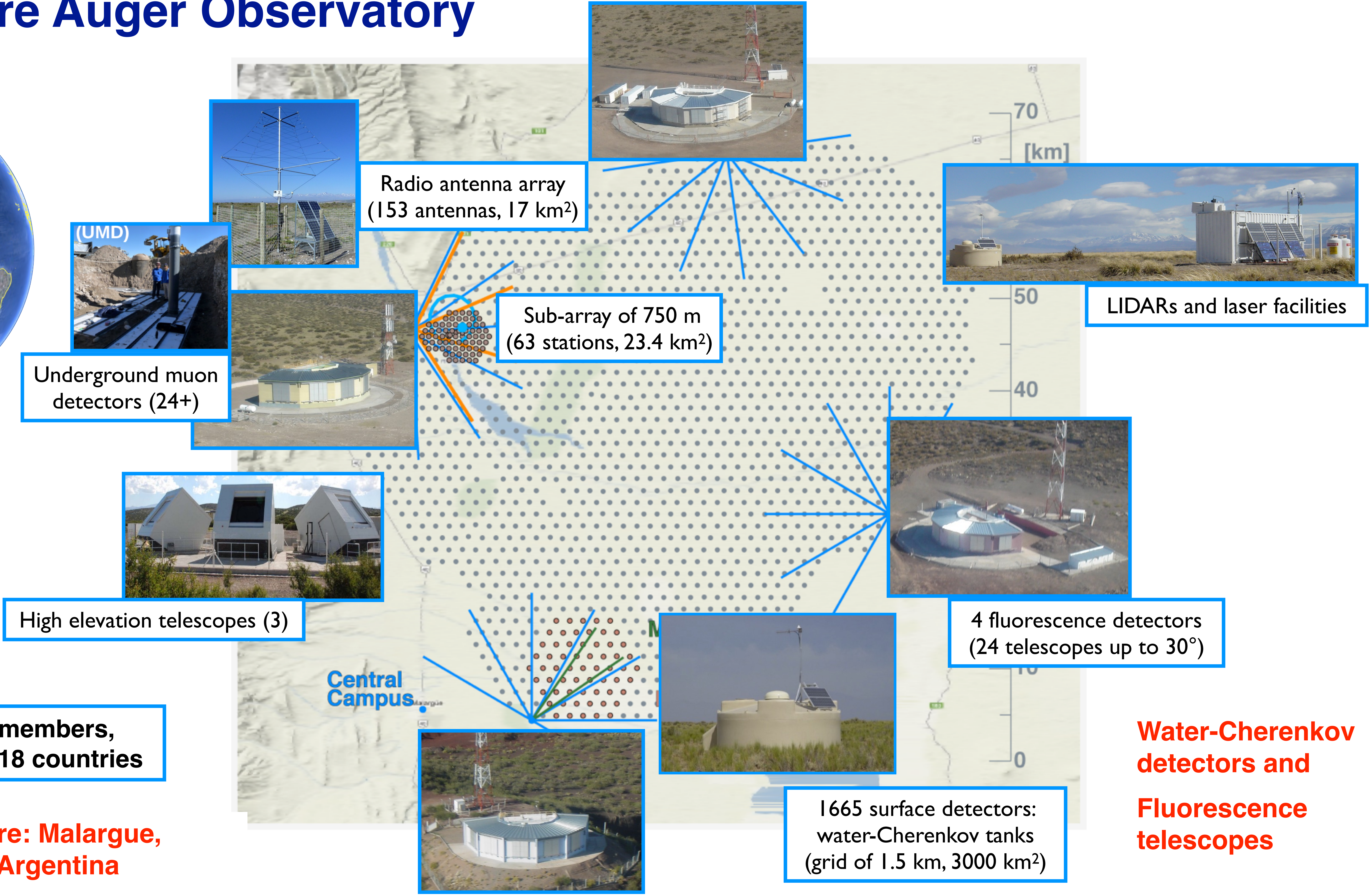
Selected Highlights of the Pierre Auger Observatory

Ralph Engel, for the Pierre Auger Collaboration

(picture curtesy S. Saffi)

The Pierre Auger Observatory

Pierre Auger Observatory
Province Mendoza, Argentina



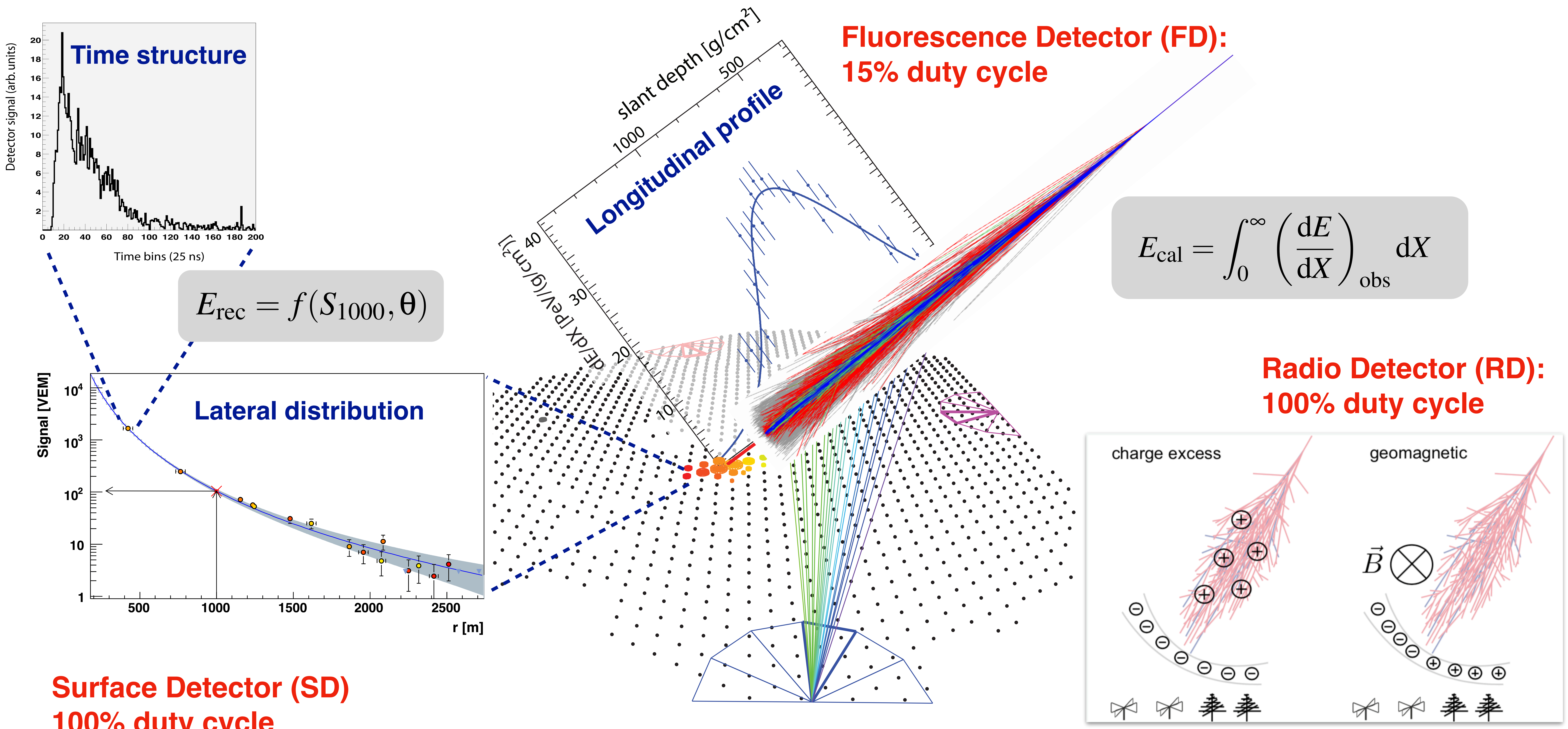
More than 400 members,
90+ institutes, 18 countries

