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Barcelona 2022

On the potential of bright, young pulsars to power ultra-high gamma-ray sources

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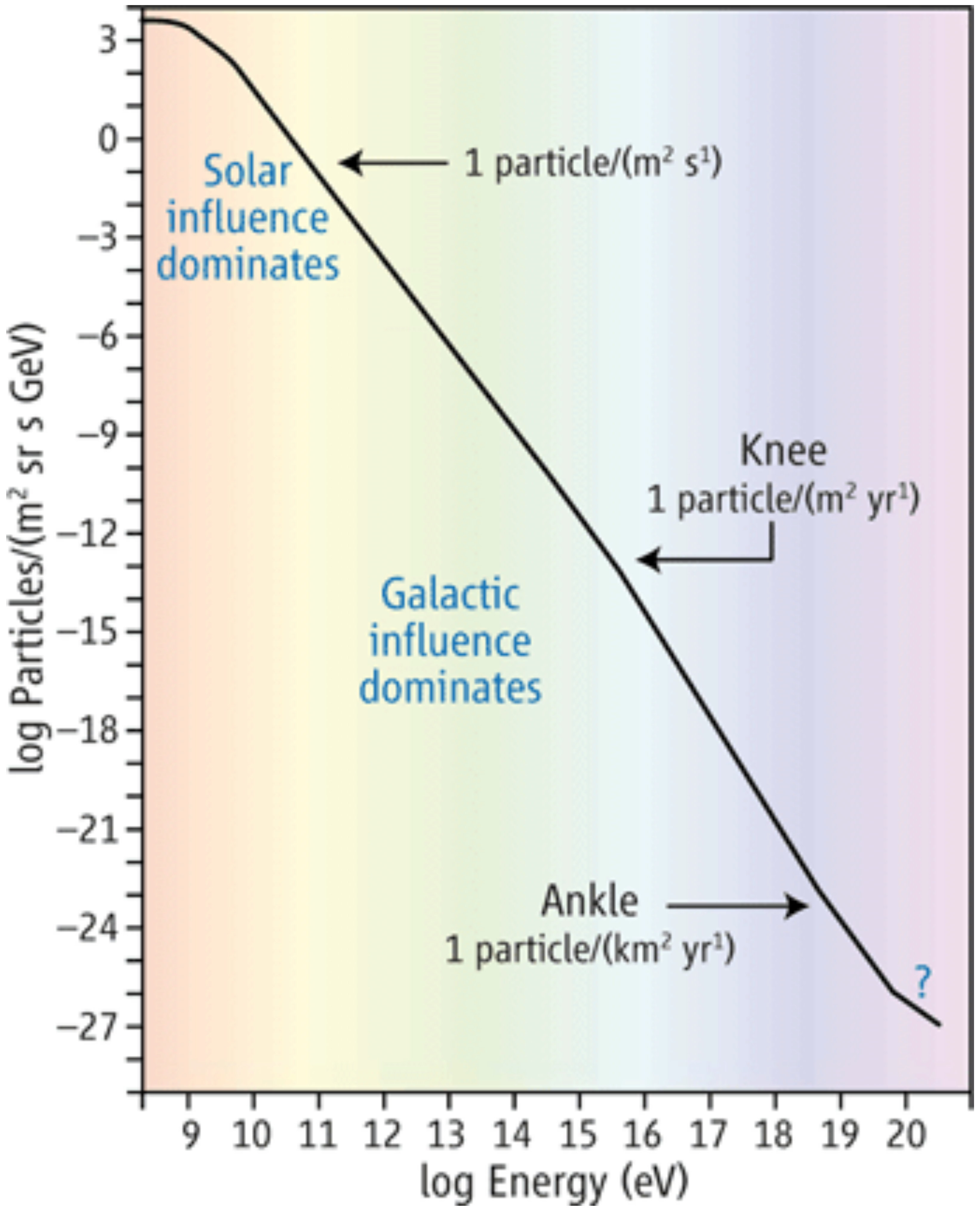
dOW *et al* 2022 *ApJL* **930** L2

Motivation

The search and identification of PeV accelerators



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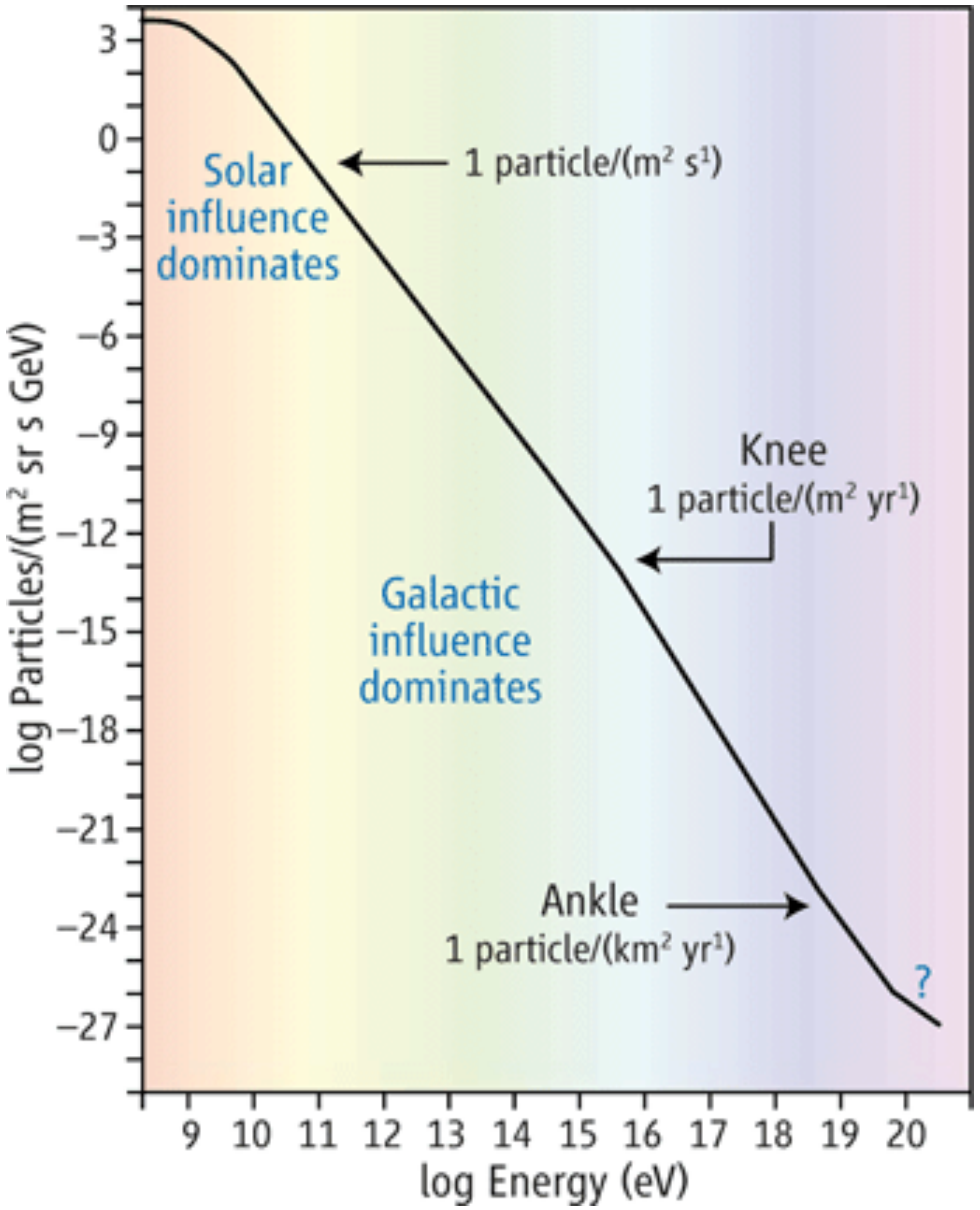

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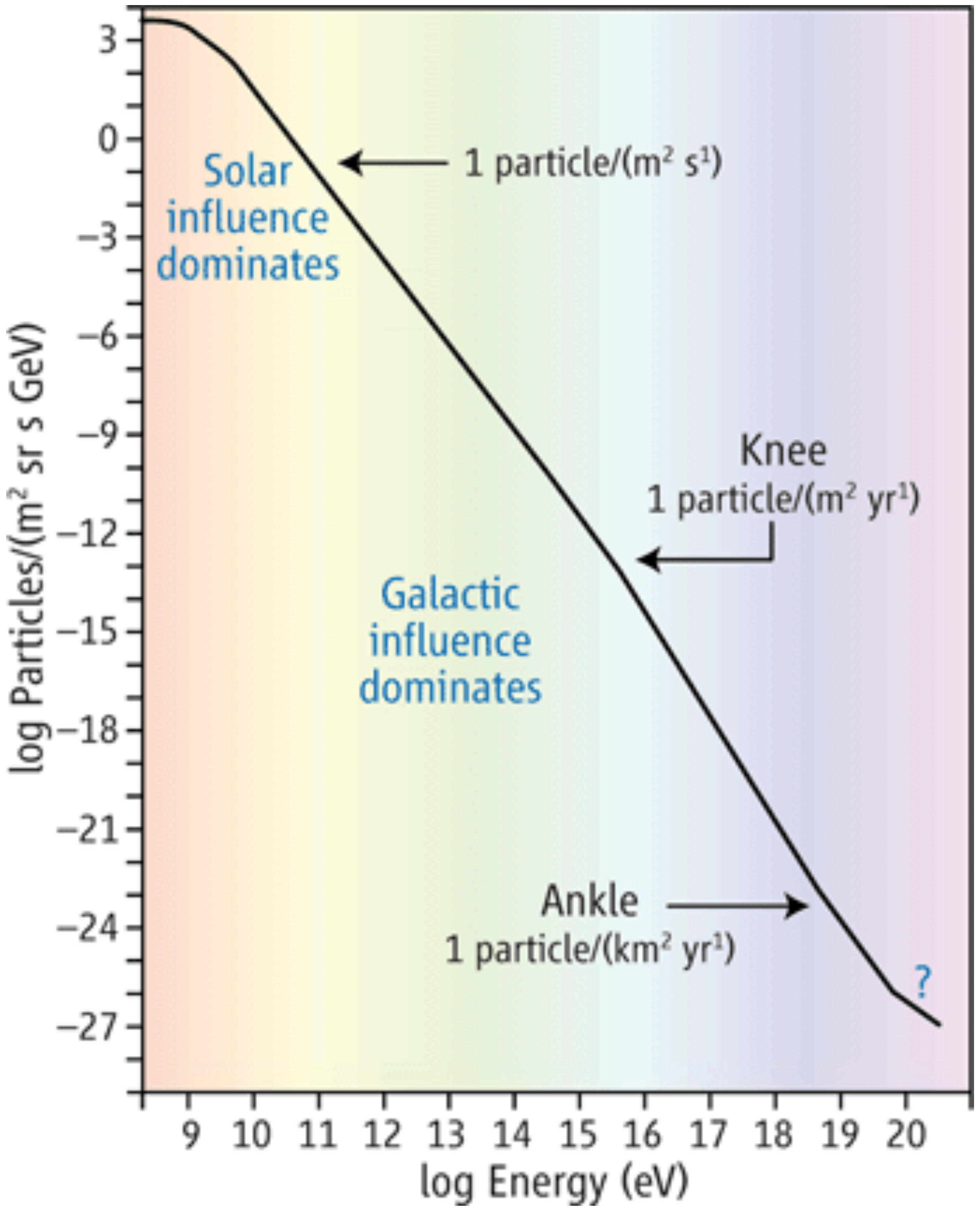
- Spectrum of Cosmic rays:
  Mainly protons (+electrons and heavier nuclei) coming from beyond the Solar system and extending >10 decades in energy



