Probing Astroparticle and Particle Physics at the Pierre Auger Observatory: highlights and perspectives

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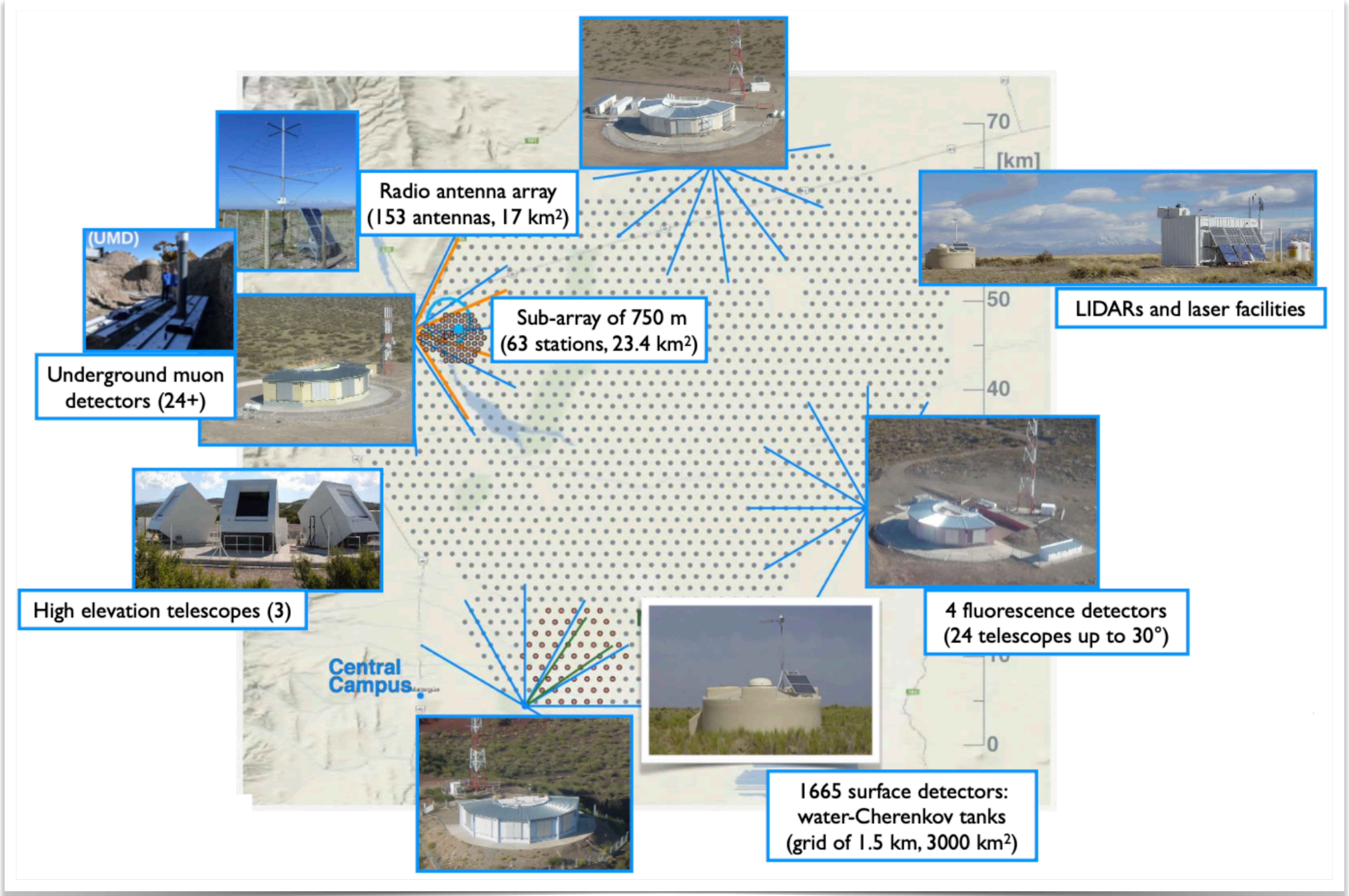
The Pierre Auger Observatory

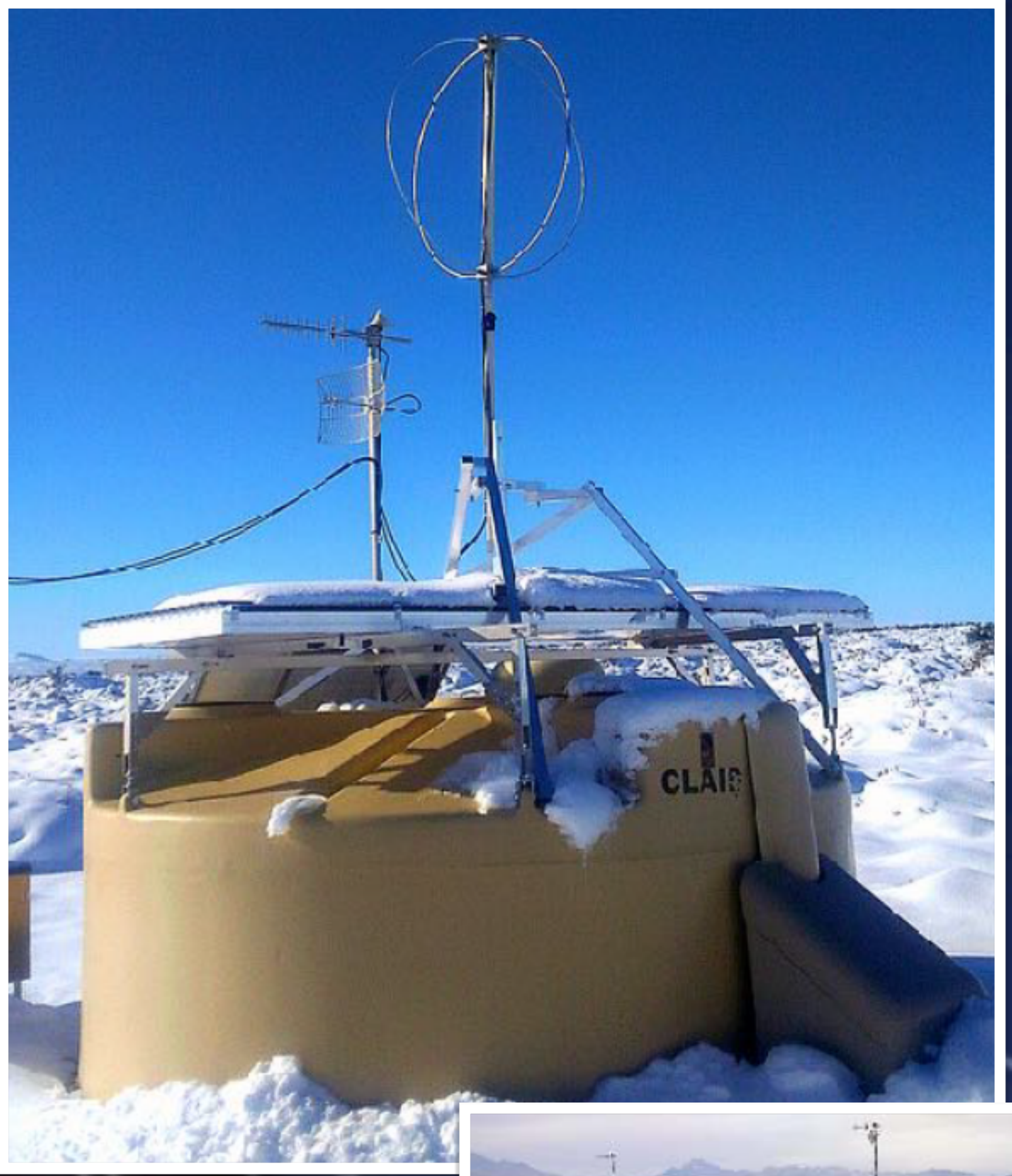
Pampa Amarilla
(Malargüe, Argentina
17 Countries
>400 members



- ✓ *1661 Water-Cherenkov stations*
  - ✓ SD1500 : 1600, 1.5 km grid;
  - ✓ SD750: 61, 750 m grid
  - ✓ SD433: 19, 433 m grid
- ✓ *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)

AugerPrime: *exploiting the richness of extensive air showers*



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 cloxer to the core***

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

Measure of the radio emission of EAS

➡ ***Radio antennas***

Direct measure of the muonic component

➡ ***Underground detectors***

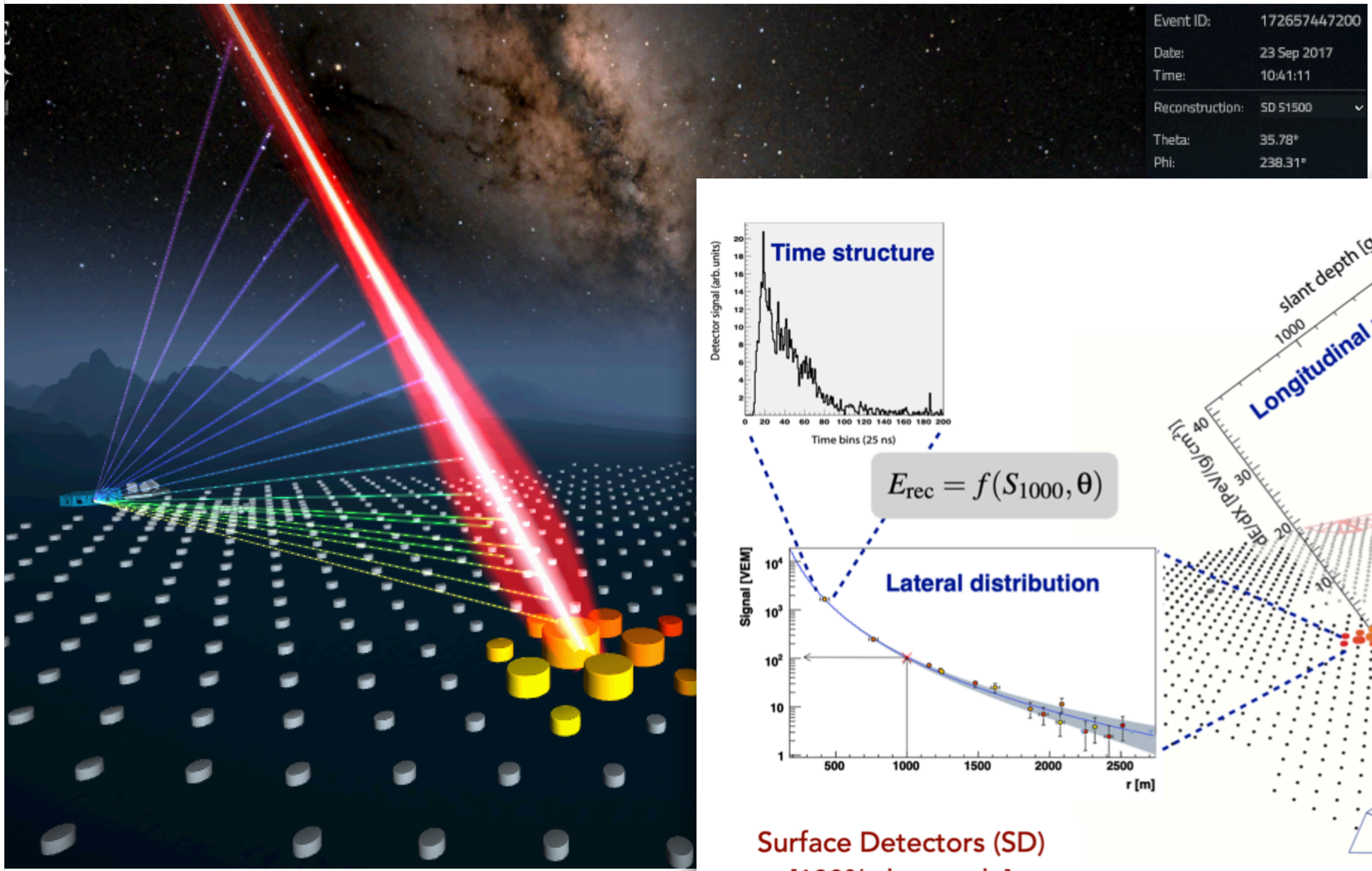
Phase 2 - the AugerPrime upgrade
Data taking from 2025 to >2035...

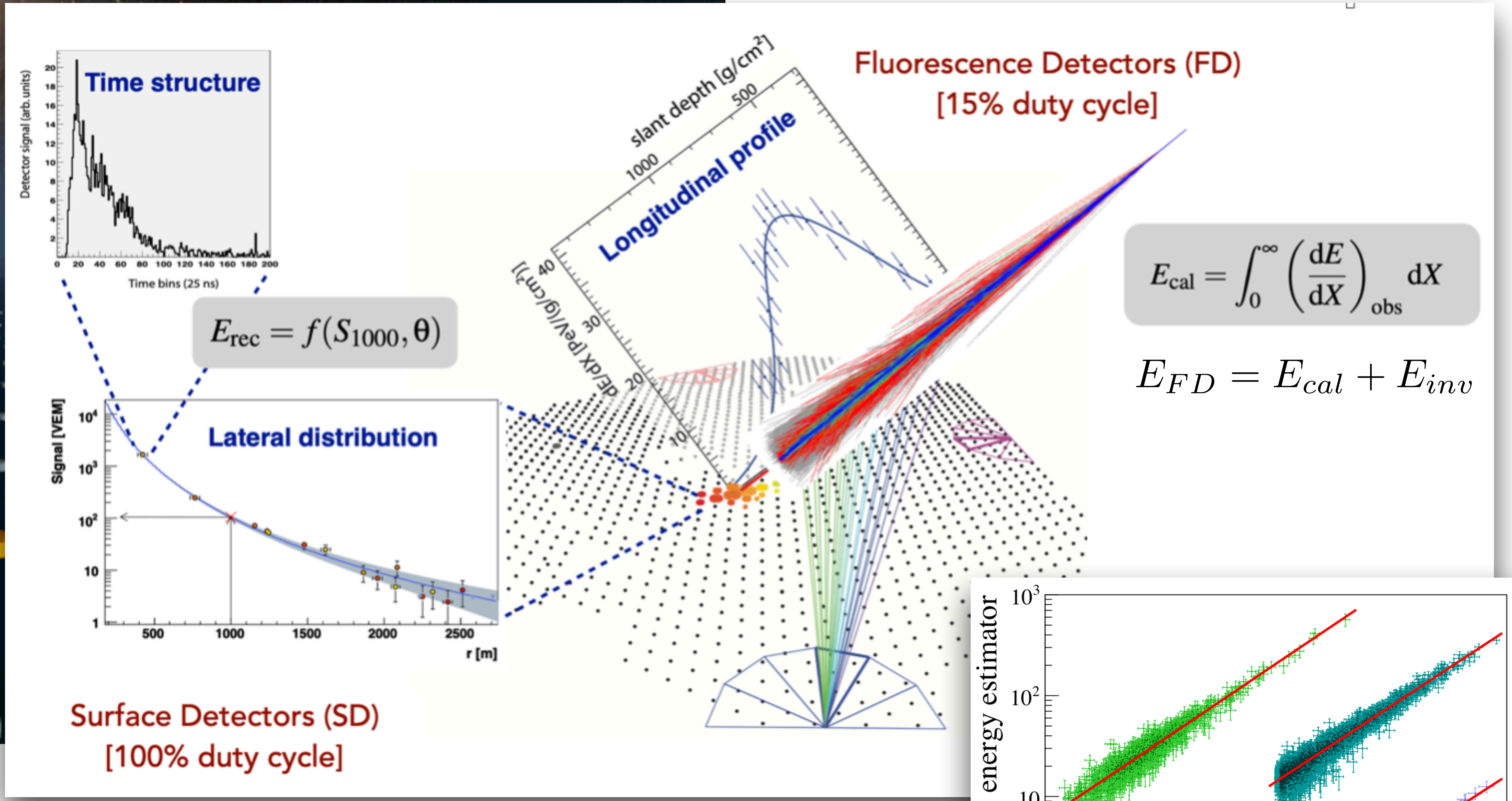
✓ + 40, 000 km² sr yr

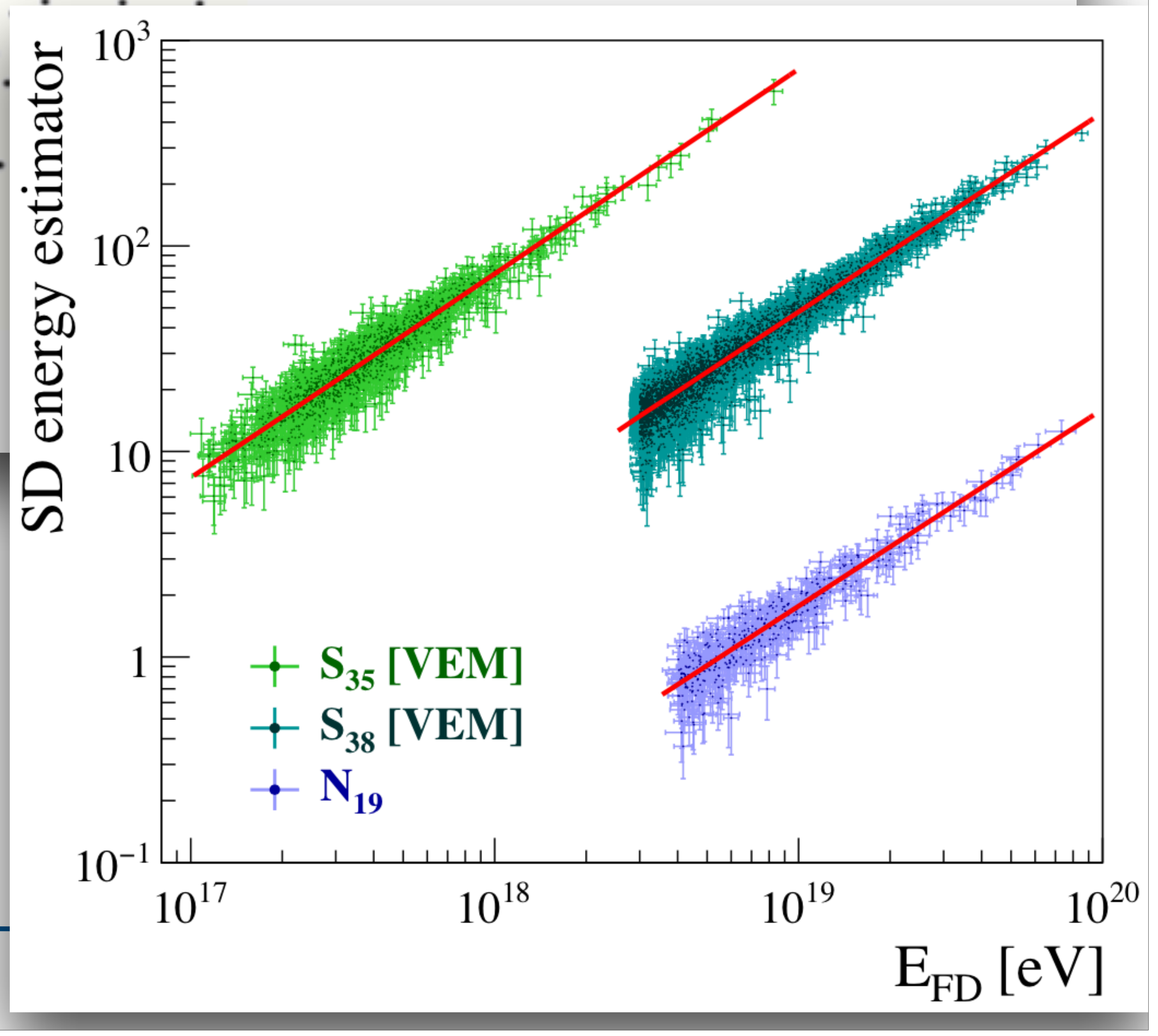
✓ Multi-hybrid events : FD, SD, SSD, RD, UMD

performing hybrid measurements and applying new analysis techniques

Hybrid technique



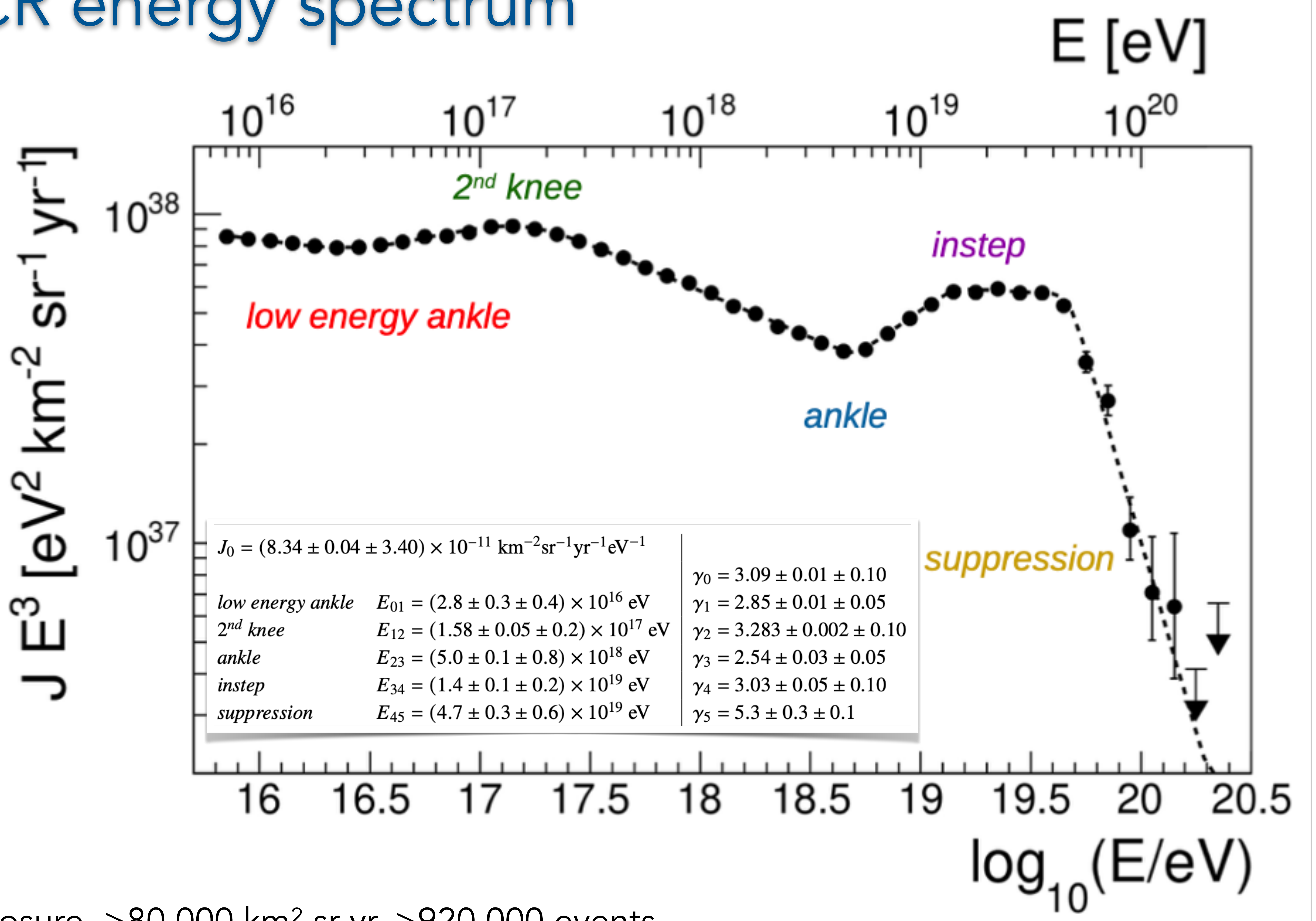




FD energy resolution ~ 8%

Systematic uncertainty 14%

The UHECR energy spectrum



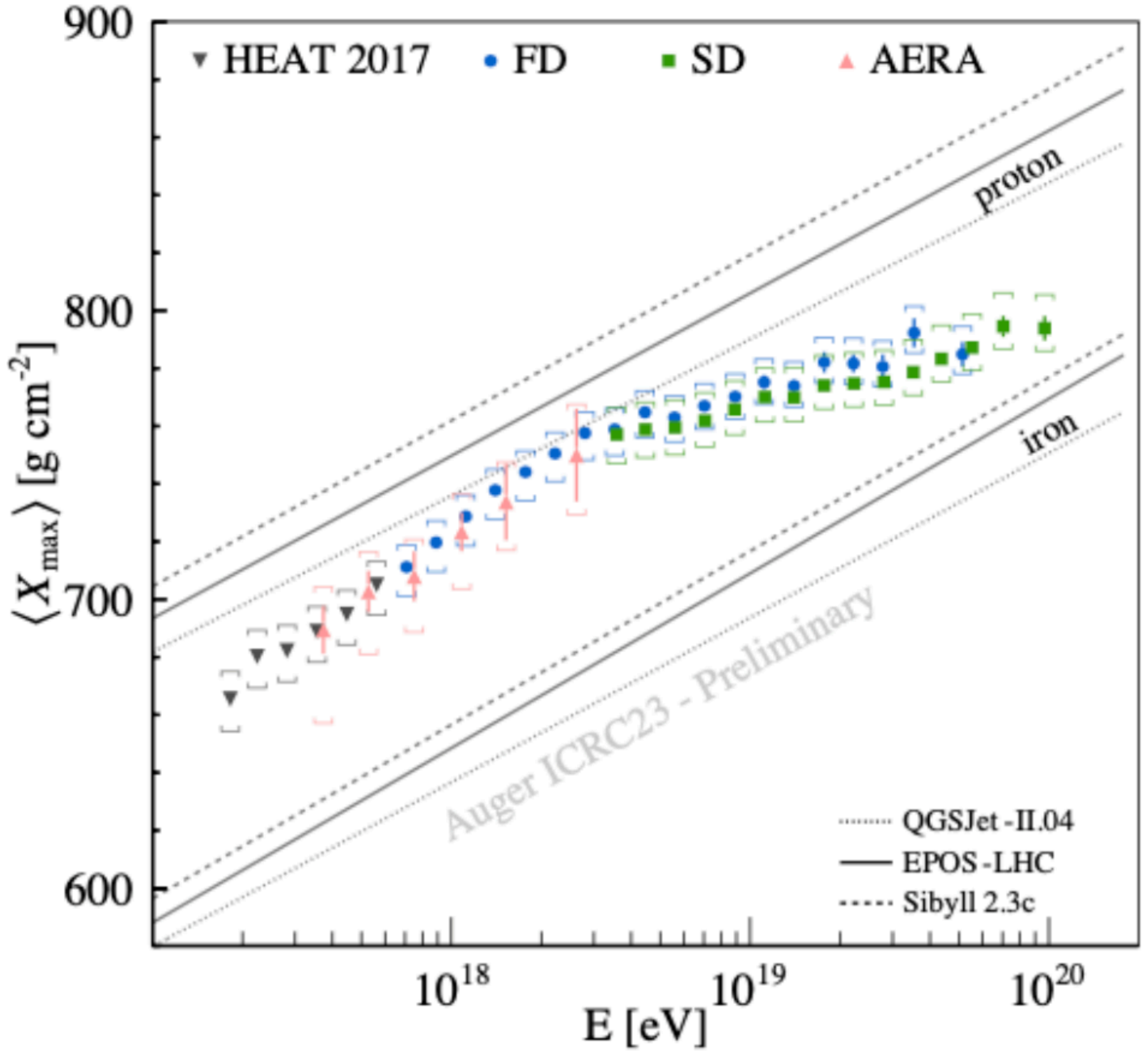
Largest available exposure, >80,000 km² sr yr, >920,000 events

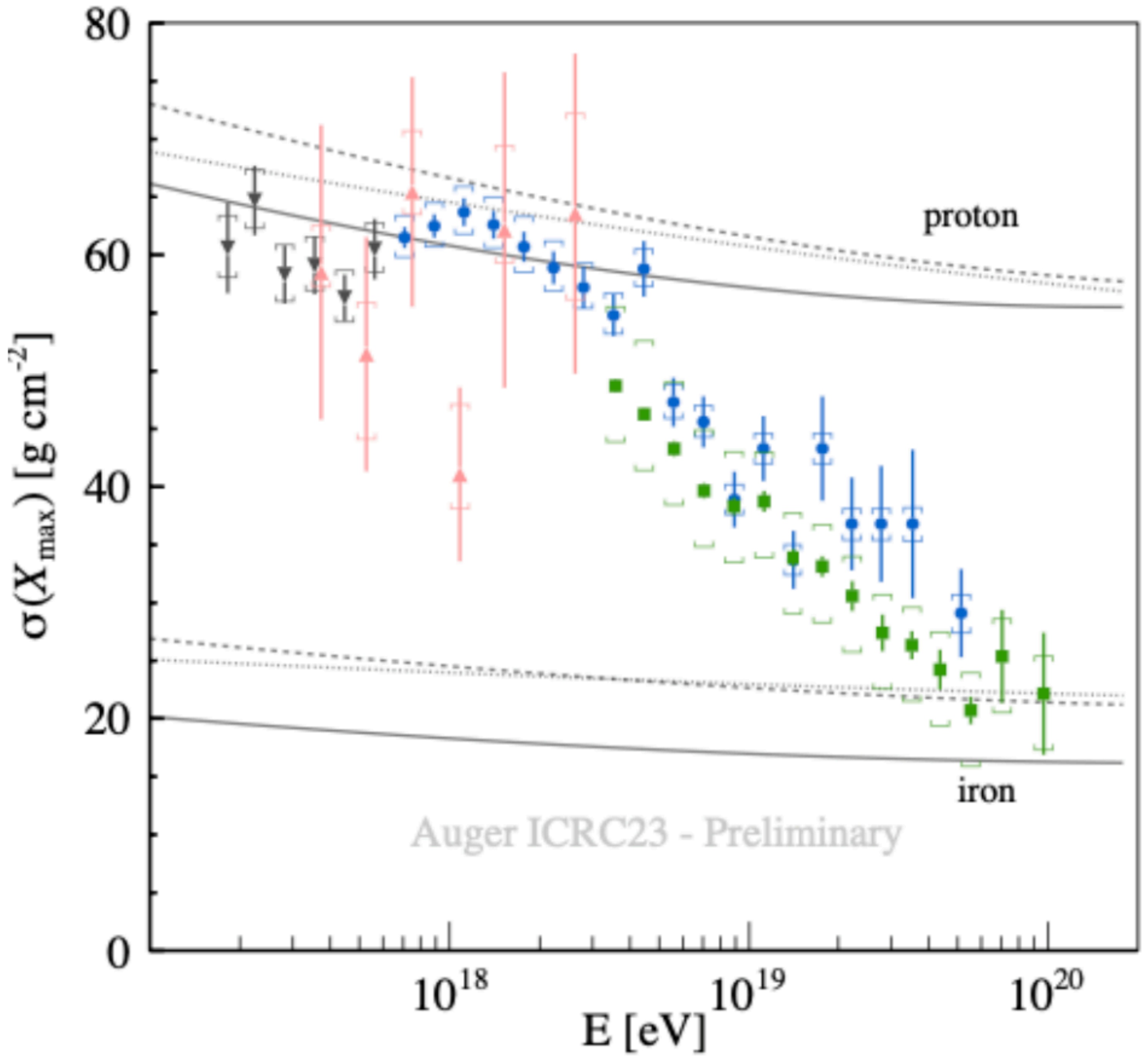
A measure completely independent of any assumptions on the primary mass

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)
- radio footprint (RD, ~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***

➡️ *The **σ** (X_{max}) at the highest energy — excludes a large fraction of protons (DNN and FD)*

— excludes the GZK as the dominant cause of the spectral cutoff

➡️ *The radio measurement provides an independent confirmation*

➡️ Interpretation in terms of A relies on LHC-tuned hadronic interaction models

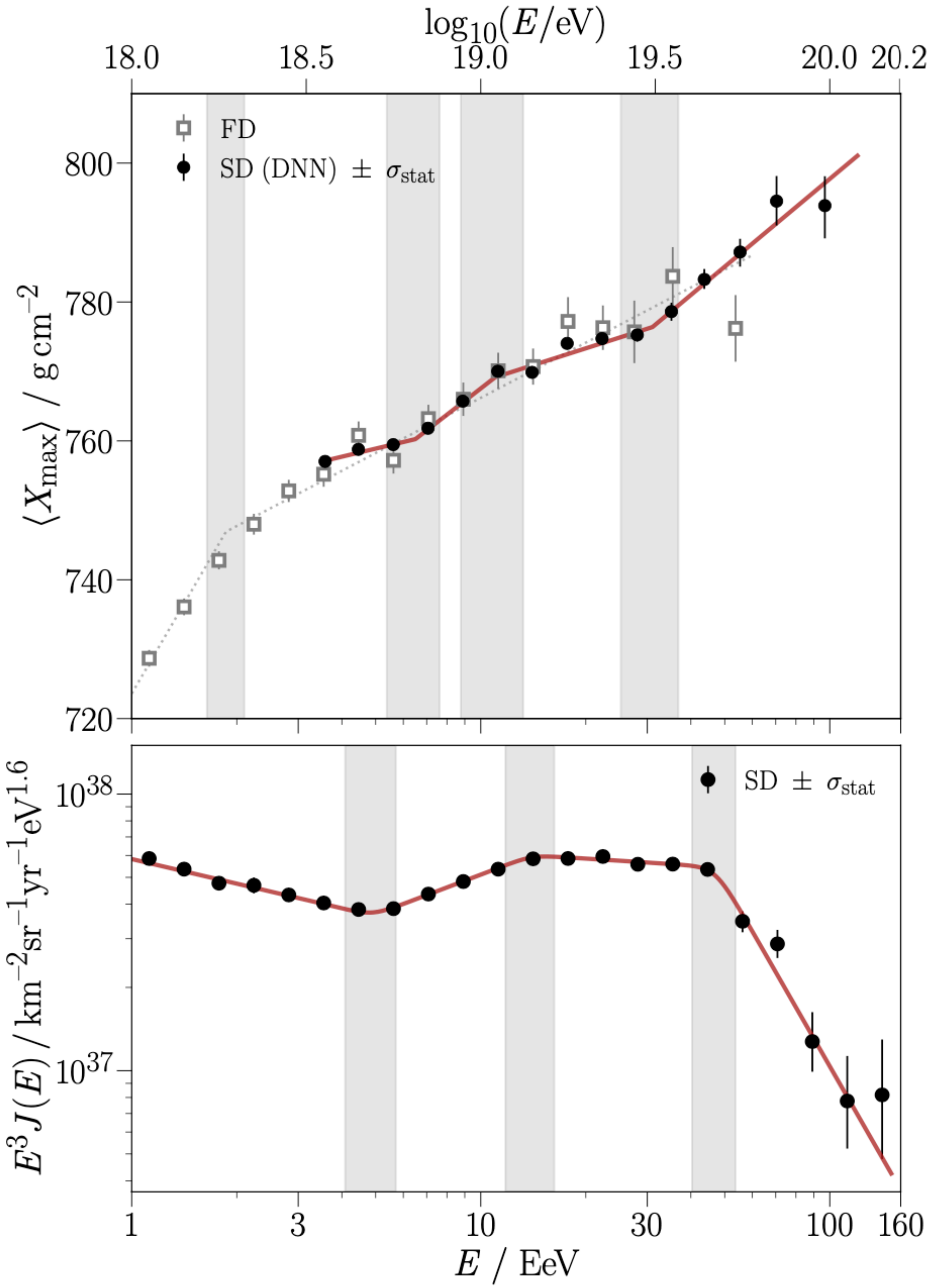
E.Mayotte, PoS(ICRC2023) 365 and refs.therein

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***

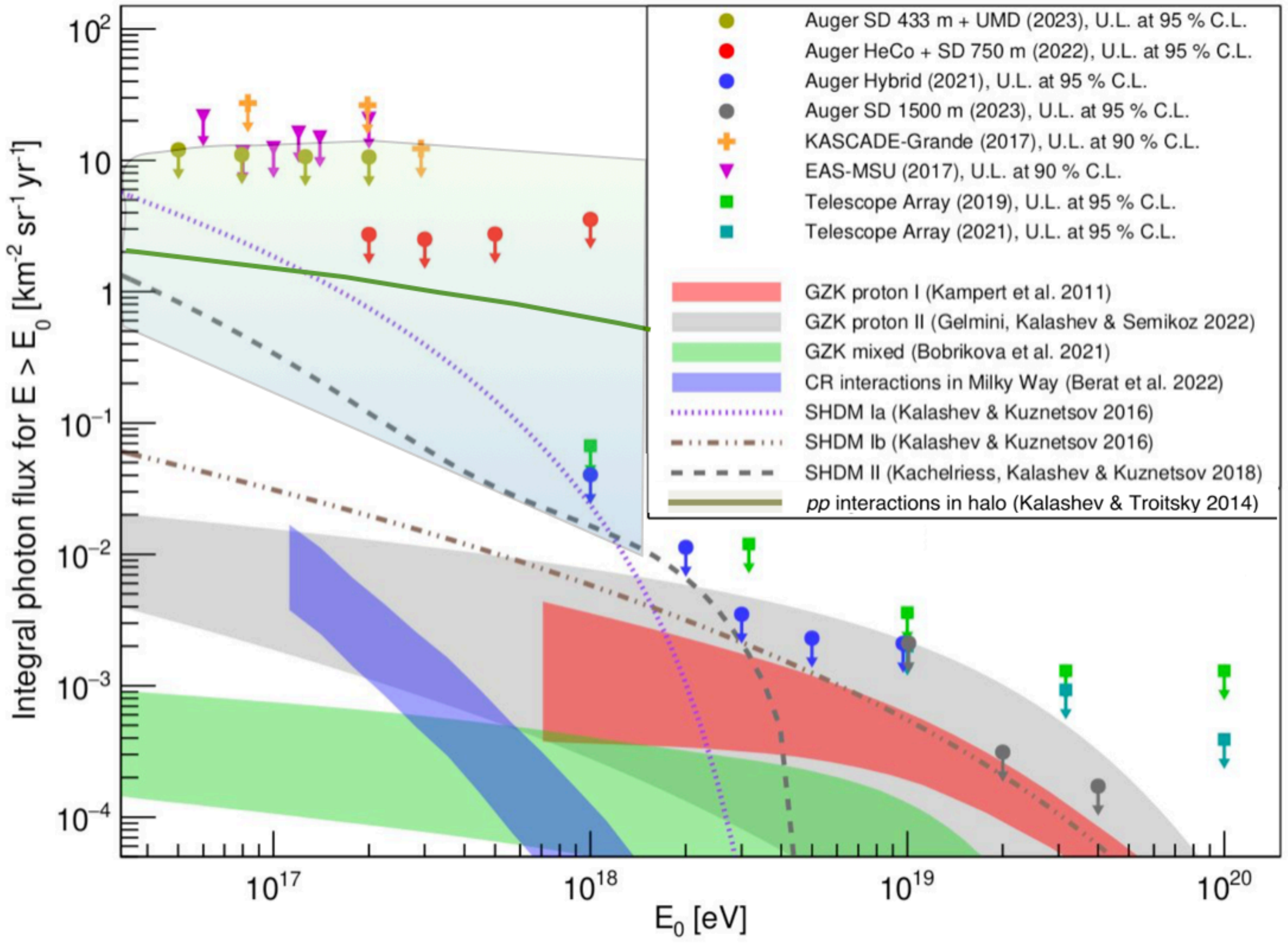
➡️kinks resembling the spectrum features
➡️in agreement with those predicted by a simplified astrophysical model

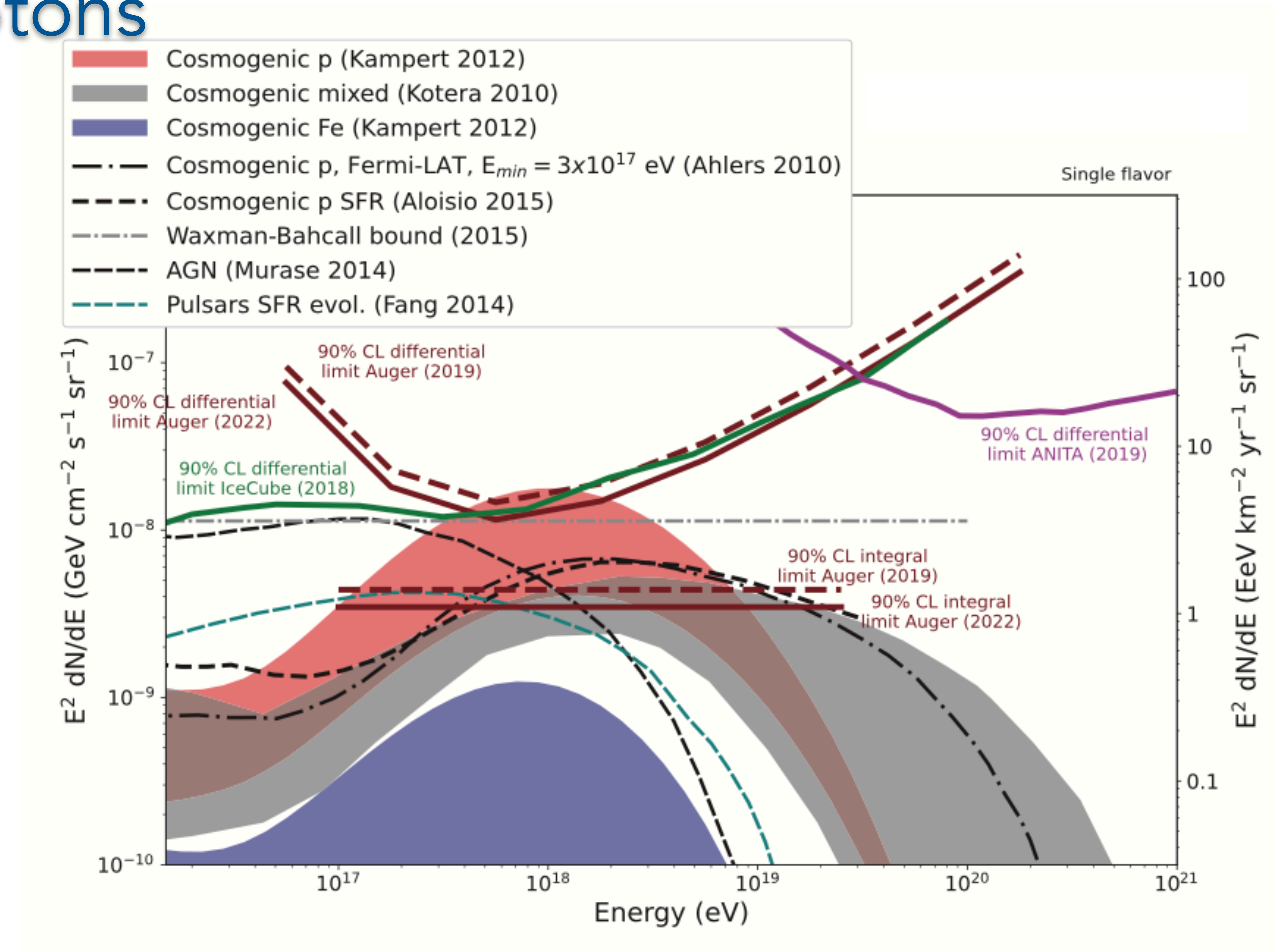
parameter val $\pm \sigma_{stat} \pm \sigma_{sys}$	3-break model val $\pm \sigma_{stat} \pm \sigma_{sys}$	energy spectrum val $\pm \sigma_{stat} \pm \sigma_{sys}$
b / g cm^{-2}	$750.5 \pm 3 \pm 13$	
D_0 / g cm^{-2} decade^{-1}	$12 \pm 5 \pm 6$	
E_1 / EeV	$6.5 \pm 0.6 \pm 1$	$4.9 \pm 0.1 \pm 0.8$
D_1 / 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., arXiv:2406.06315, arXiv:2406.06319, subm.PRD+PRL

Diffuse fluxes of neutrinos and photons





- ➡️ No candidates found; best available limits across 4 decades of energy
- ➡️ Closing the gap to lower energies

Auger Coll., JCAP 05 (2023) 021; arXiv:2406.07439 subm. to PRD; Auger Coll., ApJ 933 (2022) 125; PoS(ICRC2023) 444

- ➡️ 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

Auger Coll., JCAP 10 (2019) 022
EPJ Web.Conf.283 (2023) 04003

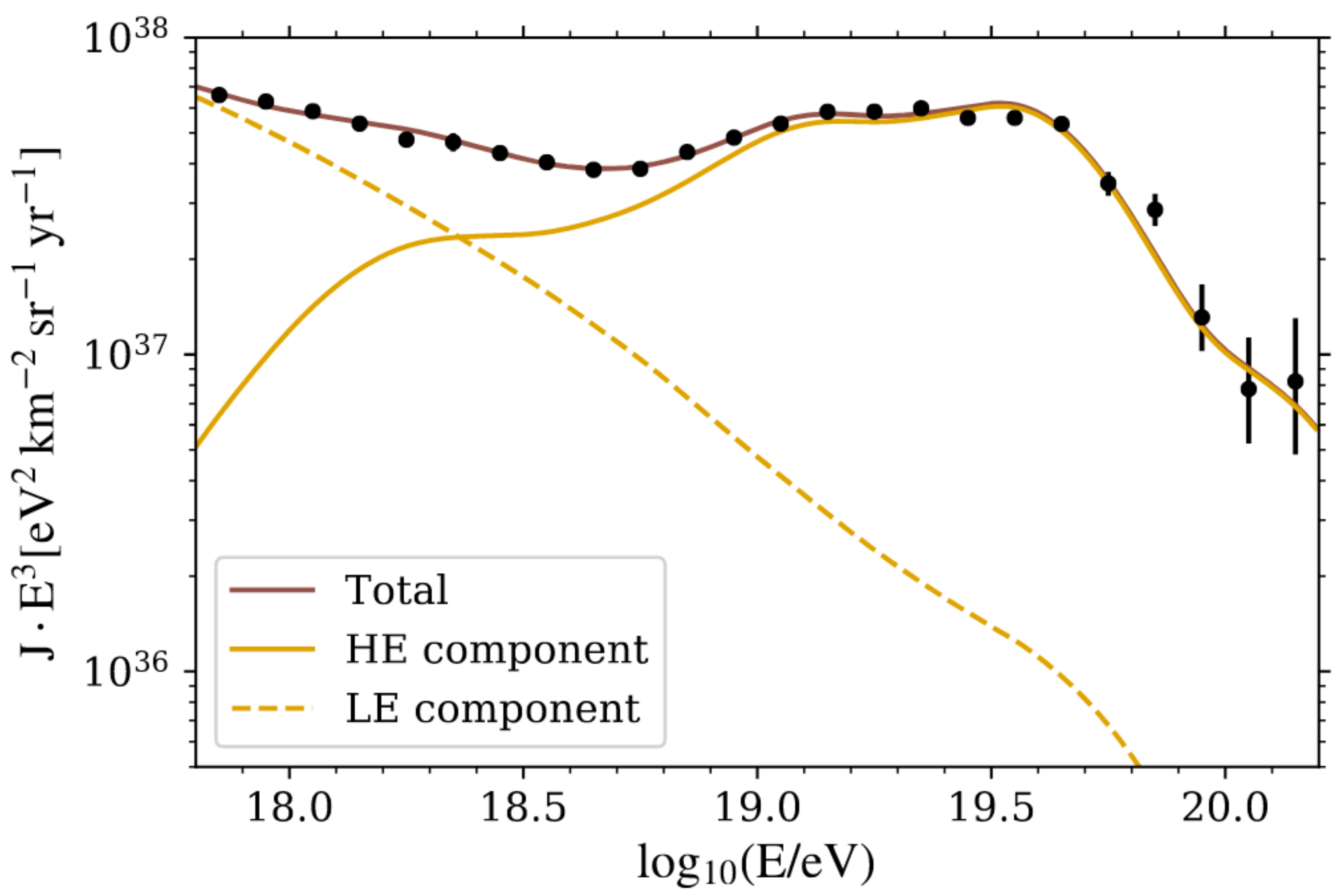
Astrophysical interpretation (energy spectrum+mass composition)

