Young pulsars powering ultra-high energy sources

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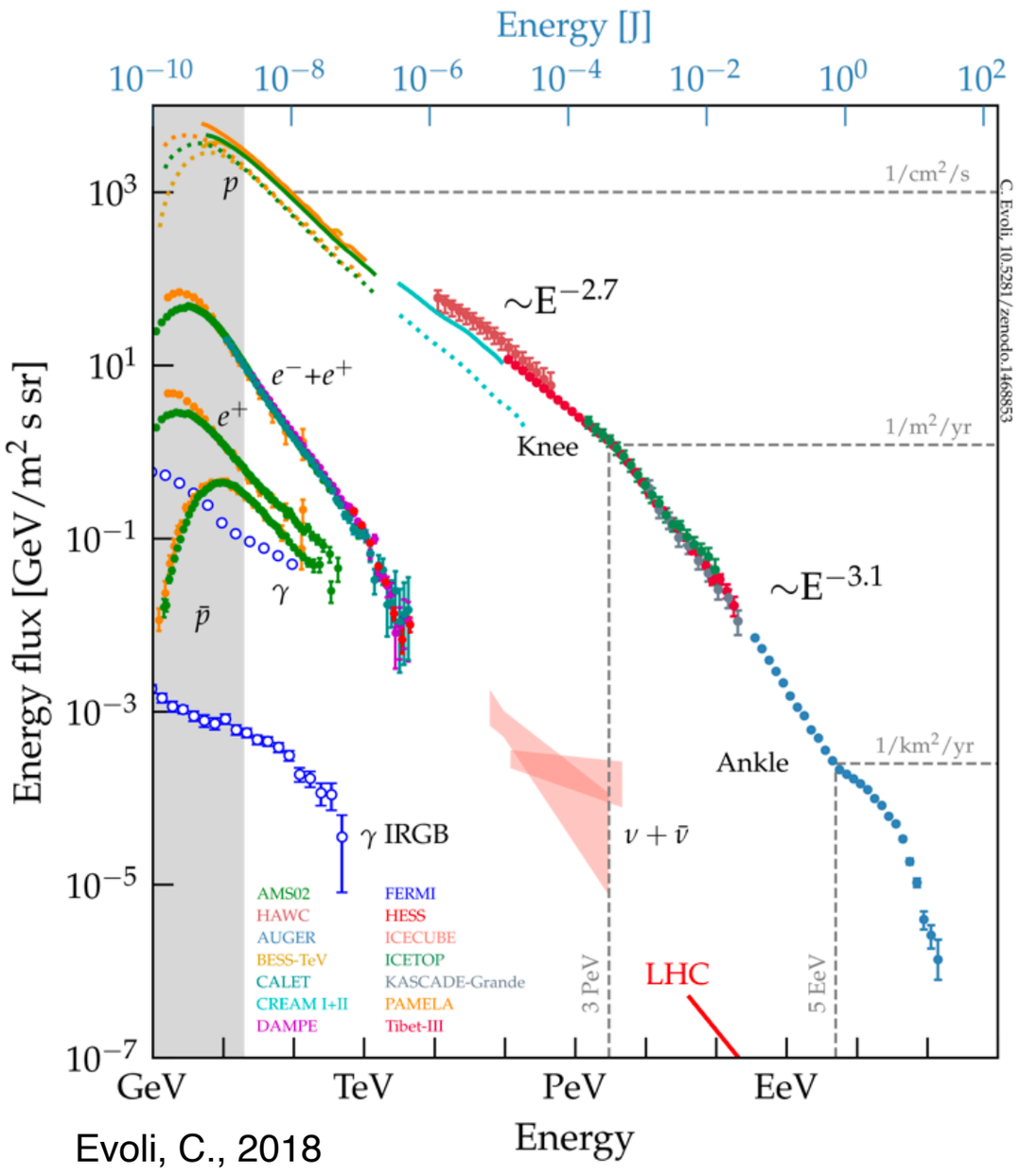
RICAP 24', 25/09/24

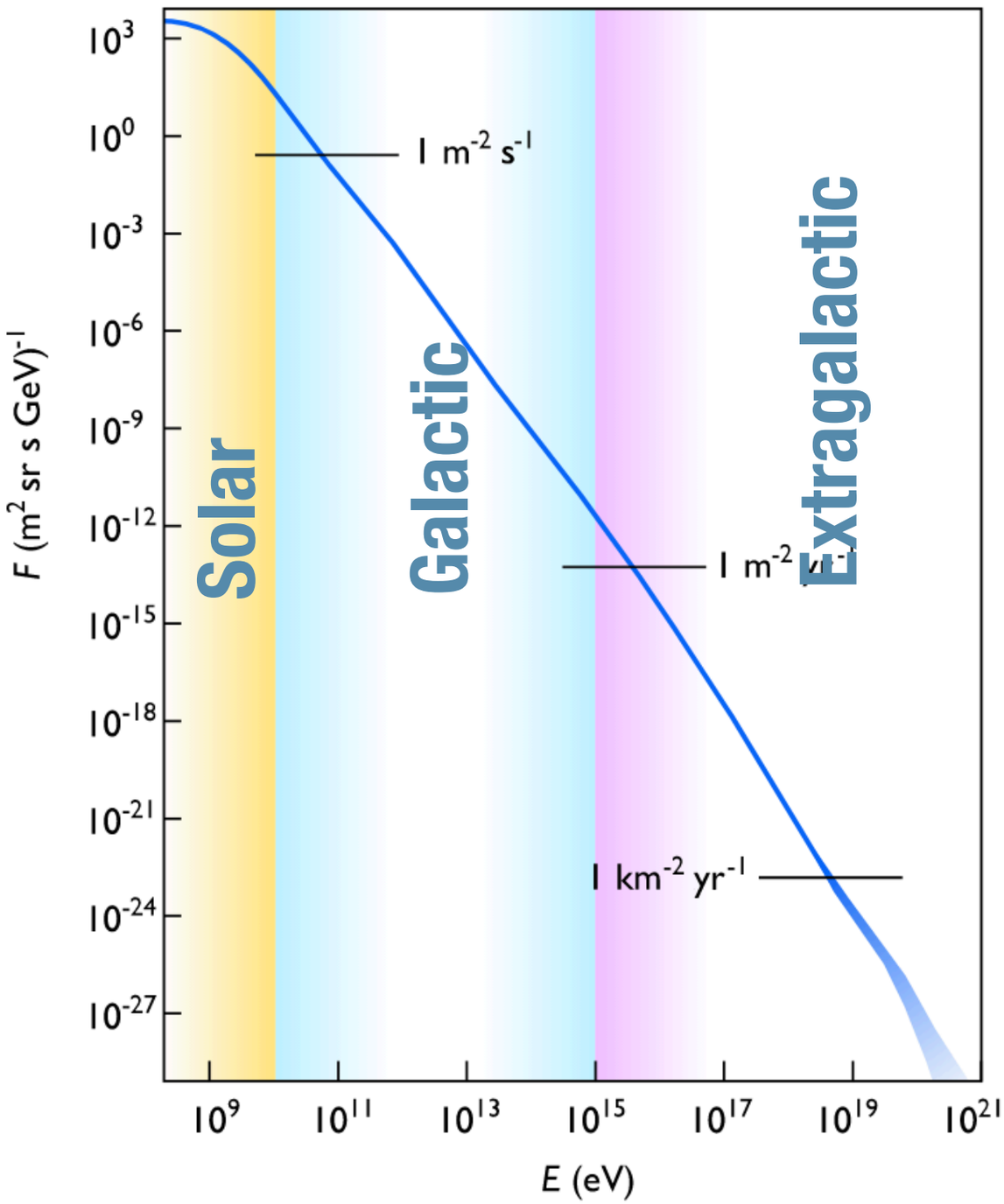
Cosmic rays: Spectrum and composition



Evoli, C., 2018

- Spectrum and composition measured by satellites, balloons and extended air shower arrays.
- Composition:
  - 90% Protons
  - 9% Helium nuclei
  - 1% Heavier nuclei, electrons, positrons, antiprotons, ...

