

## A GeV to TeV view of shell-type SNRs

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Shock acceleration by the shells of supernova remnants (SNRs) has been hypothesized to be the mechanism that produces the bulk of Galactic Cosmic Rays, possibly up to PeV energies.

SNRs have been shown to accelerate cosmic rays to TeV energies and whether SNRs are indeed efficient accelerators of protons and nuclei? And what is the maximum energy up to which they can efficiently accelerate particles? Measurements of non-thermal emission, especially in the gamma-ray regime, are essential to answer these questions.

The High-Altitude Water Cherenkov (HAWC) observatory, surveying the northern TeV gamma-ray sky, is currently the most sensitive wide field-of-view survey instrument in the VHE (very-high-energy,  $>100$  GeV) range and has recorded more than five years of data. The Large Area Telescope (LAT) onboard the Fermi satellite has been surveying the GeV gamma-ray sky for more than ten years. Combining measurements from both instruments allows the study of gamma-ray emission from SNRs over many orders of magnitude in energy. In this presentation, I will show measurements of VHE gamma-ray emission from Fermi-LAT-detected SNRs with the HAWC Observatory.

## 1. Introduction

Shell-type supernova remnants (SNRs) have been considered as potential sources of Galactic cosmic rays due to two main arguments (see [\[1\]](#) and references therein). First, diffusive shock acceleration provides a mechanism for the expanding SNR shell to accelerate charged particles to relativistic speeds. Second, given the estimated rate of supernova explosions in the galaxy, average energy released, and the predicted acceleration efficiencies of SNRs, these objects are expected to have sufficient power to sustain the measured intensity of Galactic cosmic rays.

In particular, young SNRs (hundreds of years old) are thought to be efficient accelerators of cosmic rays. Middle-aged SNRs (up to tens of thousands of years) can still be surrounded by a population of previously accelerated cosmic rays. However, it is unclear if SNRs do indeed have the ability to accelerate particles up to the so-called “knee”, a break in the cosmic-ray energy spectrum around a few PeV, which is thought to indicate the maximum energy in the *Galactic* component of cosmic rays.

Any SNR that accelerates cosmic-ray protons to relativistic energies should also produce non-thermal gamma-ray emission due to interactions of these protons with the interstellar medium in/near the remnant. These interactions produce (among other things) neutral pions, which in turn decay into gamma rays. This emission mechanism is referred to as *hadronic emission*. The gamma-ray energy spectrum is predicted to follow the underlying cosmic-ray energy spectrum. Any feature in the cosmic ray spectrum such as a break or cutoff should also be seen in gamma rays, at slightly lower energies. Thus, we can use the gamma-ray energy spectrum from GeVs to hundreds of TeV to investigate cosmic-ray acceleration up to PeV energies in SNRs.

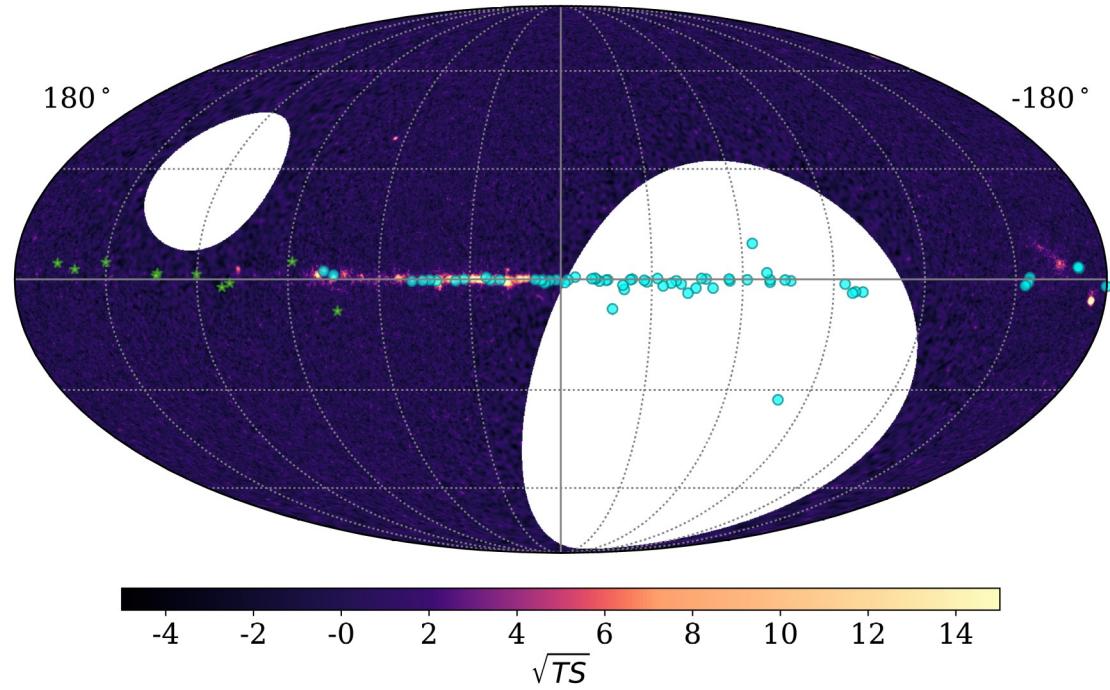
SNRs accelerating electrons to relativistic energies are also expected to produce non-thermal gamma-ray emission due to inverse Compton scattering of the CMB (or in some cases, infrared or optical photon fields) and/or Bremsstrahlung processes in the presence of the latter. electrons are also expected to emit synchrotron radiation at lower wavelengths (radio to X-ray, depending on the ambient magnetic field). These emission mechanisms are referred to as *leptonic* emission. In fact, most known SNR shells have been detected in radio surveys.

