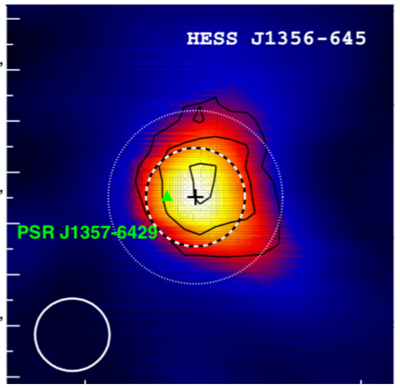


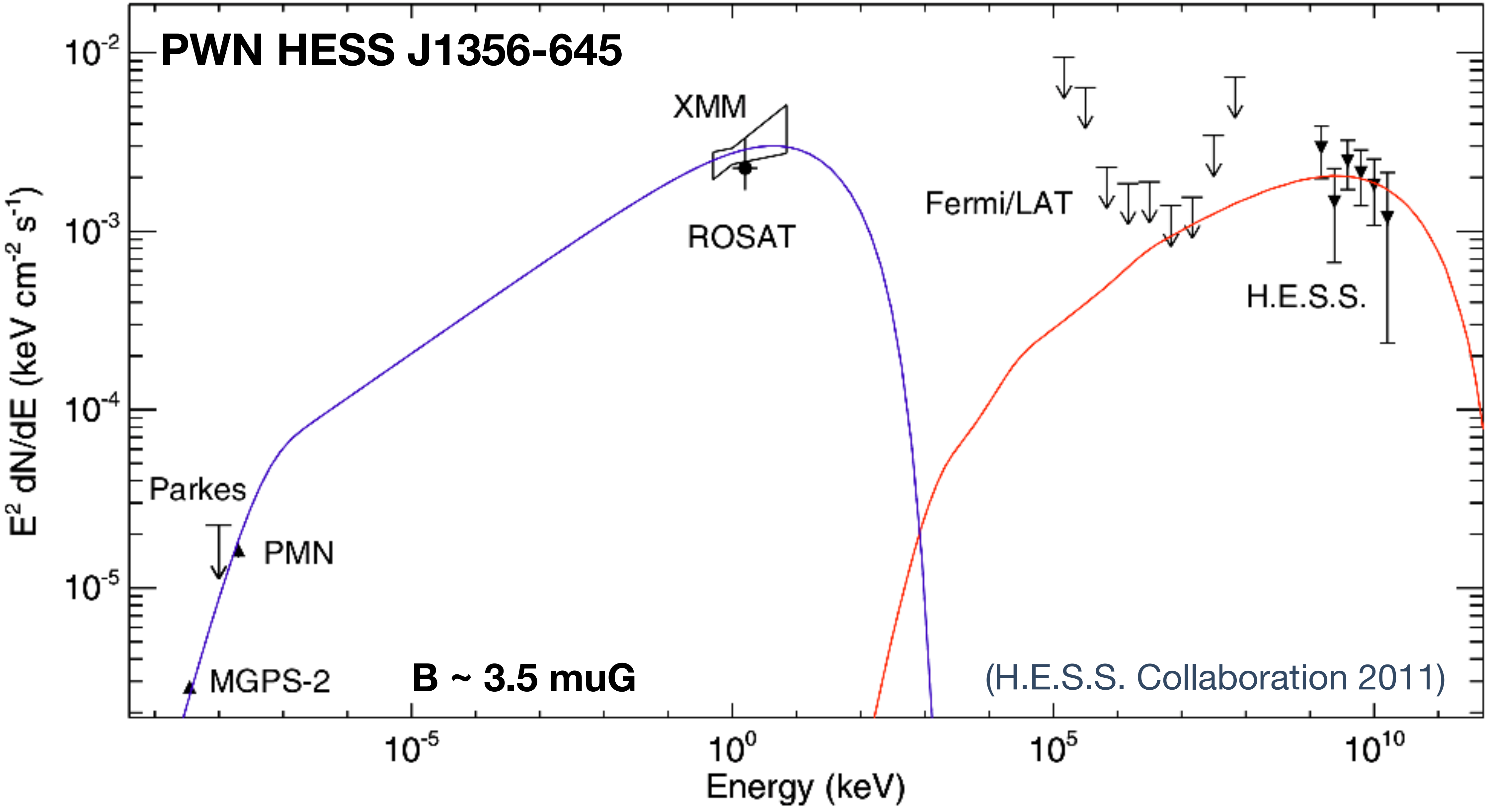
- Pulsed emissions in radio/X-rays/gamma rays (not from the same region)
- Cut-off in gamma for E < 10 GeV

Broadband nonthermal emission from PWNe









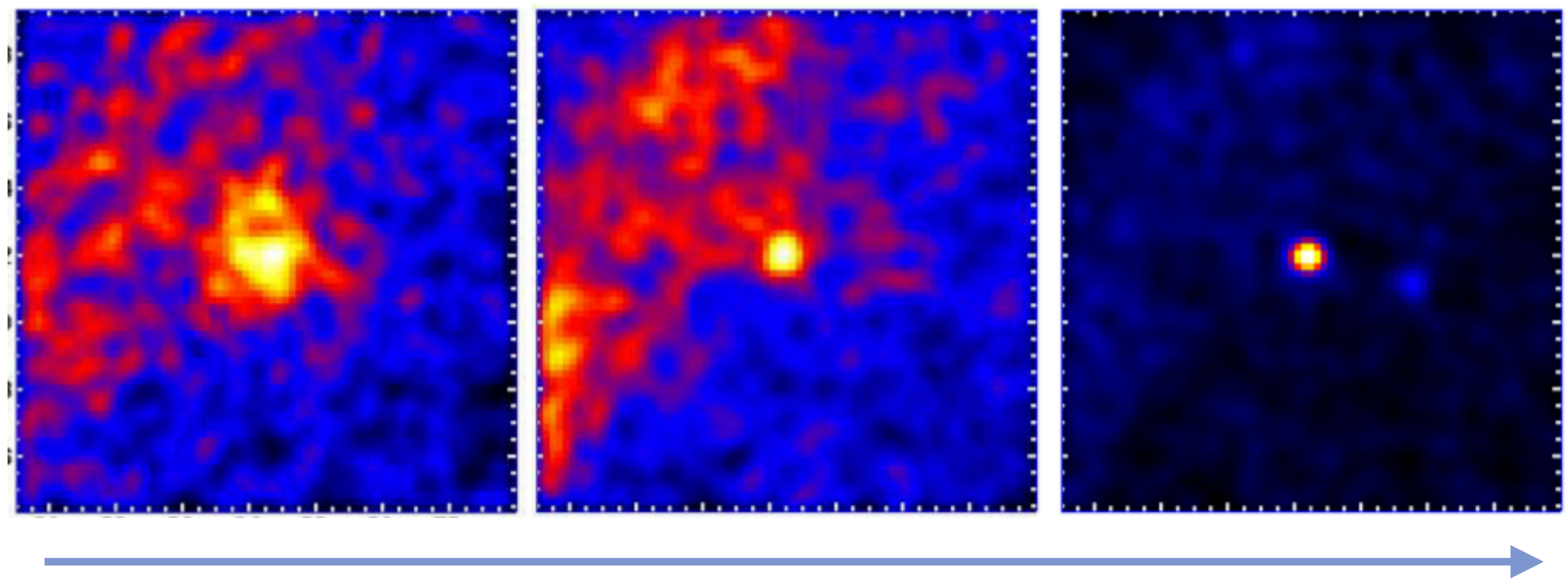
~ 5 GeV PWNe (11 candidates, Acero et al. 2013)

~ 30 TeV PWNe - most numerous TeV Galactic sources (~ 20%)

Gamma-ray emitting PWNe

Crab Nebula

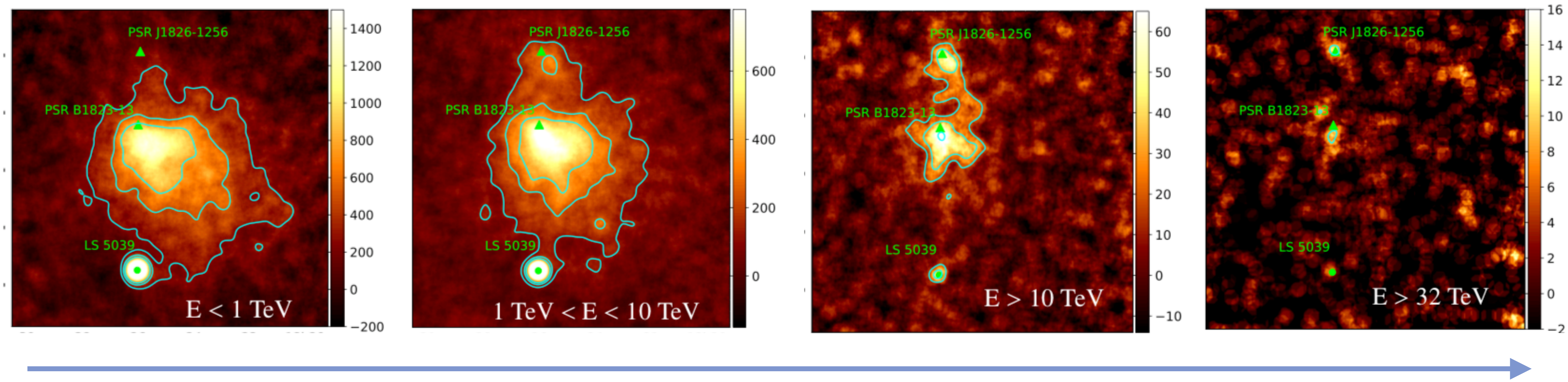
(Fermi-LAT Collaboration 2009)



Energy

HESS J1825-137

(H.E.S.S. Collaboration 2011)



Energy

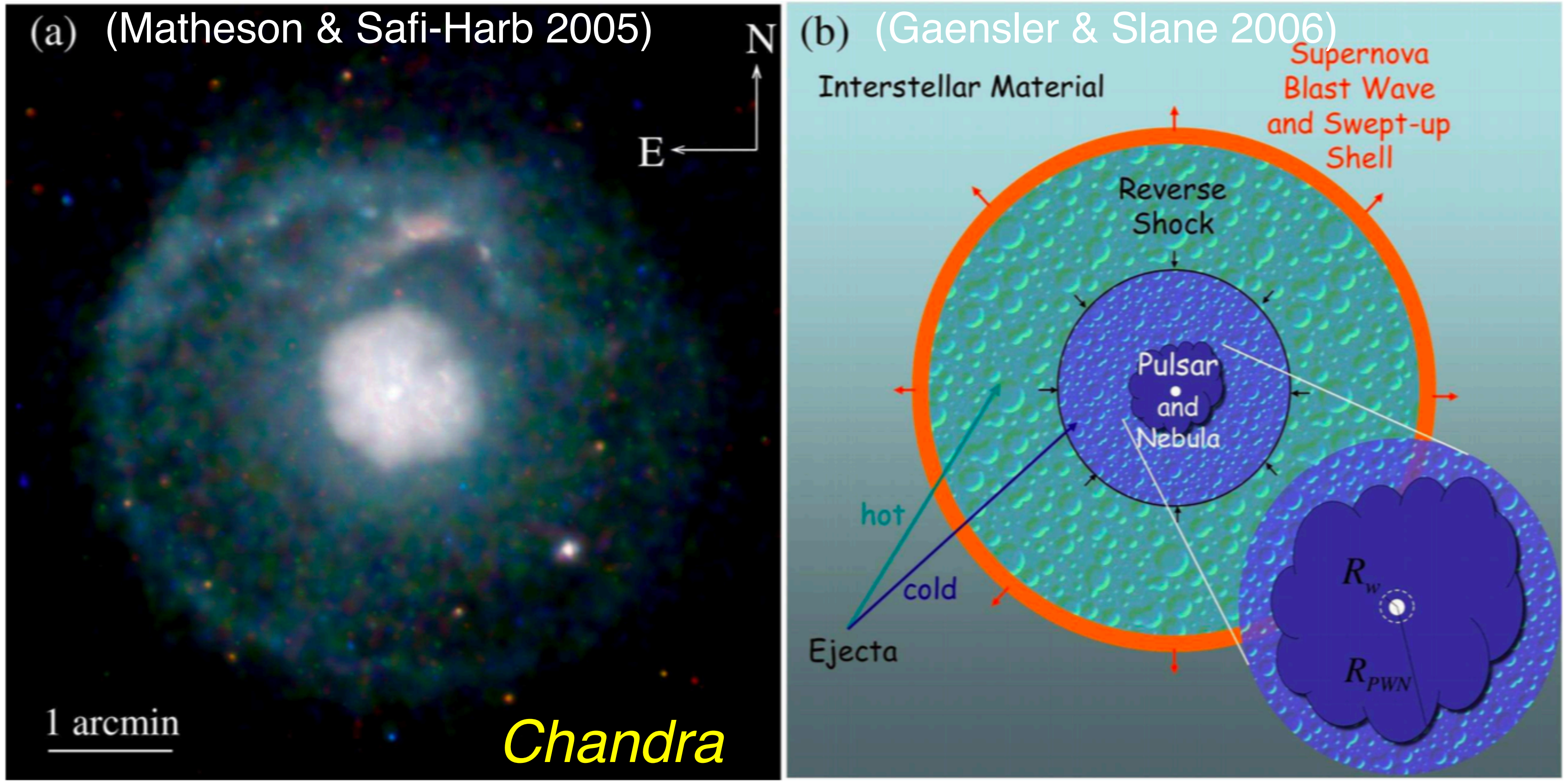
PWN often extended
(unless very far)

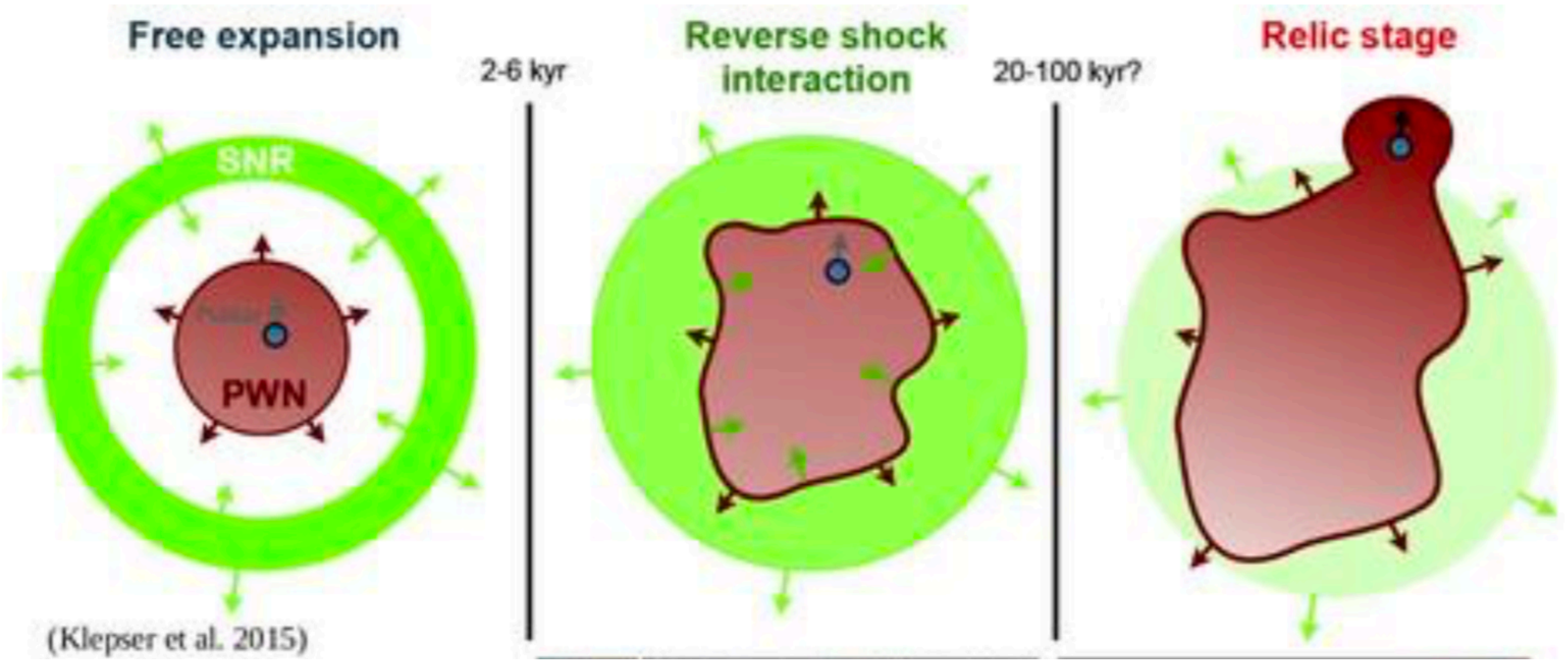
Extent shrinks close to the PSR

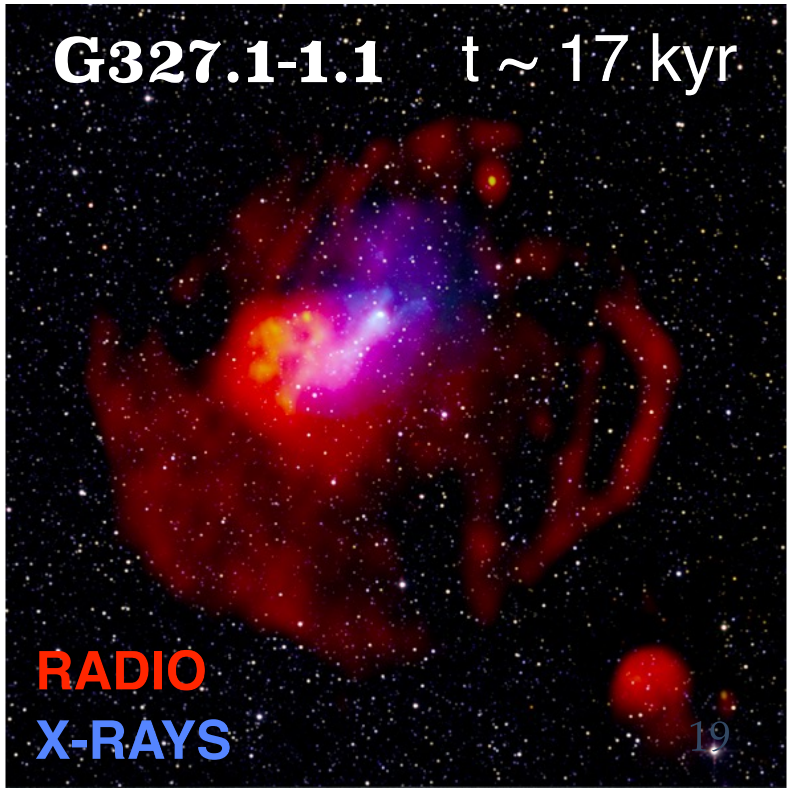
Composite supernova remnants

G21.5-0.9

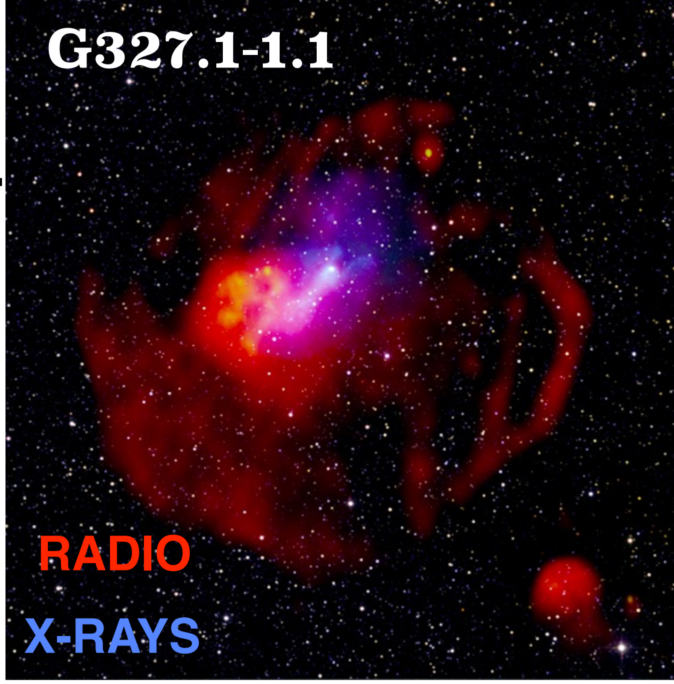
t ~ 1 – 2 kyr



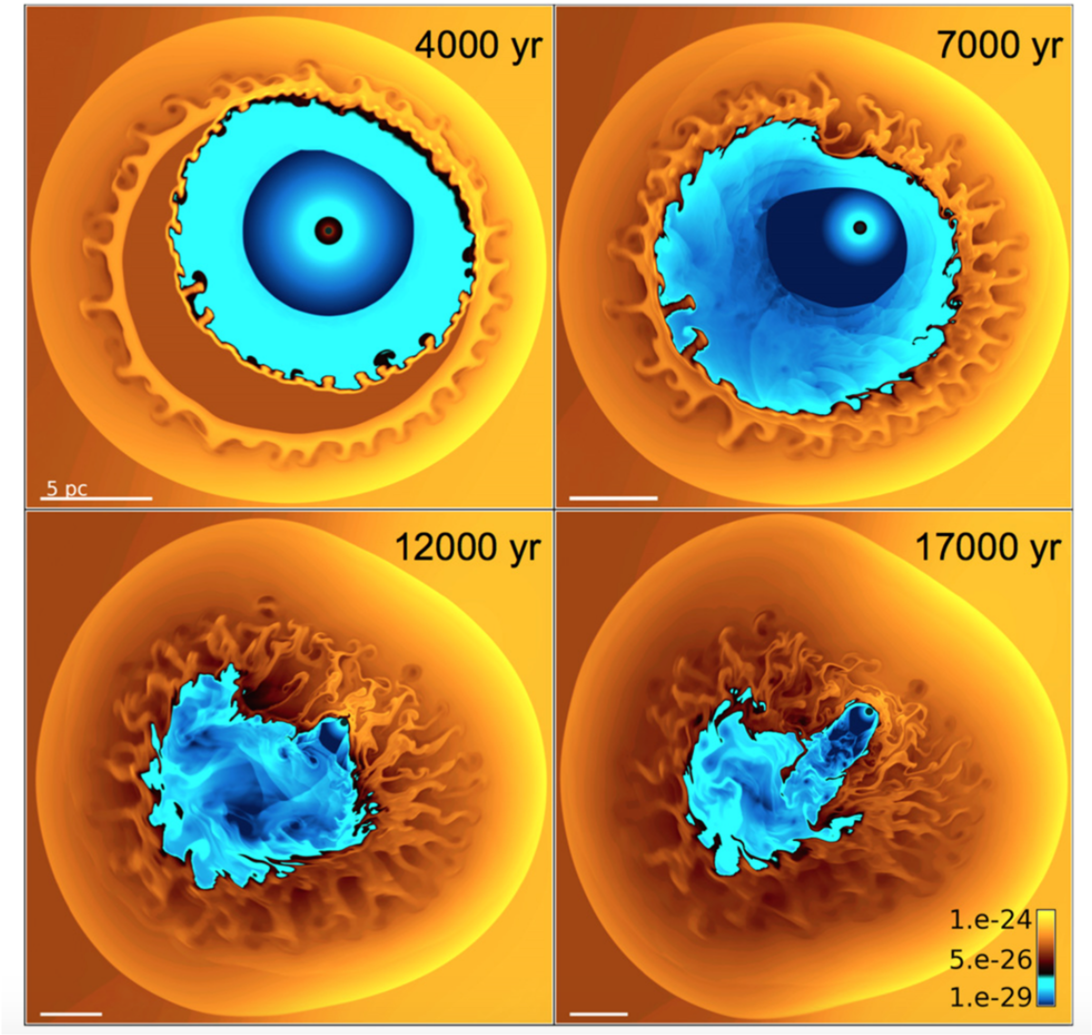


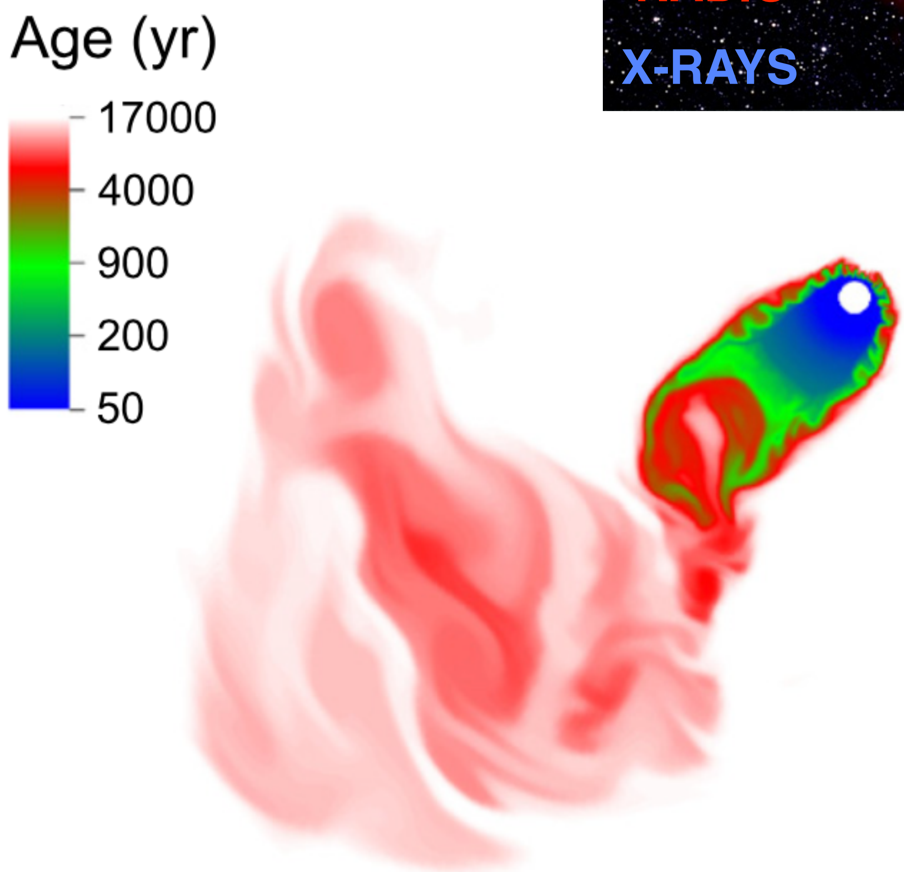


Composite supernova remnants



Relic PWN embedded in the SNR G327.1–1.1:



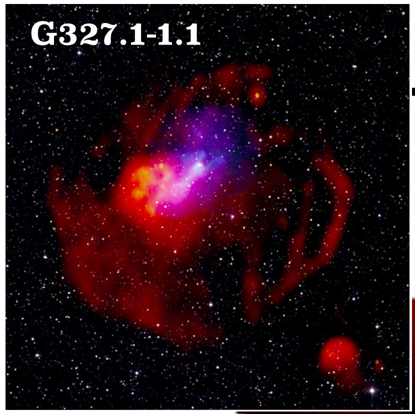


(Temim et al, 2015)

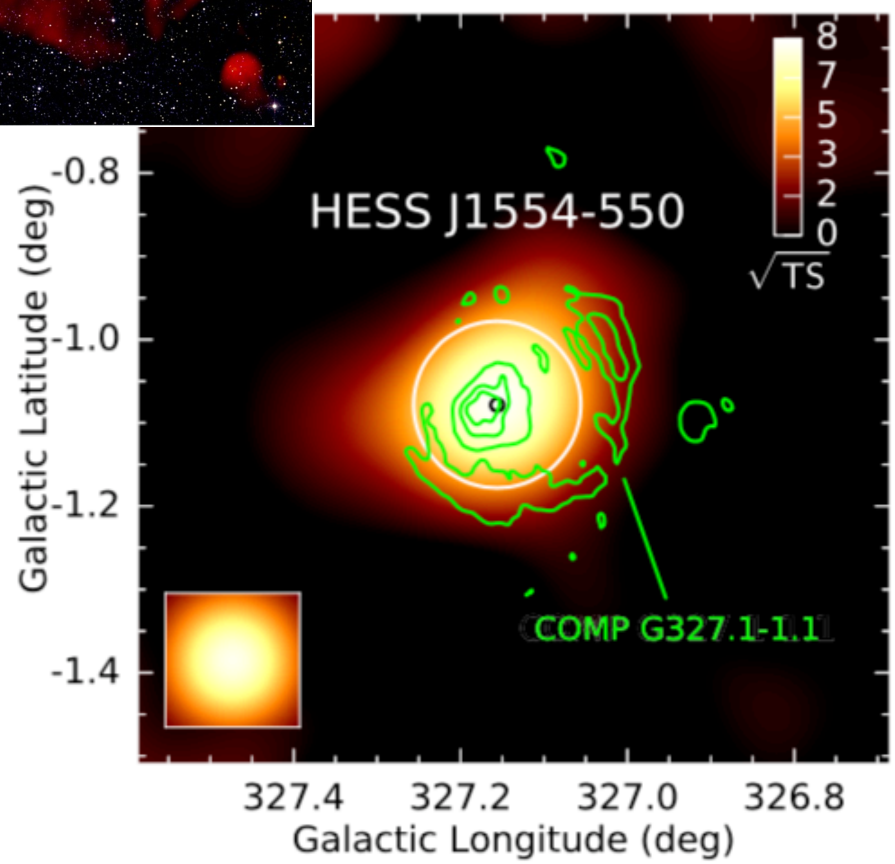
Youngest e- loose rapidly their energy **close to the PSR**

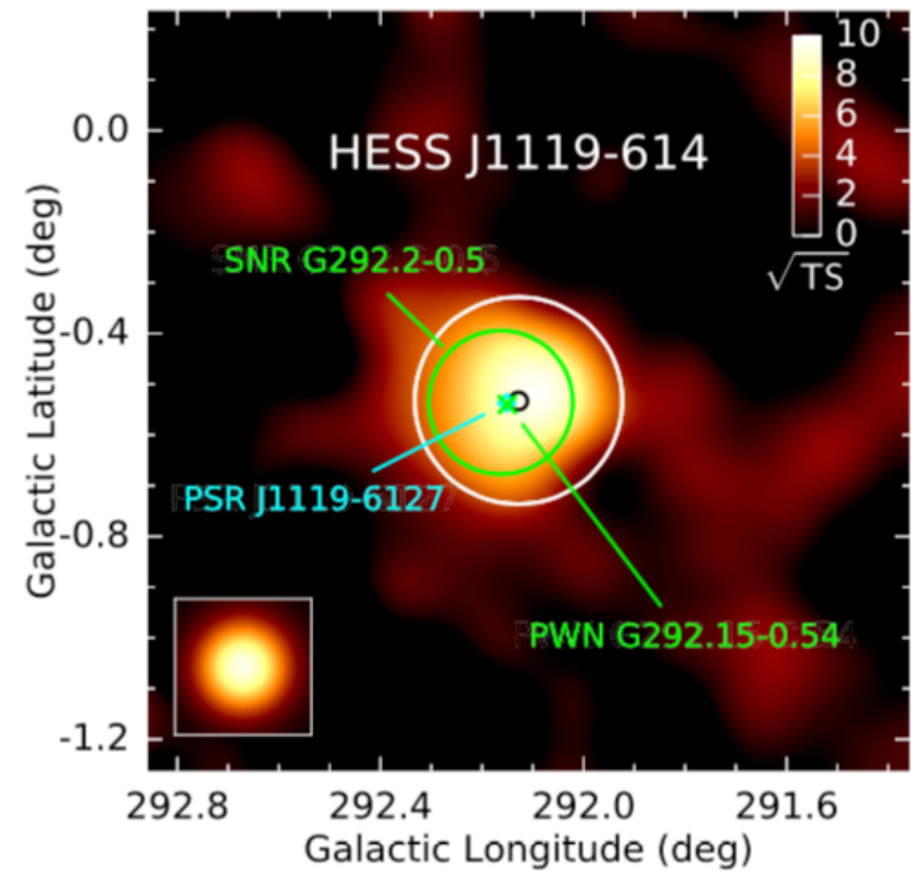
Oldest e- still undergo synchrotron and IC scattering **far away from the PSR**

Composites SNRs seen with H.E.S.S.



(H.E.S.S Collaboration 2018)





TeV emission from the PWN

- Spatial coincidence with the radio PWN
- VHE emission < SNR size

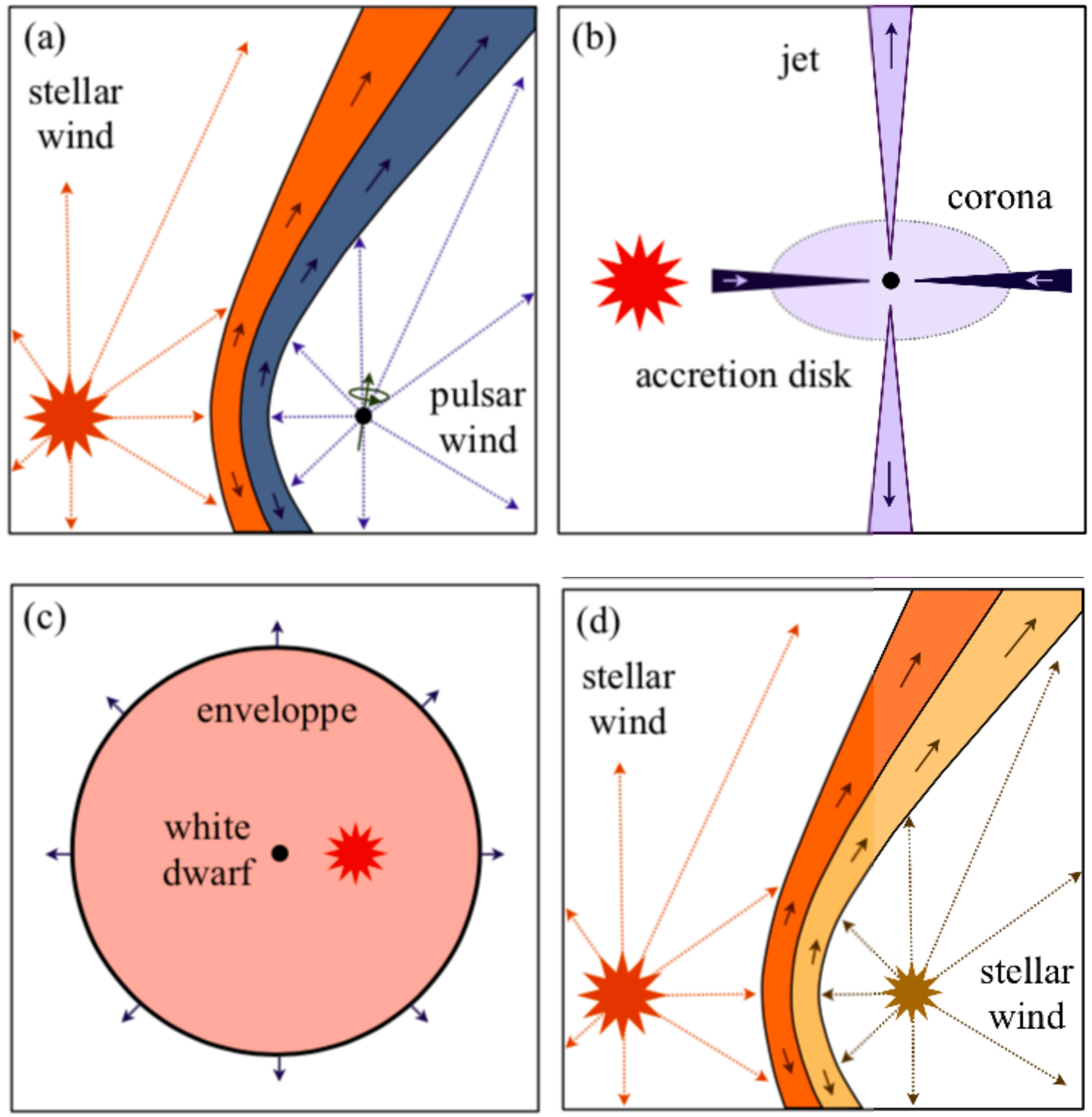
Not clear whether the emission comes from the PWN or the SNR (or both)

- VHE centroid compatible with the X-ray PWN

Difficult to disentangle emission from components nested within a small radius

Binaries

(Dubus 2015)



High/low-mass gamma-ray binaries

HE and VHE emission close to periastron

Microquasars (X-ray binaries)

HE emission from the jet (VHE emitters? - 4.9 sigma with MAGIC)

Novae

HE emitters - **No VHE** emission

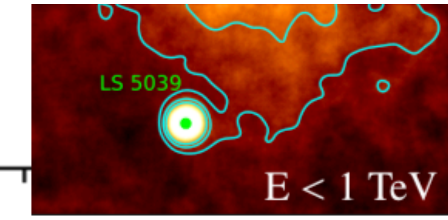
Colliding winds

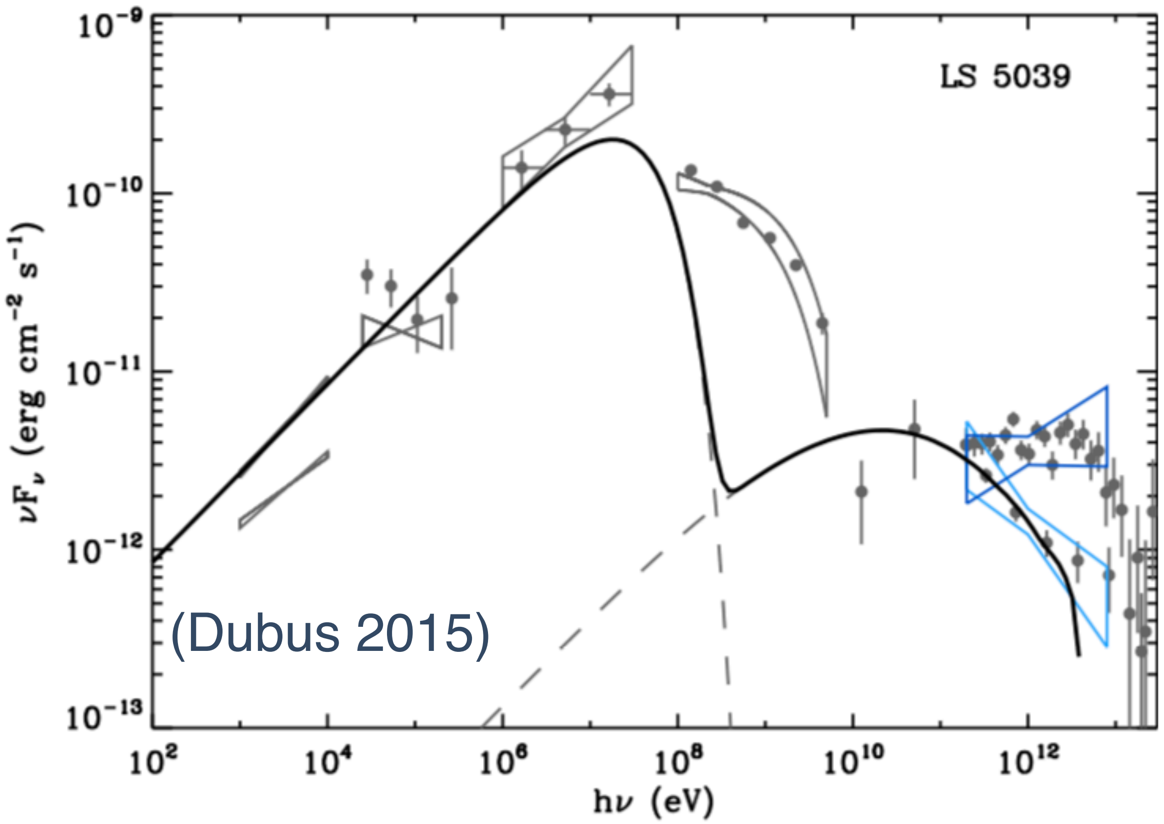
Vs = 1000 - 2000 km s^{-1}
Only Eta Car detected in **HE and VHE**

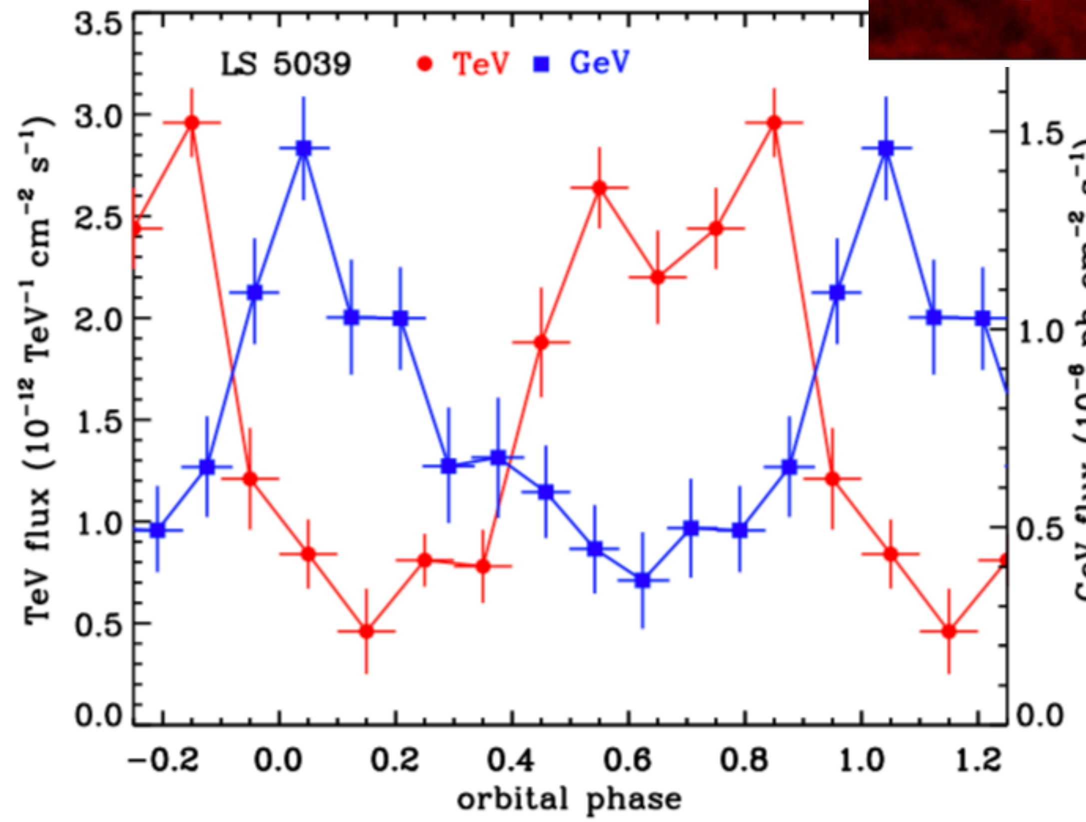
Lower CR efficency for other systems?
Small wind shock fraction?
Instable shock compared to SNR?

