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Towards searching for photons from galactic PeVatrons with energies beyond the PeV range

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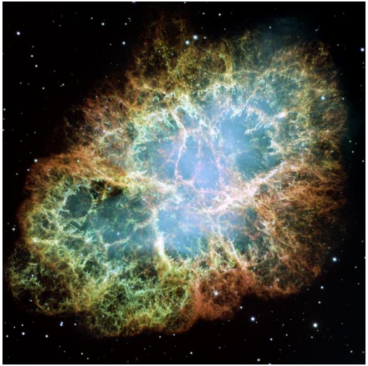
PeVatrons as Sources

- PeVatrons: galactic sites of lepton/hadron acceleration up to PeV energies
- Potentially responsible for cosmic rays up to the knee ($\approx 3 - 4\,\mathrm{PeV}$)
- Acceleration mechanisms not fully understood yet but there are theories: (e.g. A.M. Hillas (1984))
  - shock front (Fermi) acceleration
  - direct acceleration through extended electric fields
- potential PeVatron objects: pulsars and pulsar wind nebulae, supernova remnants, etc.

Crab Pulsar: one of the first identified PeVatrons

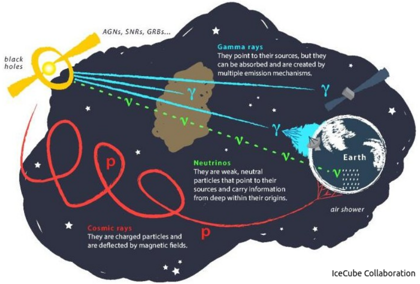


Hubble image of Crab Nebula, NASA/ESA/JPL/Arizona State Univ.

Photon emission from PeVatrons

- Hadronic mechanism: creation of neutral pions through interactions of hadrons with nuclei → pion decay: $\pi^0 \rightarrow 2\gamma$

- Leptonic mechanisms:
  - Bremsstrahlung produced due to acceleration of electrons
  - Inverse Compton scattering of accelerated electrons on soft photons (e.g. cosmic microwave background) (Casanova (2022), P. Cristofari (2021), M. Cardillo and A. Giuliani (2023))



IceCube Collaboration

Photons can be used to probe PeVatrons

- Photon energies are roughly one order of magnitude lower than hadron energies, close to lepton energies (e.g. P. Cristofari (2021), T. Sudoh, T. Linden, D. Hooper (2021))
  - example: $1.42\,\mathrm{PeV}$ photon (measured by LHAASO) implies $\approx 10\,\mathrm{PeV}$ hadrons

Observation of PeV photons from PeVatrons

Crab Nebula: (HAWC Coll. (2020))

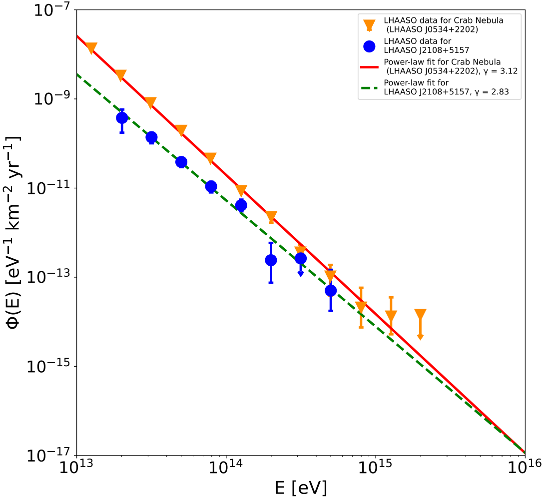
- maximum observed energy: $0.88\,\mathrm{PeV}$ (LHAASO Coll. (2021) I)
- power-law fit:

$$\frac{dN}{dE} = 2.64 \times \left(\frac{E}{10^{13}\,\mathrm{eV}}\right)^{-3.12} \frac{10^{-8}}{\mathrm{eV\,km^2\,year}}$$

