BERGISCHE UNIVERSITÄT WUPPERTAL

PIERRE AUGER OBSERVATORY

Search for New Physics with upward-going Air Showers in Auger

Karl-Heinz Kampert
for the Pierre Auger Collaboration

ISVHECRI 2024, Puerto Vallarta

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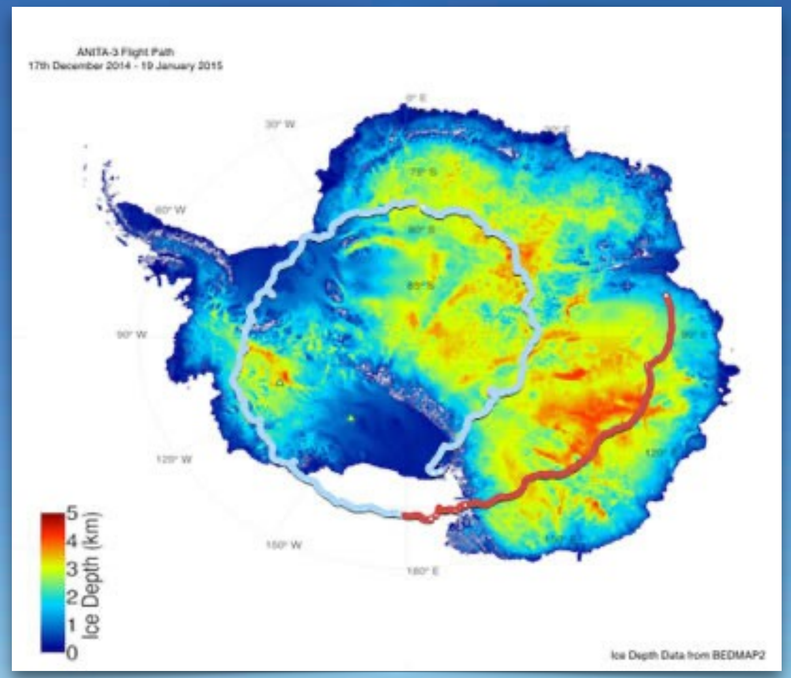
Outline:

- ANITA Anomalous Events
- Search for up-going showers in Auger
- Comparison with ANITA observation
- Constraints to BSM Physics

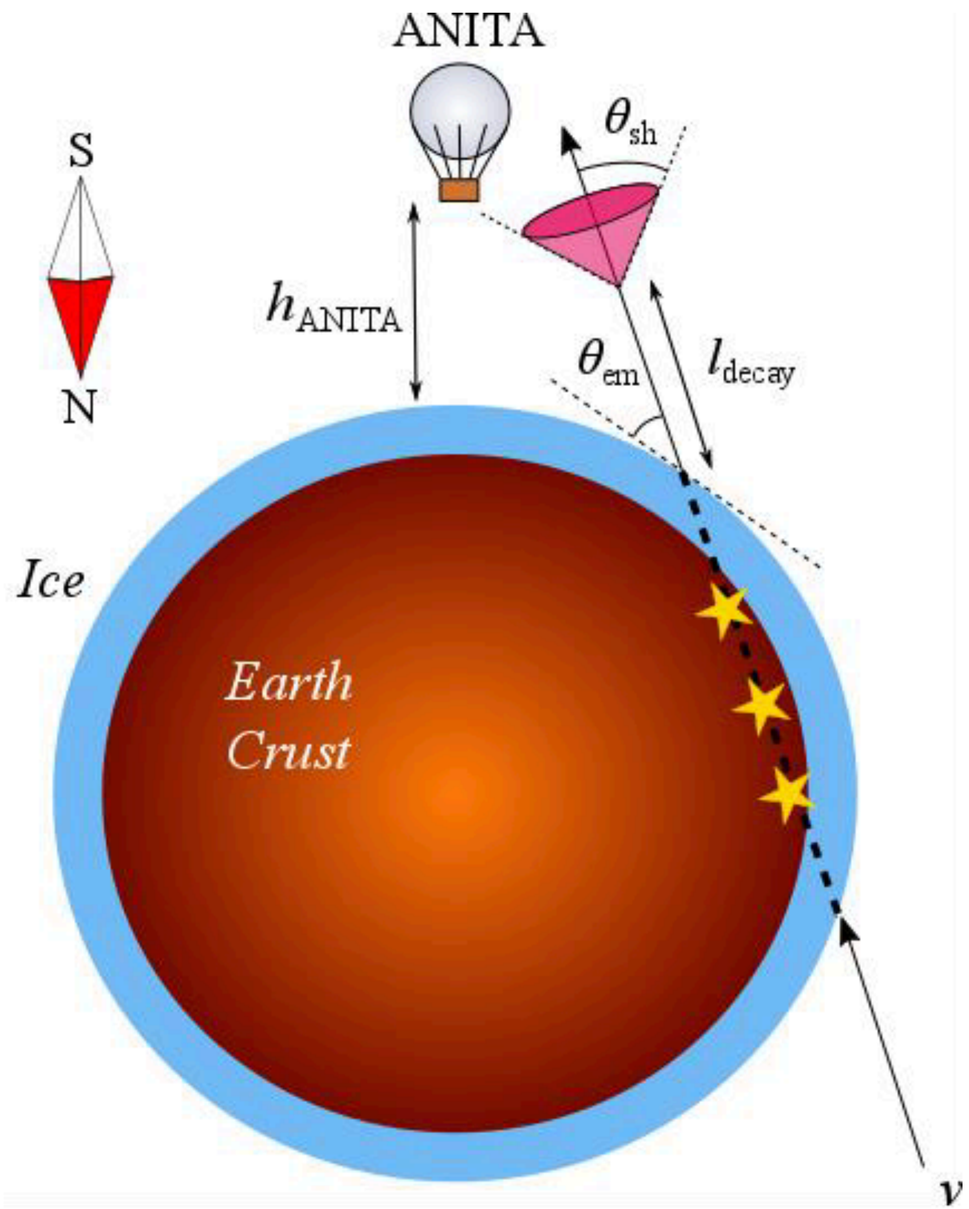
ANtarctic Impulse Transient Antenna

ANITA



2014-2015
37 km above Antartica
22 days
48 antennas

Observation of Upward-propagating EAS



ANITA-I and -III observed one anomalous up-going event, each

- emergence angles: 27° and 35°
- energies $\mathcal{O}$(1 EeV)
- no polarity inversion, as from reflected events

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

$p_{SM}(\varepsilon_\tau > 0.1\text{EeV})$ for $\varepsilon = 1$ EeV $\approx 5 \cdot 10^{-8}$

Fox, Sigurdsson, Murase et al.
arXiv: 1809.09615

Some Possible Interpretations

SM-origin upward-going Extensive Air Showers (EAS) excluded…

Pure SM, down-going

- Downward-going events, interacting with the geomagnetic field [de Vries, Prohira, '19]
- Downward-going events, reflected by sub-layers of the ice sheet [Shoemaker, Kusenko, Munneke, Romero-Wolf, Schroeder, Siegert, '19]

BSM, down-going

- Axionic UHECR reflecting on the ice [Esteban, Lopez-Pavon, Martinez-Soler, Salvado, '19]
- Askaryan emission in the Ice, induced by heavy dark matter [Hooper, Wegsman, Deaconu, Vieregg, '19]

BSM, up-going

- SUSY interpretations [Fox, Sigurdson, Murase et al., '18, Collins, P. S. Bhupal Dev, and Y. Su, '18, Altmannshofer, ,20]
- Sterile neutrino, or Axion Quark Nuggets, or Axions converting in the Earth [Cherry, Shoemaker, '19, Huang, '18], Liang ,21, Nicoladis , '20]

DM → SM scattering, up-going

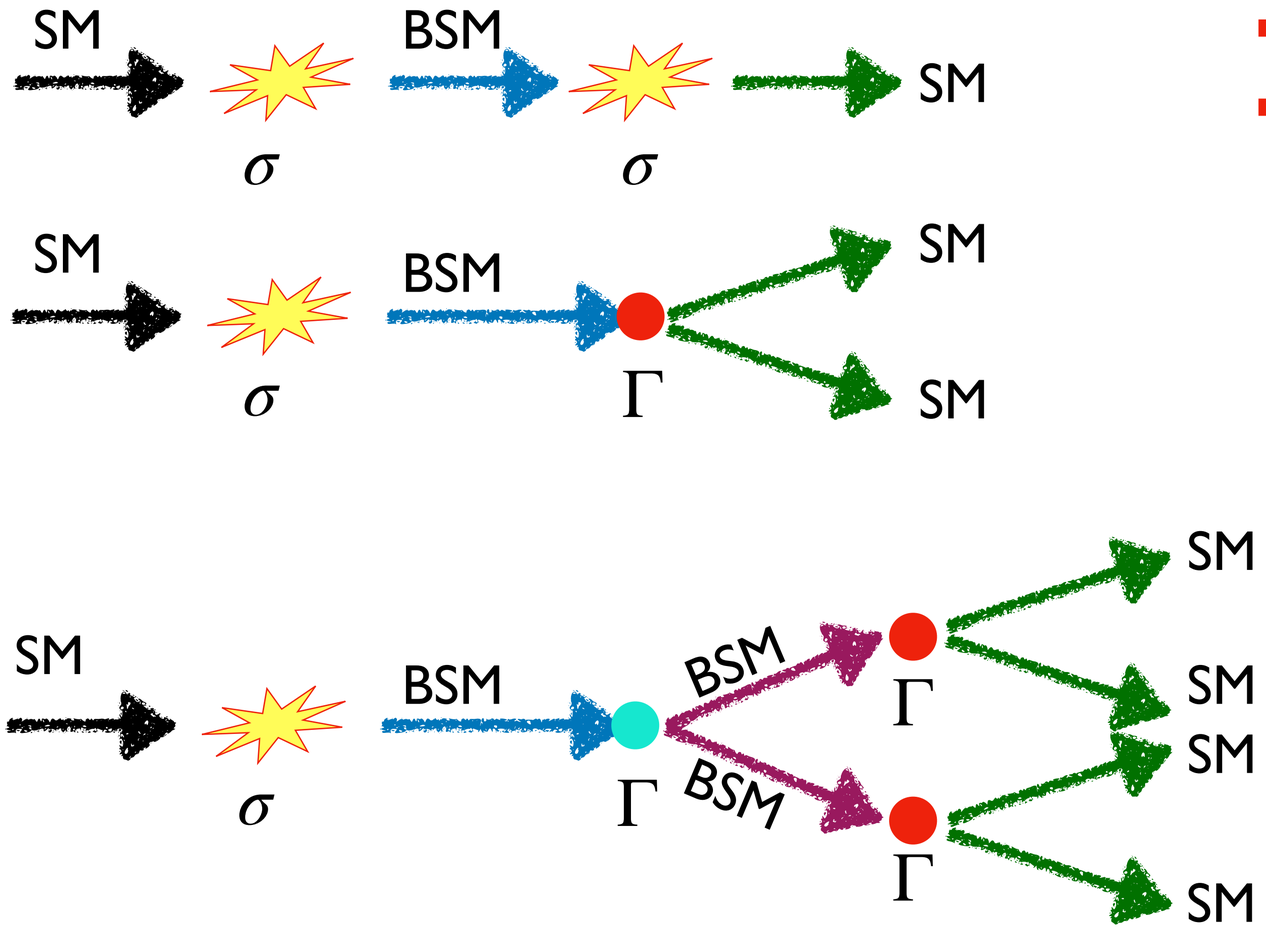
- Dark Matter decaying into leptons [Cline, Gross, Xue '19]

DM → BSM scattering, up-going

- Dark Matter decaying into RH neutrinos [Heurtier, Mambrini, Pierre '19]
- Inelastic Boosted Dark Matter [Heurtier, Kim, Park, Shin, '19]