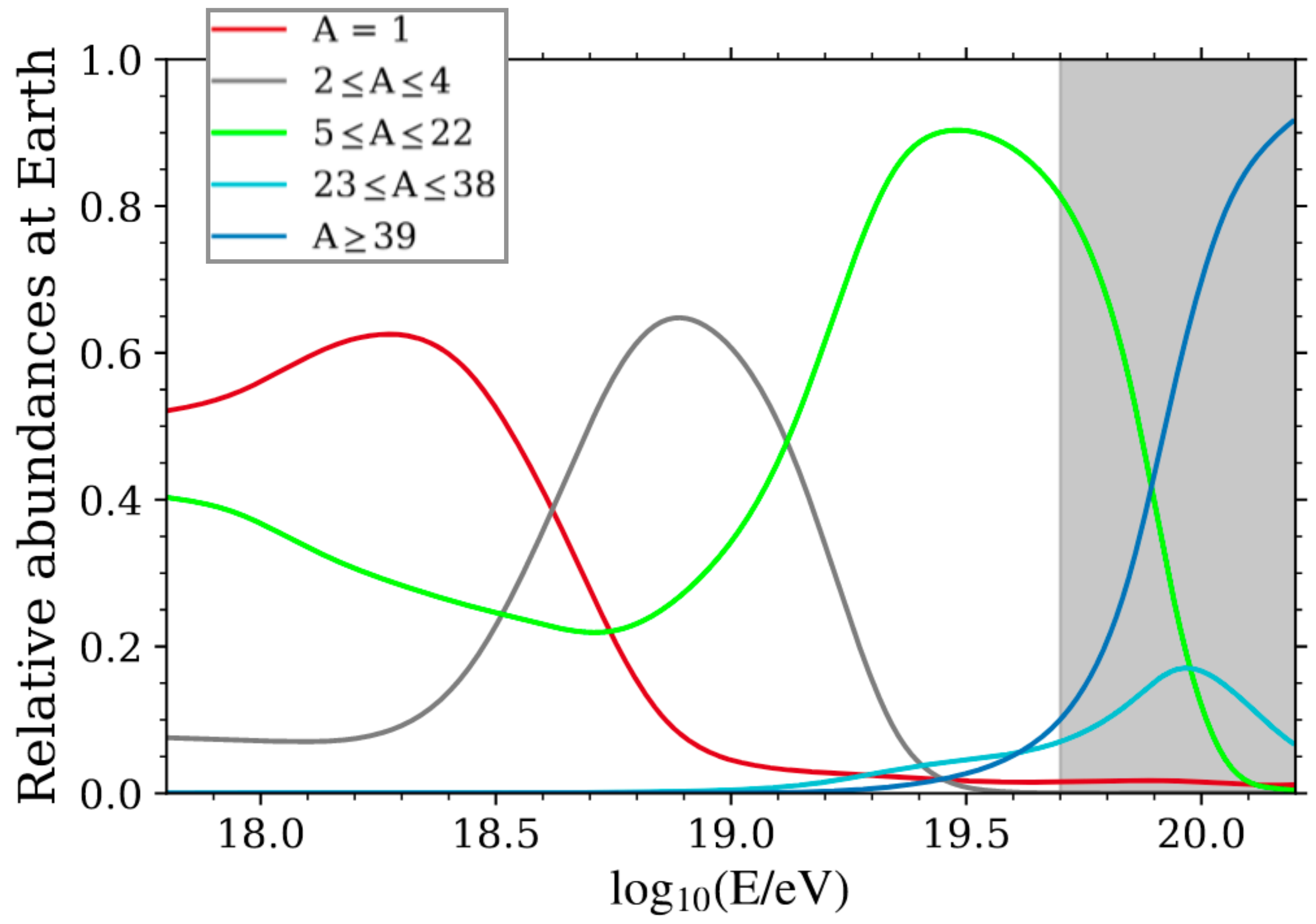
Basic scenario:
— 2 populations of EG identical sources, uniformly distributed
— power law injected energy spectrum + rigidity cutoff
— ***propagation only*** (no in-source interactions considered)

Auger Coll., JCAP05 (2023) 024

Best description of the observed energy spectrum and composition at Earth:

1/ a hard HE component with low rigidity cutoff
2/ a soft LE component with unconstrained rigidity cutoff
3/ a (possible) additional component





Ankle ~ 5 EeV:
Interplay between the two popolations

Instep ~ 10 EeV:
interplay between He and CNO primary masses

+ absence of cosmogenic ν and ɣ

+ low cutoff
Indication for a suppression mainly due to exhaustion of the sources

➡️Best fit evolution of sources: LE population m=3, HE population m=0

Similar conclusion from more refined models (in-source+propagation)

➡️Luminosity density *~ 6 x 10^{44} erg Mpc^{-3} yr^{-1}* by continuously emitting sources to supply UHECR above the ankle

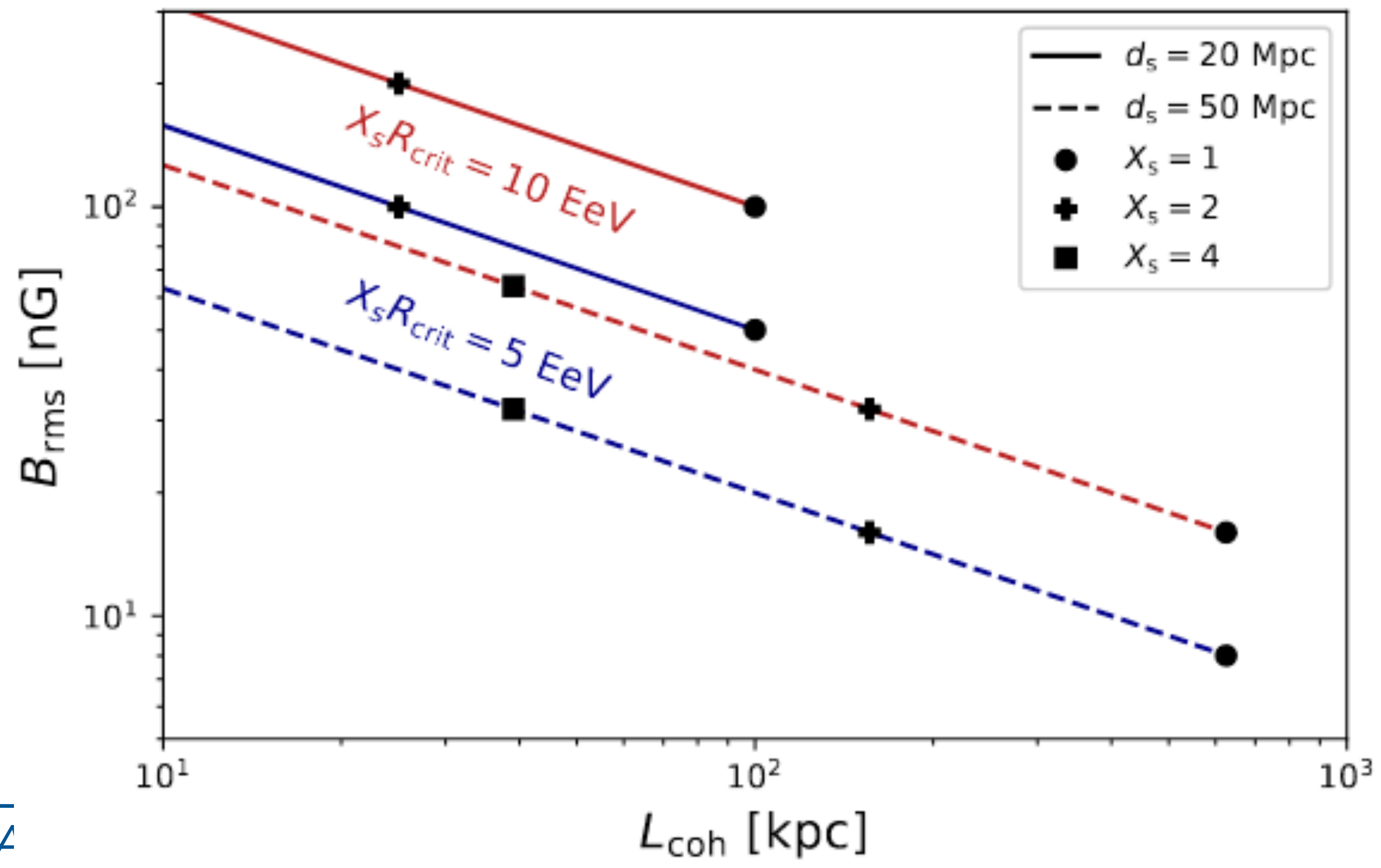
Astrophysical interpretation - the magnetic horizon effect

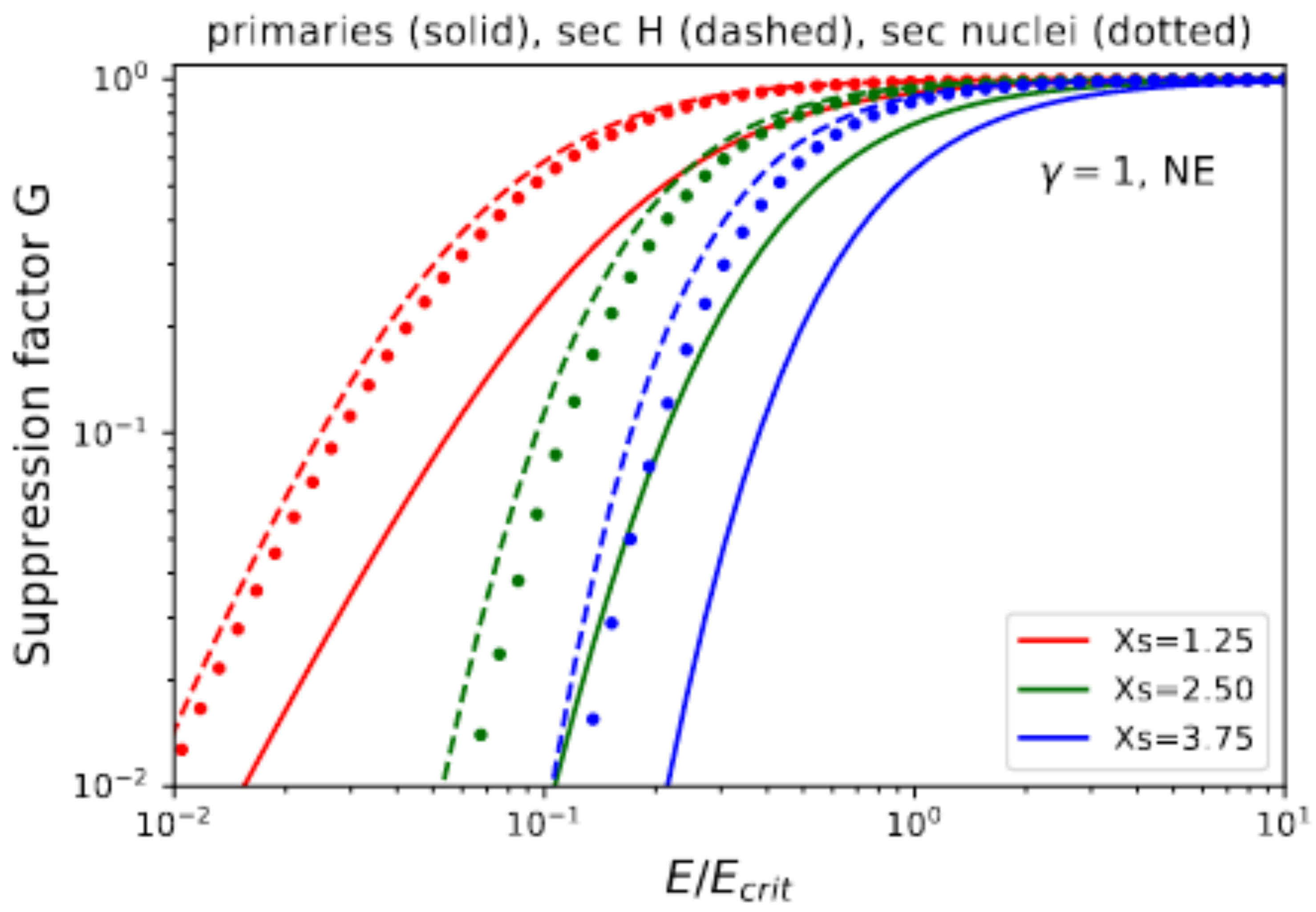
Auger Coll., arXiv:2404.03533

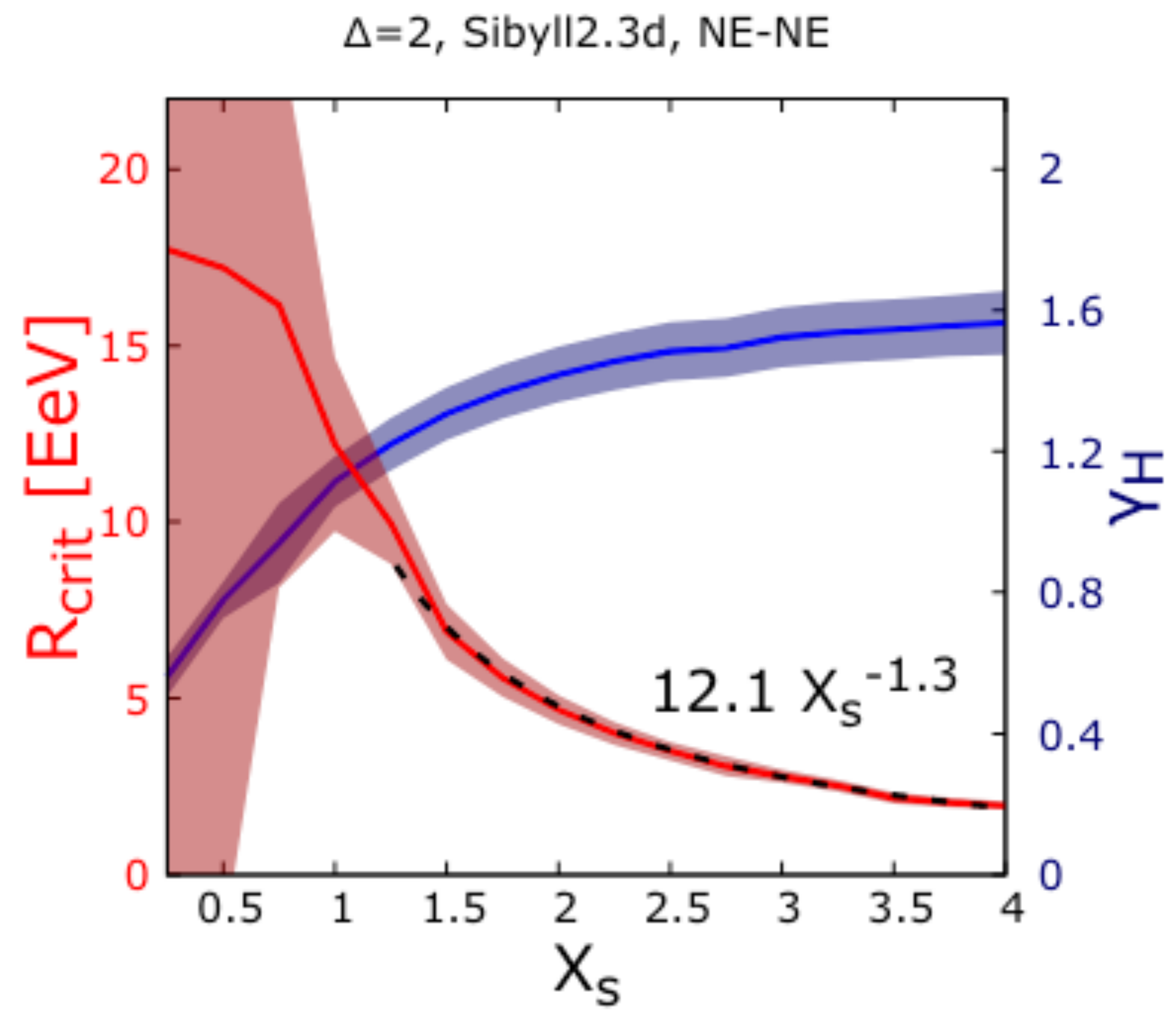
EG magnetic fields between Earth and the closest sources can affect the observed spectrum, reducing the low-rigidity particle flux

Suppression factor $$G(E) \equiv \frac{J(E)}{J(E)_{d_S \to 0}}$$

Normalized intersource distance $$X_s \simeq \frac{d_s}{10\ Mpc}\sqrt{\frac{25\ kpc}{L_{coh}}}$$







➡️The spectrum is softer for larger R_{crit} (E_{crit}= Z R_{crit})

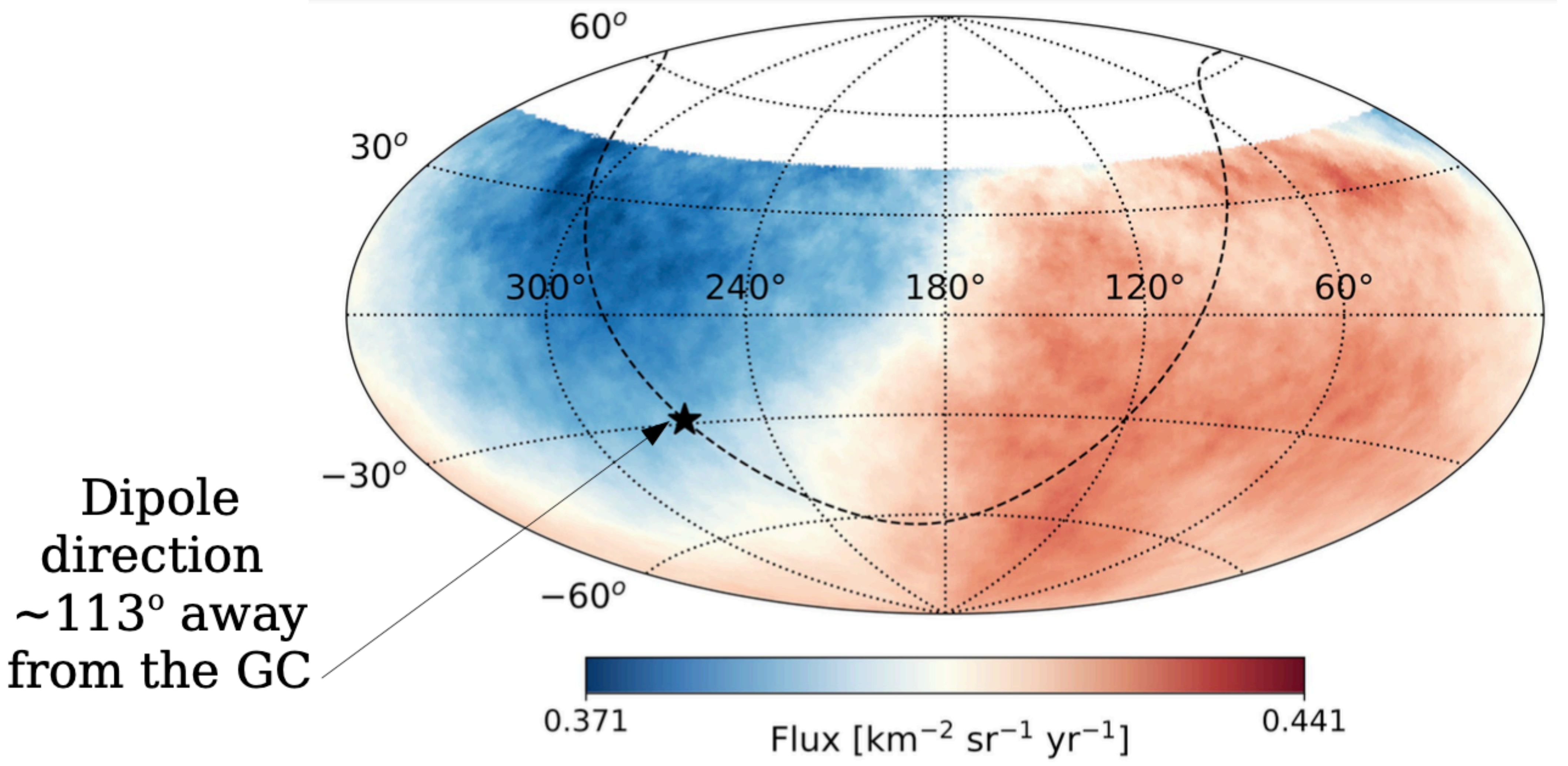
➡️The magnetic horizon plays a role if

$$X_s R_{crit} \simeq 5 \text{ to } 10 \text{ EeV}$$

Implying strong EGMF $\mathcal{O}$(10-200) nG in the Local Supercluster

Large scale anisotropy: Auger results

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

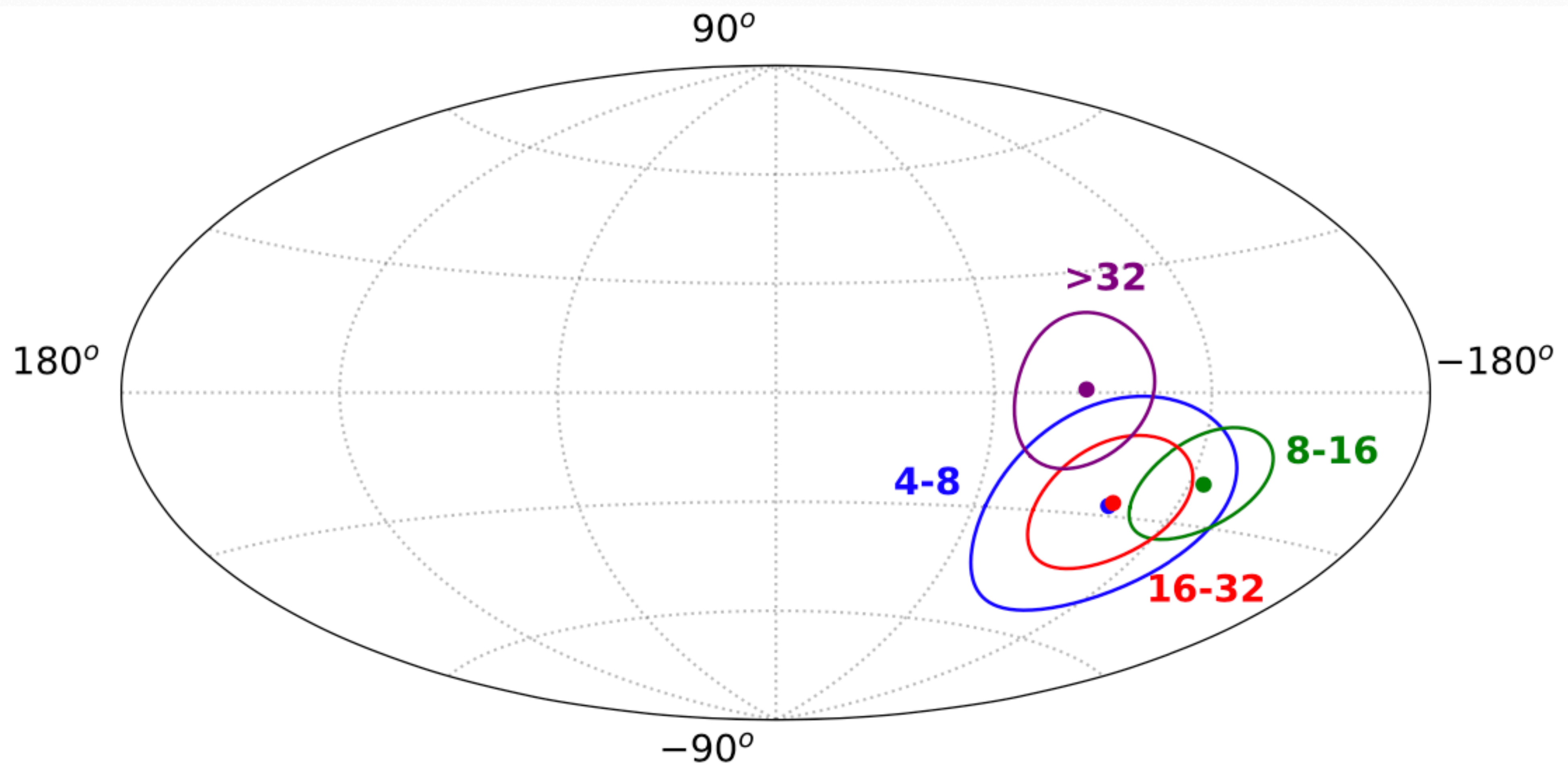


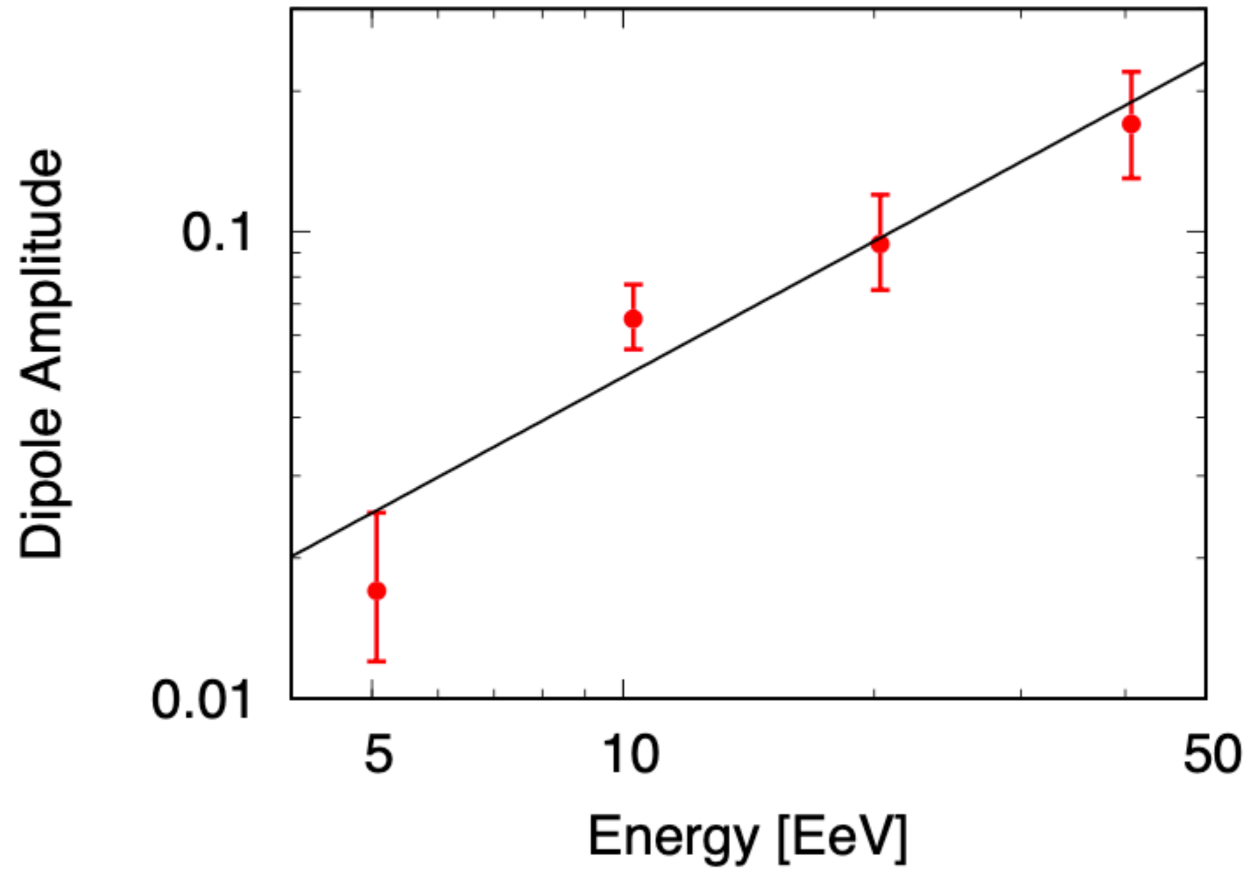
Equatorial coordinates, smoothed by a top-hat window of 45°.

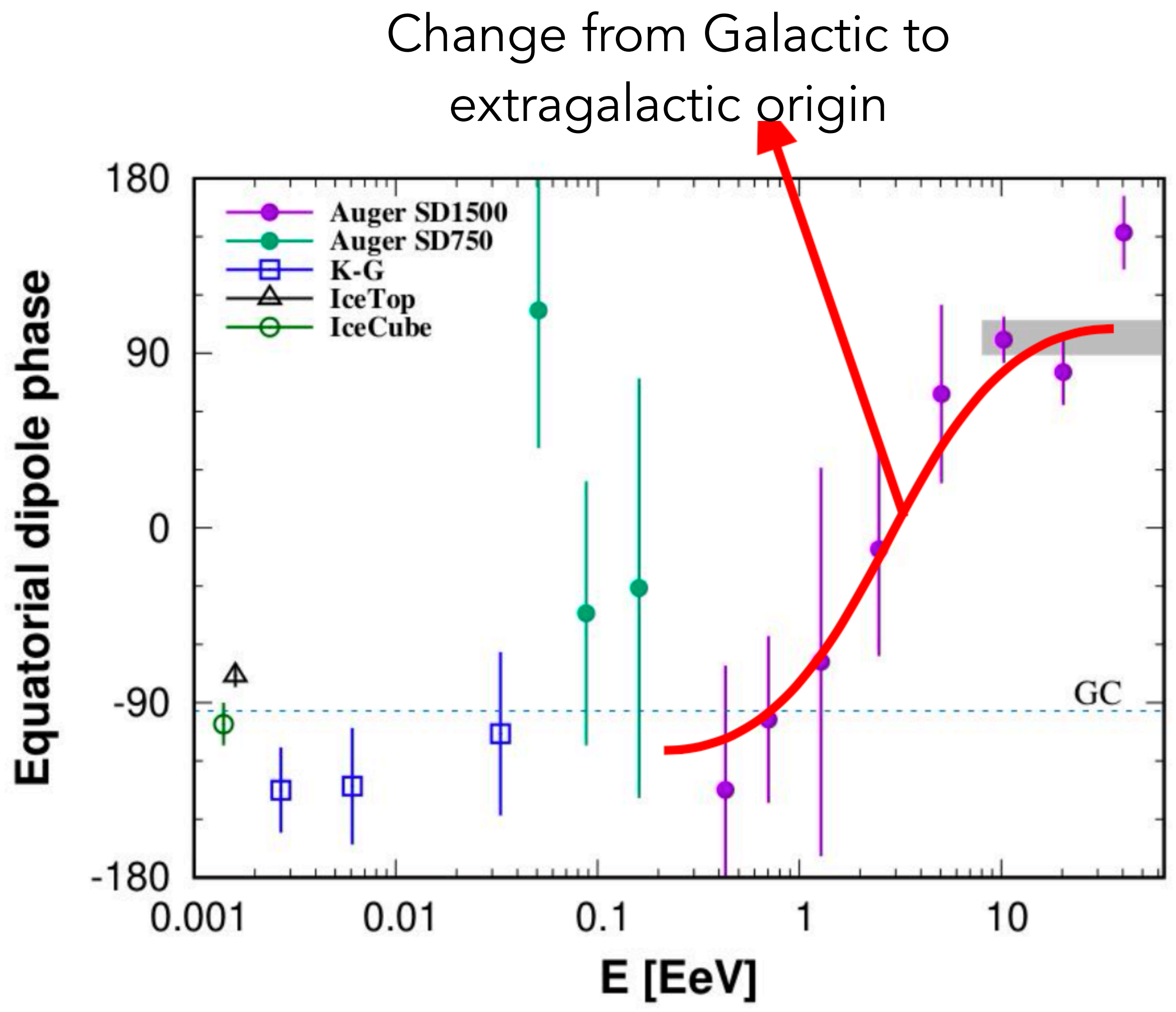
Extremely large exposure ($\vartheta < 80^0$) :123,000 km^2 sr yr

➡️<u>Observation</u> 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

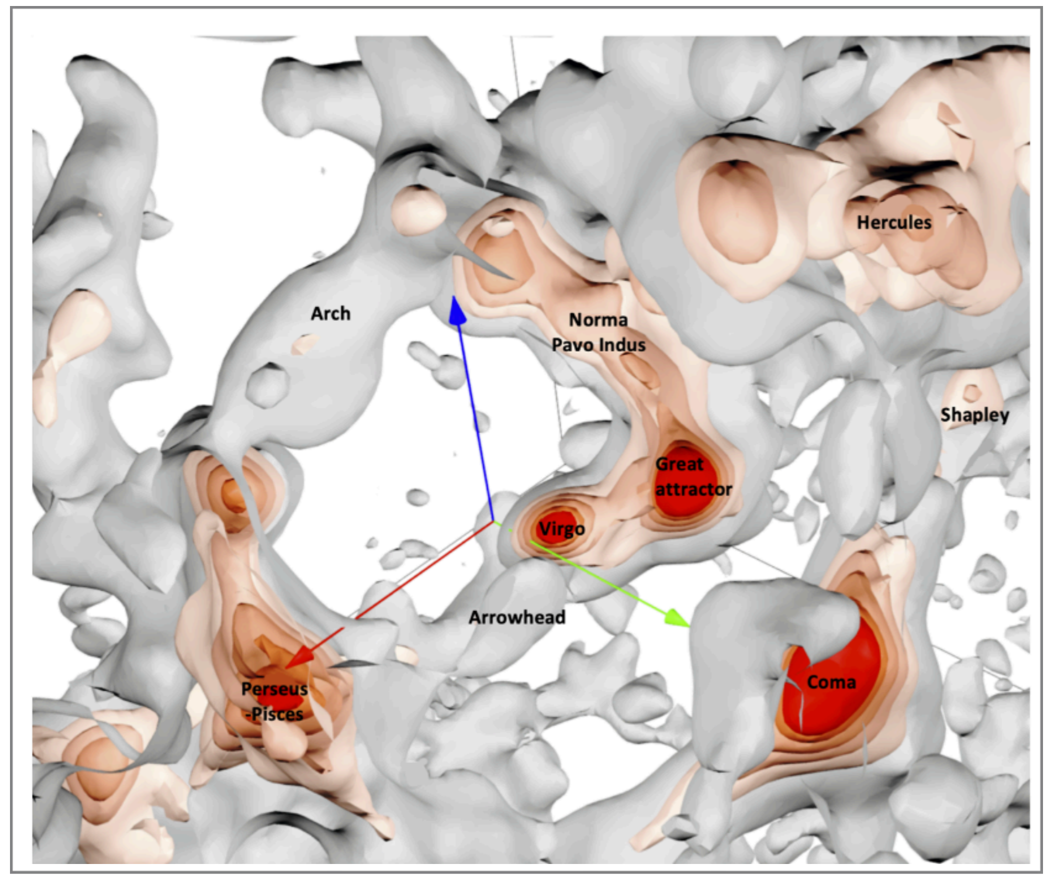


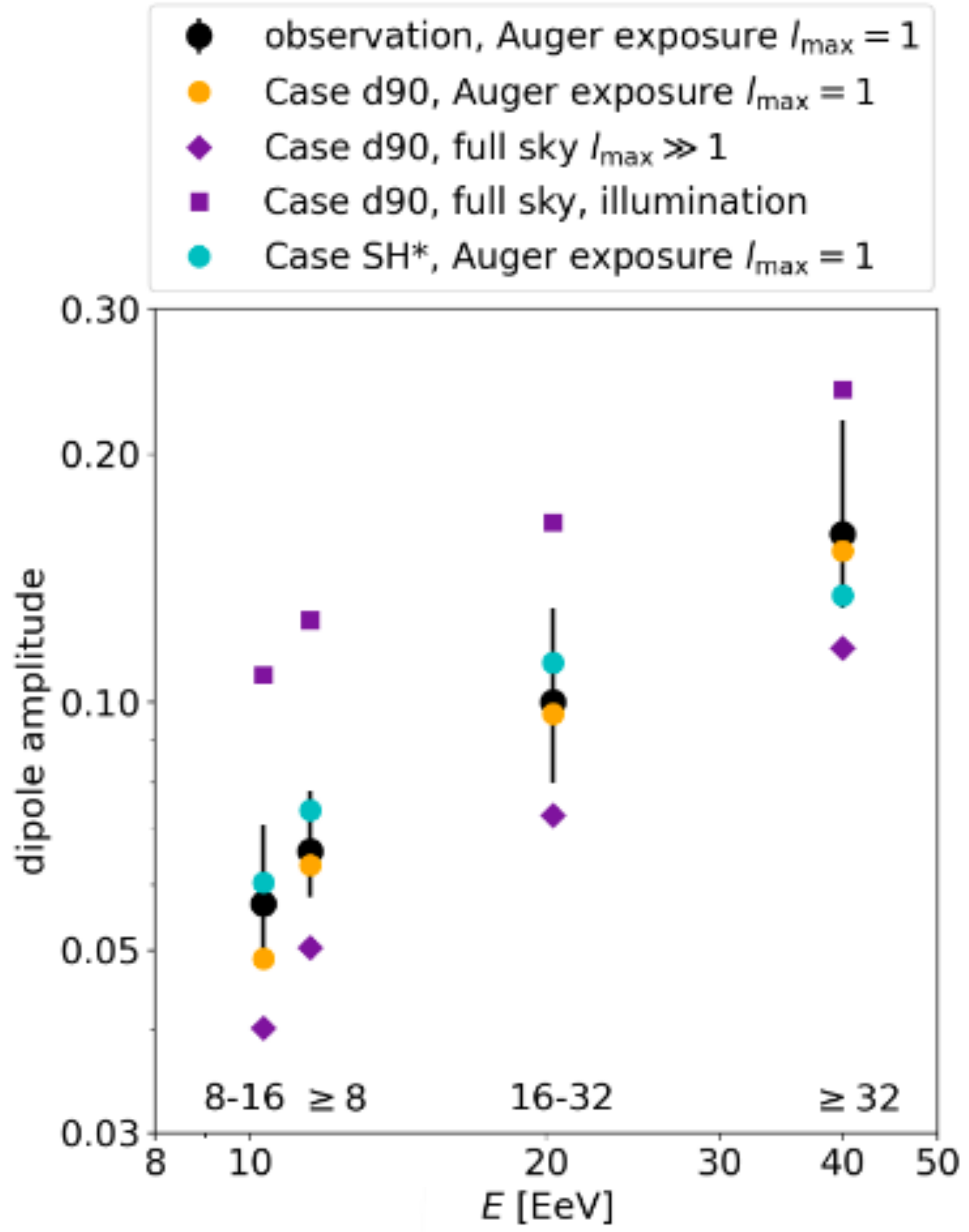




Large scale anisotropy: interpretation

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

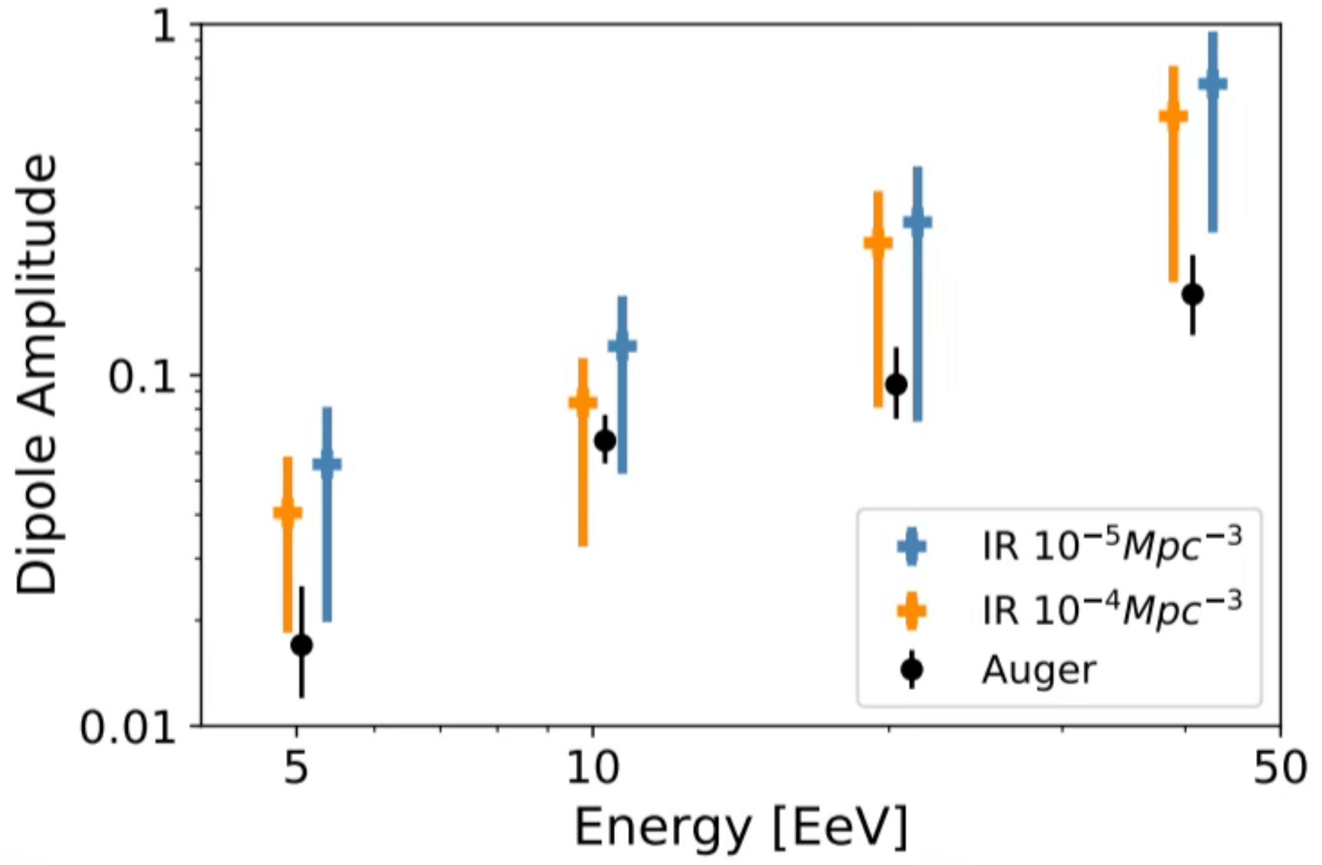


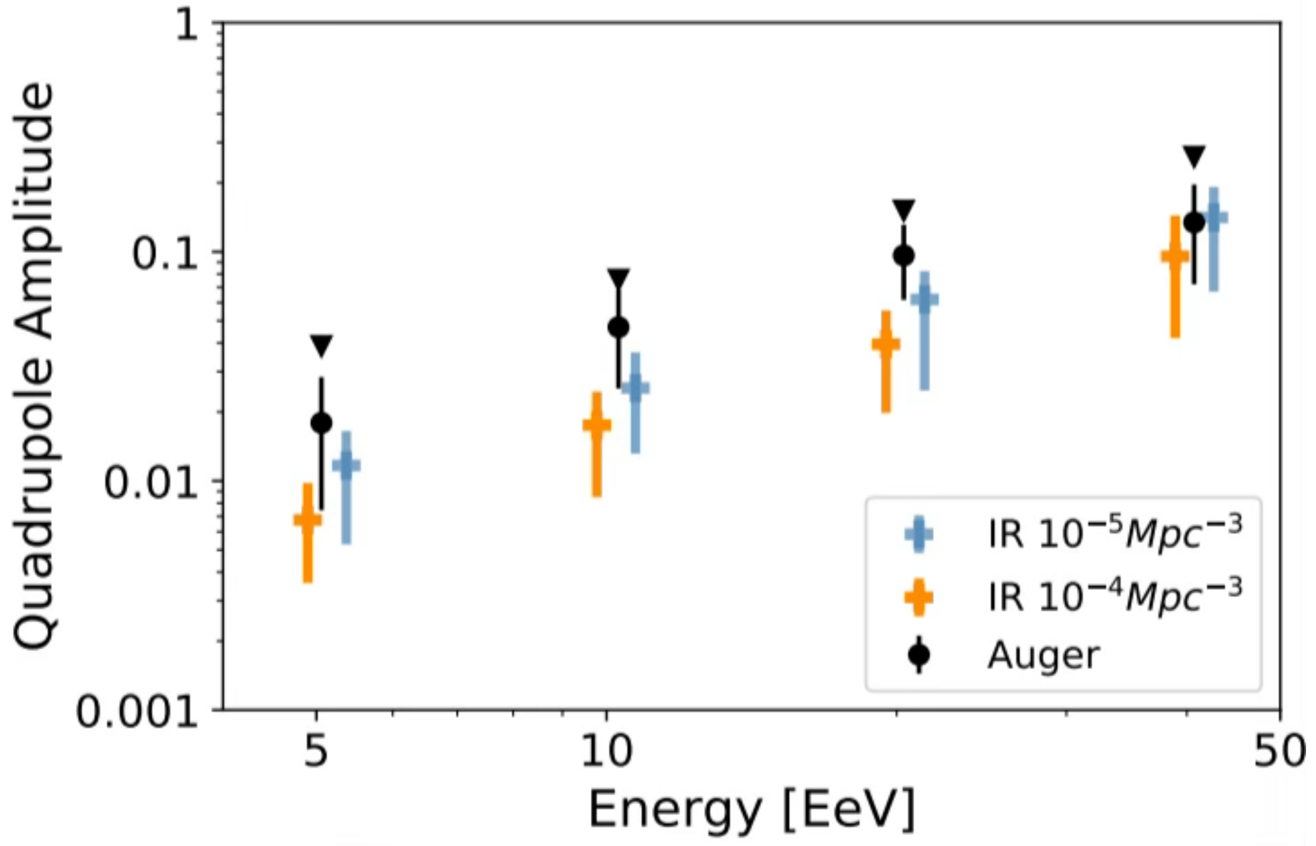


The observed anisotropy and its evolution with energy is well described as a signature of the local large scale distribution of matter

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

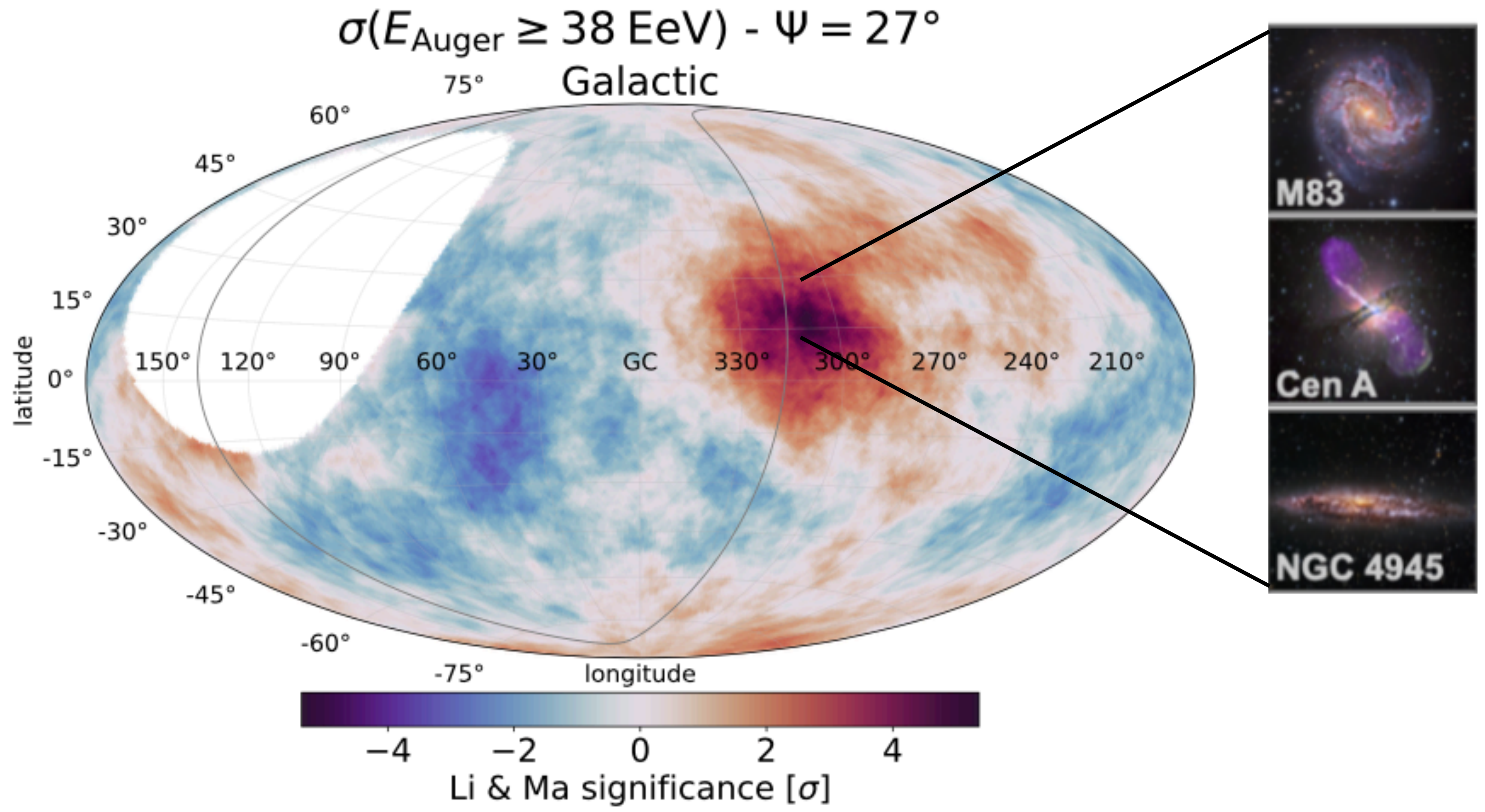
Auger Coll., subm.ApJ

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

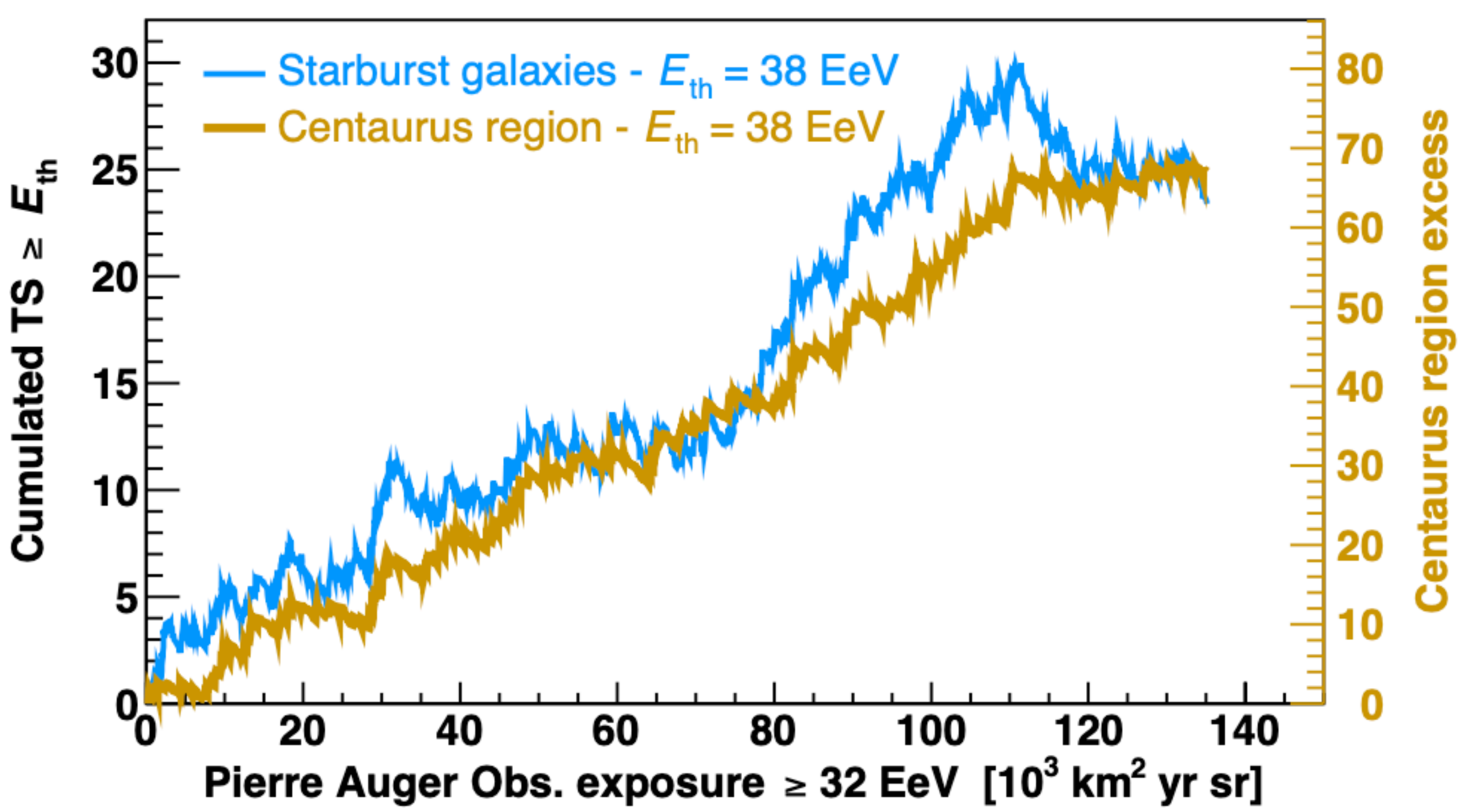
➡️(165000±15000) km² sr yr would allow us to reach 5σ

