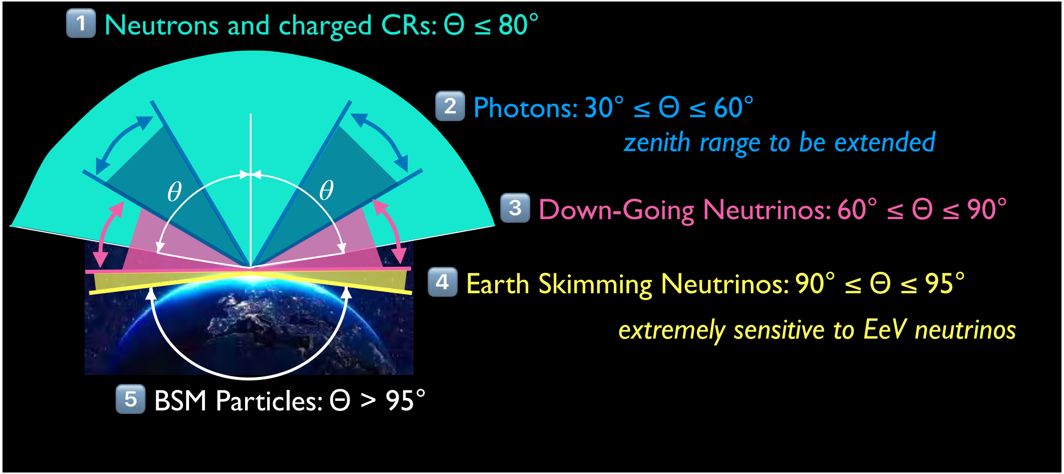
Multi-messenger studies at the Pierre Auger Observatory

Ioana C. Mariș for the Pierre Auger Collaboration

Universite Libre de Bruxelles

AHEAD 2024, Pisa

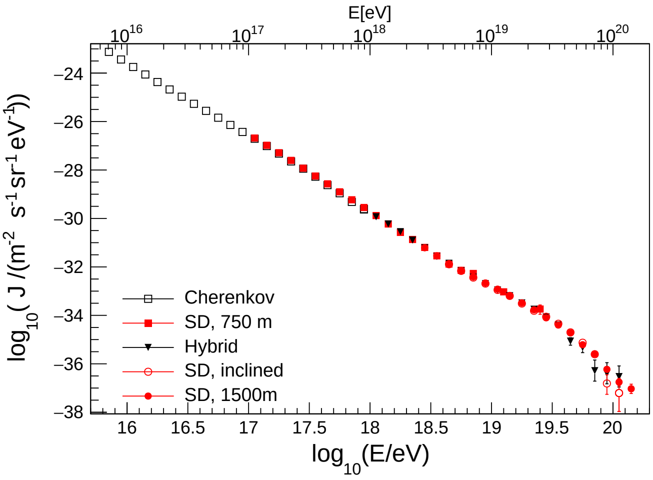
Pierre Auger Observatory: a 4π Multi-Messenger Observatory

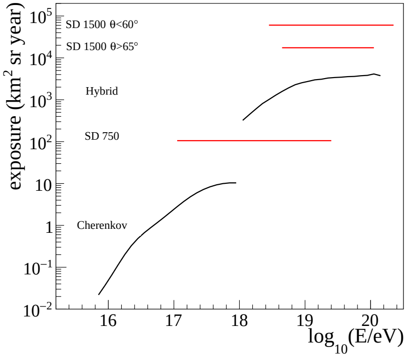


@Karl-Heinz Kampert

By construction a cosmic rays Observatory is also a γ, ν, and neutron Observatory

