SUGAR MADISON 2024

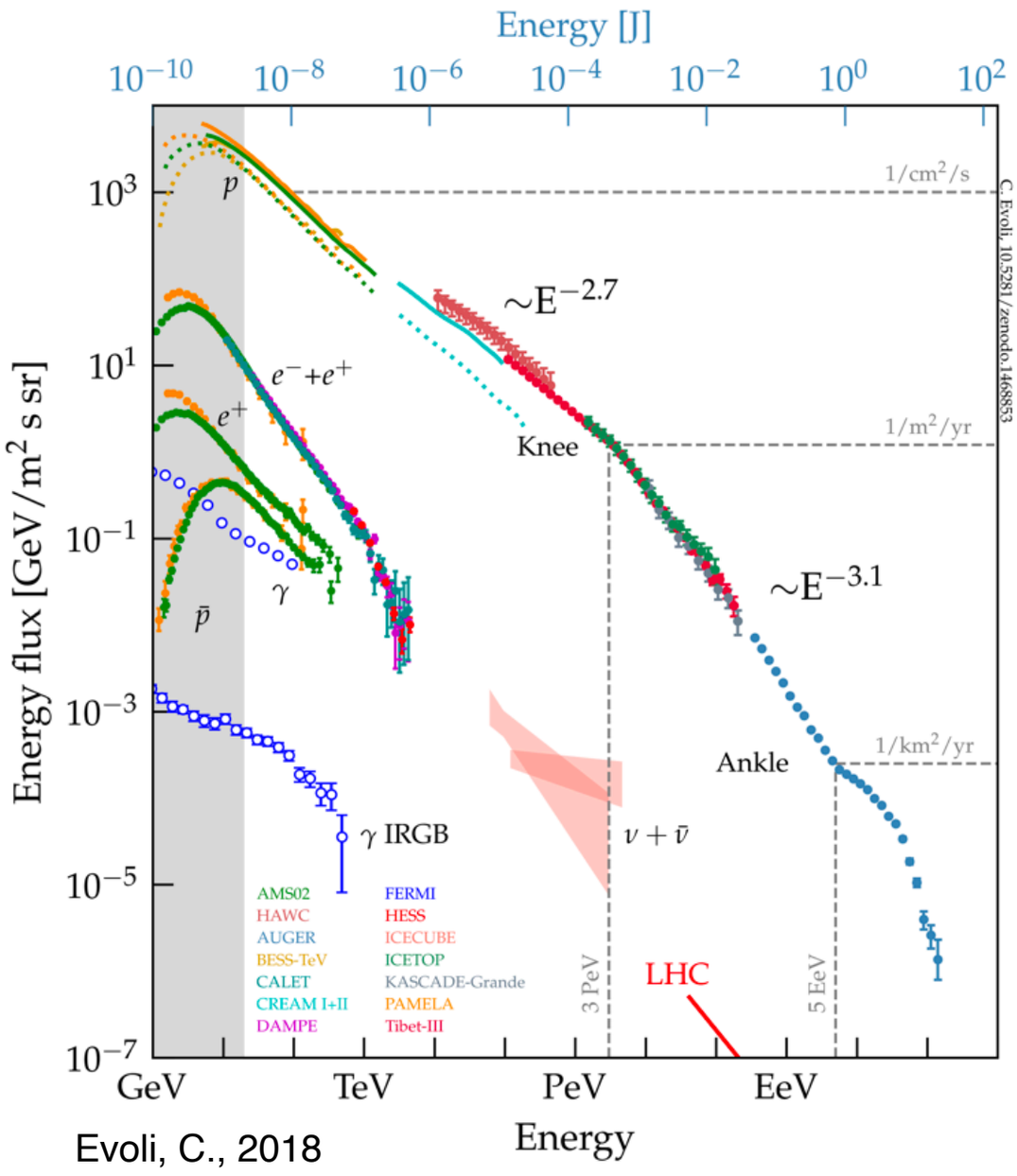
SEARCHING FOR THE SOURCES OF GALACTIC COSMIC RAYS

Galactic gamma-ray PeVatron observations and non-thermal processes in galactic sources

Rubén López-Coto
Instituto de Astrofísica de Andalucía, Granada, Spain
SUGAR 2024, 16/10/24

INSTITUTO DE ASTROFÍSICA DE ANDALUCÍA
EXCELENCIA SEVERO OCHOA
CSIC

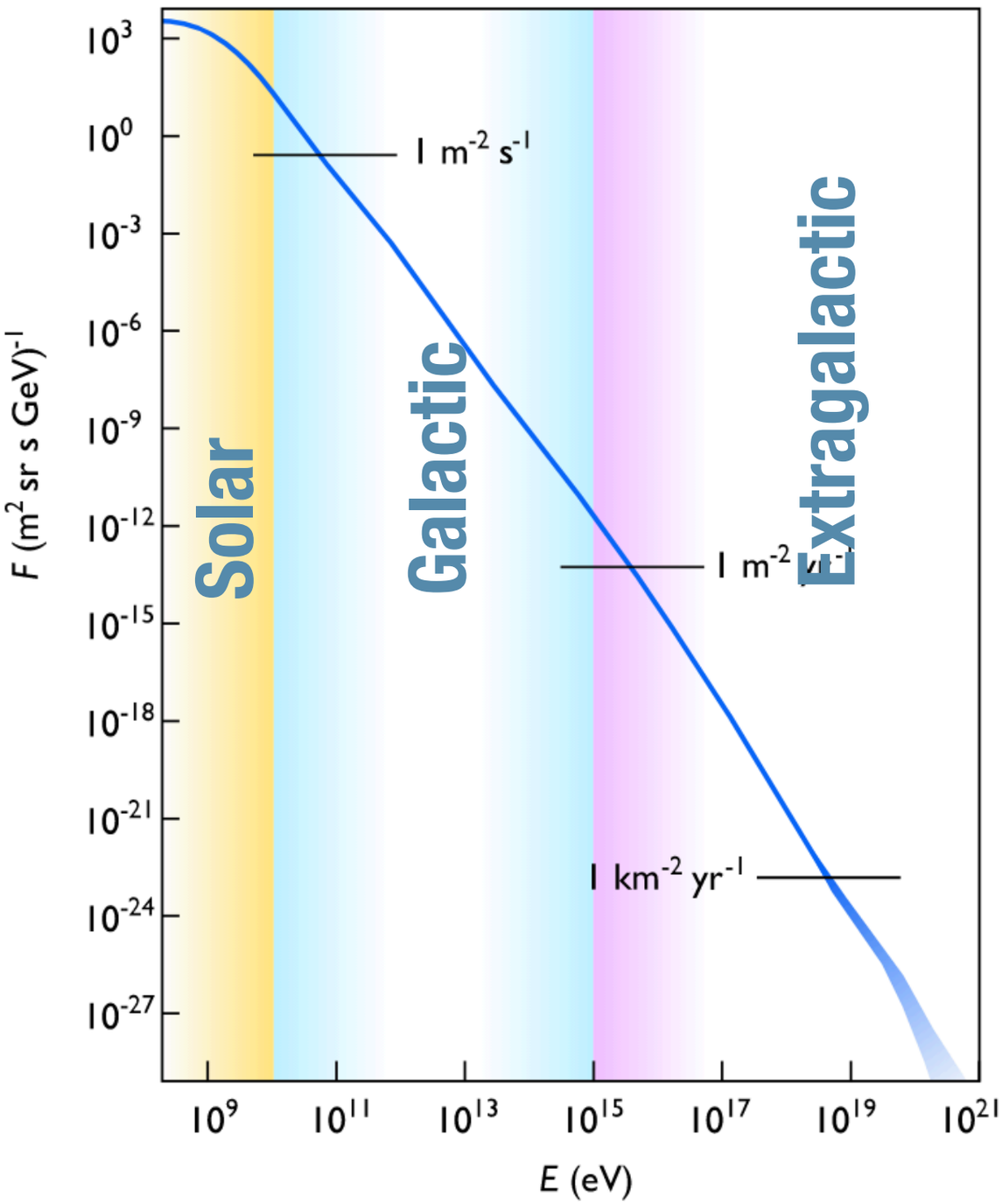
Cosmic rays: Spectrum and composition



Evoli, C., 2018

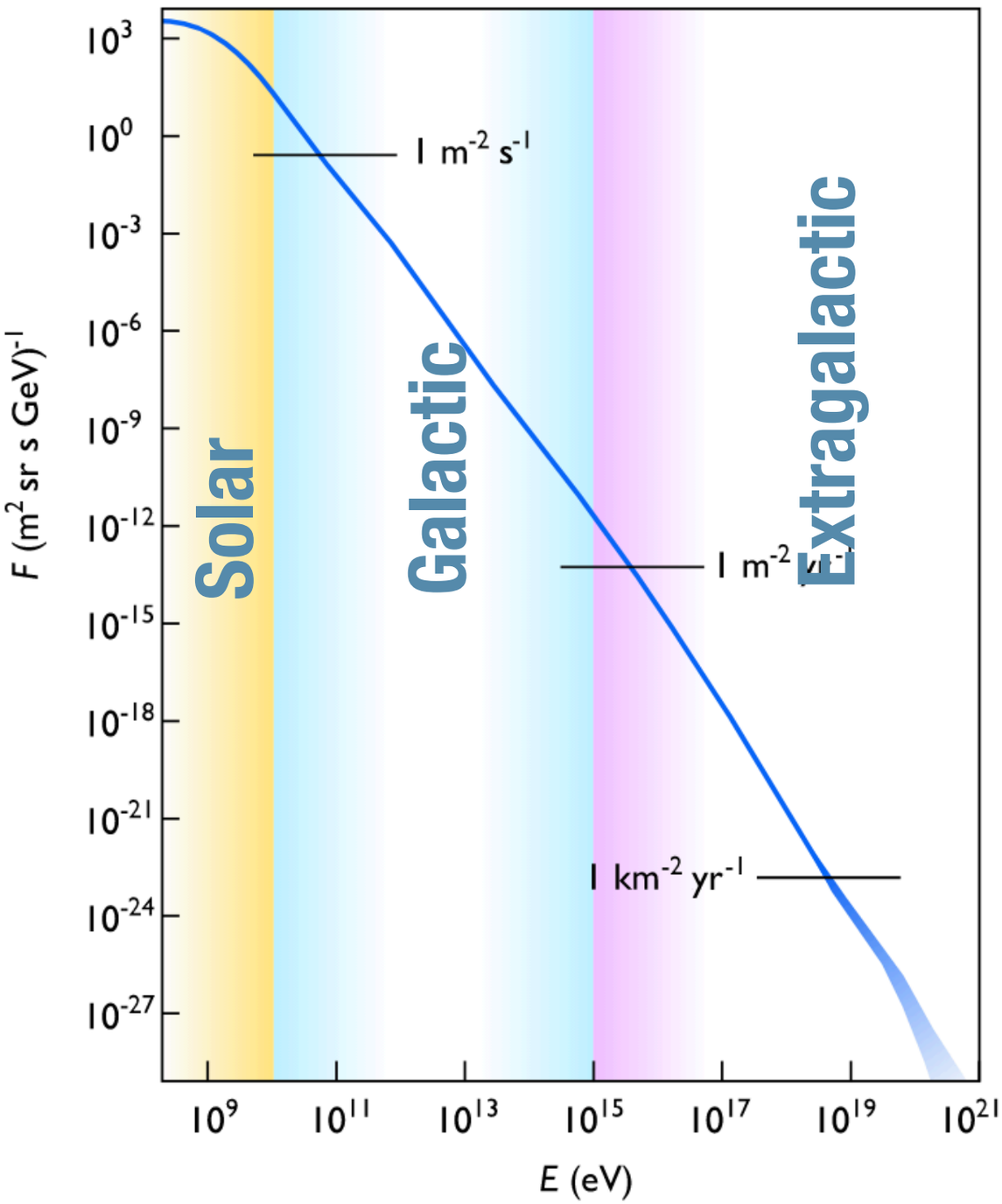
- Spectrum and composition measured by satellites, balloons and extended air shower arrays.
- Composition:
  - 90% Protons
  - 9% Helium nuclei
  - 1% Heavier nuclei, electrons, positrons, antiprotons, ...

Cosmic rays: Origin



- Spectrum and composition measured by satellites, balloons and extended air shower arrays.
- Composition:
  - 90% Protons
  - 9% Helium nuclei
  - 1% Heavier nuclei, electrons, positrons, antiprotons, ...
- Different origin:
  - Solar (E < 1 GeV)
  - Galactic (1 GeV < E < ~PeV)
  - Extragalactic (E > PeV)

Cosmic rays: Origin

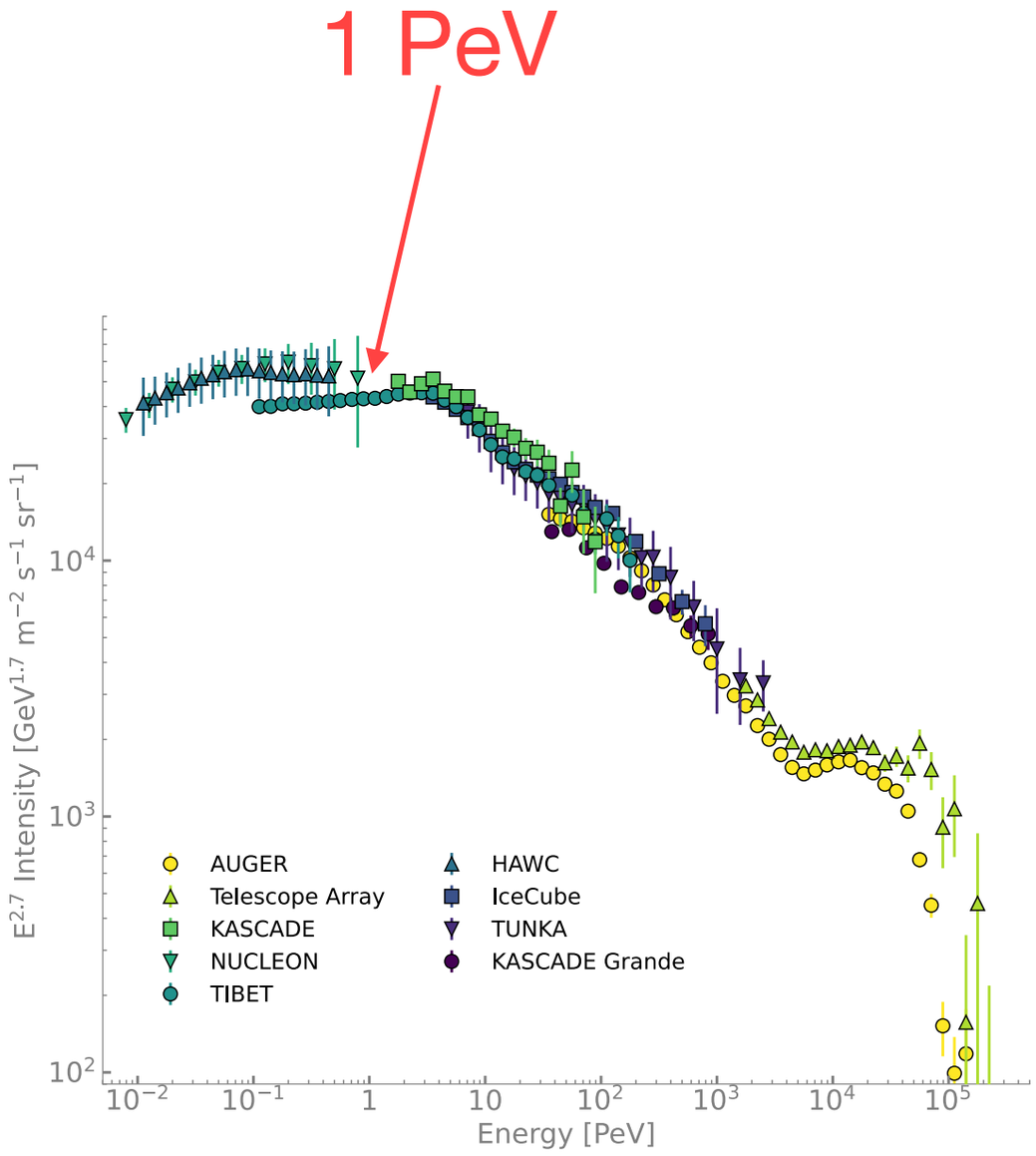


- Spectrum and composition measured by satellites, balloons and extended air shower arrays.
- Composition:
  - 90% Protons
  - 9% Helium nuclei
  - 1% Heavier nuclei, electrons, positrons, antiprotons, ...
- Different origin:
  - Solar ($E < 1$ GeV)
  - Galactic (1 GeV $< E <$ ~PeV)
  - Extragalactic ($E >$ PeV)

What is the origin of Galactic Cosmic Rays?

