A search for neutron fluxes from Galactic candidate sources using data from the Pierre Auger Observatory

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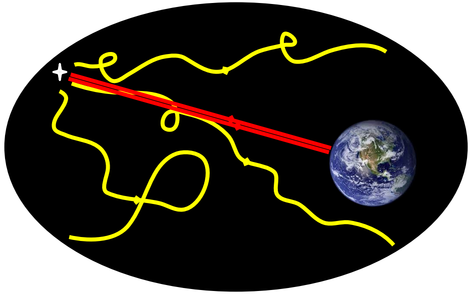
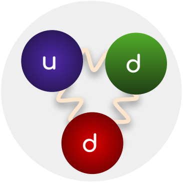
Why study neutral particles in cosmic rays?



Since neutral particles are not deflected by magnetic fields, their arrival directions point directly to their sources.



Neutron

β-decay

mean lifetime

15 minutes

→

mean traveled distance

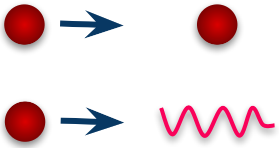
9.2 kpc × (E/EeV)

Galactic center: 8.3 kpc from Earth

Neutron production

$$p + p \rightarrow n + p + \pi^+$$

$$p + \gamma \rightarrow n + \pi^+$$



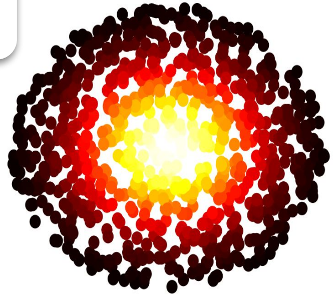
Other possibilities:

Spallation/photodisintegration process

It is not possible to distinguish between an air shower initiated by a proton or a neutron.

We would identify a **neutron flux** through an **excess** of cosmic ray events around a given direction

Estimating the probability density



We assign a weight representing the probability density of an event coming from the direction of the target:

$$w_i = \frac{1}{2\pi\sigma_i^2}\exp\left(-\frac{\xi_i^2}{2\sigma_i^2}\right)$$

ξ_i : angular distance

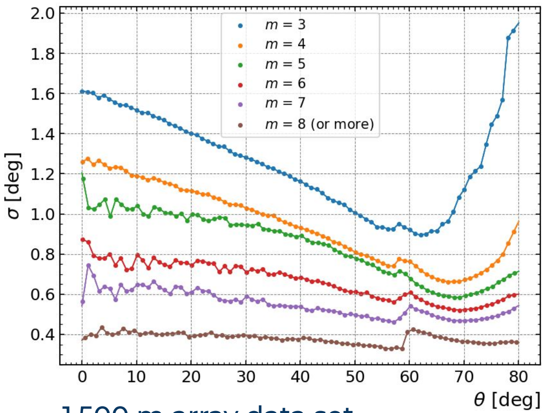
σ_i

Parameterization

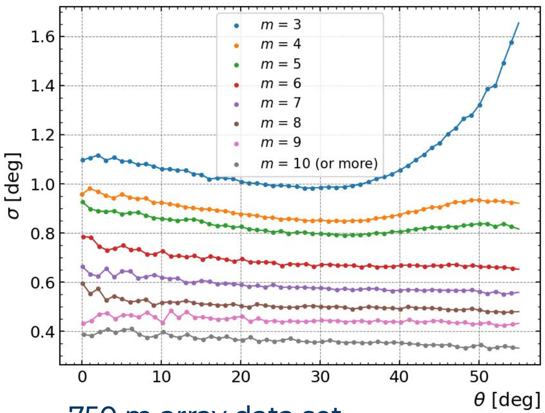
in zenith angle and multiplicity

$$\sigma = \sqrt{(\Delta\theta)^2 + (\sin\theta_0\Delta\varphi)^2}$$

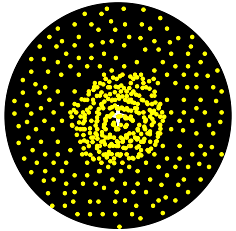
median value



1,500 m array data set



750 m array data set



How can we identify a neutron flux?

