INFN
Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DEGLI STUDI DE L'AQUILA

PIERRE AUGER OBSERVATORY

NU | Neutrinos & Muons

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

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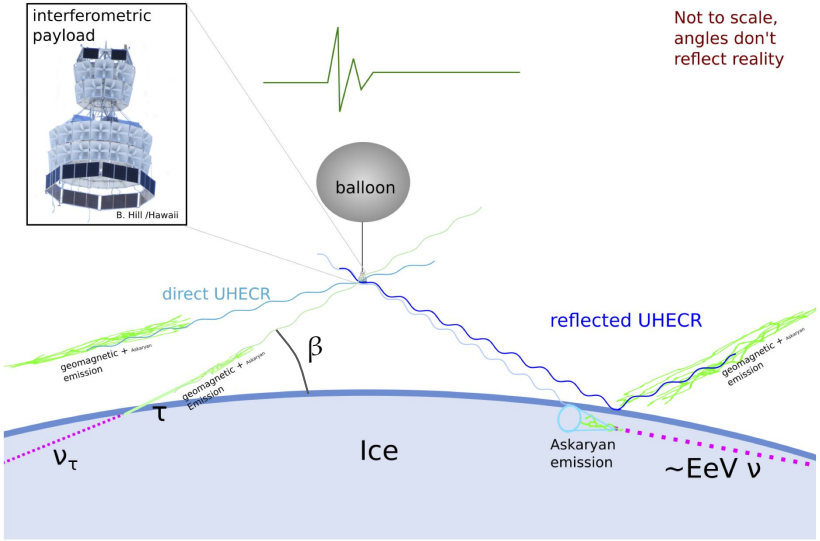
37th International Cosmic Ray Conference
14/07/2021

ANITA anomalous events

- The ANITA experiment detected two anomalous events with non-inverted polarity → consistent with upward-going showers observed directly by ANITA
  - $E_{1,2} \gtrsim 0.2$ EeV $\approx 10^{17.8}$ eV
  - $\beta_1 \approx 27°$ and $\beta_2 \approx 35°$

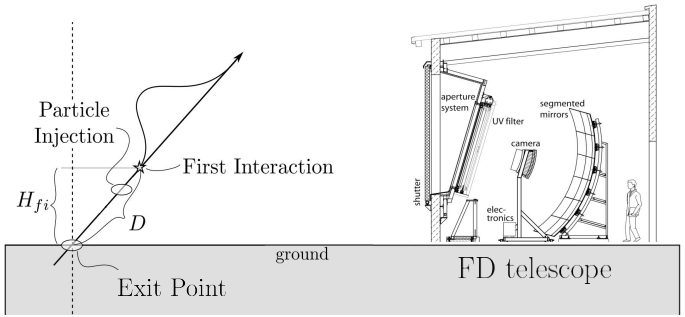
- If those events are due to ν_τ they appear challenging to reconcile with the predictions of the standard model



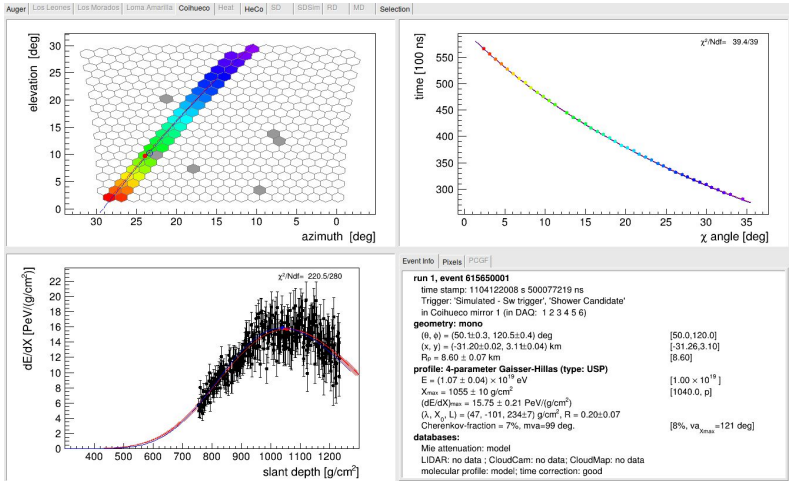
The Auger FD is sensitive to these events → upward-going showers simulated and reconstructed within the Offline Framework → **exposure calculation for upward-going showers**