… and more than 4 decades in energy



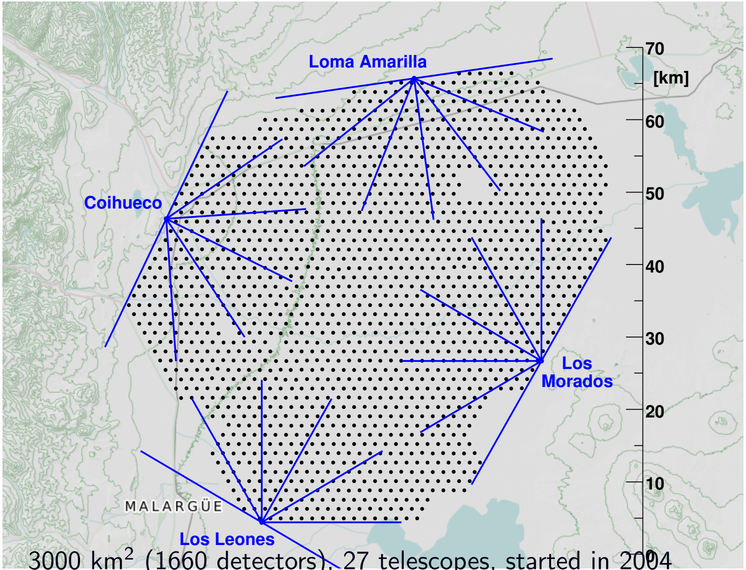


A unique infrastructure combining several techniques

Auger coll., PRL 125 (2020) 121106,

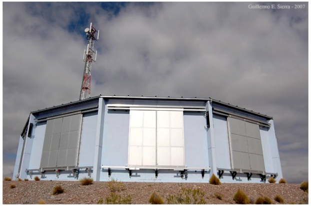
Eur. Phys. J. C 81 (2021) 966,

The Observatory (Malargue, Argentina)



3000 km^2 (1660 detectors), 27 telescopes, started in 2004

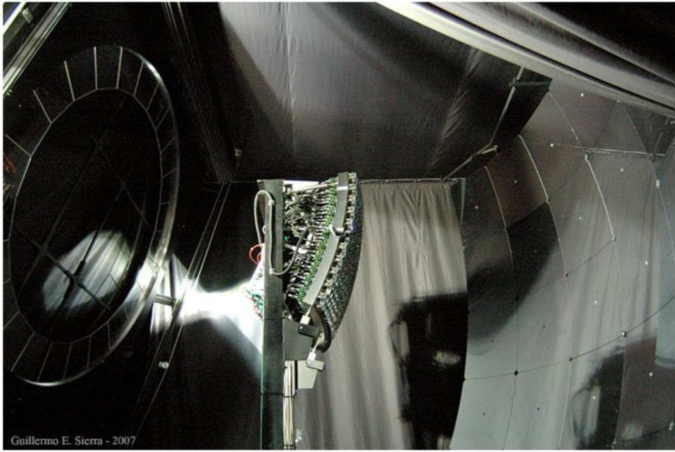
Fluorescence Telescopes



Surface detectors

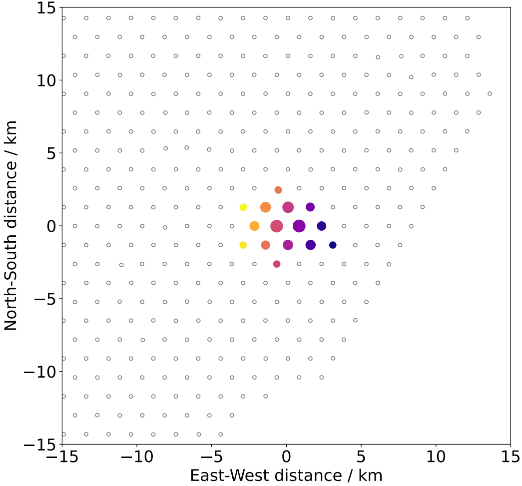
- 3 triagular grids spaced by 1500 m, 750 m, and 433 m

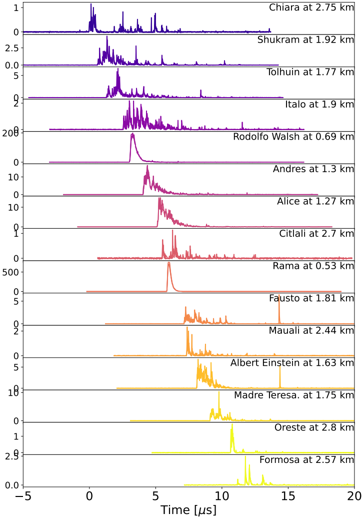
Auger coll., NIM A 798 (2015) 172-213


Guillermo E. Sierra - 2007

Examples of the higest energy events

Auger: 72 EeV, 36 degrees



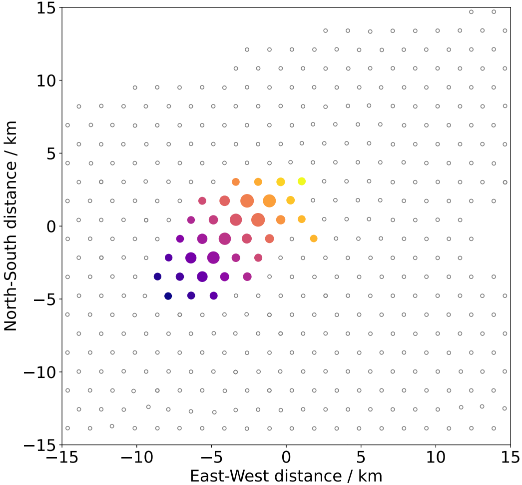


Auger coll. ApJS 264 50 (2023)

