PROCEEDINGS OF SCIENCE

Towards Searching for UHE Photons from Galactic PeVatrons: Estimating Fluxes and Constraining Spectral Parameters

Marcus Niechciol,[a] Chiara Papior[a,*] and Markus Risse[a]

[a] *Center for Particle Physics Siegen, University of Siegen, Walter-Flex-Str. 3, 57072 Siegen, Germany*

E-mail: papior@hep.physik.uni-siegen.de

The recent discoveries of PeV photons from galactic sources by gamma-ray observatories were unexpected and exciting. Some source spectra reveal no visible cutoff, posing the question how far the photon emission extends into the ultra-high-energy (UHE, here beyond 10 PeV) regime. We evaluate if and under which conditions giant air shower observatories like the Pierre Auger Observatory can contribute to test the UHE luminosity of the detected PeV γ-sources. Based on our previous analysis, we include the latest observations of V4641 Sgr (by HAWC) and of LHAASO J1819-2541 (by LHAASO). Comparing extrapolated photon fluxes to existing directional upper limits from the Pierre Auger Observatory in the energy range 200−3000 PeV, the parameter range when extrapolating the flux from V4641 Sgr North can be constrained already now. We conclude that the constantly improving sensitivity of air shower arrays will deliver relevant information on the UHE luminosity of PeV γ-sources, particularly if the energy threshold can be lowered to reduce the gap between gamma-ray and air shower observatories.

The 39th International Cosmic Ray Conference (ICRC2025)
15 -24 July –, 2025
Geneva, Switzerland

ICRC 2025
The Astroparticle Physics Conference
Geneva July 15-24, 2025

*Speaker

PoS(ICRC2025)795

1. Introduction

Cosmic photons of ever-increasing energy are being detected. In the last years, the maximum photon energies have increased from the high TeV range to the low PeV range with measurements performed by wide-field gamma-ray observatories such as Tibet ASγ [1], HAWC [2] and LHAASO [3]. Both the LHAASO and the HAWC collaborations published observations of photons with energies in the PeV range from (Galactic) sources. These sources of energetic photons play an important role in current multimessenger astronomy as the emission of photons hint at the acceleration of charged particles, which makes the sources of such photons potential cosmic-ray sources. Due to the acceleration of particles to at least PeV energies, these sources are commonly referred to as "PeVatrons." While the exact mechanisms responsible for the particle acceleration are still being investigated, the emission of energetic photons is an expected by-product of the acceleration process of both leptons or hadrons (see, e.g., [4–6]). During the acceleration of leptons, photons are emitted mostly via Bremsstrahlung and inverse Compton scattering. Hadronic acceleration processes produce photons via decay of neutral pions which are generated when hadrons interact with surrounding radiation fields or matter present at acceleration sites. Depending on the initial particle and the production process, photon energies are about a factor of 3 – 10 below the energy of the accelerated charged particle. Therefore, a photon with an energy in the low PeV range indicates that acceleration up to and beyond the high PeV range occurs in PeVatrons. There are different source candidates at which the acceleration can take place; supernova remnants, pulsars, pulsar wind nebulae or microquasars are a few well-kown examples but superbubbles or young massive star clusters are potential sources as well (see, e.g., [4–6]).

The measured photon spectra can often be fit with a power-law, however some measured spectra clearly indicate a cutoff towards higher energies. The spectra that continue without an indication of a cutoff prompt the question of how far the spectra extend in energy. Detecting photons in the high PeV range, would aid in understanding the production of cosmic rays at the highest energies. Also upper limits on the flux of PeV photons would still be of great interest for the multimessenger community.

To approach this goal, it is beneficial to estimate the prospects of measuring photons with energies in the medium to high PeV range with current and future instruments. Additionally, investigating potential improvements for future research projects, can push the energy frontier of photon observations towards ultra-high energies (UHE, $E \geq 10\,\text{PeV}$). Both the HAWC and LHAASO observatories are limited by their exposure, directly correlated with their size. Giant air-shower arrays are mostly known for the detection of charged cosmic-ray particles but can be used for photon searches as well. The currently largest observatory of this kind is the Pierre Auger Observatory [7], and the collaboration has recently begun to lower the energy threshold towards 100 PeV and below [8, 9].