… and many more

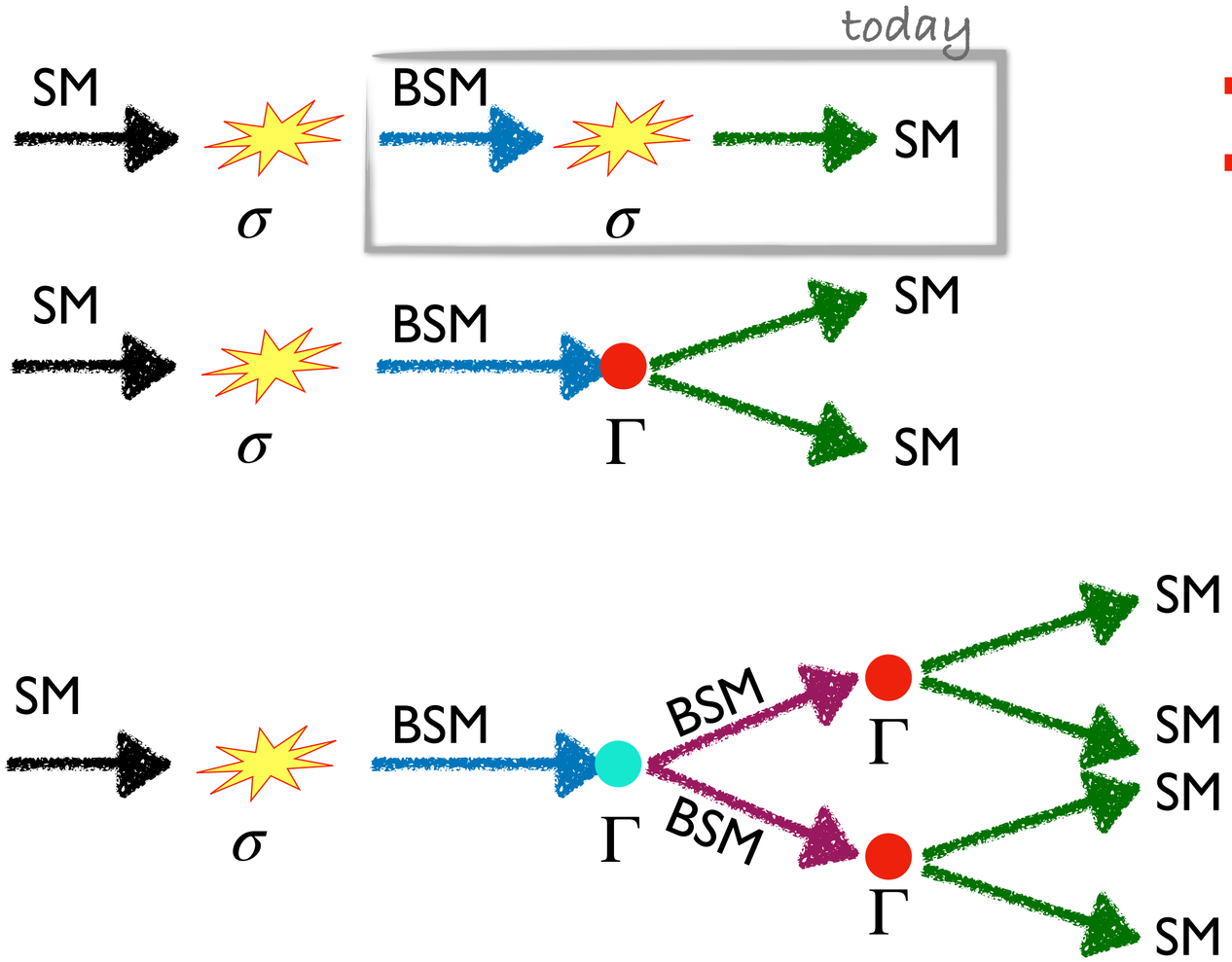
BSM Interactions and UHECR propagation



- energy decreases with # interactions
- energy and angular distribution affected by interaction topologies

• • •

BSM Interactions and UHECR propagation



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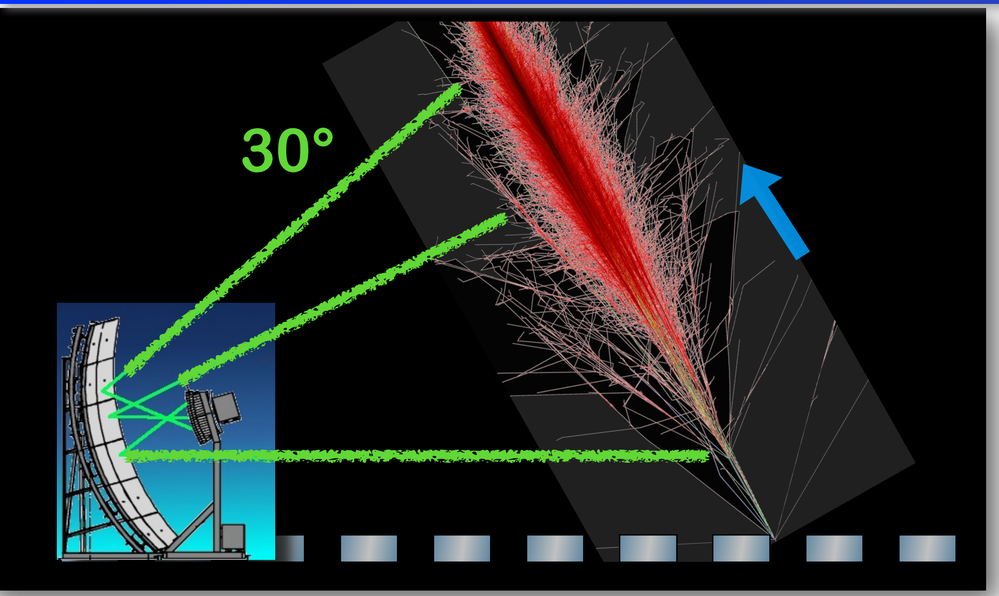
Test of ANITA observations by Auger FD



★ Auger Fluorescence Telescopes are sensitive to upwards going air showers

★ 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 EAS

Key Steps in Simulations and Analysis

- determine signal detection efficiency as a fct of shower energy, elevation angle, and starting point in atmosphere
- determine reconstruction quality (energy, geometry, …)
- 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, verified with 10% of data (burn sample))

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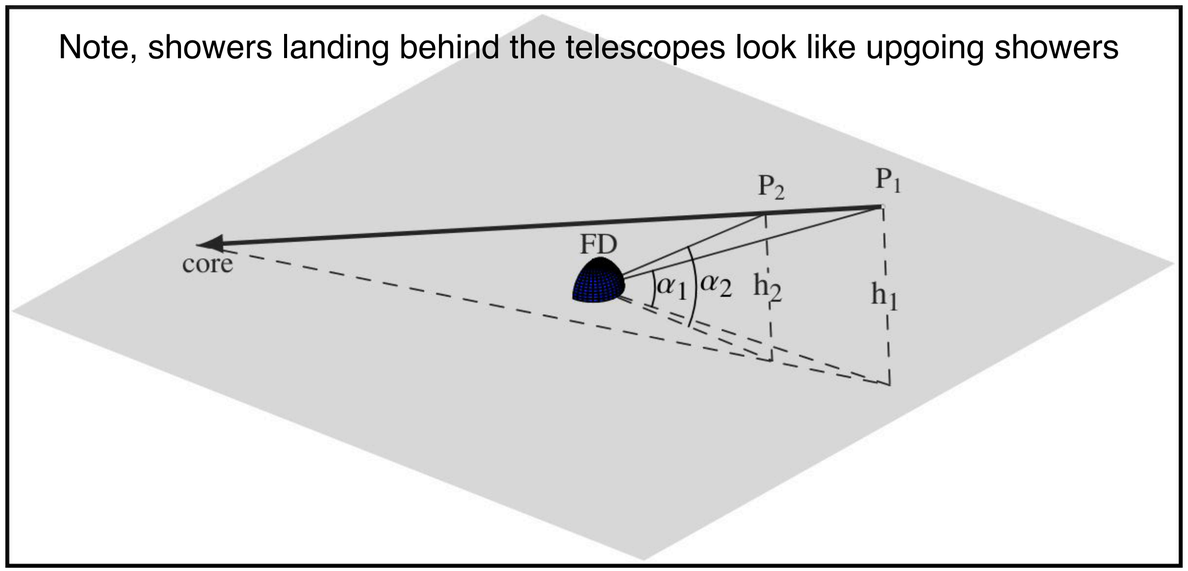

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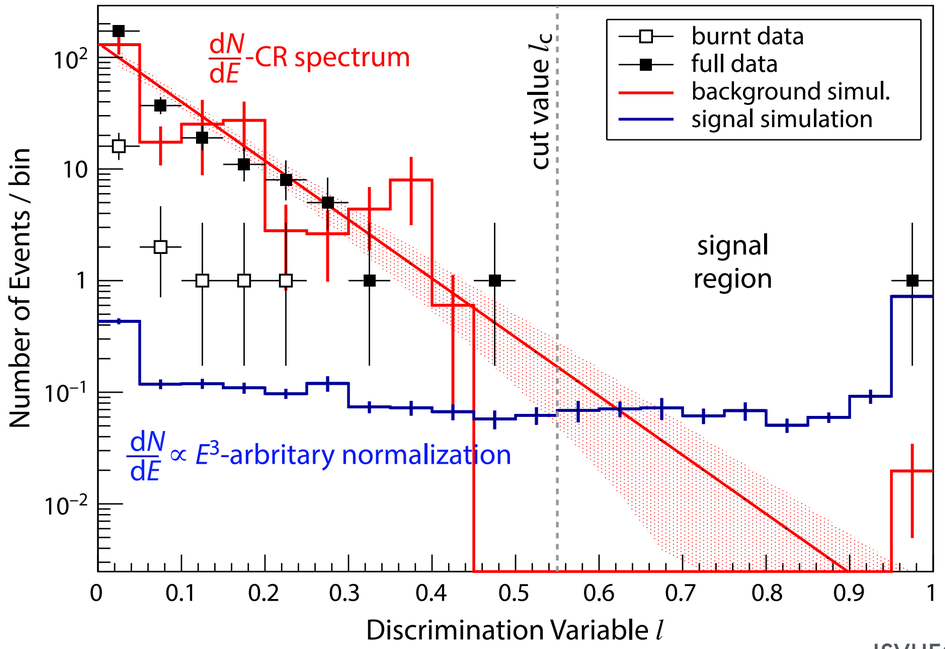

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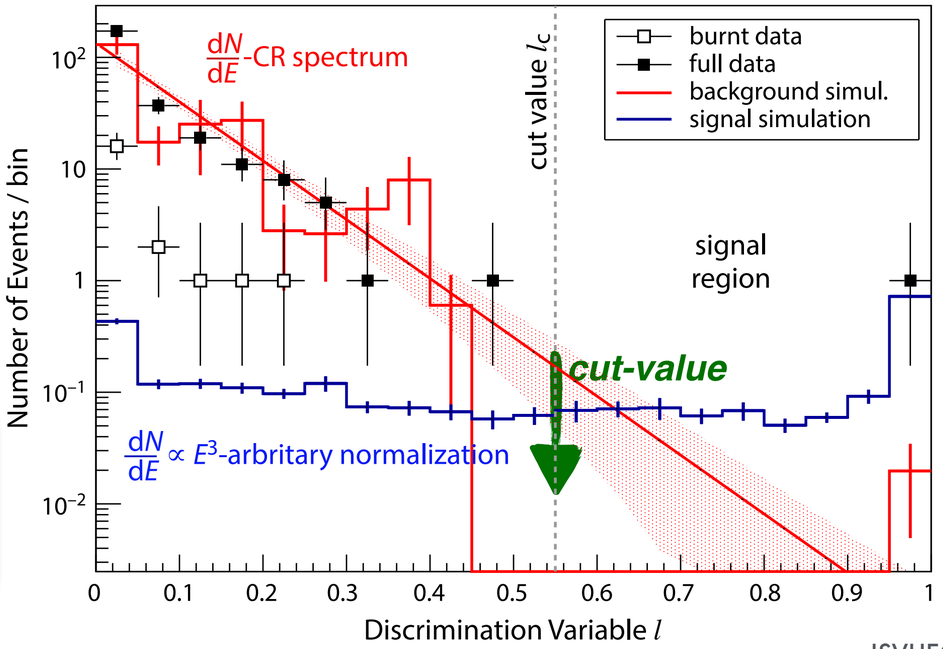
- expect 0.27±12 events after unblinding