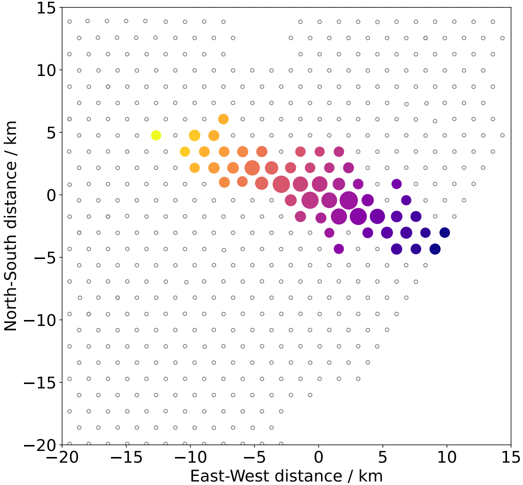
Time distribution of signals recorded to follow the detailed structure of the air-shower front

More inclined air-showers

Auger: 165 EeV, 59 degrees



Auger: 50 EeV, 77 degrees



opendata.auger.org, 20/03/2024, release 3, DOI 10.5281/zenodo.10488964

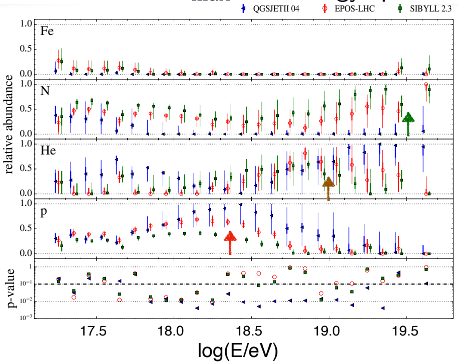
Cosmic rays and multi-messenger physics

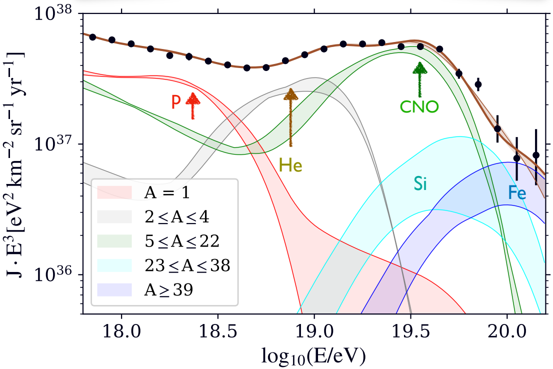
- Constraining EHE ($> 10^{20}$ eV) source properties: maximum rigidity, chemical environment, source luminosity
- Constraining source classes with anisotropies
- Redshift evolution of UHECR sources
- From clustering: constrain galactic and extra-galactic B-fields
- A robust input to calculations of the expected flux of cosmogenic particles

MM is more than multi-wavelength and more than studying transient events

Mass composition and energy spectrum

Combined fit of $X_{\max}$ and energy spectrum

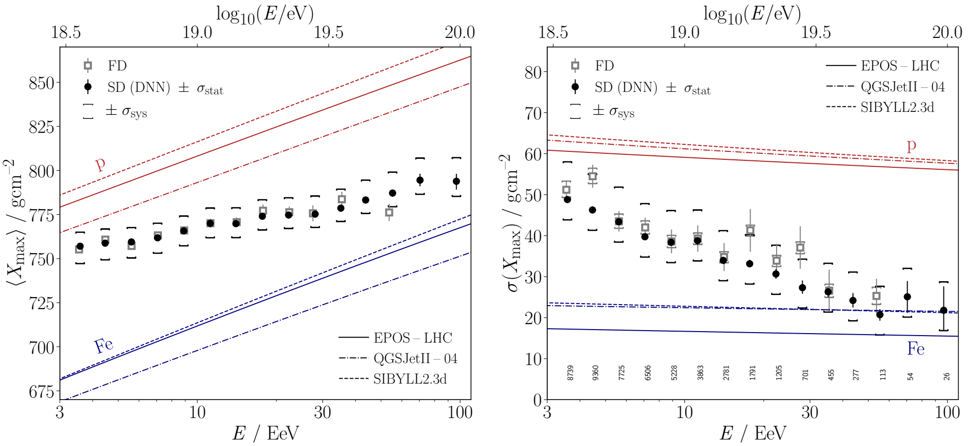




Source properties: rigidity $\log(R_{\max} \approx 18.15\mathrm{V} \rightarrow$ flux suppression dominated by the end of the UHECR spectrum, not by propagation

