TAMBO touch base meeting

Oct. 18, 2022

Earth-Skimming neutrinos at the Pierre Auger Observatory

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PIERRE AUGER OBSERVATORY

IGFAE Instituto Galego de Física de Altas Enerxías

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

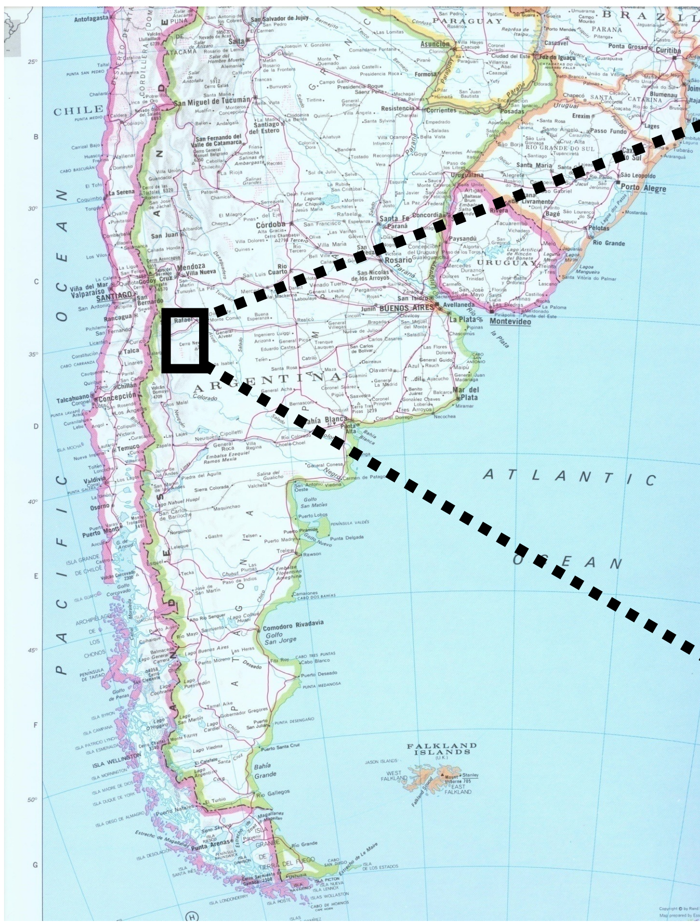
XUNTA DE GALICIA

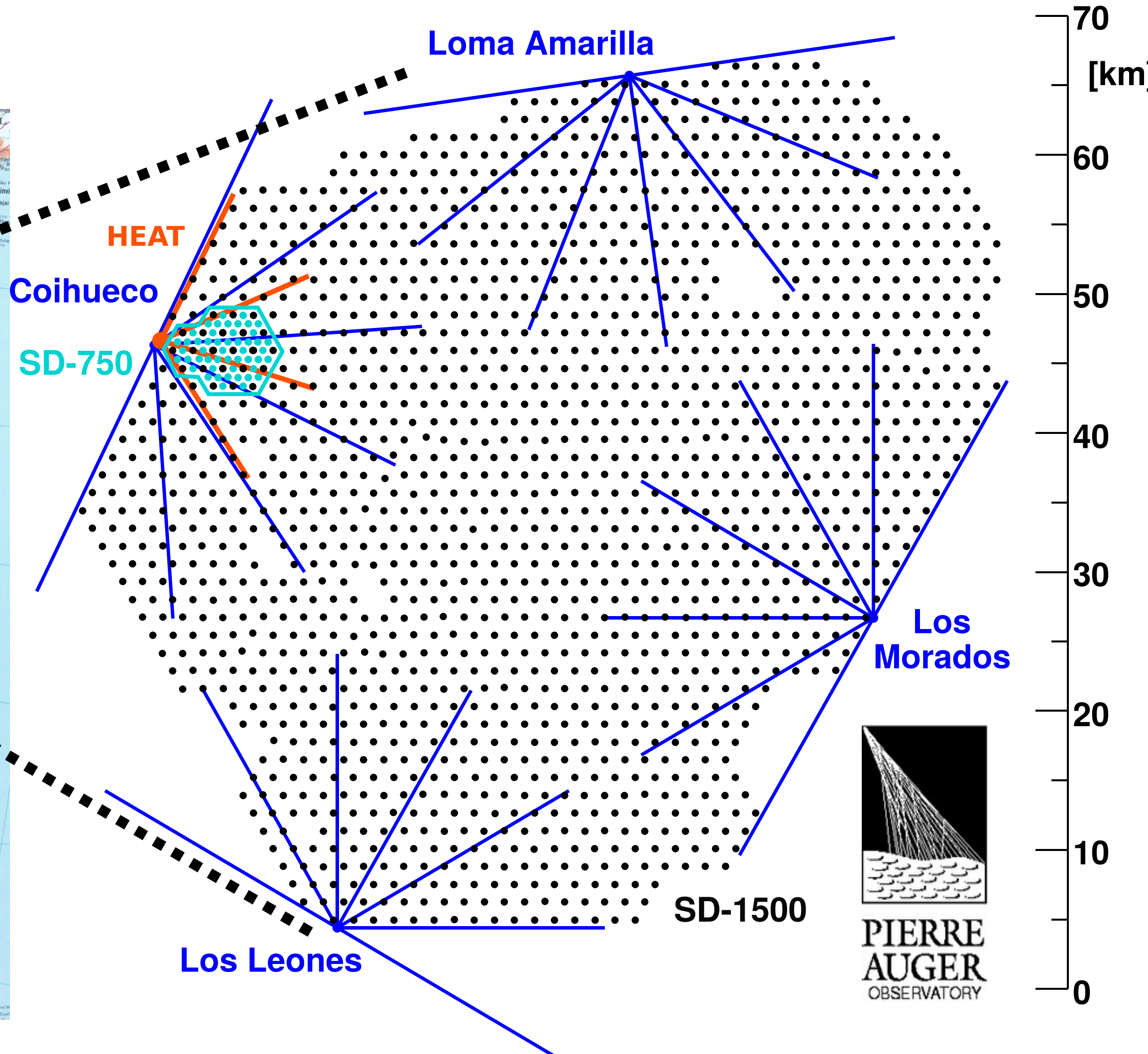
The Pierre Auger Observatory
Malargüe, Mendoza (Argentina)

Largest Ultrahigh Energy ($E > 10^{17}$ eV) Cosmic-Ray detector in the world

- **SD1500** = Surface Detector array of 1600 water Cherenkov stations (~ 3000 km^2)
- **SD750** = 61 water Cherenkov stations (~ 27 km^2)

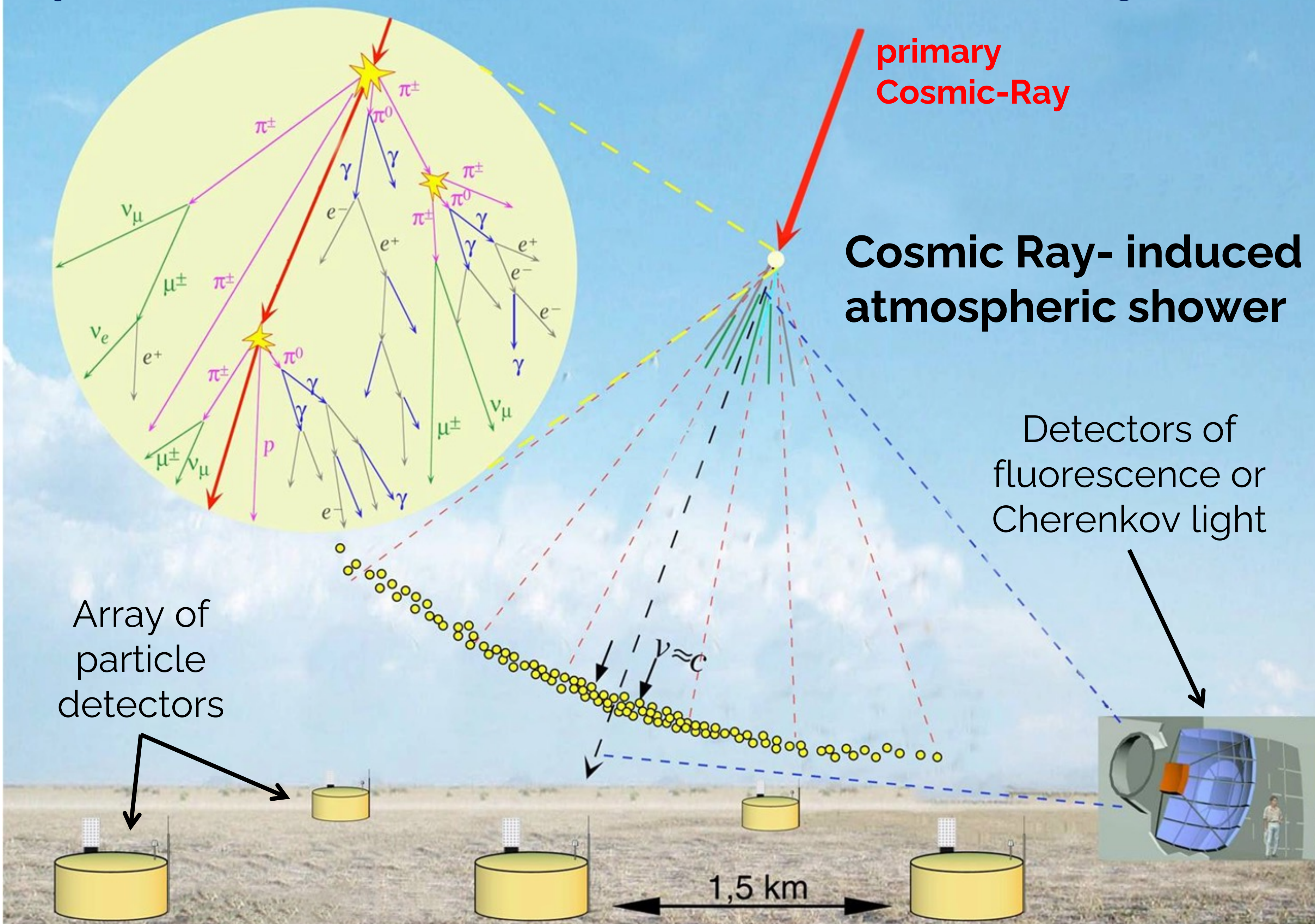
FD = 4 Fluorescence (24 + 3) detectors

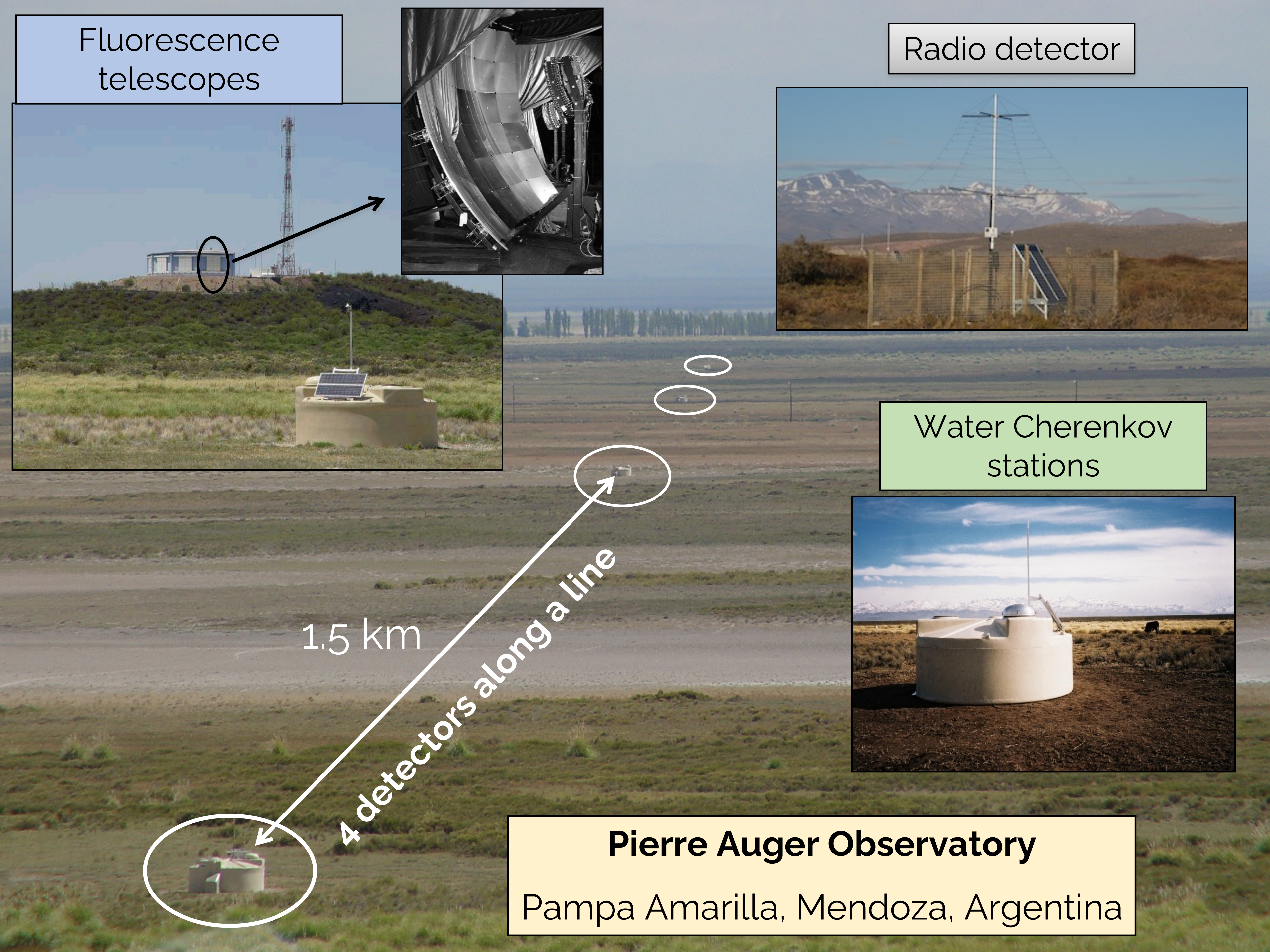




Pierre Auger, NIMA **798** (2015) 172–213

Hybrid detection of UHECR-induced showers in Auger




Fluorescence telescopes
Radio detector
Water Cherenkov stations
1.5 km
4 detectors along a line
Pierre Auger Observatory
Pampa Amarilla, Mendoza, Argentina

Building the Surface Detector (SD) of the Pierre Auger Observatory

Design targets of SD:

- ✓ Self-contained & autonomous Surface Detector stations
- ✓ In-situ calibration of SD stations (by cosmic-ray muons)
- ✓ 100% duty cycle
- ✓ Measurement of time structure of signals of shower front
- ✓ Sensitivity to showers arriving at large zenith angles

Pierre Auger, NIMA **798** (2015) 172–213

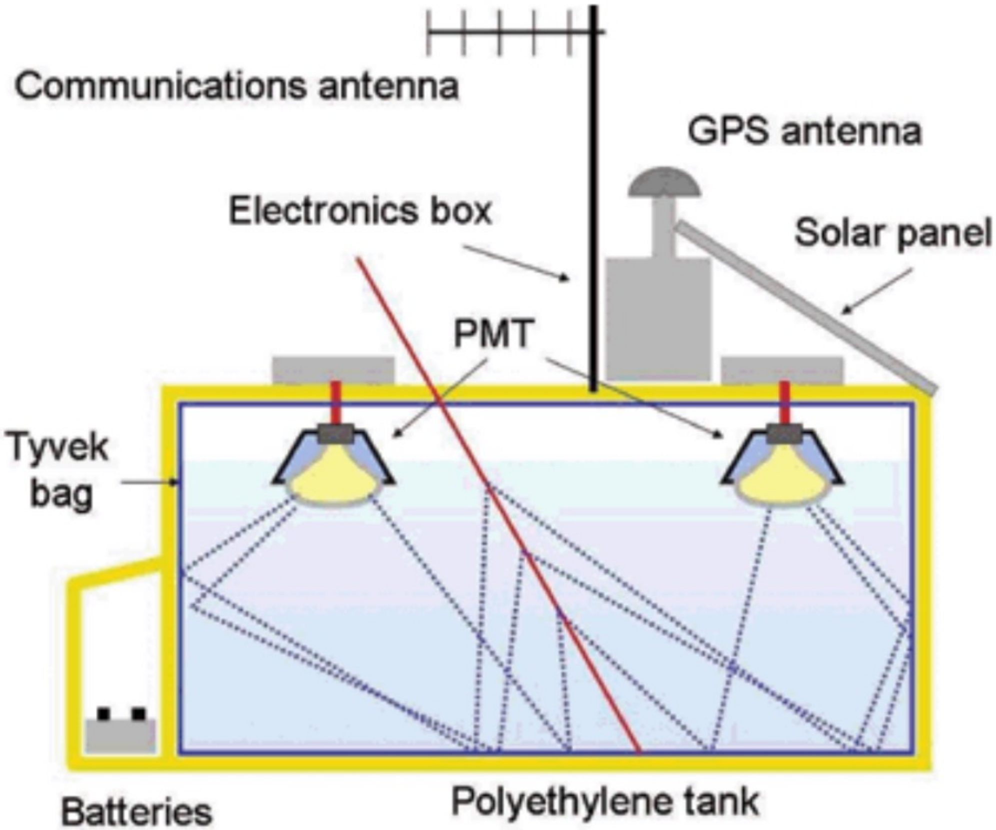
Timeline

- Conceived in 1991
- Site selection 1995
- Engineering Array 2001
- Construction started 2002
- First data 2004. First physics 2005
- Full Auger construction ended 2008
- Taking data continuously

with full Auger for the last 14 years

Assemblying SD stations → **Deploying** → **Filling with water & installing electronics**

