EPS-HEP CONFERENCE
07-11 JULY, 2025
PALAIS DU PHARO
MARSEILLE, FRANCE

# Investigating upward-going showers using the Fluorescence Detector of the Pierre Auger Observatory

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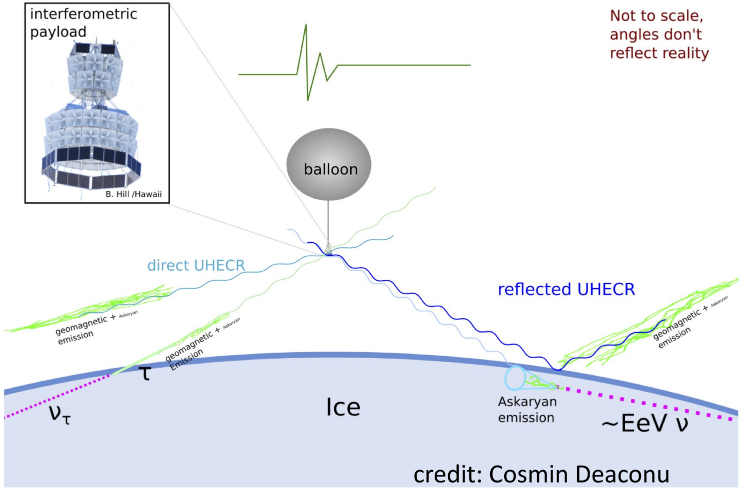
# Outline

- Motivation: the ANITA anomalous events
- Search for upward-going showers with FD
- Comparison of Auger upper limits with ANITA observations
- Tau-induced air showers scenario
- Two simple BSM models

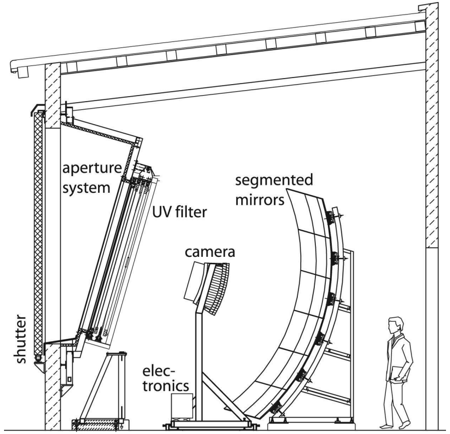
# ANITA anomalous events

- Observation of two steeply upward-going air showers with non-inverted polarity, consistent with the direct detection of upward-going showers by ANITA[1]
- $E_{1,2} > 0.2$ EeV
- zenith $\theta_1 \simeq 117°$ and $\theta_2 \simeq 125°$ (elevations 27° and 35°)
- Challenging to reconcile with Standard Model predictions




The Fluorescence Detector of the Pierre Auger Observatory is sensitive to upward-going air showers

➢ Simulate and reconstruct upward-going air-showers within the Offline framework to calculate the FD exposure to upward-going air showers

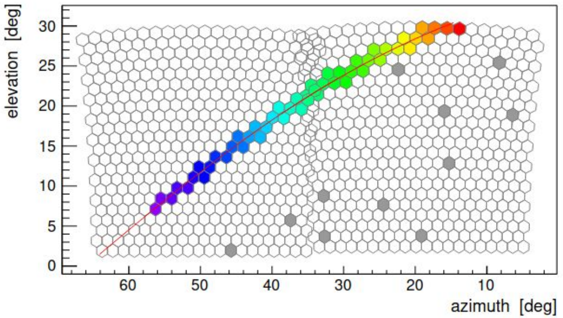


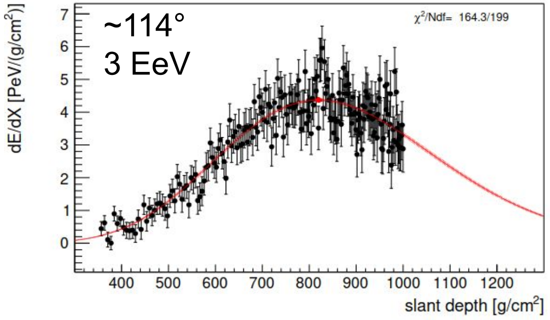

[1] P.W. Gorham et al. (ANITA Collaboration), *Phys. Rev. Lett.*, **121**, 161102, 2018