Assuming steady extra-galactic sources: very hard nuclear spectra escaping sources

Soon: mass composition using deep learning



First measurement of the fluctuations up to 100 EeV using the surface detector, further constrains on the source properties

Greisen-Zatsepin, Kuzmin effect and the cosmogenic particles

$$p + \gamma_{\mathrm{CMB}} \Rightarrow p + \pi^0$$

$$\pi^0 \to \gamma\gamma$$

$$p + \gamma_{\mathrm{CMB}} \Rightarrow n + \pi^+$$

$$\pi^+ \to \nu_e,\, \nu_\mu$$

Thershold energy for protons:

$$E_{\mathrm{thr}} \approx 6 \times 10^{19}\,\mathrm{eV}$$

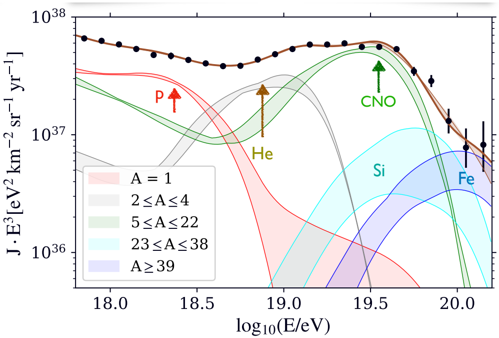
...almost no protons above E_{thr}

Photo-disintegration of nuclei

$$A + \gamma_{\mathrm{CMB}} \to (A-1) + p, n$$

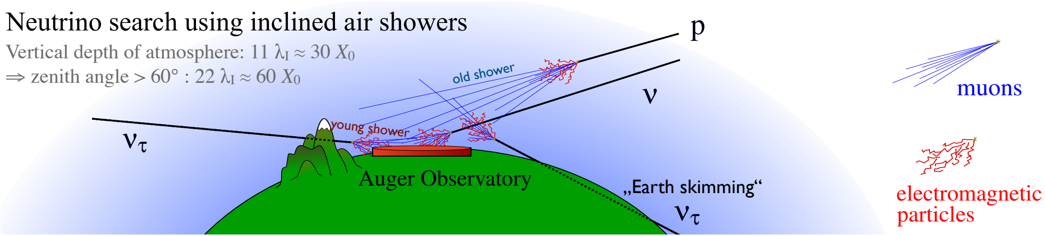
$$E_{\mathrm{thr}} \approx 5 \times 10^{19}\,\mathrm{eV}$$

$$E_\nu \approx E_A/A$$



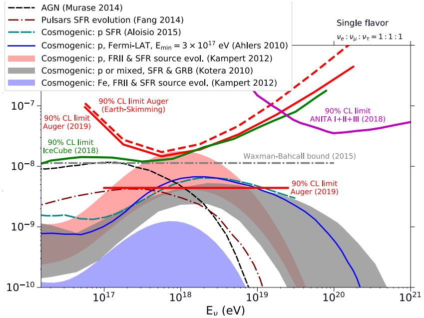
Expected cosmogenic fluxes much lower than in a pure proton composition

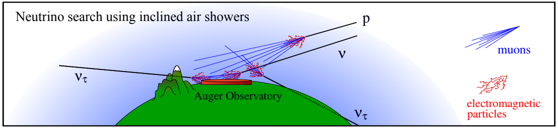
Search for neutrinos



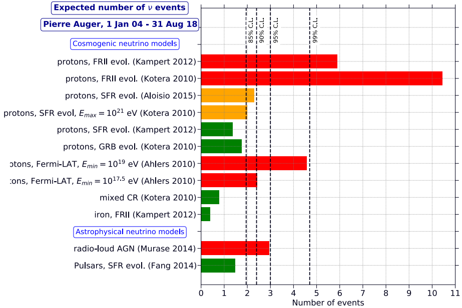
Based on the time distribution of signals: search for "young showers" containing a large fraction of electromagnetic particles
(hadronic initiated showers highly attenuated, just very energetic muons reaching the detectors)

