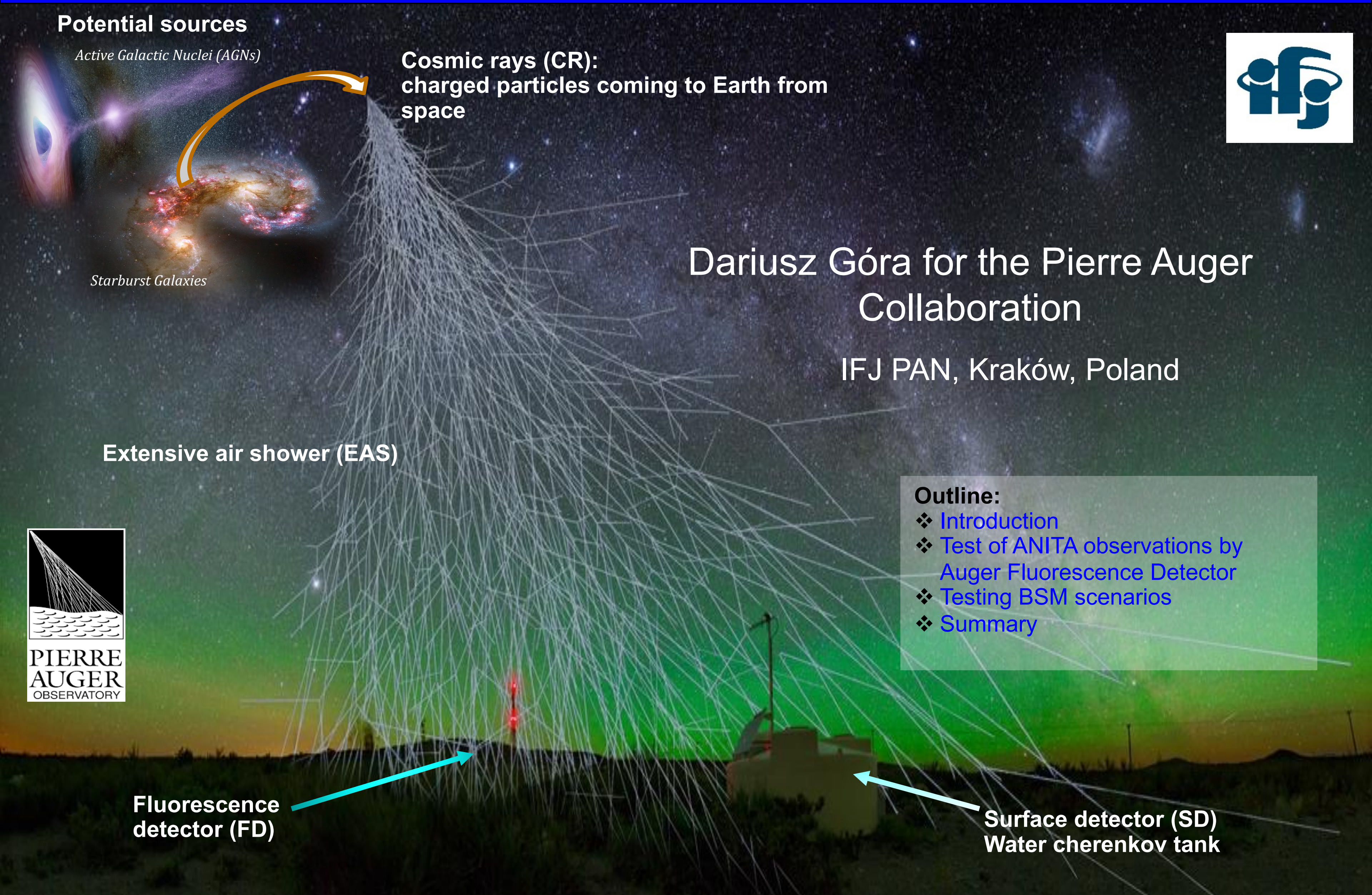
Constraints on Beyond the Standard Model (BSM) upward-going air showers using the Pierre Auger Observatory data

Dariusz Góra for the Pierre Auger Collaboration

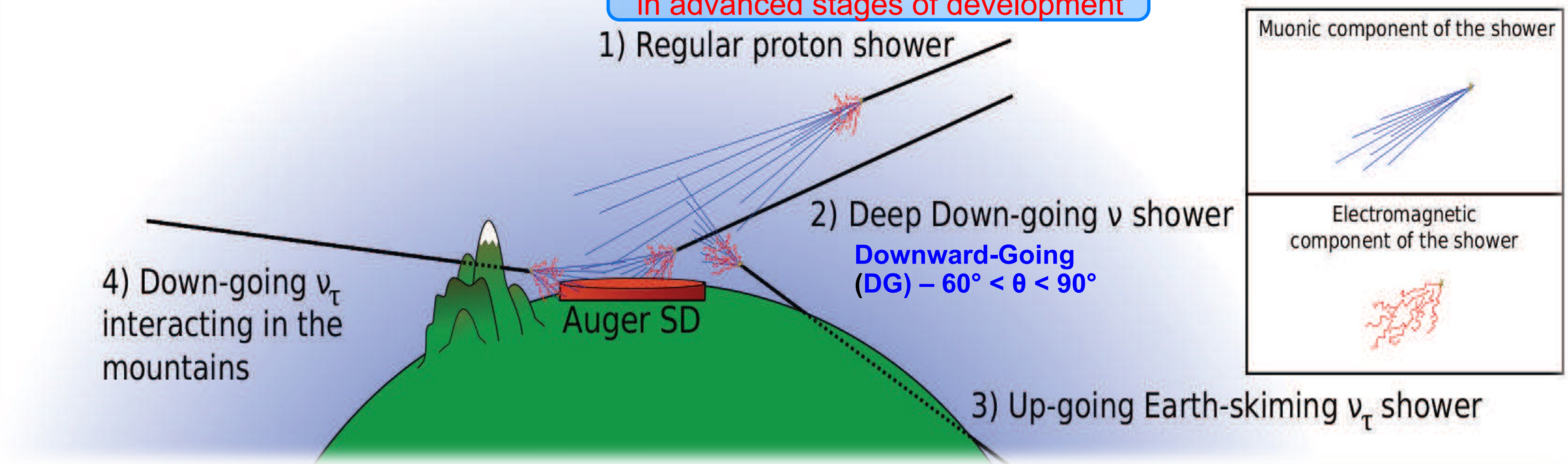
IFJ PAN, Kraków, Poland



Outline:
- Introduction
- Test of ANITA observations by Auger Fluorescence Detector
- Testing BSM scenarios
- Summary