Cosmic rays: Origin



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  - Galactic (1 GeV $< E <$ ~PeV)
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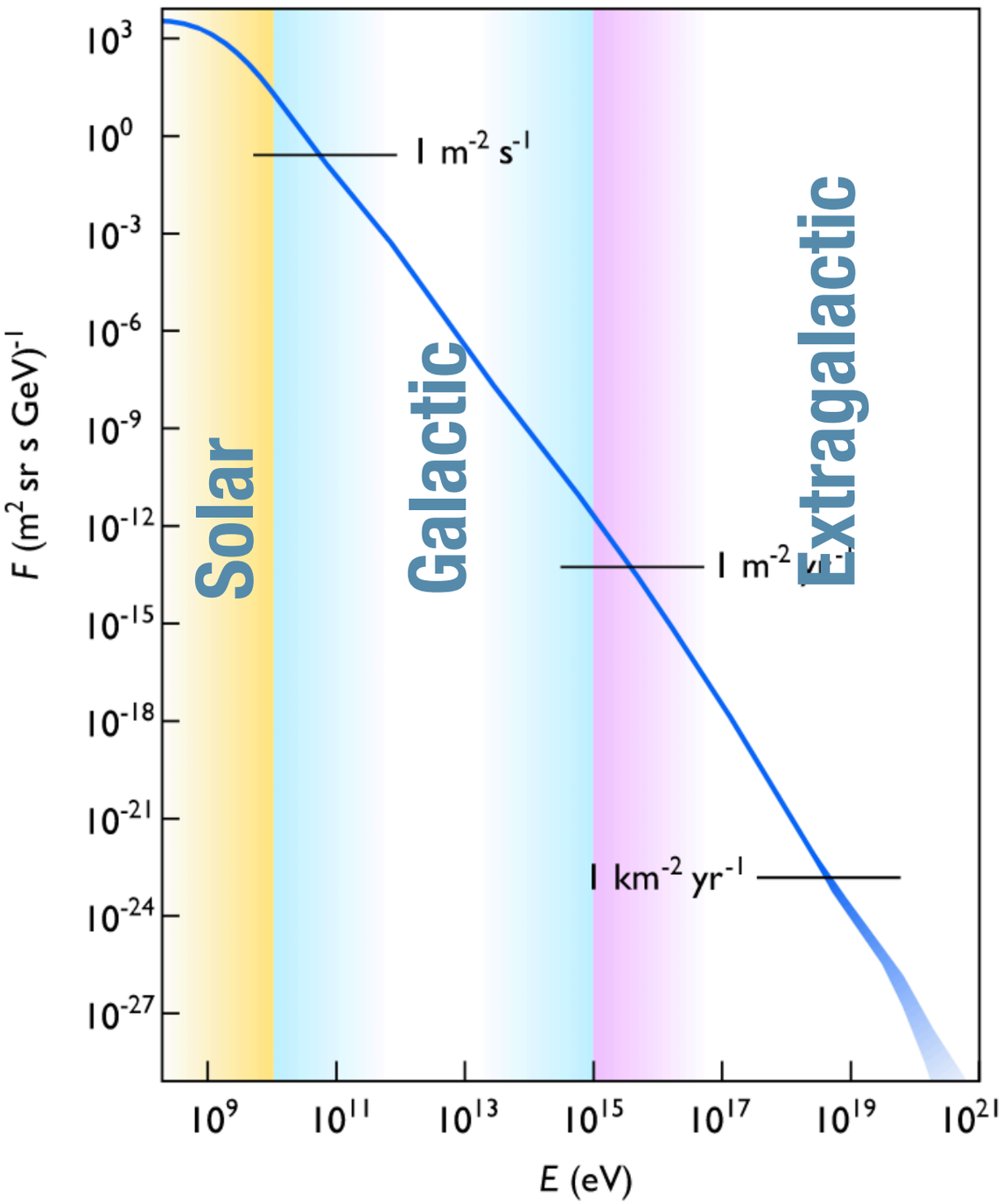

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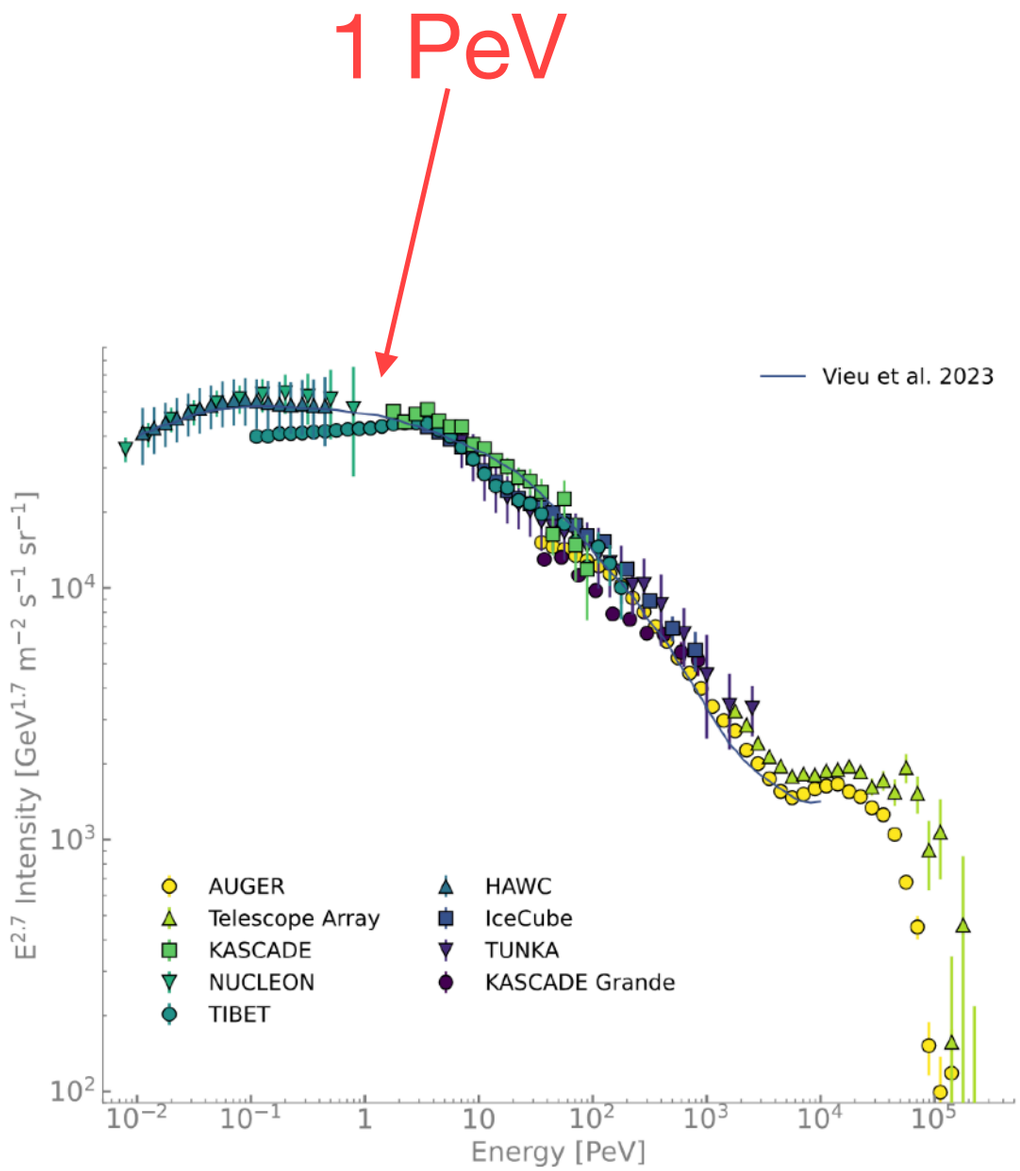
  - Extragalactic (E > PeV)

What is the origin of Galactic Cosmic Rays?

