A coherent view on UHECRs from the Pierre Auger Observatory

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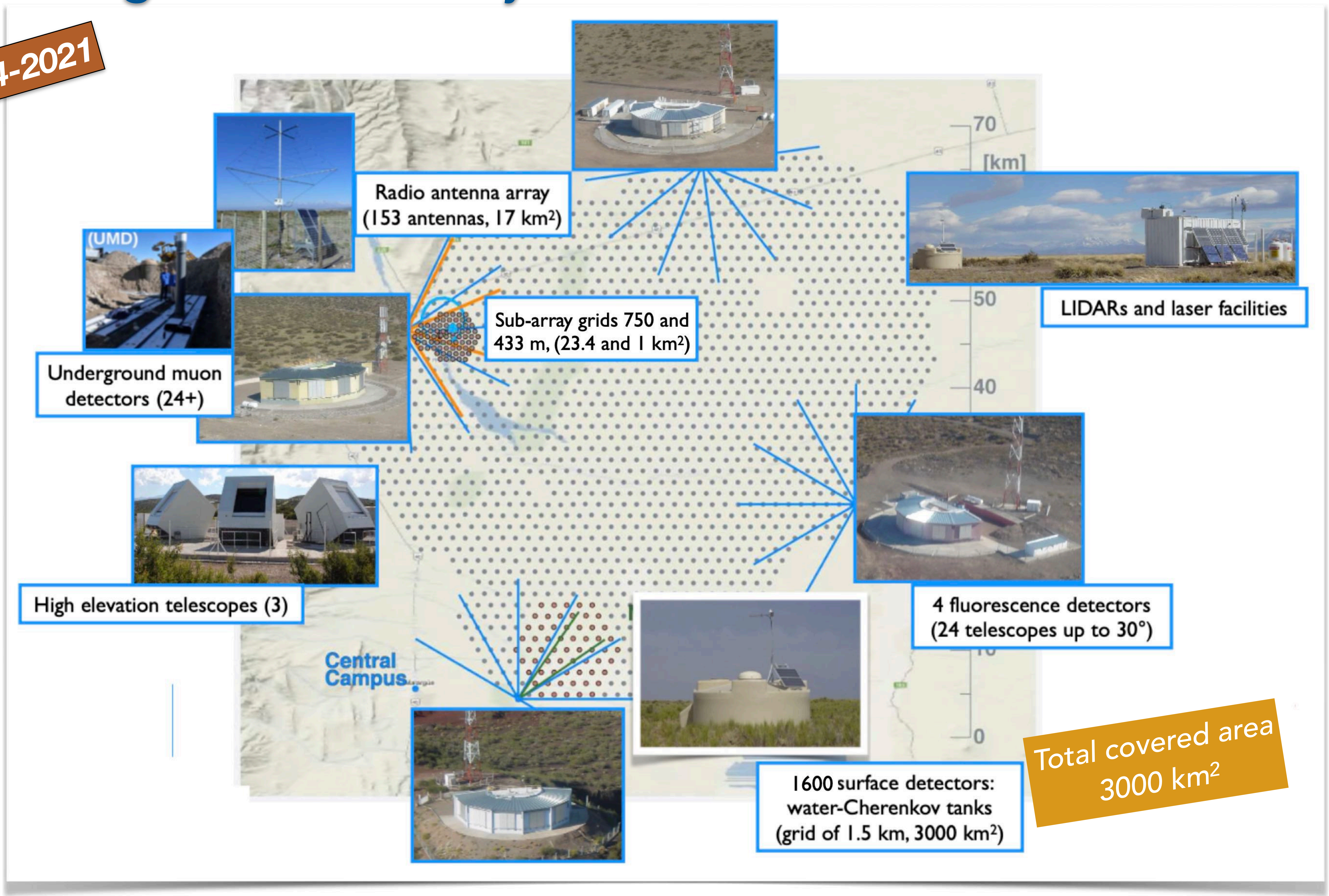
Conference in memory of Veniamin Sergeyevich Berezinsky

L'Aquila, GSSI   *October 1-3,2024*

The Pierre Auger Observatory

Pampa Amarilla
(Malargüe, Argentina
17 Countries
>400 members

2004-2021



- 1665 Water-Cherenkov stations:
  - SD1500 : 1600, 1500 m grid; E_{thr}~2.5 EeV
  - SD750: 61, 750 m grid; E_{thr}~0.1 EeV
  - SD433: 19, 433 m grid; E_{thr}~0.03 EeV

- 4 Fluorescence sites:
  - 24 telescopes, 1-30^0 FoV
  - 3 High Elevation Telescopes, 30-60^0 FoV

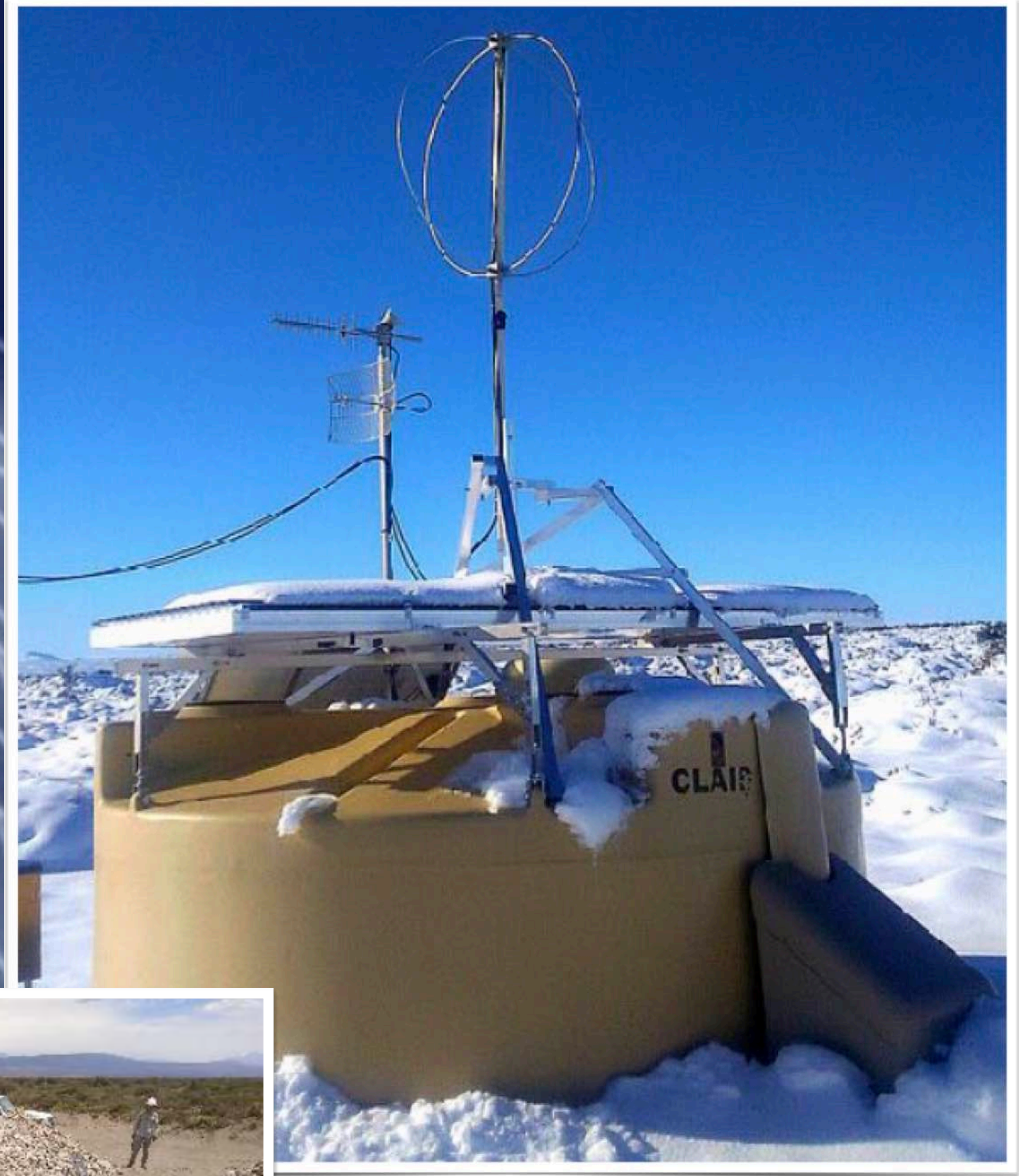
- Engineering arrays:
  - AERA: 153 radio antennas
  - UMD: 24 underground muon detectors

Geolocalization: (−69.0° longitude, −35.4° latitude)


Communications antenna
GPS antenna
Electronics box
Solar panel
PMT
Tyvek
bag
Batteries
Polyethylene tank
ALAIDE
1.5 km
aperture
system
UV filter
segmented
mirrors
camera
shutter
elec-
tronics

AugerPrime: *exploiting the richness of extensive air showers*

2025-2035



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***

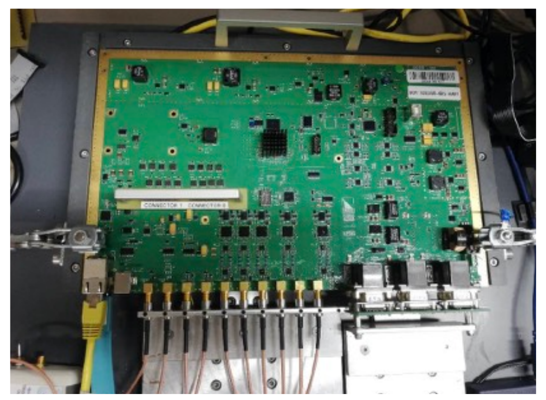
Measure of the radio emission of EAS

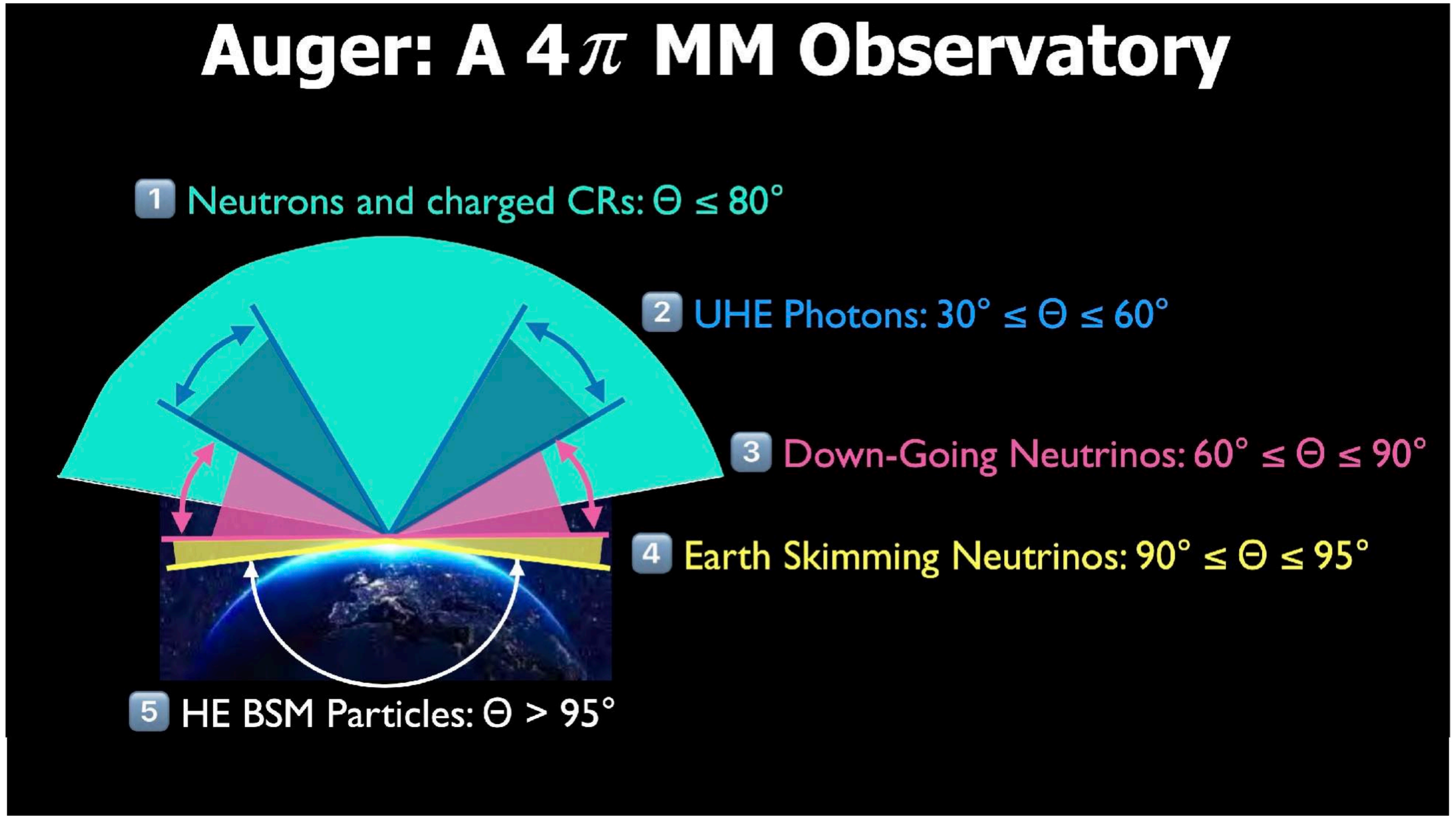
➡ ***Radio antennas***

Direct measure of the muonic component

➡ ***Underground detectors***

New electronics : ***faster FADC (120 MHz), larger dynamic range***





Auger Observatory: measures charged UHECRs

- Energy spectrum
- Nuclear composition
- Anisotropies
- Information on UHE hadronic interactions

Provides the largest exposure to UHE photons

- Diffuse flux of UHE photons
- Steady photon point sources
- Follow-up searches in coincidence with transients

Allows studies on UHE neutrinos

- Diffuse flux of UHE neutrinos
- Steady neutrino point sources
- Follow-up searches in coincidence with transients

…on Galactic neutron sources

and searches on BSM effects

This talk: experimental results from Phase I (2004-2021) and prospects for Phase II (2025-2035)

Interpretation covered in the talk by Denise Boncioli

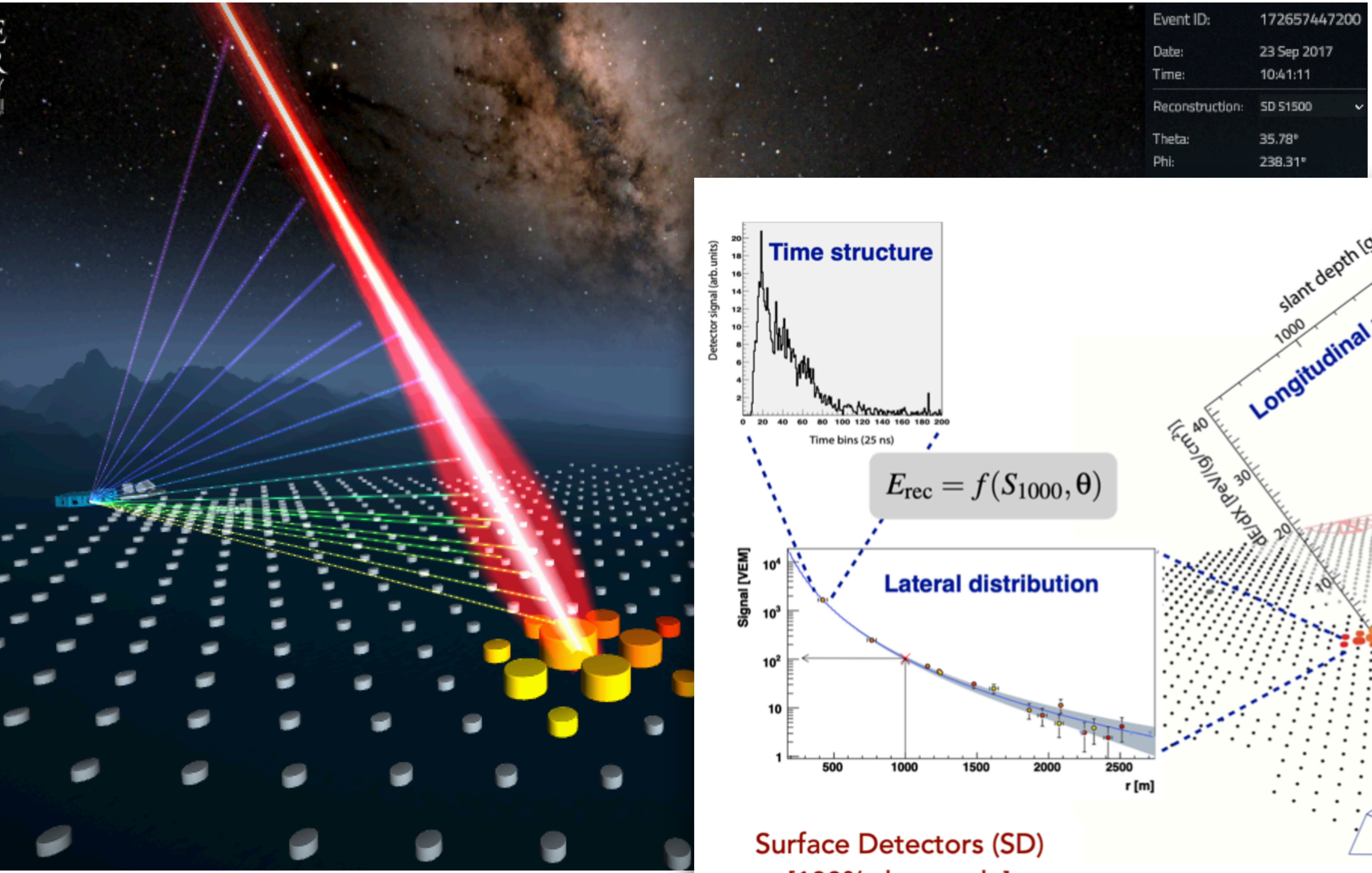
Take home message

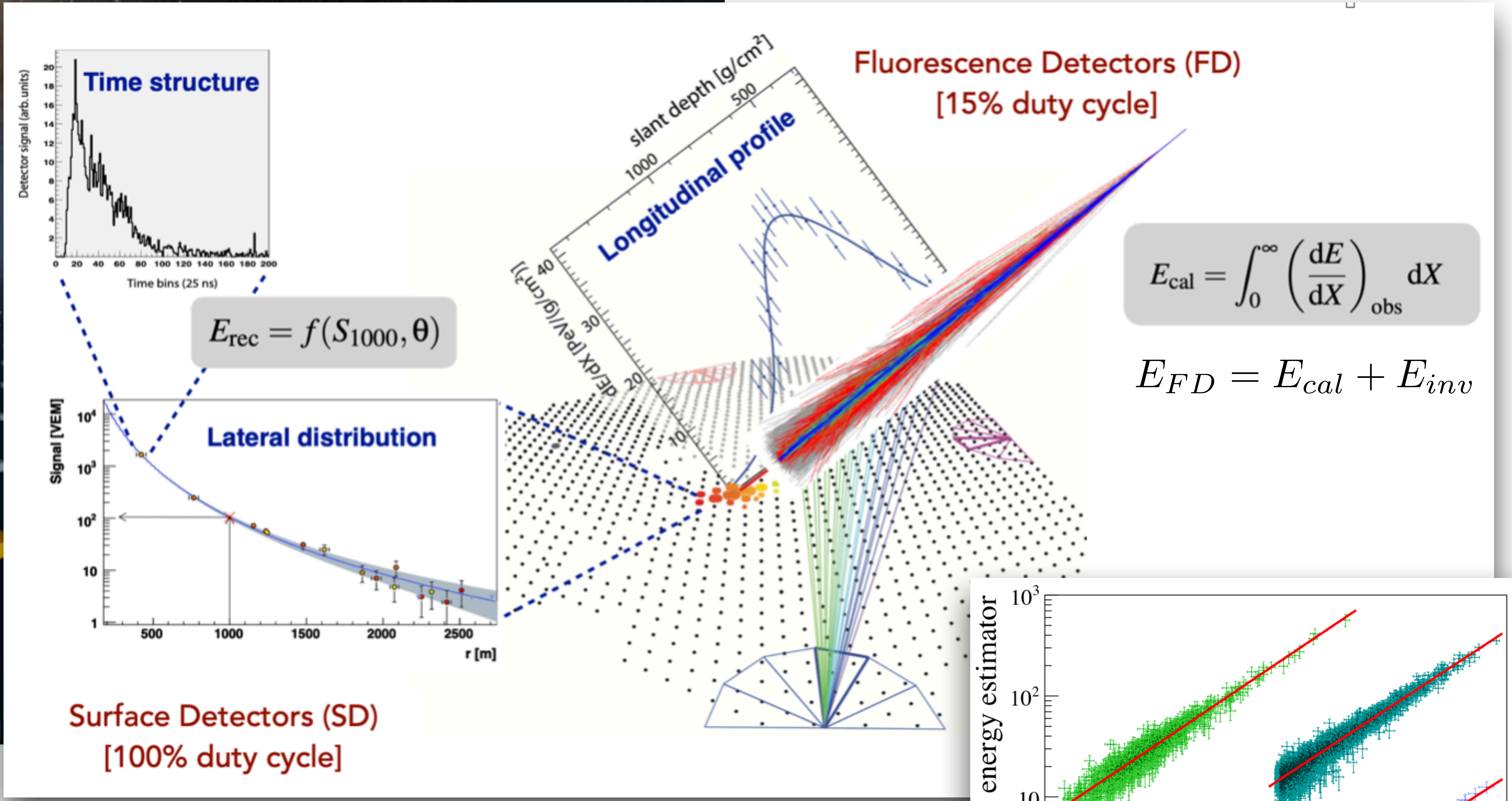
A global, coherent view emerges from the analyses of the data collected at the Pierre Auger Observatory, dispelling the pre-existing UHECR picture

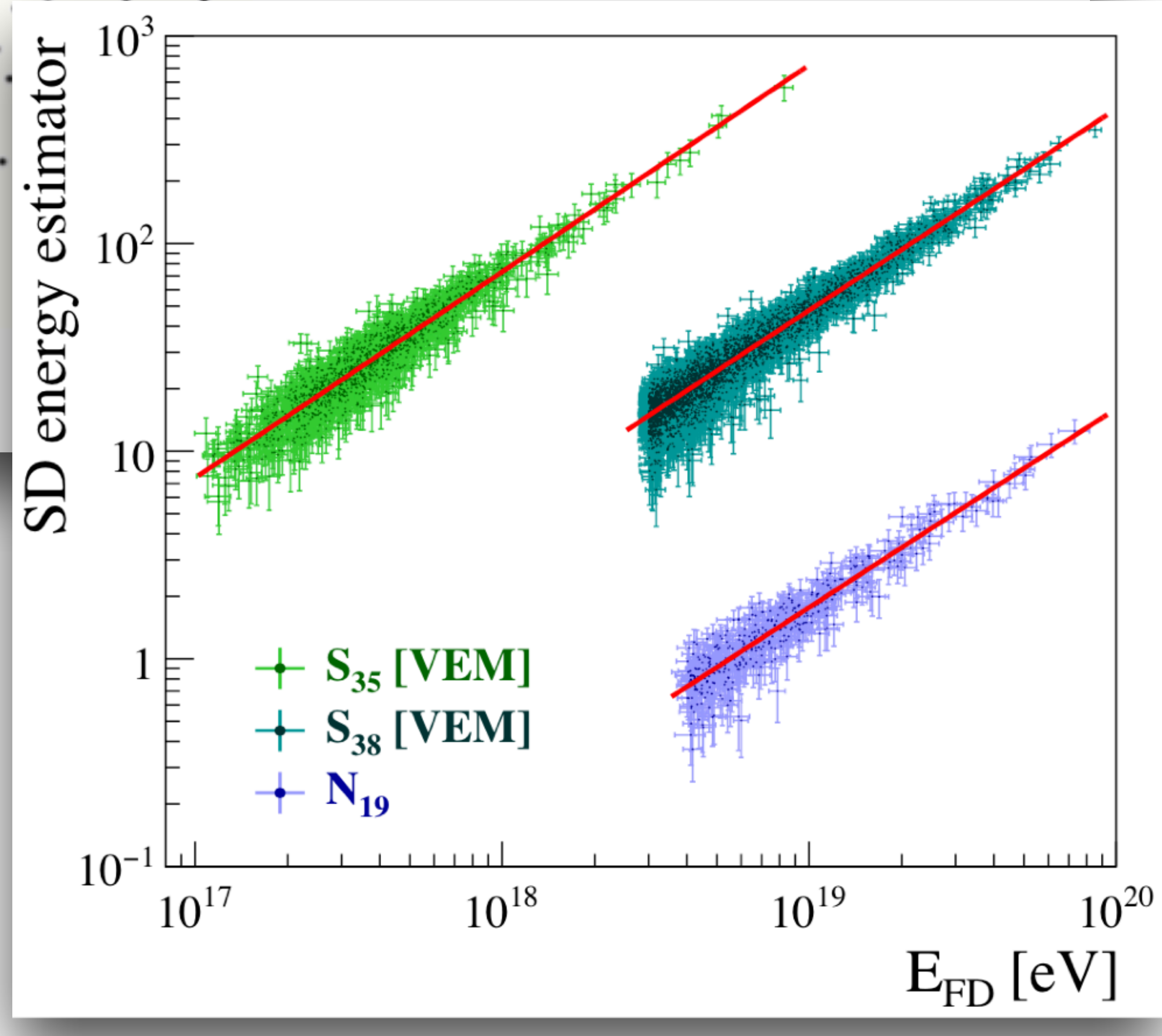
Valuable inputs to phenomenological models

Information about hadronic interactions and constraints on BSM effects

Hybrid technique



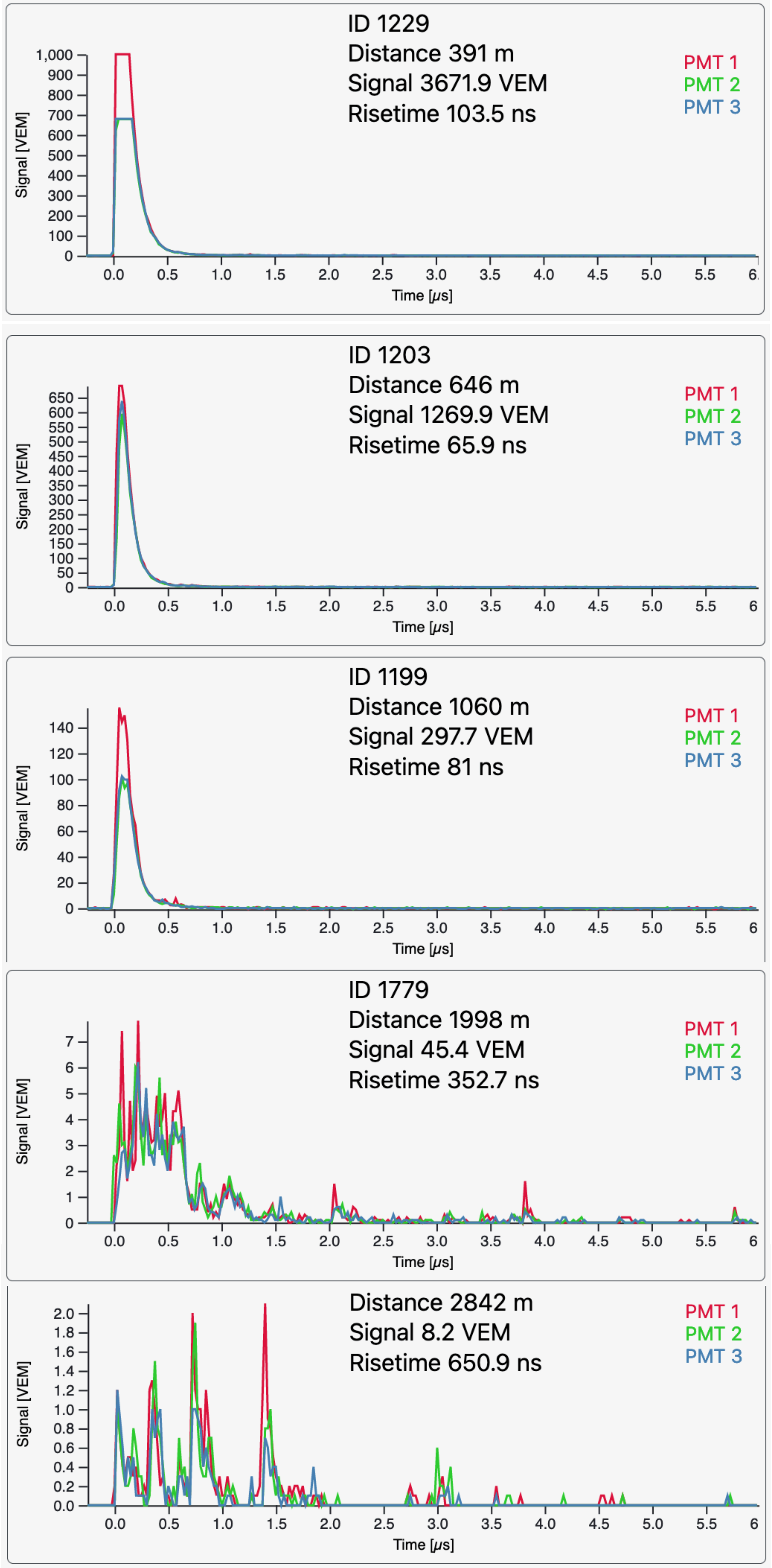


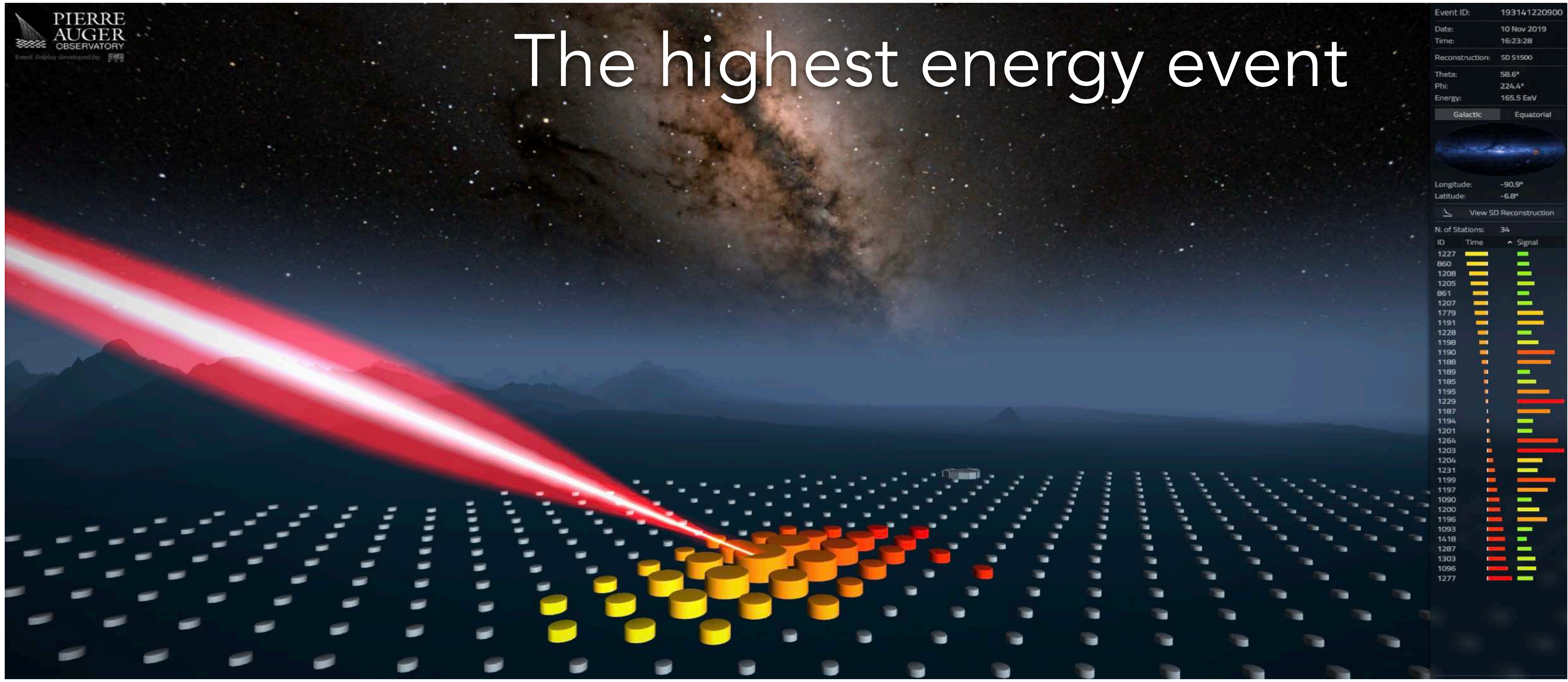


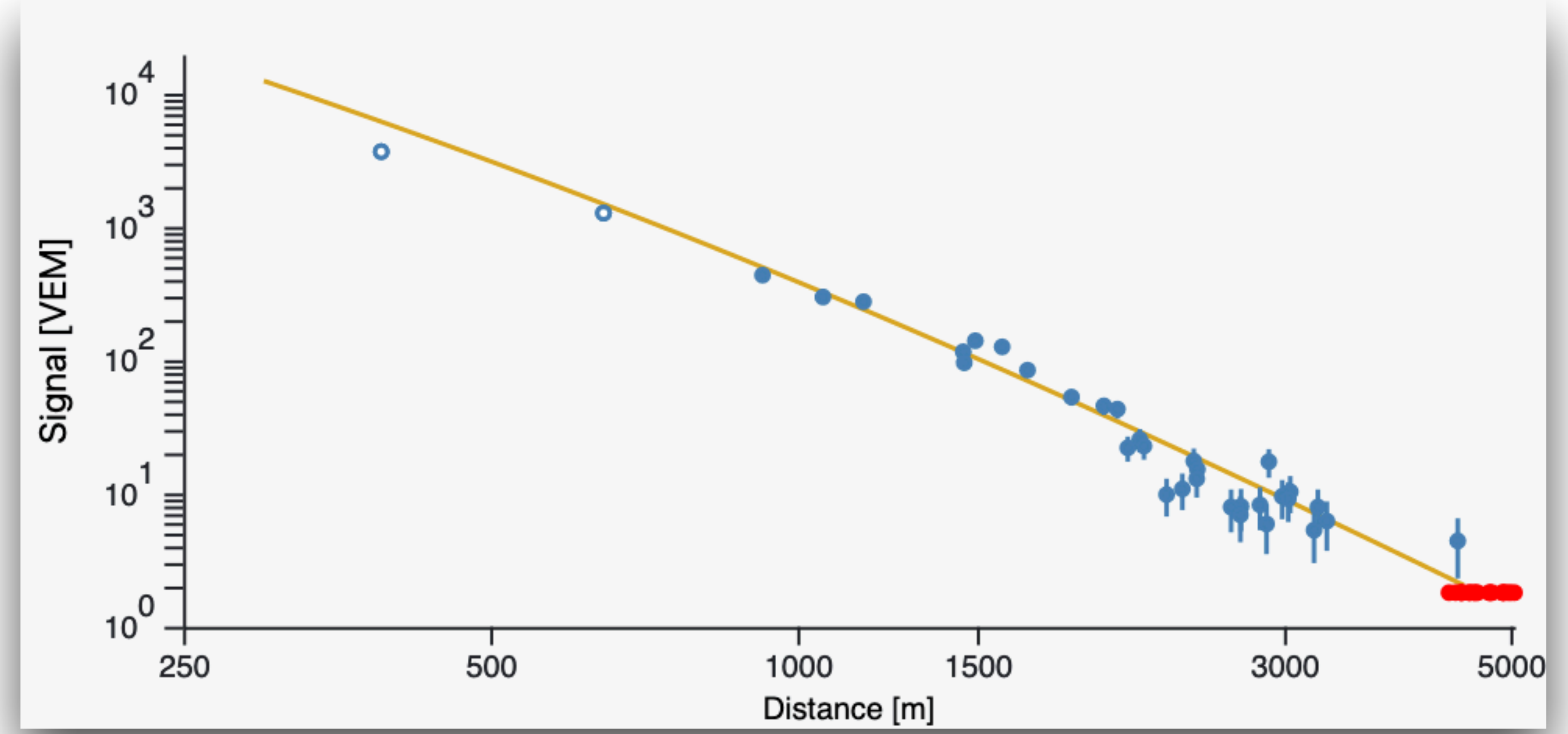
FD energy resolution ~ 8%

Systematic uncertainty 14%

The highest energy event

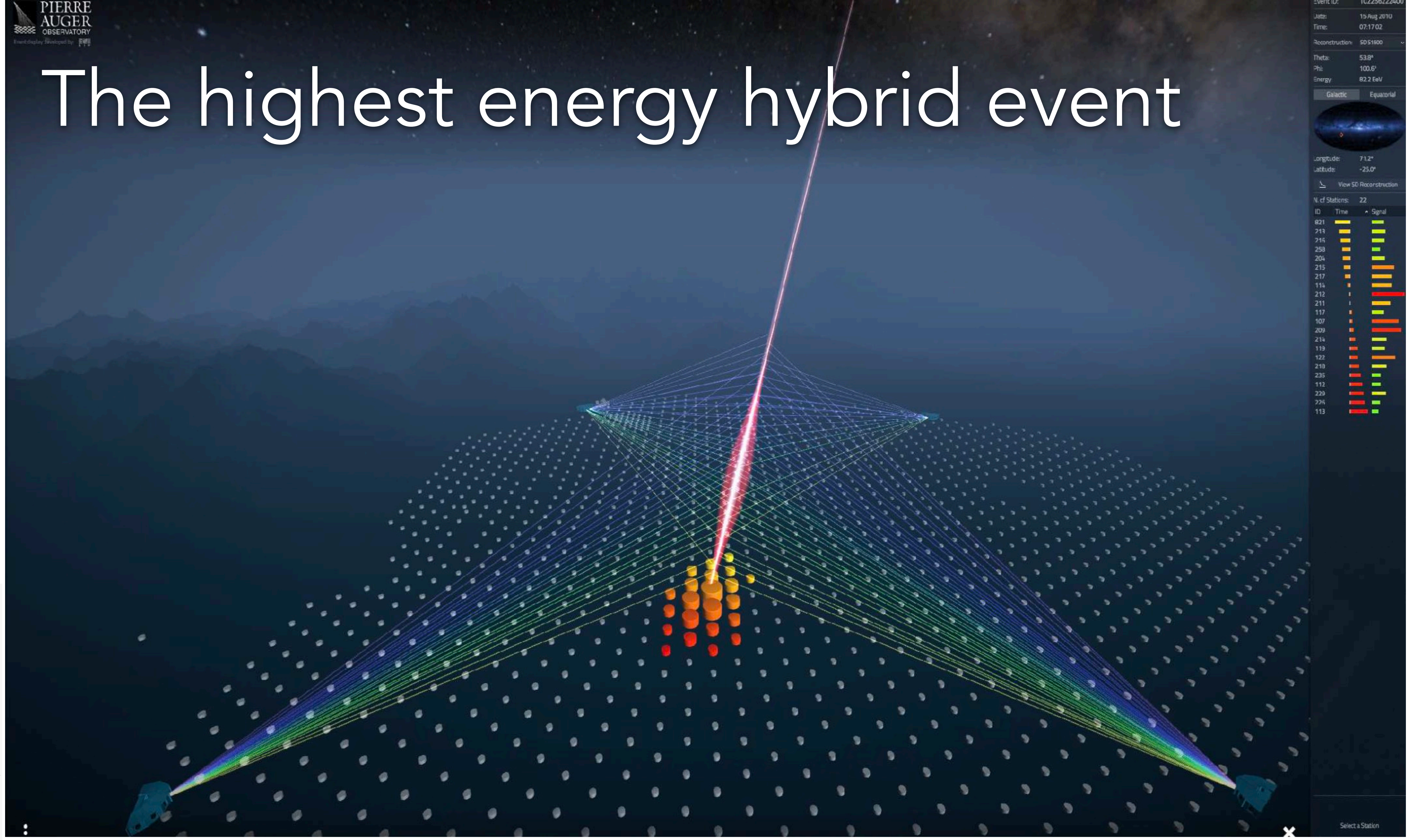




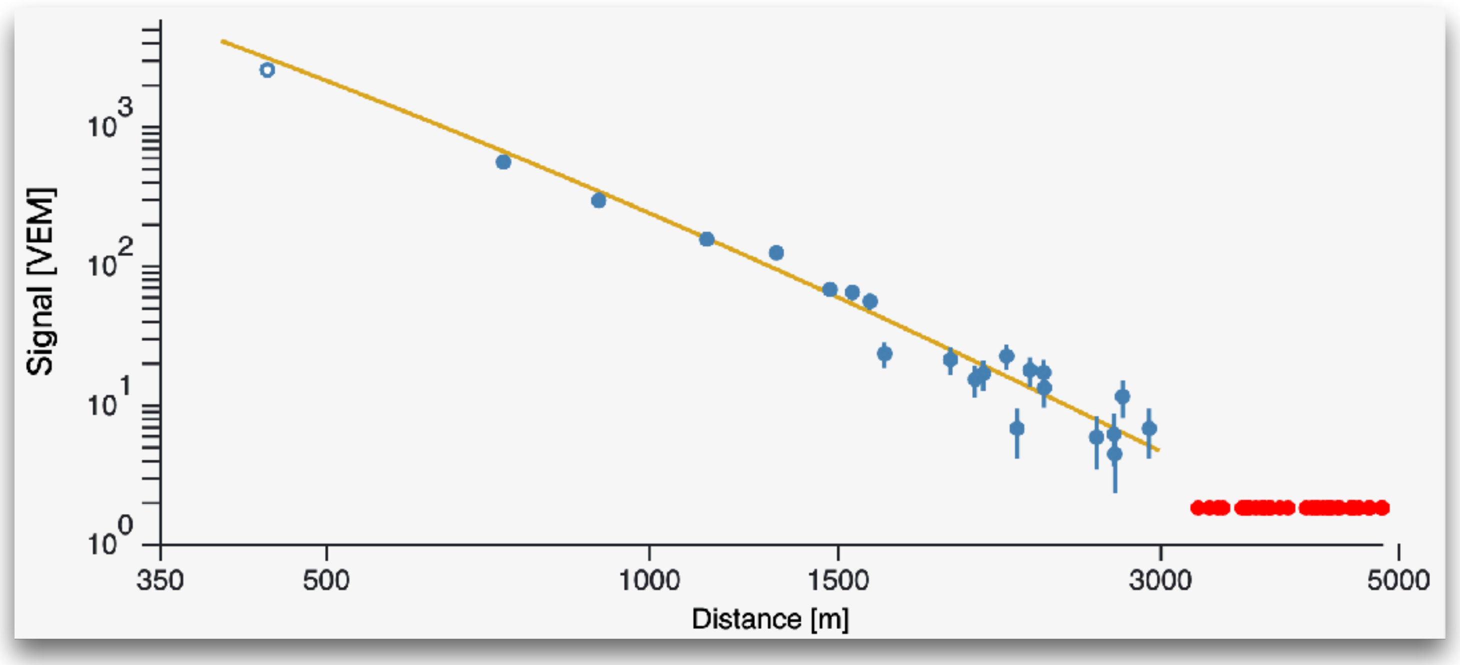


Date	2019-11-10
Energy	166±13 EeV
θ	58.6°
ϕ	224.4°
β	-2.0
$t_{1/2}(1000)$	98±3 ns
δ	-52.0°
α	128.9°
Multiplicity	34

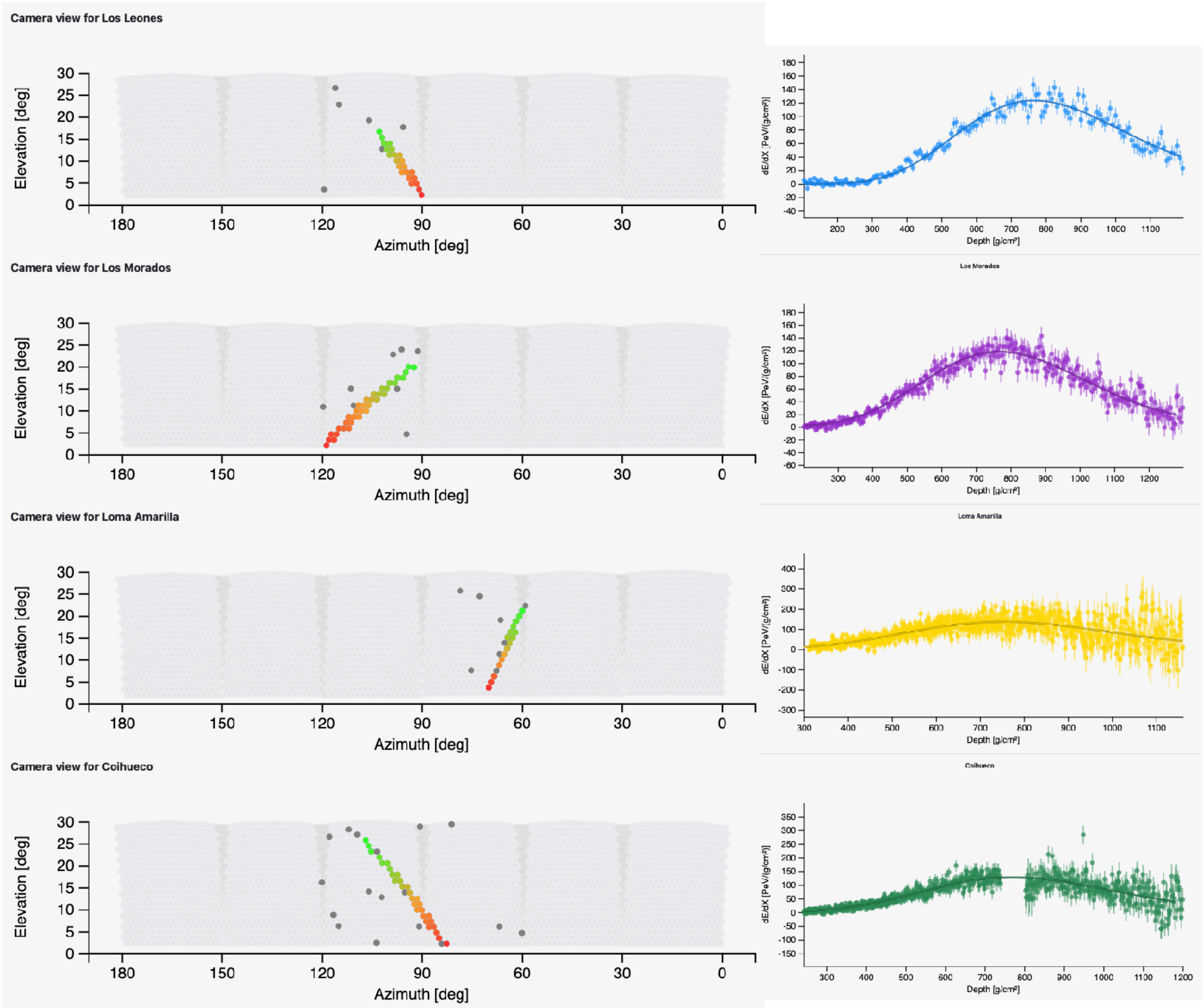
The highest energy hybrid event



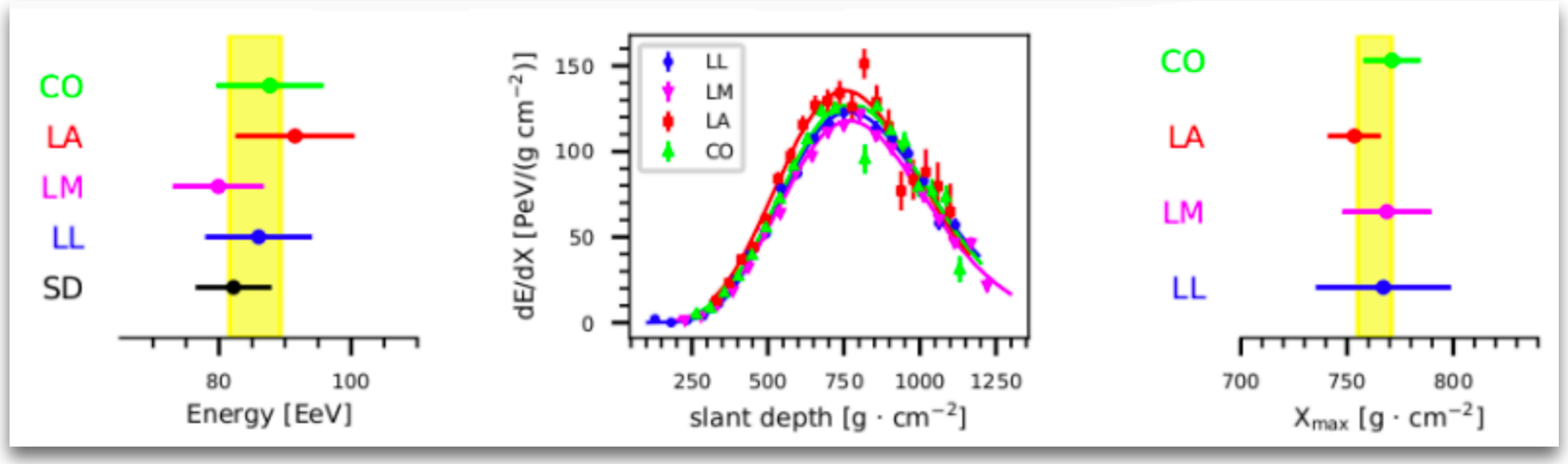
SD rec



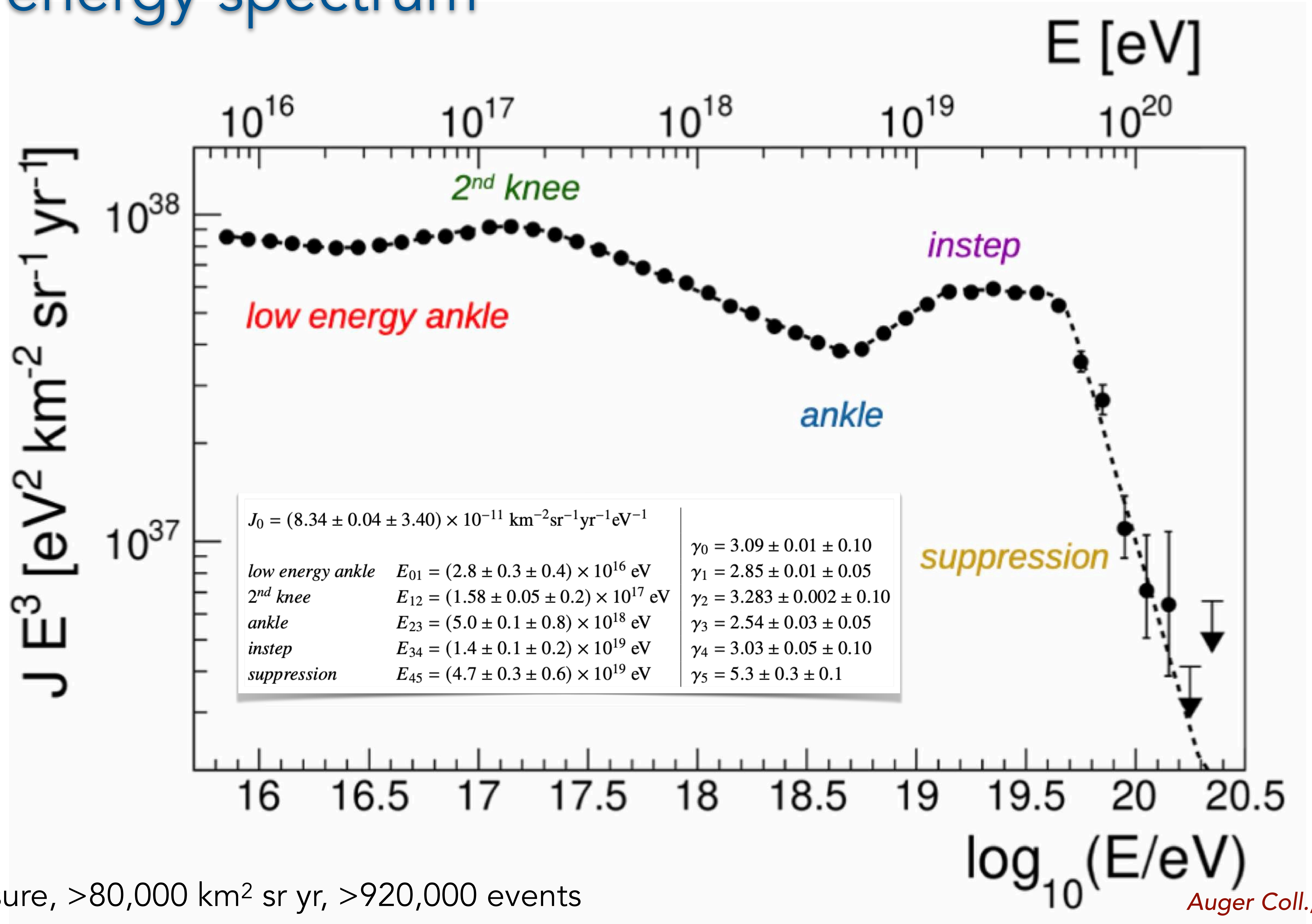
Energy	82±7 EeV
θ	53.8°
ϕ	100.6°
β	-2.1
$t_{1/2}(1000)$	127±5 ns
δ	17.8°
α	324.5°
Multiplicity	22



