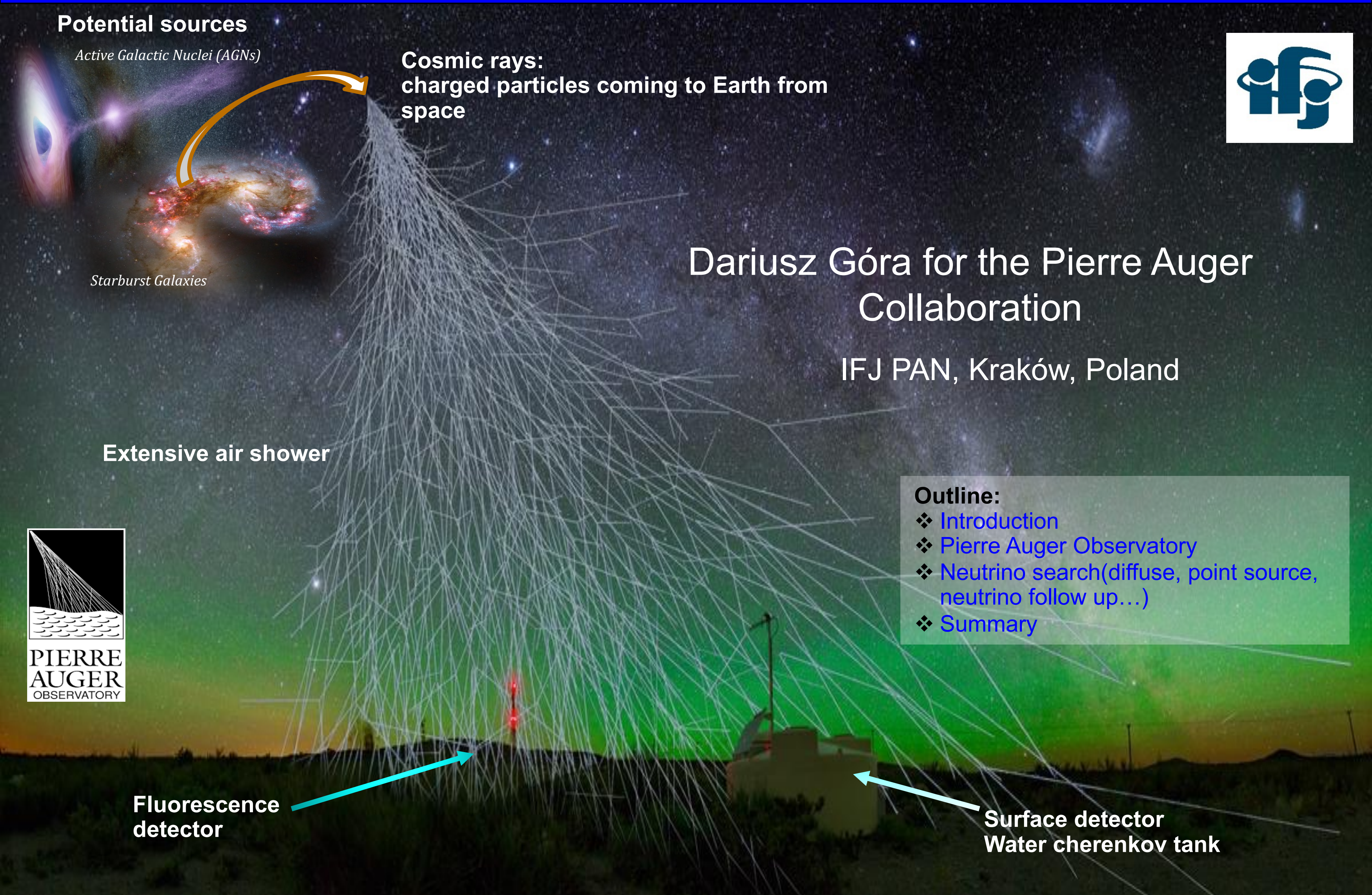
Search for ultra-high energy neutrinos in the Pierre Auger Observatory



Dariusz Góra for the Pierre Auger Collaboration

IFJ PAN, Kraków, Poland

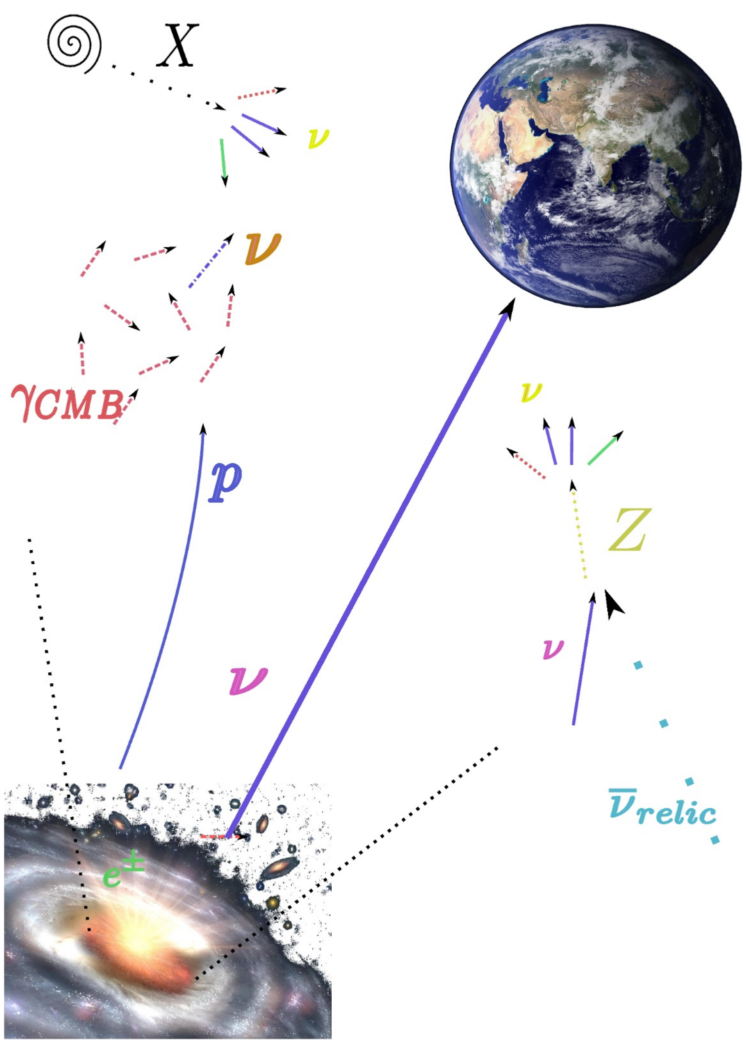
Outline:

- Introduction
- Pierre Auger Observatory
- Neutrino search(diffuse, point source, neutrino follow up…)
- Summary

Introduction

- Ultra-high energy neutrinos arise from decays of charged pions:

$$p + p(\gamma) \rightarrow \pi^{\pm} + X$$
$$\hookrightarrow \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu)$$
$$\hookrightarrow e^{\pm} + \bar{\nu}_\mu(\nu_\mu) + \nu_e(\bar{\nu}_e)$$
$$p + p(\gamma) \rightarrow \pi^{0} + X$$
$$\hookrightarrow 2\gamma$$



- At sources (AGNs, GRBs, SNRs,…):
  $\nu_e : \nu_\mu : \nu_\tau = \mathbf{1 : 2 : 0}$

- Flavor oscillations over cosmological distances produces also tau neutrinos:
  $\nu_e : \nu_\mu : \nu_\tau \sim \mathbf{1 : 1 : 1}$

- Neutrinos are also produced in interactions of cosmic rays with microwave background (cosmogenic/GZK neutrinos)

Pierre Auger Observatory is also a neutrino detector

Pierre Auger Collaboration

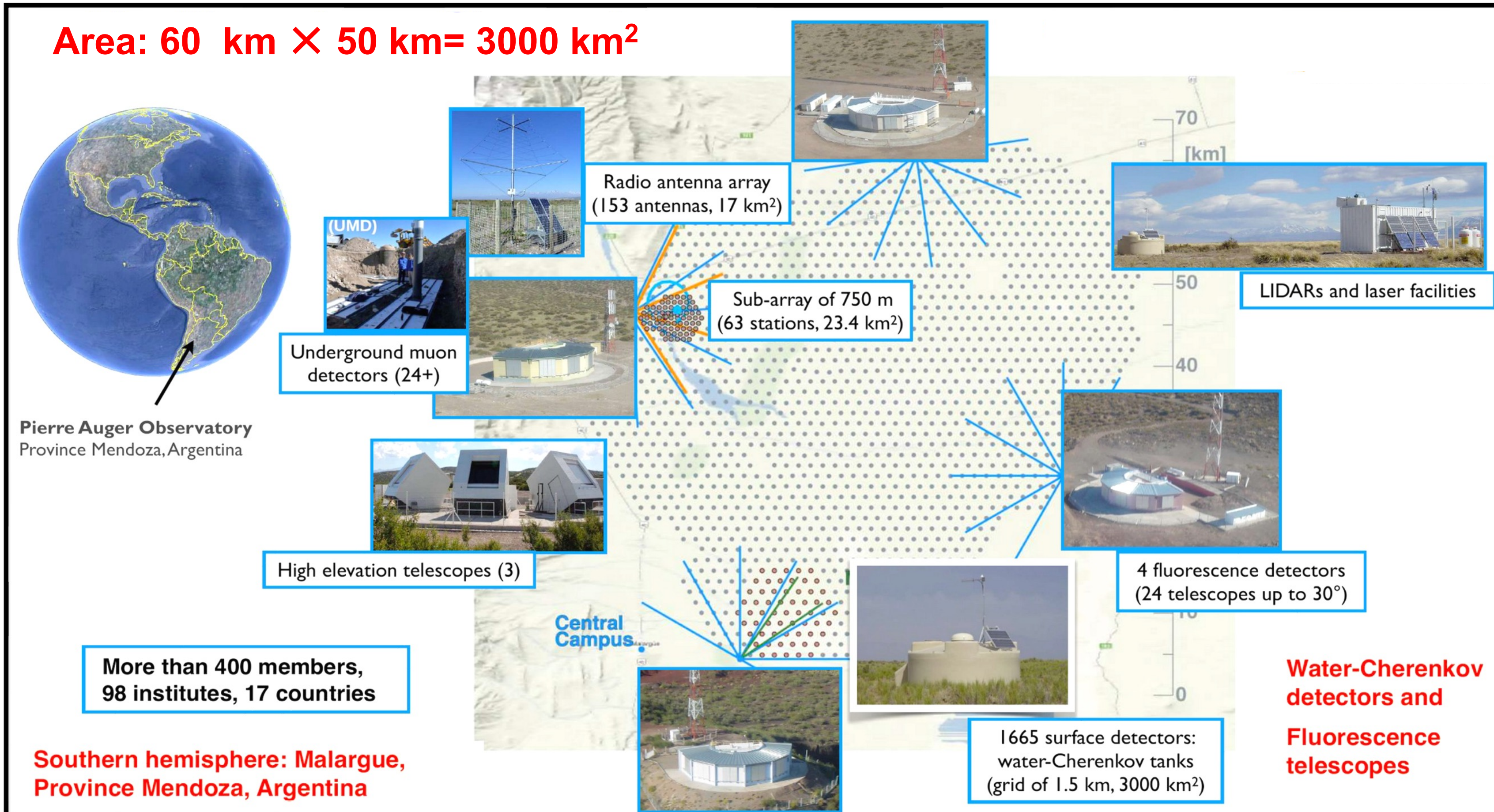
around 500 members from 18 countries

- Argentina
- Australia
- Belgium
- Brazil
- Colombia
- Czech Republic
- France
- Germany
- Italy
- Mexico
- Netherlands
- Peru
- Poland
- Portugal
- Romania
- Slovenia
- Spain
- USA

