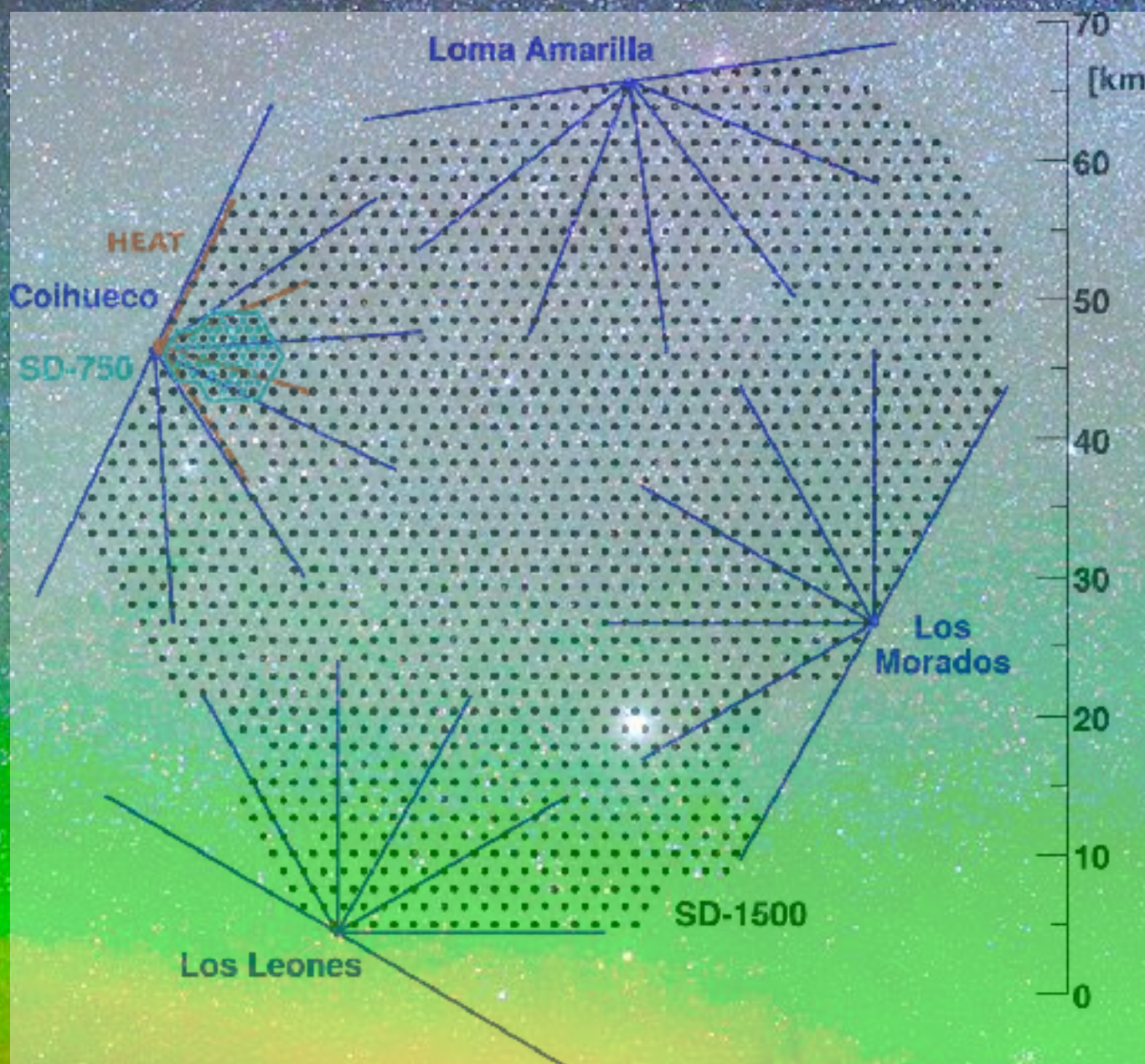


Searches for ultra-high-energy neutrinos and upward-going showers at the Pierre Auger Observatory

Baobiao Yue
for the Pierre Auger Collaboration
UCLouvain, June 17th, 2025



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WUPPERTAL

bayue@uni-wuppertal.de



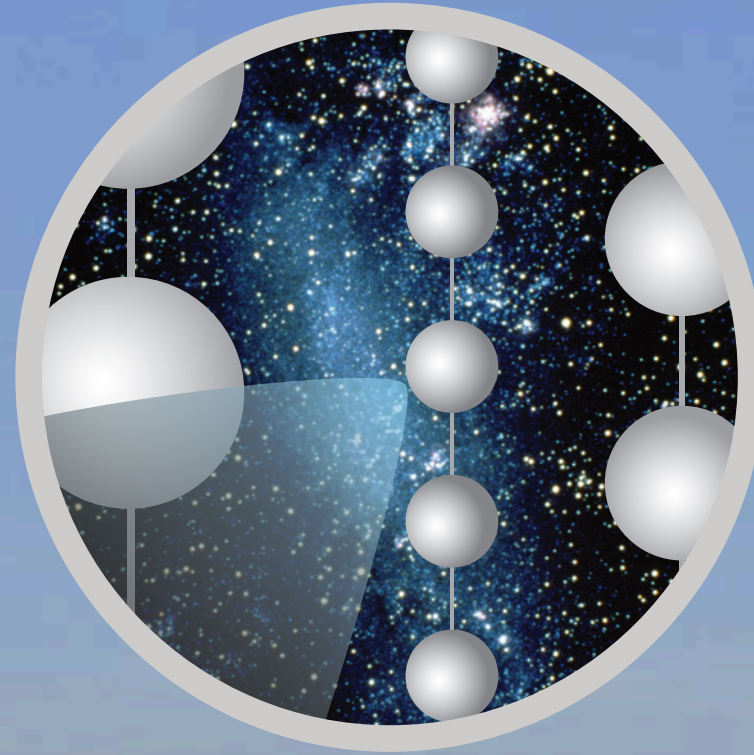
Astroparticle group in the University of Wuppertal, Germany



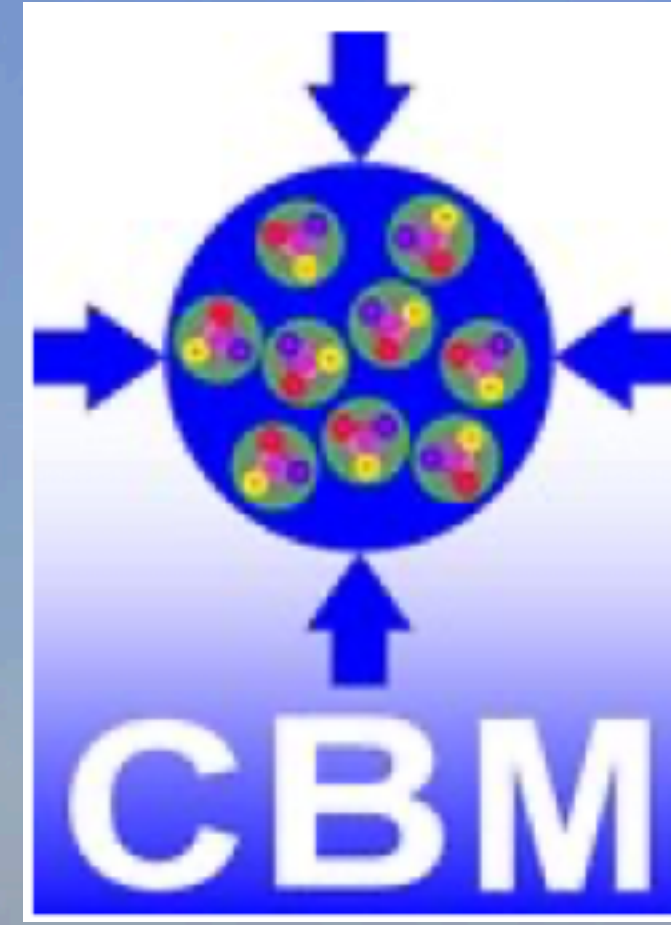
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PIERRE
AUGER
OBSERVATORY



ICECUBE



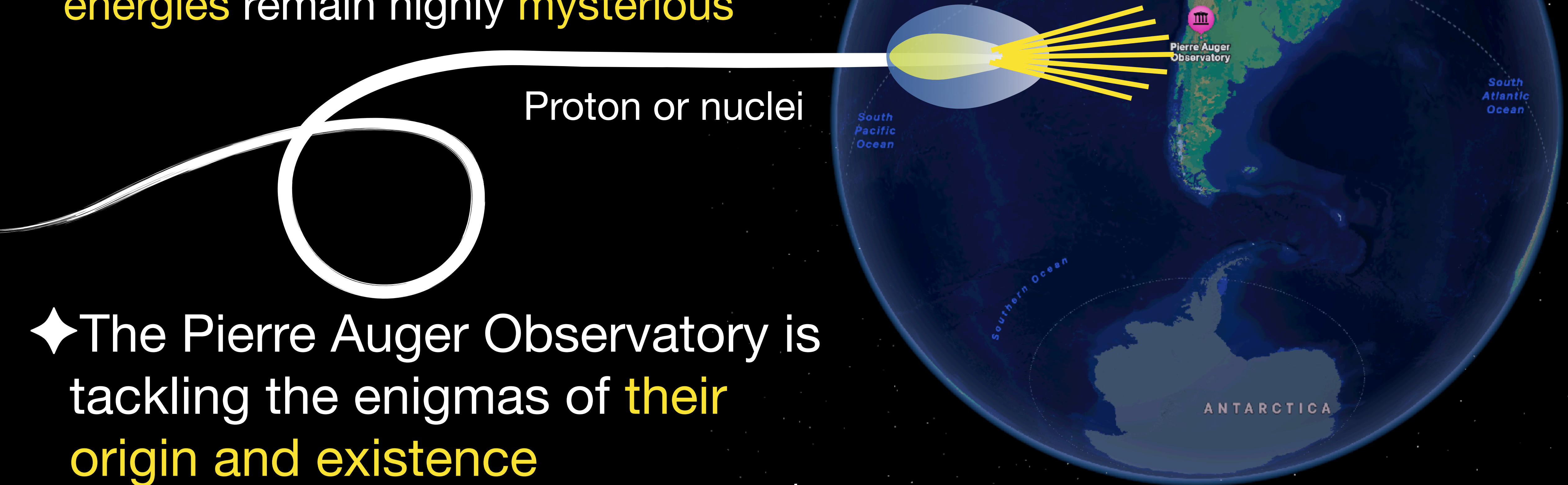
Outline

1. Introduction for the Pierre Auger Observatory
2. Search for UHE neutrinos
3. Search for up-going showers
4. Up-going showers from BSM
5. The AugerPrime upgrade

1, Introduction for the Pierre Auger Observatory

The Pierre Auger Observatory

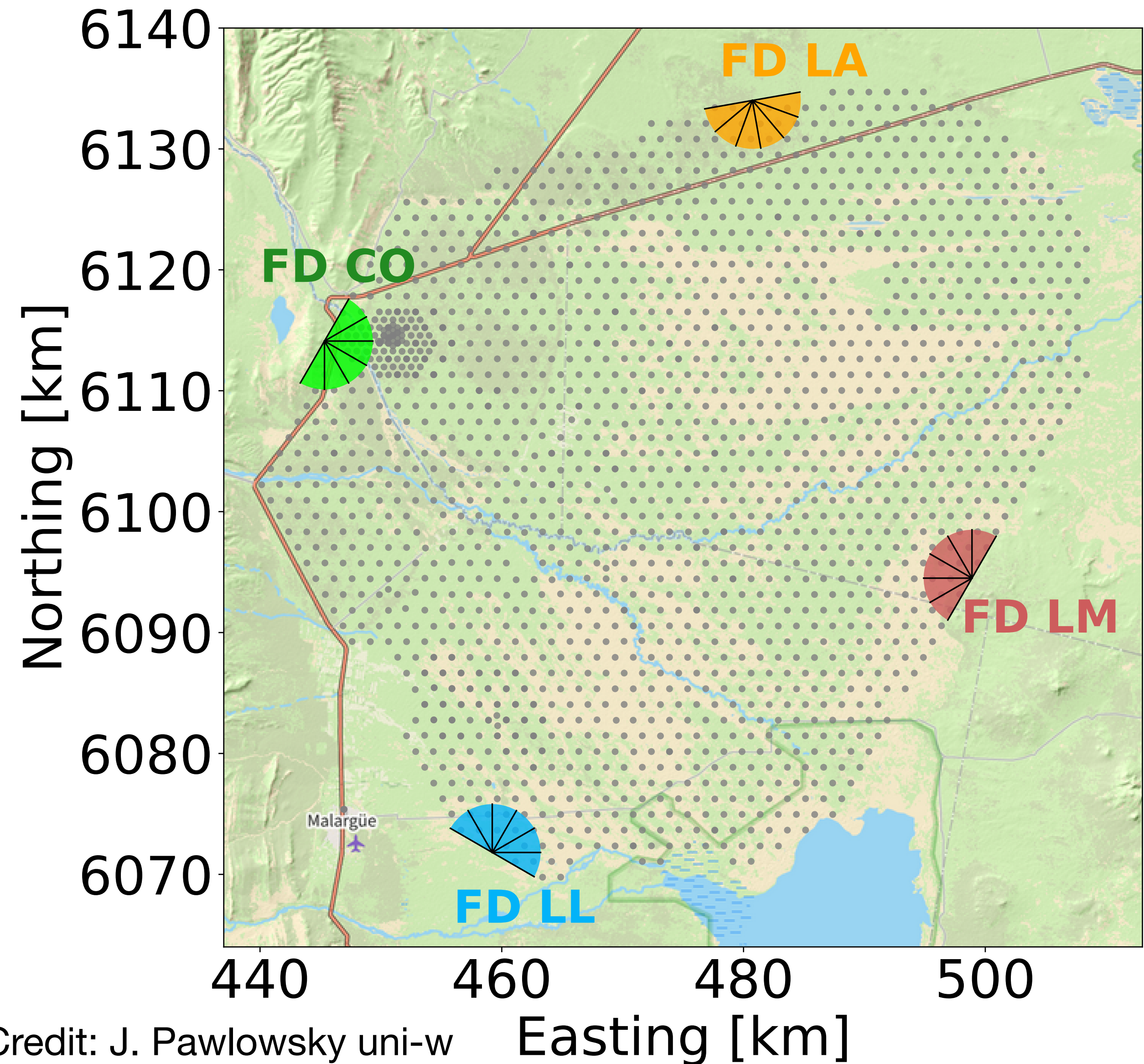
- ◆ The observatory was designed to detect **cosmic rays** at Malargüe of **Argentina** ($E > 10^{17}$ eV)
- ◆ The cosmic ray with **extremely high energies** remain highly **mysterious**



- ◆ The Pierre Auger Observatory is tackling the enigmas of **their origin and existence**

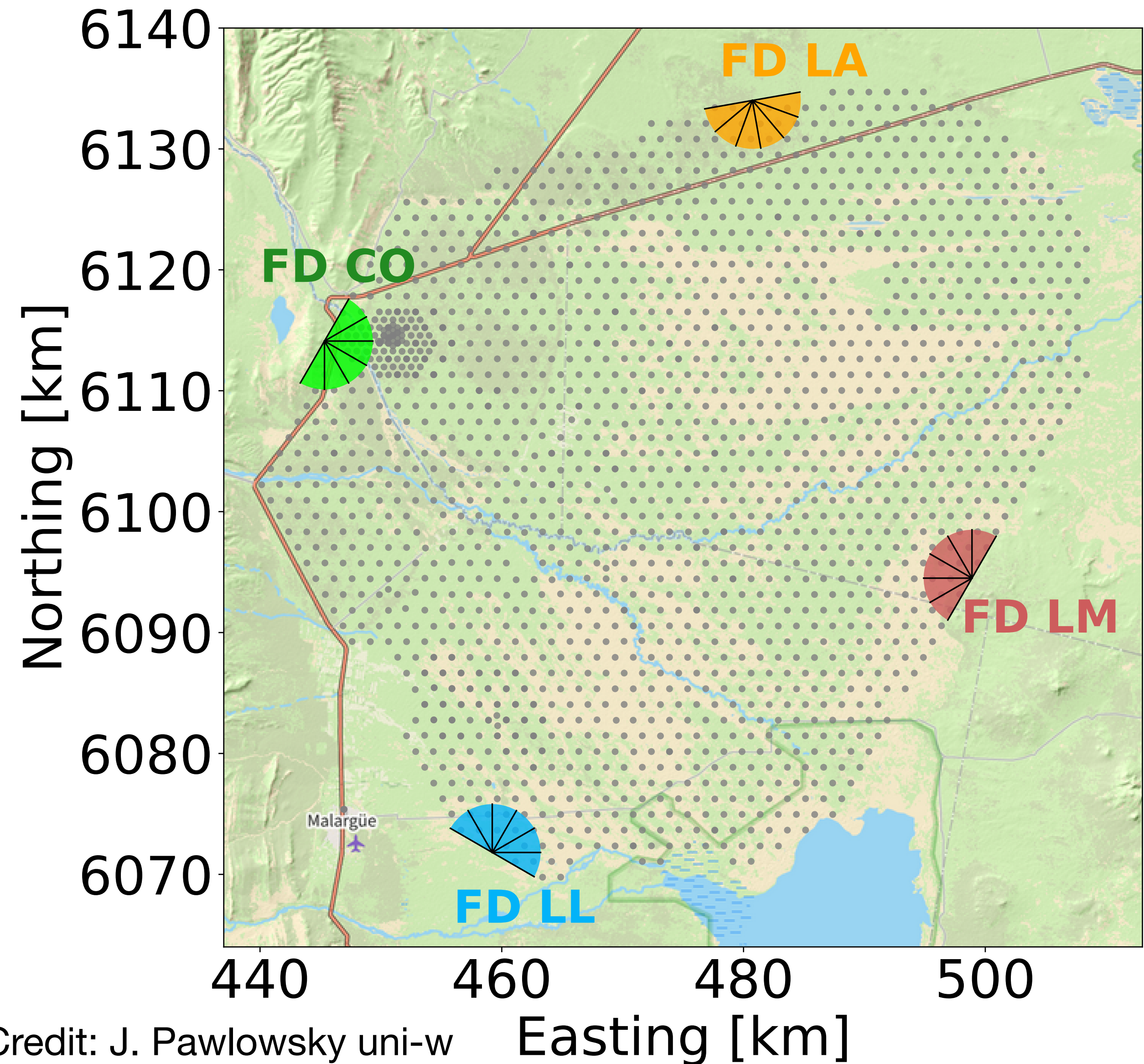
The Pierre Auger Observatory

- ✦ The observatory has created a detection area of **3,000 km²**, containing 1,600 water-Cherenkov stations (surface detector) and 4 Fluorescence sites at the edge of the array.



The Pierre Auger Observatory

- ✦ The observatory has created a detection area of **3,000 km²**, containing 1,600 water-Cherenkov stations (surface detector) and 4 Fluorescence sites at the edge of the array.
- ✦ **Auger = ~10 x Louvain-la-Neuve or Brussels (33 km²)** 🧐



Surface detector



Surface detector

GPS



- ◆ 1,600 in total
- ◆ 1.5 km apart from each other, 3000 km²
- ◆ ~100% duty circle

Electronics

Battery

A communication antenna



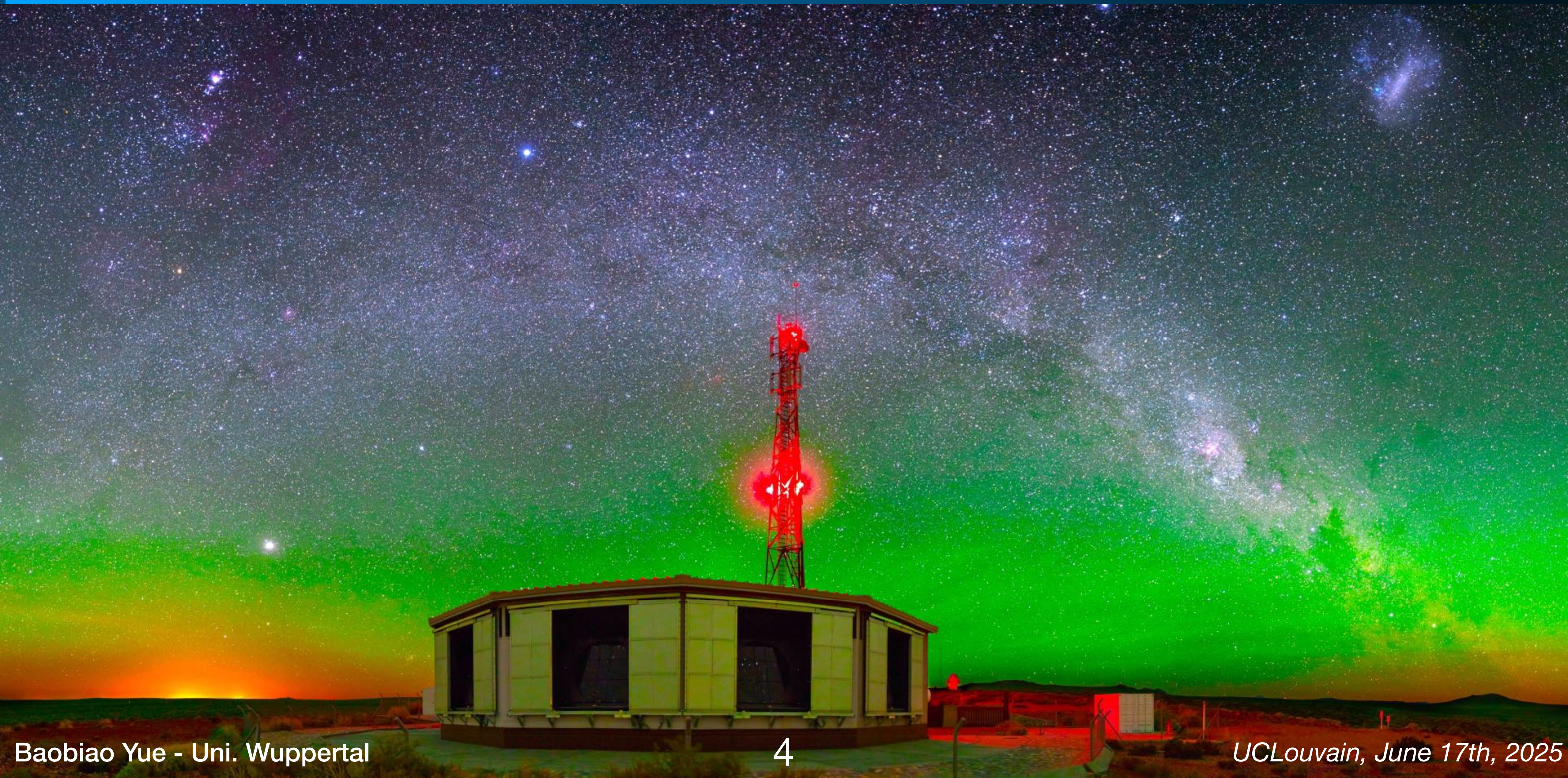
I'm FD

Solar panel

Three 9" photomultiplier tubes

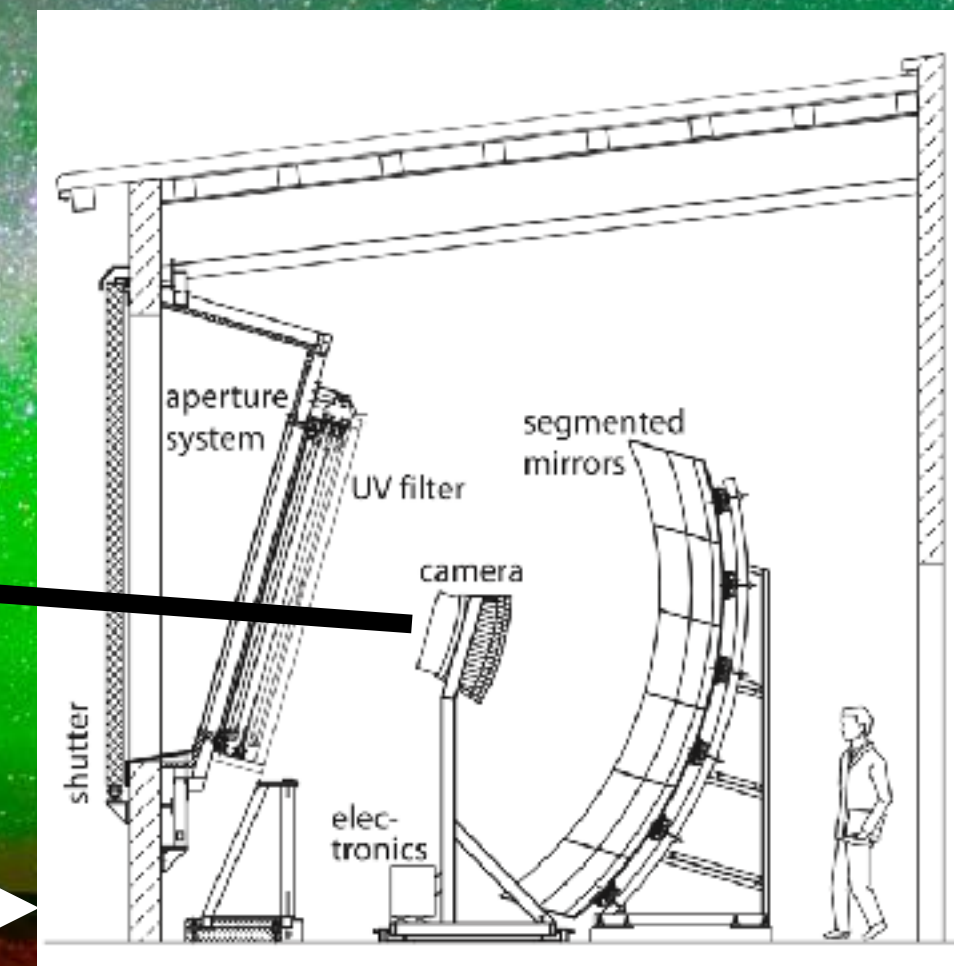
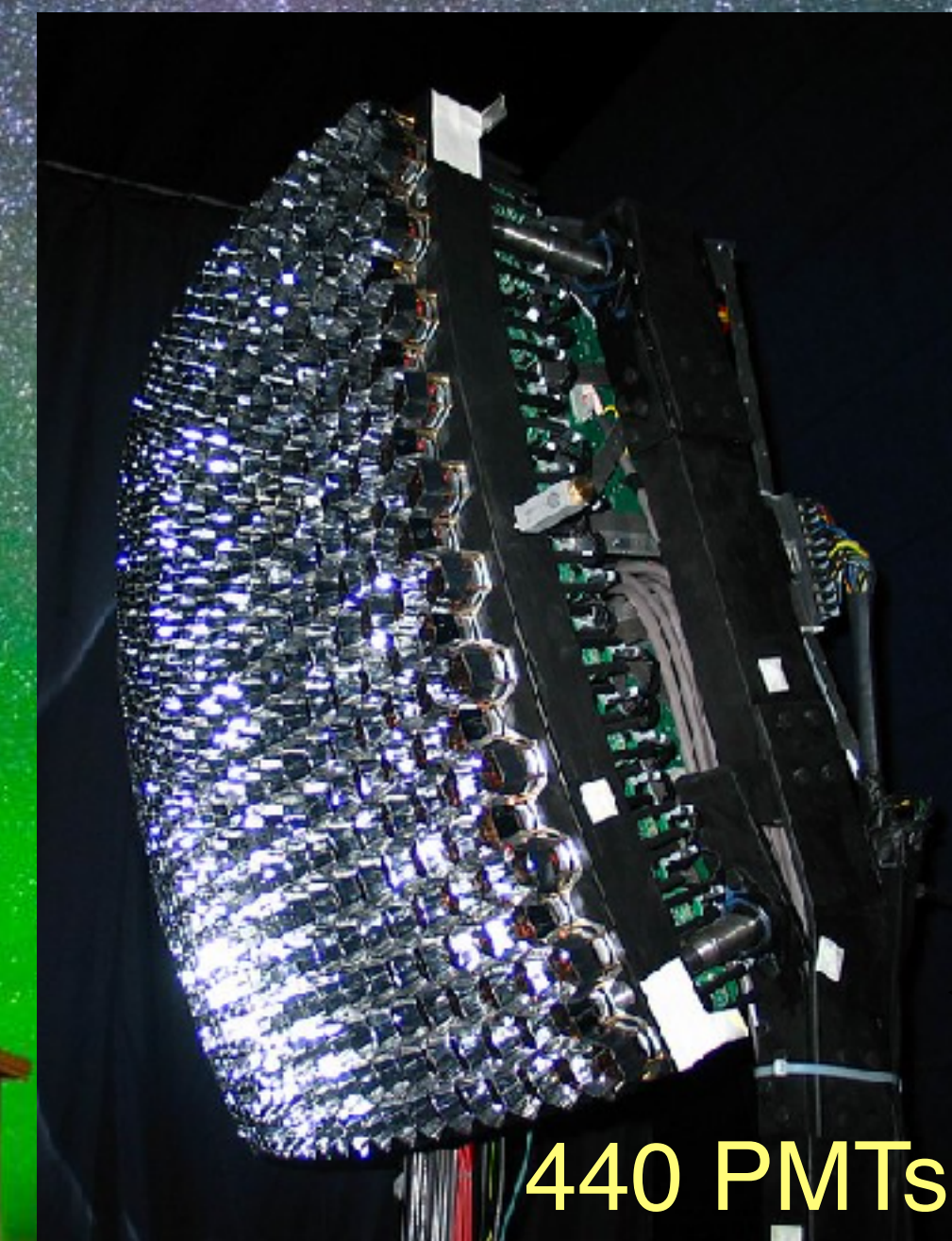
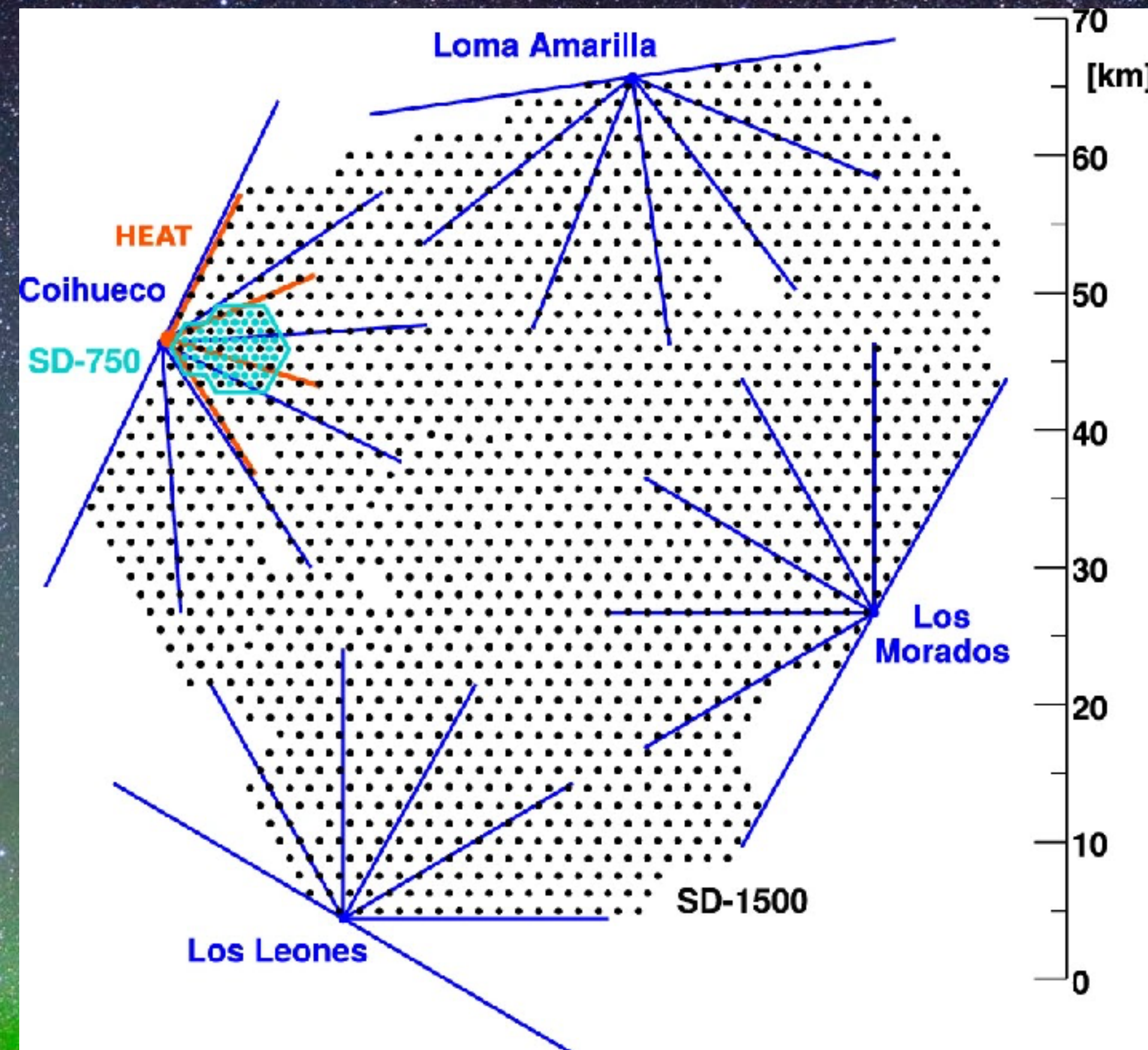
12 tons of ultra-pure water

Fluorescence detectors

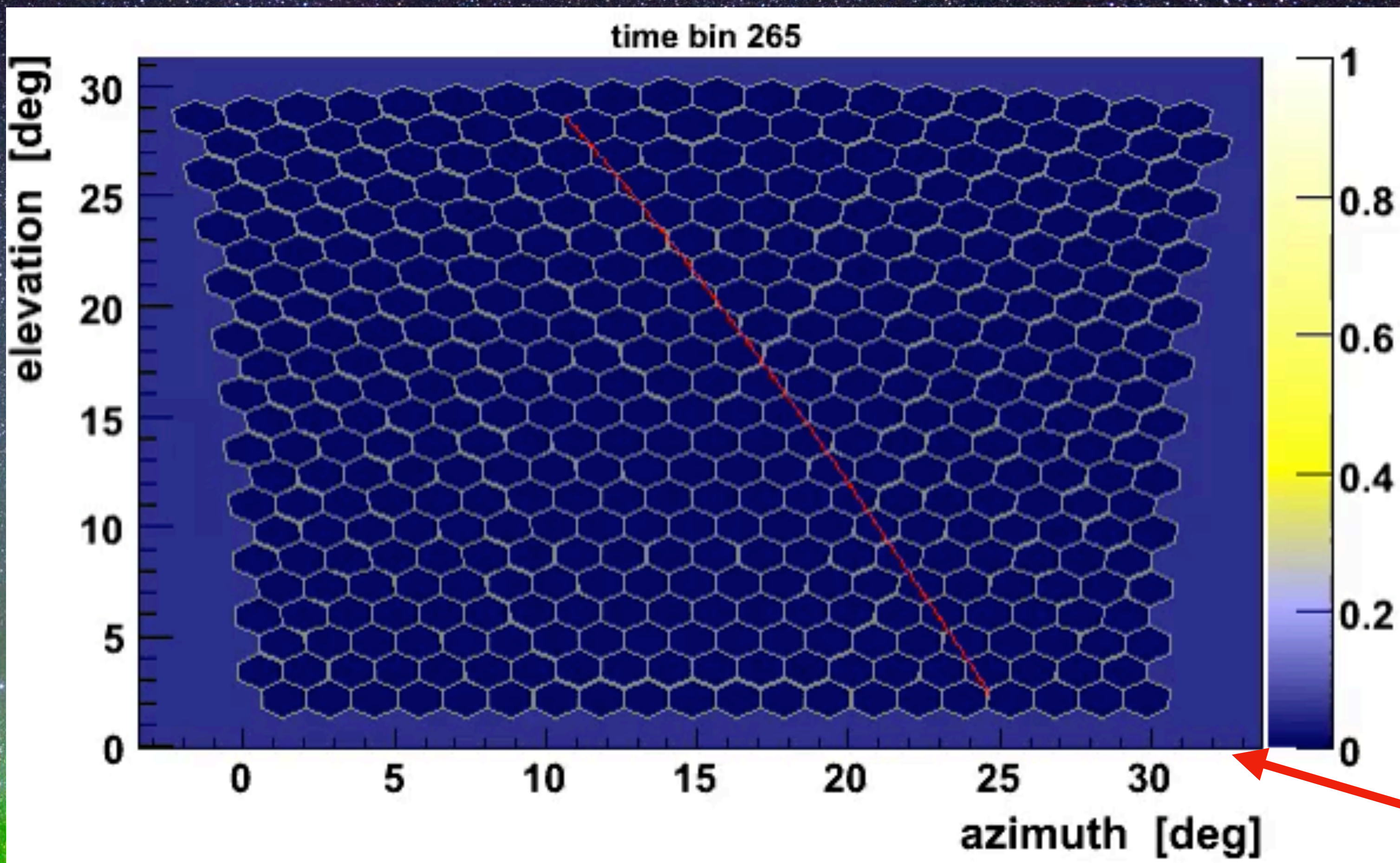


Fluorescence detectors

- ◆ 4 Fluorescence sites
- ◆ 24 telescopes, $1\text{--}30^\circ$ FoV
- ◆ 3 high-elevation, $30\text{--}60^\circ$ FoV (HEAT)
- ◆ ~14% duty circle: data taking only in very dark, moonless and cloudless night



Fluorescence detectors

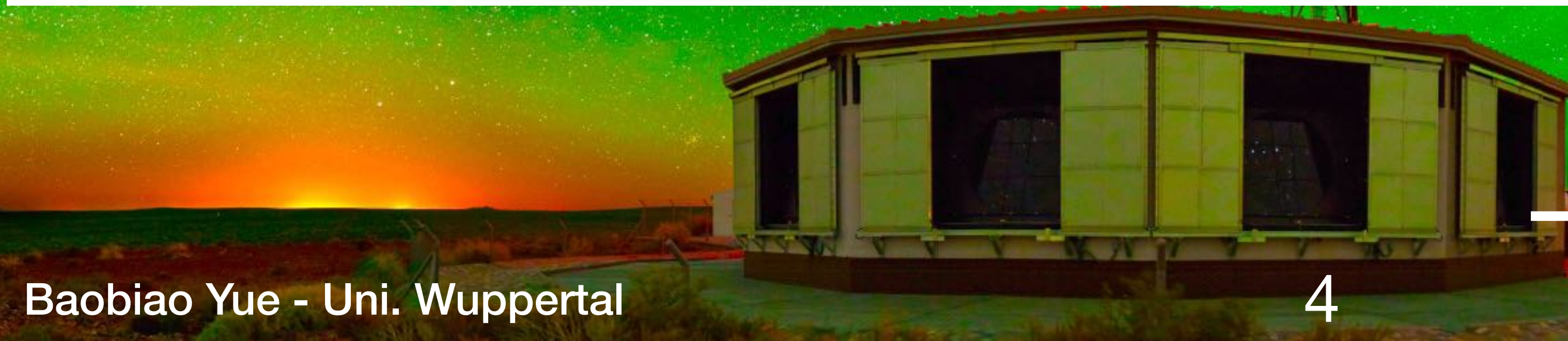
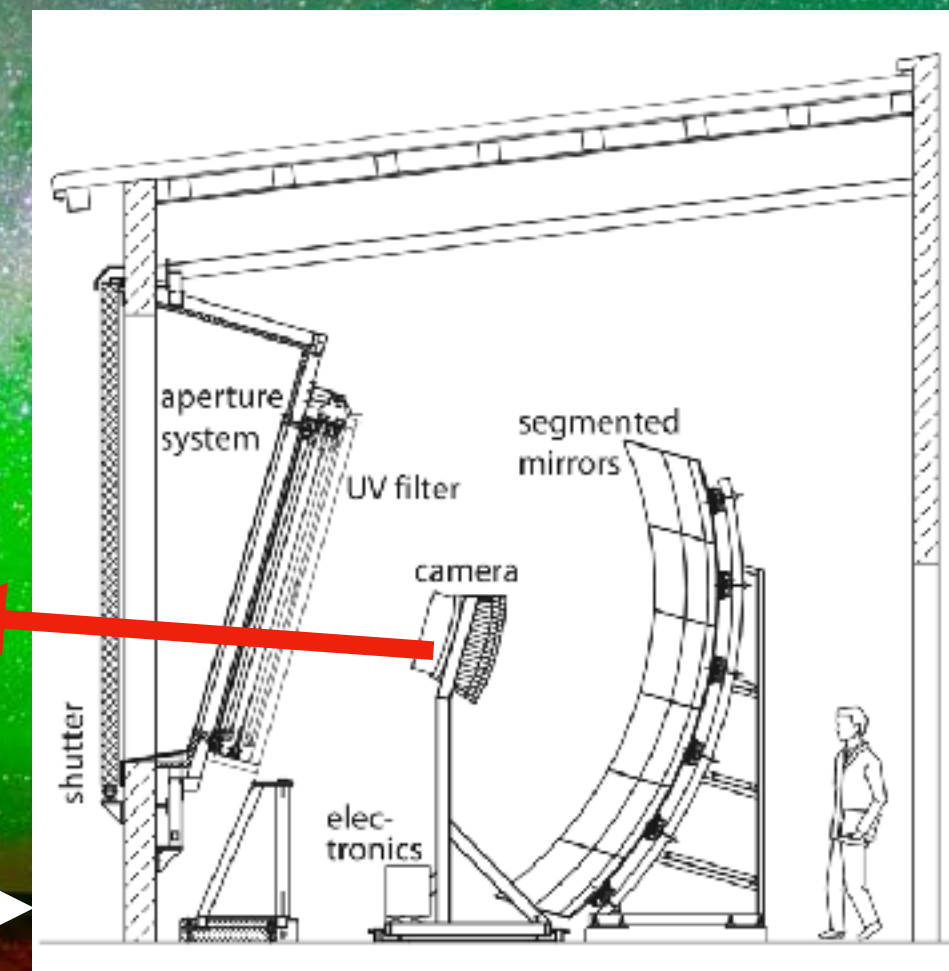
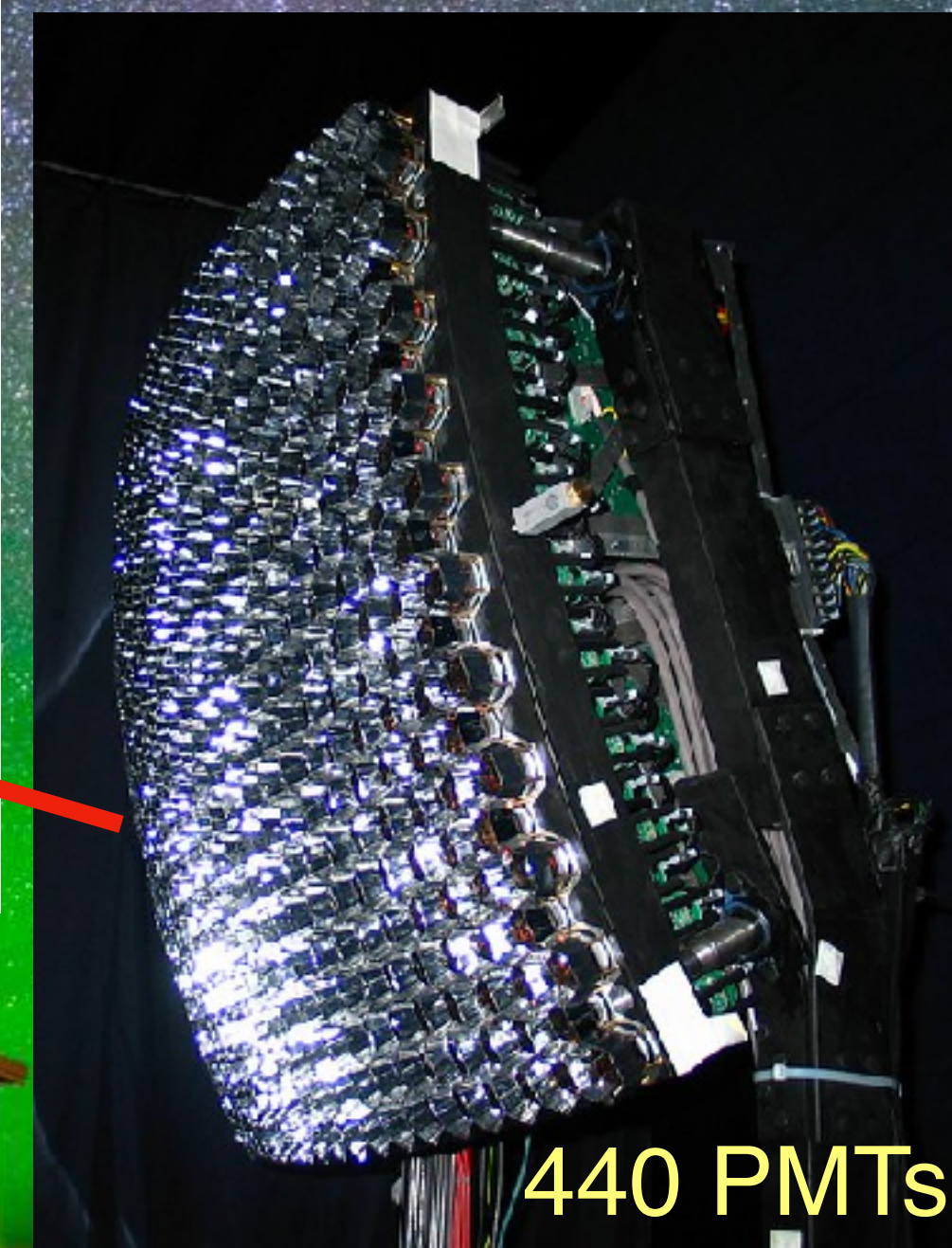


ance sites

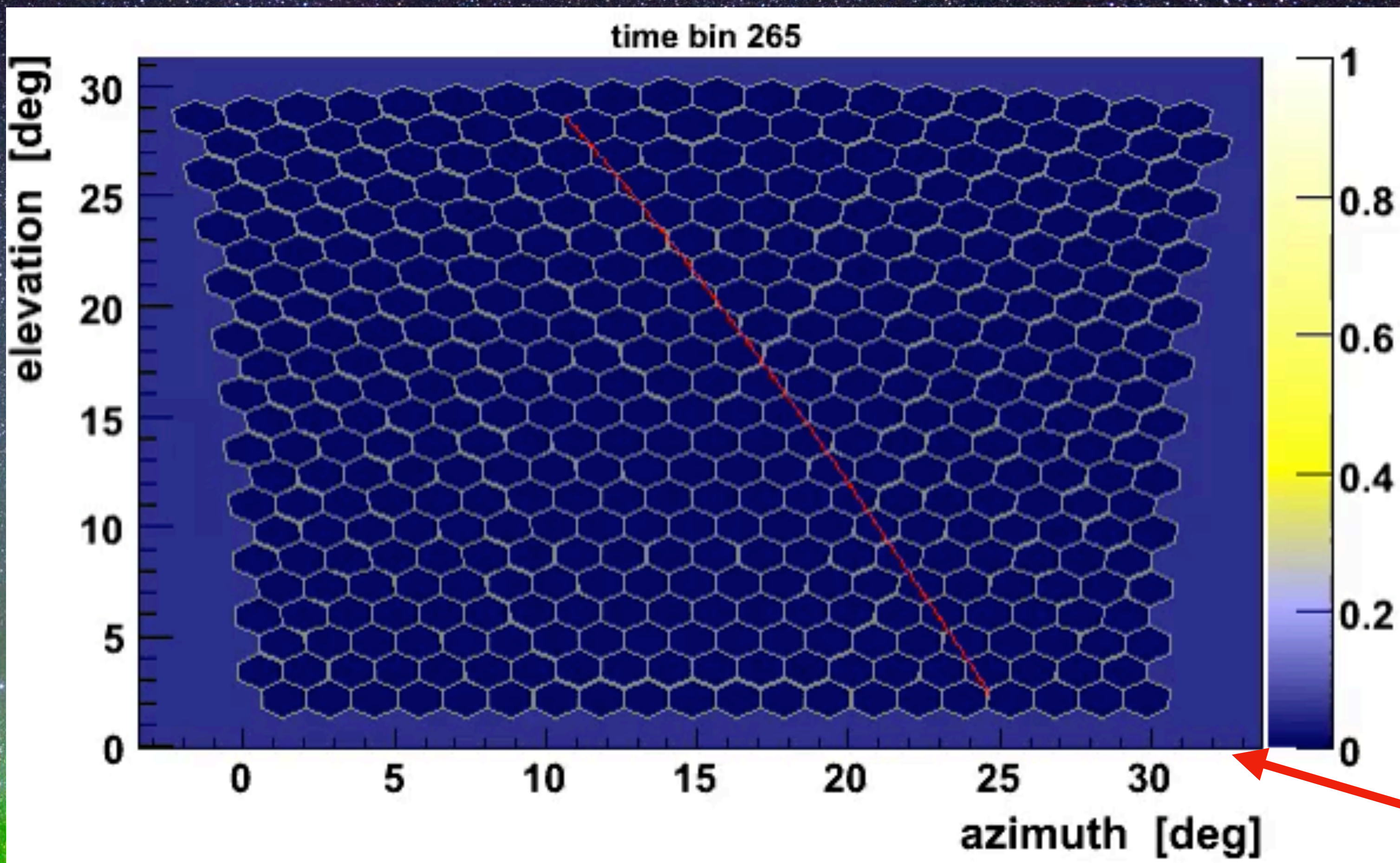
es, 1-30° FoV

tion, 30-60° FoV (HEAT)

circle: data taking only in very dark,
and cloudless night



Fluorescence detectors

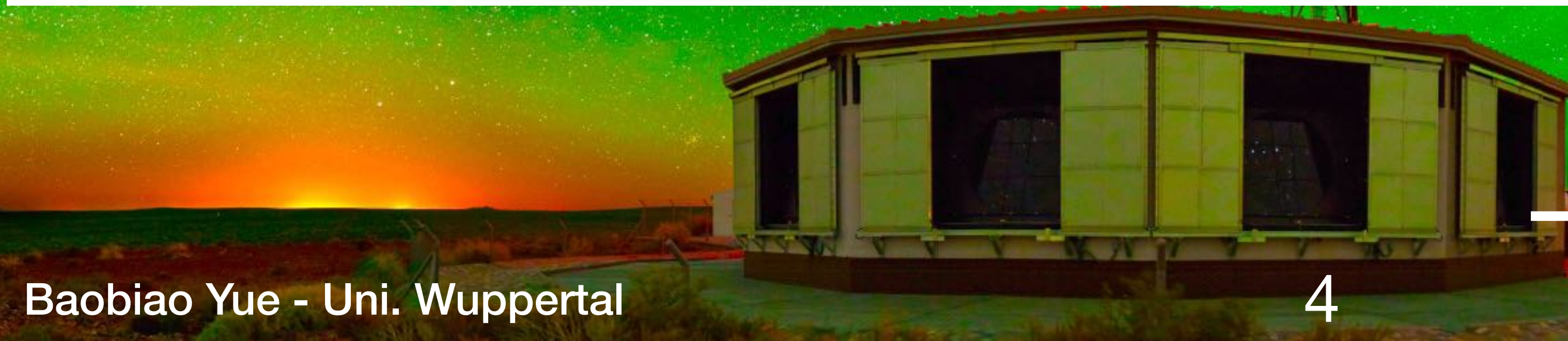
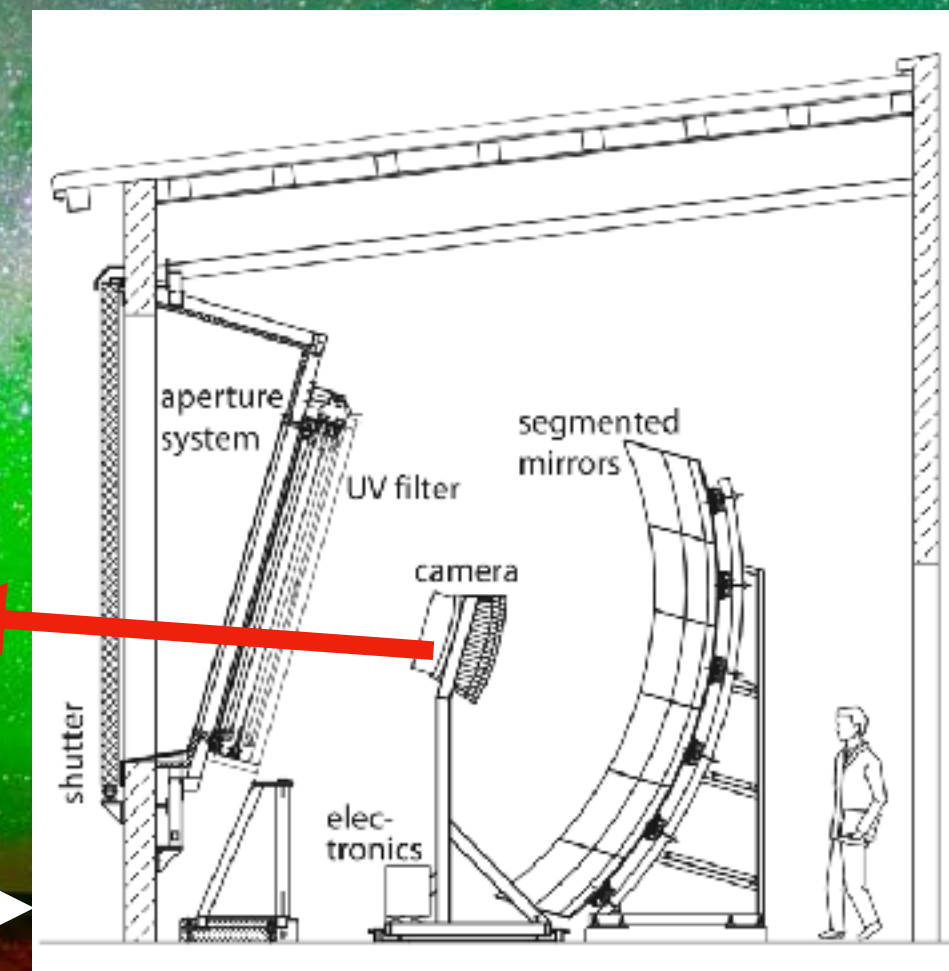
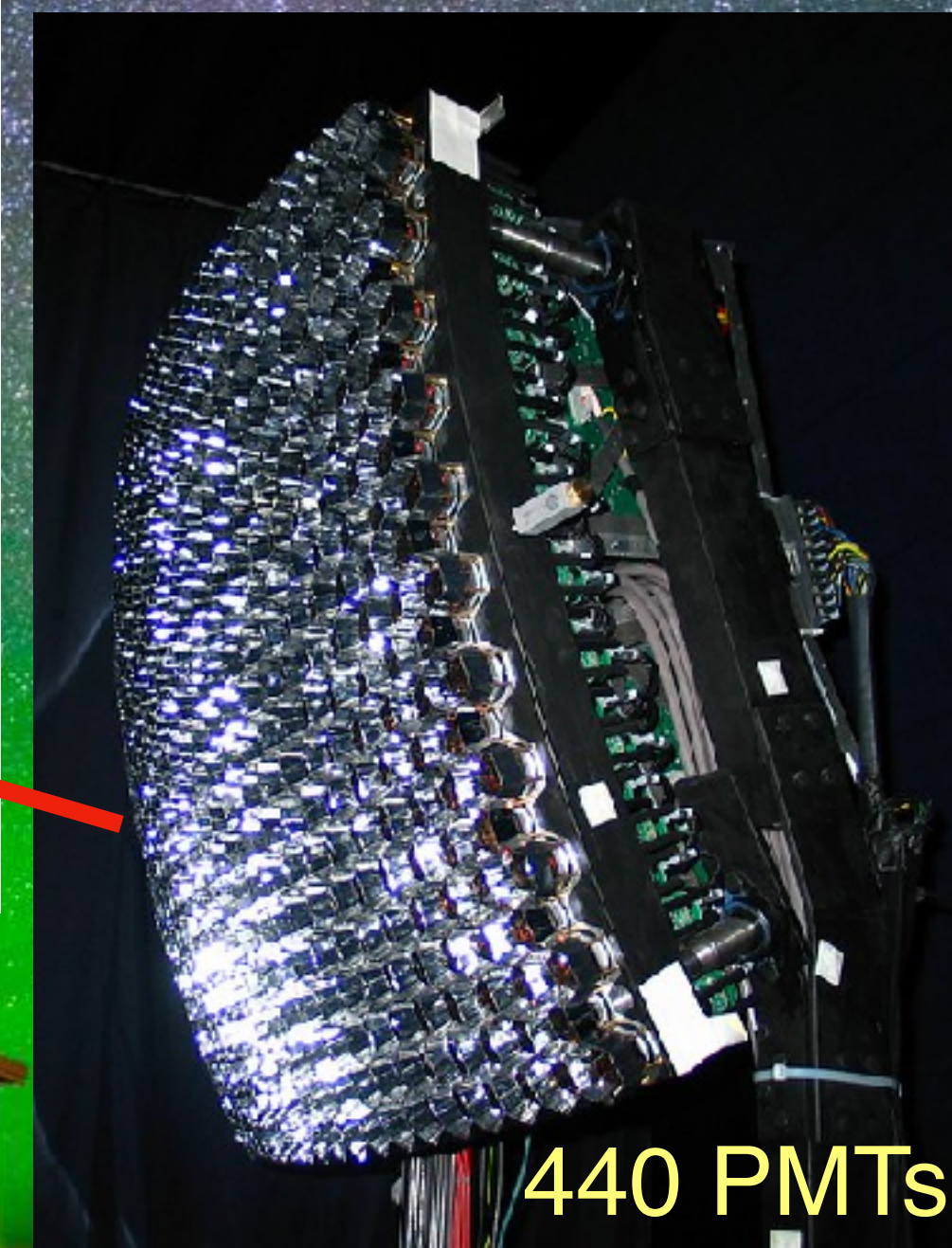