Nonthermal emission from the binary LS 5039

LS 5039: a high-mass gamma-ray binary







E^{-2} electron scattering on photons from the star (isotropic approx. and no cooling)

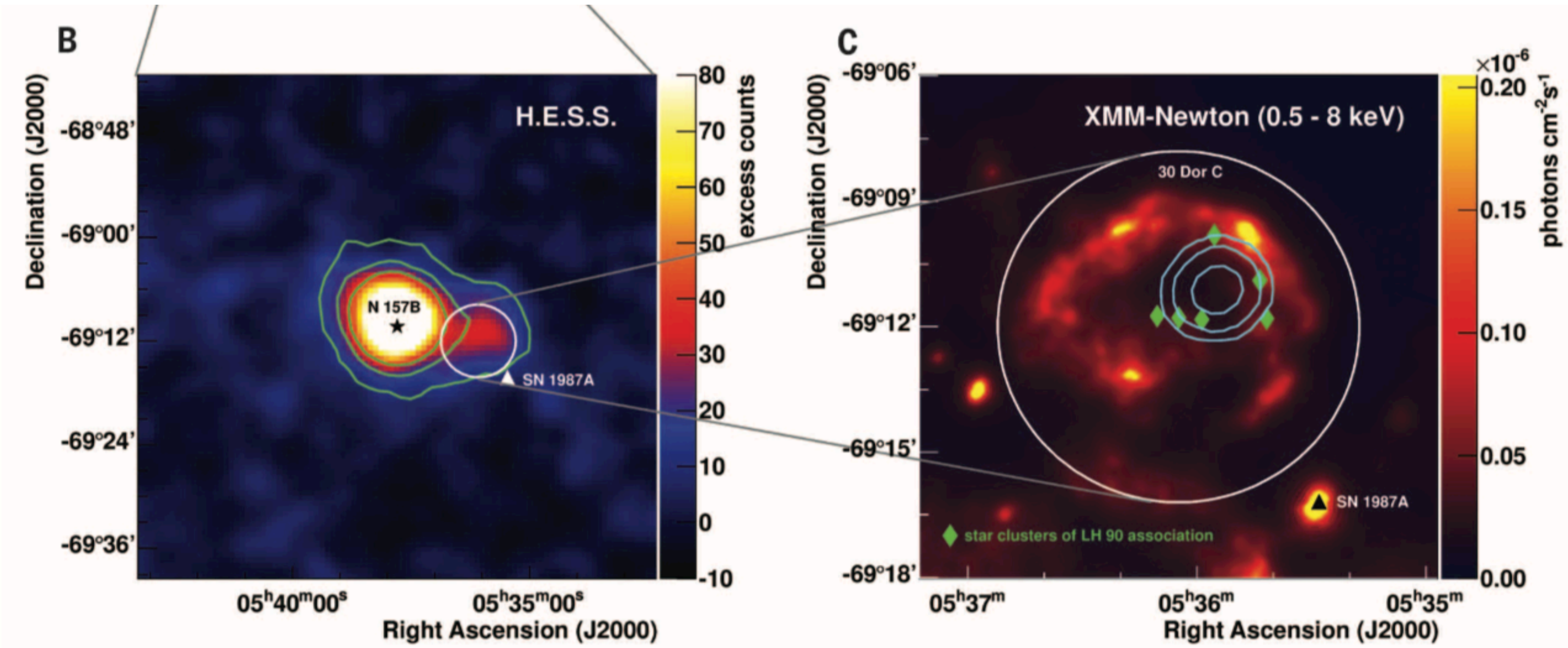
- MeV / GeV / TeV spectra not simply connected
- Fluxes modulated on the orbital period with different phasing

Complex spectrum
=> different population of HE particles and/or emission mechanisms

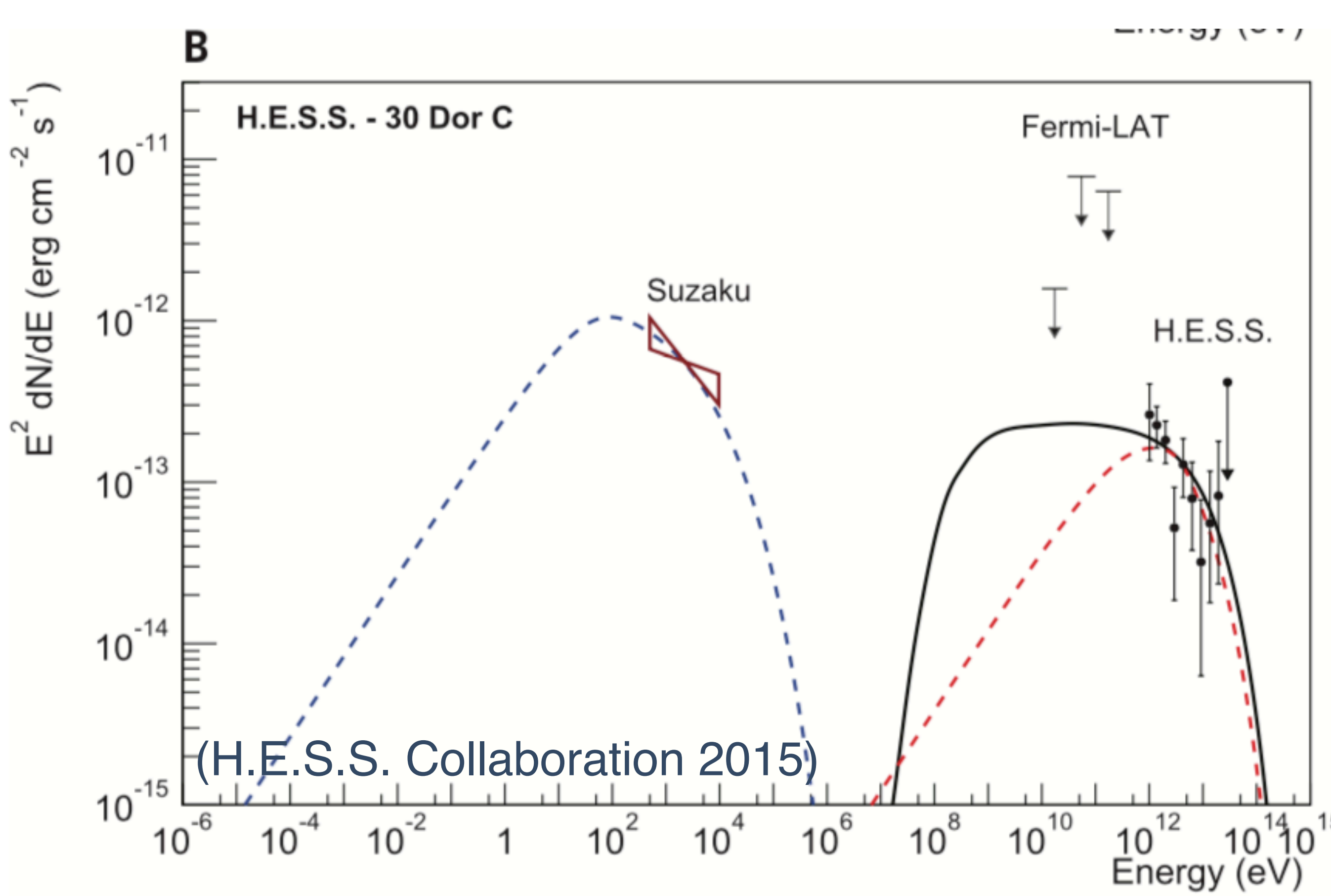
Binaries: more than a dozen at HE, roughly 5 at VHE

Superbubbles and Star forming regions

- Supperbubbles: detection of 30 Dor C in the LMC with H.E.S.S. (largest X-ray synchrotron shell)



Stellar winds and SNe



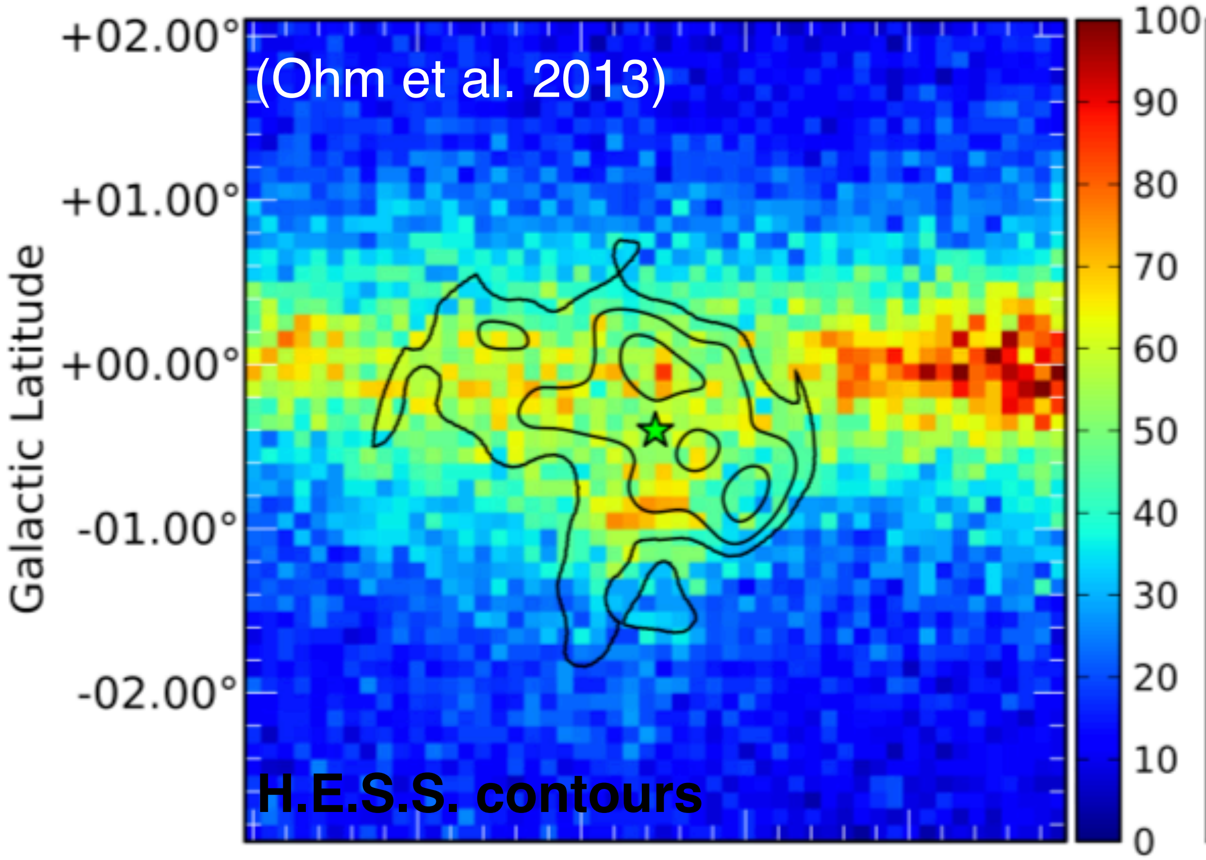
(H.E.S.S. Collaboration 2015)

Superbubbles and Star forming regions

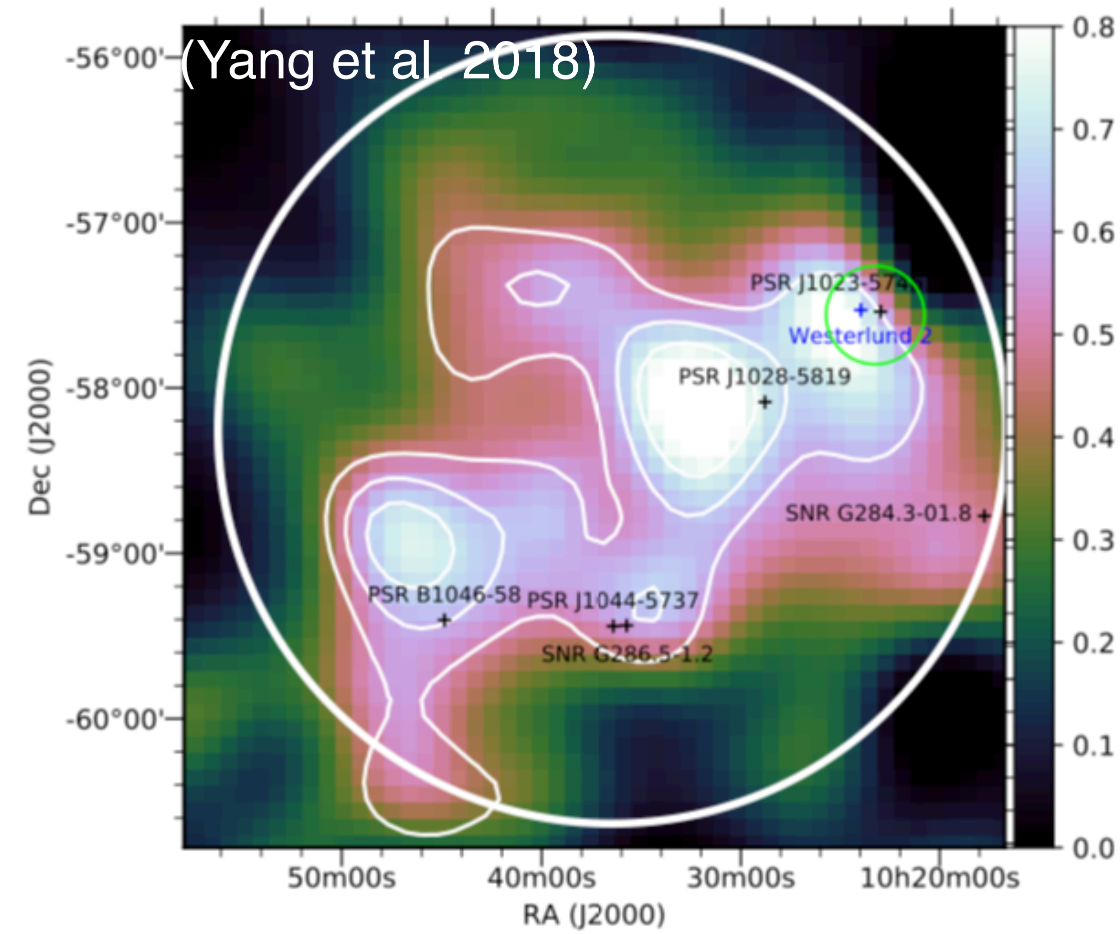
- Star forming regions

Among most massive young stellar clusters in the Milky Way

Westerlund 1



Westerlund 2



Could be diffusing protons accelerated by multiple SNRs and cluster winds

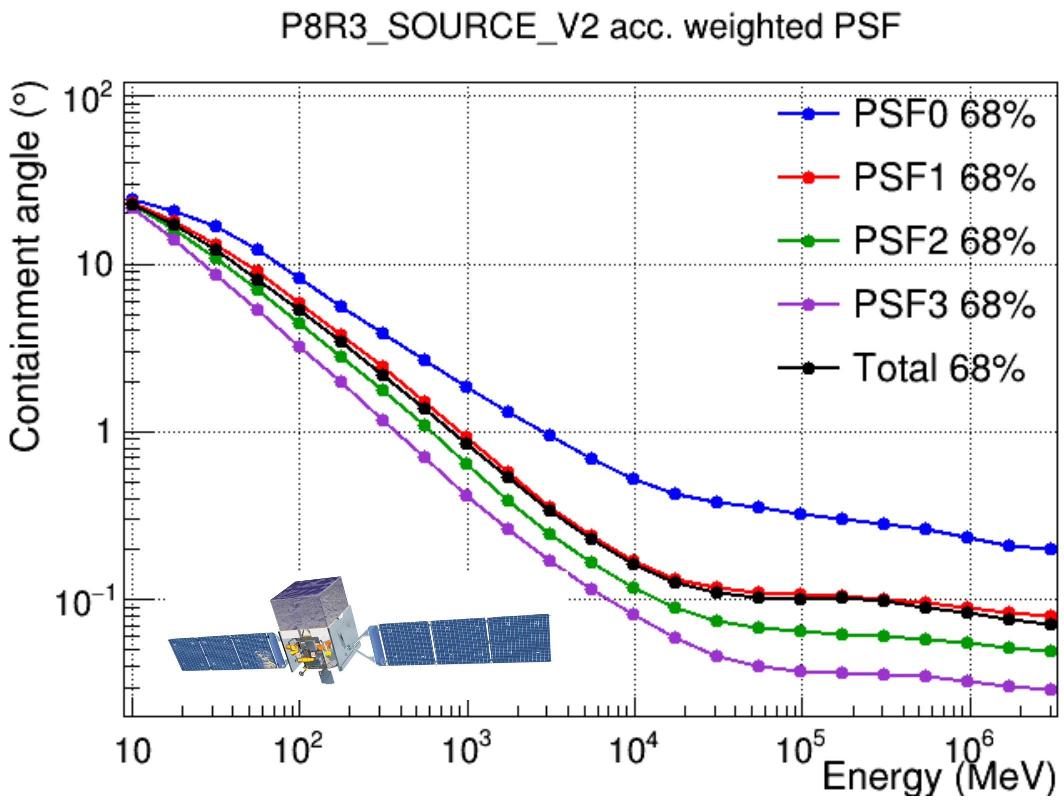
Origin of the emission unclear (large source confusion; and too high W_p or too low $\mathcal{D}$)

GeV versus TeV range

GeV

Pulsar studies
Probing the signature of the pion bump

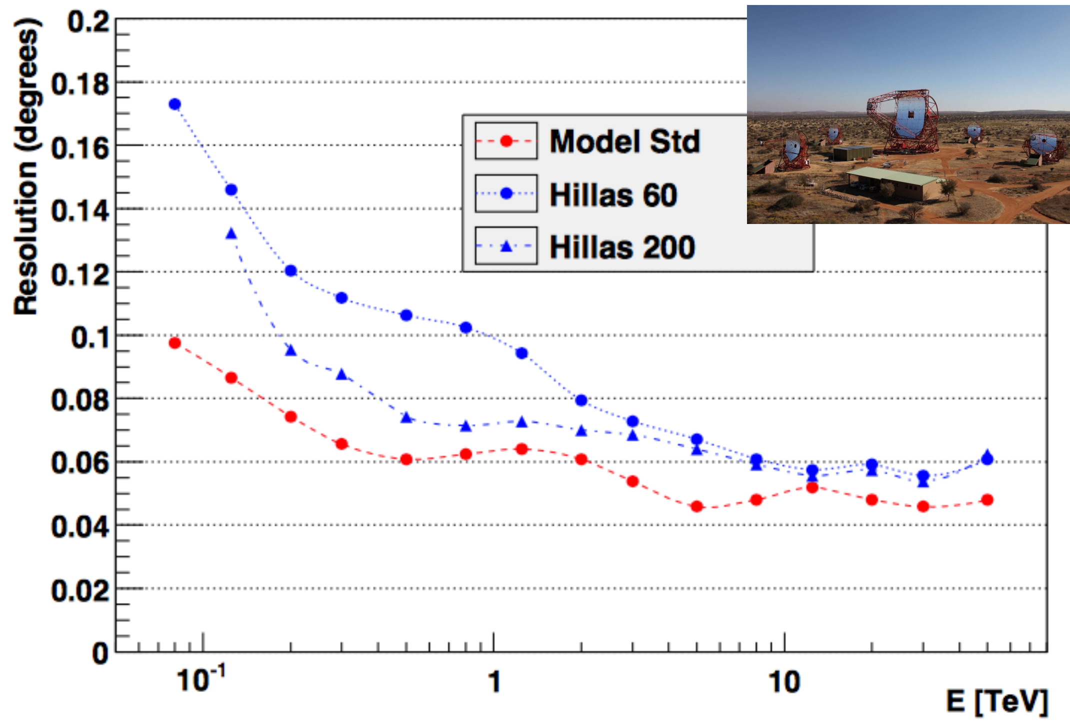
Fermi:
All-sky coverage
Angular resolution (PSF) is energy-dependent



TeV

Cut-off energy investigation
Search for PeVatron accelerators (photons with energy > 100 TeV)

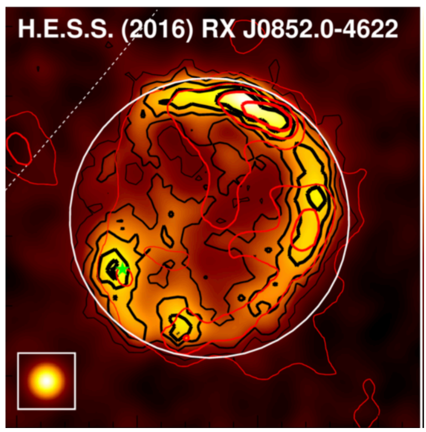
H.E.S.S.:
Relatively small field of view (~ 3.5°)
PSF slightly energy-dependent



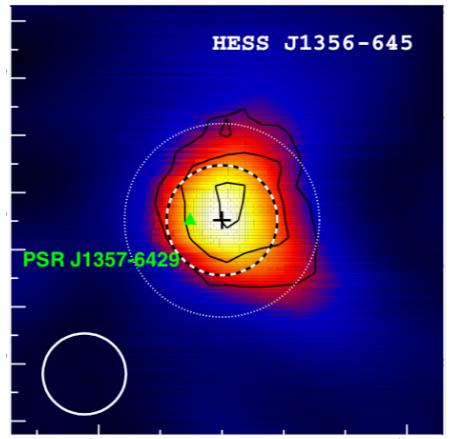
Connection between GeV and TeV energies necessary to understand the origin of the emission

Take home messages - Part I

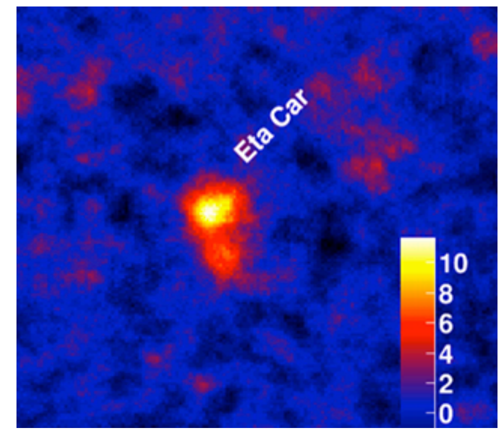
- High diversity of gamma-ray sources in the Galaxy



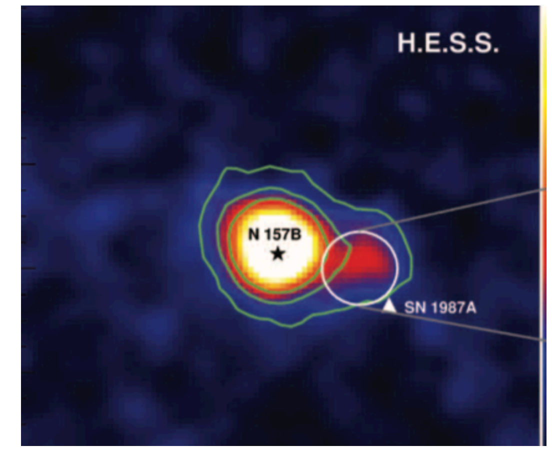
SNRs



PSRs, PWNe

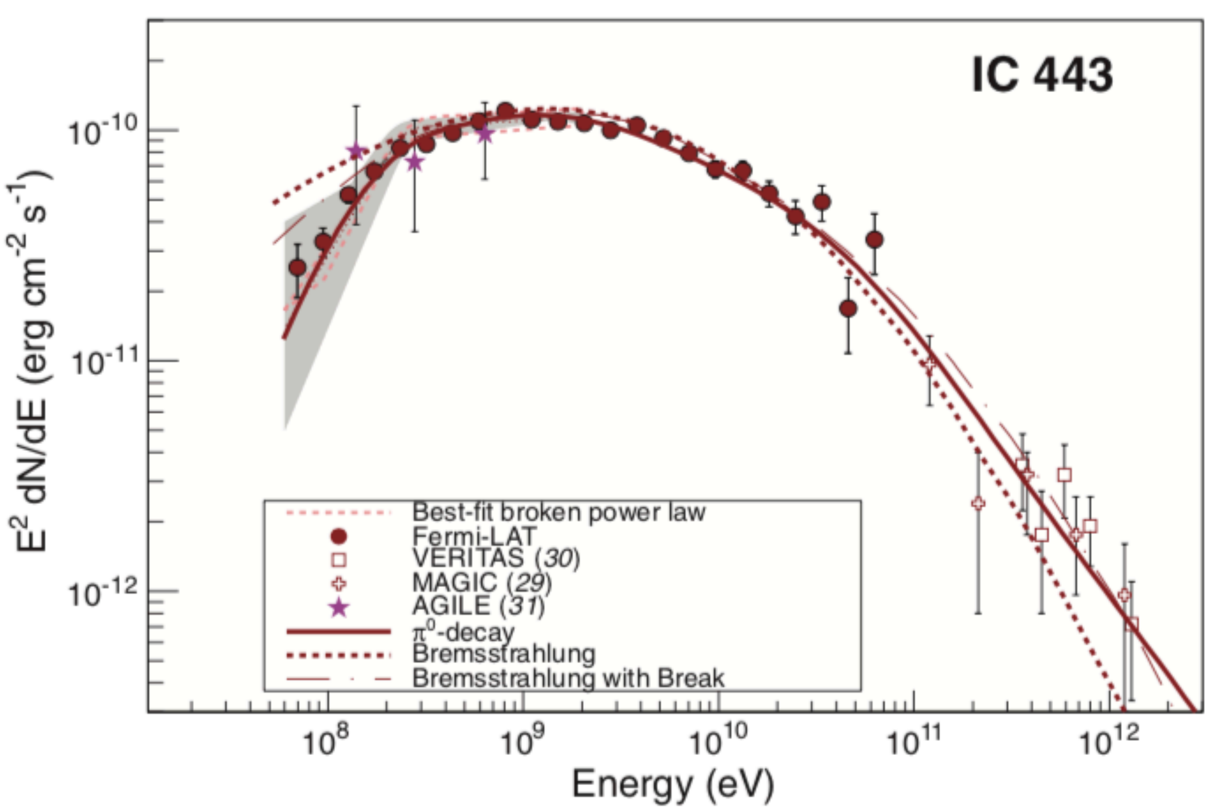


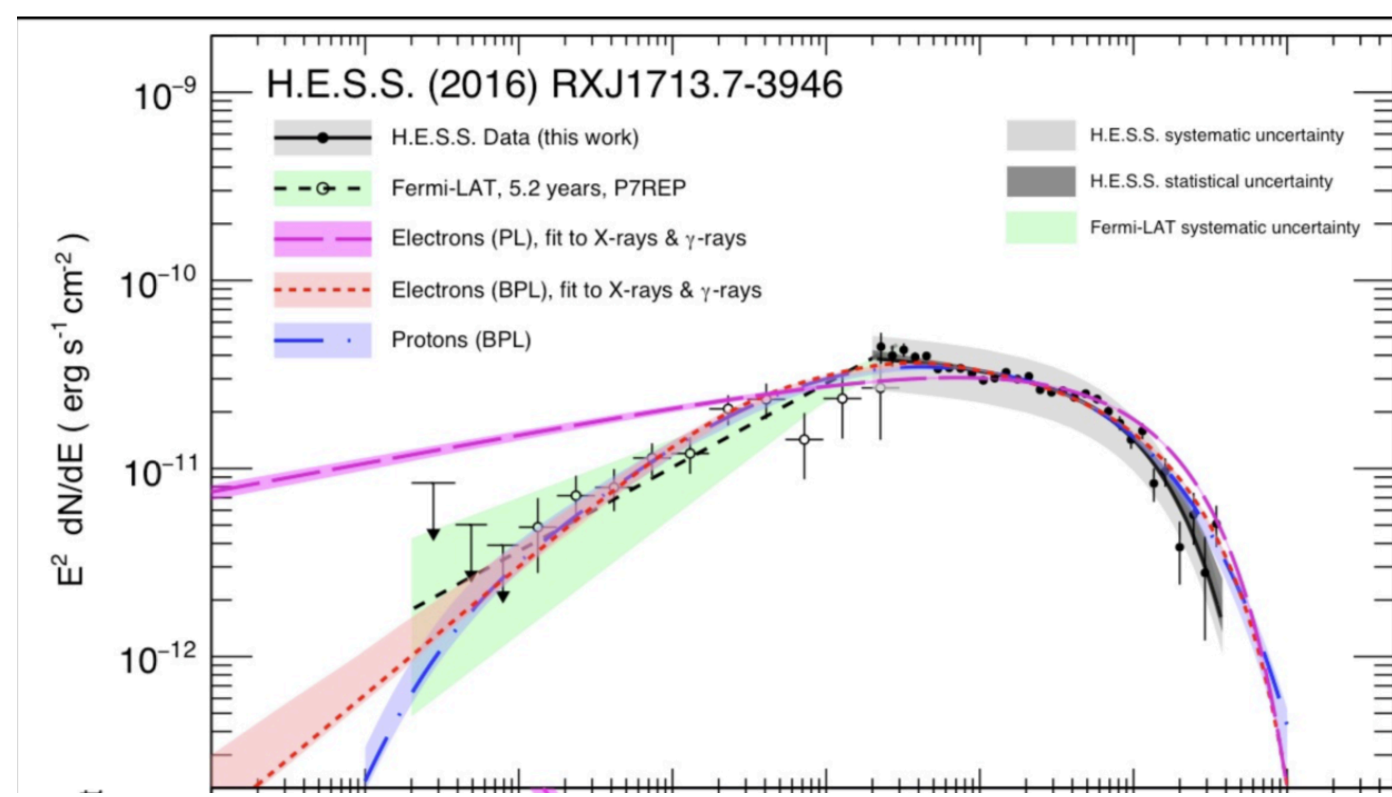
Binaries



Superbublles, SFR

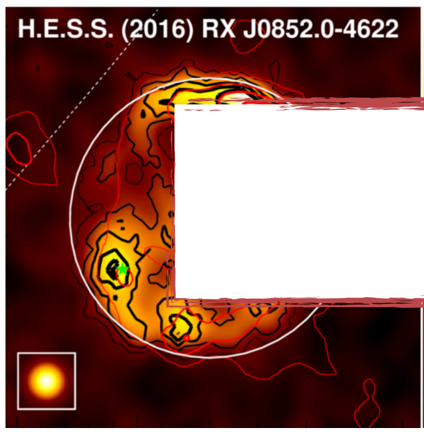
- Where are the Galactic cosmic-ray accelerators?