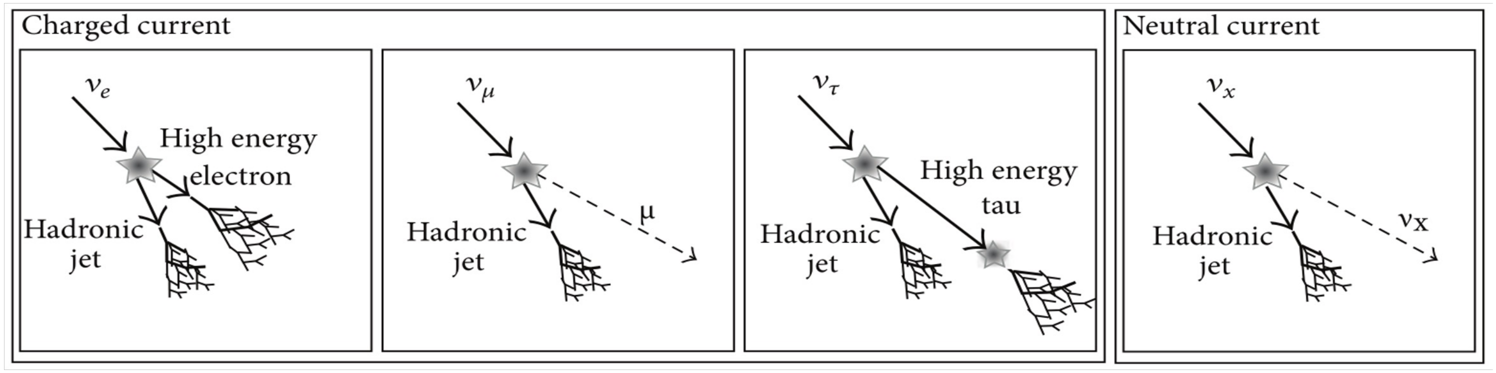
Method of neutrino identification

Background from hadronic events in advanced stages of development



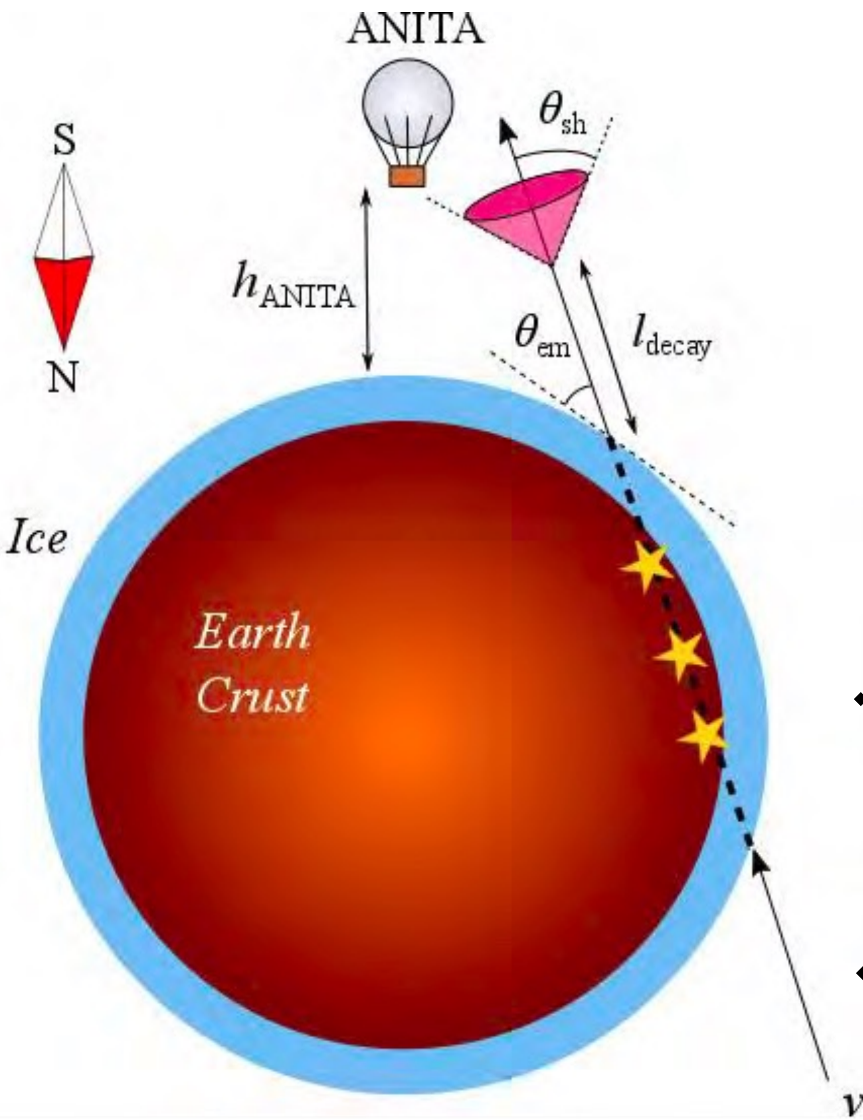
Downward-Going (DG) – 60° < θ < 90°

Earth-Skimming (ES) – zenith angles 90° < θ < 95°



Candidates for neutrino showers are searched among nearly horizontal showers

Search for Upward-Going (UG) Air Showers



- ANITA has detected two anomalous events with non-inverted polarity, consistent with upward-going showers:
  $E_{1,2} \approx 0.2$ EeV; exit angle ≈ 30°

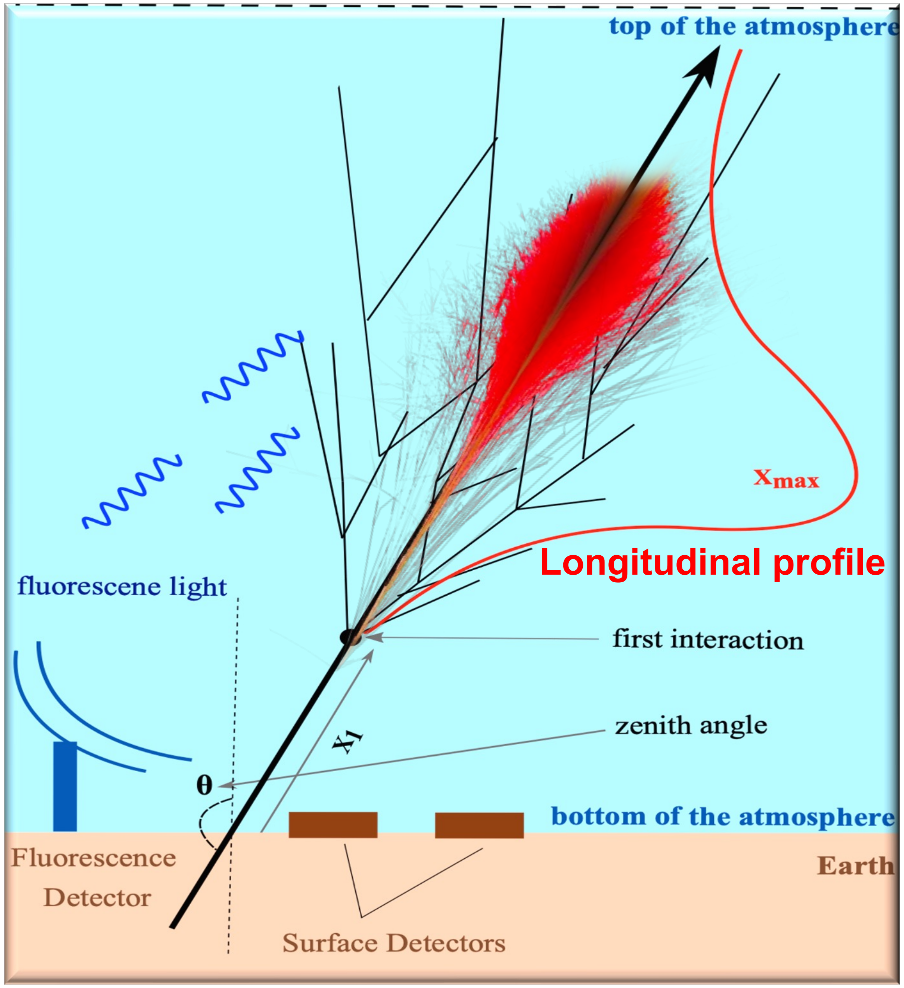
Gorham et al., PRL 117 (2016) 7
PRL 121 (2018) 16

Why „anomalous"?
Neutrinos at these energies from such directions will be absorbed in the Earth: Earth chord lengths ≈ 7000 km, $\lambda_{int} \approx 280$ km

- Fervent debate about interpretation:
  - observational artefact ?
  - **Beyond Standard Model (BSM) physics?**
    (ν's cannot penetrate Earth at these energies)

- BSM could explain it: Dark matter, sterile neutrinos, SUSY particles – could result in the production of τ-leptons

Test of ANITA observations by Auger Fluorescence Detector



- Auger FluorescenceTelescopes are sensitive to upwards going air showers

The propagation of electromagnetic component is producing isotropic fluorescence light

- ANITA did not provide (publish) exposure for the detected events

➡ **Flux of up-going events** was not known ➡ collaborated with ANITA to calculate it

- Auger fluorescence detector is expected to provide an exposure larger than that of ANITA, but no reconstruction available upwards-going extensive air showers

Key Steps in Simulations and Analysis

- determine reconstruction quality (energy, geometry, longitudinal profile…) The Global Fit (GF) reconstruction is used to simultaneously find the arrival direction, the impact point, and the Gaiser Hillas energy deposition that best fit the complete pixel data.)

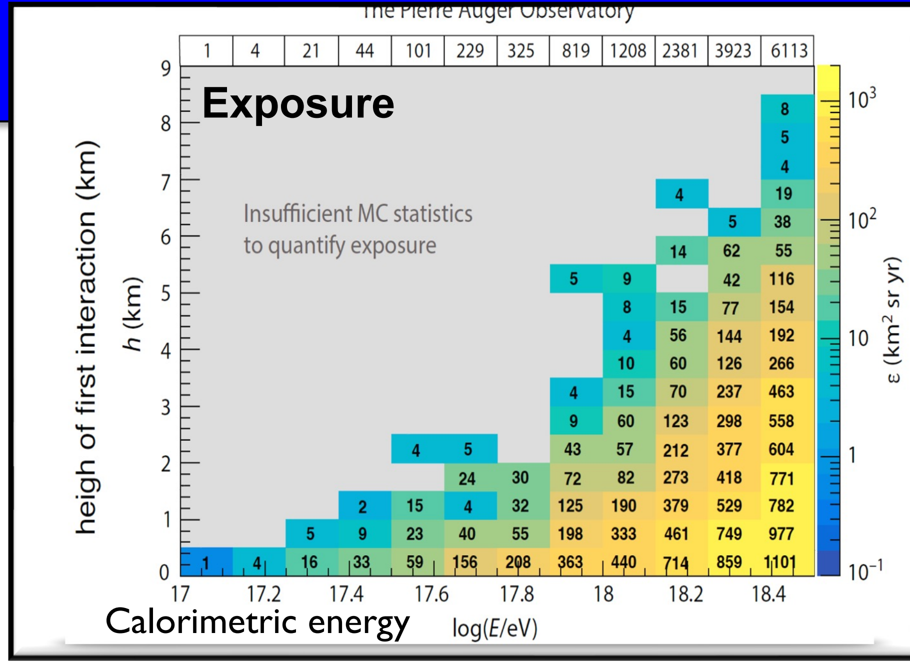
- determine signal detection efficiency as a fct of shower energy, elevation angle, and starting point in atmosphere

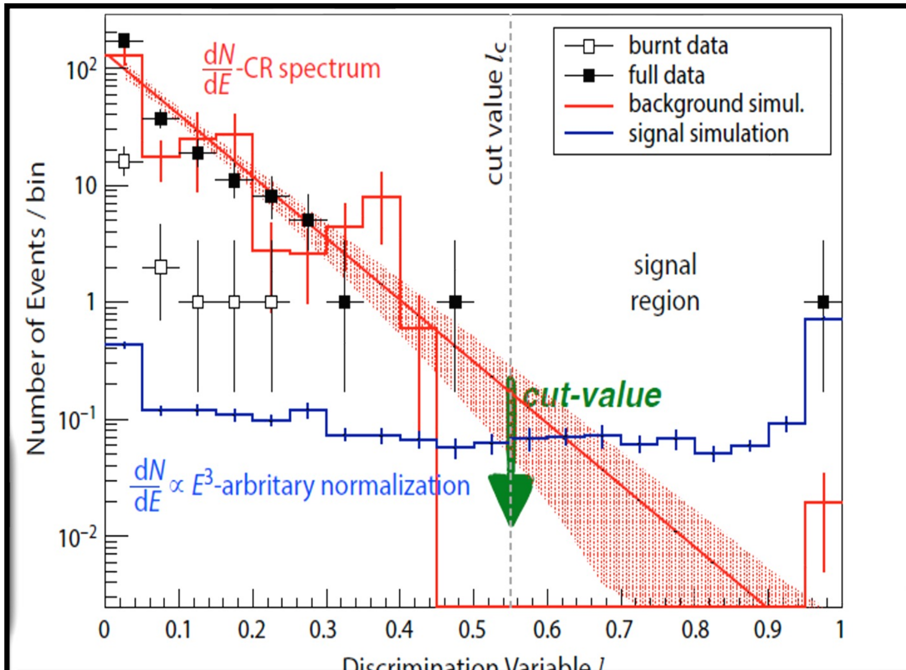
- determine background from misidentified downgoing showers