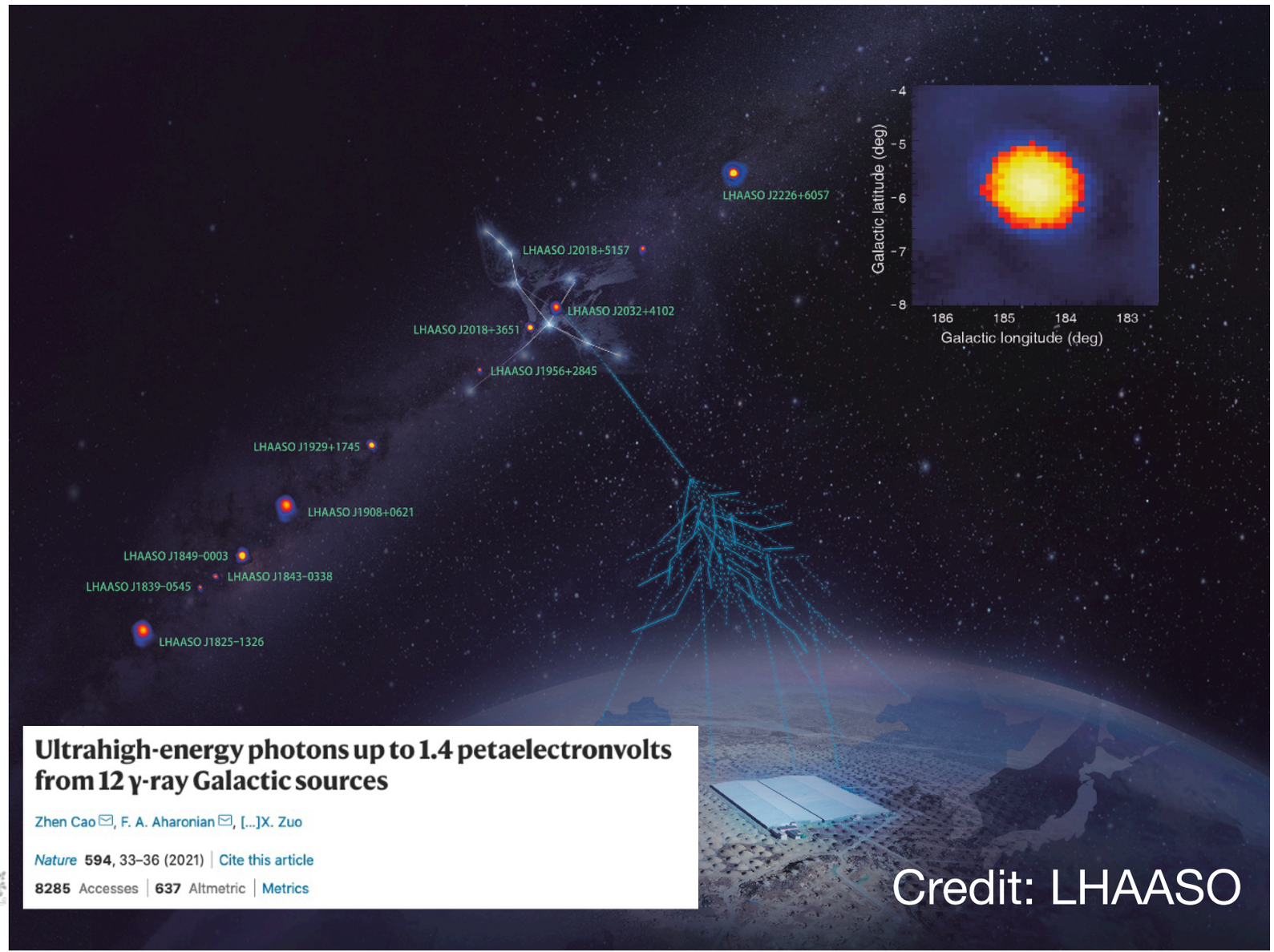
PeVatrons

- The term “PeVatron” usually refers to accelerators which are able to accelerate particles at energies > 1 PeV
  - This definition is independent of the particle nature (electron or heavy nuclei)
- Why are they so important?
  - The change of spectral index at the *knee* points to a change of dominant source accelerator
  - Origin of **Galactic Cosmic rays** => Need to get particles accelerated up to PeV energies.

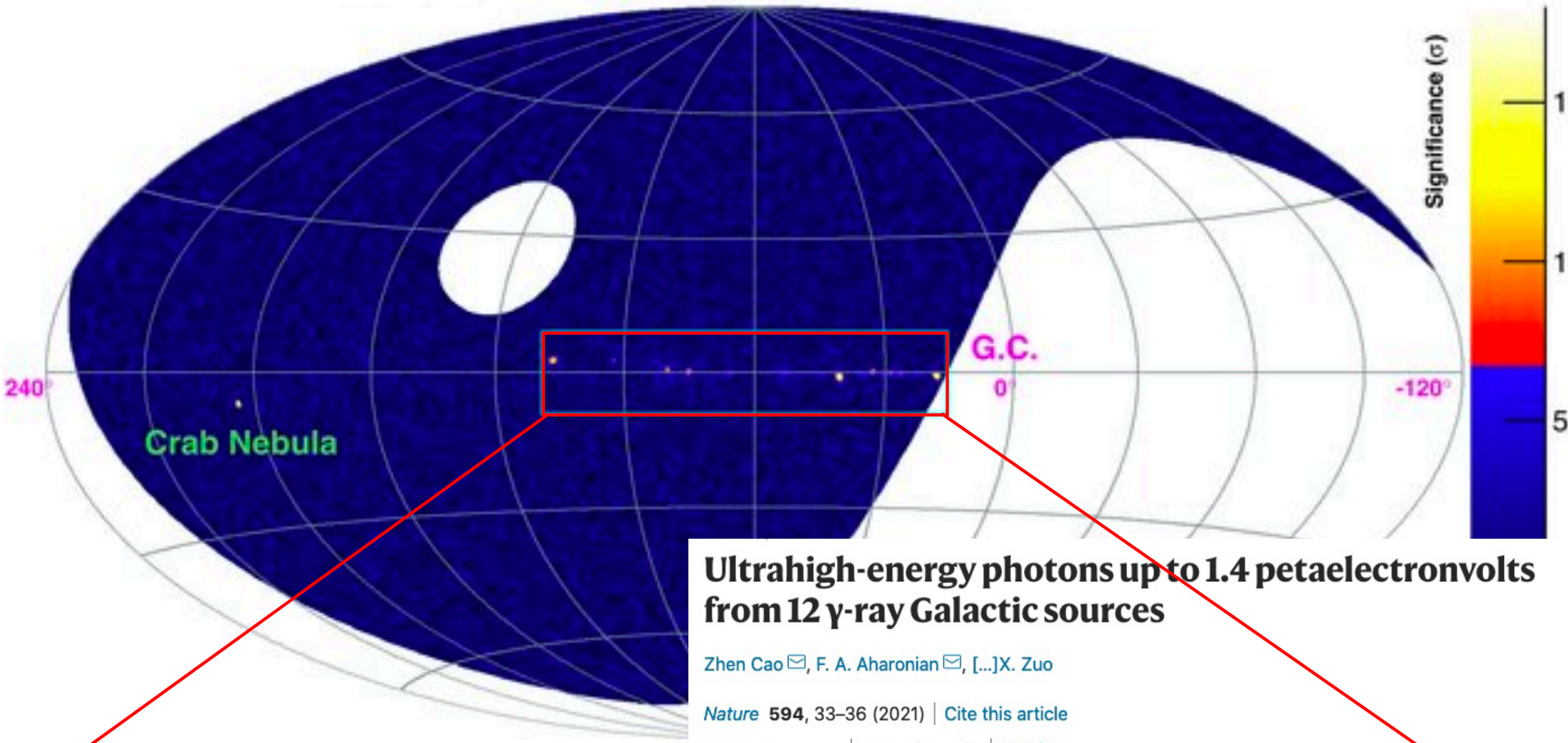


PeVatrons: a hot topic nowadays

- Latest results from several experiments have increased the interest on the study of PeVatrons
  - SNRs struggle to reach the PeV goal.
  - LHAASO results on sources emitting gamma rays up to PeV energies.



