Searches for UHE neutrinos and upward-going showers with the Pierre Auger Observatory

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for the Pierre Auger Collaboration

UHECR 2024 Symposium
Malargüe, Mendoza (Argentina) 17 – 21 Nov. 2024

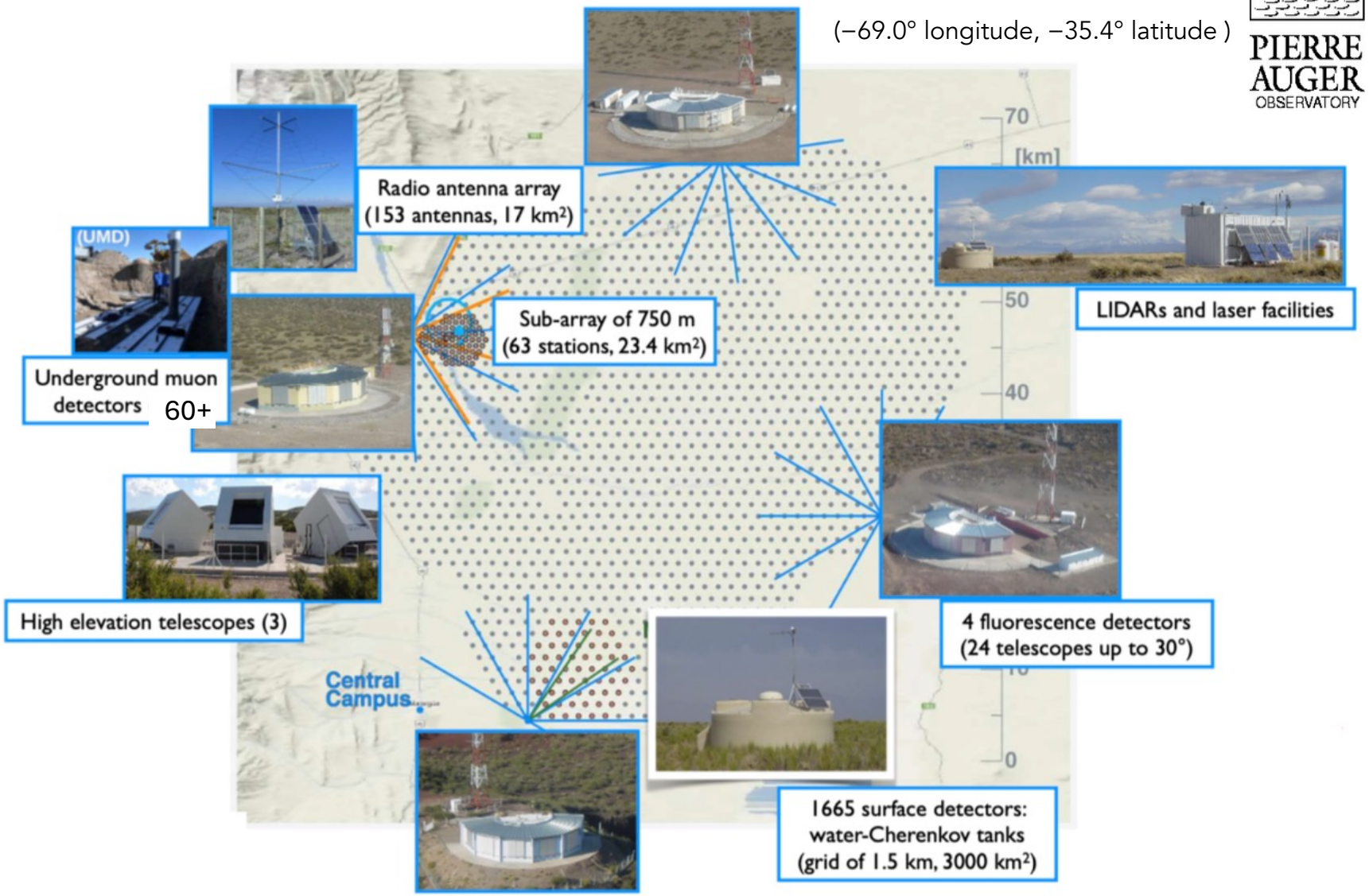
Cofinanciado pola Unión Europea
Fondos Europeos

The Pierre Auger Observatory

Phase I data taking configuration 2004 – 2021

Malargüe, Mendoza (Argentina)

(−69.0° longitude, −35.4° latitude)



This talk:

Search for UHE neutrinos

Data 2004 - 2021

Surface detector SD1500

1665 water-Cherenkov stations
1.5 km grid. Area 3000 km^2

Search for upward-going showers

Data 2004 - 2018

4 Fluorescence sites

24 telescopes, 1-30° FoV
3 High-Elevation, 30-60° FoV

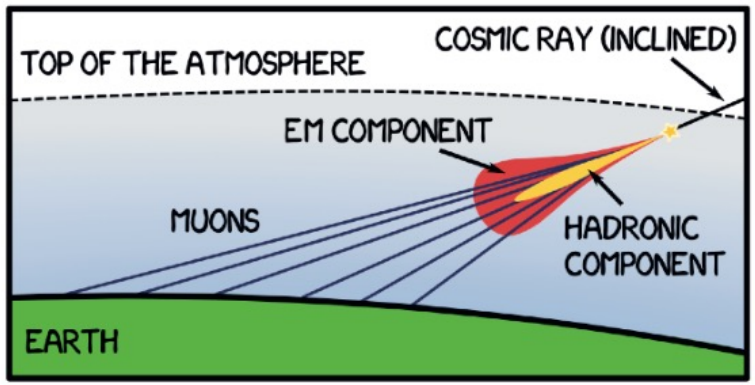
Pierre Auger,
NIMA **798** (2015) 172–213

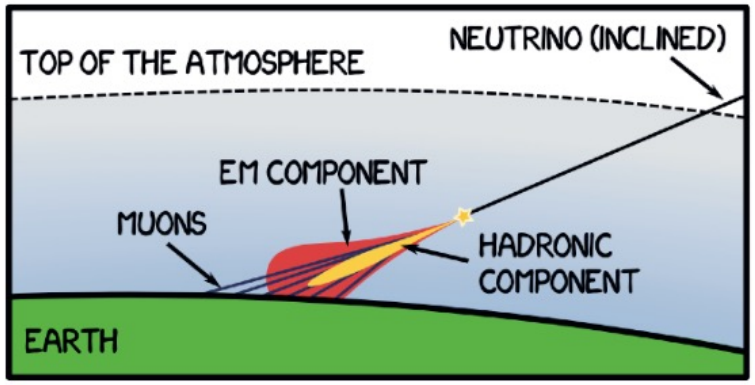
Search for UHE neutrinos

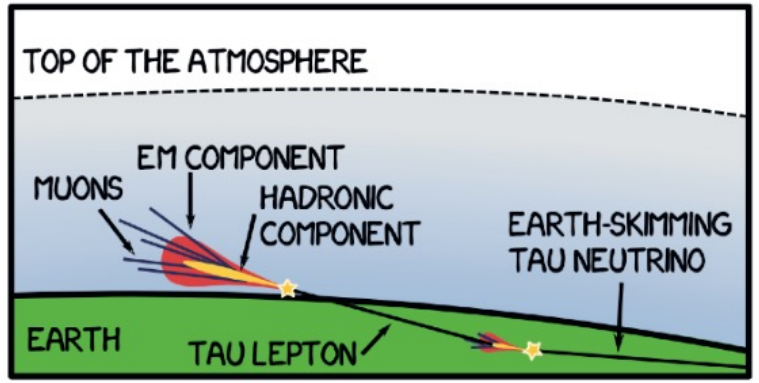
Search for neutrinos with the Pierre Auger Surface Detector

Pierre Auger
JCAP **10** (2019) 022

M. Niechciol
PoS (ICRC2023)







Protons & nuclei at high inclination angles initiate showers high in atmosphere

⇒ Shower front at ground mainly composed of **muons** (electromag. component absorbed in atmosphere)

⇒ Small relative time delays

Neutrinos can initiate inclined showers close to ground

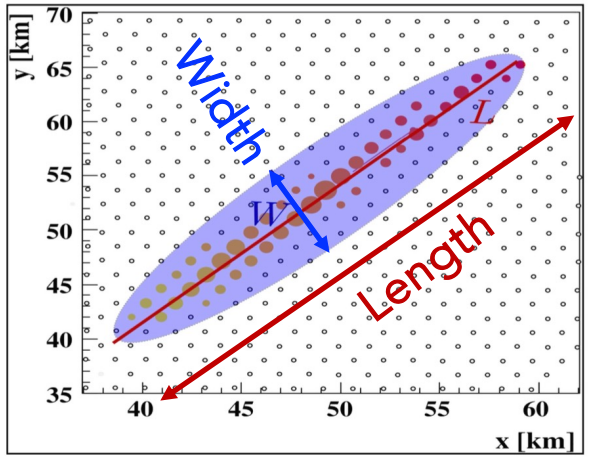
⇒ Shower front at ground consists of **electromag. + muonic** components

⇒ Large relative time delays of electromagnetic particles

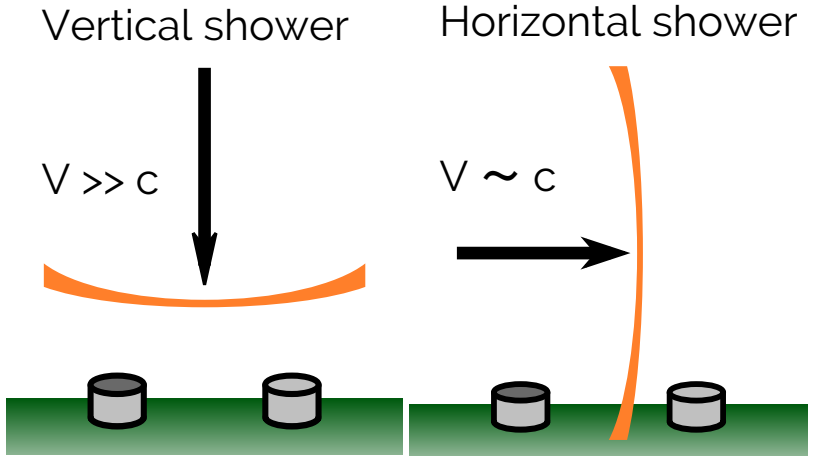
Neutrino signature → **inclined showers ($\theta > 60°$)** developing close to ground

Selection of inclined showers

Elongated footprint of shower on ground



Apparent velocity of propagation of trigger along major axis (Length)



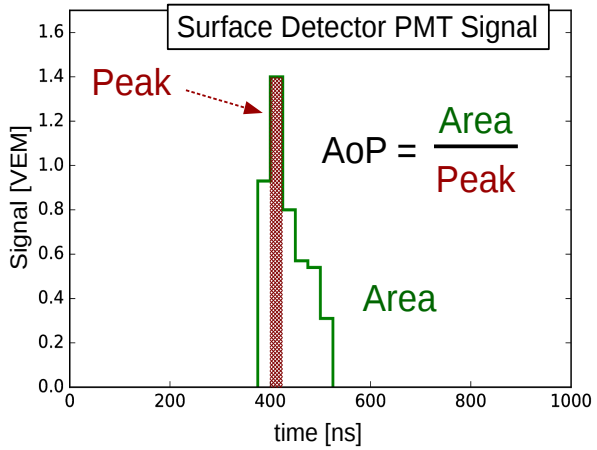
Reconstructed θ > 60° or > 75°

Identifying neutrinos

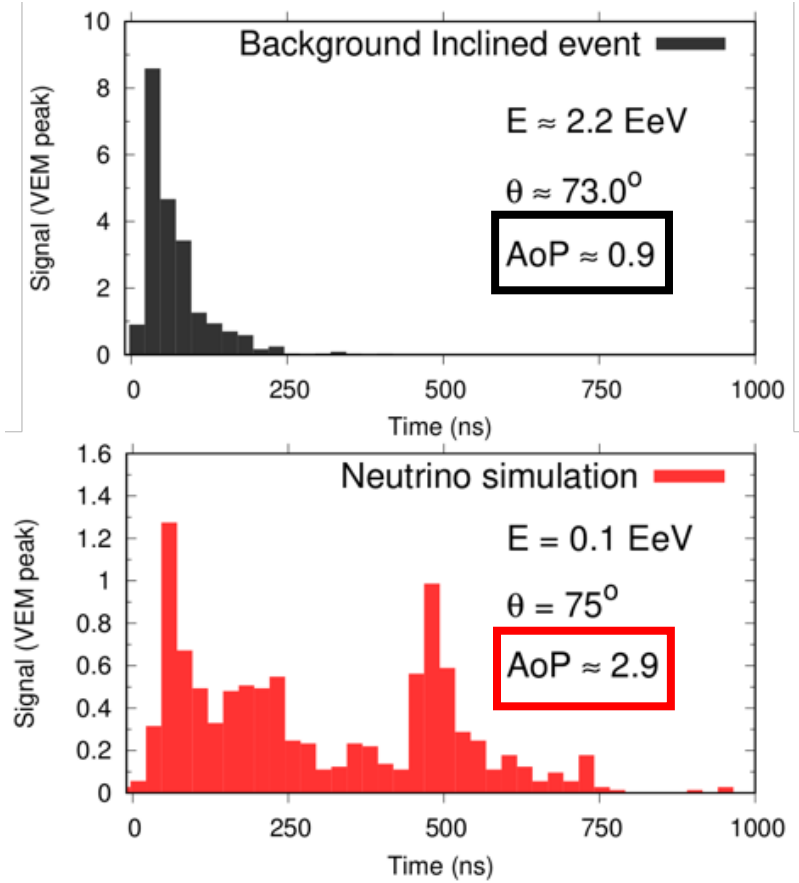
electromagnetic component induces extended signals in **time** traces recorded with Water-Cherenkov detectors

⇒ signal traces with large values of **Area-over-Peak** (AoP)

Definition of Area-over-Peak (AoP)



