PROCEEDINGS OF SCIENCE

Searches for UHE neutrinos and upward-going showers at the Pierre Auger Observatory

Baobiao Yue[a,*] **for the Pierre Auger Collaboration**[b]

[a] *Faculty of Mathematics and Natural Sciences, University of Wuppertal, 42119 Wuppertal, Germany*

[b] *Observatorio Pierre Auger, Av. San Martín Norte 304, 5613 Malargüe, Argentina*

Full author list: https://www.auger.org/archive/authors_2025_11.html

E-mail: spokespersons@auger.org

The Pierre Auger Observatory plays a crucial role in detecting the most energetic particles in the Universe, including cosmic rays and neutrinos, to unravel their origins and contribute to multi-messenger astronomy. For the past two decades, during its Phase I, the Observatory has been actively searching for ultra-high-energy (UHE) neutrinos with energies above 0.1 EeV. These neutrinos can travel horizontally through the atmosphere or skim the Earth's crust, producing young air showers that can be detected by the Surface Detector Array, comprising 1,660 water-Cherenkov stations spread over an area of 3,000 km^2. Searches have been conducted for both point sources and diffuse flux. In addition, the Fluorescence Detector, consisting of 27 telescopes, has been used to search for upward-going air showers, motivated by the detection of 'anomalous' events by the ANITA instrument. In this contribution, we summarize the scientific results of these searches and discuss their astrophysical implications.

Presented at the 32nd International Symposium on Lepton Photon Interactions at High Energies
Madison, Wisconsin, USA
August 25-29, 2025

*Speaker

1. Introduction

The origin and production mechanisms of ultra-high-energy cosmic rays (UHECRs, $E \gtrsim 1$EeV) remain long-standing questions in astroparticle physics. All models predict accompanying ultra-high-energy neutrinos from charged-pion decays, produced either within the sources ("astrophysical" neutrinos) or during UHECR propagation through background radiation fields ("cosmogenic" neutrinos).

The Pierre Auger Observatory [1], located near Malargüe, Argentina, is the largest UHECR detector worldwide. Its hybrid design combines a Surface Detector (SD) array and a Fluorescence Detector (FD). The SD1500 consists of about 1660 water-Cherenkov stations on a 1500 m triangular grid, covering ~3000 km^2 with nearly 100% duty cycle, sampling the lateral particle distributions at ground. The FD comprises 27 telescopes at four sites and records the longitudinal shower development on clear, moonless nights, yielding a duty cycle of ~15%.

The Antarctic Impulsive Transient Antenna (ANITA), flown on long-duration balloons over Antarctica, has detected radio impulses consistent with UHECR air showers reflected from the ice. In addition, two anomalous upward-going events have been reported [2, 3]. These are not compatible with reflected UHECRs and may originate from upward-going air showers induced by τ decays from UHE ν_τ interactions in the Earth. However, their arrival directions and energies imply strong neutrino attenuation, requiring fluxes already constrained by IceCube and Auger [4–6].

In this contribution, we present the analysis of data collected with the SD1500 in the search for UHE neutrinos, as well as an FD study targeting upward-going air showers.

2. Search for UHE neutrinos

A key challenge in the search for UHE neutrinos is distinguishing neutrino-induced air showers from the overwhelming background of proton and heavier nuclei. At large zenith angles ($\theta \gtrsim 60°$), cosmic rays interact high in the atmosphere. Therefore, their electromagnetic component is largely absorbed and mainly muons reach the ground. Neutrinos, due to their much smaller cross-section, may interact deep in the atmosphere and thus produce detectable electromagnetic signals even for nearly horizontal showers. This provides a characteristic signature in the SD. Another channel arises from Earth-skimming ν_τ that interact in the crust and produce τ leptons which decay in the atmosphere, generating slightly upward-going showers that can trigger the SD.

The analysis is therefore divided into Earth-skimming (ES, 90°–95°) and downward-going (DG, 60°–90°) channels. The DG channel is further separated into DGL (58.5°–76.5°) and DGH (75°–90°). Shower discrimination relies on variables describing the spread of the 25 ns-binned traces, exploiting the broader time distribution expected from electrons with multiple scattering relative to the narrow signals induced by muons. In the ES channel, the average area-over-peak ($\langle$AoP$\rangle$) serves as the main observable [7]. For DG, additional observables based on individual AoP values are combined using a Fisher discriminant analysis [7].

