Overview of UHE neutrino searches at the Pierre Auger Observatory

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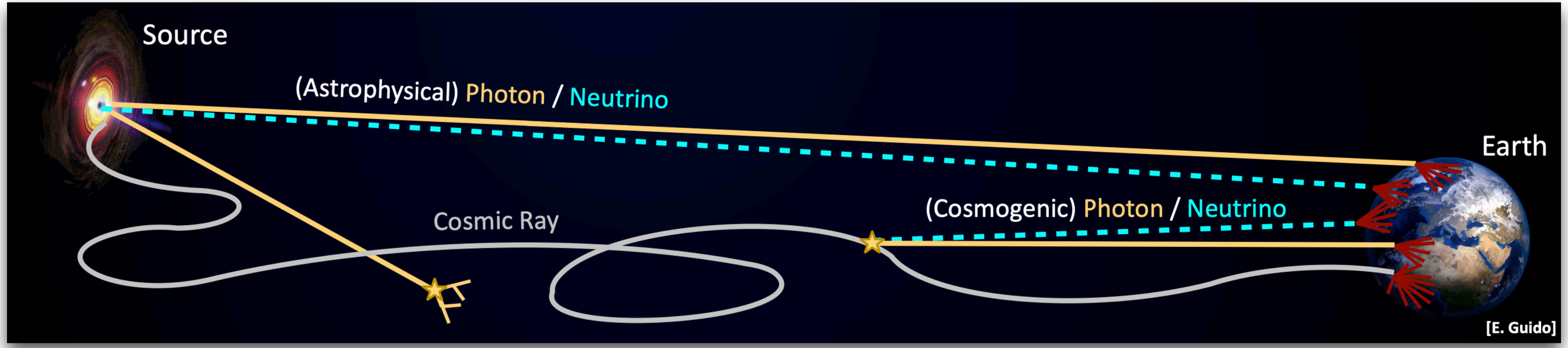
ICHEP 2024
17-24 July 2024, Prague

Why neutrinos and UHECRs?



$$p + \gamma \rightarrow \Delta^+ \longrightarrow \pi^0 + p$$
$$\pi^+ + n$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

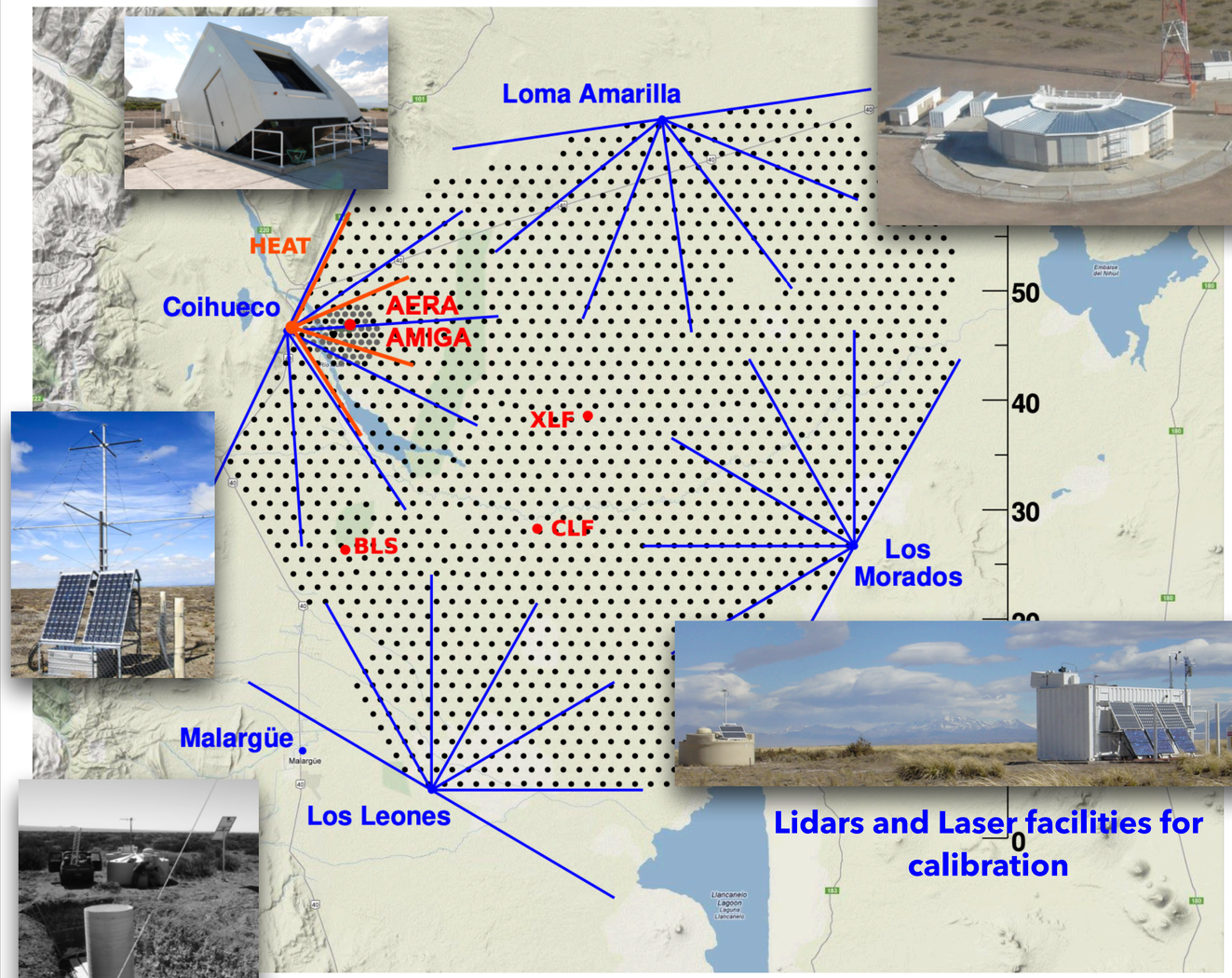
$$p + p \rightarrow \pi^+ / \pi^- / \pi^0$$

Astrophysical neutrinos: produced by interactions of cosmic rays in **astrophysical sources**

Cosmogenic neutrinos: produced by interactions of cosmic rays in **extragalactic propagation**

-> The same reactions can be induced also by heavier nuclei (but with higher threshold)

The **Pierre Auger Observatory** at a glance



Southern hemisphere:
Malargue, Province Mendoza, Argentina

Surface detector (SD)
- 1600 stations in 1.5 km grid, 3000 km^2 E > $10^{18.5}$ eV
- 61 stations in 750 m grid, 23.5 km^2, E > $10^{17.5}$ eV
- 19 stations in 433 m grid, E > 6 10^{16} eV

Fluorescence detector (FD)
- 24 telescopes in 4 sites, FoV: 0-30^o, E>10^{18} eV
- HEAT (3 telescopes), FoV: 30 - 60^o, E>10^{17} eV

Auger Engineering Radio Array (AERA)
- 153 antennas in 17 km^2 array, E> 4 10^{18}eV

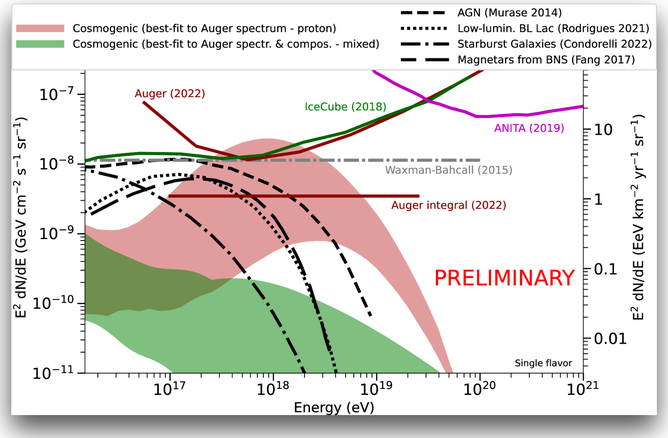
Underground muon detector
- 19(61) stations in 433(750)m array $10^{16.5}$<E< 10^{19} eV

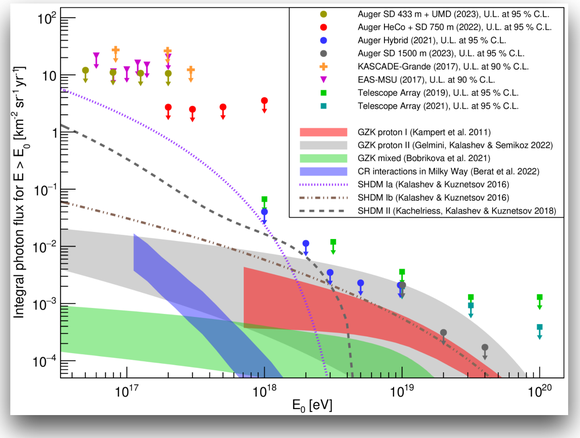
Auger Phase I data taking from 2004 on (from 2008 with the full array) to 2023
Auger Phase II data taking from 2024 to 2035

Slide by F. Salamida, Auger highlight @ICRC2023

The **global picture of UHECR results**

- Features in the energy spectrum
- Changes in mass composition
- Extragalactic origin from anisotropy signal
- Coherent results with non-observation of cosmogenic particles