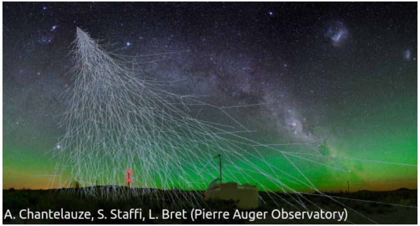
LHAASO J2108+5157: (LHAASO Coll. (2021) II)

- maximum observed energy: $0.43\,\mathrm{PeV}$ (LHAASO Coll. (2021) I)
- power-law fit:

$$\frac{dN}{dE} = 5.01 \times \left(\frac{E}{2\times10^{13}\,\mathrm{eV}}\right)^{-2.83} \frac{10^{-10}}{\mathrm{eV\,km^2\,year}}$$

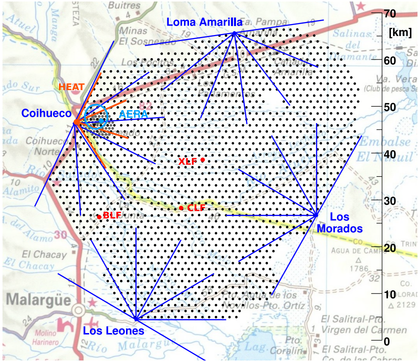


Can we measure PeVatron photons at even higher energies with giant air-shower arrays?



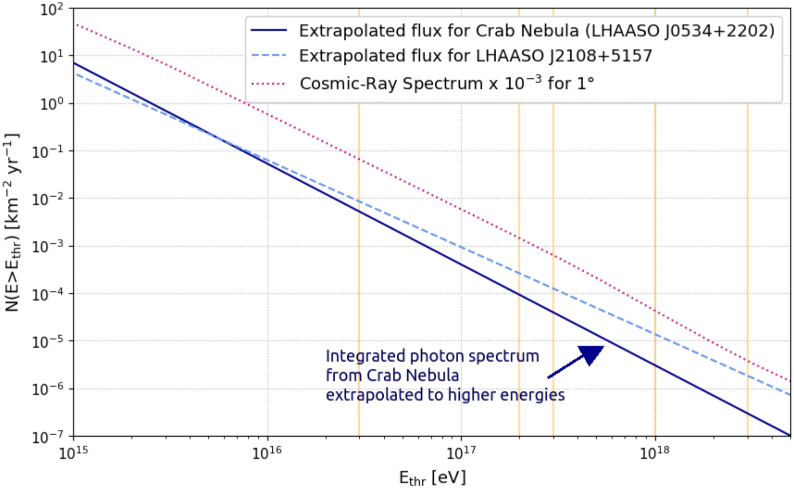
- measurement of secondary particles in air-showers
- challenges: differentiating between hadron- and photon-induced air-showers

The Pierre Auger Observatory as an example of giant-air shower arrays: present minimum energy: $3 \times 10^{16}\,\mathrm{eV}$

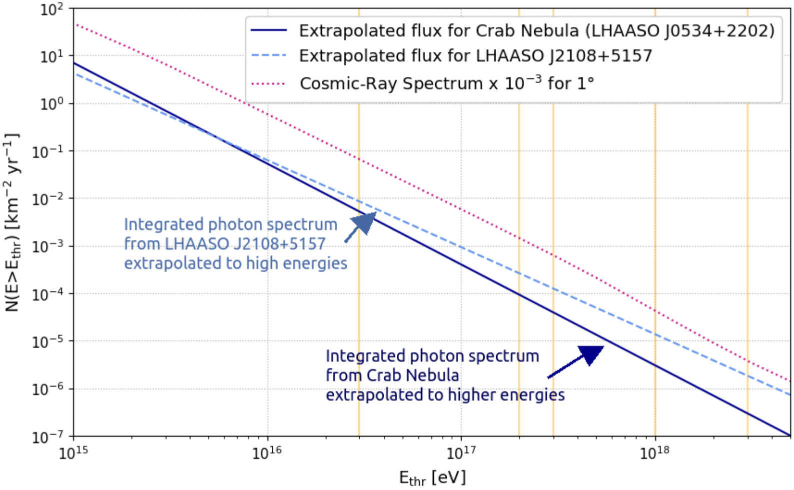


Pierre Auger Coll. Universe 4, 128 (2018)