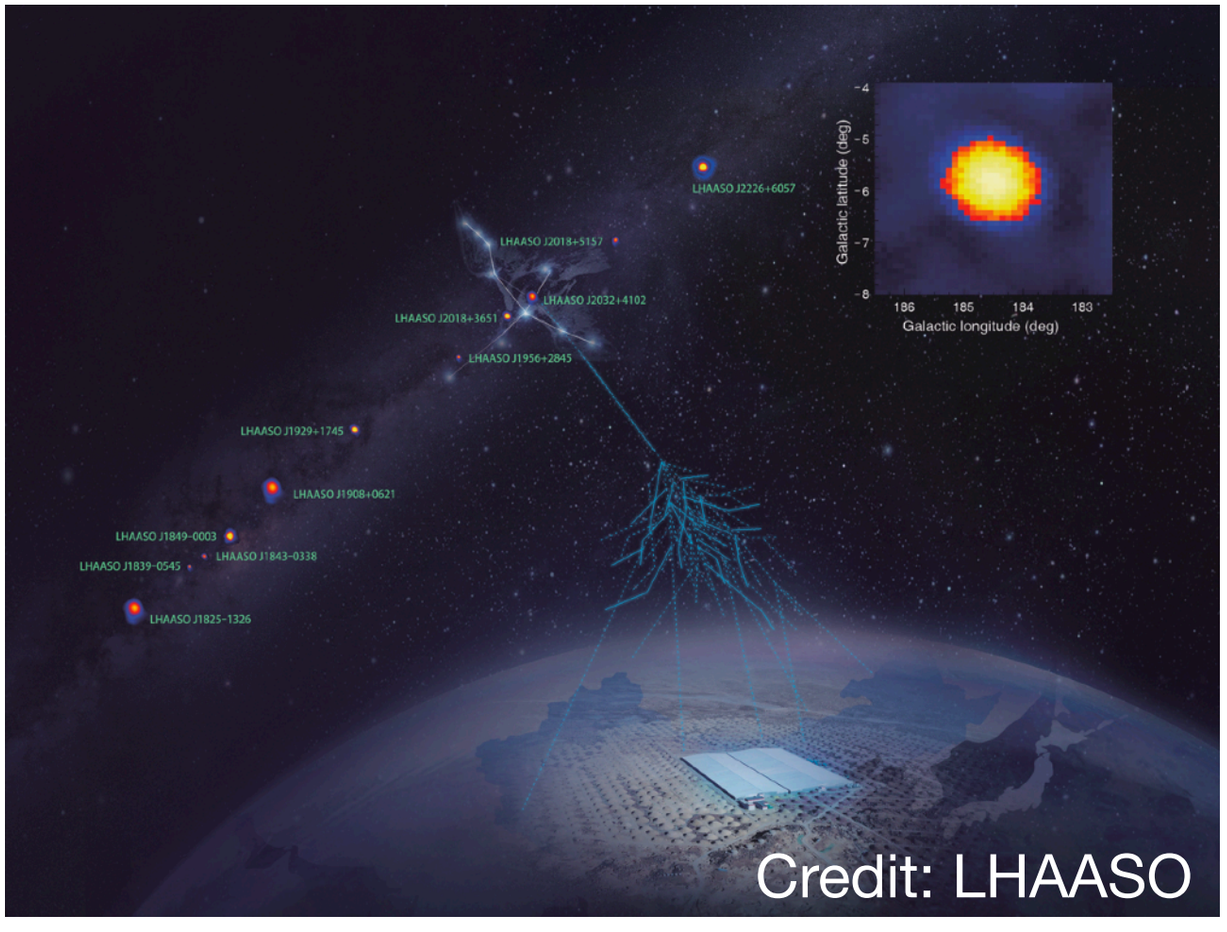
PeVatrons

- 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.
- Composition at the knee also unknown
  - Maximum rigidity needed depends on composition.



PeVatrons: a hot topic nowadays

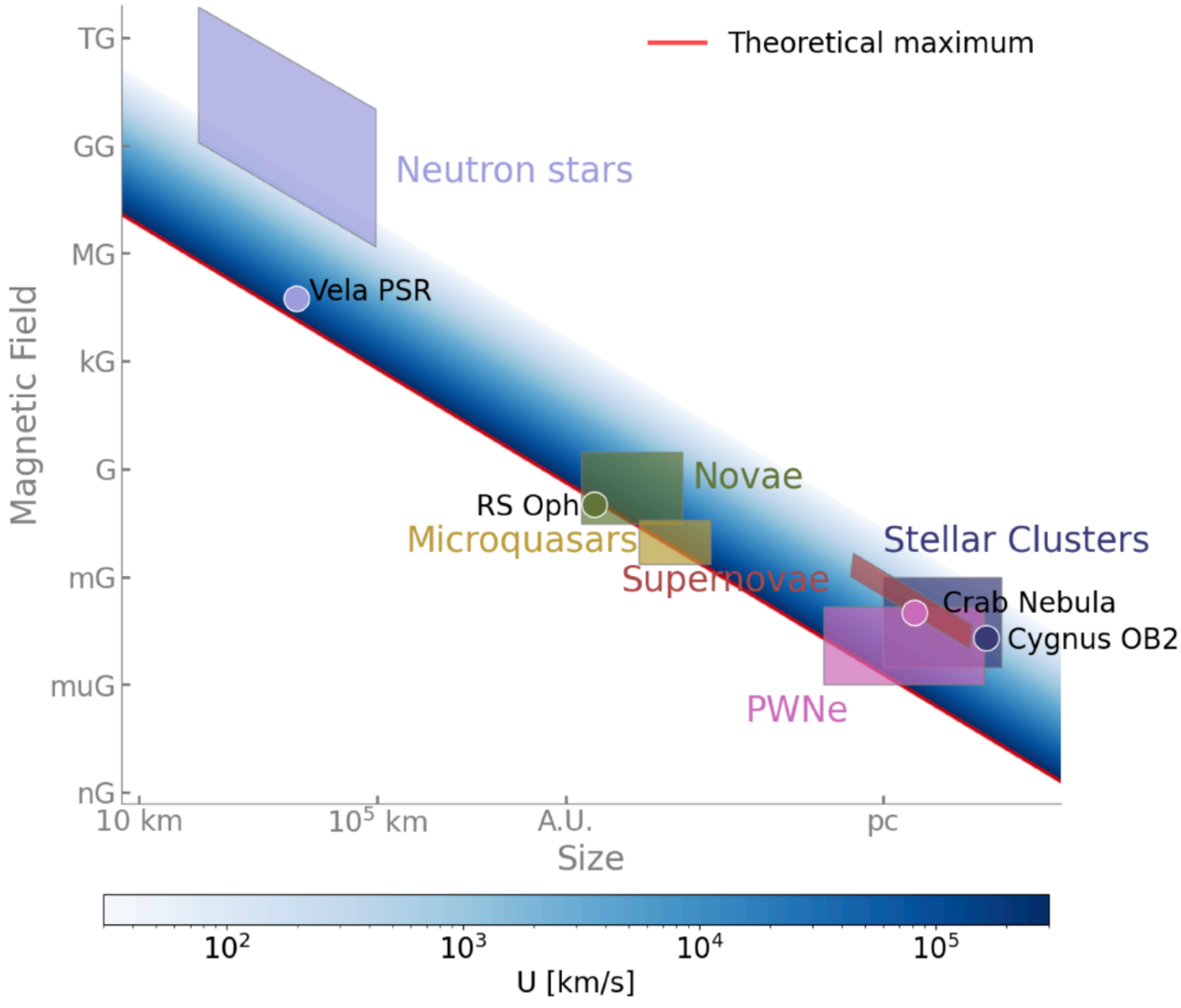
- Latest results from several experiments have increased the interest on the study of PeVatrons
  - SNRs struggle to reach the PeV goal.
  - Star forming regions observed by IACTs and wide FoV instruments.
  - Microquasars???
  - LHAASO results on sources emitting gamma rays up to PeV energies.
    - Are they protons or electrons?



Cosmic ray acceleration

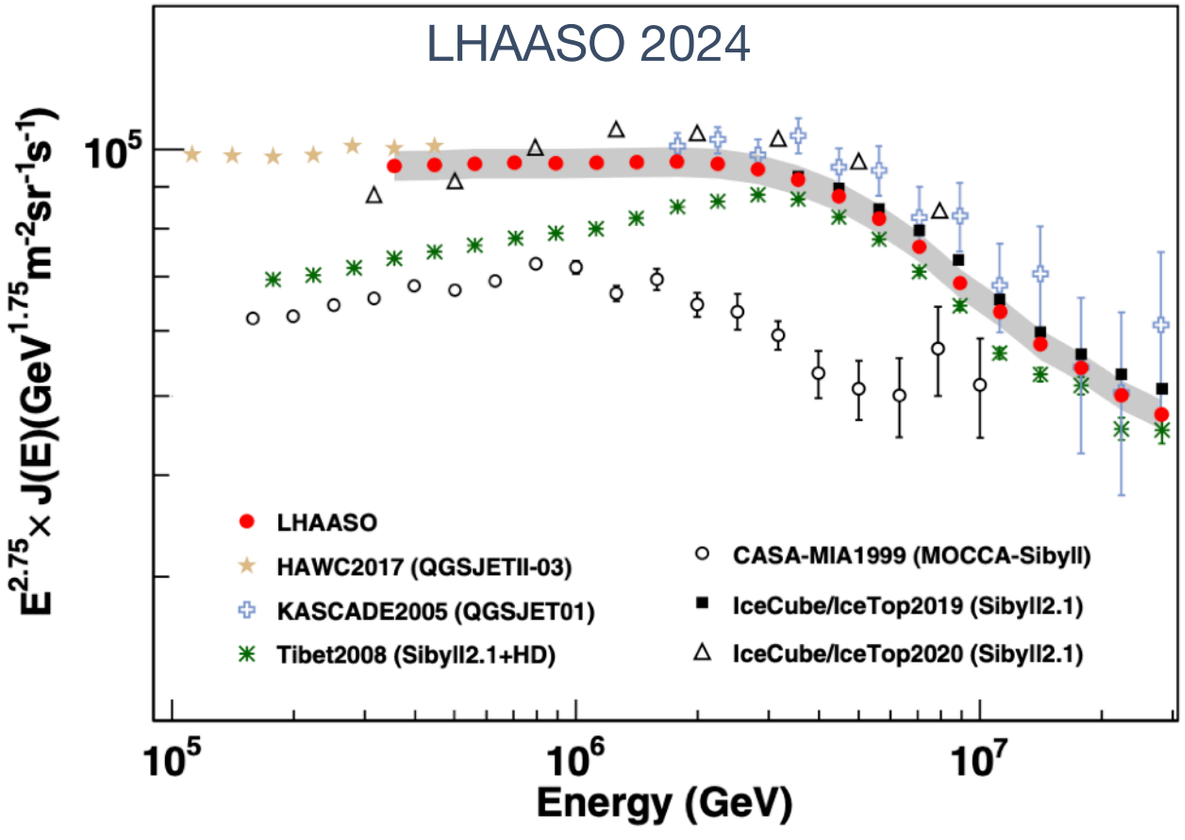
- Acceleration in each source type is limited by its **magnetic field** and **size**

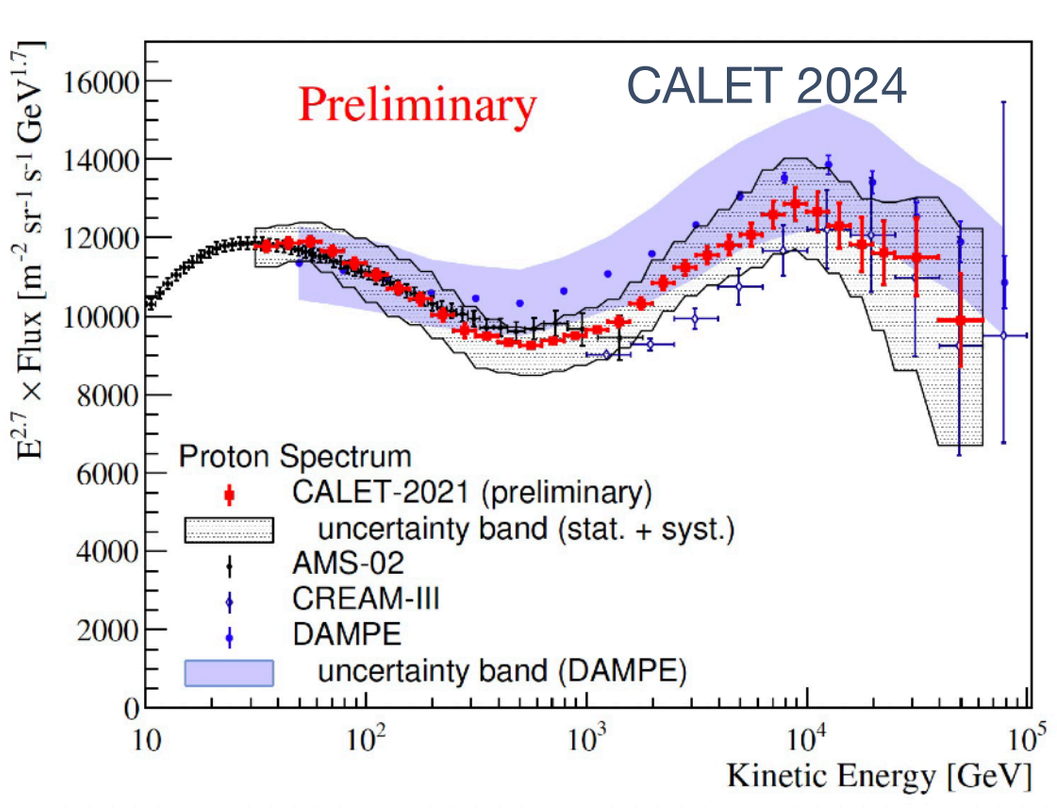
$$E_{max} \approx 1 \left(\frac{u}{10^3\ \mathrm{km/s}}\right) \left(\frac{R}{\mathrm{pc}}\right) \left(\frac{B}{\mu\mathrm{G}}\right) \mathrm{TeV}$$



PeVatrons: a hot topic nowadays

- Particle spectrum shows general trends, but the proton spectrum is subjected to statistics and systematic errors: this could broaden the range of possible PeVatrons.
- Latest results from CALET/DAMPE show that the region below 1 PeV is not as featureless as we thought

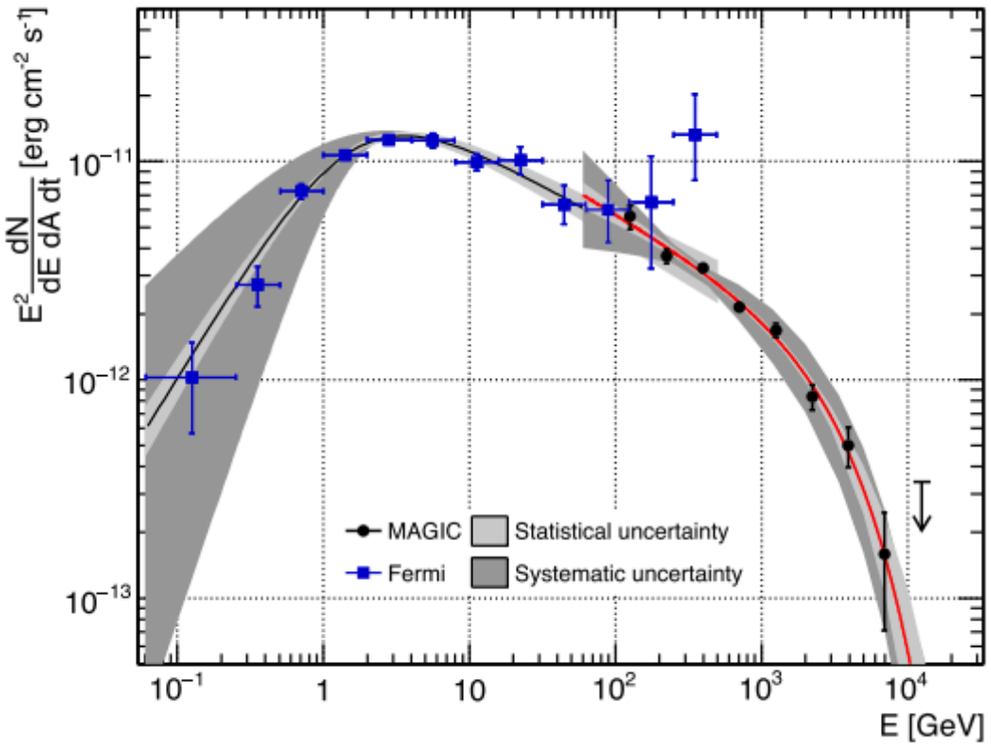




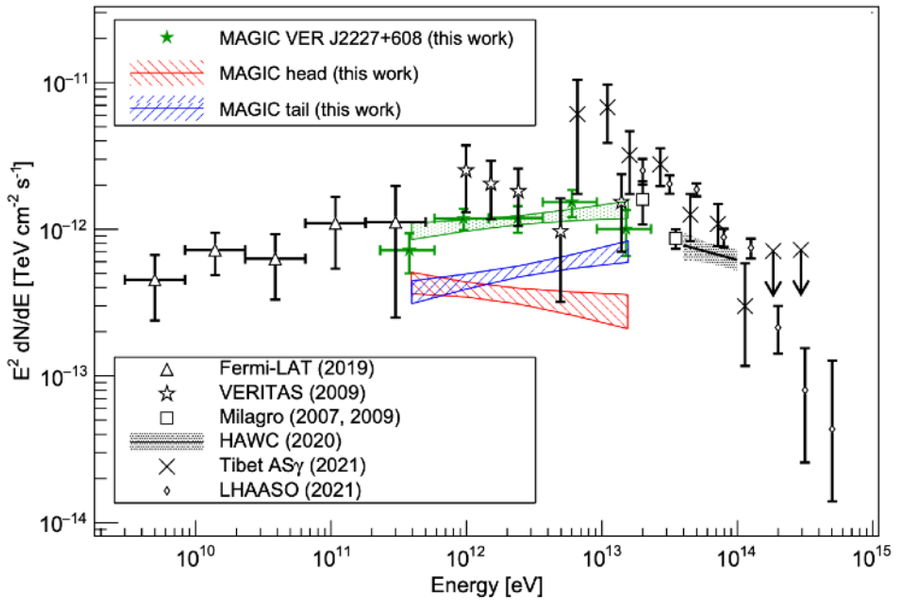
Main candidate: Supernova Remnants

- Most popular historical candidate to explain Galactic Cosmic Rays
  - Phenomenologically favored over the years.
- SNRs provide a huge **energy budget** and enough **number of sources** to explain:
  - The whole galactic hadronic CR flux
  - Anisotropy
- BUT
  - No firm evidence of proton acceleration beyond few hundred TeV.
  - From theory, only powerful and rare SNRs reach PeV energies.
- The Challenge: known SNRs do not seem to be PeVatrons at present