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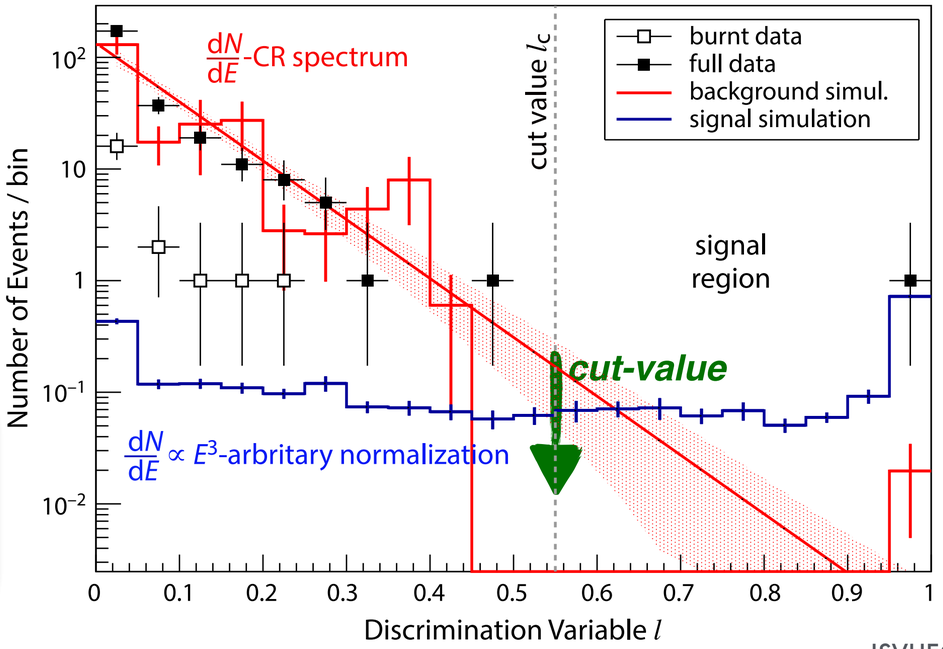
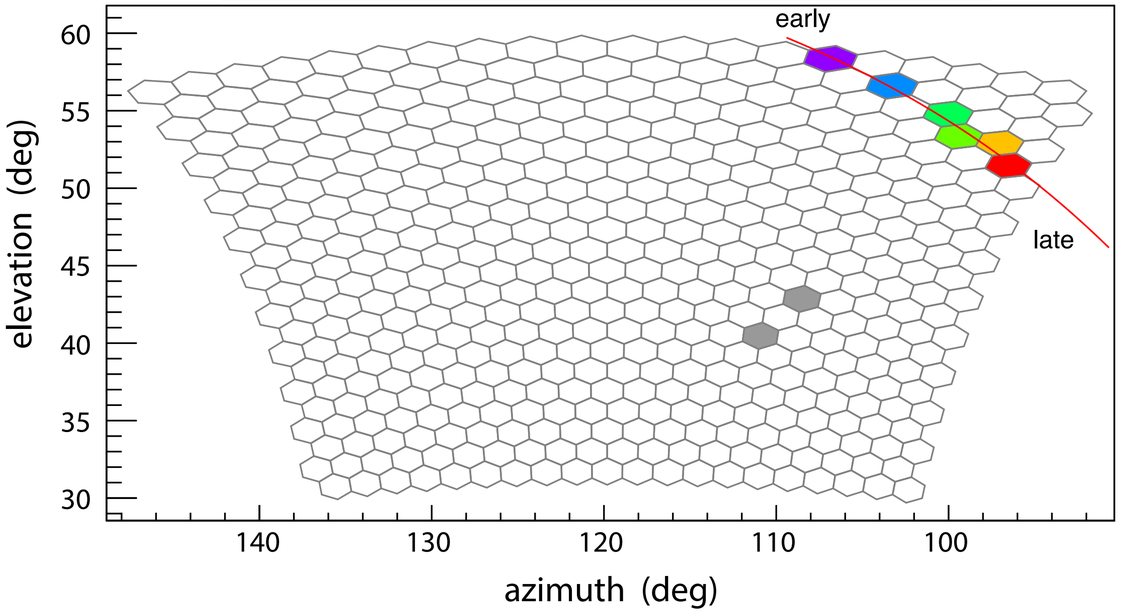
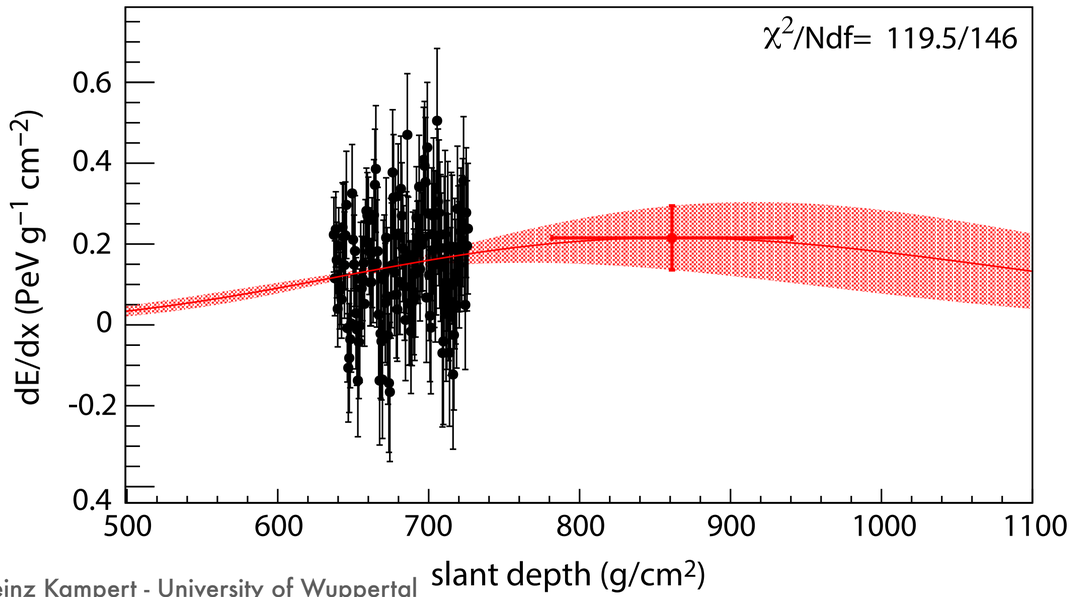
- expect 0.27±12 events after unblinding
- found 1 event, typical background features



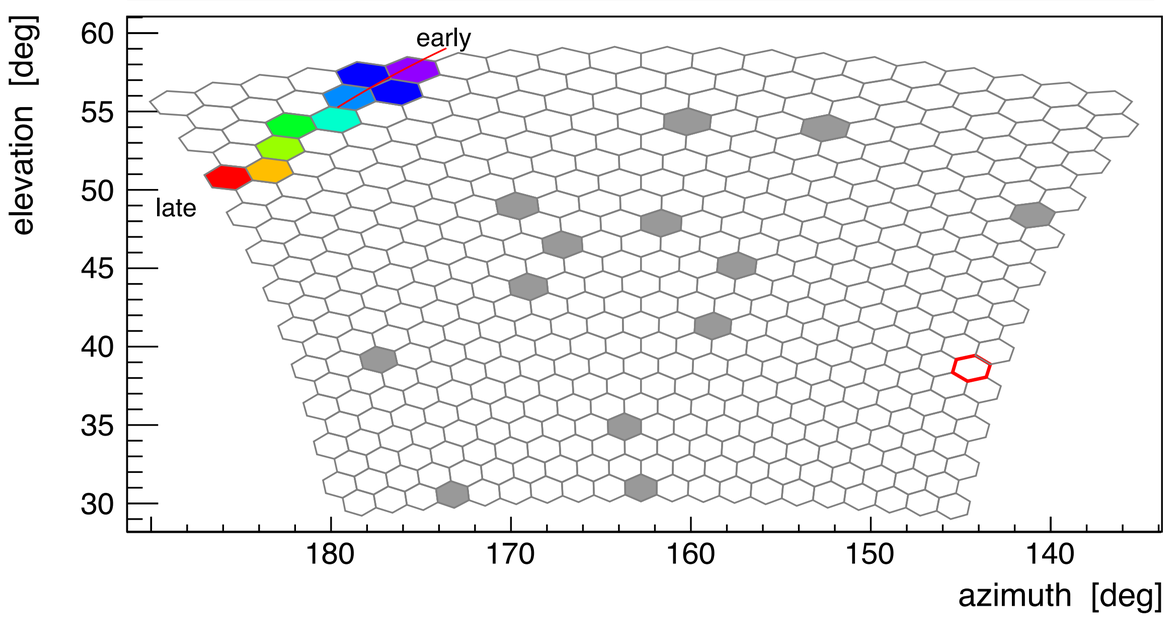
Upwards Reconstructed Bkg-Event

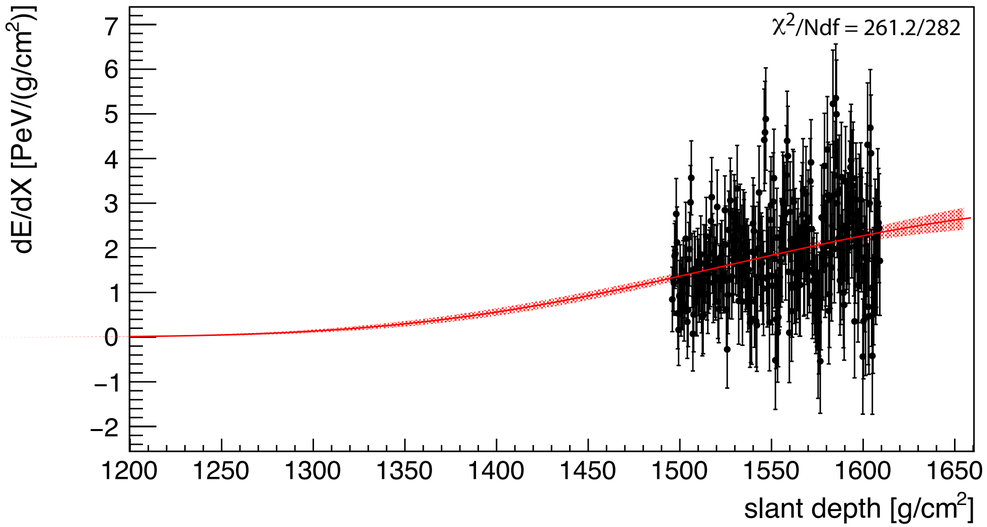
one Background event in full data sample



