Searches of UHE neutrinos at the Pierre Auger Observatory: recent results and future prospects

Roberto Mussa (INFN Torino)

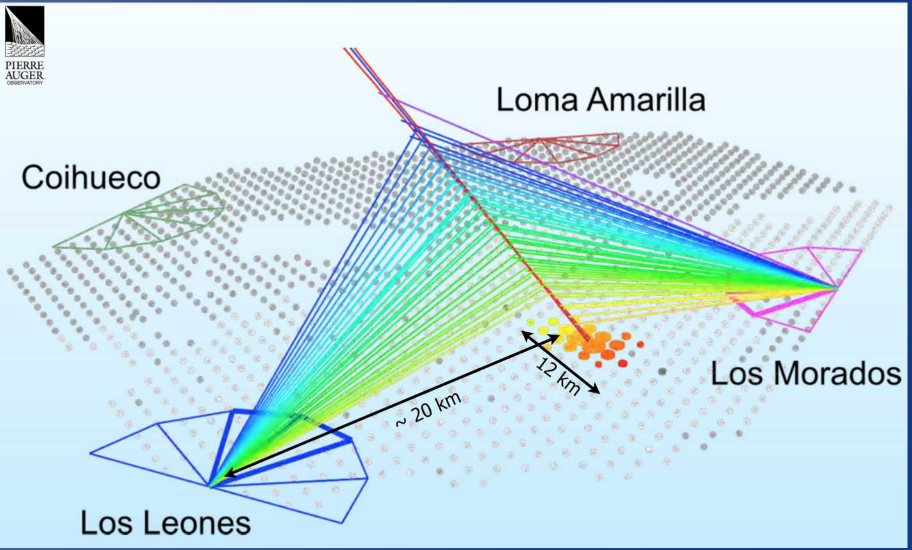
Tribute to John Learned's 85^{th} birthday

Workshop on Ghost Particle Hunting:
Neutrino Physics and its Applications to World Peace

UH Manoa, April 30 2025

Pierre Auger Observatory

Malargüe,Mendoza, Argentina (35°28′S,69°20′W)
1660 detectors,1.5 km spacing, *1.4-1.5 km asl*
Detection of Cherenkov light from $\mu^{\pm}$,$e^{\pm}$,γ
3000 km^2 effective area, 12 tons of H_2O per detector
100% duty cycle, angular resolution <1°
Threshold Energy (including the infilled areas): $10^{16.8}$ eV;
3 PMTs /SD detector unit

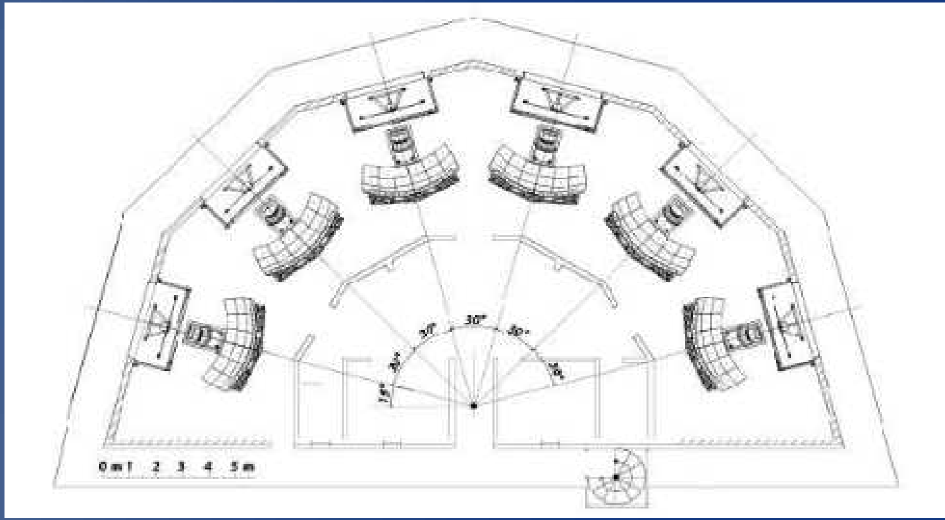


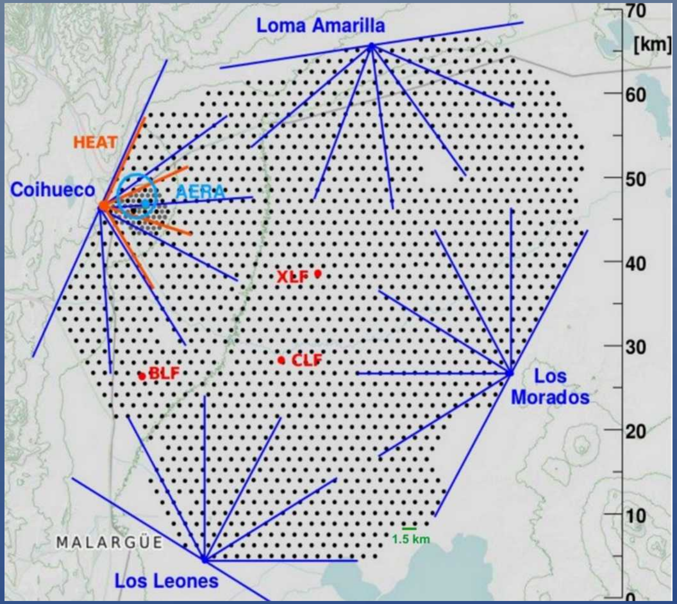
2004-2022: Phase 1 Data

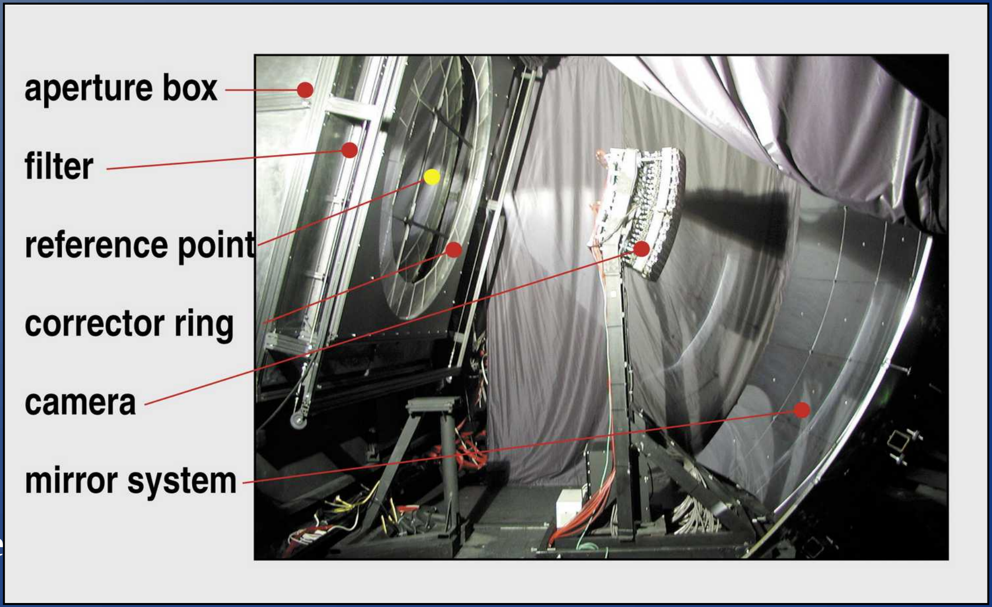
2023-2035: Phase 2 Data with Upgraded Observatory (AugerPrime)

Fluorescence Detector

24 telescopes in 4 eyes
FD camera: 440 PMTs / telescope
Mirror area: 11m² Field of View: 6x30°x30° for each FD
UV filter: 300-420 nm
Buffering 1000 time bins, 100 ns each: a 10 Mfps camera !
Duty cycle ~12% (1/2 moon cycle)
Angular resolution ~ 0.6°



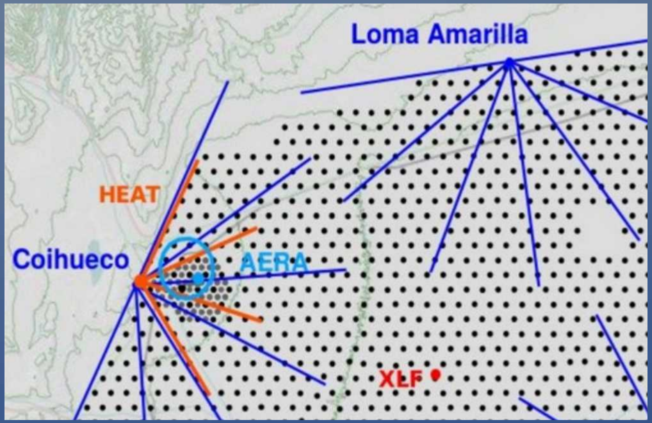


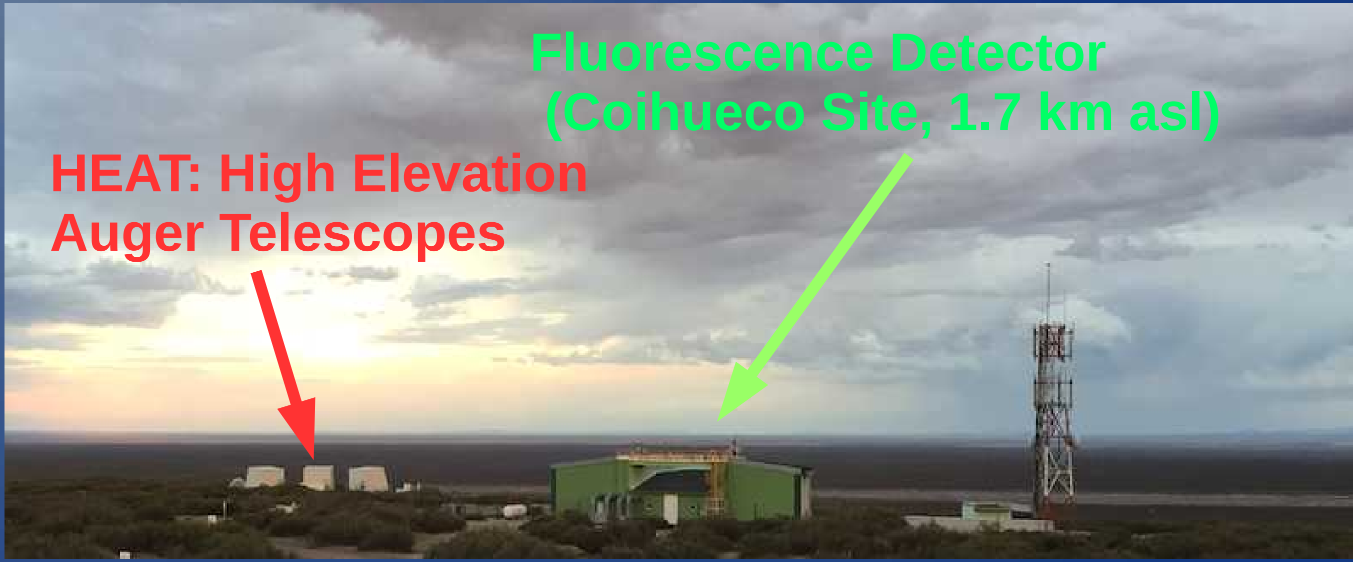


Fluorescence Detector - HEAT

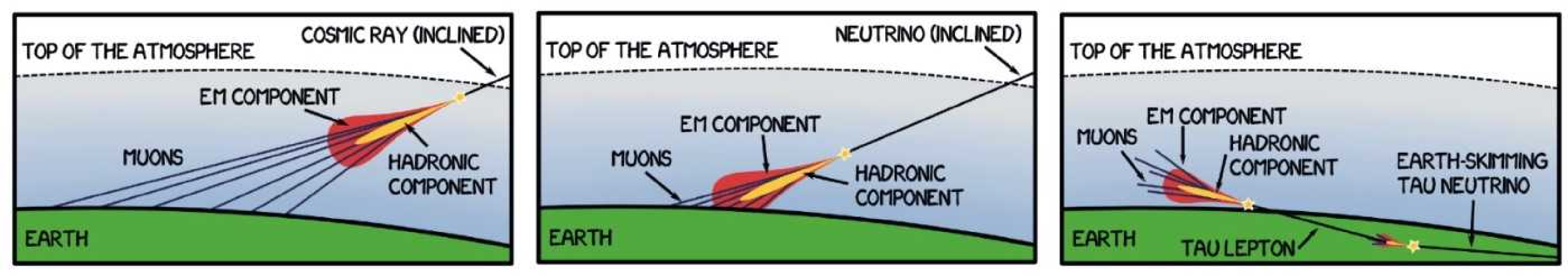
3 Fluorescence Detectors with :
- Elevation axis : 45°
- FoV = 30° – 60°
- Goal: detect low energy cosmic ray showers
- DAQ: 100 μs traces, 50 ns bins

Complementing the SD-750 array downhill





Nuclei vs neutrinos in Pierre Auger SD



- Inclined showers from protons & nuclei originate high up in the stratosphere
- At ground, the shower front is dominated by the muonic component
- Small relative time delay between muons and EM component

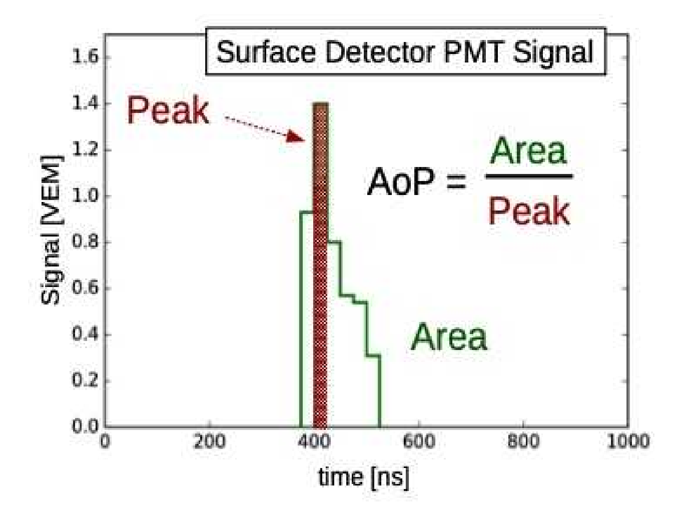
Inclined showers from neutrinos originate deep inside the Earth’s troposphere, either from nu-air interaction or from interaction with Earth surface layer (Earth skimming tau neutrinos)