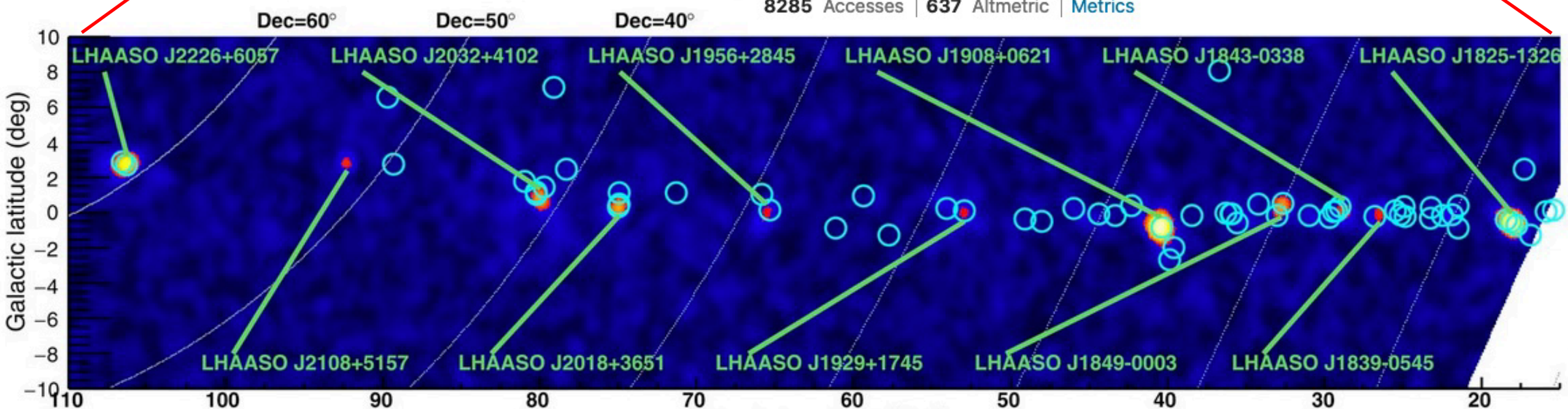
LHAASO Sky @ >100 TeV

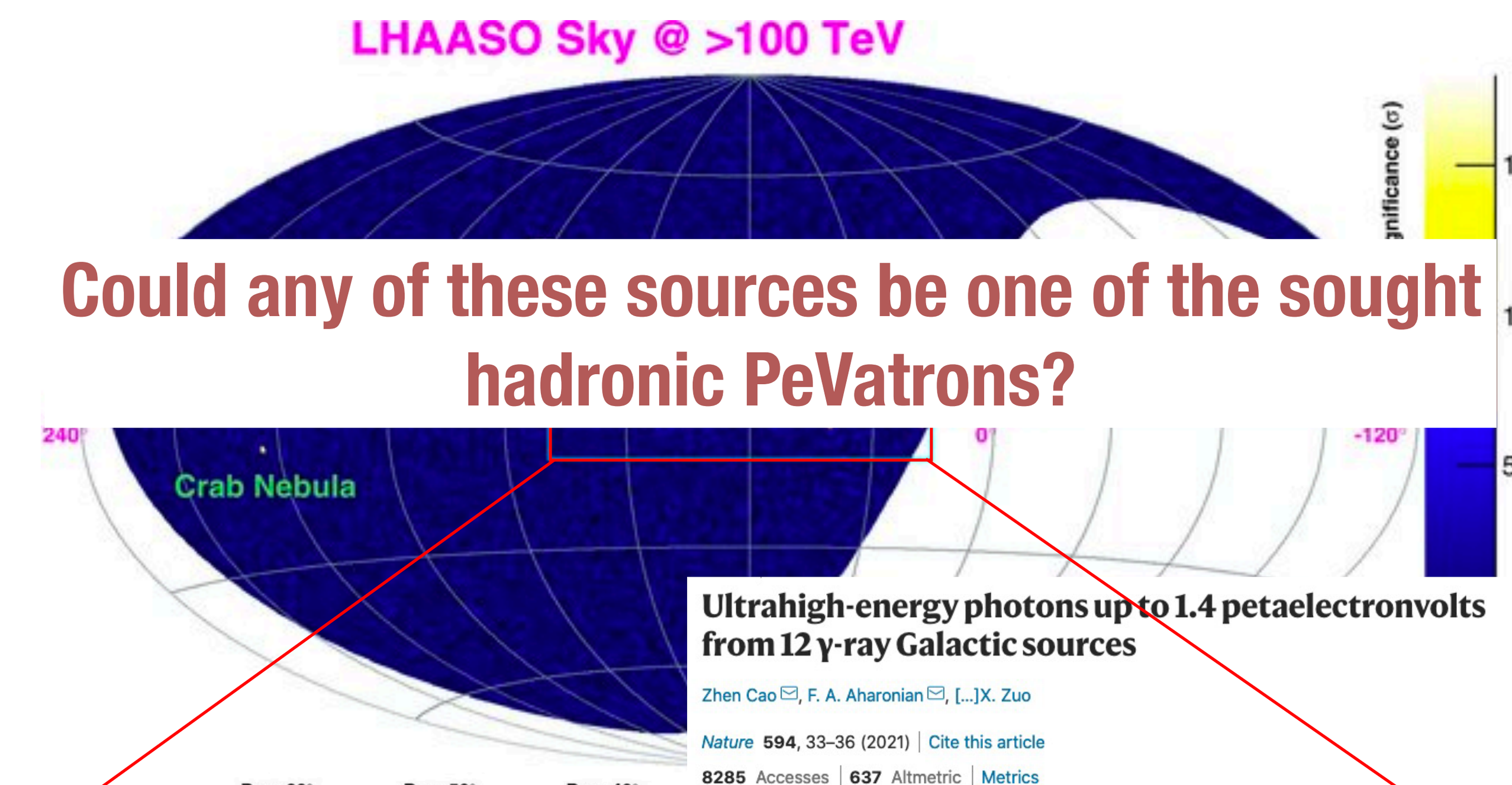


Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources

Zhen Cao ✉, F. A. Aharonian ✉, [...]X. Zuo

Nature **594**, 33–36 (2021) | Cite this article





Could any of these sources be one of the sought hadronic PeVatrons?