The search follows a blind procedure: a small burn sample is used to define cuts that select inclined events and identify those with large electromagnetic components. Final thresholds on $\langle$AoP$\rangle$ (ES) or on the Fisher discriminant (DG) are chosen to yield fewer than one expected background

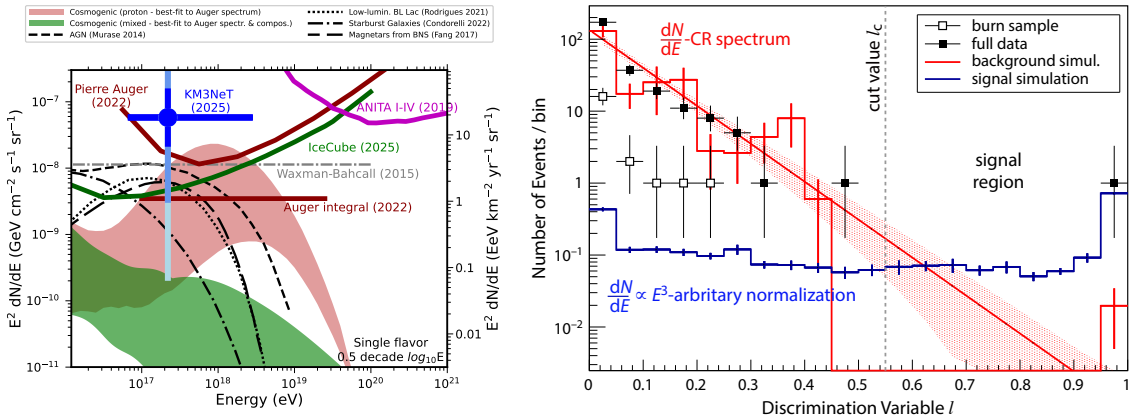

Figure 1: Left: Upper limits on the diffuse flux of neutrinos, both integral (straight solid line) as well as differential (curved solid line). Also shown are upper limits from IceCube and ANITA and the expected neutrino fluxes under different theoretical assumptions and scenarios, including ones based on Auger data (cf. [8]). For details and references see [7]. Right: Distributions of the discriminating variable l, as defined in Eq. (1), for a simulated isotropic background weighted and normalized with the measured UHECR spectrum in the energy range 10^{17} eV to 10^{20} eV (red histogram with an exponential fit and its uncertainty band); the signal simulation with energy $10^{16.6}$ eV to $10^{18.5}$ eV weighted with an E^{-3} spectrum and arbitrarily normalized to one event (blue histogram); and the data distributions, both for the 10% burn sample and the full data set (open and filled symbols). The cut value l_c discriminating signal and background is indicated by the vertical dashed line.

event over decades of exposure. These cuts are then applied to the full dataset from January 1, 2004 to December 31, 2021.

No neutrino candidates are found in any channel. Upper limits on a diffuse flux of the form $\phi = k \times E_\nu^{-2}$ are obtained; for energies between 10^{17} and 2.5×10^{19} eV, the 90% C.L. limit is $k = 3.5 \times 10^{-9}$ GeV cm^{-2} s^{-1} sr^{-1}. Energy-binned limits (in 0.5 $\log_{10}(E_\nu/\text{eV})$ bins) illustrate the energy dependence of the sensitivity, with the best performance around 10^{18} eV. Limits from Auger, IceCube, and ANITA, together with model predictions, are shown in Fig.1 (left). These results constrain several classes of cosmogenic and astrophysical models. In particular, pure-proton cosmogenic models with strong source evolution are strongly disfavored, while mixed-composition models predict fluxes generally an order of magnitude below current sensitivity. Some AGN neutrino-production scenarios are excluded, and models involving BL-Lacs, magnetars, or starburst galaxies are increasingly constrained.

3. Search for upward-going showers

Two anomalous upward-going events detected during the ANITA I and ANITA III flights have attracted considerable attention, especially since Standard Model (SM) interpretations in terms of upward-going ν_τ have been largely ruled out [4–6]. This has motivated scenarios beyond the SM, invoking new particles that could generate upward-going showers [9–11]. To probe such possibilities, we performed a dedicated search for upward-going air showers in data recorded with the FD of the Pierre Auger Observatory [12].