- apply data cleaning, e.g. discard laser events data sample

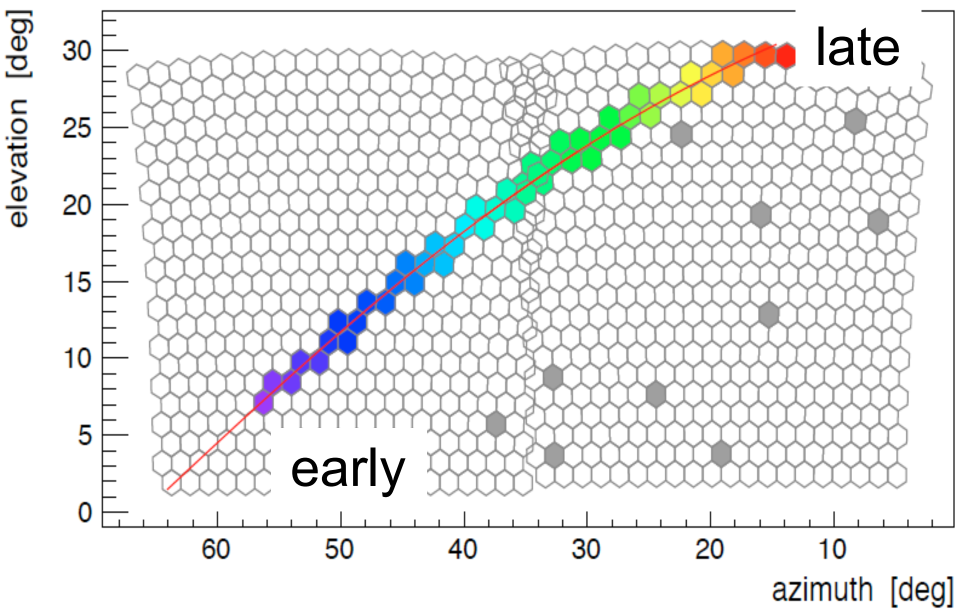
- apply proper cuts to maximise flux sensitivity (blind analysis of 14 years of data, verified with 10% of data (burn sample))

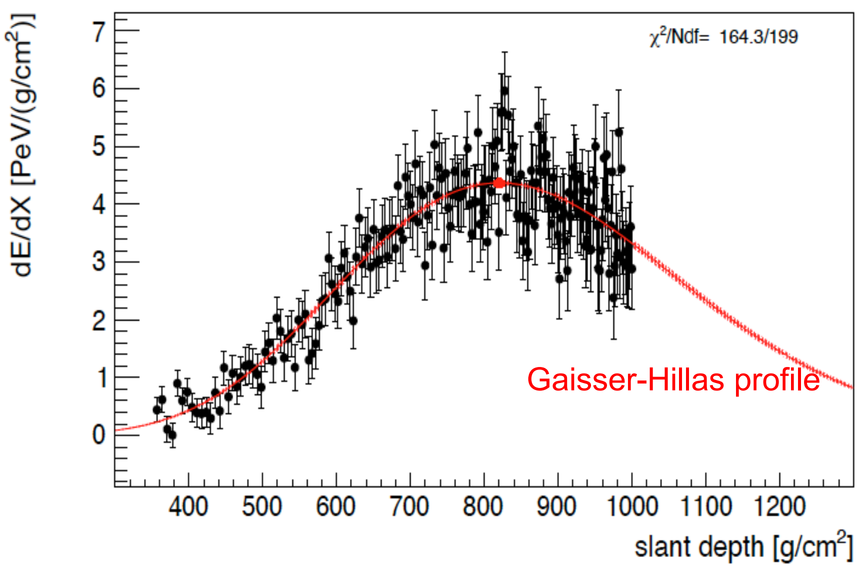
E. De Vito *et al.* [Pierre Auger Collaboration] PoS(ICRC2023)1099, also sumbitted to PRL





Simulated Upwards-Going signal event





- **Simulated upwards-going event**

E = 3 EeV

Θ = 114.2° (elevation angle 24.2°)

X_{max} = 844 g/cm^2

discrimination parameter $\ell=1$

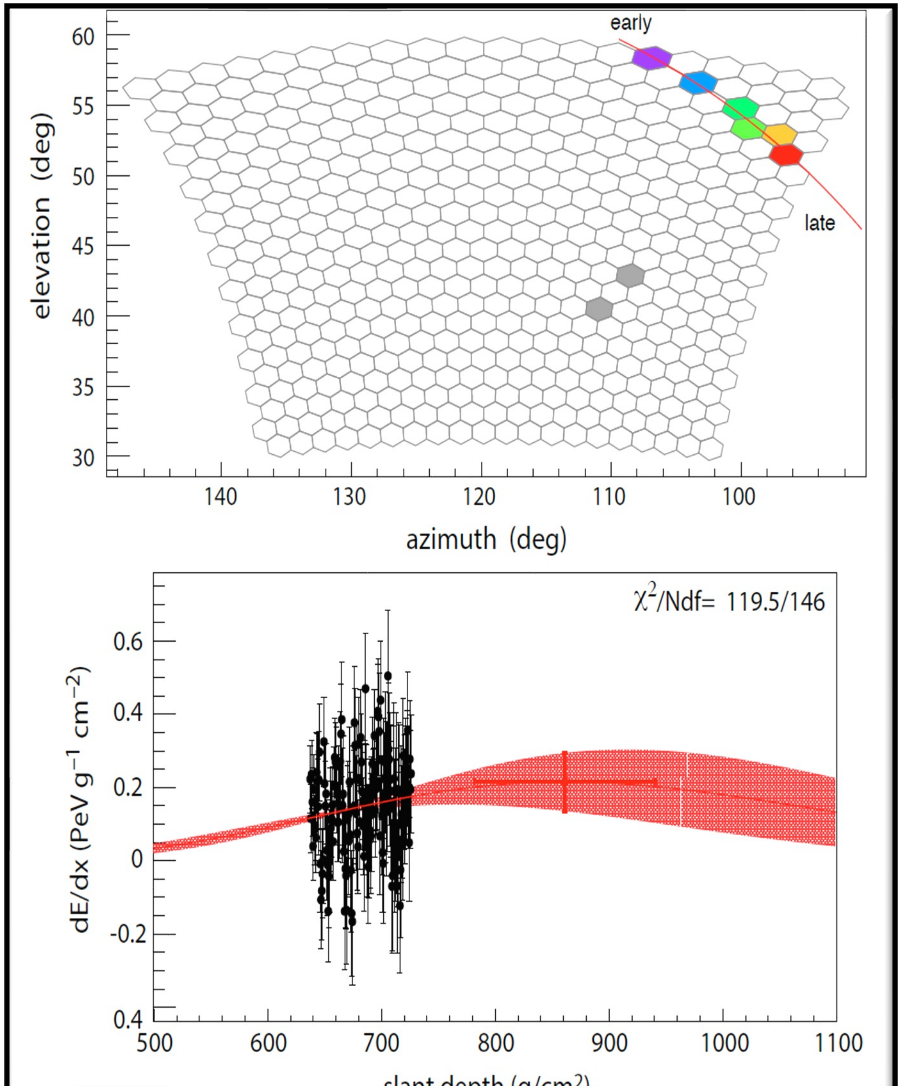
Two independent values of the maximum likelihoods, L_{down} and L_{up}, that can be compared to discriminate between events that are more likely to be downward-going ($L_{down} > L_{up}$) and vice-versa

Discrimination variable *l* from GF:

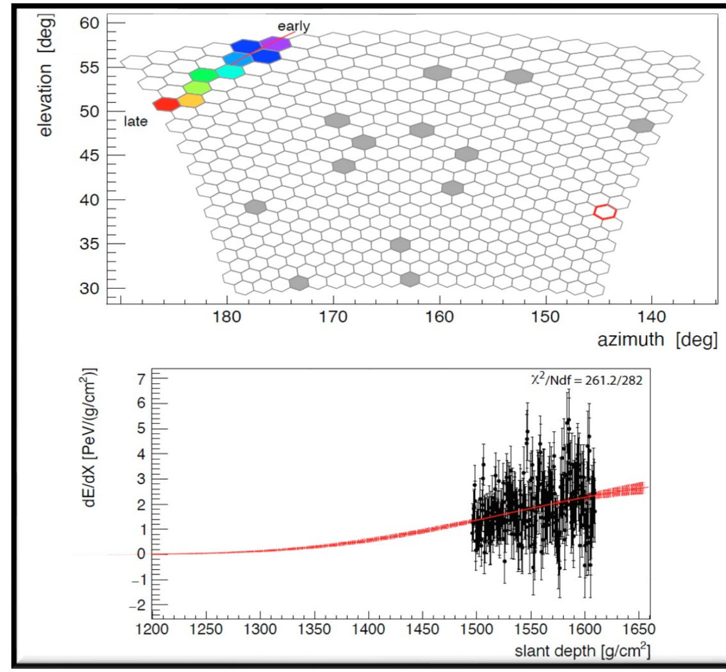
$$l = \frac{\arctan(-2\log(L_{down}/\max(L_{down}, L_{up}))/50)}{\pi/2}$$