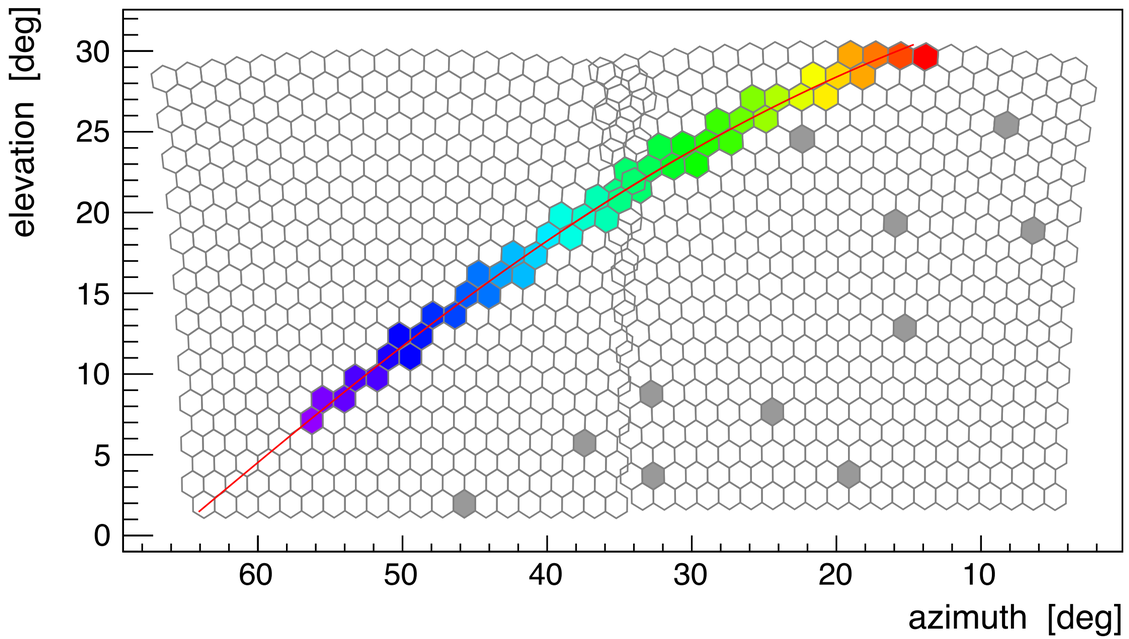


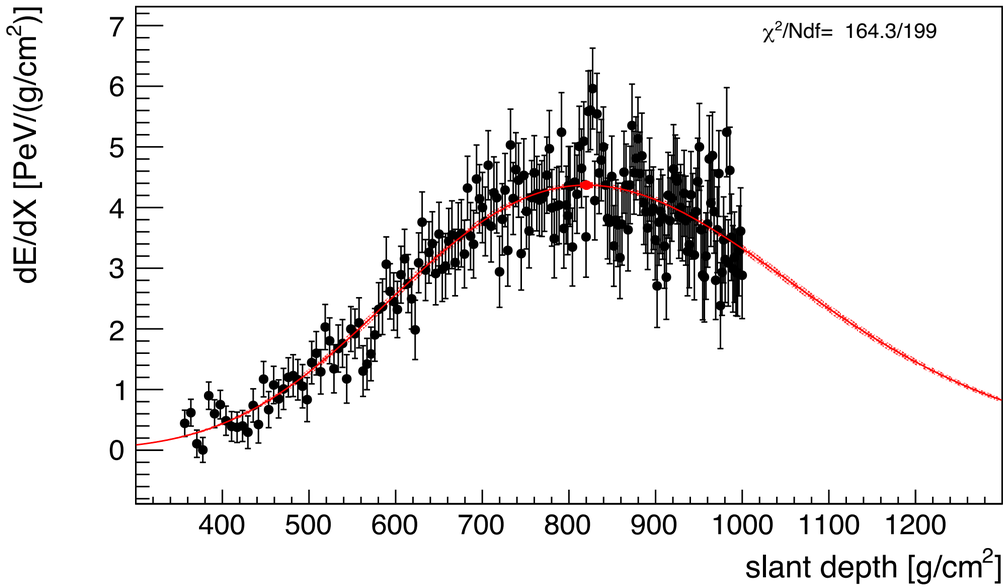
simulated down-going event (landing behind telescope)





Simulated Upwards-Going event





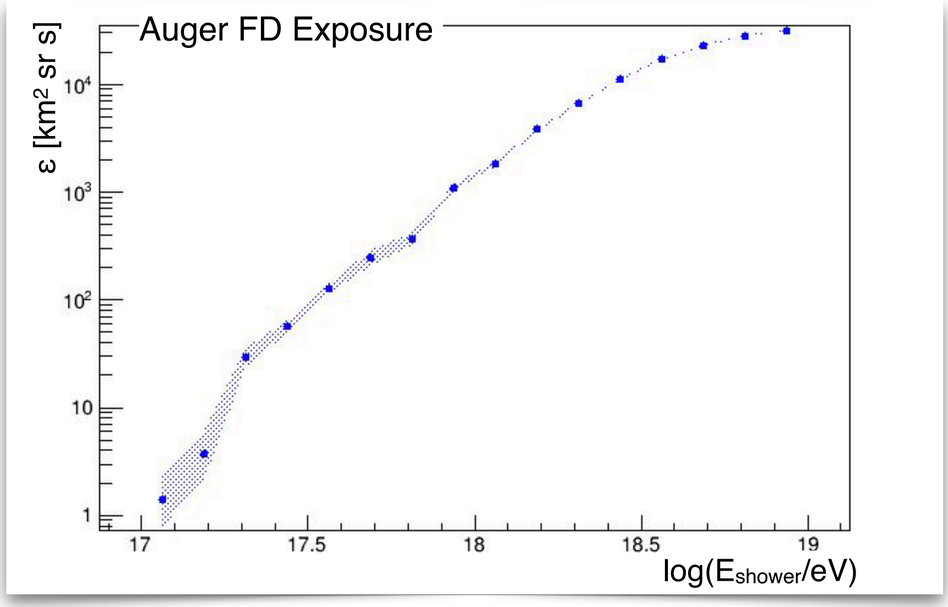
E = 3 EeV

Θ = 114.2° (elevation angle 24.2°)

X_{max} = 844 g/cm²

discrimination parameter ℓ=1

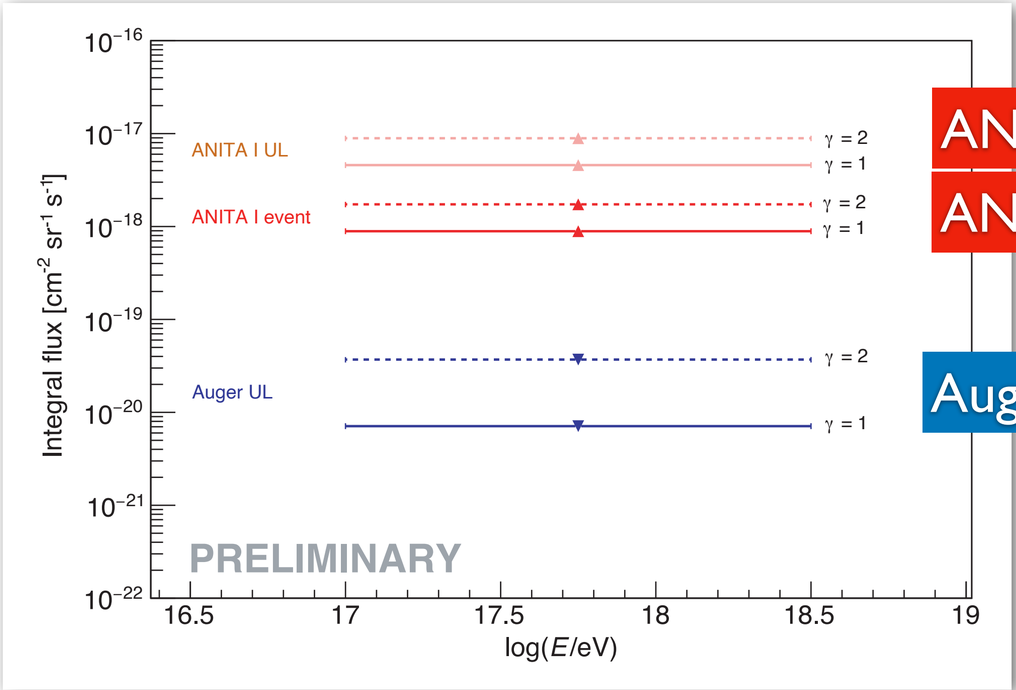
Exposure and resulting Flux Bounds after unblinding



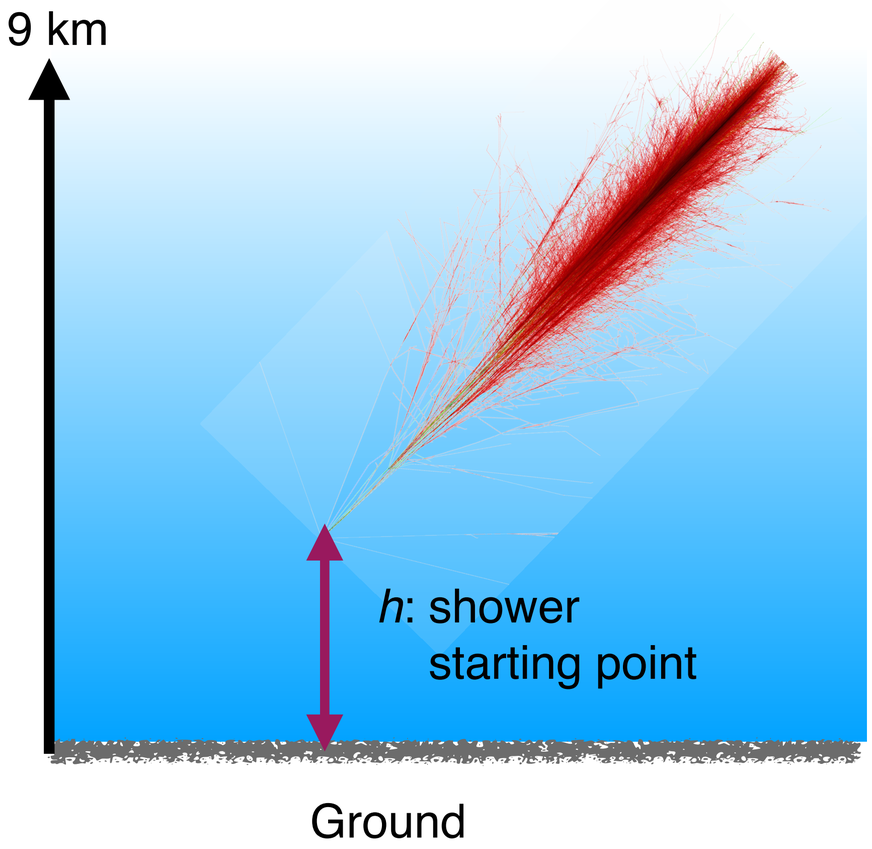
- one event found after unblinding, consistent with expected bkg (poorly reconstructed event, typical for background)
- exposure calculated for different zenith angular bins
- using Rolke, the integral upper limit above 10^{17} eV is:

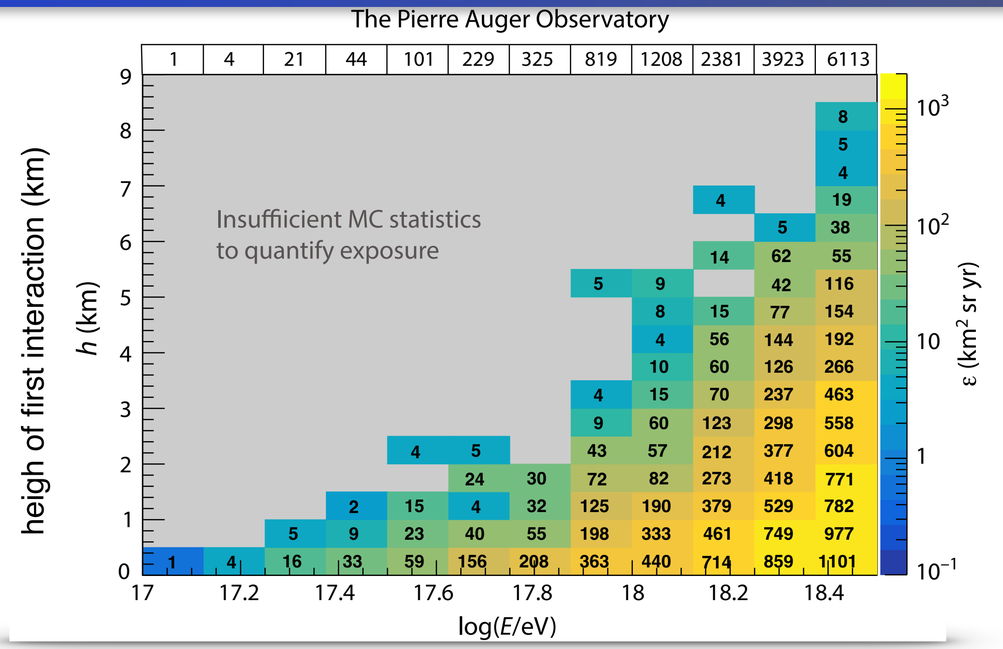
- $(7.2 \pm 0.2) \cdot 10^{-21}$ cm^{-2} s^{-1} sr^{-1} weighting exposure with E^{-1}
- $(3.6 \pm 0.2) \cdot 10^{-20}$ cm^{-2} s^{-1} sr^{-1} weighting exposure with E^{-2}

Would have expected several 10's to 100's of events in Auger under conservative assumptions



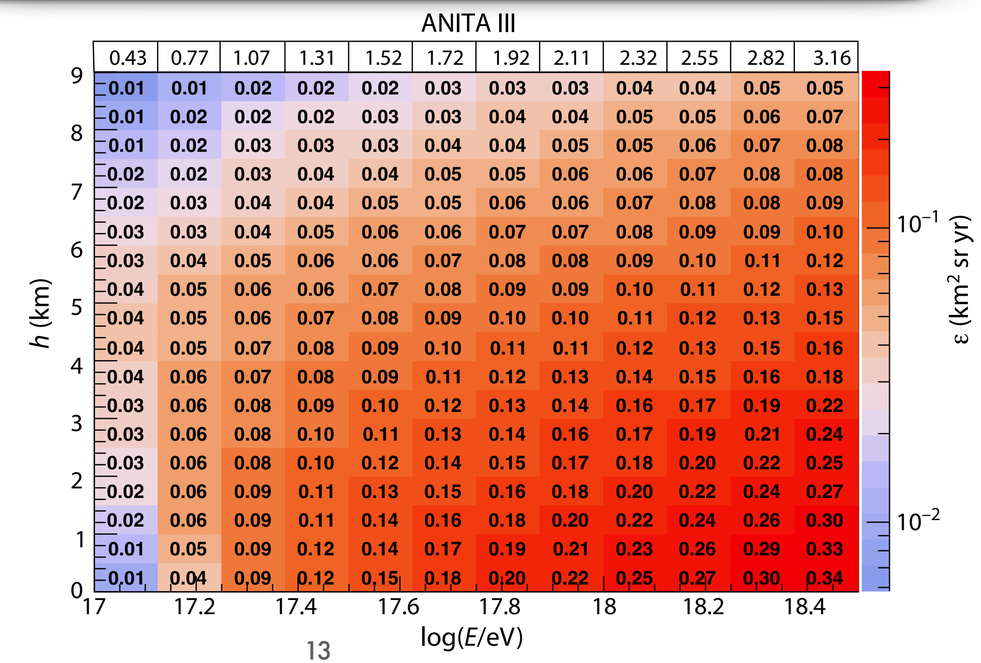
Comparing Auger and ANITA 2D Exposures





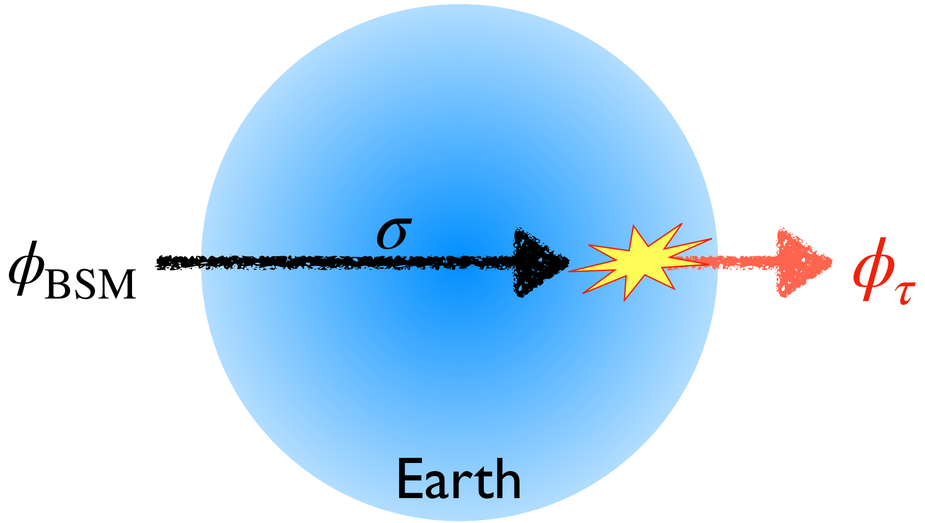
Auger

Note difference in absolute scales !



ANITA

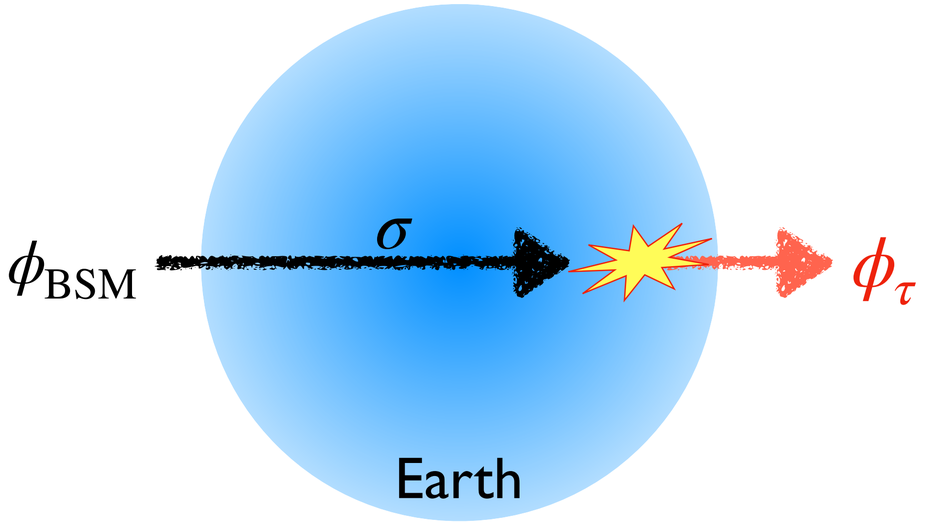
Testing BSM Scenarios



Can test σ_{BSM} if

- σ is small enough to let BSM pass through, and
- at the same time large enough to suffer interactions near surface, so that τ's can escape and generate shower

Testing BSM Scenarios



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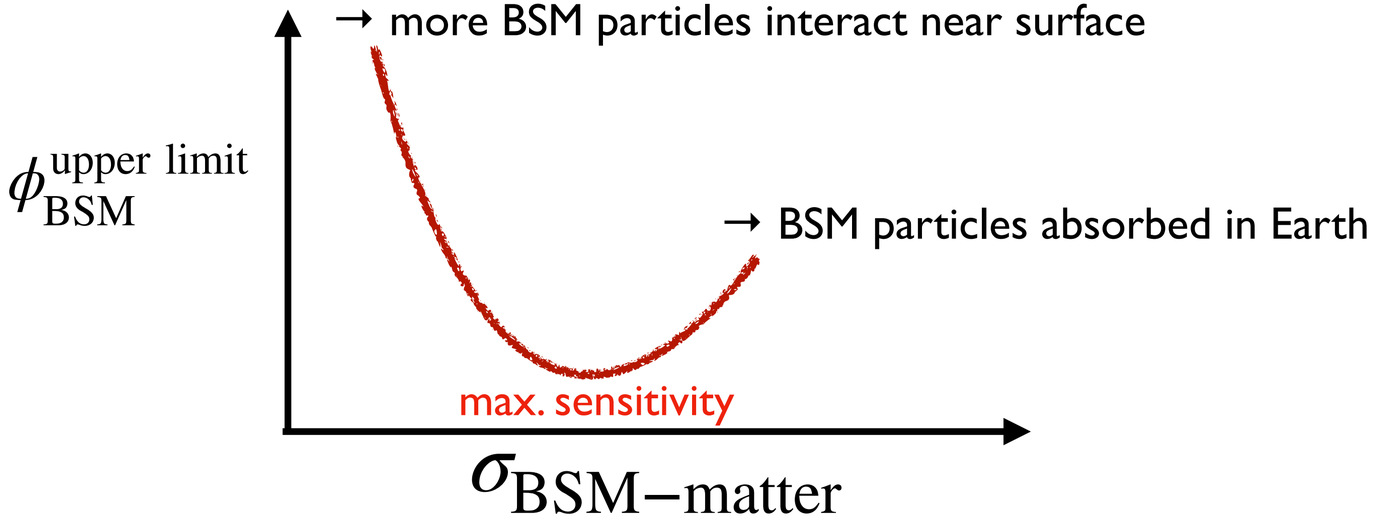

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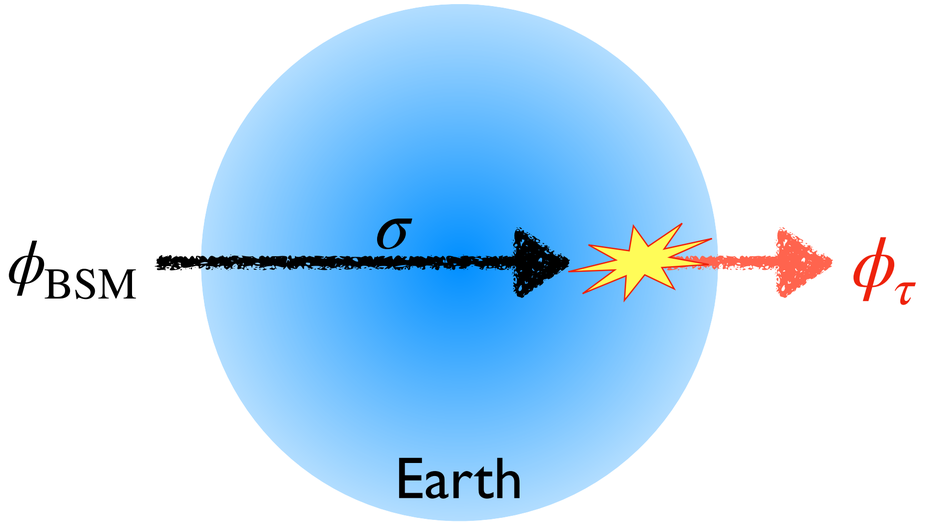