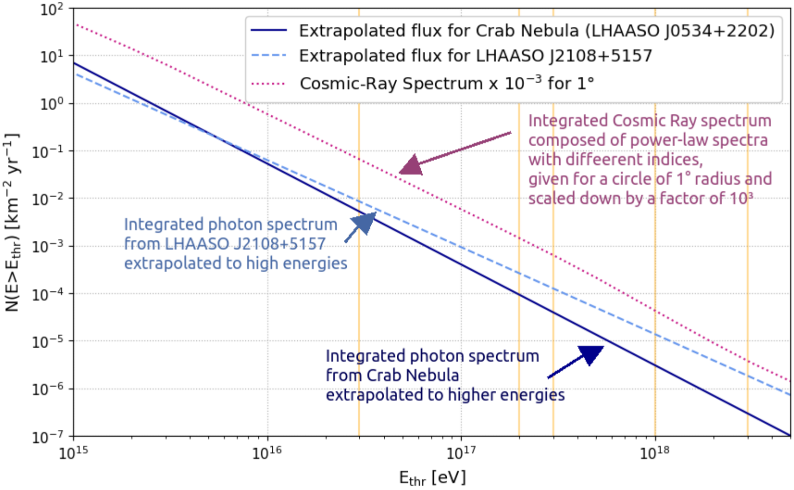
Comparing photon spectra and cosmic ray background



Comparing photon spectra and cosmic ray background



Comparing photon spectra and cosmic ray background

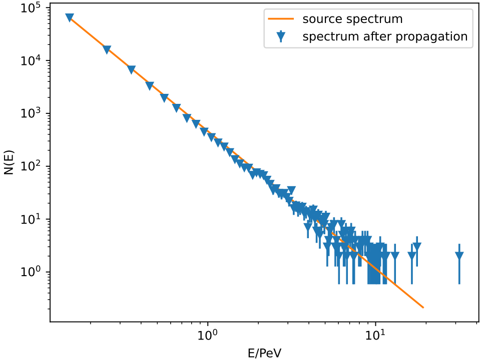


Likelihood of measurement at giant air-shower array

Detector parameters		$N_\gamma(E > E_{thr}) \times A \times 10\,\mathrm{yr}$ for a source like		$N_{CR}(E > E_{thr}) \times A \times 10\,\mathrm{yr}$
Area A $[\mathrm{km}^2]$	Energy threshold E_{thr} $[\mathrm{eV}]$	Crab Nebula	LHAASO J2108+5157	per point source
1.95 (cf. Auger SD-433)	3×10^{16}	0.101	0.165	1337.4
27.5 (cf. Auger SD-750)	3×10^{17}	0.011	0.034	173.1
3000 (cf. Auger SD-1500)	3×10^{18}	0.009	0.055	114.6
27.5 (cf. Auger Hybrid, HeCo + SD-750)	2×10^{17}	0.004	0.011	61.1
3000 (cf. Auger Hybrid, FD + SD-1500)	1×10^{18}	0.014	0.062	194.9

Detail studies with CRPropa: Are photon spectra diminished by propagation effects?

CRPropa: simulation framework to study the propagation of ultra-high-energy nuclei and other particles



- initial photon spectrum: $dN/dE \sim E^{-\gamma}$ with $\gamma = 2.5$
- distance of propagation: 2 kpc
- at low distances, propagation effects are almost negligible

Conclusion and Outlook: Can we measure PeV-EeV photons from PeVatrons?

- Detection of PeV-EeV photons with Pierre Auger-like detector currently challenging but might be possible in the future
  - increasing detector area or decreasing minimum energy increases likelihood of detection
  - improving background rejection is beneficial as well
  - contribution of several source beneficial for detection of diffuse spectrum
- Work in progress: CRPropa Crosscheck $\rightarrow$ Can we neglect propagation effects?

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