Water-Cherenkov stations



- Records **Cherenkov light in water** produced by the passage of charged shower particles mainly **muons and electrons + positrons**
- **Photons** can also convert in water and produce a shower inside the tank

Cylindrical polyethylene (tough) tank

Colored beige to blend with landscape

3.6 m diameter, 1.2 m height

530 kg + 12 tons of water

Three 9-inch PMT looking downwards

Reflective inner Surface (liner)

Self-powered 1solar panel + 12 V batteries

Power consumption: 10 Watts

Wireless communication with central data acquisition system

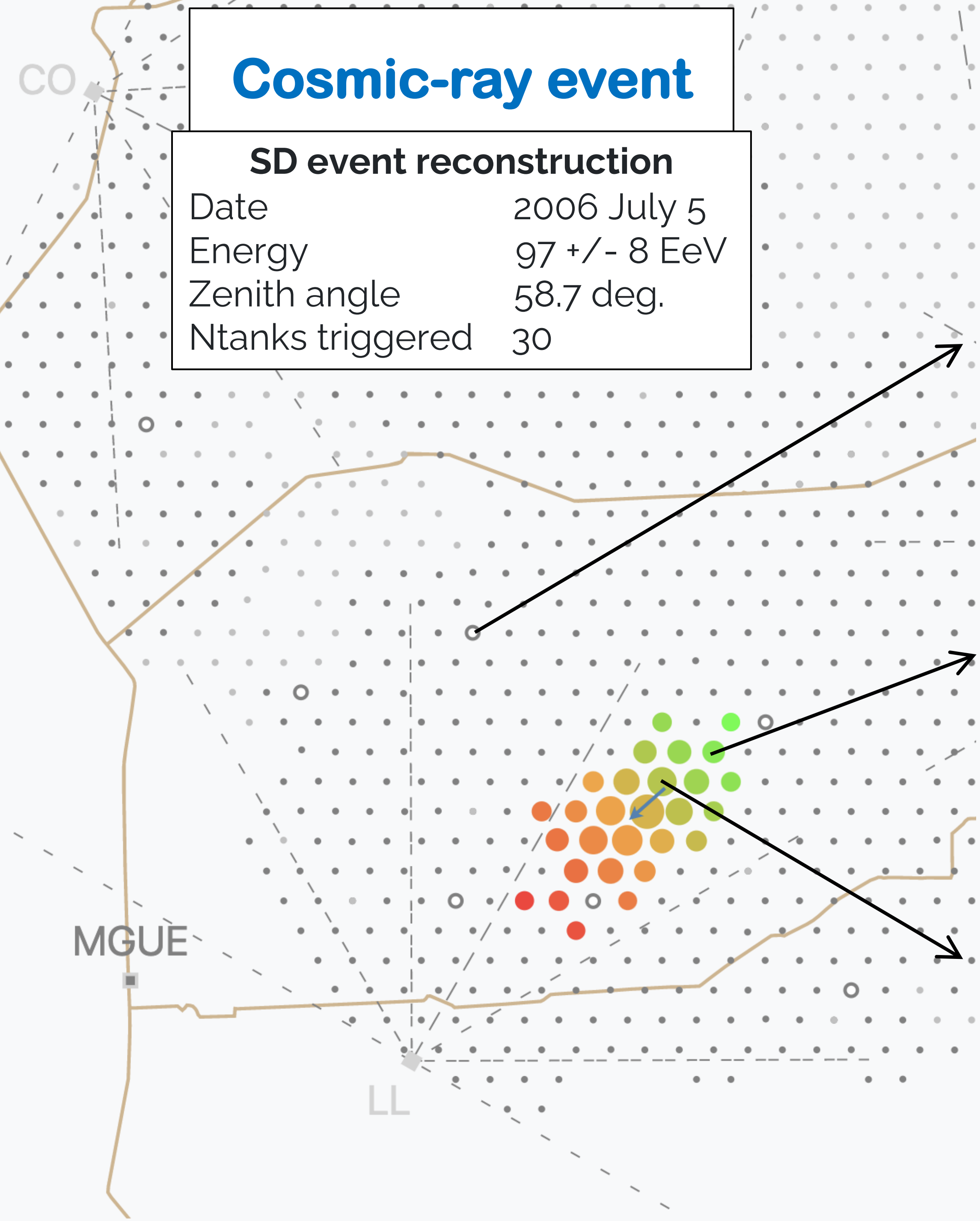
GPS receiver

Electronics protected by aluminum dome

Cosmic-ray event

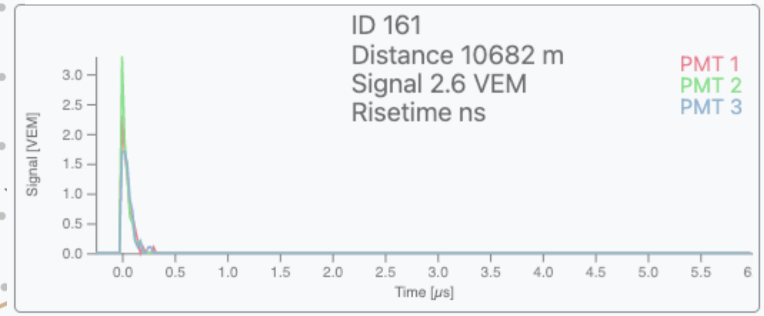
SD event reconstruction

Date	2006 July 5
Energy	97 +/- 8 EeV
Zenith angle	58.7 deg.
Ntanks triggered	30

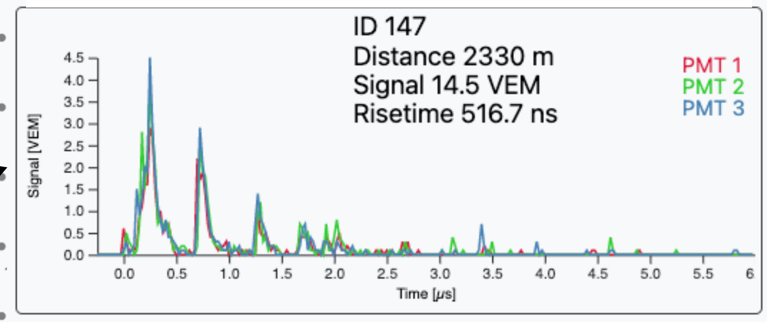


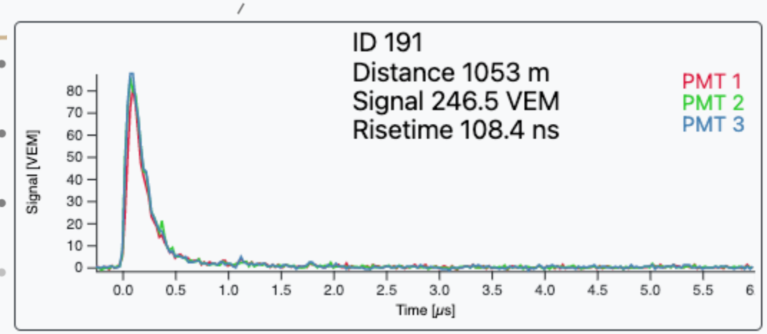
Signals are digitized in FADC traces with 25 ns time resolution

A random coincidence station



Two of the stations used for reconstruction





https://opendata.auger.org/

Calibration of Water-Cherenkov stations

There are **1600 stations in the SD1500** that behave slightly different from each other.

Calibration

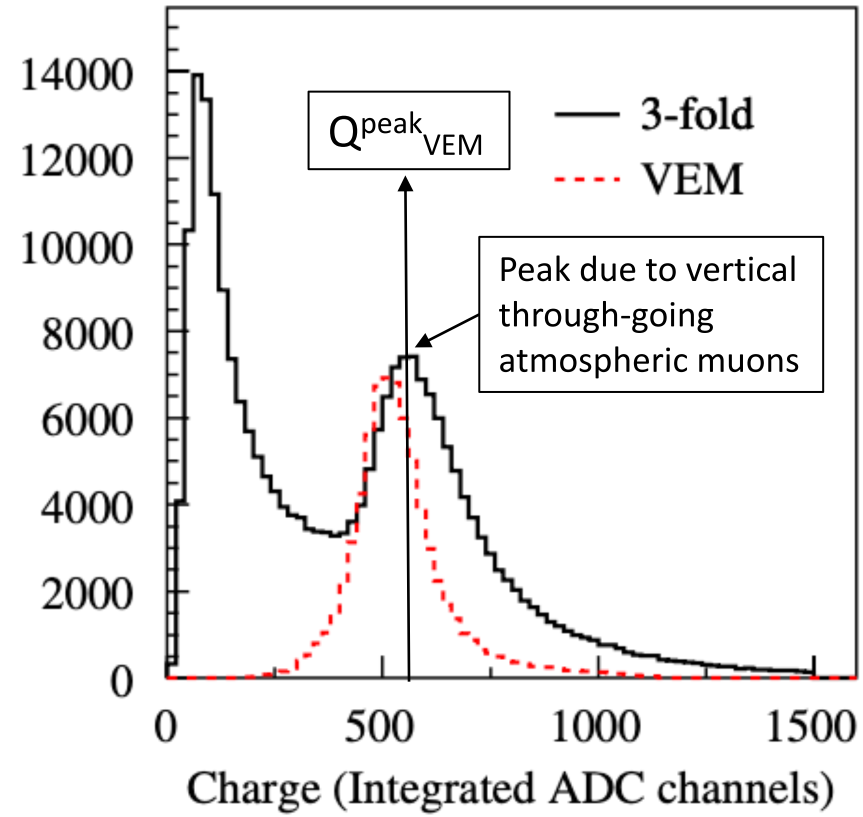
Cherenkov light is measured in units of the signal produced by a vertical & central through-going muon, a **vertical-equivalent muon (VEM).**

The **goal of SD calibration** is to measure the value of 1 VEM in "electronic" units.

→ Conversion to units of VEM needed to provide a **common reference level**

Atmospheric muons pass through each SD detector at a rate 2500 Hz and produce a **peak in the charge histogram** collected every minute.

The peak of the charge distribution Q^{peak}_{VEM} is 1.09 VEM and provides the conversion.



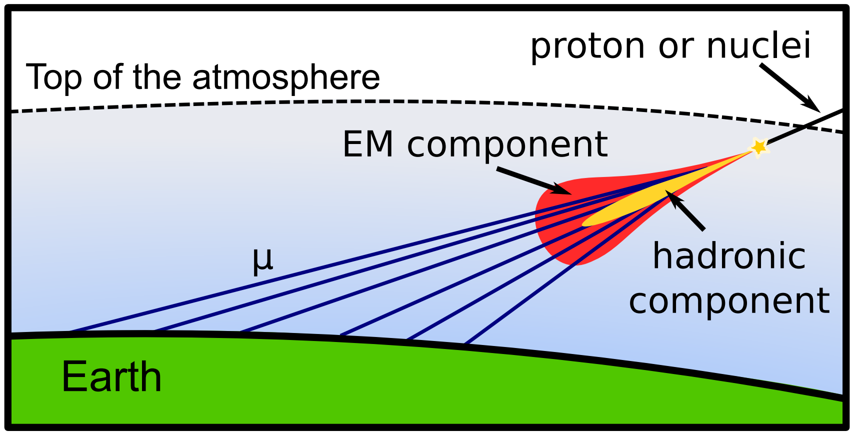
Charge histogram (in black) from an SD station, triggered by a 3-fold coincidence between all 3 PMTs.

X. Bertou et al., NIMA **568** (2006) 839–846

Search for UHE neutrinos with Auger SD1500

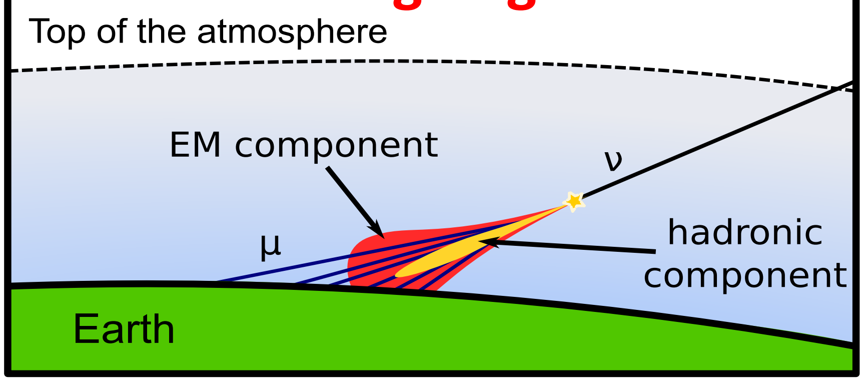
Inclined showers (θ > 60 deg.) are the key to identification of UHE neutrinos

(Background) Cosmic Ray

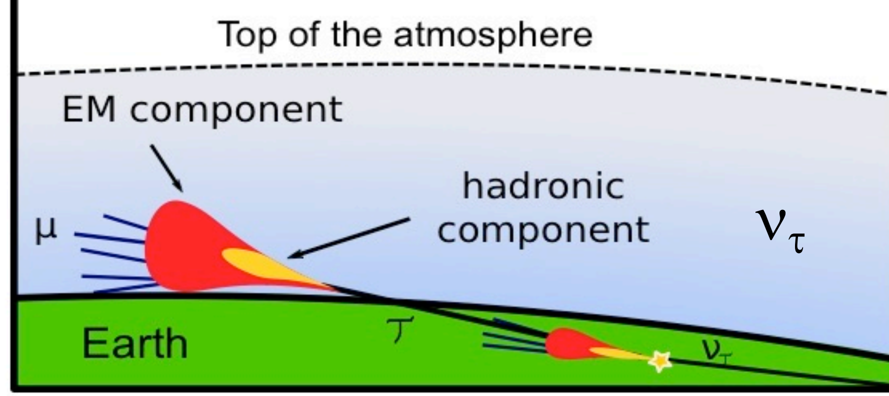


- **Protons & nuclei** initiate inclined showers high in the atmosphere => Shower front at ground mainly composed of **muons** (electromag. component absorbed in atmosphere).
- **Neutrinos** can initiate **"deep" showers** close to ground => Shower front at ground: **electromag. + muonic** components