In this study, we investigate how and under which conditions it is possible for giant air-shower arrays to contribute to testing the UHE luminosity of PeV γ-sources. Sources observed with power-law spectra without cutoff and with high photon fluxes are selected and their spectra are extrapolated to higher energies. Based on our recent publication [10], we include recent, new PeV photon observations. The expected photon numbers for different energy ranges together with directional upper limits on photon fluxed are calculated and, in one case of a detected PeV γ-source, the continuation of the measured spectrum can be constrained with directional limits provided by the Pierre Auger Observatory.

2. Current measurements

Three sources have been selected from a variety of publications by the LHAASO and HAWC collaborations. The Crab Nebula (LHAASO J534+2202u) and LHAASO J2031+4052u*, both published in the LHAASO catalog [11], have been already discussed in a previous publication [10]. Additionally, the recent observations from the direction of the microquasar V4641 Sagittarius are investigated. This source has been resolved in two components by HAWC (V4641 Sgr North and South) [12] and observed as a single one by the LHAASO (LHAASO J1819-2541) [13]. Because the spectral parameters of V4641 North and South are quite similar, only V4641 North will be discussed here. In Fig. 1 we show the data (if available) and the power-law fits provided by the collaborations of these sources. The spectra follow a power-law of the form $\Phi_\gamma(E) = \Phi_0 \times (E/E_0)^{-\Gamma}$, where Φ_0 denotes the differential photon flux at the pivot energy E_0 and Γ is the spectral index.

3. Extrapolated UHE photon fluxes

Motivated by the lack of cutoffs in the observations, the power-law spectra are extrapolated into the UHE regime. The integrated photon flux, based on the central values of the observations, is shown in Fig. 2 as a function of the threshold energy E_{thr}. Also the cosmic-ray flux from a circle of 1° radius is displayed (see [10] for details).

The new observations lead to UHE photon extrapolations that significantly surpass those from the previously investigated sources, e.g. by about a factor 10 for $E_{\text{thr}} \simeq 10$ PeV compared to LHAASO J2031+4052u*. Due to the hard spectral index, the UHE extrapolations for V4641 Sgr North exceed those for LHAASO J1819-2541, and nominally even approach the cosmic-ray background at $E_{\text{thr}} \simeq 1000$ PeV.

Propagation effects were not accounted for as they were shown to be rather moderate on galactic scales for benchmark estimates of the integrated UHE photon flux [10]. This also holds for the new observations with an estimated source distance of ~6.5 kpc. As an illustration, results from simulations using CRPropa 3.2 [15] are shown in Fig. 3: photons of fixed initial energy have been injected. For different propagation distances, the fraction of photons arriving at Earth without interaction is extracted. As expected, the effect is largest at a few PeV (e.g., about one-third of the photons surviving without interaction after 8 kpc). The fraction quickly increases towards the UHE regime (and, hence, when focussing on integrated numbers), for closer sources and when taking secondary UHE photons from the cascades into account.

4. Prospects for Photon Observation

To estimate the potential of possibly observing UHE photons from PeV γ-sources, the detector parameters like the area and the energy threshold have to be considered. As an example, the Pierre Auger Observatory is chosen as the largest air shower detector. Still, the results can be easily transferred to other current or future observatories. The goal of these benchmark studies is not to

