Selected Highlights of the Pierre Auger Observatory

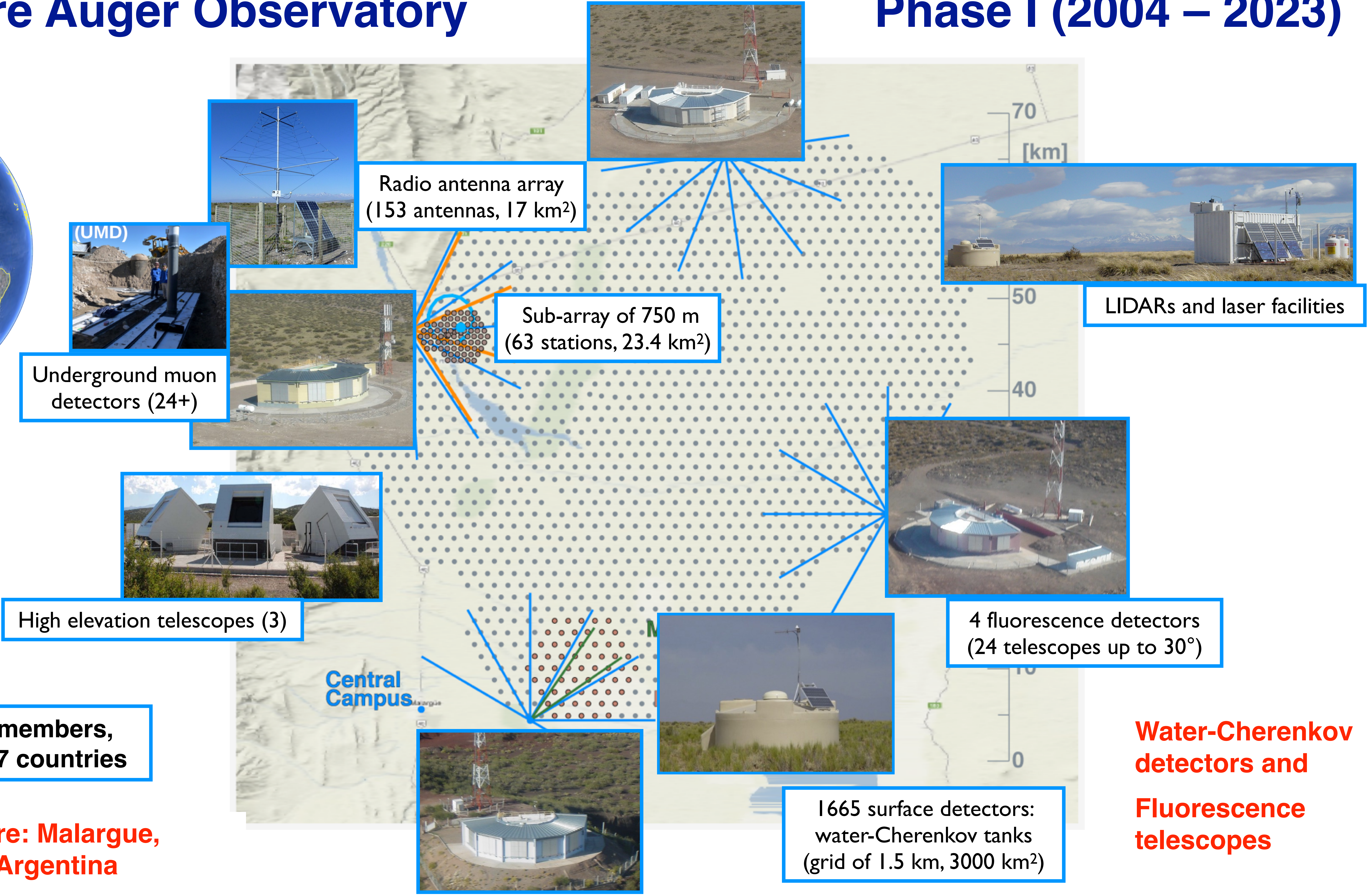
Ralph Engel, for the Pierre Auger Collaboration

(picture curtesy S. Saffi)

The Pierre Auger Observatory

Phase I (2004 – 2023)

Pierre Auger Observatory
Province Mendoza, Argentina



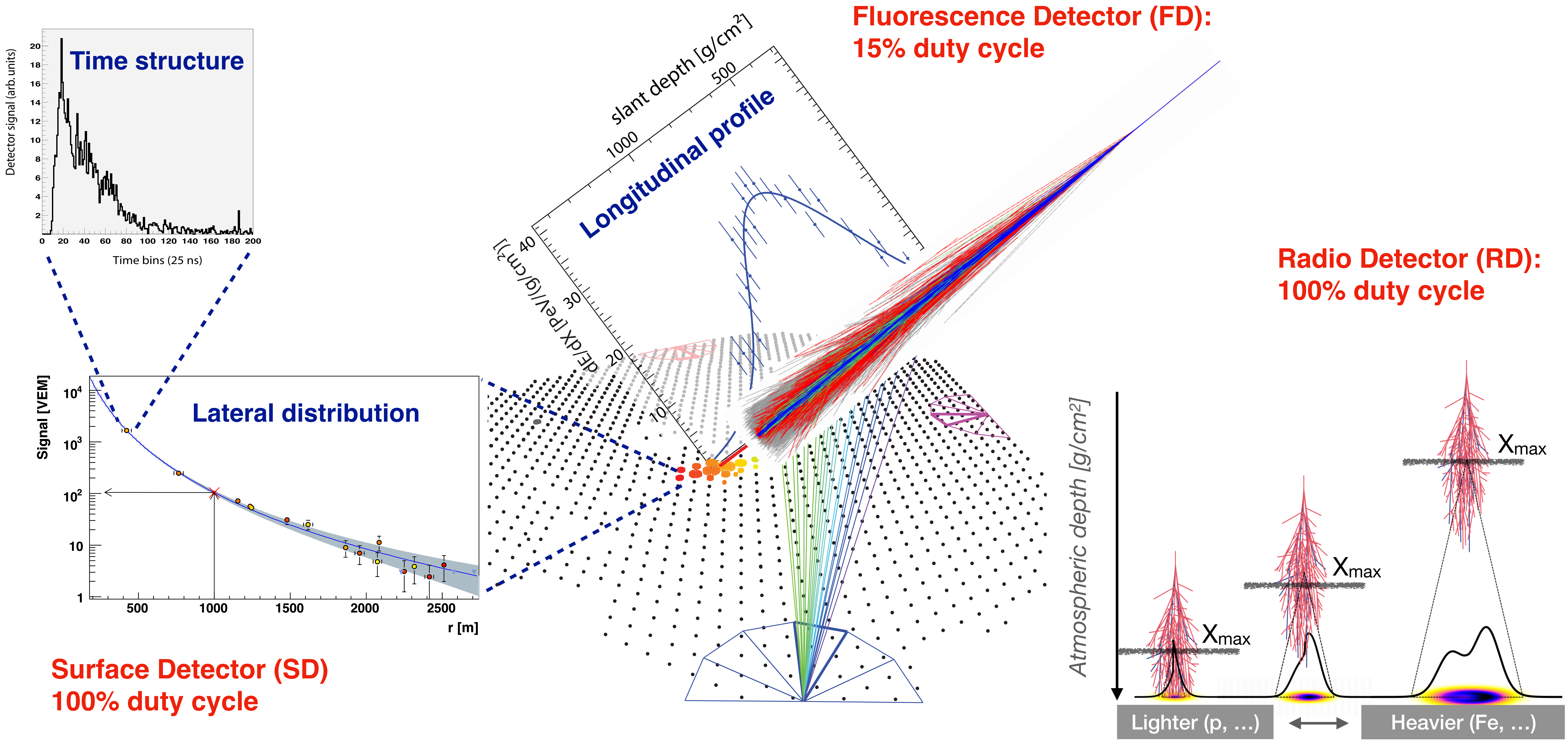
More than 400 members,
90 institutes, 17 countries

Southern hemisphere: Malargue, Province Mendoza, Argentina

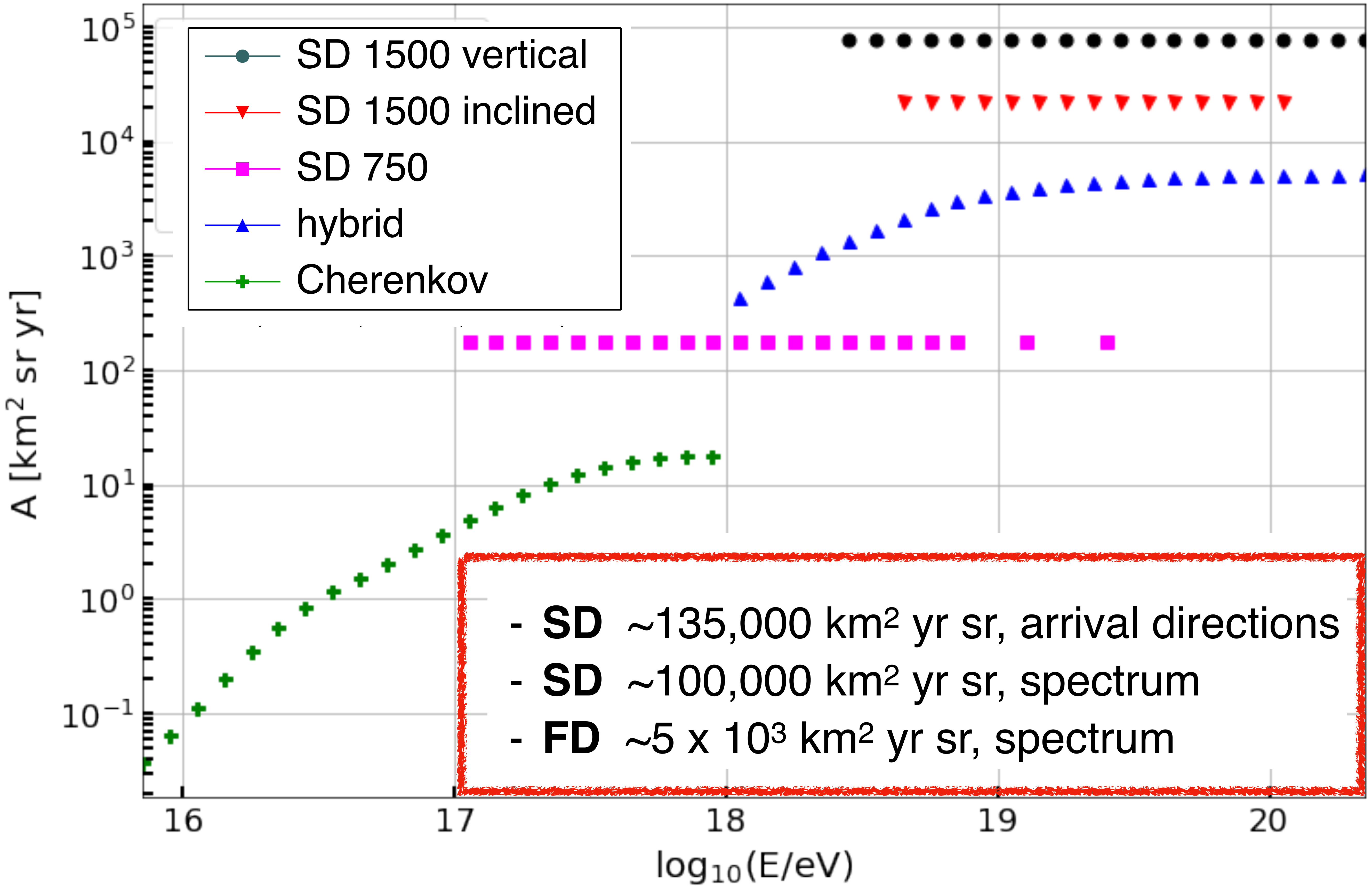
Water-Cherenkov detectors and

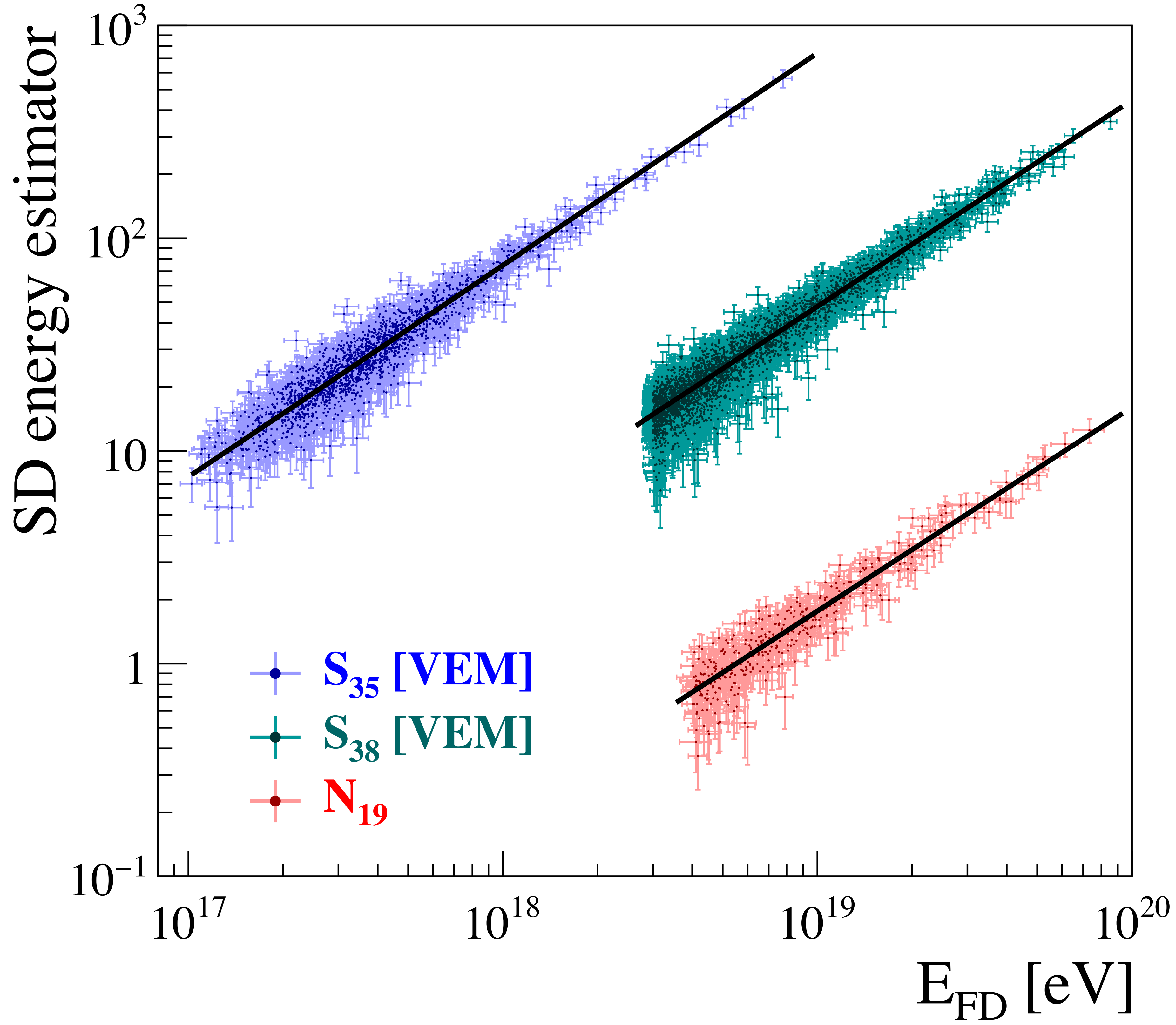
Fluorescence telescopes

Air shower observables (hybrid observation)



Exposure Phase I and calibration of Auger data sets





$$E_{\rm FD} = AS_{35}^B$$

E > 10^{17} eV
σ(E) : 25% - 10%

$$E_{\rm FD} = AS_{38}^B$$

E > $10^{18.4}$ eV
σ(E) : 22% - 7%

$$E_{\rm FD} = AN_{19}^B$$

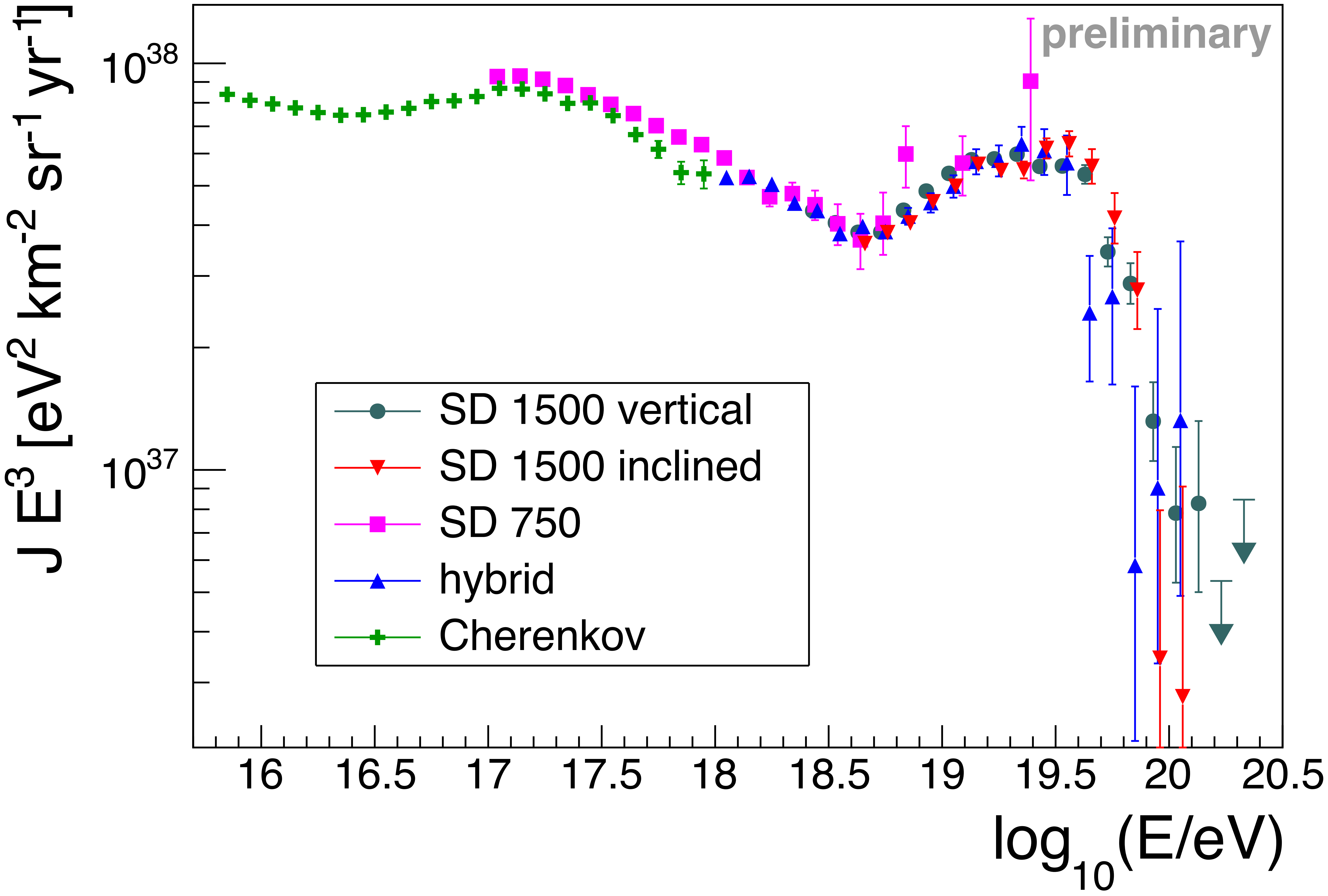
E > $10^{18.6}$ eV
σ(E) ~ 19%

SD 1500 m vertical – S_{38}
- S(1000)+CIC
- threshold 2.5 EeV

SD 750 m – S_{35}
- S(450)+CIC
- threshold 0.1 EeV

SD 1500 m inclined – N_{19}
- scaling parameter
- threshold 4 EeV

Energy spectra of Auger Observatory

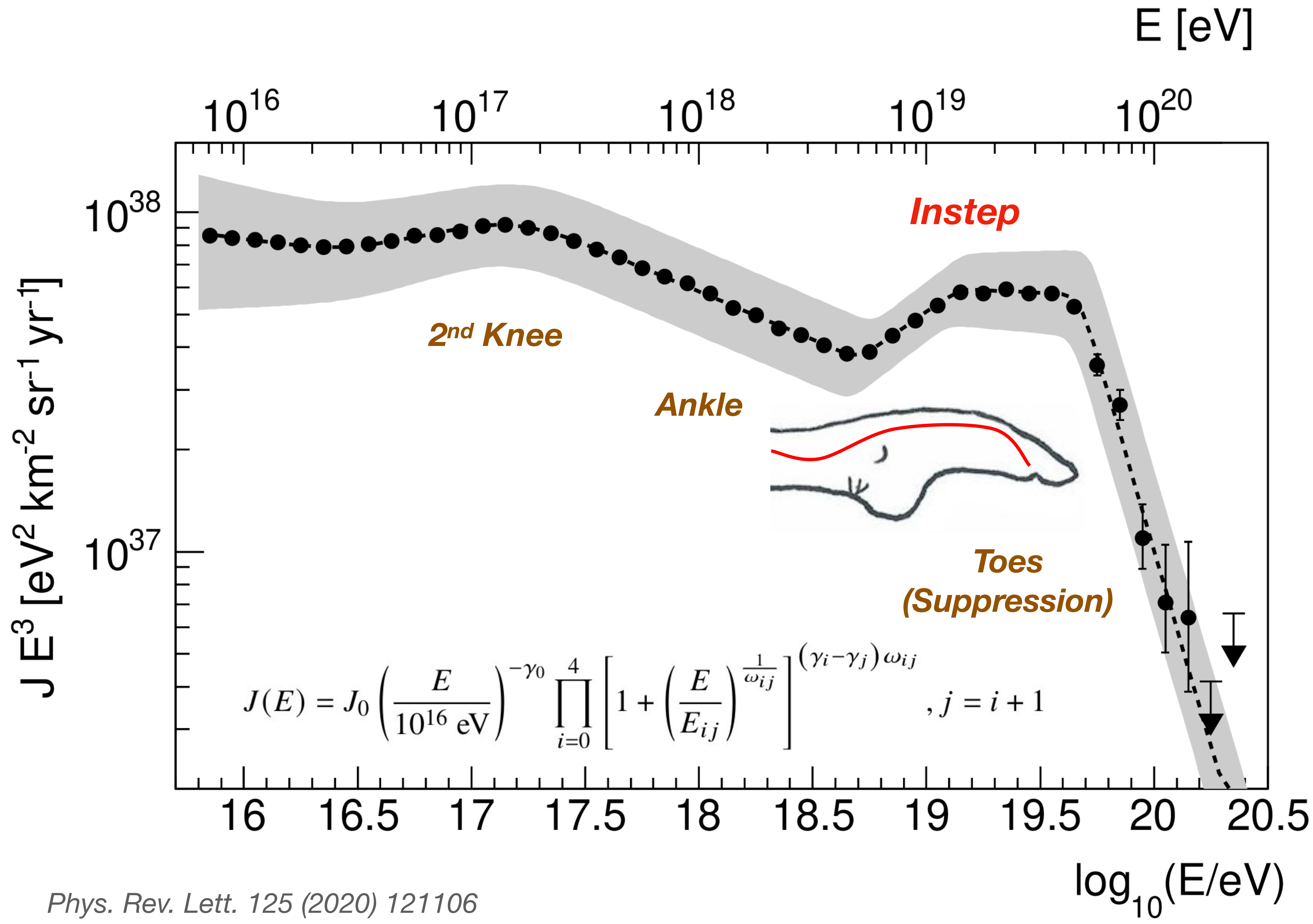


Cherenkov:	0°<θ<60°	E> 6×10^{15} eV
750m:	0°<θ<55°	E> 3×10^{17} eV
Hybrid:	0°<θ<60°	E> 3×10^{18} eV
1500m:	0°<θ<60°	E> 3×10^{18} eV
1500m:	60°<θ<80°	E> 4×10^{18} eV

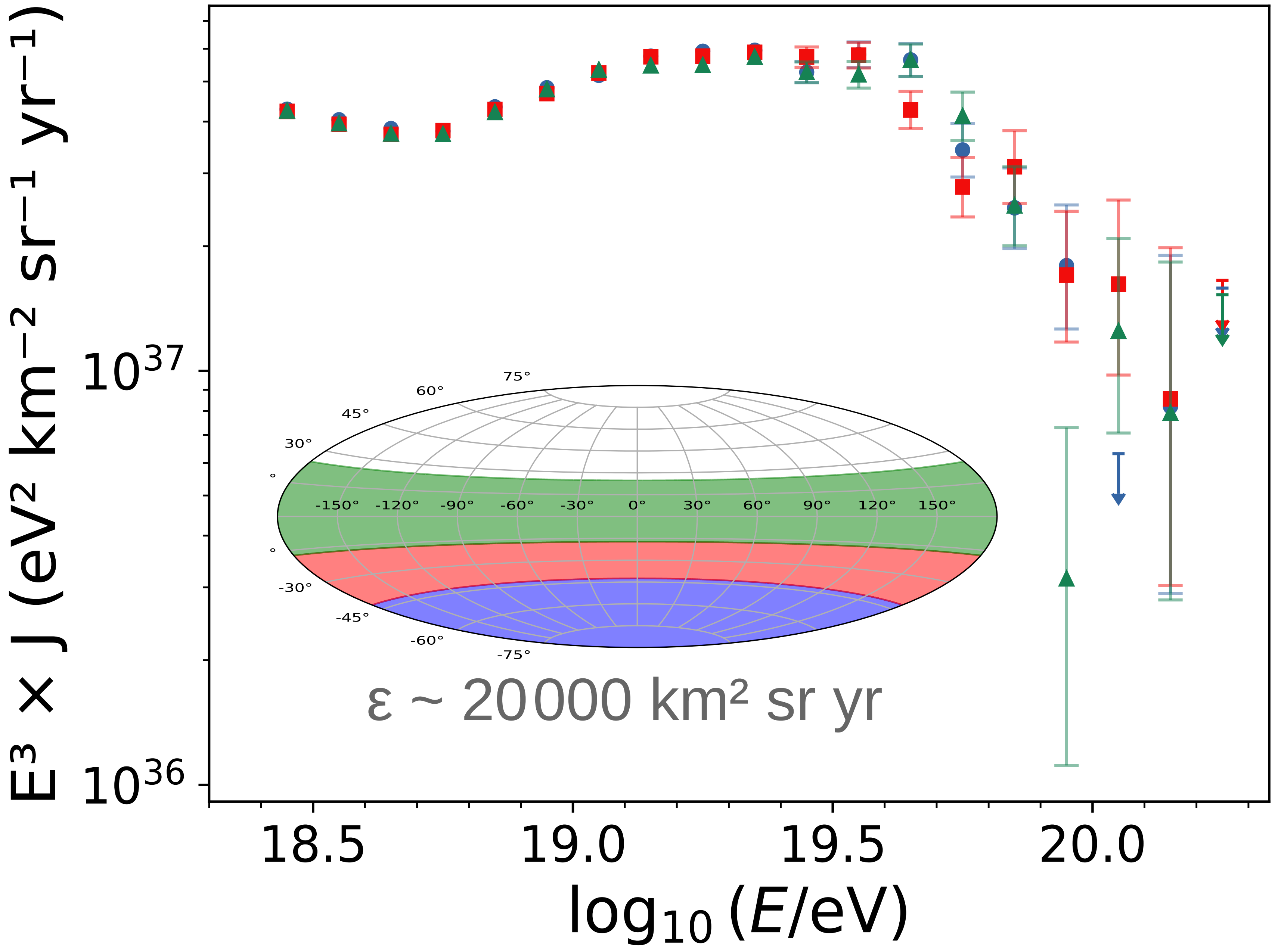
Systematic uncertainty
of energy scale

$$\Delta E/E = 14\%$$

Combined energy spectrum of Auger Observatory



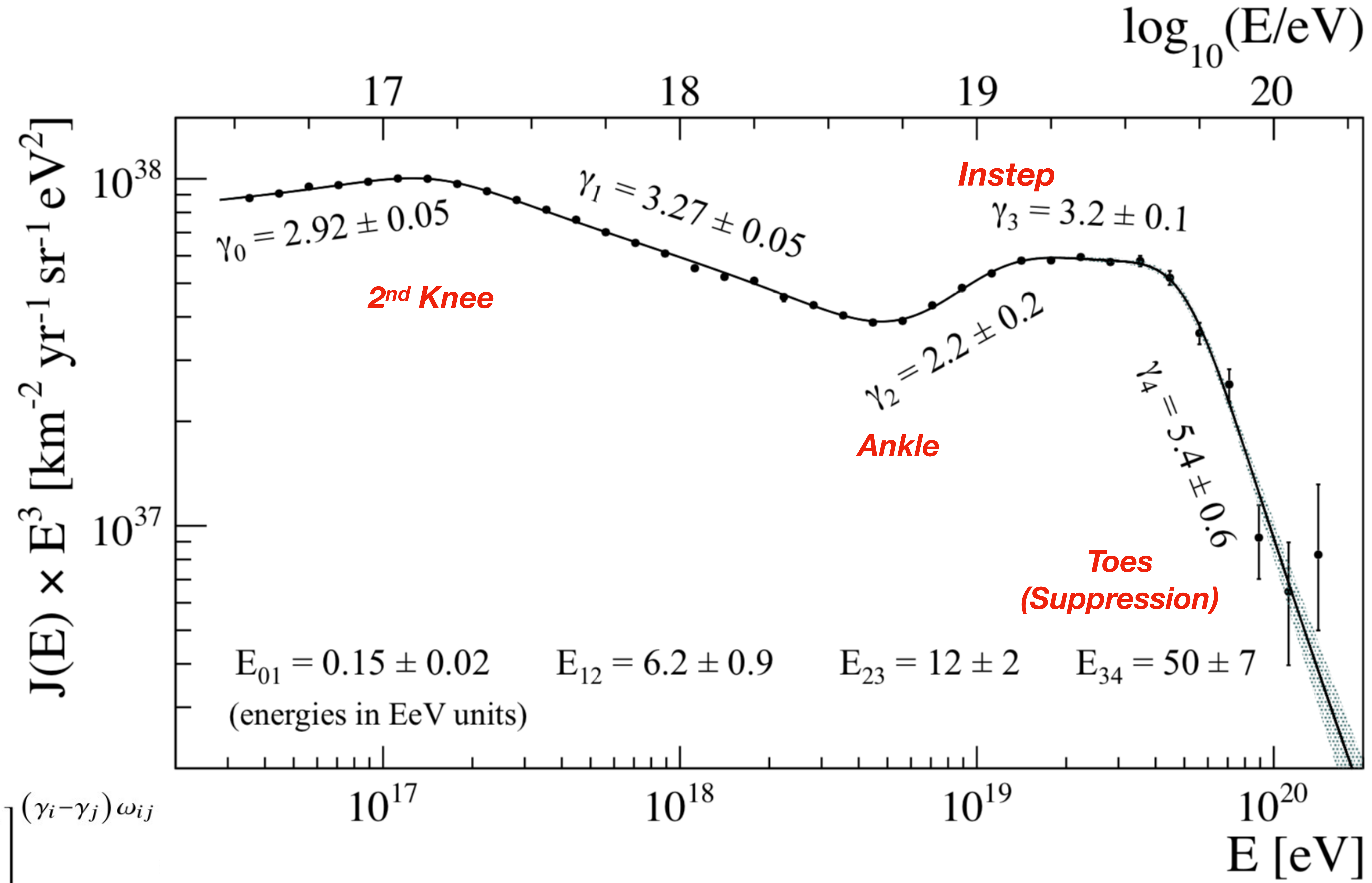
Phys. Rev. Lett. 125 (2020) 121106
Phys. Rev. D102 (2020) 062005
Eur. Phys. J. C81 (2021) 966



No declination dependence found beyond the expectation from dipole

Combined energy spectrum of Auger Observatory

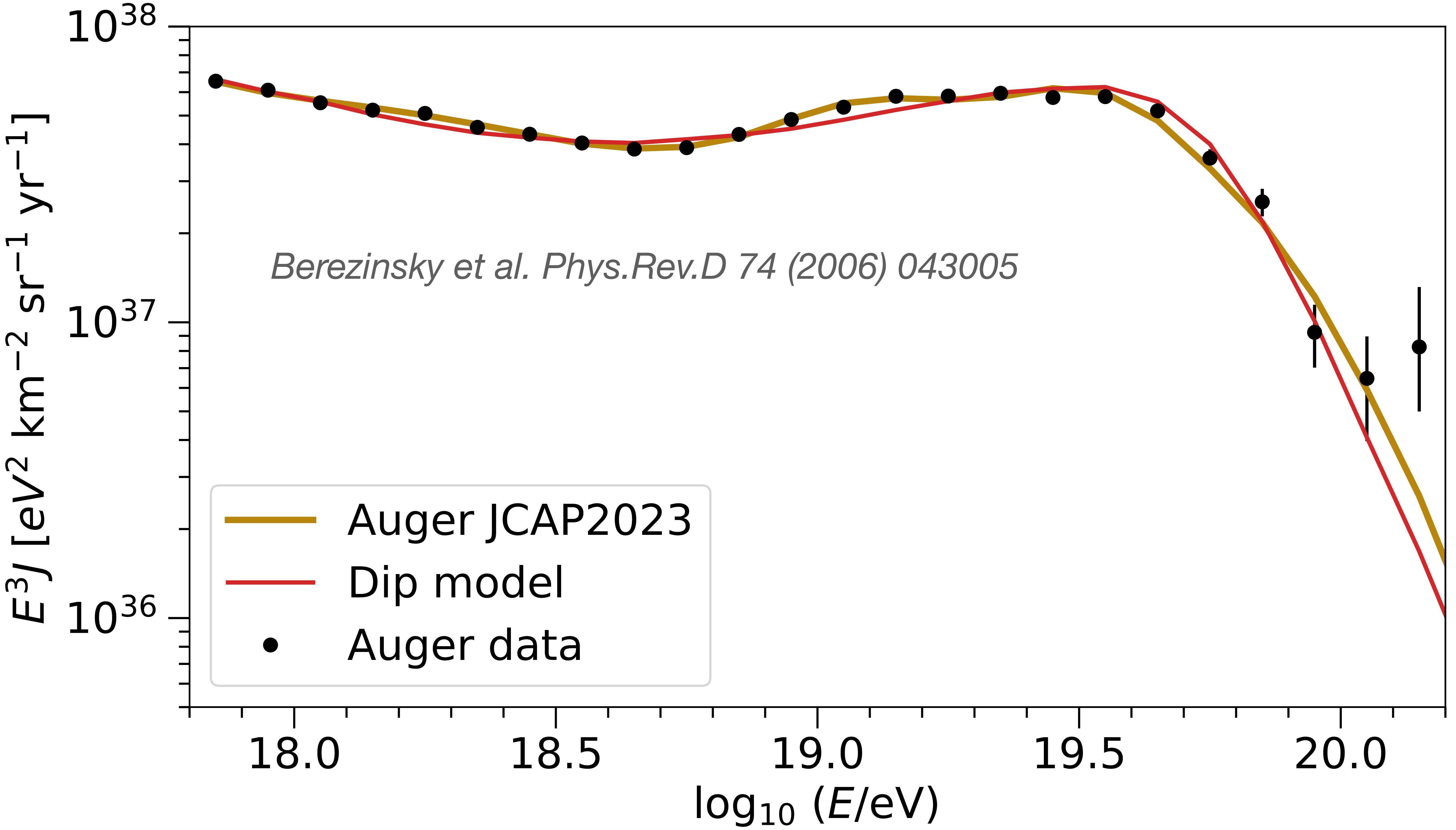
Phys. Rev. Lett. 125 (2020) 121106
Phys. Rev. D102 (2020) 062005
Eur. Phys. J. C81 (2021) 966

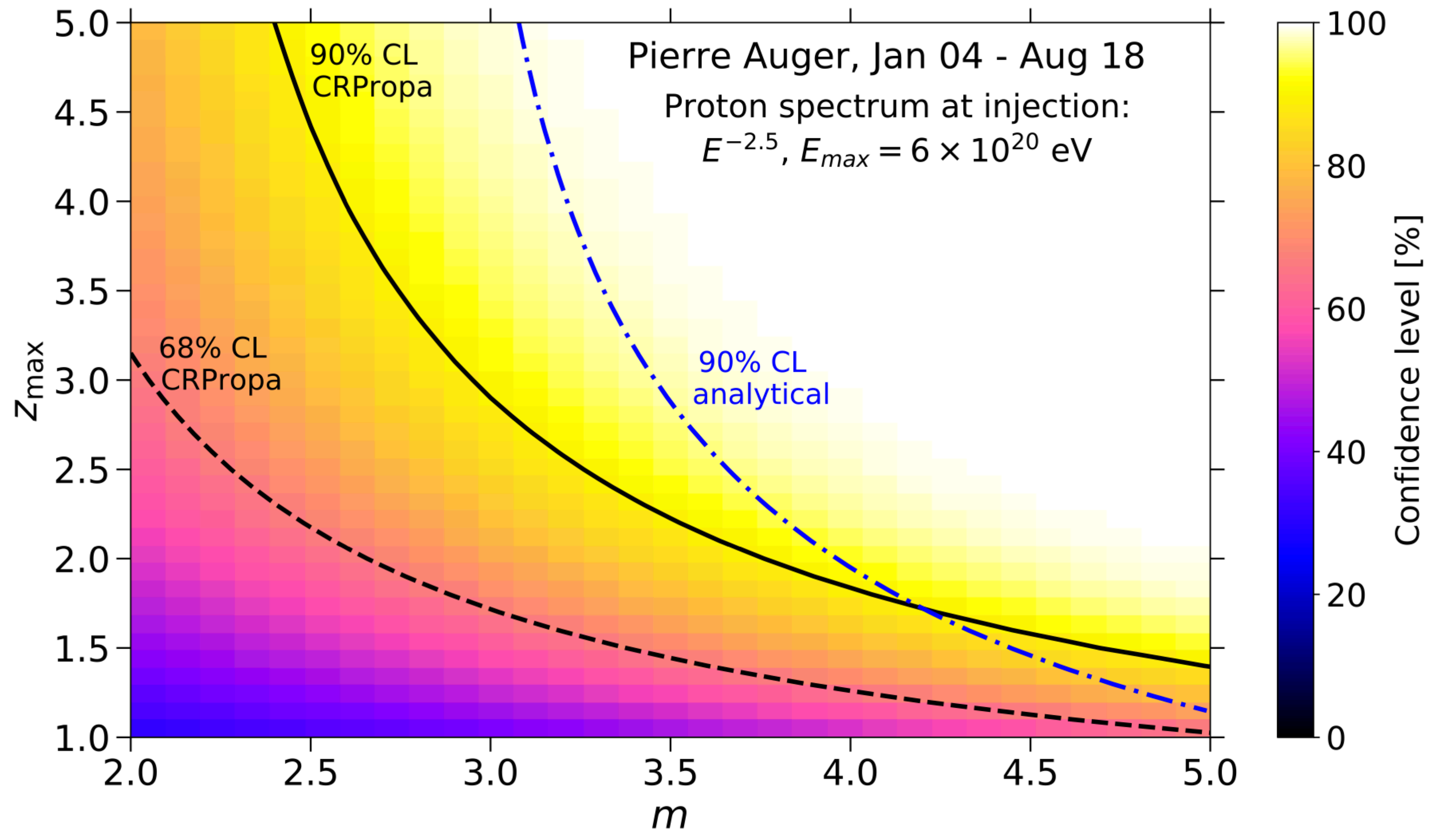


Fit just a parametrization, no physics assumptions

$$J(E) = J_0 \left(\frac{E}{10^{16}\ \mathrm{eV}}\right)^{-\gamma_0} \prod_{i=0}^{4} \left[1 + \left(\frac{E}{E_{ij}}\right)^{\frac{1}{\omega_{ij}}}\right]^{(\gamma_i - \gamma_j)\,\omega_{ij}}$$

Combined energy spectrum of Auger Observatory





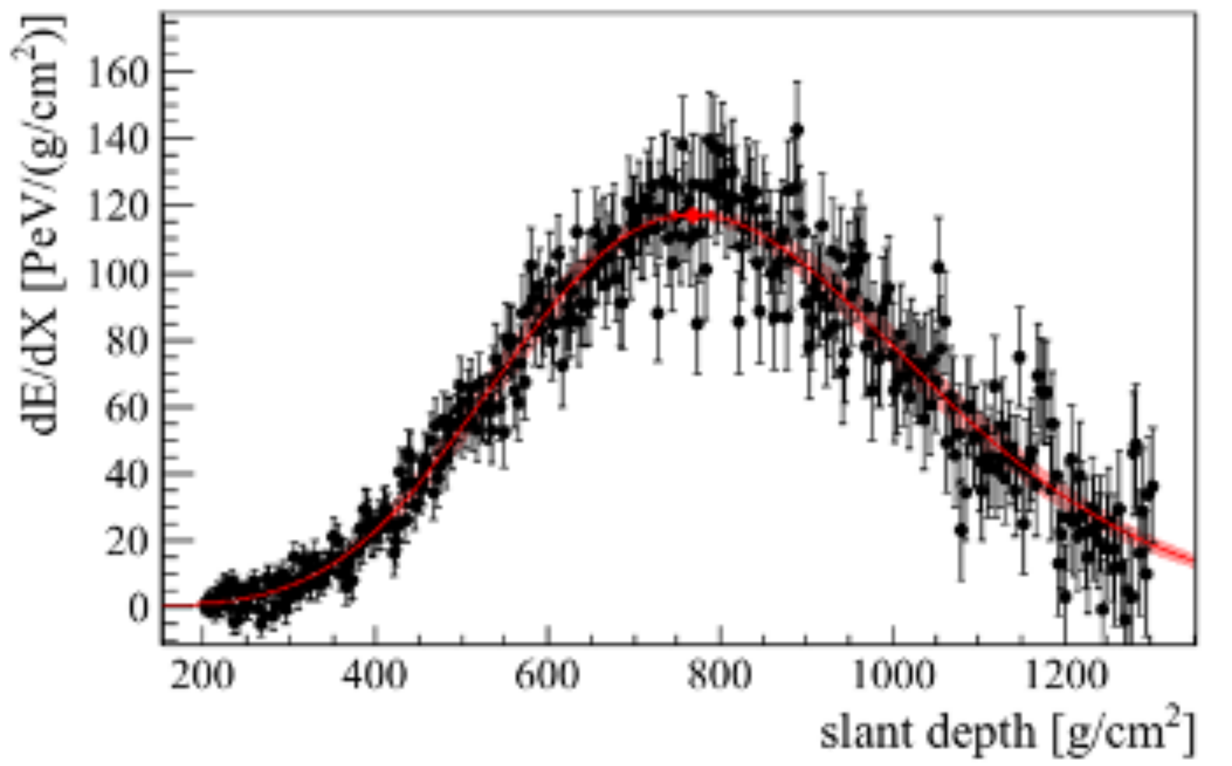
Dip model with proton composition:

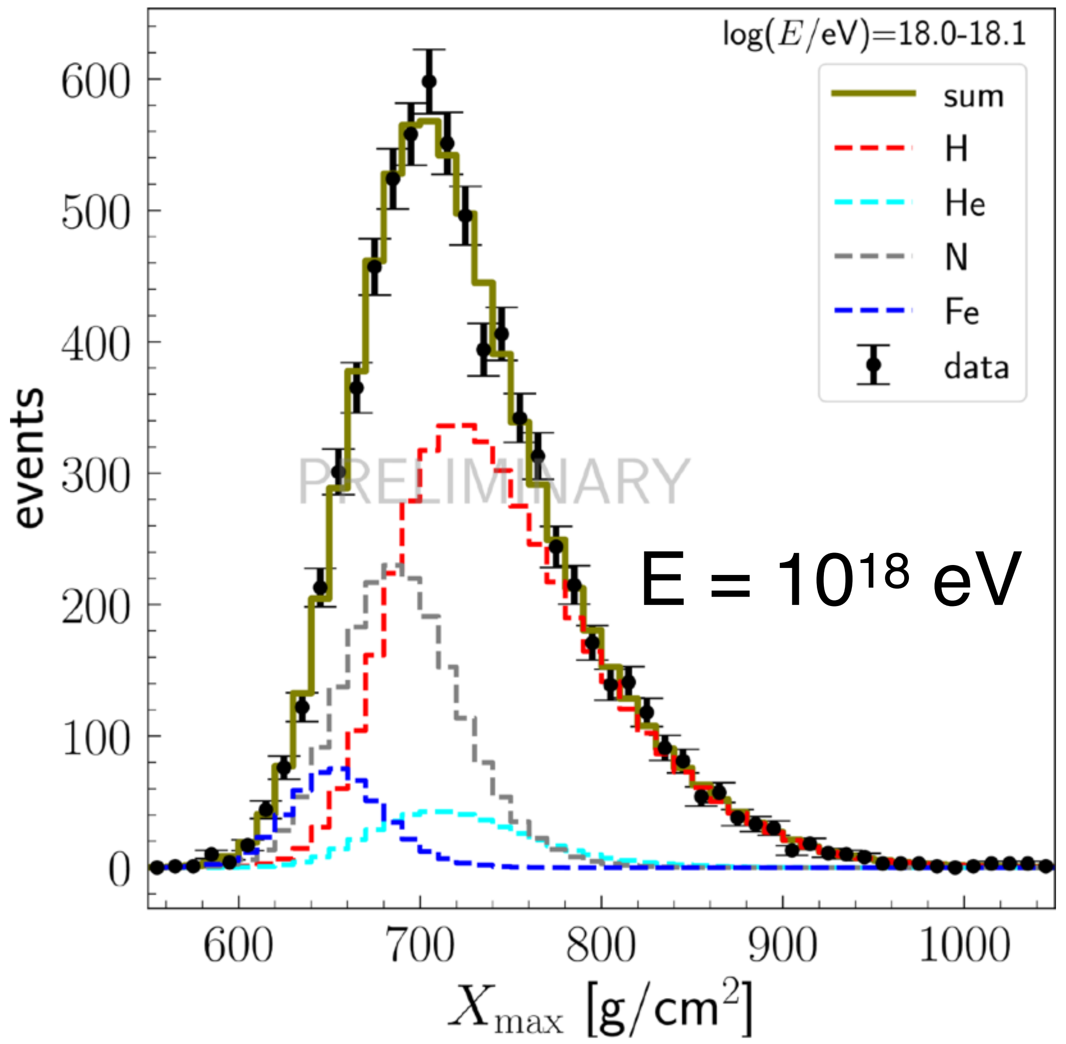
- **spectrum features not reproduced**
- **neutrino flux would be too high**

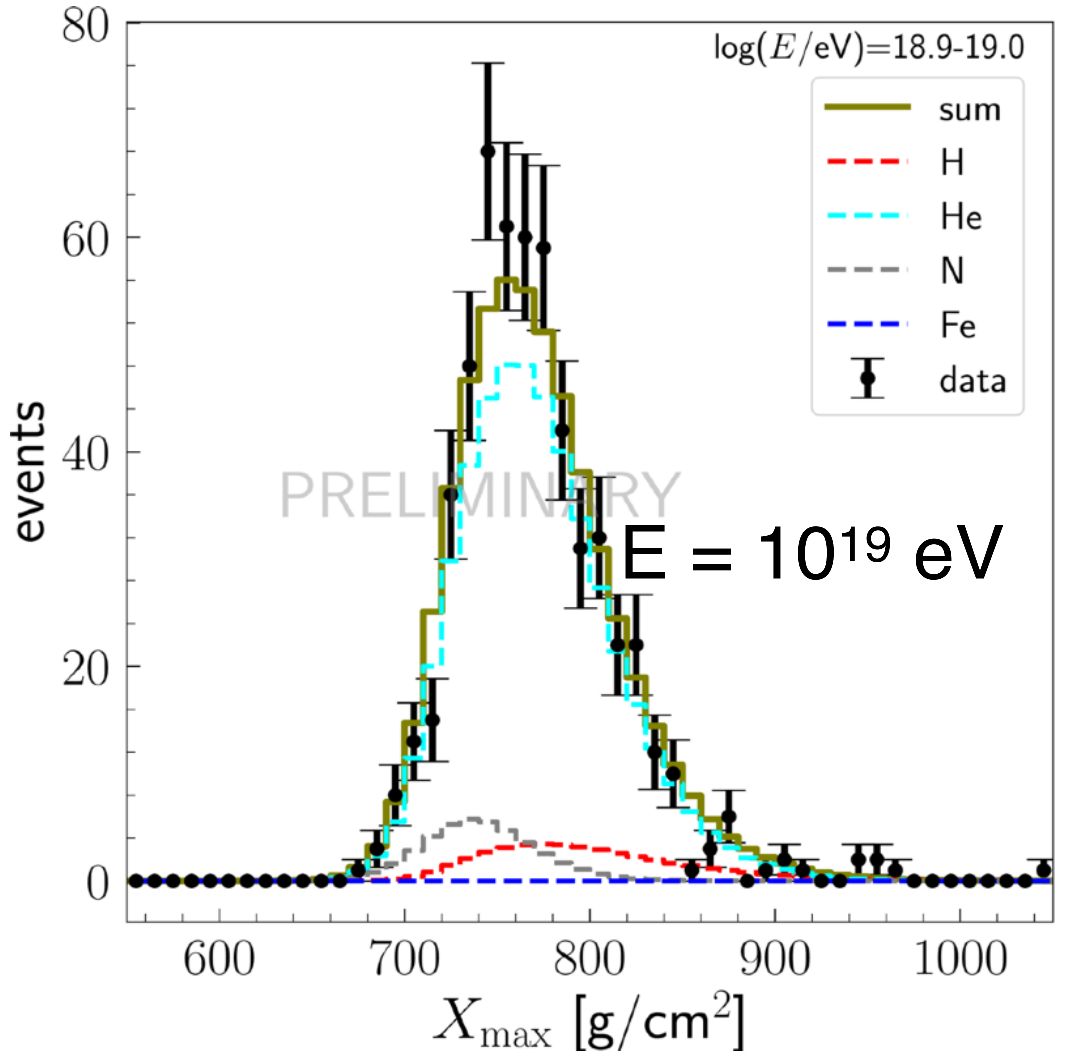
(Boncioli, Auger, UHECR 2024)

