PIERRE AUGER OBSERVATORY

Search for upward-going showers consistent with the anomalous ANITA events with the Fluorescence Detector of the Pierre Auger Observatory

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SEZIONE DI LECCE

Outline

- State of the art and research motivation:
  - the “anomalous” observation by ANITA
- The Pierre Auger Observatory
- Search for upcoming showers:
  - Simulations
  - Data
  - Unblinding
  - FD exposure
  - Comparison with ANITA
- Conclusion

ANITA: a balloon experiment for UHE neutrinos

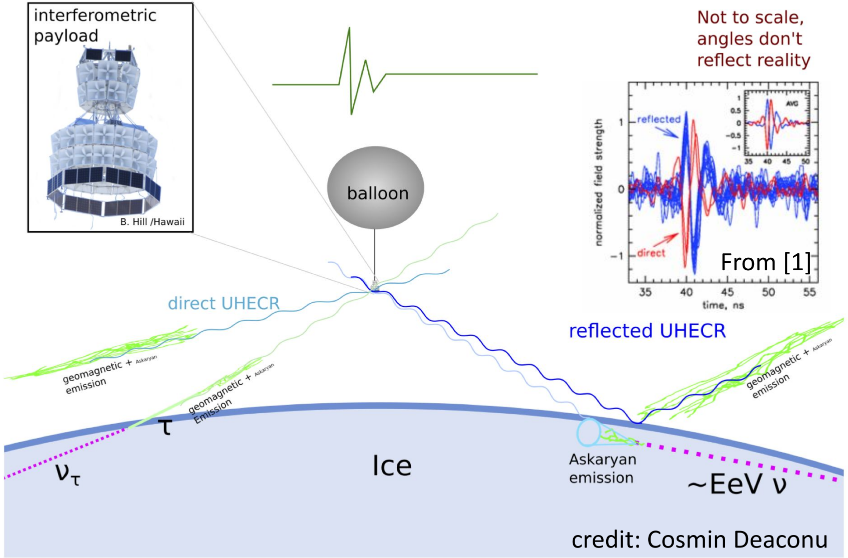
The **AN**tarctic **I**mpulsive **T**ransient **A**ntenna is a balloon experiment, flying 37 km over the Antarctica to observe radio signals originating from ice.

The main goal is to observe radio pulses arising from neutrino-induced electromagnetic cascades developing inside the ice (Askaryan effect*)

Ultra High Energy Cosmic Rays also geomagnetically emits radio pulses due to the deviation of shower electrons and positrons by the Earth's magnetic field.

ANITA detected two "anomalous" events of high energy (> 0.5 x 10^{18} eV) well below the horizon with no reflection

Fervent debate on the interpretation (neutrinos, DM, ecc.). IceCube and Auger have a much larger exposure and should see more events



*A particle traveling faster than the phase velocity of light inside a dense dielectric, such as ice, emits a cone of coherent radio pulses, also known as Askaryan radiation.

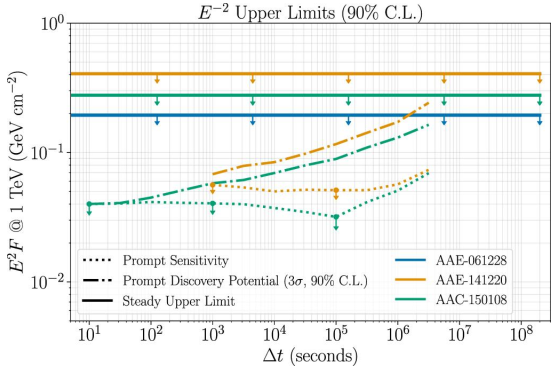
The IceCube view

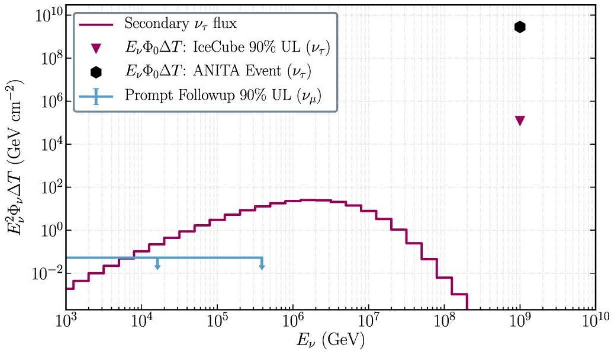
IceCube is a neutrino experiment in the Antarctica for the observation of High Energy Neutrinos with 86 strings and ~5000 optical sensor to detect the neutrino-induced showers generated inside ~1km^3 of Antarctica ice

The IceCube Collaboration performed 3 analyses related to the ANITA anomalous detection:

- *prompt* - spatial and temporal coincidence of IceCube events in short time windows centered at each ANITA event
- *rolling* - spatial and temporal clustering of IceCube events (no coincidence required)
- *steady* - only spatial clustering of IceCube events in the direction of each ANITA event

No relevant excess found in either of the three analyses





IceCube upper limit is several orders of magnitude lower than the flux implied by ANITA!

