Galactic Plane Survey

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INAF/IASF Palermo

AVENGe workshop, Roma, 29/05/2023

Why a gamma-ray Galactic Plane Survey?

1) About a hundred of VHE sources in our Galaxy

2) Census of the Galactic gamma-ray source populations

3) Increase the number of very-high energy Galactic sources

4) Find promising targets for follow-up observations

5) Production of catalogues

6) Possible discovery of new and unexpected phenomena in our Galaxy

Why a gamma-ray Galactic Plane Survey?

The goal will be to scan a large fraction ($-60° < l < 60°$) of the Galactic plane aiming at:

1) A complete and systematic study of the Galactic VHE sources

2) Comprehension of the physical mechanisms responsible for the source VHE emission

3) Discovery of new sources

5) Constrain emission models (hadronic vs leptonic)

6) Spectral and morphological studies

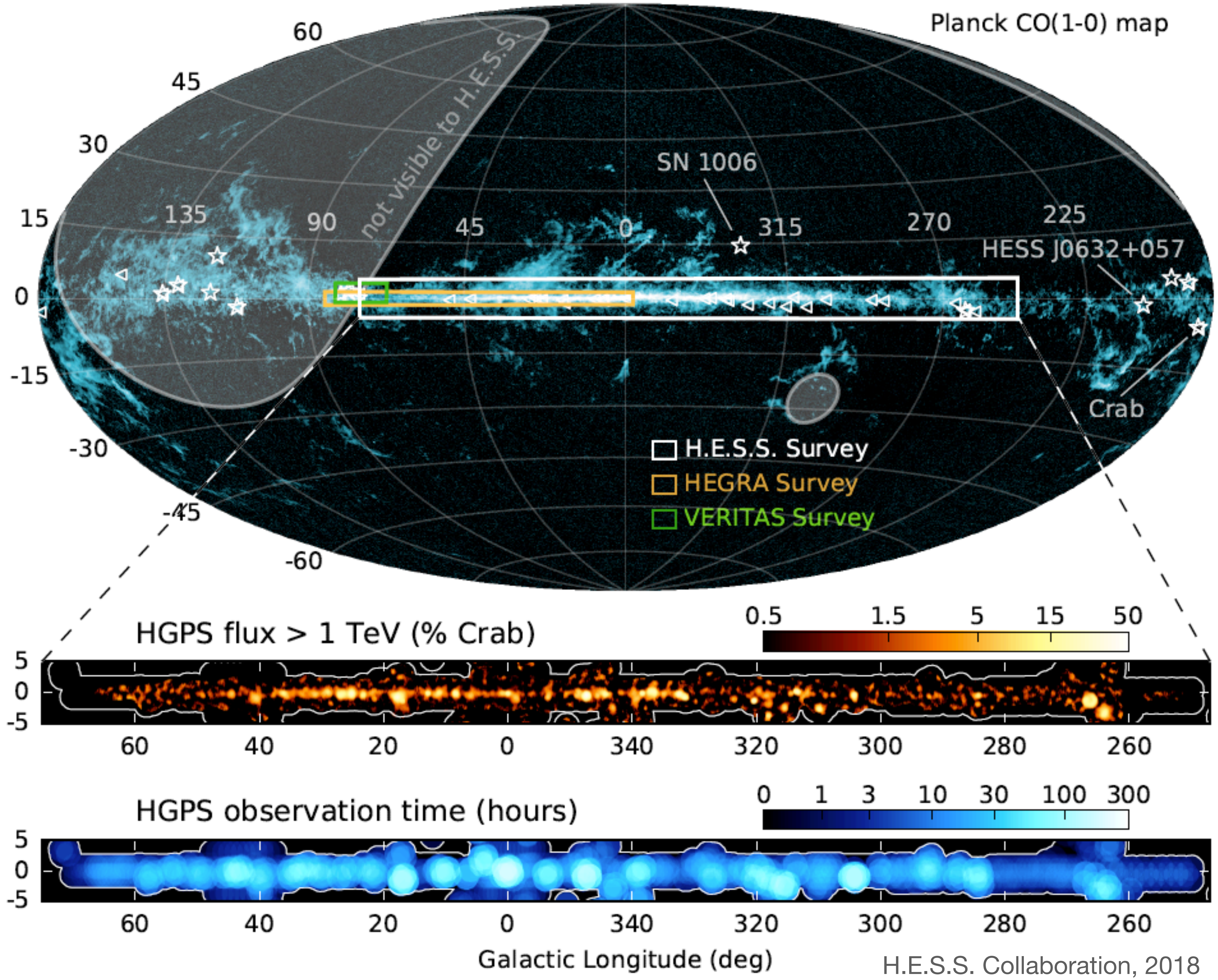
7) Population studies

8) Discovery of Pevatrons and investigation on their nature

9) Mapping and characterising the diffuse emission

10) Transients

HESS Galactic Plane Survey



H.E.S.S. Collaboration, 2018

65°< l < 250°, -3° < b < 3°

A total of ~2700 hr and
78 detected sources

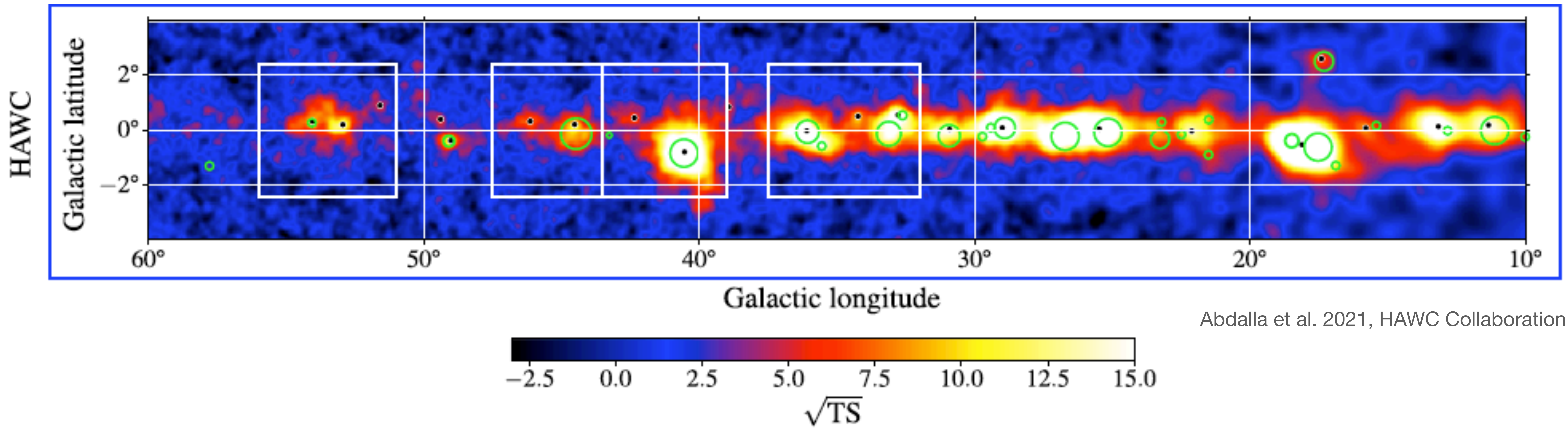
Population composed of
Pulsar Wind Nebulae (PWN),
Supernova remnants (SNR),
gamma-ray binaries

PWN are the largest population
at TeV energies

A number of sources not yet
firmly identified!

HAWC Galactic Plane Survey

0° < l < 110° and 150° < l < 240°



Abdalla et al. 2021, HAWC Collaboration

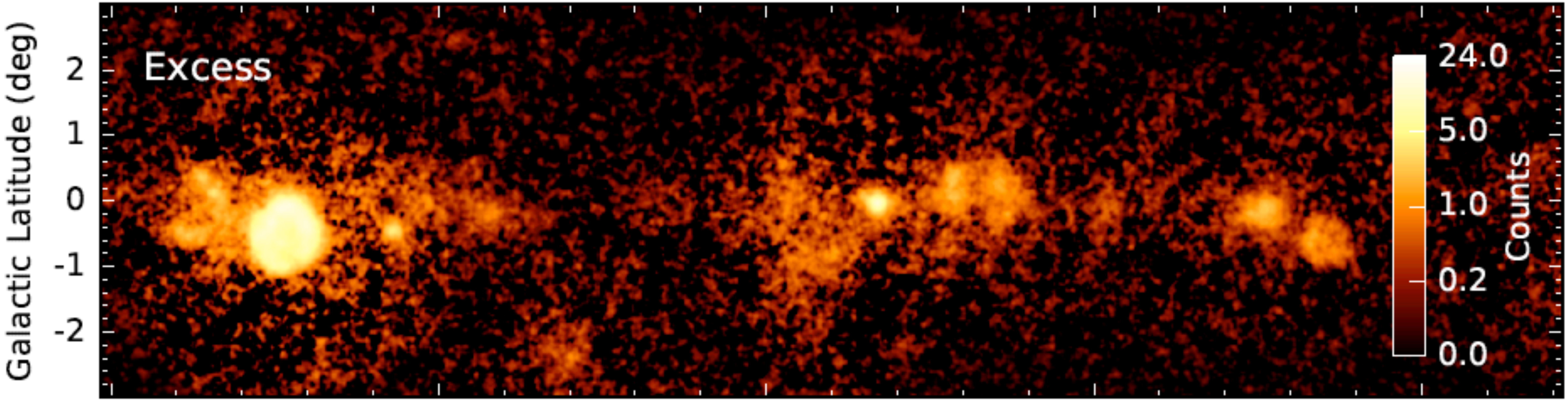
A total of 65 sources in the third HAWC catalogue

HAWC sources at energies of ~100 TeV!

General issues

The central Galaxy regions may suffer of source confusion

Need to characterise and quantify the effect of the diffuse gamma-ray emission



H.E.S.S. Collaboration, 2018

Fast transients request dedicated analyses and techniques

GPS with CTA

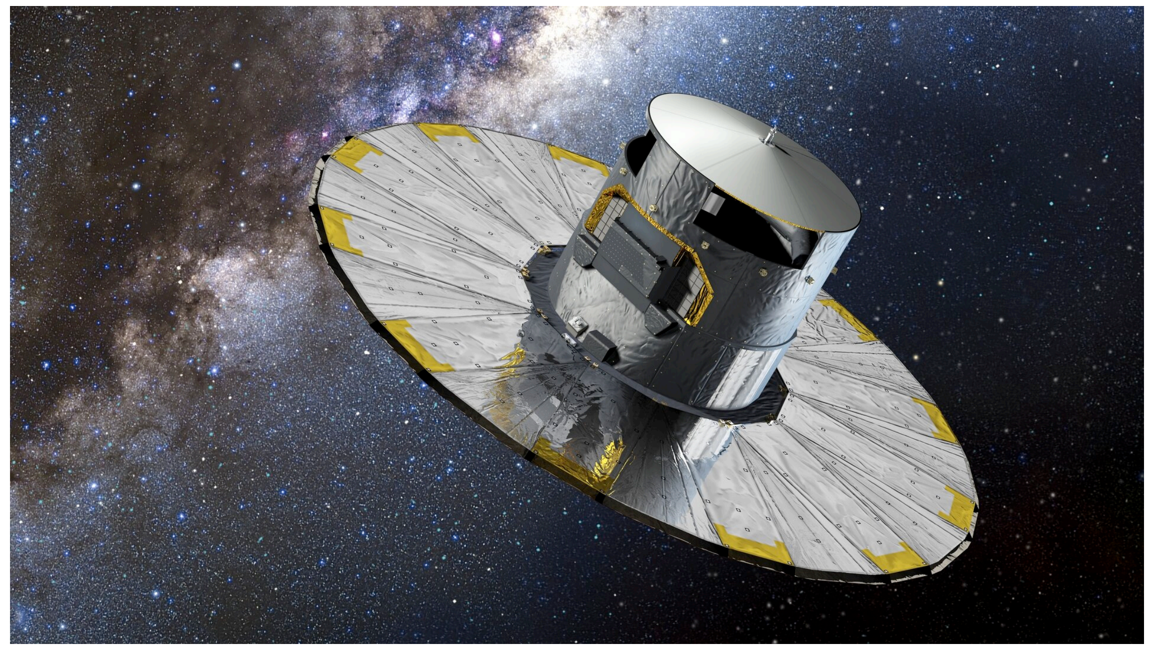
Coverage of northern and southern sky;

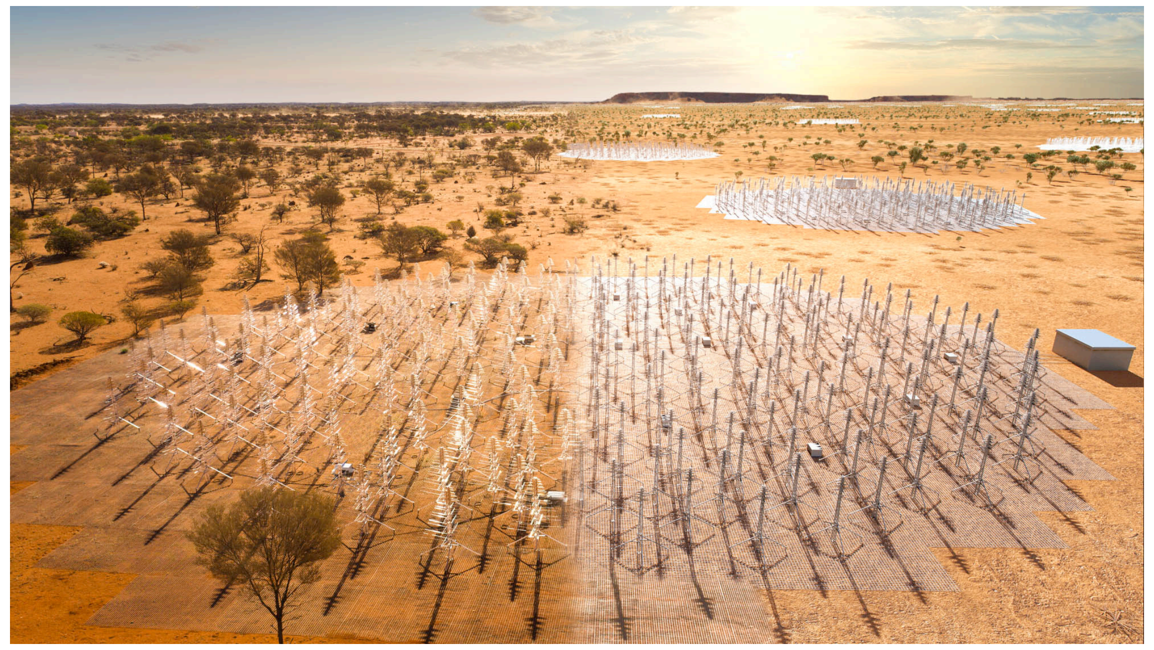
Improved sensitivity (a few mCrab?);

Improved angular resolution (a few arcmin);

Sinergy with other multi-wavelength facilities;

Increment of the number of sources of a factor of ~5?