ance sites

es, 1-30° FoV

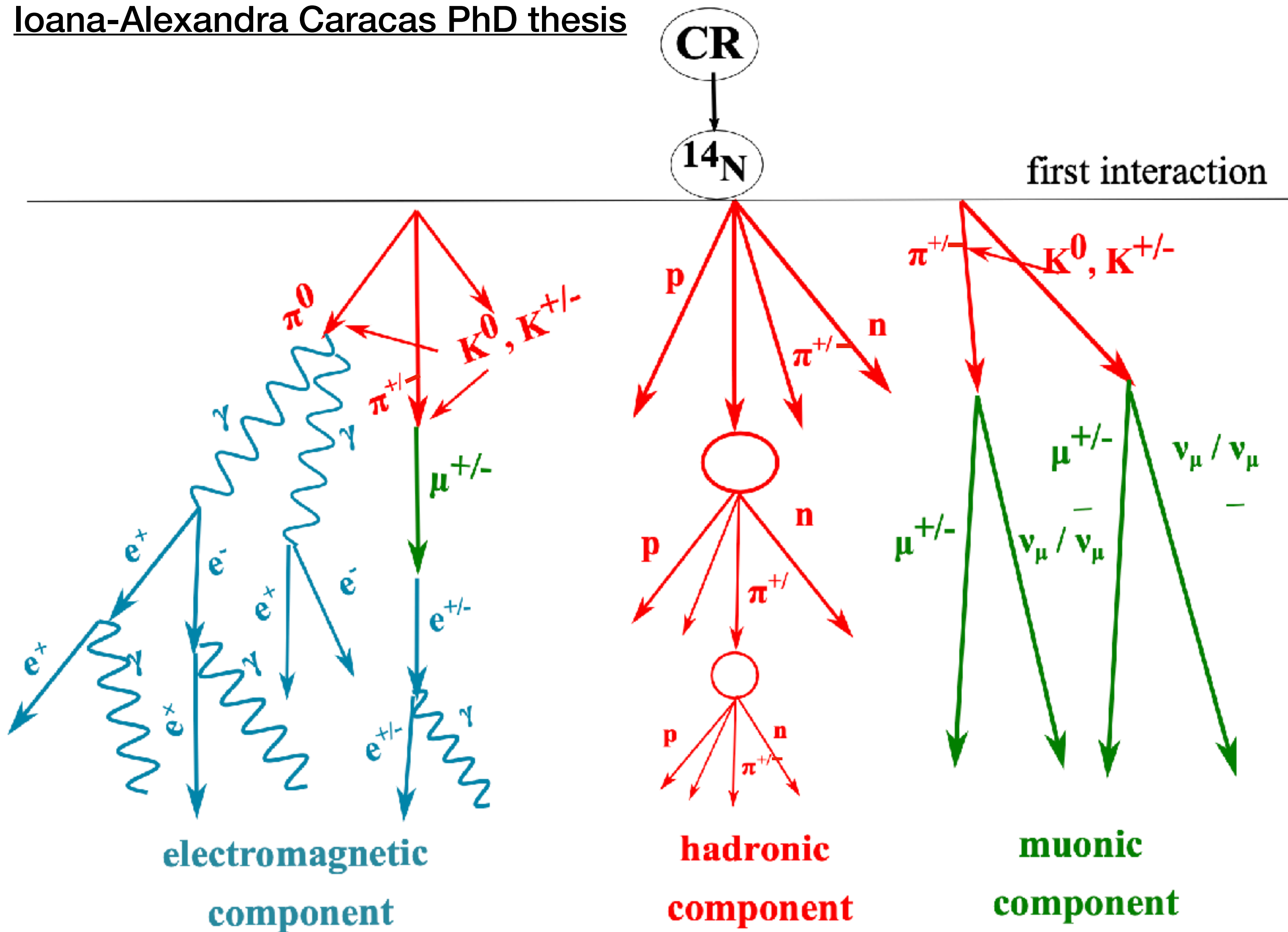
tion, 30-60° FoV (HEAT)

circle: data taking only in very dark,
and cloudless night

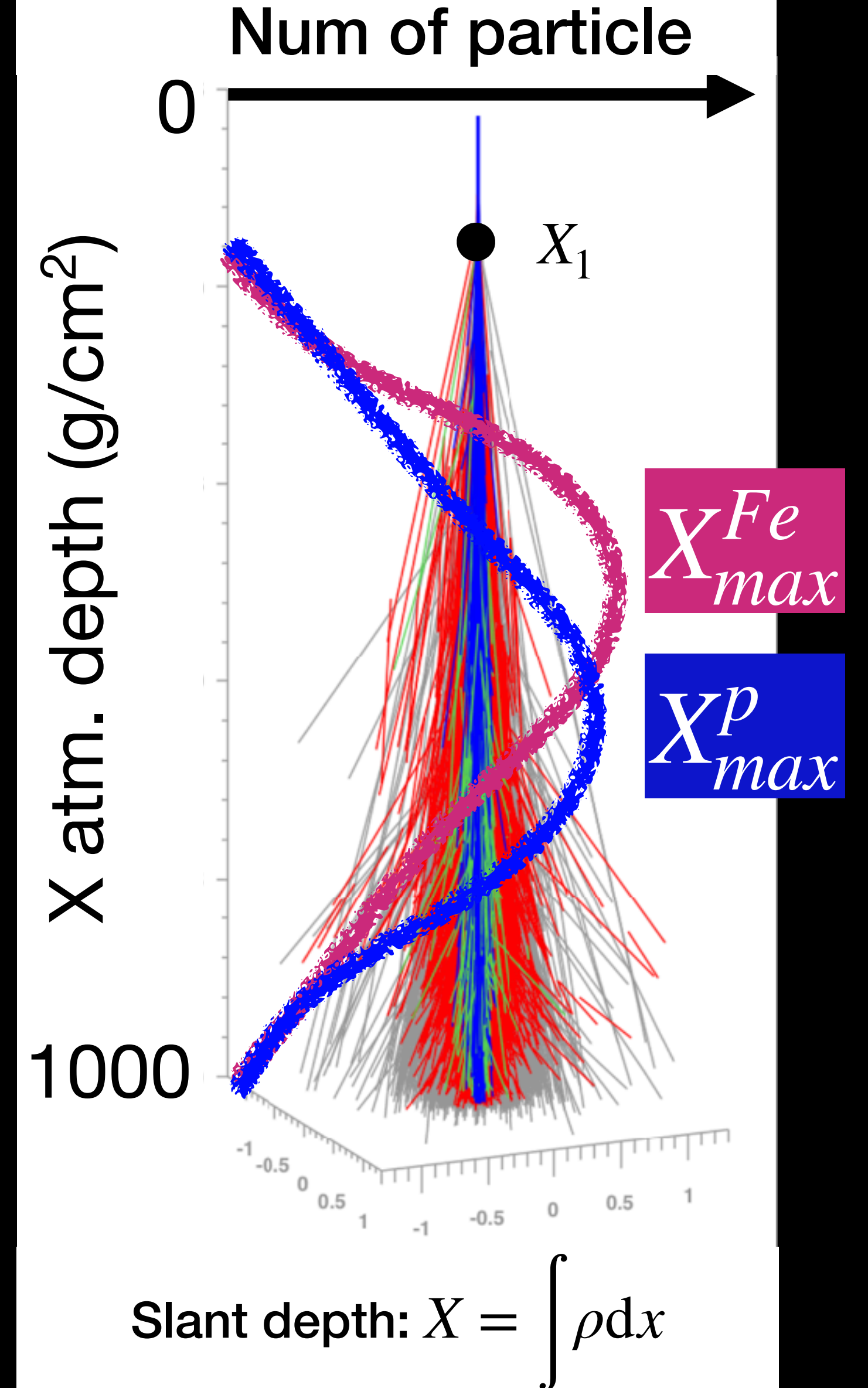


Extensive air showers

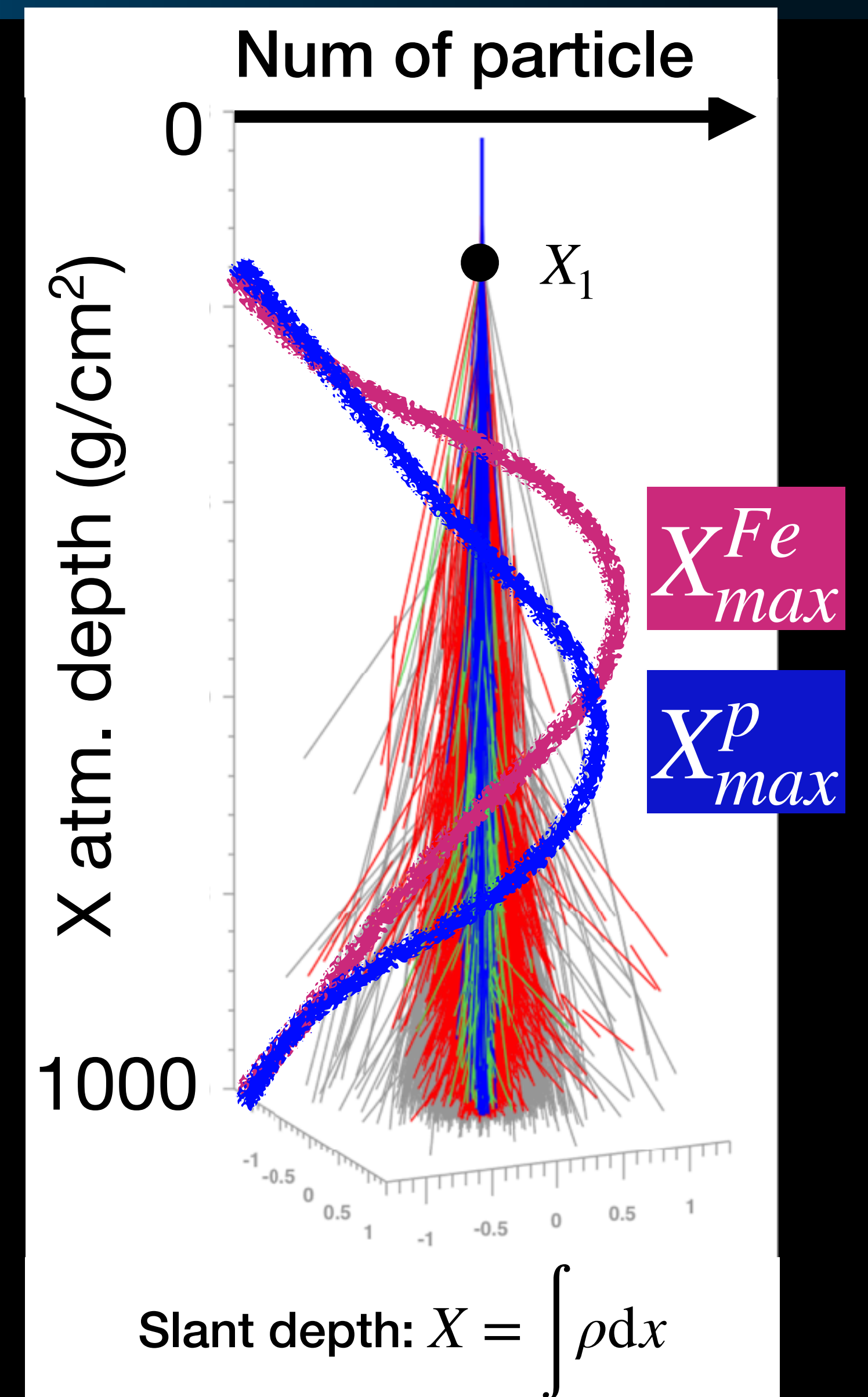
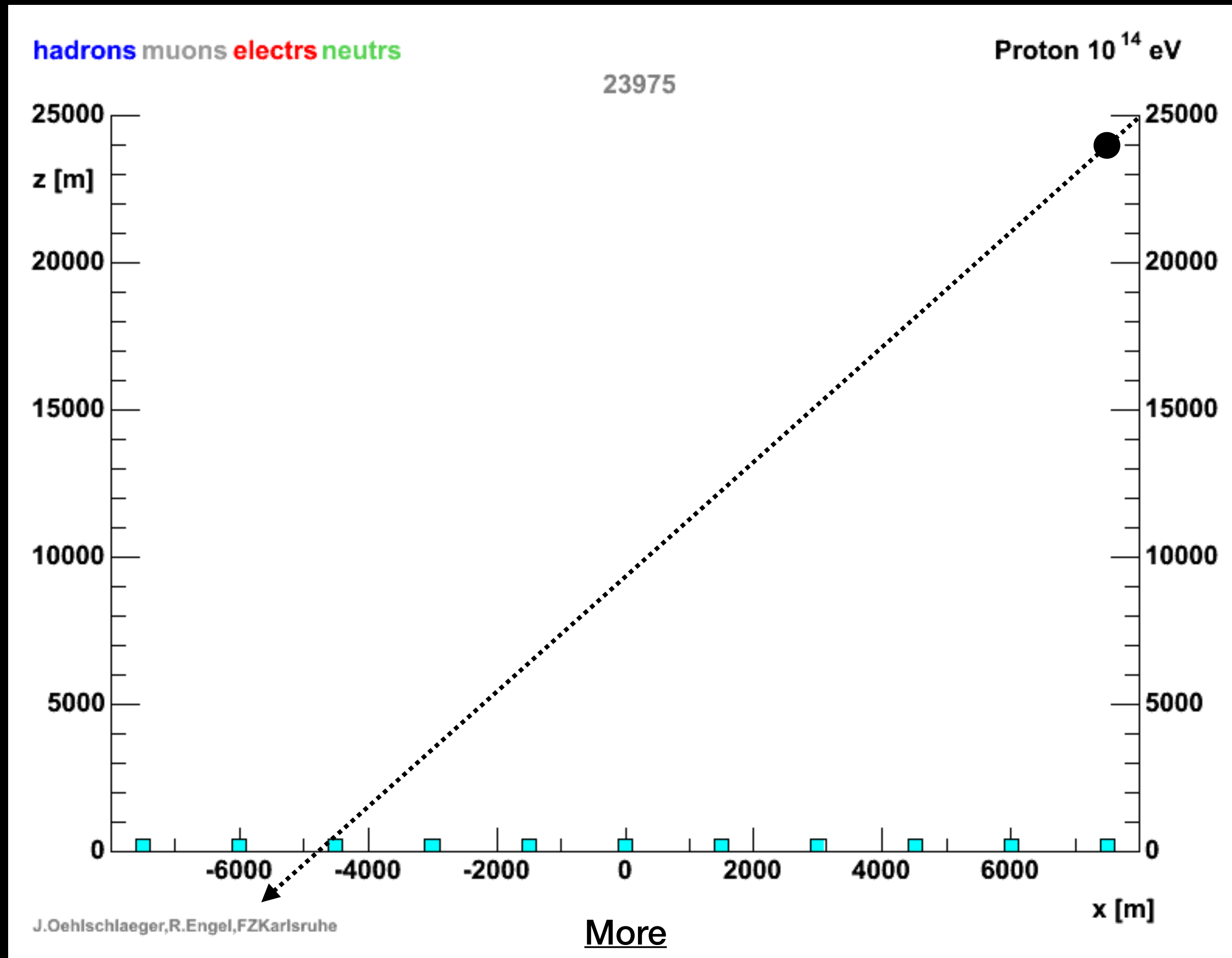
Ioana-Alexandra Caracas PhD thesis



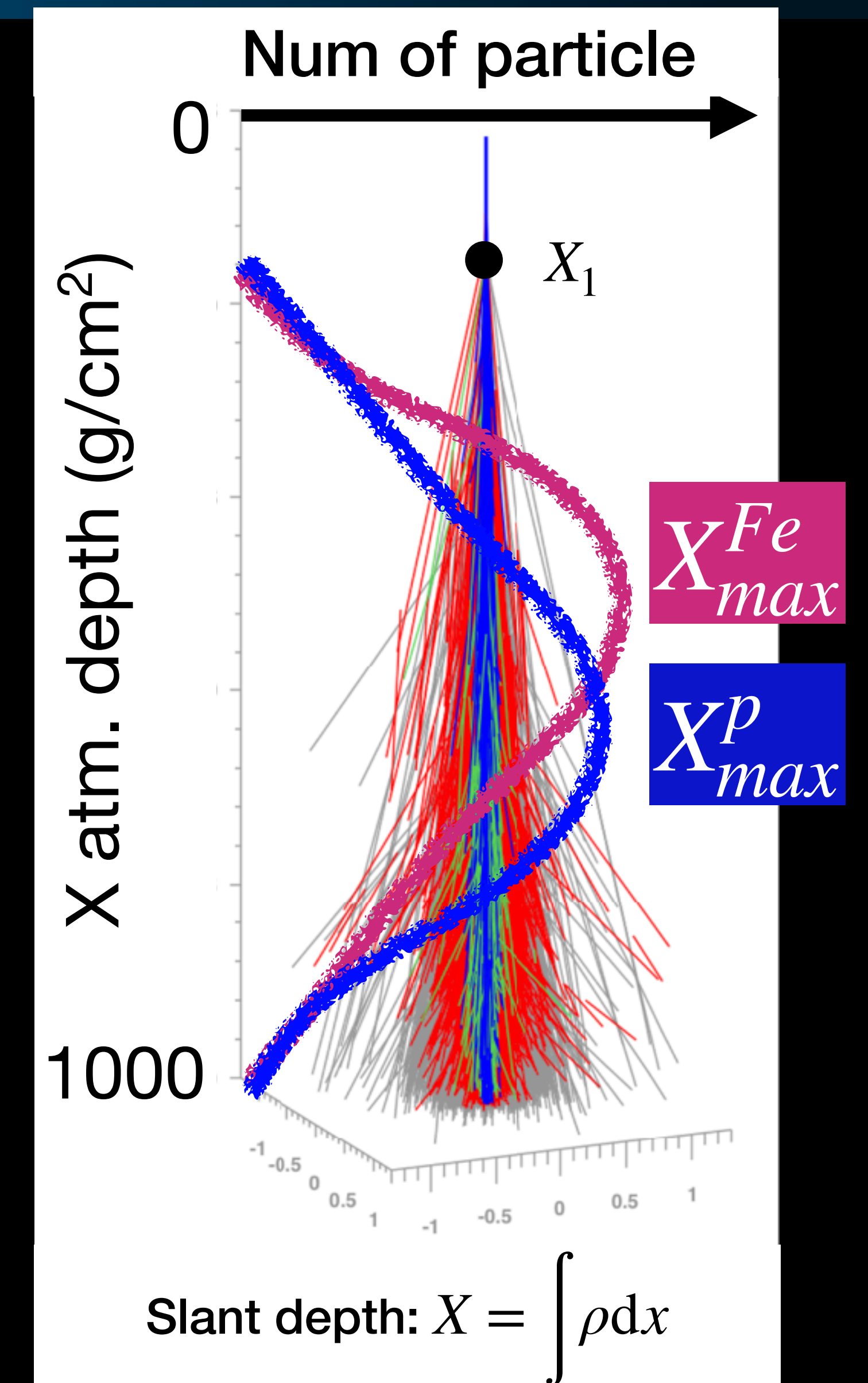
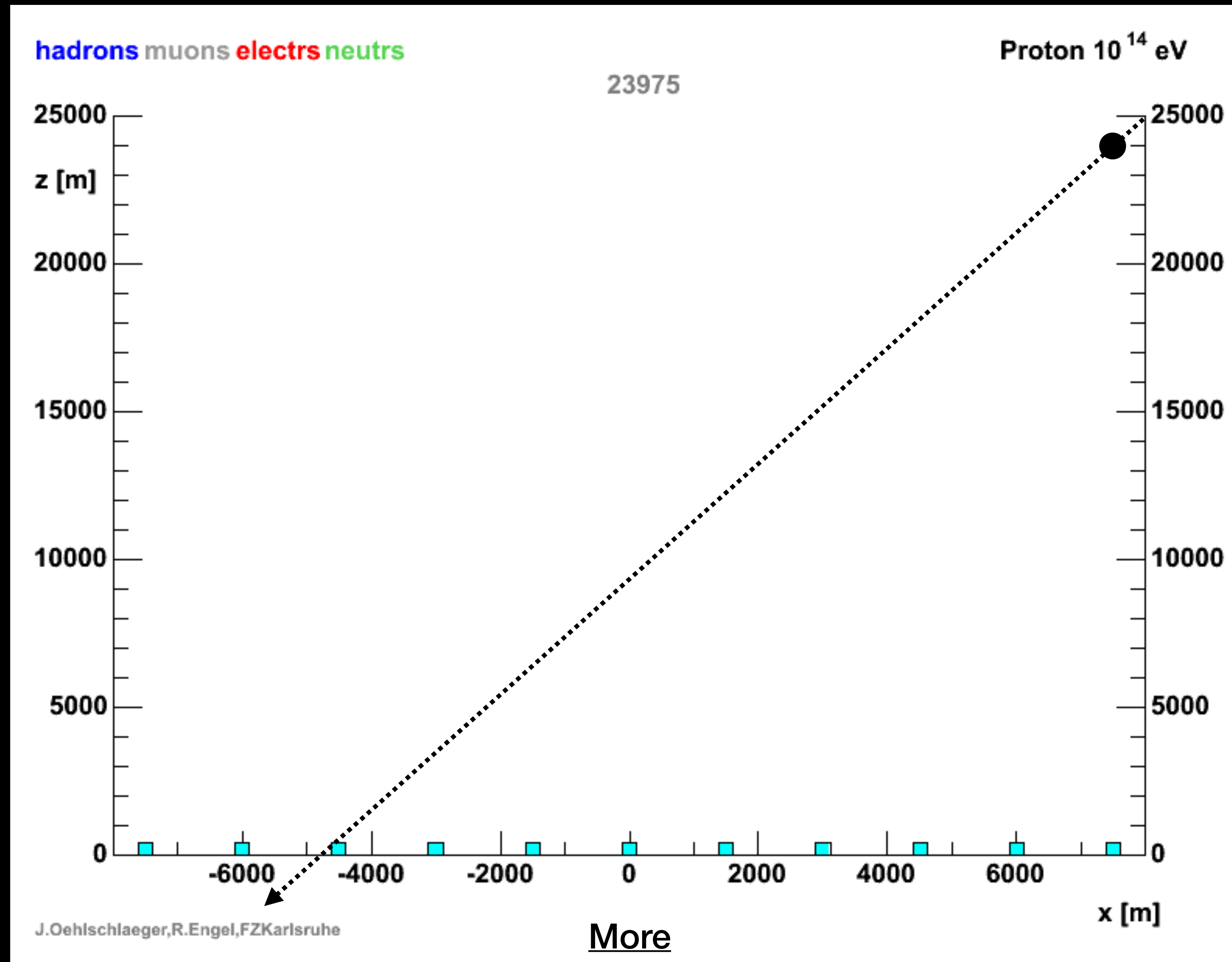
(The most energy from the primary)



Extensive air showers



Extensive air showers



Hybrid event

Event ID: 081847955000
Time: 03 Jul 2008 12:05:57
Energy: 56.83 EeV
Number of Stations: 24

Open data example

$$E = 5.683 \times 10^{19} \text{ eV}$$
$$\theta = 54.12^\circ$$

First interaction

Los Leones

Coihueco

Loma Amarilla

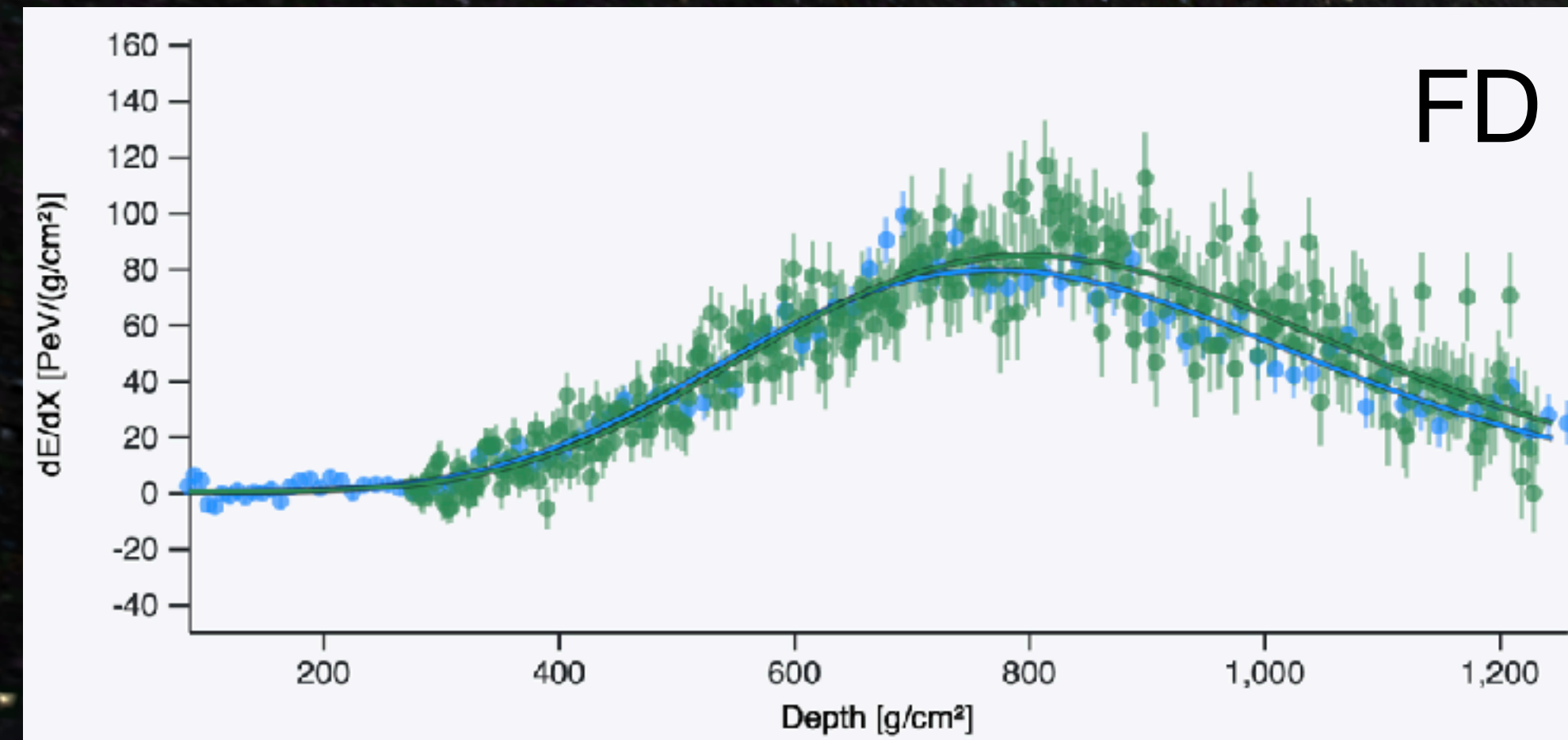
Hybrid event

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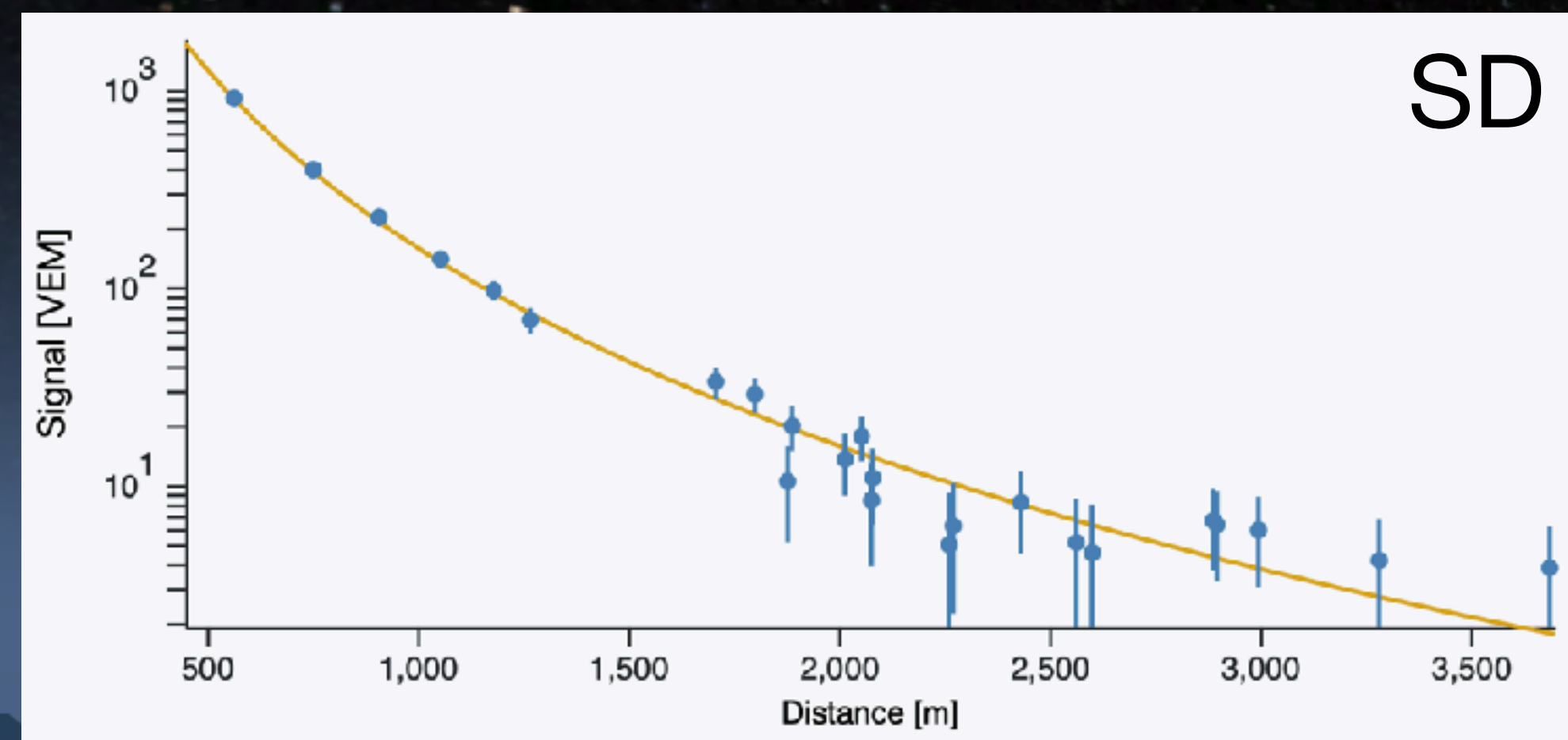
Open data example

$$E = 5.683 \times 10^{19} \text{ eV}$$
$$\theta = 54.12^\circ$$

FD



SD



First interaction

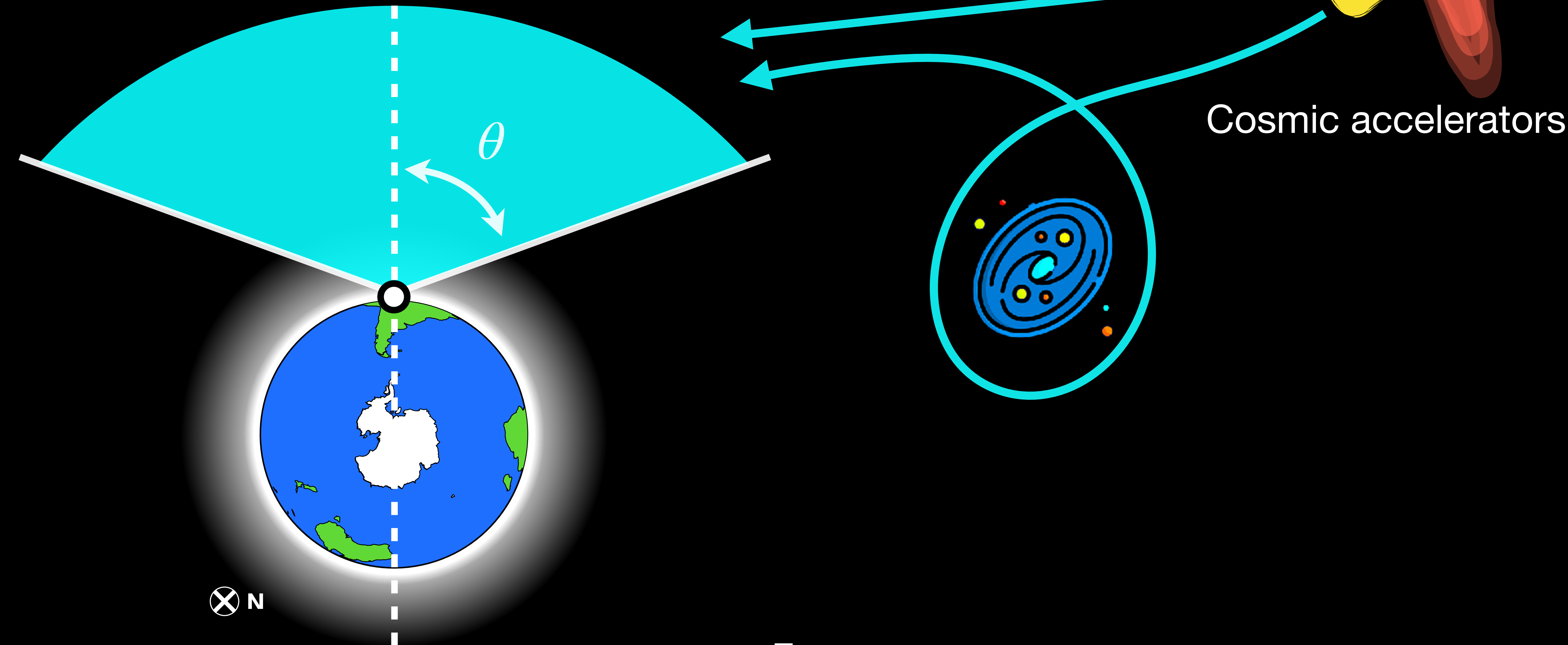
Los Leones

Coihueco

Loma Amarilla

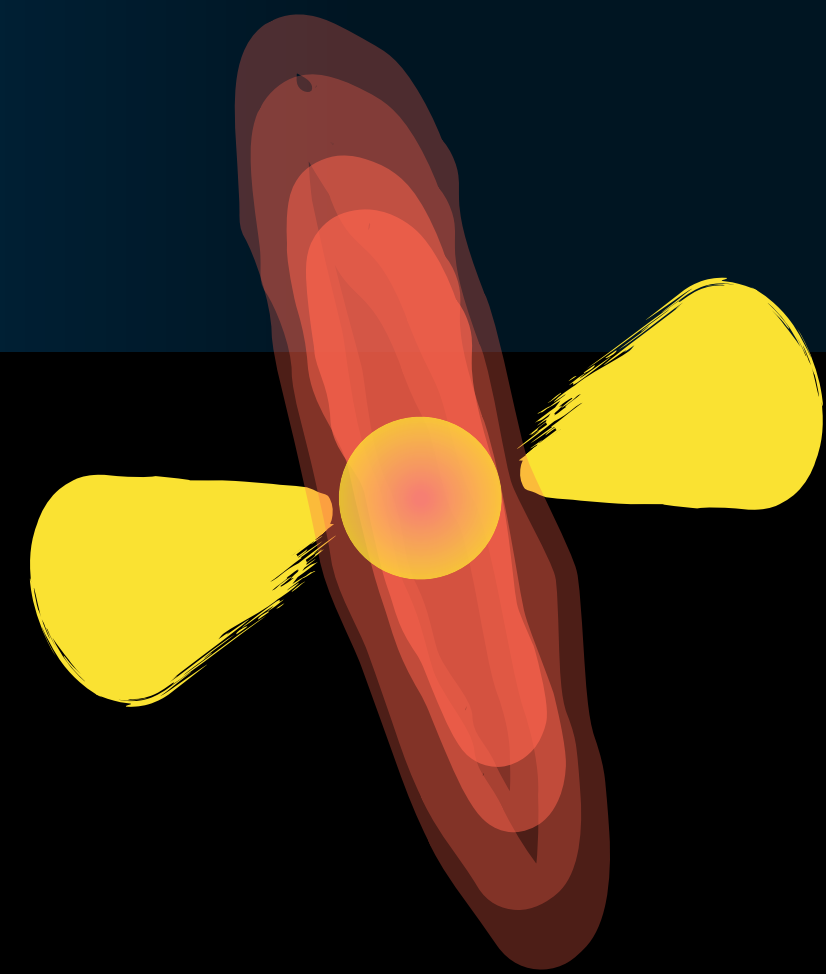
Auger: A 4π MM observatory

1 neutron and charged CRs: $\theta < 80^\circ$

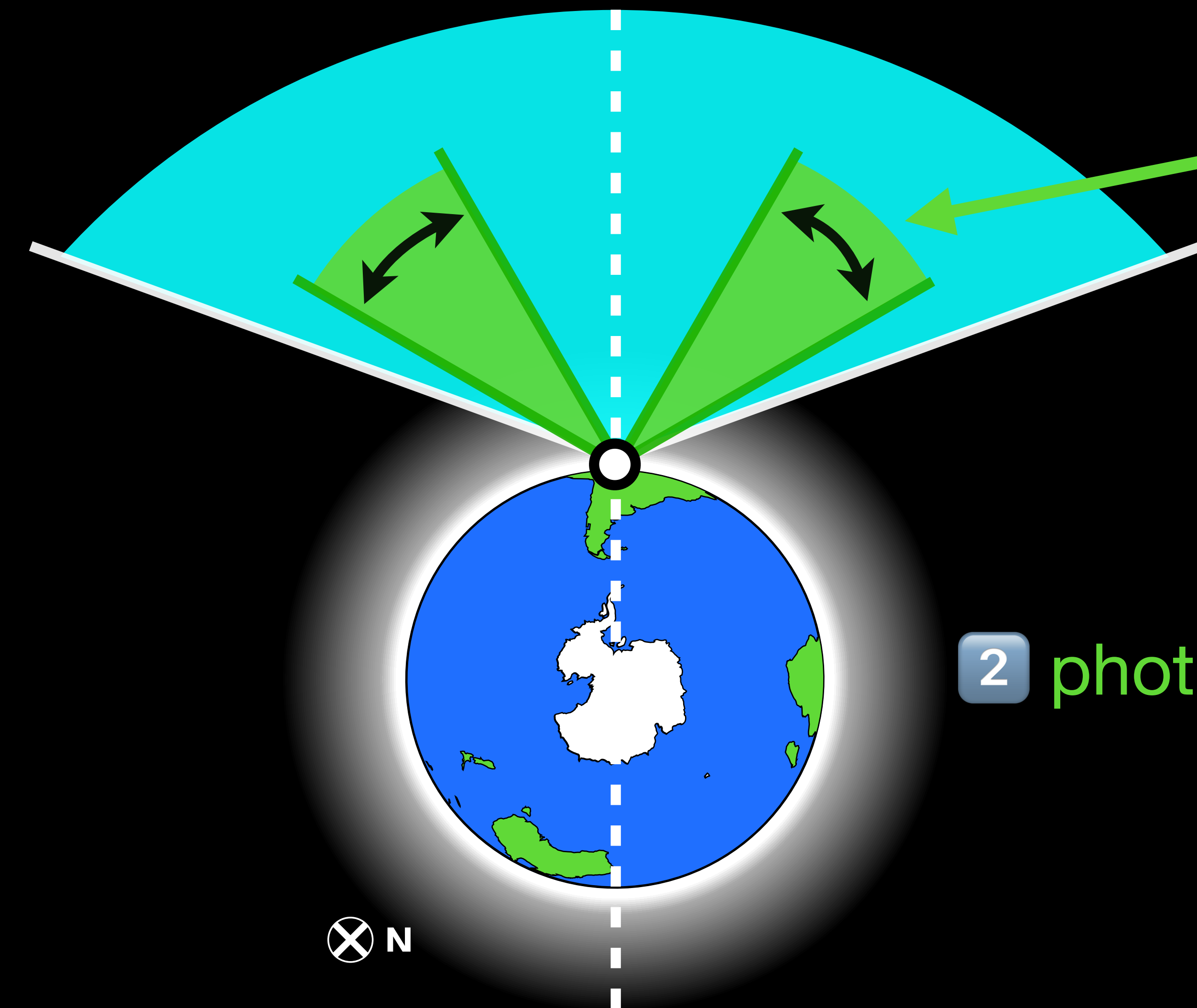


Auger: A 4π MM observatory

1 neutron and charged CRs: $\theta \leq 80^\circ$



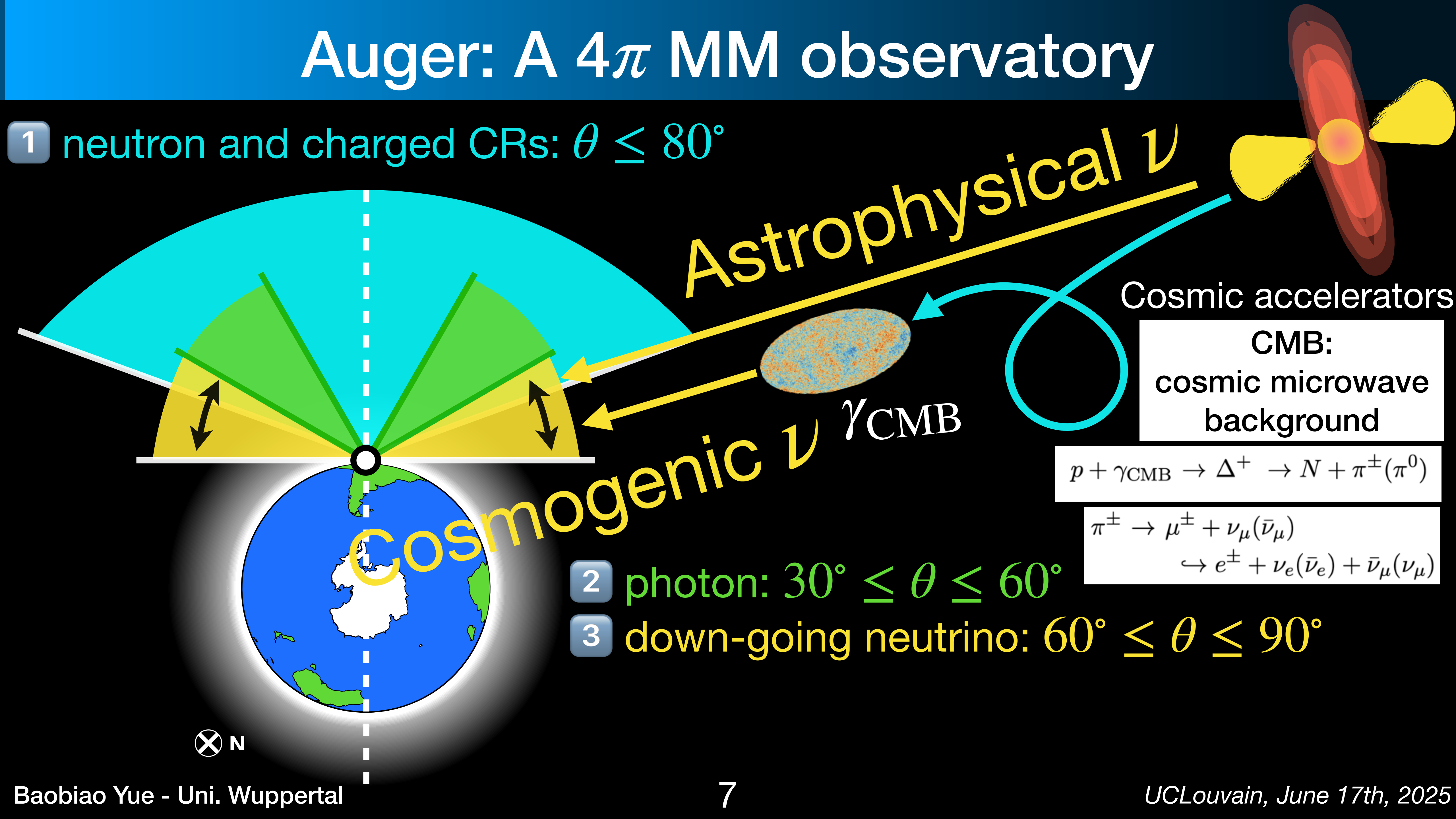
Cosmic accelerators



2 photon: $30^\circ \leq \theta \leq 60^\circ$, to be extended

Auger: A 4π MM observatory

1 neutron and charged CRs: $\theta \leq 80^\circ$

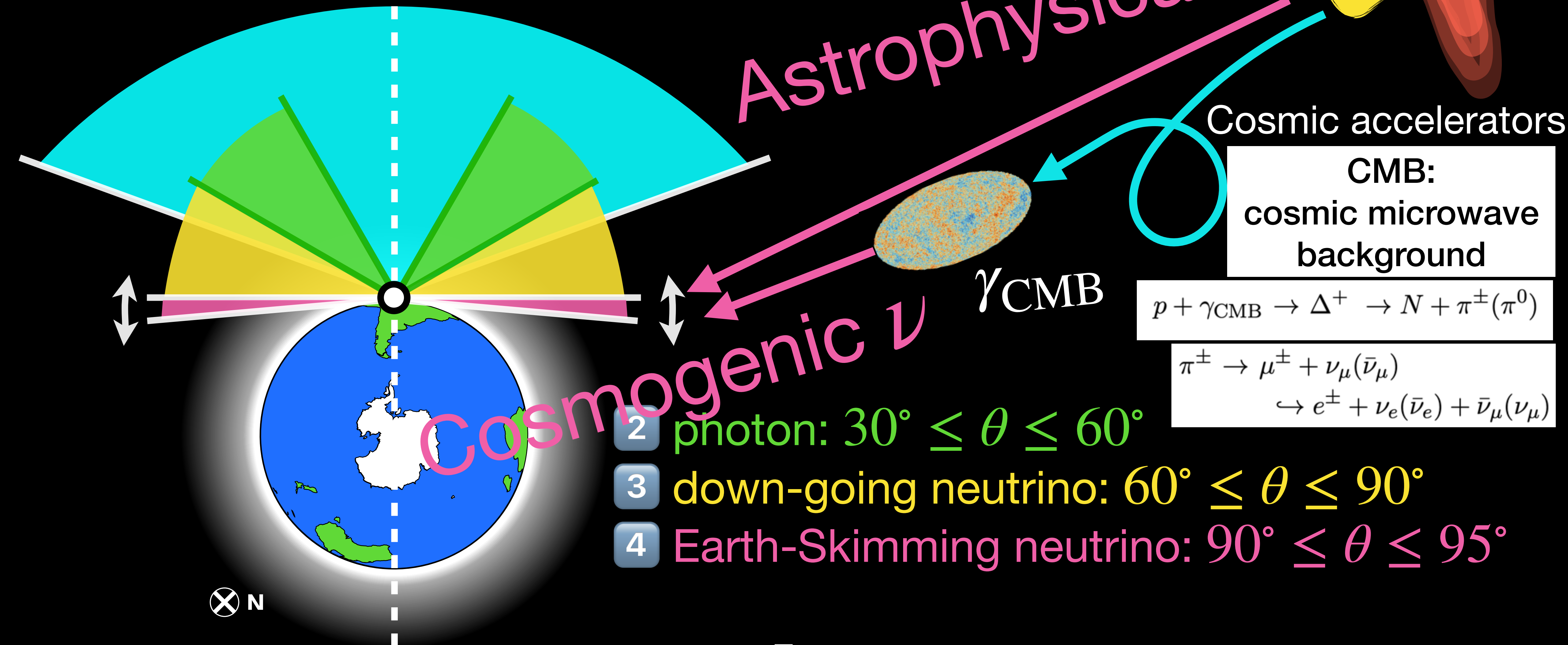


2 photon: $30^\circ \leq \theta \leq 60^\circ$

3 down-going neutrino: $60^\circ \leq \theta \leq 90^\circ$

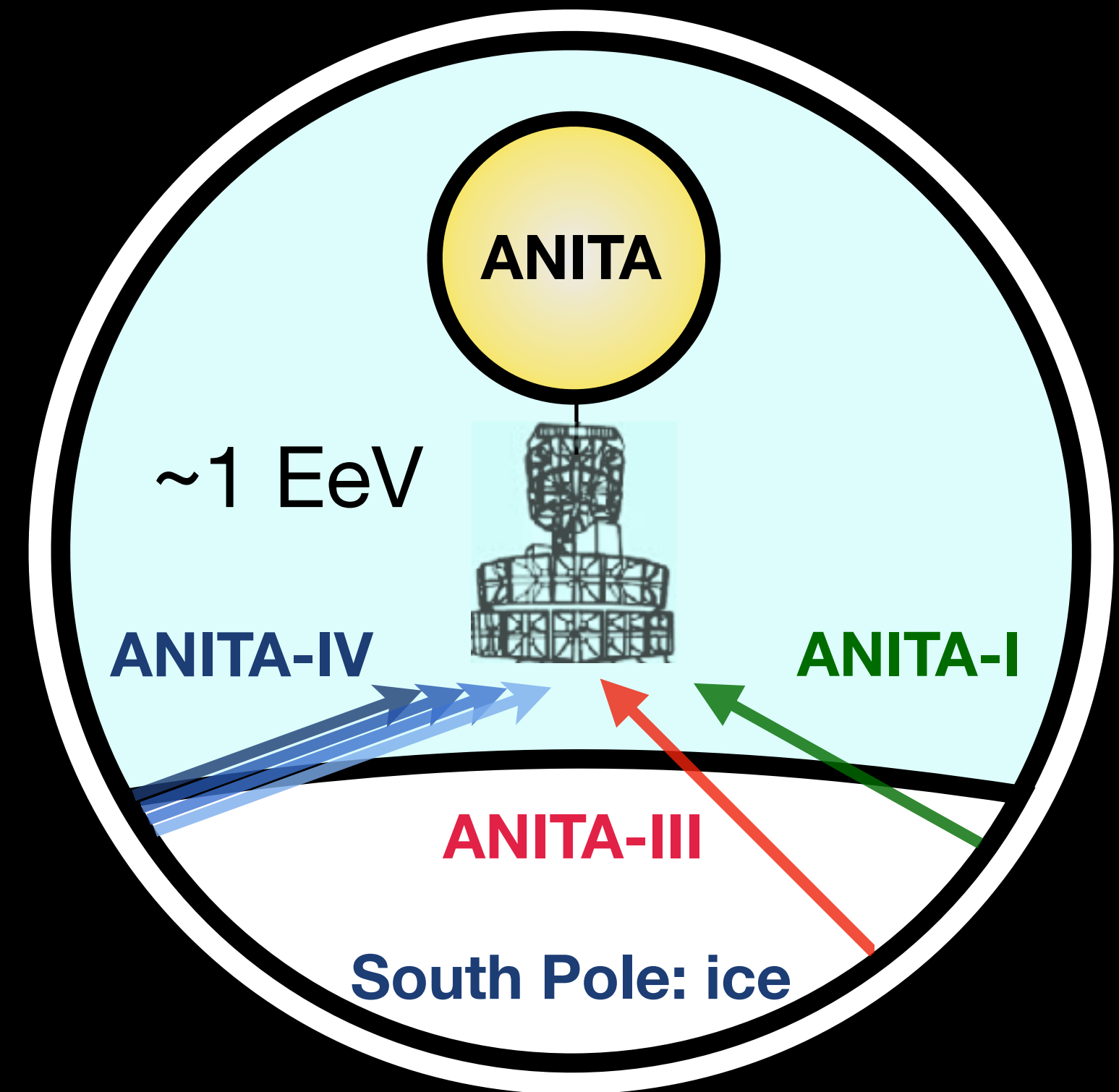
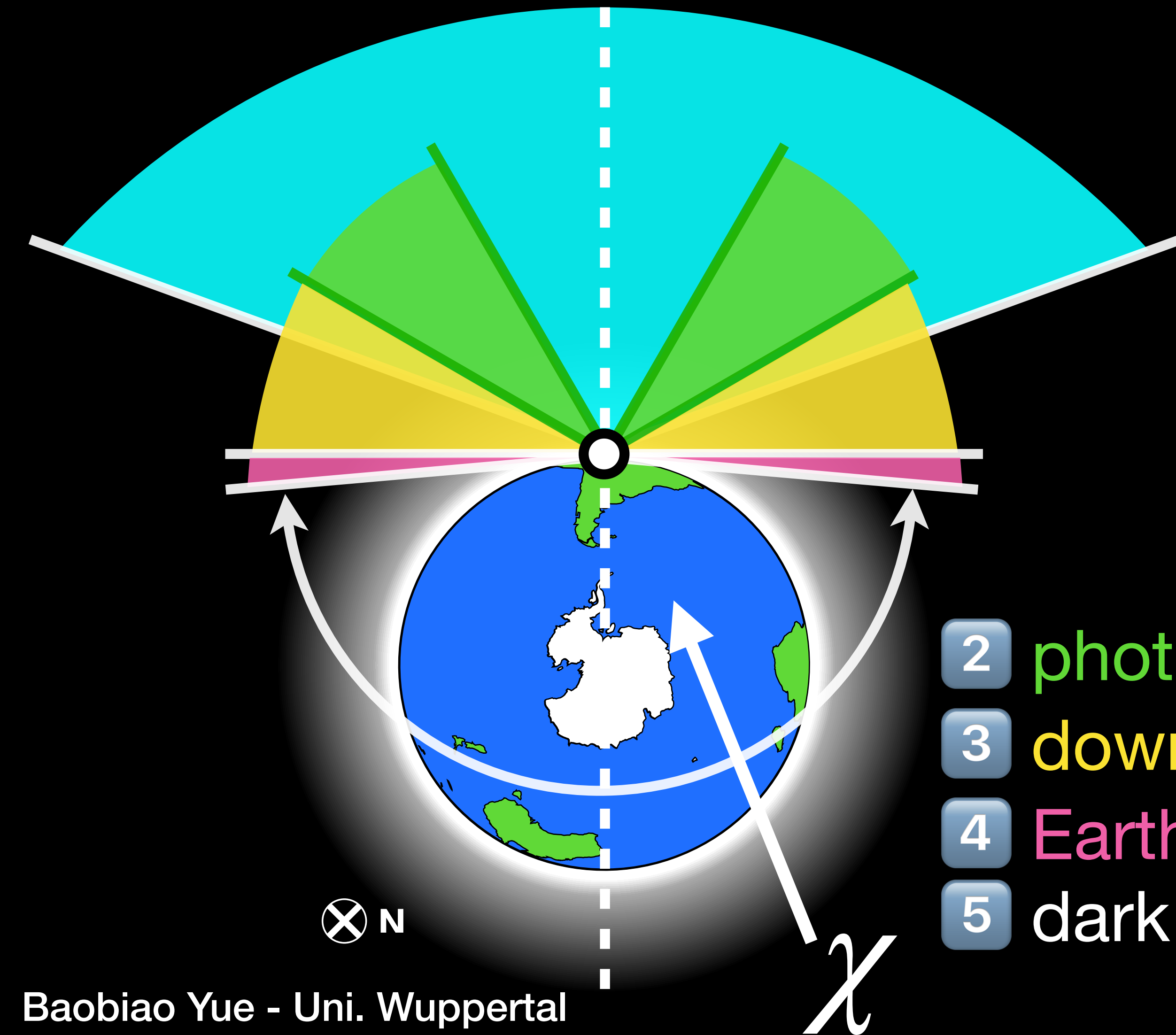
Auger: A 4π MM observatory

