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Search for Ultra-high-energy Neutrons from Galactic Sources with the Pierre Auger Observatory

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Abstract

Deflections in the propagation of charged ultra-high-energy cosmic rays (UHECRs) caused by magnetic fields make the identification of their sources challenging. On the other hand, the arrival directions at Earth of neutrons point directly to their origin. The emission of UHECRs from a source is expected to be accompanied by the production of neutrons in its vicinity through interactions with ambient matter and radiation. Since free neutrons travel a mean distance d kpc^{-1} = 9.2 (E EeV^{-1}) before decaying, a neutron flux in the EeV range could be detected on Earth from sources of UHECRs in our Galaxy. Using cosmic-ray data from Phase I of the Surface Detector of the Pierre Auger Observatory, we search for neutron fluxes from Galactic candidate sources. We select more than 1000 objects of astrophysical interest, stacking them into target sets. The targets all have decl. within the exposure of the Observatory, ranging from $-90°$ up to $+45°$ for energies above 1 EeV (and up to $+20°$ for energies down to 0.1 EeV). Given that a neutron air shower is indistinguishable from a proton one, there is a significant background due to cosmic rays. A neutron flux from the direction of a candidate source would be identified by a celestial density of events that significantly exceeds the expected density of cosmic rays for that direction. No significant excess is found at any tested target direction, and an upper limit on the neutron flux is calculated for each candidate source.

Unified Astronomy Thesaurus concepts: Ultra-high-energy cosmic radiation (1733); Galactic cosmic rays (567); Cosmic rays (329); High energy astrophysics (739)

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1. Introduction

Neutral particles can be used to study sources of ultra-high-energy cosmic rays (UHECRs) since they are not deflected by magnetic fields, and their arrival directions on Earth point directly to their origin. Neutral particles are expected to be produced in the vicinity of the sources of UHECRs. In particular, ultra-high-energy (UHE) neutrons are expected to be produced near any source accelerating protons and nuclei due to nuclear collisions, pion photoproduction, and photodisintegration of UHE nuclei. Although free neutrons are unstable, with a mean lifetime of ∼878 s (Particle Data Group 2024), in the ultrarelativistic regime, they travel a mean distance d of around d kpc^{-1} ≈ 9.2 (E EeV^{-1}) before decaying. This range is comparable to typical Galactic scales, so a neutron flux from Galactic sources could be detected in the EeV range.

Among neutral particles, photons are easier to distinguish from the bulk of the nuclei cosmic rays (CRs), as the air showers they induce in the atmosphere have different characteristics. Indeed, extensive studies have been carried out to search for photon-like events at the highest energies, with no detection so far (see The Pierre Auger Collaboration 2024; and references therein). On the other hand, neutrons induce air showers that are indistinguishable from those generated by protons. However, neutron fluxes can be identified in an indirect way through an excess of events around the direction of their sources.[95] We search for such excesses, comparing the observed CR density with the one expected from an isotropic distribution, as done in previous studies by the Pierre Auger Collaboration (The Pierre Auger Collaboration 2012, 2014a), albeit with a different method.

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[95] Note that an EeV proton deflects about ∼50° while traveling 1 kpc in a transverse field of $\mathcal{O}(\mu\,\mathrm{G})$, so we do not expect significant excesses due to protons at these energies.

The dominant processes to create energetic neutrons and photons are pion-production interactions in which a UHE charged hadron interacts with ambient photons or nuclei. Neutrons are produced in charge-exchange interactions, while photons are the result of the decay of neutral pions (for a review on the neutron production, see, e.g., G. A. Medina-Tanco & A. A. Watson 2001; M. Bossa et al. 2003; V. Cavasinni et al. 2006; L. A. Anchordoqui et al. 2007a; The IceCube Collaboration 2016). The likelihood of charge-exchange interactions that produce neutrons is of the same order of magnitude as that of producing neutral pions. On average, neutral pions carry only a small fraction of the parent proton energy, whereas a neutron acquires most of it. Neutrons can also be produced by photodisintegration of CR nuclei. In this case, the photon emitted typically carries an energy about 3 orders of magnitude lower than the ejected neutron (L. A. Anchordoqui et al. 2007b). Therefore, we expect the hadronic production of neutrons to exceed that of photons at the same energy. Moreover, muon-poor showers initiated by photons are typically reconstructed with energies lower than the actual energy of the primary photon because the reconstruction methods based on the measurements of the shower size are calibrated on the bulk of the measured showers, which are induced by nuclei (The Pierre Auger Collaboration 2023a). In contrast, neutron-induced showers are indistinguishable from those initiated by protons and are thus reconstructed at their true energy. For these reasons, a source of UHECRs is more detectable by a flux of neutrons than by a flux of photons if the source is within the neutron-decay distance.