Signal simulation

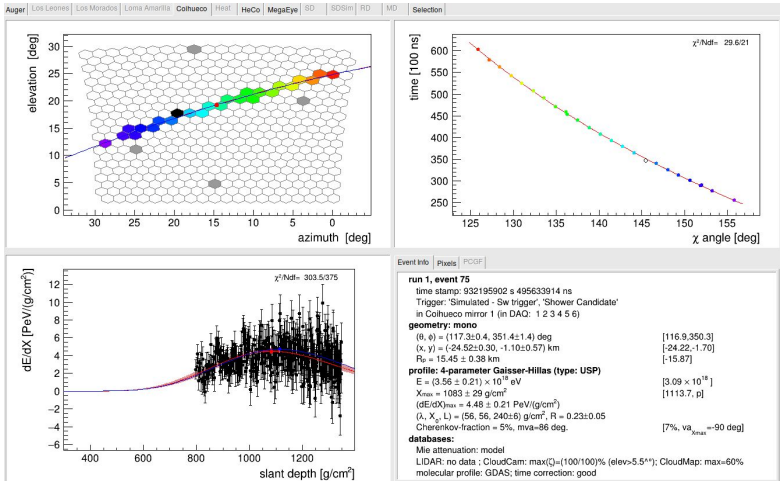
- **Primaries**: protons → adaptable to other scenarios
  → **I. A. Caracas, PoS(ICRC2021)913**
- **Energy range**: $\log_{10}(E_{cal}/eV) \in [16.5, 18.5]$
- **Zenith angle range**: $\theta_{zenith} \in [110 , 180]°$



downward-going simulation



upward-going simulation



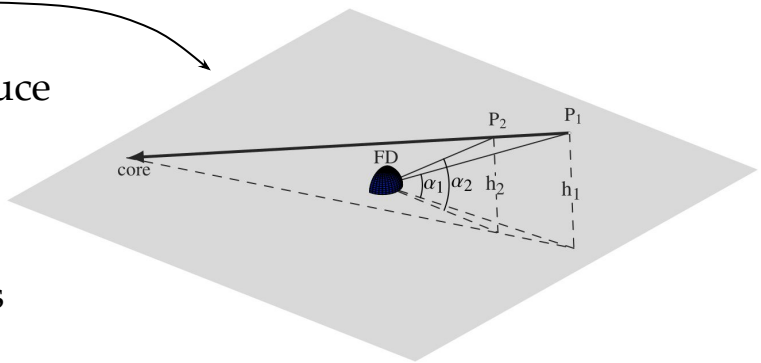
Background simulation

- Downward-going events with specific geometries can mimic upward-going events in a monocular reconstruction

- Also events with a core far away from the array can produce background and need to be simulated

- Background simulation:
  - **Primaries:** helium, nitrogen, iron nuclei and protons
  - **Energy range**: $\log_{10}(E/eV) \in [17, 20]$
  - **Zenith angle range**: $\theta_{zenith} \in [0 , 90]°$

- Reconstruction is performed in two modes → **likelihood from the two reconstruction used to discriminate between more likely downward-going or upward-going showers**