By summing all the weights in the data set, we obtain the **cosmic ray density** at the position of the target:

$$\rho_{\text{obs}} = \sum_{i}^{N} w_i$$

We can compare the observed CR density with the CR density obtained from an isotropic distribution:

$$\rho_{\text{scr}}$$

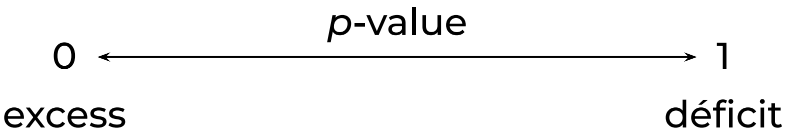
Scrambling technique

We sampled 2 events:

simulated event

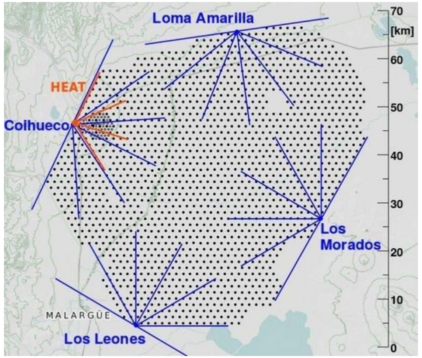
- **Event 1:** UTC
- **Event 2:** θ, σ
- An azimuth angle from a uniform distribution between 0 and 2π

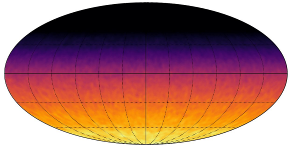
The *p*-value is the fraction of the 10,000 simulated data sets with a CR density greater than the observed value.



Data set

Events recorded by the Surface Detector (SD) between
January 1, 2004 and **December 31, 2022** (1,500 m array)
August 1, 2008 and **December 21, 2022** (750 m m array)





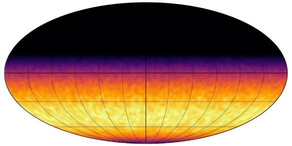
–90° ≤ dec ≤ 45°

2,661,606 events

2,011,357 | 382,809 | 267,440

1 EeV
2 EeV
3 EeV

Energy



–90° ≤ dec ≤ 20°

1,505,412 events

1,088,012 | 249,642 | 167,758

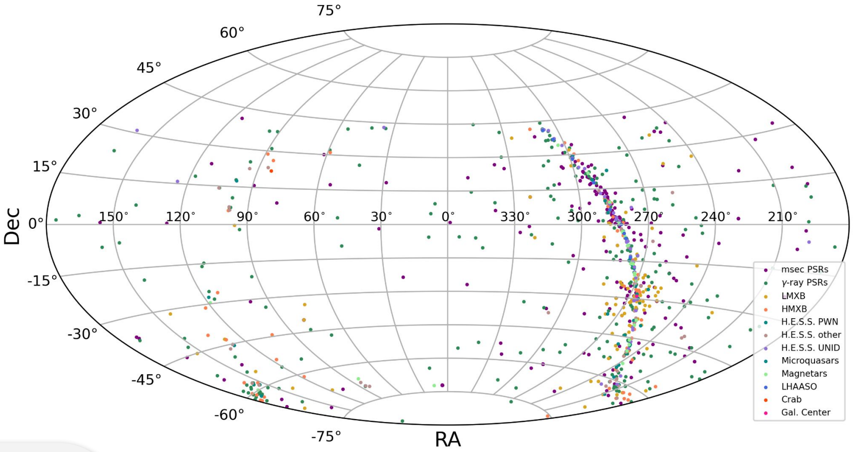
0.1 EeV
0.2 EeV
0.3 EeV

Energy

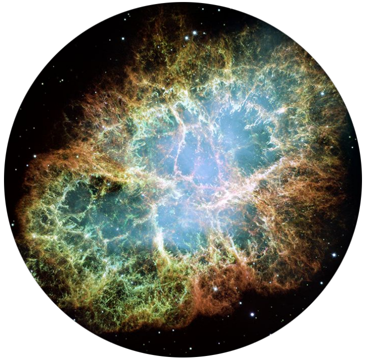
Target sets

12 target sets resulting in a total of **888** sources with a declination up to **45°**.

Of those, **166** are within a distance ⩽ **1 kpc** and have a declination up to **20°**.

