

PIERRE  
AUGER  
OBSERVATORY



Istituto Nazionale di Fisica Nucleare  
SEZIONE DI LECCE



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## The Fifth Gravi-Gamma-Nu Workshop 9-11 Oct 2024

# Multimessenger studies at the Pierre Auger Observatory

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<sup>a</sup>Università del Salento and INFN Lecce

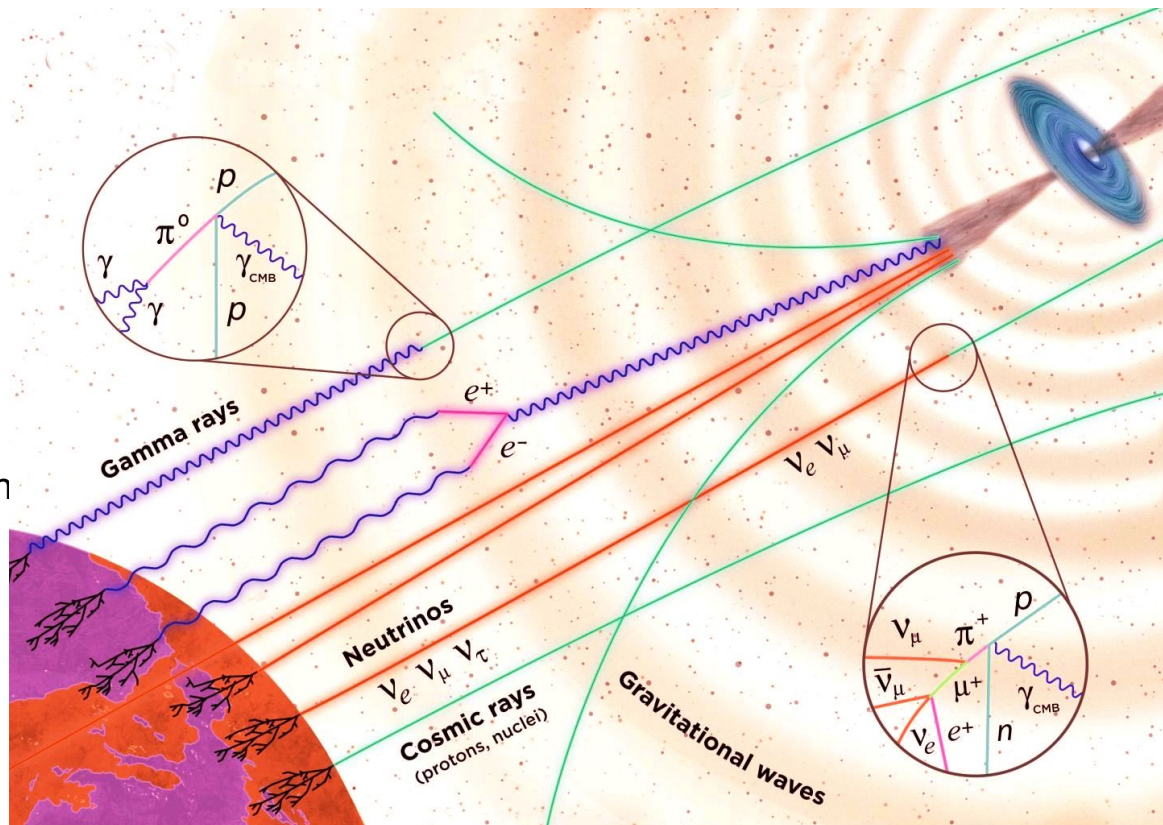
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# Multi-Messenger astrophysics

Ultra-High-Energy Cosmic Rays observatories have sensitivity to photons and neutrinos in a wide energy range

It is possible to do diffuse and targeted searches of neutral messengers at the highest energies

Unique contribution to Gravitational Wave follow-ups in the multi-wavelength search in combination with mergers



# The Pierre Auger Observatory

## Surface Detector (SD):

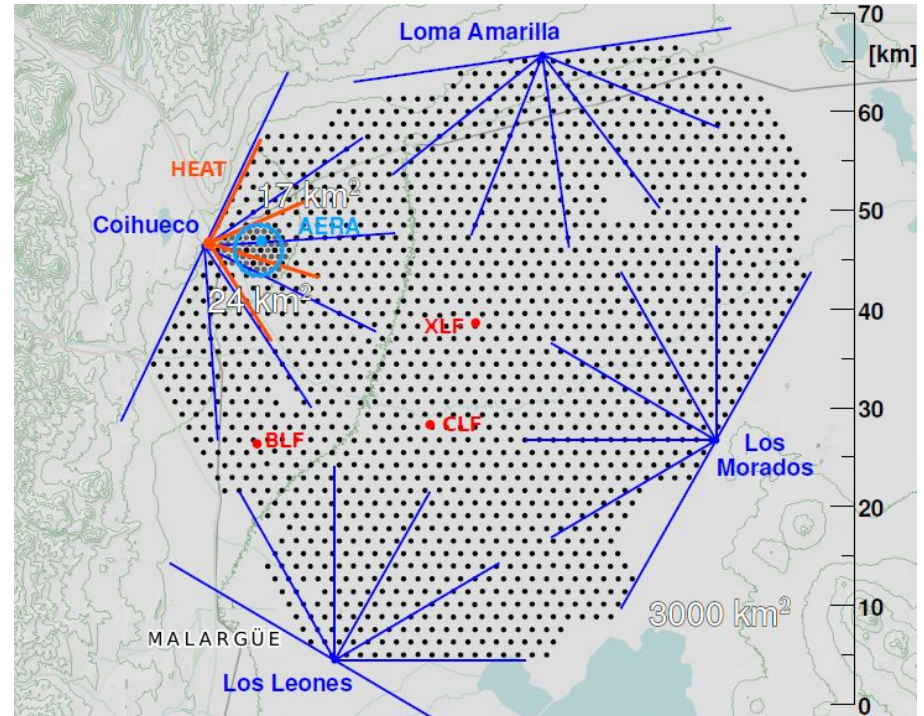
- 1600 Water Cerenkov Detectors at 1.5 km (~3000 km<sup>2</sup>) + 31 stations at 0.75 km
- measure particle density at the ground