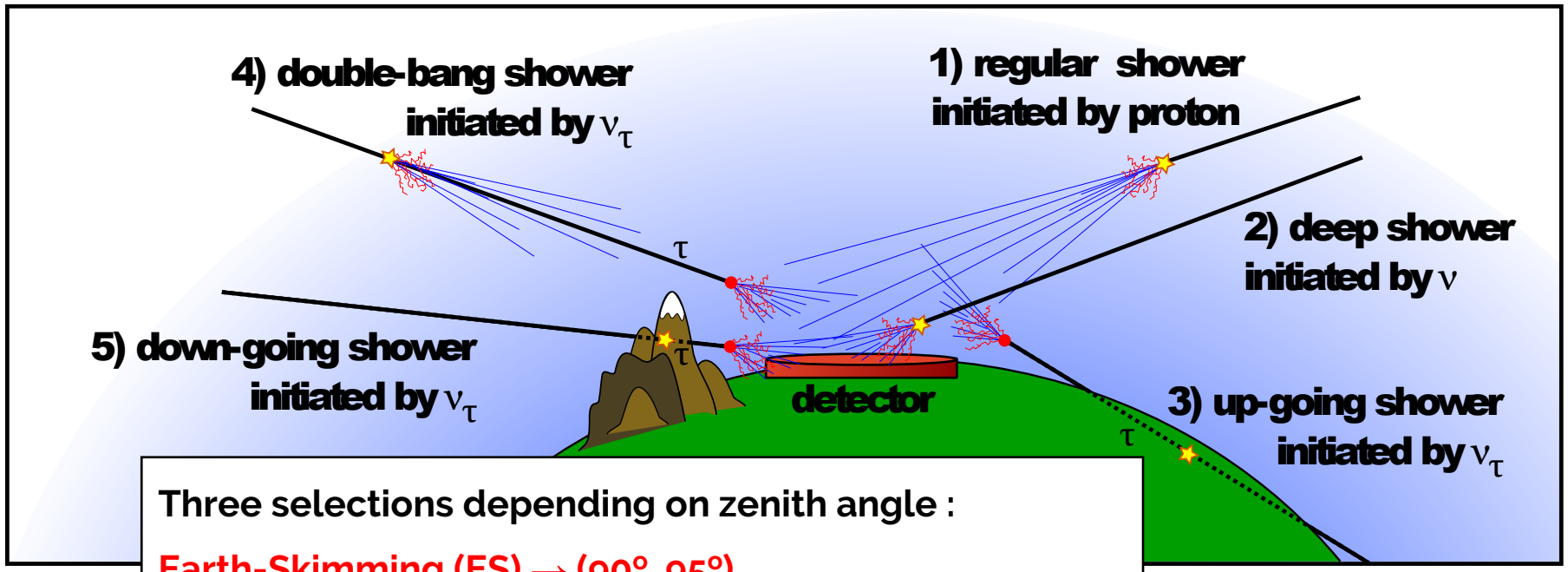
Traces of individual stations

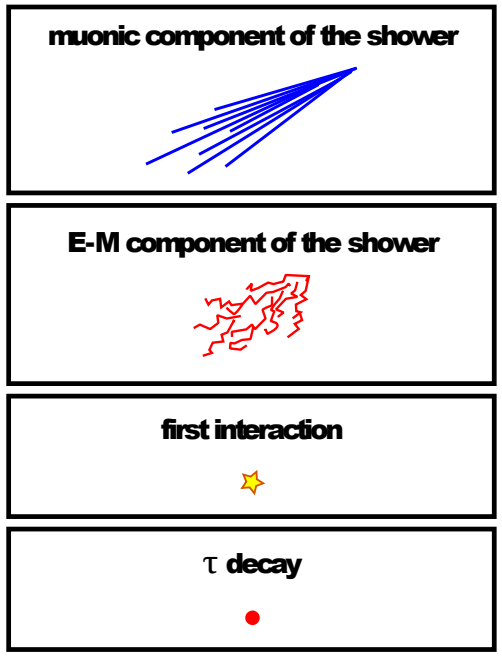


Neutrino identification based on AoP

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

Sensitivity to all neutrino flavours & channels





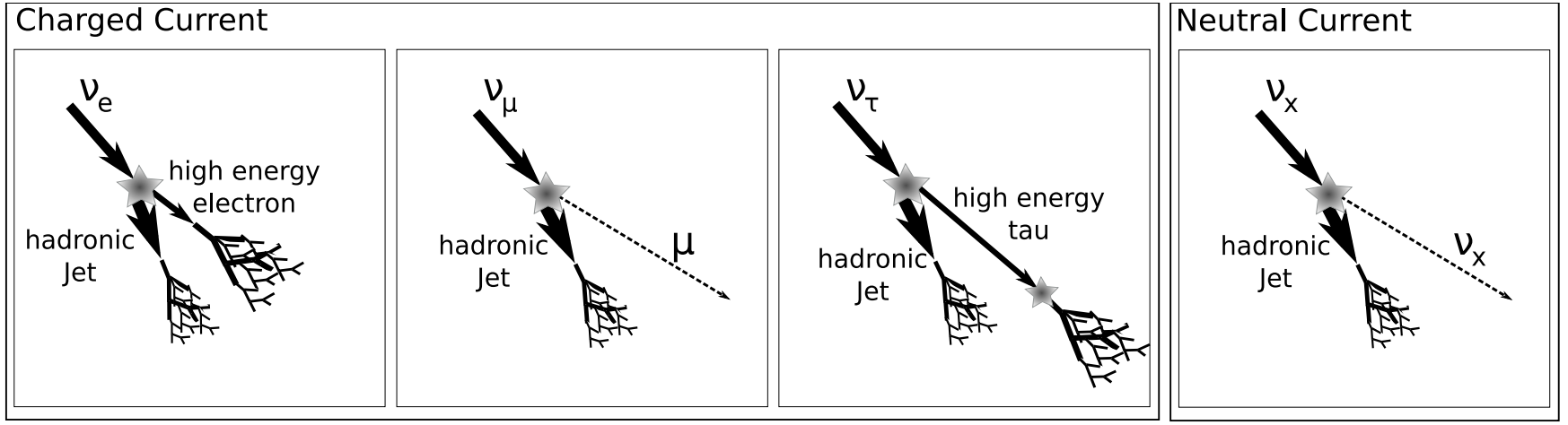
Three selections depending on zenith angle :

Earth-Skimming (ES) → (90°, 95°)

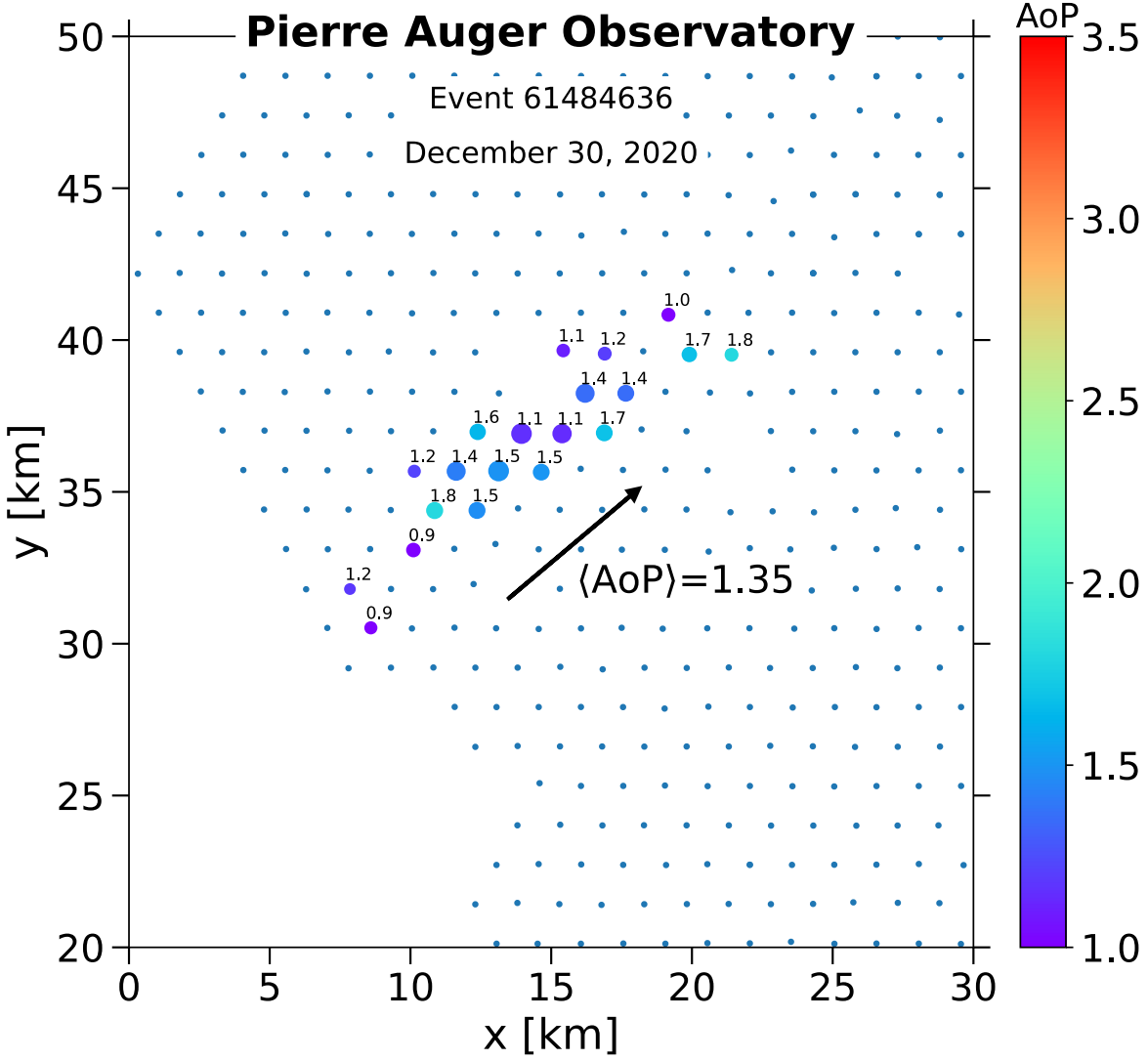
Downward-going high-angle (DGH) → (75°, 90°)

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

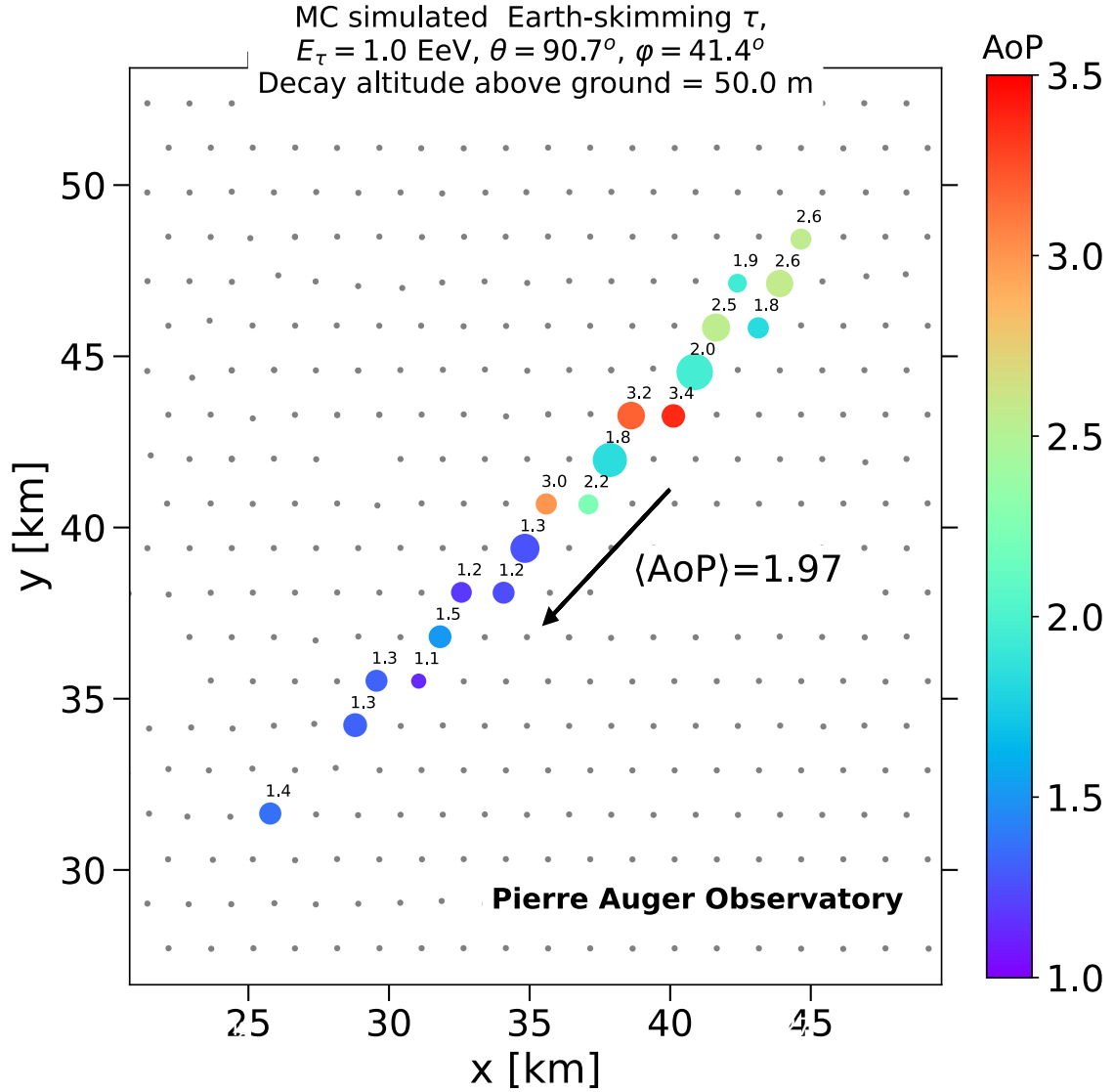
Pierre Auger Collab., PRD **91**, 092008 (2015)



Background (UHECR) inclined event in data



Monte Carlo simulation Earth-Skimming τ neutrino



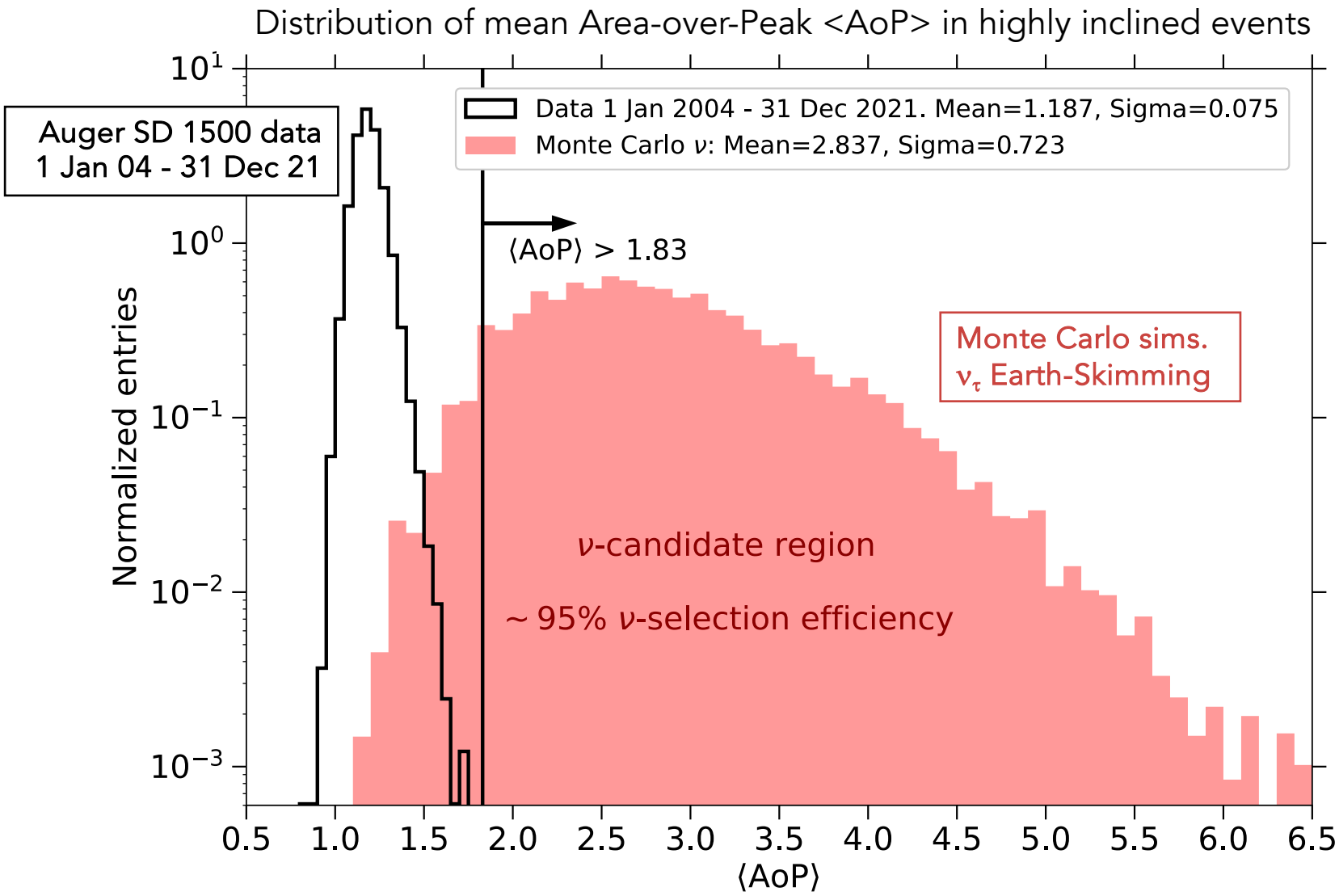
Numbers on top of each station indicate AoP

<AoP> is the discriminating observable for Earth-Skimming ν

Data unblinding. Example: Earth-Skimming channel

Pierre Auger
JCAP **10** (2019) 022

M. Niechciol for Auger
PoS(ICRC2023)1488



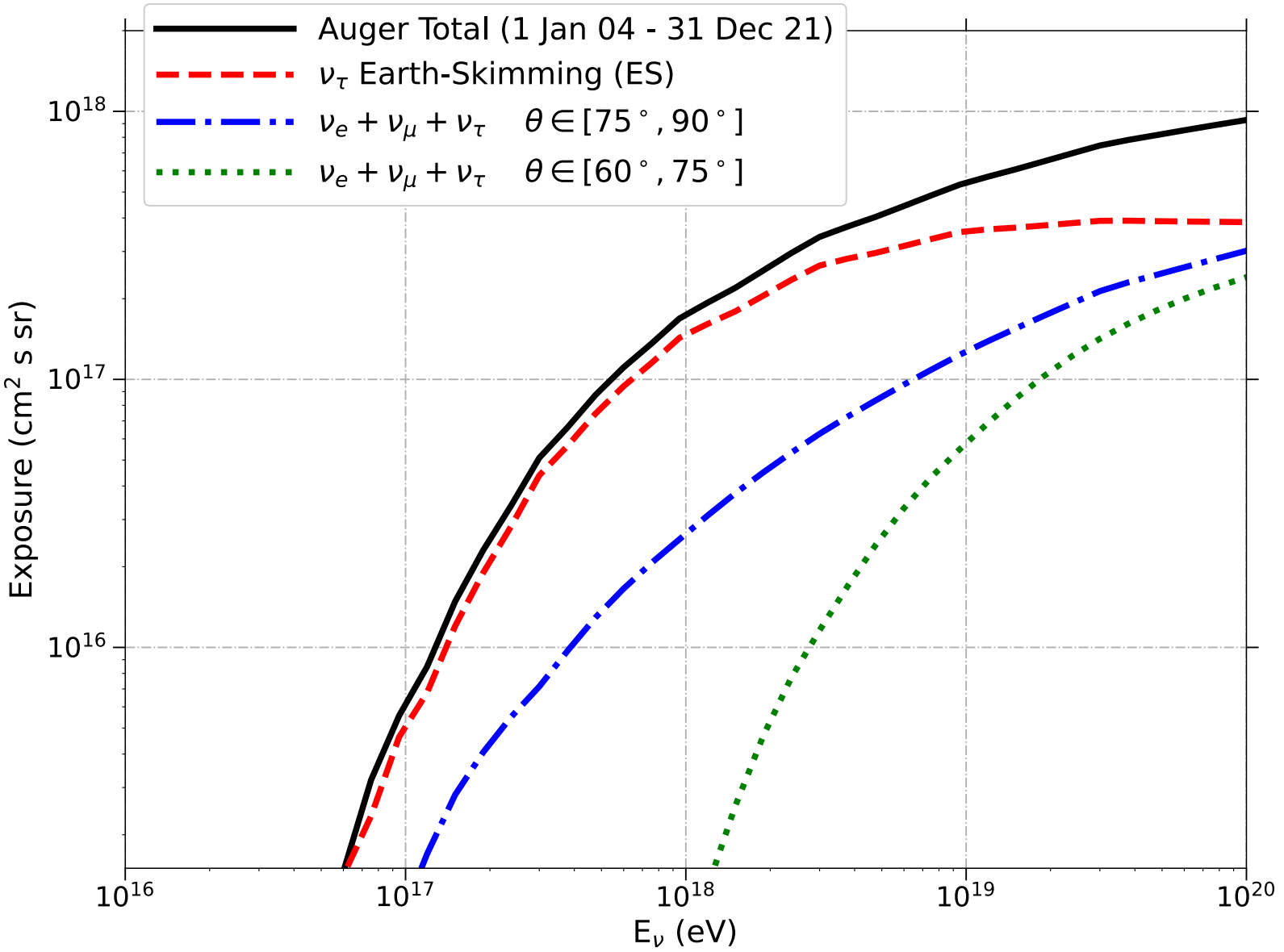
No candidates found in Earth-Skimming or Downward-going channels