Southern hemisphere: Malargue, Province Mendoza, Argentina

Water-Cherenkov detectors and

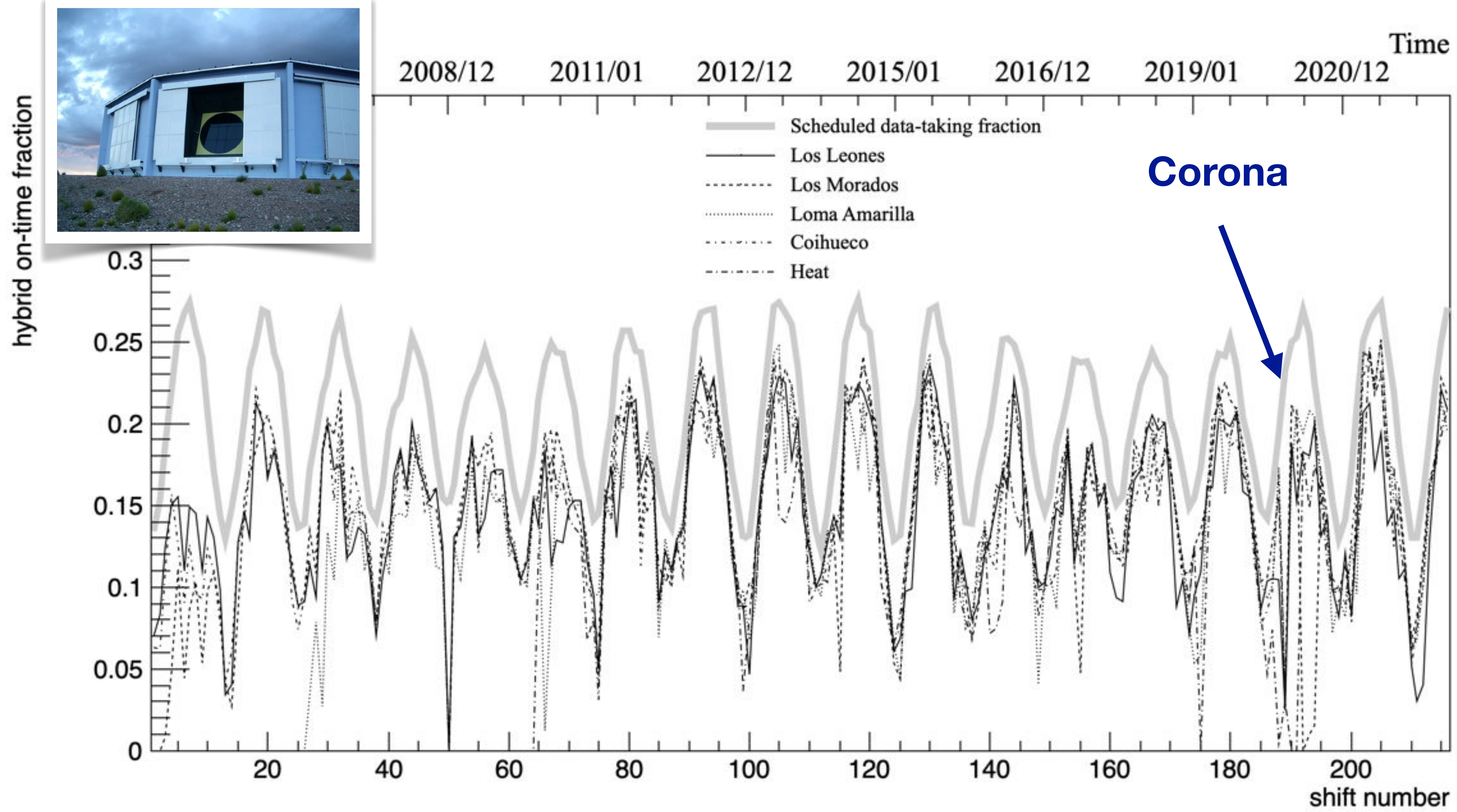
Fluorescence telescopes

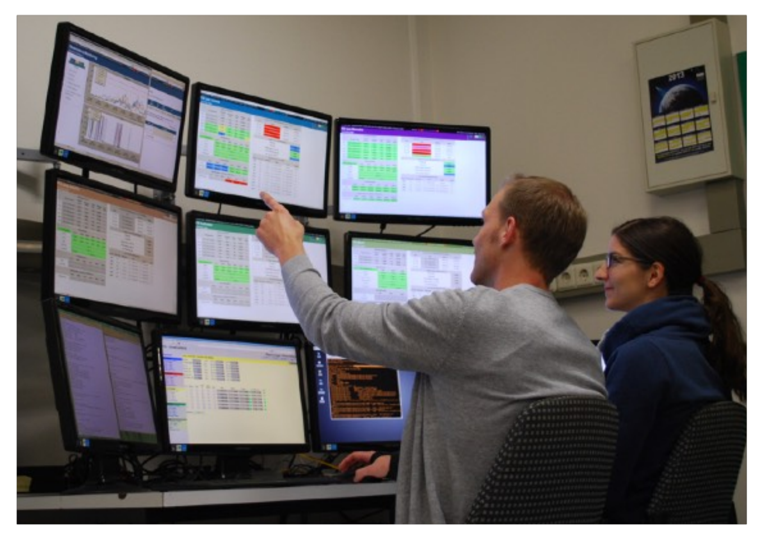
Air shower observables (hybrid observation)



Surface Detector (SD)
100% duty cycle

Phase I: more than 15 equivalent years of data



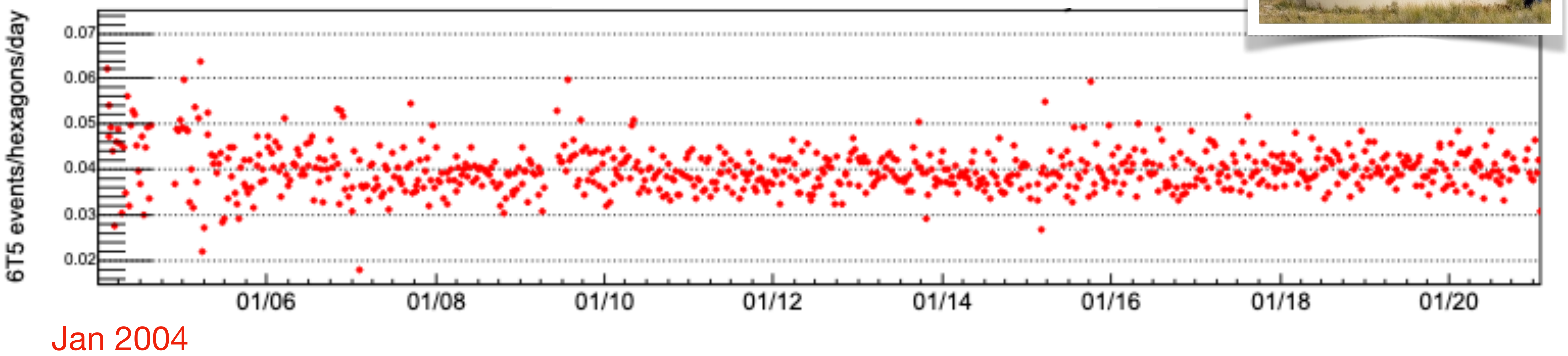


Remote control rooms

More than 215 shifts of 15-20 days each
Constant 85% of max. possible data taking time