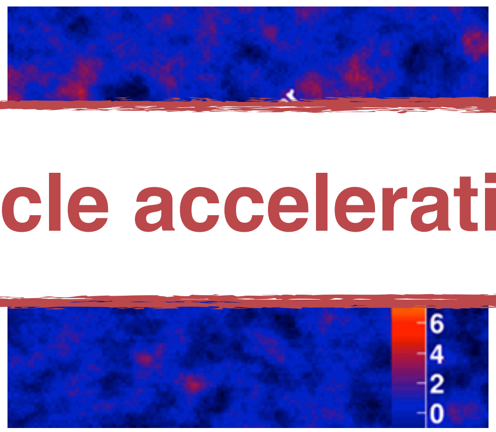


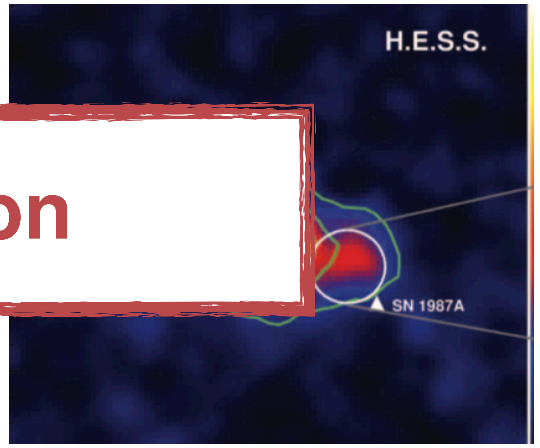


Take home messages - Part I

- High diversity of gamma-ray sources in the Galaxy



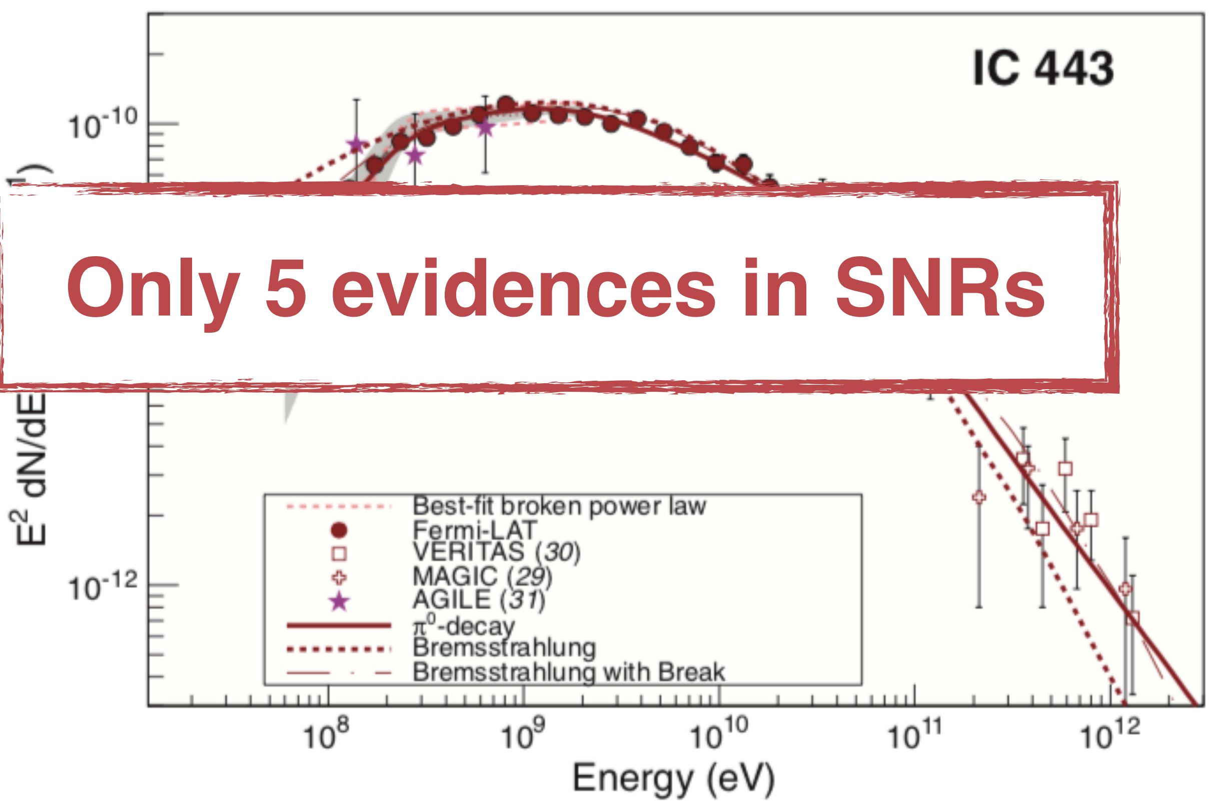




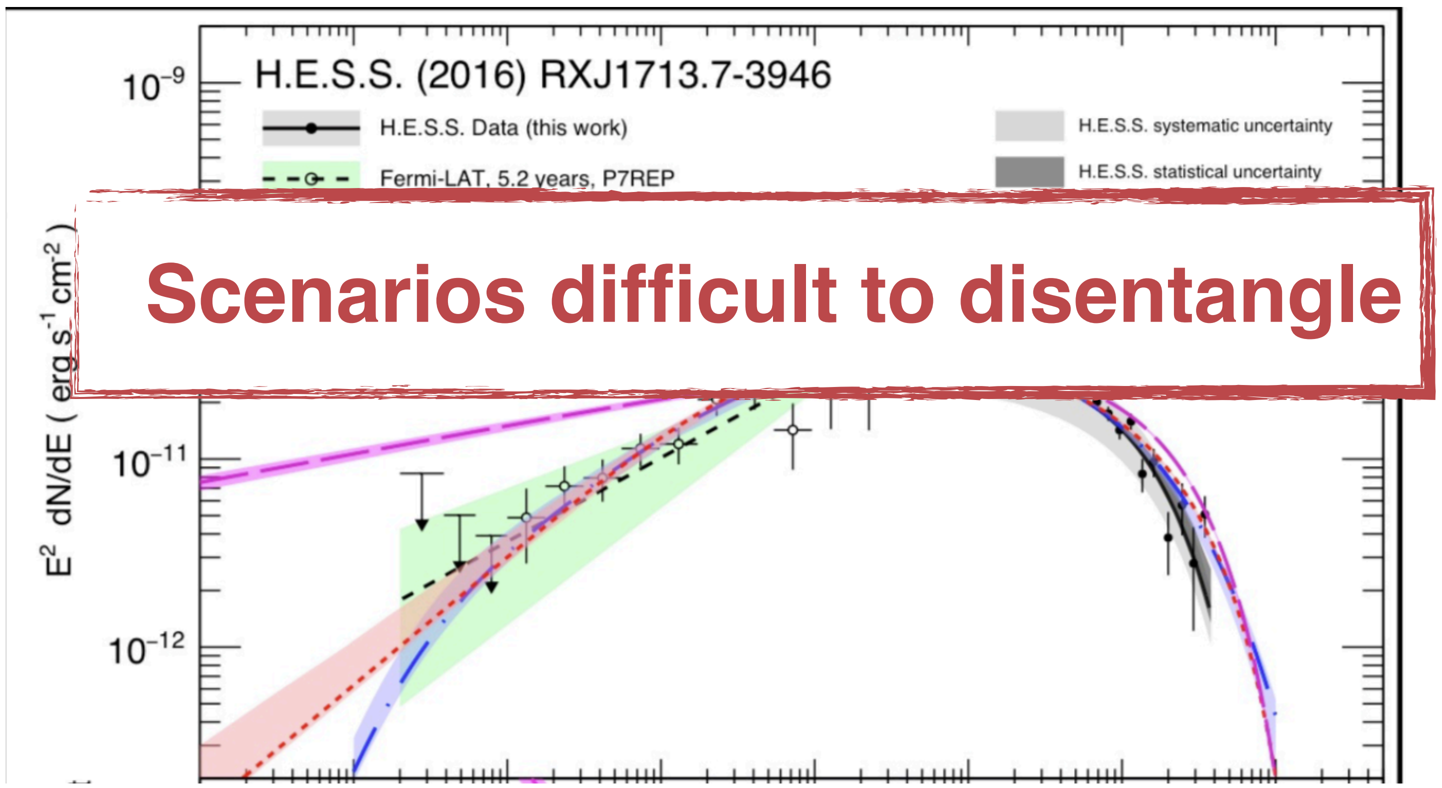
Efficient particle acceleration

SNRs | **PSRs, PWNe** | **Binaries** | **Superbublles, SFR**

- Where are the Galactic cosmic-ray accelerators?



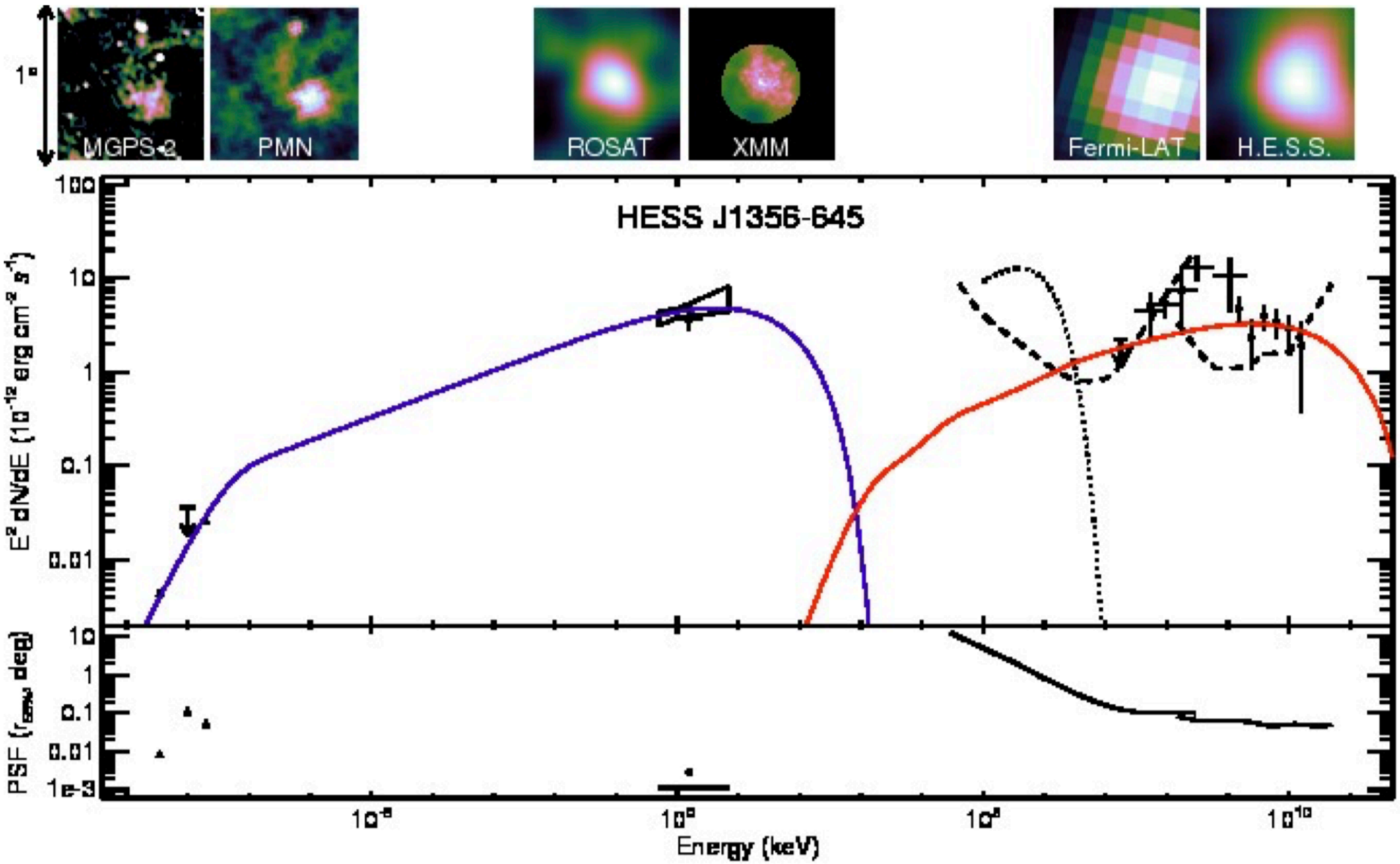
Only 5 evidences in SNRs



Scenarios difficult to disentangle

Difficulties in gamma-ray analyses

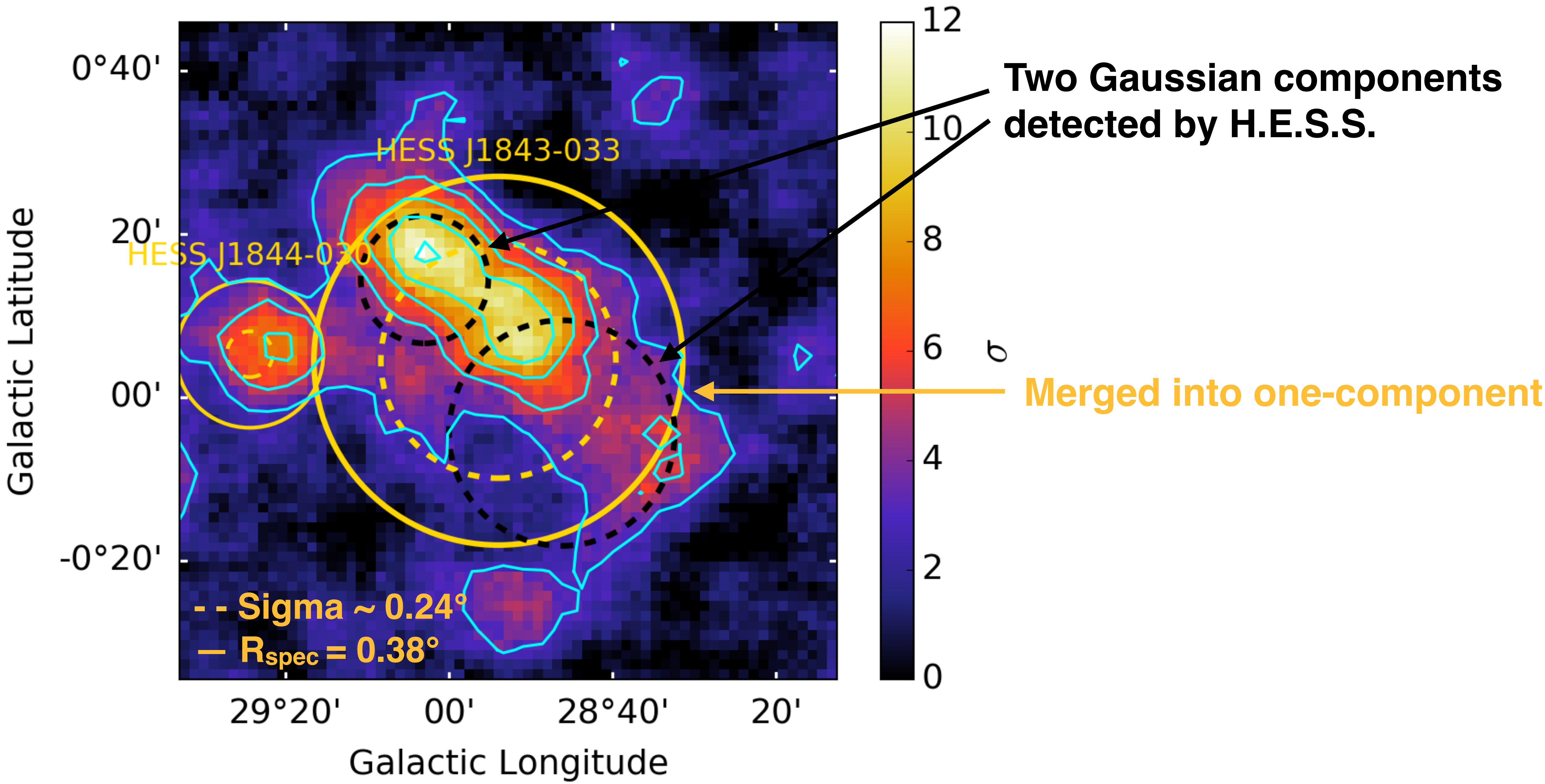
- PSF larger than that of most radio and X-ray instruments!



(Reynolds et al., 2017)

Difficulties in gamma-ray analyses

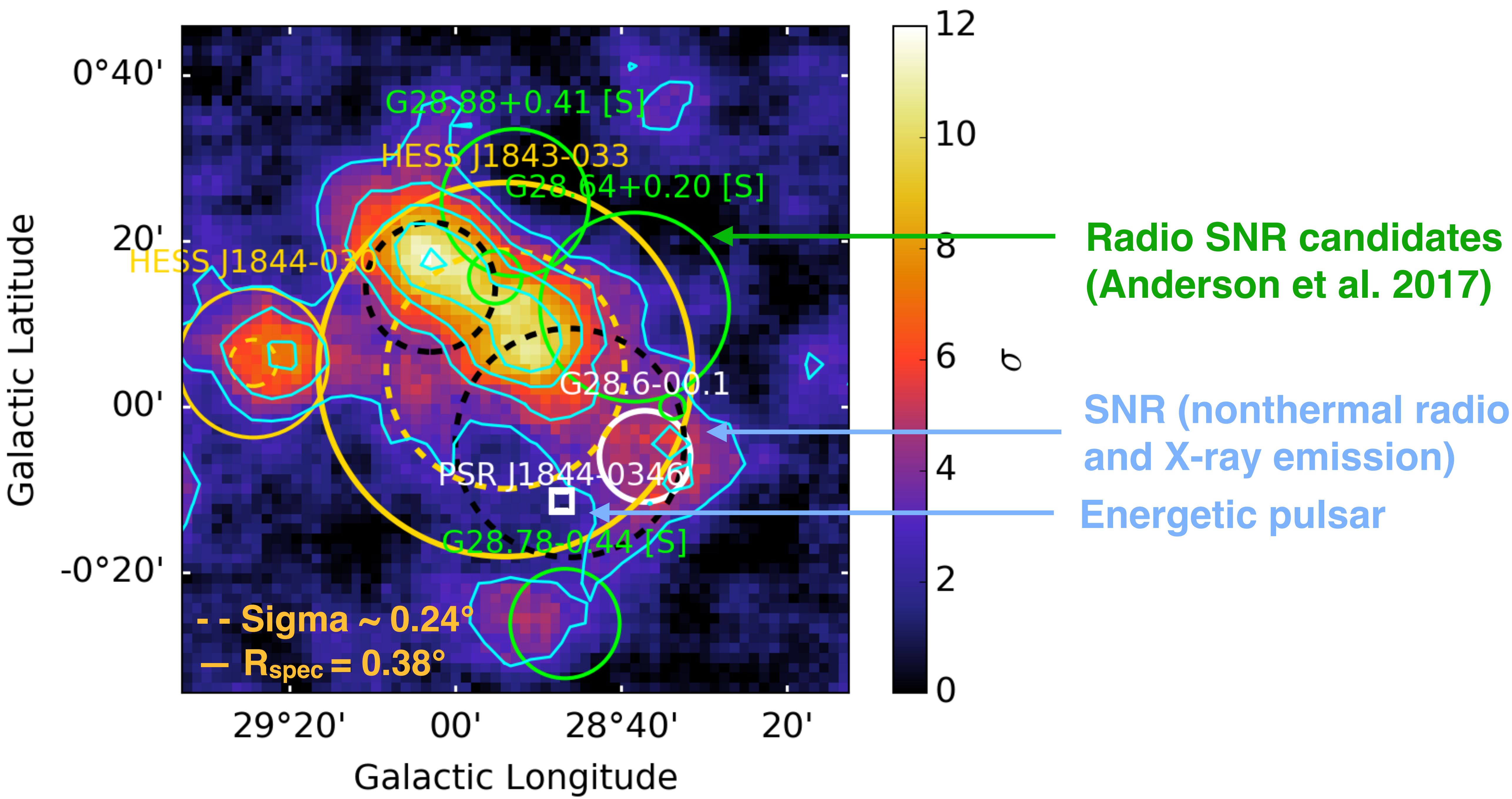
- Source confusion



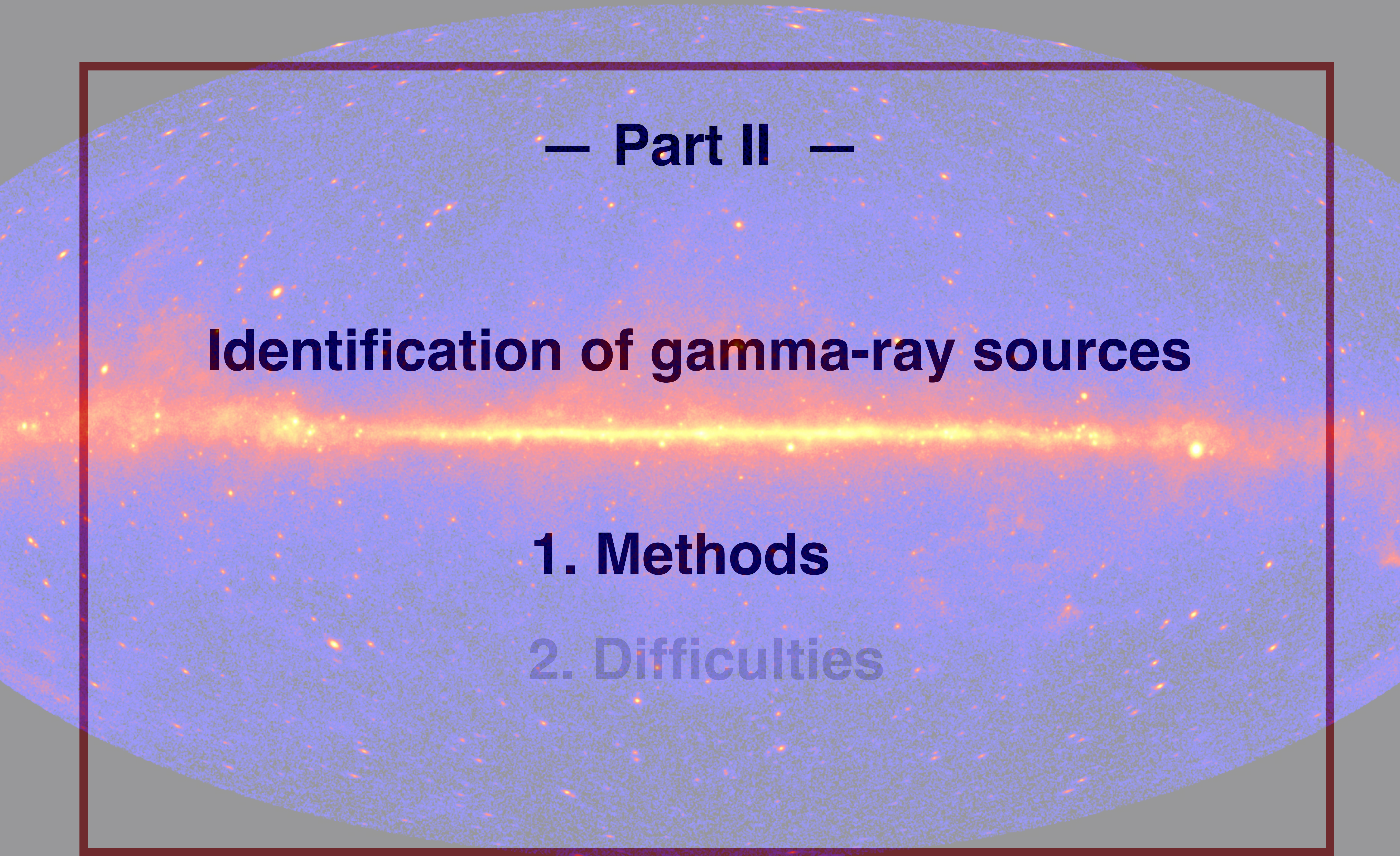
Significance map from **H.E.S.S Collaboration (2018)**

Difficulties in gamma-ray analyses

- Source confusion



Significance map from **H.E.S.S Collaboration (2018)**



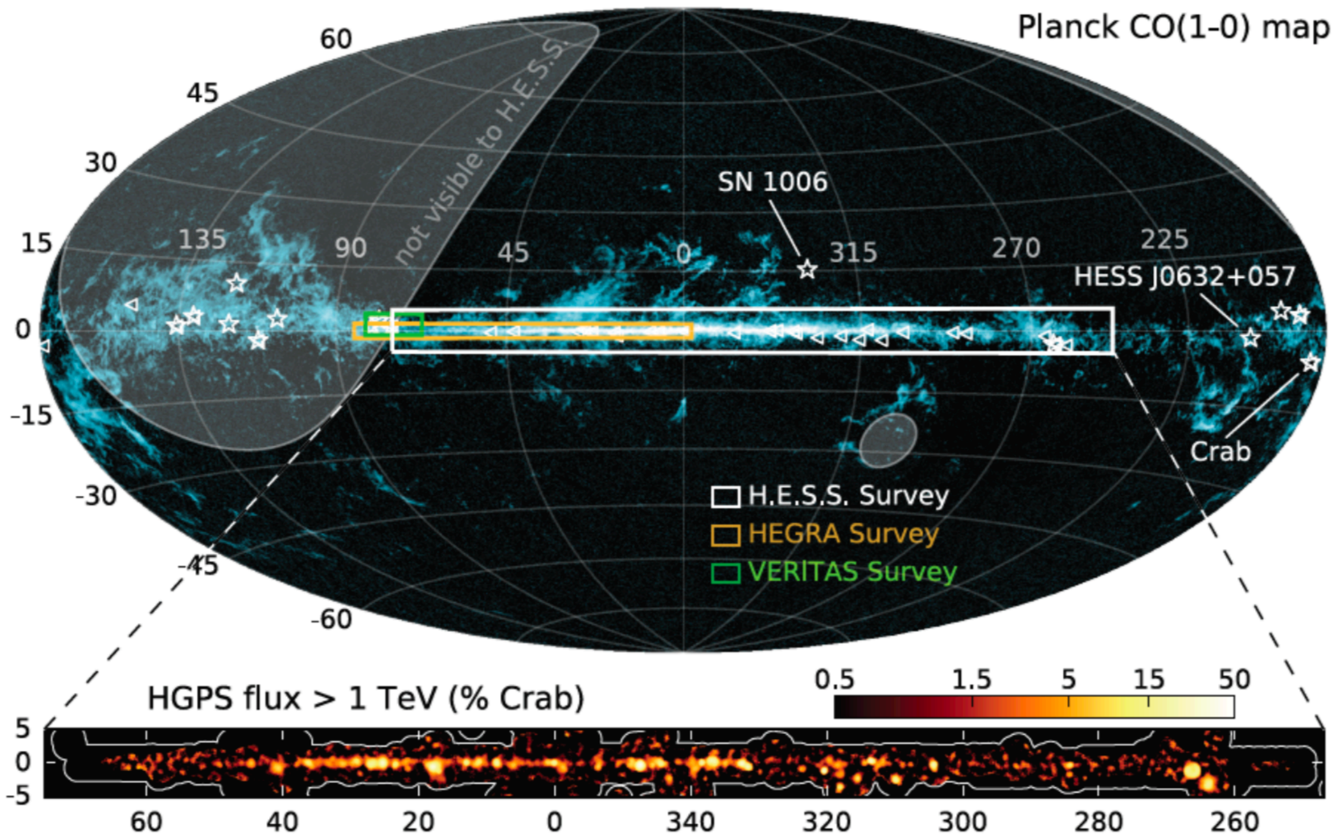
— Part II —

Identification of gamma-ray sources

1. Methods

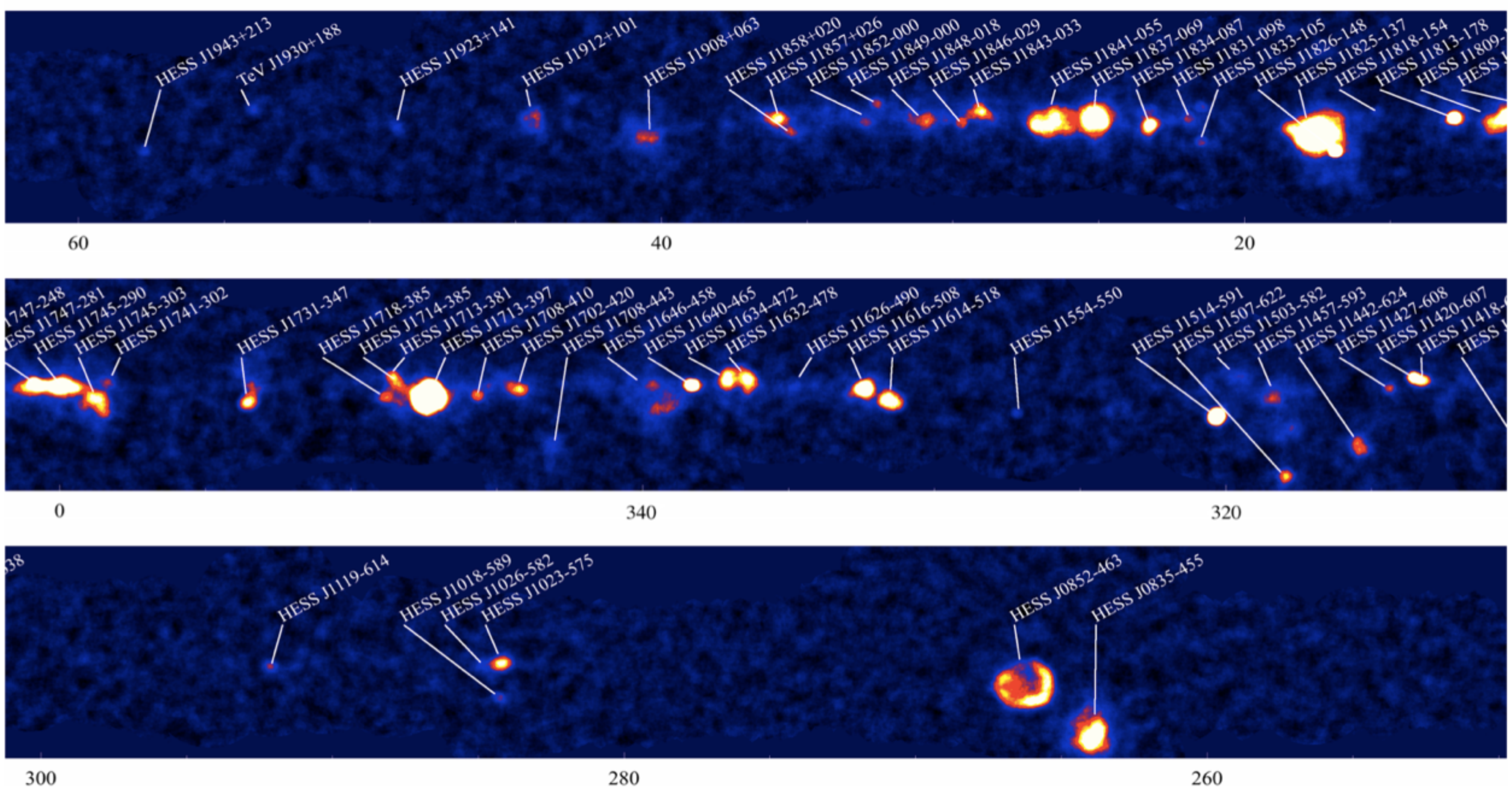
2. Difficulties

The H.E.S.S. Galactic Plane Survey



- ~ 2700 observation hours
- PSF ~ 0.08°
- Sensitivity <= 1.5% Crab

(H.E.S.S Collaboration 2018)



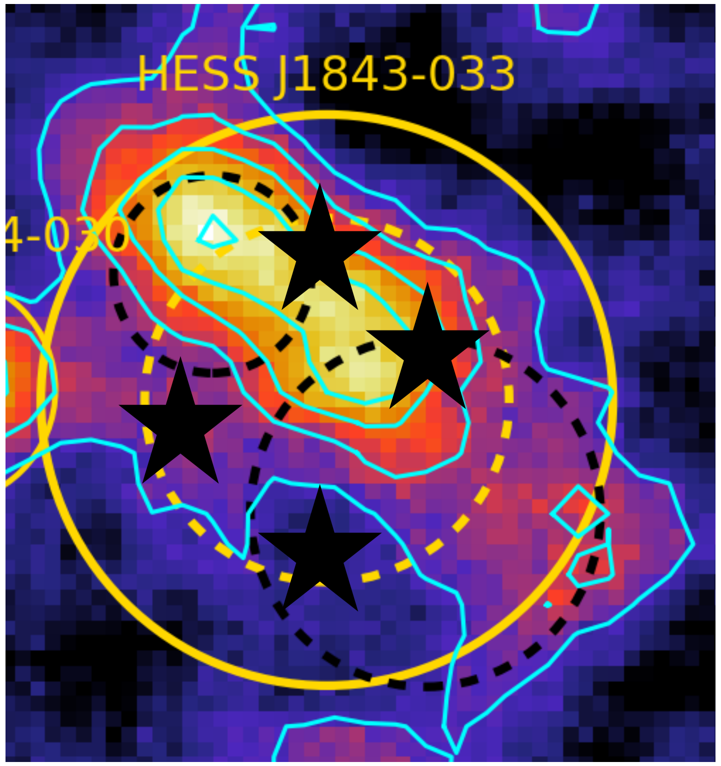
Deepest Galactic scan at VHE

250° < l < 65°
|b| < 3.5°

Association process

Catalogs: PSRs, « SNRcat », Fermi-LAT (3FGL, 2FHL), 20 extern analyses

★ **Associations**

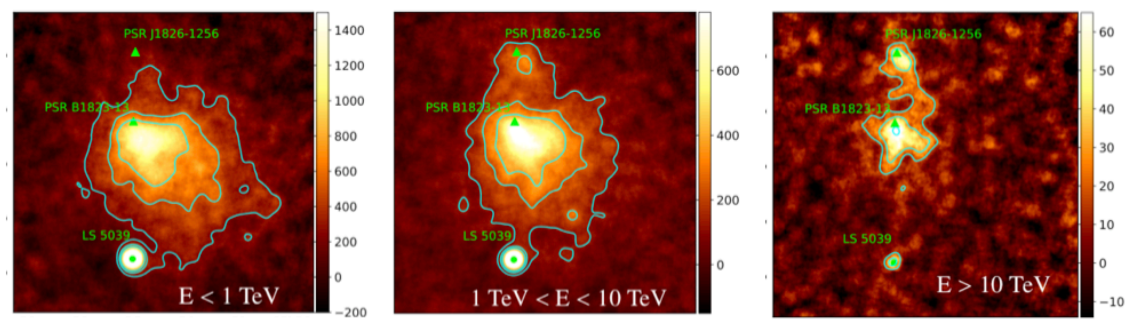


Note that VHE PWNe are often offset from its PSR and extended beyond its X-ray counterpart

Firm identifications

Identification criterion

1. Correlated multi-wavelength (MWL) variability
2. Matching MWL morphology
3. Energy-dependent gamma-ray morphology due to the cooling of energetic electrons as they are transported away from the pulsar



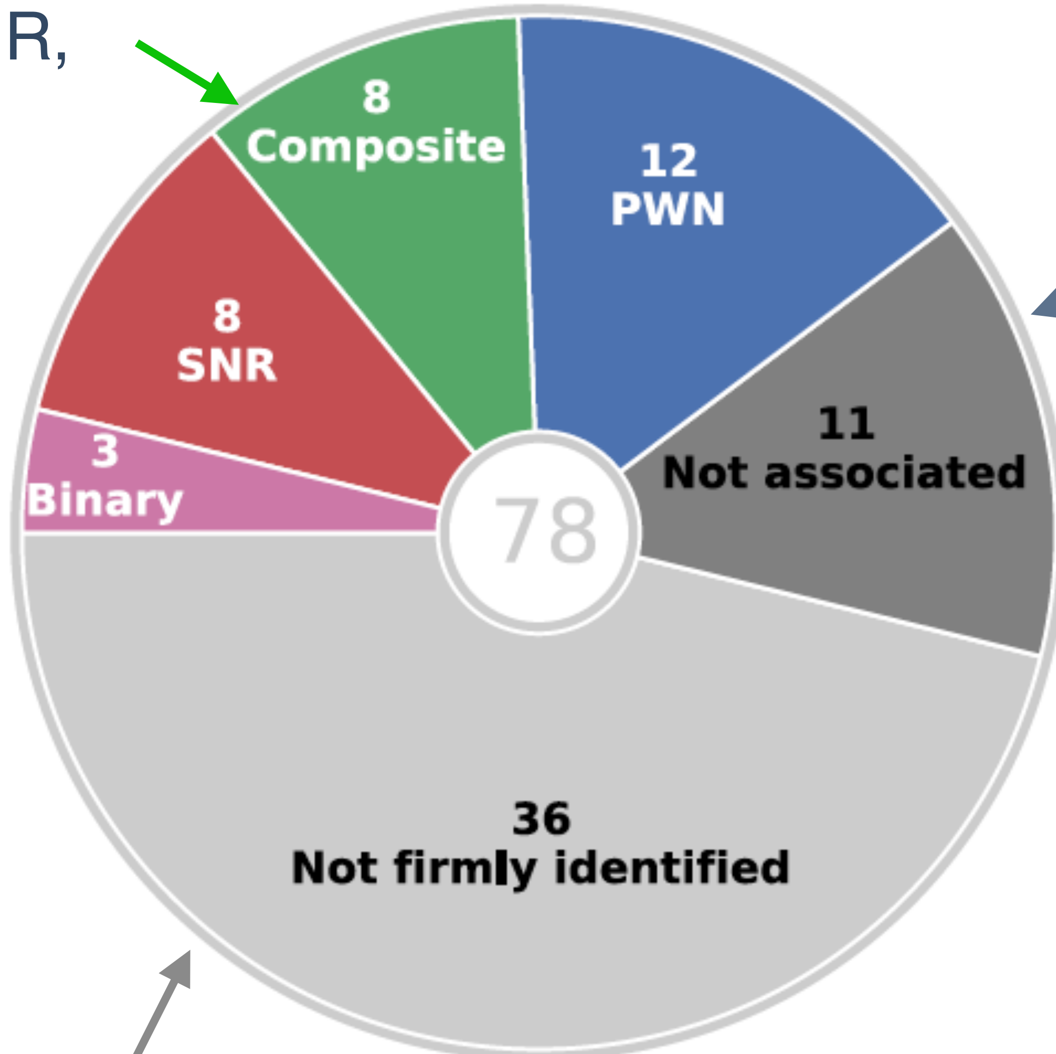
Compact binary systems: Point-like sources + variability also seen at lower energies

SNRs: Extended sources (provided the SNR is sufficiently large and close) + nonvariable + possible shell morphology with MWL counterparts

PWNe: MWL counterparts and energy-dependent morphology

Population in the HGPS

Emission from the SNR, the PWN, or both

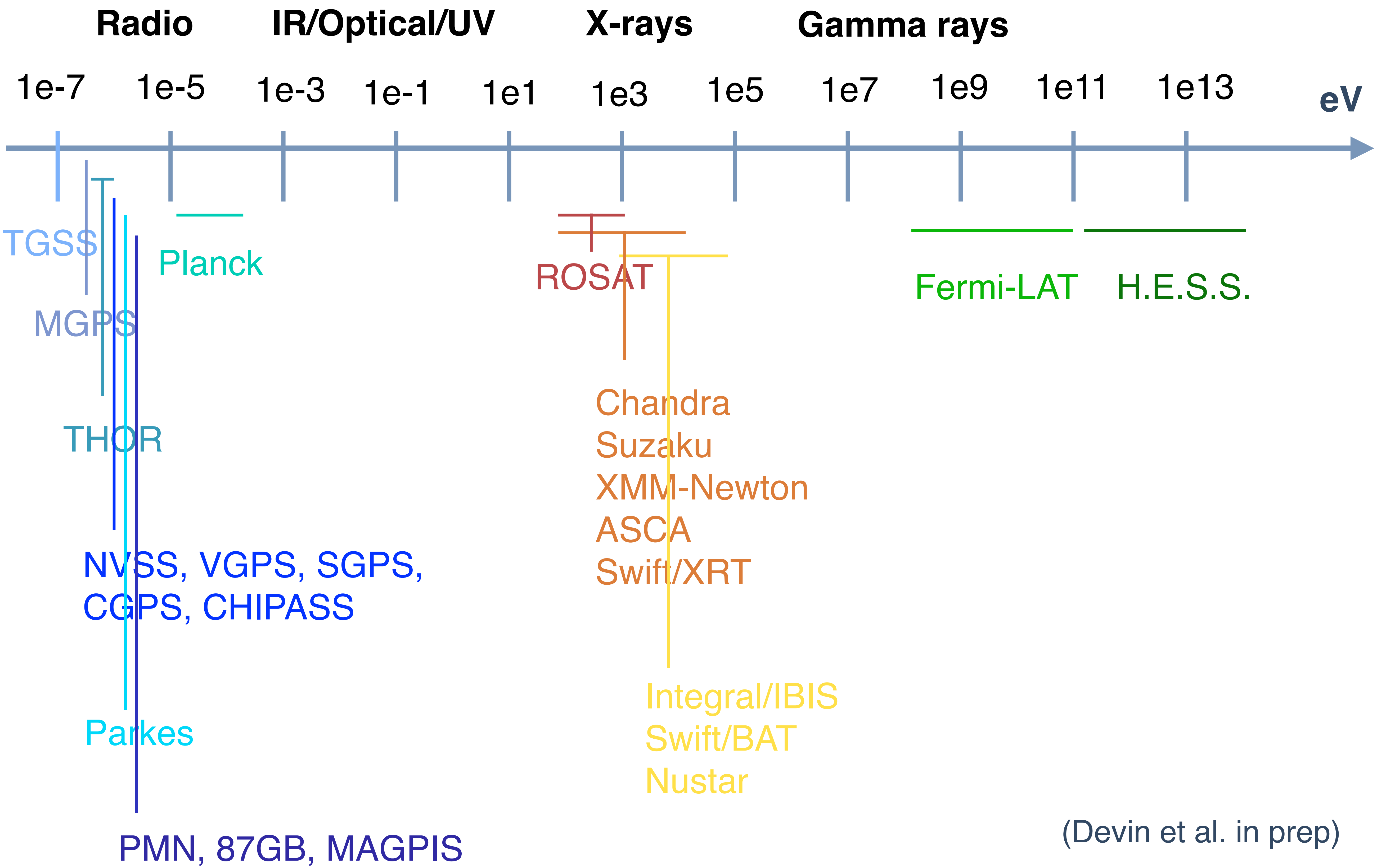


No cataloged objects spatially coincident with the H.E.S.S. source

- Contributions from multiple sources (in complex regions)
- Several possible scenarios

More than half of the HGPS sources are not firmly identified!