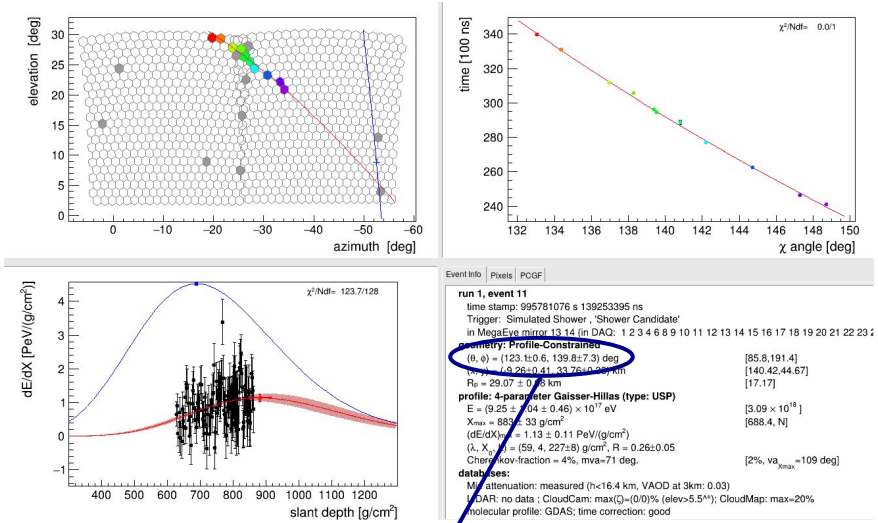


$\alpha_1 < \alpha_2$
$h_1 > h_2$

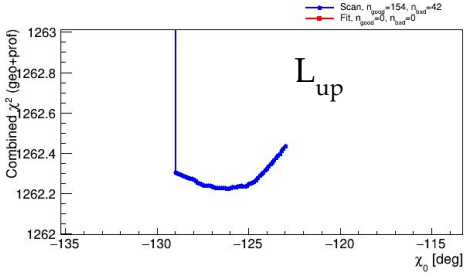
Signal from P_1 reaches the FD before the signal from P_2 → downward-going event reconstructed as upward-going

Reconstruction of background events

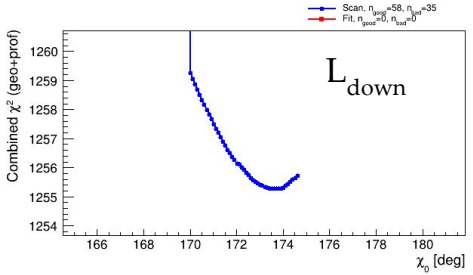
- Same event reconstructed both in upward and downward mode



likelihood from the reconstruction in upward mode



likelihood from the reconstruction in downward mode



$L_{down} > L_{up}$

θ_{zenith} = 123.1 deg → **downward-going event reconstructed as an upward-going event**

Defining $L_{up,down} = \max(L_{down}, L_{up})$, $\mathbf{-2\log(L_{down}/(L_{up,down})}$ **can be used to discriminate background events**

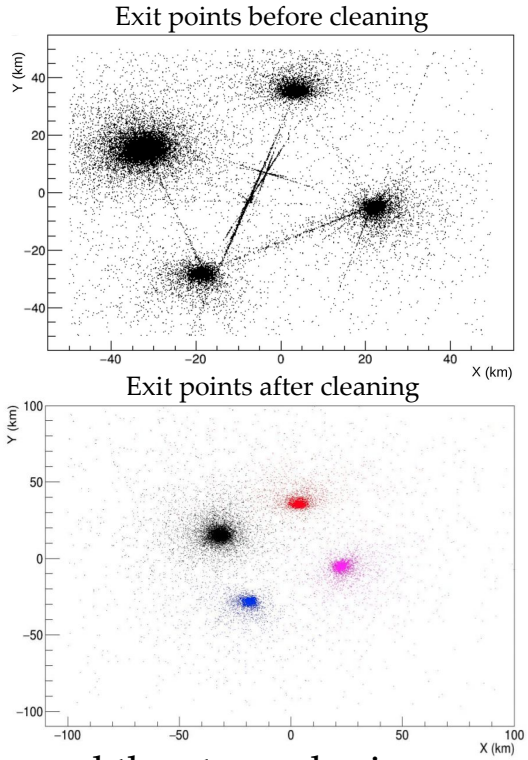
Data cleaning using a burn sample

- A blinded analysis is performed → to remove untagged laser events, used to monitor the atmosphere, data are cleaned using a burn data sample (10% of the FD data from 14 years of operation)

➢ Lidar shots have in most cases a specific frequency of 333 Hz → they pile up in a GPSMicroSecond%3000 histogram

➢ CLF and XLF have a known position → the angle that define the intersection of the shower detector plane (SDP) with the ground can be used to identify the associated event