Galactic Plane Survey paper (under SAPO review: in discussion with the internal referees)

GPS with CTA

However, the predicted number of sources from other facilities has a number of caveats:

1) The extrapolation of the spectrum often does not assume cut-offs

2) The number of PWN can be even higher if we consider that are usually dimmer at HE than VHE

3) SNRs may exhibit spectral breaks at HE-VHE

4) The inner regions are crowded so the number of predicted sources can be smaller

Some open questions

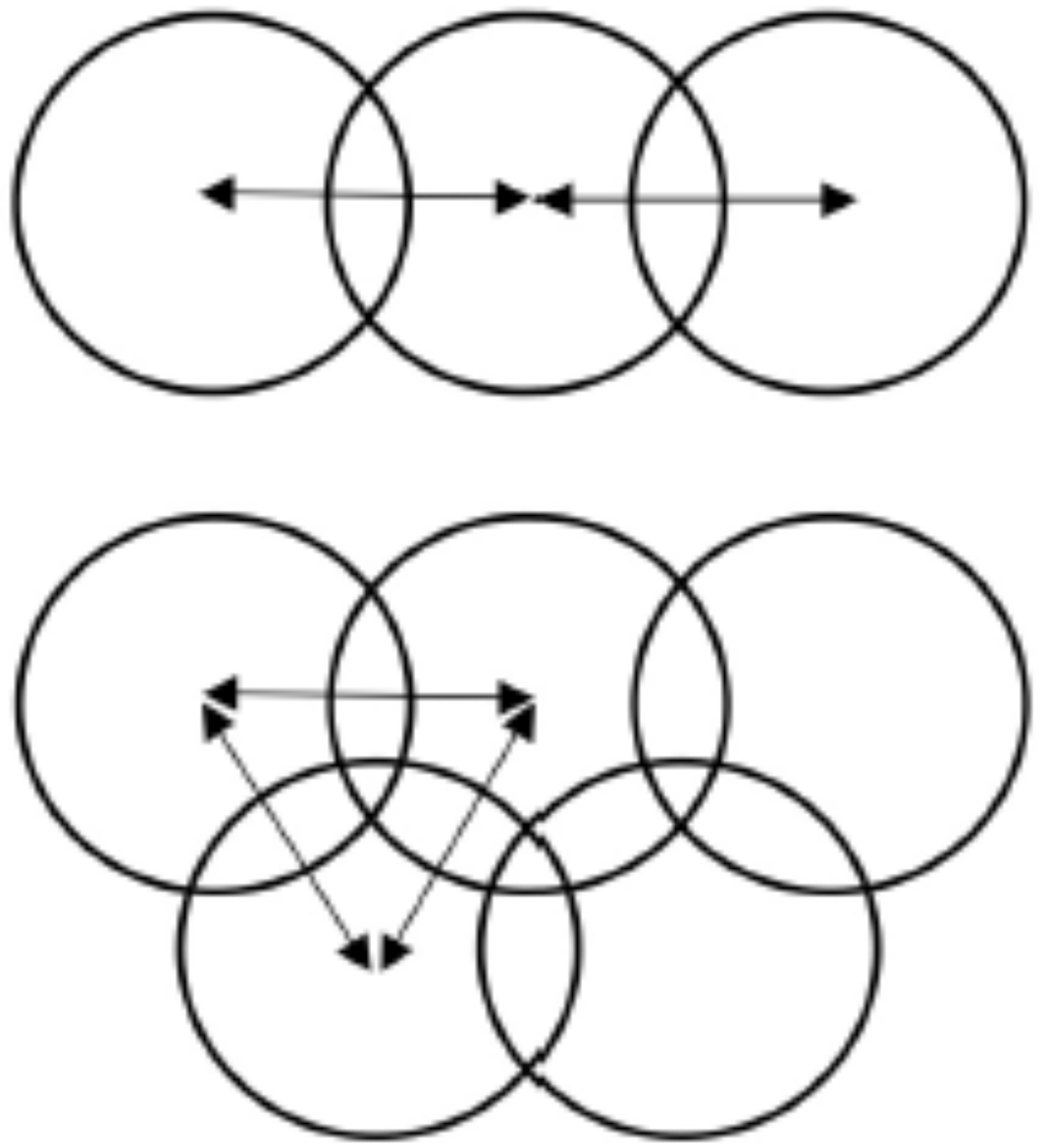
- How and where are protons and nuclei accelerated to PeV energies?

- How are particles accelerated in relativistic shocks?

- What is the impact of cosmic rays on the interstellar medium (ISM), and how do they propagate?

- What is the role of external photon fields, jet content, and geometry in distinguishing jet sources, such as pulsars and microquasars?

Previous requirements



- Dark time observations only
- Zenith angles < 50°
- Good weather conditions
- Both CTA-North and CTA-South, full array
- Certain regions should be observed with high exposure(e.g. Sagittarius-Carina arm, the Cygnus region..)
- 10 years of observations, with a minimum of ~1000 hr for CTA-S and 600 hr in CTA-N.
- Program to start in the first two years of observations (short-term)

Previous estimates

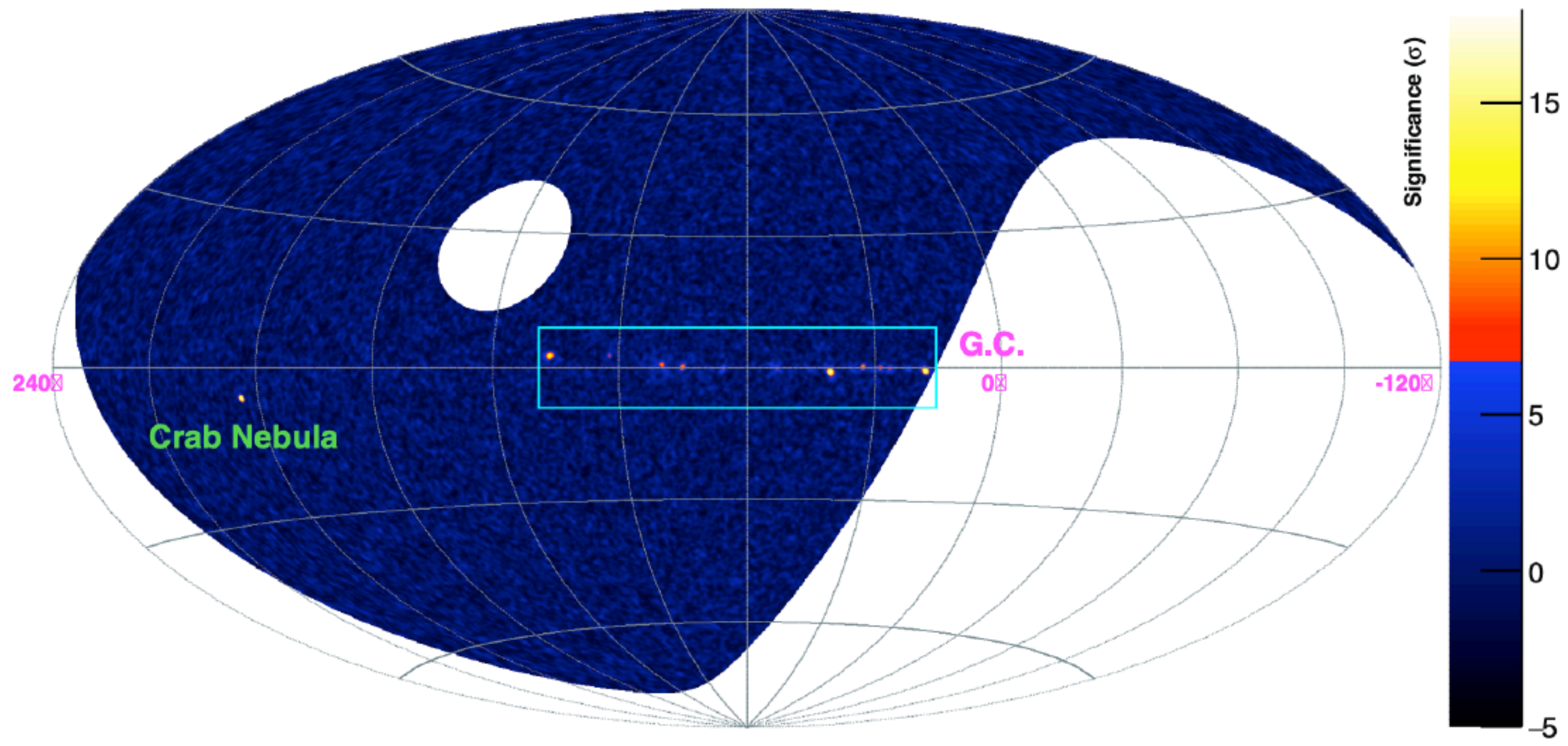
	STP (Years 1 – 2)		LTP (Years 3 – 10)	Total (Years 1 – 10)	
Galactic Longitude	Hours	Sensitivity	Hours	Hours	Sensitivity
SOUTH					
300° – 60° , Inner region 240° – 300° , Vela, Carina 210° – 240°	300	**2.7 mCrab**	480 180 60	780 180 60	**1.8 mCrab** **2.6 mCrab** **3.1 mCrab**
NORTH				1020	
60° – 150° , Cygnus, Perseus 150° – 210° , anti-Centre, etc.	180	**4.2 mCrab** Sensitivity at 125 GeV	270 150	450 150	**2.7 mCrab** **3.8 mCrab**
				600	

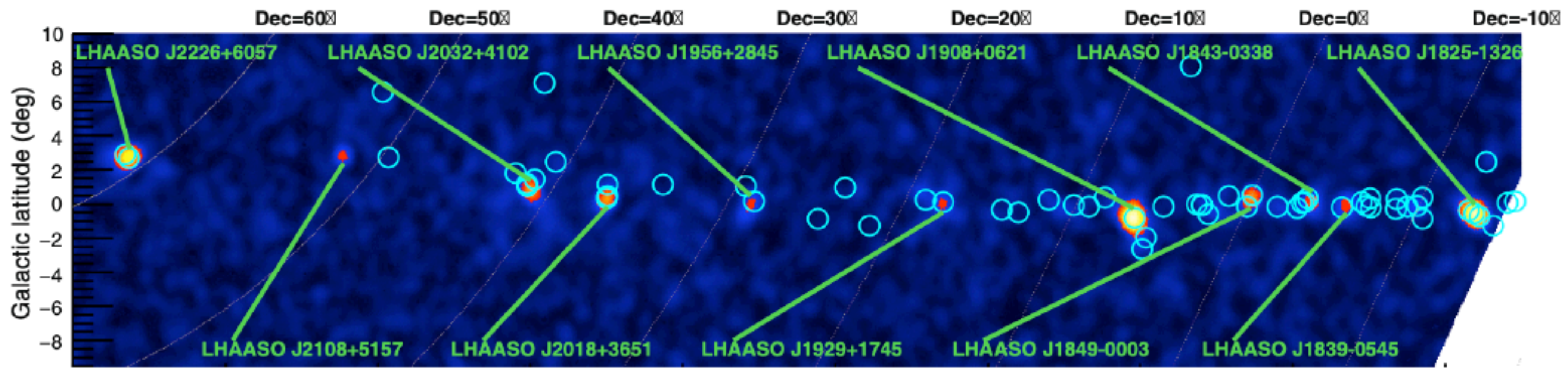
Science with CTA, CTA Collaboration, 2017

To be updated according to the new configurations (although preliminary works do not show significant changes)!

See Franz Long's talk

What's new: Pevatrons! YESTERDAY!