Cas A. MAGIC Collaboration, 2017

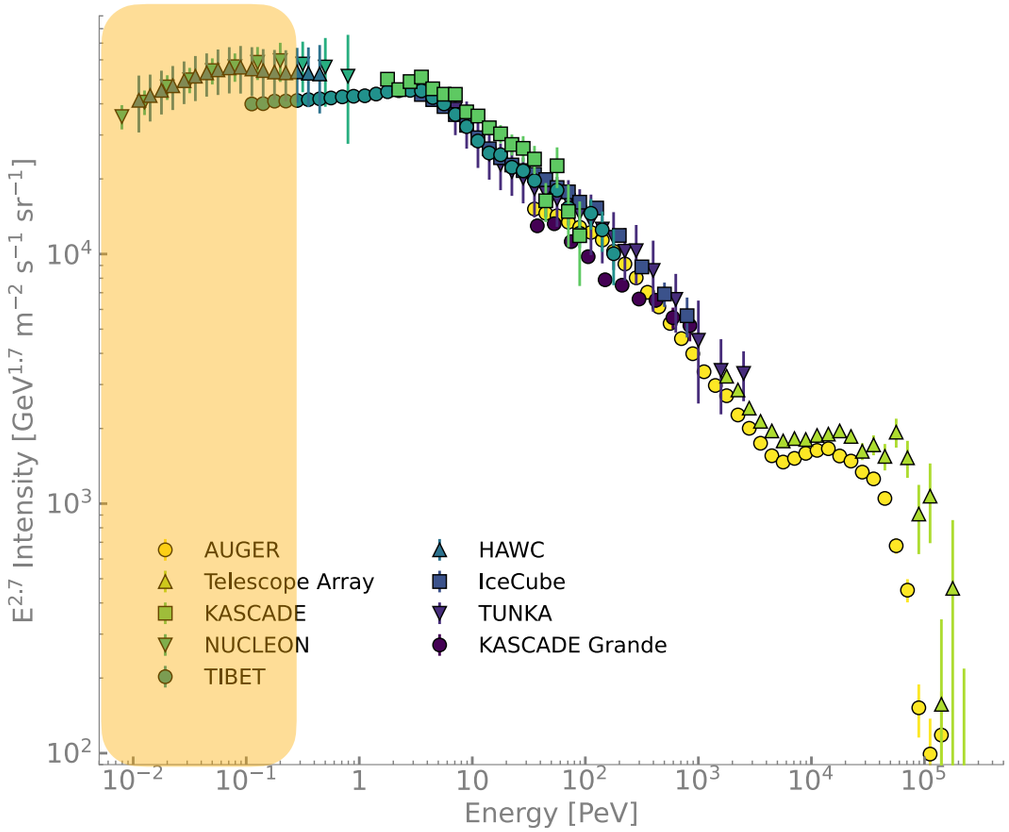


Boomerang, MAGIC Collaboration 2022



The origin of the Galactic Cosmic Rays

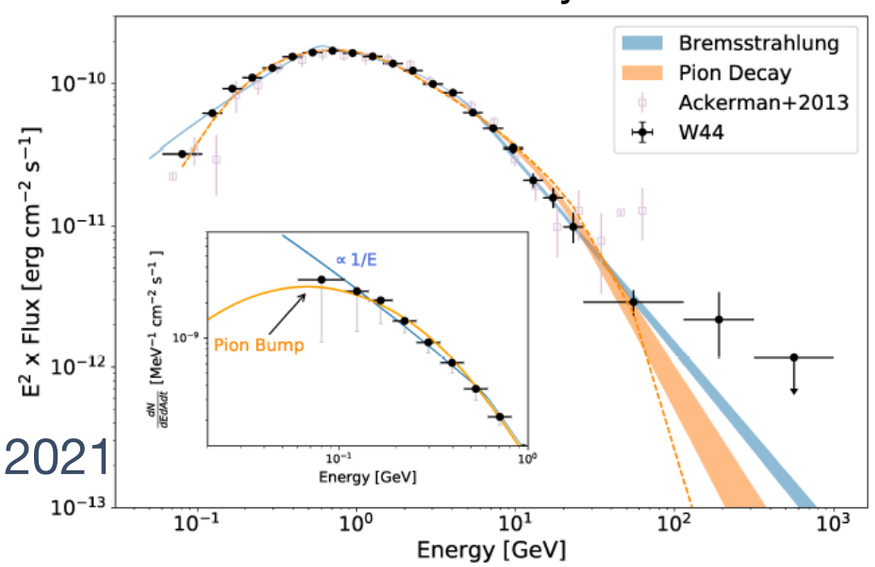
The Sub-PeV regime



- General agreement: most of the low energy particles comes from Supernova Remnants
  - Experimental evidences & theoretically comfortable

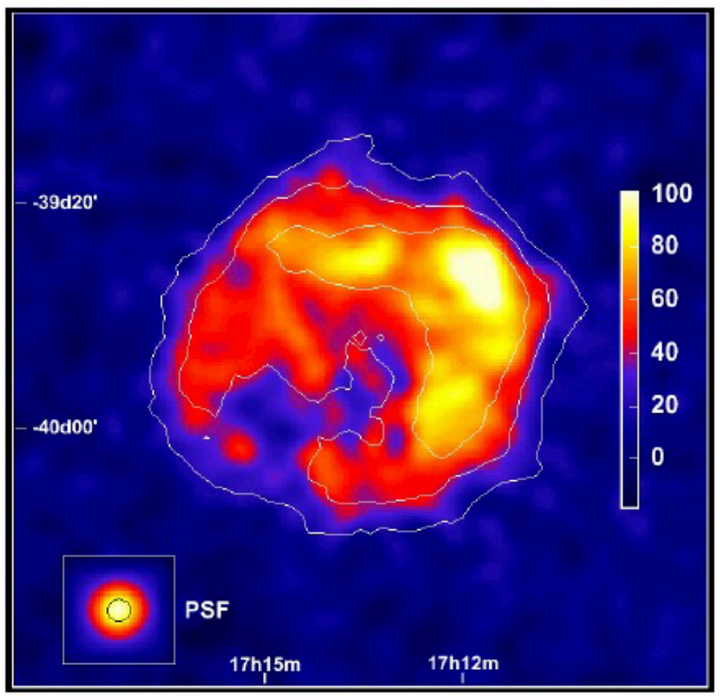
Experimental evidences:

Pion Decay



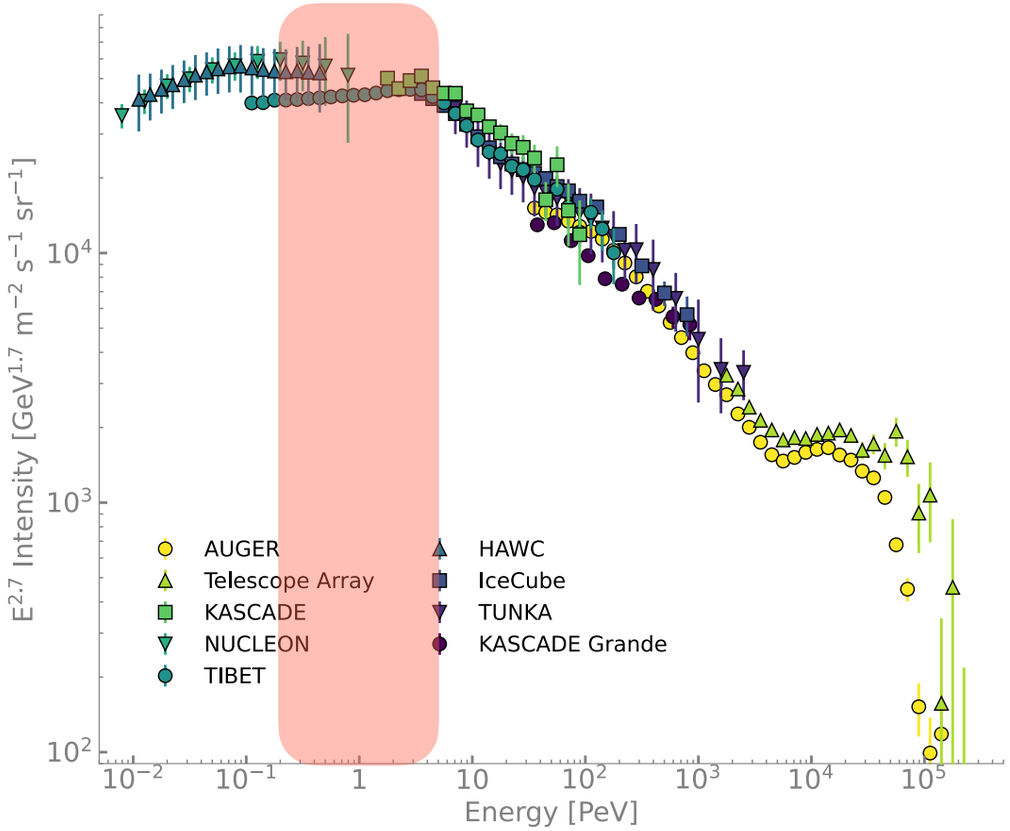
Peron et al. 2021

Morphology



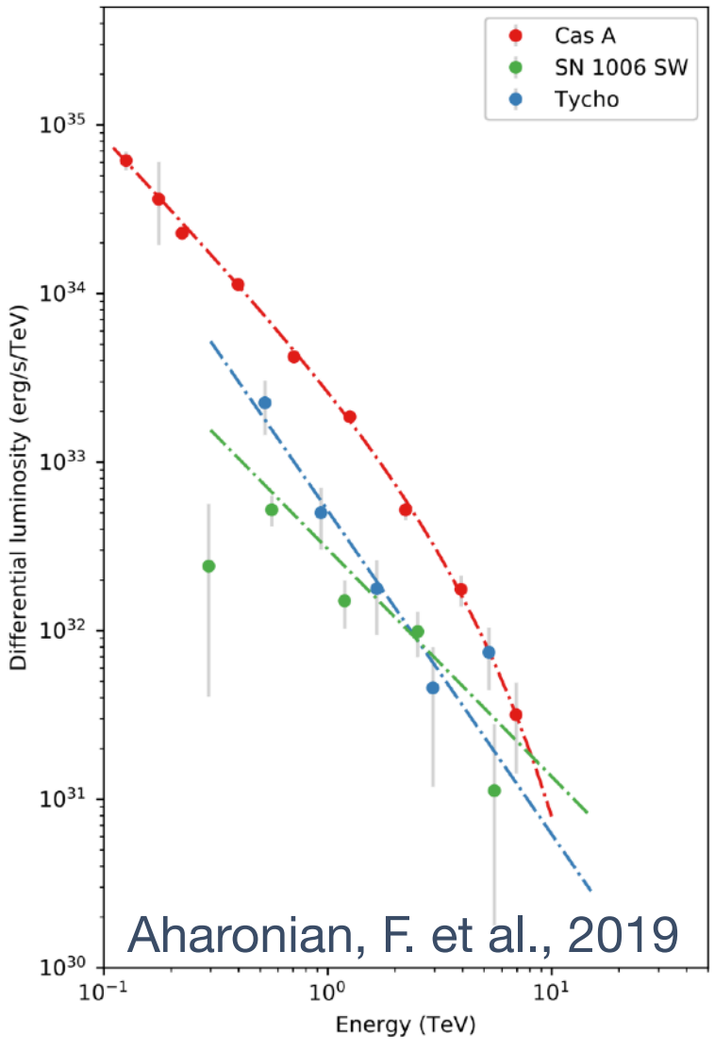
The origin of the Galactic Cosmic Rays

~hundreds of TeV to few PeV



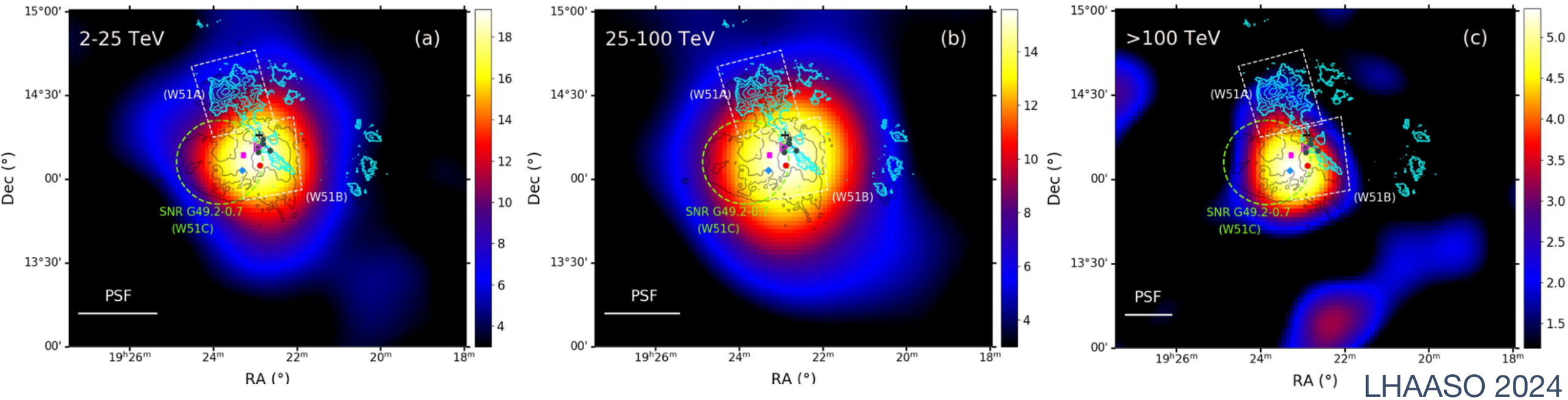
- The challenge to the standard paradigm: known young SNRs do not seem to reach PeV energies

Experimental evidences:



PeV acceleration? in Supernova Remnants

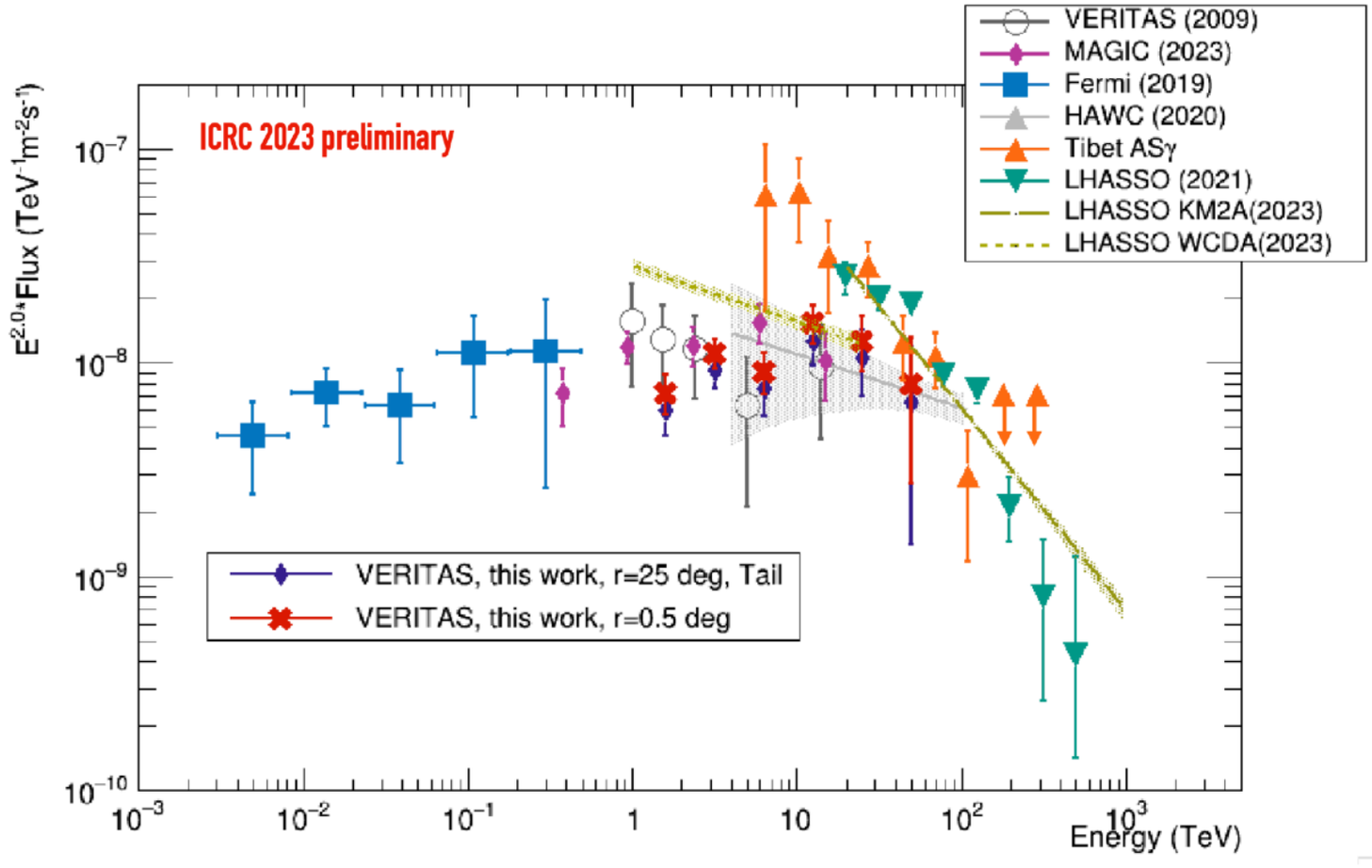
- **W51C** measured by MAGIC, HESS, HAWC, LHAASO… up to ~hundreds of TeV
  - still favoring hadronic models (with cut-off at 400 TeV) to explain the emission
  - approaching (but not reaching) the holy-grail PeV



LHAASO 2024

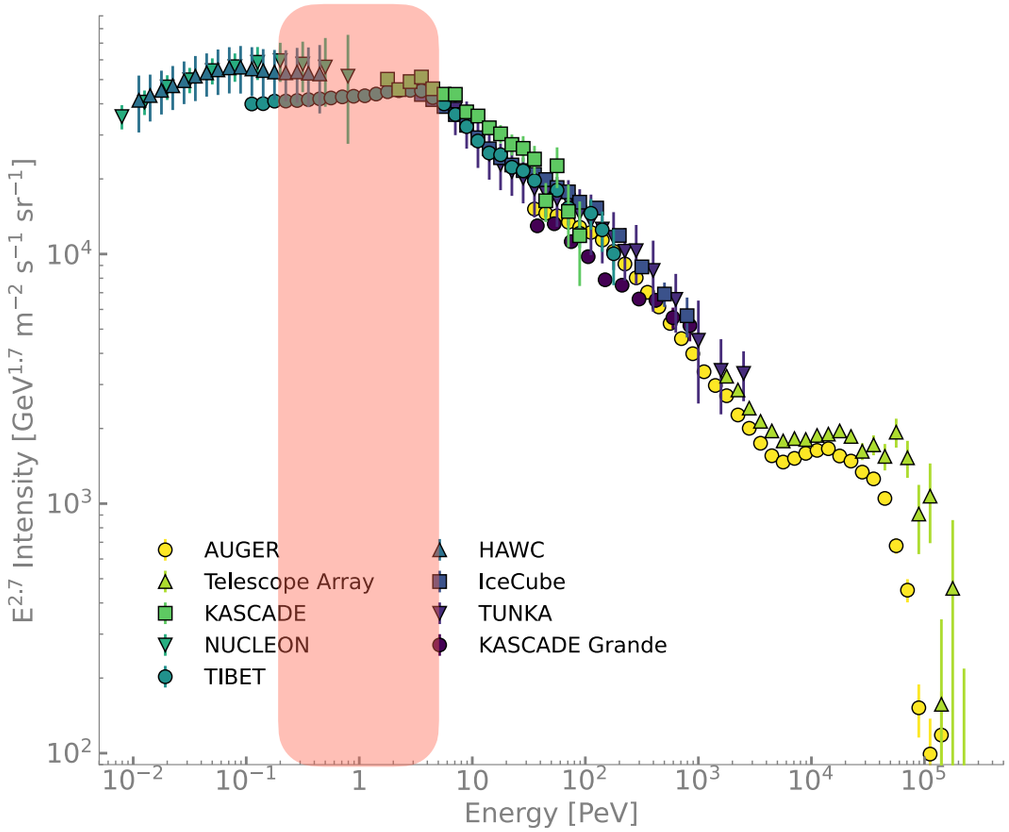
PeV acceleration? in Supernova Remnants

- **SNR G106.3+2.7** (Boomerang)
  - HAWC, VERITAS, MAGIC, LHAASO, Tibet AS-γ…
    - Spectrum measured up to ~500 TeV.
    - Origin unclear