Multi-wavelength data exploitation



(Devin et al. in prep)

Multi-wavelength data exploitation

- **Radio spectral index**

Thermal or nonthermal emission?

$$S_\nu \propto \nu^\alpha \qquad \alpha_{\rm SNR} \sim -0.5 \qquad \alpha_{\rm PWN} \sim -0.3 - 0$$

Thermal emission: $\alpha_{\rm th} \geq 0$

- **X-ray/TeV data**

Mean magnetic field?

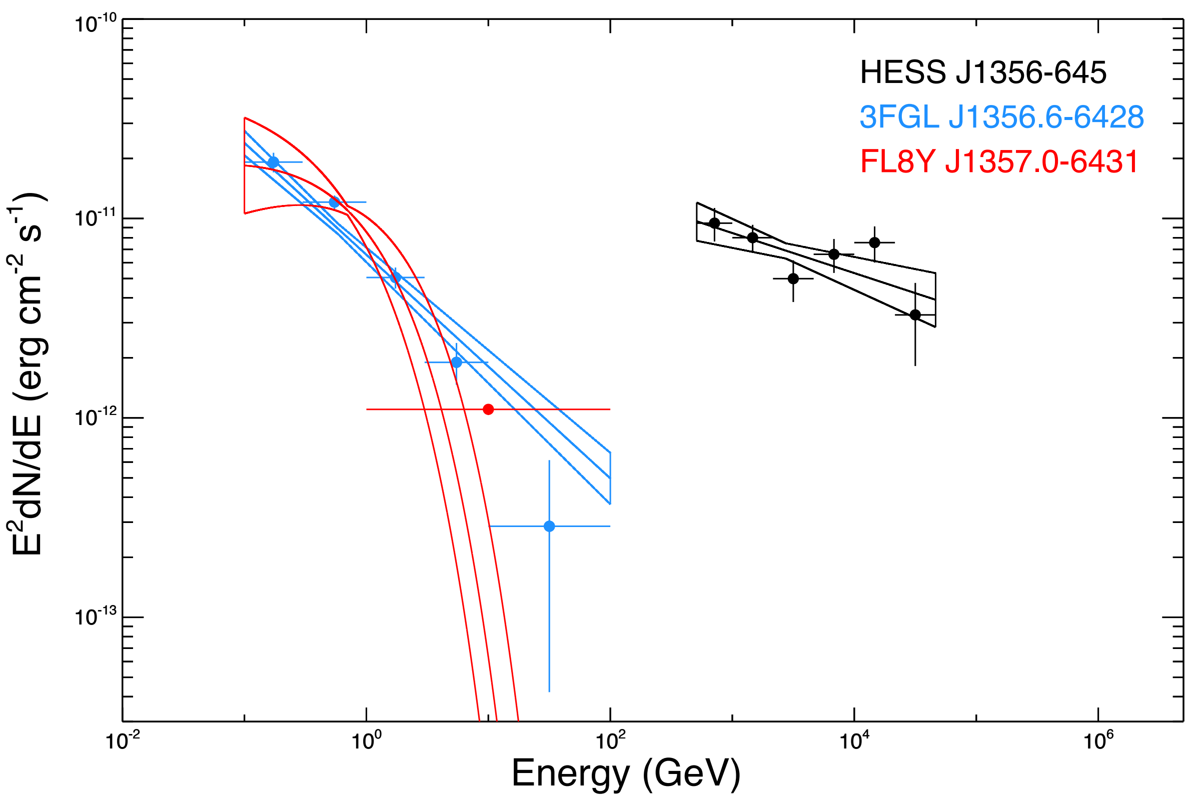
One-zone model in the Thomson regim: $\Gamma_{\rm X} = \Gamma_{\rm TeV}$

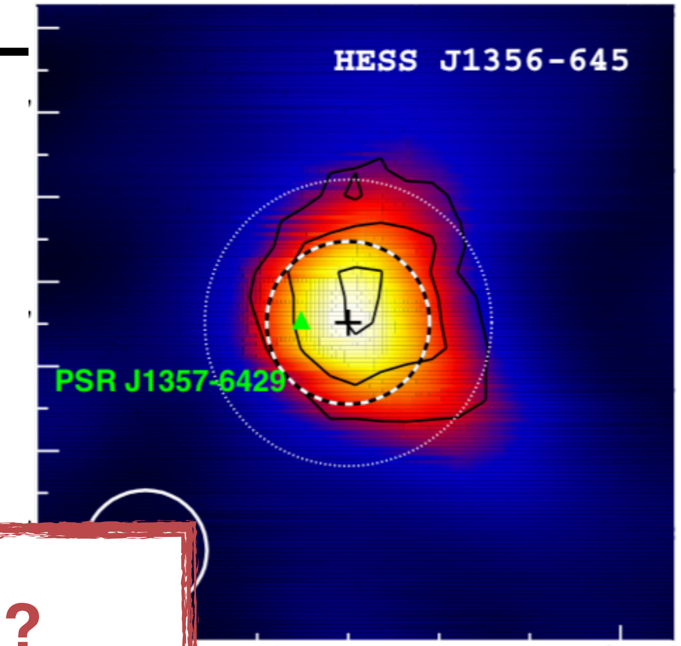
$$\frac{B}{10\ \mu G} \simeq {\rm G}(\Gamma) \times \left(\frac{F_{\rm SYN}}{F_{\rm IC}} \times \frac{E^{2-\Gamma}_{2,{\rm IC,TeV}} - E^{2-\Gamma}_{1,{\rm IC,TeV}}}{E^{2-\Gamma}_{2,{\rm SYN,keV}} - E^{2-\Gamma}_{1,{\rm SYN,keV}}} \right)^{1/\Gamma}$$

$B_{\rm PWN} \sim 3 - 10\ \mu G$ (evolved PWNe) $\qquad B_{\rm SNR} \sim 15 - 20\ \mu G$ (linear DSA)

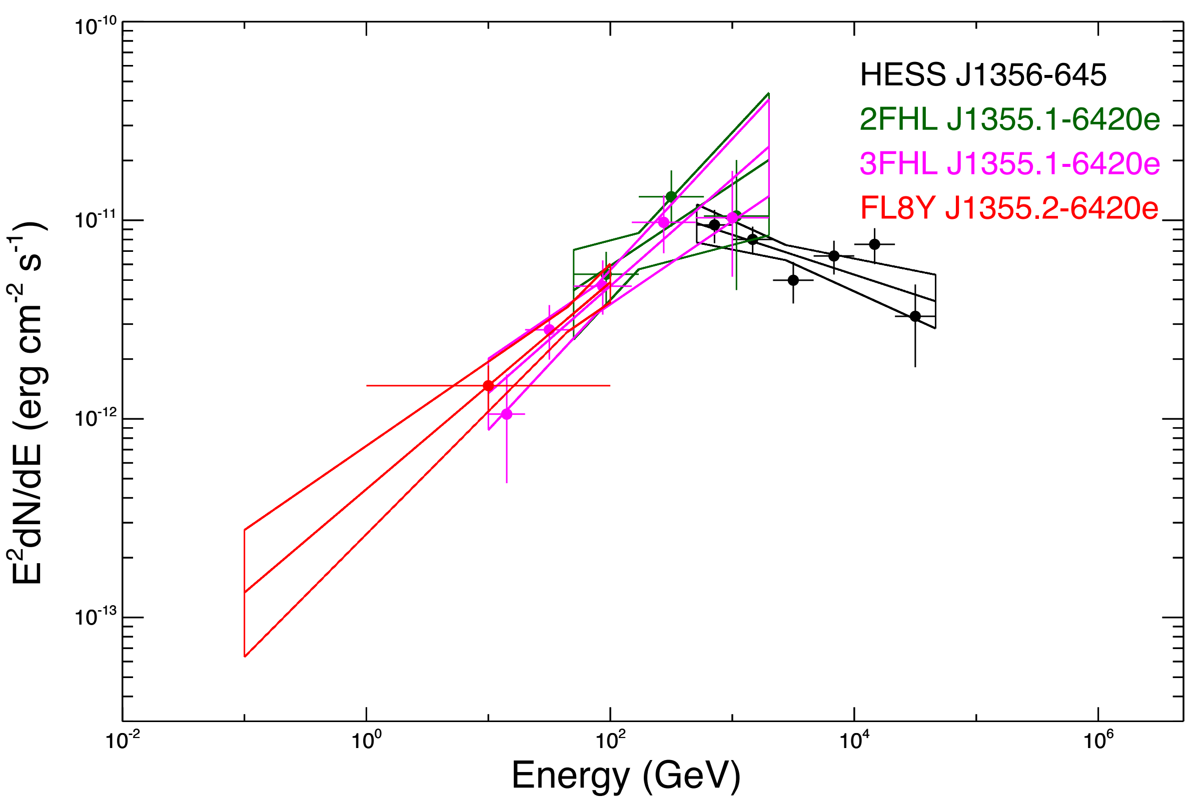
Multi-wavelength data exploitation

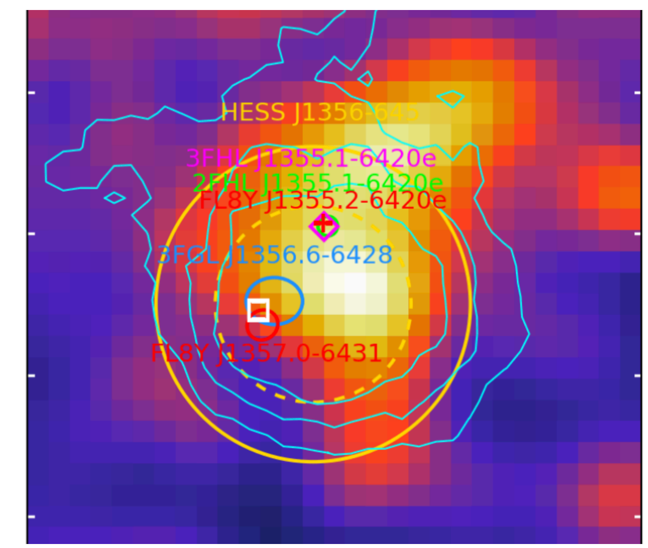
- **Fermi-LAT counterparts**





PSR-like spectrum?

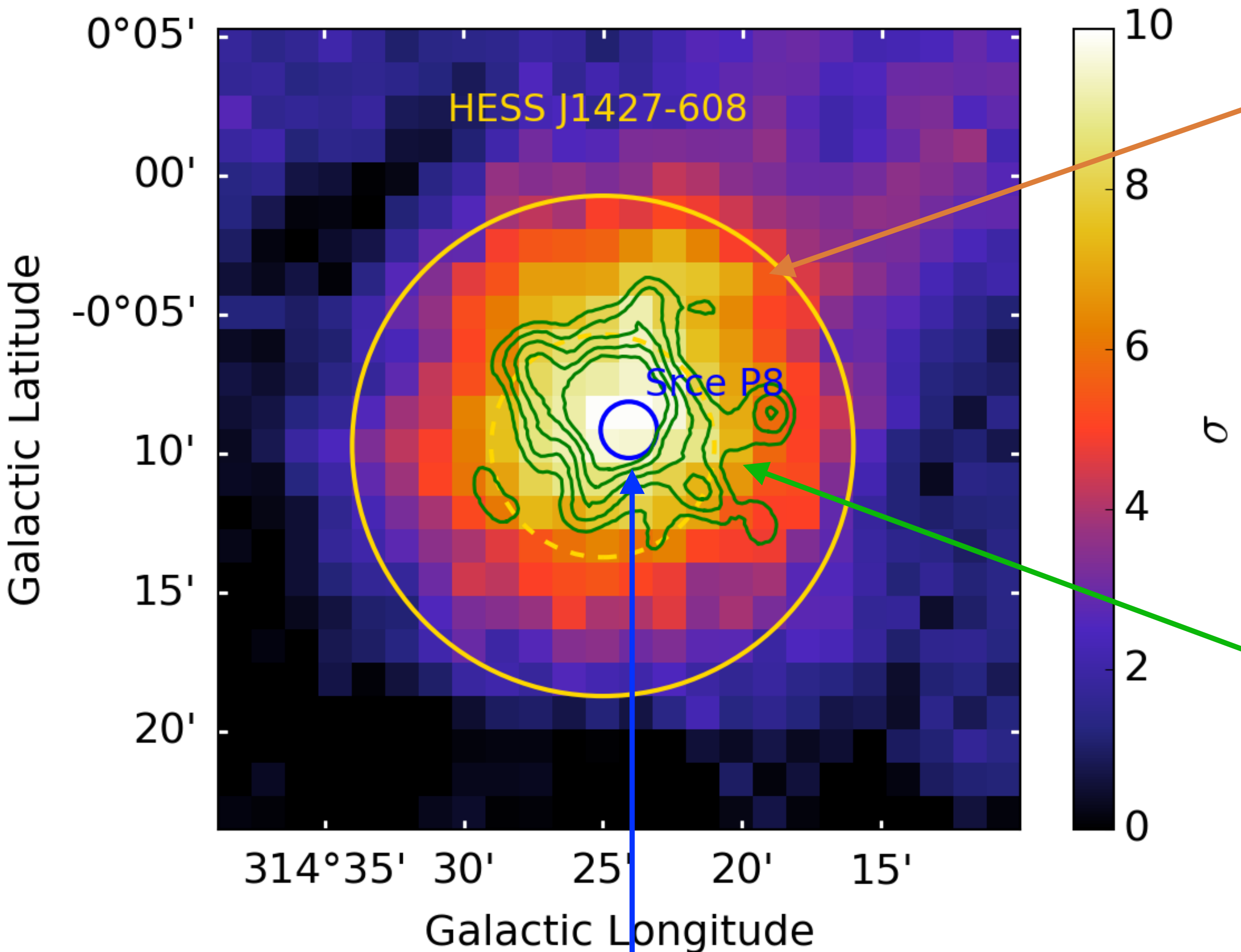




PWN or SNR spectrum?

The unidentifed source HESS J1427-608

H.E.S.S. significance map



- **Point-like source in the HGPS**

$R_{spec} = 0.15°$ $\sigma < 0.067$ deg

- ***S**uzaku* **extended source**

(Fujigana et al., 2013)

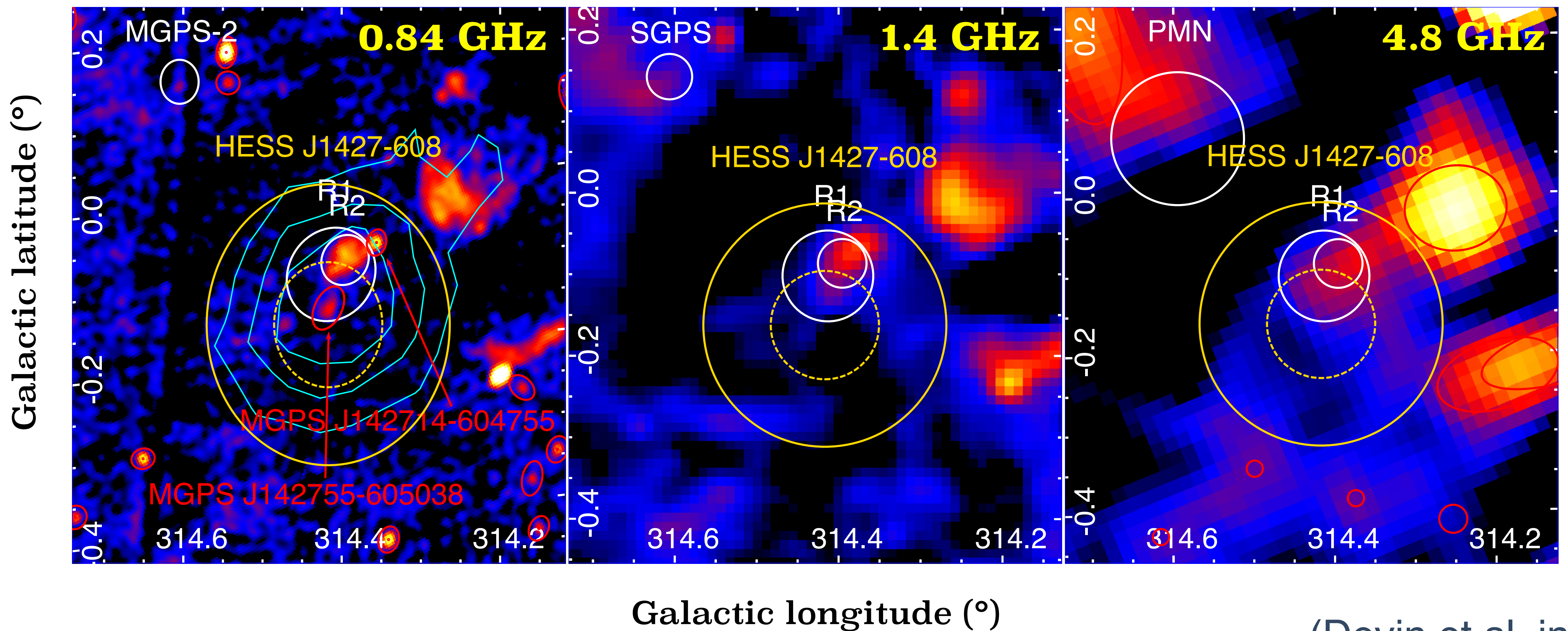
$$\Gamma_X = 3.1^{+0.6}_{-0.5}$$

$$N_H = 1.1^{+0.29}_{-0.25} \times 10^{23}\ \mathrm{cm}^{-2}$$

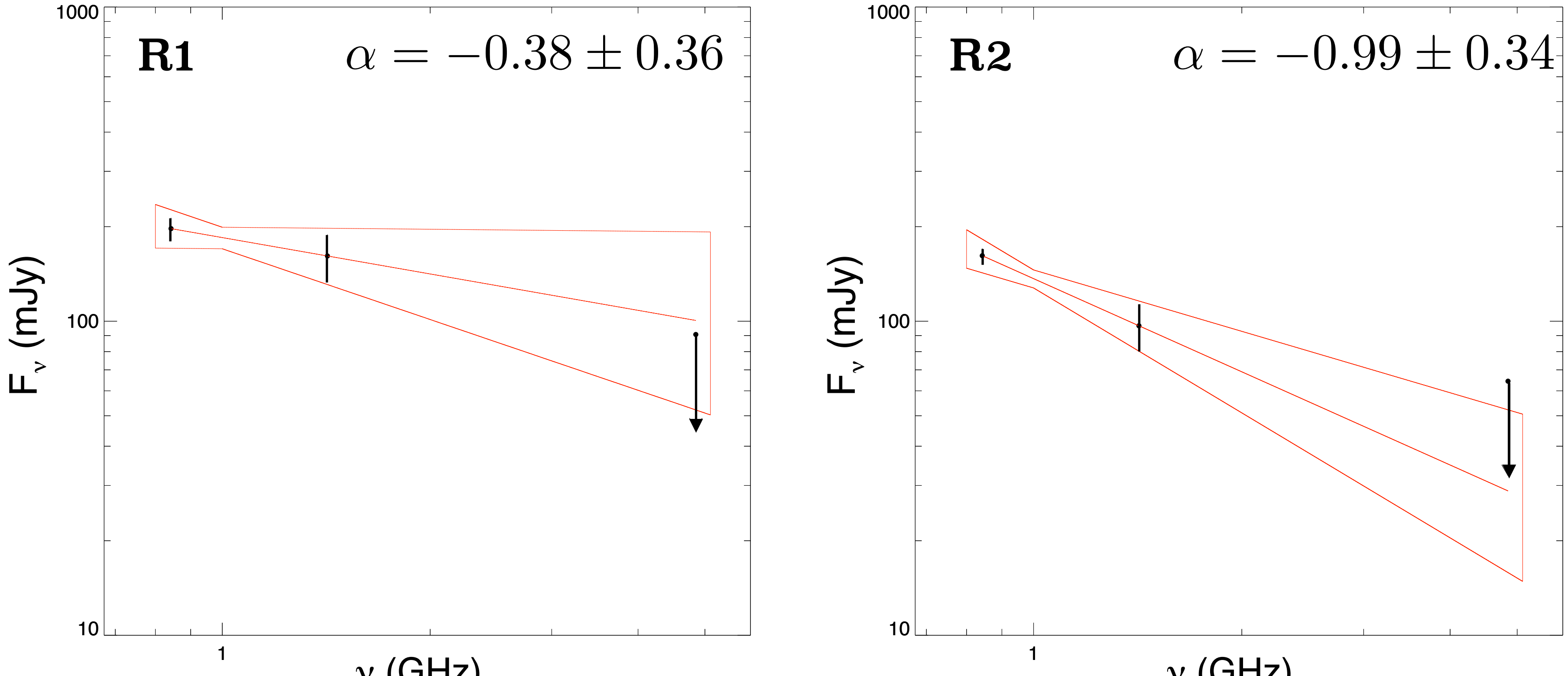
- **Point-like *Fermi*-LAT source**

(Guo et al., 2018)

HESS J1427—608 - radio observations

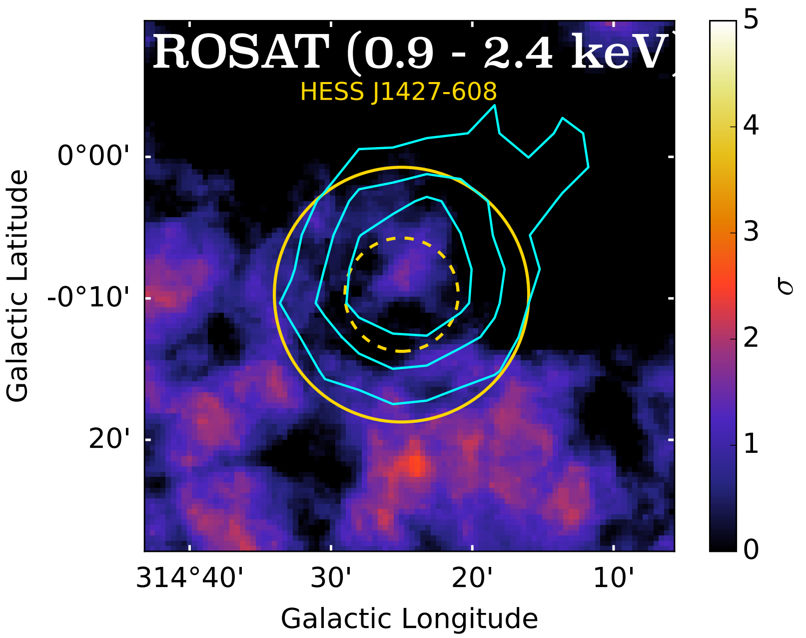


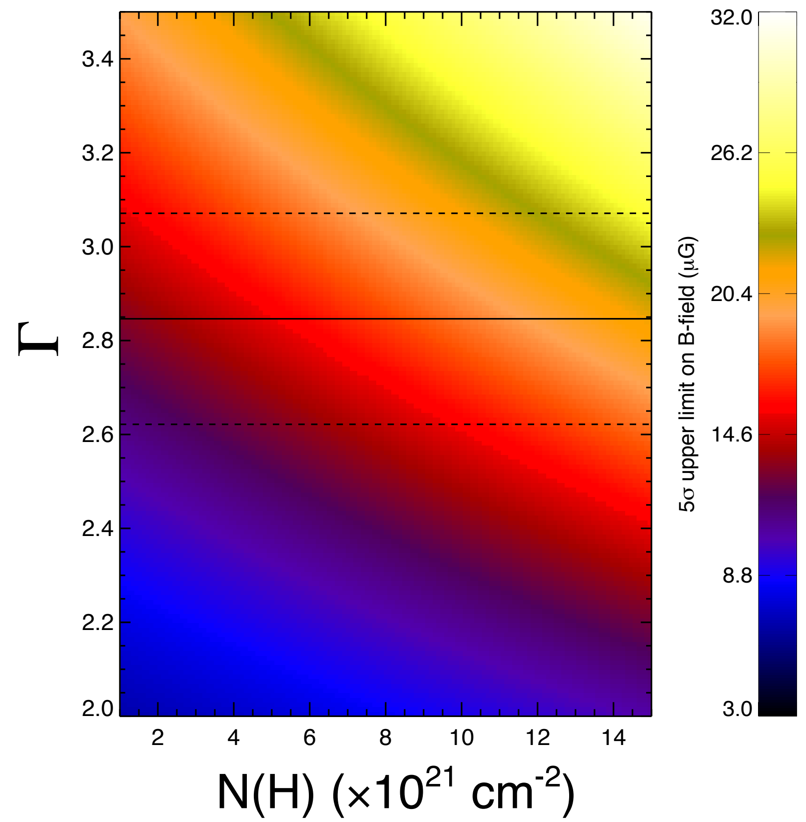
(Devin et al. in prep)



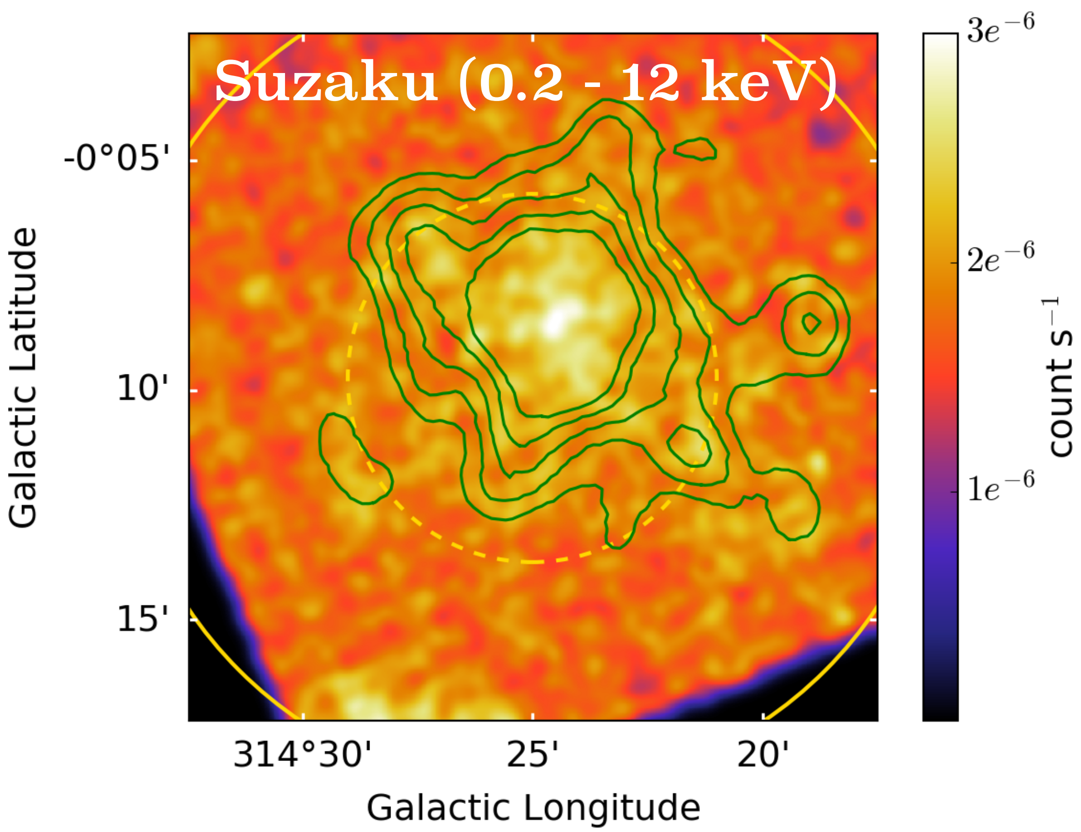
Nonthermal emission

HESS J1427—608 - X-ray observations





No tight constrain on B



$$F_{2-10\ \mathrm{keV}} = 8.9^{+3.6}_{-2.0} \times 10^{-13}\ \mathrm{erg\ s^{-1}\ cm^{-2}}$$

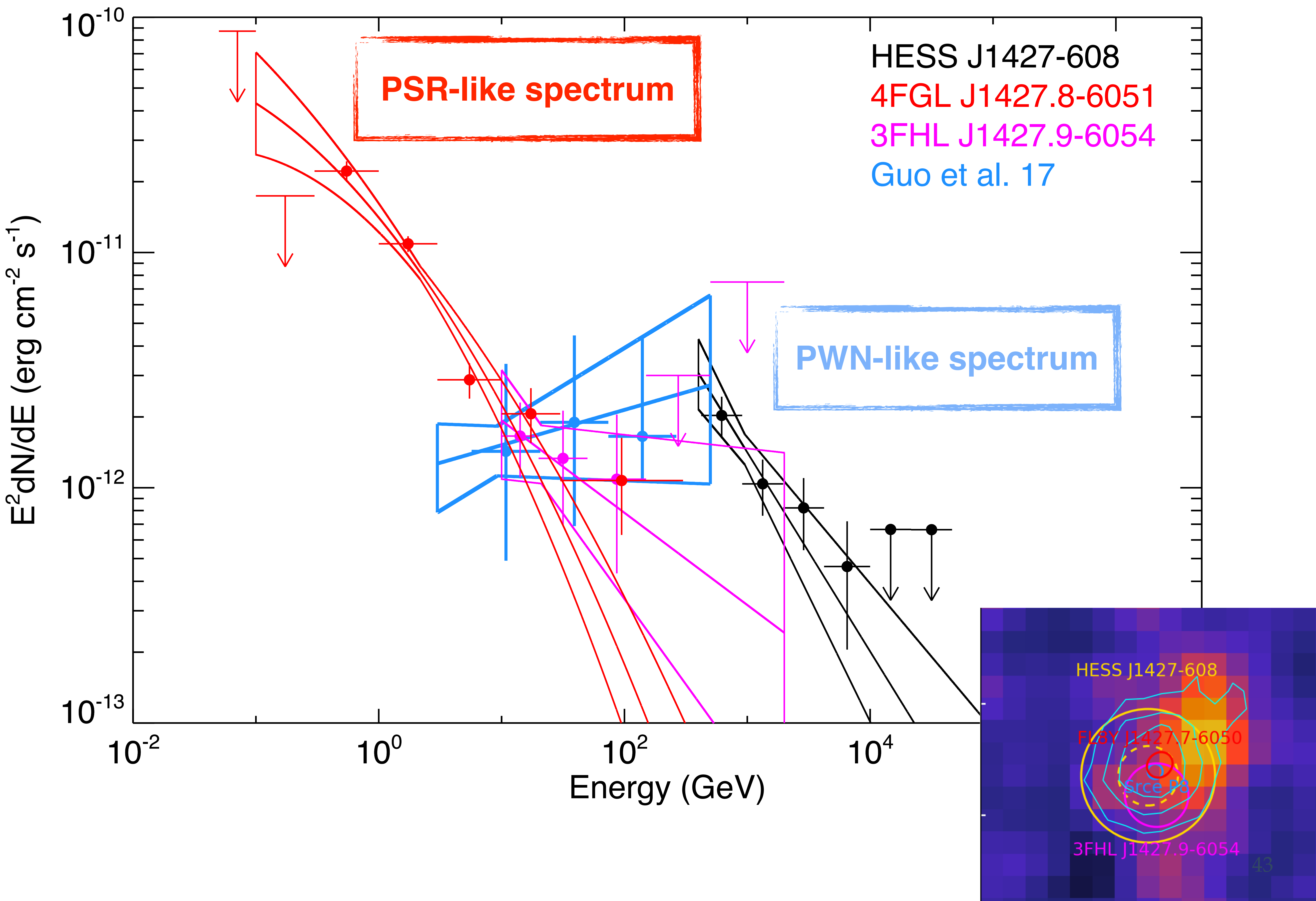
$$\Gamma_{\mathrm{HGPS}} = 2.85 \pm 0.22$$ (Fujigana et al., 2013)

$$\Gamma_{\mathrm{X}} = \Gamma_{\mathrm{HGPS}} \qquad (\Gamma_{\mathrm{X}} = 3.1^{+0.6}_{-0.5})$$

$$B = 10.9\ [7.7 - 15.4]\ \mu G$$

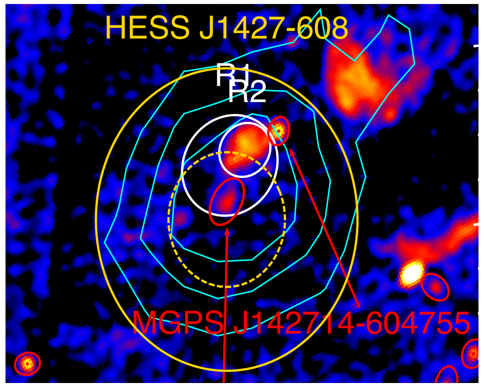
Similar to that obtained for evolved PWNe

HESS J1427—608 - GeV observations



HESS J1427—608: a strong PWN candidate

- **Radio:** extended source with $\alpha = -0.38 \pm 0.36$

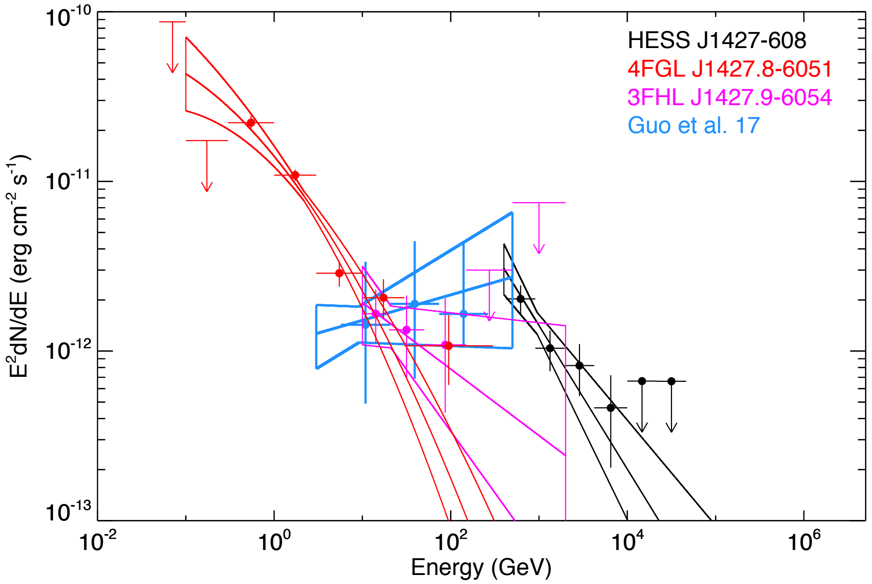


=> Nonthermal emission

- **Rayons X:** extended source with $B \sim 10\ \mu G$

=> Similar to that obtained for evolved PWNe

- **GeV:**



=> PSR + PWN-like spectrum

Need more observations in X-rays to detect the putative PSR!

