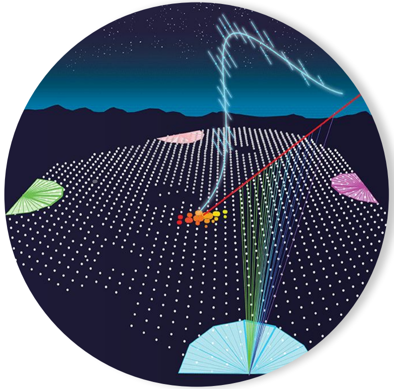
A search for neutron fluxes from Galactic candidate sources



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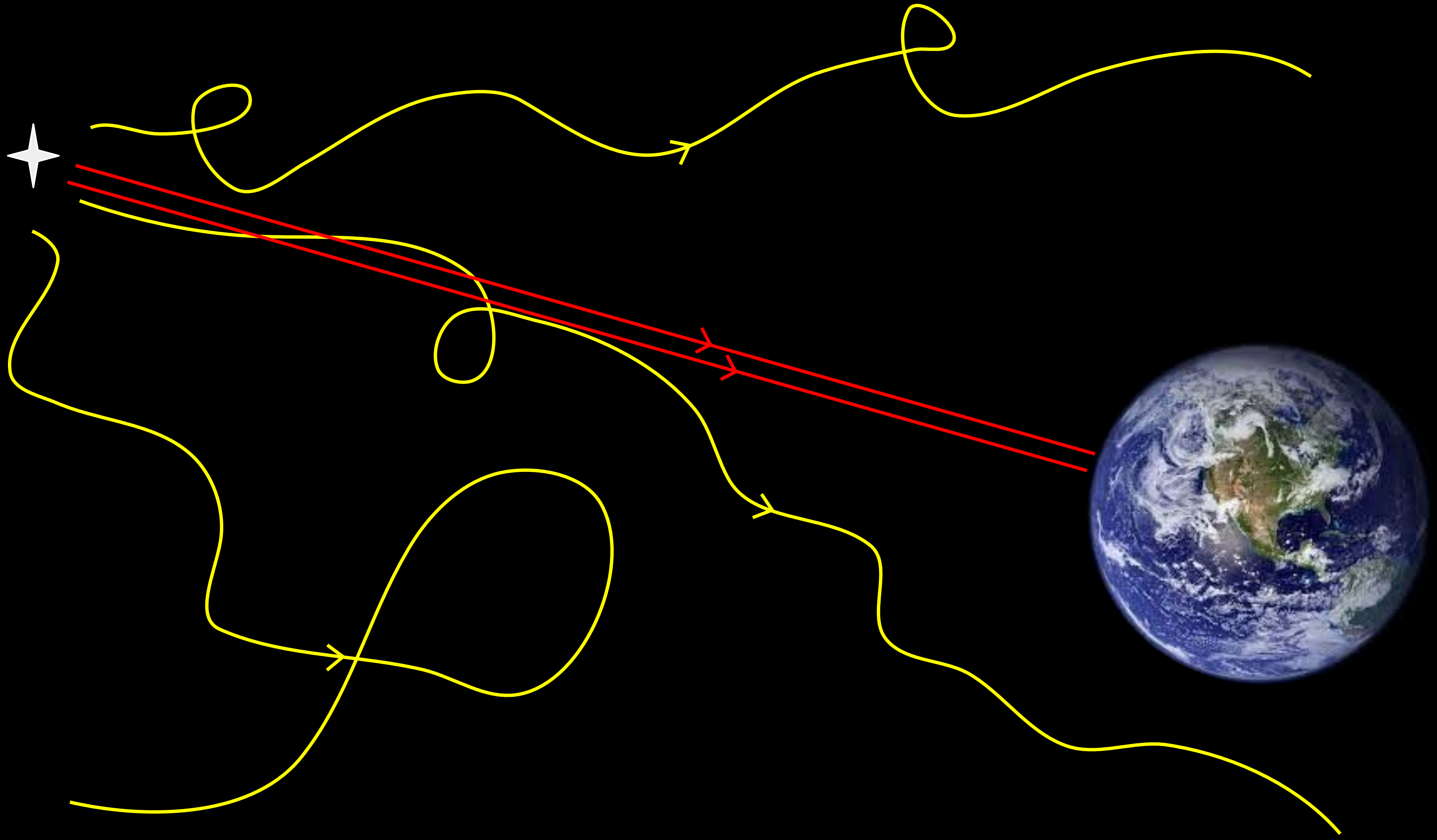
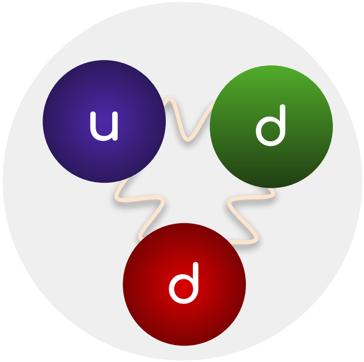
PIERRE AUGER OBSERVATORY