HAWC is a large-field-of-view gamma-ray observatory sensitive in the energy range from hundreds of GeV to hundreds of TeV. HAWC has been surveying the northern TeV gamma-ray sky since 2015 and in its latest catalog reports 65 gamma-ray sources [\[2\]](#).

The Large Area Telescope (LAT) aboard the *Fermi* satellite has been surveying the gamma-ray sky in the energy range from tens of MeV to 2 TeV for more than ten years now. The 10-year *Fermi*-LAT data release (4FGL-DR2 [\[3\]](#)) contains 24 firmly identified shell-type SNRs and an additional 19 sources that are less firmly associated with SNRs, as well as 96 sources classified as “spp” type, indicating potential association with a PWN and/or SNR. At least three SNRs (IC 443, W44, and W51C) show a significant spectral feature, the “pion bump” at around 100 MeV, indicating that the gamma-ray emission is dominated by hadronic processes. However, for many other SNRs, it is currently not clear if the gamma-ray emission is dominated by hadronic or leptonic processes.

Several SNRs have also been detected at TeV energies. As of 2021/02/16, TeVCat1, a listing of TeV gamma-ray sources seen by HAWC and other ground-based gamma-ray observatories such as

<sup>1</sup><http://tevcat.uchicago.edu/>



**Figure 1:** HAWC's all-sky significance map for the point source search, based on 1523 days of observation, in Galactic coordinates [2]. White areas of the sky are not observed by HAWC. Green stars mark the position of shell-type SNRs and SNR candidates from the LAT catalogs as described in Section A. Aqua circles mark SNRs and SNR candidates that do not pass the selection criteria (outside of HAWC's field of view or overlapping with significant gamma-ray emission seen by HAWC).

the imaging air-Cherenkov telescopes H.E.S.S., MAGIC, and VERITAS, lists 16 VHE gamma-ray sources associated with shell-type SNRs and 11 sources ascribed to the interaction of SNRs with nearby molecular clouds. However, many of these sources show spectral softening or a cutoff between GeV and TeV energies, indicating that those SNRs may *not* be able to accelerate cosmic rays up to PeV energies.

Here, we perform a search for TeV gamma-ray emission from GeV-emitting SNRs, focussing on SNRs that are not significantly detected by HAWC. Upper limits on the TeV gamma-ray flux will be determined. For SNRs where the upper limits are below the extrapolation from the GeV gamma-ray spectrum, we will have shown the presence of a break or cutoff in the spectrum, and can relate upper limits on the cutoff energy in the gamma-ray spectrum to the cutoff energy in the underlying proton or electron spectrum.

This contribution describes the source selection and analysis method. The results will be provided in a separate, peer-reviewed paper (currently under preparation).

## 2. Data and Analysis Methods

### 2.1 Source Selection

GeV-detected shell-type supernova remnants (SNRs) and SNR candidates were selected from the following four catalogs released by the *Fermi*-LAT collaboration:

- The LAT 10-year Source Catalog (4FGL-DR2, [3, 6]),
- The Third Fermi-LAT Catalog of High-Energy Sources (3FHL, [7]),
- Extended Sources in the Galactic Plane (FGES, [8]), and
- The First LAT Supernova Remnant Catalog (1SC, [9]).