## Fluorescence Detector (FD):

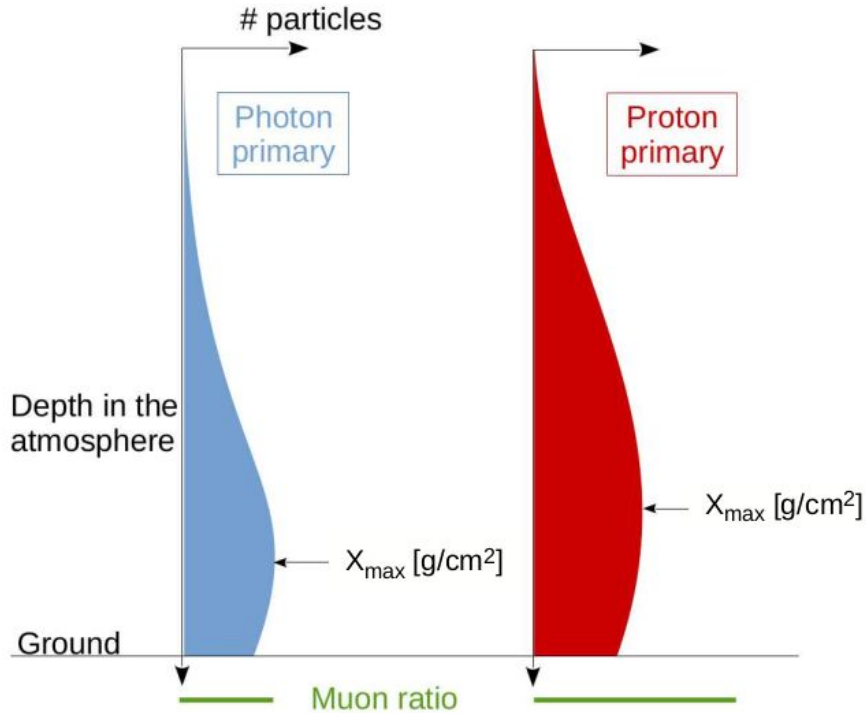
- 24 telescopes in 4 sites (FoV 1° - 30°) + 3 high elevation telescopes (FoV 30° - 60°)
- longitudinal profile with a calorimetric measurement

Precise measurement using **hybrid (SD+FD)** technique

AugerPrime adding new detectors (SSD, Radio antennas, Underground Muon Detectors) and faster electronics to increase our sensitivity



# UHE Photon induced air showers



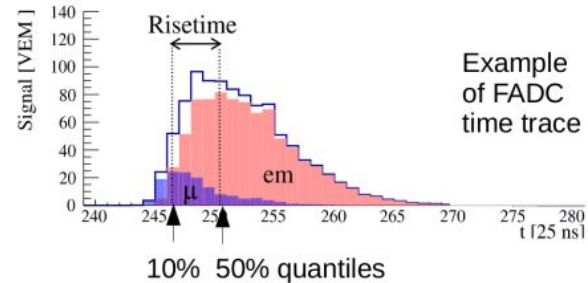
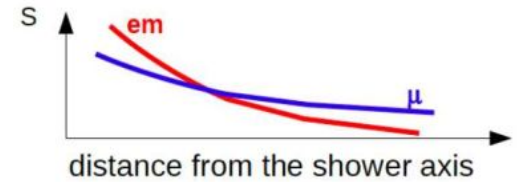
Photons interact deeper in the atmosphere and develop a nearly pure electromagnetic shower (wrt Cosmic Rays)

→ higher  $X_{\max}$

→ steeper LDF

→ smaller footprint

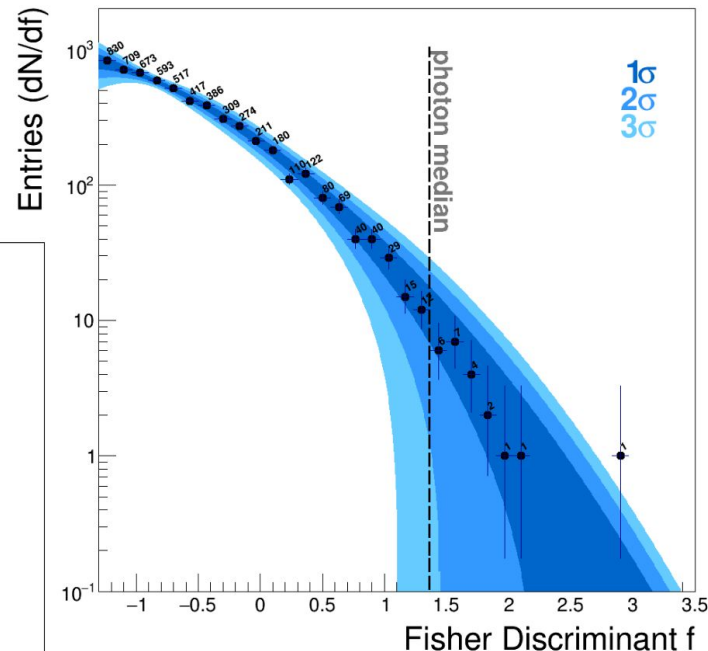
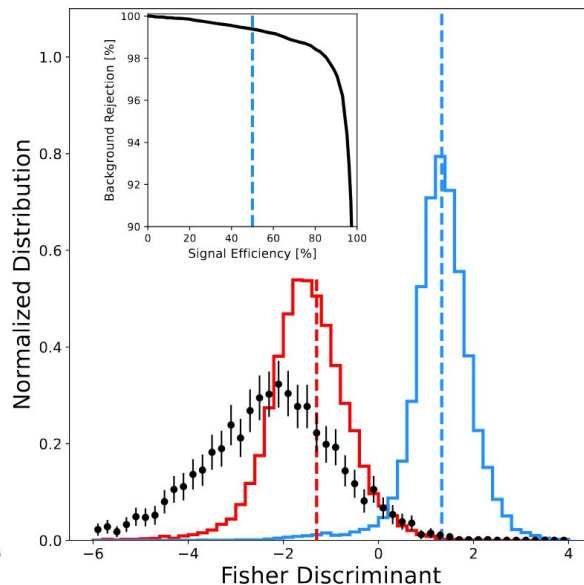
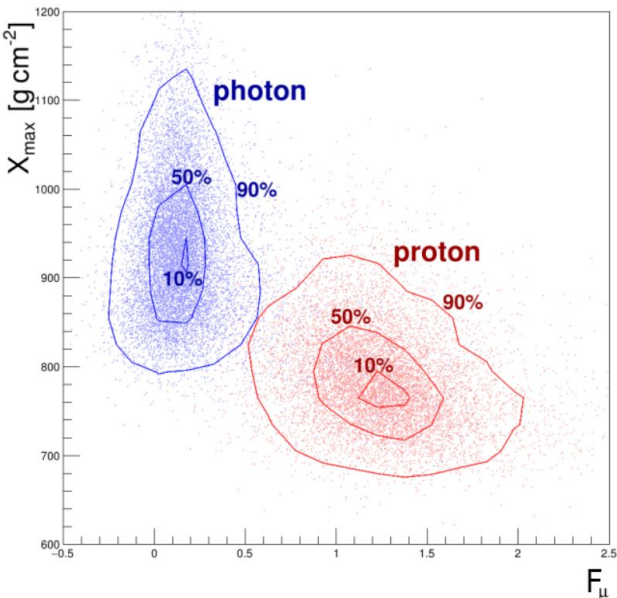
→ larger signal