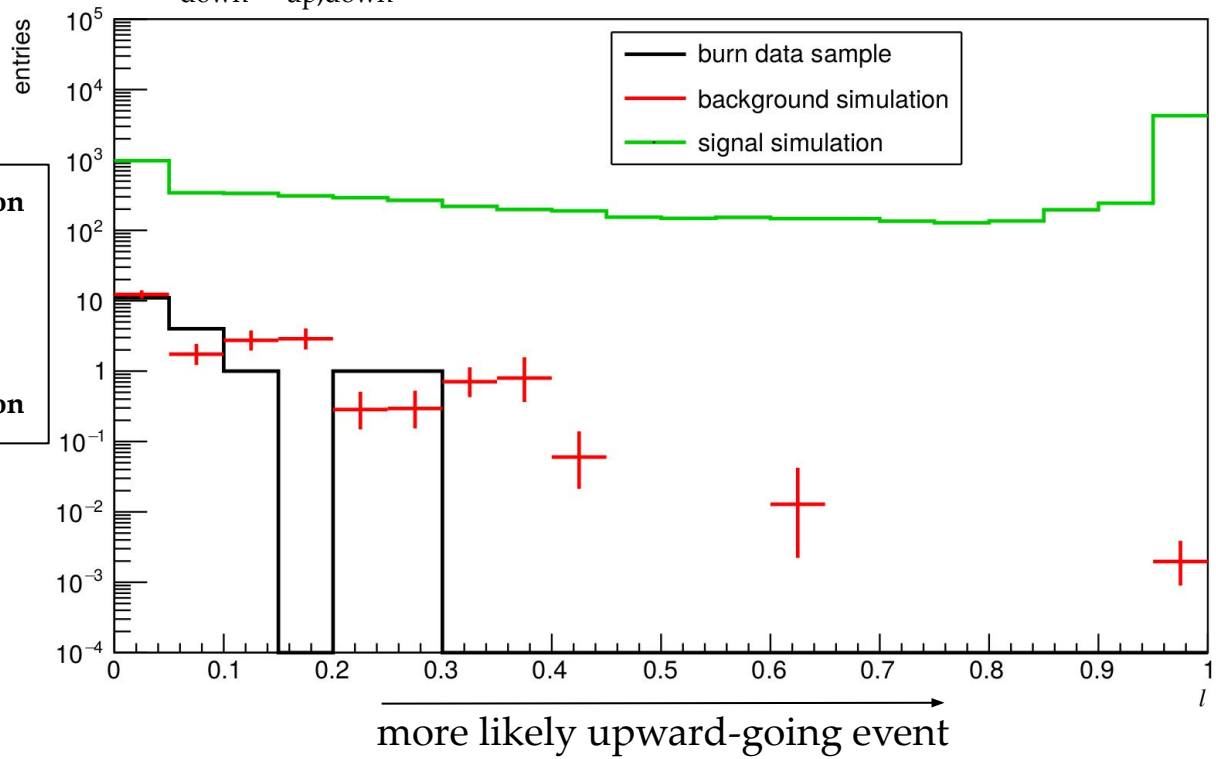
Untagged lasers identified by searching for excesses in the 2D histogram GPSMicroSecond%3000 vs AzimuthSDP for each FD site



- A set of selection cuts to preserve the quality of both the reconstruction and the atmospheric conditions has been defined and applied to burn sample and both signal and background simulation

Likelihood ratio based variable distribution

- Variable l = atan(-2log($L_{down}/L_{up,down}$)/50)/(π/2) defined between 0 and 1

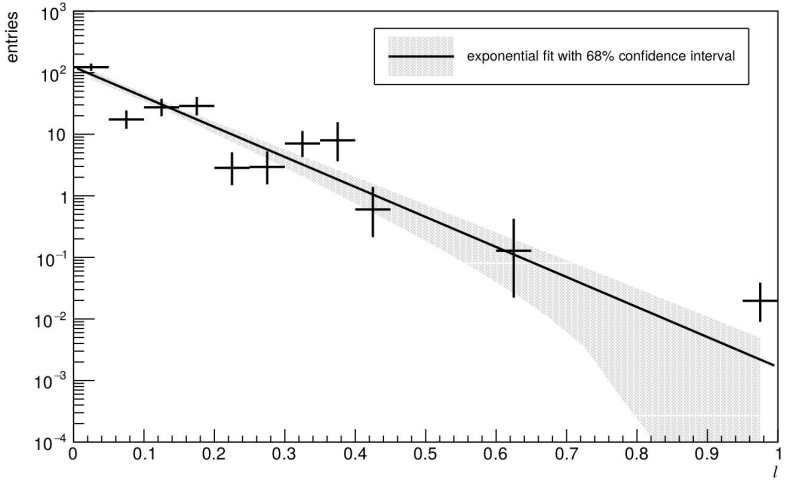


background simulation weighted to burn sample → good agreement between burn sample and background simulation