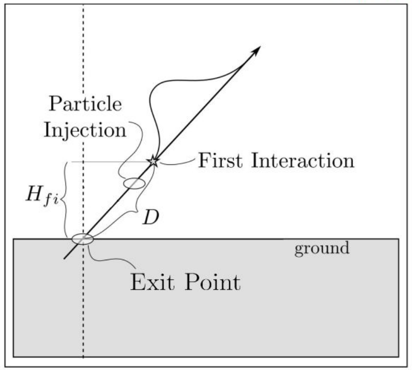
# Signal simulations

- Actual status of all components of the FD detector and realistic atmospheric conditions taken into account in the simulation
- Primary protons, easily adaptable to other scenarios
- Energy → log(E/eV) ∈ [16.5, 19] , 2 x $10^7$ showers simulated with $E^{-1}$ spectrum
- Very important to calculate the FD detection efficiency with high precision below $10^{17.5}$ eV for the comparison with ANITA
  - 4.5 x $10^7$ additional showers below $10^{17.5}$ eV
  - more accurate exposure calculation at the lowest energies
- Zenith → θ ∈ [110°, 180°] (elevation [20°, 90°])
- Generation area → 100 x 100 $km^2$
- Height of first interaction → [0, 9] km above ground

From [2]




[2] A. Abdul Halim et al. (Pierre Auger Collaboration), *Phys. Rev. Lett.*, **134**, 121003, 2025

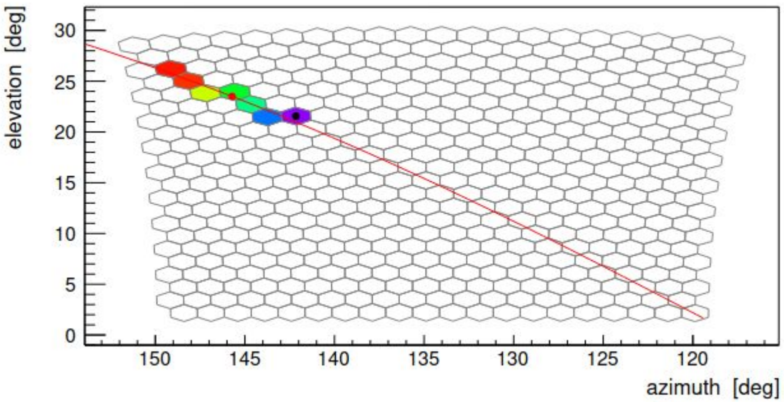
# Background simulations

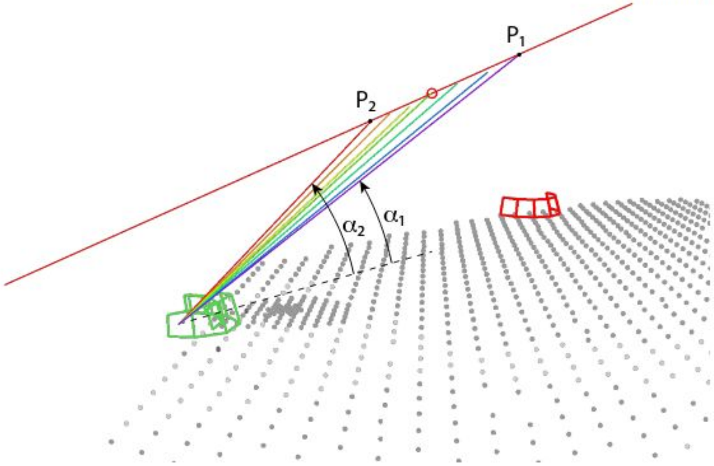
From [2]

- Downward-going Cosmic Rays can mimic upward-going track in the FD camera
- For example an highly-inclined event landing behind the telescope can generate an upward-going track
- Primaries → protons + helium, nitrogen and iron nuclei, re-scaled to the CR spectrum
- Energy → log(E/eV) ∈ [17, 20]
- 2.5 x $10^8$ showers simulated:

  → 1.6 x $10^8$ with zenith θ ∈ [0°, 100°]

  → 0.9 x $10^8$ with zenith θ ∈ [60°, 100°]