Cygnus region

LHAASO discovered 12 Pevatrons at >100TeV

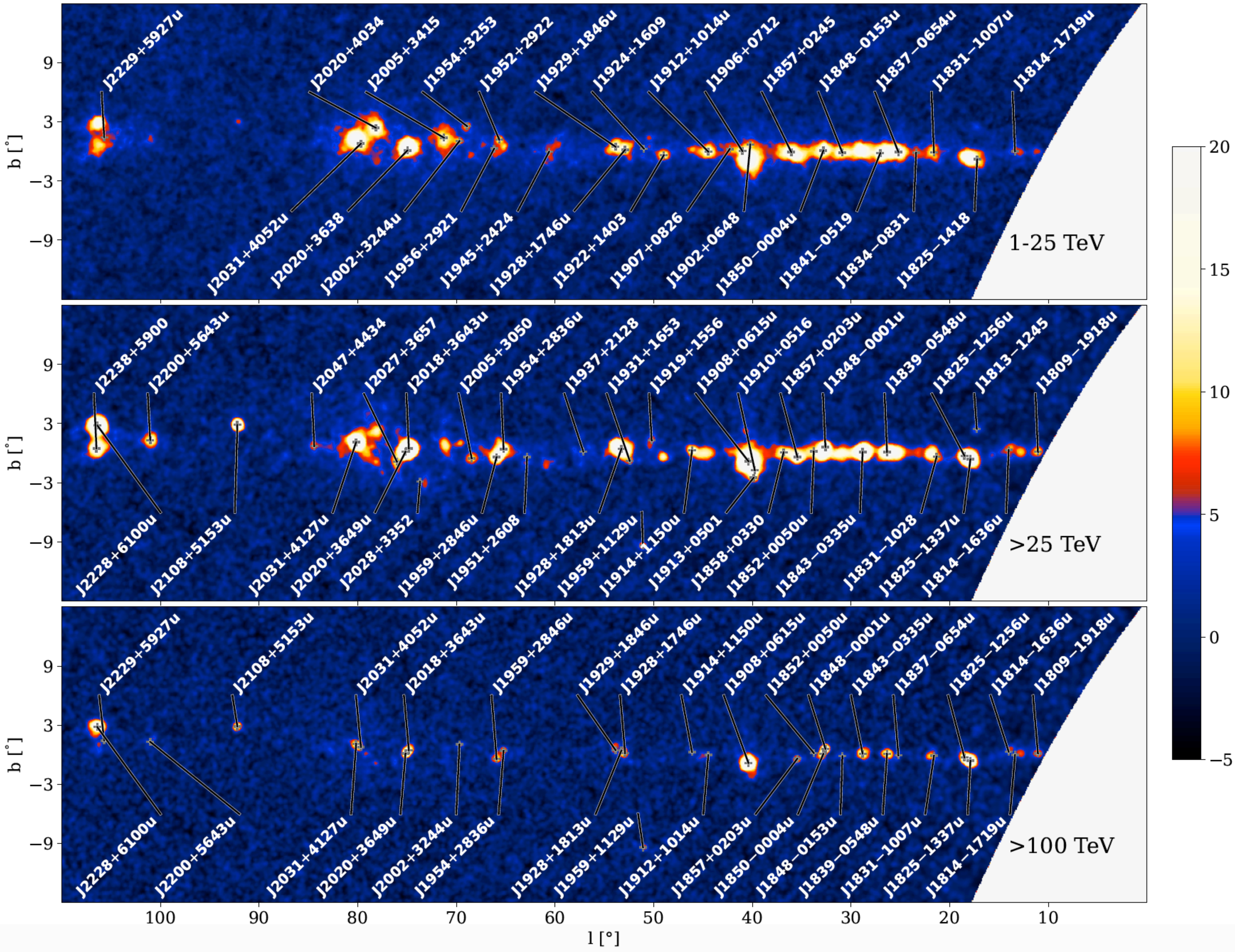
Table 1 | UHE γ-ray sources

Source name	RA (°)	dec. (°)	Significance above 100 TeV (×σ)	E_{max} (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ± 0.11	1.00(0.14)
LHAASO J1825-1326	276.45	−13.45	16.4	0.42 ± 0.16	3.57(0.52)
LHAASO J1839-0545	279.95	−5.75	7.7	0.21 ± 0.05	0.70(0.18)
LHAASO J1843-0338	280.75	−3.65	8.5	$0.26\ {-0.10}^{+0.16}$	0.73(0.17)
LHAASO J1849-0003	282.35	−0.05	10.4	0.35 ± 0.07	0.74(0.15)
LHAASO J1908+0621	287.05	6.35	17.2	0.44 ± 0.05	1.36(0.18)
LHAASO J1929+1745	292.25	17.75	7.4	$0.71\ {-0.07}^{+0.16}$	0.38(0.09)
LHAASO J1956+2845	299.05	28.75	7.4	0.42 ± 0.03	0.41(0.09)
LHAASO J2018+3651	304.75	36.85	10.4	0.27 ± 0.02	0.50(0.10)
LHAASO J2032+4102	308.05	41.05	10.5	1.42 ± 0.13	0.54(0.10)
LHAASO J2108+5157	317.15	51.95	8.3	0.43 ± 0.05	0.38(0.09)
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ± 0.19	1.05(0.16)

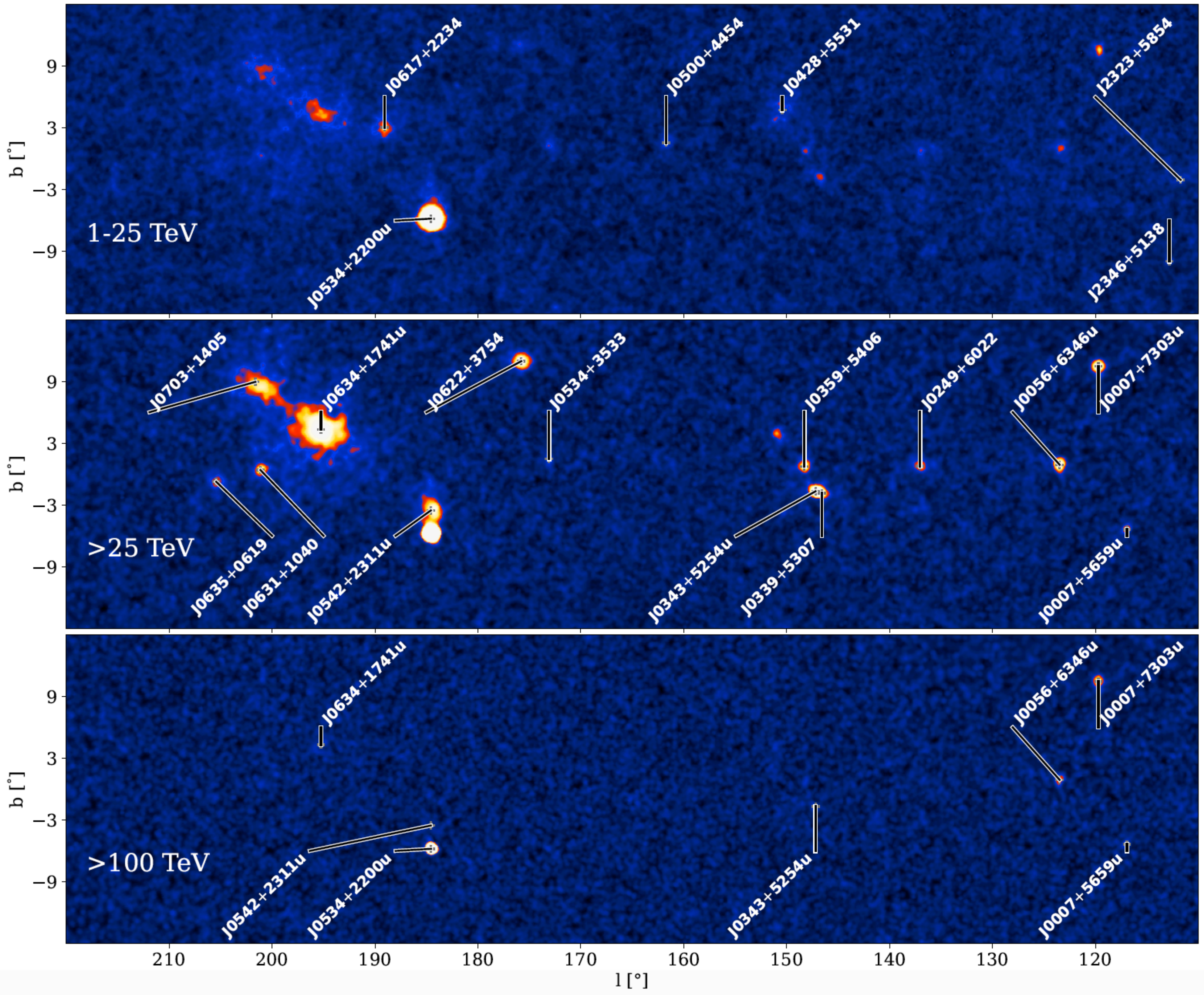
Celestial coordinates (RA, dec.); statistical significance of detection above 100 TeV (calculated using a point-like template for the Crab Nebula and LHAASO J2108+5157 and 0.3° extension templates for the other sources); the corresponding differential photon fluxes at 100 TeV; and detected highest photon energies. Errors are estimated as the boundary values of the area that contains ±34.14% of events with respect to the most probable value of the event distribution. In most cases, the distribution is a Gaussian and the error is 1σ.

See Cardillo's talk

What’s new: Pevatrons! TODAY!!

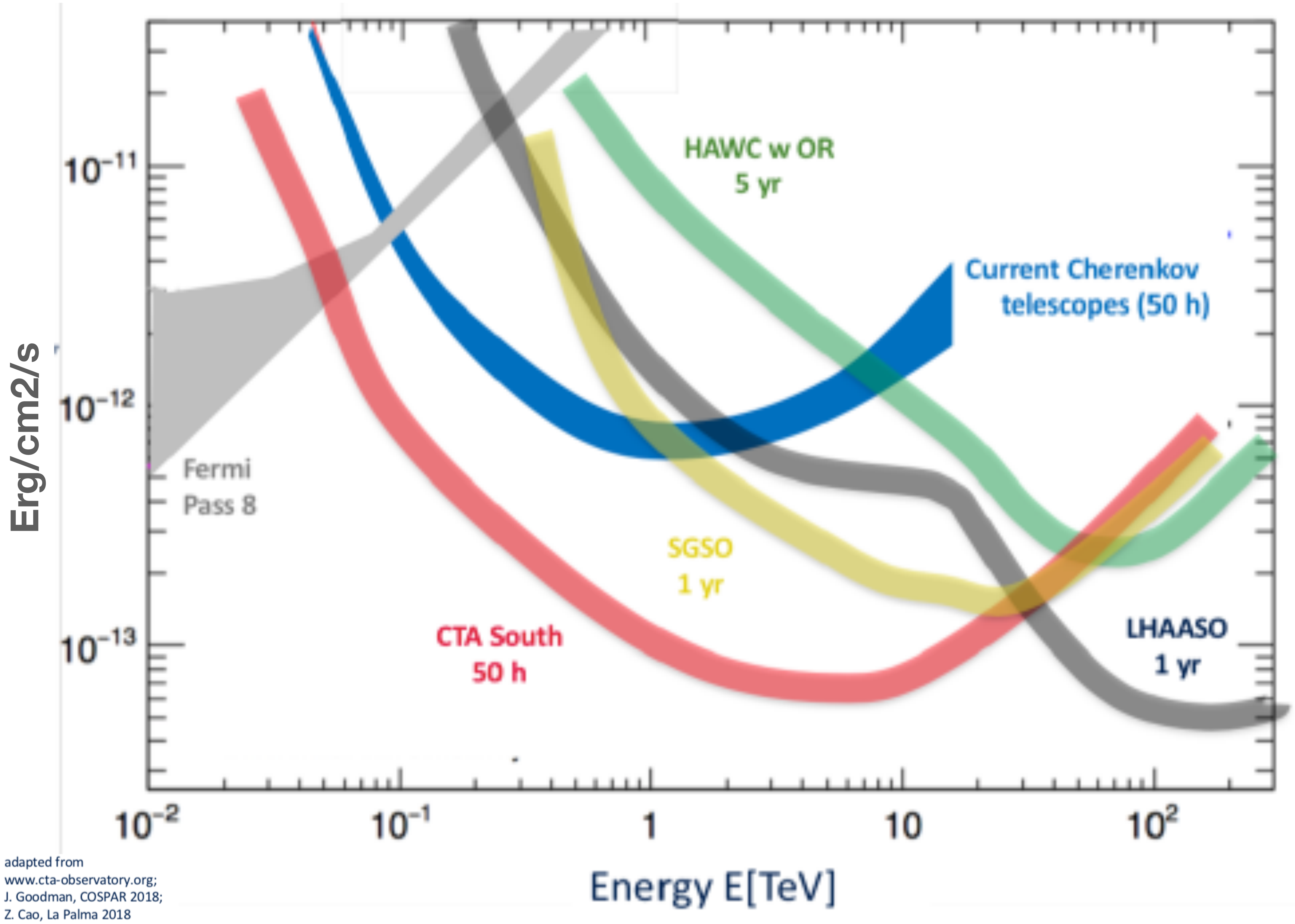


LHAASO Collaboration, 2023 today



43 new Pevatrons with significance >4sigma!!

What's new: Pevatrons!



adapted from
www.cta-observatory.org;
J. Goodman, COSPAR 2018;
Z. Cao, La Palma 2018