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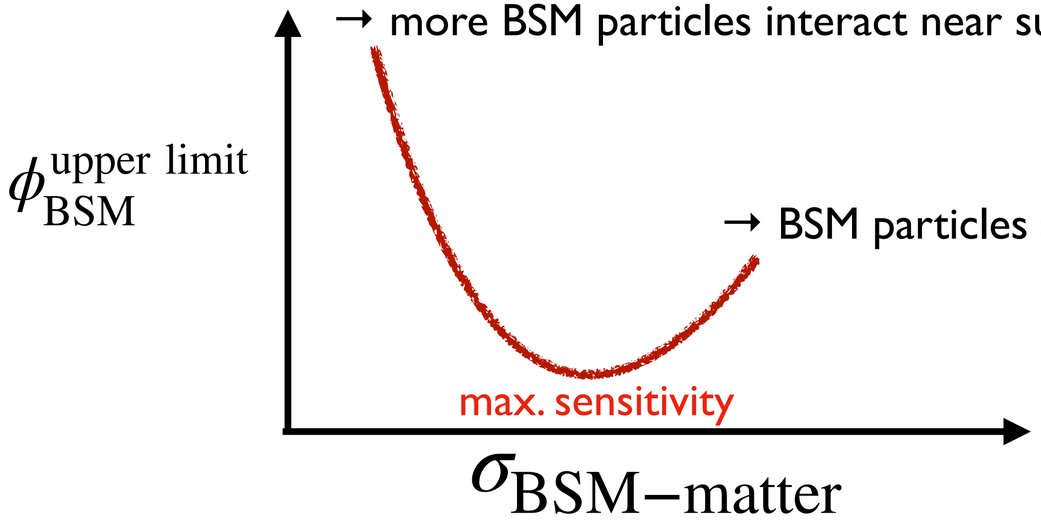
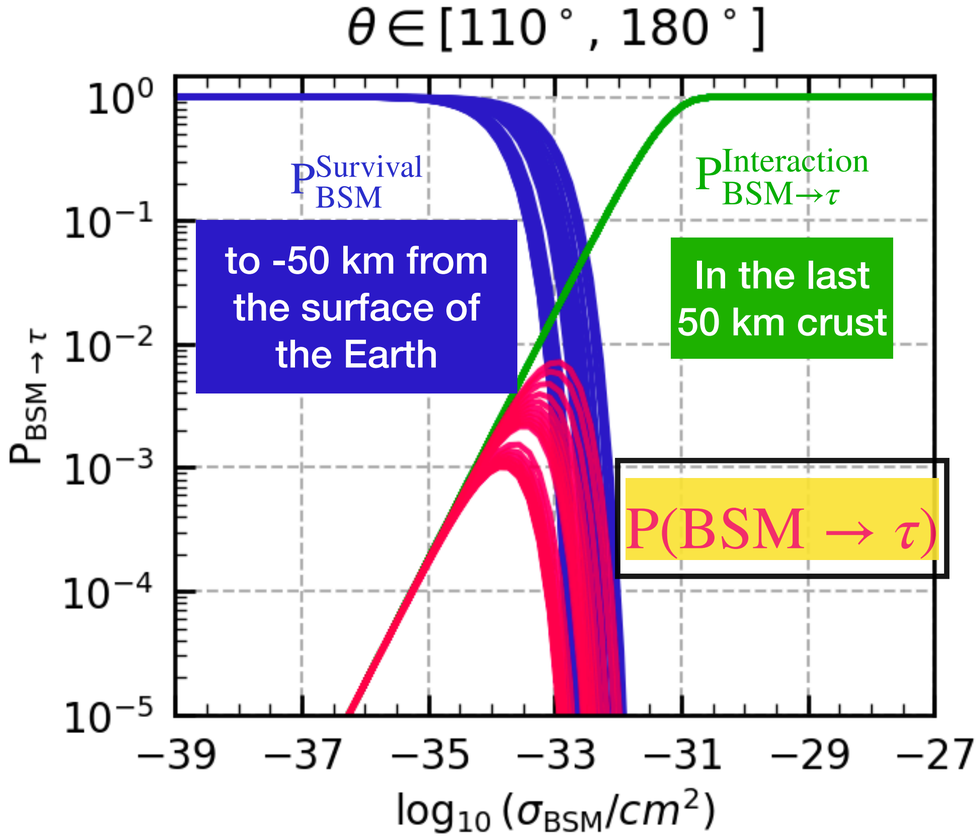
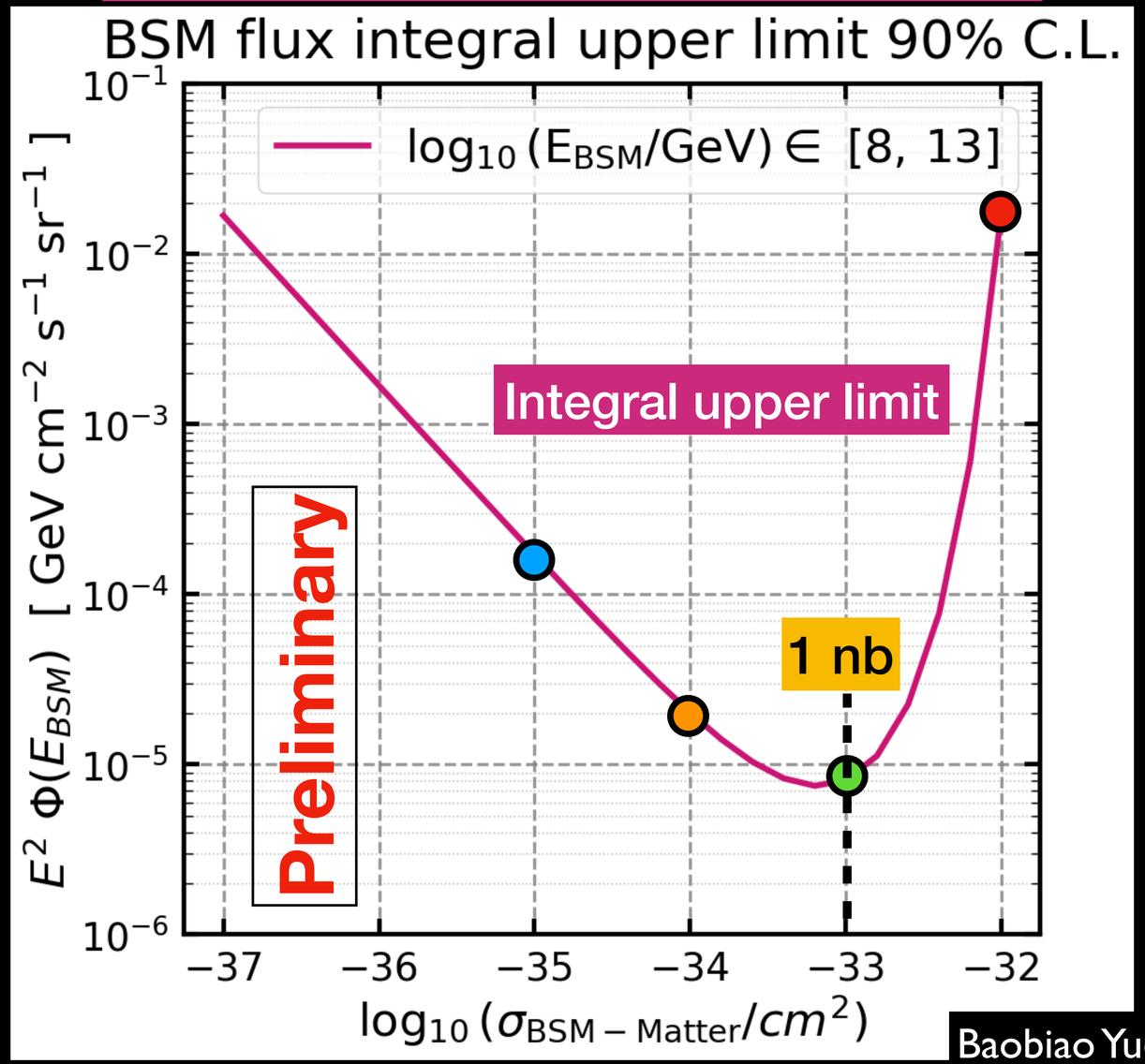




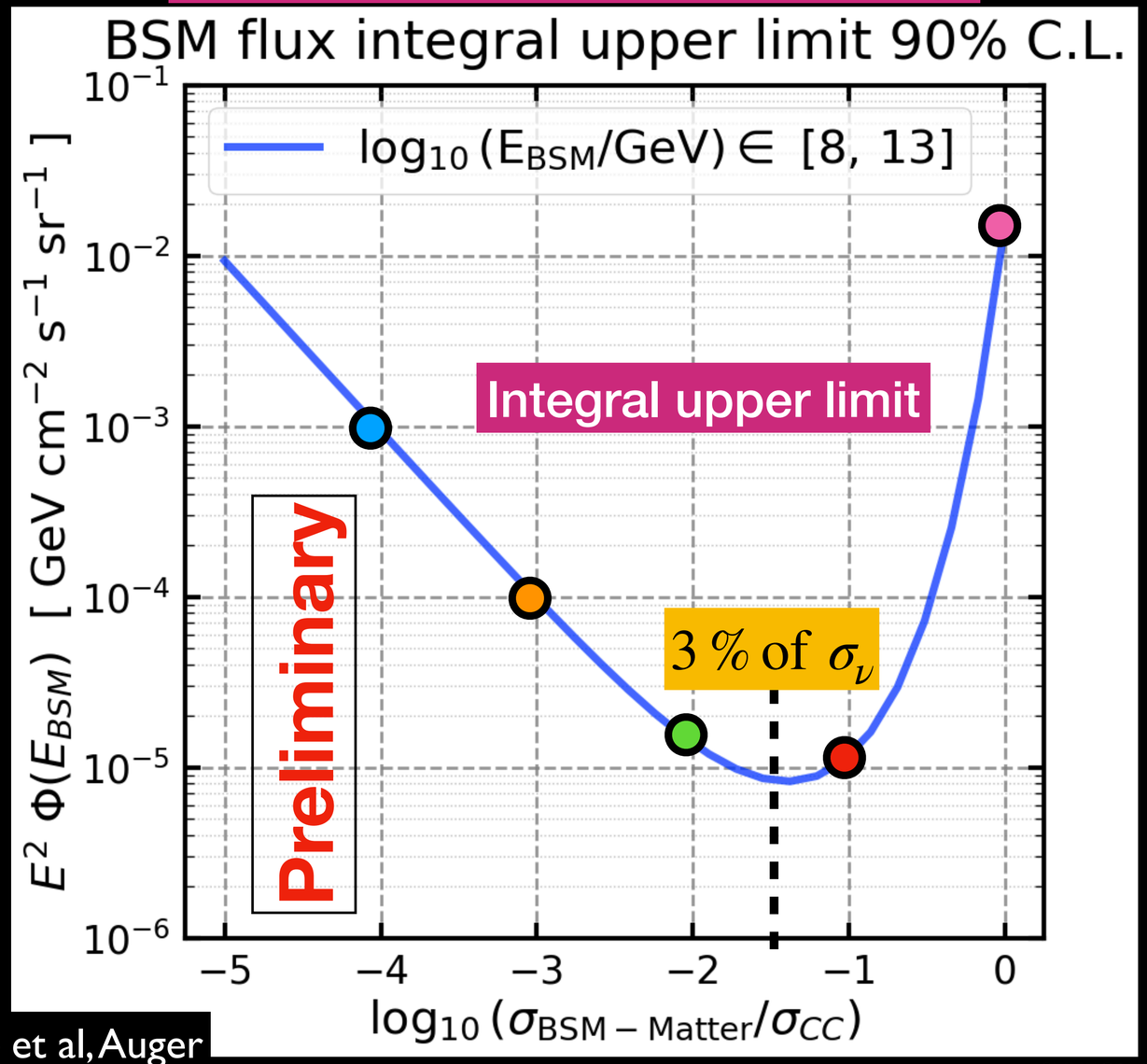
BSM-Bounds: $\phi_{BSM}^{90\%C.L.}$ BSM σ $\tau + X$