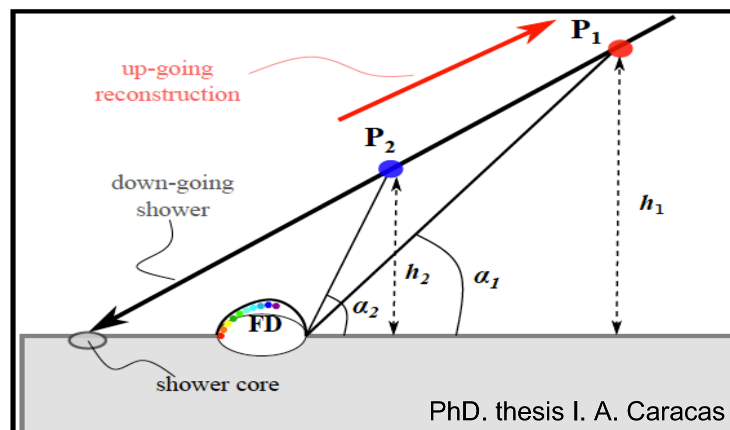
Upwards Reconstructed Bkg-Event

- **One Background event in full data sample**

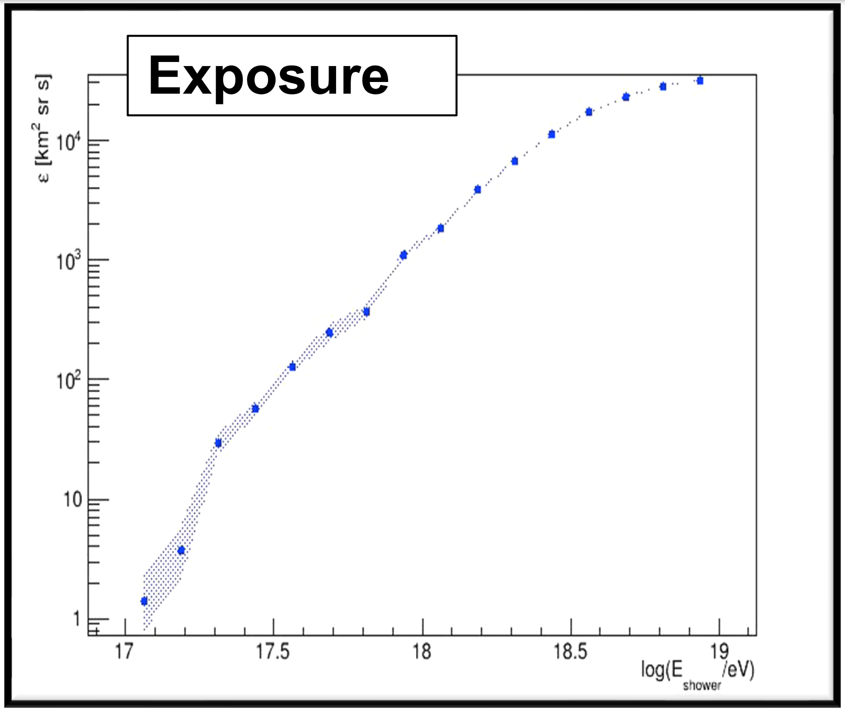


- **Simulated down-going event (landing behind telescope)**



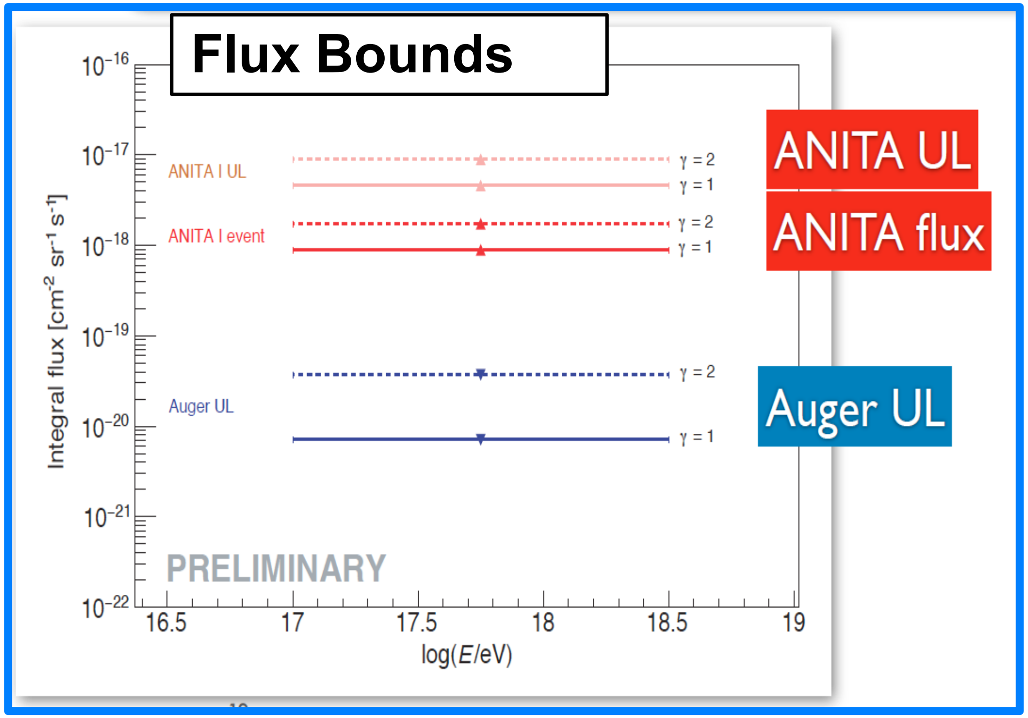


Exposure and resulting Flux Bounds after unblinding



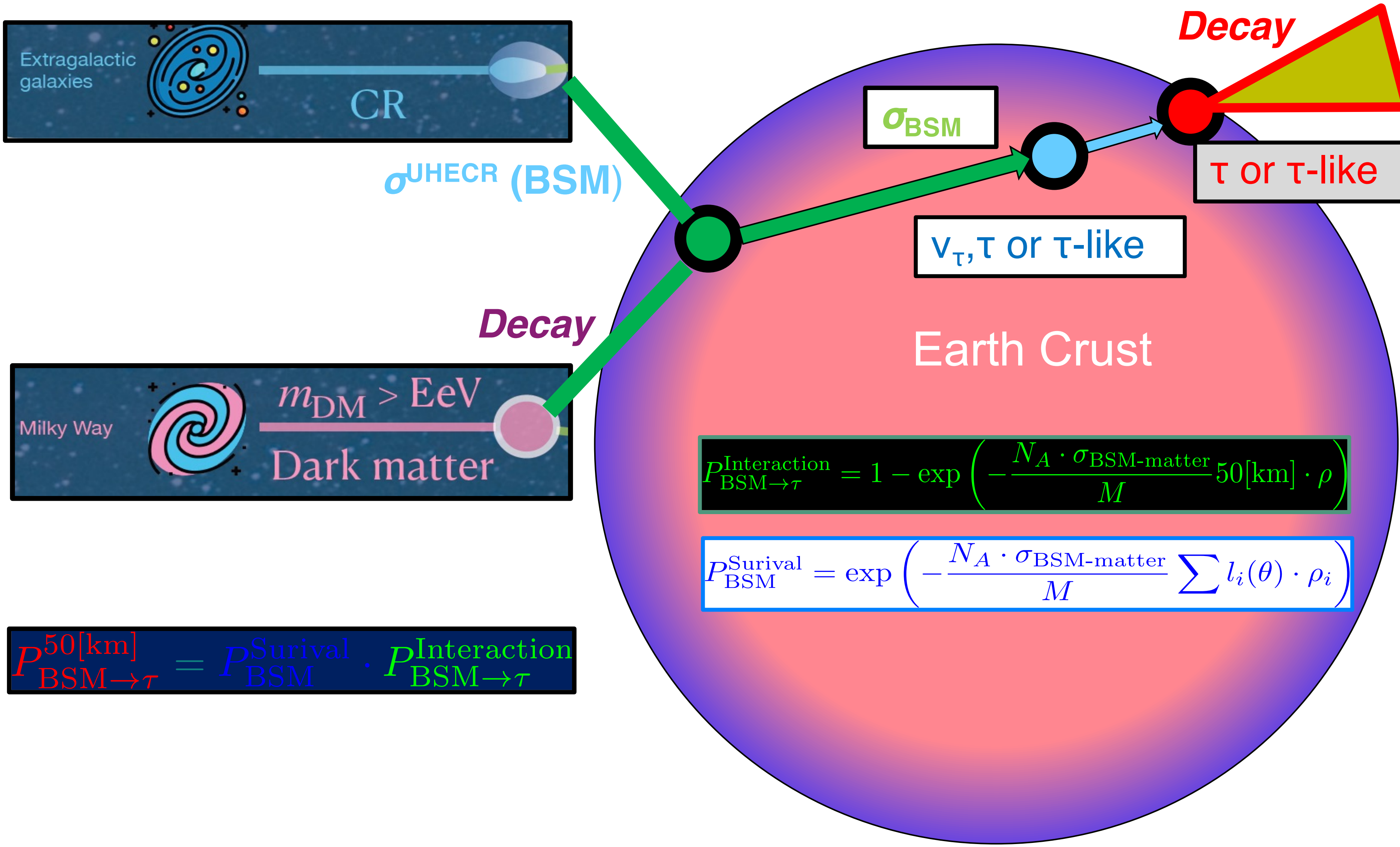
- Energy spectrum can be normalized to the anomalous observations demanding one expected event after folding with the ANITA I or III exposures.
- Would have expected several **10's to 100's** of events in Auger under conservative assumptions

- one event found after unblinding, consistent with expected bkg (poorly reconstructed event, typical for background)
  - ➡ exposure calculated for different zenith angular bins
  - ➡ using Rolke, the integral upper limit above 10^{17} eV is:



- $(7.2 \pm 0.2) \cdot 10^{-21}$ cm^{-2} s^{-1} sr^{-1} weighting exposure with E^{-1}
- $(3.6 \pm 0.2) \cdot 10^{-20}$ cm^{-2} s^{-1} sr^{-1} weighting exposure with E^{-2}

Testing BSM scenarios



$$P^{\text{Interaction}}_{\text{BSM}\to\tau} = 1 - \exp\left(-\frac{N_A \cdot \sigma_{\text{BSM-matter}}}{M} 50[\text{km}] \cdot \rho\right)$$

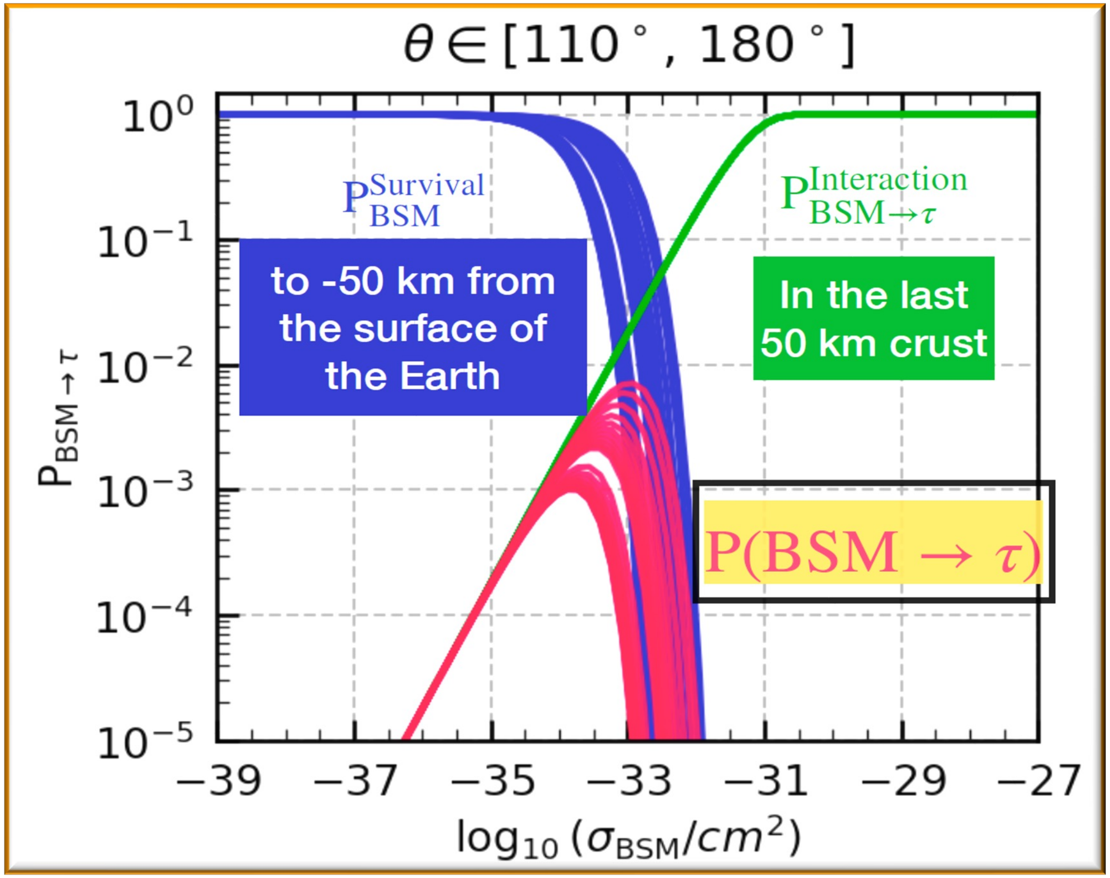
$$P^{\text{Surival}}_{\text{BSM}} = \exp\left(-\frac{N_A \cdot \sigma_{\text{BSM-matter}}}{M} \sum l_i(\theta) \cdot \rho_i\right)$$

$$P^{50[\text{km}]}_{\text{BSM}\to\tau} = P^{\text{Surival}}_{\text{BSM}} \cdot P^{\text{Interaction}}_{\text{BSM}\to\tau}$$

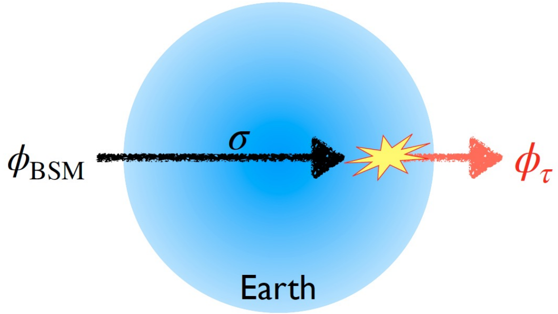
Null observations ➡ Upper limits

Testing BSM scenarios

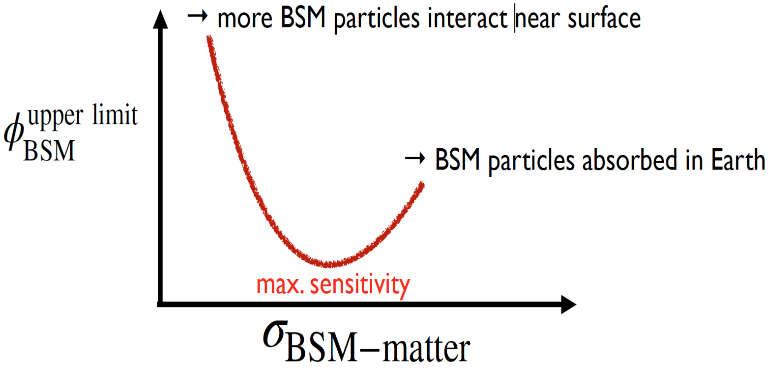
- **Can test if cross section is small enough** to let BSM pass through, and at the same time large enough to suffer interactions near surface, so that's can escape and generate shower in atmosphere