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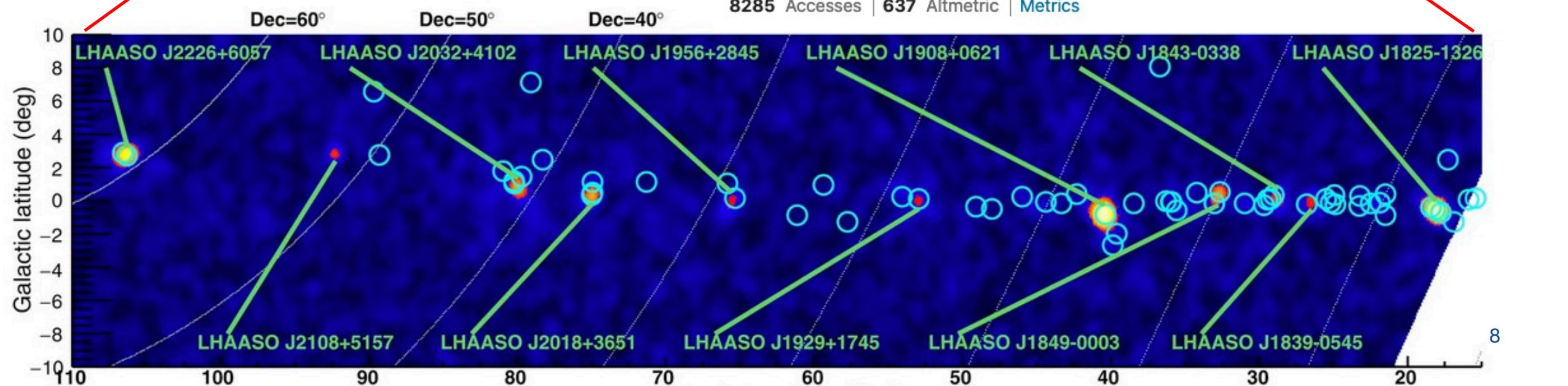
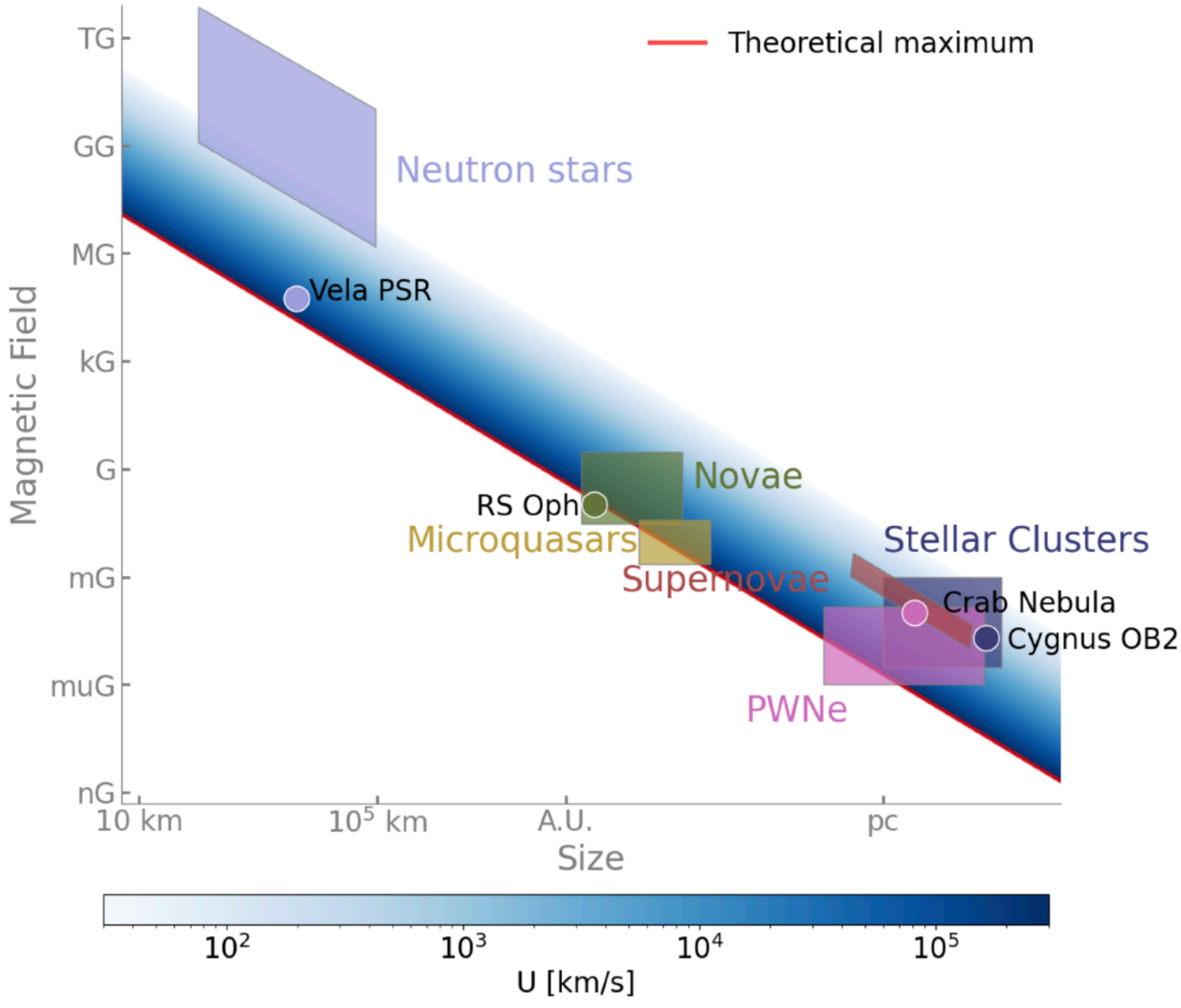


Cosmic ray acceleration

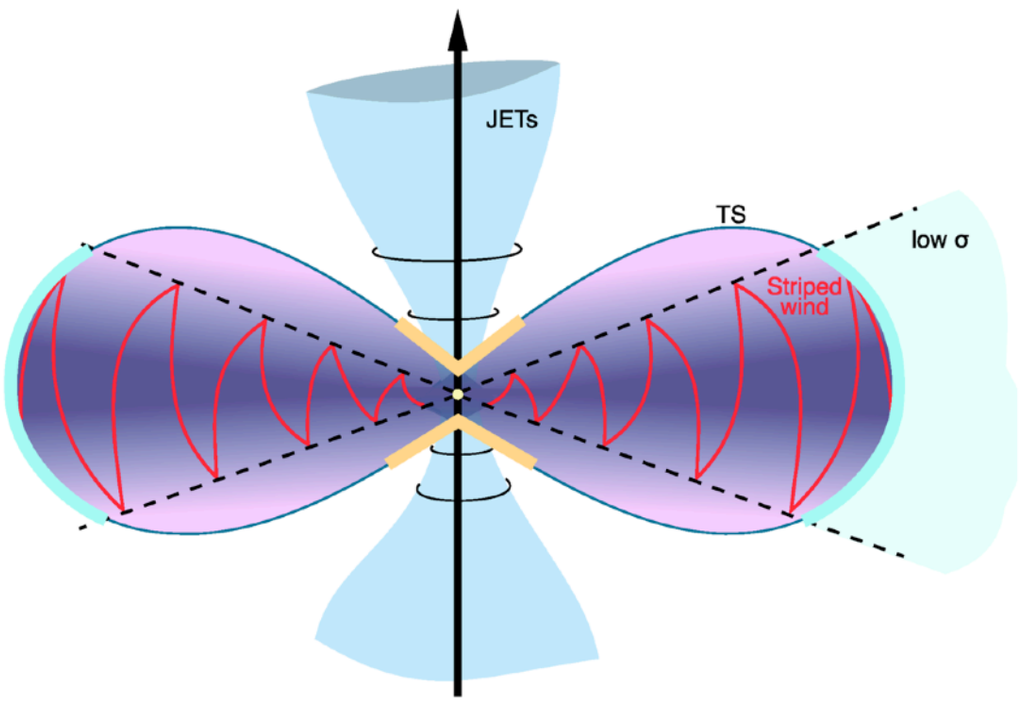
- Acceleration in each source type is limited by its **magnetic field** and **size**

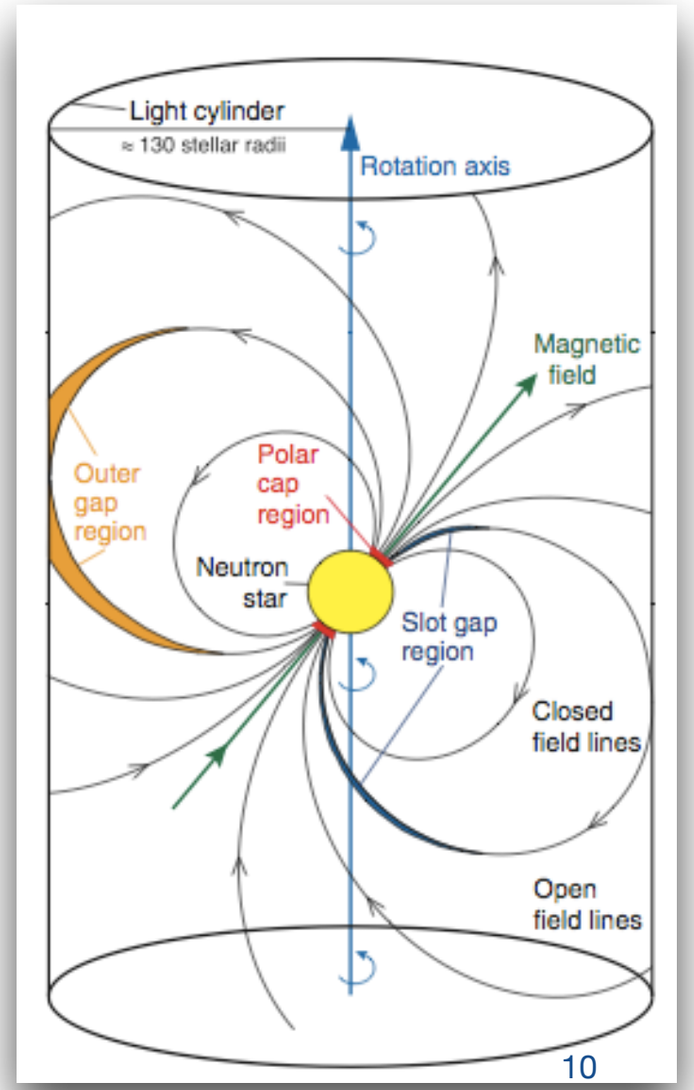
$$E_{max} \approx 1 \left(\frac{u}{10^3\ \mathrm{km/s}}\right) \left(\frac{R}{\mathrm{pc}}\right) \left(\frac{B}{\mu\mathrm{G}}\right) \mathrm{TeV}$$