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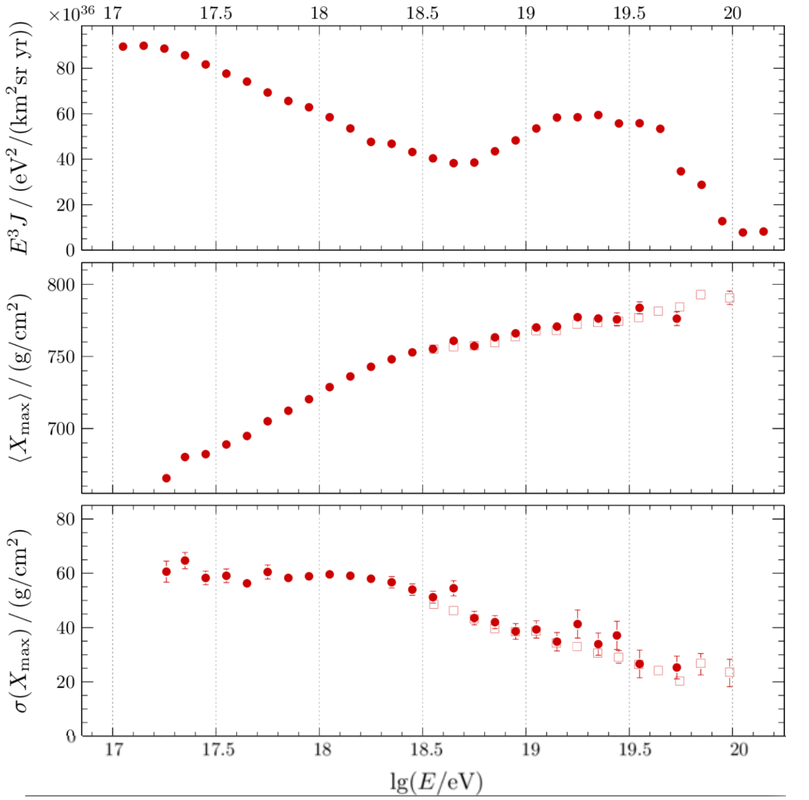
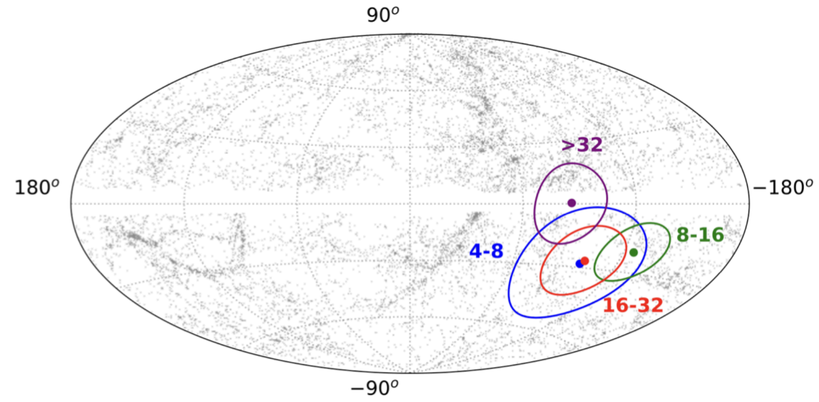
Energy spectrum

Mass composition

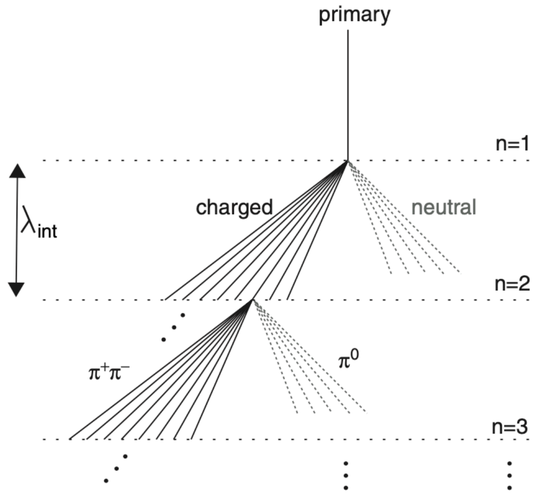
Anisotropy





The Pierre Auger Collab. ICRC23

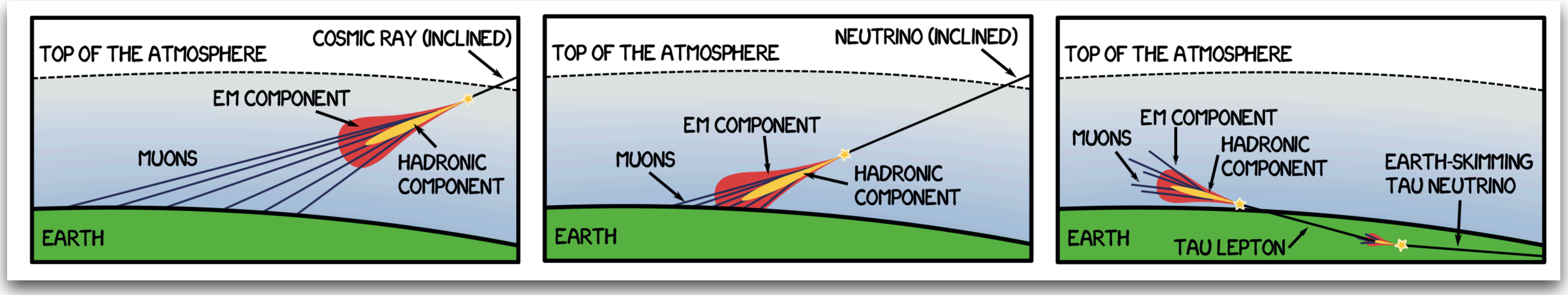
How to search for neutrinos



Measurements at UHE happen through the observation of extensive air showers (also for neutrinos and photons!)

How to search for neutrinos:

- **Inclined showers** with electromagnetic component (down-ward going **DG**)
- **Upgoing showers** from Earth-skimming tau neutrinos



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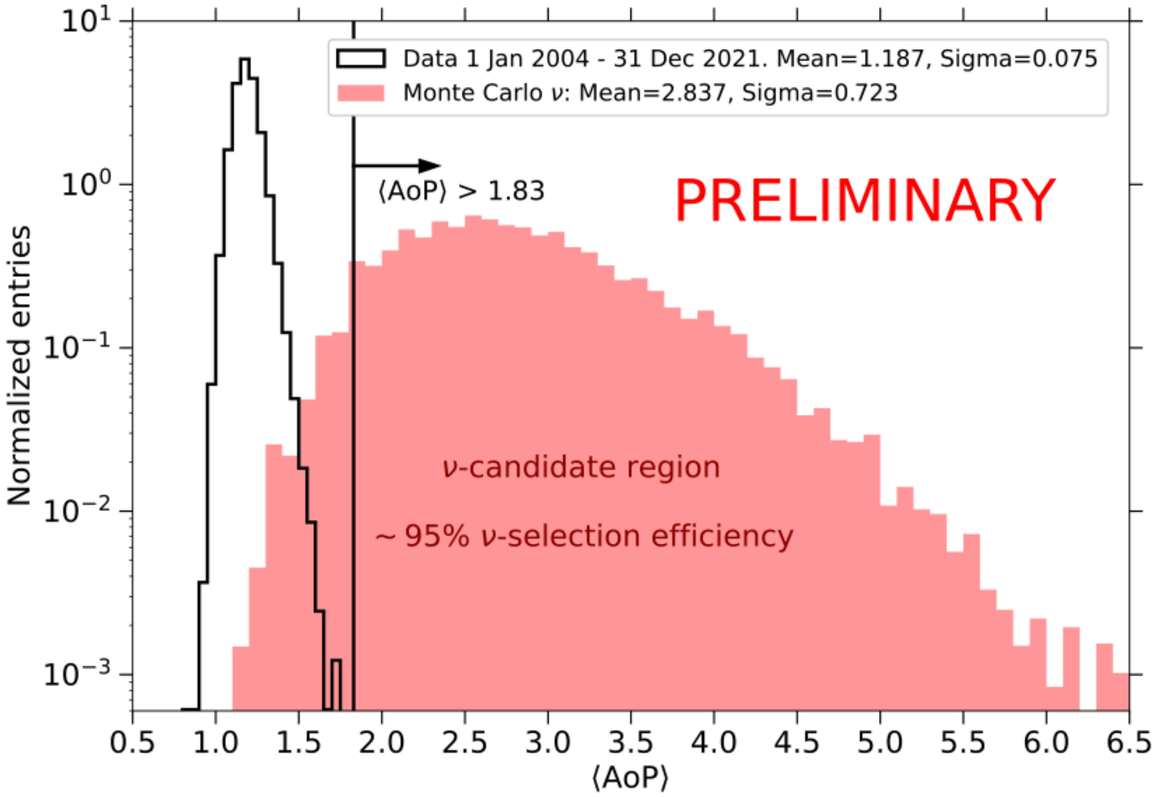
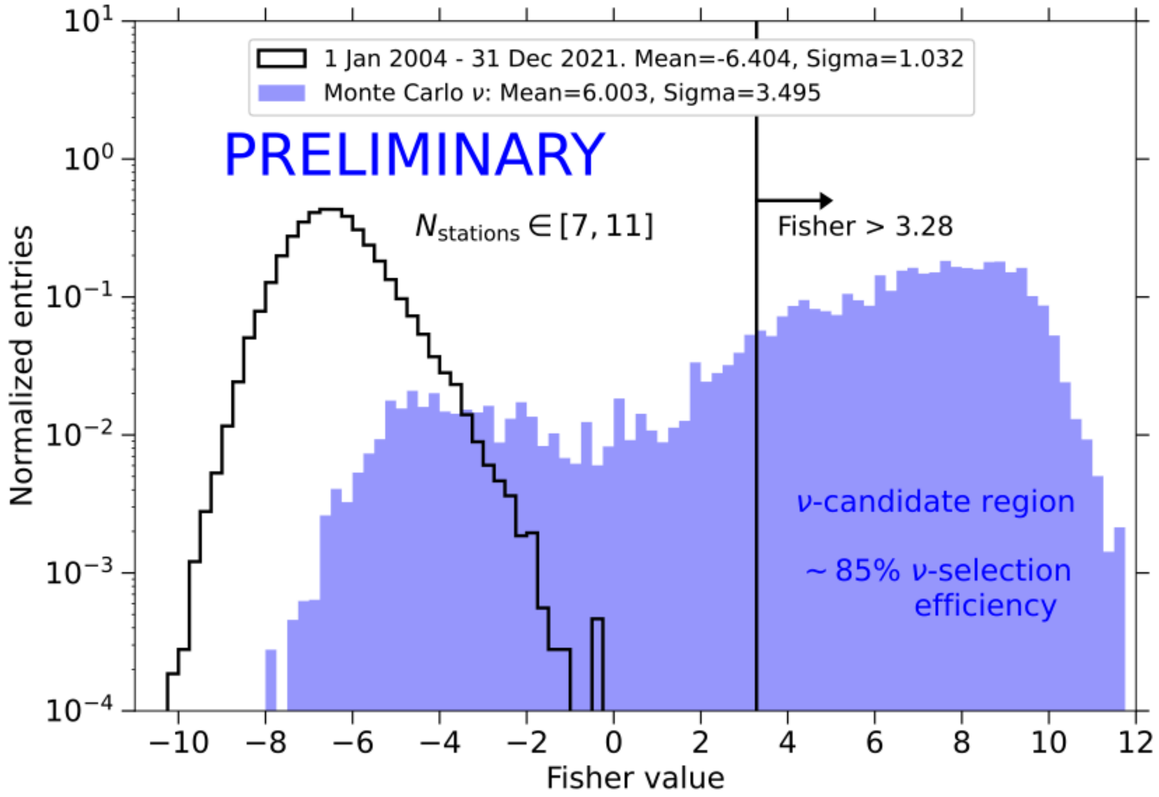