1 neutron and charged CRs: $\theta \leq 80^\circ$



Auger: A 4π MM observatory

1 neutron and charged CRs: $\theta \leq 80^\circ$



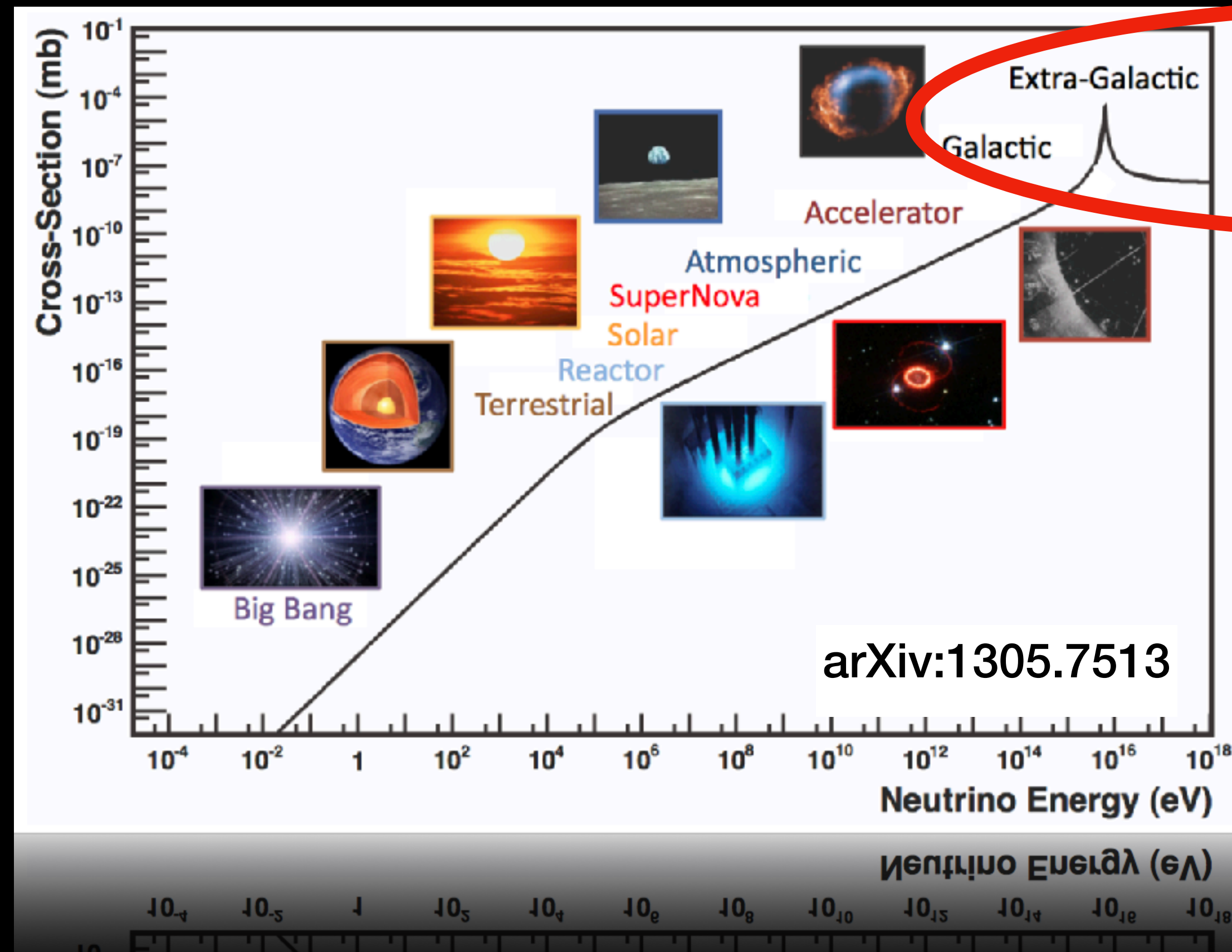
2 photon: $30^\circ \leq \theta \leq 60^\circ$

3 down-going neutrino: $60^\circ \leq \theta \leq 90^\circ$

4 Earth-Skimming neutrino: $90^\circ \leq \theta \leq 95^\circ$

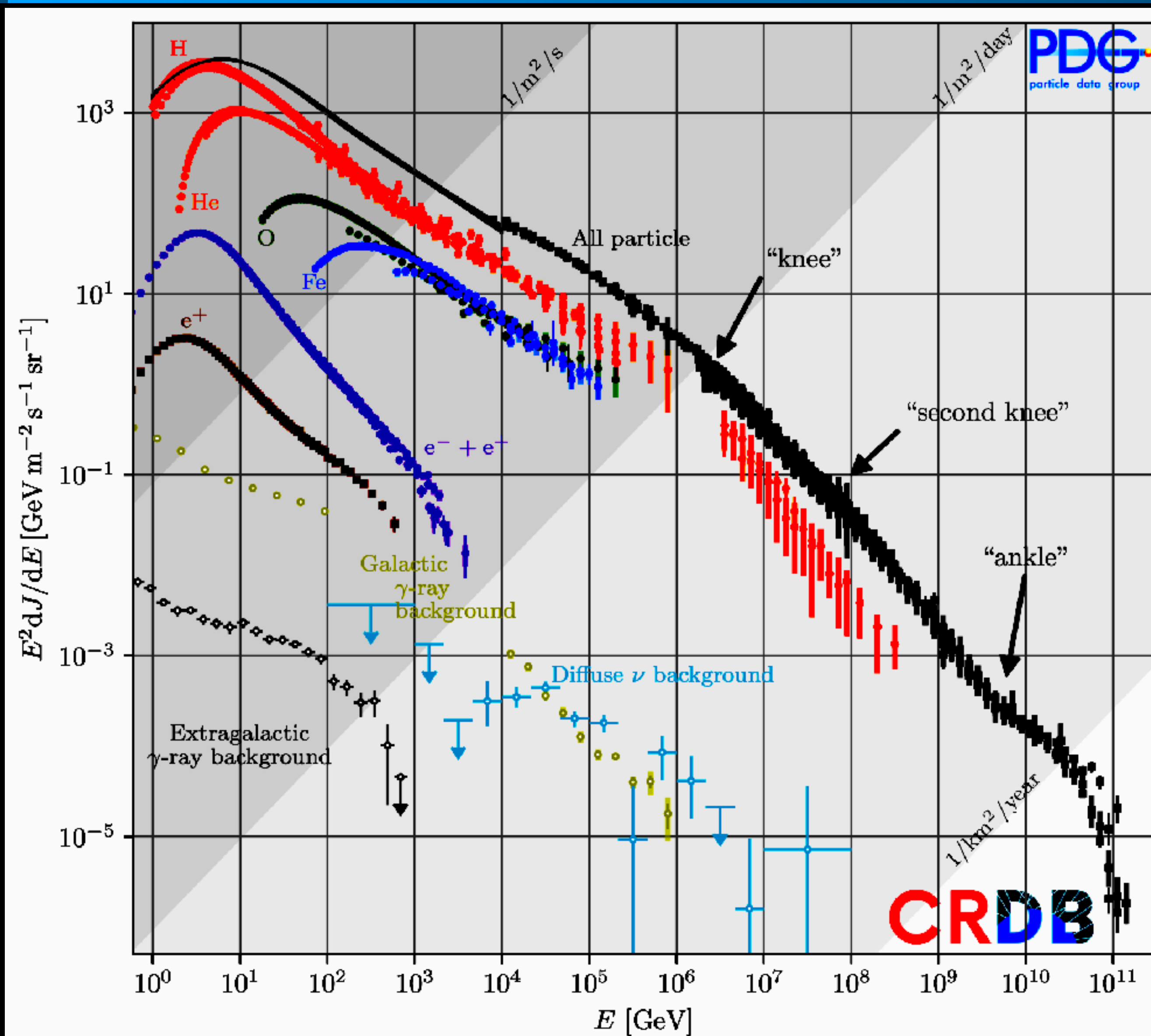
5 dark matter: $\theta \geq 90^\circ$

2, Search for UHE neutrinos

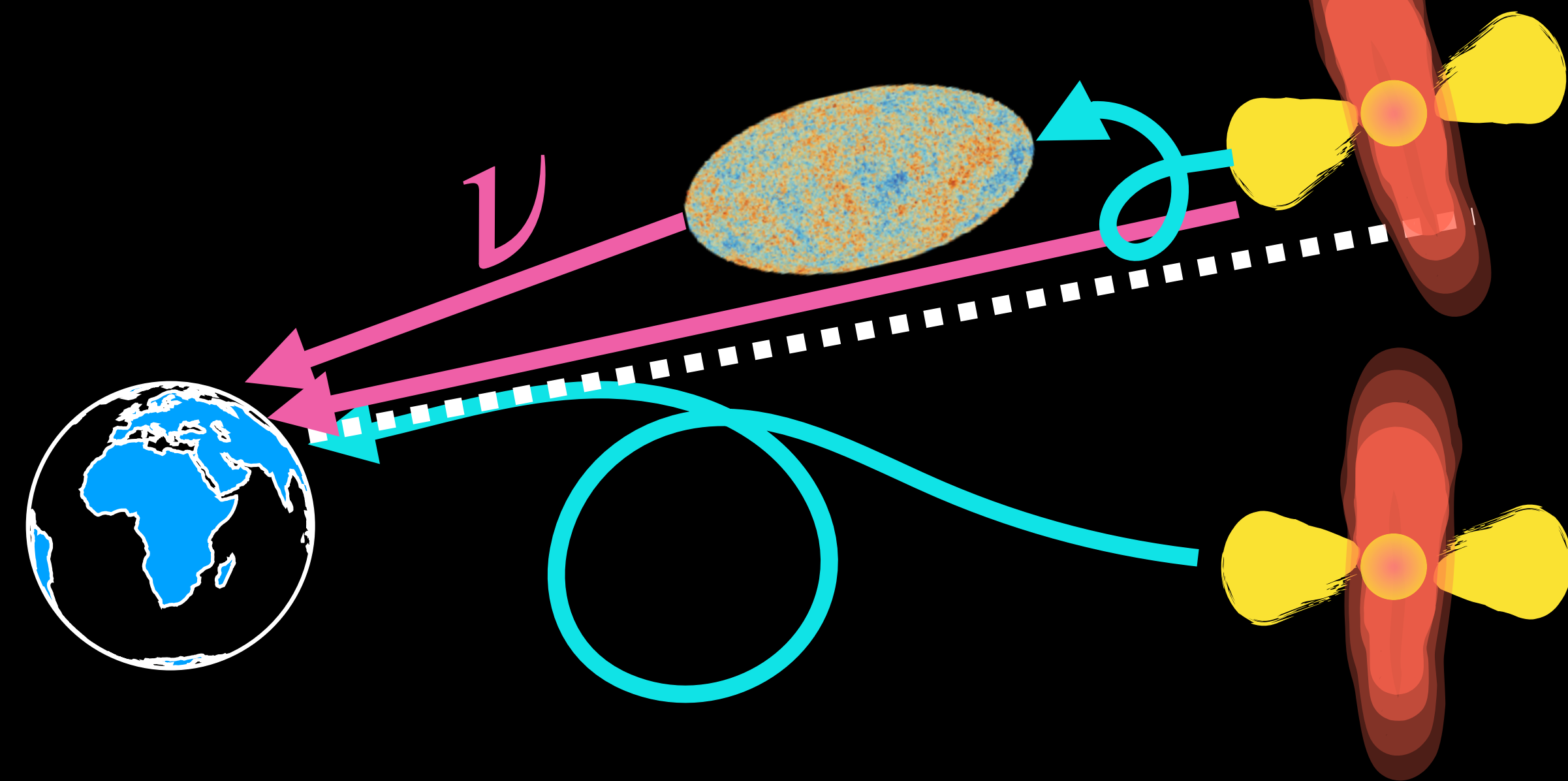


$$E_\nu > 100 \text{ PeV}$$

The cosmic ray mystery



Where are the highest energy cosmic rays coming from?



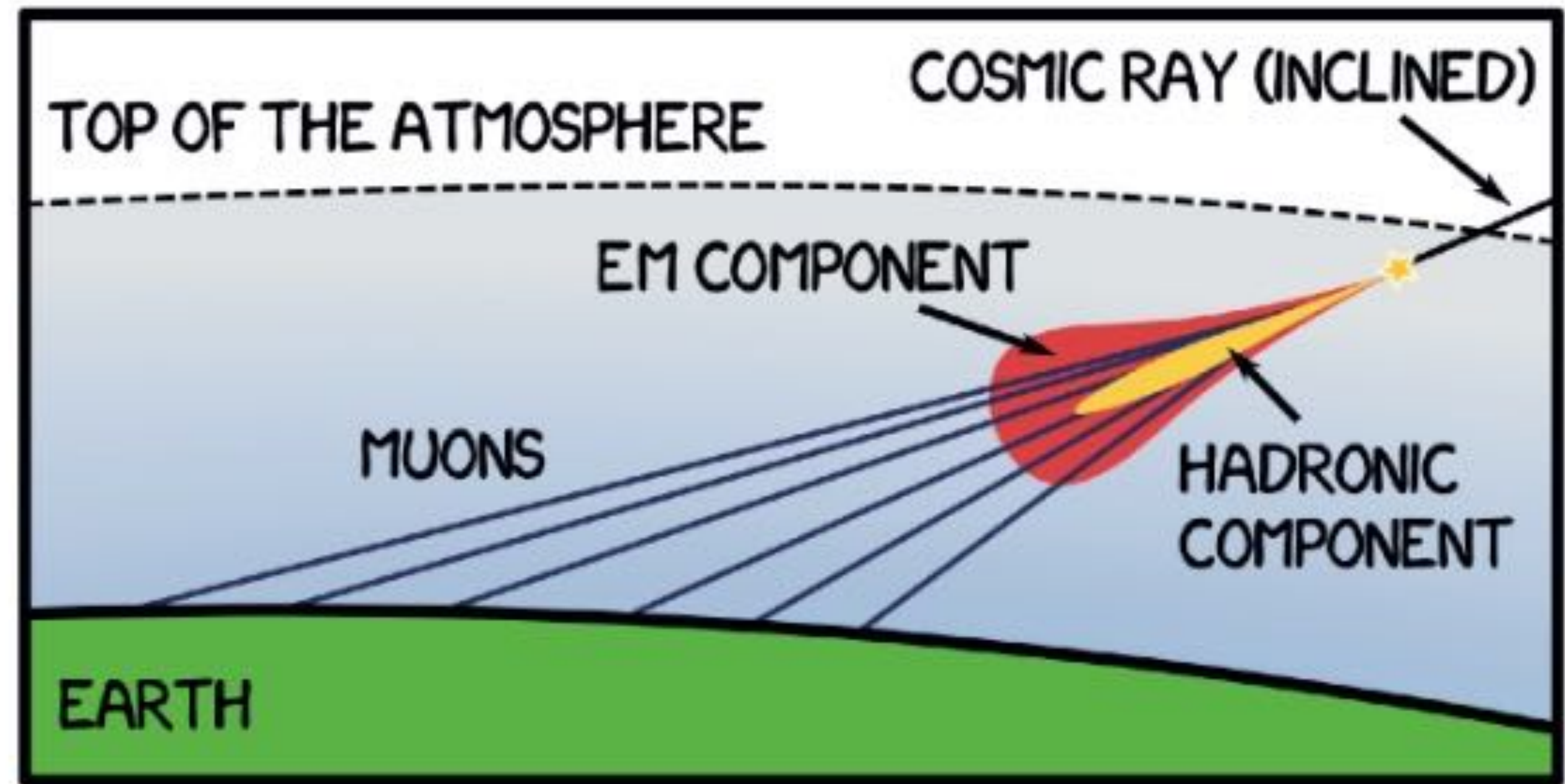
- The magnetic field bends their propagation path during the propagation process

UHE neutrinos can help to answer!

Search for neutrinos with the Surface Detector

Cosmic ray background

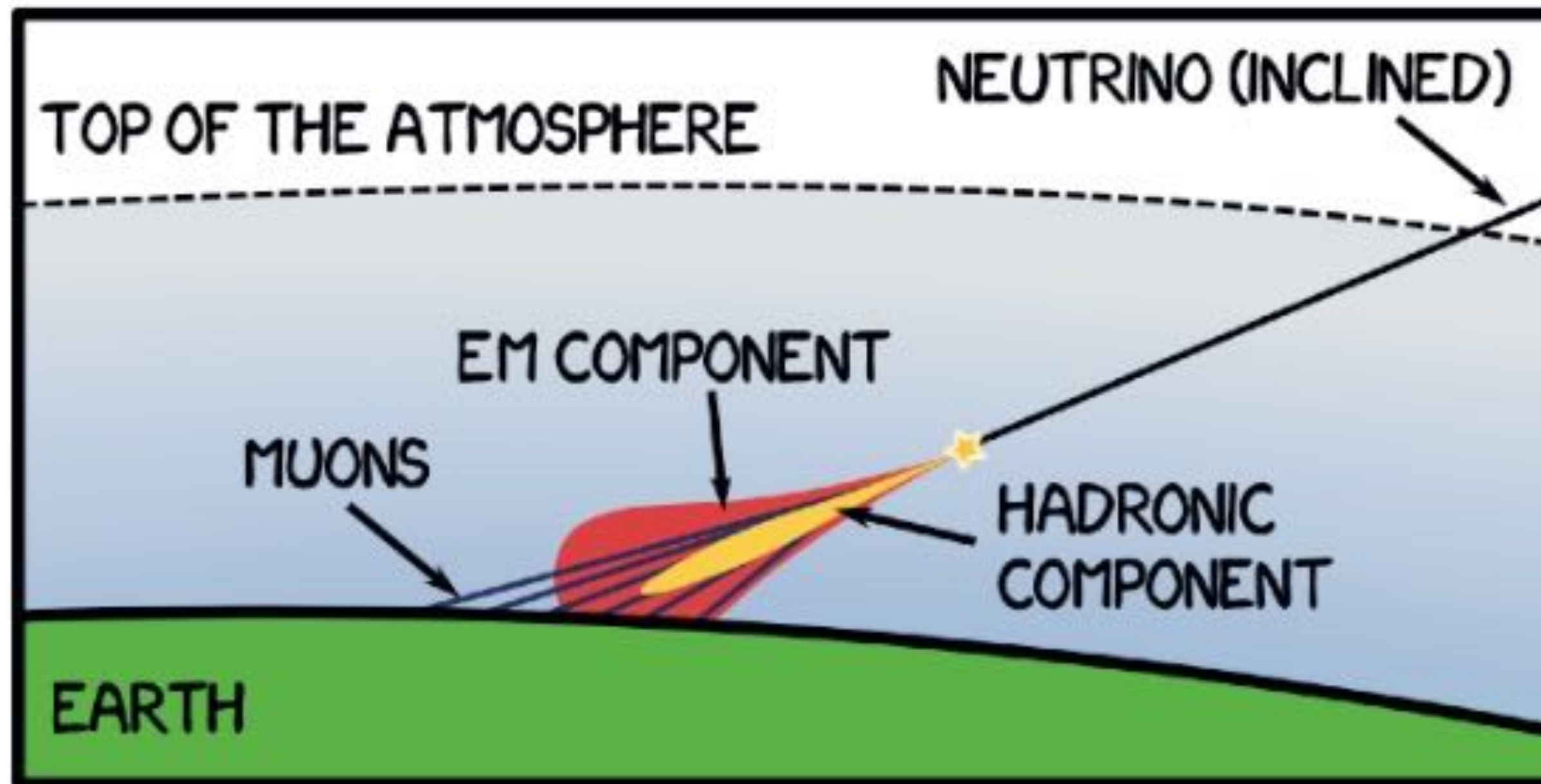
- ◆ **Protons & nuclei** at high inclination angles initiate showers high in atmosphere
 - ➡ Shower front at ground mainly composed of muons (electromagnetic component absorbed in atmosphere)
 - ➡ Small relative time delays



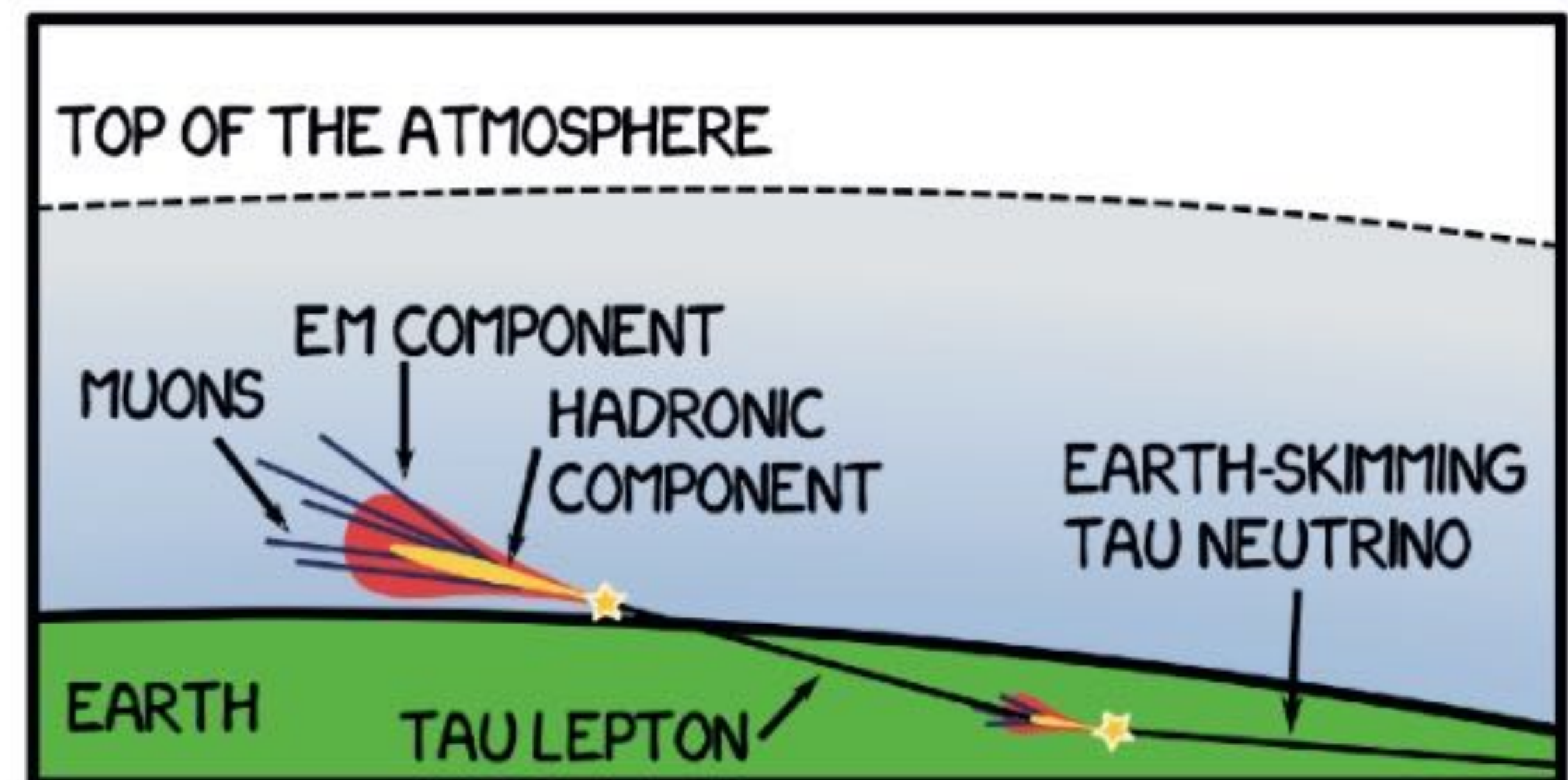
Pierre Auger JCAP 10 (2019) 022

Search for neutrinos with the Surface Detector

Down-going neutrinos



Earth-Skimming neutrinos

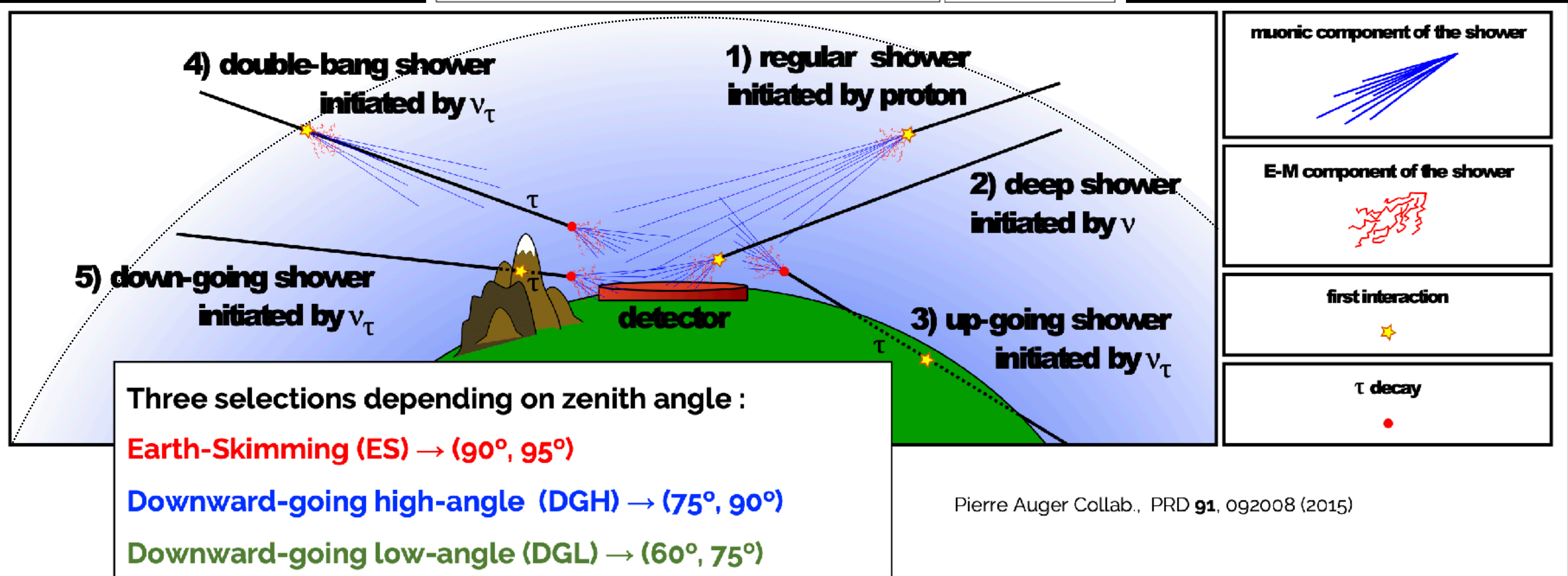
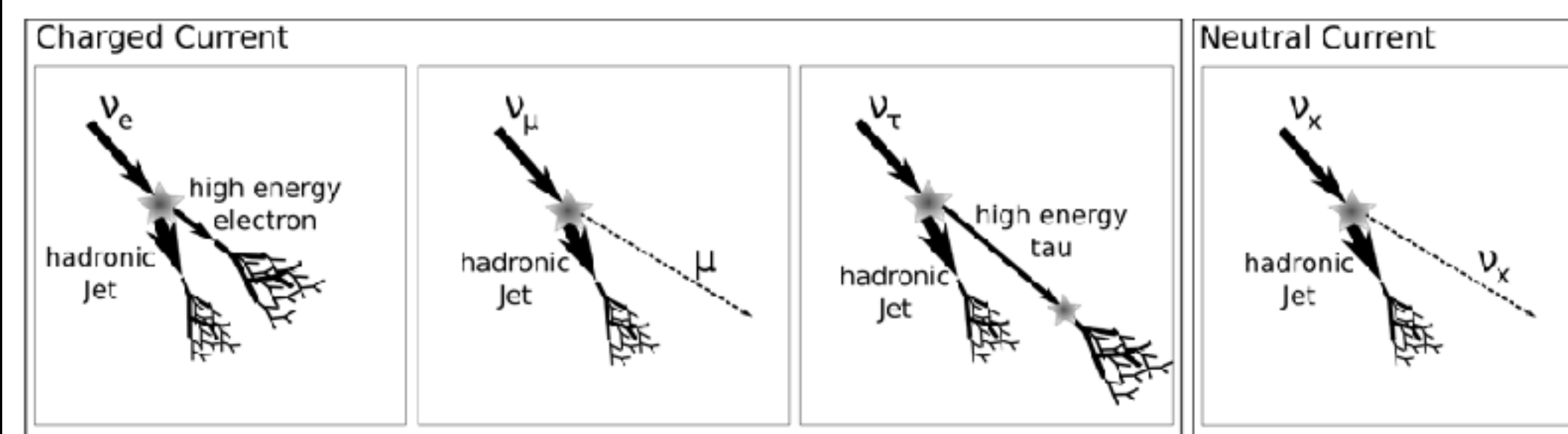


Pierre Auger JCAP 10 (2019) 022

- ◆ **Neutrinos** can initiate inclined showers close to ground
 - ➡ Shower front at ground consists of electromagnetic + muonic components
 - ➡ Large relative time delays of electromagnetic particles

Neutrino signature → inclined showers ($\theta > 60^\circ$) developing close to ground

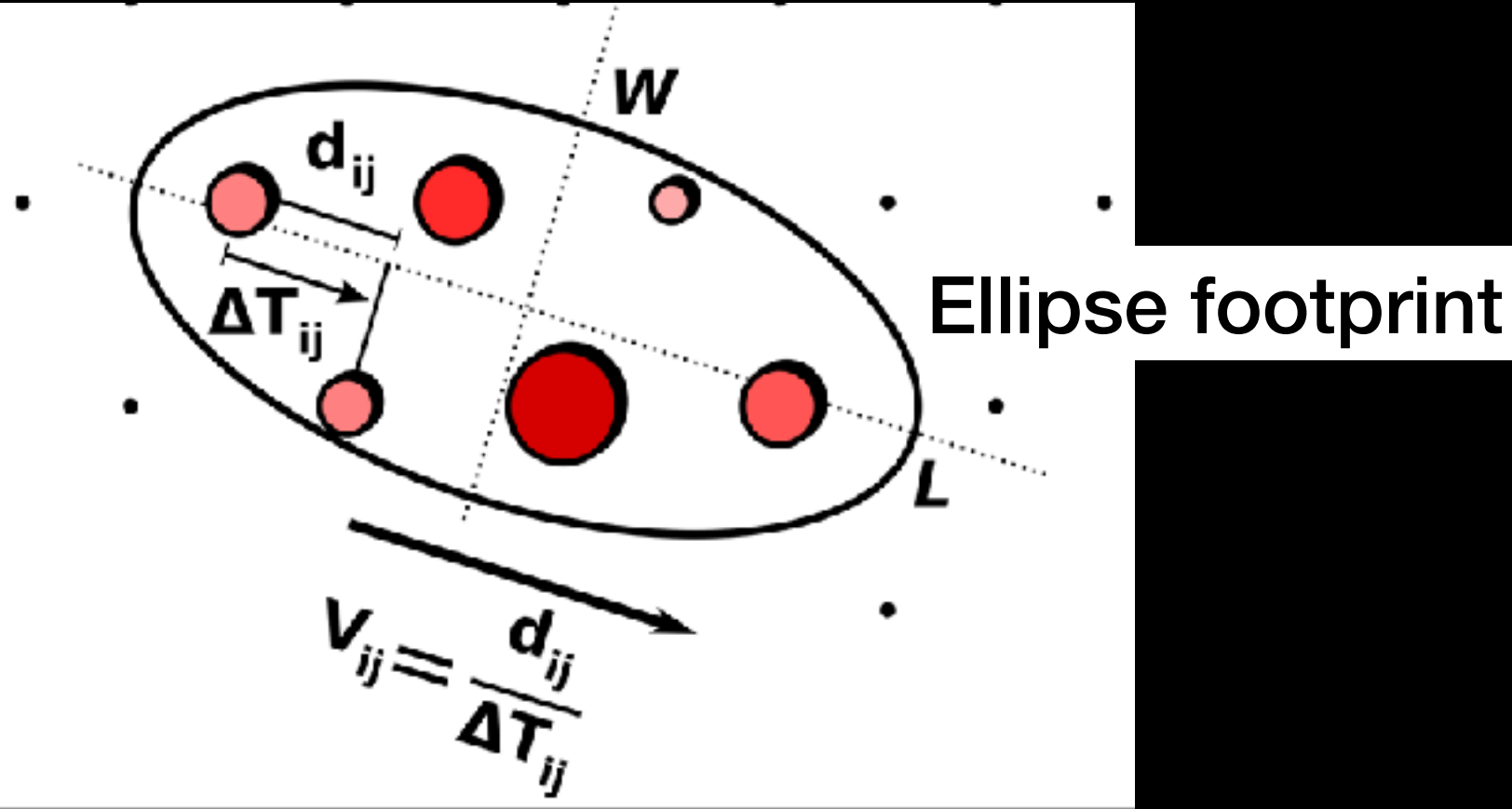
Sensitivity to all neutrino flavours & channels



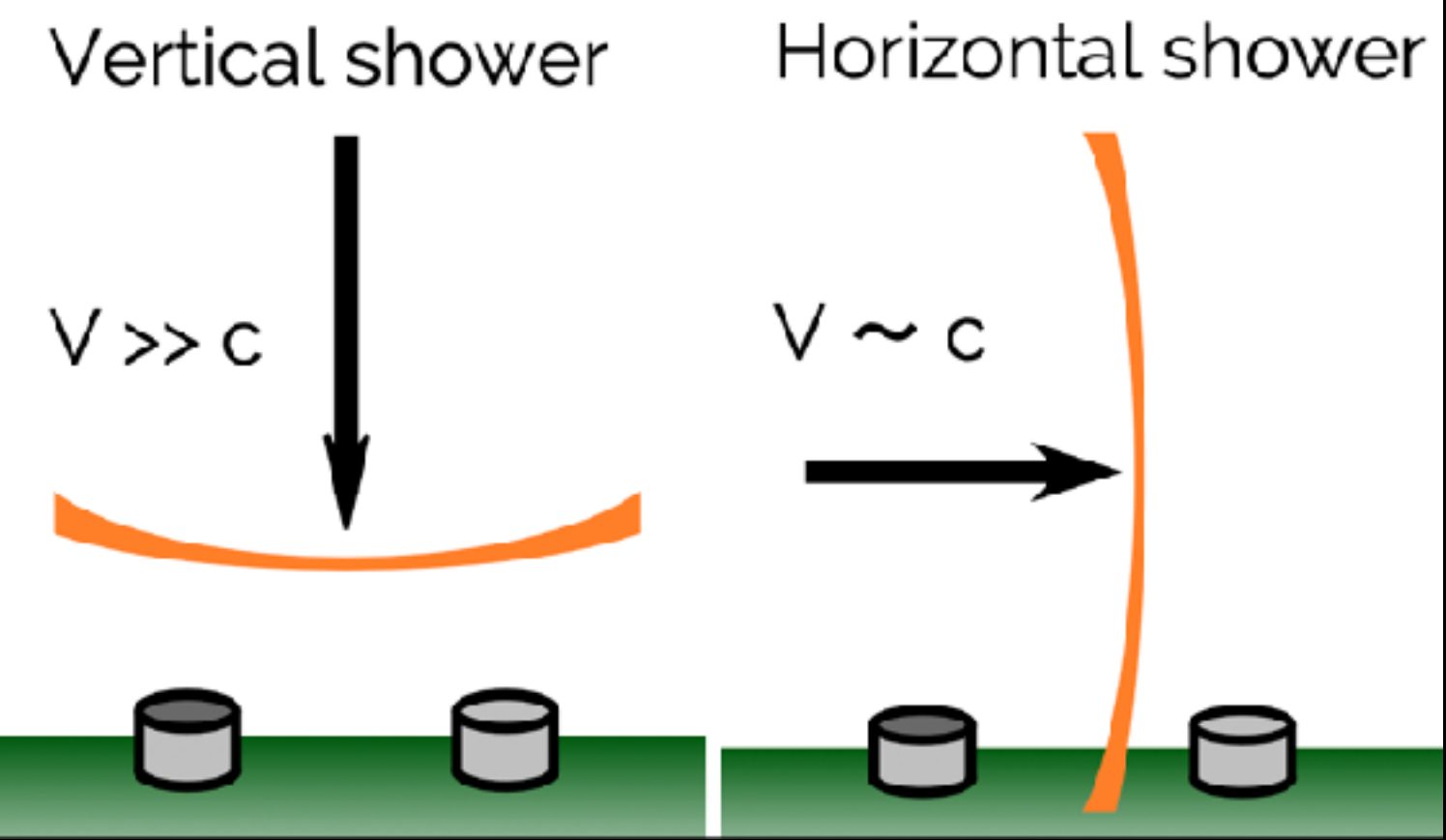
Pierre Auger Collab., PRD **91**, 092008 (2015)

Selection of inclined showers

1, Elongated footprint of shower on ground



2, Apparent velocity V of propagation of shower front at ground along major axis L

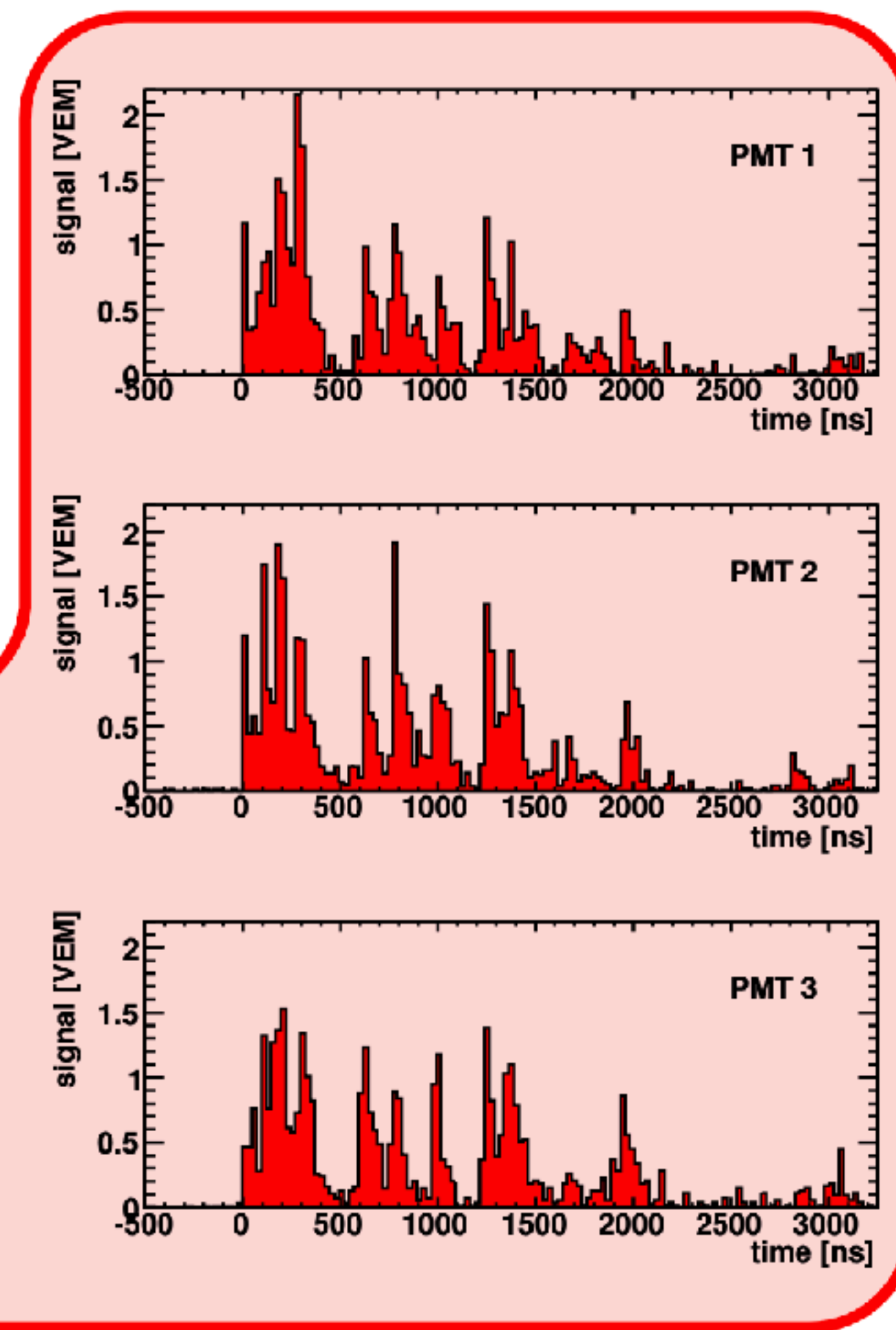
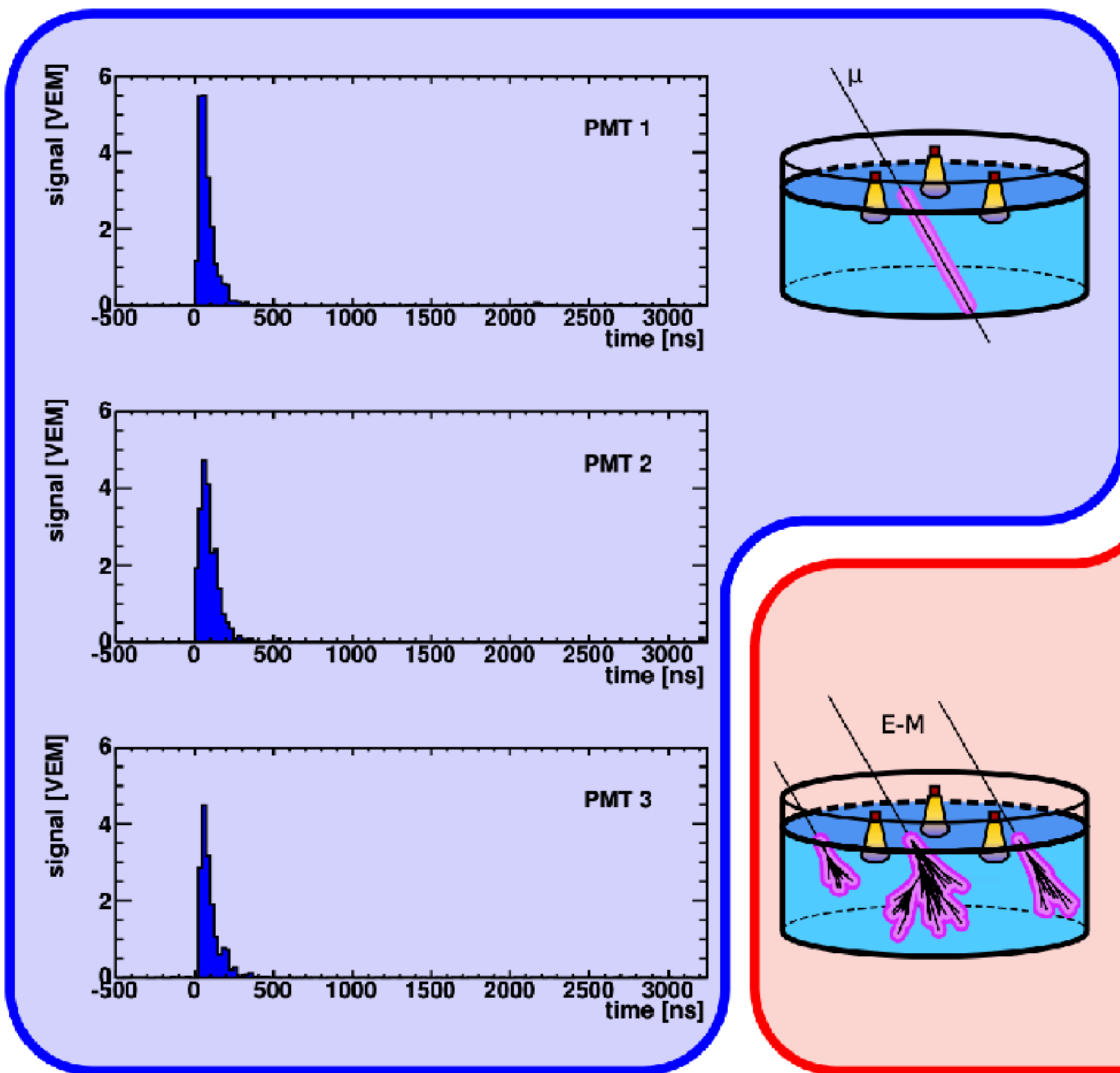


Selection	Earth-skimming (ES)	Downward-going <i>high</i> angle (DGH)	Downward-going <i>low</i> angle (DGL)
Flavours & Interactions	ν_τ CC	ν_e, ν_μ, ν_τ CC & NC	ν_e, ν_μ, ν_τ CC & NC
Angular range	$\theta > 90^\circ$	$\theta \in (75^\circ, 90^\circ)$	$\theta \in (60^\circ, 75^\circ)$
N° of Stations (N_{st})	$N_{st} \geq 3$	$N_{st} \geq 4$	$N_{st} \geq 4$
Inclined Showers	$L/W > 5$ $\langle V \rangle \in (0.29, 0.31) \text{ m ns}^{-1}$ $\text{RMS}(V) < 0.08 \text{ m ns}^{-1}$	$L/W > 3$ $\langle V \rangle < 0.313 \text{ m ns}^{-1}$ $\text{RMS}(V)/\langle V \rangle < 0.08$	— — —

Identifying neutrinos

With the SD, we can distinguish muonic from electromagnetic shower fronts (using the time structure of the signals in the water Cherenkov stations).

Muonic shower front: narrow signals



EM shower front: broad signals

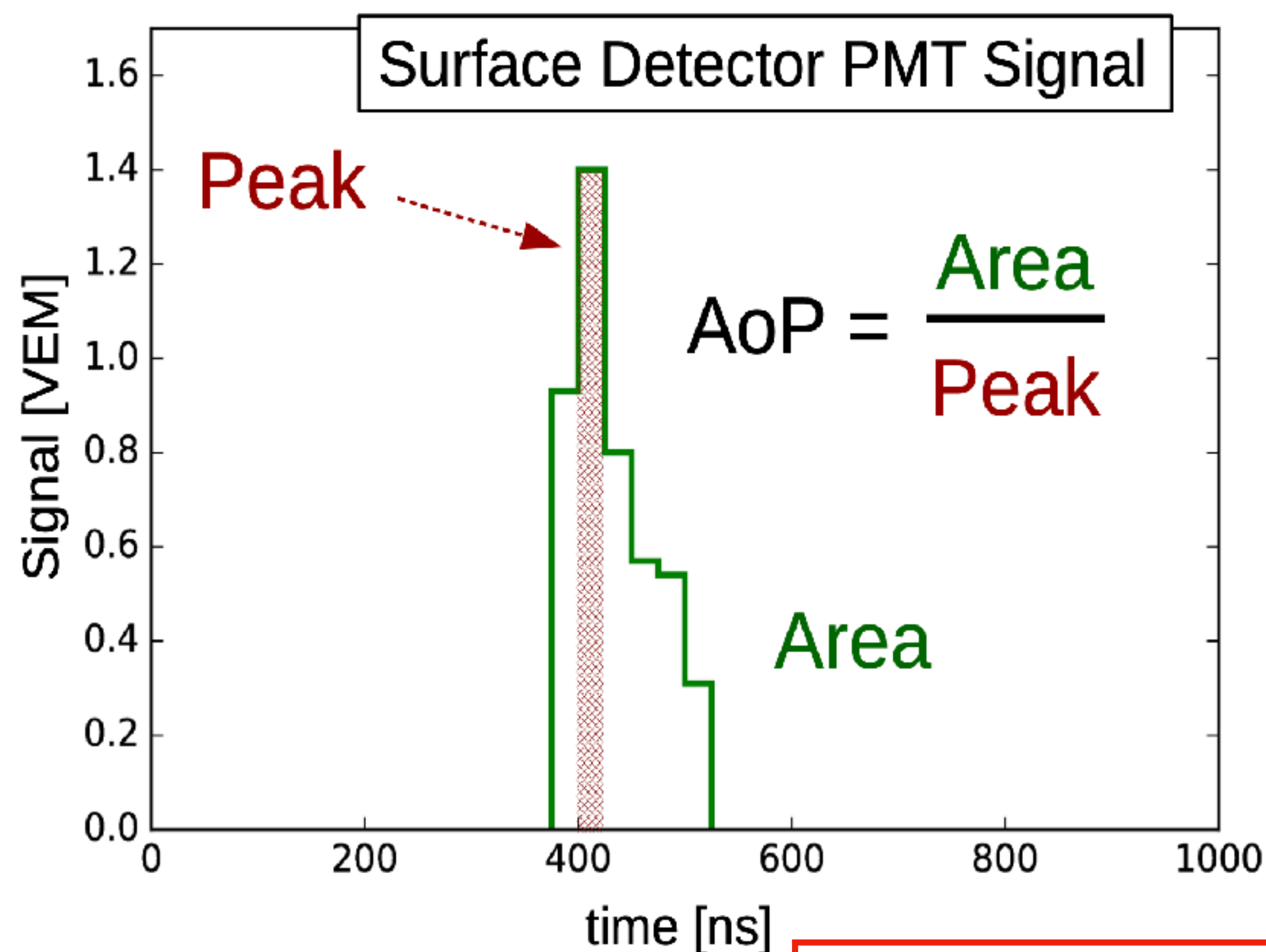
Electromagnetic component induces extended signals in time traces recorded with Water-Cherenkov detectors

Slide from Karl-Heinz Kampert

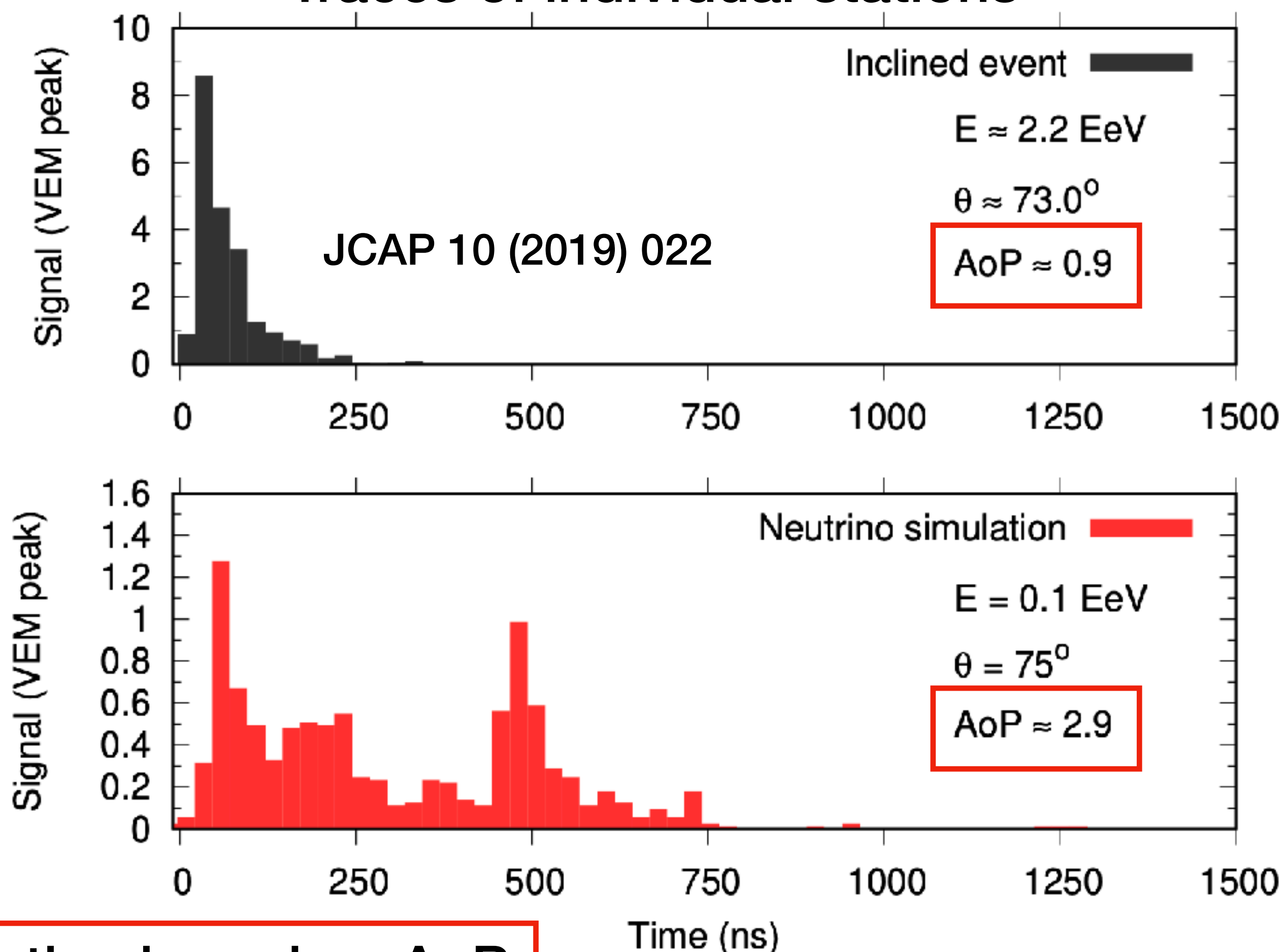
Identifying neutrinos

➔ **Signal traces with large values of Area-over-Peak (AoP)**

Definition of Area-over-Peak (AoP)