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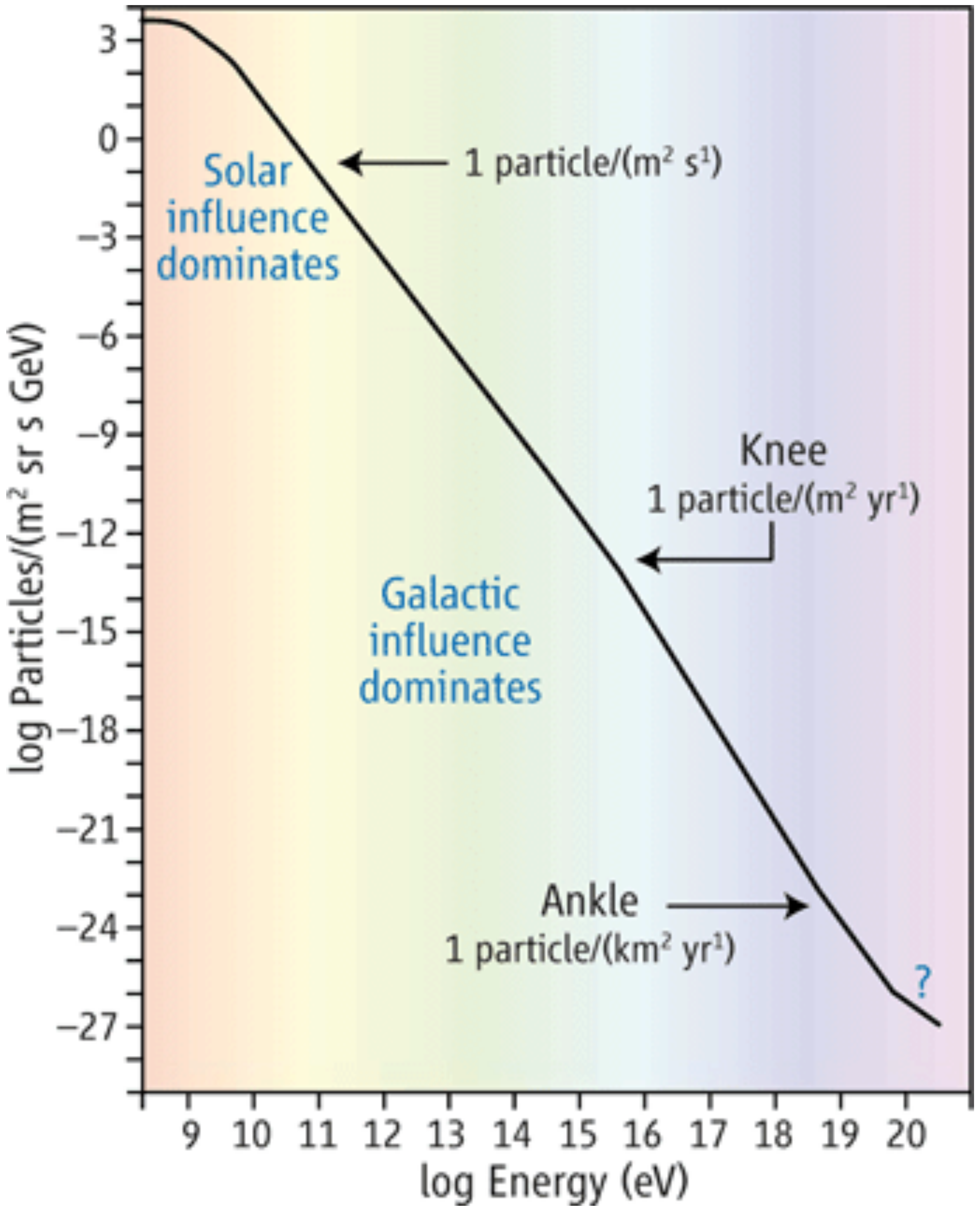

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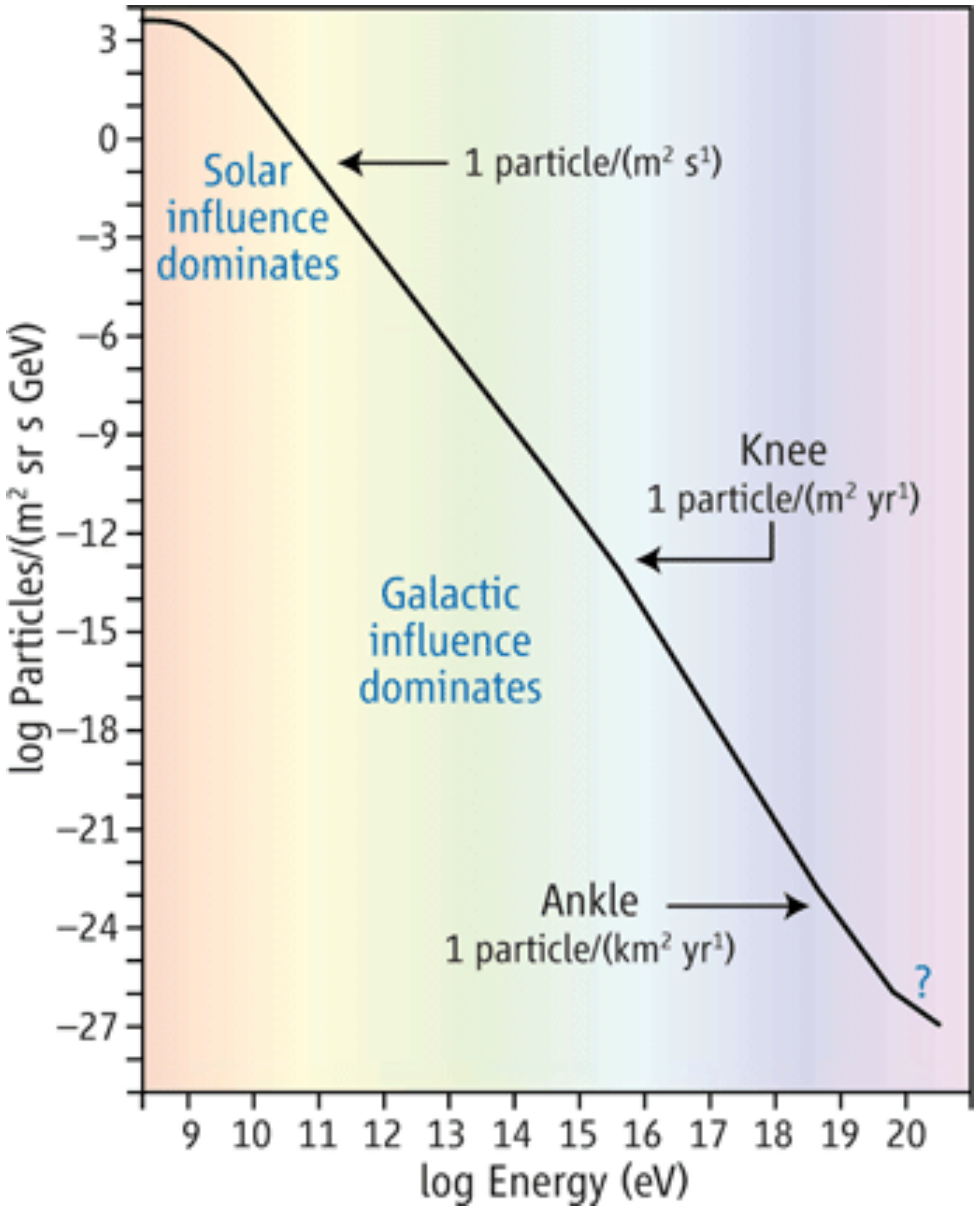
- Now we can see these PeV sources thanks to LHAASO
  Cao et al, 2021

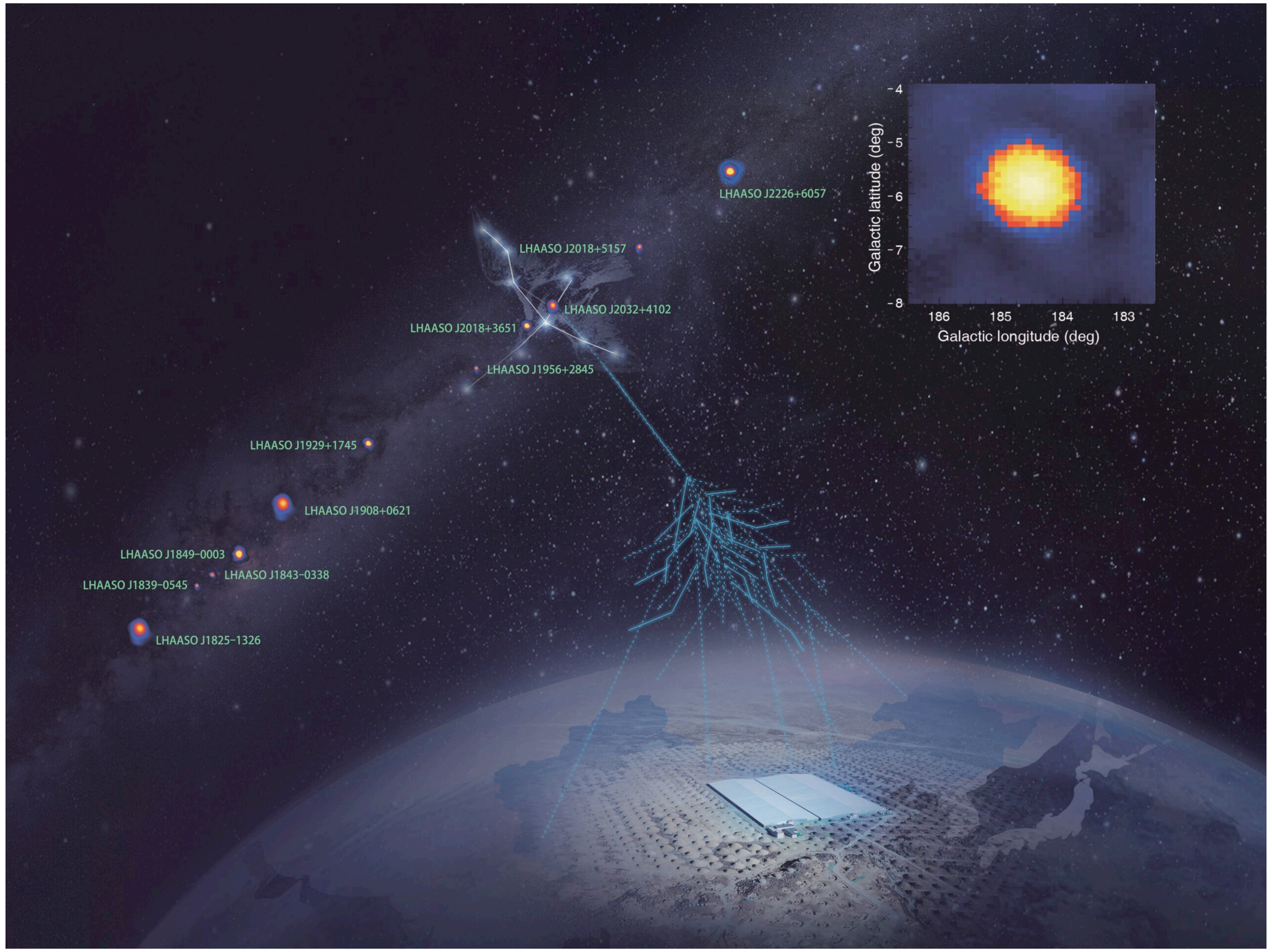


Motivation

LHAASO sources above 100 TeV

Cao et al, 2021

- LHAASO discovered 12 sources extending their spectrum up to PeV energies
- First observational signature of an overall population of gamma-ray sources accelerating particles to ~PeV energies