located near Malargue, Argentina

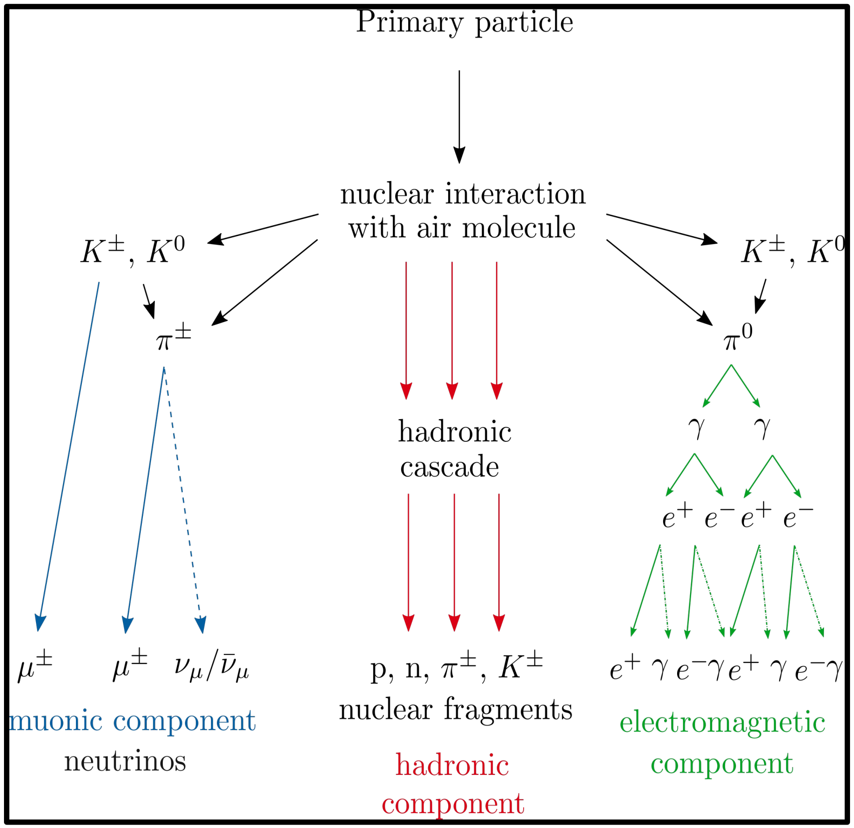
Pierre Auger Observatory: hybrid detector

Fluorescence detector (FD)	Surface detector (SD)
duty cycle 15%	duty cycle 100%
24 + 3 fluorescence telescopes	**1660** water-Cherenkov detectors



Highest energy cosmic rays > 10^{18} eV (UHECRs)

At ultra-high energies (> 10^{18} eV), particle physics beyond the reach of Earth's colliders

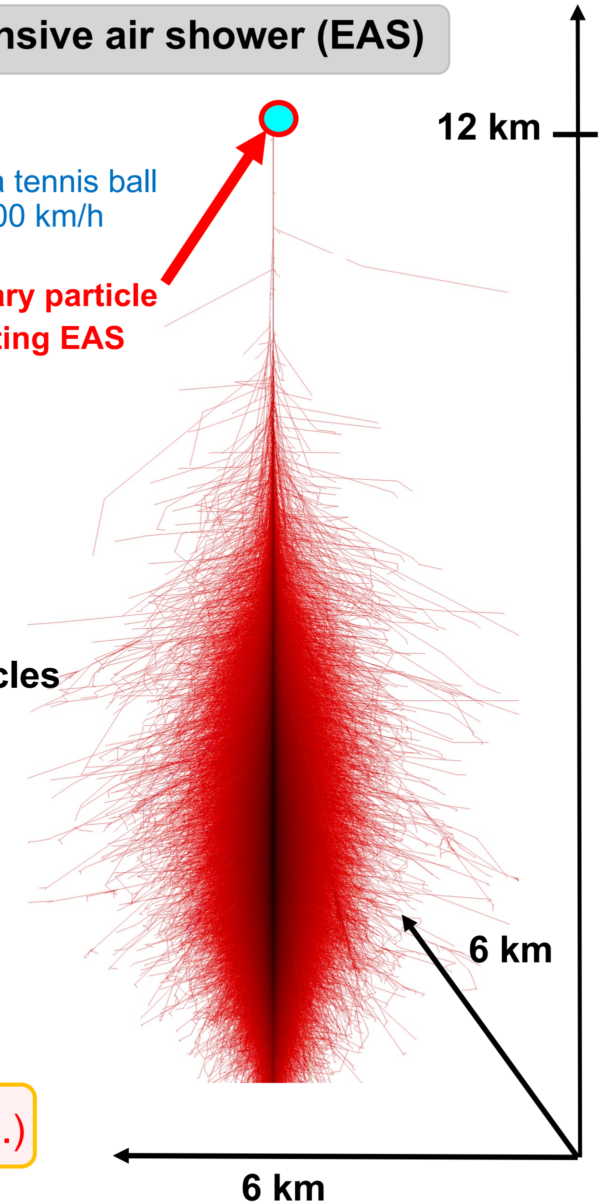


Extensive air shower (EAS)

EAS with 10^{20} eV:
kinetic energy of a tennis ball speeding about 100 km/h

Primary particle initiating EAS

Shower particles
~ $\mathcal{O}(10^{12})$

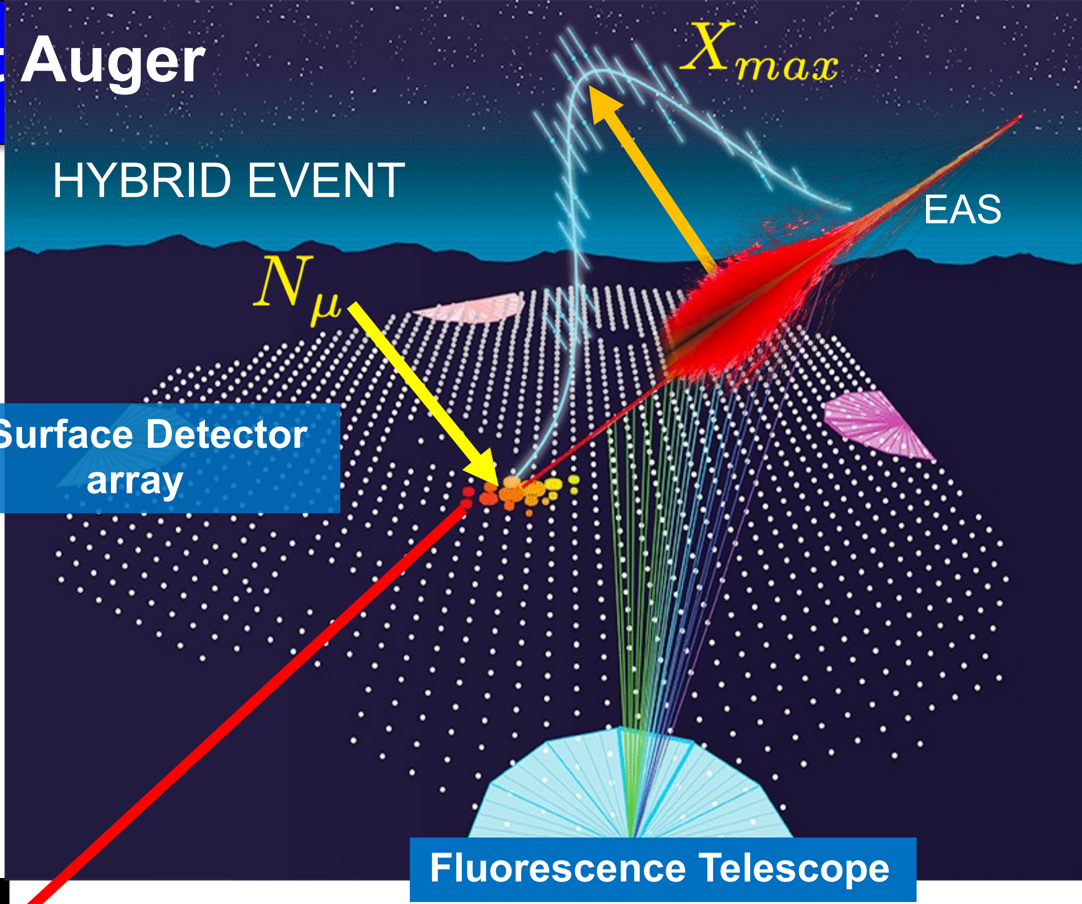


Possibility to study hadron interactions for LHC x 30 energy (in C.M.)

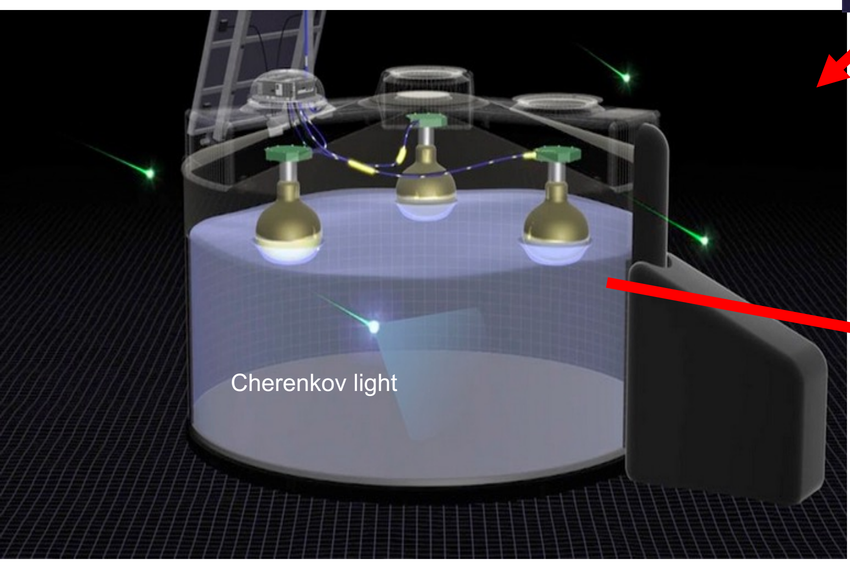
Observables of interest at Auger

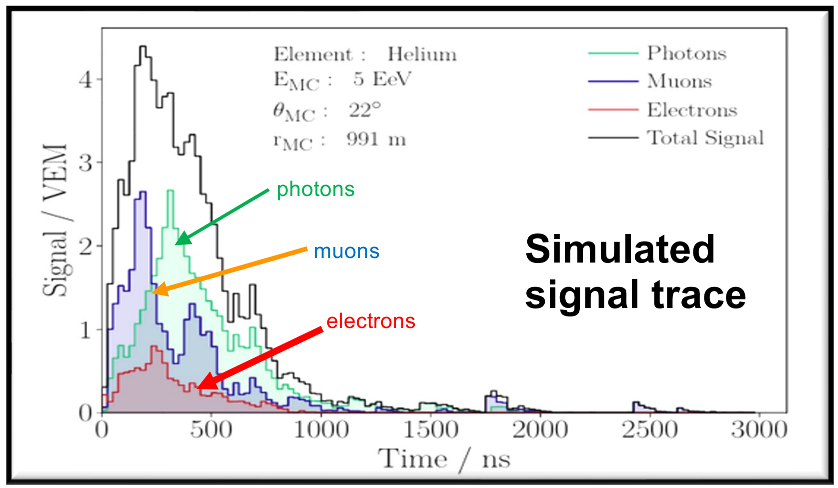
❖ **Fluorescence Detectors (FD):**
Depth of maximum development X_{max}
Currently the most precise mass estimator

❖ **Surface Detectors (SD):**
Number of muons at ground N_{μ}
Measure the arrival time of secondary particles of the shower at the ground