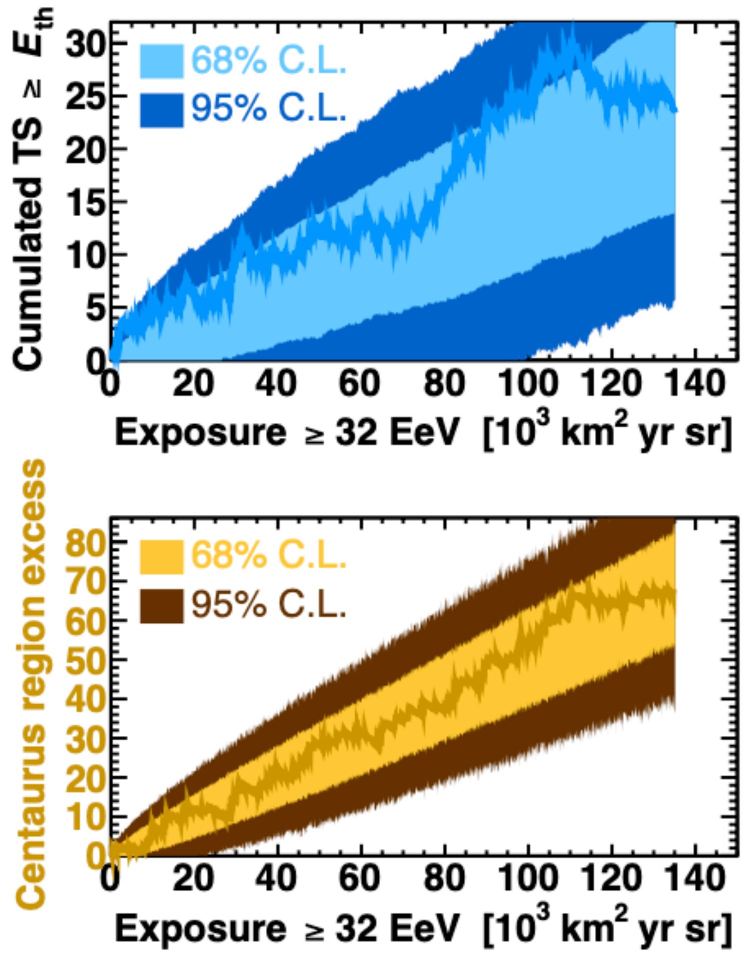


2/ catalog-based search

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





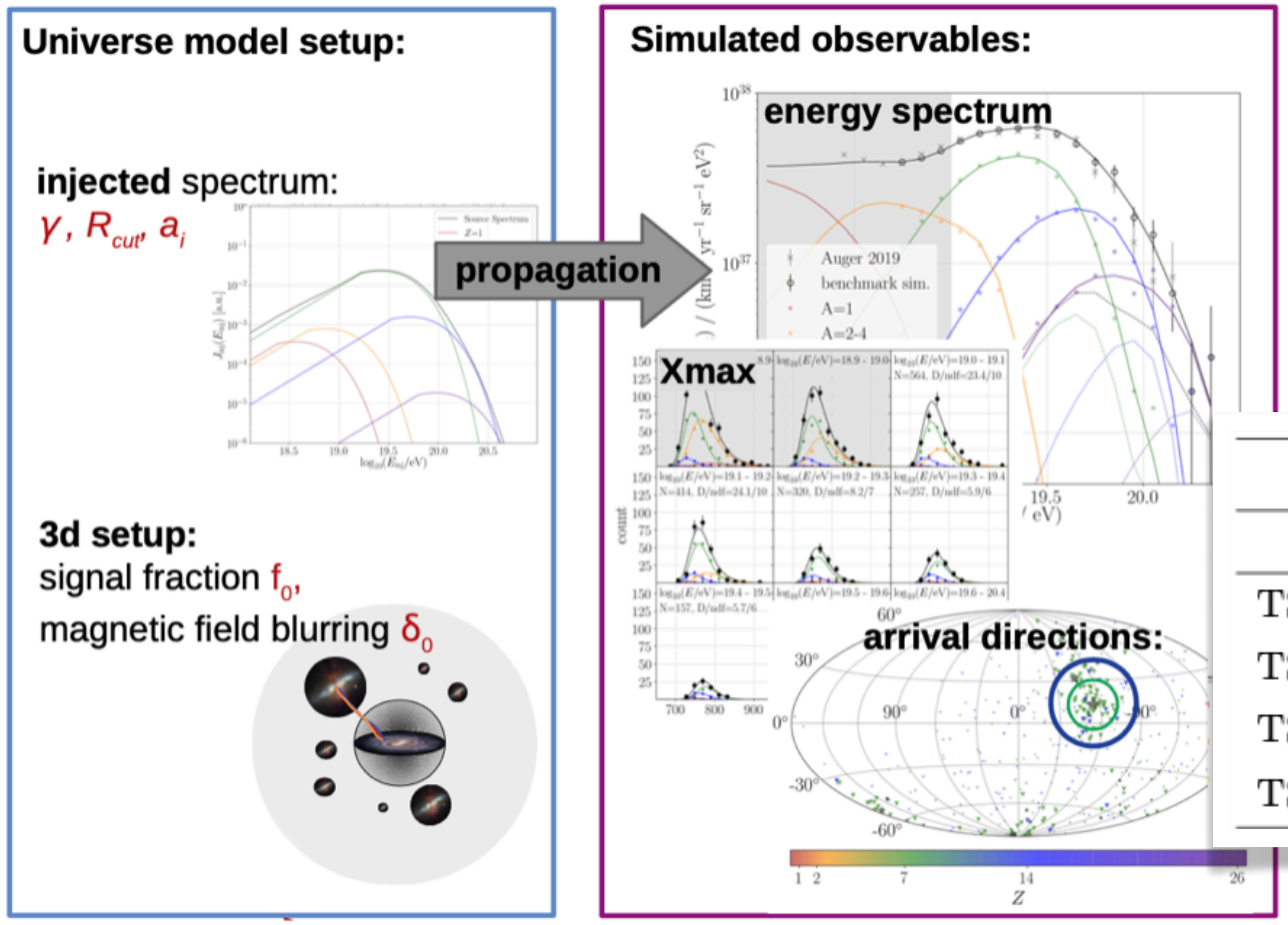
➡️All models capture an overdensity in Centaurus region (CenA, NGC4945, M83)

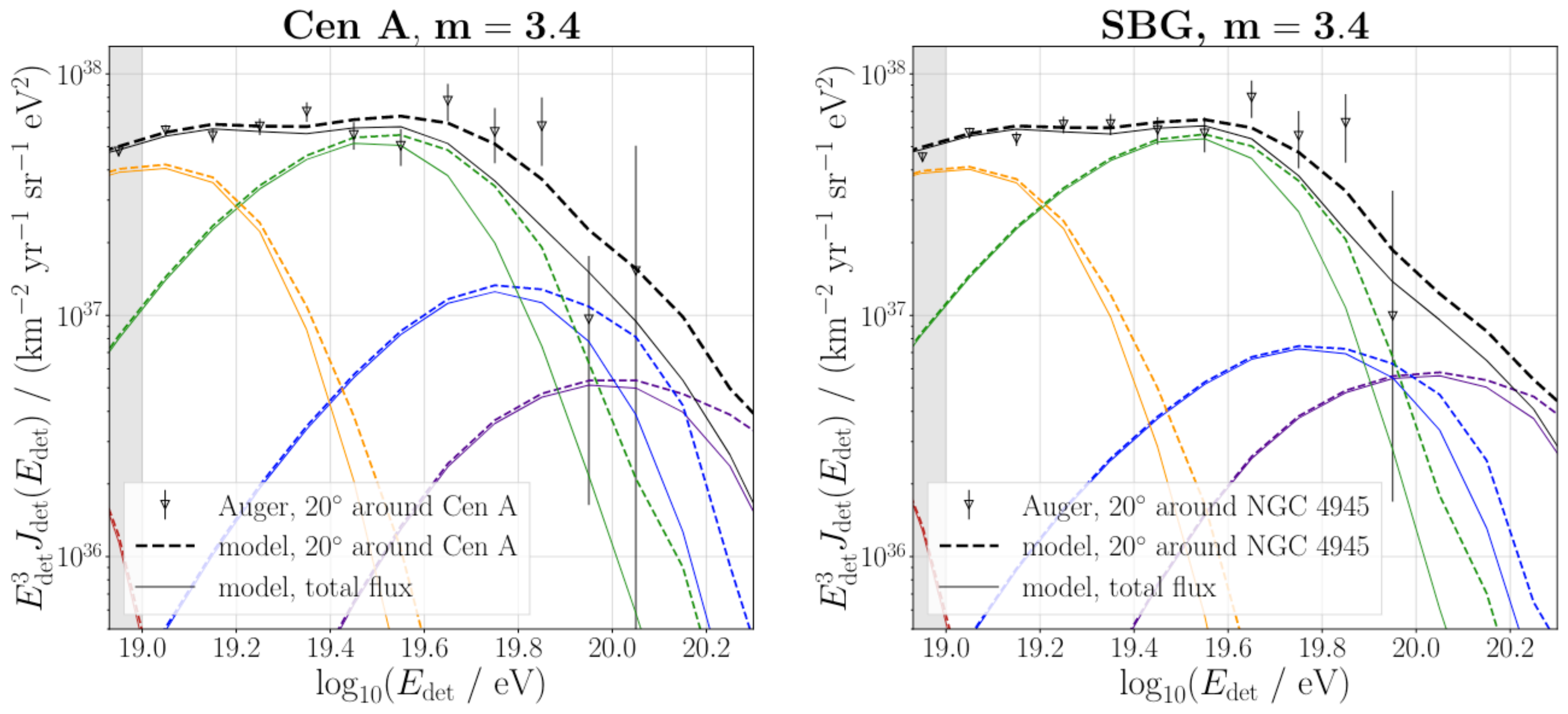
➡️The SBG model points to a milder excess close to NGC253

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

Astrophysical interpretation

(energy spectrum+mass composition+arrival directions)





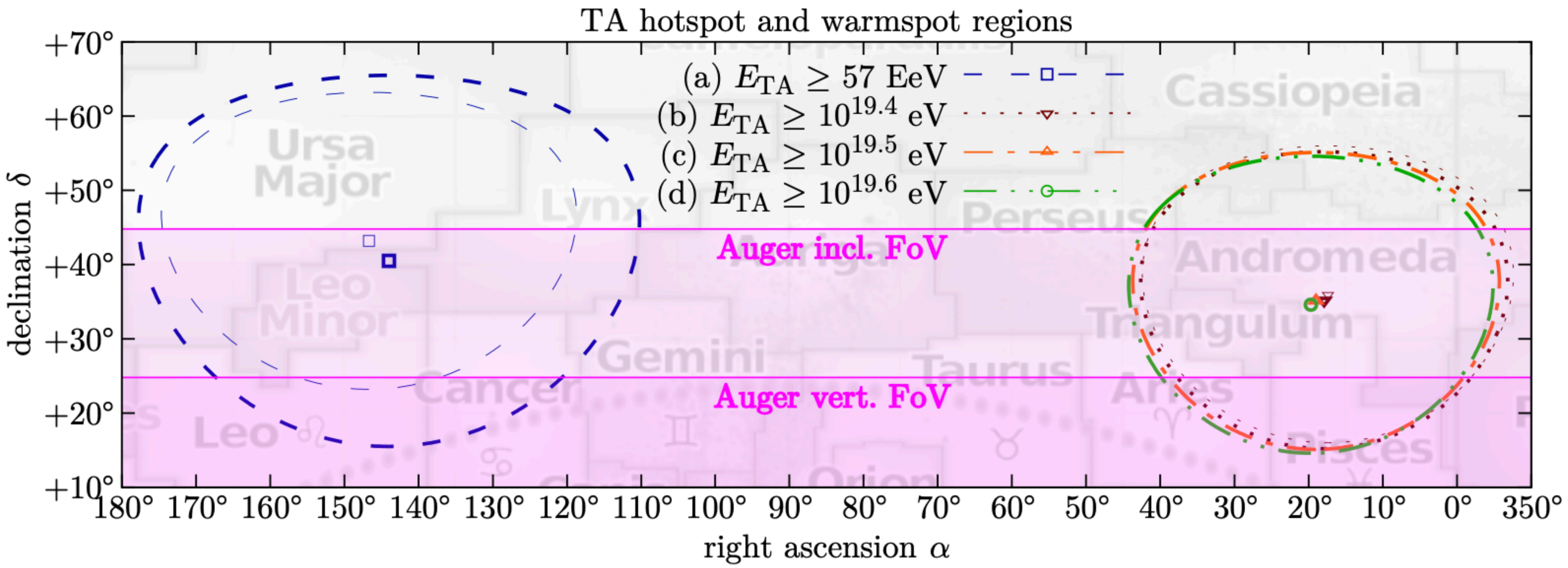
	Cen A, $m = 0.0$		Cen A, $m = 3.4$		SBG, $m = 3.4$		γAGN, $m = 5.0$	
		+ syst		+ syst		+ syst		+ syst
TS_{tot}	22.8	17.3	22.2	19.1	27.6	25.6	23.9,[a]	9.8,[a]
TS_E	−0.1	−1.4	−0.4	−1.1	−5.2	−4.5	26.8	3.9
$TS_{X_{max}}$	1.9	0.2	1.8	1.0	6.2	2.0	−0.8	6.4
TS_{ADs}	20.9	18.7	20.8	19.0	26.6	27.1	−2.1	−3.0

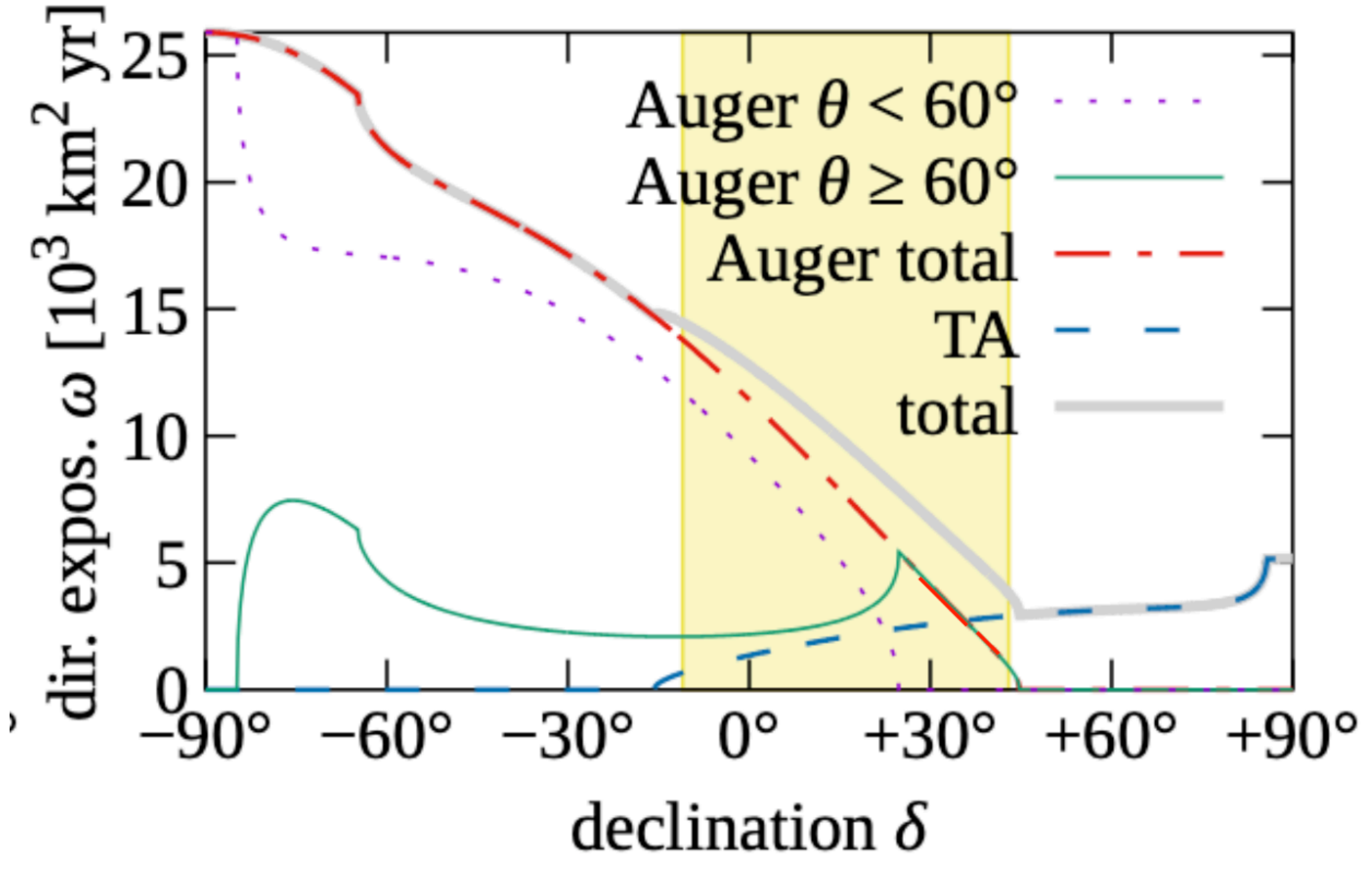
- Data well described by a model with f ~ 20% from SBGs and δ~20⁰ at 40 EeV, N-dominated hard injection spectrum
- Significance of SBG model ~4.5σ, contribution of Centaurus A dominant (~80%)
- **χ-AGN sources disfavoured** (not possible when considering only energy and mass composition)

Auger Coll., JCAP 01 (2024) 022

Differences between Northern and Sourthern sky?

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





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

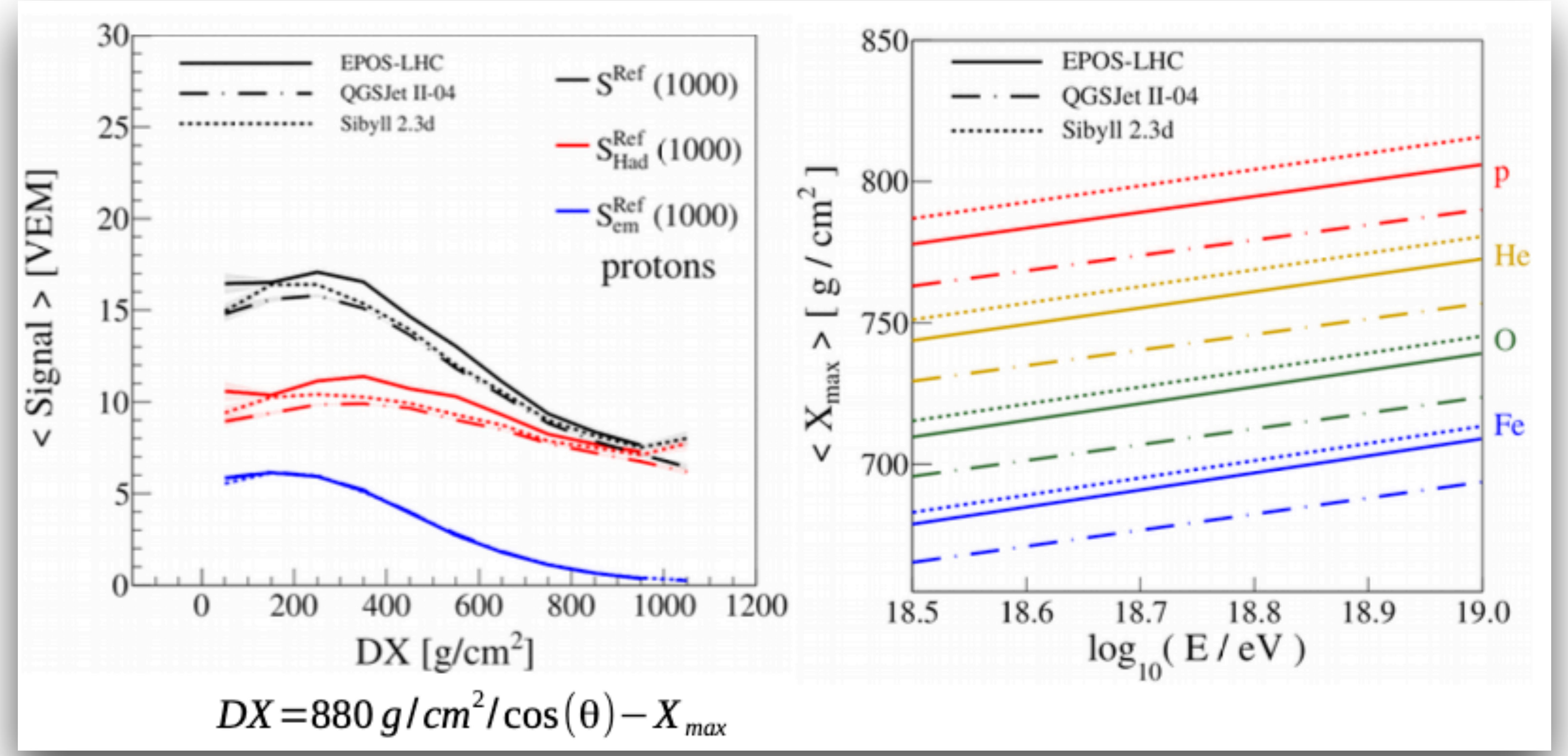
	$(\alpha_0, \delta_0)\,[°]$	E^{TA}	N^{TA}_{obs}	N^{TA}_{exp}	σ^{TA}_{post}	E^{Auger}	N^{Auger}_{obs}	N^{Auger}_{exp}	σ^{Auger}_{Li-Ma}
PPSC	(17.4, 36.0)	25.1	95	61.4	3.1σ	20.1	68	69.3	-0.2σ
	(19.0, 35.1)	31.6	66	39.1	3.2σ	25.3	40	45.2	-0.8σ
	(19.7, 34.6)	39.8	43	23.2	3.0σ	31.8	27	26.5	0.1σ
TA hot spot	(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 —> at variance with 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

Testing the predictions of hadronic models

Reference	Test	Energy/EeV	$\theta/^\circ$	Epos-LHC	QGSJet-II-04	SIBYLL 2.3d
PRD 90 (2014) 122005+122006	X_{max} moments	~3 to 50	0 to 80	●	✗	● (2.3c)
Phys. Lett. B 762 (2016) 288	X_{max}: $S(1000)$ correlation	3 to 10	0 to 60	●	✗	● (2.3c)
PRD 91 (2015) 032003+059901	Mean muon number *[inclined events]*	~10	~67	✗	✗	✗
Eur.Phys.J. C80 (2020) 751	Mean muon number *[direct measurement]*	0.2 to 2	0 to 45	✗	✗	...
PRL 126 (2021) 152002	Fluctuation of muon number	4 to 40	~67	●	●	●
PRD 90 (2014) 012012	Muon production depth	20 to 70	~60	✗	●	...
PRL 117 (2016) 192001	$S(1000)$	~10	0 to 60	✗	✗	...

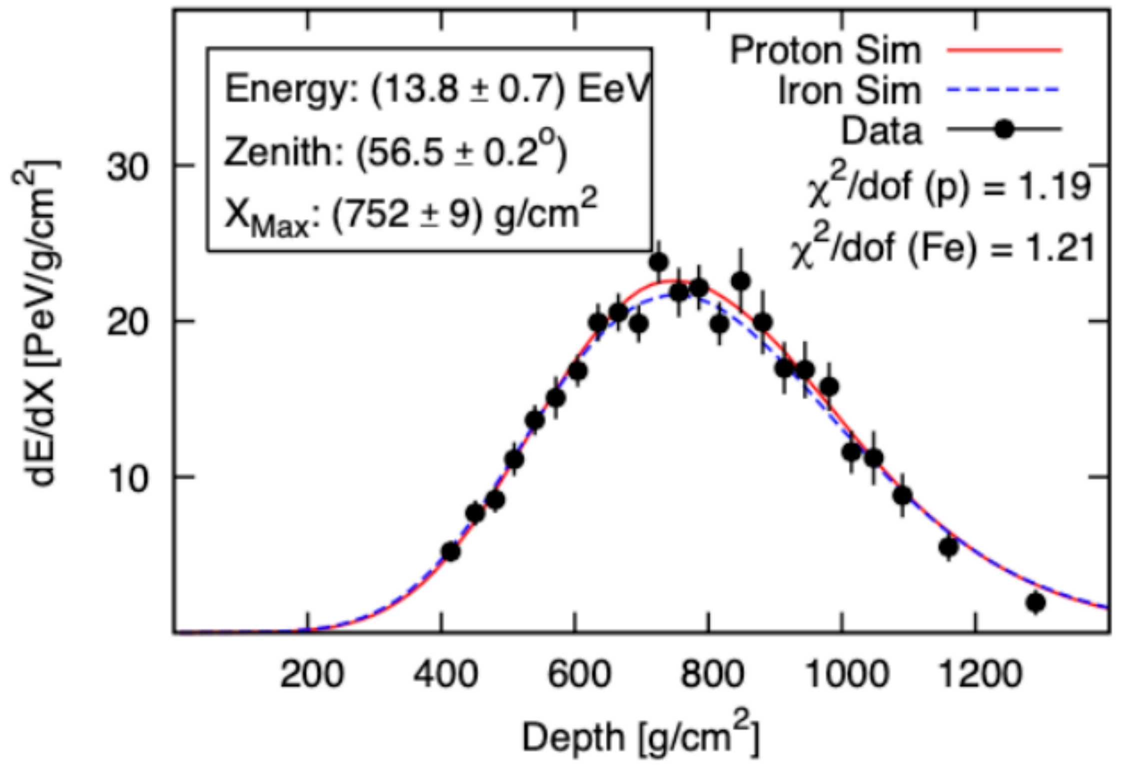


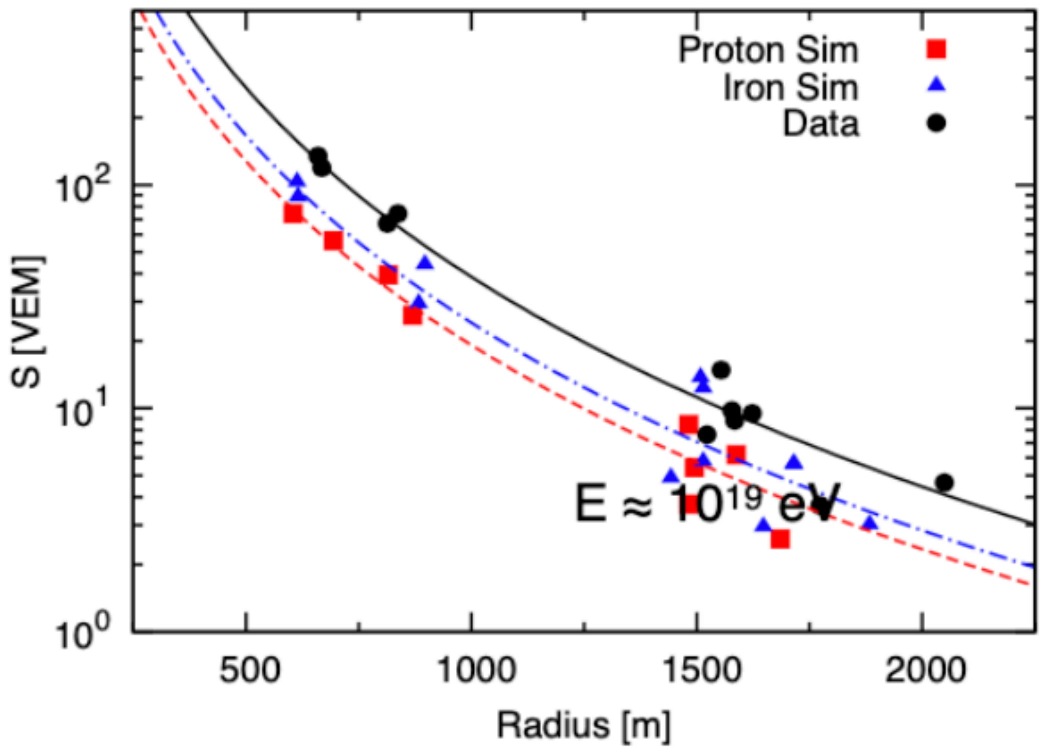
Observable	Δ models	Δ (p-Fe)
$<X_{max}>$	~30 g cm^{-2}	~100 g cm^{-2}
$\sigma(X_{max})$	~5 g cm^{-2}	~40 g cm^{-2}
S(1000)	~3 VEM	~6 VEM

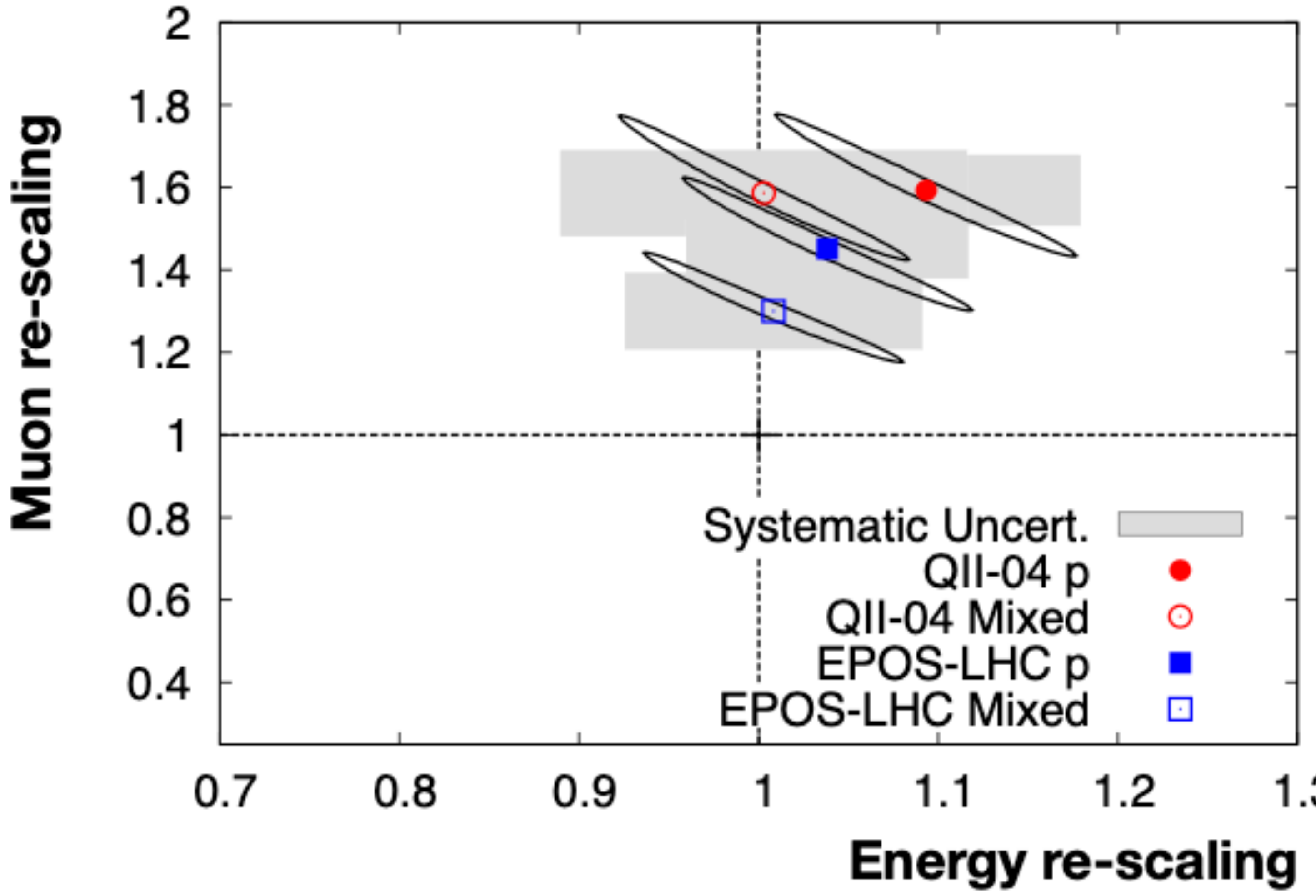
The muon puzzle

Vertical events (<65⁰)

Auger Coll., PRL117 (2016) 192001







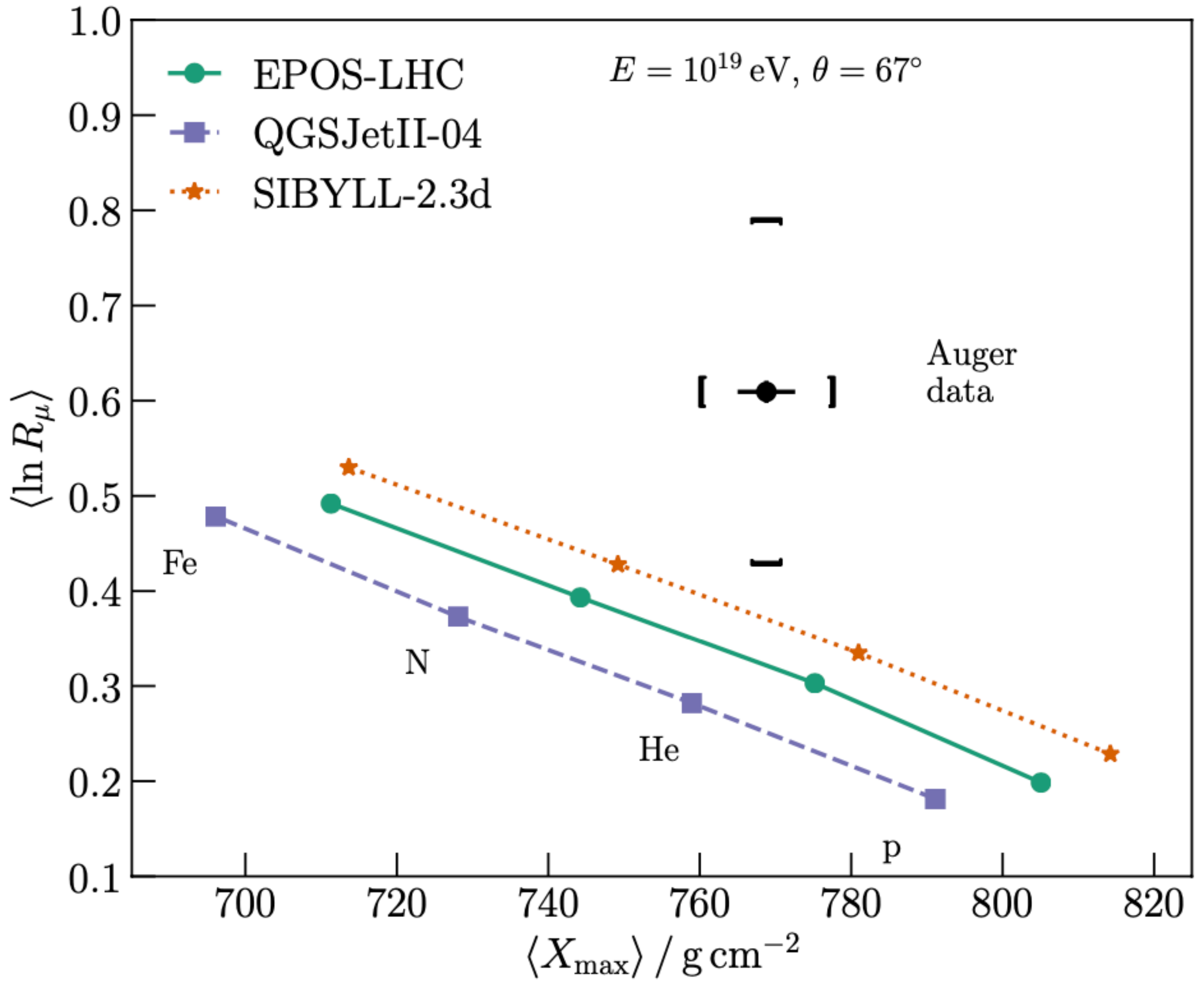
No energy rescaling needed

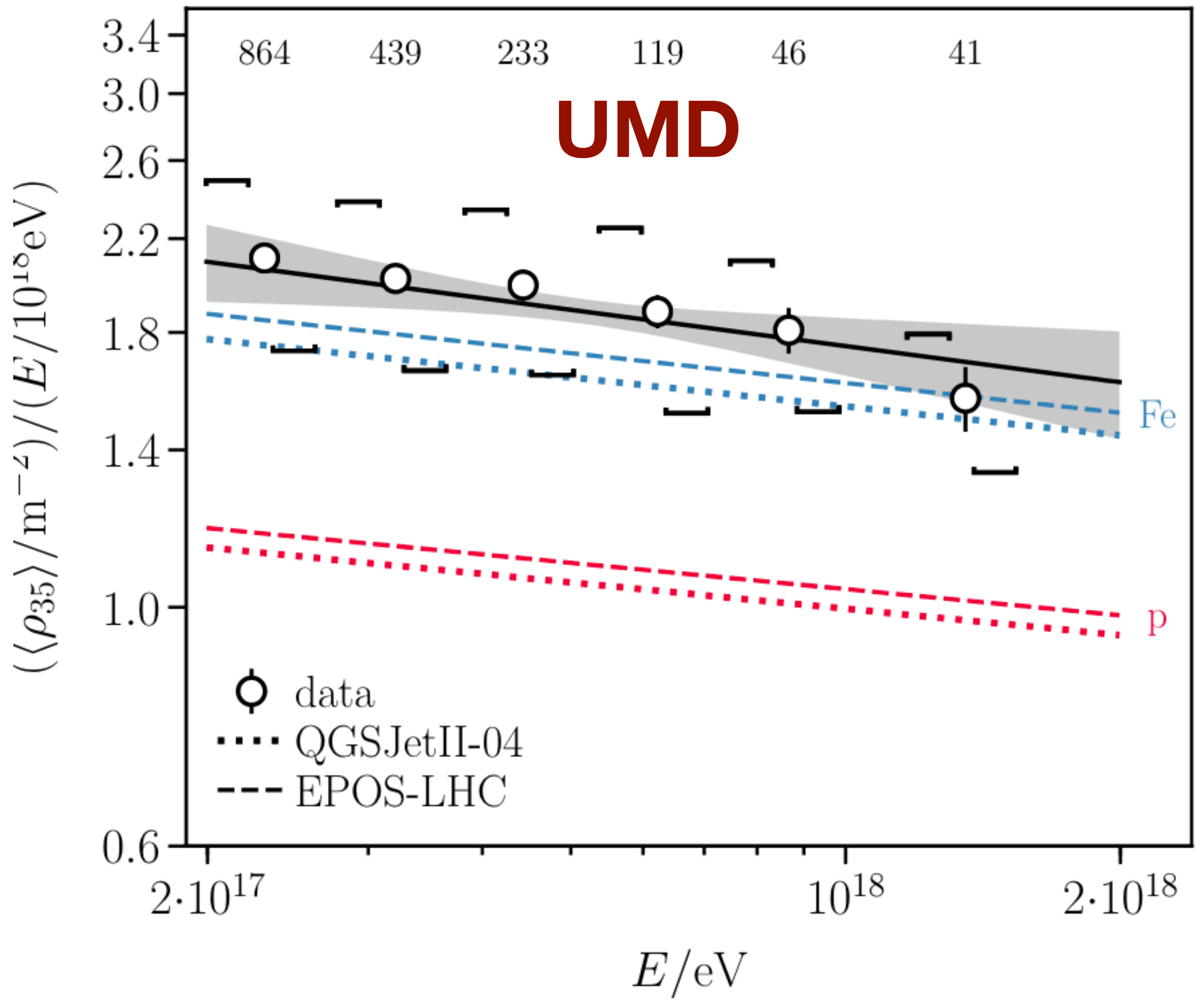
More muons in data

muon rescaling between 1.2 and 1.8

Direct muon measurement in vertical showers (<45⁰)

Auger Coll., Eur.Phys.J. C80 (2020) 751





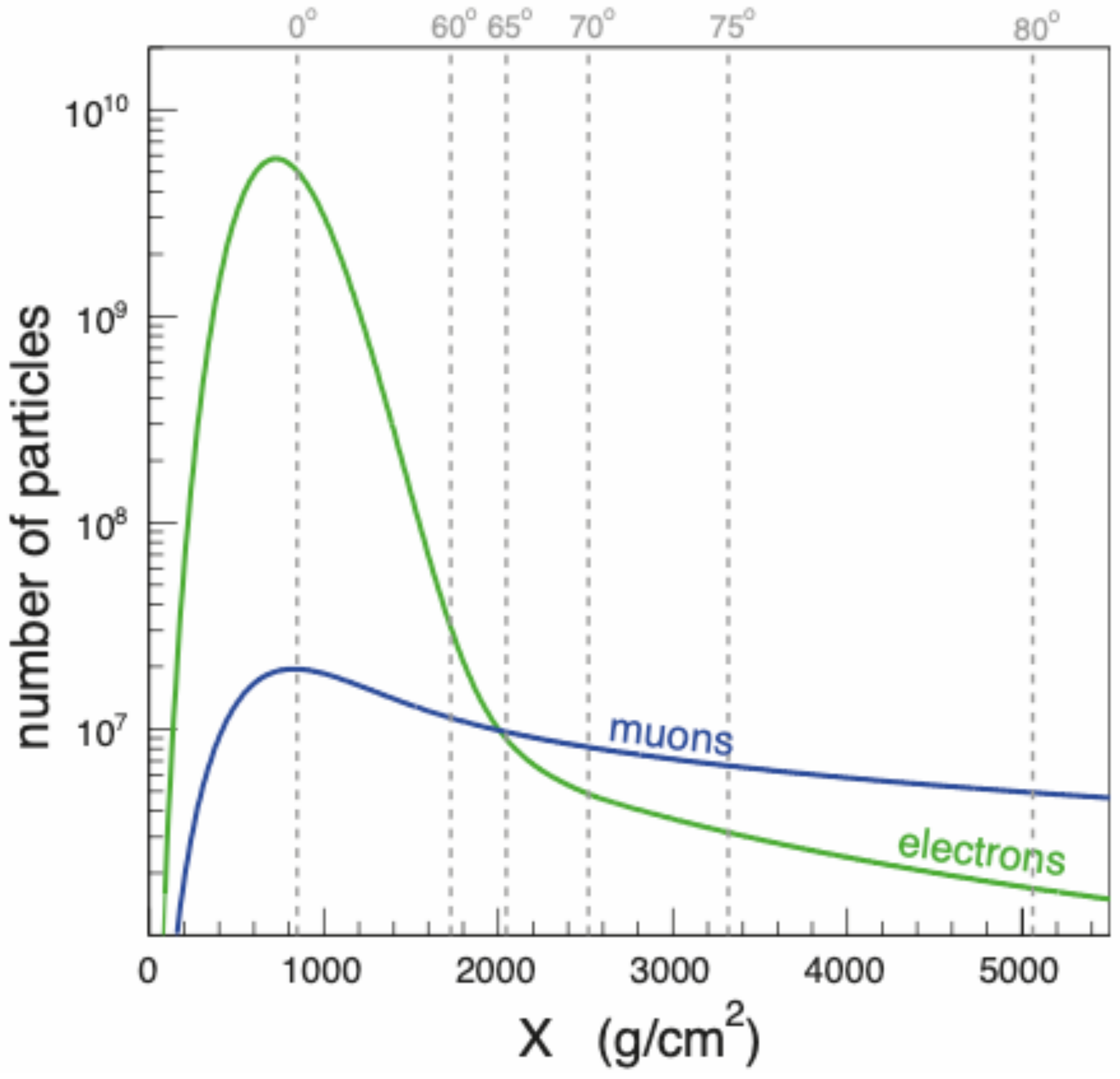
Consistently more muons in data

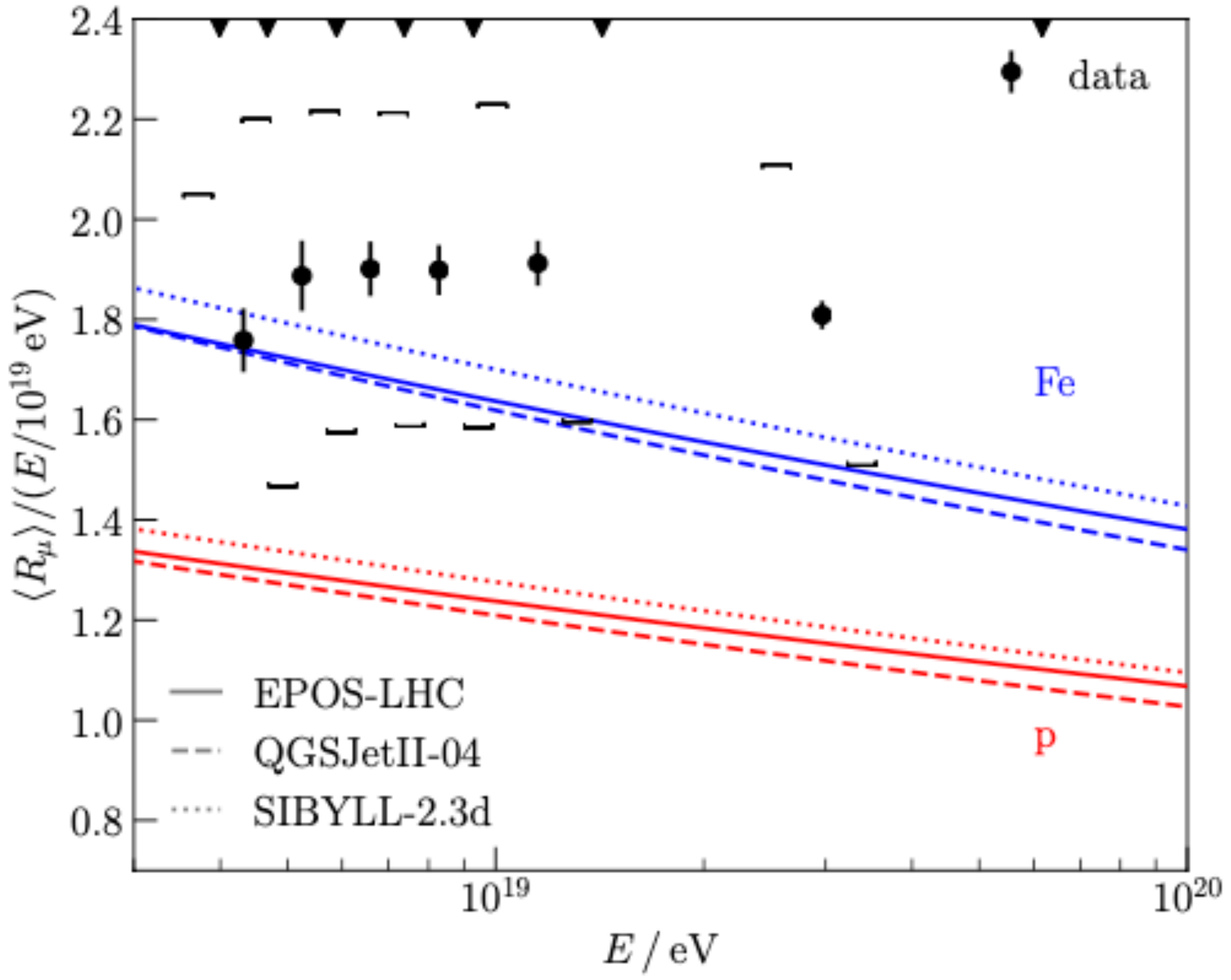
The discrepancy starts already at 2 10^{17} eV