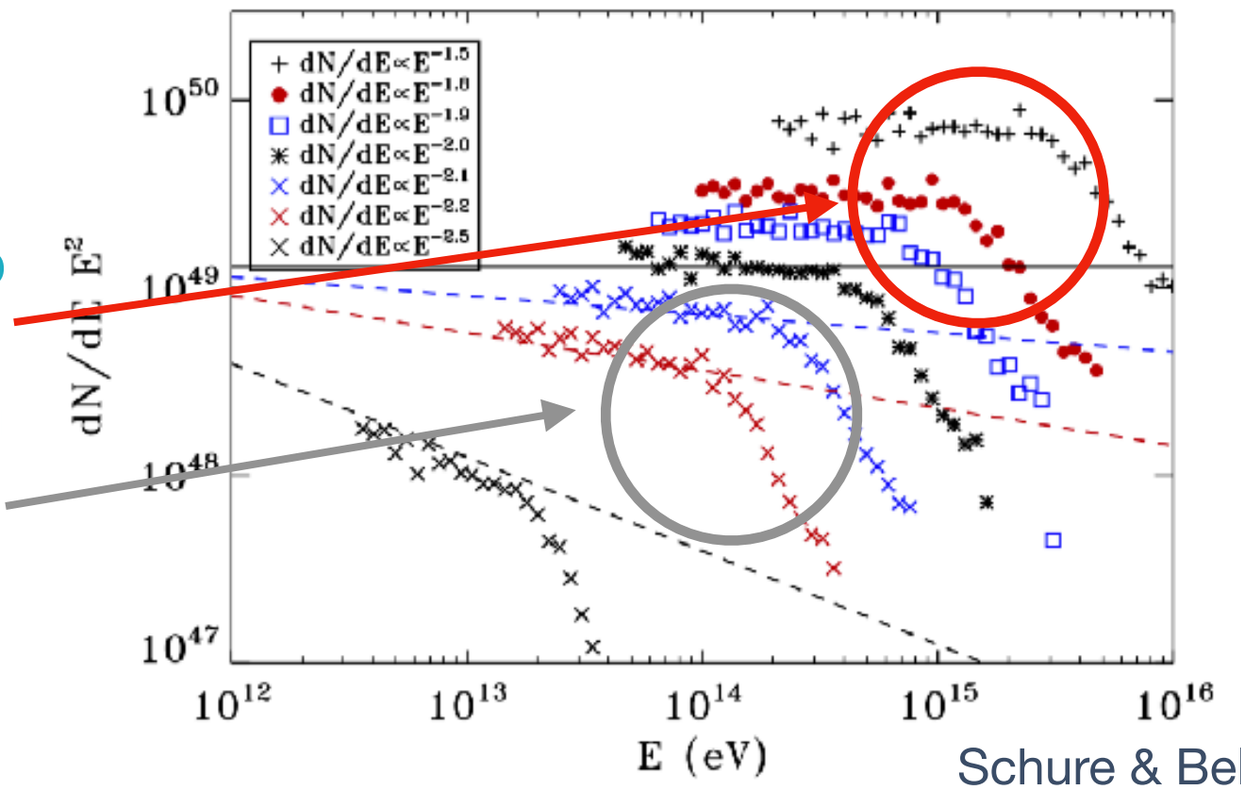
The origin of the Galactic Cosmic Rays

~hundreds of TeV to few PeV



- Theoretical estimations:
  - We need young SNRs in dense winds (type II)
  - We need escape of particles upstream to produce confining magnetic fields

- Knee at the right energy => too hard injection spectrum
- Softer -more natural- injection spectrum => high energies not reached



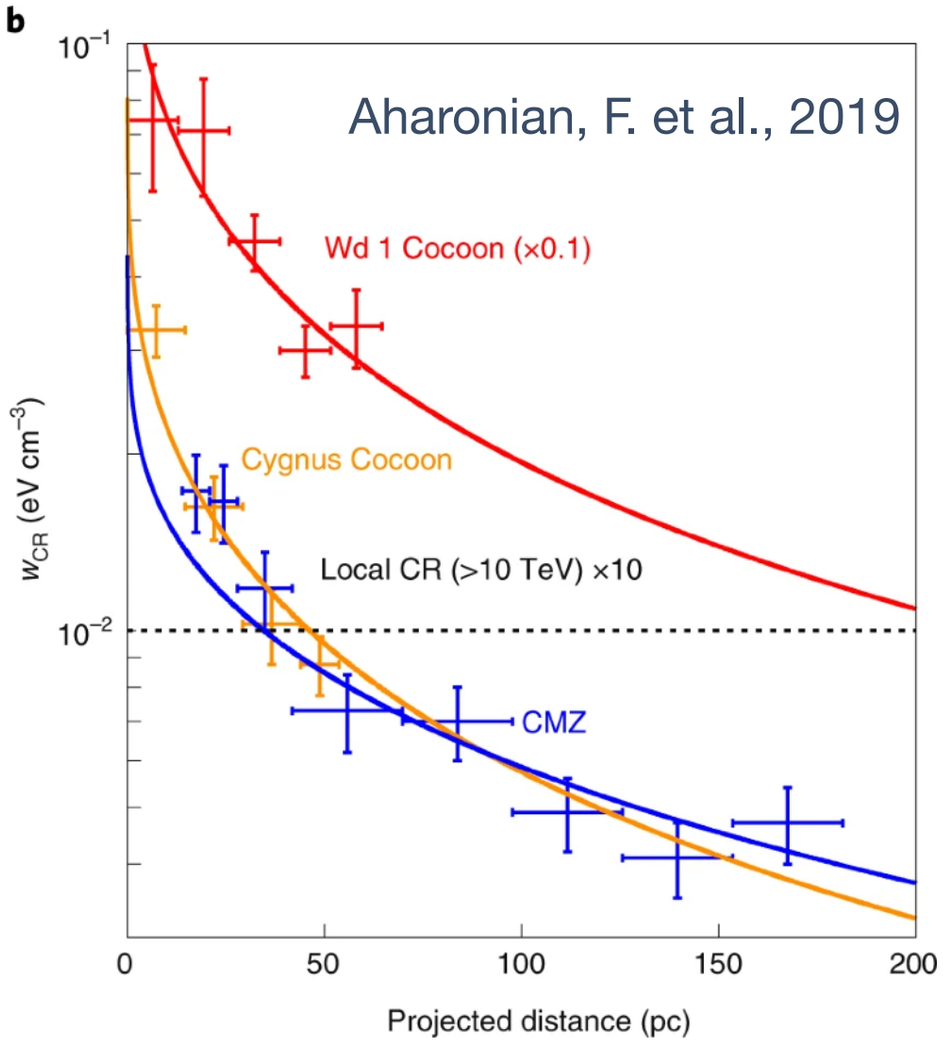
Schure & Bell 2014

The origin of the Galactic Cosmic Rays

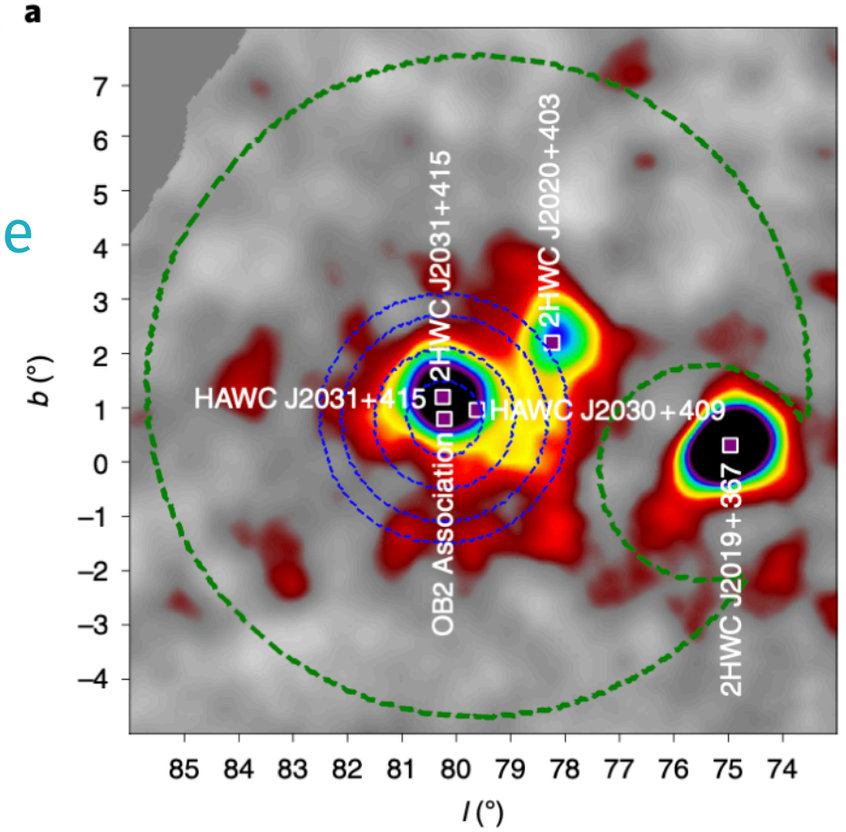
~hundreds of TeV to few PeV

- Possible ideas to solve the problem…
  - Early phase SNRs in the <100 yrs (highest density / fastest shock velocity) are the ones accelerating PeV CRs.
  - SNRs we don't know?
  - Some candidates may reach almost the PeV regime
    - W51C, Boomerang…
  - Two source population hypothesis: a source type that provides the bulk of CRs (SNRs) and another one that provides the highest energies?
    - Other accelerators: Stellar clusters / SNRs in Stellar clusters / Galactic Center / Microquasars / …

Alternatives



- Stellar Clusters as PeVatrons
  - They have gained interest in the last few years.
  - Results from different gamma-ray experiments seem to point to parent-population spectra extending up to > 100 TeV energies
  - Almost sure hadronic origin of this emission.
- Galactic Center? Fermi Bubbles?
  - We trace particle acceleration through diffuse emission
- Microquasars?
  - Very recent results show gamma-ray emission up to hundreds of TeV