Sources were selected from these catalogs as follows:

- 1SC sources with the “classification” property given as “classified” (meaning, classified as SNRs).
- 4FGL-DR2 and 3FHL sources with source type “SNR” (firmly identified as a shell-type SNR) or “snr” (less firmly associated with a shell-type SNR).
- 3FHL sources associated with a 4FGL-DR2 SNR/snr source (via the “ASSOC\_FHL” property)
- FGES sources not associated with a known PWN, given the associations listed in the FGES paper and the source types in the 3FHL, 4FGL-DR2, and TeVCat 2.
- 3FHL and 4FGL-DR2 sources of type “spp”<sup>3</sup> within 30° of a previously selected FGES or 1SC source.

Sources were required to have declinations (J2000) between  $-25^\circ$  and  $65^\circ$  to lie within HAWC’s field of view.

Using the HAWC significance maps upon which the 3HWC catalog [2] was based, SNRs were selected that did not overlap with regions where HAWC detects significant gamma-ray emission.

As all four LAT catalogs used different datasets and different energy ranges, a single SNR may be detected in only a subset of the catalogs. Additionally, SNRs detected in multiple catalogs may be found at slightly different locations or with different morphologies. Sources within 30° of each other were considered to be in the same “region” if their extensions were also similar, which each region likely corresponding to the same physical source.

Table 1 shows the ten selected SNRs and SNR candidates<sup>2</sup> that are found in more than one catalog, leading to 21 sources to be studied.

### 2.2 HAWC Data analysis

#### 2.2.1 Dataset and Analysis Software

The analysis presented here is based on 1523 days of data recorded by HAWC. The same dataset was used for 3HWC, the third HAWC catalog. More details about the dataset can be found in [2].

HAWC-internal software was used for data reduction (calibration, event reconstruction, background rejection and binning). The multi-mission maximum likelihood (3ML) framework [10] with the HAWC accelerated likelihood plugin (HAL) [11] was used to analyze the binned data.

<sup>2</sup><http://tevcat.uchicago.edu>

<sup>3</sup>“Sources of unknown nature but overlapping with known SNRs or PWNe and thus candidates to these classes.”

**Table 1:** SNRs and SNR candidates selected as described in Section 2. All sources in the catalog are included. RA and Dec are the Right Ascension and Declination of the source center (J2000 epoch). Ext. is the extension (radius for sources modeled with a disk morphology, approximate radius or semi-major axis of a circle or ellipse covering the emission region for sources with irregular morphologies). Thin lines delineated between “regions” (e.g., the first three sources are all presumed to be associated with the same physical object).

Name	Association	RA [°]	Dec [°]	Ext. [°]	Shape	$\pm \sqrt{\frac{1}{T} S}$
3FHL J2051.0+3040e	Cygnus Loop	312.75	30.67	1.65	CygnusLoop.fits	0.60
4FGL J2051.0+3049e	Cygnus Loop	312.75	30.83	1.65	CygnusLoop.fits	0.44
SNR074.0-08.5		312.77	30.90	1.74	Disk	0.66
SNR089.0+04.7		311.15	50.42	0.97	Disk	-0.07
4FGL J2045.2+5026e	HB 21	311.32	50.44	1.19	Disk	-1.34
SNR109.1-01.0		345.41	58.83	0.00		-0.41
4FGL J2301.9+5855e	CTB 109	345.49	58.92	0.25	Disk	-0.50
3FHL J2301.9+5855e	CTB 109	345.49	58.92	0.25	Disk	-0.50
FGES J2302.0+5855		345.49	58.92	0.25	Disk	-0.50
SNR111.7-02.1		350.85	58.83	0.00		0.46
4FGL J2323.4+5849	Cas A	350.86	58.82	0.00		-0.45
3FHL J2323.4+5848	Cassiopeia A	350.87	58.82	0.00		0.44
4FGL J0025.3+6408	Tycho	6.34	64.15	0.00		-1.21
3FHL J0025.5+6407	Tycho	6.38	64.13	0.00		-1.20
4FGL J0221.4+6241e	HB 3	35.36	62.69	0.80	Disk	-0.01
4FGL J0222.4+6156e	W 3	35.62	61.94	0.60	W3.fits	-0.52
4FGL J0427.2+5533e	SNR G150.3+04.5	66.82	55.55	1.51	Disk	-0.22
3FHL J0427.2+5533e	SNR G150.3+4.5	66.82	55.55	1.51	Disk	1.10
FGES J0427.2+5533		66.82	55.55	1.52	Disk	1.11
4FGL J0500.3+4639e	HB 9	75.08	46.66	1.00	HB9.fits	-1.28
4FGL J0526.7+4254	SNR G166.0+04.3	81.69	42.92	0.00		0.00