Hybrid rec



The UHECR energy spectrum



Largest available exposure, >80,000 km^2 sr yr, >920,000 events

A measure completely independent of any assumptions on the primary mass

It provides constraints on source properties, injected masses, interactions/escape

Auger Coll., Phys.Rev.D102 (2020) 062005
Auger Coll., Phys.Rev.Lett. 125 (2020) 121106
Auger Coll., Eur. Phys. J. C 81 (2021) 966
V.Novotny, PoS(ICRC2021) 324
A.Brichetto, PoS(ICRC2023) 398

The UHECR mass composition

Measurement from the

- longitudinal profile (FD, ~15% Duty Cycle)
- temporal and lateral distributions (SD, ~100% DC) + DNN
- radio footprint (AERA, ~100% DC)

$$\langle X_{max} \rangle = \langle X_{max} \rangle_p + f_E \langle lnA \rangle$$

$$\sigma^2(X_{max}) = \langle \sigma^2_{sh} \rangle + f_E \sigma^2(lnA)$$

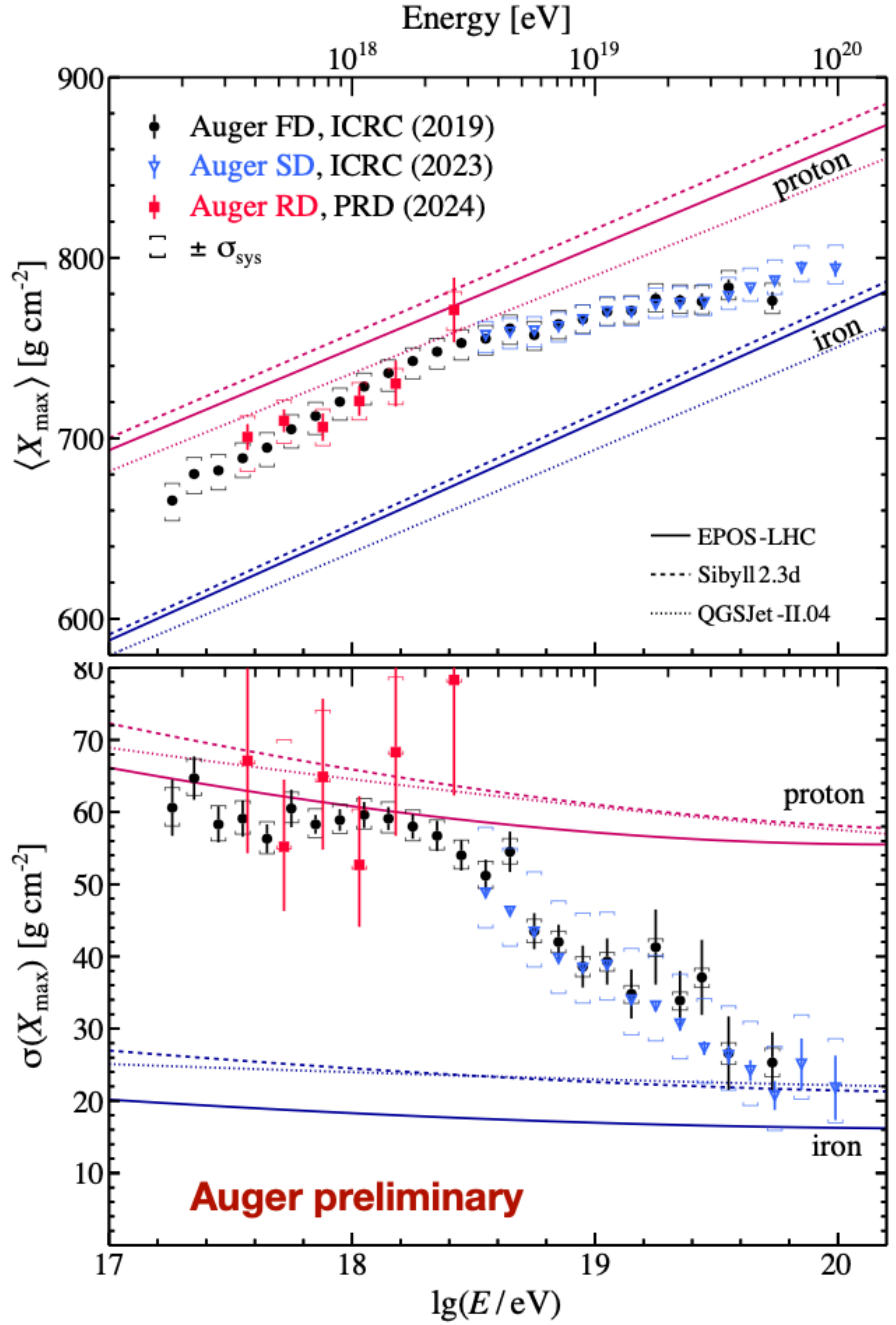
➡*The <X_{max}> gets lighter up to ~2 10^{18} eV and heavier above this energy, incompatible with pure composition*

➡*The **σ** (X_{max}) at the highest energy*

— excludes a large fraction of protons (DNN and FD)

— excludes the GZK as a dominant reason for the spectral cutoff

➡*The radio measurement provides an independent confirmation*



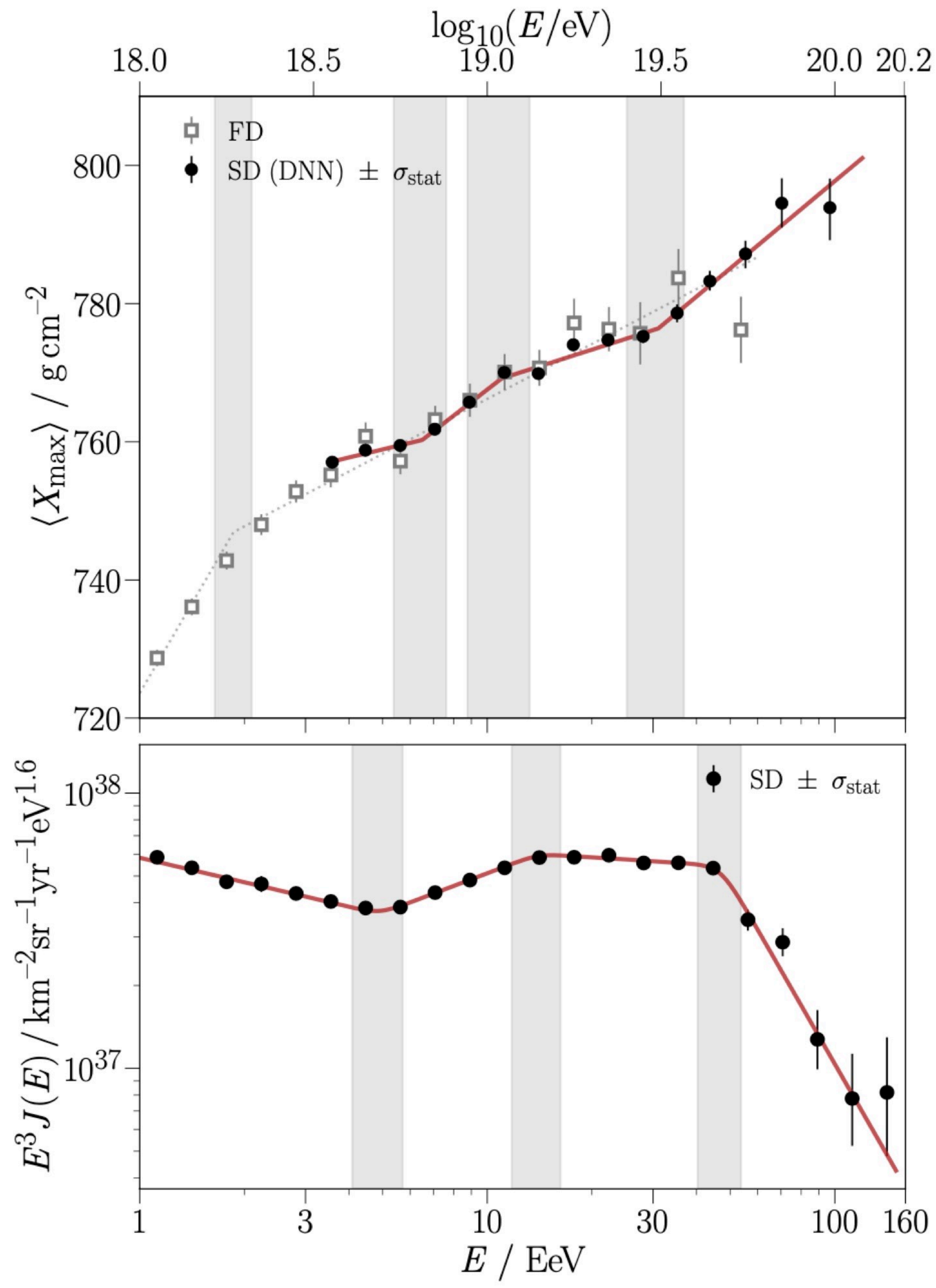
FD: Phys.Rev.D90 (2014) 122005+122006
SD: Phys.Rev. D96 (2017) 122003
SD/DNN: J.Glombitza, PoS(ICRC2023) 278, subm.Phys.Rev.D+Phys.Rev.Lett.
RD: Phys.Rev.Lett. 132 (2024) 021001+Phys.Rev.D109 (2024) 022002
+ review E.Mayotte, PoS(ICRC2023) 365

Changes in the elongation rate (SD+DNN)

Elongation rate in agreement with that found with FD
Clear evidence of a structure in ER, best described with a three-break model:
constant ER rejected at 4.4σ ⟶ ***incompatible with pure composition***

➡ kinks resembling the spectrum features
➡ supported by independent SD-based measurements (Delta method)
➡ in agreement with those predicted by a simplified astrophysical model

parameter val ± σ_{stat} ± σ_{sys}	3-break model val ± σ_{stat} ± σ_{sys}	energy spectrum val ± σ_{stat} ± σ_{sys}
b / g cm^{-2}	$750.5 \pm 3 \pm 13$	
D_0 / g cm^{-2} decade^{-1}	$12 \pm 5 \pm 6$	
E_1 / EeV	$6.5 \pm 0.6 \pm 1$	$4.9 \pm 0.1 \pm 0.8$
D_1 / g cm^{-2} decade^{-1}	$39 \pm 5 \pm 14$	
E_2 / EeV	$11 \pm 2 \pm 1$	$14 \pm 1 \pm 2$
D_2 / g cm^{-2} decade^{-1}	$16 \pm 3 \pm 6$	
E_3 / EeV	$31 \pm 5 \pm 3$	$47 \pm 3 \pm 6$
D_3 / g cm^{-2} decade^{-1}	$42 \pm 9 \pm 12$	



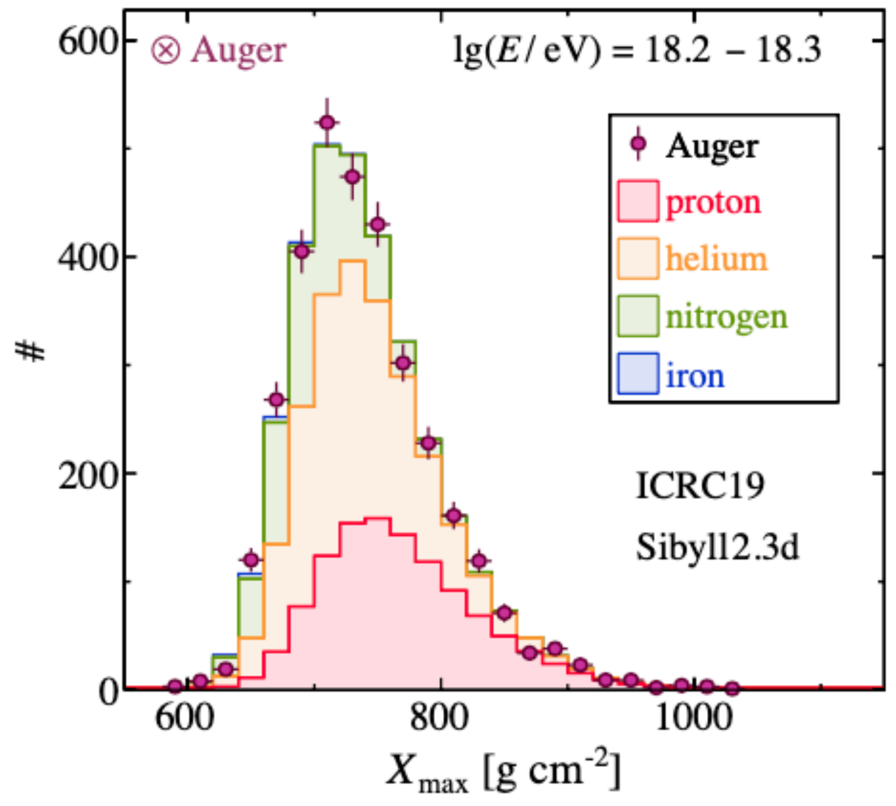
Auger Coll., JINST 16 (2021) P07019
SD/DNN: J.Glombitza, PoS(ICRC2023) 278, subm.Phys.Rev.D+Phys.Rev.Lett.

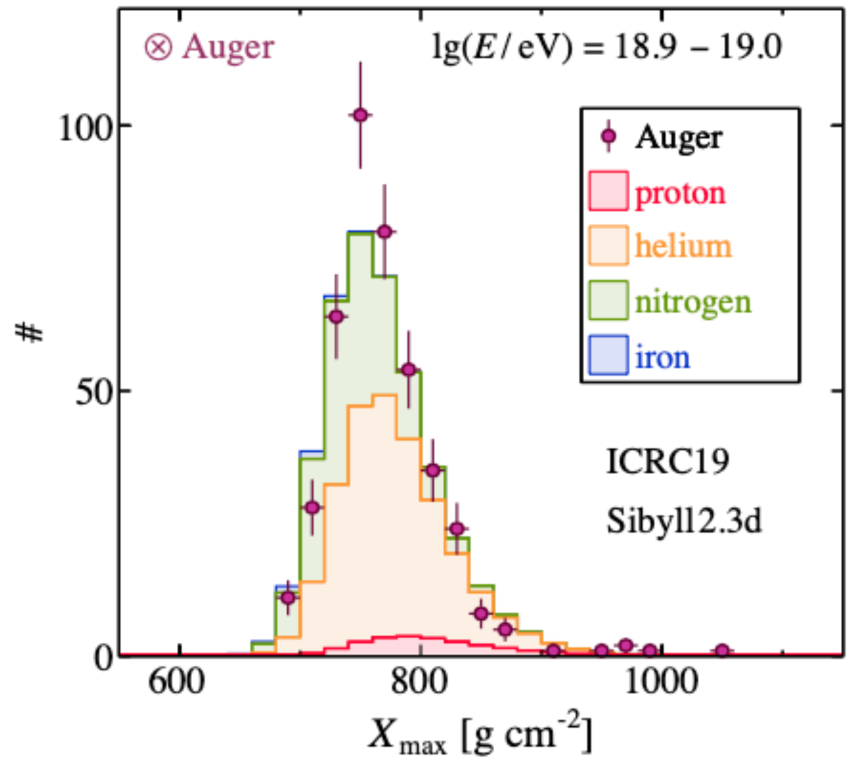
The UHECR mass composition

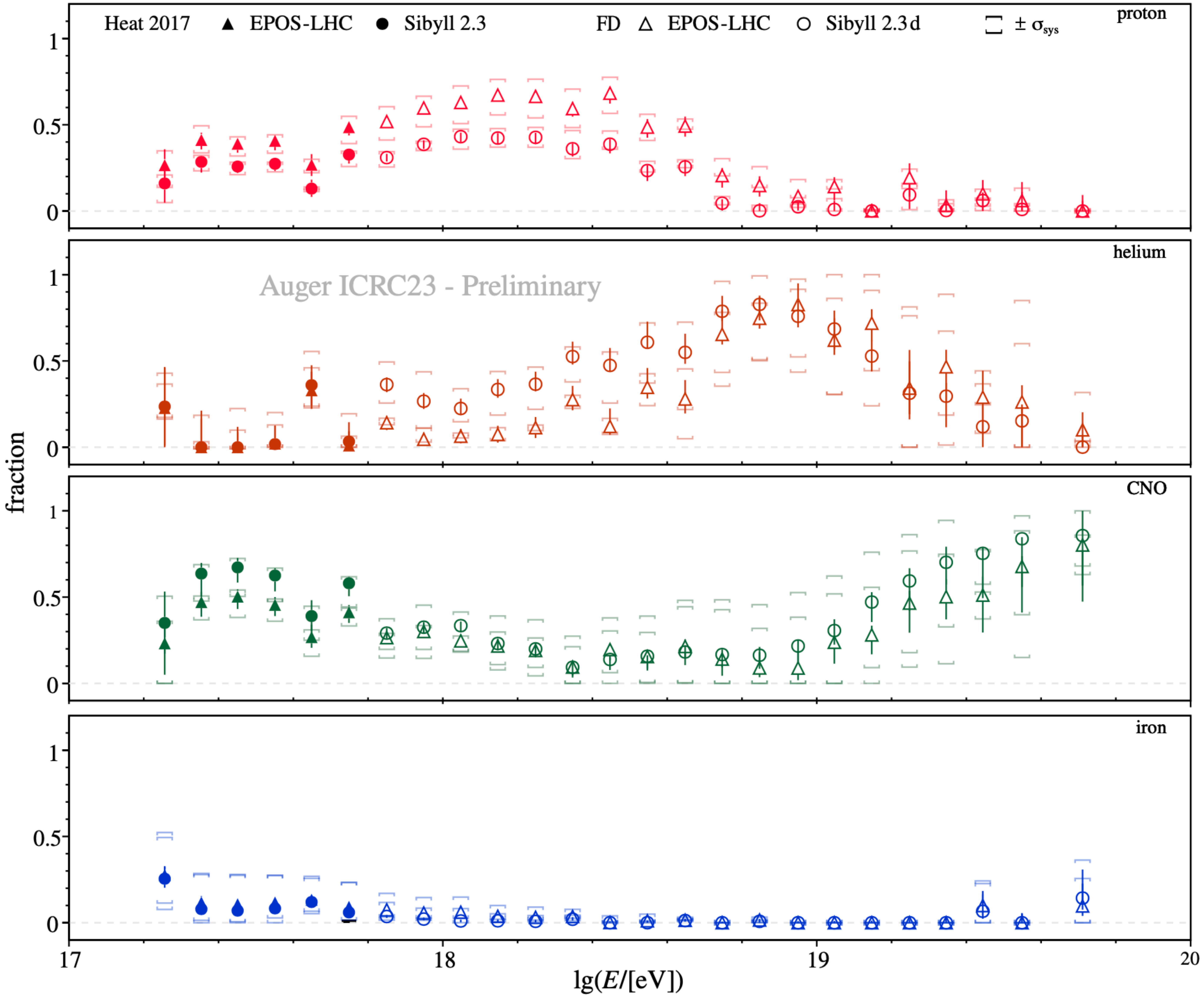
The fractions of elements can be derived from model dependent fits of the X_{max} distributions

- Provide model dependent information on the mass evolution

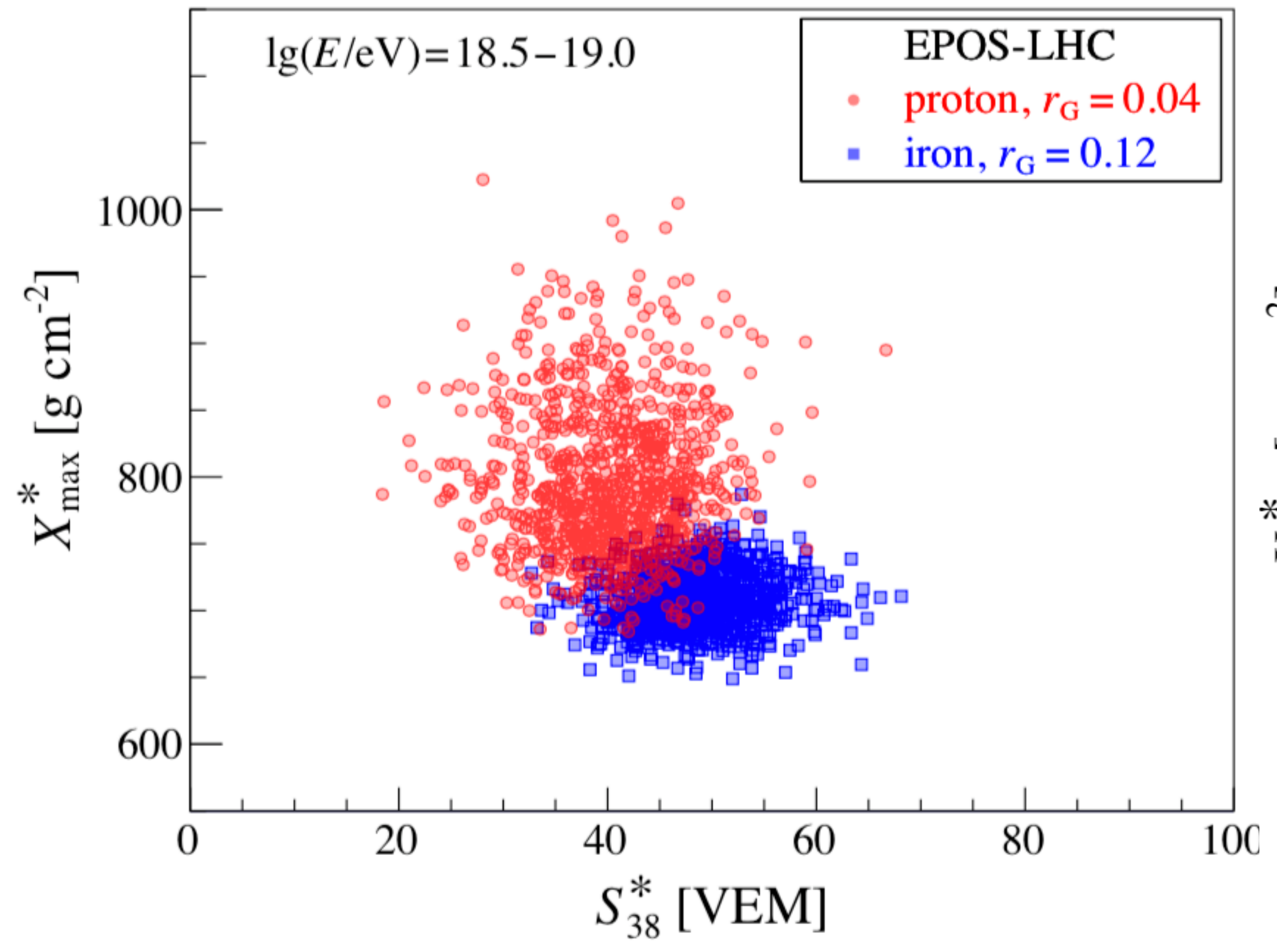
→in line with E_{max} ~a few EeV x (Z or A)

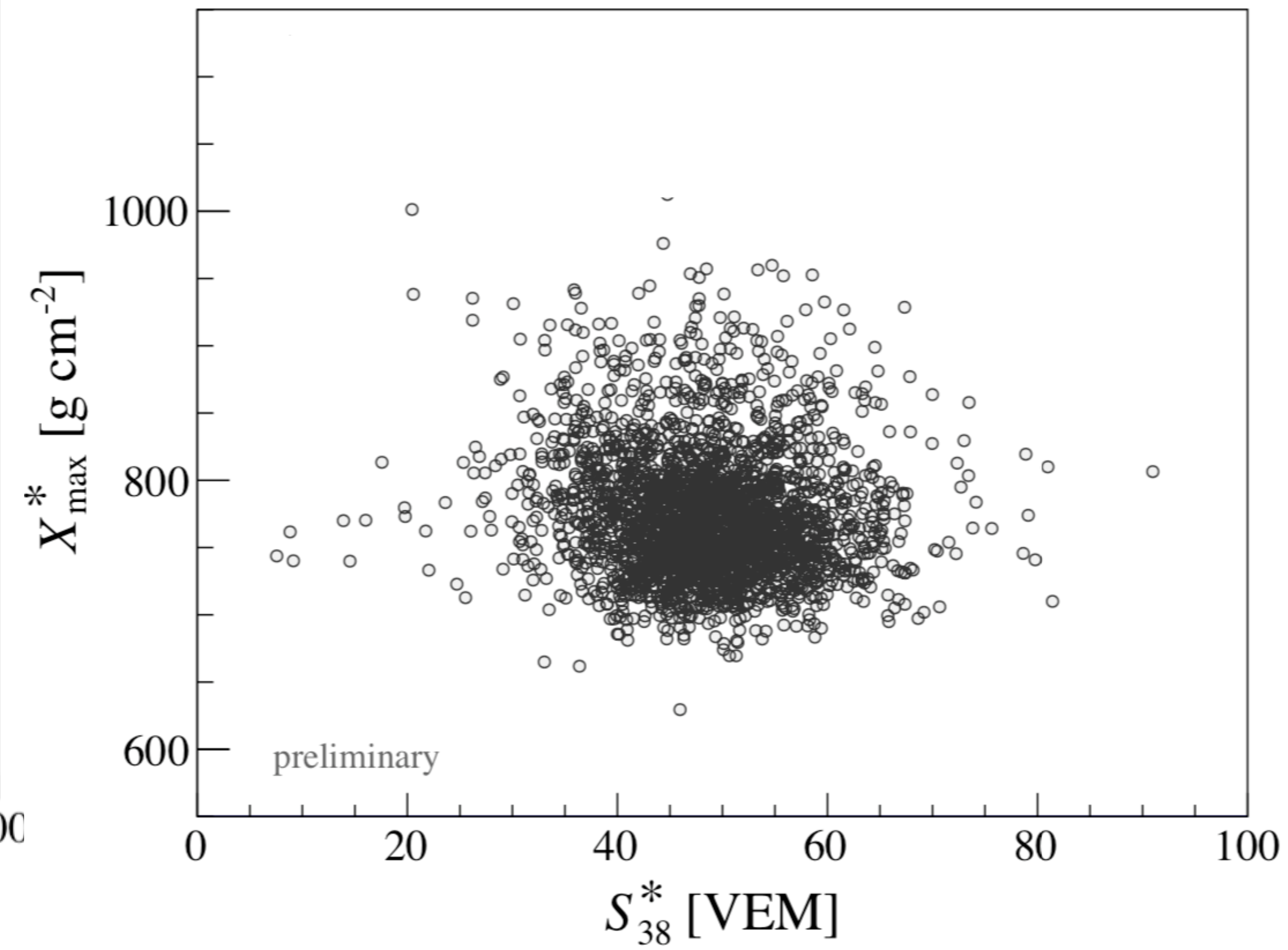


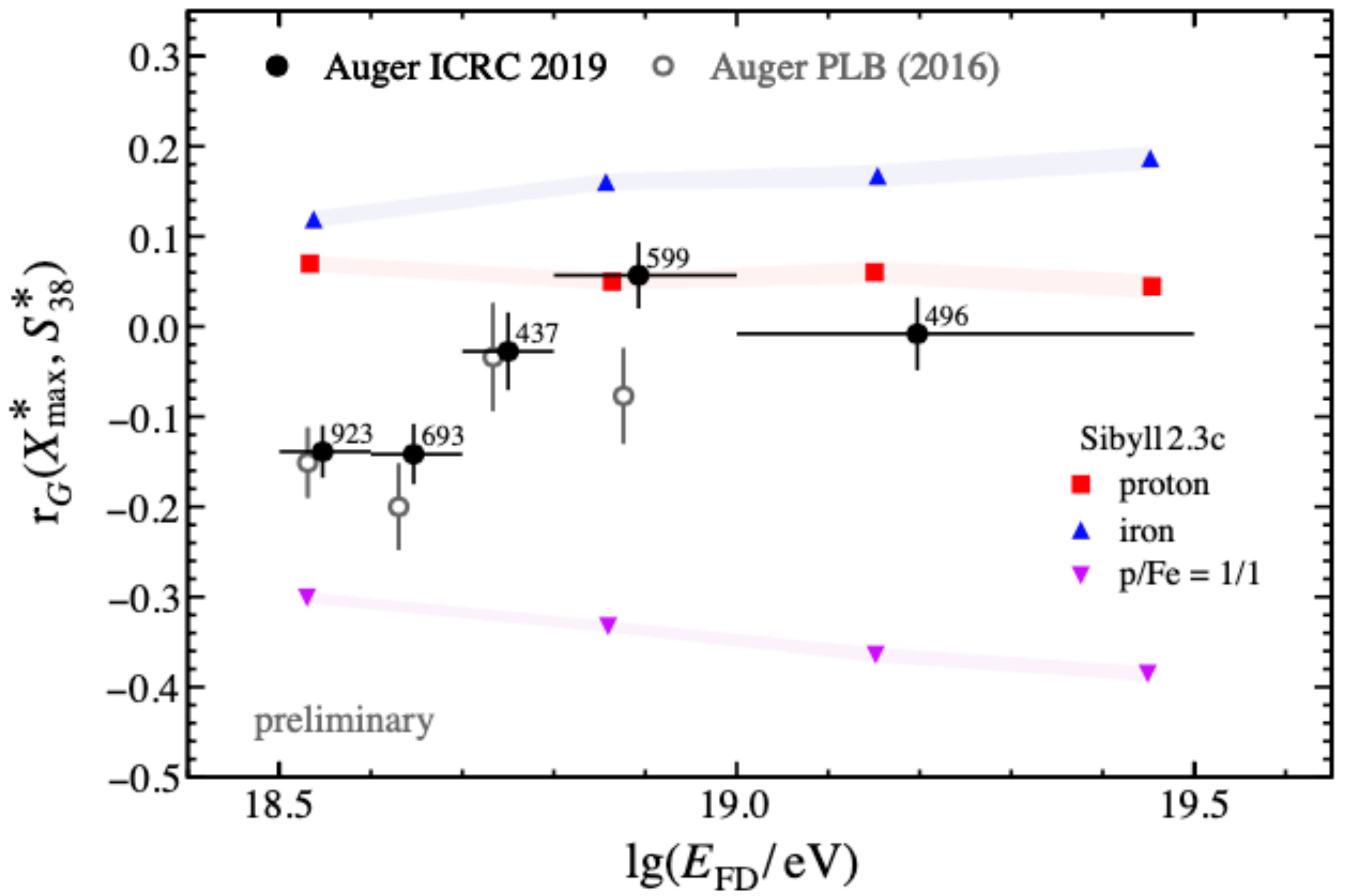


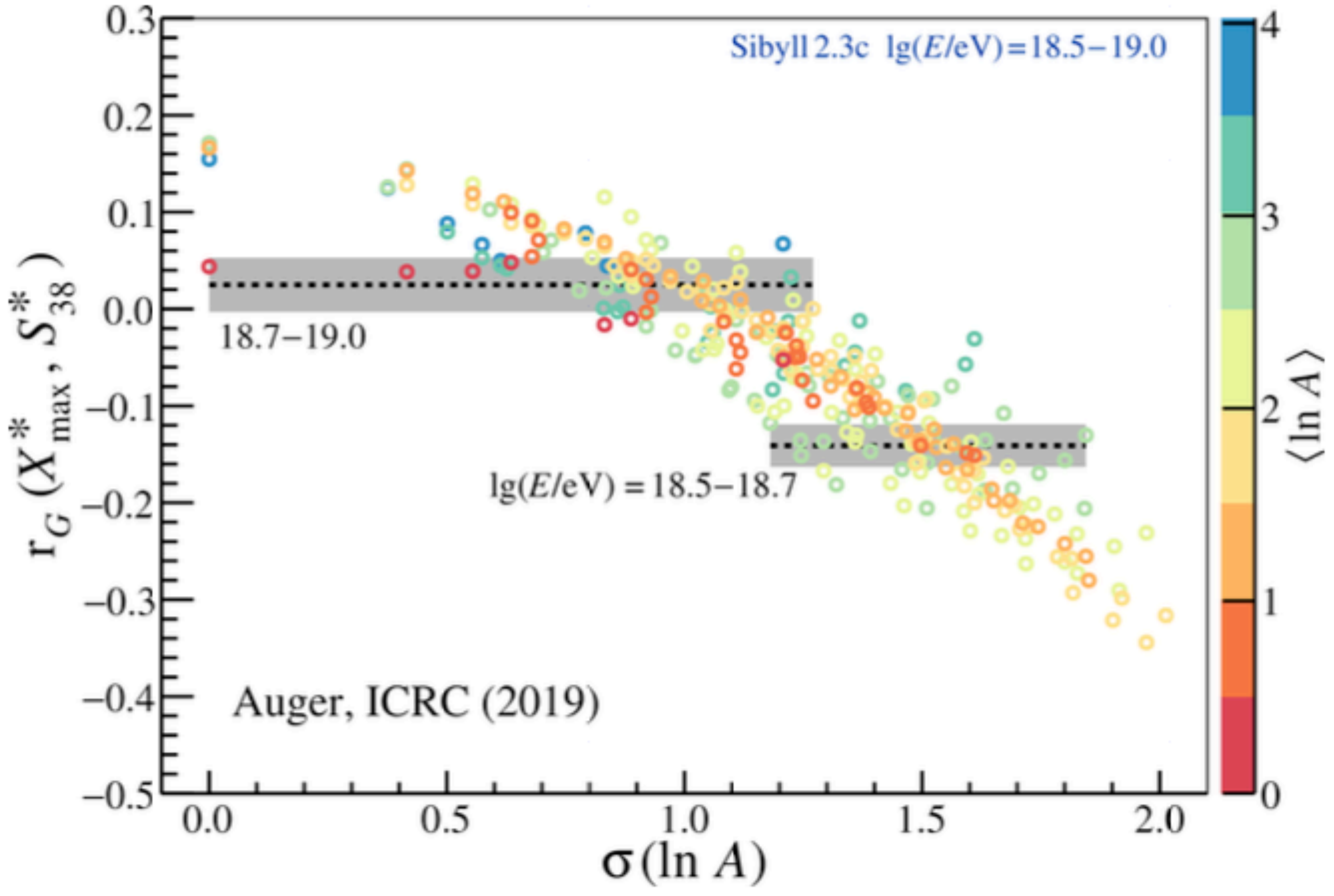


Heavy or light? An independent measurement at the ankle









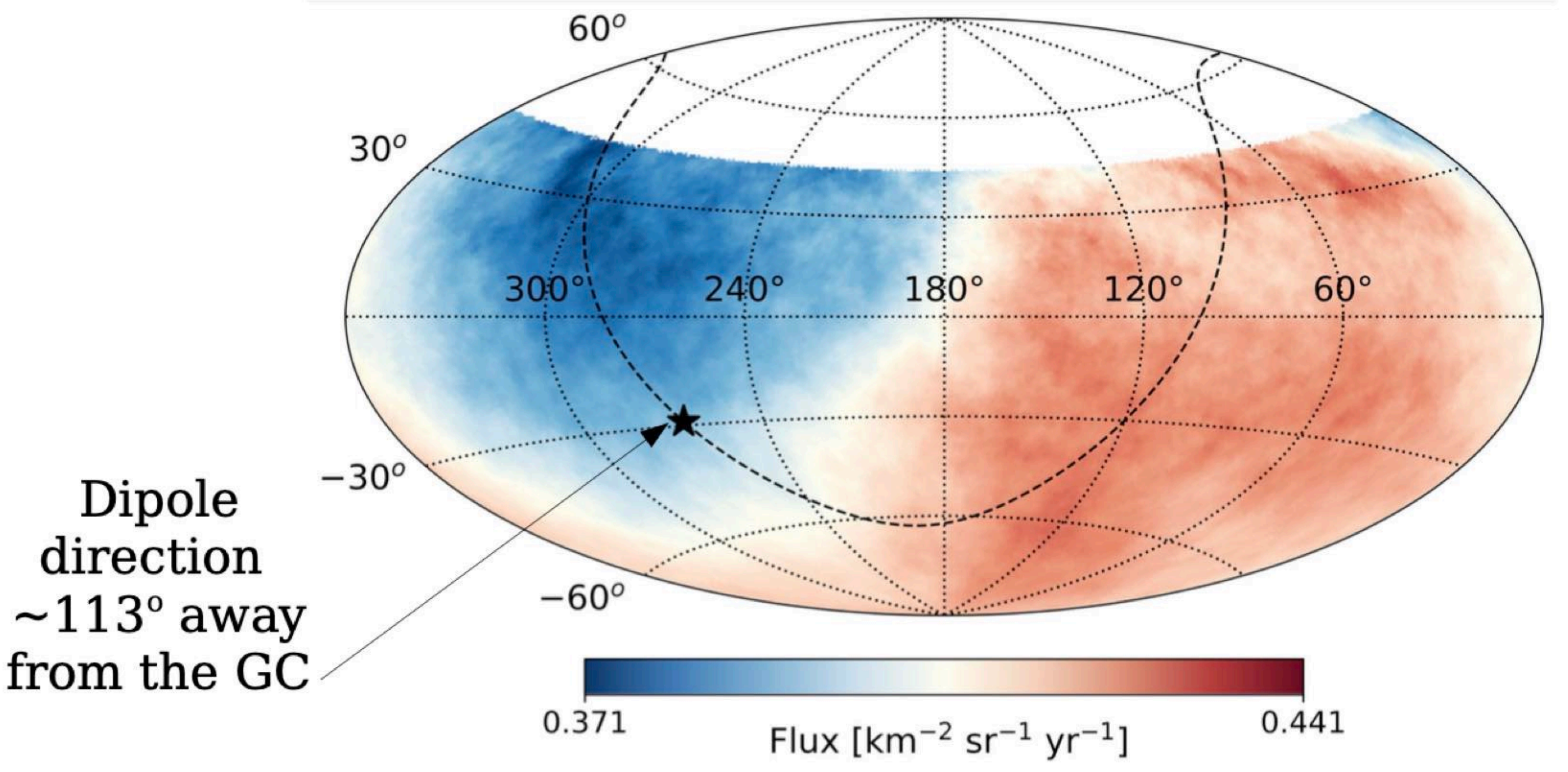
Around the ankle ($10^{18.5}$-10^{19} eV) the composition is mixed (6.4**σ** from 0), compatible with **σ**(lnA)>1.0 and as such with nuclei heavier than He (p-He mixing would give **σ**(lnA)=0.7)

At higher energies it appears less mixed

Analysis not affected by detector systematics or by hadronic interaction models uncertainties

Auger Coll., Phys.Lett. B762 (2016) 288
E.Mayotte, PoS(ICRC2023) 365

Large scale anisotropy: Auger results

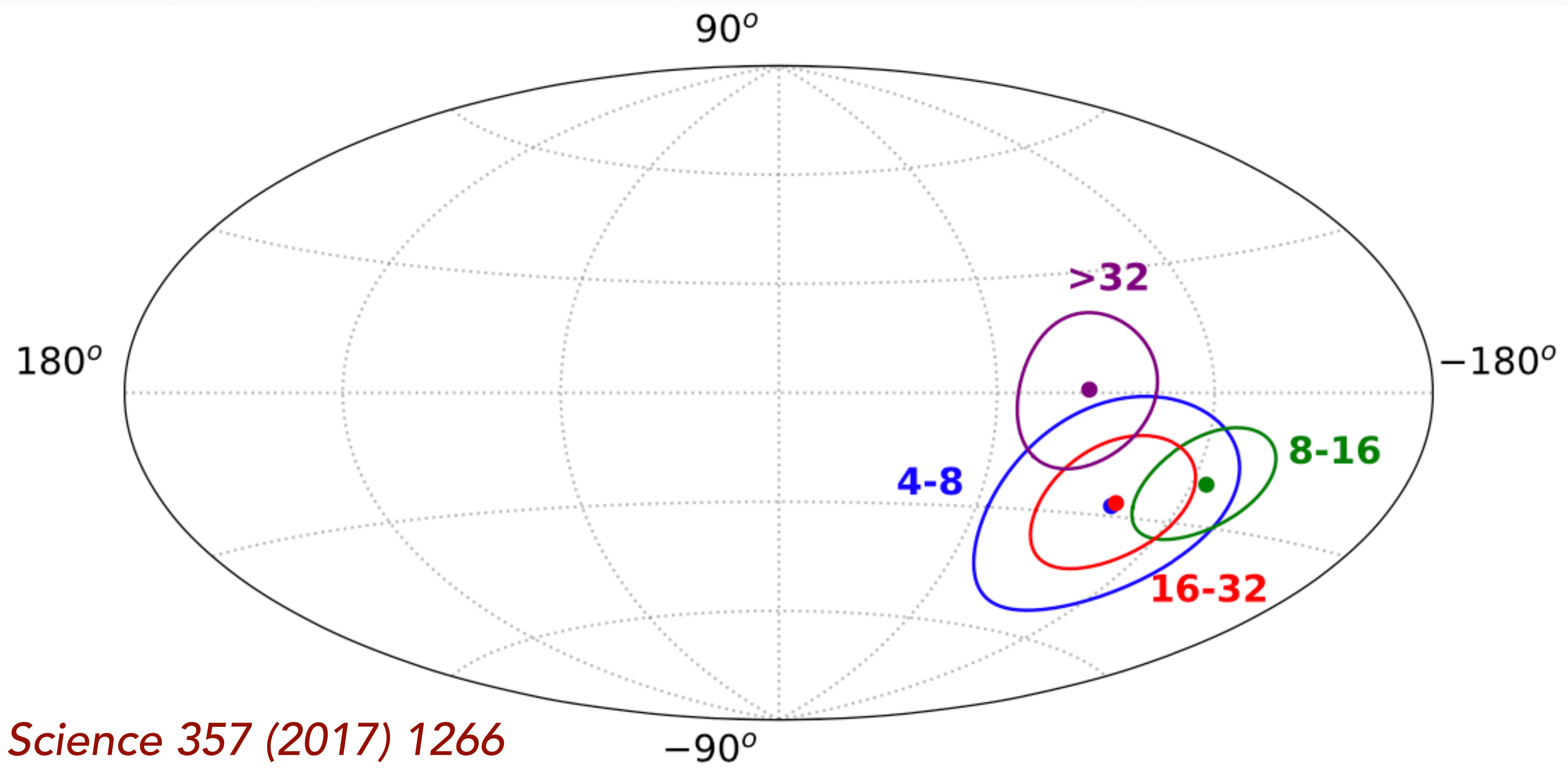


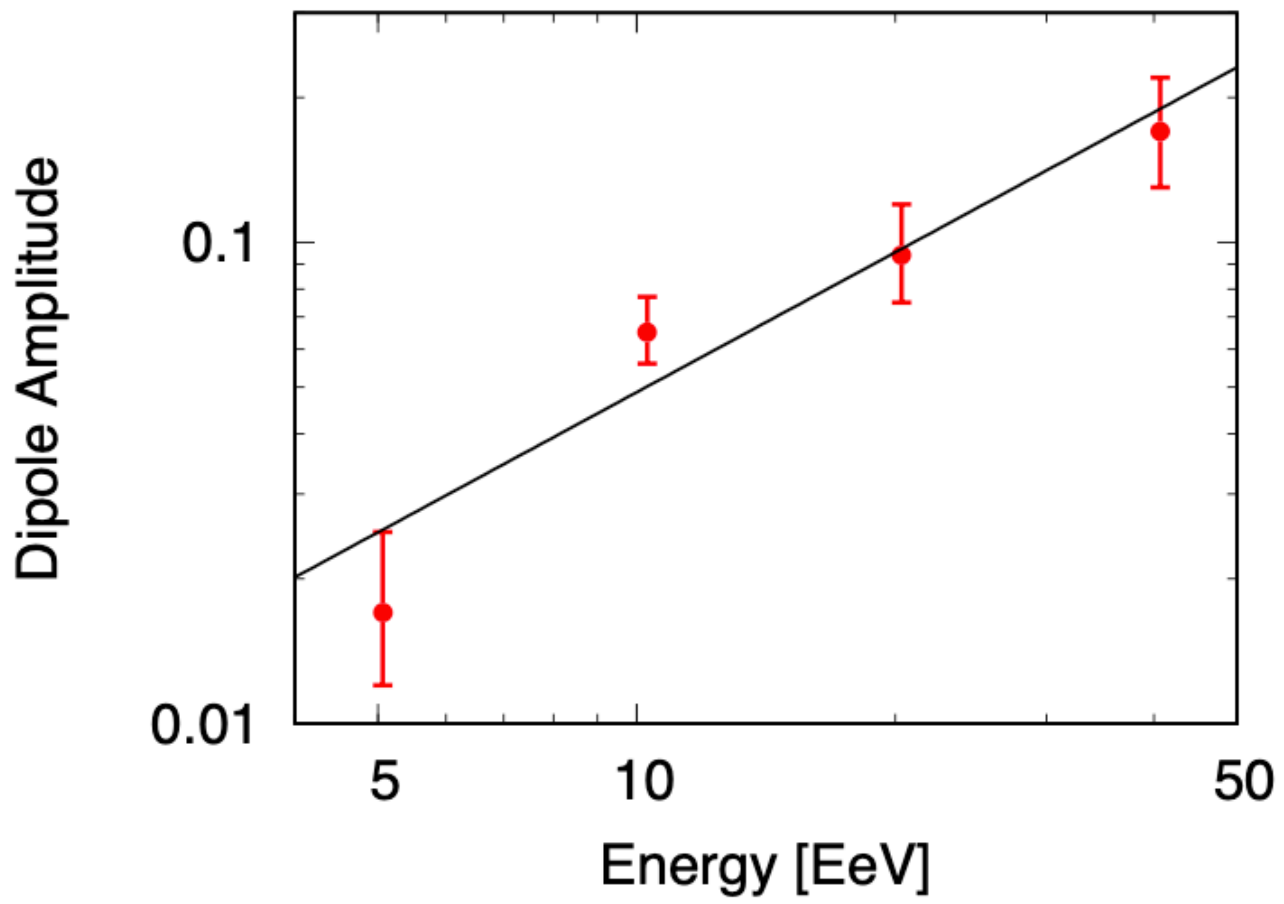
Equatorial coordinates, smoothed by a top-hat window of 45°.