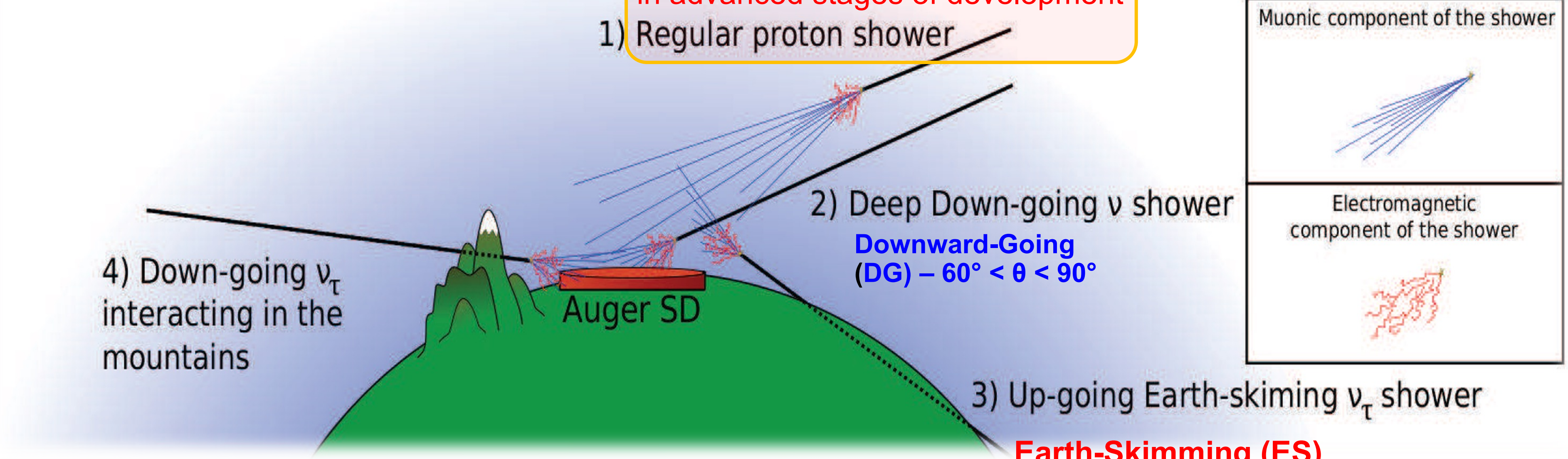
Surface detector stations





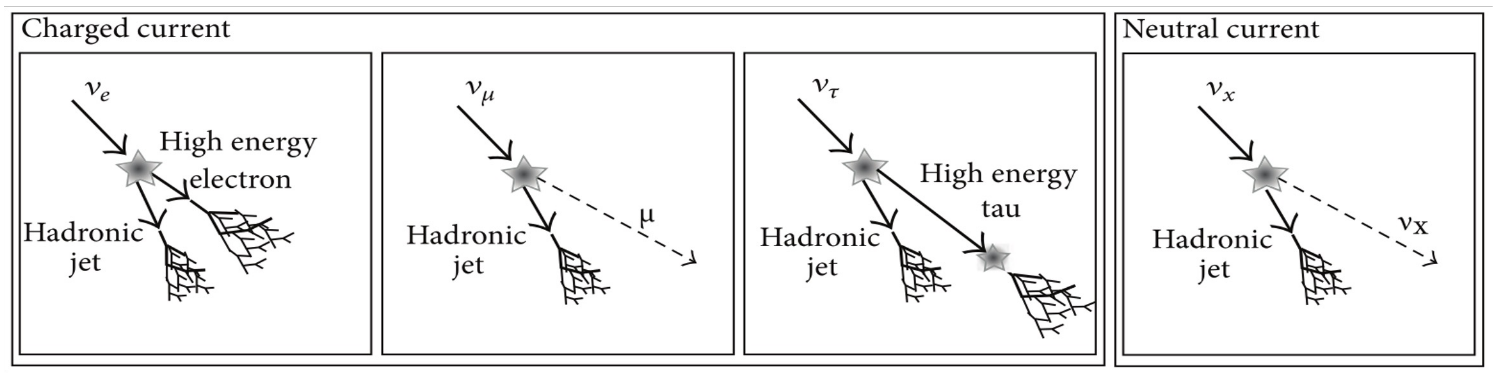
Method of neutrino identification

Background from hadronic events in advanced stages of development



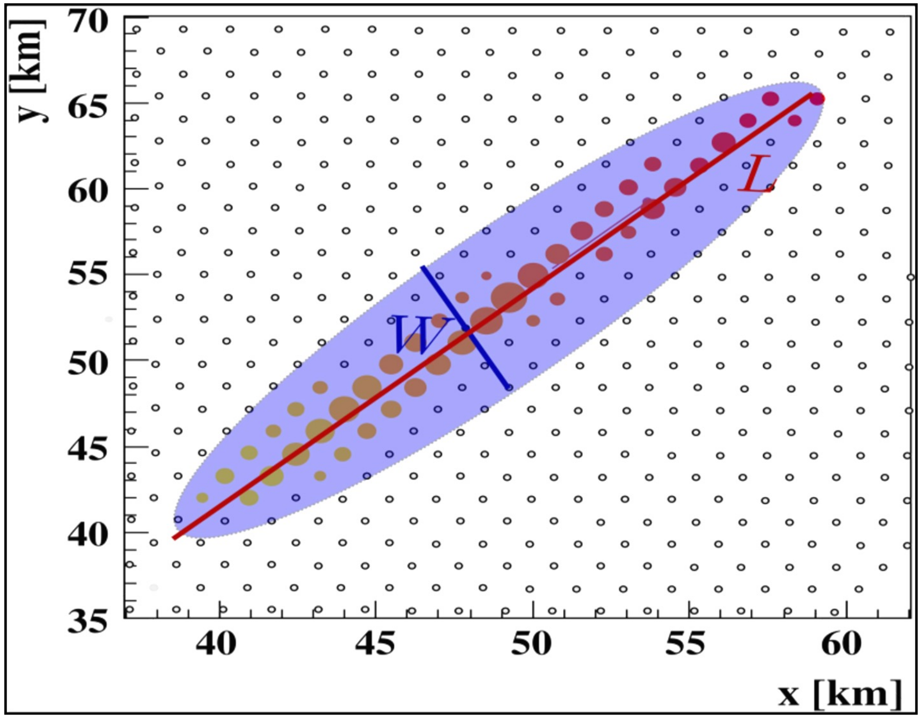
Downward-Going (DG) – 60° < θ < 90°

Earth-Skimming (ES) – zenith angles 90° < θ < 95°



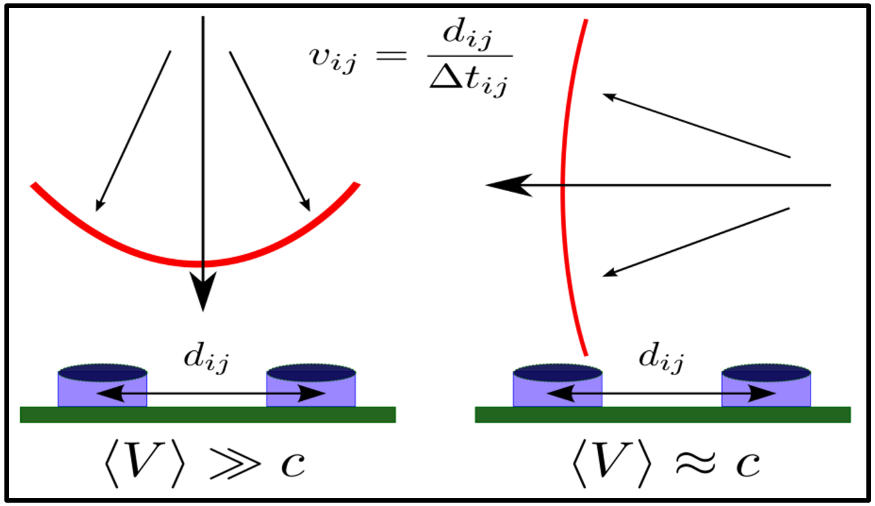
Candidates for neutrino showers are searched among nearly horizontal showers

Identification of inclined showers



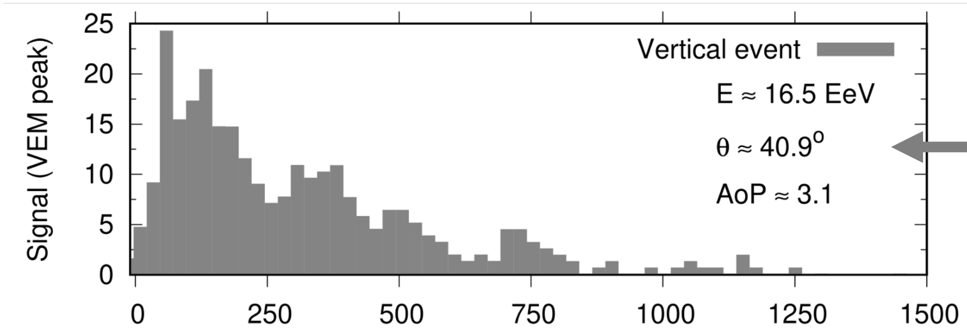
Surface detectors
triggered by inclined air showers
form highly elongated patterns

Apparent speed of the trigger between stations is close to the speed of light



Discrimination of neutrino showers

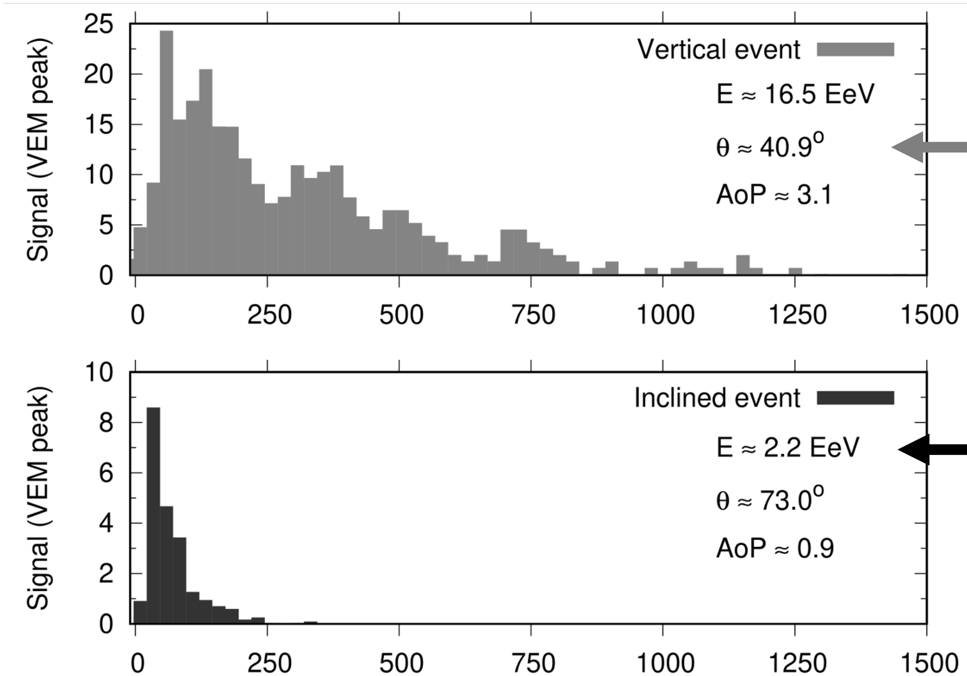
Showers at different stages of development produce different signals in the Surface Detector stations



"young" showers",
with large electromagnetic component
– longer signals

Discrimination of neutrino showers

Showers at different stages of development produce different signals in the Surface Detector stations