The inferred energies of the ANITA events depend on the altitude at which the showers start. Simulations of showers with starting heights $0 < h < 9\,\mathrm{km}$ indicate that the ANITA I (III) anomalous event, with elevation angle 27.4° (35.0°) corresponding to zenith angles $\theta = 116.7°$ (124.5°), requires minimum energies of about 0.2 EeV (0.15 EeV) for showers starting at $h \sim 5\,\mathrm{km}$ ($h > 5\,\mathrm{km}$) [4]. Guided by these results, our FD search is restricted to zenith angles $\theta > 110°$ (elevation > 20°), for which only the FD is sensitive, and to energies $E > 0.1\,\mathrm{EeV}$.

FD shower reconstruction uses a standard two-step method (geometry from pixel timing plus a Gaisser-Hillas profile fit) and an alternative Global Fit (GF) exploiting all pixels [13]. Upward or downward going is inferred from the pixel time sequence. In the absence of SD information, various misreconstructed cosmic-ray showers and upward-going monitoring laser shots can mimic upward-going showers. A 10% burn sample is therefore used to characterize these backgrounds and define selection cuts.

A blind analysis is then implemented. Simulations and the burn sample are used to optimize the selection, which is subsequently applied to FD data from January 1, 2004 to December 31, 2018. Background UHECR showers (proton, helium, nitrogen, iron) are generated with CONEX over 0.1-100 EeV, weighted to the measured spectrum [14]. Signal simulations consist of upward-going proton showers in the range 0.03-10 EeV, with starting altitudes between $h = 0$ and 9 km and impact points sampled over a $100 \times 100\,\mathrm{km}^2$ area centered on the SD array.

Selection cuts optimized with simulations are applied sequentially. Events must pass laser vetoes, satisfy quality requirements on atmospheric conditions and cloud coverage, have at least six triggered pixels, and be reconstructed as upward-going by a simple time-geometry fit. A GF reconstruction is then used to require consistency with a shower-like dE/dX profile and good reconstruction quality, including $\theta > 110°$. After all cuts, 255 events remain from the original 7.6×10^6 events.

To further discriminate between upward-going showers (signal) and UHECR events (background), we use a likelihood-ratio variable

$$l = \frac{\arctan\left[\ln\left(\frac{\max(L_{\mathrm{up}}, L_{\mathrm{down}})}{L_{\mathrm{down}}}\right) \cdot \zeta\right]}{\pi/2}, \tag{1}$$

where $l \in [0, 1]$ and larger values favour the upward-going hypothesis. If $L_{\mathrm{down}} > L_{\mathrm{up}}$, then $l = 0$, while $l = 1$ if only the event can only be reconstructed upward. The parameter ζ is chosen such that signal events with $L_{\mathrm{up}} > L_{\mathrm{down}}$ are approximately uniformly distributed in l. The final cut $l > l_c$ is optimized to minimize the upper limit on the integral flux, yielding $l_c = 0.55$ and an expected background of $n_{\mathrm{bkg}} = 0.27 \pm 0.12$ events.

Applying all cuts to the full data set yields one candidate event with $l = 1$, six triggered pixels, and moderate reconstruction quality [12]. Its properties are compatible with background expectations, and similar events are found in UHECR simulations. The results are shown at Fig. 1 (right).

Using the same selection on signal simulations, we compute the effective area and exposure of the FD to upward-going showers as functions of energy and starting altitude. The exposures of ANITA I and III are derived analytically following [4]. The resulting FD exposure exceeds that of ANITA by factors between 2 and 2000 in the zenith range $110° \leq \theta \leq 130°$ [12].

If the ANITA events are interpreted as upward-going showers, the flux required to produce one event in each ANITA flight would imply an expectation of $10-70$ events in the Auger FD, depending on the assumed energy spectrum and altitude distribution (uniform in altitude or motivated by τ decays). Given that only one event consistent with background is observed, upward-going showers cannot account for the anomalous pulses detected by ANITA, which thus remain unexplained.

The FD and ANITA exposures also differ in their dependence on shower altitude. The FD is most sensitive to low-altitude showers close to the detector and has limited sensitivity to showers starting at higher altitudes or with unusual longitudinal profiles. While such effects could reduce the expected FD event number, they would be difficult to reconcile with the scenarios of SM particle decays and interactions.