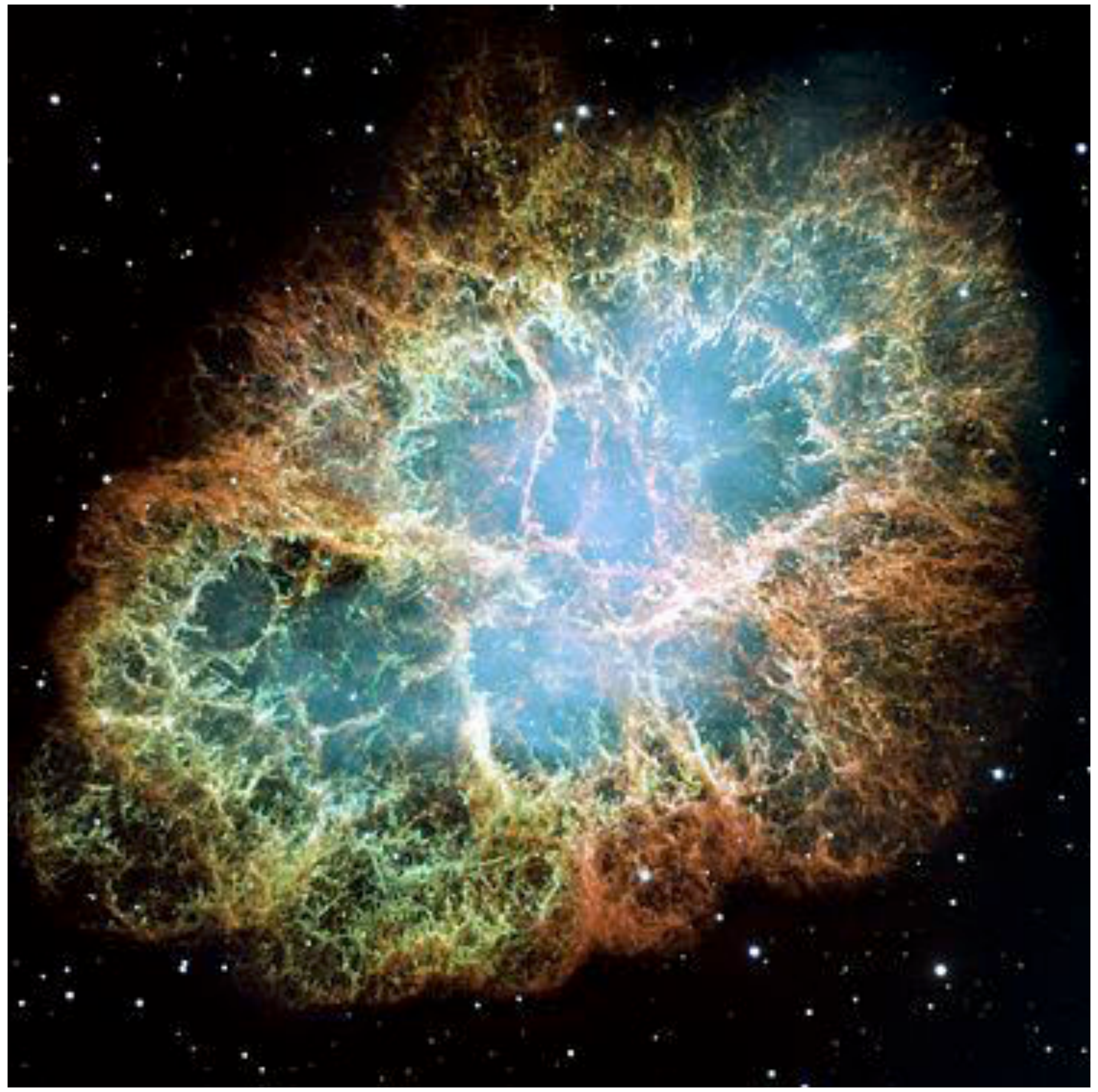
Credits to F. Aharonian

CTA will have the best sensitivity at < 30-40 TeV

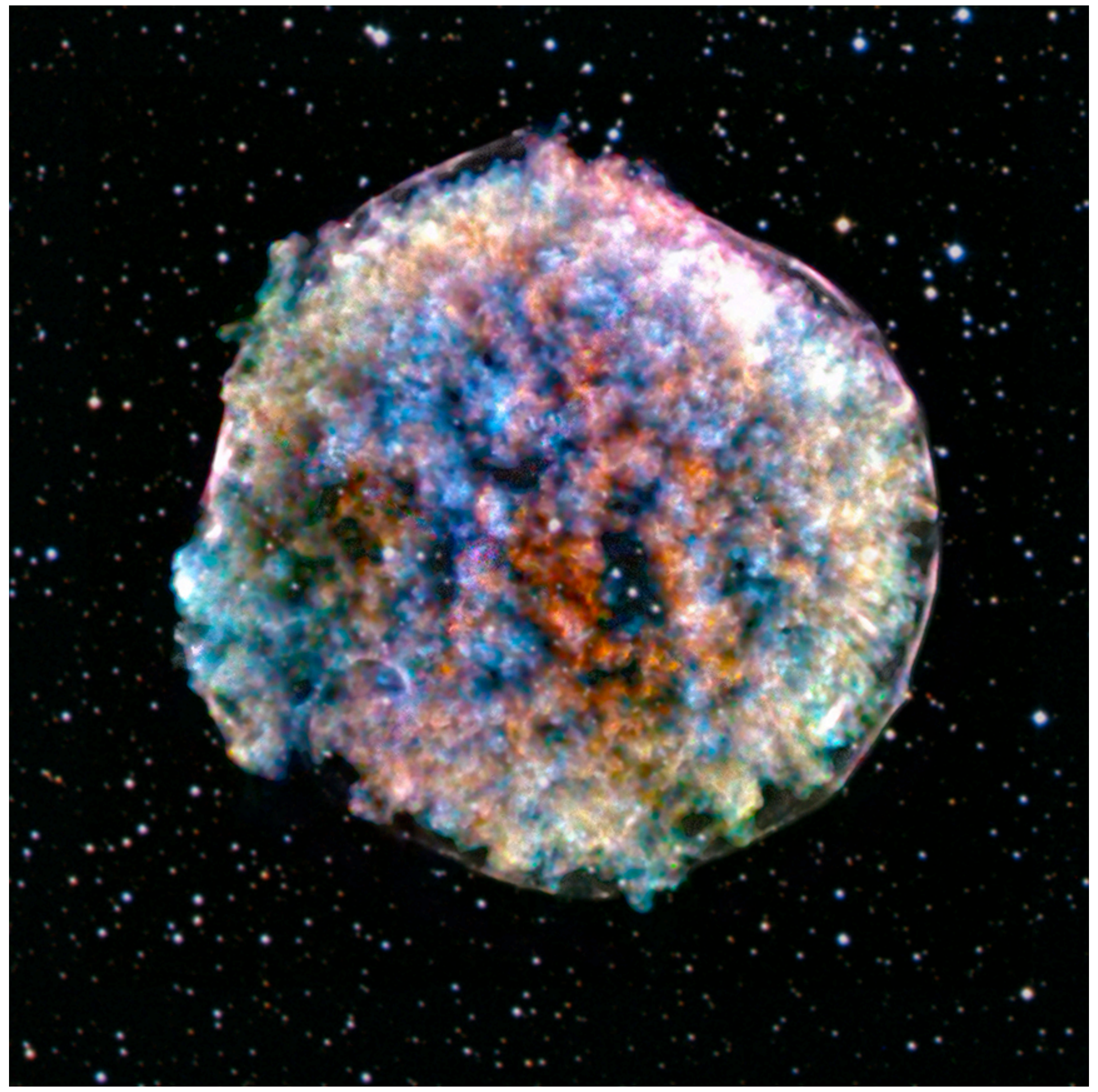
Crucial to constrain the spectral shape and connect to the LHAASO detections at >100 TeV

It will allow us to constrain the Pevatron nature of a source

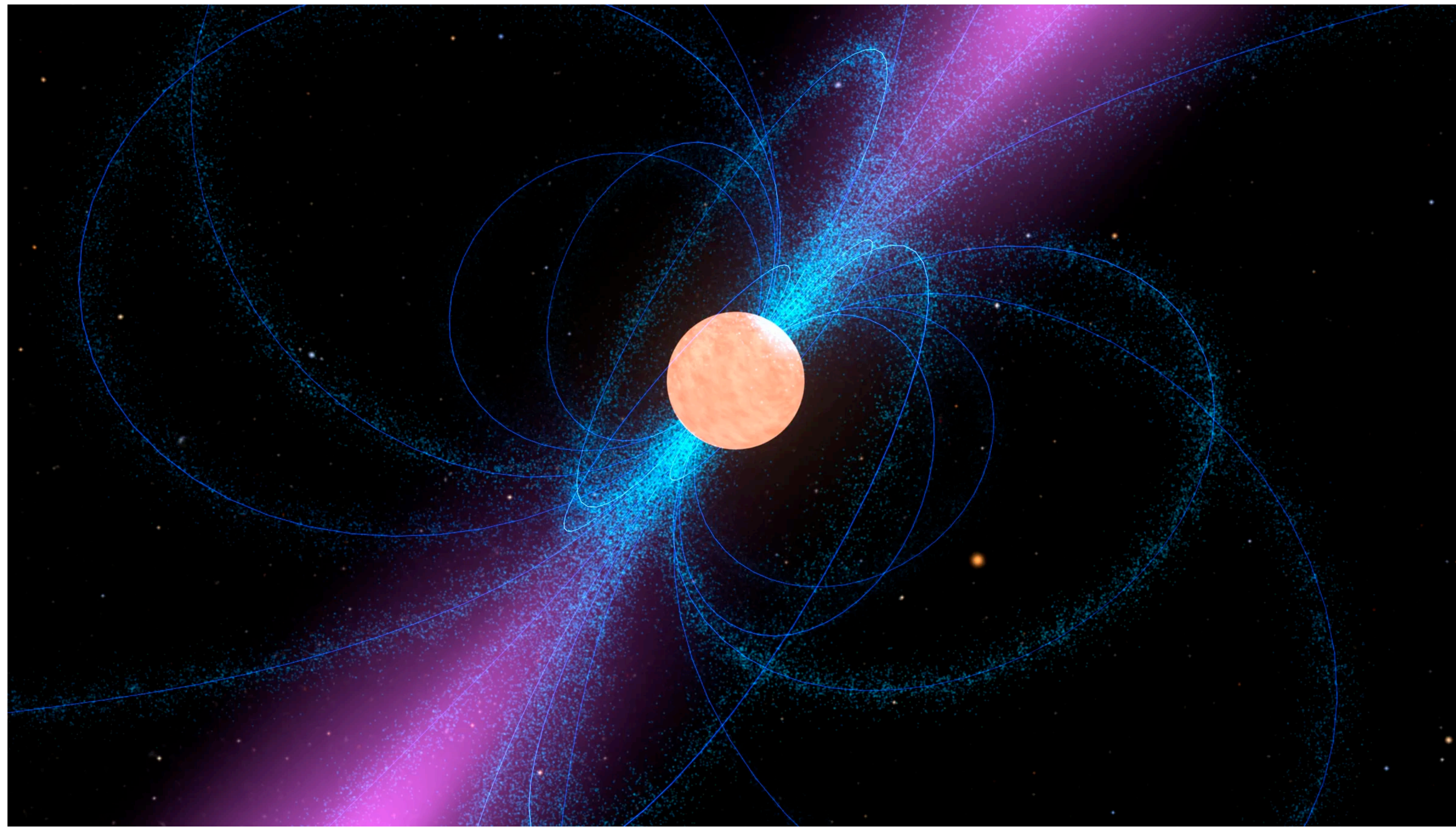
Source populations



PWN

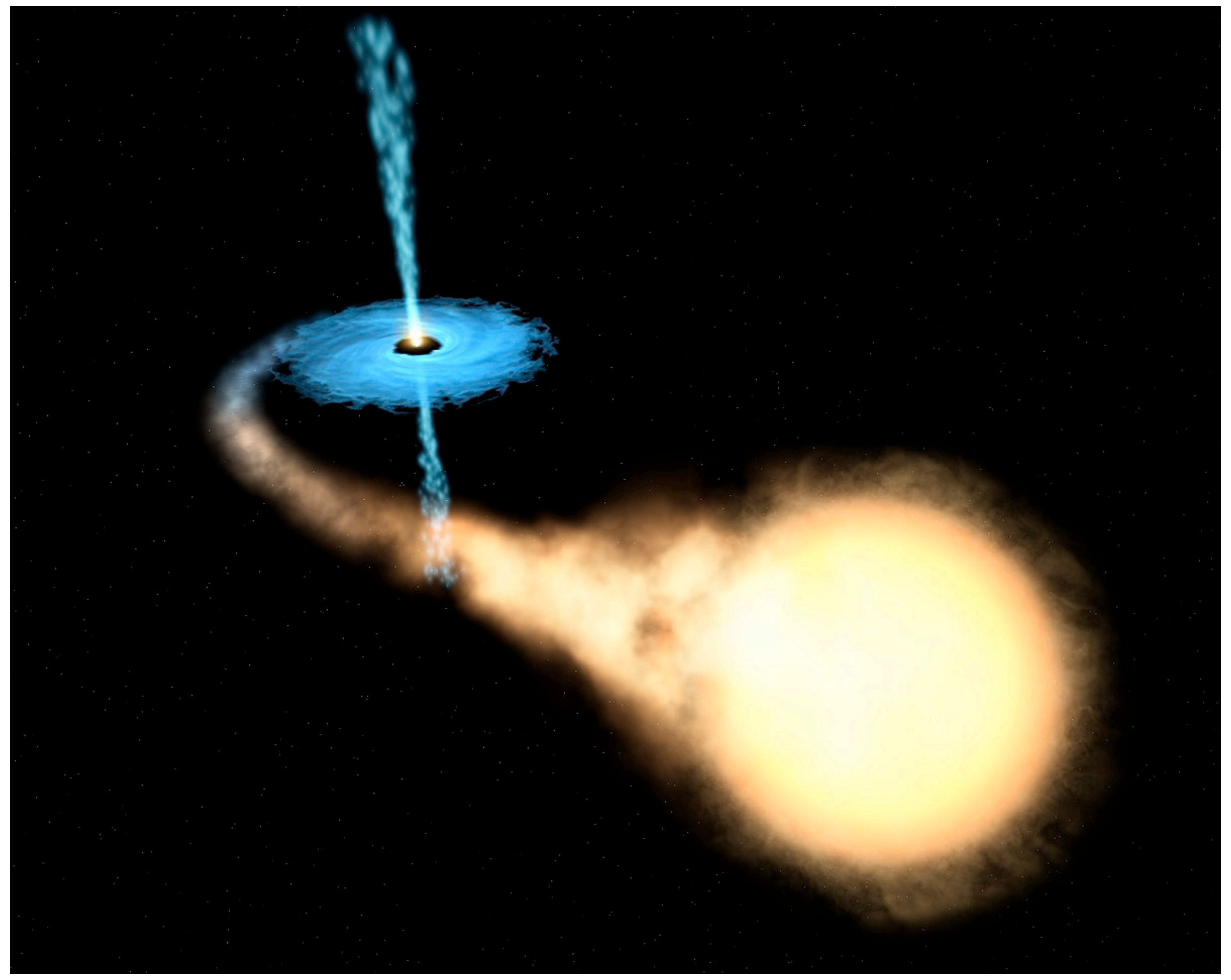


SNR



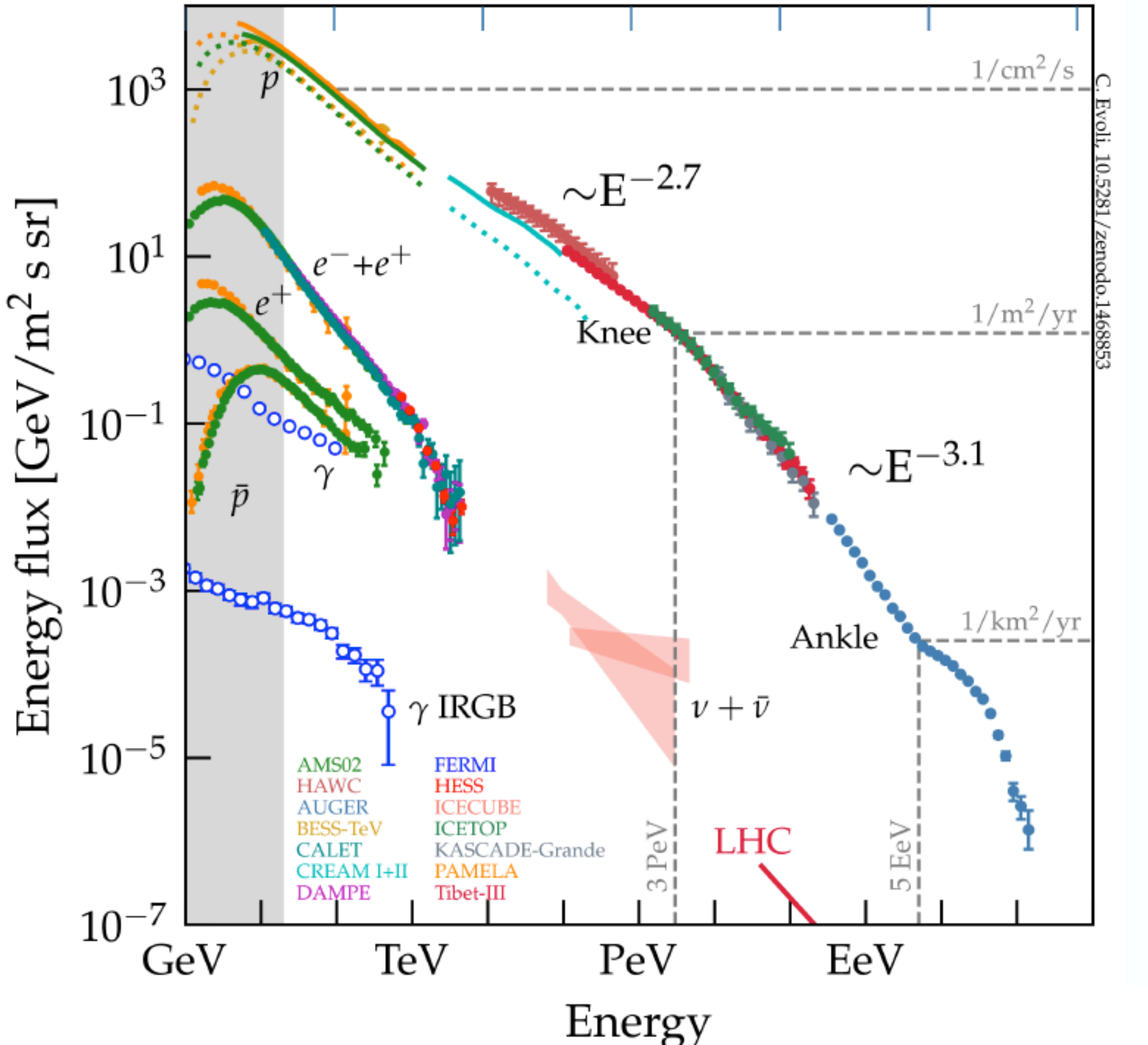
Pulsar

Gamma-ray binaries



Star clusters

Source populations



Are these sources responsible for cosmic rays at the knee?