Extremely large exposure ($\vartheta < 80^0$) :123,000 km^2 sr yr above 4 EeV

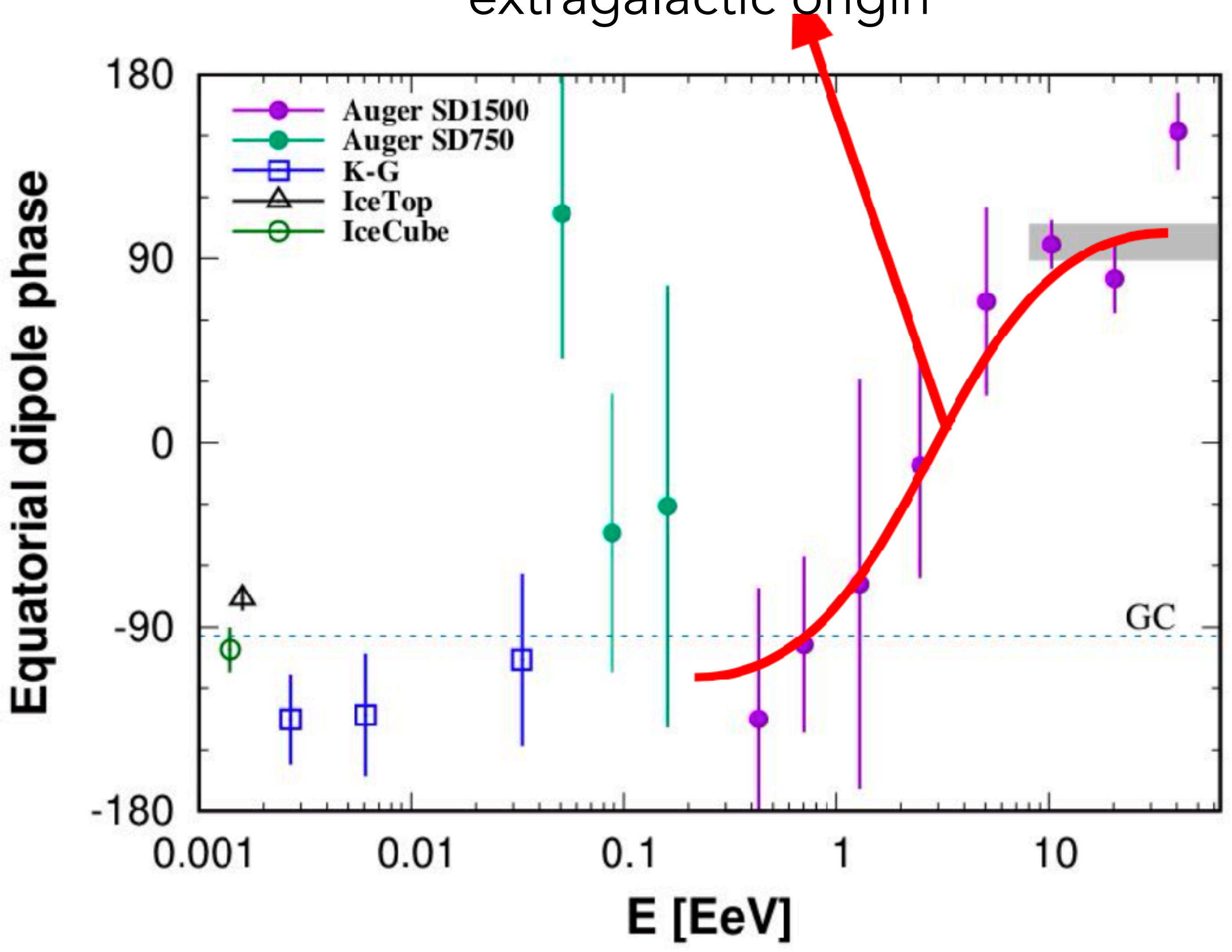
➡ Observation of dipolar anisotropy for E≳8 10^{18} eV
Significance **6.9σ** above 8 EeV, **5.7σ** at E=8-16 EeV

➡ Dipole direction ~113^0 away from the Galactic Center:
Extragalactic origin of UHECR above 8 EeV





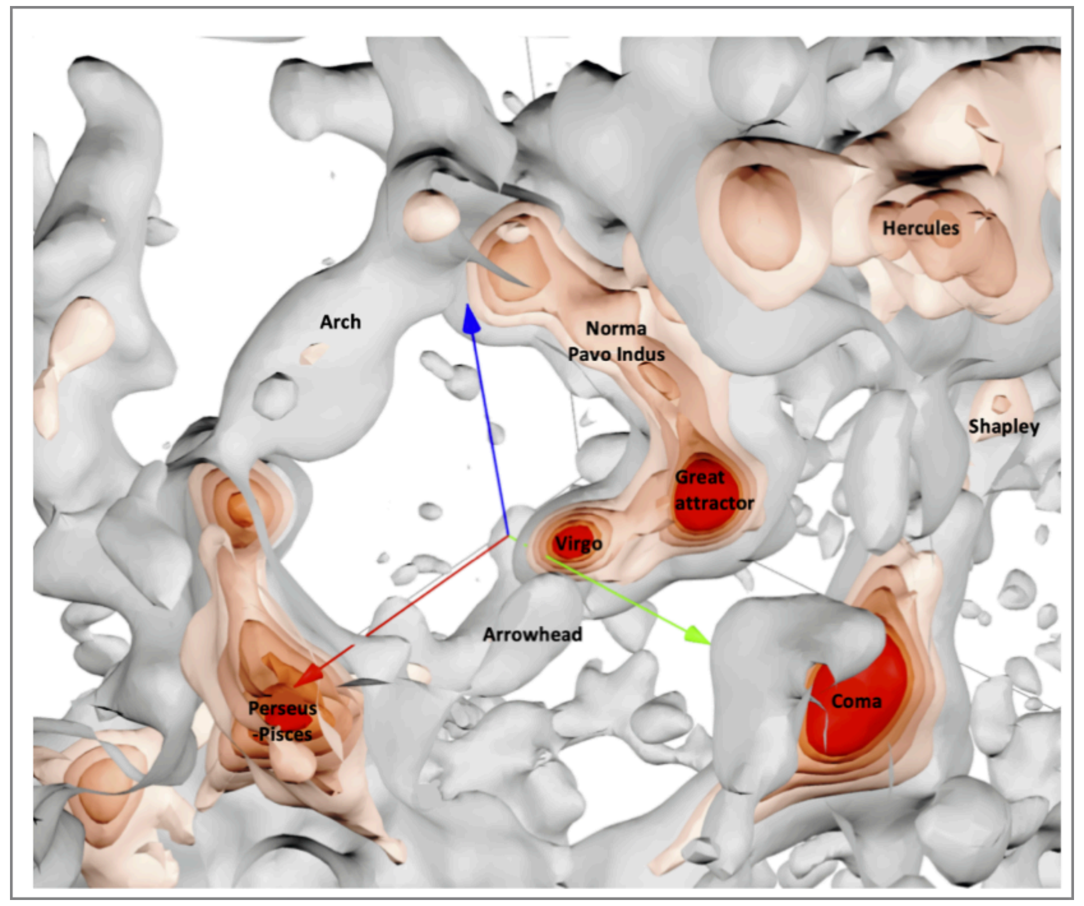
Change from Galactic to extragalactic origin

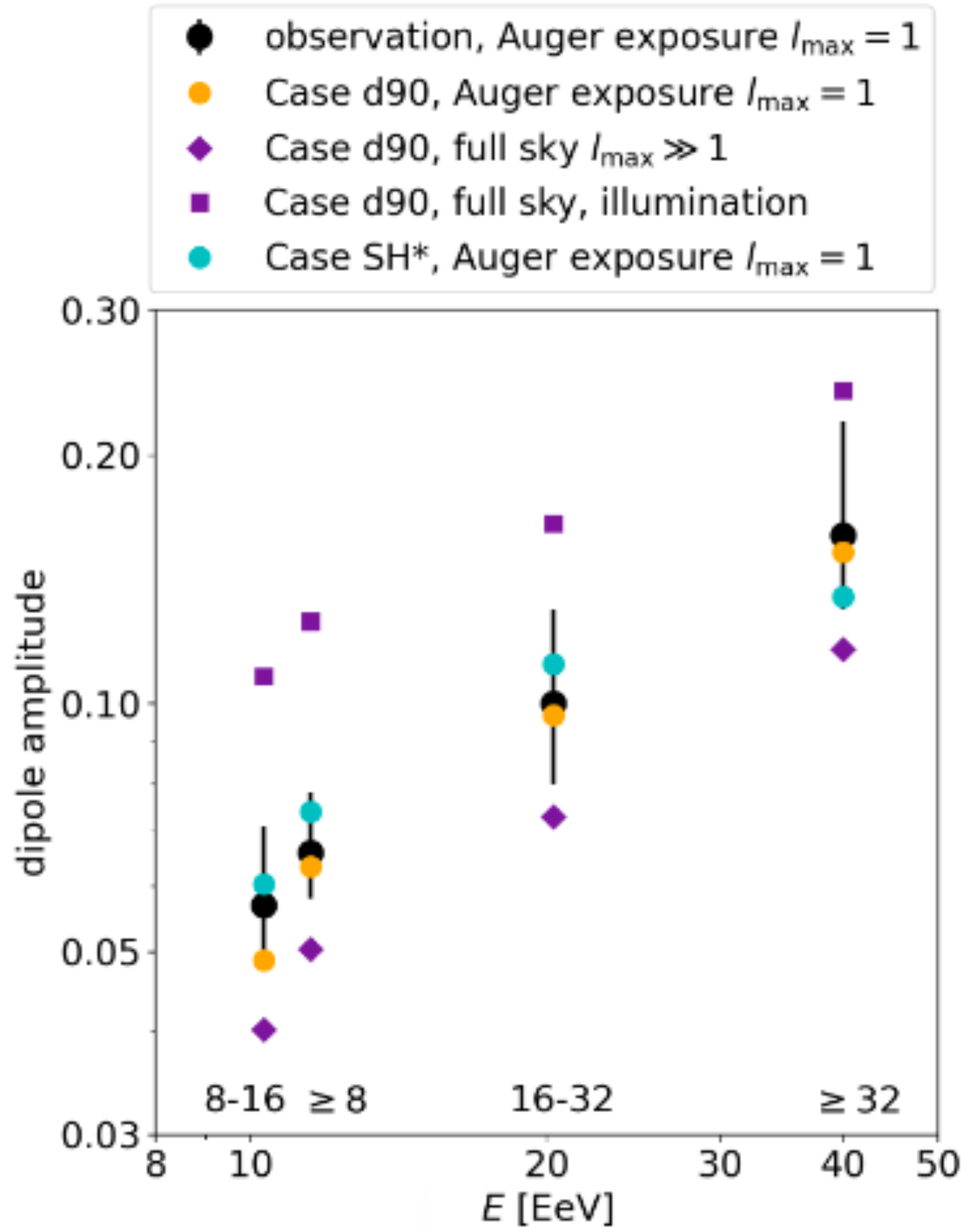


Auger Coll., Science 357 (2017) 1266
Auger Coll., Astrophys. J. 868 (2018) 4
G.Golup, PoS(ICRC2023) 252, subm.ApJ

Large scale anisotropy: interpretation

Complex interplay of
- Mass composition
- Source distributions
- Magnetic fields deflections

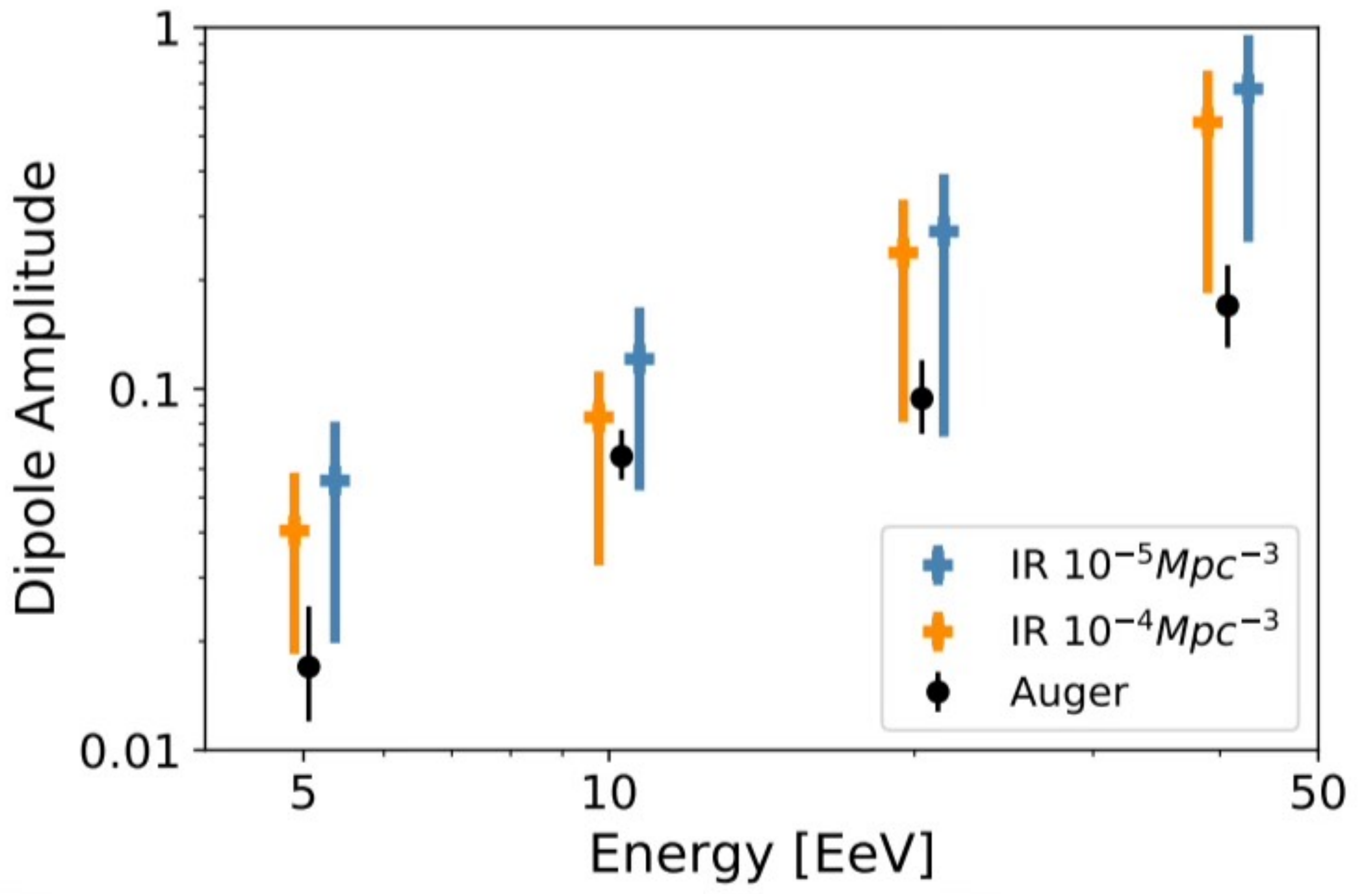


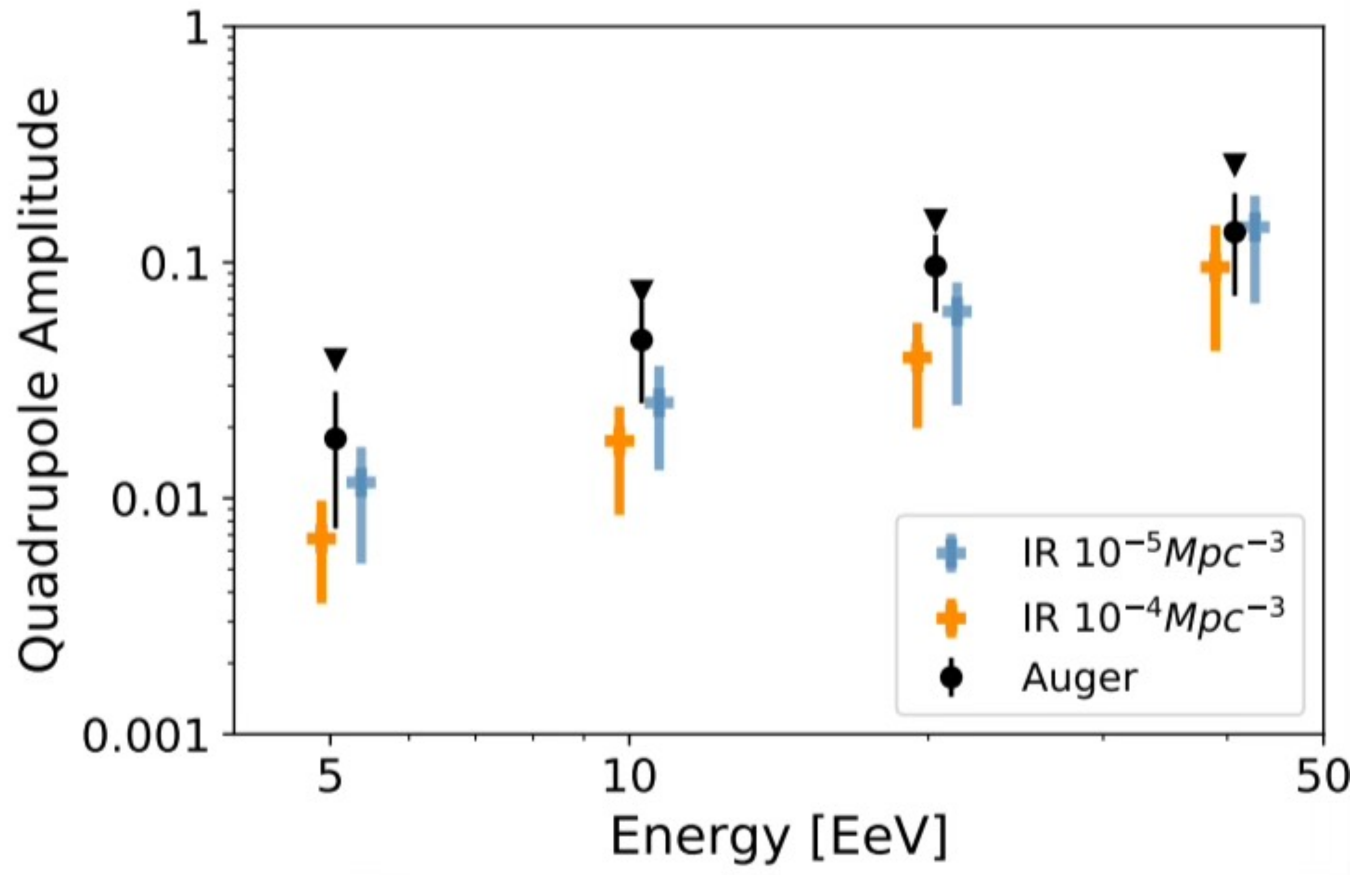


The observed anisotropy and its evolution with energy is well described as a signature of the local large scale distribution of matter

Not consistent with pure protons >8 EeV: require mixed composition (unless dipole not due to LSS)

C.Ding et al., ApJ 913 (2021) L13





Assuming equally luminous sources from 2MASS, two different source densities + model for HE component from our best fit of composition
— consistency with data
— some tension with small quadrupole amplitudes

Auger Coll., subm.ApJ

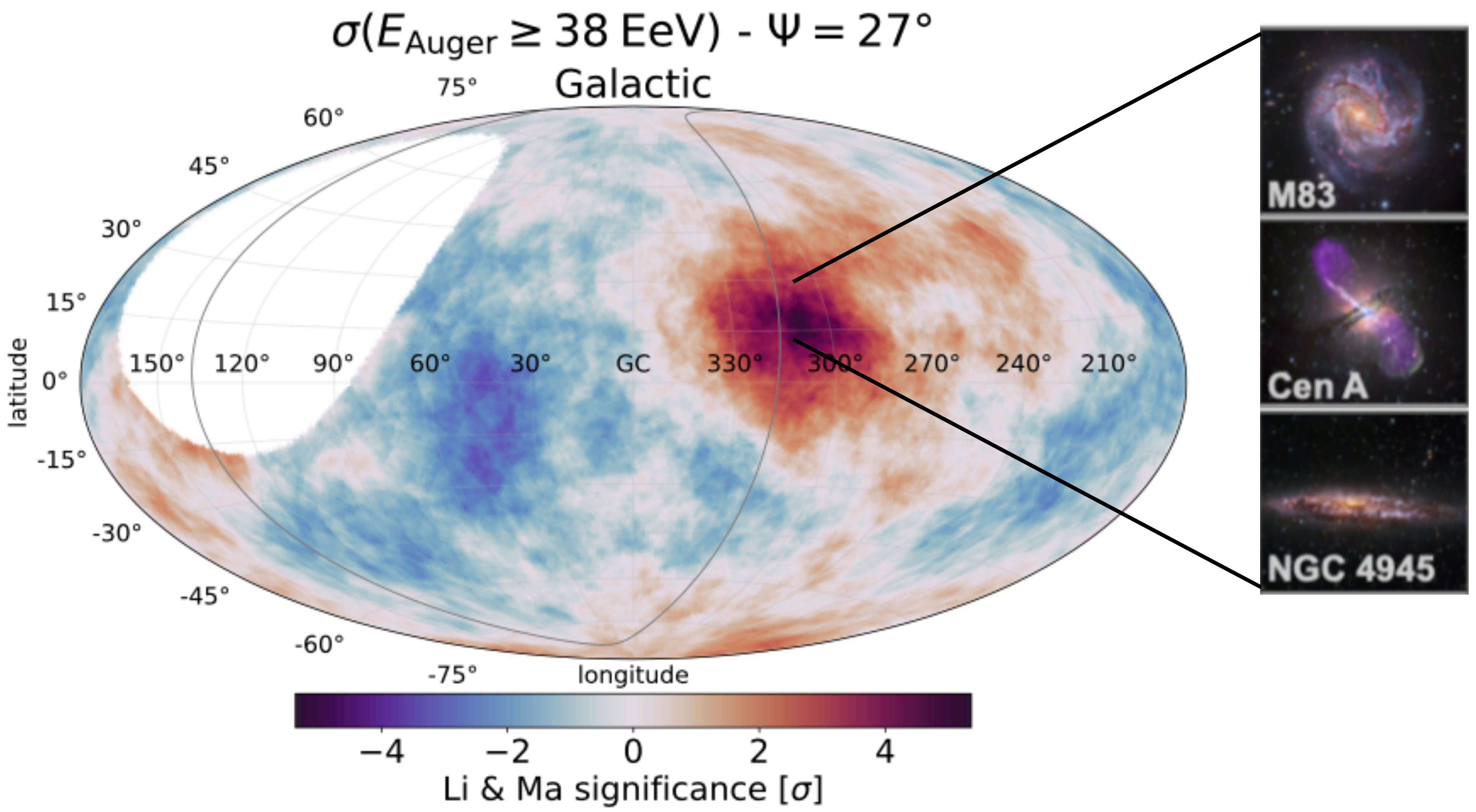
The UHE sky from Auger

1/ all sky search for overdensities: scan in energy and in top-hat radius

Centaurus region: **4.0σ** significance at E_{thr}=38 EeV at ψ=27⁰

➡ 135,000 km² sr yr for E>32 EeV

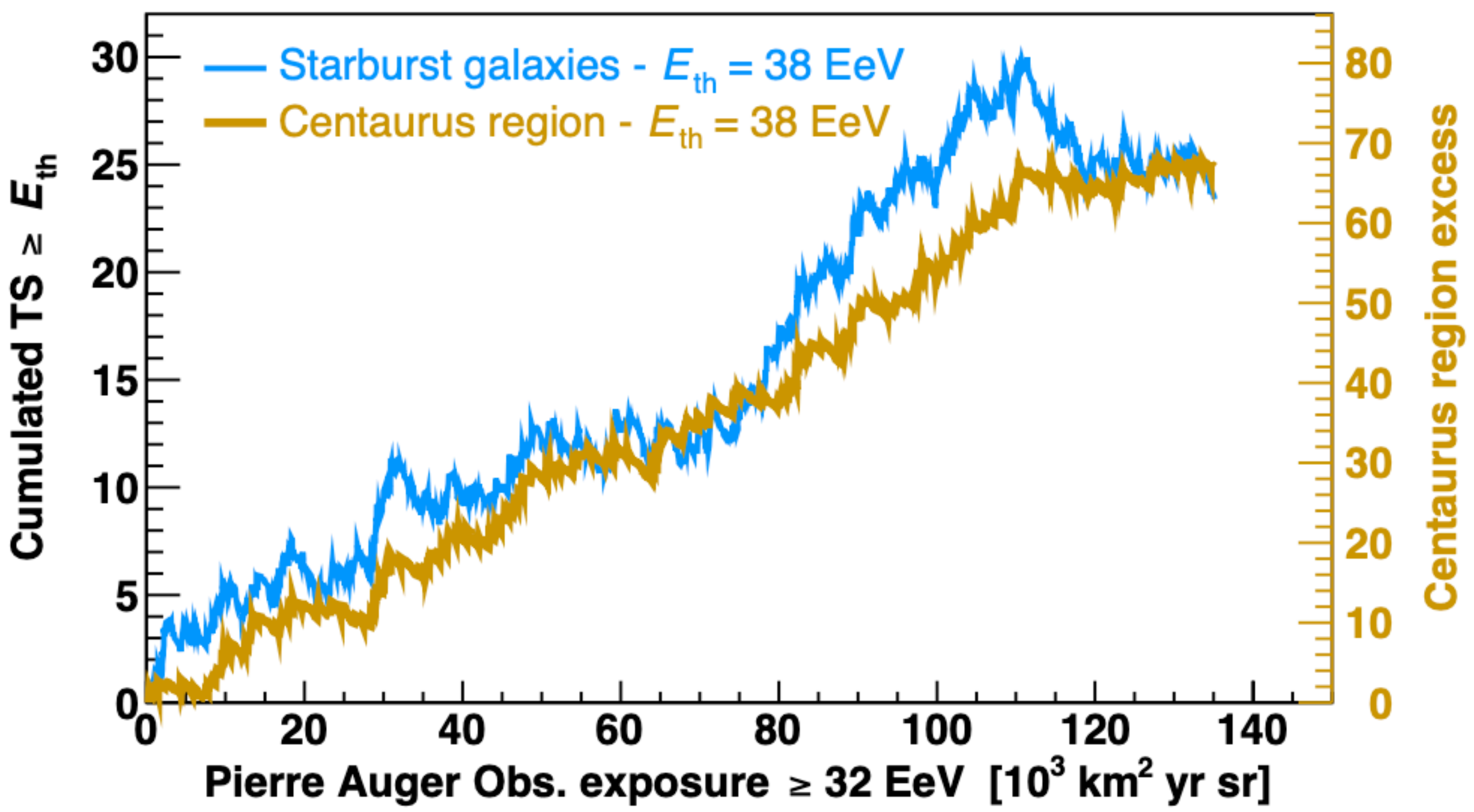
➡ (165000±15000) km² sr yr would allow us to reach 5σ

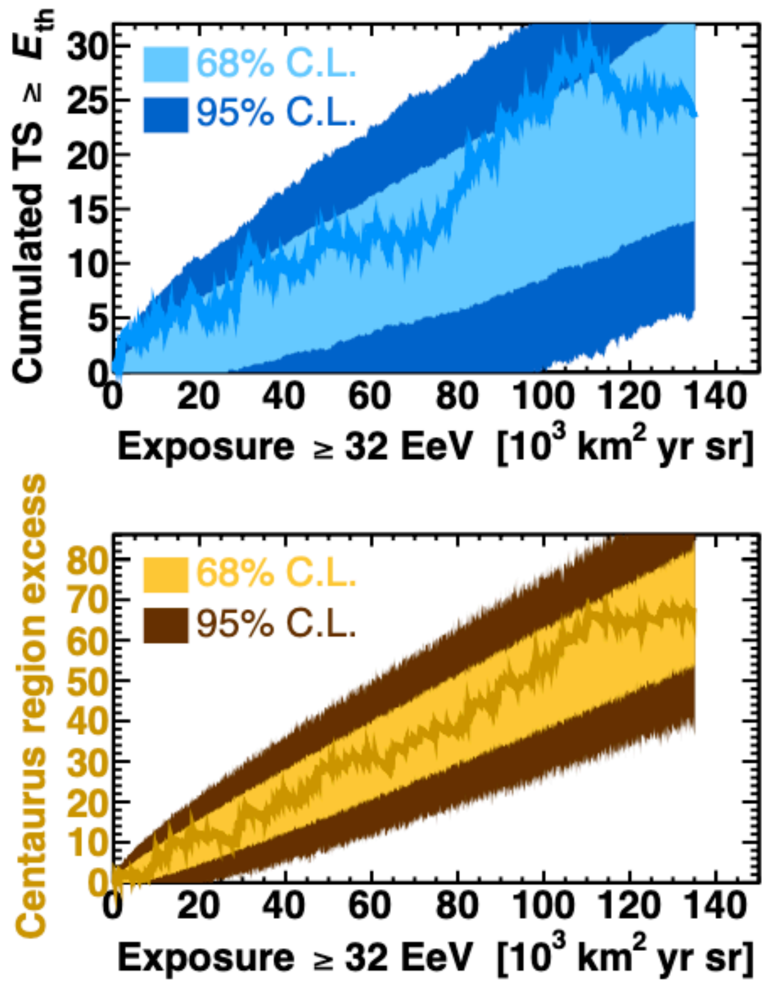


2/ catalog-based search

Analysis: unbinned maximum-likelihood analysis vs isotropy
Sky model: [**α**×sources + (1-**α**)×isotropic] ⊗ Fisher(**θ**)

Catalog	E_{th} [EeV]	Ψ [°]	α [%]	TS	Post-trial p-value	
All galaxies (IR)	38	24^{+15}_{-8}	14^{+8}_{-6}	18.5	6.3×10^{-4}	➡ 3.2σ
Starbursts (radio)	38	25^{+13}_{-7}	9^{+7}_{-4}	23.4	6.6×10^{-5}	➡ 3.8σ
All AGNs (X-rays)	38	25^{+12}_{-7}	7^{+4}_{-3}	20.5	2.5×10^{-4}	➡ 3.5σ
Jetted AGNs (γ-rays)	38	23^{+8}_{-7}	6^{+3}_{-3}	19.2	4.6×10^{-4}	➡ 3.3σ





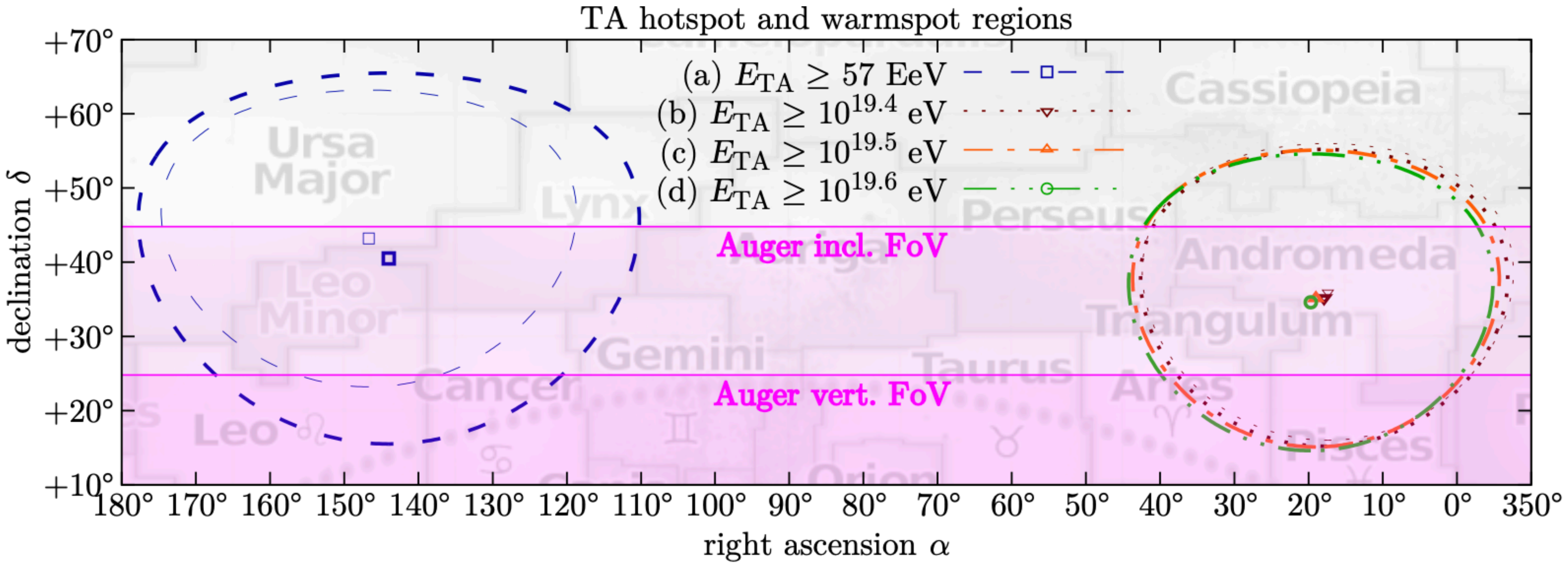
➡ All models capture an overdensity in Centaurus region (CenA, NGC4945, M83)

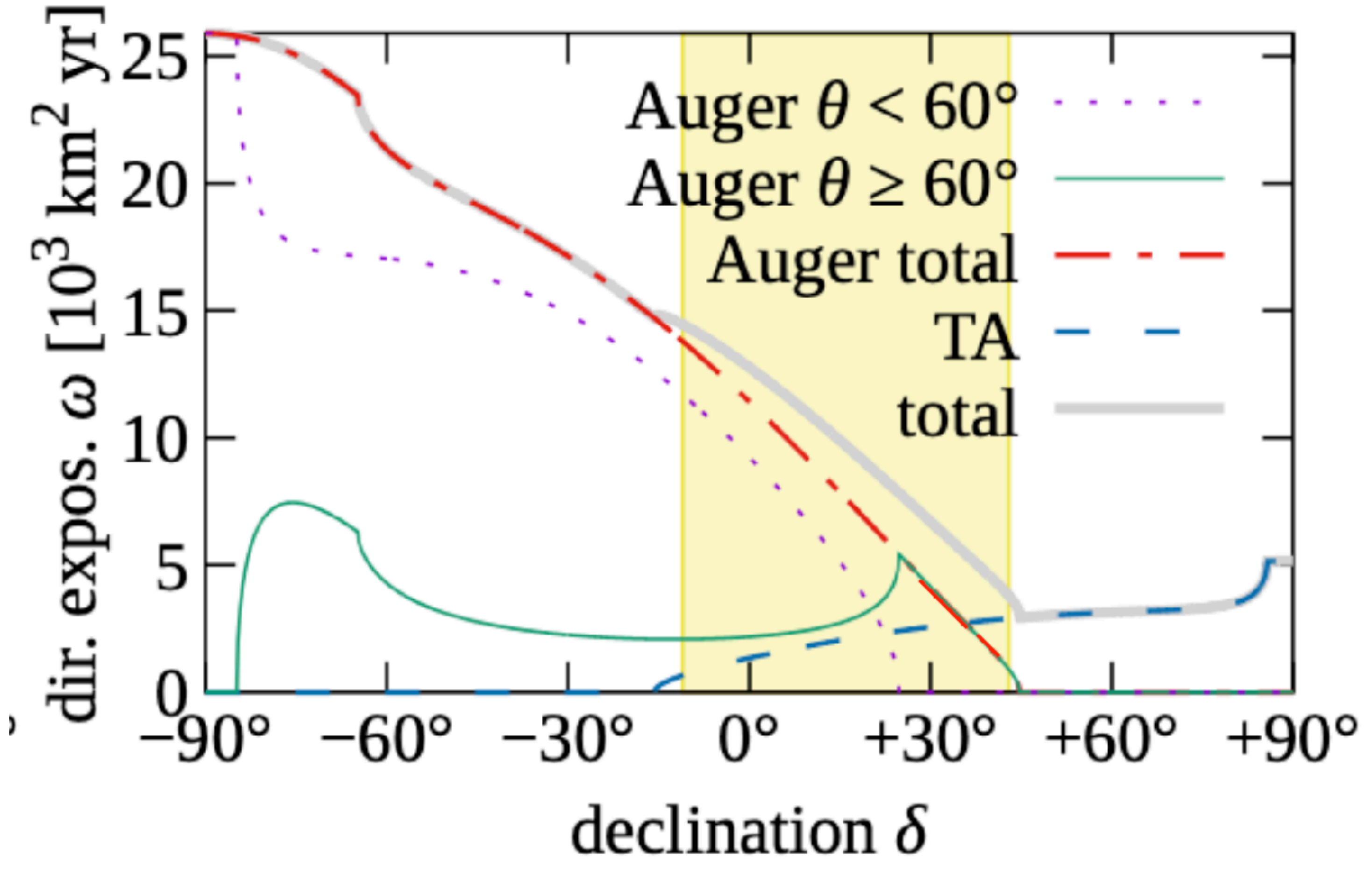
➡ The SBG model points to a milder excess close to NGC253

G.Golup, PoS(ICRC2023) 252, subm.ApJ
Auger Coll., ApJ 935 (2022) 170

Differences between Northern and Sourthern sky?

Using vertical+inclined events we have partial coverage of the Northern sky





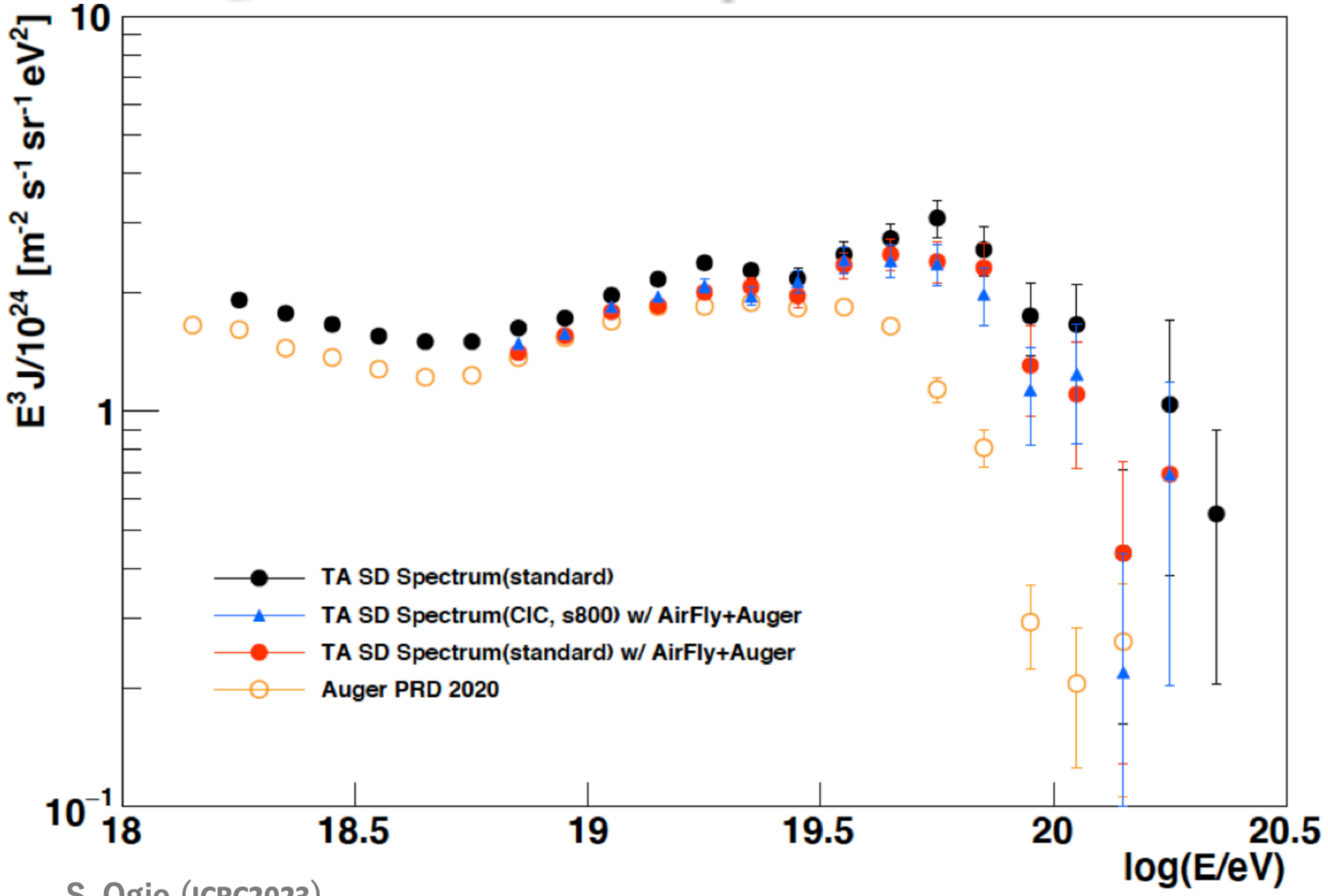
	$(\alpha_0, \delta_0)\,[°]$	E^{TA}	N^{TA}_{obs}	N^{TA}_{exp}	σ^{TA}_{post}	E^{Auger}	N^{Auger}_{obs}	N^{Auger}_{exp}	σ^{Auger}_{Li-Ma}
PPSC	(17.4, 36.0)	25.1	95	61.4	3.1σ	20.1	68	69.3	−0.2σ
	(19.0, 35.1)	31.6	66	39.1	3.2σ	25.3	40	45.2	−0.8σ
	(19.7, 34.6)	39.8	43	23.2	3.0σ	31.8	27	26.5	0.1σ
TA hot spot	(144.0, 40.5)	57	44	16.9	3.2σ	45.6	7	10.1	−1.0σ

➡ confirmation of the Centaurus region as most significant excess (4.0σ post-trial), extended to lower energies (20 EeV)

➡ no hints for excesses in the TA "spots" with data of comparable size —> currently not supporting the claim of TA that the declination dependence of the UHECR energy spectrum is due to the presence of excesses in particular regions of the Northern sky

G.Golup, PoS(ICRC2023) 252, subm.ApJ

Auger-TA comparison : the energy spectrum



S. Ogio (ICRC2023)

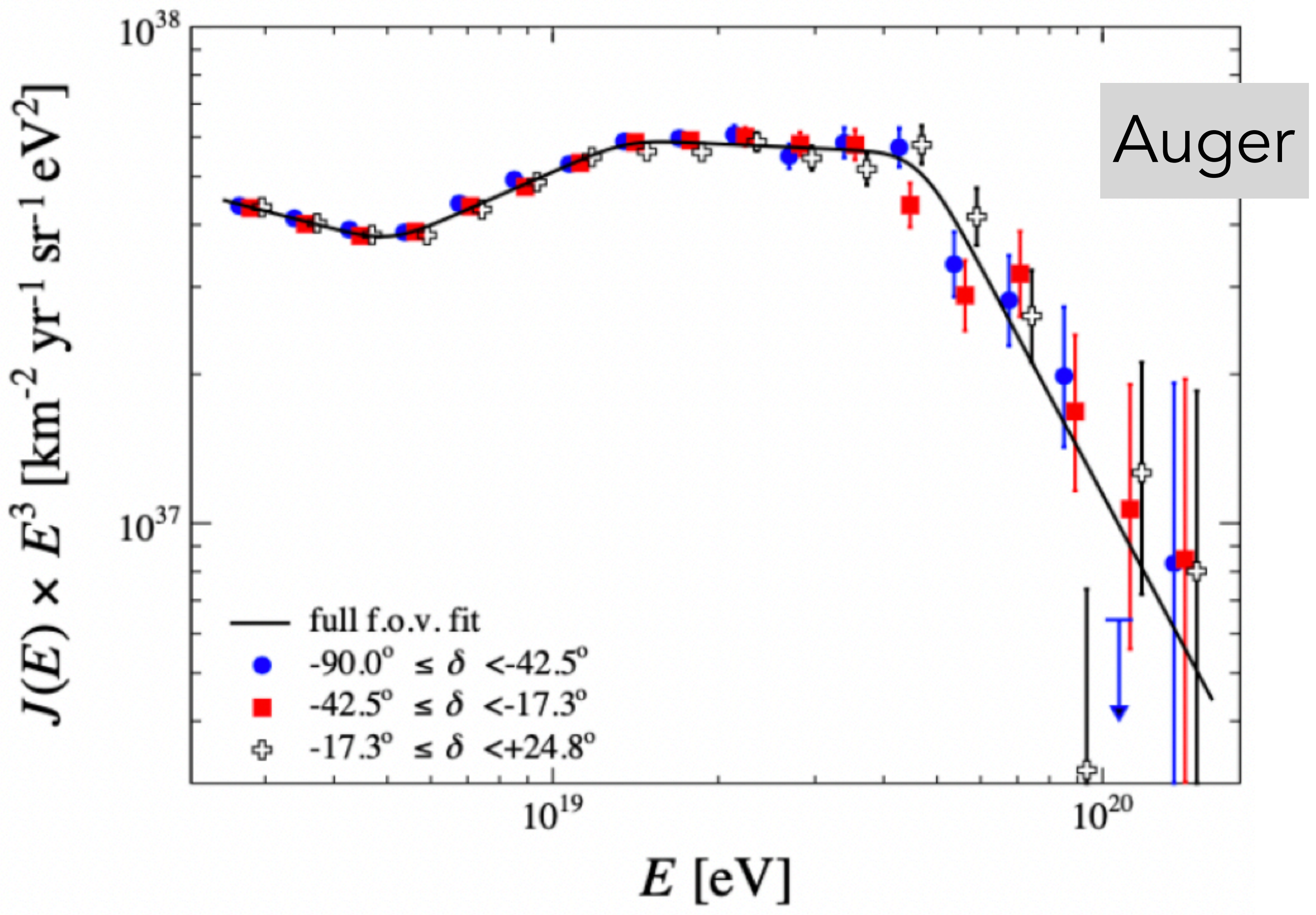
Good example of common working group

TA now using
— the same fluorescence yield (previously off by ~ -14%)
— the invisible energy (data-driven) correction of Auger (previously off by ~ +7%)

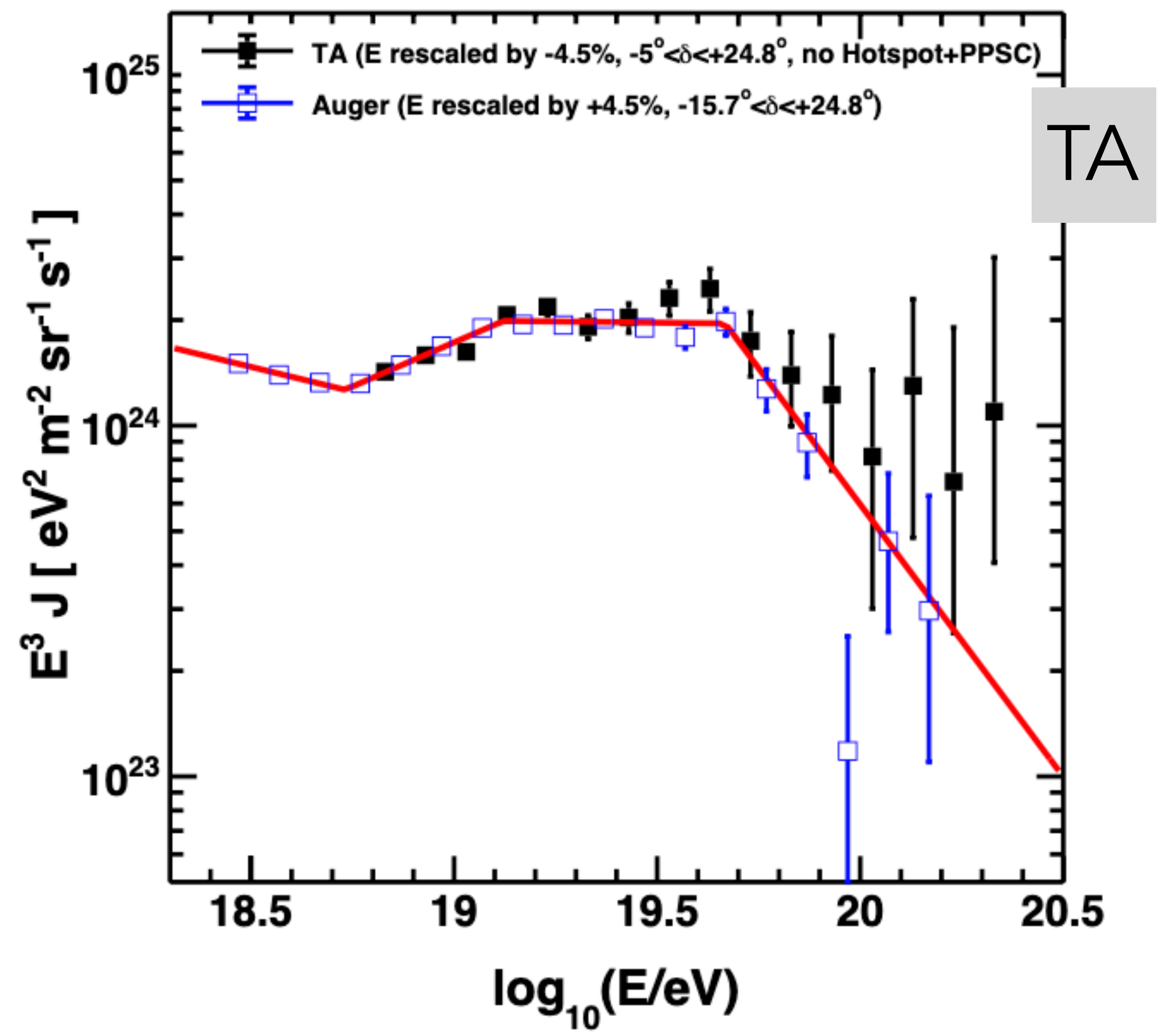
➡ E≲$10^{19.5}$ eV : good agreement (~1% difference)

S.Ogio, PoS(ICRC2023) 400
K.Fujisue, TeVPA2023

➡ E>$10^{19.5}$ eV: persistent difference.
— no declination dependence found in Auger
— TA first claim of a declination dependence (3.5σ):
$\log_{10}E_{break}$=19.64±0.04 for lower δ
$\log_{10}E_{break}$=19.84±0.02 for higher δ
TA second claim: 1.8σ difference in common decl.band if subtracting spots