Ultra high energy neutrinos: cosmogenic fluxes





(JCAP 10 (2019) 022, JCAP 11 (2019) 004)

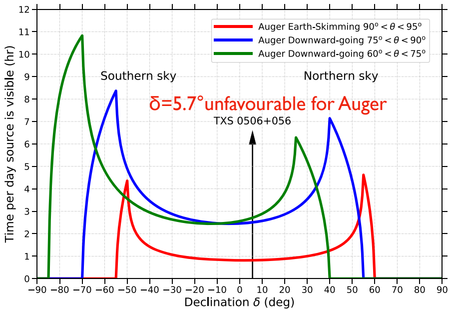


Expectations:

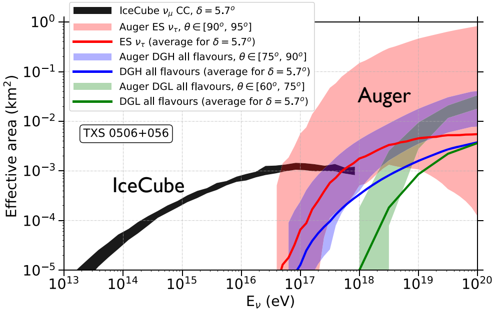
- pure p: about 6 ν
- pure Fe: about 0.4 ν
- max. energy scenarion: 0.001 ν

Search for neutrinos from TXS 0506+56

daily visibility in ES channel of Auger: < 1 hrs



effective area in comparison to IceCube

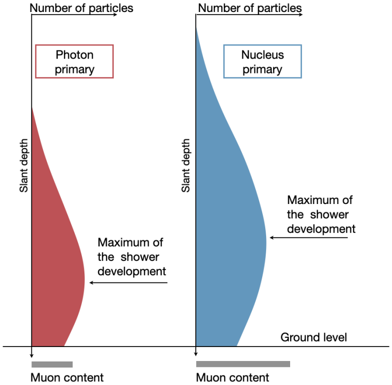


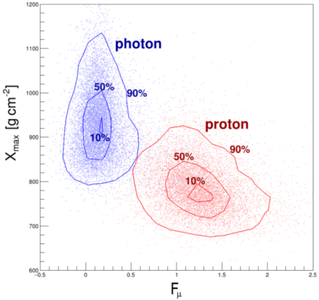
IceCube observed a 290 TeV nu from the direction of TXS 0506+59 during a flaring state

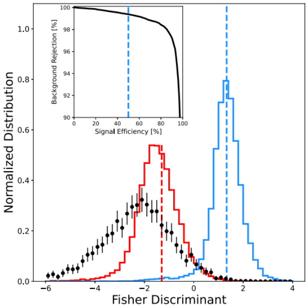
see also talk by Anna Frankoviak

Unfortunate none seen by Auger during the flare

Search for ultra-high-energy photons



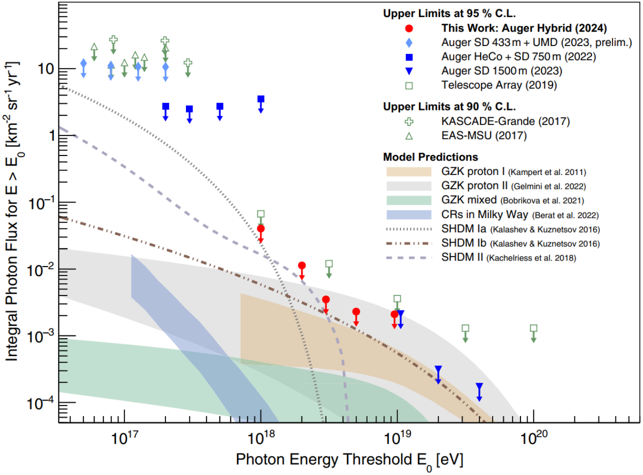




Deep showers with very low muon content

Searches done combining several detectors: fluorescence detectors (X_{max}), water-Cherenkov detectors, buried scintillators (muonic component)