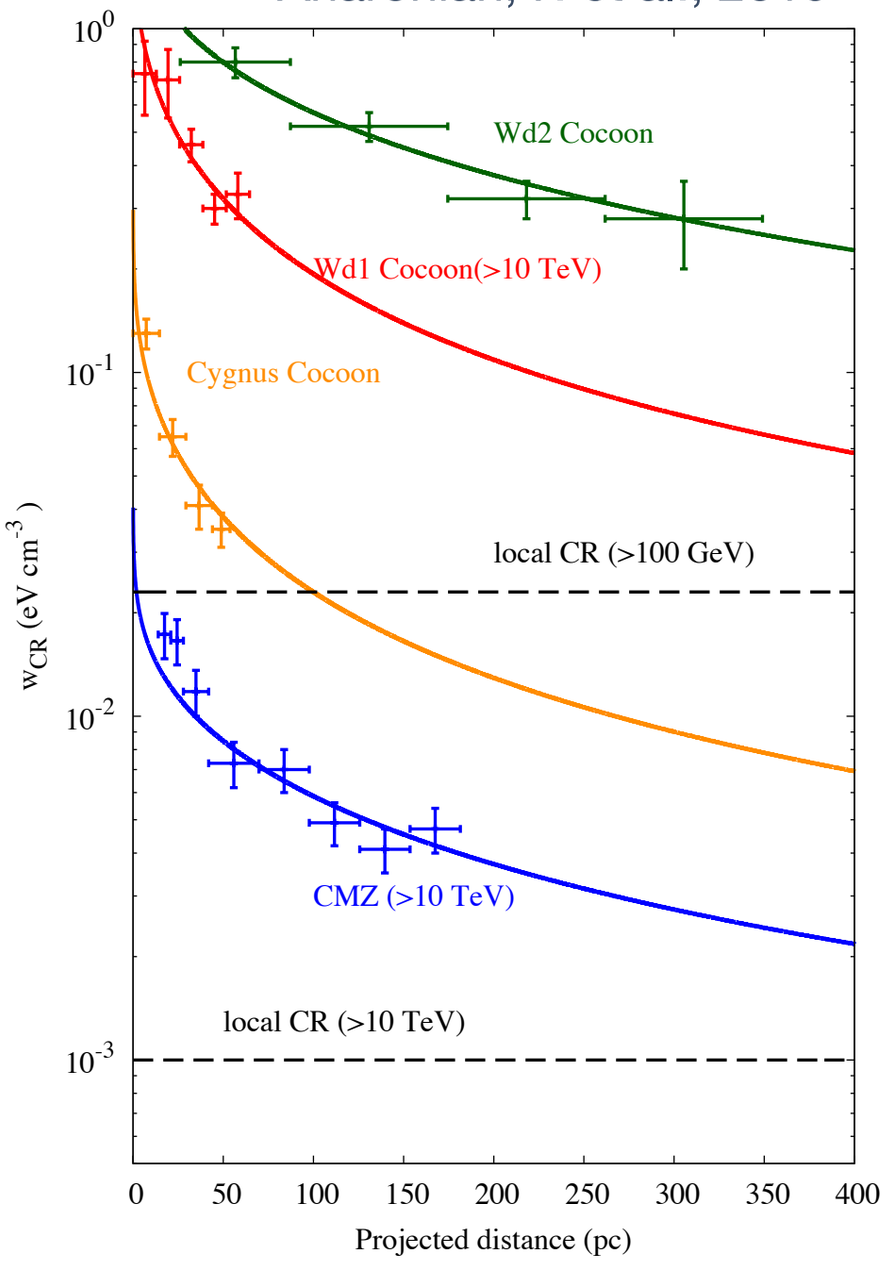


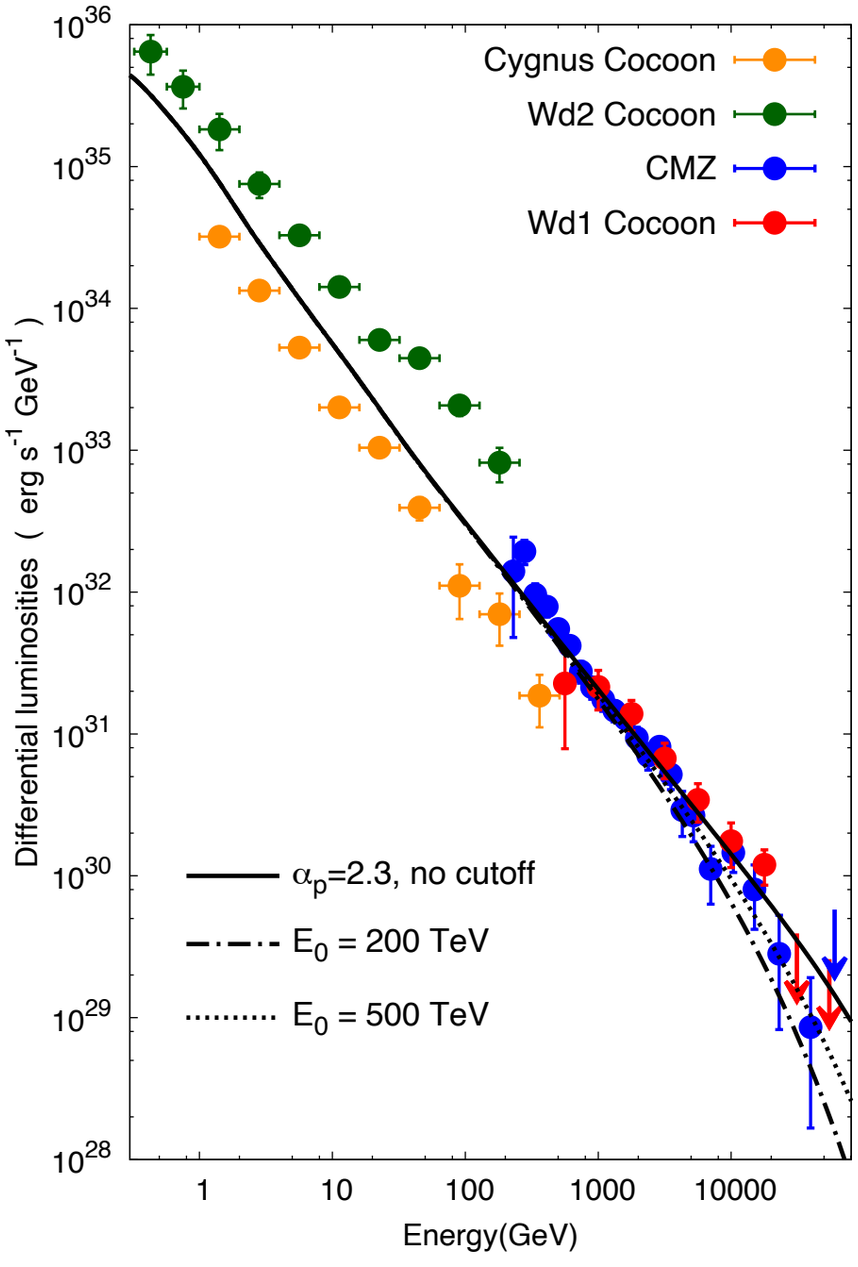
Cygnus Cocoon, HAWC, 2019

Stellar Clusters

- Exciting observations reviving stellar clusters as PeVatrons

Aharonian, F. et al., 2019



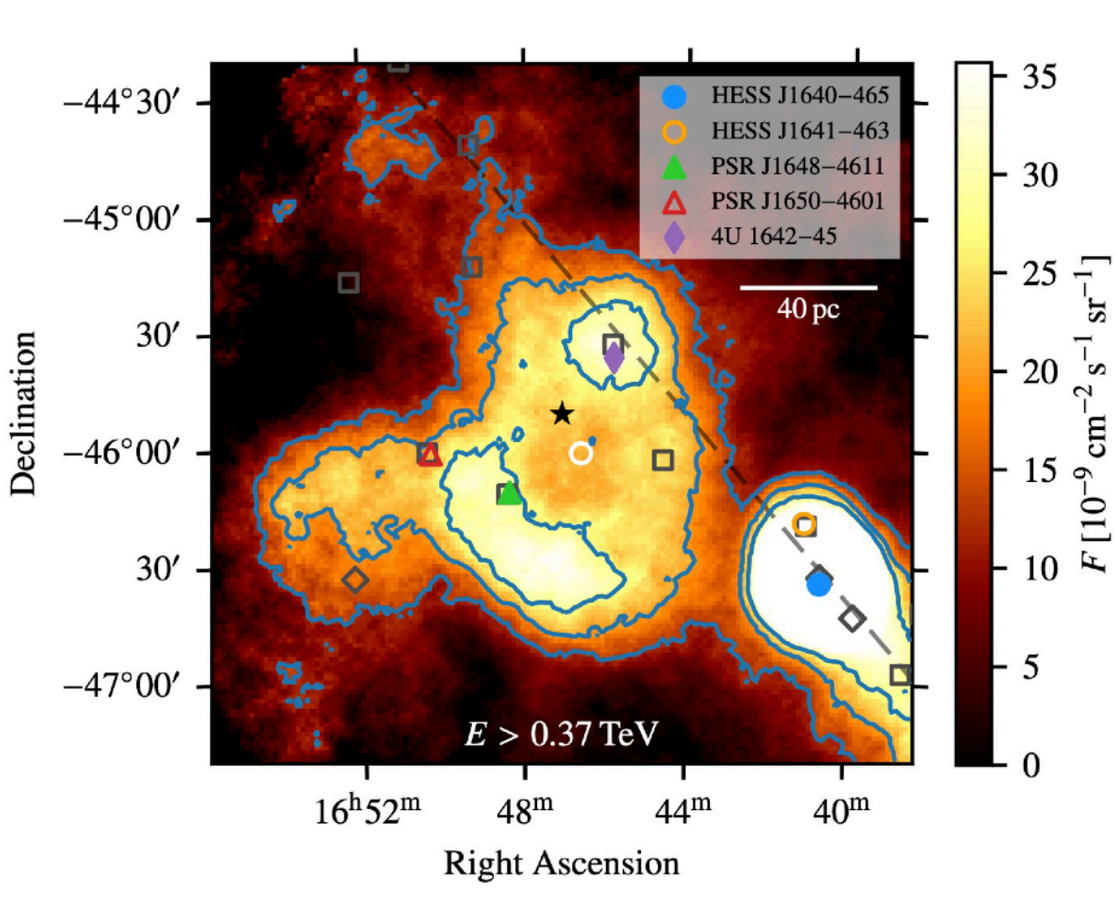


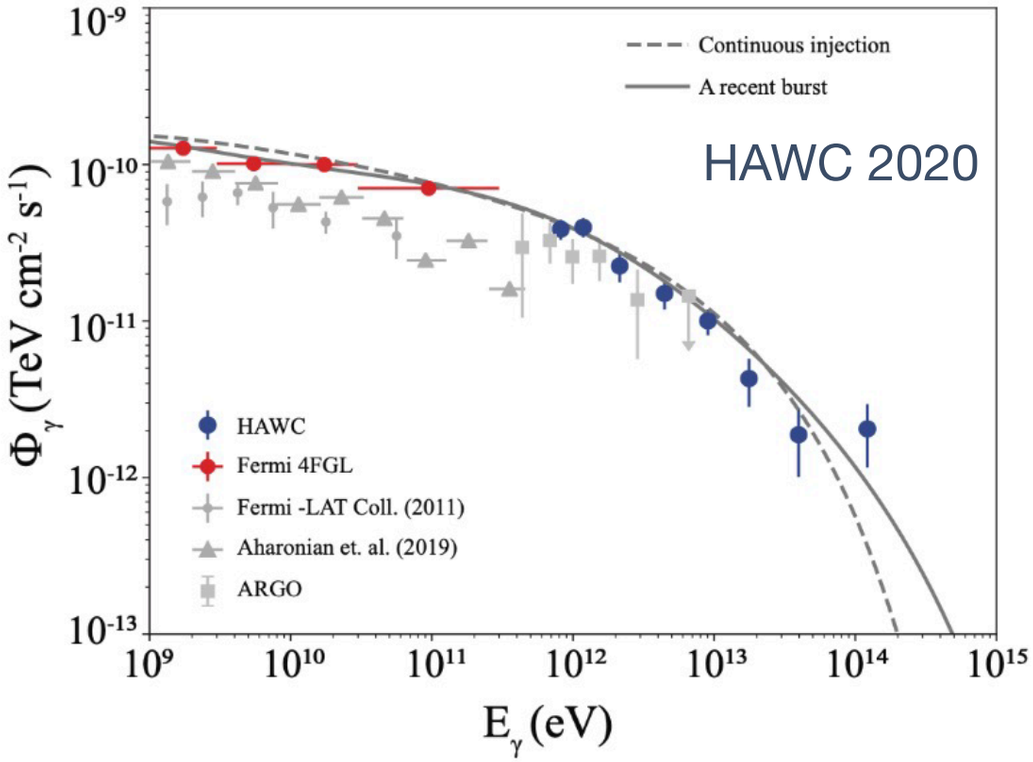
- 1/r morphology points towards a continuous particle injection by a central source

Stellar Clusters

Experimental evidences:

- Cygnus Cocoon accelerates particles up to ~hundreds of TeV (or even up to PeV!)

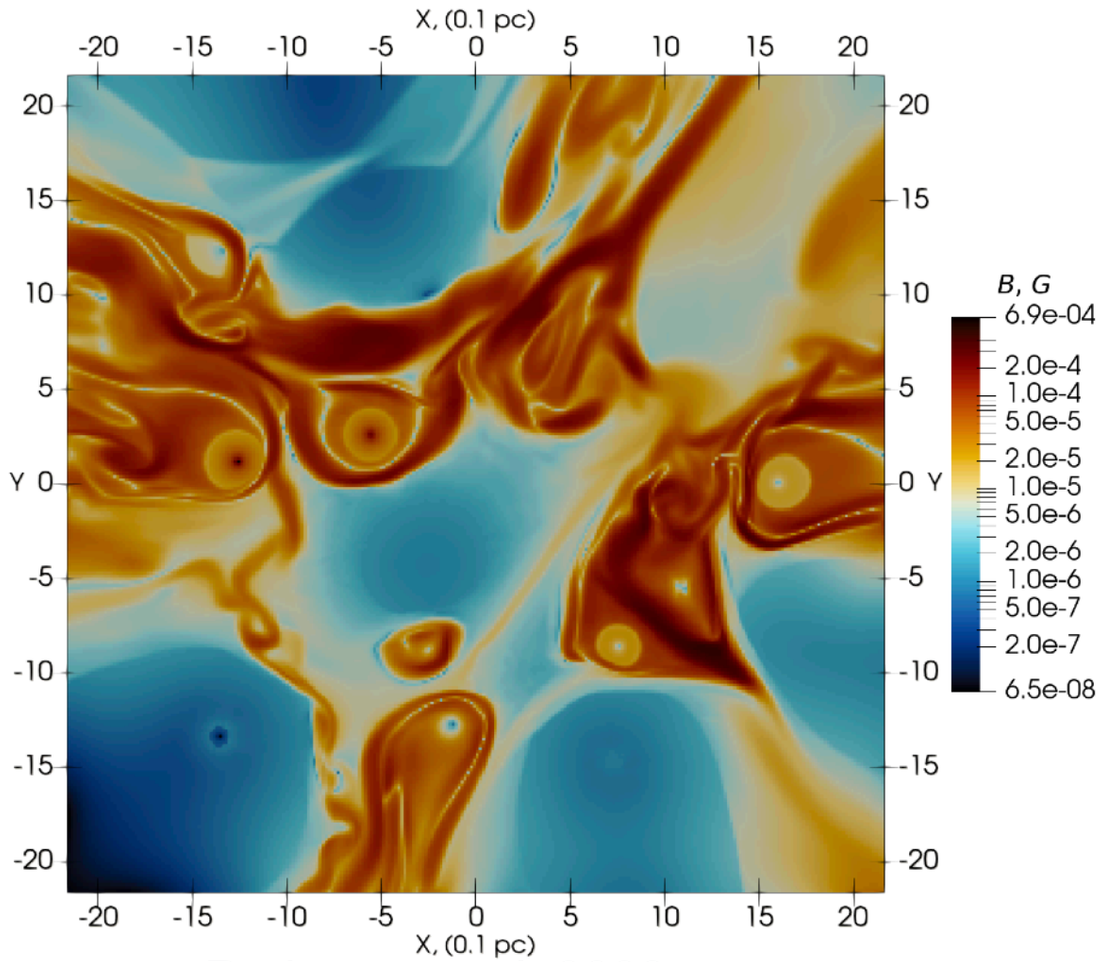




- Westerlund 1 shows a complex morphology
- Emission may be explained by leptons accelerated in the region [Härer et al. 2023]

HESS 2022

Stellar Clusters



Badmaev et al. 2022

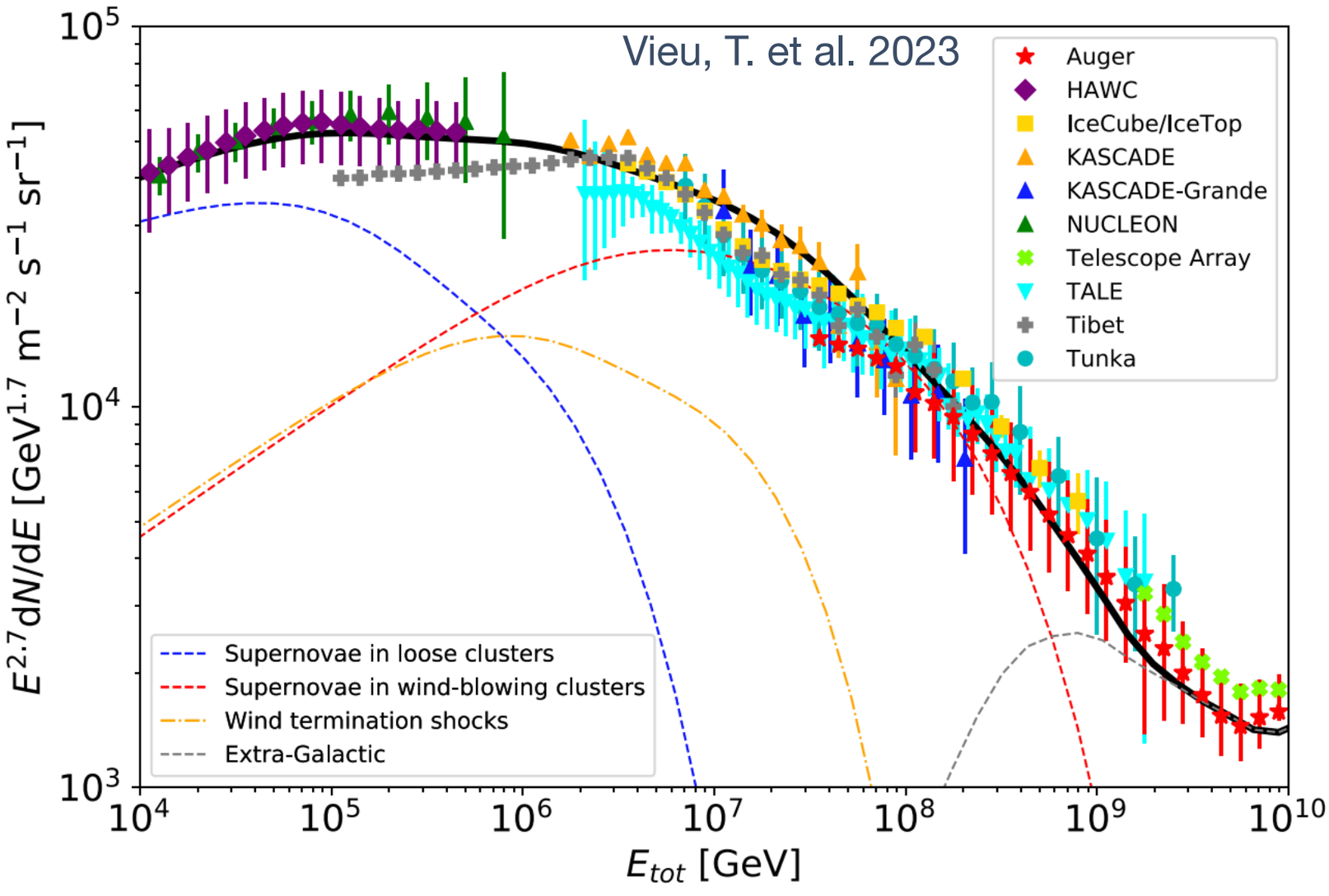
Backed up up by **theoretical** works:

- Large magnetic fields and size
- Fast outflows as in SNRs
- Energetics << than in SNRs

Hillas Criterium:

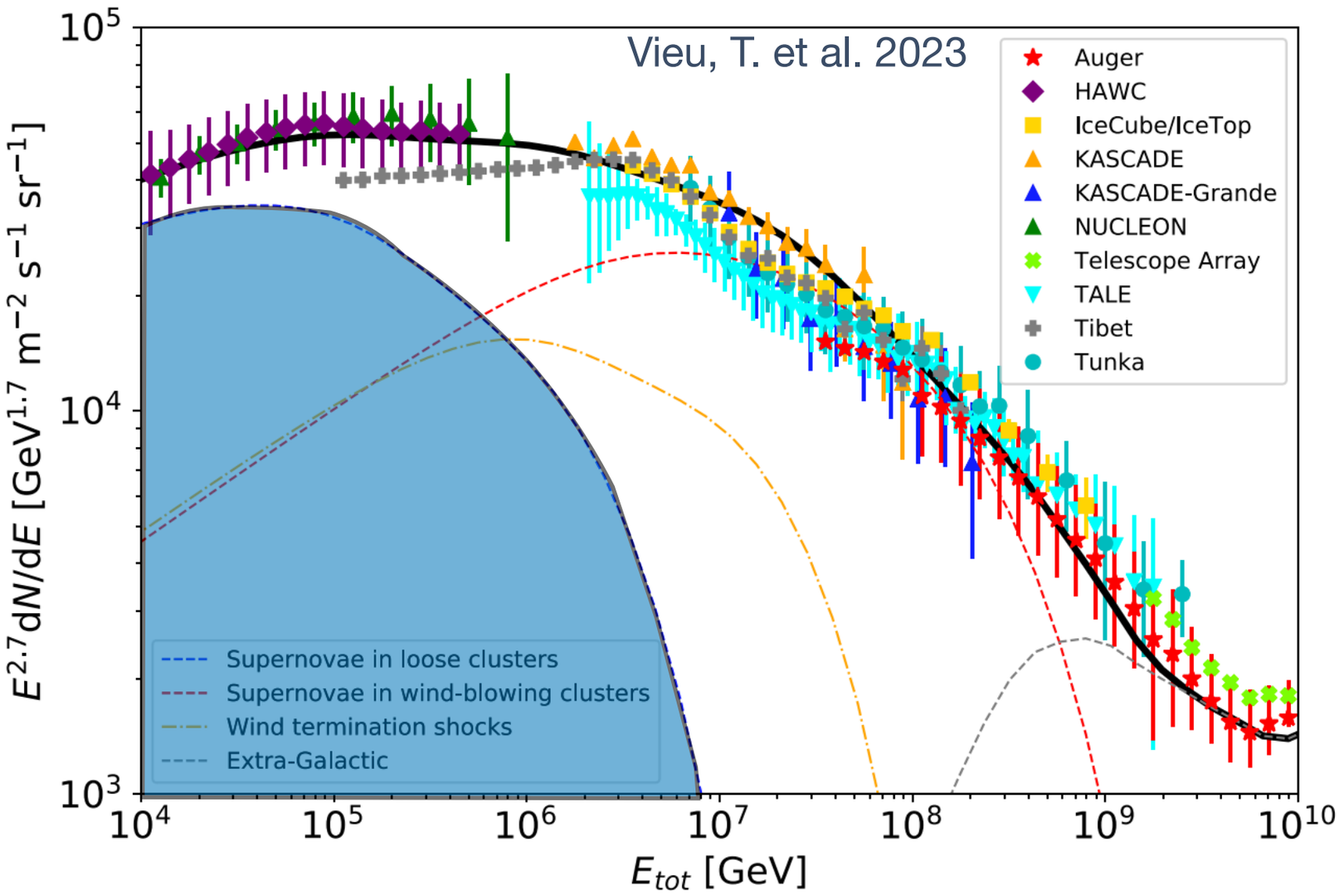
$$E_{max} \sim \left(\frac{q}{c}\right) B_s u_s R_s$$

Two source population hypothesis



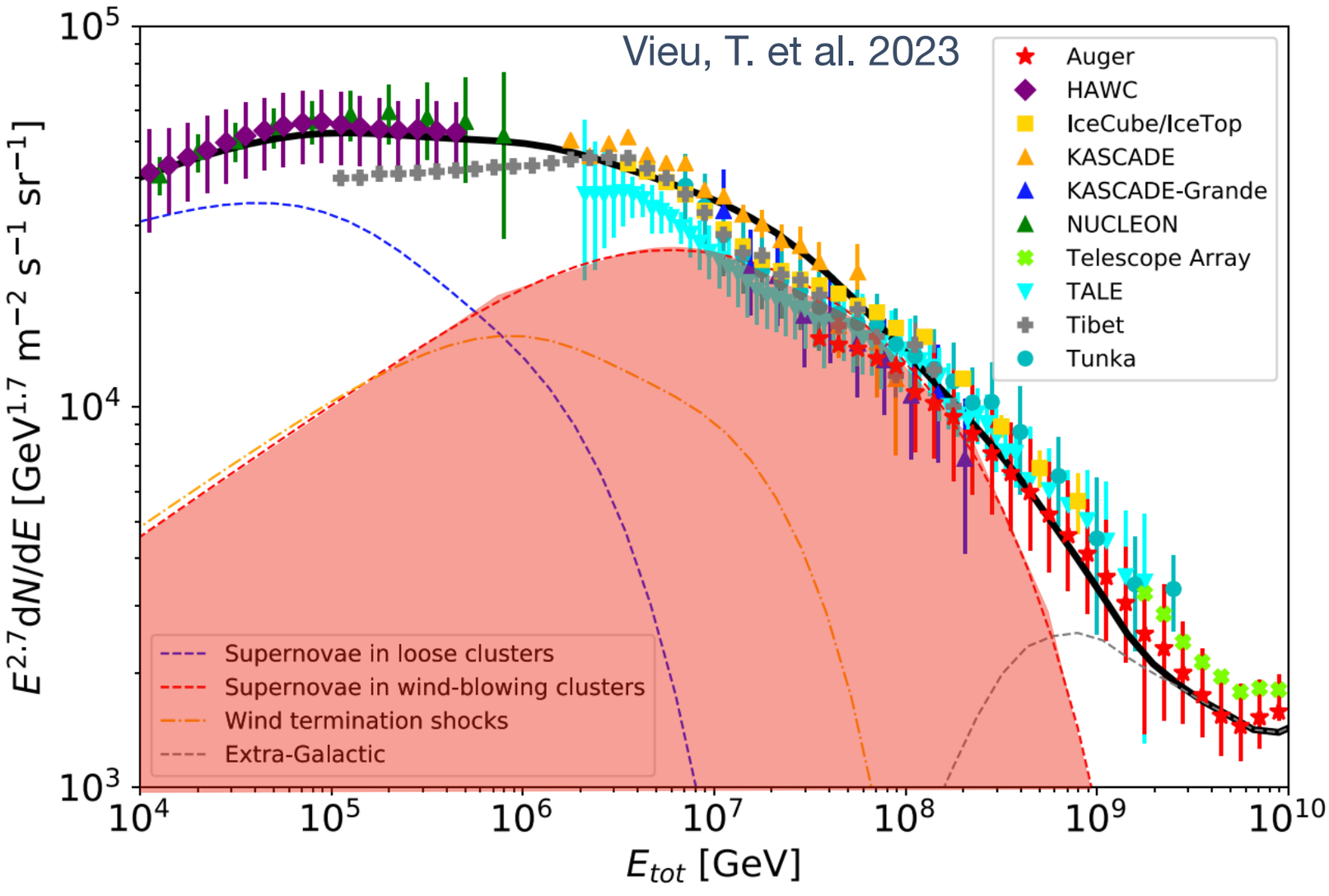
Two source population hypothesis

- Two source population hypothesis: a source type that provides the bulk of CRs (SNRs) and another one that provides the highest energies?