1 Jan 2024 - 31 Dec 2021

- Large neutrino selection efficiency
- Low expected background 1/50 yr
- Sensitivity limited by exposure not limited by background

Exposure (1 Jan 2004 – 31 Dec 2021)

M. Niechciol for Auger
PoS(ICRC2023)1488

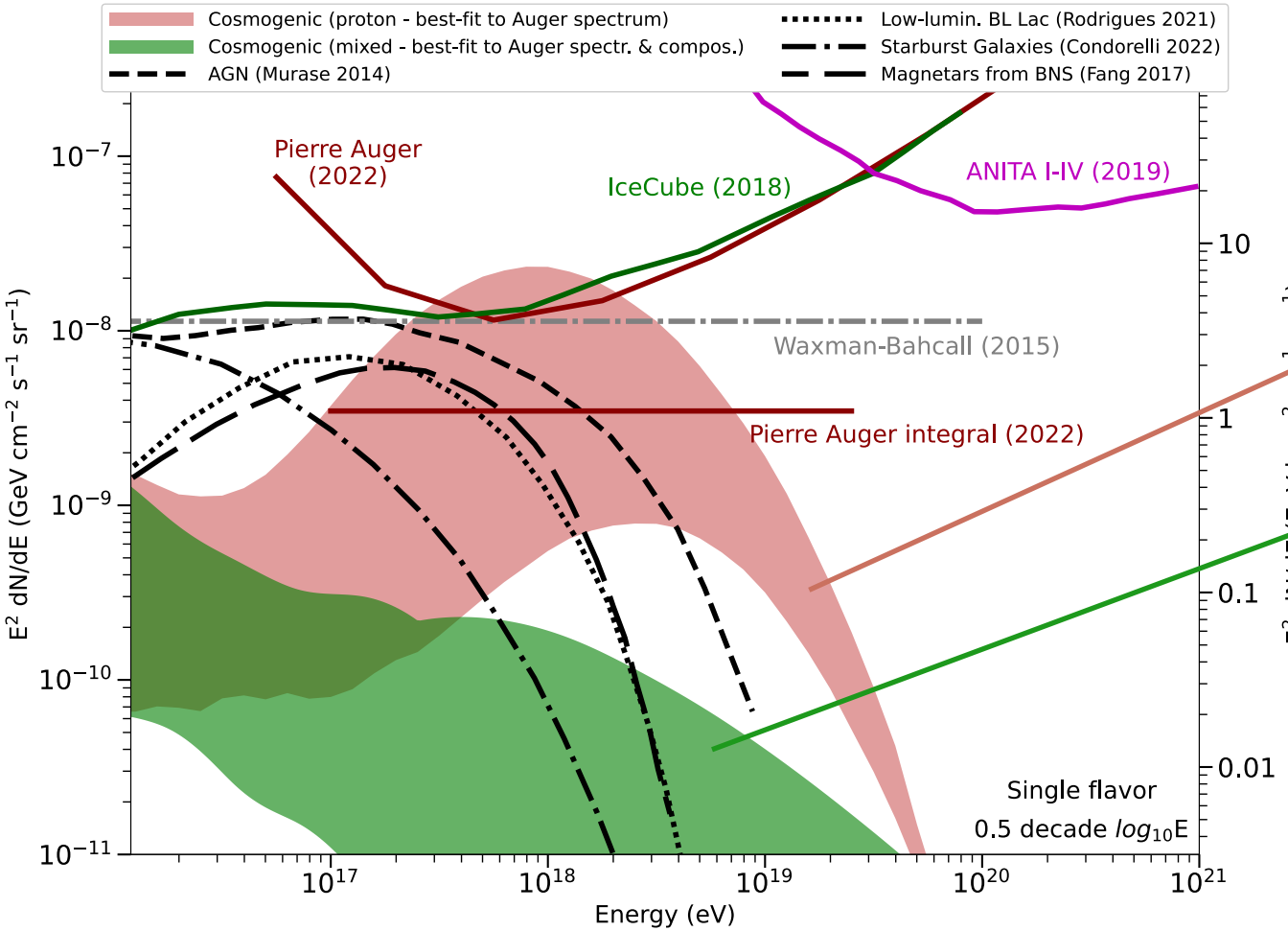


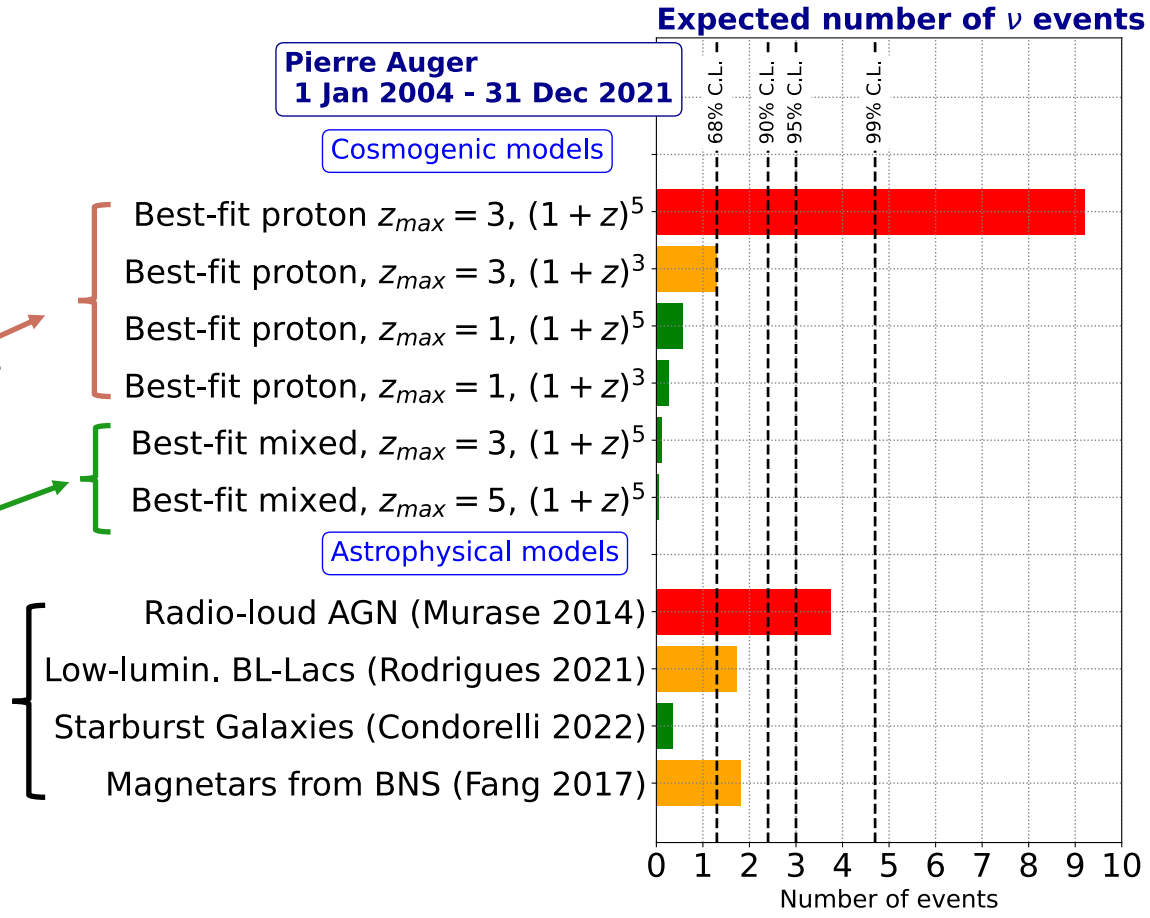
Neutrino flavor	Fractional contribution to event rate (E^{-2} flux)
ν_e	10 %
ν_μ	4 %
ν_τ	86 %

Upper limits to diffuse flux & event rates in Auger SD

1 Jan 2004 – 31 Dec 2021

- Best sensitivity slightly below 1 EeV
- Auger limits constrain models assuming pure proton primary cosmic beam





M. Niechciol for Auger
PoS(ICRC2023)1488

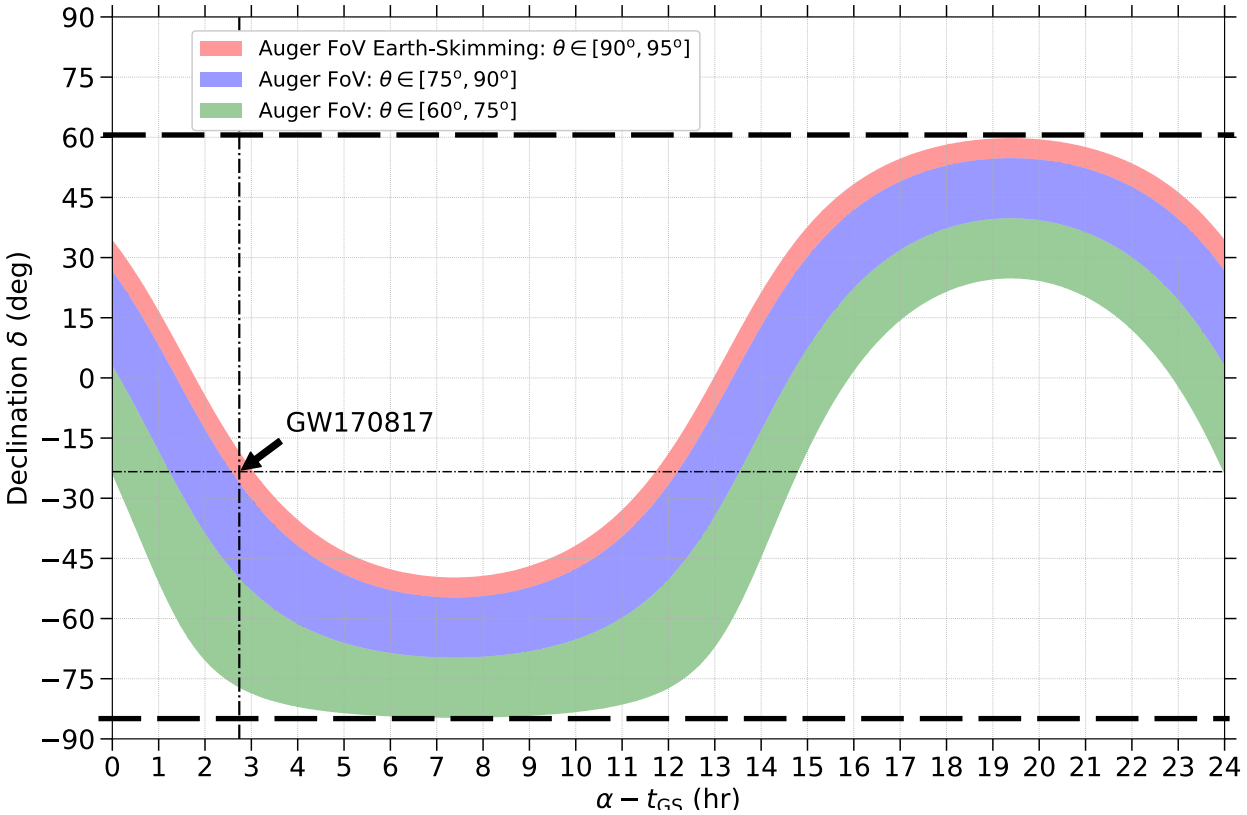
Invited review talk today by O. Deligny on constraints on BSM physics from EAS and from UHE gamma-ray and neutrino searches

Search for point-like transient sources of UHEν

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

IceCube,
ApJLett. 835, 151 (2017)

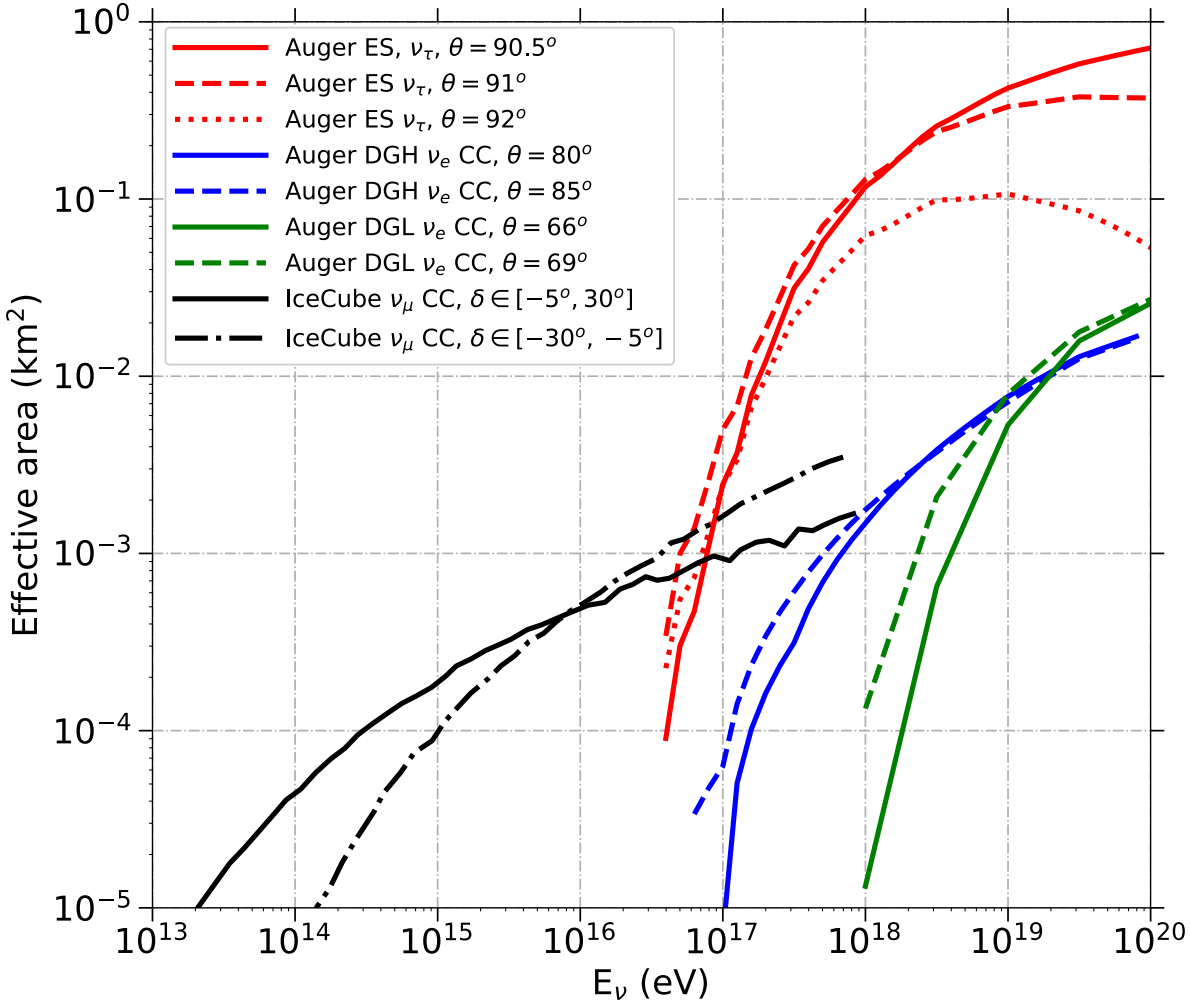
Instantaneous sky coverage of Auger



Instantaneous field-of-view covers ~ 30% of the sky:
Earth-Skimming (5%) + Donward-going (25%)