Multiple curves are for different zenith angles

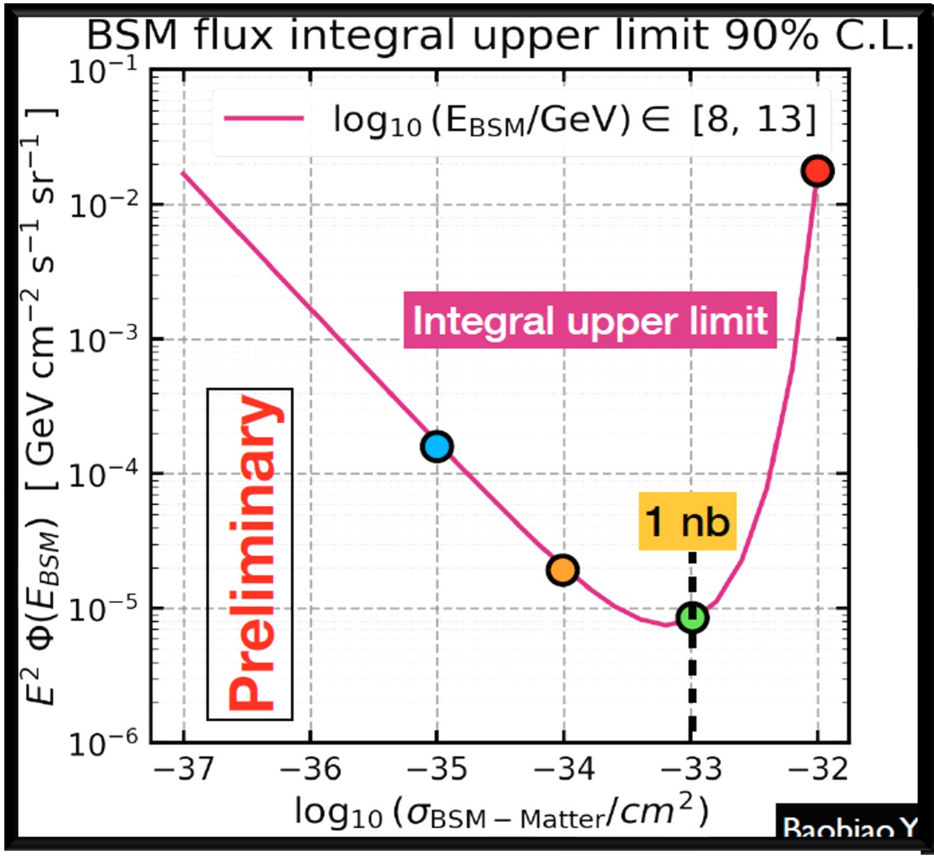


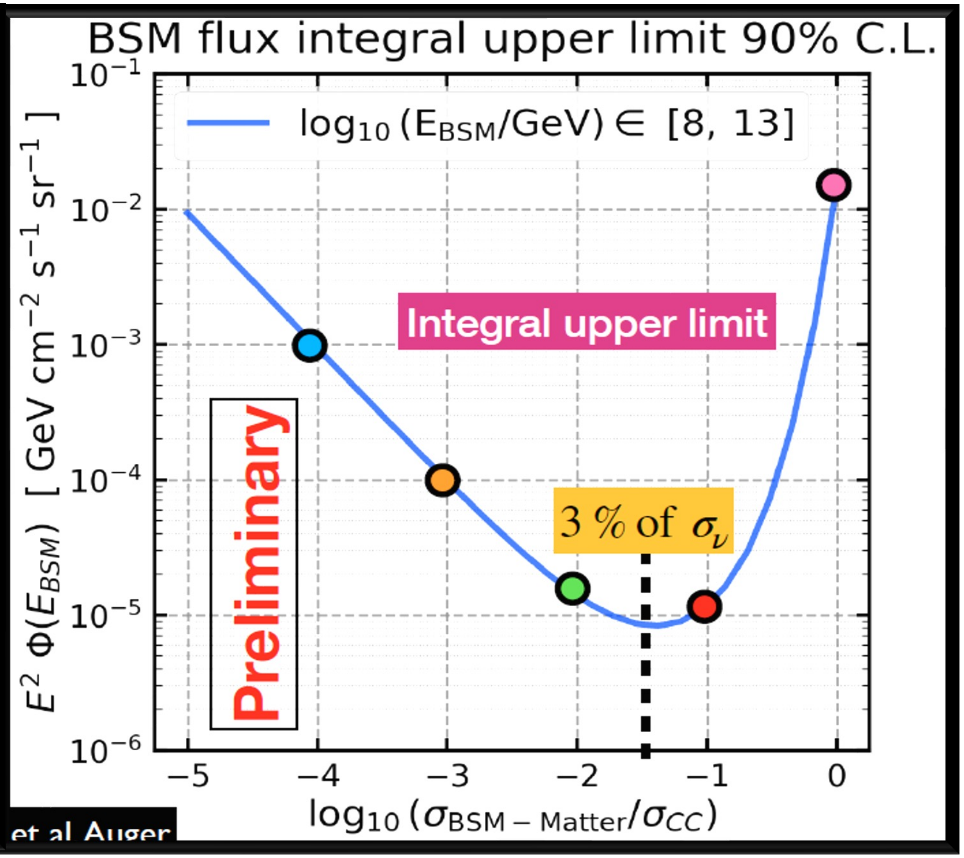
$$\phi_\tau(E,\theta) = \phi_{\rm BSM}(E,\theta)\cdot P^{50[\rm km]}_{\rm BSM\to\tau}$$



BSM flux integral upper limits

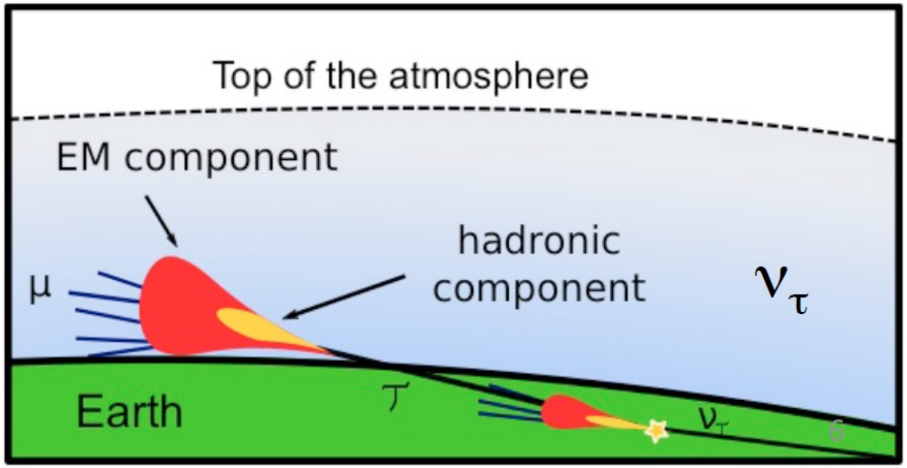
- ❖ **assuming energy independent cross section**
- ❖ **assuming BSM cross section ∝ $\sigma(\nu_\tau)$**





Baobiao Y et al Auger

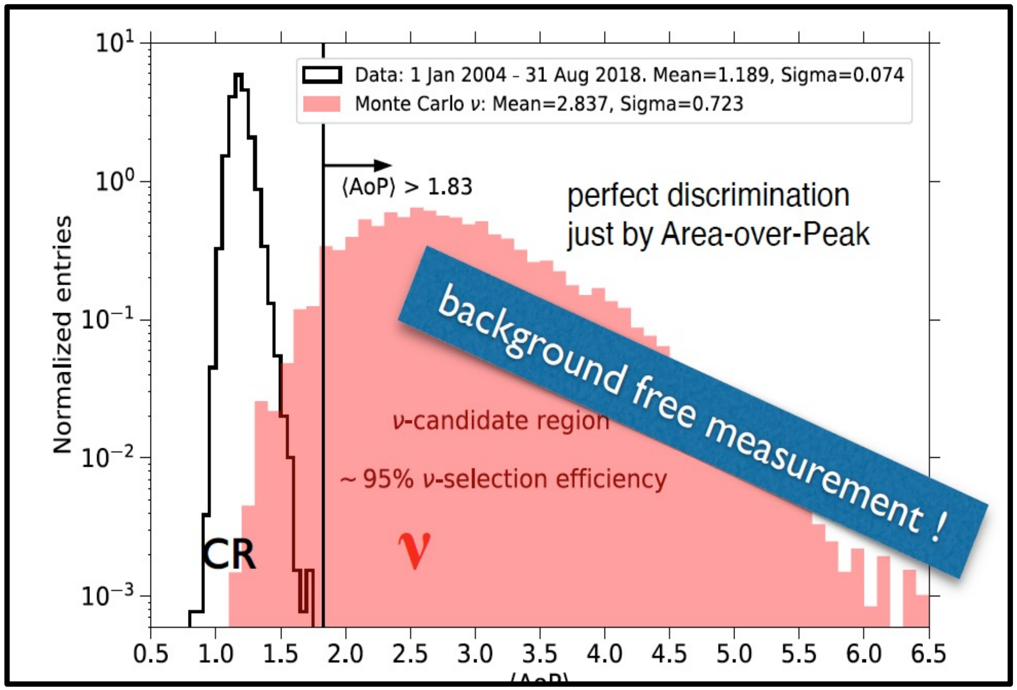
Earth-Skimming (ES) showers in Surface Detector Array



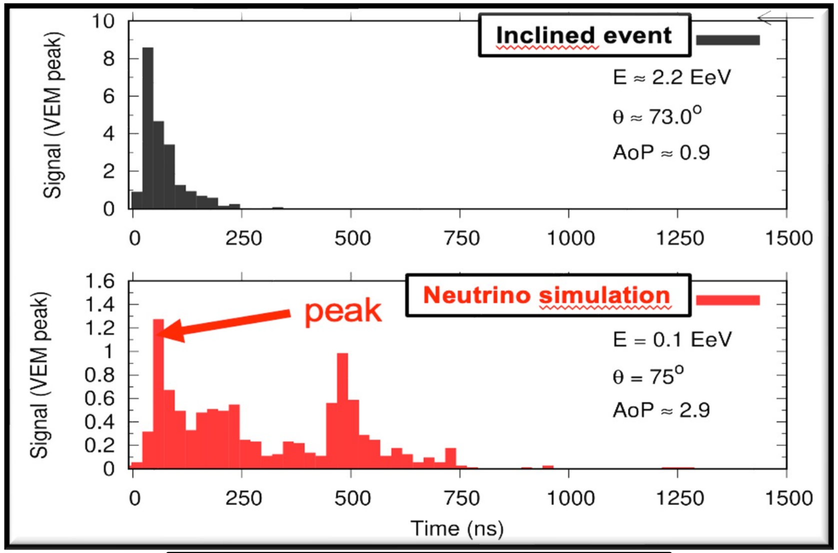
- **advantage:** ~ 100% duty cycle, 95% $\boldsymbol{\nu_\tau}$ selection efficiency at E_τ **> $10^{17.5}$** eV