Downward-going neutrino



Upcoming tau neutrino

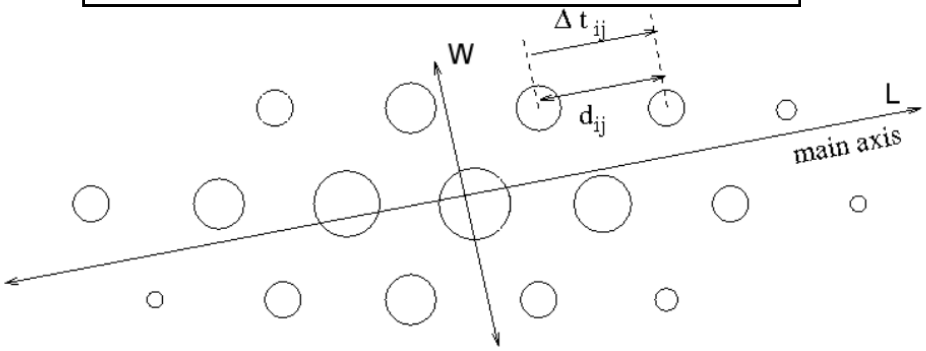


In Auger: Neutrino signature → **inclined showers** that develop close to ground

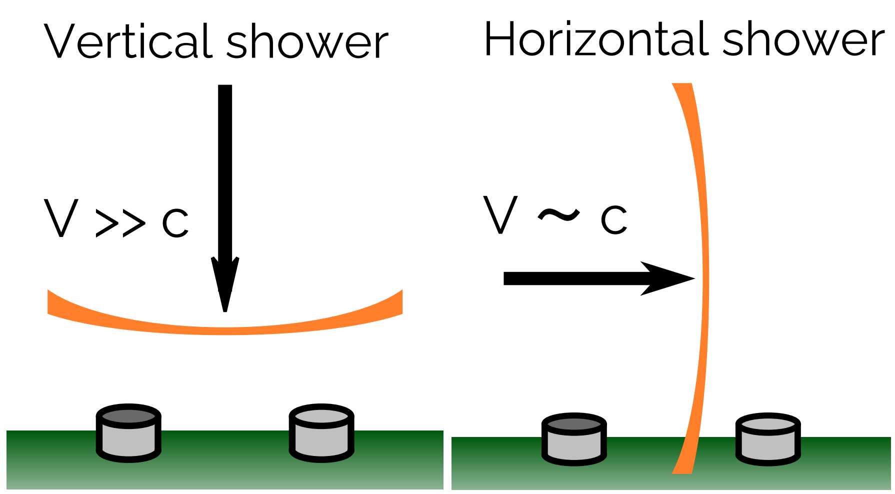
In TAMBO: Neutrino signature → **more vertical showers** (from other side of valley)

Selection of inclined showers: 3 observables

(1) Elongated footprint of shower on the ground



(2) Apparent velocity V of propagation of shower front at ground along major axis L



(3) Reconstructed θ > 60 deg

Identifying neutrinos in Auger data

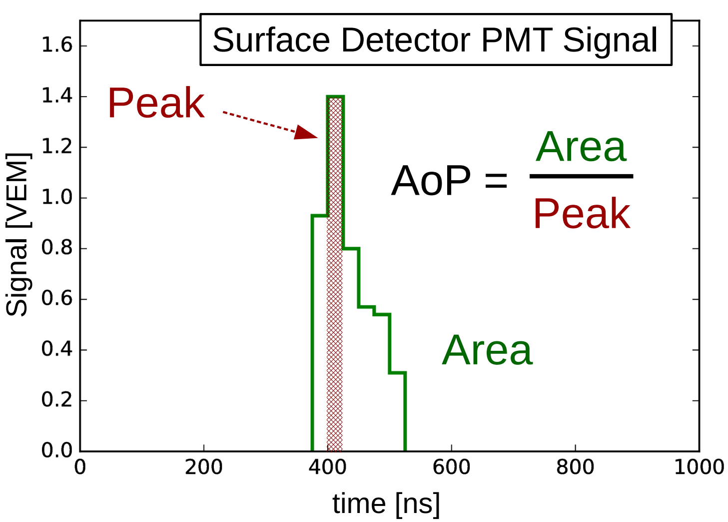
Water Cherenkov stations do NOT efficiently separate muons from electrons but, the **electromagnetic component induces extended signals in time** in the FADC traces

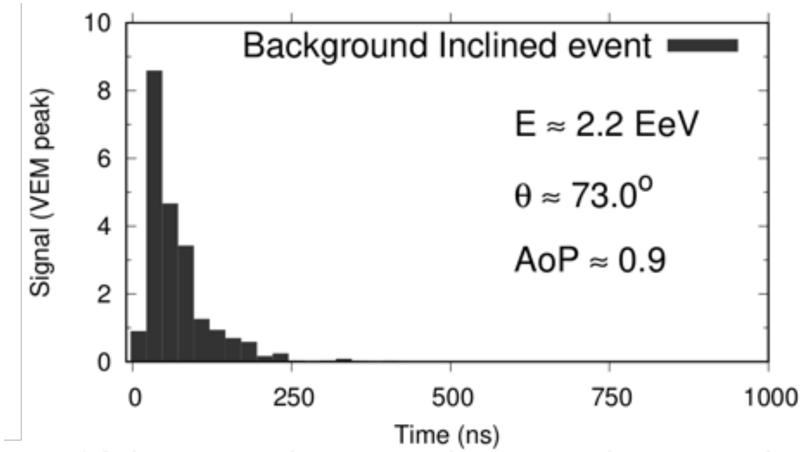
⇒ induce Time-over-Threshold (ToT) triggers in the SD stations

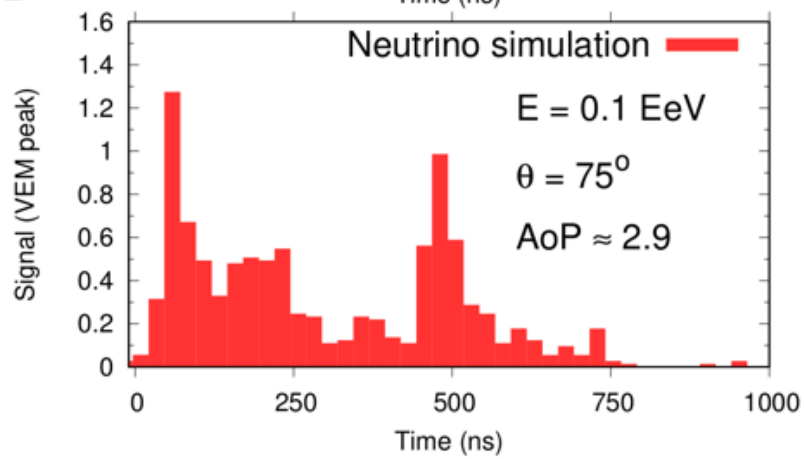
and/or

⇒ have large **Area-over-Peak** (AoP) value (AoP ∼ 1 muonic front)

Definition of Area-over-Peak (AoP)



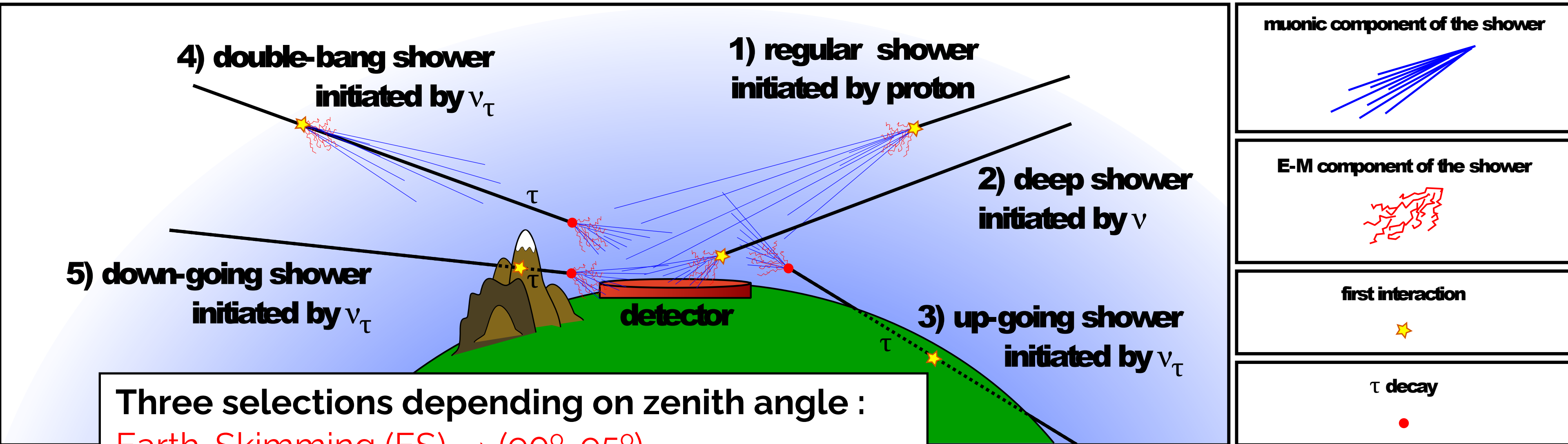




Searching for neutrinos ⇒
Searching for inclined showers with stations with large values of Area-over-Peak

Pierre Auger, PRD **91**, 092008 (2015)

Sensitivity to all flavours & channels in Auger



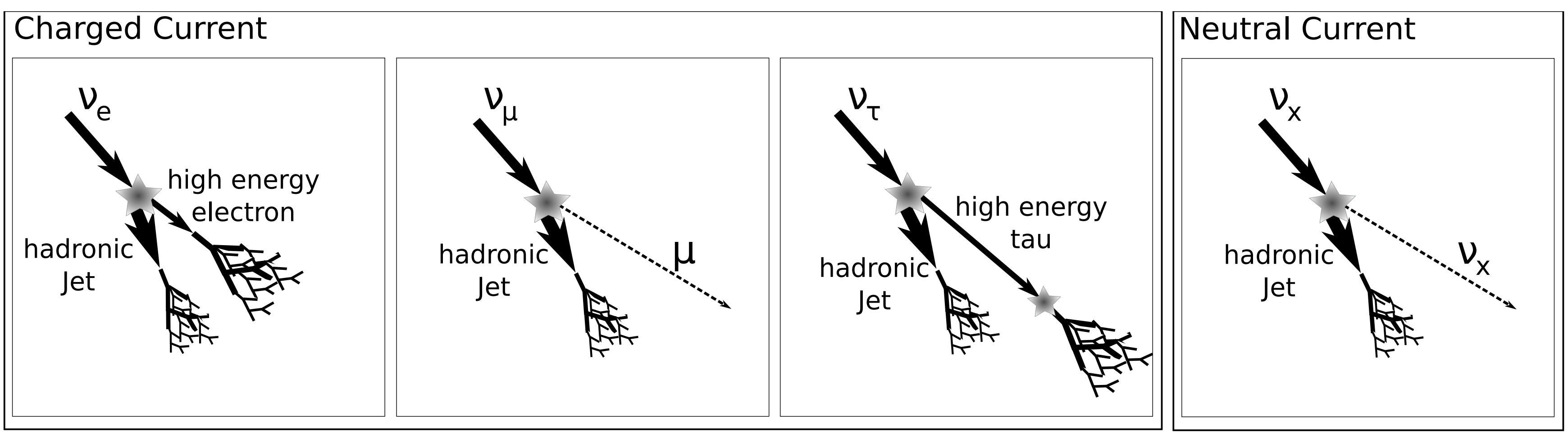
Three selections depending on zenith angle :

Earth-Skimming (ES) → (90°, 95°)

Downward-going high-angle (DGH) → (75°, 90°)

Downward-going low-angle (DGL) → (60°, 75°)

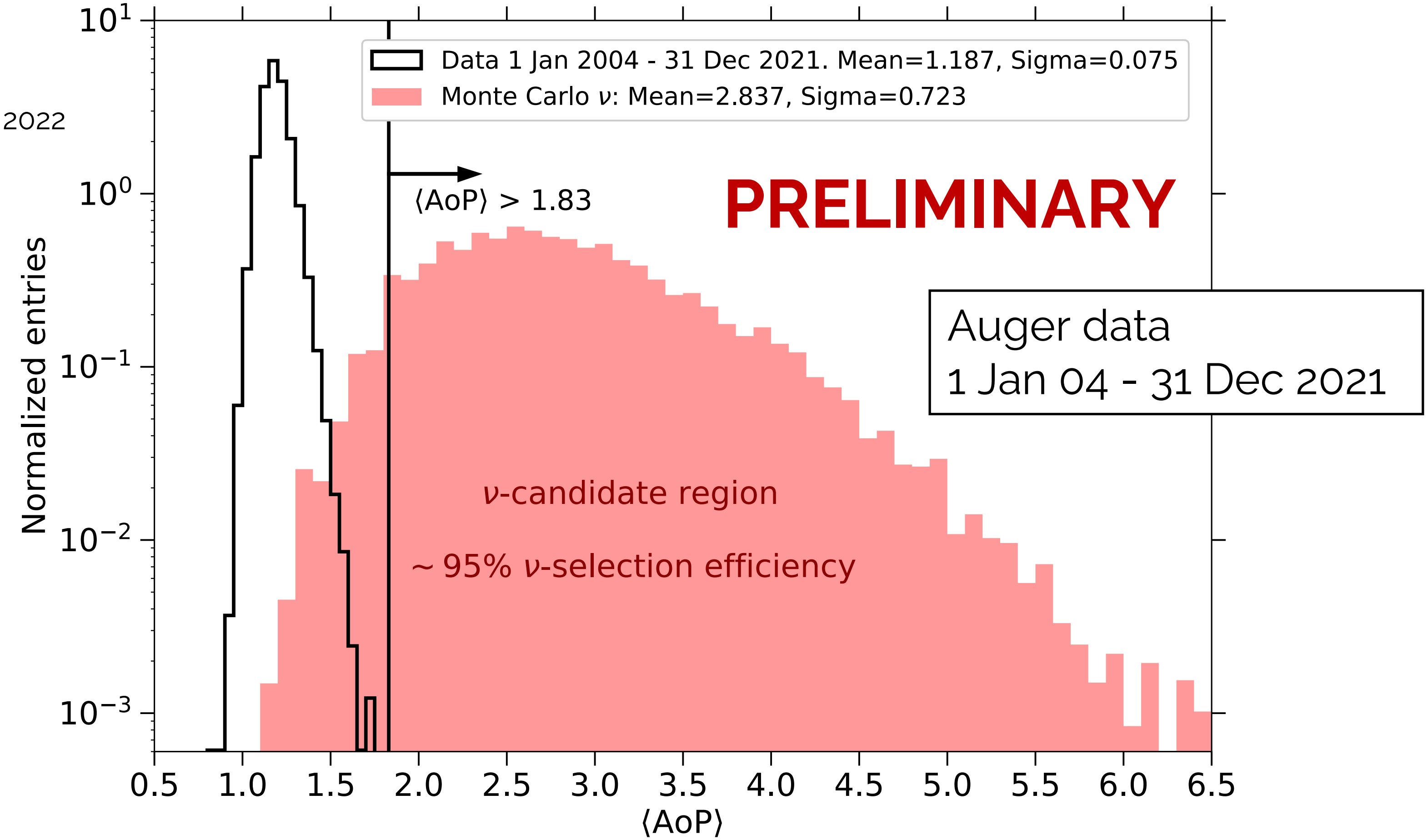
More details on selections in
Pierre Auger Collab., PRD **91**, 092008 (2015)



Data unblinding: Earth-Skimming channel

Distribution of mean Area-over-Peak <AoP> in highly inclined events

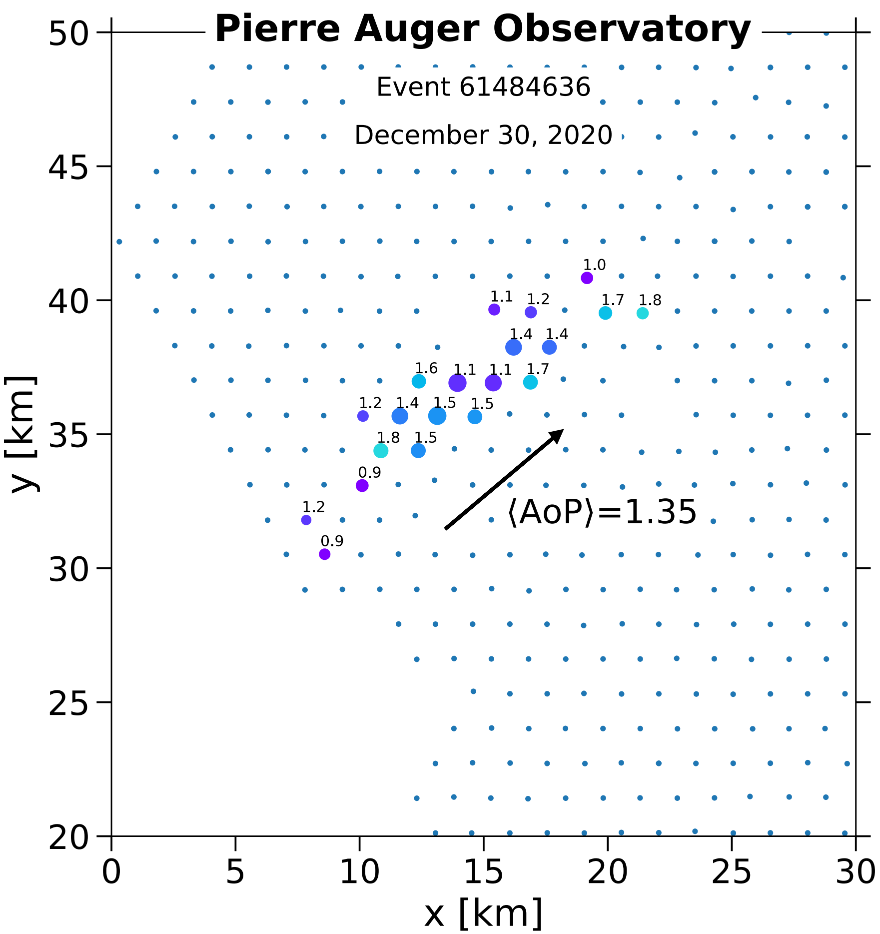
- Pierre Auger JCAP **10** (2019) 022
- Auger at UHECR 2022 L´Aquila (Italy)