The Role of Pulsars/PWNe

- It is very-well known that electrons and positrons get accelerated in pulsars and their environments
    - Also likely other sources, but these are the primary ones for which we have proof





Leptonic PeVatrons

- It is very-well known that electrons and positrons get accelerated in pulsars and their environments
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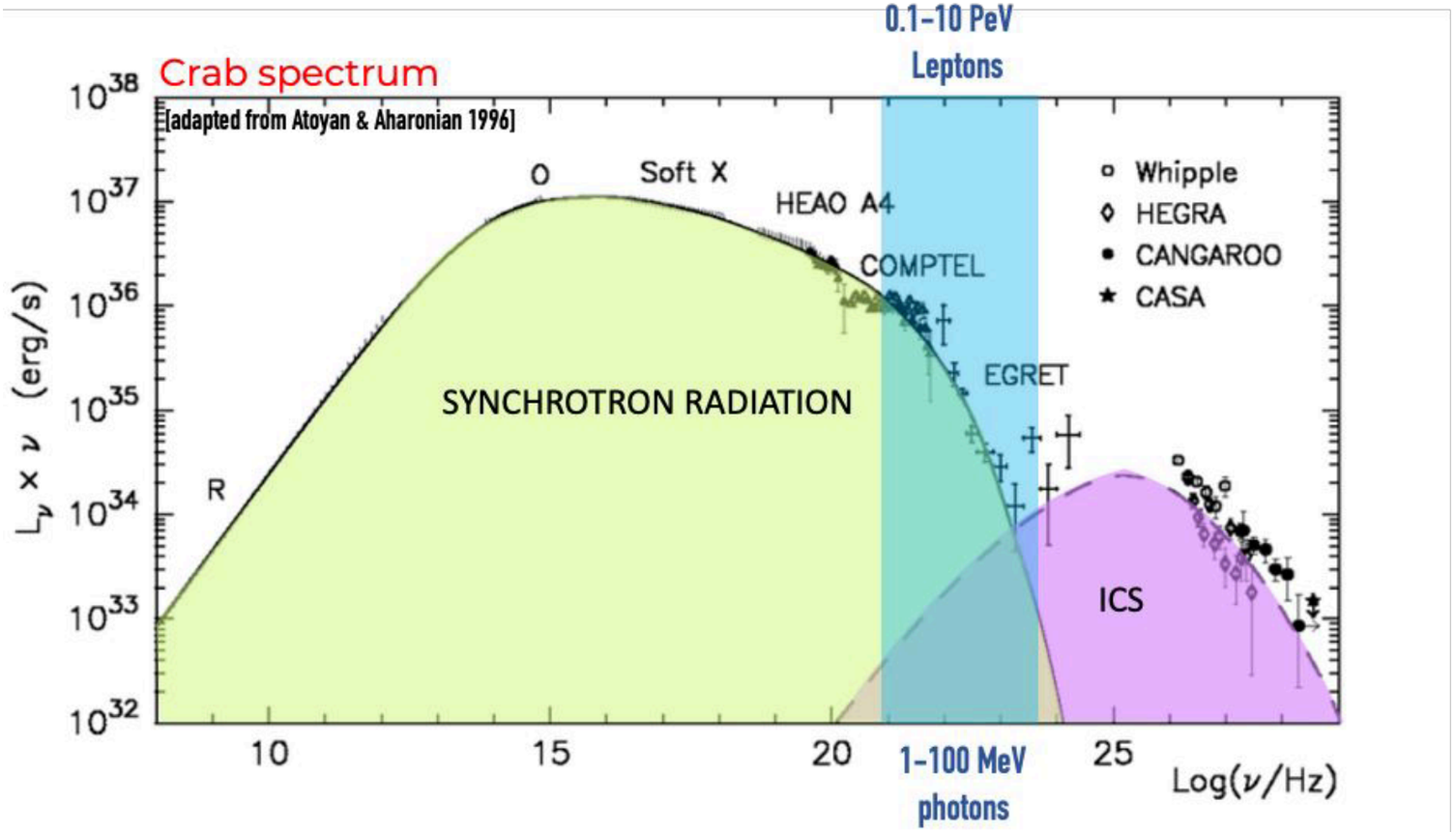
- The only known PeVatron since many years is the Crab Nebula
    - Can also other sources accelerate particles up to PeV energies?



The Role of Pulsars/PWNe

- Our study:
    - search for pulsars within 1 deg from the location of LHAASO sources.
- Study if these pulsars can provide enough acceleration power to produce the gamma rays detected at E > 1 PeV
    - But we have reasonable doubts about how particles get accelerated by Diffusive Shock Acceleration, which maximum energy they reach and so on, so…
    - What is the energy limit?

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- Our study:
  - search for pulsars within 1 deg from the location of LHAASO sources.
- Study if these pulsars can provide enough acceleration power to produce the gamma rays detected at E > 1 PeV
  - But we have reasonable doubts about how particles get accelerated by Diffusive Shock Acceleration, which maximum energy they reach and so on, so...
  - What is the energy limit?
- Maximum energy is given by the maximum potential drop that you can get from a pulsar
  - The **potential drop** between the pulsar ($V = (\dot{E}/c)^{1/2}$) and infinity (V=0) gives you the maximum energy that can be reached for individual particles
  - This gives you the maximum energy of electrons, that can be related to the maximum energy of gammas in the Klein-Nishina regime:

$$E_{\gamma,\mathrm{max}} \approx 0.9 \dot{E}_{36}^{0.65} \ \mathrm{PeV}$$

Physical limits

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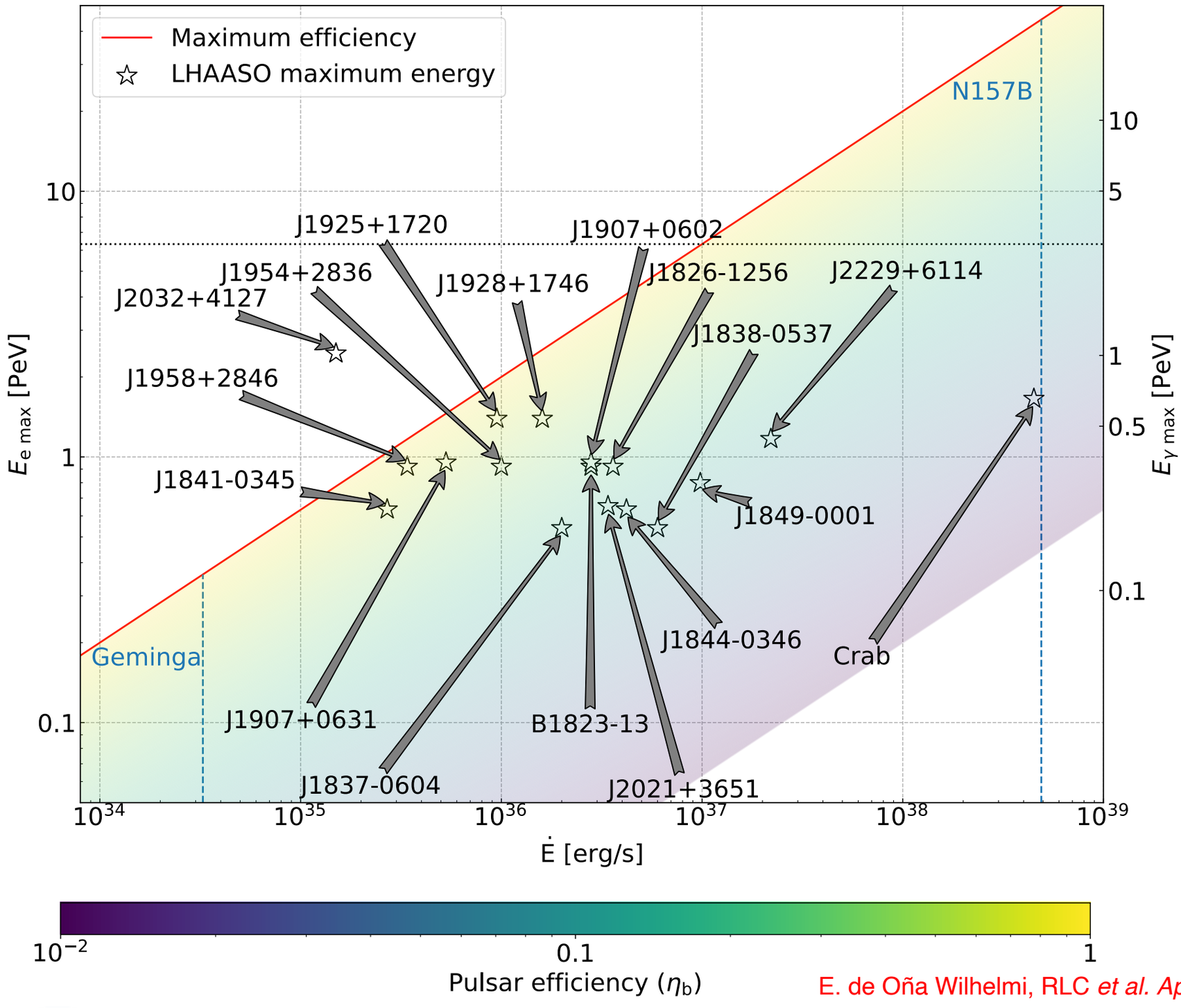