Example of FADC time trace

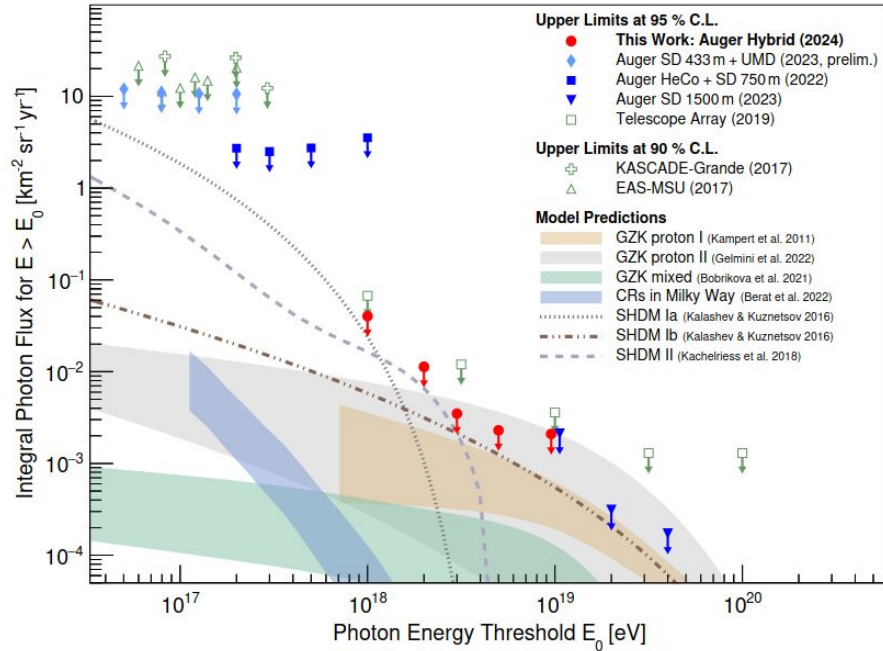
# UHE Photon above 1 EeV using shower universality

- $F_{\mu}$  calculated using a model based on shower universality, used as a proxy for muon content
- Signal efficiency 50%, bkg rejection 99.9%
- **Data:** 1 Jan 2005 - 31 Dec 2017
- **Exposure**  $\sim 1000 \text{ km}^2 \text{ sr yr}$



**22** candidates, consistent with the expectation of  $30 \pm 15$ , estimated using 5% data

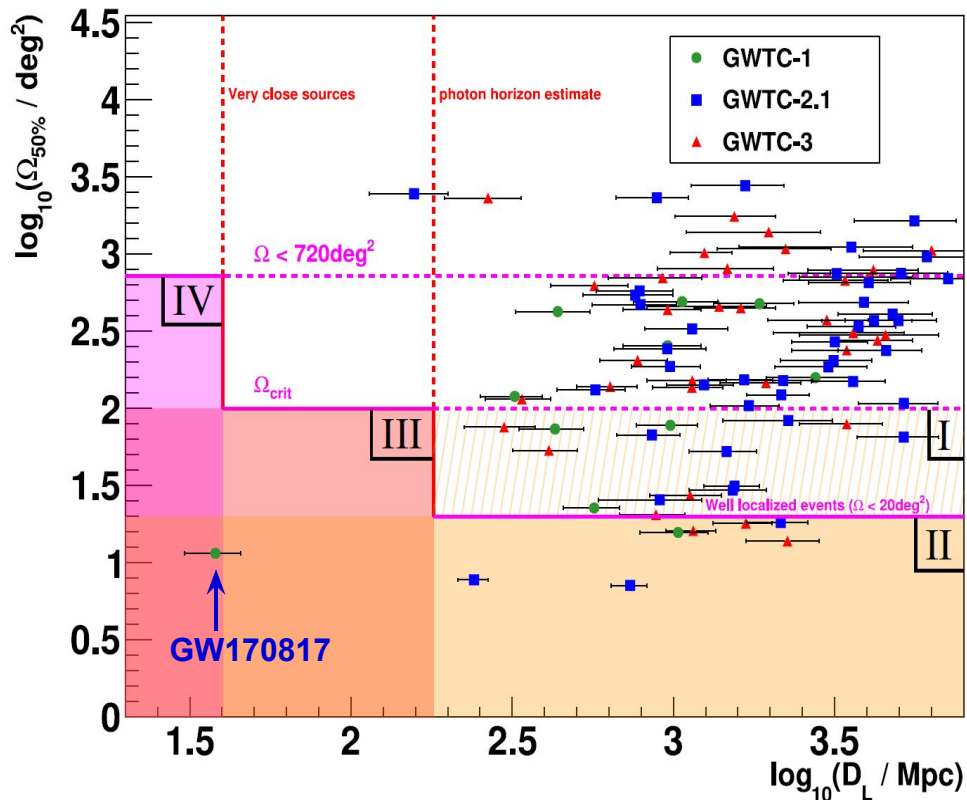
# Photons upper limits



PoS(ICRC2023)238 SD 433 m + UMD  
Ap. J. 933 (2022)125 SD 750 m + HeCo  
arXiv:2406.07439 Auger hybrid (accepted PRD)  
PoS(ICRC2019)398 Auger SD 1500 m

- Limits across 4 decades in energy
- Disfavouring top-down models
- Constraining mass and lifetime of dark matter particles
- Constraining cosmogenic fluxes (need more exposure)
- With Auger Phase II more information to better discriminate the primary particle

# GW follow-up photon searches



- $(D_L < \infty \quad \text{and} \quad \Omega_{50\%} < 100 \text{ deg}^2)_{\text{short}}$  “class I”
- $(D_L < \infty \quad \text{and} \quad \Omega_{50\%} < 20 \text{ deg}^2)_{\text{long}}$  “class II”
- $(D_L < 180 \text{ Mpc} \quad \text{and} \quad \Omega_{50\%} < 100 \text{ deg}^2)_{\text{long}}$  “class III”
- $(D_L < 40 \text{ Mpc} \quad \text{and} \quad \Omega_{50\%} < 720 \text{ deg}^2)_{\text{long,short}}$  “class IV”.