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LHAASO sources above 100 TeV

Cao et al, 2021

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)

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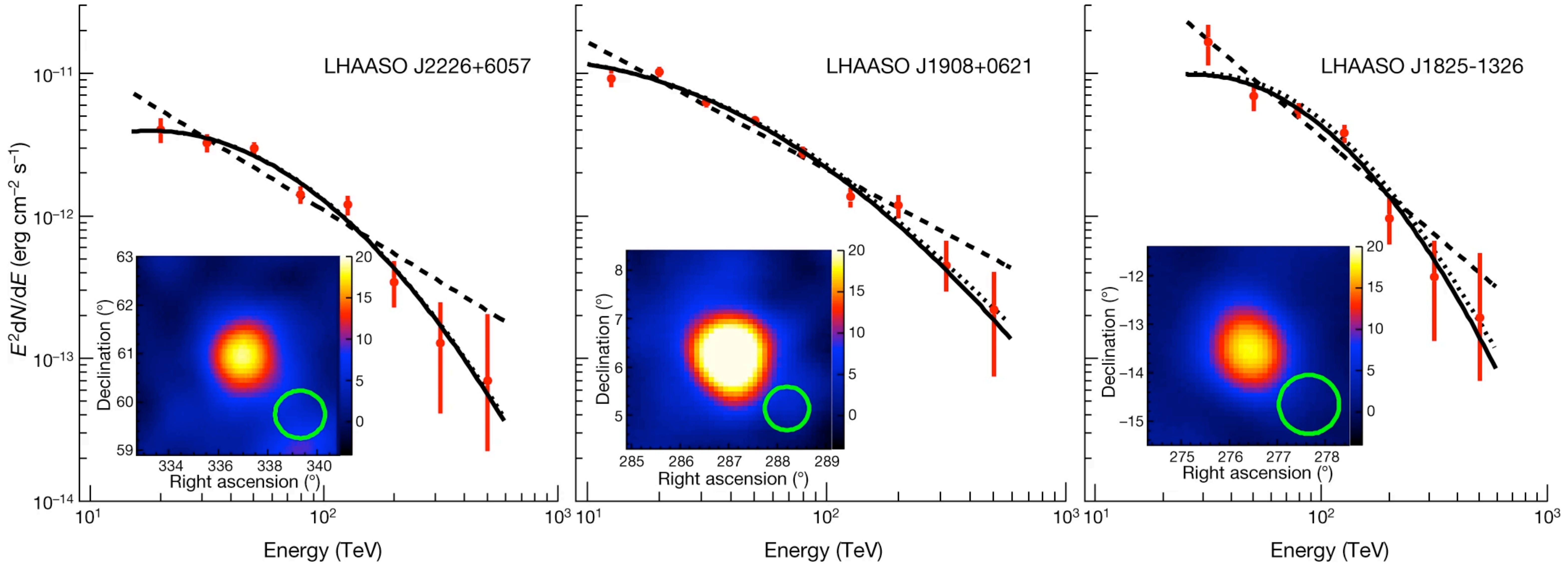


large source (~1 degree)

=> identification of the accelerator is complex

very steep spectra

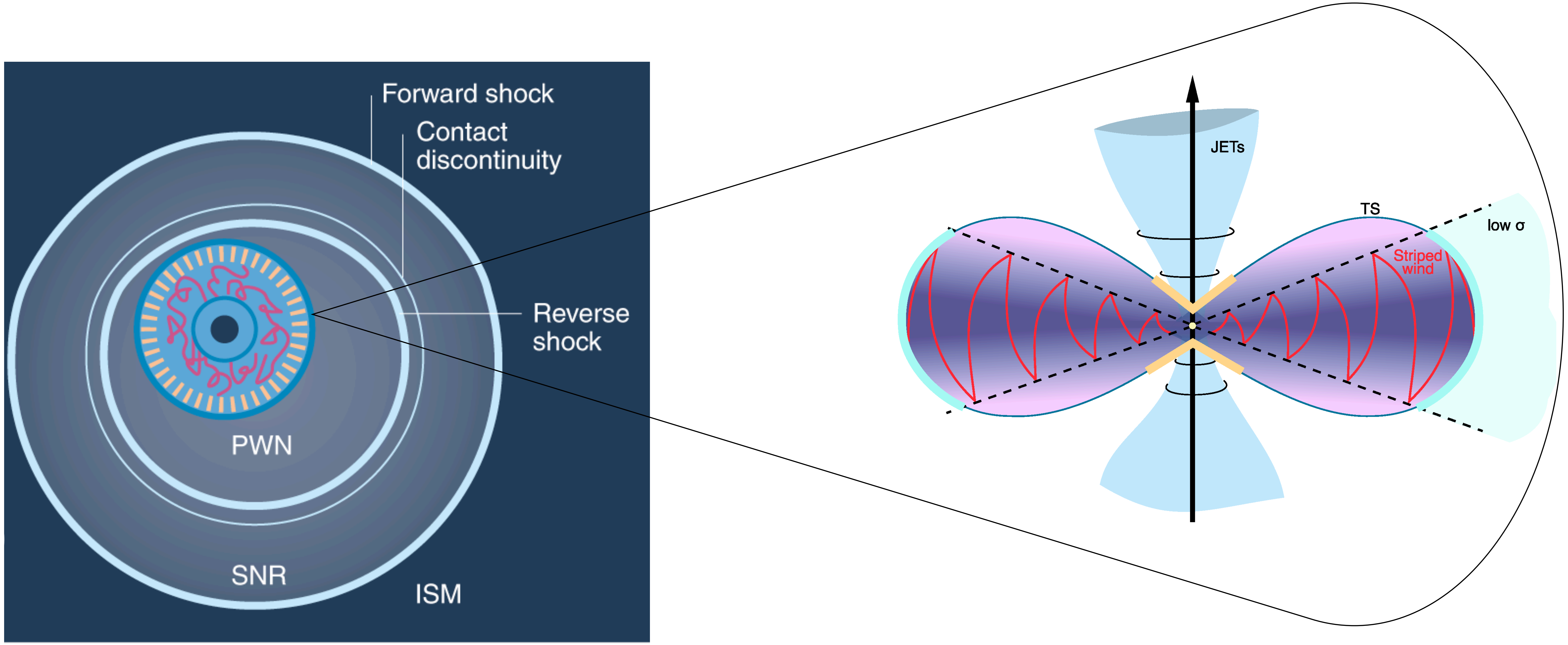
=> still compatible with the leptonic scenario (Breuhaus+2022)

Can pulsars power the PeV particles observed by LHAASO?

DESY.

Pulsars as Effective PeV accelerators

The role of pulsars/PWNe



Lopez-Coto, dOW et al, 2022

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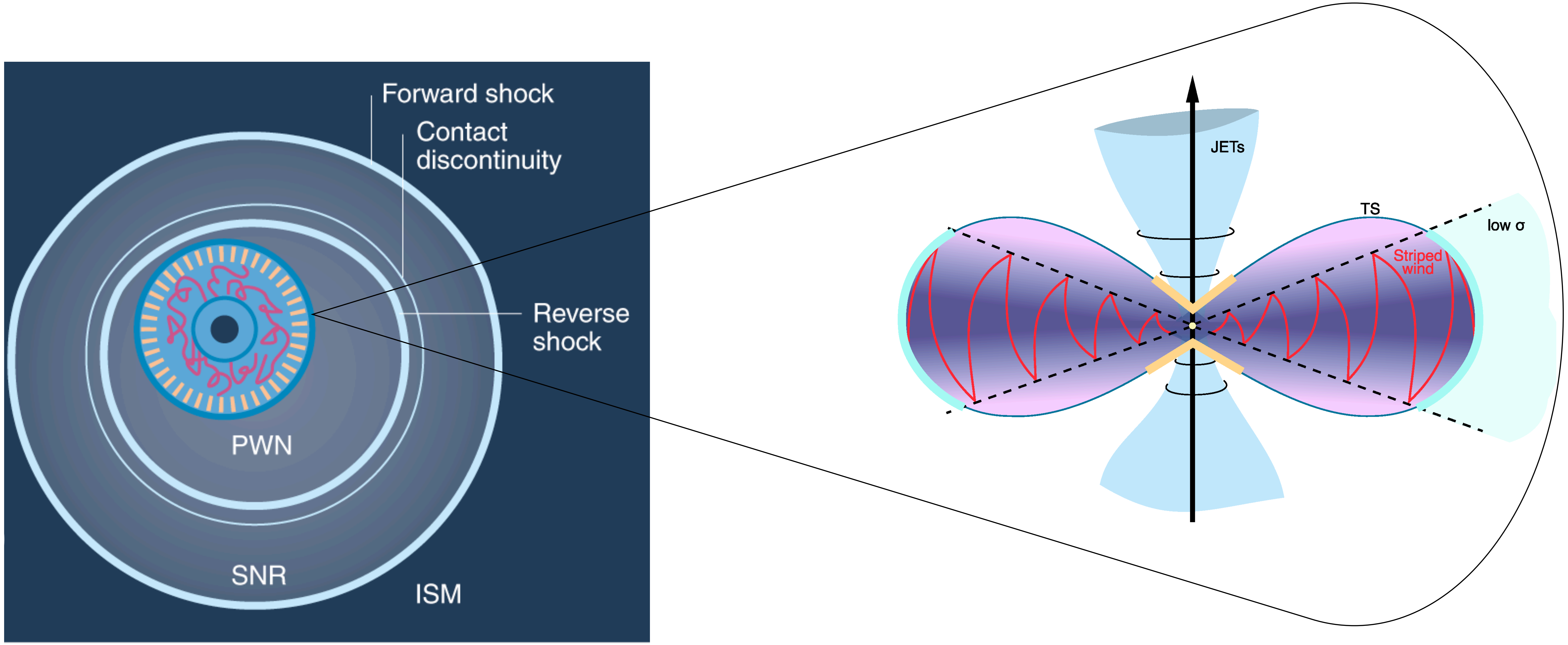