- For the ES channel, AoP averaged over the triggered stations in SD events is used
- For the DG channel, individual AoP are considered and subsequently combined in a Fisher analysis
- **No candidate events identified**

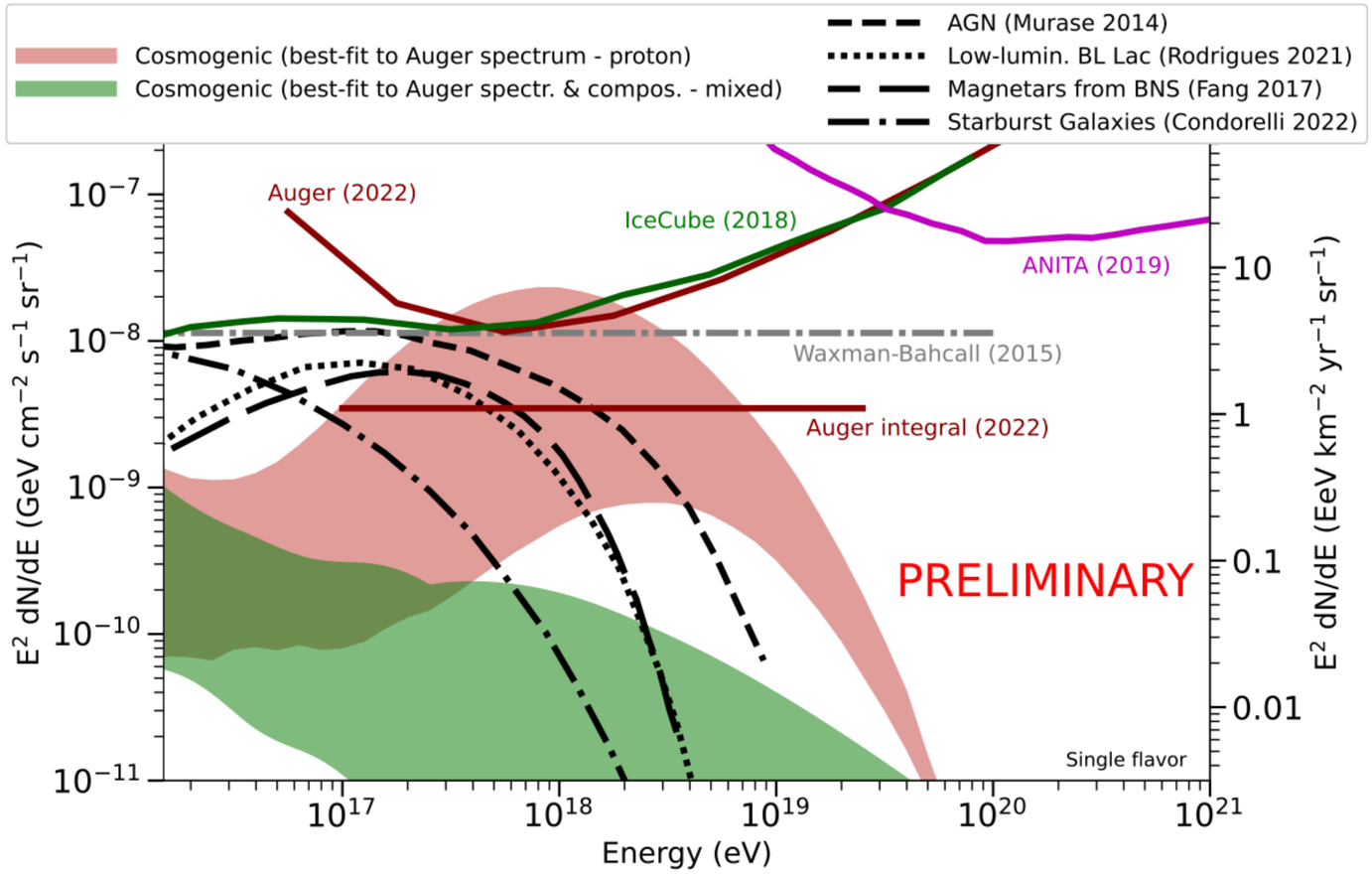
Upper limits on the diffuse flux

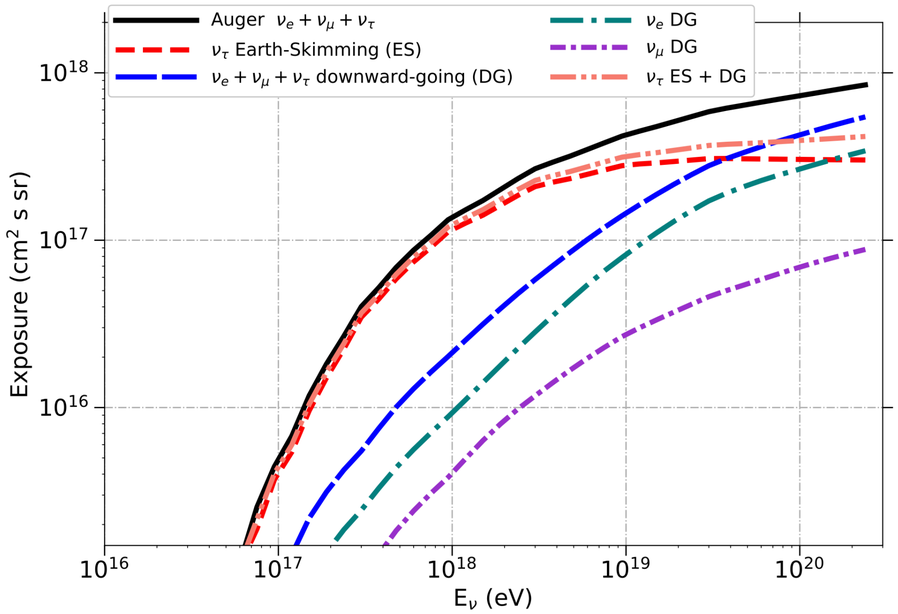
The Pierre Auger Collab. JCAP 2019

- Assumption: $\phi = k \cdot E_\nu^{-2}$

$$N_{\rm evt} = \int_{E_\nu} \mathcal{E}_{\rm tot}(E_\nu)\ \phi(E_\nu)\ {\rm d}E_\nu.$$

$$k_{90} = \frac{2.39}{\int_{E_\nu} E_\nu^{-2}\ \mathcal{E}_{\rm tot}(E_\nu)\ {\rm d}E_\nu},$$





Several classes of models of neutrino production, both cosmogenic and astrophysical, can be constrained thanks to the upper limit

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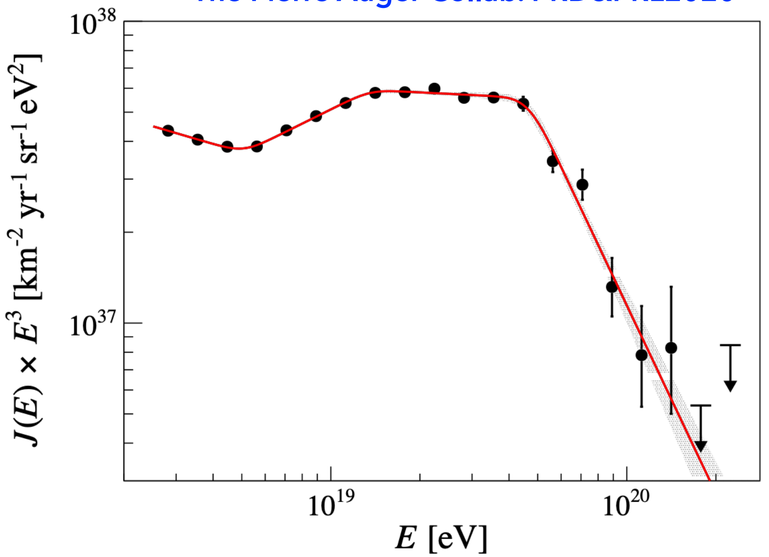
Constraints on UHECR scenarios with (non) observation of neutrinos

The Pierre Auger Collab. PRD&PRL2020



$$\frac{dN}{dE} \propto f_A \left(\frac{E}{10^{18}\text{eV}} \right)^{-\gamma} \times f_{cut}(E, Z_A R_{cut}) \times (1+z)^m$$