Previous searches carried out by the Pierre Auger Collaboration did not detect any excess ascribable to a neutron flux (The Pierre Auger Collaboration 2012, 2014a). In this work, we present updated results of the targeted search for point sources of neutrons, extending the maximum zenith angle from 60° to 80° for events above 1 EeV, which allows us to reach a decl. up to 45°. We also lower the energy threshold, investigating events with energies between 0.1 and 1 EeV with zenith angles up to 55°, reaching a decl. up to +20°. Additionally, in this work, we update the analysis method compared to previous studies. We compare the celestial density of CRs observed at the direction of the target with the density expected from an isotropic distribution. However, instead of using a top-hat function to define an acceptance solid angle, as in previous analyses, we compute, and sum, the probability density of every event at the direction of a targeted source, accounting for the arrival direction of each event as well as an estimate of the event-by-event angular uncertainty. The sum of all the event probability functions is the celestial CR density function (particles per unit solid angle).

2. Datasets

The Pierre Auger Observatory is the largest facility in the world designed to study UHECRs. It is located in Argentina, at a latitude of $\sim-35°$. The events used in this work were recorded by the Surface Detector (SD) array from 2004 January 1, up to 2022 December 31, the so-called Phase I of the Observatory. The SD is an array of 1660 water-Cherenkov detectors (WCDs) arranged in a triangular grid, covering an area of approximately 3000 km^2 with a duty cycle $\sim$100% (The Pierre Auger Collaboration 2015). While the spacing of 1600 WCDs is 1500 m, 60 additional stations were deployed in an area of around 24 km^2, with a reduced spacing of 750 m in this subarray. Hereafter, the dataset recorded with this portion of the array will be referred to as the SD-750 dataset, while the one with 1500 m spacing will be referred to as SD-1500. For both datasets, the most stringent selection criteria are used, accepting events in which all six nearest neighboring grid positions of the station with the highest signal were occupied by stations that were operational.[96]

In this analysis, we consider events recorded with the SD-1500 array with an energy above 1 EeV and zenith angles up to 80°. Events with zenith angles up to 60° are reconstructed with a different algorithm (The Pierre Auger Collaboration 2020a) than those in the zenith range from 60° to 80° (The Pierre Auger Collaboration 2014b). In the following, we will refer to the former as *vertical* and the latter as *inclined* events.

The total exposure of the SD-1500 array, considering the full Phase I of the Observatory and after applying quality cuts, is 110,000 km^2 sr yr, yielding 2,654,574 events with $E \geqslant 1$ EeV. Following previous studies by the Pierre Auger Collaboration on the search for point sources of neutrons, we divide the dataset into three independent energy ranges: 1 EeV $\leqslant E <$ 2 EeV (2,009,321 events), 2 EeV $\leqslant E <$ 3 EeV (382,576 events), and $E \geqslant 3$ EeV (262,677 events). The analysis is performed separately on these energy intervals, as well as on the cumulative range $E \geqslant 1$ EeV.

The SD-750 dataset contains events recorded from 2008 August 1 to 2022 December 31. The total exposure of the SD-750 array, after applying the quality cuts and including zenith angles up to 55°, is 408 km^2 sr yr, resulting in 1,455,168 events between 0.1 and 1 EeV. This dataset has been divided into three independent energy ranges: 0.1 EeV $\leqslant E <$ 0.2 EeV (1,069,076 events), 0.2 EeV $\leqslant E <$ 0.3 EeV (236,367 events), and 0.3 EeV $\leqslant E \leqslant$ 1 EeV (149,725 events). The analysis is performed in these three energy ranges plus the cumulative dataset with events with energies between 0.1 and 1 EeV.

3. Target Sets

We search for neutron emission from astrophysical candidate sources. These sources are divided into 12 different target sets. We selected candidate sources with a decl. up to +45°, resulting in a total of 1092 target directions investigated using the SD-1500 dataset. For the analysis using the SD-750 dataset, we select sources within a measured distance of 1 kpc, ensuring that the neutron flux can reach Earth within approximately one attenuation length across all energy ranges. Given that the SD-750 dataset contains events with a zenith angle up to 55°, only sources with a decl. less than +20° can be considered. Therefore, of the 1092 sources selected for the SD-1500 analysis, 70 met the criteria and were included in the analysis with the SD-750 dataset. If a candidate source is in more than one catalog, we consider it only in the most exclusive target set, i.e., the one with fewer objects. Based on the angular resolution of the Observatory (The Pierre Auger Collaboration 2020a), whenever multiple targets from the same set are found within less than 0.°2, we treat them as one single effective source. This happens in particular in the case of multiple sources in the same star cluster. Indeed, in almost all cases, the quoted distance in the reference catalog was the

[96] For events with zenith angle between 60° and 80°, where the stations surrounding the core are likely to have similar signals, the reference station is the one closest to the reconstructed shower core rather than the one with the highest signal. This a posteriori selection is introduced to ensure that the choice of the reference station is robust wrt statistical fluctuations of the signal

same for the merged targets. The complete list of the target sets used is as follows:

1. *Millisecond pulsars (R. N. Manchester et al. 2005).* We consider 196 targets, of which 23 are considered in the analysis below 1 EeV.
2. *γ-ray pulsars as observed by the Fermi Satellite (S. Abdollahi et al. 2020).* We use an updated catalog version with respect to (wrt) The Pierre Auger Collaboration (2014a), including the new data available. We select 261 targets, of which 33 are considered in the analysis below 1 EeV.
3. *Low- and high-mass X-ray binaries, from F. Fortin et al. (2024) and F. Fortin et al. (2023), respectively.*[97] In total, we consider 267 low-mass X-ray binaries (LMXBs) and 139 high-mass X-ray binaries (HMXBs), and 6 and 2, respectively, for the analysis below 1 EeV.
4. *Three classes of TeVγ-ray emitters, selected from the TeVCat 2.0 catalog (S. P. Wakely & D. Horan 2008), choosing Galactic objects.*[98] The three classes are pulsar wind nebulae (TeV γ-ray - PWNe), other identified TeV γ-ray sources (TeV γ-ray - other), and unidentified TeV γ-ray sources (TeV γ-ray - UNID). These catalogs have been updated since The Pierre Auger Collaboration (2014a), in which only H.E.S.S. data were used. In total, 31 TeV γ-ray - PWNe, 44 TeV γ-ray - other, and 74 TeV γ-ray - UNID targets are tested. For the analysis below 1 EeV, three PWN and three other identified sources are used.
5. *Microquasars, from S. Chaty.*[99] Of the 15 sources considered, none are tested in the energy interval below 1 EeV.
6. *Magnetars, from S. A. Olausen & V. M. Kaspi (2014) and F. C. Zelati et al. (2018).*This catalog has been updated since The Pierre Auger Collaboration (2014a). We test 27 sources, none of which are considered at energies below 1 EeV.
7. *Gamma PeVatrons, as labeled in the TeVCat 2.0 catalog, including sources detected by the Large High Altitude Air Shower Observatory (Z. Cao et al. 2024).* It is the first time this catalog is considered in the search for sources of EeV neutrons. Of the 36 sources tested, 1 is considered for the energy interval below 1 EeV.
8. *Galactic center.*
9. *Crab Pulsar (S. P. Wakely & D. Horan 2008).* This target was not considered in The Pierre Auger Collaboration (2014a) since events with zenith angles greater than 60° were not included, leaving the Crab Pulsar outside the field of view of that analysis.

The position of the effective source is taken to be that of the brightest of the individual objects, while its flux corresponds to the sum of their fluxes.

4. Method

A neutron flux can be identified as an excess of events around its source direction. To search for excesses, we compare the observed CR density to the expected density from an isotropic distribution of arrival directions, considering the exposure of the Observatory, following the method introduced in The Pierre Auger Collaboration (2023b). The CR density is calculated as the sum of the probability densities of all events in the dataset. This density is evaluated in each target direction. The probability density of the ith event evaluated at the direction of the jth target is given by

$$w_{ij} = \frac{1}{2\pi\sigma_i^2}\exp\left(-\frac{\xi_{ij}^2}{2\sigma_i^2}\right), \tag{1}$$

where ξ_{ij} is the angular distance between the arrival direction of ith event and the direction of the jth target, and σ_i is the angular uncertainty of the event. Although the reconstruction provides an estimate of the angular uncertainty for each event, these estimates can exhibit fluctuations. For this reason, the angular uncertainty is parameterized based on data in bins of zenith angle and multiplicity (the number of WCDs triggered during an event). For the SD-1500 dataset, we use different parameterizations for vertical and inclined events. For the events considered in this work, the resulting values of σ_i are within the range 0°.2–1°.4. The observed CR density at the position of the jth target is then the sum of the probability densities over the N events in the dataset, $\rho_j^{\mathrm{obs}} = \sum_{i=1}^{N} w_{ij}$.

The signal expected from an isotropic distribution is estimated using simulated datasets based on a scrambling technique (G. Cassiday et al. 1990). An event is simulated by randomly sampling two events from the dataset and extracting the arrival time from one of them and the zenith angle and the angular uncertainty from the other. By sampling the zenith angle and the angular uncertainty from the same event, we ensure that the angular uncertainty distribution of the simulated datasets follows the observed one. An azimuth angle is randomly sampled from a uniform distribution. Each scrambled dataset has the same number of events as the observed one and is treated as the observed one, evaluating the weight for each simulated event using Equation (1), and then summing over all events to obtain the simulated CR density ρ_j^{sim}. This technique accounts for the exposure of the Observatory, providing a reliable estimate of the background contribution. We simulate 10,000 scrambled datasets. The p-value associated to the jth target is then defined as the fraction of these simulated datasets in which ρ_j^{sim} was equal to or greater than ρ_j^{obs}. When reporting the smallest p-value of a target set, one has to account for the multiple trials within the same target set. We hence penalize the p-value using $p_j^{*}=1-(1-p_j)^M$, where M is the number of targets in the set. The penalized p-value represents the probability of obtaining, by chance, a p-value less than or equal to p_j, given a set of M p-values sampled from a uniform distribution between 0 and 1.