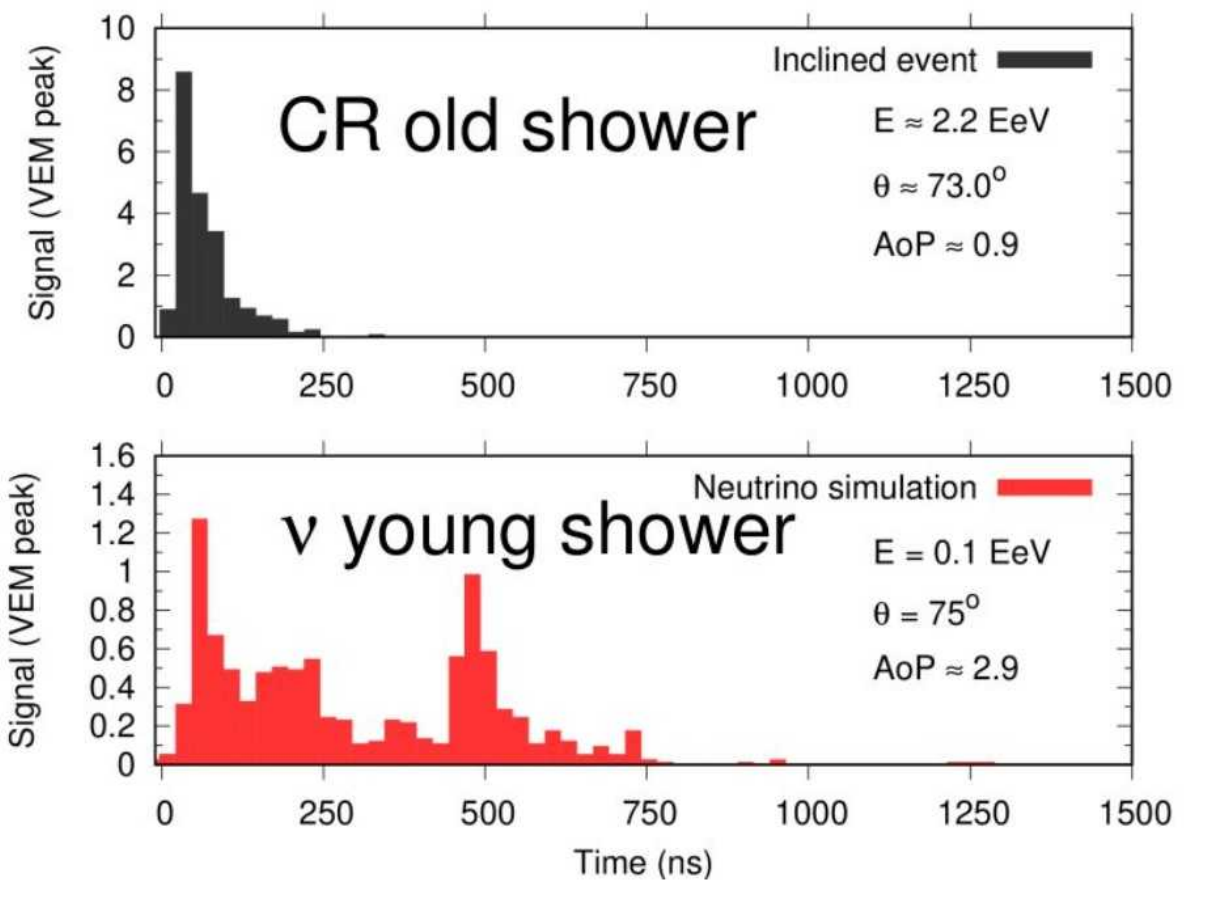
Large residual EM component at ground in the shower front

Large relative time delay between particles in the EM shower

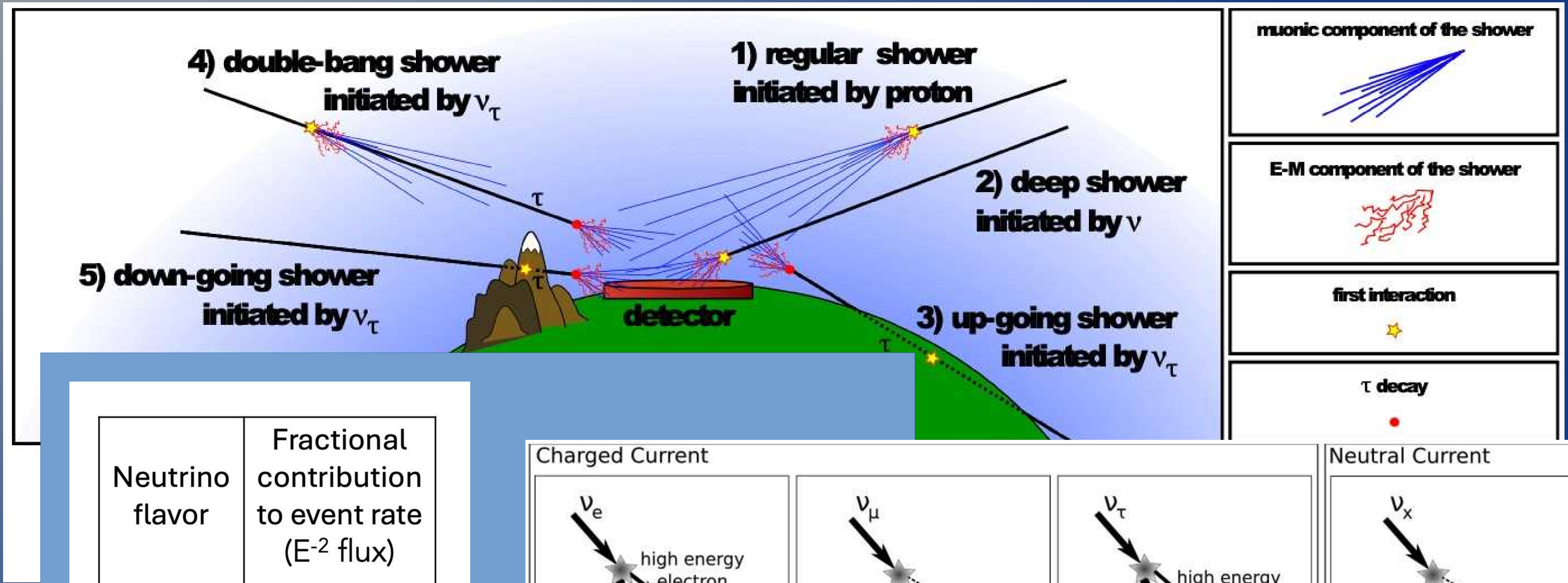
Neutrino candidate signature in AoP = Area over Peak

Ideal proxy for inclined young showers with high EM content

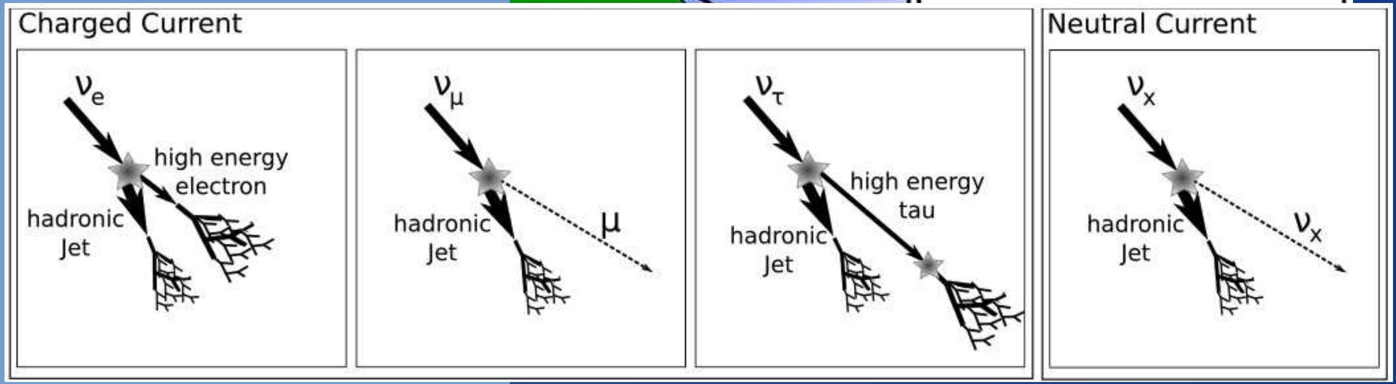




Sensitivity to different neutrino flavors

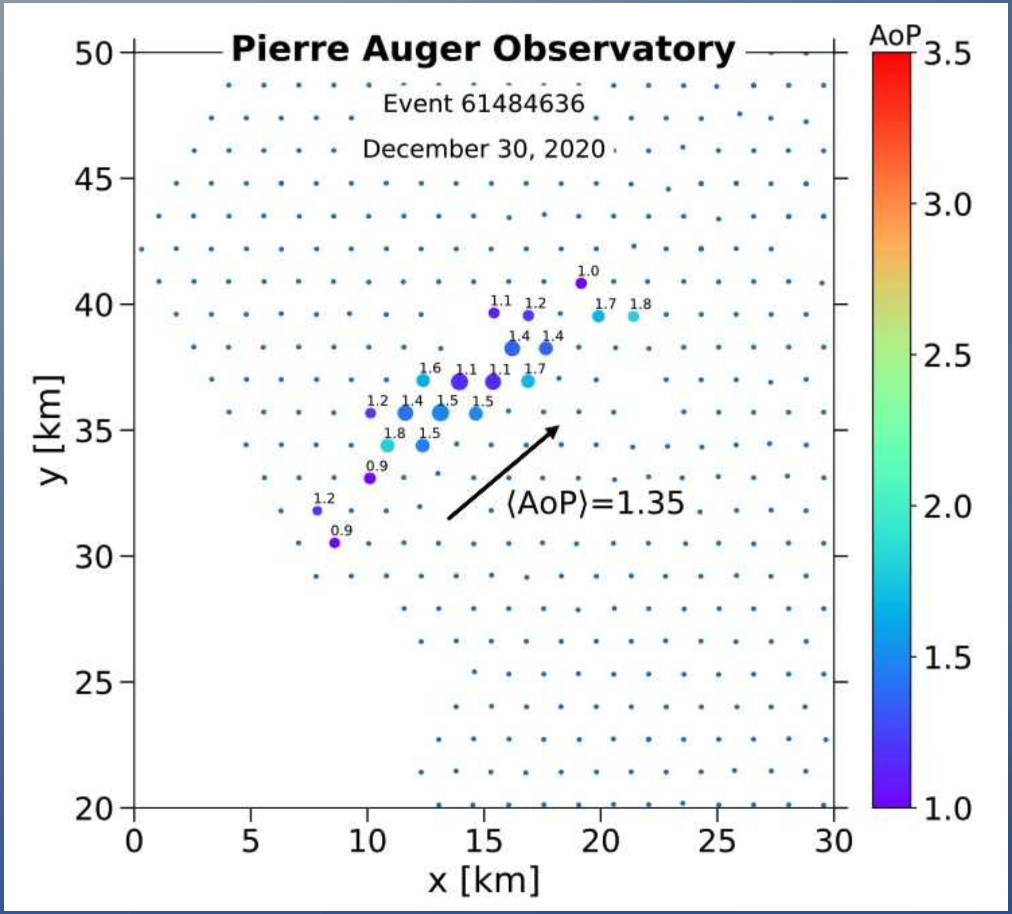


Neutrino flavor	Fractional contribution to event rate (E^{-2} flux)
ν_e	10 %
ν_μ	4 %
ν_τ	86 %

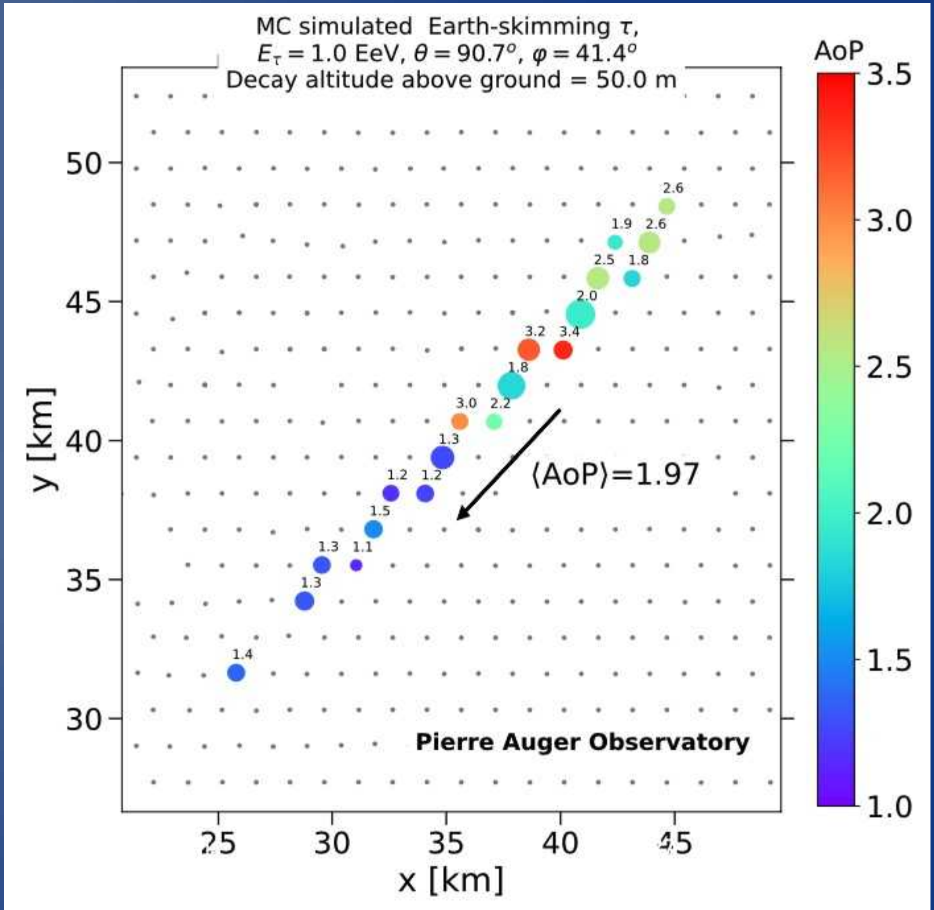


Phys.Rev.D 91 (2015) 092008

AoP to discriminate neutrino showers in SD



Very inclined CR shower (data)