— Part II —

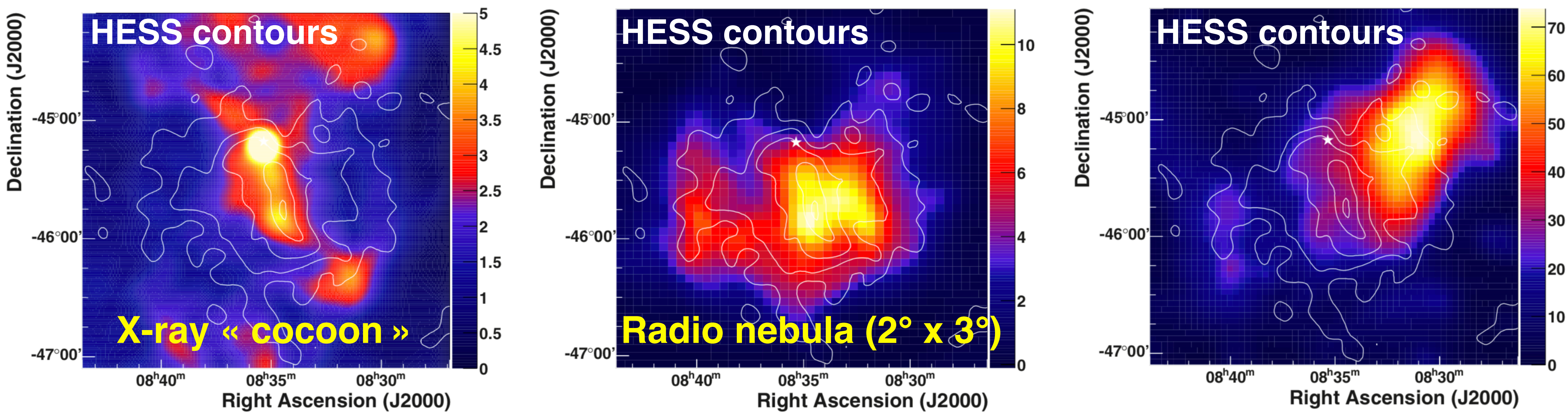
Identification of gamma-ray sources

1. Methods

2. Difficulties

The puzzling case of the PWN Vela X

(HESS Collaboration 2012)



X-rays (ROSAT) **Radio (Parkes)** **GeV (Fermi)**

- PSR B033-45: $\tau_c = 11 \text{ kyr} \quad \dot{E} = 6.9 \times 10^{36} \text{ erg s}^{-1}$ **(d = 290 pc)**

VHE morphology:

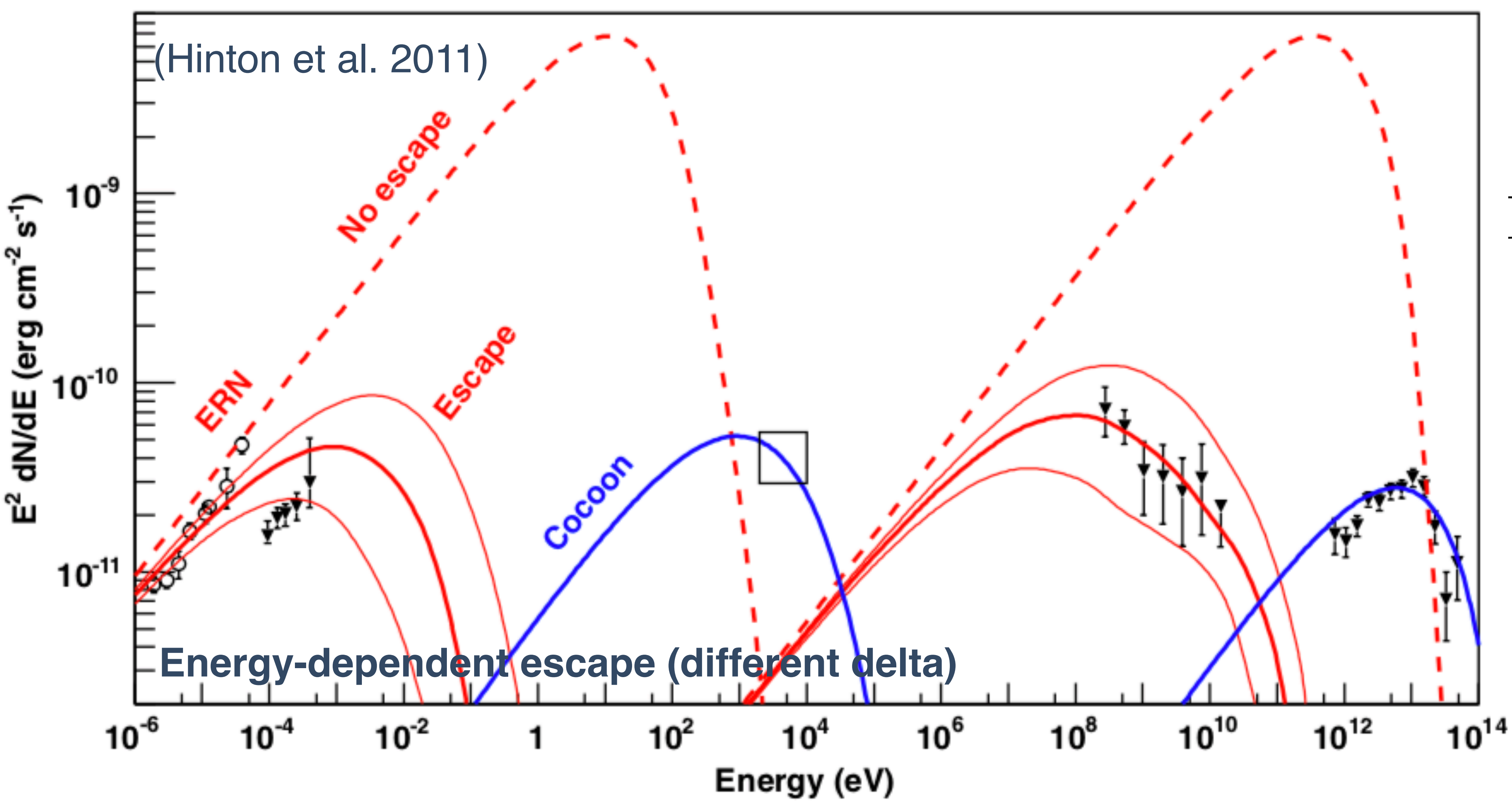
— **35% X-ray like:** difference can be explained by cooling times
— **65% radio-like:** another electron population?

The puzzling case of the PWN Vela X

Fermi-LAT steepening of the spectrum cannot be explained by cooling given the condition in the nebula (for $E_e < 10$ TeV, $t > 30$ kyr and $t_{age} = 10$ kyr)

=> Could be **escaping particles**

No cooling in cocoon ($s_e = 2$, $E_{cut} = 70$ TeV, B = 4.5 muG)



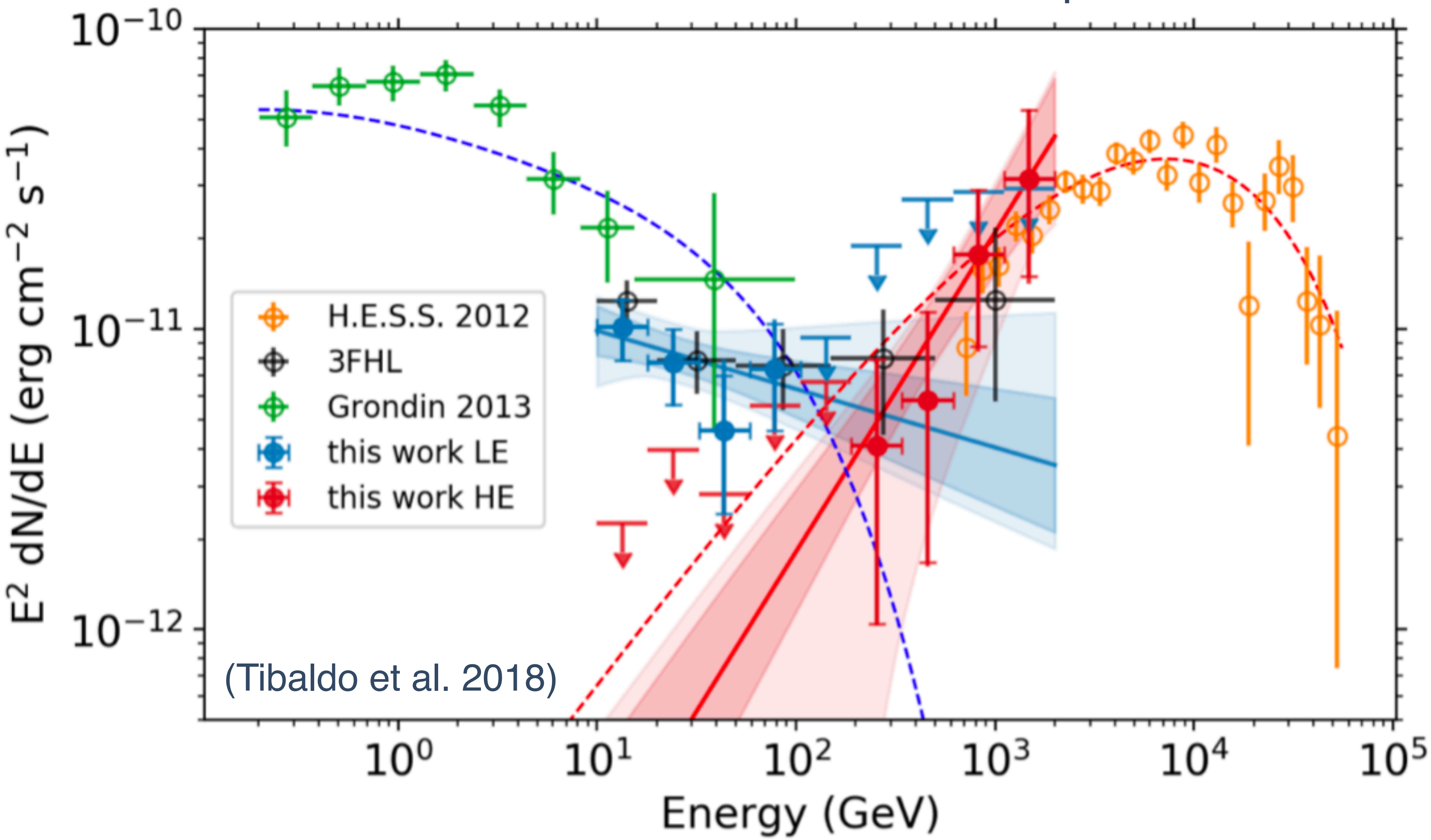
$$\Gamma_{\rm GeV} = 2.41 \pm 0.09$$

$$\Gamma_{\rm TeV} = 1.32 \pm 0.06$$

The puzzling case of the PWN Vela X

Best-fit disk (E < 100 GeV) => high correlation with radio
Best-fit disk (E > 100 GeV) => overlapping cocoon

2 different components in the Fermi-LAT band



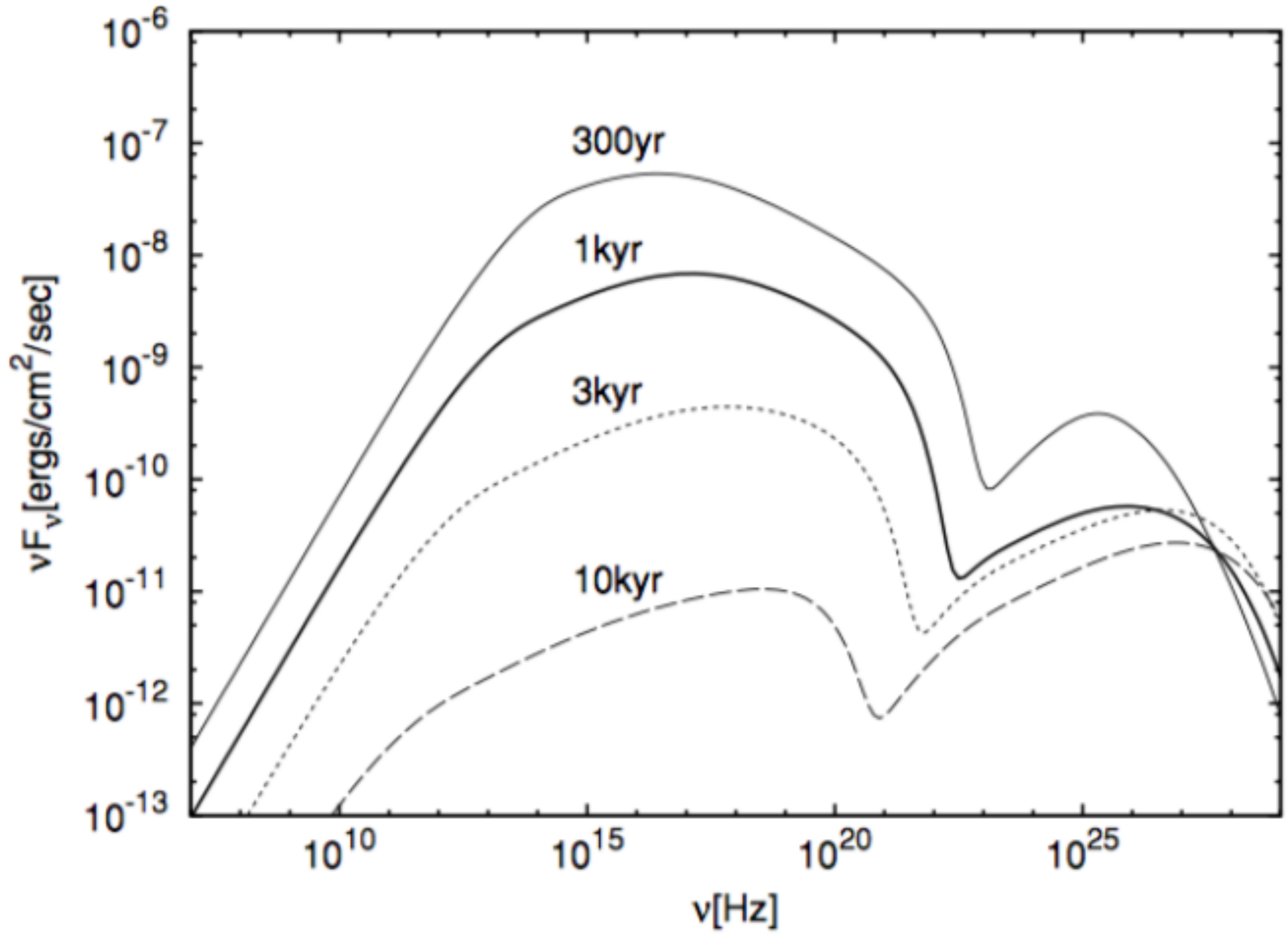
Multi-wavelength data interpretation puzzling for nearby and complex sources!

The « dark TeV sources »

- **Ancient PWNe**

Evolution of the SED with time:

(Tanaka & Takahara, 2010)

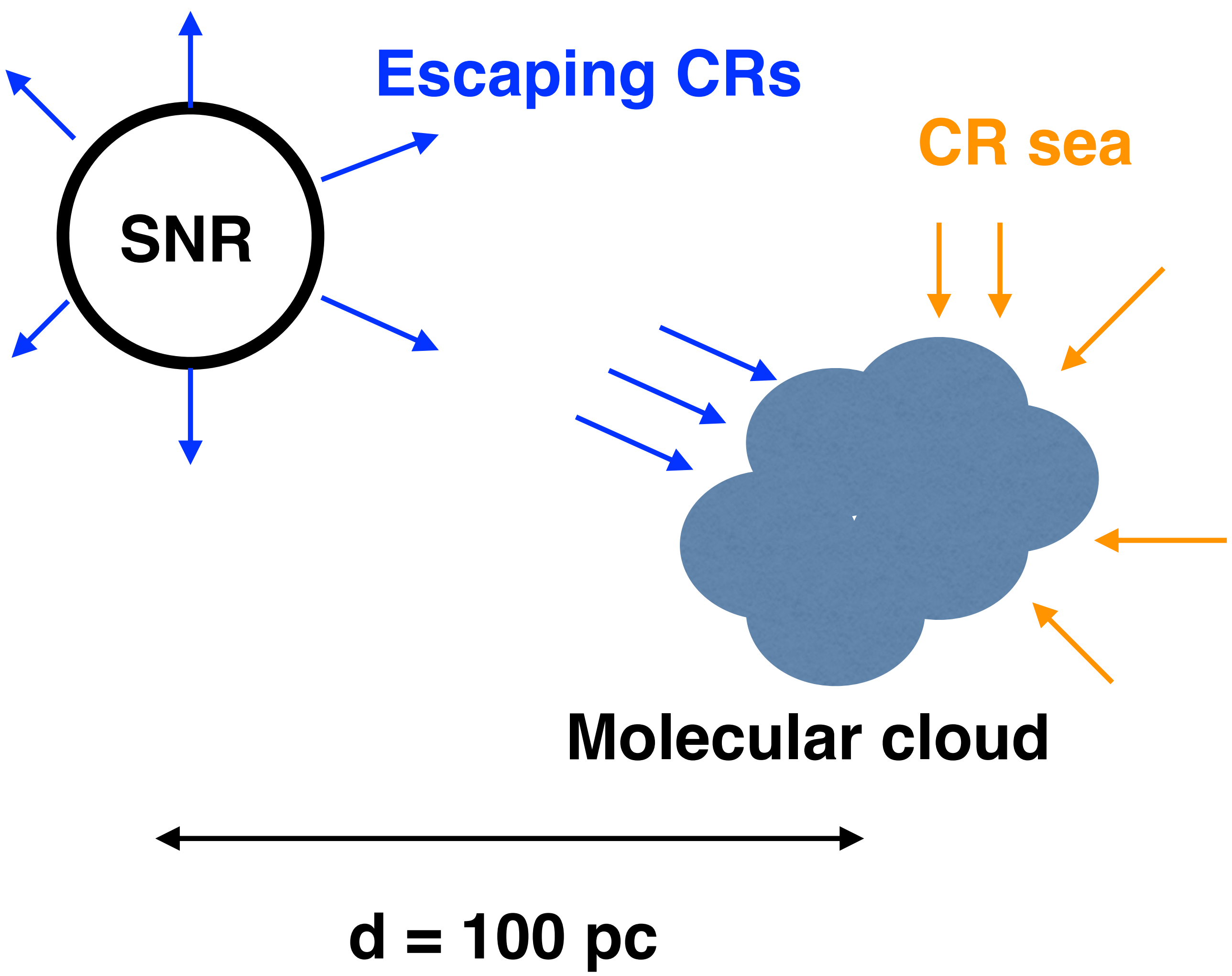


Ancient PWNe dark at other wavelengths (B decreases with time)

The « dark TeV sources »

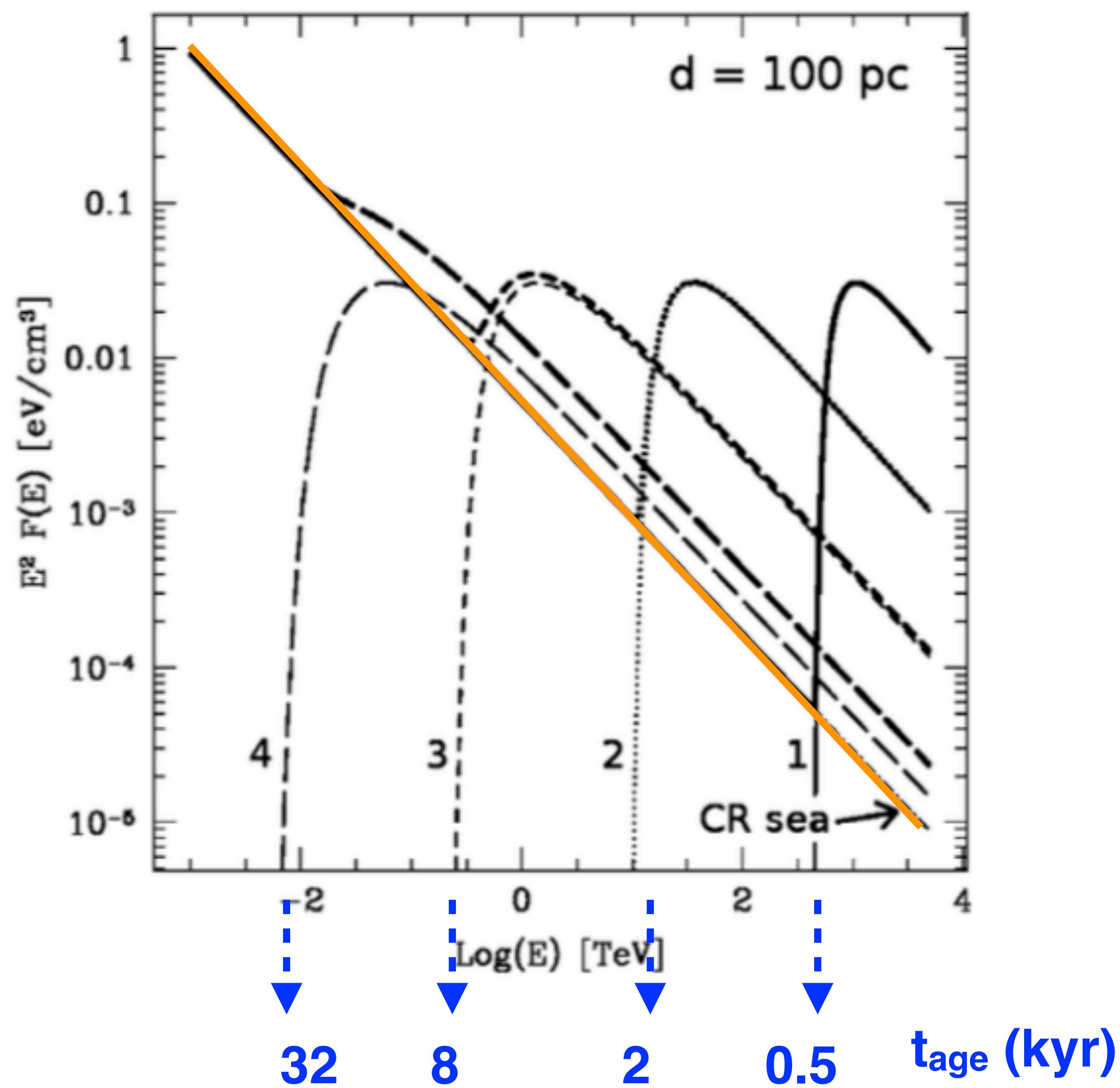
(Gabici et al, 2009)

- **Molecular clouds illuminated by cosmic rays**



(E51 = 1, d = 1 kpc, M = 10^5 solar masses)

CR spectrum at the location of the cloud:



Highest energy CRs leave the SNR first and diffuse faster than lower energy CRs

=> Sharp low-energy cut-off moving to lower and lower energies with time

The « dark TeV sources »

- **Molecular clouds illuminated by cosmic rays**

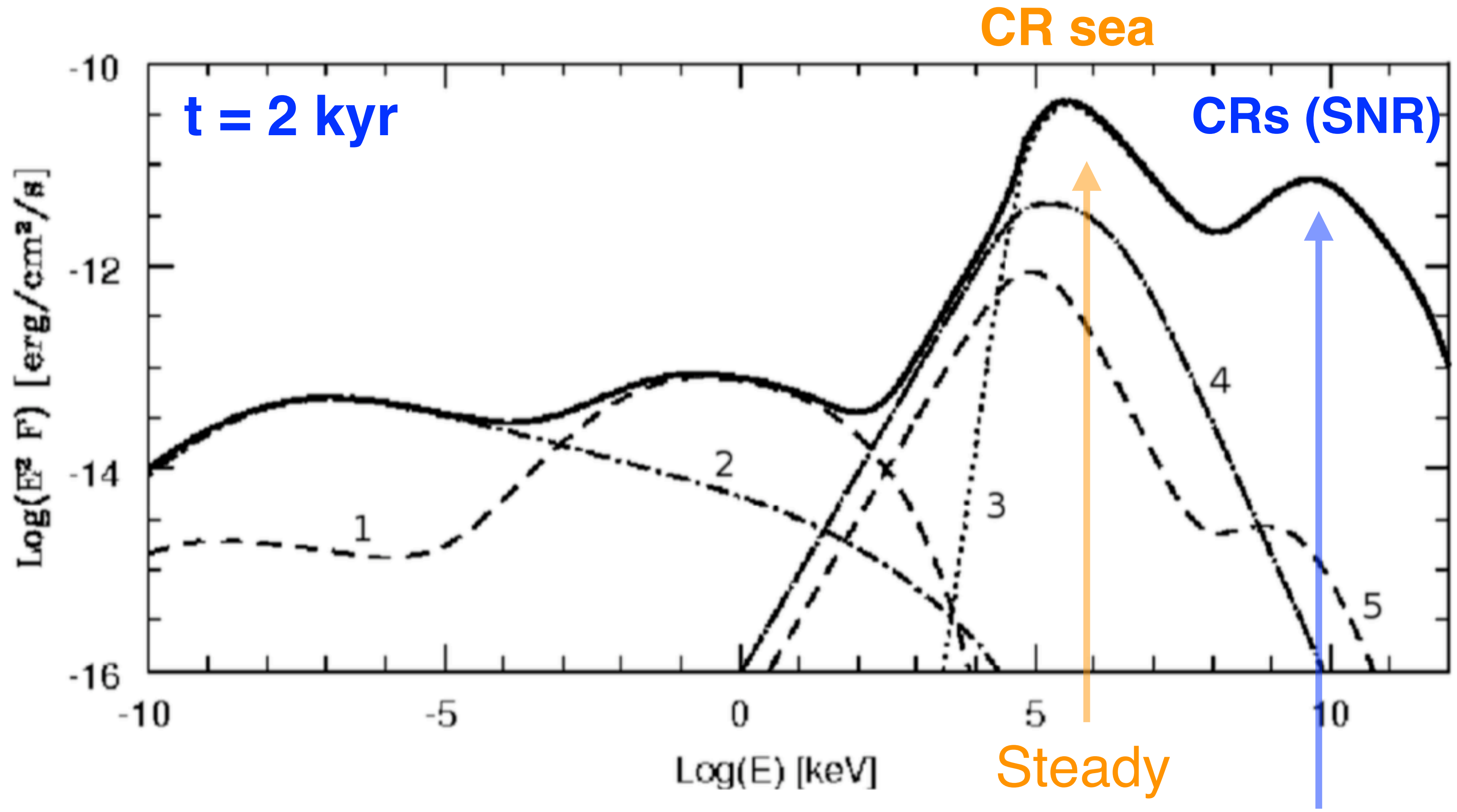
(Gabici et al, 2009)

Broadband spectrum of the cloud:

3: Neutral pion decay

2 and 4: Synchrotron and Bremsstrahlung from background CR electrons

1 and 5: Synchrotron and Bremsstrahlung from secondary electrons



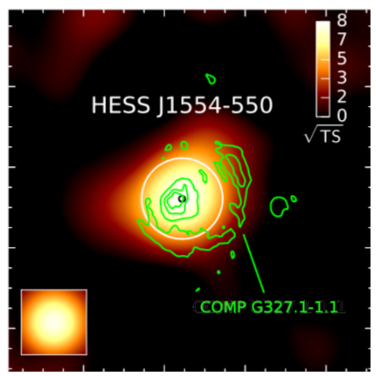
Depends on d, t and n_{cl}

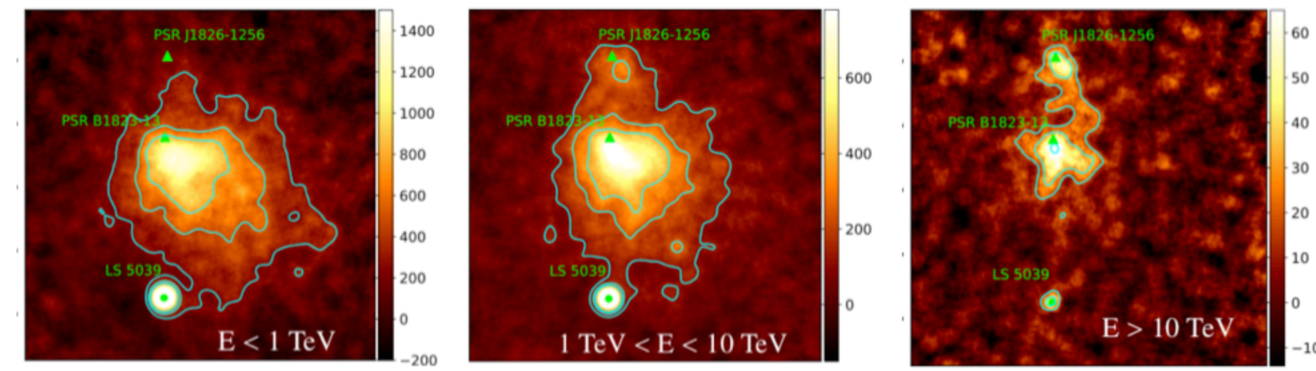
Concave gamma-ray spectrum and faint emission at other wavelengths

=> Physics itself limits the identification of these so-called « **dark TeV sources** »

Take home messages - Part II

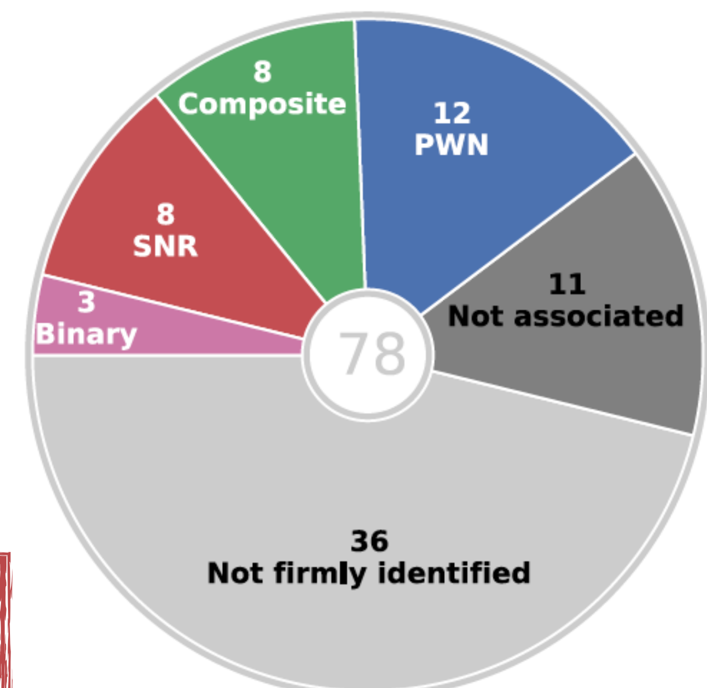
- Identification of gamma-ray sources relies on **MWL counterparts (or constrain), variability studies and energy-dependent morphology**





- More than half of the HGPS sources are **unidentified**

- Identification not always straightforward



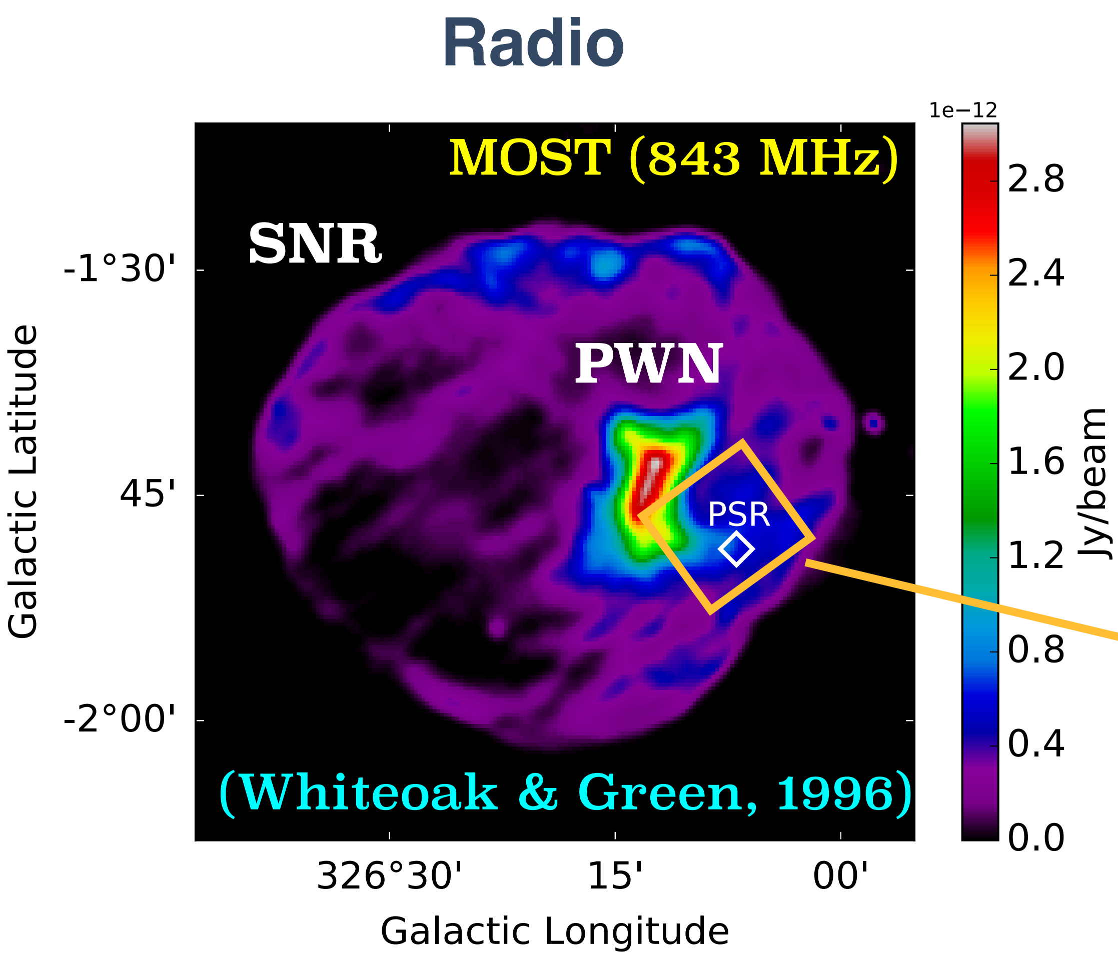
Nearby and complex sources (PWN Vela X)

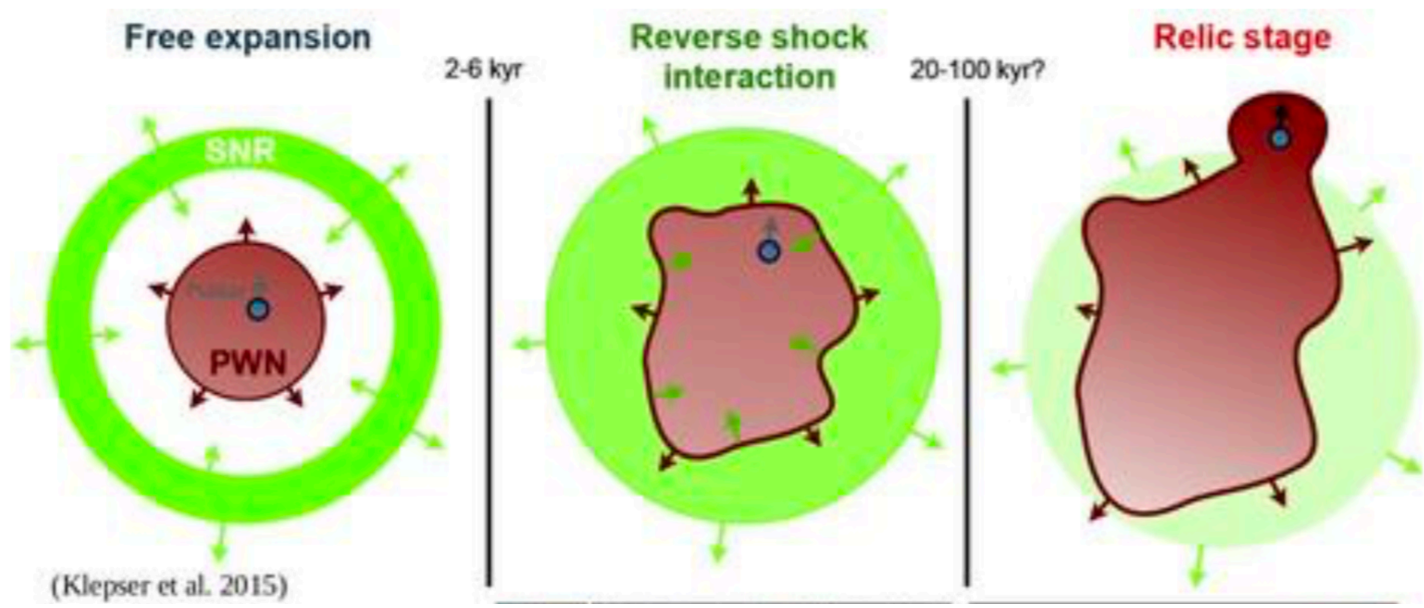
Dark TeV sources (illuminated MCs and ancient PWNe)

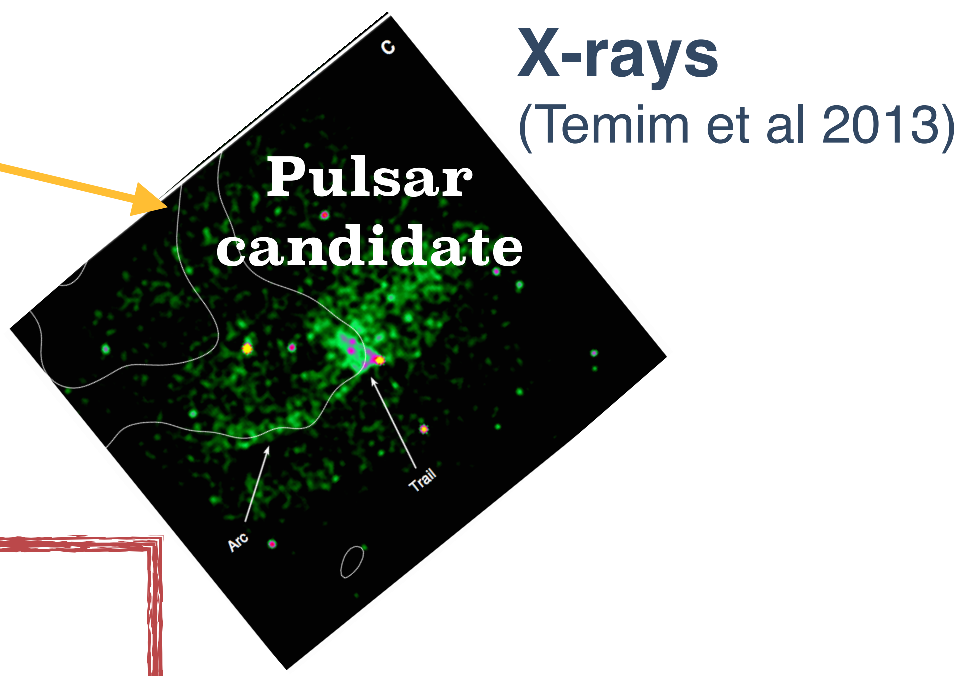
— Part III —

Identification and analysis of the gamma-ray emission from a composite supernova remnant