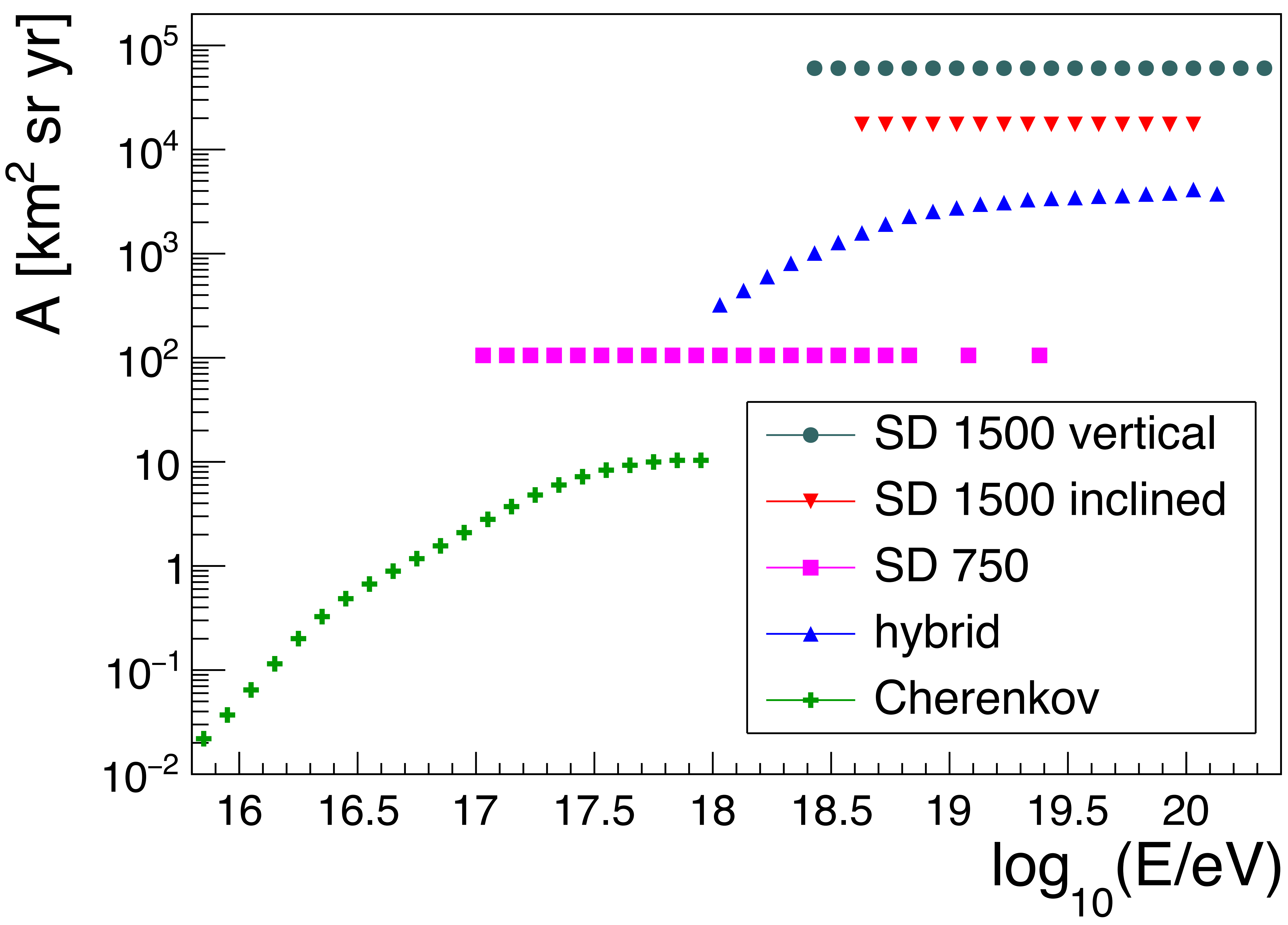
Staff in Malargue

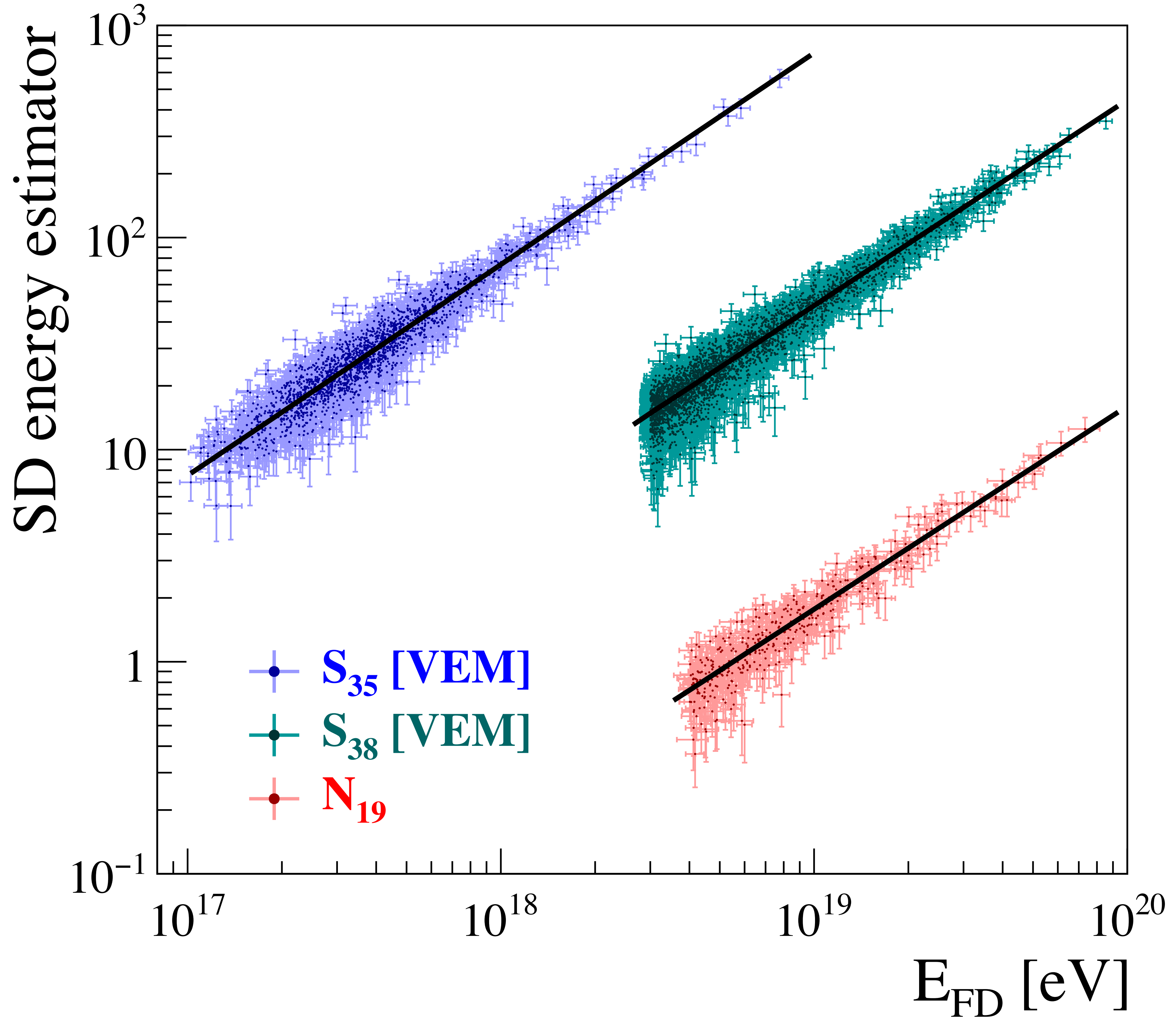
Array event rate E > $3x10^{18}$ eV



The Auger Collaboration in Malargue – November 2022

Exposure and calibration of Auger data sets





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

$$E_{\rm FD} = A S_{35}^B$$

E > 10^{17} eV
σ(E) : 25% - 10%

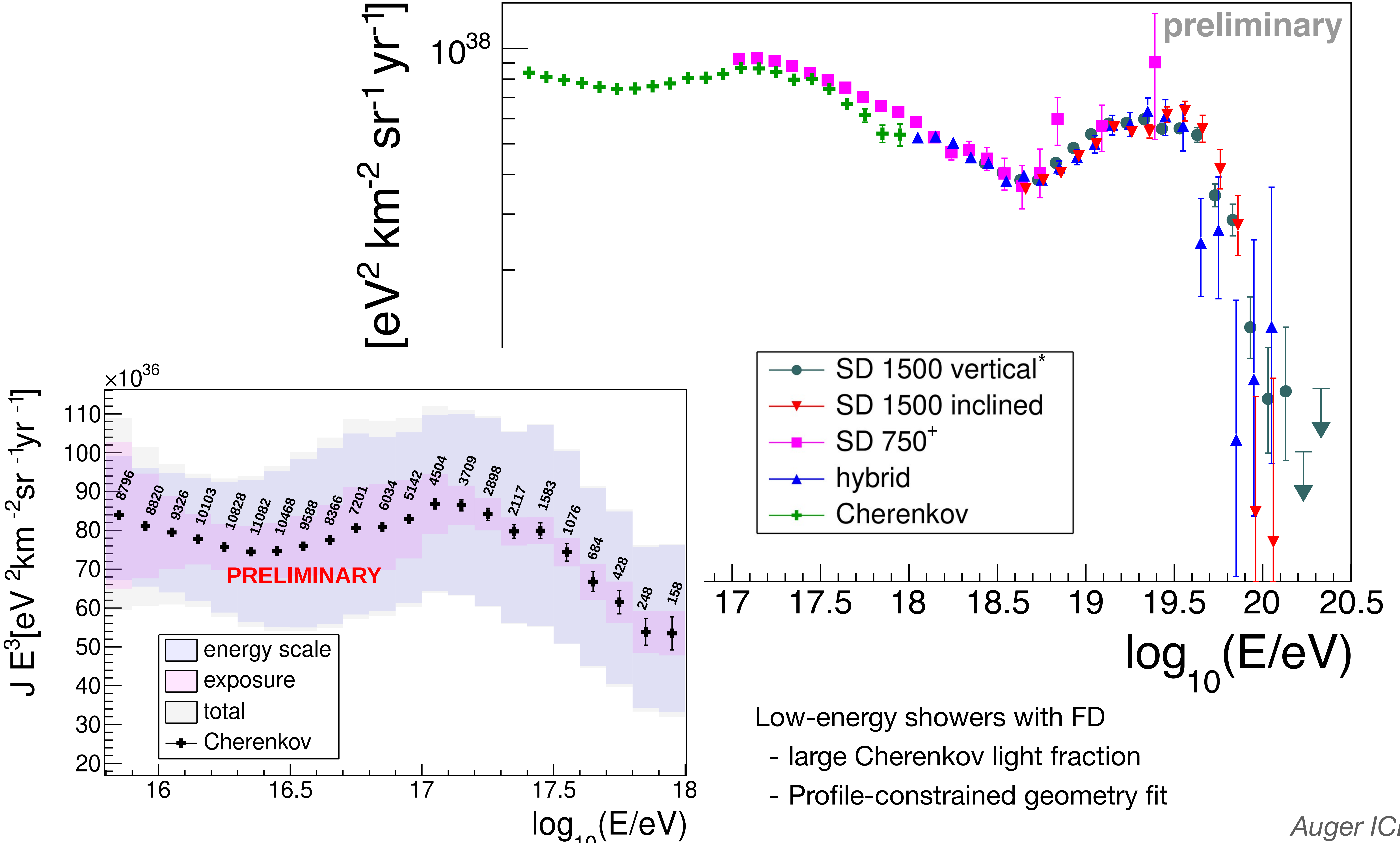
$$E_{\rm FD} = A S_{38}^B$$

E > $10^{18.4}$ eV
σ(E) : 22% - 7%

$$E_{\rm FD} = A N_{19}^B$$

E > $10^{18.6}$ eV
σ(E) ~ 19%

Individual and combined energy spectra



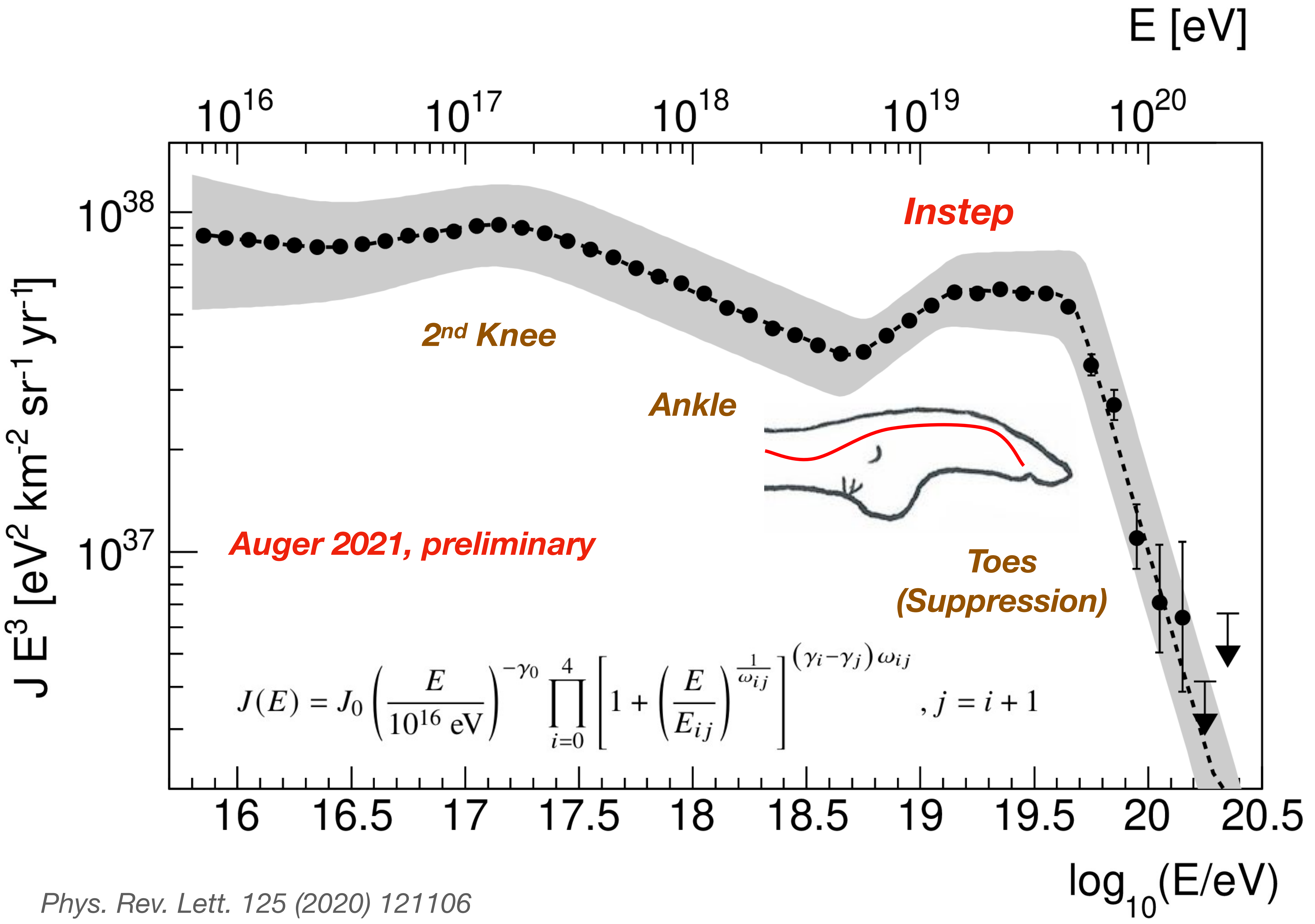
Normalisation shifts after combination of all spectra:

<1% SD-1500 m vertical
+5% SD-1500 m inclined
-2% SD-750 m
<1% Hybrid
+7% Cherenkov

Low-energy showers with FD
- large Cherenkov light fraction
- Profile-constrained geometry fit