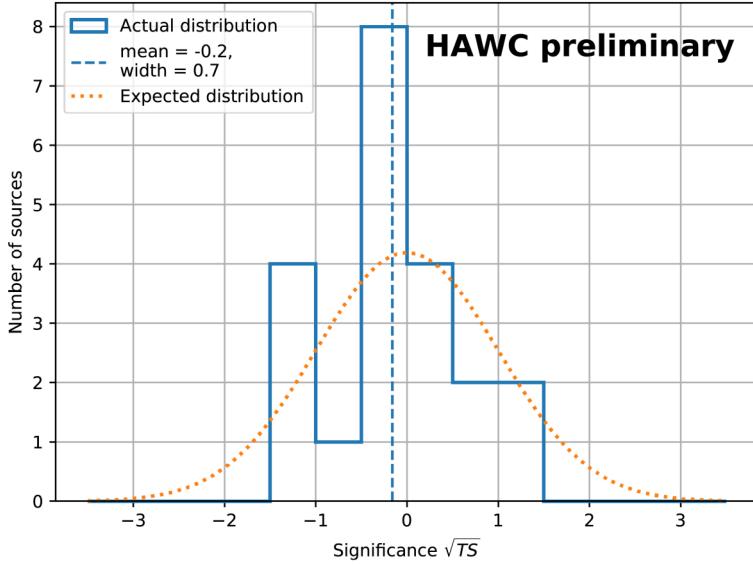
Each source was fit separately with a region of interest (ROI) centered on the source and with a radius of 5° for point sources, 5° + source extension (see Table 1) for extended sources.

### 2.2.2 Source Modeling

Each source was modeled according to the position and morphology (disk or external template) given in the relevant LAT catalog. All parameters related to the morphology were kept fixed in the analysis.

For the spectrum, two separate analyses were carried out (one using the spatial model as described above):

1. The spectral shape was modeled according to the relevant LAT catalog, using a free normalization. A normalization parameter was introduced which scales the flux normalization relative to the extrapolation from the LAT energies.
2. The spectral shape was modeled according to the relevant LAT catalog, multiplied by an



**Figure 2:** Distribution of the detection significances from Table 1. The expected distribution is a Gaussian distribution with mean 0 and width 1.

exponential cutoff  $\exp^{-\frac{E}{E_c}}$  with free cutoff energy  $E_c$ . In this case, all other parameters including the normalization were kept fixed.

A forward-fold likelihood fit (see [10]) was performed to find the best-fit values of the normalization constants or the cutoff energy  $E_c$ . For the first case, we also determined the test statistic  $T \approx -2 \ln \frac{L_0}{L_s}$ , where  $L_s$  is the value of the likelihood at the best-fit values and  $L_0$  is the value of the likelihood without the source in question (i.e., with  $\sqrt{TS} = 0$ ).  $\pm \sqrt{T}$  then corresponds to the detection significance of a given source, where we chose the negative sign if and only if

### 2.2.3 Upper Limit Determination

As none of these sources were detected by HAWC, the most we can do is to set upper limits on the flux normalization. If the upper limit on  $s$  is above 1, that would mean that the non-detection of the given source is compatible with the extrapolation of the GeV spectrum to TeV energies (meaning, the source could be just too weak for HAWC to be able to see it) and we are not able to constrain its spectrum further. However, for sources with an upper limit on  $s$  below one, we can conclude that the HAWC non-detection is inconsistent with the extrapolation of the GeV spectrum to TeV energies — meaning that the spectrum must have a break or cutoff at TeV energies or above. We can try to set an upper limit on such a cutoff.

In both cases (upper limit on the normalization scale factor and upper limit on the cutoff energy  $E_c$ ), the limits were obtained from the likelihood profile. 90% confidence level upper limits correspond to a 3.28 increase in the log-likelihood.

## 2.2.4 Systematic Uncertainties

The systematic uncertainties due to the modeling of the HAWC detector were taken into account as described in [2], with the addition of the systematic uncertainty due to the source spectrum assumed in the preparation of the detector response ~~for~~ point sources, we also accounted for HAWC's systematic pointing uncertainty by letting the source positions float within the uncertainty and profiling over the source position when calculating the upper limit.

## 3. Results

Figure 2 shows the significance distribution. The distribution is compatible with a Gaussian distribution with mean 0 and width 1 as expected from the “background-only” case, indicating that there is no evidence for sub-threshold TeV emission in the selected sample of GeV-detected SNRs and SNR candidates.

## 4. Outlook

Full results including upper limits on the TeV emission from GeV detected SNRs ~~will~~ be presented in a dedicated publication (under preparation).

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