Search for time directional coincidence with 91 GW events from LIGO/Virgo

4 classes defined based on localization and distance

2 time windows: “short”  $\Delta t$  1000s centered at  $t_{\text{GW}}$  and “long”  $\Delta t$  1 day after it

Class IV best for  $\gamma$  sources, Classes I-II-III may point to new physics

# GW follow-up photon searches

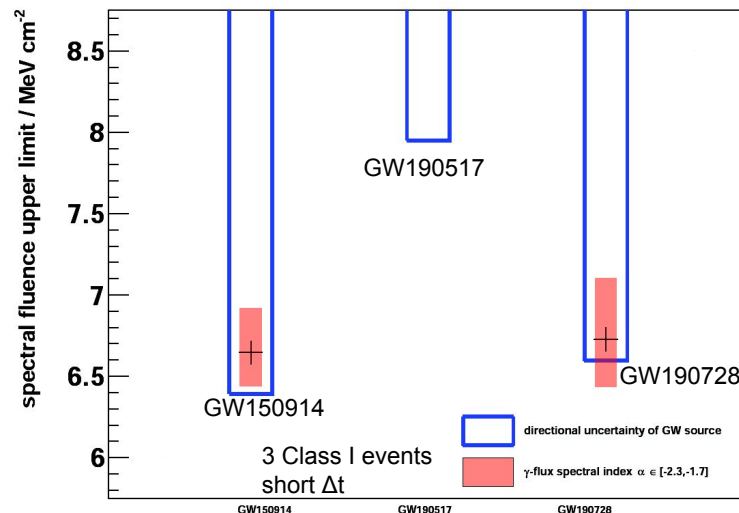
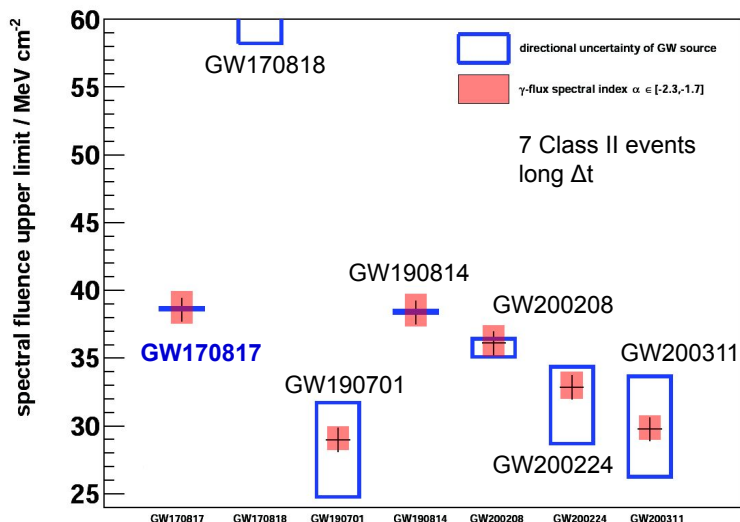
7 events in Class II, 3 in Class I

No candidate found for any GW event → flux upper limits

First ever limits on  $\gamma$  from GW at UHE

$$\frac{d\Phi_\gamma^{\text{GW}}}{dE_\gamma}(E_\gamma) = k_\gamma E_\gamma^\alpha \longrightarrow k_\gamma^{\text{UL}} = \frac{N_\gamma^{\text{UL}}}{\int_{E_0}^{E_1} dE_\gamma E_\gamma^\alpha \mathcal{E}(E_\gamma, \theta_{\text{GW}}, \Delta t)}$$

$$\mathcal{F}_\gamma^{\text{UL}} = \int_{t_0}^{t_1} \int_{E_0}^{E_1} dt dE_\gamma E_\gamma \frac{d\Phi_\gamma^{\text{GW}}}{dE_\gamma}$$





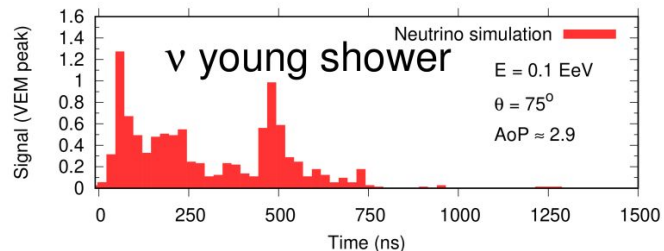
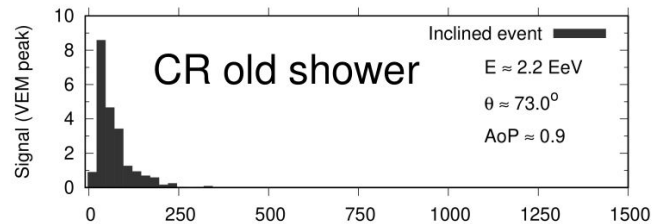
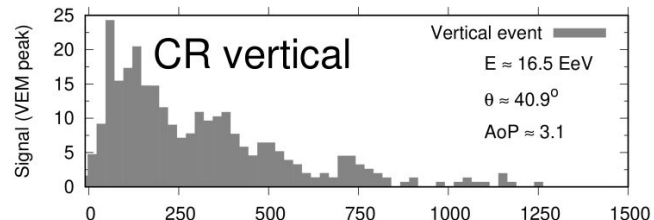
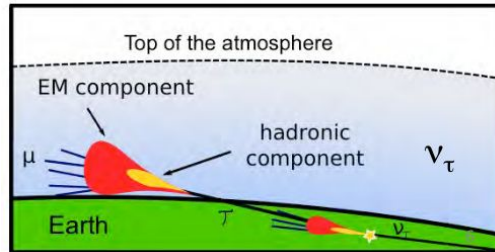
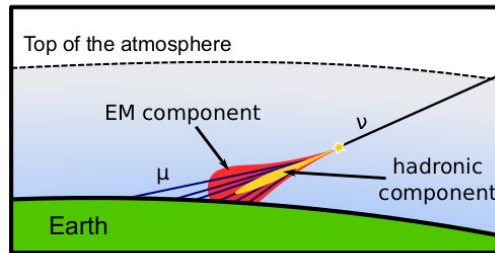
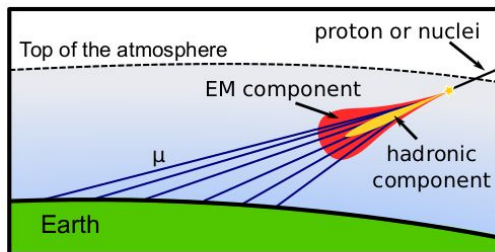
# Inclined shower and UHE Neutrino signature

The EM component in inclined **CR** showers (zenith  $> 60^\circ$ ) almost completely absorbed by the atmosphere.