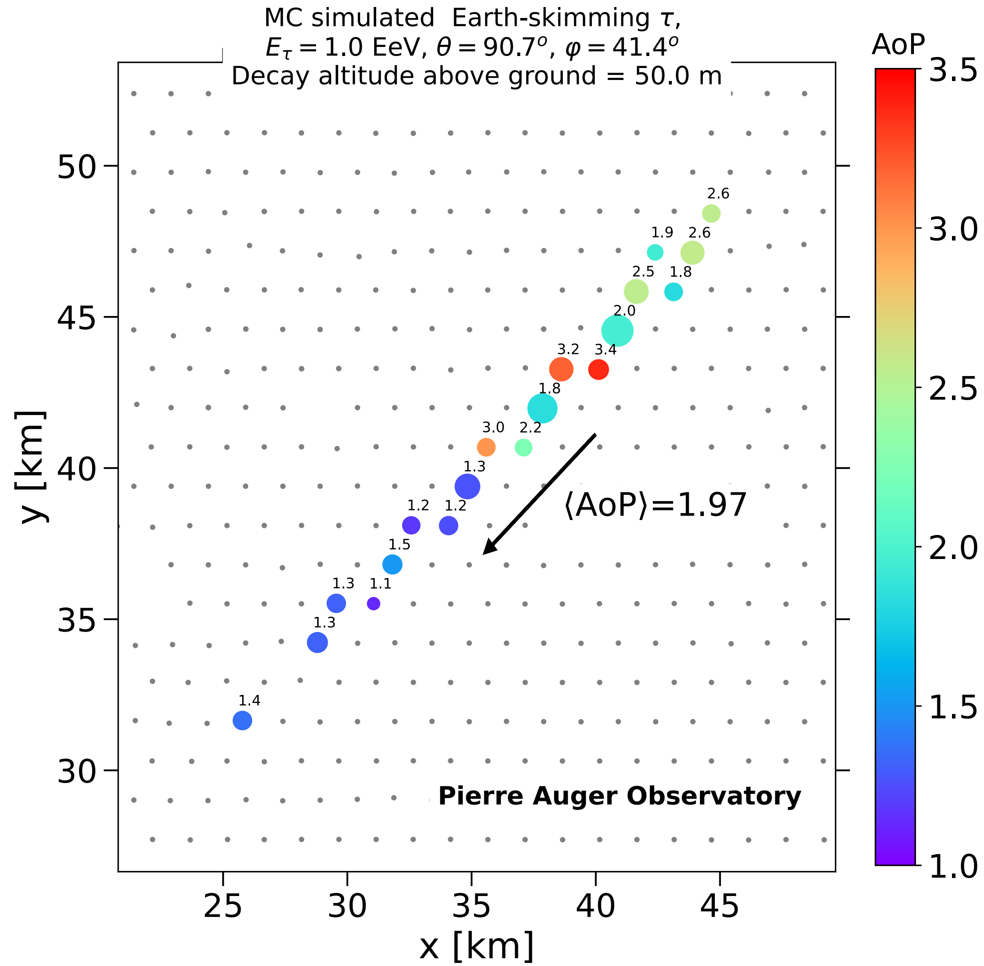


No neutrino candidates in the Earth-Skimming channel
Large neutrino-selection efficiency => sensitivity dominated by exposure, NOT by background

Background (UHECR) inclined event in data

Monte Carlo simulation Earth-Skimming neutrino





- Black arrow parallel to projection of shower axis on ground
- Numbers on top of each station indicate <AoP> - the discriminating observable for Earth-Skimming ν

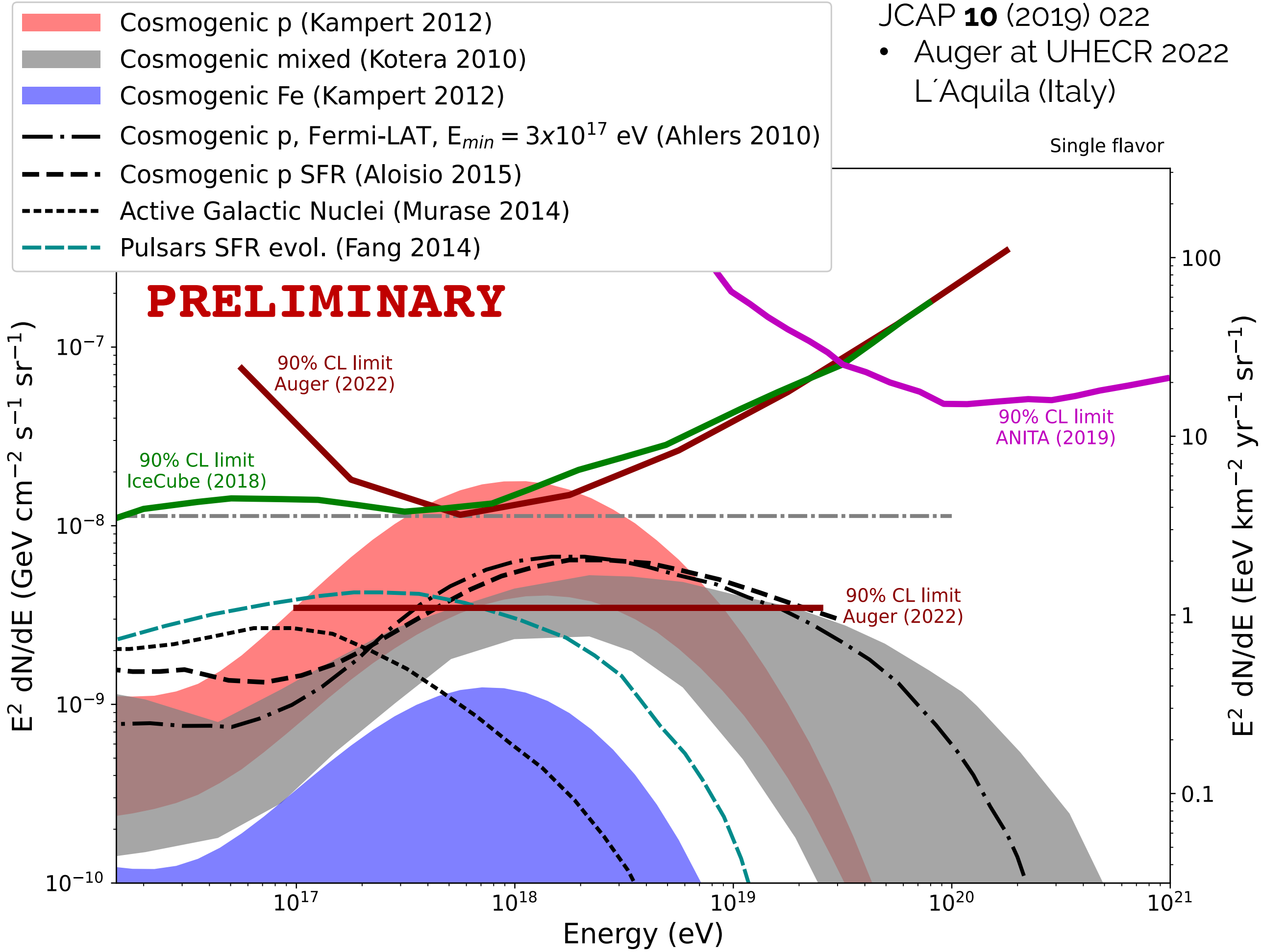
Upper limit to diffuse flux of UHE neutrinos

- Pierre Auger JCAP **10** (2019) 022
- Auger at UHECR 2022 L´Aquila (Italy)

Auger data:
1 Jan 2004 – 31 Dec 2021

Flavor of neutrino	Fractional contribution to event rate
ν_e	10 %
ν_μ	4 %
ν_τ	86 %

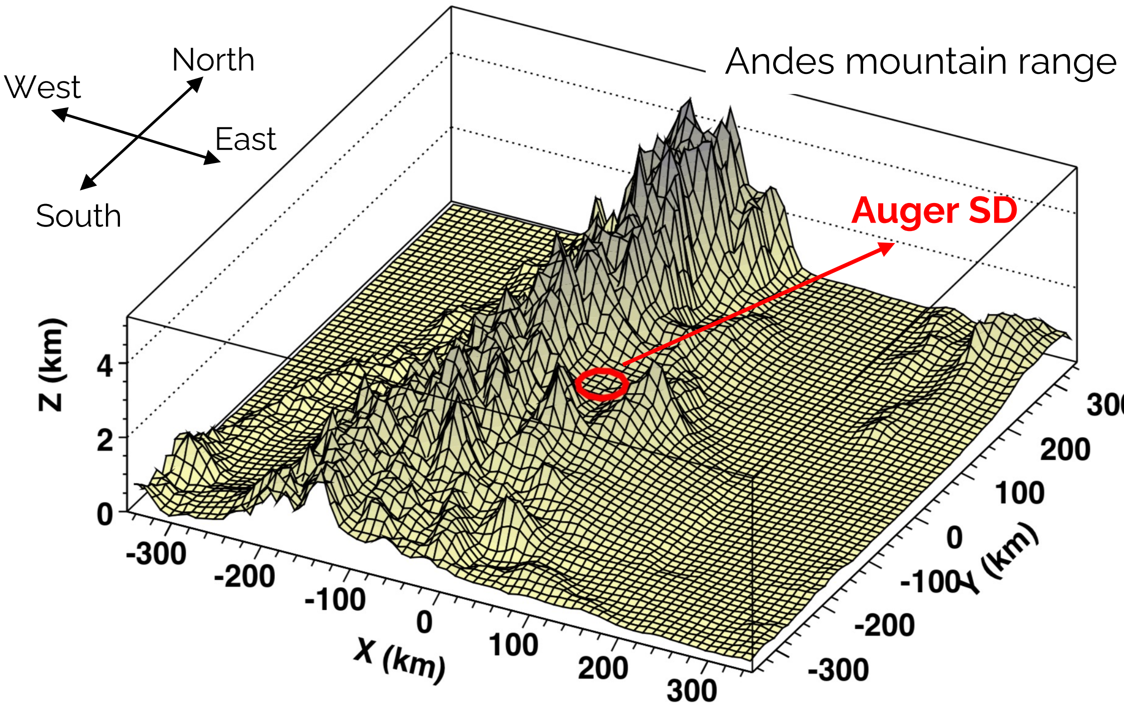
(assuming an E^{-2} flux)



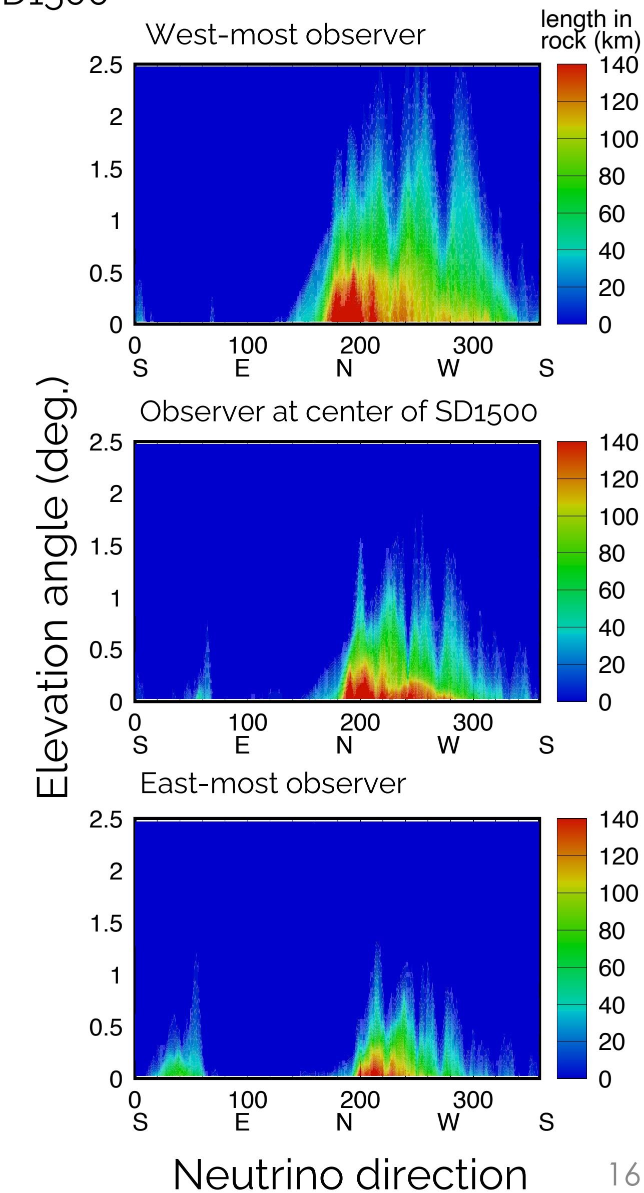
- **No neutrino candidates** in data Jan 04 – Dec 21 => restrictive upper limits to neutrino flux in the cosmic particle beam at EeV energies.
- **Very small background** to ν identification => Auger sensitivity limited by exposure
- UHEν are produced in interactions of UHECR ⇒ Auger limits constrain models assuming pure proton primary cosmic beam

Role of topography at Auger site

Digital Elevation map of the Auger site



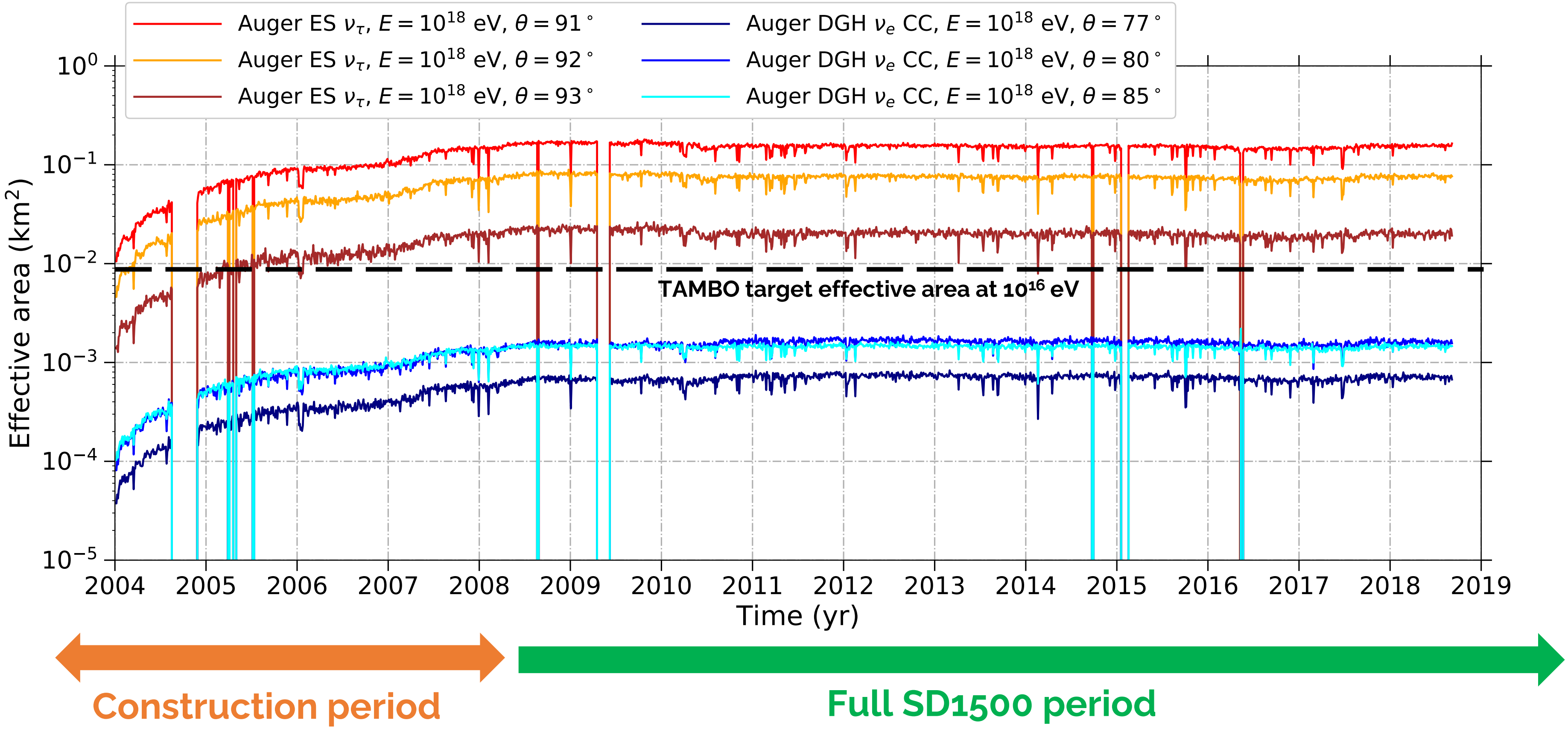
Length in rock (km) vs direction for observers at different locations in the SD1500