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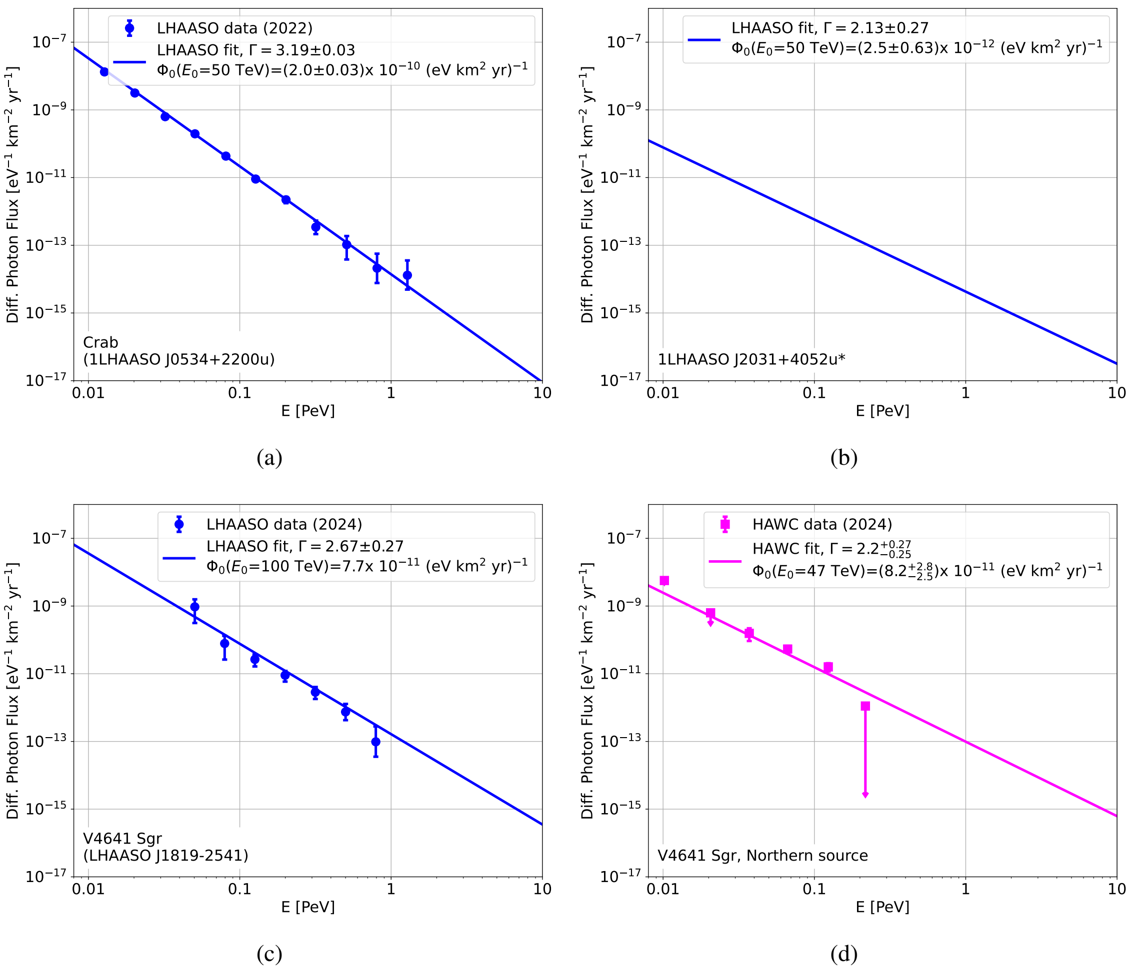

Figure 1: Data (if available) and power-law fits of selected PeV γ-sources: (a) Crab [11, 14], (b) LHAASO J2031+4052u* [11], (c) LHAASO J1819-2541 [13], (d) V4641 Sgr North [12]

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estimate the capability of *the* Pierre Auger Observatory to measure photons from *the* Crab but rather to estimate the potential of measuring photons from a source *like* the Crab (i.e., one with similar spectral features) with an observatory *like* the Pierre Auger Observatory. Therefore, the individual source visibility is not taken into account here.