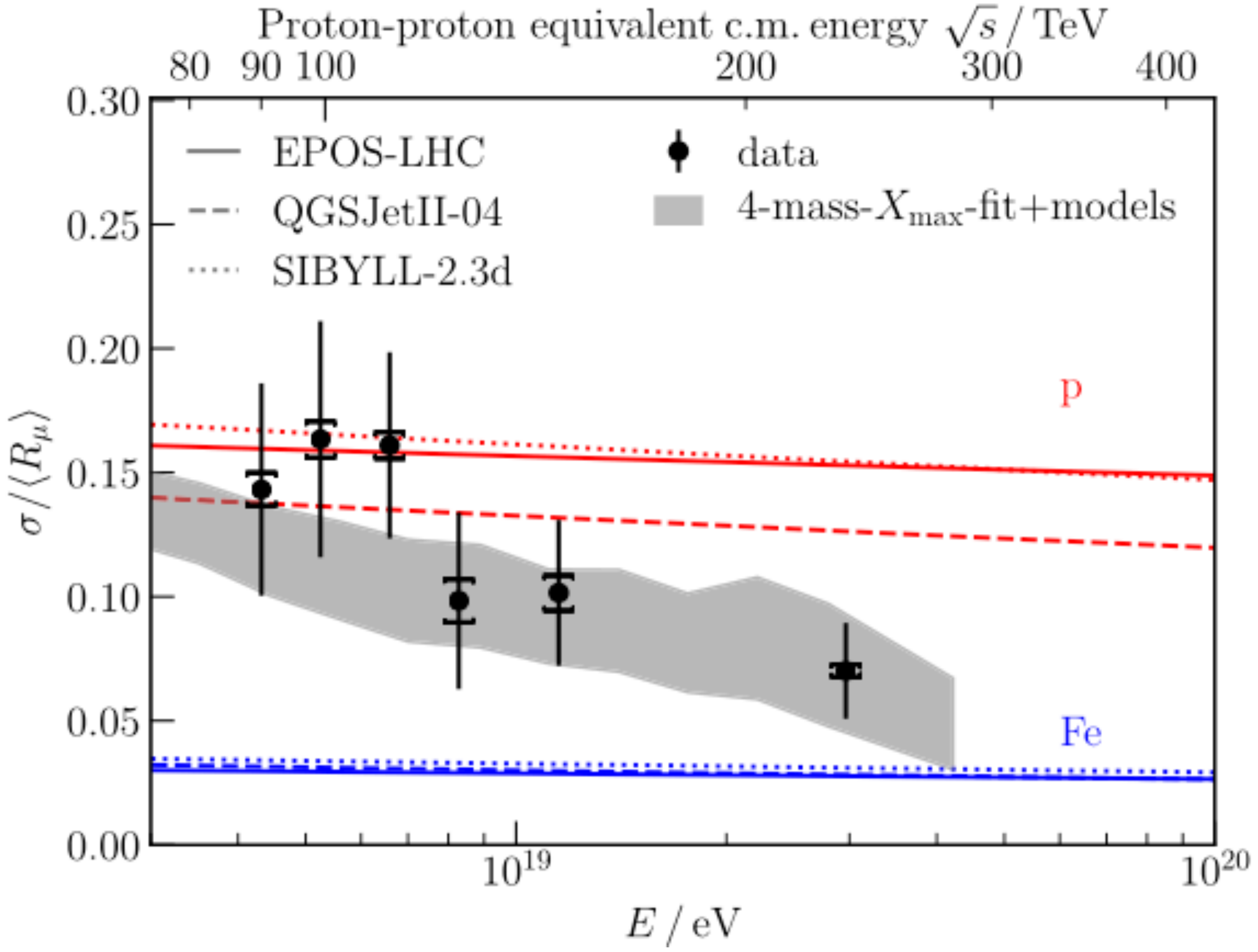
The muon puzzle

Auger Coll., PRD91 (2015) 032003+059901
Auger Coll., PRL 126 (2021) 152002

Inclined events (>65^0)







The muon deficit in simulations is confirmed

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)

$$\left(\frac{\sigma(N_\mu)}{N_\mu}\right)^2 \simeq \left(\frac{\sigma(\alpha_1)}{\alpha_1}\right)^2 + \left(\frac{\sigma(\alpha_2)}{\alpha_2}\right)^2 + \ldots + \left(\frac{\sigma(\alpha_c)}{\alpha_c}\right)^2$$

Most likely scenario: accumulation of small deviations along the generations

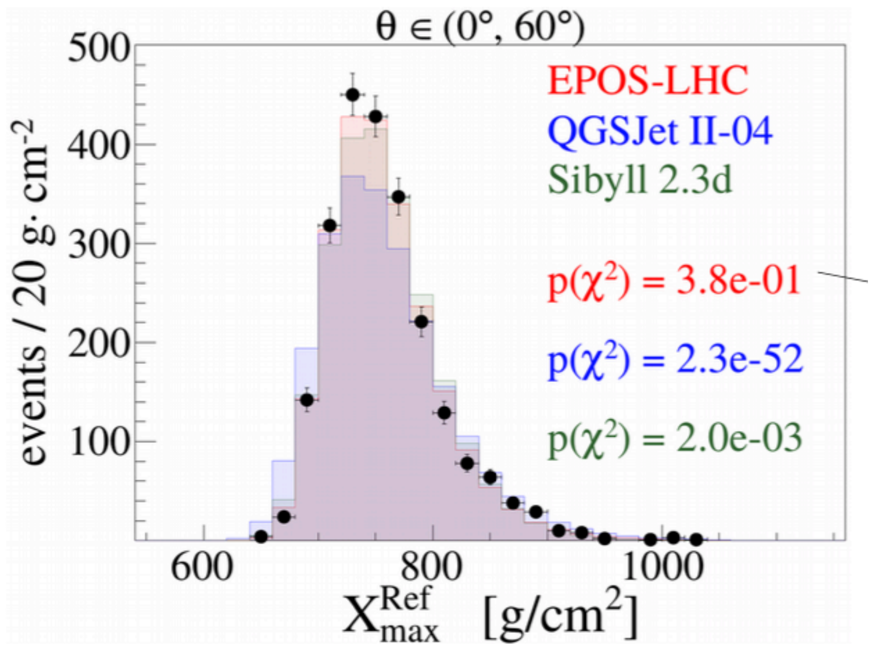
Testing the predictions of hadronic models

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

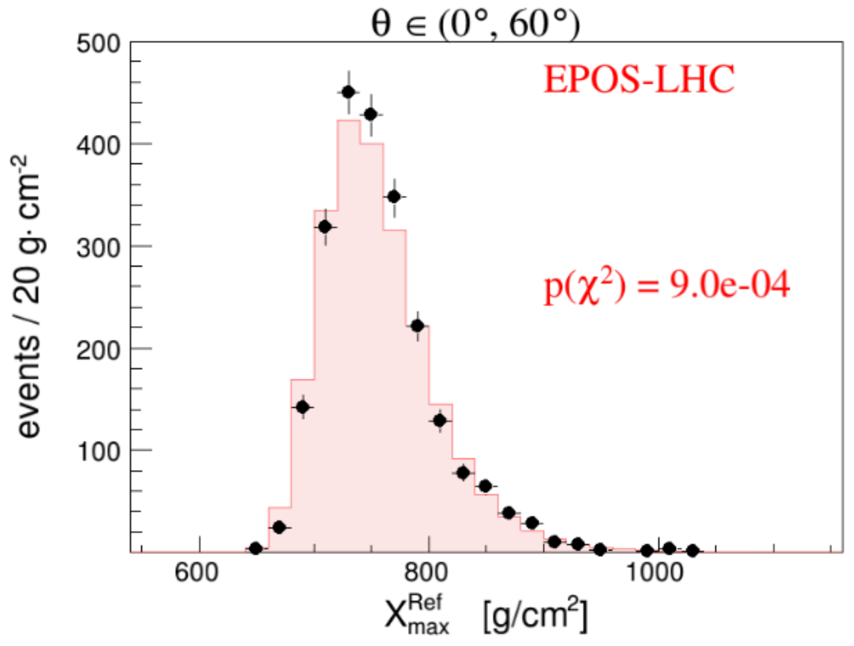
ad-hoc adjustments

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

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

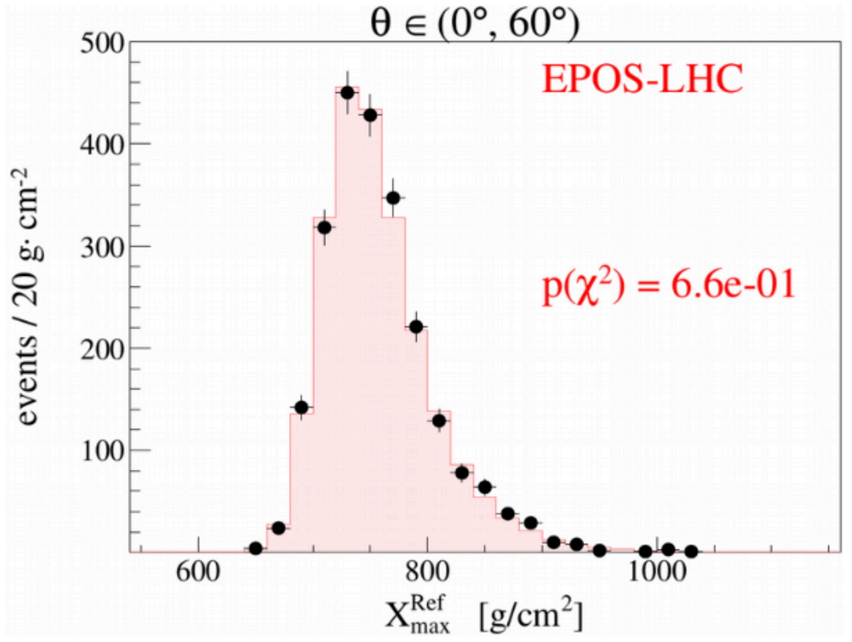


Combined fit of the [X_{max},S_{1000}] distributions without any adjustments



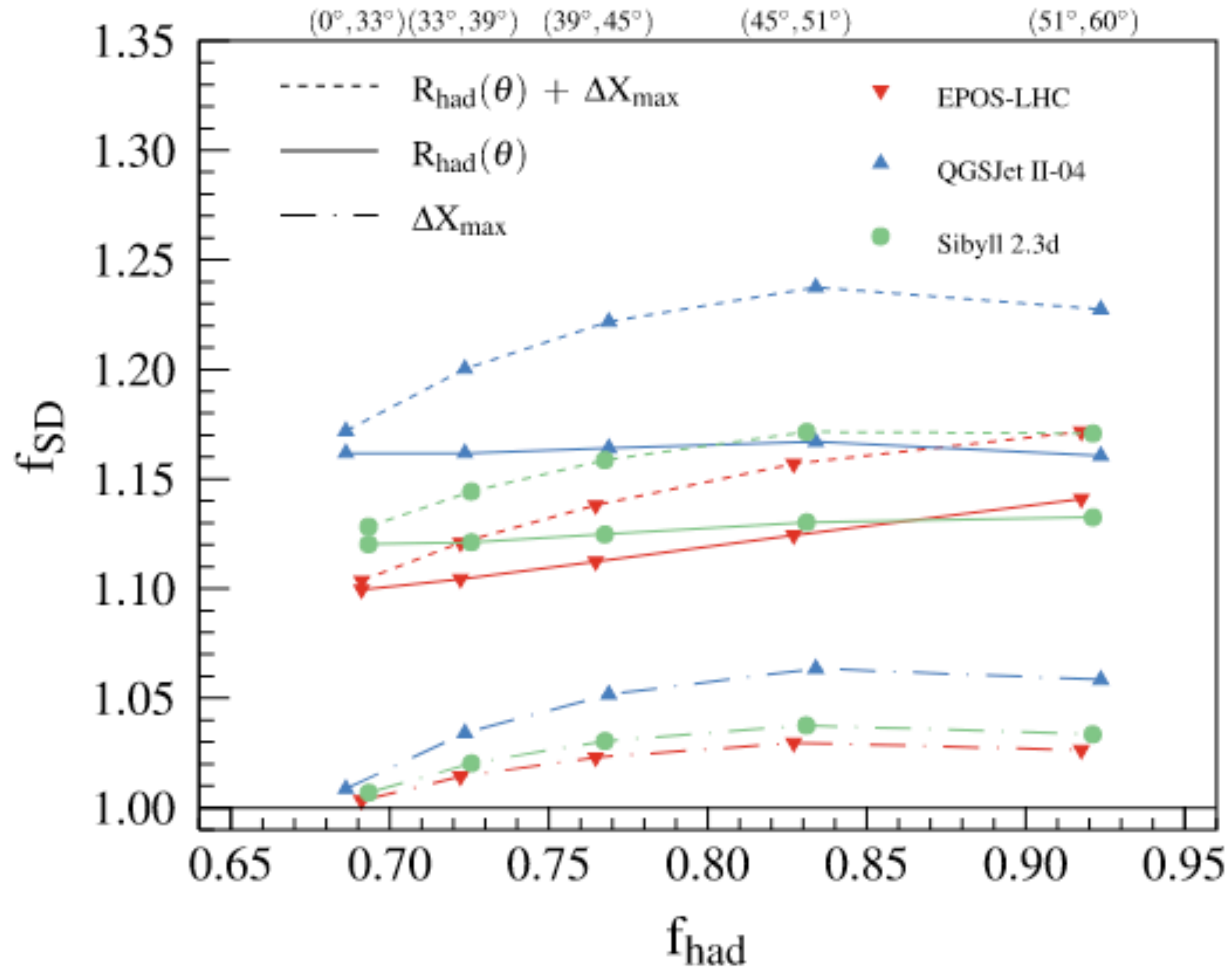
Combined fit of the [X_{max},S_{1000}] distributions with angular dependent muon rescaling $R_{had}(\vartheta)$

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



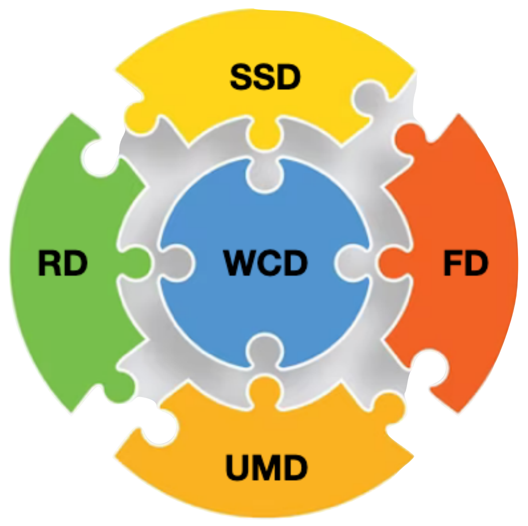
Best description of data if models modified such that :

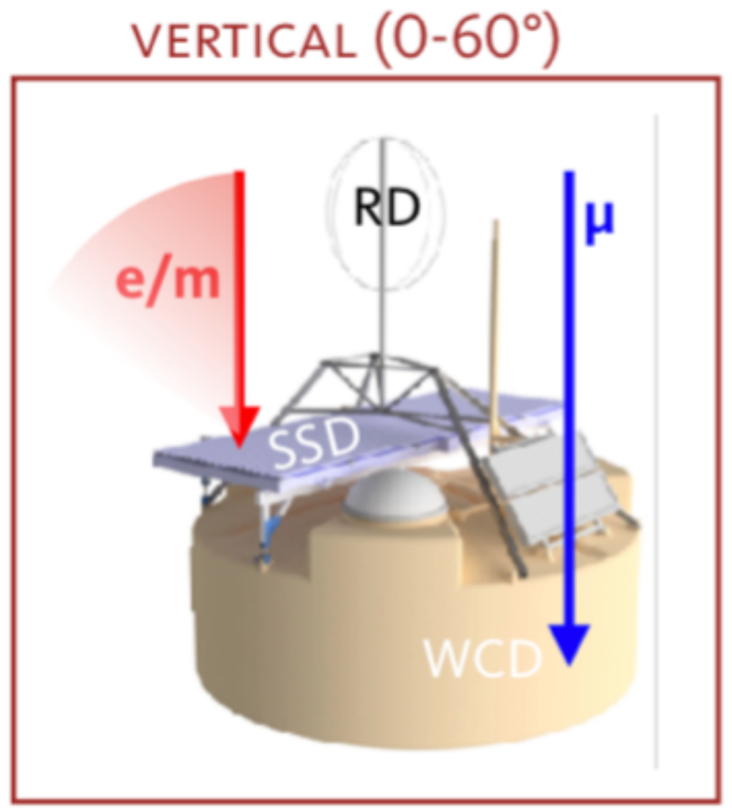
X_{max} deeper by 20-50 g cm^{-2}

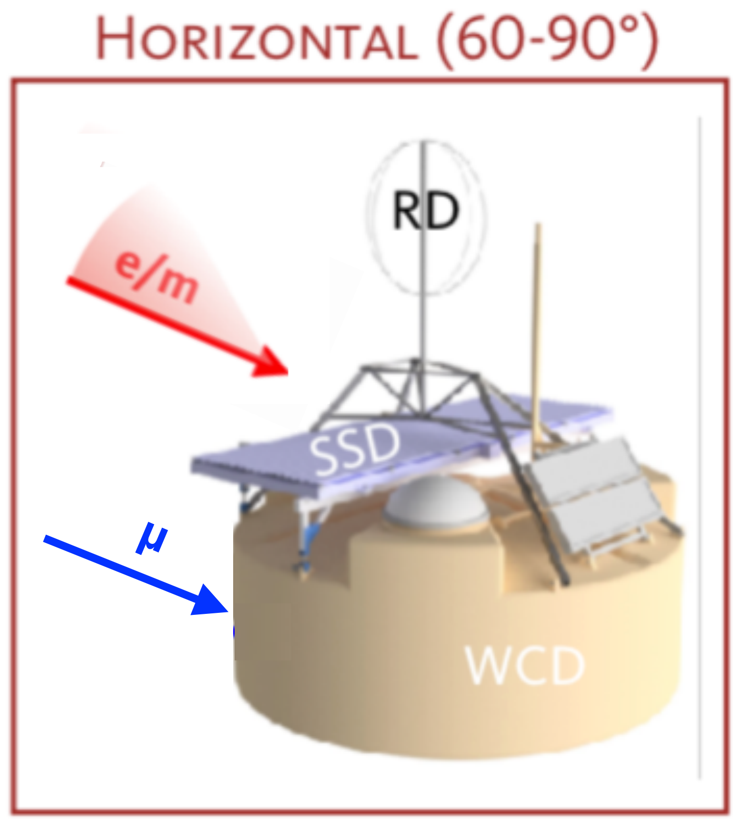
S_{had} increased by 15-25%

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

AugerPrime: 2025 → 2035…..



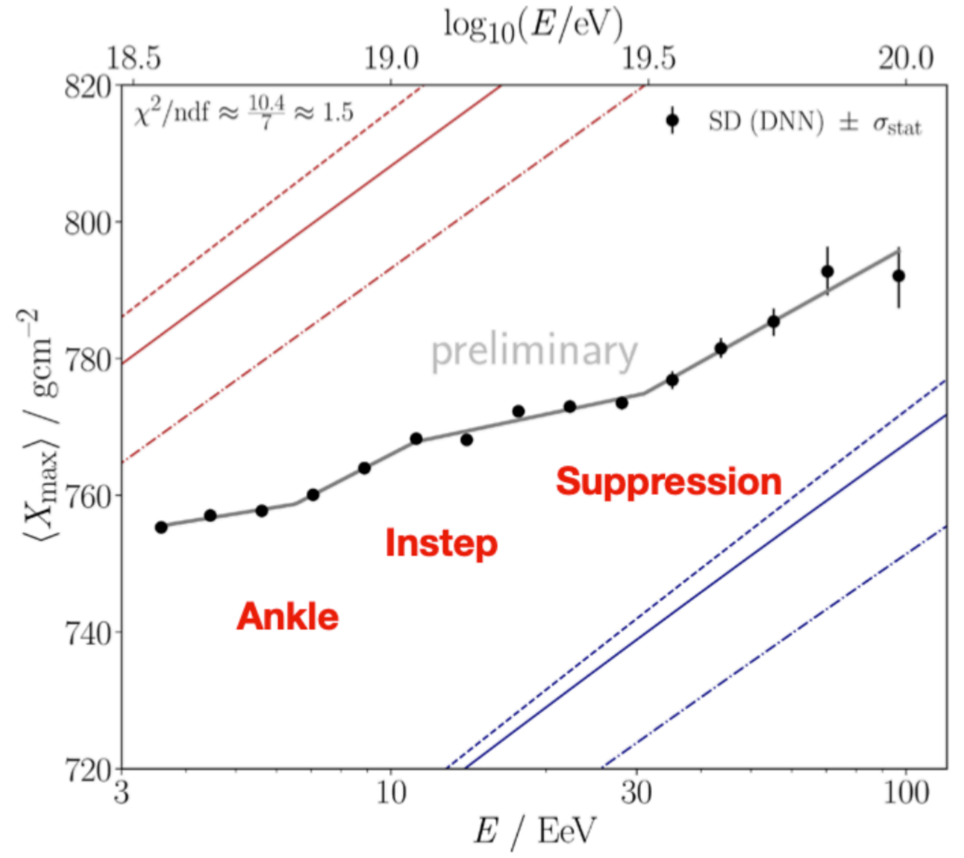


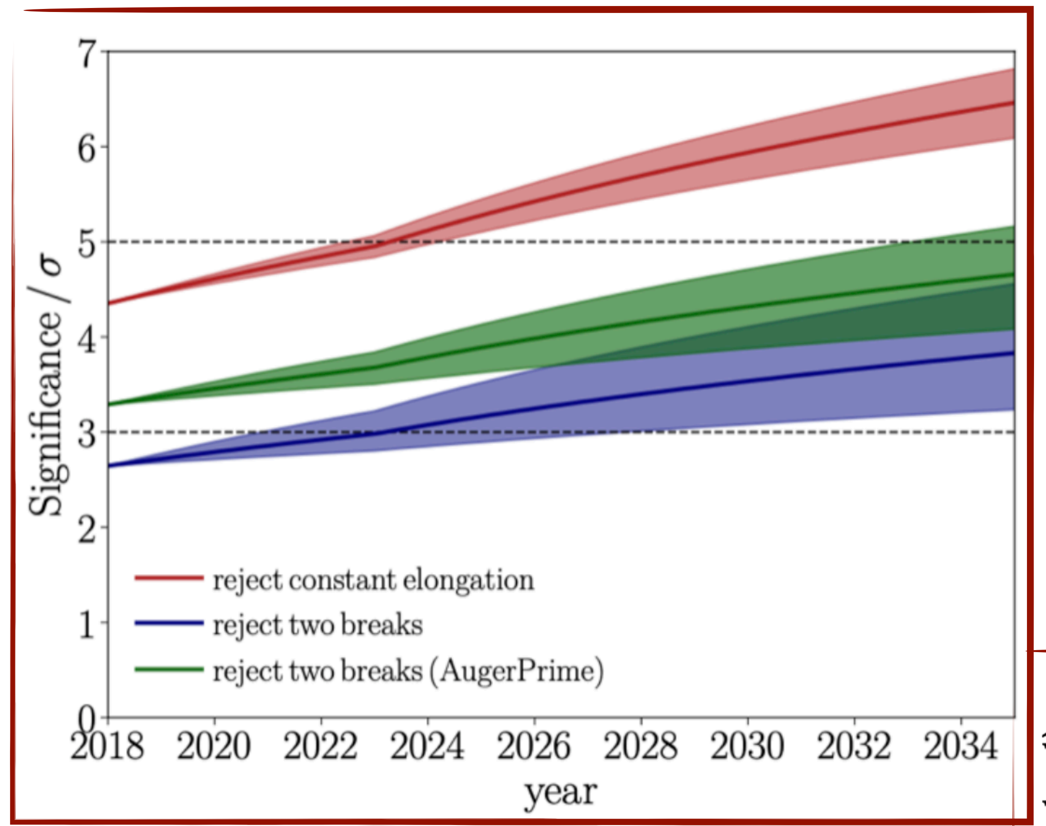


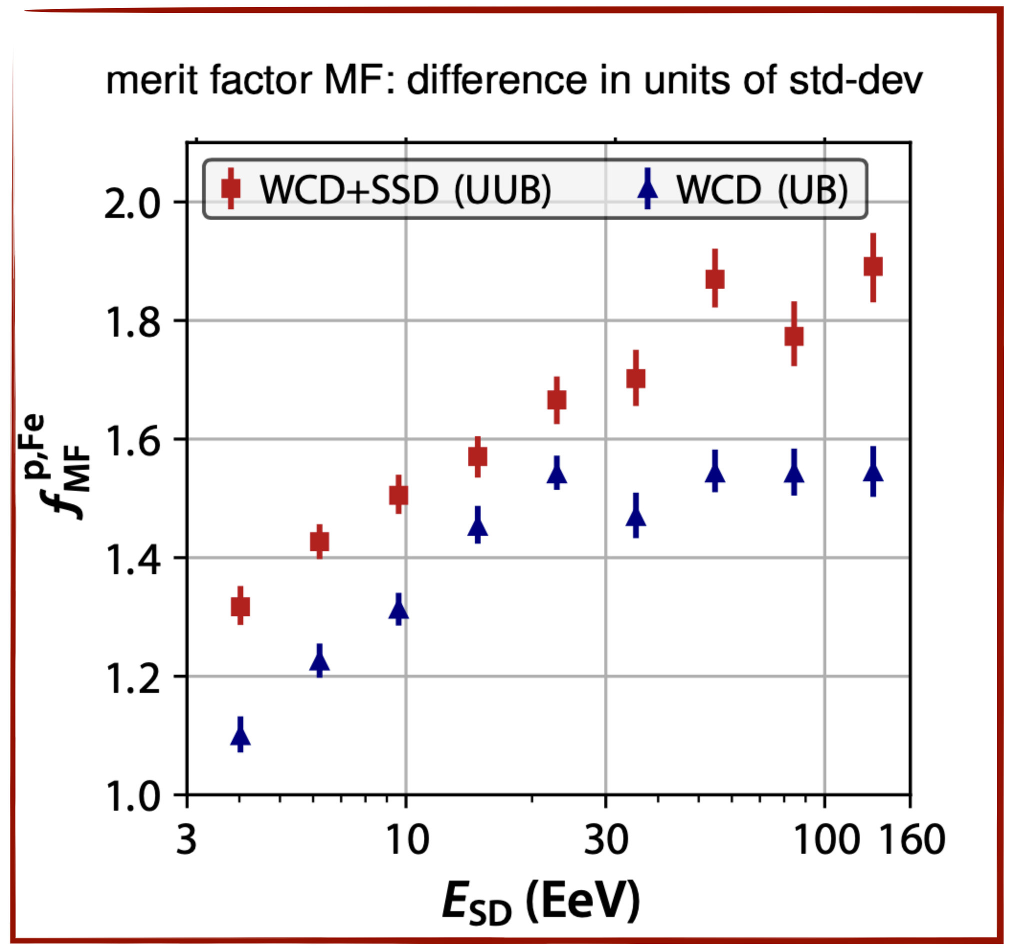
WCD/SSD/RD can collect multi-hybrid events with a 100% duty cycle

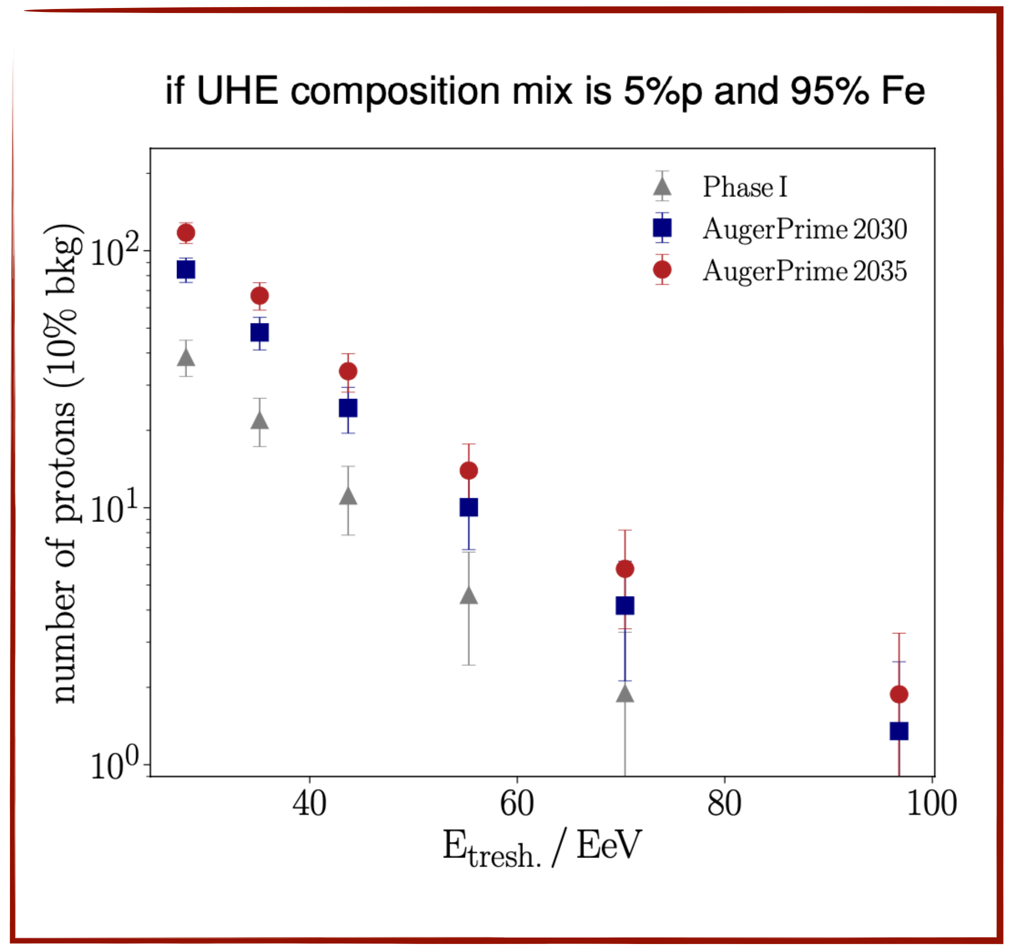
Separation of shower components can be obtained

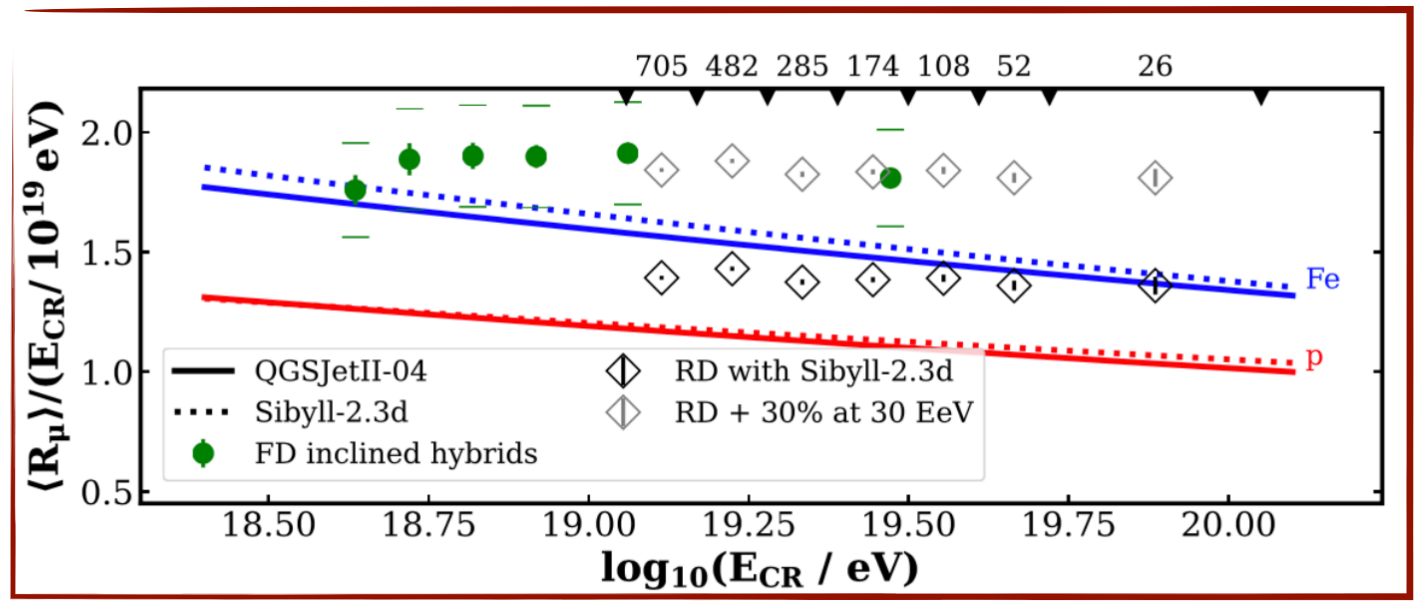
- by WCD/SSD for events up to ~60^0
- by WCD/RD for inclined events >60^0
- by WCD/SSD/UMD extending the mass sensitivity to the lower energies and improving the photons/hadrons discrimination
- With UUB we will enhance the sensitivity of triggers to electromagnetic signals

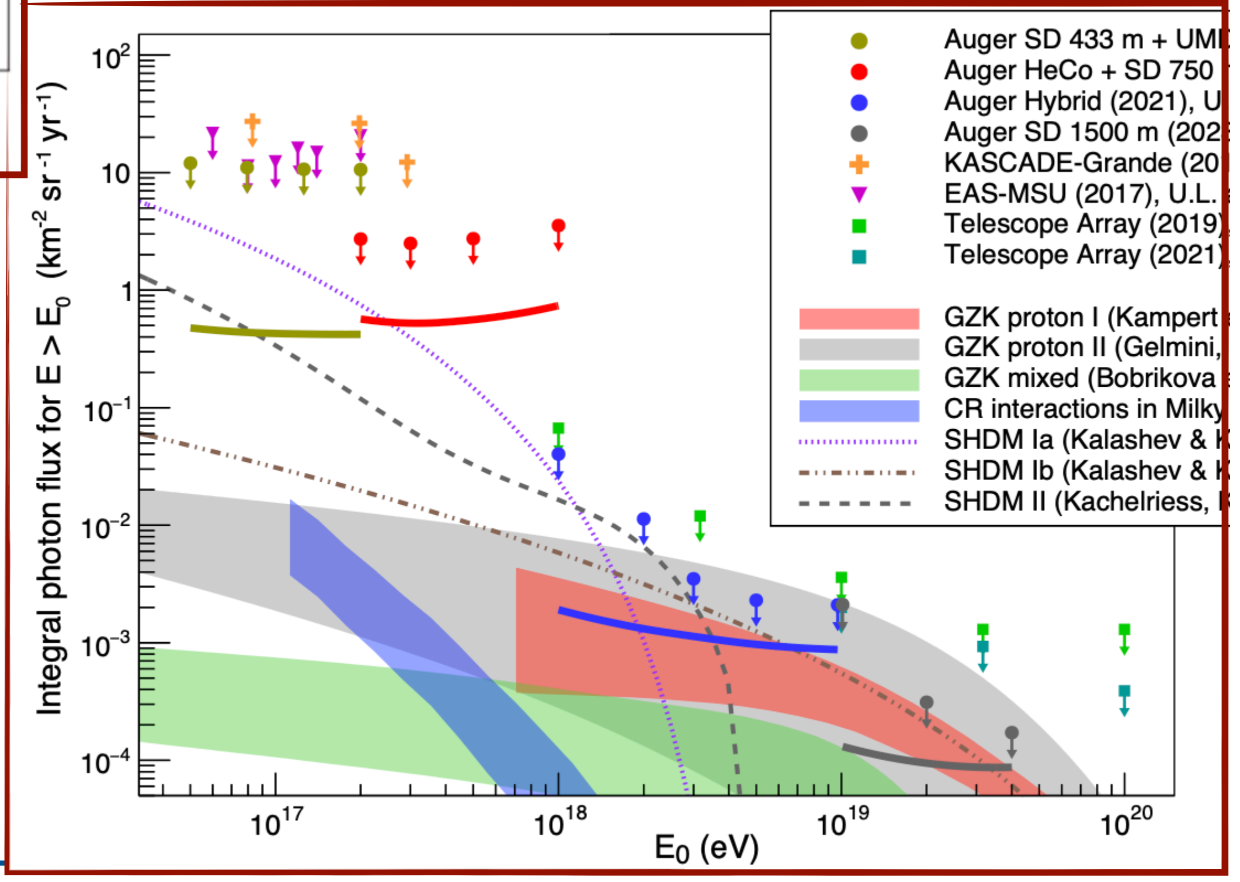


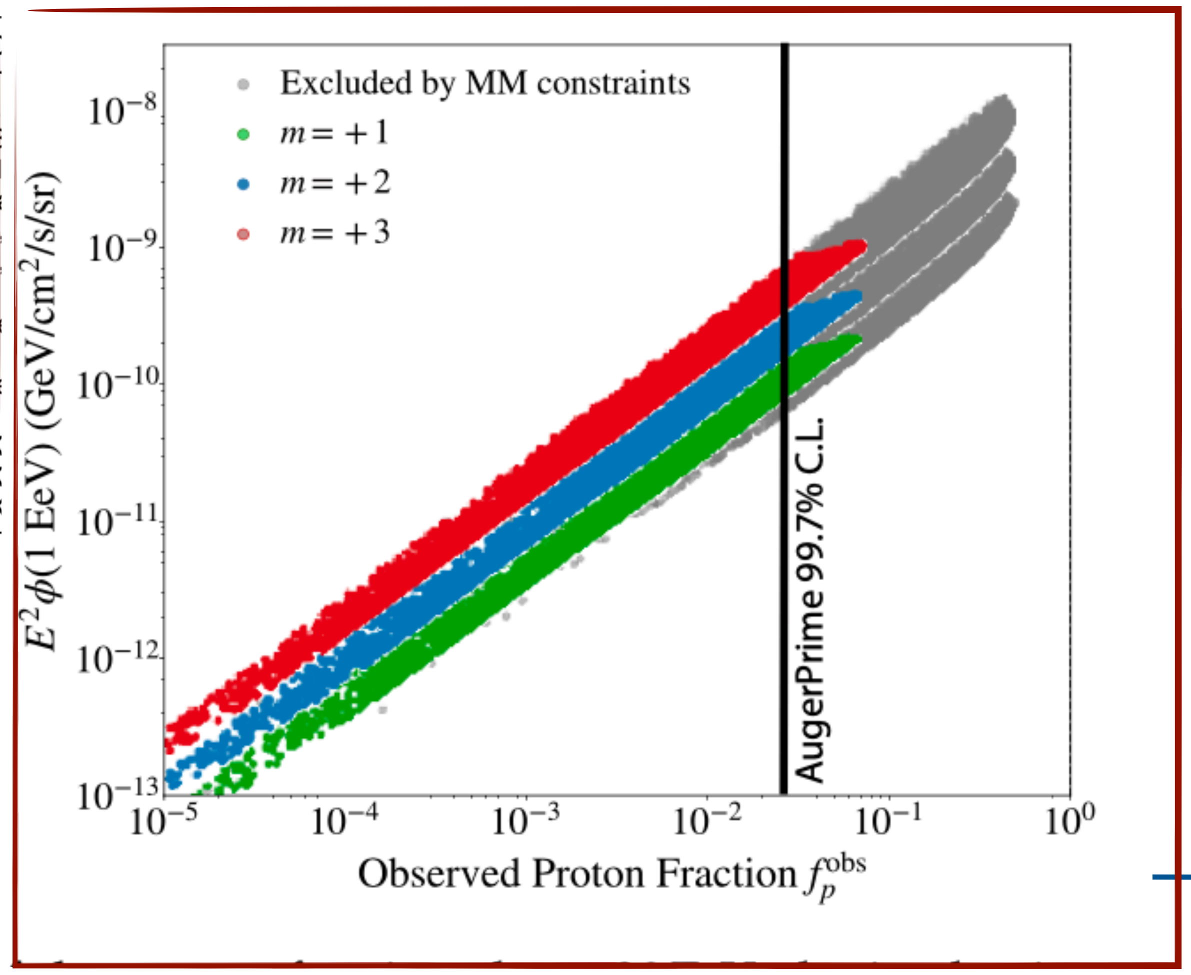










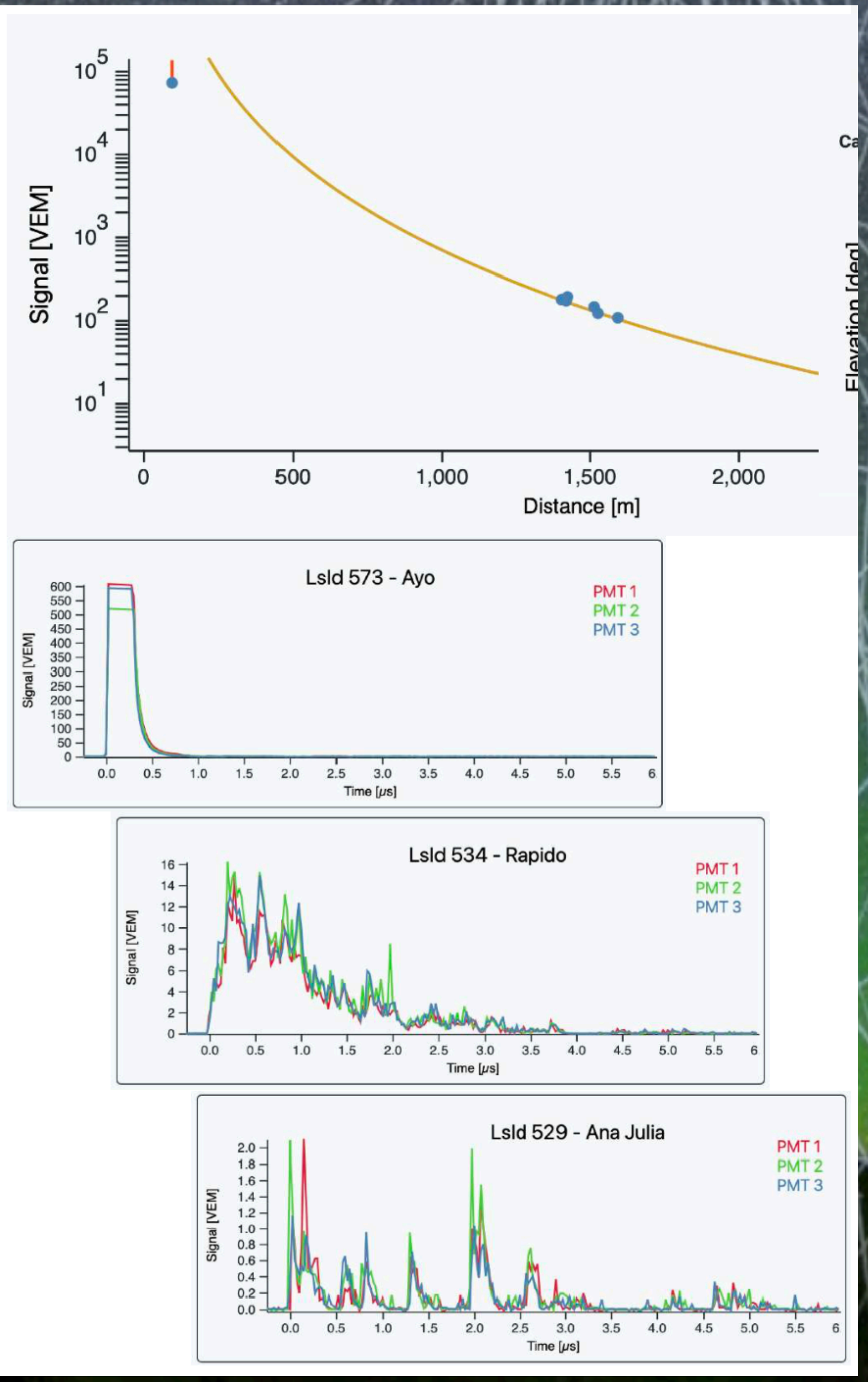


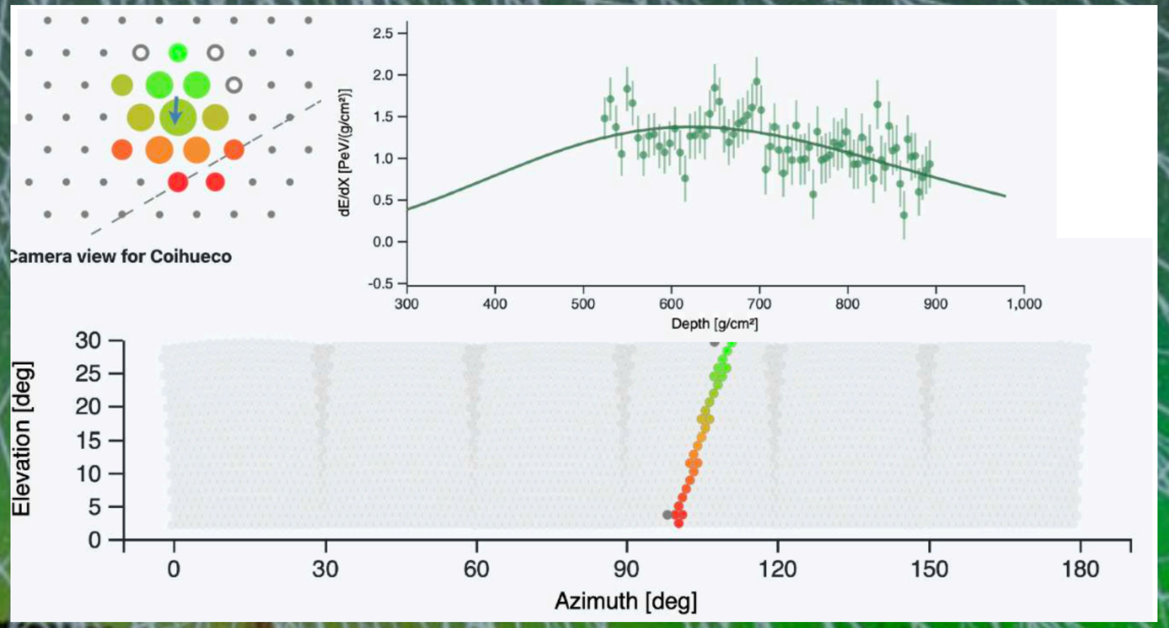
The Auger Public Data Release

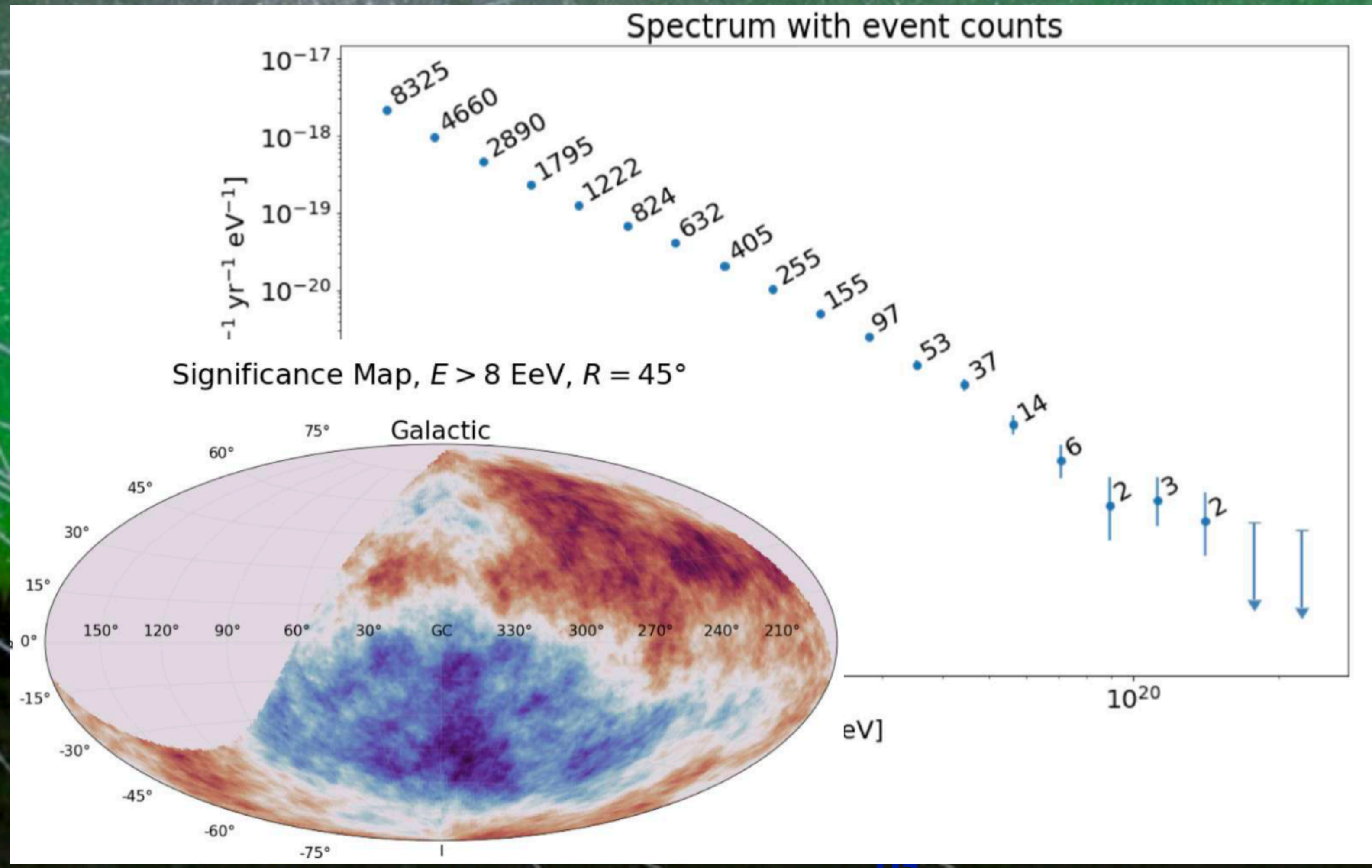
Following the Auger Collaboration Open Data Policy, the Pierre Auger Open Data is the public release of 10% of the Pierre Auger Observatory cosmic-ray data published in recent scientific papers and at International conferences. The release also includes 100% of weather and space-weather data collected 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** — the released datasets and their complementary data
- **Visualize** — an online look at the released pseudo raw cosmic-ray data
- **Analyze** — example analysis codes in online python notebooks to run on the datasets
- **Catalog** — of the highest-energy cosmic rays
- **Outreach** — a page dedicated to the general public