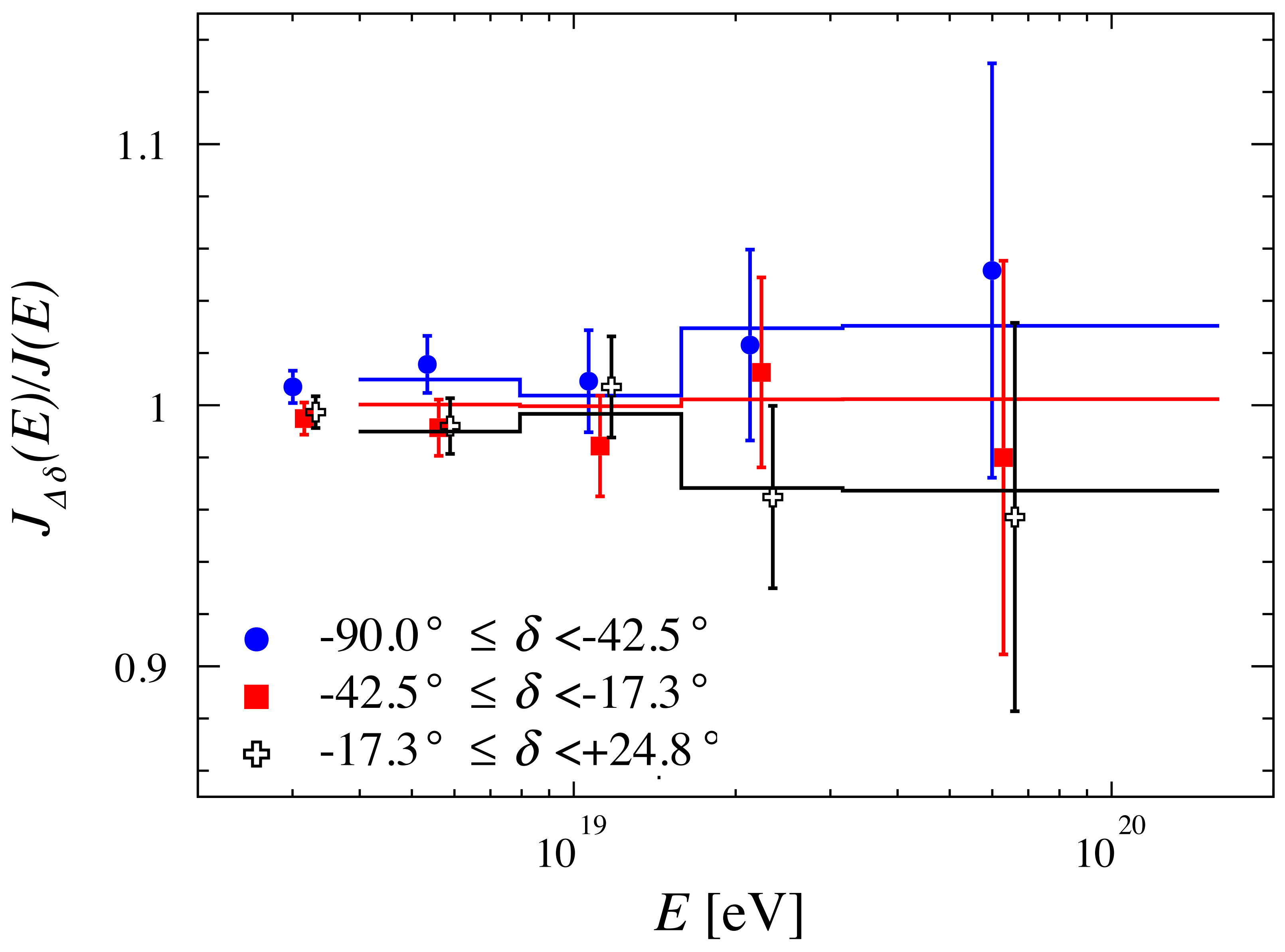
Auger ICRC 2021, PoS(ICRC2021)691

Energy spectrum (ii)



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

Declination dependence of spectrum



Lines: Expectation from observed dipole

Uncertainty dominated by 14% sys. energy scale

$\gamma_0 = 3.09 \pm 0.01 \pm 0.10$

$E_{01} = (2.8 \pm 0.3 \pm 0.4) \times 10^{16}$ eV

$\gamma_1 = 2.85 \pm 0.01 \pm 0.05$

$E_{12} = (1.58 \pm 0.05 \pm 0.2) \times 10^{17}$ eV

$\gamma_2 = 3.283 \pm 0.002 \pm 0.10$

$E_{23} = (5.0 \pm 0.1 \pm 0.8) \times 10^{18}$ eV

$\gamma_3 = 2.54 \pm 0.03 \pm 0.05$

$E_{34} = (1.4 \pm 0.1 \pm 0.2) \times 10^{19}$ eV

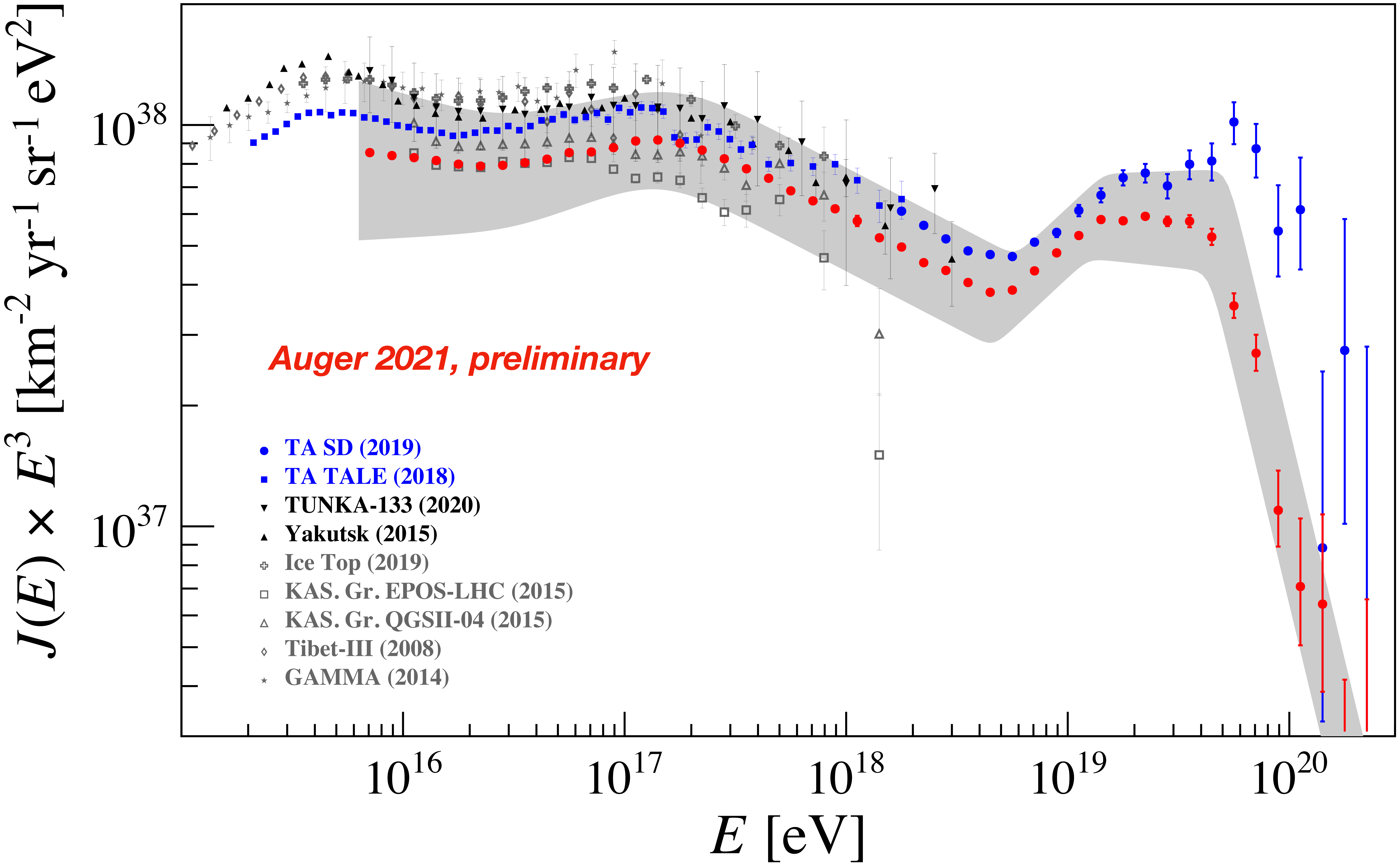
$\gamma_4 = 3.03 \pm 0.05 \pm 0.10$

$E_{45} = (4.7 \pm 0.3 \pm 0.6) \times 10^{19}$ eV

$\gamma_5 = 5.3 \pm 0.3 \pm 0.1$

$J_0 = (8.34 \pm 0.04 \pm 3.40) \times 10^{-11}$ km^{-2} sr^{-1} yr^{-1} eV^{-1}

Energy spectrum – comparison with other data



- Other experiments shown without sys. uncertainties
- Auger has smallest sys. uncertainty on energy scale (14%)