From [2]

What about Auger?

The Pierre Auger Observatory

The Pierre Auger Observatory is the largest and most precise detector of Ultra High Energy Cosmic Rays thanks to its two main detectors

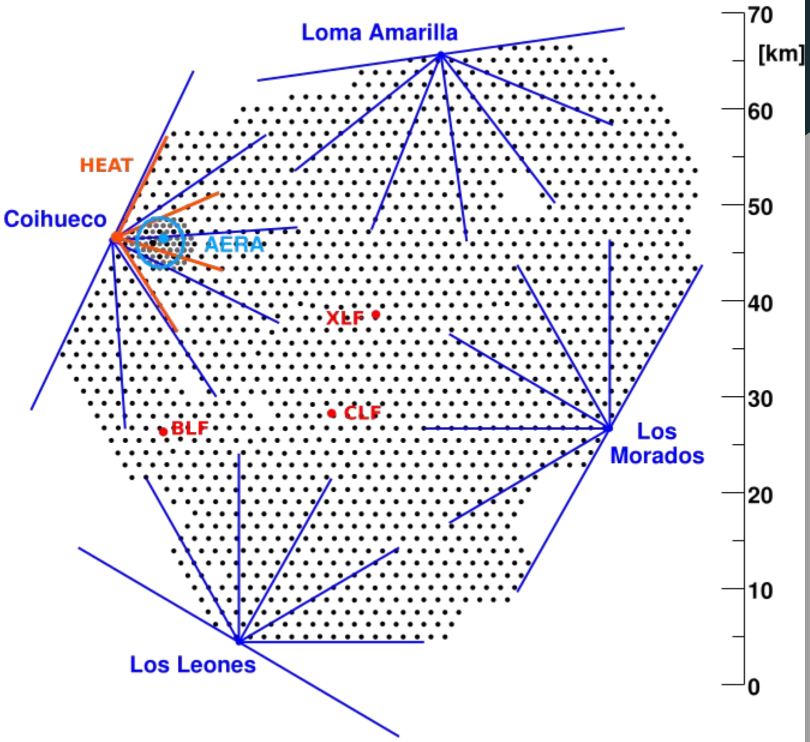
Surface Detector (SD):

- 1660 Water Cherenkov Detectors (grid of 1.5 km for a total 3000 km^2, each black dot represents one station)
- ~100% duty cycle, measures particle density at ground

Fluorescence Detector (FD):

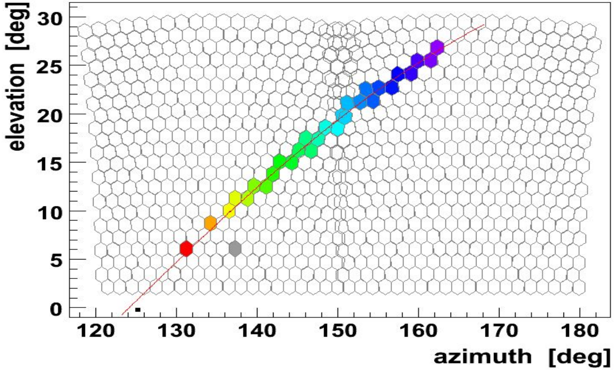
- 24 telescopes in 4 locations (blue lines) + 3 high elevation telescopes (red lines), 30° FoV
- ~15% duty cycle, measures longitudinal profile

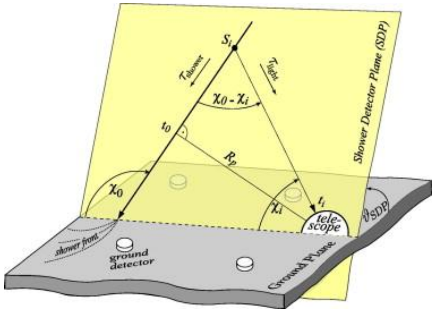
But also a denser WCD region (infill), radio array (AERA), underground muon detectors (AMIGA)

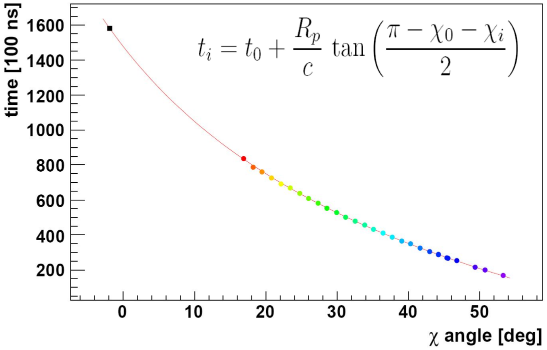


Auger: the FD monocular reconstruction

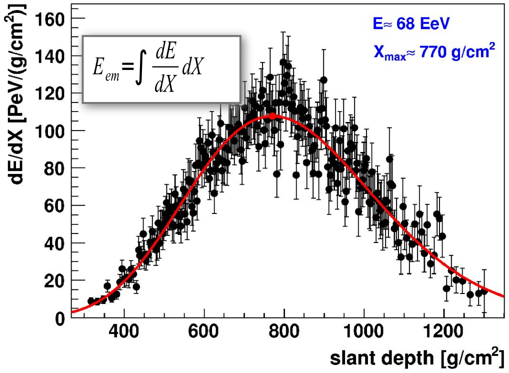
The event in the camera → Shower-Detector-Plane → Time-fit