A neutron flux upper limit (UL) is derived for each target as follows. From the 10,000 simulated datasets, we have 10,000 simulated values for the density at the target, assuming that there is no flux of neutrons. We can study how the density would increase with a neutron signal by adding artificially created neutron events from the target direction. For each artificial event, a parameterized angular uncertainty is sampled from the dataset. A two-dimensional Gaussian distribution of that uncertainty is used to sample an angular offset between

[97] We obtained the flux in the X-band from the cross-referenced Swift 2SXPS (P. A. Evans et al. 2020) counterparts.
[98] http://tevcat2.uchicago.edu/
[99] www.aim.univ-paris7.fr/CHATY/Microquasars/microquasars.html

Table 1
Results for the Combined Analysis for Different Energy Ranges Using the SD-1500 Dataset

Class	No.	Unweighted Combined p-value Energy Range (EeV)				No.	Weighted Combined p-value Energy Range (EeV)			
		$\geqslant 1$	1–2	2–3	$\geqslant 3$		$\geqslant 1$	1–2	2–3	$\geqslant 3$
msec PSRs	196	0.22	0.33	0.13	0.57	127	0.64	0.86	0.011	0.80
γ-ray PSRs	261	0.49	0.22	0.63	0.95	154	0.078	0.034	0.46	0.59
LMXB	267	0.79	0.93	0.0078	0.86	104	0.32	0.22	0.23	0.84
HMXB	139	0.78	0.77	0.15	0.91	79	0.51	0.57	0.90	0.11
TeV γ-ray - PWNe	31	0.86	0.85	0.38	0.73	23	0.027	0.0086	0.045	0.83
TeV γ-ray - other	44	0.59	0.85	0.11	0.40	19	0.16	0.49	0.26	0.094
TeV γ-ray - UNID	74	0.90	0.90	0.80	0.54	16	0.17	0.42	0.16	0.21
Microquasars	15	0.23	0.33	0.34	0.56	15	0.88	0.87	0.71	0.59
Magnetars	27	1.0	1.0	0.80	0.62	20	0.97	0.86	0.72	0.73
γ-PeVatrons	36	0.11	0.15	0.45	0.33	18	0.20	0.50	0.15	0.24
Crab	1	0.63	0.45	0.27	0.94	…	…	…	…	…
Gal. Center	1	0.88	0.84	0.61	0.69	…	…	…	…	…

Note. The weighted analysis takes into account the distance and relative intensity of each source and is applied only to the targets where the relevant information is available.

the target and the arrival direction, and also to give the Gaussian density at the target direction based on that offset as in Equation (1). The resulting density from the artificial event is added to $\rho^{\rm sim}$, and this is done separately for each of the 10,000 simulated densities $\rho^{\rm sim}$. The procedure is then repeated so that each $\rho^{\rm sim}$ includes the contribution from two artificial events, then three, and higher numbers. Let f_n denote the fraction of simulations with n added artificial events for which the density is less than the observed density $\rho_j^{\rm obs}$. Note that 1–f_0 is the p-value that was obtained with no artificial events added to simulations. The fraction f_n decreases as n increases, and the procedure of adding artificial events terminates when

$$f_n \leqslant (1 - \mathrm{CL}) f_0. \quad (2)$$

Here, CL is the confidence level (e.g., $CL = 0.95$ for the 95% confidence UL to be derived here), and n is then the UL on the number of neutron events. This follows Zech's definition of an UL $s_{\rm UL}$ given by

$$P(\leqslant k|b + s_{\rm UL}) = (1 - \mathrm{CL})\, P(\leqslant k|b), \quad (3)$$

where $P(\leqslant k|b)$ is the probability of obtaining a count k or less given a mean background b. The UL on the neutron flux is the upper limit on the number of neutrons divided by the directional exposure. The directional exposure is obtained by dividing the expected density by the CR intensity. The expected density is the average obtained from 10,000 scrambled datasets. The CR intensity is obtained by integrating the spectral shape described in The Pierre Auger Collaboration (2020b). From the neutron particle flux, we also compute the upper limit on the energy flux, assuming an E^{-2} spectrum as in previous works (The Pierre Auger Collaboration 2012, 2014a).