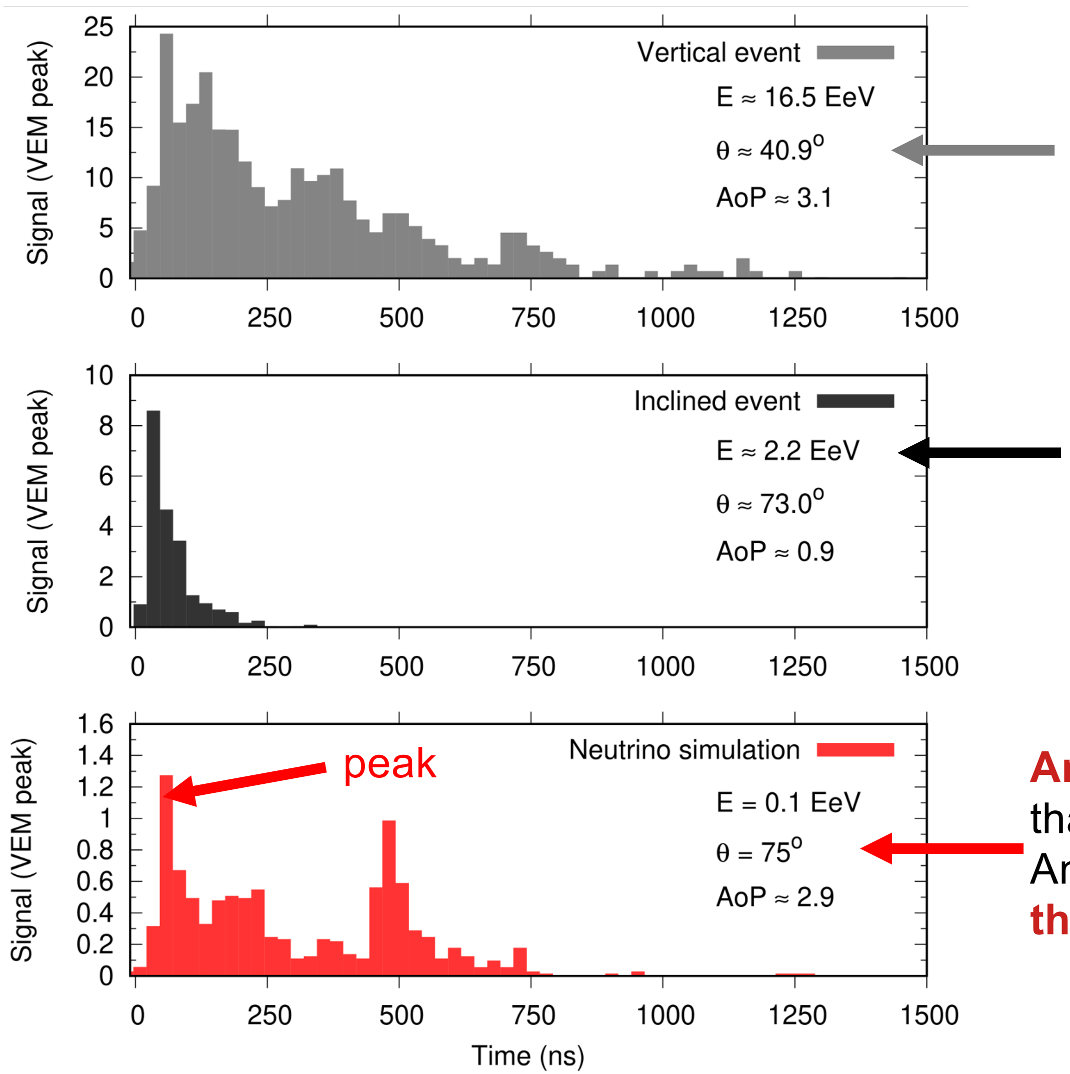


"young" showers",
with large electromagnetic component
– longer signals

"old" showers",
with only muonic component remaining
– shorter, more peaked signals

Discrimination of neutrino showers

Showers at different stages of development produce different signals in the Surface Detector stations



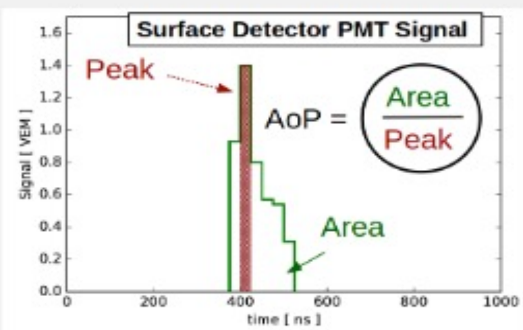
"young" showers",
with large electromagnetic component
– longer signals

"old" showers",
with only muonic component remaining
– shorter, more peaked signals

Area-over-peak is the observable that reflects these differences in the signals And **allows us to discriminate the hadronic and neutrino events**

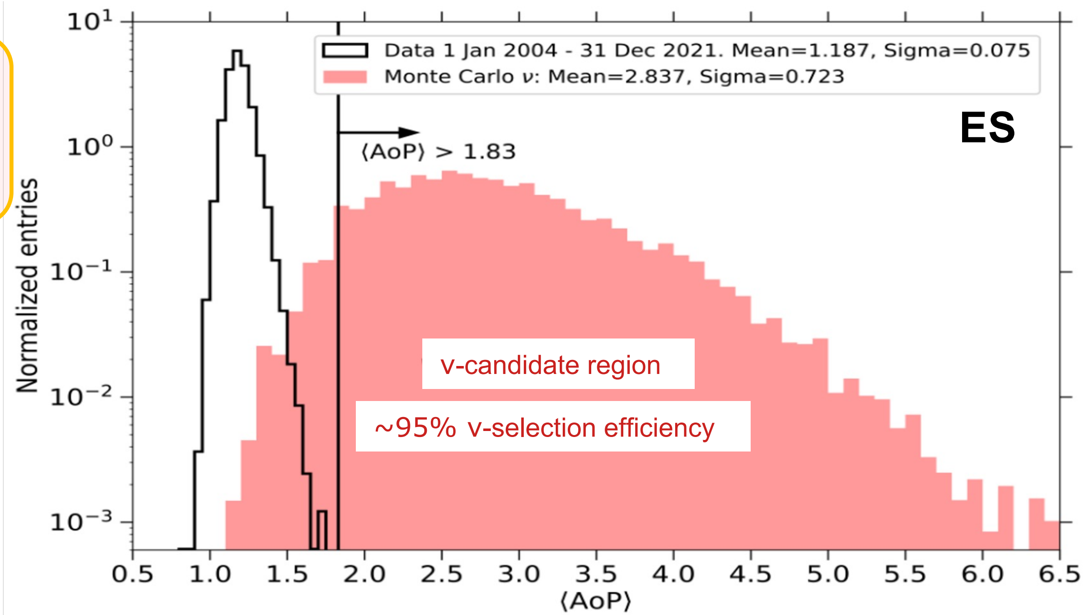
Discrimination of neutrino showers

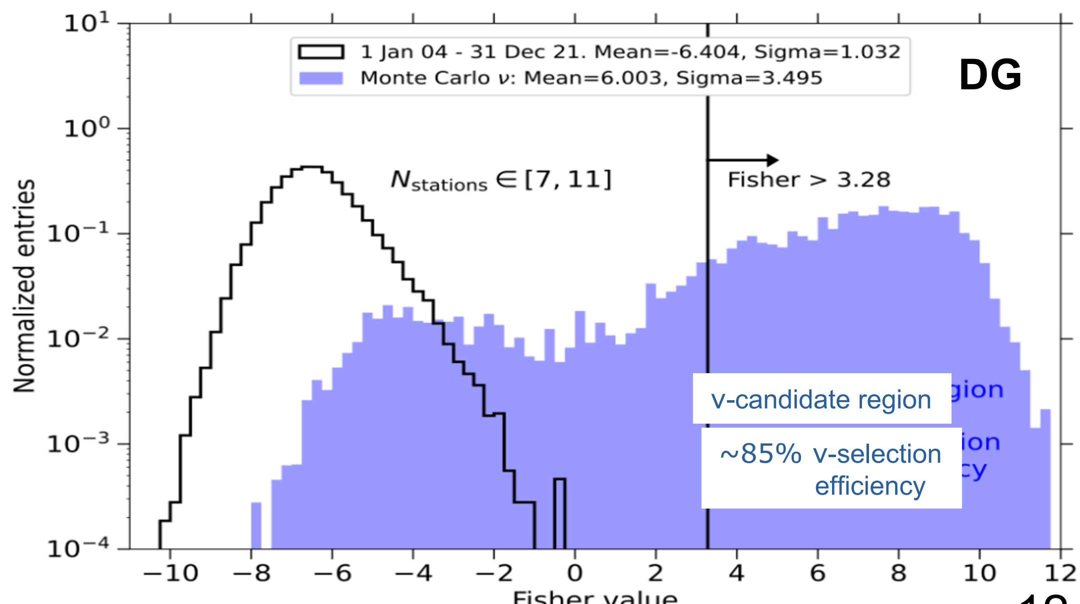
Cut for the neutrino candidates is chosen to get 1 background event per 50 years of observations