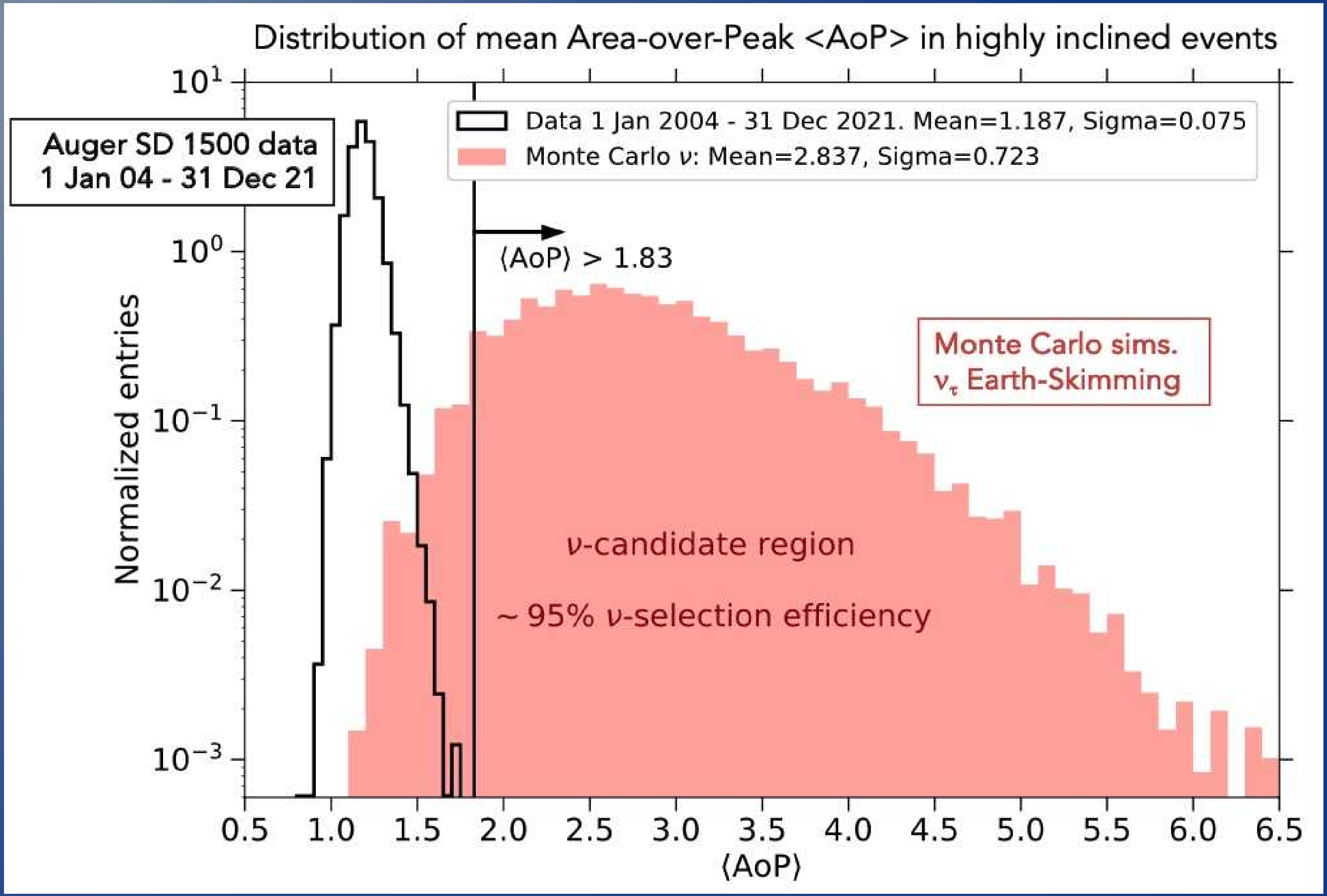
Simulated earth-skimming ν_τ shower

AoP cut optimization in SD 1500 data

Pierre Auger Coll., JCAP 10 (2019) 022
M. Niechciol for Auger PoS(ICRC2023)1488

<AoP> is optimized for all the different channels and energies

We expect <1 background event in 50 years



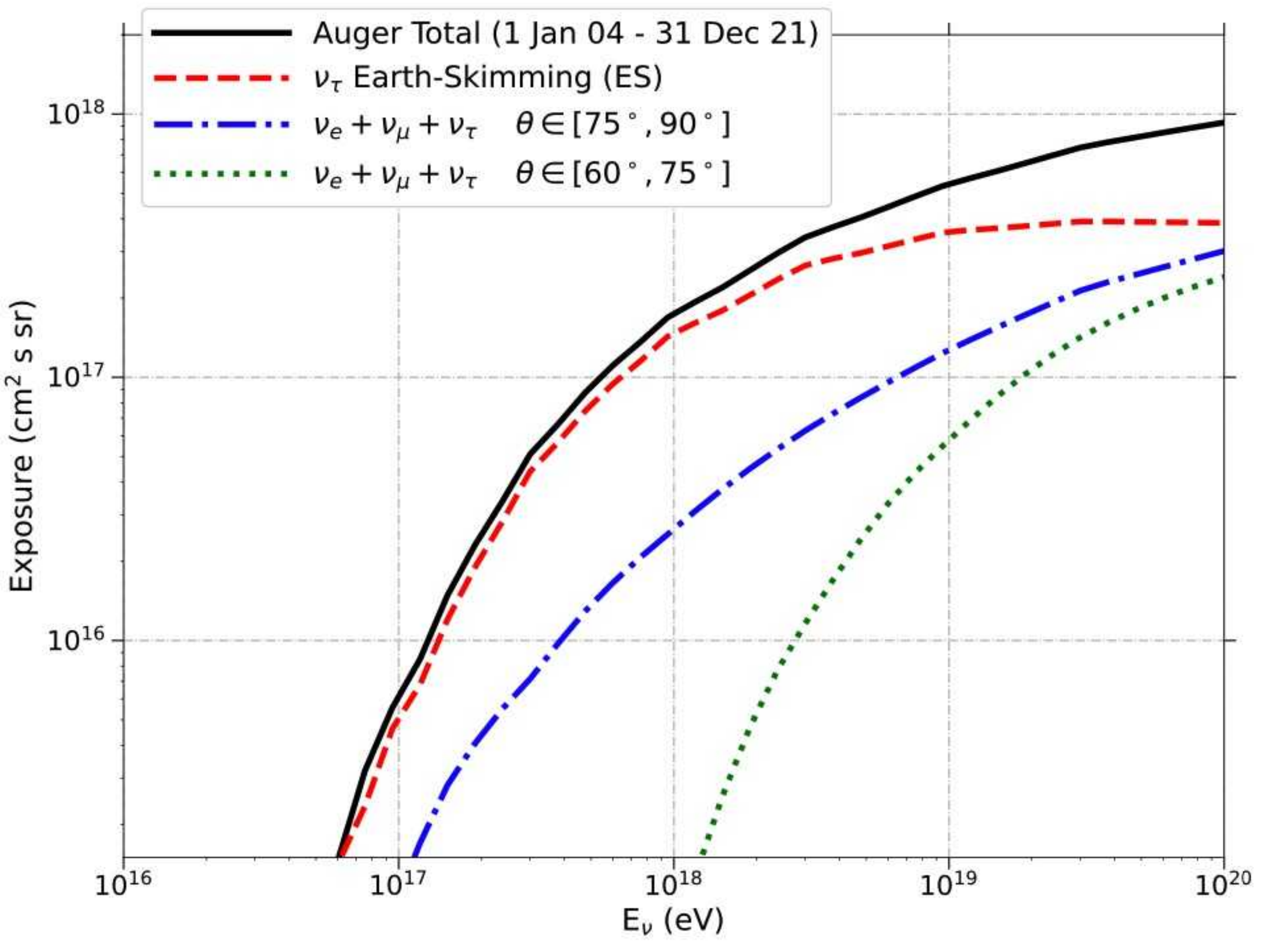
Auger SD Exposure (1/1/2004-31/12/2021)

Neutrino samples divided in 3 subsets:

- Earth skimming (90º,95º)

- Downgoing high-angle (DGH)

- Downgoing low angle (DGL)



Earth skimming dominate at lower energies

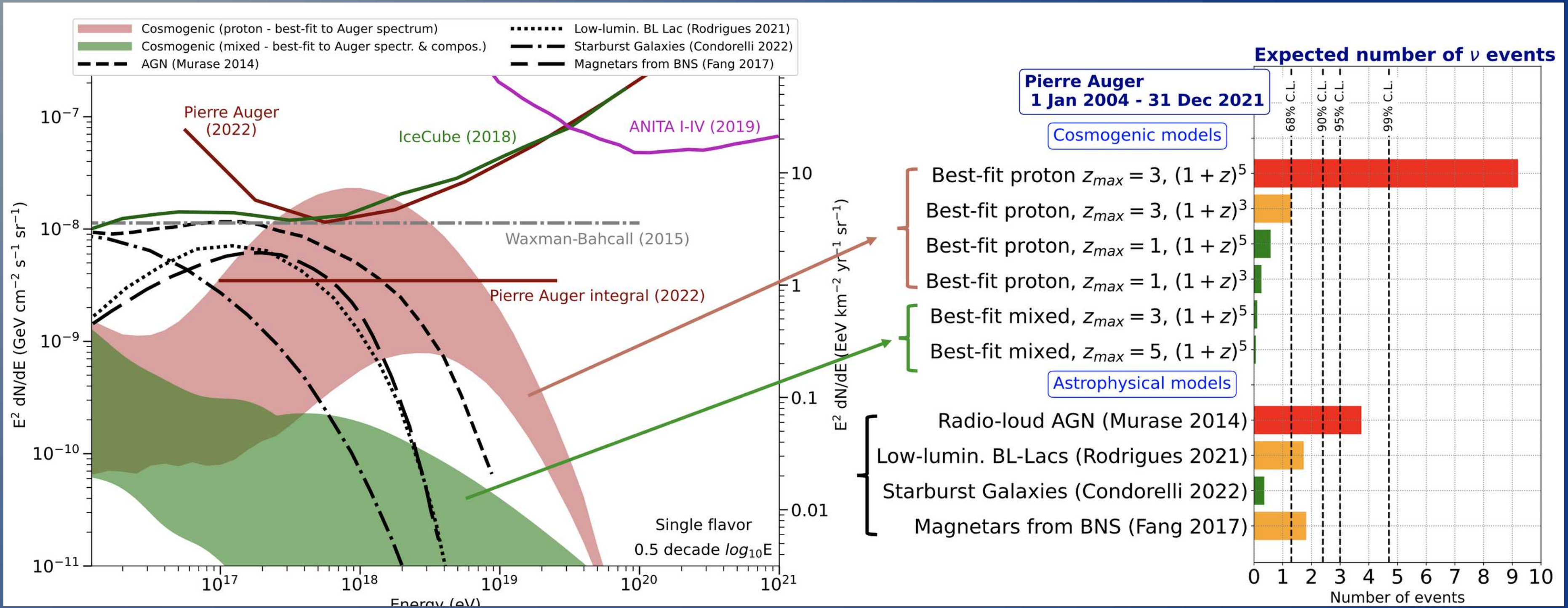
DG channels become relevant for UHEν

Pierre Auger Coll., JCAP 10 (2019) 022
M. Niechciol for Auger PoS(ICRC2023)1488

April 30,2025

Diffuse Flux Limits

Pierre Auger Coll., JCAP 10 (2019) 022
Update:
M. Niechciol for Auger PoS(ICRC2023)1488

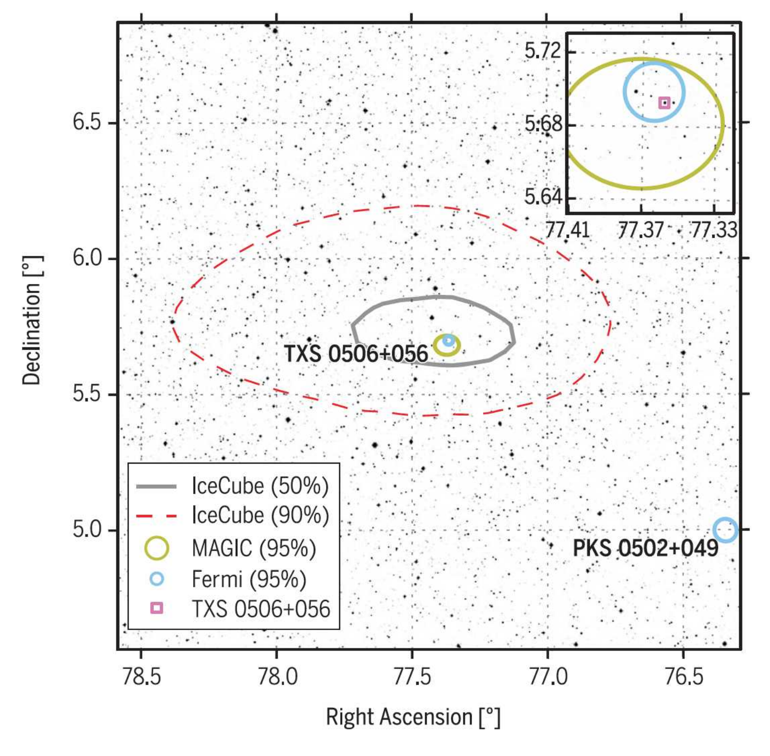


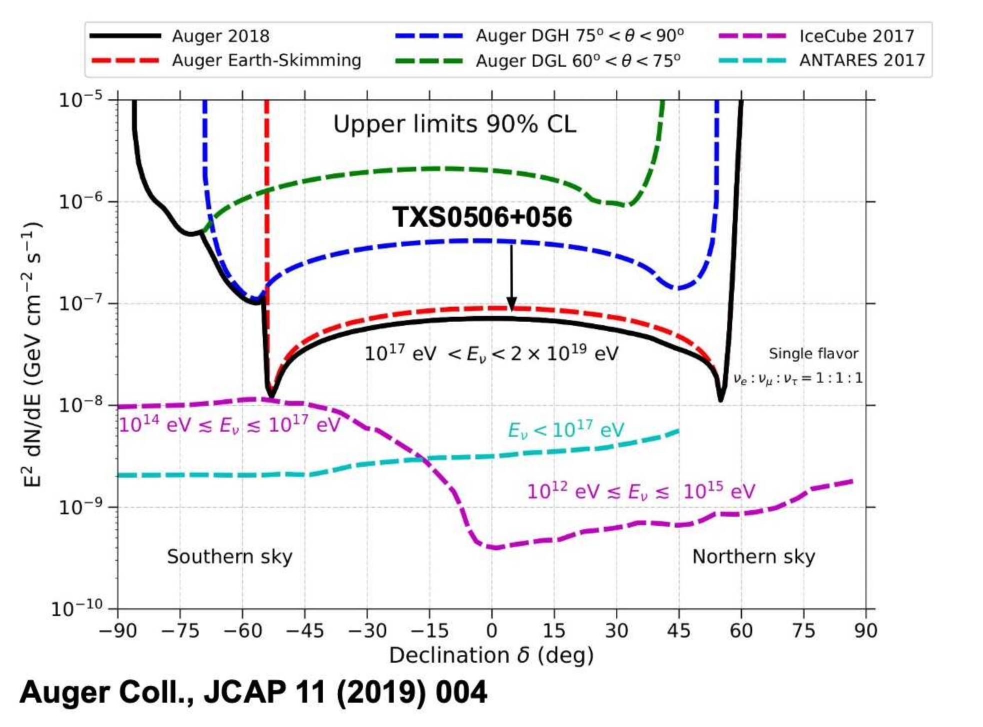
We found NO candidates

Maximum sensitivity at 1 EeV, where Auger limits constrain models assuming pure protons