In addition to analyzing the target directions individually, we perform a stacked analysis, as done in The Pierre Auger Collaboration (2014a), by calculating the combined significance of each class of candidate sources with an unweighted and a weighted combination of the individual p-values of the targets. A class containing multiple targets with small p-values can have a combined p-value that is small compared to any of the individual p-values. We use the Fisher formula (R. A. Fisher 1925) to calculate the combined significance. The chance probability of a product (Π) of $M p$-values sampled from a uniform distribution to be lower than or equal to the product ($\Pi_{\rm obs}$) of the M actual p-values p_j is

$$\mathcal{P}(\Pi \leqslant \Pi_{\rm obs}) = \Pi_{\rm obs} \sum_{j=0}^{M-1} \frac{(-\ln \Pi_{\rm obs})^j}{j!} = 1 - \mathrm{Poisson}(\geqslant M;\, -\ln \Pi_{\rm obs}), \quad (4)$$

where Poisson($\geqslant k; \mu$) is the Poisson probability of finding k or more occurrences when the expected number is μ. We also evaluate the combined p-value including statistical weights. The weight of a target is proportional to its directional exposure, to its measured electromagnetic flux, and to the attenuation factor due to neutron decay for its distance. The statistical weights are proportional to these factors, and normalized in a way that the sum of all the weights in a target set is equal to 1. We follow the same procedure to evaluate the weighted combined p-value as in The Pierre Auger Collaboration (2014a). Since we do not have flux and distance information for some of the candidate sources, we calculate the weighted combined p-value using only those with complete information.[100] The unweighted combined p-value is evaluated for all candidate sources in each set.

5. Results

We present the results of the combined analysis in Tables 1 and 2, for the SD-1500 and SD-750, respectively. We report, separately for the unweighted and weighted combined analyses, the number of sources used in each target set as well as the combined p-value for different energy ranges. The results for the most significant target in each set are presented in Tables 3 and 4 for the SD-1500 and SD-750 datasets, respectively. For each target reported, we present its direction in equatorial coordinates, the observed and expected CR density at its direction, the upper limit on the flux and the energy flux, the p-value, and the penalized p-value considering

[100] In the case of the gamma PeVatrons and the unidentified TeV γ-ray sources, the distance was not considered for the weight as that information was not available for the majority of the candidate sources in the target set.

Table 2
Results for the Combined Analysis for Different Energy Ranges Using the SD-750 Dataset

Class	No.	Unweighted Combined p-value Energy Range (EeV)				No.	Weighted Combined p-value Energy Range (EeV)			
		$\geqslant$0.1	0.1–0.2	0.2–0.3	$\geqslant$0.3		$\geqslant$0.1	0.1–0.2	0.2–0.3	$\geqslant$0.3
msec PSRs	23	0.53	0.30	0.54	0.66	20	0.60	0.59	0.89	0.083
γ-ray PSRs	33	0.47	0.69	0.042	0.69	33	0.92	0.88	0.84	0.51
LMXB	6	0.73	0.81	0.83	0.45	5	0.92	0.89	0.94	0.31
HMXB	2	0.21	0.25	0.33	0.084	2	0.48	0.11	0.56	0.98
TeV γ-ray - PWNe	2	0.66	0.54	0.27	0.36	2	0.79	0.83	0.88	0.13
TeV γ-ray - other	3	0.62	0.58	0.39	0.81	2	0.43	0.42	0.17	0.86
γ-PeVatrons	1	0.21	0.23	0.069	0.68	⋯	⋯	⋯	⋯	⋯

Note. The weighted analysis takes into account the distance and relative intensity of each source and is applied only to the targets where the relevant information is available.

Table 3
Results for the Most Significant Target in Each Target Set Obtained Using the SD-1500 Dataset for the Energy Range above 1 EeV

Class	R.A. (deg)	Decl. (deg)	ρ^{obs} (deg^{-2})	ρ^{exp} (deg^{-2})	Flux UL (km^{-2} yr^{-1})	E-flux UL (eV cm^{-2} s^{-1})	p-value	p-value (penalized)
msec PSRs	277.12	6.42	72.64	57.49	0.024	0.17	0.00070	0.13
γ-ray PSRs	296.63	−54.05	144.60	124.22	0.014	0.10	0.00020	0.051
LMXB	117.14	−67.75	160.57	140.62	0.013	0.095	0.0027	0.51
HMXB	212.01	−61.98	147.51	131.02	0.012	0.086	0.0051	0.51
TeV γ-ray - PWNe	128.75	−45.60	127.63	117.18	0.0096	0.070	0.025	0.55
TeV γ-ray - other	98.25	5.79	66.70	58.41	0.016	0.12	0.037	0.81
TeV γ-ray - UNID	305.02	40.76	13.35	7.25	0.090	0.65	0.020	0.78
Microquasars	308.11	40.96	13.84	7.01	0.099	0.73	0.011	0.15
Magnetars	275.57	−16.07	96.35	91.29	0.0085	0.062	0.14	0.98
γ-PeVatrons	292.25	17.75	45.92	36.63	0.027	0.20	0.023	0.56
Crab	83.63	22.01	27.95	29.44	0.014	0.10	0.63	0.63
Gal. Center	266.42	−29.01	98.71	104.25	0.0036	0.027	0.88	0.88

Note. The upper limits are computed at 95% confidence level. The penalization accounts for the number of targets tested in each target set.