A.Aab et al., PRD 102 (2020) 062005

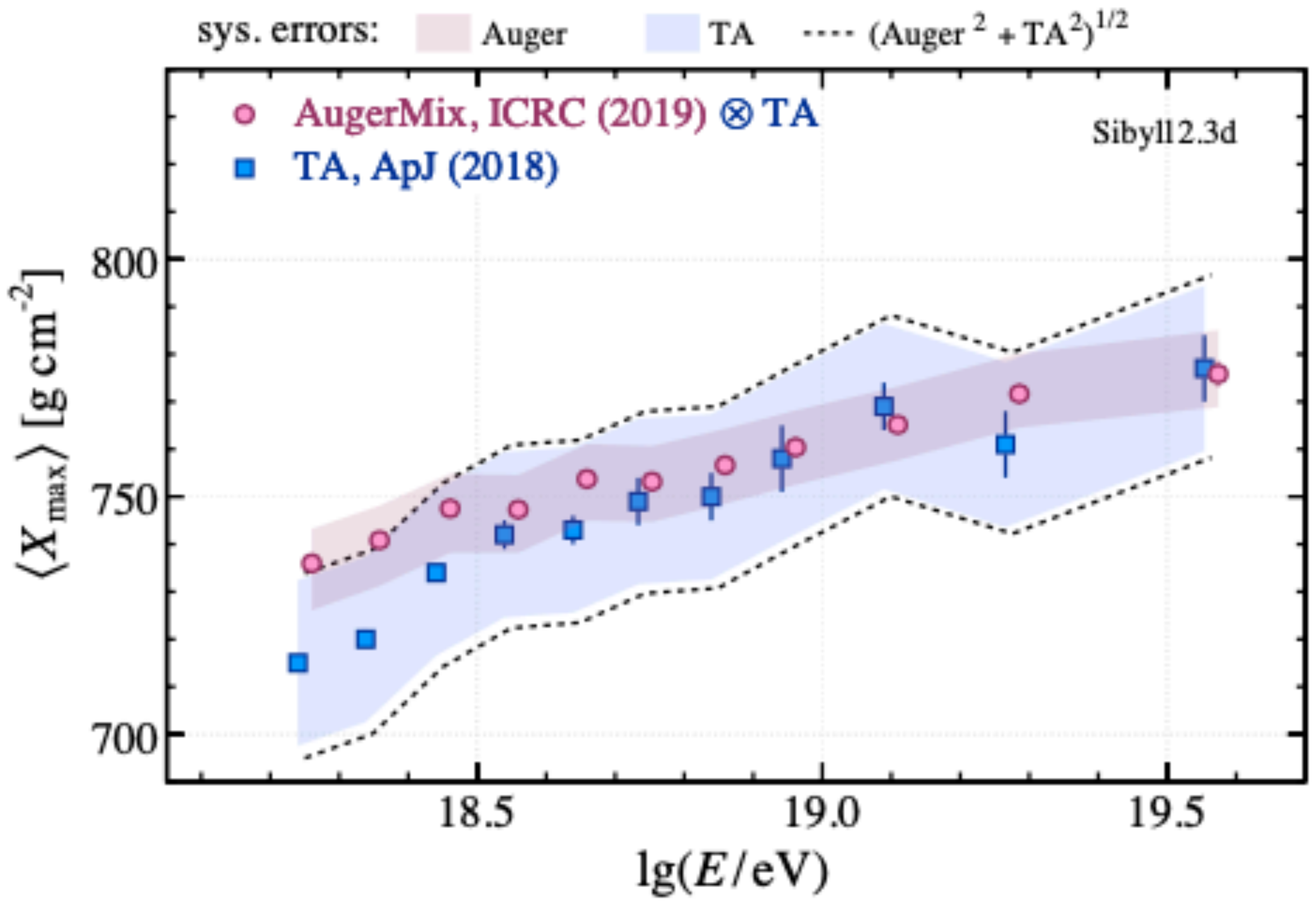


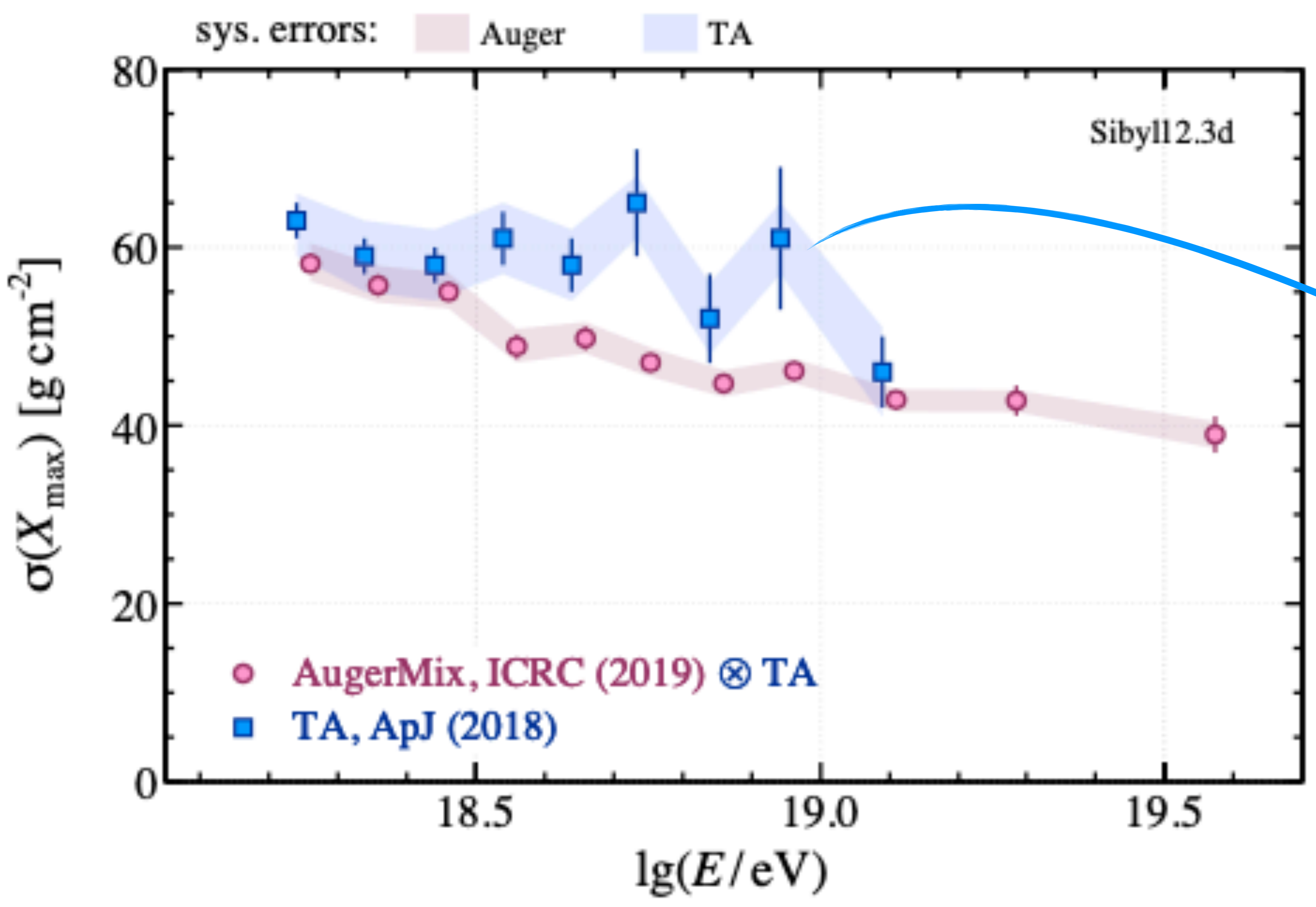
R.Abbasi et al., arXiV:2406.08612

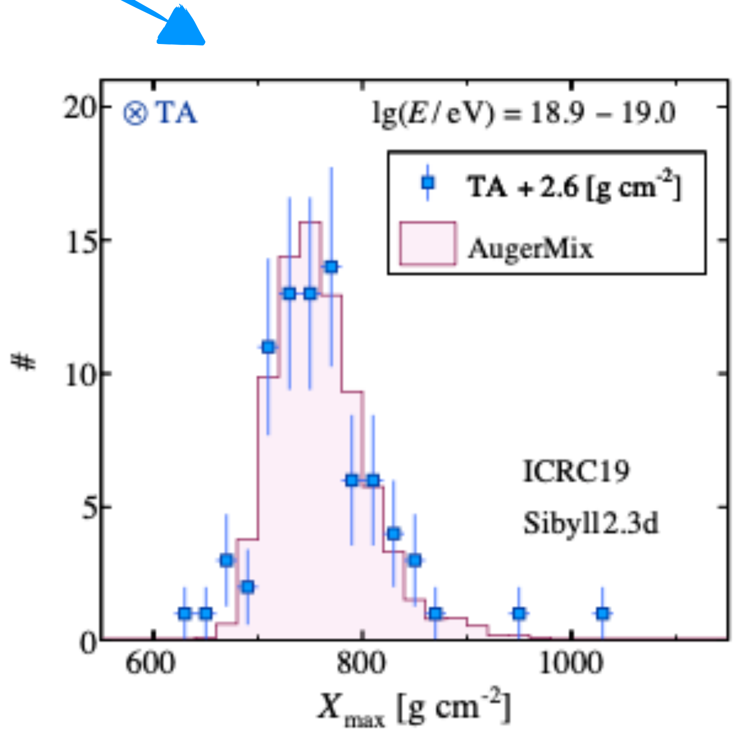
Auger-TA comparison : the mass composition

No direct comparison of X_{max} distributions is possible: Auger measurement unbiased, TA one folded with detector effects

Auger best fit composition as input to the TA simulations; the resulting distributions are compared to the TA X_{max} results







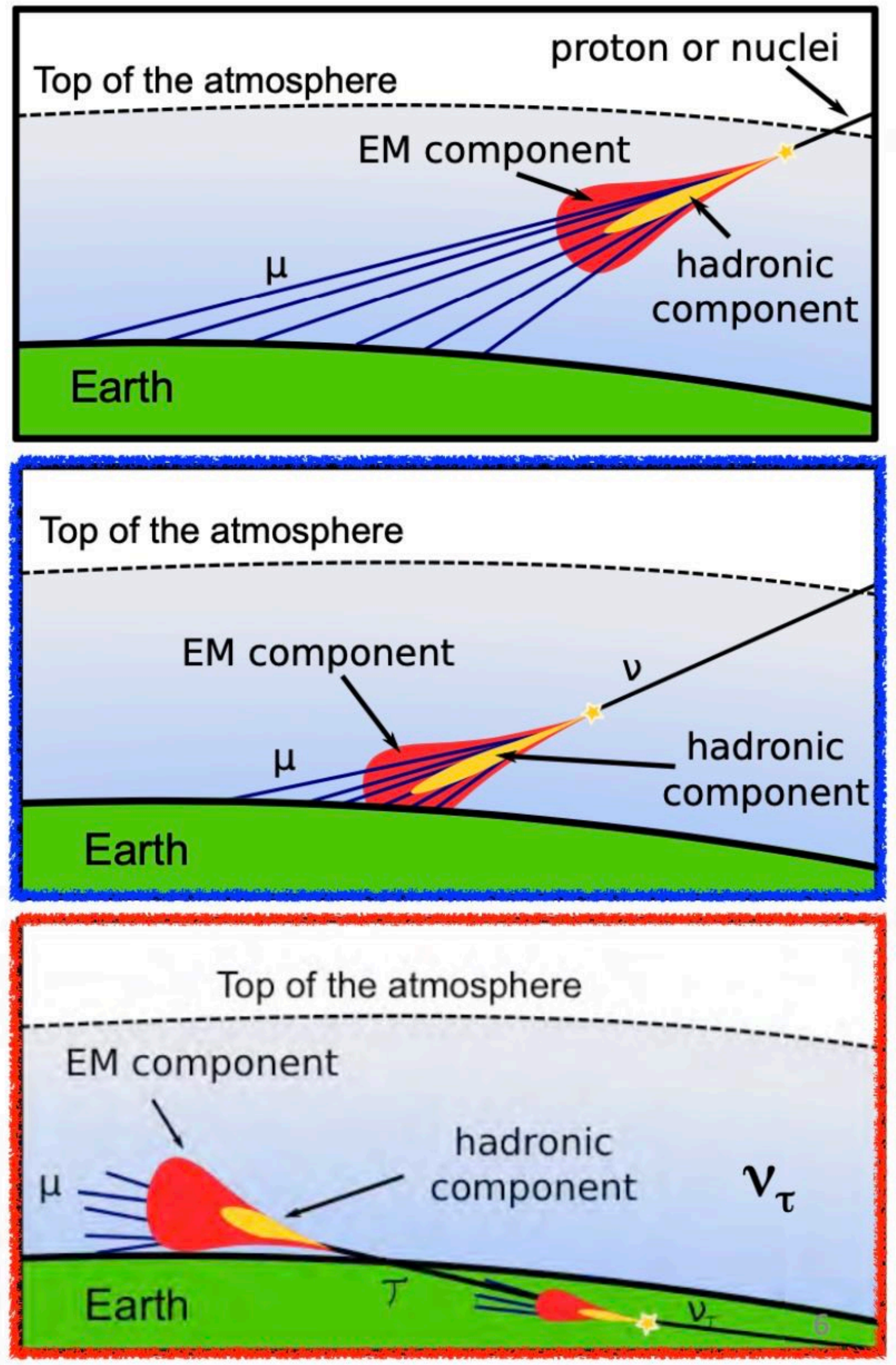
The Auger and TA measurements of $\langle X_{max} \rangle$ and $\sigma(X_{max})$ are compatible at the current level of statistics and understanding of systematic uncertainties

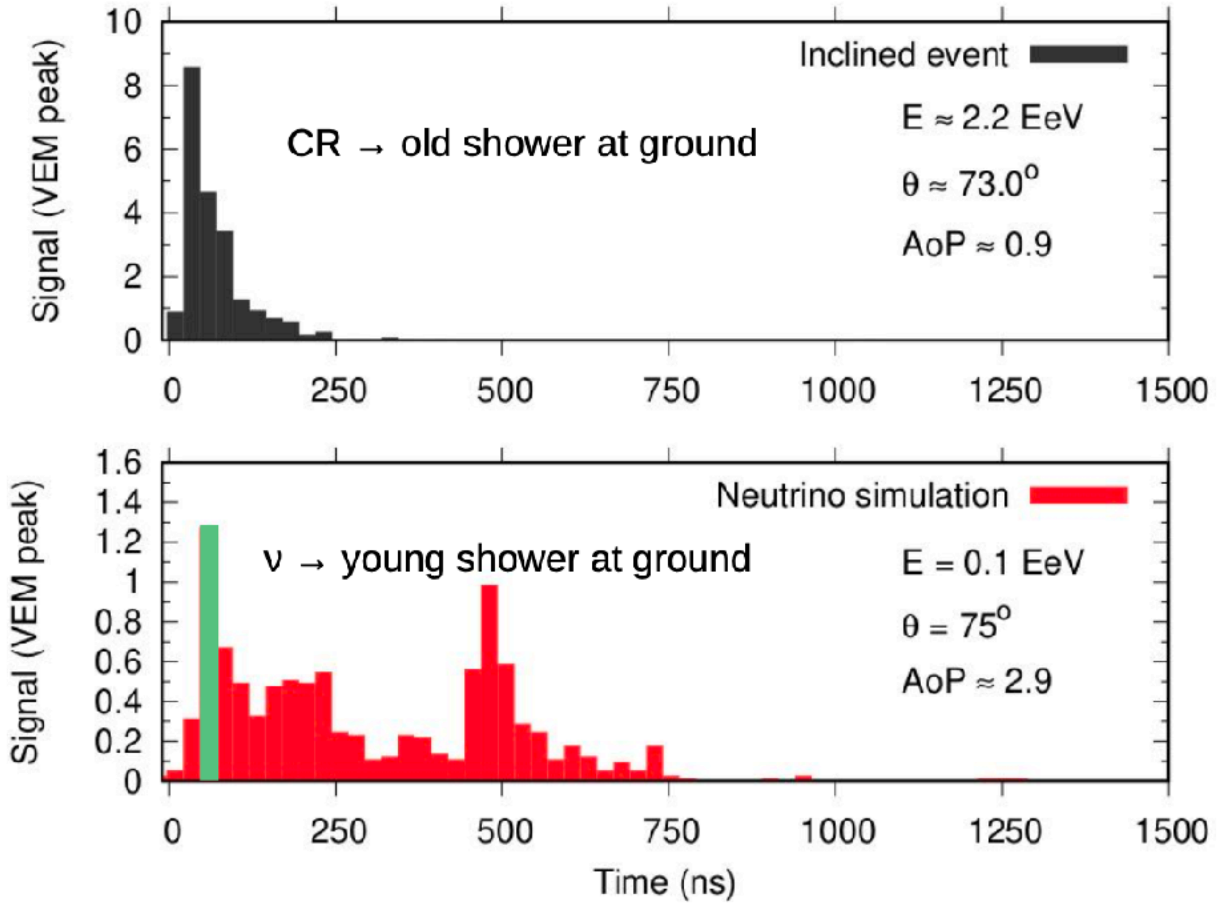
A.Yushkov, for the Joint WG, PoS(ICRC2023) 249

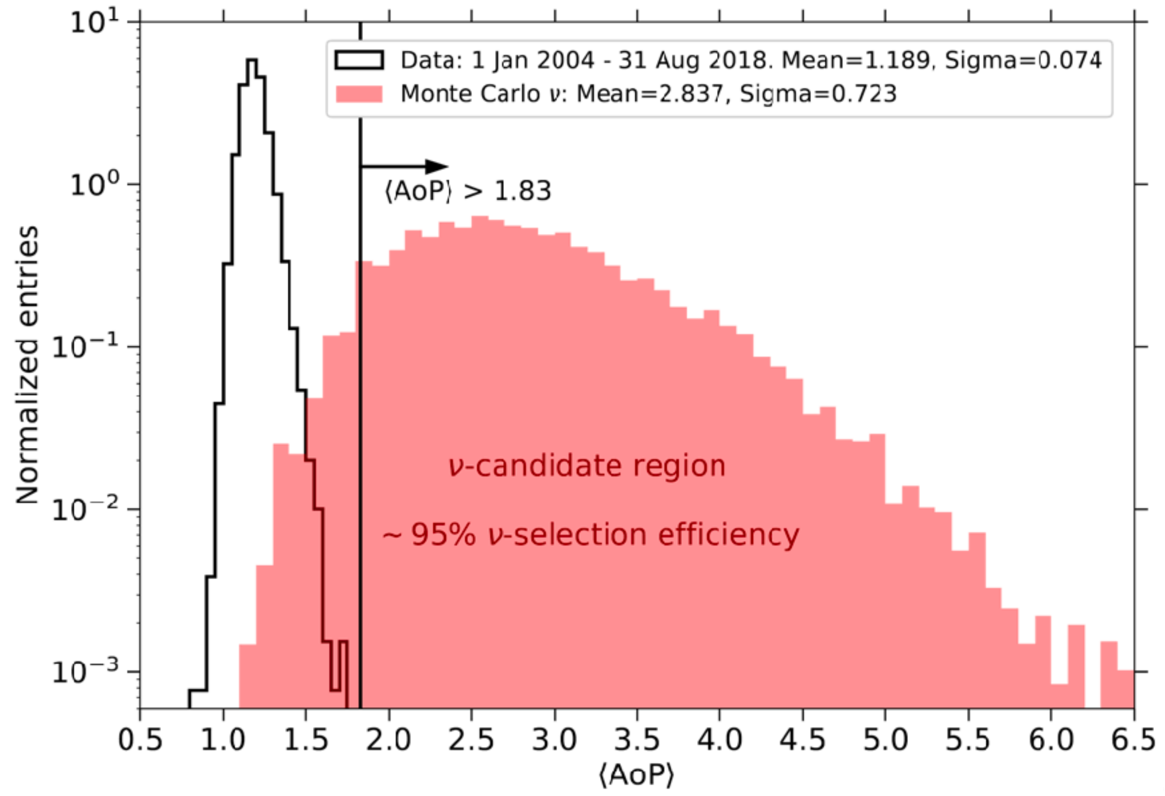
➡Auger can exclude a pure composition with very high statistical confidence

➡TA cannot exclude the Auger composition as their statistical and systematic uncertainties are too large

Detecting neutrinos in Auger







Neutrino-induced air showers:

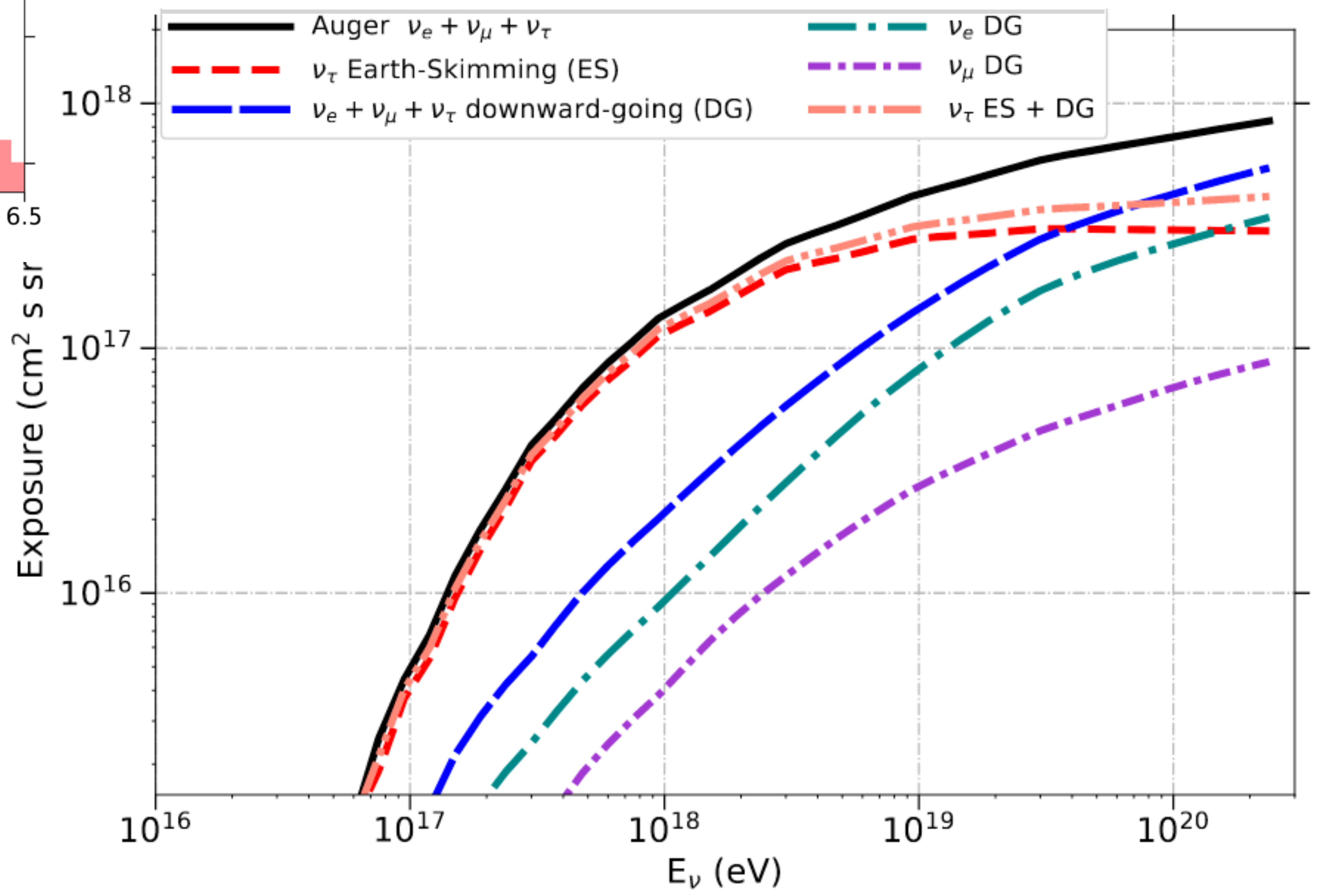
- deep showers
- em+μ component at ground

They can be identified by

- selecting inclined showers
- with large electromagnetic component
- with large Area over Peak (~1 for muonic showers)

Among inclined showers we select

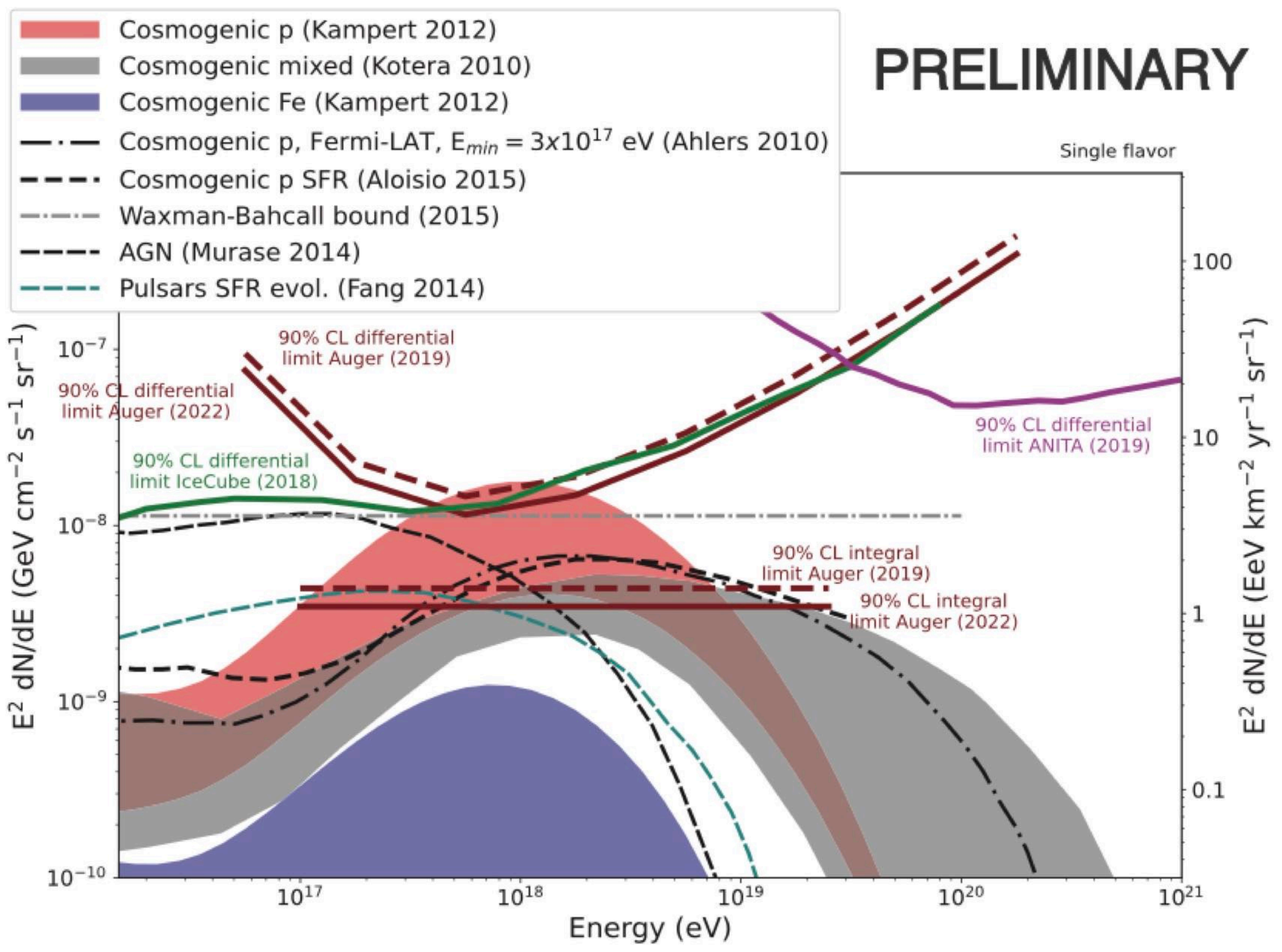
- Earth-skimming (ES) : 90^0-95^0
- Downgoing at high angle (DGH): 75^0-90^0
- Downgoing at low angle (DGL): 60^0-75^0

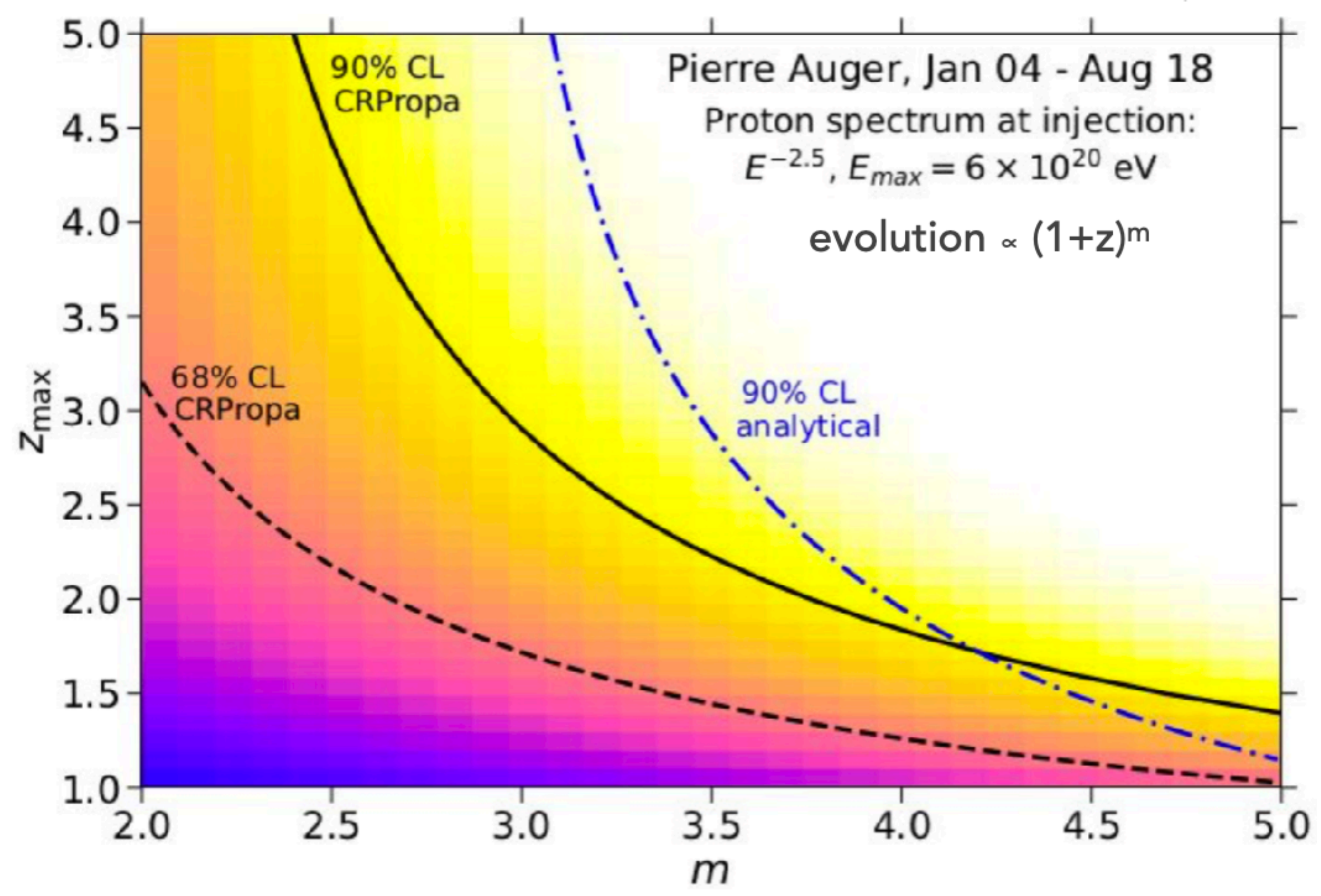


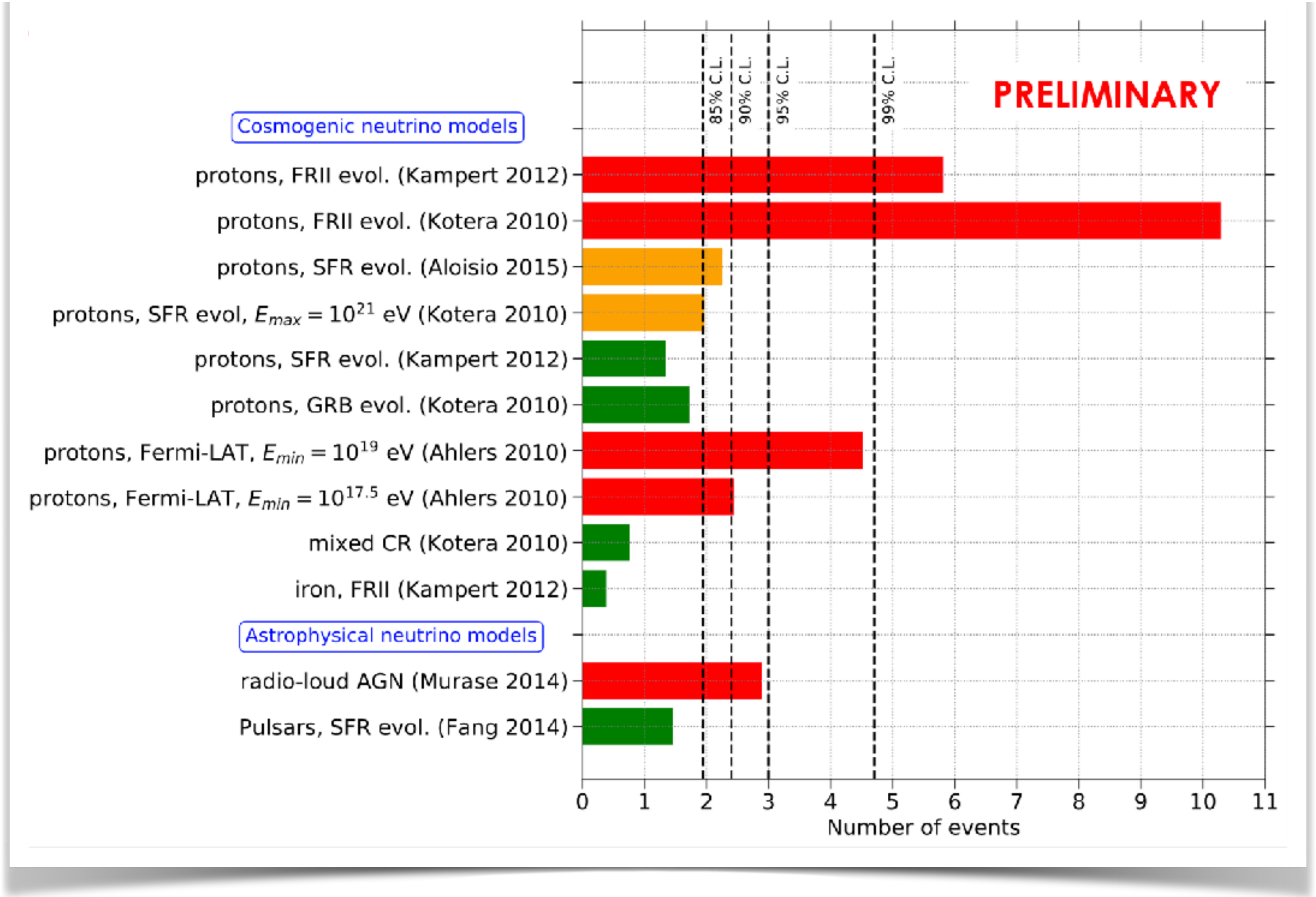
ES	79%
DGH	18%
DGL	3%

ν_τ	86%
ν_e	10%
ν_μ	4%

Search for a diffuse flux of neutrinos





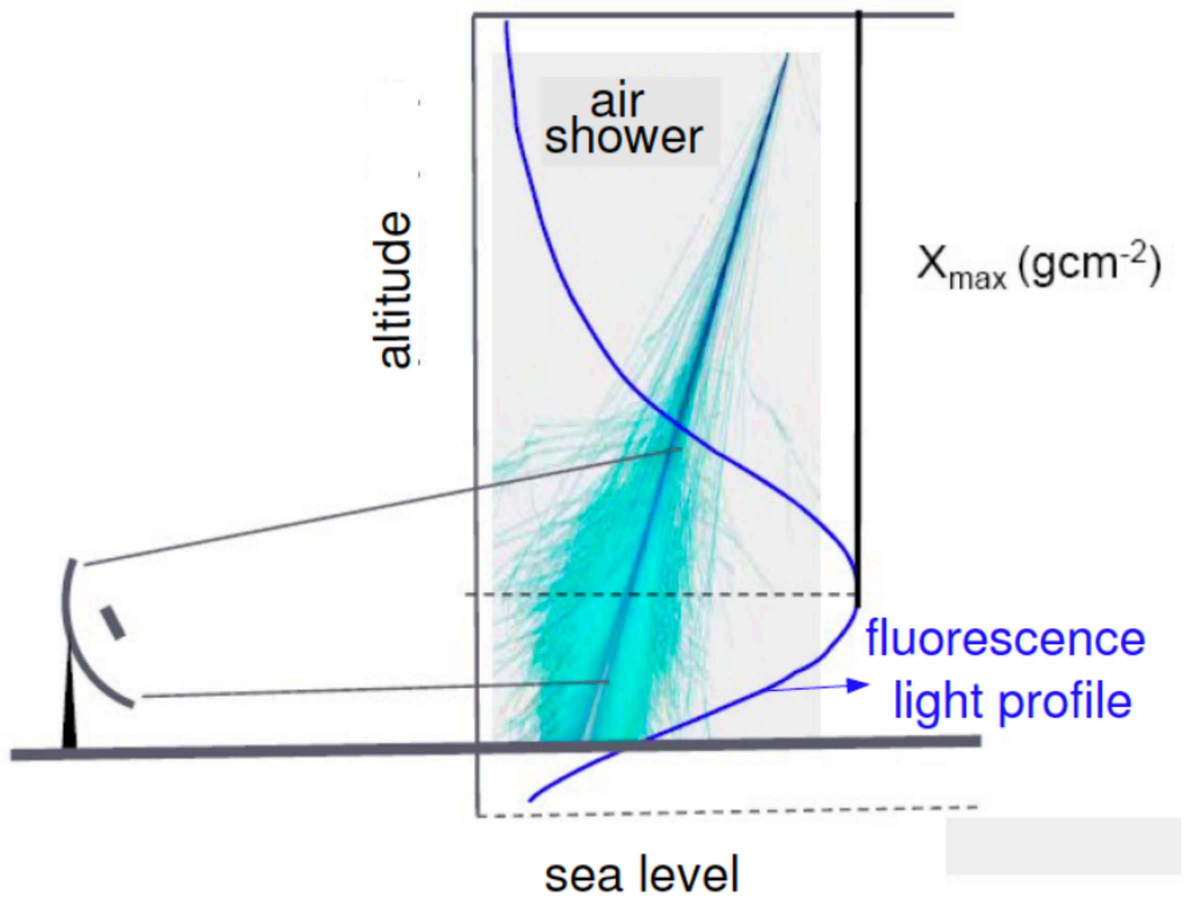


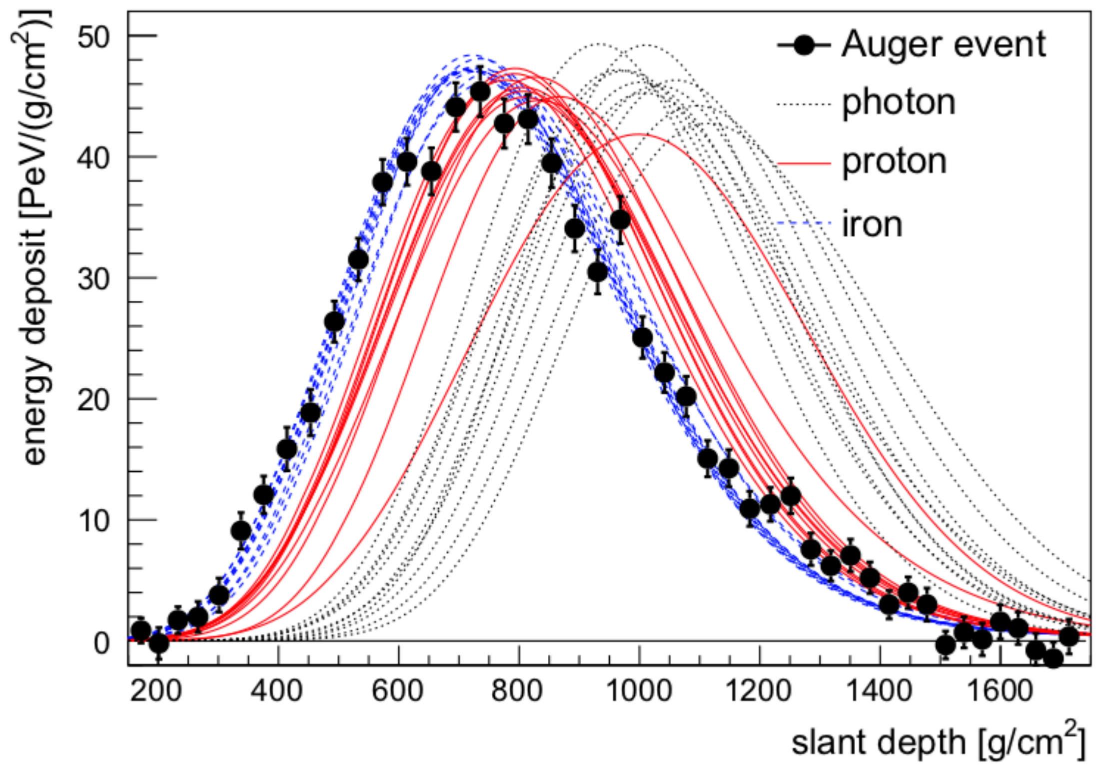
- ➡ No candidates found; best sensitivity slightly below 10^{18} eV
- ➡ Background very low, sensitivity limited by exposure
- ➡ Aperture comparable to that of IceCube if source direction is favourable

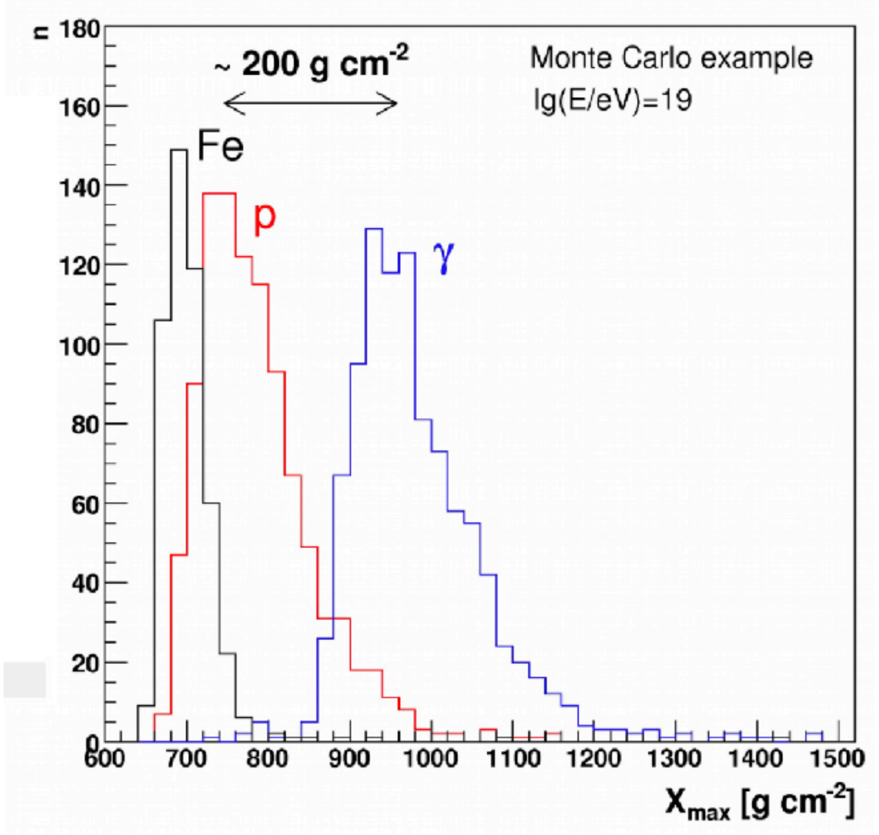
- ➡ Constraints on models assuming proton composition: independent confirmation of result from composition analysis
- ➡ Exclusion of a significant part of the (z,m) parameter space from non observation of neutrinos

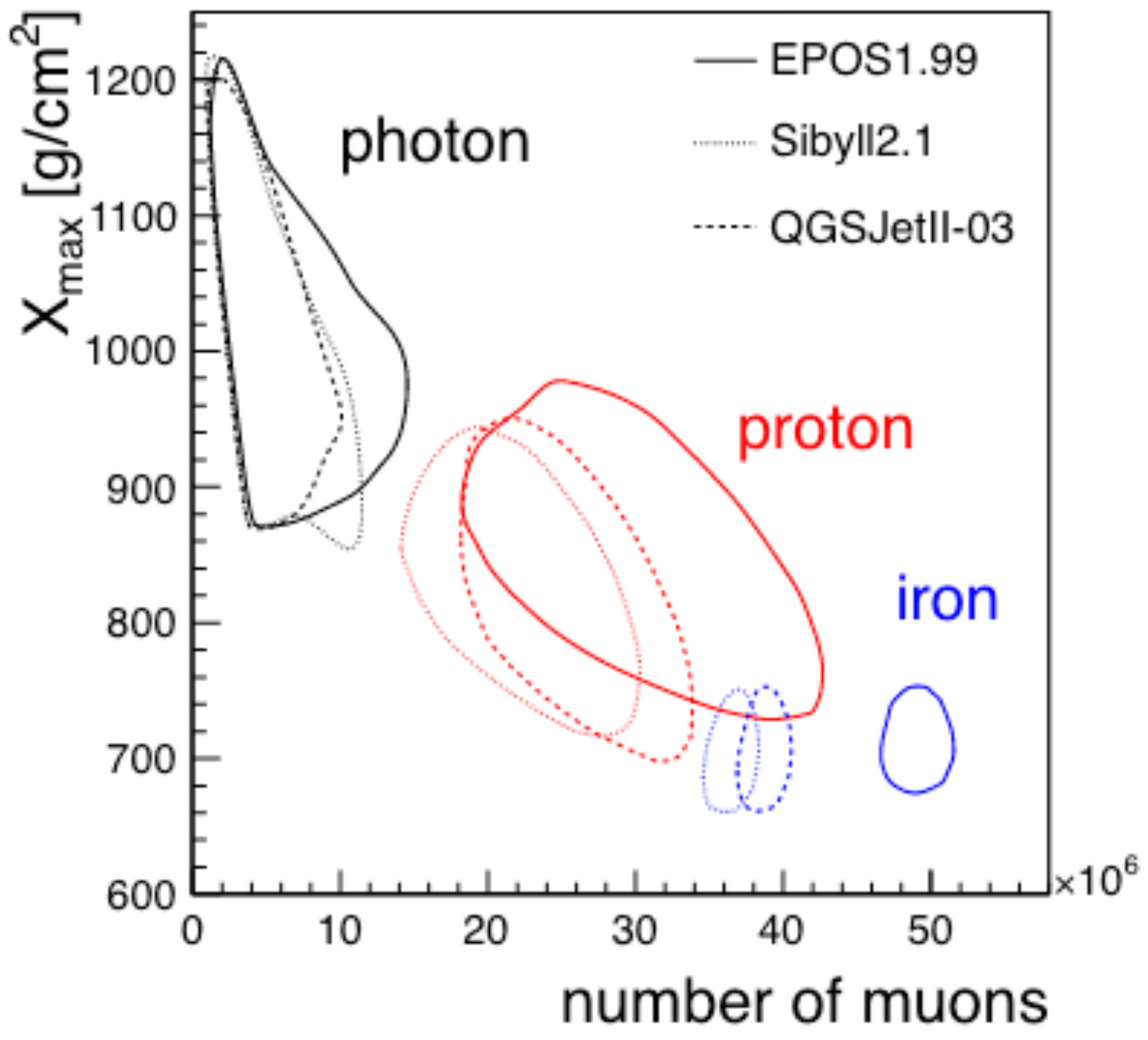
Auger Coll., JCAP 10 (2019) 022, M.Niechciol, PoS(ICRC2023) 1488

Detecting photons in Auger





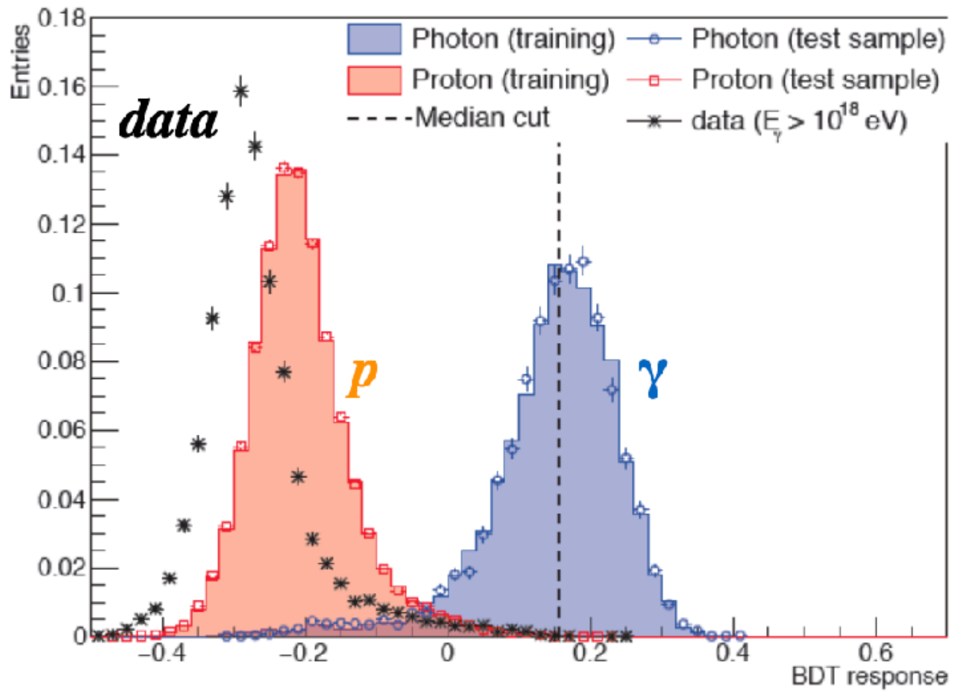




Photon-induced air showers are almost purely electromagnetic:

- deeper X_{max}
- μ-poor
- steeper lateral distribution
- spreaded in arrival time

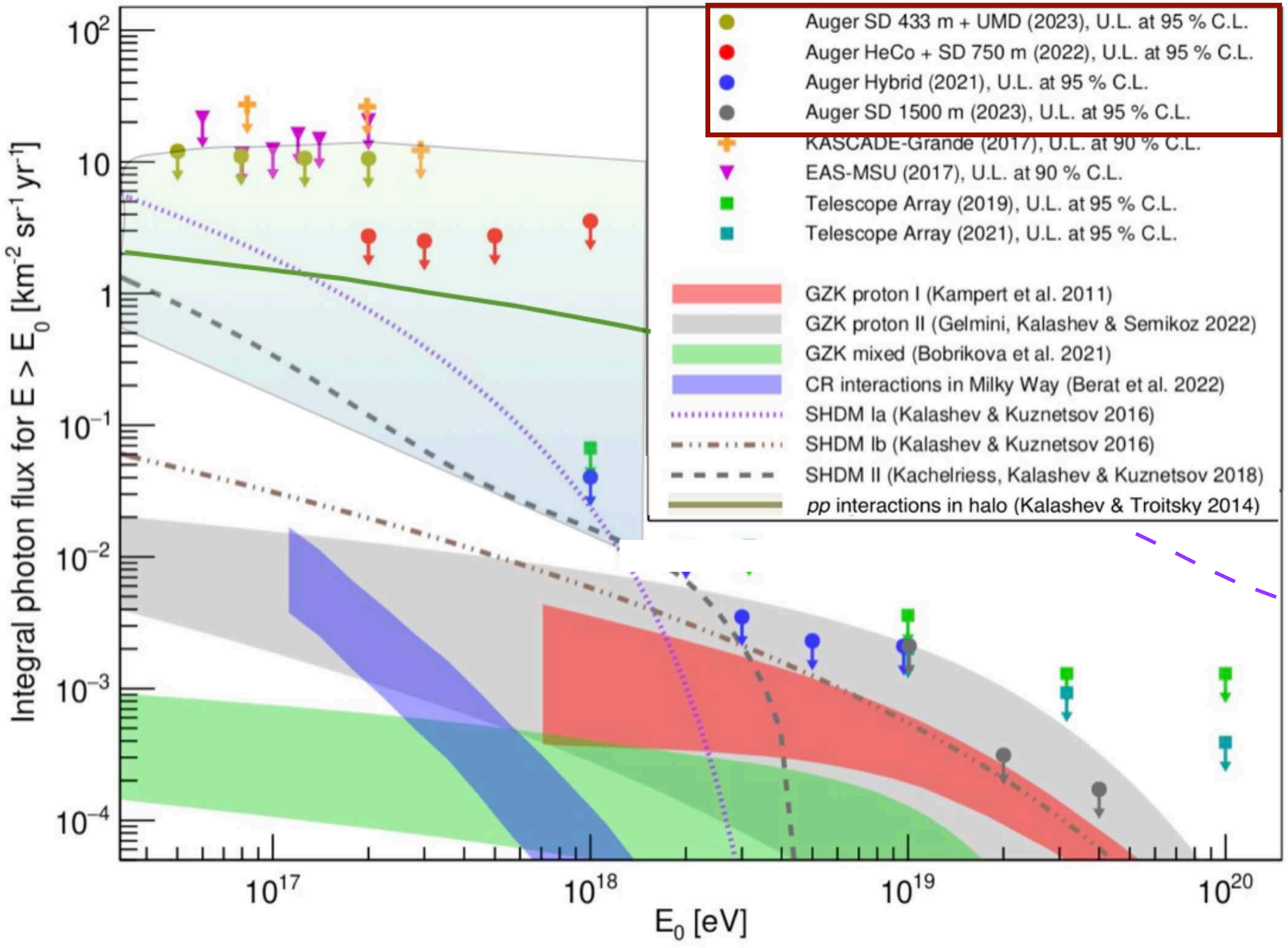
Energy range [eV]	Detectors	Exposure [km² sr yr]	Observables	Cit.
>5 10^{16}	UMD - SD433	0.6	Muon densities in SD433	N.Gonzalez, PoS(ICRC2023) 238
>0.2 10^{18}	SD750 and FD	2.5	X_{max}, N_{st}, SD750 signals	Astrophys. J. 933 (2022) 125
>10^{18}	SD1500 and FD	1000	X_{max}, F_{μ} (SD1500)	Phys.Rev.D110 (2024) 062005
>10^{19}	SD1500	17000	LDF, risetime in SD1500	JCAP 05 (2023) 021