- In this plot:
  - all pulsars located within one degree from the LHAASO sources
- Below the red line, pulsars have enough power to produce the observed gamma energy.
- Above the line, the observed gamma energy is higher than the pulsar's power output.
- Caveat: maximum energy of pulsars with high magnetic field may be dominated by synchrotron losses.

E. de Oña Wilhelmi, RLC *et al. ApJL* **930** L2 2022

Physical limits

E. de Oña Wilhelmi, RLC *et al. ApJL* **930** L2 2022

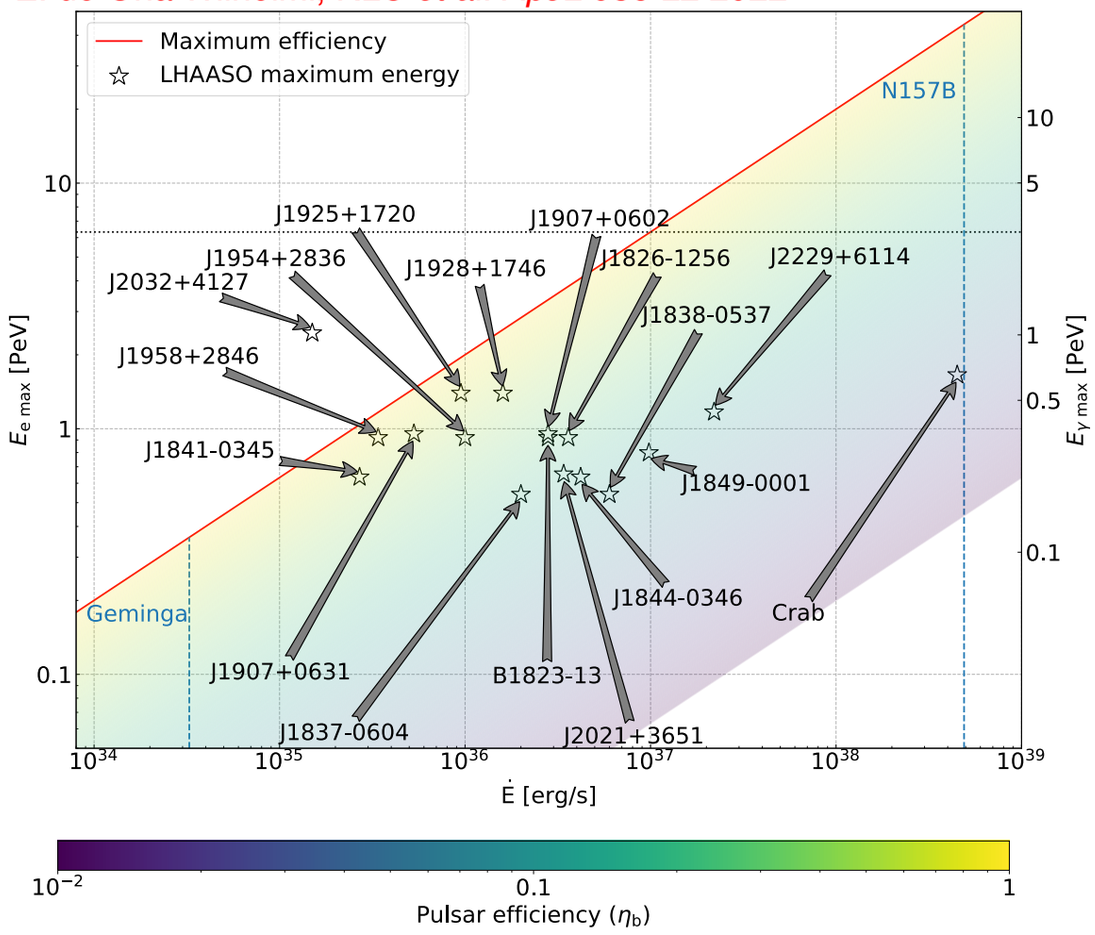


Table 2
LHAASO Ultrahigh-energy Sources and Putative Associated Pulsars, with the Corresponding Constraints on the Maximum Energy and Magnetic Field

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

- All sources but two can be explained with the visible pulsars in their neighbor
  - one of them (LHAASO J2108+5157) does not have any associated pulsar
  - the second (LHAASO J2032+4102) has a pulsar not powerful enough to produce the observed gamma-ray emission

Conclusions

- Quest for hadronic PeVatrons continues
    - The discovery of a population of UHE gamma-ray sources was indicative of Cosmic Ray acceleration up to PeV energies.
    - but according to our work, this acceleration may be accounted for by leptons accelerated by nearby pulsars and inverse Compton scattering CMB.

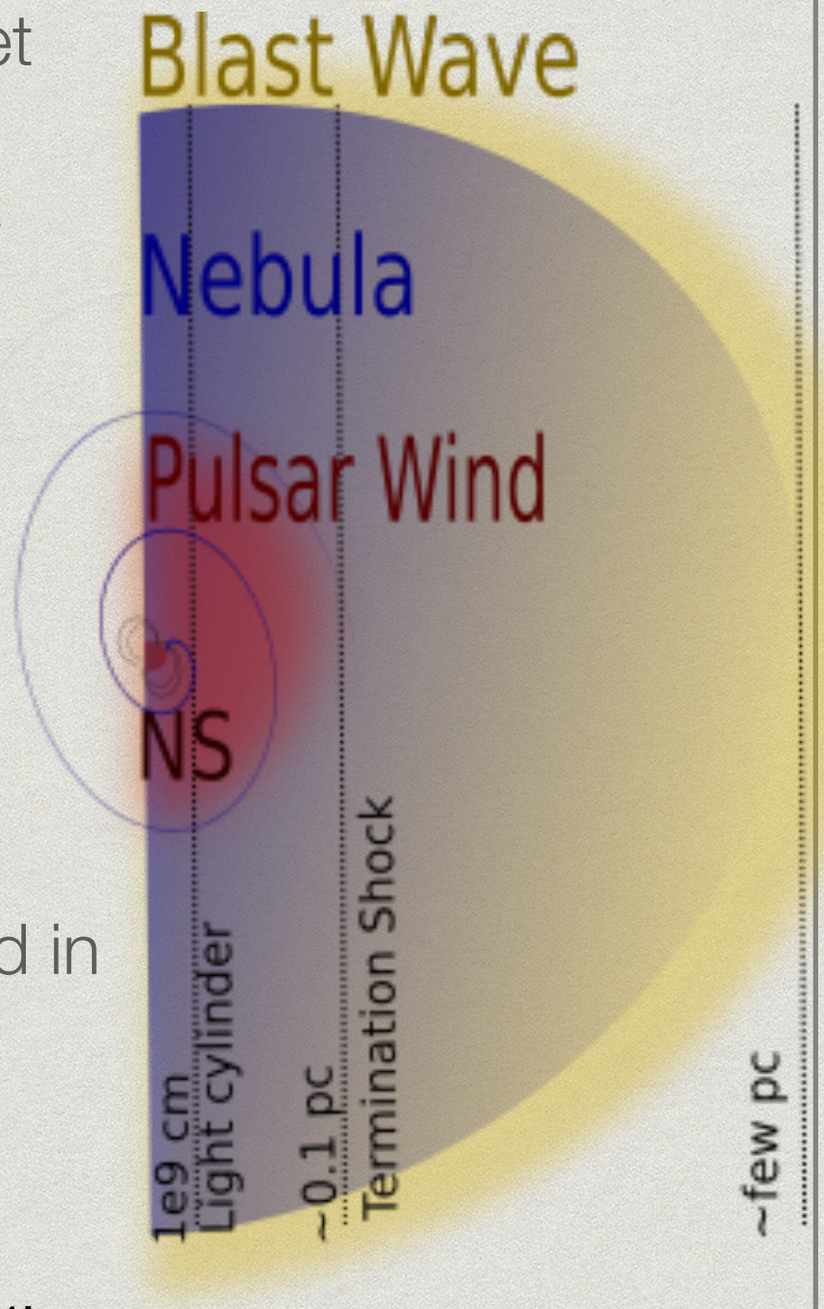
- We found an universal relation between the maximum gamma-ray energy that can be achieved by a pulsar and its spin-down power.
    - model-independent, may help in the future whenever more of UHE sources are discovered. [*ApJL* **930** L2 2022]