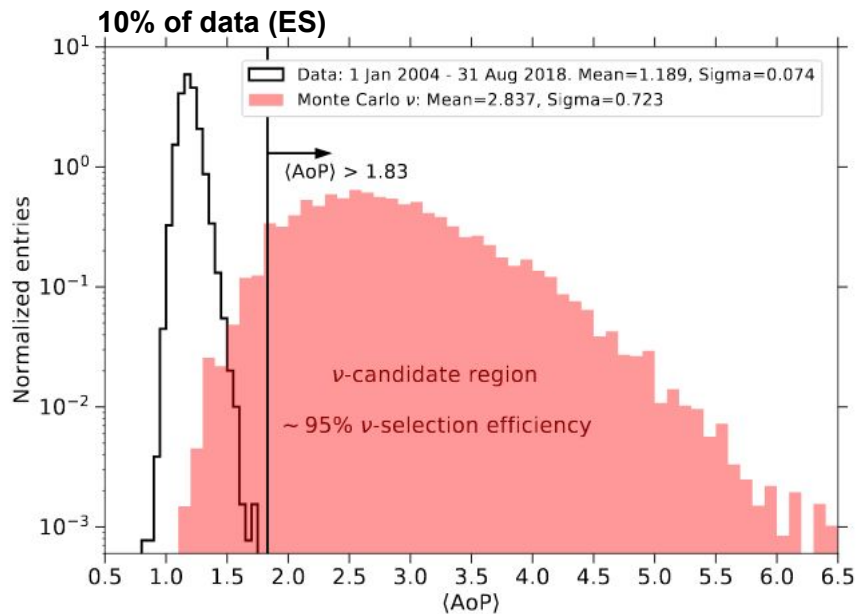
On the other hand, neutrinos have younger shower  
 → broader signal in inclined event can be a neutrino signature

3 main channels:

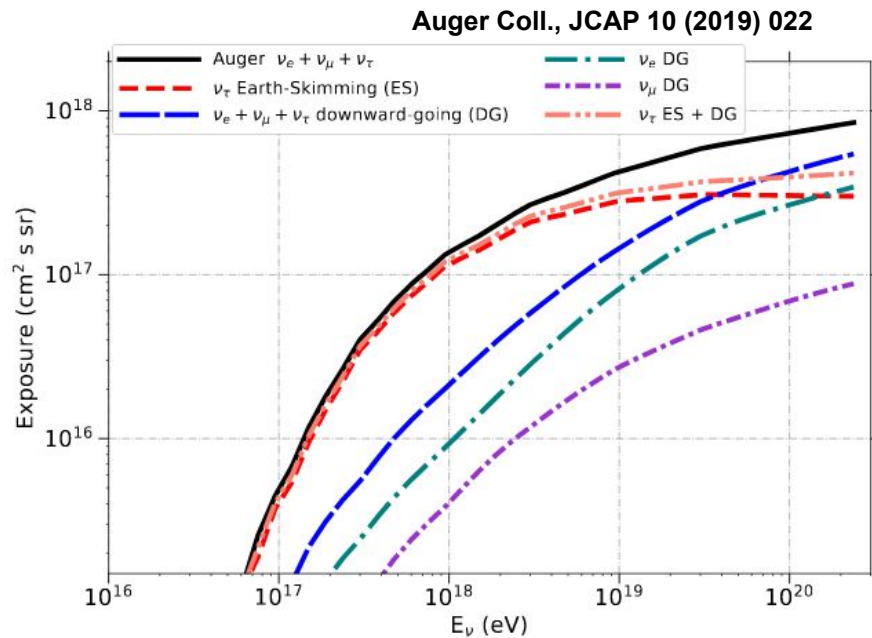
- **Down-Going Low** ( $60^\circ$ - $75^\circ$ )
- **Down-Going High** ( $75^\circ$ - $90^\circ$ )
- **Earth-Skimming** ( $90^\circ$ - $95^\circ$ )



# UHE Neutrino data selection



- **Area over Peak** is the sensitive variable
- Cut tuned on all the different channels
- Expected <1 bkg event in 50 years

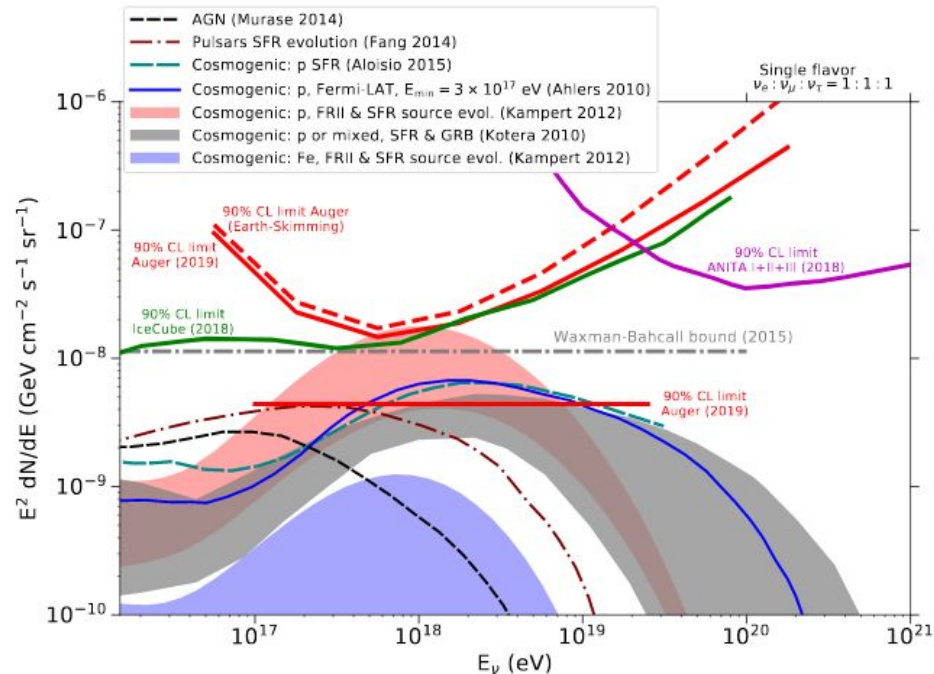


- Exposure dominated by the ES channel
- DG channels become relevant at higher energies (ES neutrinos absorbed in Earth)

# Diffuse flux limits on UHE Neutrino

- **NO candidates found**
- Maximum sensitivity at  $\sim 1 \text{ EeV}$
- Integral upper limits constraints different models.
- Expected up to **6** events in case of pure proton composition, **2** in case of p or mixed, **0.4** in case of pure iron
- Our increase in exposure allow us to disfavour pure proton models