Discrimination Methods

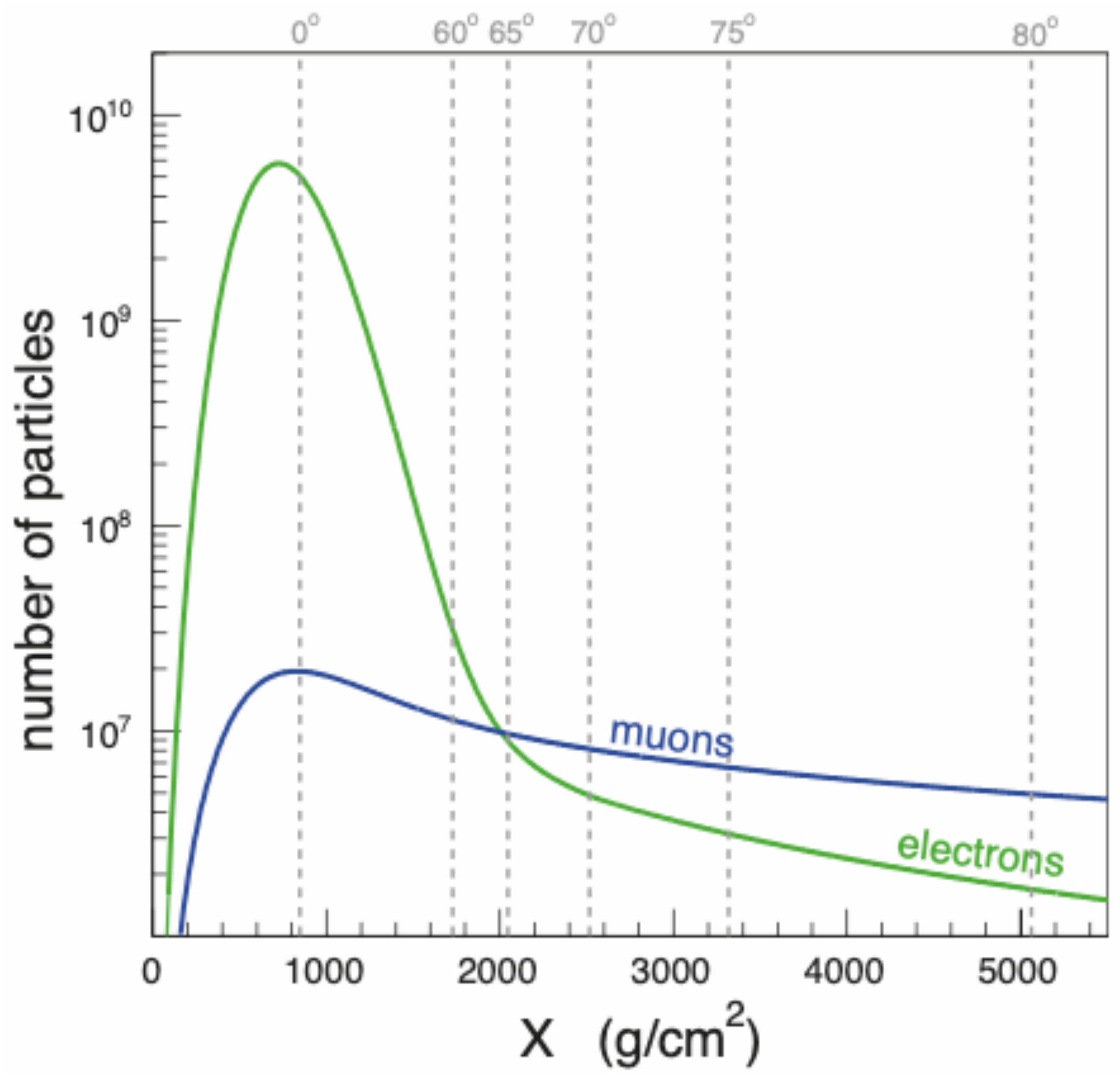
Different observables combined into a single discriminator
Candidate cut: median of the discriminant distribution (50% efficiency)
Measured and simulated events passing the cut are compared

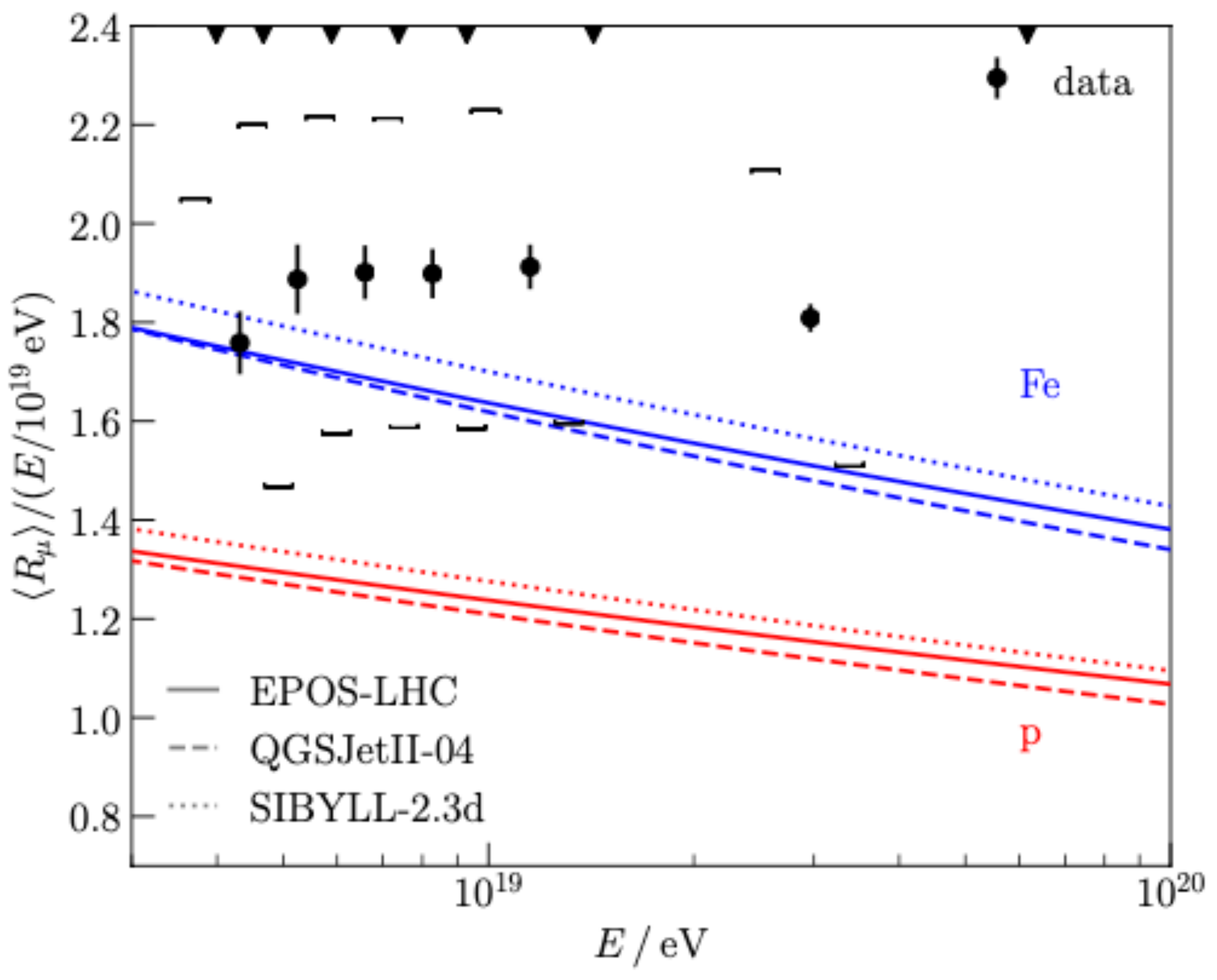
Search for a diffuse flux of photons

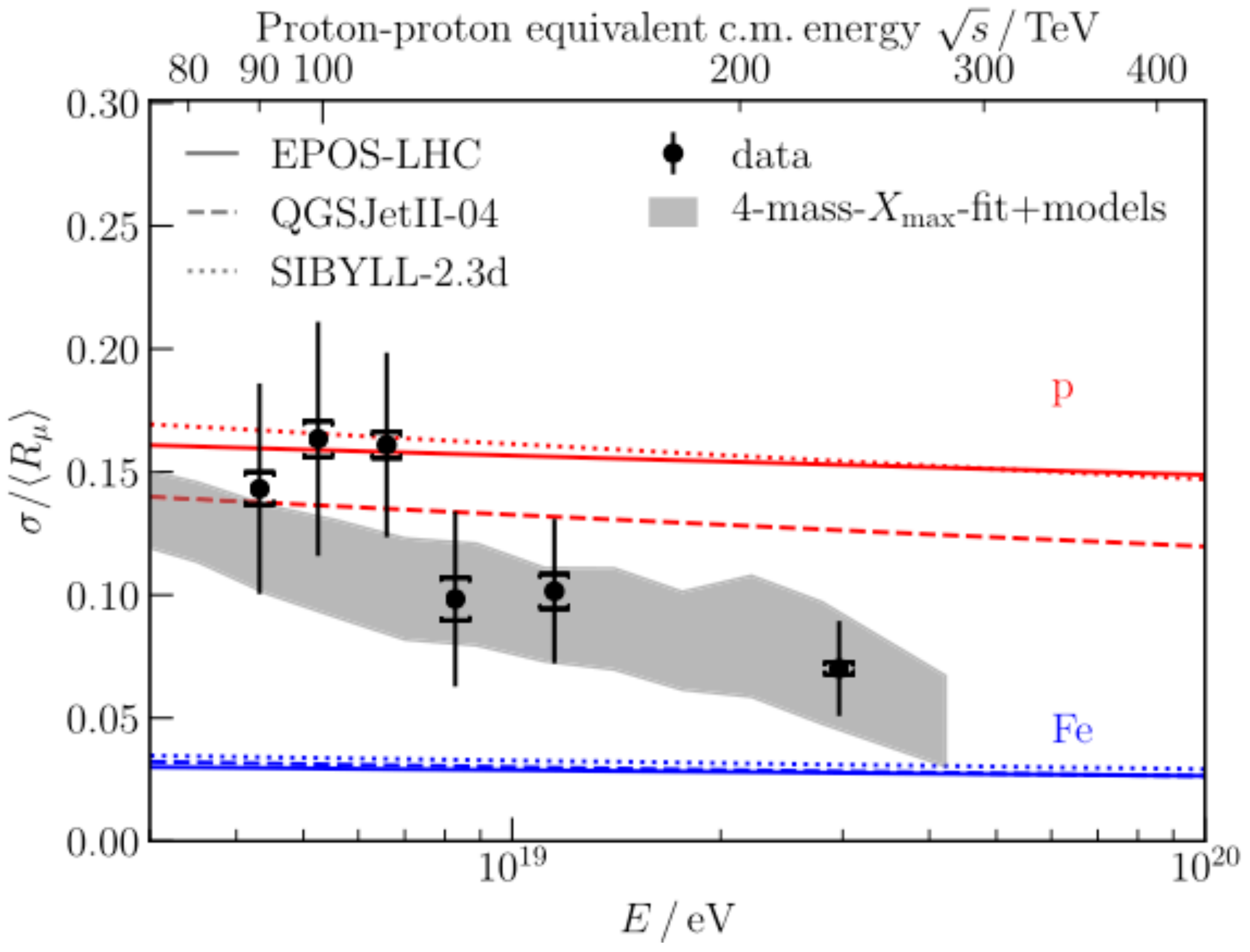


- ➡ Limits provided across 4 decades in energy
- ➡ Start closing the gap to the smaller air-shower experiments
- ➡ Exotic models excluded
- ➡ Below 10^{18} eV: most stringent limits available
- ➡ At the highest energies, most optimistic models of cosmogenic photon flux can be probed and excluded

The muon puzzle







On the contrary, post-LHC models describe well the fluctuations of energy partition in the first interaction up to UHE (~70% of which are due to the first interaction)

The muon deficit in simulations is confirmed by independent measurements:

— indirect muons in inclined events
— top-down analysis of vertical events
— direct muons in hybrid events
Discrepancy starting for E≳10^{17} eV

Most likely scenario: accumulation of small deviations along the generations

Auger Coll., PRL 126 (2021) 152002

L.Cazon et al., Astrop.Phys. 36 (2012) 211
Auger Coll., PRD91 (2015) 032003+059901
Auger Coll., PRL117 (2016) 192001
Auger Coll., Eur.Phys.J. C80 (2020) 751

Beyond the standard model

Search for Lorentz invariance violation

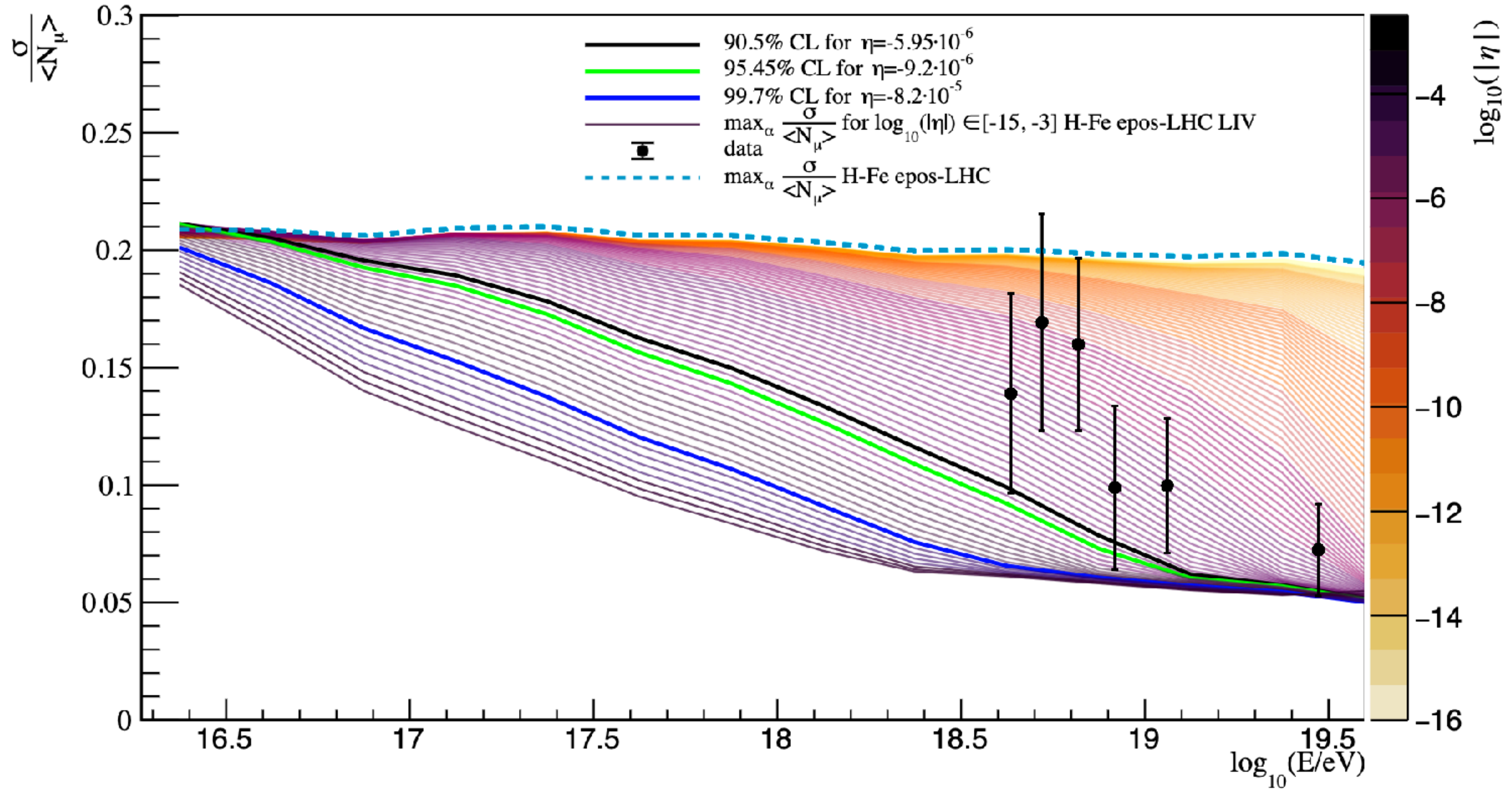
Effects suppressed for low energy and short travel distances : UHECRs !!!

$$E_i^2 - p_i^2 = m_i^2 + \sum_{n=0}^{N} \delta_i^{(n)} E_i^{2+n} = m_i^2 + \eta_i^{(n)} \frac{E_i^{2+n}}{M_{Pl}^n}$$

$$\gamma_{\rm LIV} = \frac{E}{m_{\rm LIV}} \qquad \tau = \gamma_{\rm LIV}\tau_0$$

In air shower development
for $\eta^{(n)}<0$, decay of π^0 forbidden
EM component decreasing, hadronic one increasing

$$\pi^0 \rightarrow \gamma\gamma \qquad \tau_0 = 8.4 \cdot 10^{-17}\,\mathbf{s}$$



*C.Trimarelli, EPJ Web of Conf. **283**, 05003 (2023)*
Auger Coll., JCAP 01 (2022) 023

Super-heavy dark matter searches

Overdensity of SHDM in the galatic halo:

$$\delta = \frac{\delta_X^{halo}}{\rho_X^{extr}} = \frac{\rho_{DM}^{halo}}{\Omega_{DM}\rho_c} \simeq 2 \times 10^5$$

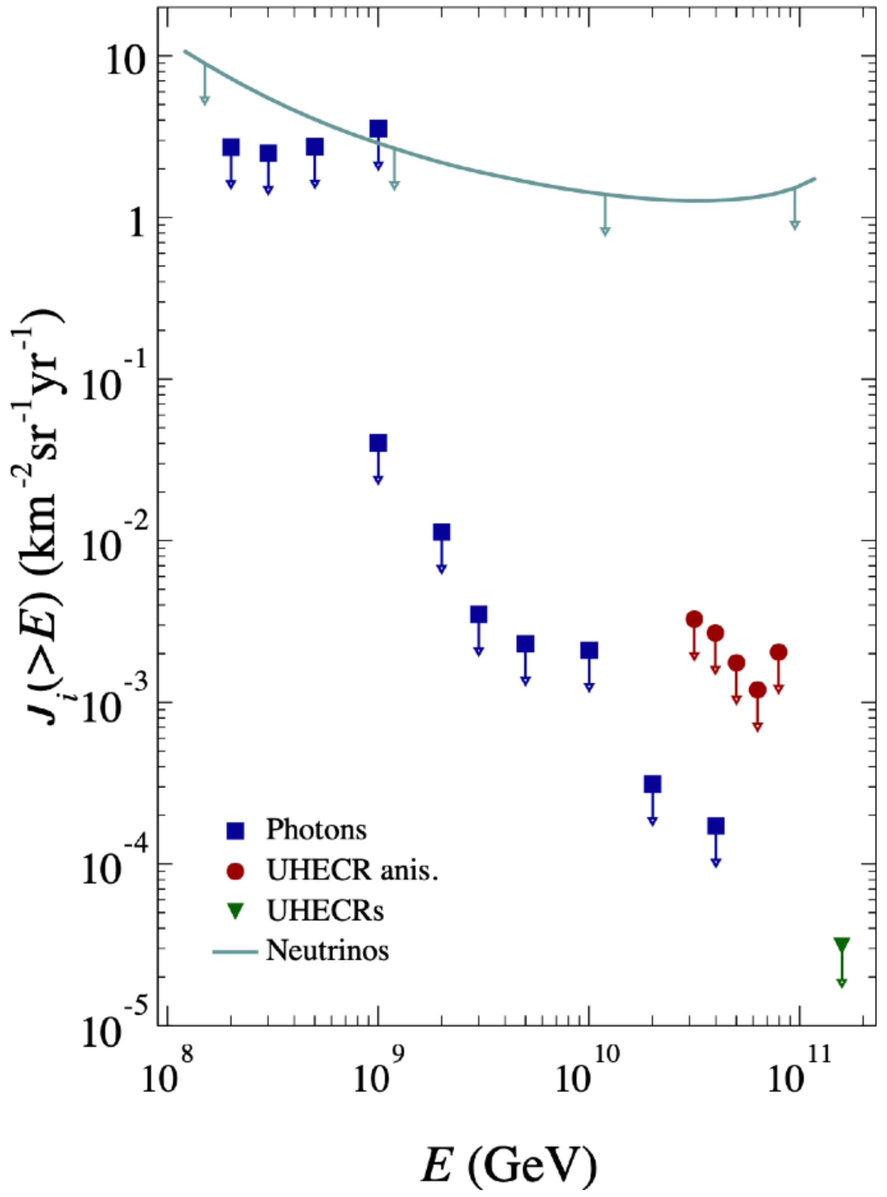
Berezinsky V. et al., Phys.Rev.Lett.79 (1997) 4302

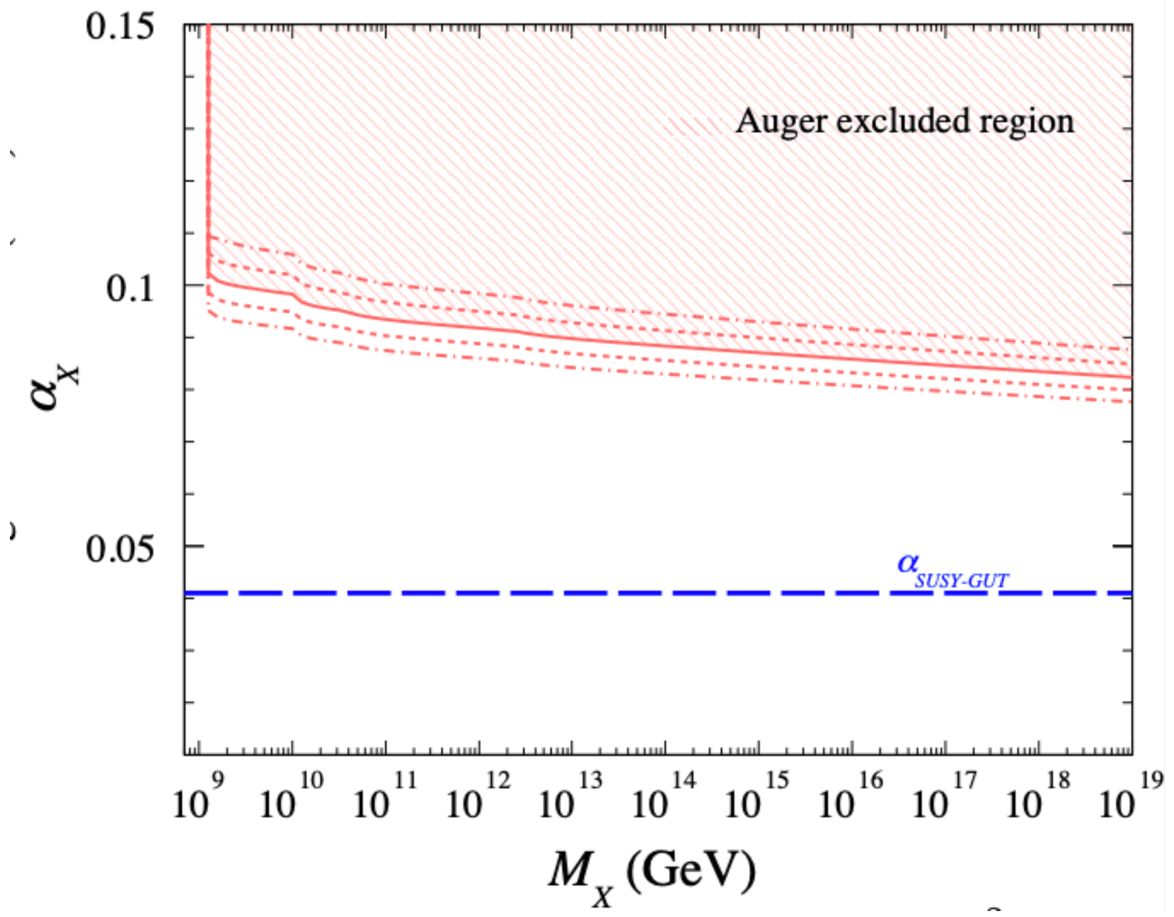
Flux of secondaries from SHDM decay ($i = \gamma, \nu, \bar{\nu}, N, \bar{N}$):

$$J_i^{\rm gal}(E) = \frac{1}{4\pi M_X c^2 \tau_X} \frac{dN_i}{dE} \int_0^\infty ds\, \rho_{\rm DM}(\mathbf{x}_\odot + \mathbf{x}_i(s;\mathbf{n})).$$

Free parameters

$$\tau_X = \hbar M_X^{-1} \exp(4\pi/\alpha_X)$$





Auger Coll., Phys. Rev. D 107 (2023) 042002
Auger Coll., Phys. Rev. Lett. 130 (2023) 061001
Auger Coll., Phys. Rev. D 109 (2024) L081101

What have we learned from data?

A radical change with respect to the past paradigm of the UHECRs

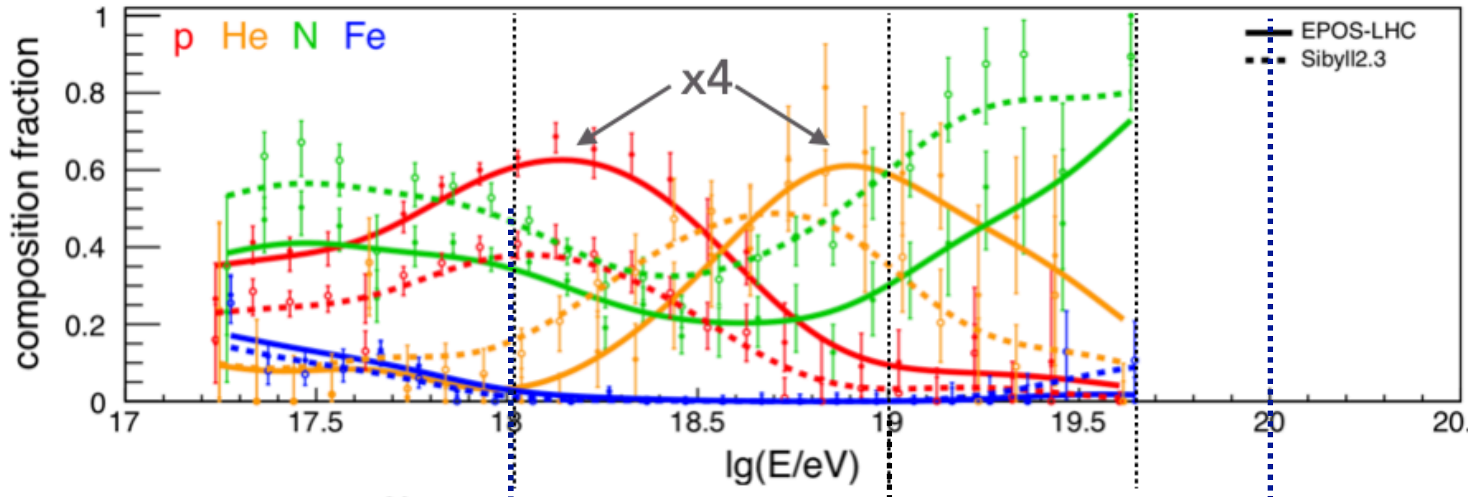
- ***the UHECRs are NOT predominantly protons,*** but the fraction of heavier nuclei increases with energy above ~2 10^{18} eV. Supported by
  — different and independent measurements
  — the non observation of cosmogenic photons and neutrinos
- There is room for a small fraction of protons above $10^{19.5}$ eV (see talk of D.Boncioli)

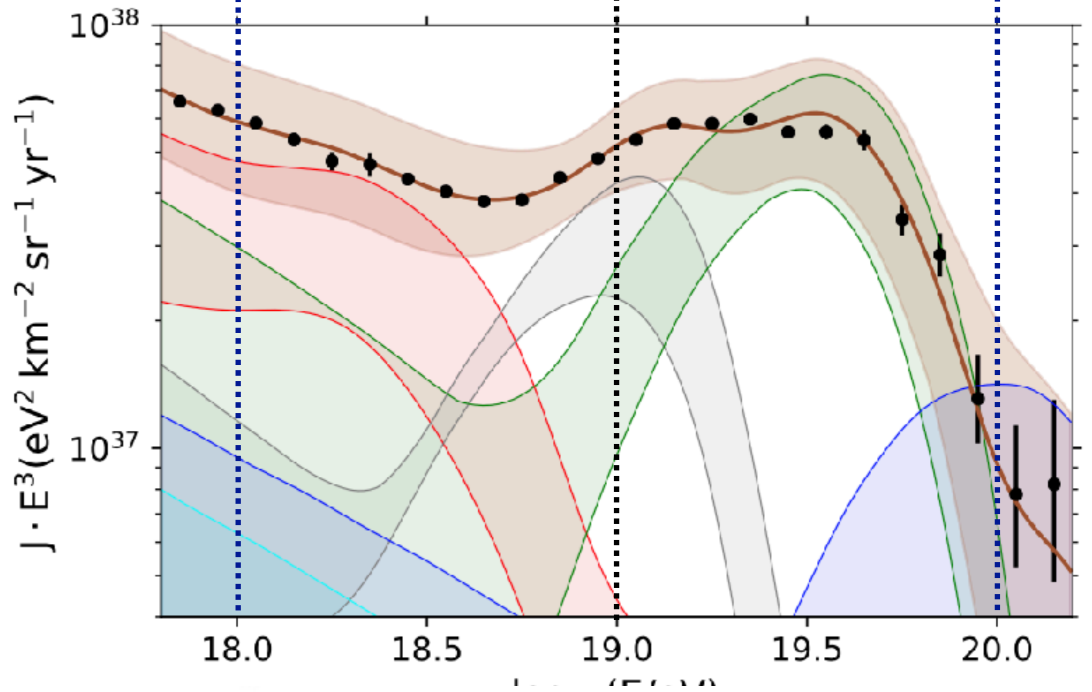
- ***the spectrum features*** are clearly identified without relying on hypoheses on composition or sources
- ***the shape of the spectrum*** reflects the different contributions in mass
- no hints for anisotropy in Northern sky up to 45^0 in declination (vertical+inclined events)

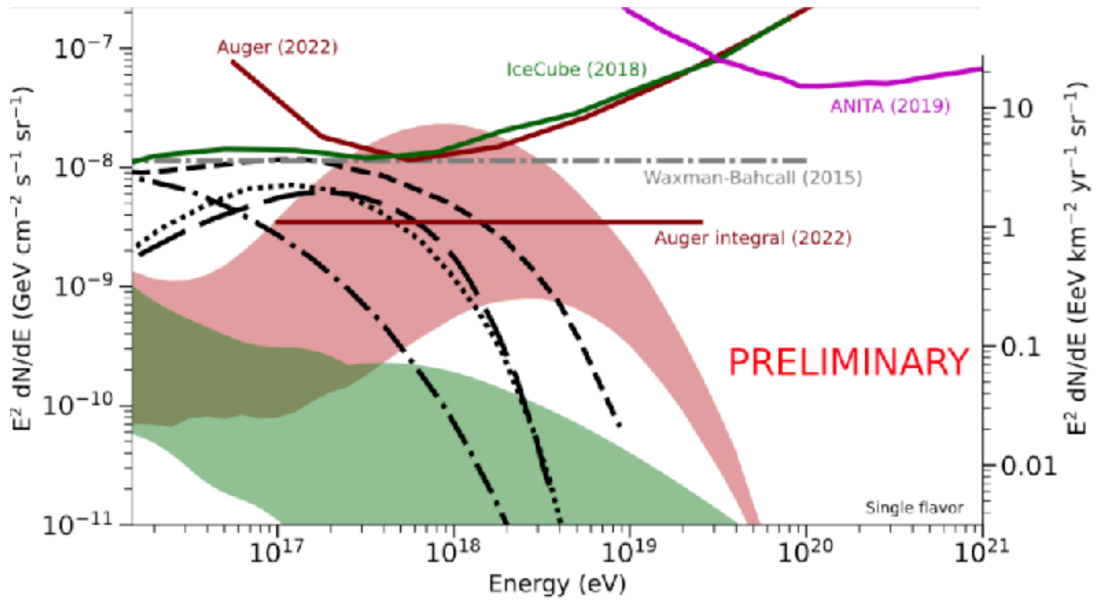
- ***observation of a dipolar anisotropy*** $\gtrsim$***8 EeV*** : EG origin of these UHECRs
- hints of correlation with the SBGs above 40 EeV
- *no composition difference* from Northern to Southern hemisphere below $10^{19.5}$ eV

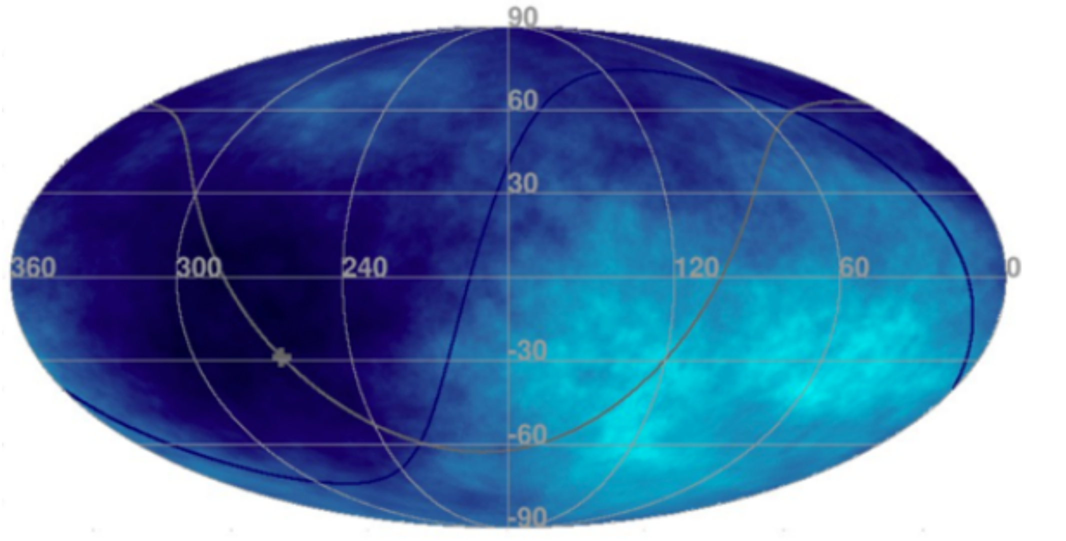
- ***the transition region*** is placed around the second knee. Supported by
  — the measured composition, which becomes lighter above the 2nd knee up to ~ $2{\times}10^{18}$ eV
  — the smooth transition from isotropy to a dipolar anisotropy above 8 EeV
  — the exclusion of H+He mix in the ankle region at >5σ

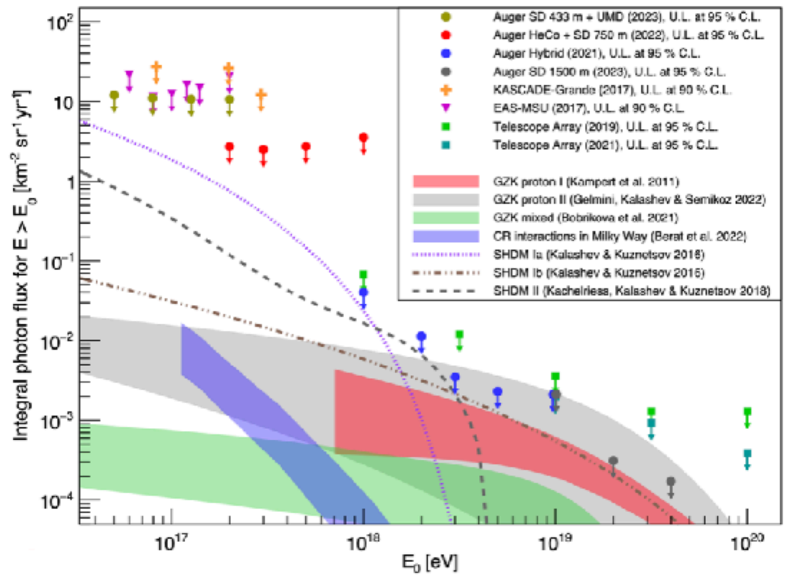
- Valuable information about hadronic interactions at UHE: μ deficit in models due to pile-up effects along the shower development
- Constraints to effects of physics beyond standard model

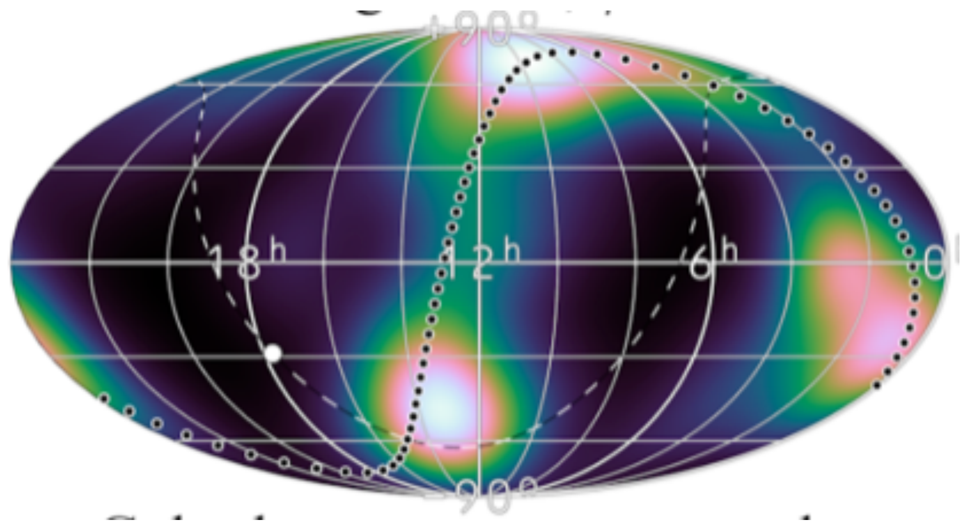


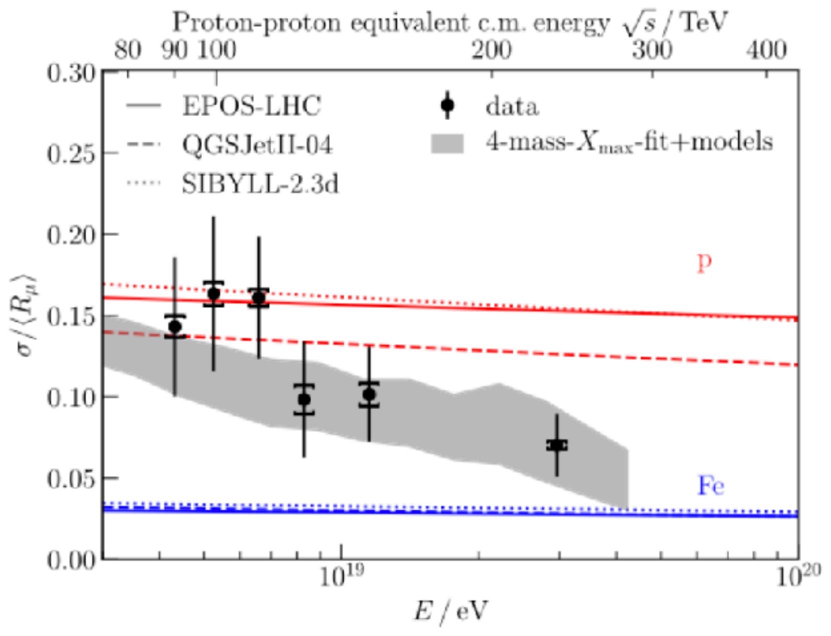


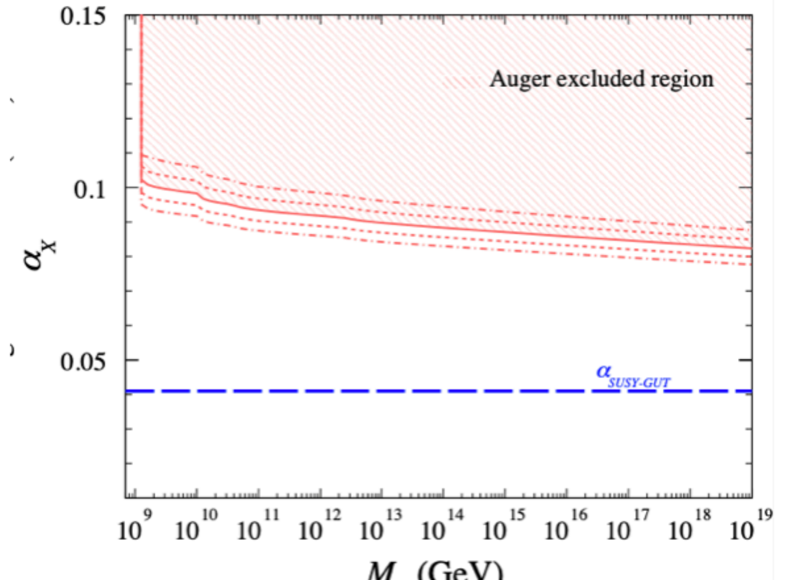






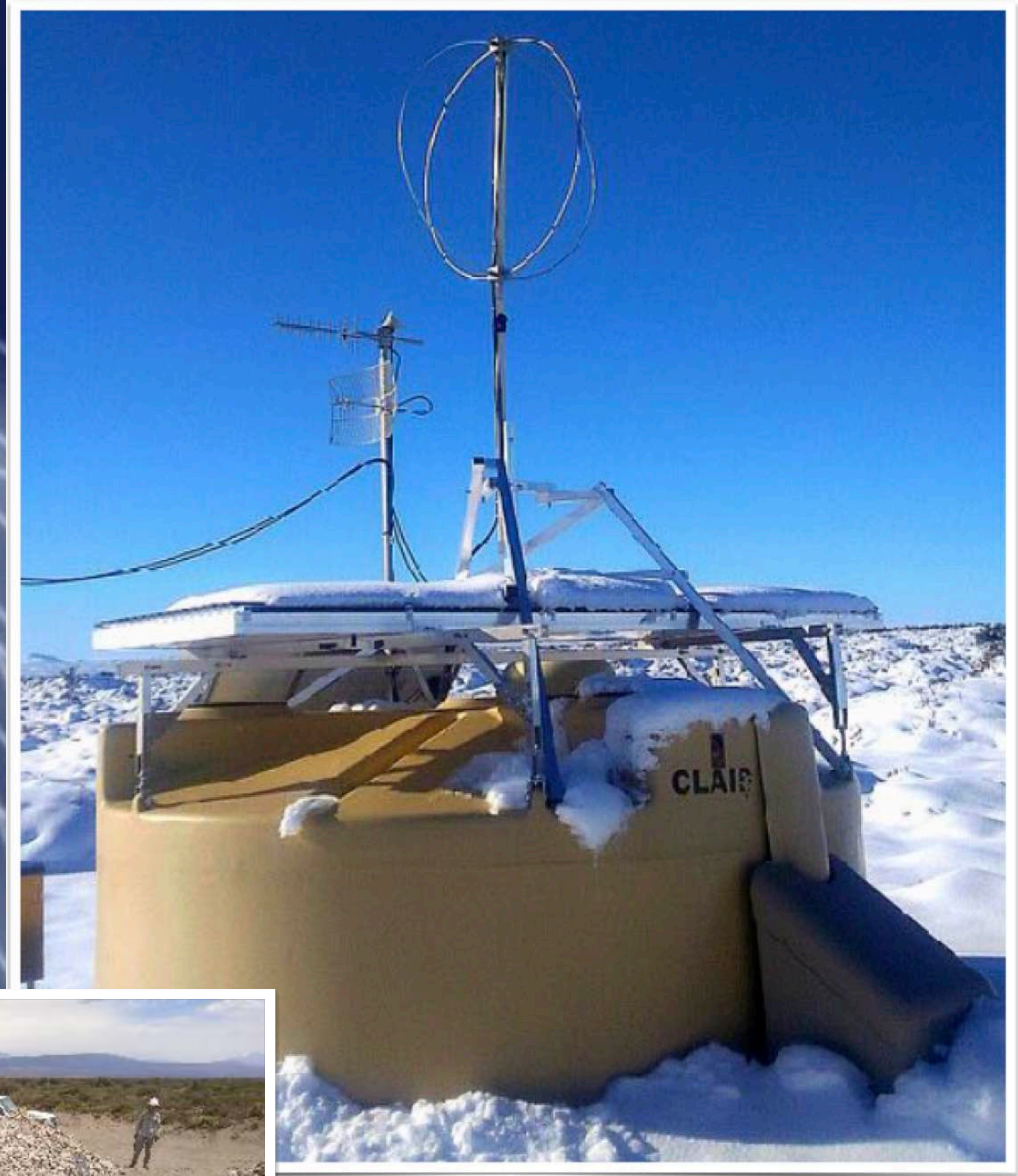






AugerPrime: *exploiting the richness of extensive air showers*

2025-2035



More insight in the mass composition
+ increased statistics

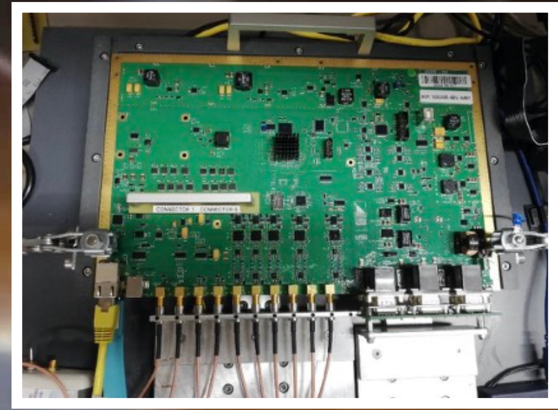
Measure of the longitudinal development of the extensive air showers (EAS) while crossing the atmosphere
➡ ***Fluorescence telescopes***

Discrimination between the electromagnetic and muonic components of the EAS
➡ **Water Cherenkov Stations** and ***Scintillators***

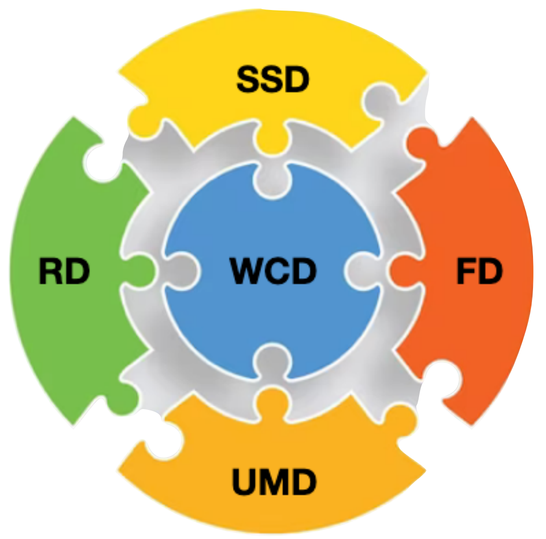
Measure of the radio emission of EAS
➡ ***Radio antennas***

Direct measure of the muonic component
➡ ***Underground detectors***

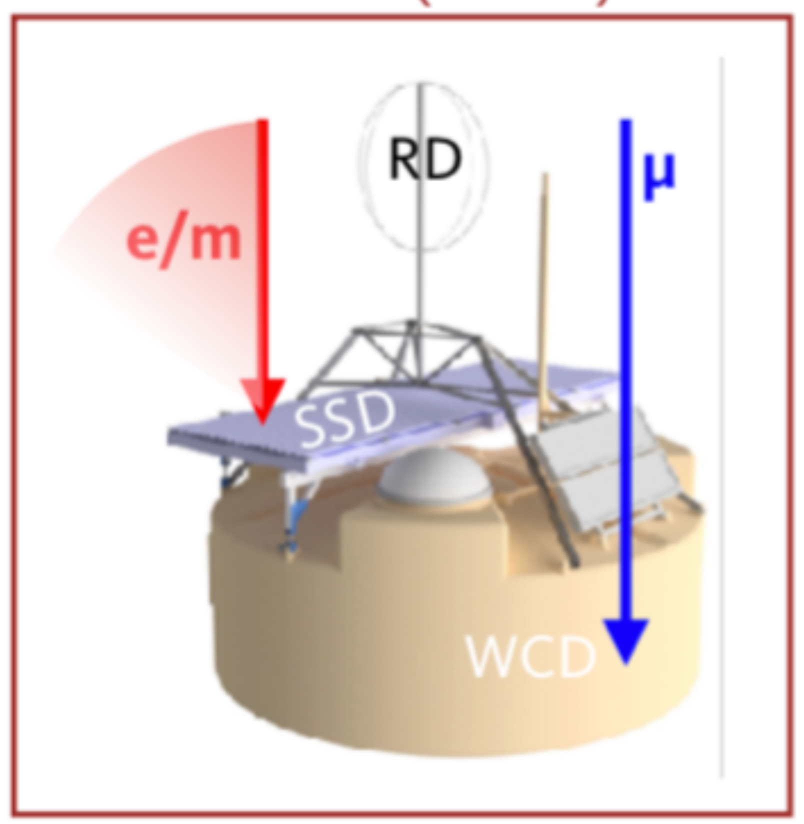
New electronics : ***faster FADC (120 MHz), larger dynamic range***



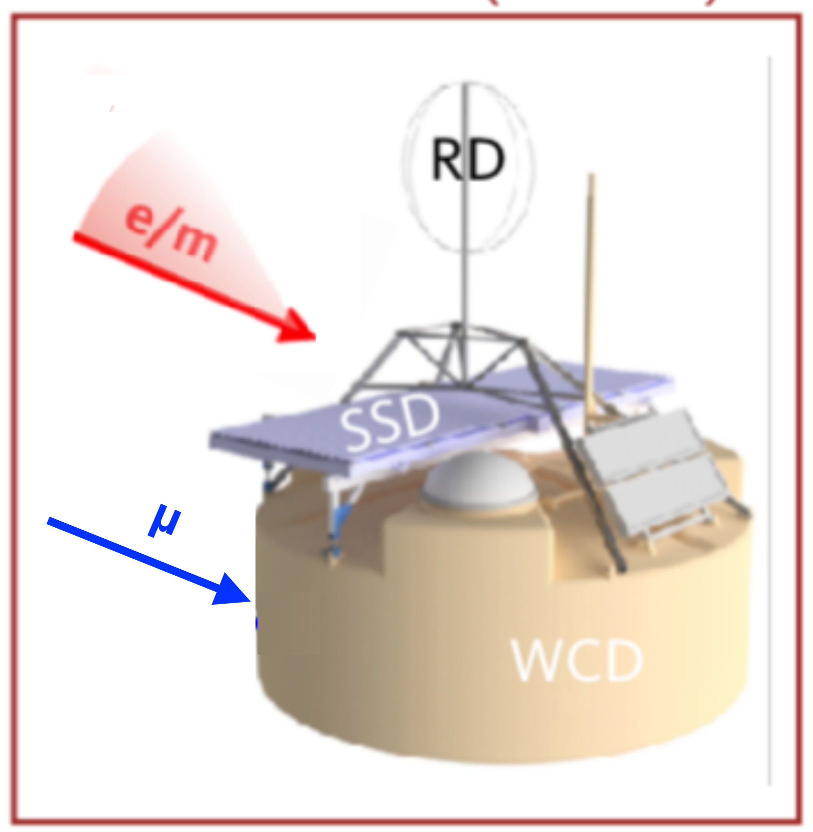
AugerPrime: 2025 → 2035…..