Auger is sensitive to potential sources of UHE neutrinos between **close to South Celestial Pole to + 60 deg North =>** there is always a time window during a sidereal day in which source is in FoV

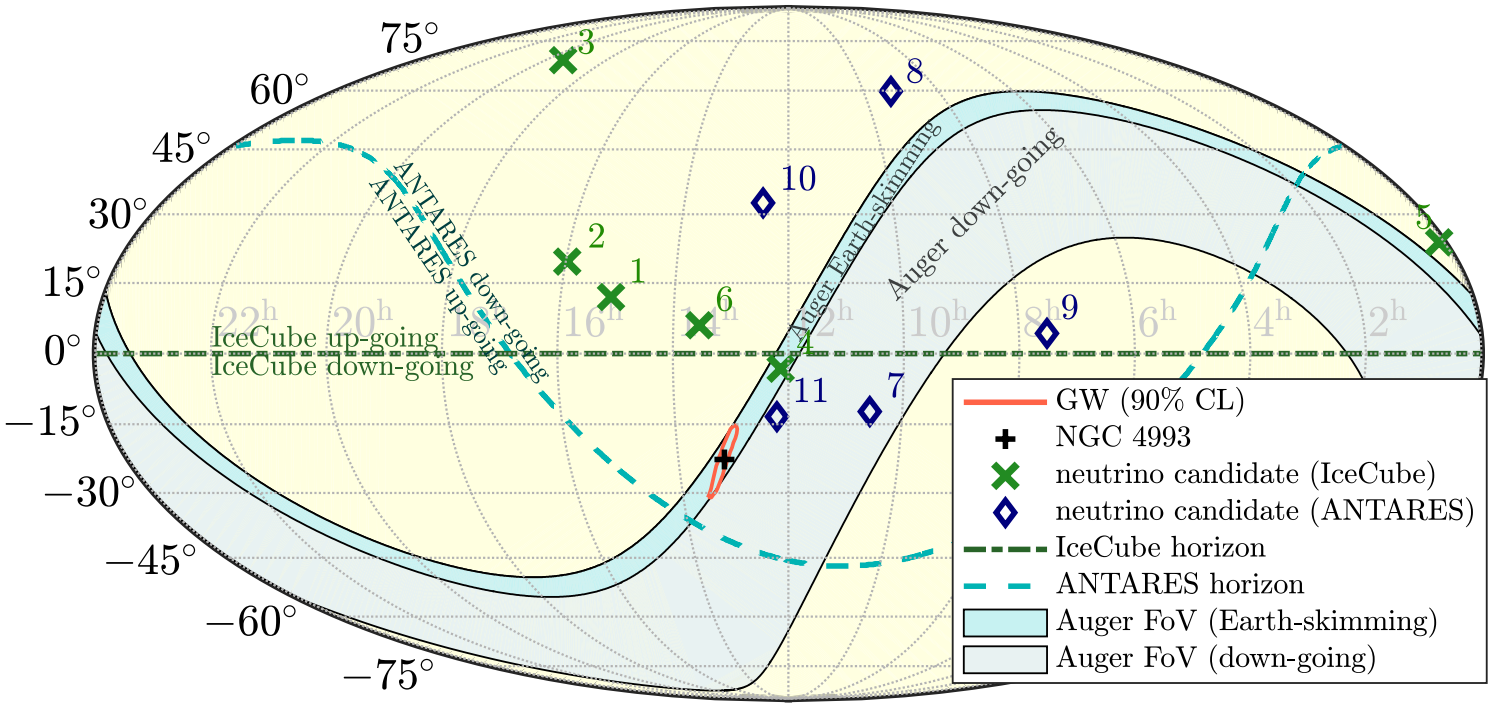
Effective area



Large peak effective areas, close to 1 km^2

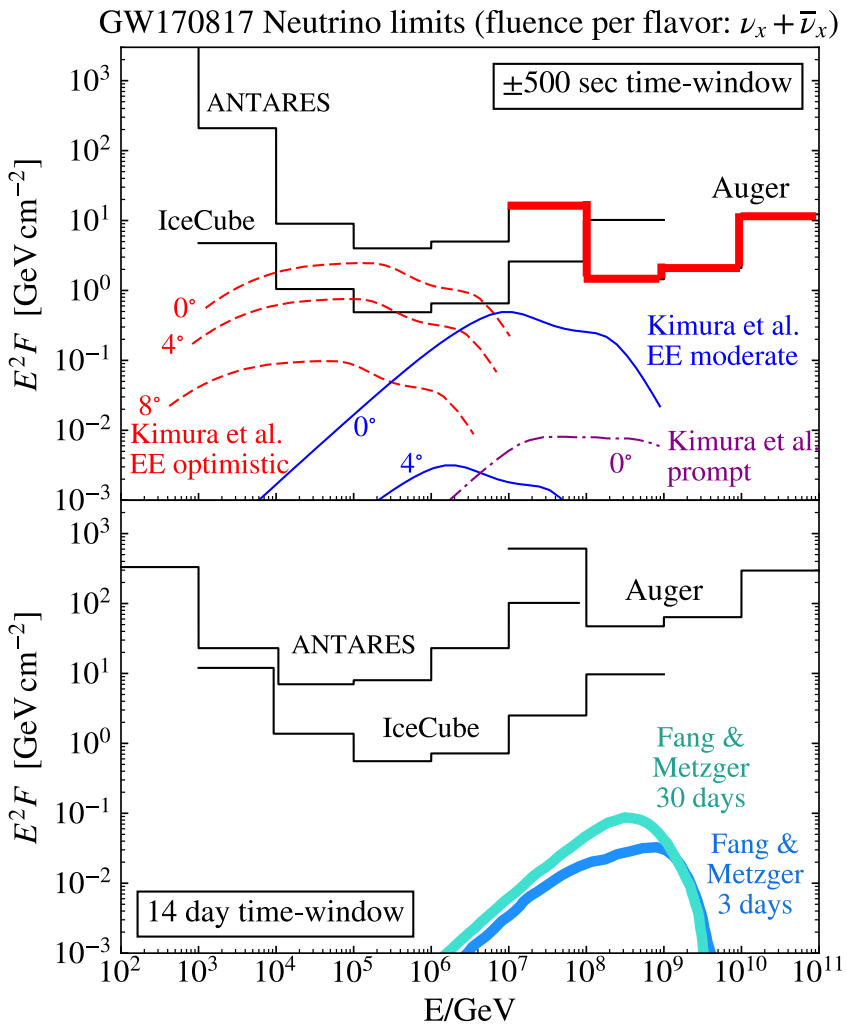
Follow-up of GW170817 in neutrinos
Binary Neutron Star Merger + short GRB

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



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

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



Lack of neutrino detection consistent with expectations from short GRB viewed at large off-axis angle $\gtrsim 20°$

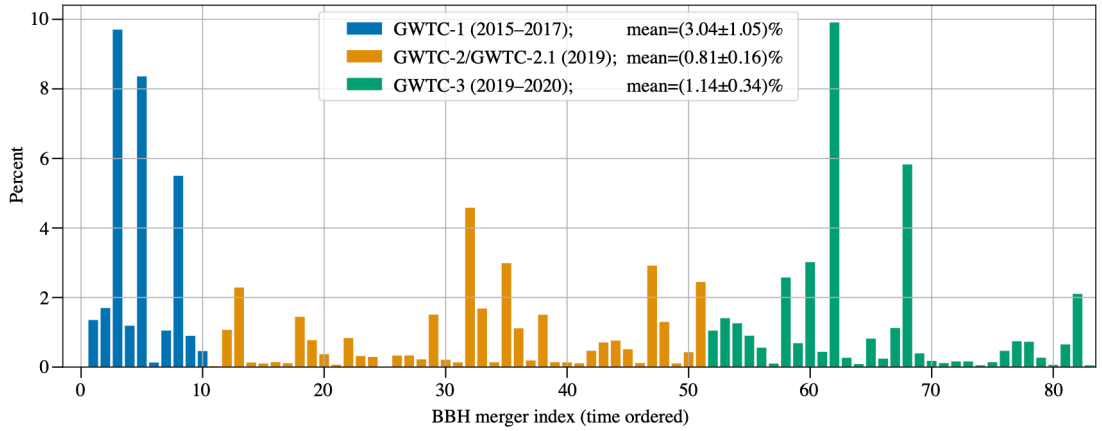
Multimessenger activities with Auger

IceCube. Science **361**, 146 (2018)
Pierre Auger. ApJ., **902**, 105 (2020)

Follow-up of 83 BBH mergers detected in GW by Ligo-Virgo

- No candidate neutrinos from any of the BBH mergers
- Stacking limit => ratio of energy emitted in UHE neutrinos to that emitted in GWs < 5%

Fractional contribution of each BBH to statcking limit

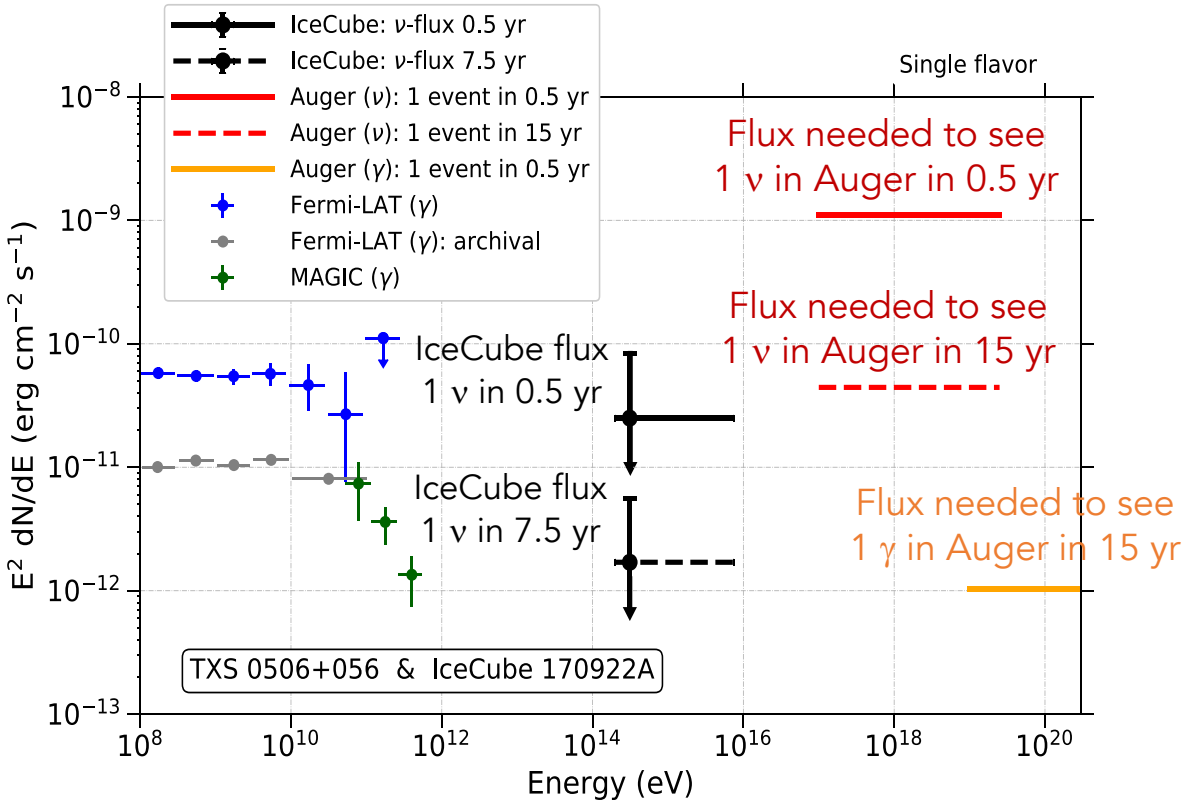


BBH GW151226 + GW170608 + GW191226 alone contribute ∼ 28% to the total stacking limit

M. Schimp for Auger, PoS(ICRC2021)968

Follow-up of TXS 0506+056 blazar

- **22 Sep. 2017** High-Energy ν discovered by IceCube coincident with gamma-ray blazar
- No candidate neutrinos from direction of TXS @ EeV in Auger
- **First upper limits to UHE neutrino (& photon) flux from an identified neutrino source**

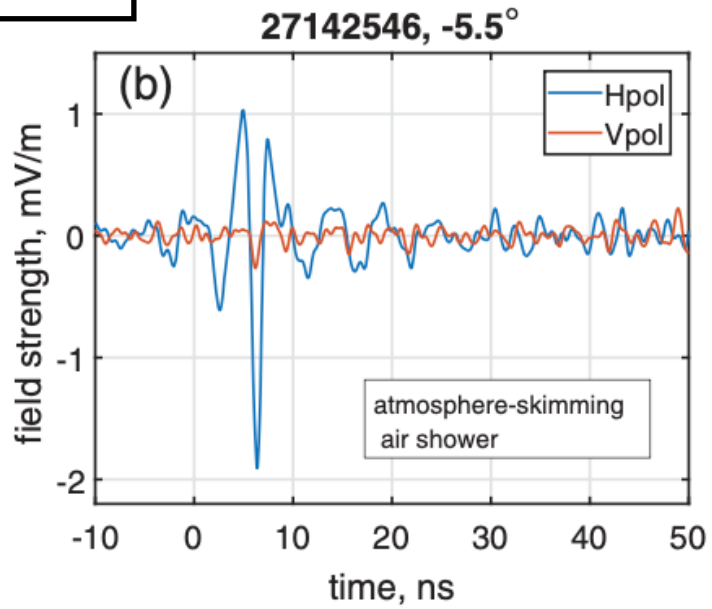


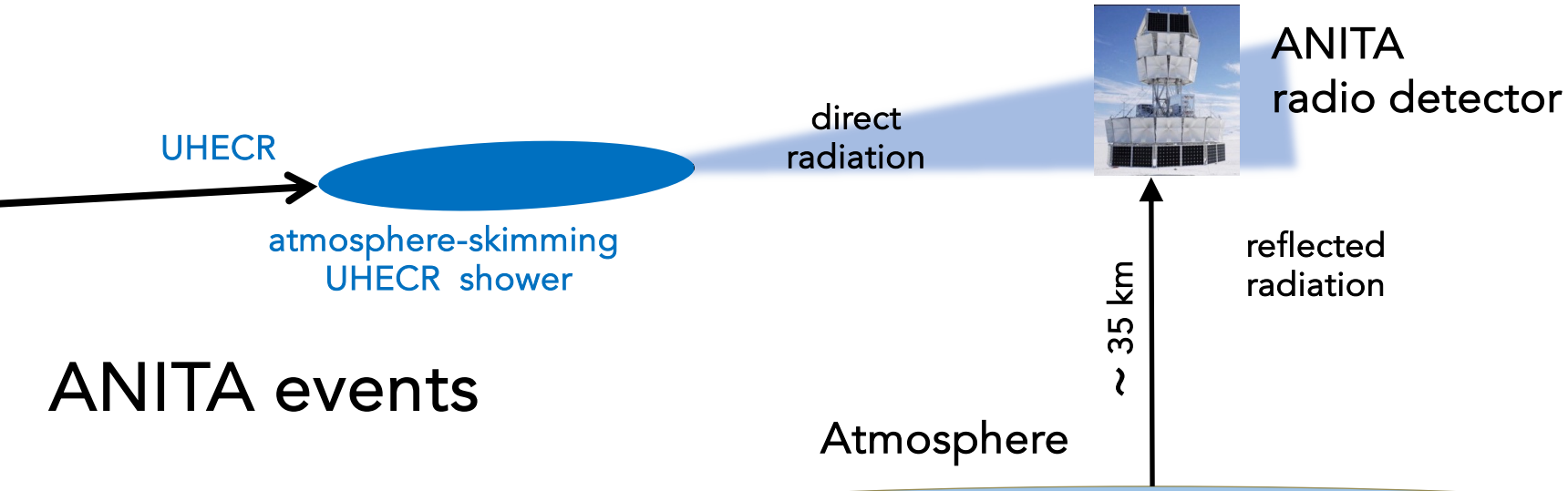
Search for Upward-going showers

ANITA events

DIRECT CR event (stratospheric)

dominant horizontal polarization of pulses consistent with geomagnetic effect





ANITA events

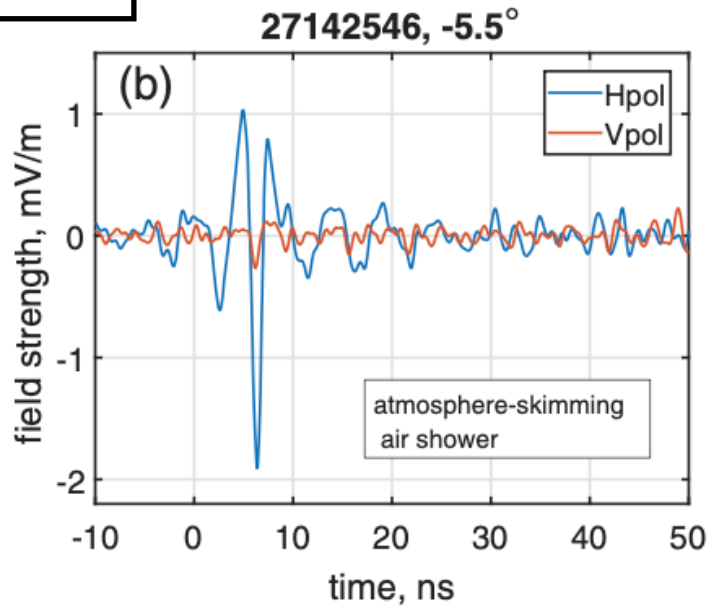
ANITA I - PRL **117**, 071101 (2016)
ANITA III - PRL **121**, 161102 (2018)