UHE ν's from Point-like sources: TXS0506+056

2017/09/22: Rebirth of MM neutrino astronomy (after SN1987A)





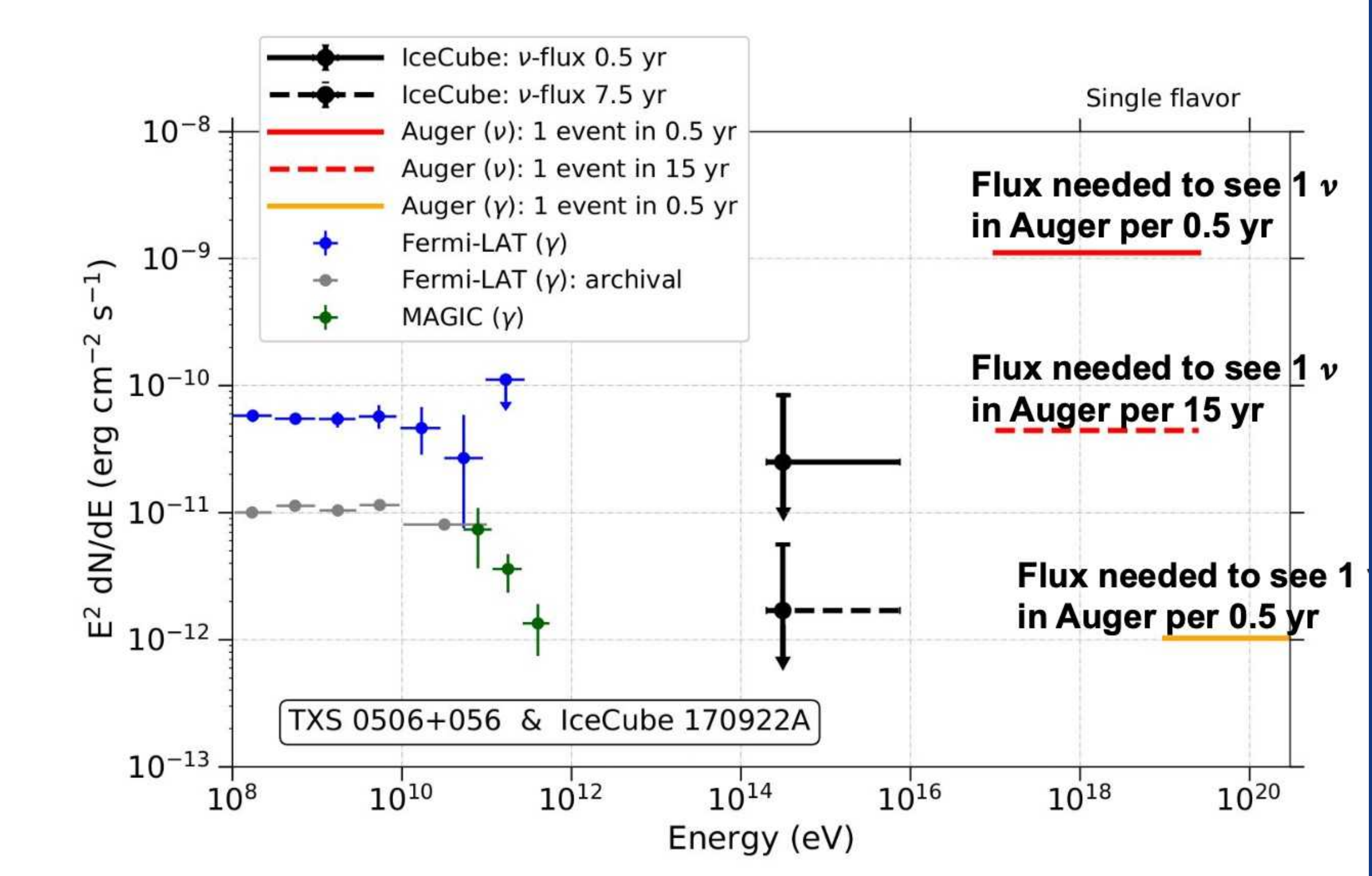
Auger sensitivity changes with source location and transient timing

TXS 0506+056 declination not ideal

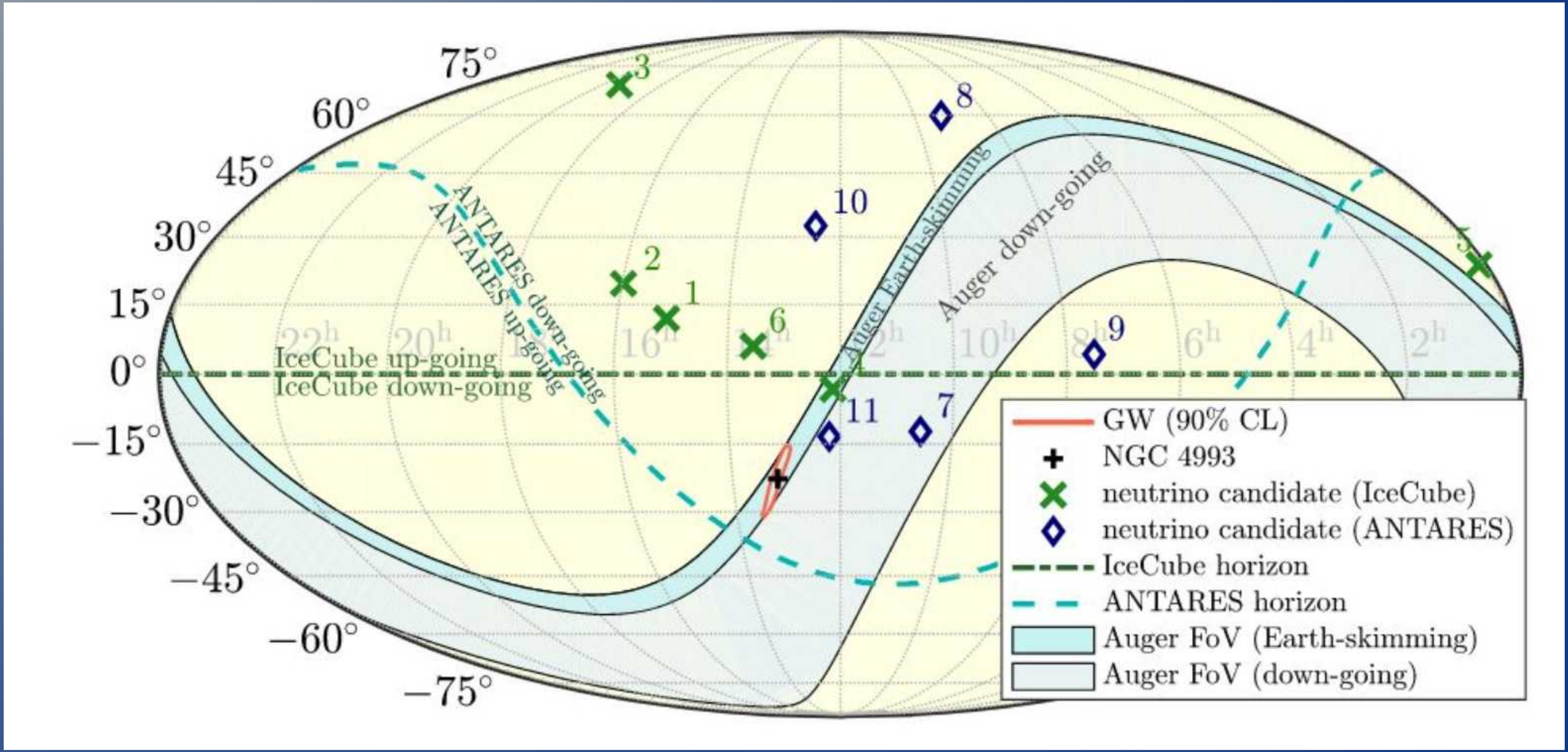
UHE ν's from Point-like sources: TXS0506+056

The source was not in Auger field of view at the time of the neutrino detection

The reference flux assumes 1 event detected in either 0.5 or 15 years



UHE ν's from Point-like sources: GW170817



UHE ν's from Point-like sources: GW170817

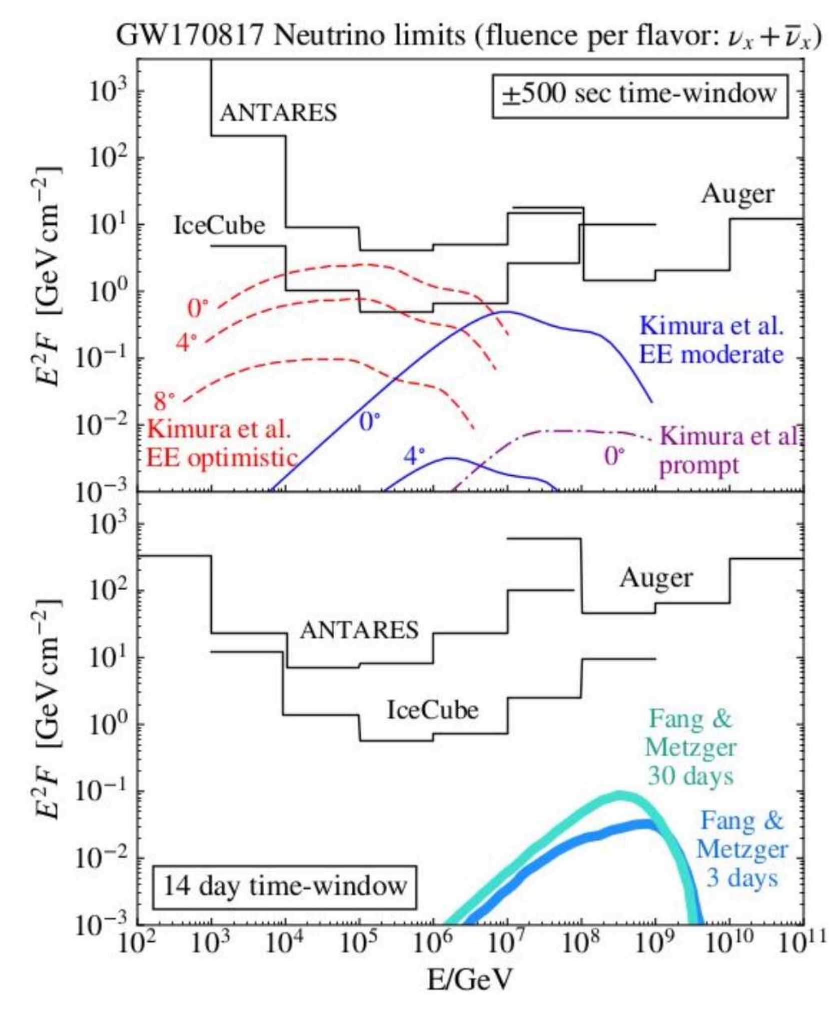
The source was in the earth-skimming ν field of view

No candidate was found either in the short (within ±500 s) or in the long (within ±14 d) time window.

The non-observation is anyway consistent with emission from a short GRB viewed at an off-axis angle greater than 20º.

Auger sets unique upper limits on the total energy transported by UHE ν ($0.1 < E_\nu < 25$ EeV) from NS mergers:

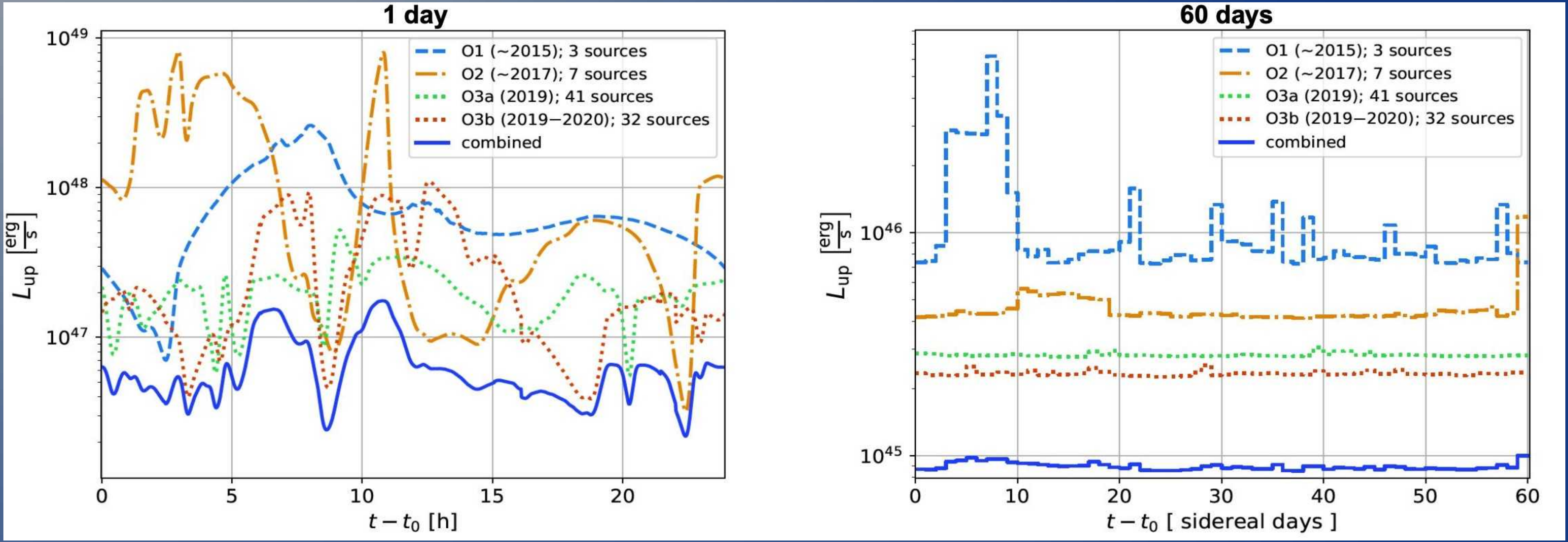
$E < 6.9\ 10^{-4}\ M_\odot$ (within ±500s)
$E < 2.3\ 10^{-2}\ M_\odot$ (within ±14 d)