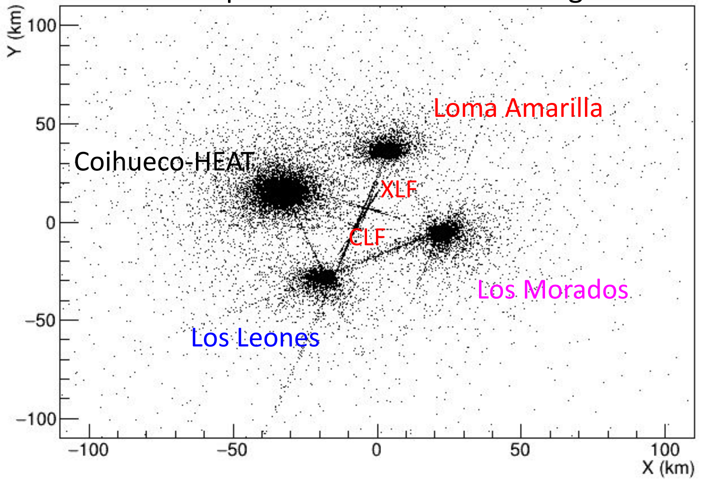


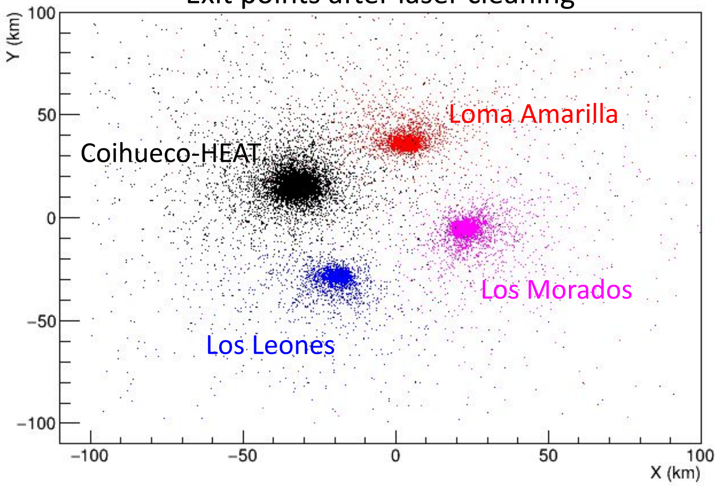
# Data cleaning

- Blind analysis on 10% of FD data from 14 years of operations (2004-2018, 0.8 x $10^6$ events) to identify and remove untagged laser events used for atmospheric monitoring
- Pre-selection cuts applied on data and simulations requiring
  - successful reconstruction and good atmospheric conditions
- Laser removed based on their specific GPS time tag and position inside the SD array

Exit points before laser cleaning




Exit points after laser cleaning

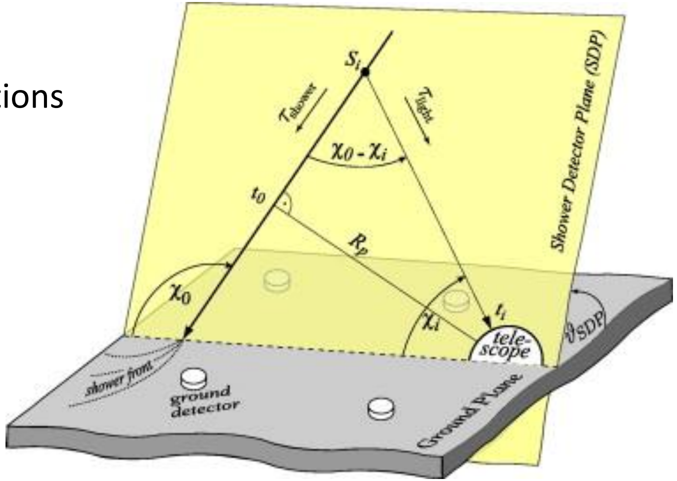



Images from [3] E. De Vito for the Pierre Auger Collaboration, *PoS(ICRC2023)*1099