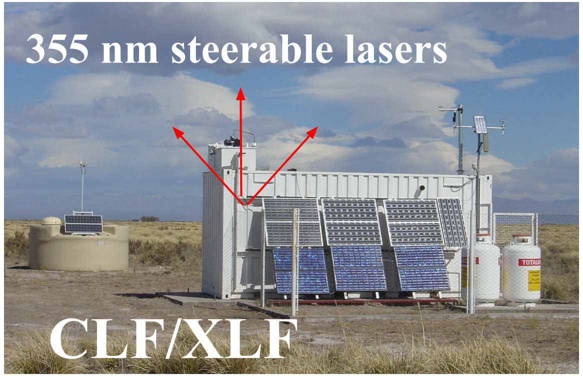


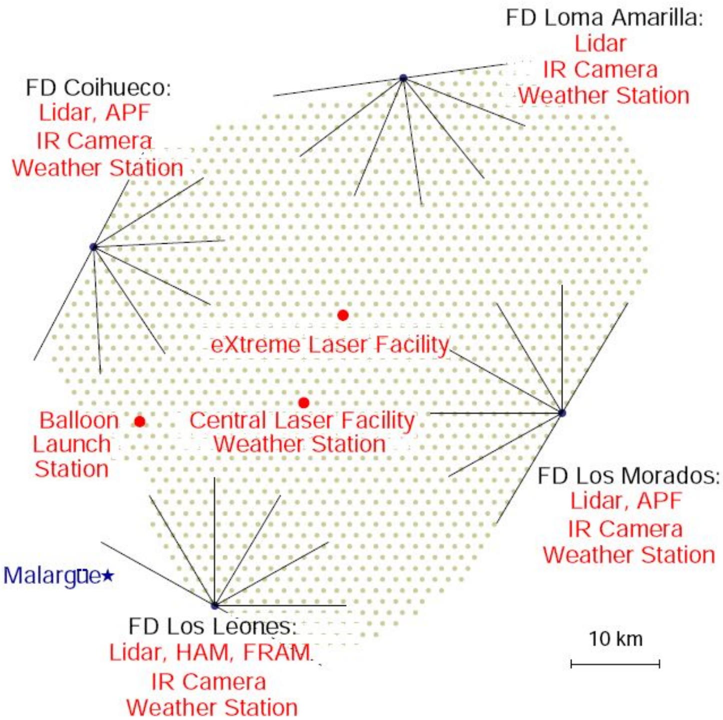
ADC counts → Light at telescope → Energy deposit profile



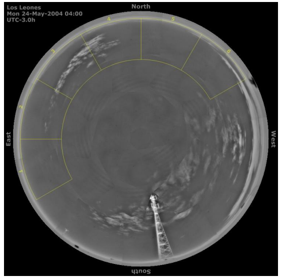
Very important to constantly monitor the atmospheric conditions: any variation in temperature, pressure, humidity influences the shower development in the atmosphere

Auger: atmospheric monitoring





backscatter Lidar



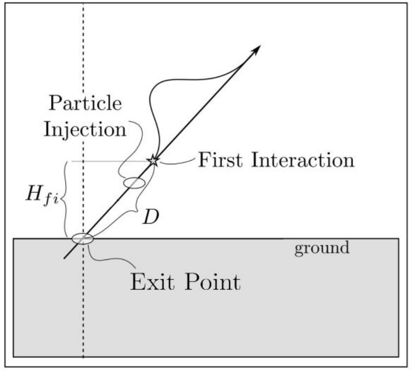
IR cloud cameras

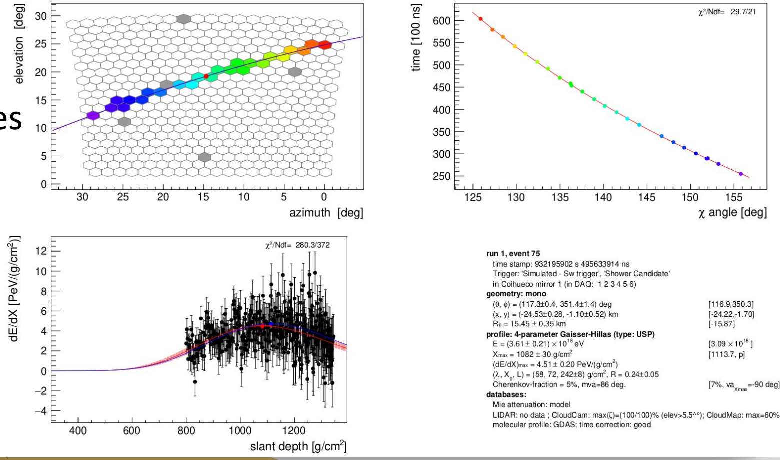
Laser shots and lidars are tracked during night of DAQ and removed from data