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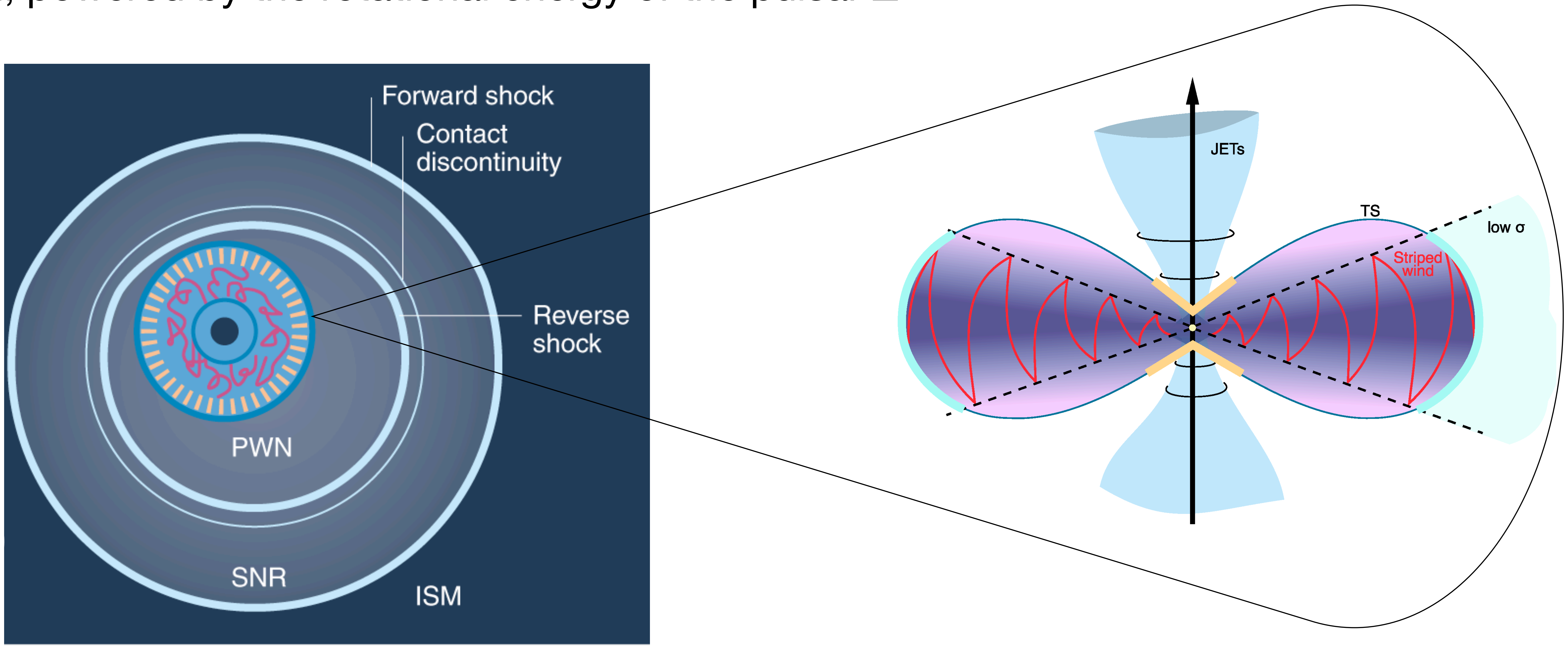
Pulsars as Effective PeV accelerators

The role of pulsars/PWNe

- Pulsars (and PWNe) are one of the most efficient sources in the gamma-ray regime via inverse Compton mechanism, powered by the rotational energy of the pulsar $\dot{E}$



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- Pulsars (and PWNe) are one of the most efficient sources in the gamma-ray regime via inverse Compton mechanism, powered by the rotational energy of the pulsar $\dot{E}$
- Many of the LHAASO sources lie within likely TeV PWNe (eg. HESS J1825-137, HESS J1849-000, HESS J1930+188, VER J2019+368…)
- The Crab Nebula is the only identified accelerator to PeV energies

Pulsars as Effective PeV accelerators

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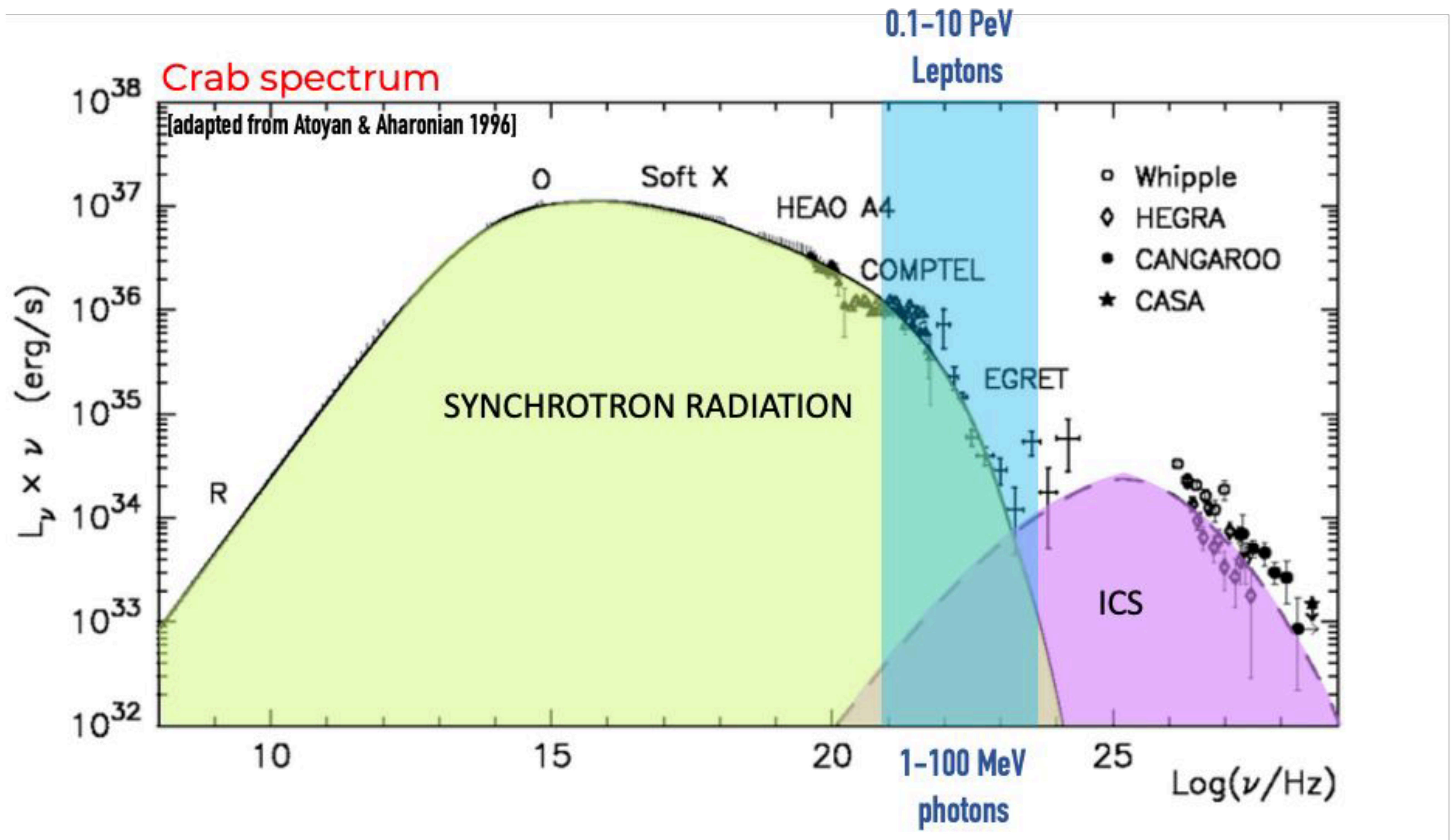

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Energetic Pulsars as PeVatron Counterparts

Minimum requirements to be a plausible counterpart

1. **To have enough energy budget to explain the gamma-ray luminosity emitted via inverse Compton**
   => Limit on the fraction of the spin-down energy transferred to high energy particles

$$W_{e,\gamma} < W_{e,PSR}$$

The total energy made available by the pulsar in the form of gamma-ray emitting electrons

$$W_{e,PSR} = \gamma_{eff}\dot{E}\tau_{loss}$$

The total energy in electrons responsible for IC radiation

$$W_{e,\gamma} = L_\gamma \tau_{IC}$$

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$$\gamma_{eff} = \frac{L_{\gamma}}{\dot{E}}\left(1 + \frac{\tau_{IC}}{\tau_{syn}}\right) = 10^{-4}\frac{L_{\gamma,32}}{\dot{E}_{36}}(1 + 260\ E_{e,15}^{1.7}B_{-5}^{2})$$

Energetic Pulsars as PeVatron Counterparts

Minimum requirements to be a plausible counterpart

2. **To be able to reach the maximum energy observed**

Acceleration carried out by electric field (expect for non-ideal cases)
=> Maximum will be defined by the maximum potential drop

$$\Phi_{\rm PSR} = (\dot{E}/c)^{1/2}$$

$$\Phi_{\infty} = 0$$

$$\rightarrow \quad E_{\rm max} = q(\dot{E}/c)^{1/2} \quad \rightarrow \quad E_{\rm max} \approx 2\, \eta_e\, \eta_{\rm B}^{1/2}\, \dot{E}_{36}^{1/2} \ \ \rm PeV$$

ratio between the electric and magnetic strength $\eta_e \leq 1$ in MHD flow

fraction of pulsar wind energy flux transferred to magnetic field $\eta_B \leq 1$ by energy conservation

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Independent on the particle nature!

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If electrons AND >100 TeV

photon field up scattered is 2.7K CMB => $E_{\rm e} \simeq 2.15\ E_{\gamma,15}^{0.77}$ PeV

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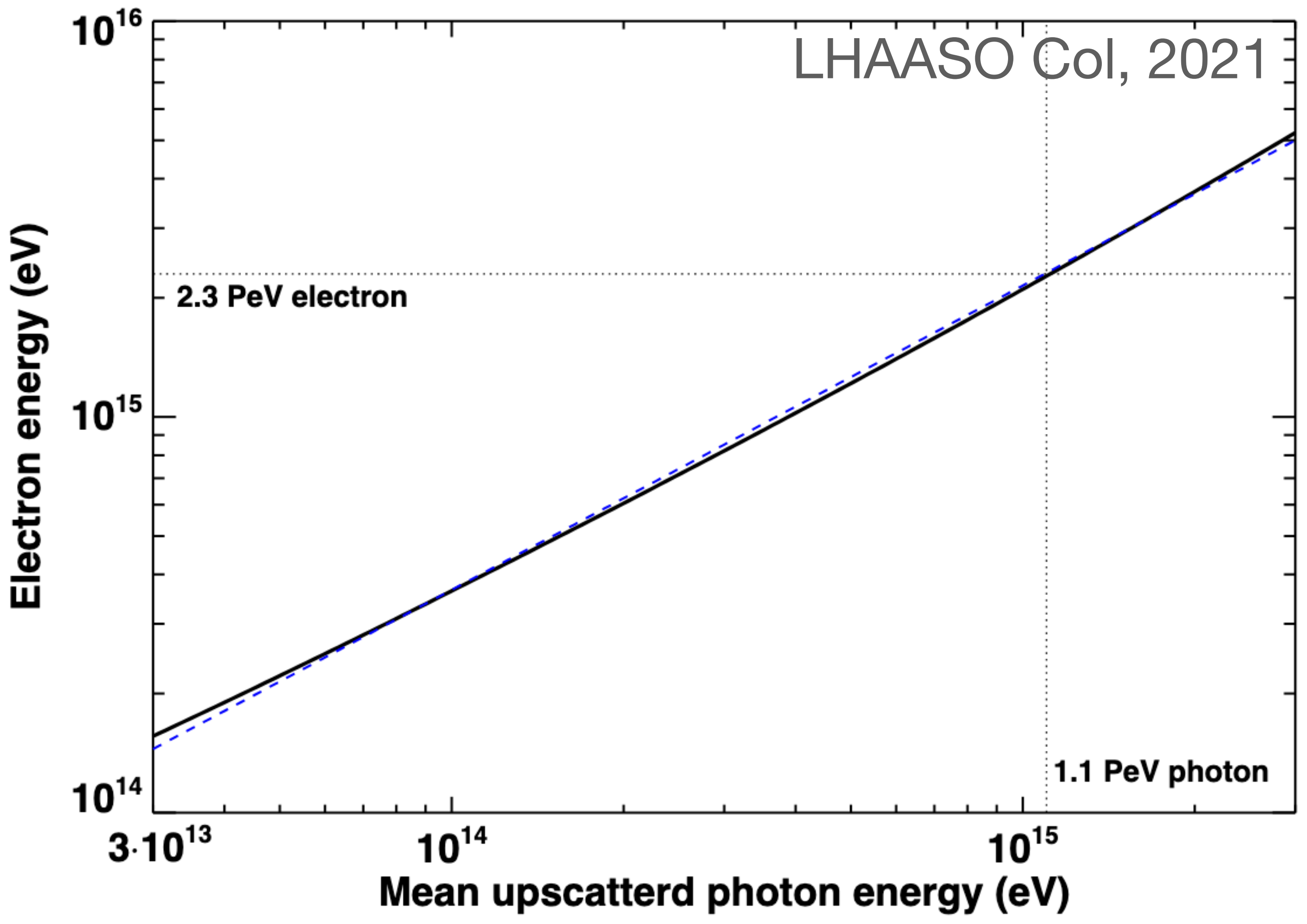