Table 4
Results for the Most Significant Target in Each Target Set Obtained Using the SD-750 Dataset for the Energy Range between 0.1 and 1 EeV

Class	R.A. (deg)	Decl. (deg)	ρ^{obs} (deg^{-2})	ρ^{exp} (deg^{-2})	Flux UL (km^{-2} yr^{-1})	E-flux UL (eV cm^{-2} s^{-1})	p-value	p-value (penalized)
msec PSRs	358.96	0.85	40.39	34.41	2.0	15.0	0.026	0.46
γ-ray PSRs	284.58	−22.28	74.45	65.62	1.5	11.0	0.015	0.39
LMXB	292.71	5.52	27.56	25.39	1.7	12.0	0.20	0.73
HMXB	190.71	−63.06	78.60	73.30	1.1	7.9	0.11	0.21
TeV γ-ray PWNe	98.12	17.37	4.47	4.20	3.8	28.0	0.37	0.61
TeV γ-ray - other	258.39	−39.76	80.08	76.92	0.86	6.3	0.22	0.53
γ-PeVatrons	98.48	17.77	4.44	3.65	4.8	35.0	0.21	0.21

Note. The upper limits are computed at 95% confidence level. The penalization accounts for the number of targets tested in each target set.

the total number of candidate sources in the target set. None of the penalized p-values reached the 3σ threshold, indicating the absence of statistically significant evidence of a neutron flux coming from the tested directions across all energy ranges considered.

The lack of statistically significant p-values has allowed us to place significant upper limits on the neutron emission from the targets, which can be compared to the observed electromagnetic emission. In Figure 1, we show the upper limits we obtain compared to the electromagnetic spectral energy distributions for the Galactic center (GC) and the Crab Pulsar. In the supplementary material of this paper, machine-readable tables including the full results for all the tested targets are available.

6. Conclusions

In this work, we performed an updated search for neutron fluxes from more than 1000 Galactic sources. We have not detected any statistically significant overdensity that would be

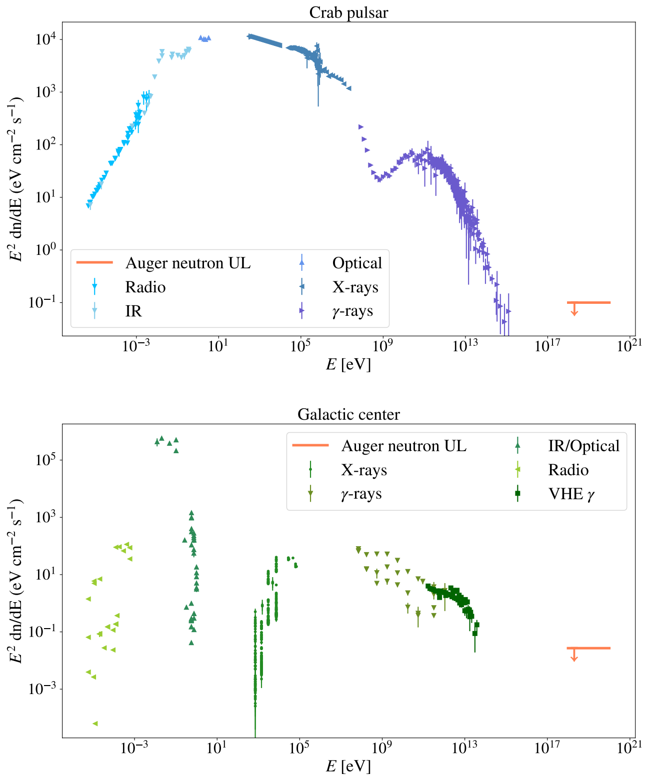

Figure 1. Spectral energy distributions (SEDs) for the Crab Pulsar (top) and the Galactic center (bottom). For the Crab Pulsar, the electromagnetic SED is from L. Dirson & D. Horns (2023) with data available in D. Horns (2022). For the Galactic center, the majority of data is obtained through the tool SED Builder (https://tools.ssdc.asi.it/SED) with data from A. J. Bird et al. (2010), E. L. Wright et al. (2010), Planck Collaboration et al. (2014), R. S. Dixon (1970), J. J. Condon et al. (1998), and Joint IRAS Science Working Group (1986) with the manual addition of very-high-energy-γ data from MAGIC (MAGIC Collaboration et al. 2020), Veritas (C. B. Adams et al. 2021), and H.E.S.S. (H.E.S.S. Collaboration et al. 2018).

associated with a neutron flux from any of the tested directions in the considered energy ranges.