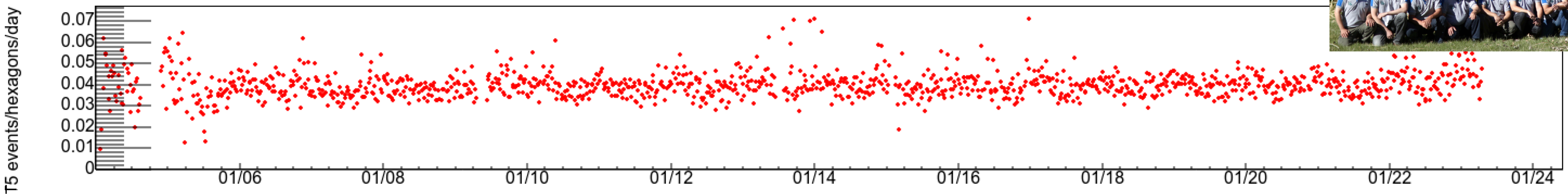


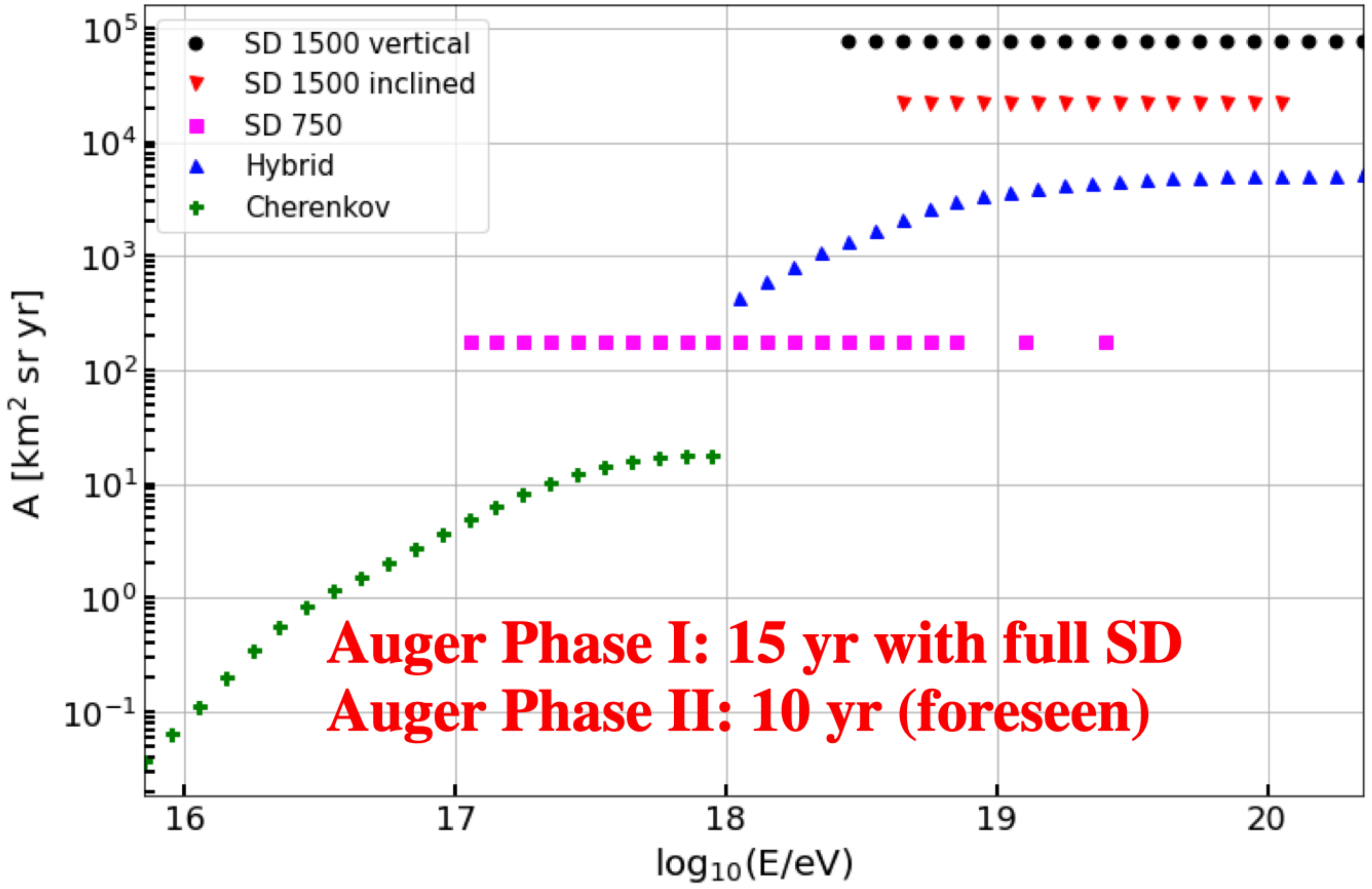
https://opendata.auger.org/

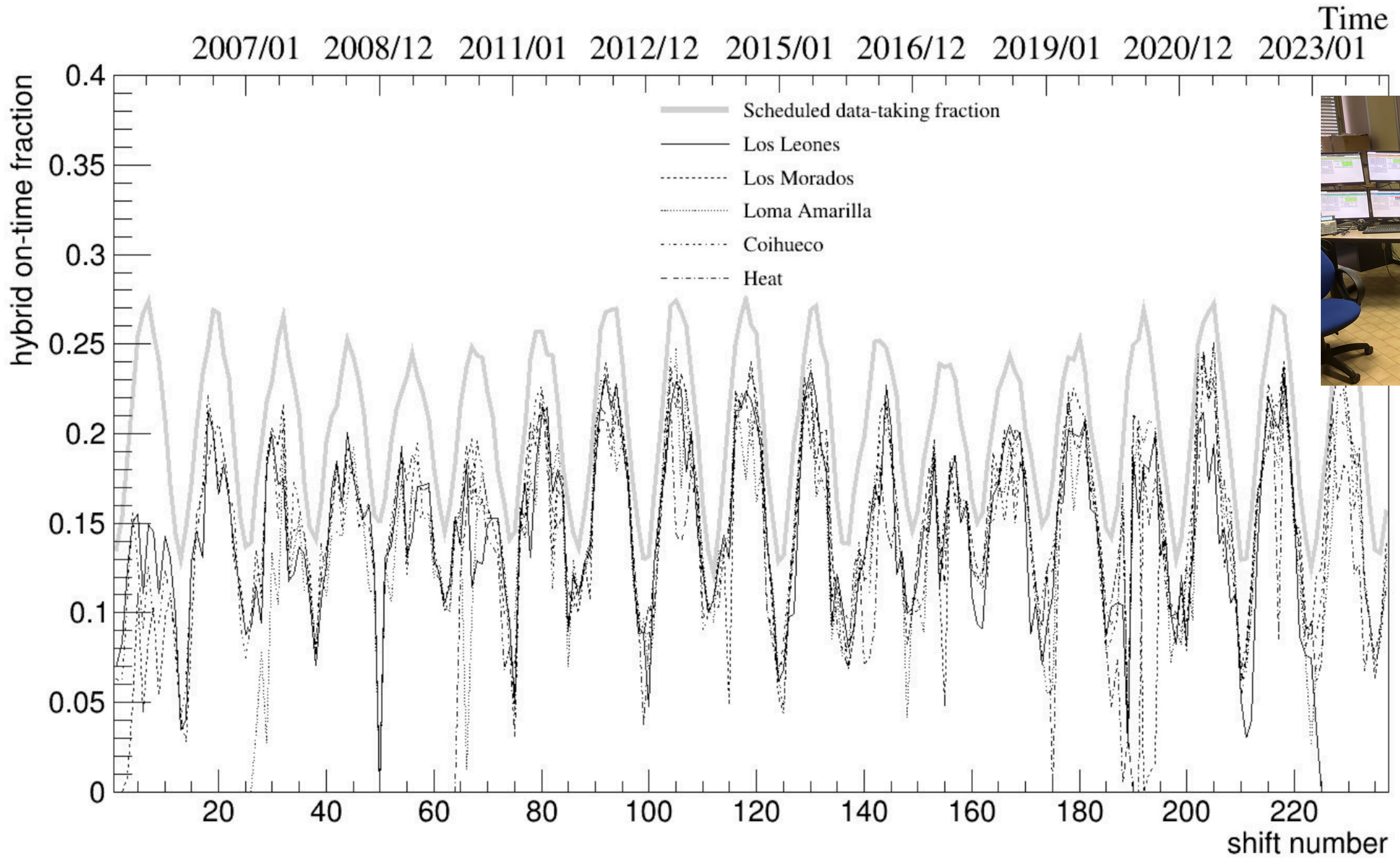
DOI:10.5281/zenodo.4487612

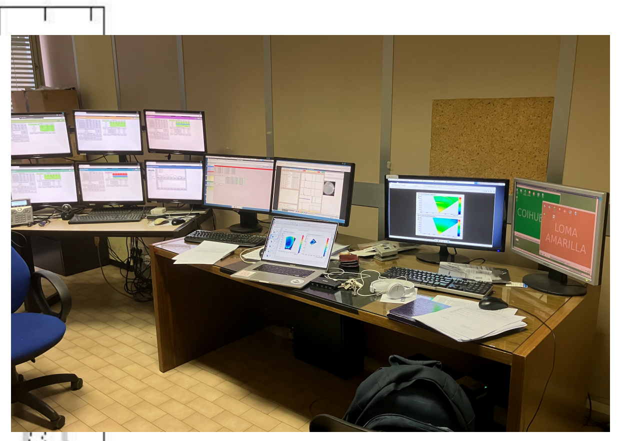
Backup

Auger data - Phase I





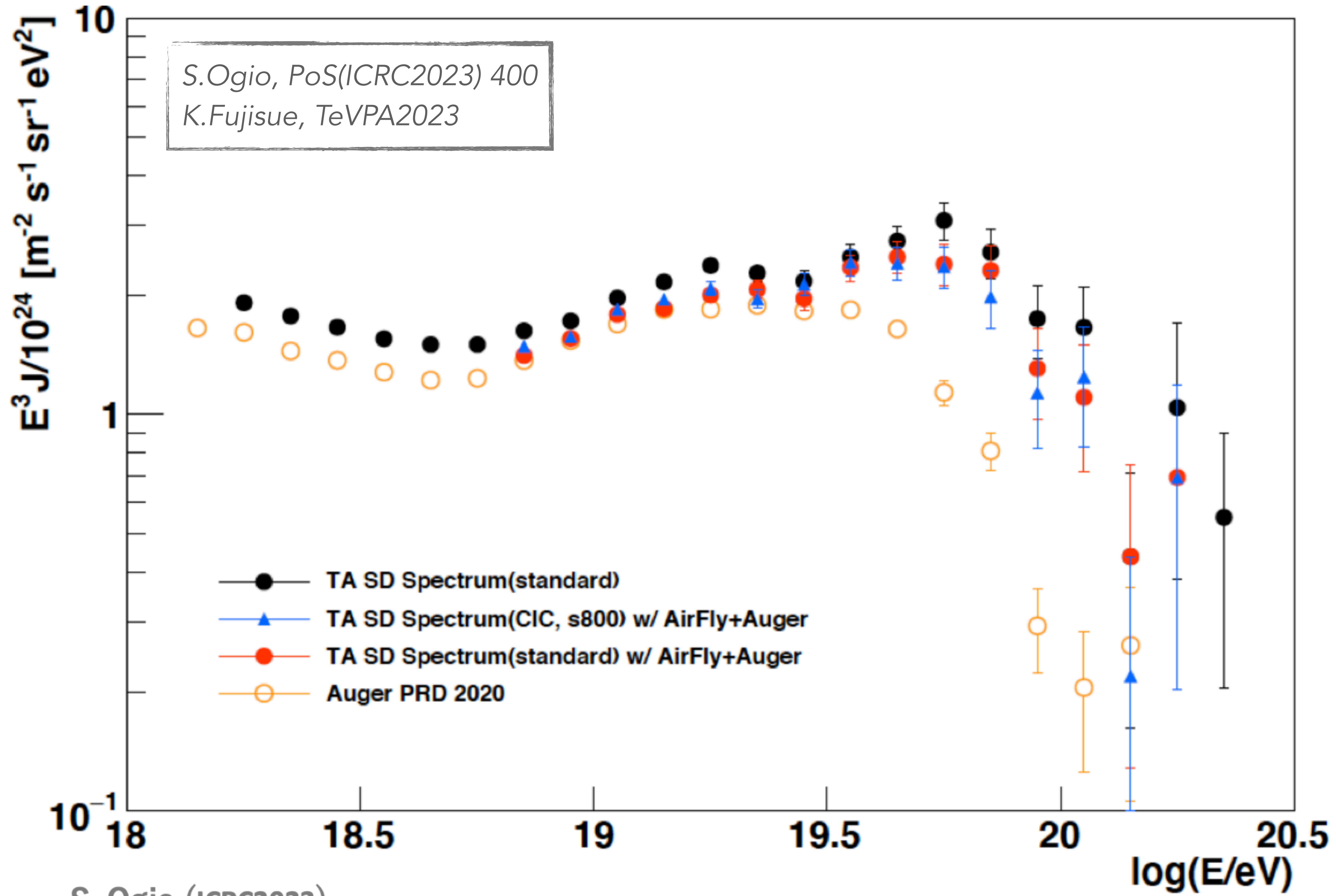




The largest worldwide exposure:

- ➡️ ~100,000 km² sr yr for the measure of the spectrum by SD
- ➡️ ~ 5,000 km² sr yr for the measure of the spectrum by FD
- ➡️ ~135,000 km² sr yr for the search of anisotropies

Differences between Northern and Sourthern sky?



S. Ogio (ICRC2023)

Compatibility of spectra from Auger and TA up to $10^{19.5}$ eV within few % when TA uses

— the same fluorescence yield (previously off by ~ -14%)

— the invisible energy (data-driven) correction of Auger (previously off by ~ +7%)

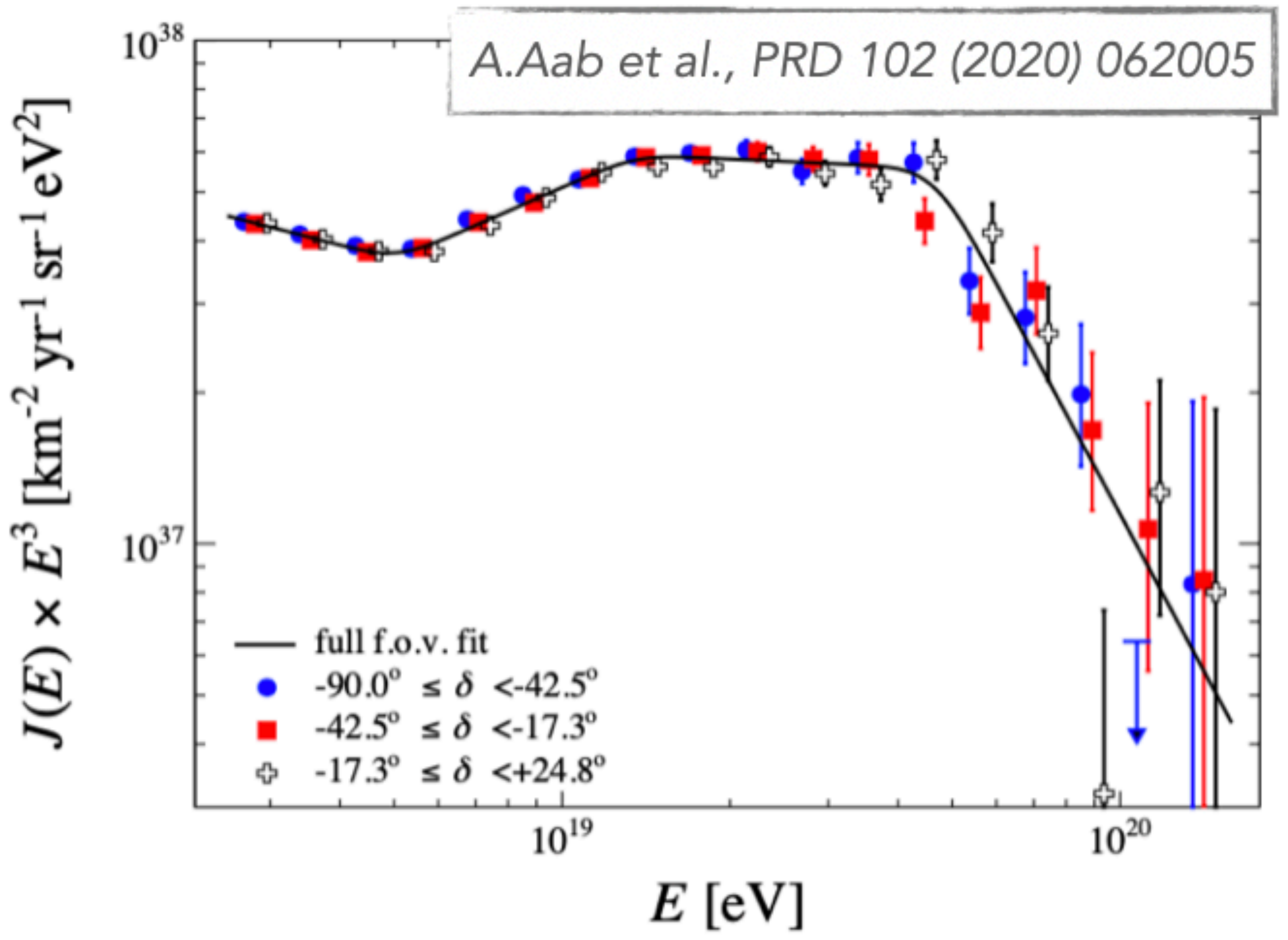
Difference at higher energy :

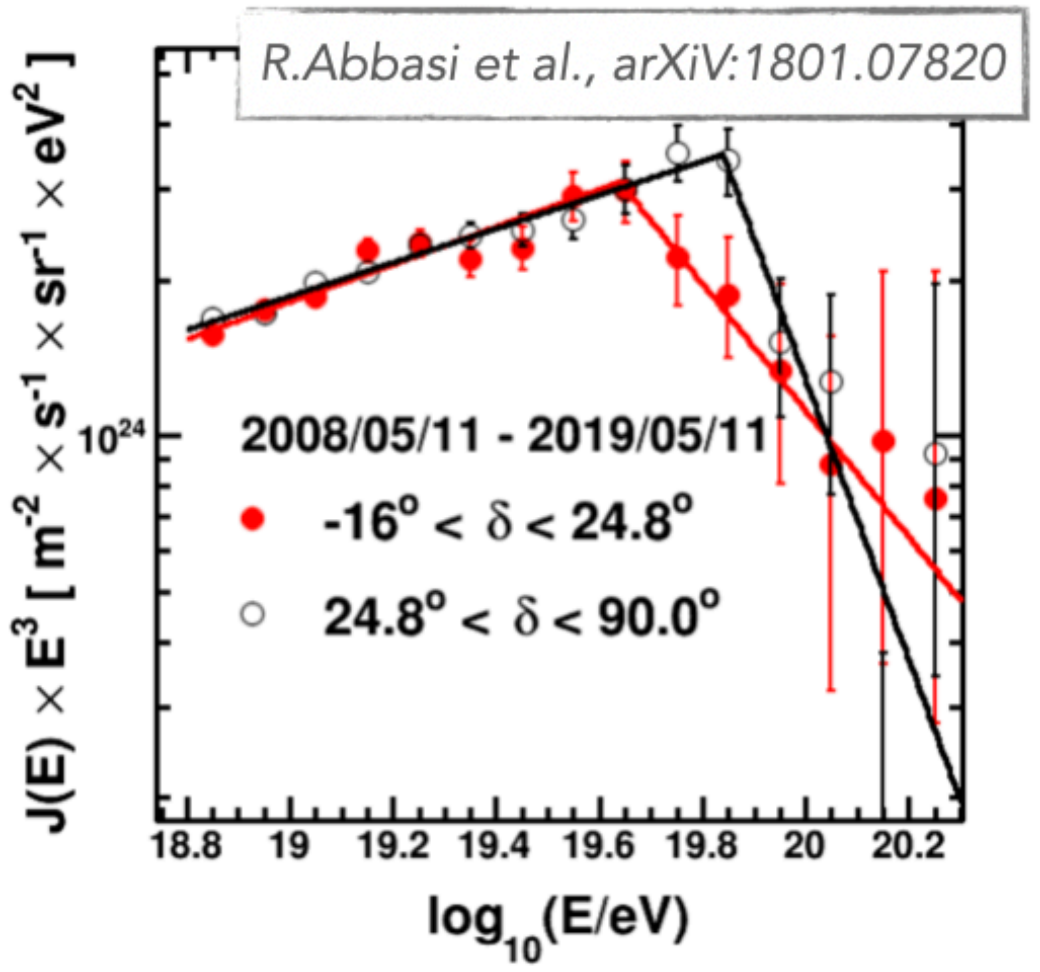
— **no declination dependence found in Auger**

— TA claim of a declination dependence (3.5σ):

$\log_{10}E_{break}=19.64\pm0.04$ for lower δ

$\log_{10}E_{break}=19.84\pm0.02$ for higher δ

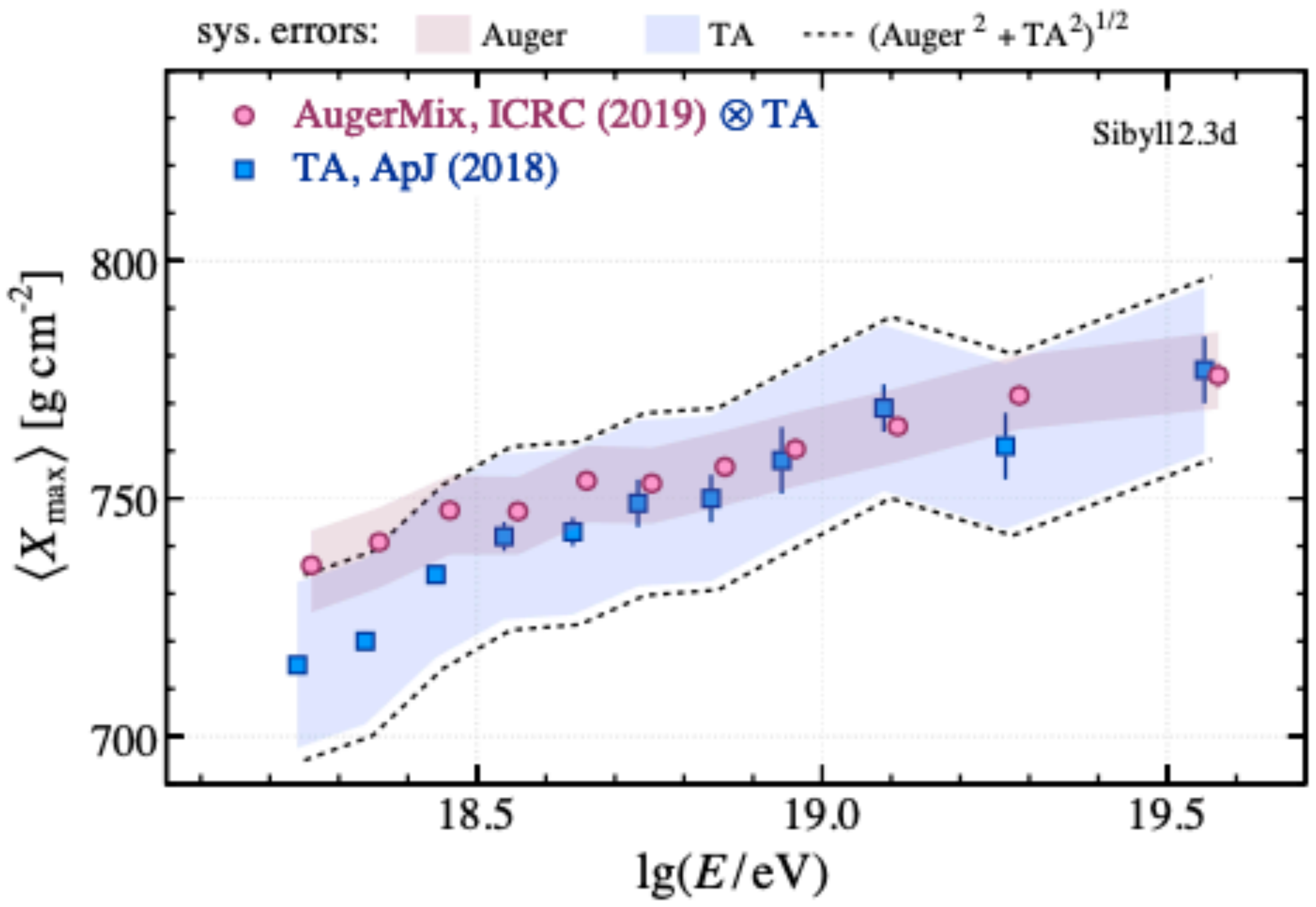


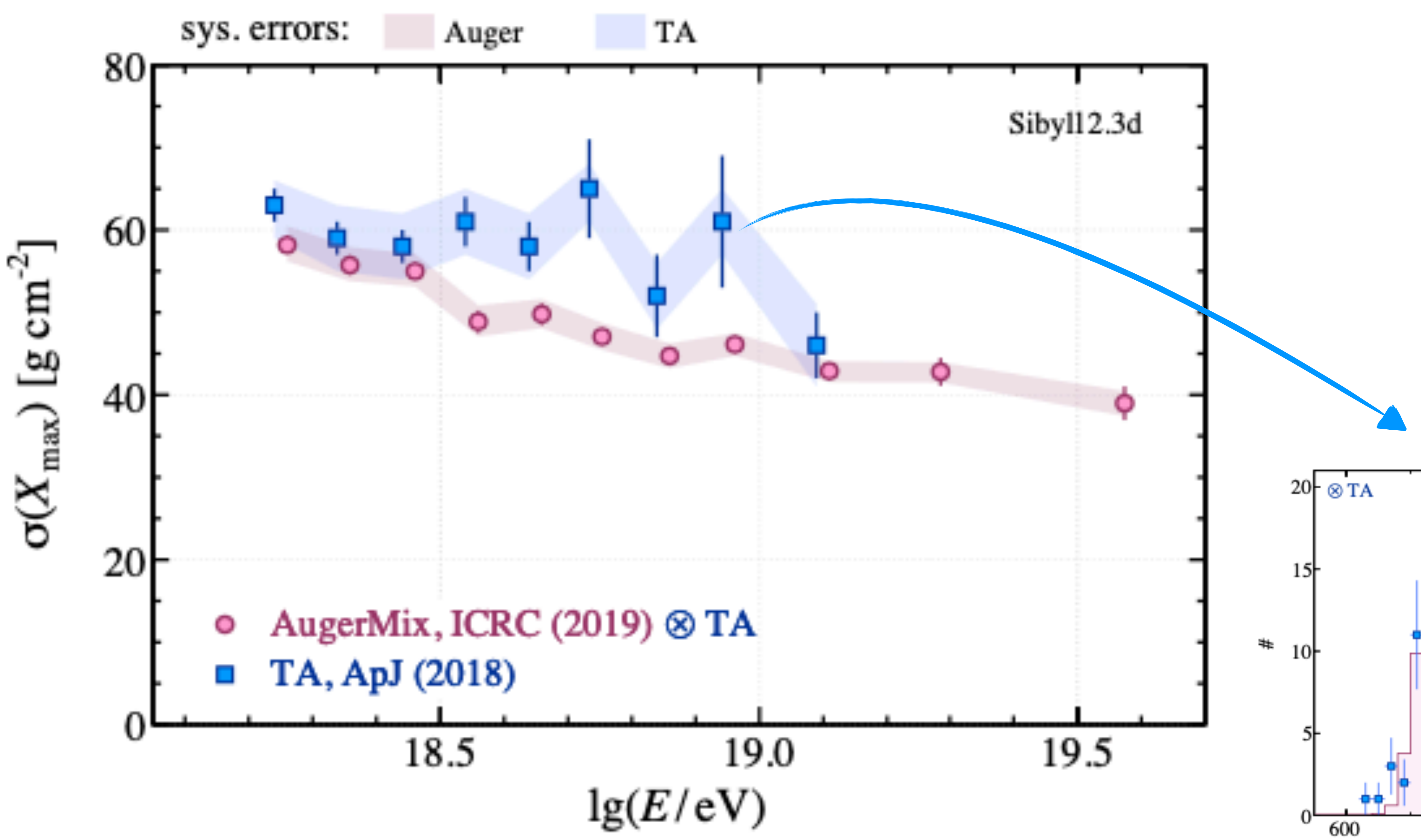


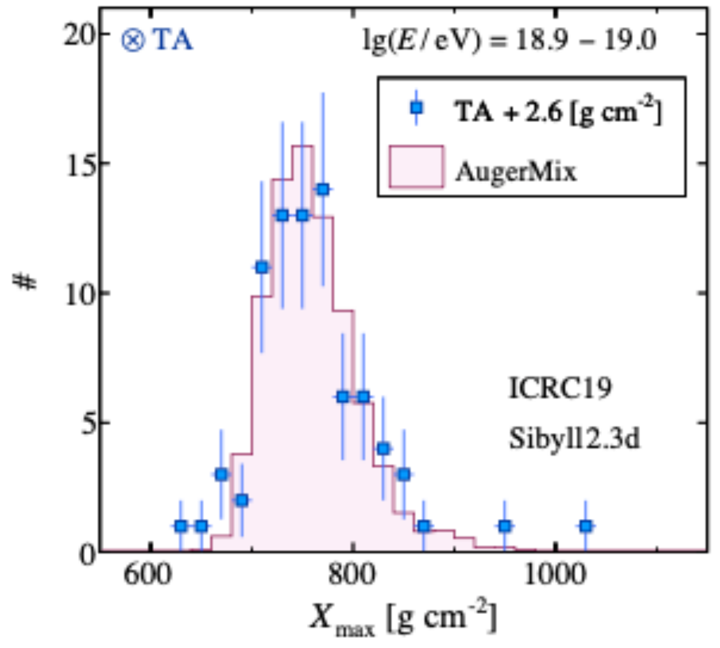
Auger-TA comparison : the mass composition

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







TA data consistent with proton and also with Auger-mix at least up to $10^{19.5}$ eV

Auger data on the contrary are incompatible with pure composition (4.4σ exclusion of constant ER)

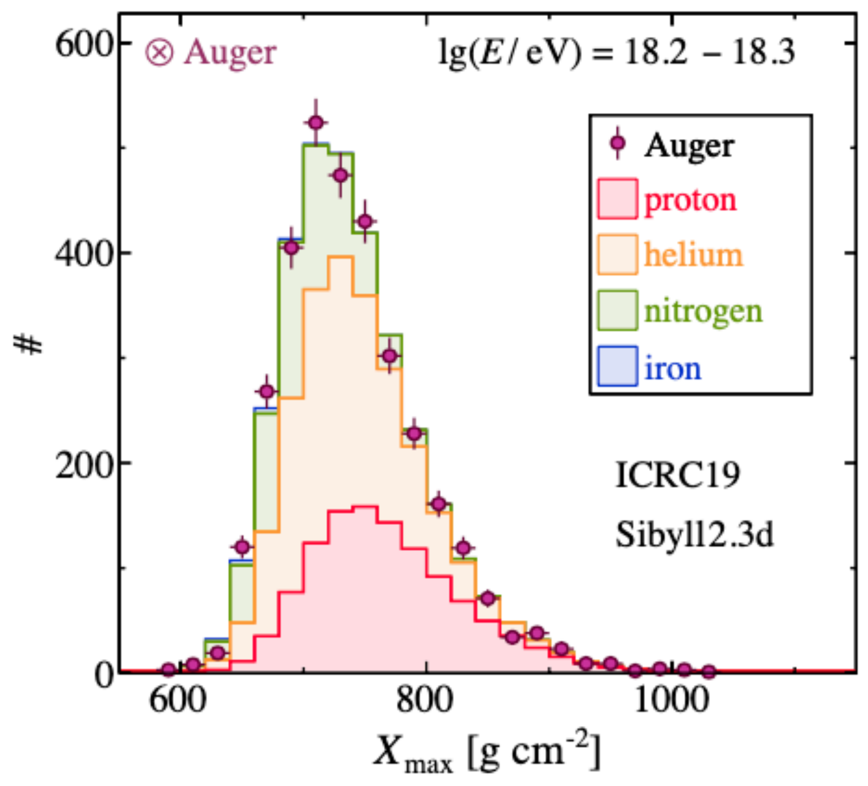
A.Yushkov, Joint Auger+TA WG
PoS(ICRC2023) 249

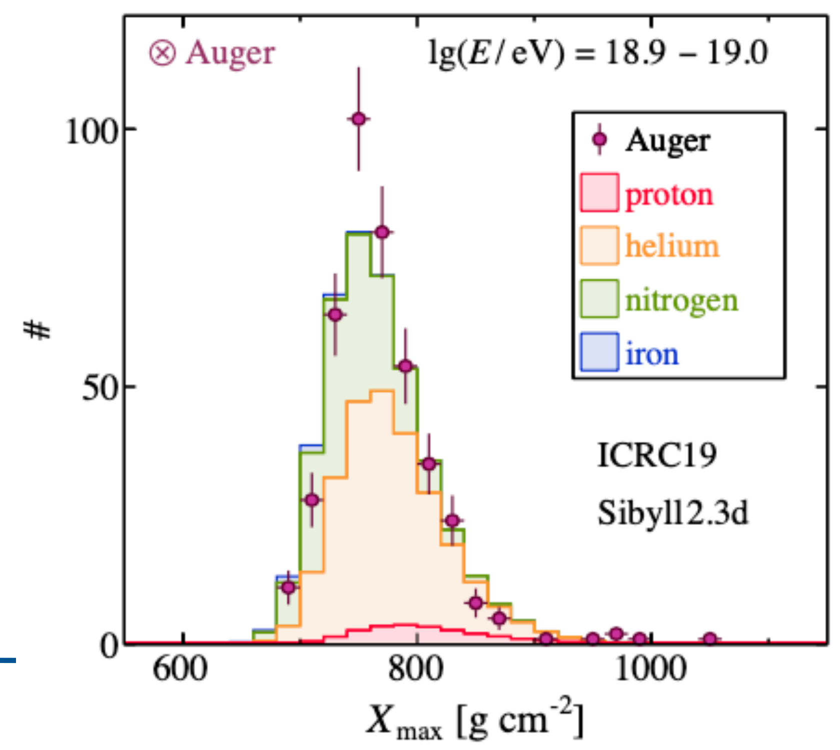
The UHECR mass composition

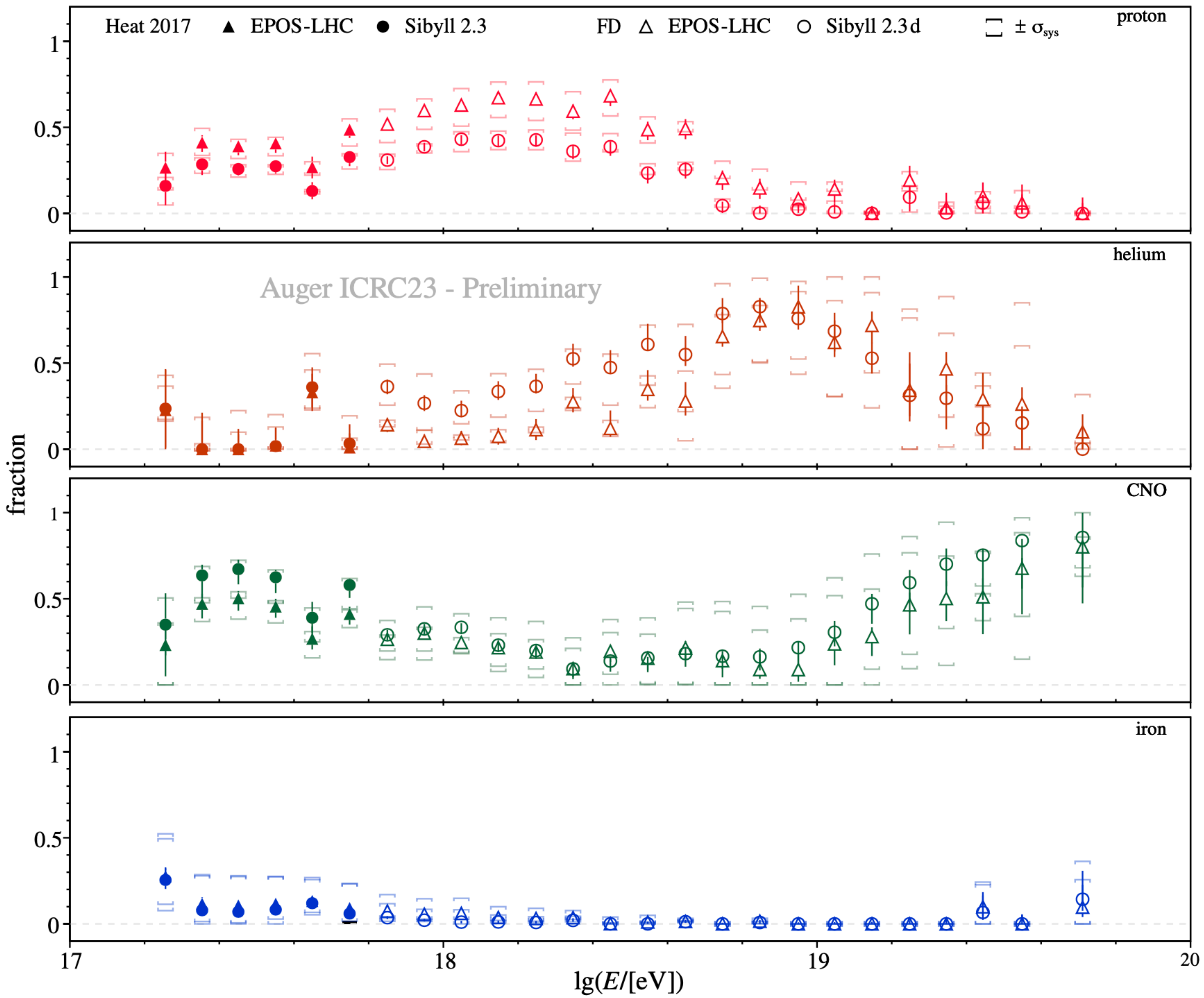
The fractions of elements can be derived from model dependent fits of the X_{max} distributions

- Provide model dependent information on the mass evolution

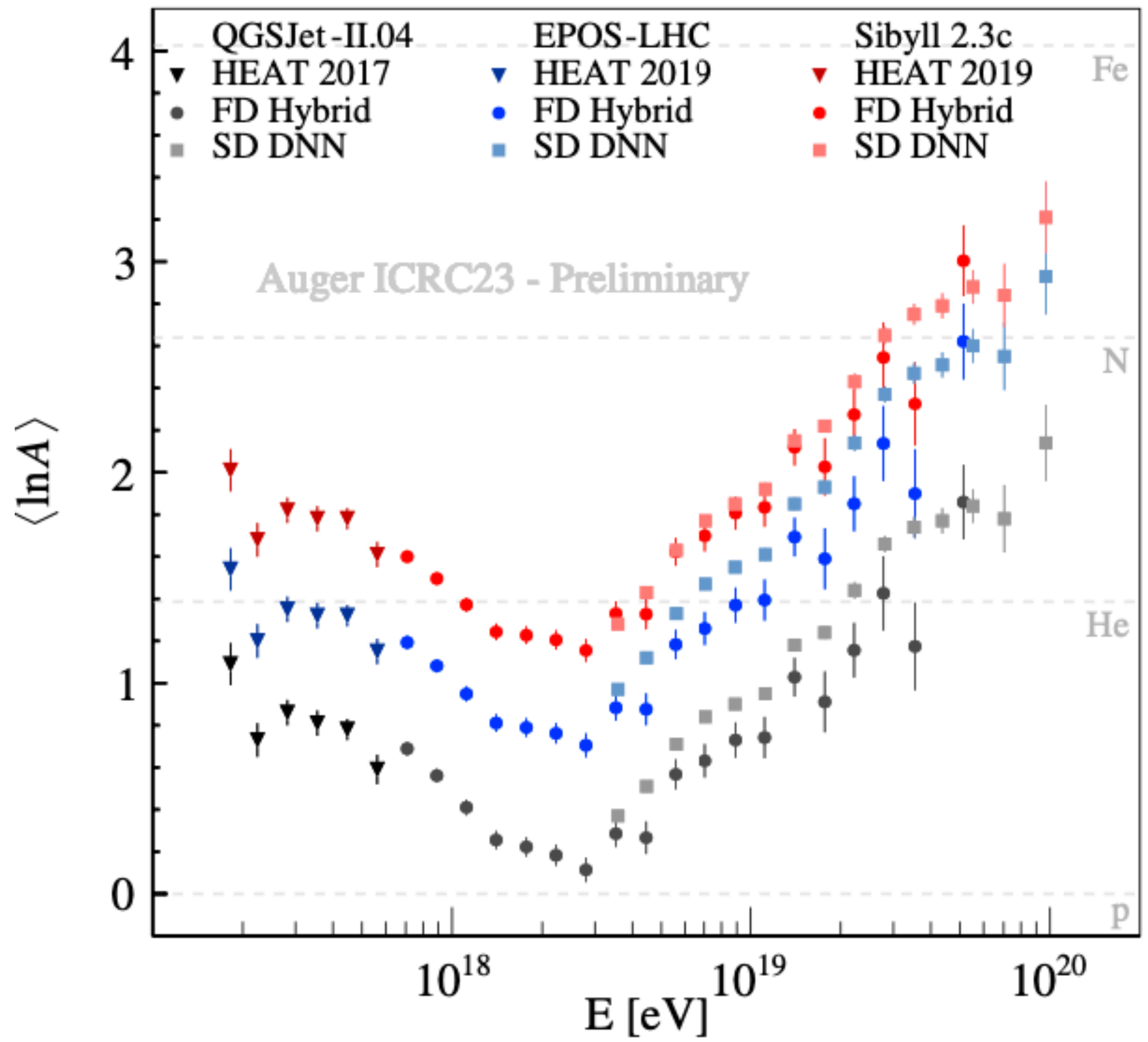
→in line with E_{max} ~a few EeV x (Z or A)

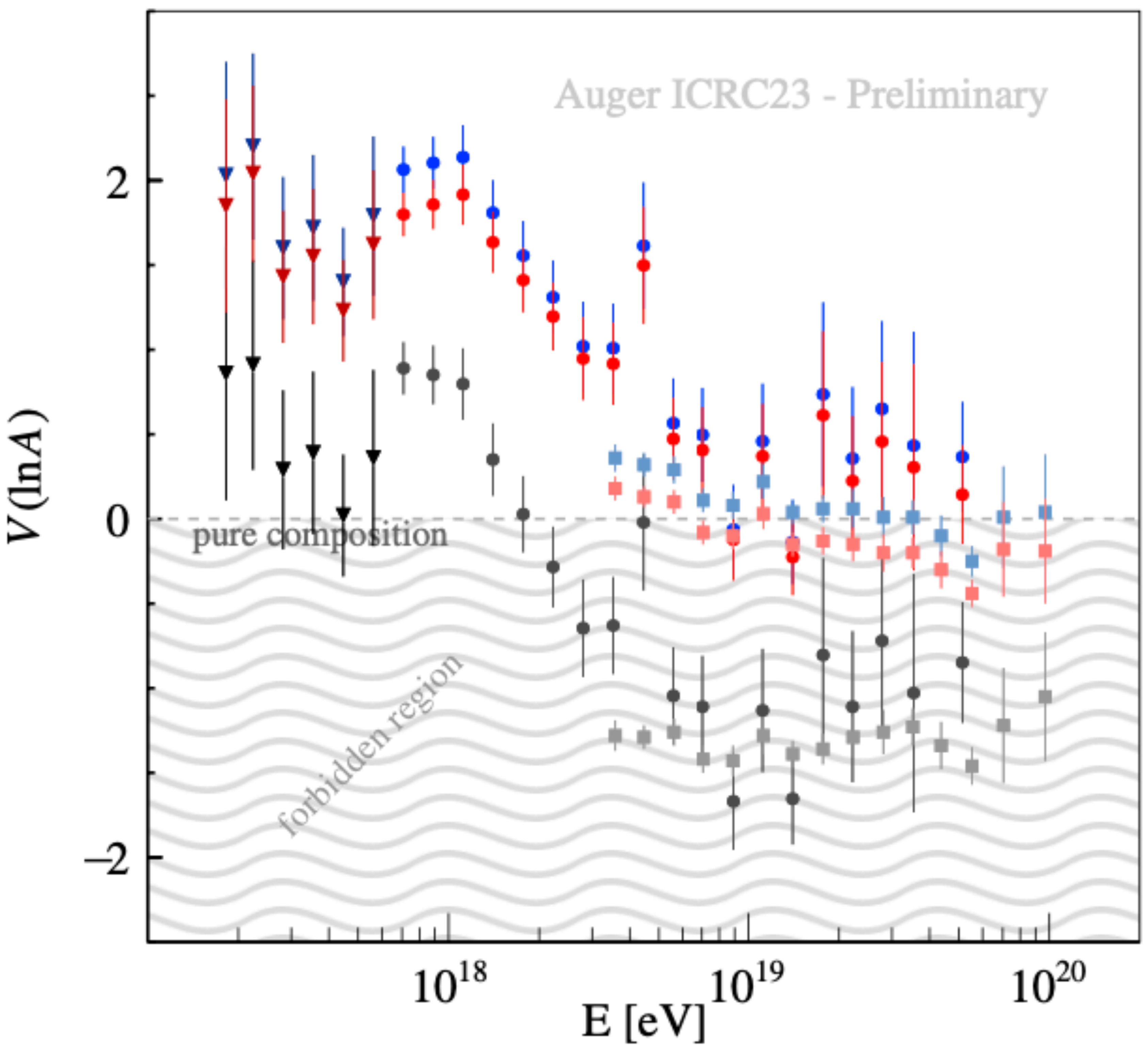






The UHECR mass composition





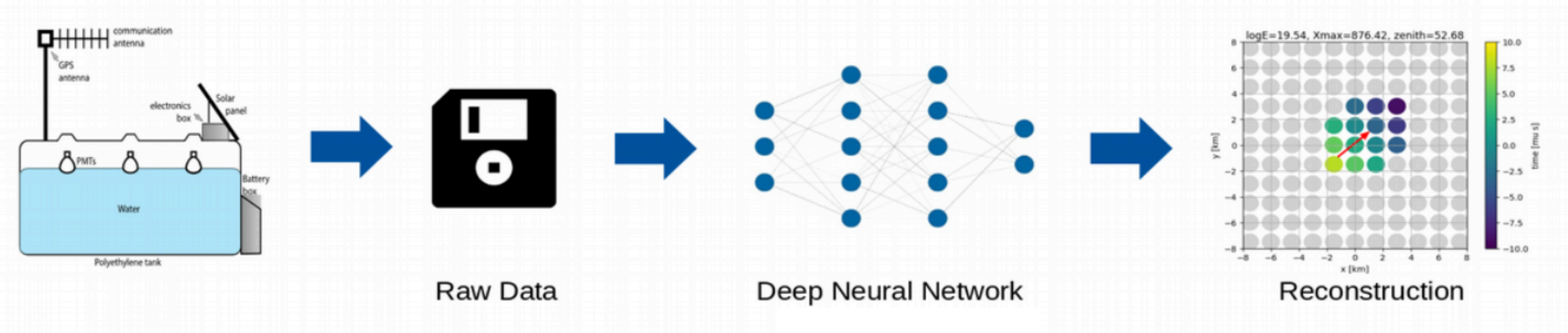
$$\langle \ln A \rangle = \frac{\langle X_{\max} \rangle - \langle X_{\max} \rangle_p}{f_E}$$