$$\frac{d\phi}{dE} \propto E^{-2}$$

assuming energy independent cross section

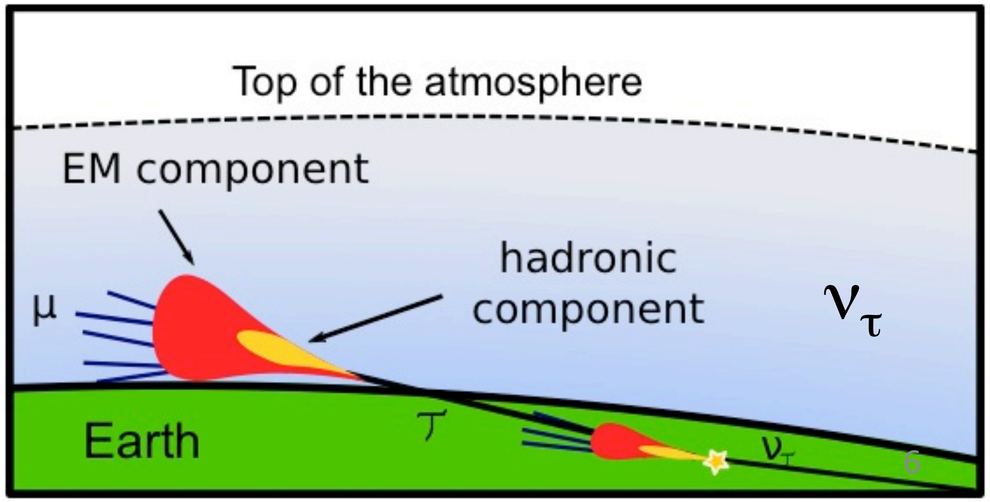


assuming BSM cross section $\propto \sigma(\nu_\tau)$

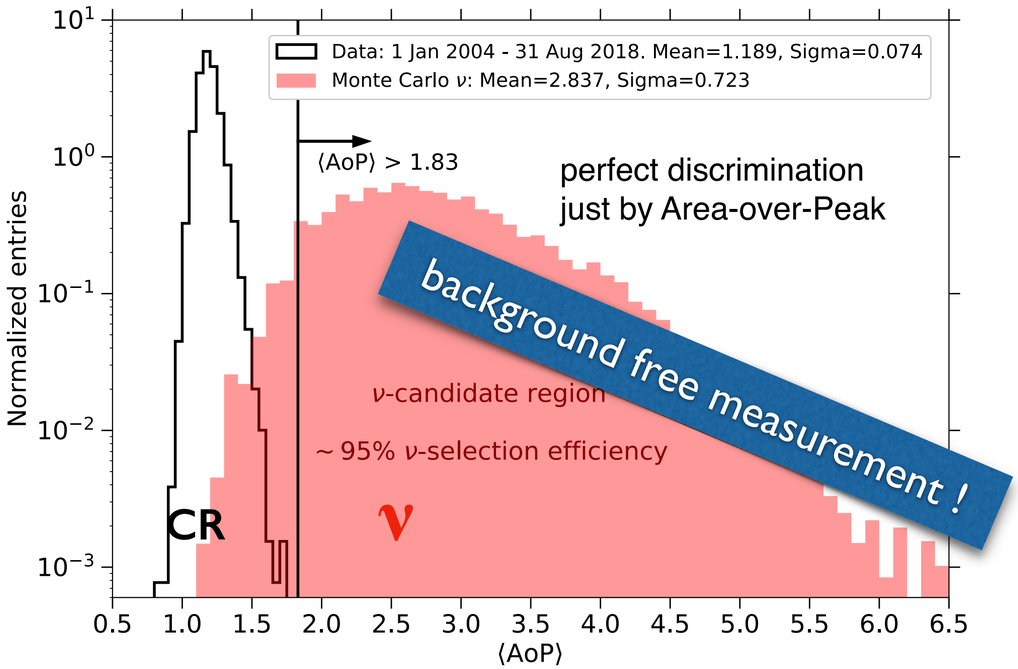


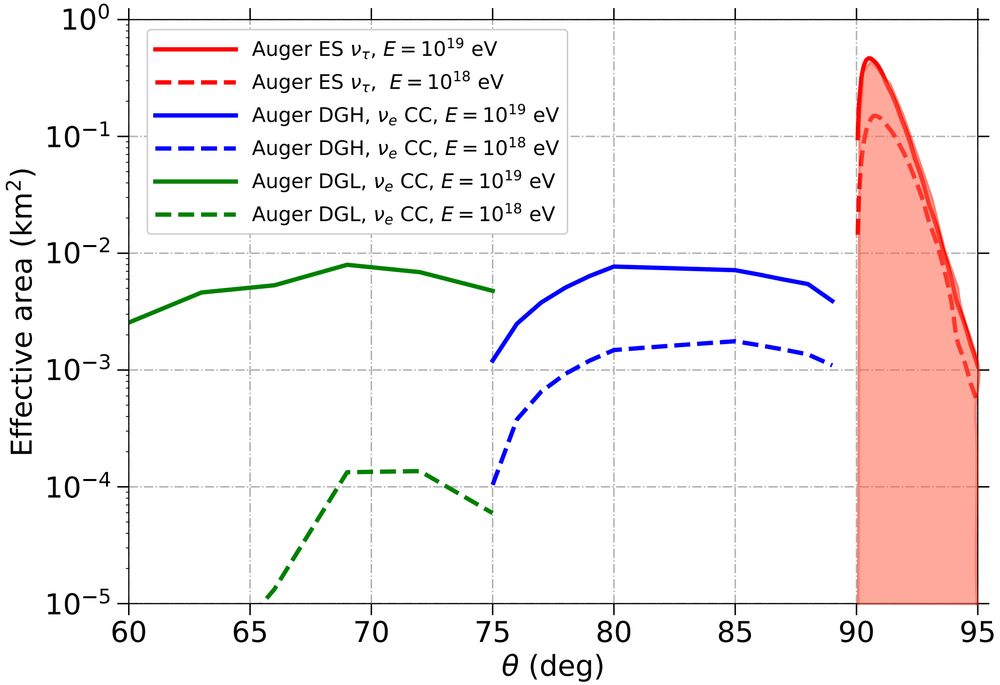
Baobiao Yue et al, Auger

Earth Skimming Showers in Surface Detector Array



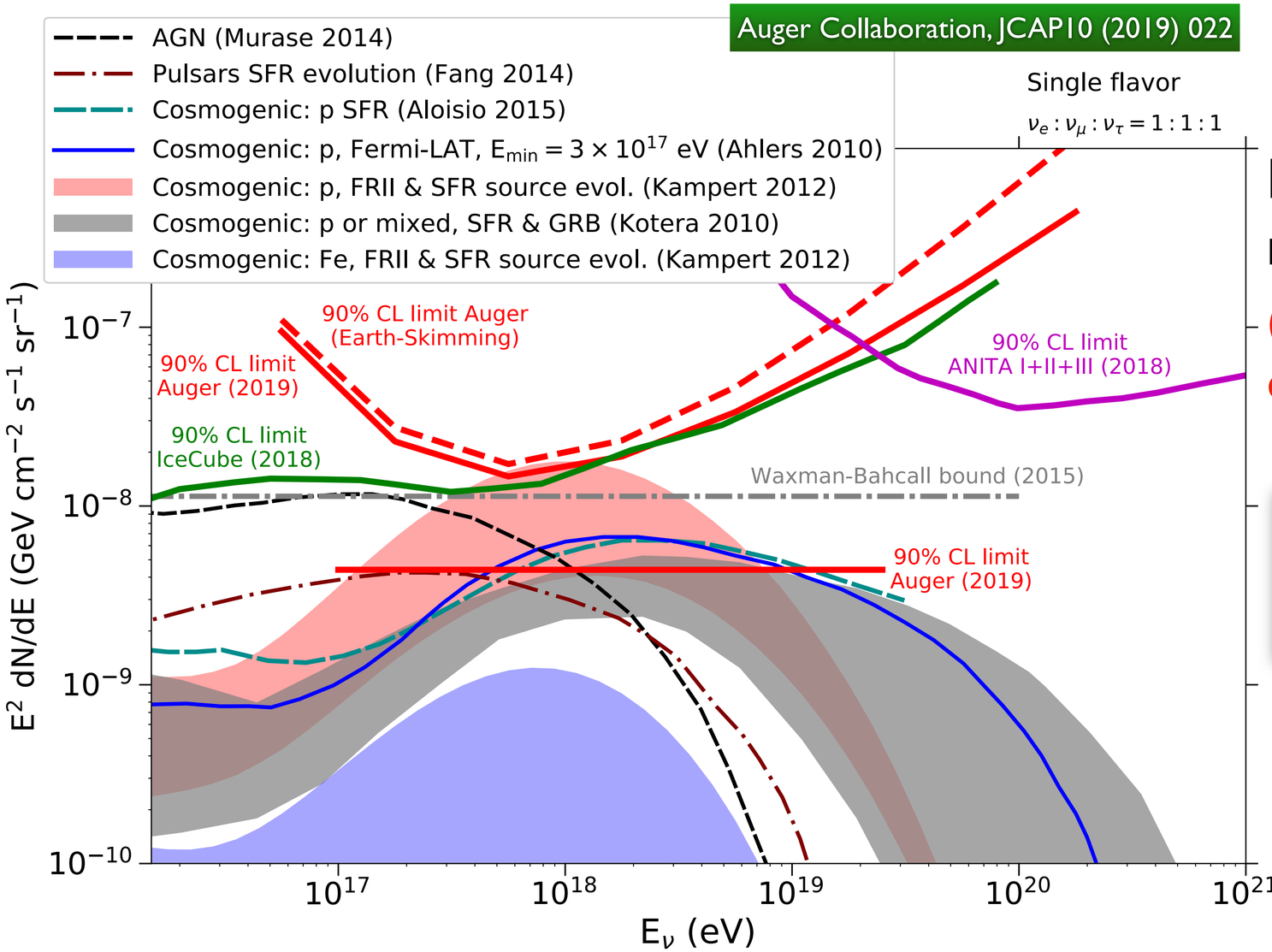
- advantage:
  - ~ 100% duty cycle,
  - ~ 95% ν_τ selection efficiency at $E_\tau > 10^{17.5}$ eV
  - ~ one background event in 50 years
- disadvantage:
  only small solid angle: $90^\circ \leq \theta \leq 95^\circ$