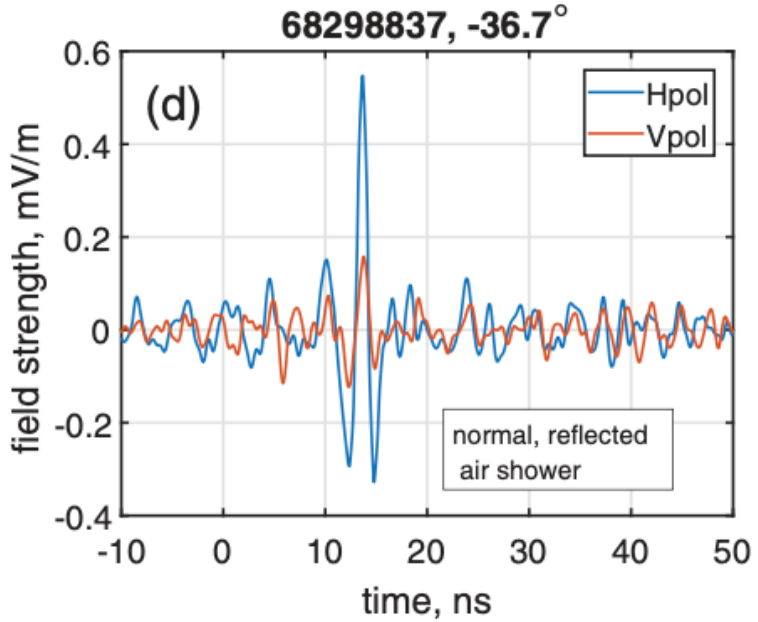
ANITA events

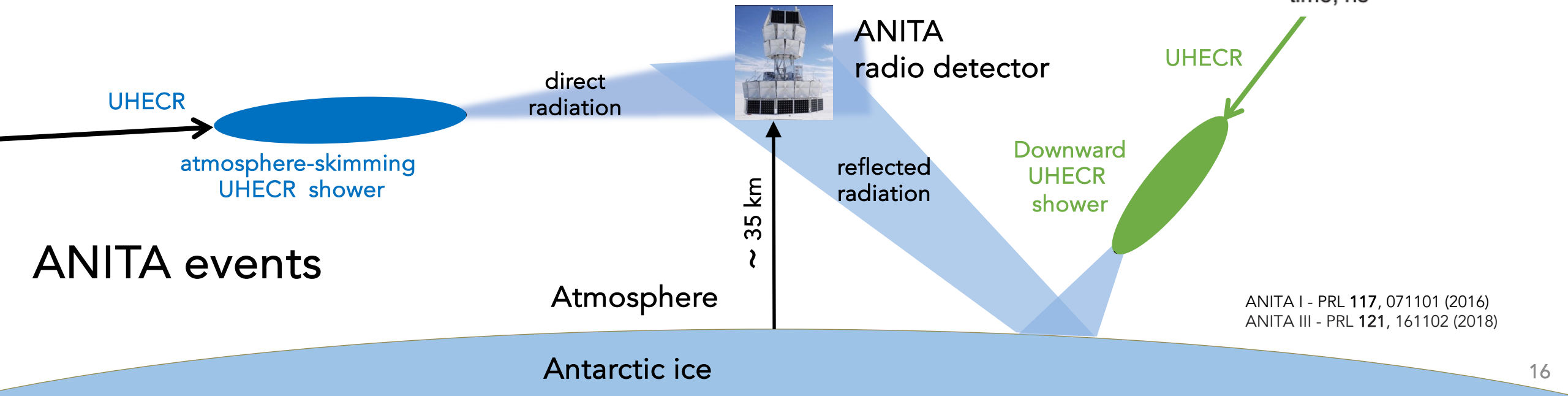
DIRECT CR event (stratospheric)

dominant horizontal polarization of pulses consistent with geomagnetic effect

REFLECTED CR event (polarity inversion)





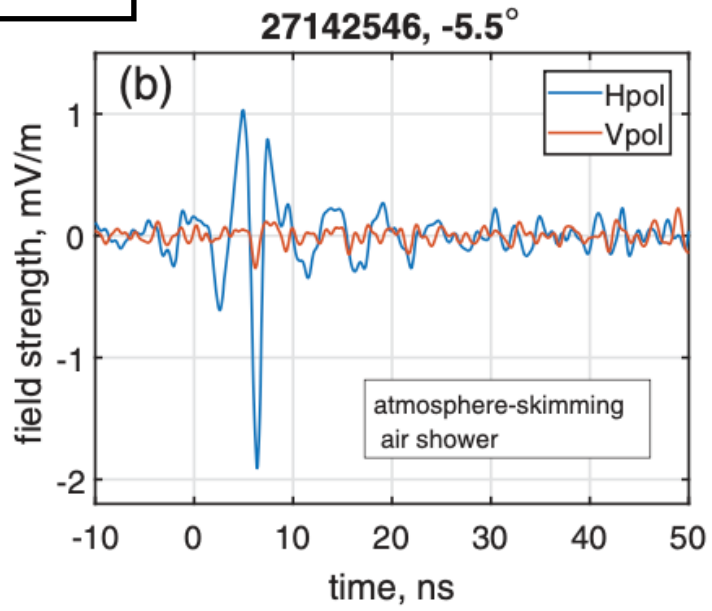


ANITA events

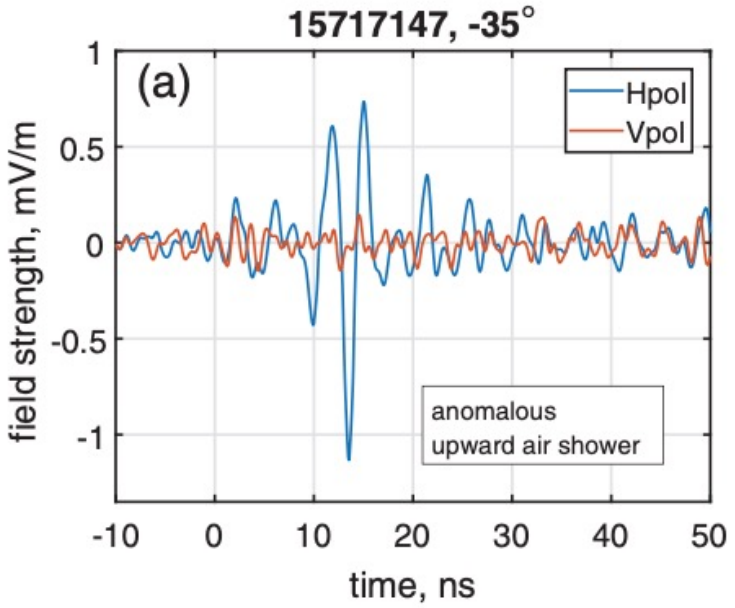
ANITA I - PRL **117**, 071101 (2016)
ANITA III - PRL **121**, 161102 (2018)

ANITA events

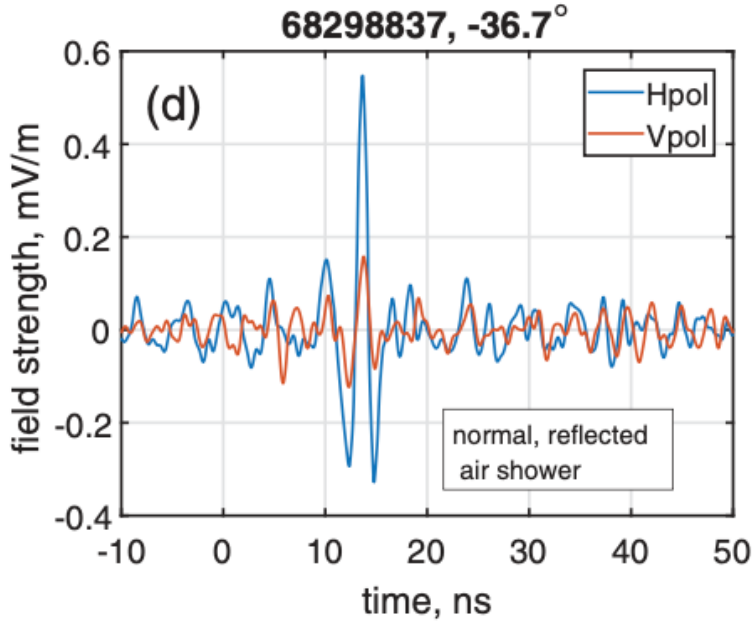
DIRECT CR event (stratospheric)

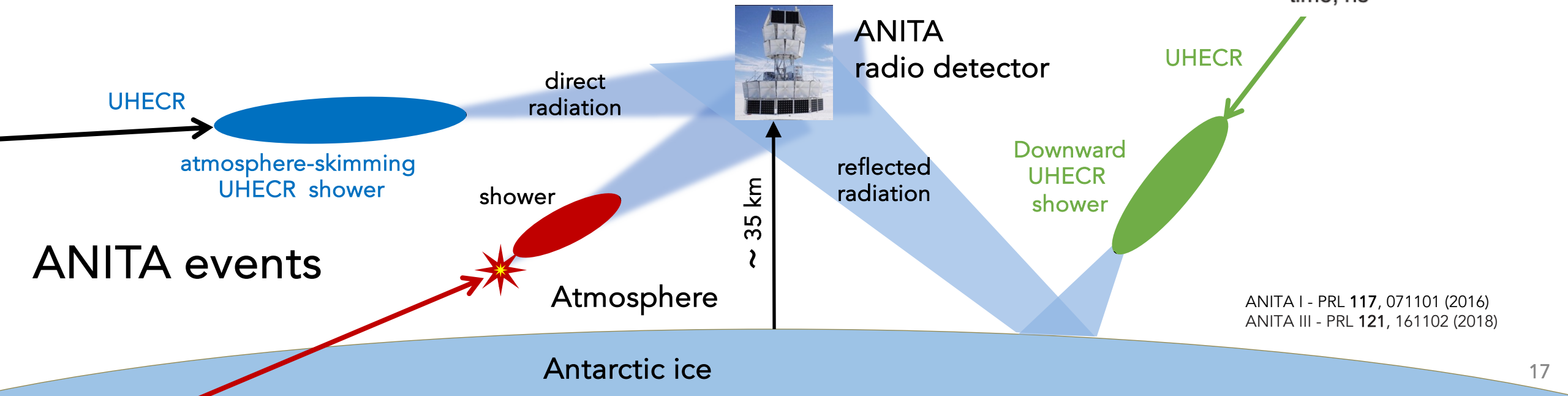


ANOMALOUS event (wrong polarity for CR)



REFLECTED CR event (polarity inversion)





ANITA events

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

ANITA anomalous events & Auger FD

2 anomalous events at elevation angles: -27.4° & -35°

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

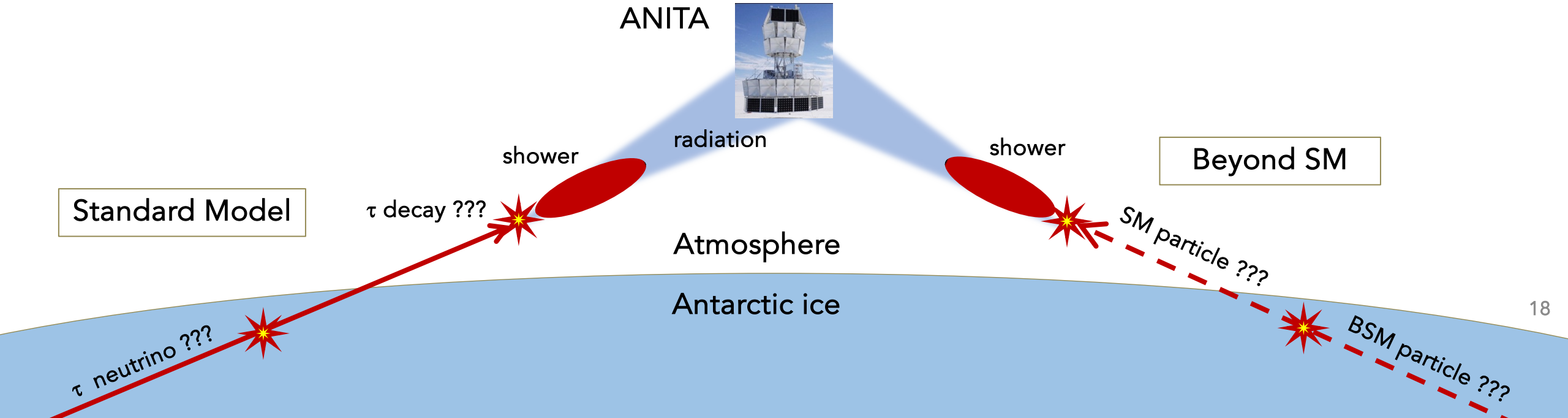
⇒ Search for upcoming showers with Auger

Standard Model (SM) origin:

- Tau showers from neutrino interactions? Discarded
- Other radiation mechanisms (TR air/ice or ice/air)? Discarded

Beyond SM (BSM) origin?

If "anomalous" events are from air showers the Fluorescence Detector could also observe upward-going showers ⇒
use FD data 1 Jan 2004 – 31 Dec 2018
$\theta_{rec} > 110°$

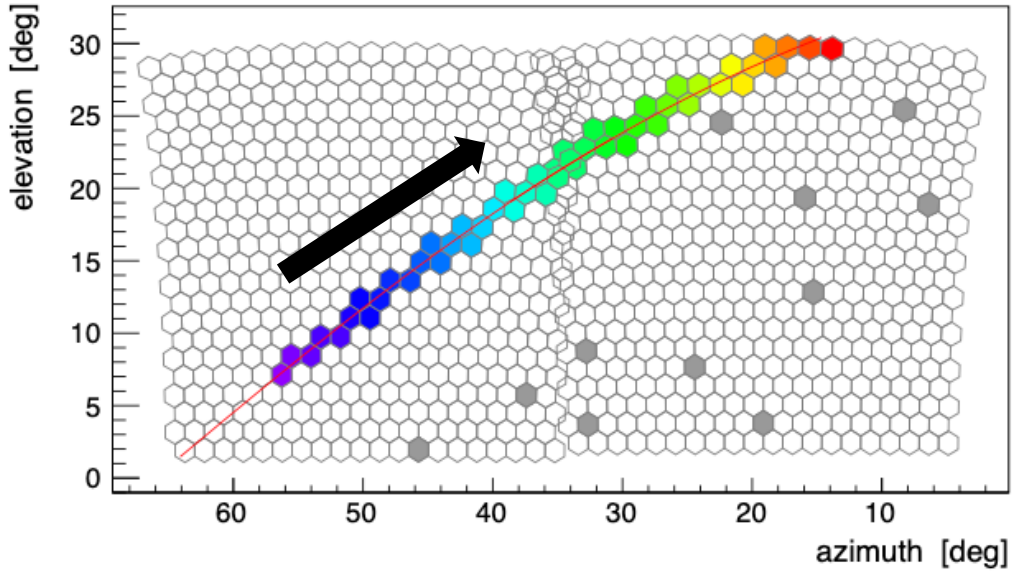


Signal: Upward-going Monte Carlo event

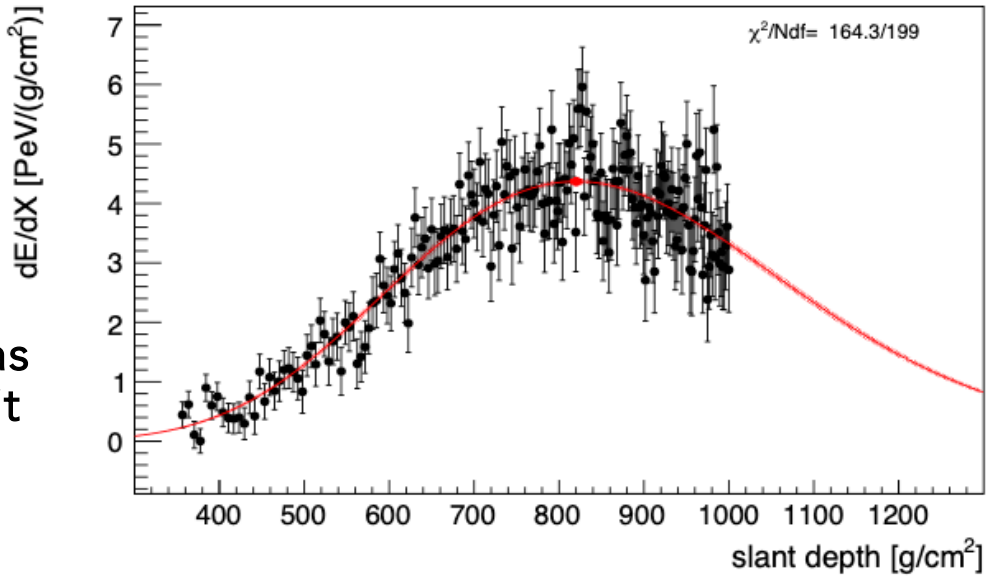
Fluorescence Detector pixel camera

Early pixels

Late pixels



reconstructed as upward-going



Fitted Gaisser-Hillas profile of E deposit

Main challenge of analysis:

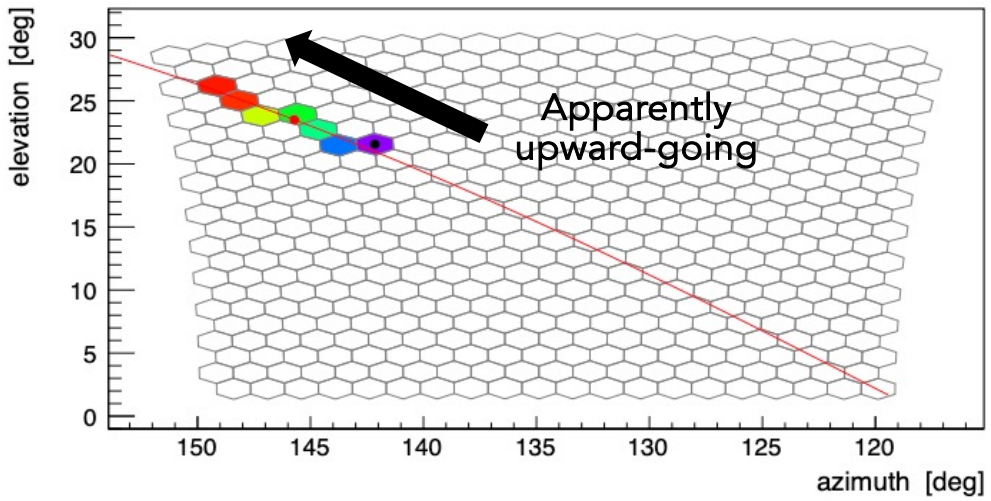
In absence of any signal from the Surface Detector, i.e. using only the time sequence and profile:

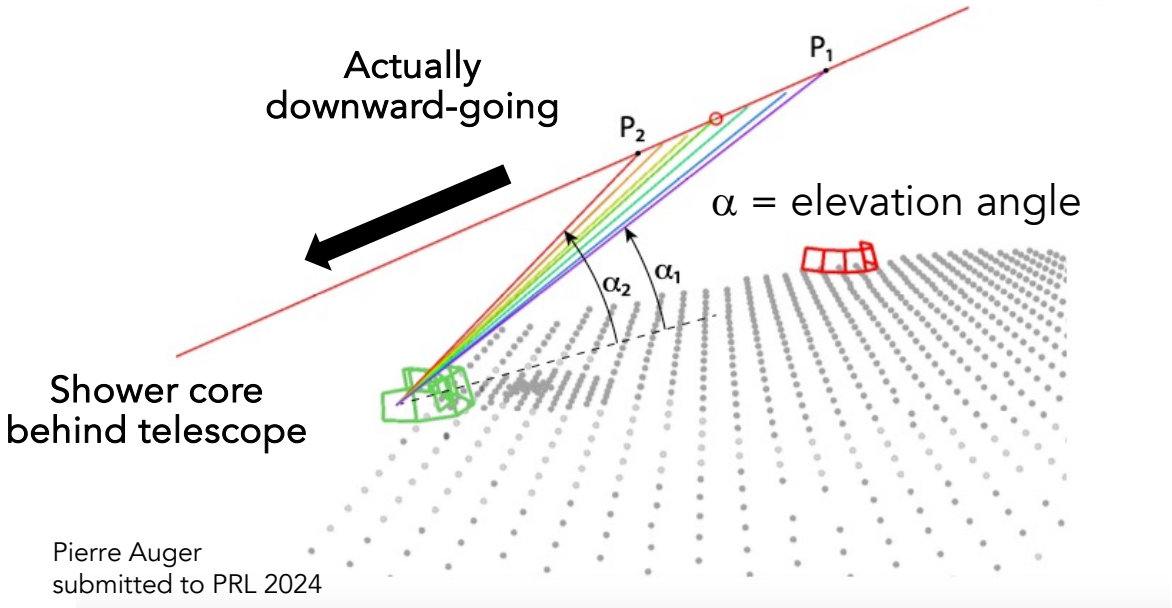
- UHECR downward-going events with specific geometries, can be reconstructed as upward-going => background
- some events even admit an upward- and downward-going reconstruction simultaneously

Pierre Auger
submitted to PRL 2024

Potential background real event

Reconstructed downward-going event
with core falling outside array





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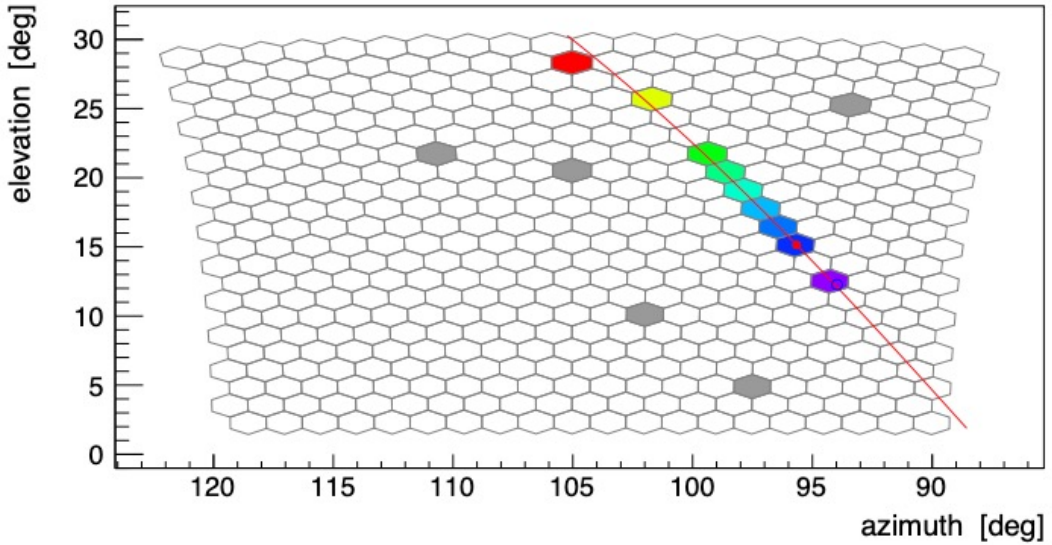
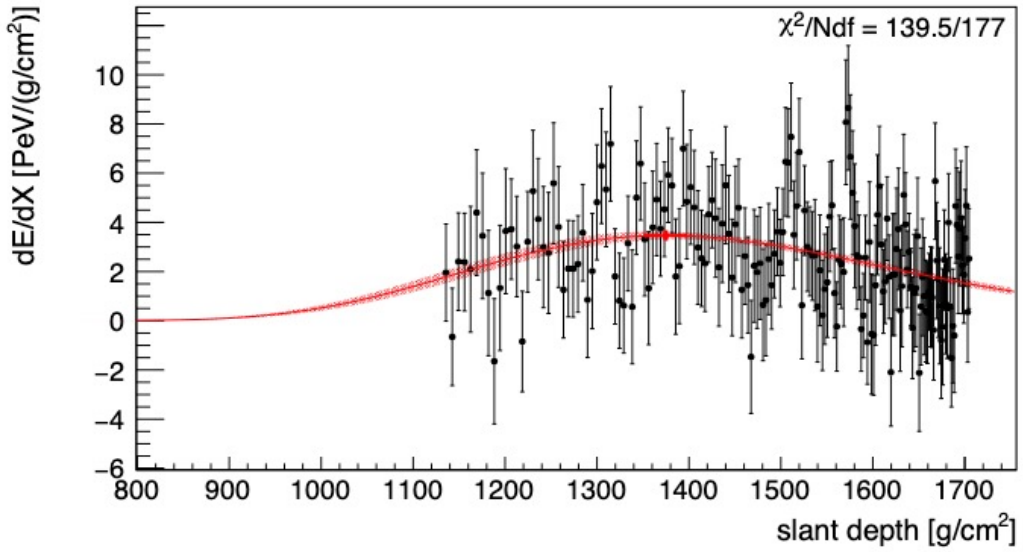
Background Monte Carlo event

Quasi-horizontal event θ_{MC}=89.6°
reconstructed as upward-going θ_{rec}~116.6°

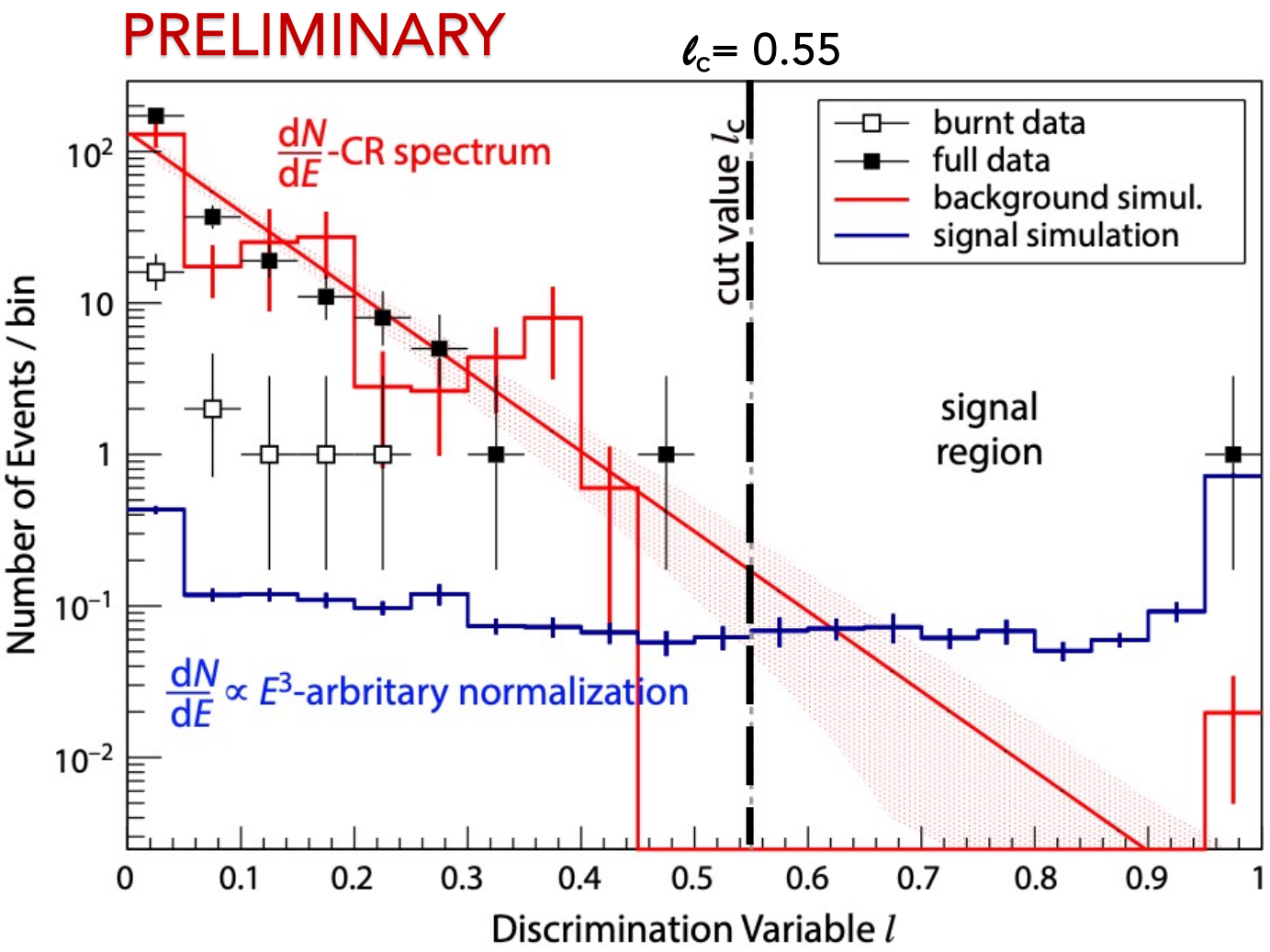
Early pixels

Late pixels





Discriminating upward-going showers



After all cuts to reject background:

some events admit both upward- & downward-going reconstructions

Discrimination based on ratio of maximum likelihood of upward & downward reconstructions L_{up}/L_{down}

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

$L_{down} > L_{up}$ => $\ell = 0$

$L_{up} > L_{down}$ => $\ell \in [0,1]$

L_{up} only => $\ell = 1$

Cut value at ℓ_c= 0.55 optimized minimizing MC background & maximizing sensitivity

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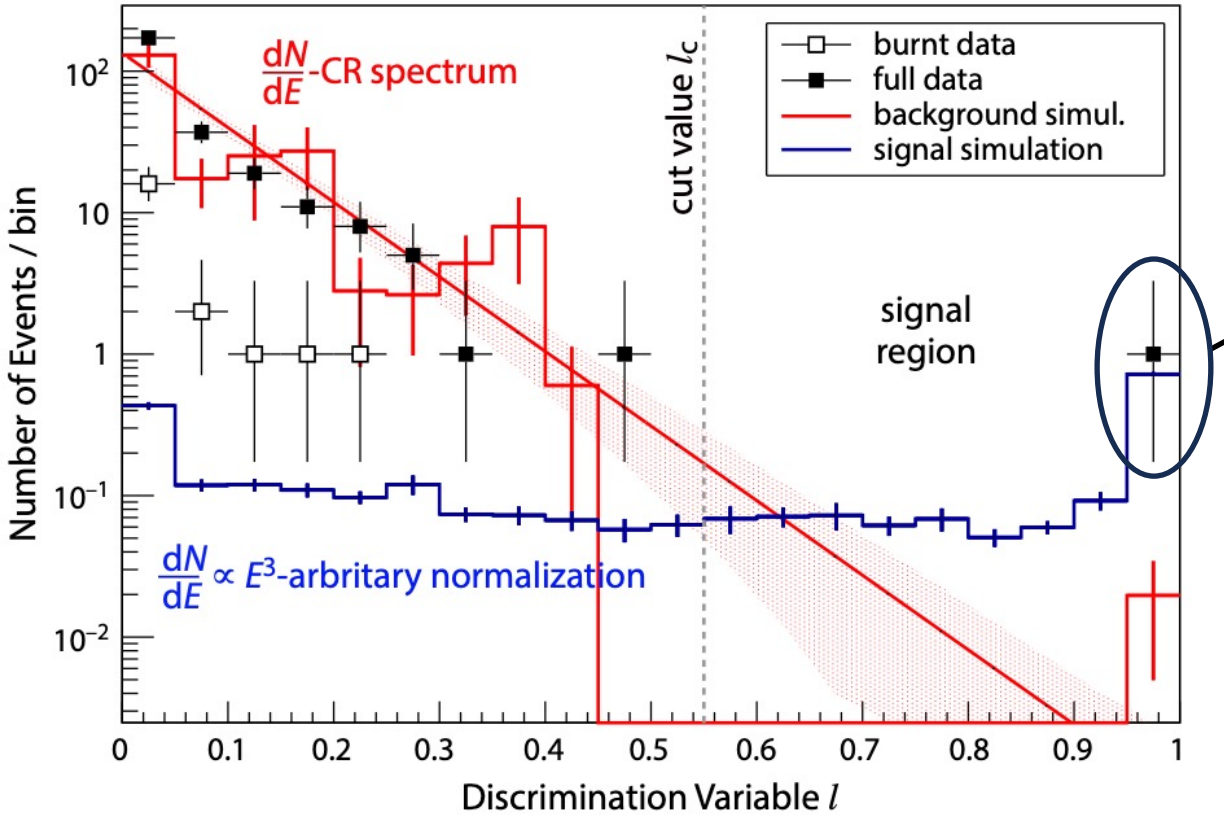
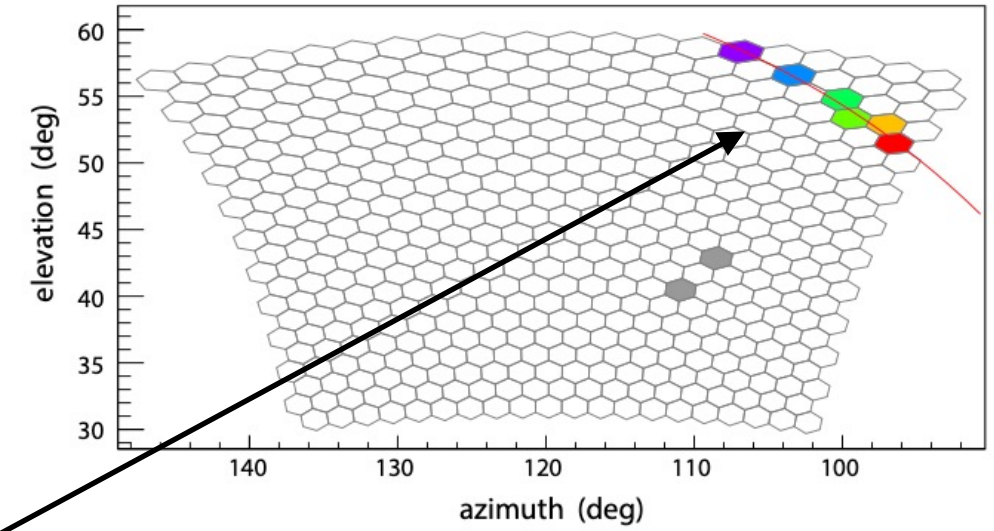
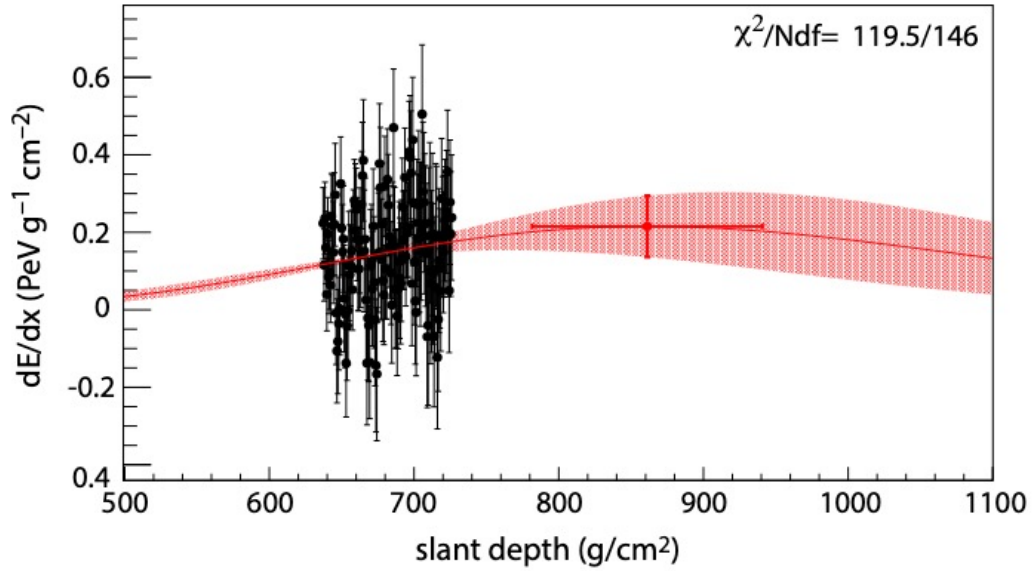
Discriminating upward-going showers