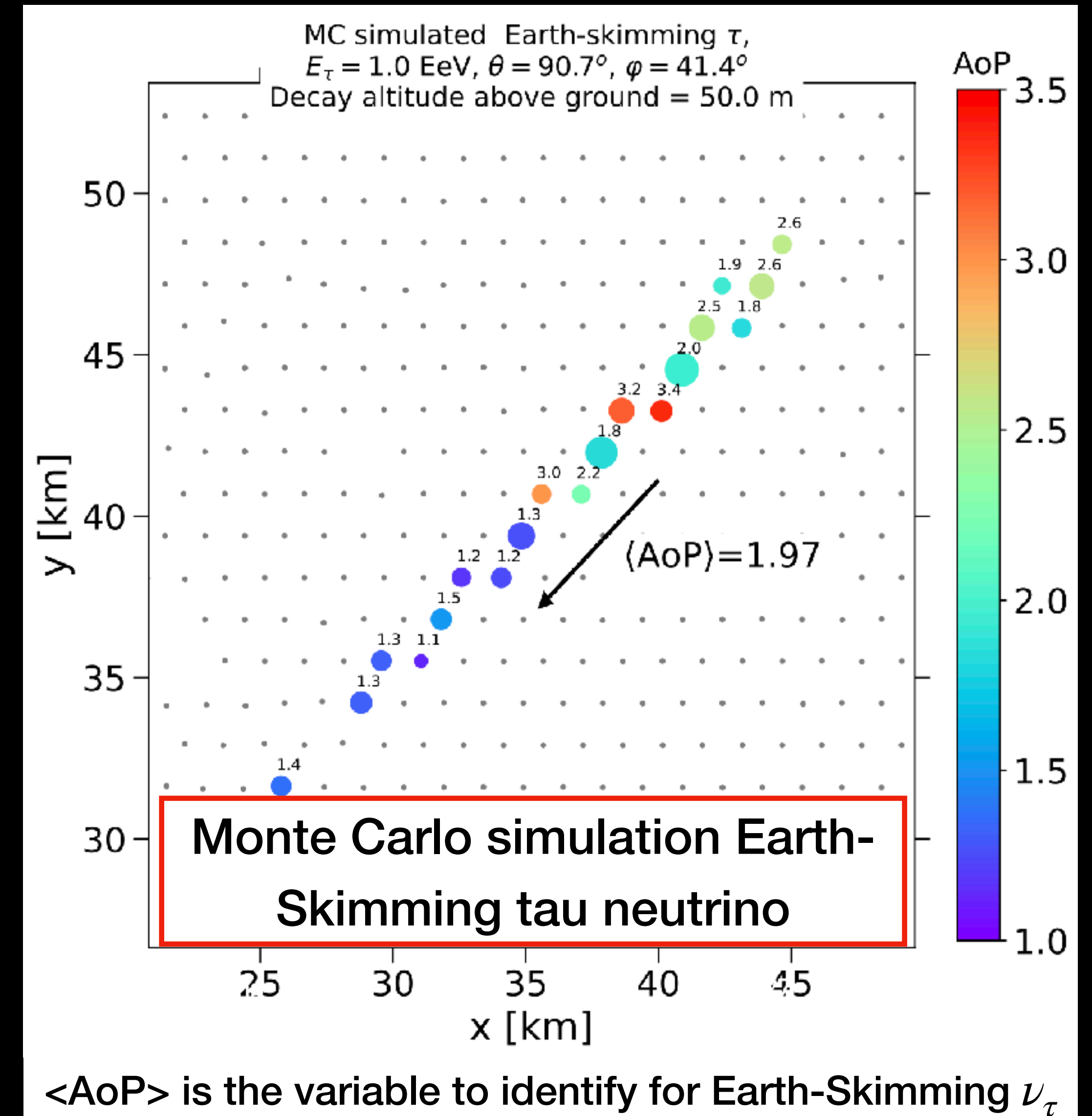
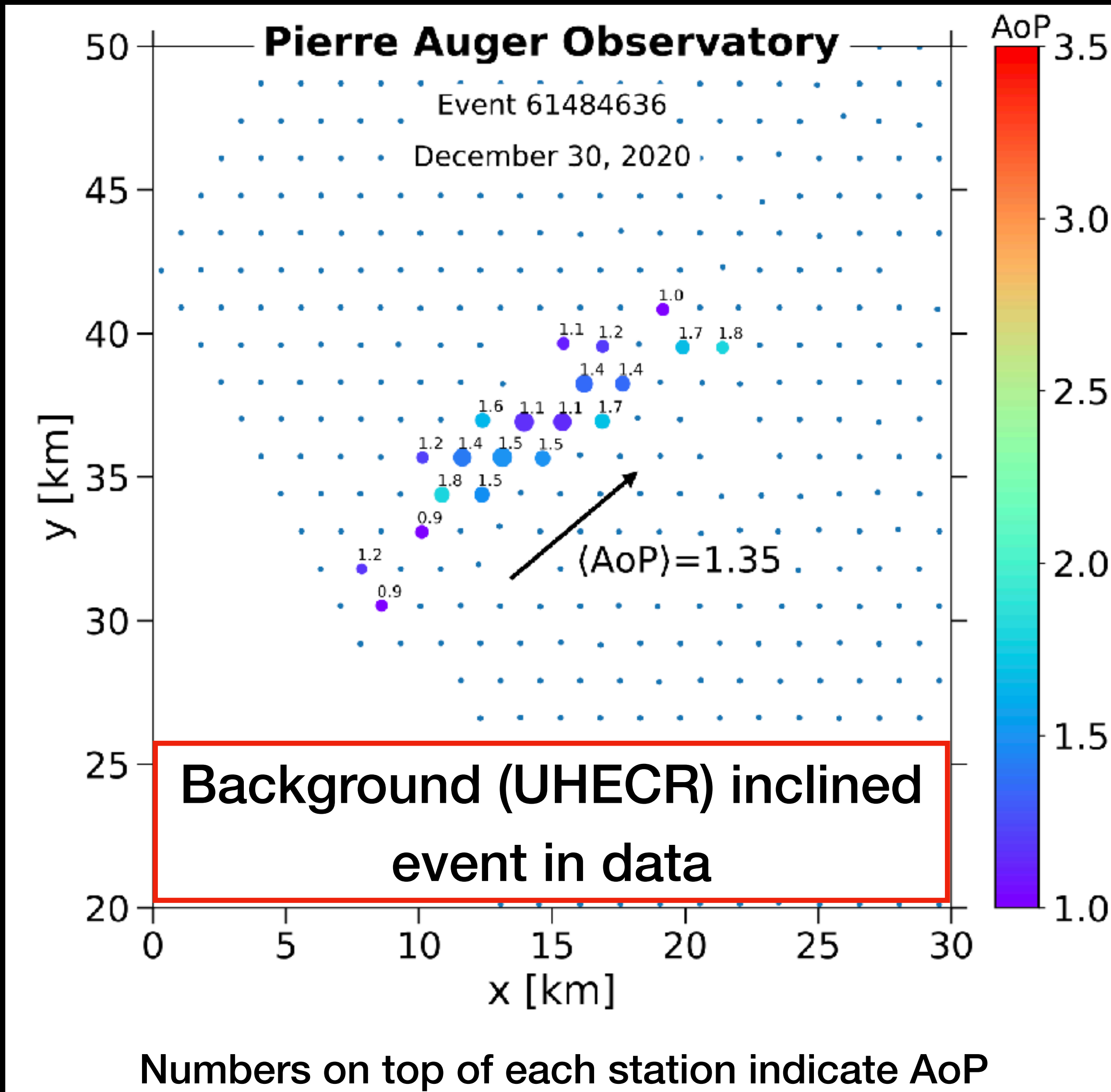


Traces of individual stations

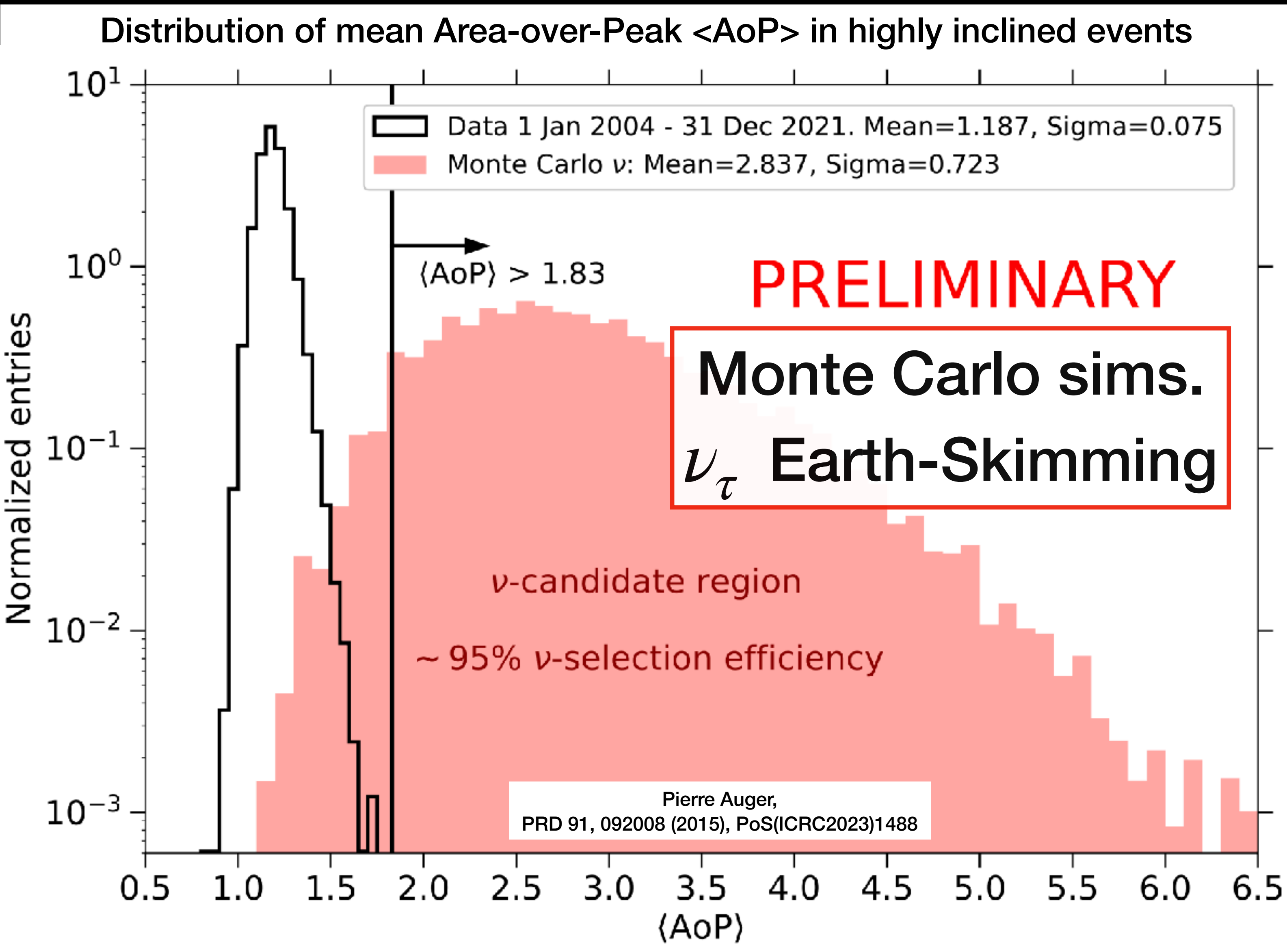


Neutrino identification based on AoP

Identifying neutrinos



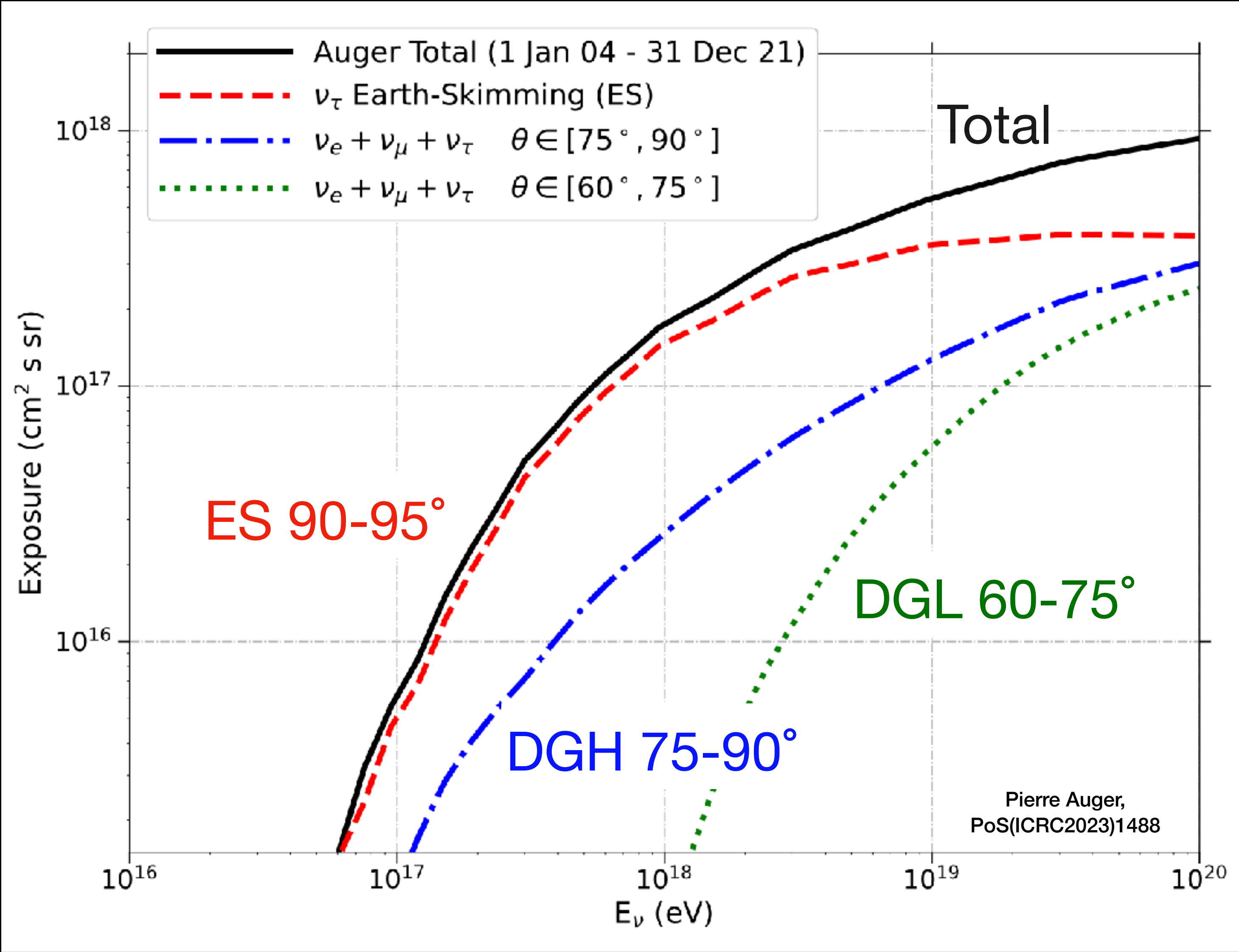
Data unblinding example: Earth-Skimming channel



**No candidates found in
Earth-Skimming or
Downward-going channels
1 Jan 2024 - 31 Dec 2021**

- ◆ Large neutrino selection efficiency
- ◆ Low expected background 1/50 yr
- ◆ Sensitivity limited by exposure not limited by background

Exposure (1 Jan 2004 – 31 Dec 2021)

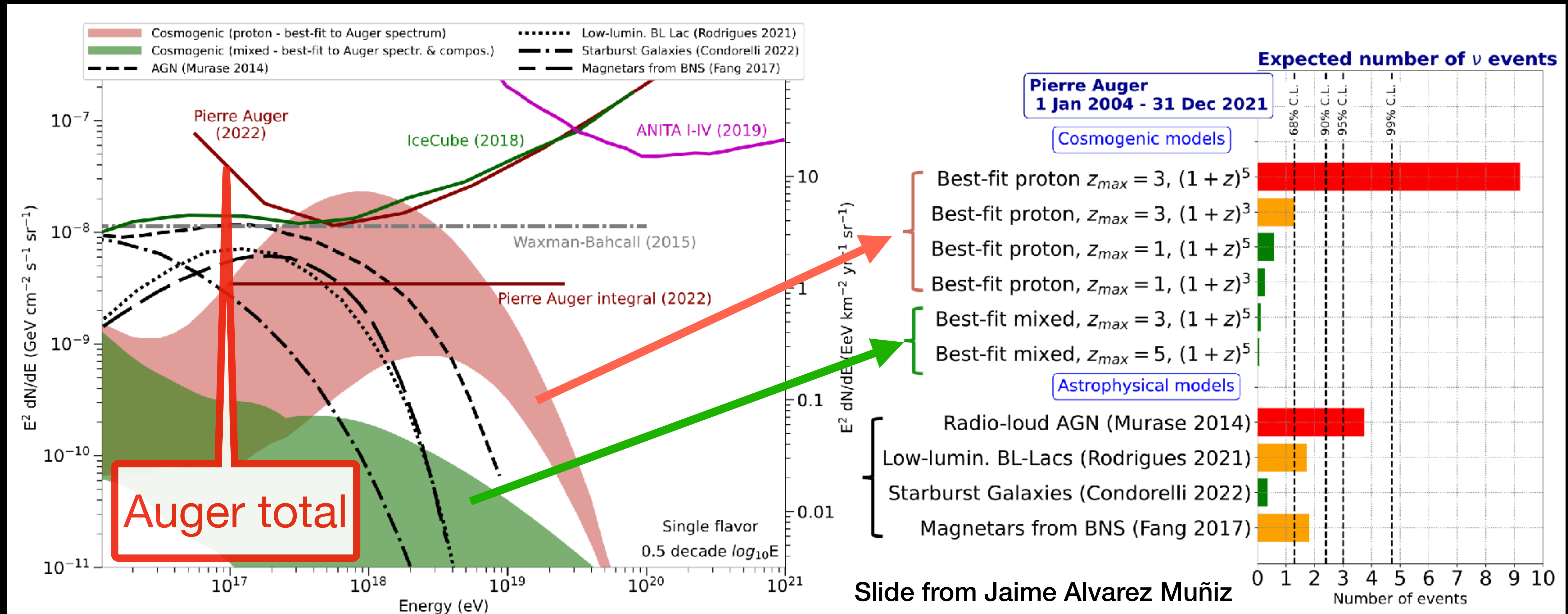


Neutrino flavor	Fractional contribution to event rate (E^{-2} flux)
ν_e	10 %
ν_μ	4 %
ν_τ	86 %

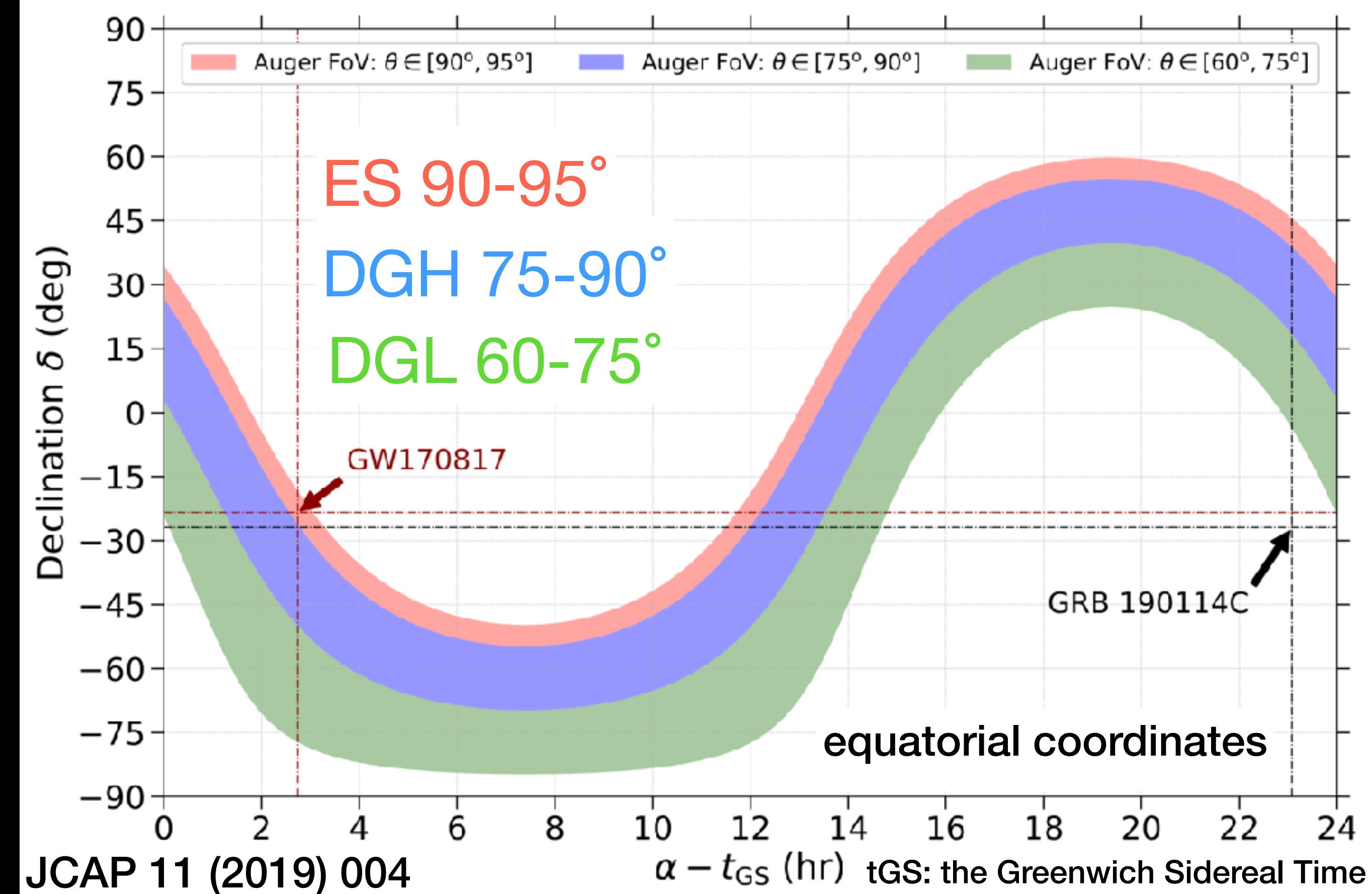
Upper limits to diffuse flux and event predictions

1 Jan 2004 – 31 Dec 2021

- ✦ Best sensitivity slightly below 1 EeV
- ✦ Auger limits constrain models assuming pure proton primary cosmic beam

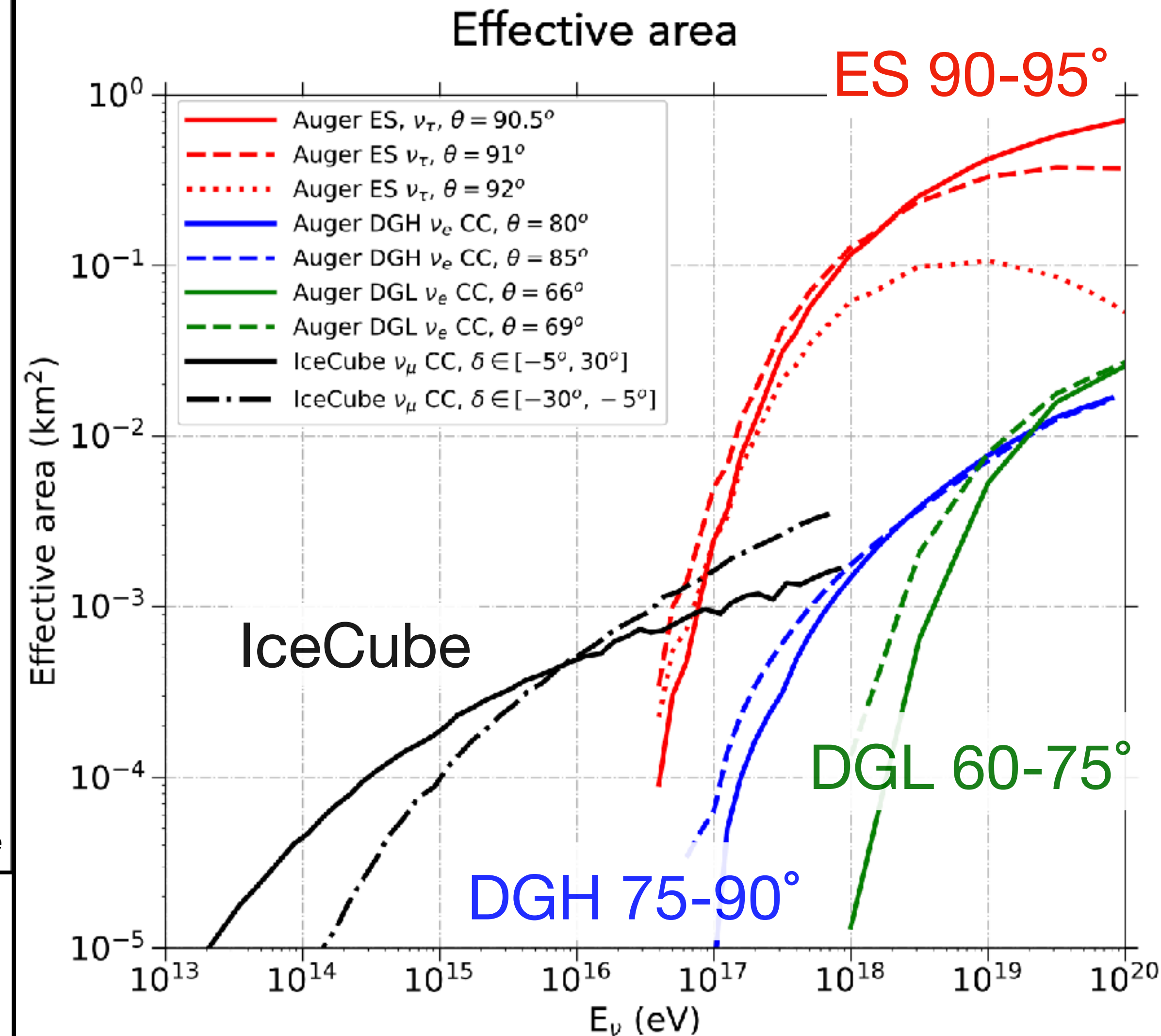


Search for point-like transient sources of UHE ν



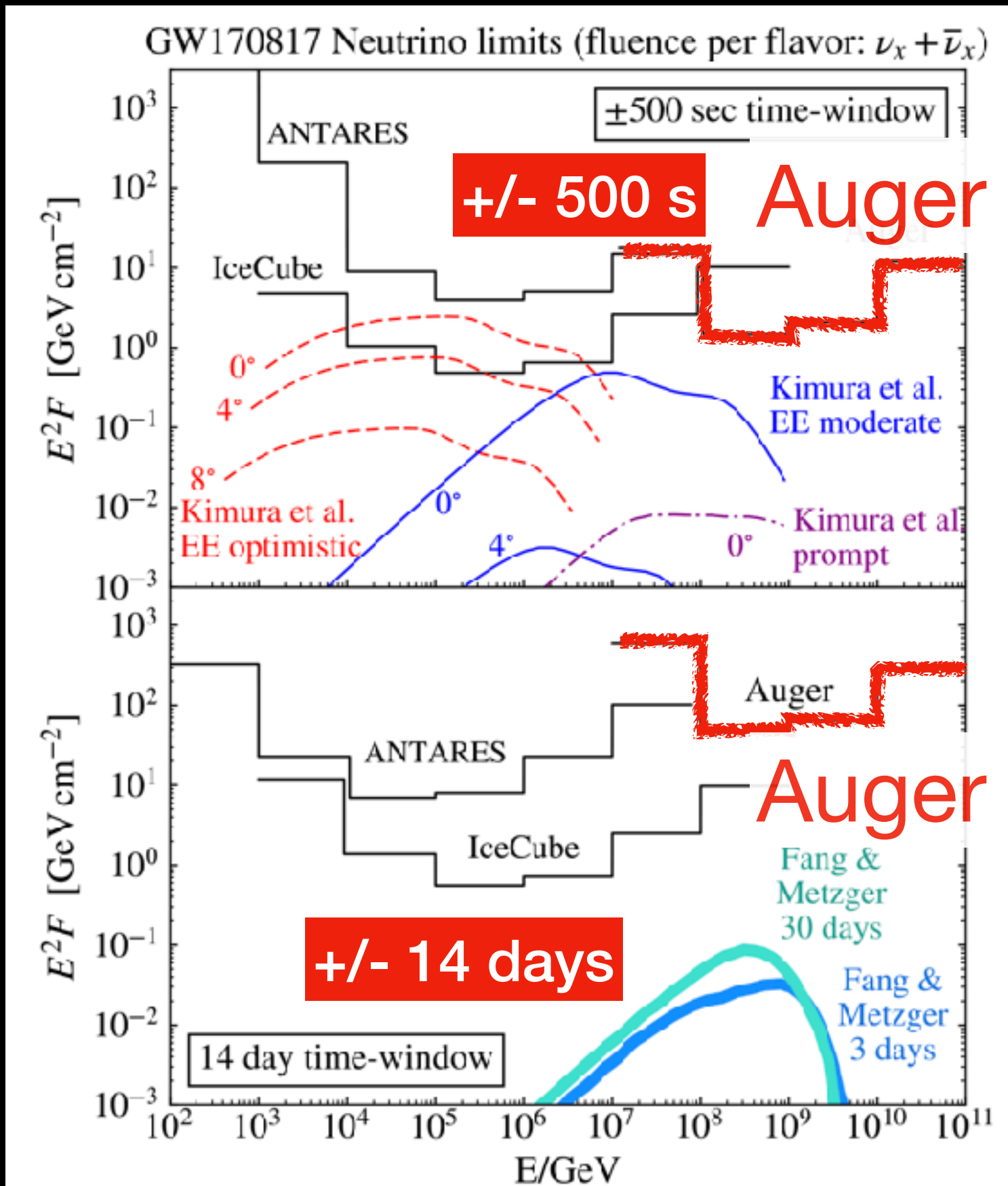
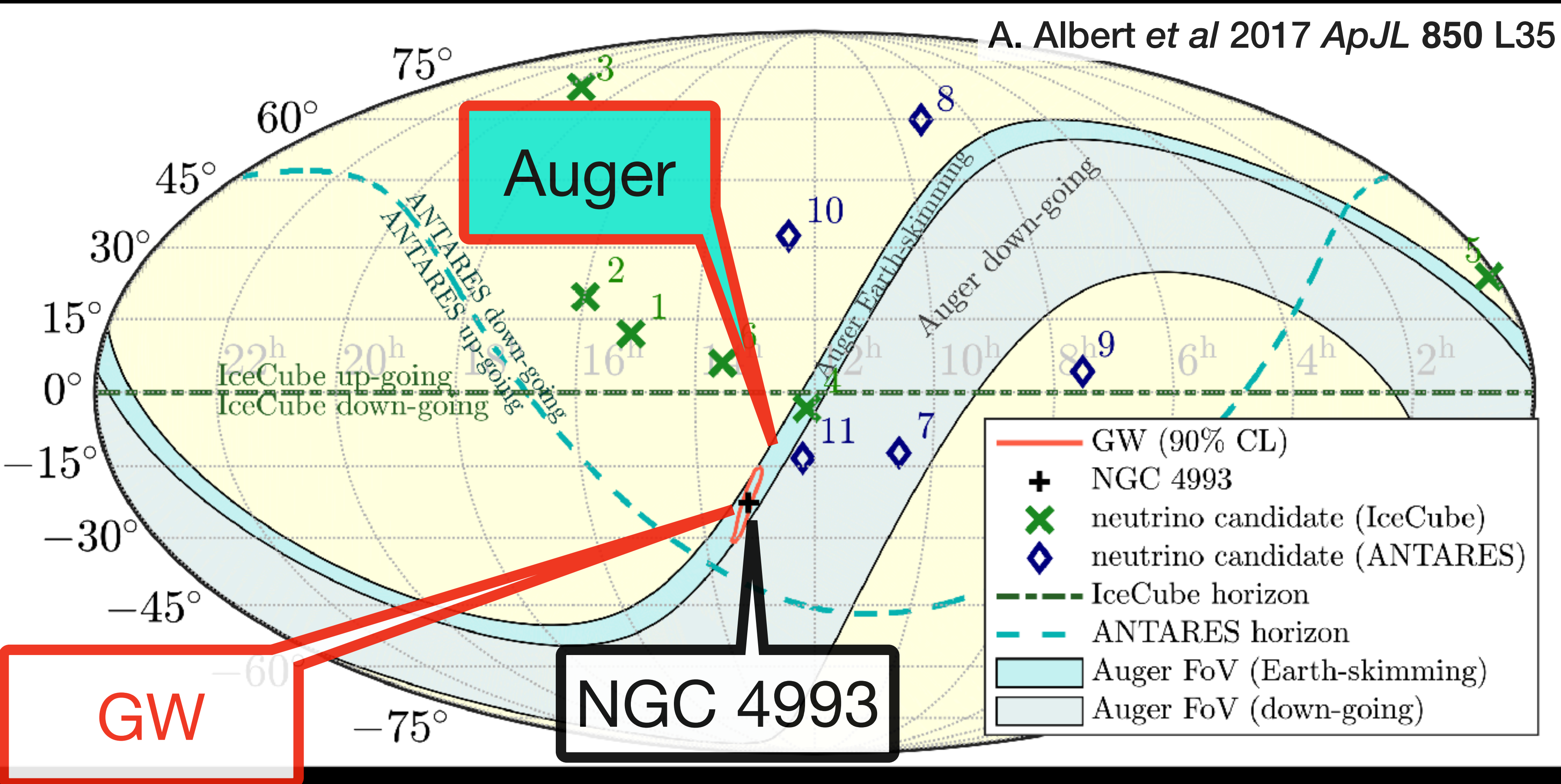
Instantaneous field-of-view covers ~30% of the sky: Earth-Skimming (5%) + Donward-going (25%)

Auger is sensitive to potential sources of UHE neutrinos between close to South Celestial Pole to + 60 deg North => there is always a time window during a sidereal day in which source is in FoV



Large peak effective areas, close to 1 km²

Follow-up of GW170817 in neutrinos Binary Neutron Star Merger + short GRB



✦ The NS-NS merger was in an optimal position at the instant of GW emission for the detection of UHE tau neutrinos with Auger

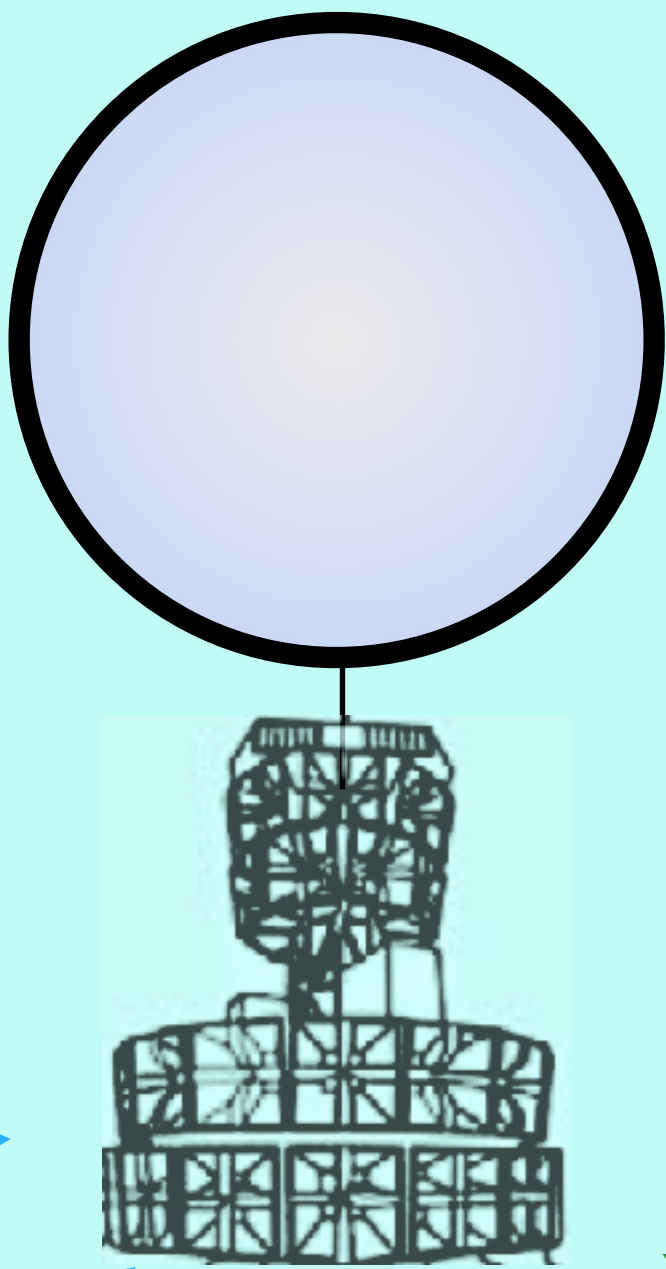
✦ Lack of neutrino detection consistent with expectations from the associated short GRB viewed at large off-axis angle $\gtrsim 20^\circ$

3, Search for up-going showers

Abnormal up-going showers in ANITA

The Antarctic Impulsive
Transient Antenna (ANITA)

- ◆ Neutrino will be absorbed in these directions
- ◆ BSM particles?



	Energy (EeV)	θ (degree)	Day
ANITA-I	0.6	117.4	17
ANITA-III	0.56	125	7

~35 km altitudes

UHECR

Polarity inversion

South Pole: ice

ANITA-III

PRL 121, 161102 (2018)

Propagation length 6000–7000 km

ANITA-I

PRL 117, 071101 (2016)

Test of ANITA observations by Auger FD

Surface Detector (SD)



Test of ANITA observations by Auger FD

Up-going (UG)

Surface Detector (SD)

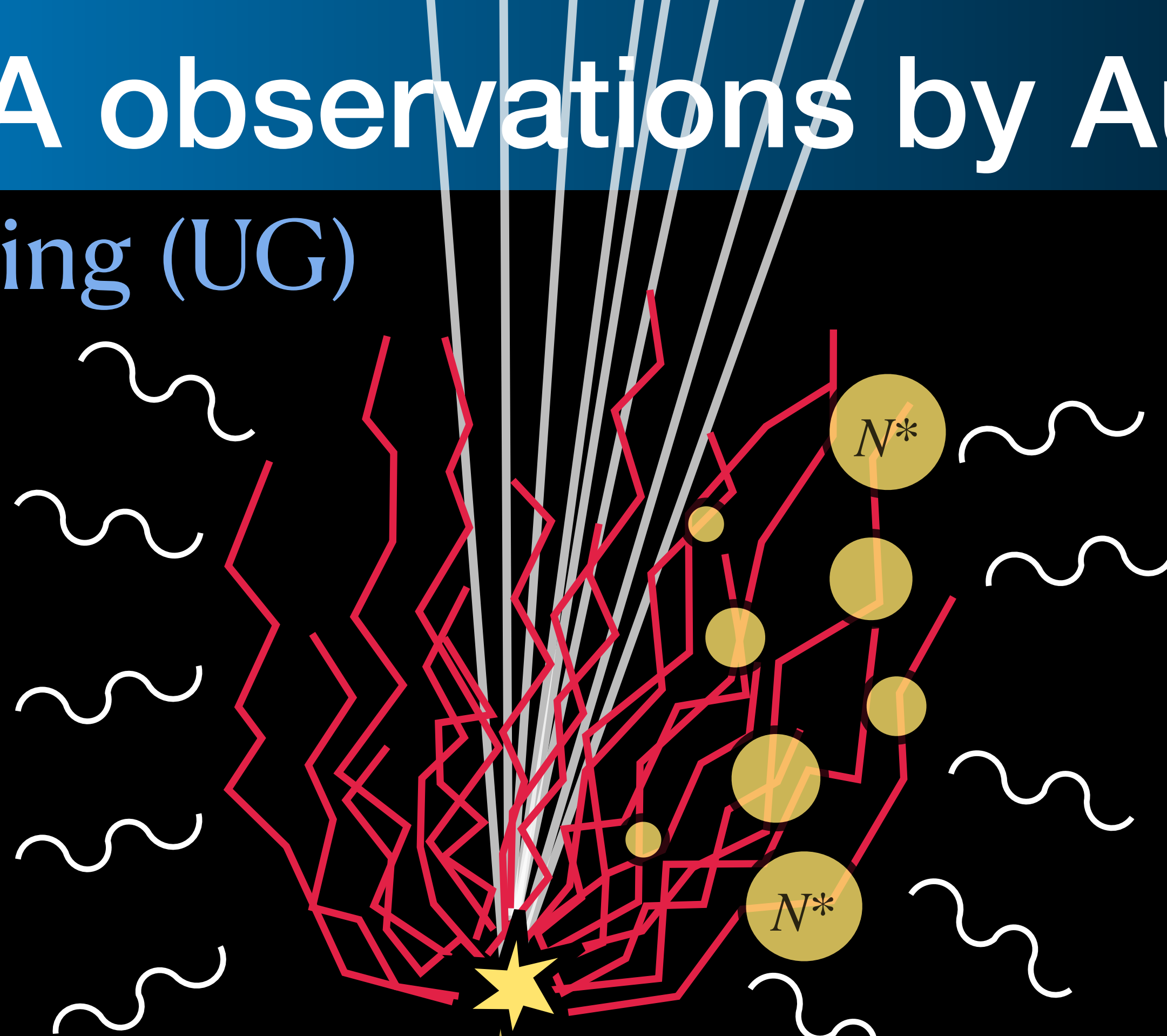


Test of ANITA observations by Auger FD

Up-going (UG)

UV band

Surface Detector (SD)



Test of ANITA observations by Auger FD

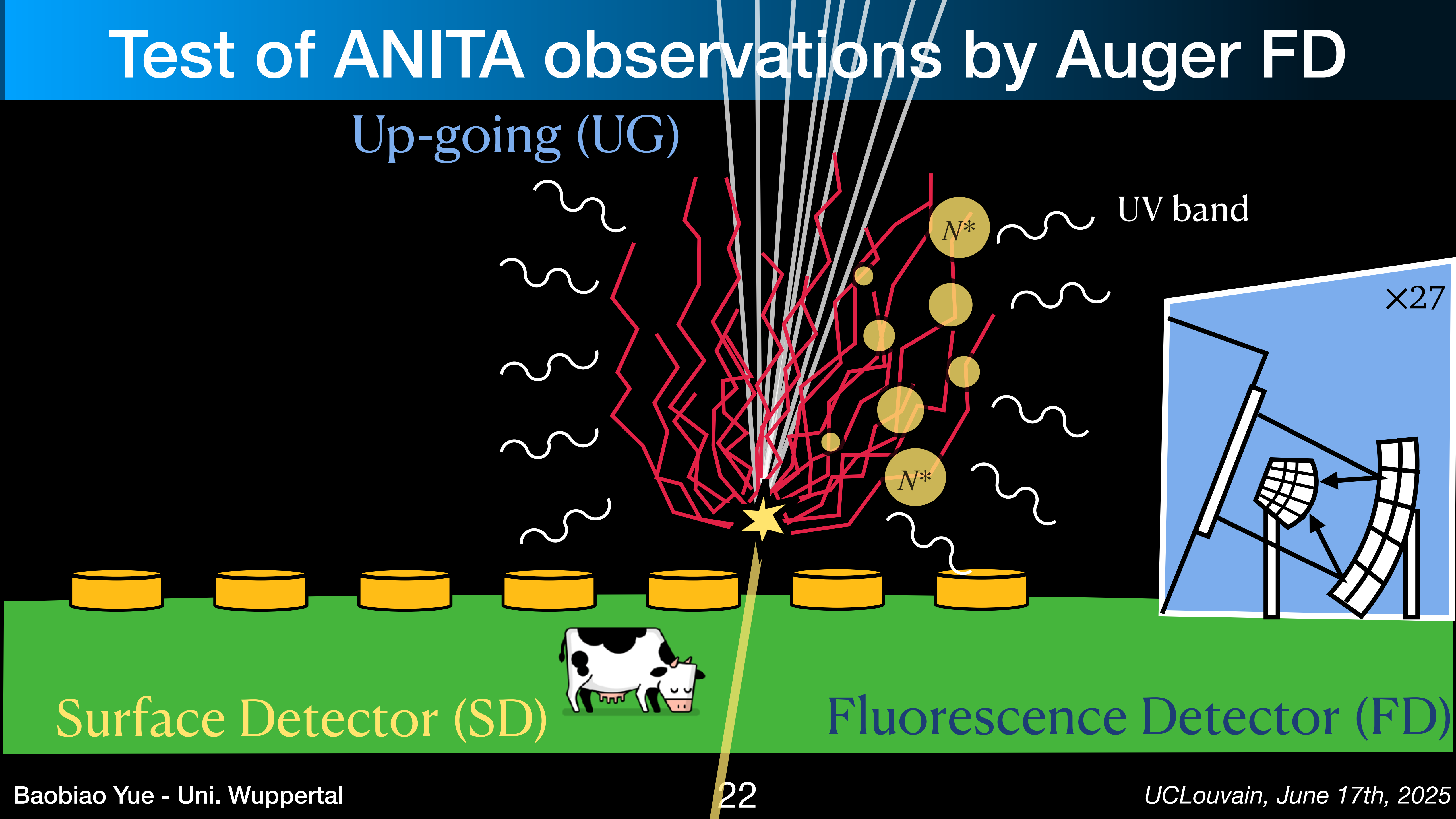
Up-going (UG)

UV band

Surface Detector (SD)

Fluorescence Detector (FD)

x27



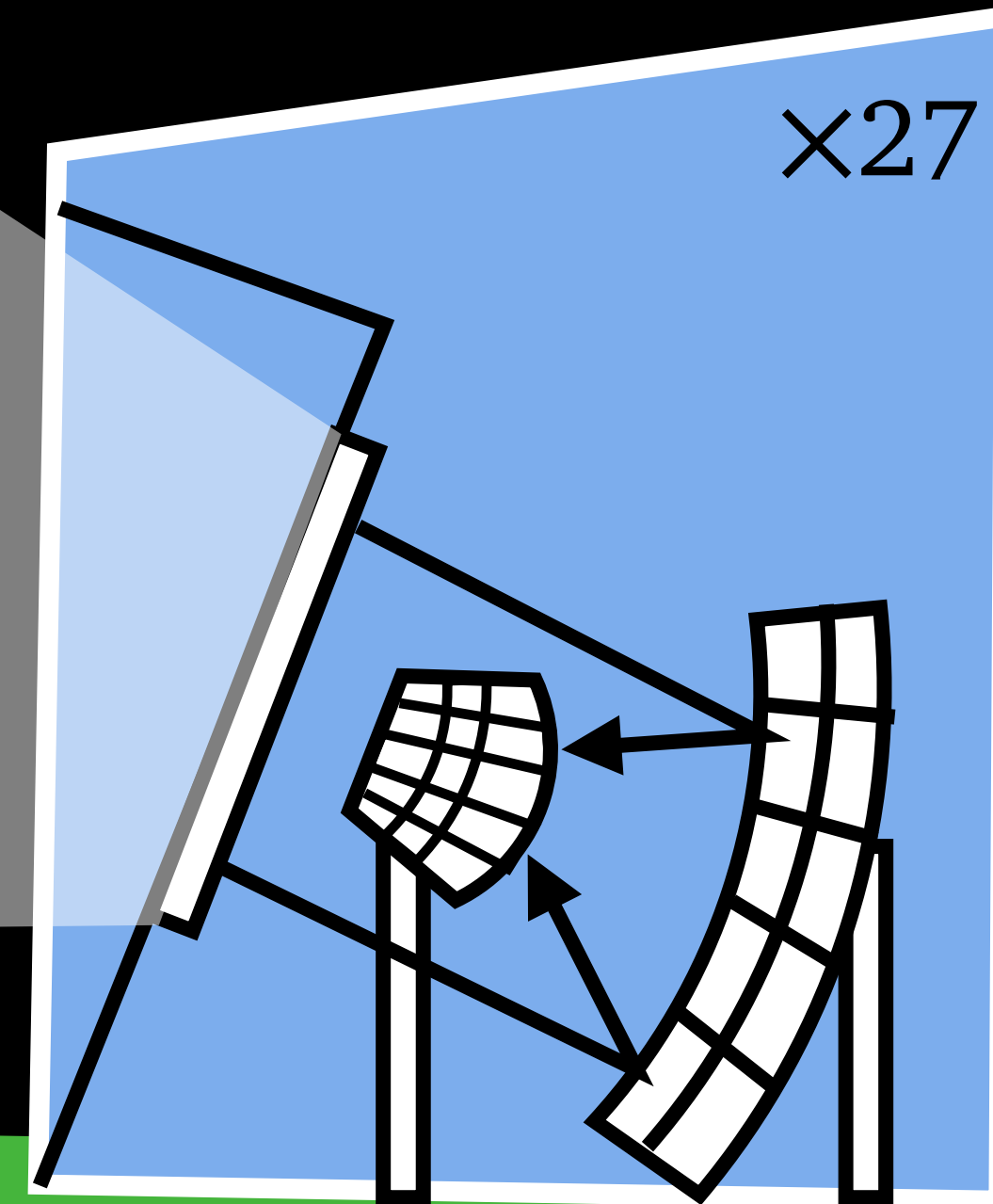
Test of ANITA observations by Auger FD

Up-going (UG)

UV band

Surface Detector (SD)

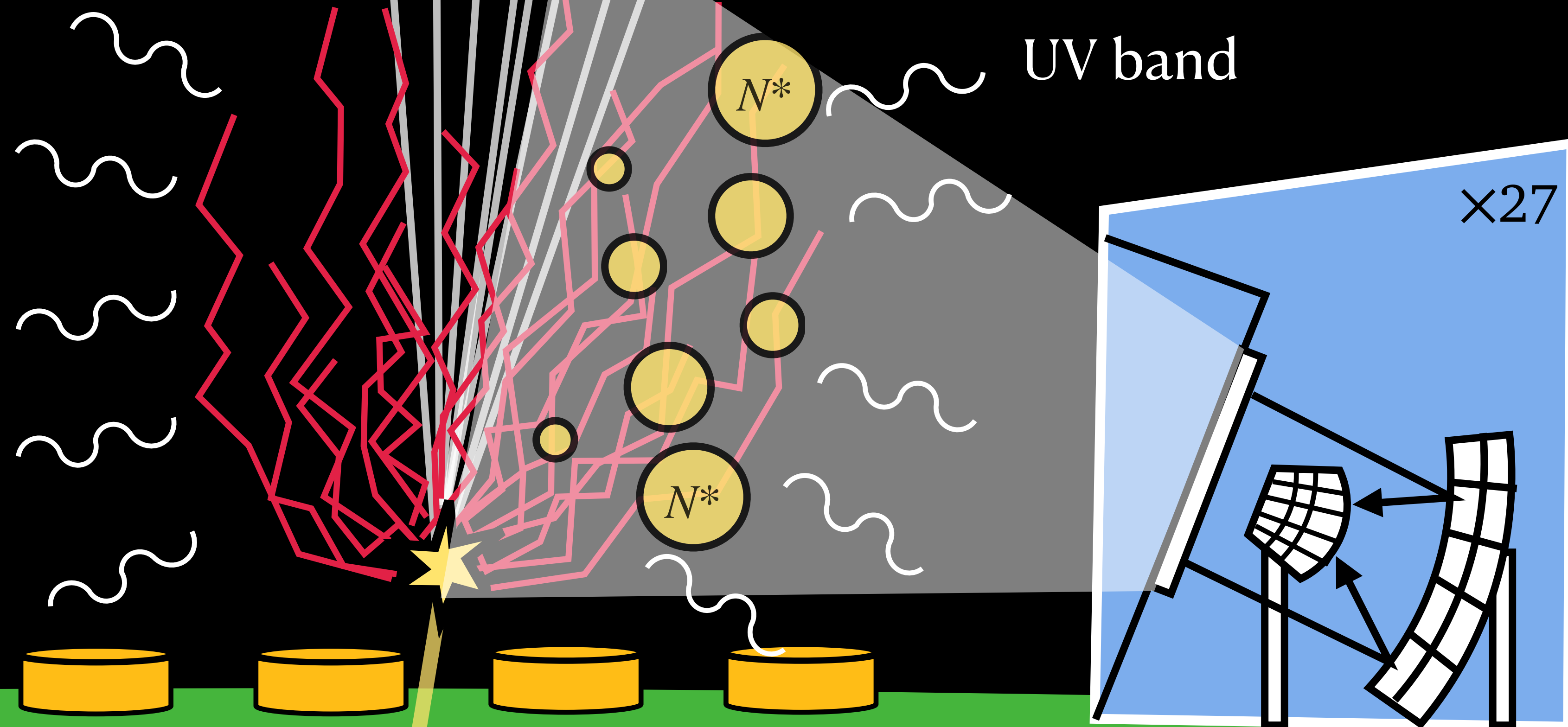
Fluorescence Detector (FD)



Test of ANITA observations by Auger FD

Up-going (UG)

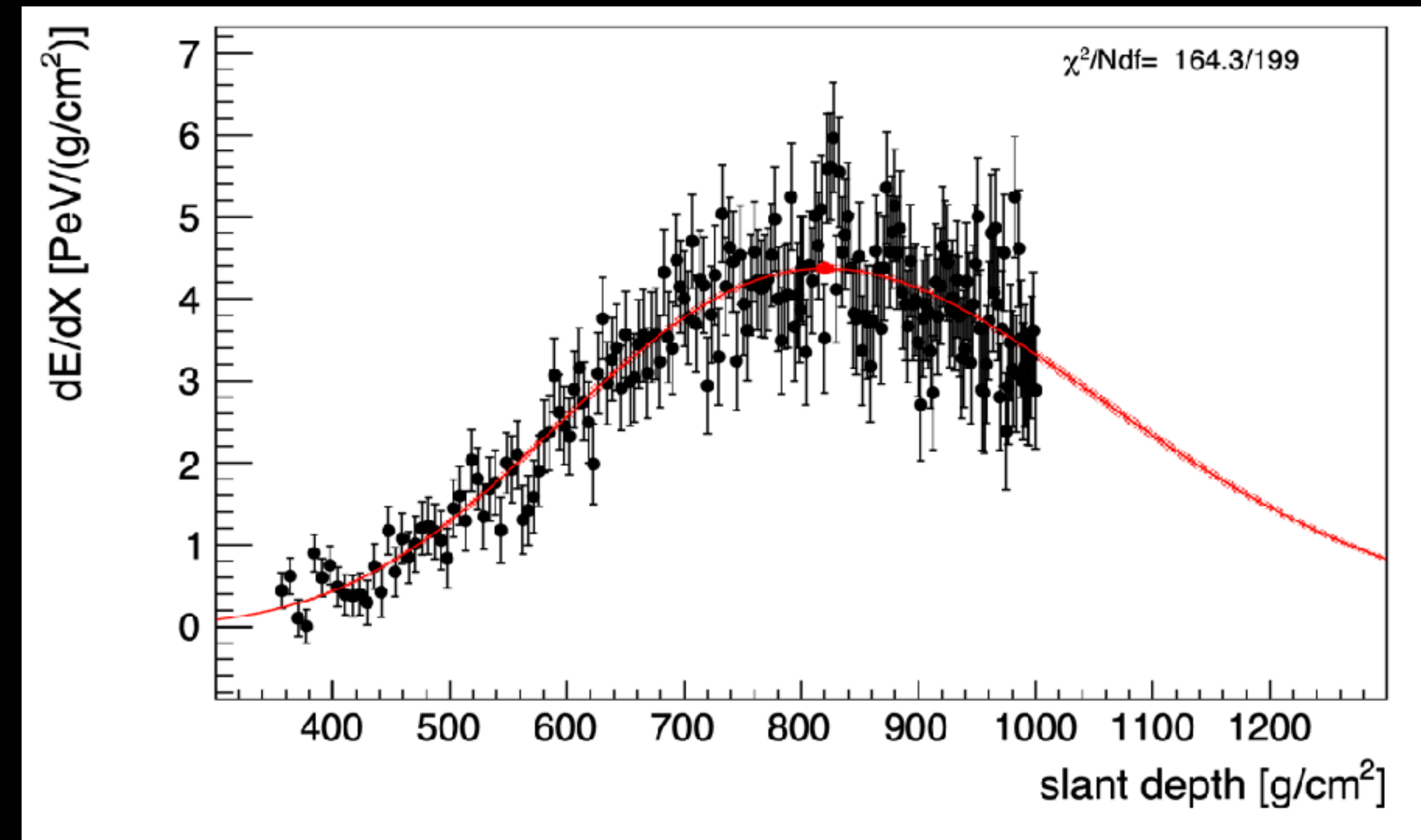
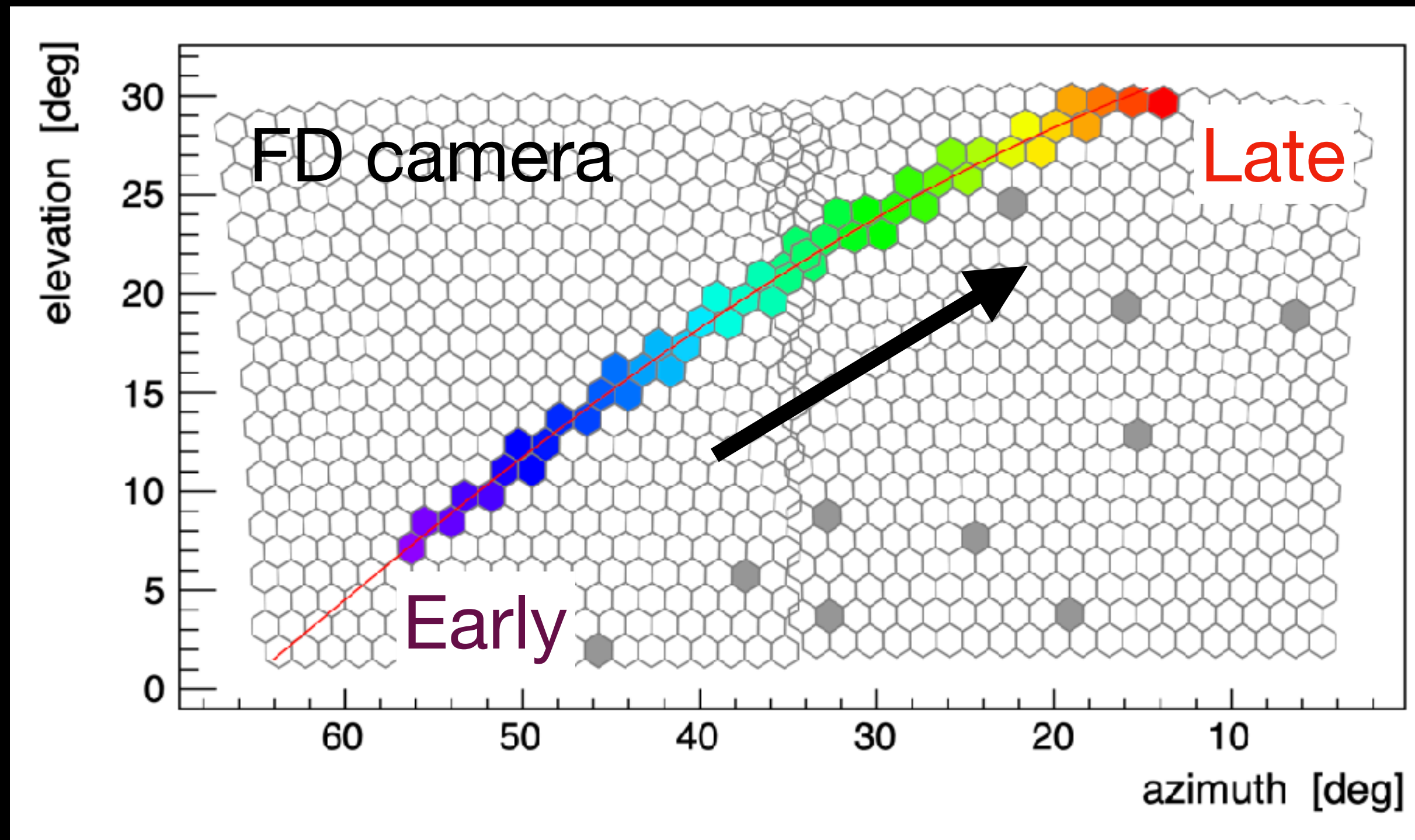
- ♦ Auger FD is sensitive to up-going air showers
- ♦ ANITA did not provide (publish) exposure for the detected events
- ♦ **Flux of up-going events was not known**
- ♦ collaborated with ANITA to calculate it