- The measured spectrum (and composition) can be fitted with an astrophysical model depending on the characteristics of the UHECR sources, taking into account the extragalactic propagation (see The Auger Collab. JCAP2017,2013,2024)

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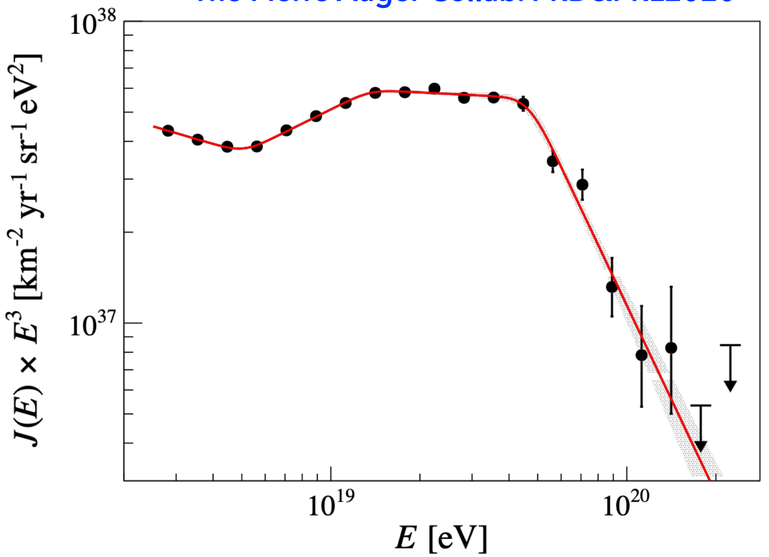

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$$\hookrightarrow \phi(E_\nu) \longrightarrow N_{evt} = \int_{E_\nu} \epsilon(E_\nu)\phi(E_\nu) dE_\nu$$

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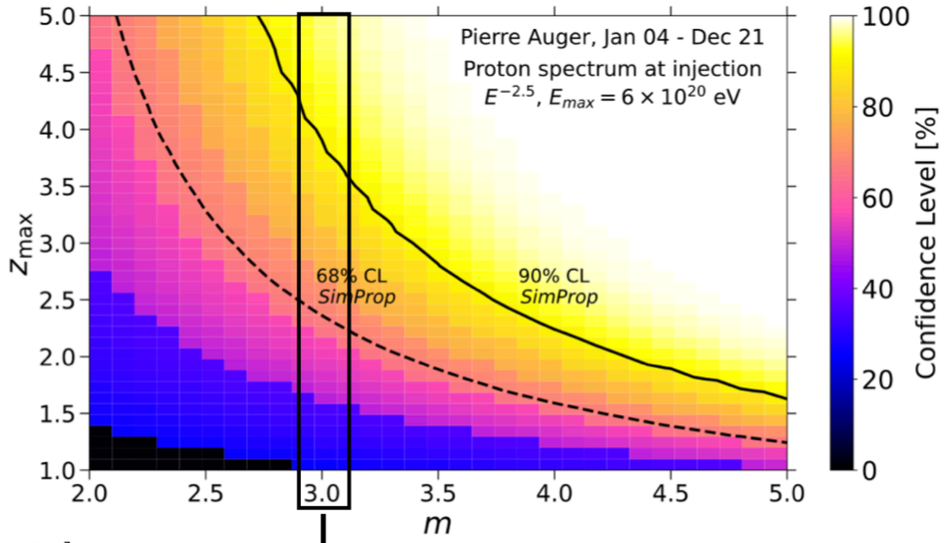

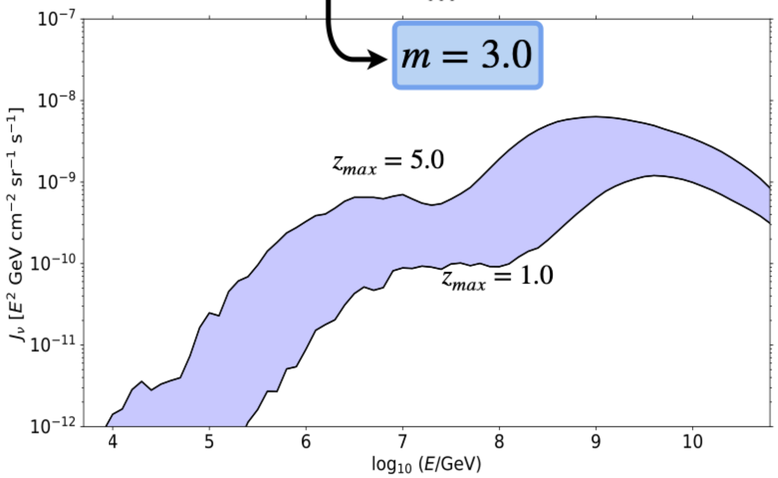

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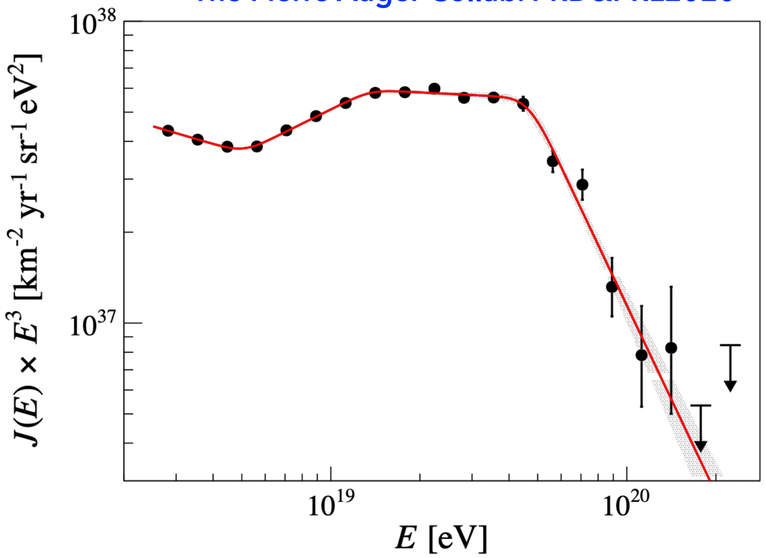

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- The measured spectrum (and composition) can be fitted with an astrophysical model depending on the characteristics of the UHECR sources, taking into account the extragalactic propagation (see The Auger Collab. JCAP2017,2013,2024)

- **Cosmogenic models involving a pure-proton composition and a strong evolution of the sources with redshift are excluded due to the non-observation of neutrinos**
- Multimessenger analyses can constrain UHECR scenarios (source distribution and mass composition)

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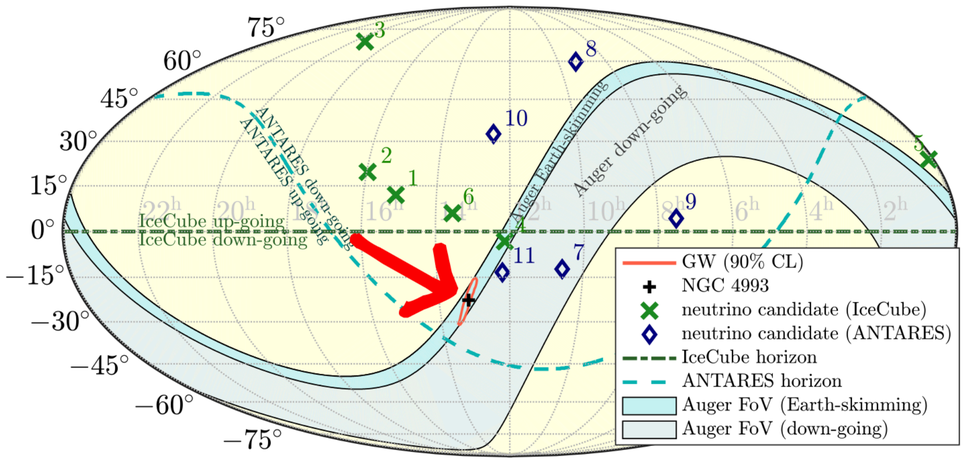
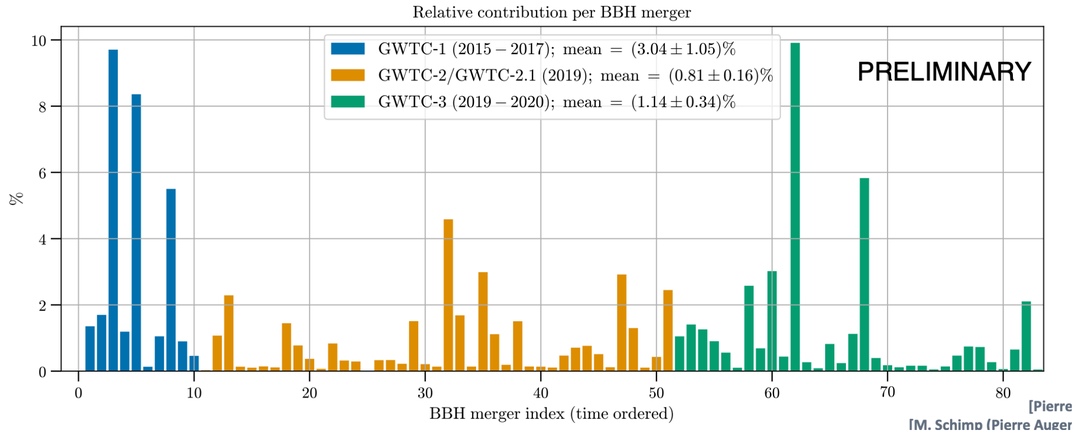
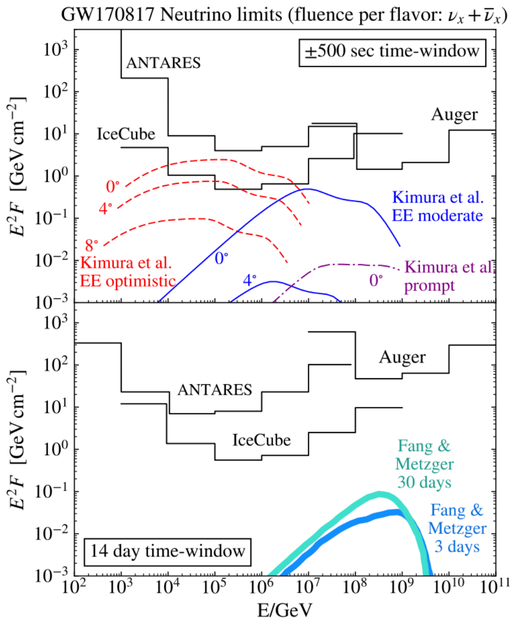
GW follow-up searches