The extrapolated numbers of UHE photons and background cosmic rays above the threshold energies for different detectors at the Pierre Auger Observatory are listed in Tab. 1. The main surface detector (SD) of the Pierre Auger Observatory covers an area of 3000 km^2 and can detect particles with energies above $E_{\text{thr}} \simeq 3000$ PeV. The smaller arrays cover areas of 27.5 km^2 and 1.95 km^2 with energy thresholds of 300 PeV and 30 PeV, respectively. Hybrid measurements with the fluorescence detectors (FD) are considered for the two larger arrays as well. This reduces the threshold energy, however, it decreases the runtime to 15% as the FDs can be operated only during dark moonless nights. Assuming an observation period of ten years, the expected particle numbers for SD-only measurements are displayed in the middle block of Tab. 1 and the hybrid measurements

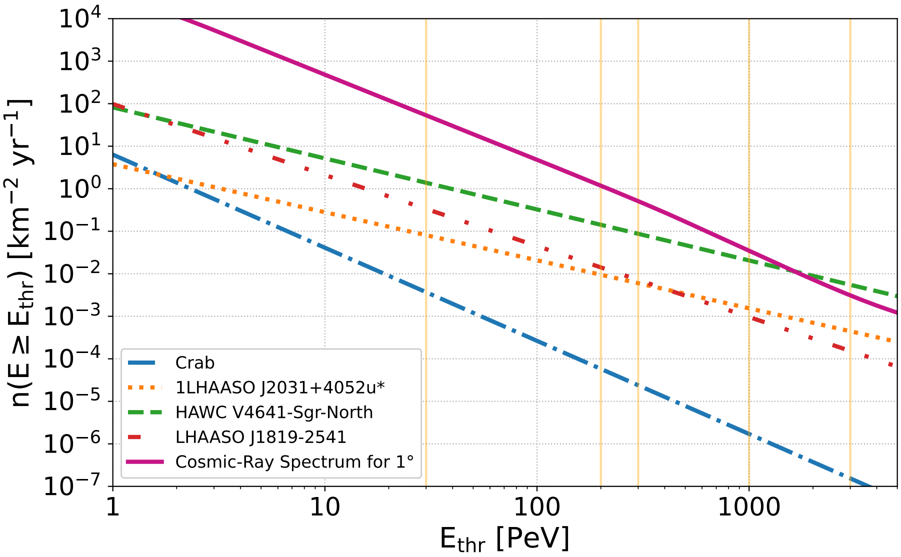

Figure 2: Integral number of photons n_γ and number of cosmic rays (from a circle of 1° radius) reaching Earth per unit area and time as a function of the threshold energy E_{thr}.

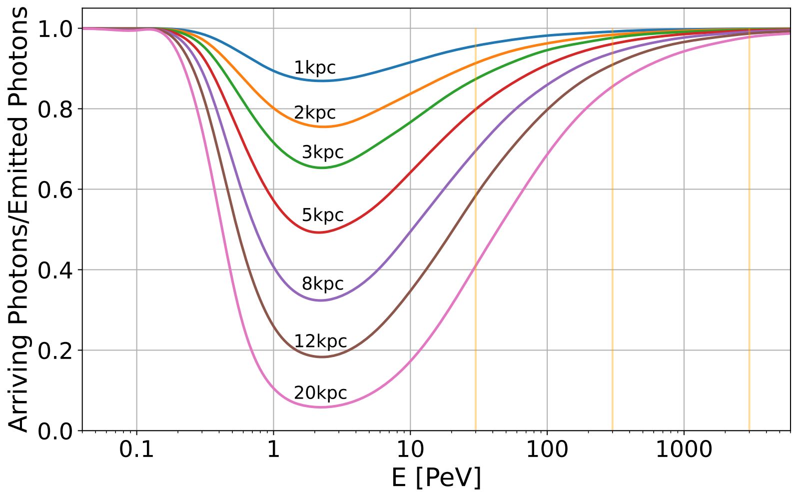

Figure 3: The fraction of photons arriving at Earth without interaction as a function of the initial photon energy is given for a selection of source distances.

are displayed in the right block.