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Minimum requirements to be a plausible counterpart

2. **To be able to reach the maximum energy observed**

It is not sufficient to be able to accelerate the particles => we need to overcome the radiation loses:

$$\tau_{\rm acc} = \tau_{\rm loss} \quad \cdots\cdots \quad \tau_{\rm sync} \simeq 4 \times 10^9 E_{e,15}^{-1} B_{-5}^{-2}\ {\rm s}$$

$$\tau_{\rm acc} = E_{\rm e}/(\eta_e e B_{\rm TS} c)$$

$$E_{\gamma\ \rm max} \approx 5 \eta_e^{0.65} B_{-5}^{-0.65}\ \ {\rm PeV}$$

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The limit on the energy will be given by the interplay between the two expression above

Application to the LHAASO sources

Method

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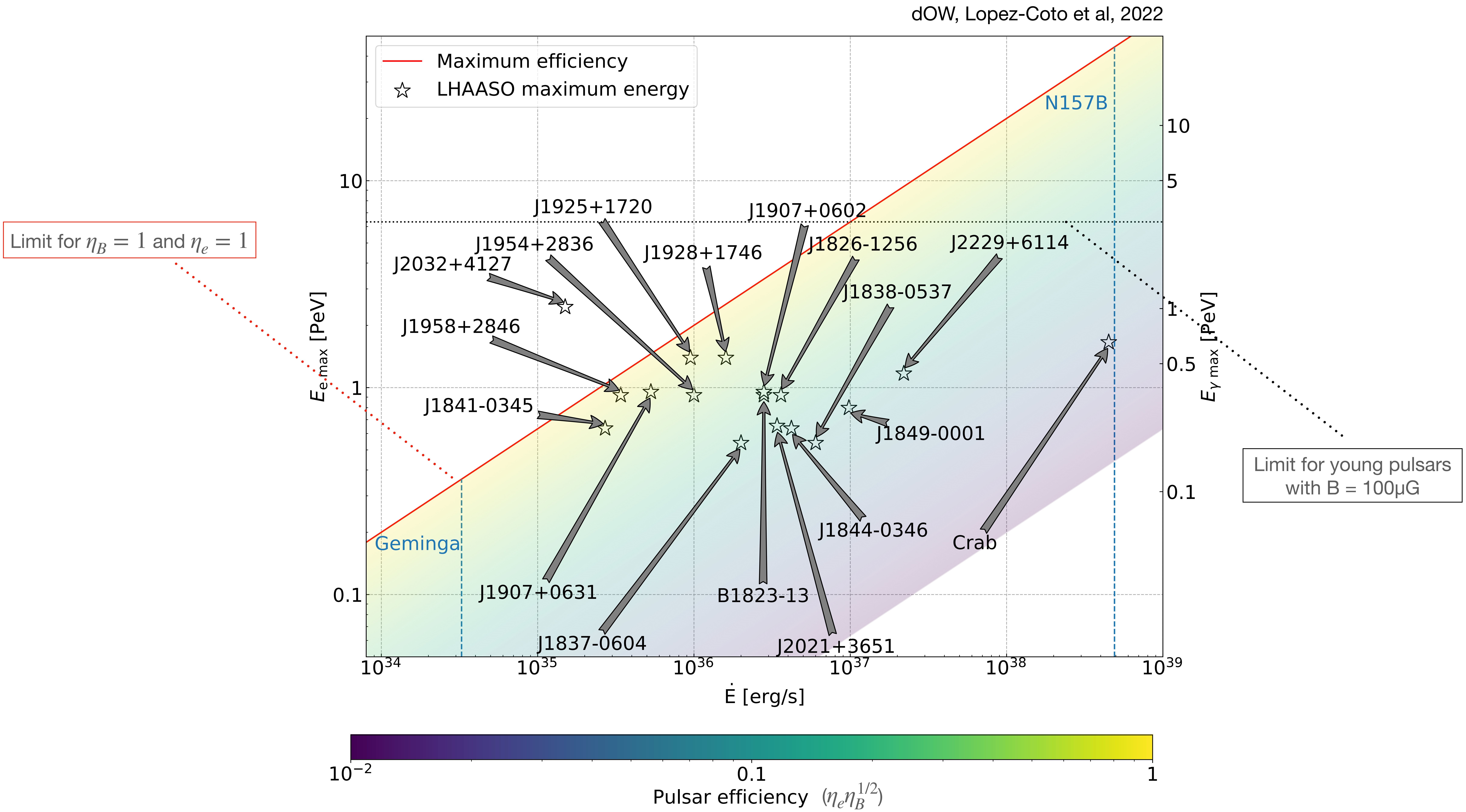
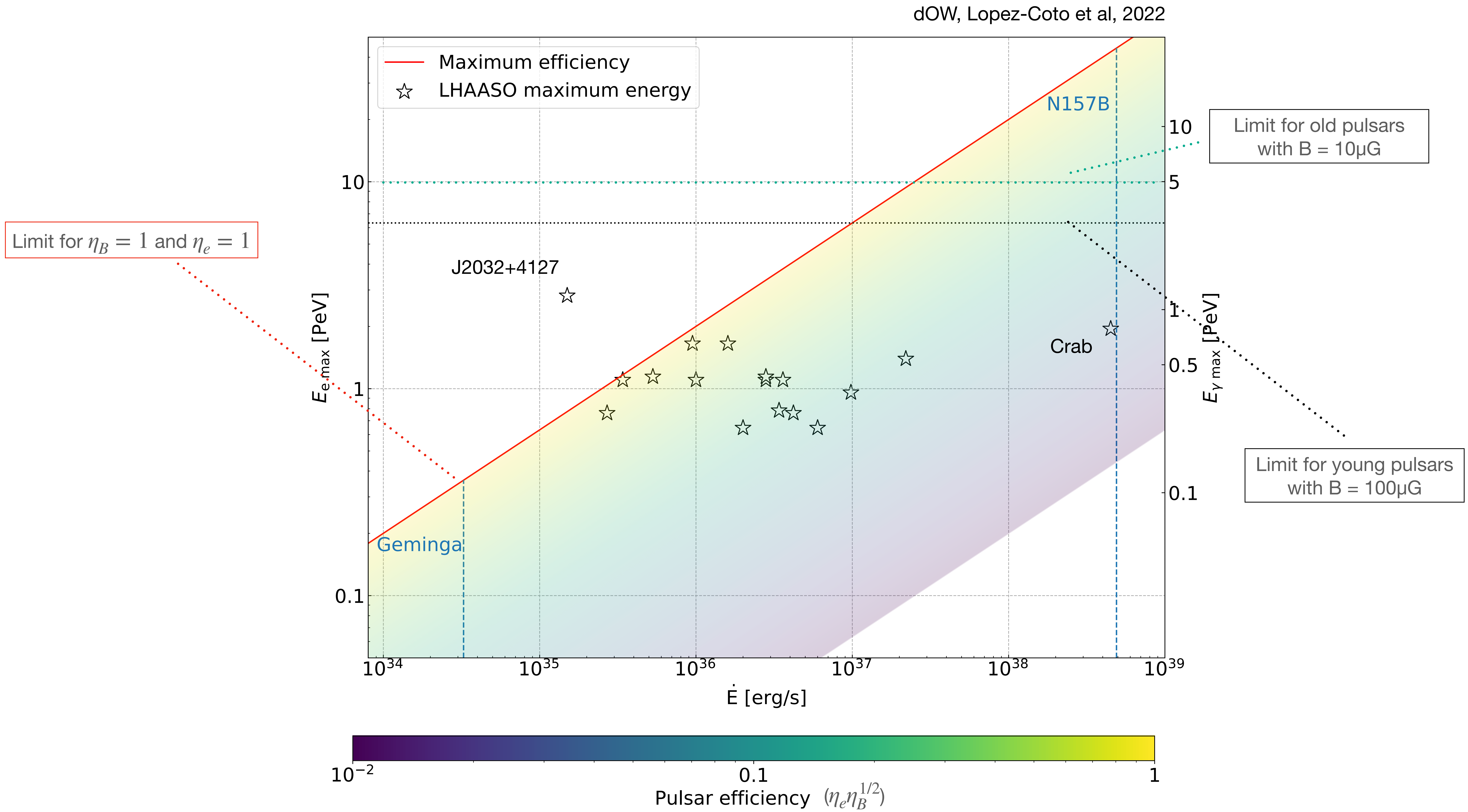


dOW, Lopez-Coto et al, 2022
Maximum efficiency
LHAASO maximum energy
N157B
Limit for $\eta_B = 1$ and $\eta_e = 1$
J1925+1720
J1907+0602
J1954+2836
J1928+1746
J1826-1256
J2229+6114
J2032+4127
J1838-0537
J1958+2846
J1841-0345
J1849-0001
J1844-0346
Crab
Geminga
J1907+0631
B1823-13
J1837-0604
J2021+3651
Limit for young pulsars with B = 100μG
$E_{e\ max}$ [PeV]
$E_{\gamma\ max}$ [PeV]
Ė [erg/s]
Pulsar efficiency $(\eta_e \eta_B^{1/2})$



dOW, Lopez-Coto et al, 2022
Maximum efficiency
LHAASO maximum energy
N157B
Limit for old pulsars with B = 10μG
10
5
Limit for $\eta_B = 1$ and $\eta_e = 1$
J2032+4127
$E_{e\,max}$ [PeV]
$E_{\gamma\,max}$ [PeV]
1
0.5
Crab
Limit for young pulsars with B = 100μG
0.1
Geminga
10^{34}
10^{35}
10^{36}
10^{37}
10^{38}
10^{39}
Ė [erg/s]
10^{-2}
0.1
1
Pulsar efficiency $(\eta_e \eta_B^{1/2})$