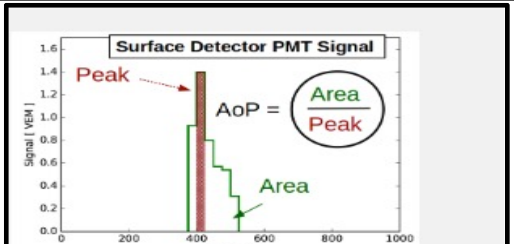
~ one background event in 50 years

- **disadvantage:** only small solid angle: $90^\circ \leq \theta \leq 95^\circ$



Area–over-Peak

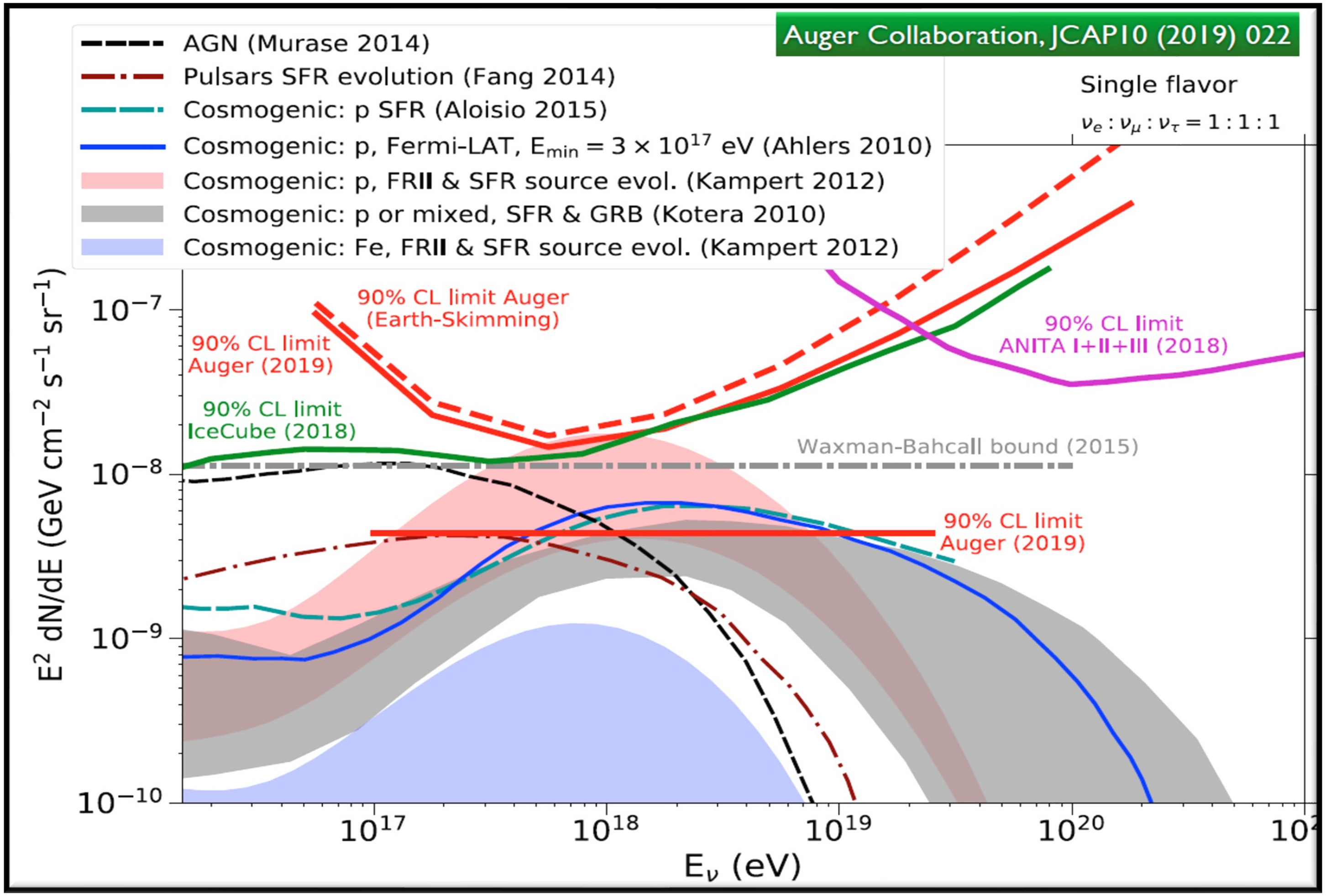




AoP – main discriminating variable

Earth-Skimming (ES) showers in Surface Detector Array

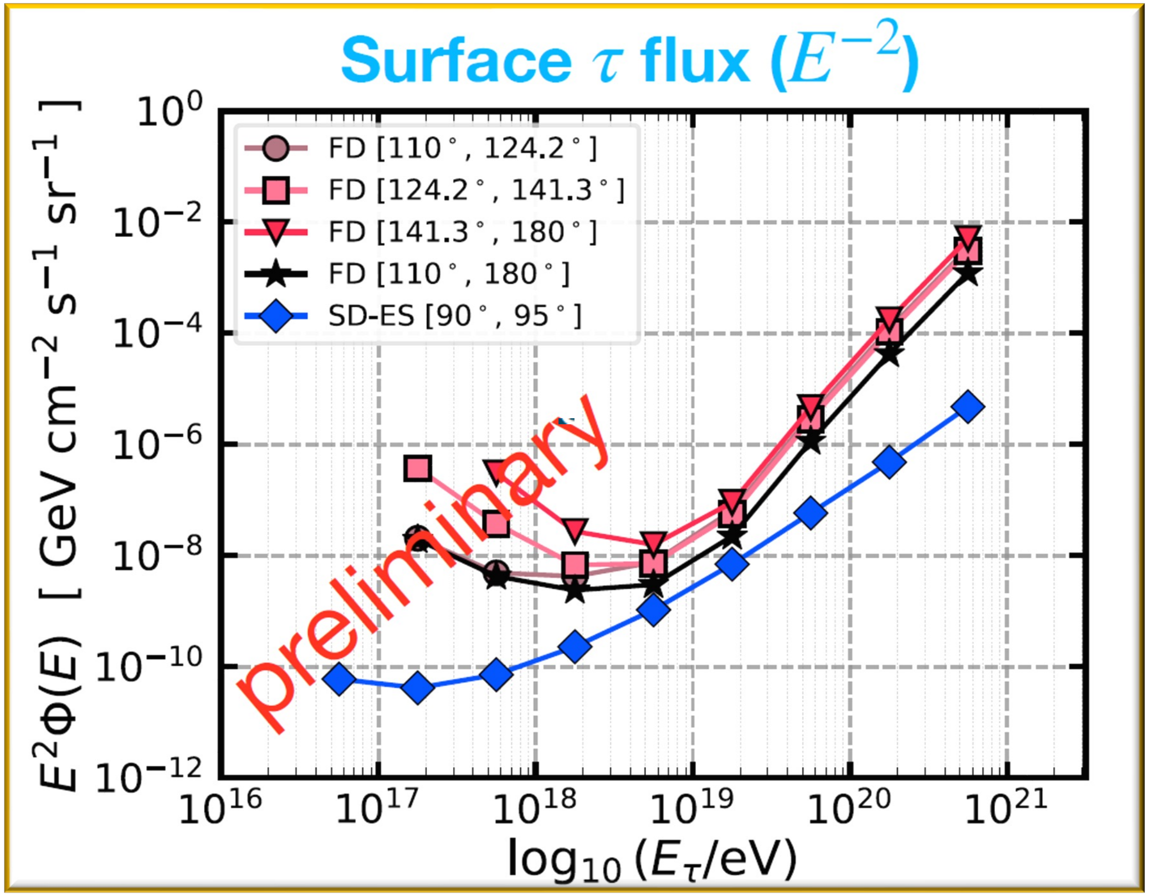
- ❖ Best present bounds on cosmogenic neutrinos from Auger & Icecube
- ❖ (in Auger dominated by ES channel, despite its small solid angle!)



- ❖ We can use the ES channel (flux limits) to test any (BSM→ τ) model

τ - related scenarios

- 50-km generation flux: generated more than 50 km underground can't escape the Earth. **Surface flux: upper limits of flux on the ground.**

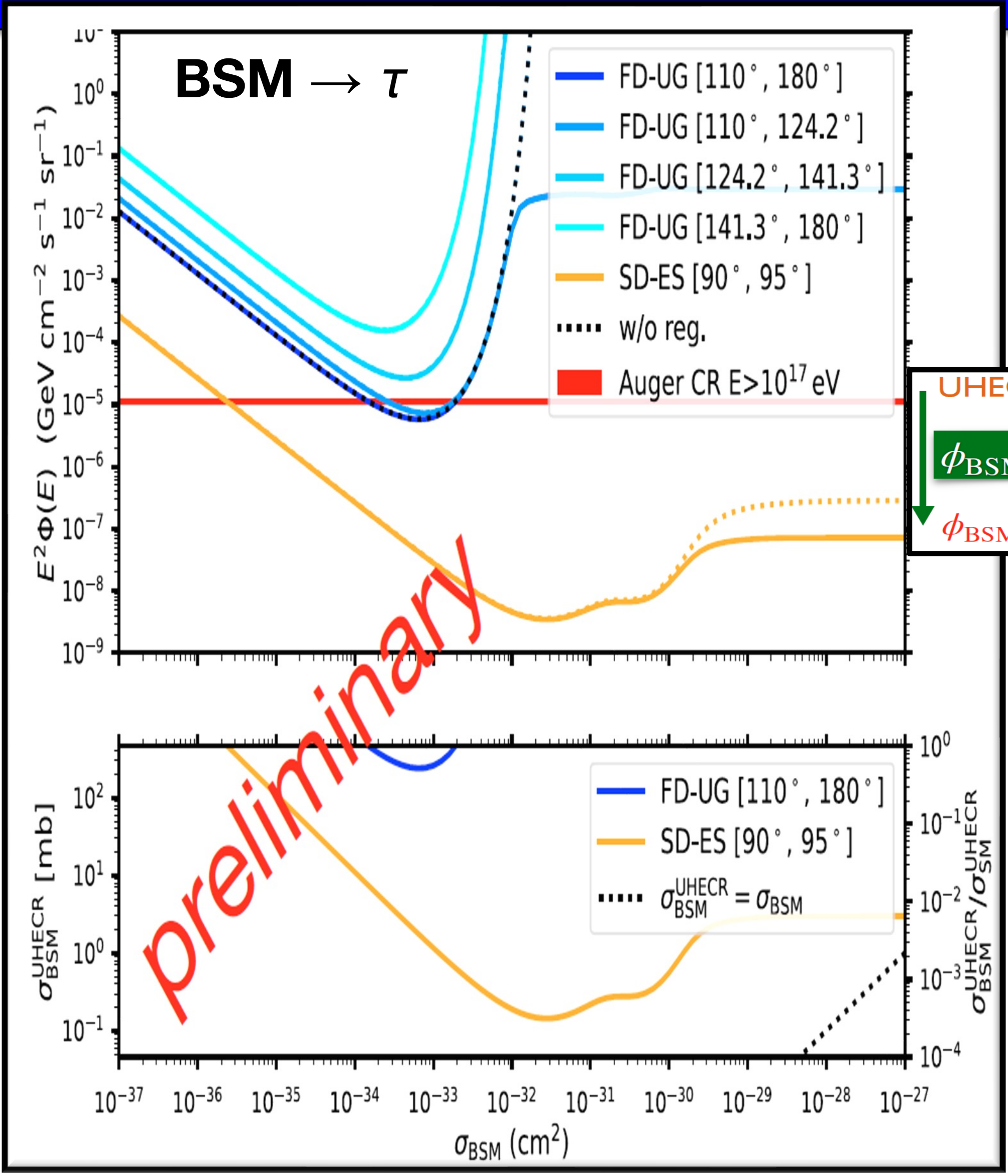


$$\phi_\tau(E,\theta) = \phi_{\text{BSM}}(E,\theta) \cdot P^{50[\text{km}]}_{\text{BSM}\to\tau}$$

B. Yue for the Pierre Auger Collaboration, NEUTRINO 2024

- These upper limits can be converted to any related scenarios

BSM scenario constraint → τ



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UHECR flux (E>10¹⁷ eV)

$\phi_{\rm BSM} < 10^{-3} \times \phi_{\rm UHECR}$

$\phi_{\rm BSM}$ bounds from ES-SD incl. τ regeneration

- This gives a possibility to constrains models in which UHECRs produce BSM

Summary

The Pierre Auger Observatory is sensitive to up-going showers in FD and SD.