The composite SNR G326.3-1.8







SNR radius = 0.3°

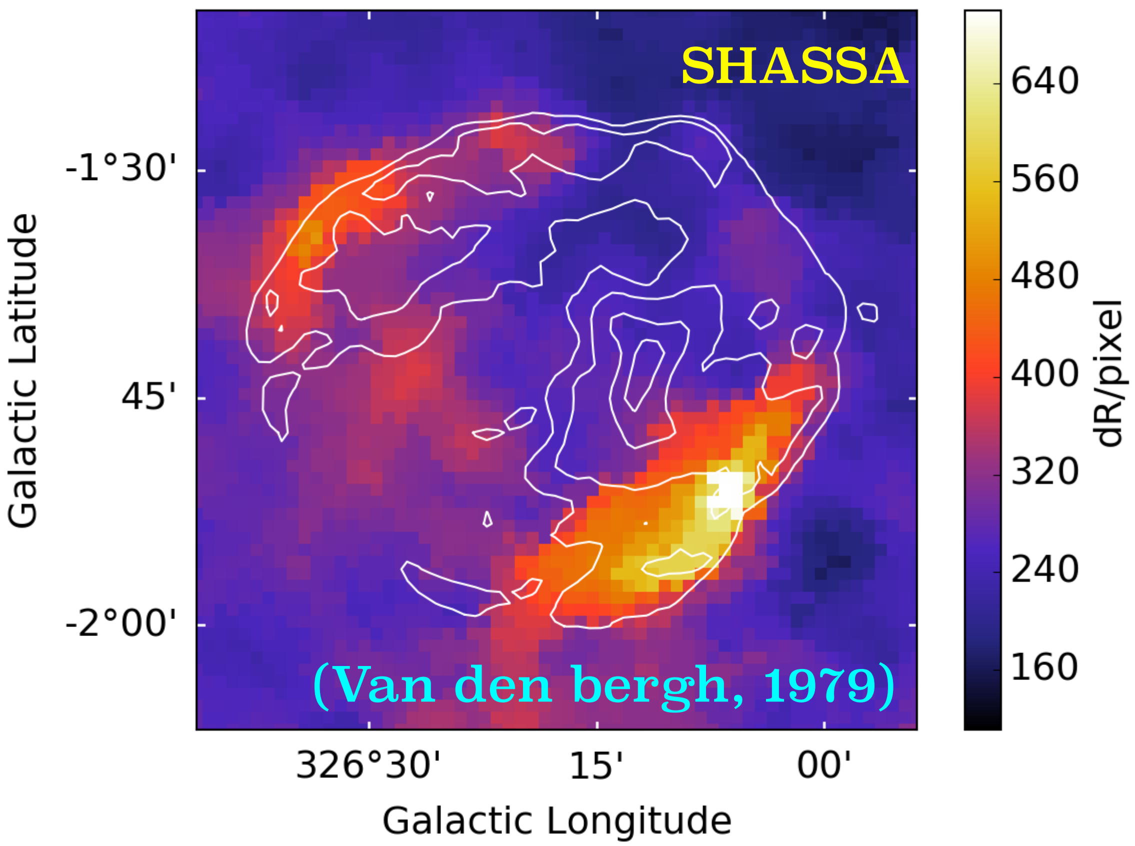
PWN likely crushed by the SNR reverse shock

Sedov-Taylor phase (Temim et al., 2013):

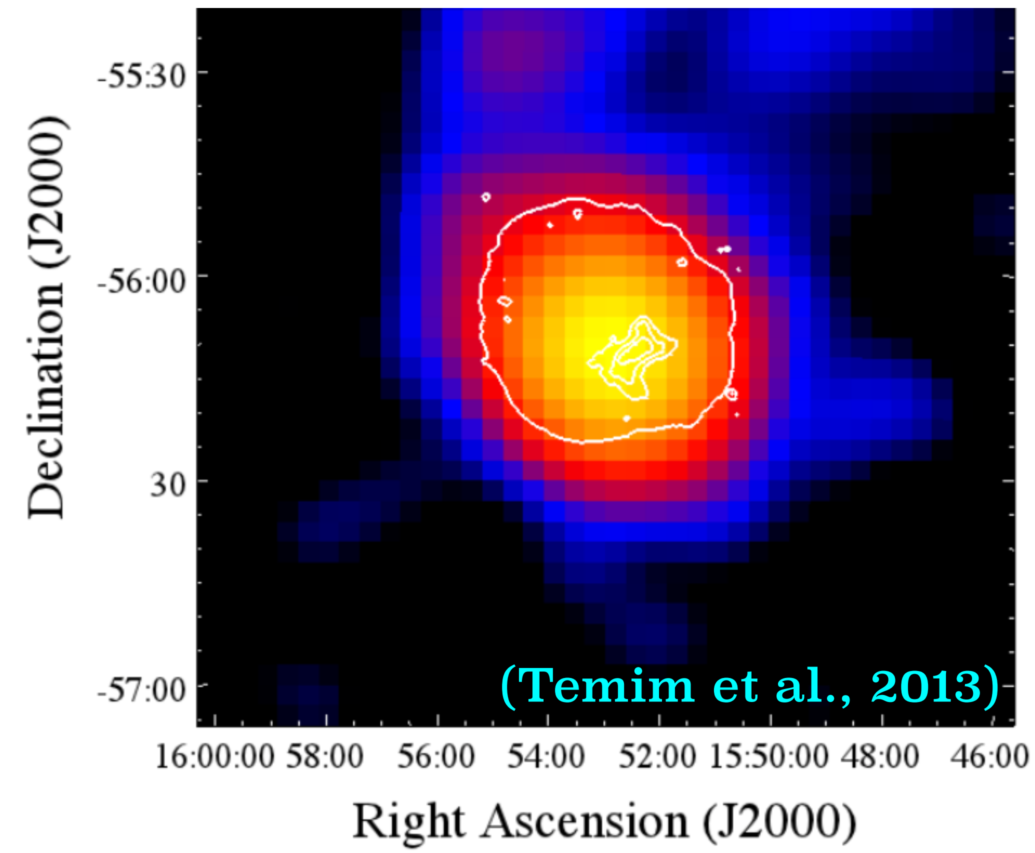
d = 4.1 kpc, age = 16 500 yr, V_{shock} = 500 km s^{-1}, n_0 = 0.1 cm^{-3}

The composite SNR G326.3-1.8

$\mathrm{H}\alpha$ **(Optical)**



Gamma



- Interaction of the shock with dense material

=> NE and SW parts of the SNR have already entered the radiative phase

=> The origin of the gamma-ray emission was uncertain (PWN or SNR?)

Preparing the analysis

Modeling the region of interest

- Starting with the latest Fermi-LAT source catalog, diffuse emissions and IRFs
- Likelihood fit of the spectral parameters of the sources in the model **simultaneously** with those of the Galactic and isotropic diffuse emissions

XML model definition file to fit:

```
<source name="3FGL J1510.2-5754" type="PointSource">
    <spectrum type="PowerLaw">
      <parameter free="0" max="10000" min="0.0001" name="Prefactor" scale="1e-12" value="3.489012031" />
      <parameter free="0" max="10" min="0" name="Index" scale="-1" value="2.51926" />
      <parameter free="0" max="500000" min="30" name="Scale" scale="1" value="1095.514771" />
    </spectrum>
    <spatialModel type="SkyDirFunction">
      <parameter free="0" max="360" min="-360" name="RA" scale="1" value="227.57" />
      <parameter free="0" max="90" min="-90" name="DEC" scale="1" value="-57.9156" />
    </spatialModel>
  </source>
```

Test of a presence of a source in each pixel with a generic spectrum: $\frac{dN}{dE} = A \times E^{-2}$

Test Statistic: $\mathrm{TS} = 2 \times (\log\mathrm{L}_1 - \log\mathrm{L}_0)$

Likelihood **with** the source (L_1)

Likelihood **without** the source (L_0)

Add sources in the model where TS > 25

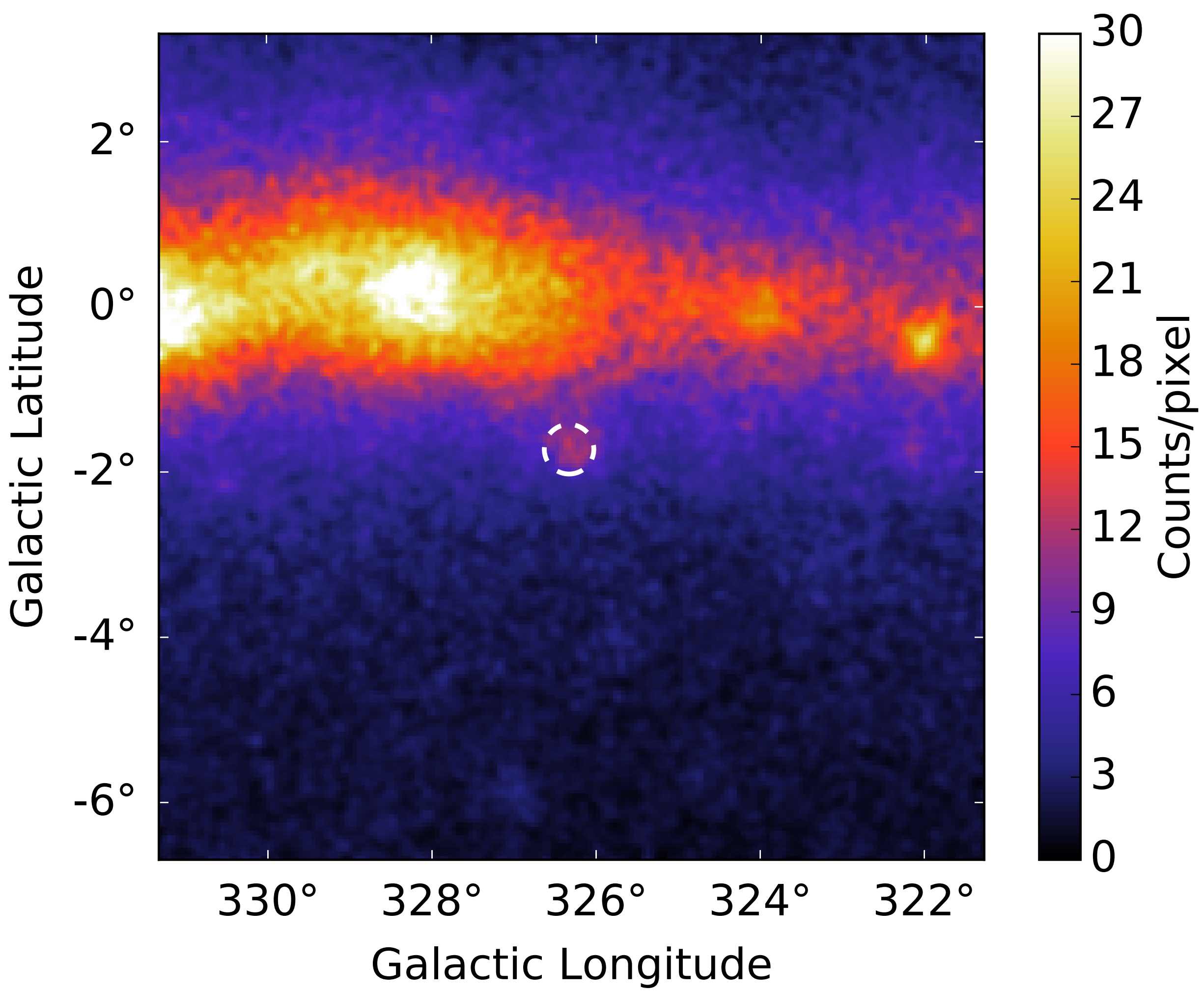
Preparing the analysis

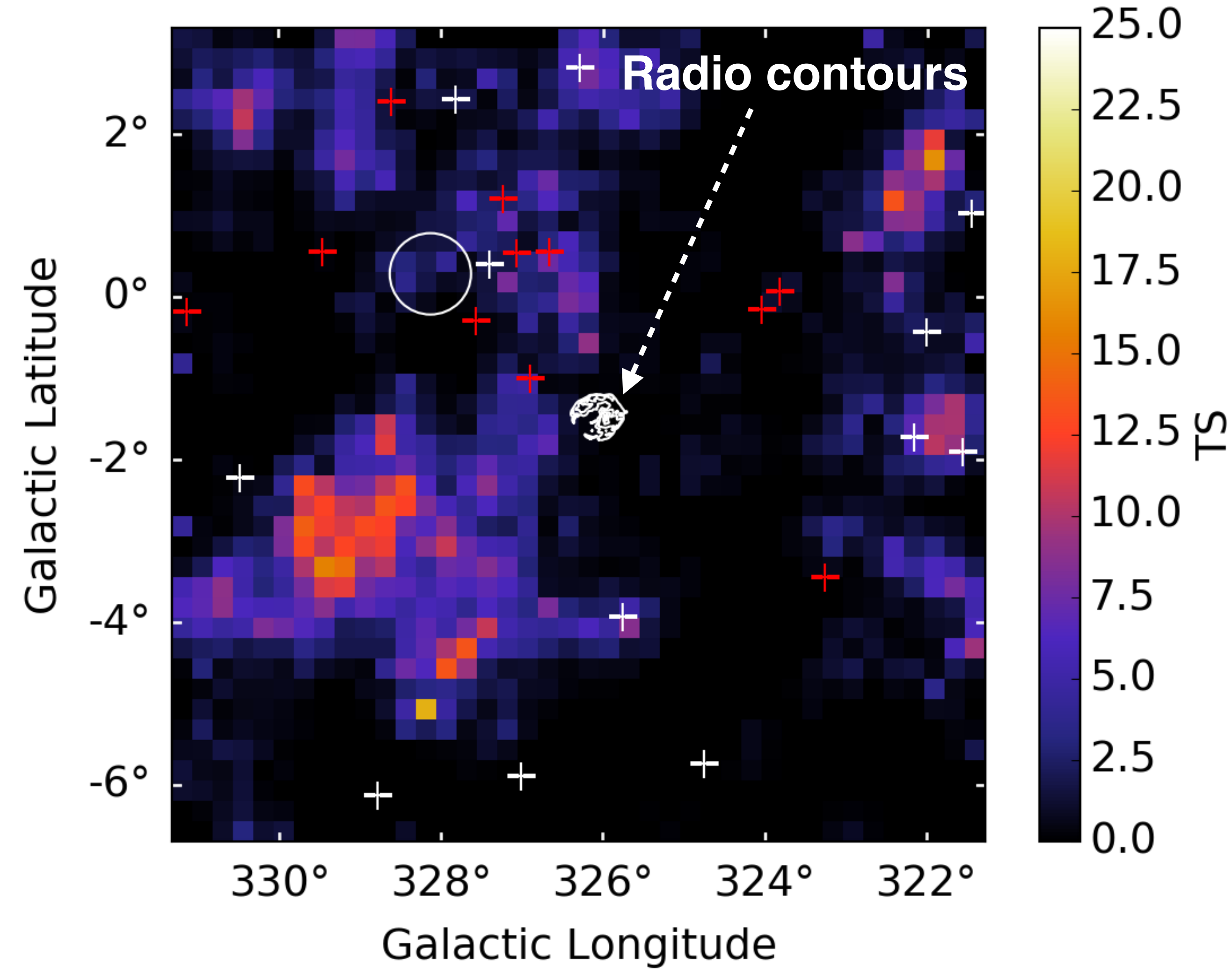
Modeling the region of interest

- 6.5 years of Fermi-LAT data from 300 MeV to 300 GeV
- Selected events with the best angular reconstruction quality

11 sources added in the model with TS > 25

Count map and residual TS map (300 MeV - 300 GeV):

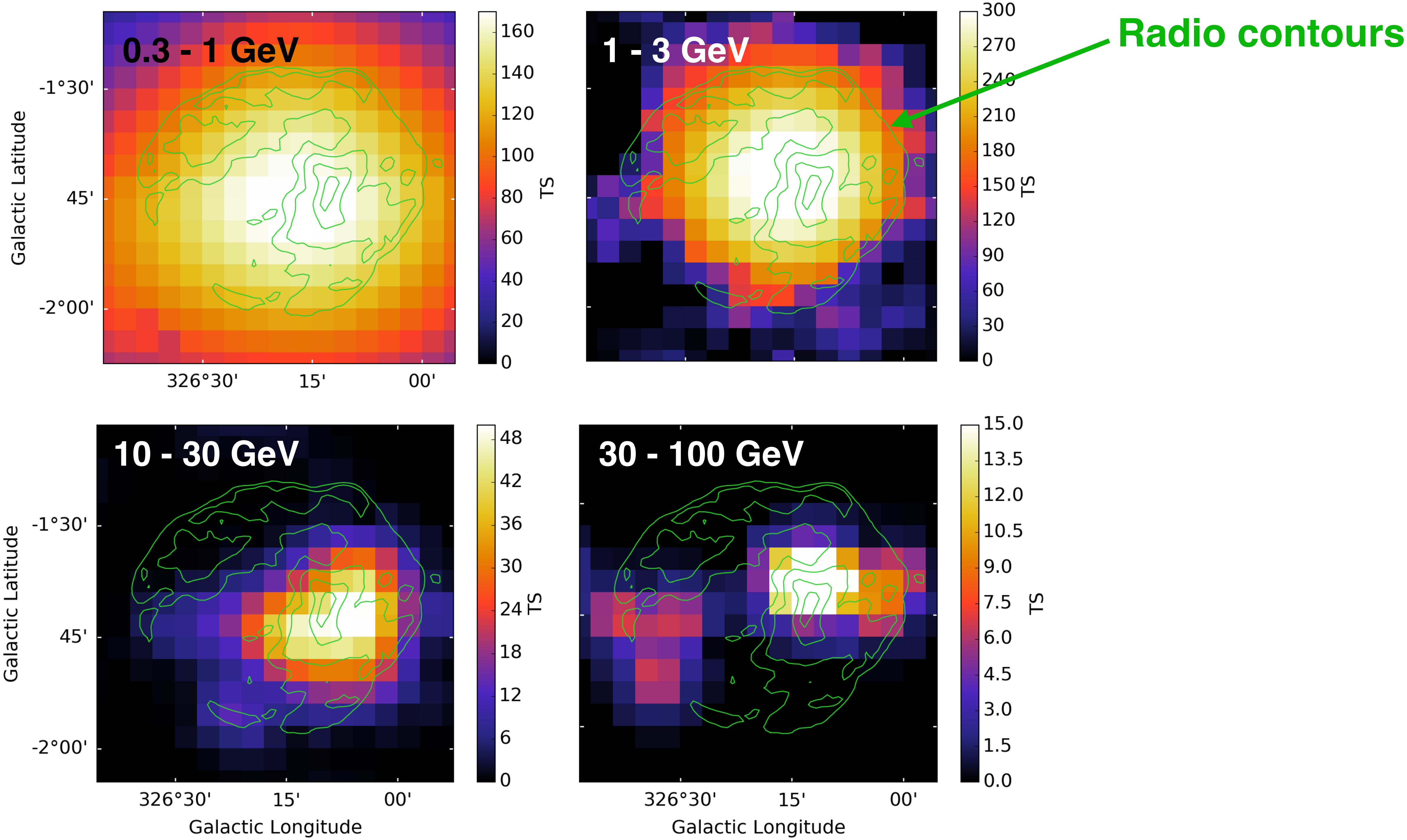




Emission from G326.3-1.8 described with 2 Fermi-LAT cataloged sources

Morphological analysis

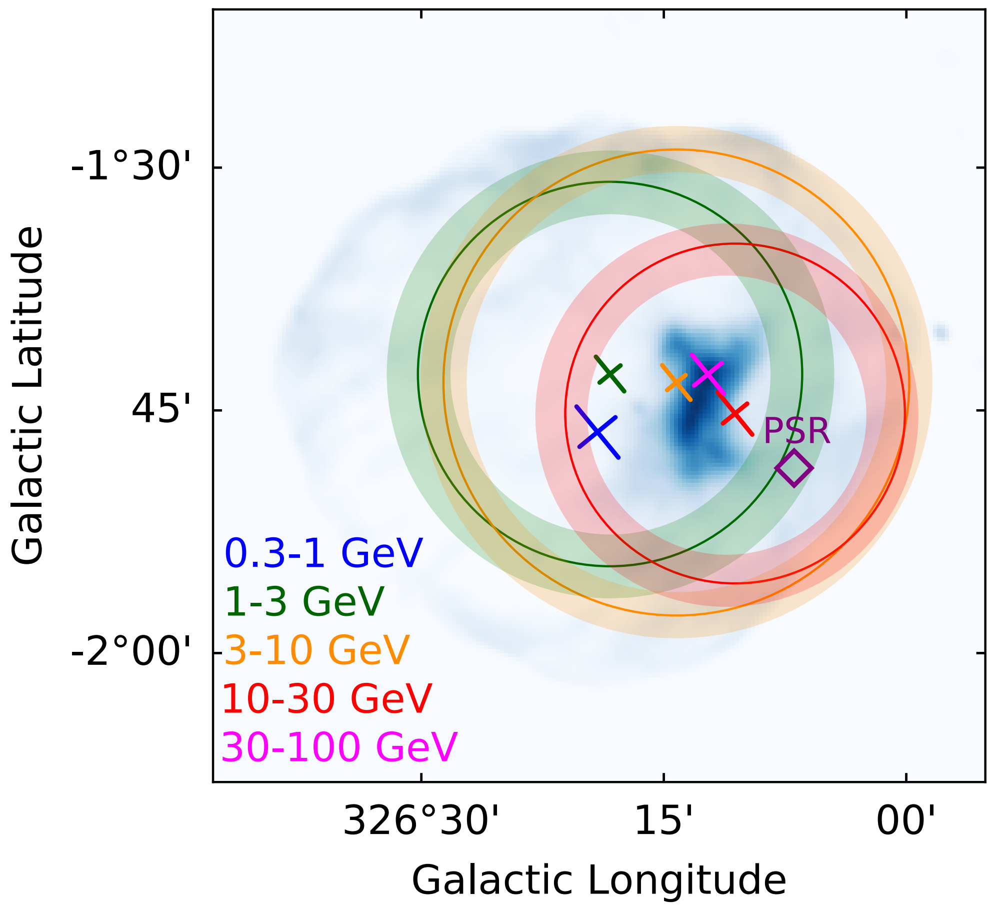
Residual TS maps (without the Fermi-LAT sources in the model):

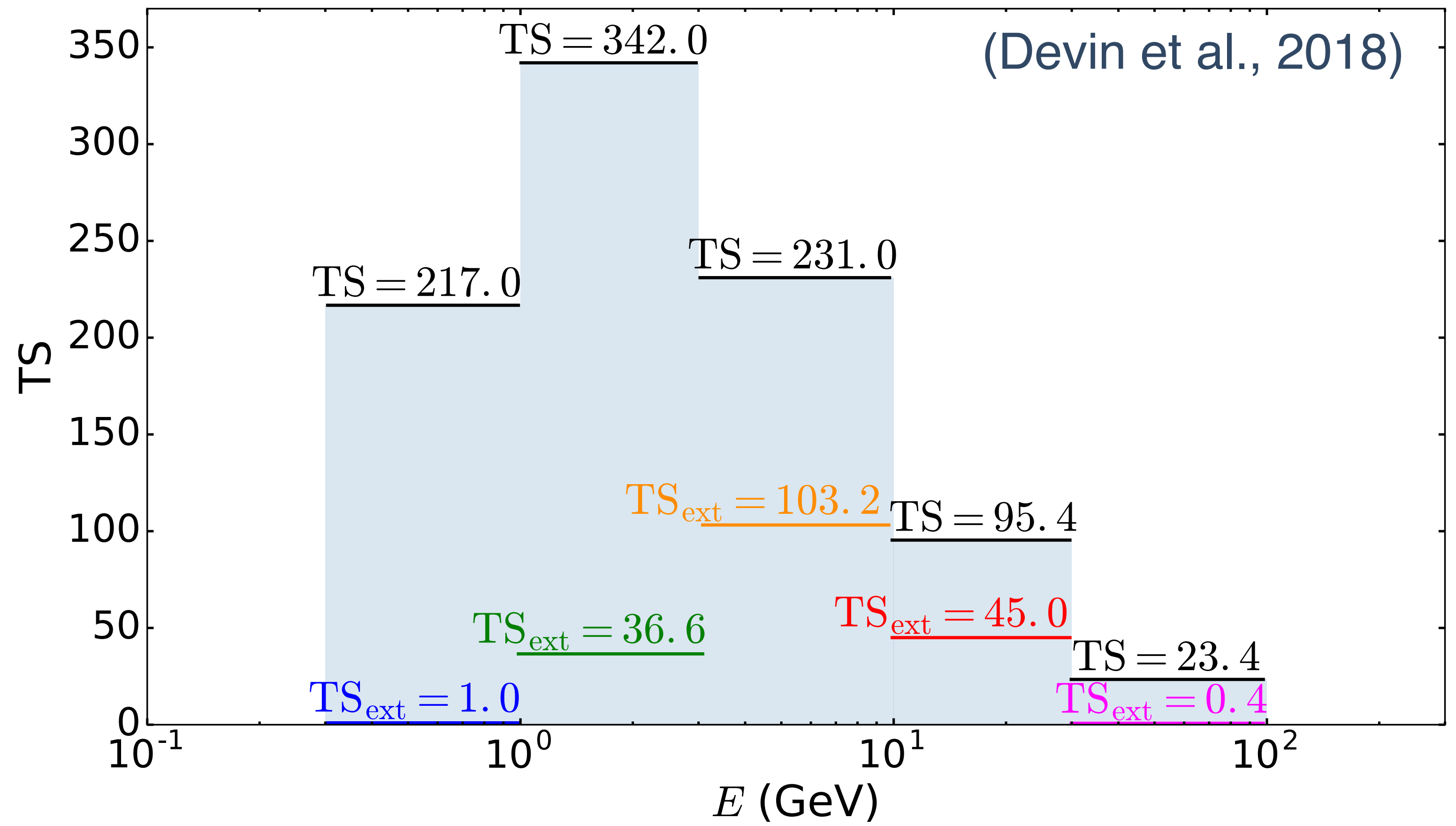


Energy-dependent morphology shrinking towards the PWN at higher energy

Morphological analysis

Morphological fit using a 2D symmetric Gaussian in different energy bands





$$\mathrm{TS_{ext}} = 2 \times (\log\mathrm{L_{ext}} - \log\mathrm{L_{point-source}})$$

Extension significance = $\sqrt{\mathrm{TS_{ext}}}$

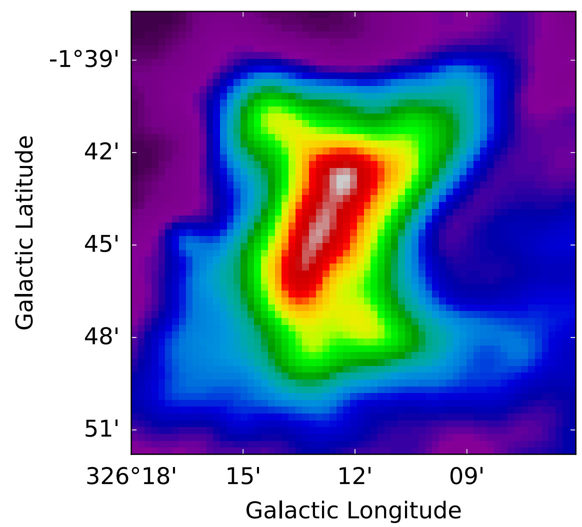
Gamma-ray emission significantly extended from 1 GeV to 30 GeV

Emission comes from the PWN at high energy

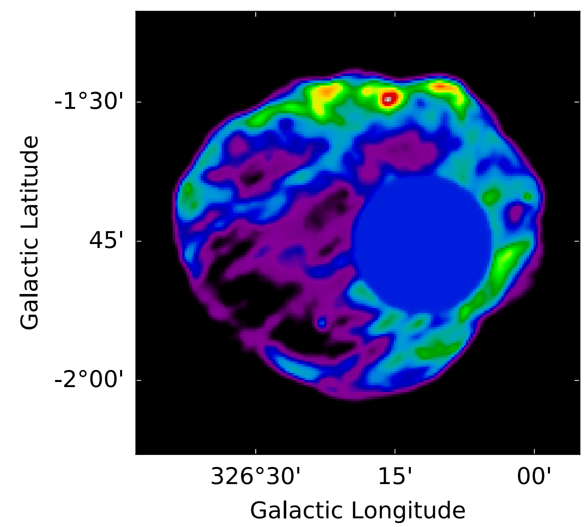
Morphological analysis

Templates

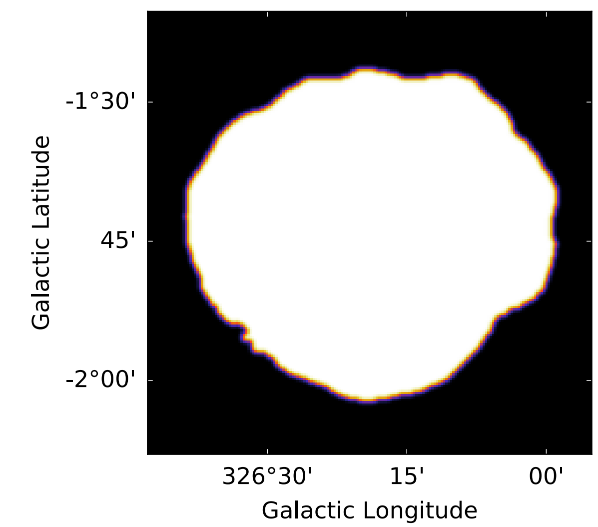
radio PWN



radio SNR



SNR mask



(uniform emission)

(Devin et al., 2018)

Spatial models	TS	N_{dof}	TS_{PWN}
Radio PWN	593.4	2	—
Point source	503.3	4	—
Point source + radio PWN	661.4	6	158.1
Disk	681.8	5	—
Disk + radio PWN	694.8	7	13.0
Radio SNR	667.3	2	—
Radio SNR + radio PWN	683.0	4	15.7
SNR mask	670.3	2	—
SNR mask + radio PWN	696.4	4	26.1

(1 GeV — 300 GeV)

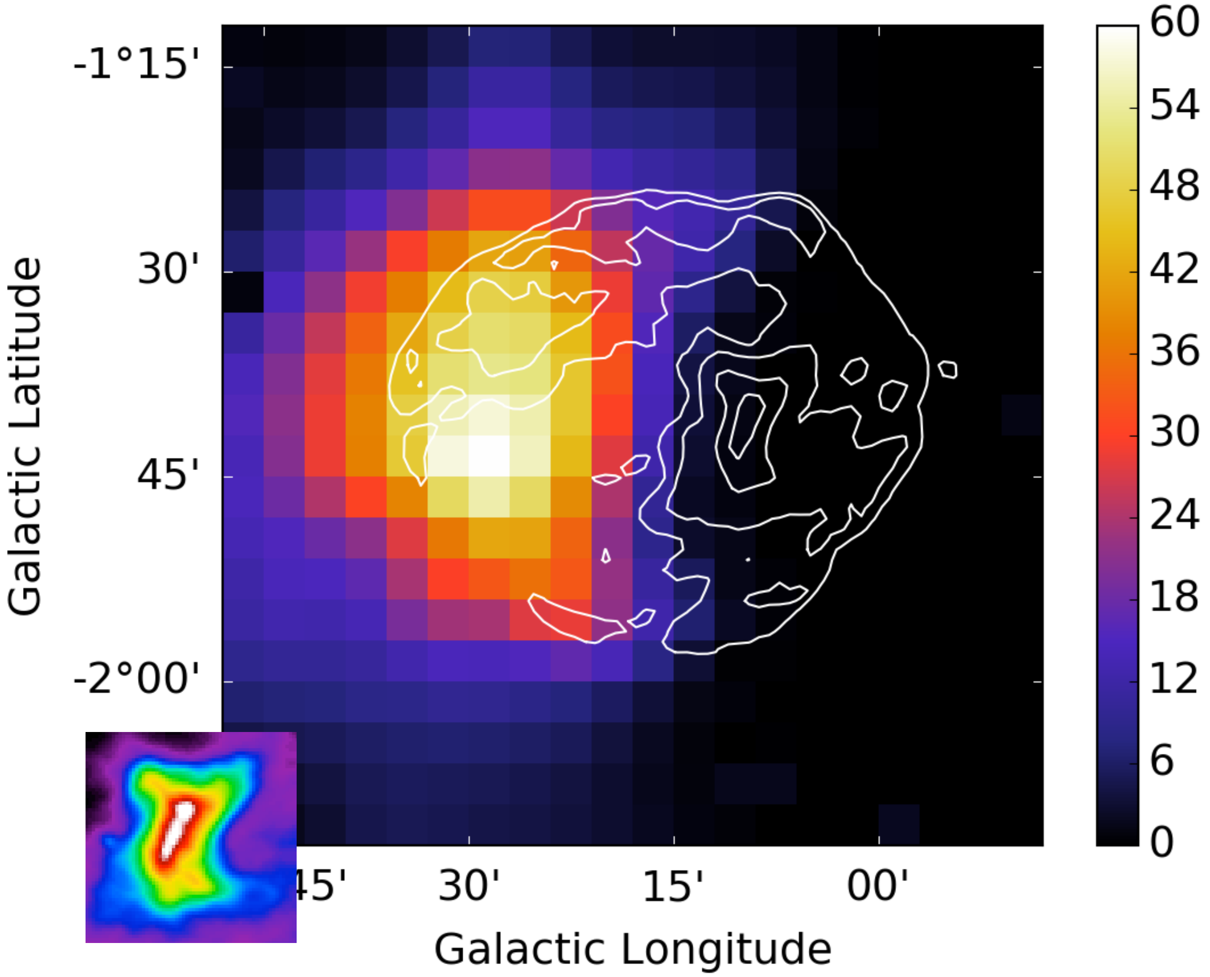
Best-fit one-component model

Best-fit two-component model

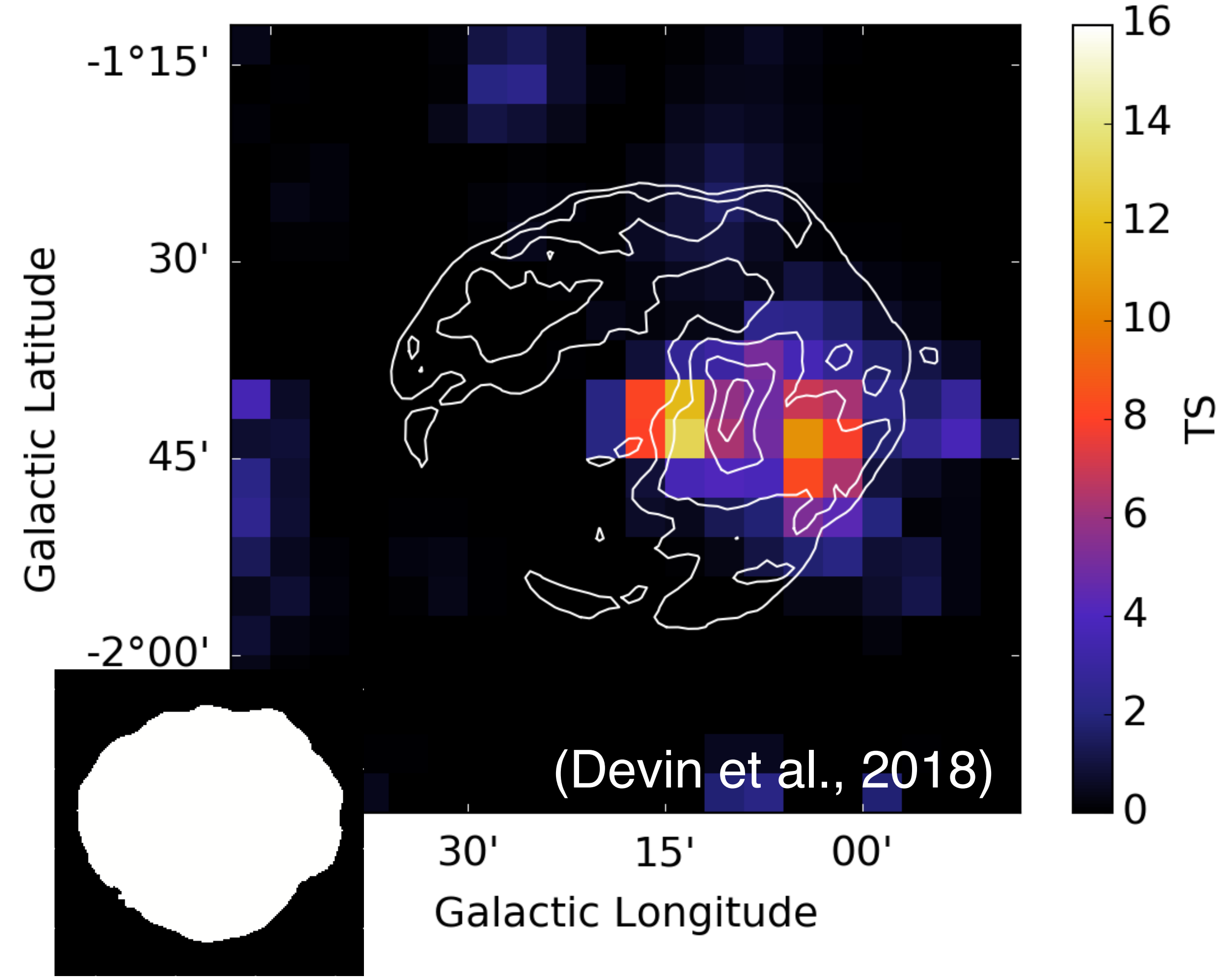
Morphological analysis

Residual TS maps (1 GeV — 300 GeV)

Only the **radio PWN** included:



Only the **SNR mask** included:



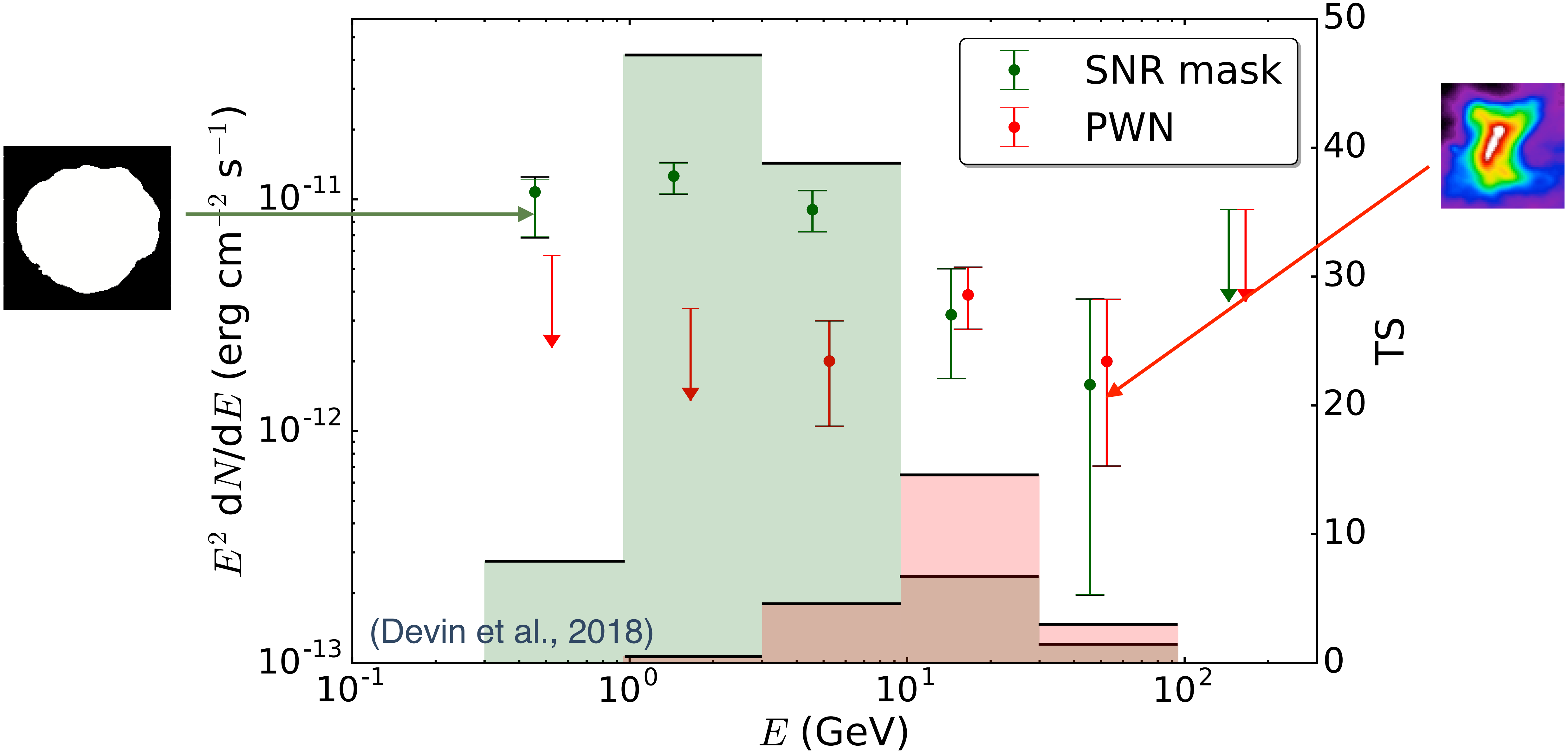
Showing the minimal contribution of the other component

Spectral analysis

- **Spectral separation bewteen the two components (SNR + PWN):**
Soft spectrum for the SNR and **hard spectrum** for the PWN

$\Gamma_{\mathrm{SNR}} = 2.17 \pm 0.06$

$\Gamma_{\mathrm{PWN}} = 1.79 \pm 0.12$



- **SNR dominates the gamma-ray emission**

Broadband nonthermal modeling of the SNR emission

Particle spectrum

Power law with an exponential cut off (+ break for the electrons)

$$\tau_{\rm sync} = (1.25 \times 10^3) \times E_{\rm TeV}^{-1} B_{100}^{-2} \ \ {\rm yr}$$

$$\tau_{\rm acc} = 30.6 \times \frac{3r^2}{16(r-1)} \times k_0 \times E_{\rm TeV} B_{100}^{-1} u_{\rm sh,3}^{-2} \ \ {\rm yr}$$

$$t_{\rm age} = \tau_{\rm sync}$$

$$E_{\rm b} \propto B^{-2} \times t_{\rm age}^{-1}$$

e-: $t_{\rm acc} = \min(\tau_{\rm sync}, t_{\rm age})$ $E_{\rm max} \propto \min(B^{-1/2} V_s, B V_s^2 \times t_{\rm age})$ (age-limited)

p: $t_{\rm acc} = t_{\rm age}$ $E_{\rm max} \propto B V_s^2 \times t_{\rm age}$

With d = 4.1 kpc, age = 16 500 yr, V_{shock} = 500 km s^{-1}, n_0 = 0.1 cm^{-3} (Temim et al., 2013)

$$R_s = 1.15 \left(\frac{E}{\rho_0} \right)^{\frac{1}{5}} t^{\frac{2}{5}}$$

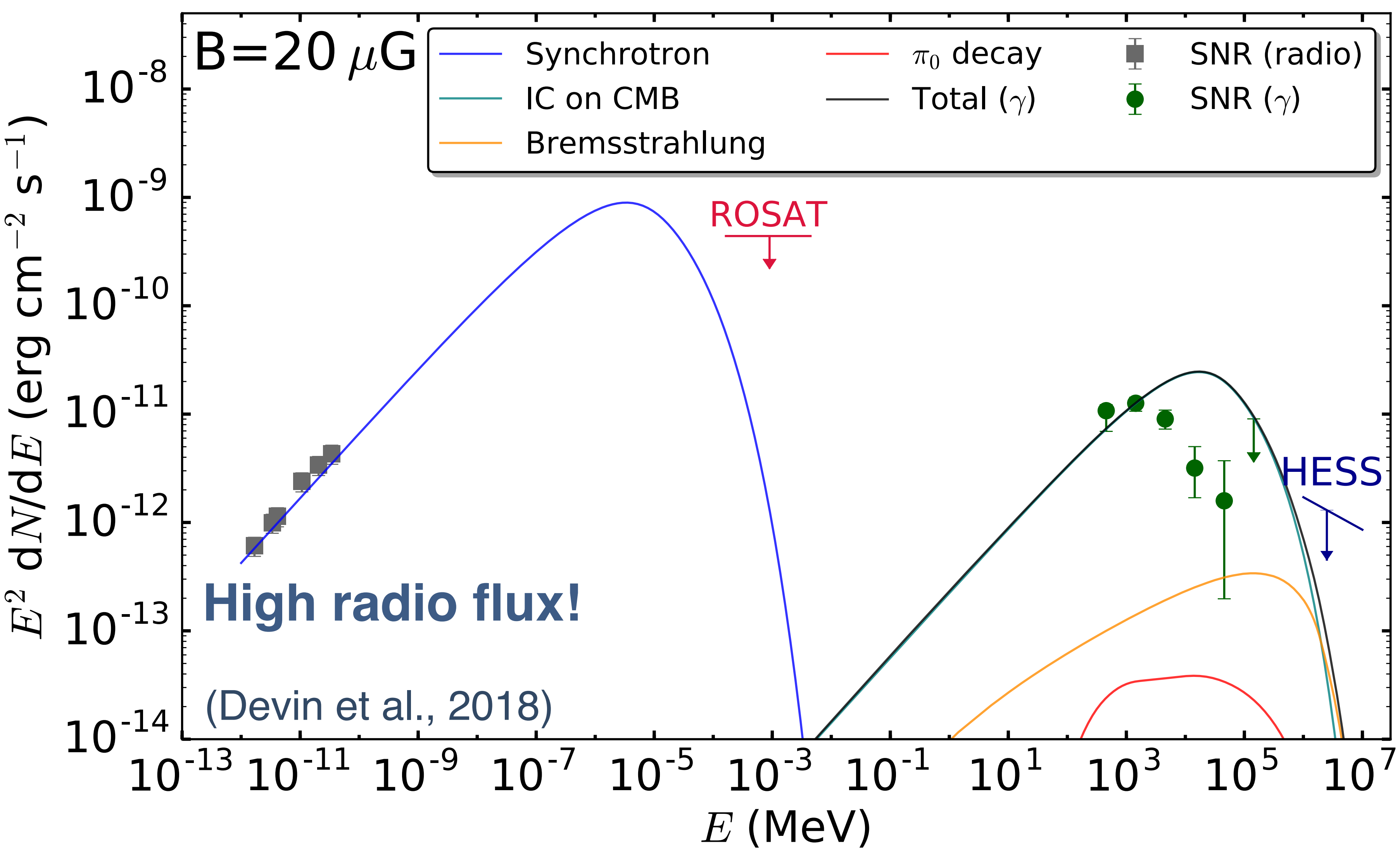
$$E_{\rm SN} = 5 \times 10^{50} \ {\rm erg}$$

Broadband nonthermal modeling of the SNR emission

- **SNR - Leptonic scenario**

Break and maximum energy are calculated:

Scenario	Model	B (μG)	W_p (erg)	K_{e-p}	$\Gamma_{e,1}/\Gamma_{e,2}$	E_b (TeV)	$E_{max,e}$ (TeV)	Γ_p	$E_{max,p}$ (TeV)	n_0 (cm^{-3})
Leptonic	consistent	20	$5\times10^{49*}$	0.5	1.8/2.8	1.9*	2.3*	2*	2.7*	0.1*



10% of E_{SN} transmitted to CR protons:

$$W_p = 5\times10^{49}\ \text{erg}$$

↓

$$K_{ep} = 0.5\ (>> 0.01)$$

$$W_e = 2.5\times10^{49}\ \text{erg}$$

=> Energetic in electrons too high + Cut-off IC at too high energy

Broadband nonthermal modeling of the SNR emission

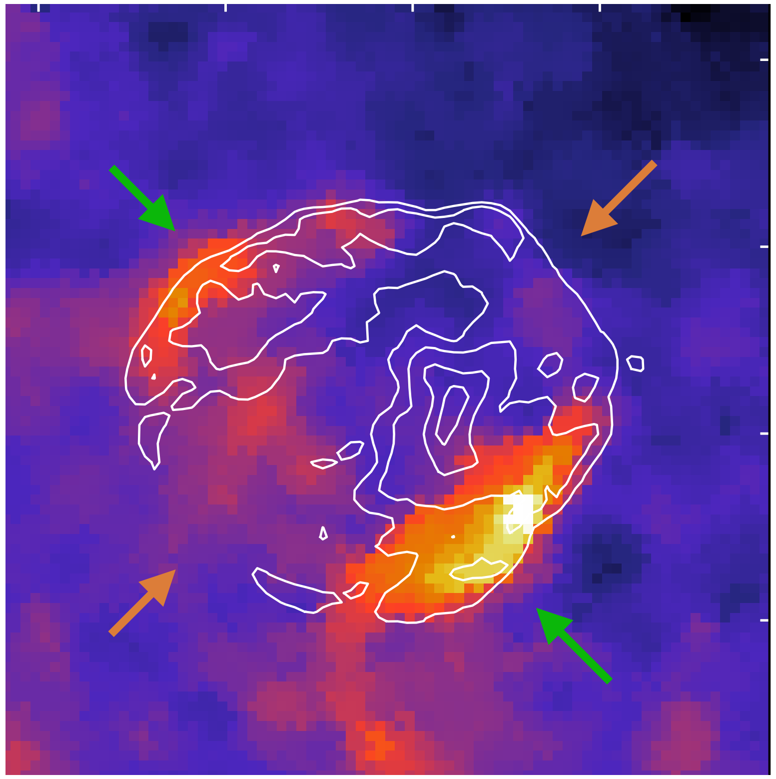
- **SNR - Hadronic scenario**

$\mathrm{H}\alpha$ => evidence of the interaction of the shock with dense material (facilitating proton-proton interactions)

Parts of the shock in two different phases:

➡ **Sedov-Taylor phase** (main shock: $v_s = 500 \text{ km s}^{-1}$)

➡ **Radiative phase** (radiative shock: $v_s = 150 \text{ km s}^{-1}$)



Broadband nonthermal modeling of the SNR emission

(following Uchiyama et al., 2010)

- **SNR - Hadronic scenario**

Upstream in the clouds

$$u_{\rm sh,cl} = k\sqrt{\frac{n_0}{n_{0,\rm cl}}} \times u_{\rm sh},$$

$$u_{sh} = 500 \text{ km s}^{-1}$$

$$n_0 = 0.1 \text{ cm}^{-3}$$

$$u_{sh,cl} = 150 \text{ km s}^{-1}$$

→ $$n_{0,cl} = 1.88 \text{ cm}^{-3}$$

$$B_{0,\rm cl} = b\sqrt{\frac{n_{0,\rm cl}}{\rm cm^{-3}}}\ \mu{\rm G},$$

→ $$B_{0,cl} = 4.11\ \mu G$$

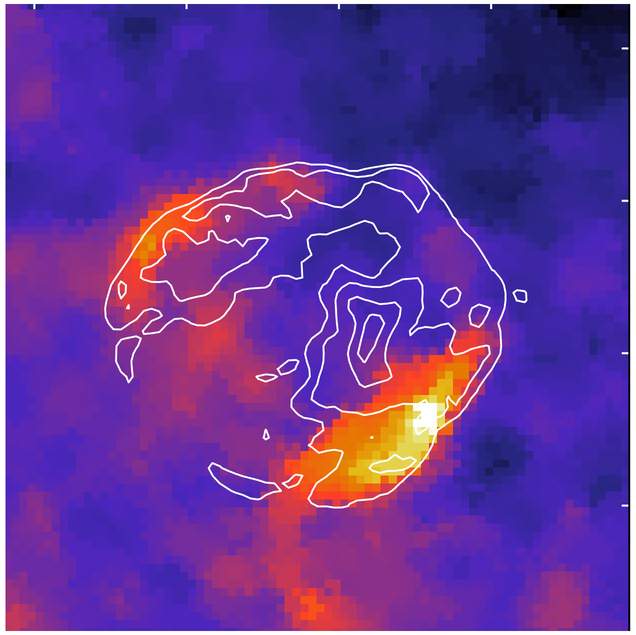
$$\frac{B_{\rm m}^2}{8\pi} = k^2 n_0 \mu_{\rm H} u_{\rm sh}^2,$$

→ $$B_m = 158\ \ \mu G$$

$$B_{\rm m} = \sqrt{\frac{2}{3}} \times \left(\frac{n_{\rm m}}{n_{0,\rm cl}}\right) \times B_{0,\rm cl},$$

$$n_{\rm m} = \sqrt{\frac{3}{\pi\mu_{\rm H}}} \times \frac{B_{\rm m}^2}{4b \times u_{\rm sh,cl}}.$$

→ $$n_m = 88.3 \text{ cm}^{-3}$$

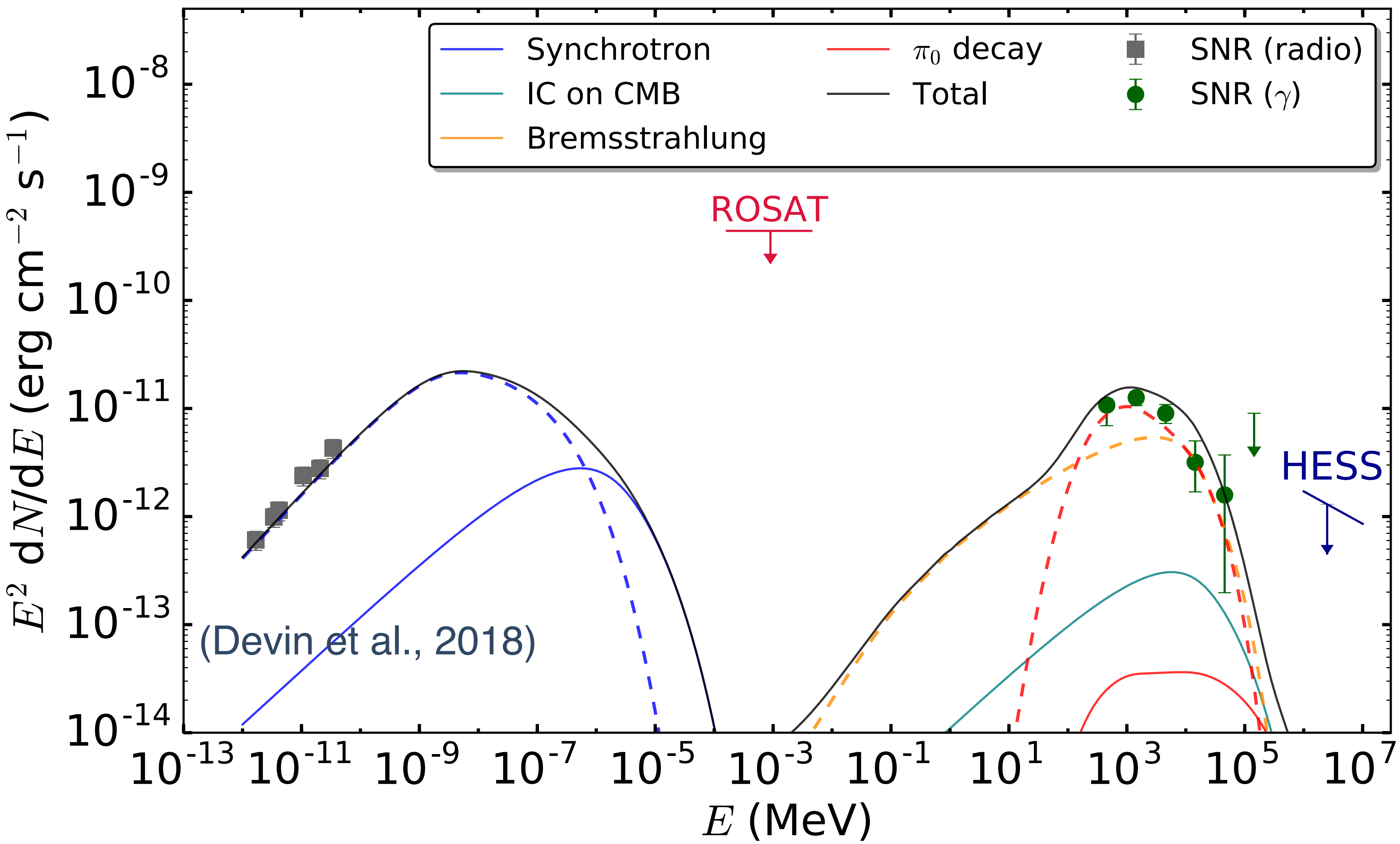


Downstream in the cooled regions

Broadband nonthermal modeling of the SNR emission

- **SNR - Hadronic scenario**

Scenario	Model	B (μG)	W_p (erg)	K_{e-p}	$\Gamma_{e,1}/\Gamma_{e,2}$	E_b (TeV)	$E_{max,e}$ (TeV)	Γ_p	$E_{max,p}$ (TeV)	n_0 (cm^{-3})
Hadronic										
main shock	consistent	10	5×10^{49}	0.03	$2/3^*$	1.4^*	1.4^*	2^*	1.4^*	0.1^*
radiative shock	consistent	13.6^*								1.88^*
cooled regions		158^*	1.9×10^{49}	0.03	1.8/2.8	0.02^*	0.08^*	2^*	0.08^*	88.3^*



- - Radiative shock

3.8% of E_{SN}

transmitted to CR protons

$$W_e = 5.7 \times 10^{47} \text{ erg}$$

— Main shock

`10% of E_{SN}

transmitted to CR protons

$$W_e = 1.5 \times 10^{48} \text{ erg}$$

Emission from the radiative shock dominates the broadband emission

Conclusions of the analysis

- Evidence of a **two-component contribution** (PWN + SNR)

+

- **First morphological and spectral separation** between two nested gamma-ray components (here in a composite system)

- Broadband spectrum of the SNR explained by the **emission from the radiative shock**

=> New indication for proton acceleration in SNR

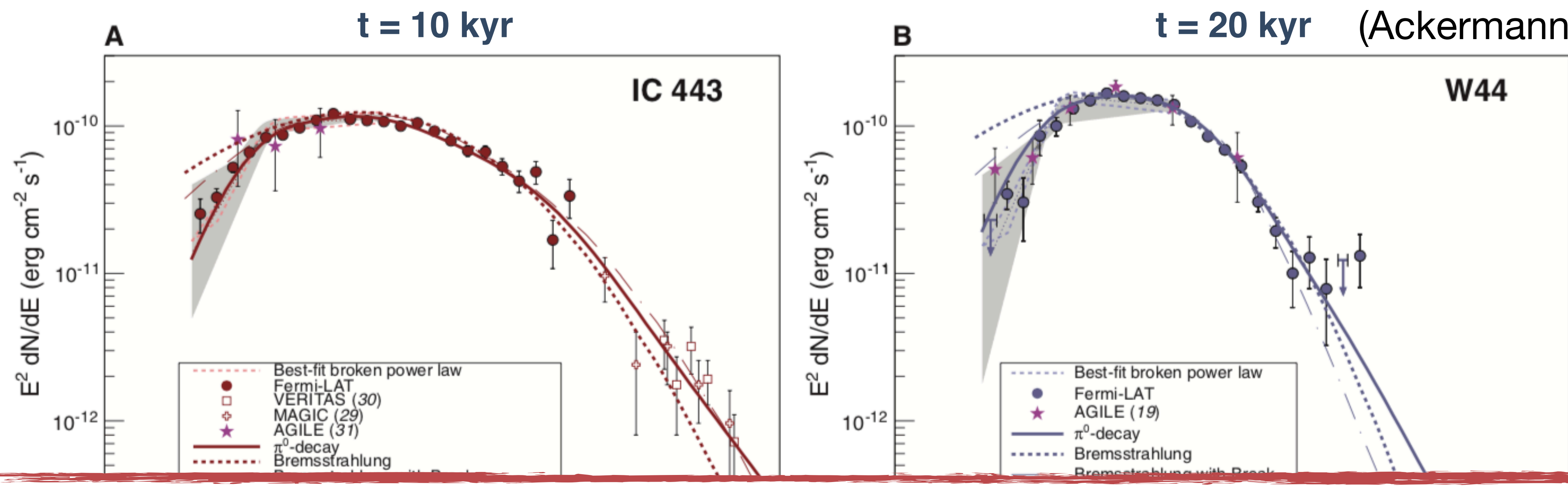
=> G326.3–1.8 = perfect example of Galactic CR accelerators: accelerating the two components (leptonic and hadronic) of the cosmic-ray spectrum

— Part IV —

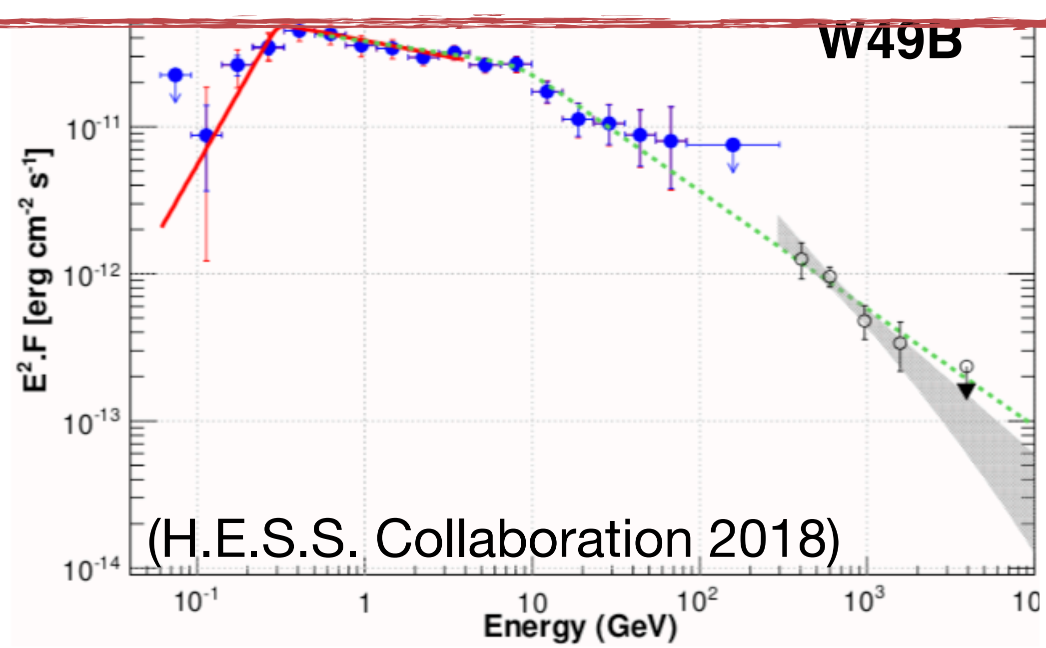
Searching for Galactic PeVatrons

Proton acceleration in SNRs

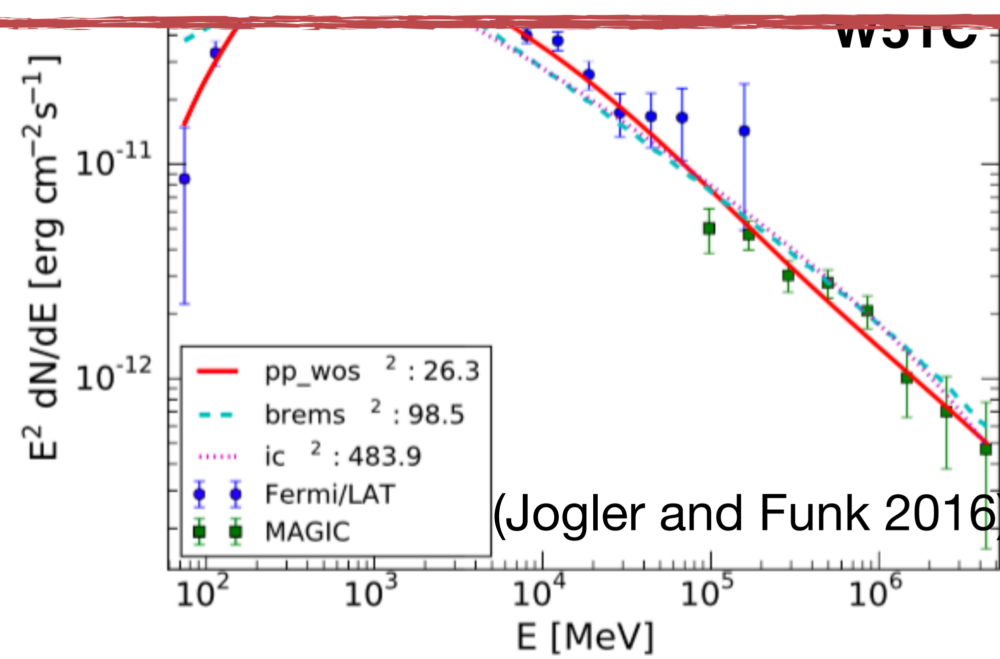
(Ackermann et al. 2013)



No PeV protons! Are these SNRs too evolved?



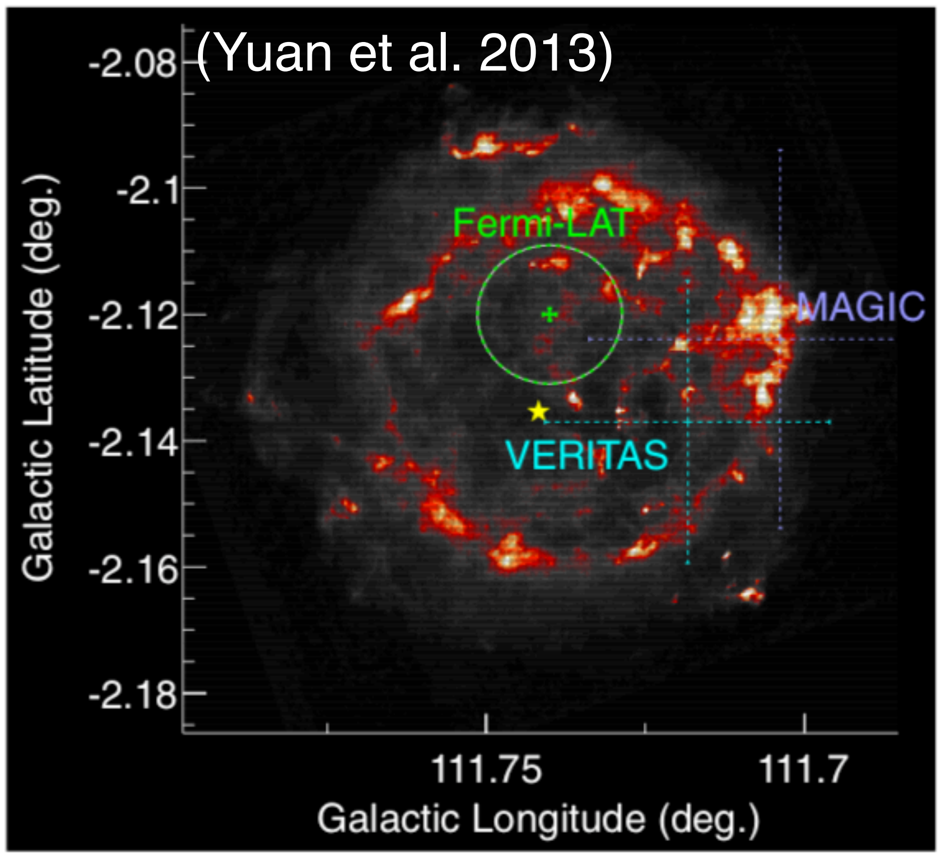
(H.E.S.S. Collaboration 2018)

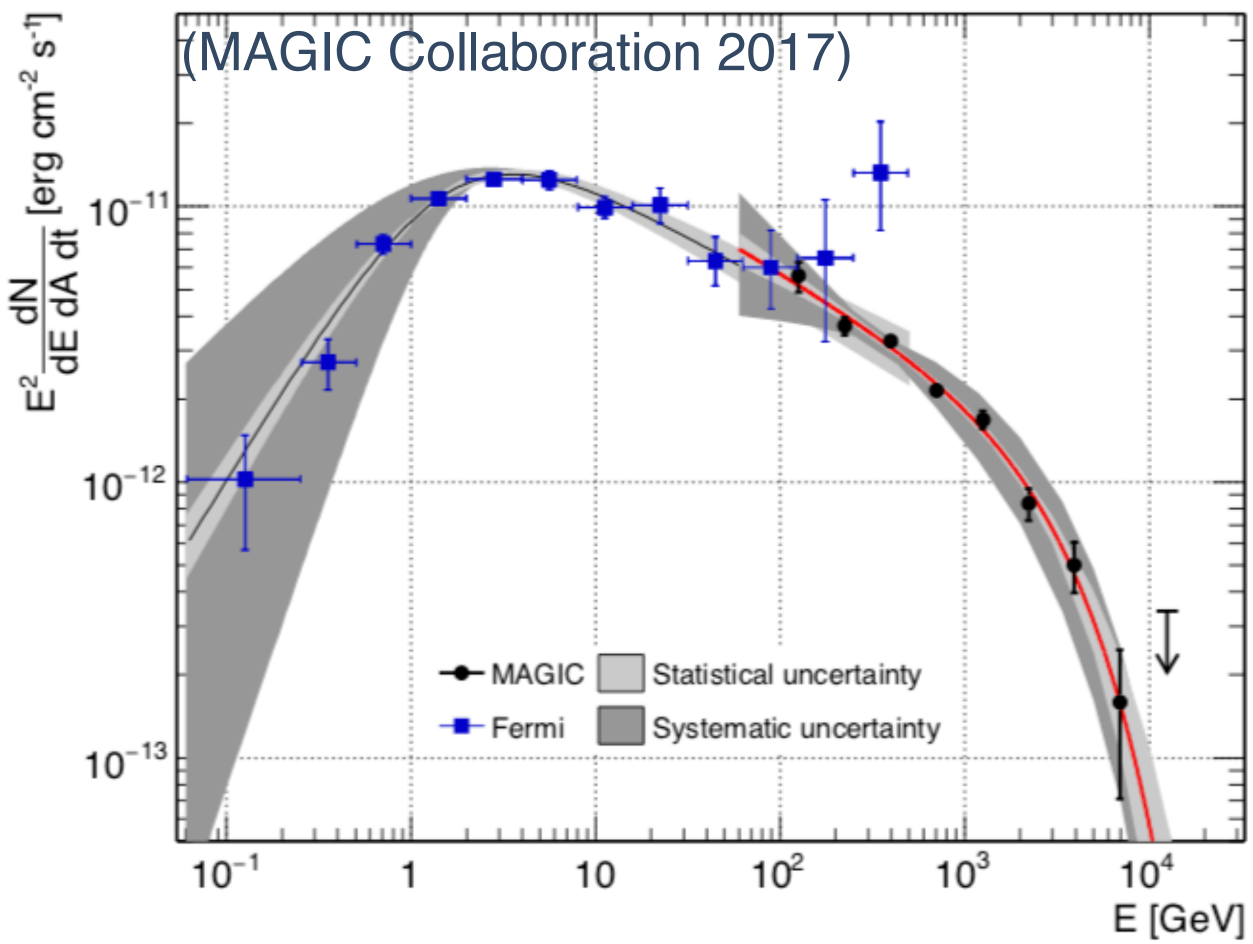


(Jogler and Funk 2016)

Looking at young SNRs

The SNR Cassiopeia A (350 yr) - One of the youngest Galactic SNR propagating into a dense circumstellar wind (and n_H = 10 cm^{-3} in the post-shock region)

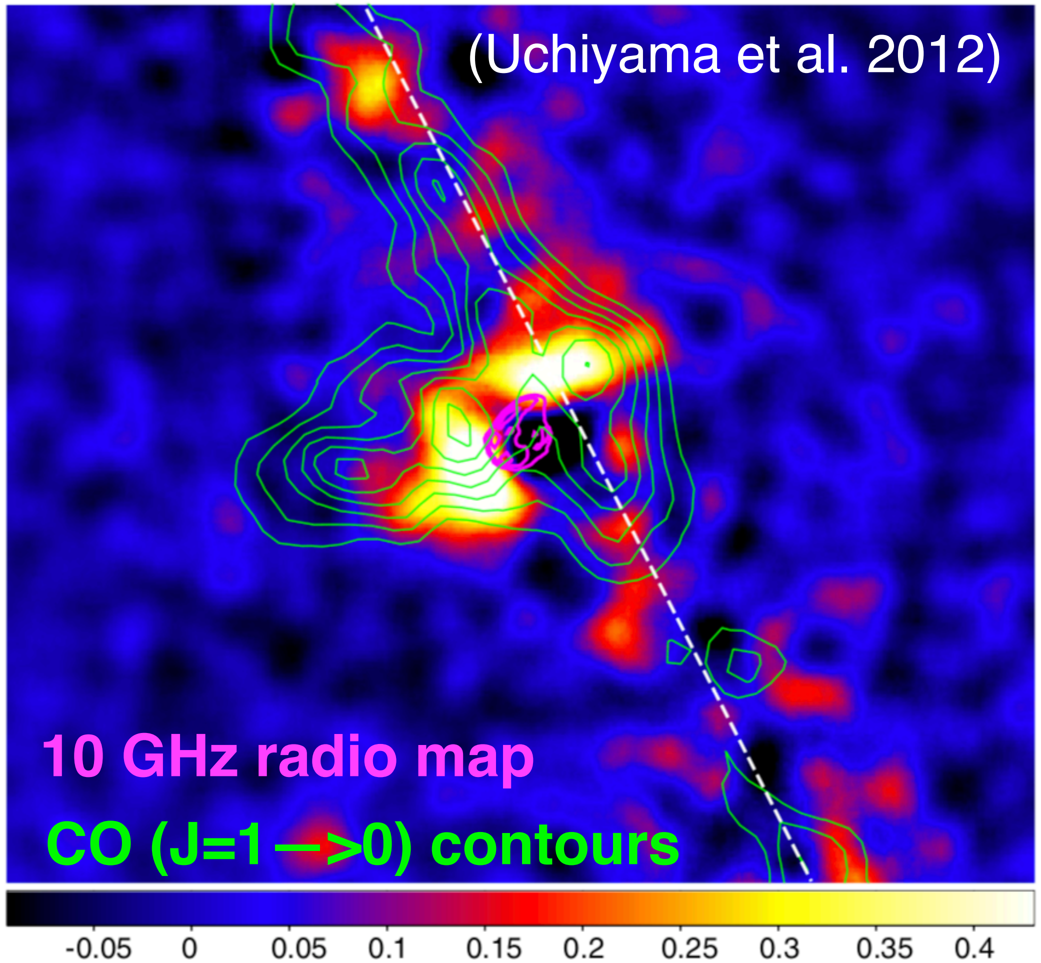




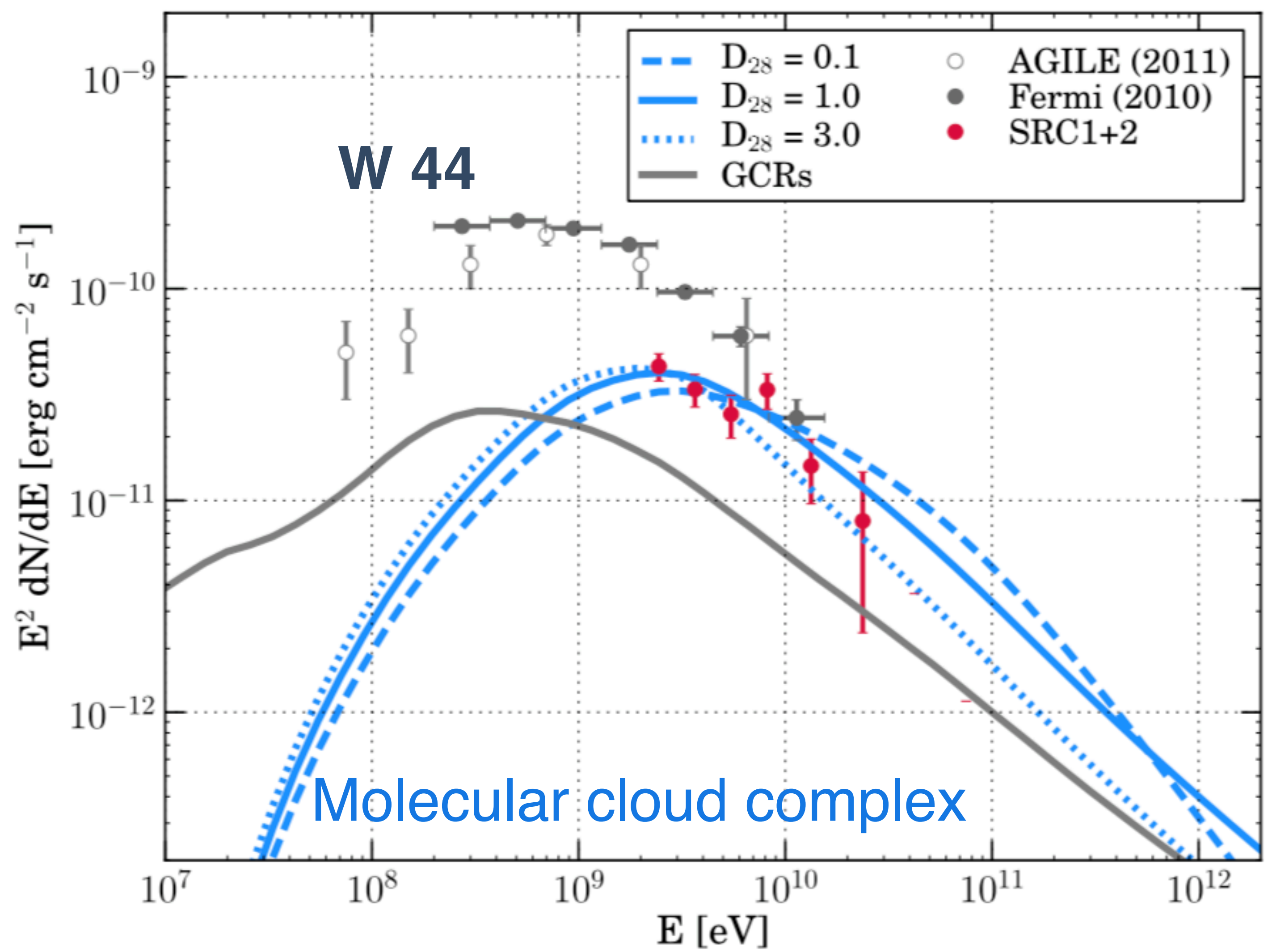
- Pion bump detected but E_{max} = 12 TeV: Have PeV particles already escaped?