PRELIMINARY

One event found in 1 Jan 2004 - 31 Dec 2018
Consistent with expected background of 0.27 ± 0.12 events from MC cosmic ray showers reconstructed as upward-going.







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Auger FD vs ANITA exposure

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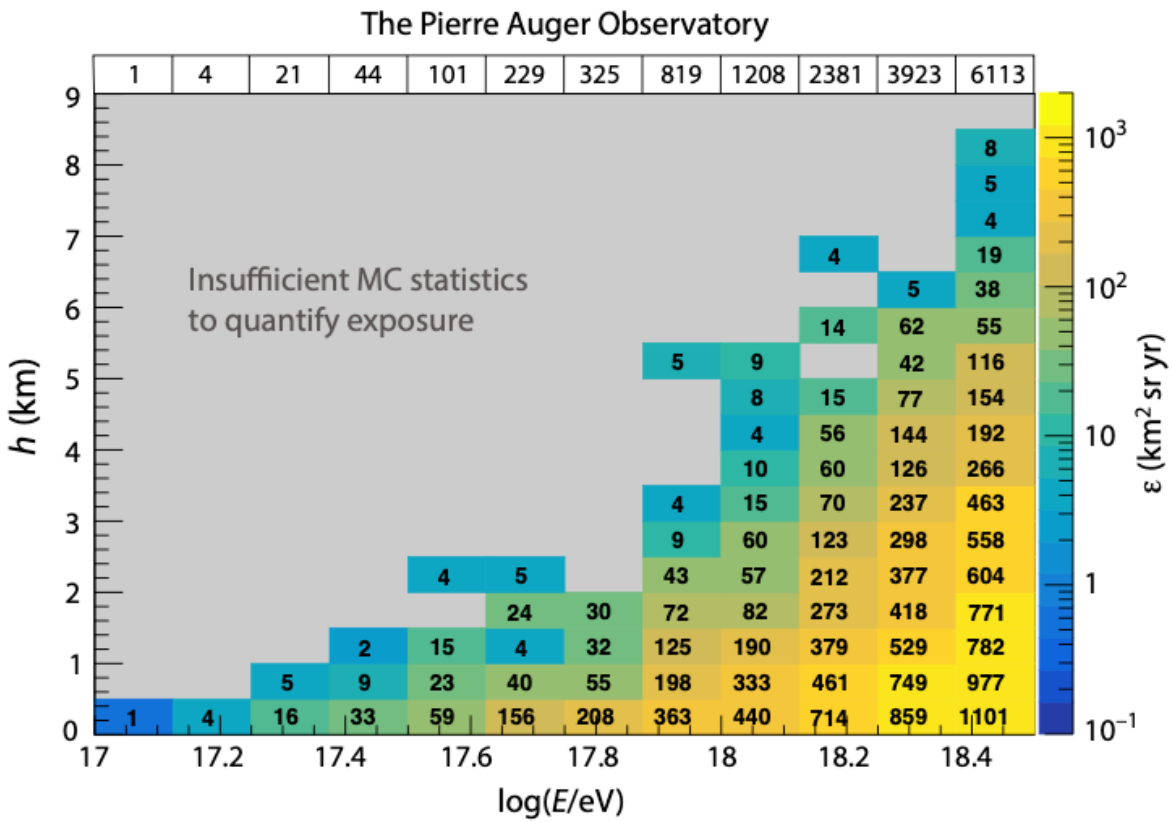
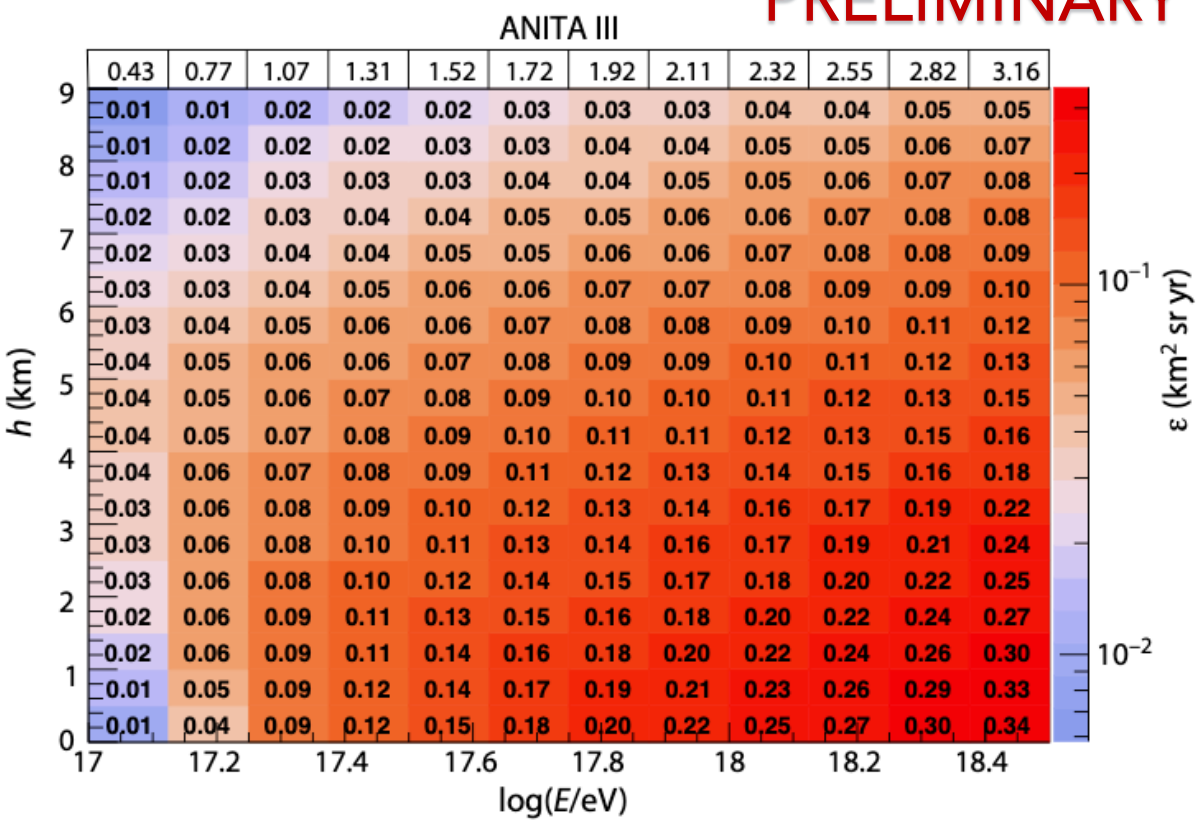
Exposure as a function of shower energy and height of shower injection

PRELIMINARY





Auger FD exposure: θ ∈ [110°, 130°] is 2 - 2000 larger than **ANITA-III (I) exposure: θ ∈** [110°, 130°]

Normalizing several $E^{-2} \rightarrow E^{-5}$ spectra to 1 event in ANITA I or III
=> 8 → 69 events expected in Auger, while only 1 event compatible with background has been observed

Auger non-observation of upward-going showers effectively dismisses the interpretation of the anomalous events as upward-going showers

Conclusions

UHEν have been searched with the Surface Detector of the Pierre Auger Observatory

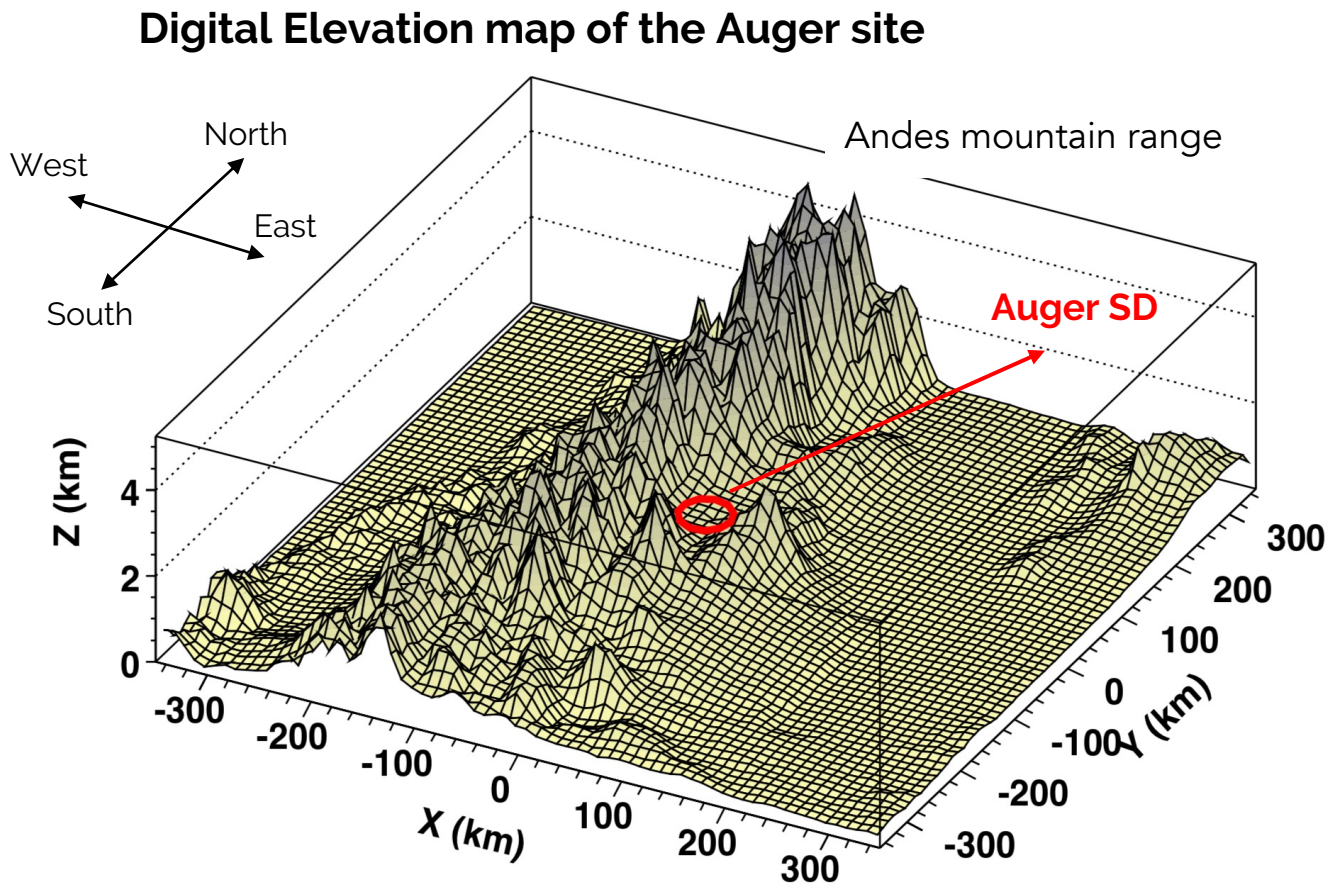
- No candidates found 1 Jan 2004 – 31 Dec 2021
- Competitive limits to diffuse fluxes, most sensitive around 1 EeV
  - Pure proton cosmogenic neutrino models constrained
- Large instantaneous sensitivity to bursting sources in Earth-Skimming FoV
- Auger is a key actor in Multimessenger Astronomy at UHE
  - Follow-up of BNS, BBH, flaring blazars, etc…

Searches for upward-going showers with the Fluorescence Detector of the Pierre Auger Observatory

- 1 event found, compatible with background, in Jan 2004 - Dec 2018
- Dismissing a shower origin of ANITA anomalous events that remain mysterious…