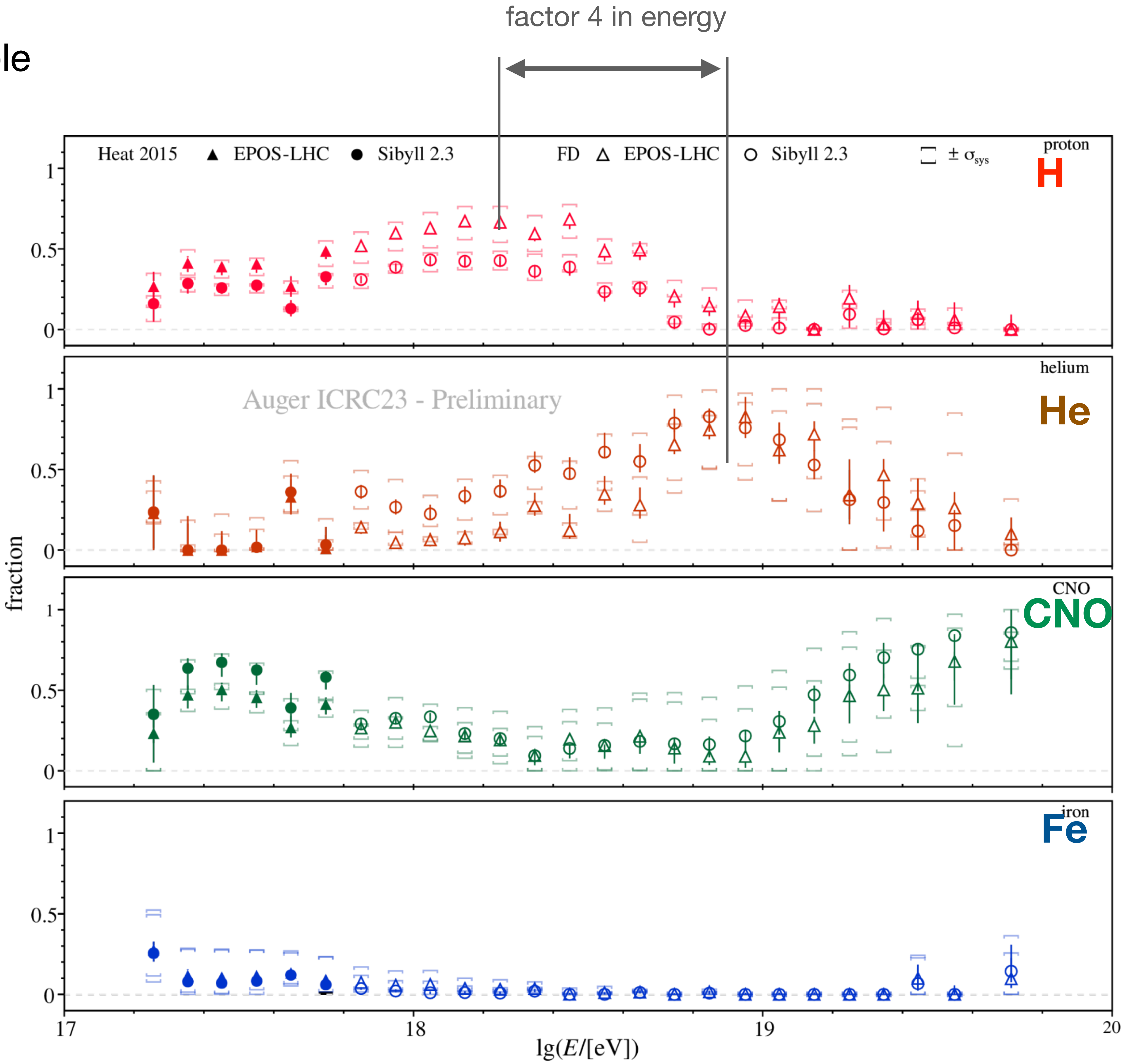
Mass composition from longitudinal shower profile

Depth of shower maximum as composition-sensitive observable





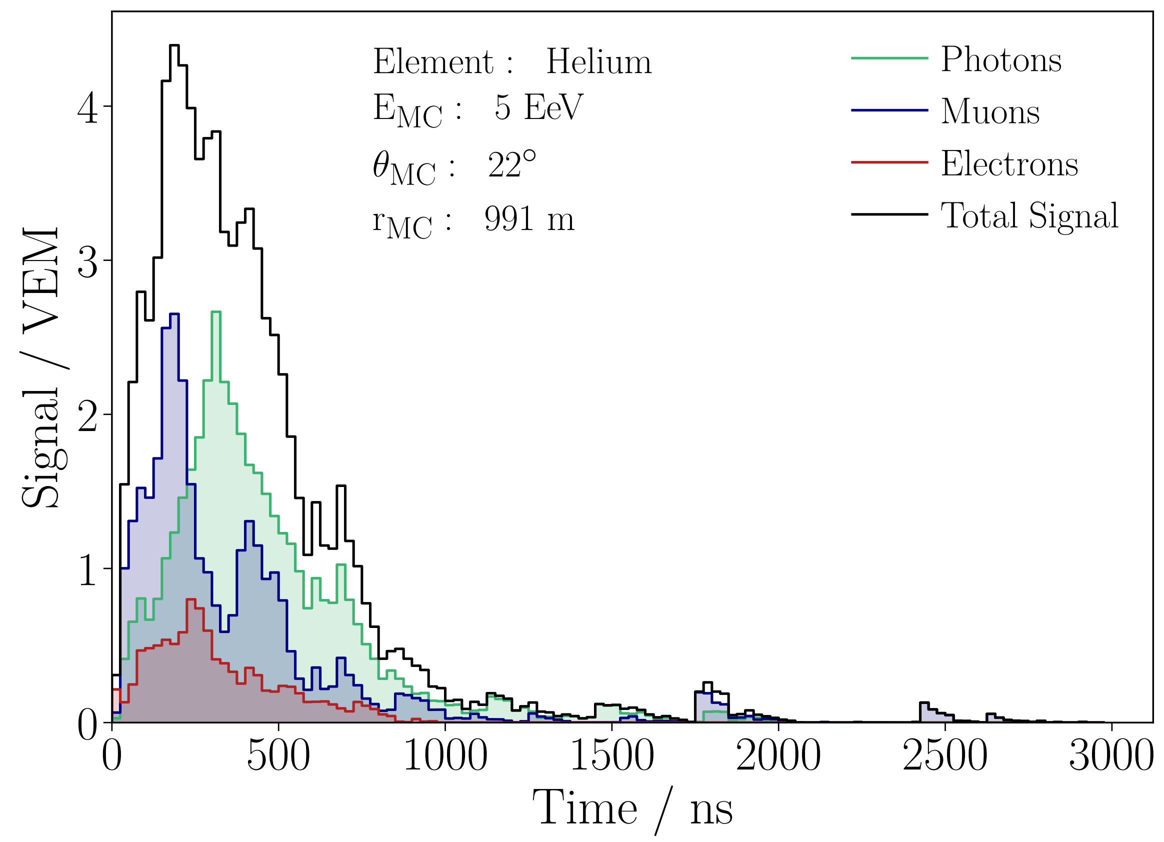


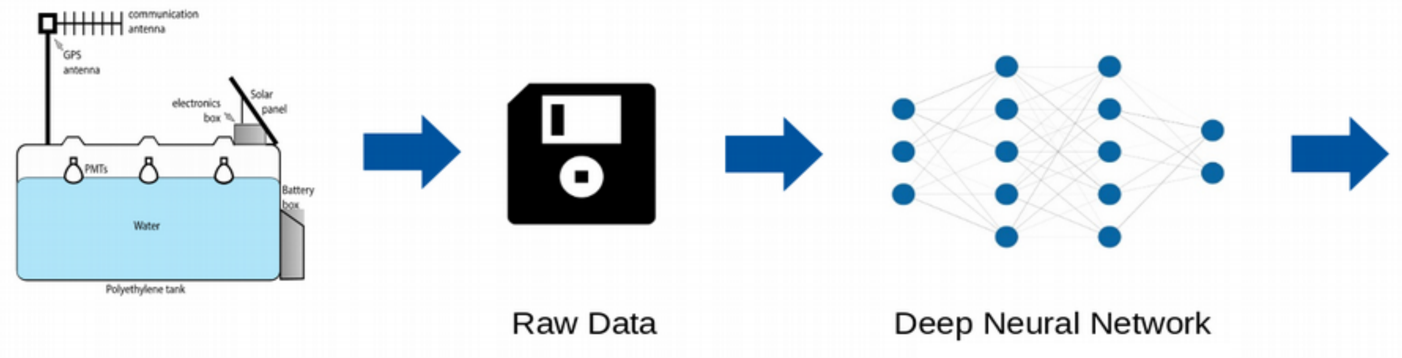


(Auger, Phys. Rev. D90 (2014), 122005 & 122005, ICRC 2023)

Mass composition from surface detector data

Simulated signal of one surface station

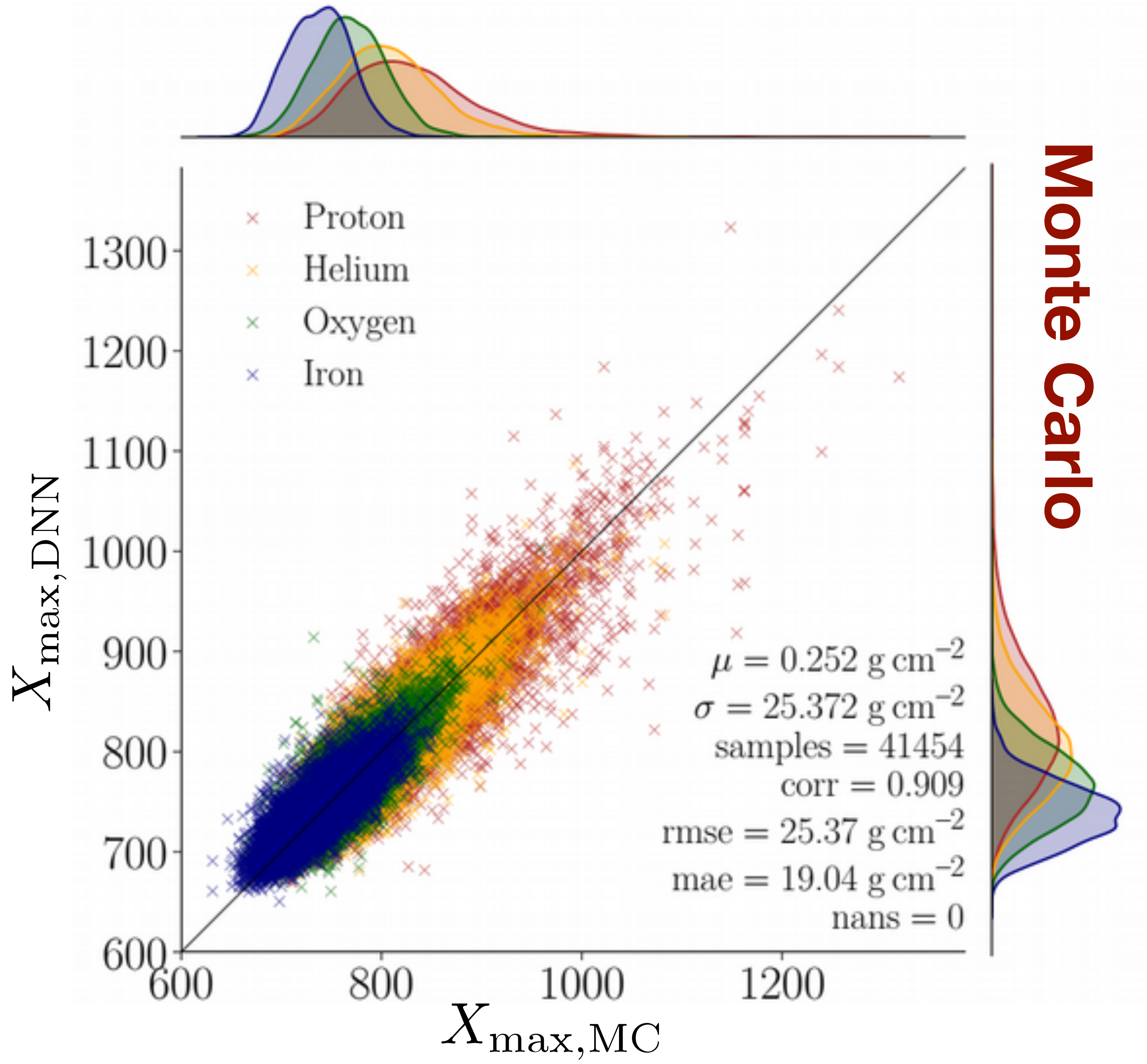


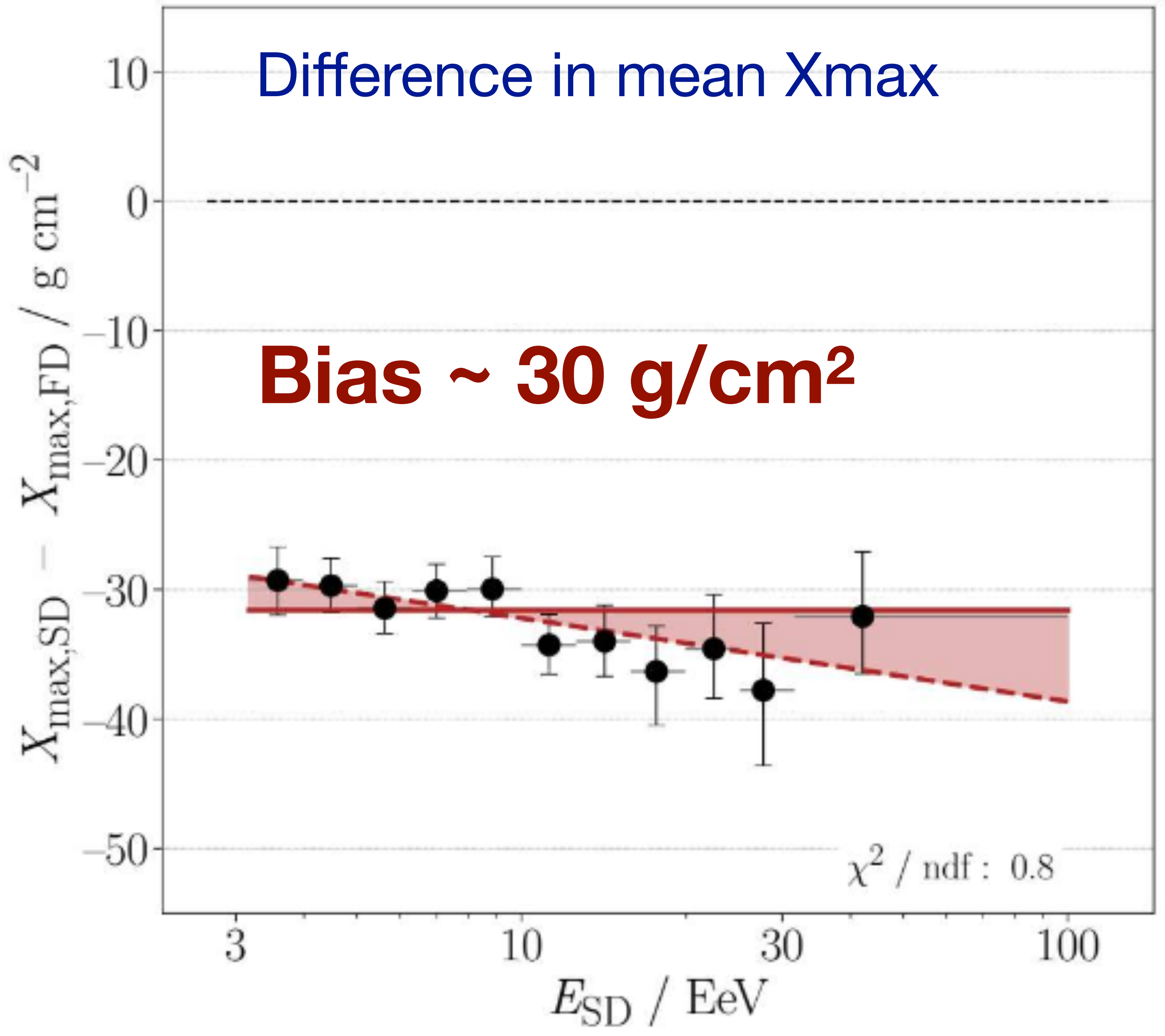


Reconstructing Xmax with DNNs: ultimate check with hybrid data

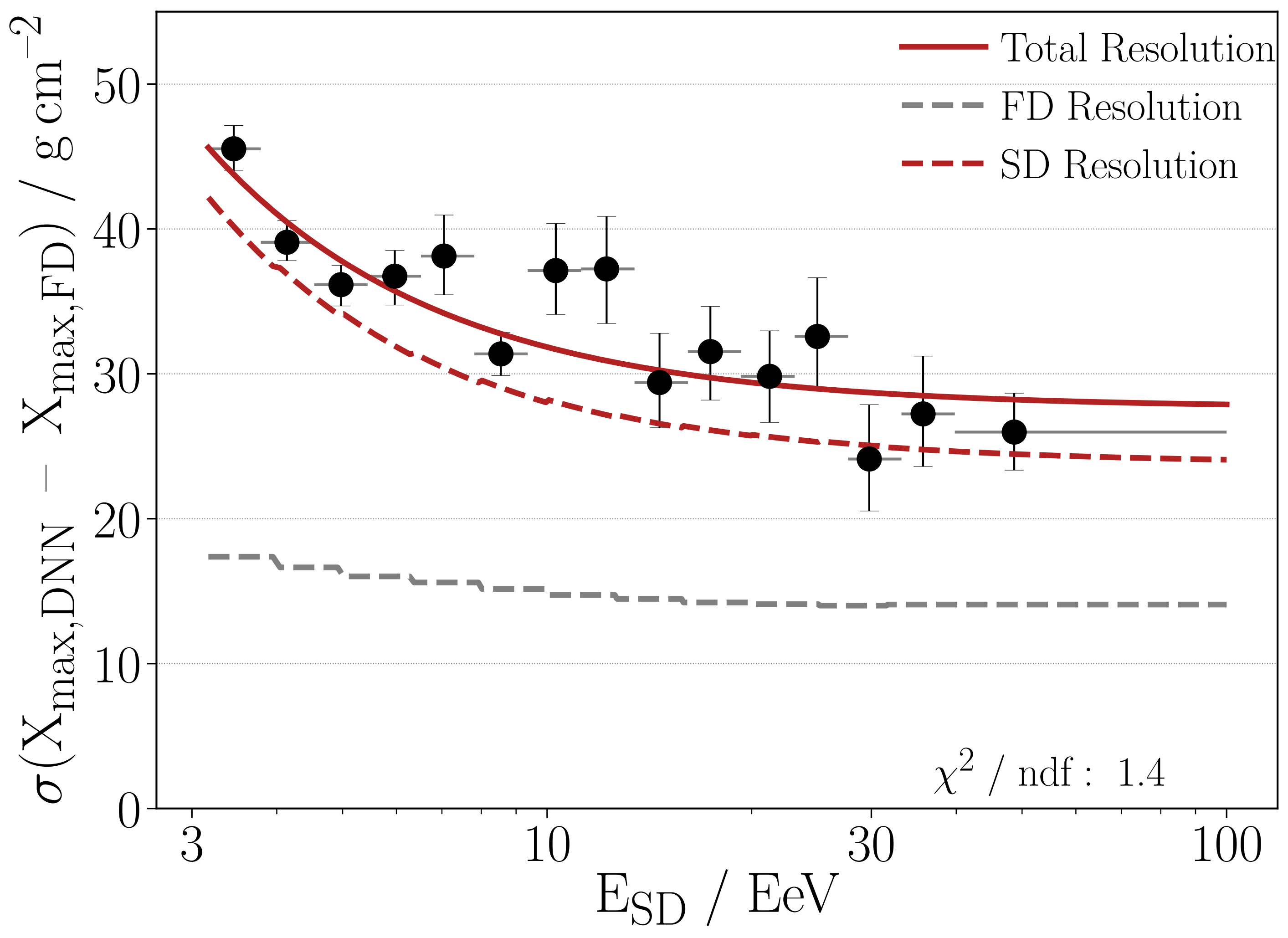
(Auger, JINST 16 (2021) P07019)

Monte Carlo

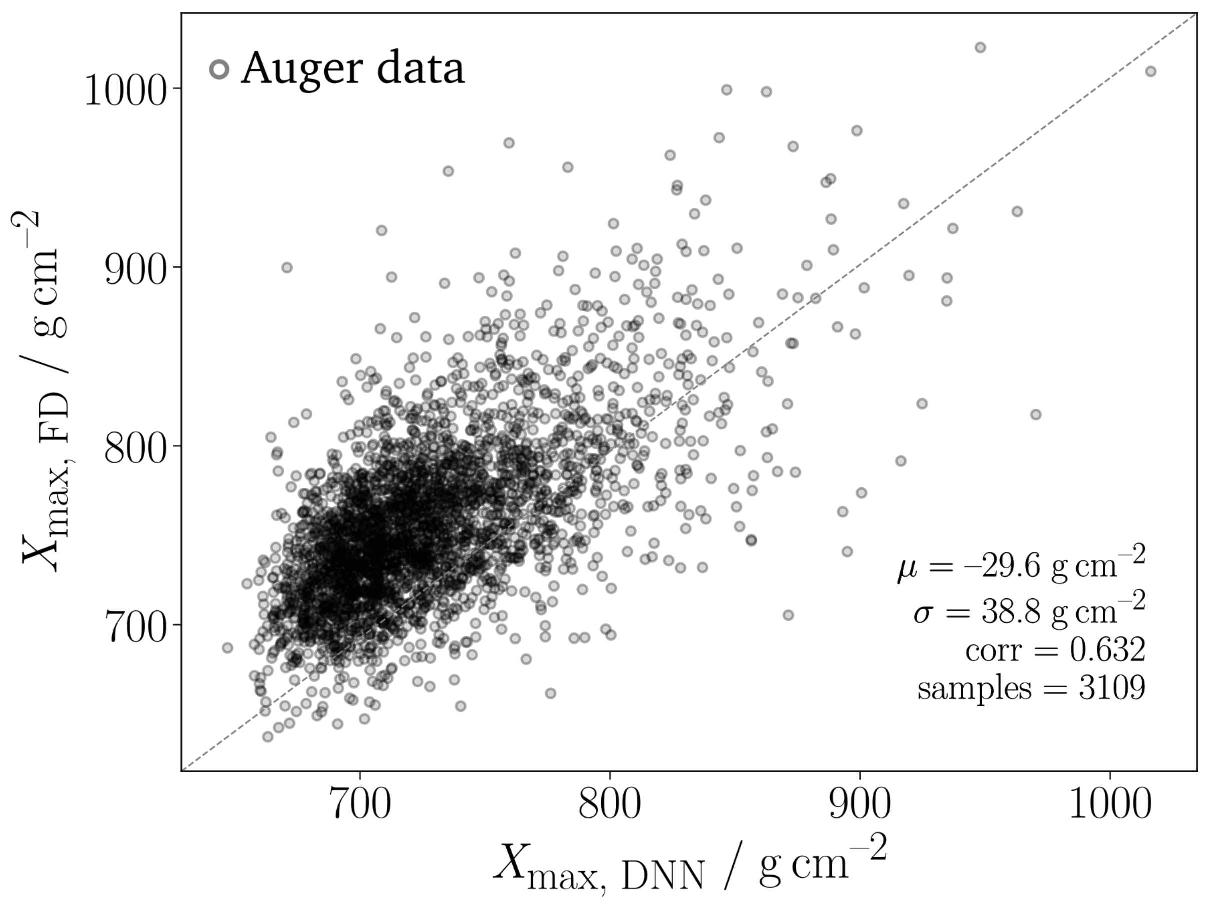




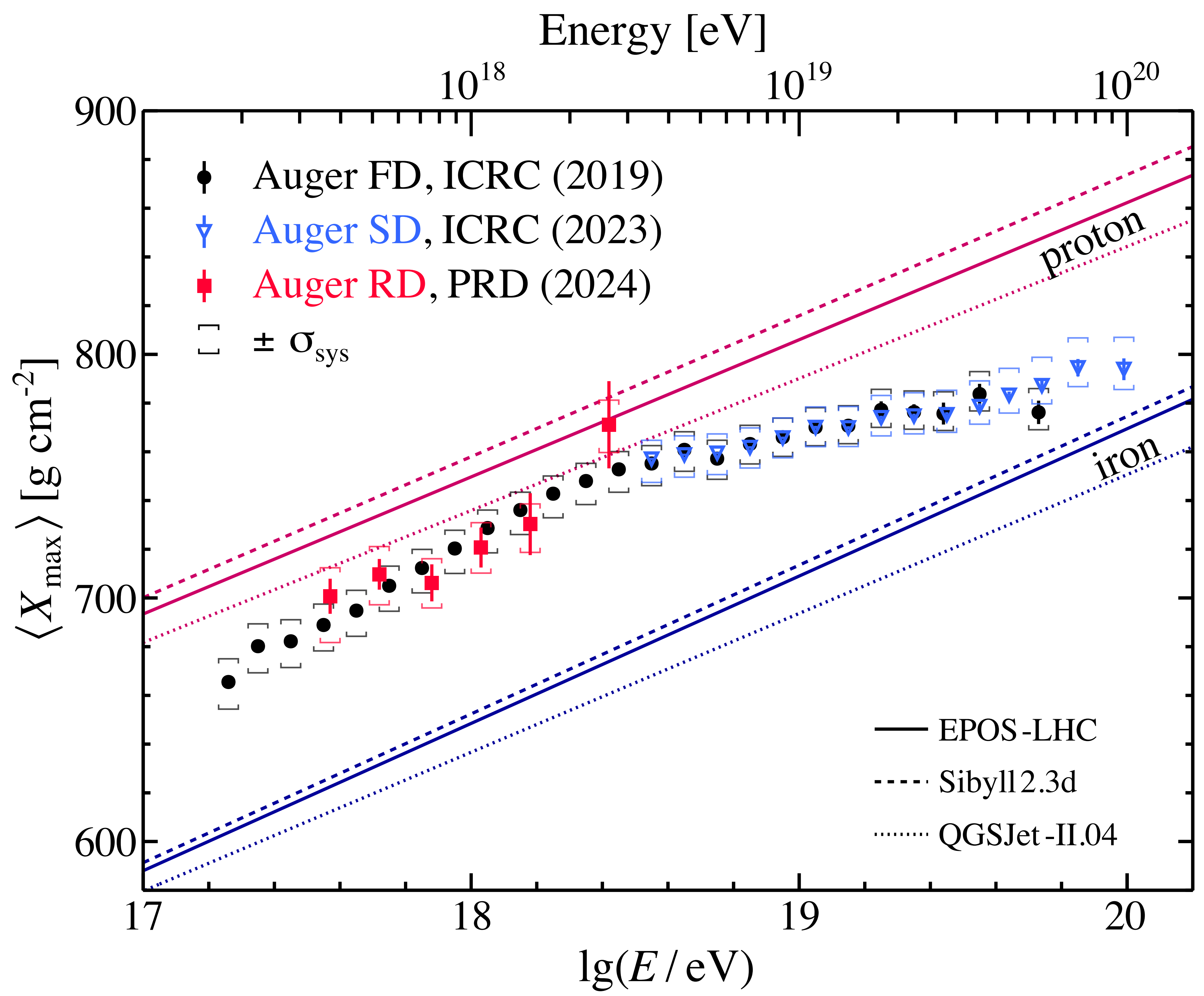
Shower-by shower Xmax resolution

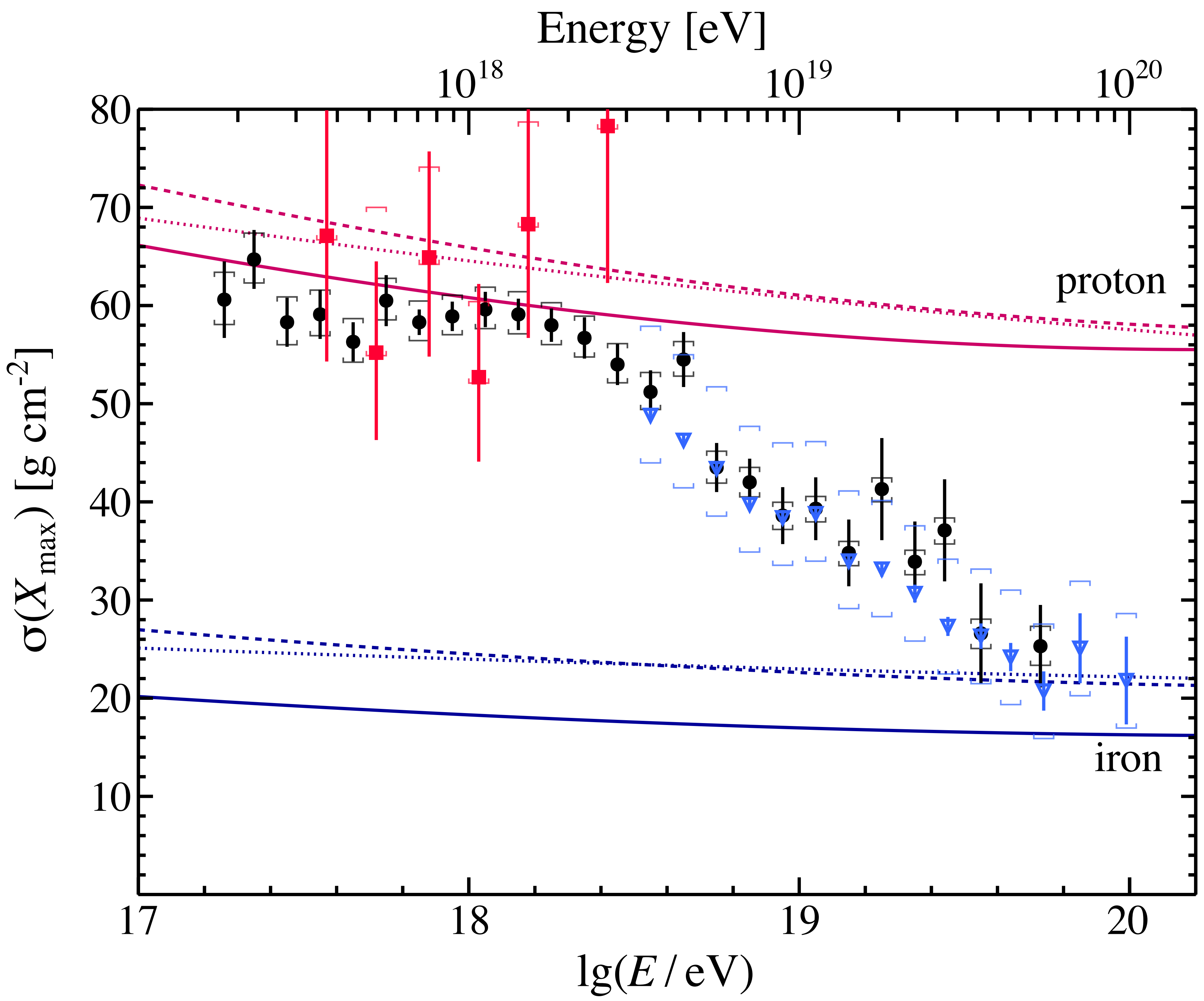


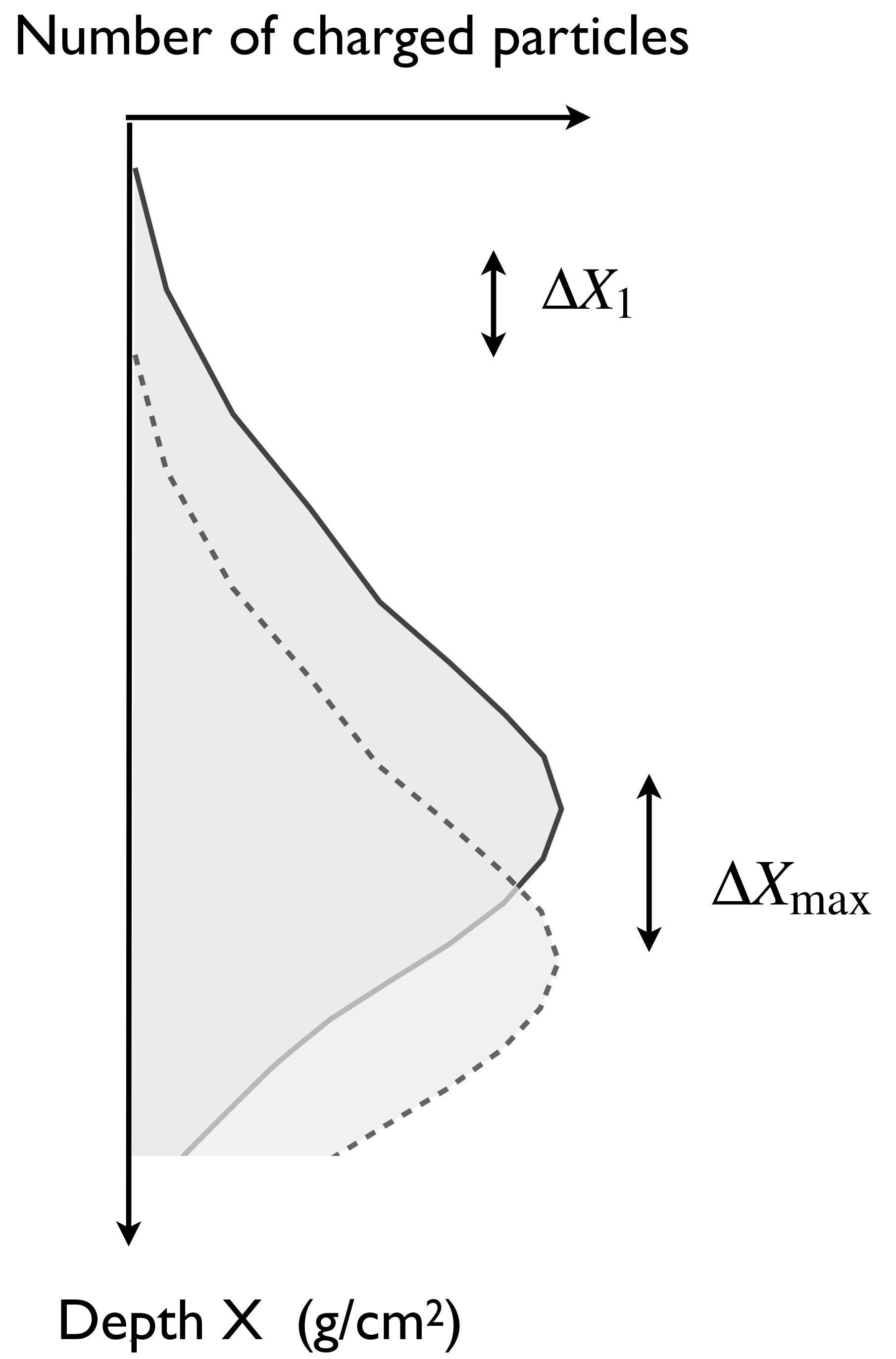
Hybrid data



Mass composition results of Auger Observatory







$$\frac{dP}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}}$$

$$\sigma_{X_1,p} \sim 45 - 55\,\mathrm{g/cm^2}$$
$$\sigma_{X_1,Fe} \sim 10\,\mathrm{g/cm^2}$$

$(E \sim 10^{18}\,\mathrm{eV})$

Important: LHC-tuned interaction models used for interpretation

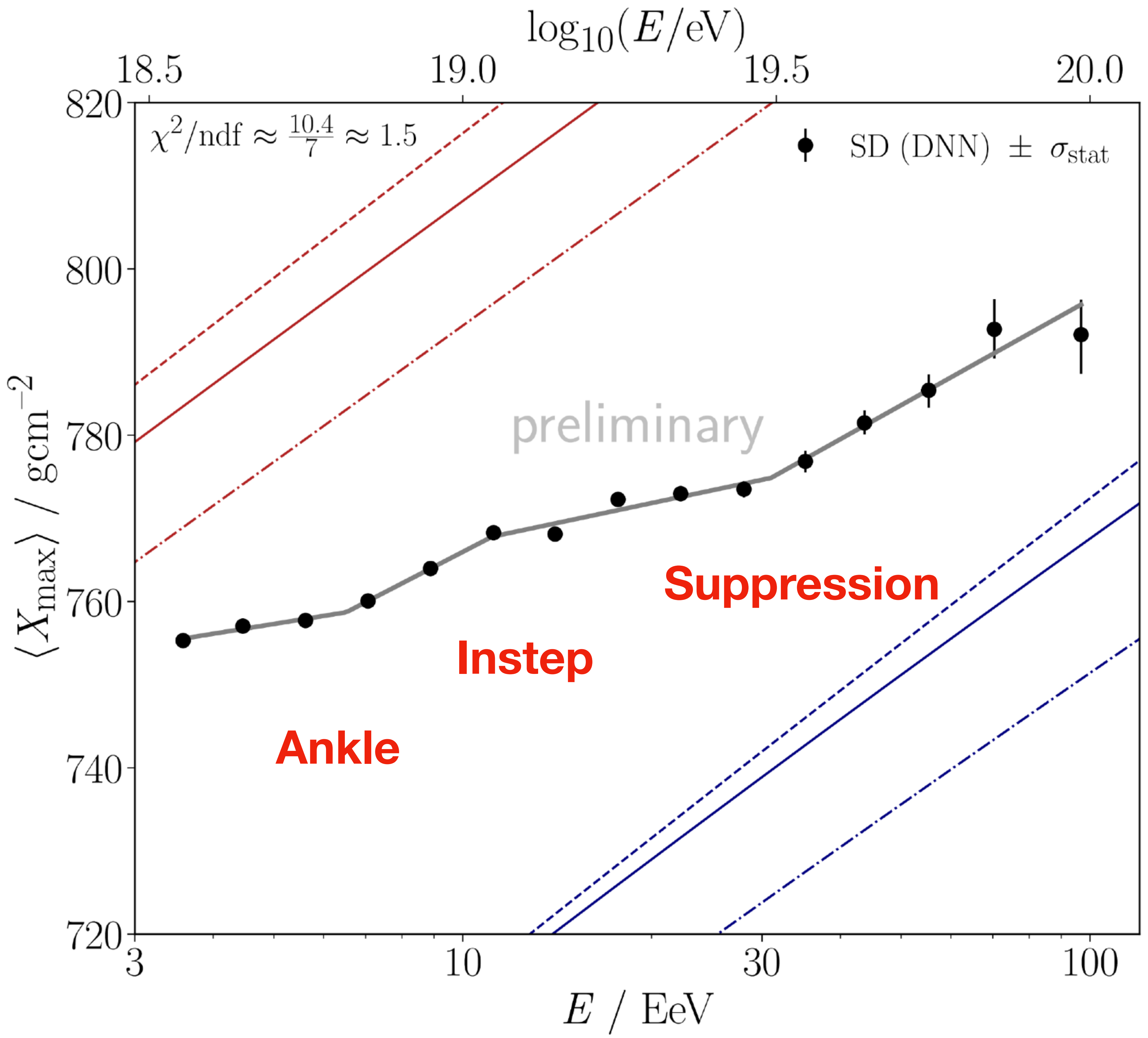
(FD telescopes: PRD 90 (2014), 122005 & 122005, updated ICRC 2023)

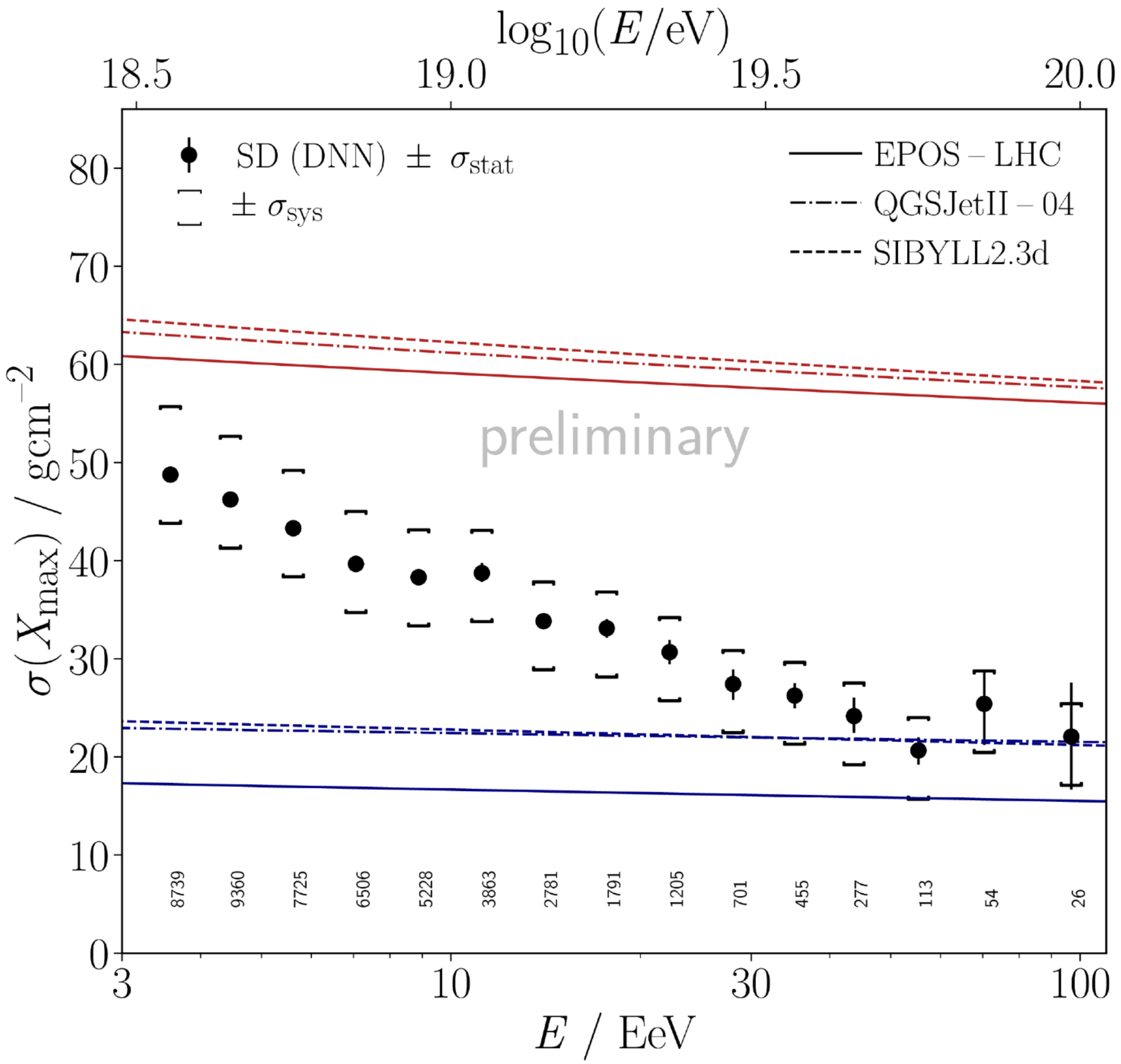
(SD risetime: Phys. Rev. D96 (2017), 122003)

(AERA/radio: PRL & PRD 2023)

(SD DNN: to appear in PRL & PRD)

Model-independent observation in DNN data set

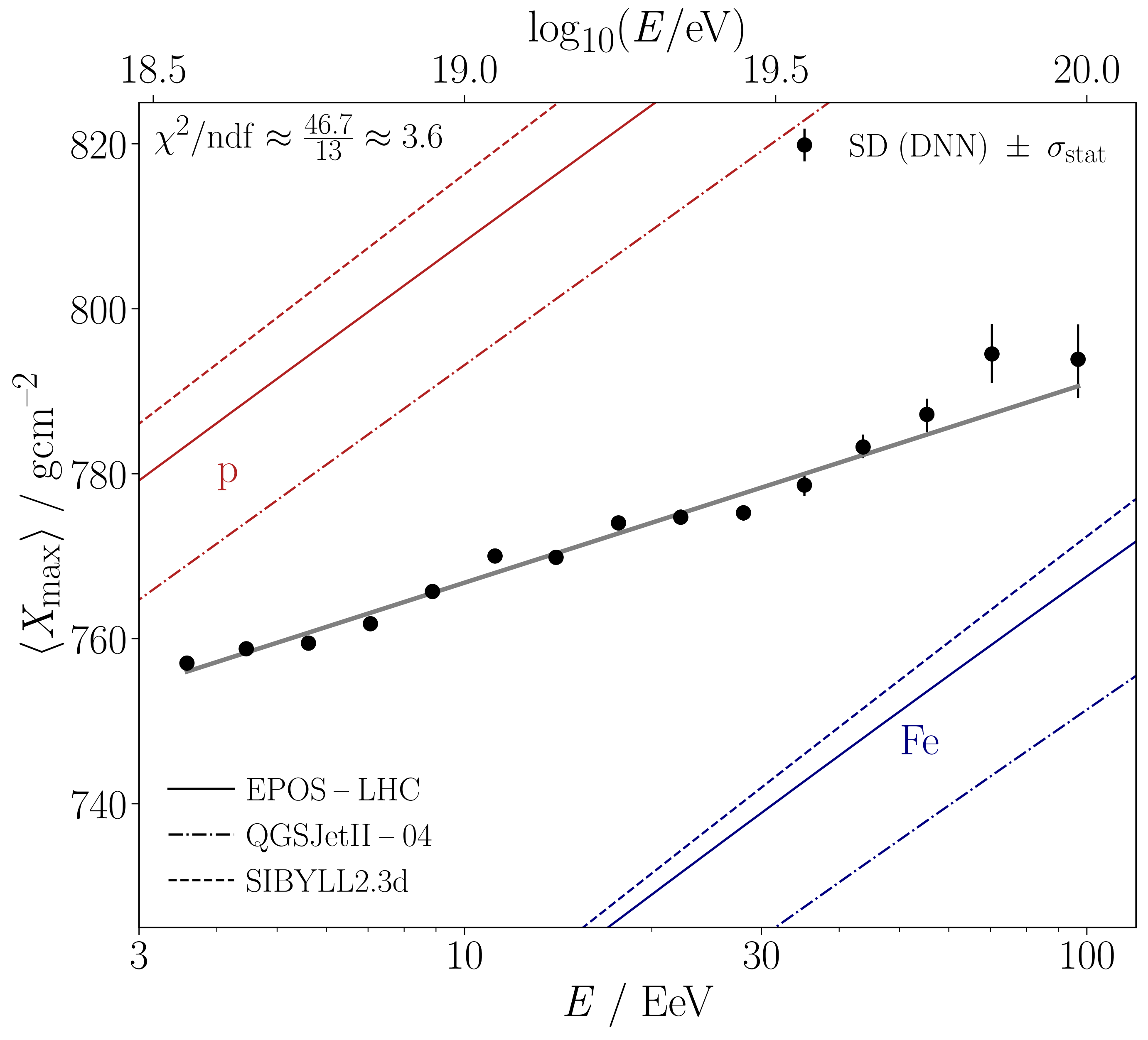




Energy-independent elongation rate excluded at 4.4 sigma

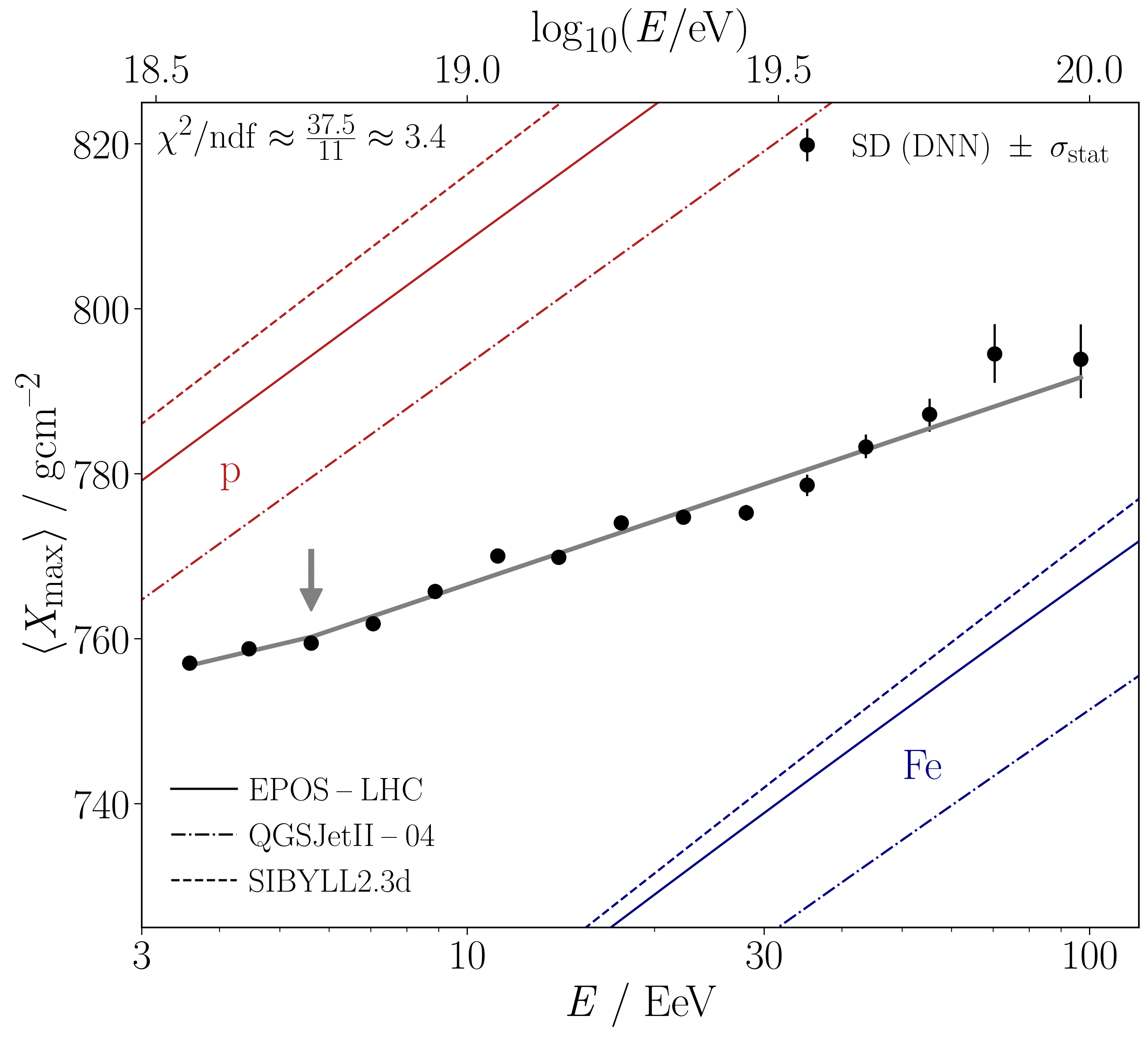
Breaks of elongation rate correlated with breaks in energy spectrum