Two source population hypothesis

- Fits CR composition
- But still to be proven…

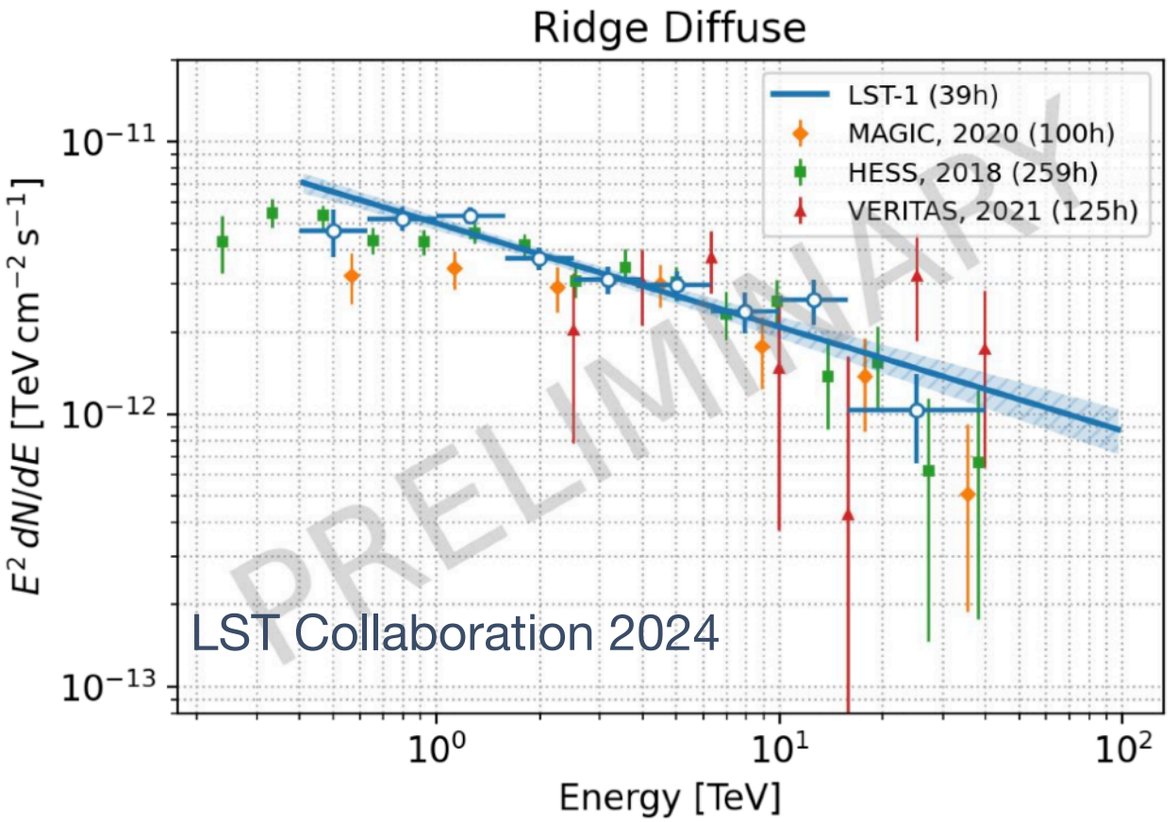


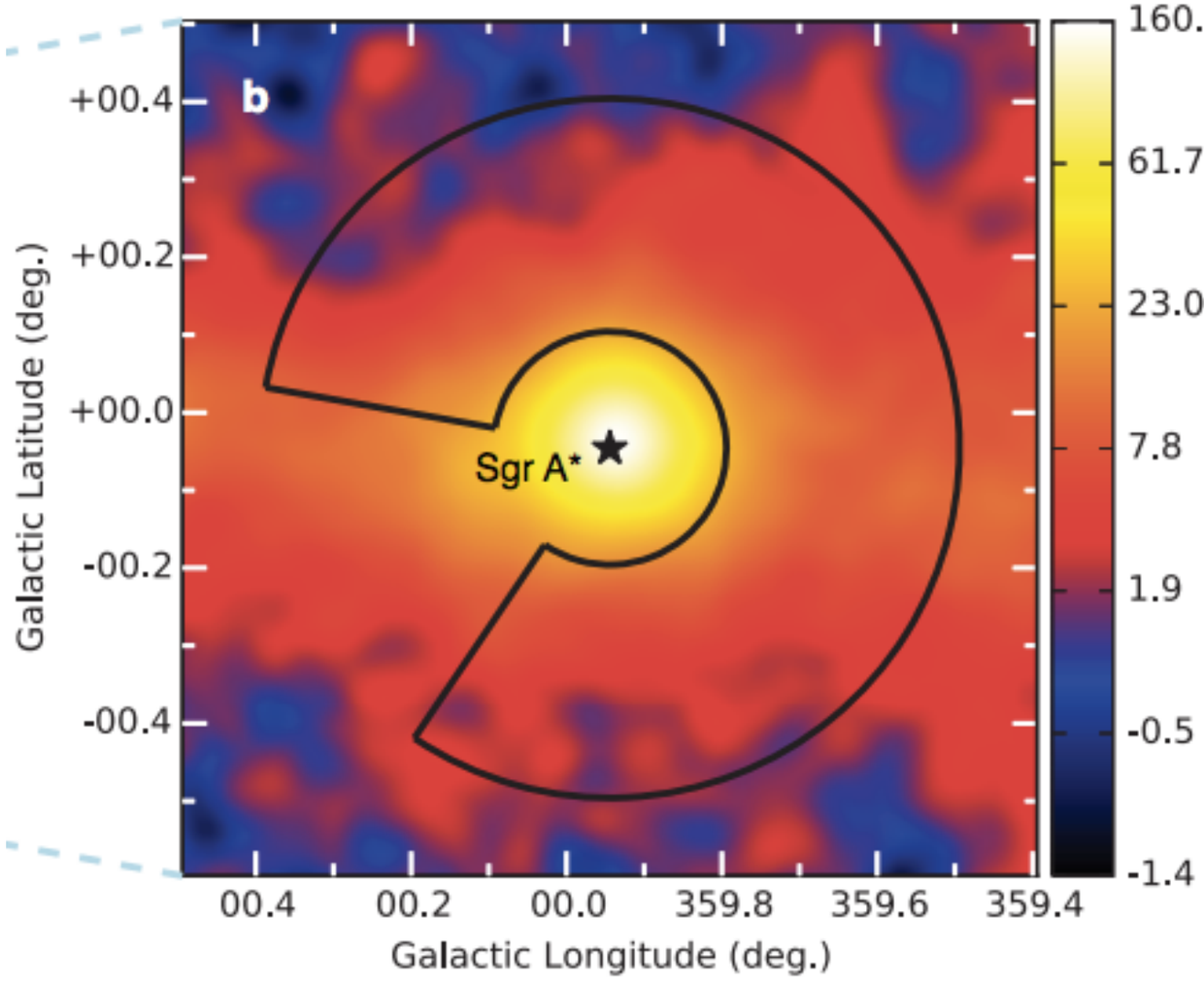
Two source population hypothesis

- Fits CR composition
- But still to be proven…

- Stellar Cluster: Some problems
  - Radial profile sometimes does not follow 1/r
  - Product of CRs and gas distribution -> Might not strictly have to follow it...
    - Depends on the center of gravity
- Massive clusters are large and messy: difficult to prove the association of gamma rays with the stellar cluster.
  - Better resolution in the gamma-ray instruments and neutrino detectors is needed

PeV acceleration?
Galactic Center

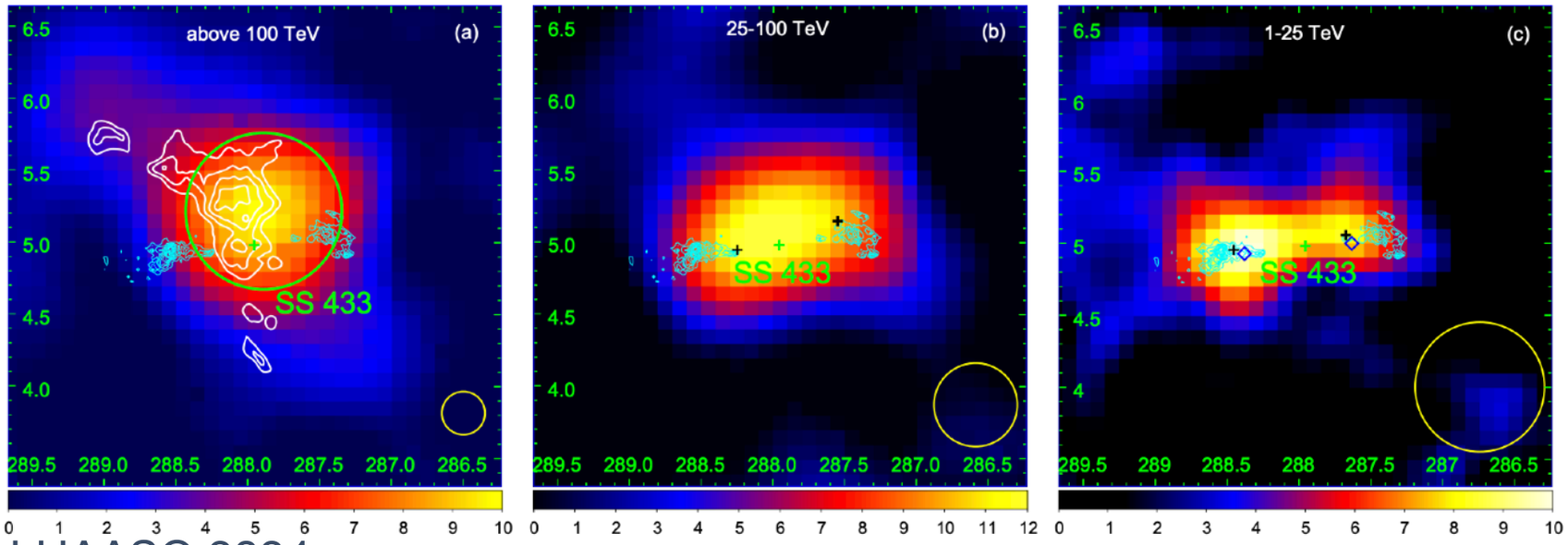


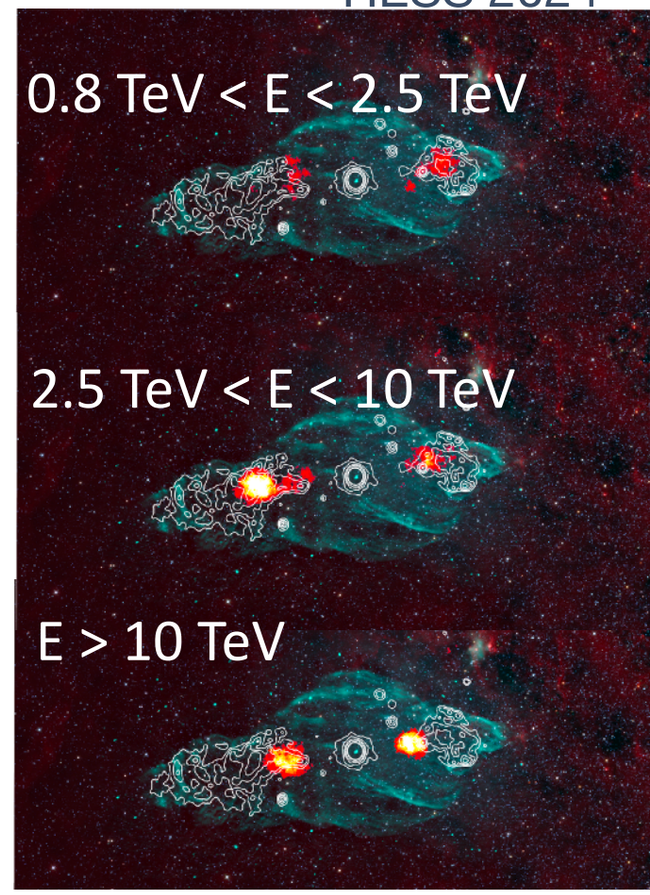


- Continuous injection of protons into CMZ up to PeV :
  - a PeVatron(s) within 10 pc of GC
- SMBC in GC (Sgr A*) operating as a PeVatron? or acceleration happening elsewhere?

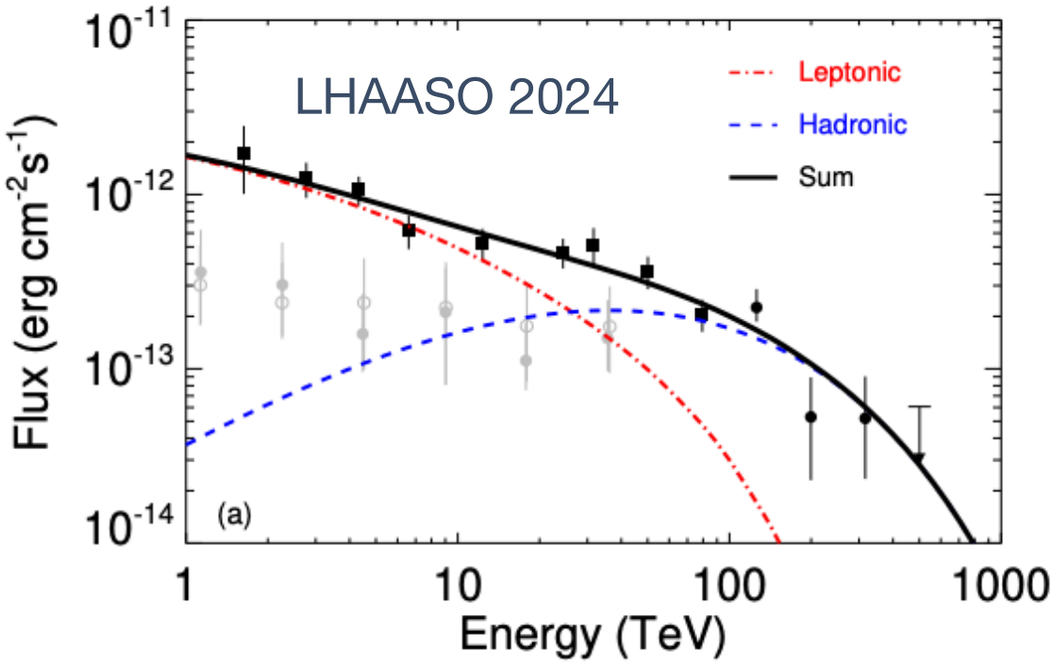
Other accelerators?
The microquasar SS 433

what about regions close to Black Holes?