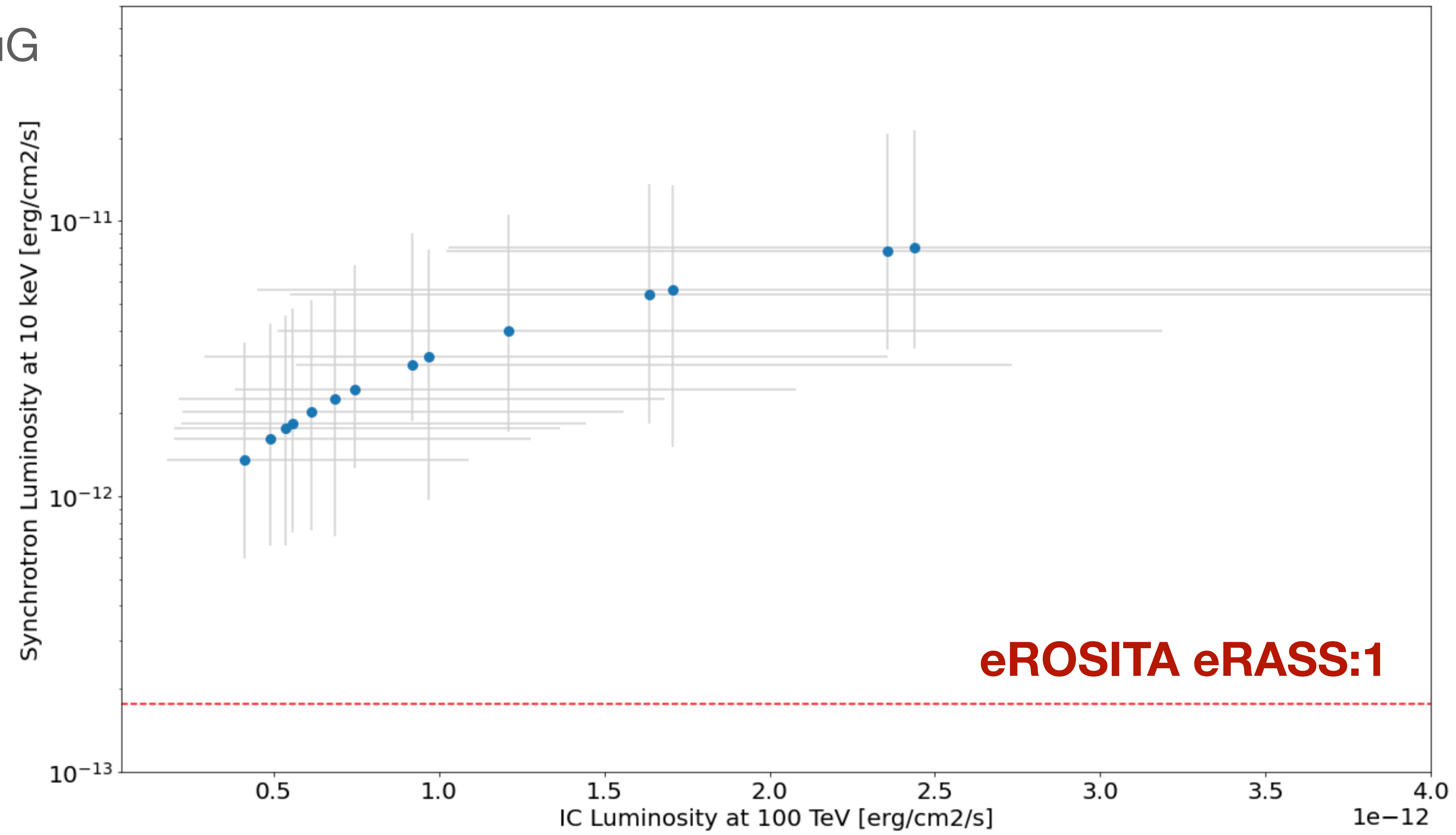
dOW, Lopez-Coto et al, 2022

LHAASO Source	Pulsar	$E_{\gamma\ max}$ [PeV]	E_{max} [PeV]	B_{max} [μG]
J1825-1326	J1826-1256	2.06	3.79	38
	B1823-13	1.77	3.35	14
J1839-0545	J1837-0604	1.44	2.83	33
	J1838-0537	2.78	4.90	$\gg$100
J1843-0338	J1841-0345	0.41	1.04	12
	J1844-0346	2.25	4.10	$\gg$100
J1849-0003	J1849-0001	3.71	6.26	$\gg$100
J1908+0621	J1907+0602	1.77	3.35	30
	J1907+0631	0.63	1.46	9
J1929+1745	J1925+1720	0.91	1.95	9
	J1928+1746	1.26	2.53	14
J1956+2845	J1954+2836	0.94	2.00	37
	J1958+2846	0.47	1.17	22
J2018+3651	J2021+3651	1.99	3.69	102
J2032+4102	J2032+4127	0.28	0.77	7
J2108+5157				
J2226+6057	J2229+6114	5.89	9.38	64

- The majority of the source can be, in principle, powered by energetic pulsars in a 1degree region
- We derive upper limits to the magnetic field (the efficiency provides the most constraining limit)

$$\gamma_{\rm eff} = \frac{L_\gamma}{\dot{E}}\left(1 + \frac{\tau_{\rm IC}}{\tau_{\rm syn}}\right) = 10^{-4}\frac{L_{\gamma,32}}{\dot{E}_{36}}(1 + 260\ E_{e,15}^{1.7} B_{-5}^{2})$$

B=3 uG

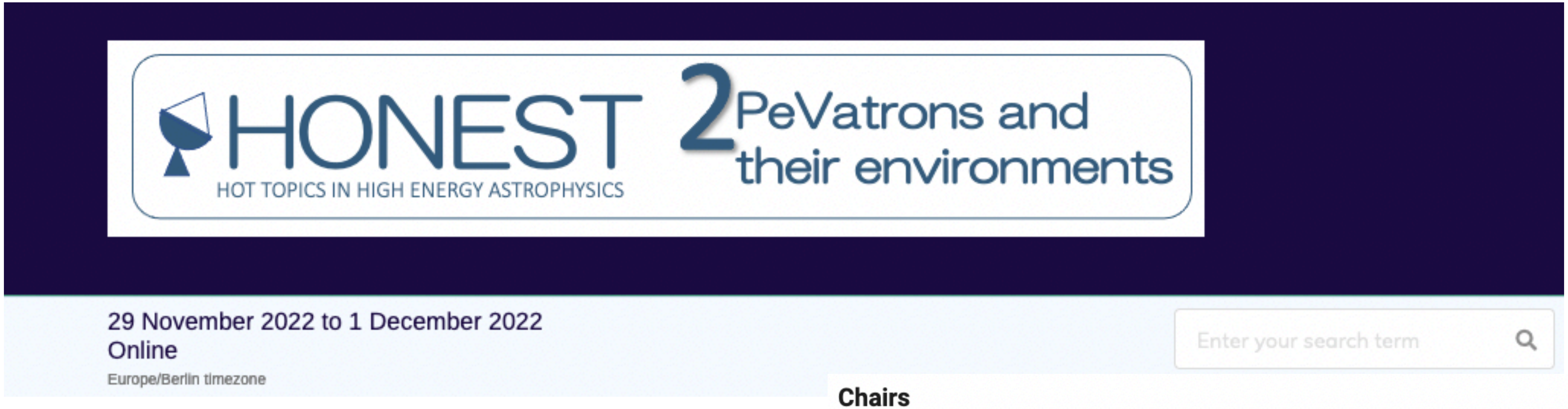


Summary

- Bright pulsars can in theory accelerate particles (electrons and protons) to the observed PeV energies => Two of the LHAASO sources cannot be explained by pulsars in the FoV
- For young pulsars with magnetic field of ~100 μG, the maximum energy is constraint by the synchrotron losses, whereas for older ones (~few μG) by the potential drop
- We constrain the maximum photon energy in Geminga to less than 200 TeV, whereas the Crab twin (N157B) in the LMC could also be an efficient accelerator.
- The synchrotron counterpart of the 100 TeV IC nebula should be bright in the X-ray domain => eROSITA
- More constraints should come from the size of the gamma-ray emission (in preparation)

Summary

The search of sources accelerated particles up to PeV energies continues
https://indico.desy.de/event/34265/



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Emma de Oña Wilhelmi (DESY Zeuthen)

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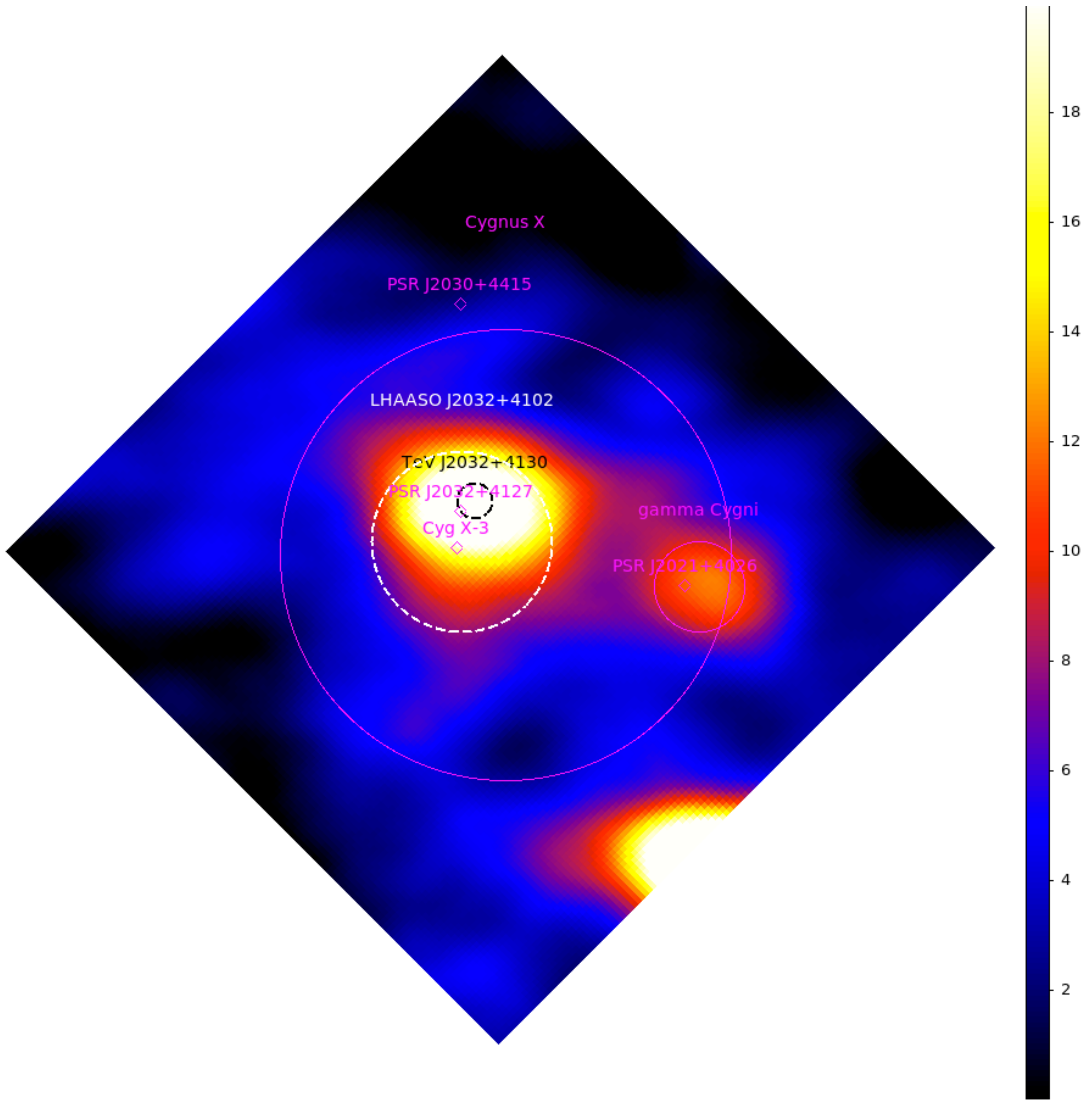
Petra Huentemeyer (Michigan Tech University)
Jim Hinton (MPIK)
Sarah Recchia (INFN Torino)
Roberta Zanin (CTA Observatory)
Cao Zhen (IHEP)