(Auger to appear in PRL & PRD 2406.06315, 2406.06319)



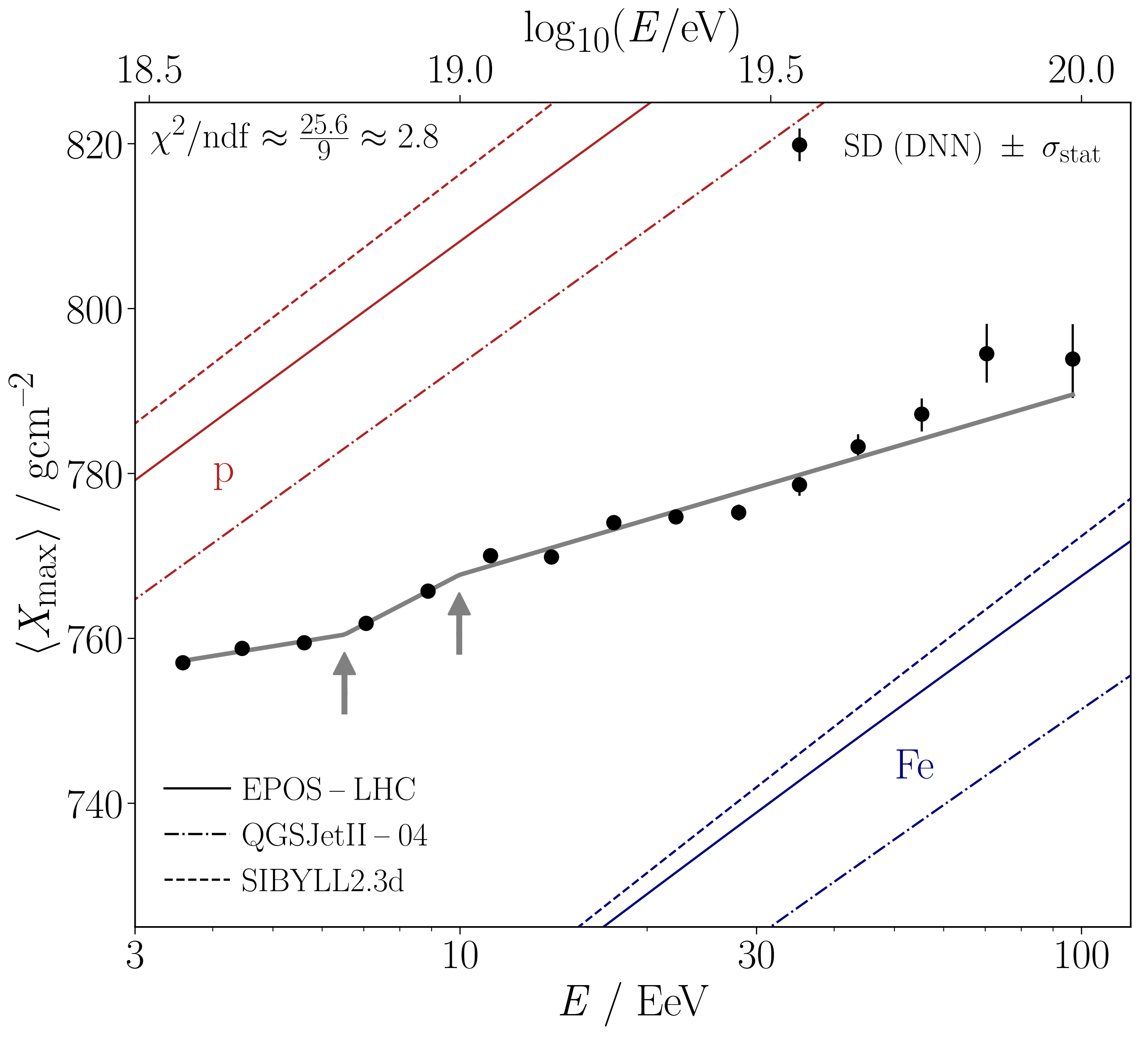
log10(E/eV)
18.5
19.0
19.5
20.0
χ2/ndf ≈ 46.7/13 ≈ 3.6
SD (DNN) ± σstat
⟨Xmax⟩ / gcm−2
820
800
780
760
740
p
Fe
EPOS − LHC
QGSJetII − 04
SIBYLL2.3d
3
10
30
100
E / EeV

(a)



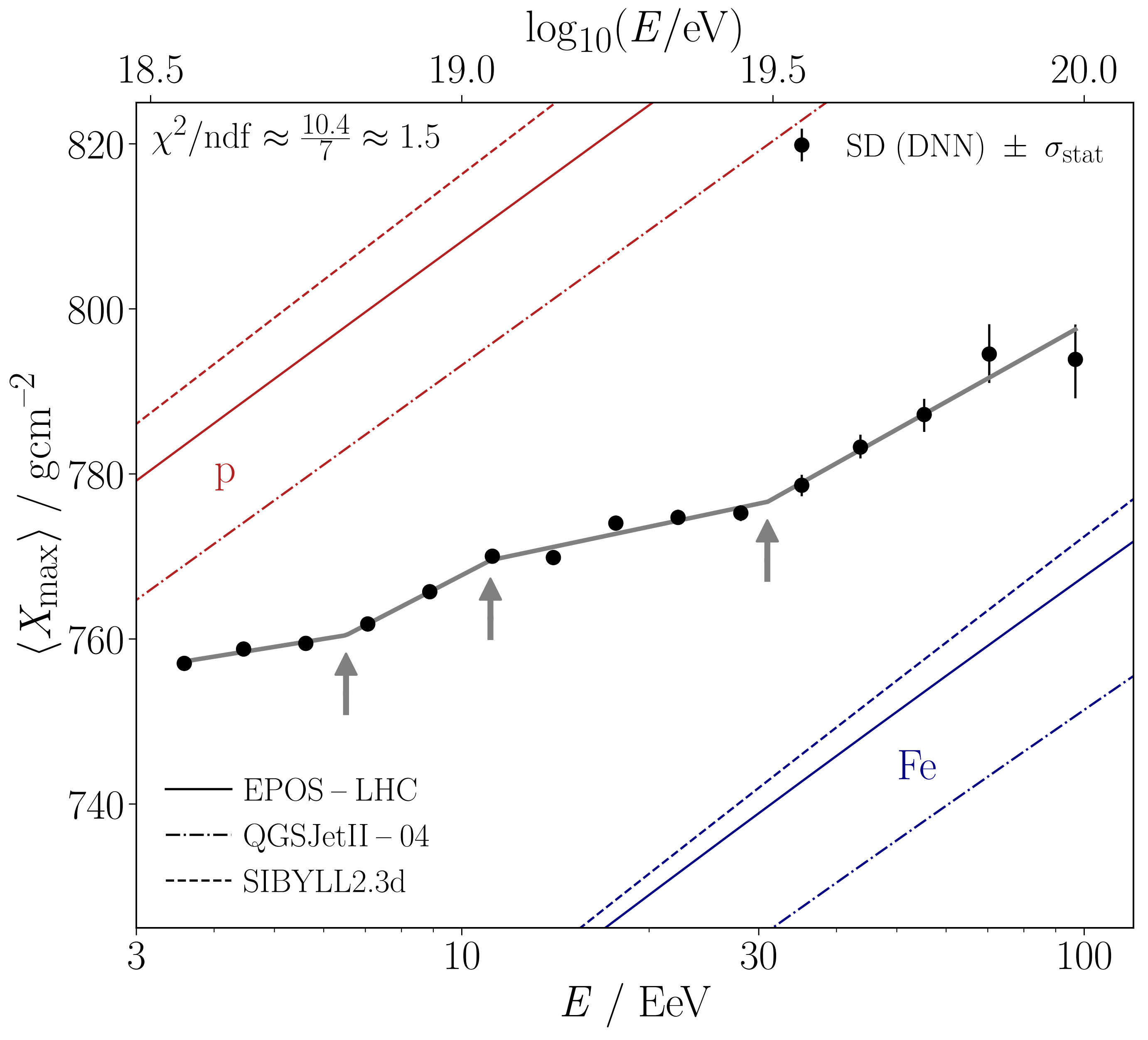
log10(E/eV)
18.5
19.0
19.5
20.0
χ2/ndf ≈ 37.5/11 ≈ 3.4
SD (DNN) ± σstat
⟨Xmax⟩ / gcm−2
820
800
780
760
740
p
Fe
EPOS − LHC
QGSJetII − 04
SIBYLL2.3d
3
10
30
100
E / EeV

(b)



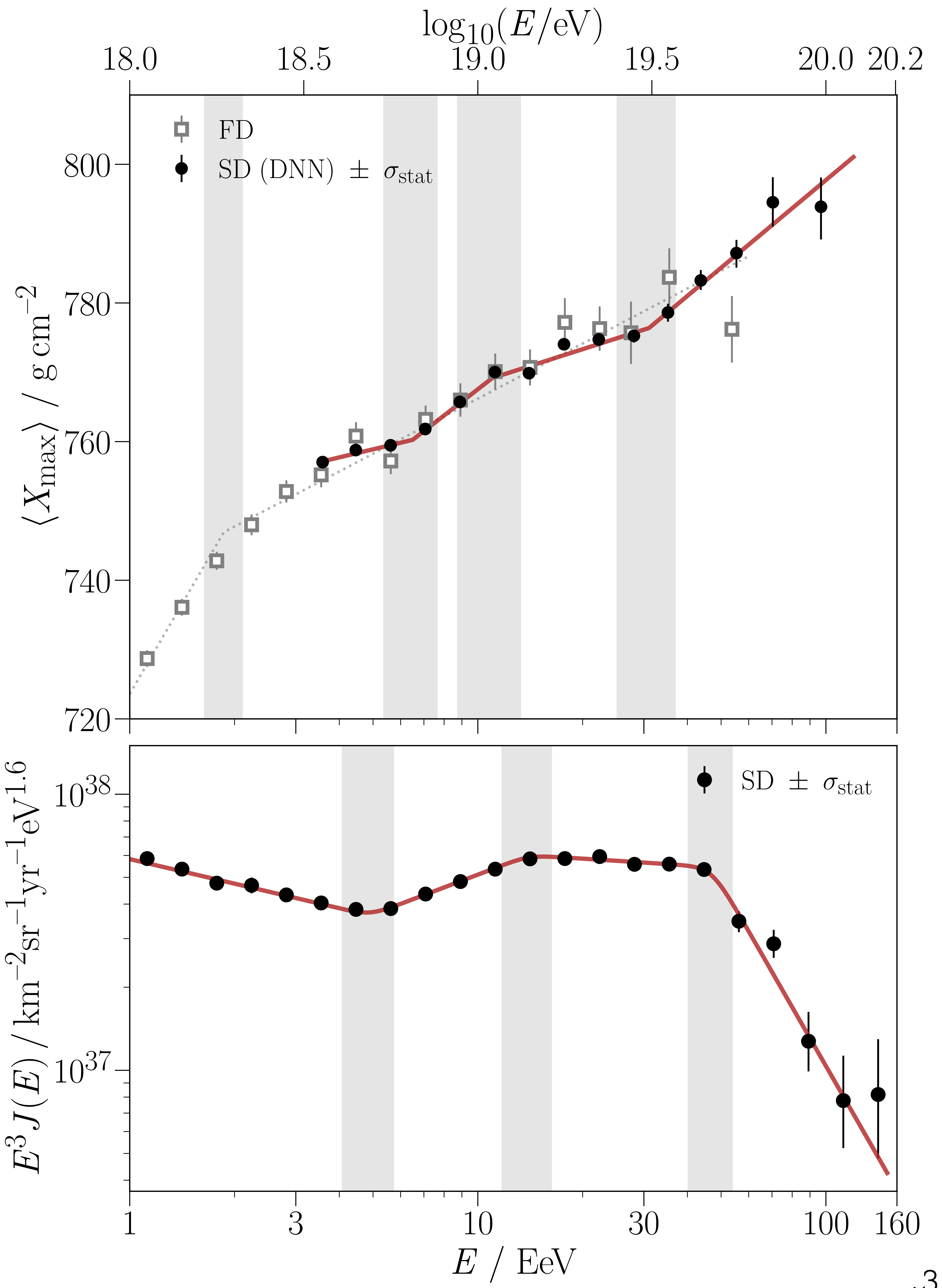
log10(E/eV)
18.5
19.0
19.5
20.0
χ2/ndf ≈ 25.6/9 ≈ 2.8
SD (DNN) ± σstat
⟨Xmax⟩ / gcm−2
820
800
780
760
740
p
Fe
EPOS − LHC
QGSJetII − 04
SIBYLL2.3d
3
10
30
100
E / EeV

(c)



log10(E/eV)
18.5
19.0
19.5
20.0
χ2/ndf ≈ 10.4/7 ≈ 1.5
SD (DNN) ± σstat
⟨Xmax⟩ / gcm−2
820
800
780
760
740
p
Fe
EPOS − LHC
QGSJetII − 04
SIBYLL2.3d
3
10
30
100
E / EeV

(d)

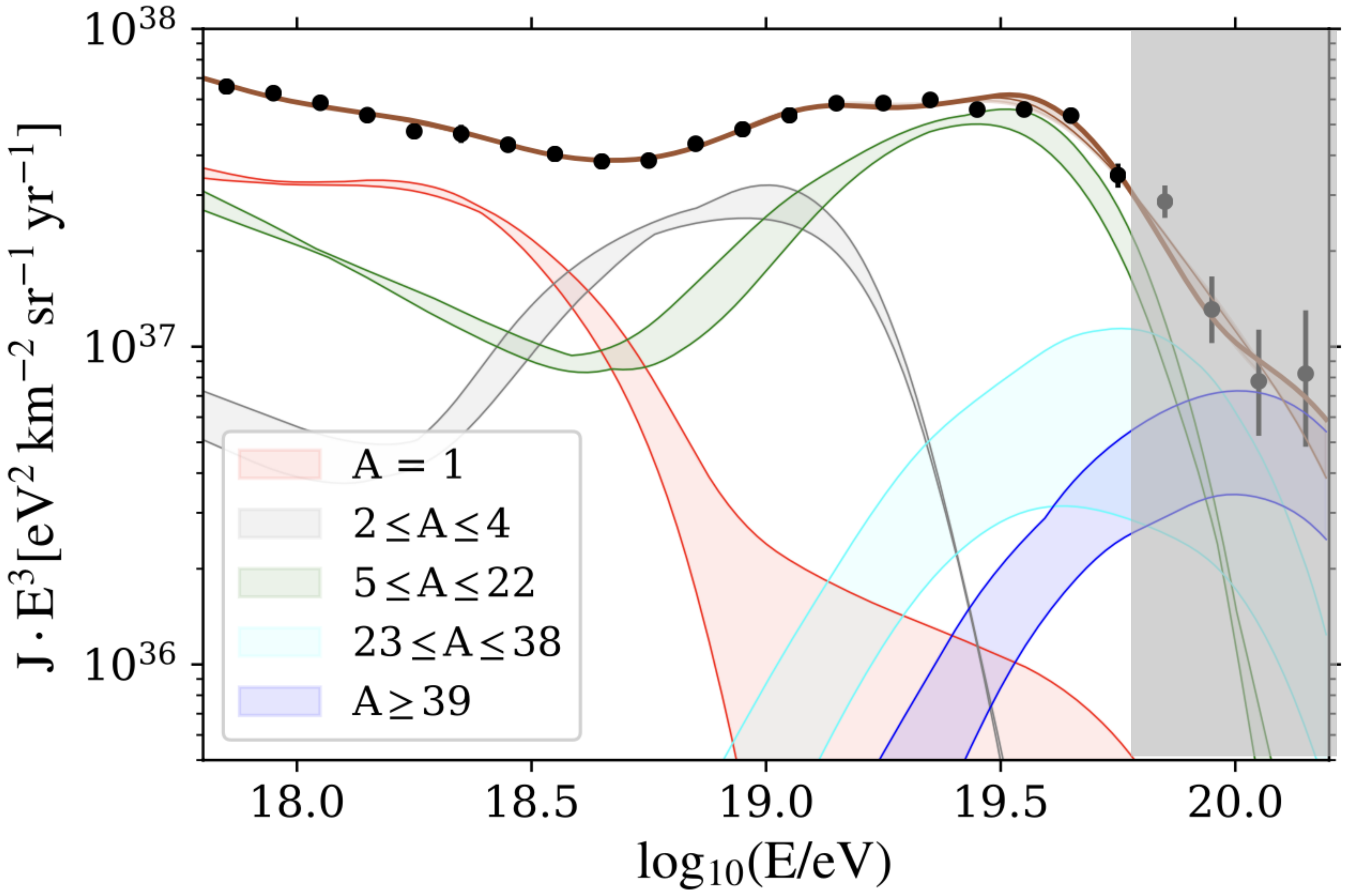


log10(E/eV)
18.0
18.5
19.0
19.5
20.0
20.2
FD
SD (DNN) ± σstat
⟨Xmax⟩ / g cm−2
800
780
760
740
720
SD ± σstat
E3 J(E) / km−2sr−1yr−1eV1.6
10^38
10^37
1
3
10
30
100
160
E / EeV

.3

Model calculations for mass composition and flux

(Auger, JCAP 05 (2023) 024 & JCAP 01 (2024) 022 & JCAP 07 (2024) 094)



Flux suppression due mainly to limit of injection energy of sources

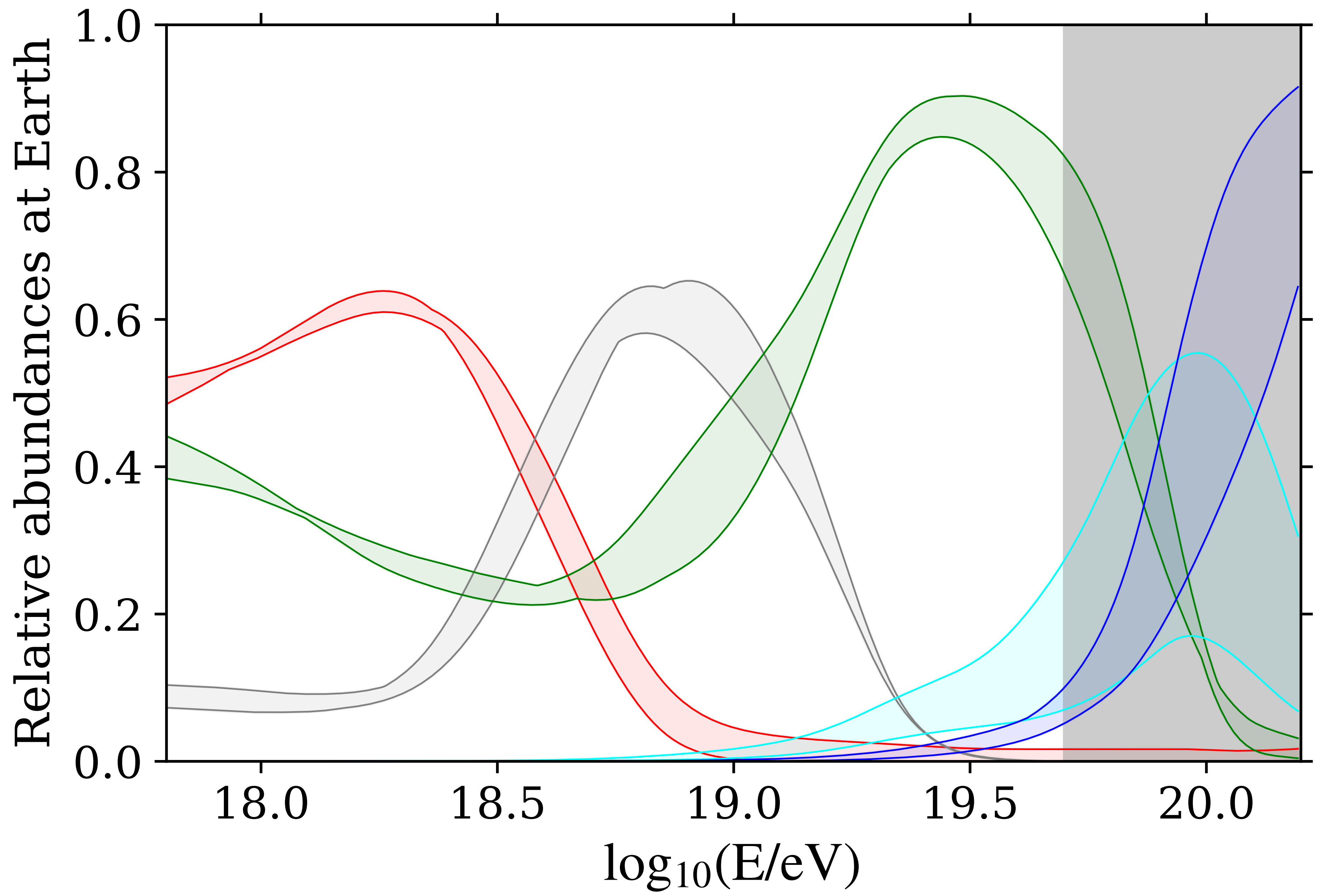
New problem of limited source variance (Ehlert et al. PRD 2023)

Assumption: source injection spectra universal in rigidity $R = E/Z$ (acceleration, scaling with charge Z)

$$E_{\mathrm{p,cut}} = 1.4 \ldots 1.6 \times 10^{18}\,\mathrm{eV}$$

Exceptionally hard injection spectrum

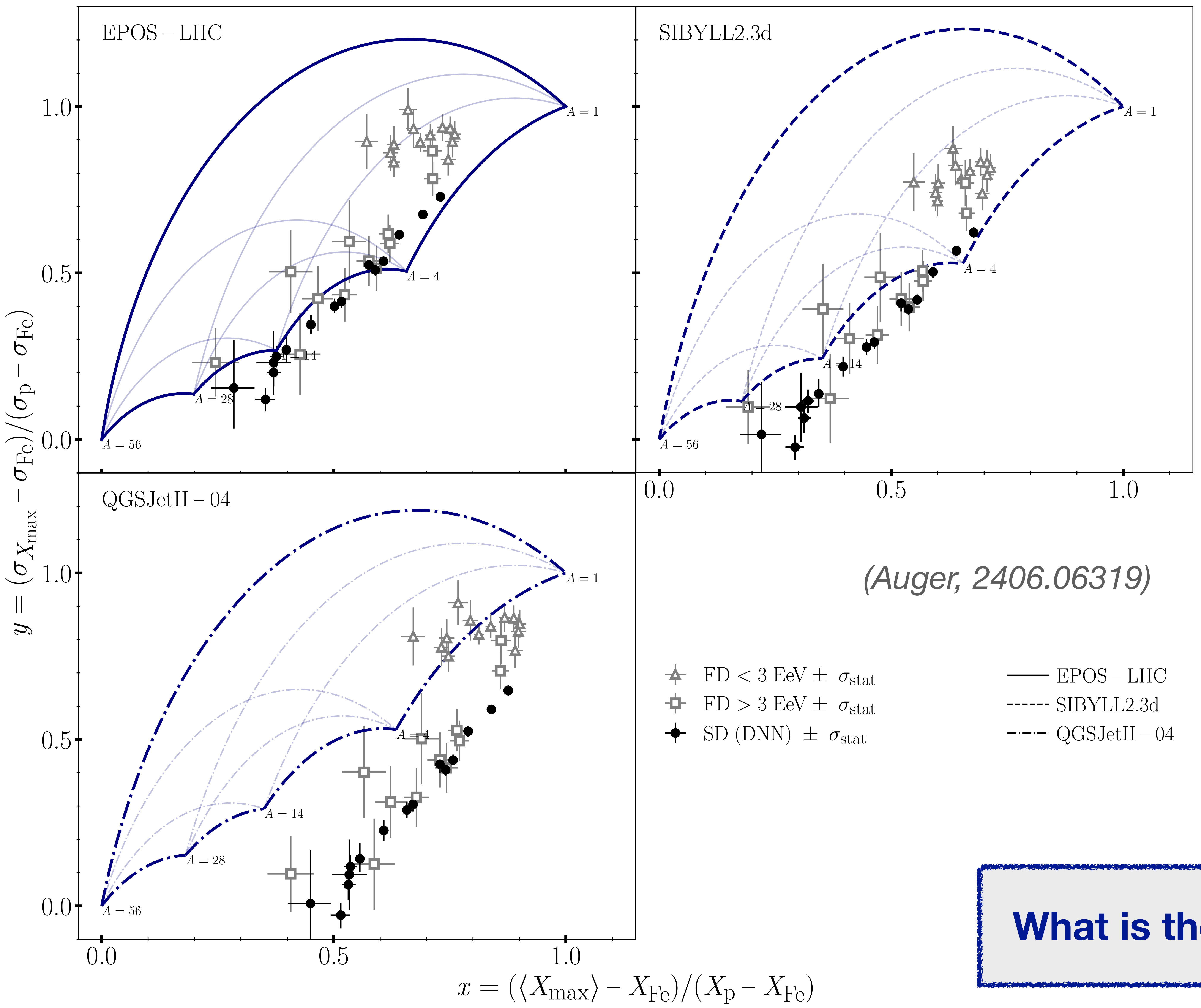
$$\frac{\mathrm{d}N}{\mathrm{d}E} \sim E^{1.5 \ldots 2}$$



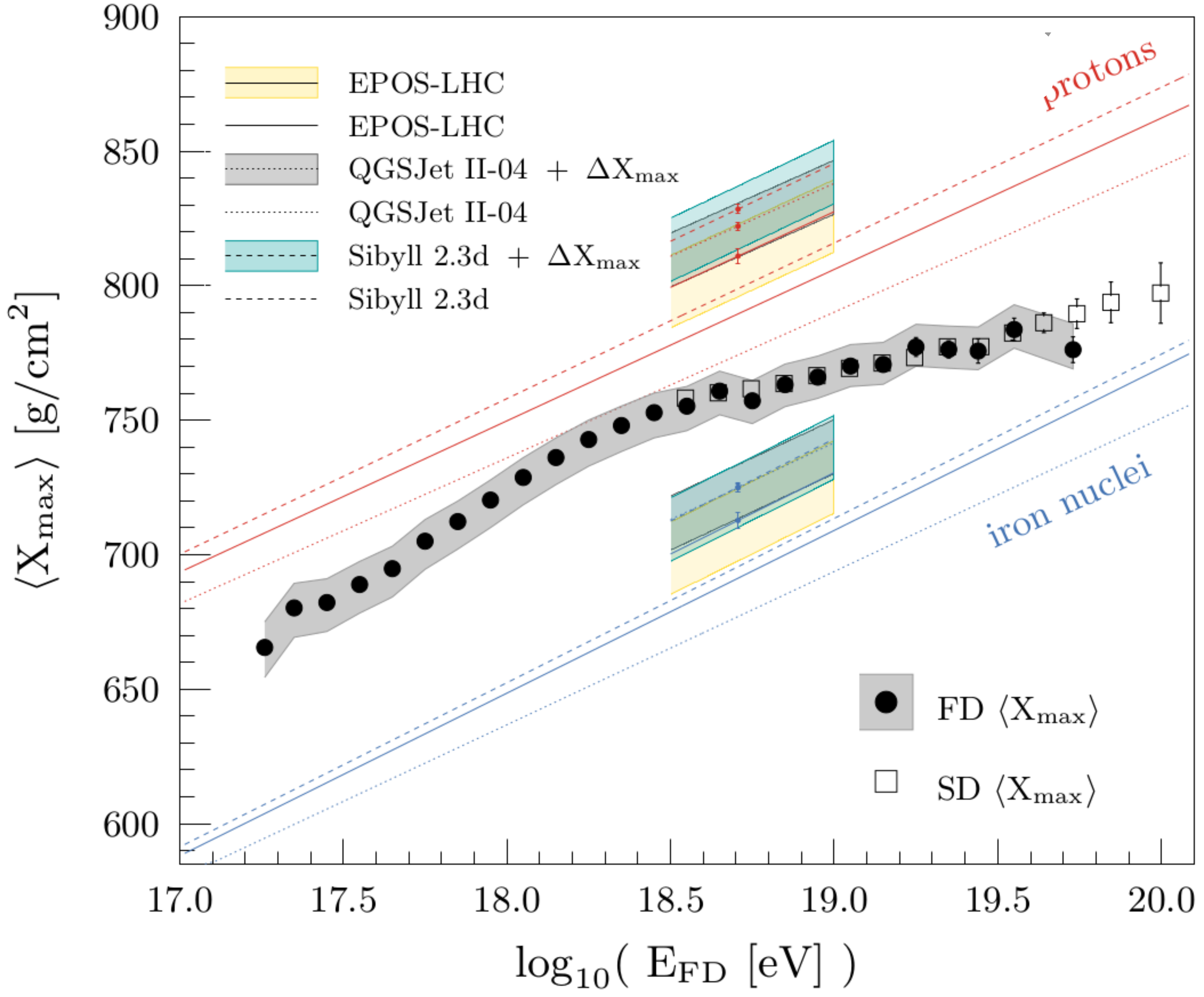
No direct composition data

Index depends on suppression function

Apparent tension with hadronic interaction models



(Auger, 2406.06319)



(Auger, PRD 109 (2024) 102001)

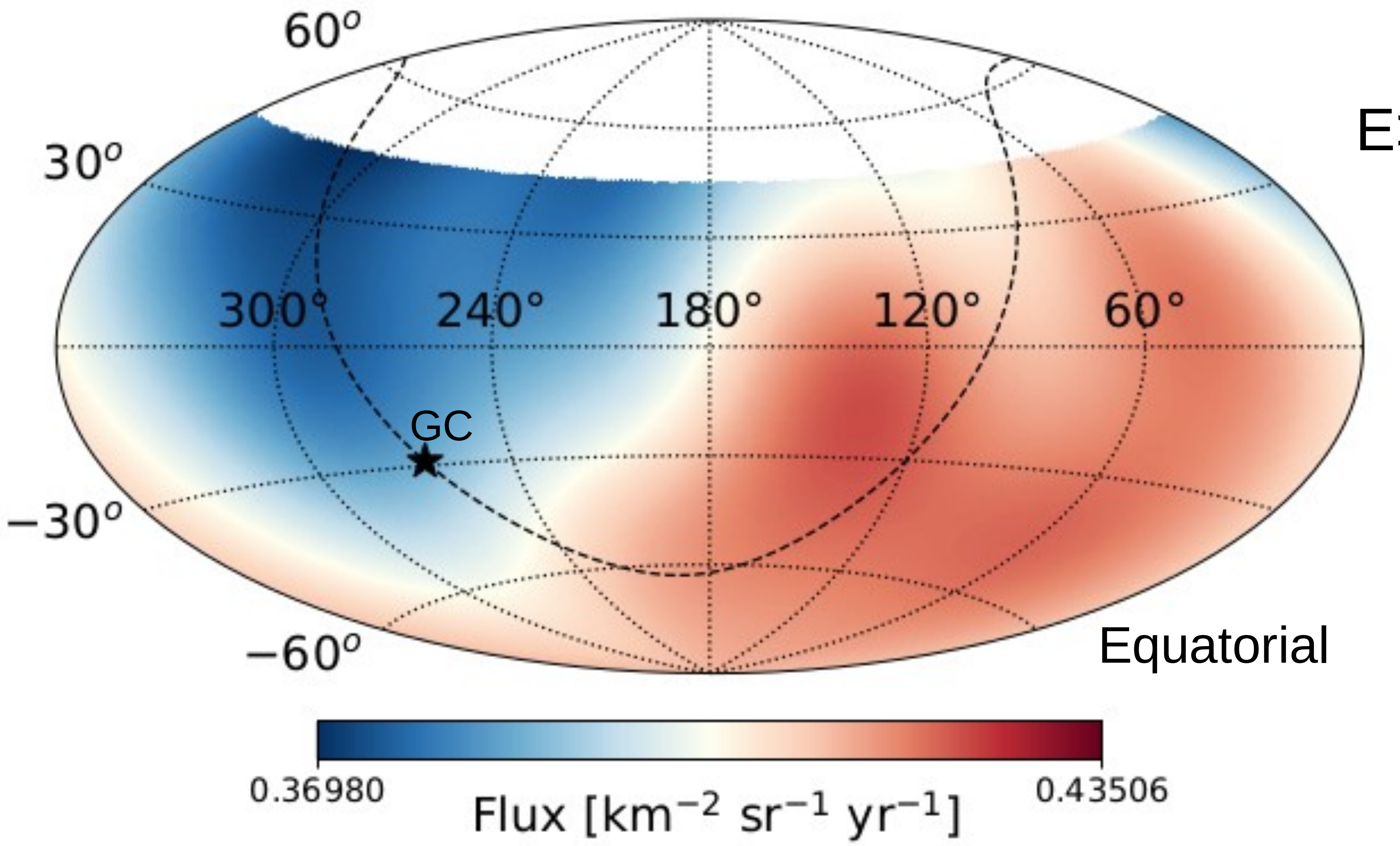
What is the true uncertainty of the model predictions?

Arrival directions – large angular scales (dipole)

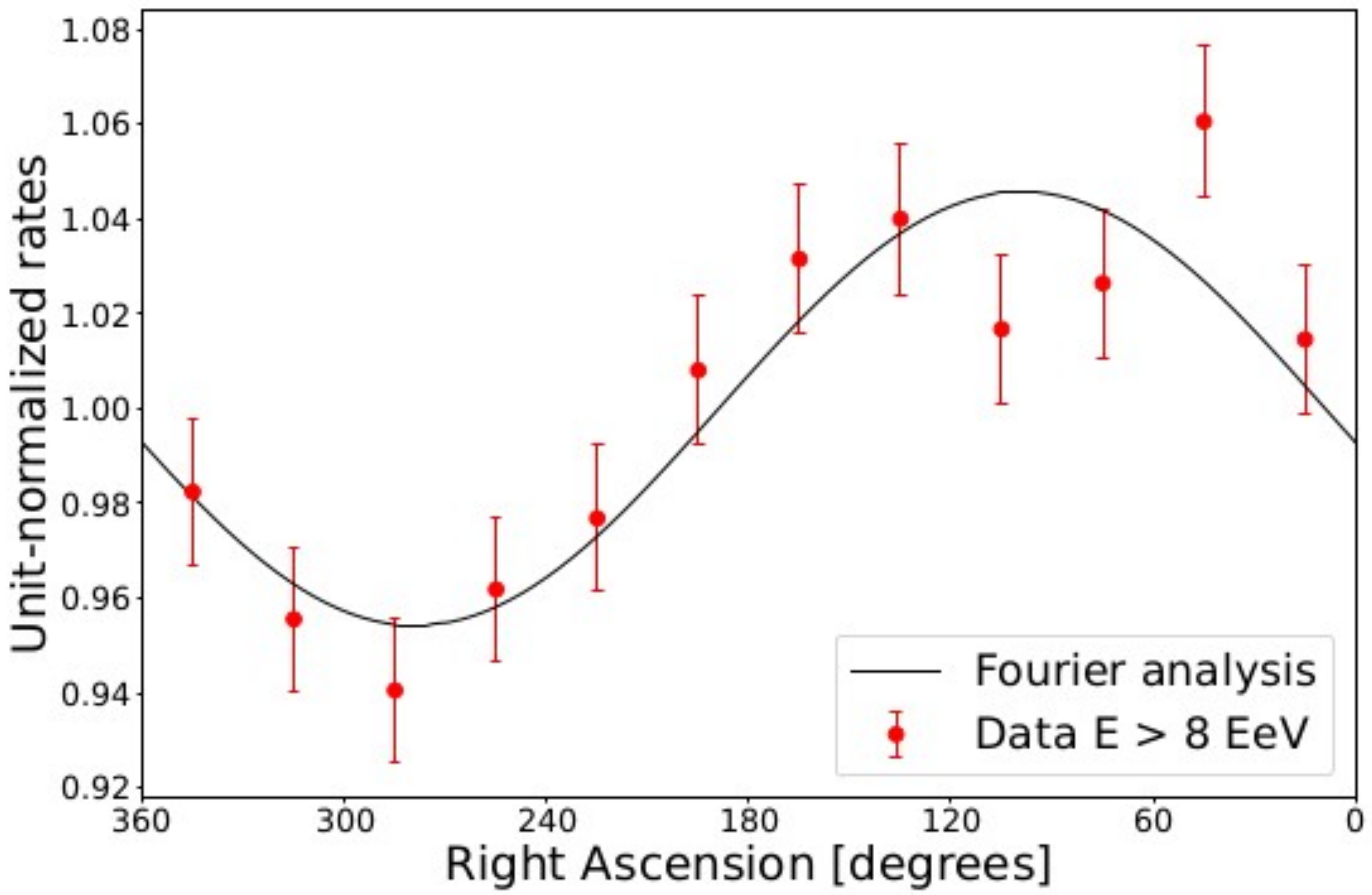
physicsworld TOP 10 BREAKTHROUGH 2017

Science 357 (2017) 1266)

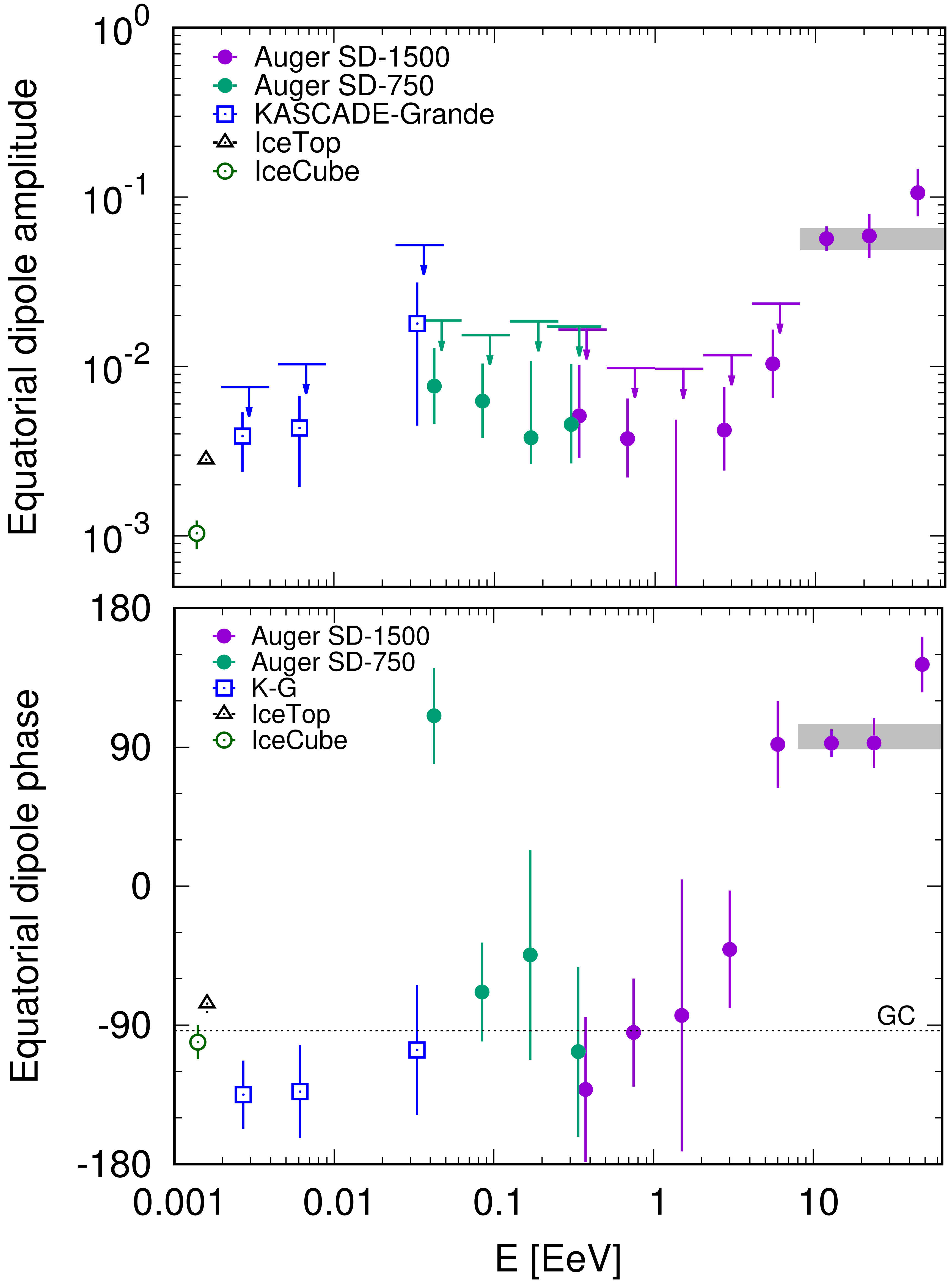
E [EeV]	N	$d_\perp$ [%]	d_z [%]	d [%]	α_d [°]	δ_d [°]	$P(\geq r_1^\alpha)$
4-8	118,722	$1.0^{+0.6}_{-0.4}$	-1.3 ± 0.8	$1.7^{+0.8}_{-0.5}$	92 ± 28	-52^{+21}_{-19}	0.14
≥ 8	49,678	$5.8^{+0.9}_{-0.8}$	-4.5 ± 1.2	$7.4^{+1.0}_{-0.8}$	97 ± 8	-38^{+9}_{-9}	8.7×10^{-12} (6.8σ)
8-16	36,658	$5.7^{+1.0}_{-0.9}$	-3.1 ± 1.4	$6.5^{+1.2}_{-0.9}$	93 ± 9	-29^{+11}_{-12}	1.4×10^{-8} → 5.7σ
16-32	10,282	$5.9^{+2.0}_{-1.8}$	-7 ± 3	$9.4^{+2.6}_{-1.9}$	93 ± 16	-51^{+13}_{-13}	4.3×10^{-3}
≥ 32	2,738	11^{+4}_{-3}	-13 ± 5	17^{+5}_{-4}	144 ± 18	-51^{+14}_{-14}	9.8×10^{-3}

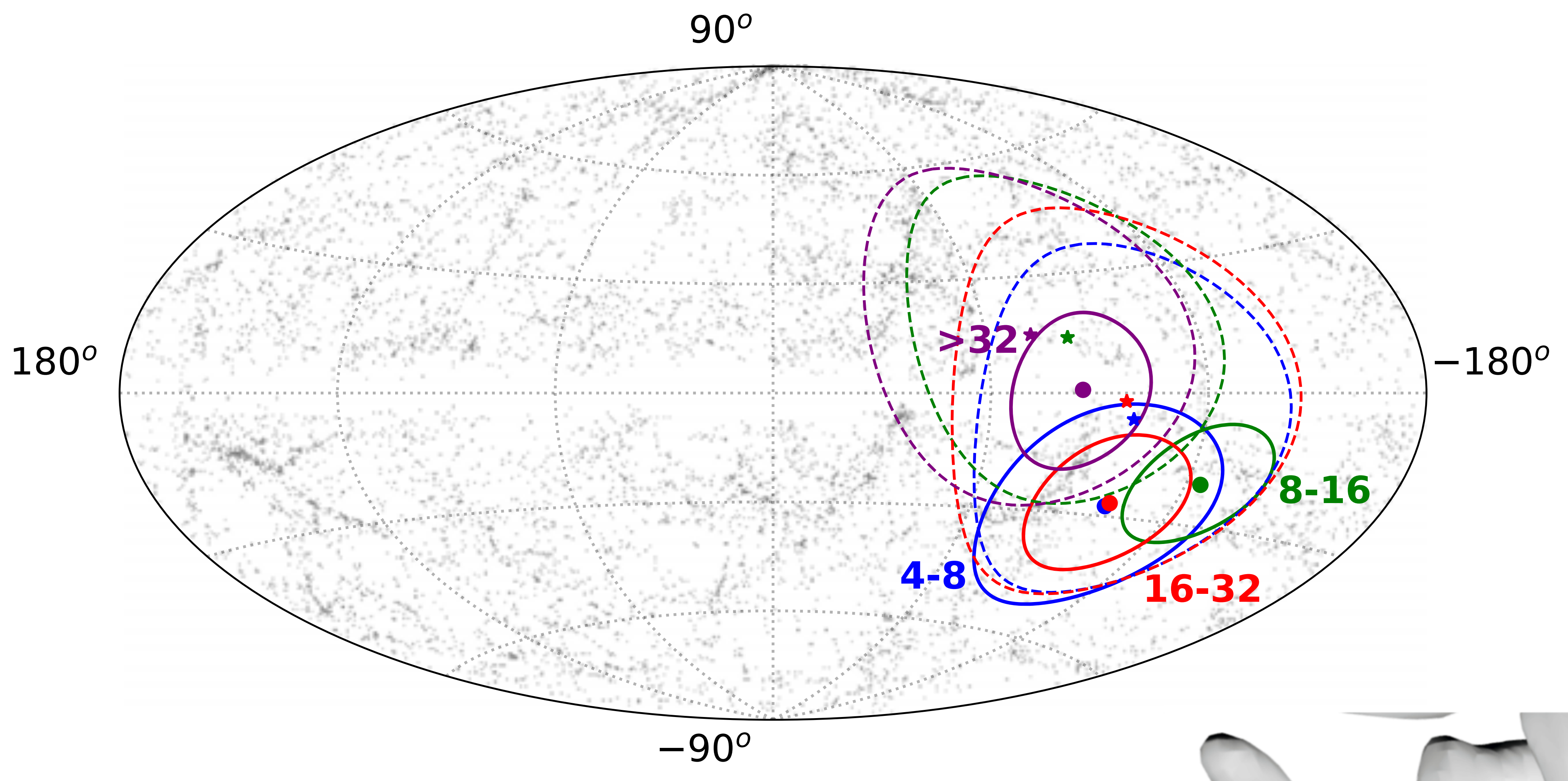


E>8 EeV



Arrival directions – large angular scales (dipole)