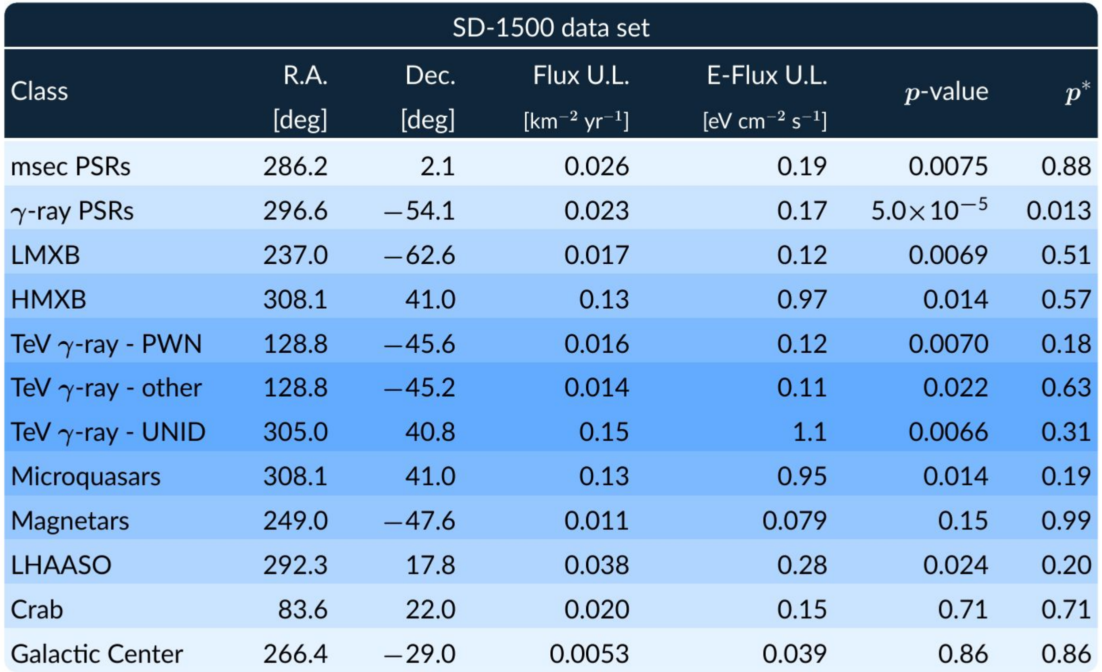


- Millisecond Pulsars
- γ-ray Pulsars
- Low Mass X-ray Binaries
- High Mass X-ray Binaries
- γ TeV emitters - Pulsar Wind Nebulae
- γ TeV emitters - Other

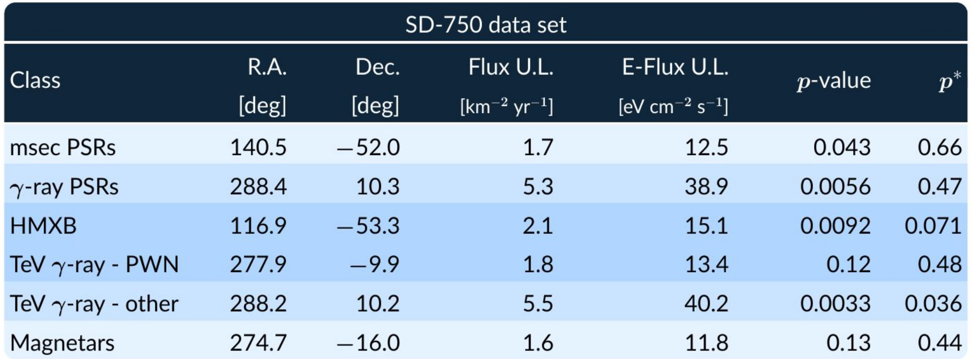


- γ TeV emitters - UNIDentified
- Microquasars
- Magnetars
- **LHAASO PeVatrons**
- **Crab Nebula**
- Galactic Center

Results



SD-1500 data set						
Class	R.A. [deg]	Dec. [deg]	Flux U.L. [km^{-2} yr^{-1}]	E-Flux U.L. [eV cm^{-2} s^{-1}]	p-value	p^*
msec PSRs	286.2	2.1	0.026	0.19	0.0075	0.88
γ-ray PSRs	296.6	-54.1	0.023	0.17	5.0×10^{-5}	0.013
LMXB	237.0	-62.6	0.017	0.12	0.0069	0.51
HMXB	308.1	41.0	0.13	0.97	0.014	0.57
TeV γ-ray - PWN	128.8	-45.6	0.016	0.12	0.0070	0.18
TeV γ-ray - other	128.8	-45.2	0.014	0.11	0.022	0.63
TeV γ-ray - UNID	305.0	40.8	0.15	1.1	0.0066	0.31
Microquasars	308.1	41.0	0.13	0.95	0.014	0.19
Magnetars	249.0	-47.6	0.011	0.079	0.15	0.99
LHAASO	292.3	17.8	0.038	0.28	0.024	0.20
Crab	83.6	22.0	0.020	0.15	0.71	0.71
Galactic Center	266.4	-29.0	0.0053	0.039	0.86	0.86