Ligo-Virgo, Antares, IceCube, Auger, ApJL 850 (2017) L35

UHE ν's from stacked BBH mergers

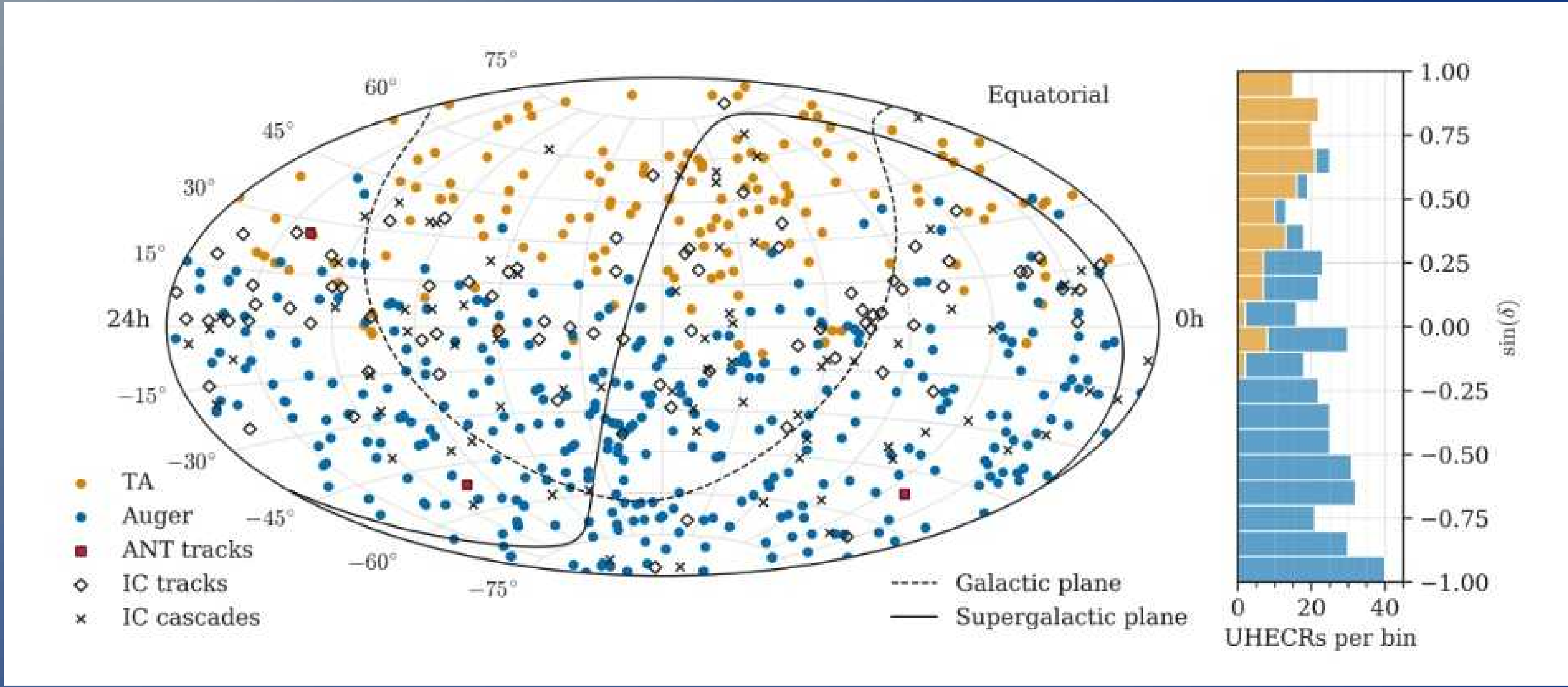
L.Perrone, EPJ Web of Conf 283, 04004(2023)



Auger searched for neutrino candidates after 93 BBH mergers: no candidates found.
Upper limits (90% CL) on E_{tot} emitted via UHEν in BBH mergers:
~ 5.2 10^{51} erg, corresponding to ~0.3% of the solar mass, <1% of the GW energy

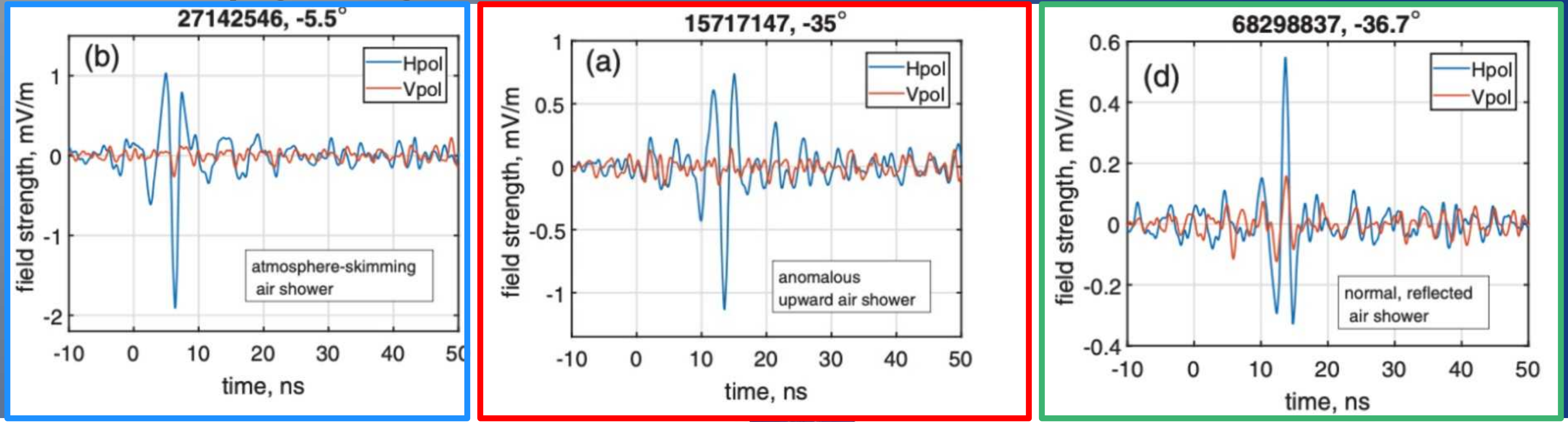
Correlations between UHECR and High Energy ν's ?

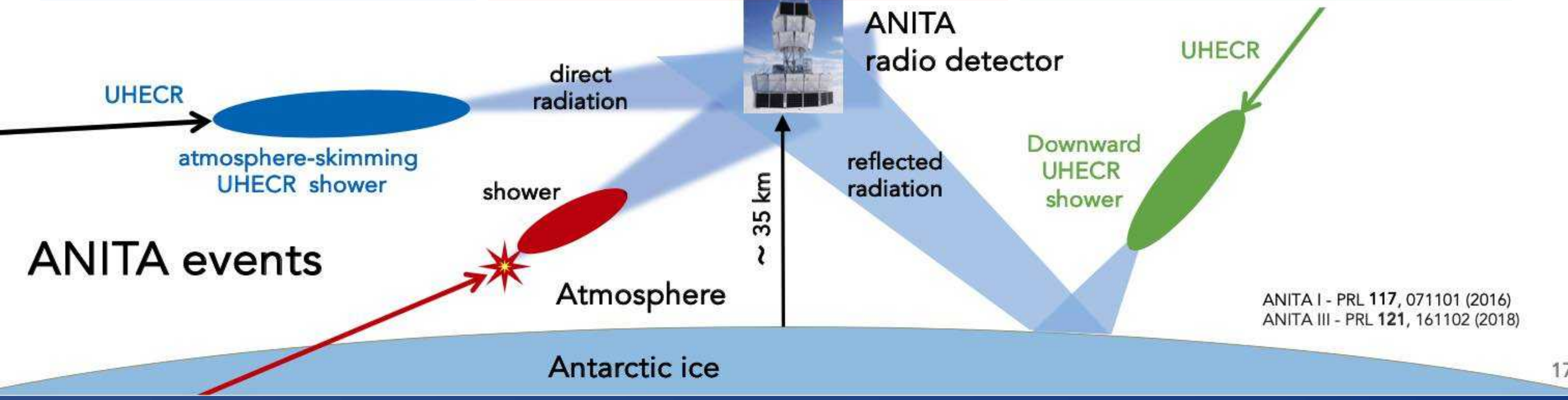
IceCube,ANTARES,Auger,TA, Astroph.J., 934(2022)164



Search for correlations between UHECR directions (> 50 EeV) from TA+Auger and Antares+IceCube tracks directions yield results consistent with isotropy.

ANITA upgoing neutrinos





ANITA I - PRL **117**, 071101 (2016)
ANITA III - PRL **121**, 161102 (2018)

ANITA anomalous events in Auger FD

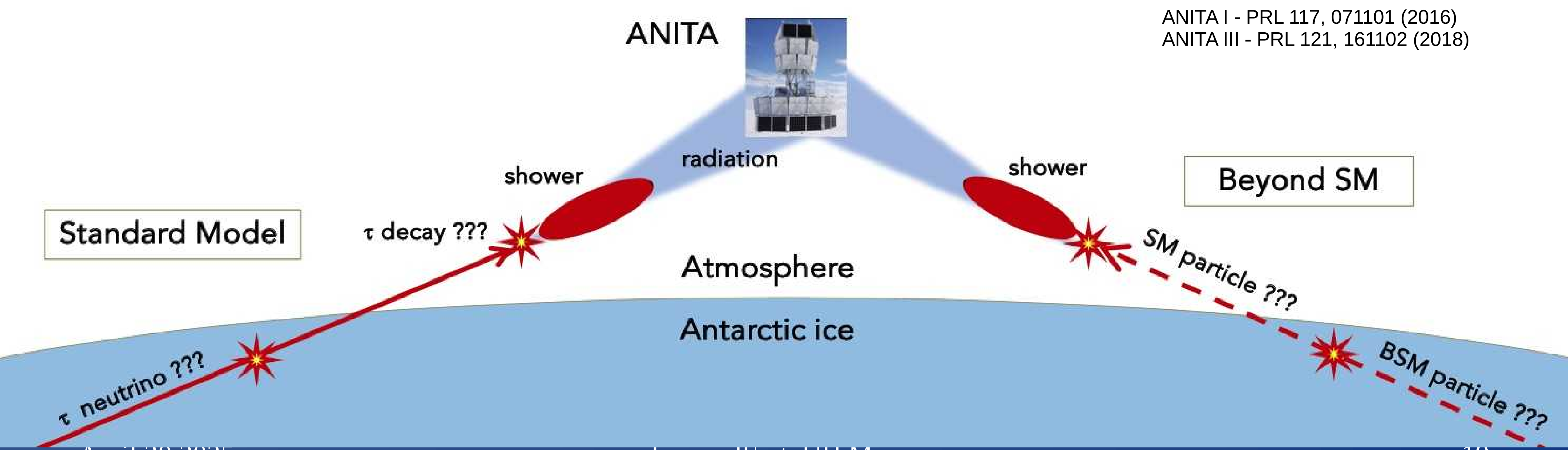
NEW:
Auger collab. - PRL 134 12,121003 (2025)

Standard model interpretations:
- Showers from τ neutrino interactions? NO
- Transition Radiation in ice/air interface? NO

Origin Beyond Standard Model (BSM):
- BSM particle producing a SM particle in ice???

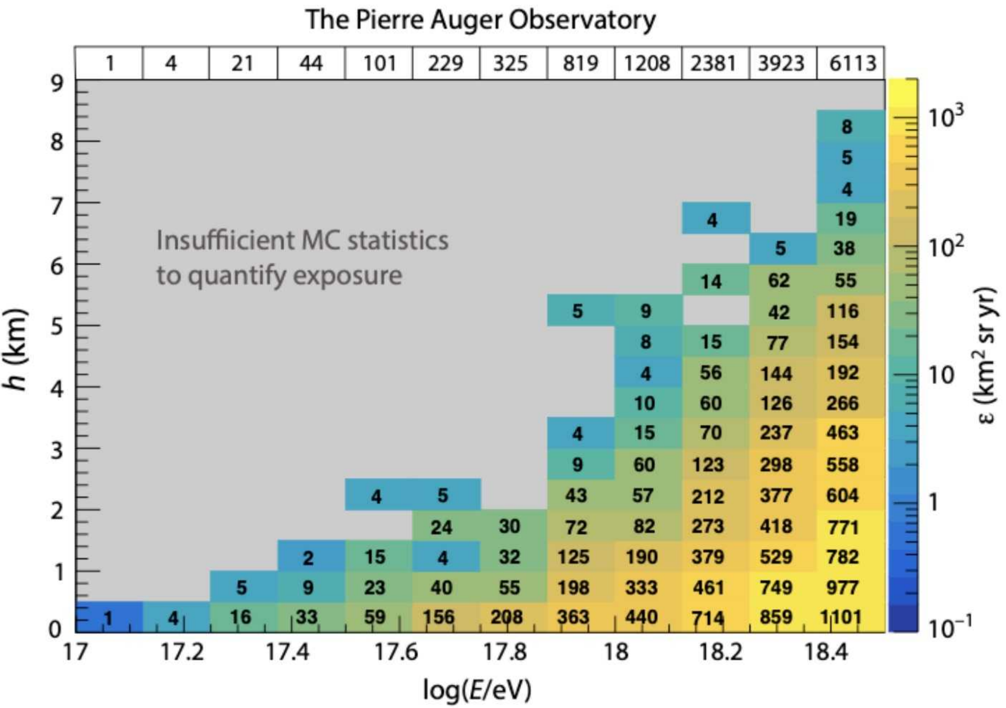
We searched for anomalous upward-going ν showers in FD data (1/1/2004-31/12/2018)