cut value on l has been tuned by minimizing the upper limit

Background discrimination with likelihood ratio based cut

- Background parameterization: exponential fit (exp(ax+b))



weighted likelihood fit

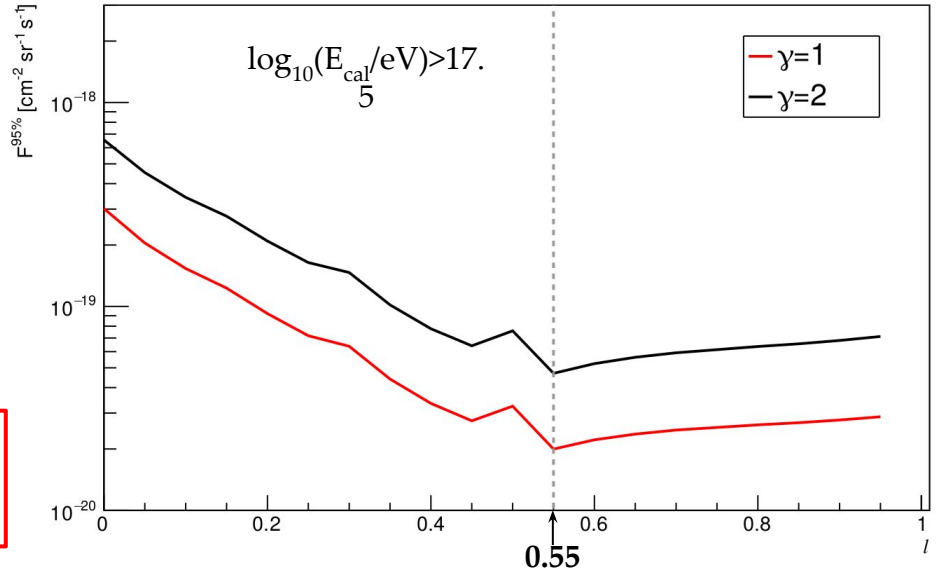
cut value can be tuned with the UL minimization

$$F^{95\%} = \frac{N^{95\%}}{<\varepsilon>}$$

$N^{95\%}$ → Method of Rolke with $n_{obs} = n_{bkg}$

$<\varepsilon>$ → mean exposure

$$<\varepsilon> = \frac{\int_{E_{min}}^{E_{max}} \varepsilon(E_{cal}) E_{cal}^{-\gamma} dE}{\int_{E_{min}}^{E_{max}} E_{cal}^{-\gamma} dE}$$



Cut to select more likely upward-going events: $l > 0.55$

Results

- Using the exponential fit and the cut $l > 0.55$, the expected number of background events is:

$$\mathbf{n_{bkg} = 0.45 \pm 0.18}$$

- After the unblinding of the data **1 event** has been observed to pass all the selection criteria. This number is consistent with the expected number of background events

Using Rolke the integral upper limit for $\log_{10}(E_{cal}/eV)>17.5$ with $n_{bkg} = 0.45 \pm 0.18$ and $n_{obs} = 1$ is:

➔ $\mathbf{3.6 \times 10^{-20}\ cm^{-2}\ sr^{-1}\ s^{-1}}$ if exposure is weighted with $\mathbf{E^{-1}}$

➔ $\mathbf{8.5 \times 10^{-20}\ cm^{-2}\ sr^{-1}\ s^{-1}}$ if exposure is weighted with $\mathbf{E^{-2}}$

We intend to compare these results with ANITA I and III observations

Differential tables of exposure

Differential exposure vs calorimetric energy and height of first interaction

$$\frac{d\varepsilon}{dH}(E_{cal_{sim}}, H) = 2\pi S_{gen}\Delta T \sum_i \frac{n(E_{cal_{sim}}, cos(\theta_i), H_i)}{N(E_{cal_{sim}}, cos(\theta_i), H_i)} \frac{1}{\Delta H_i} cos(\theta_i)\Delta cos(\theta_i)$$