Search for emission from escaped CRs interacting with the surrounding material (fainter than the one from CR accelerated in the SNR but last longer)

Escaping cosmic rays from the SNR W44?



<= Background-subtracted count map



D = 100 pc, M = 5 x 10^5 solar masses

Solving the diffusion equation:

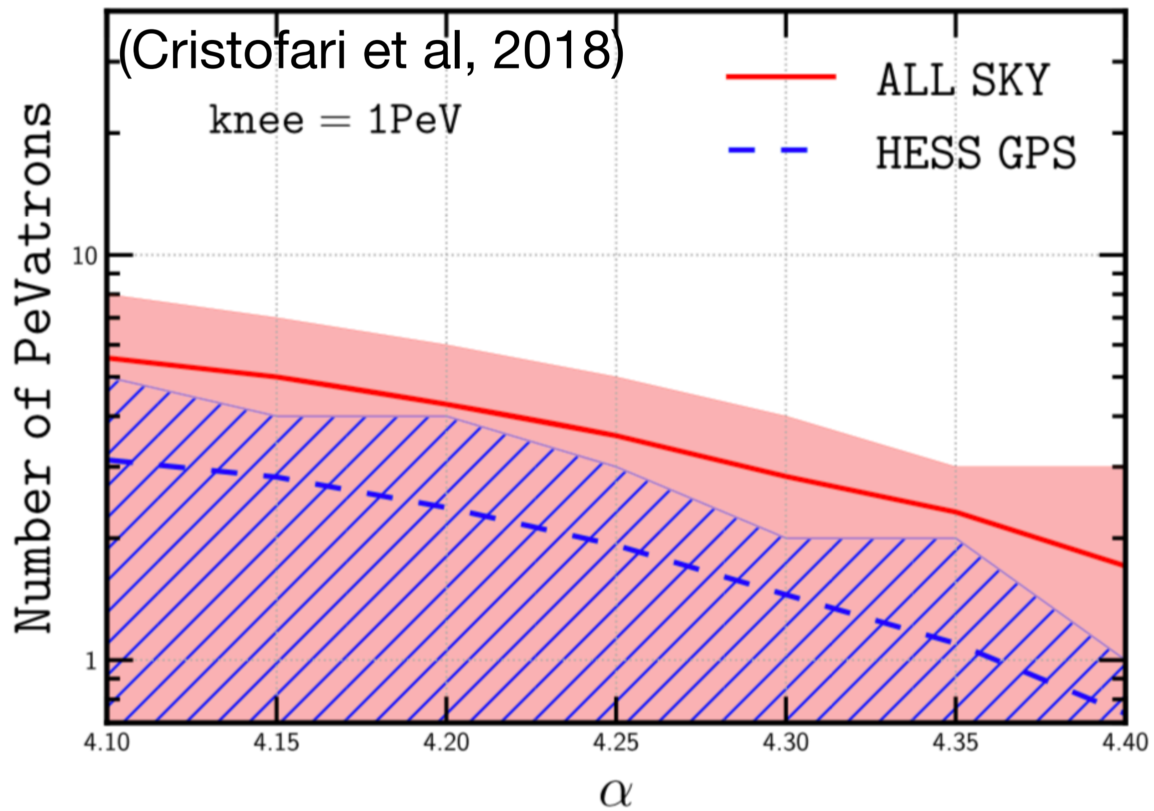
W_{esc} = (0.3–3) x 10^{50} erg

Strenghtens SNRs as main sources of Galactic CRs

Can we detect PeV particles in SNRs?

Simulated SNRs in the Galaxy with E_{max} = 1 PeV at the transition between the free expansion and Sedov-Taylor phase

Number of PeVatrons with integrated flux above 1 TeV > 1% Crab Nebula (HESS sensitivity):



Compatible with no detection

Depends on the particule spectra, and large fluctuations between different realizations in the Galaxy

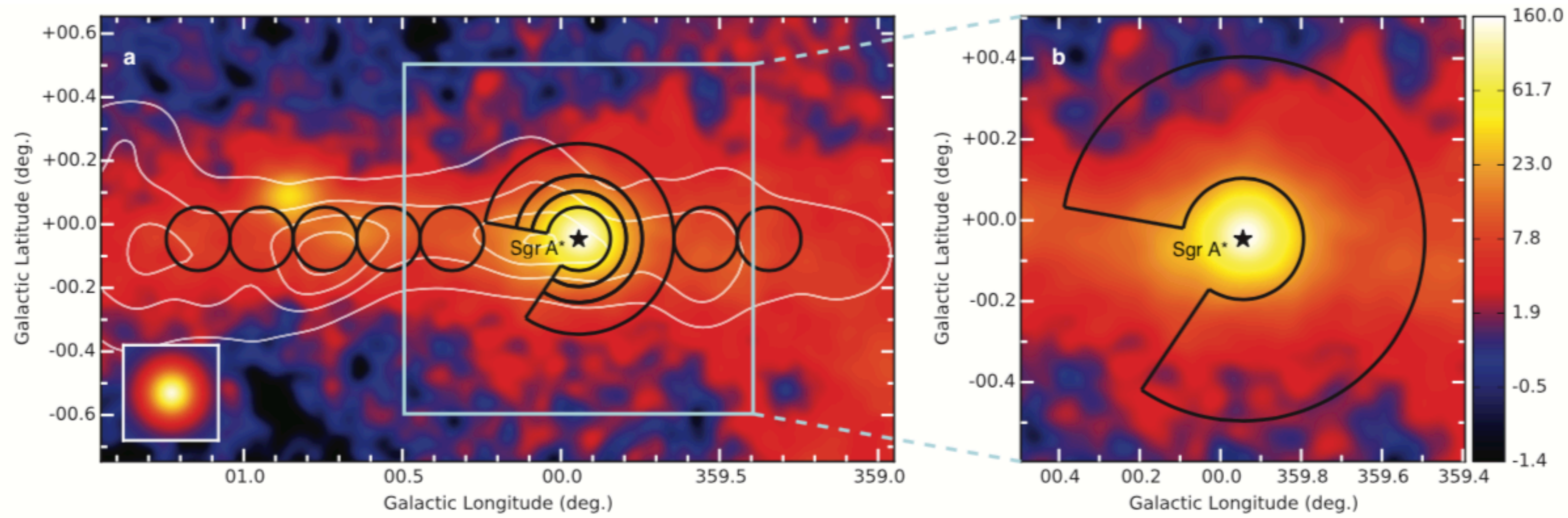
More optimistic situation if E_{max} = 3 PeV

Hard particle spectrum	**Steeper spectrum**
~ 3.1 (HGPS)	~ 0.7 (HGPS)
~ 5.5 (All sky)	~ 1.7 (All sky)

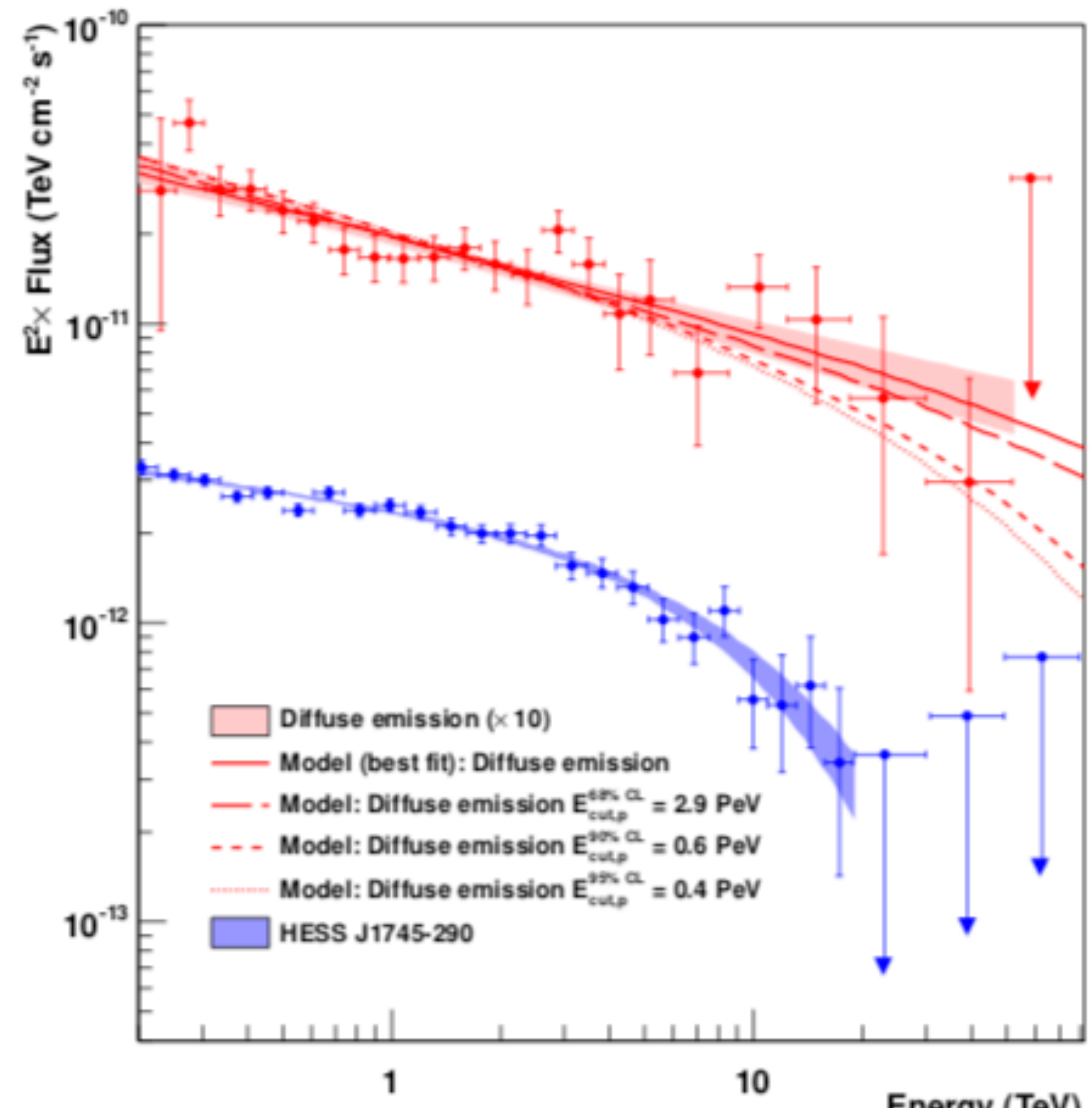
Detection of PeV particles in SNRs challenging

Detection of a PeVatron in the Galactic center

Diffuse emission around Sgr A*

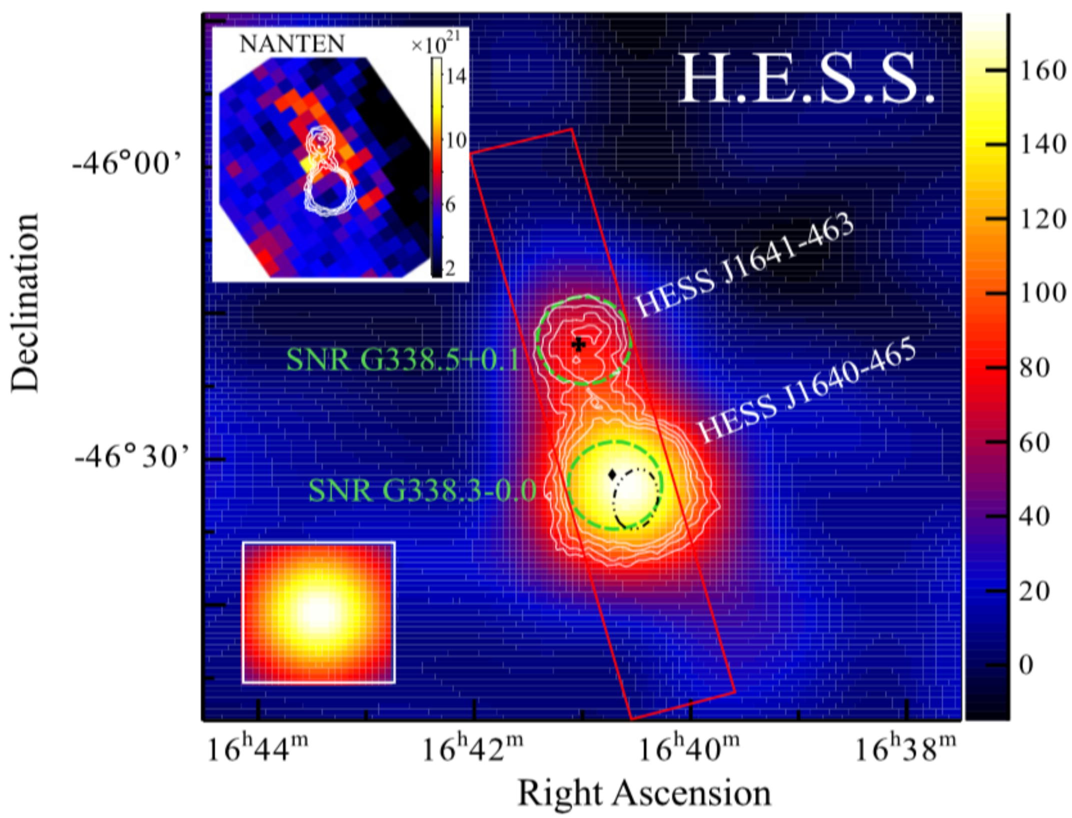


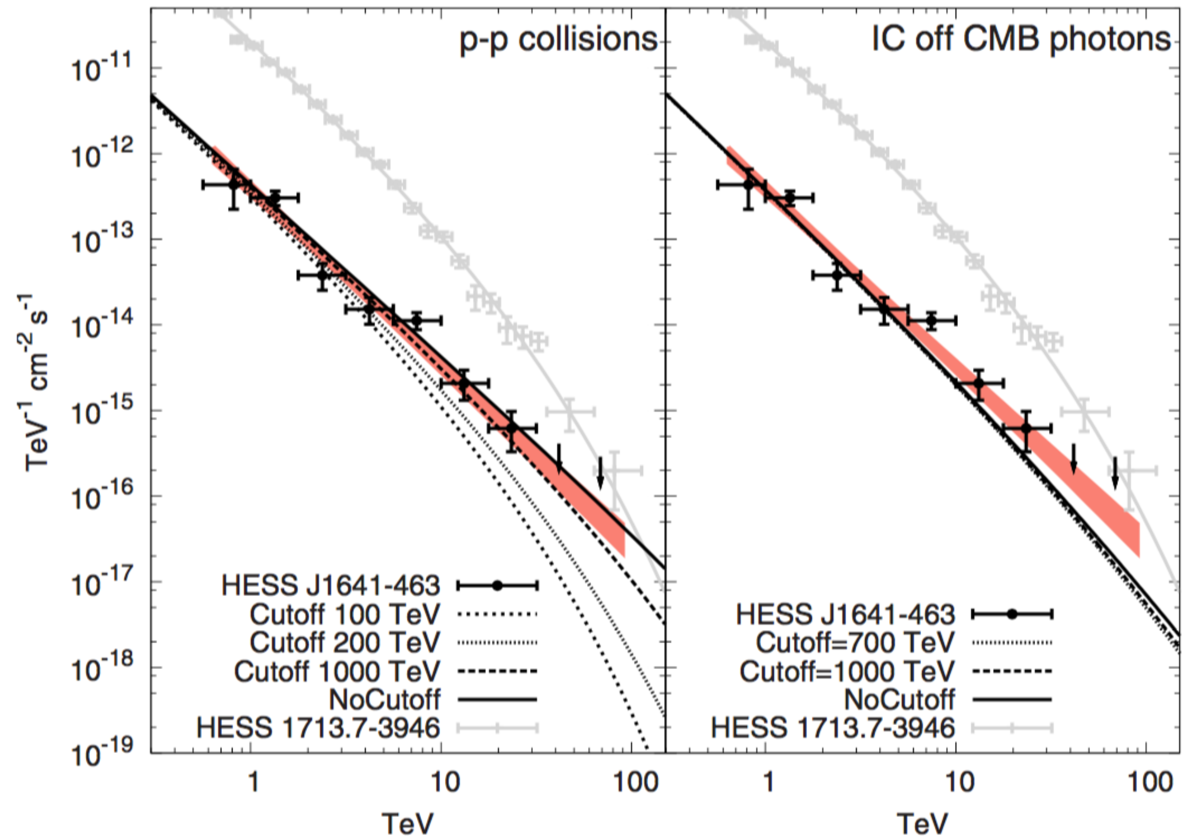
PeV particles produced in the accretion flow or further away have been proposed (accretion rate not sufficent to explained the flux of CR up to the knee => more activity in the past?)



PeVatron candidates

- HESS J1641-463



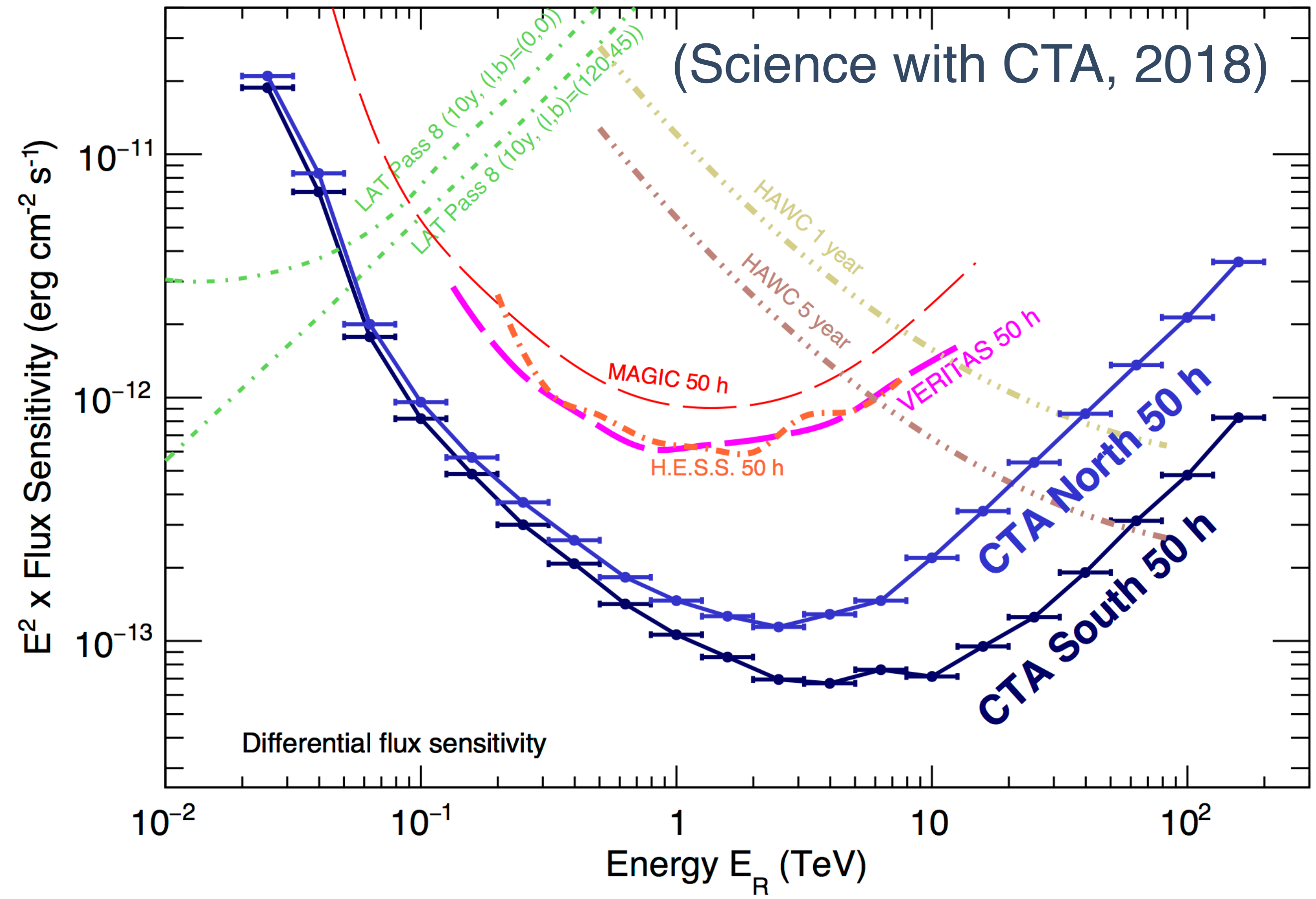


Another PeVatron?

- Other candidates: HESS J1826-130, HESS J1741-302 (unidentified sources)

The CTA era

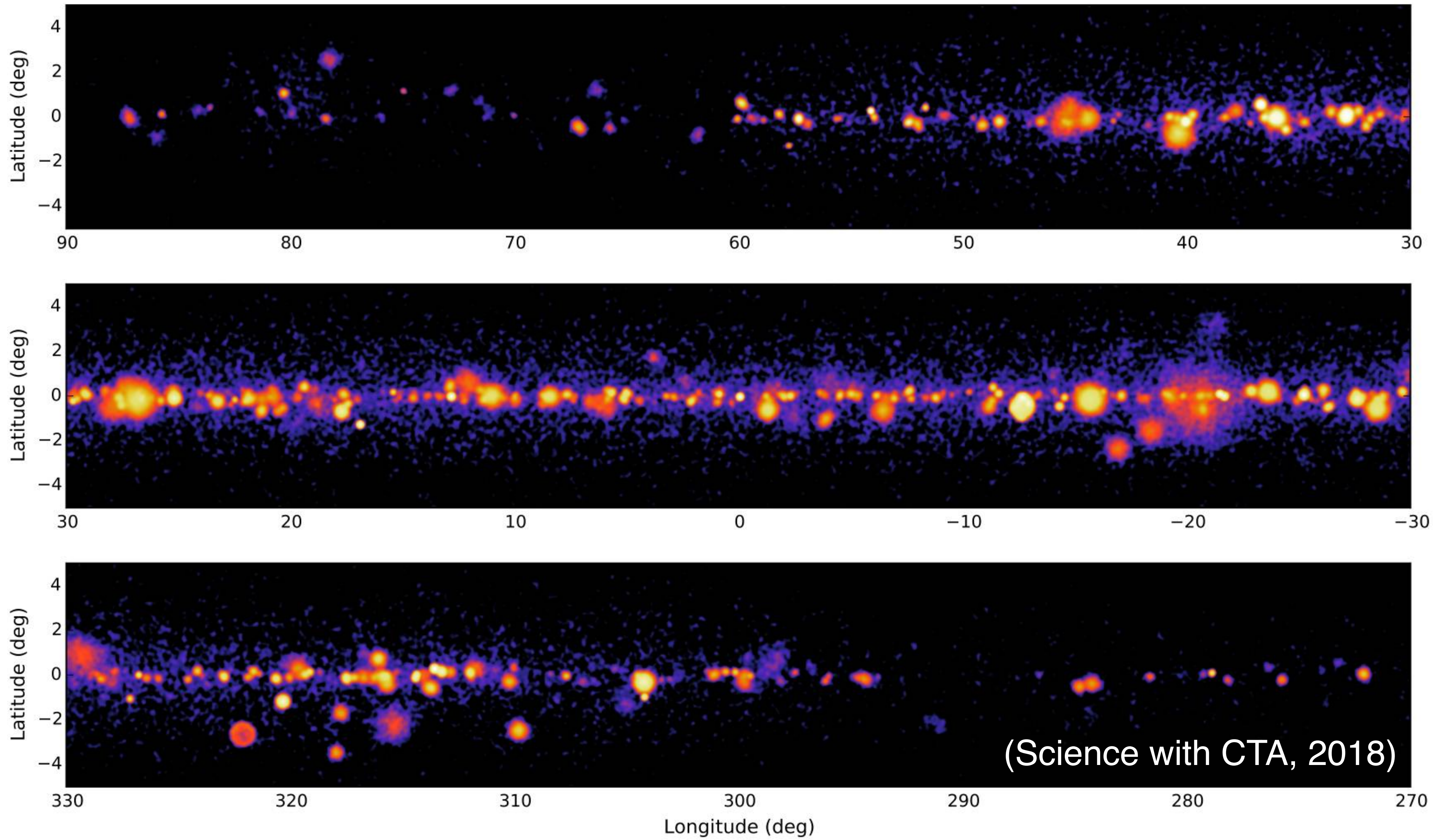
19 telescopes (North) + 99 (South)



- One order of magnitude more sensitive than current Imaging Atmospheric Cherenkov Telescopes (IACTs like H.E.S.S., VERITAS, MAGIC)
- PSF: 5 times better than current IACT instruments

The CTA era

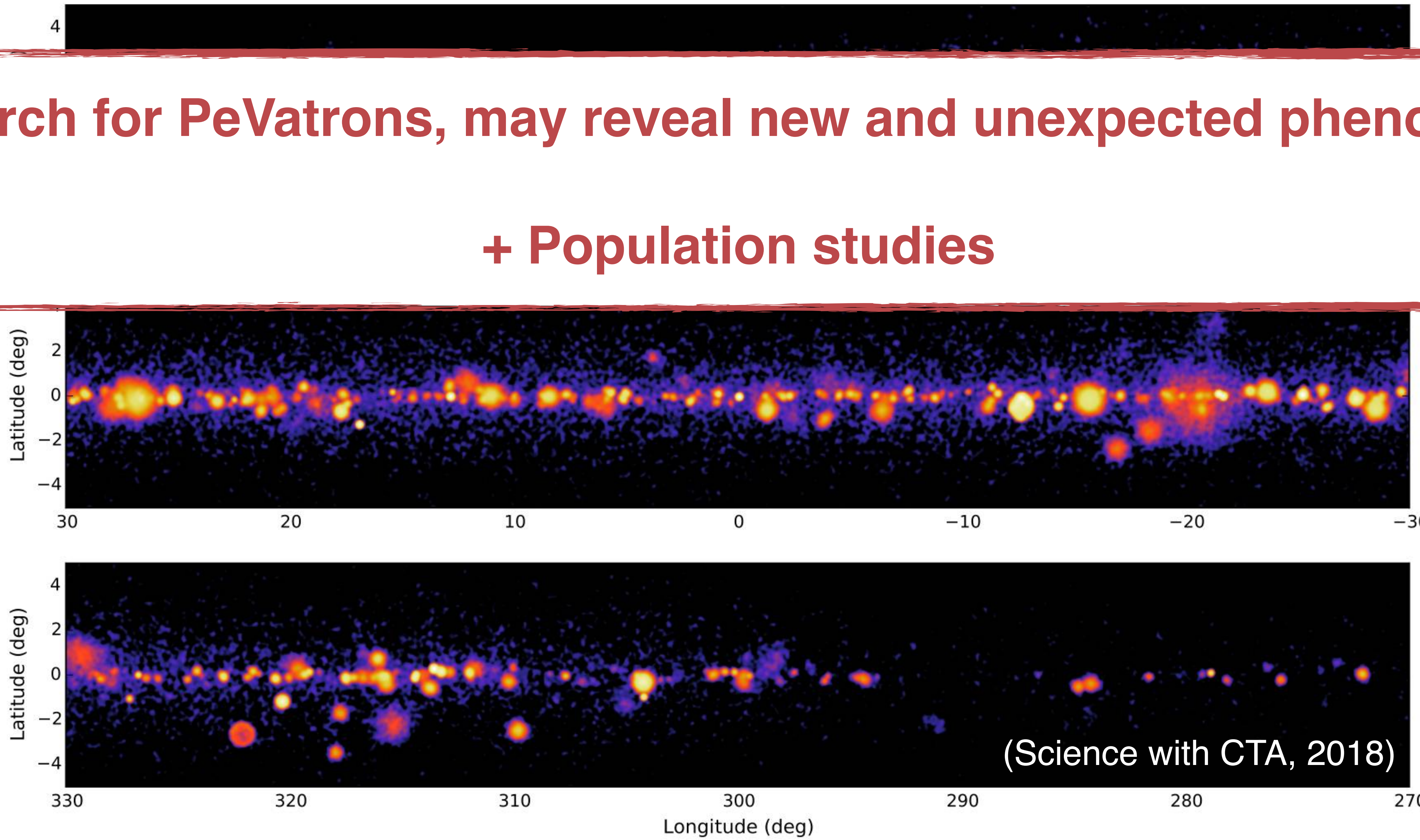
Simulation of the Galactic Plane Survey with CTA:



Renaud, 2009: 300 - 500 sources (1 - 3 mCrab sensitivity)
Dubus et al 2013: 20 - 70 SNRs and 300 - 600 PWNe

The CTA era

Simulation of the Galactic Plane Survey with CTA:



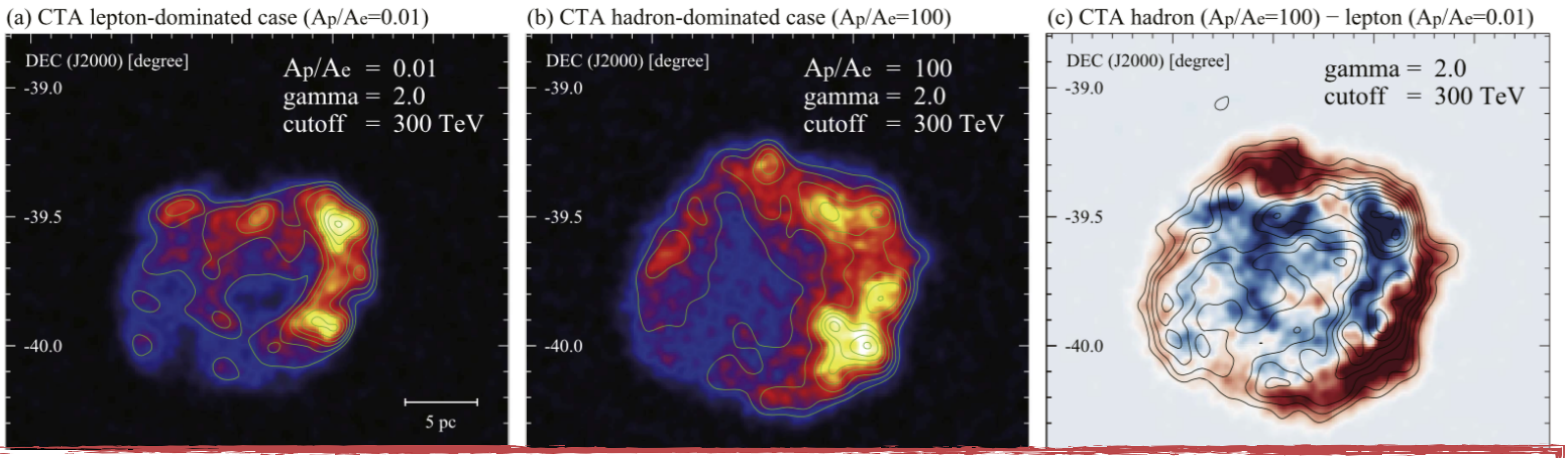
Search for PeVatrons, may reveal new and unexpected phenomena

+ Population studies

Renaud, 2009: 300 - 500 sources (1 - 3 mCrab sensitivity)
Dubus et al 2013: 20 - 70 SNRs and 300 - 600 PWNe

The CTA era

Simulation of the emission from the SNR RX J1713-3946 in case of a leptonic and hadronic scenario:

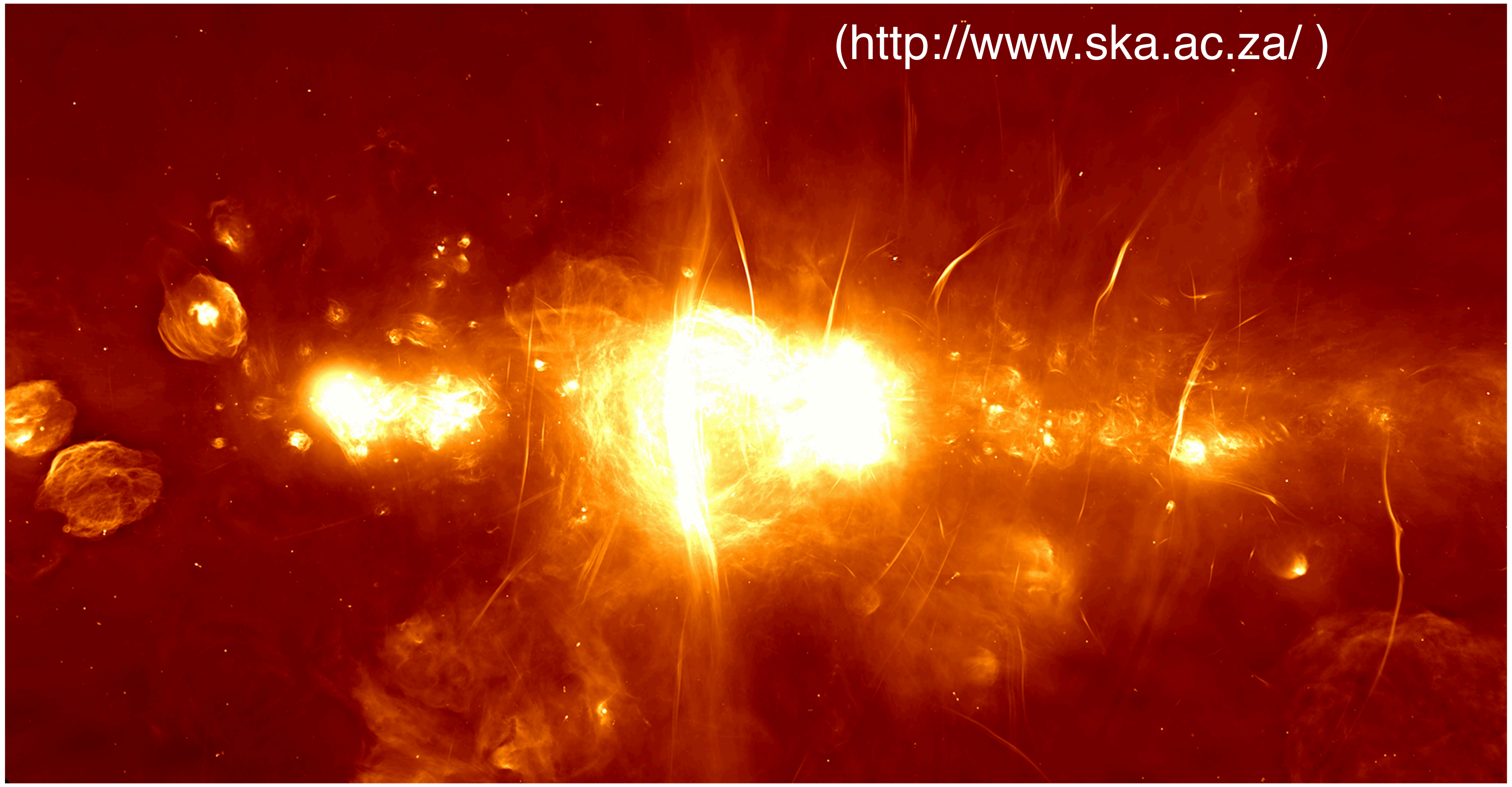


Detailed morphological studies to separate lepton/hadron components

CTA will be able to differenciate between these scenarios for large and bright TeV sources (like also Vela Junior)

Synergy with other instruments

- Radio : SKA



MeerKAT image of the Galactic Center region (2° x 1°) revealing new filamentary structures

- Optical (LSST)
- X-rays (eROSITA: large-field-of-view instrument, SVOM, Athena)
- Gamma rays (eASTROGAM: 0.3 — 100 MeV, LHASSO, HAWC)

General conclusions

- The recent gamma-ray field has offered new insights on the Galactic sky

High diversity of sources accelerating CRs!

Population studies will help understand CR acceleration in these objects

- Search for PeVatrons is of primary concern

No PeV particles detected in SNRs!

Better sensitivy and PSF to probe photons > 100 TeV and detect potential PeV halos around SNRs

- Studies of molecular clouds illuminated by cosmic rays are promising to
  => identify a large amount of gamma-ray sources
  => constrain the particles' diffusion coefficient

Synergy with advanced radio and X-ray instruments may detect secondary electrons

General conclusions

Large amount of questions still open:

- Which sources are the Galactic PeVatrons?
- When does the SNR shock become most efficient? (Non detection of gamma rays from SN 1987A implies $W_{CR} < 1\% \, E_{SN}$)
- New type of sources still unrevealed?
- What is the electron-to-proton ratio close to Galactic sources?
- Etc …

Future instruments will help answer these questions:

so much exciting science to be done!