# Reconstruction and event selection

- Data and simulations reconstructed with an iterative procedure combining the profile reconstruction with the geometry, testing upward (negative $\chi_0$) and downward (positive $\chi_0$) solutions
- Selection criteria requiring compact pattern of pixels in the FD camera, θ > 110° and observed fraction of longitudinal profile > 80 g cm$^{-2}$
- The likelihood of the combined fit, $L_{down}$ and $L_{up}$, can be used to compare the two reconstructions

From [4]




- Definition of a new variable for the comparison of the two reconstructions

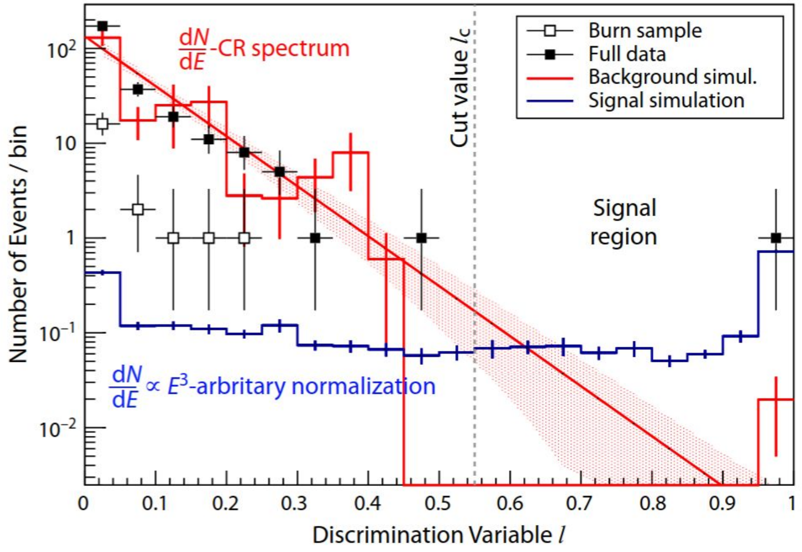
$$l = \frac{\arctan\{\ln[\max(L_{\rm up}, L_{\rm down})/L_{\rm down}] \times \zeta\}}{\pi/2}$$

$0 \leq l \leq 1$, if $l = 0$ downward favoured, if $l \rightarrow 1$ upward favoured

[4] D. Kuempel, K.-H. Kampert, M. Risse, *Astrop. Phys.*, **30**, 4, 2008

# Expected background and signal identification

- Distribution of variable *l* for data (black, 10% of the total) signal simulations (blue) background simulations (red)
- Background weighted to CR spectrum and scaled to the burn sample fraction ⟶ good agreement with data
- Cut is at ***l* > 0.55** with expected background for the full sample of $\mathbf{n_{bkg} = 0.27 \pm 0.12}$




From [2]

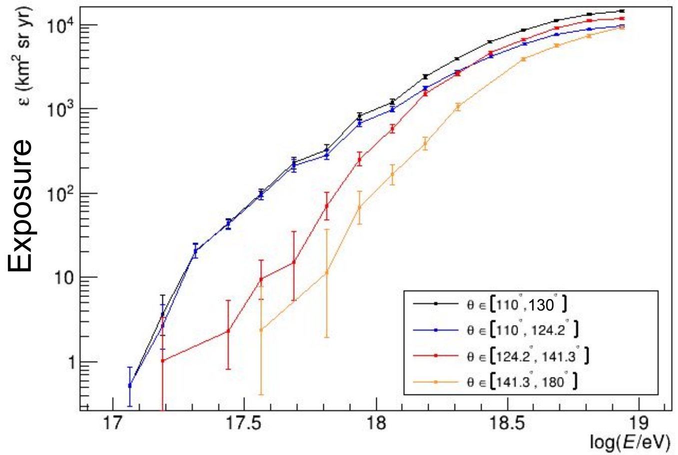
$$l = \frac{\arctan\{\ln[\max(L_{\mathrm{up}}, L_{\mathrm{down}})/L_{\mathrm{down}}] \times \zeta\}}{\pi/2}$$