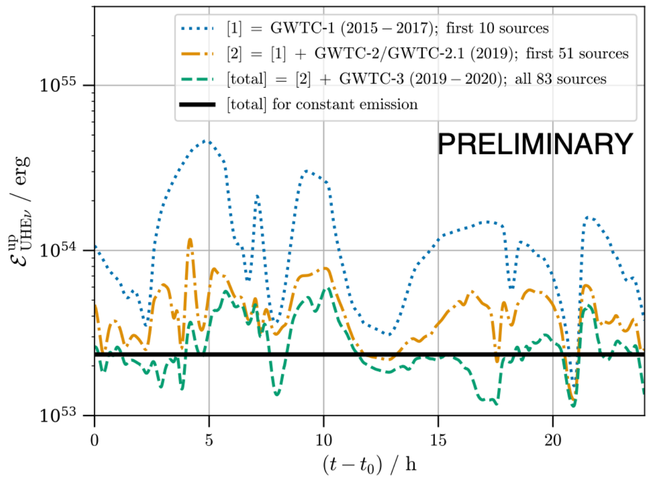




- Example of follow-up (GW170817)
  - Source within the FoV of the ES channel at the time of the event
  - Auger limits complement those of IceCube and ANTARES



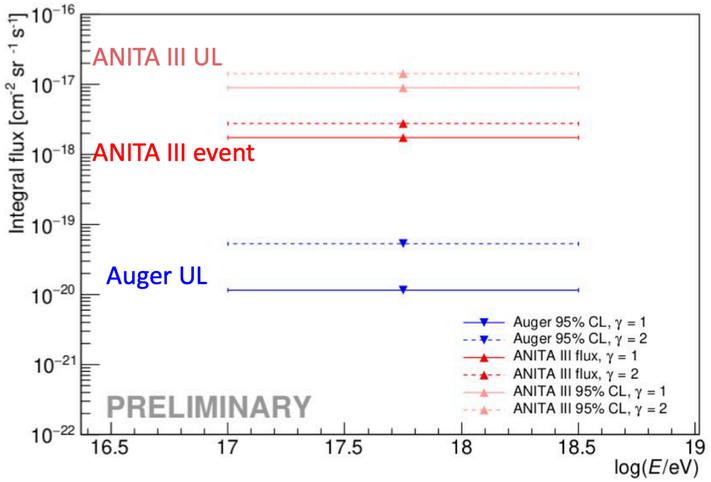
- Stacking analysis of binary BH mergers, for hypothetical emissions after 24 hours and 60 days after the merger, to constrain luminosity in neutrinos



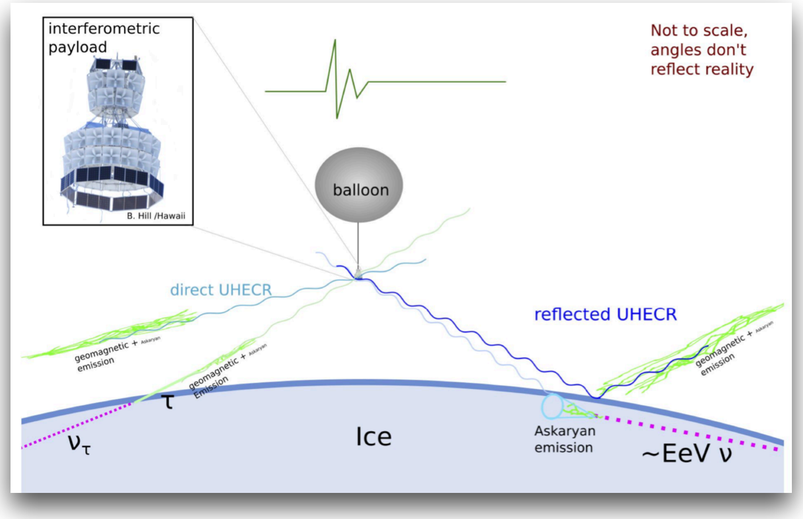
Antares, IceCube, Pierre Auger, Ligo Scientific and Virgo Coll., ApJL 2017

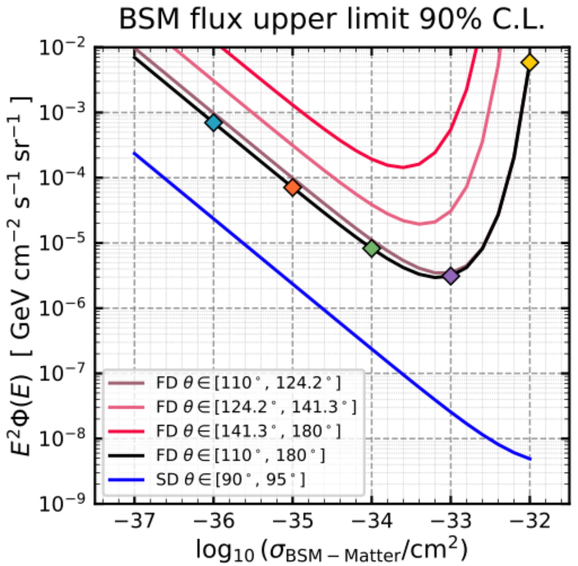
The Pierre Auger Collab. ICRC21

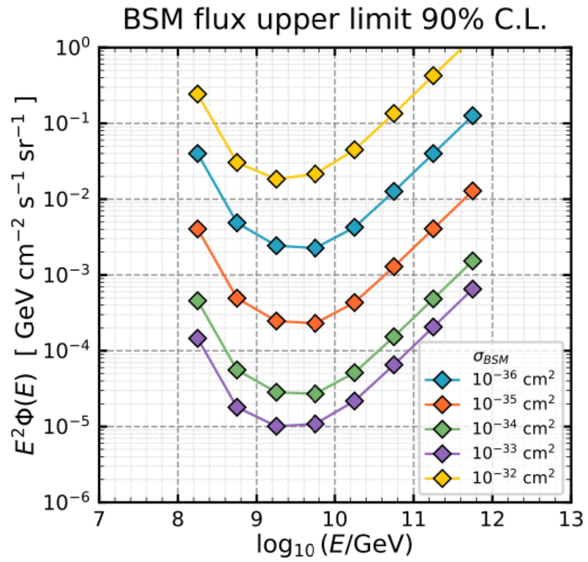
Neutrinos and tests of BSM physics



- ANITA reported the detection of two anomalous events appearing from below the horizon with shower energies exceeding 0.2 EeV
- Auger found one candidate event, compatible with background





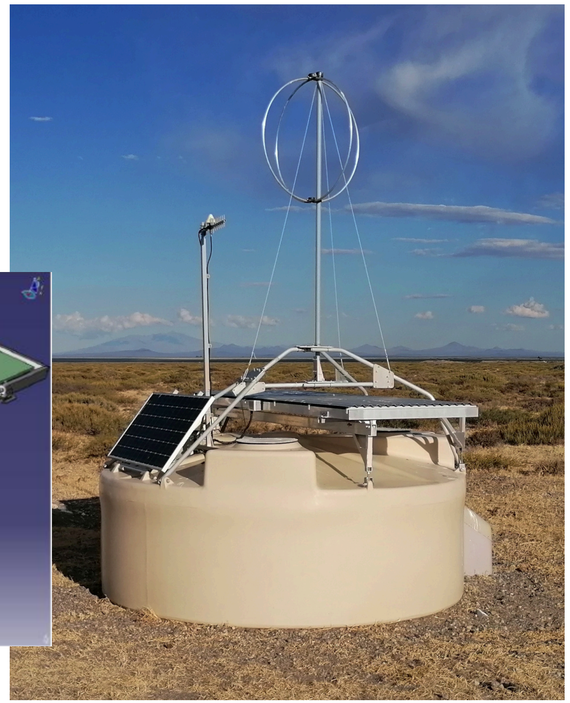


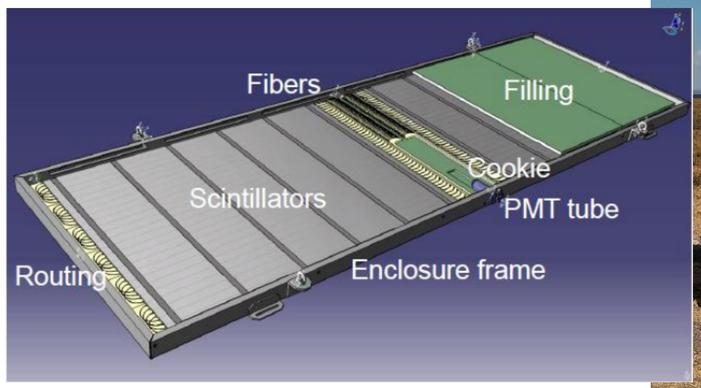
- They could be due to tau leptons decaying in the atmosphere; this is not consistent with neutrino interactions within the SM of particle physics
- Beyond standard model scenarios can be tested (processes - constant cross section - where BSM particles produce tau leptons interacting in the crust)