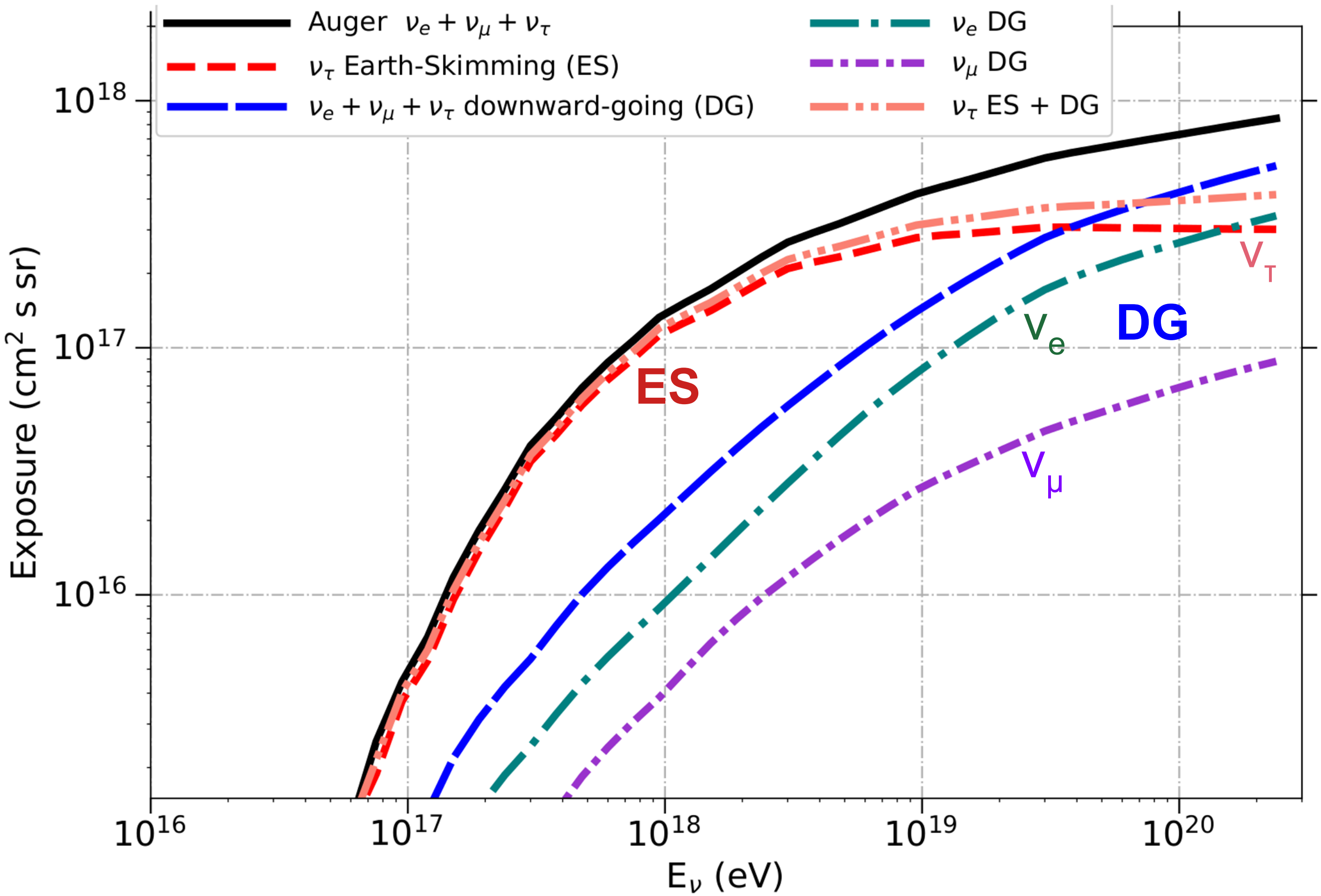
AoP – main discriminating variable

- **No candidate events have been found in any of the channels**





Exposure of the Observatory



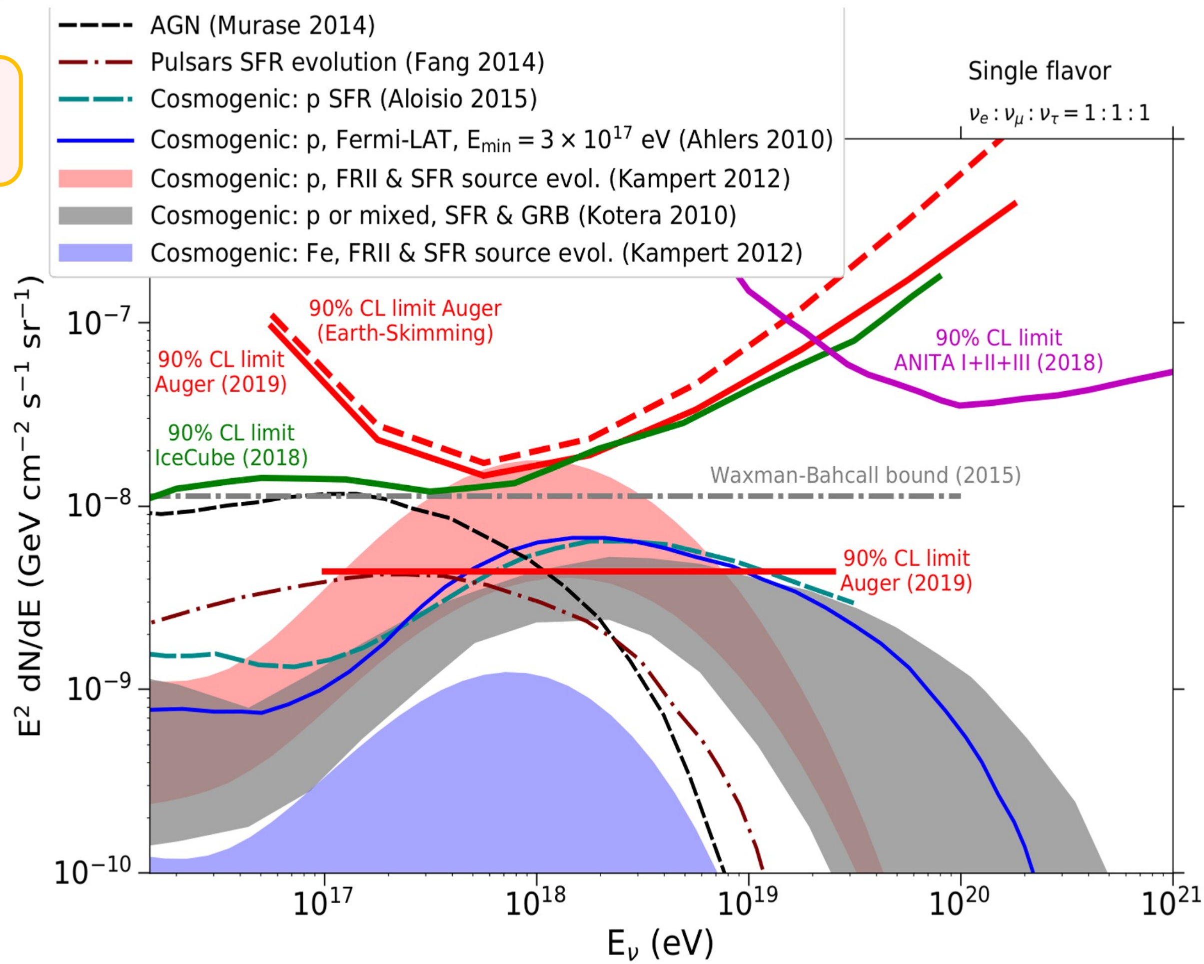
Sensitivity, up to 4 × 10^{19}, is dominated by **ES** – larger target mass

At higher energies tau more likely to decay higher above ground – **DG** channels become more significant

Upper limits of neutrino flux

Best sensitivity around 1 EeV
– comparable to that of IceCube

Contributions from different
- channels: **ES 79%, DG 21%**
- flavors: ν_e **10%,** $\boldsymbol{\nu_\mu}$ **4%,** $\boldsymbol{\nu_\tau}$ **86%**



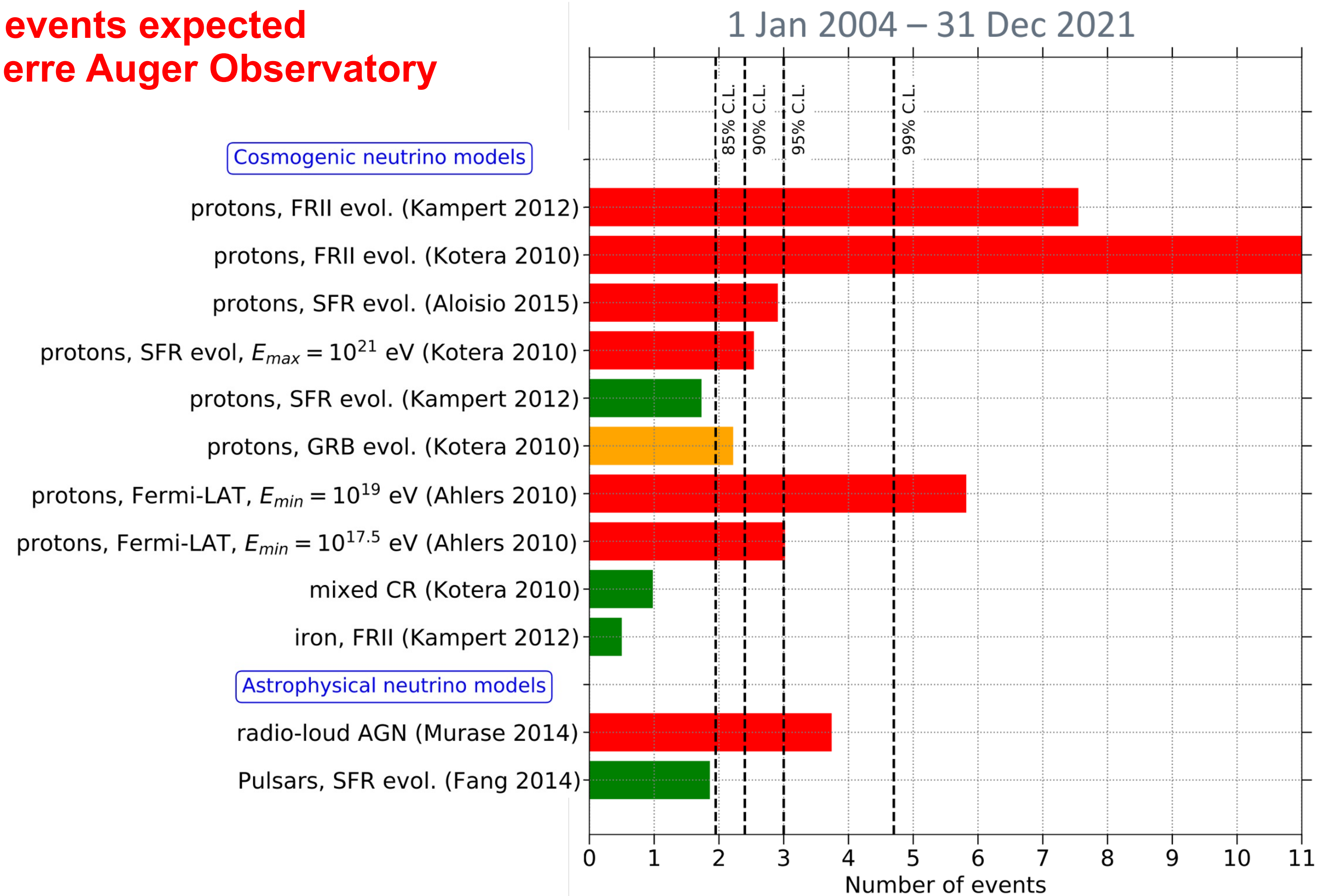
neutrino searches at Auger: *JCAP 01 (2016) 037, PRD 94 (2016) 122007, ApJ Lett. 850 (2017) L35, JCAP 10 (2019) 022, 11 (2019) 004; ApJ 902 (2020) 105*

Integral limit for neutrino energies $10^{17} < E < 2.5 \times 10^{19}$ eV:

~ 4.4 10^{-9} GeV cm^{-2} s^{-1} sr^{-1}

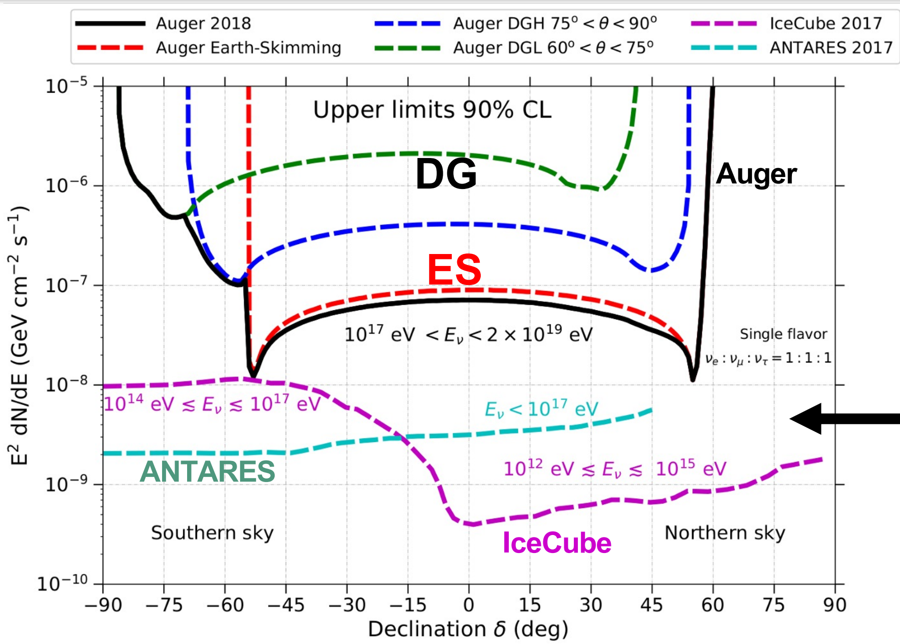
Constraints on source models

Number of events expected from the Pierre Auger Observatory



- ❖ Pure-proton models strongly disfavored
- ❖ Larger statistics needed to constrain mixed-composition models