❖ Recently, null-observations of UG shower in FD were found and are now extended to ES shower in SD.

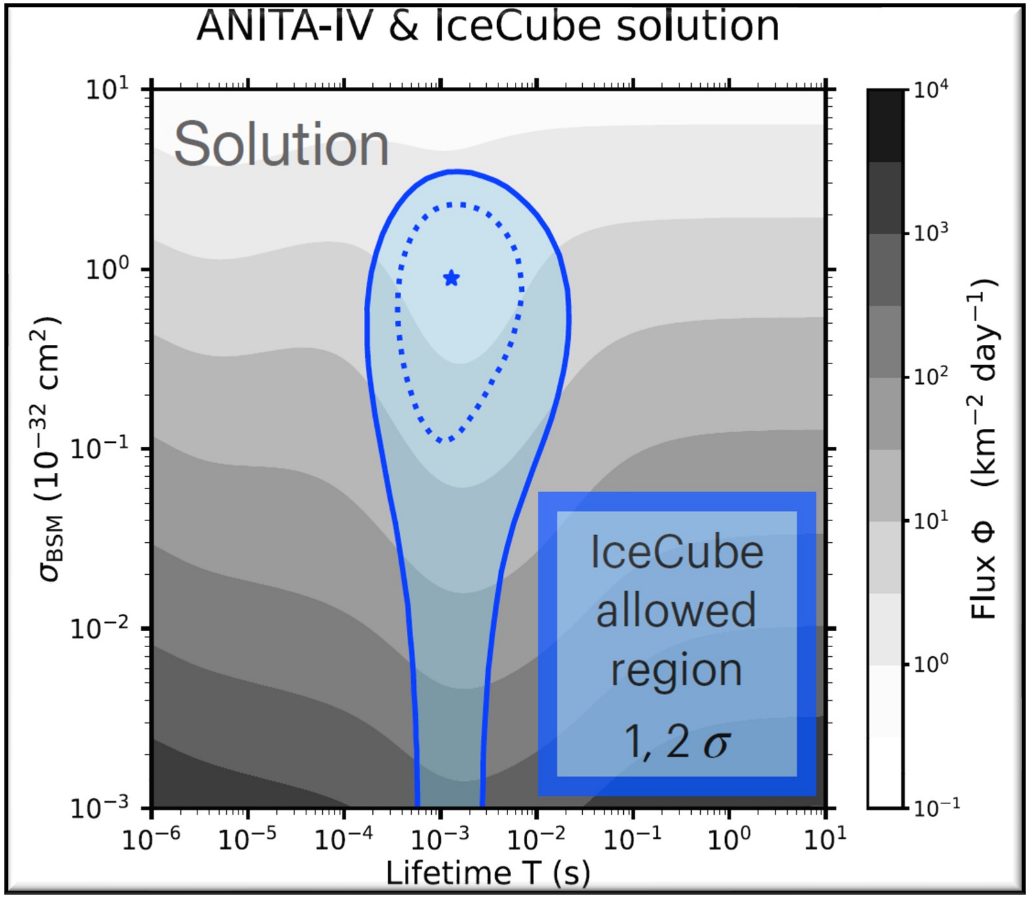
❖ Model independent scenarios with BSM and BSM have been well constrained.

❖ Flux upper limits has been given: these limits can be converted to any related tau scenario.

Backup slides:

❖ BSM -like interpreted for the four anomalous events in ANITA-IV has been ruled out by using FD-UG and SD-ES data.

BSM-like scenario → τ: ANITA-IV anomalous events



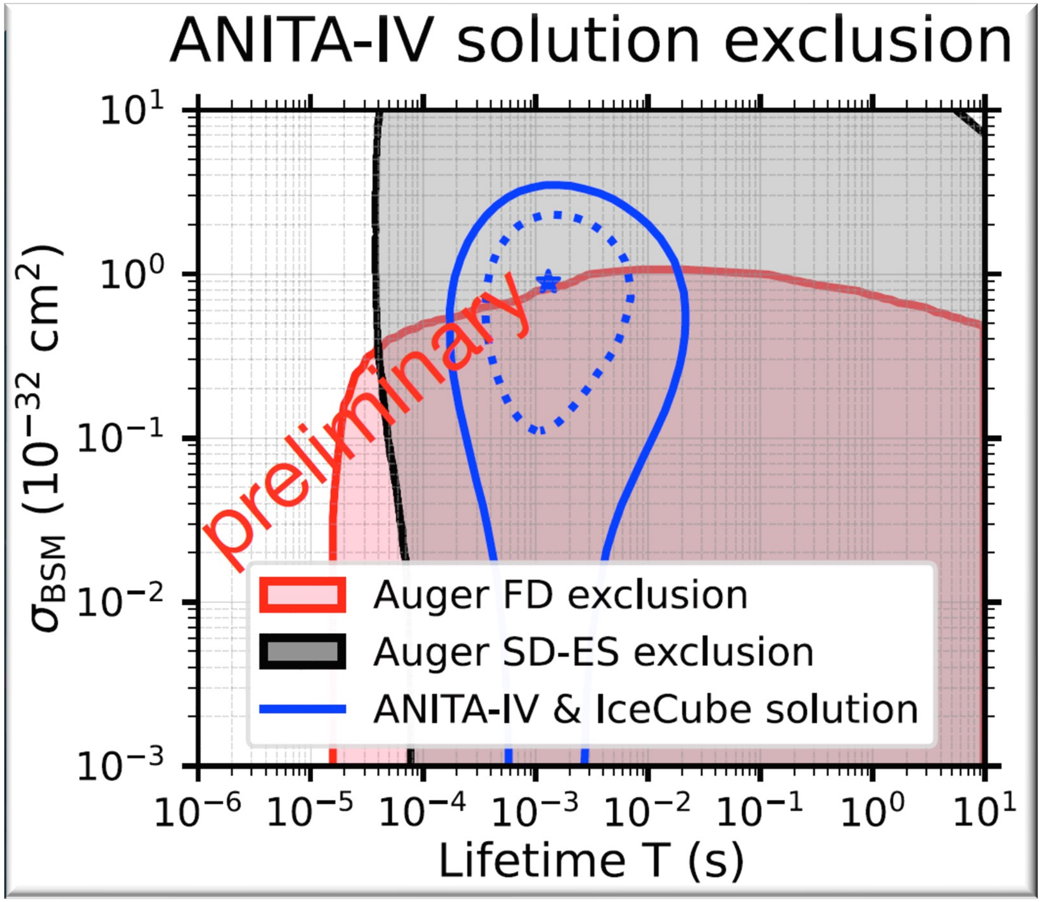
T. Bertolez-Marinez et all JHEP 07 (2023)

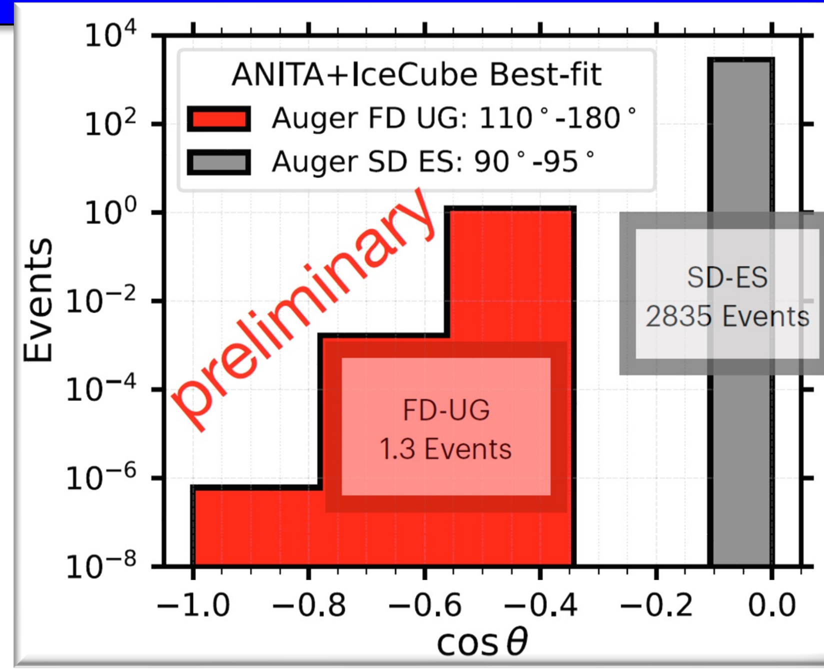
- T. Bertolez-Marinez et all. propose to explain ANITA-IV events by introducing BSM – like model (1-100 EeV).
- BSM particle can generate a long-lived particle, τ-like, which can decay (energy-independent T) and doesn't have energy loss.
- The null-observation at IceCube set a constraint to the parameter space with an allowed region.
- Regeneration:
  τ-like ➡ BSM ➡ τ-like
  is considered .

$$\text{Best fit: } \sigma_{\rm BSM} = \mathbf{8.9 \times 10^{-33}}\,\text{cm}^{\mathbf{2}}, \mathbf{T = 1.3 \times 10^{-3}}\,\text{s, and } \mathbf{\Phi = 1.8}\ \text{km}^{\mathbf{-2}}\text{day}^{\mathbf{-1}}$$

BSM - like scenario → τ: ANITA-IV anomalous events

Auger predictions and exclusion





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❖ The Null-observations of FD-UG and SD-ES exclude the allowed region of BSM - like infered from the Null-observation of IceCube.