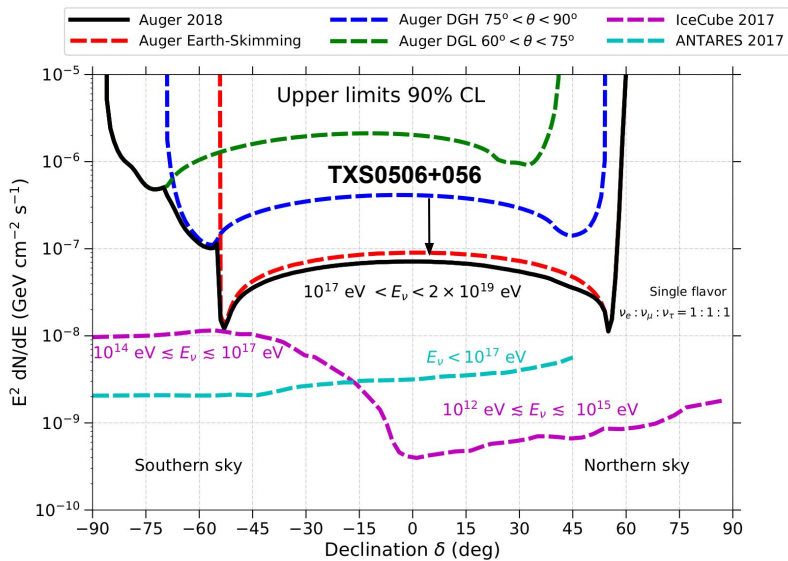
Auger Coll., JCAP 10 (2019) 022



# Point like sources of UHE Neutrino

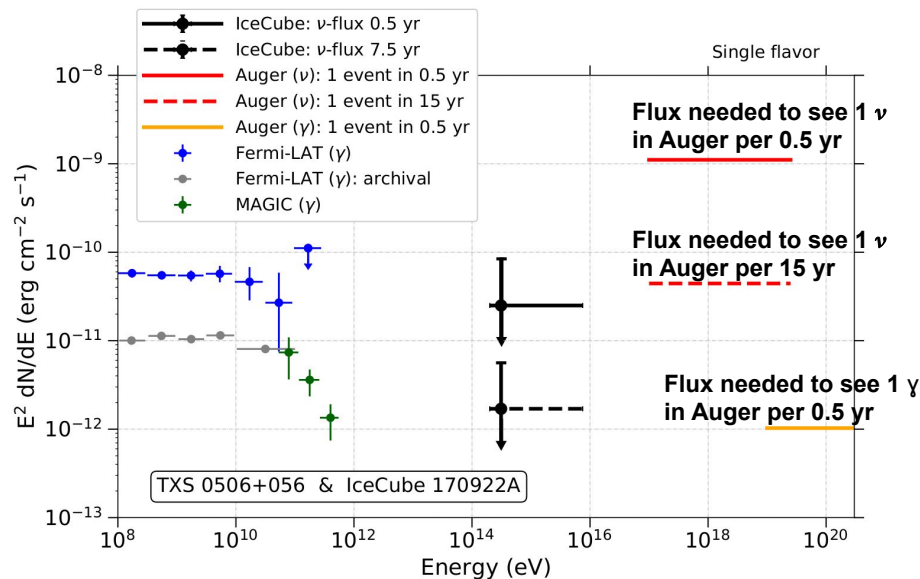
Sensitivity strongly depends on source location and event timing

TXS 0506+056 declination  $\sim 5.7^\circ$ , not optimal in all declination channels



Auger Coll., JCAP 11 (2019) 004

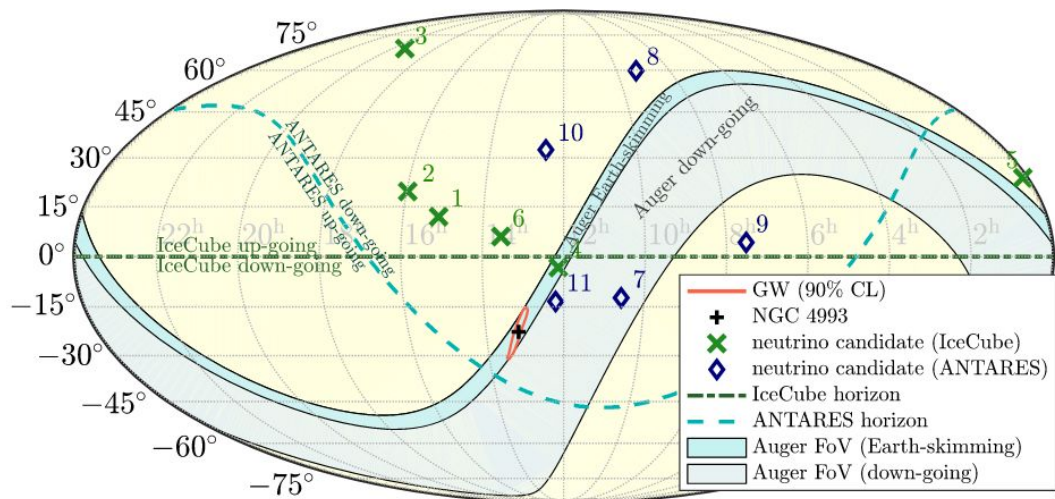
Auger Coll., ApJ 902 (2020) 105



TXS 0506+056 was not in our FoV at the time of neutrino detection

Reference flux assuming 1 events in Auger per 0.5 and 15 years

# Neutrino follow-up searches: GW170817

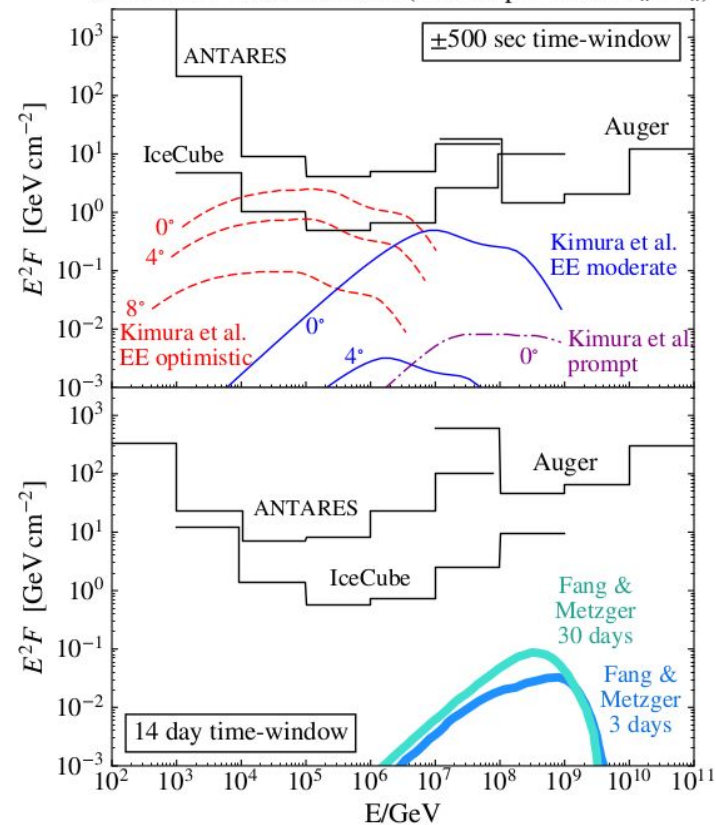


Source in the field of view of ES neutrinos

No candidate found in short ( $\pm 500$ s) or long (14 days) time windows

Non observation is consistent with the expectation from a sGRB viewed at off-axis angle  $> 20^\circ$

GW170817 Neutrino limits (fluence per flavor:  $\nu_x + \bar{\nu}_x$ )