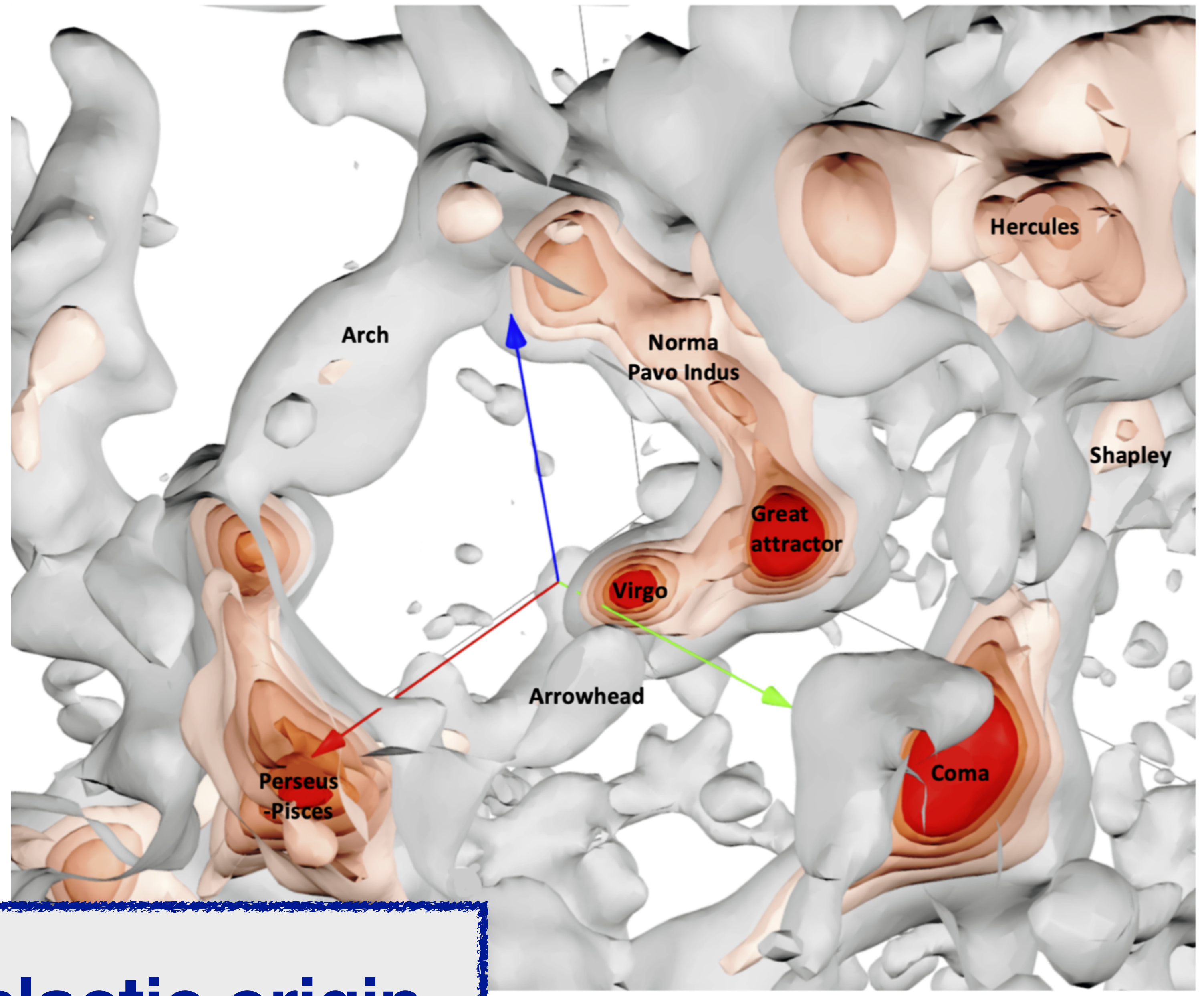




2MASS IR catalog,
source density 10^{-4} Mpc^{-3}

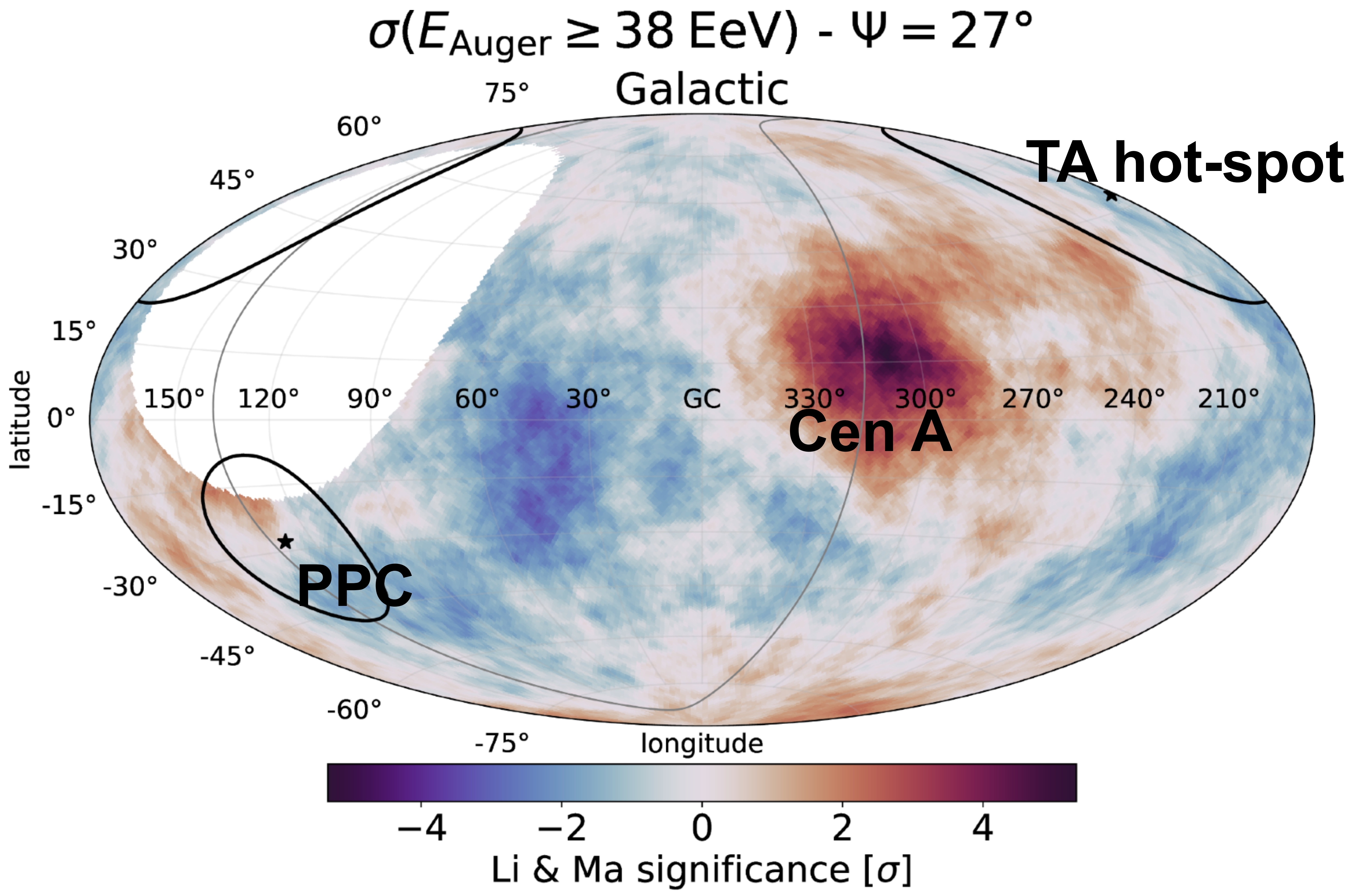
(Auger, ApJ 976 (2024) 48)

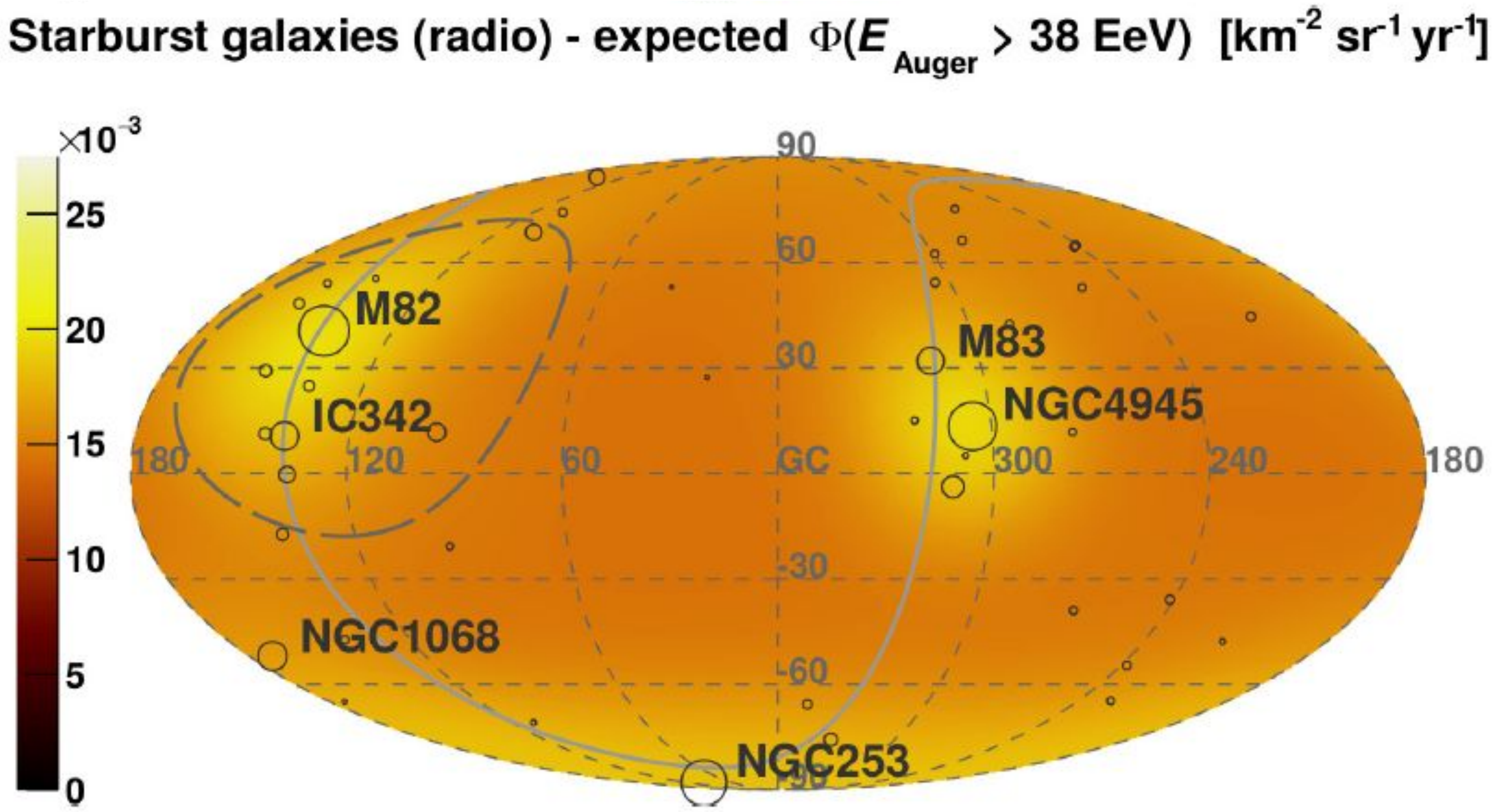
(Ding, Globus & Farrar ApJ 913 (2021) L13)

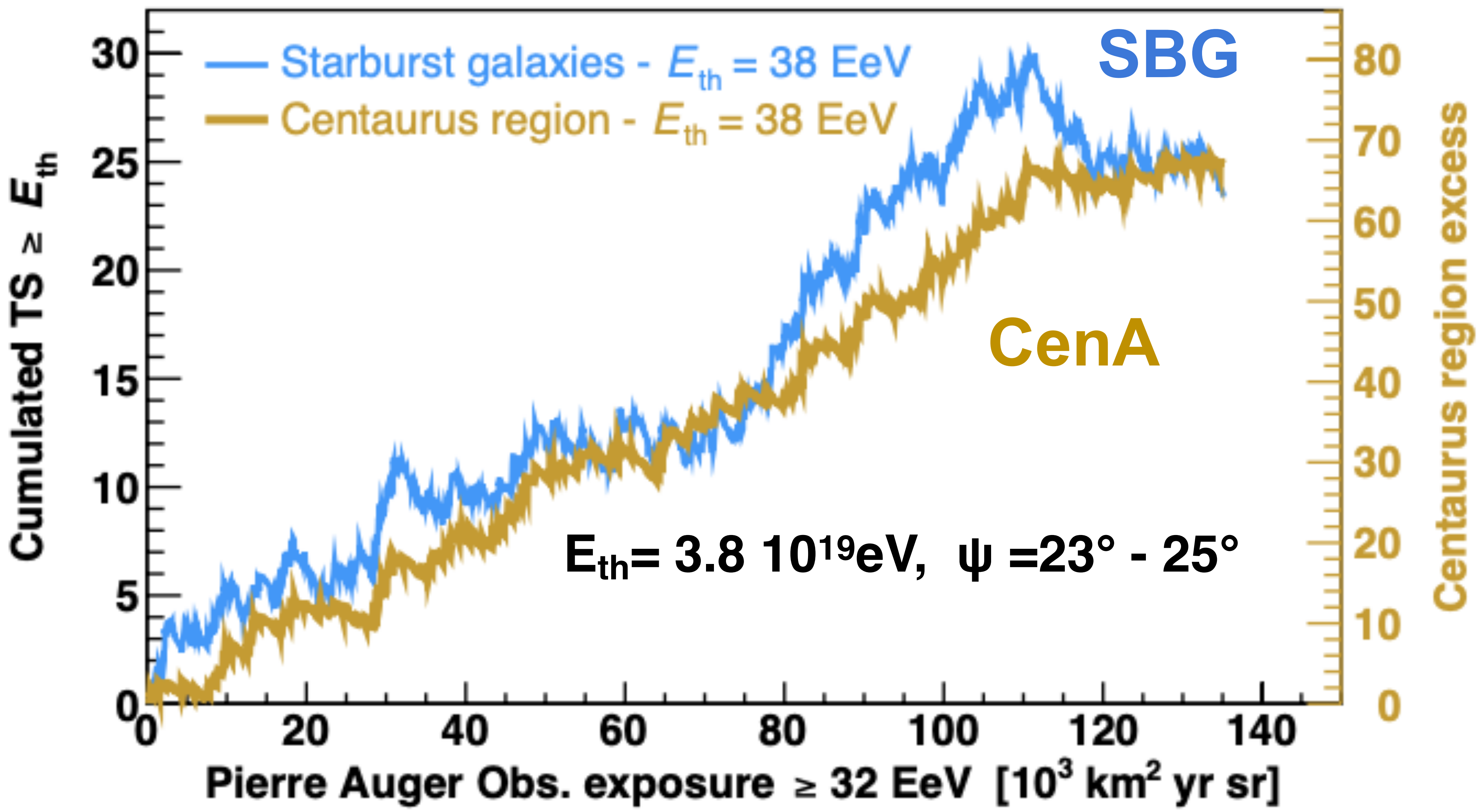


Dipole compatible with extragalactic origin

Arrival directions – high-energy anisotropy searches







Centaurus A: E > 3.8 10^{19} eV, ~27° radius, 4.0 σ (post trial)

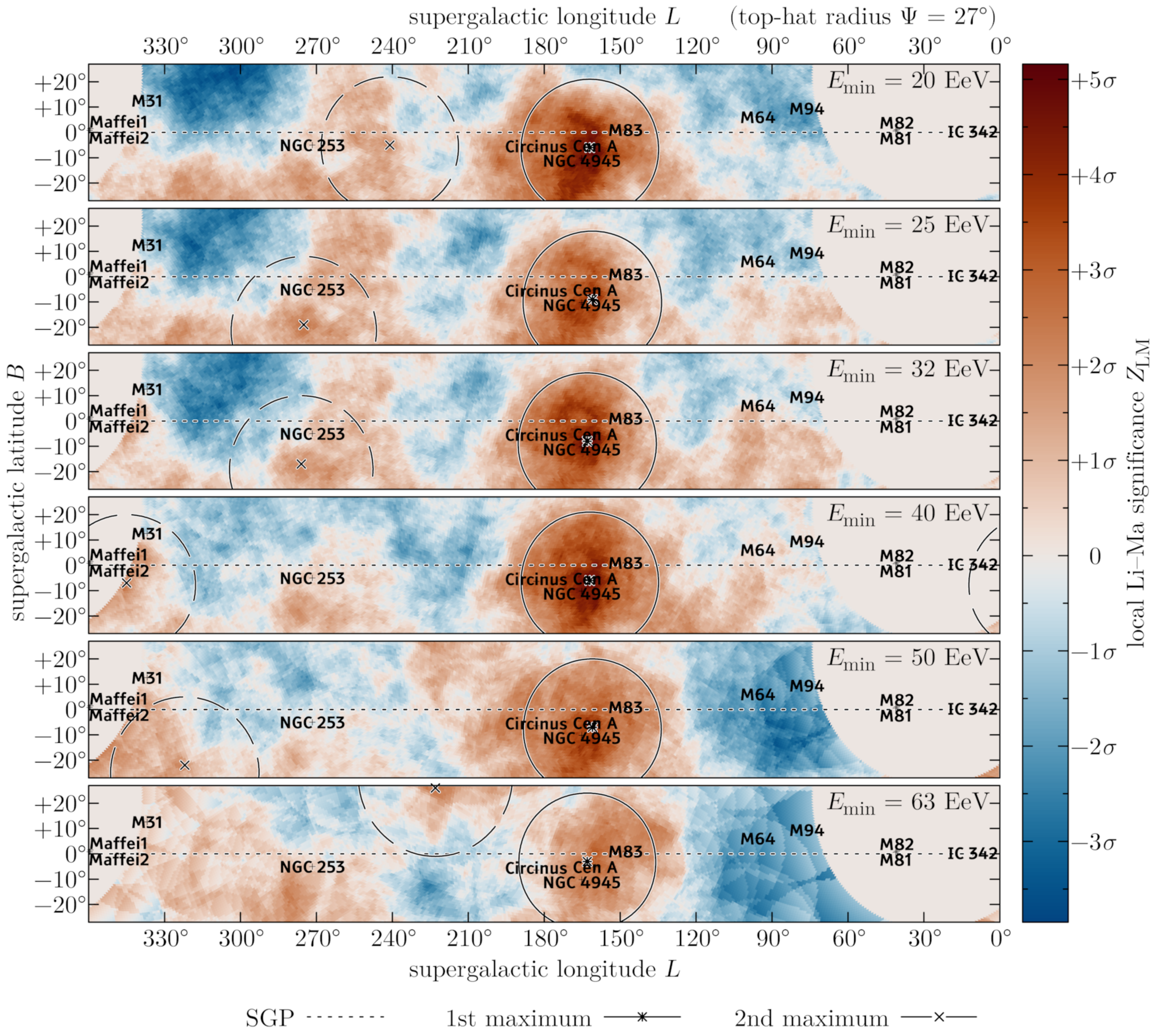
Starburst galaxies: E > 3.8 10^{19} eV, ~25° radius, 3.8 σ (post trial)

Discovery level of 5σ expected after 2025

First probe of TA over-densities thanks to inclined showers

(Astrophysical Journal, 935:170, 2022, update ICRC 2023)

Arrival directions – high-energy anisotropy searches



Search for first & second maximum

1st maximum

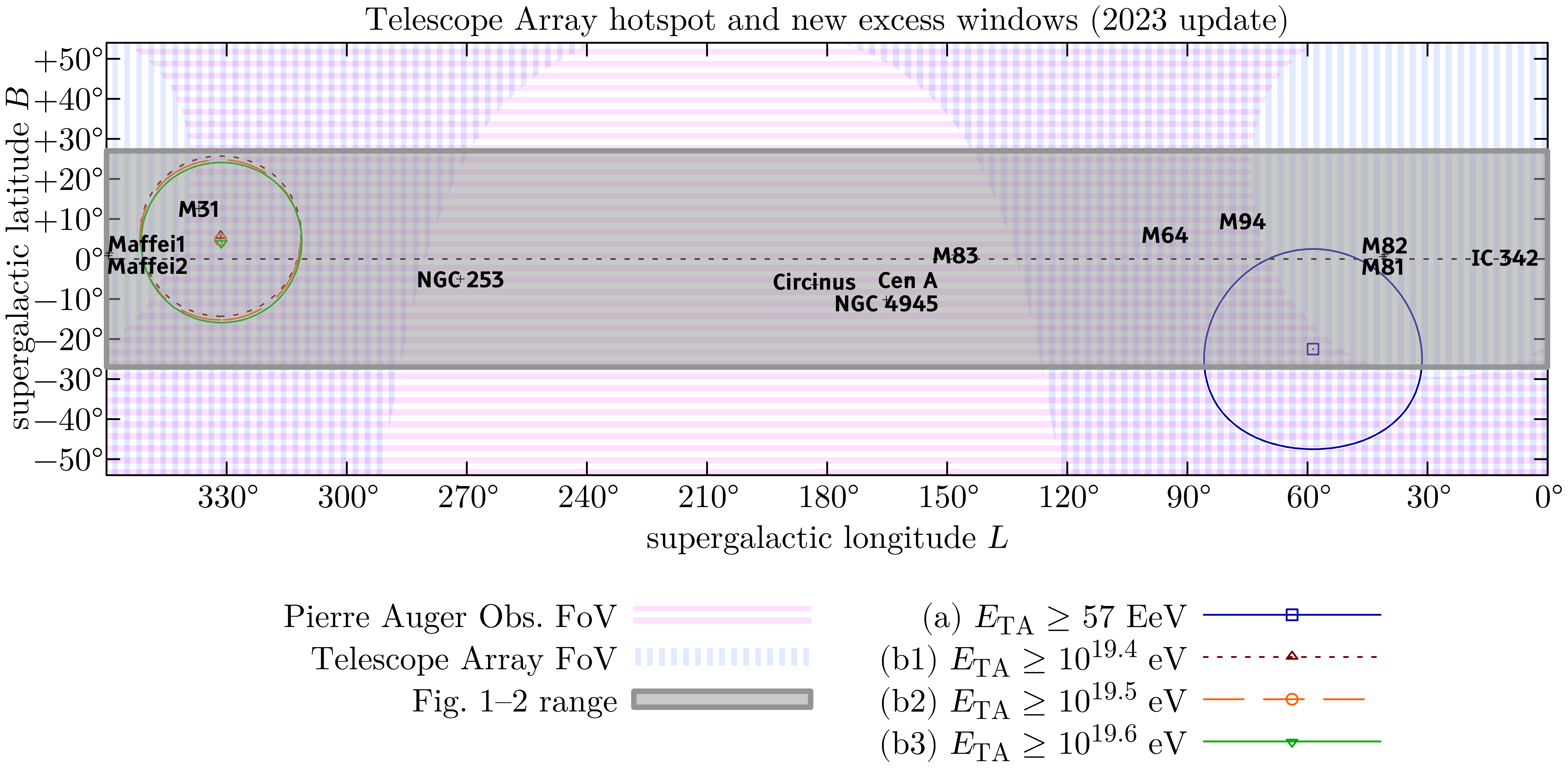
$E_{\rm min}$	$N_{\rm tot}$	L	B	$\frac{\mathcal{E}_{\rm in}}{\mathcal{E}_{\rm tot}}$	$N_{\rm bg}$	$N_{\rm in}$	$\frac{\Phi_{\rm in}}{\Phi_{\rm out}}$	$Z_{\rm LM}$	99% U.L.
20 EeV	8832	162°	−6°	9.56%	829.	990	$1.19^{+0.04}_{-0.04}$	$+5.2\sigma$	1.29
25 EeV	5380	161°	−9°	9.56%	504.	608	$1.21^{+0.05}_{-0.05}$	$+4.2\sigma$	1.33
32 EeV	2936	163°	−8°	9.68%	276.	363	$1.32^{+0.08}_{-0.07}$	$+4.7\sigma$	1.50
40 EeV	1533	162°	−6°	9.56%	140.	208	$1.49^{+0.11}_{-0.11}$	$+5.1\sigma$	1.77
50 EeV	713	161°	−7°	9.56%	64.4	103	$1.60^{+0.18}_{-0.16}$	$+4.2\sigma$	2.05
63 EeV	295	163°	−3°	9.56%	26.3	46	$1.75^{+0.30}_{-0.26}$	$+3.3\sigma$	2.54

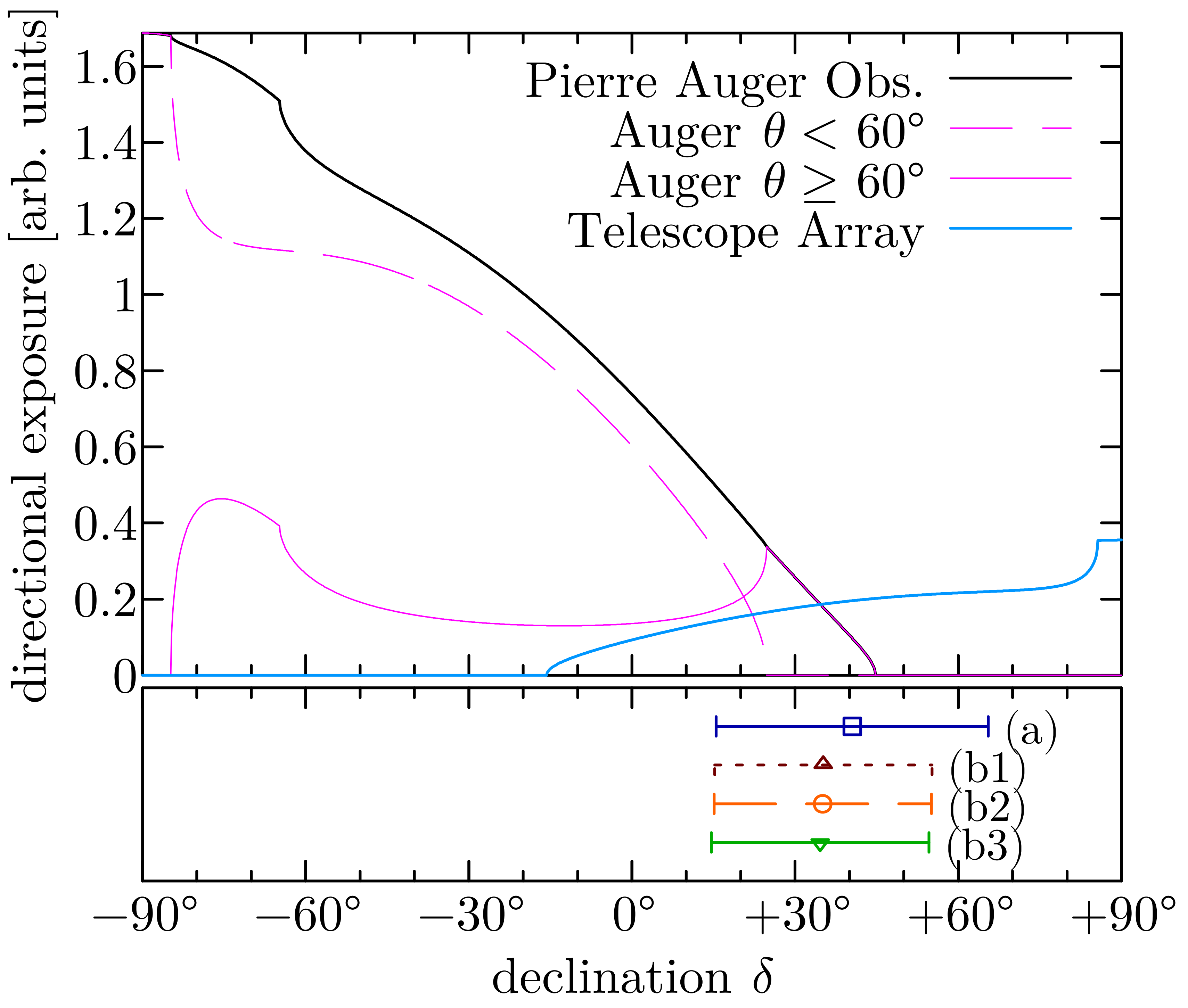
2nd maximum

$E_{\rm min}$	$N_{\rm tot}$	L	B	$\frac{\mathcal{E}_{\rm in}}{\mathcal{E}_{\rm tot}}$	$N_{\rm bg}$	$N_{\rm in}$	$\frac{\Phi_{\rm in}}{\Phi_{\rm out}}$	$Z_{\rm LM}$	99% U.L.
20 EeV	8832	241°	−5°	10.27%	900.	971	$1.08^{+0.04}_{-0.04}$	$+2.2\sigma$	1.17
25 EeV	5380	275°	−19°	8.00%	426.	482	$1.13^{+0.05}_{-0.05}$	$+2.6\sigma$	1.26
32 EeV	2936	276°	−17°	7.89%	229.	264	$1.15^{+0.08}_{-0.07}$	$+2.2\sigma$	1.34
40 EeV	1533	345°	−7°	1.00%	15.2	26	$1.71^{+0.36}_{-0.32}$	$+2.5\sigma$	2.68
50 EeV	713	322°	−22°	3.69%	25.9	39	$1.51^{+0.26}_{-0.23}$	$+2.4\sigma$	2.20
63 EeV	295	223°	+26°	9.56%	26.7	42	$1.57^{+0.28}_{-0.25}$	$+2.6\sigma$	2.31

Cen A ~ 3.1σ post trial, all others below 2.7σ

Arrival directions – high-energy anisotropy searches

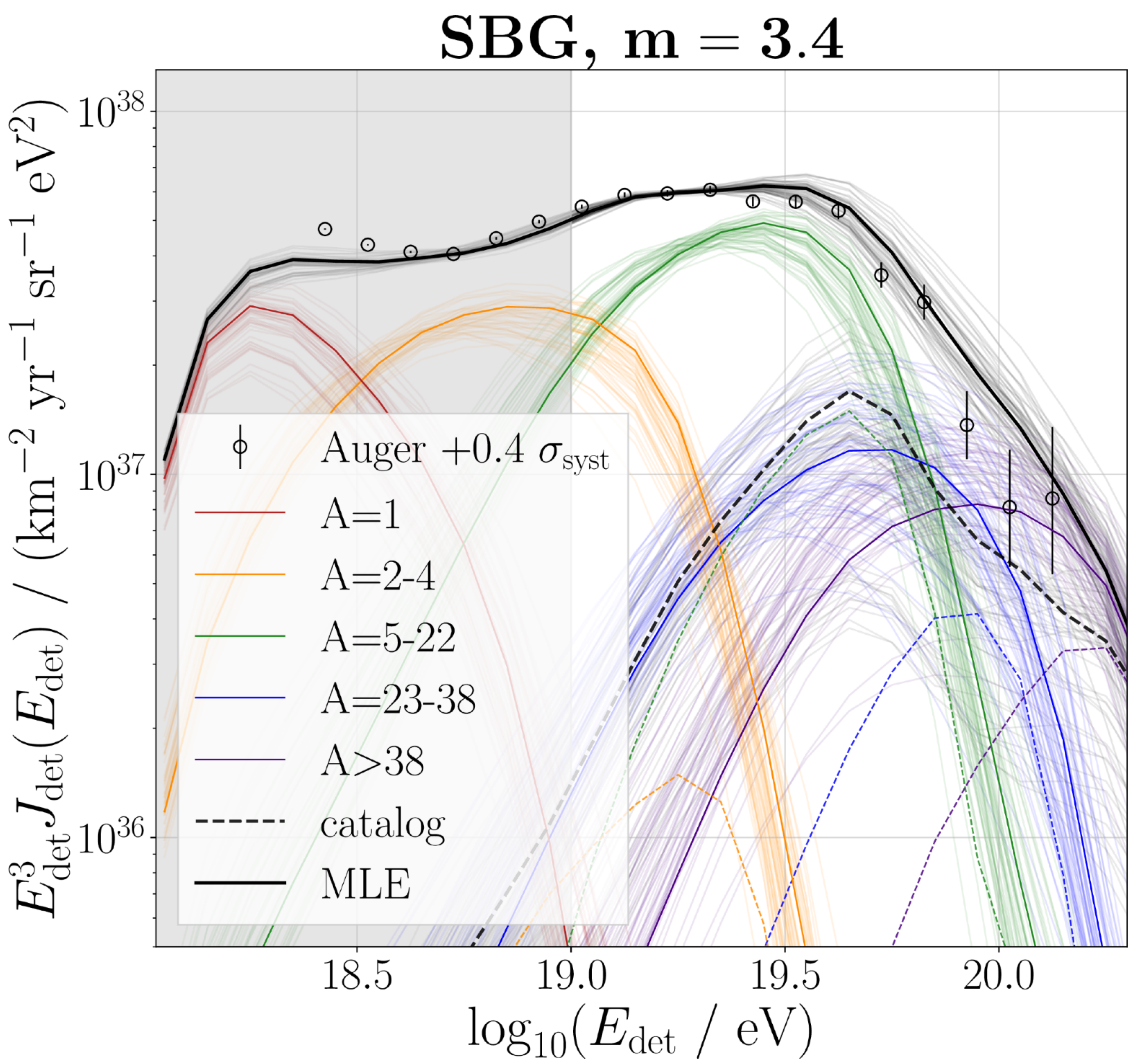




	Telescope Array									Pierre Auger Observatory							
	$E_{\min}$	N_{tot}	$\frac{\mathcal{E}_{\text{in}}}{\mathcal{E}_{\text{tot}}}$	N_{bg}	N_{in}	$\frac{\Phi_{\text{in}}}{\Phi_{\text{out}}}$	Z_{LM}	99% L.L.	post-trial	$E_{\min}$	N_{tot}	$\frac{\mathcal{E}_{\text{in}}}{\mathcal{E}_{\text{tot}}}$	N_{bg}	N_{in}	$\frac{\Phi_{\text{in}}}{\Phi_{\text{out}}}$	Z_{LM}	99% U.L.
(a)	57 EeV	216	9.47%	18.0	44	$2.44^{+0.44}_{-0.39}$	$+4.8\sigma$	1.60	2.8σ	44.6 EeV	1074	1.00%	10.7	9	$0.84^{+0.31}_{-0.25}$	-0.5σ	1.76
(b1)	$10^{19.4}$ eV	1125	5.88%	64.0	101	$1.58^{+0.17}_{-0.16}$	$+4.1\sigma$	1.22	3.3σ	20.5 EeV	8374	0.84%	70.1	65	$0.93^{+0.12}_{-0.11}$	-0.6σ	1.23
(b2)	$10^{19.5}$ eV	728	5.87%	41.1	70	$1.70^{+0.22}_{-0.20}$	$+4.0\sigma$	1.25	3.2σ	25.5 EeV	5156	0.84%	43.5	39	$0.90^{+0.15}_{-0.14}$	-0.7σ	1.29
(b3)	$10^{19.6}$ eV	441	5.84%	24.6	45	$1.83^{+0.31}_{-0.27}$	$+3.6\sigma$	1.23	3.0σ	31.7 EeV	2990	0.87%	26.0	27	$1.04^{+0.21}_{-0.19}$	$+0.2\sigma$	1.61

(Auger, ICRC 2023 UHECR 2024)

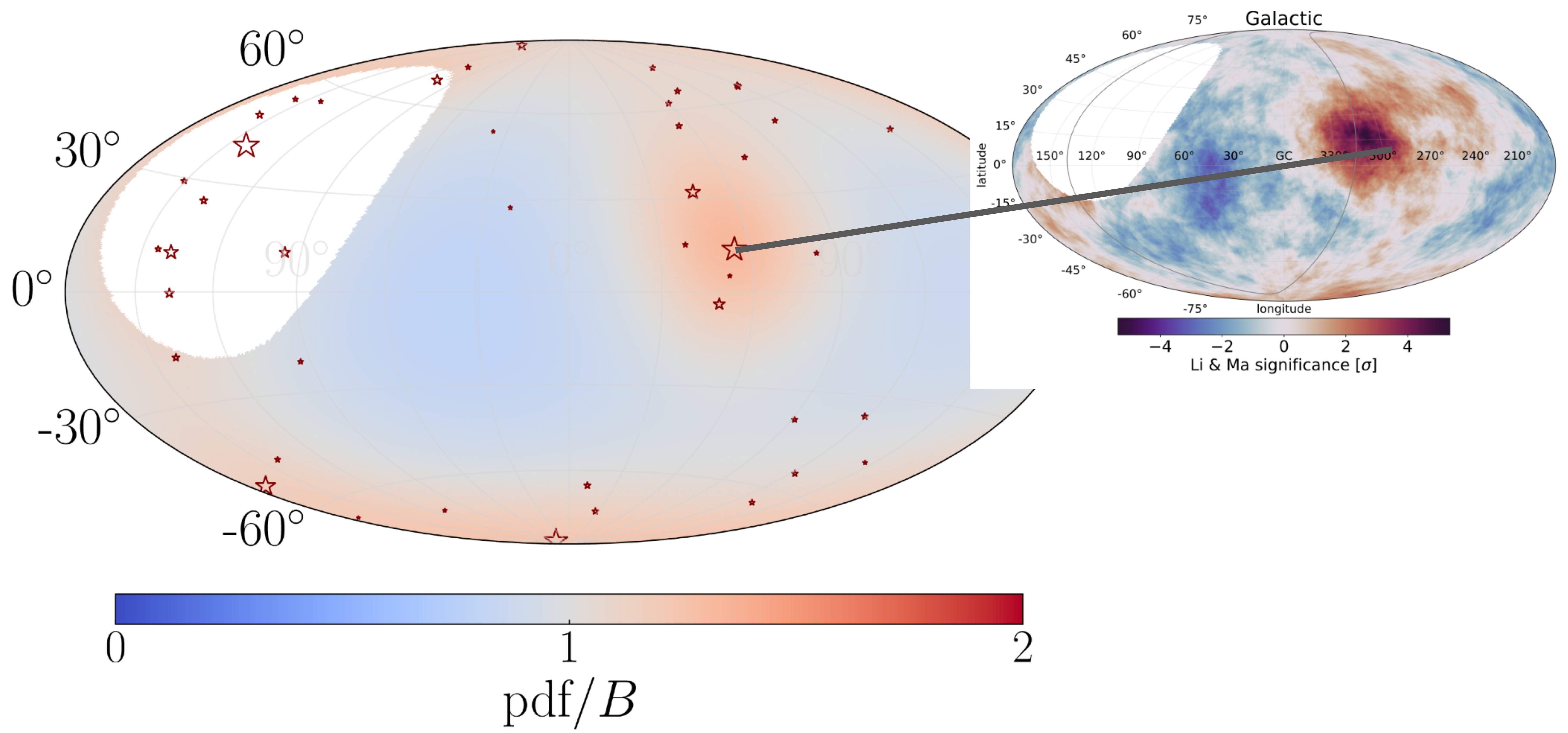
Combined fit spectrum, mass composition & anisotropy



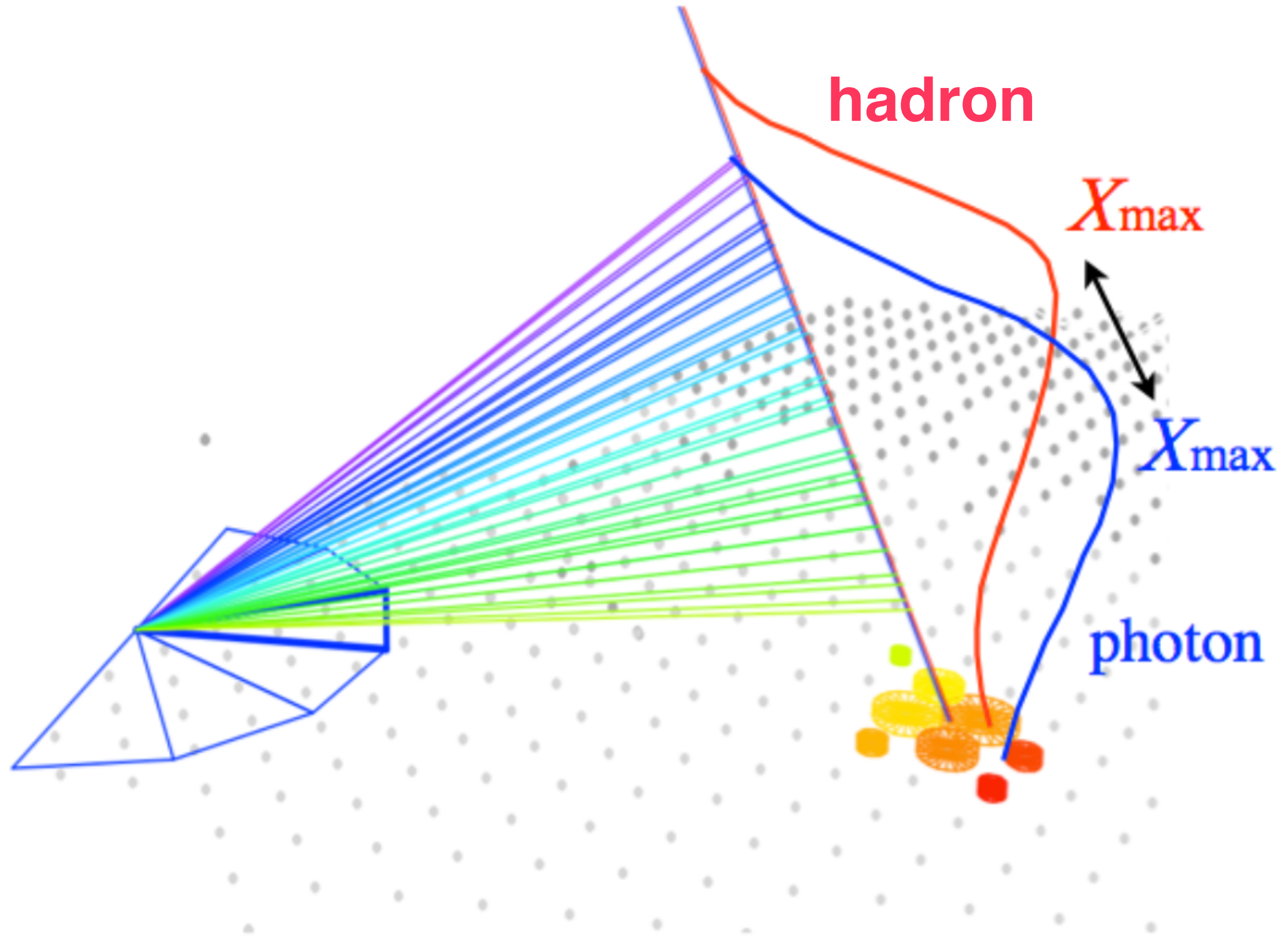
(Auger, JCAP 01 (2024) 022)

Fit with additional model parameters: magnetic field blurring, catalog contribution fraction

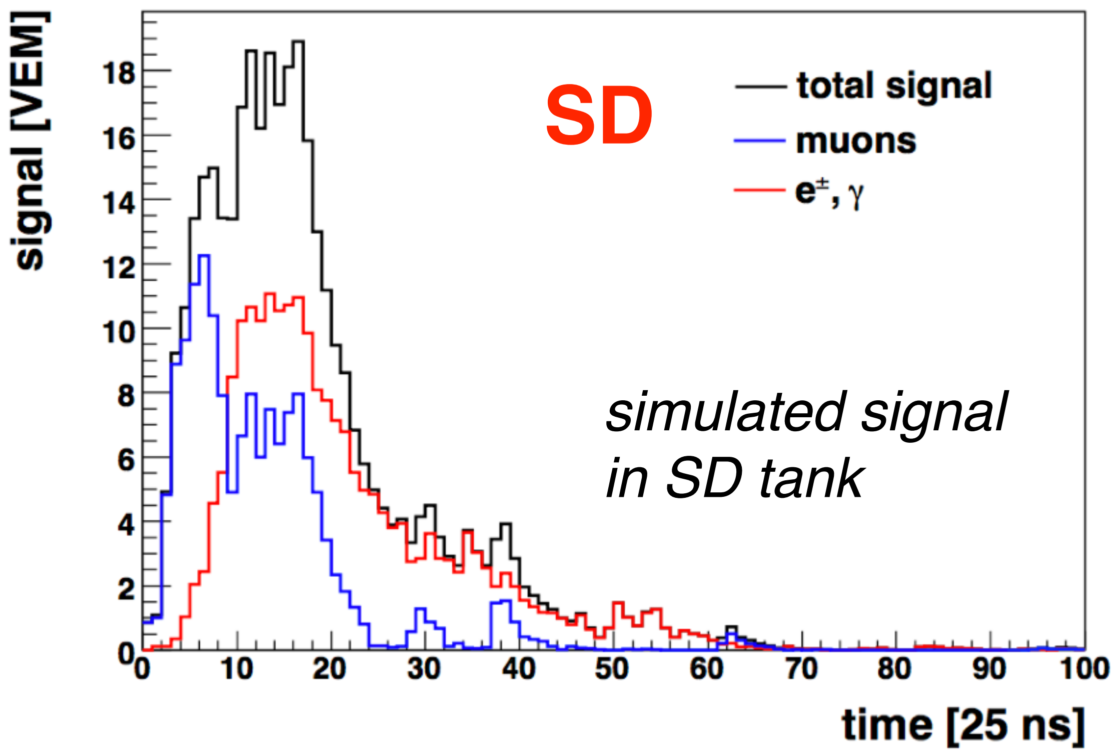
- signal fraction of 20% for SBG catalog;
- main contribution from Centaurus region,
- results compatible with standard combined fit
- significance of TS is ~4.5 σ
- but no coherent deflection



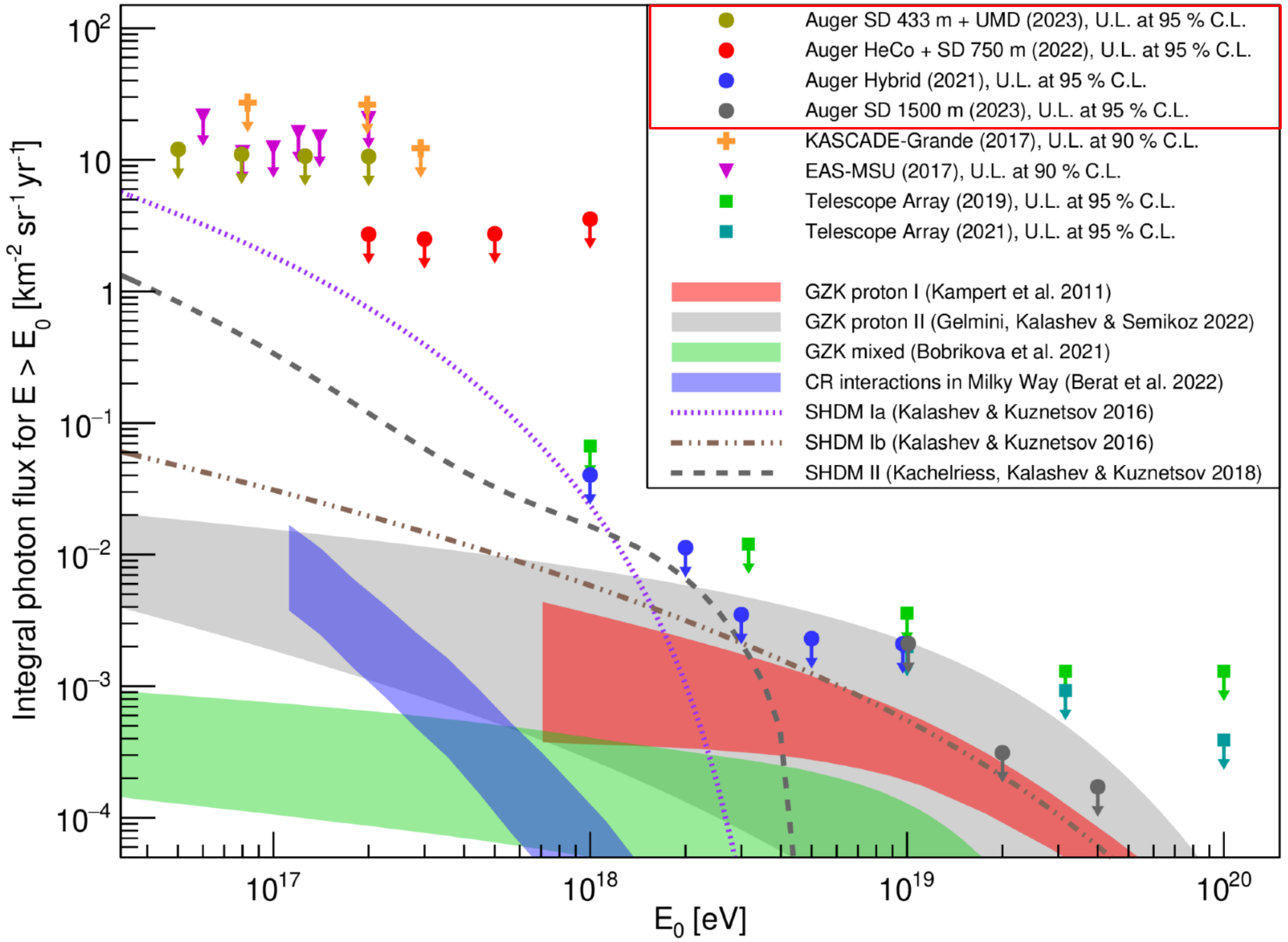
Multi-messenger physics – photons



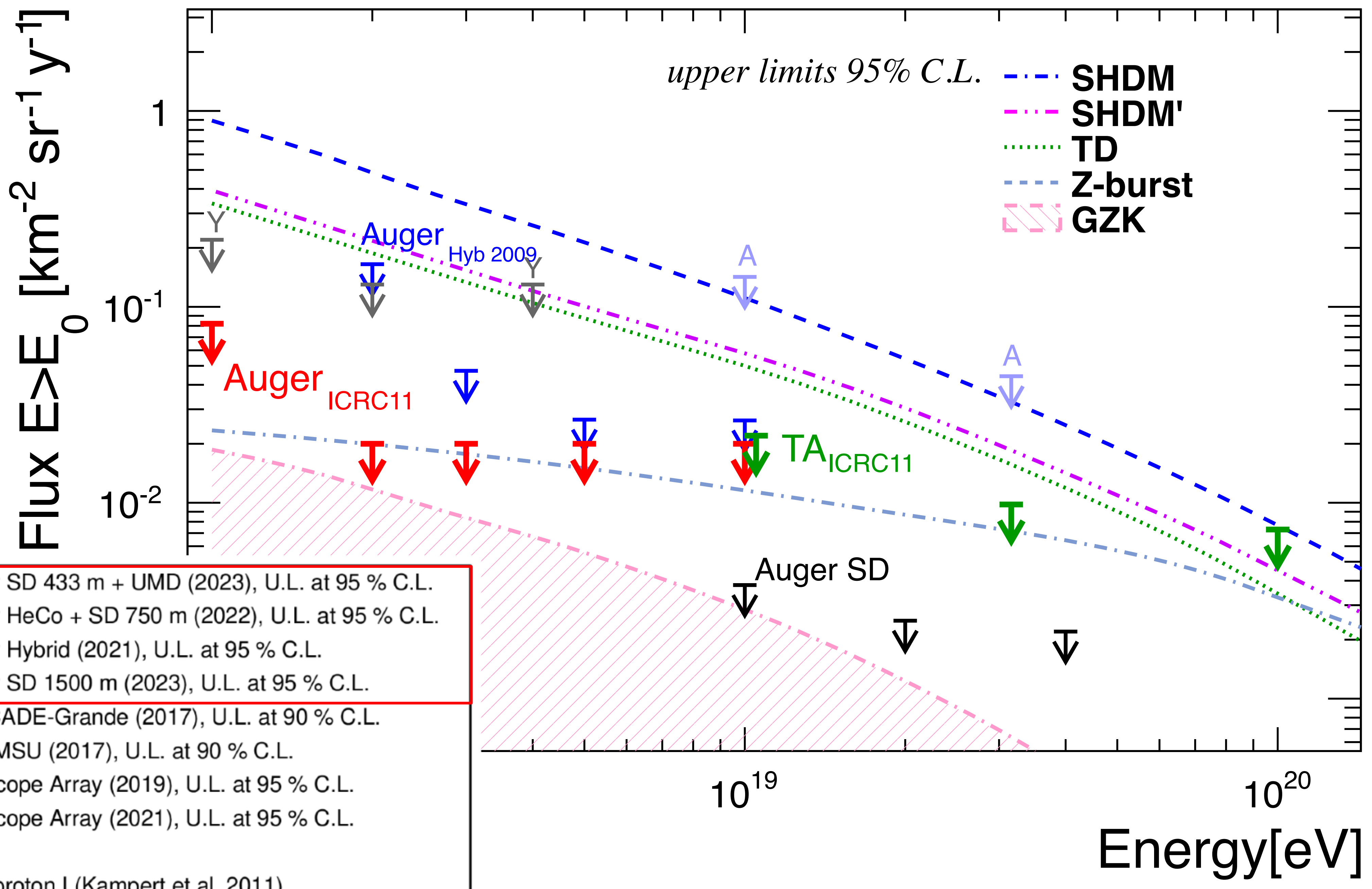
Photons interact deeper (larger X_{max}), fewer muons (rise time, lateral slope)