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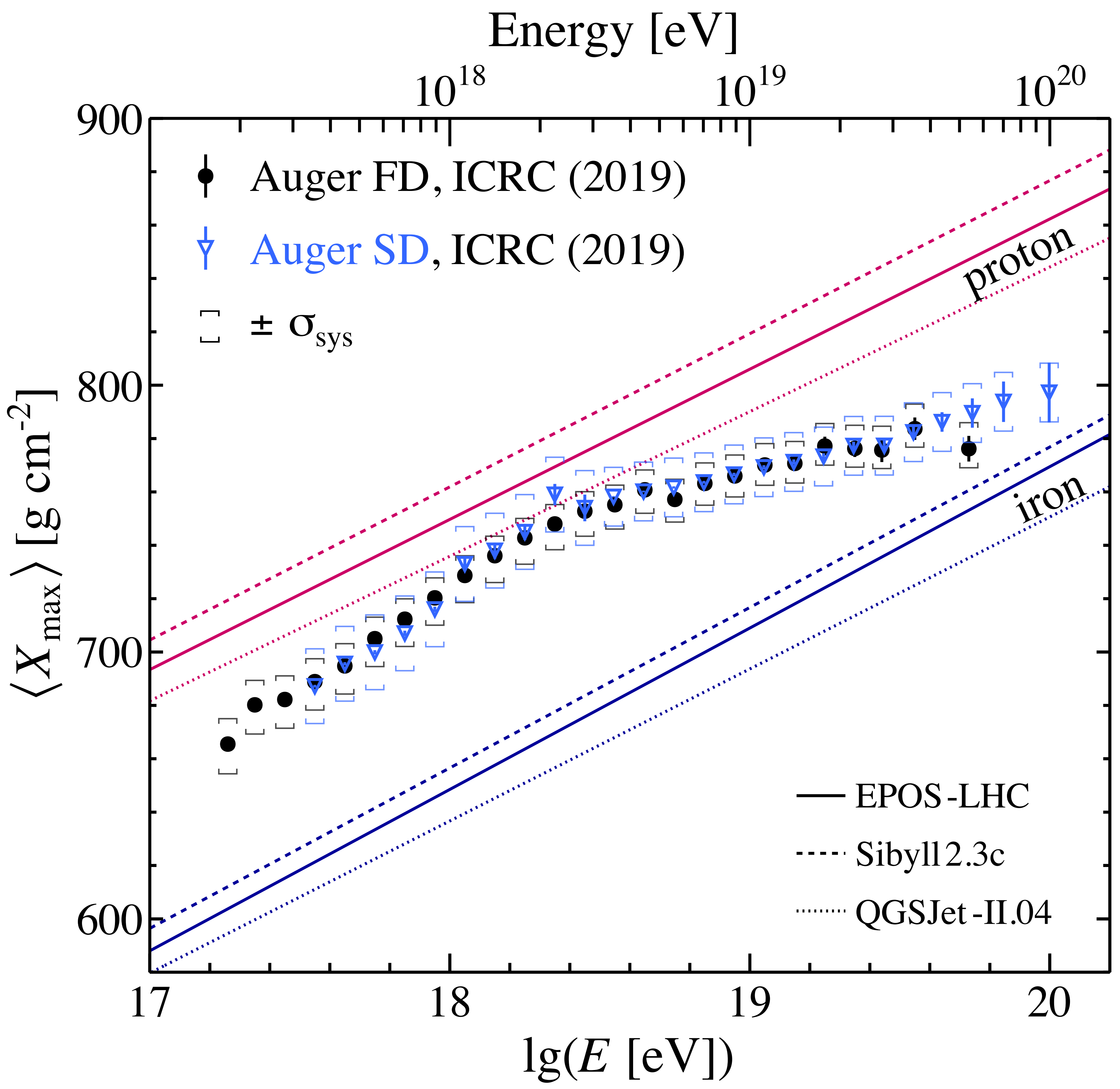
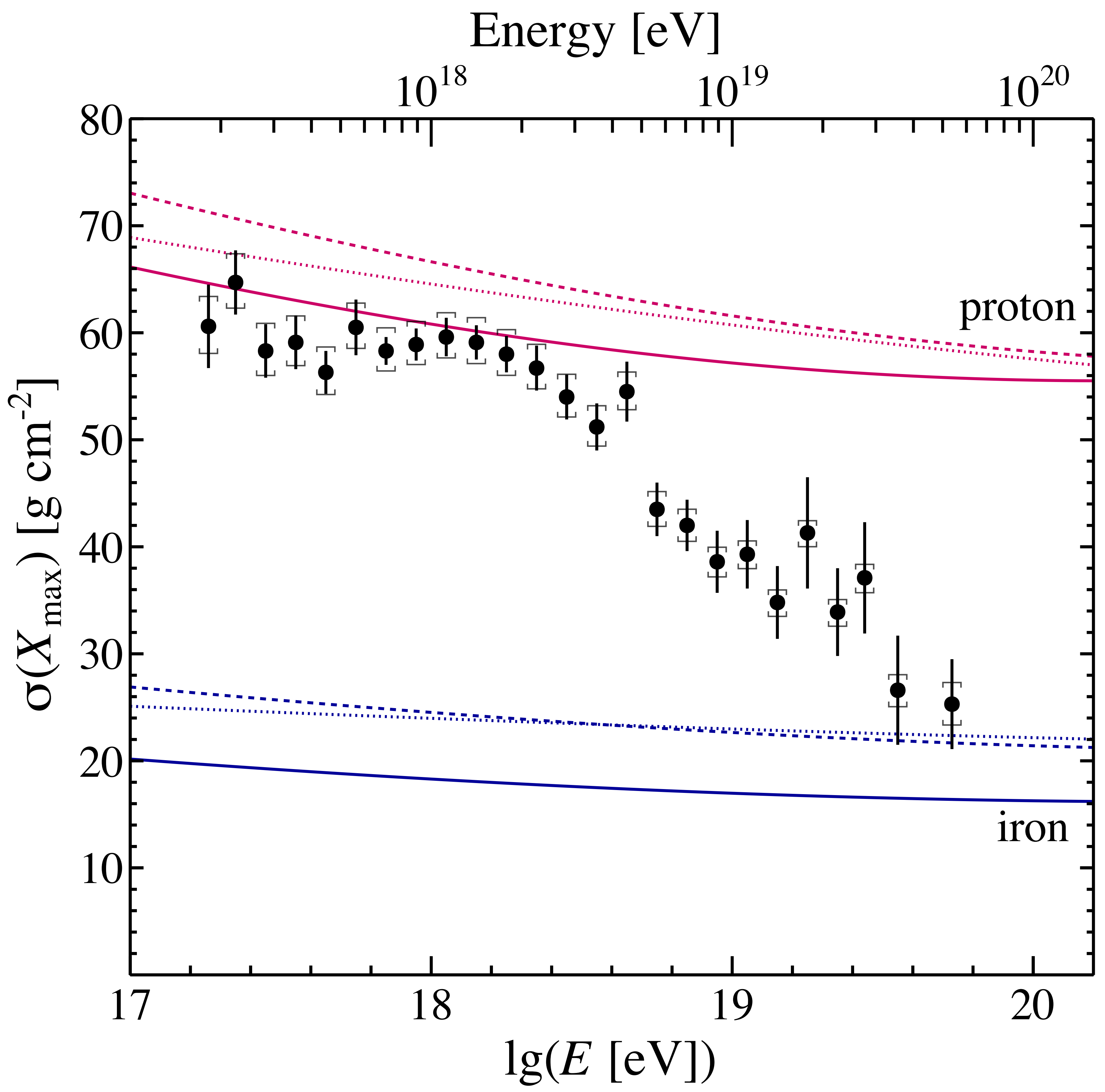
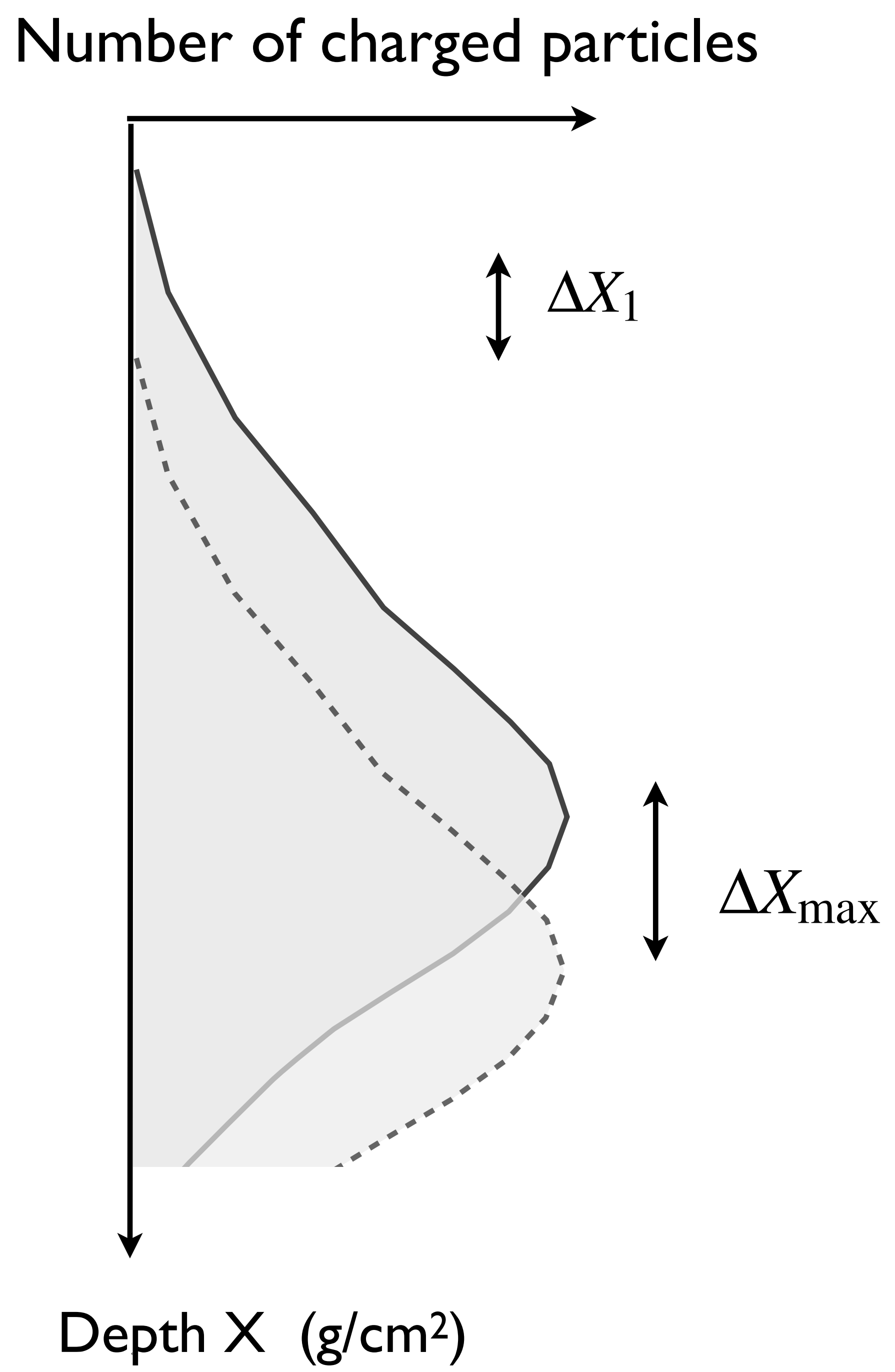
Mass composition results (i)







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

Important: LHC-tuned interaction models used for interpretation

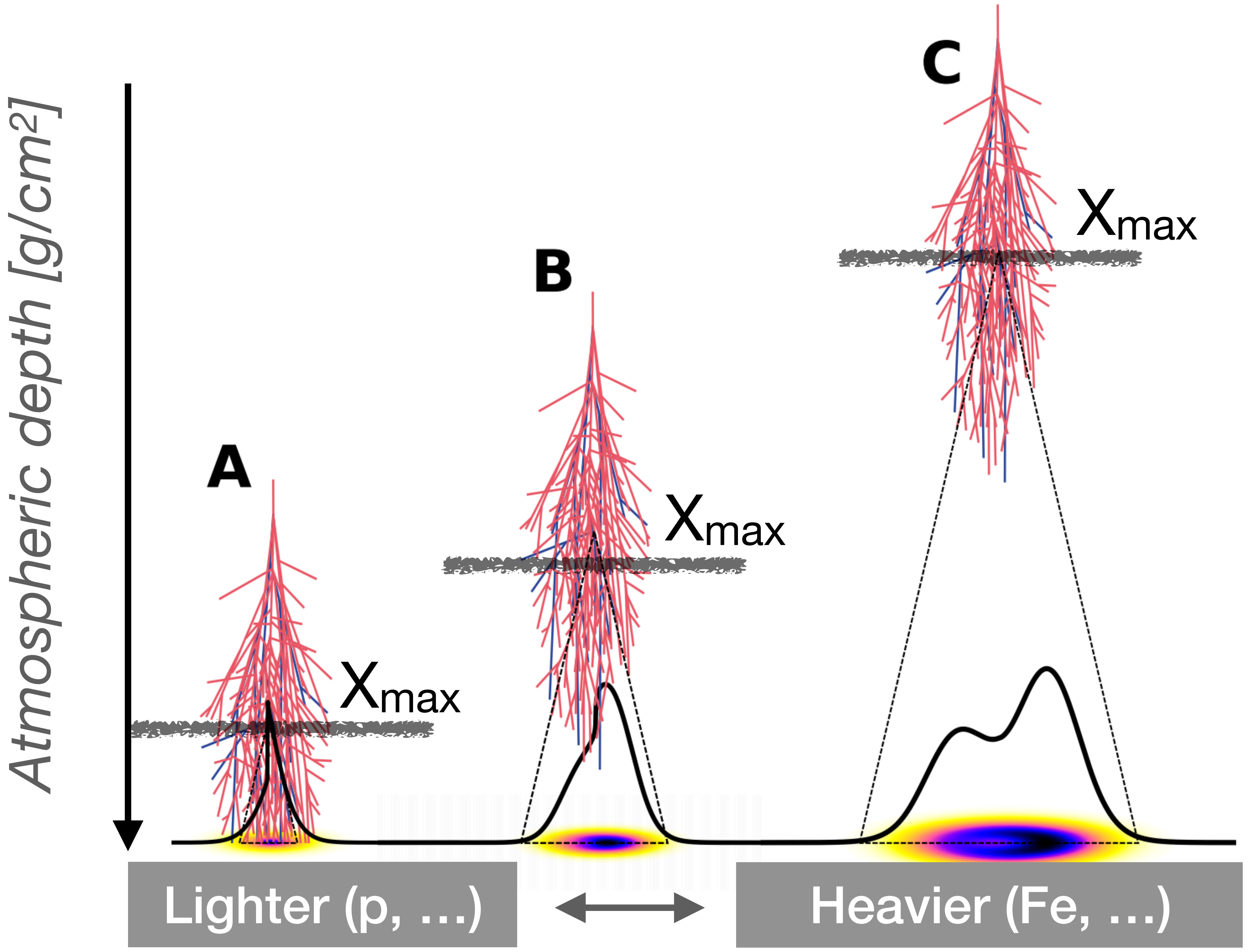
$$\sigma_{X_1,\text{p}} \sim 45 - 55\,\text{g/cm}^2$$
$$\sigma_{X_1,\text{Fe}} \sim 10\,\text{g/cm}^2$$