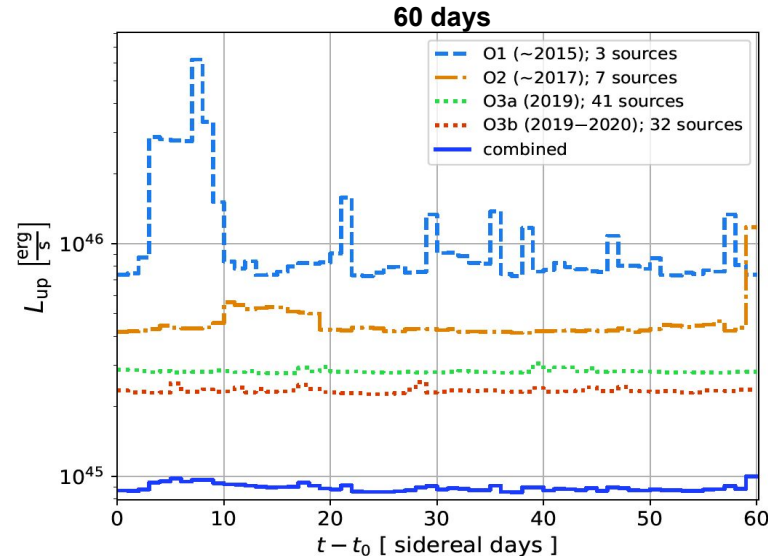
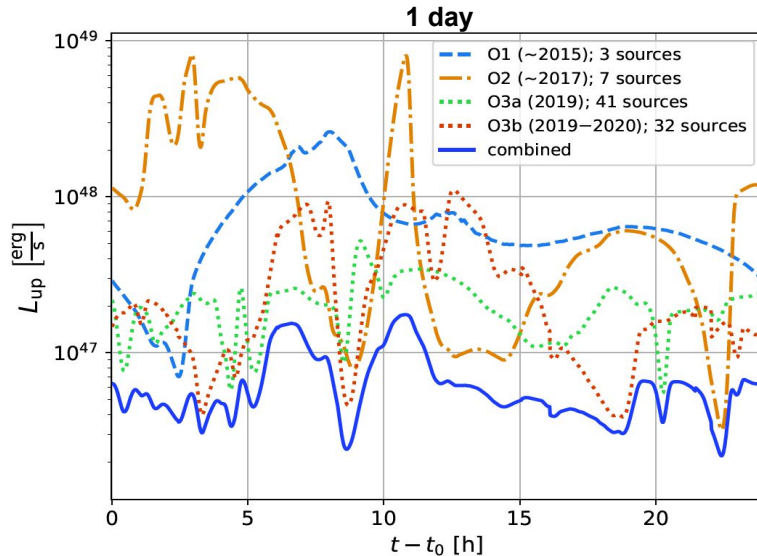


# BBH follow-up: stacked $\nu$ searches

Look for time and directional coincidence with 93 BBH mergers from LIGO/Virgo runs O1-O3

No candidates found for any event inspected

Limits on the total energy emitted in neutrinos is  $<5.2 \times 10^{51}$  erg  $\rightarrow$  more than 2 orders of magnitude lower than the radiated GW energy



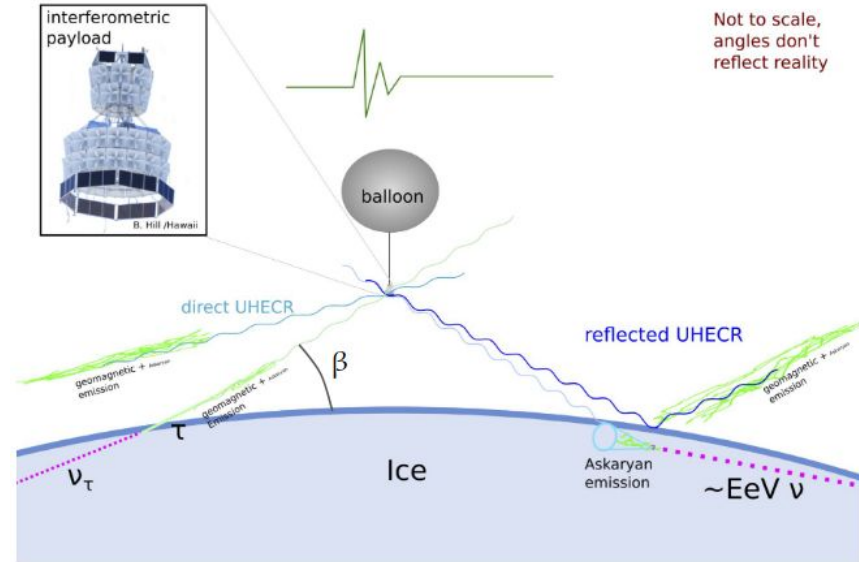
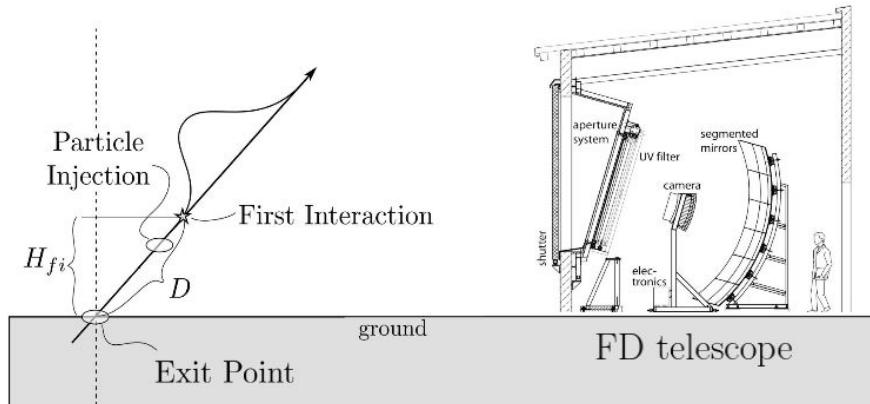
# Search for FD up-going air showers

Two “anomalous” events detected by **ANITA** with non-inverted polarity  
→  $E \sim 0,2 \text{ EeV}$  exit angle  $\sim 30^\circ$

Fervent debate about the interpretation

Highly inclined events cannot be observed with SD  
→ Dedicated search using 14 years of FD data