Summary

- The Pierre Auger Observatory measures UHECRs with unprecedented precision, and offers exposure to neutrino searches
- Upper limits to diffuse neutrino fluxes, and sensitivity to constrain UHECR models
  - Cosmogenic neutrino fluxes can provide information especially on the cosmological evolution of sources and on the mass composition (proton fraction at the highest energies)
- Follow-up searches to gravitational-wave events
- Constraining power to BSM physics (ANITA events, DM and sterile neutrinos, see Auger PRD 2024)

- Increasing constraining capability and sensitivity to neutrinos with **AugerPrime**





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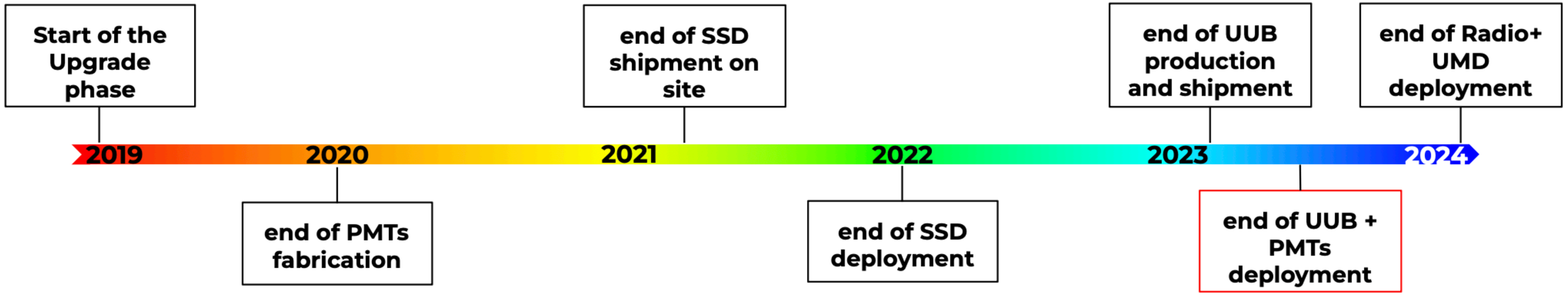
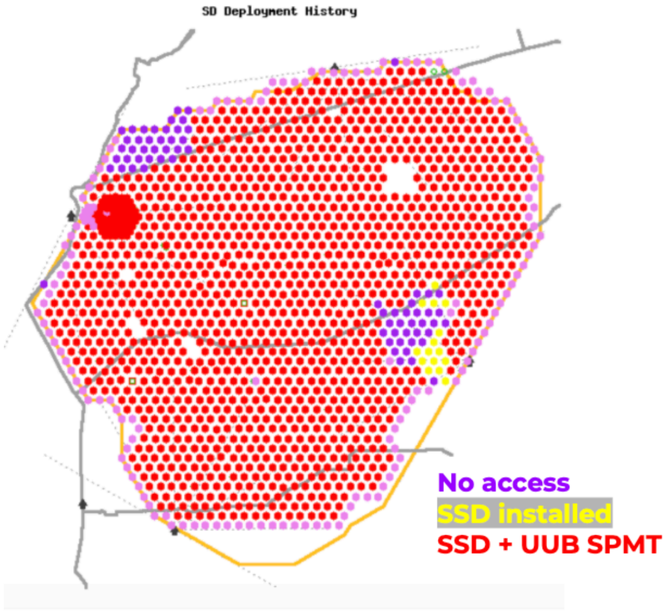
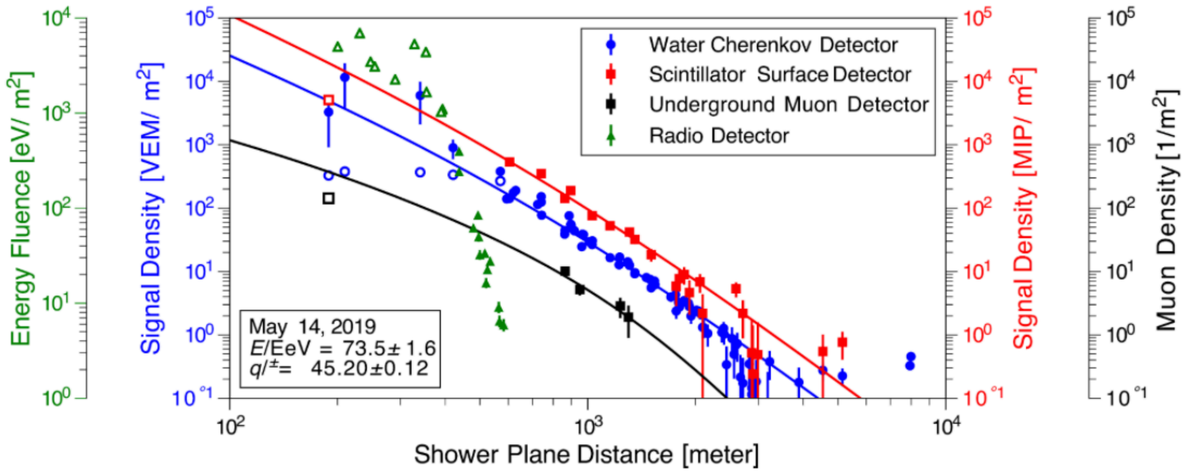
BACKUP slides

AugerPrime

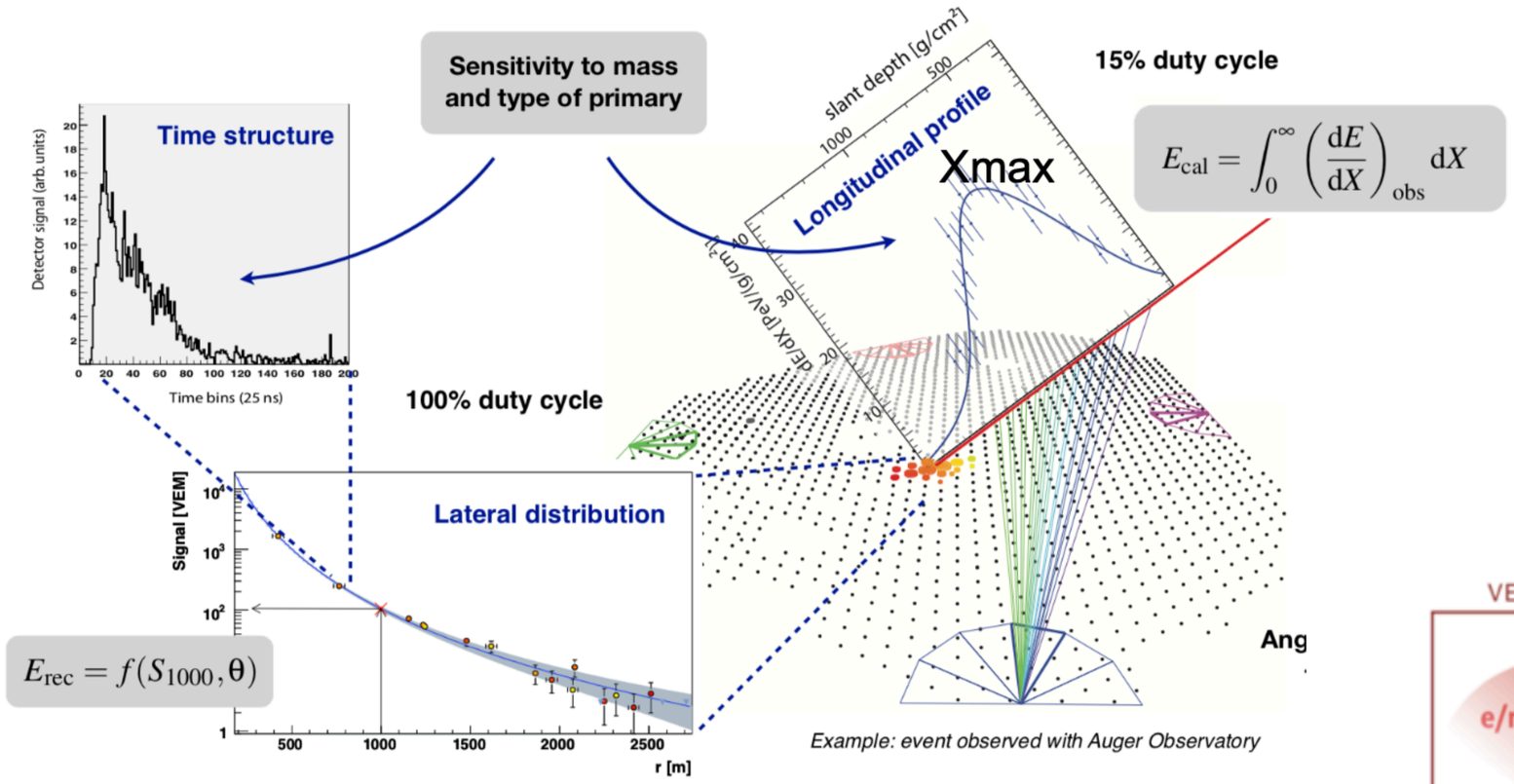






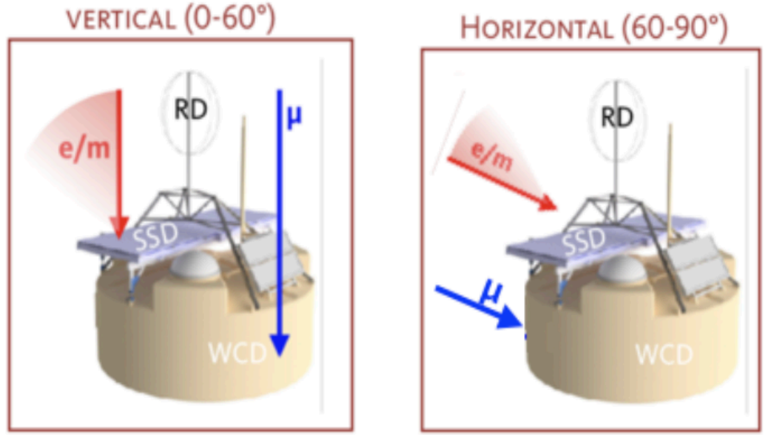
Slide by F. Salamida, Auger highlight @ICRC2023