Surface Detector (SD)

Fluorescence Detector (FD)

Signal: Upward-going Monte Carlo event



$$E = 3 \text{ EeV}, \theta = 114.2, X_{max} = 844 \text{ g/cm}^2$$

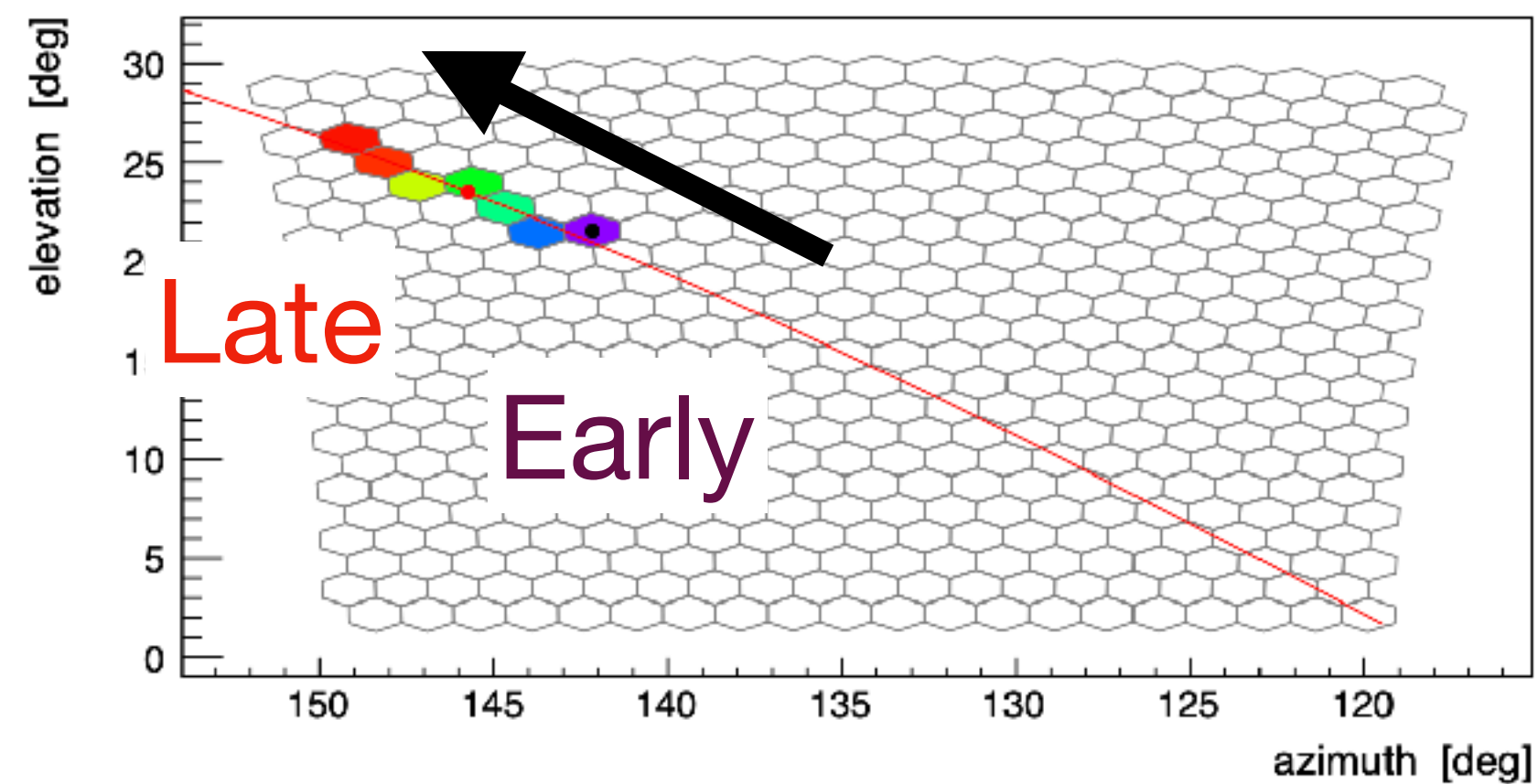
Main challenge of analysis:

- ♣ In **absence** of any signal from the **Surface Detector**, i.e. using only the time sequence and profile:
 - ➡ UHECR downward-going events with specific geometries, can be reconstructed as up-going => background
 - ➡ some events even admit an upward- and downward-going reconstruction simultaneously

Background

Potential background real event

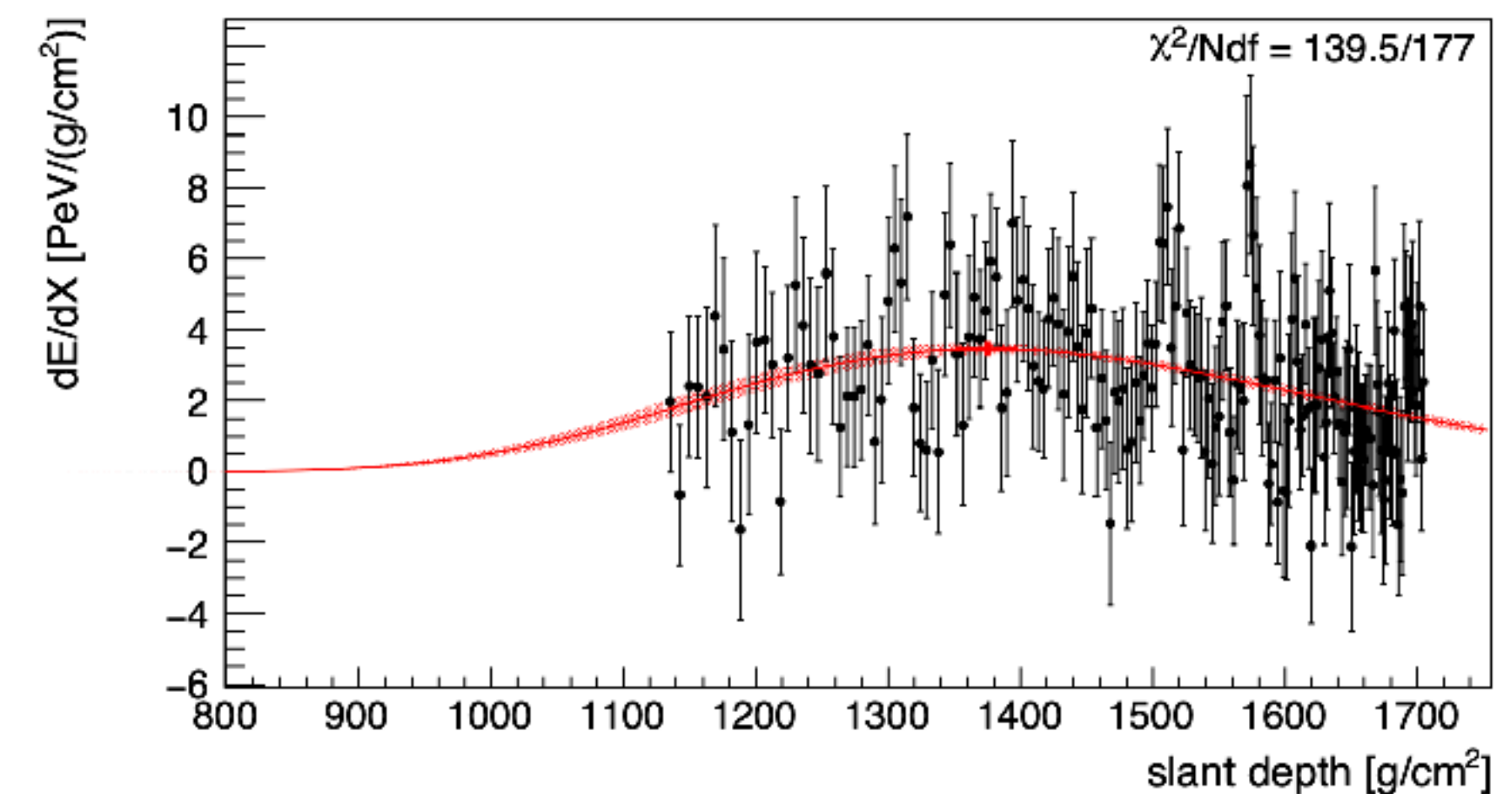
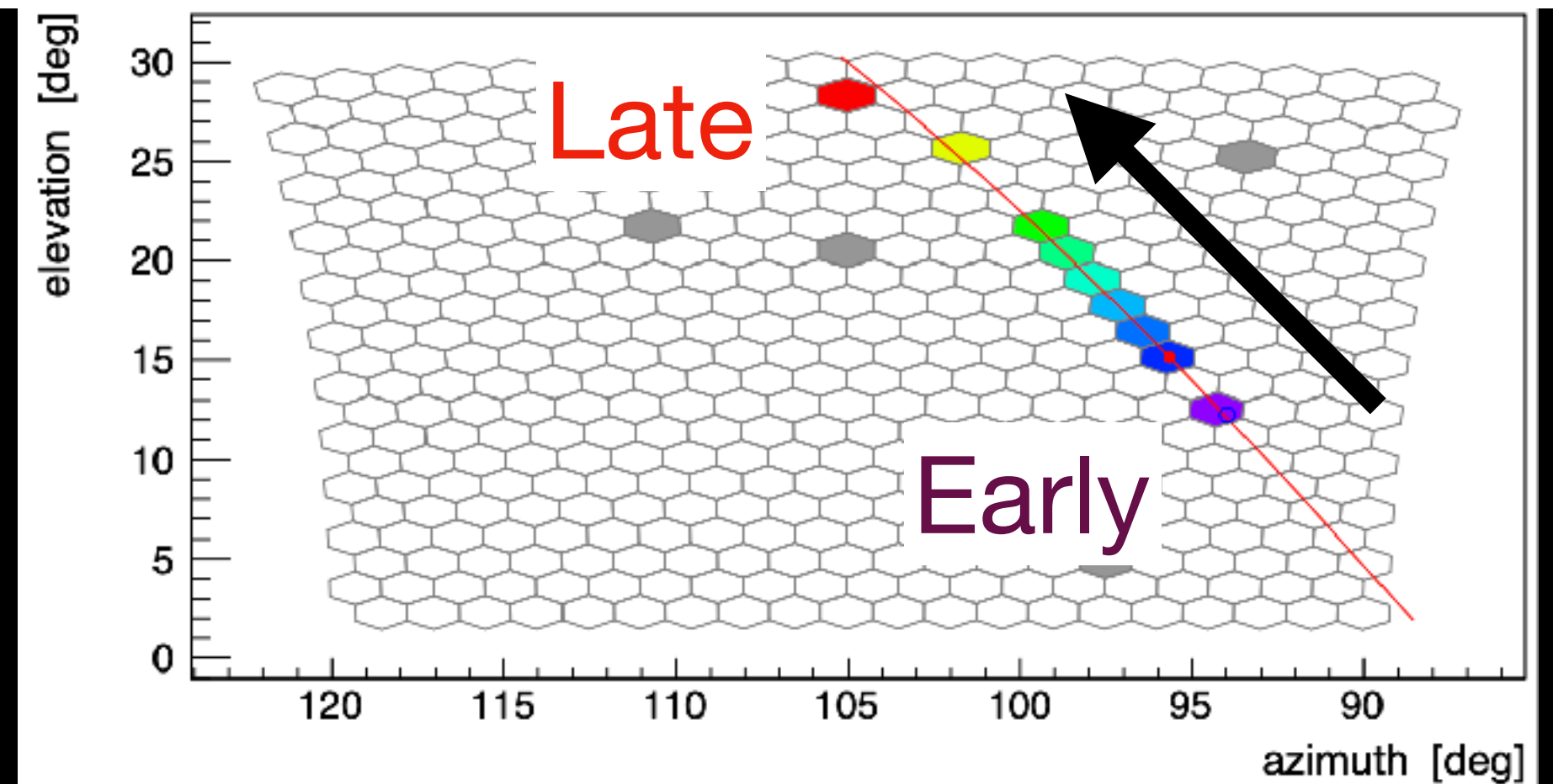
Reconstructed downward-going event with core falling outside array



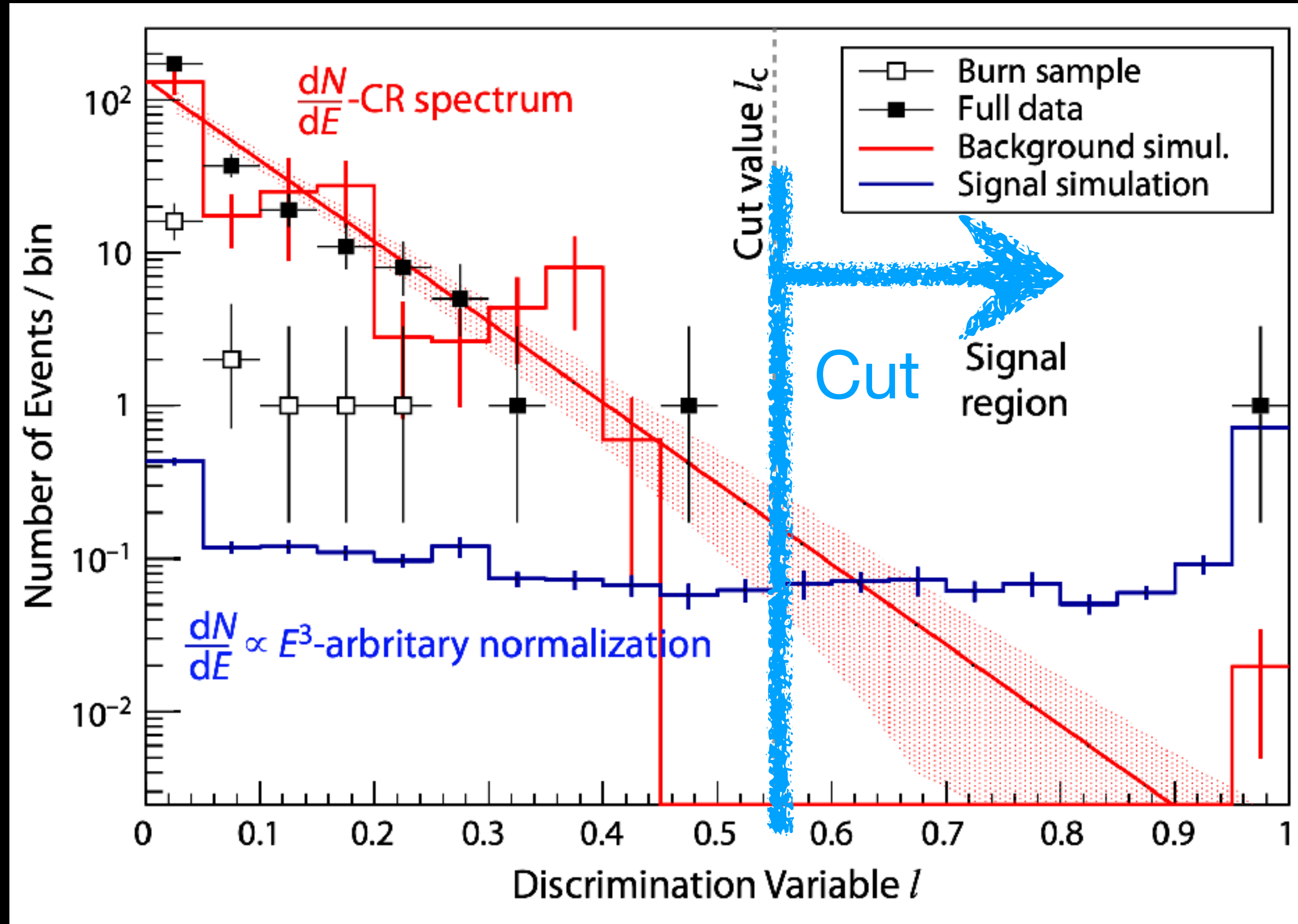
Shower core
behind telescope

Background Monte Carlo event

Quasi-horizontal event $\theta_{MC} = 89.6^\circ$ reconstructed as up-going $\theta_{rec} = 116.6^\circ$

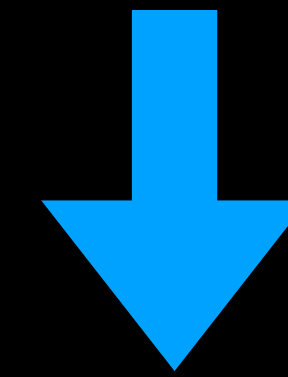


Discriminating upward-going showers



After all cuts to reject background

some events admit both upward- & downward-going reconstructions



Discrimination based on ratio of maximum likelihood of upward & downward reconstructions

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

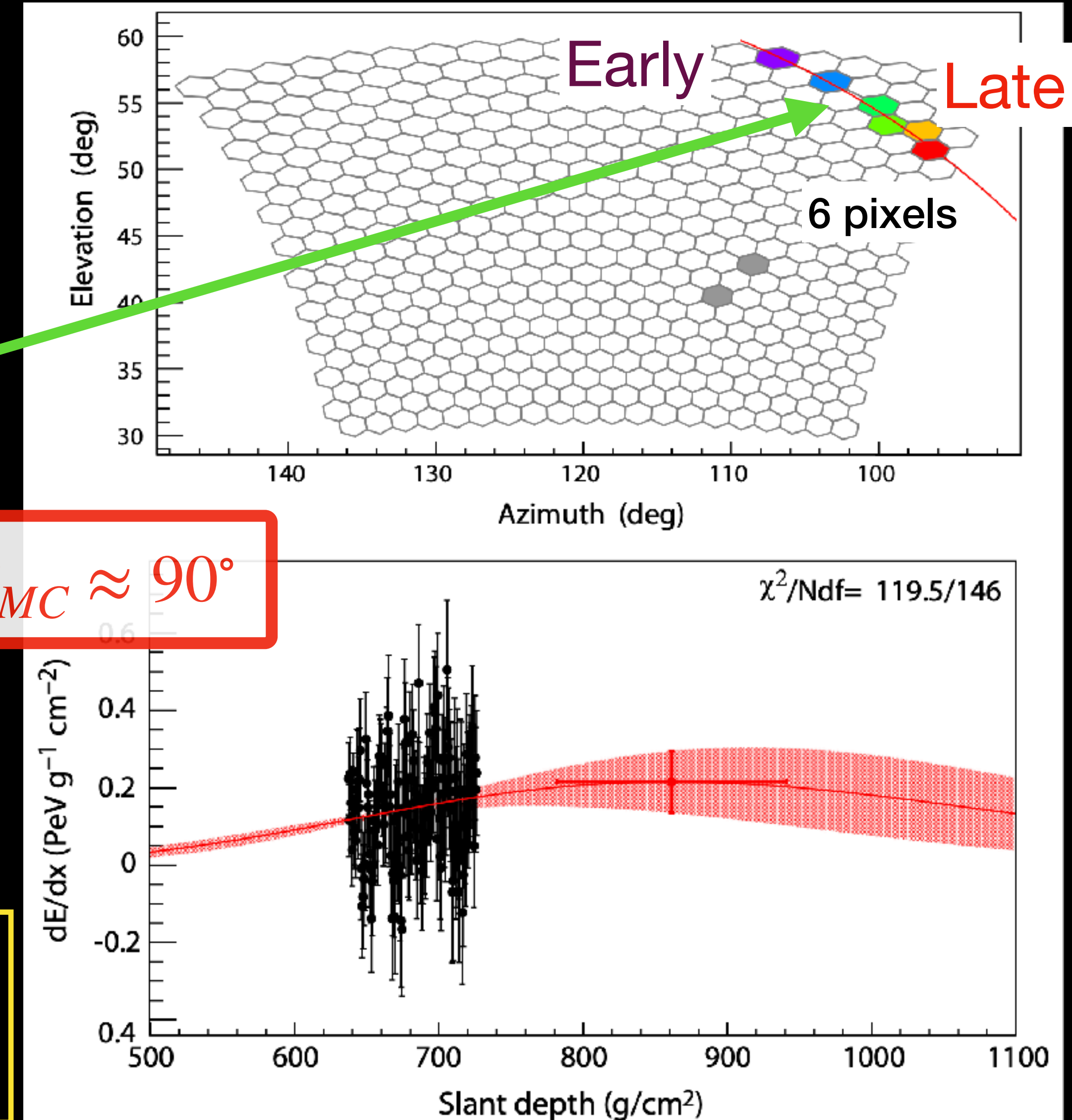
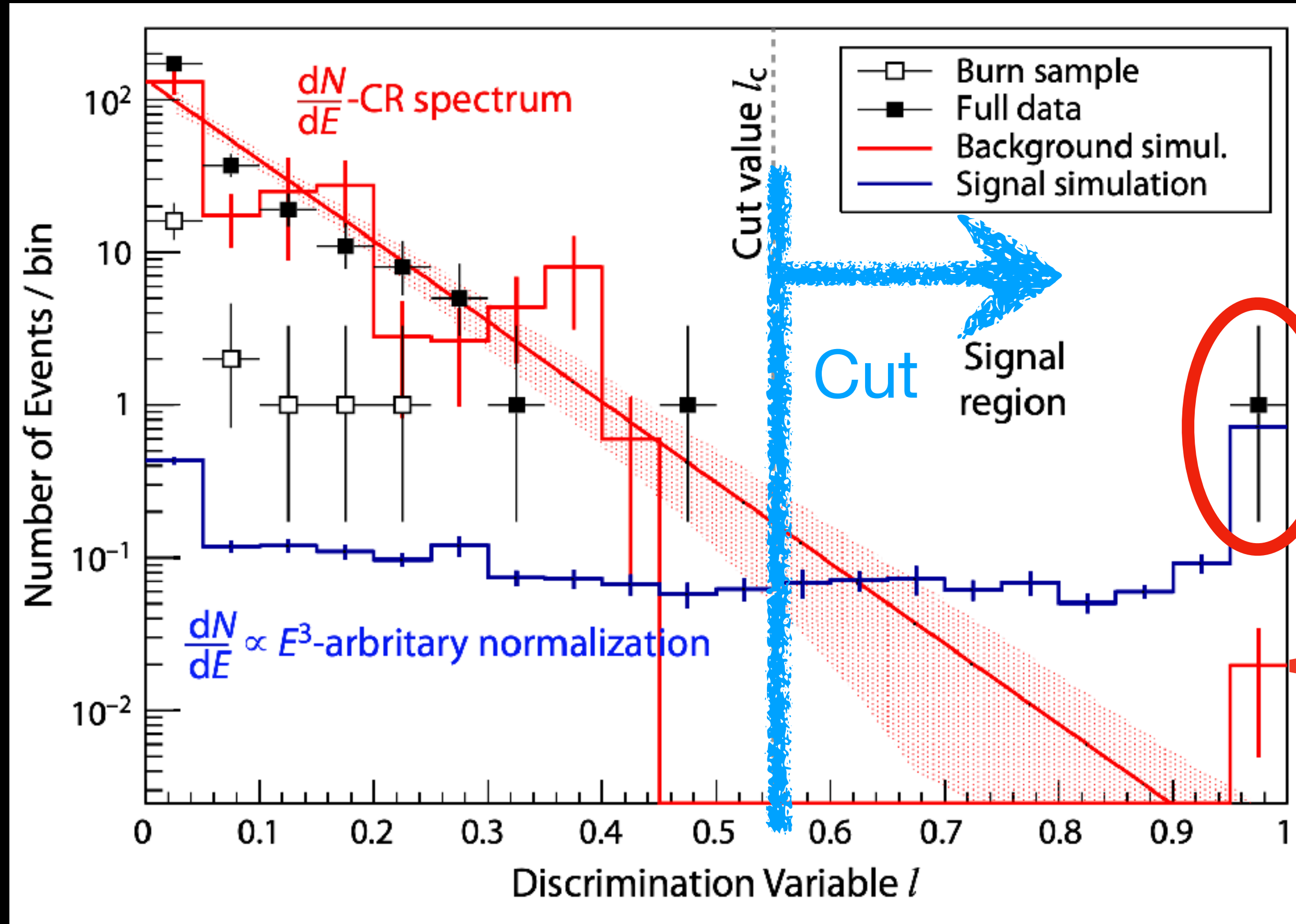
$$L_{down} > L_{up} : l = 0$$

$$L_{down} < L_{up} : l \in [0,1]$$

$$L_{up} \text{ only} : l = 1$$

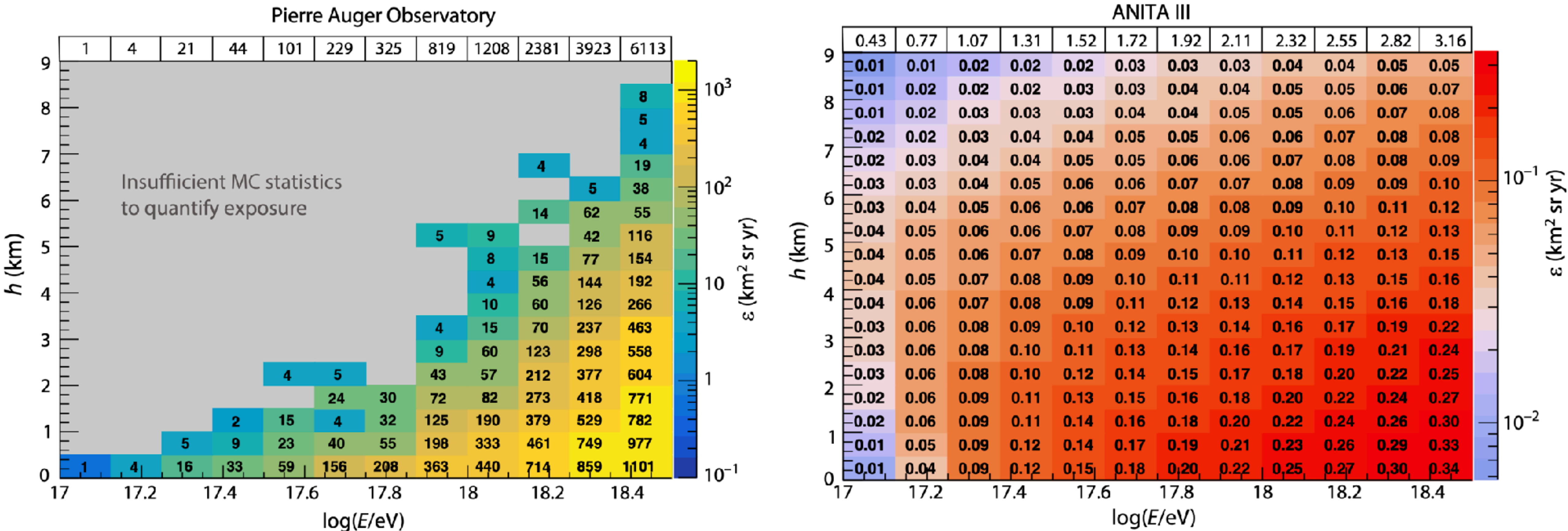
Cut value at $l_c = 0.55$ optimized minimizing MC background & maximizing sensitivity

Discriminating upward-going showers



One event found in 1 Jan 2004 - 31 Dec 2018
 Consistent with expected background of 0.27 ± 0.12 events
 from MC cosmic ray showers reconstructed as upward-going

Auger FD and ANITA exposure comparison



$\theta \in [110^\circ, 130^\circ]$ to contain the abnormal events

Auger FD exposure is 2 - 2000 larger than ANITA-III (I) exposure

Normalizing several E-2 $\rightarrow$ E-5 spectra to 1 event in ANITA I or III

In tension

⊙

➡

8-69 events expected in Auger, while only 1 event compatible with background has been observed

4, Up-going showers scenarios from Beyond Standard Model

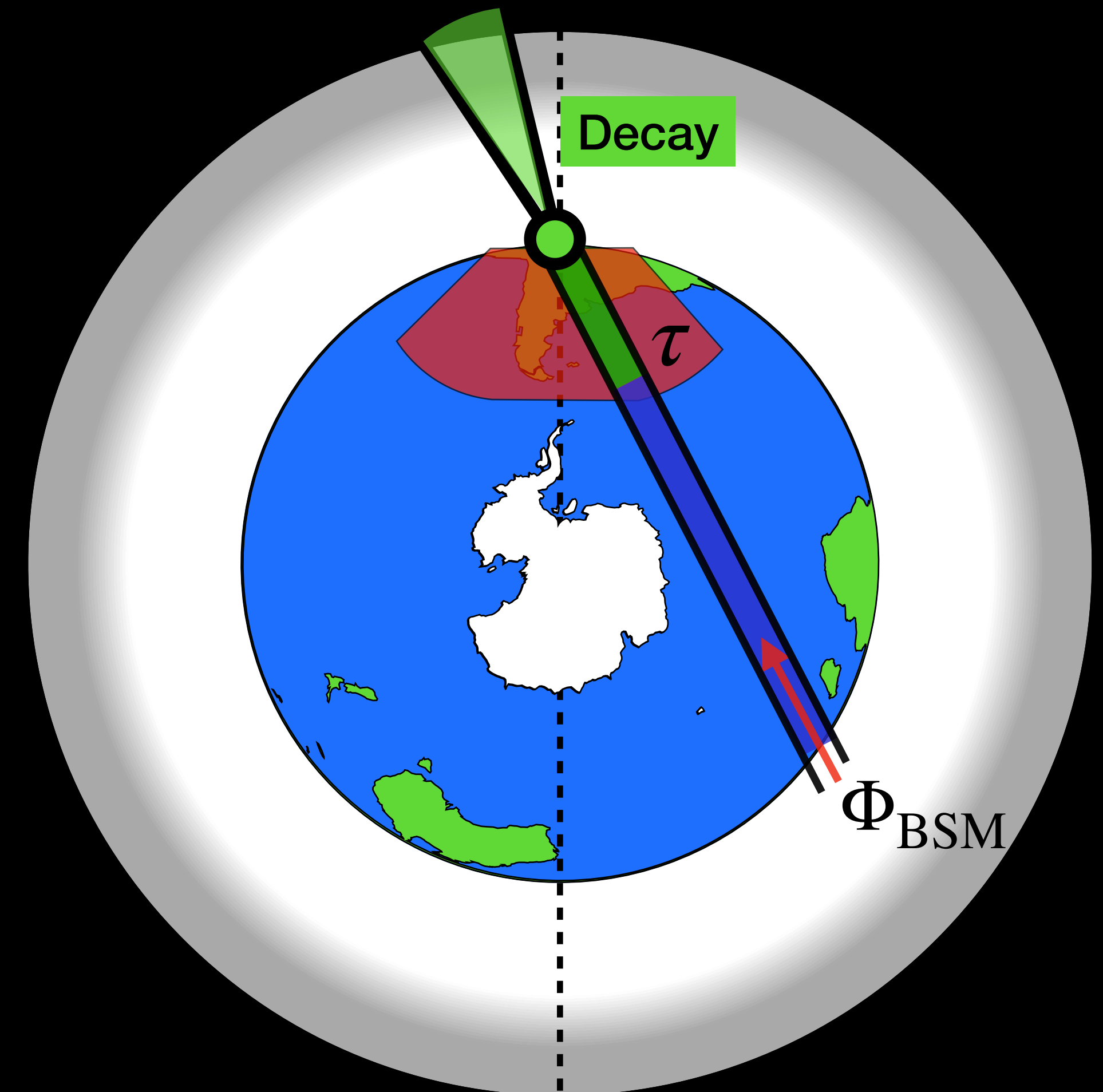
Which particle can cause up-going showers in the Air?

☉ The final state

- ✦ won't be absorbed inside the Earth quickly
 - ➔ ν , μ and τ
- ✦ The final state will interact (or decay) in the air
 - ➔ ν : air density too less
 - ➔ μ : too long lifetime
 - ➔ τ : possible long propagation length and short lifetime
- ✦ Or BSM particle

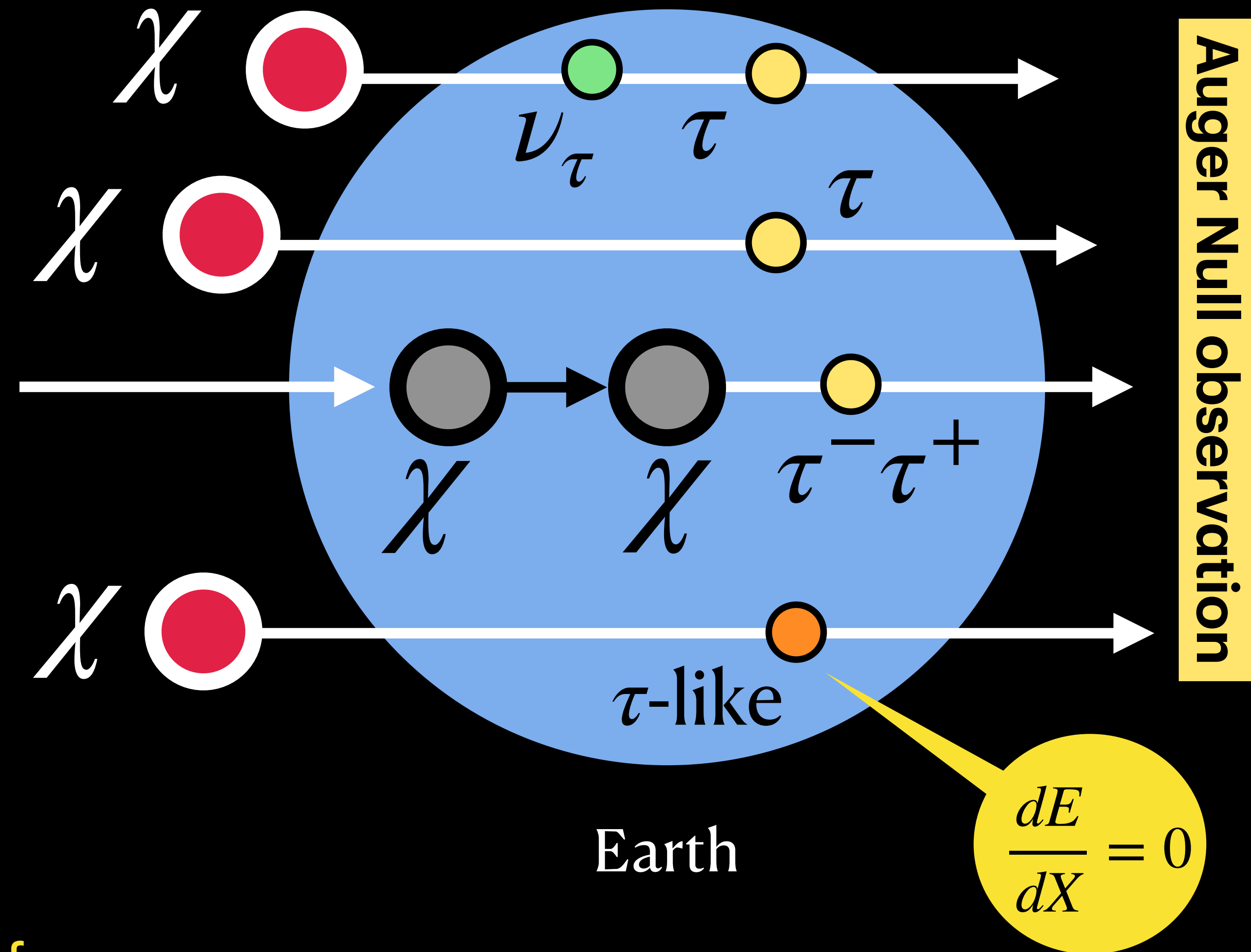
☉ The primary particle

- ✦ ν : too large cross section
- ✦ BSM particle: dark matter with small cross section



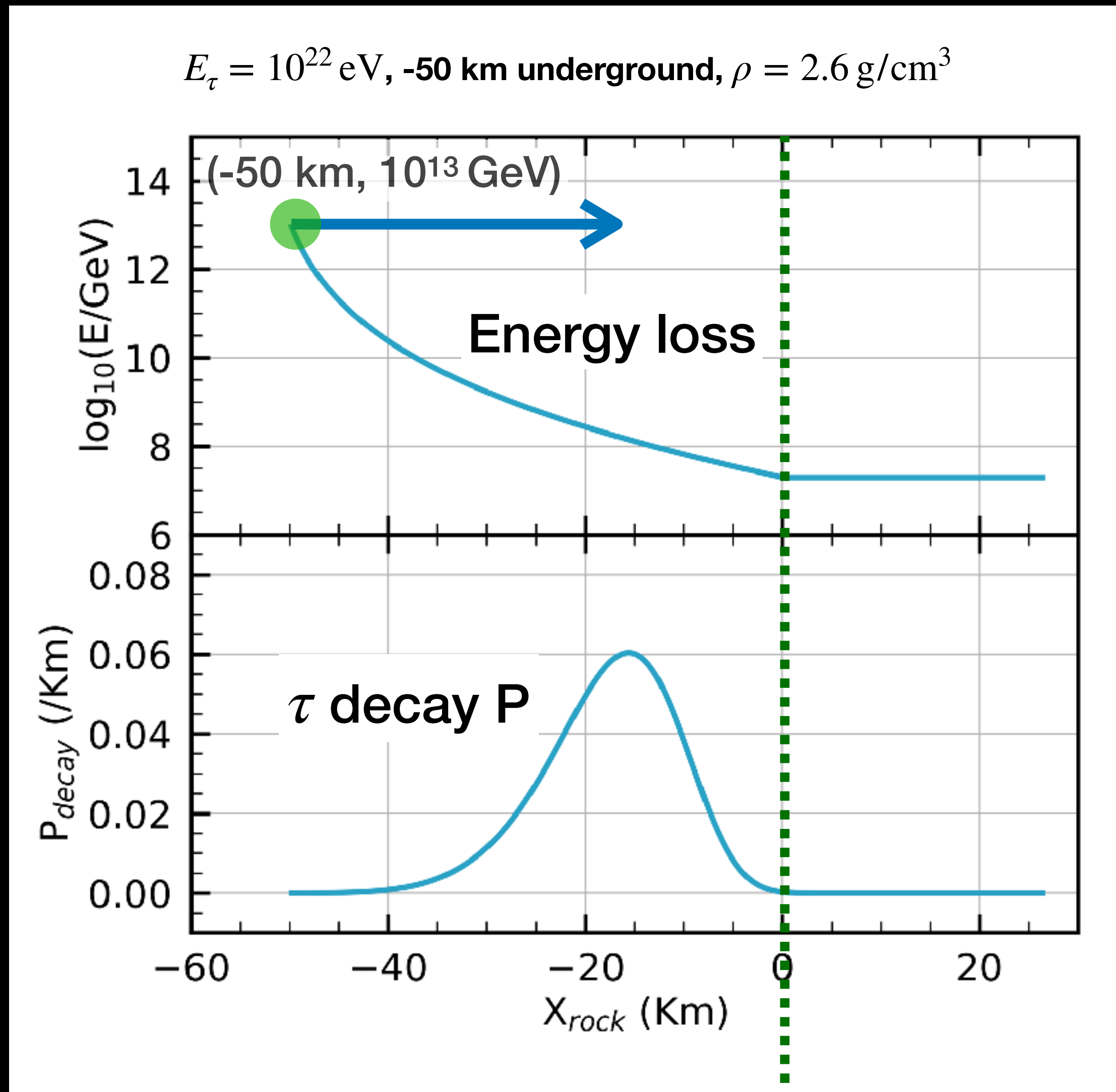
BSM scenarios

1. BSM - τ model
2. BSM - ν_τ model (backup slides)
3. BSM - τ -like model [*JHEP* 07 (2023) 005]
 - τ -like particle: no energy loss
 - Unknown lifetime
4. Dark matter captured with electron or nucleus inside the Earth. IceCube paper: *Eur. Phys. J. C* (2025) 85:490
 - Annihilation: $\chi + \chi \rightarrow \nu\bar{\nu}$ or $\tau^-\tau^+$...



1, 2, 3 Reference

1, BSM - τ model: Tau propagation in the Earth



Tau energy loss: $-\left\langle \frac{dE_\tau}{dX} \right\rangle = \alpha + \beta E_\tau$

* α : ionization process

* β : bremsstrahlung, pair production and
photonuclear (ALLM, ASW) processes

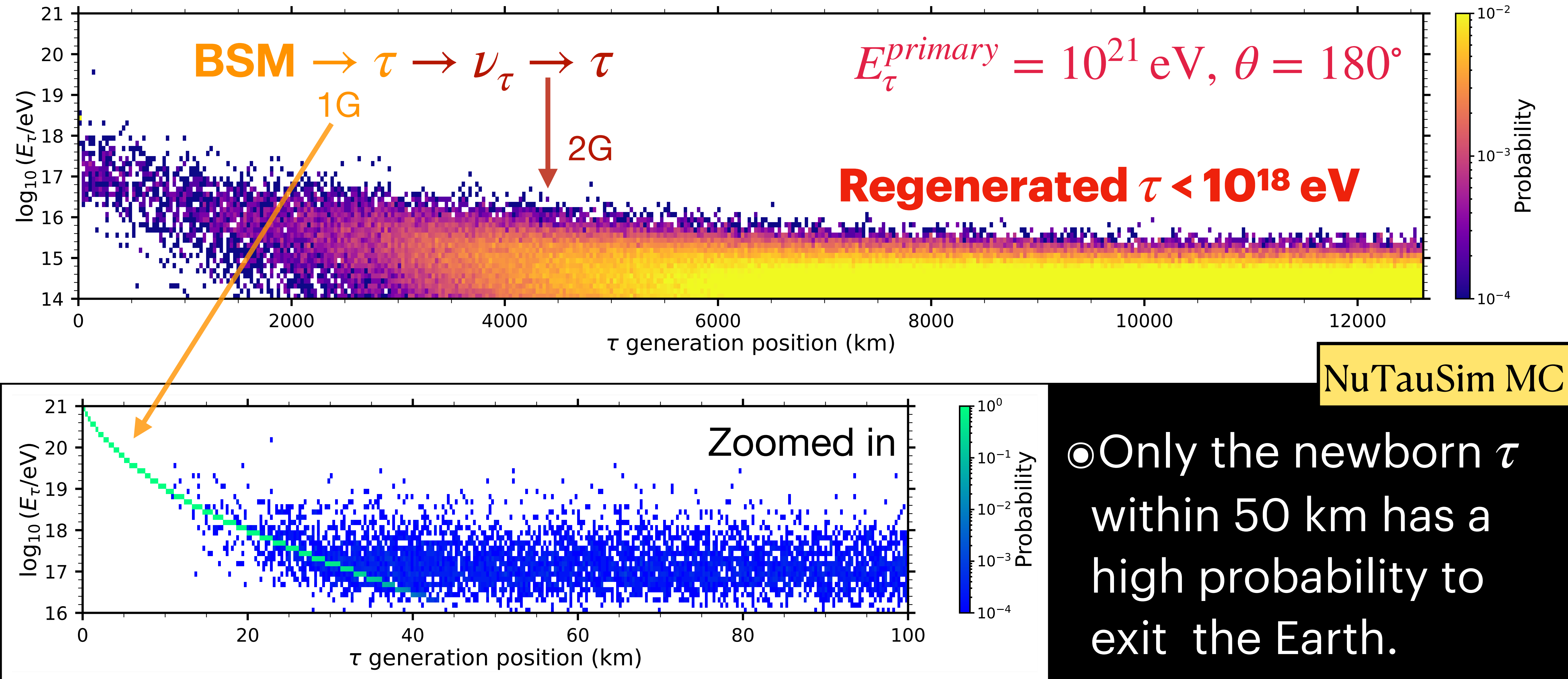
Tau decay length is decreasing due to tau energy loss when propagating

50 km is the maximum distance tau can propagation inside the Earth

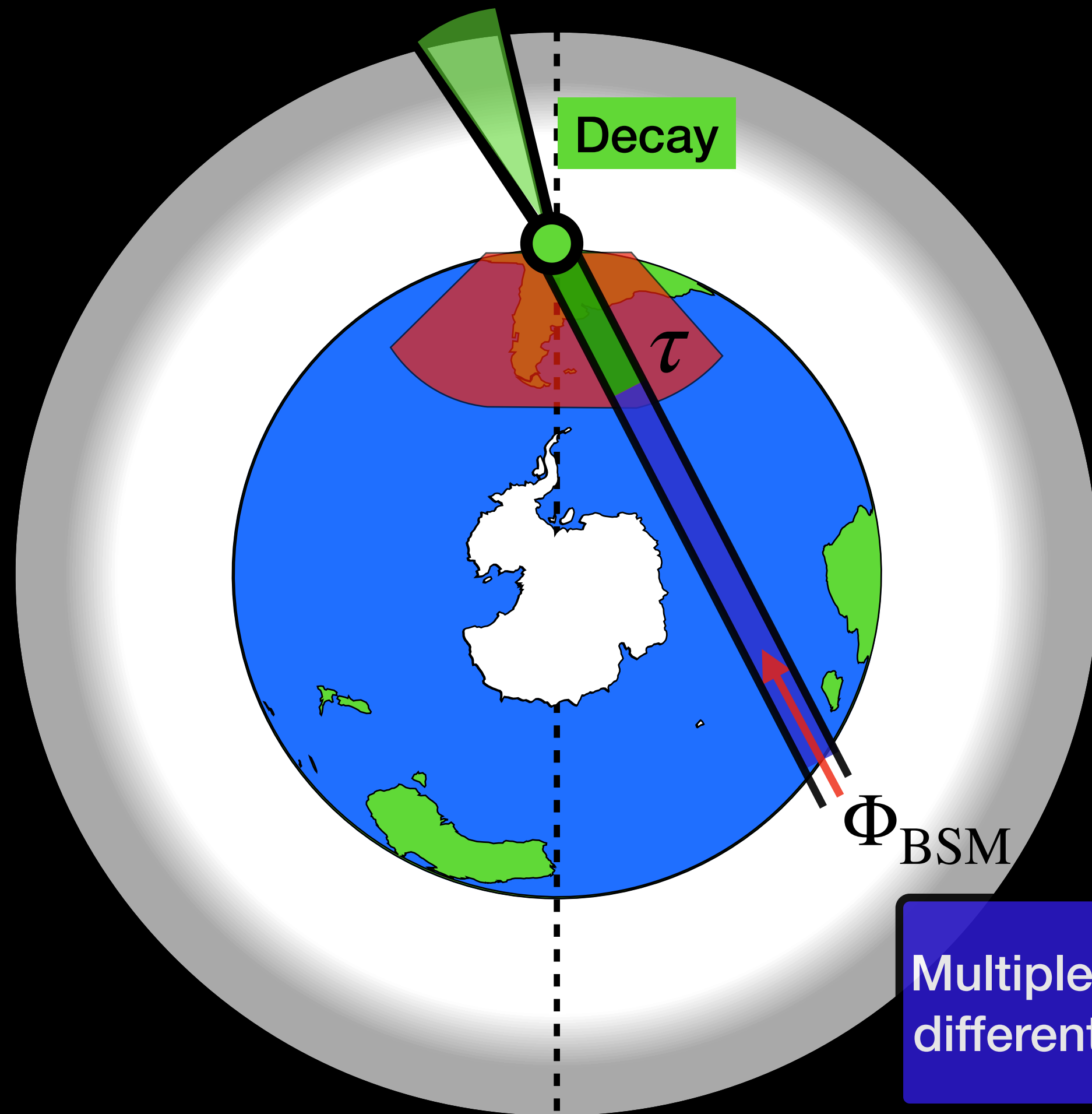
ALLM: arXiv:hep-ph/9712415

ASW: Phys. Rev. Lett. 94, 022002 (2005)

1, BSM - τ model: Tau propagation simulation

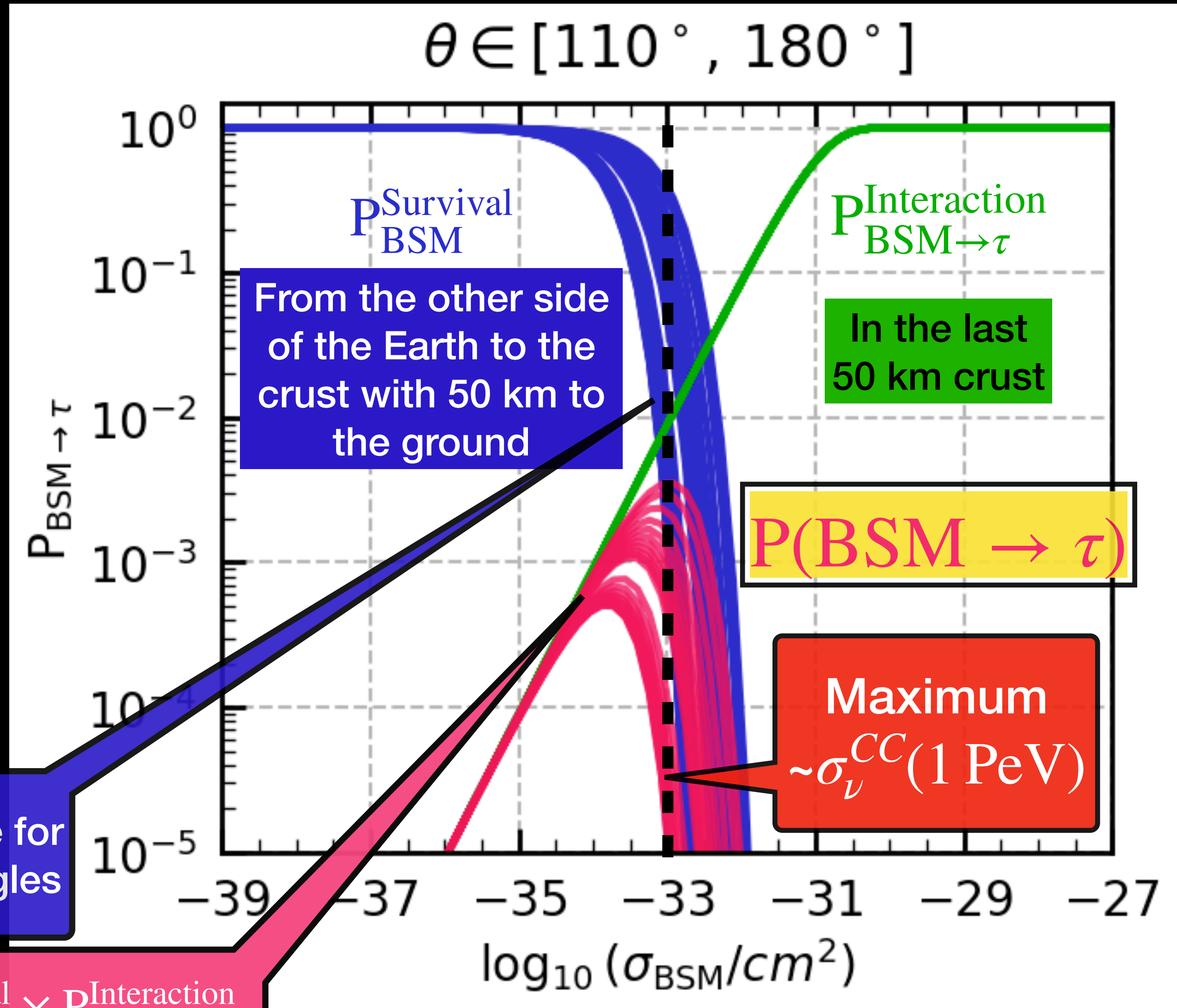


1, BSM - τ model: sensitive cross-section



Multiple curves are for different zenith angles

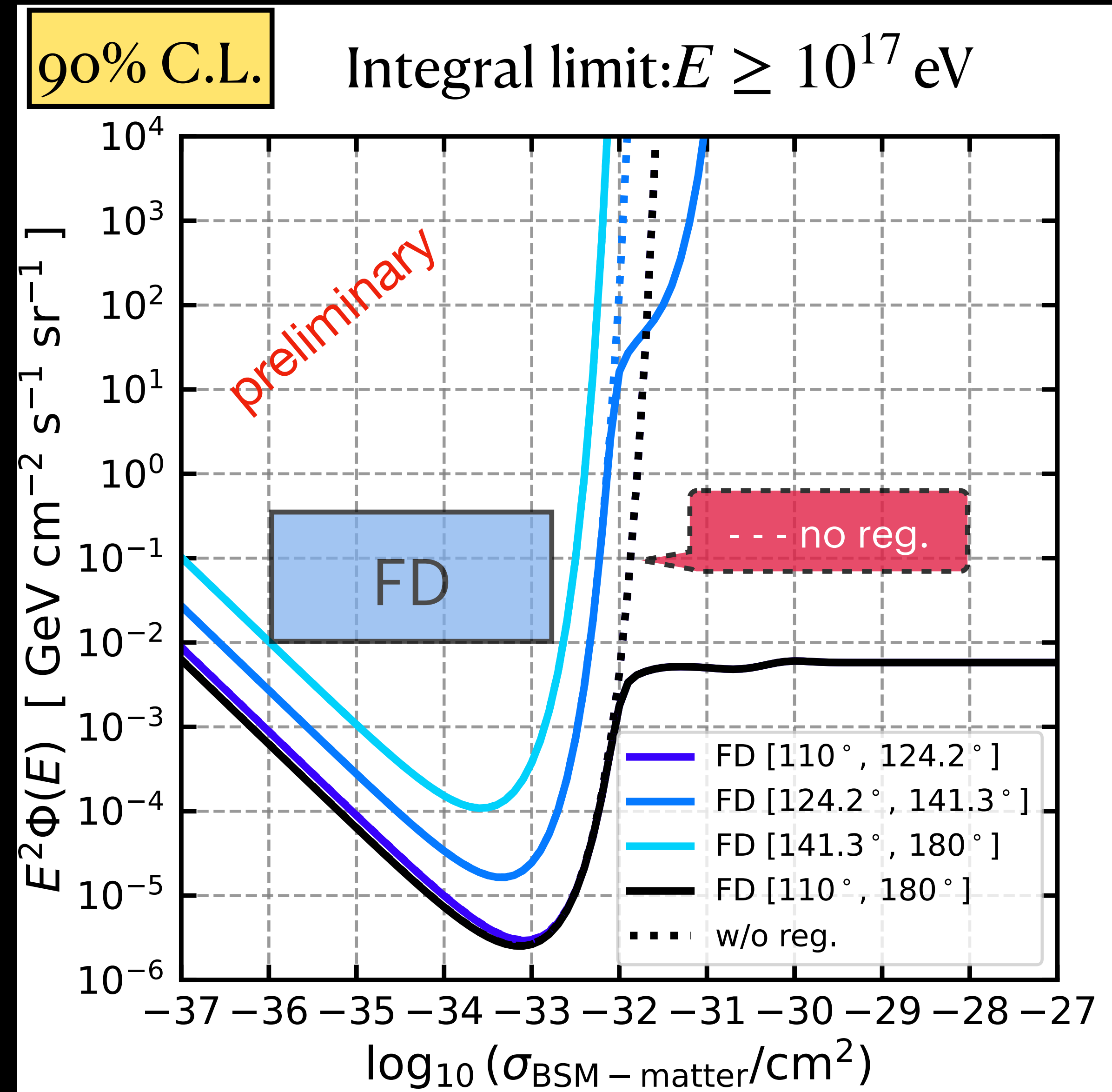
$$P(\text{BSM} \rightarrow \tau) = P_{\text{Survival}}^{\text{BSM}} \times P_{\text{Interaction}}^{\text{BSM} \rightarrow \tau}$$