(Auger, ICRC 2023 & UHECR 2024)



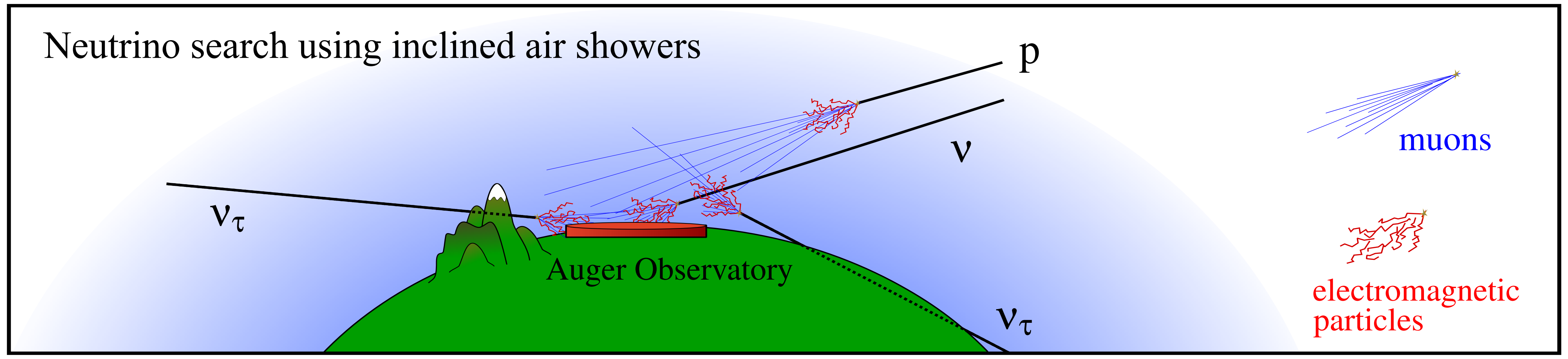
(Auger, 2006 – 2011)



Top-down processes as dominant sources excluded

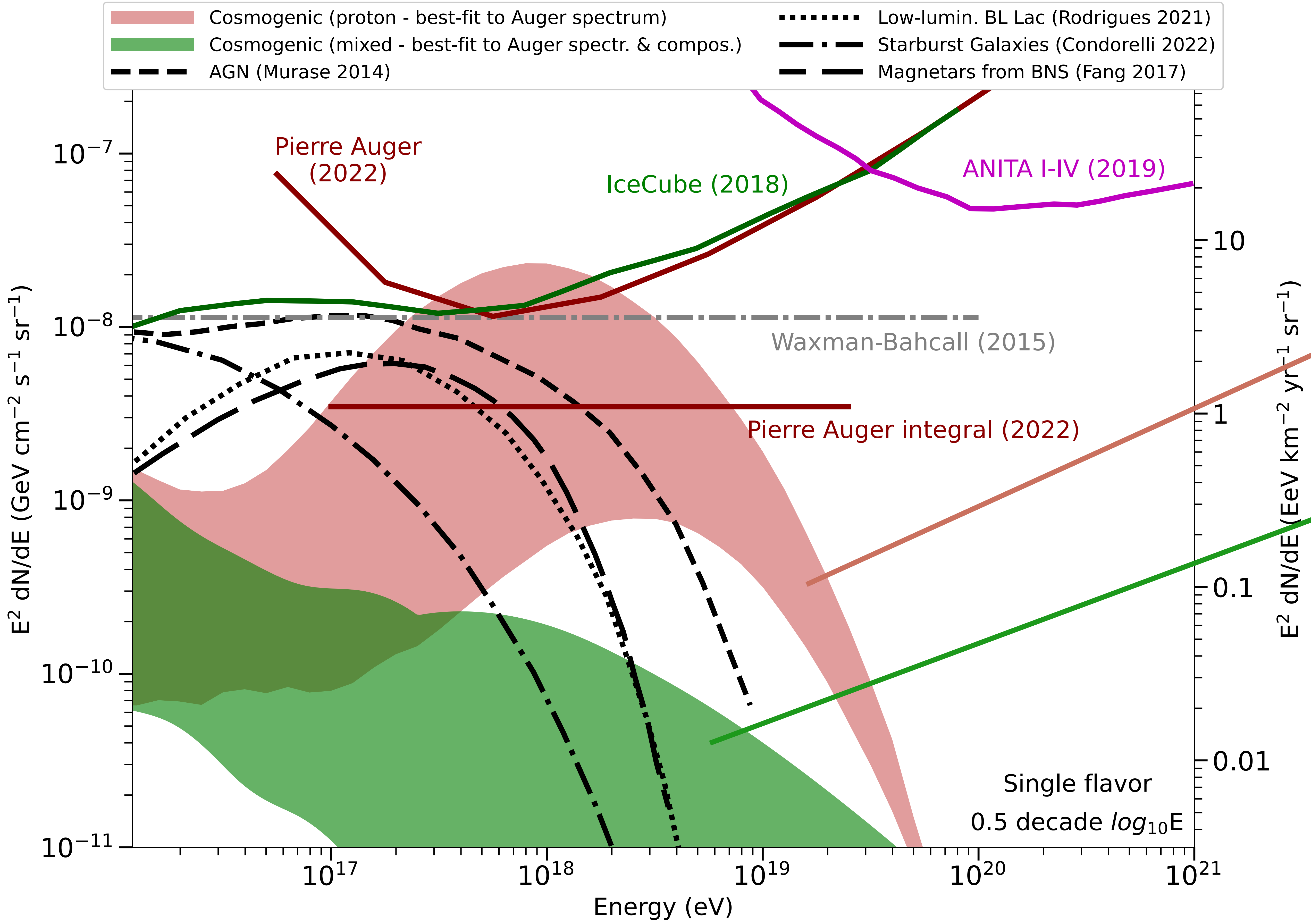
Sensitivity reaches GZK predictions

Multi-messenger physics – neutrinos



Aperture comparable to IceCube at highest energies
Limits constrain astrophysical neutrino models

(Auger, UHECR 2024)



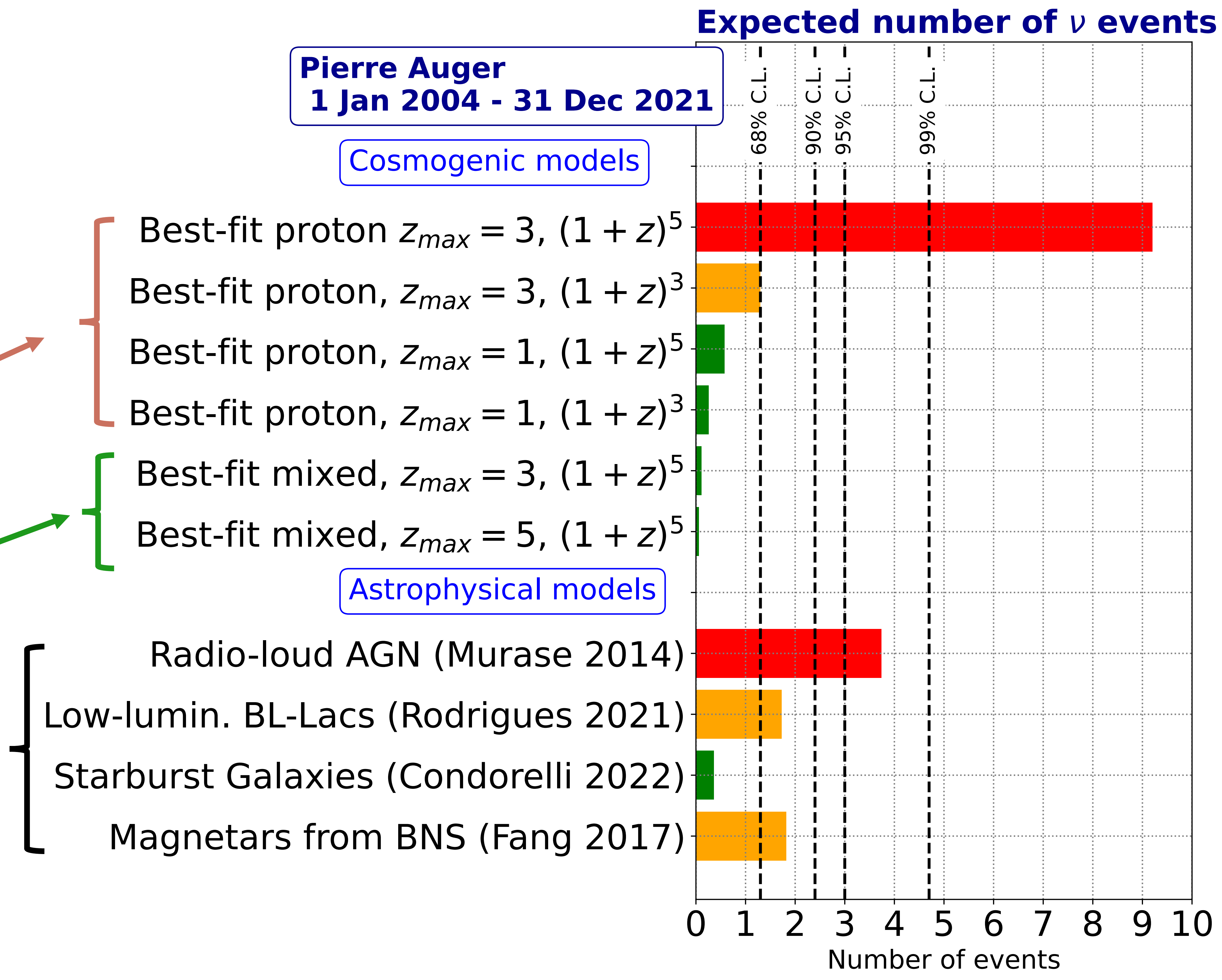


Photo credit: Tobias Schulz

Phase II: upgrade of the Observatory – AugerPrime

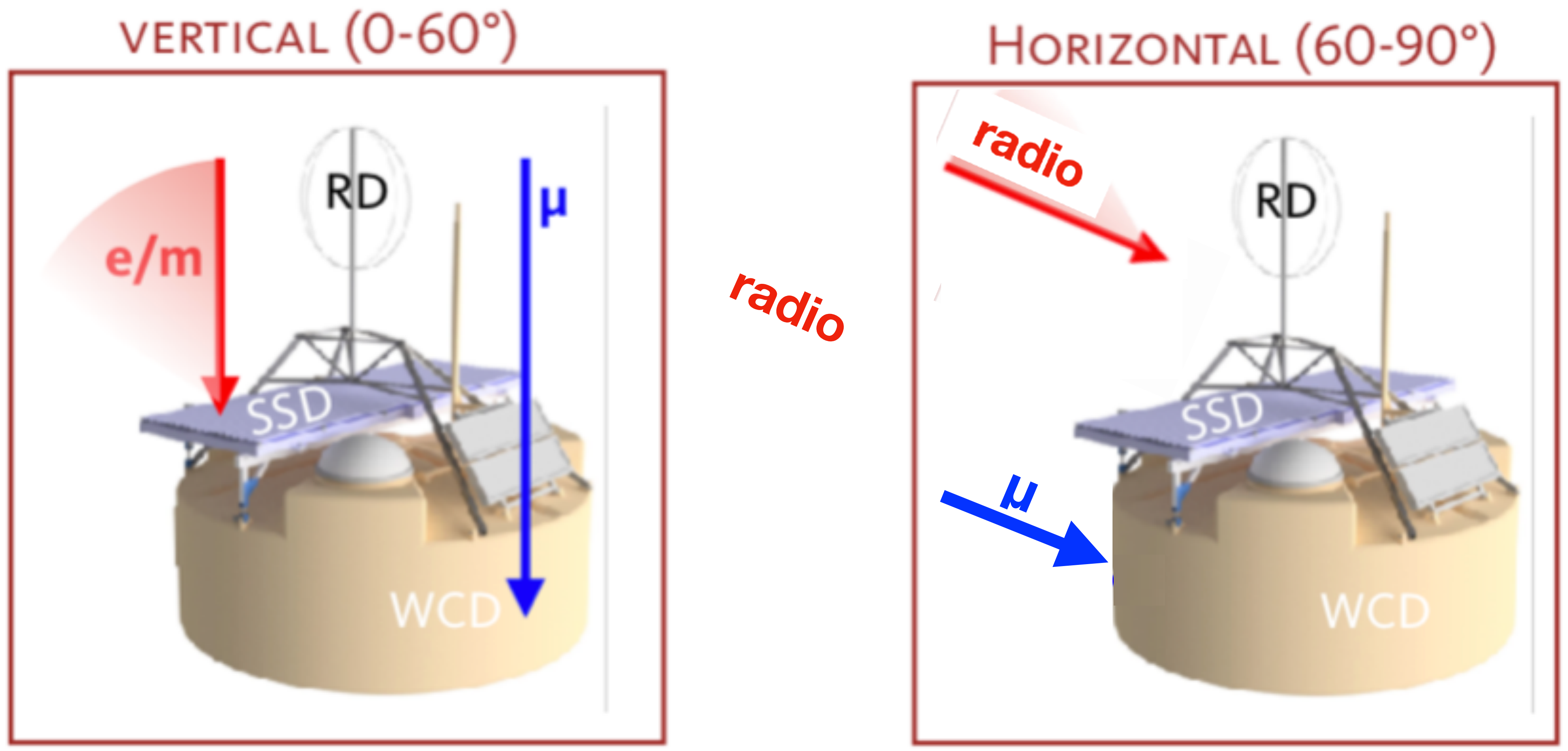
Physics motivation

- Composition measurement up to 10^{20} eV
- Composition selected anisotropy
- Particle physics with air showers
- Much better understanding of **new and old** data

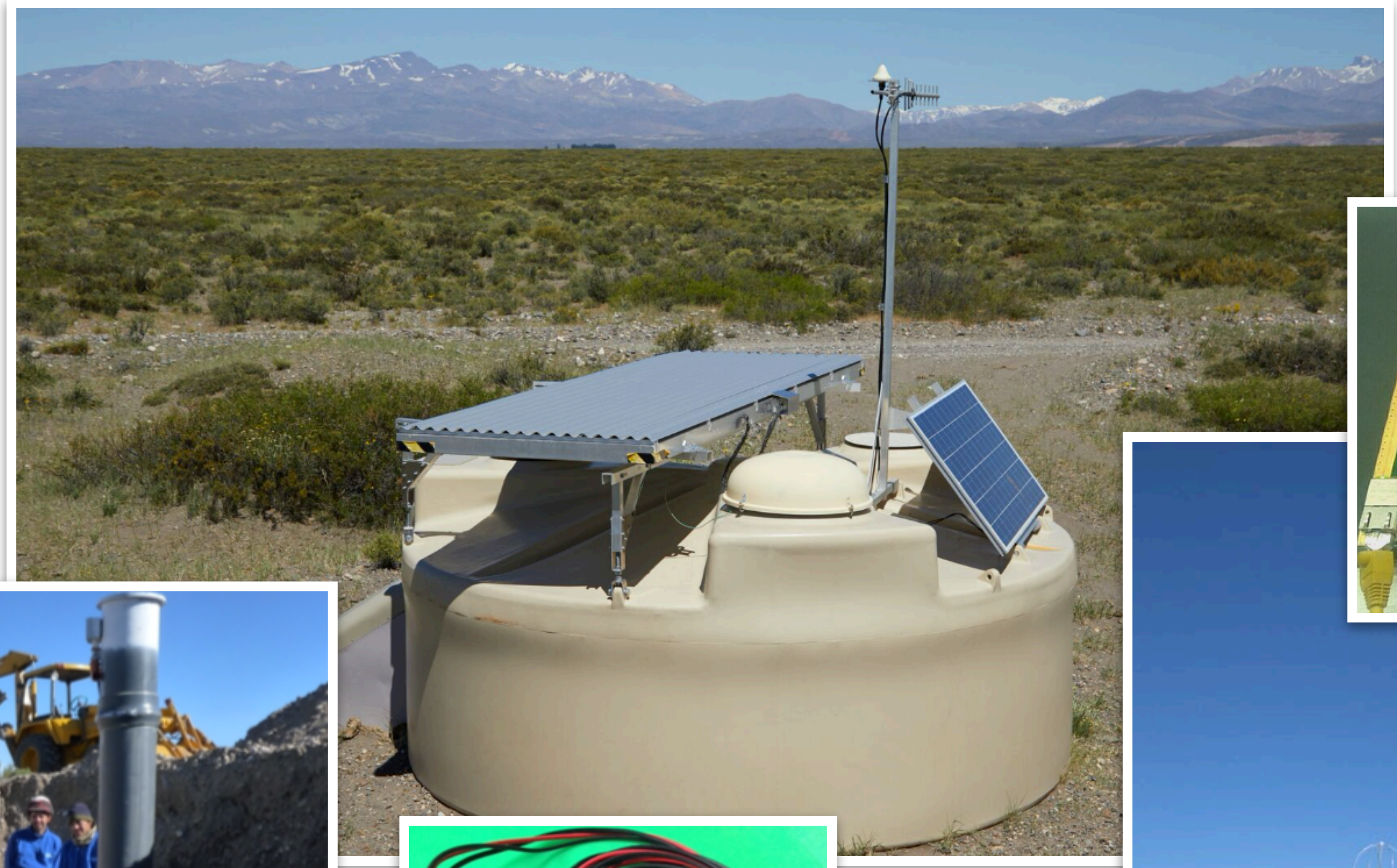
Components of AugerPrime

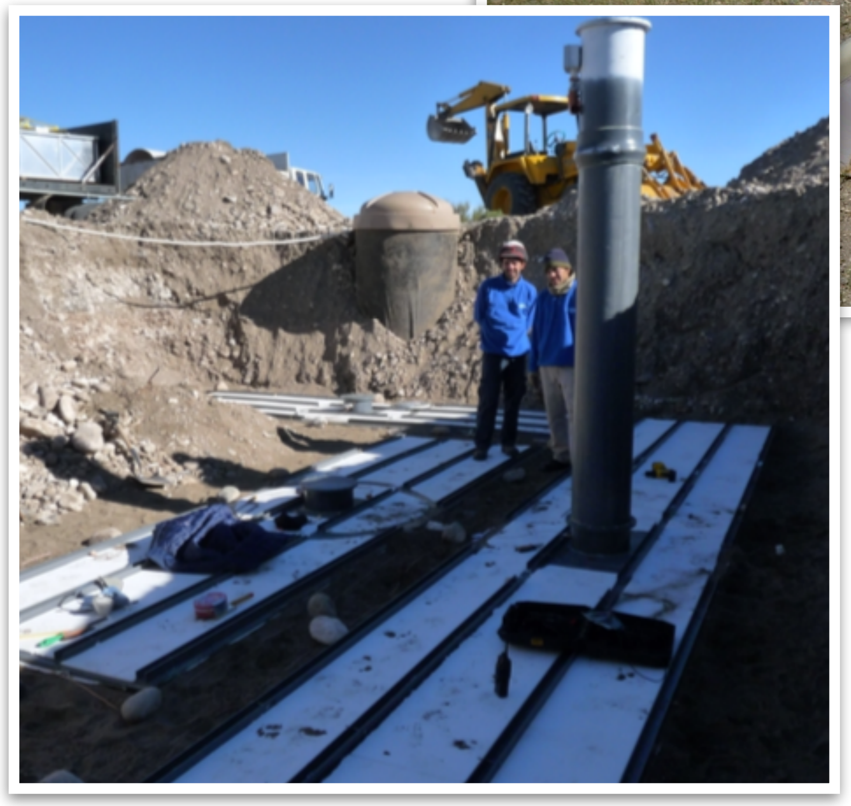
- 3.8 m^2 scintillator panels (SSD)
- New electronics (40 MHz -> 120 MHz)
- Small PMT (dynamic range WCD)
- Radio antennas for inclined showers
- Underground muon counters (750 m array, 433 m array)
- Enhanced duty cycle of fluorescence tel.

Composition sensitivity with 100% duty cycle



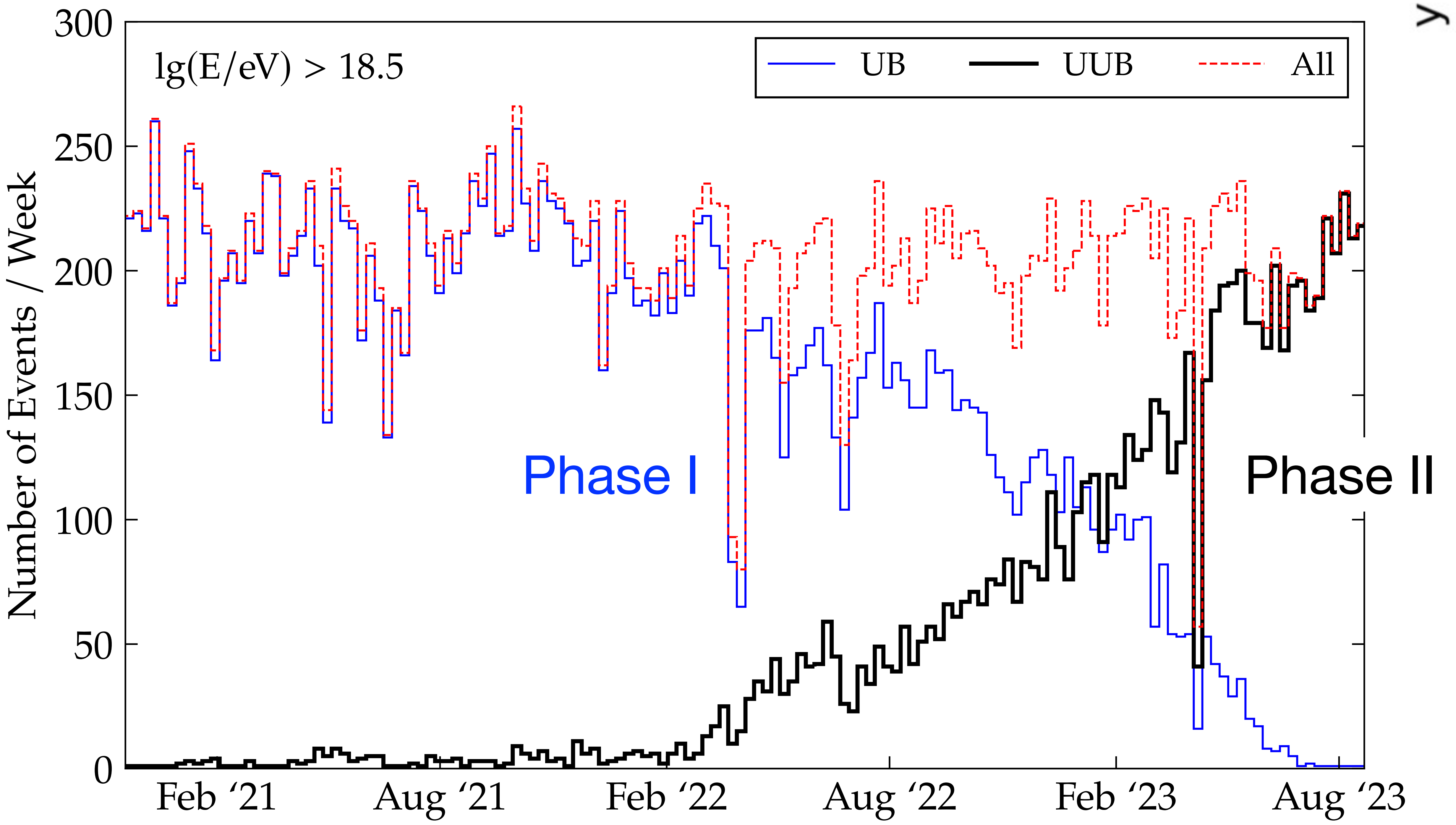
(AugerPrime design report 1604.03637)

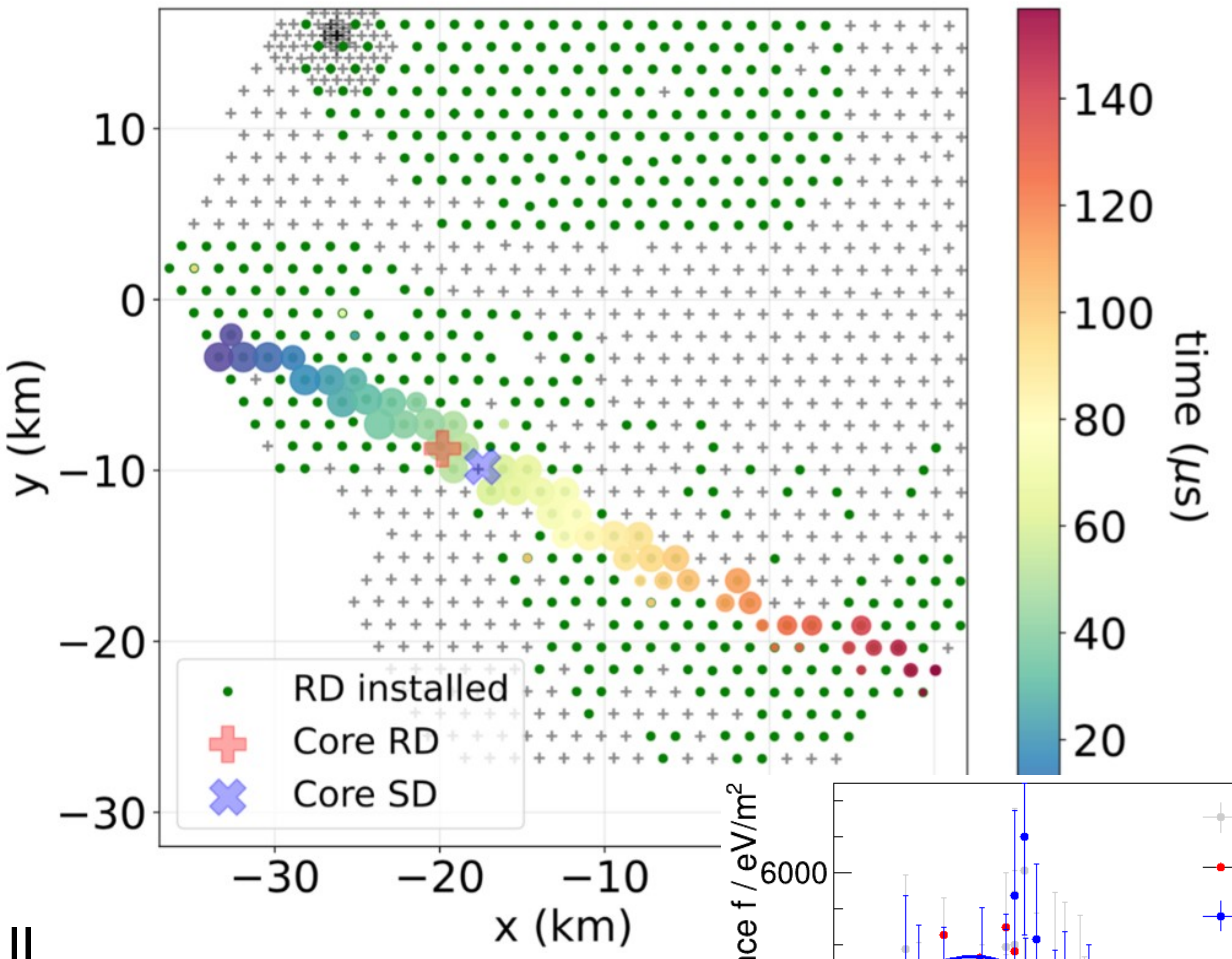




Upgrade of Auger Observatory completed

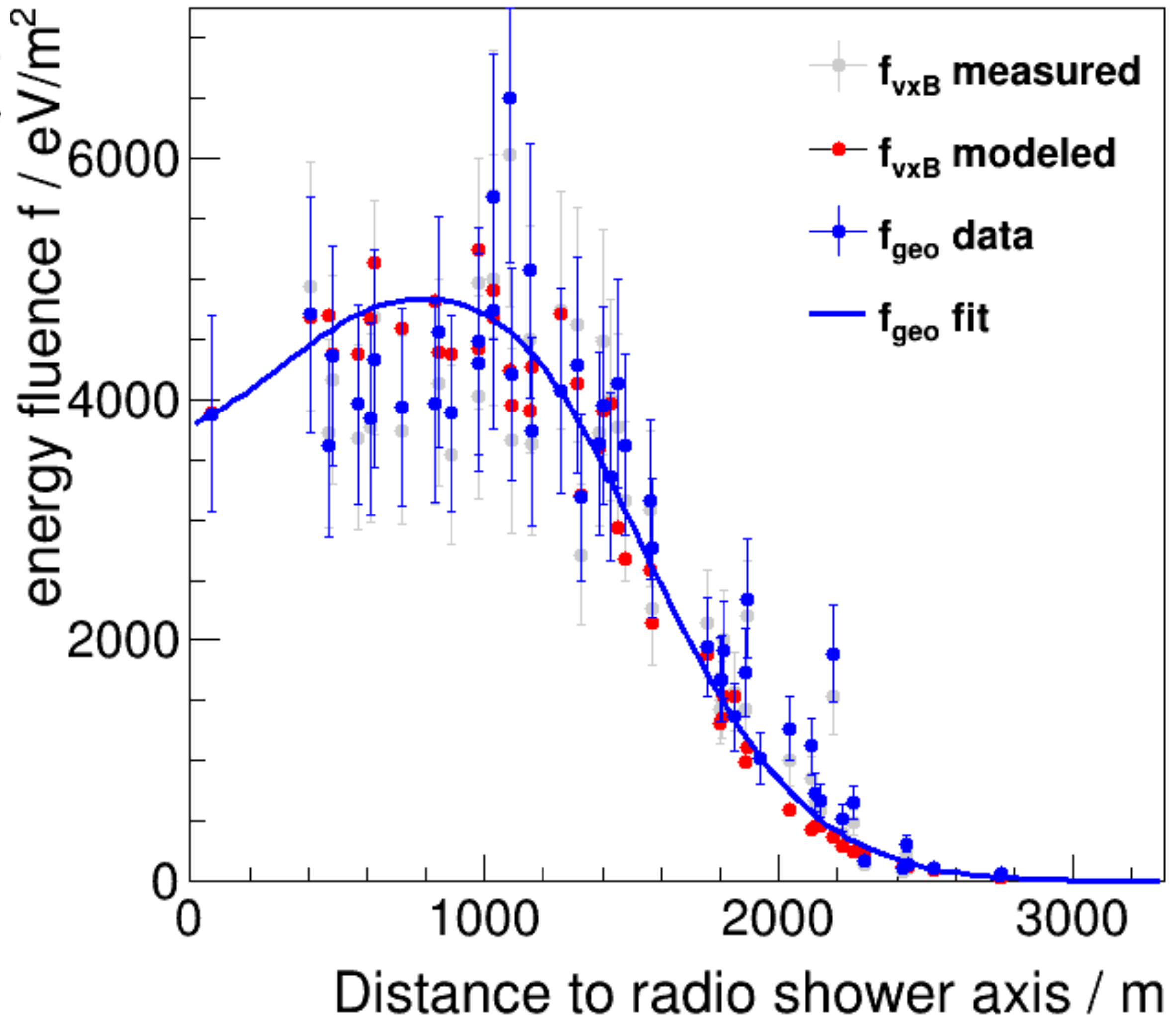
Event rate of surface array



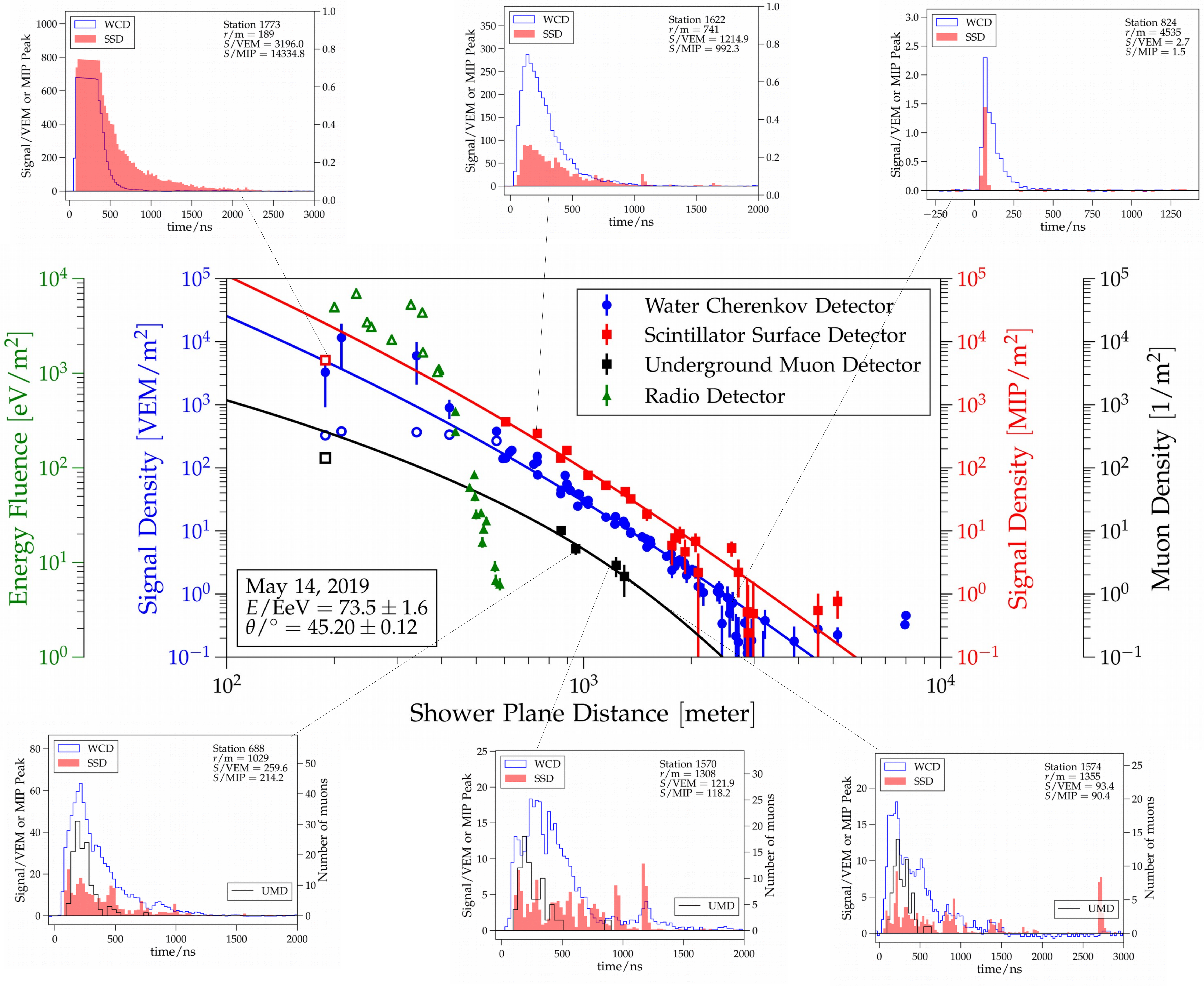


Early radio event

$E \sim 3.8 \times 10^{19}\,\mathrm{eV}$



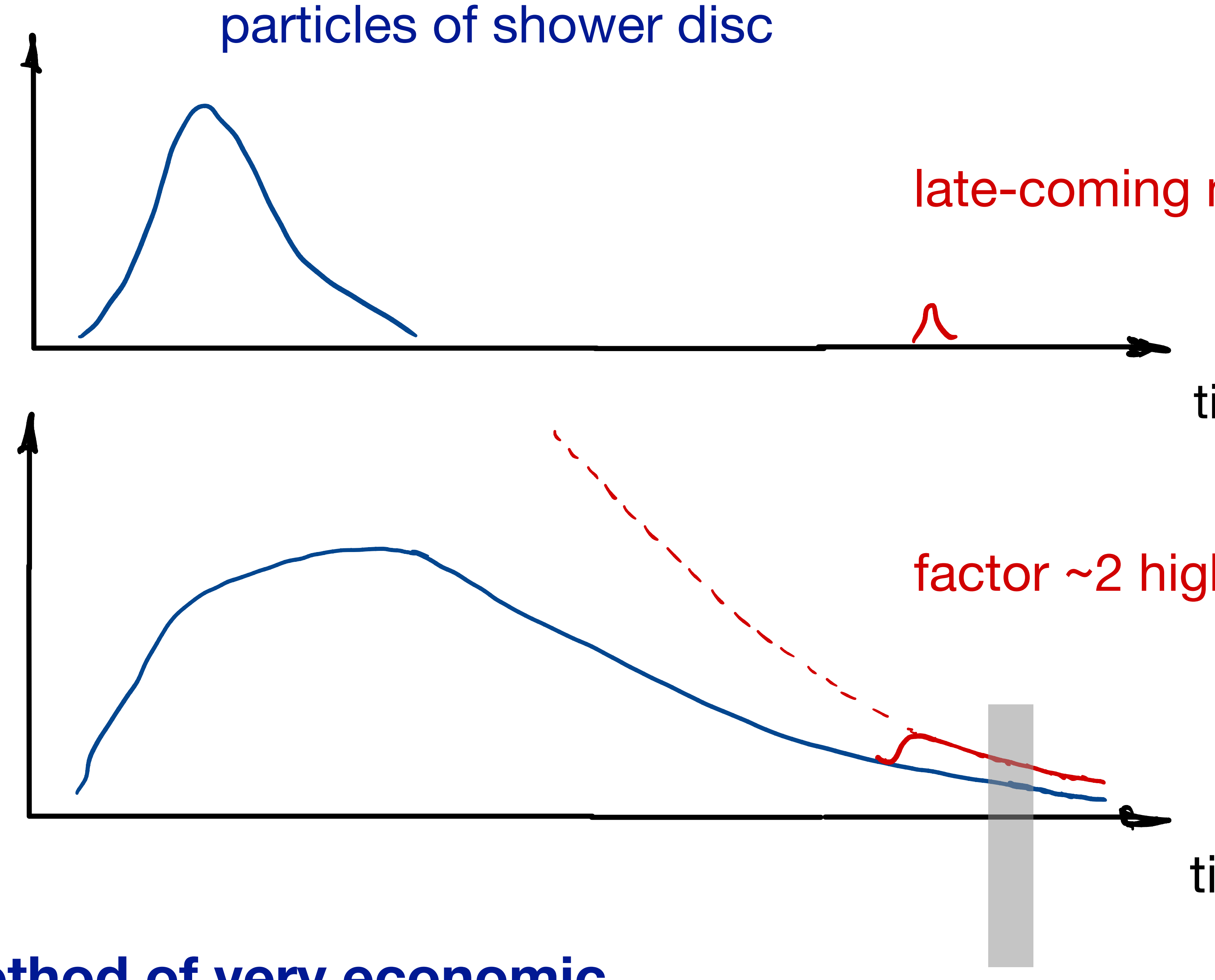
Example of rich information in data of Phase II



Sub-luminal particles: neutrons in scintillators

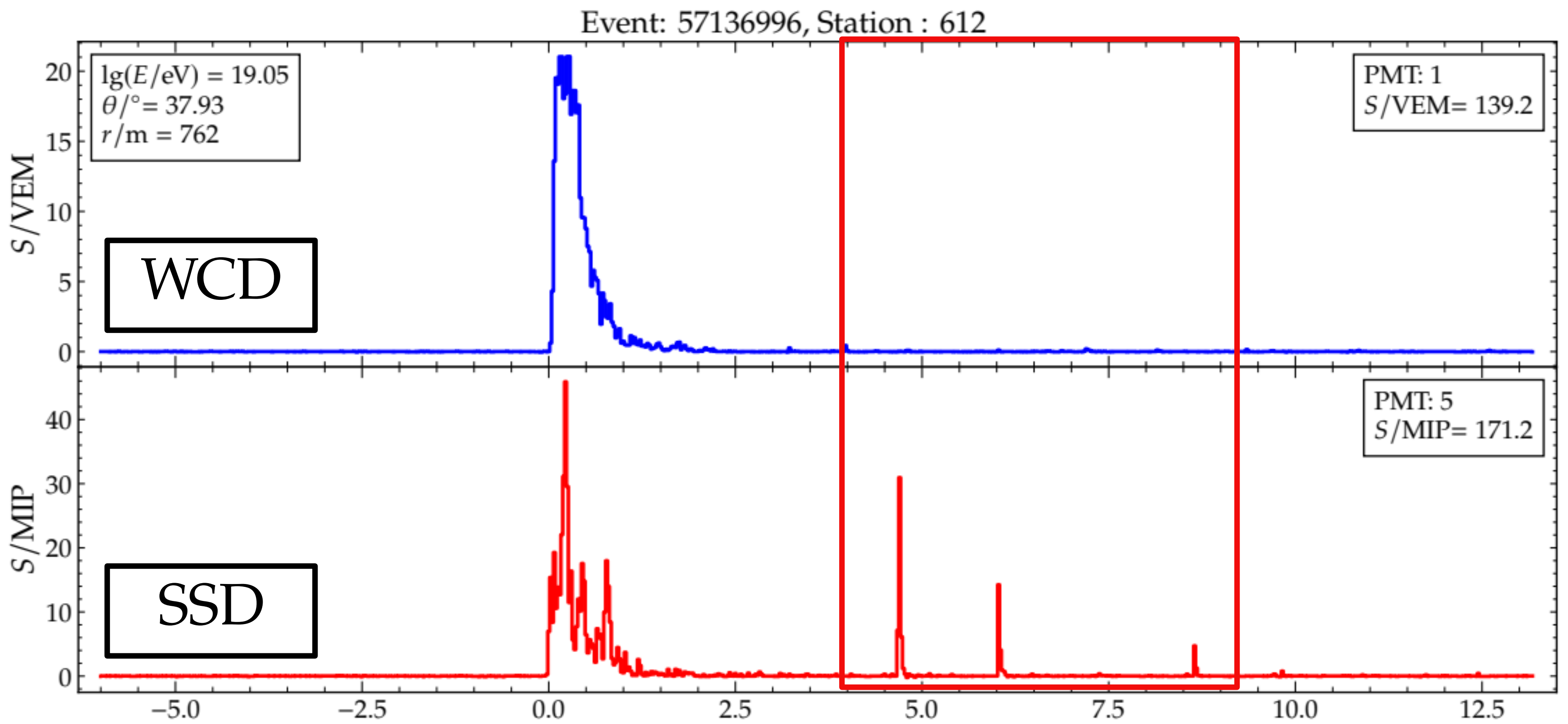
Observation of late pulses already reported by Linsley 1984

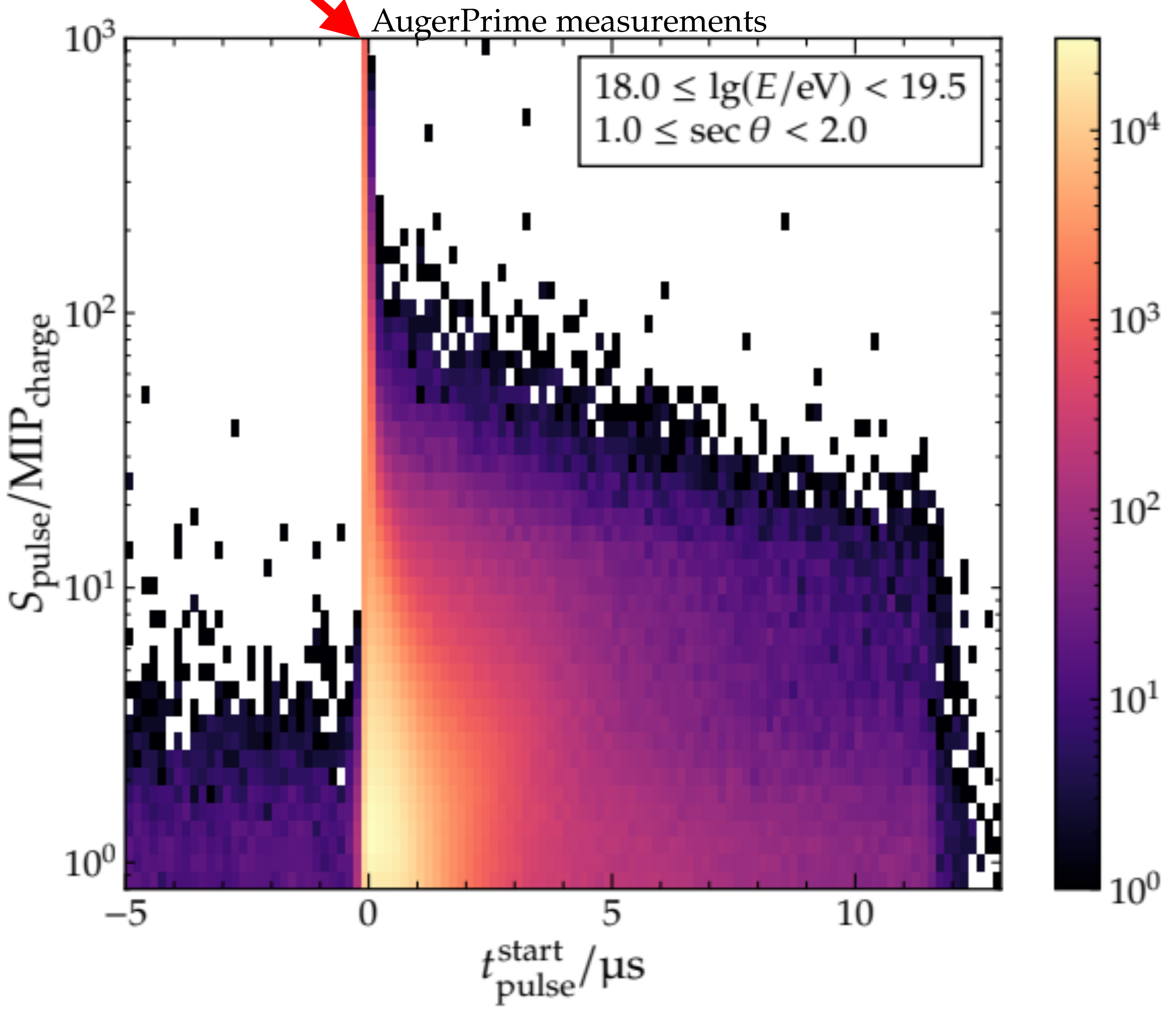
Possible impact depending on measurement principle



Classic method of very economic charge integration in EAS arrays (AGASA, Yakutsk)

(Drescher & Farrar, Astropart Physics 24 (2005) 372)