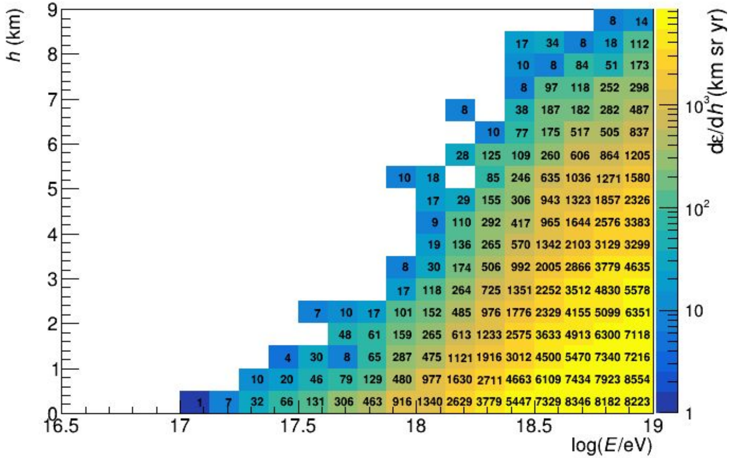
*l* = 0 downward favoured

*l* ⟶ 1 upward favoured

# Exposure and upper limits

From [3]




- One event found after the unblinding, consistent with expected background
- FD exposure as a function of the shower energy (top), calculated for different zenith sub-ranges
- Exposure as a function of the shower energy and the height of first interaction (bottom)
- Using Rolke[5], the integral upper limit to the flux of upgoing showers above $10^{17}$ eV:

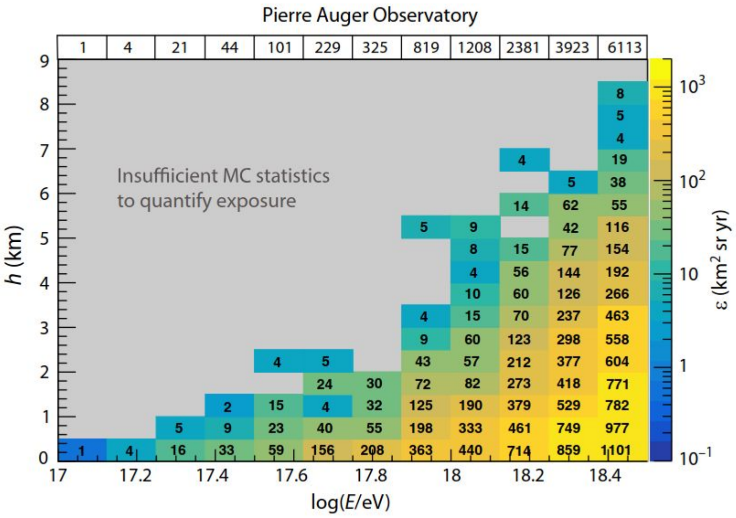
→ **$(7.2 \pm 0.2)\times10^{-21}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$** assuming a $E^{-1}$ spectrum

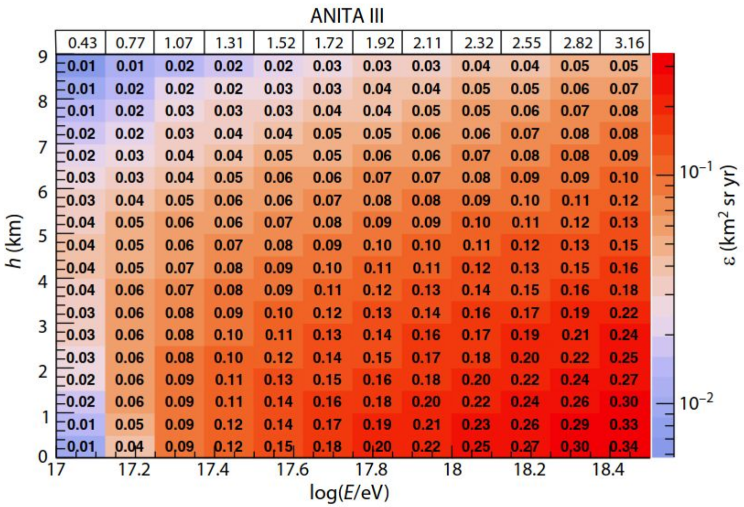
→ **$(3.6 \pm 0.2)\times10^{-20}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$** assuming a $E^{-2}$ spectrum

[5] Limits in presence of nuisance parameters. W. Rolke, A.M. Lopez, J. Conrad, *Nucl. Instrum. Meth. A*, **551** (2005).