VERTICAL (0-60°)



HORIZONTAL (60-90°)

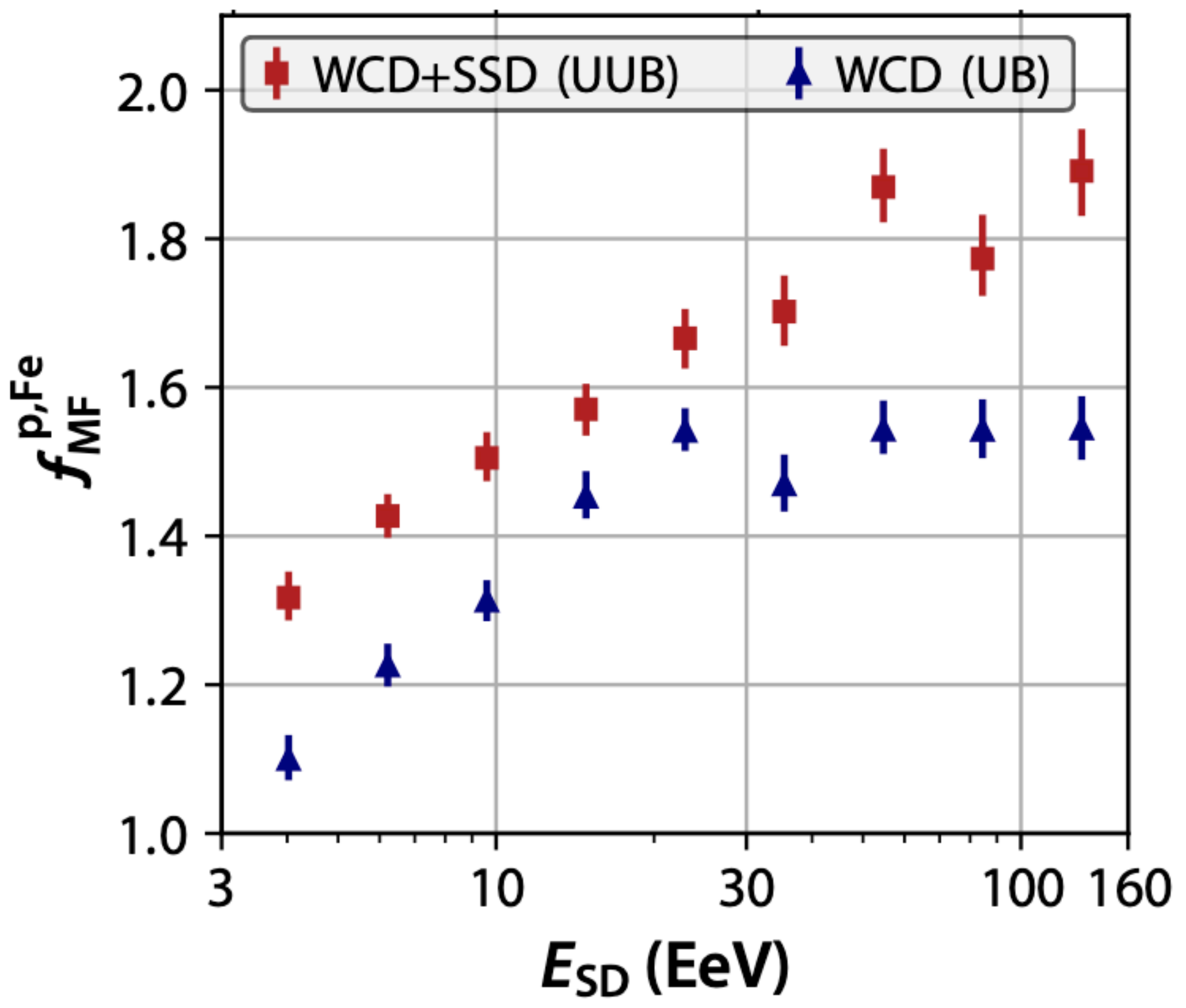


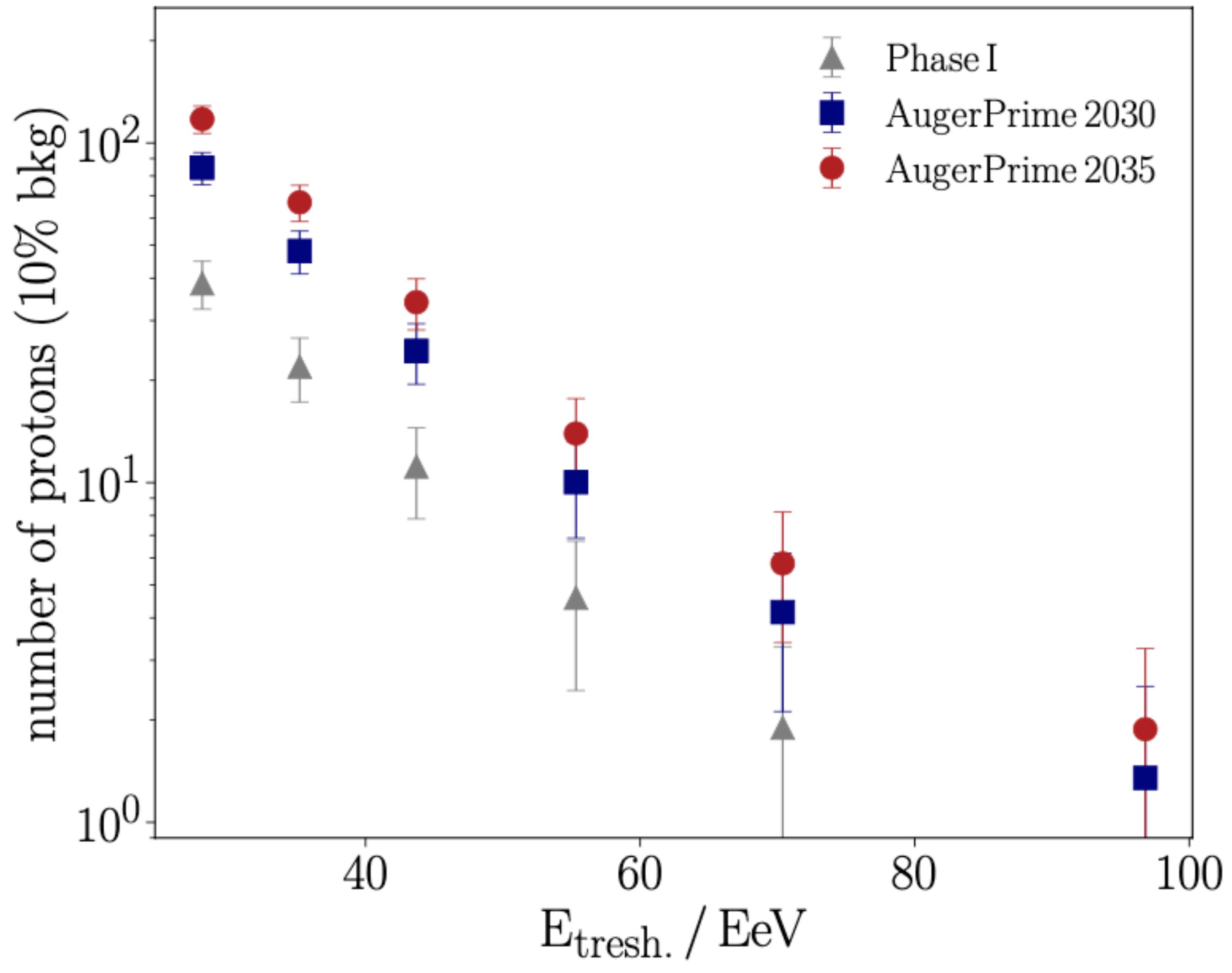
WCD/SSD/RD can collect multi-hybrid events with a 100% duty cycle

Separation of shower components can be obtained

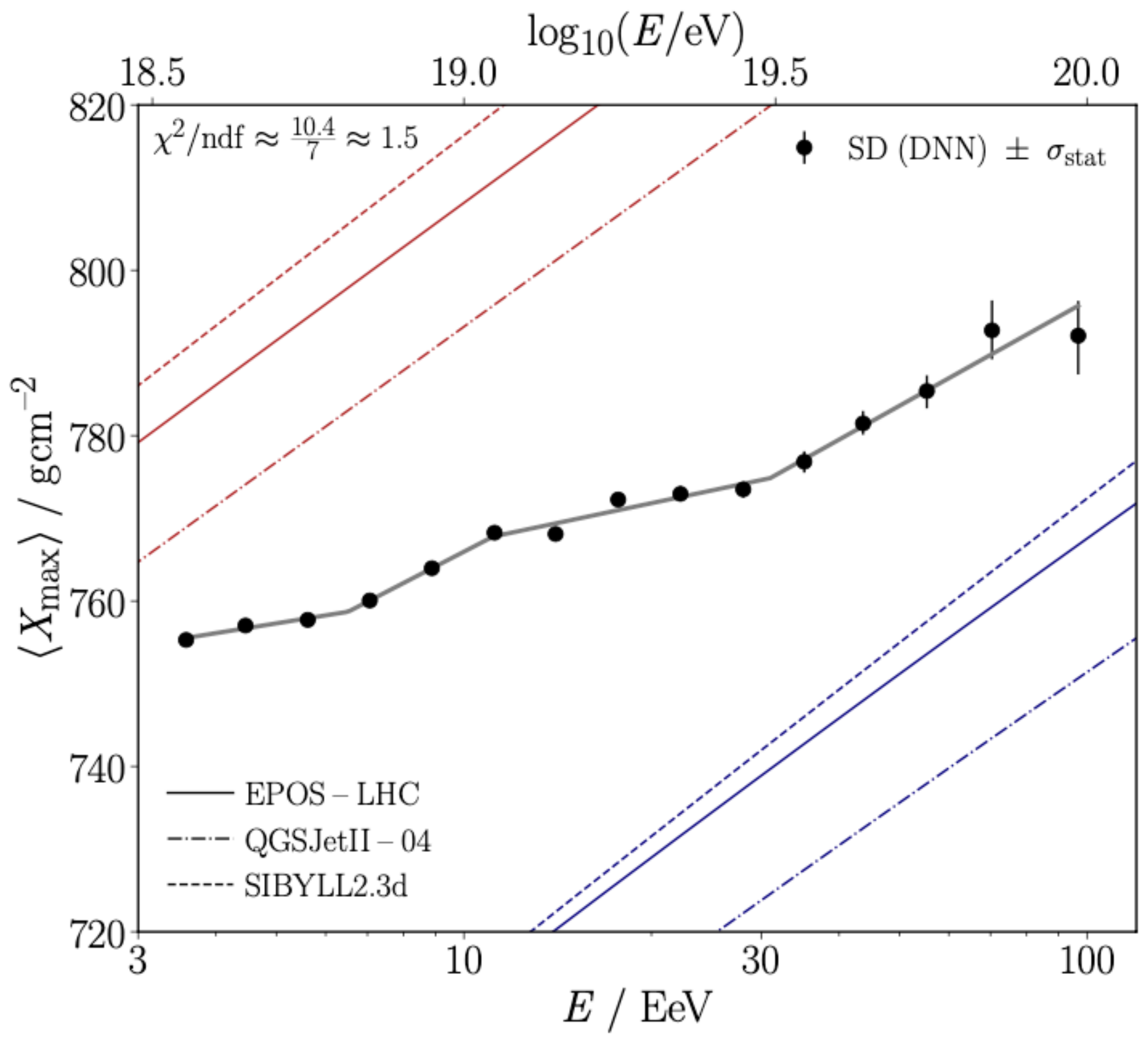
- by WCD/SSD for events up to ~60^0
- by WCD/RD for inclined events >60^0
- by WCD/SSD/UMD extending the mass sensitivity to the lower energies and improving the photons/hadrons discrimination
- With UUB we will enhance the sensitivity of triggers to electromagnetic signals

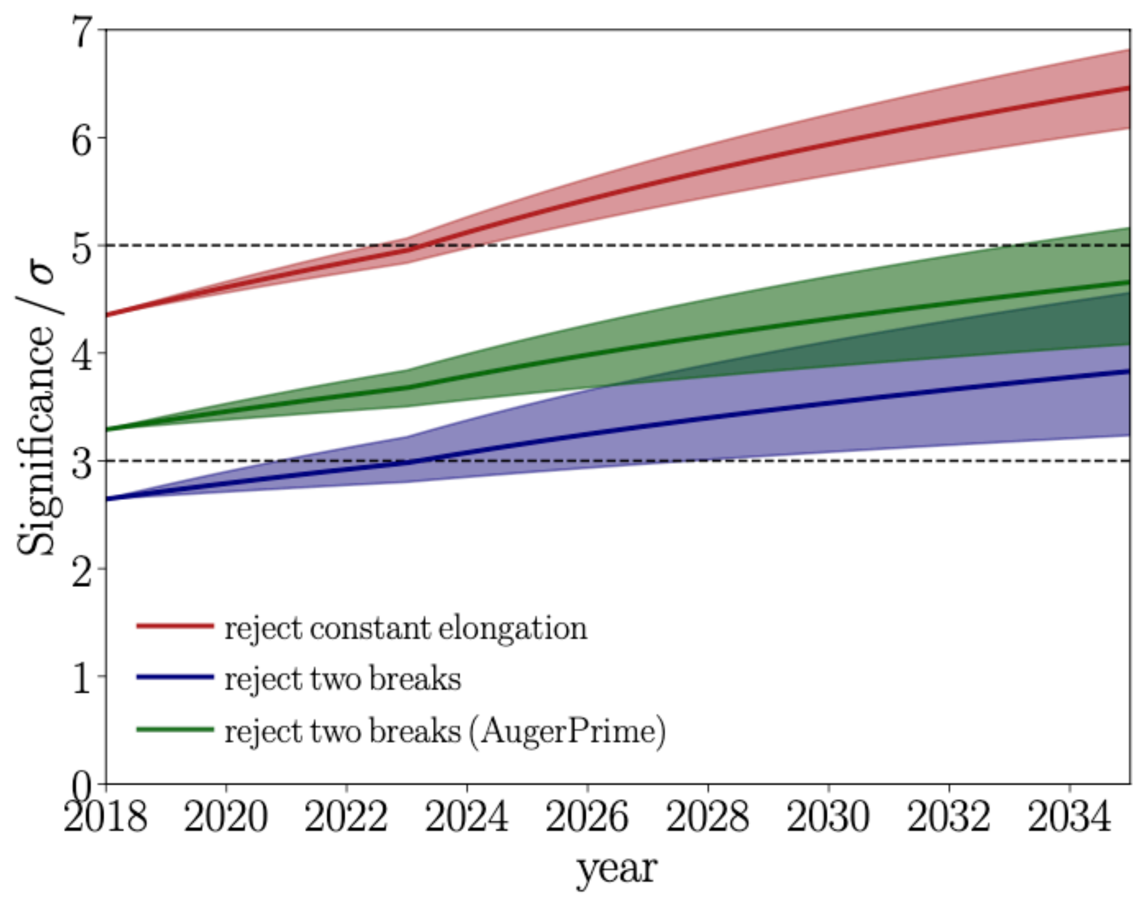
UHECR Mass using WCD+SSD





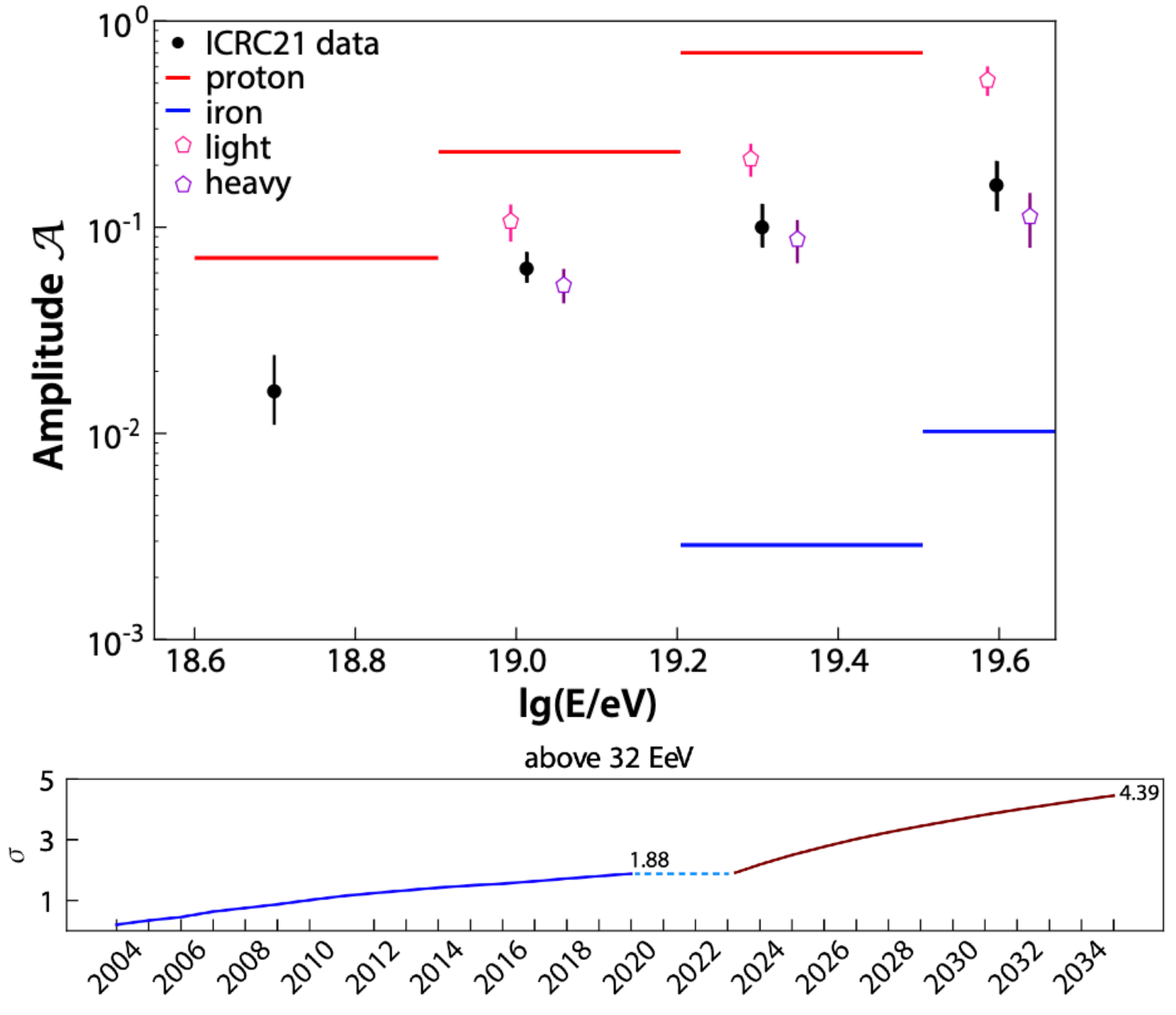
Time evolution of the significance of breaks



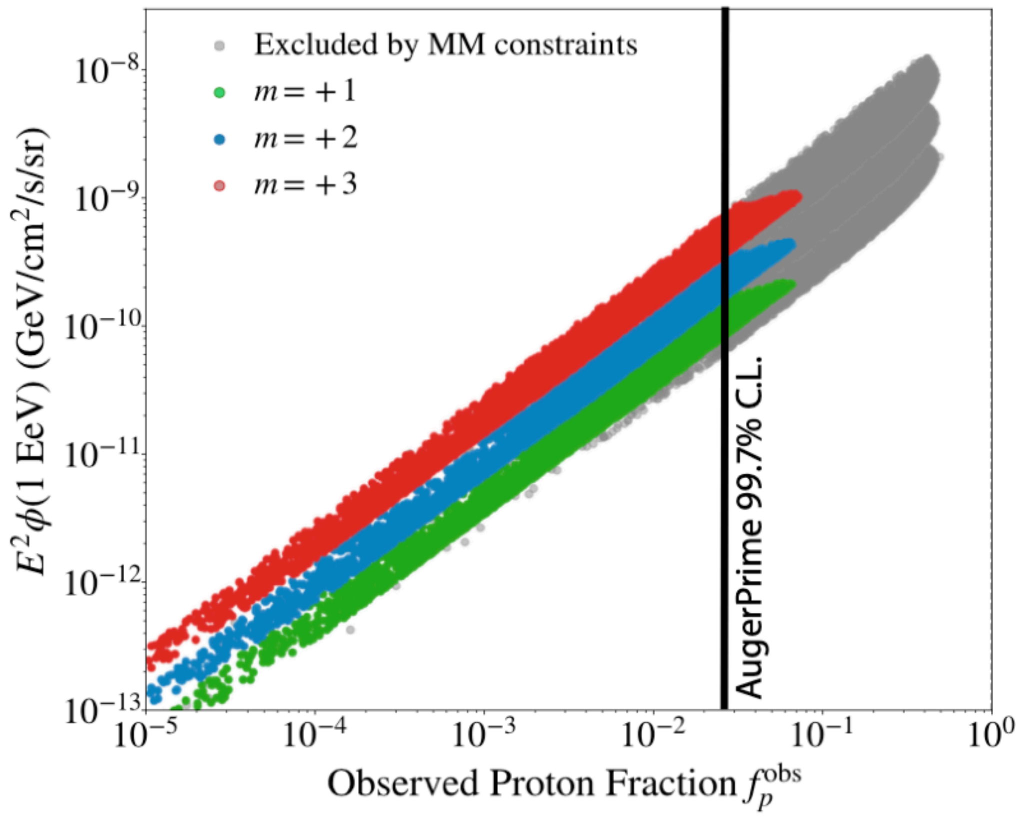


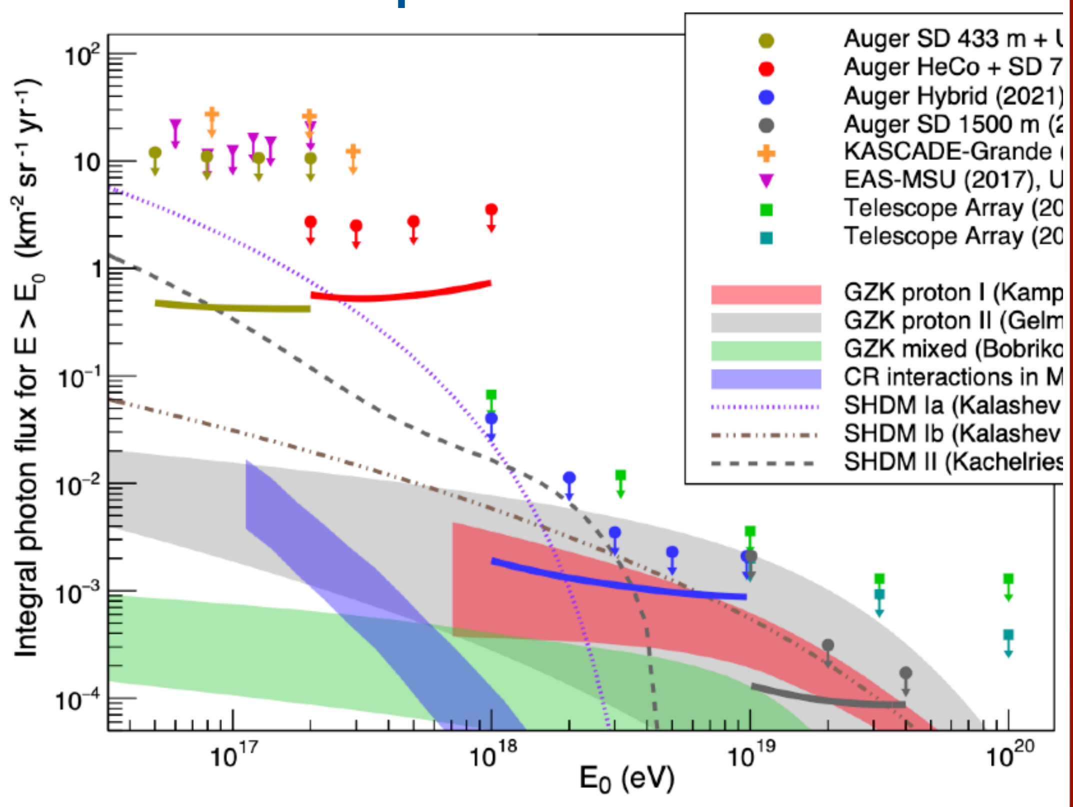
AugerPrime: 2025 → 2035…..

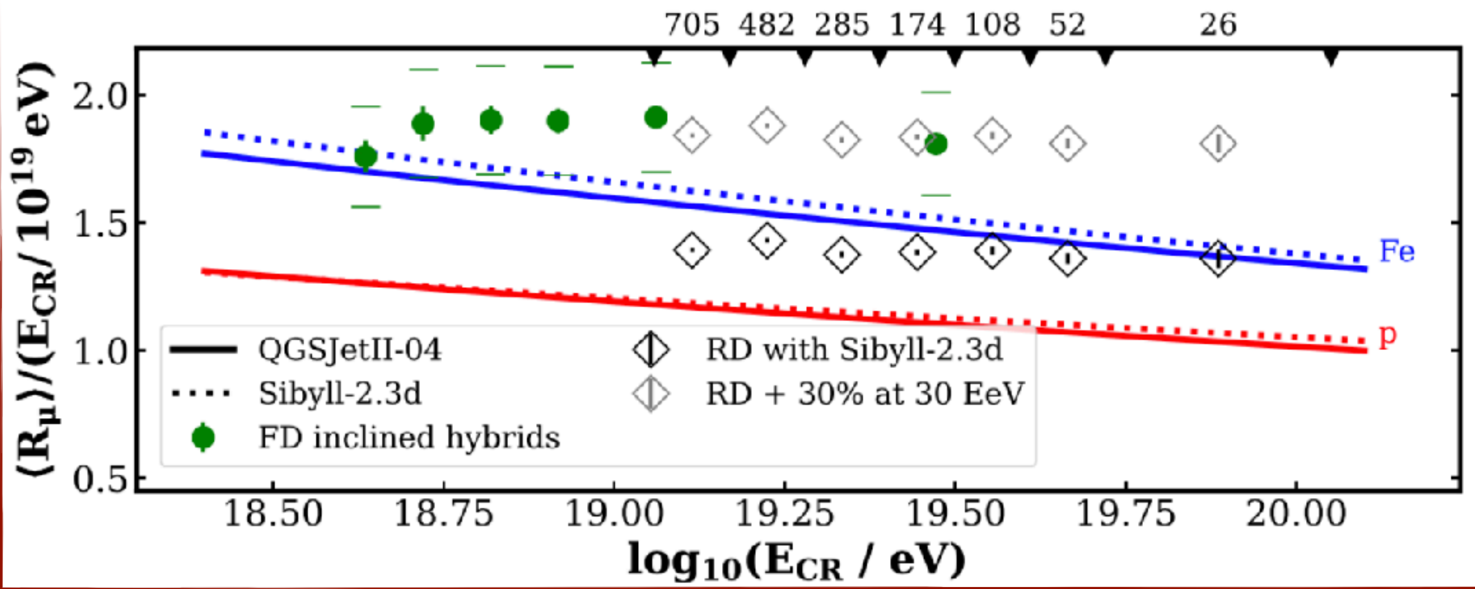
Amplitude of dipolar anisotropy



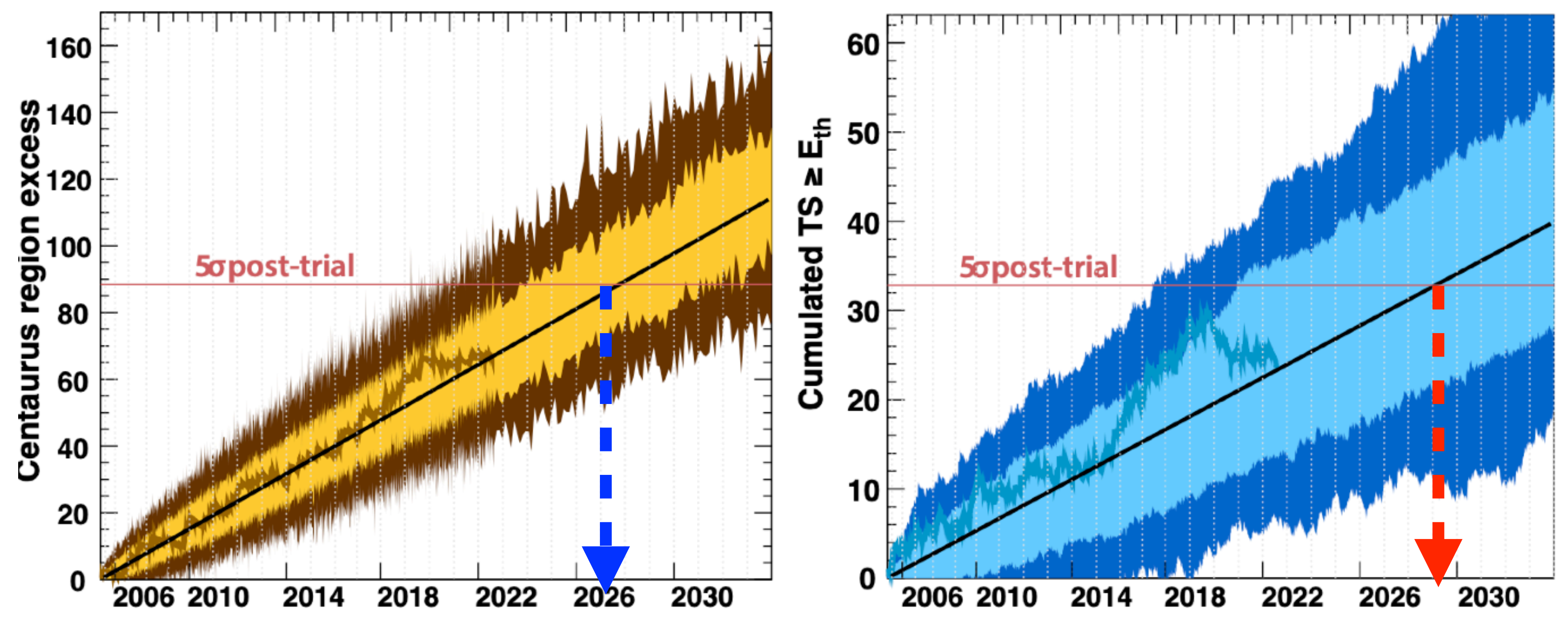
Neutrinos and photons

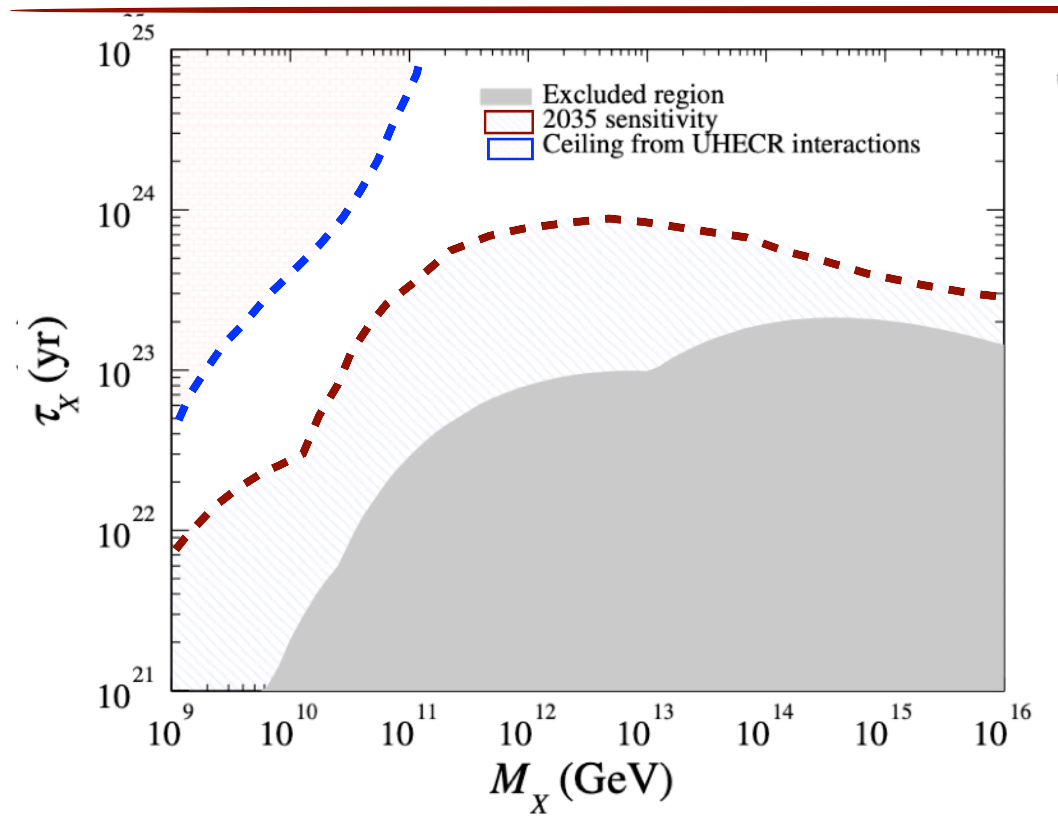


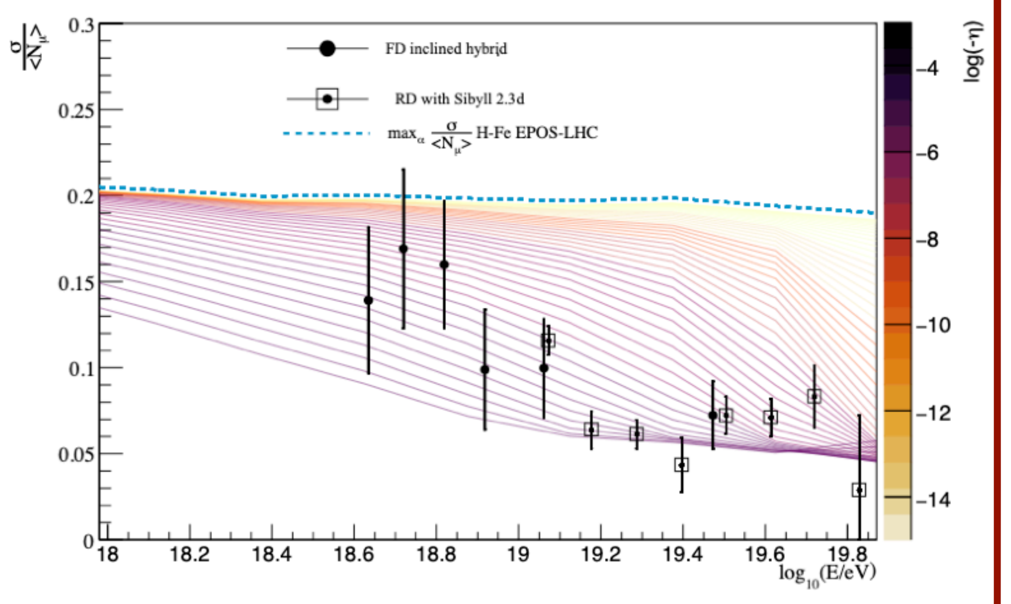




Intermediate scale anisotropies



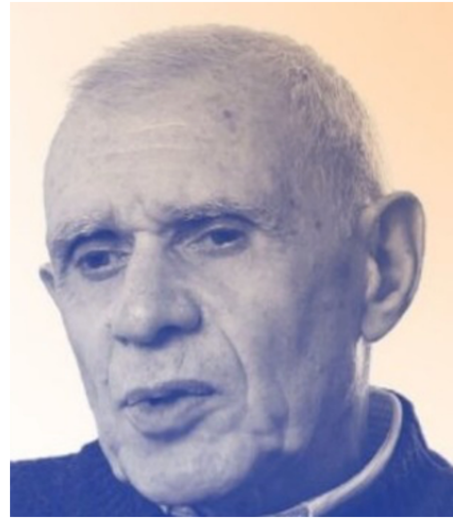




The Pierre Auger Observatory

Phase I [2004-2021]: a radical change in our view of UHECRs

A lot of discussion and criticism, but also a never ending interest in understanding the data!
A lesson for all of us



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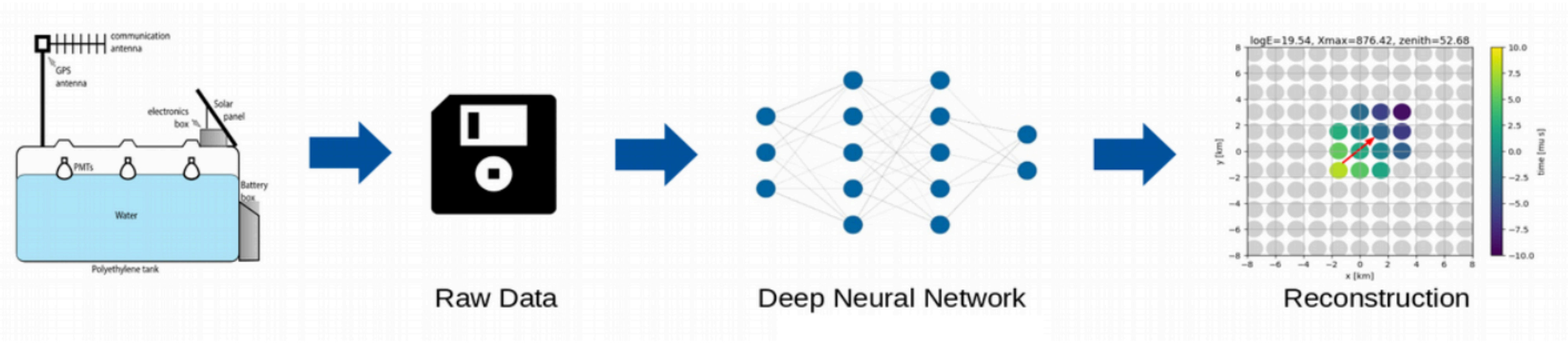
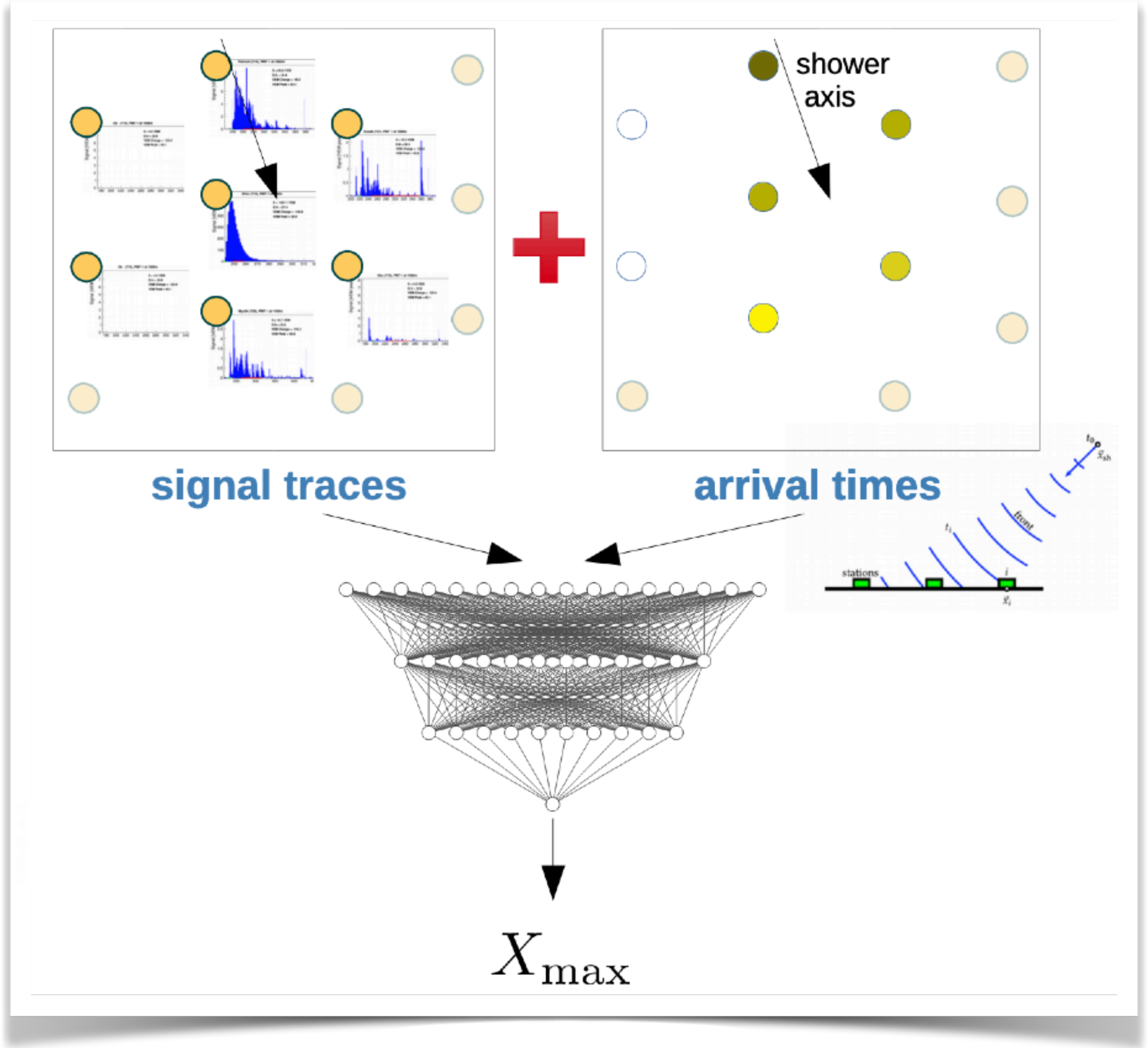
Phase II [2025-2035]: more statistics and more insight on the UHECR nuclear mass composition

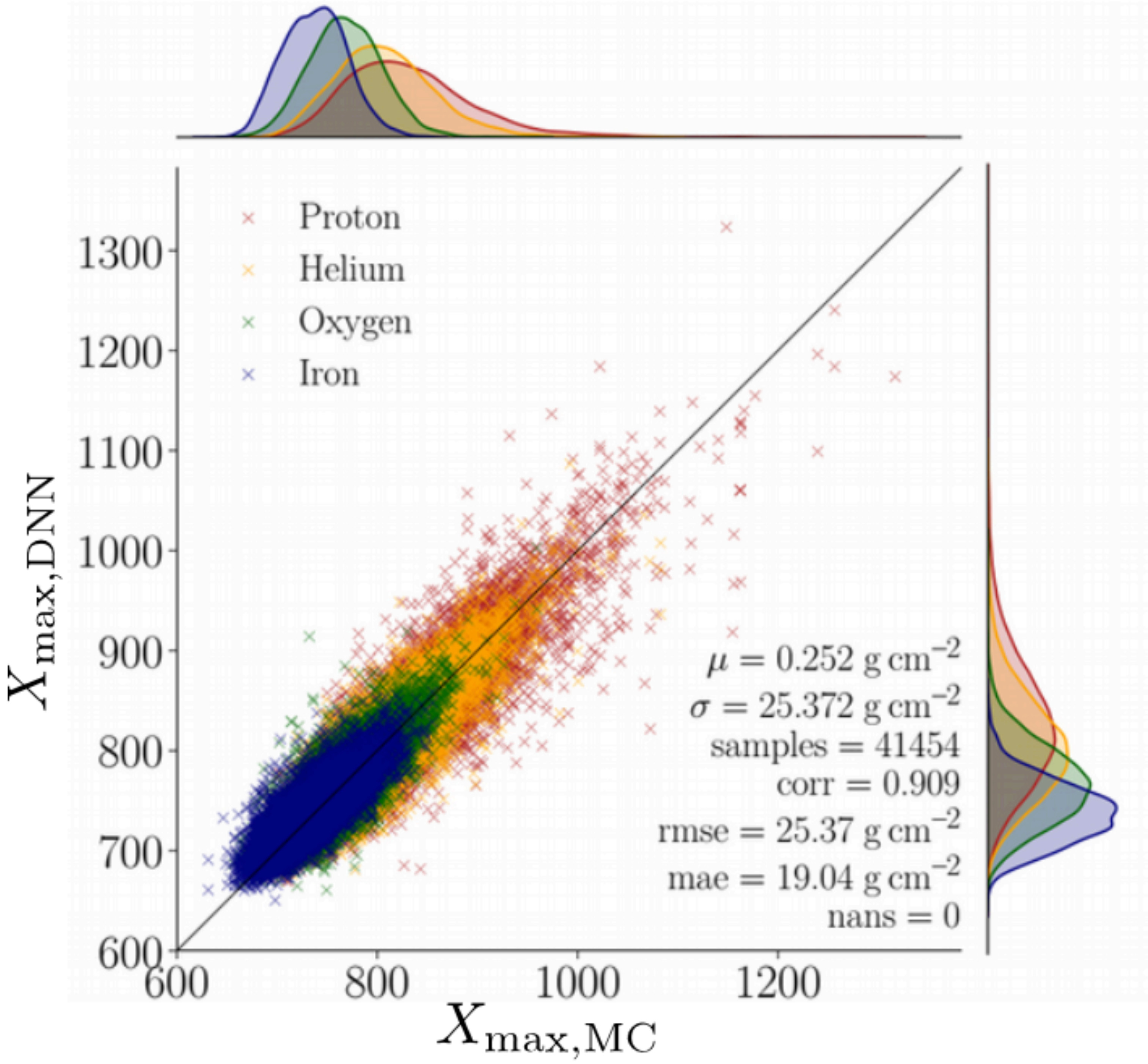
A bright future !