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG





Neutron

β-decay

mean lifetime

15 minutes

→

mean traveled distance

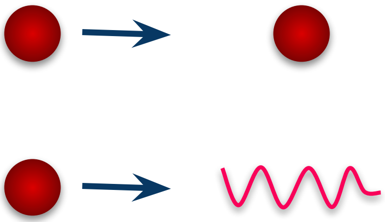
9.2 kpc × (*E*/EeV)

Galactic center: 8.3 kpc from Earth

Neutron production

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

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



Pierre Auger Collaboration

Targeted search
2014

2012
Blind search

Vertical data set

Vertical $0° \leqslant \theta \leqslant 60°$

Inclined $60° \leqslant \theta \leqslant 80°$

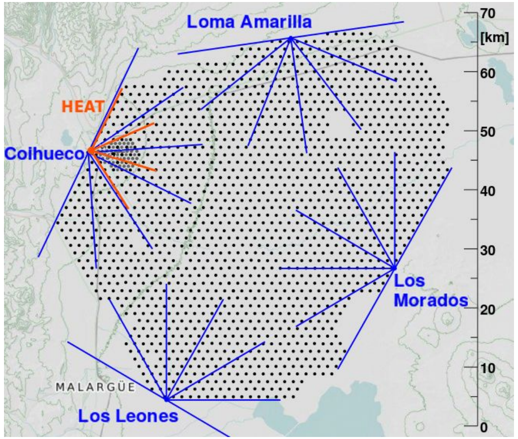
Infill $0° \leqslant \theta \leqslant 55°$

Goals

Update the **vertical** full array data set
FoV: $-90° \leqslant \delta \leqslant 25°$ - Energy: $\geqslant$ 1 EeV

Study new data sets
Infill - FoV: $-90° \leqslant \delta \leqslant 20°$ - Energy: $\geqslant$ 0.1 EeV
Inclined - FoV $-85° \leqslant \delta \leqslant 45°$ - Energy $\geqslant$ 1 EeV

Update the target sets with new candidate sources



Data set

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

1,500 m array data set

Events above 1 EeV

$-90° \leq \text{dec} \leq 45°$

Energy range	**No. events**
1 EeV – 2 EeV	2,011,357
2 EeV – 3 EeV	382,809
≥ 3 EeV	267,440
≥ 1 EeV	2,661,606

750 m array data set

Events above 0.1 EeV

$-90° \leq \text{dec} \leq 20°$

Energy range	**No. events**
0.1 EeV – 0.2 EeV	1,088,012
0.2 EeV – 0.3 EeV	249,642
≥ 0.3 EeV	167,758
≥ 0.1 EeV	1,505,412

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

Probability density method

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

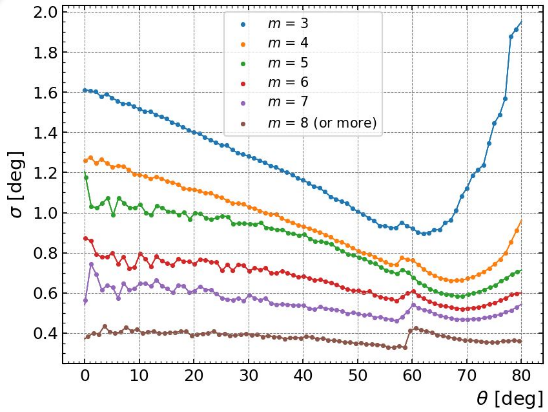
σ_i →

Parameterization

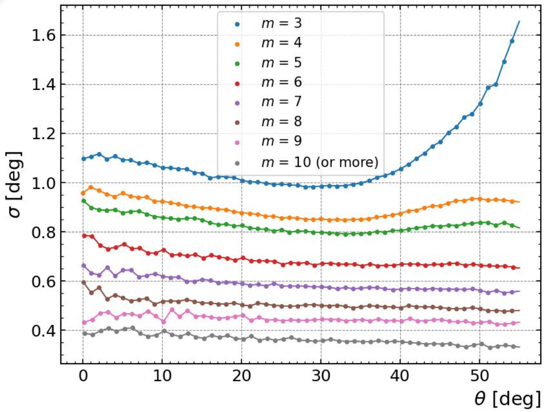
in zenith angle and multiplicity

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

└ 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.

p-value

0 ⟷ 1

excess — déficit

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

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

SD-1500 array

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

$$p^* = 1 - (1 - p)^{N}$$

N → Total number of targets in a target set

261 γ-ray pulsars

SD-750 array

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

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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, besides the update of the blind search.

Thank you!