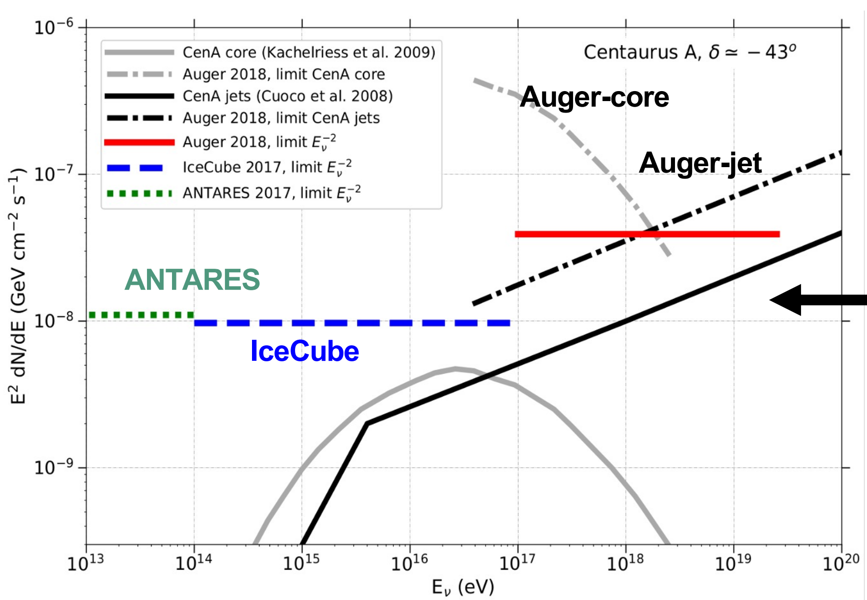
Point sources



Large field of view

- declination between -85° and +60°

Upper limits on point-like flux of ultra-high energy neutrinos



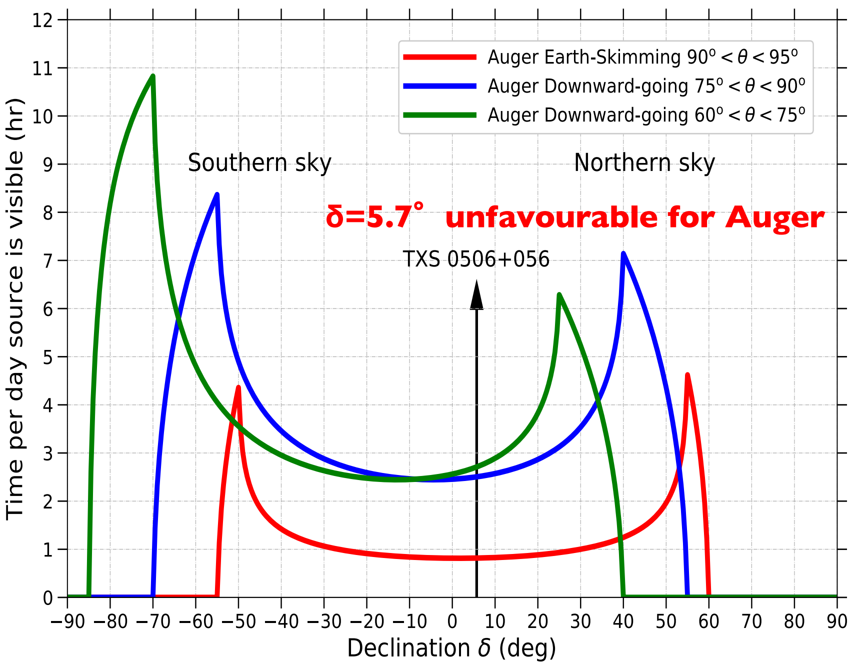
Upper limits on neutrino flux from the Centaurus A – larger statistics needed to verify model predictions

A. Aab et al JCAP11(2019)004

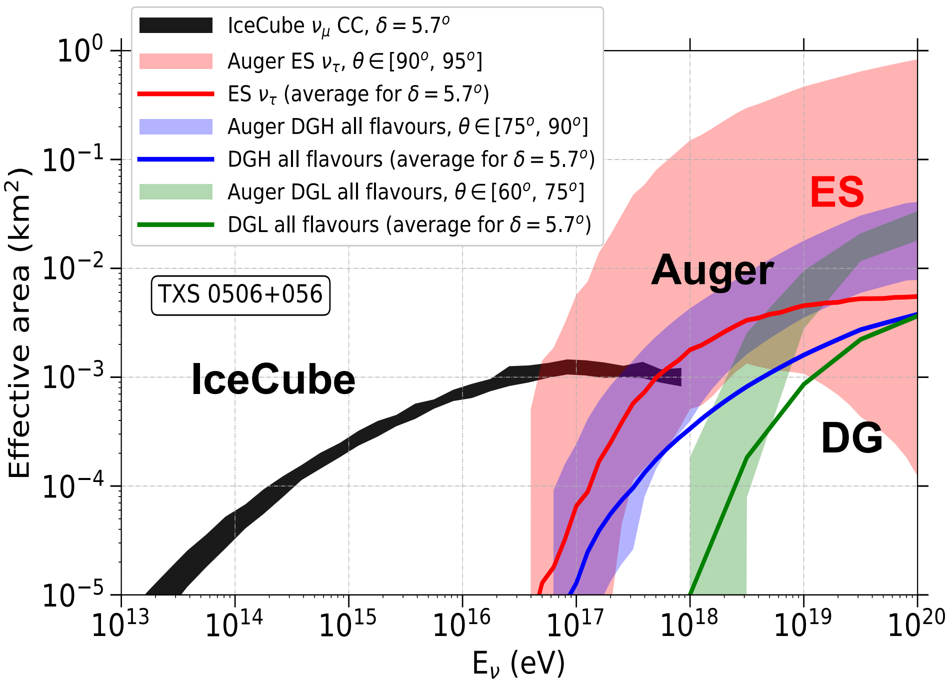
Search for nu’s from TXS 0506+56

❖ In Sept. 2017, IceCube observed a 290 TeV nu from the direction of TXS 0506+59 during a flaring state; Science 361, 146 (2018)

Daily visibility in ES in channel of Auger: < 1 hrs



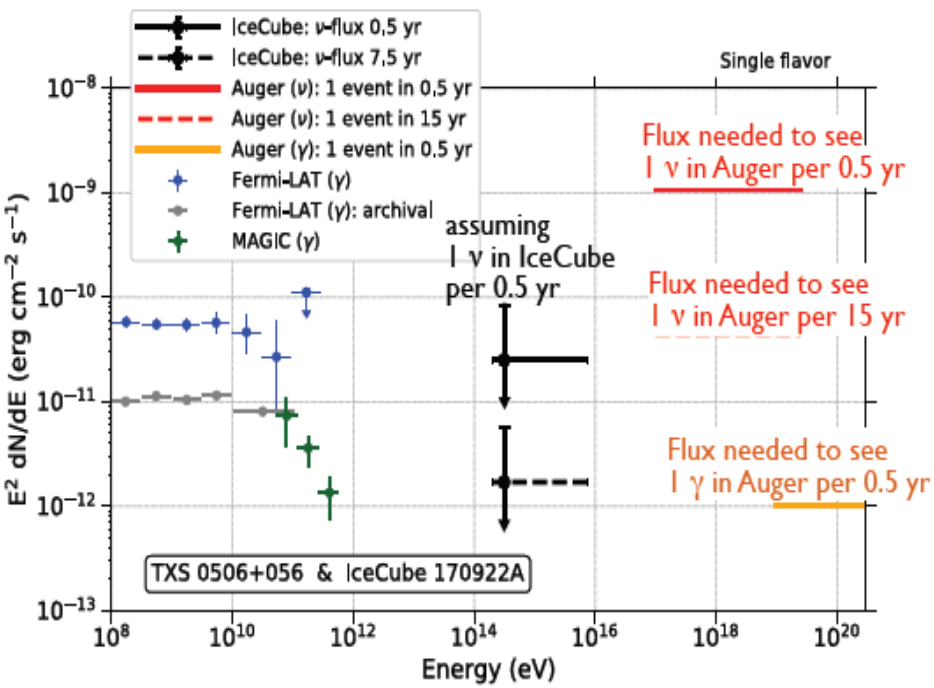
effective area in comparison to IceCube



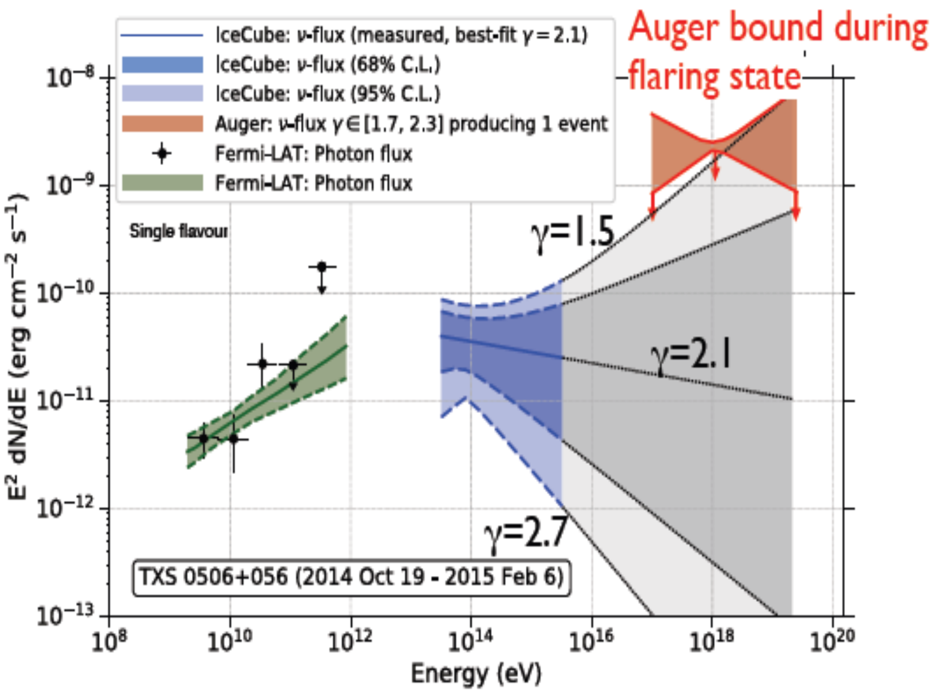
Auger Collaboration, ApJ 902 (2020) 105

Search for nu's from TXS 0506+56

Flux comparison from single event assuming E^{-2} spectrum



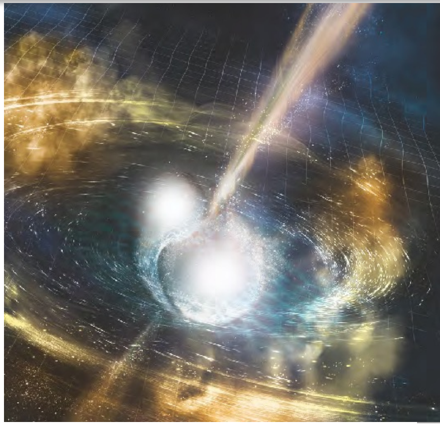
Sensitivity of Auger to 110 days „ν flaring state"

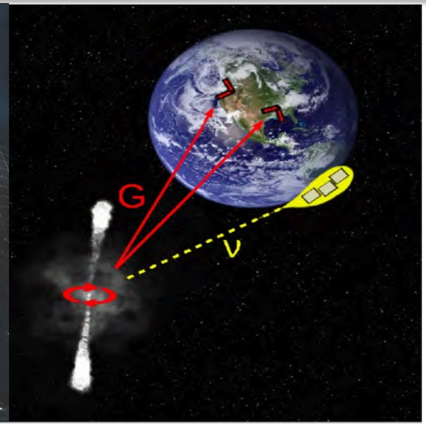


- Expected to detect a neutrino in Auger only in case of hard neutrino spectra (+2**σ** allowance of IceCube)