huge instantaneous effective area

Bounds on cosmogenic neutrino fluxes



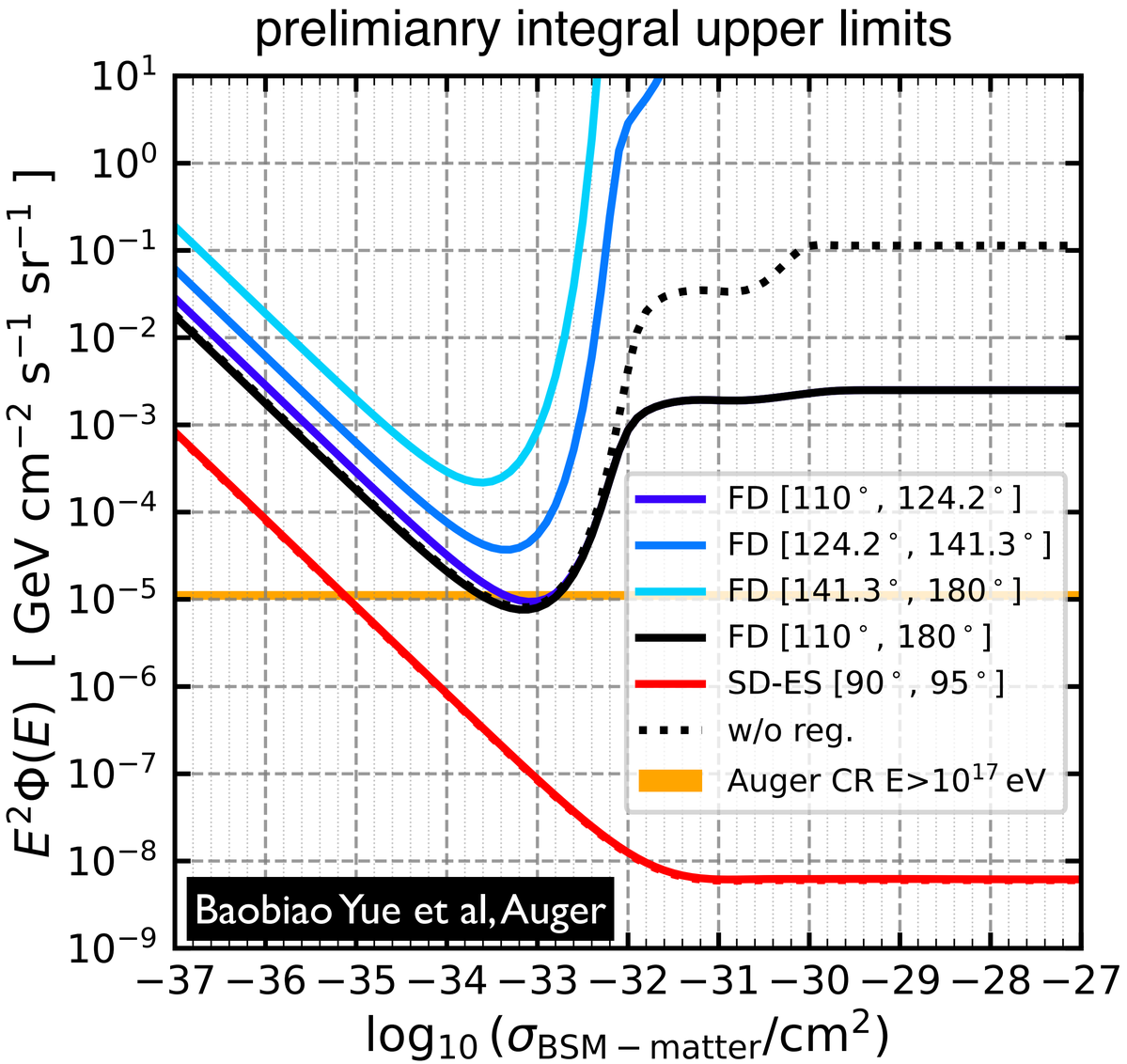
Best present bounds on cosmogenic neutrinos from Auger & Icecube

(in Auger dominated by ES channel, despite its small solid angle!)

We can use the ES channel to test any (BSM $\rightarrow \tau$) model

Analysis in progress, but simple scaling yields good estimate….

BSM flux limits including Earth Skimming channel

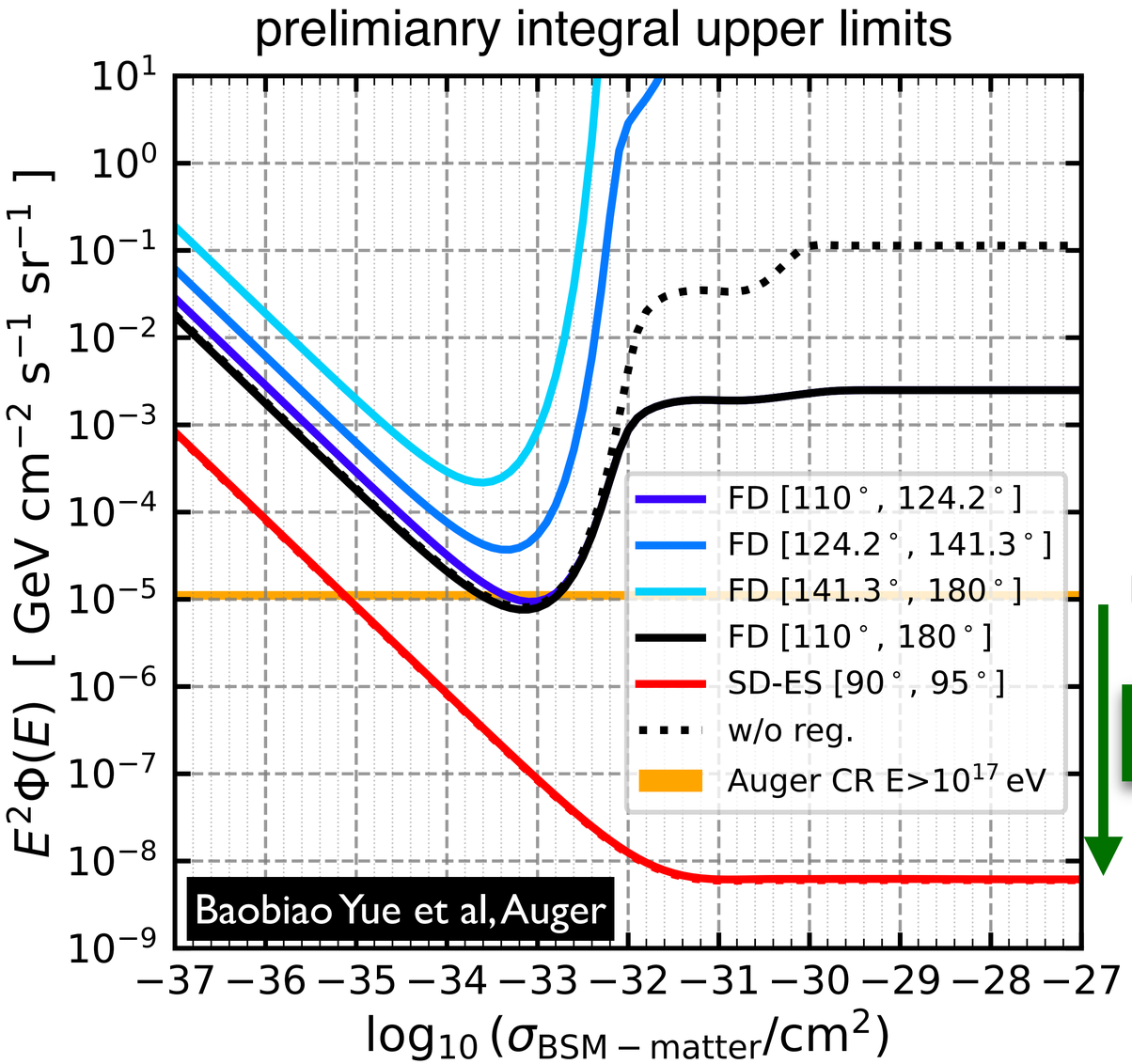


$$\frac{d\phi_{\mathrm{BSM}}}{dE} \propto E^{-2}$$

ϕ_{BSM} bounds from FD incl. τ regeneration

ϕ_{BSM} bounds from ES-SD incl. τ regeneration

BSM flux limits including Earth Skimming channel



$$\frac{d\phi_{\mathrm{BSM}}}{dE} \propto E^{-2}$$

ϕ_{BSM} bounds from FD incl. τ regeneration

UHECR flux (E>10^{17} eV)

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

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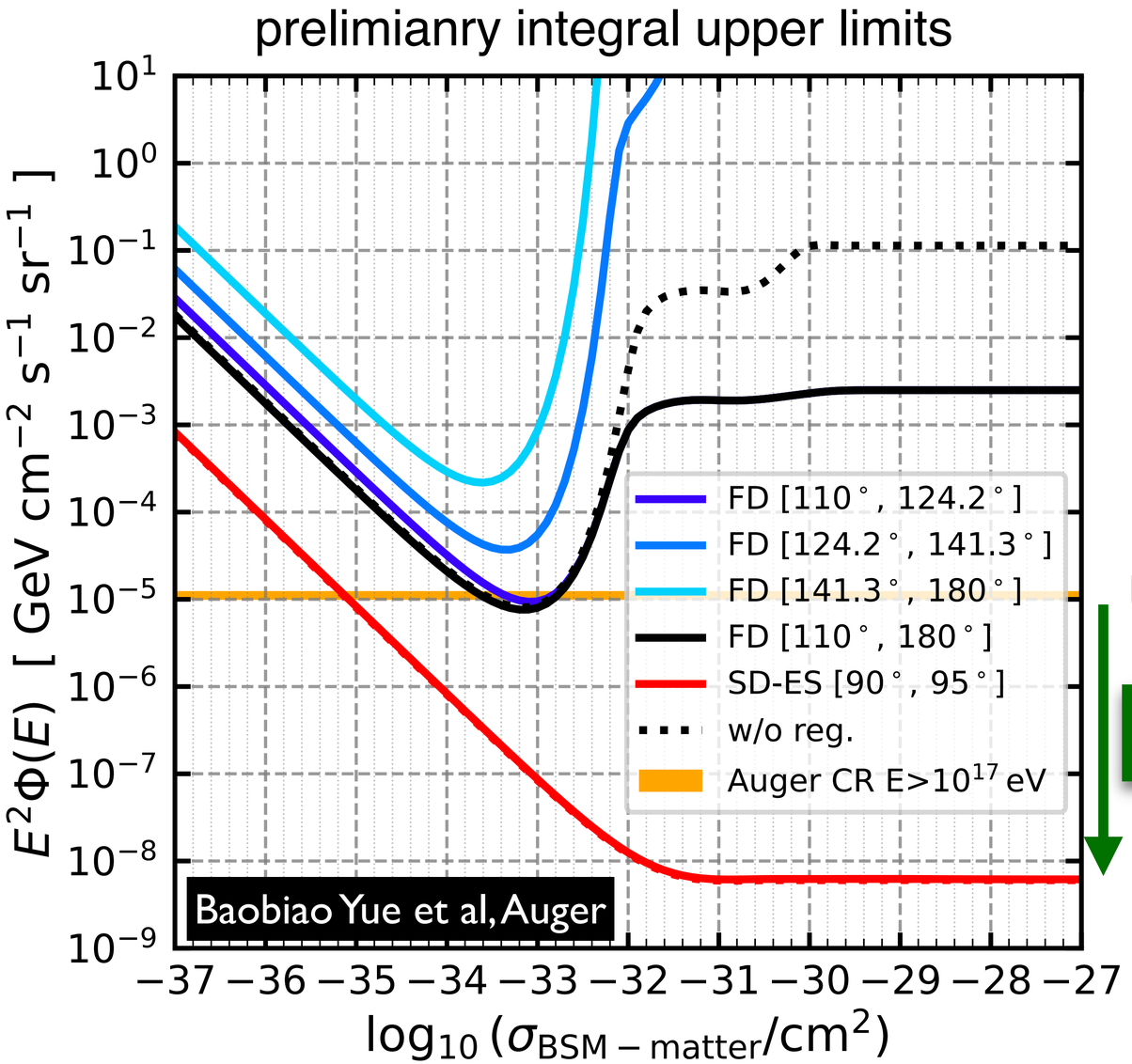

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ϕ_{BSM} bounds from FD incl. τ regeneration

UHECR flux (E>10^{17} eV)

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

constrains models in which UHECRs produce BSM

ϕ_{BSM} bounds from ES-SD incl. τ regeneration

Summary and Conclusions

- The Pierre Auger Observatory is a 4π Multi-Messenger Observatory for UHECR, Photons, Neutrinos, and BSM particles
- The sensitivity up upwards-going air showers allowed us to check the ANITA „anomalous events“
- We would have expected (under sensible assumptions) some 100's of events in the Auger fluorescence telescopes → strong tension with ANITA
- We can translate the bounds on upwards-going showers to
  - bounds of tau's created in the Earth crust, and
  - bounds of BSM particles as a function of their (unknown) cross section