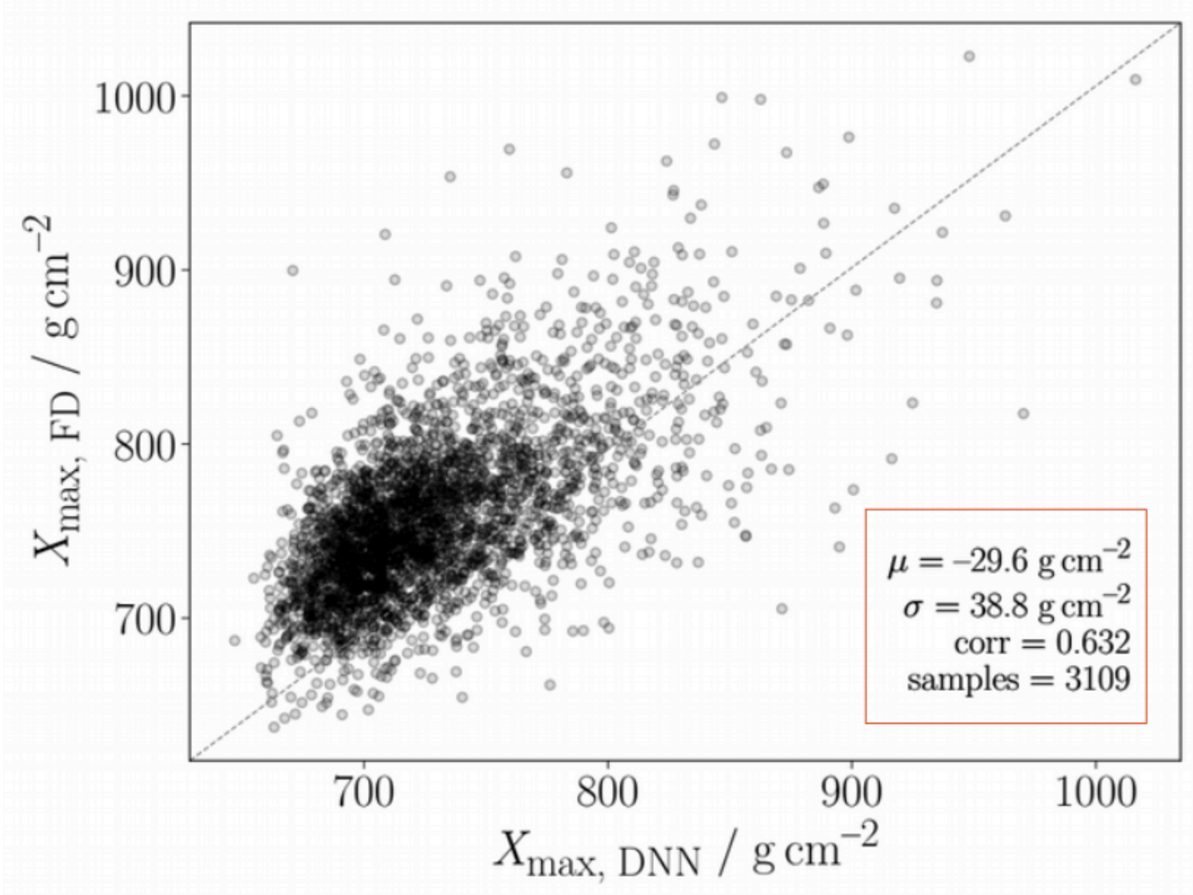
BACKUP

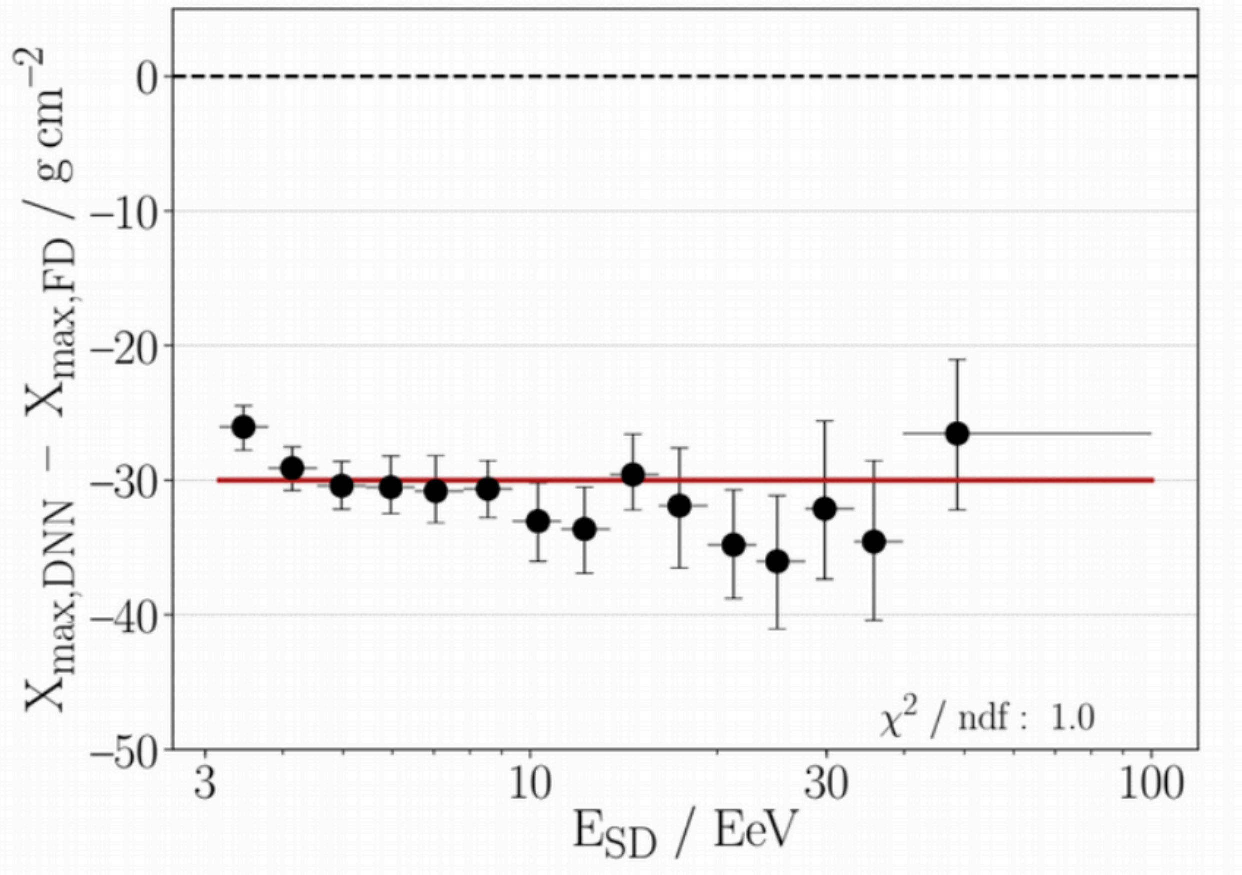
Multi-hybrid events and Machine learning





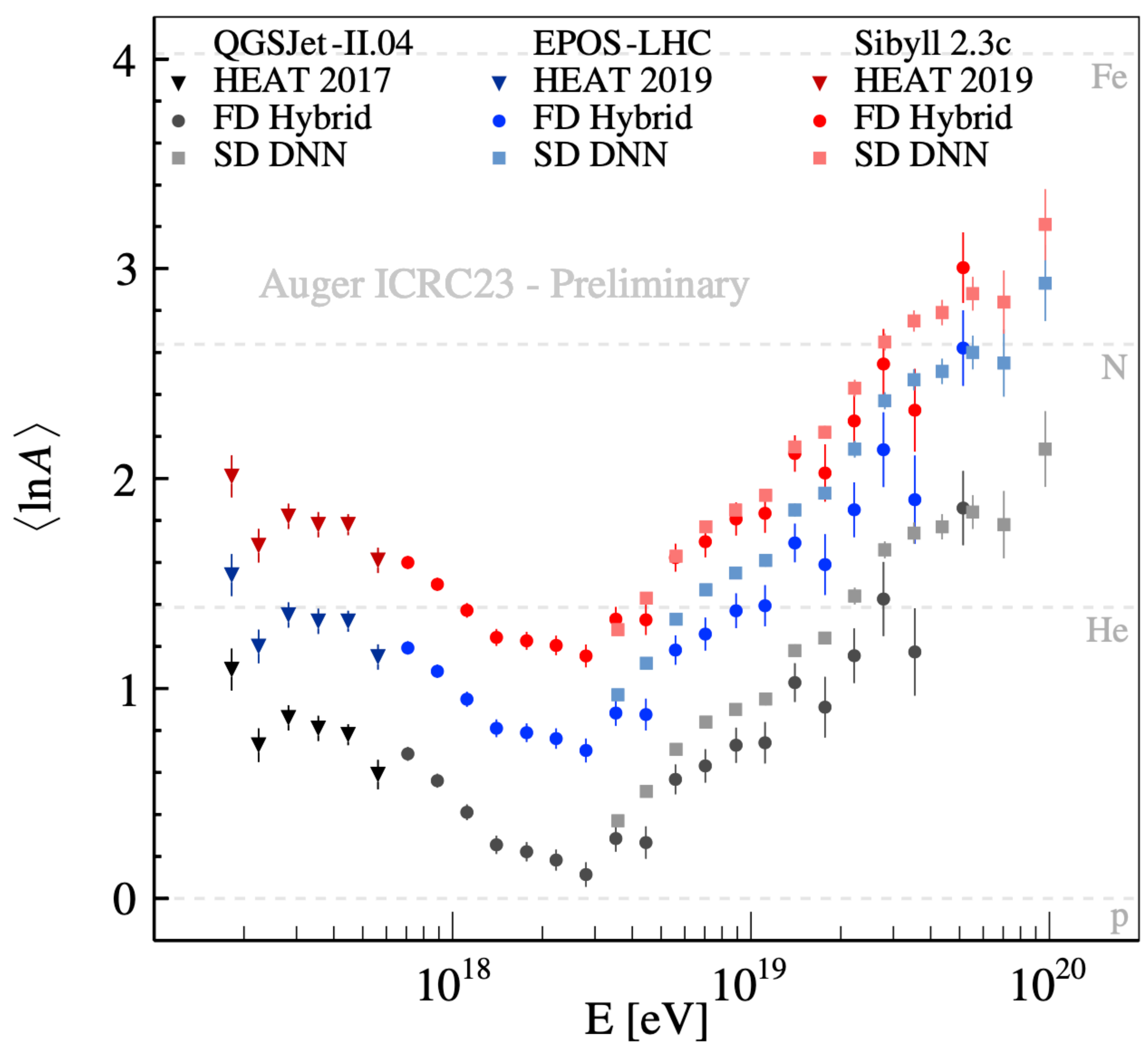


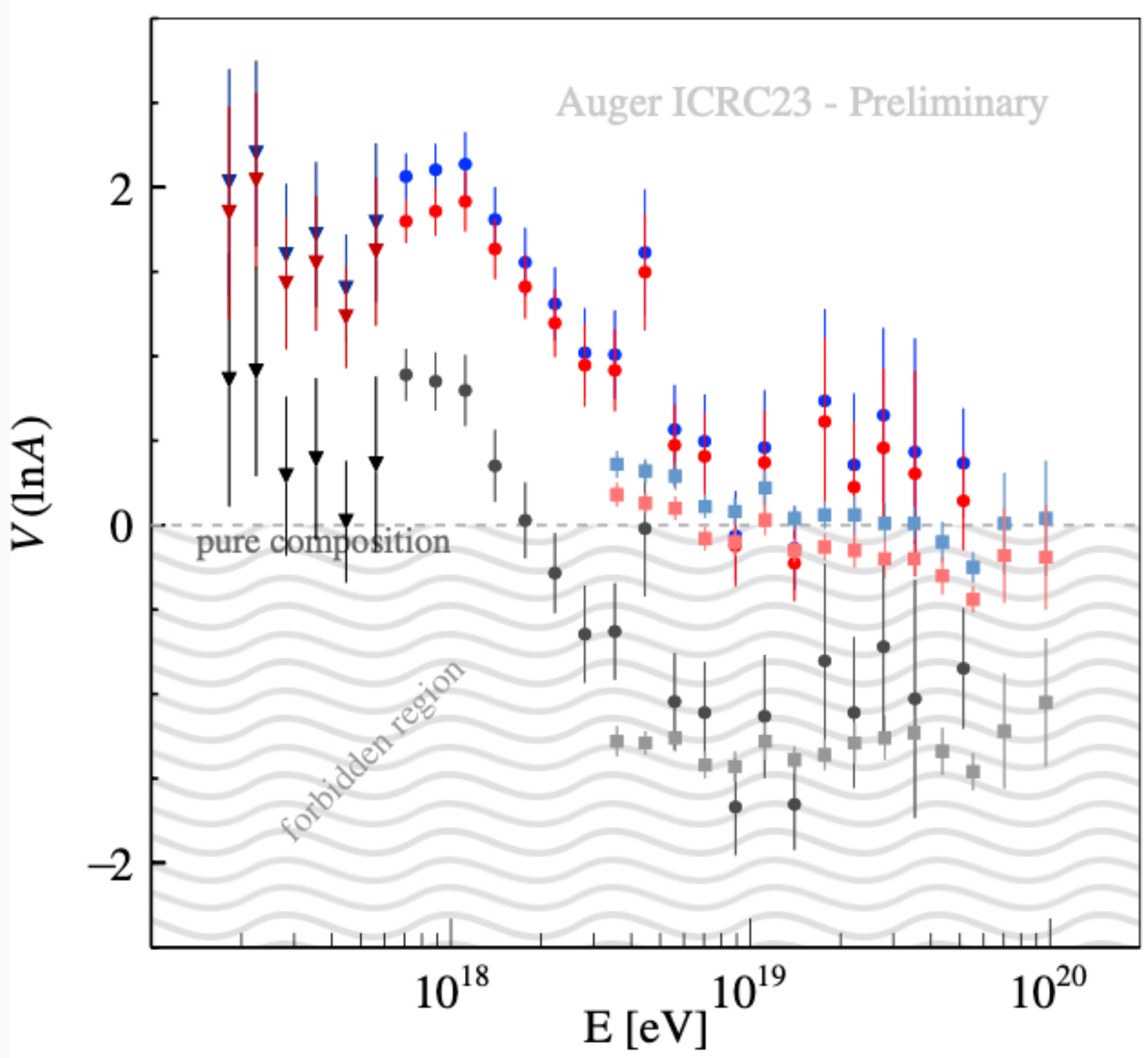




powerful Machine Learning techniques need to be cross-checked by means of multi-hybrid measurements!

lnA: mean and variance



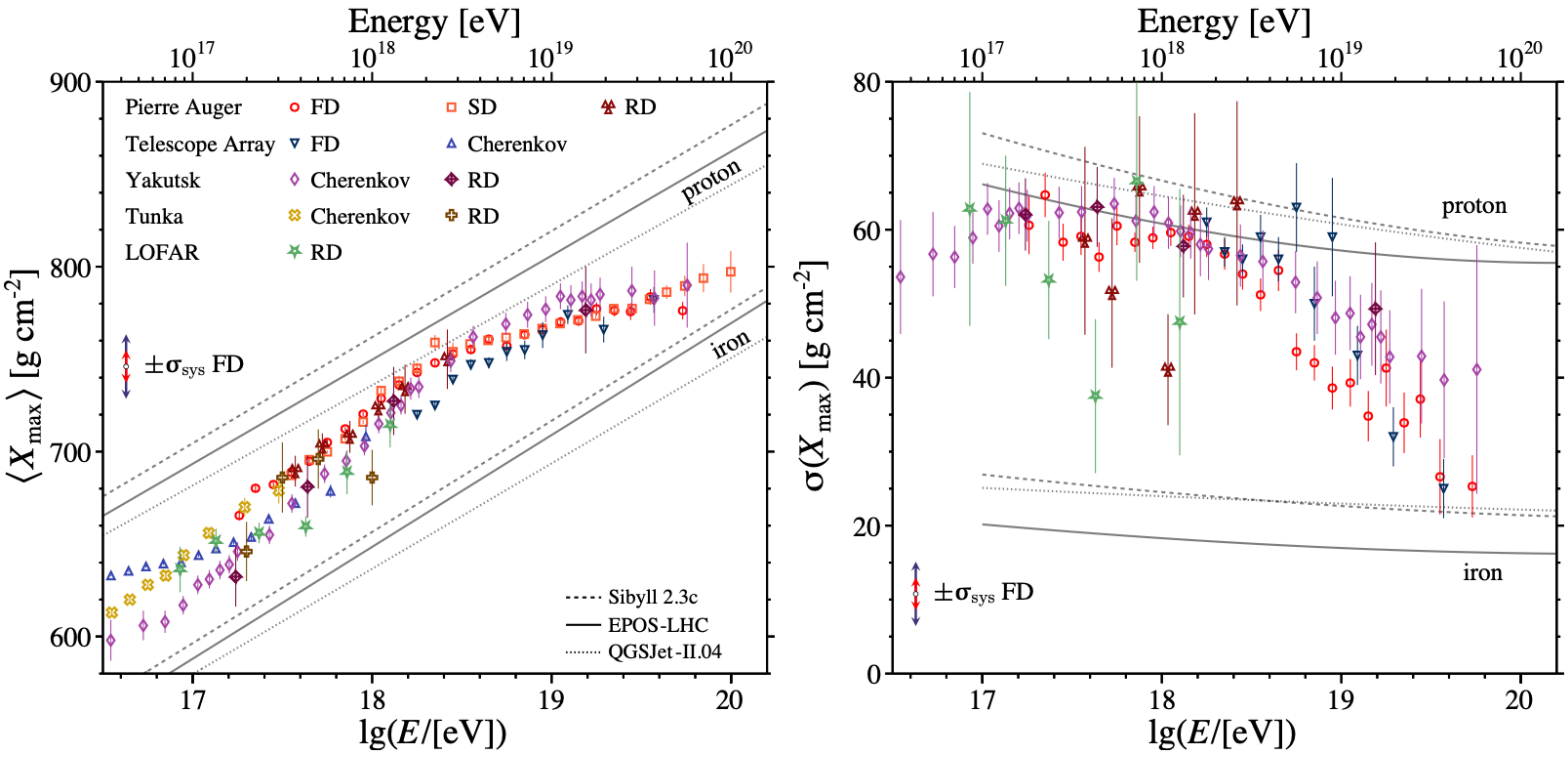


$$\langle \ln A \rangle = \frac{\langle X_{\max} \rangle - \langle X_{\max} \rangle_p}{f_E} .$$

$$\sigma^2_{\ln A} = \frac{\sigma^2(X_{\max}) - \sigma^2_{\text{sh}}(\langle \ln A \rangle)}{b\ \sigma_p^2 + f_E^2}$$

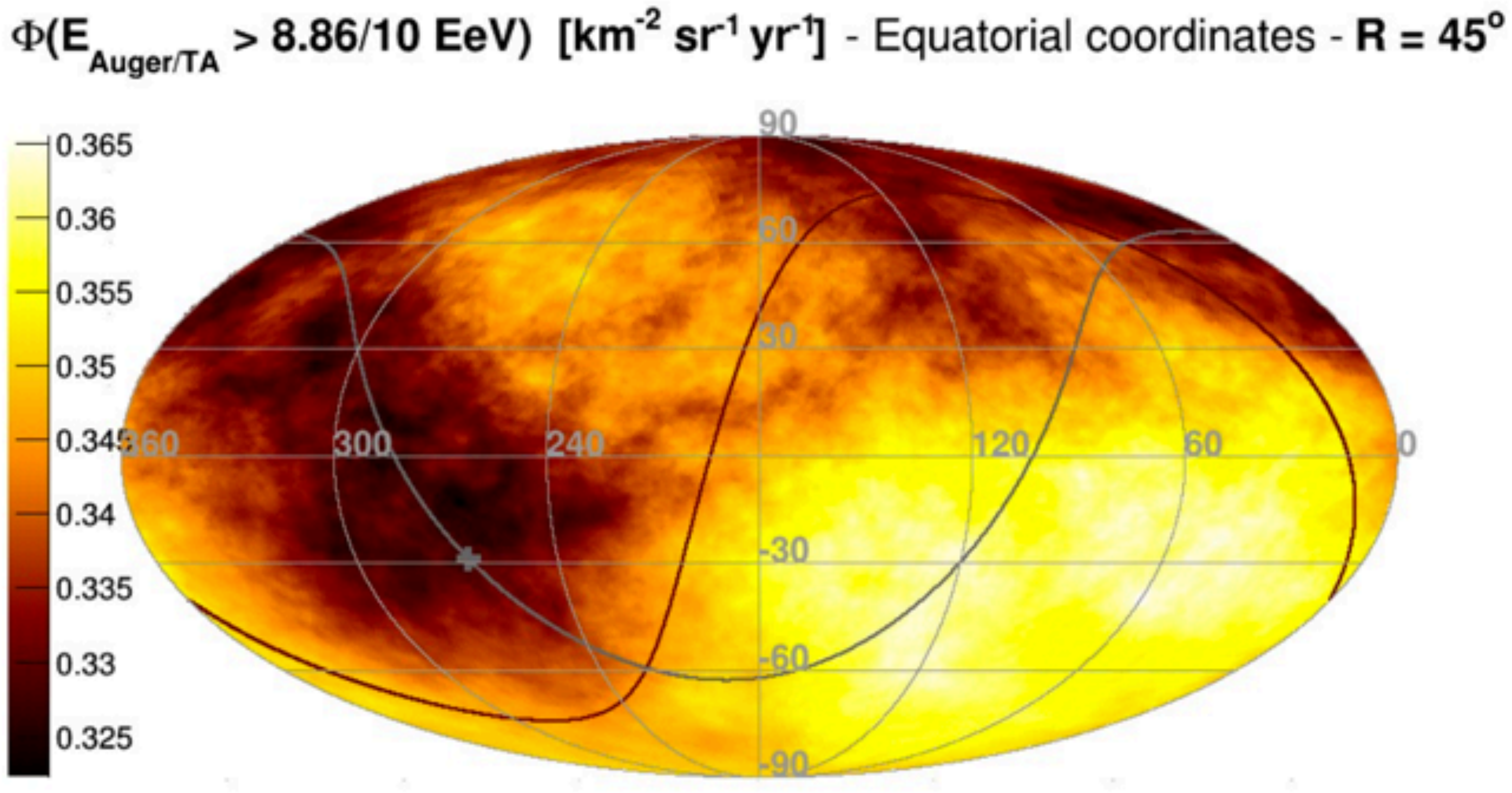
- ➡ The lightest composition is found at 2-3 EeV
- ➡ Maximum A around CNO to Si
- ➡ The primary beam is highly mixed up to 1 EeV, getting purer with increasing energy: 1-2 components only above 10 EeV
- ➡ Unphysical results for V(lnA) from QGSJet-II.04 - not to be used in composition studies

Depth of shower maximum - world data set



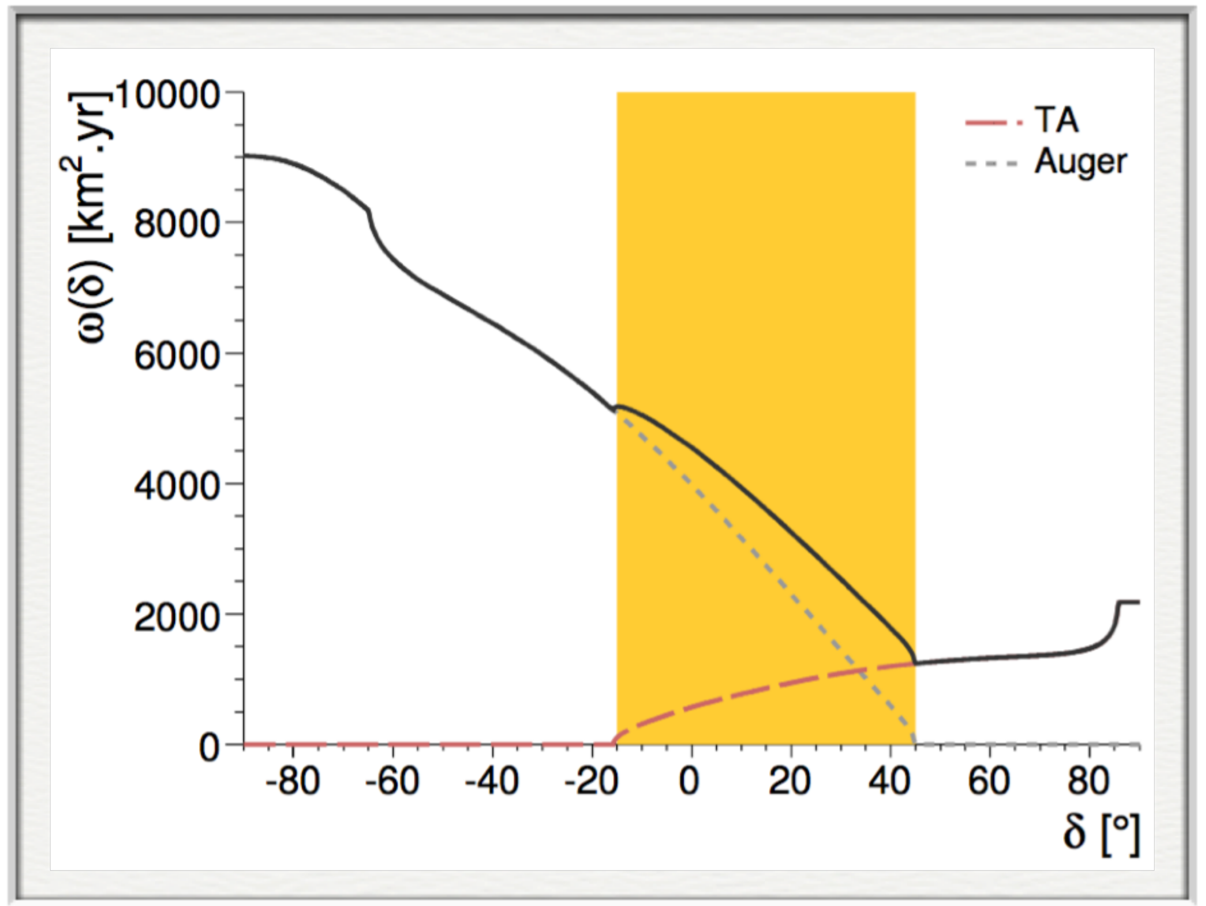
Compilation from A.Coleman et al., Snowmass - Astrop.Phys.147 (2023) 102794

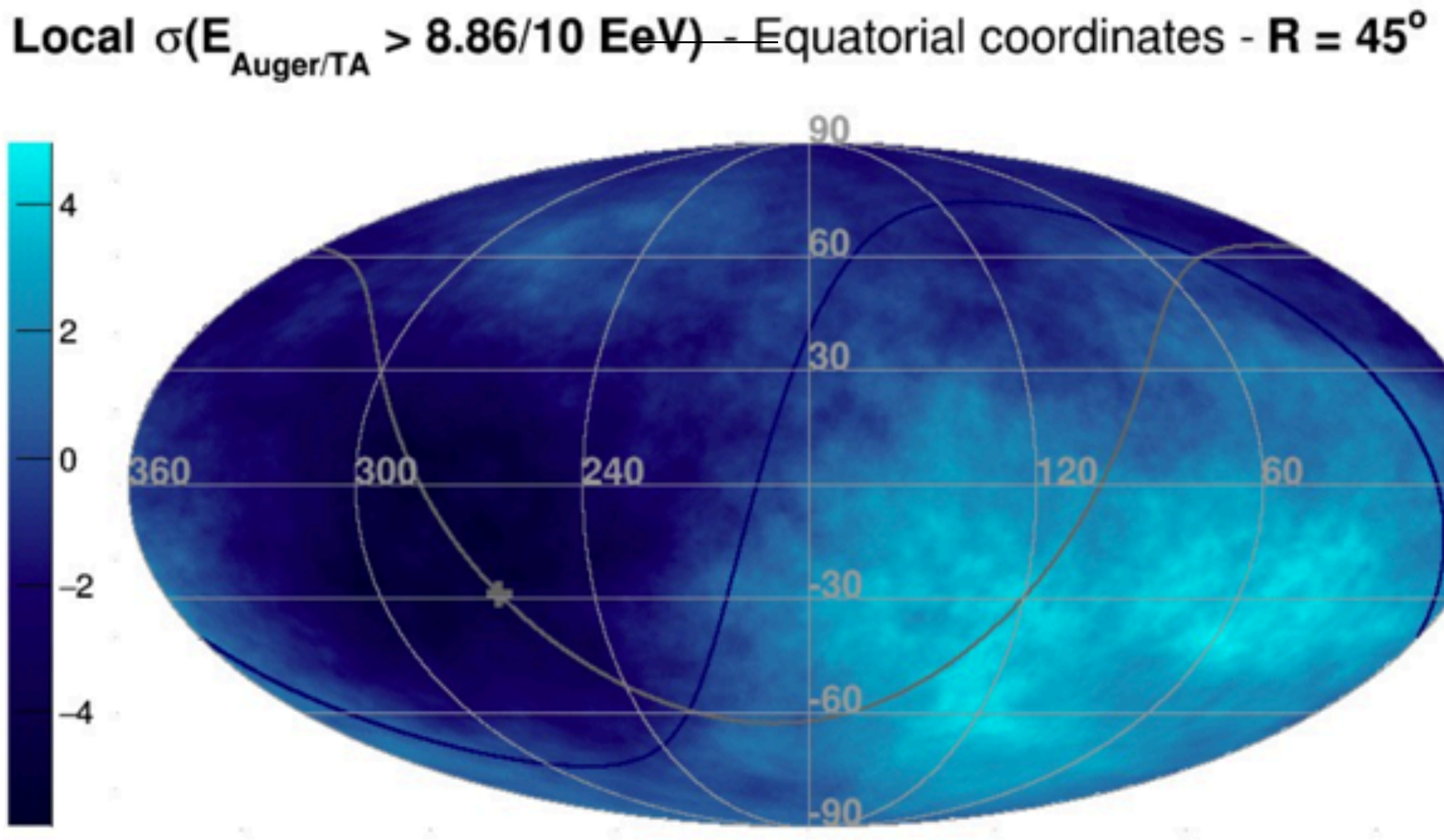
Large scale anisotropy: full sky results



Flux

- scatter plots of arrival directions immediately interpretable
- equal sensitivity anywhere in the sky
- upper limits uniform over the sky
- no need for methods to re-weight individual exposures



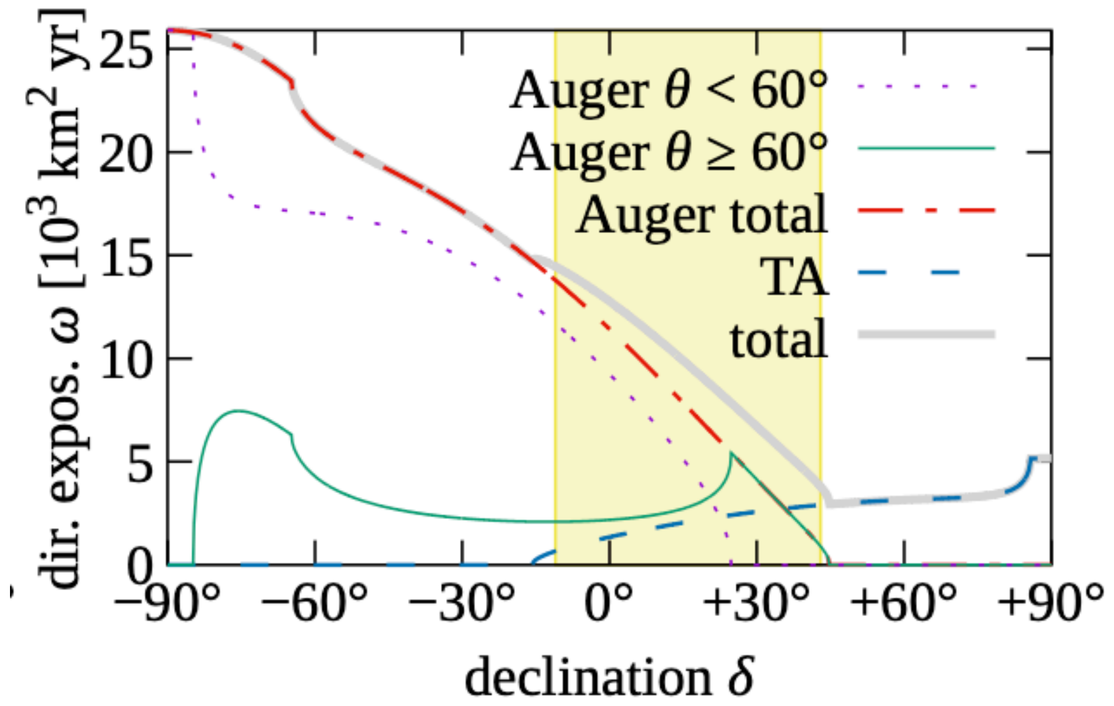


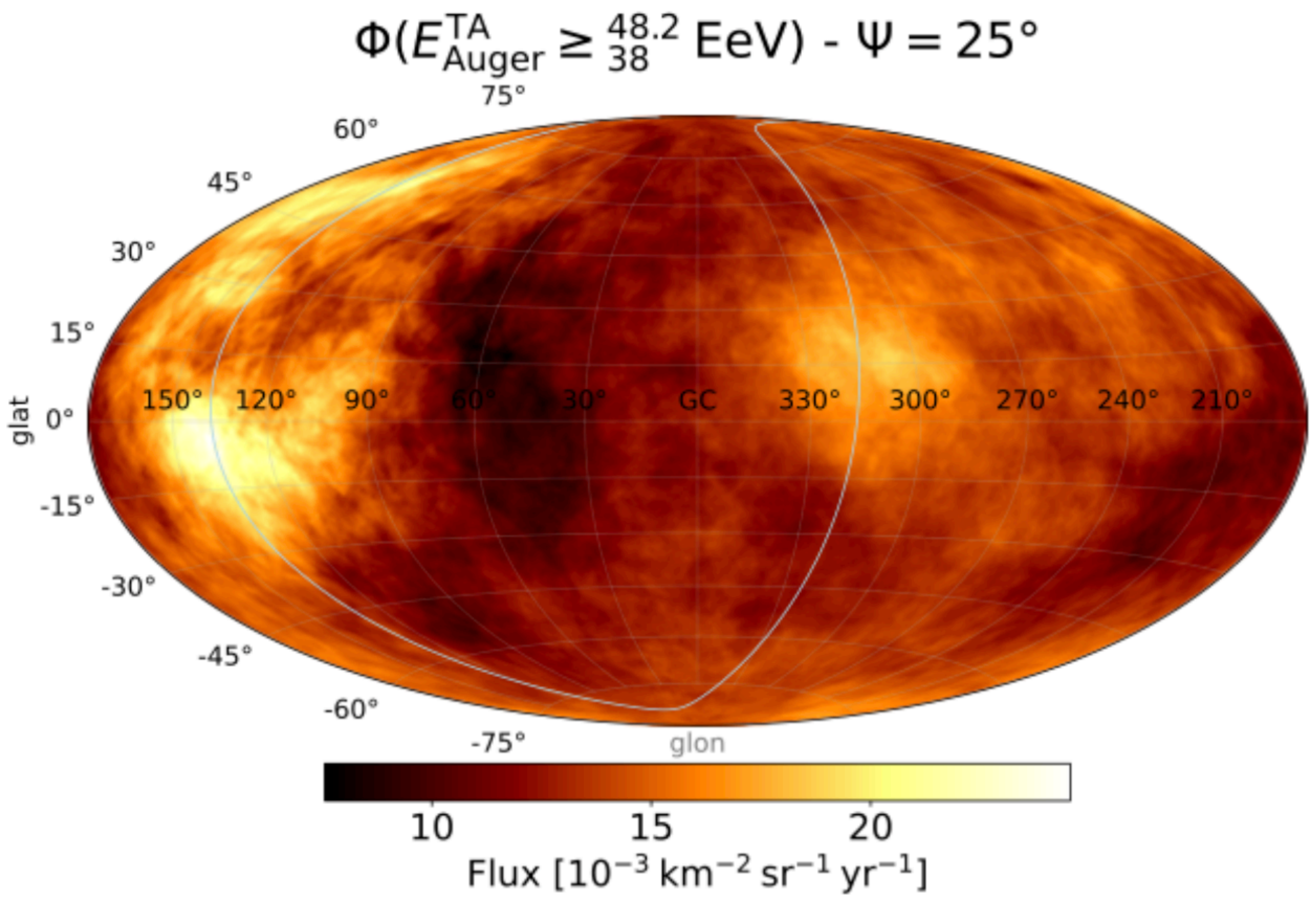
Significance: $\sigma \propto \sqrt{\varphi\omega}$

The UHE sky from Auger+TA

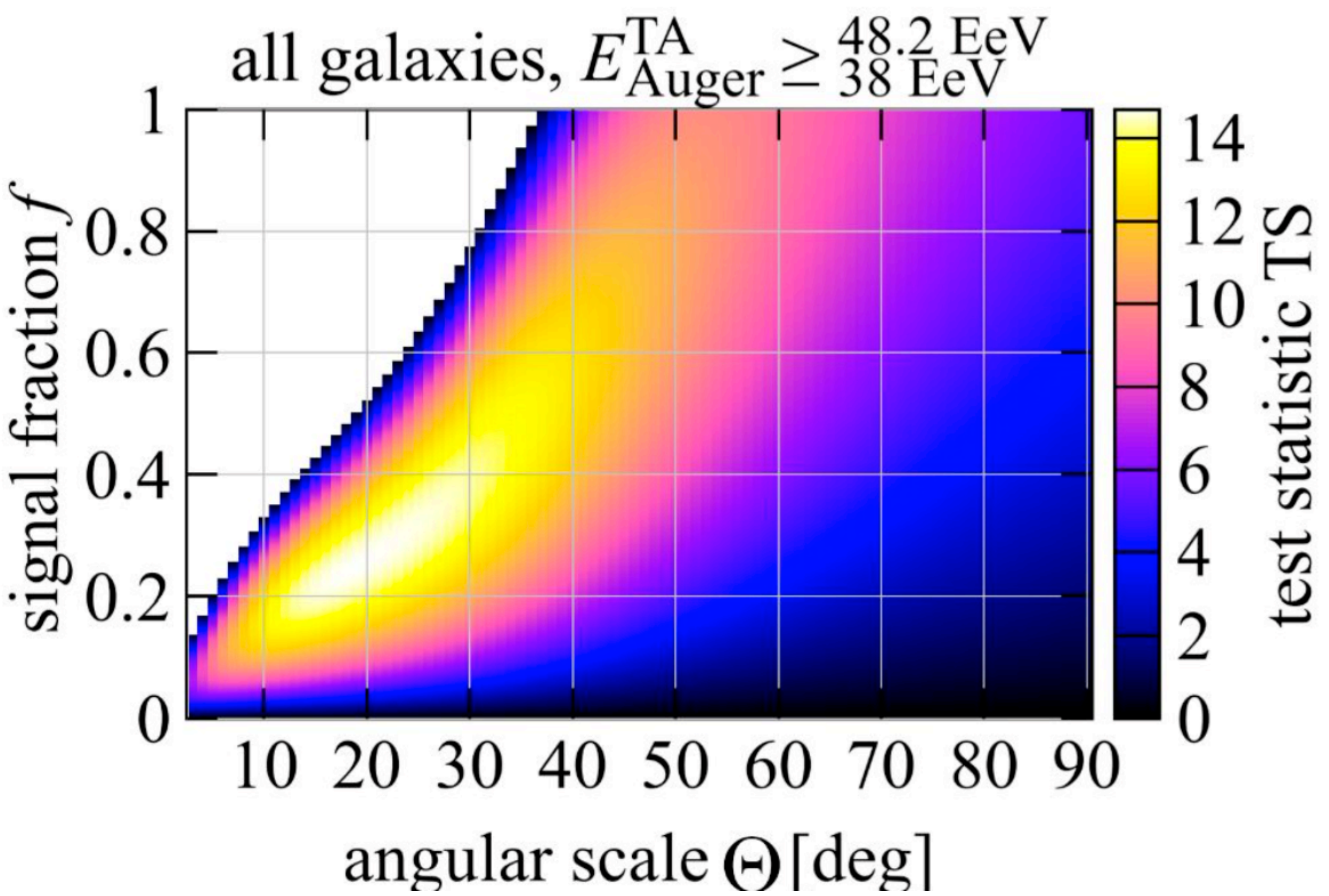
2004-2022 Auger, 2008-2022 TA: 3340 events for $E^{TA}_{Auger} \geq^{40.2\ EeV}_{32\ EeV}$

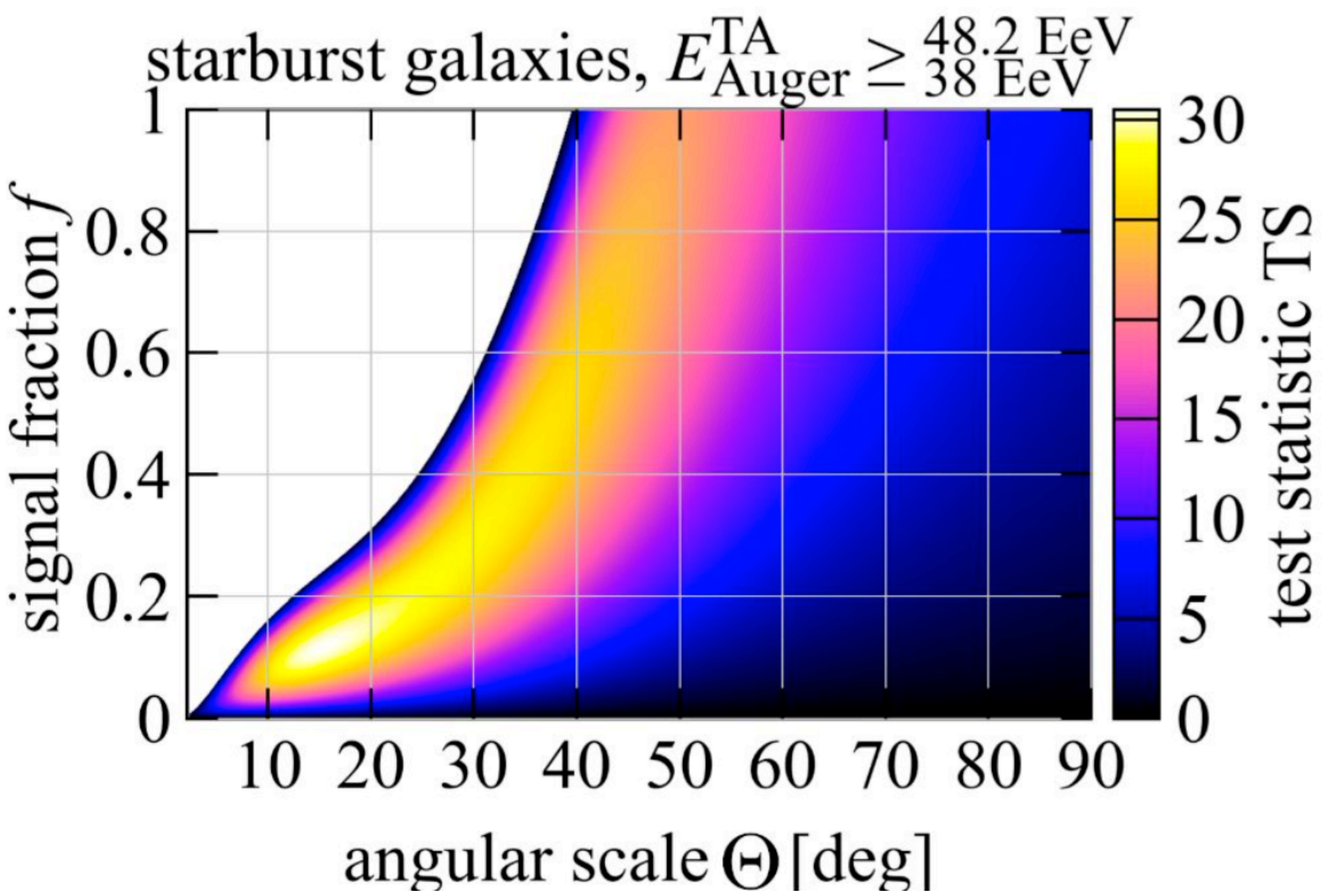
Exposure 135,000 km² sr yr for Auger, 17,500 km² sr yr for TA





Catalog	E_{Auger} threshold	E_{TA} threshold	Θ	f	TS	post-trial significance
All Galaxies	38 [40]	48.2 [51]	18.7 [29]	24.8 [41]	14.7 [14.3]	2.8σ [2.7σ]
Starburst Galaxies	38 [38]	48.2 [49]	15.4 [15.1]	11.7 [12.1]	30.5 [31.1]	4.6σ [4.7σ]





Spots found

— in the southern hemisphere (Centaurus region and M253)

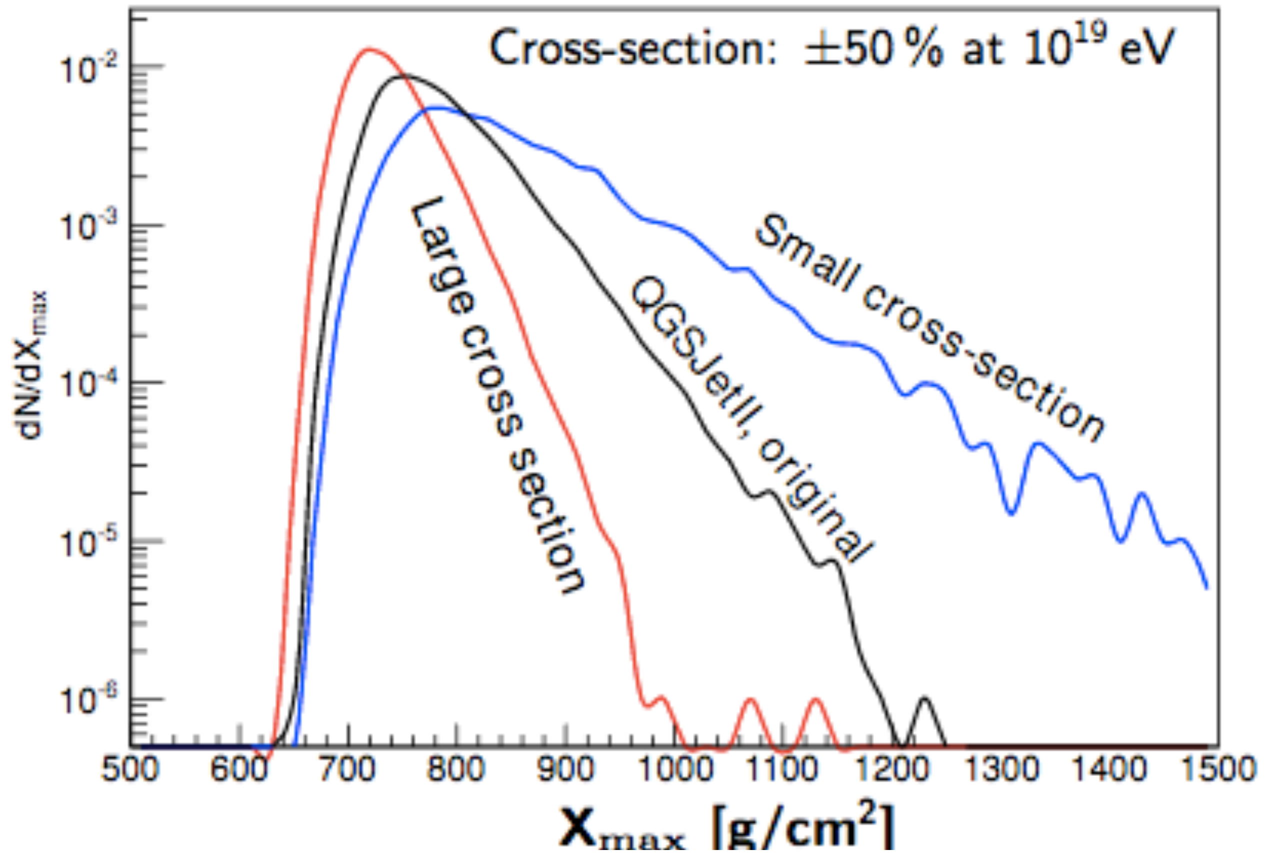
— in the northern hemisphere (Ursa Major region and M31/Triangulum/Perseus-Pisces region)

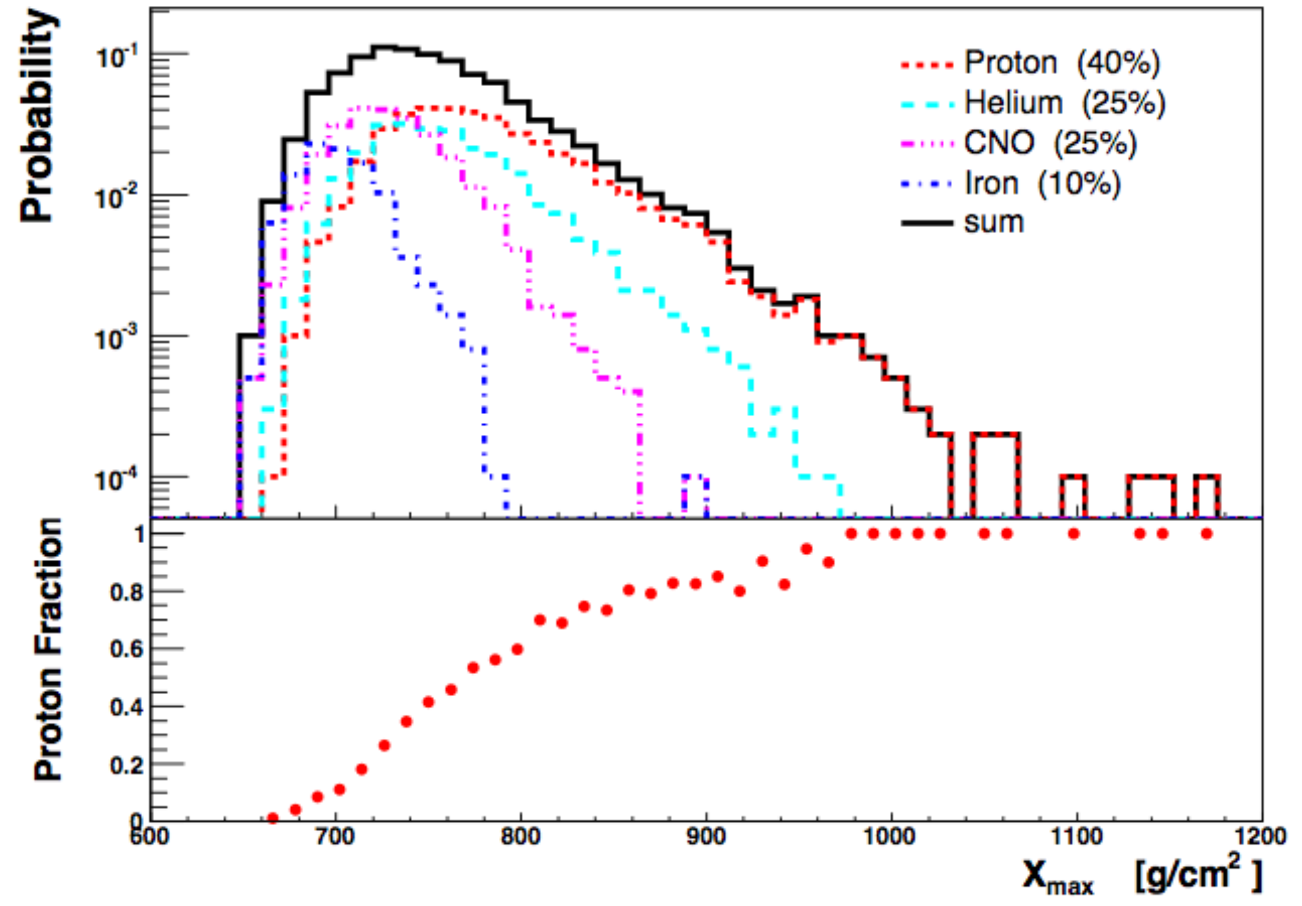
L.Caccianiga, PoS(ICRC2023) 521
Auger, ApJ 935 (2022) 170

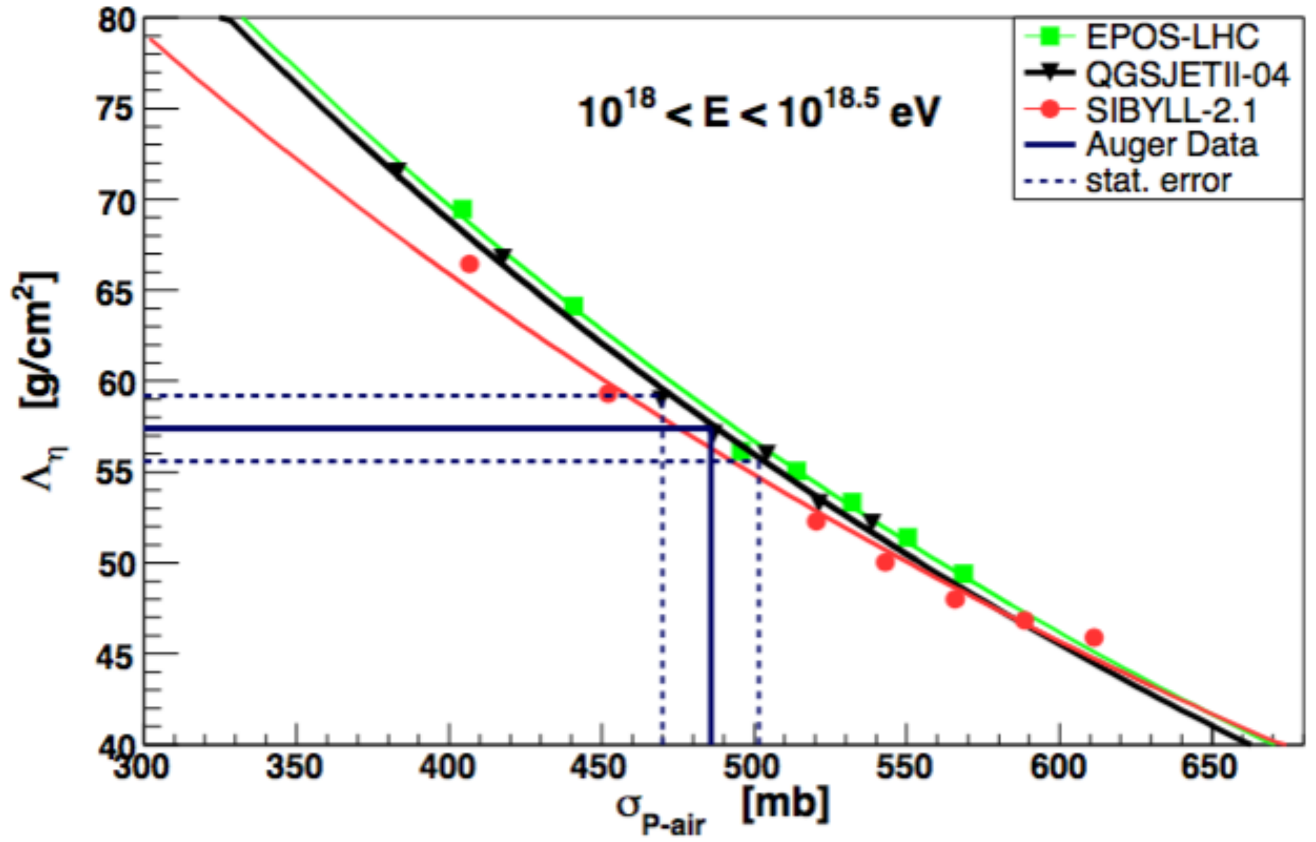
Expected statistics in Phase II

Table 2: Expected integral number of events above several energies for 10 years of data taking in the AugerPrime configuration. For SD-1500, we consider events up to zenith angle $\theta = 60°$. Inclined air showers ($60° < \theta < 80°$) add about 30% to the exposure.