Search for upward-going air shower with the FD: Simulations

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

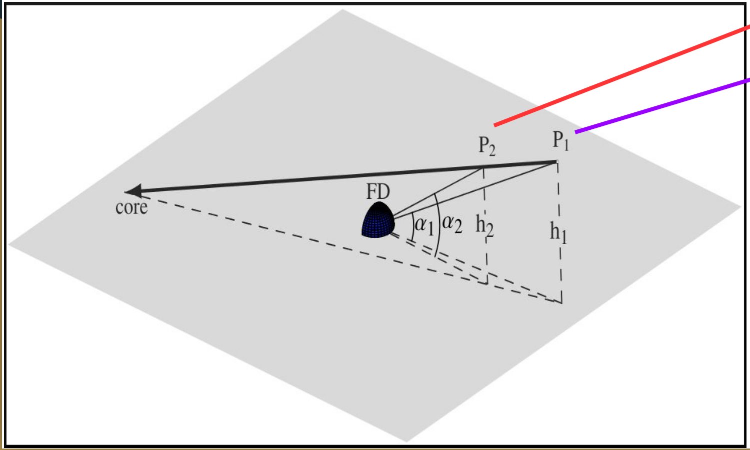




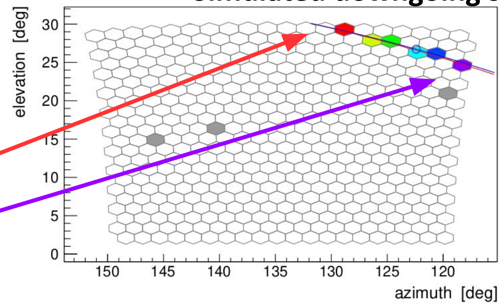
Background simulations

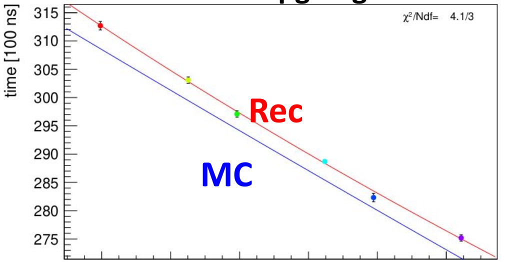
- Downward-going Cosmic Rays can mimic upward-going track in the FD camera
- Primaries → protons + helium, nitrogen and iron nuclei, re-scaled to the CR spectrum
- Energy → log(E/eV) ∈ [17, 20], 2.5 x 10^8 showers simulated
- Zenith → θ ∈ [0°, 90°]

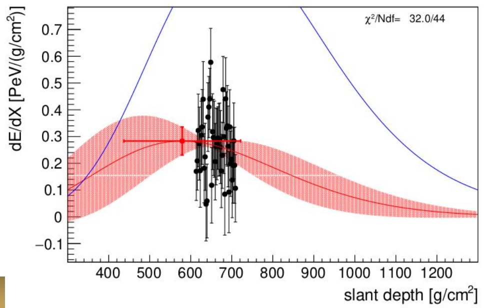
Example of a downgoing shower looking upgoing



Simulated downgoing shower reconstructed as upgoing







Simulated θ≃76.5°

reconstructed 115.5°

geometry: mono

(θ, ϕ) = (115.5±1.6, 225.2±4.8) deg	[76.5,285.5]
(x, y) = (3.13±0.43, 27.68±0.44) km	[5.98,62.28]
R_p = 5.29 ± 0.20 km	[11.49]

profile: 4-parameter Gaisser-Hillas (type: USP)

E = (2.31 ± 0.48 ± 0.11) × 10^{17} eV	[6.92 × 10^{17}]
X_{max} = 579 ± 142 g/cm²	[701.5, N]
$(dE/dX)_{max}$ = 0.28 ± 0.05 PeV/(g/cm²)	
(λ, X_0, L) = (57, -282, 221±10) g/cm², R = 0.26±0.05	
Cherenkov-fraction = 7%, mva=93 deg.	[7%, va_{Xmax}=27 deg]

databases:

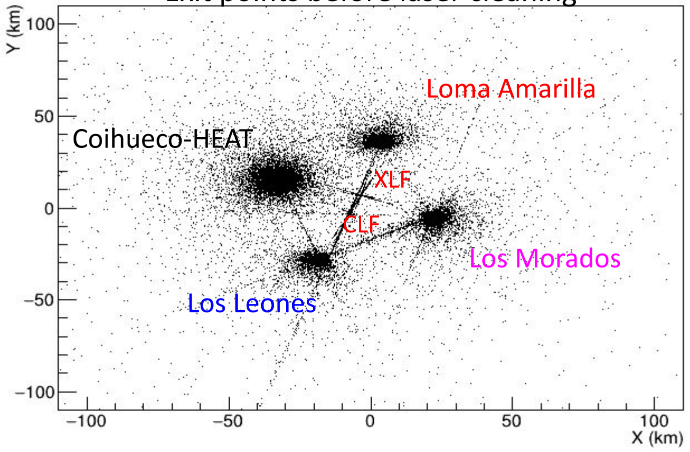
Mie attenuation: measured (h<16.4 km, VAOD at 3km: 0.01)
LIDAR: no data ; CloudCam: max(ζ)=(0/0)% (elev>5.5^°); CloudMap: no data
molecular profile: GDAS; time correction: good

Search for upward-going air shower with the FD: Data

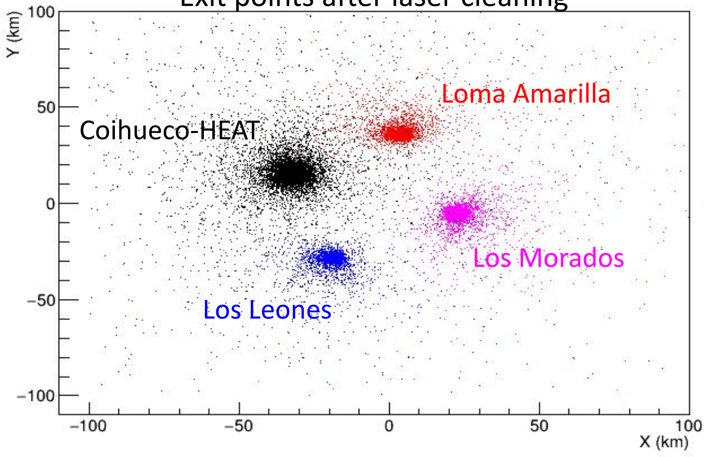
Data cleaning

- 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

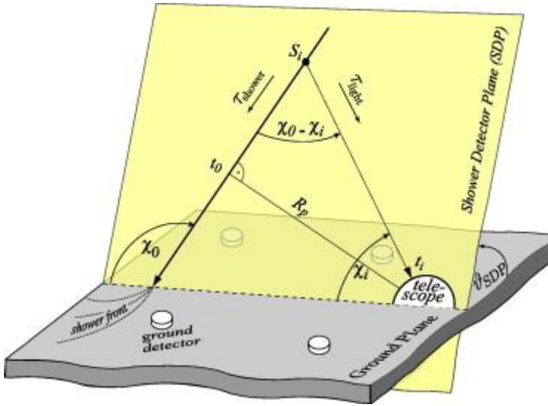


PCGF reconstruction and event selection

- Data and simulations reconstructed with an iterative procedure combining the profile reconstruction with the geometry, testing upward (negative χ_0) and downward (positive χ_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
- Definition of a new variable for the comparison of the two reconstructions

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

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

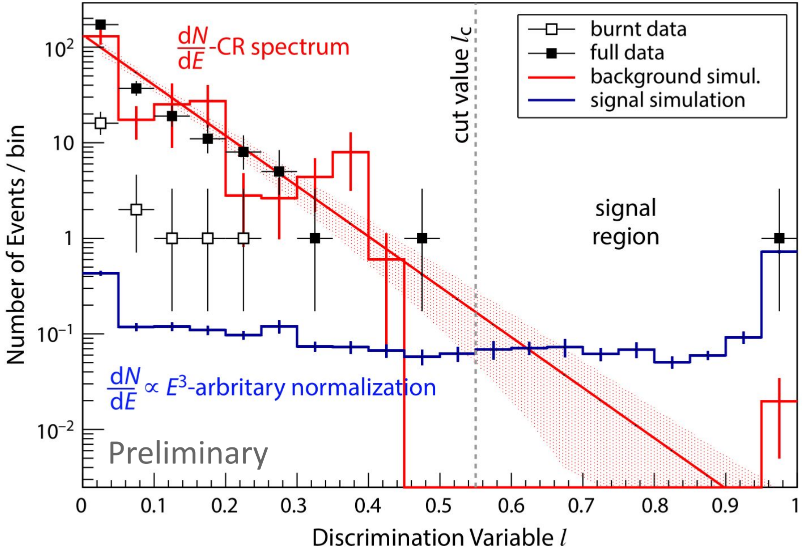


Selection cut

Distribution of *l* for burn data (black), background sim (red) and signal sim (blue).