- Topography affects both the **Earth-Skiming (90° – 95°)** channel and to **downward-going (88° – 90°)** neutrinos
- Topography **contributes (roughly) with 17% to the TOTAL neutrino event rate** (assuming an E^{-2} flux)

Stability of the SD1500 array of Pierre Auger

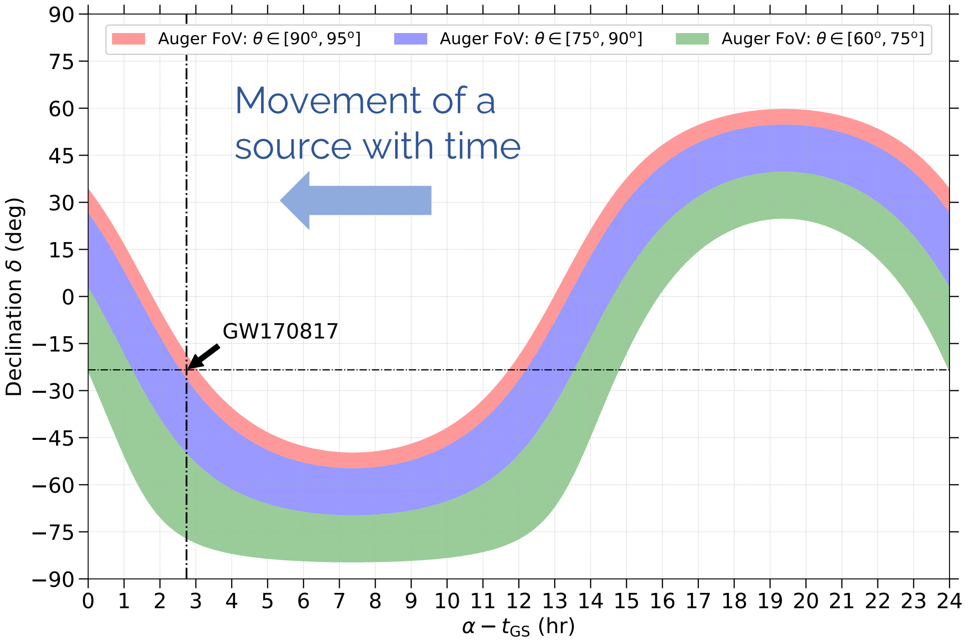
Effective area vs time for different neutrino channels



Pierre Auger
JCAP **11** (2019) 004

Sky coverage of Auger SD1500

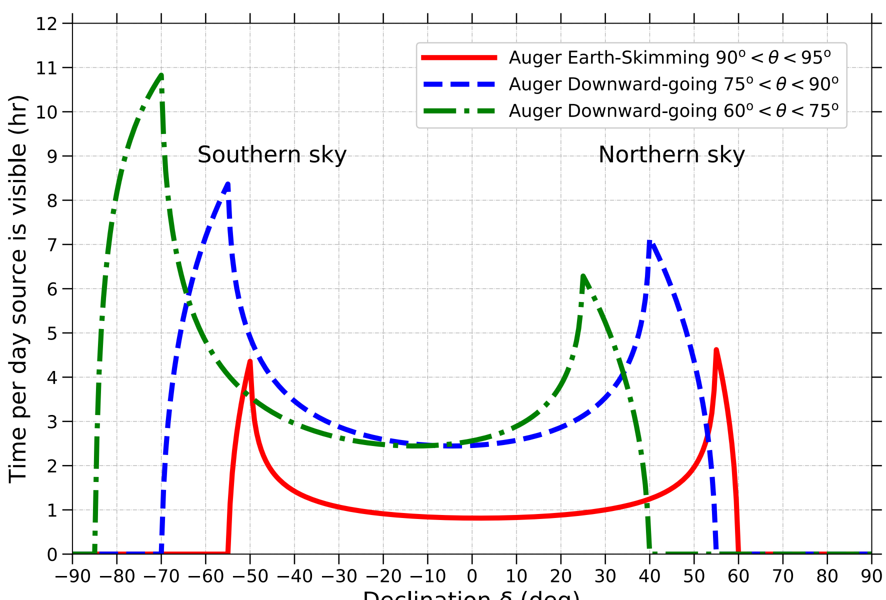
Instantaneous sky coverage



Auger "sees" **~ 30% of the sky at each instant of time** in the zenith angle ranges where sensitivity to UHE neutrinos is largest.

Covering all right ascensions (due to 100% duty cycle)

Time per day (hr) a source is visible vs declination

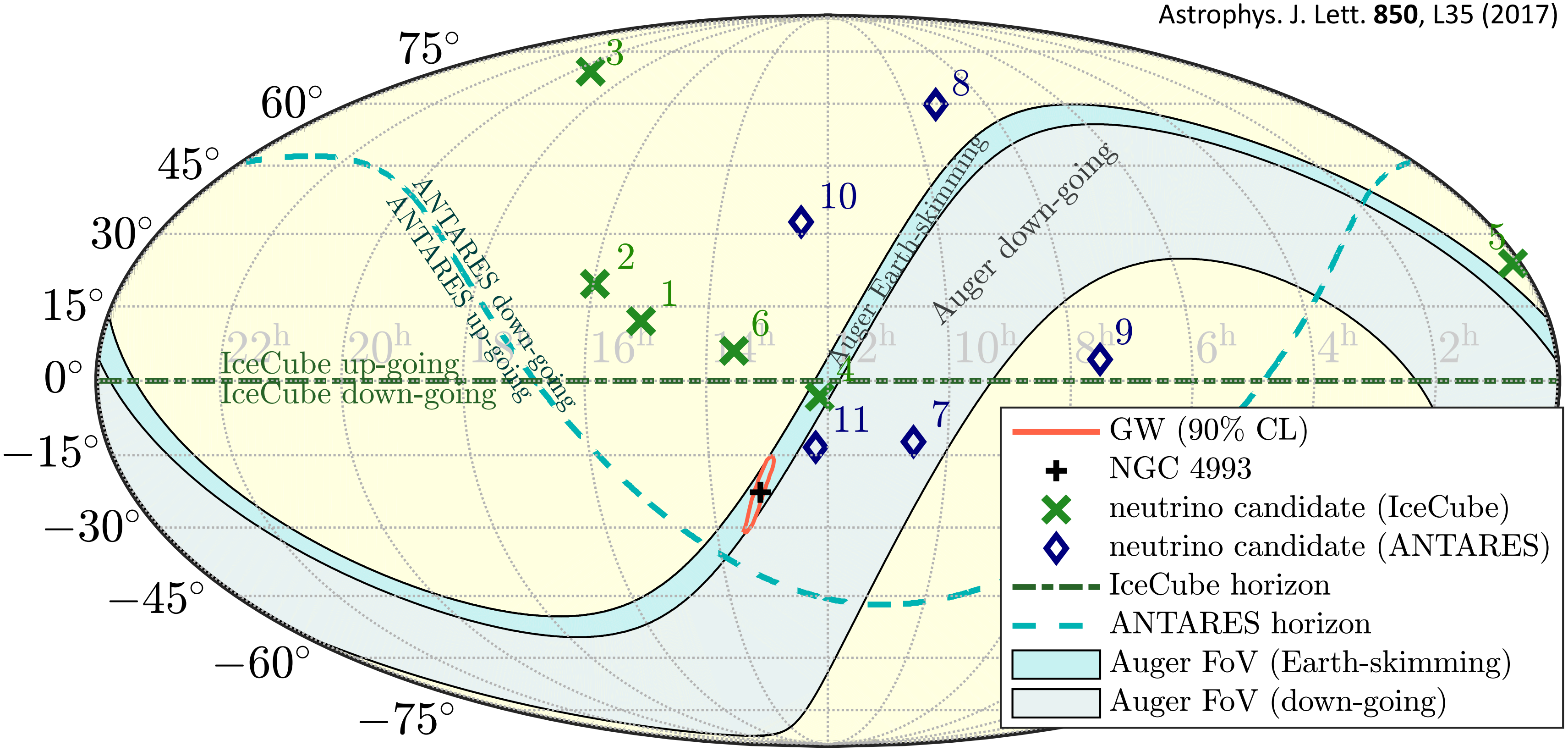


Sensitivity to UHE neutrinos in declination ranges between **close to South Celestial Pole to 60 deg North**

Pierre Auger
JCAP **11** (2019) 004

Follow-up of GW170817 in neutrinos
Binary Neutron Star Merger + short GRB

ANTARES, IceCube, Auger, LIGO & Virgo
Astrophys. J. Lett. **850**, L35 (2017)

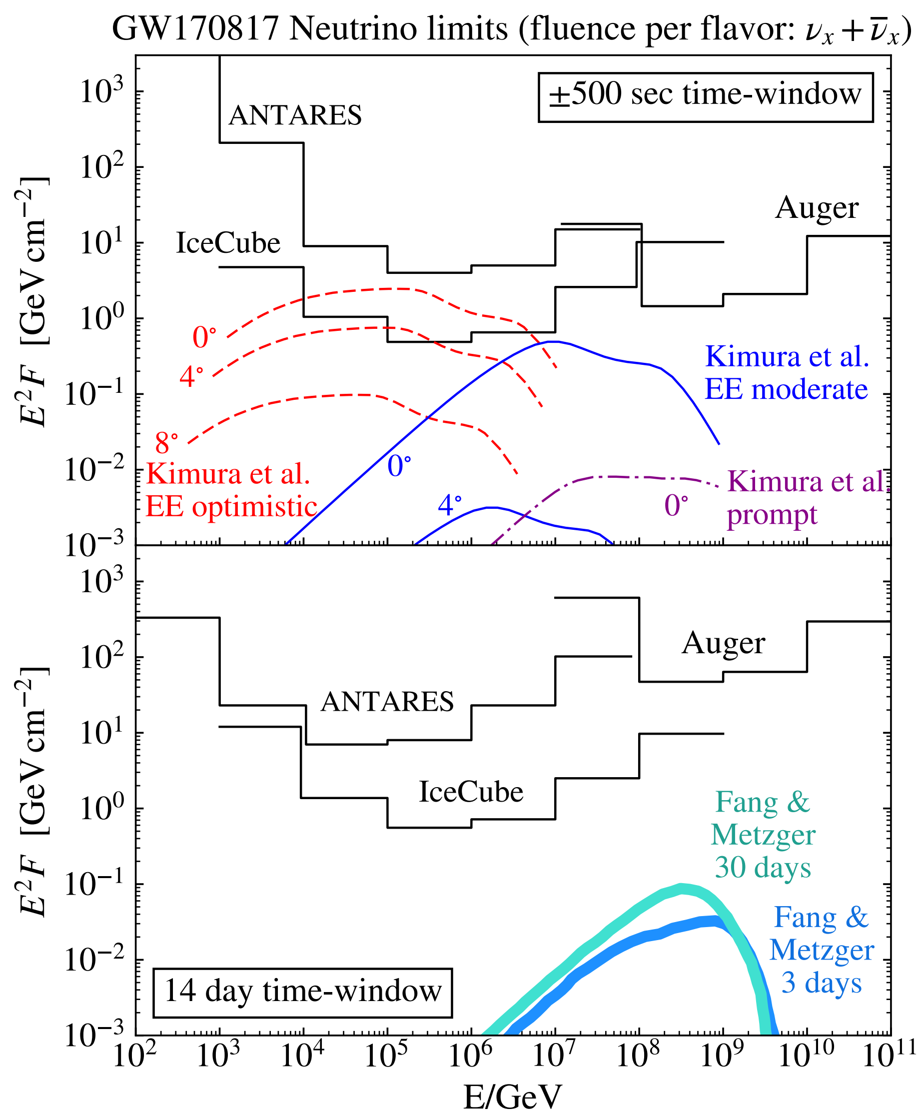


The NS-NS merger was in an **optimal position** for the detection of UHE tau neutrinos from Auger at the instant of emission of GW170817

Limits to ν from Binary NS-NS event GW170817: ANTARES, Auger & IceCube

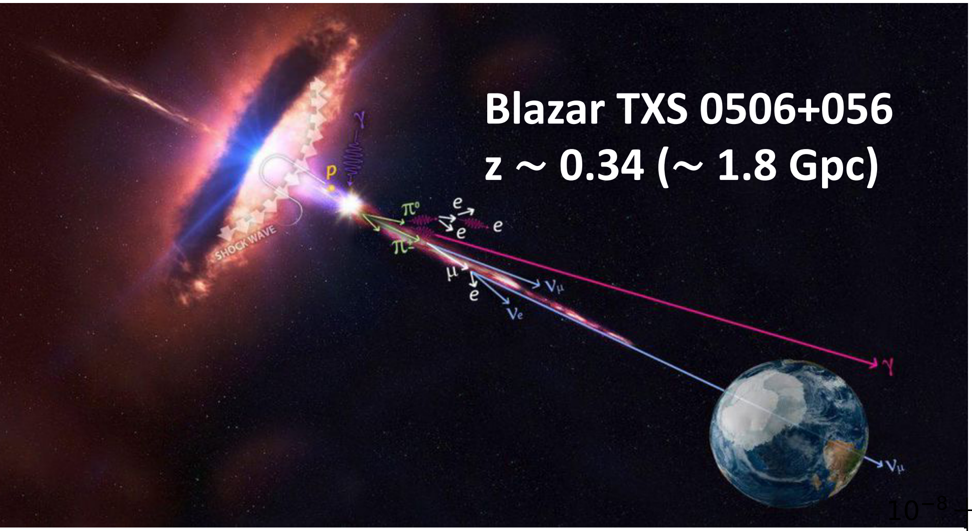
- Neutrino limits based on non-observation in ± 500 sec & +14 days-time windows

- Lack of neutrino detection consistent with expectations from a short GRB viewed at a large off-axis angle ≳ 20° (in agreement with LIGO/Virgo & GRB observations)



ANTARES, IceCube, Auger, LIGO & Virgo
Astrophys. J. Lett. **850**, L35 (2017)