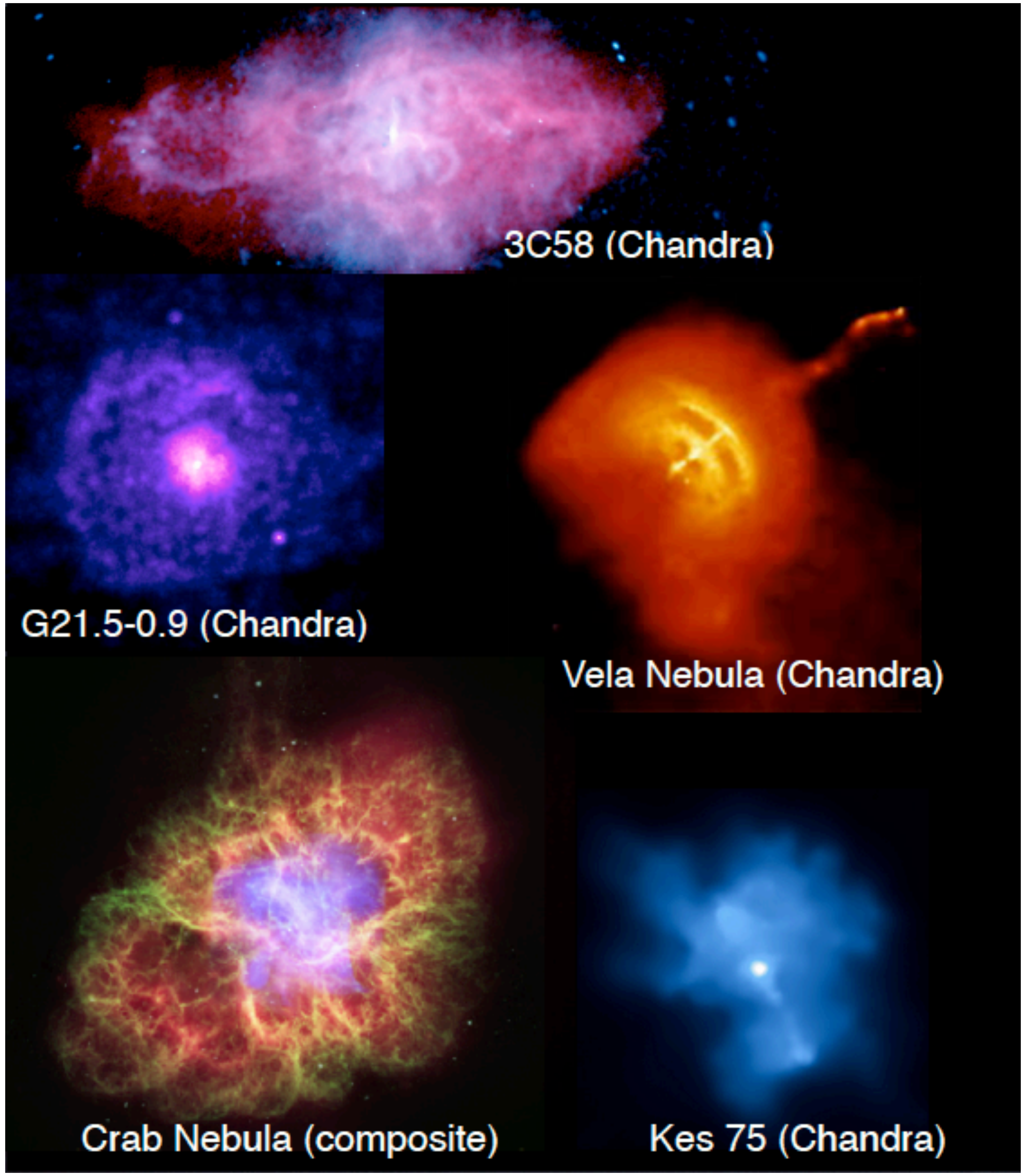
Protons should be accelerated up to ~1 PeV

Although the exact position of the knee is still matter of debate (0.5-3 PeV)

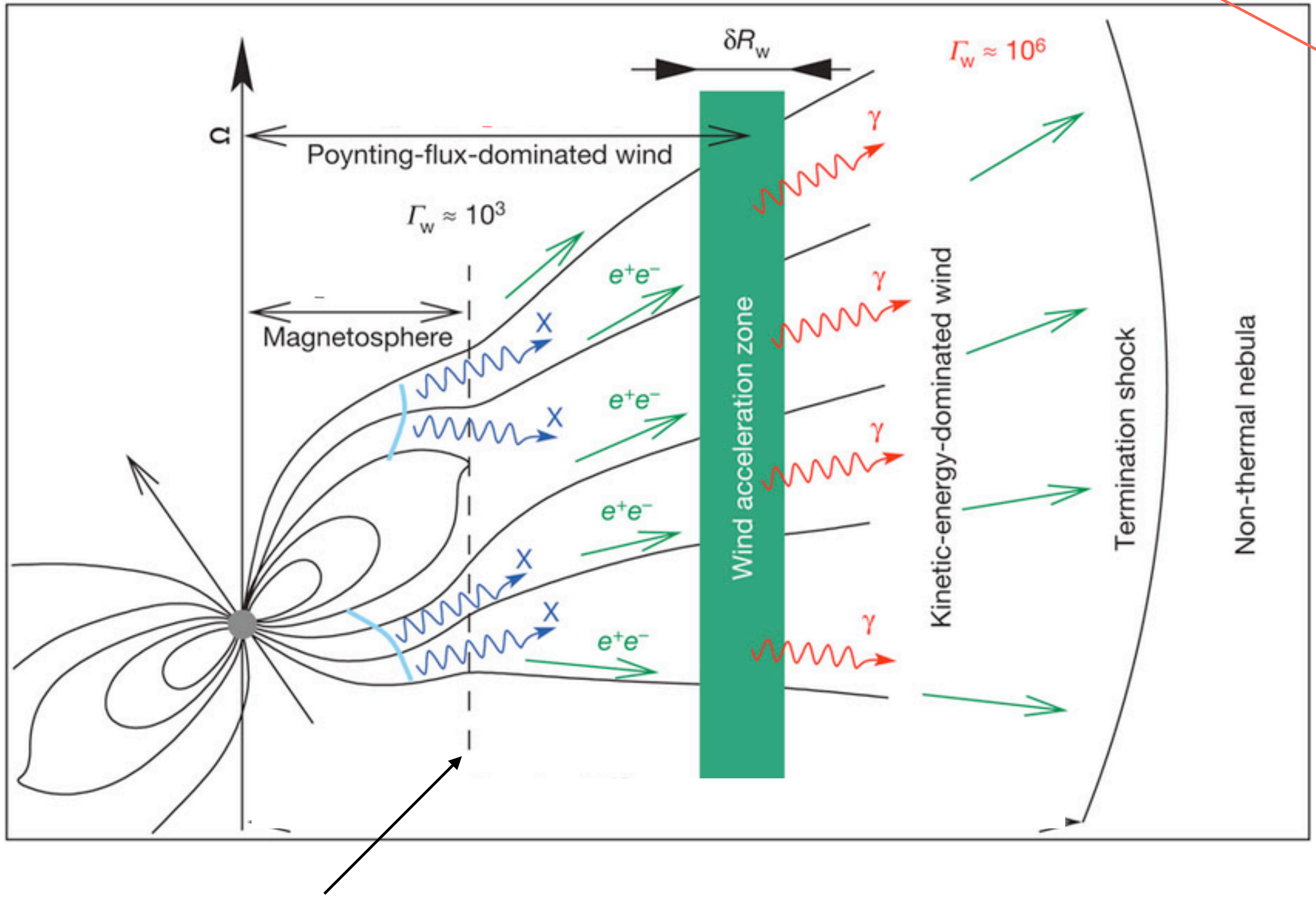
Pulsar wind nebulae

See Bucciantini and Rigoselli's talk

The largest population of VHE source



Credits: E. Amato



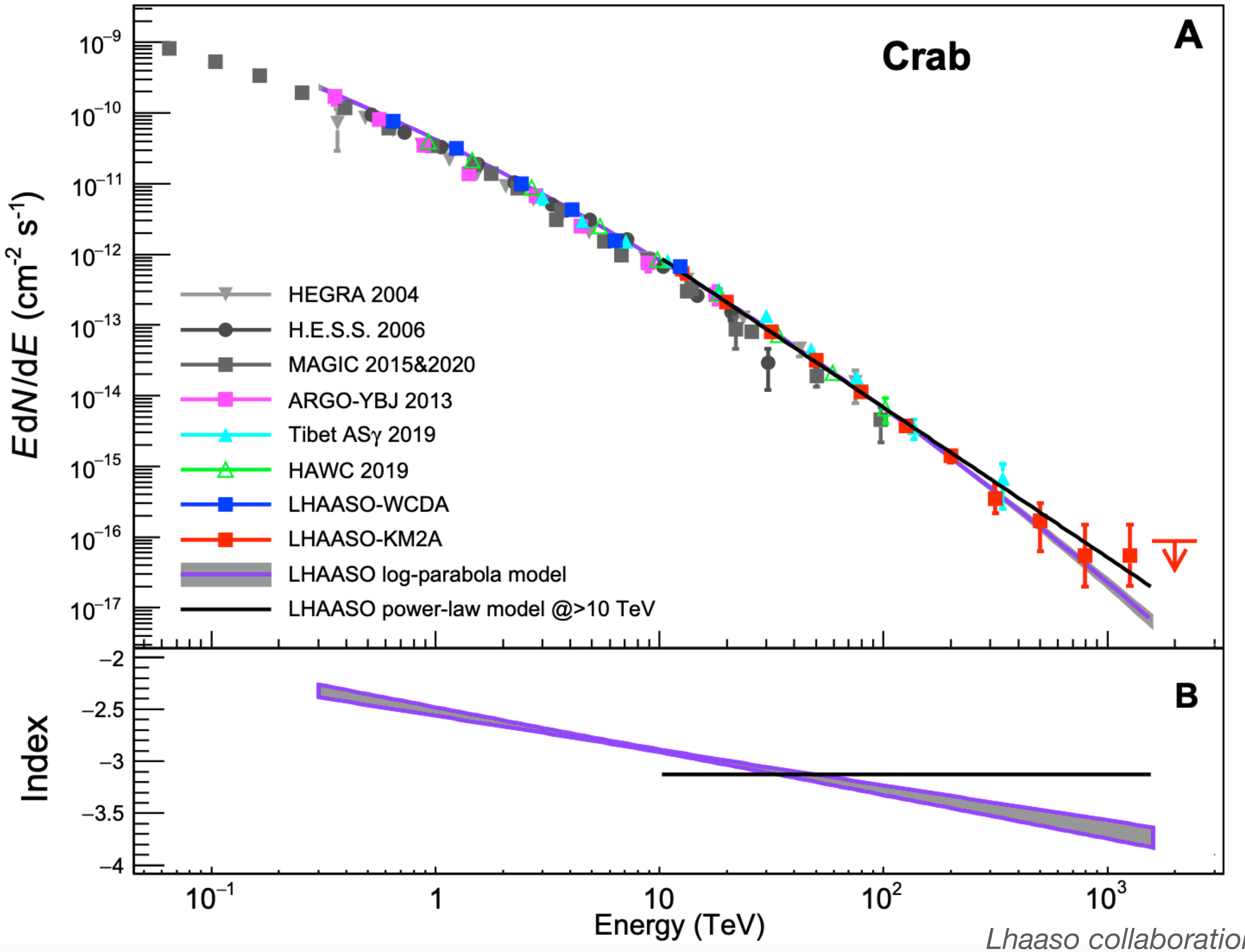
$$\dot{E} \approx \frac{B_\star^2 R_\star^6 \Omega^4}{c^3} = I\Omega\dot{\Omega}$$

The stars spins down and emits a wind of energetic particles

Pulsar wind nebulae

LHAASO detected the Crab Nebula at > 1 PeV

The only PWN at PeV till now!



Lhaaso collaboration, 2021

Inverse Compton scattering of CMB?