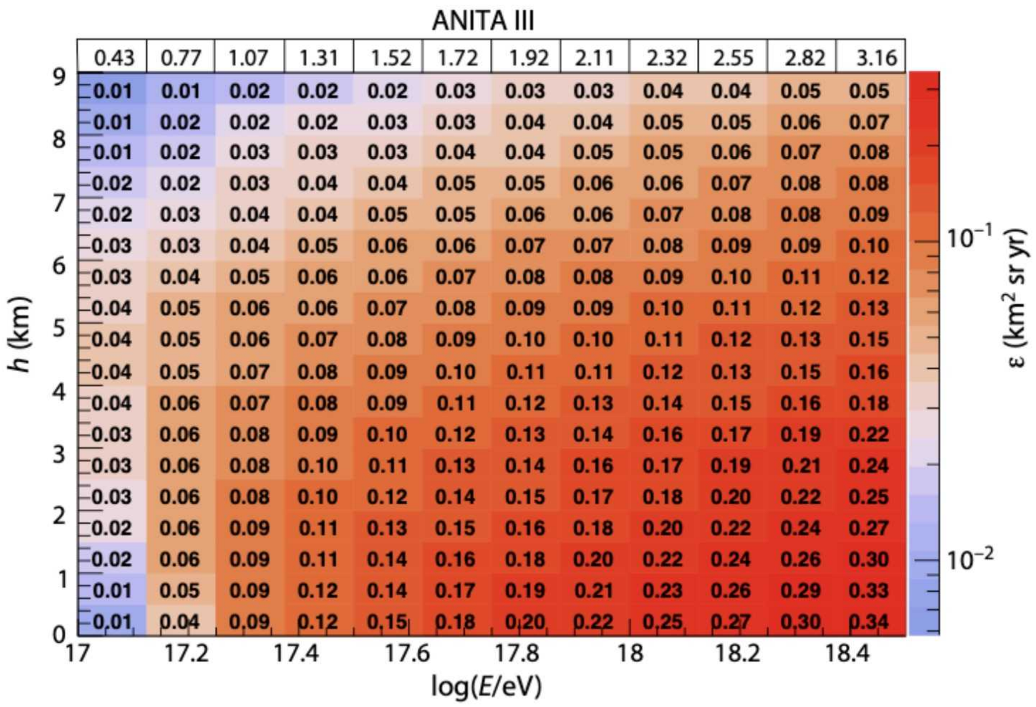
ANITA I - PRL 117, 071101 (2016)
ANITA III - PRL 121, 161102 (2018)



Auger vs ANITA Exposures

Auger collab. - PRL 134 12,121003 (2025)

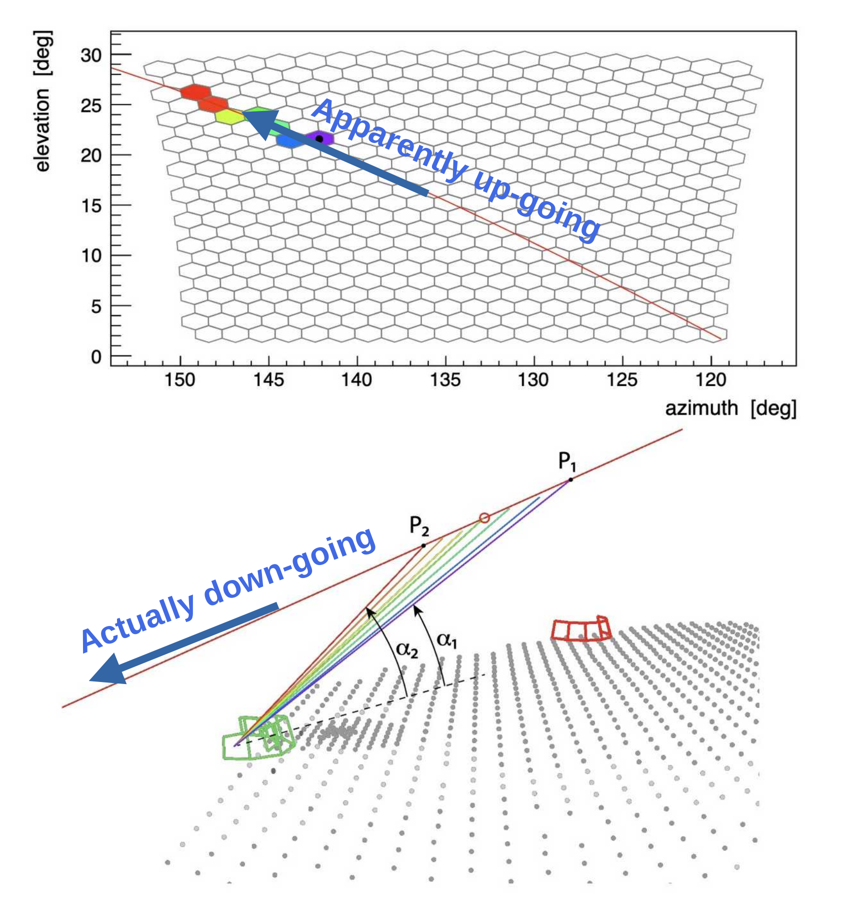




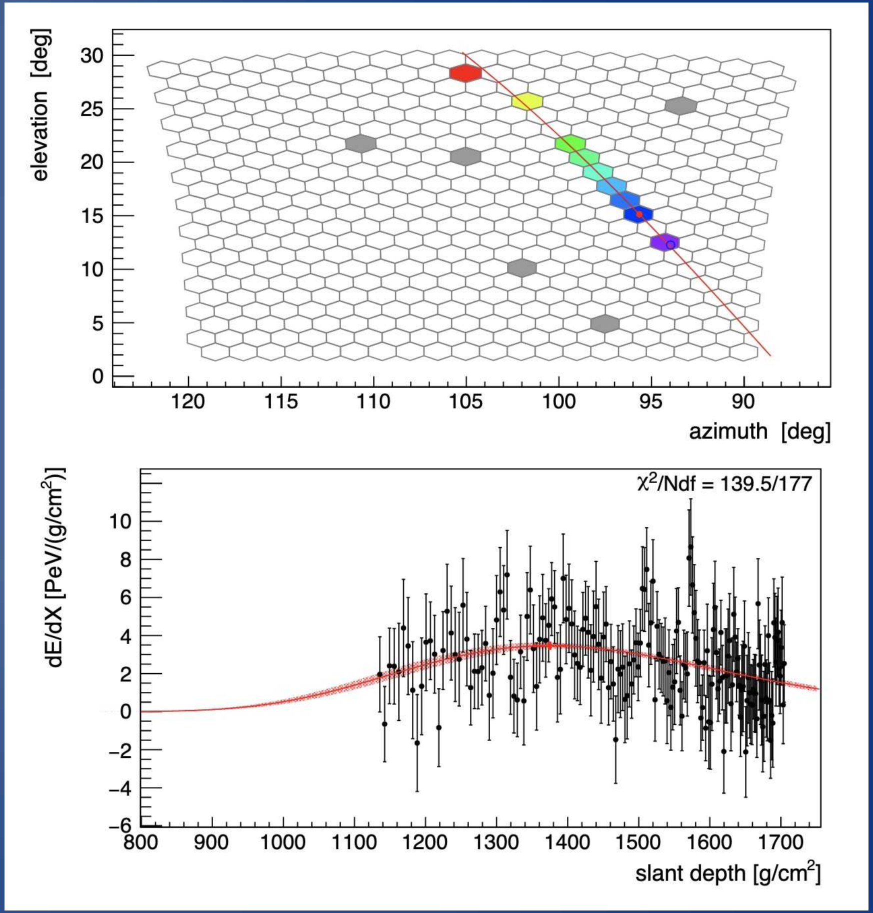
In the θ range [110°-130°] , the Auger FD exposure is 2 to 2k times larger than ANITA-III (I) exposure.
We expect to detect 8(69) events, assuming E^{-2} (E^{-5}) spectra in Auger .

Auger: up vs downgoing events

Auger collab. - PRL 134 12,121003 (2025)

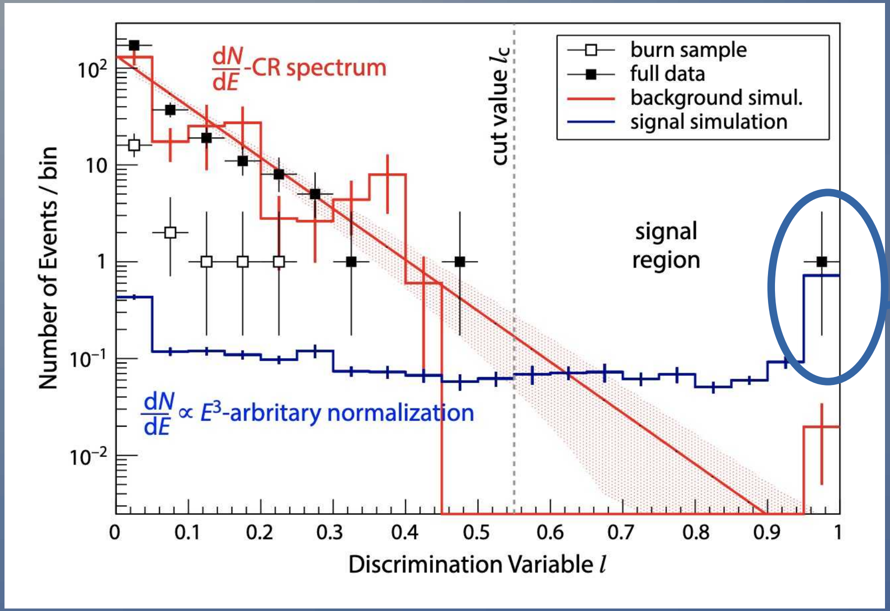


Real Event (potential background)

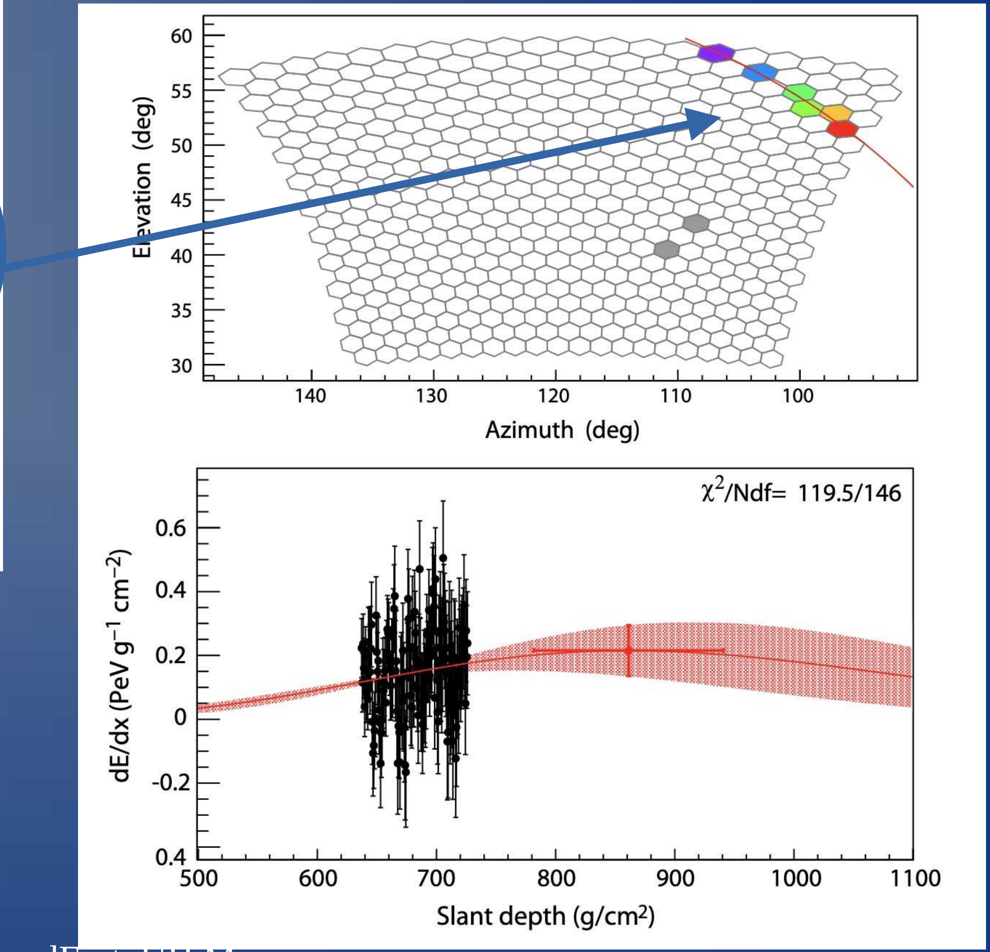


Simulated Event (θ_{MC}=89.6°,θ_{rec}=116.6°)

Auger result: one event observed



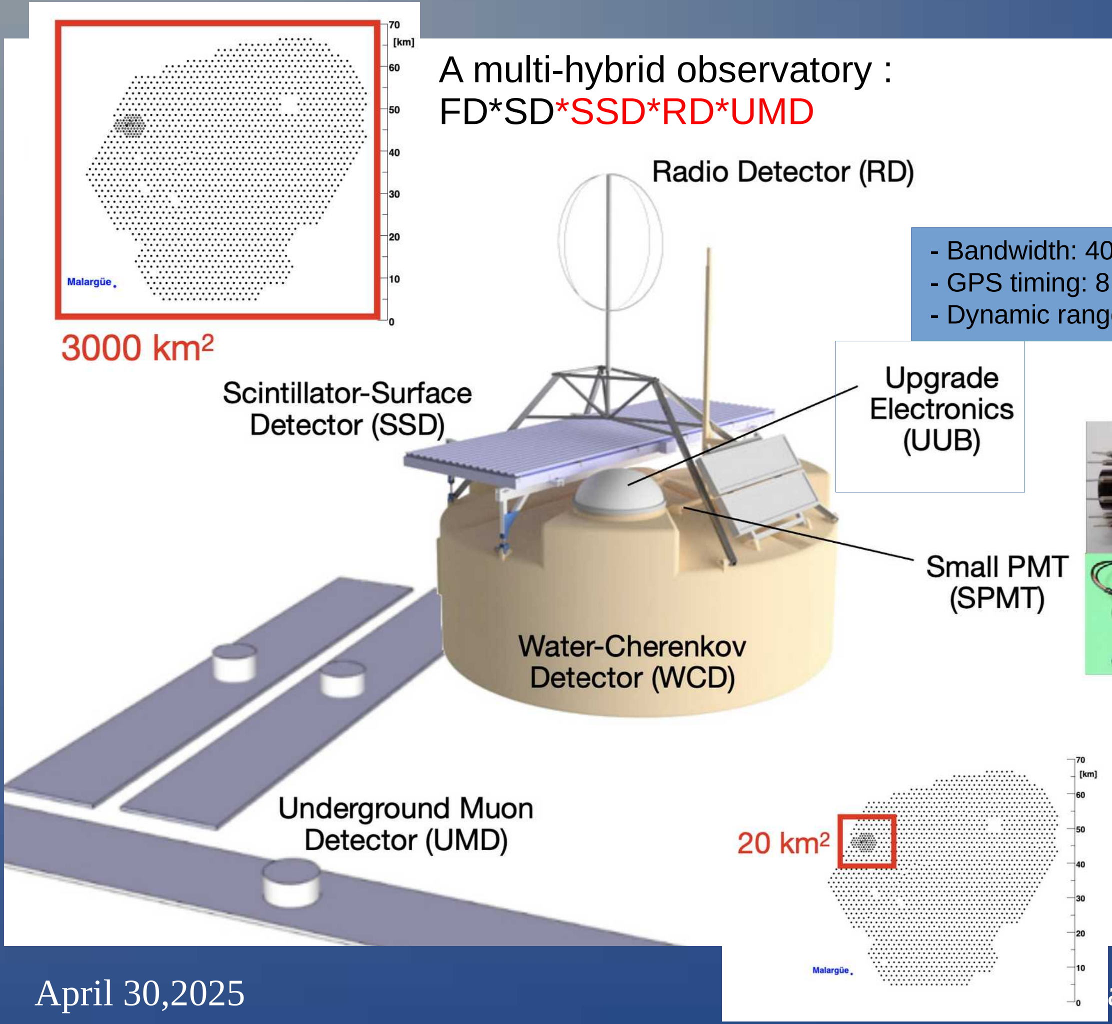
$$l = \frac{\arctan\{\ln[\max(L_{\mathrm{up}}, L_{\mathrm{down}})/L_{\mathrm{down}}] \times \zeta\}}{\pi/2}$$



Only one event survived our cuts.
Expected background: 0.27 ± 0.12 events
MC: CR showers reconstructed as up-going.