Multimessenger Astronomy at UHE with Auger



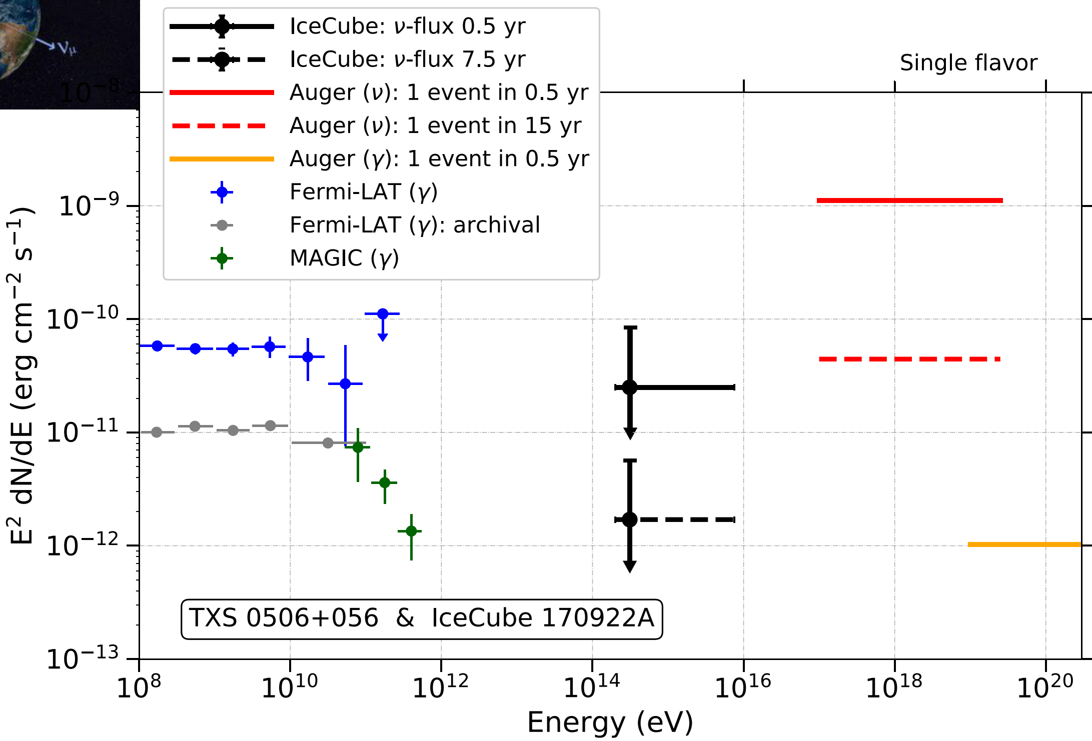
22 Sep. 2017 High-Energy ν discovered by IceCube directionally coincident with gamma-ray blazar (AGN) TXS 0506+056. **First identified source of high-energy astrophysical neutrinos**

IceCube Collab. et al. Science **361**, 146 (2018)

No candidate neutrinos from direction of TXS @ EeV energy in Auger

⇩

First upper limits to the UHE neutrino & photon flux from an identified neutrino source



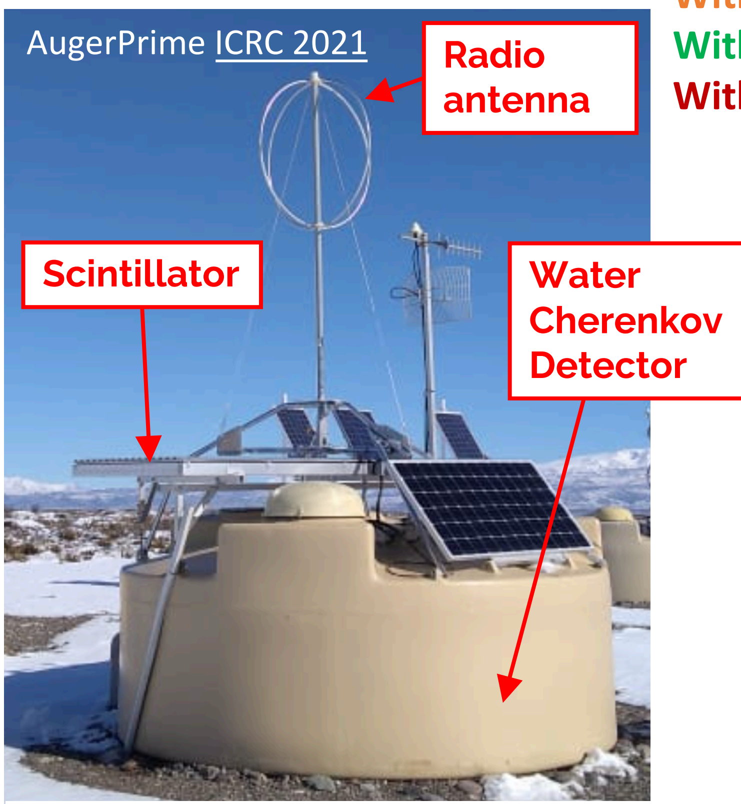
Pierre Auger. Astrophys. J., **902**, 105 (2020)

Extension of the Auger Observatory: AugerPrime

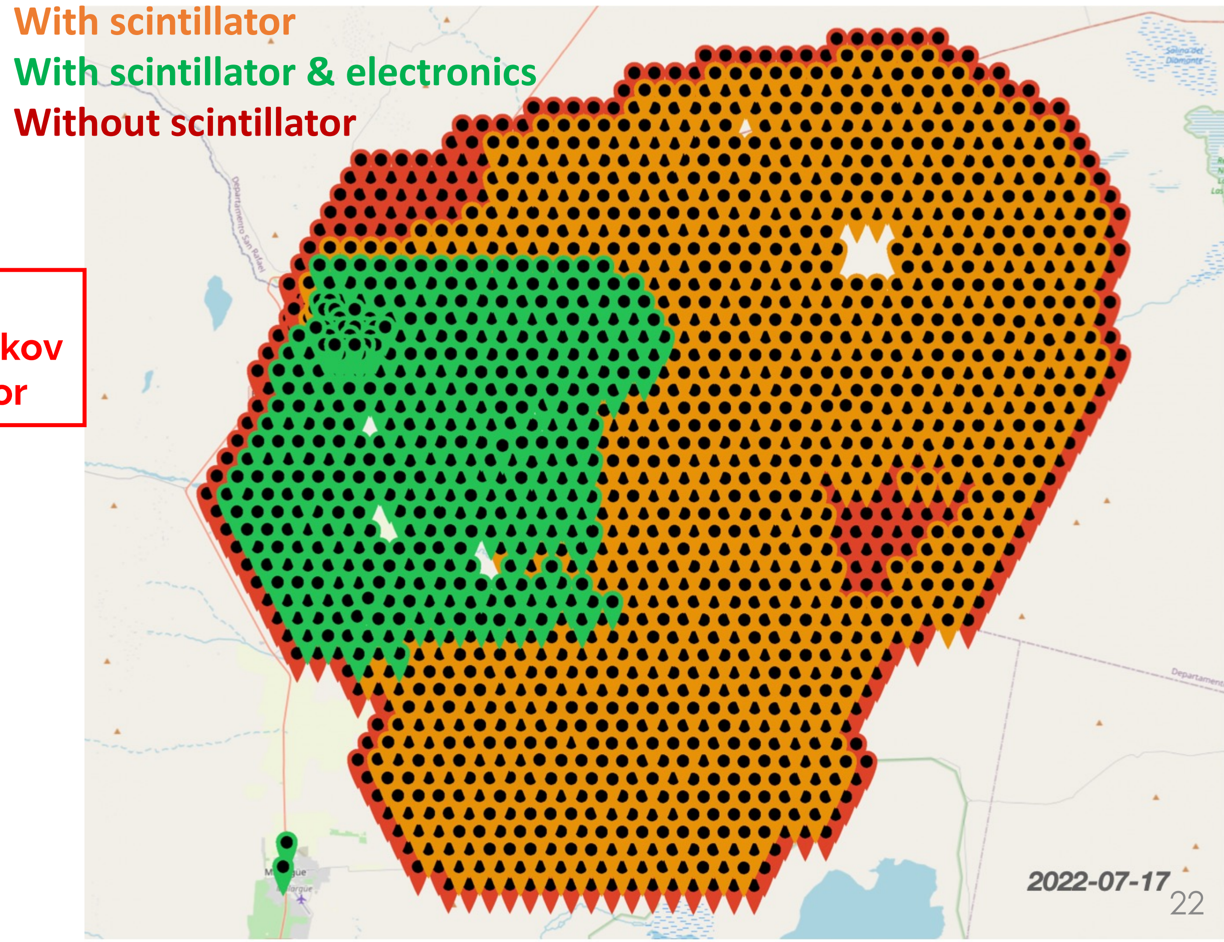
Instrument water-Cherenkov stations with ~4 m² **scintillators & antennas on top**

Improve composition determination on shower-by-shower basis (the enhanced discrimination of muon & electromagnetic component should benefit ν detection)

Timeline: Data taking with upgraded array until **2025 (possibly until 2030)**



Fully-equipped AugerPrime Surface Detector station

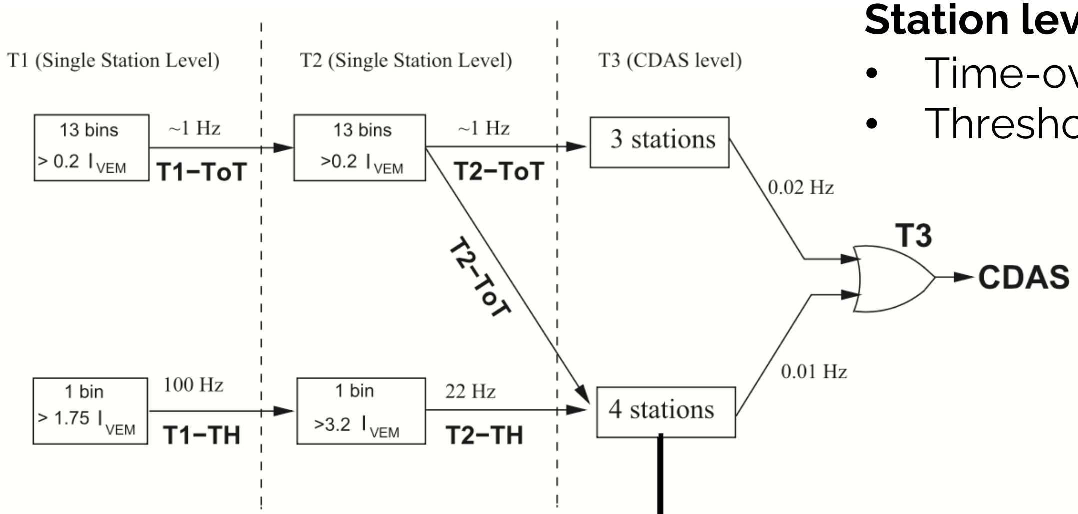


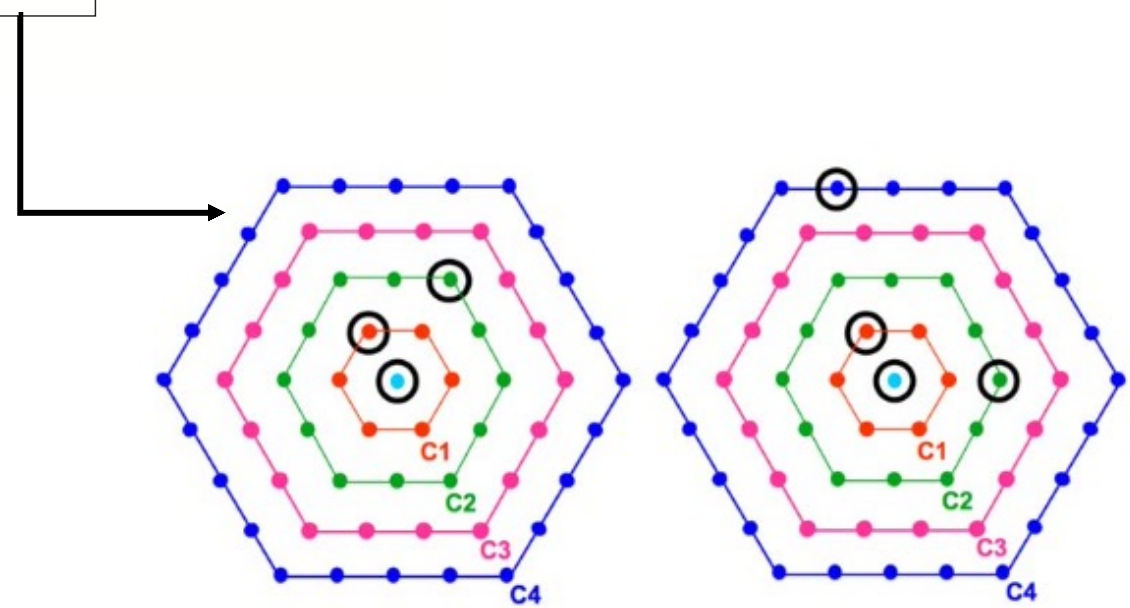
Thank you for the invitation and for your attention

Trigger of the SD1500

Station level triggers (T1, T2):

- Time-over-Threshold (ToT)
- Threshold (TH)





Event triggers (T3)

- ToT2C1 & 3C2
- 2C1 & 3C2 & 4C4

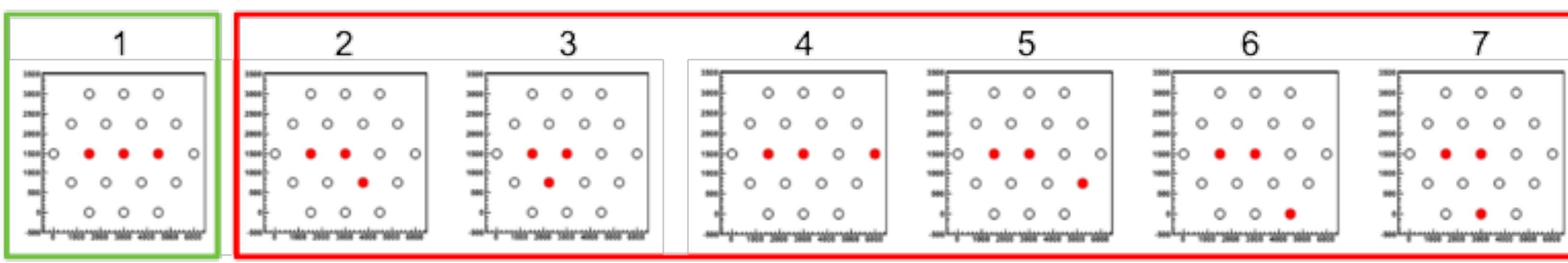
Inclined and young shower cuts

Earth-skimming analysis
$90^\circ < \theta < 95^\circ$

- Inclined showers:
  - L/W > 5
  - <V> ∈ [0.29, 0.31] m ns^{-1}
  - RMS(V) < 0.08 m ns
  - $\theta_{rec} > 75^\circ$
  - If $N_{st} = 3$: only config. 1
- Young showers:
  - <AoP> > 1.83
  - If $N_{st} = 3$: $AoP_{min} > 1.4$