Background weighted to CR spectrum. Good agreement between data and background

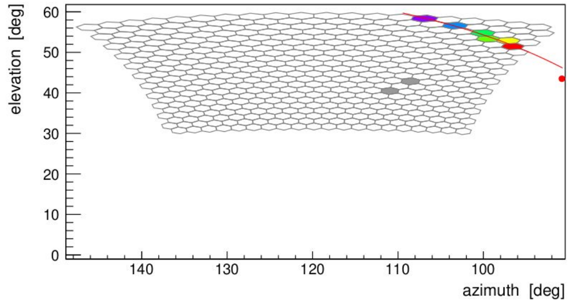
Cut value is set at *l* = 0.55 with an expected background of n_{bkg} = 0.27 ± 0.12 after the unblinding

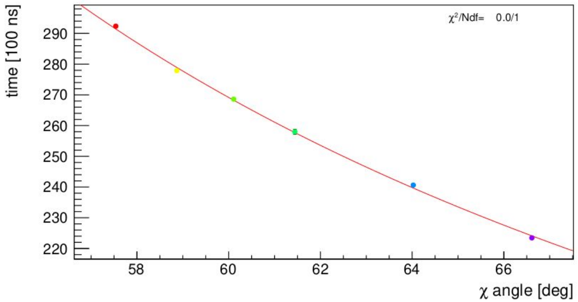


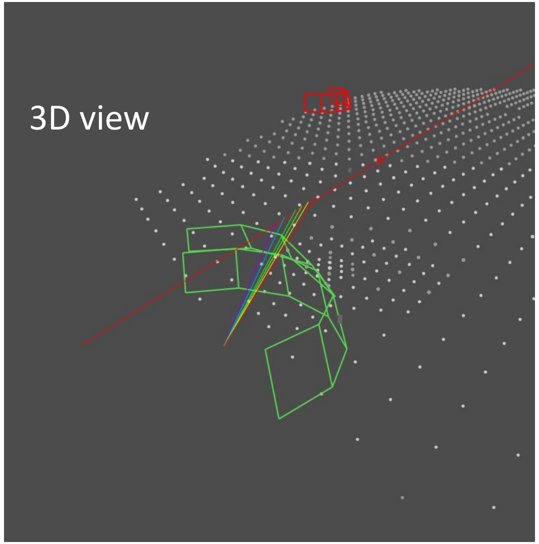
Search for upward-going air shower with the FD: Unblinding, exposure calculation and comparison with ANITA

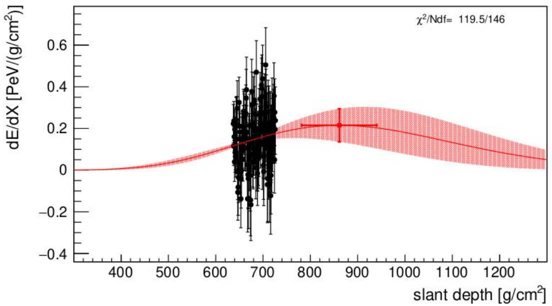
Unblinding data

After the unblinding one event passed all the selection criteria with *l* = 1. The event is clipping the upper right corner of HEAT Telescope 2. Not a laser, probably a downward-going event whose PCGFdown reconstruction failed because of too few pixels. We don't consider it a candidate, but we keep it