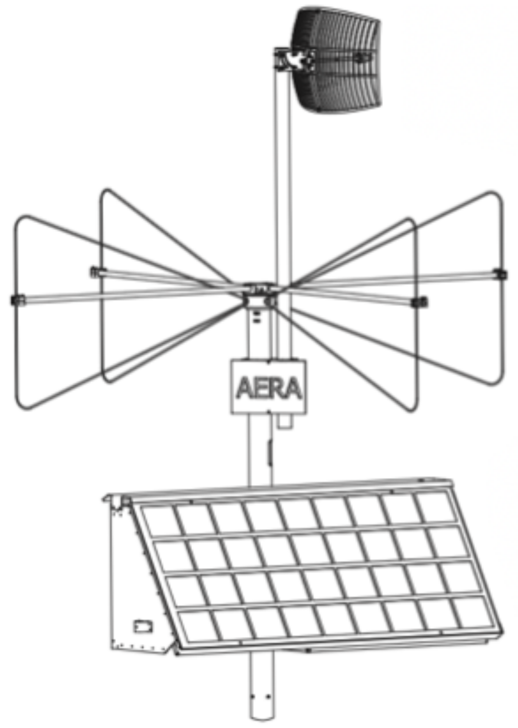
$(E \sim 10^{18}\,\text{eV})$

(Phys. Rev. D90 (2014), 122005 & 122005, updated ICRC 2019)

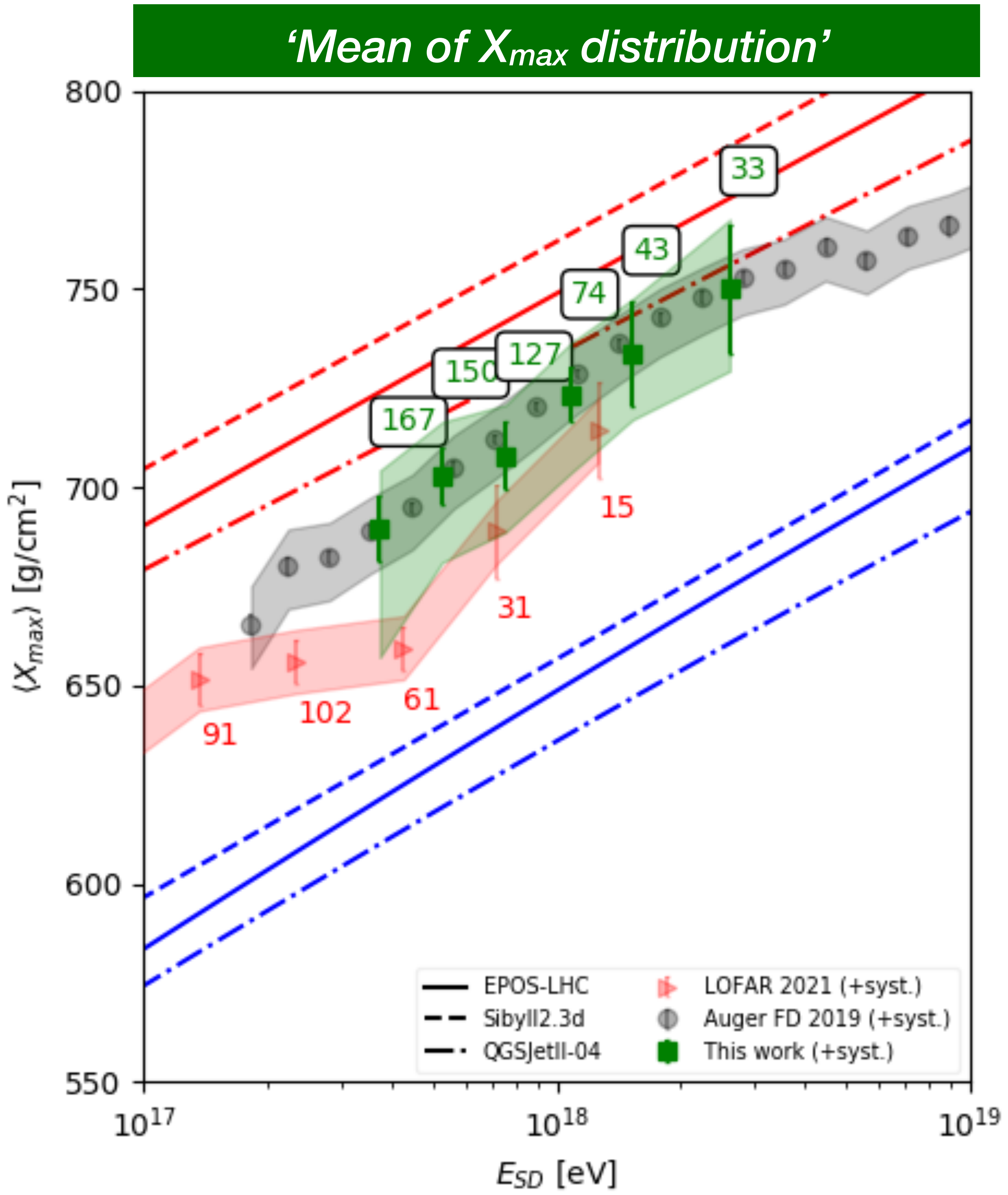
(Phys. Rev. D96 (2017), 122003)

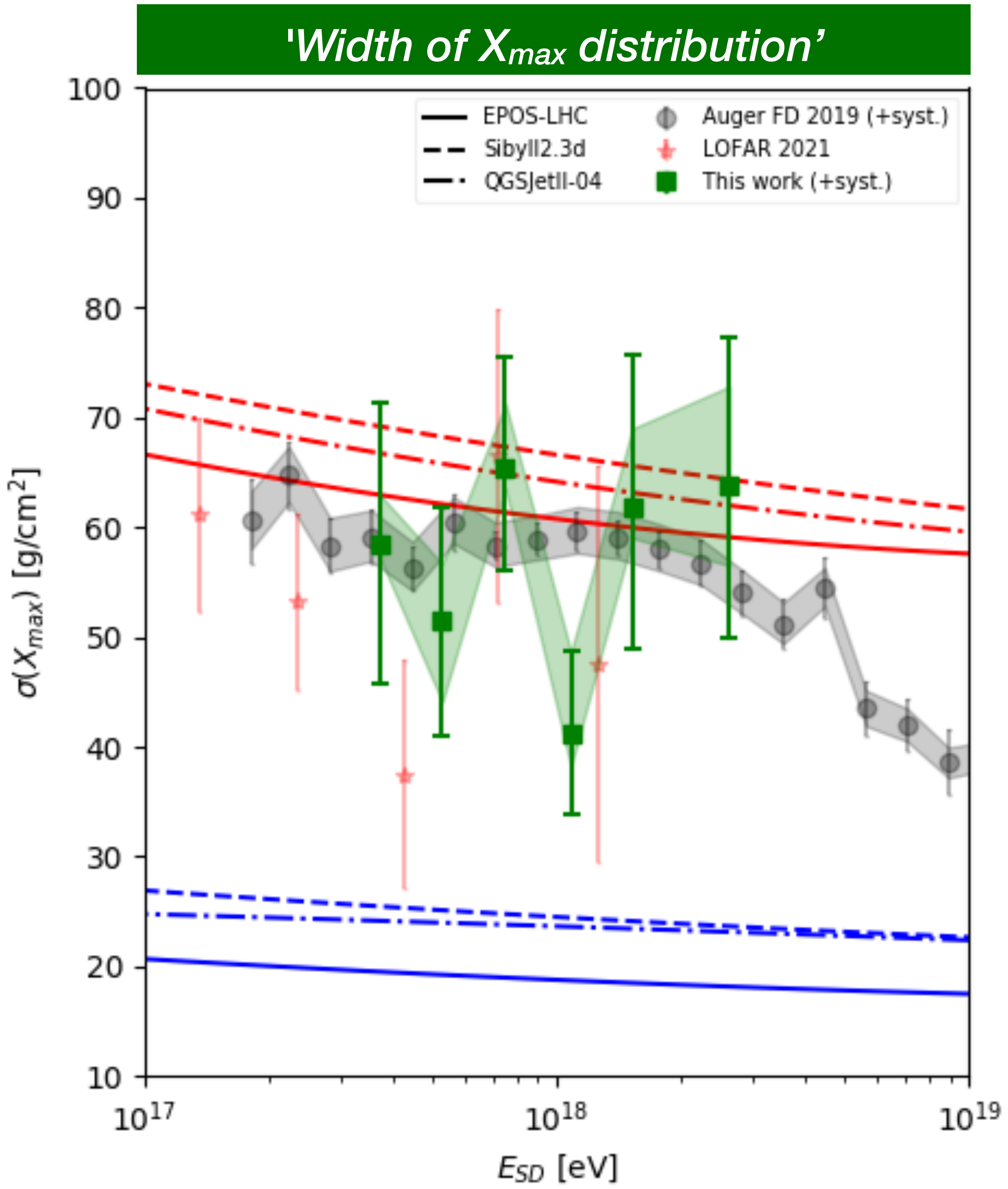
Mass composition results (ii)





Auger Engineering Radio Array (AERA)