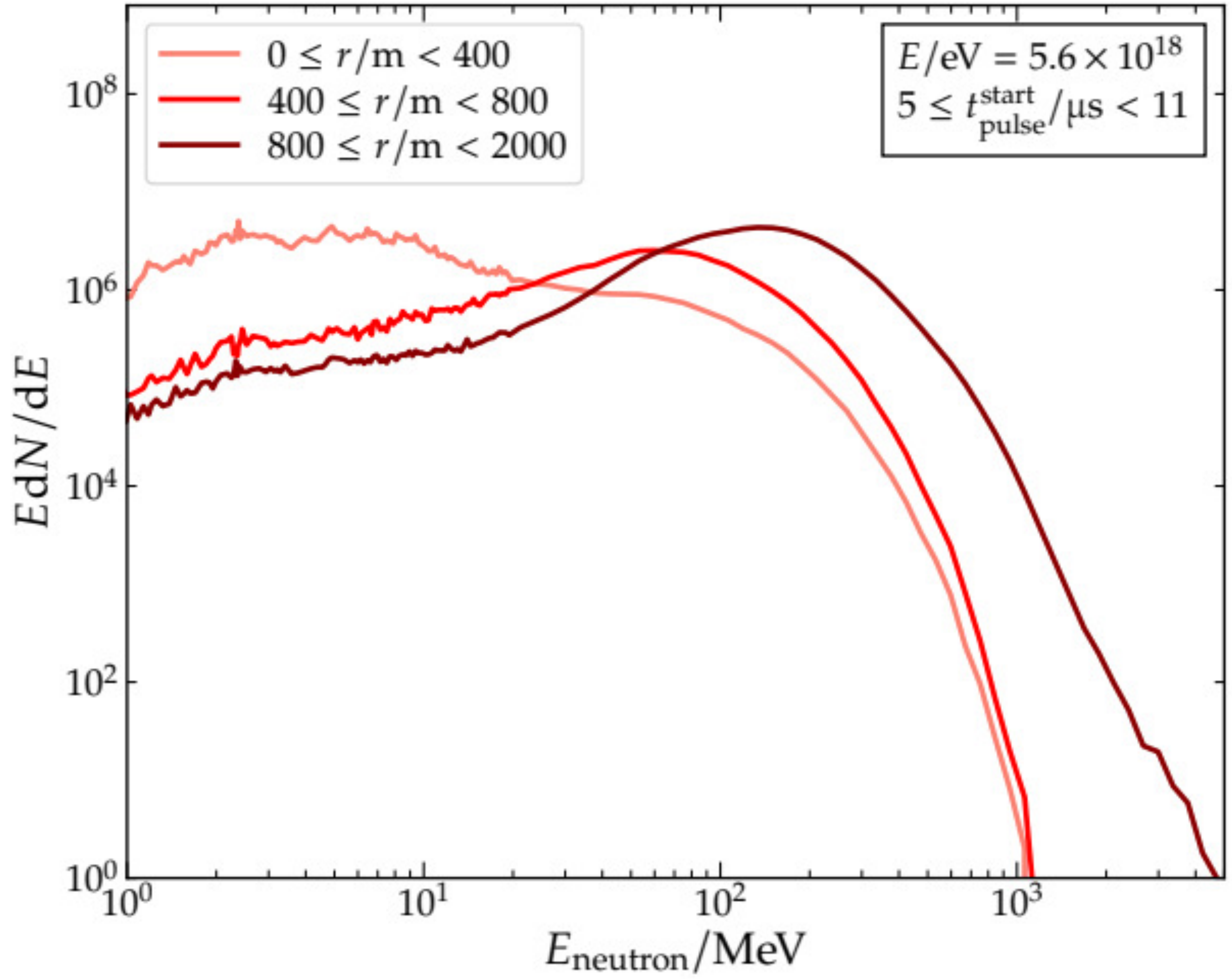




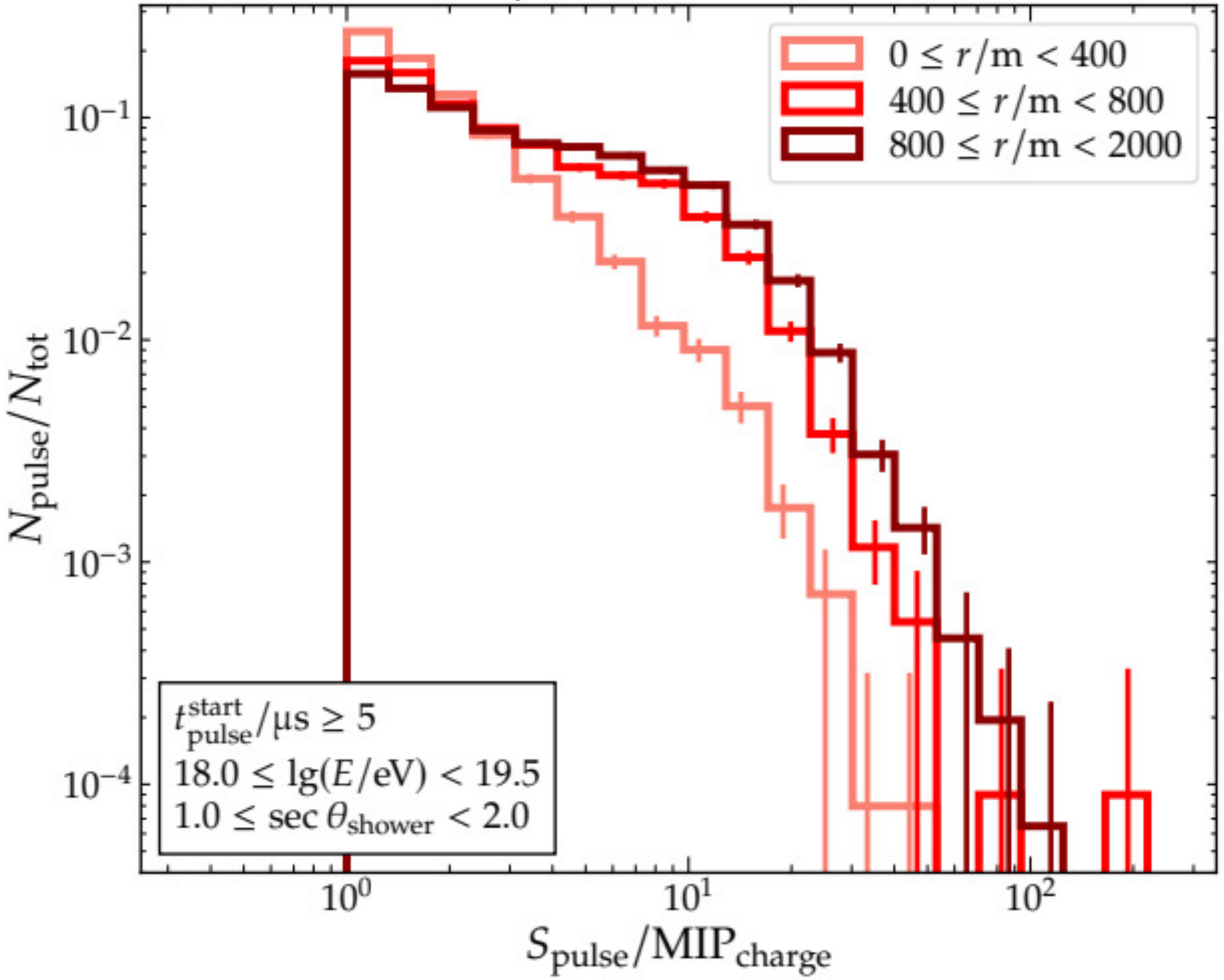
(Auger, UHECR 2024)

Sub-luminal particles: neutrons in scintillators

Simulations from A. Ferrari; arXiv:2406.11702



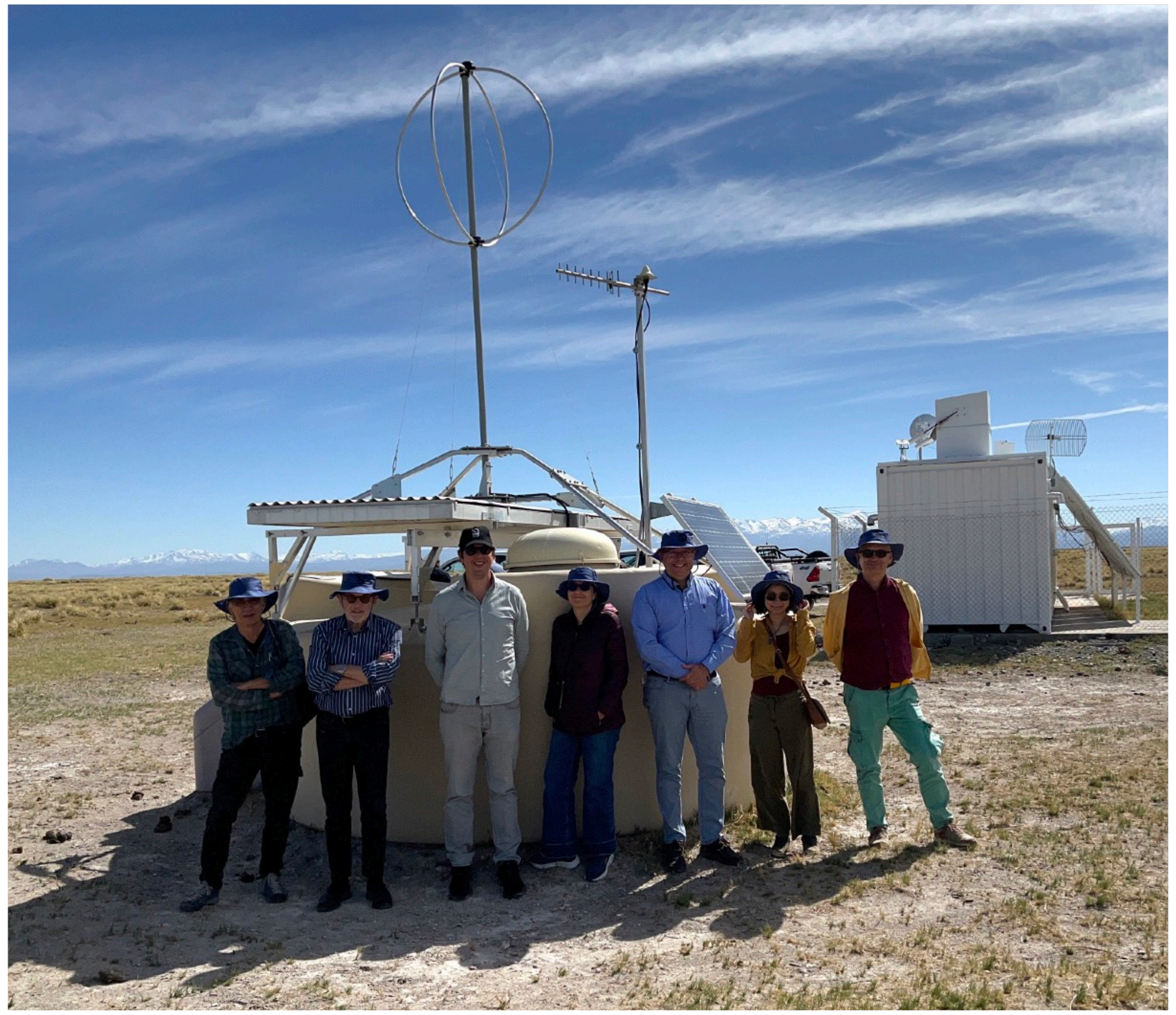
AugerPrime measurements



Time window for search selects "universal" neutron component

(Schulz, Auger, UHECR 2024)

Extension of Auger data taking until 2035



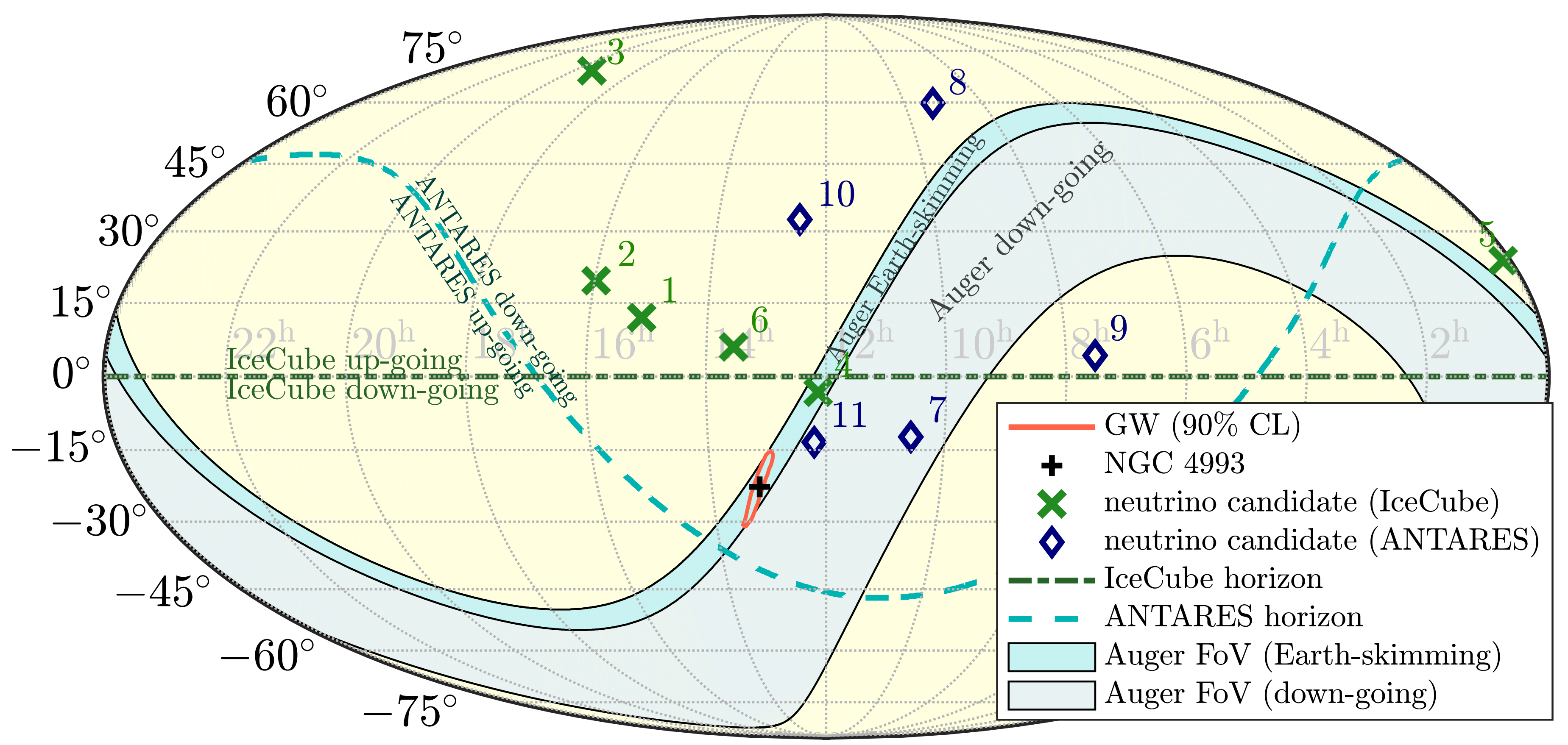
Nov. 2023: AugerPrime review

Nov. 16, 2024: extension of International Agreement for Auger Phase II

Supplementary material

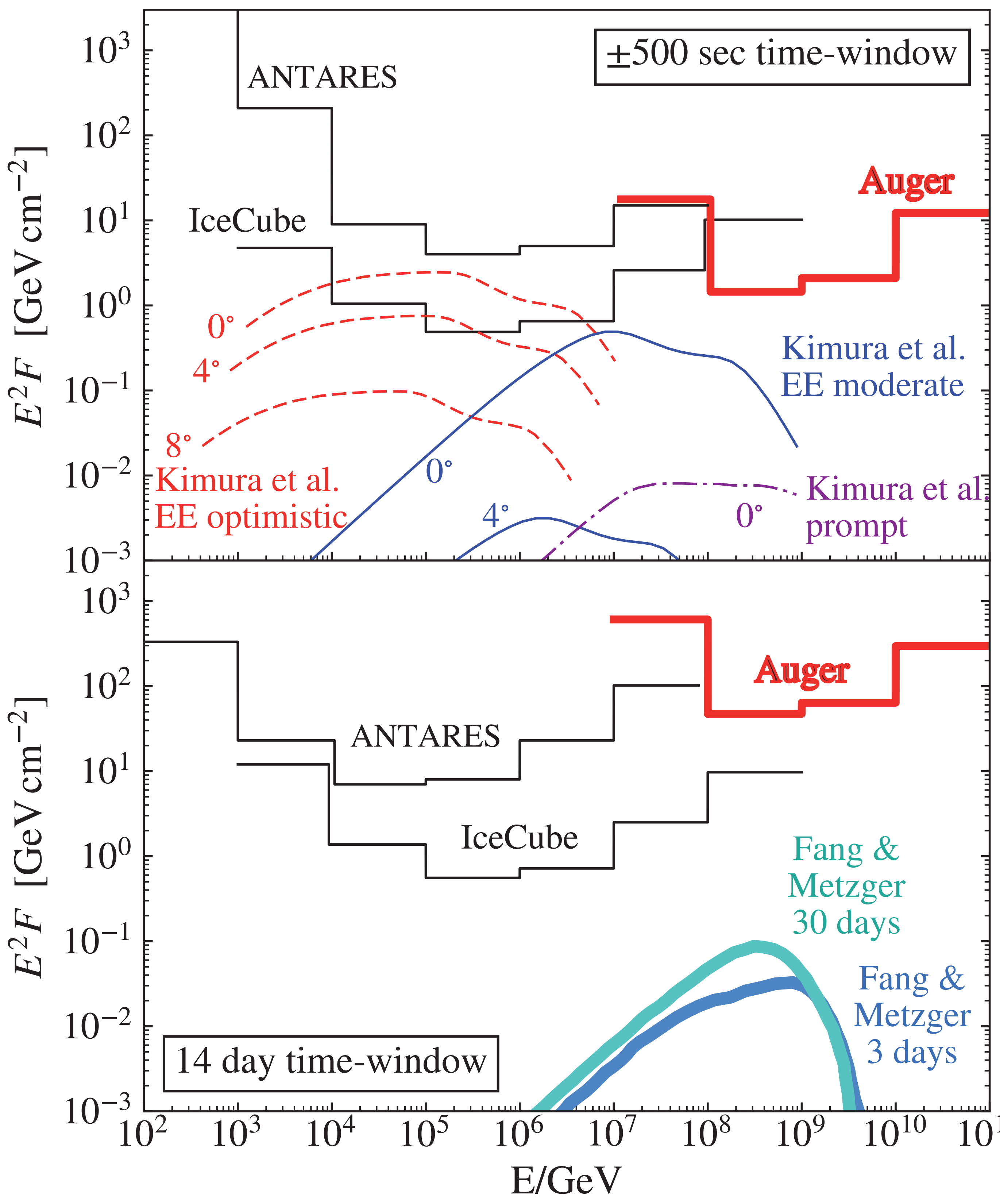
Multi-messenger observation of sources

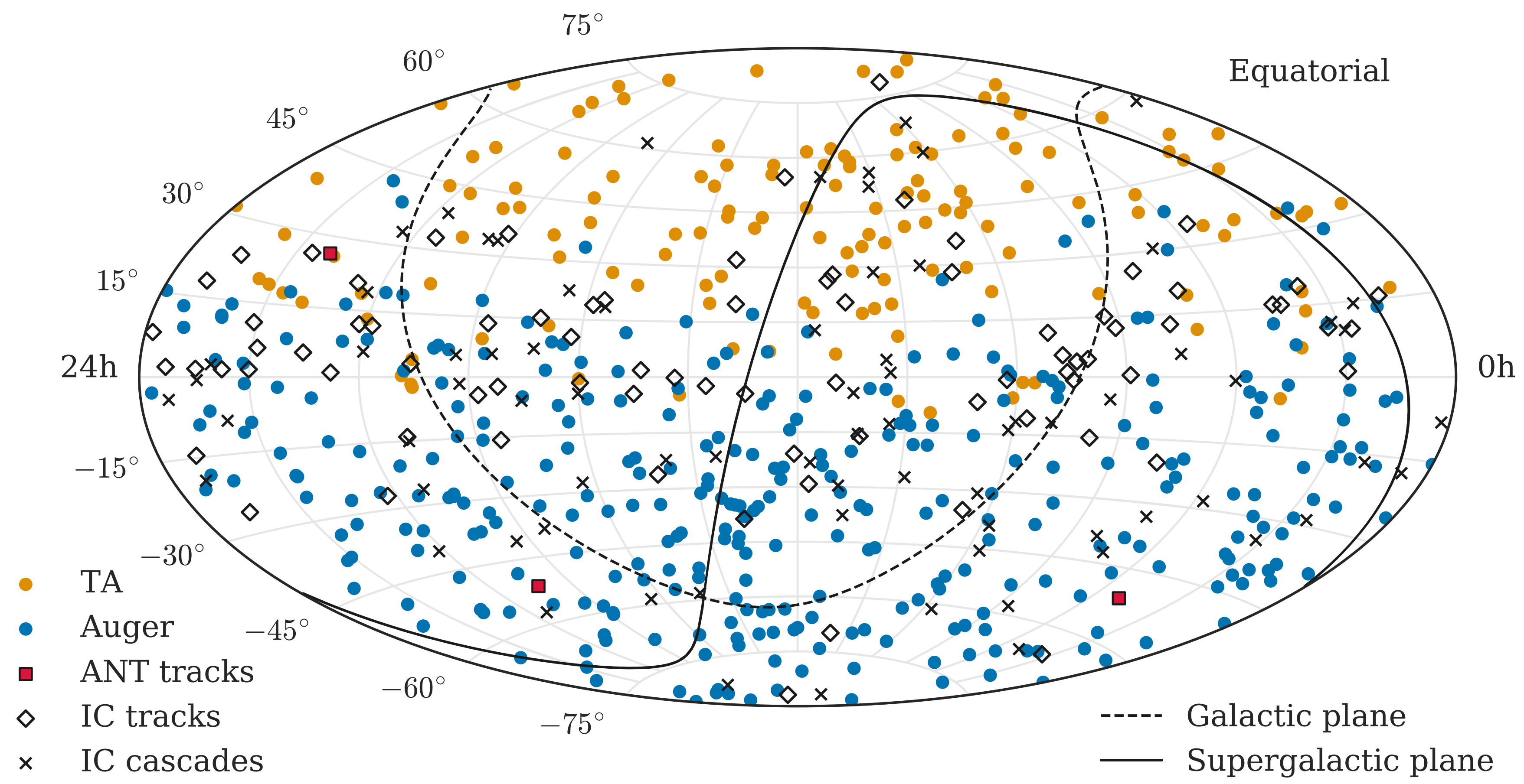
Analysis of individual events
Stacking analysis of BBH mergers



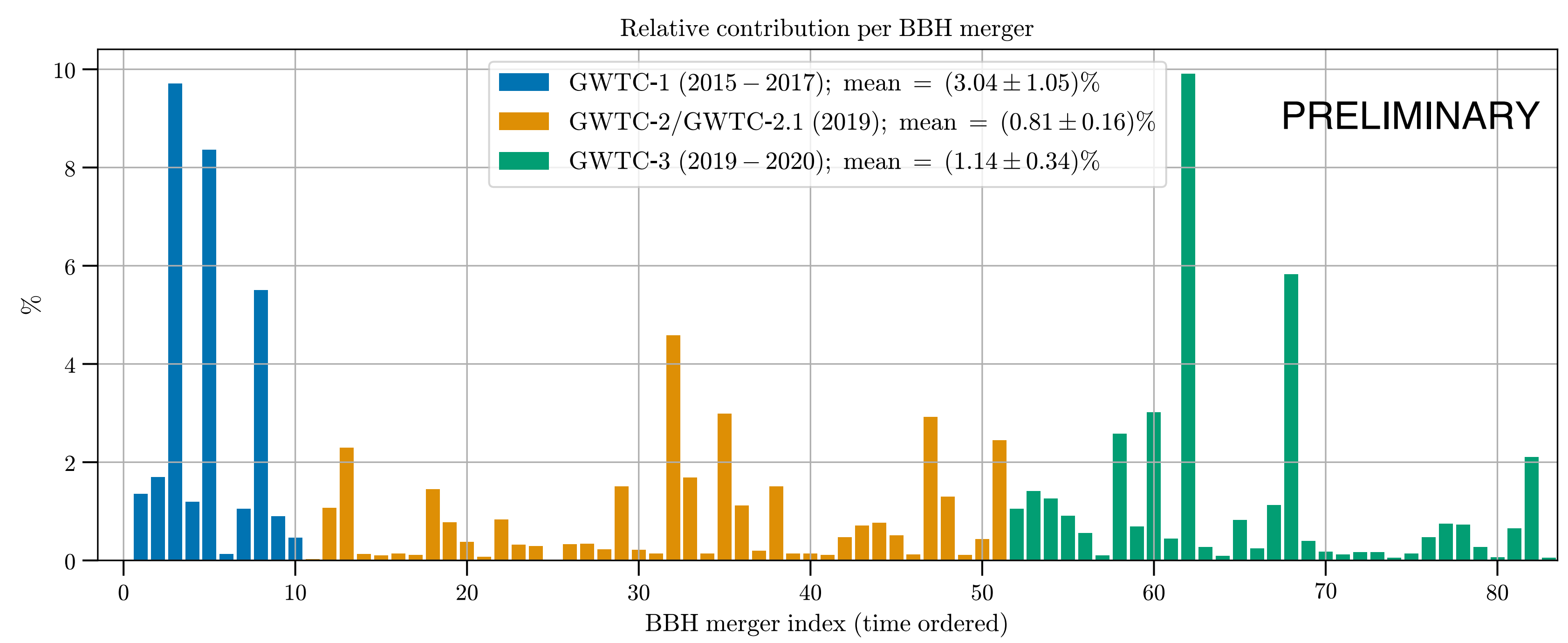
GW170817

ApJL (2017), special issue (70 collaborations)





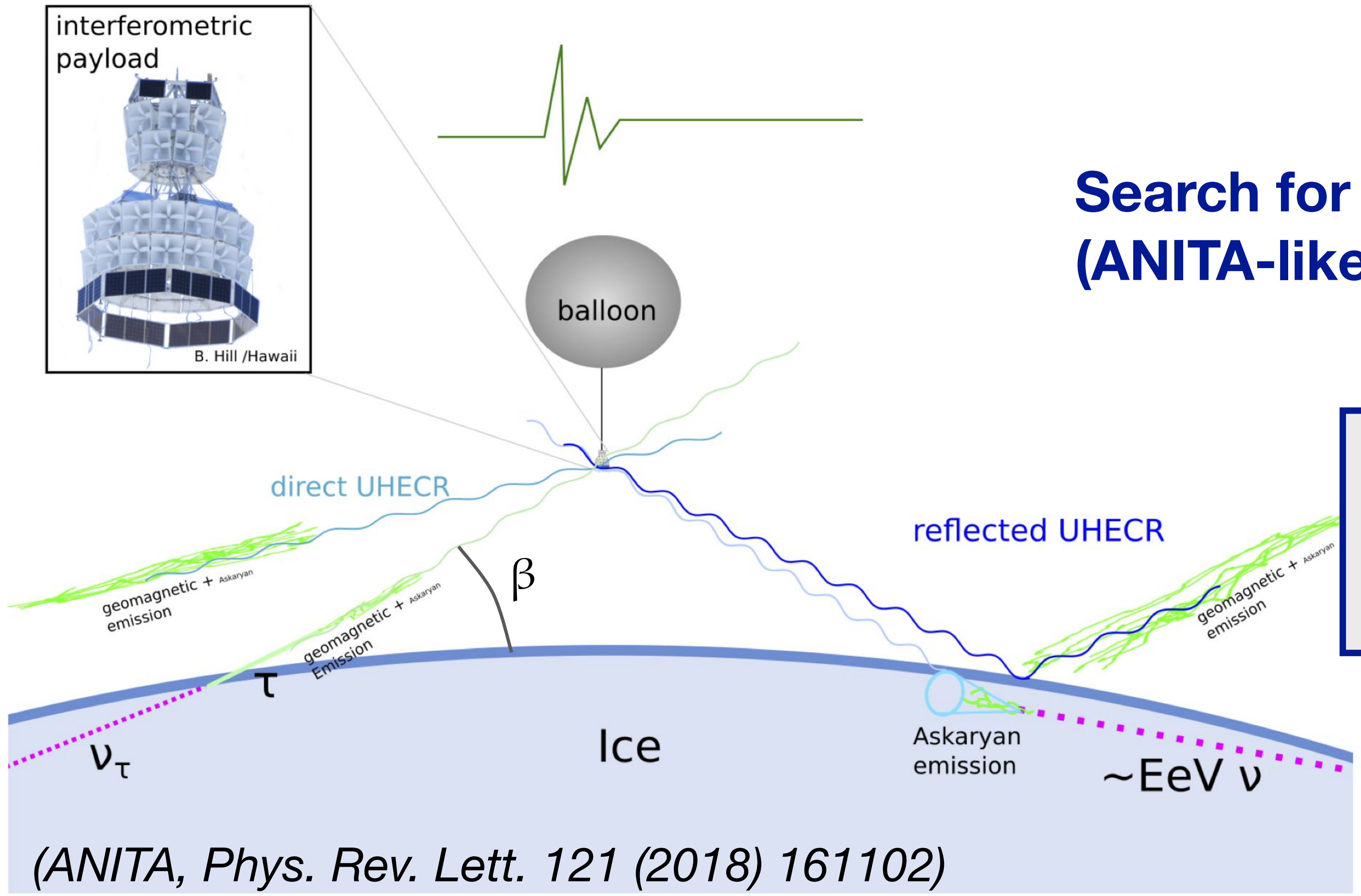
(Auger ICRC 2023)



Search for spatial neutrino and UHECR correlations (ApJ 934 (2022) 164)

Instantaneous aperture comparable to IceCube if direction of source is favorable
Multi-messenger: searches for neutrinos and photons in coincidence with GW events

Fundamental physics studies and searches

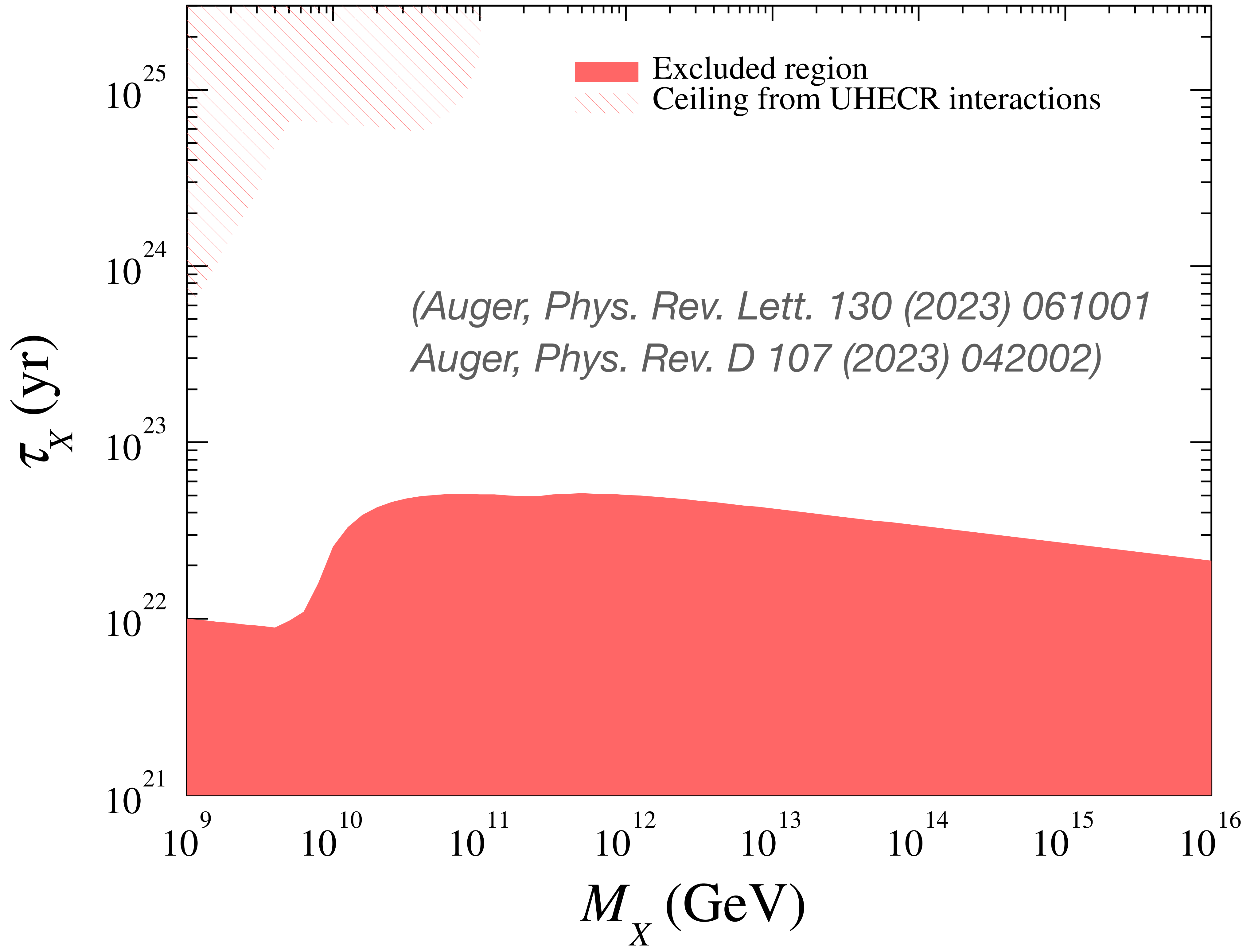


(ANITA, Phys. Rev. Lett. 121 (2018) 161102)

Search for upward going showers (ANITA-like events)

No ANITA-like events seen
~10x exposure of ANITA

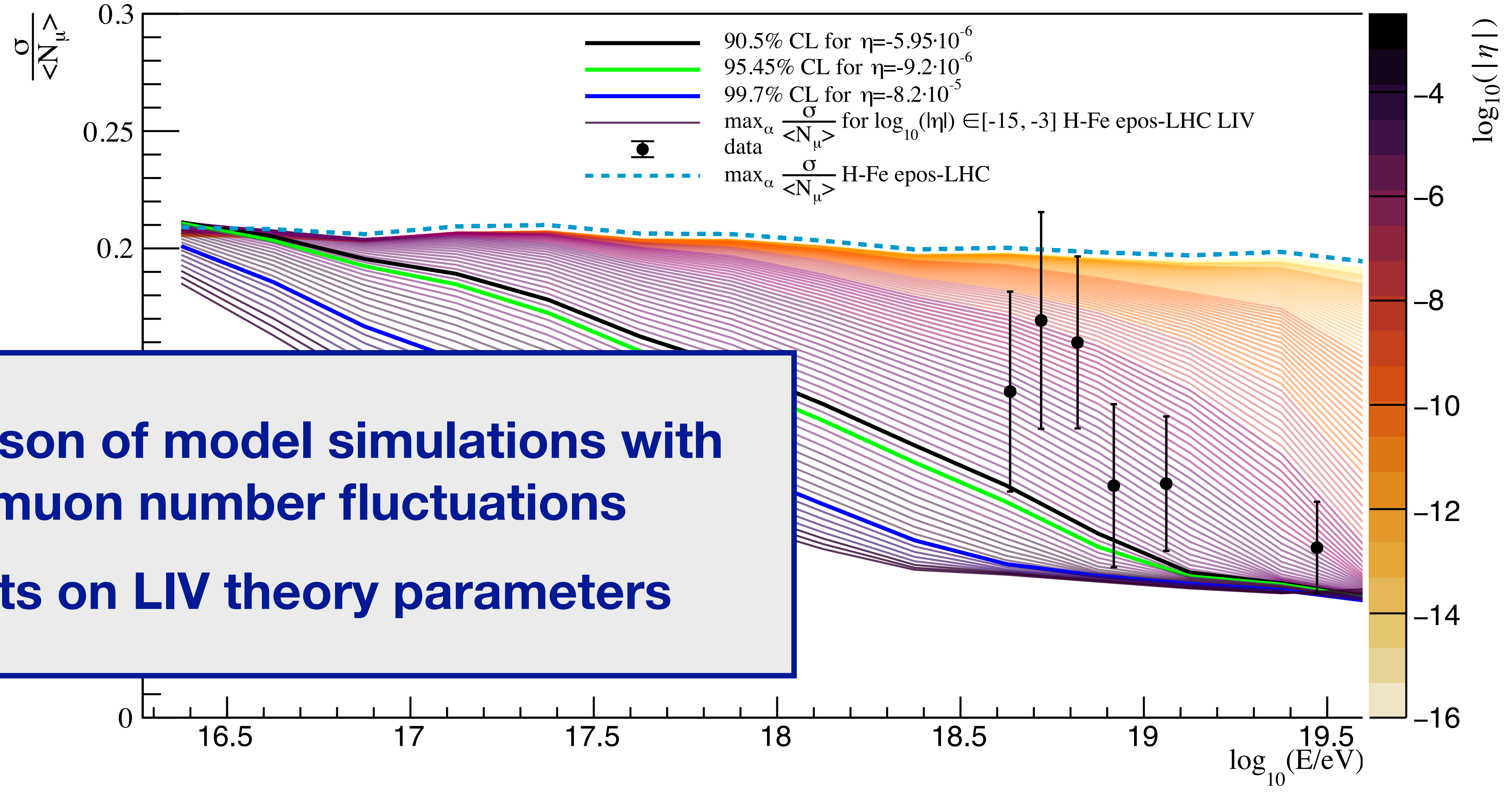
Photon and neutrino limits at ultra-high energy



(Auger, Phys. Rev. Lett. 130 (2023) 061001
Auger, Phys. Rev. D 107 (2023) 042002)

Limits on parameters of SHDM models (mass, lifetime, decay through instanton processes)

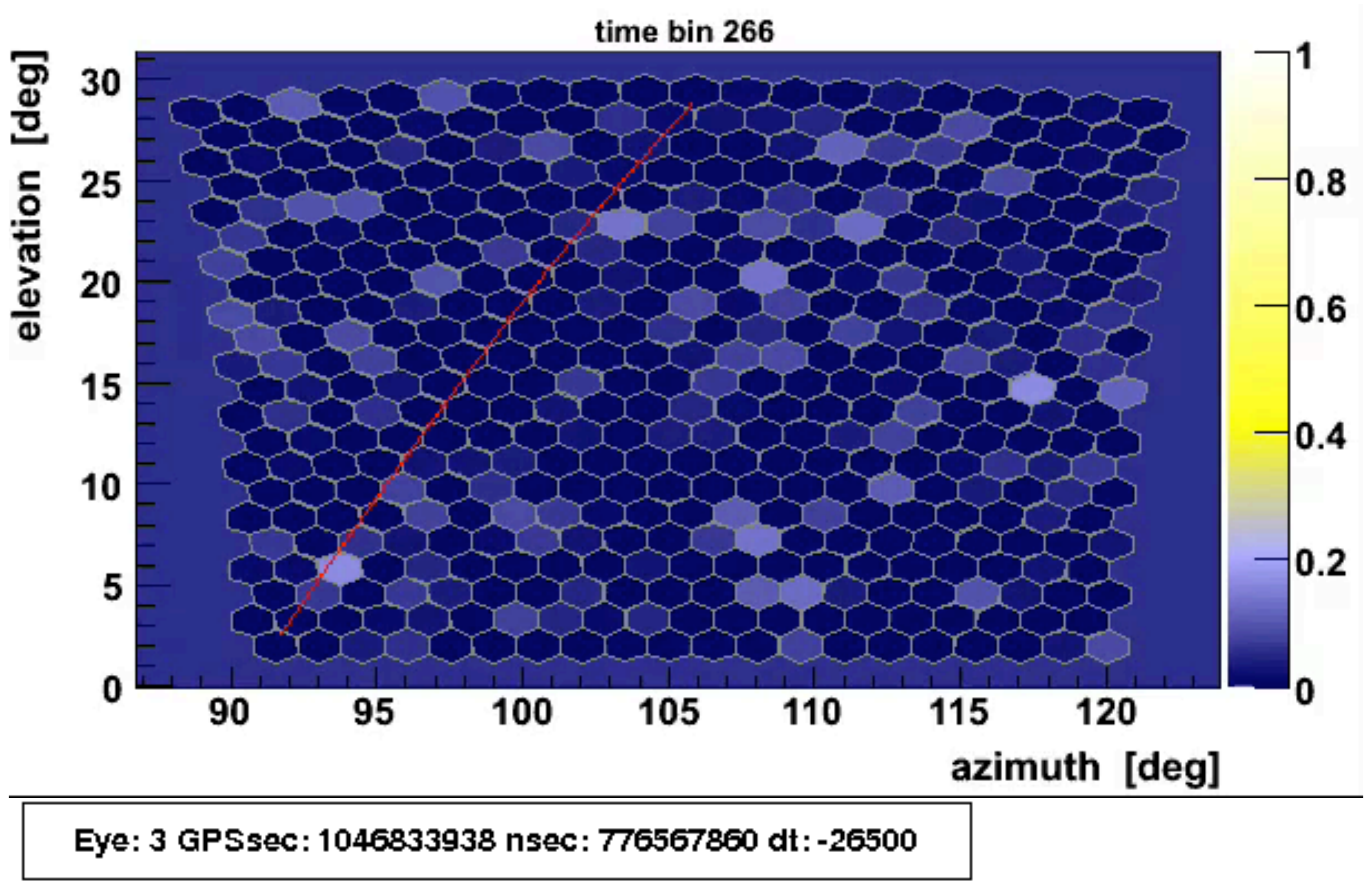
Lorentz-dilated lifetime of neutral pions

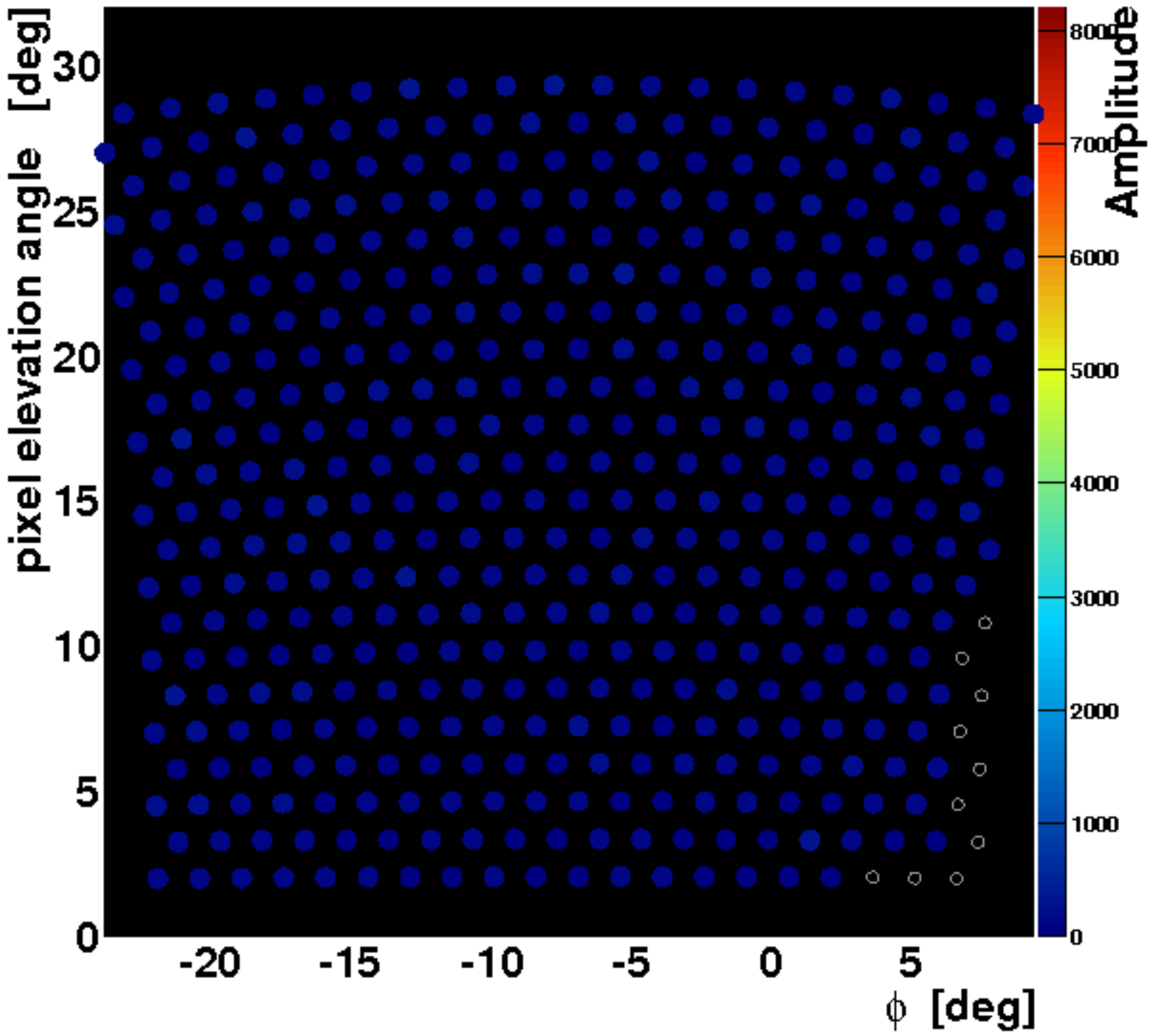


Comparison of model simulations with data on muon number fluctuations

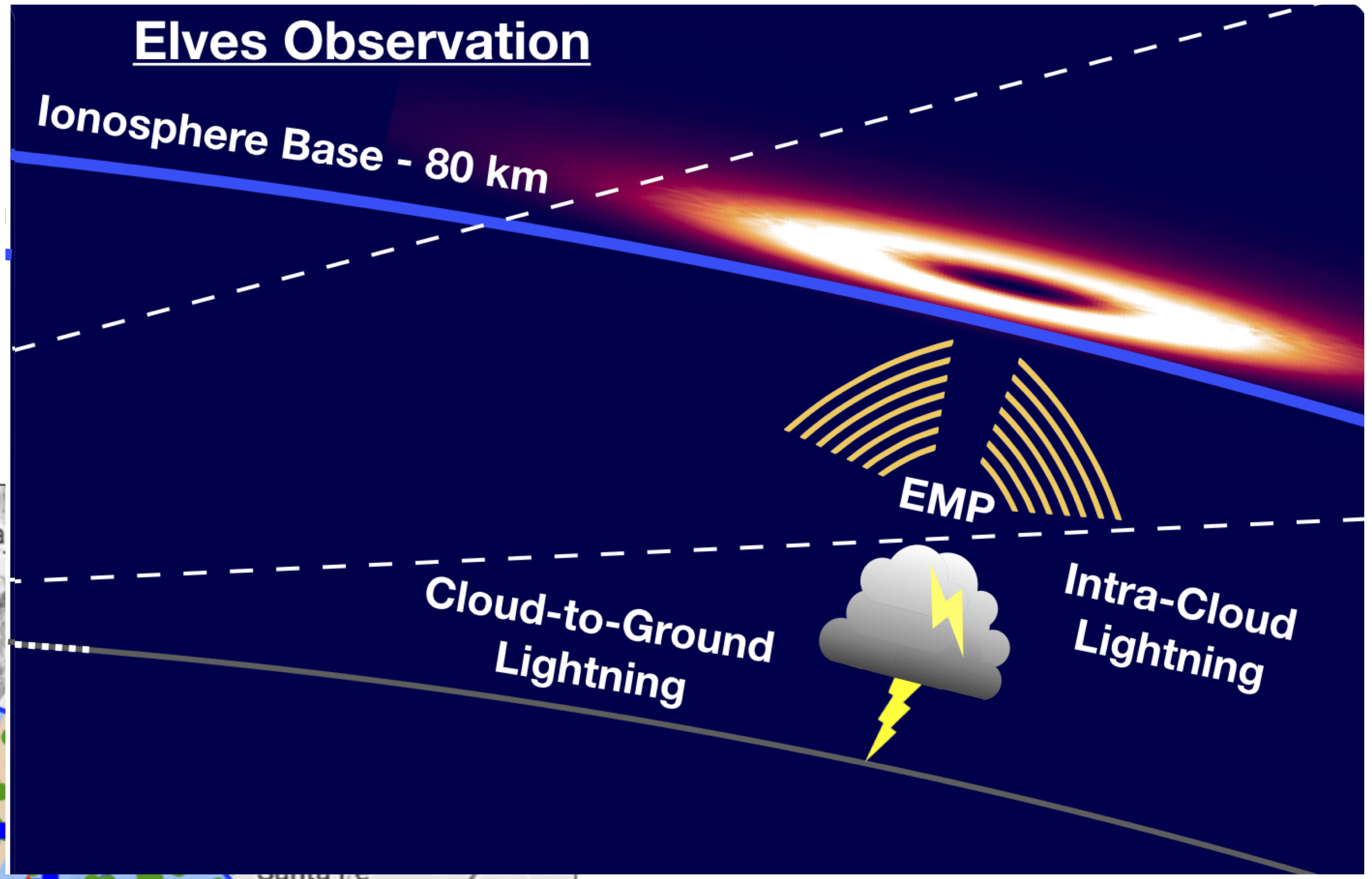
New limits on LIV theory parameters

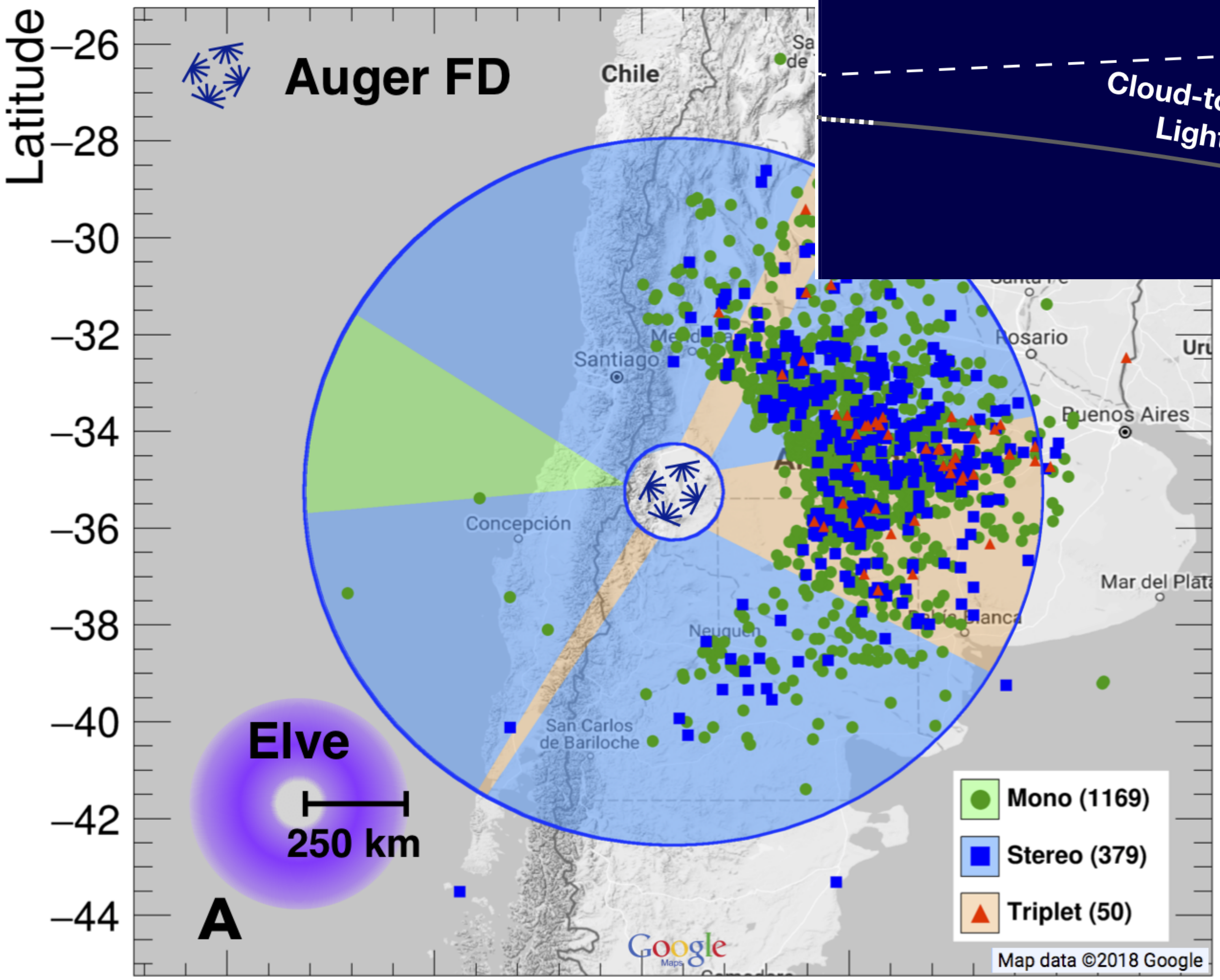
Atmospheric and geo-physics observations