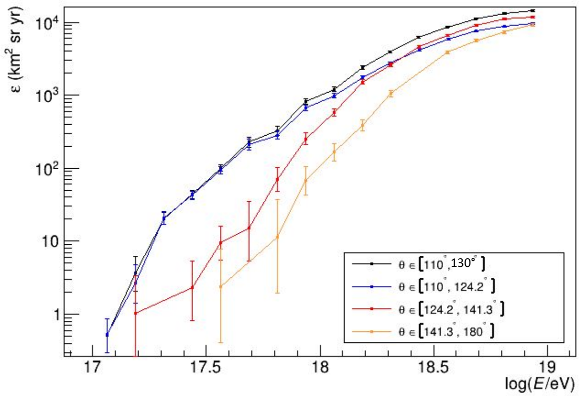


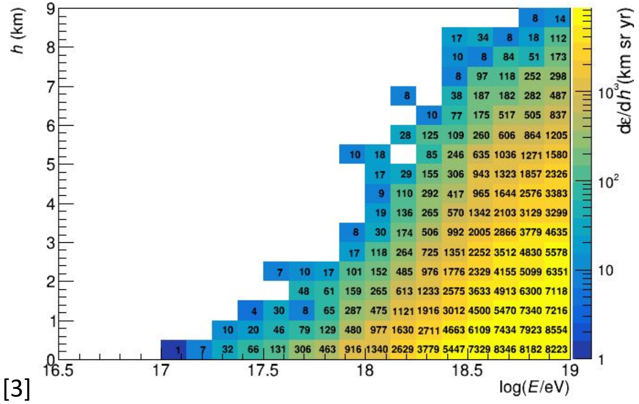




run 2685, event 3603
time stamp: 1203043828 s 609409371 ns
Trigger: unknown, 'Shower Candidate'
in MegaEye mirror 26 (in DAQ: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27)
geometry: Profile-Constrained
$(\theta, \phi) = (118.3\pm3.1, 141.5\pm2.0)$ deg
$(x, y) = (-34.28\pm0.21, 18.08\pm0.28)$ km
$R_p = 1.86 \pm 0.00$ km
profile: 4-parameter Gaisser-Hillas (type: USP)
$E = (1.83 \pm 0.70 \pm 0.09) \times 10^{17}$ eV
$X_{max} = 861 \pm 80$ g/cm^2
$(dE/dX)_{max} = 0.22 \pm 0.08$ PeV/(g/cm^2)
$(\lambda, X_0, L) = (57, -8, 224\pm9)$ g/cm^2, $R = 0.26\pm0.05$
Cherenkov-fraction = 5%, mva=144 deg.
databases:
Mie attenuation: measured (h<16.4 km, VAOD at 3km: 0.03)
LIDAR: no data ; CloudCam: max(ζ)=(0/0)% (elev>5.5^°); CloudMap: max=0%
molecular profile: GDAS; time correction: good

FD exposure





From [3]

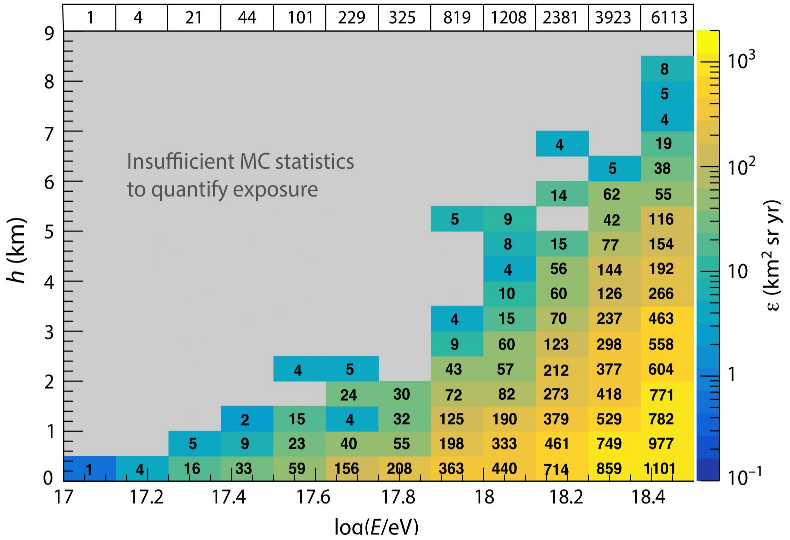
- FD exposure as a function of the shower energy (top), calculated for different zenith sub-ranges, useful also to test different scenarios
- Exposure as a function of the shower energy and the height of first interaction (bottom)
- Using Rolke, the integral upper limit to the flux of upgoing showers above 10^{17} eV:

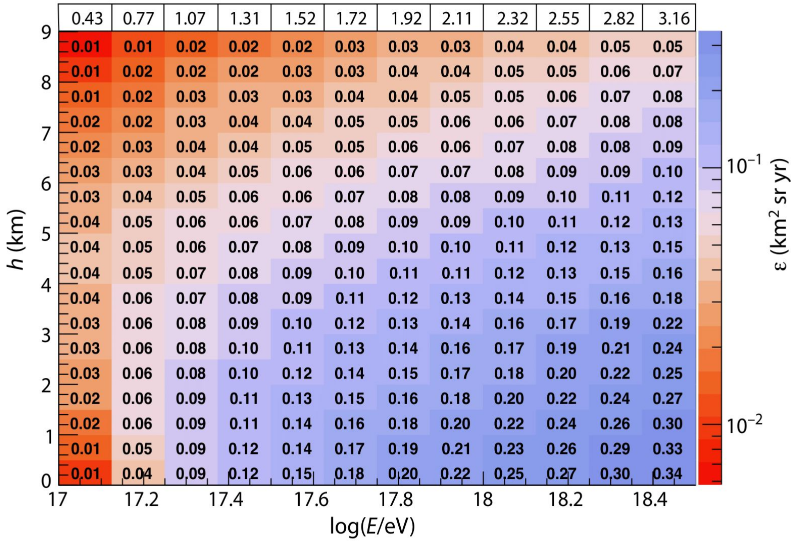
  → **$(7.2 \pm 0.2)\times10^{-21}$ cm^{-2} s^{-1} sr^{-1}** assuming a E^{-1} spectrum