AugerPrime Upgrade: SSD, RD, UMD

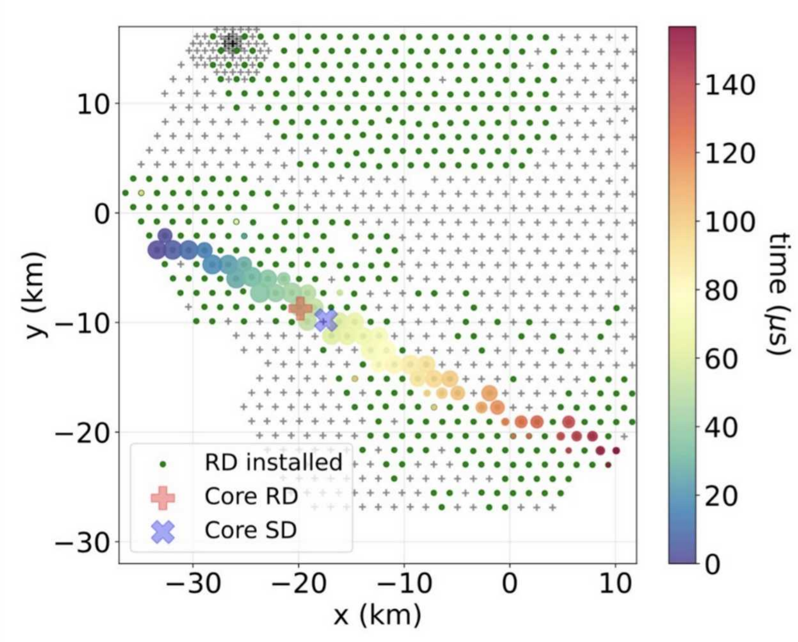
A multi-hybrid observatory :
FD*SD*SSD*RD*UMD

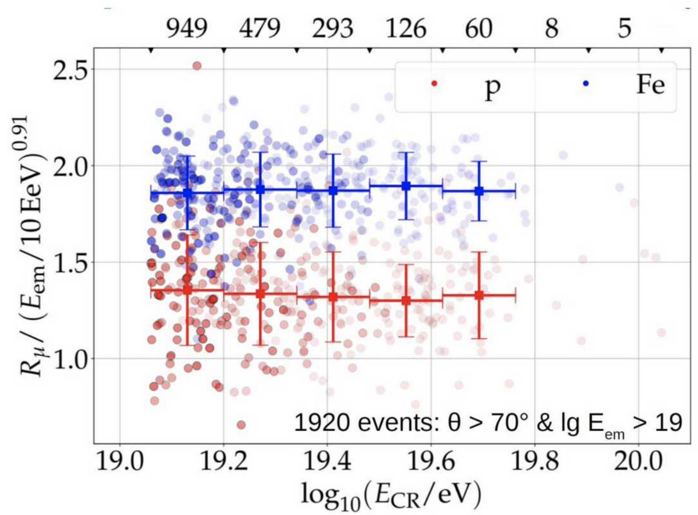


- Bandwidth: 40 → 120 MHz
- GPS timing: 8 → 5 ns
- Dynamic range: 10 → 12 bits

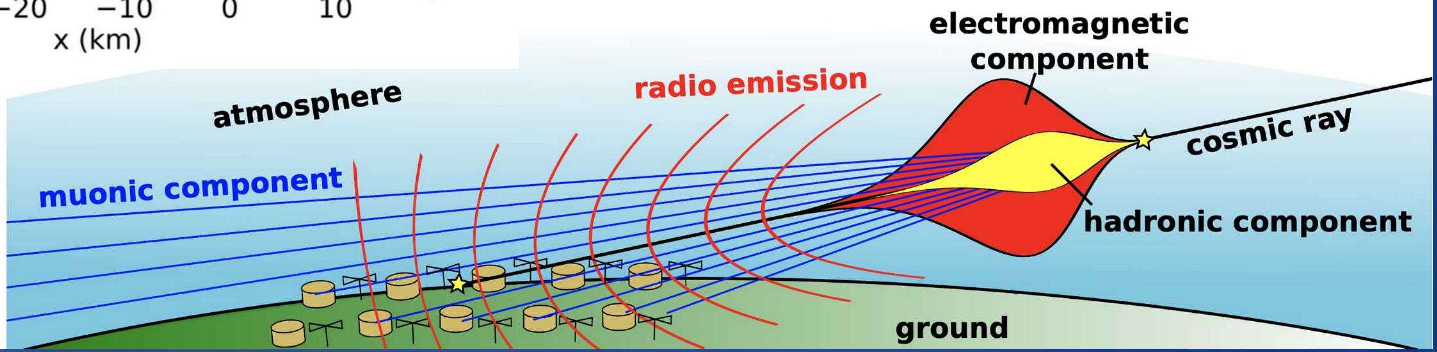
AugerPrime Upgrade: inclined events RD-SD

Real Event:
$E_{SD} \sim E_{RD}$=37 EeV
$\theta_{SD} \sim \theta_{RD}$=84.7º

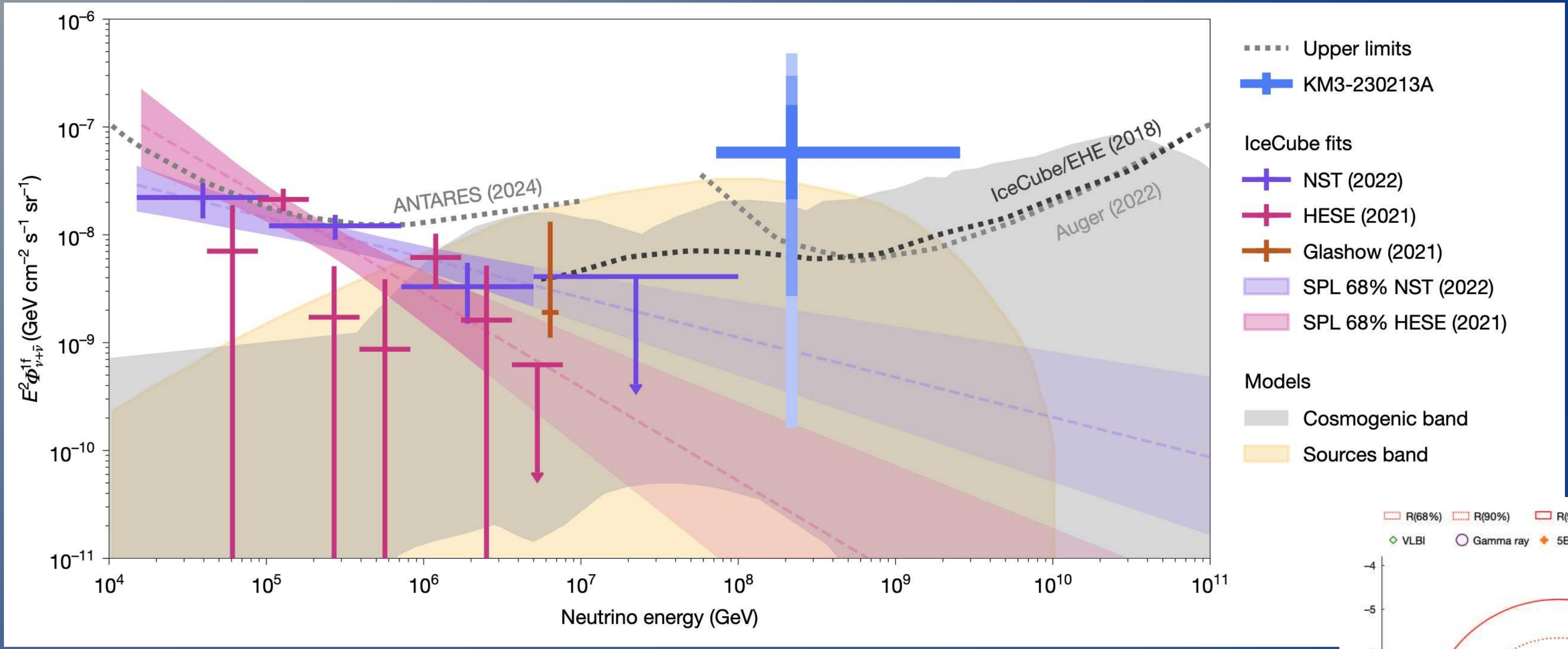


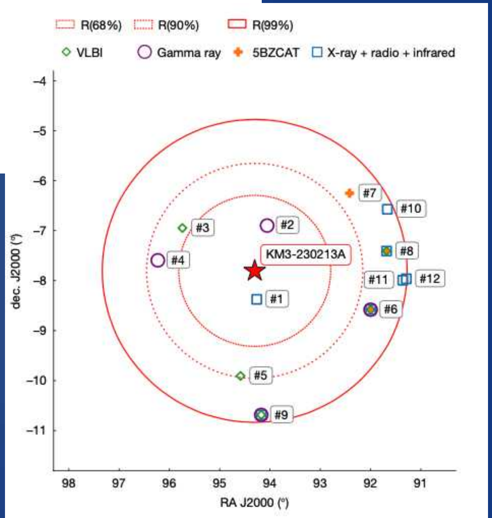


Prospects:
enhanced sensitivity to UHEν's with RD*SD:
- Fe-p discrimination
- INFILL allows access to lower energies



KM3NET event on Feb.13, 2023

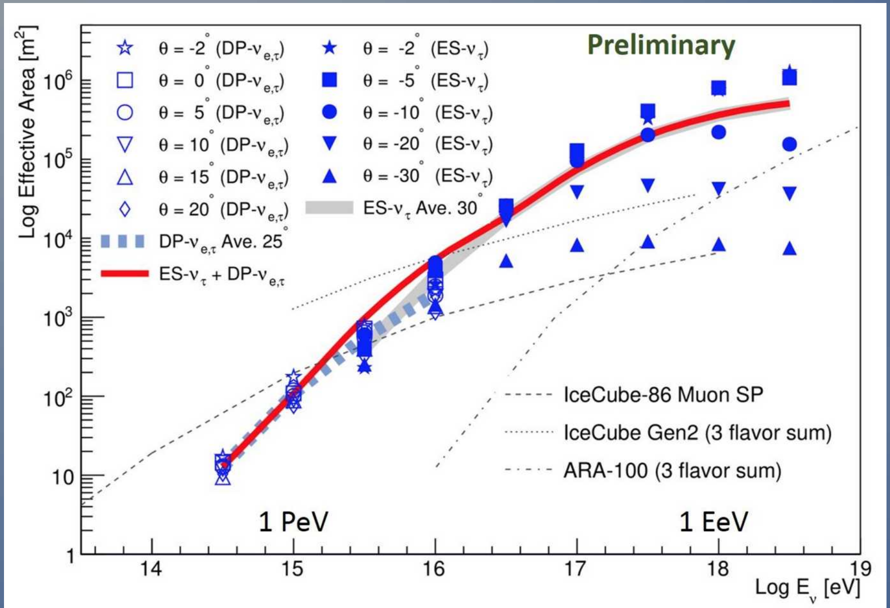


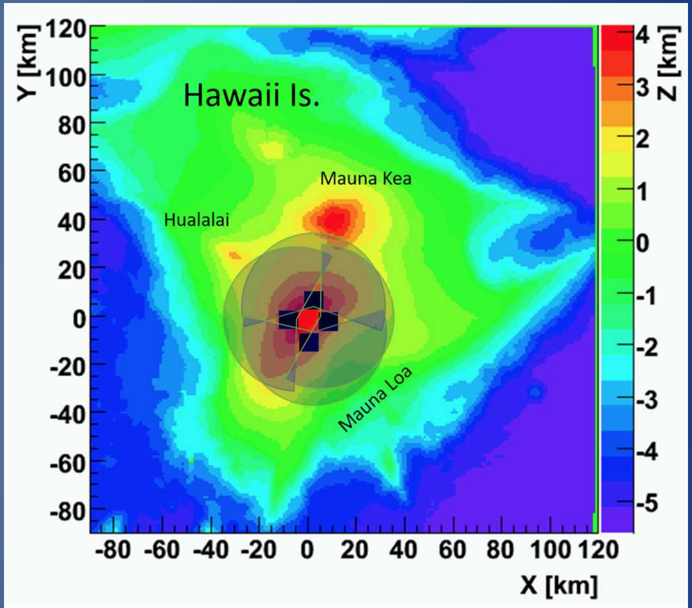


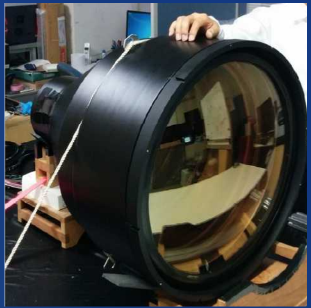
KM3NET, Nature 638(2025) 376

Can we improve Auger sensitivity at lower energies (50-500 PeV range)?