As already seen in Fig. 2, the extrapolated photon numbers for the Crab are by far the lowest with a maximum of 0.072 photons at the smallest infill array. For LHAASO J1819-2541 the highest photon number of 6.5 is also reached at the smallest infill array. Due to the difference in spectral indices, the highest photon numbers for LHAASO J2031+4052u* and V4641 Sgr North are reached in the largest SD array with 13 and 165 photons, respectively. 165 photons is also the highest overall photon number obtained for any of the extrapolations, surpassing even the cosmic-ray background.

Table 1: Extrapolated numbers of UHE photons and cosmic rays for different combinations of detector area and energy threshold, based on detector parameters at the Pierre Auger Observatory [7, 9], for flux extrapolations following the four exemplary sources. The numbers are given for an observation period of ten years. The two last columns refer to hybrid measurements, for which a reduced duty cycle of 15% has been taken into account.

	Exemplary detector parameters				
Area A [km^2]	1.95	27.5	3000	27.5	3000
Energy threshold E_{thr} [PeV]	30 (cf. Auger SD 433 m)	300 (cf. Auger SD 750 m)	3000 (cf. Auger SD 1500 m)	200 (cf. Auger FD + SD 750 m)	1000 (cf. Auger FD + SD 3000 m)
$n_\gamma(E \geq E_{\text{thr}}) \times A \times 10\,\text{yr}$ for a source like					
Crab	0.072	0.0066	0.0046	0.0024	0.0077
1LHAASO J2031+4052u*	1.6	1.7	13	0.39	6.9
V4641 Sgr North	27	24	165	5.9	92
LHAASO J1819-2541	6.5	2.0	4.6	0.6	4.3
$n_{\text{CR}}(E \geq E_{\text{thr}}) \times A \times 10\,\text{yr}$ per 1° radius					
	1082	146	96	47	148

5. Constraining Spectral Parameters

The extrapolated photon numbers for V4641 Sgr North are such high that they exceed current directional upper limits on photon numbers in the energy range of 200−3000 PeV published by the Pierre Auger Collaboration [16]. A zoomed skymap of upper limits around the location of V4641 Sgr North can be seen in Fig. 4, where the circles mark the 95% upper limit and the 39% containment radius of V4641 Sgr North and 1LHAASO J1819-2541, respectively. The experimental upper limits on the photon flux in the circled region add up to 0.059 km^{-2} year^{-1} from the V4641 Sgr North region and 0.27 km^{-2} year^{-1} from the LHAASO J1819-2541 region.

For LHAASO J1819-2541, the extrapolated photon flux from LHAASO data in the same energy range is 0.005 km^{-2} year^{-1}, well below the upper limit. No constraints on the spectral parameters can be made. The extrapolated photon flux for V4641 Sgr North from HAWC data (central value) is 0.130 km^{-2} year^{-1} which exceeds the upper limit by more than a factor 2. It is therefore possible to constrain the spectral parameters which the extrapolation is based on. We focus here on Γ as it has the dominating impact. The results can be seen in Fig. 5 where the extrapolated photon flux is shown as a function of Γ. The upper limit on the photon number is indicated by a horizontal line. The region of the plot where the photon flux exceeds the upper limit can be excluded. This gives rise to a lower limit on the spectral index of $\Gamma \geq 2.29$ which excludes the central value of $\Gamma = 2.2$ but is covered within the quoted experimental uncertainty.