# 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 and $\theta \in [110°, 130°]$
- Comparison of Auger and ANITA exposures in the same energy and zenith ranges
- Assuming a spectral index γ = 3 (5), we expect 69 (8.1) in Auger for a uniform distribution in height or 34 (11) for the *h* distribution expected from tau decay

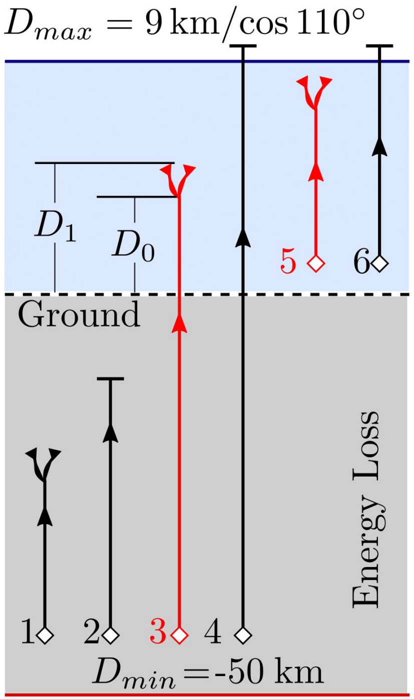



From [2]

# Tau-induced air showers

- Auger exposure obtained using protons, easily scalable to other particles (e.g. taus) by folding it with the corresponding FD detection efficiency
- Dedicated simulations of tau leptons generated within ~50 km below the Earth crust
- NuTauSim[6] used for the propagation and TAUOLA[7] used for decays
- Taus can propagate through the Earth crust and generate an air shower
- 3 and 5 are the most relevant cases where the shower develops in the atmosphere and can be observed with FD

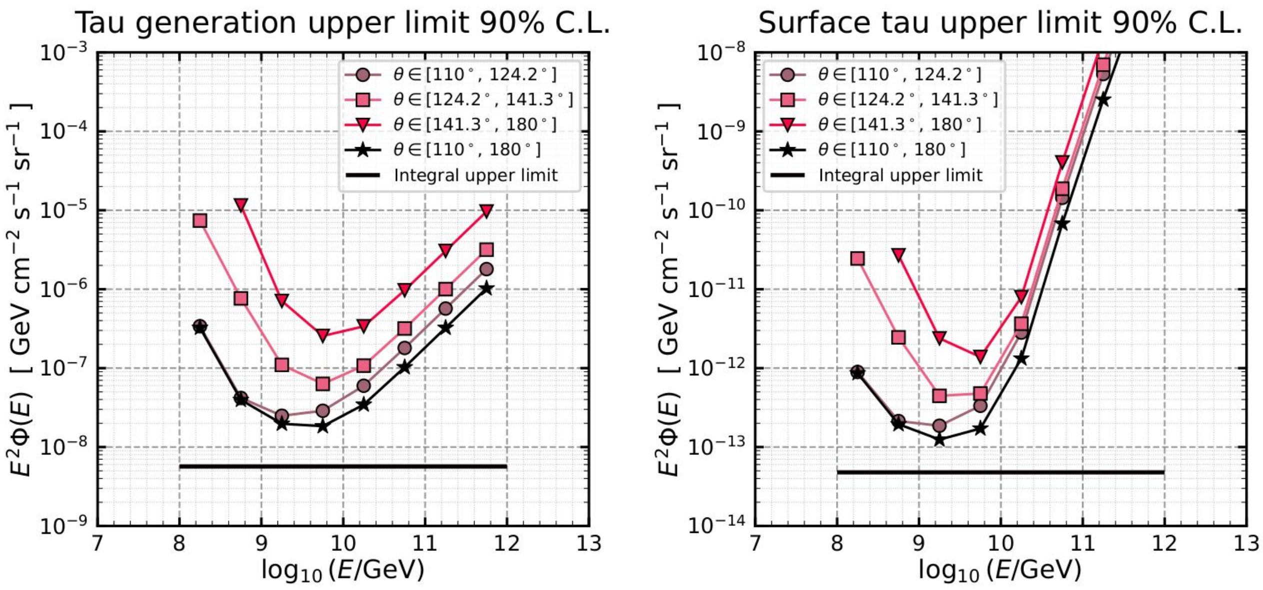




[6] J. Alvarez-Muniz, W.R. Carvalho Jr, K. Payet, A. Romero-Wolf, H. Schoorlemmer, E. Zas, *Phys. Rev. D*, **97** (2018) 023021.
[7] N. Davidson *et al.*, *Computer Physics Communications*, **183**, 3 (2012) pp.821-843