ASHRA -NTA: Neutrino Telescope Array





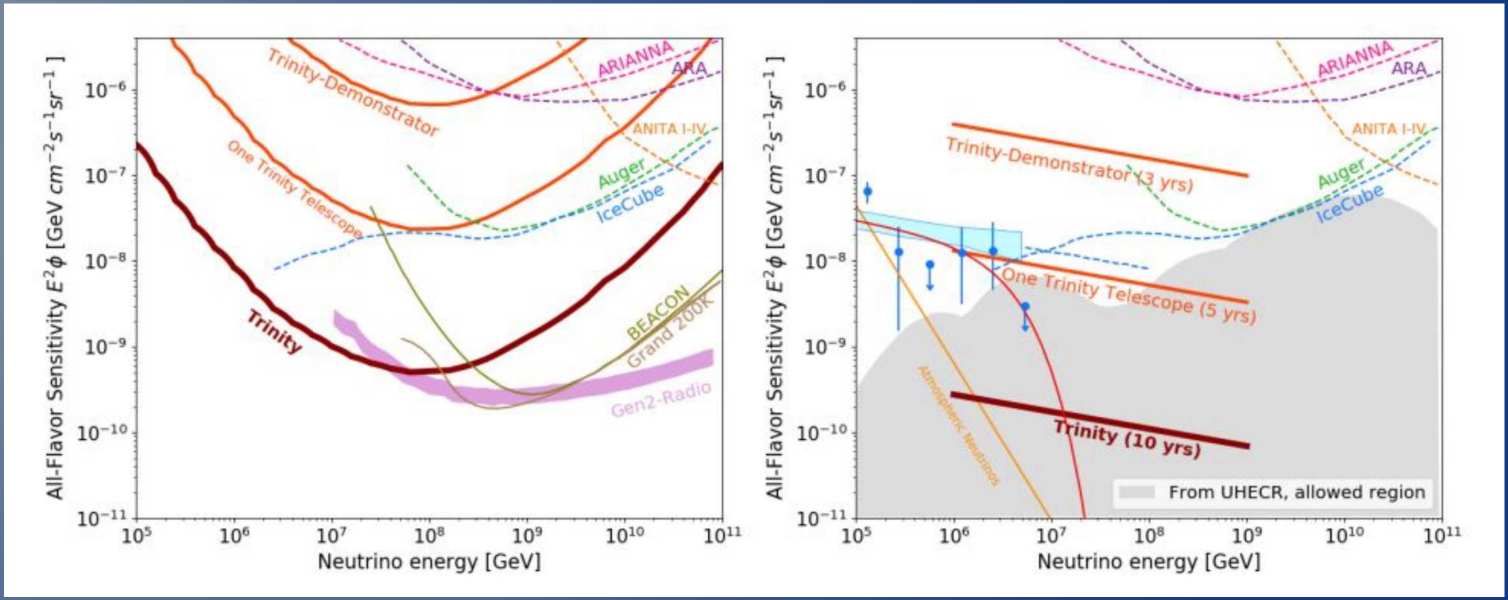


John on ASHRA site (~2005?)

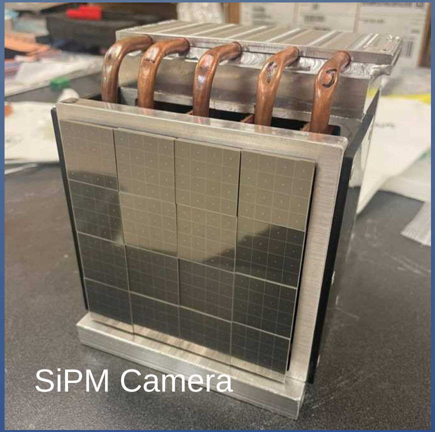
ASHRA site 2019

TRINITY


Demonstrator (Frisco Peak UT)



Otte Phys. Rev. D 99, 083012 (2019)

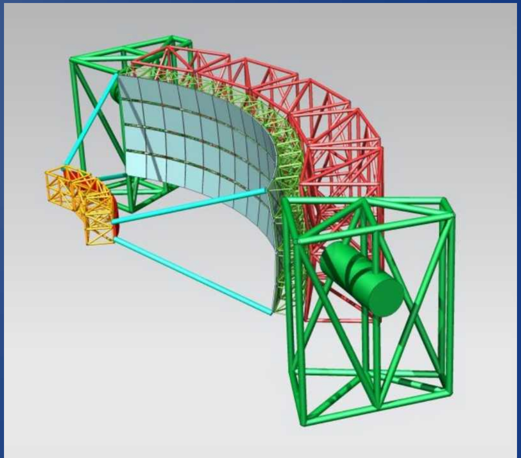

SiPM Camera

Demonstrator : A=1.5 m^2 at Frisco Peak UT

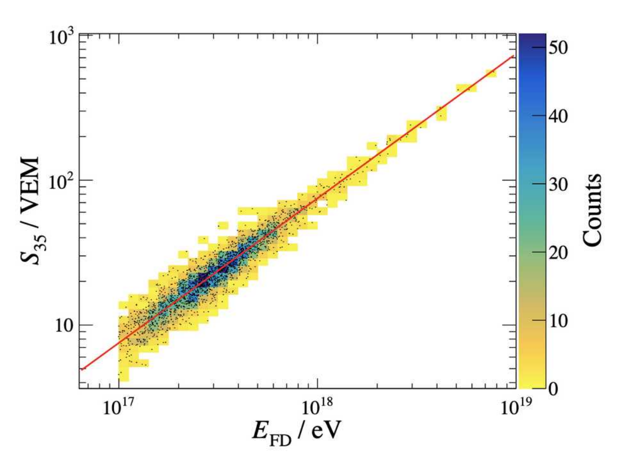
Telescope 5ºx60º , 68mirrorsx1m^2 , A=16 m^2
3300 SiPM pixes , 100MSamples/s

Trinity full fledge: O(10) Trinity Telescopes

More projects: Magic/CTA, Tambo ...

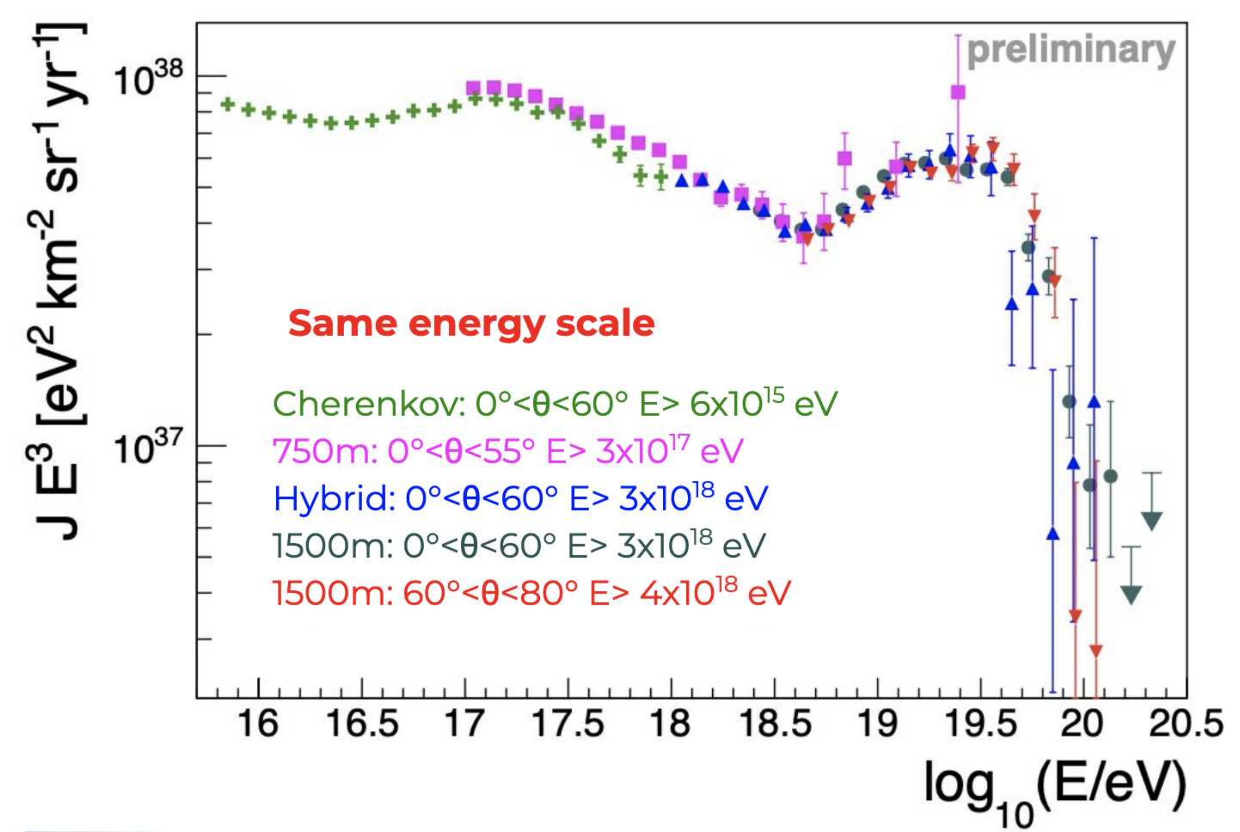


Auger : sensitivity down to ~100 PeV

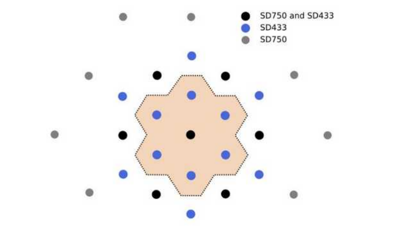


FD*SD750: Eur. Phys. J. C (2021) 81:966

F.Salamida, Volcano Workshop 2024

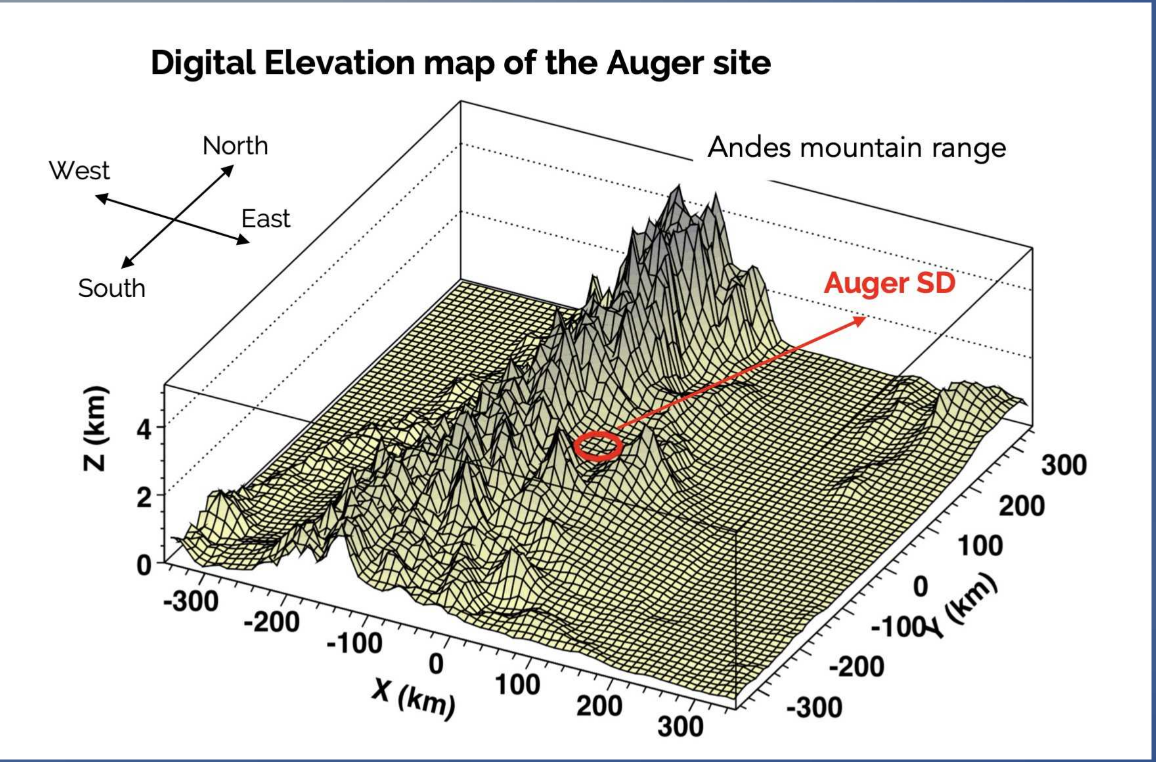


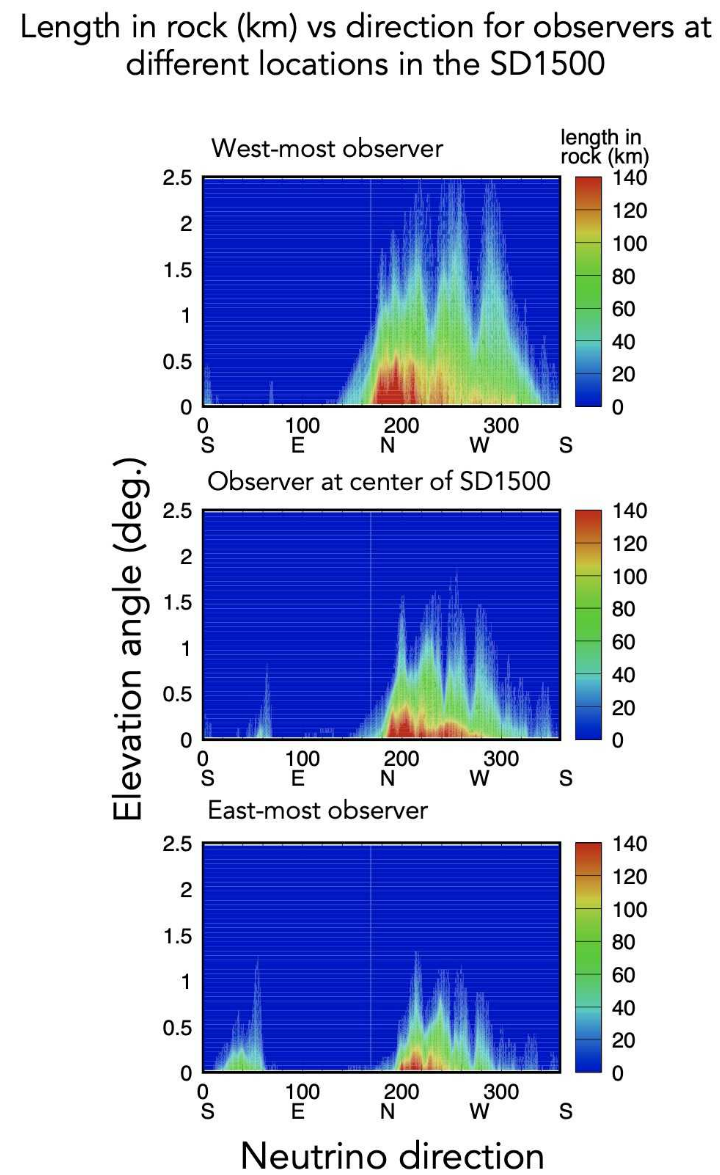
Robust observation of the 2nd knee at 230 PeV also with SD-433



Auger topography

J.Alvarez Muniz UHECR 2024





Work in progress:
- FD simulations to enhance our stereo/hybrid sensitivity down to lower energies
- Offline reprocessing of Phase I data
- Design of new triggers. Night sky background studies

STAY TUNED !

Hau'oli lā hānau, John !