It has not been considered yet that the upper limits on the photon number are calculated based on the assumption of a spectrum with a spectral index of 2.0 [16]. By varying the spectral index towards higher values, the upper limit increases. The effect, however, is rather minor. We can conclude that it is unlikely for the spectrum of V4641 Sgr North to continue up to the highest

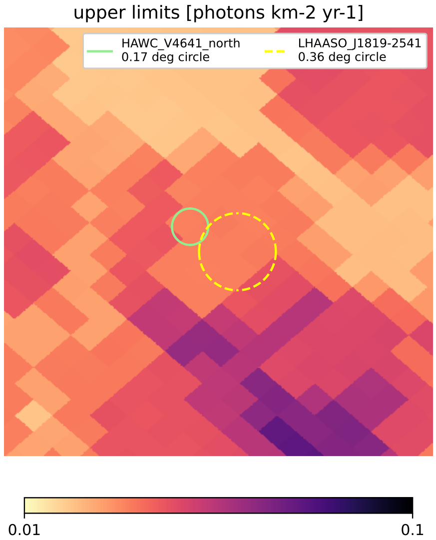

Figure 4: Directional upper limits around the location of V4641 Sgr. The 95% extension upper limit (0.17°) of V4641 Sgr North and the 39% containment radius (0.36°) of LHAASO J1819-2541 are marked as a green and yellow circles, respectively.

energies with a spectral index of $\Gamma = 2.2$ (or below). This shows that giant air shower observatories can constrain the UHE luminosity of PeV γ-sources already with present upper limits.

6. Discussion

We have updated our previous analysis [10] to evaluate the potential of giant air shower observatories to search for UHE photons PeV γ-sources. Specifically, we inspected the new observations of V4641 Sgr North (by HAWC) and of LHAASO J1819-2541 (by LHAASO). Comparing extrapolated photon fluxes to directional upper limits from the Pierre Auger Observatory in the energy range 200−3000 PeV, the range allowed for the spectral index Γ can be constrained, including the observed central value in case of V4641 Sgr North. Thus, first tests of the UHE luminosity of PeV γ-sources are already possible in special cases. The sensitivity of air shower observatories will improve with continuous data taking and, in particular, by lowering the energy thresholds to reduce the gap between gamma-ray and air shower observatories.

Acknowledgements

This work was supported by the German Research Foundation (DFG Project No. 508269468).

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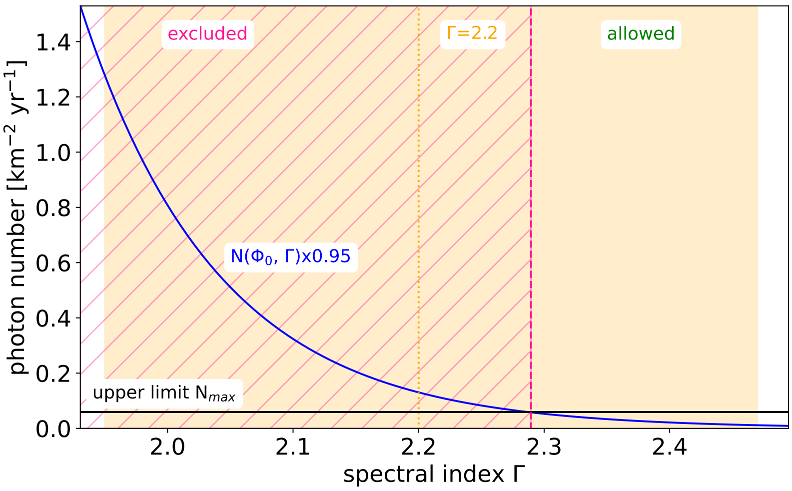

Figure 5: Variation of the extrapolated photon number $N(\Phi_0, \Gamma)$ with $\Gamma = 2.2^{+0.27}_{-0.25}$ and $\Phi_0(E_0 = 47\,\text{TeV}) = 8.2^{+2.8}_{-2.5} \times 10^{-11}\,\text{eV}^{-1}\,\text{km}^{-1}\,\text{year}^{-1}$ in the energy range 200–3000 PeV. $\Gamma = 2.2$ is marked as a yellow line, the error region is marked as a yellow band. The excluded region ($\Gamma \leq 2.29$) where the photon number exceeds the upper limit of $0.059\,\text{km}^{-2}\,\text{year}^{-1}$ (marked as a horizontal black line) is hatched in red.

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