FD sensitivity depends on  $E$  and  $H_{fi}$  of the primary particle

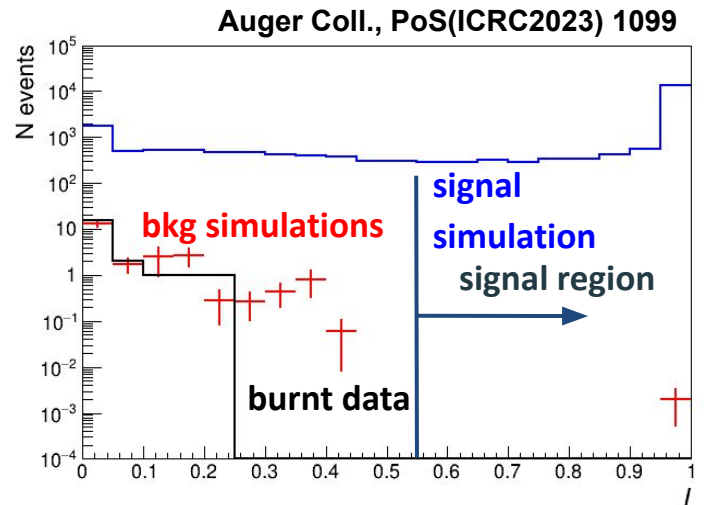
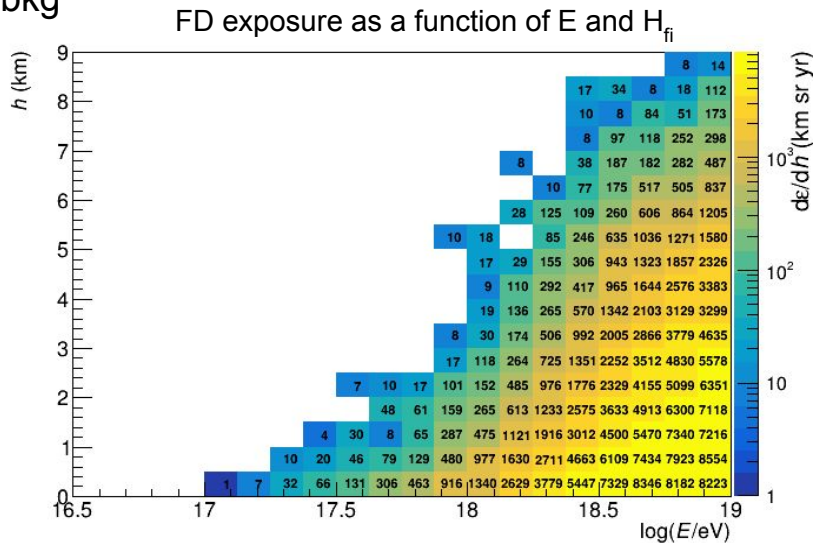


# FD sensitivity and candidate selection

Upward-going showers can be misreconstructed as downgoing, so each shower in both data and simulation is reconstructed both in “upward” and downward mode and then compared

Good agreement between data and bkg, expected  $\sim 0.27$  in the full sample

→ 1 “candidate” found in the full sample, compatible with the expected bkg



$$l = \frac{\arctan(-2 \log(L_{\text{down}} / \max\{L_{\text{down}}, L_{\text{up}}\}) / 50)}{\pi/2}$$

$L_{\text{down(up)}}$  likelihood of the best downward (upward) reconstruction  
 $l = 0$  downward favoured

$l \rightarrow 1$  upward favoured

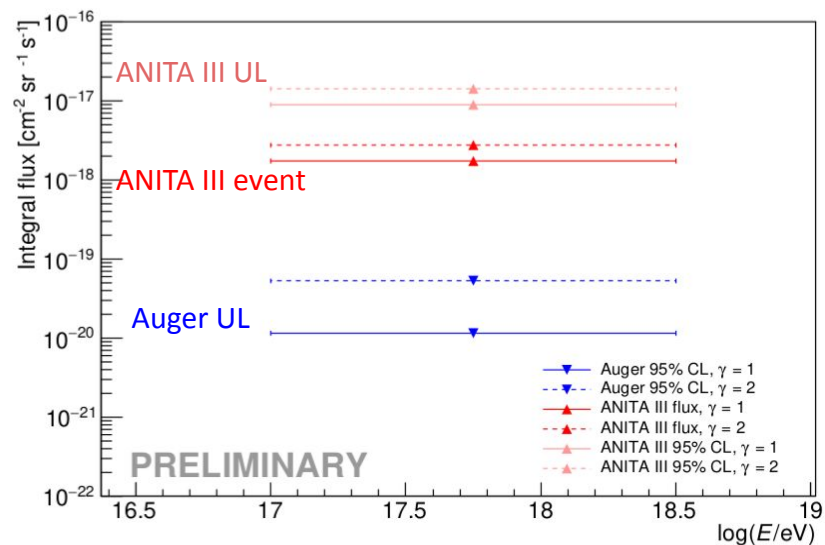
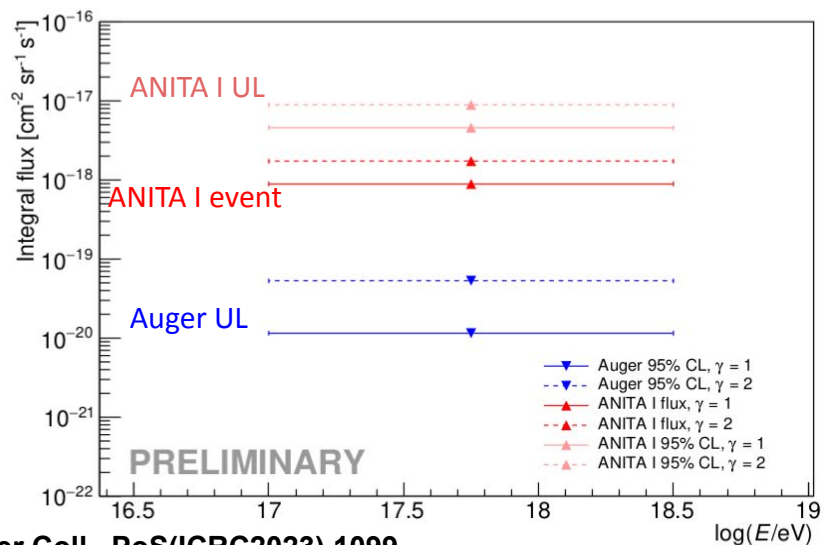


# Comparison with ANITA observations

Joint effort with members of the ANITA Collaboration to make an analytic calculation of ANITA exposure for the two anomalous events between  $10^{17}$  eV and  $10^{18.5}$  eV with  $\theta \in [110^\circ, 130^\circ]$

Auger upper limits are 100 and 30 times lower than ANITA fluxes (red) in case of  $E^{-1}$  and  $E^{-2}$  spectra respectively

2-D Auger exposures can also be used to study interesting BSM scenarios (see [PoS\(ICRC2023\) 1095](#))



# Conclusion

- The Pierre Auger Observatory participates in the joint international effort within the multi-messenger astrophysics community
- Actively sends and receive alerts to/from the GCN; SD data stream is also sent to the AMON and Deeper Wider Faster (DWF)
- We have excellent sensitivity to photons and neutrinos in the EeV range
  - the non-observation provides important results, setting stringent limits and constraining exotic scenarios
- Waiting for AugerPrime high-quality data
  - multi-hybrid events with WCD, SSD, RD, UMD
  - better separation of shower components
  - improved photons/hadrons discrimination

**Thank you for your attention!**