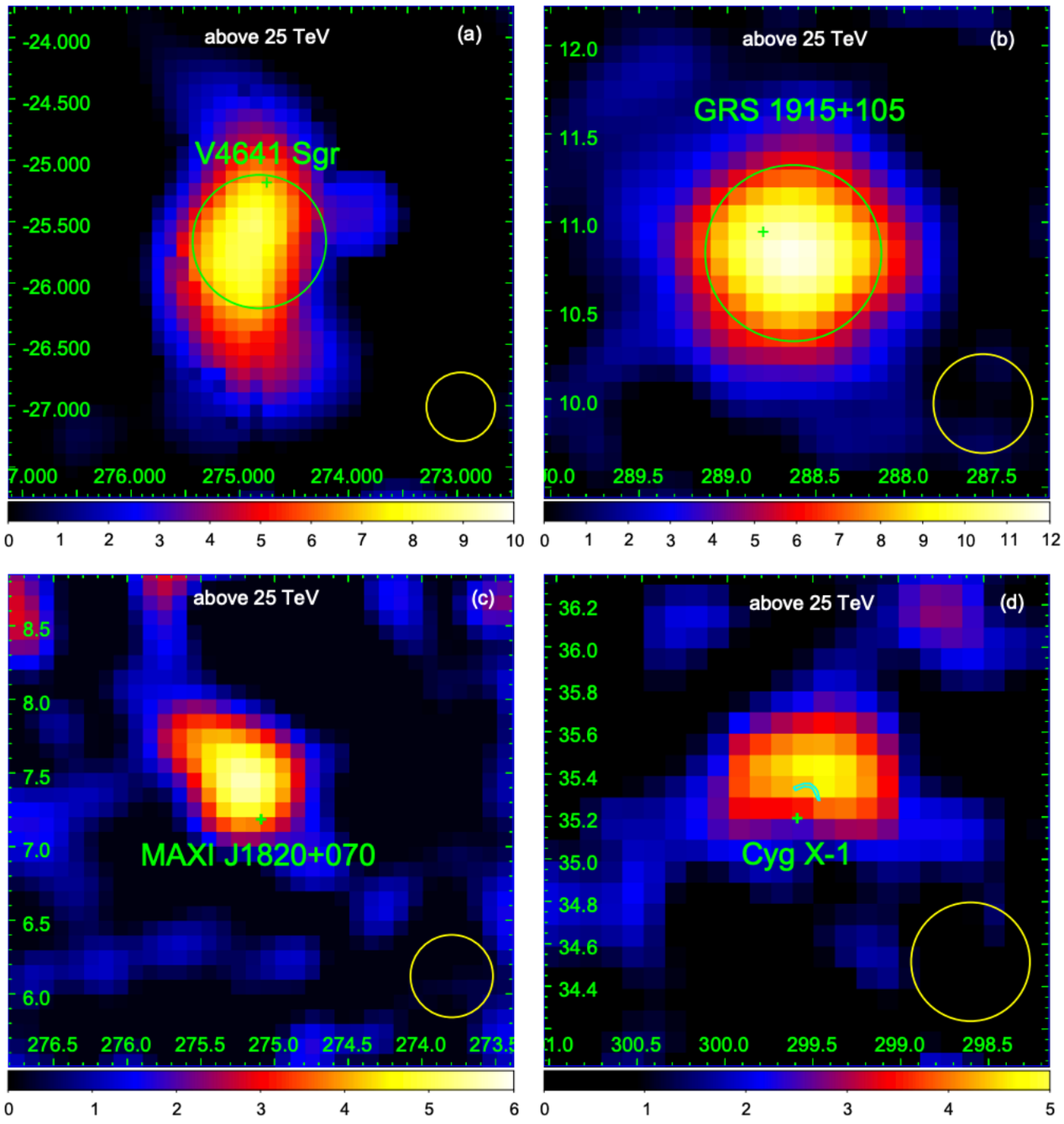


- The microquasar SS 433
  - HAWC/HESS observations favor a leptonic origin of the emission
  - LHAASO sees emission coincident with molecular clouds not coincident with the jets



Other accelerators? Microquasars

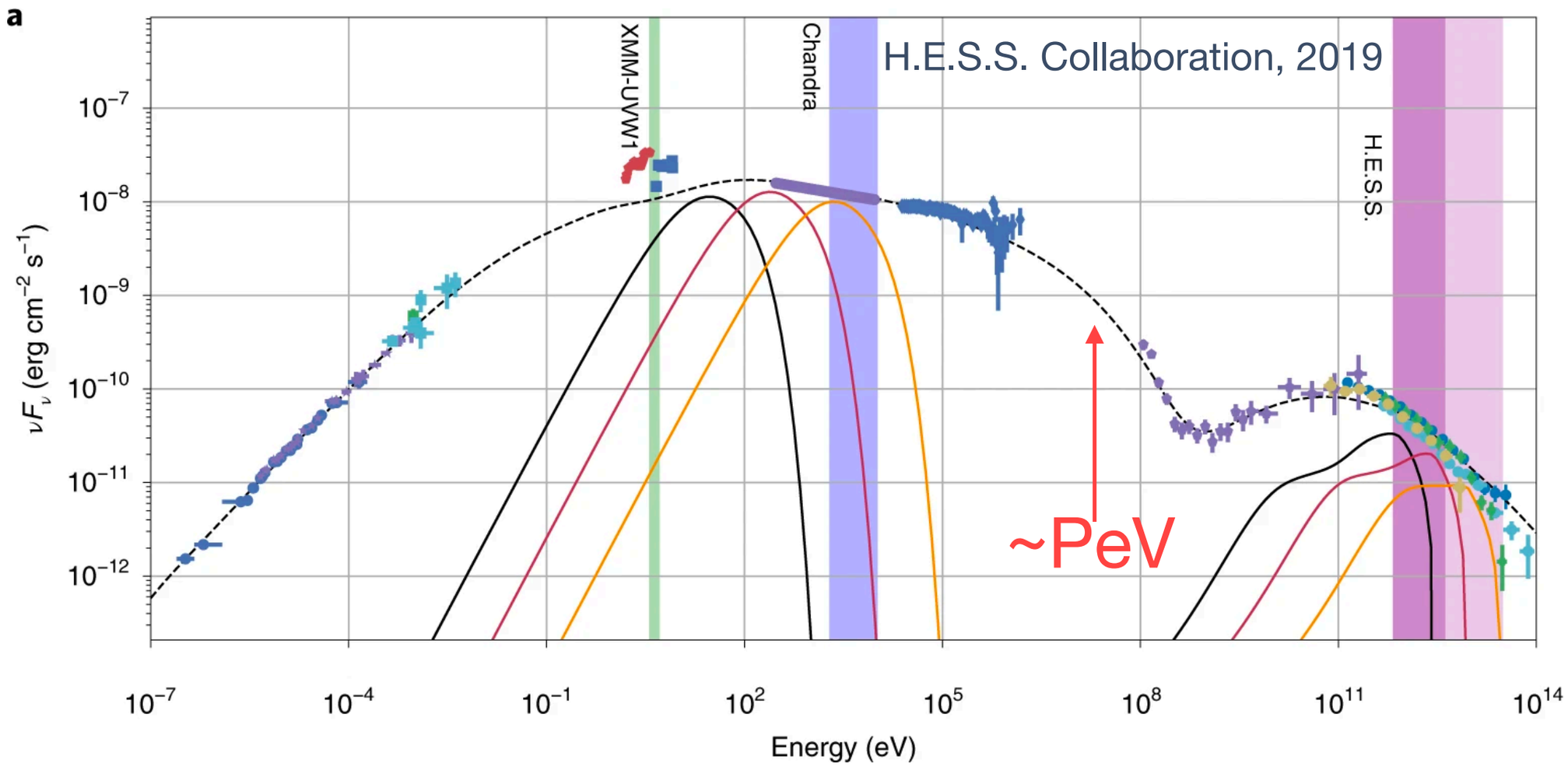
- Gamma rays up to hundreds of TeV detected from 4 additional microquasars
  - GRS 1915, Cyg X-1, MAXI J1820 reach beyond 100 TeV and the origin is under debate
  - V4641 Sgr emission is likely of hadronic origin (claim to be accelerating up to 10 PeV protons!)



LHAASO 2024

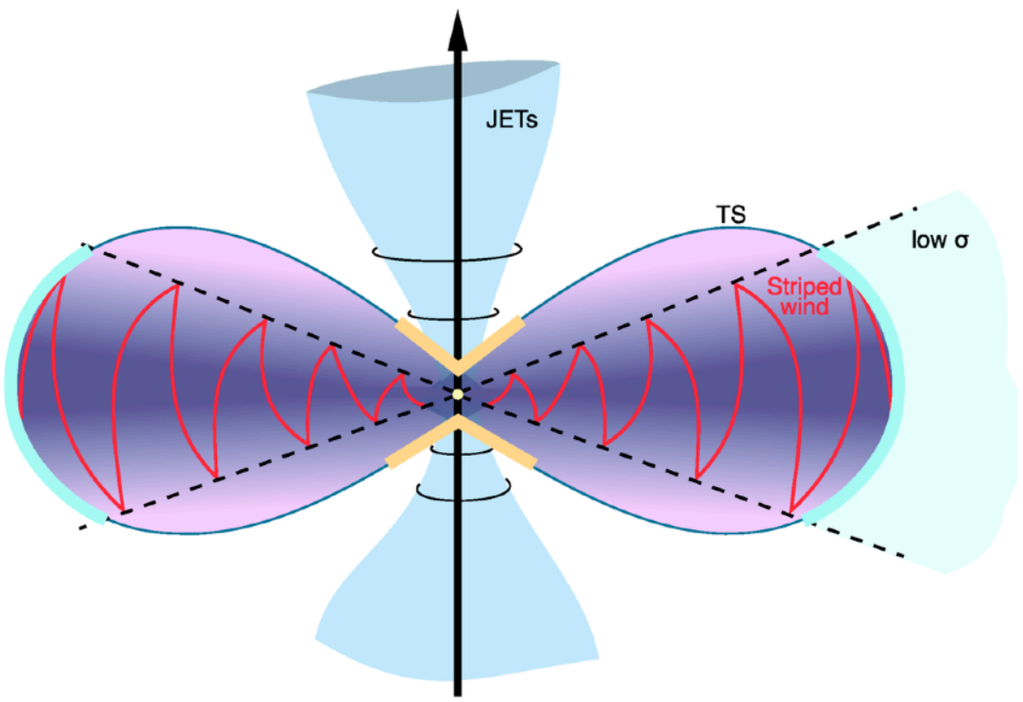
Leptonic PeVatrons

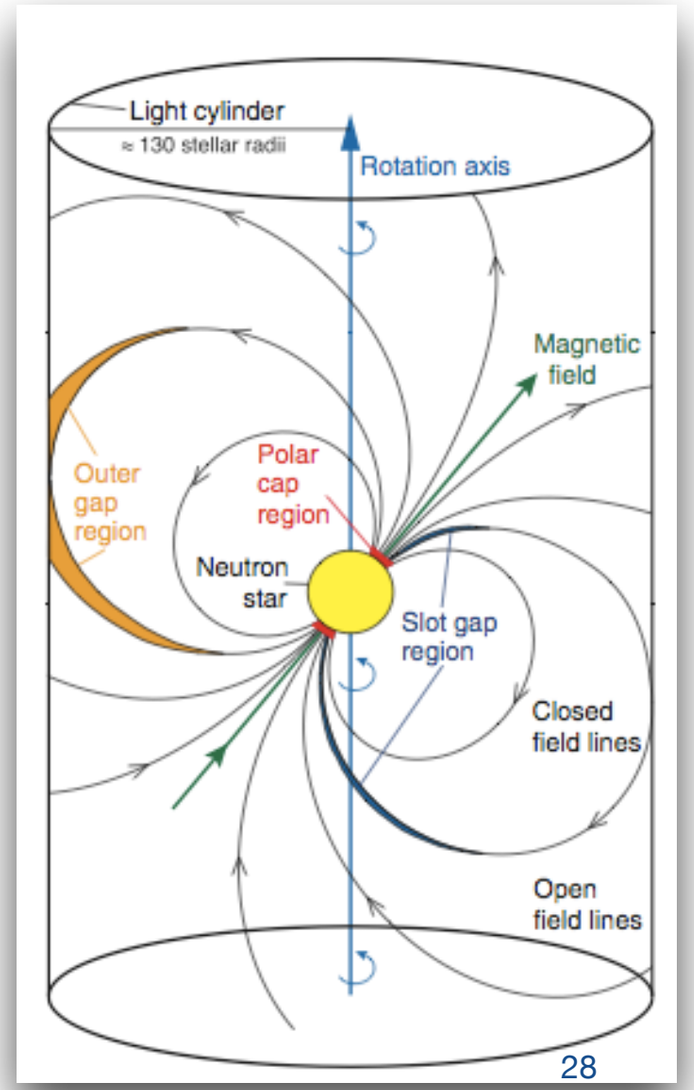
- Leptonic CR accelerators known since several decades
  - Crab Nebula as an example leptonic PeVatron.



The Role of Pulsars/PWNe

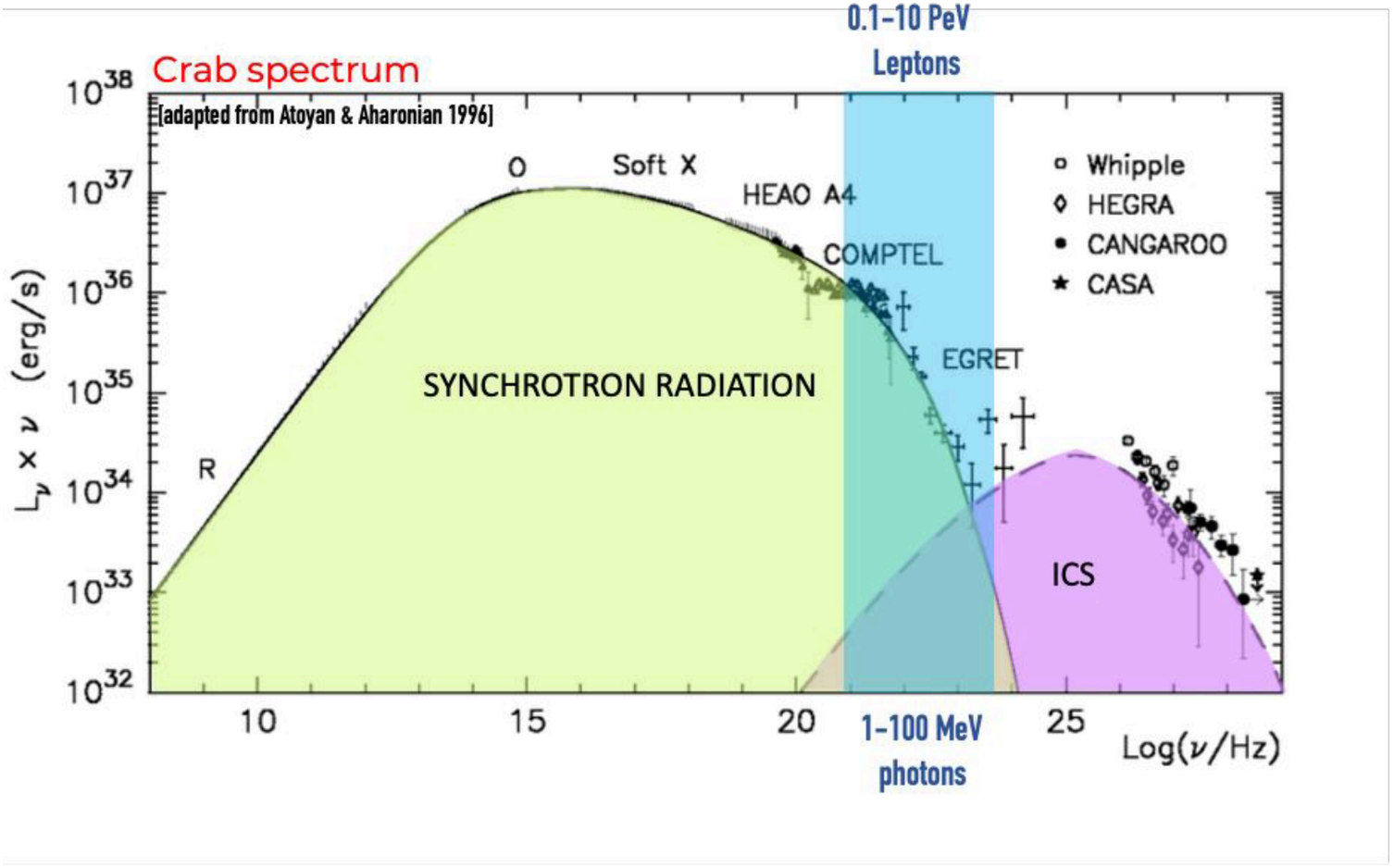
- It is very-well known that electrons and positrons get accelerated in pulsars and their environments
  - Also likely other sources, but these are the primary ones for which we have proof





Leptonic PeVatrons

- It is very-well known that electrons and positrons get accelerated in pulsars and their environments
  - 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?



The Role of Pulsars/PWNe

- Our study [Wilhelmi, RLC et al. 2022]:
  - 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?

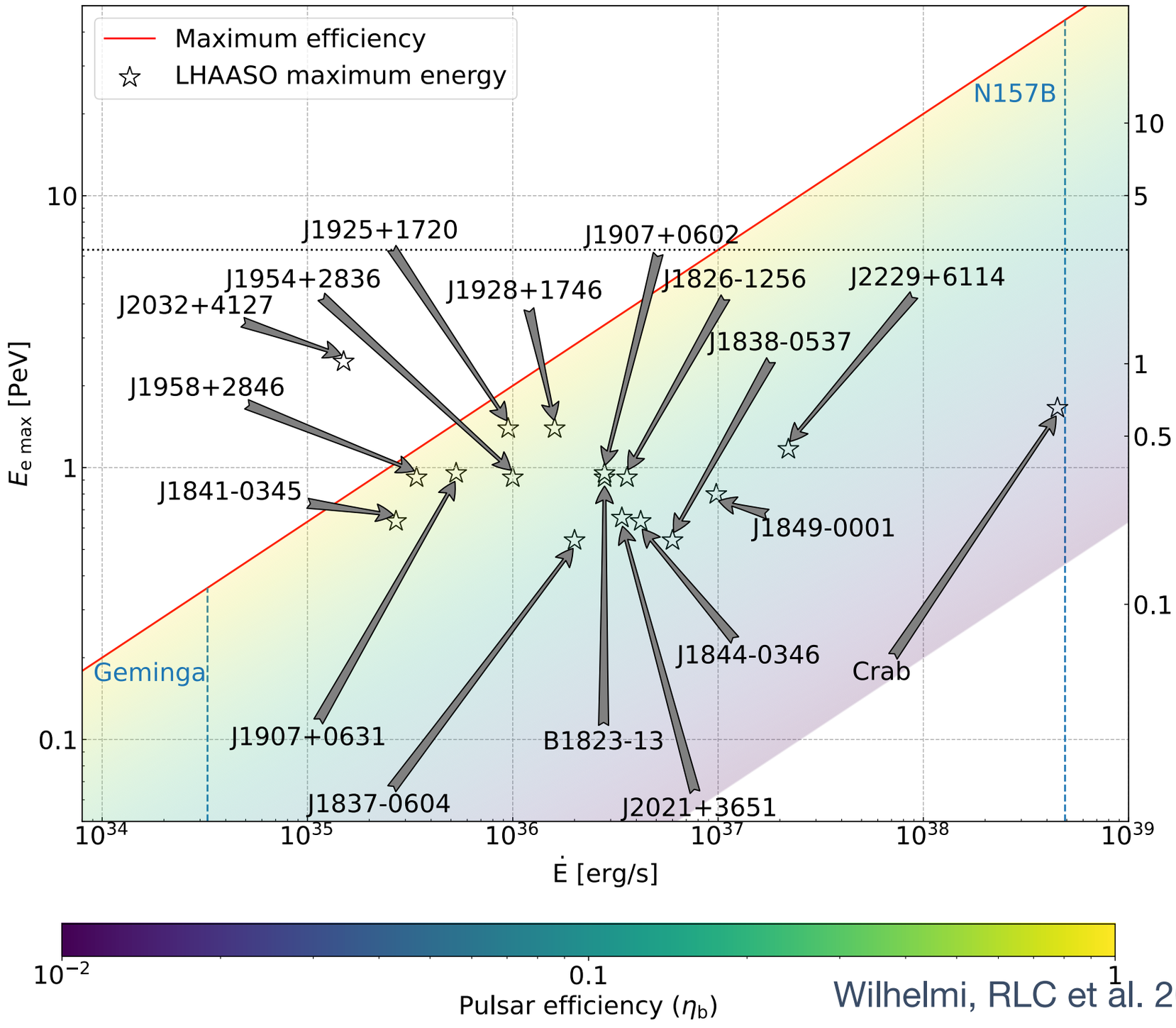
The Role of Pulsars/PWNe

- Our study [Wilhelmi, RLC et al. 2022]:
  - 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:

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

Physical limits

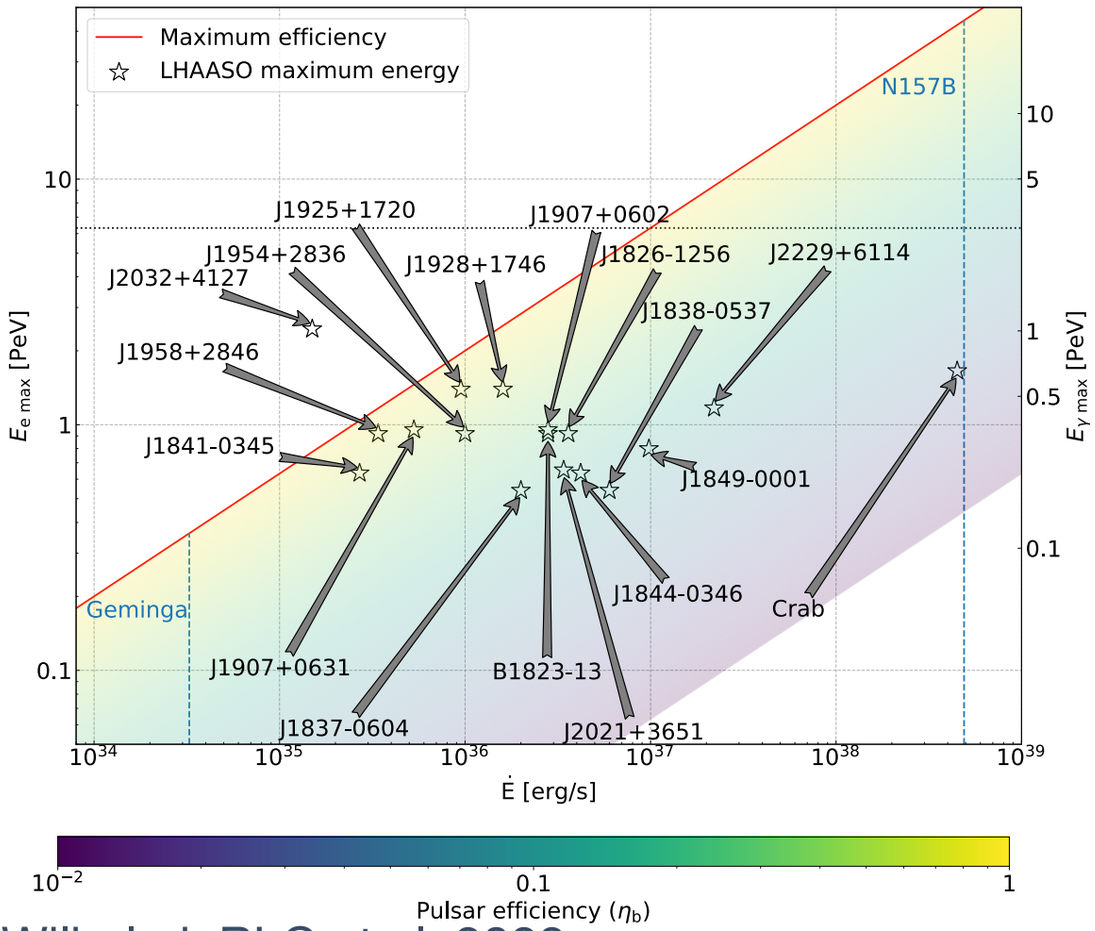
$$E_{\gamma,\max} \approx 0.9 \dot{E}_{36}^{0.65} \ \text{PeV}$$



- 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.

Wilhelmi, RLC et al. 2022

Physical limits



Wilhelmi, RLC et al. 2022

Table 2

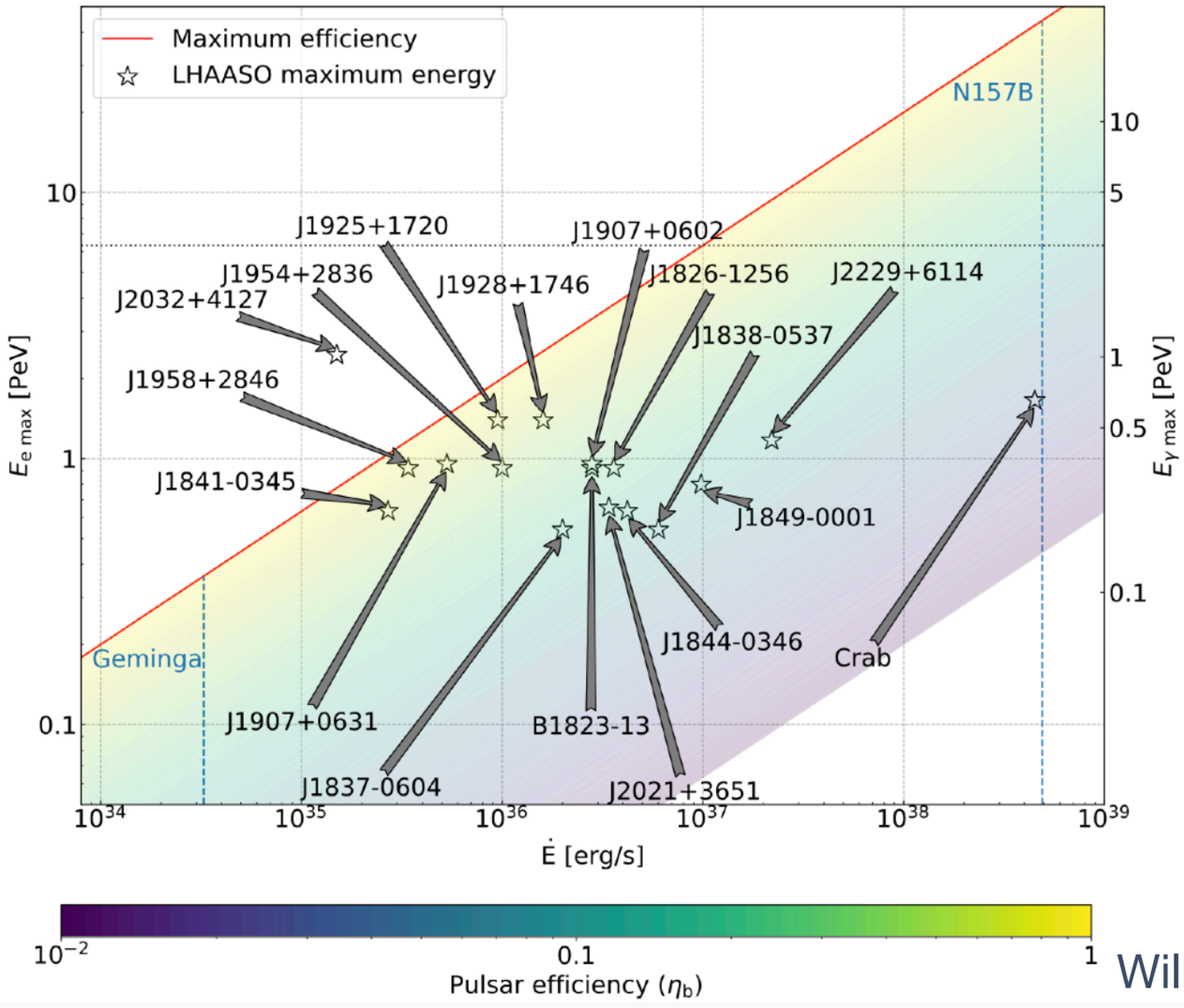
LHAASO Ultrahigh-energy Sources and Putative Associated Pulsars, with the Corresponding Constraints on the Maximum Energy and Magnetic Field

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

Do not forget leptons

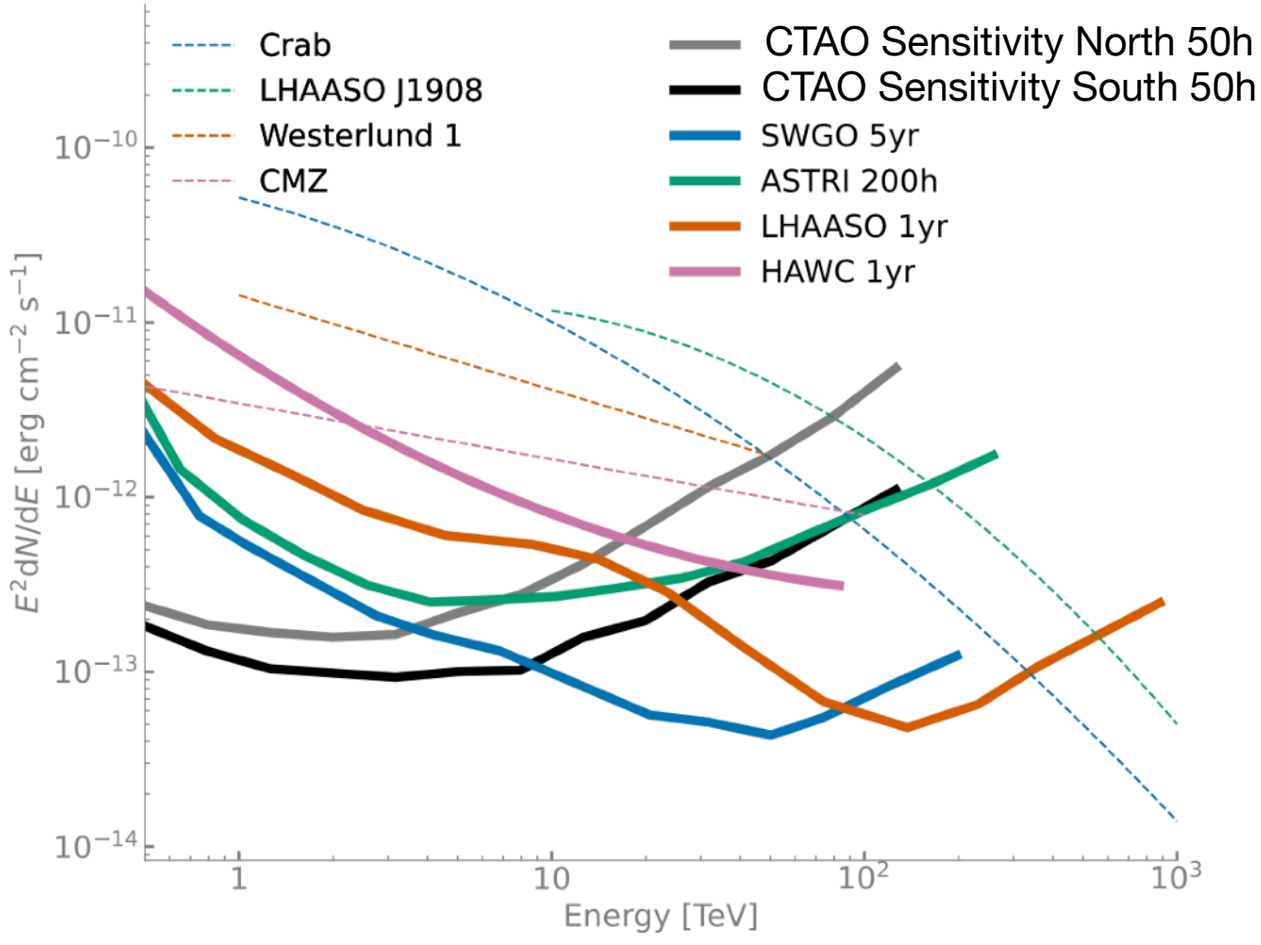
- Leptonic CR accelerators known since several decades
  - Can most of the gamma-ray sources emitting in the ~hundreds of TeV gamma-ray energy range be explained via leptonic emission? => YES!



Wilhelmi, RLC et al. 2022

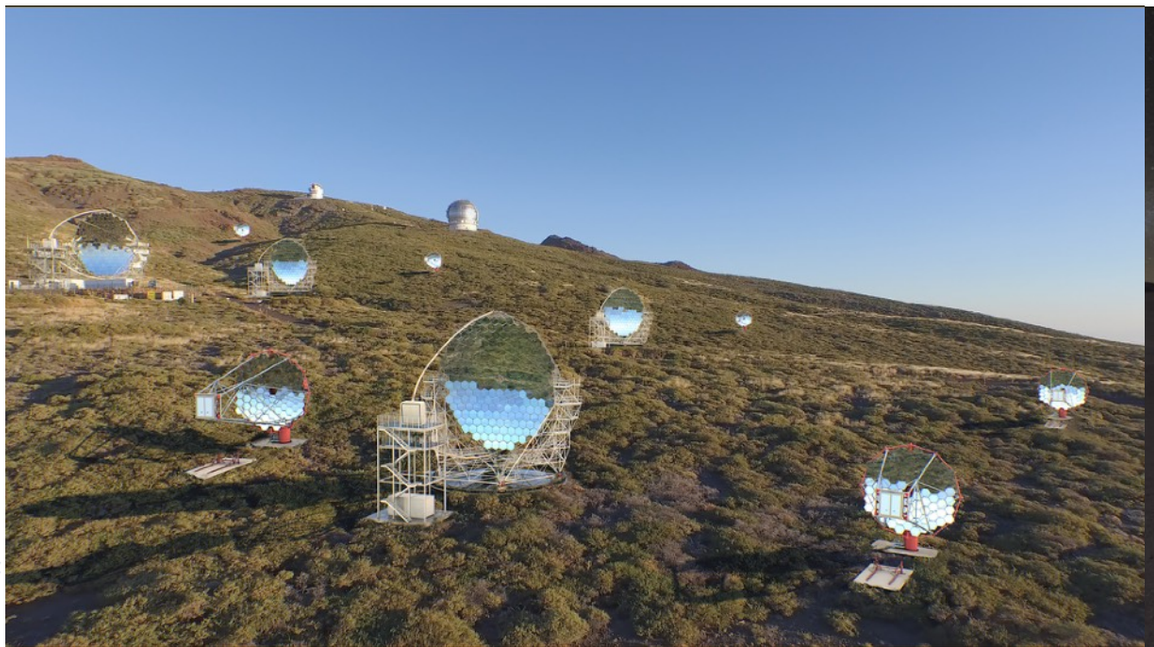
The future of the field

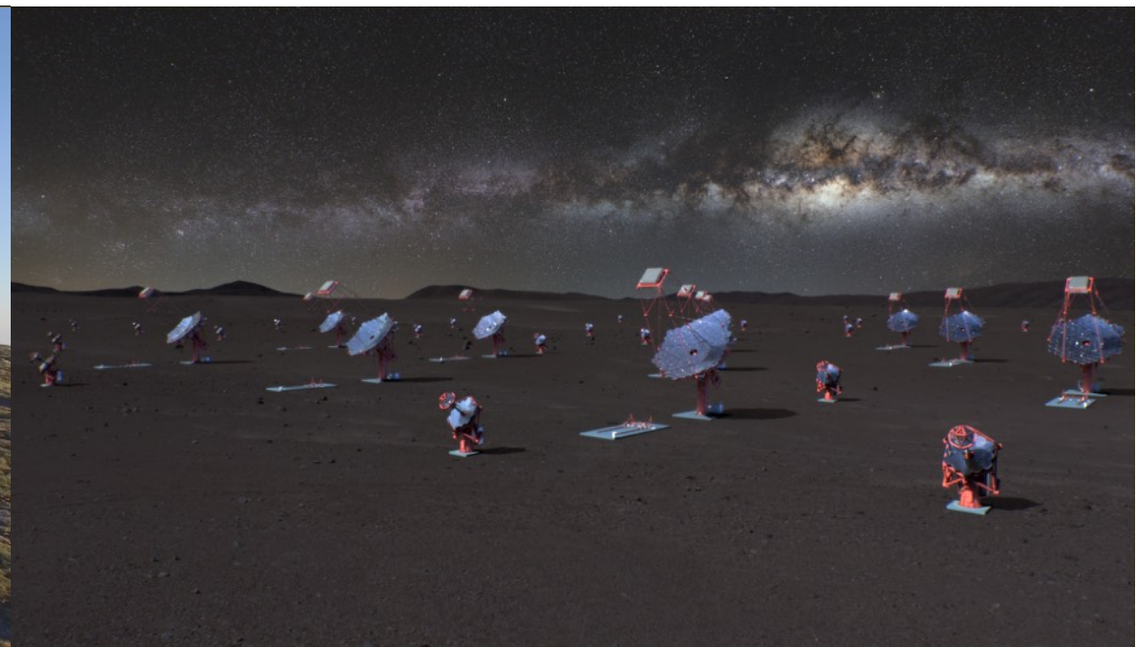
- We are getting new results every day by particle arrays and Cherenkov telescopes that are closing on the mystery (and opening new questions!)
- Forthcoming instruments like CTAO, SWGO or ASTRI Mini-Array will target the highest energy range.
  - The highest energies with better angular and energy resolution will be at reach.
  - The mystery is close to be solved!



Conclusions

- We are closer to solve the PeVatron puzzle than in the past
  - New measurements are reaching the energy limits of the photons that need to be produced by this acceleration.
  - Several theoretical developments try to push the models to the limits.
- Current and forthcoming instruments will solve the problem by:
  - Measuring the multi-TeV spectrum of SNRs
  - Studying the extended emission of star-forming regions
  - Distinguishing between leptonic and hadronic emission in sources like microquasars
- Stay tuned!





IAA INSTITUTO DE ASTROFÍSICA DE ANDALUCÍA


SUGAR
MADISON
2024
SEARCHING FOR THE SOURCES OF GALACTIC COSMIC RAYS

Thanks!