# Tau-induced air showers

- Tau simulations used to calculate the FD detection efficiency and then folded with Auger exposure
- Tau upper limits considering all generated taus (left) or only those exiting the Earth (right)

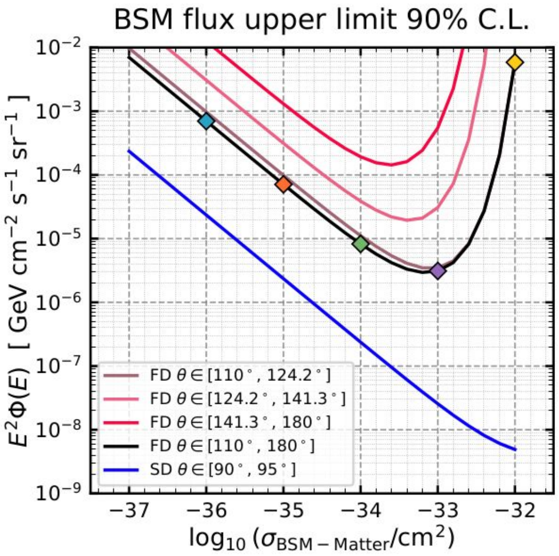


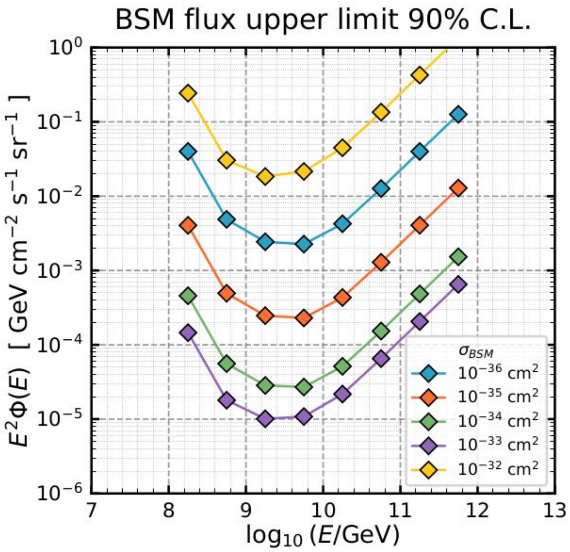

From [8]


[8] B. Yue for the Pierre Auger Collaboration, *PoS(ICRC2023)*1095

# The reduced cross section BSM model: first scenario

- At these energies, the Earth is opaque to neutrinos. On the other hand BSM particles could in principle produce tau leptons if their interaction cross section with matter is sufficiently low
- We study a model in which a BSM particle produces a tau-lepton which then generate an upward-going air shower as a function of the unknown particle cross section
- First scenario with a constant cross section at all energies