Auger Collaboration, ApJ 902 (2020) 105

Neutrino Upper Limits for GW170817

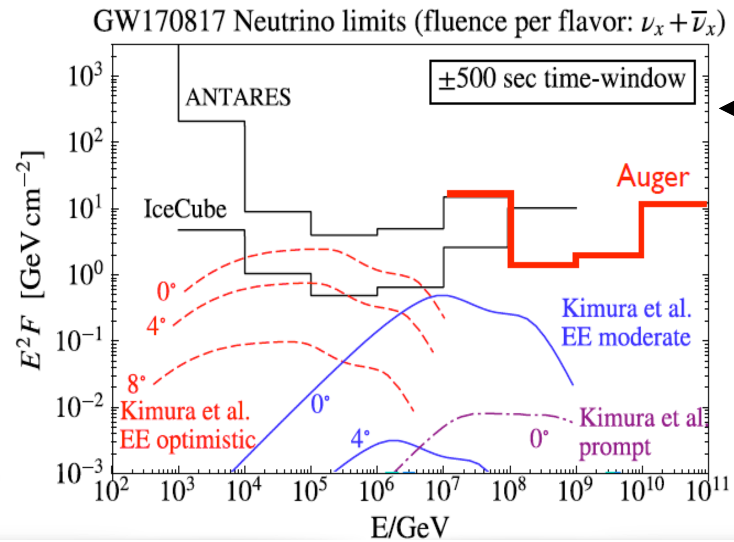




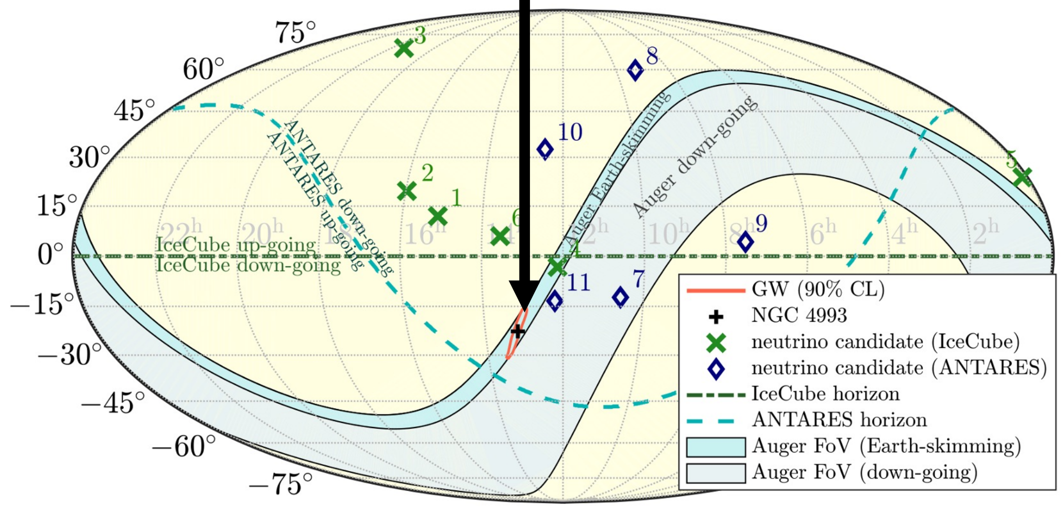
Due to Earth's rotation point sources move across fields of view of different channels

- daily transits up to 4-5 hours in ES and up to 11 hours in DG channels

Monitoring emission of transient events possible at respective times of day



Gravitational event at optimal position for neutrino observation at Auger



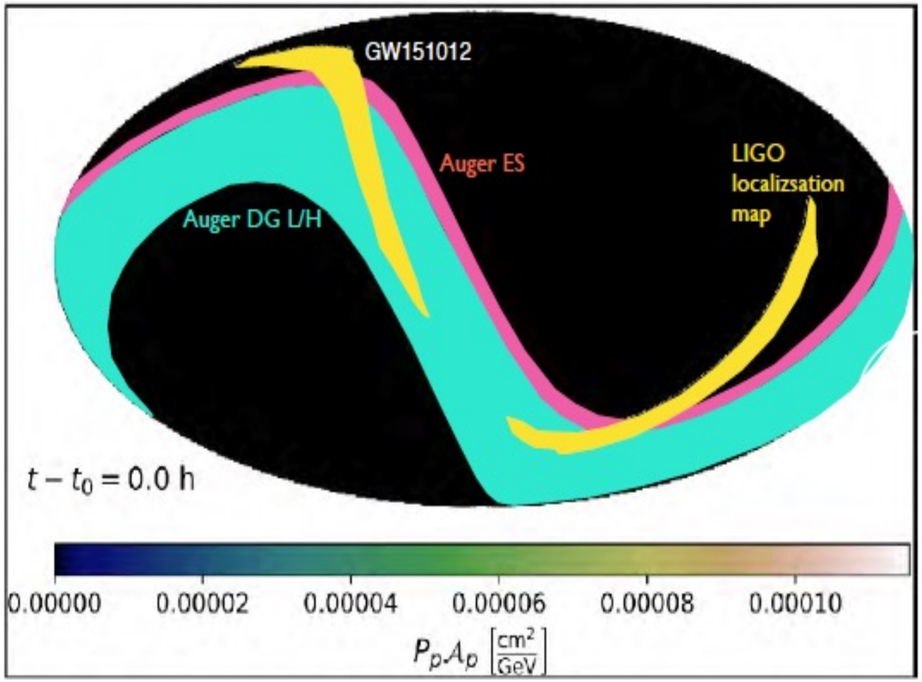
Absence of neutrino consistent with jet vieved at > 20 deg angle

May have seen neutrinos if jet were pointing towards us

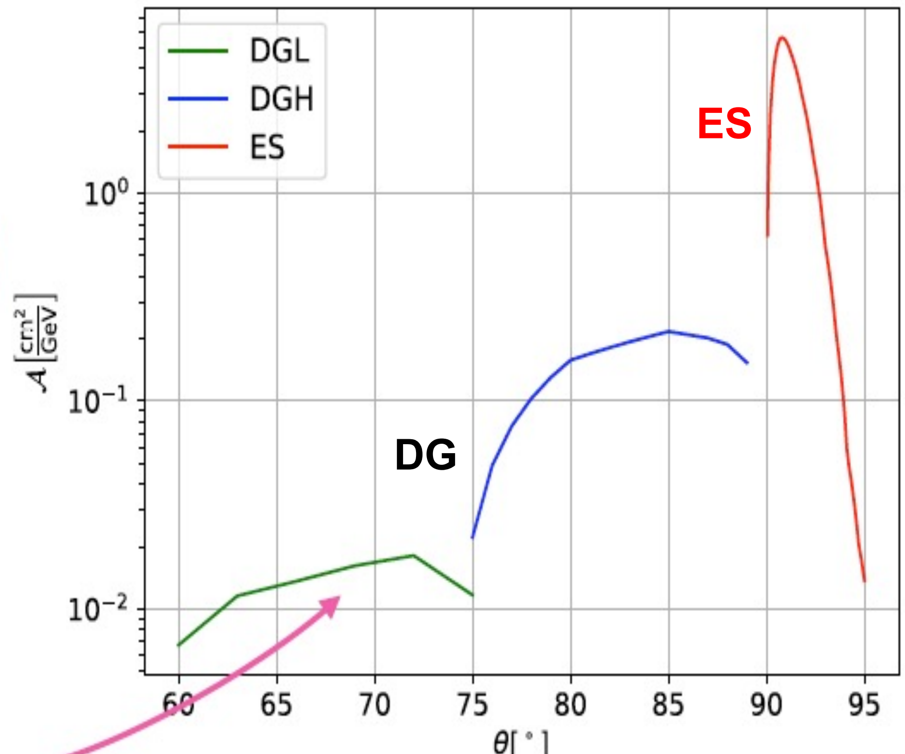
Astrophys. Journ. Lett., 850:L35 18

Combining BBH Mergers

- **Pierre Auger Observatory participates in joint multi-messenger observations**: data stream sent to AMON, alerts sent to/received from Global Coordinate Network, automatic gravitational wave follow-ups



PoS (ICRC2021) 968



$$N_{\nu,i} = L_i \Delta t \sum_s \frac{\sum_p P_{p,s} \mathcal{A}_{p,s,i}}{d_s^2}$$

solid angle integration; sum over all sources; luminosity distance of source; effective area

Number of expected neutrinos per source proportional to weighted overlap area integrated over time

L_i: Neutrino luminosity (to be constrained)

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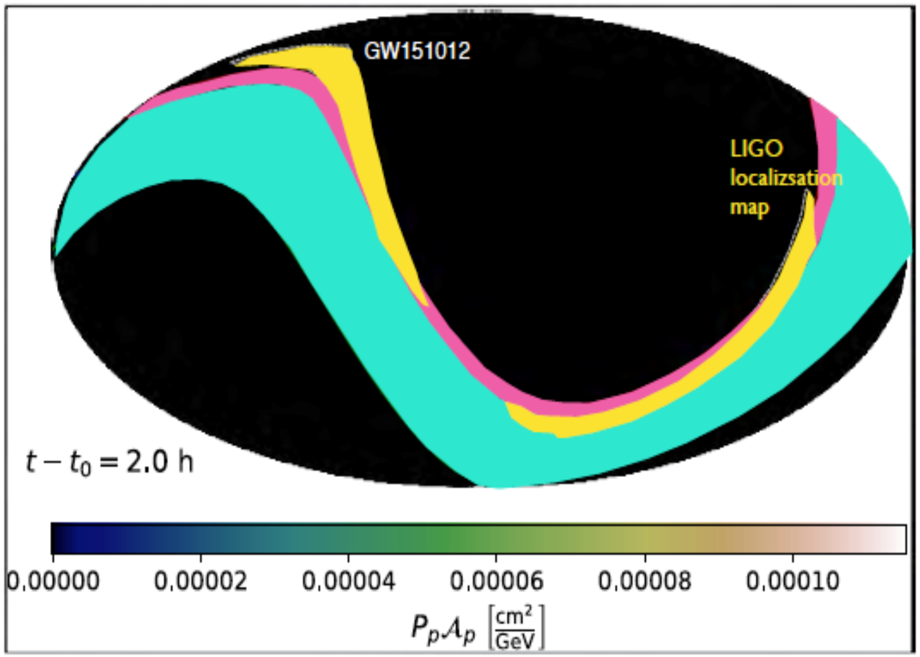

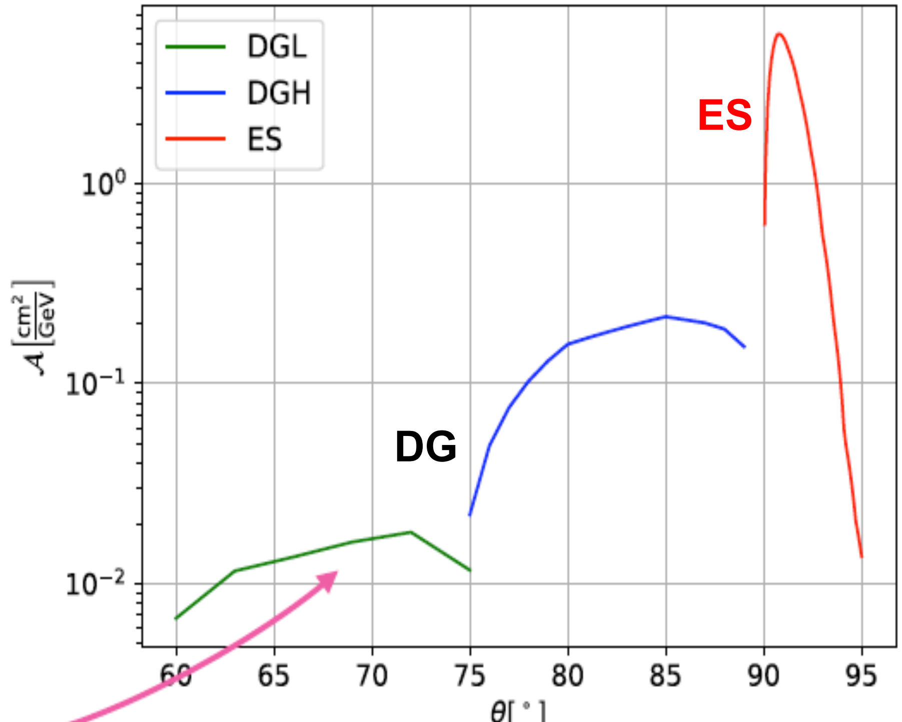

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Isotropic Neutrino Luminosity Bound