The hybrid concept



STRATEGY

- Measure the same air showers with independent detectors (**hybrid events**)
- use hybrids (10% duty cycle) to calibrate the entire SD data sample (100% duty cycle)



In the near future Multi-Hybrid events with AugerPrime

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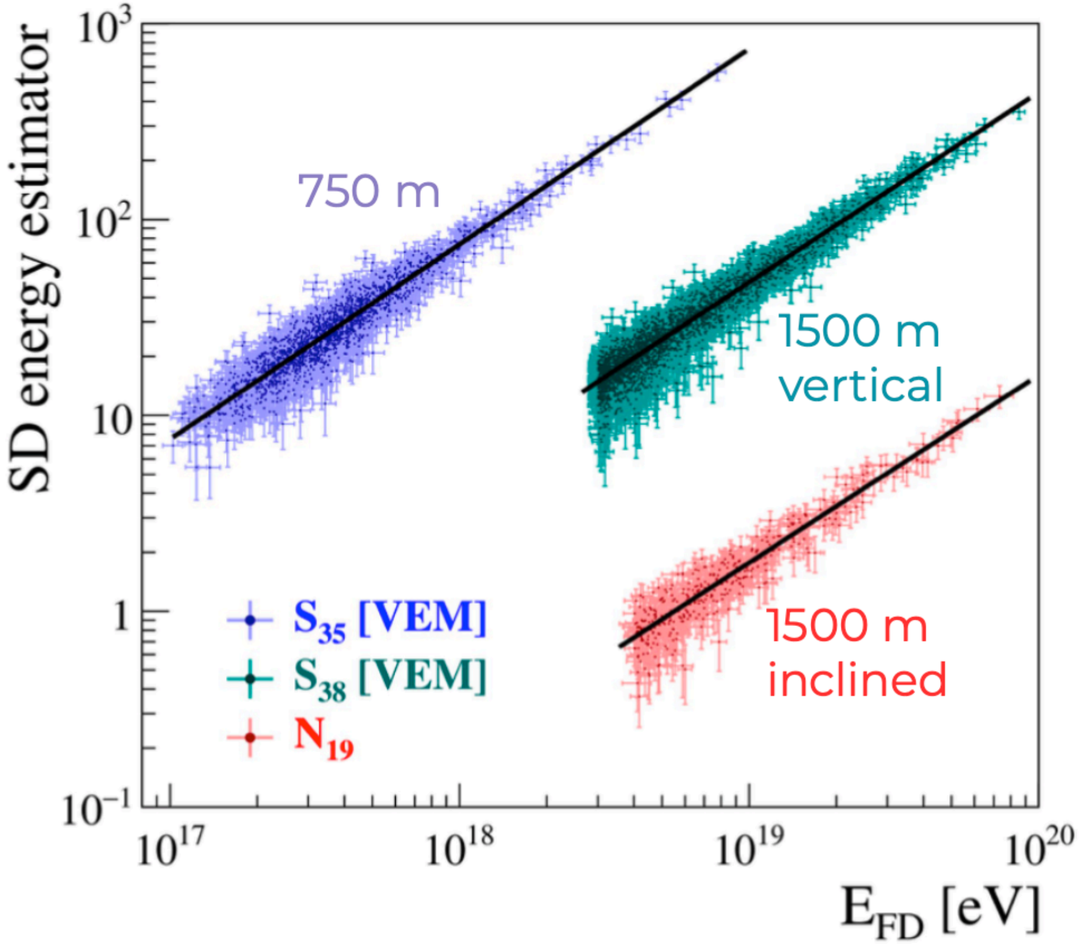
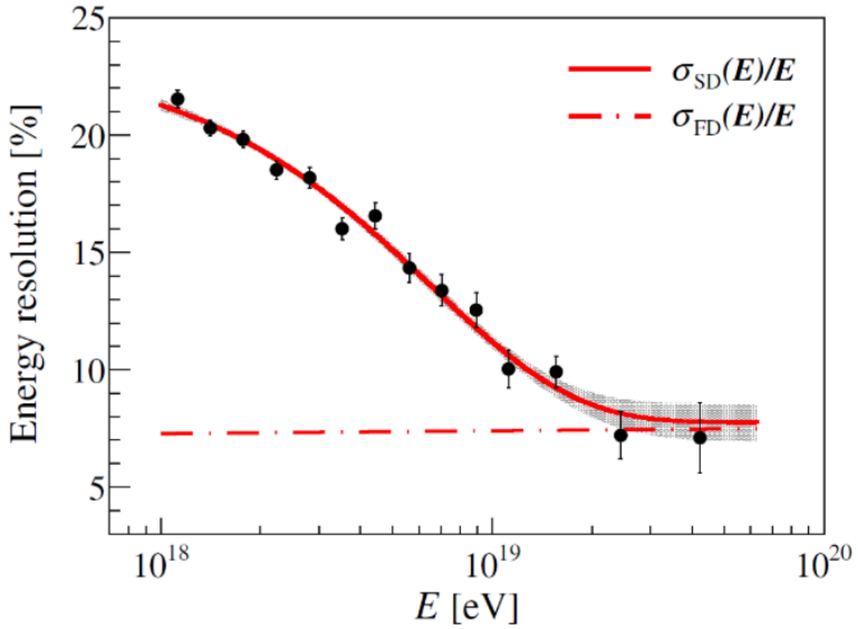
Energy calibration





Energy resolution

SD: < 20% (zenith < 60° and E > 2.5 10^{18} eV)

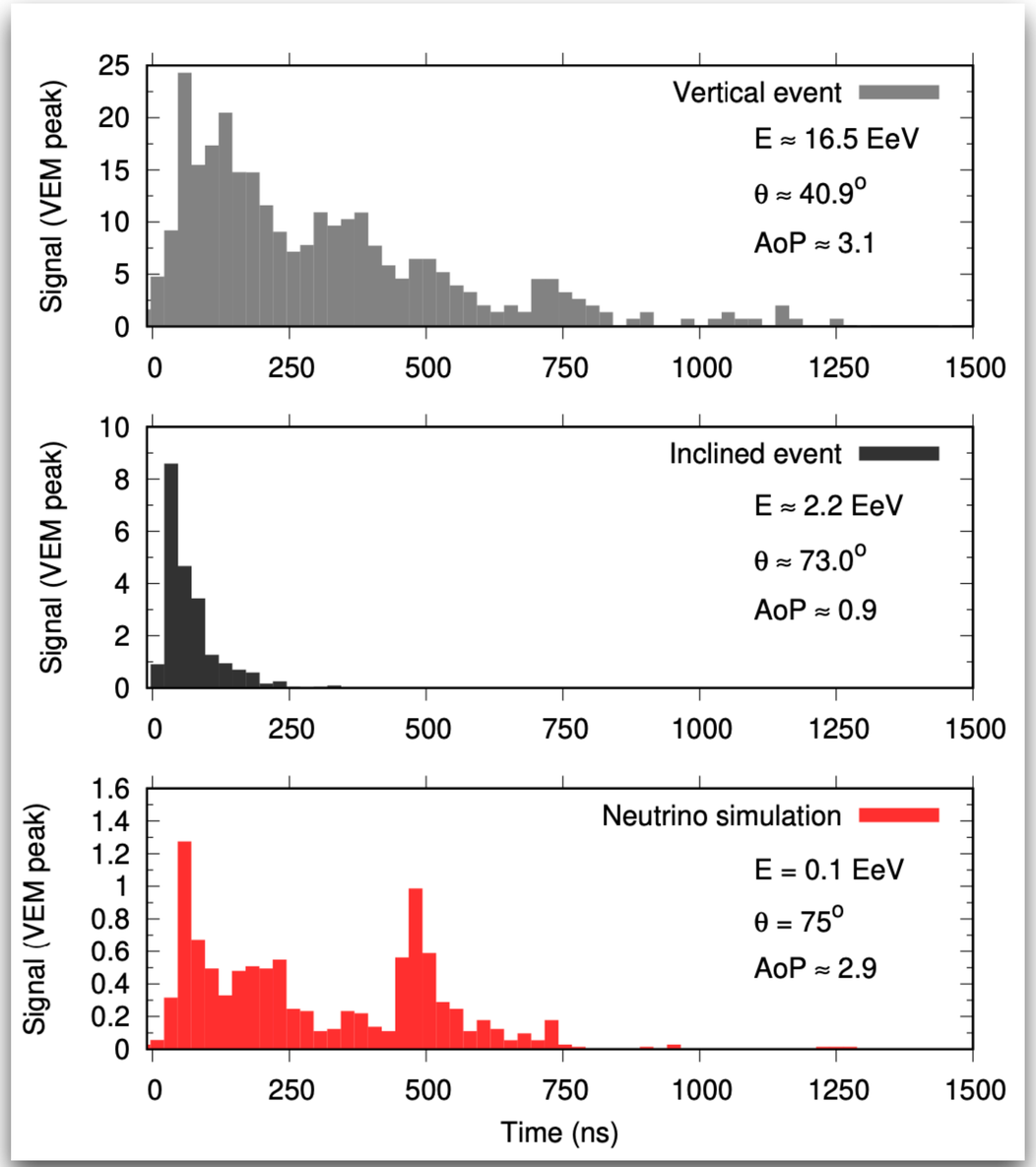
Hybrid: 6-8 % Hybrid [ICRC 2019

Energy scale systematics

14% (from FD)