We established upper limits of the neutron flux for all tested directions, considering a total exposure larger by a factor ∼3 compared to The Pierre Auger Collaboration (2014a). The sky coverage of the analysis was also extended, up to a decl. of +45°. In addition, we reduced the energy threshold to 0.1 EeV for sources located within the neutron-decay length and decl. up to +20°. The upper limits presented in this work are, on average, improved by a factor of ∼2 compared to those reported in The Pierre Auger Collaboration (2014a) for the same targets. These results are the most stringent direct constraints on hadronic acceleration in Galactic sources above 100 PeV and can be used to constrain astrophysical models of production of UHECRs.

The aim of this work was to search for steady sources of neutrons in our Galaxy. However, many of the targets tested in this analysis show variability in their electromagnetic emission. Our time-averaged upper limits do not constrain a burst whose integrated flux is small compared to the total background for that target. A search for flares or variability that matches what is observed through electromagnetic fluxes is forthcoming. Additionally, we plan to perform an updated blind search over the whole sky, as presented in The Pierre Auger Collaboration (2012), and a dedicated search along the Galactic plane.

The Pierre Auger Observatory has recently entered its so-called Phase II, following the *AugerPrime* upgrade (The Pierre Auger Collaboration 2019). The enhanced observatory will improve our ability to distinguish showers produced by heavy nuclei. Removing them will reduce the background, enhancing the sensitivity of future neutron searches.

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Appendix
Full Results

We report in Table 5 the upper limits obtained with the analysis performed with the SD-1500 array. In the printed version, only the two objects that show the lowest flux upper limit for each target set are reported. The machine-readable table available online includes the results for all the 1092 targets considered, in the same format. Similarly, in Table 6, the results for the analysis with data coming from the SD-750 array are reported.

Table 5
Upper Limits at 95% Confidence Level in All the Energy Bins Considered for the Analysis with the 1500 m Array

Class	R.A. (deg)	Decl. (deg)	1–2 EeV		2–3 EeV		⩾3 EeV		⩾1 EeV	
			Flux UL	E-flux UL	Flux UL	E-flux UL	Flux UL	E-flux UL	Flux UL	E-flux UL
CRAB	83.63	22.01	1.75e-02	1.28e-01	5.20e-03	3.80e-02	1.18e-03	8.63e-03	0.014	1.02e-01
GC	266.42	−29.01	4.06e-03	2.97e-02	1.46e-03	1.07e-02	8.68e-04	6.33e-03	0.00365	2.66e-02
GAMMA_PSR	168.03	−61.13	3.03e-03	2.21e-02	1.16e-03	8.49e-03	9.09e-04	6.63e-03	0.00232	1.69e-02
GAMMA_PSR	270.32	−24.85	3.08e-03	2.25e-02	1.38e-03	1.01e-02	9.06e-04	6.61e-03	0.00237	1.73e-02
GAMMA_PSR	...	…	…	…	…	…	…	…	…	…
HMXB	107.4	−16.1	4.13e-03	3.01e-02	1.23e-03	8.99e-03	8.26e-04	6.03e-03	0.000174	1.27e-03
HMXB	266.19	−27.23	3.01e-03	2.20e-02	1.35e-03	9.87e-03	8.80e-04	6.43e-03	0.00231	1.69e-02
HMXB	...	…	…	…	…	…	…	…	…	…
LMXB	270.29	−25.08	2.91e-03	2.13e-02	1.52e-03	1.11e-02	9.04e-04	6.60e-03	0.0022	1.61e-02
LMXB	290.65	−17.28	3.33e-03	2.43e-02	1.36e-03	9.93e-03	6.55e-04	4.78e-03	0.00239	1.75e-02
LMXB	...	…	…	…	…	…	…	…	…	…
MGN	257.2	−40.15	5.90e-03	4.30e-02	6.09e-04	4.44e-03	7.95e-04	5.80e-03	0.00349	2.55e-02
MGN	251.79	−45.87	5.54e-03	4.04e-02	9.39e-04	6.85e-03	7.64e-04	5.58e-03	0.00363	2.65e-02
MGN	...	…	…	…	…	…	…	…	…	…
MQSR	269.5	−25.13	3.24e-03	2.36e-02	1.52e-03	1.11e-02	1.05e-03	7.70e-03	0.00299	2.18e-02
MQSR	237.5	−56.07	3.78e-03	2.76e-02	1.22e-03	8.89e-03	1.19e-03	8.72e-03	0.00354	2.58e-02
MQSR	...	…	…	…	…	…	…	…	…	…
PeV	273.52	−17.31	5.44e-03	3.97e-02	1.51e-03	1.10e-02	4.95e-04	3.62e-03	0.00342	2.50e-02
PeV	273.72	−16.62	6.91e-03	5.04e-02	9.14e-04	6.67e-03	6.62e-04	4.84e-03	0.00397	2.90e-02
PeV	...	…	…	…	…	…	…	…	…	…
TeV_OTHER	251.71	−45.82	5.26e-03	3.84e-02	9.40e-04	6.86e-03	7.65e-04	5.58e-03	0.0035	2.55e-02
TeV_OTHER	278.21	−9.38	3.34e-03	2.44e-02	2.70e-03	1.97e-02	1.28e-03	9.31e-03	0.00364	2.65e-02
TeV_OTHER	...	…	…	…	…	…	…	…	…	…
TeV_PWN	84.43	−69.17	3.16e-03	2.31e-02	1.51e-03	1.10e-02	8.05e-04	5.87e-03	0.00269	1.96e-02
TeV_PWN	215.04	−60.76	2.91e-03	2.12e-02	1.49e-03	1.08e-02	1.37e-03	1.00e-02	0.00342	2.50e-02
TeV_PWN	...	…	…	…	…	…	…	…	…	…
TeV_UNID	257.1	−41.09	3.43e-03	2.50e-02	1.09e-03	7.94e-03	9.22e-04	6.73e-03	0.00305	2.23e-02
TeV_UNID	277.24	−9.99	2.33e-03	1.70e-02	2.84e-03	2.08e-02	9.06e-04	6.62e-03	0.00341	2.49e-02
TeV_UNID	...	…	…	…	…	…	…	…	…	…