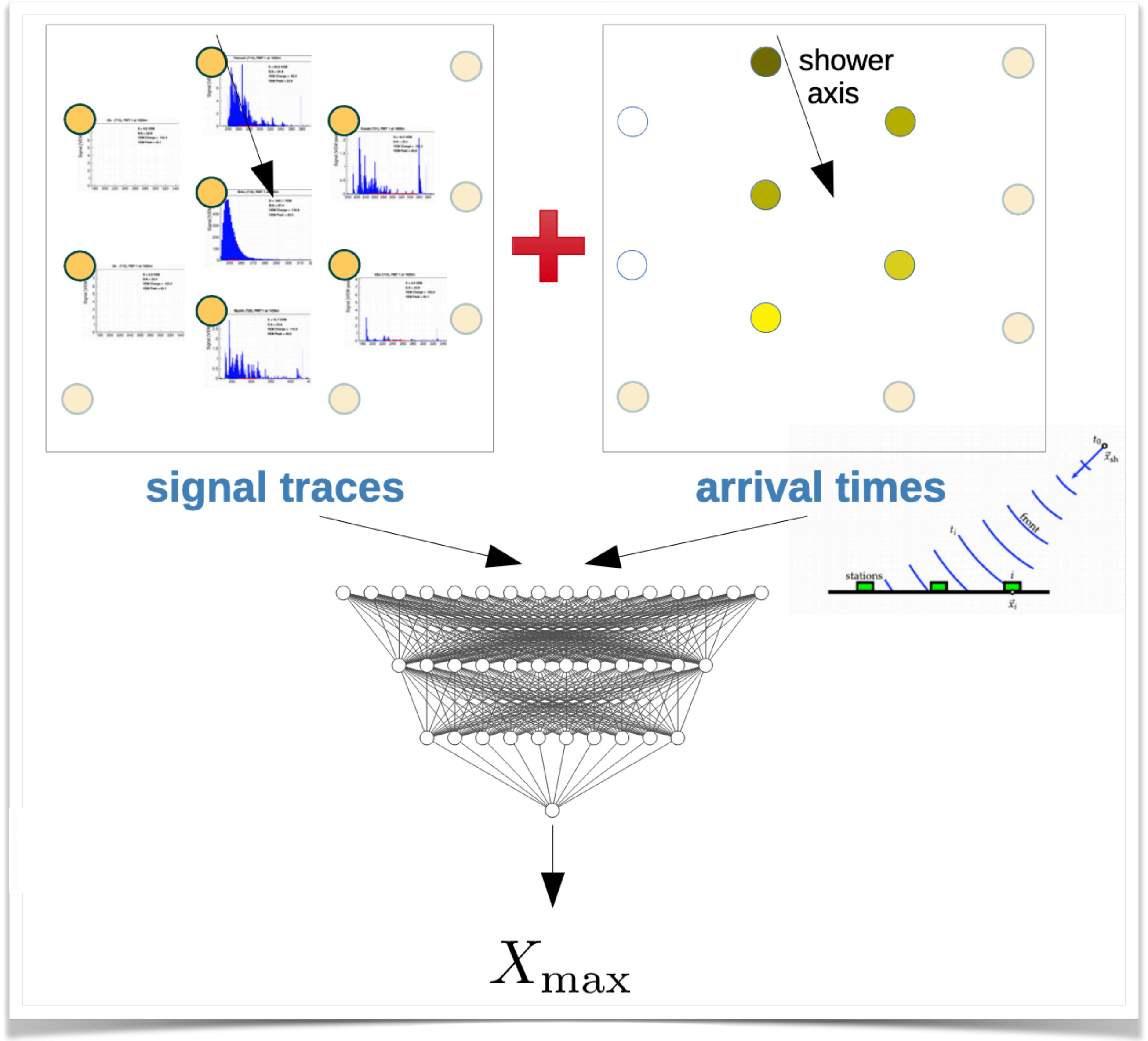
$$\sigma^2_{\ln A} = \frac{\sigma^2(X_{\max}) - \sigma^2_{\rm sh}(\langle \ln A \rangle)}{b\ \sigma^2_p + f^2_E}$$

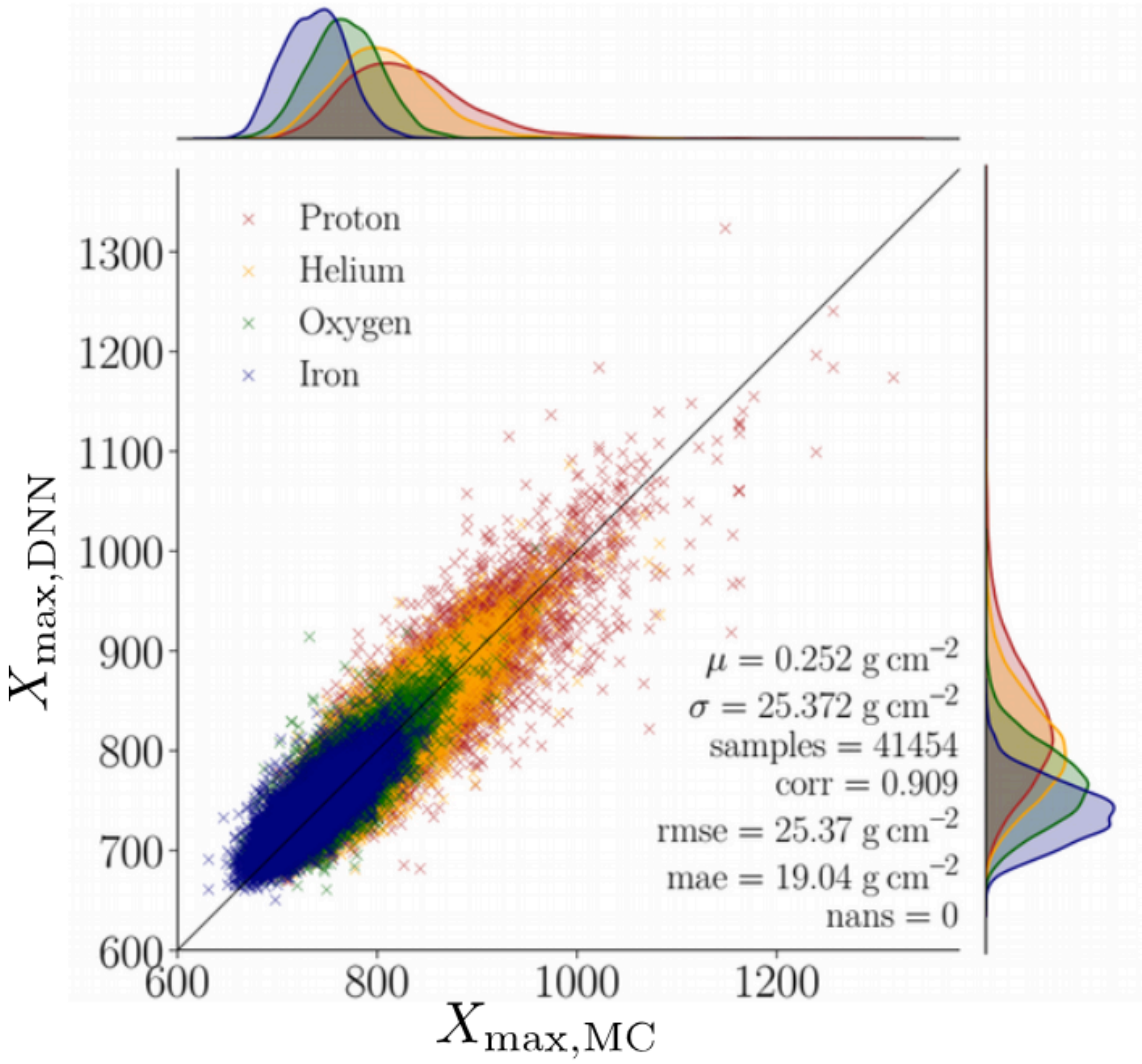
$f_{(E)}$, a, b depend on hadronic interactions

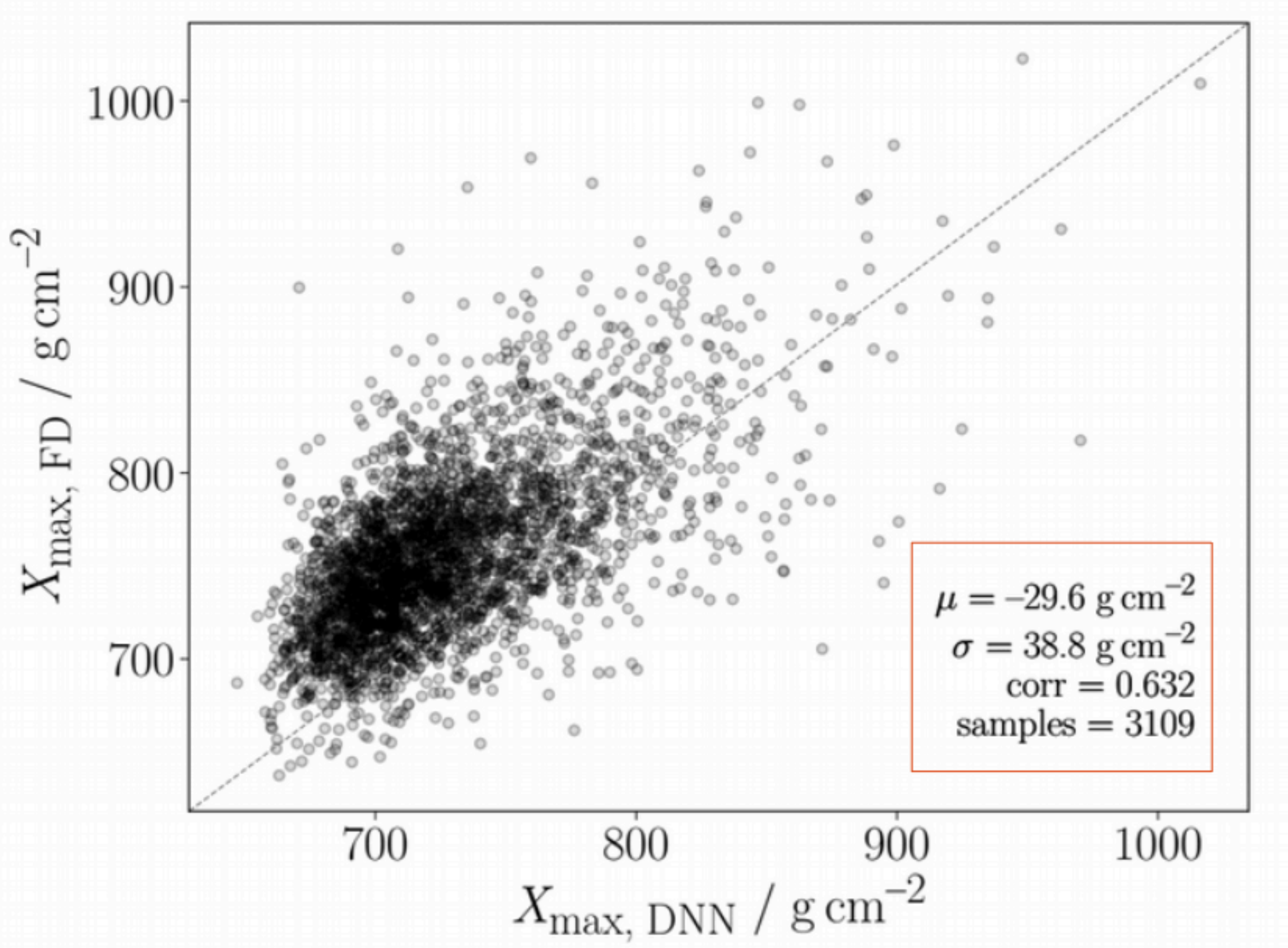
- Impressive agreement between FD and SD derived measurements
- QGSJetII-04 not suitable to describe the data

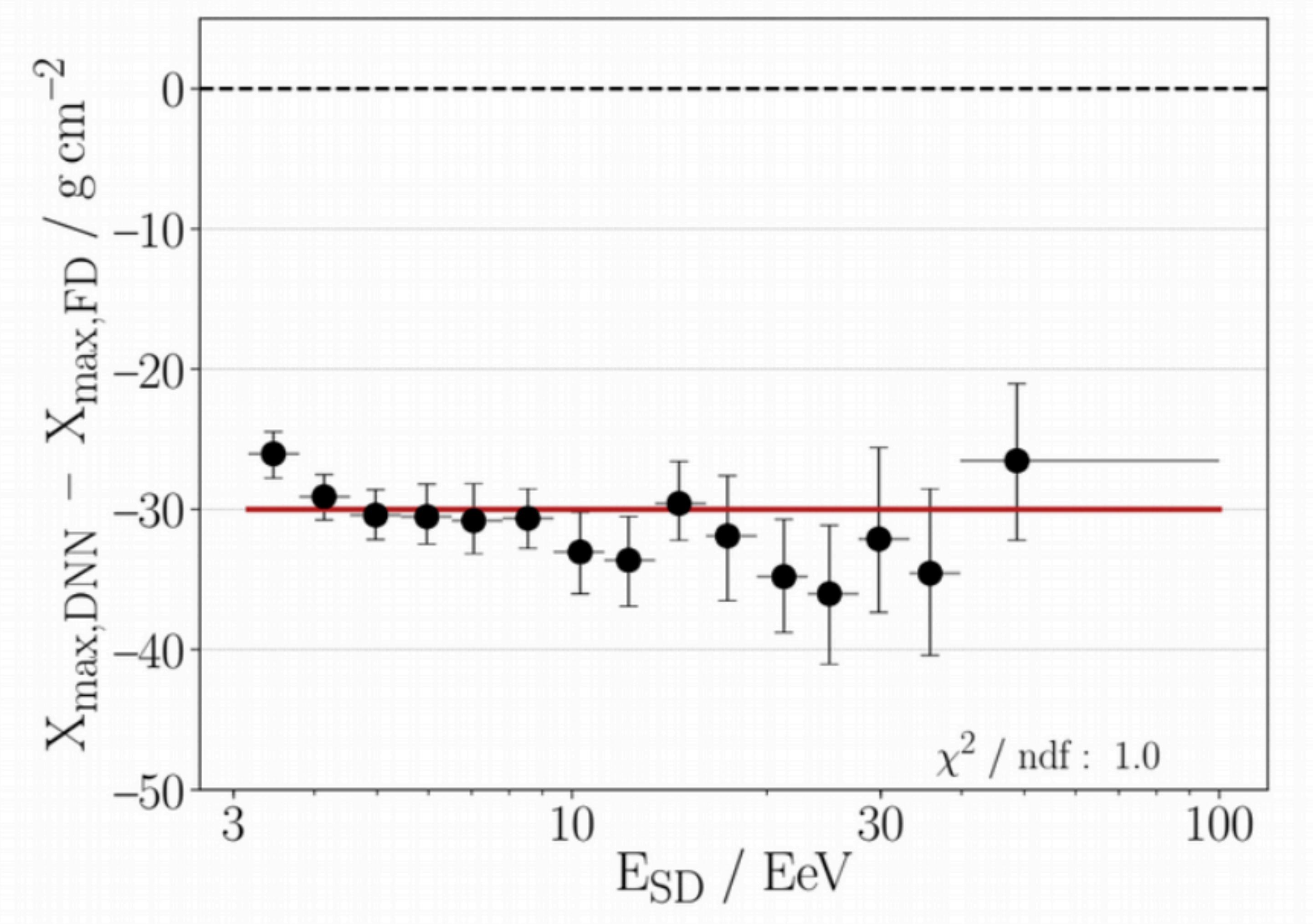
Multi-hybrid events and Machine Learning







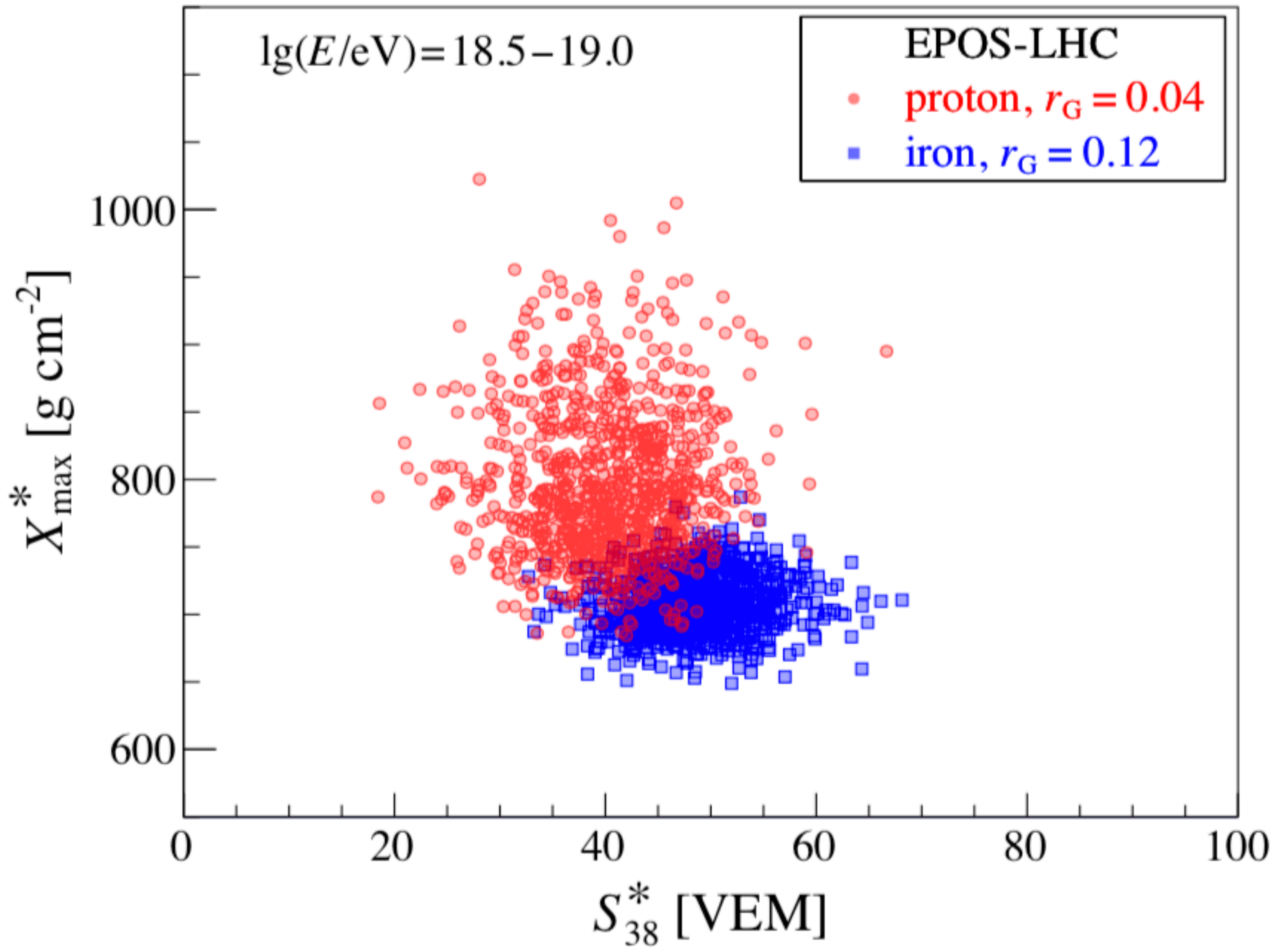


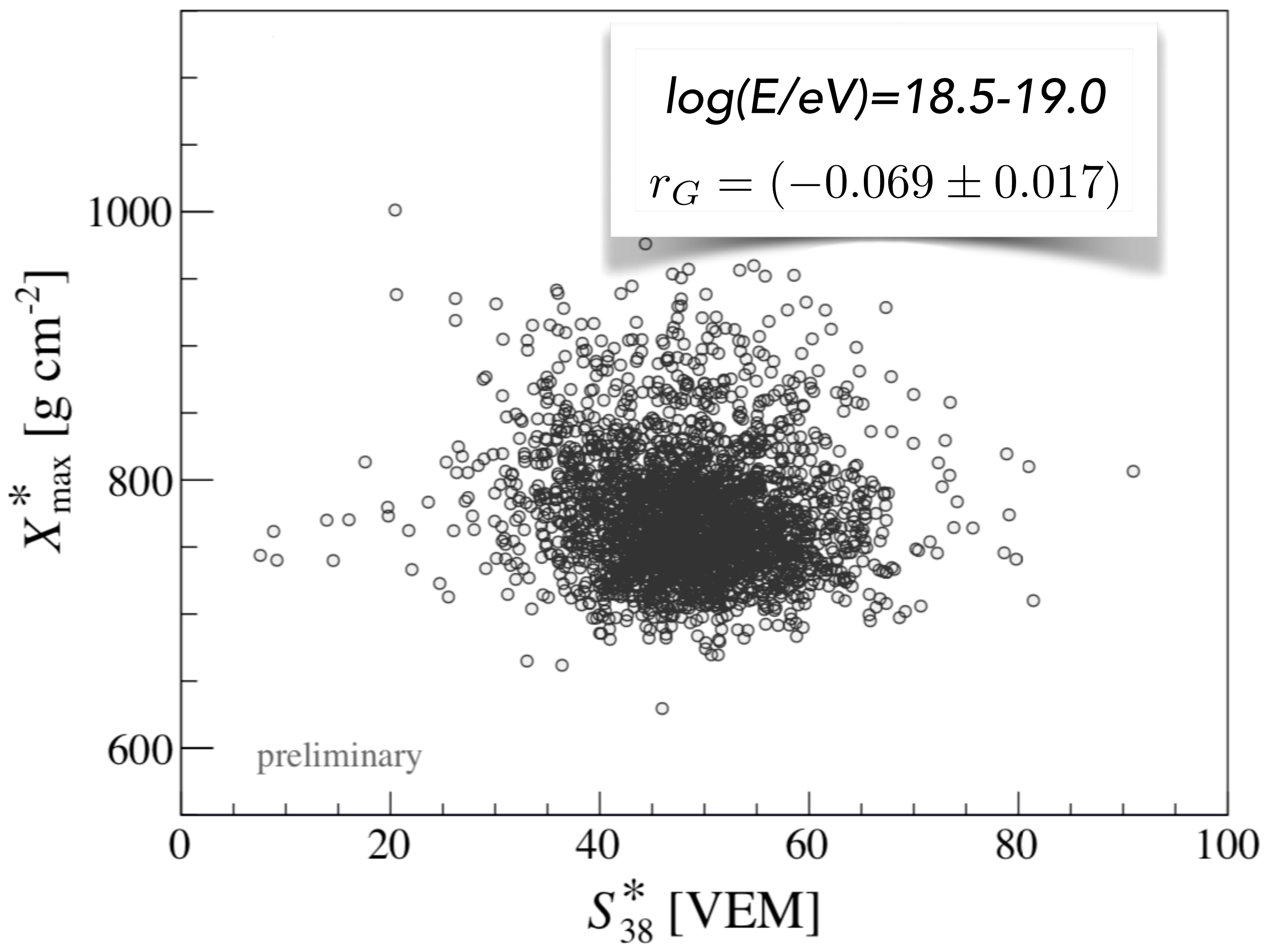


powerful Machine Learning techniques need to be cross-checked
by means of multi-hybrid measurements!

Heavy or light? An independent measurement

Auger Coll., Phys.Lett. B762 (2016) 288
A.Yushkov, PoS(ICRC2019) 482



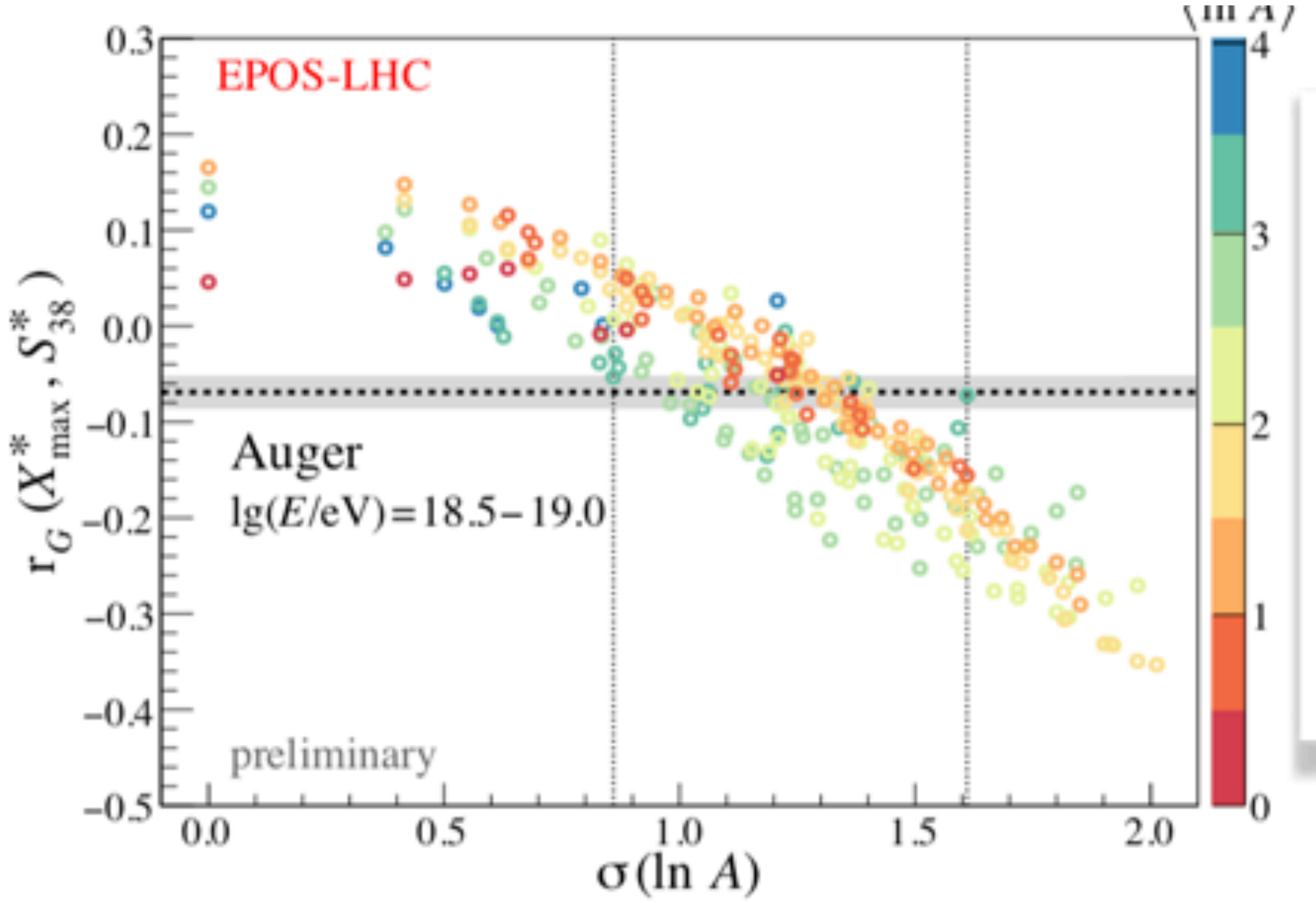


Abow the ankle

$$r_G = (0.025 \pm 0.028)$$

Below the ankle

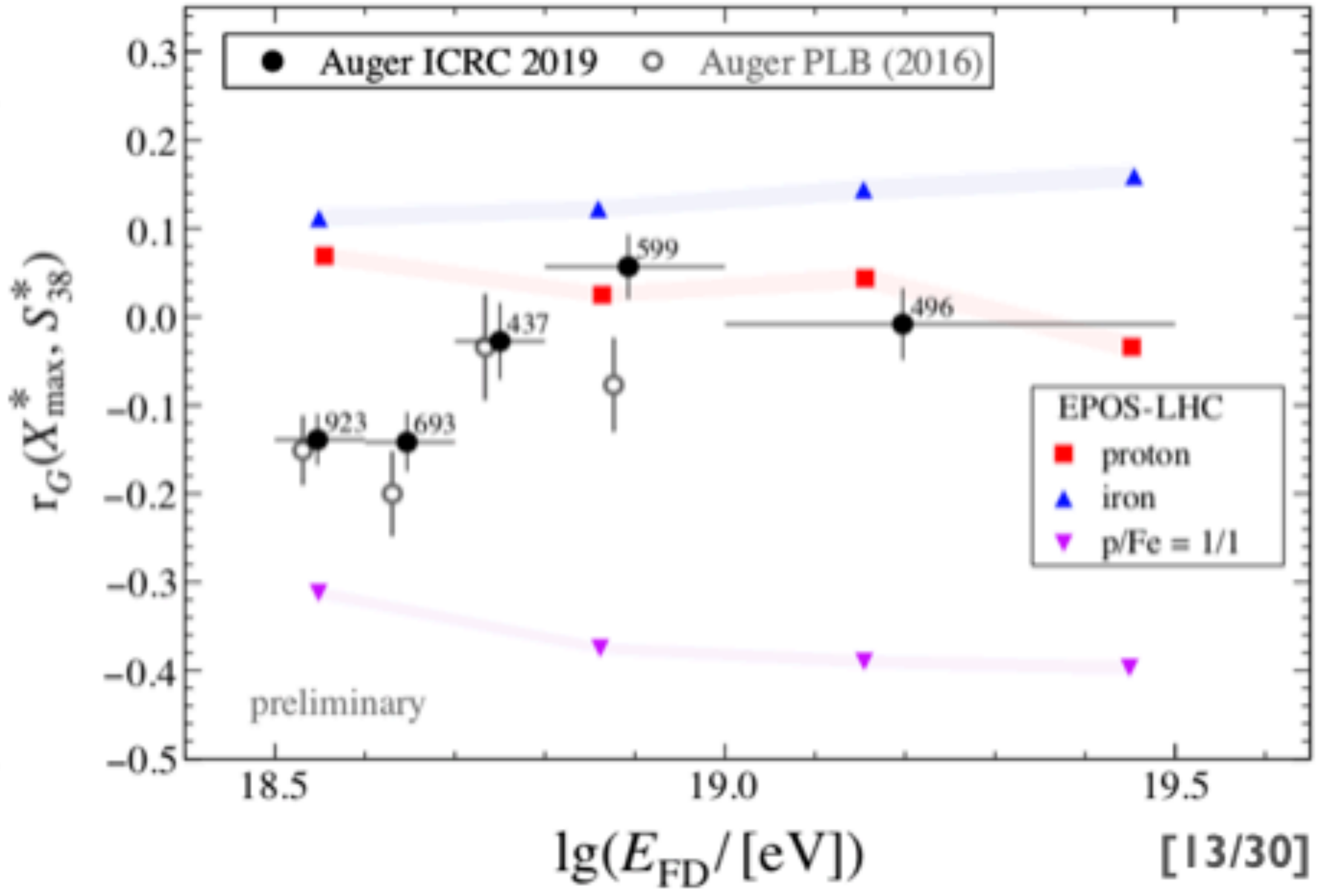
$$r_G = (-0.141 \pm 0.022)$$



Data compatible with 0.85 ≤σ(lnA)≤1.60
same for all models

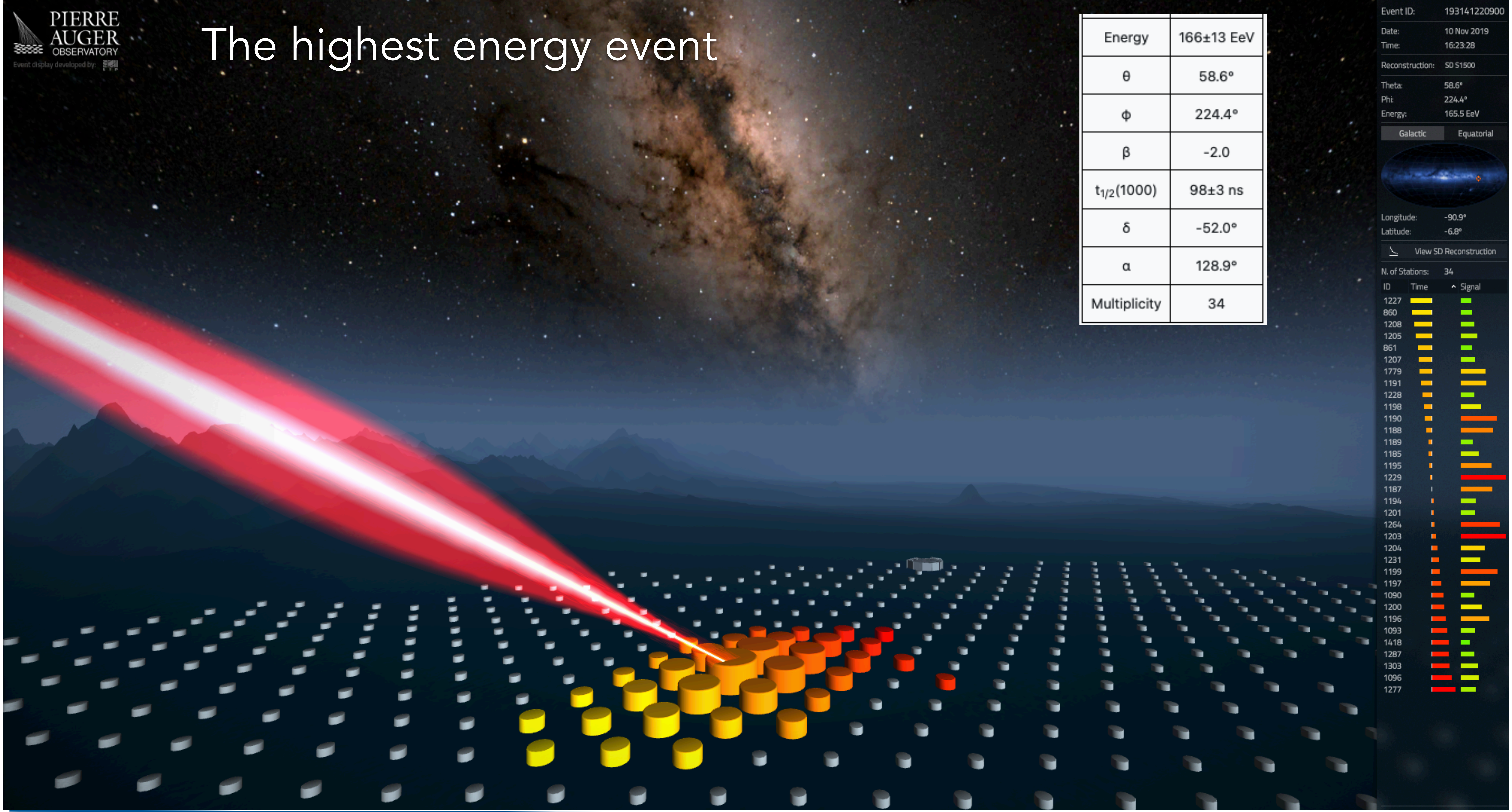
Up to the ankle pure or (p+He) compositions excluded at >6σ

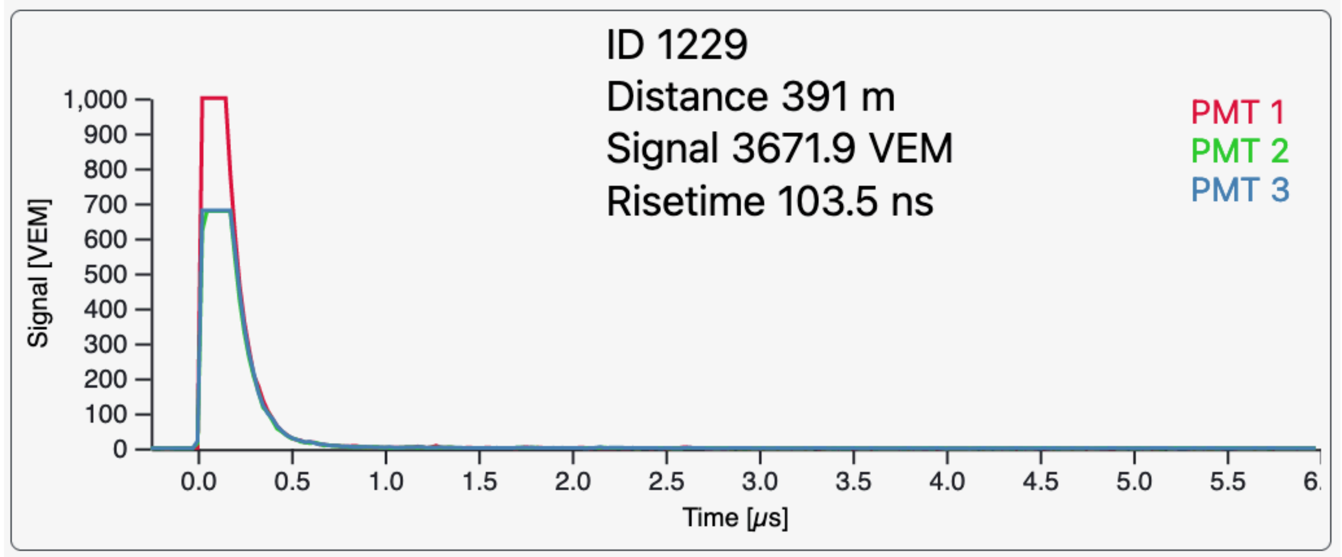
At higher energies, correlation consistent with less mixed composition

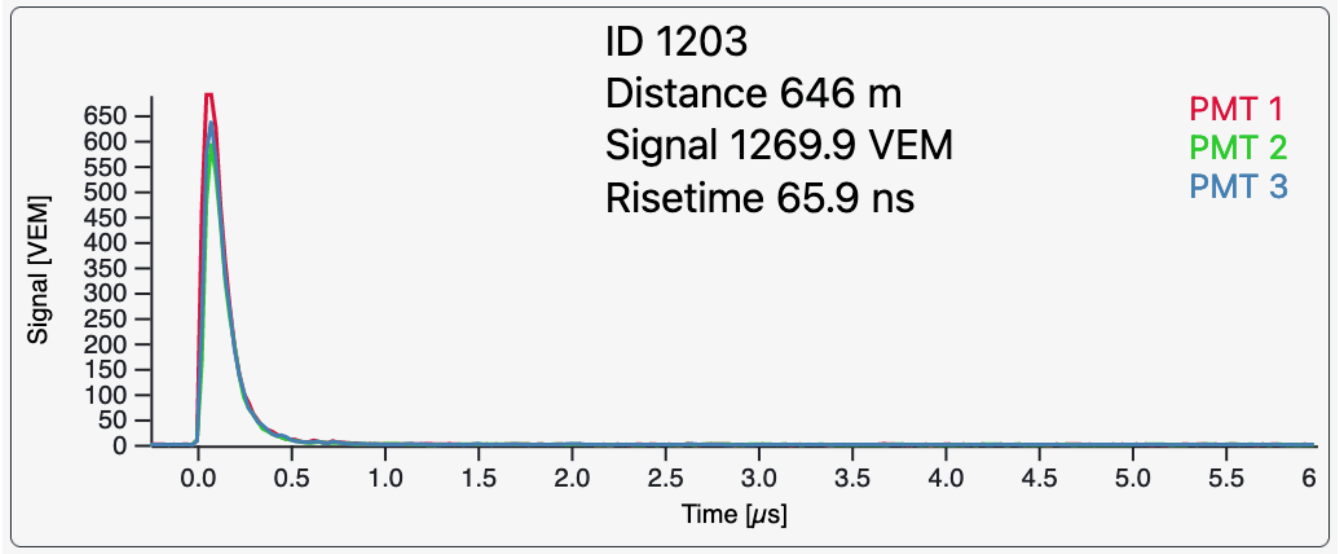


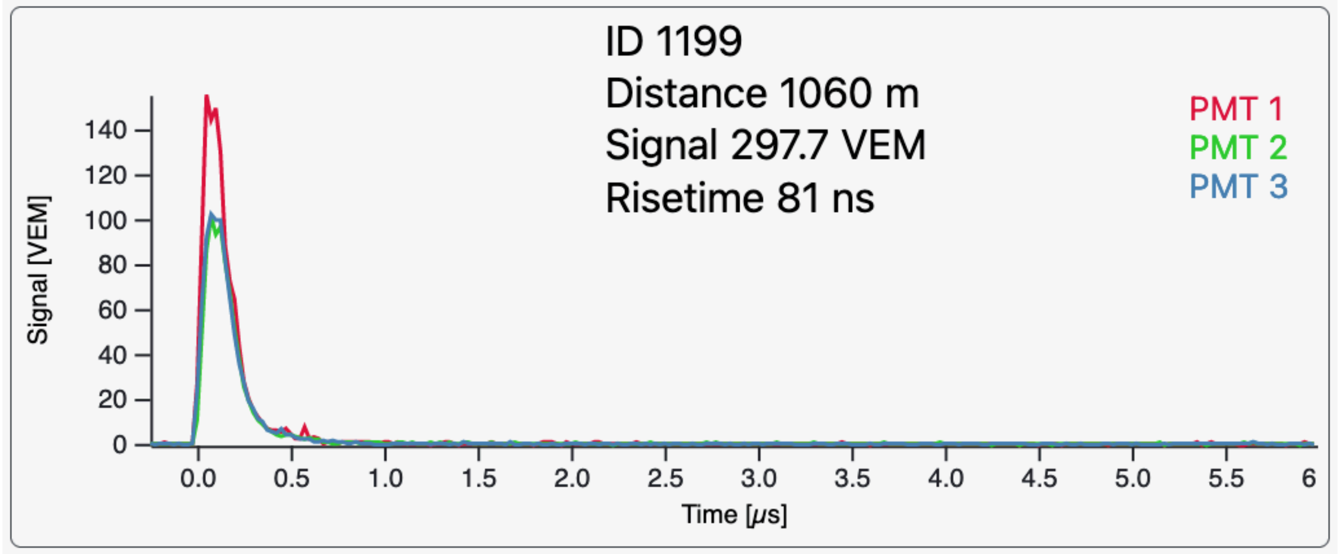
The highest energy event

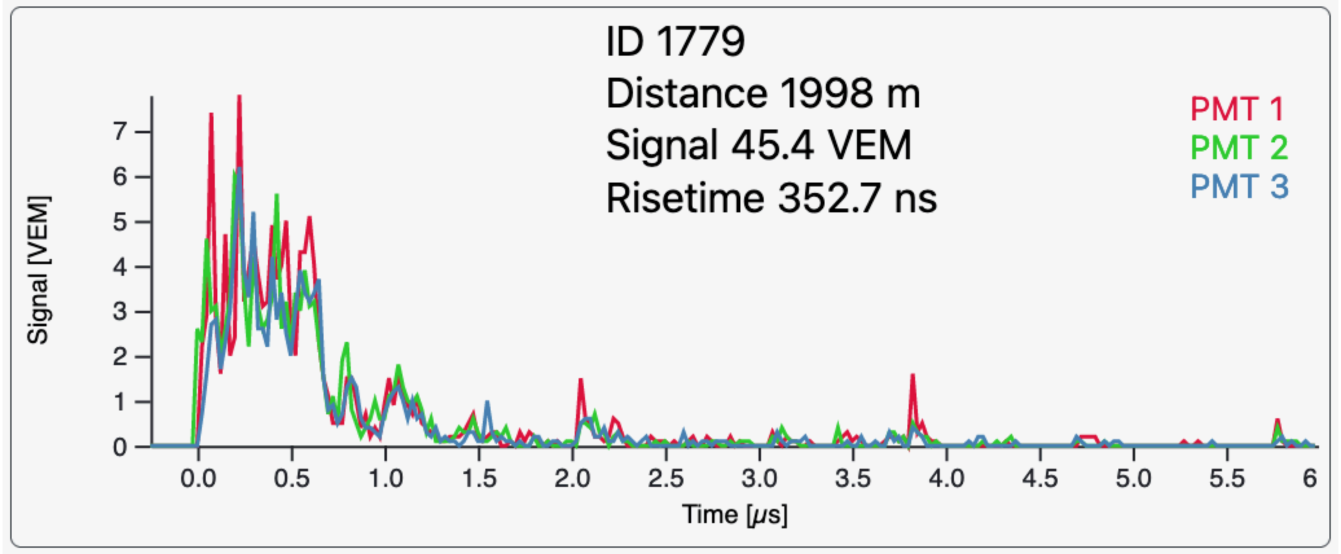
Energy	166±13 EeV
θ	58.6°
ϕ	224.4°
β	-2.0
$t_{1/2}(1000)$	98±3 ns
δ	-52.0°
α	128.9°
Multiplicity	34