4. Conclusions

The search for UHE neutrinos with the SD of the Pierre Auger Observatory has yielded no candidates in the period from January 1, 2004 to December 31, 2021. As a result, competitive upper limits have been set on the diffuse neutrino flux, with the best sensitivity around 1 EeV and strong constraints on cosmogenic models assuming a pure proton composition. In parallel, searches for upward-going showers with the FD of the Pierre Auger Observatory, motivated by the anomalous events reported by ANITA, have been performed. Between January 1, 2004 and December 31, 2018, only one event was found, consistent with background expectations. Given the significantly larger exposure of the Auger FD compared to ANITA, at least ~ 10 upward-going events would be expected under various assumptions on the energy flux slope and decay height distribution. The observation of only one event that is compatible with background disfavors a shower origin for the ANITA anomalous events, leaving their nature still unresolved.

References

[1] Pierre Auger collaboration, *The Pierre Auger Cosmic Ray Observatory*, *Nucl. Instrum. Meth. A* **798** (2015) 172 [1502.01323].

[2] ANITA collaboration, *Characteristics of Four Upward-Pointing Cosmic-Ray-like Events Observed with ANITA*, *Phys. Rev. Lett.* **117** (2016) 071101 [1603.05218].

[3] ANITA collaboration, *Observation of an Unusual Upward-Going Cosmic-Ray-like Event in the Third Flight of ANITA*, *Phys. Rev. Lett.* **121** (2018) 161102 [1803.05088].

[4] A. Romero-Wolf et al., *A comprehensive analysis of anomalous ANITA events disfavors a diffuse tau-neutrino flux origin*, *Phys. Rev. D* **99** (2019) 063011 [1811.07261].

[5] I. Safa, A. Pizzuto, C.A. Argüelles, F. Halzen, R. Hussain, A. Kheirandish et al., *Observing EeV neutrinos through Earth: GZK and the anomalous ANITA events*, *JCAP* **01** (2020) 012 [1909.10487].

[6] S. Chipman, R. Diesing, M.H. Reno and I. Sarcevic, *Anomalous ANITA air shower events and tau decays*, *Phys. Rev. D* **100** (2019) 063011 [1906.11736].

[7] Pierre Auger collaboration, *Probing the origin of ultra-high-energy cosmic rays with neutrinos in the EeV energy range using the Pierre Auger Observatory*, *JCAP* **10** (2019) 022 [1906.07422].

[8] C. Petrucci and P.A. Collaboration, *Investigating the UHECR characteristics from cosmogenic neutrino limits with the measurements of the Pierre Auger Observatory*, in *Proceedings of Science (ICRC2023)*, vol. 444, p. 1520, 2024, DOI.

[9] D.B. Fox, S. Sigurdsson, S. Shandera, P. Mészáros, K. Murase, M. Mostafá et al., *The ANITA Anomalous Events as Signatures of a Beyond Standard Model Particle, and Supporting Observations from IceCube*, 1809.09615.

[10] J.H. Collins, P.S. Bhupal Dev and Y. Sui, *R-parity Violating Supersymmetric Explanation of the Anomalous Events at ANITA*, *Phys. Rev. D* **99** (2019) 043009 [1810.08479].

[11] L. Heurtier, Y. Mambrini and M. Pierre, *A Dark Matter Interpretation of the ANITA Anomalous Events*, *Phys. Rev. D* **99** (2019) 095014 [1902.04584].

[12] Pierre Auger collaboration, *Search for the Anomalous Events Detected by ANITA Using the Pierre Auger Observatory*, *Phys. Rev. Lett.* **134** (2025) 121003 [2502.04513].

[13] V. Novotny and P.A. Collaboration, *Measurement of the spectrum of cosmic rays above* $10^{16.5}$ *eV with Cherenkov-dominated events at the Pierre Auger Observatory*, in *Proceedings of the 36th International Cosmic Ray Conference (ICRC2019)*, p. 374, 2019.

[14] Pierre Auger collaboration, *Measurement of the cosmic-ray energy spectrum above* 2.5×10^{18} *eV using the Pierre Auger Observatory*, *Phys. Rev. D* **102** (2020) 062005 [2008.06486].