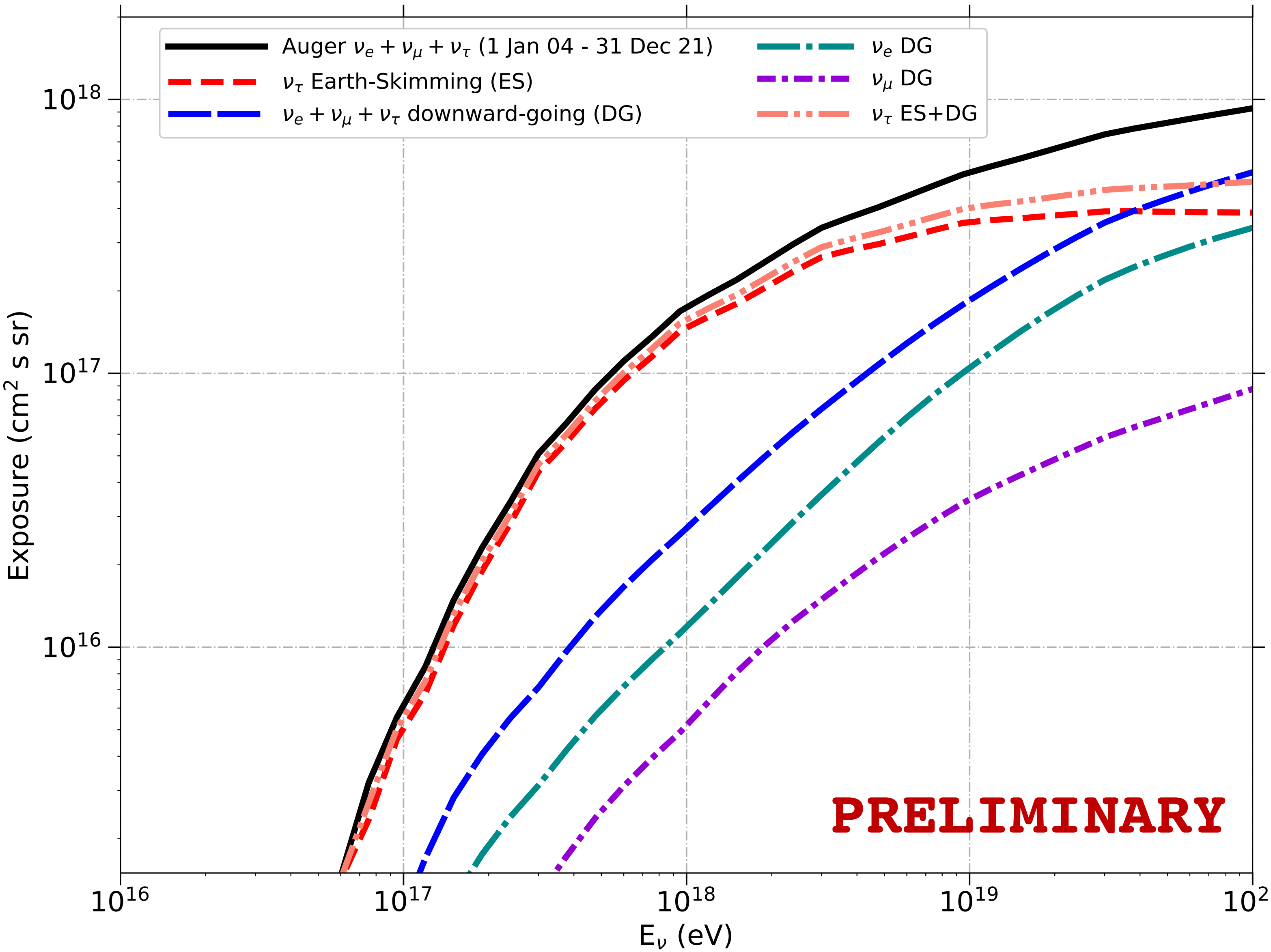
Downward-going high analysis
$75^\circ < \theta < 90^\circ$

- Inclined showers:
  - L/W > 3
  - <V> < 0.313 m ns^{-1}
  - RMS(V)/<V> < 0.08
  - $\theta_{rec} > 75^\circ$
- Young showers:
  - Fisher cut

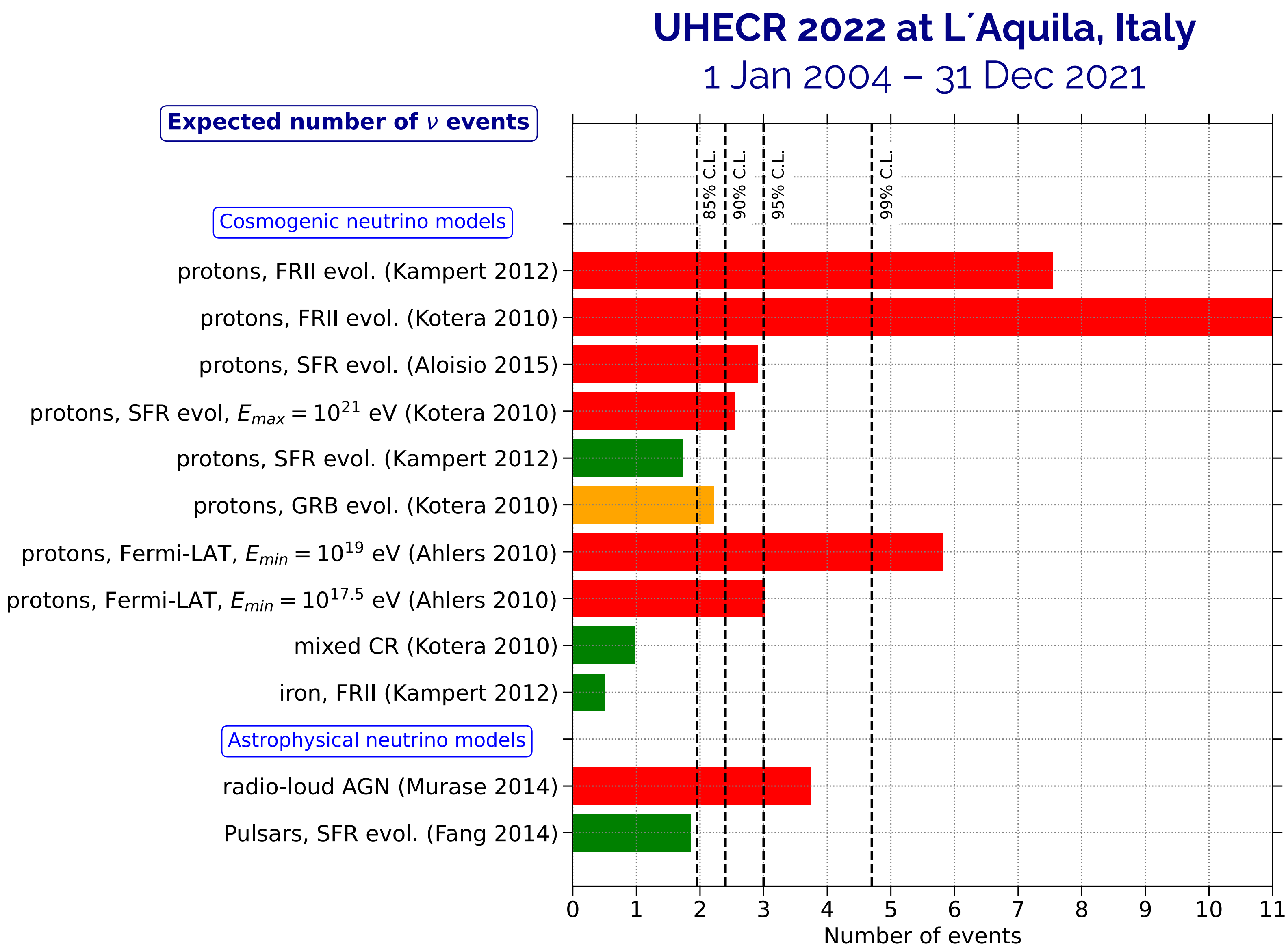


Exposure of SD1500: 1 Jan 2004 – 31 Dec 2021

- Pierre Auger JCAP **10** (2019) 022
- Auger at UHECR 2022 L´Aquila (Italy)



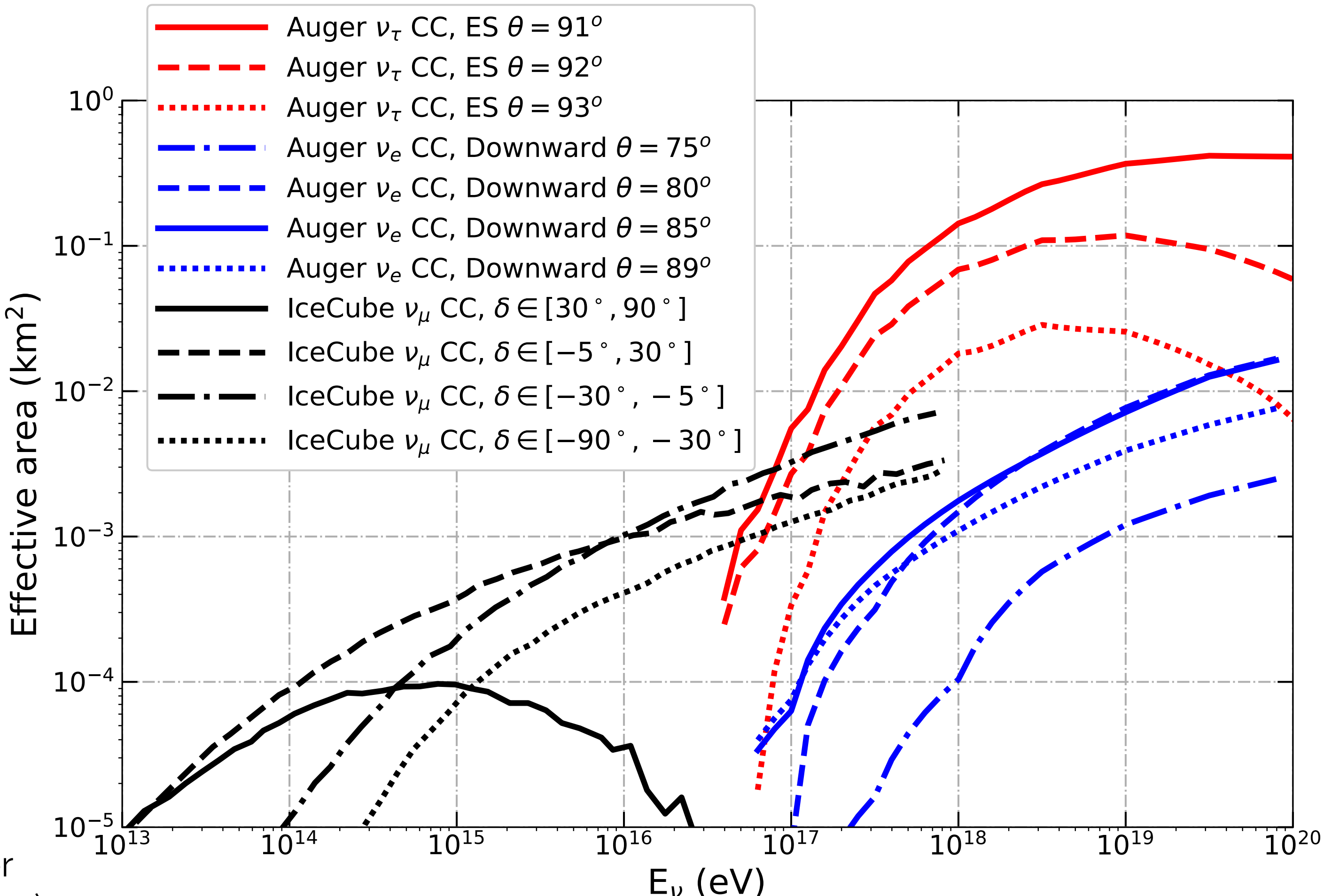
Expected neutrino event rate for selected models



Instantaneous effective area A_{eff}: sensitivity to transient sources

$$\dot{N}_\nu = \int d\Omega \int_0^\infty dE\, A_{\rm eff}\,(E,\,\Omega) \times F_\nu\,(E_\nu,\,\Omega)$$

Large area of SD of Auger => **unrivalled sensitivity to transient point-like sources at EeV** (as long as source is located in sky in the FoV of Earth-Skimming channel).



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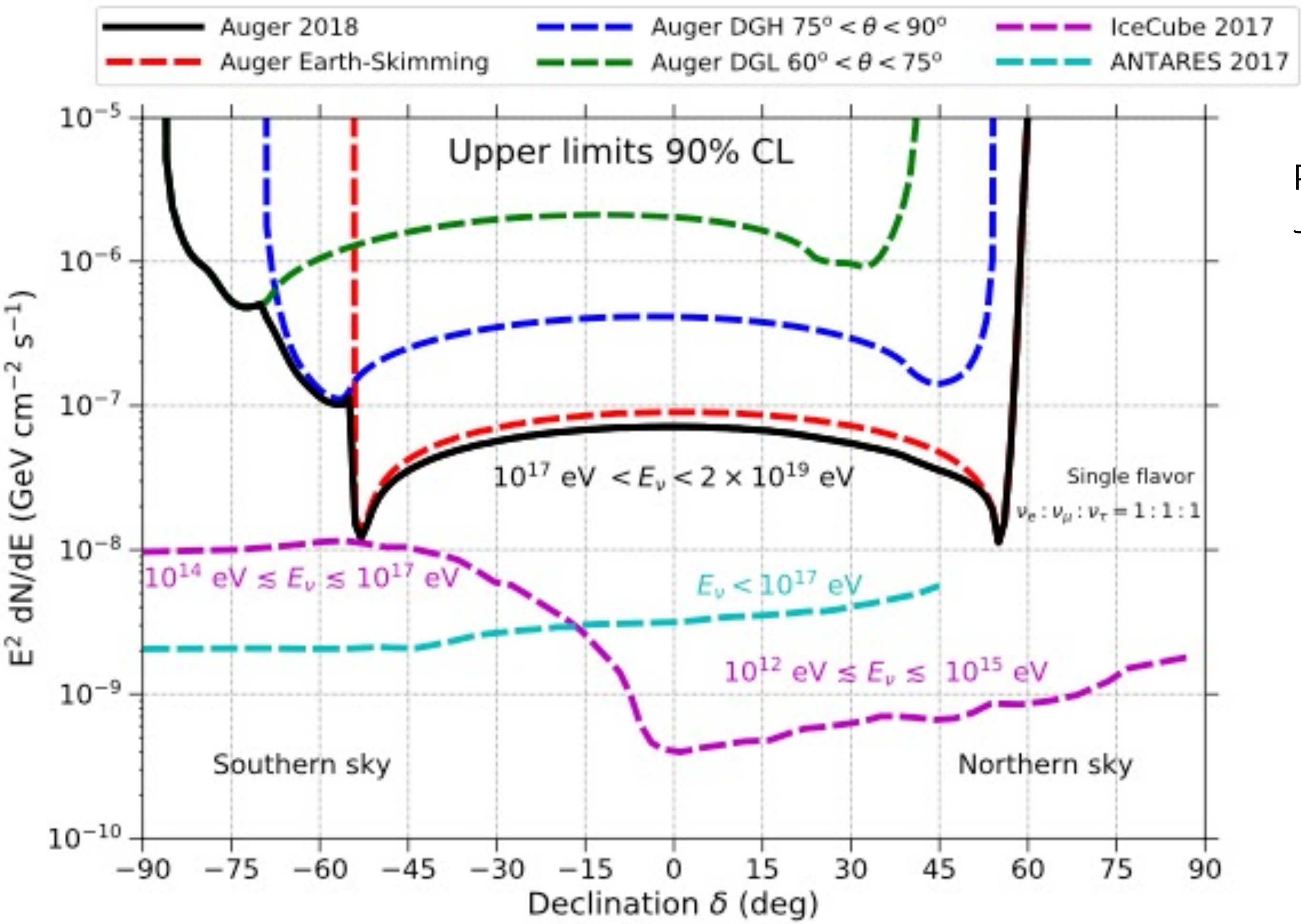
Limits to point-like & steady neutrino sources

Broad range in declination where n can be efficiently identified with Auger: two "sweet" spots around declinations -55° and +55°



Pierre Auger
JCAP **11** (2019) 004

NOTE:
complementary energy ranges of experiments

IceCube, Astrophys.J. **835**, 151 (2017) ANTARES, PRD **96**, 082001 (2017)