Example: observation of elves with FD telescopes





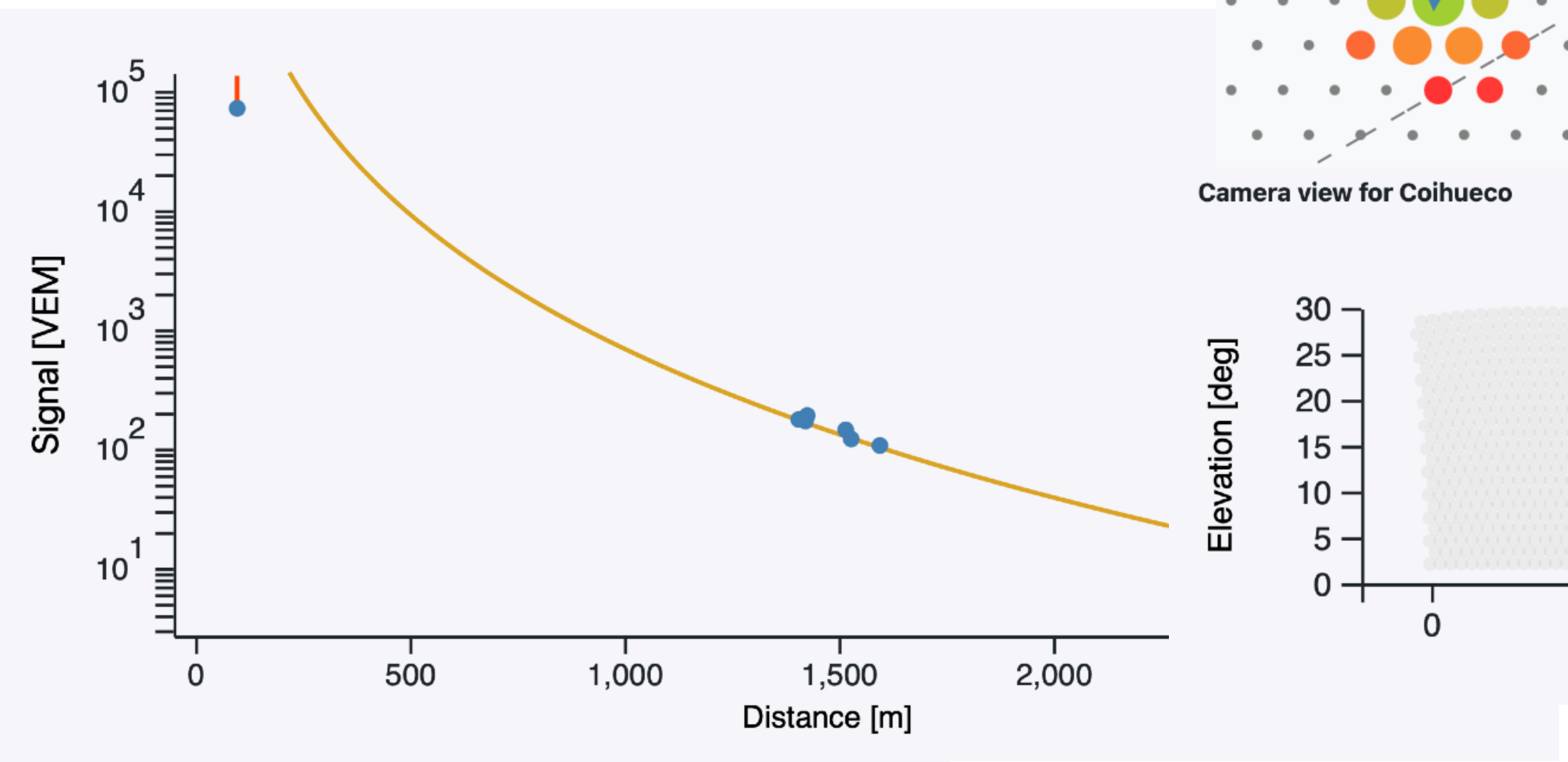
1600 elves

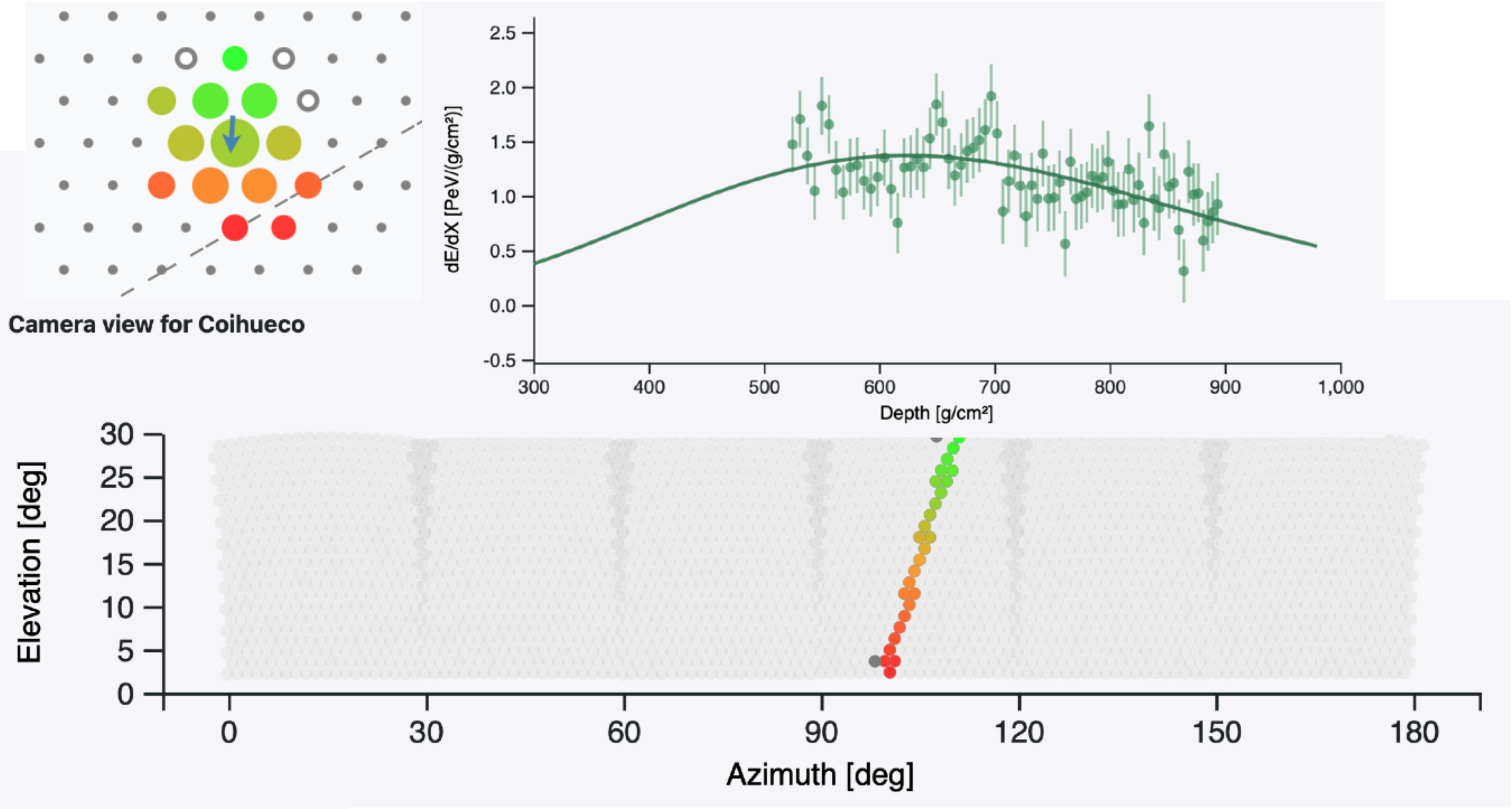
(Auger, Earth and Space Sciences, 2020)

An invitation: Auger open data

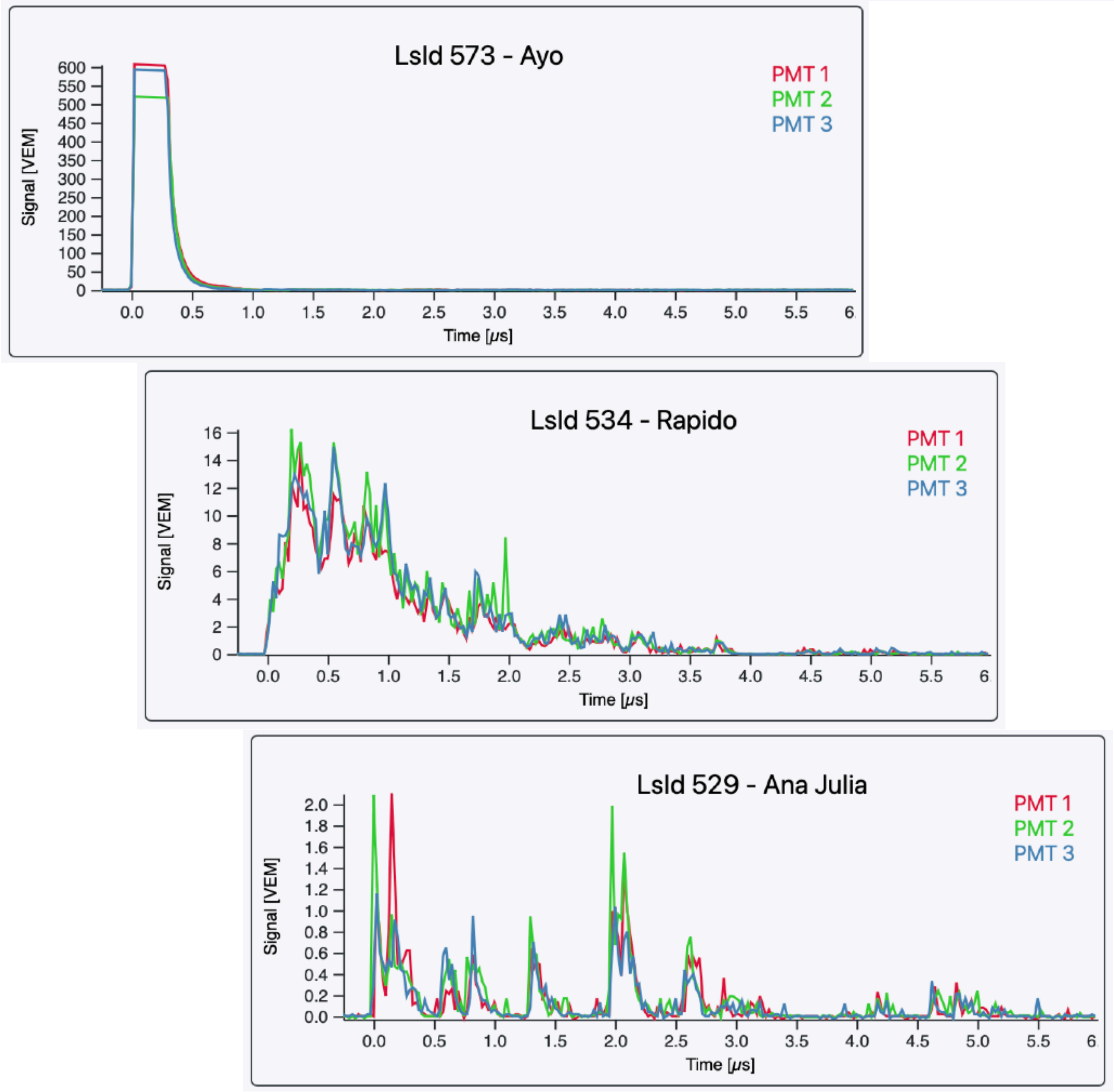
opendata.auger.org

DOI:10.5281/zenodo.4487613





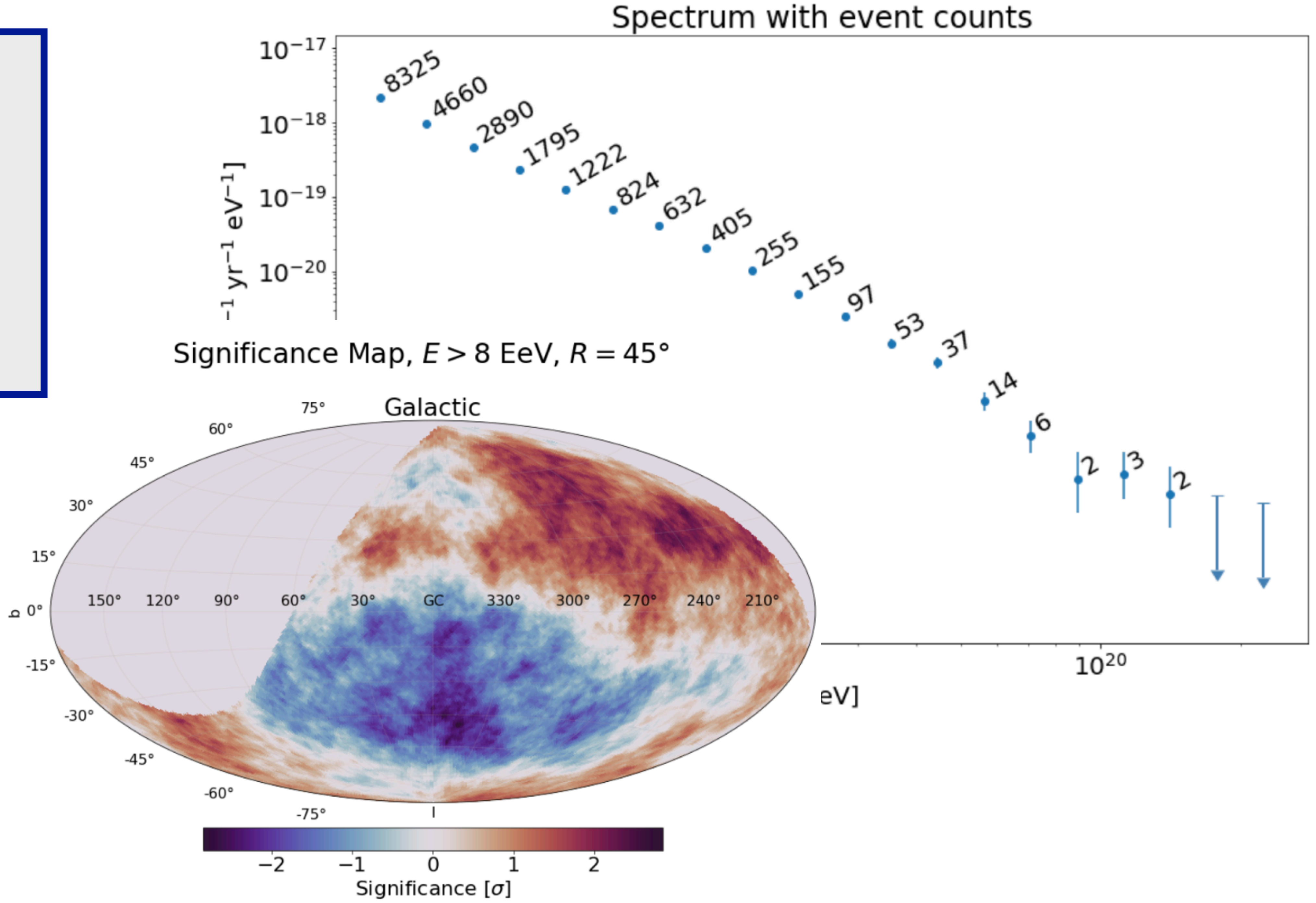

```
In [19]:
Y_0val = FC_CL * 0.9

plt.title("Spectrum with event counts")
plt.errorbar(bin_energy18[cut_nz], flux, [flux_lower, flux_upper], fmt="o")
plt.errorbar(bin_energy18[cut_z], FC_CL, Y_0val, uplims=True, marker="None", color="steelblue",
             markeredgecolor="r", markerfacecolor="r", linewidth=2.0, linestyle="None", capsize
=5)
plt.xscale("log")
plt.yscale("log")
plt.xlabel('E [eV]')
plt.ylabel(r'J$^{Raw}$(E) [km$^{-2}$ sr$^{-1}$ yr$^{-1}$ eV$^{-1}$]')

# expand the range in y to have space for the labels and upper limits
plt.ylim(flux[flux > 0].min()*0.01, flux.max()*7)

# add the counts to the points
for E, J, count in zip(bin_energy18, flux, h):
    if count > 0:
        plt.annotate(count, (E, J), rotation=30, va='bottom')
```



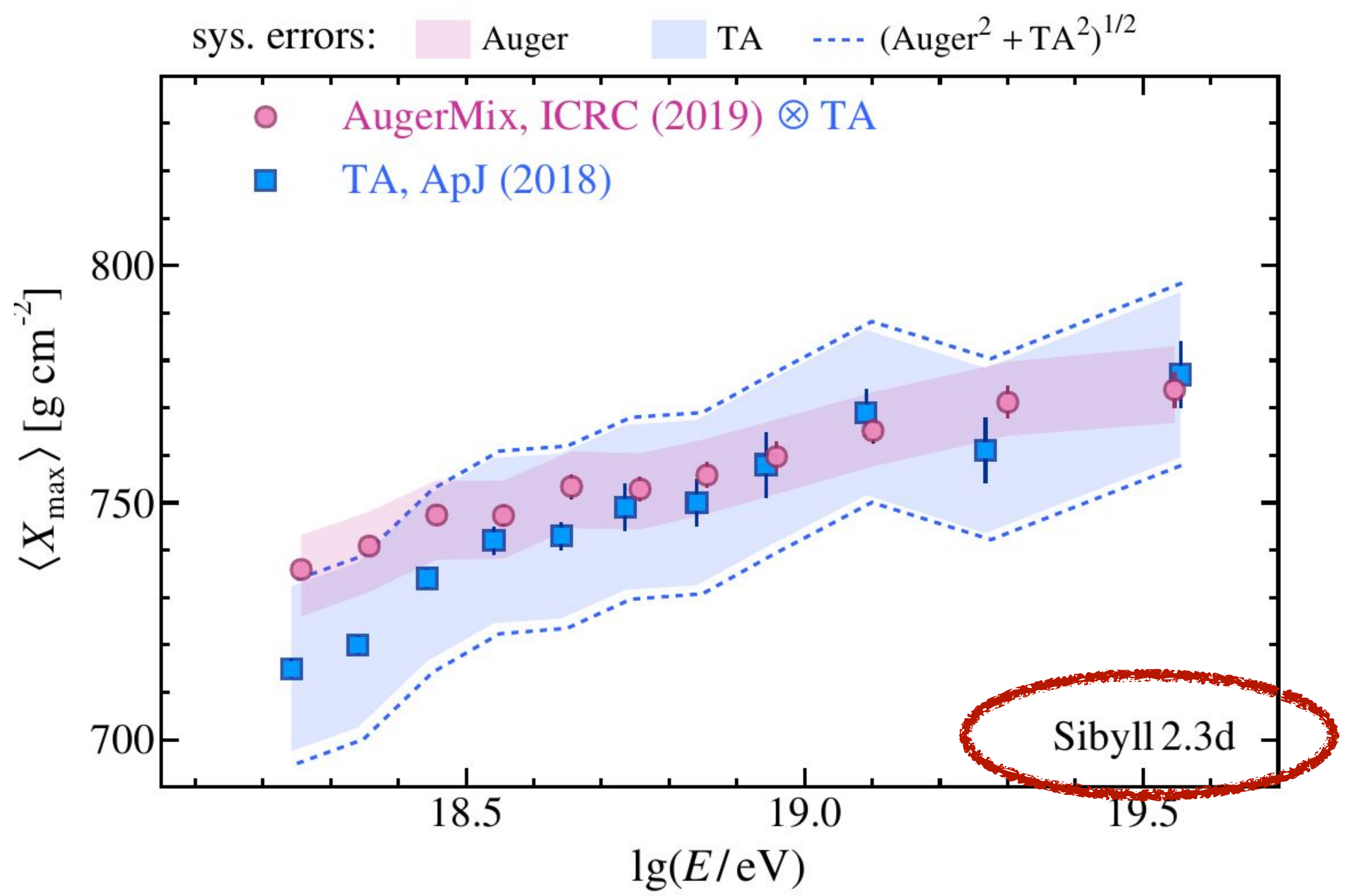
Currently 10% of Auger vertical data
Research-level data in JSON format
Online visualization of events
Data analysis scripts for science plots

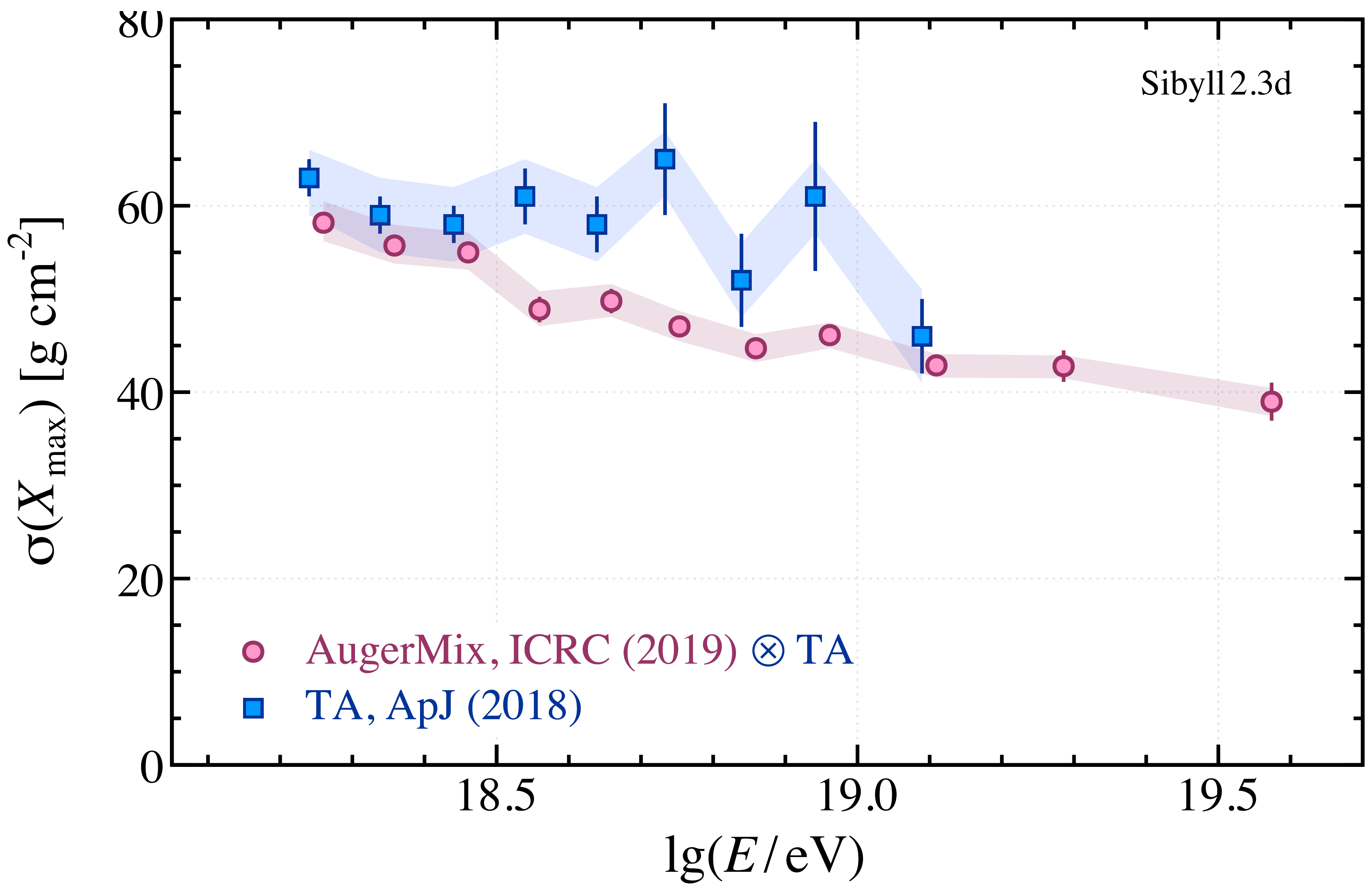
You are welcome to use this data

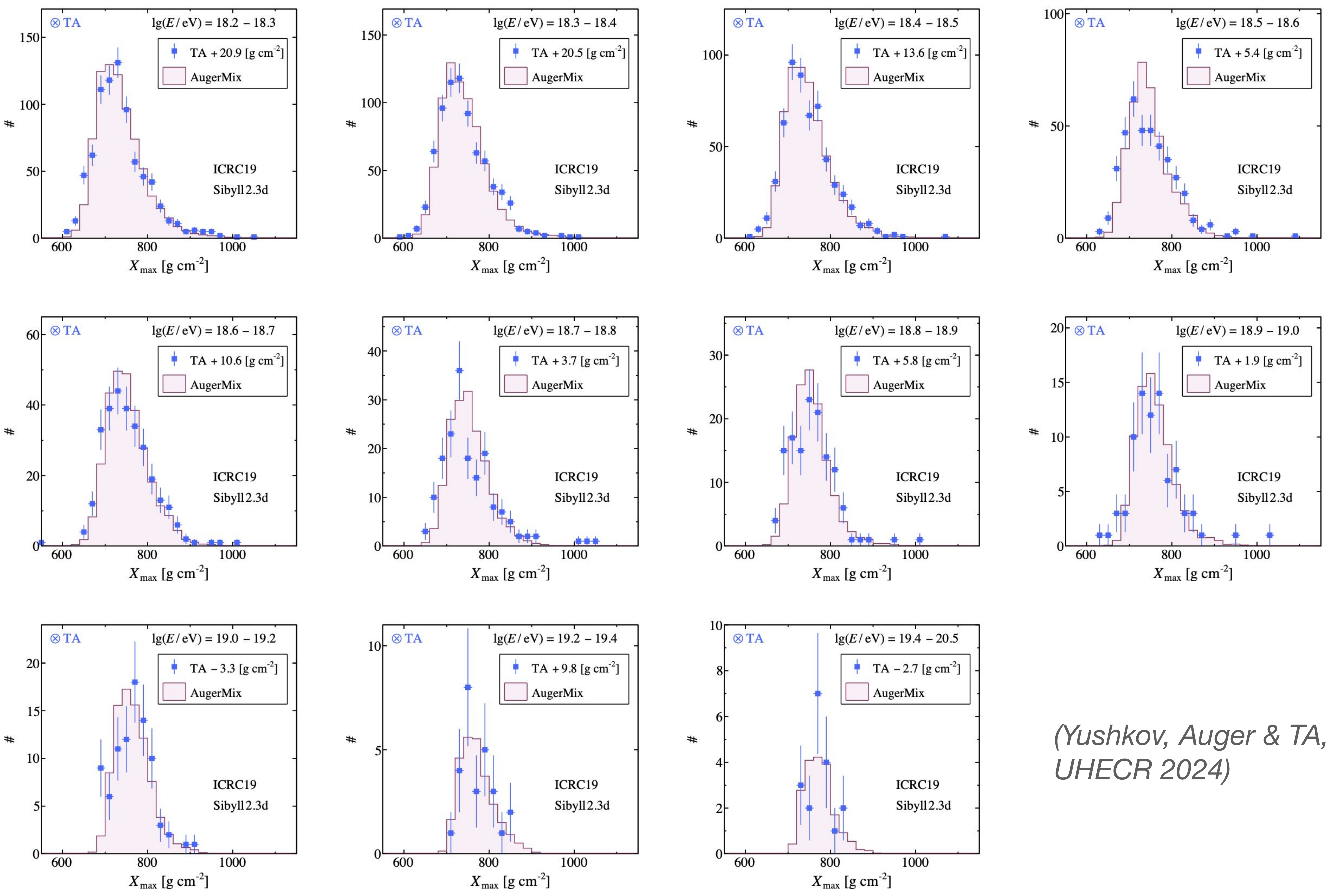
If you have a great idea what to look for we can work with you to apply your analysis also to the full data set



Auger-TA comparison of X_{max} distributions (2022)





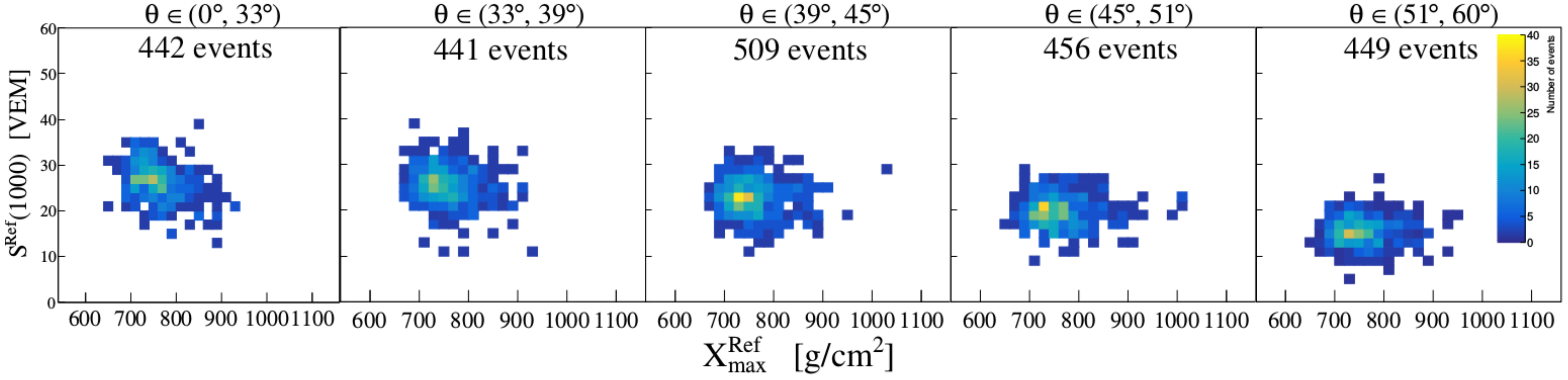


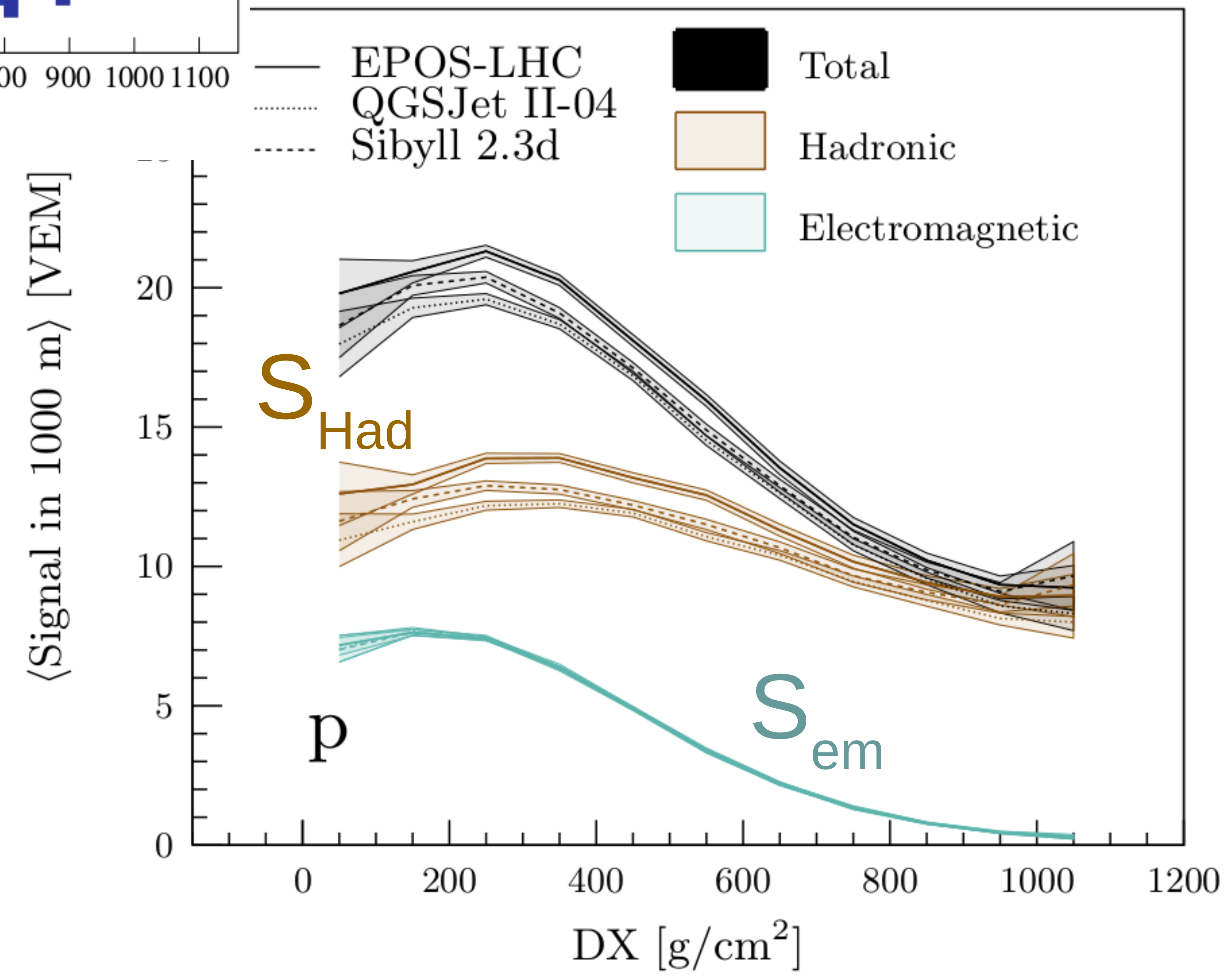
(Yushkov, Auger & TA, UHECR 2024)

Joint working group: no significant difference found

Test: modification of hadronic interaction models

2297 high-quality showers for $\log_{10}(E_{FD}\,[eV]) =$ **18.5-19.0**, θ < 60°





Aim: fit both Xmax and S1000 distributions simultaneously

- Approximate universal depth profile of shower components
- Rescale hadronic component (muons)
- Shift mean depth of shower maximum

ad-hoc adjustments

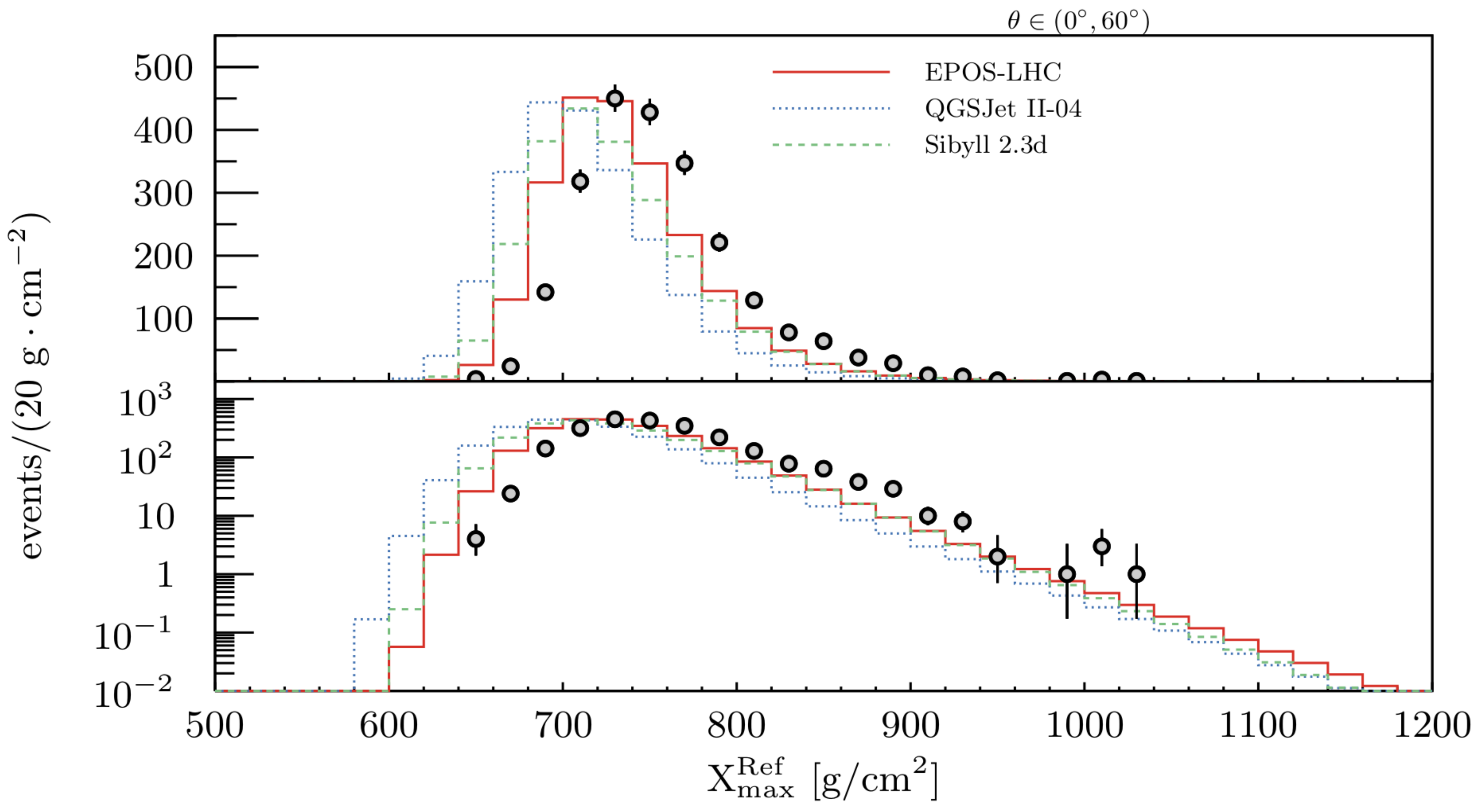
$$X_{max} \rightarrow X_{max} + \Delta X_{max}$$

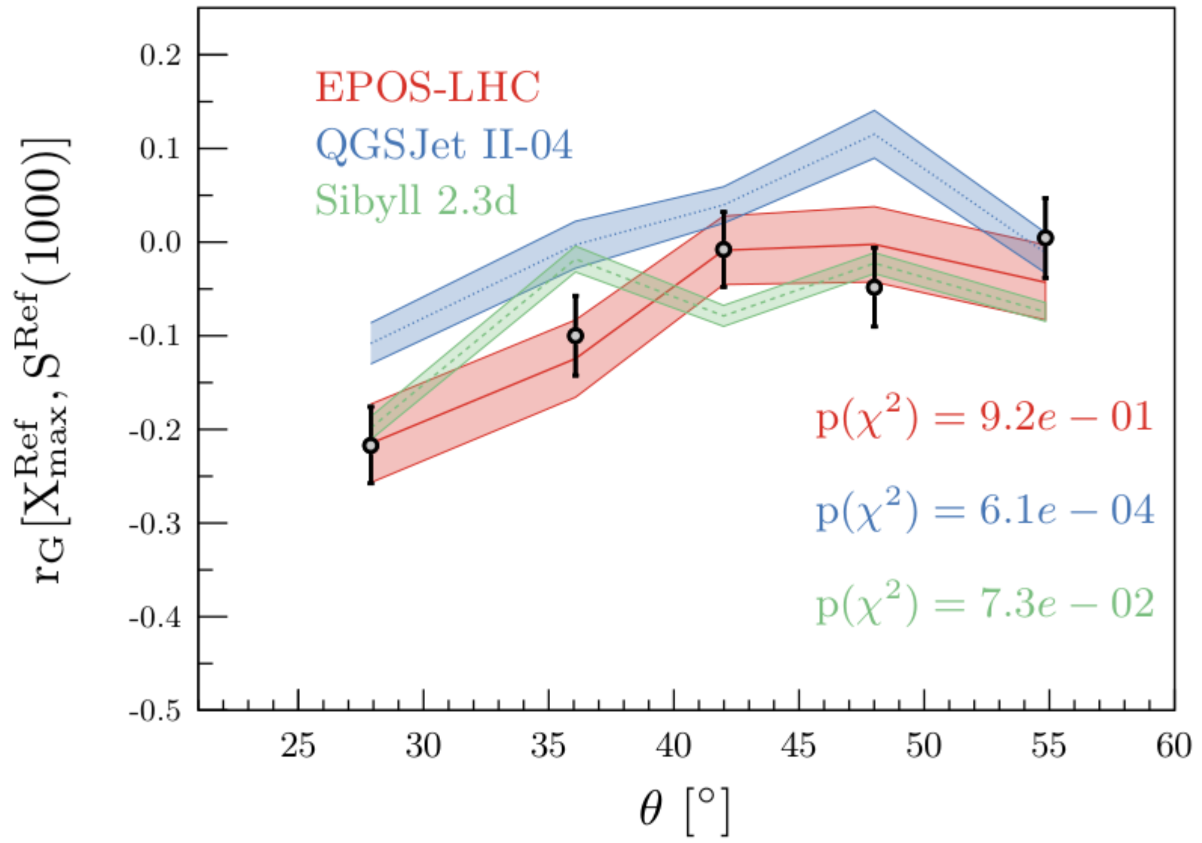
$$S_{Had}(\theta) \rightarrow S_{Had}(\theta) \cdot R_{Had}$$

New !