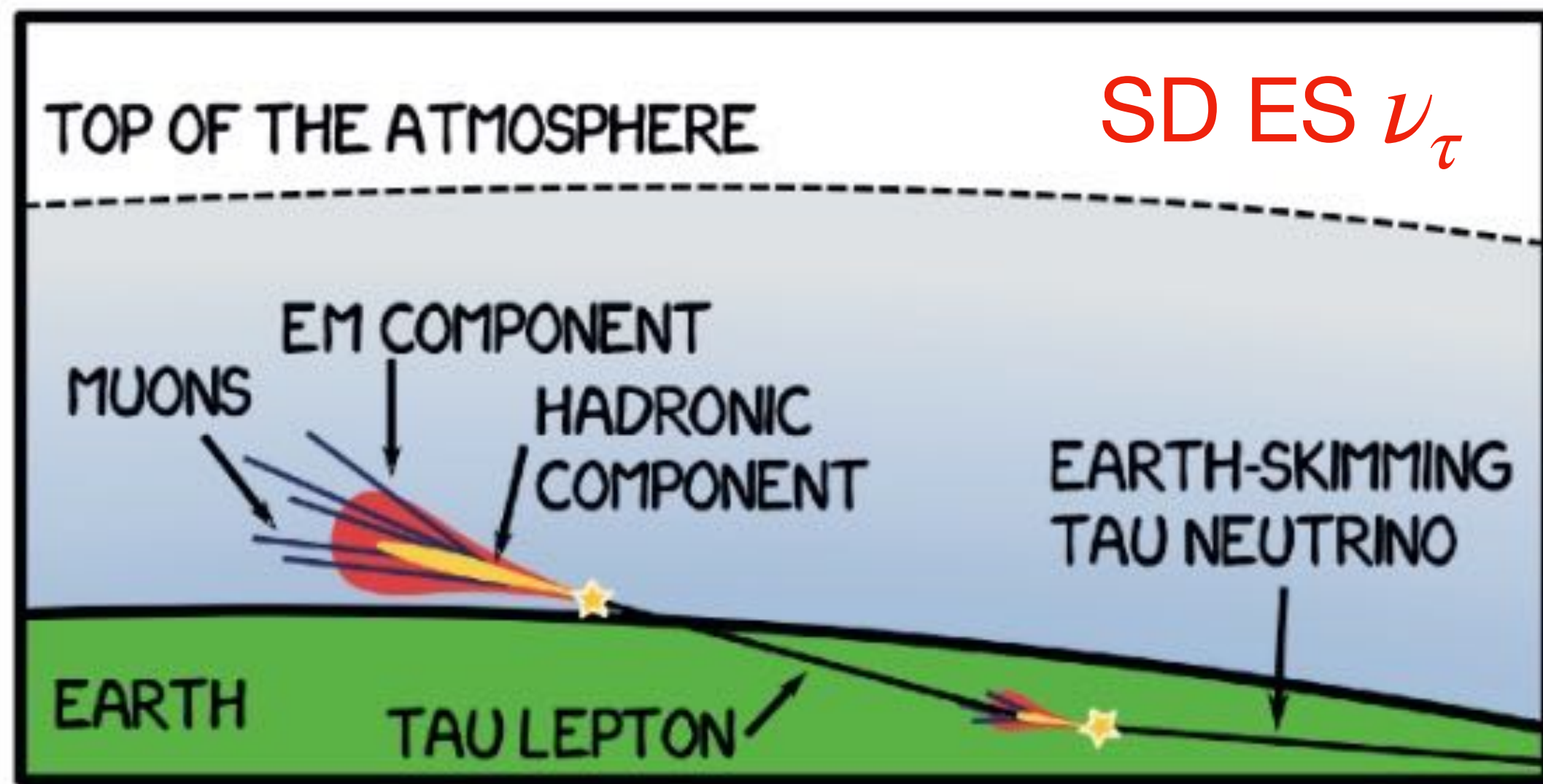
1, BSM - τ model: BSM flux upper limit



- ✦ Assuming energy independent cross section
- ✦ FD up-going exposure:
 $\theta \in [110^\circ, 180^\circ], \log_{10}(E/\text{eV}) \in [17, 21]$
- ✦ $d\Phi_{\text{BSM}}/dE \propto E^{-2}$ diffuse flux



1, BSM - τ model: BSM flux upper limit

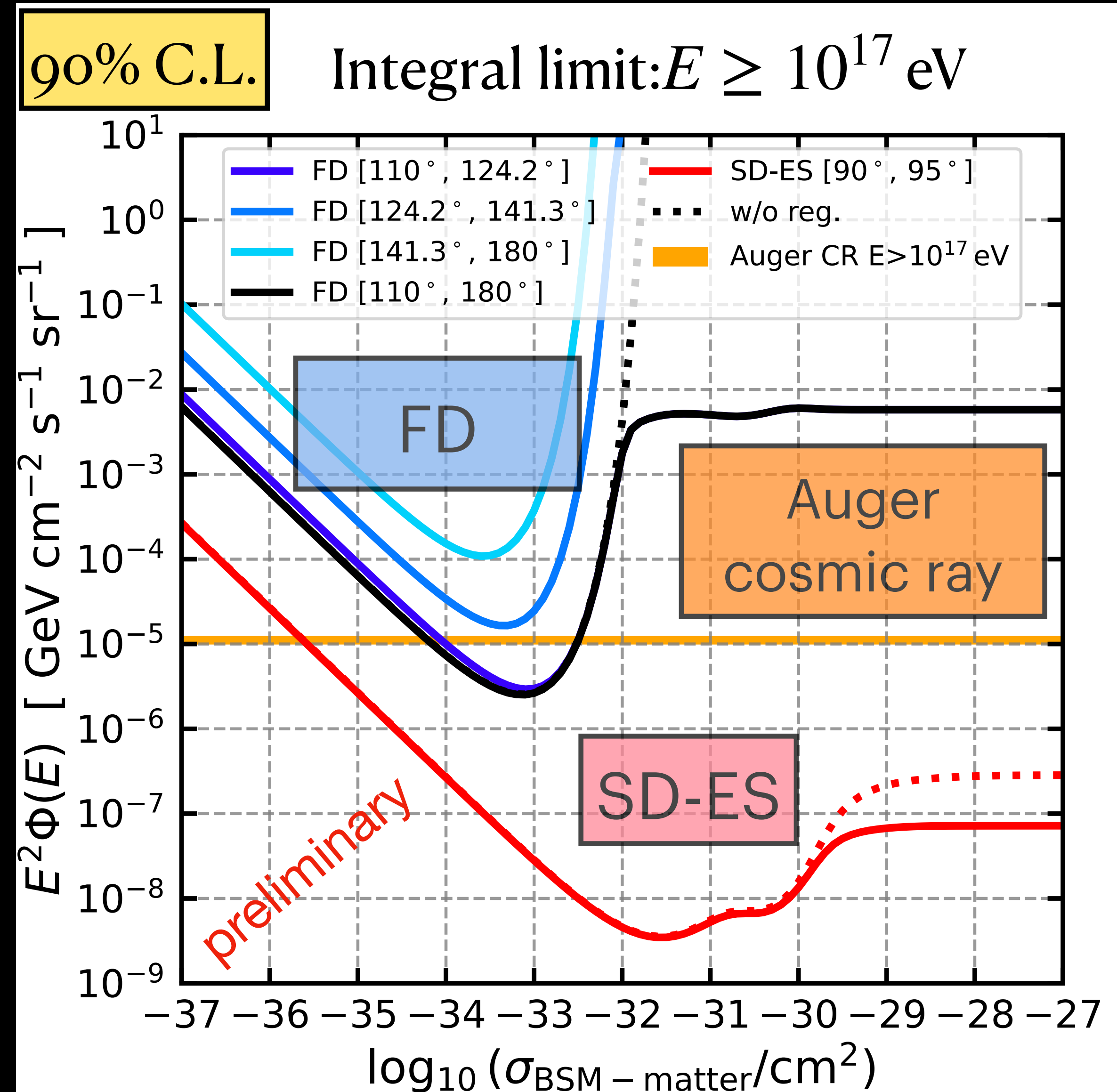


UHECR flux ($E > 10^{17}$ eV)

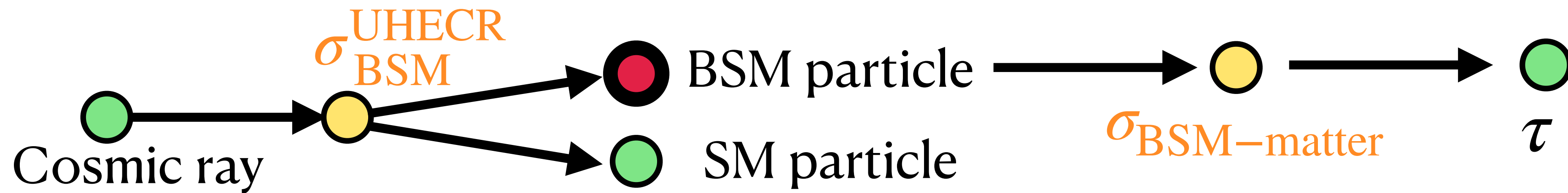
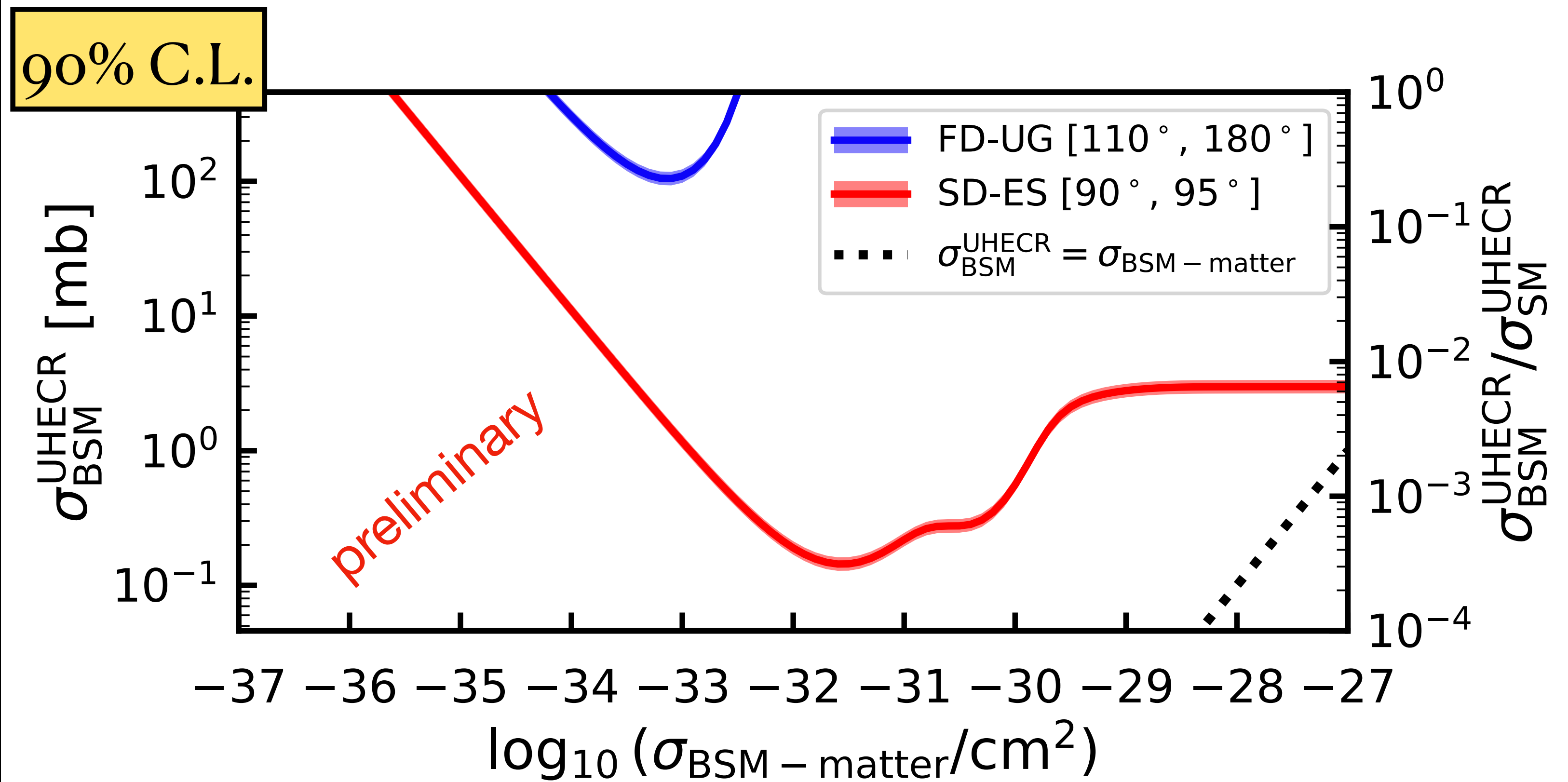
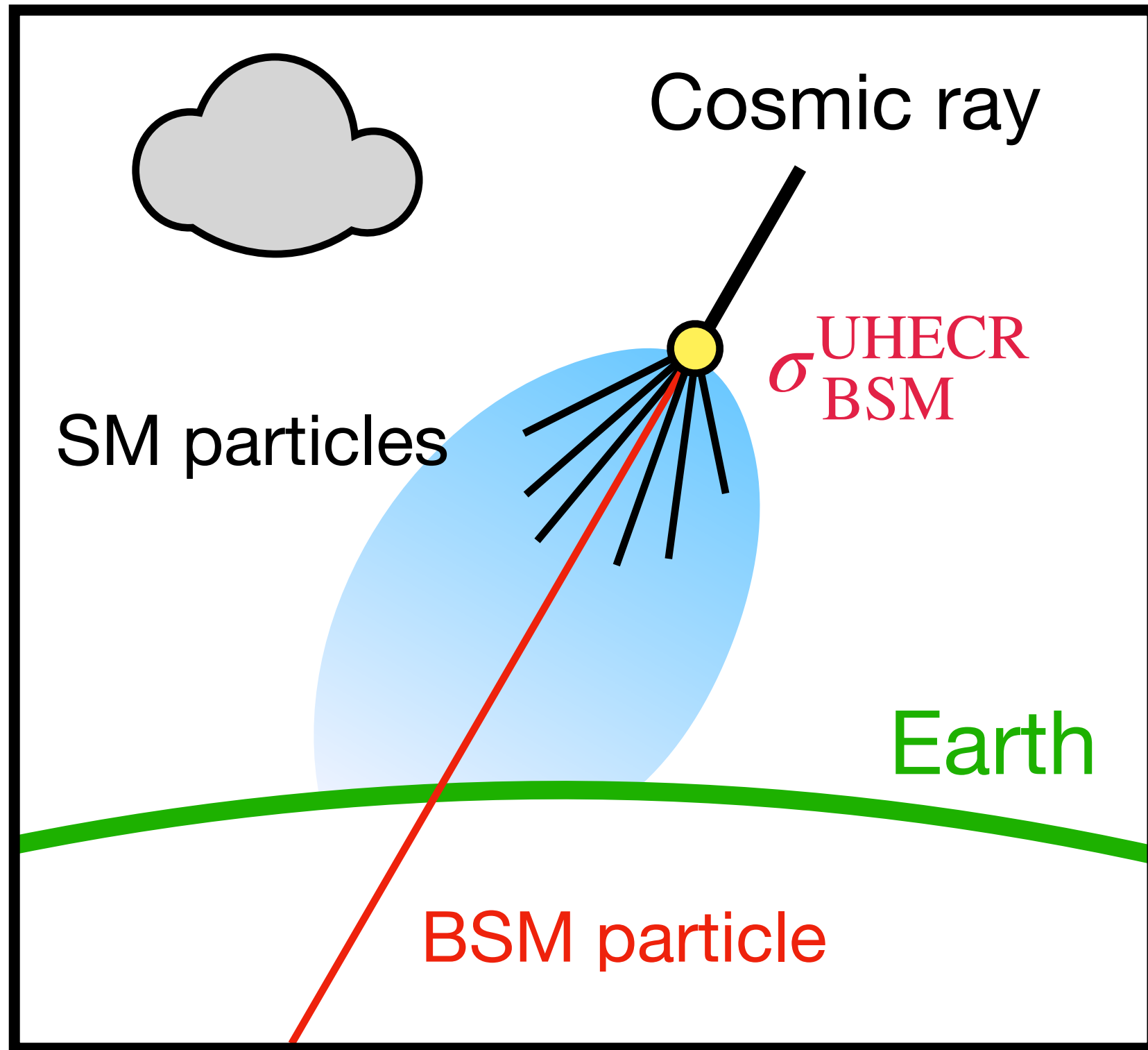
Constrains models in which UHECRs produce BSM particles

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

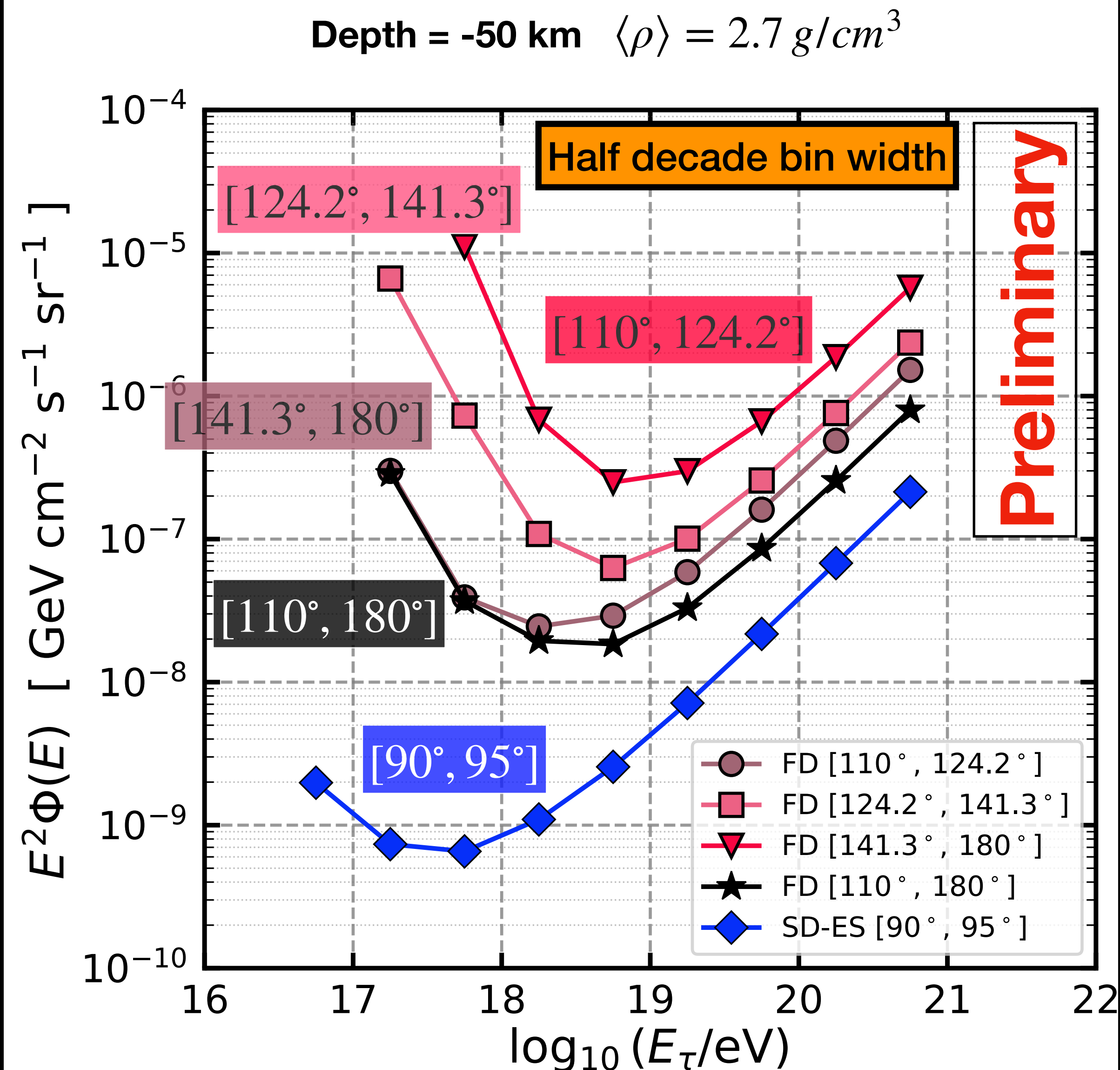
Φ_{BSM} from SD-ES



1, BSM - τ model: BSM particle production in air showers



Upper limit of tau flux

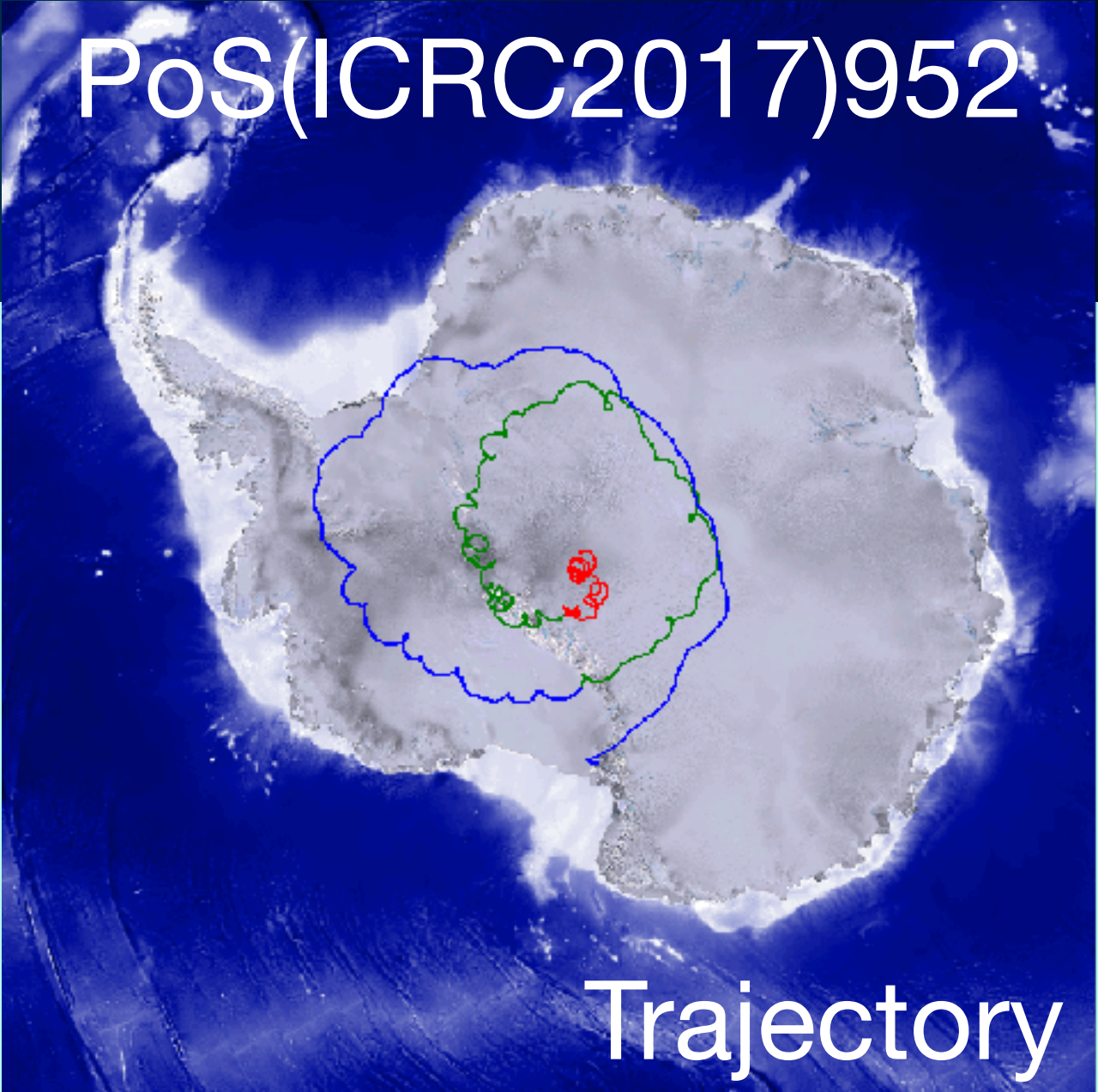
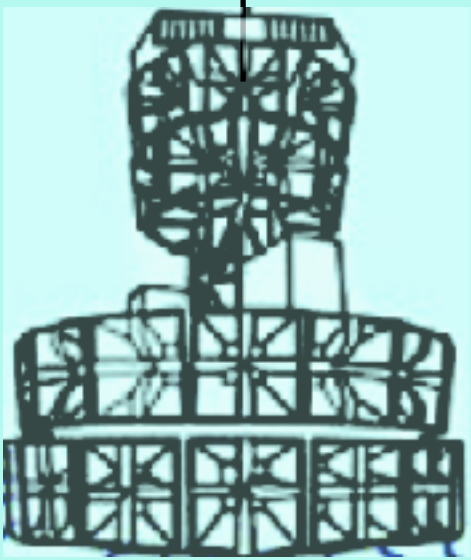


- ✦ Tau generation flux is the integrated tau generated over 50 km depth in the crust
- ✦ **One** event found: consistent with the background expectation 0.27 ± 0.12 events (PRL 134, 121003 (2025))
- ✦ The Feldman Cousins (FC) method:
 - * $B_g = 1$, $N_{90\%} = 3.28$
- ✦ $N_{\text{predicted}}(E_\tau^{\text{primary}} \in [E_{\text{min}}, E_{\text{max}}]) = N_{90\%}$ to obtain the upper limit of Φ_τ in $[E_{\text{min}}, E_{\text{max}}]$

3, BSM - τ -like model

PoS(ICRC2017)952

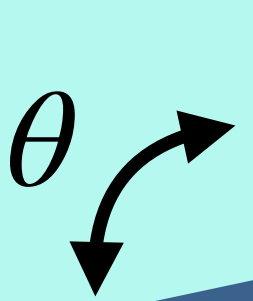
The corresponding flux is in tension with non-observations from IceCube and Auger.



Trajectory

PRL 126, 071103 (2021)
ANITA-IV

	Energy (EeV)	θ (degree)	Day
ANITA-IV	0.8, 0.9, 1.5, 3.9	96.7, 96.7, 96.2, 96.1	28



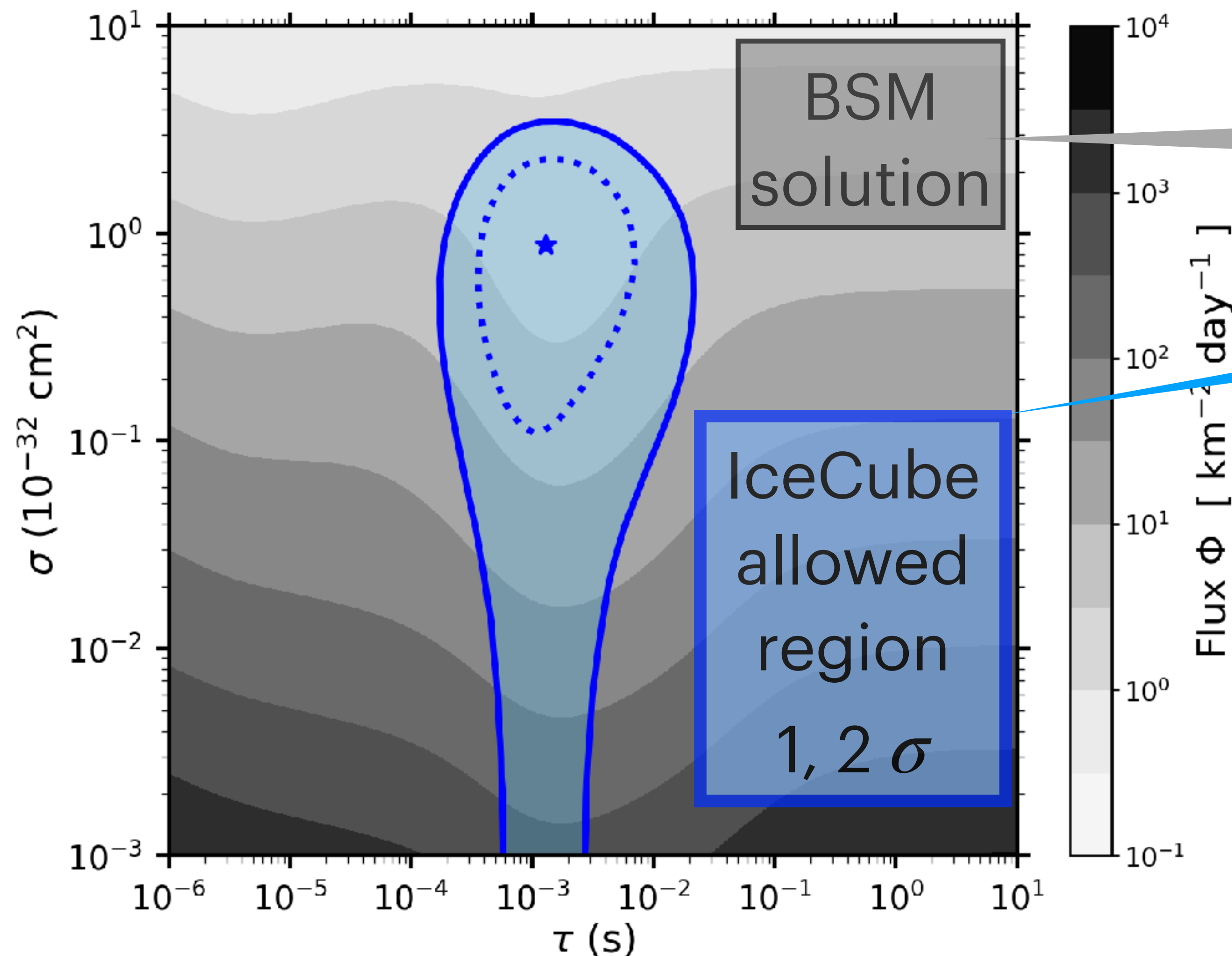
1 degree below the horizon

30–39 km altitudes

South Pole: ice

3, BSM - τ -like model

ANITA-IV & IceCube solution



BSM solution for
ANITA-IV 4 events

BSM solution
combined with
non-observation
in IceCube

JHEP 07 (2023) 005

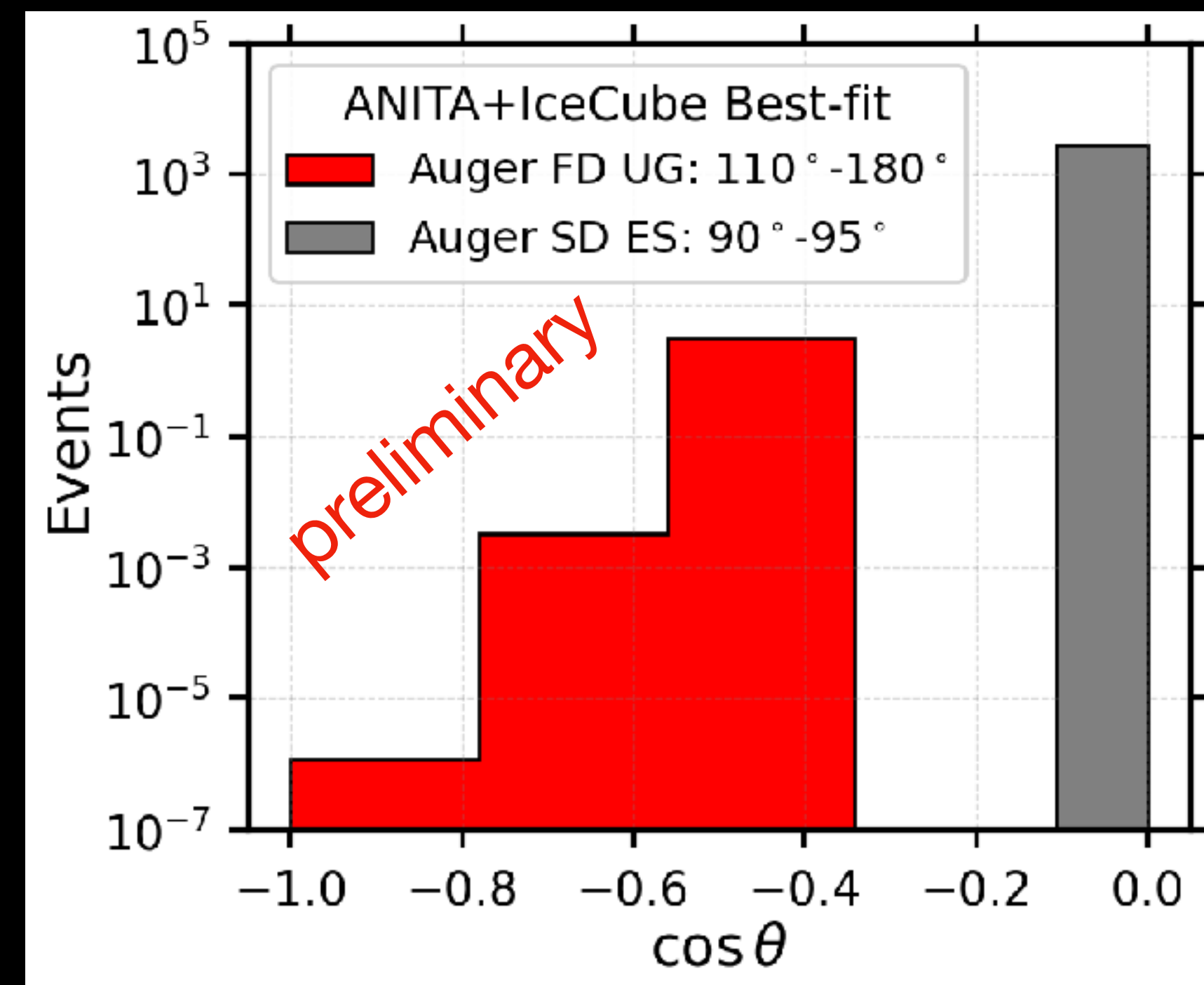
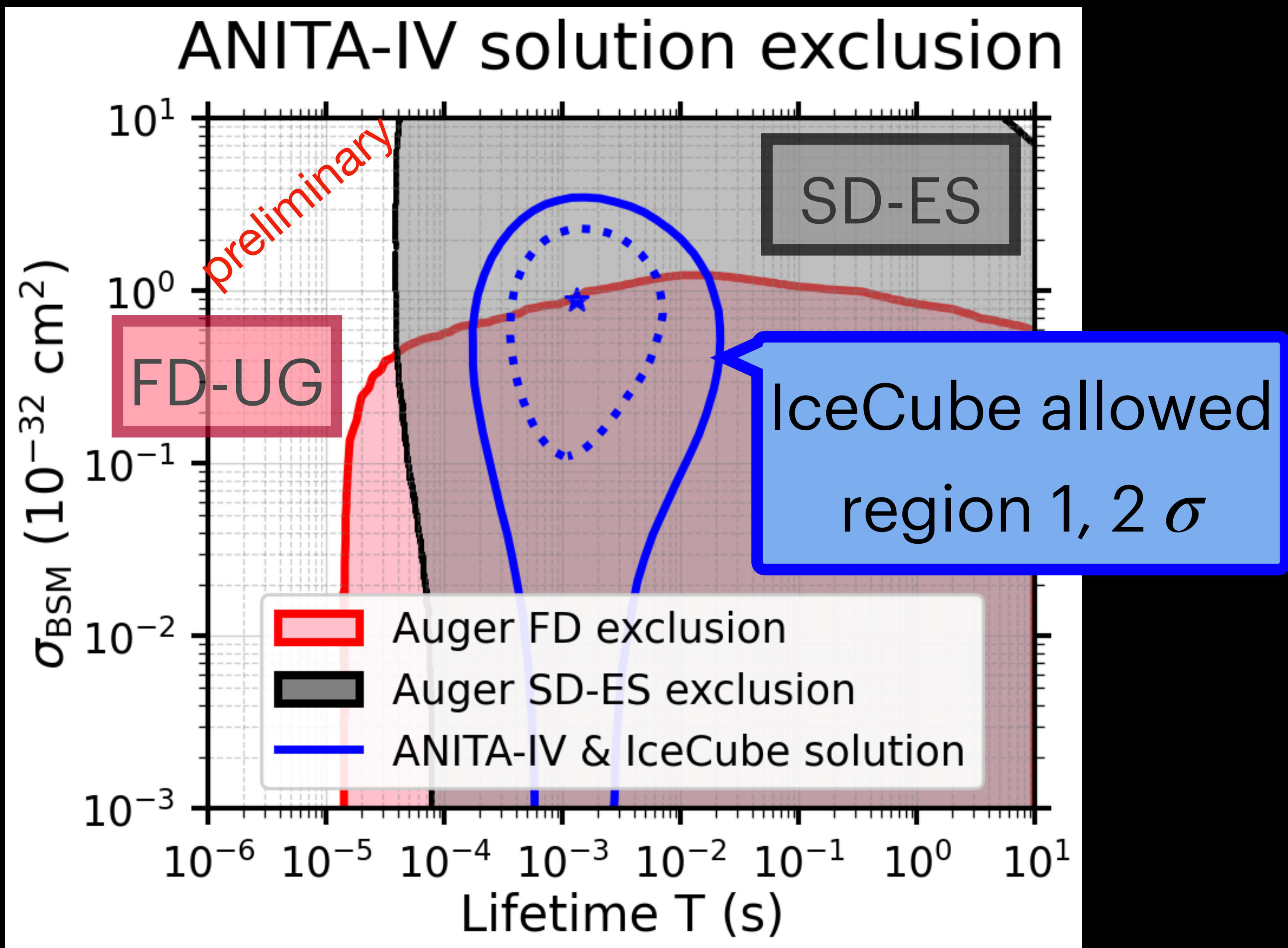
Diffuse BSM flux (E^{-1}) in (1, 100) EeV

Absorption ($\sigma_{\text{BSM-matter}}$) and
regeneration are considered

Best fit: $\sigma = 8.9 \times 10^{-33} \text{ cm}^2$, $\tau =$
 $1.3 \times 10^{-3} \text{ s}$ (@1EeV), and $\Phi = 1.8$
 $\text{ km}^{-2} \text{ day}^{-1}$.

90% C.L.

3, BSM - τ -like model



Best fit:

FD up-going showers: ~ 3 events

SD ES: ~ 2835 events

Excluded

5, The AugerPrime upgrade

AugerPrime: exploiting the richness of extensive air showers

Phase 1 :
data taking from 2004 to end of 2021

- ✓ Over 120, 000 km² sr yr for anisotropy studies
- ✓ Over 90, 000 km² sr yr for spectrum studies

...2022-2024

*transition period (commissioning)
to AugerPrime*

Phase 2 - the AugerPrime upgrade
Data taking from 2025 to >2035...

- ✓ + 40, 000 km² sr yr
- ✓ Multi-hybrid events : FD, SD, SSD, RD, UMD



**More insight in the mass composition
+ increased statistics**

Measure of the longitudinal development of the extensive air showers (EAS) while crossing the atmosphere

→ **Fluorescence telescopes**

Discrimination between the electromagnetic and muonic components of the EAS

→ **Water Cherenkov Stations** and **Scintillators**

→ **Larger dynamic range to measure high particle densities closer to the core**

Measure of the radio emission of EAS

→ **Radio antennas**

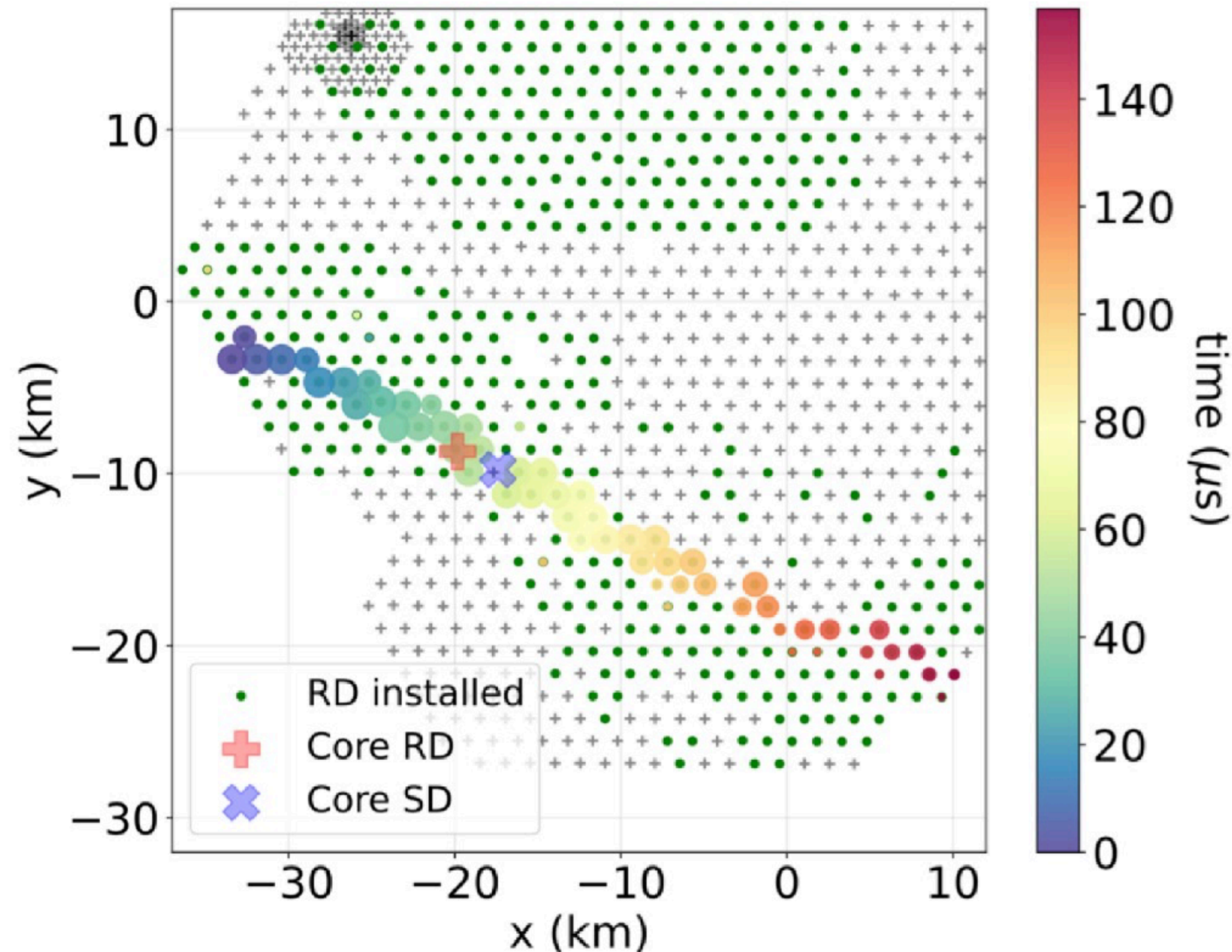
Direct measure of the muonic component

→ **Underground detectors**

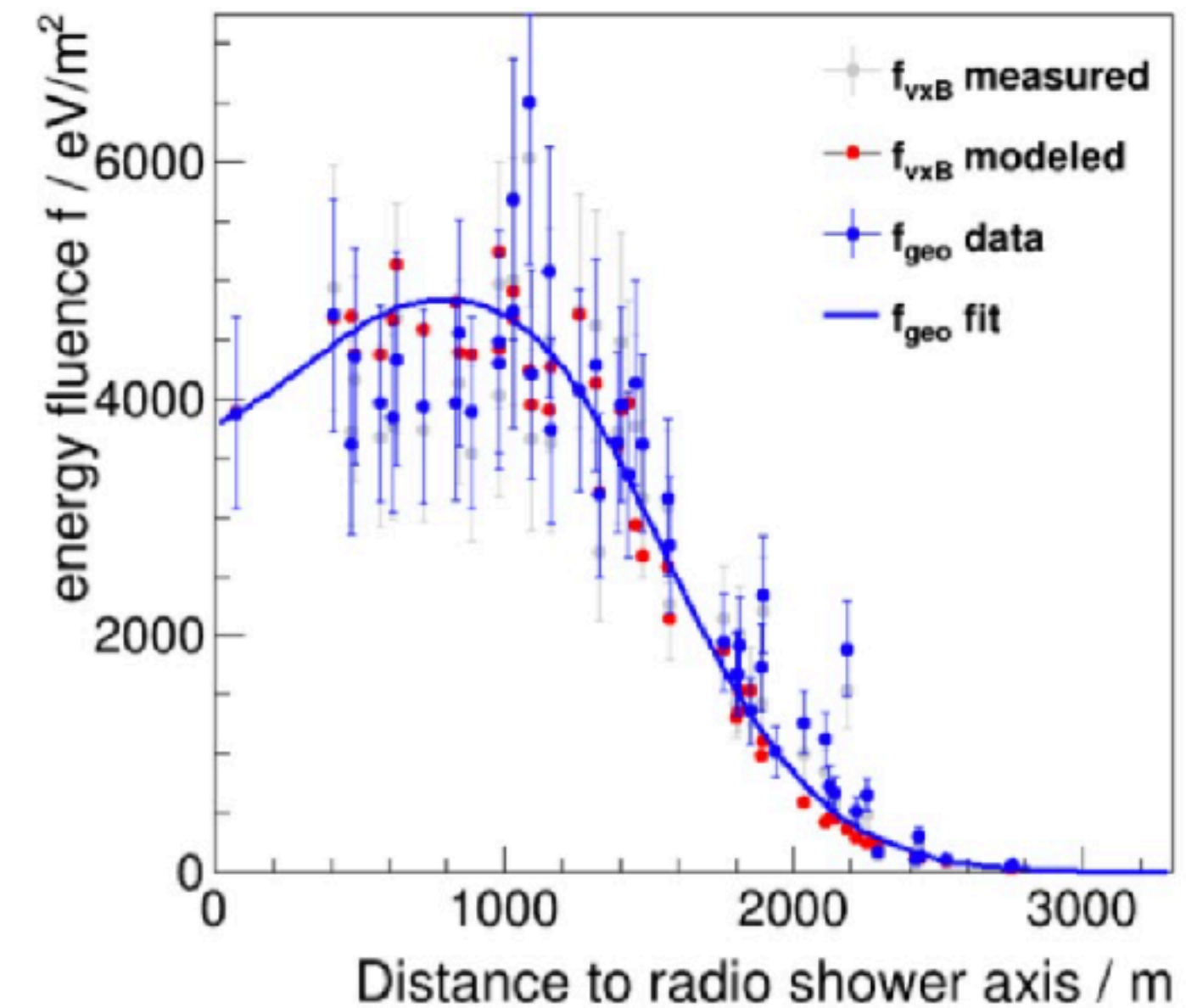
performing hybrid measurements and applying new analysis techniques

A first glimpse of RD data

- also RD-data taking is on-going: first events for commissioning are there



Event at 84.7 degree
 36 ± 3 EeV



Neutrino detection with radio antenna in the air

- Radio signal: minimal atmospheric attenuation
- Larger effective volume than particle detectors

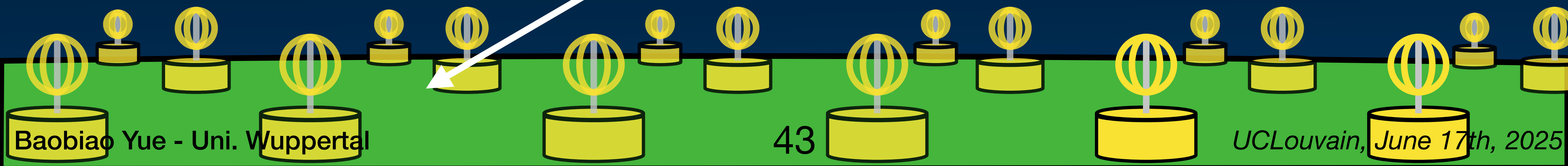
$$X_1 \approx \int_{h_1}^{h_{top}} \frac{\rho(h)}{\cos \theta} dh$$

Cosmic ray

Top of atmosphere

X_1 (p-air)
 $< 200 \text{ gcm}^{-2}$

This study will be given in
ICRC 2025. Stay tuned!



Neutrino detection with radio antenna in the air

- Radio signal: minimal atmospheric attenuation
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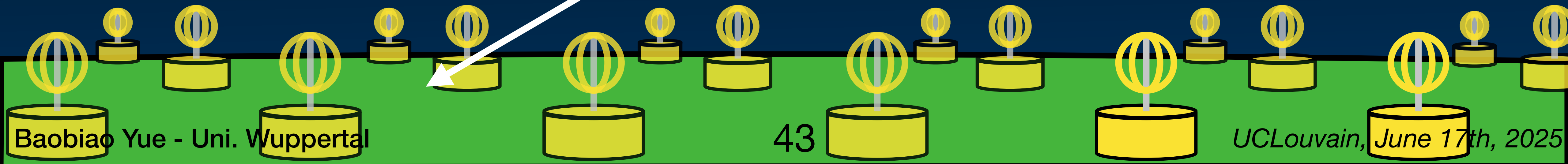
$$X_1 \approx \int_{h_1}^{h_{top}} \frac{\rho(h)}{\cos \theta} dh$$

Cosmic ray

Top of atmosphere

$X_1 (\nu)$ anywhere!

$X_1 (\text{p-air})$
 $< 200 \text{ gcm}^{-2}$



Neutrino detection with radio antenna in the air

- Radio signal: minimal atmospheric attenuation
- Larger effective volume than particle detectors

This study will be given in ICRC 2025. Stay tuned!

$$X_1 \approx \int_{h_1}^{h_{top}} \frac{\rho(h)}{\cos \theta} dh$$

Cosmic ray

Top of atmosphere

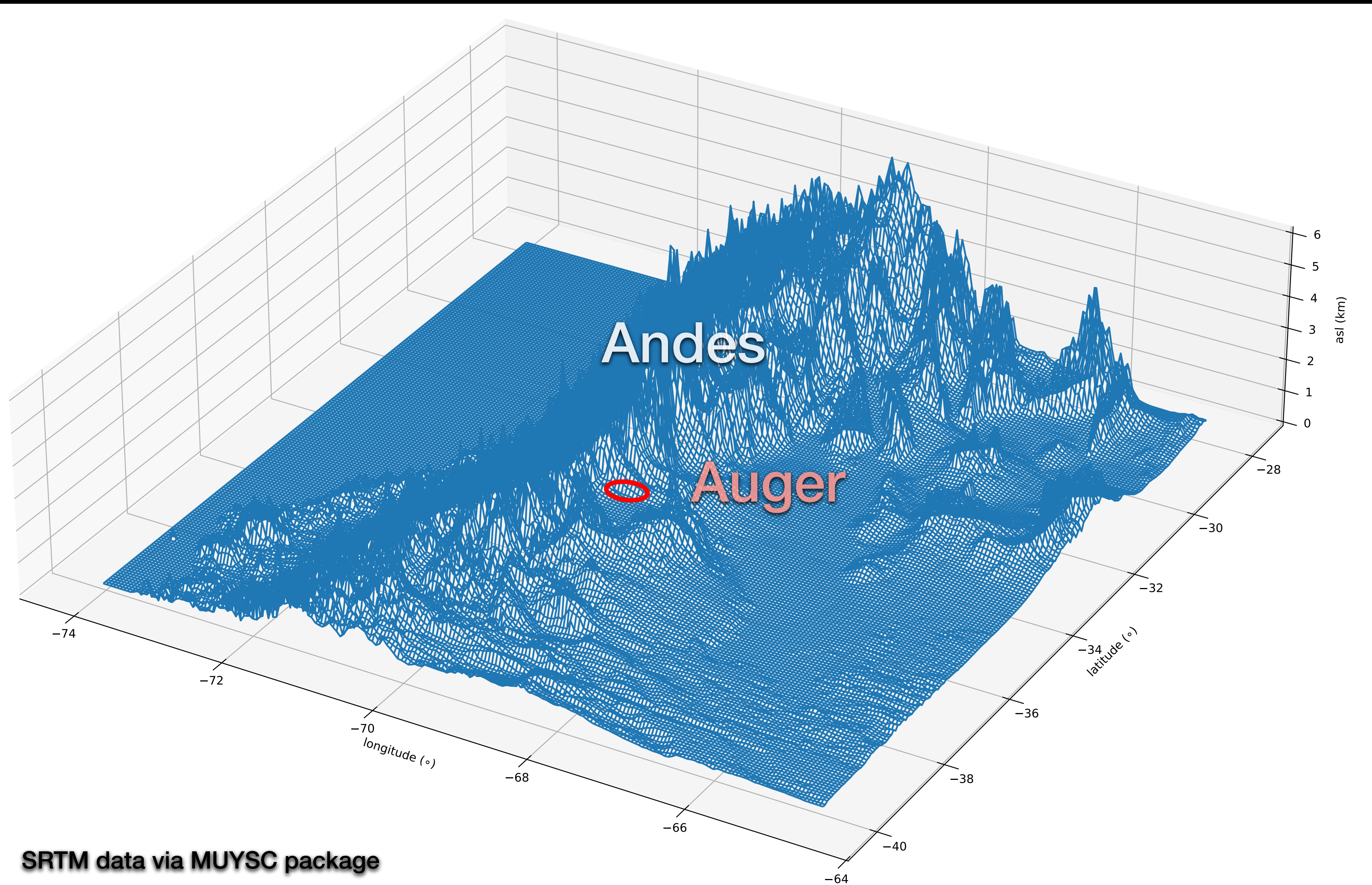
$X_1 (\nu)$ anywhere!