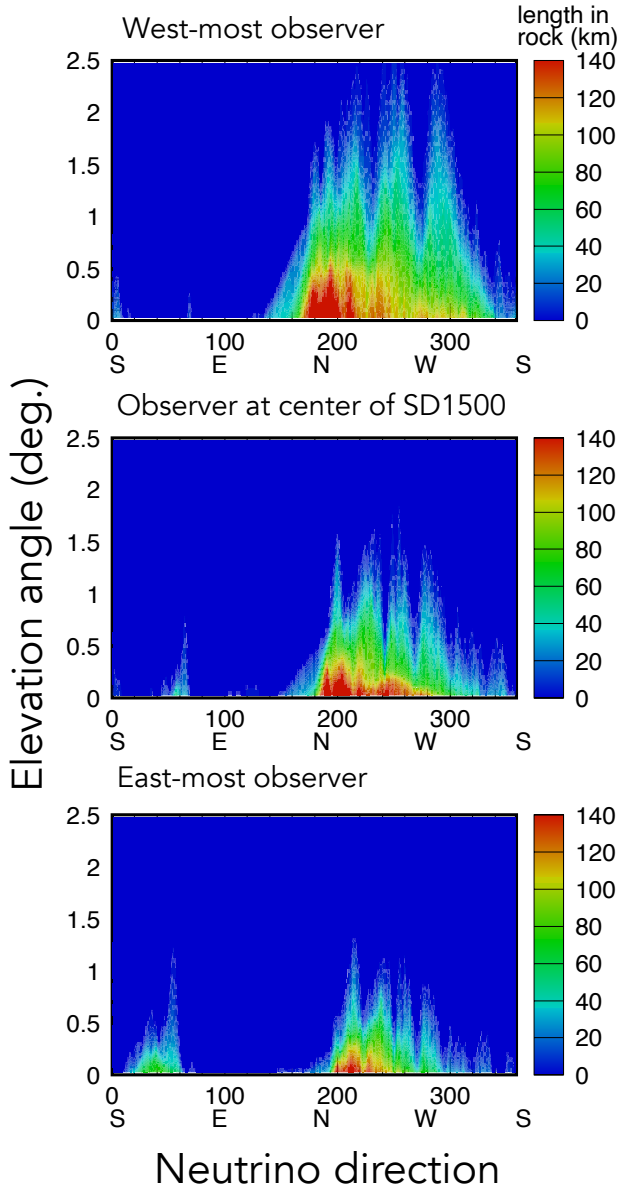
Backup

Role of topography at Auger site



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

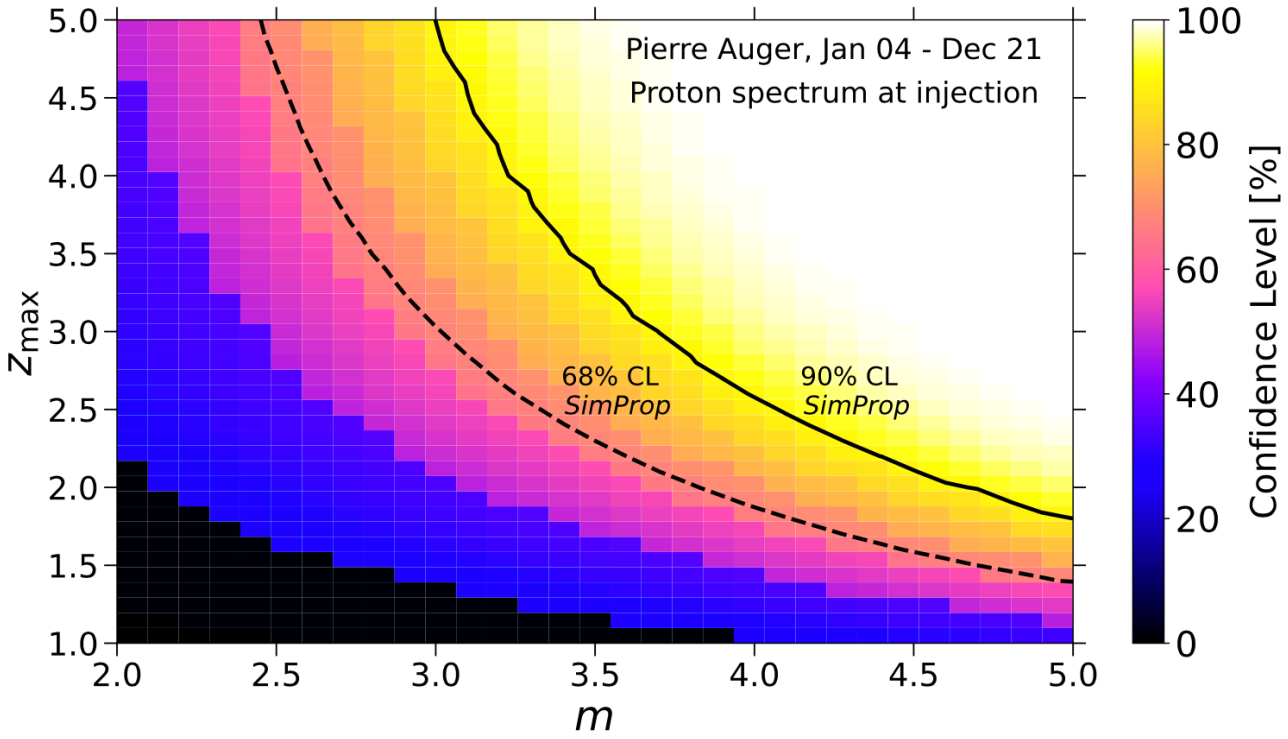
Length in rock (km) vs direction for observers at different locations in the SD1500



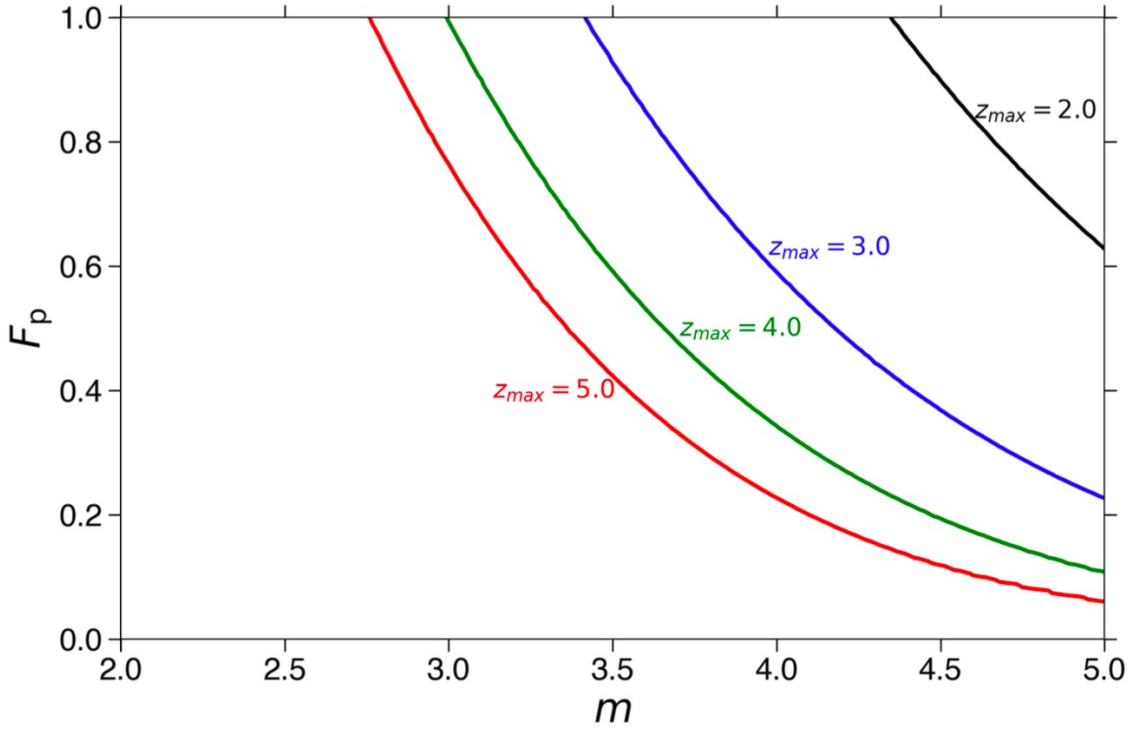
Constraints on sources of UHECR from Auger UHEν limits

Constraints on source evolution:

sources evolving as $(1+z)^m$ up to z_{max}

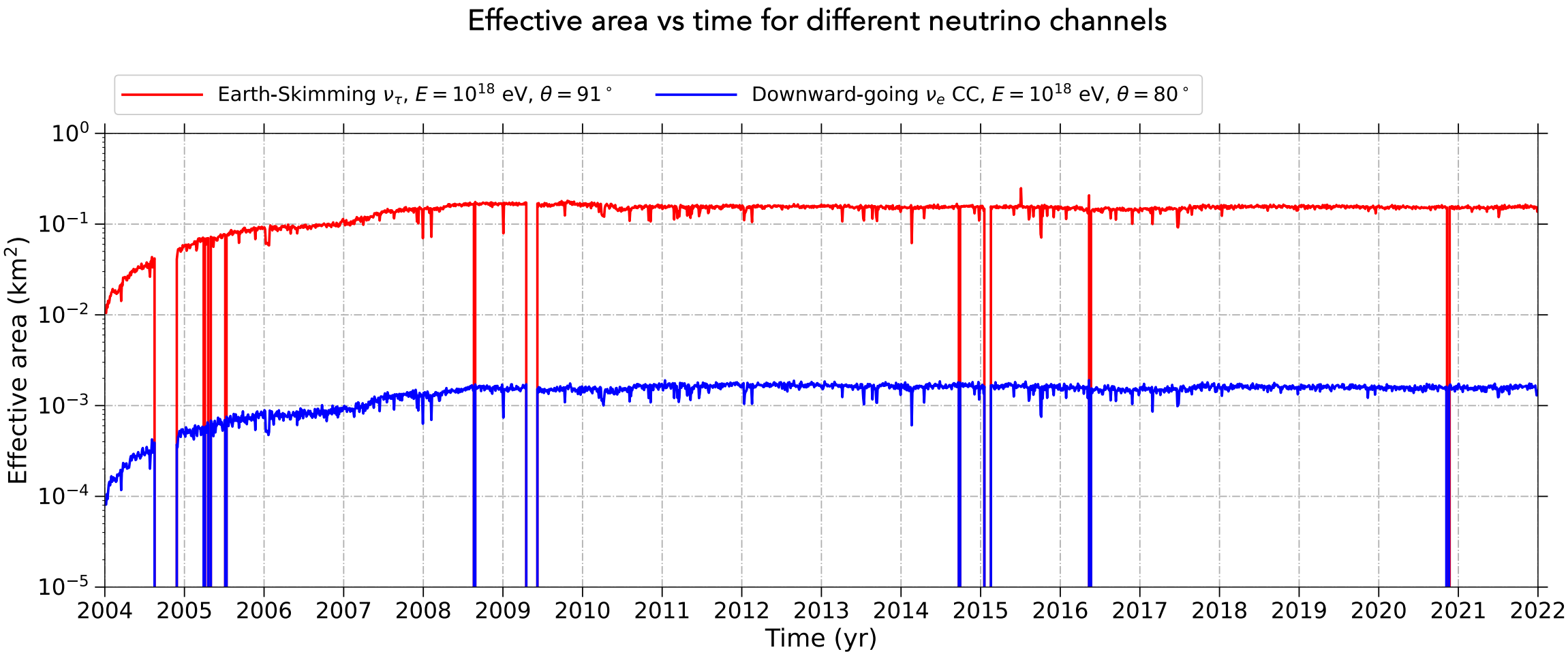


Constraints on proton fraction F_p



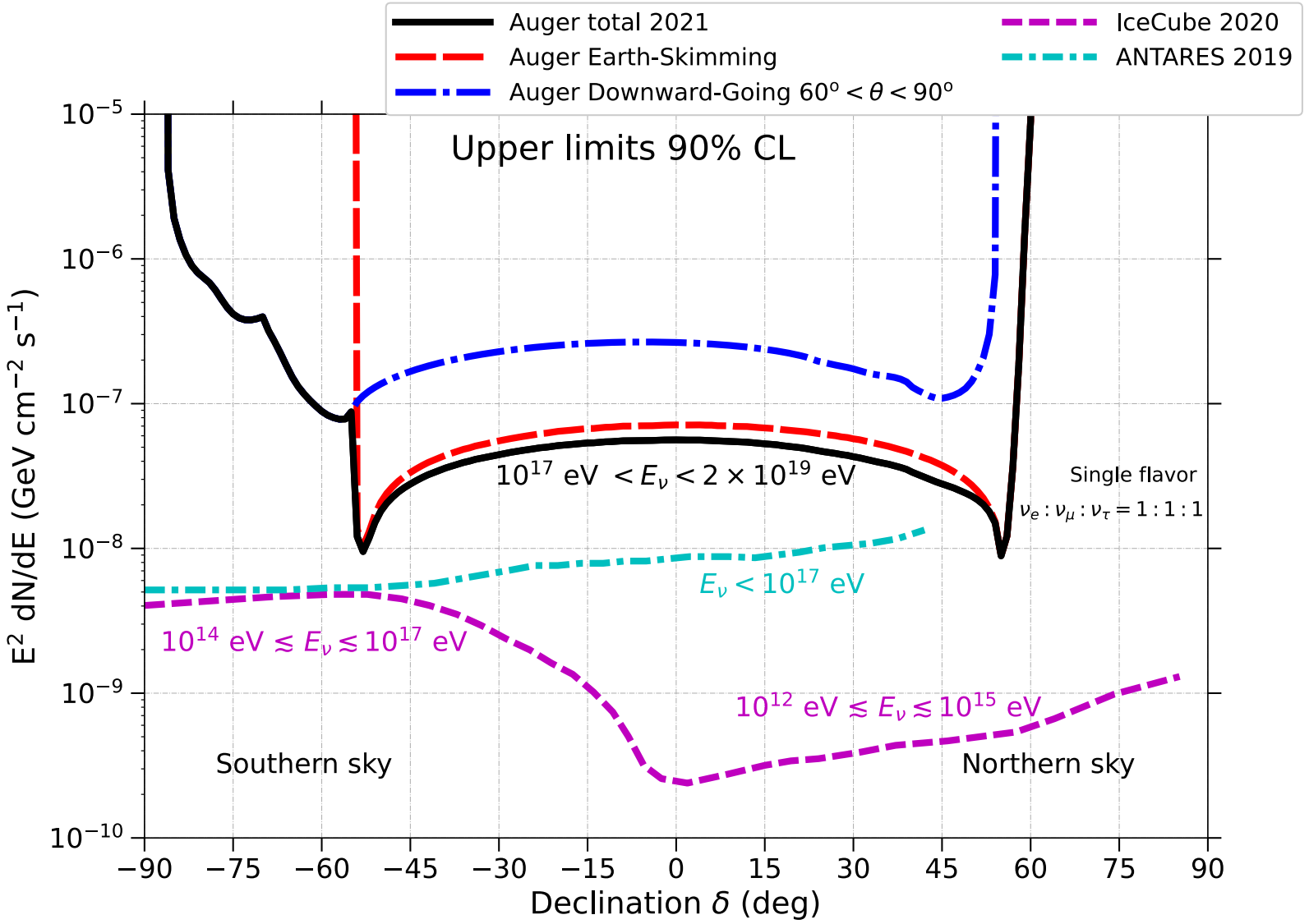
C. Petrucci for Auger
PoS(ICRC2023)1520

Stability of the SD1500 array of the Pierre Auger Observatory



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

Upper limits to steady point-like sources of UHE neutrinos



Limits complementary to those of IceCube and ANTARES

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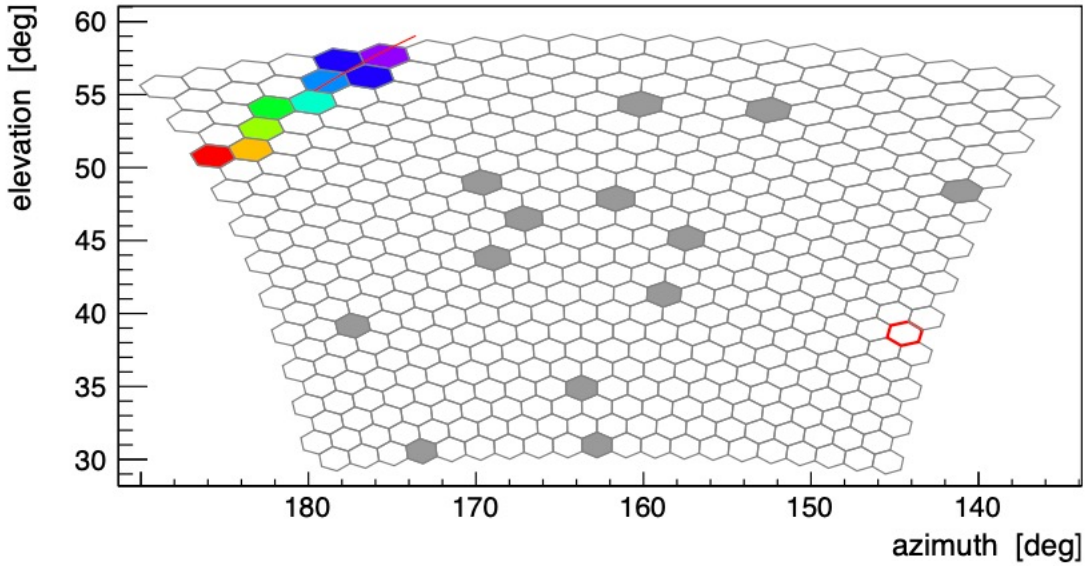
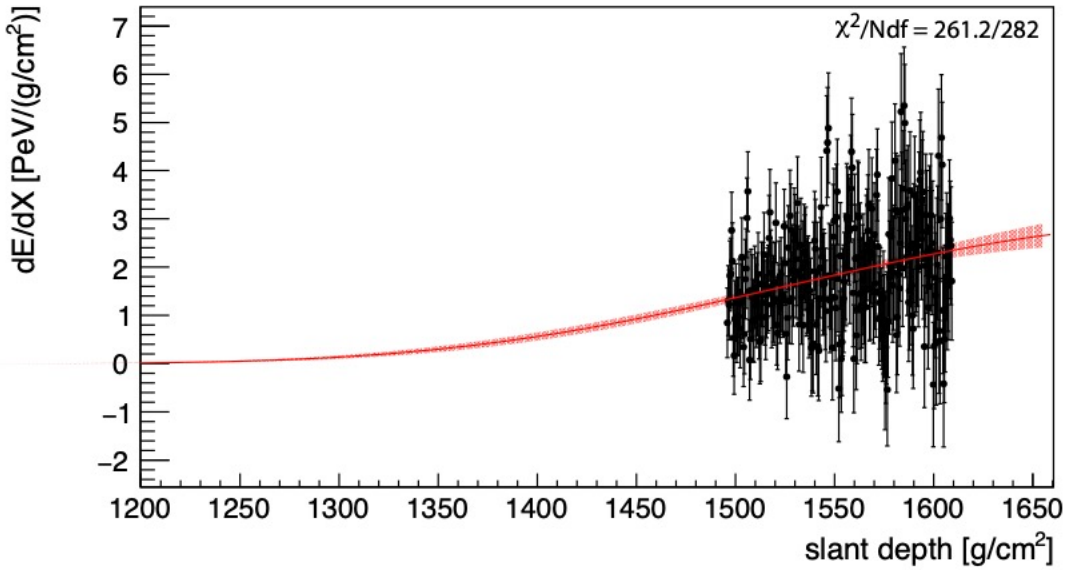
Background Monte Carlo event





Monte Carlo event θ=83°
reconstructed as downward- and upward-going

Reconstruction favors downward-going
$L_{down} > L_{up} \Rightarrow \ell = 0$