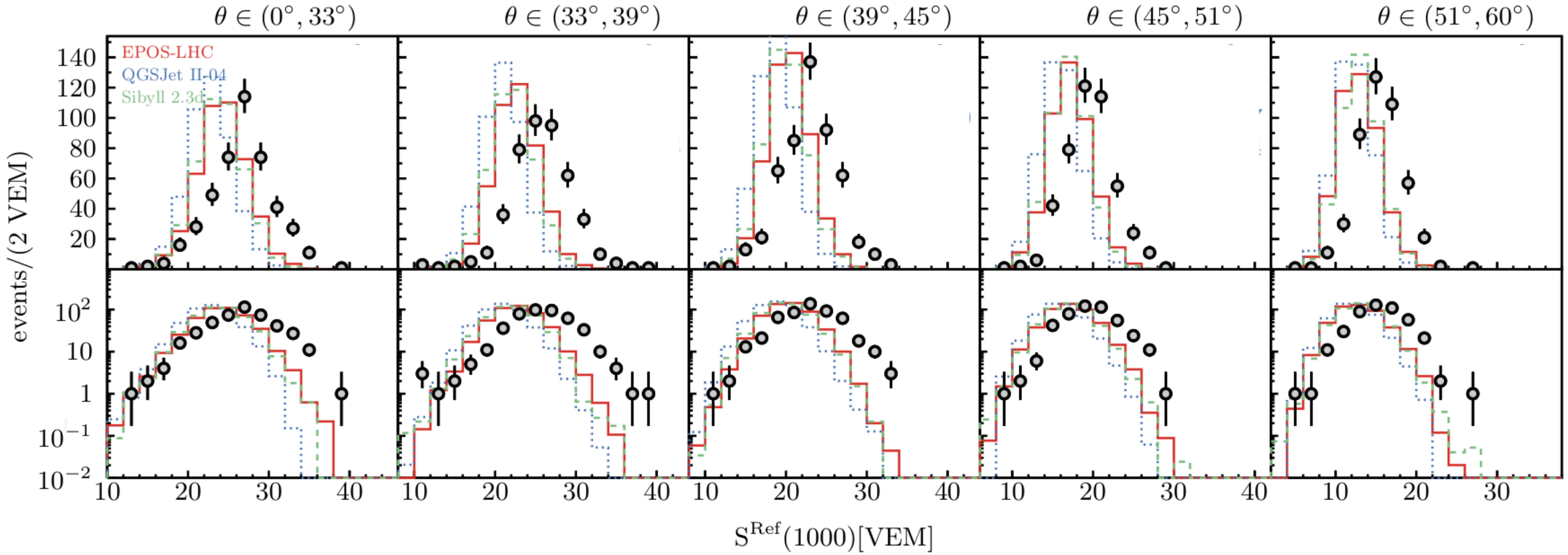
(Auger, PRD 109 (2024) 102001)

Test: 2D fit without any adjustments



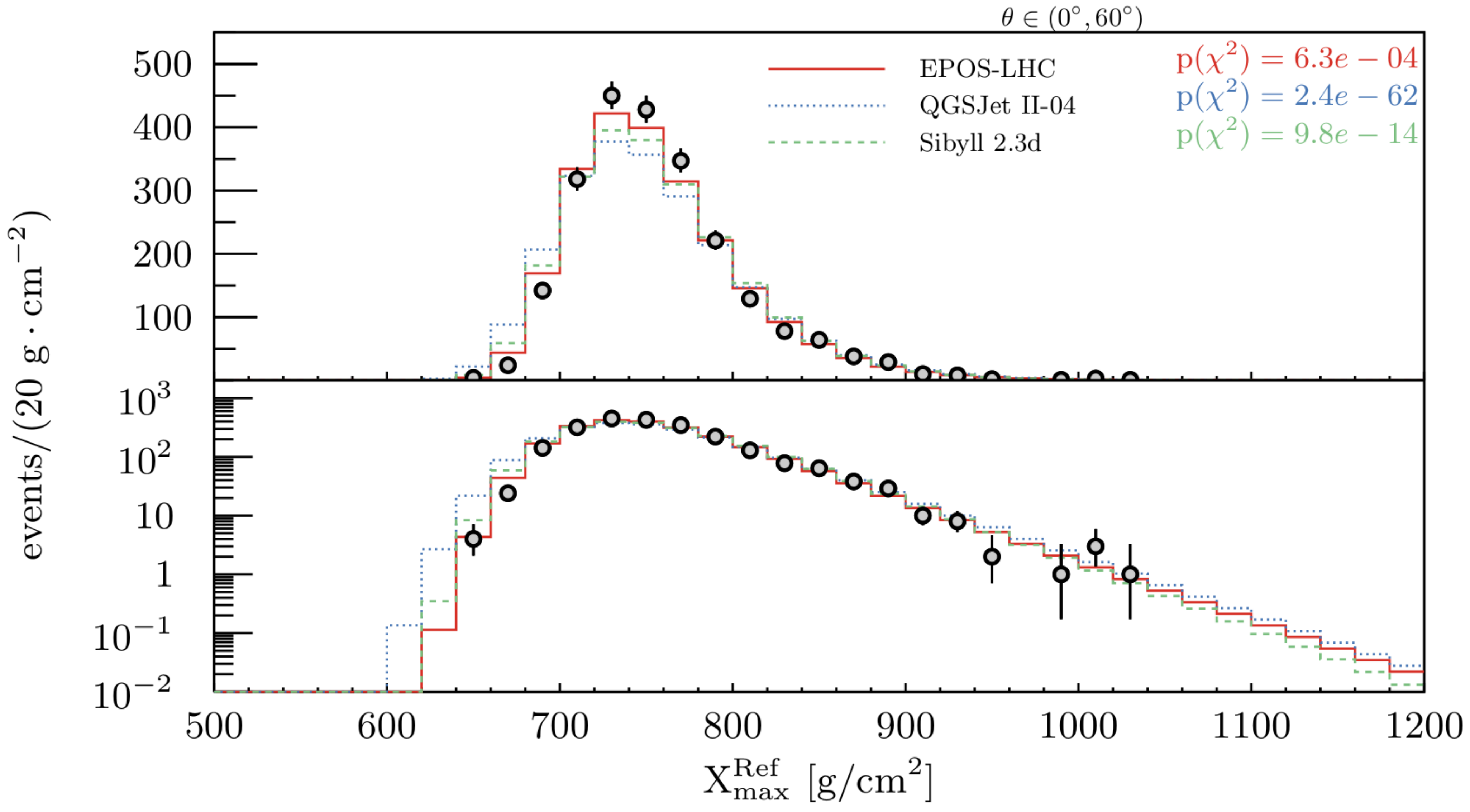


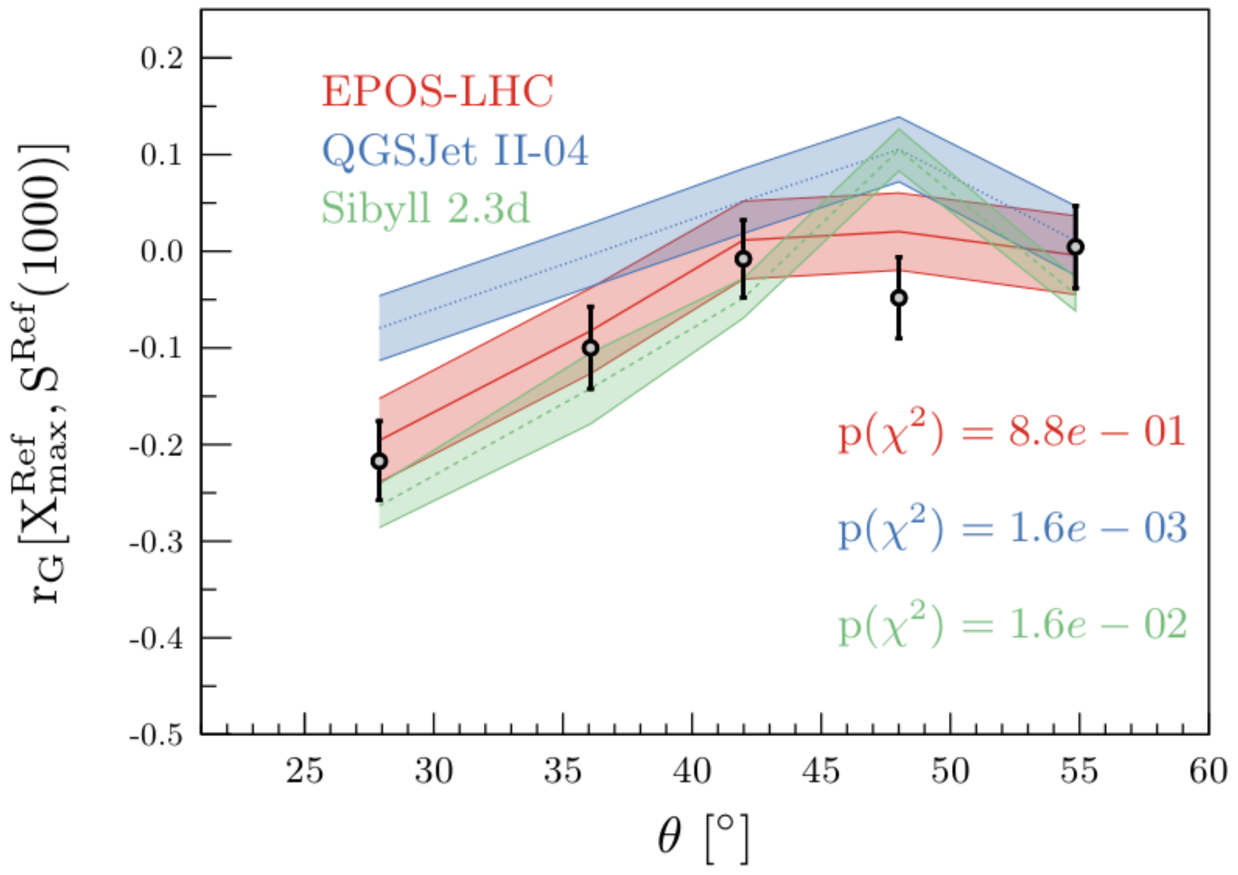
Gideon-Hollister correlation coeficient
[J. Am. Stat. Assoc. 82 (1987) 656]

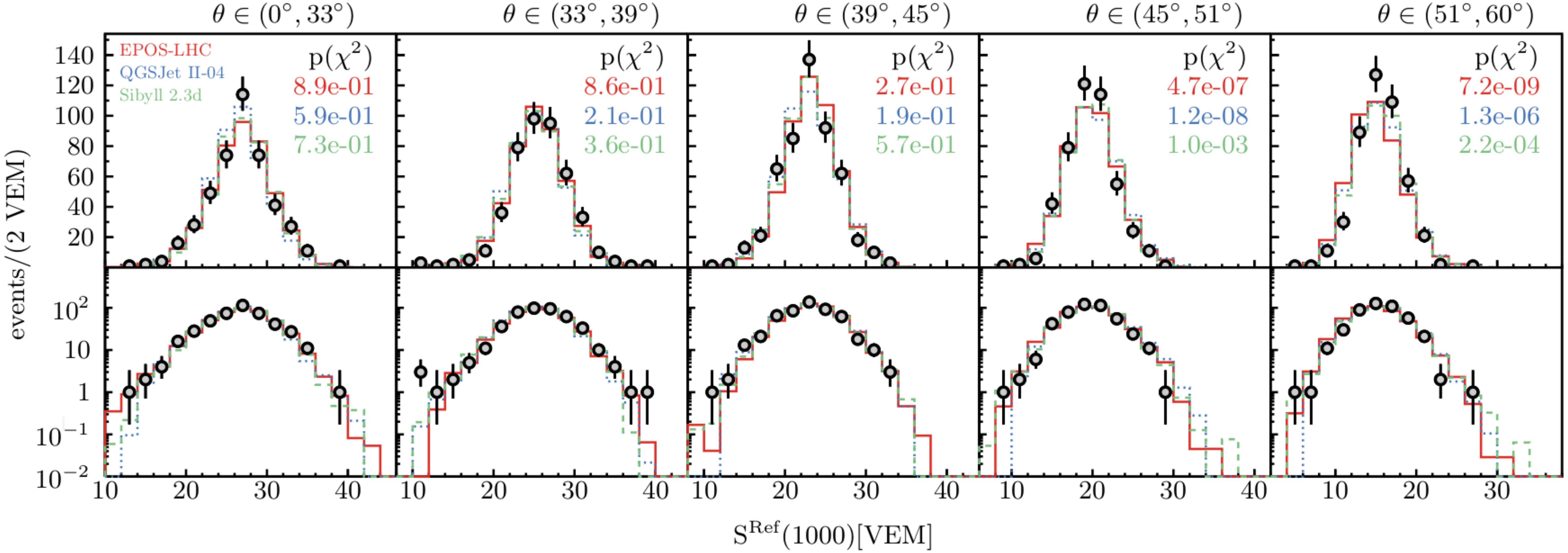


(Auger, PRD 109 (2024) 102001)

Test: 2D fit with rescaling hadronic component

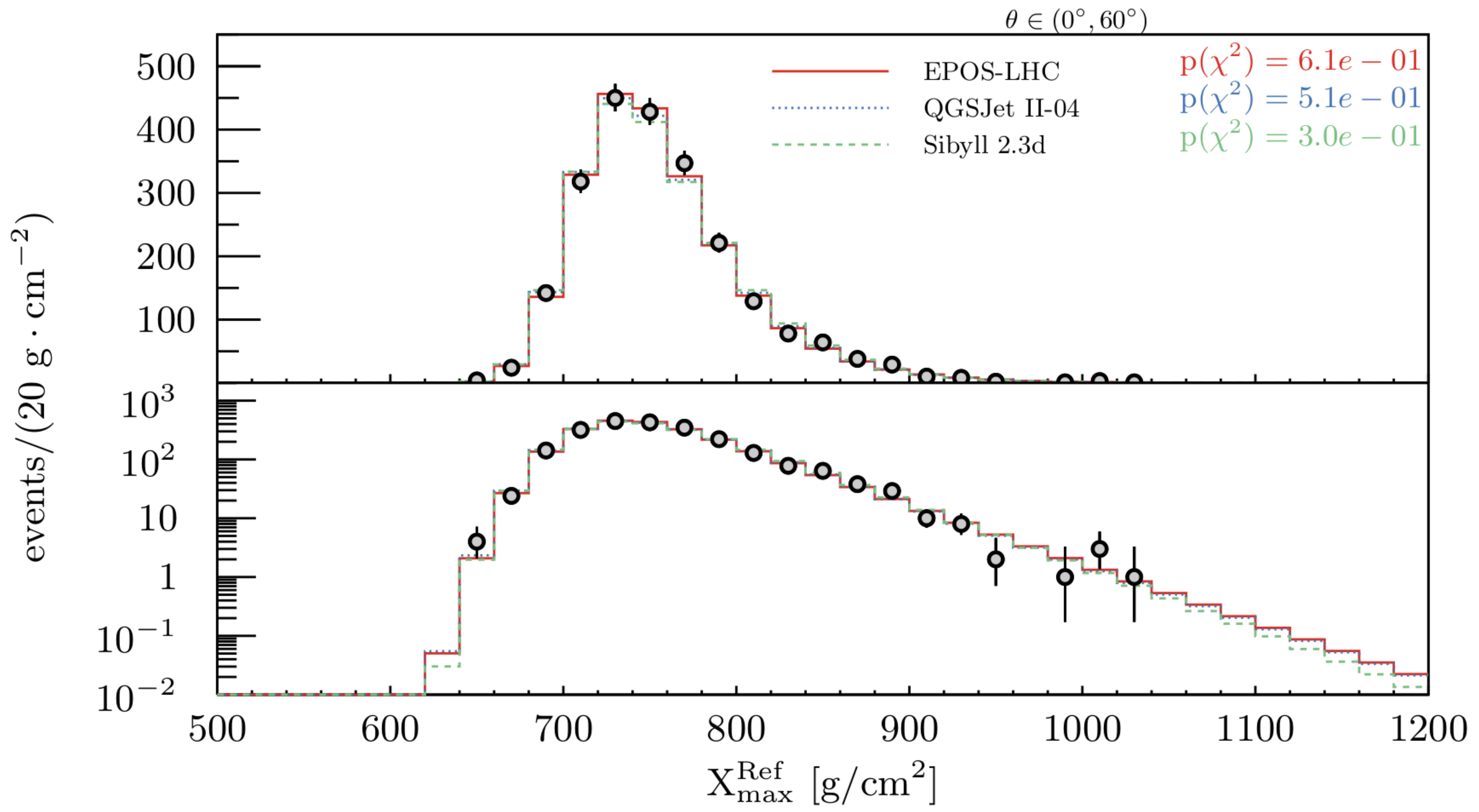


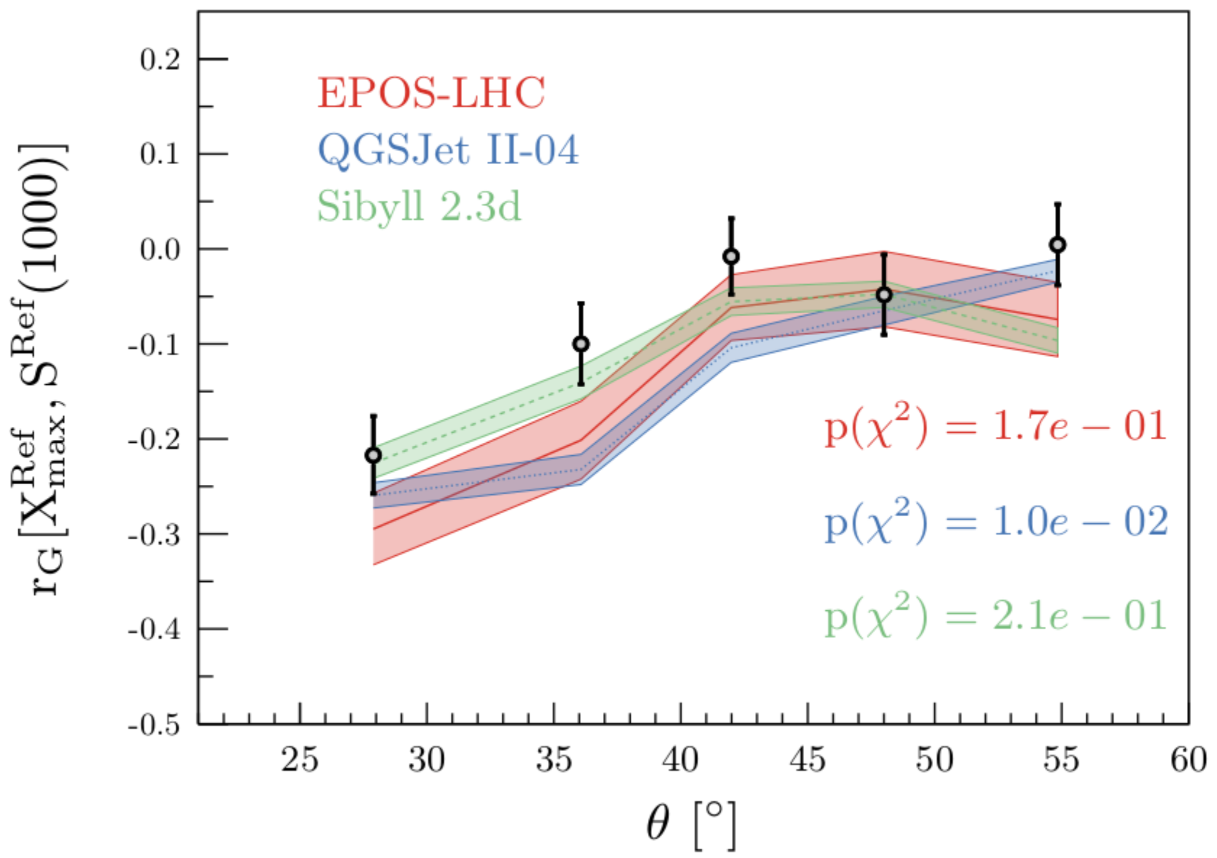


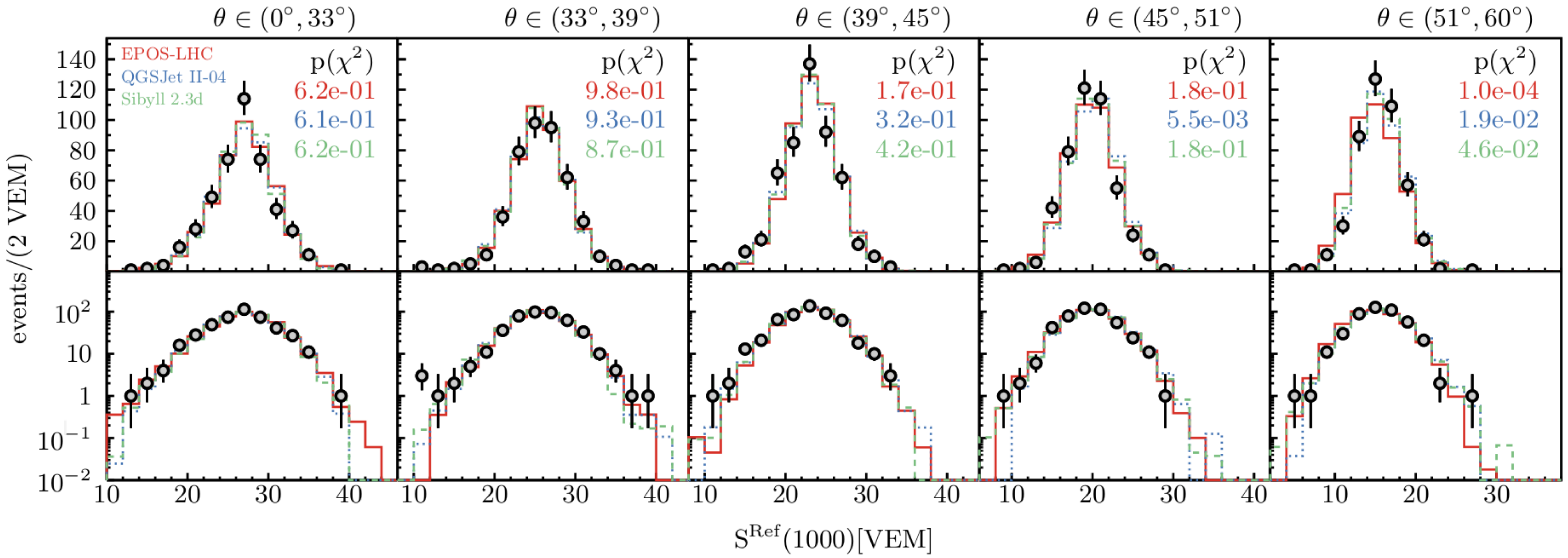


(Auger, PRD 109 (2024) 102001)

Test: 2D fit with rescaling had. component and shifting Xmax

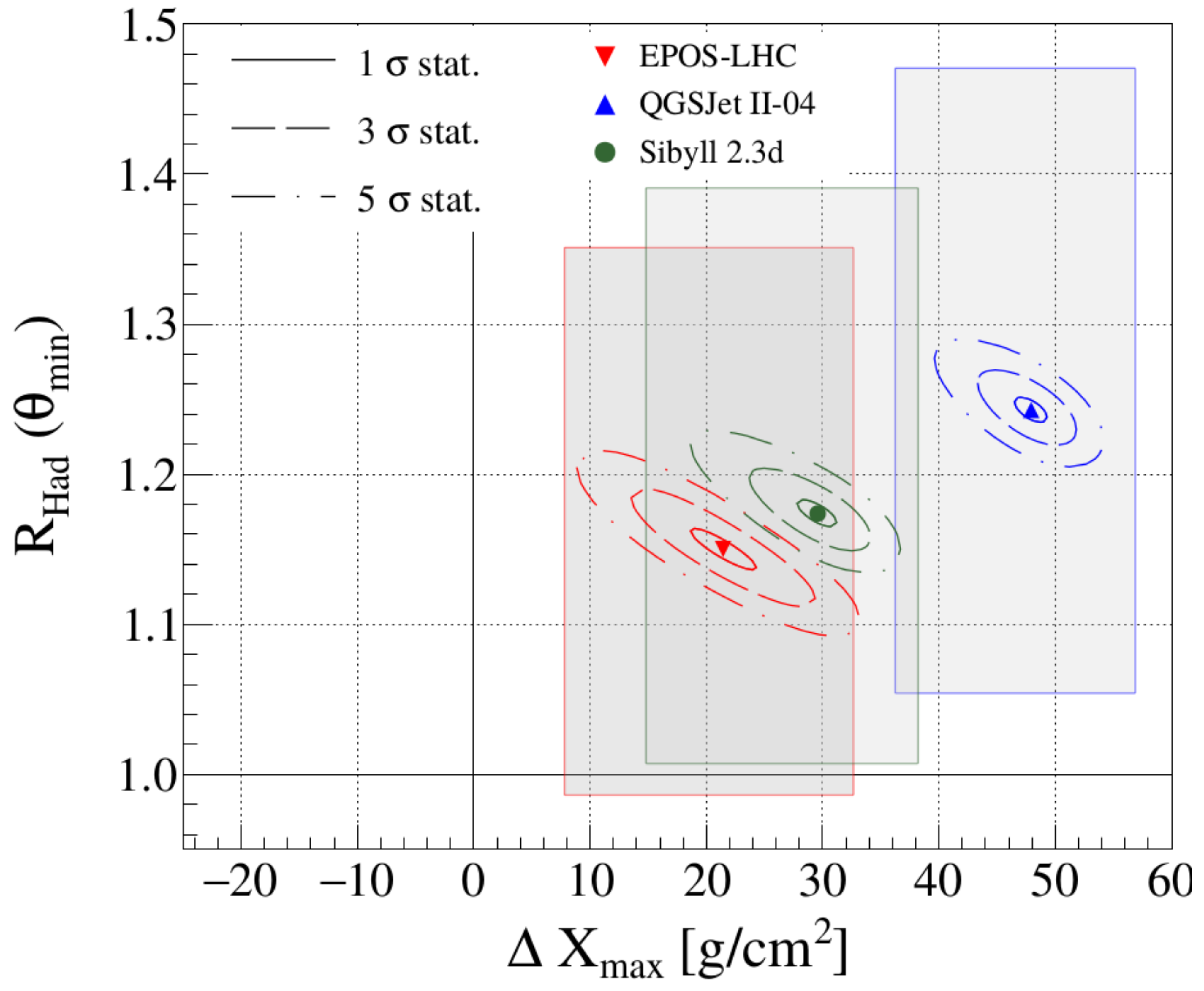


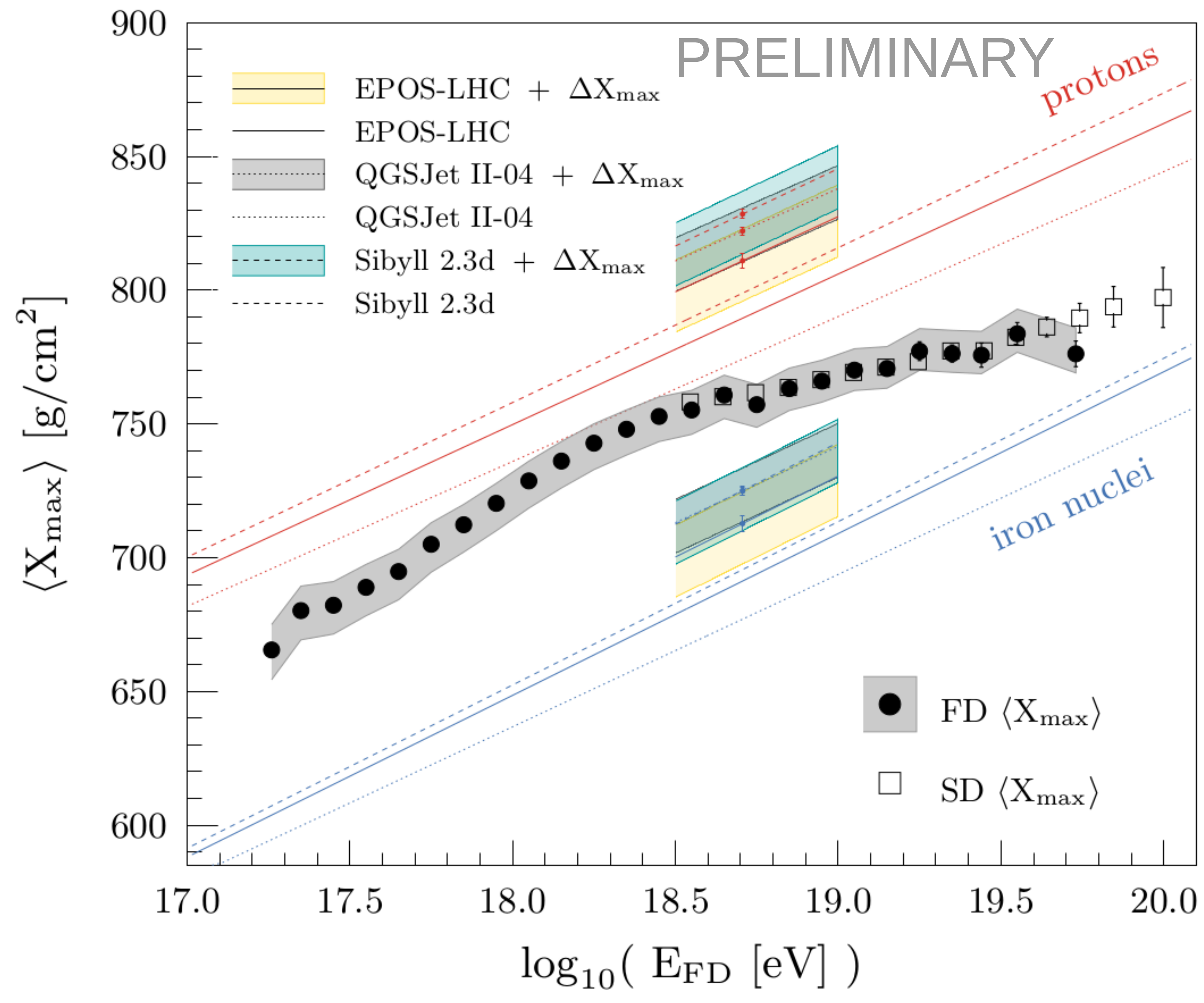




(Auger, PRD 109 (2024) 102001)

Test: modification of hadronic interaction models (ii)





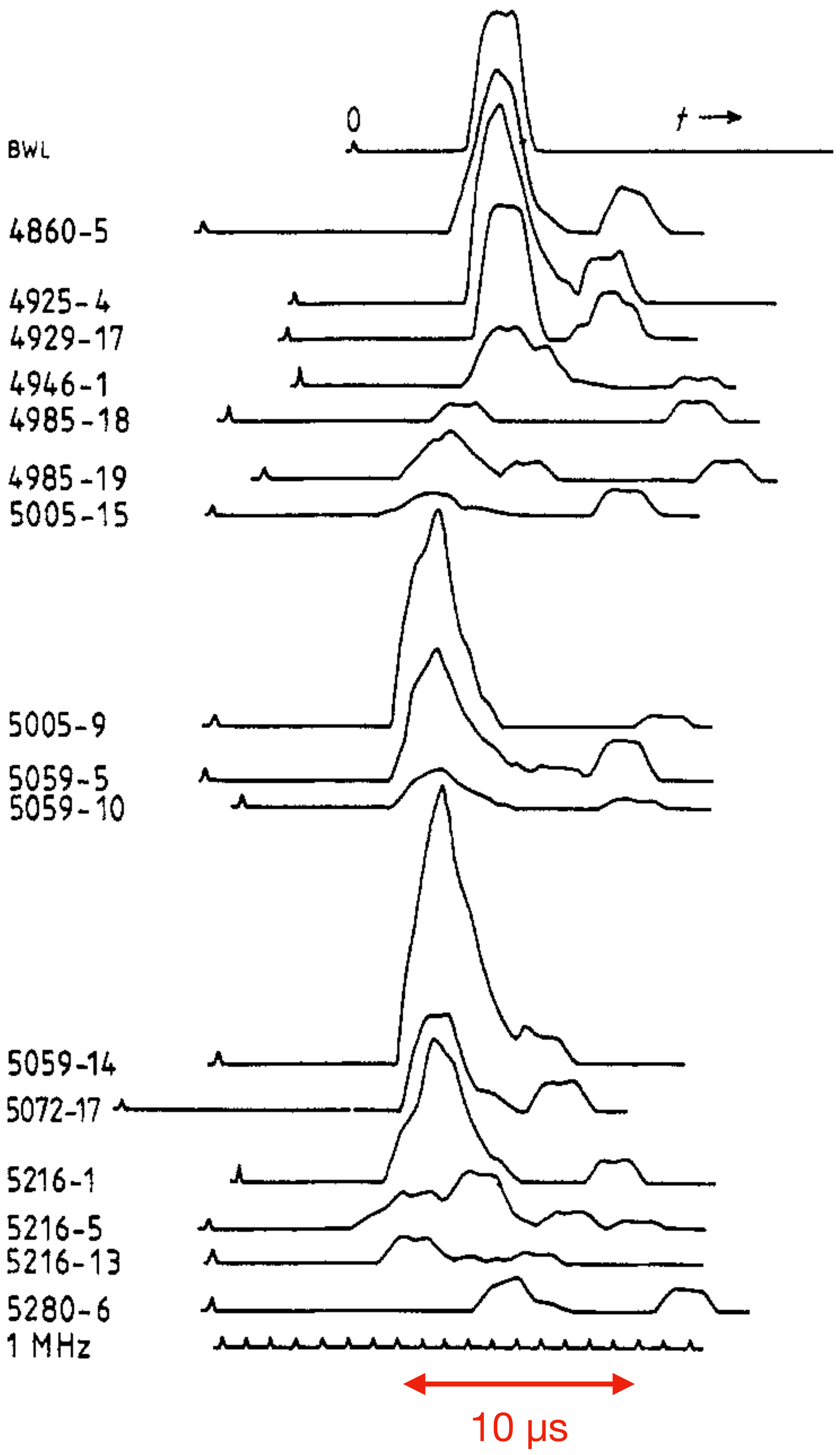
(Auger, PRD 109 (2024) 102001)

Assumption: relative fluctuations not changed

Main improvement by re-scaling muon component (attenuation, more muons at ground)

Further improvement by shifting Xmax of models to larger depth (heavier composition)

Motivation for looking for neutrons



Vulcano Ranch (1962-63)

J. Linsley
(J. Phys. G: Nucl. Phys. 10 (1984) L191)

- Sub-luminal pulses with a delay of at least 3μs
- Sometimes several pulses observed
- Typically 1 km from core, high-energy showers
- Greisen: **neutrons** as sub-luminal particles

Note by A.M. Hillas (1982)

scattered particles. The most likely cause of the pulses seems therefore to be heavily-ionizing protons generated by neutrons of 30 - 200 MeV which have performed a random walk from the central region of the shower. The neutrons are non-relativistic and suffer large-angle scattering by interactions with nuclei. (Non-relativistic muons do not deposit enough energy in a scintillator before stopping, and are not scattered so much in the last kilometre or so.) Large numbers of sub-GeV neutrons and protons are produced as recoils from the interactions of hadrons with nuclei (and also to a non-negligible extent from interactions of photons with nuclei). The number of such nucleons should be nearly proportional to shower primary energy, but if the pulses are due to individual particles, one would not expect smaller showers to show the subluminal particles as smaller-amplitude pulses, but rather to show the same large pulses though much less often. Water-Cerenkov detectors are not expected to detect these particles to any appreciable extent.

Today: Extensive literature on dedicated neutron measurements (e.g. Stenkin and others)

Comparison of expectations for muons and neutrons

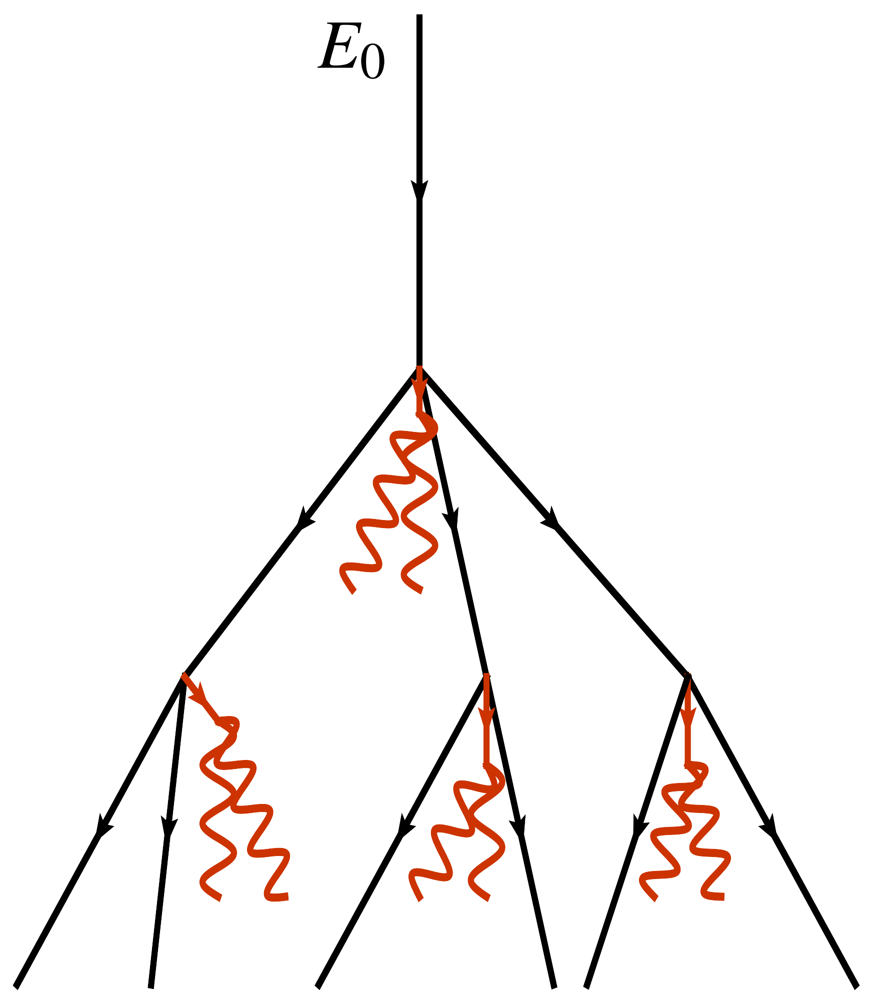
Multiplicity of charged pions

$N_{\pi^\pm,1} = n_{ch}$

$N_{\pi^\pm,2} = (n_{ch})^2$

⋮

$N_{\pi^\pm,k} = (n_{ch})^k$



$$\beta = \frac{\ln n_{ch}}{\ln n_{tot}} \sim 0.9$$

(Matthews, APP22, 2005)

(Superposition model)

$$N_\mu = \left(\frac{E_0}{E_{dec}}\right)^\beta$$

$$N_\mu^A \sim A^{1-\beta} N_\mu \sim 1.4\, N_\mu$$

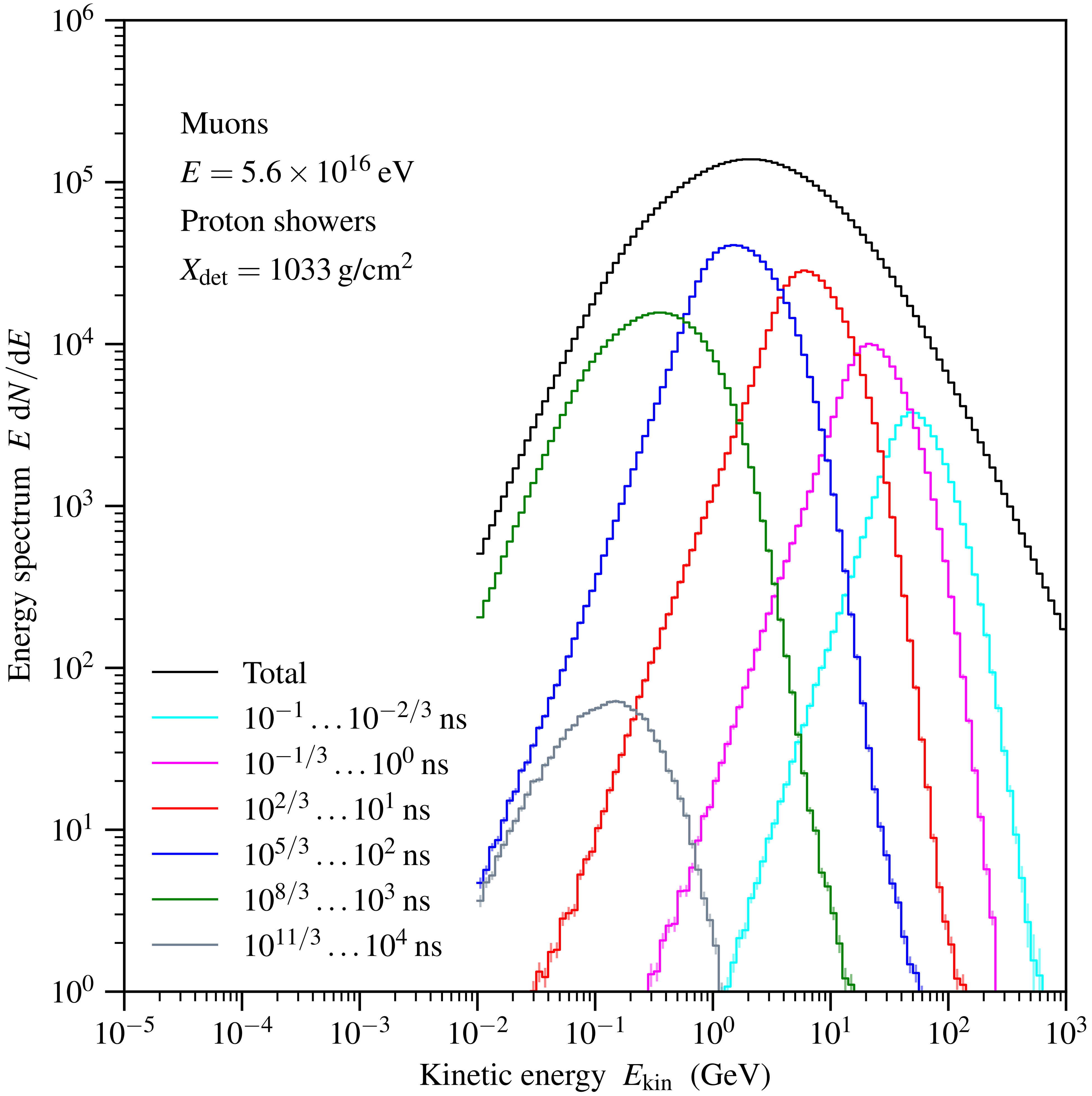
Muons

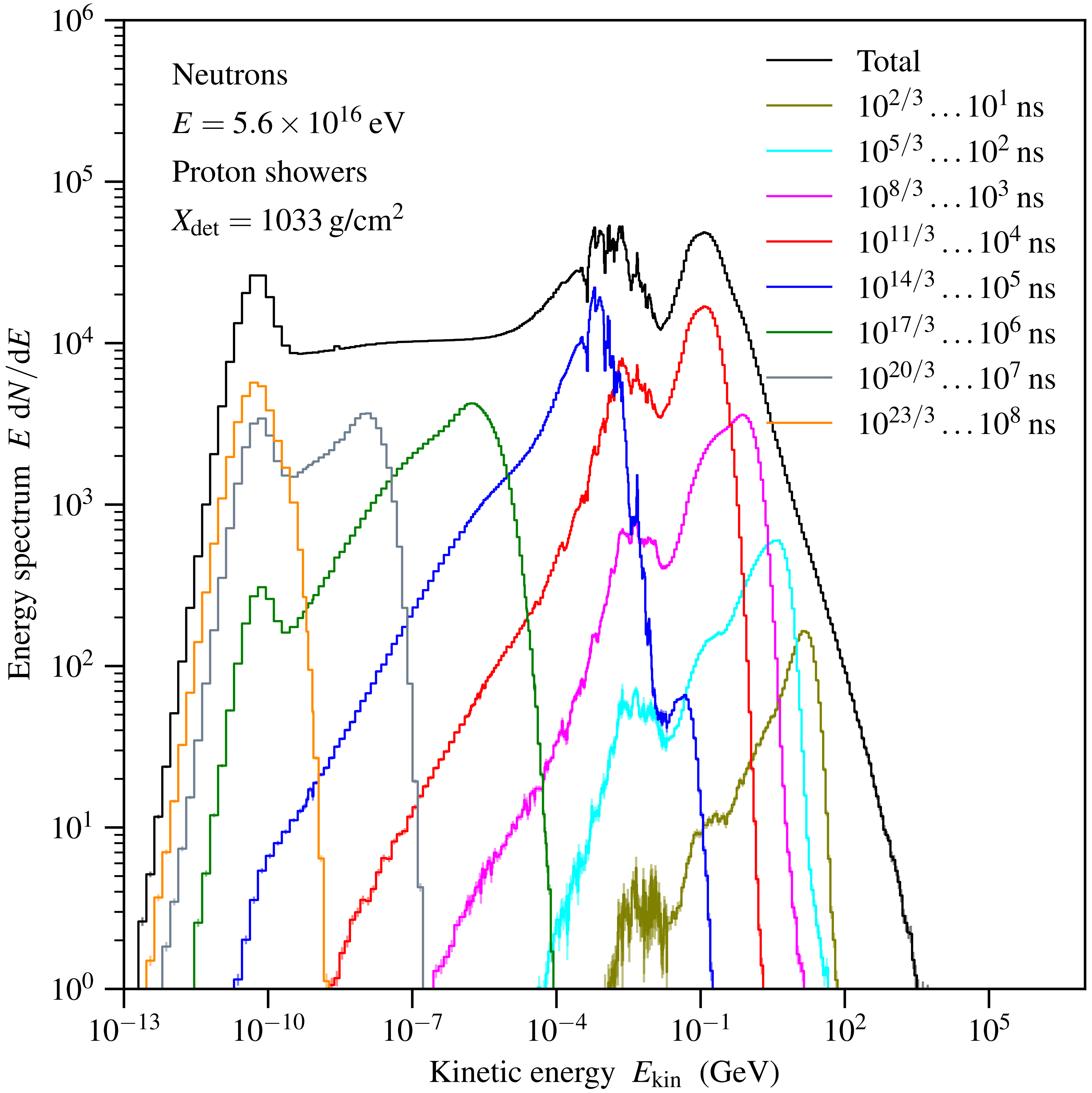
- Mainly produced in hadronic interactions through decay of charged pions and kaons
- Small energy loss, large attenuation length (~1000 g/cm²)
- Directional information approx. preserved
- Arrive early at ground (less multiple scattering than em. particles)

Neutrons

- High energy: mainly produced in hadronic interactions, baryon-antibaryon pair production
- Low-energy: photo-dissociation of air nuclei
- Energy loss due to elastic scattering, attenuation length (~100 - 150 g/cm²)
- Directional information lost, wide lateral distribution
- Bulk of neutrons arrives late with very long time delay (neutron cloud / thunder)

Air shower results: time delay distribution

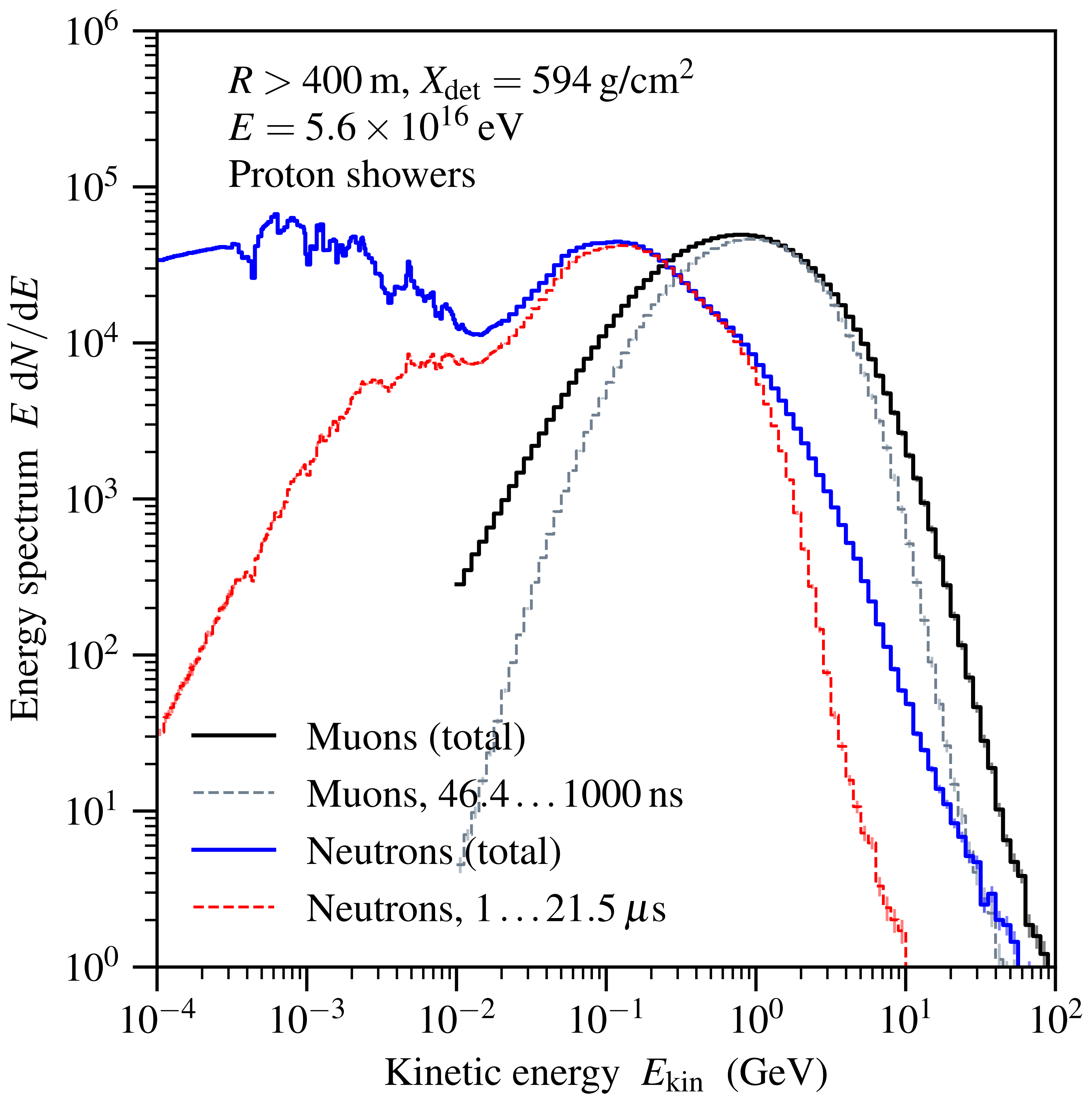


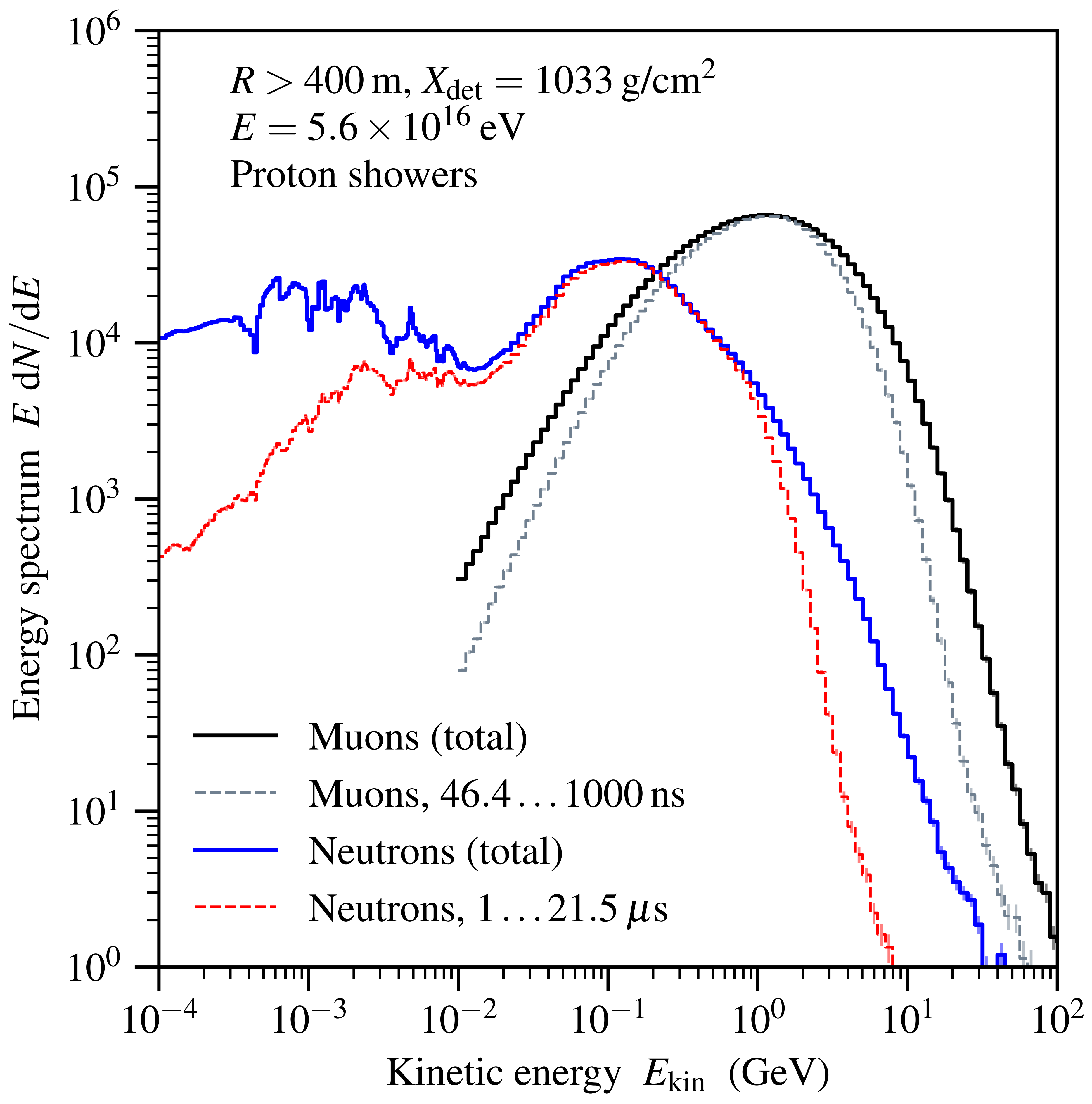


Muons: time delay of bulk of particles: 1 - 500 ns

Neutrons: time delay of high-energy particles: 1 - 20 μs, slow (thermal) neutrons up to 100 ms

Air shower results: muons vs. neutrons at large distance





Close to shower maximum: neutrons as abundant as muons

Past shower maximum: neutrons much less abundant than muons

Neutron expectations *(see 2406.11702 for details)*

Neutrons

- Interesting sub-luminal particles
- Feature-rich and very wide energy spectrum
- Notoriously difficult to detect
- Very difficult to simulate accurately (environment)
- Expected to produce late pulses in scintillators

Scaling observations

- Production ~50% hadronic, ~50% electromagnetic. dissociation
- Hadronic production scales similar to muons
- Electomag. production scales linearly with energy
- Attenuation (neutron removal) length 80 … 200 g/cm^2
- Very wide lateral distribution, wider than muons
- Typical delay in arrival time ~ 1 … 20 μs (E_{kin} > 20 MeV)
- Thermal neutrons up to ~ 100 ms

First very rough estimate of detection probabilities (%)

Neutron Energy (MeV)	Scintillator Threshold (100 e-keV)	Water Threshold (1/300 VEM)	Water Threshold (1/100 VEM)
0.0001	2.3×10^{-2}	13.7	$<10^{-3}$
0.001	1.0×10^{-2}	13.7	$<10^{-3}$
0.01	4.2×10^{-3}	13.7	$<10^{-3}$
0.1	1.3×10^{-3}	15.0	$<10^{-3}$
0.5	$<10^{-3}$	18.5	$<10^{-3}$
0.7	4.65	20.1	$<10^{-3}$
1	14.7	16.9	$<10^{-3}$
2	17.1	25.1	$<10^{-3}$
3	15.5	28.0	$<10^{-3}$
5	12.4	29.0	4×10^{-3}
10	9.78	41.3	11.1
20	7.67	49.2	19.1
30	6.46	53.2	22.8
50	4.47	58.6	30.3
100	2.87	61.8	37.5
200	2.30	63.9	44.4
500	2.31	75.3	52.3
1000	2.55	83.2	79.7