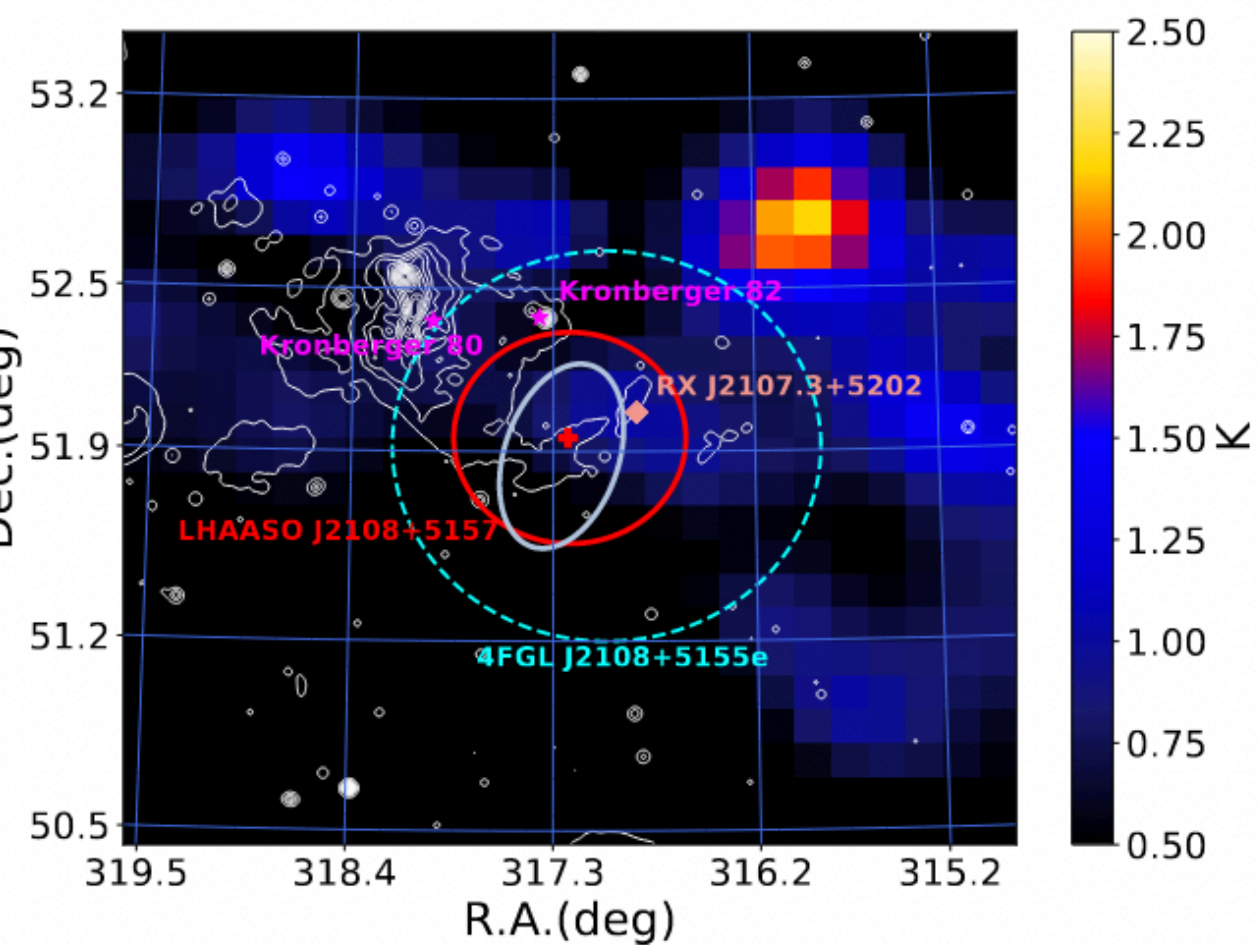
LHAASO J2032+4102



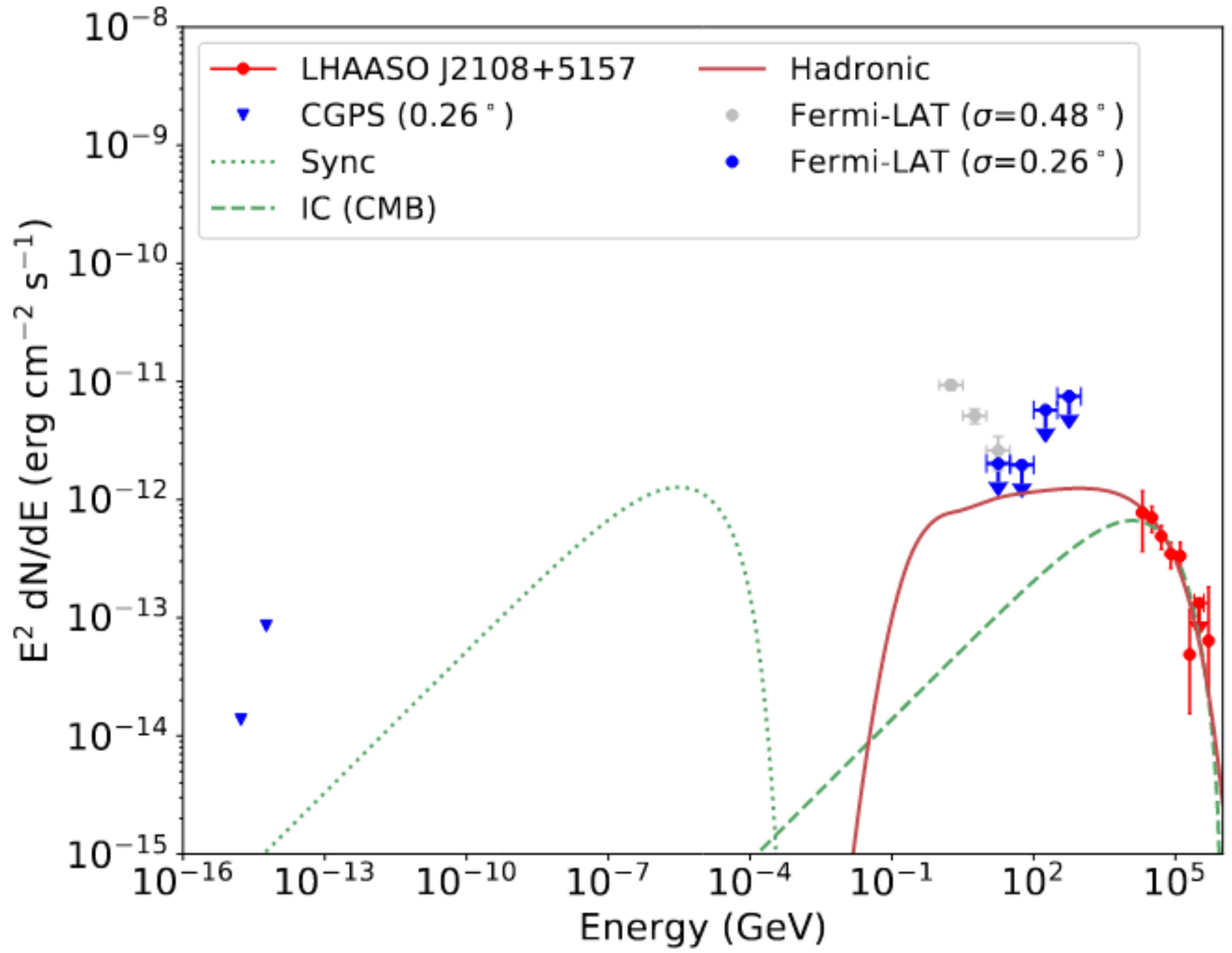
- Compact 0.15° TeV PWN
- Modulated gamma-ray emission => Binary system
- In the Cygnus region => Cocoon?

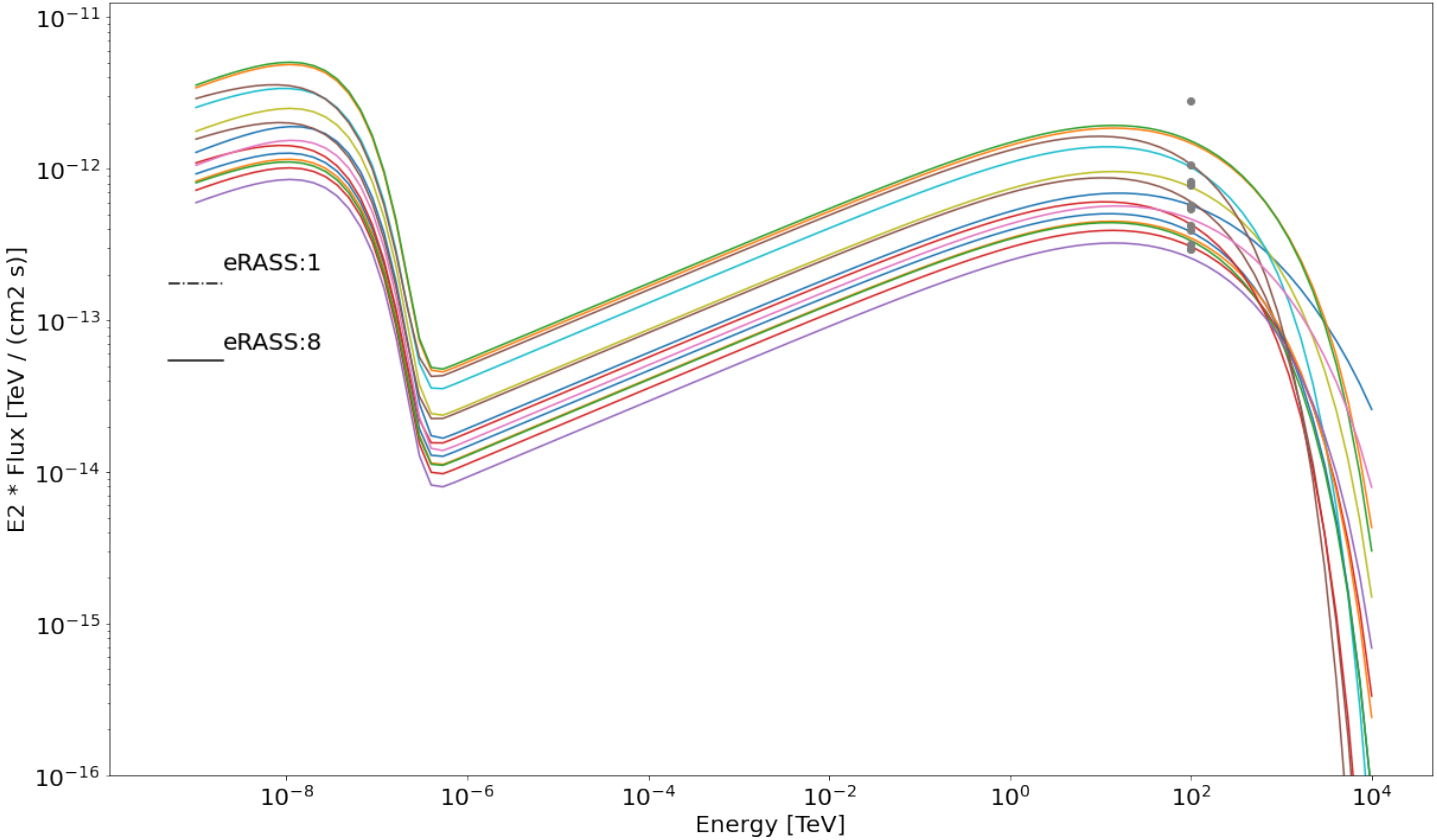
LHAASO J2108+5157

LHAASO Col., 2021



- No counterparts yet with ground-based instruments
- Detected above 25 TeV
- Relatively compact ~0.26d source