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

Comparison with ANITA

Thanks to a joint effort with members from the ANITA Collaboration, we have made an analytic calculation of the ANITA aperture for the two “anomalous” events between 10^{17} eV and $10^{18.5}$ eV and $\theta \in [110°, 130°]$



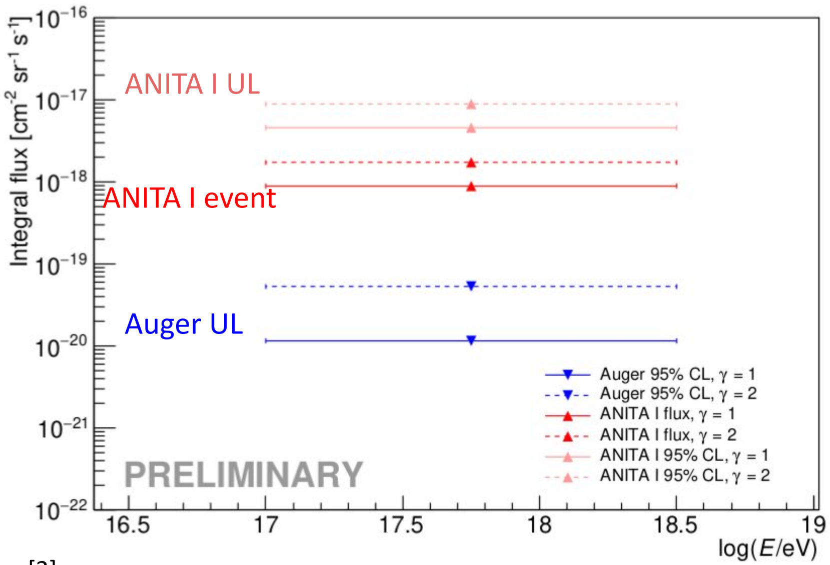


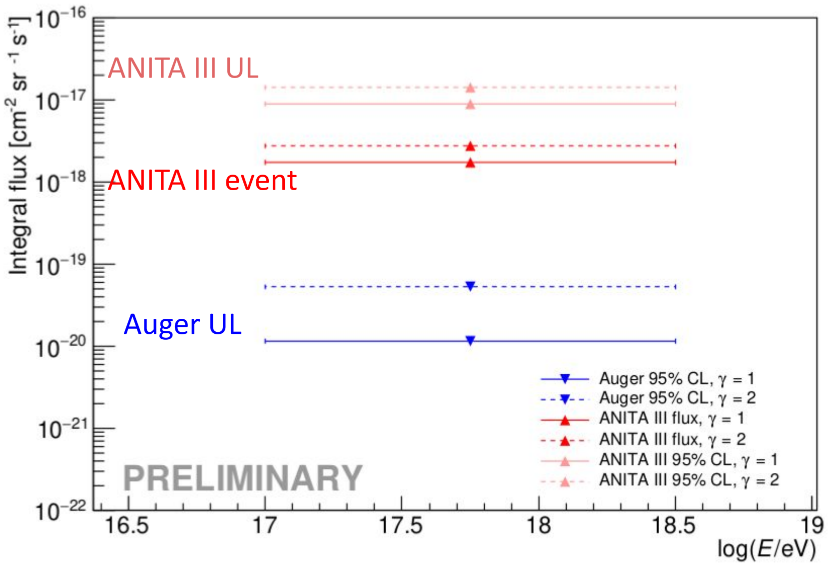
Auger (left) and Anita III (right) exposure in the same energy and zenith ranges

Comparison with ANITA

The Auger upper limit is 100 times lower than the ANITA flux if we weight the exposure with an E^{-1} spectrum and 30 times lower in case of an E^{-2} spectrum

In both cases the Auger limits are in tension with the corresponding fluxes and/or upper limits calculated from the ANITA observations





From [3]

Conclusion

- We have performed a search for upward-going air showers with the Fluorescence Detector of the Pierre Auger Observatory
- A blind analysis has been performed, defining quality selection criteria on a fraction of the full data sample
- We have used simulations to calculate the FD exposure to steeply upward-going air showers
- One event passed all the criteria and we have set an upper limit
- Our limit was found to be in tension with the two ANITA “anomalous” observations

References

[1] S. Hoover et al. (ANITA Collaboration), *Observation of Ultrahigh-Energy Cosmic Rays with the ANITA Balloon-Borne Radio Interferometer*, Phys. Rev. Lett., **105**, 151101, 2010.
[2] M.G. Aartsen et al. (IceCube Collaboration), *A Search for IceCube Events in the Direction of ANITA Neutrino Candidates*, Astrophys. J., **892**, 53, 2020.
[3] E. De Vito for the Pierre Auger Collaboration et al., *Constraint on upward-going air showers using the Pierre Auger Observatory data*, PoS(ICRC2023)1099, 2023.

Thank you for your attention!