$X_1 (\text{p-air})$
 $< 200 \text{ gcm}^{-2}$

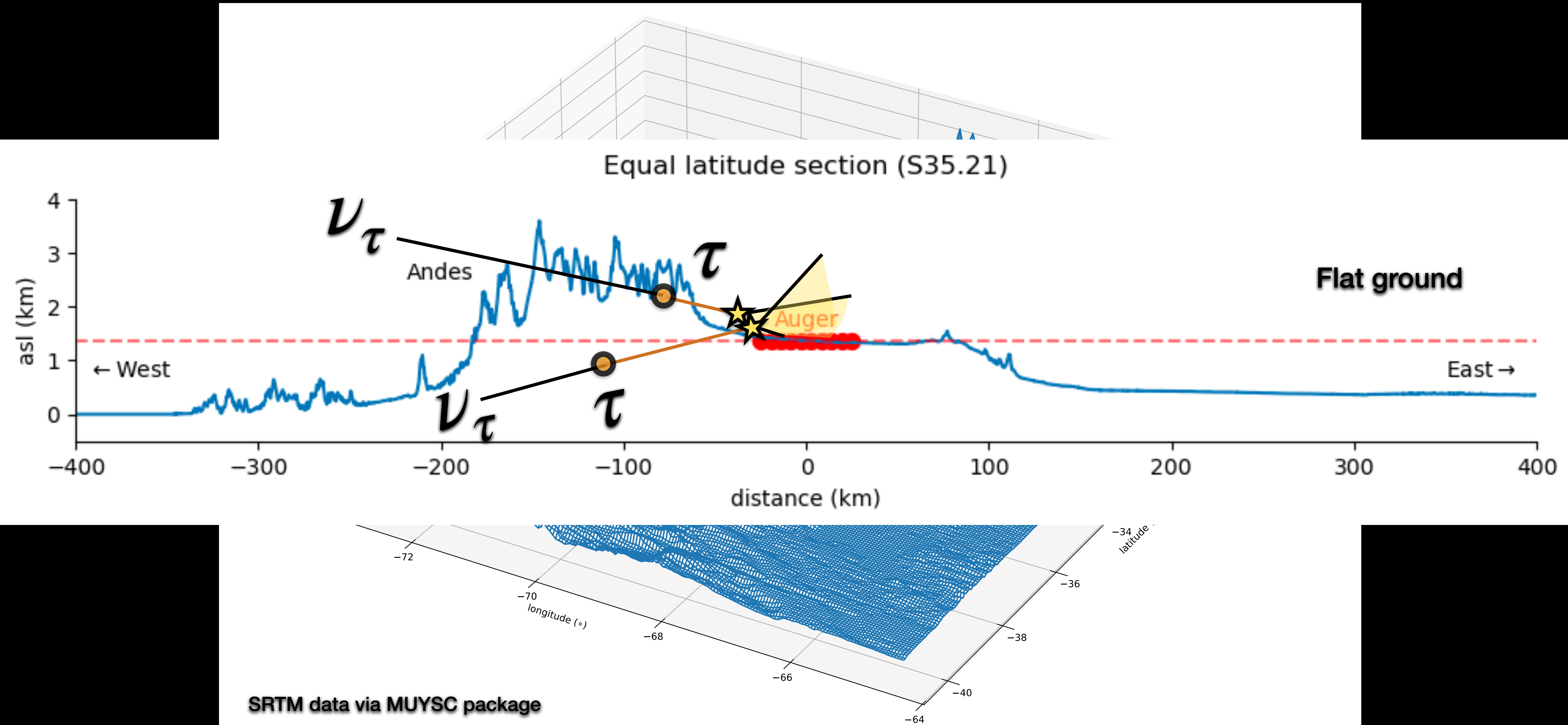
Cherenkov
cone

Coherent radio
emission

Neutrino detection with radio antenna from the Andes



Neutrino detection with radio antenna from the Andes



Summary and conclusion

- ◆ The Pierre Auger Observatory is a 4π Multi-Messenger Observatory for UHECR, Photons, Neutrinos, and BSM particles
- ◆ The sensitivity to upwards-going air showers allowed us to check the ANITA „anomalous events“
 - ➡ We would have expected (under sensible assumptions) several events in the Auger fluorescence telescopes
 - ➡ strong tension with ANITA events, which remain mysterious...
- ◆ 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
- ◆ Stay tuned for the AugerPrime upgrade — the largest radio detector in the world!

An aerial photograph of a university campus. The image shows a dense cluster of brick buildings with dark roofs, interspersed with green lawns and trees. A prominent feature is a large, modern glass-walled building on the right side. In the foreground, there's a large, curved building with a distinctive roofline. The word "Thanks!" is written in large, white, sans-serif font across the top center of the image. The overall scene is bright and sunny, with clear shadows cast by the buildings.

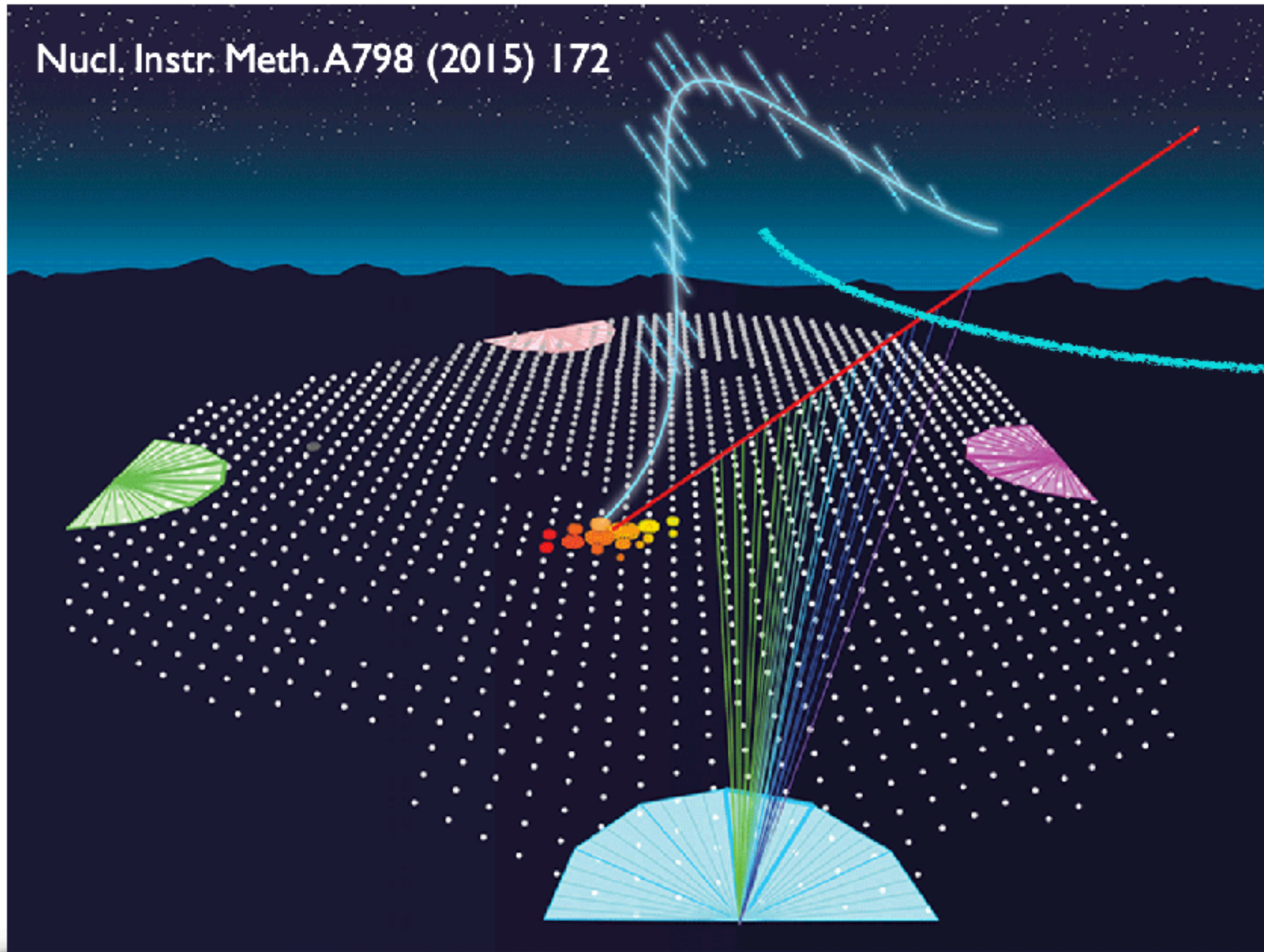
Thanks!

credit

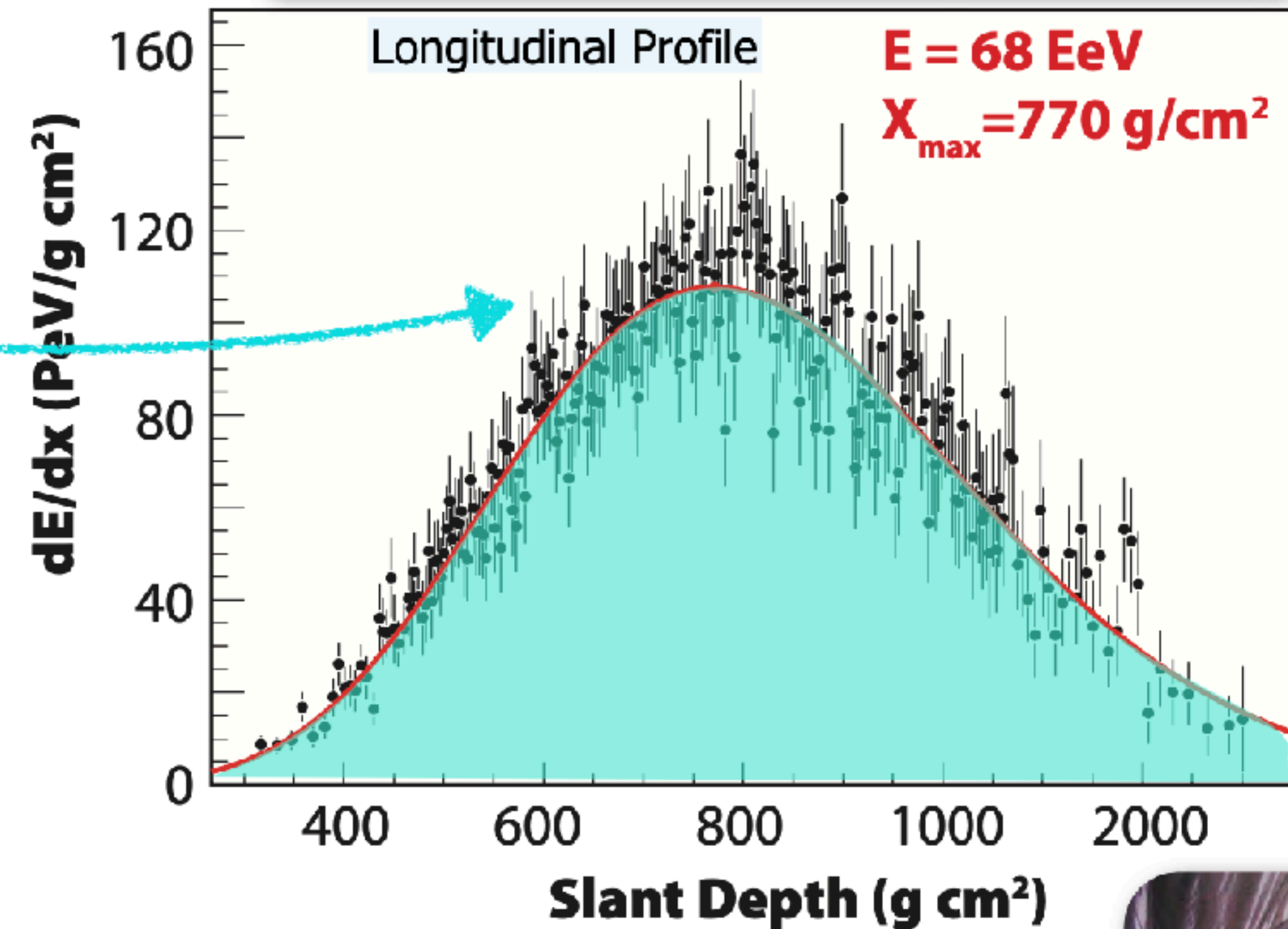
3, Up-going showers scenarios from Beyond Standard Model

Calibrating the Primary Energy

Nucl. Instr. Meth. A798 (2015) 172



absolute E-scale from light intensity

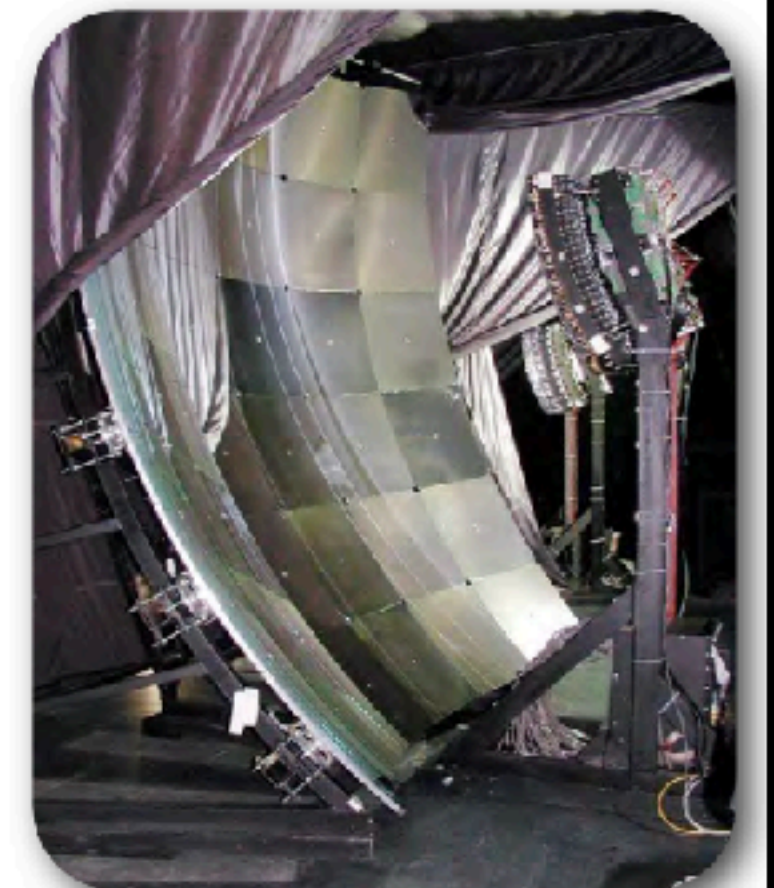


$$E_{cr} = \int \epsilon_{\gamma} \frac{dN_{\gamma}}{dx} dx = \int \frac{dE}{dx} dx$$

fluorescence yield

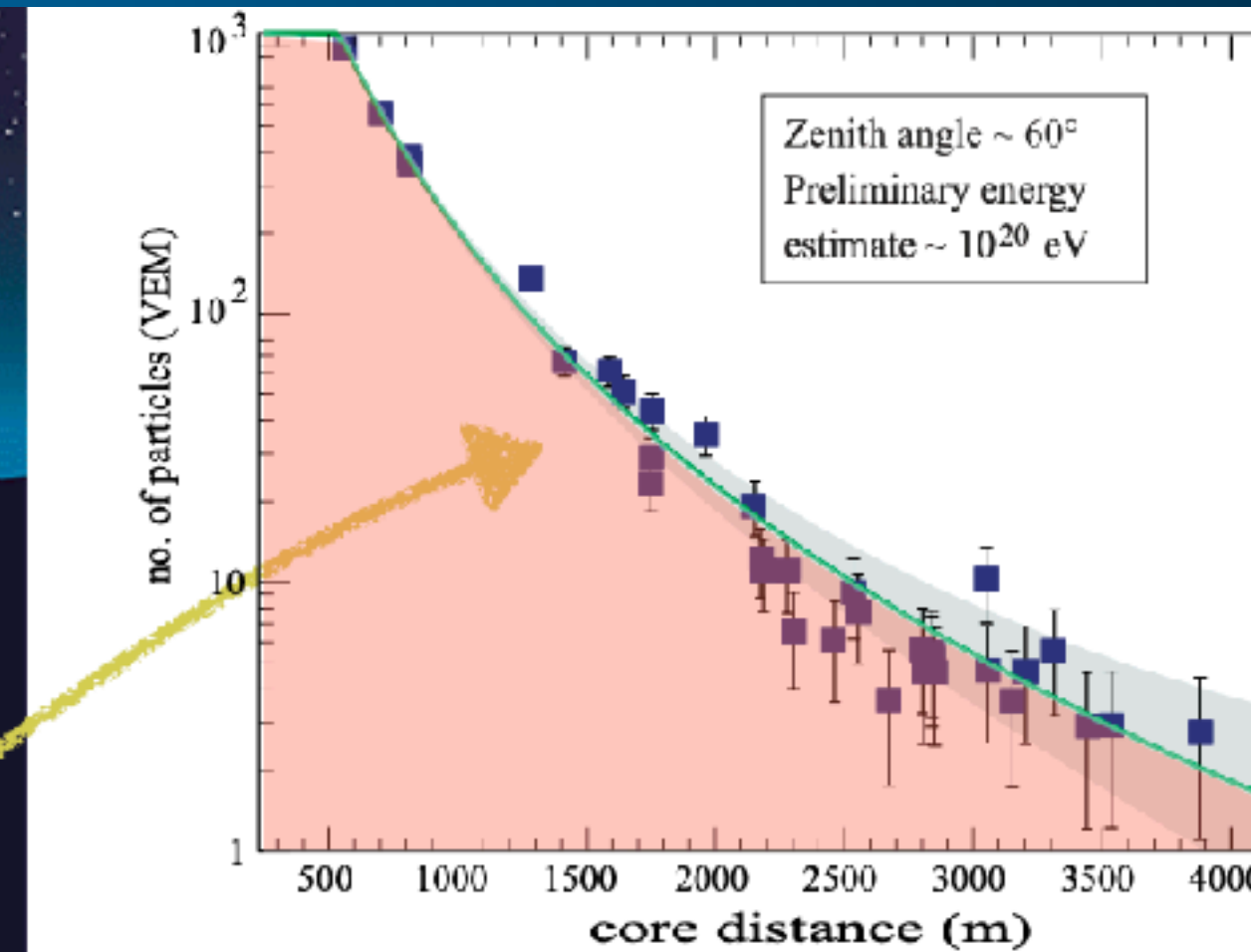
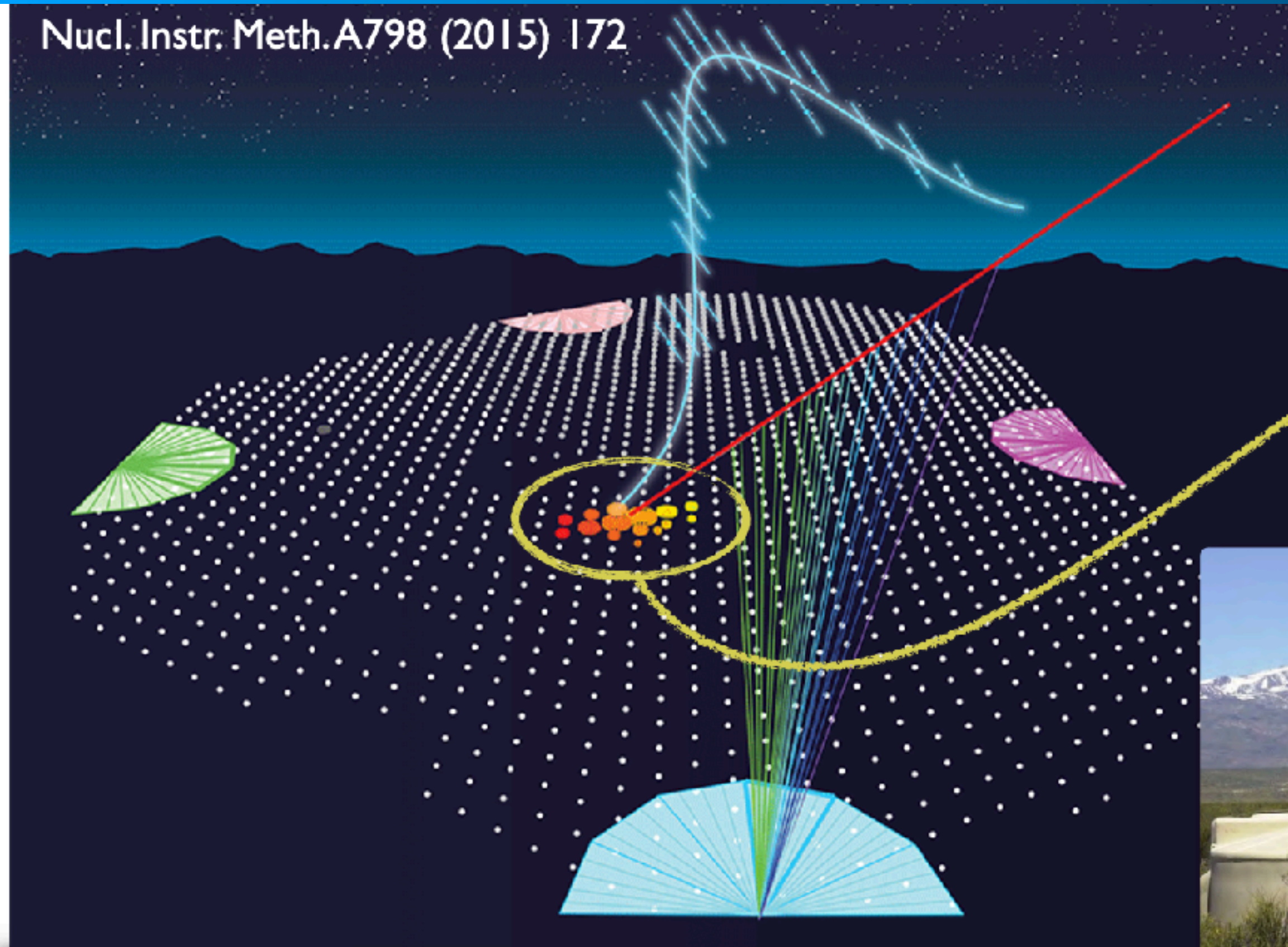


Slide from Karl-Heinz Kampert



Calibrating the Primary Energy

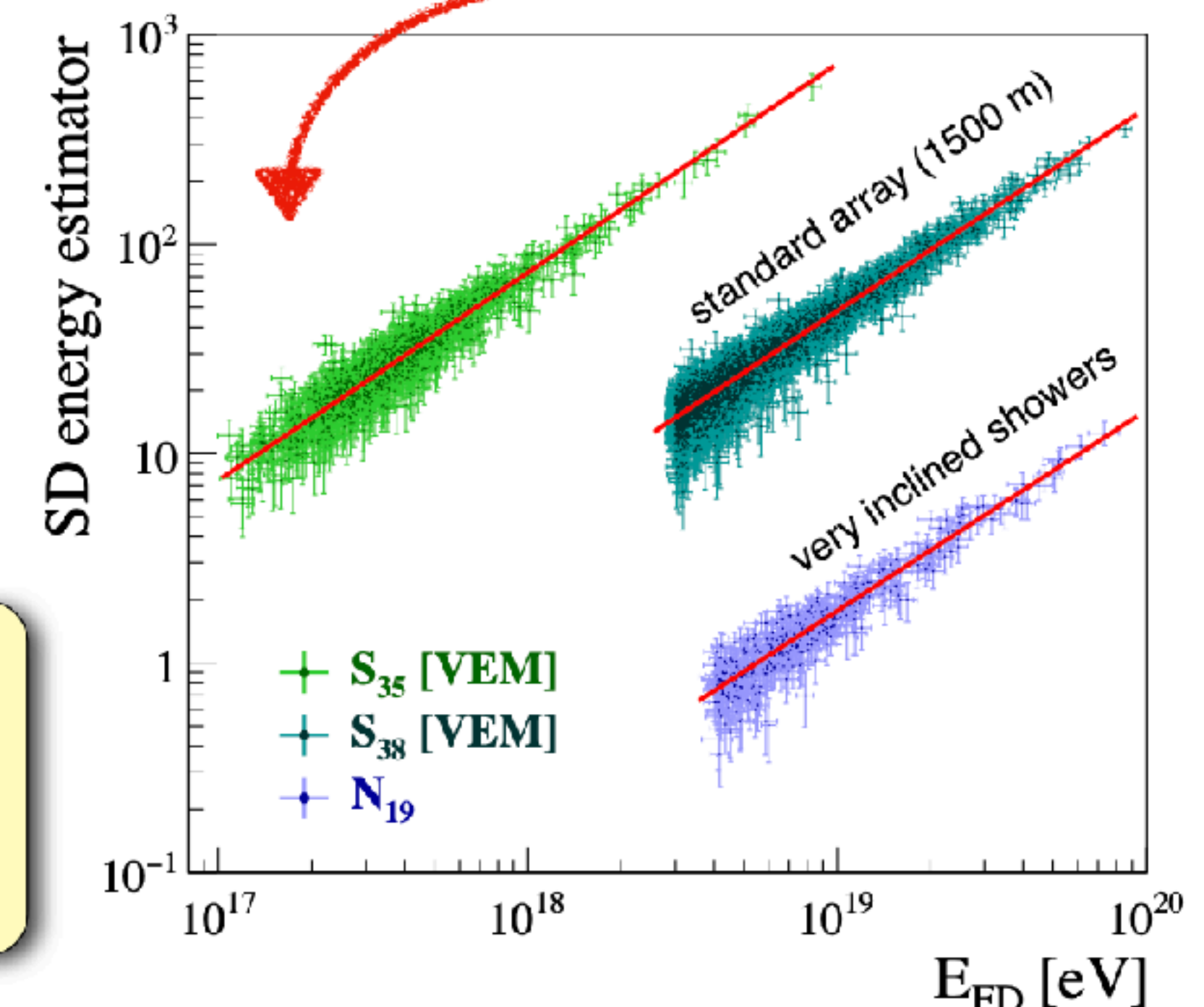
Nucl. Instr. Meth. A798 (2015) 172



Fit of particle density as a fct of distance from shower core
→ $\rho(r)$

$$S_{tot} = \int 2\pi r \rho(r) dr$$

Normalise S_{tot} to specific zenith angle → S_{38} , etc

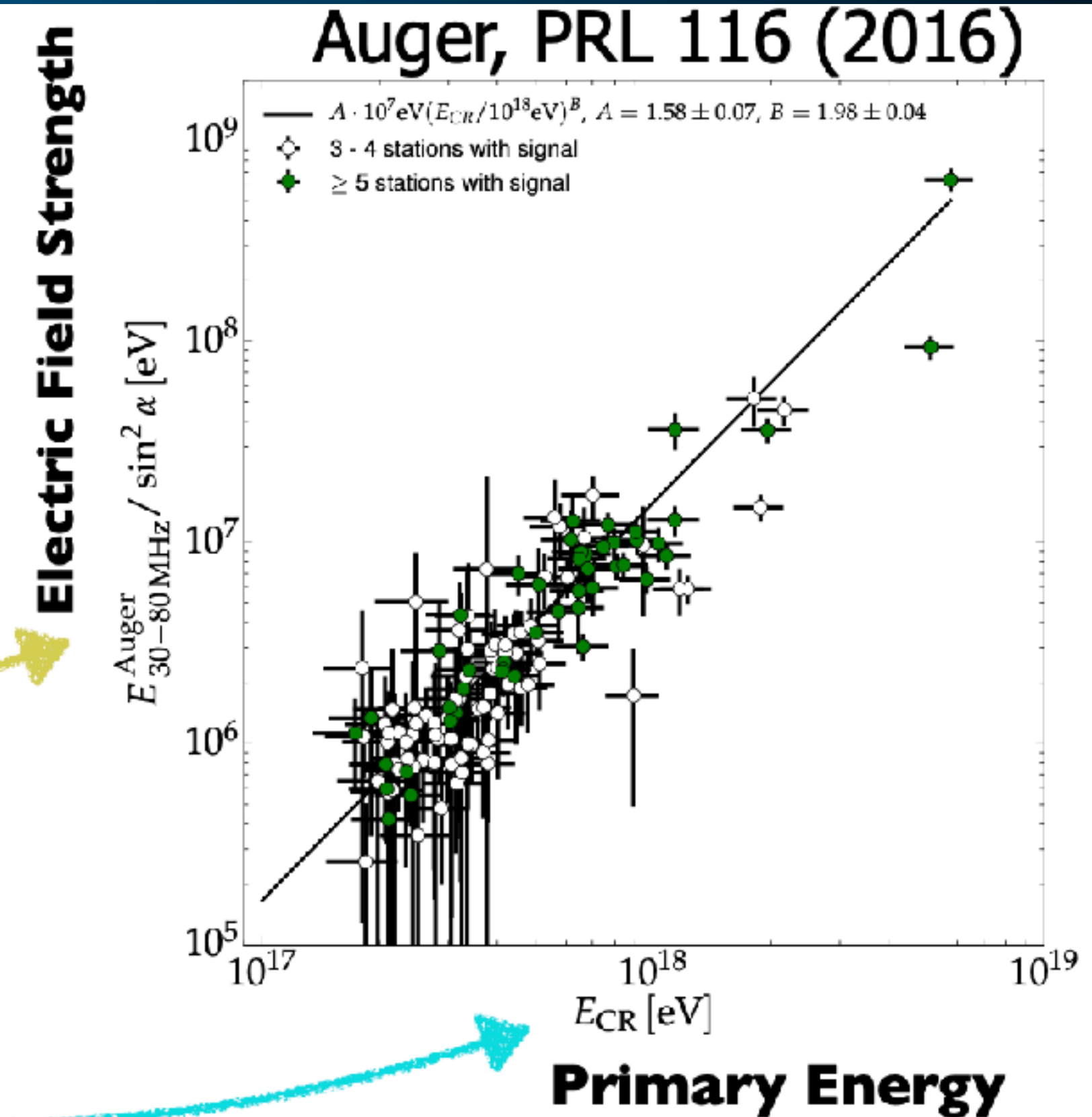
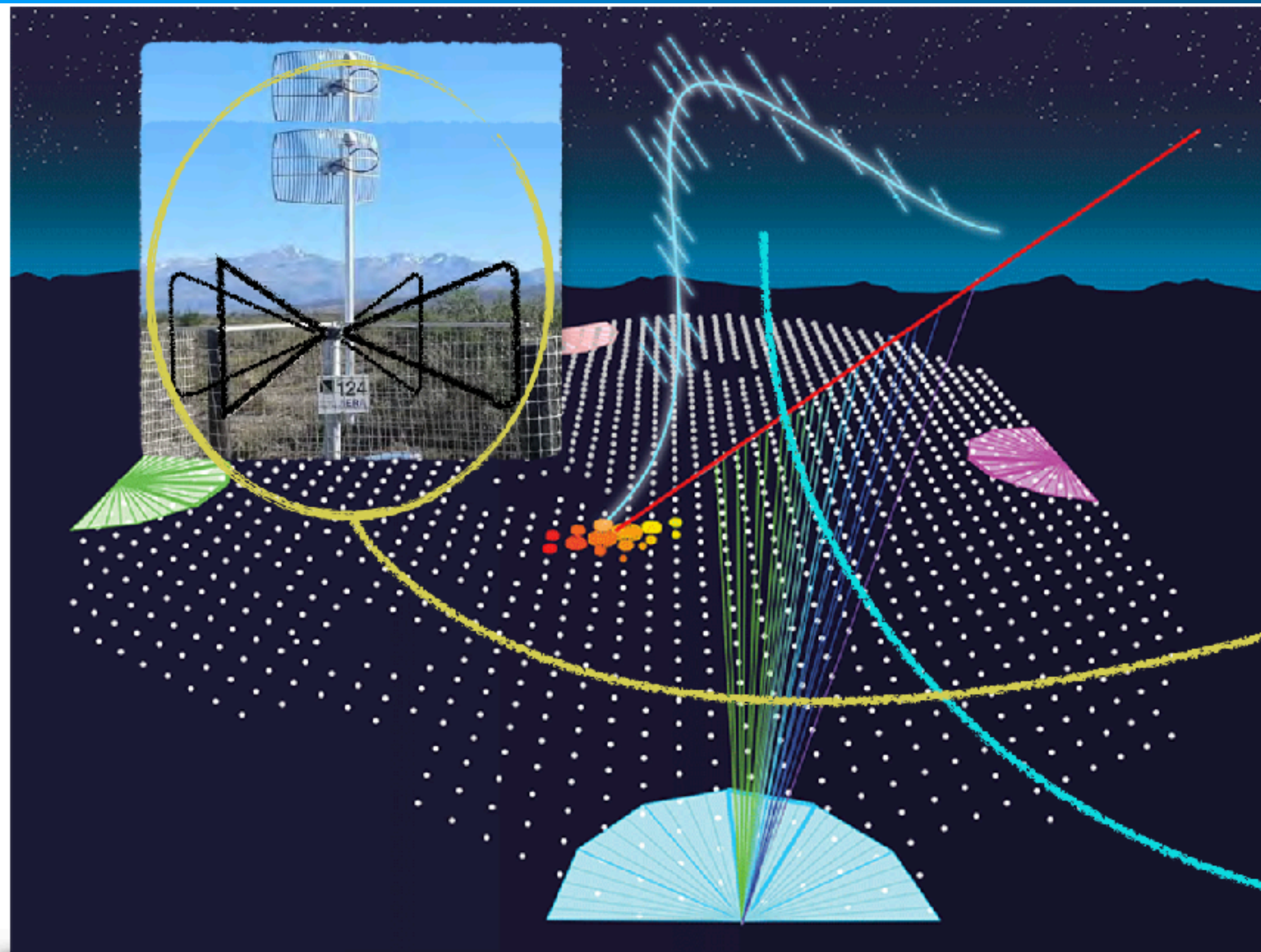


Note, this way the surface detector array is calibrated by the fluorescence telescopes, based on lab measurements!



Slide from Karl-Heinz Kampert

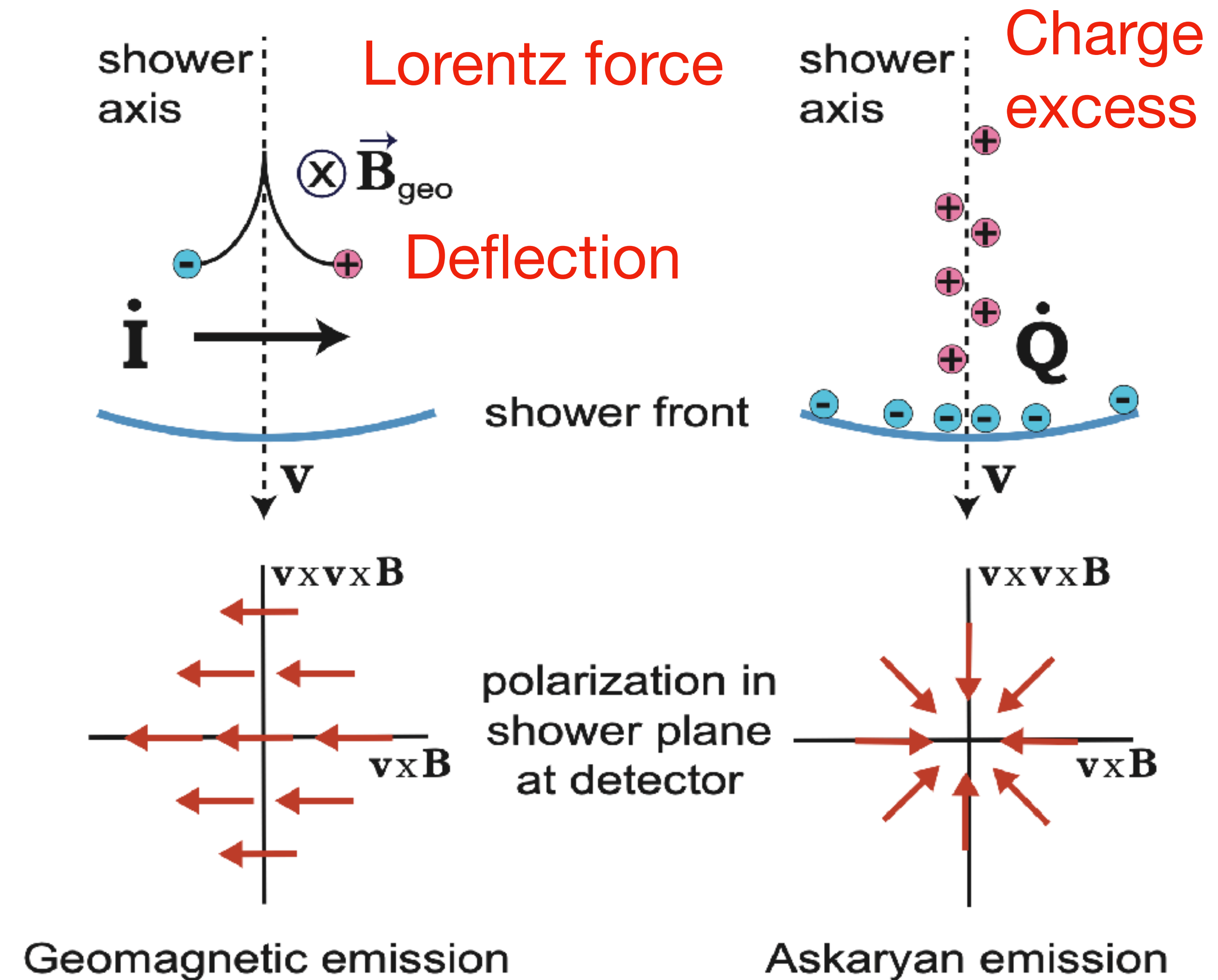
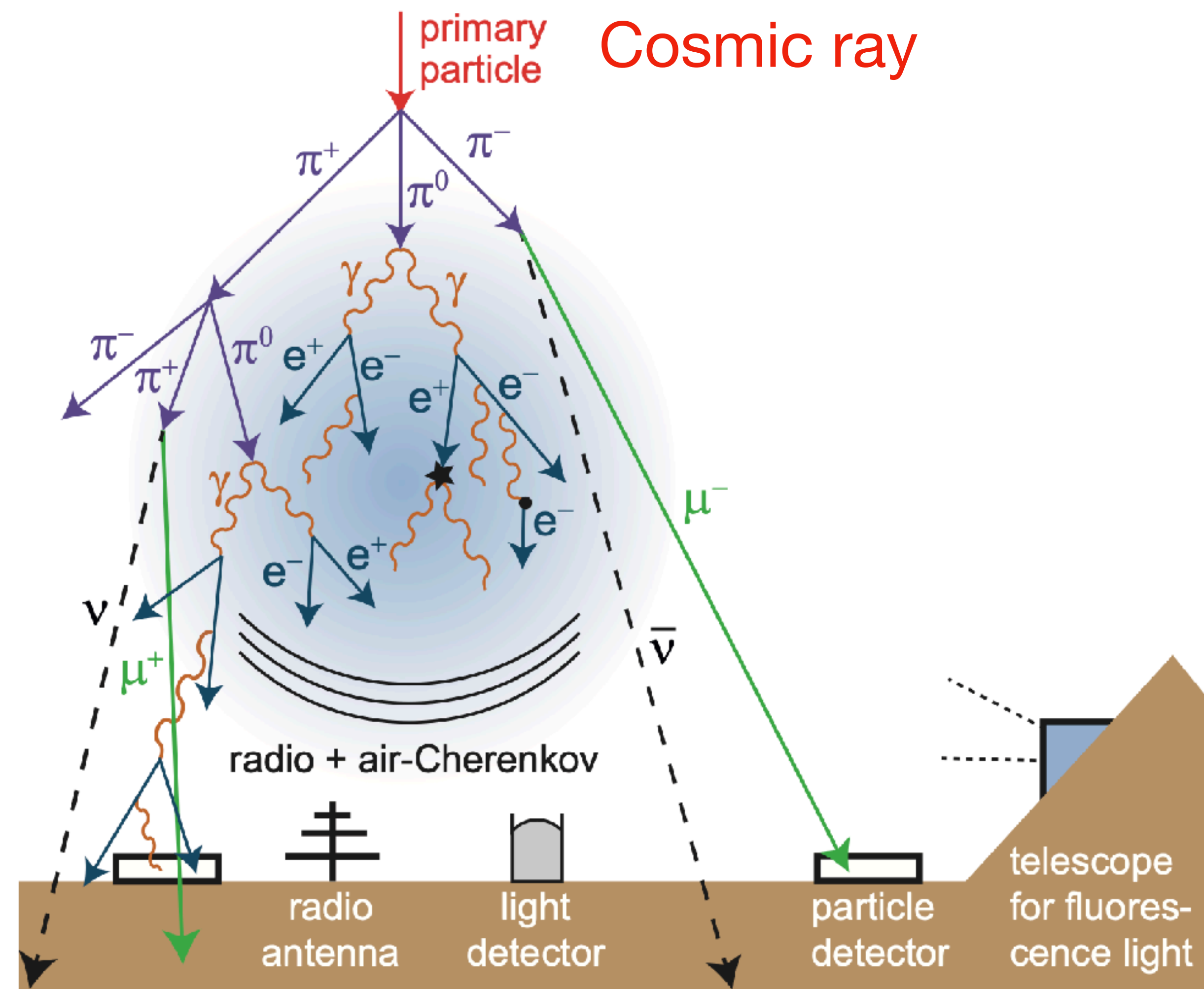
Calibrating the Primary Energy



Slide from Karl-Heinz Kampert

Absolute calibration of radio signal:
18 MeV energy radiated in radio signal @ 1 EeV

Radio emission from air showers

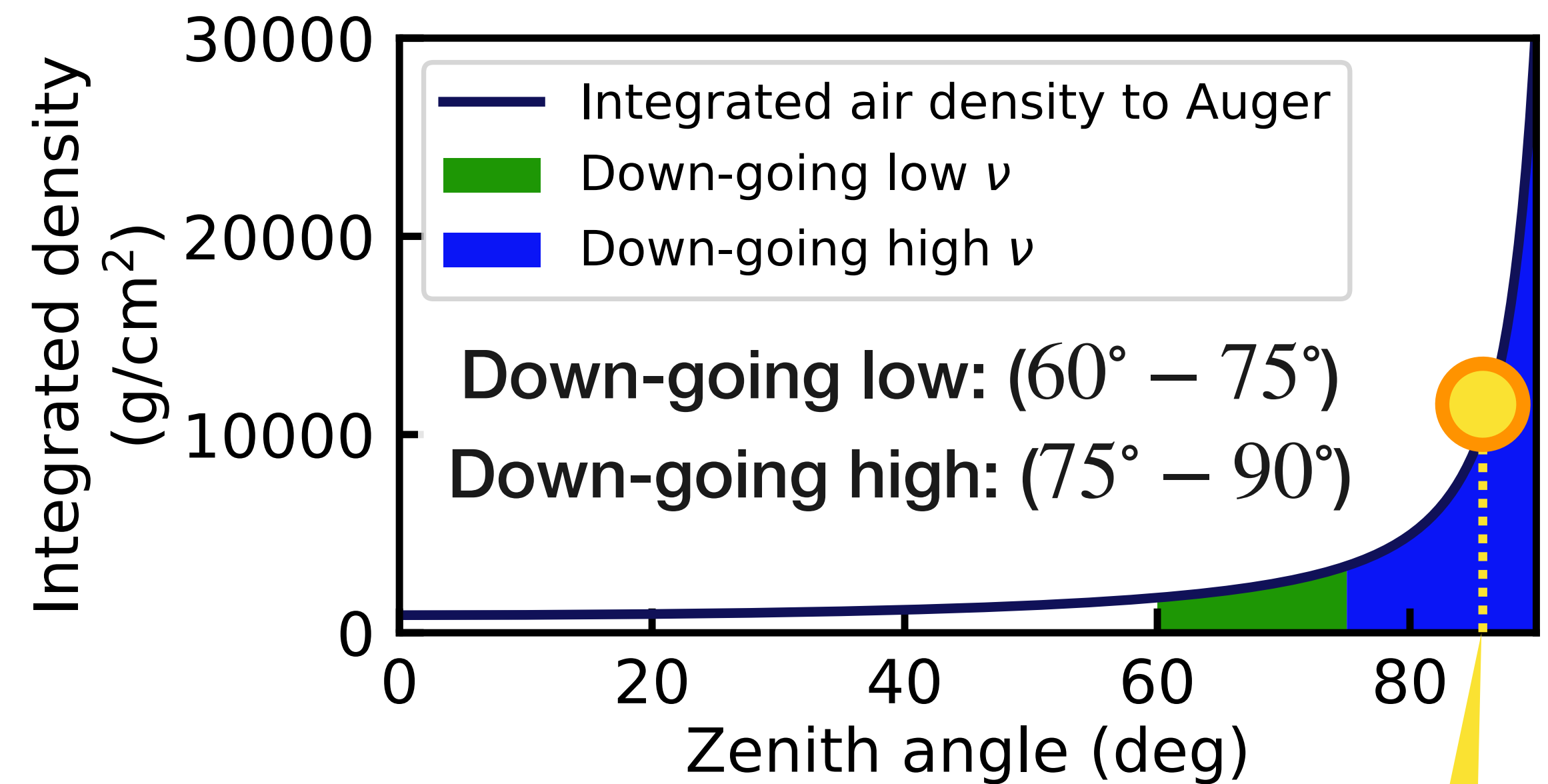
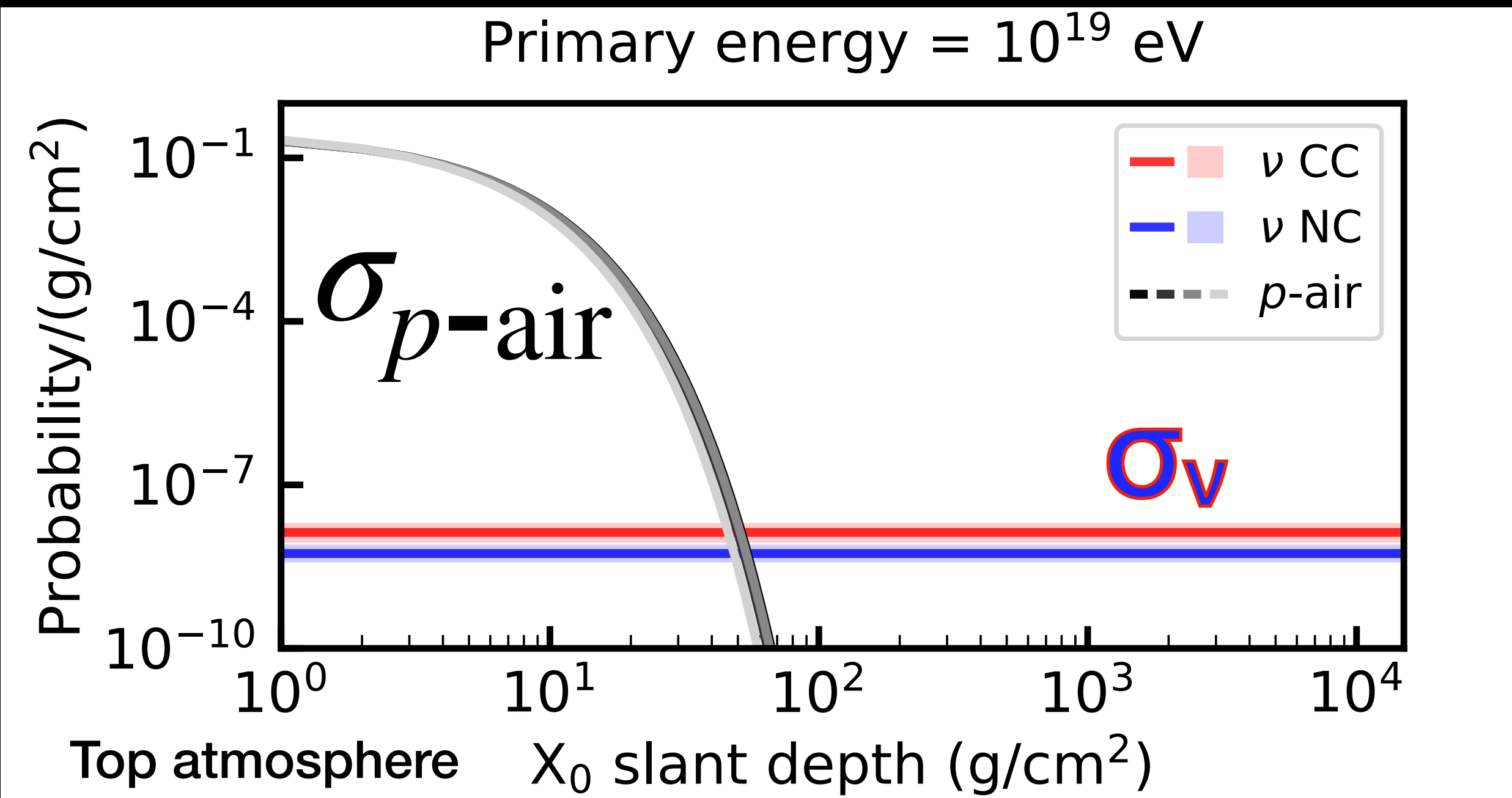


F. Schröder, Progress in Particle and Nuclear Physics 93 (2017) 1-68

Down-going Nu interaction probability

$\sigma_{p\text{-air}}$: <https://www.kaggle.com/code/augeropendata/proton-air-cross-section>
 σ_ν : PRD 83, 113009 (2011)

Curved atmosphere



85° integrated $P_{\nu_e\text{-CC}}$

10^{18} eV: 5.8×10^{-5}

10^{19} eV: 1.2×10^{-4}

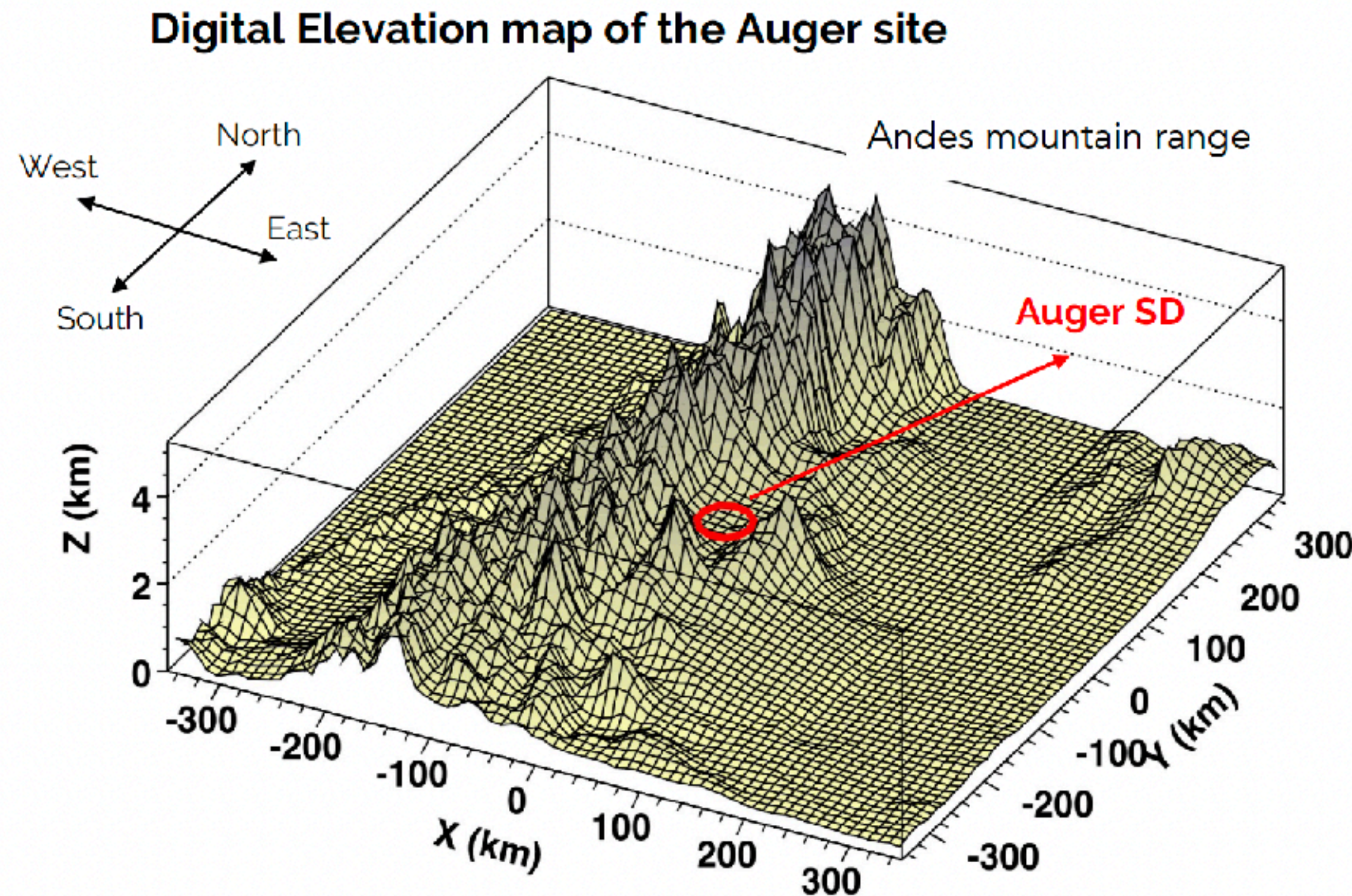
10^{20} eV: 2.4×10^{-4}

10^{21} eV: 4.5×10^{-4}

- Slant depth: the integration of matter density
- X_0 : the interaction slant depth
- More slant depth and more neutrinos — very inclined angle

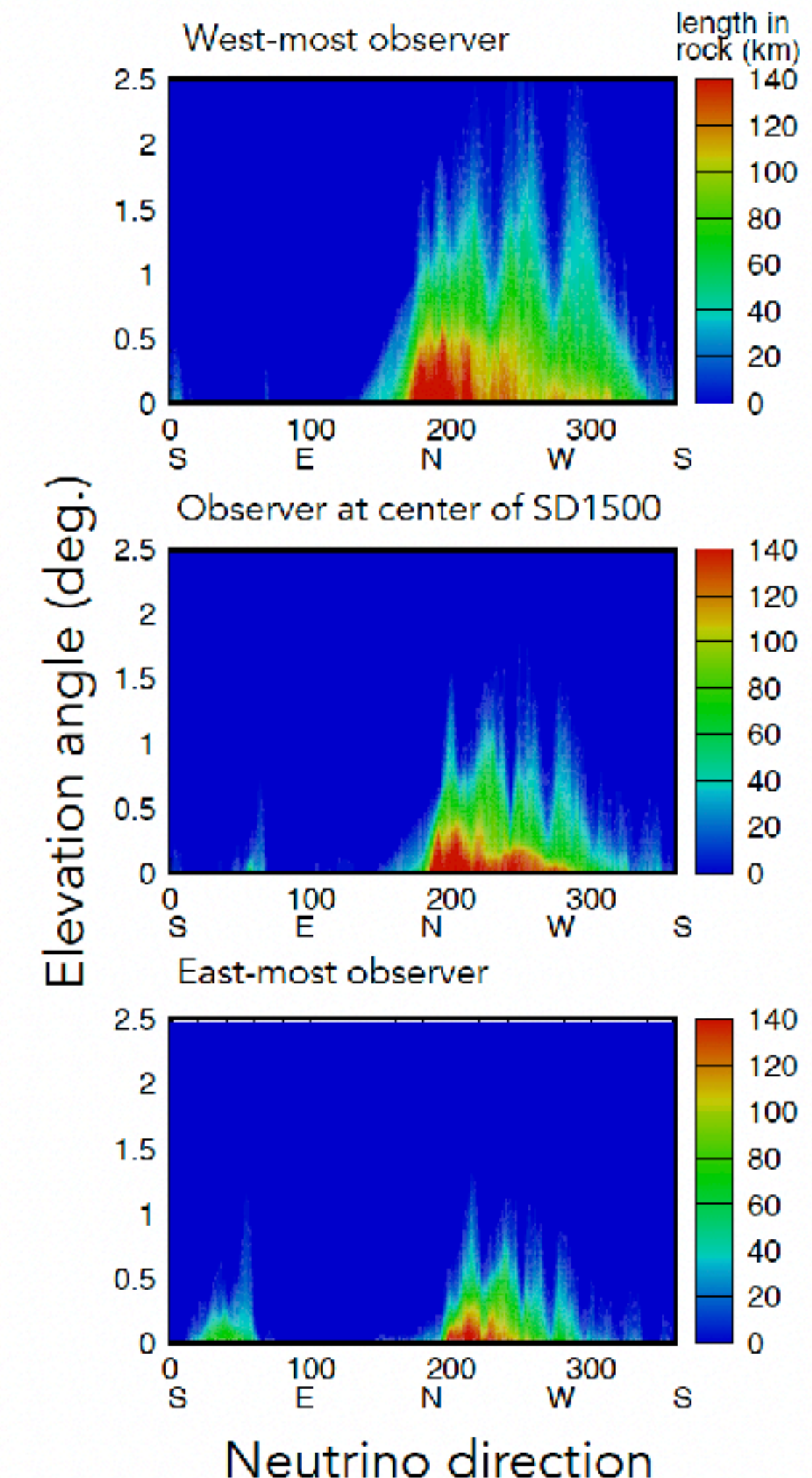
Auger Phase 1: Neutrino from the topography

Role of topography at Auger site



- Topography affects both Earth-Skimming ($90^\circ - 95^\circ$) & downward-going ($88^\circ - 90^\circ$) channels
- Topography contributes (roughly) 17% to the TOTAL neutrino event rate (assuming an E^{-2} flux)

Length in rock (km) vs direction for observers at different locations in the SD1500