Slide by F. Salamida, Auger highlight @ICRC2023

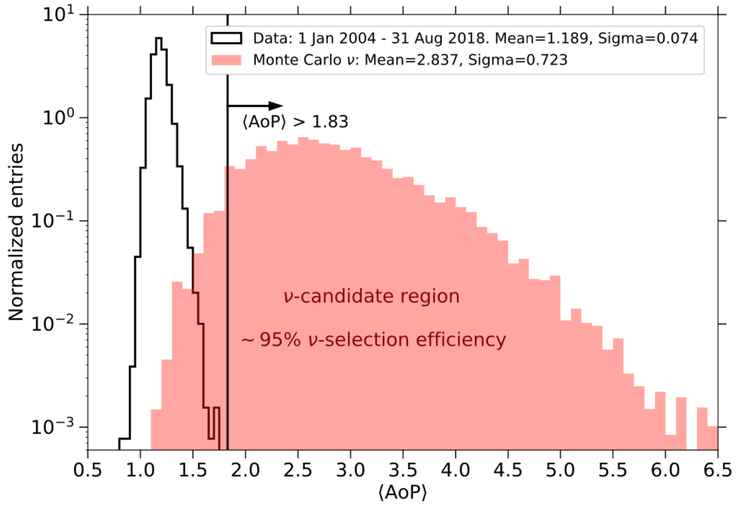
How to search for neutrinos



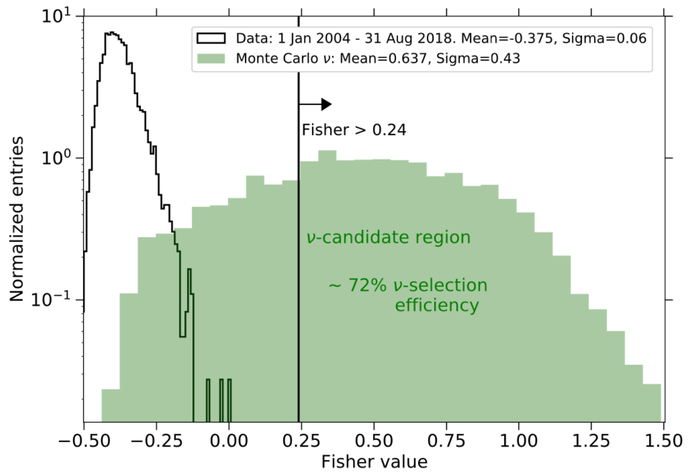
- Select showers that arrive at the SD array in the inclined directions and identify those that exhibit a broad time structure in the signals induced in the SD stations
- Information from geometry: in inclined events the pattern of the triggered SD stations exhibits an elliptical shape on the ground with the major axis of the ellipse along the azimuthal arrival direction
- Information from timing: several observables that contain information on the spread in time in the SD stations can be extracted from the time traces -> area over peak (AoP) can discriminate broad from narrow shower fronts

The Pierre Auger Collab. JCAP 2019

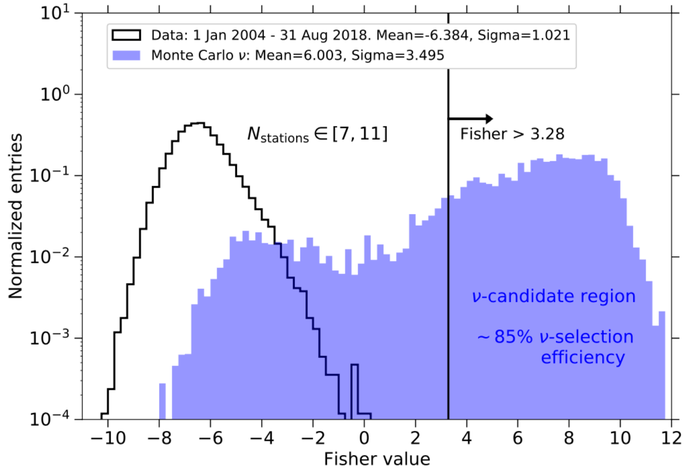
How to search for neutrinos



Earth-skimming



Downward (low zenith angle), $60<\vartheta<75$



Downward (high zenith angle) $75<\vartheta<90$

- The average value of AoP over all the triggered stations in the event is used as the only observable to discriminate between hadronic showers and ES neutrinos.
- The value of the cut on AoP is fixed using the tail of the distribution of AoP in real data, which is consistent with an exponential function

- Multivariate analysis to combine several observables that carry information on the time spread of the signals in the SD stations; observables are constructed from the AoP values of individual stations
- DWL: Selection more challenging due to the contamination from hadronic showers; the primary observables for inclined selection in the DGH case are the ratio L/W of the signal pattern of the shower at ground as well as the apparent average velocity of the signal, in addition to a simple estimate of the zenith angle
- DWH: The discriminants are constructed with ten variables that exploit the fact that, due to the large inclination of the shower, the electromagnetic component is less attenuated in the stations that are first hit by a deep inclined shower than in those that are hit last

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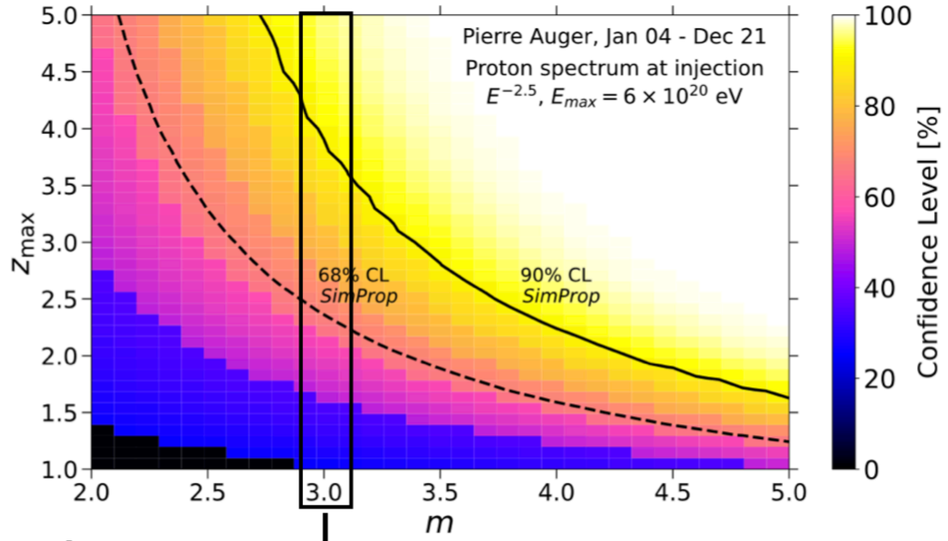
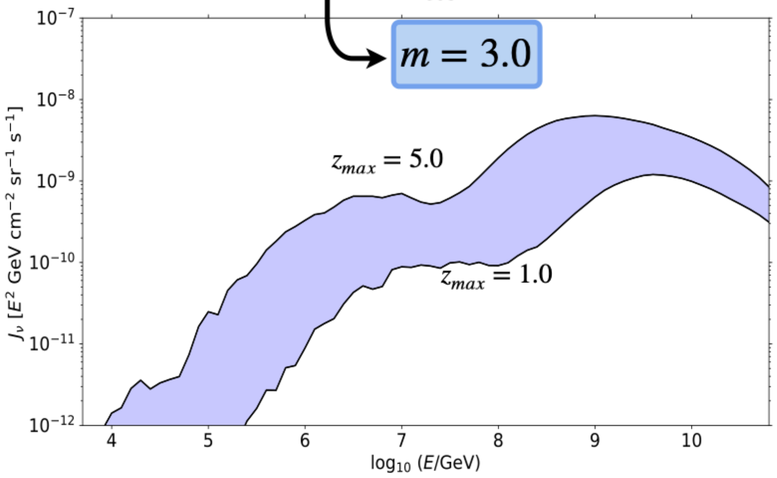
Constraints on UHECR scenarios with (non) observation of neutrinos





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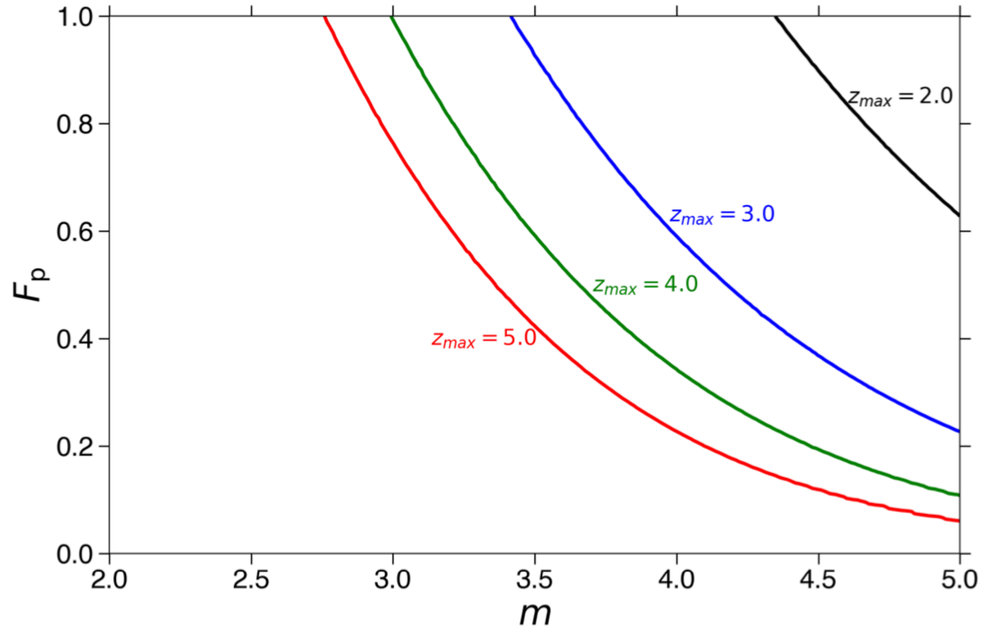

- The proton fraction at the highest energies can be constrained

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