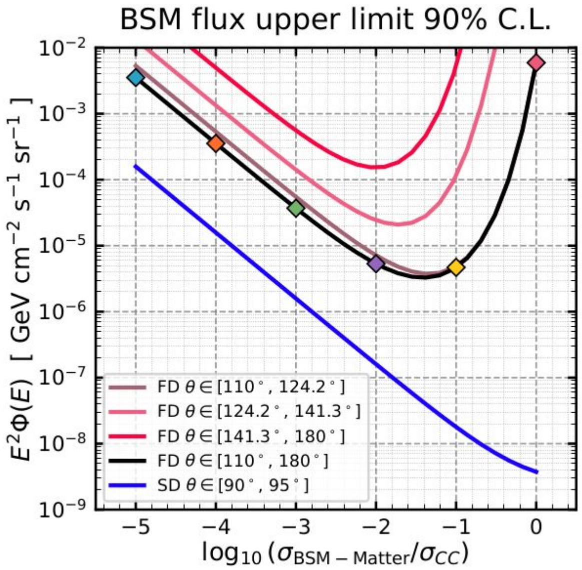



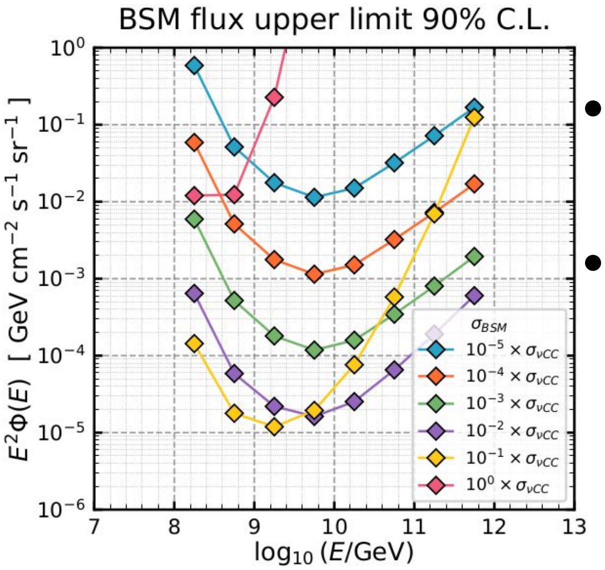

- Strongest limits at σ~ $10^{-33}$ cm$^2$
- Auger SD Earth-skimming upper limit shown in blue

From [8]

# The reduced cross section BSM model: second scenario

- Second scenario, the cross section mimics a charged current neutrino cross section scaled by a fixed factor (between $10^{-5}$ and 1)




- Strongest limits if $\sigma_{BSM}$ is 3% of neutrino charged current $\sigma_{CC}$
- Auger SD Earth-skimming upper limit shown in blue

From [8]

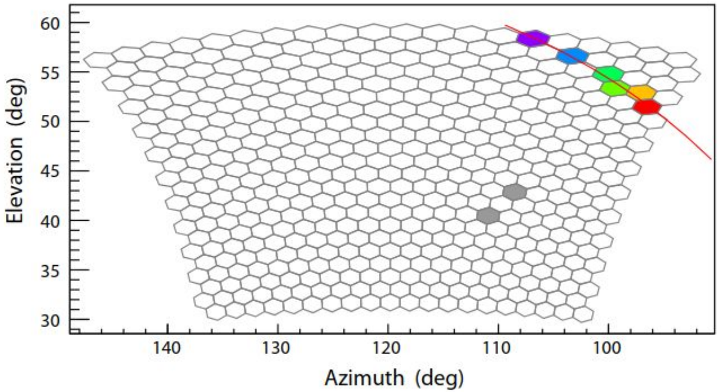
# Summary

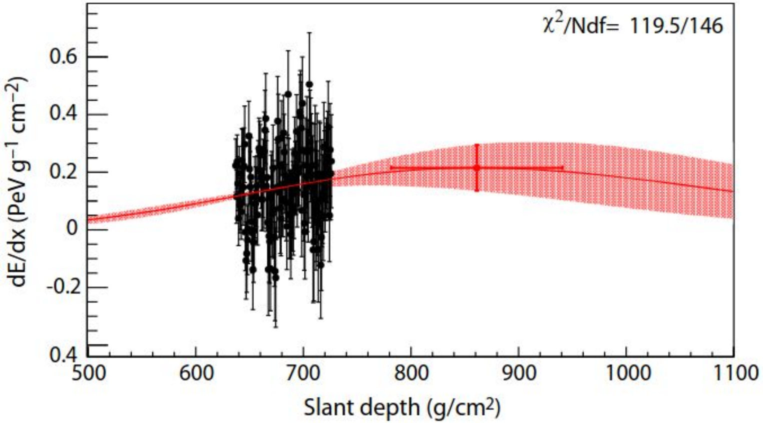
- Blind analysis searching for upward-going air showers with the Fluorescence Detector of the Pierre Auger Observatory
- One candidate found, consistent with the expected background
- Comparison of Auger and ANITA exposure shows that even under the conservative assumption of an $E^{-5}$ spectrum, we expect at least 8 events in Auger
- Upper limits converted to the case of a tau-induced air shower
- We have tested two possible scenarios of BSM particles of unknown cross section producing a tau-lepton

**Thank you for your attention!**

# Backup slides

# The “candidate”




Few pixels at the border of the FD camera

θ ≃ 118°

Short profile

Core is behind the FD telescope