$E_e \sim \gamma_e mc^2$

Implies electron accelerated at PeV energies

Pulsar wind nebulae

Are LHAASO Pevatrons leptonic? If yes, PWN are the only candidates to explain them

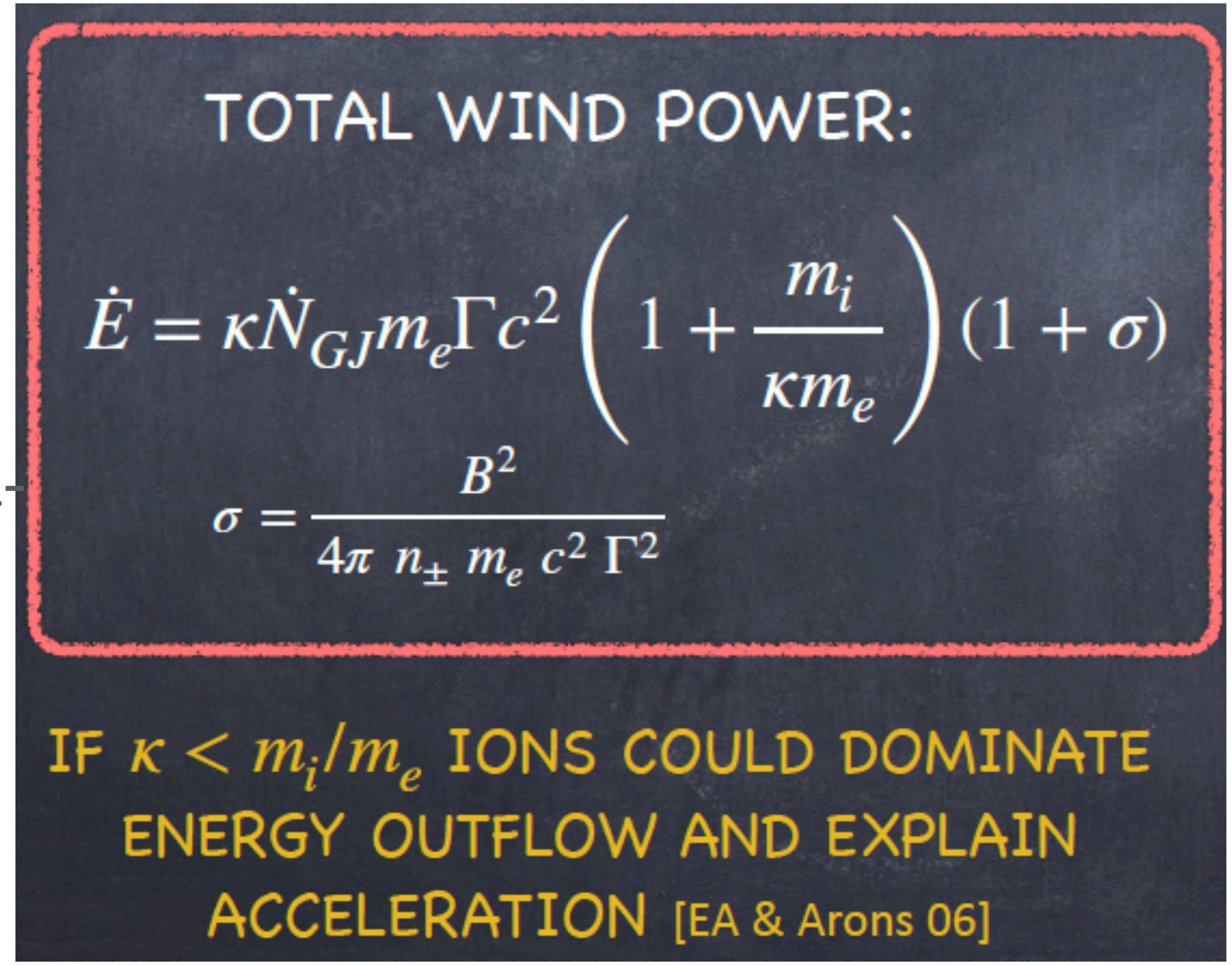
In principle, PWN are able to accelerate leptons and ions to PeV energies

Pulsar wind nebulae

Is a hadronic component possible?

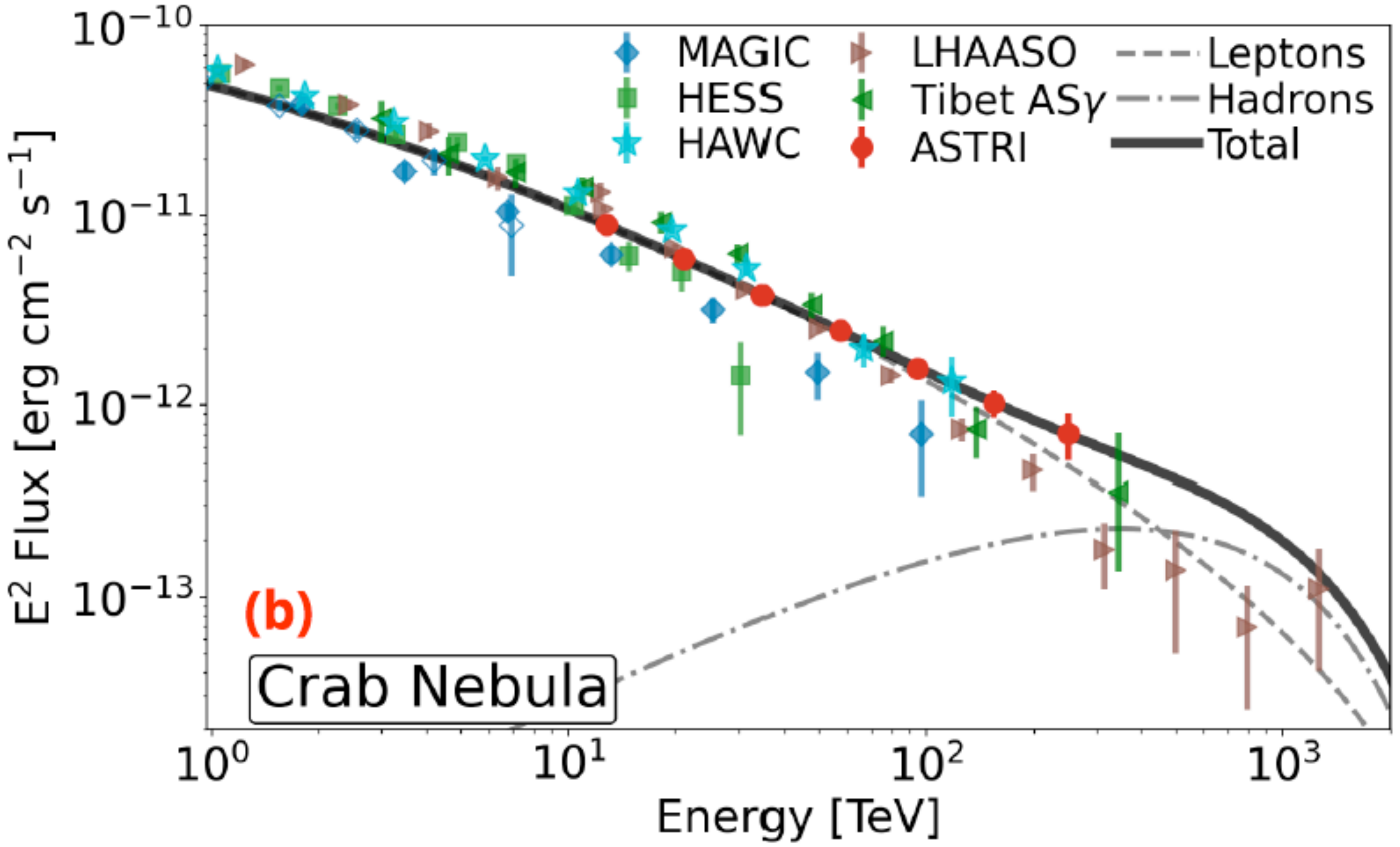
Yes, in the case of a young energetic system:

Young PWN can be a source of ultra-high energy cosmic rays!



Credits: E. Amato

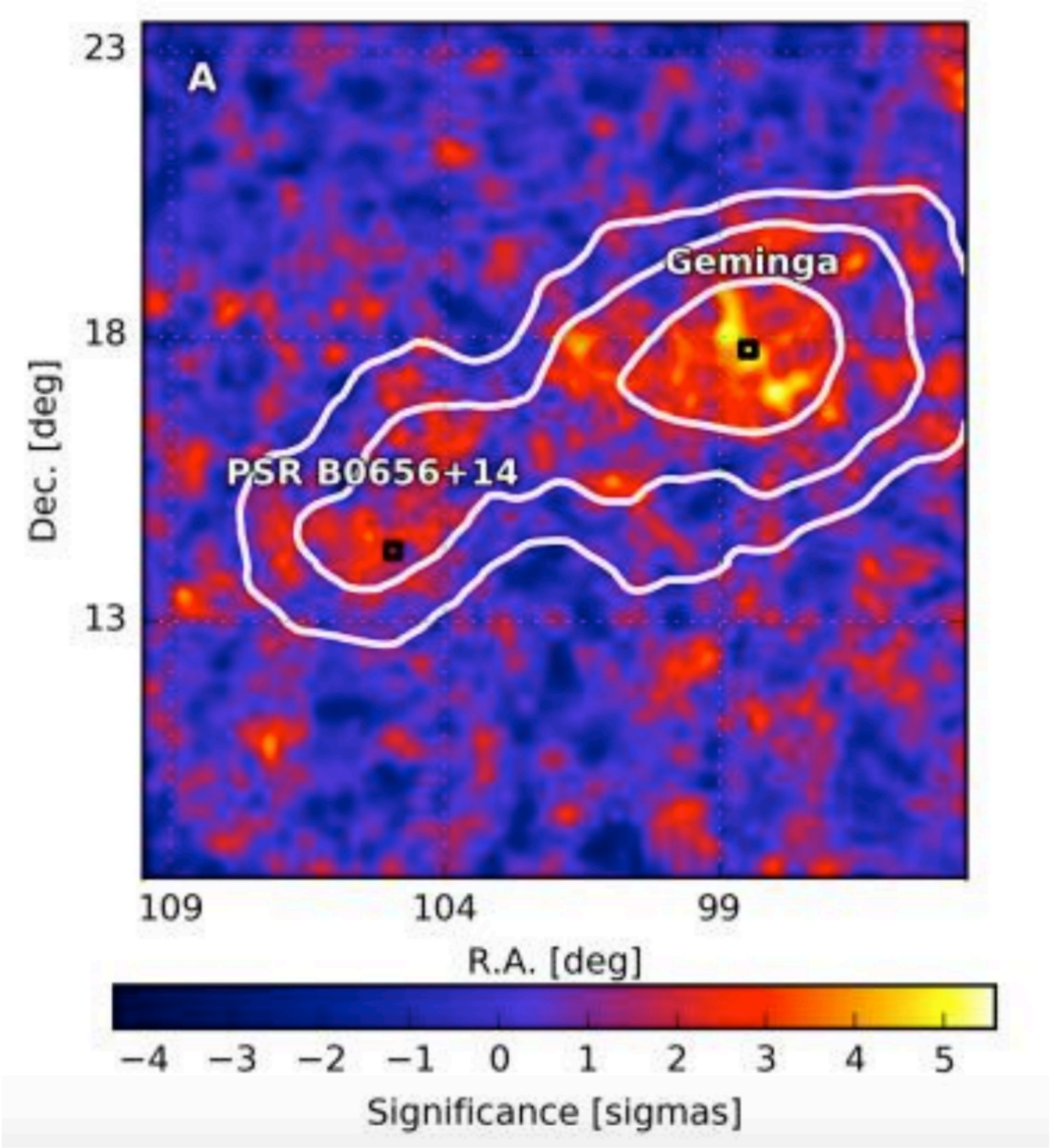
The existence of the hadron component can be hidden by the leptonic emission, but this should decrease at high energy because of the drop in the Klein-Nishina cross-section. VHE observations are crucial to determine such hadronic components!



Vercellone et al. 2021

Pulsar halos

- Pulsar halos are extended gamma-ray structures generated by electrons and positrons escaping from pulsar wind nebulae (PWNe),
- Considered a new class of gamma-ray sources

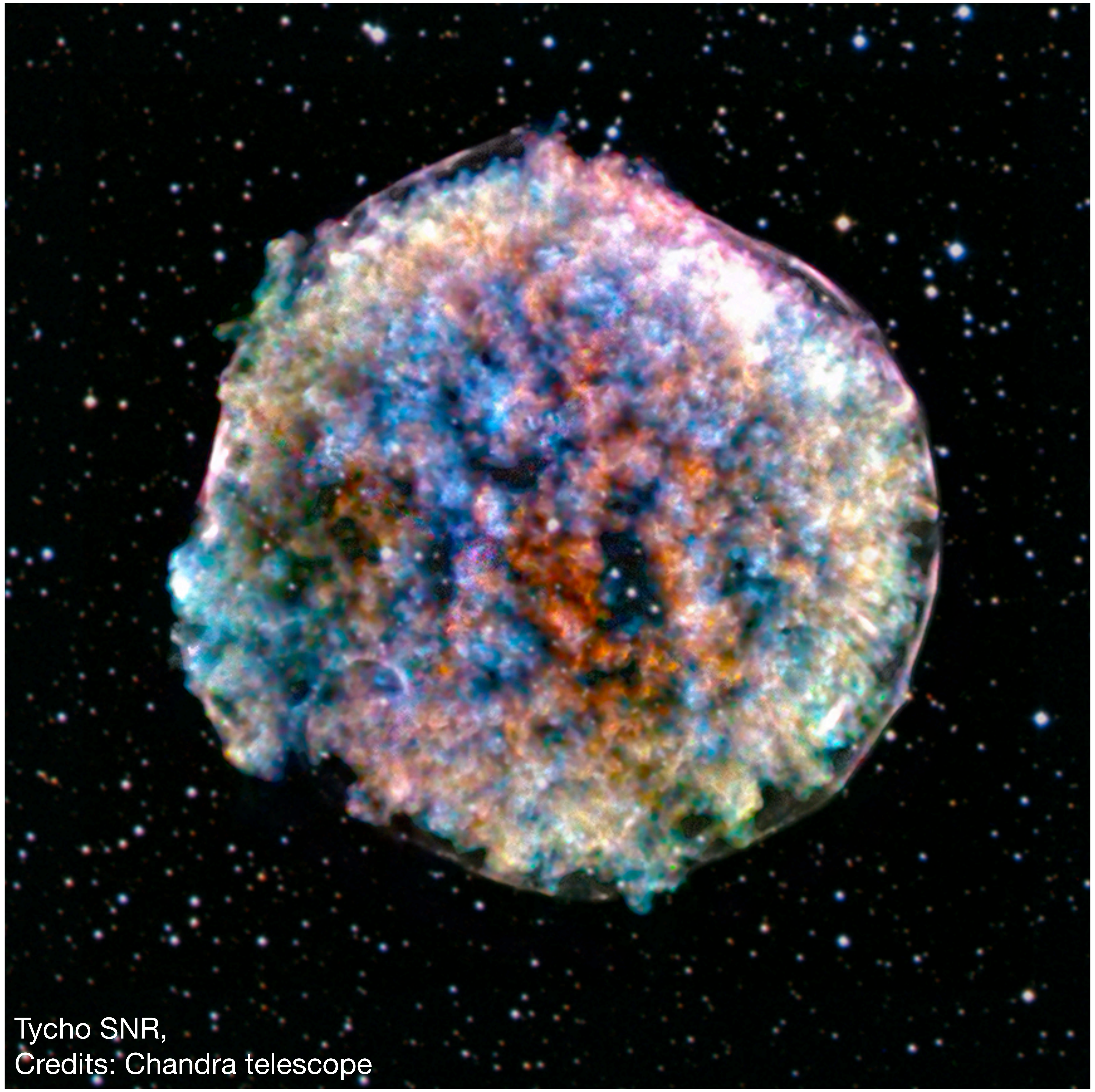


HAWC collaboration, 2017

Freely diffusing leptons scatter background photons producing gamma-ray emission

CTA, thanks to its large field of view, will be fundamental to constrain the morphology of extended halos around energetic pulsars