SD-750 data set						
Class	R.A. [deg]	Dec. [deg]	Flux U.L. [km^{-2} yr^{-1}]	E-Flux U.L. [eV cm^{-2} s^{-1}]	p-value	p^*
msec PSRs	140.5	-52.0	1.7	12.5	0.043	0.66
γ-ray PSRs	288.4	10.3	5.3	38.9	0.0056	0.47
HMXB	116.9	-53.3	2.1	15.1	0.0092	0.071
TeV γ-ray - PWN	277.9	-9.9	1.8	13.4	0.12	0.48
TeV γ-ray - other	288.2	10.2	5.5	40.2	0.0033	0.036
Magnetars	274.7	-16.0	1.6	11.8	0.13	0.44

$$p^* = 1 - (1 - p)^{\textcircled{M}} \longrightarrow$$

Number of targets in a target set

Combined analysis

SD-1500 data set

Class	No.	Combined p-value				Class	No.	Combined p-value			
		≥ 1 [EeV]	1 – 2 [EeV]	2 – 3 [EeV]	≥ 3 [EeV]			≥ 1 [EeV]	1 – 2 [EeV]	2 – 3 [EeV]	≥ 3 [EeV]
msec PSRs	283	0.90	0.79	0.20	1.0	TeV γ-ray - UNID	56	0.61	0.85	0.57	0.40
γ-ray PSRs	261	0.16	0.12	0.50	0.86	Microquasars	15	0.39	0.49	0.50	0.68
LMXB	102	0.62	0.89	0.11	0.55	Magnetars	27	0.99	0.99	0.85	0.67
HMXB	60	0.49	0.46	0.28	0.85	LHAASO	9	0.22	0.31	0.54	0.31
TeV γ-ray - PWN	28	0.24	0.52	0.072	0.49	Crab	1	0.71	0.54	0.30	0.93
TeV γ-ray - other	45	0.52	0.81	0.15	0.34	Galactic Center	1	0.86	0.78	0.72	0.67

SD-750 data set

Class	No.	Combined p-value				Class	No.	Combined p-value			
		≥ 0.1 [EeV]	0.1 – 0.2 [EeV]	0.2 – 0.3 [EeV]	≥ 0.3 [EeV]			≥ 0.1 [EeV]	0.1 – 0.2 [EeV]	0.2 – 0.3 [EeV]	≥ 0.3 [EeV]
msec PSRs	25	0.82	0.41	0.90	0.67	TeV γ-ray - PWN	5	0.43	0.72	0.12	0.36
γ-ray PSRs	113	0.53	0.70	0.29	0.38	TeV γ-ray - other	11	0.074	0.55	0.070	0.16
HMXB	8	0.33	0.68	0.069	0.28	Magnetars	4	0.31	0.48	0.26	0.21

Summary and conclusions

We performed a targeted search for point sources of neutrons in the EeV range.

We did not find any clear evidence of a neutron flux.

We established upper limits for the neutron flux.

Our analysis do not constrain short outbursts. In the future, we plan to search for correlations with transient events.

Thank you!

Backup

Upper Limit on the neutron flux

The upper limit on the number of neutrons is the number N that satisfies:

$$f_N < (1 - \mathrm{CL}) f_0$$

fraction of simulated datasets in which the density at the target is less than the observed density after adding N events

Confidence level: 95%

Directional exposure

$$\omega_{\mathrm{dir}} = \frac{\rho_{\mathrm{exp}}}{I}$$

expected CR density (obtained from simulations)

CR intensity

Flux upper limit

$$\Phi_{UL} = \frac{N_{UL}}{\omega_{\mathrm{dir}}}$$

Combined analysis

If the objects in a class are emitting neutrons, the combined *p*-value will be more significant than the individual *p*-values.

The product of the *p*-values:

$$\boxed{\Pi_0 = p_1 \cdot p_2 \cdot p_3 \cdots p_M}$$ $\longrightarrow M$ targets in a target set

The combined *p*-value:

$$\boxed{\mathcal{P}(\Pi \leq \Pi_0) = \Pi_0 \sum_{k=0}^{M-1} \frac{(-\ln \Pi_0)^k}{k!} = 1 - \text{Poisson}(M, -\ln \Pi_0)}$$

We can add a weight for each target proportional to its electromagnetic flux, its exposure, and its flux attenuation factor due to neutron decay.