E2 * Flux [TeV / (cm2 s)]
Energy [TeV]
eRASS:1
eRASS:8
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}

Pulsars Maximum energy

Hillas criterium

What is the maximum energy a particle can reach in a Galactic source?

- Acceleration is always (expect for non-ideal cases) carried out by an electric field
- For a particle with charge q, moving a distance L

$$E = q|\vec{E}|L$$

- We can define the acceleration efficiency as:

$$\eta = \vec{B}/\vec{E}$$

then:

$$E = q\eta BL$$

L = Size of the source

B = Magnetic field in the source

This two value will define the maximum energy

Pulsars Maximum energy

Hillas criterium

The maximum energy:

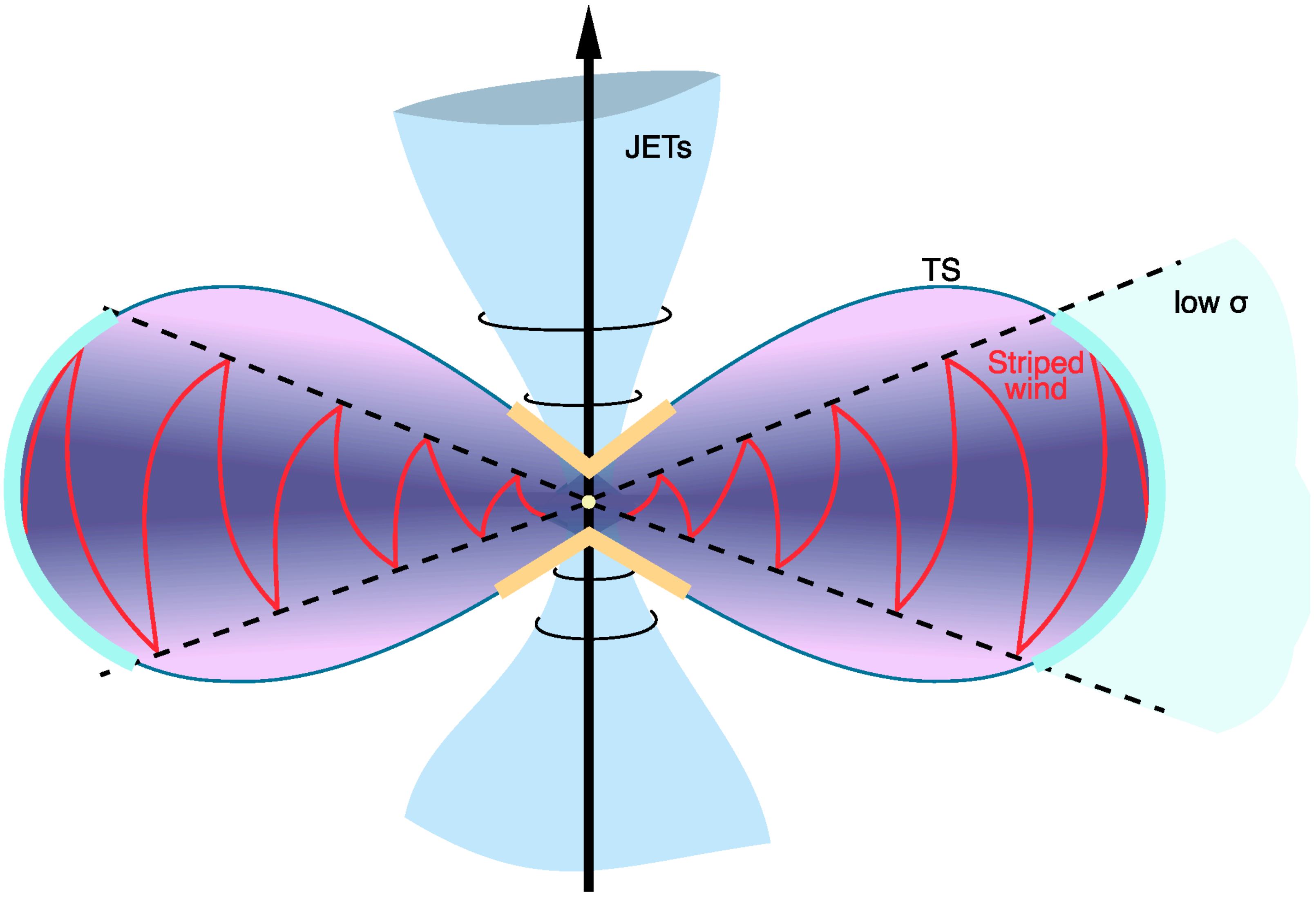
$$E_{\max} = q\eta_e B_{TS} R_{TS},$$

The magnetic density is a fraction of the pulsar wind energy flux:

$$\frac{B_{TS}^2}{8\pi} = \eta_B \frac{\dot{E}}{(4\pi R_{TS}^2 c)}$$

Then the Emax:

$$E_{\max} \approx 2\,\eta_e\,\eta_B^{1/2}\,\dot{E}_{36}^{1/2}\ \text{PeV}$$



In astrophysical environment :

$$\vec{E} = v/c\,\vec{B}$$

if $\vec{E} \sim \vec{B}$ => relativistic plasmas: PWNe

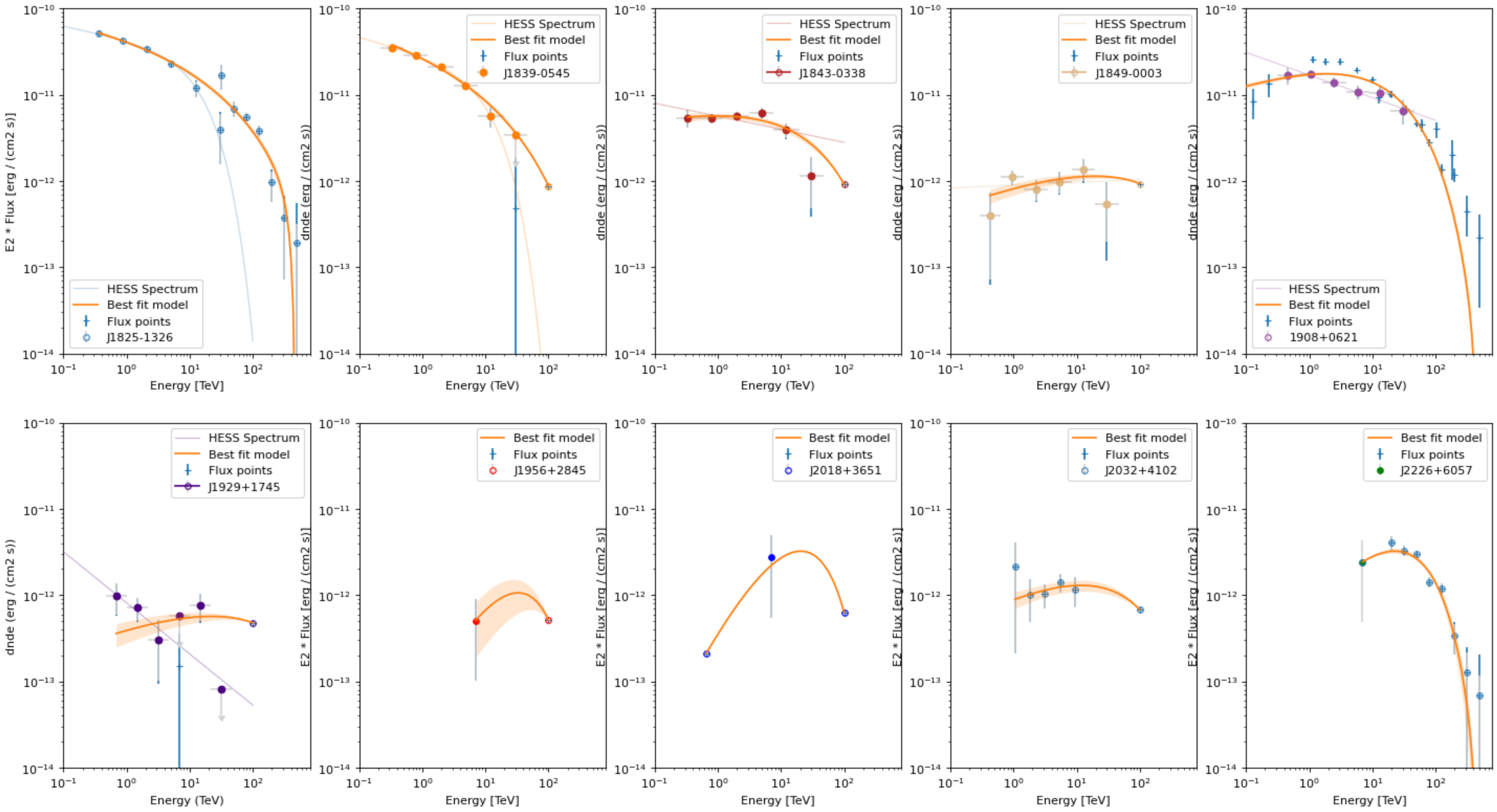
FOR PSRs Φ IS MEASURED DIRECTLY:

$$\Phi = \frac{1}{2}\left(\frac{\Omega R_*}{c}\right)^2 R_* B_*$$

$$\dot{E} = cB_*^2 R_*^2 \left(\frac{R_*^4 \Omega^4}{c^4}\right)$$

$$\Rightarrow \Phi = \sqrt{\dot{E}/c}$$

Amato et al, 2012


HESS Spectrum
Best fit model
Flux points
J1825-1326
J1839-0545
J1843-0338
J1849-0003
1908+0621
J1929+1745
J1956+2845
J2018+3651
J2032+4102
J2226+6057
E2 * Flux [erg / (cm2 s)]
dnde (erg / (cm2 s))
Energy [TeV]
Energy (TeV)