Selection of neutrinos in Auger

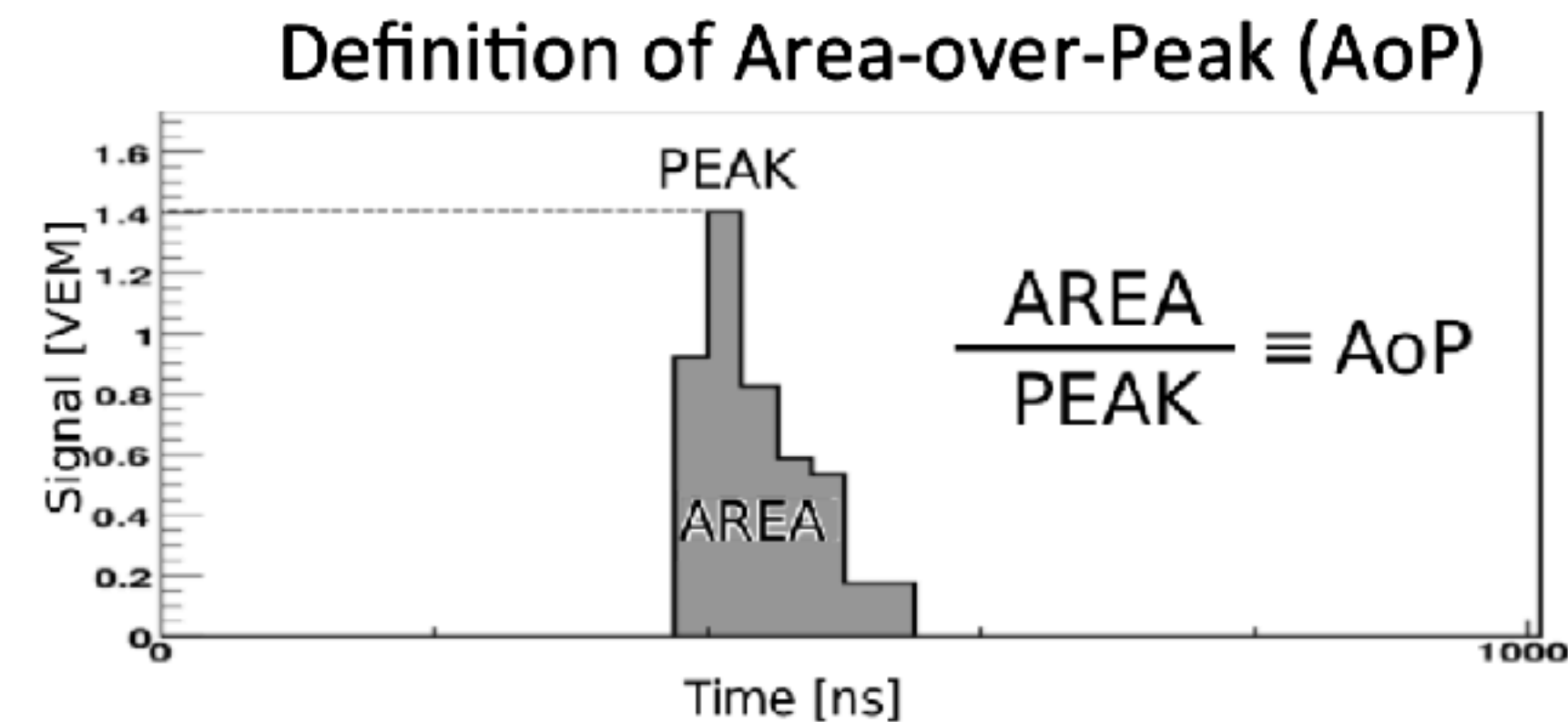
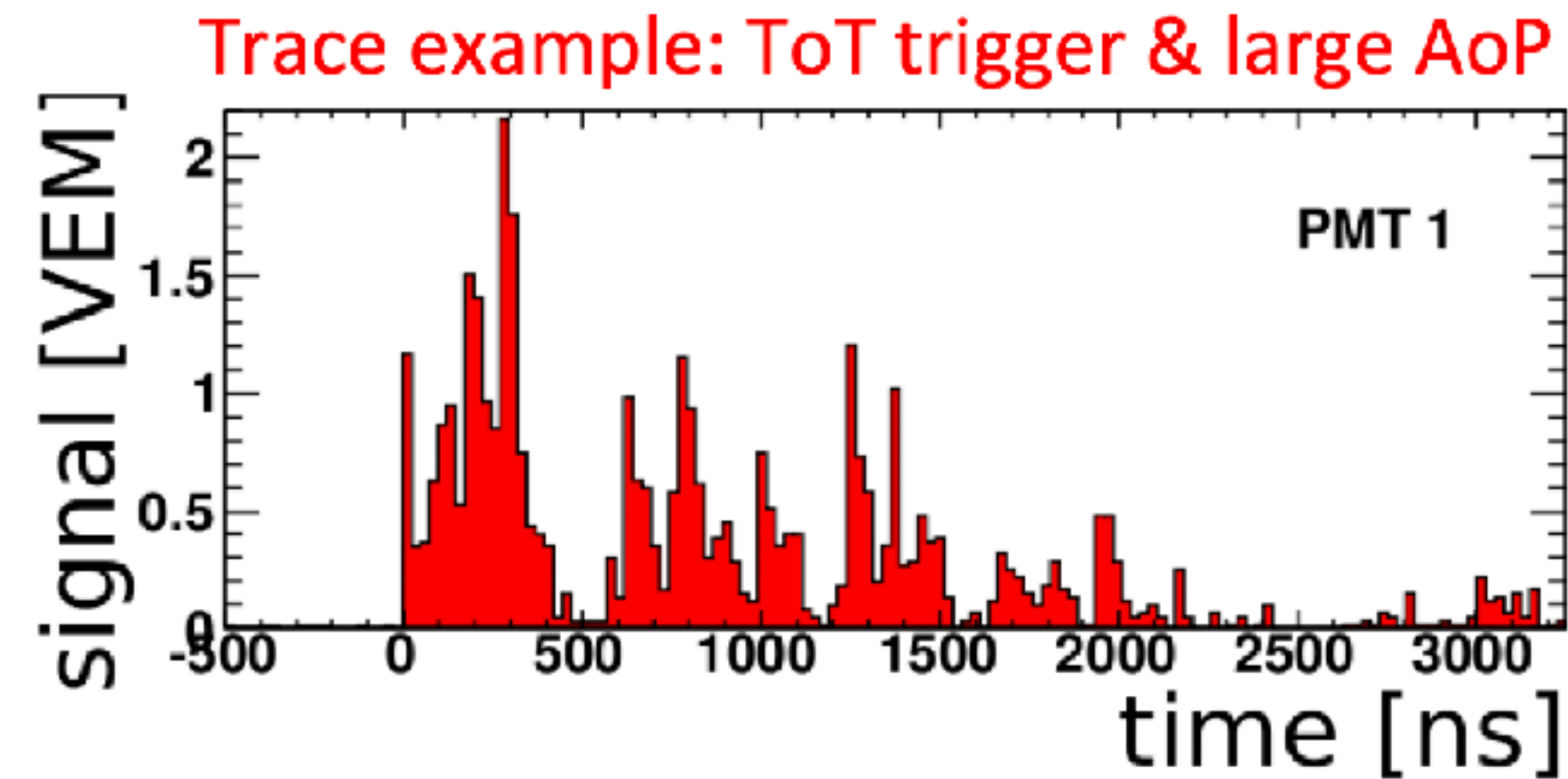
Selection	Earth-skimming (ES)	Downward-going <i>high</i> angle (DGH)	Downward-going <i>low</i> angle (DGL)
Flavours & Interactions	ν_τ CC	ν_e, ν_μ, ν_τ CC & NC	ν_e, ν_μ, ν_τ CC & NC
Angular range	$\theta > 90^\circ$	$\theta \in (75^\circ, 90^\circ)$	$\theta \in (60^\circ, 75^\circ)$
N° of Stations (N_{st})	$N_{\text{st}} \geq 3$	$N_{\text{st}} \geq 4$	$N_{\text{st}} \geq 4$
Inclined	—	$\theta_{\text{rec}} > 75^\circ$	$\theta_{\text{rec}} \in (58.5^\circ, 76.5^\circ)$
Showers	$L/W > 5$ $\langle V \rangle \in (0.29, 0.31) \text{ m ns}^{-1}$ $\text{RMS}(V) < 0.08 \text{ m ns}^{-1}$	$L/W > 3$ $\langle V \rangle < 0.313 \text{ m ns}^{-1}$ $\text{RMS}(V)/\langle V \rangle < 0.08$	— — —
Young Showers	Data: 1 January 2004 - 31 May 2010 $\geq 60\%$ of stations with ToT trigger & AoP > 1.4 Data: 1 June 2010 - 20 June 2013 $\langle \text{AoP} \rangle > 1.83$ $\text{AoP}_{\text{min}} > 1.4$ if $N_{\text{st}}=3$	Fisher discriminant based on AoP of <i>early</i> stations	$\geq 75\%$ of stations close to shower core with ToT trigger & Fisher discriminant based on AoP of <i>early</i> stations close to shower core

Table I. Observables and numerical values of cuts applied to select *inclined* and *young* showers for Earth-skimming and downward-going neutrinos. See text for explanation.

Identifying neutrinos

From the observational point of view, signals extended in time:

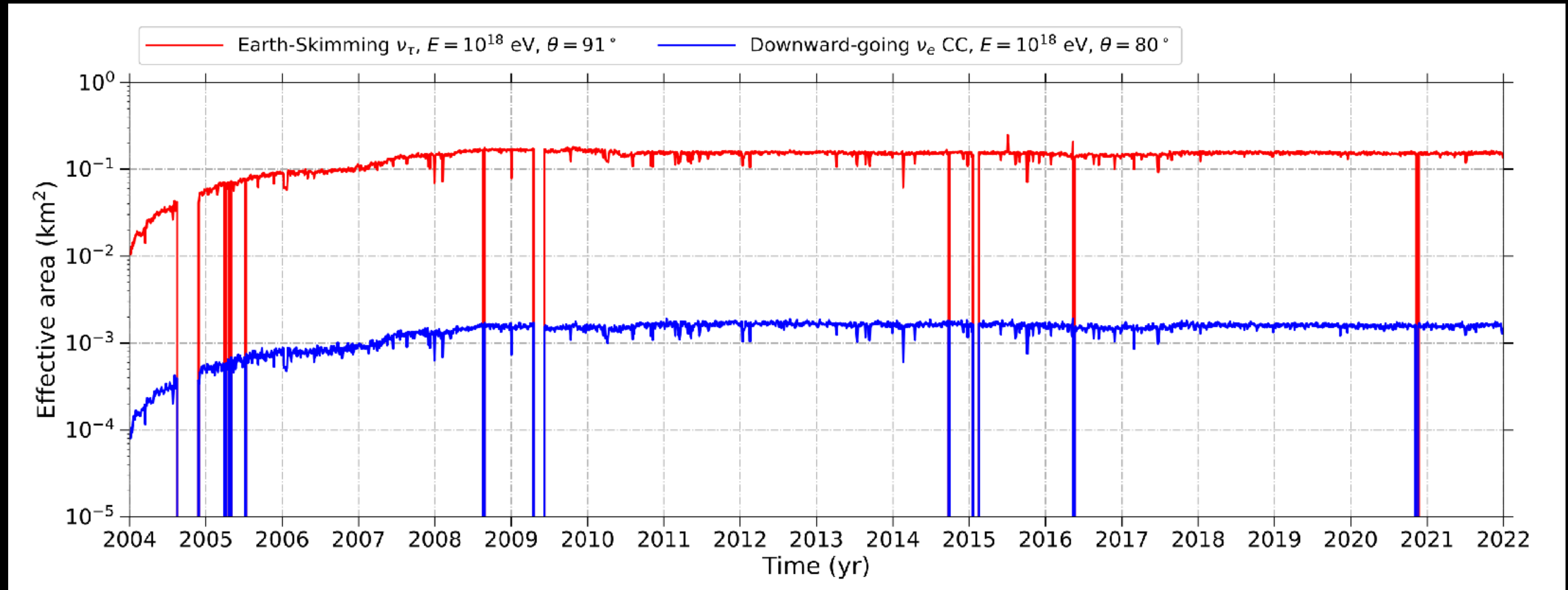
- Induce Time-over-Threshold (ToT) triggers in the SD stations
- and/or
- Have large Area-over-Peak value (AoP ~ 1 muonic front)



Searching for neutrinos $\Rightarrow$
Searching for inclined showers with stations
with ToT triggers and/or large AoP

Stability of the SD1500 array of the Pierre Auger Observatory

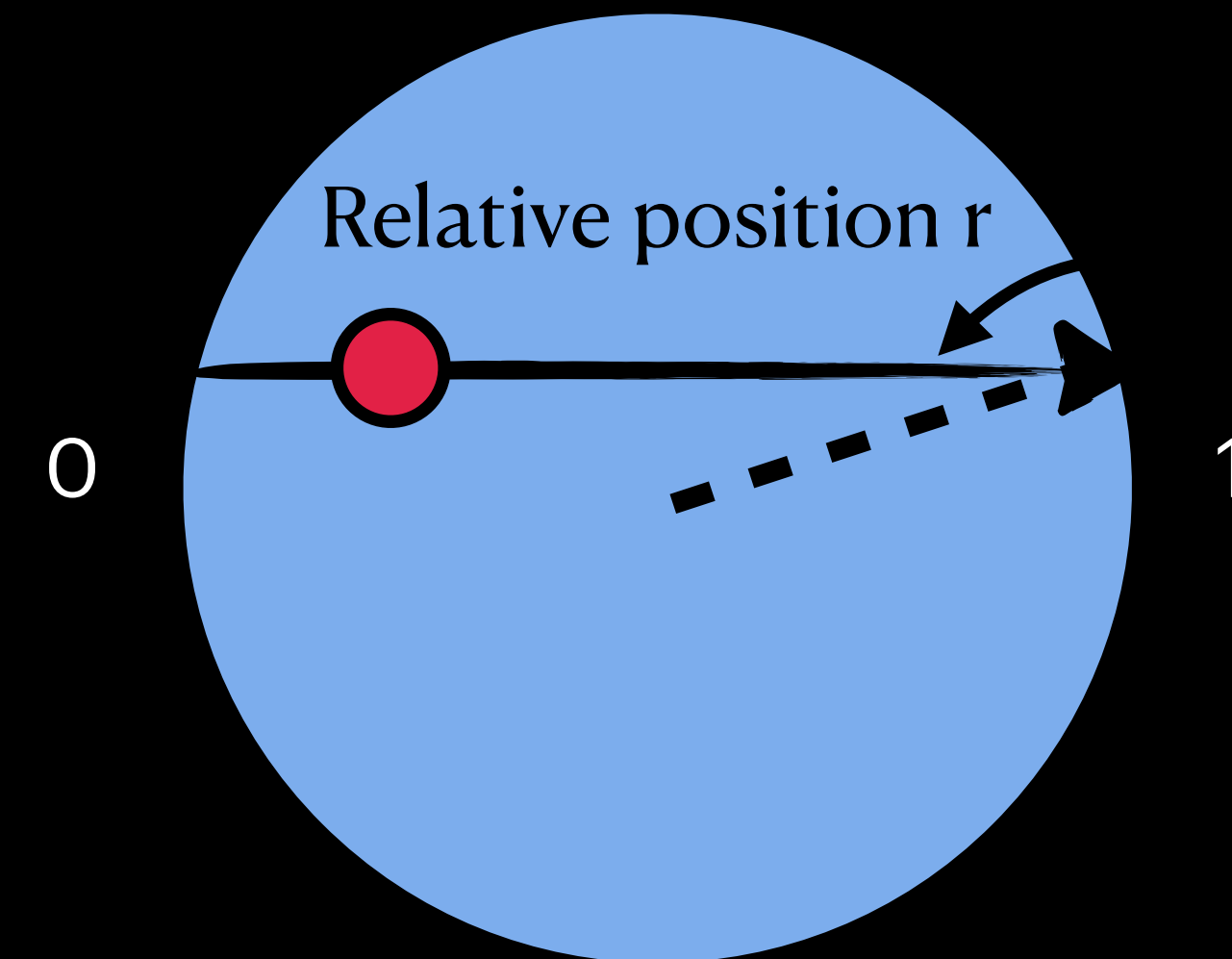
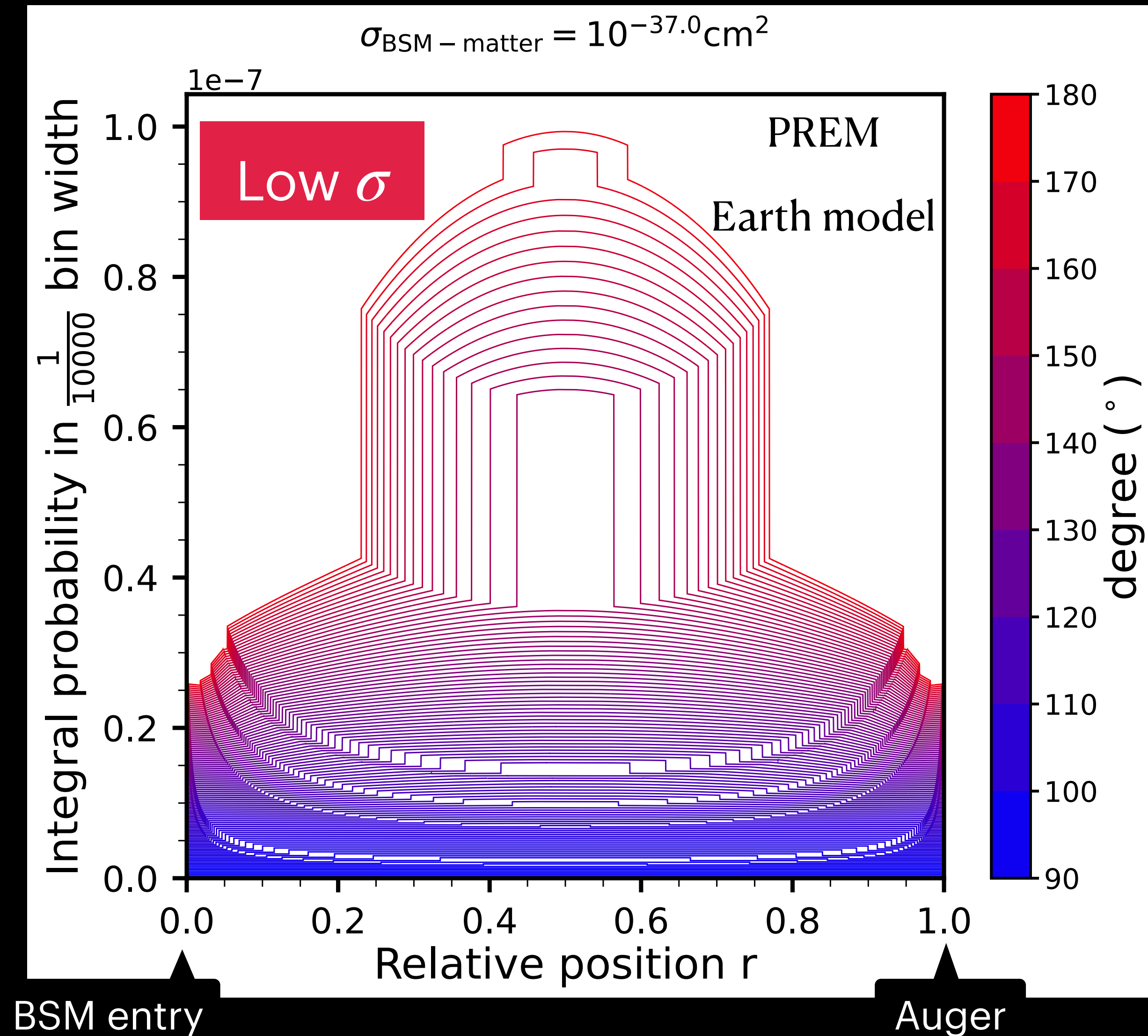
Effective area vs time for different neutrino channels



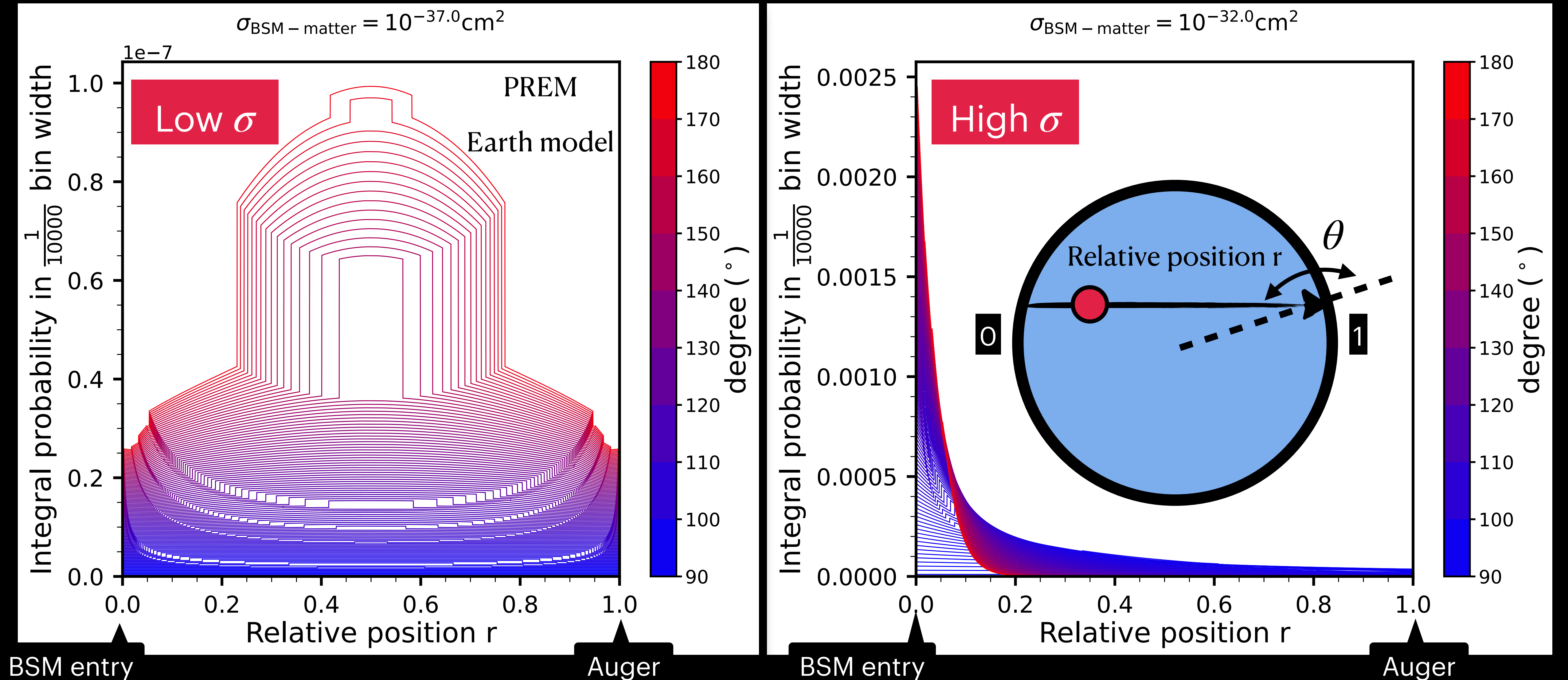
Construction period

Complete SD1500 period

BSM particle interaction profile inside the Earth



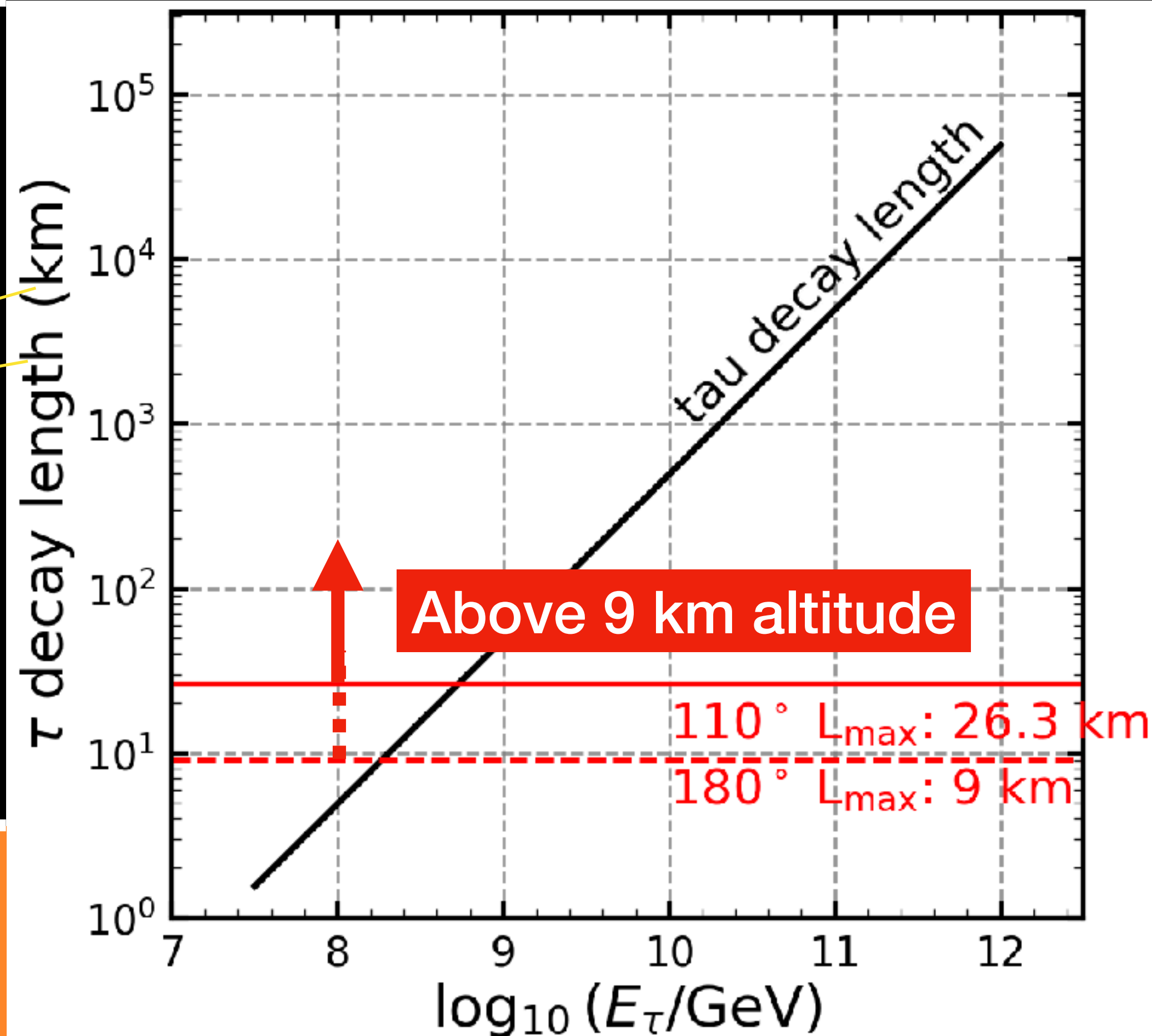
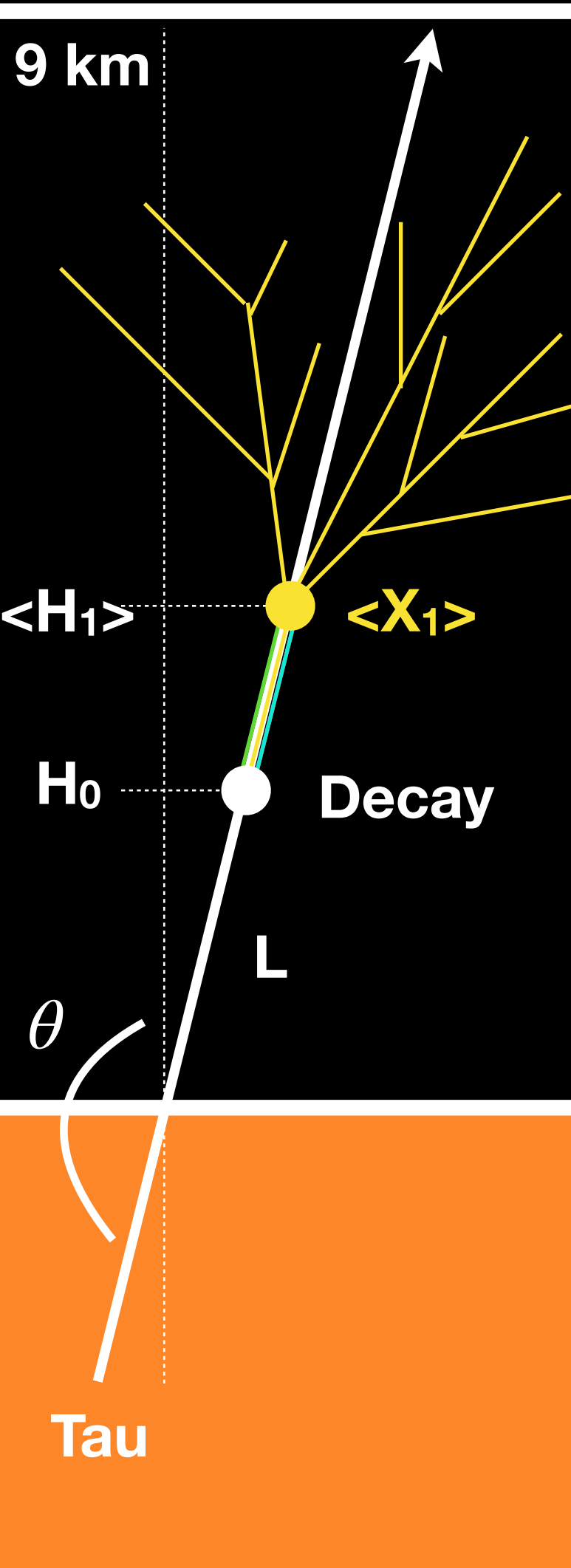
BSM particle interaction profile inside the Earth



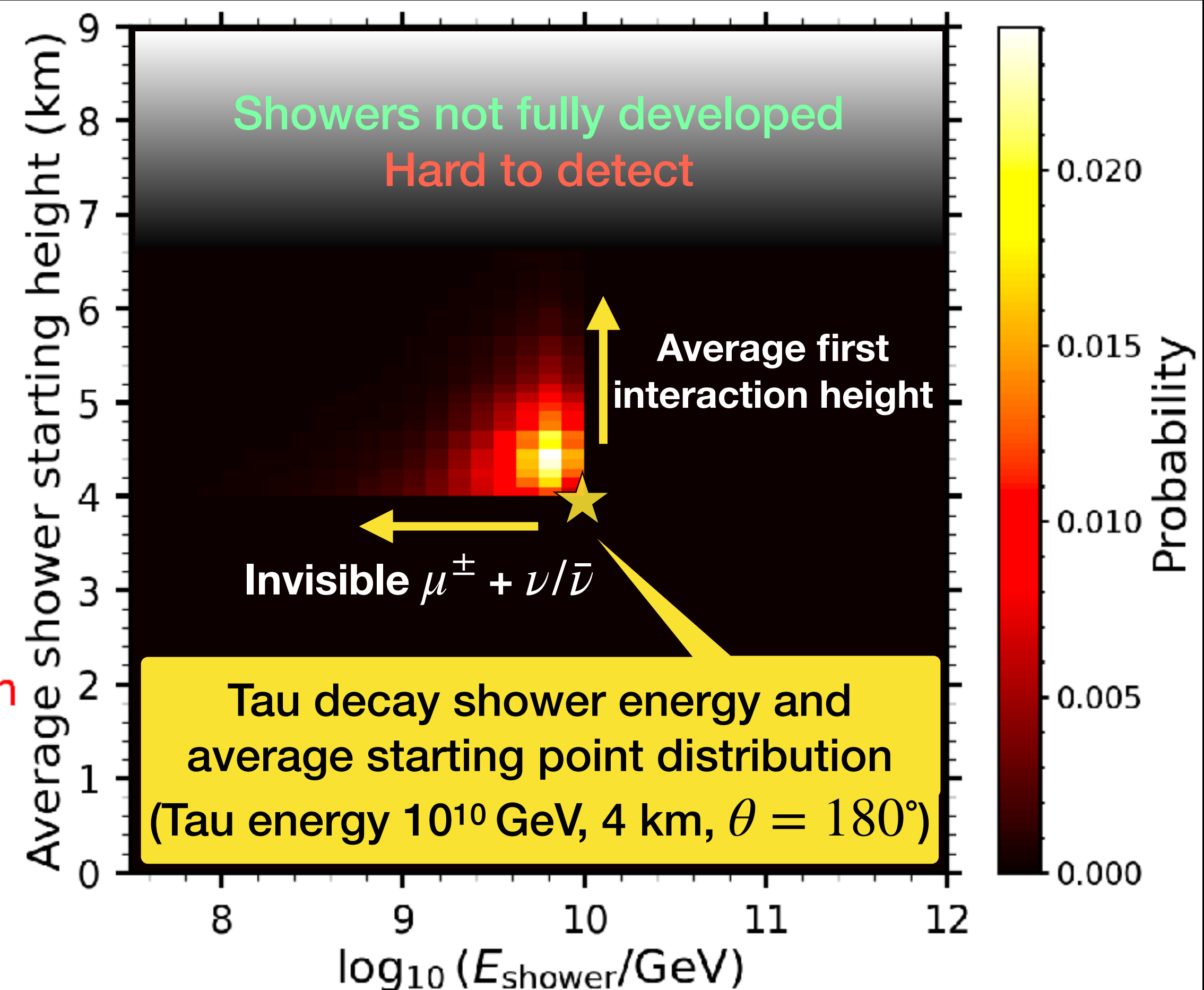
Tau decay showers and FD simulations

Simulation region

Simulation: tau decay (TAUOLA) + air density profile (TAUOLA arXiv:1002.0543)

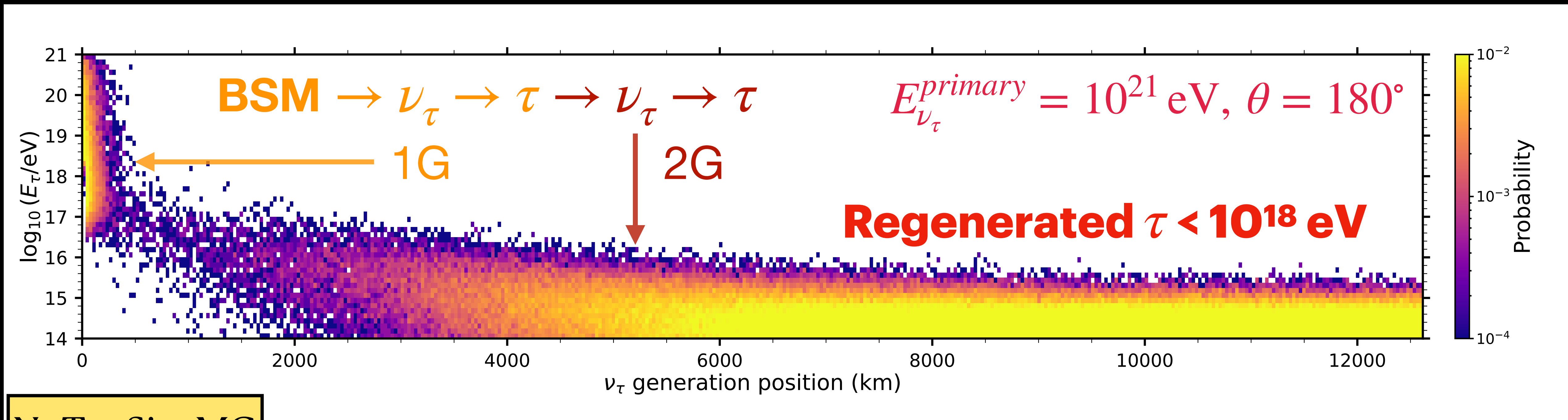


High energy taus have less probability to decay in the simulation region, where the showers are most likely to be seen.



~83% tau decay channel could be visible by FD.

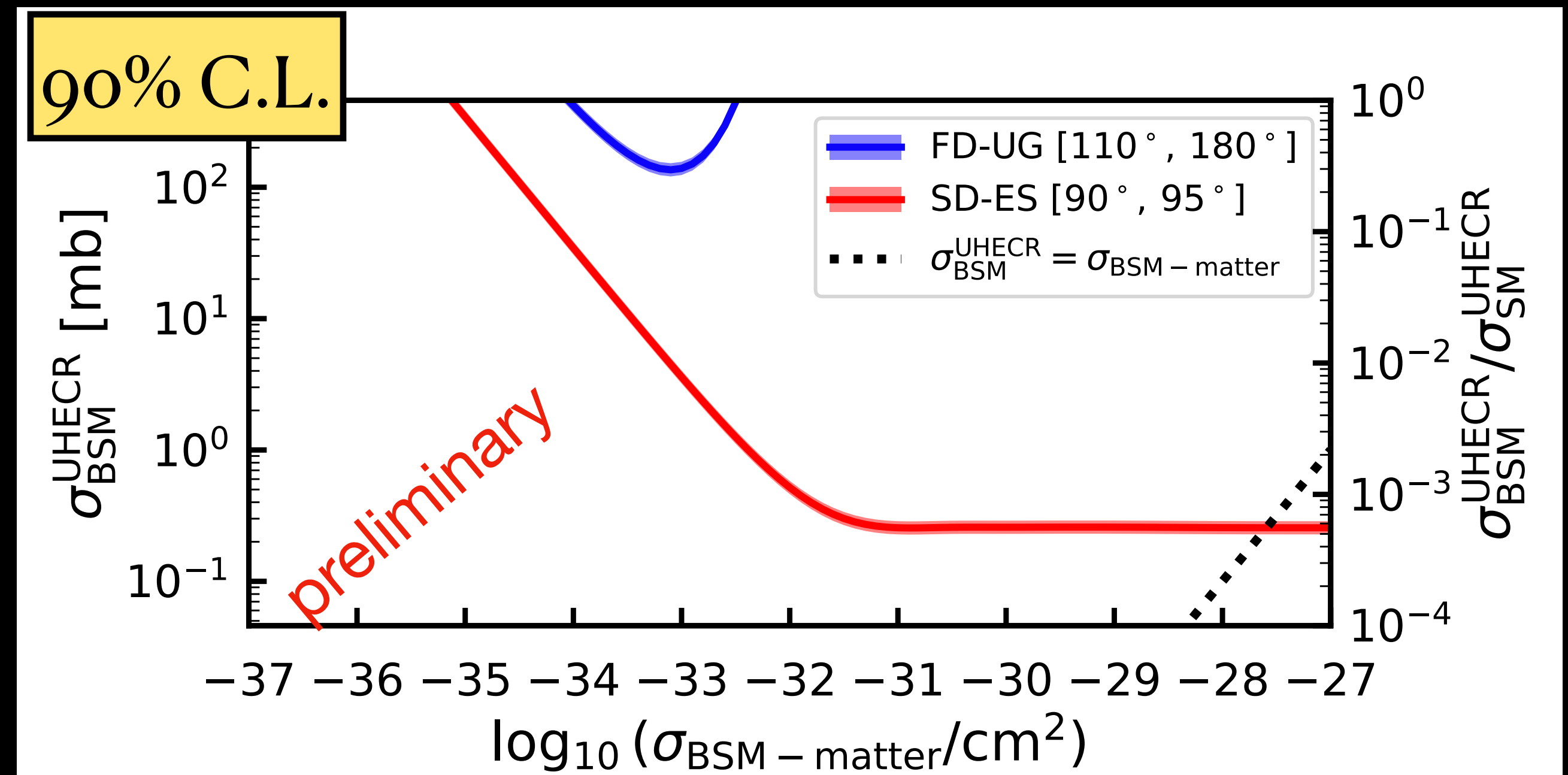
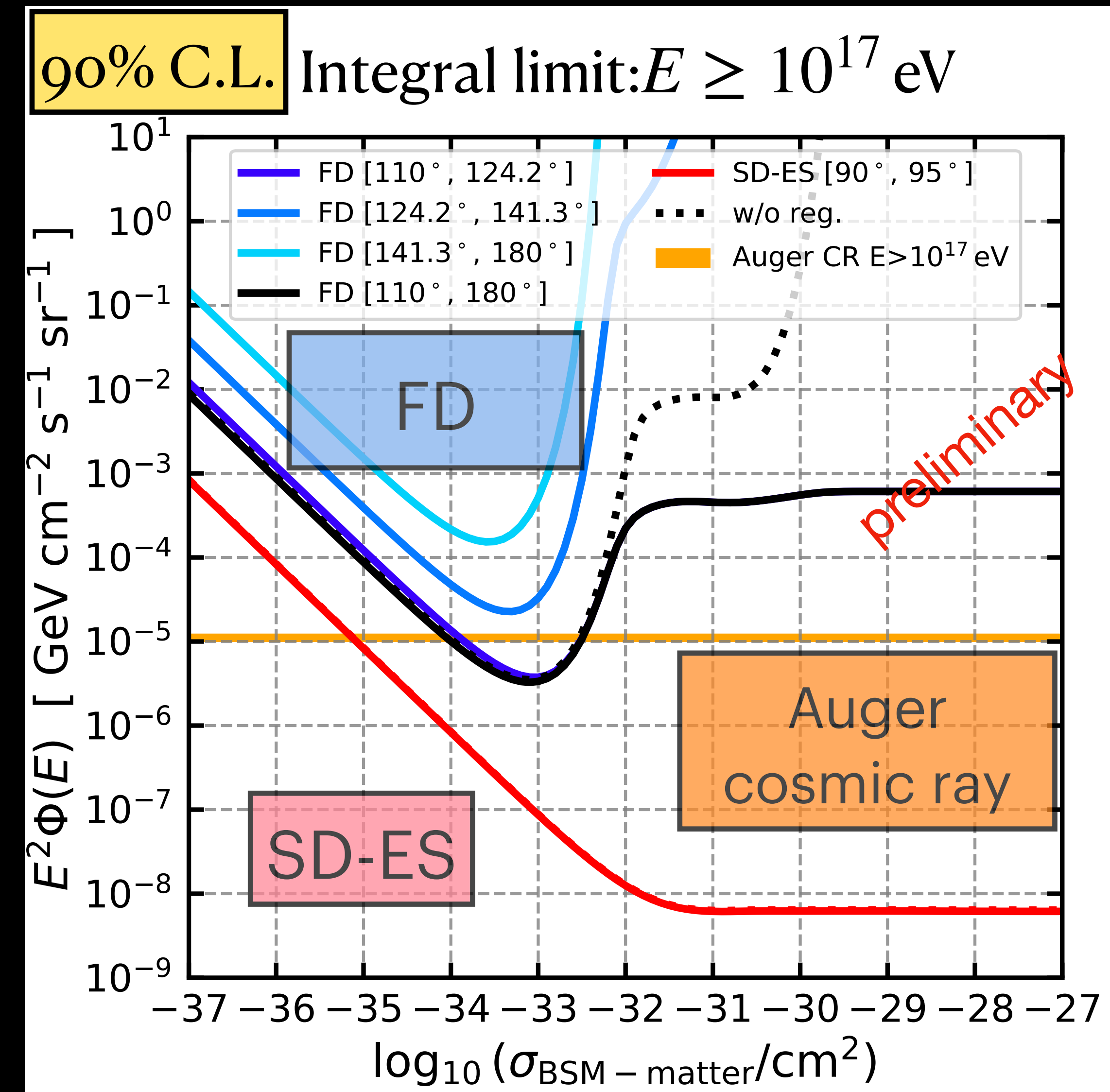
2, BSM - ν_τ model: ν_τ propagation simulation



NuTauSim MC

- BSM $\rightarrow \nu_\tau$: any newborn ν_τ generated beyond ~ 1000 km can only contribute by the regeneration.

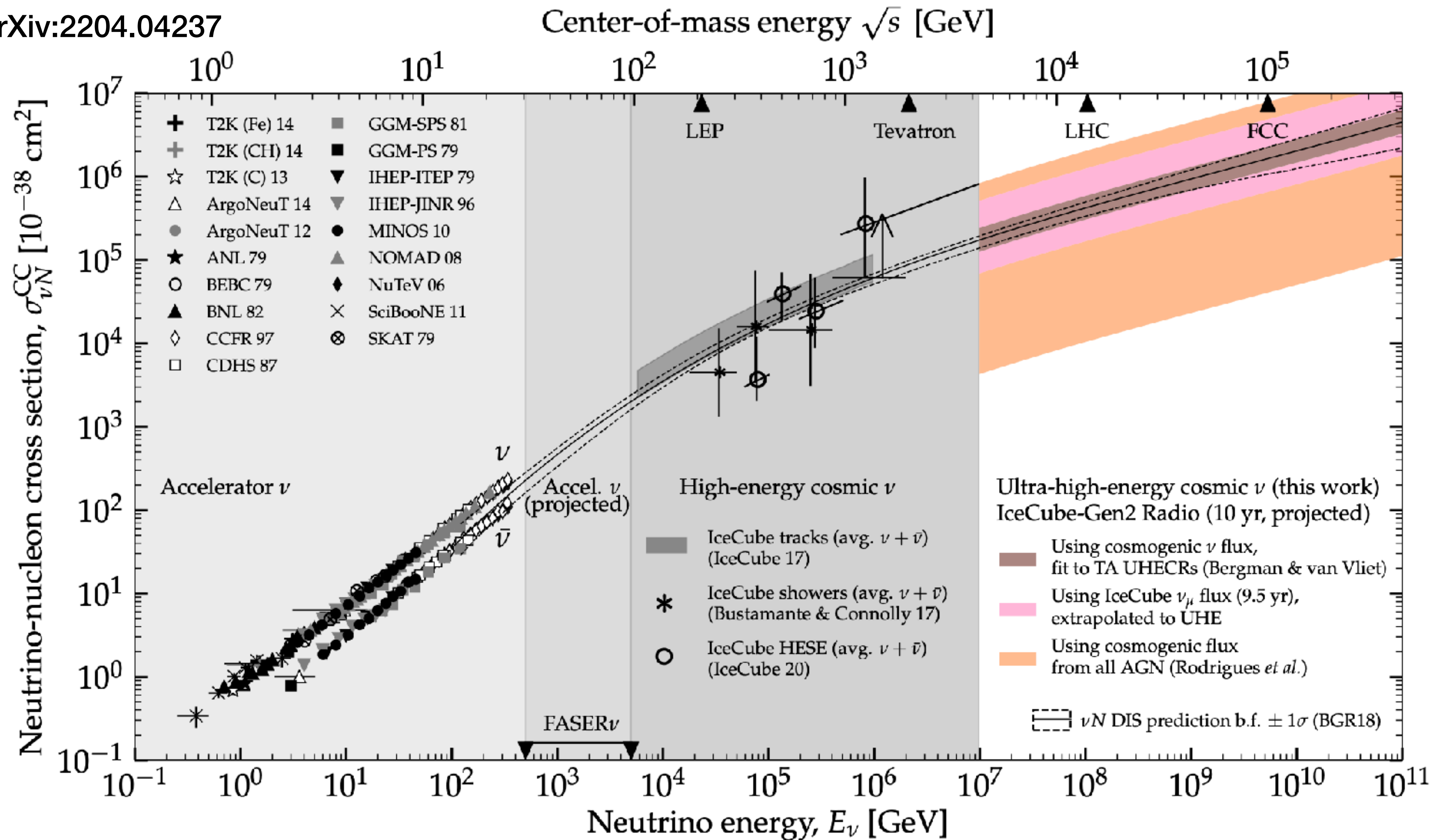
2, BSM - ν_τ model: integral upper limit



- ✦ Assuming energy independent cross section
- ✦ FD up-going exposure:
 $\theta \in [110^\circ, 180^\circ], \log_{10}(E/\text{eV}) \in [17, 21]$
- ✦ $d\Phi_{\text{BSM}}/dE \propto E^{-2}$ diffuse flux

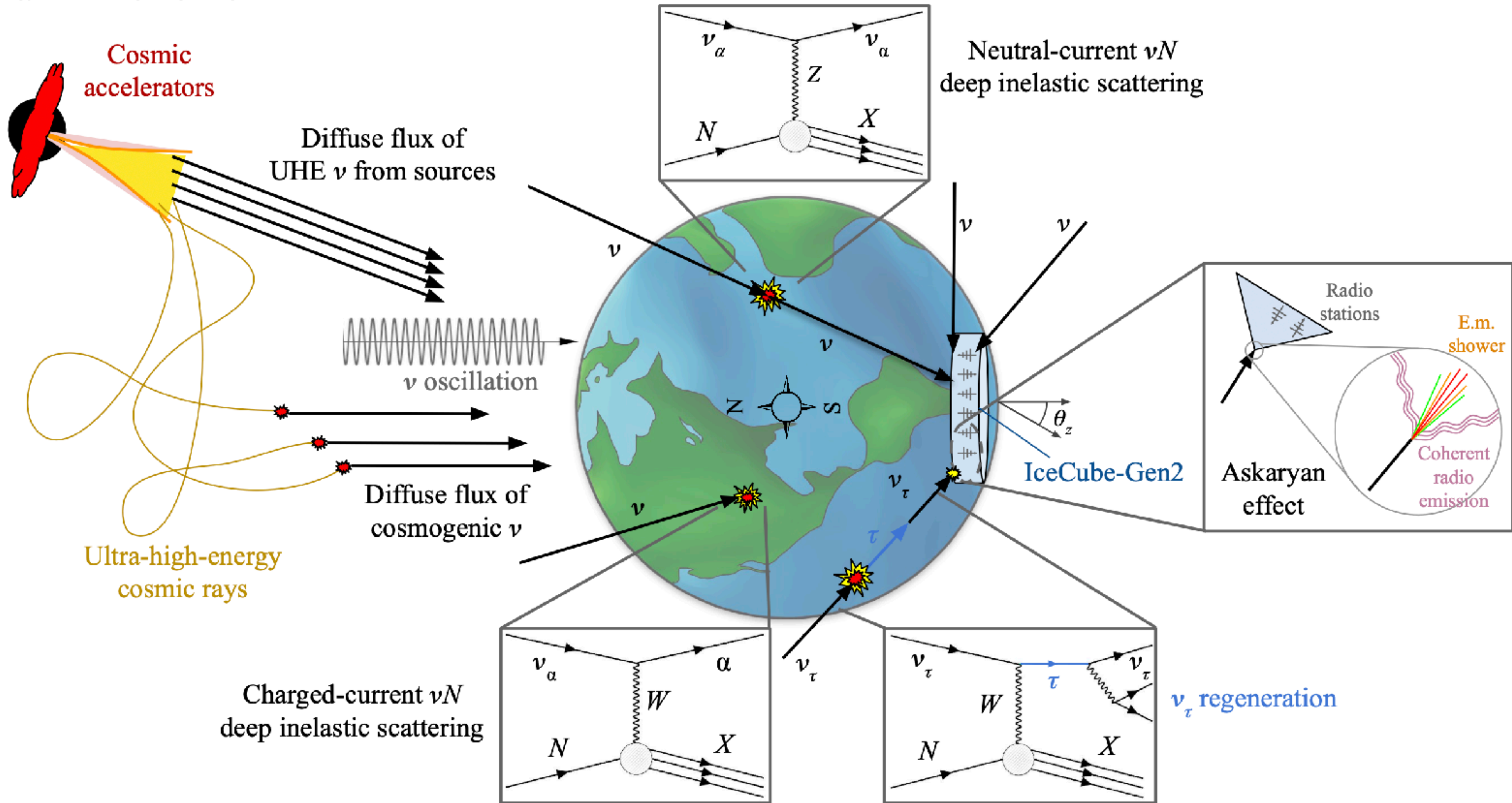
Neutrino-nucleon cross section

arXiv:2204.04237



UHE neutrino interactions

arXiv:2204.04237

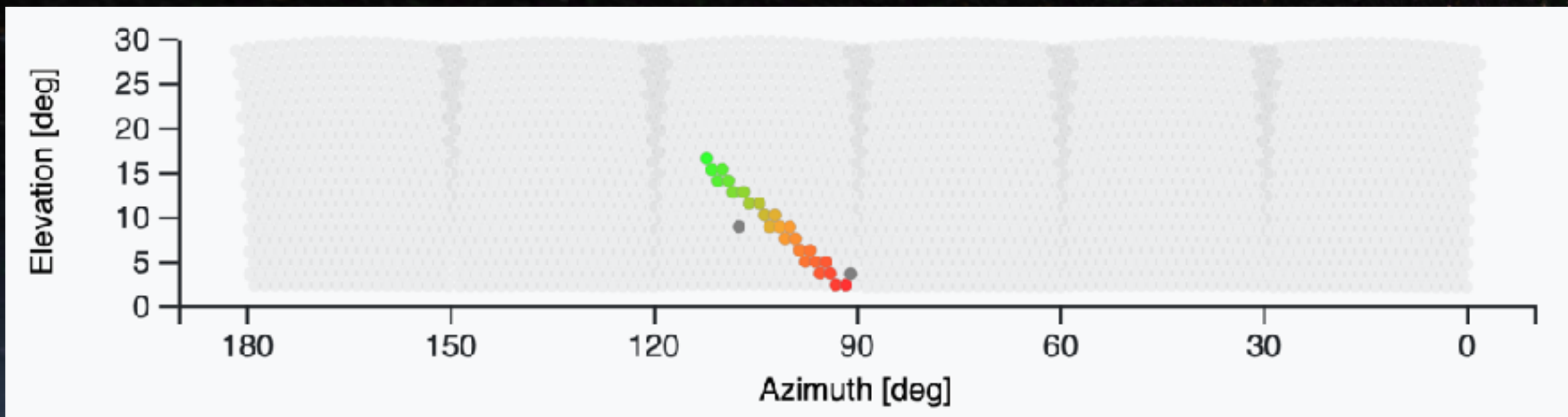
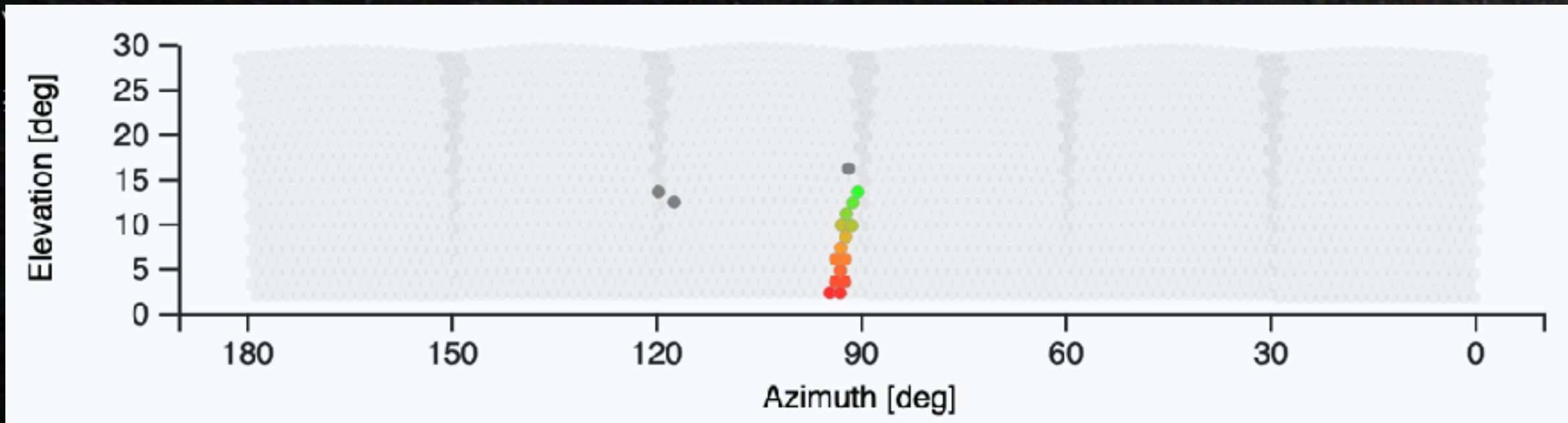


Hybrid event

Event ID: 081847955000
Time: 03 Jul 2008 12:05:57
Energy: 56.83 EeV
Number of Stations: 24

Open data example

$$E = 5.683 \times 10^{19} \text{ eV}$$
$$\theta = 54.12^\circ$$



First interaction

Los Leones

Coihueco

Loma Amarilla