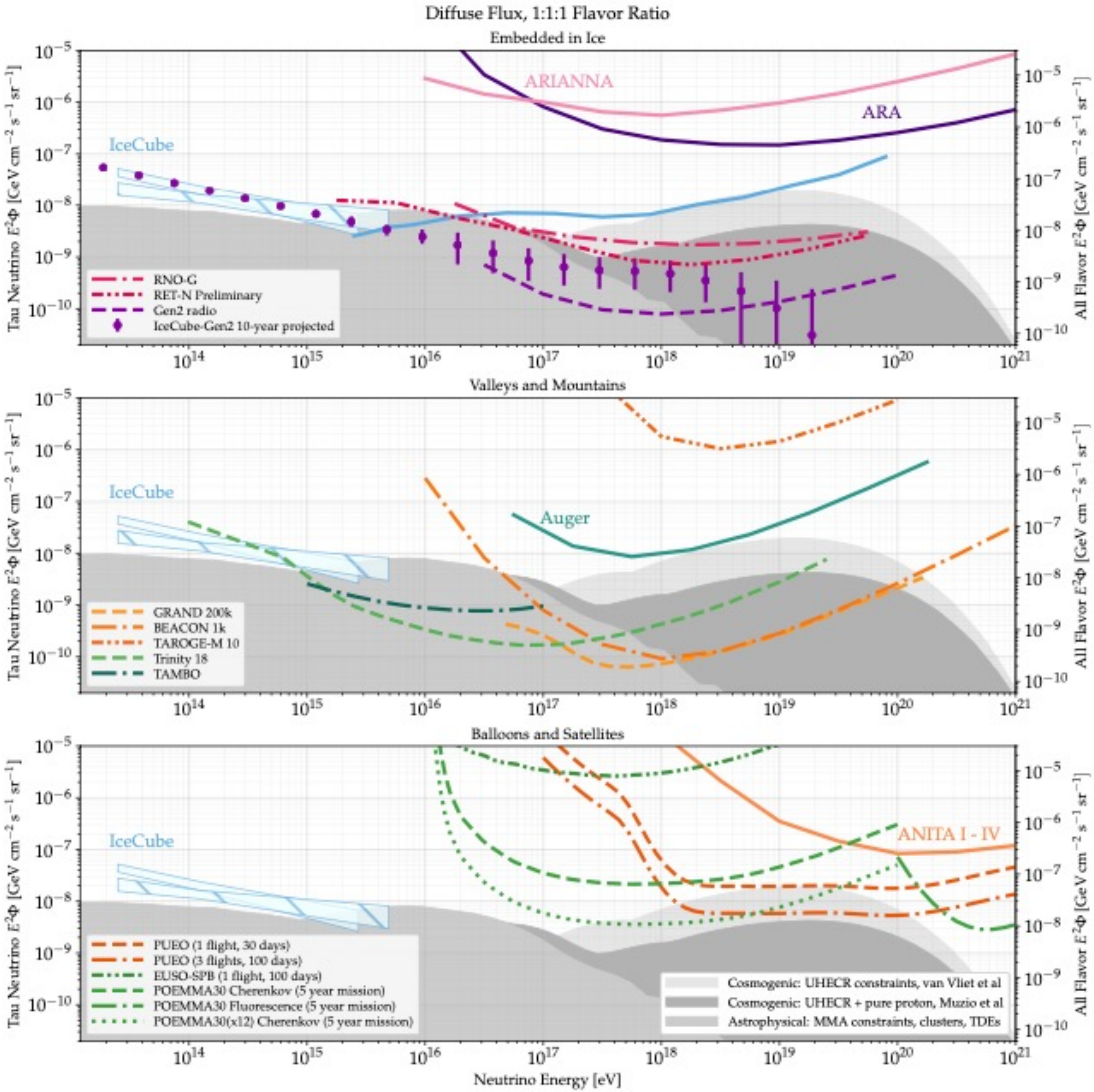
Landscape of operating and planned experiments sensitive to tau neutrinos

"*Tau Neutrinos in the Next Decade: from GeV to EeV*",
Journal of Physics G: Nuclear and Particle Physics 49, 11 (2022)

				Flavor		Technique			Neutrino Target					Geometry					
Experiments	Phase & Online Date	Energy Range	Site	Tau	All Flavor	Optical / UV	Radio	Showers	H_2O	Atmosphere	Earth's limb	Topography	Lunar Regolith	Embedded	Planar Arrays	Valley	Mountains	Balloon	Satellite
IceCube	2010	TeV-EeV	South Pole		✓	✓			✓					✓					
KM3NeT	2021	TeV-PeV	Mediterranean		✓	✓			✓					✓					
Baikal-GVD	2021	TeV-PeV	Lake Baikal		✓	✓			✓					✓					
P-ONE	2020	TeV-PeV	Pacific Ocean		✓	✓			✓					✓					
IceCube-Gen2	2030+	TeV-EeV	South Pole		✓	✓	✓		✓					✓					
ARIANNA	2014	>30 PeV	Moore's Bay		✓		✓		✓					✓					
ARA	2011	>30 PeV	South Pole		✓		✓		✓					✓					
RNO-G	2021	>30 PeV	Greenland		✓		✓		✓					✓					
RET-N	2024	PeV-EeV	Antarctica		✓		✓		✓					✓					
ANITA	2008,2014,2016	EeV	Antarctica	✓	✓		✓		✓		✓							✓	
PUEO	2024	EeV	Antarctica	✓	✓		✓		✓		✓							✓	
GRAND	2020	EeV	China / Worldwide	✓			✓			✓	✓	✓			✓		✓		
BEACON	2018	EeV	CA, USA/ Worldwide	✓			✓				✓	✓					✓		
TAROGE-M	2018	EeV	Antarctica	✓			✓				✓	✓					✓		
SKA	2029	>100 EeV	Australia		✓		✓						✓		✓				
Trinity	2022	PeV-EeV	Utah, USA	✓		✓					✓						✓		
POEMMA		>20 PeV	Satellite	✓	✓	✓				✓	✓								✓
EUSO-SPB	2022	EeV	New Zealand	✓		✓					✓							✓	
Pierre Auger	2008	EeV	Argentina	✓	✓			✓		✓	✓	✓			✓				
AugerPrime	2022	EeV	Argentina	✓	✓		✓	✓		✓	✓	✓			✓				
Telescope Array	2008	EeV	Utah, USA	✓	✓			✓		✓					✓				
TAx4		EeV	Utah, USA	✓	✓			✓											
TAMBO	2025-2026	PeV-EeV	Peru	✓				✓				✓				✓			

Operational	(white)	Date full operations began
Prototype	(light grey)	Date protoype operations began or begin
Planning	(dark grey)	Projected full operations

Expected differential 90% CL sensitivity to the diffuse neutrino flux of several experiments



"*Tau Neutrinos in the Next Decade: from GeV to EeV*",Journal of Physics G: Nuclear and Particle Physics **49**, 11 (2022)

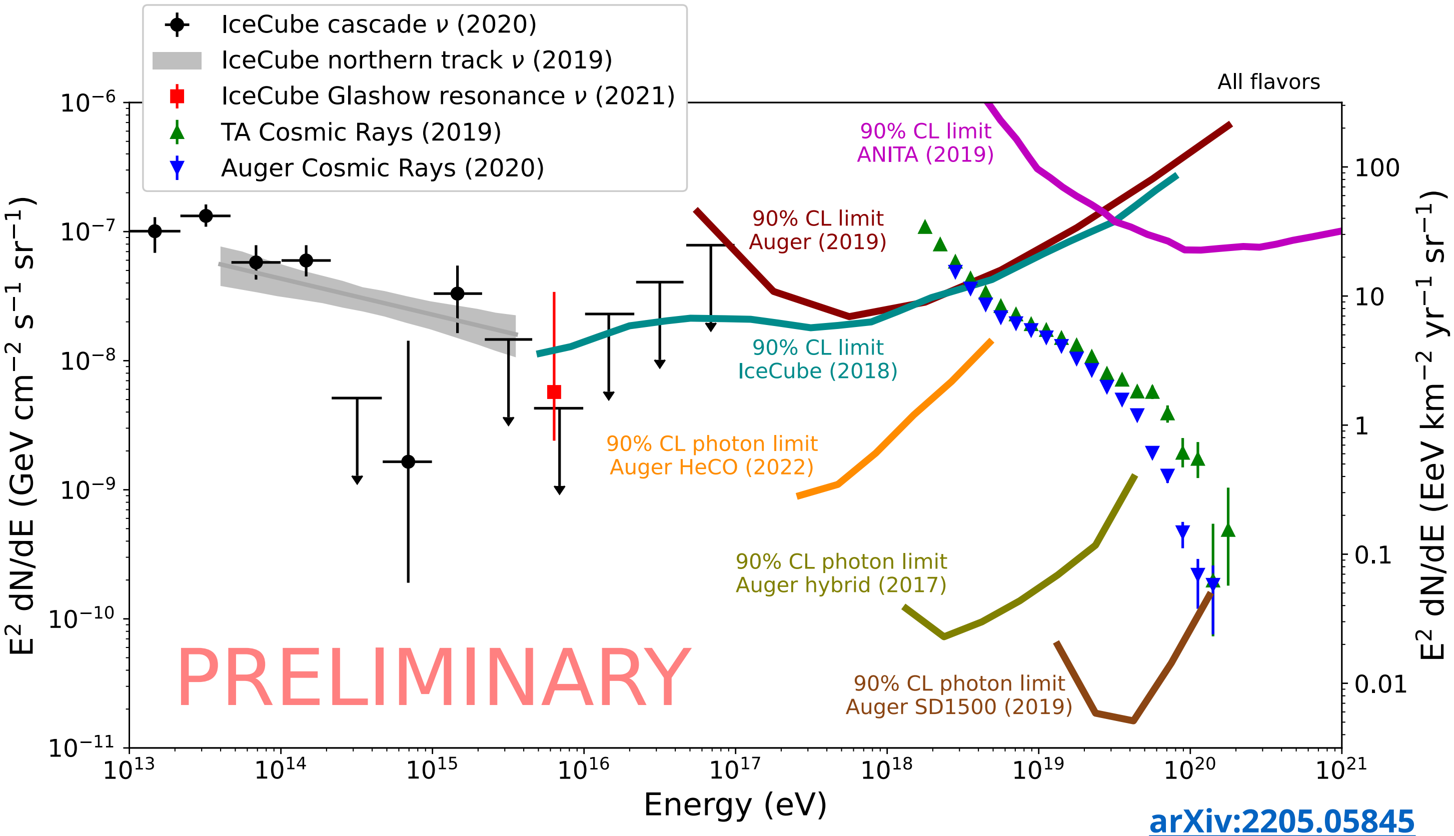
Pierre Auger UHE neutrino & photon limits

No UHE neutrino candidates found in Auger data

Pierre Auger, JCAP **10** (2019) 022
Pierre Auger, JCAP **11** (2019) 004

Multimessenger plot showing:

- Auger photon and neutrino limits
- UHECR spectrum
- IceCube neutrino fluxes and limits



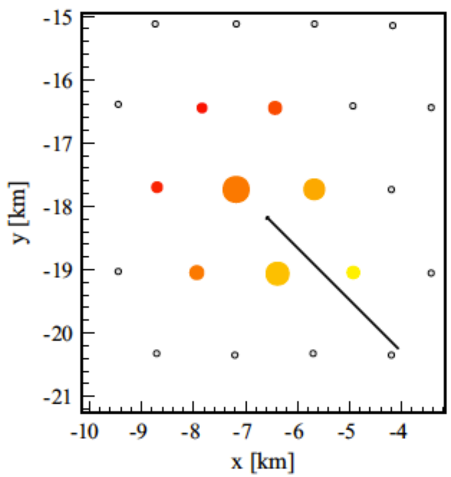
arXiv:2205.05845

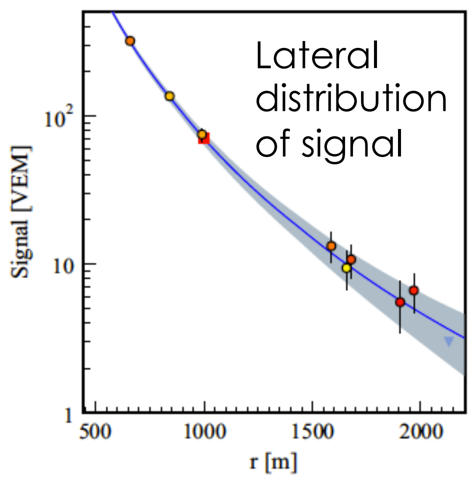
"*Ultra-High Energy Cosmic Rays (UHECRs): The Intersection of the Cosmic and Energy Frontiers*"
Snowmass 2021, submitted to Astropart. Phys.

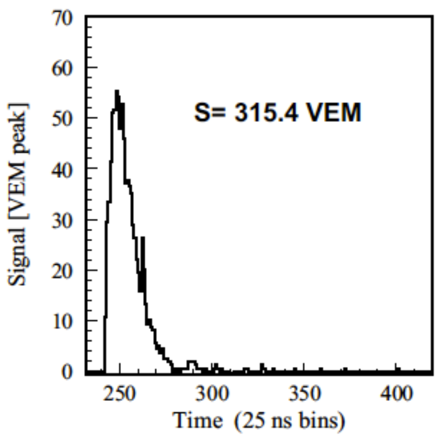
Surface Detector (SD) event

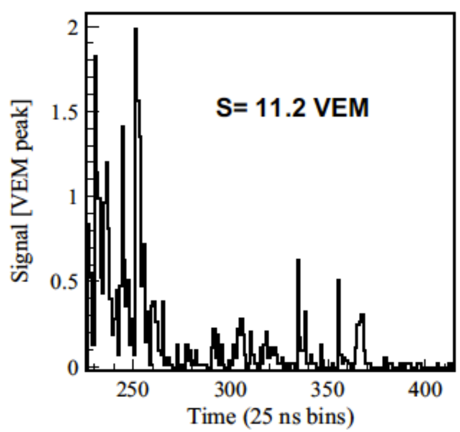
E ~ 3 x 10^{19} eV, Zenith angle ~ 28°

footprint of event



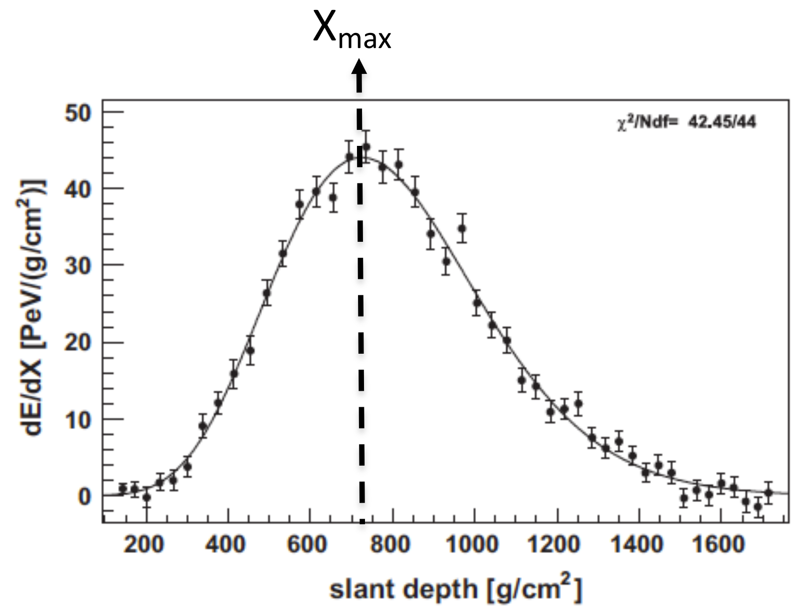






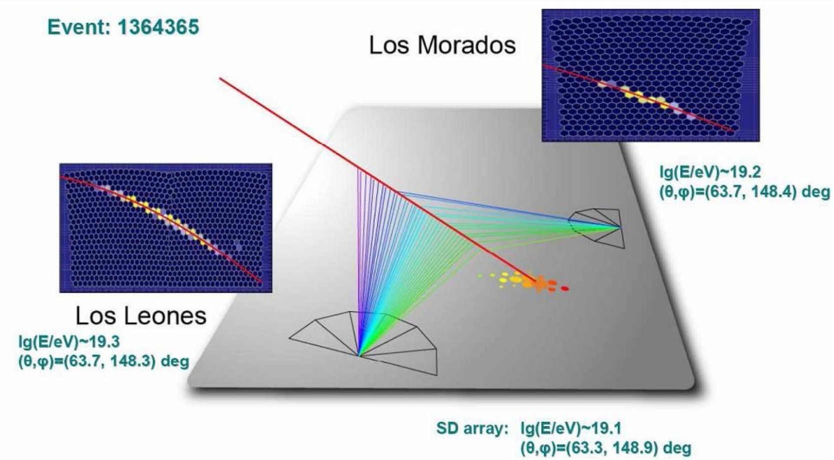
Examples of signal vs time in 2 stations (25 ns bin)

Shower profile reconstr. from Fluorescence (FD) data



Deposited energy vs depth in atmosphere

Hybrid (FD + SD) event



Monitoring & maintenance of the SD array

- The **SD data-taking runs non-stop** with almost no intervention.
  - Duty cycle > 95% in the last 15 years

- The operation of the whole SD is **monitored online**.
  - Different **alarms** are set on various parameters, if an urgent problem is detected the local staff intervenes for maintenance service.
  - Detectors are exposed to **severe environmental conditions**: thermal variations, humidity, wind, salinity, dust, flooding, ground erosion, damages caused by local fauna and vandalism or theft.

- **Detectors out of operation:**
  - **Black Tanks** (have not sent any trigger in the last 24 hours)
  - **Grey Tanks** (only one PMT out of the 3 is working).
  - A very large number of Black Tanks is due to general problems of power or communication.
  - To keep the number of Black + Gray Tanks around 40-50, about 3 field trips per week are required to some of them, and periodical maintenance trips, especially for PMTs, are conducted.