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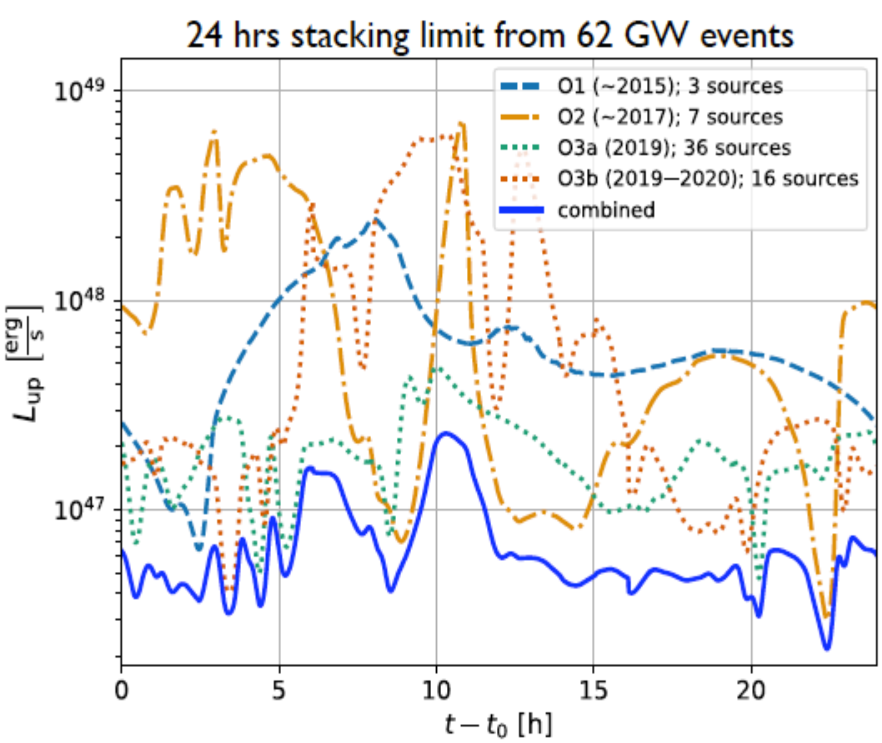
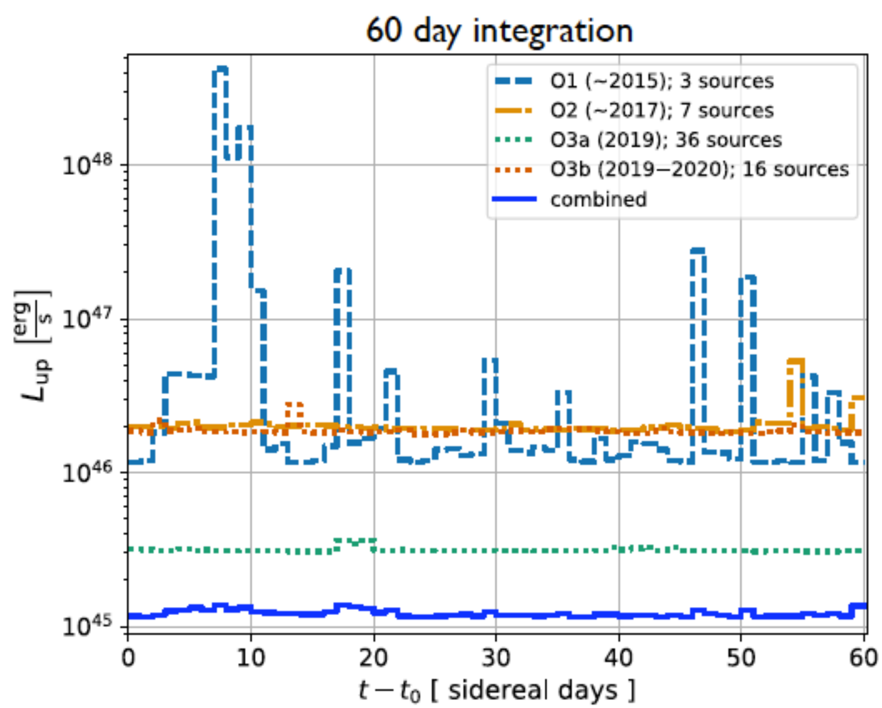
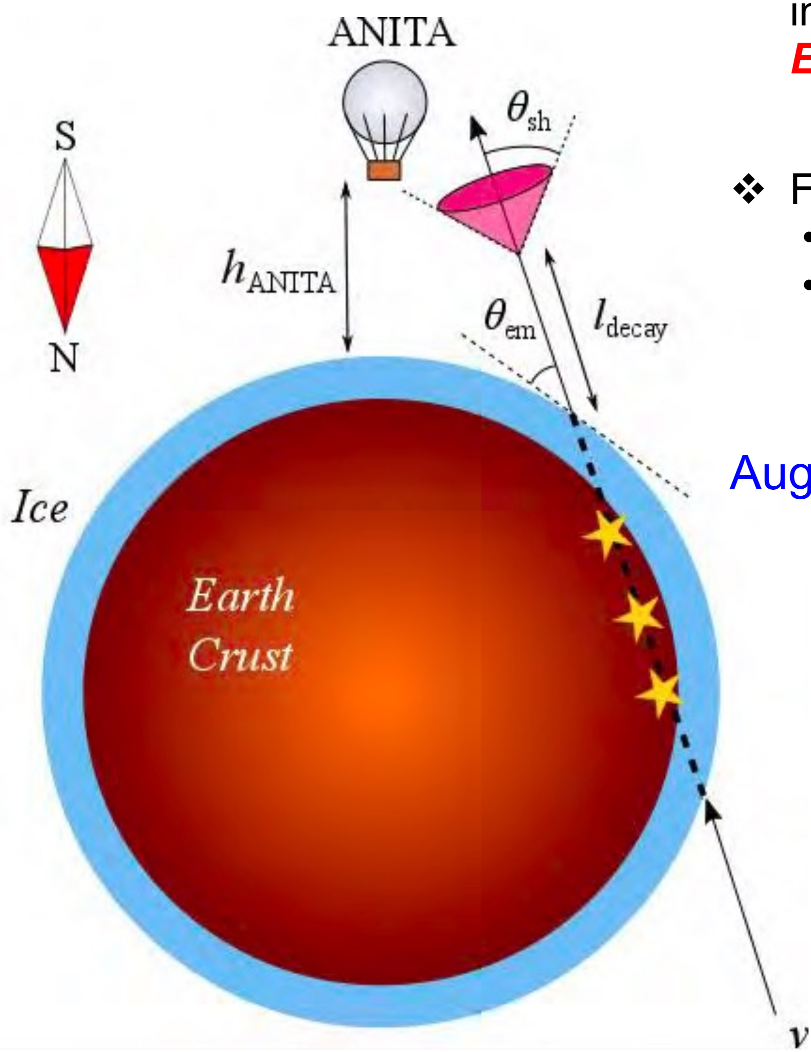




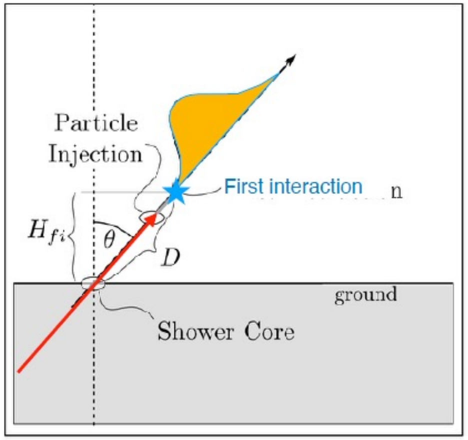
Neutrino emission energy limit ~$M_{\odot}c^2/300$ as compared to ~ $M_{\odot}c^2$ radiated GW Energy assuming isotropic emission and flux

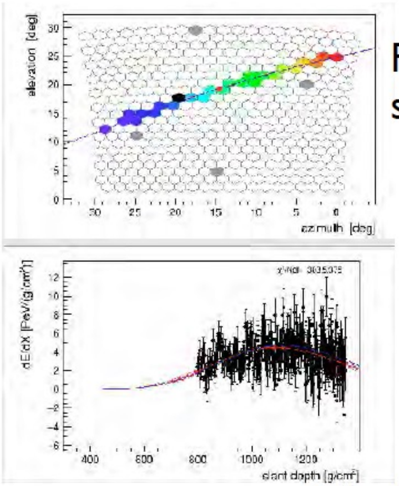
Search for Up-Going Air Showers



- ANITA has detected two anomalous events with non-inverted polarity, consistent with upward-going showers: **$E_{1,2} \approx 0.2$ EeV; exit angle ≈ 30°**
- Fervent debate about interpretation:
  - observational artefact ?
  - **Beyond Standard Model physics?** (ν's cannot penetrate Earth at these energies)

Auger has performed a dedicated search using **14 yrs**



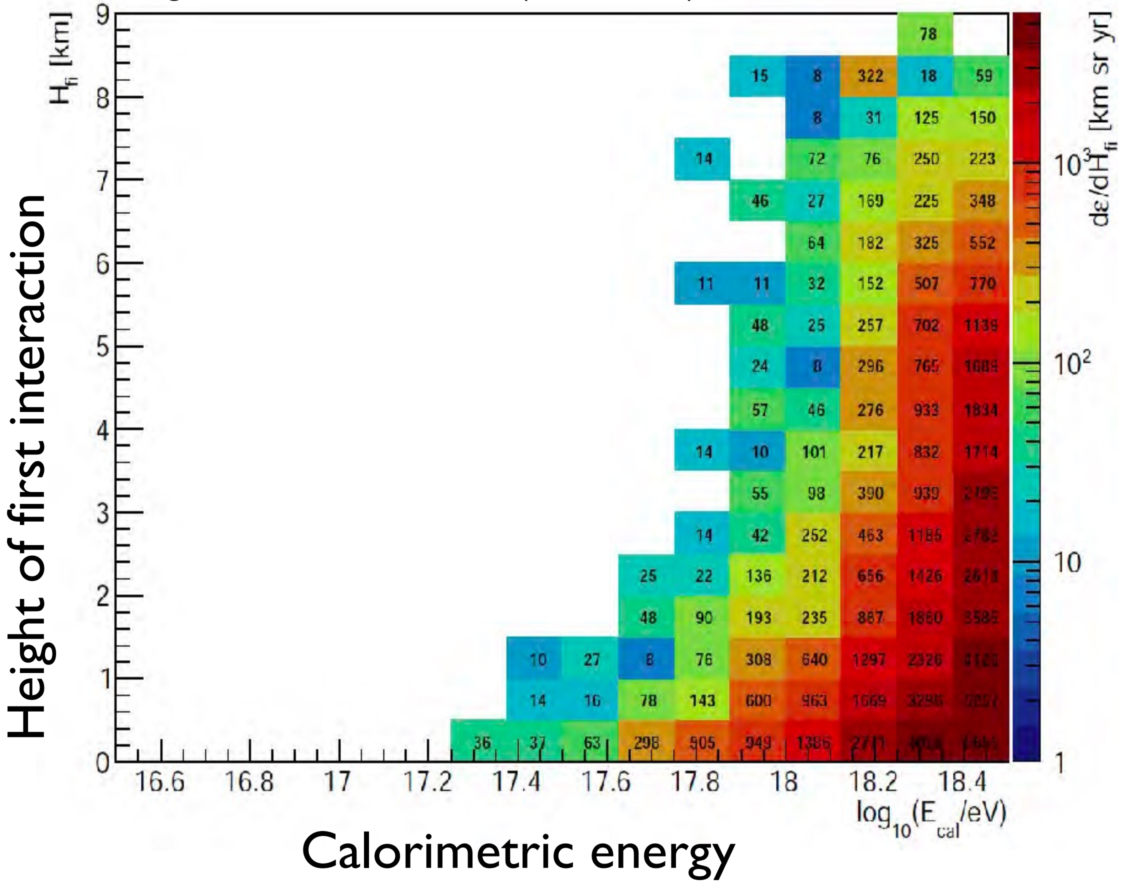


FD Signal simulation

Differential Exposure

❖ After unblinding, 1 event was found fully in line with expectation

Auger Collaboration, PoS (ICRC2021) 1140



Integral upper limit for log(E/eV)>17.5

$$F^{95\%}_{\gamma=1}(E_{\mathrm{cal}} > 10^{17.5}\,\mathrm{eV}) = 3.6 \cdot 10^{-20}\,\mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}$$

$$F^{95\%}_{\gamma=2}(E_{\mathrm{cal}} > 10^{17.5}\,\mathrm{eV}) = 8.5 \cdot 10^{-20}\,\mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}$$

publication in progress…

ANITA only published events, but did not provide their exposure
→ collaborating to provide an estimate

Summary

- Unprecedented exposure to neutrinos above 10^{17} eV
- Background-free sensitivity to EeV neutrinos
- At a wide range of declinations high sensitivity to transient point sources
- Stringent upper limits on the diffuse flux of ultra-high energy neutrinos

Pierre Auger Observatory is a prominent element in multimessager astronomy at the extreme energies

– will have even better capabilities
with the AugerPrime upgrade