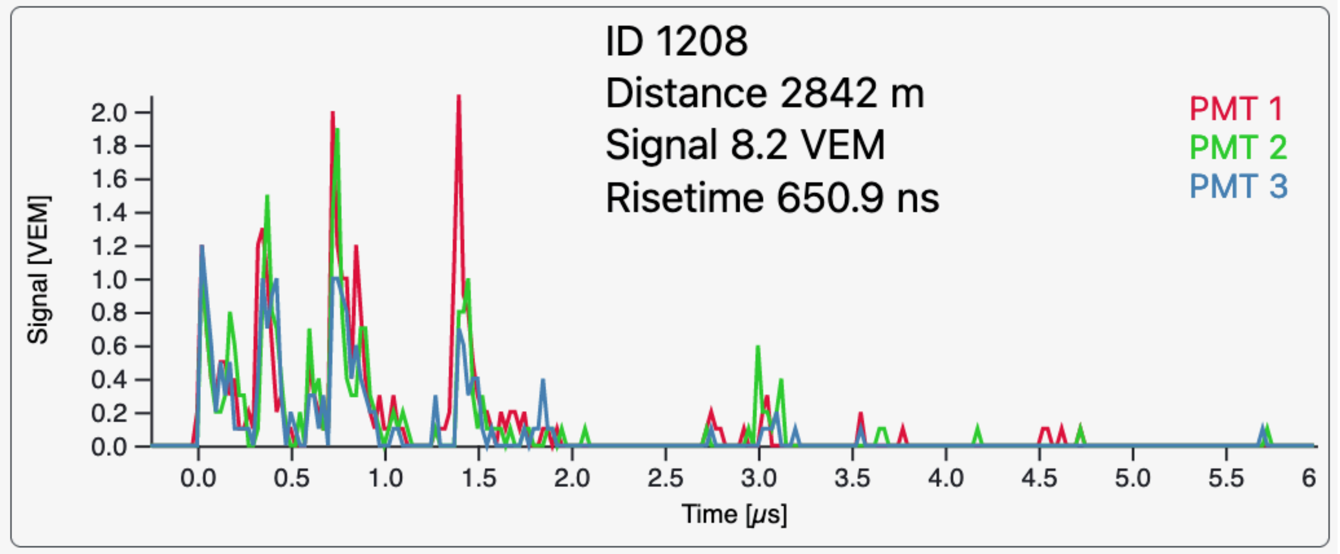


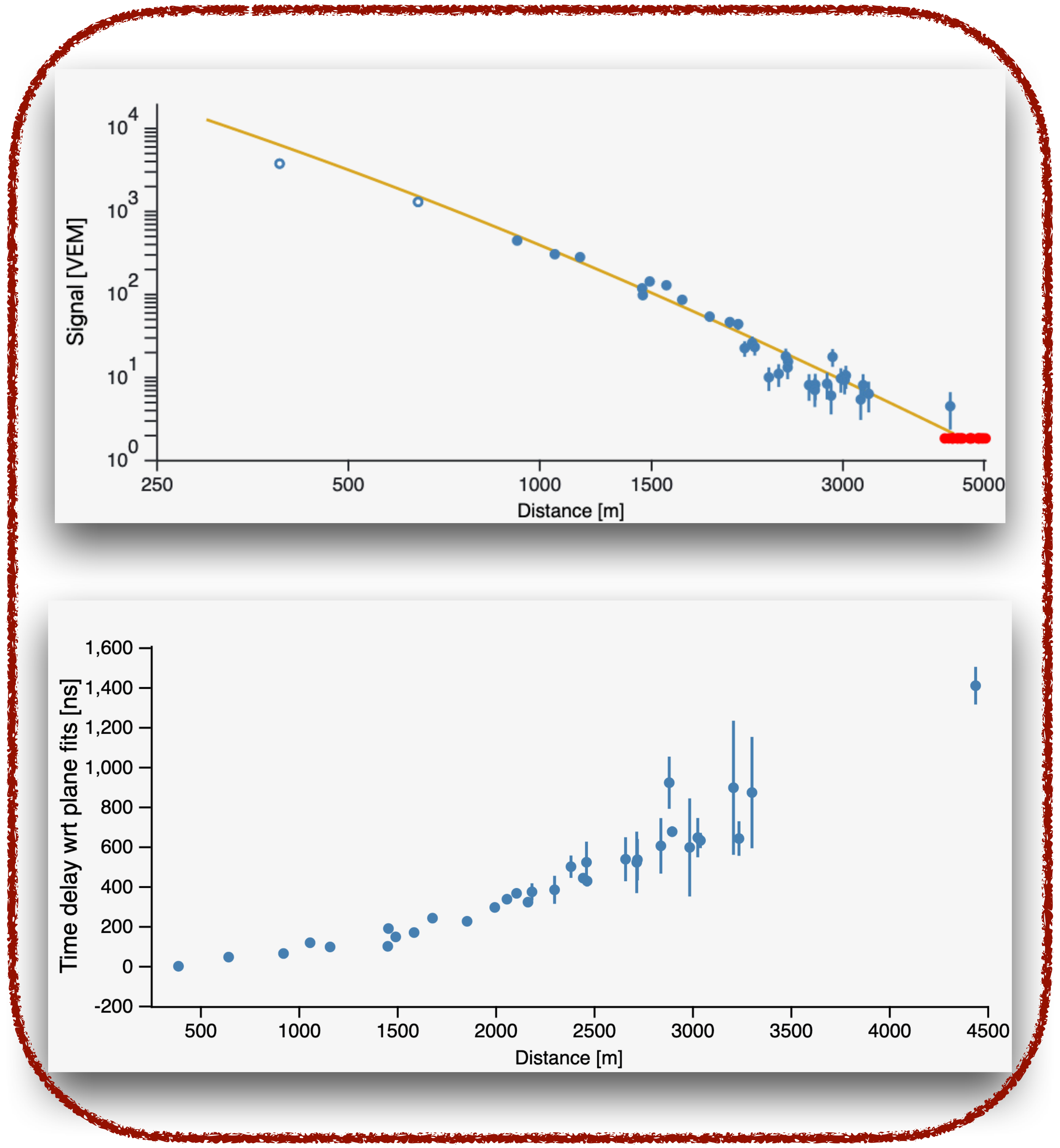






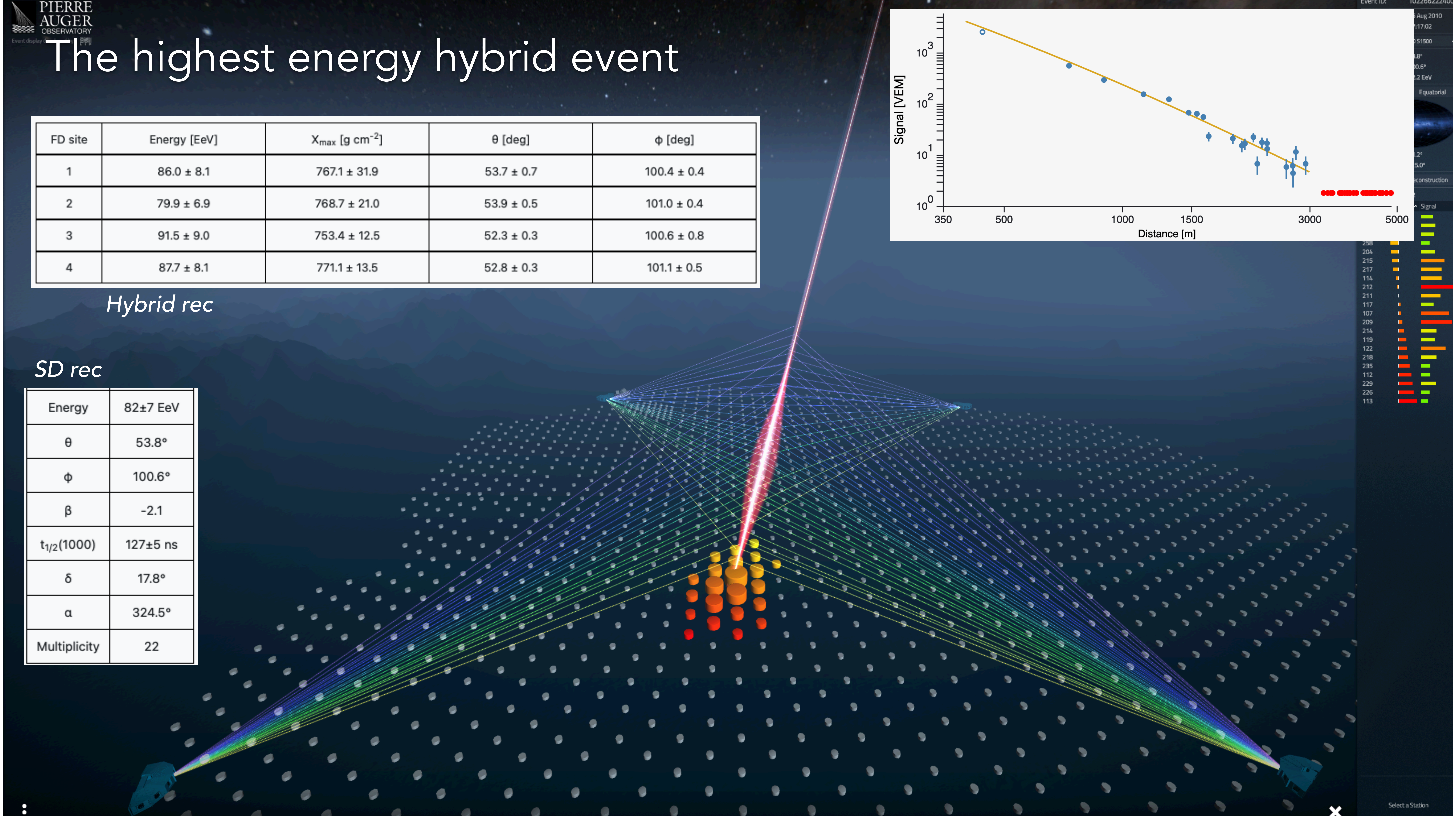






Date	2019-11-10
Energy	166±13 EeV
θ	58.6°
ϕ	224.4°
β	-2.0
$t_{1/2}(1000)$	98±3 ns
δ	-52.0°
α	128.9°
Multiplicity	34

The highest energy hybrid event

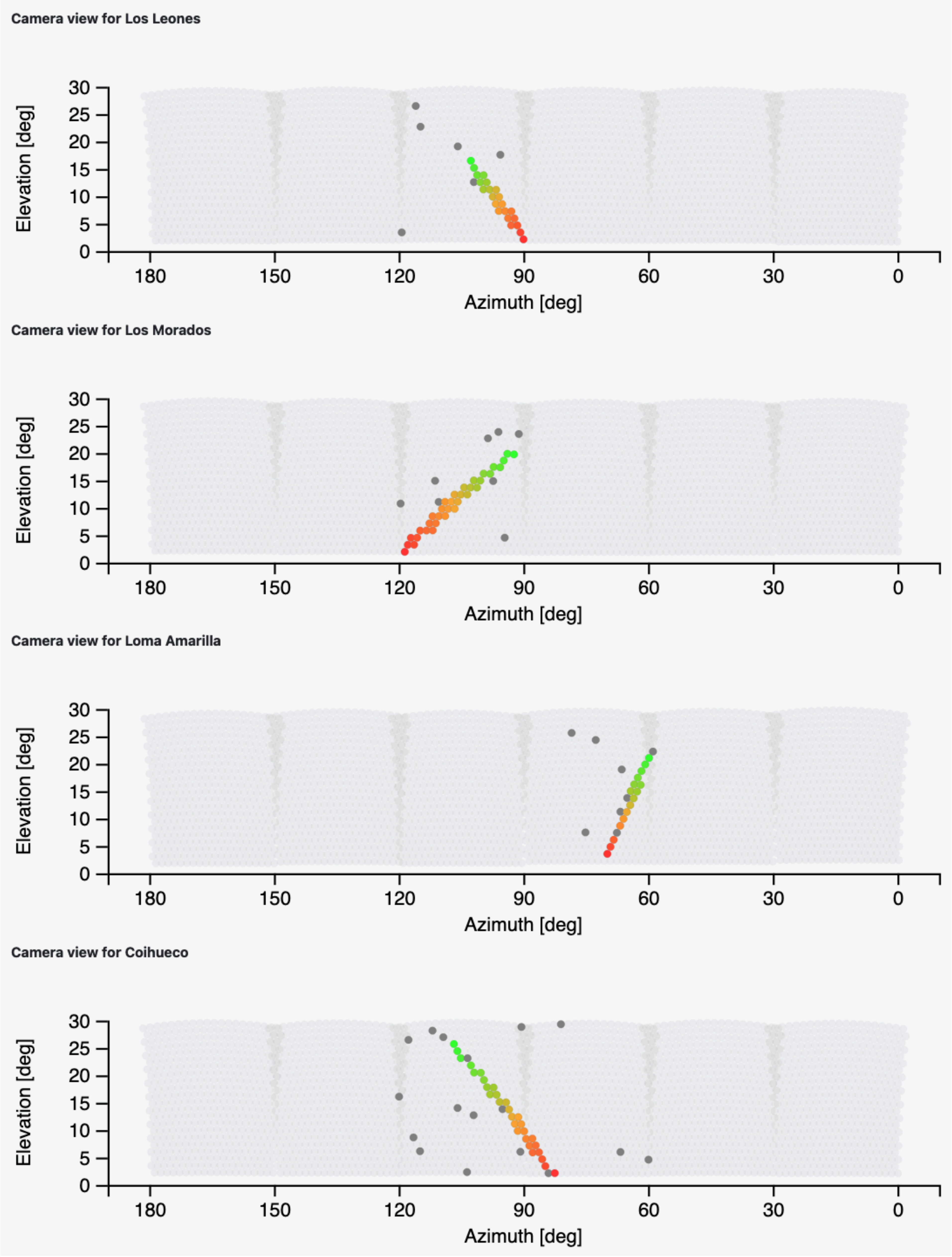


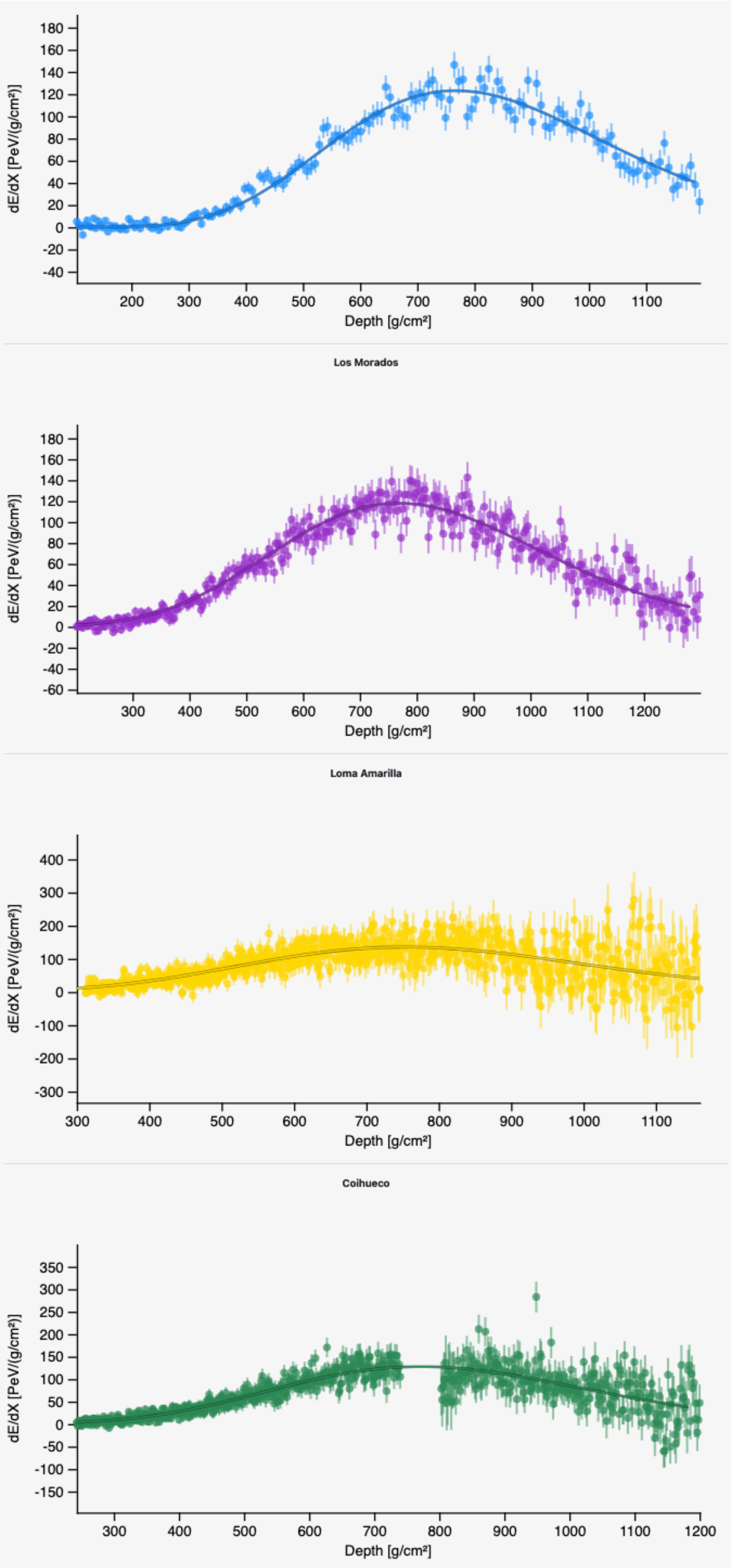
FD site	Energy [EeV]	X_{max} [g cm^{-2}]	θ [deg]	ϕ [deg]
1	86.0 ± 8.1	767.1 ± 31.9	53.7 ± 0.7	100.4 ± 0.4
2	79.9 ± 6.9	768.7 ± 21.0	53.9 ± 0.5	101.0 ± 0.4
3	91.5 ± 9.0	753.4 ± 12.5	52.3 ± 0.3	100.6 ± 0.8
4	87.7 ± 8.1	771.1 ± 13.5	52.8 ± 0.3	101.1 ± 0.5

Hybrid rec

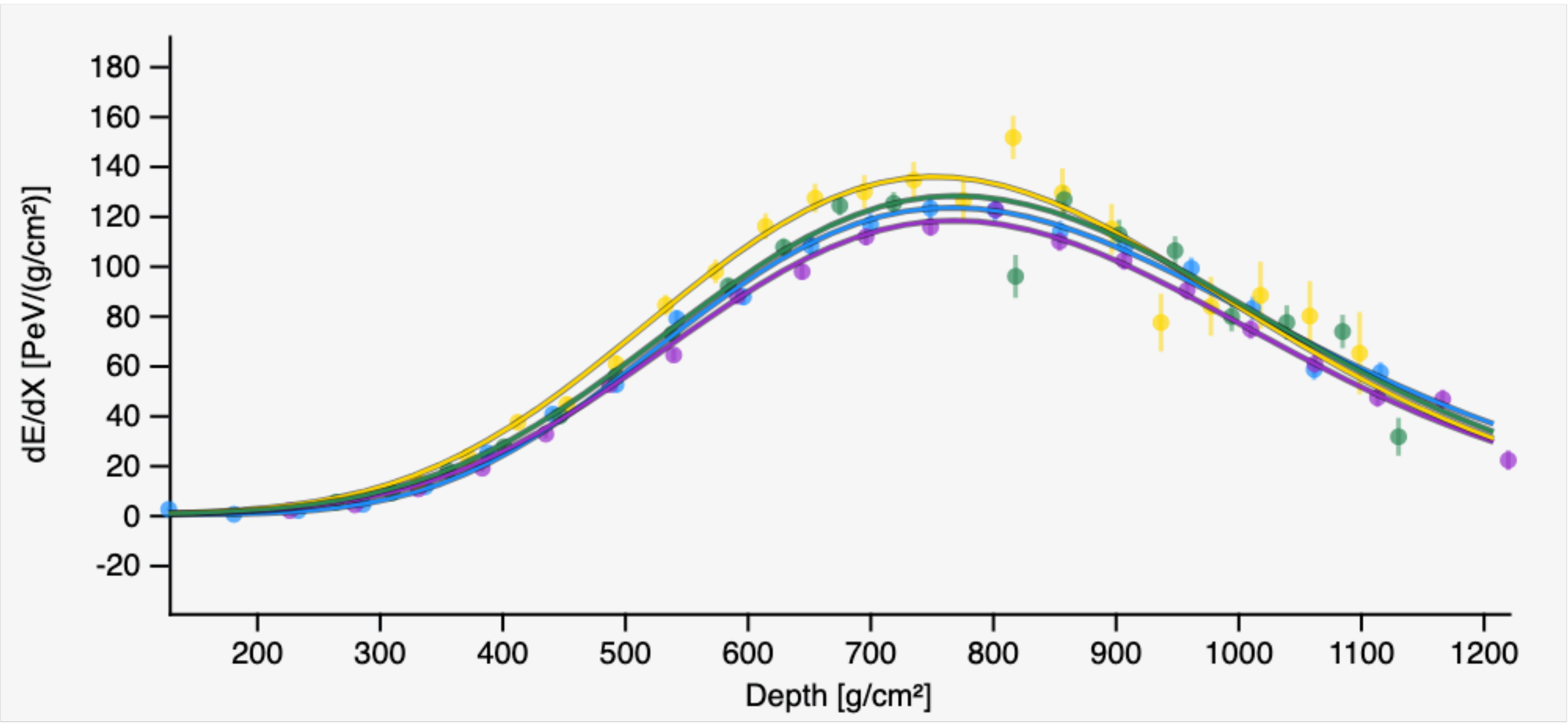
SD rec

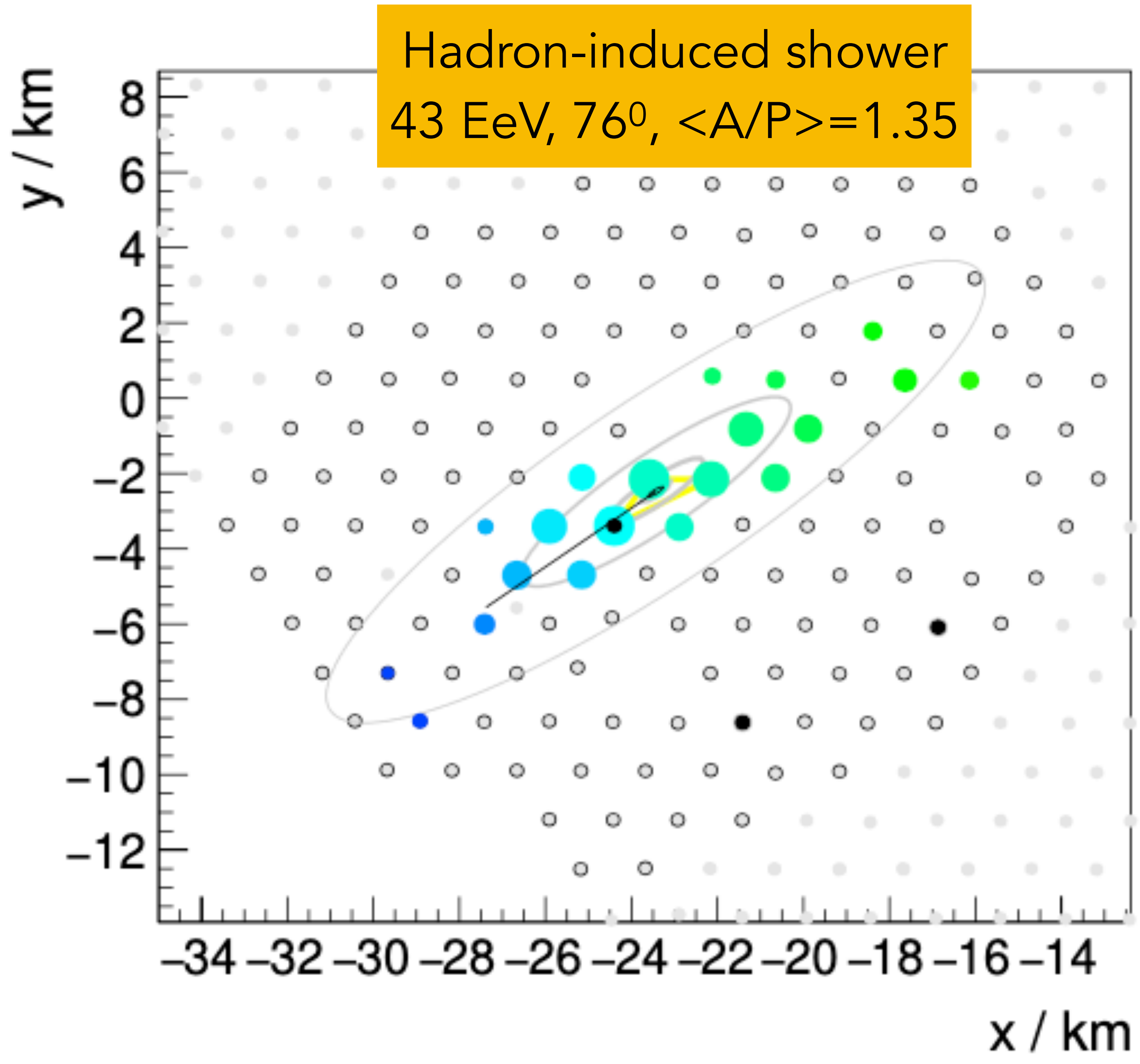
Energy	82±7 EeV
θ	53.8°
ϕ	100.6°
β	-2.1
$t_{1/2}(1000)$	127±5 ns
δ	17.8°
α	324.5°
Multiplicity	22

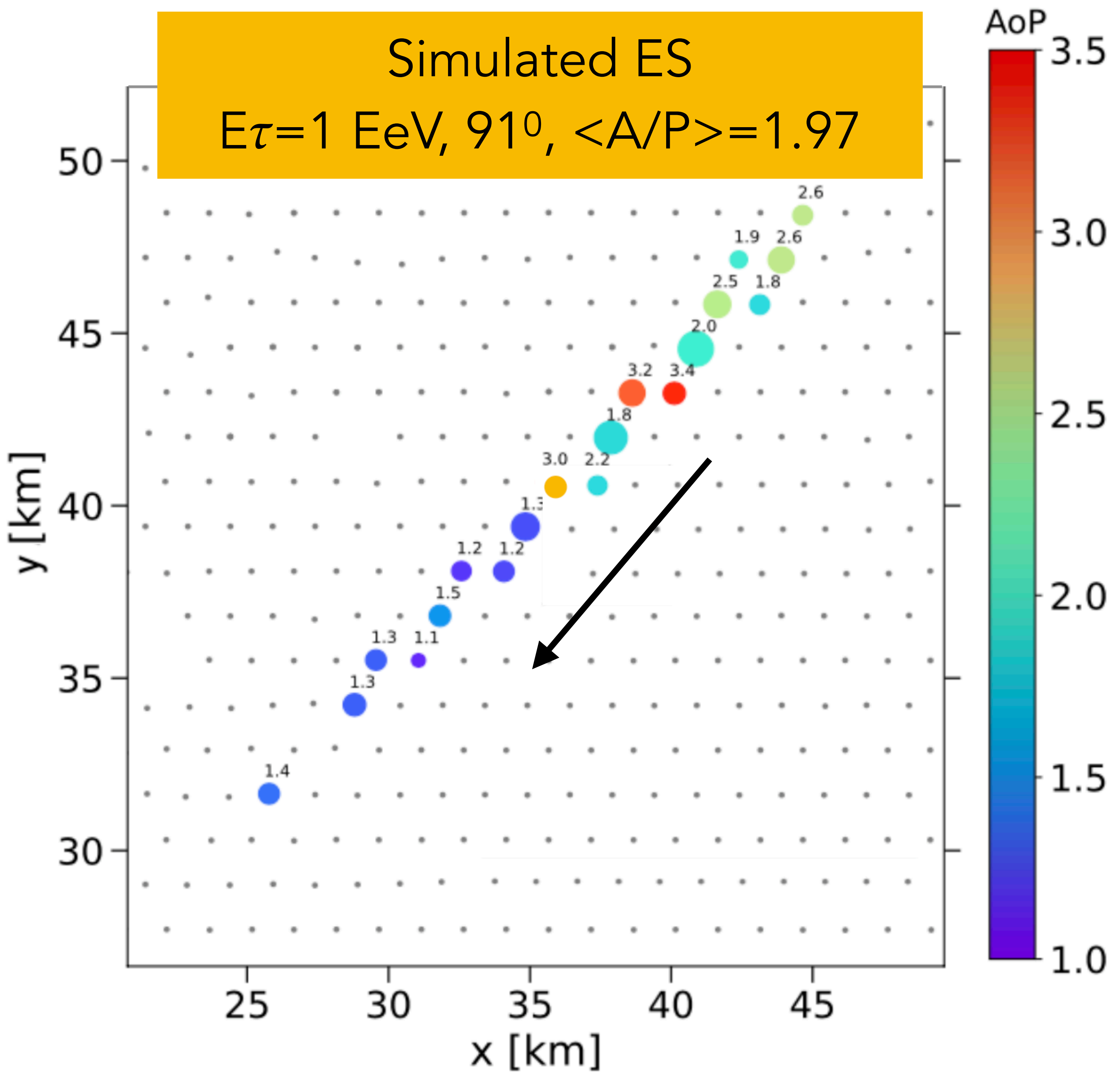


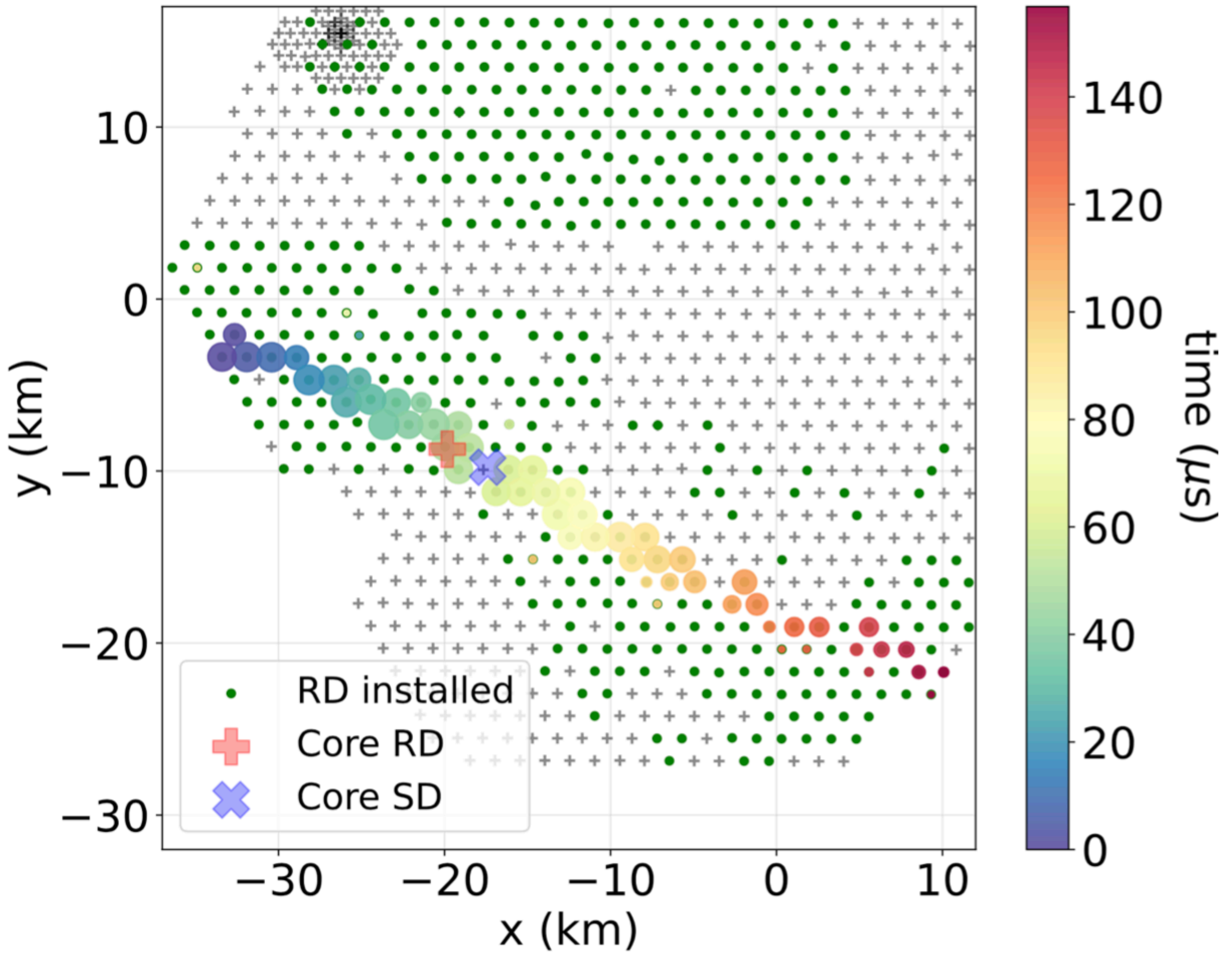


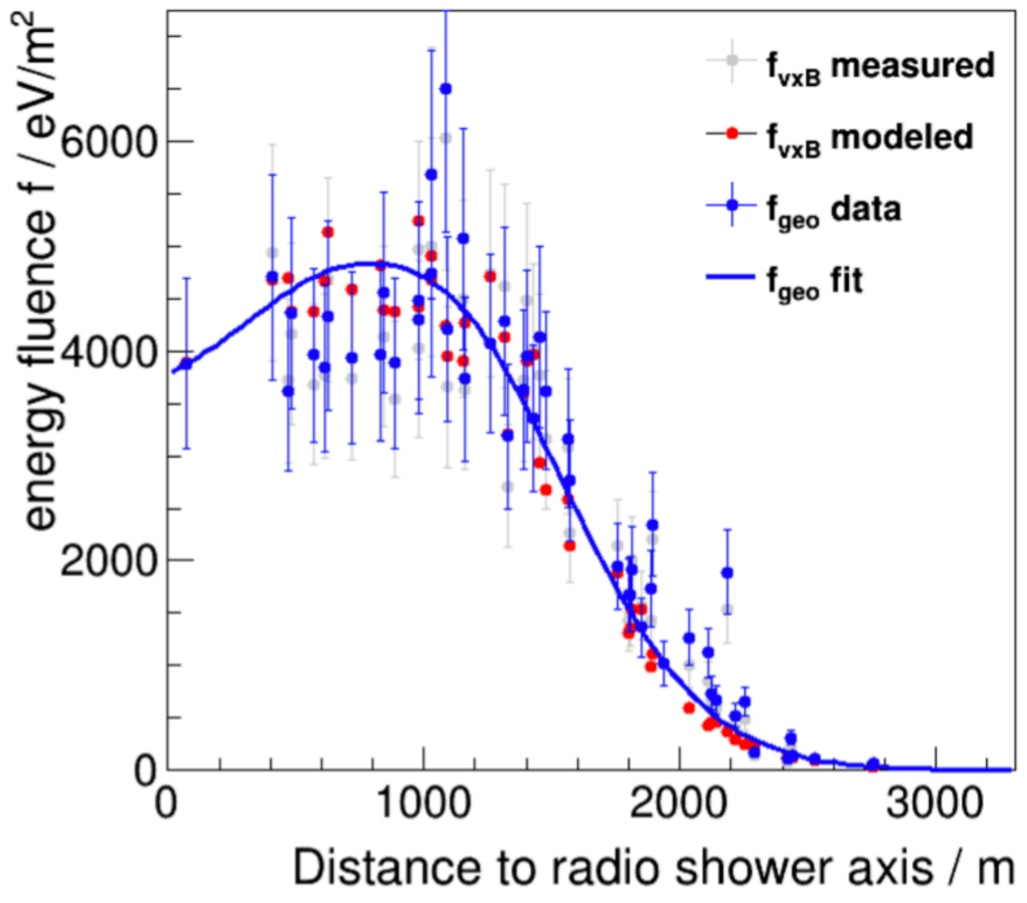
Energy	82±7 EeV
θ	53.8°
ϕ	100.6°
β	-2.1
$t_{1/2}(1000)$	127±5 ns
δ	17.8°
α	324.5°
Multiplicity	22







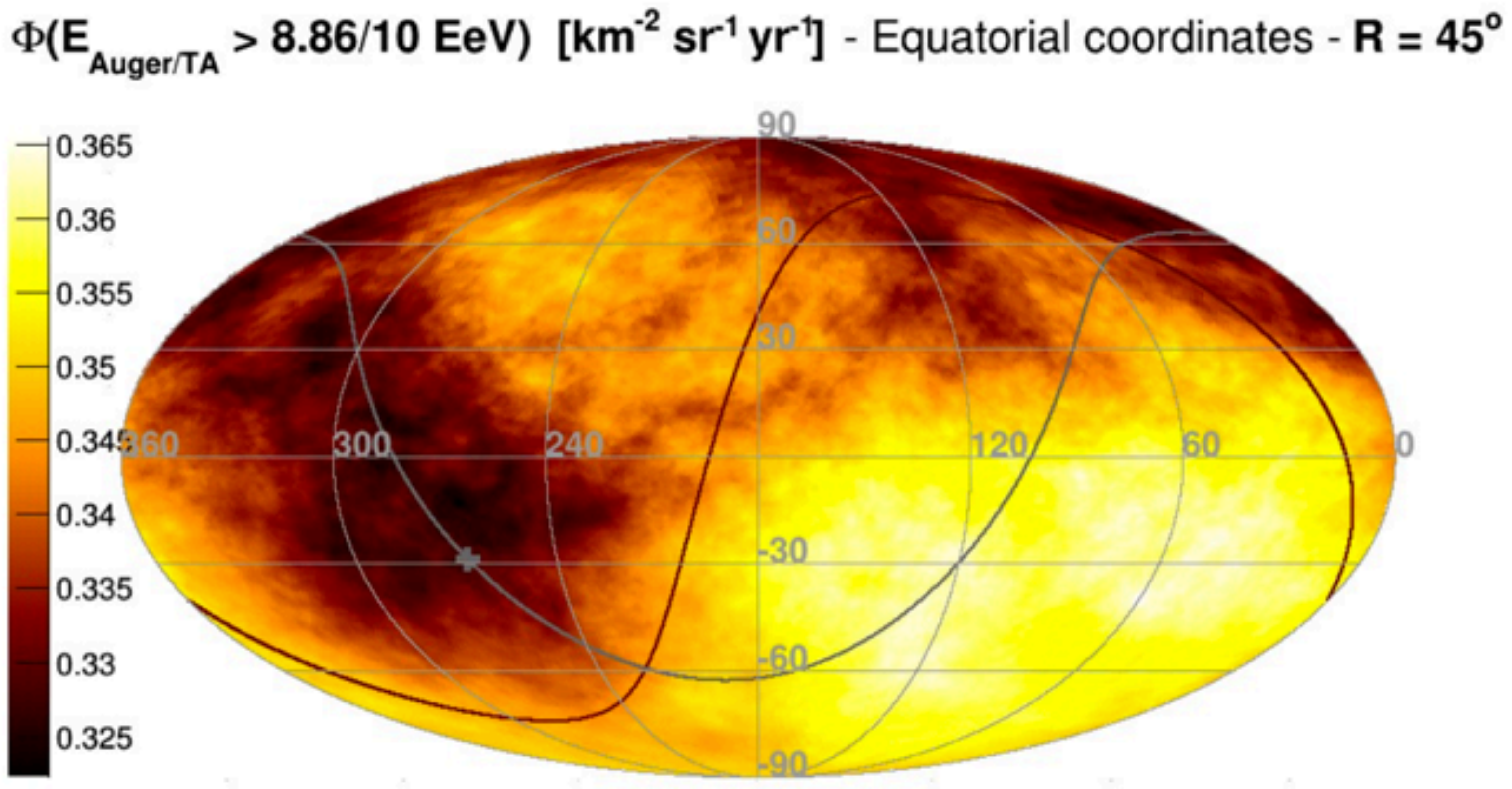




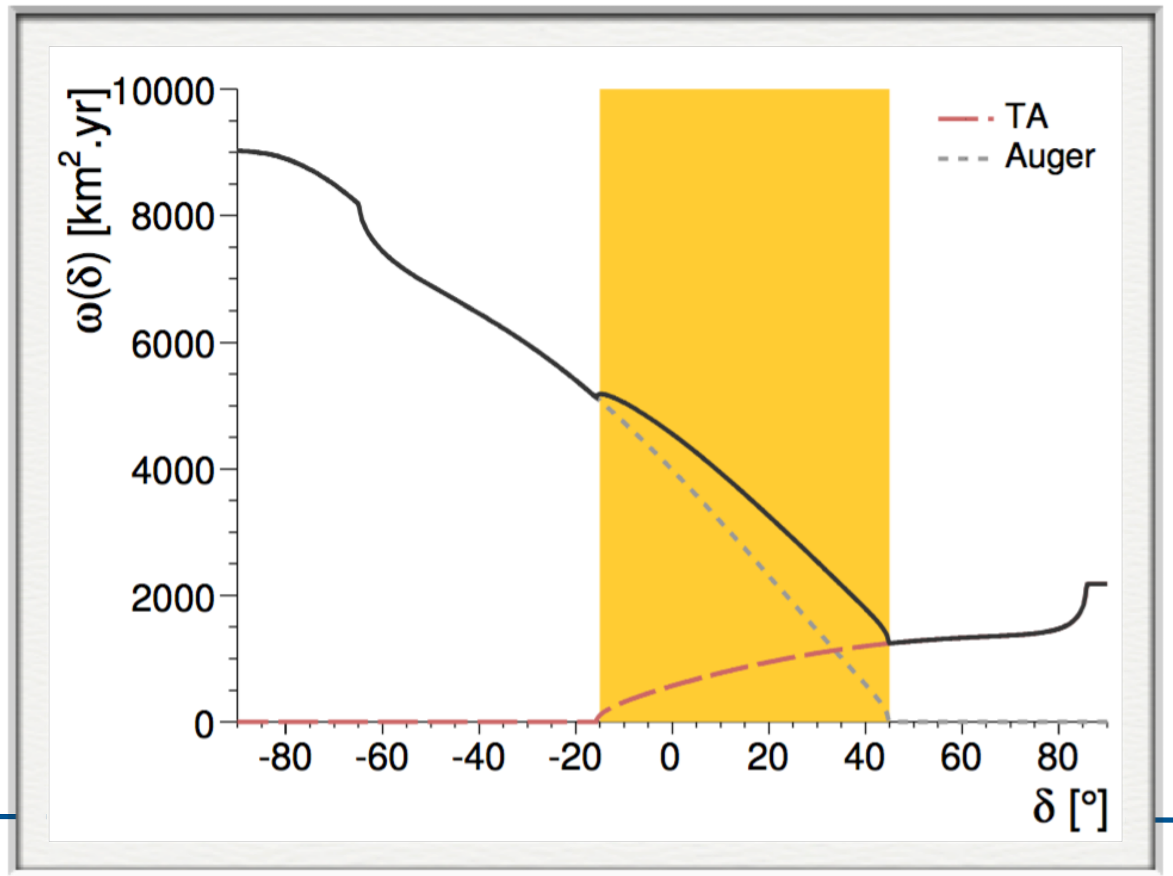
Inclined event in radio

	RD	SD
Azimuth (deg)	156.99±0.01	157±0.1
Zenith (deg)	84.7±0.01	84.7±0.1
Energy (EeV)	36.23 ± 3.34	38.55 ± 2.92
Core X (km)	-19.8	-17.40±0.88
Core Y (km)	-8.73	-9.78±0.45

Large scale anisotropy: Auger+TA full sky

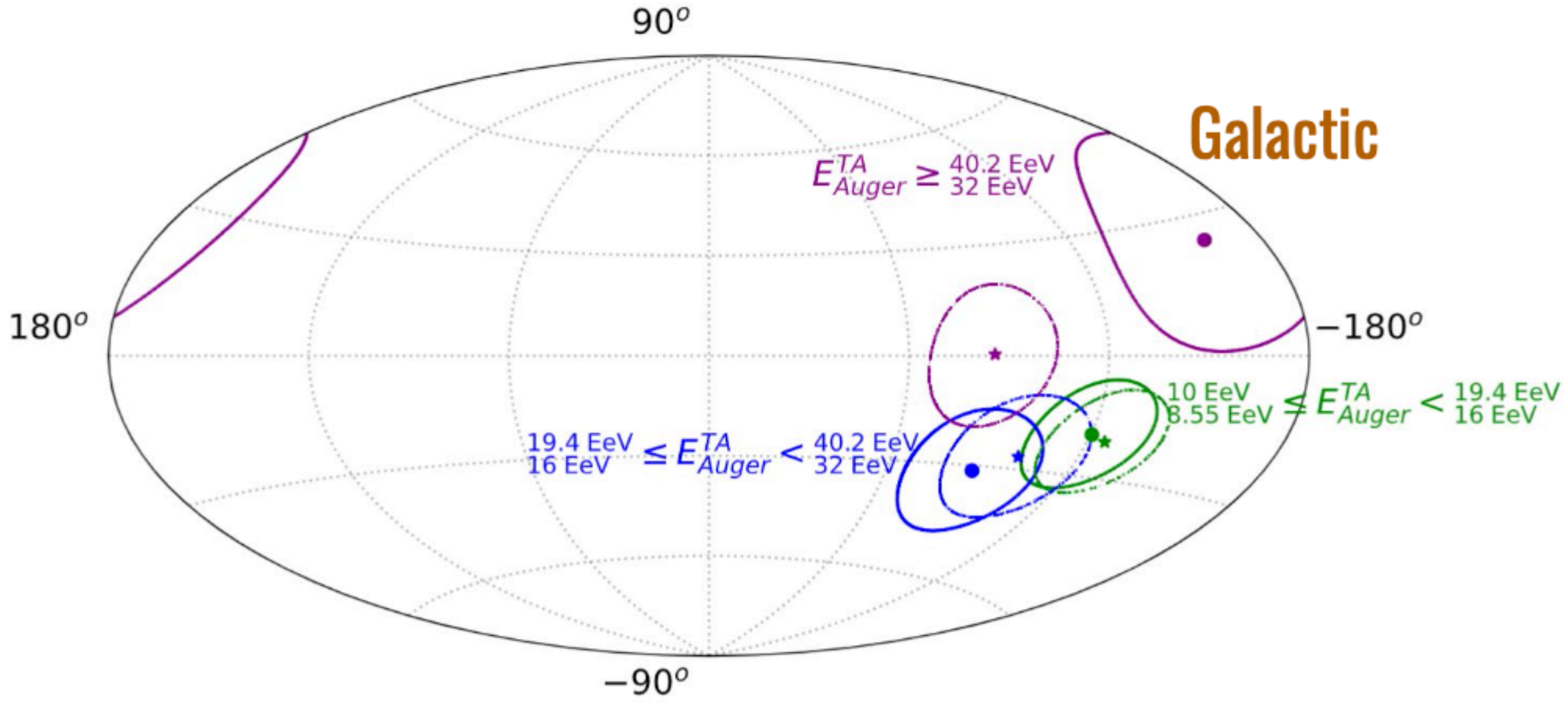


Flux

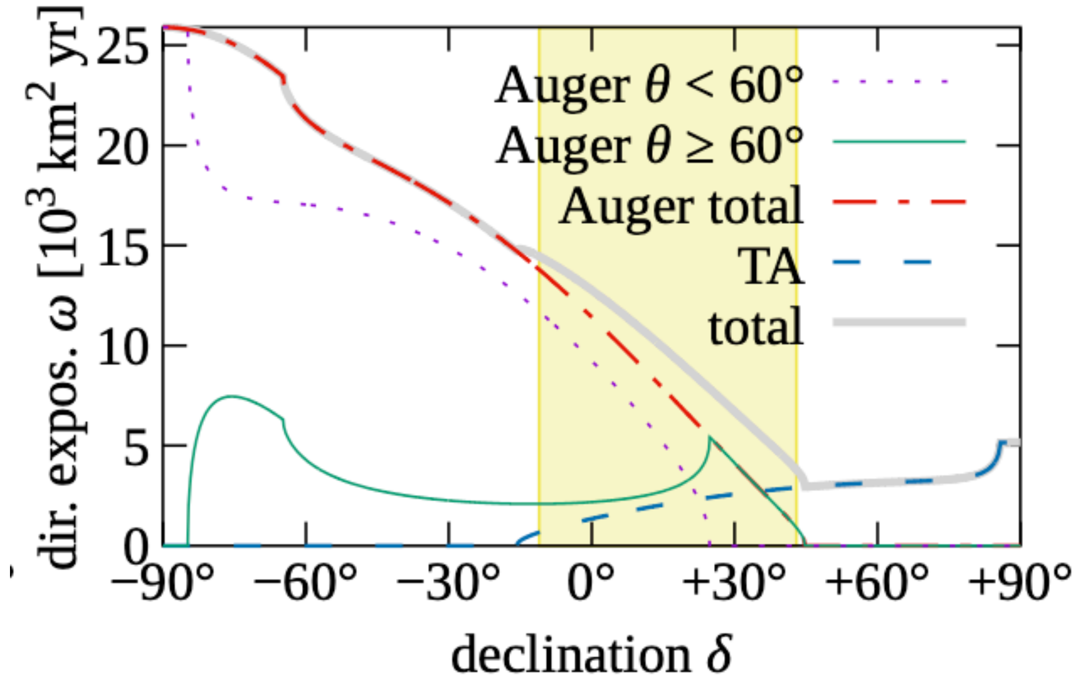


- scatter plots of arrival directions immediately interpretable
- equal sensitivity anywhere in the sky
- upper limits uniform over the sky
- no need for methods to re-weight individual exposures