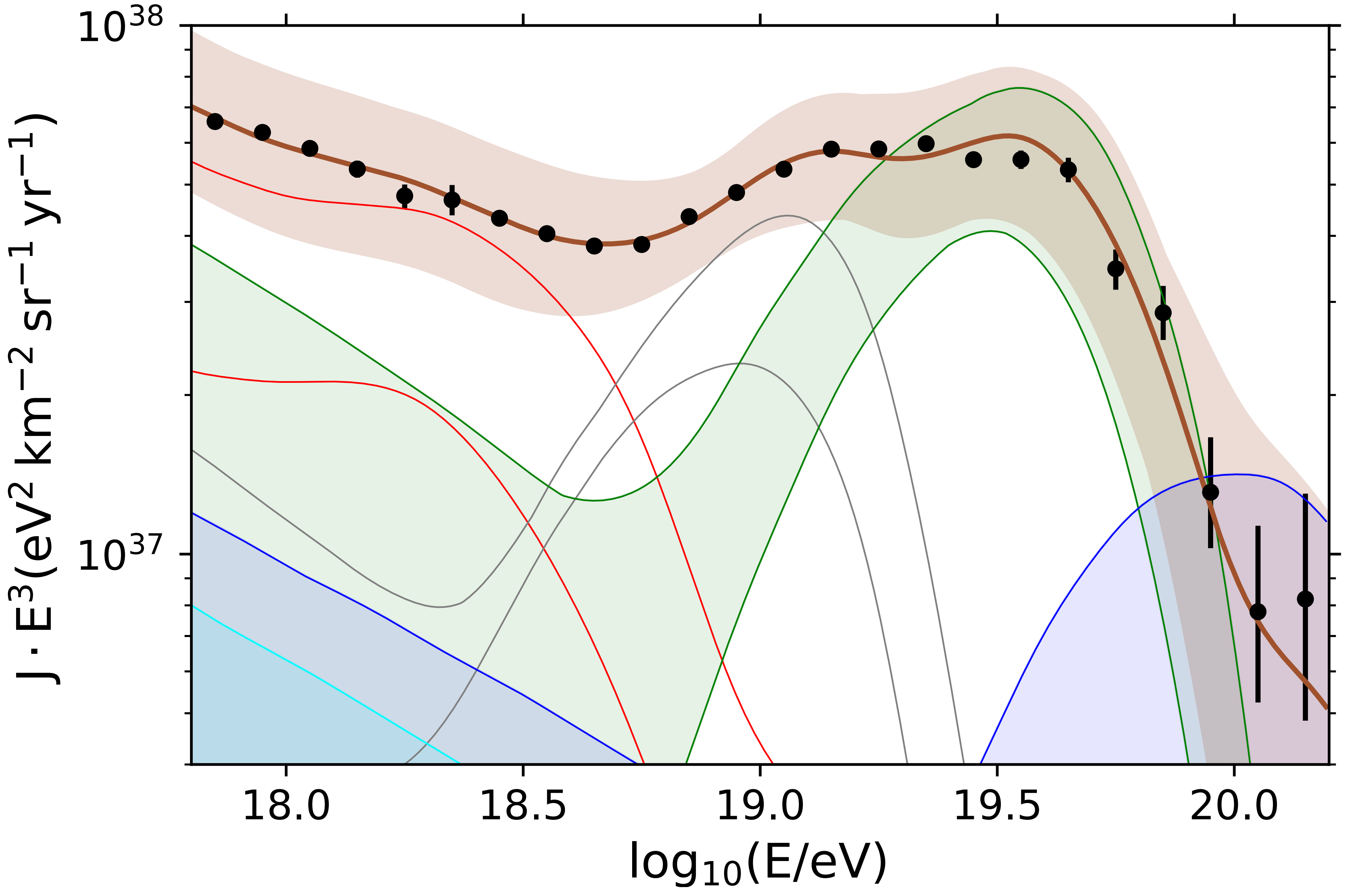




Independent confirmation of earlier Auger results

Interpretation of flux and composition data

Mass composition at Earth

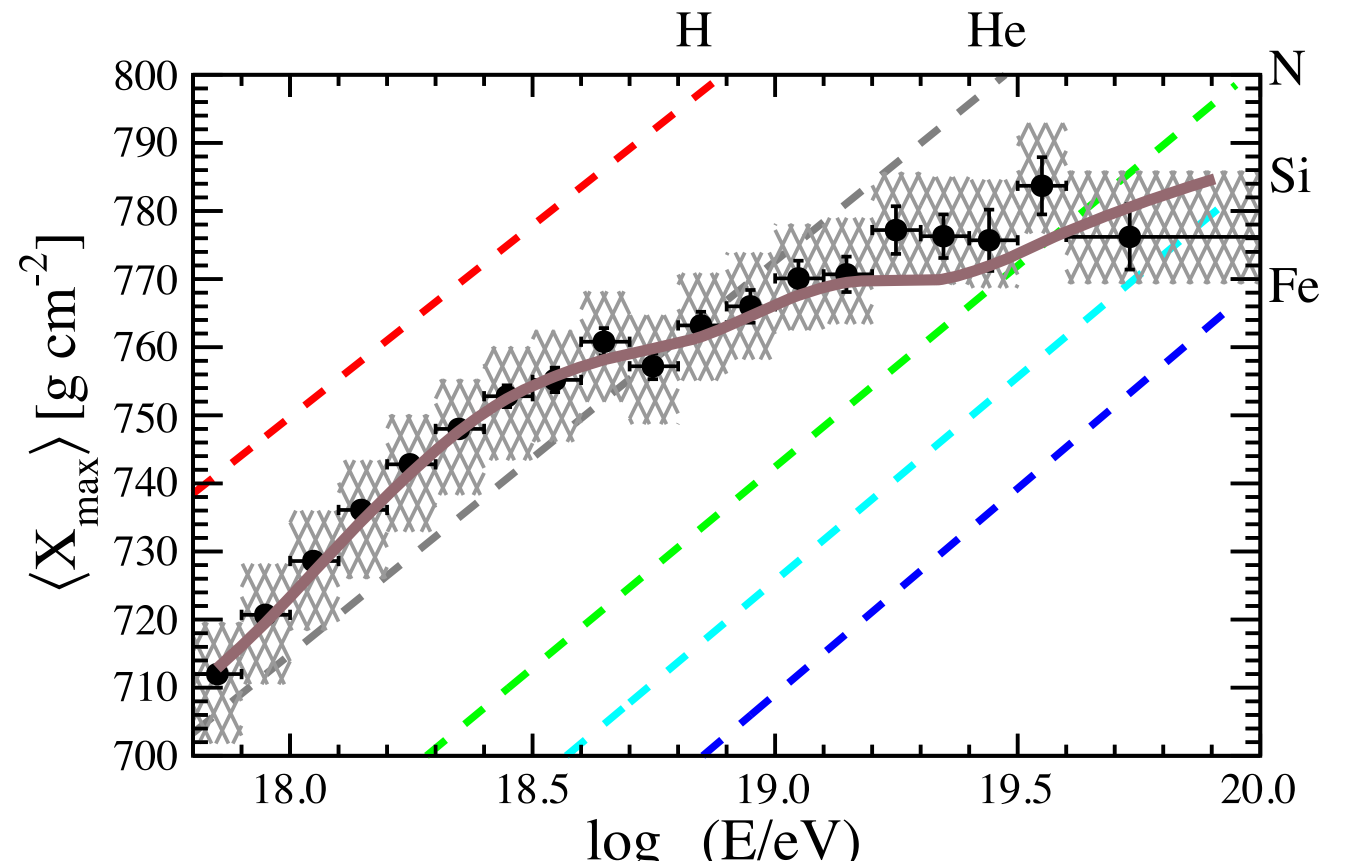


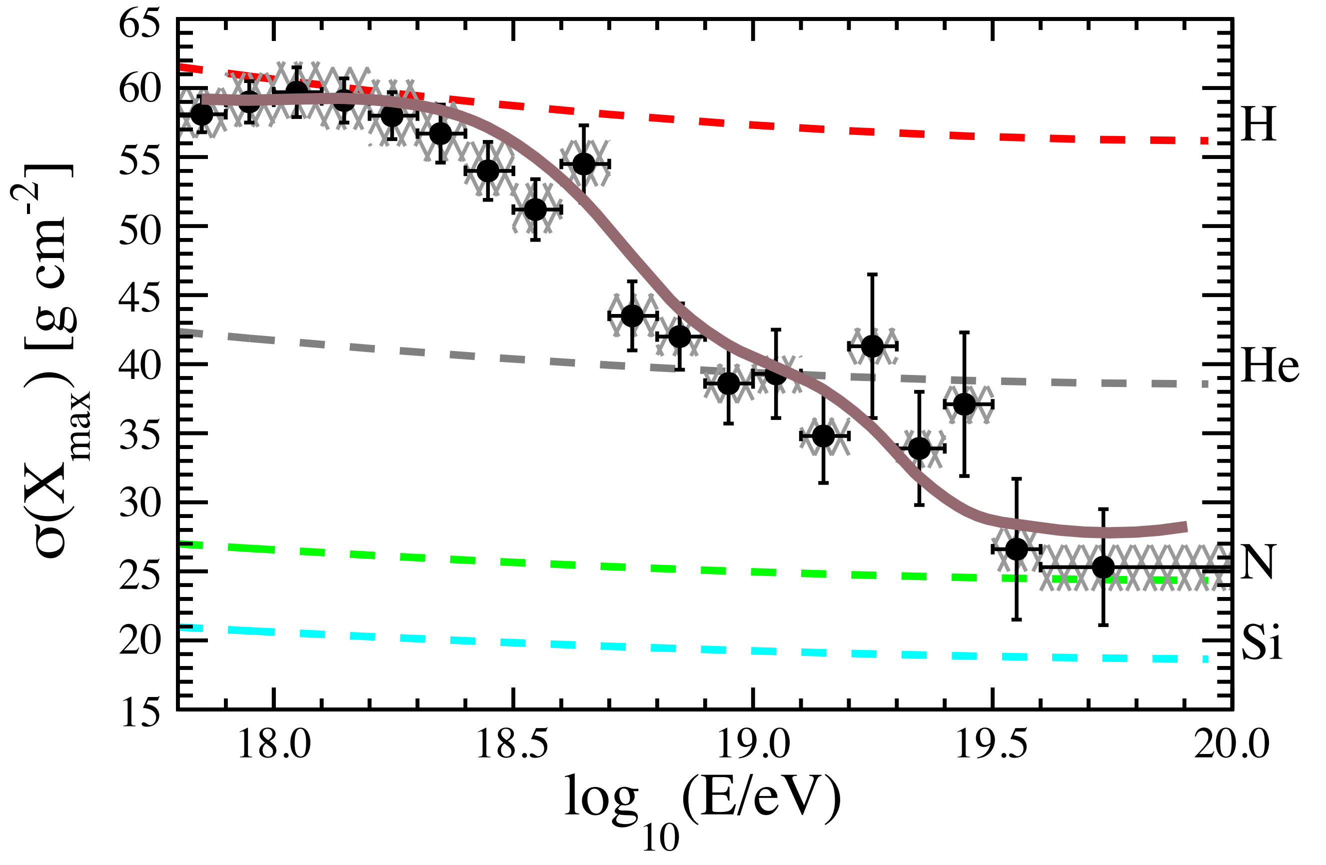
$A = 1$
$1 < A < 5$
$4 < A < 23$
$22 < A < 39$
$38 < A < 57$

Bands:
Experimental uncertainties
(model uncertainties smaller)

Energy scale: $\sigma_{sys}(E)/E = 14\,\%$

X_{max} scale: $\sigma_{sys}(X_{max}) = 6 \div 9\ \mathrm{g\,cm^{-2}}$





Different model scenarios considered for low-energy part
(transition to galactic component), similar results for total composition obtained

$$J(E) = \sum_A f_A \cdot J_0 \cdot \left(\frac{E}{E_0}\right)^{-\gamma} \cdot \begin{cases} 1, & E < Z_A \cdot R_{\mathrm{cut}}; \\ \exp\left(1 - \frac{E}{Z_A \cdot R_{\mathrm{cut}}}\right), & E > Z_A \cdot R_{\mathrm{cut}}. \end{cases}$$