	SD			FD		RD
lg(E/eV)	433	750	1500	hybrid	Cherenkov	
16.8	118000				48000	
17.5	3700	81000			4400	
18.0	270	5600		13000		
18.5	24	460	106000	3000		
19.0	5	88	13400	650		3000
19.5			1000	50		310
19.8			100	~ 5		23
20.0			12	~ 1		$\sim$3





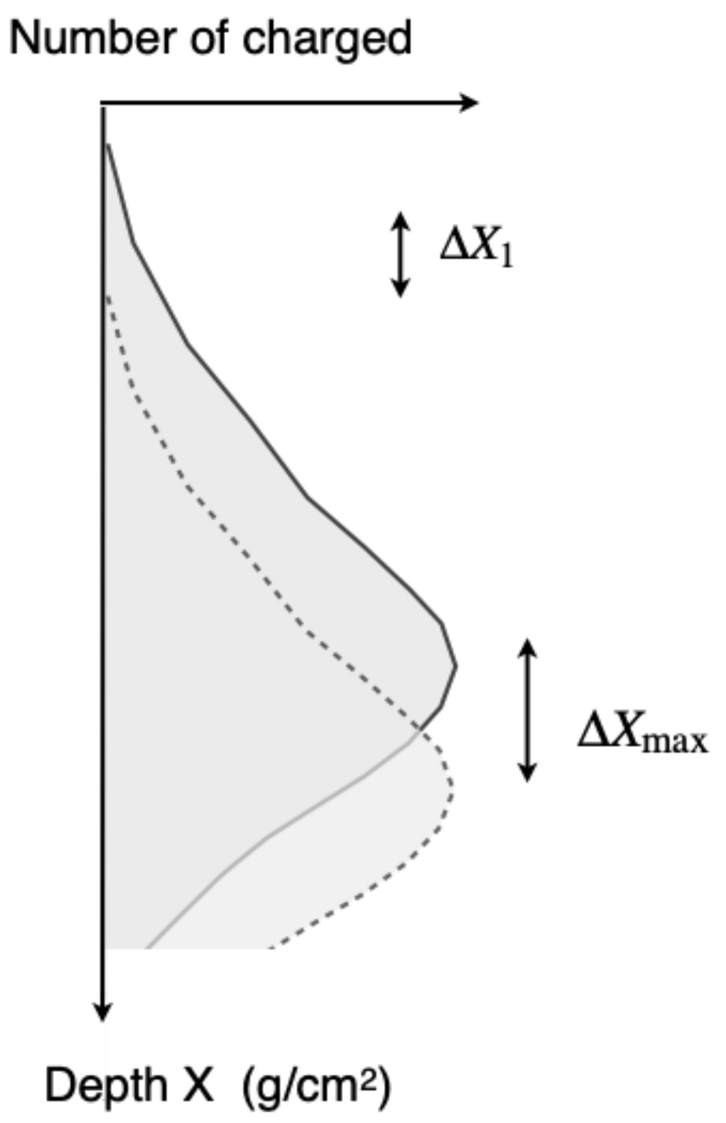


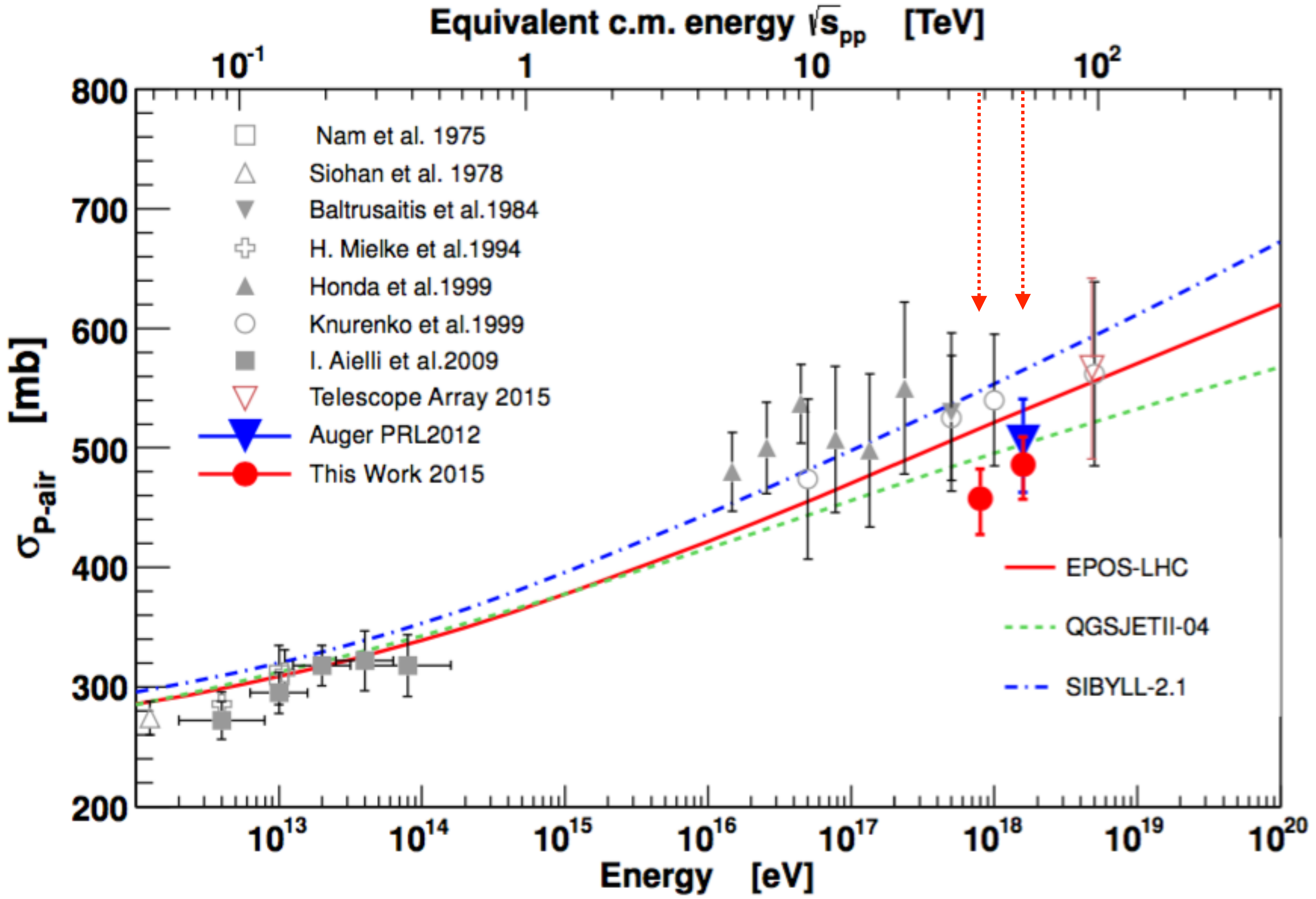
The p-Air cross section

The tail of the longitudinal distribution of X_{max} is sensitive to the p-Air cross section.
Select deeply penetrating EAS to enhance the proton fraction

$$\frac{dp}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}} \qquad \sigma_{p-Air} = \frac{< m_{Air} >}{\lambda_{int}}$$

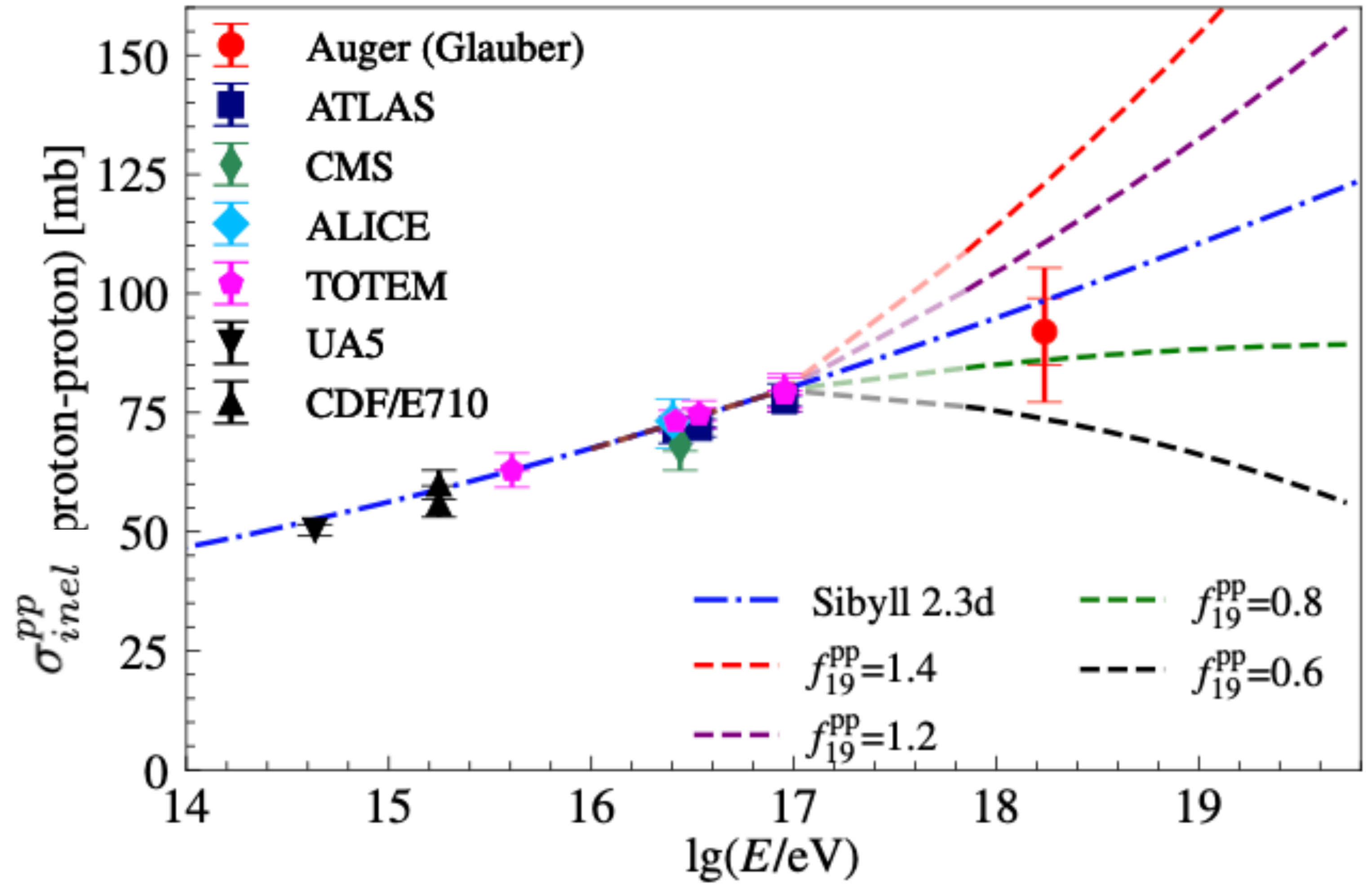
$$\frac{dN_{EAS}}{dX_{max}} \propto e^{-X_{max}/\Lambda_\eta} \qquad \lambda_{int} \longleftrightarrow \Lambda_\eta$$





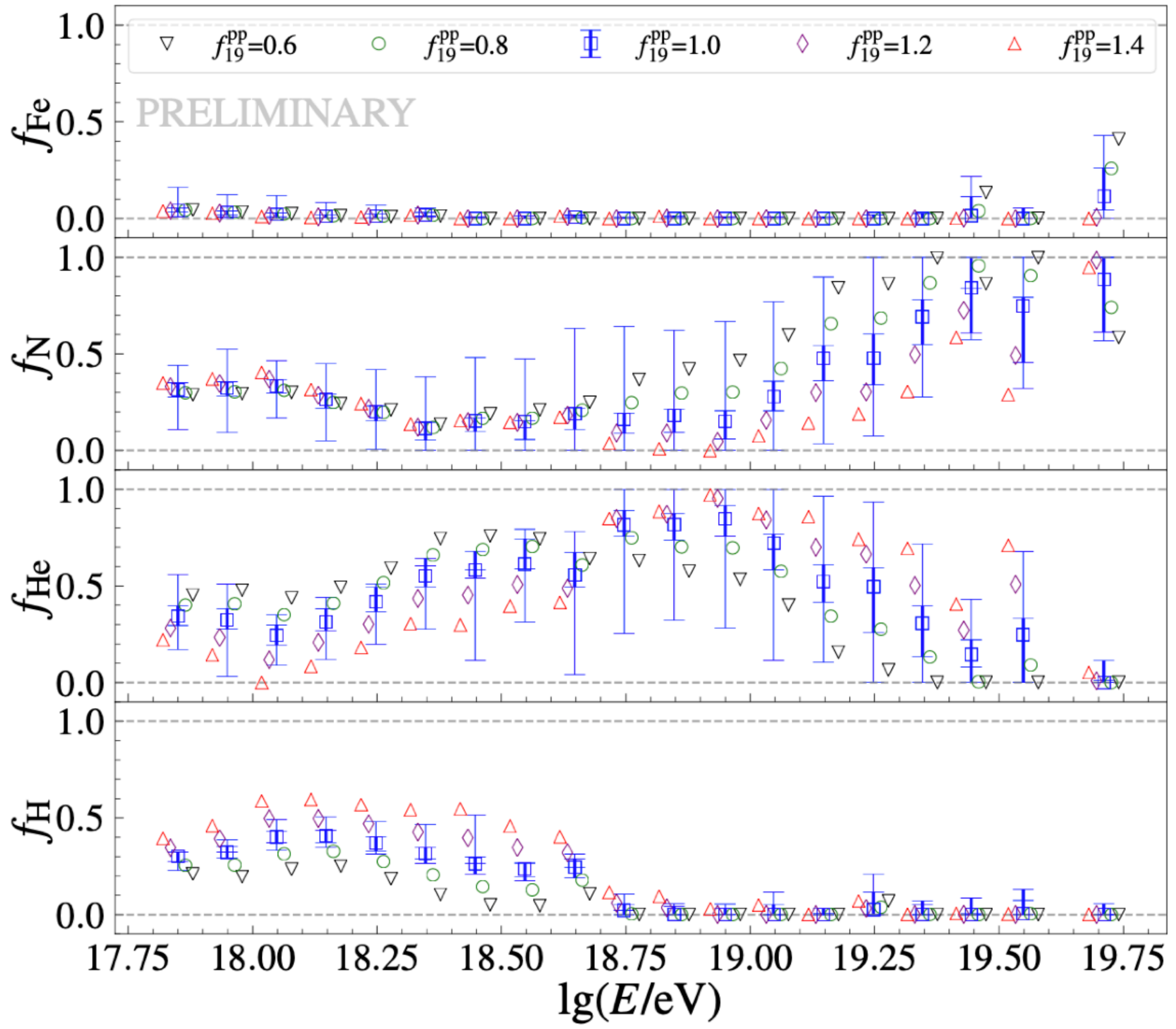
Primary mass composition and particle cross-section

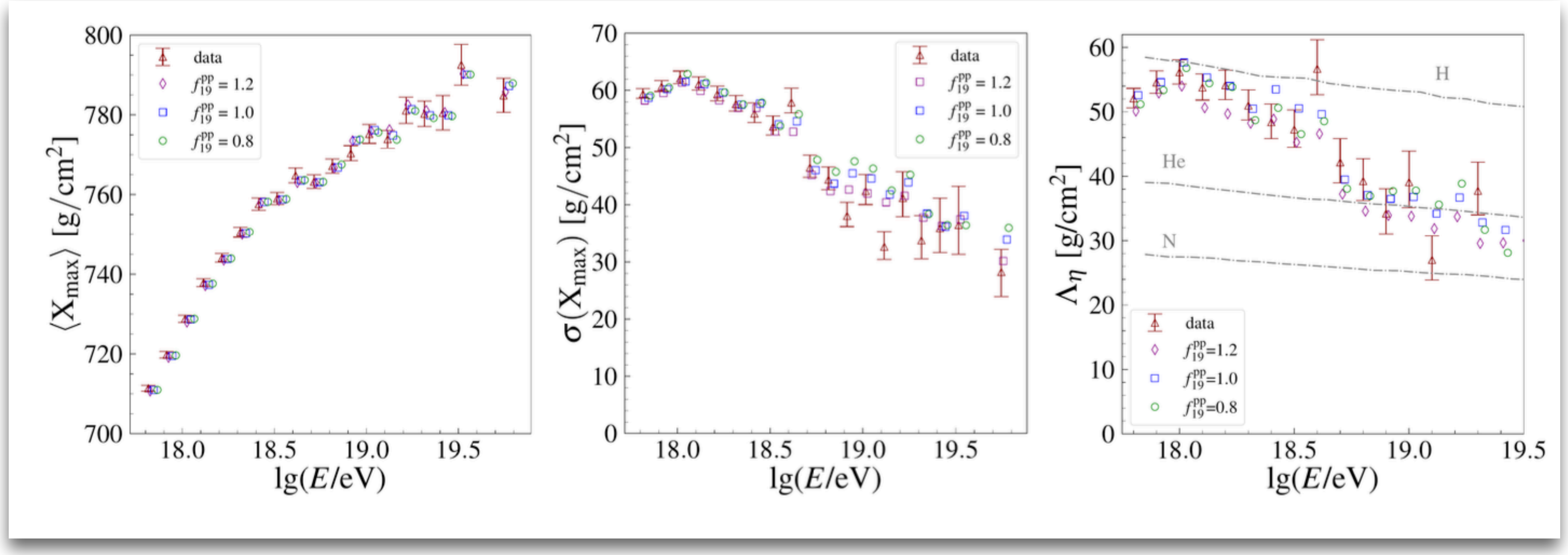
Mass composition fit with model preditions allowing altered pp interactions



$$\sigma^{pp}_{mod} = \sigma^{pp}_{orig} f(E_0, E)$$

$$f(E_0, E) = 1 + H(E - E_0)(f_{19} - 1)\frac{lg(E/E_0)}{E_1/E_0}$$





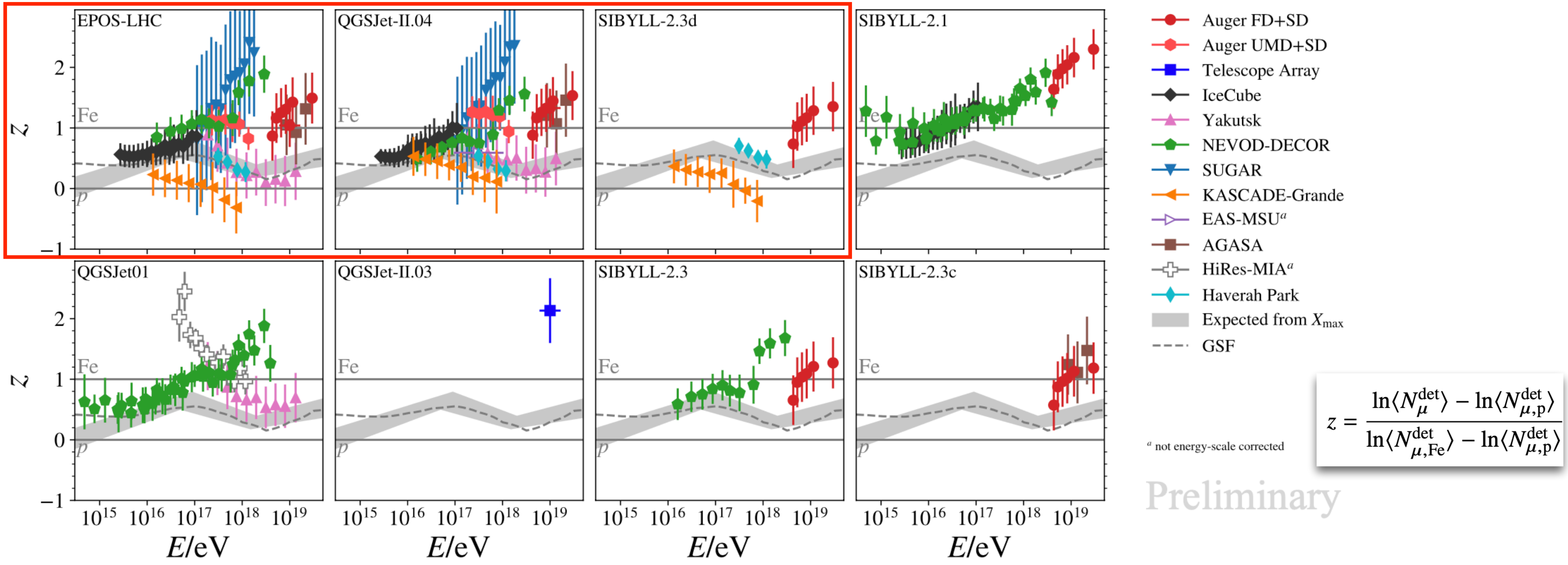
➡ the behaviour of the <Xmax> and its variance with energy is independent of modifications in σ_{pp}

➡ the individual mass groups are sensitive to them

➡ only small deviations from default composition for 20% variations in σ_{pp}

O.Tkachenko, PoS(ICRC2023) 438

The muon puzzle - world data set compilation



Compilation after application of energy shifts for common energy calibration

Need for a detailed analysis of the experimental conditions, simulations characteristics, detection methods, energy calibration techniques, etc.

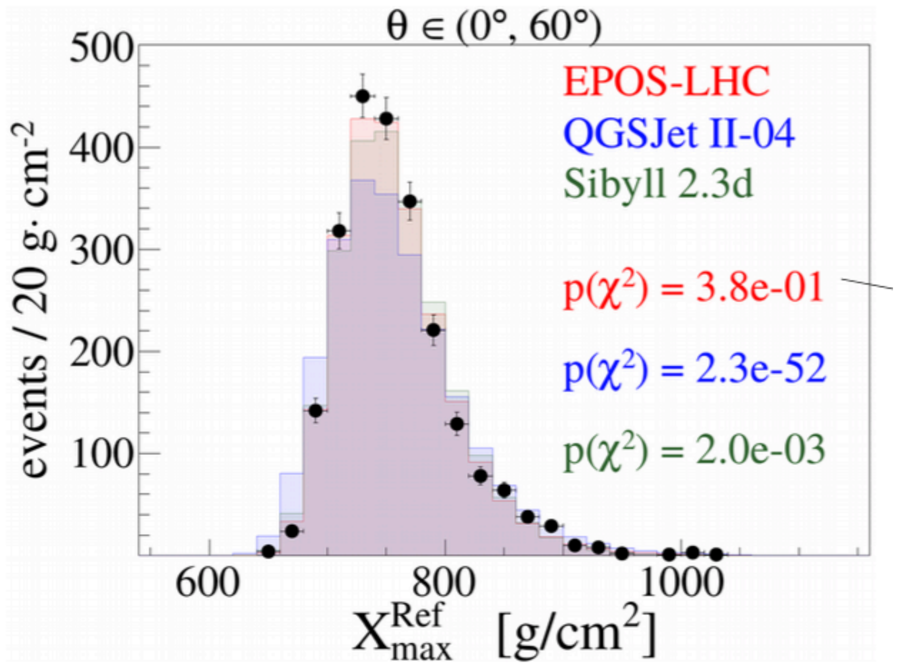
Testing the predictions of hadronic models

Global fit of the observed [X_{max},S_{1000}] distributions with templates of free mass composition and different hadronic interaction models

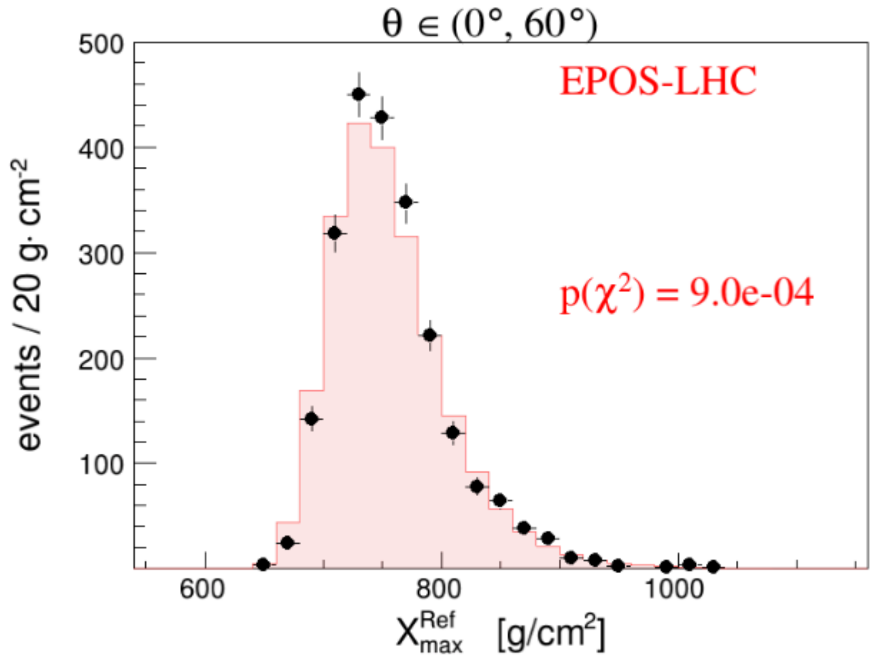
ad-hoc adjustments

$$X_{max} \rightarrow X_{max} + \Delta X_{max}$$

$$S_{Had}(\theta) \rightarrow S_{Had}(\theta) \cdot R_{Had}(\theta)$$

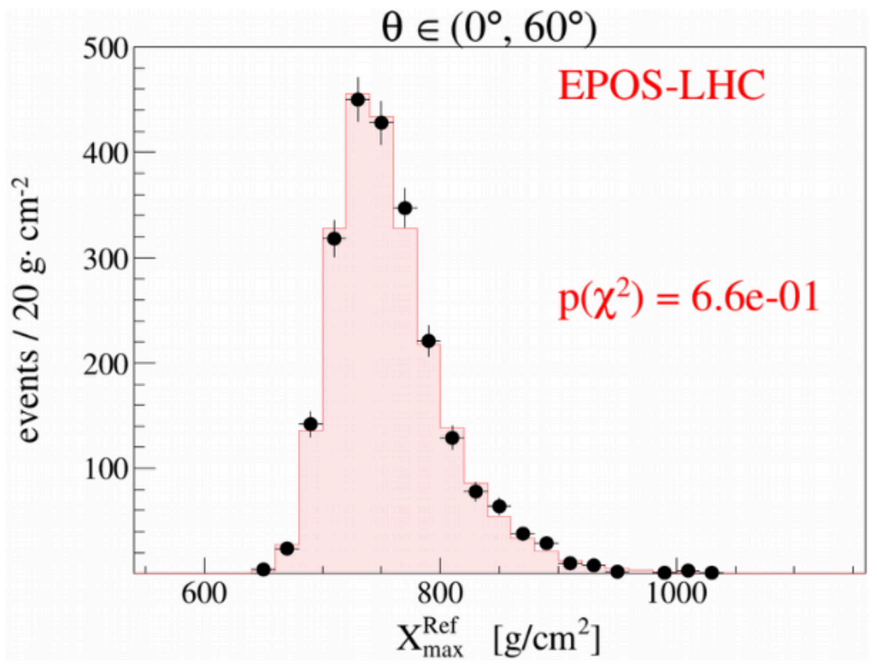


Combined fit of the [X_{max},S_{1000}] distributions without any adjustments



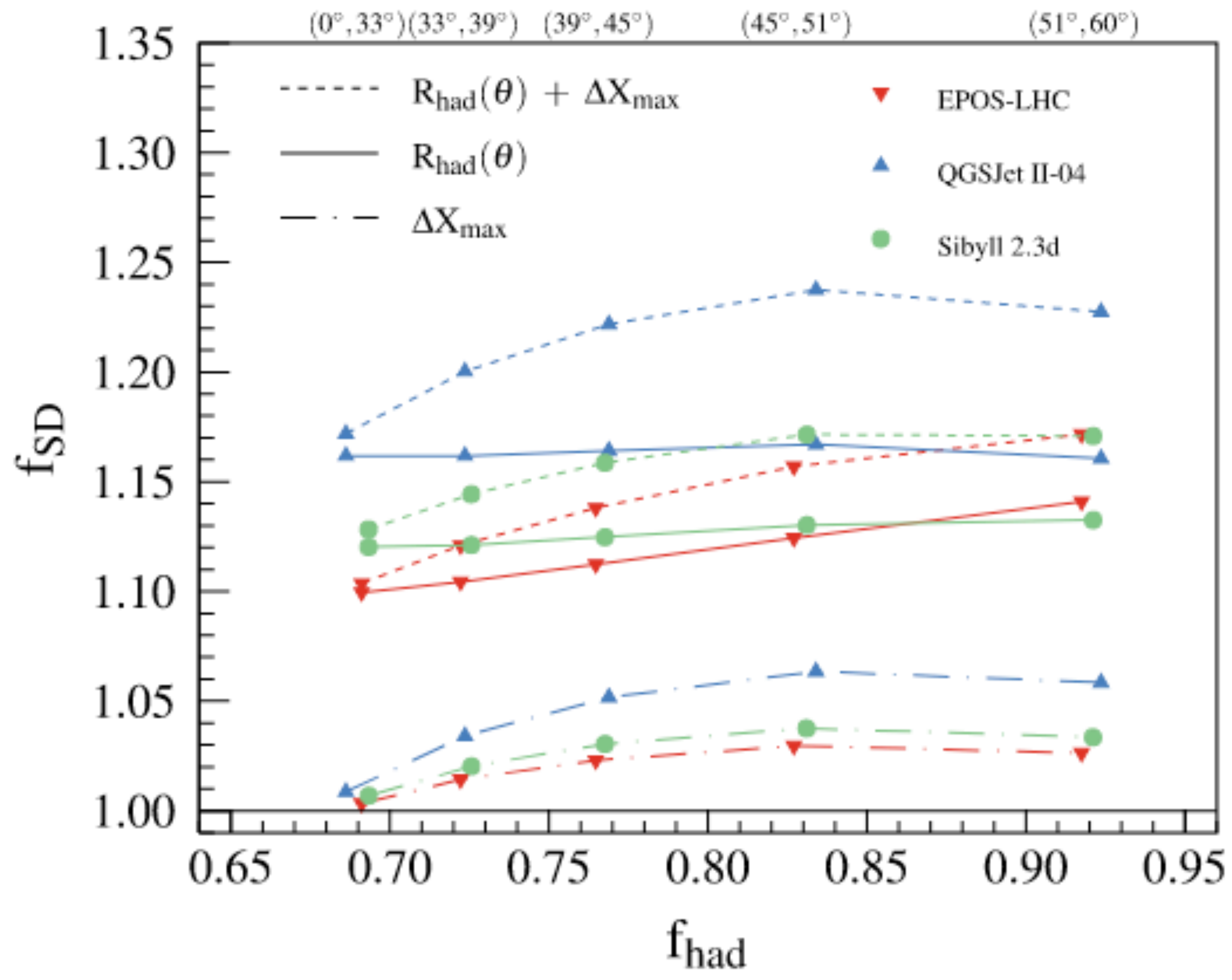
Combined fit of the [X_{max},S_{1000}] distributions with angular dependent muon rescaling $R_{had}(\vartheta)$

largest improvement



Combined fit of the [X_{max},S_{1000}] distributions with angular dependent muon rescaling $R_{had}(\vartheta)$ and shift of X_{max}

further improvement -> heavier composition



Best description of data if **models modified** such that :

X_{max} deeper by 20-50 g cm^{-2}

S_{had} increased by 15-25%

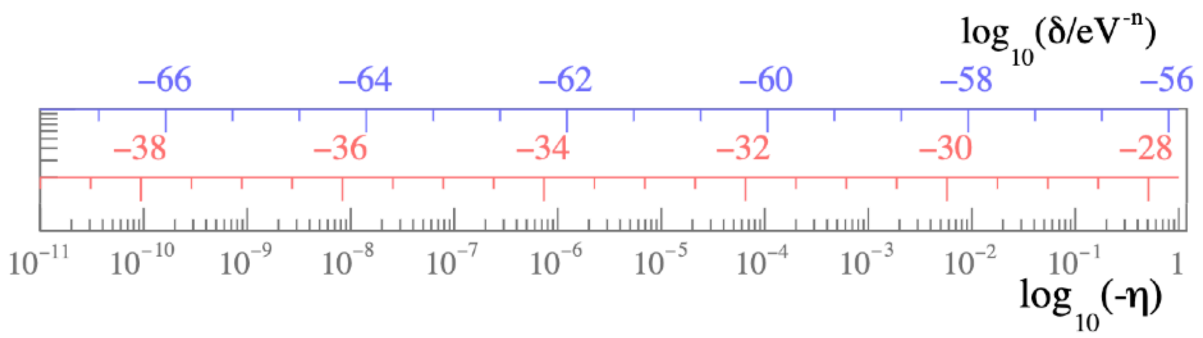
Auger Coll., Phys.Rev.D109 (2024) 102001

Search for Lorenz invariance violation

$$E_i^2 - p_i^2 = m_i^2 + \sum_{n=0}^{N} \delta_i^{(n)} E_i^{2+n} = m_i^2 + \eta_i^{(n)} \frac{E_i^{2+n}}{M_{Pl}^n}$$

Dimensional

$$\delta^{(n)} = \frac{\eta^{(n)}}{M_{\rm Pl}^n}$$

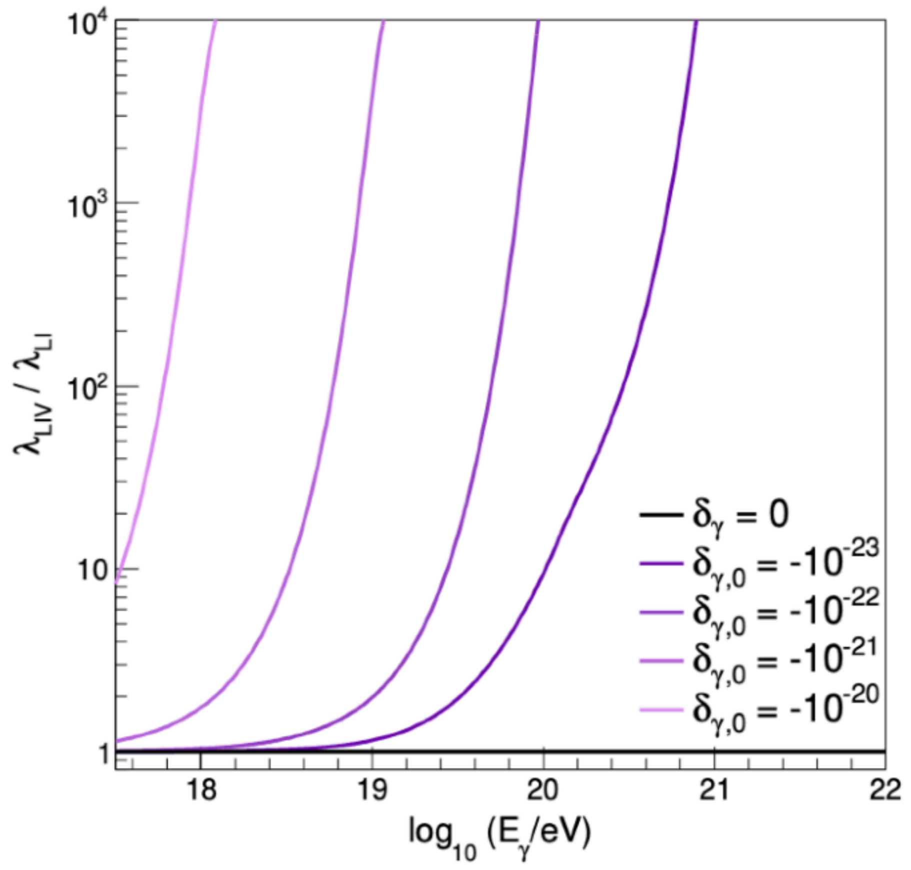


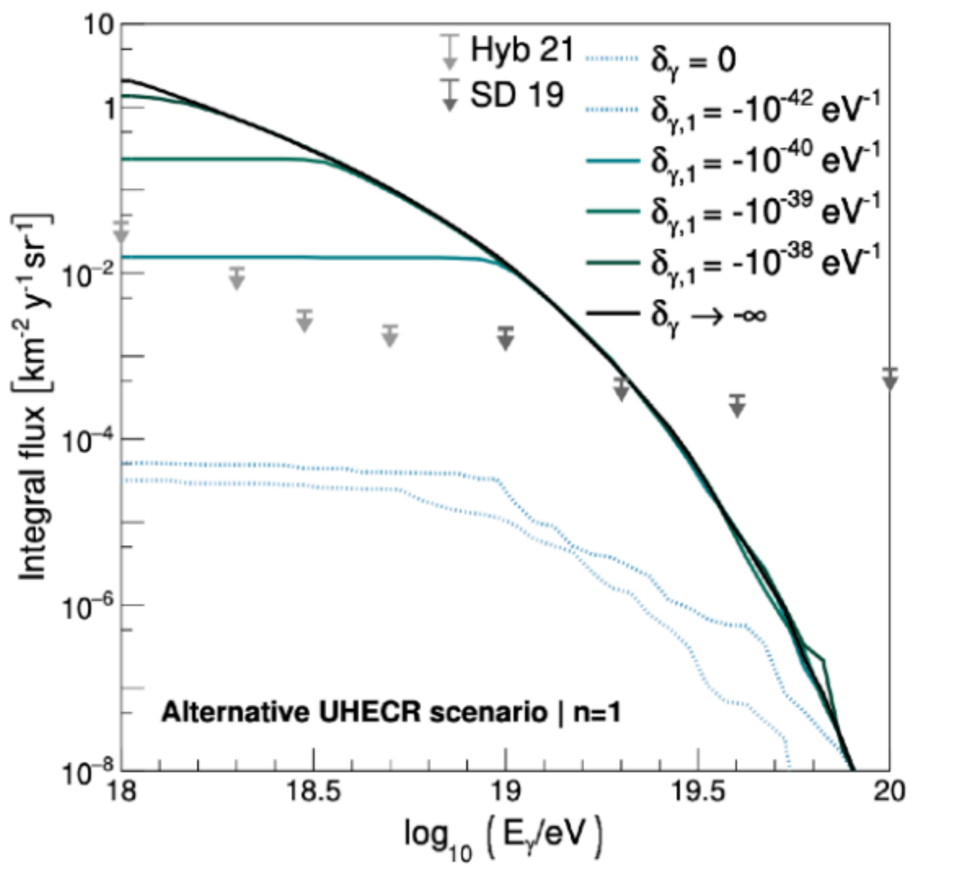
Effects suppressed for low energy and short travel distances : UHECRs !!!

Modification of CR interactions during propagation:

➡EM : pp cross section modified —> increased mean free path —> less interactions —> more photons expected

➡hadronic sector: number of interactions reduced —> if LIV lighter nuclear species needed at source to reproduce the composition



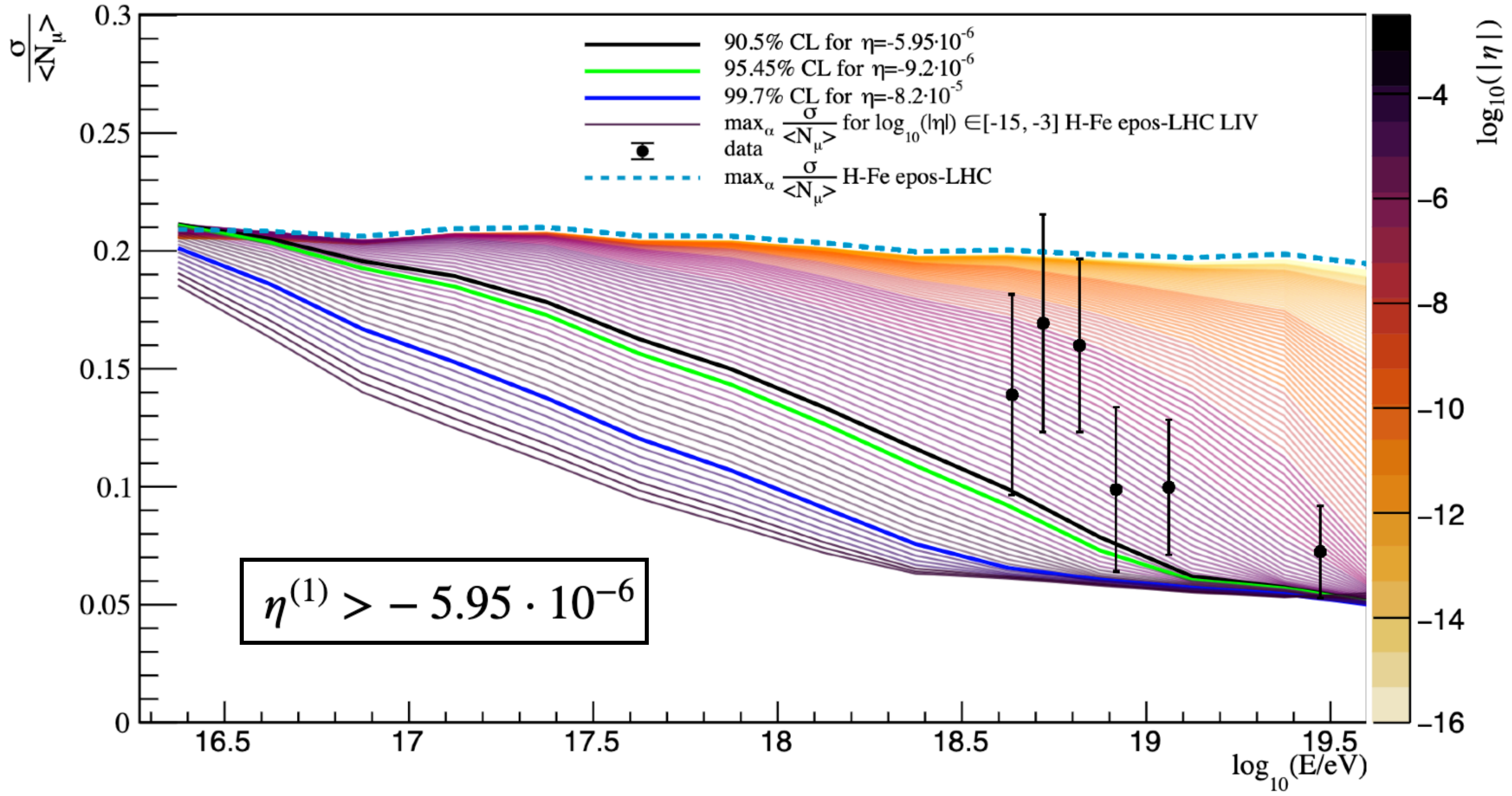


Air shower physics

- for $\eta^{(n)}<0$, decay of π^0 can become forbidden if

$$m_\pi^2 + \eta_\pi^{(n)} \frac{p_\pi^{n+2}}{M_{Pl}^n} < 0$$

- EM component decreasing, hadronic one increasing



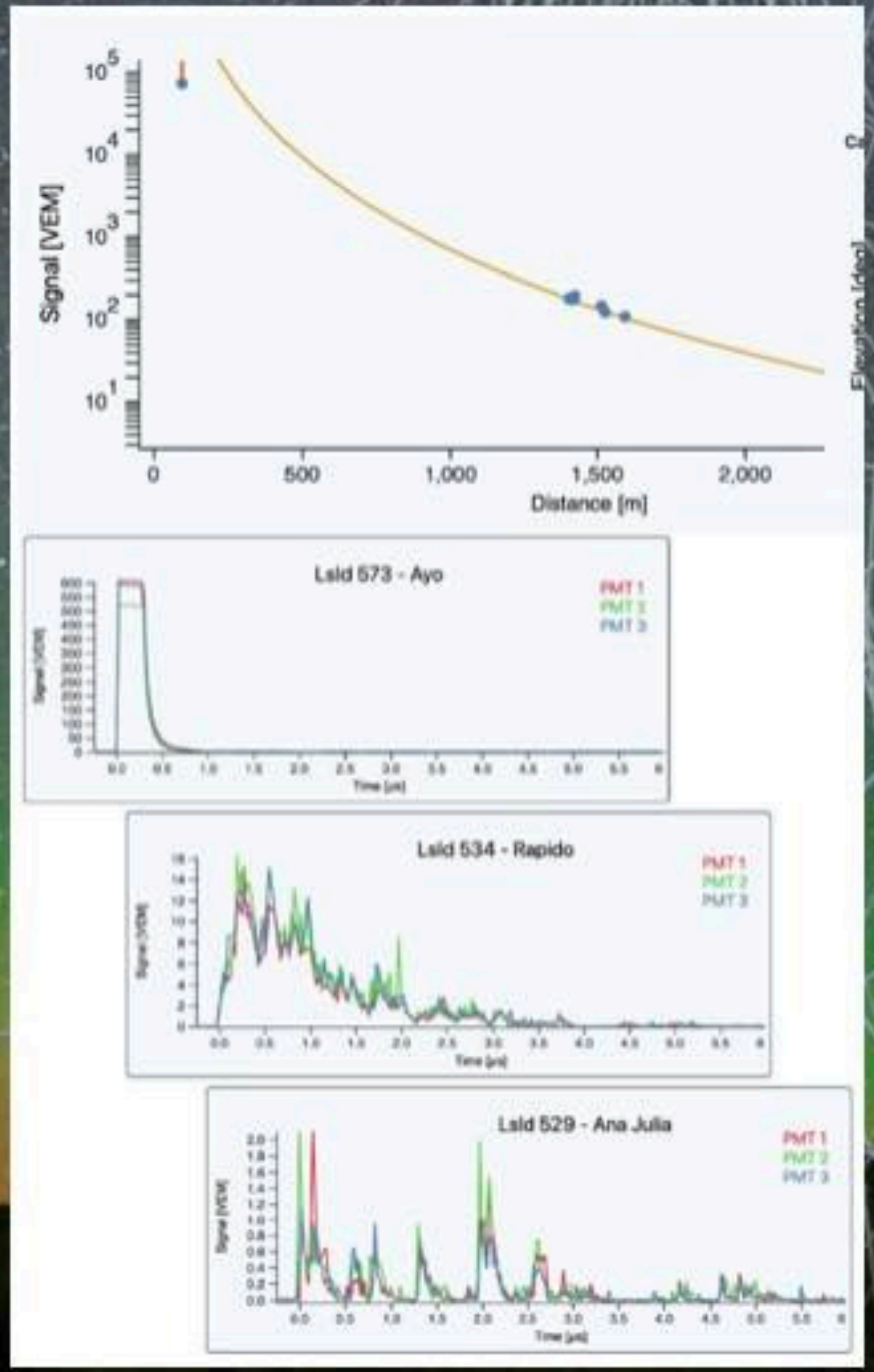
Auger Coll., JCAP01 (2022) 023
C.Trimarelli (Auger Coll.), UHECR2022

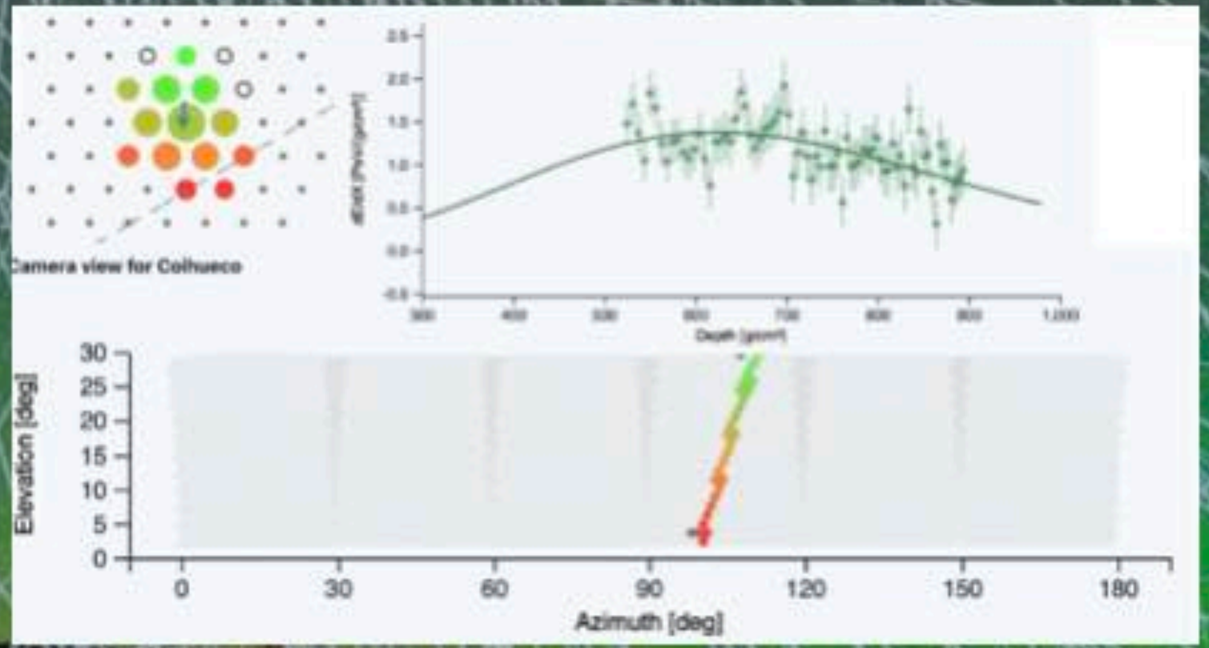
The Auger Public Data Release

Following the Auger Collaboration Open Data Policy, the Pierre Auger Open Data is the public release of 10% of the Pierre Auger Observatory cosmic-ray data published in recent scientific papers and at International conferences. The release also includes 100% of weather and space-weather data collected until 31 December 2020. This website hosts the datasets for download. Brief overviews of the Pierre Auger Observatory and of the Auger Open Data are set out below. An online event display to explore the released cosmic-ray events and example analysis codes are provided. An outreach section dedicated to the general public is also available.

All Auger Open Data have a DOI that you are required to cite in any applications or publications. These files are part of the main dataset whose DOI is 10.5281/zenodo.4487612 and always points to the current version.

Datasets	Visualize	Analyze	Catalog	Outreach
the released datasets and their complementary data	an online look at the released pseudo raw cosmic-ray data	example analysis codes in online python notebooks to run on the datasets	of the highest-energy cosmic rays	a page dedicated to the general public





https://opendata.auger.org/

DOI:10.5281/zenodo.4487612