Confirm the presence of a dipole pointing away from the GC

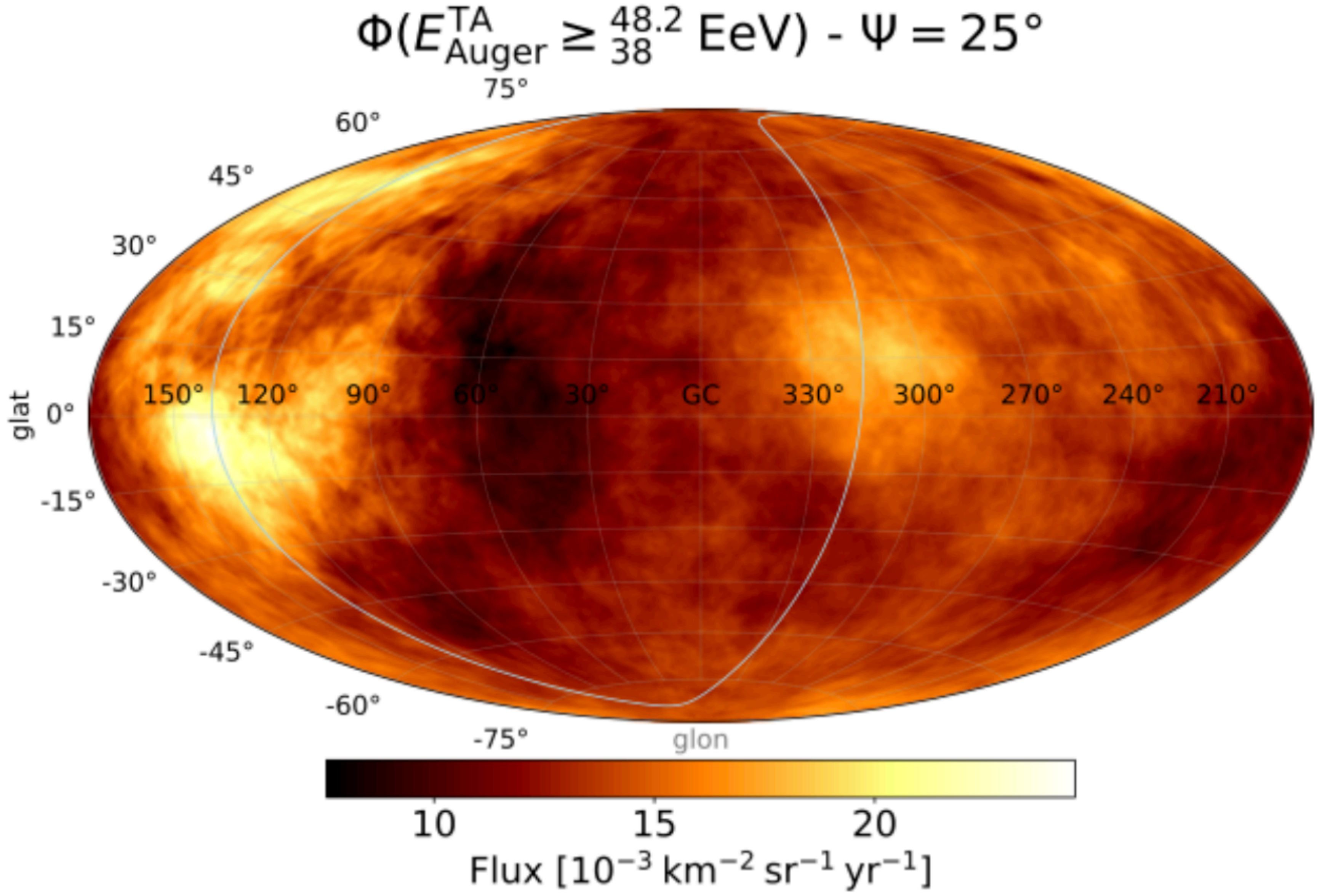


The UHE sky from Auger+TA

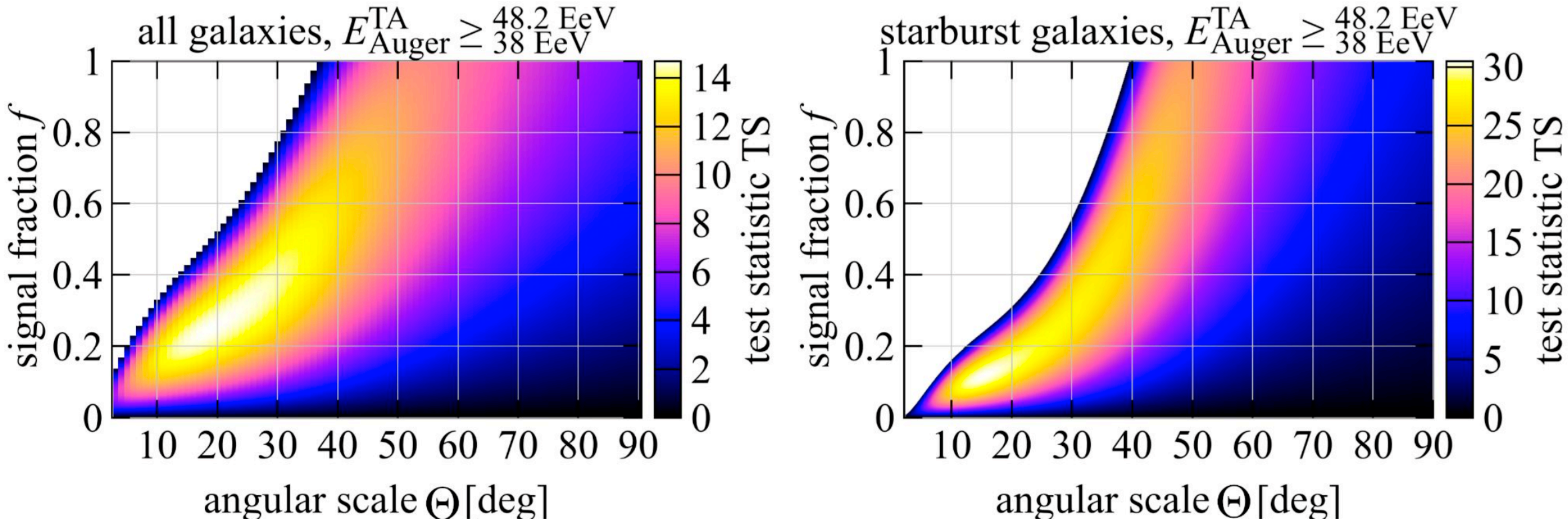


2004-2022 Auger, 2008-2022 TA: 3340 events for $E^{TA}_{Auger} \geq^{40.2\ EeV}_{32\ EeV}$

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]



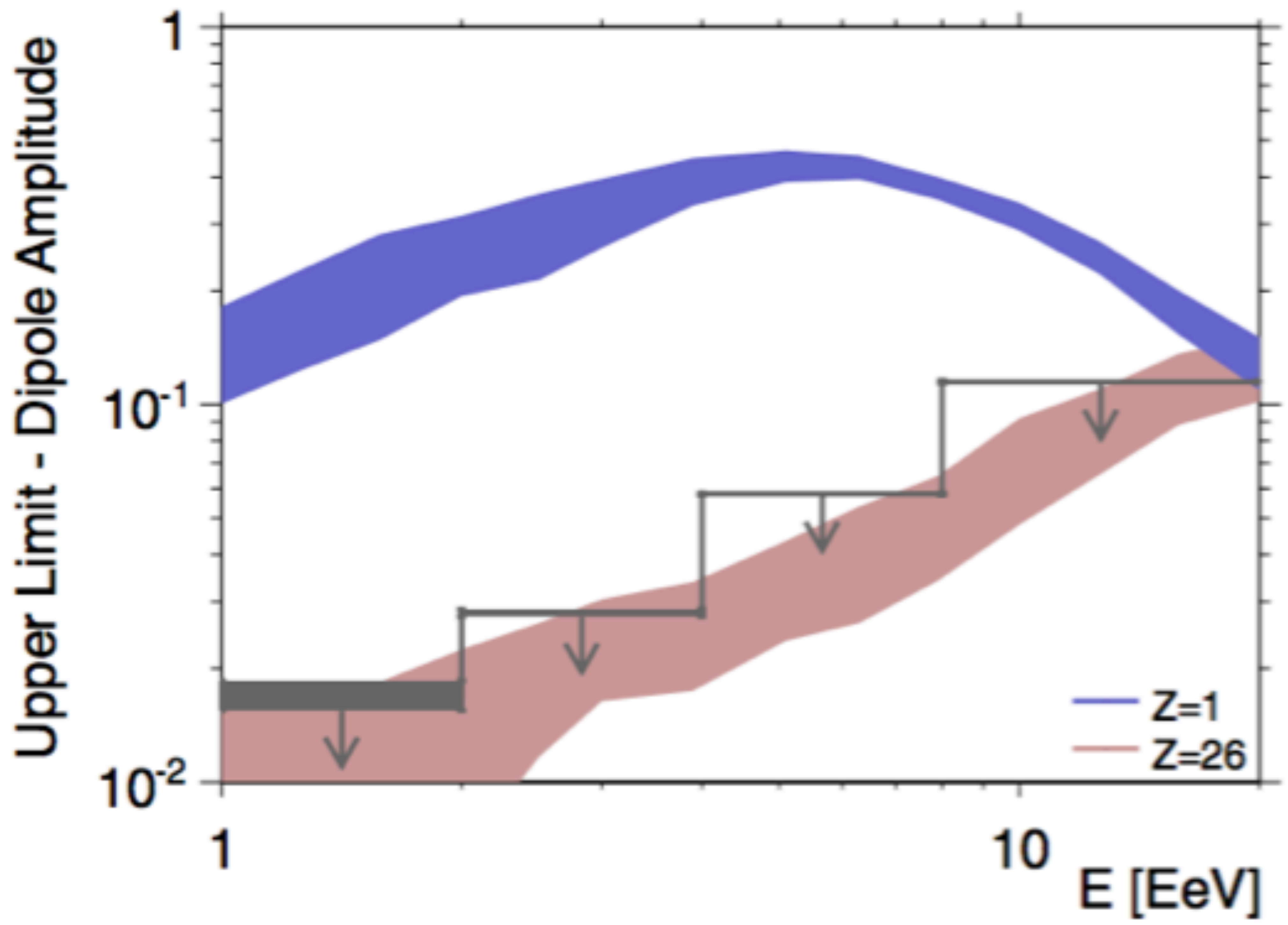
Spots found

— in the southern hemisphere (Centaurus region and M253)

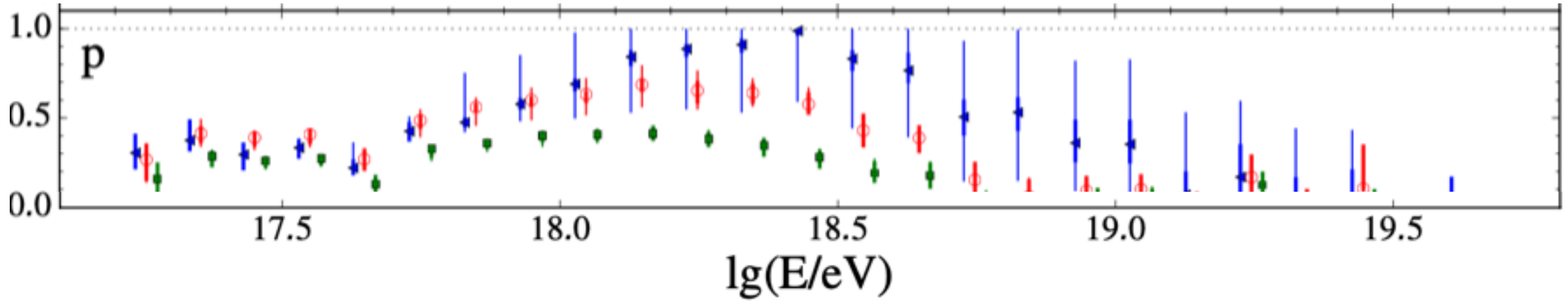
— in the northern hemisphere (Ursa Major region and M31/Triangulum/Perseus-Pisces region)

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

In the transition region



Anisotropy expectations from stationary galactic sources distributed in the disk and isotropically emitting UHECR



A Galactic origin of protons above EeV energies is disfavoured by Auger results

protons excluded by

- ➡️bounds on the dipolar component
- ➡️isotropy below 8 10^{18} eV

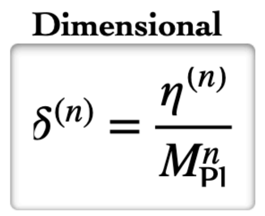
heavy nuclei excluded by

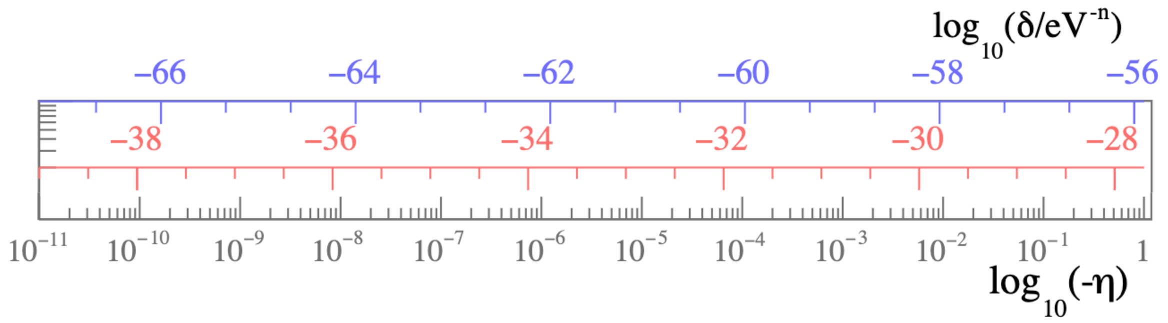
- ➡️measured light composition

Auger Coll., ApJ.Lett.762 (2013) L13

Search for Lorenz invariance violation

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



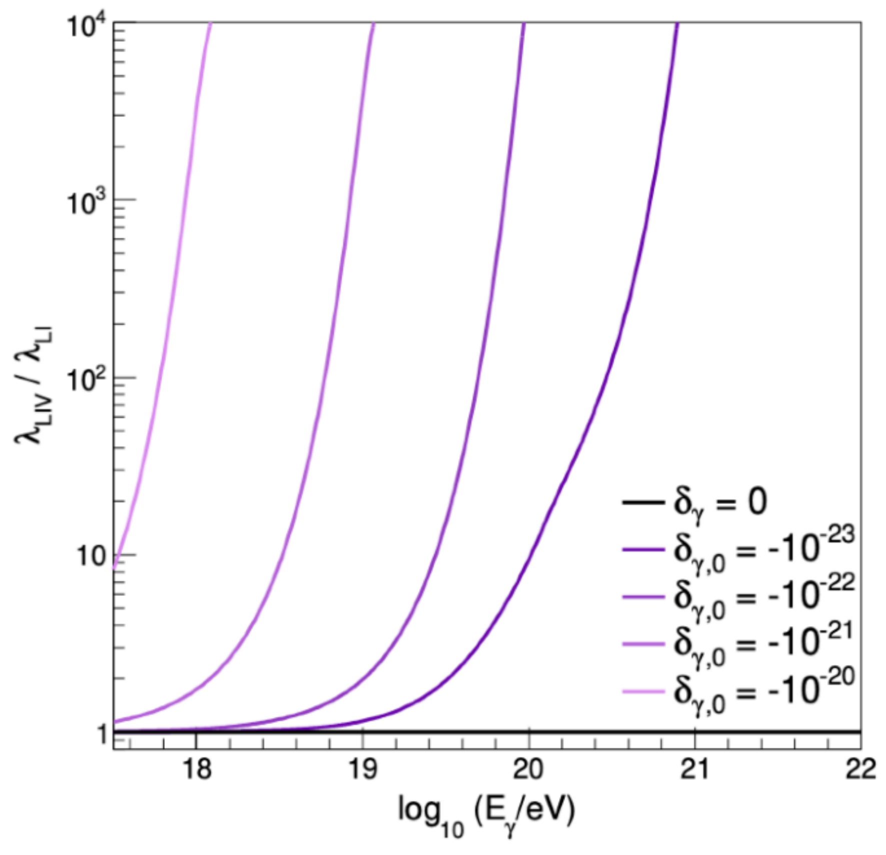


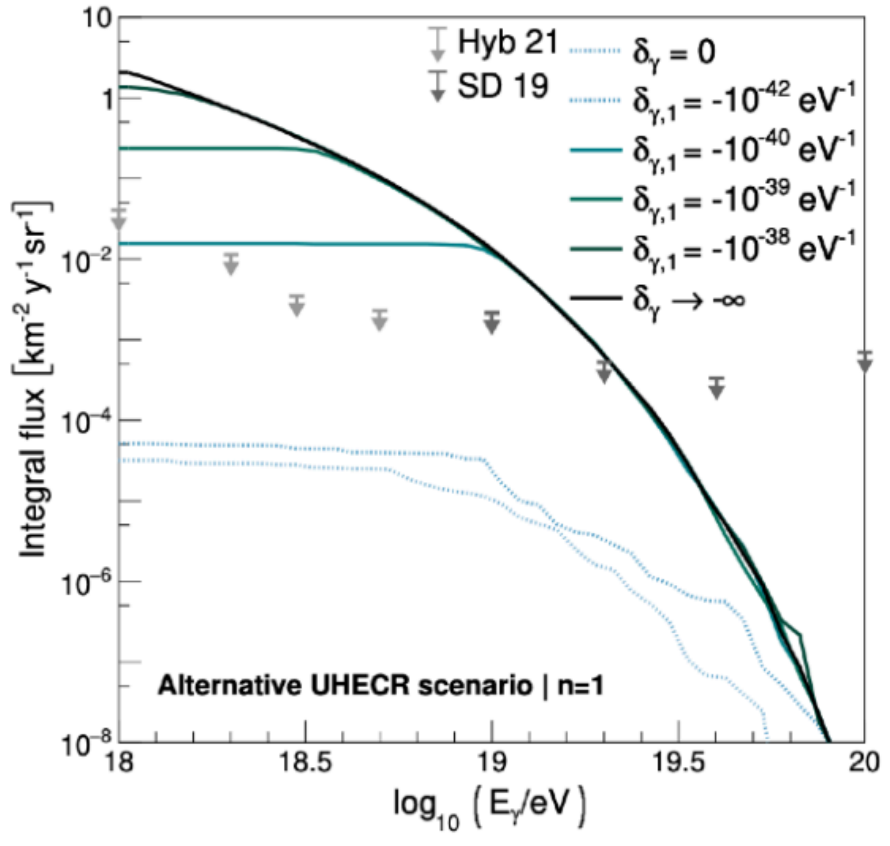
Effects suppressed for low energy and short travel distances : UHECRs !!!

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



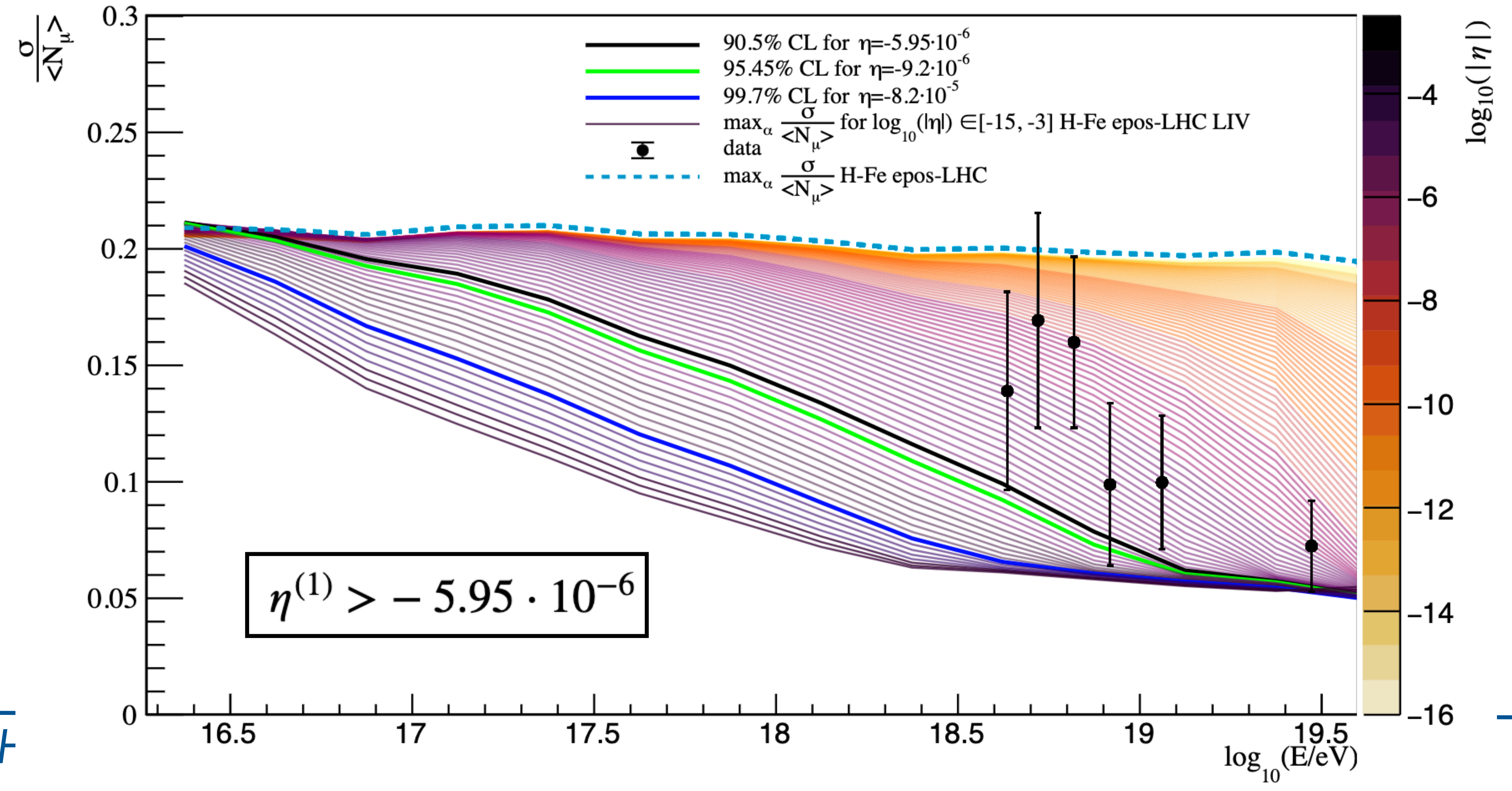


Air shower physics

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

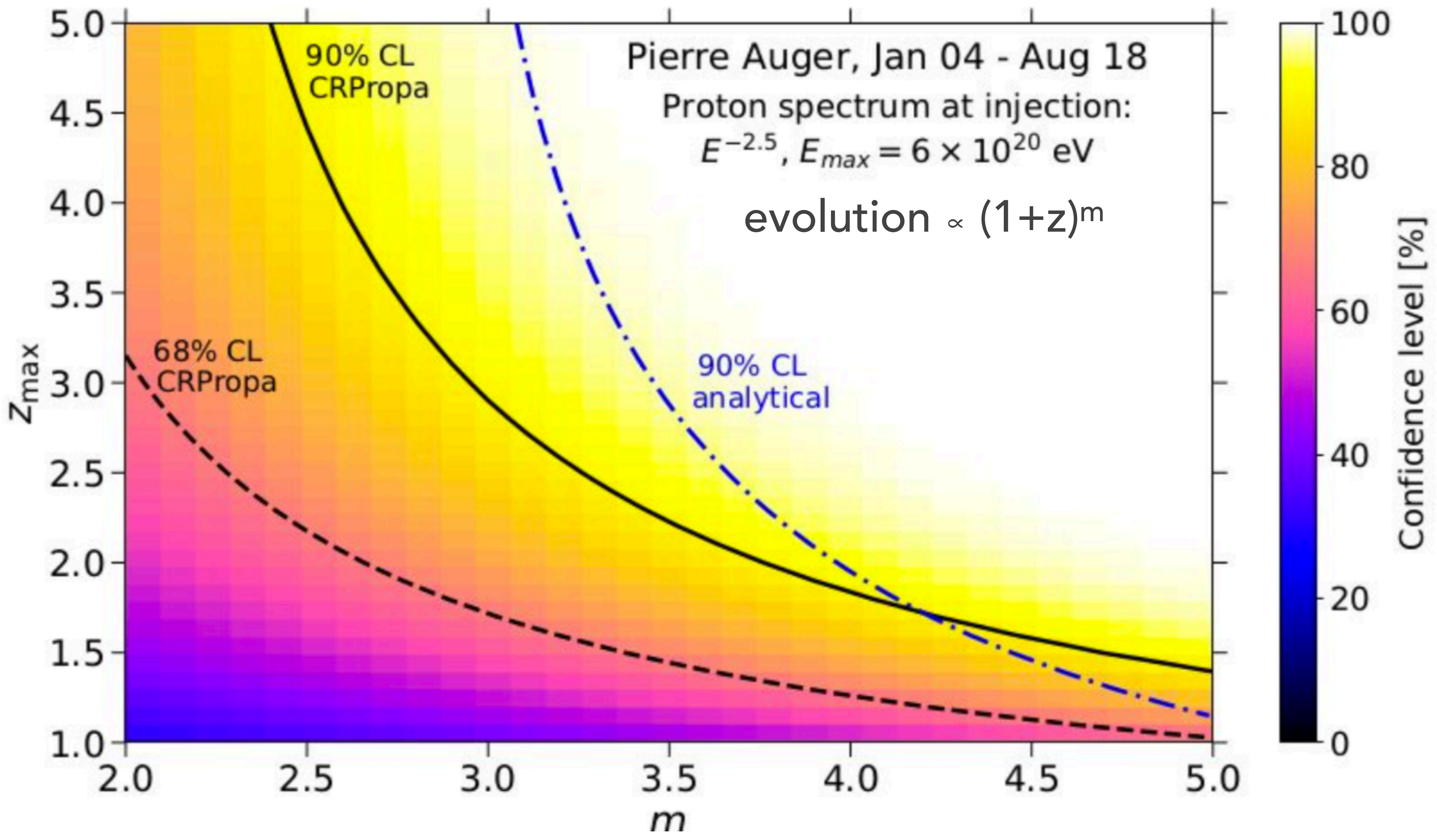
$$m_\pi^2 + \eta_\pi^{(n)} \frac{p_\pi^{n+2}}{M_{Pl}^n} < 0$$

- EM component decreasing, hadronic one increasing

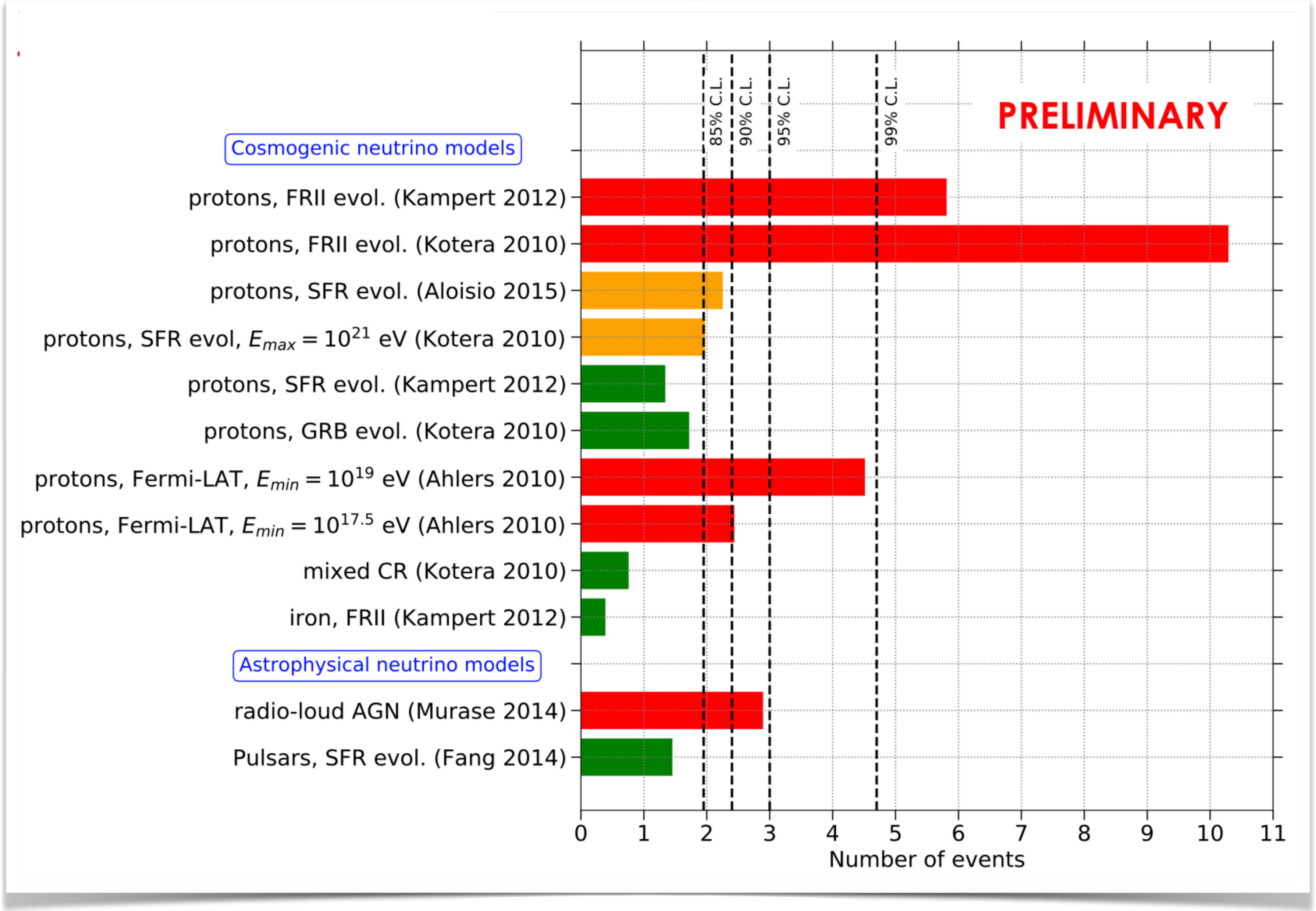


Auger Coll., JCAP01 (2022) 023
C.Trimarelli (Auger Coll.), UHECR2022

Constraints to neutrino models

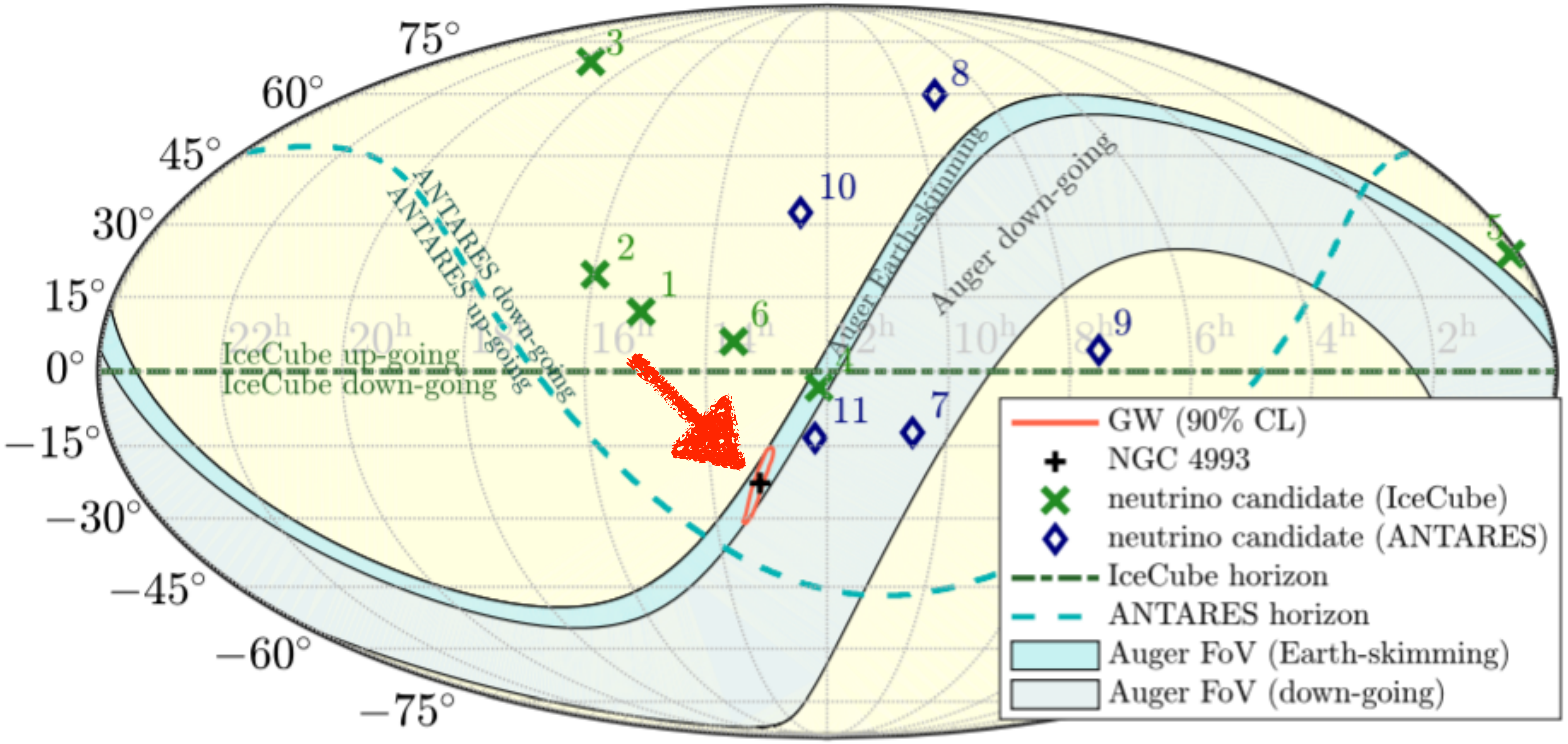


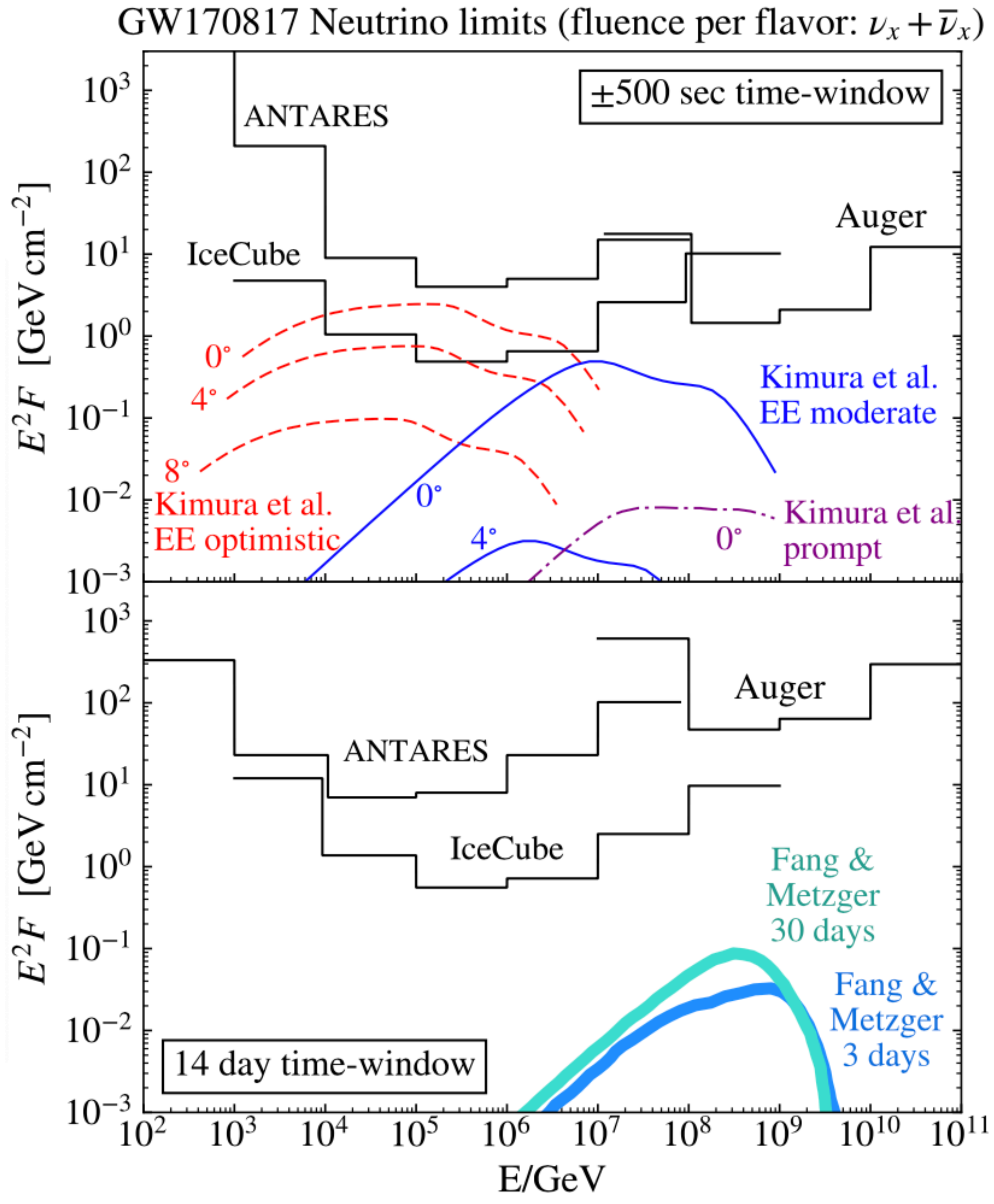
Black lines & colored background: ν fluxes obtained with Monte Carlo CRPropa 3 (A. Van Vliet et al.) - proton flux at Earth normalized to Auger spectrum at E = 7 x 10^{18} eV.
Blue line: fluxes obtained with approx. analytical approach (Yoshida et al.)



➡️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

Follow-up of GW170817 in neutrinos





- Source in the field of view of ES neutrino search
- No UHE neutrino candidates found in either coincidence windows (±500 se around the GW or in the 14 days period after it)
- Limits on the total emitted energy in the range 10^{17}-2.5 10^{19} eV

  ±500 s : < 6.9 10^{-4} $M_\odot$ +14 days : < 2.3 10^{-2} $M_\odot$

- Lack of detection consistent with expectation from a short GRB viewed at off-axis angle >20^0

LVC, ANTARES, IceCube, Auger, ApJL 850 (2023) L35

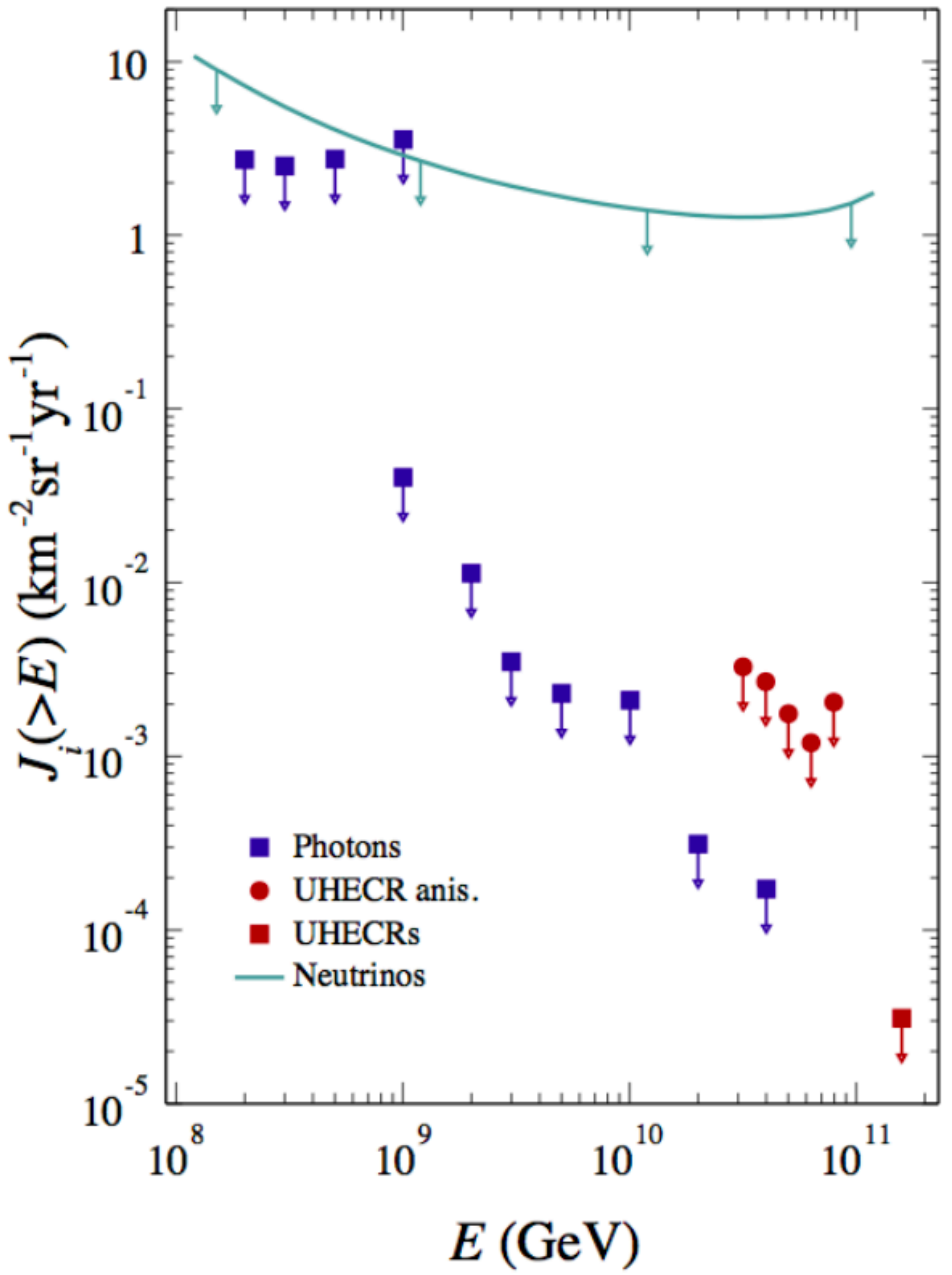
Search for SHDM

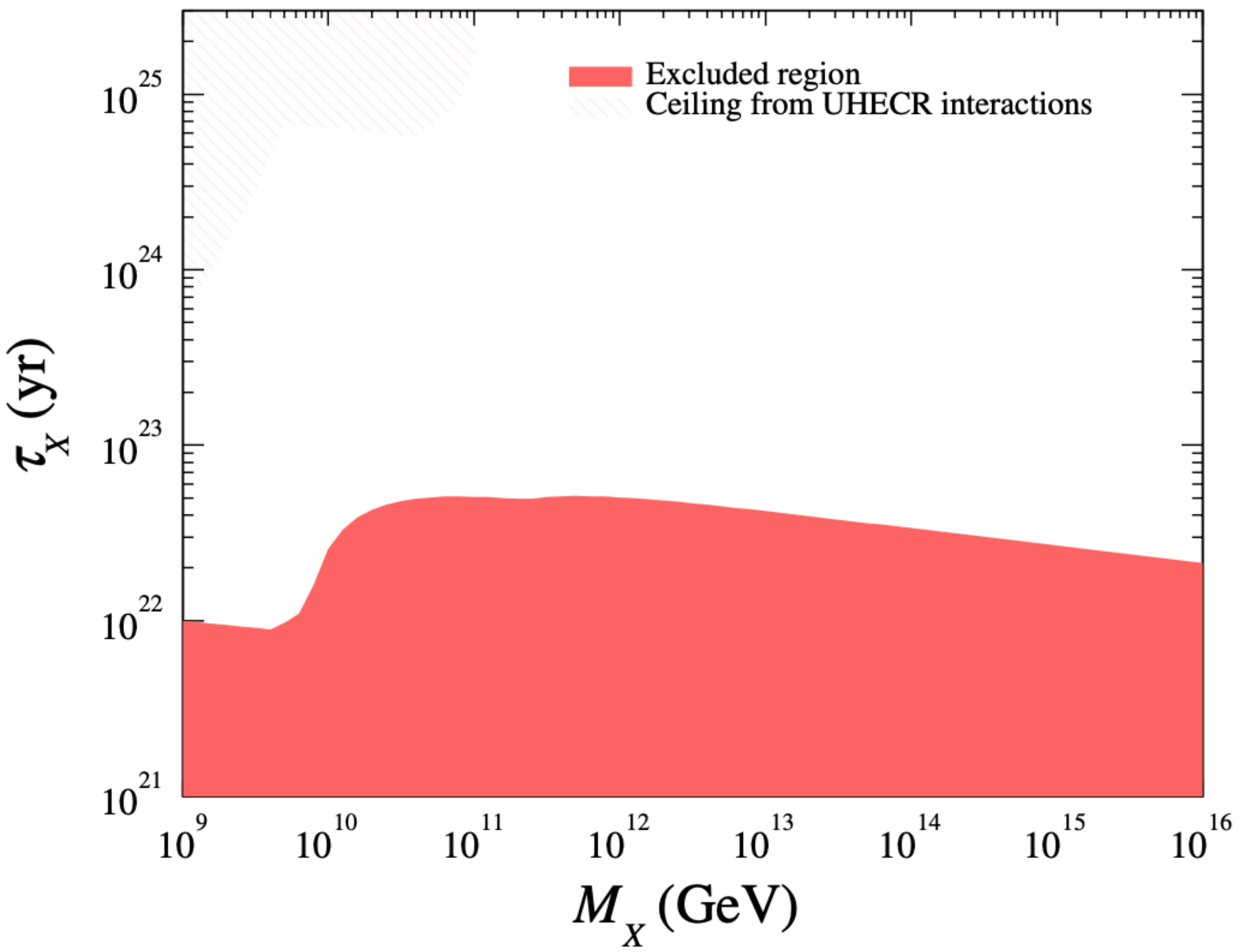
Flux of secondaries from SHDM decay ($i = \gamma, \nu, \bar{\nu}, N, \bar{N}$):

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

Free parameters

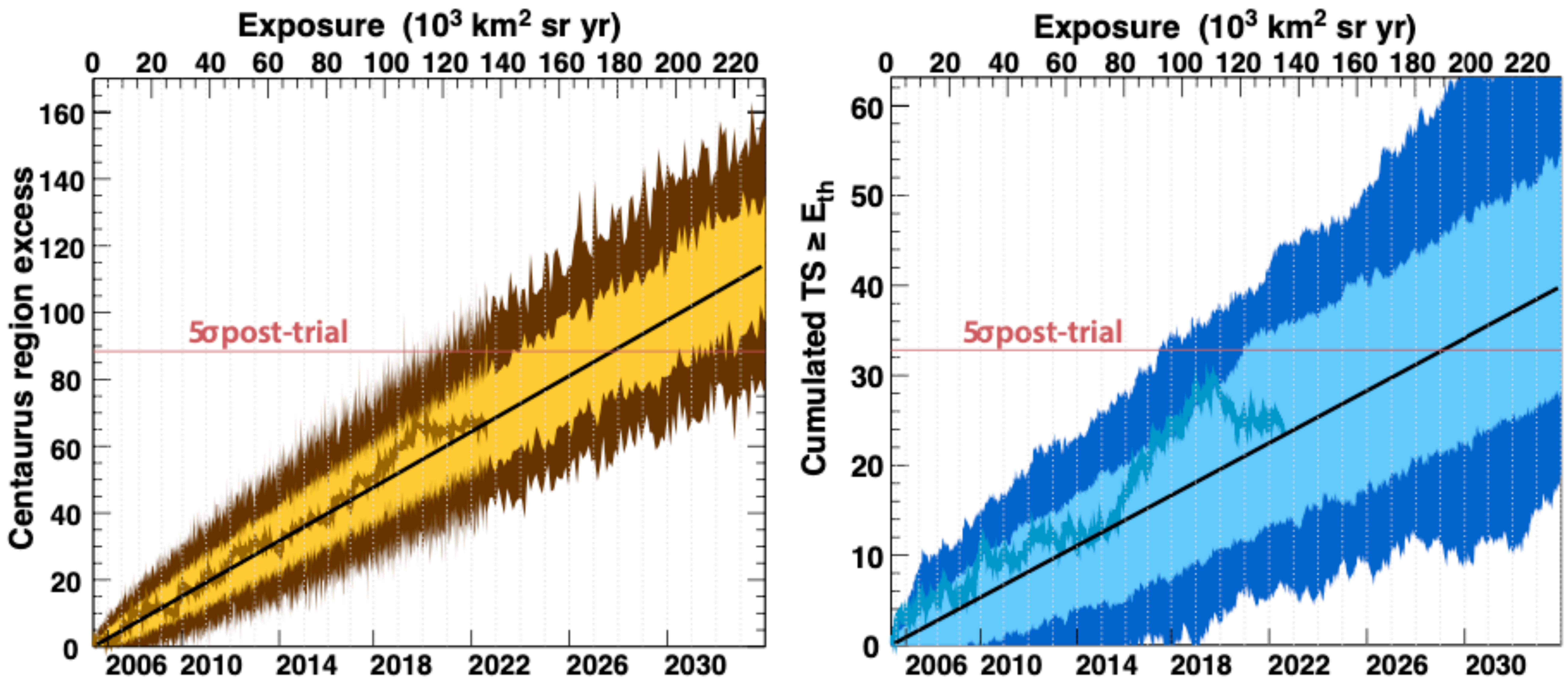
$$\tau_X = \hbar M_X^{-1} \exp(4\pi/\alpha_X)$$





Auger coll., PRD 109 (2024) L081101;
Auger coll., PRL 130 (2023) 061001;
Auger coll., PRD 107 (2023) 042002

Multi-hybrid events : intermediate scale anisotropy



- 5σ significance at reach for Centaurus A around 2027
- 5σ significance at reach for Starburst Galaxies around 2029

Composition information can improve this prediction