Supernova remnants



Tycho SNR,
Credits: Chandra telescope

Still the best candidates to produce cosmic rays

Not clear if responsible for the CR knee

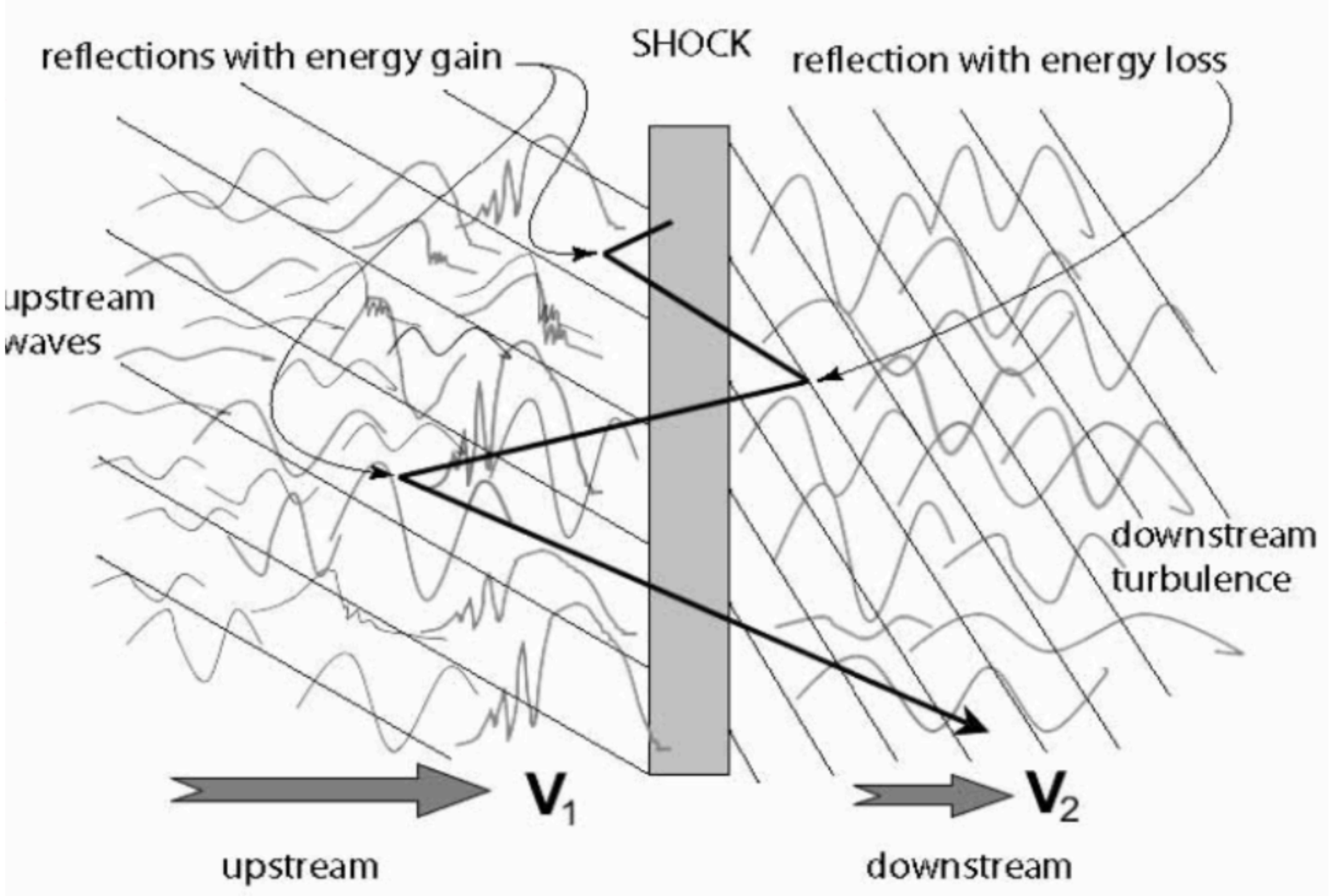
The Diffusive Shock Acceleration (DSA) is currently a solid model to describe SNR emission

Filaments at the SNR border can amplify the magnetic field

See Cardillo's talk

Supernova remnants

Multiple scatterings in the ambient medium give energy to the ejected particles



Fermi mechanism (I)

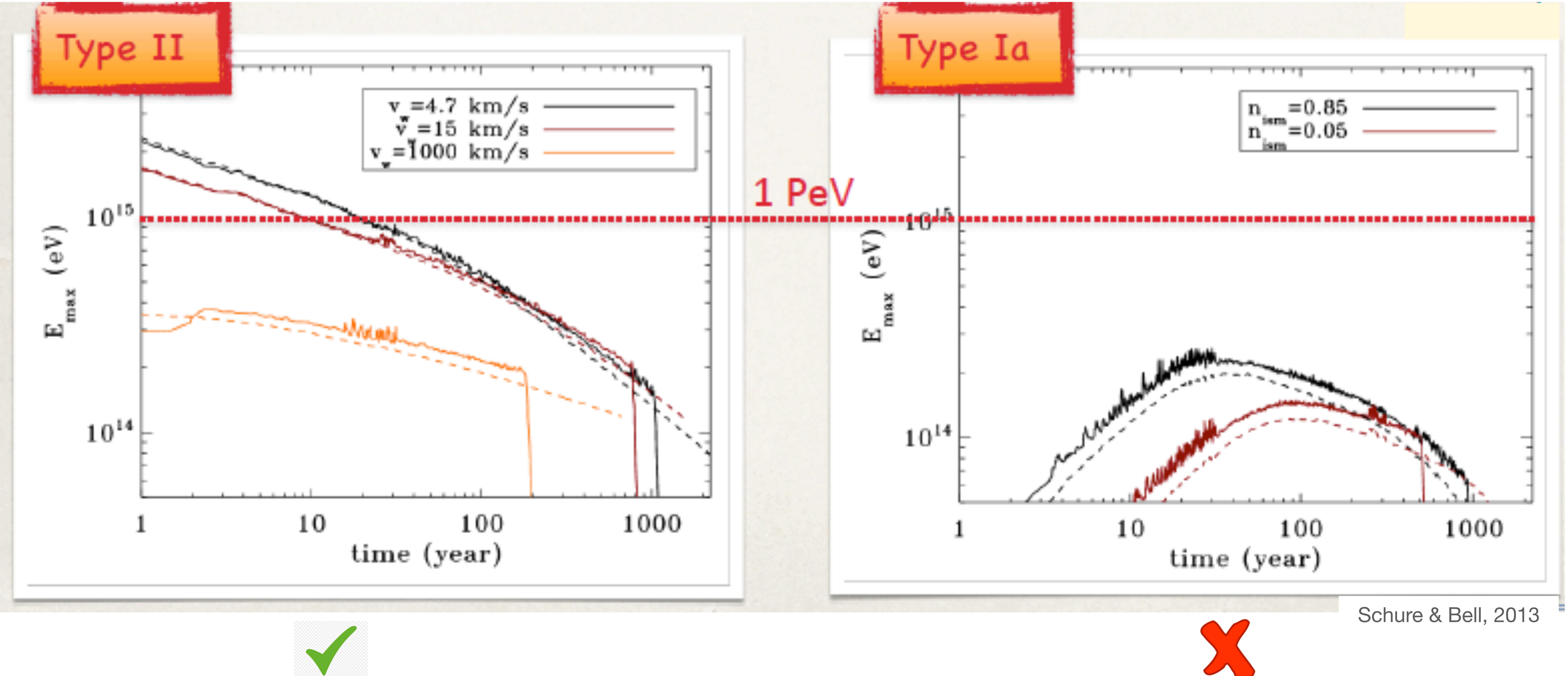
Galactic distribution of SNR is compatible with CR distribution

$$p + p \longrightarrow \gamma$$

$$\langle E_\gamma \rangle \sim 0.1\ E_p$$

Supernova remnants

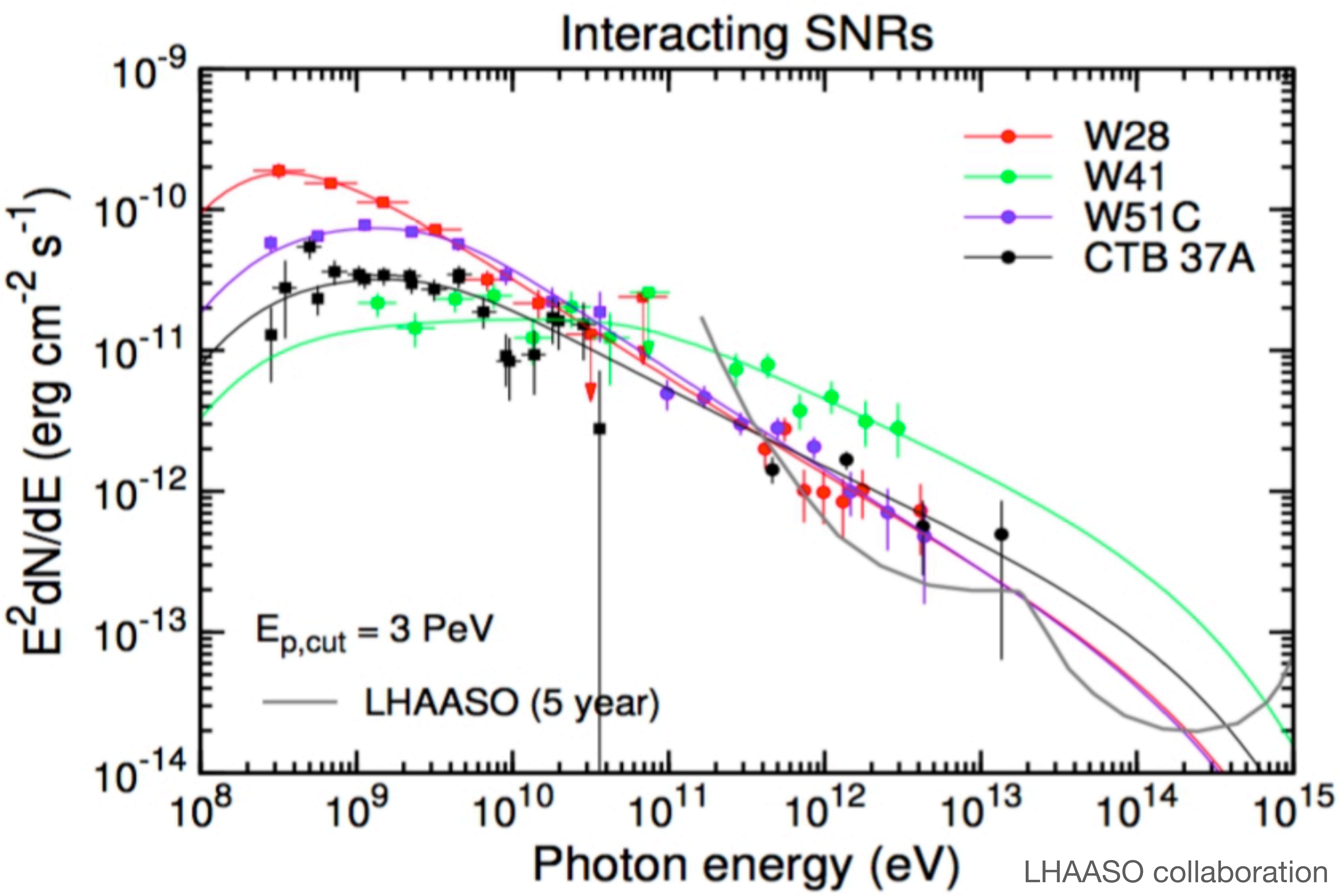
Young SNR may accelerate particles to PeV energies, but only in the first decades after the explosion and only if they are placed in dense environments



Schure & Bell, 2013

Supernova remnants

Middle age SNR might have large halos around due to confined escaping particles.
In the absence of external diffusion, entrapped particles are energetic enough to provide steep spectra



LHAASO collaboration

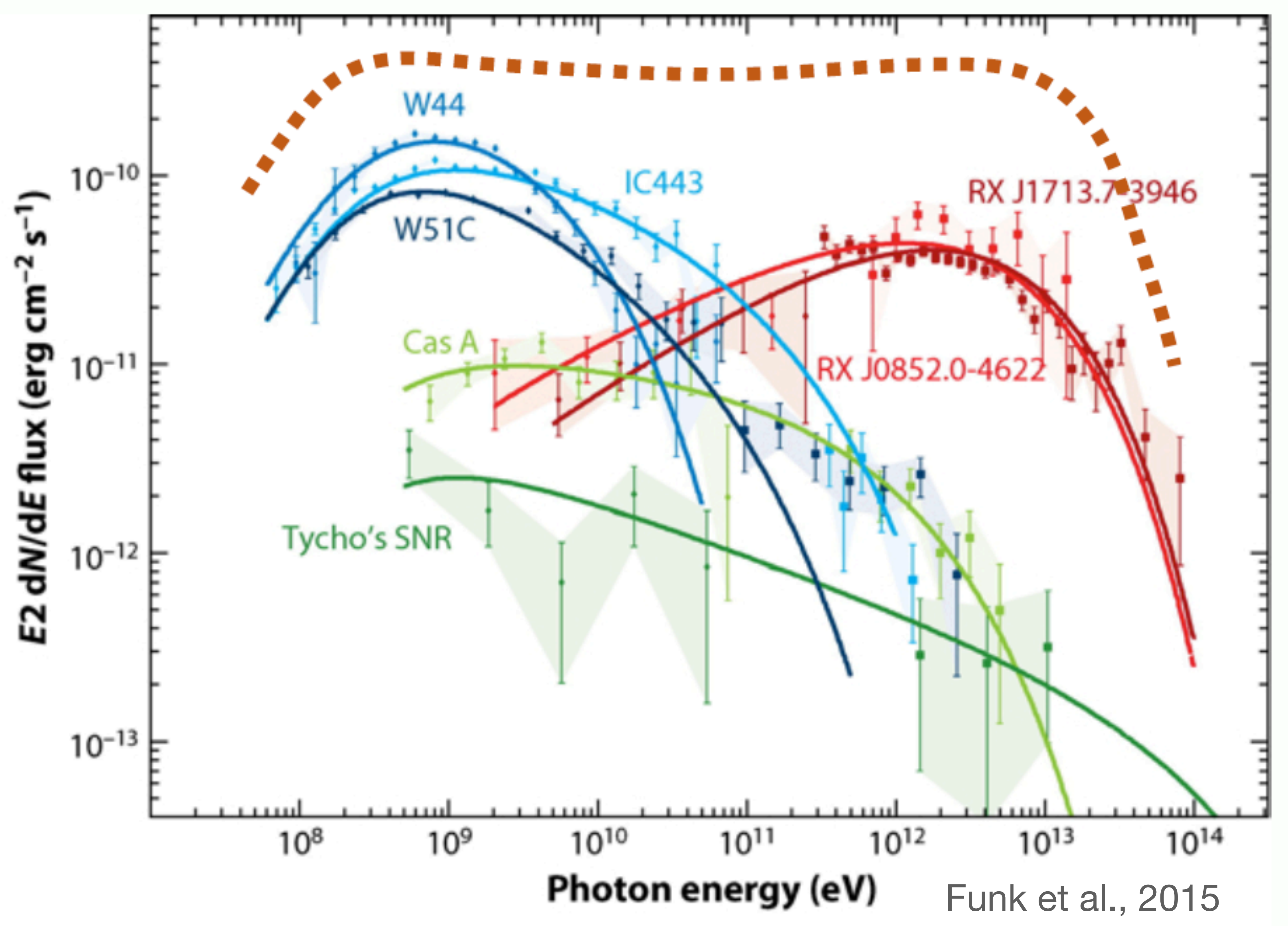
Supernova remnants

Theoretical issues still remains:

- DSA predicts a spectrum n(E) ~ E^{-2} never observed (a variety of SNR spectra)
- The spectra not extend much above a few (tens?) TeV
- Other recent theoretical studies (Bell, Malkov…)

- Environment can have an effect on the diffusion and affect the observed spectra

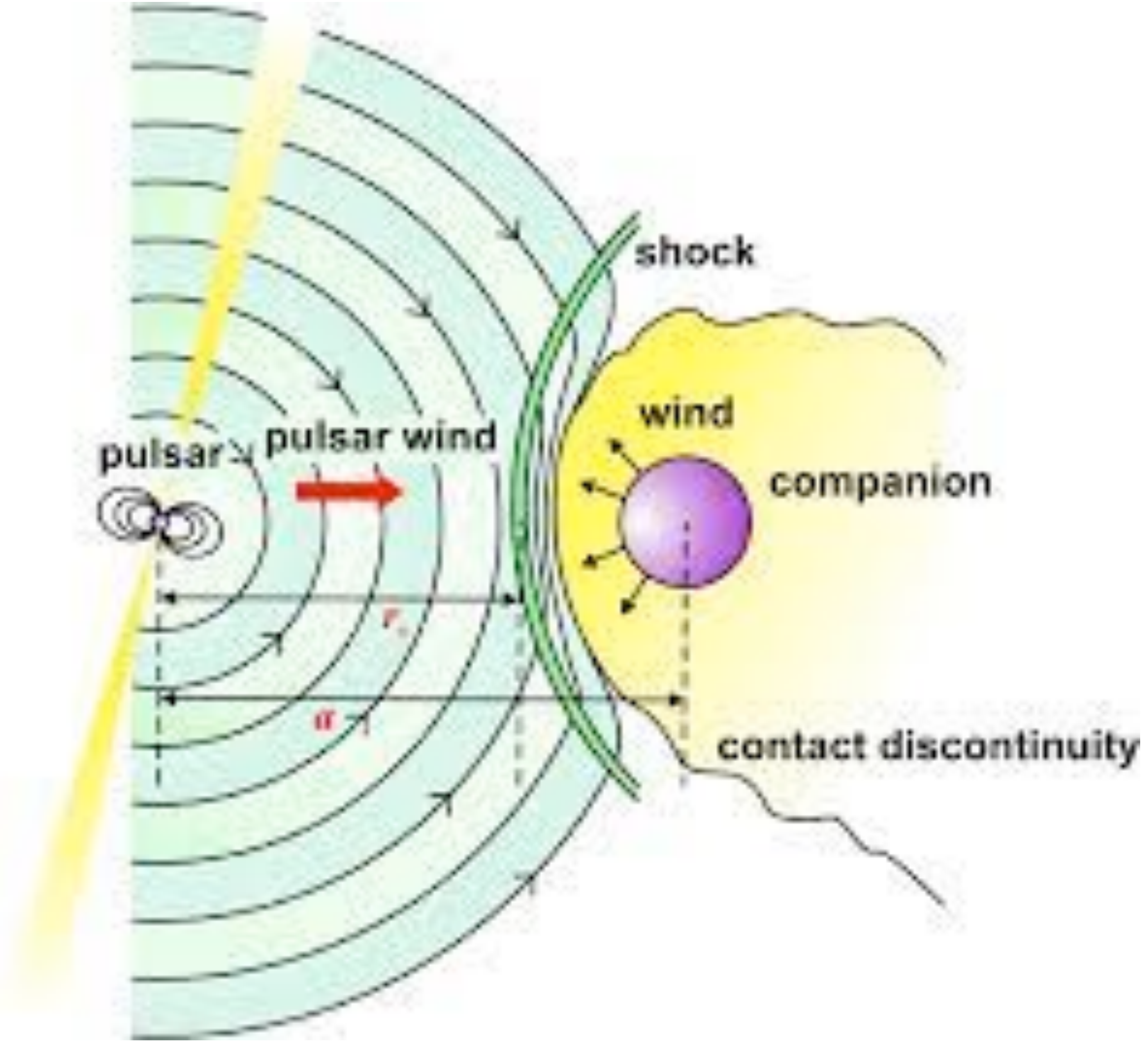
- The associations of the LHAASO Pevatrons is only for a few middle age SNR. Can middle age SNR (where diffusion is suppressed) be candidates for PeV emission?



Funk et al., 2015

Gamma-ray binaries

- To date only ~10 sources, with a giant OB star and a compact object
- For a few of them, a NS has been firmly identified (PSR B1259-63, PSR J2032+4127, LS I 61+303)!
- Some are microquasar (binaries with accretion and jet emission), SS433, Cyg X-1, GRS 1915+105;
- Emission extending to TeV energies



In the case of a NS, the wind of the pulsar interacts with the wind of the companion, producing two different shock regions. IC scattering?

See Papitto's talk

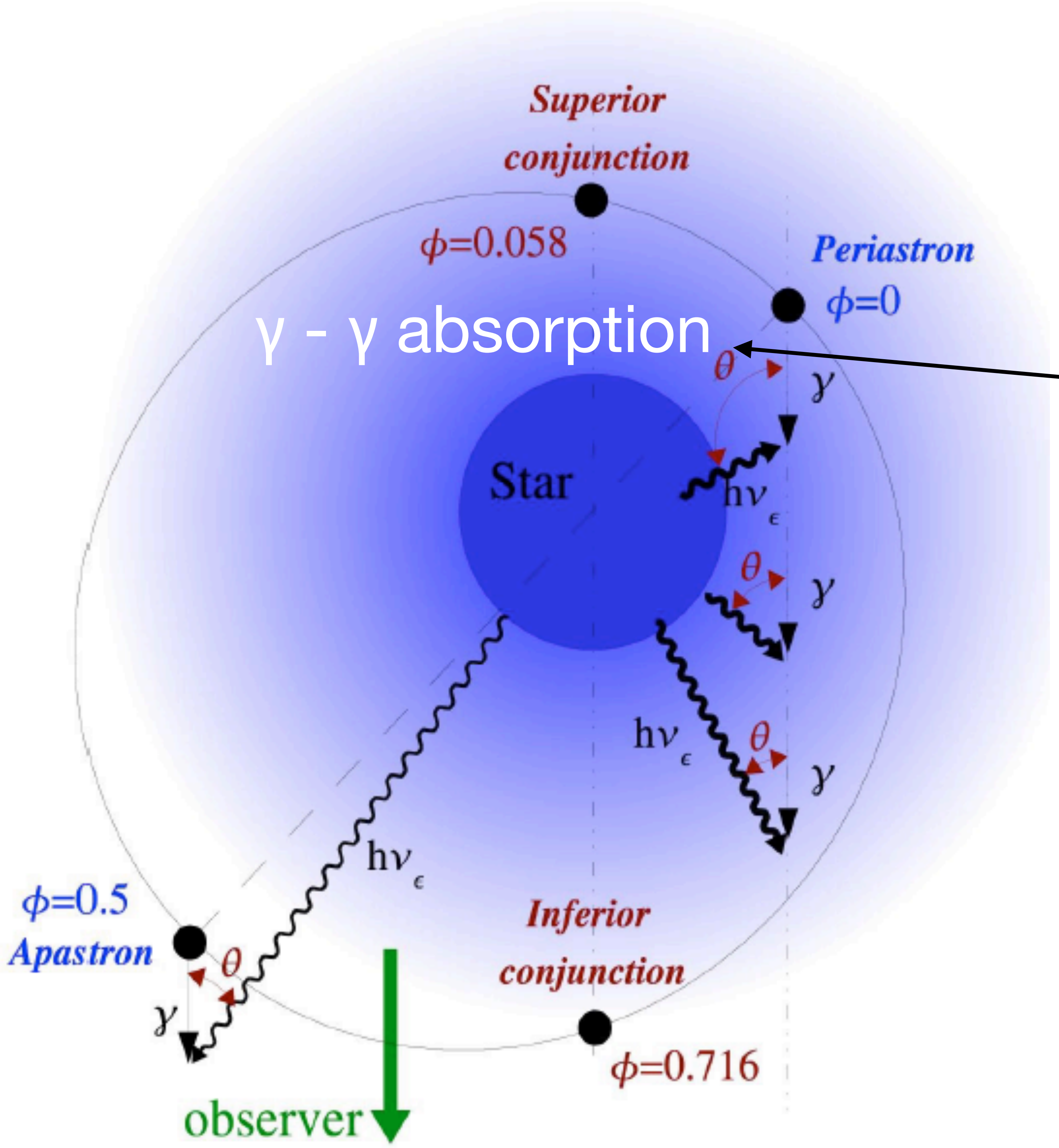
Gamma-ray binaries

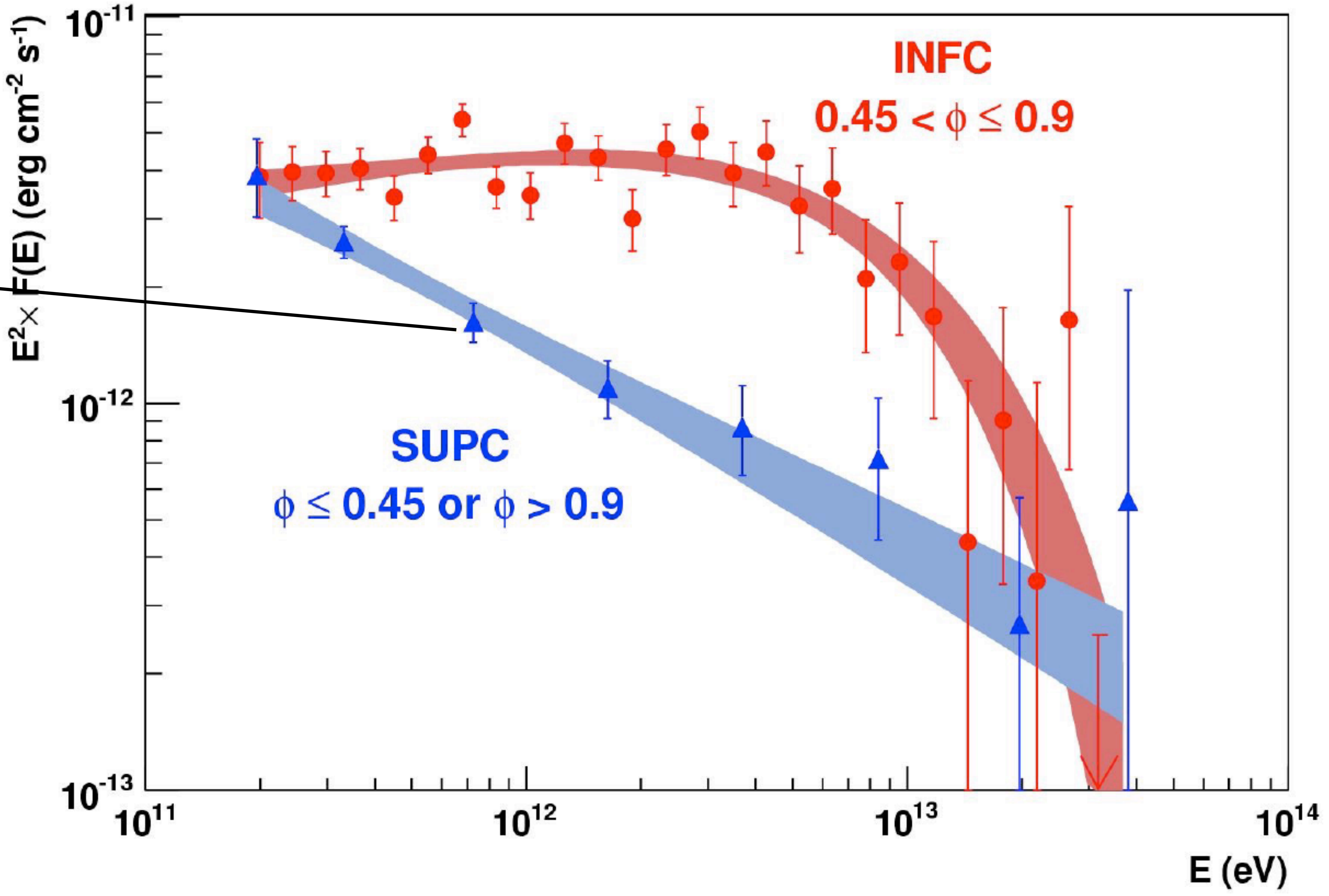
The scenario is likely leptonic (IC scattering) but the maximum emission is not expected to be > 100 TeV

In the case of gamma-ray binaries with pulsars, leptons are accelerated in the form of a wind and they do IC scattering with companion star photons —> gamma-ray emission

Some of them show orbital modulations:
LS 5039 (3.9 days)

Recent studies suggest the existence of a magnetar with a spin of ~9 s (although see Volkov et al., 2021 for an alternative explanation)





Aharonian et al. (2006c)

BACK-UP SLIDES

- ….