Note. The upper limit for flux is given in $km^{-2}\ yr^{-1}$, and the upper limit for energy flux in eV $cm^{-2}\ s^{-1}$. Each target set is truncated after two entries in the printable version, but the machine-readable table available in the online version of the paper contains all the targets tested.

(This table is available in its entirety in machine-readable form in the online article.)

Table 6
Upper Limits at 95% Confidence Level in All the Energy Bins Considered for the Analysis with the 750 m Array

Class	R.A. (deg)	Decl. (deg)	0.1–0.2 EeV		0.2–0.3 EeV		⩾0.3 EeV		⩾0.1 EeV	
			Flux UL	E-flux UL	Flux UL	E-flux UL	Flux UL	E-flux UL	Flux UL	E-flux UL
GAMMA_PSR	153.05	−42.59	2.00e-01	1.46e+00	2.79e-01	2.04e+00	4.60e-02	3.36e-01	0.113	8.27e-01
GAMMA_PSR	263.15	−31.52	3.41e-01	2.49e+00	6.67e-02	4.87e-01	1.79e-01	1.31e+00	0.323	2.35e+00
GAMMA_PSR	...	…	…	…	…	…	…	…	…	…
HMXB	104.57	−7.21	1.40e+00	1.02e+01	2.36e-01	1.72e+00	6.95e-02	5.08e-01	0.92	6.72e+00
HMXB	190.71	−63.06	6.33e-01	4.62e+00	2.89e-01	2.11e+00	2.68e-01	1.96e+00	1.08	7.90e+00
LMXB	267.72	−31.09	4.92e-01	3.59e+00	1.18e-01	8.62e-01	1.48e-01	1.08e+00	0.425	3.10e+00
LMXB	260.85	−28.63	4.60e-01	3.35e+00	1.37e-01	1.00e+00	1.50e-01	1.10e+00	0.435	3.17e+00
LMXB	...	…	…	…	…	…	…	…	…	…
MSEC	211.34	−46.93	5.37e-01	3.92e+00	1.99e-01	1.46e+00	7.55e-02	5.51e-01	0.431	3.14e+00
MSEC	260.85	−28.63	4.60e-01	3.35e+00	1.37e-01	1.00e+00	1.50e-01	1.10e+00	0.435	3.17e+00
MSEC	...	…	…	…	…	…	…	…	…	…
PeV	98.48	17.77	6.94e+00	5.07e+01	1.08e+00	7.85e+00	2.99e-01	2.19e+00	4.83	3.53e+01
TeV_OTHER	128.84	−45.18	4.96e-01	3.62e+00	1.23e-01	8.98e-01	1.22e-01	8.88e-01	0.45	3.29e+00
TeV_OTHER	133.0	−46.37	6.35e-01	4.63e+00	2.90e-01	2.12e+00	9.05e-02	6.60e-01	0.636	4.64e+00
TeV_OTHER	...	…	…	…	…	…	…	…	…	…
TeV_PWN	128.75	−45.6	4.95e-01	3.62e+00	1.23e-01	8.99e-01	1.83e-01	1.33e+00	0.506	3.69e+00
TeV_PWN	98.12	17.37	5.69e+00	4.15e+01	1.07e+00	7.82e+00	1.83e-01	1.34e+00	3.85	2.81e+01
TeV_PWN	...	…	…	…	…	…	…	…	…	…

Note. The upper limit for flux is given in $km^{-2}\ yr^{-1}$, and the upper limit for energy flux in $eV\ cm^{-2}\ s^{-1}$. Each target set is truncated after two entries in the printable version, but the machine-readable table available in the online version of the paper contains all the targets tested.

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