Exposure tables can be used to test different scenarios, like the ν_τ one

↓

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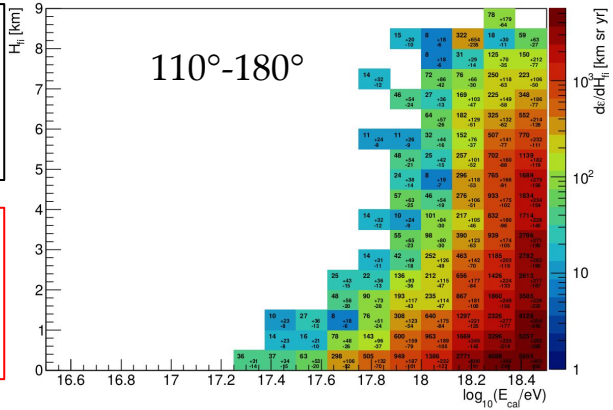

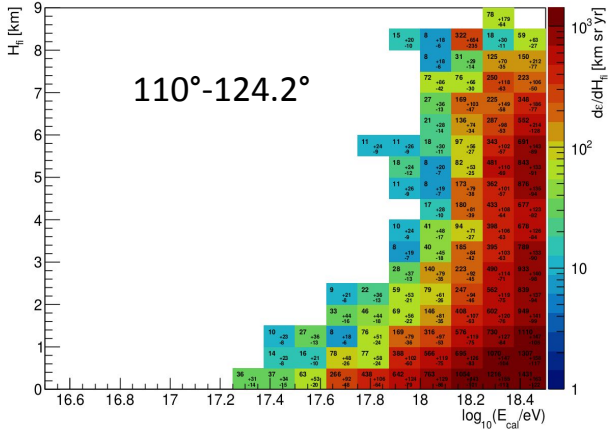

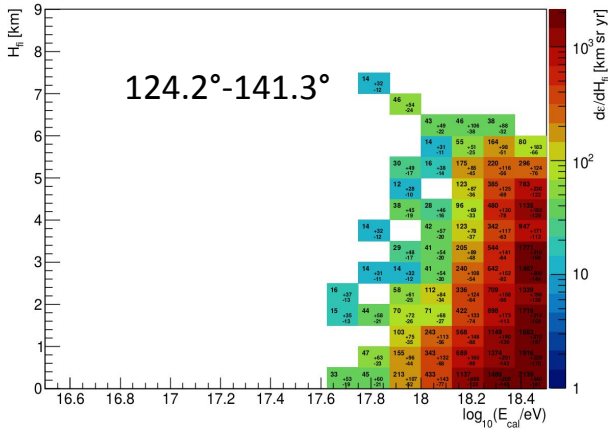

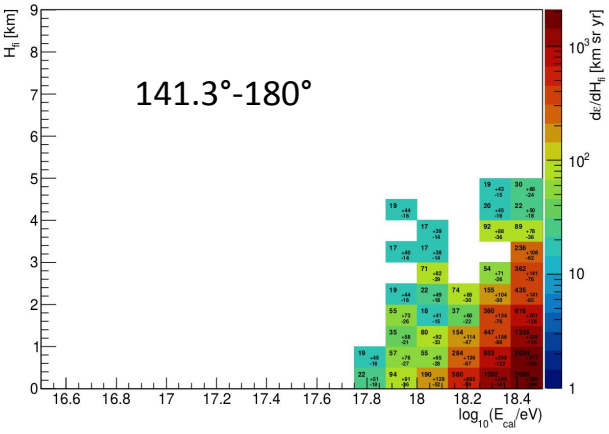

Summary

- Signal simulation of upward-going showers has been performed
- Downward-going events that can produce an upward-going signal have been simulated
- Blinded analysis → a burn data sample has been defined and used to clean the data
- A selection procedure to remove laser events that were not properly labelled has been implemented
- Selection cuts have been defined and applied to burn data sample, background simulation and signal simulation
- A selection cut to discriminate between background and signal events has been defined and studied
- The expected number of background events is $n_{bkg} = 0.45 \pm 0.18$. After the unblinding $n_{obs} = 1$ observed event has been found and an integral upper limit has been derived
- Differential tables of exposure have been provided
- Plans to compare exposure to ANITA observations