- Keep searching for your hadronic PeVatrons!
    - The hunt for PeVatrons as the origin of the most energetic photons observed in the Galaxy, Nature Astronomy **8**, 425–431 (2024)

Backup

Leptonic PeVatrons

- It is very-well known that electrons and positrons get accelerated in pulsars and their environments
    - Also likely other sources, but these are the primary ones for which we have proof
- The only known PeVatron since many years is the Crab Nebula
    - Can also other sources accelerate particles up to PeV energies?
- Acceleration to the highest energies is not produced in the pulsar magnetosphere
    - but at the wind termination shock



Associated pulsars

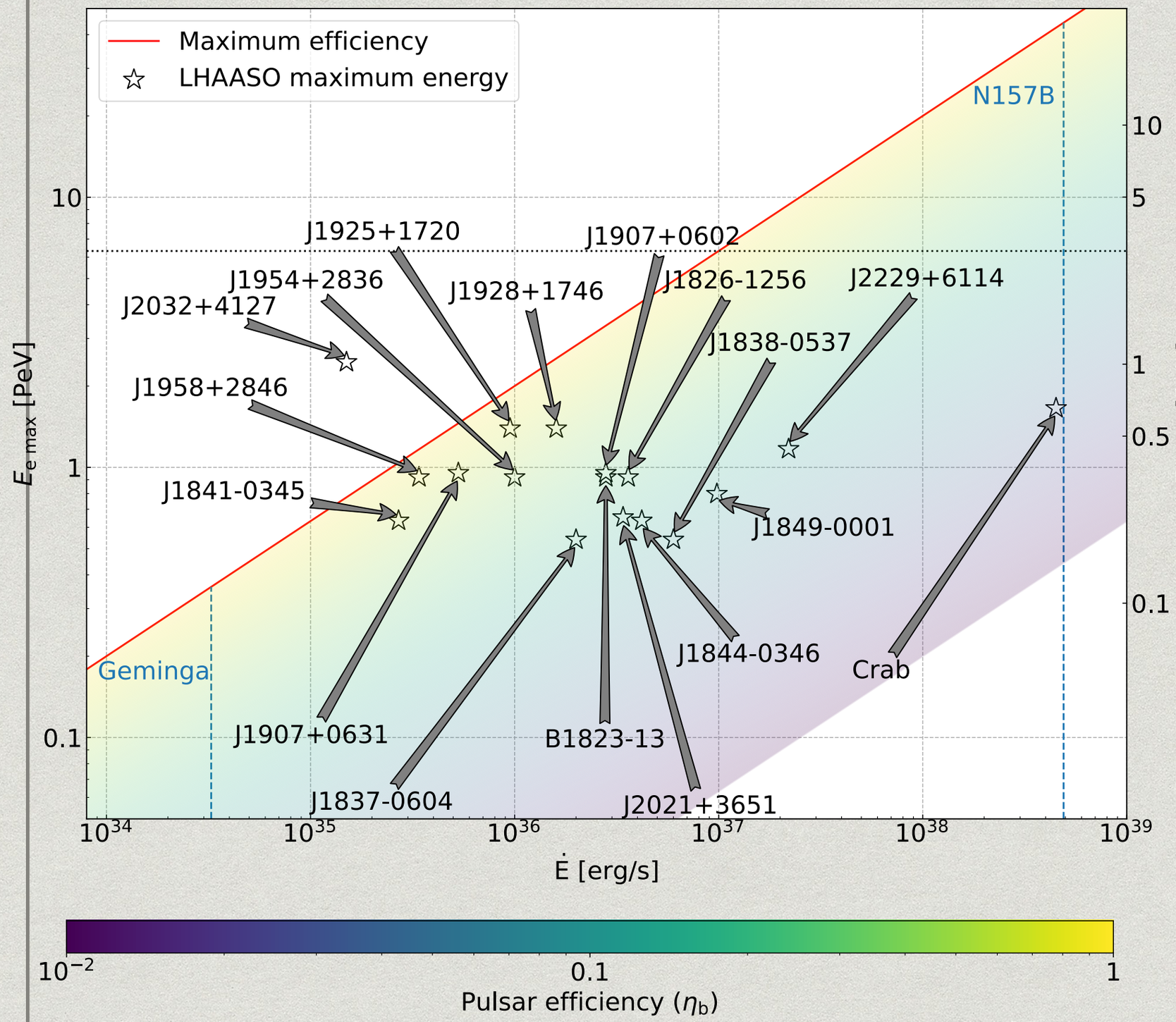
Table 1
LHAASO Ultrahigh-energy Sources, Together with the Bright, Young Pulsars Located within 1° of the LHAASO Source and Their Characteristics

LHAASO Source	Pulsar	Separation (deg)	$\dot{E}$ $\times 10^{36}$ (erg s^{-1})	Age (kyr)	Distance (kpc)	Flux $_{100TeV}$ (c.u.)	$E_{\gamma\ LHAASO}$ (PeV)	$E_{e\ LHAASO}$ (PeV)
J1825-1326	J1826-1256	0.51	3.6	14.4	1.55	3.57	0.42	1.06
	B1823-13	0.16	2.8	21.4	3.61	3.57	0.42	1.06
J1839-0545	J1837-0604	0.61	2.0	33.8	4.77	0.70	0.21	0.63
	J1838-0537	0.25	6.0	4.9	...	0.70	0.21	0.63
J1843-0338	J1841-0345	0.37	0.3	55.9	3.78	0.73	0.26	0.74
	J1844-0346	0.41			...	0.73	0.26	0.74
J1849-0003	J1849-0001	0.10			...	0.74	0.35	0.92
J1908+0621	J1907+0602	0.32	2.8	19.5	2.37	1.36	0.44	1.10
	J1907+0631	0.33	0.5	11.3	3.40	1.36	0.44	1.10
J1929+1745	J1925+1720	0.94	0.9	115.0	5.06	0.38	0.71	1.60
	J1928+1746	0.07	1.6	82.6	4.34	0.38	0.71	1.60
J1956+2845	J1954+2836	0.44	1.0	69.4	1.96	0.41	0.42	1.06
	J1958+2846	0.54	0.3	21.7	1.95	0.41	0.42	1.06
J2018+3651	J2021+3651	0.42	3.4	17.2	1.80	0.50	0.27	0.75
J2032+4102	J2032+4127	0.41	0.1	201.0	1.33	0.54	1.42	2.79
J2108+5157								
J2226+6057	J2229+6114	0.38	22.0	10.5	3.00	1.05	0.57	1.35

$$E_e \simeq 2.15 E_{\gamma,15}^{0.77}\ \text{PeV}$$

Note. The two rightmost columns display the maximum energy quoted by Cao et al. (2021) and its corresponding energy in electrons, using the formulation in Khangulyan et al. (2014).

Electron vs gamma energy



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