Bounds on photon flux

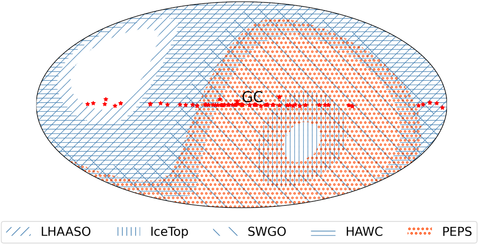


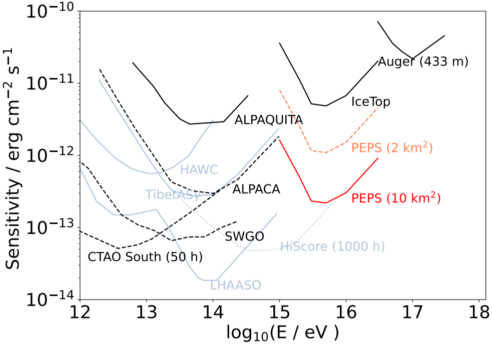
Photon limits start to constrain cosmogenic photon fluxes of p-sources and SHDM models

Can we lower the energy threshold to measure photons?

Probing Extreme PeVatron Sources (PEPS)

Idea: build a 10 km^2 denser array in the same area as the underground muon detectors using double liner water-Cherenkov detectors (Phase I of 2 km^2 in the next years)



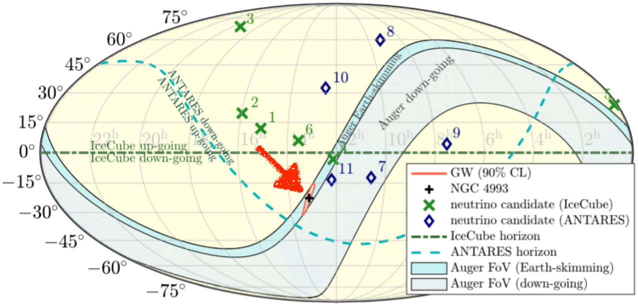


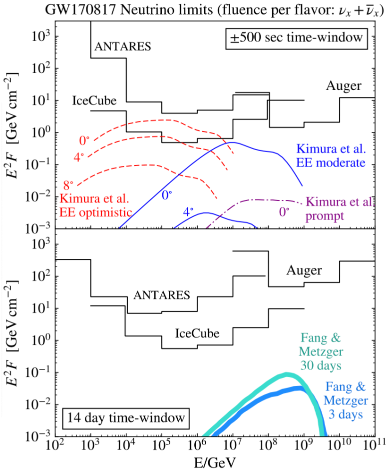
Lower the energy threshold down to ≈1 PeV: Tens of events expected for similar sources as LLHASO in the *no flux suppression scenarios*

Very good coverage of the southern sky and of the galactic center

supported by Auger Collaboration (not an Auger project yet)

Follow-up of GW170817





LVC, ANTARES, IceCube, Auger, ApJL 850 (2017) L35

- Source in the field of view of ES neutrino search
- No UHE neutrino candidates found in either coincidence windows (±500 sec around the GW or in the 14 days period after it)
- Limits on the total emitted energy in the range 10^{17}-$2.5\ 10^{19}$ eV

  ±500 s : $< 6.9\ 10^{-4}\ M_\odot$ +14 days : $< 2.3\ 10^{-2}\ M_\odot$

- Lack of detection consistent with expectation from a short GRB viewed at off-axis angle $>20^0$

Conclusions and outlook

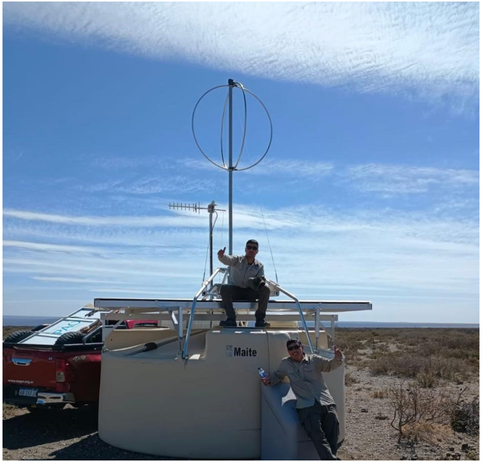
UHECRs ($> 10^{19}$eV) accessible only by cosmic rays

They provide important information for the multi-messenger physics (EHE neutrinos, photons, source composition,...)

... and benefit from the counterpart observations (neutrinos, photons, GWs, B-fields)

Pierre Auger Observatory partner in follow-up observations: ACME, AMON

Auger Phase II data within the next 10 years will provide valuable data to the MM physics



Last radio antenna installed 17 days ago