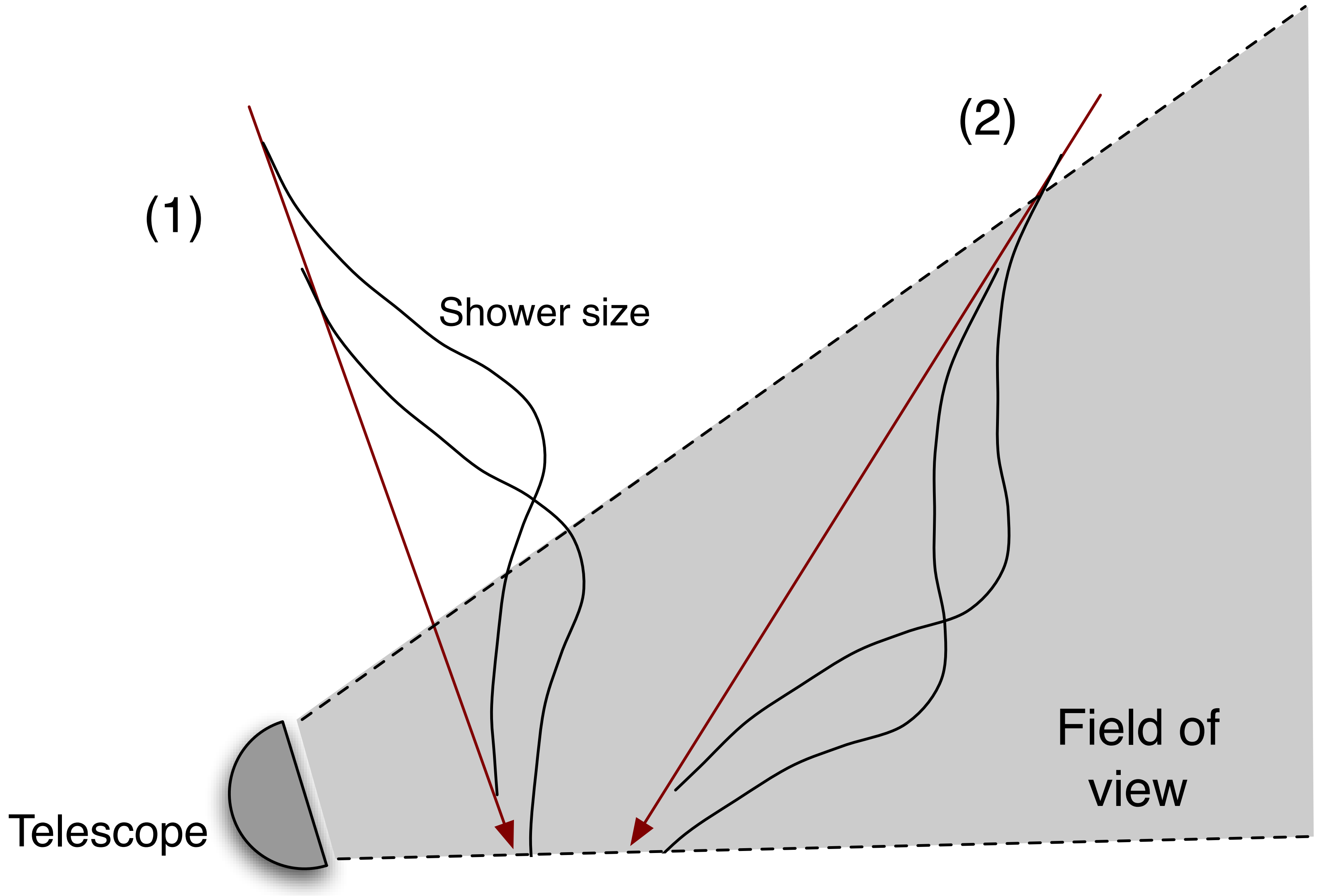
$$R_{\mathrm{cut}} = 1.4 \ldots 1.6 \times 10^{18}\,\mathrm{V}$$

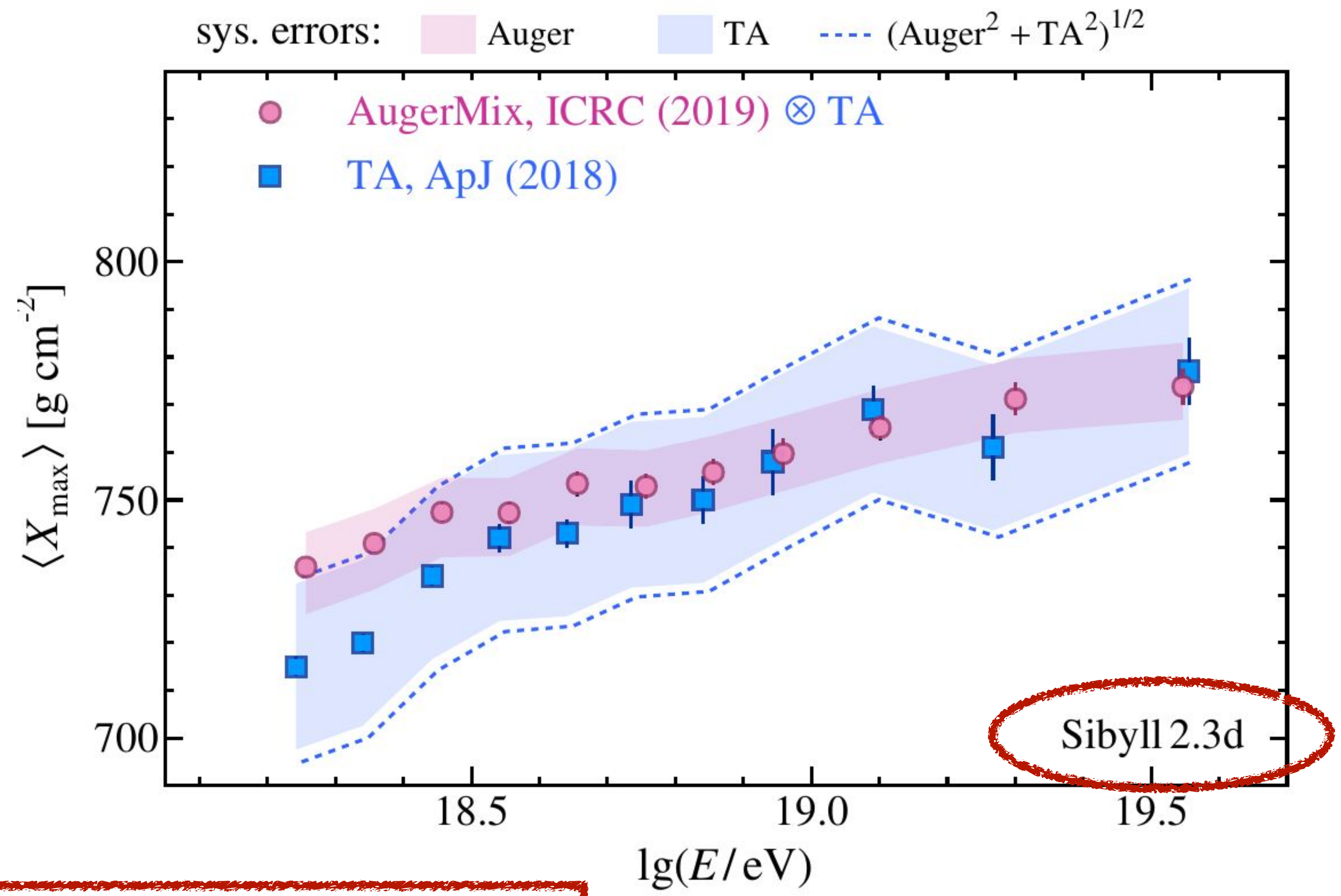
Flux suppression superposition of injection maximum energy and propagation energy losses

Extragalactic index very hard, but no really good handle on this parameter

(Auger, UHECR 2022, ICRC 2021)

Auger-TA comparison of X_{max} distributions



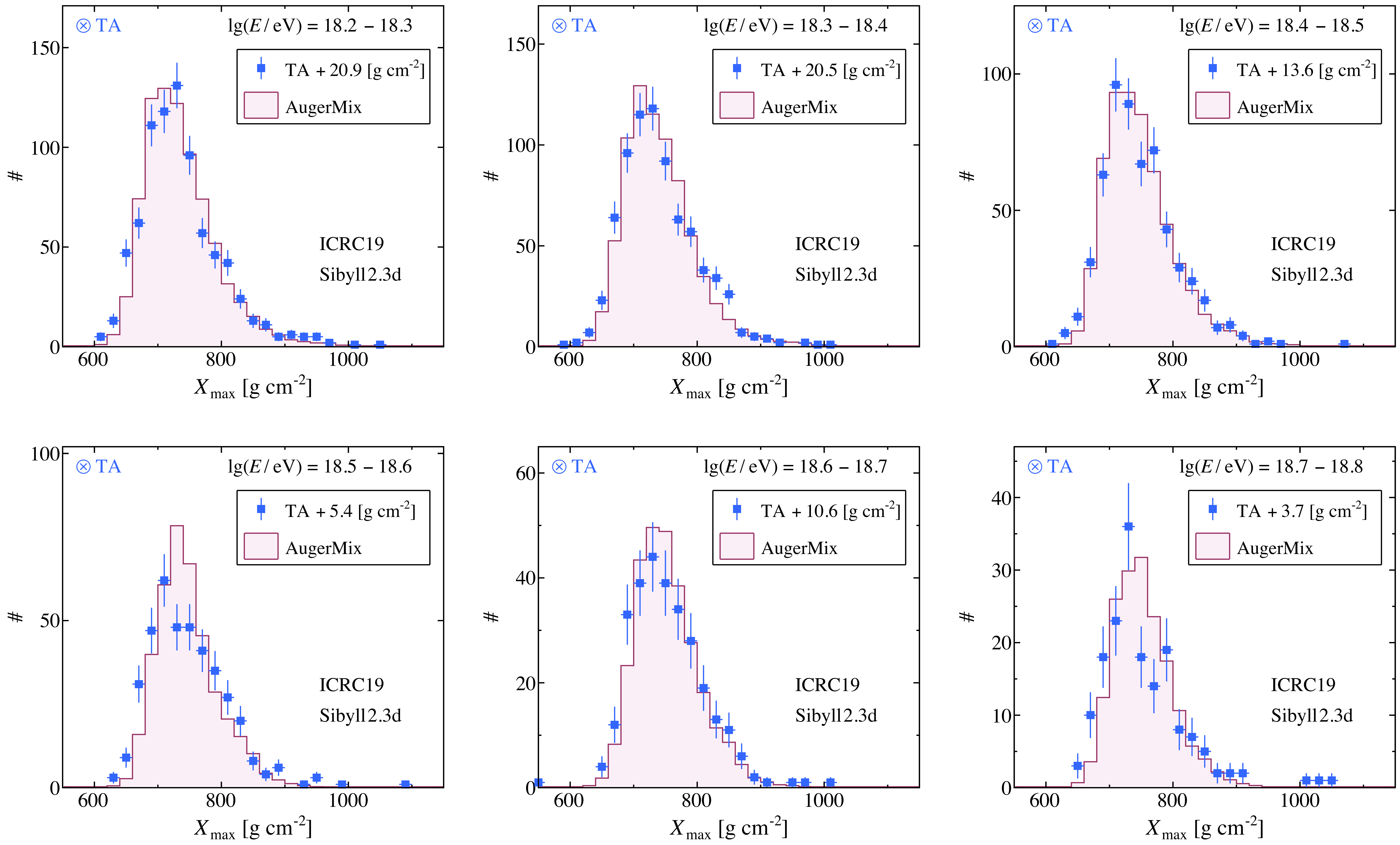


This representation agrees with TA $<X_{max}>$ measurements well, but there is disagreement at some energies in $\sigma(X_{max})$. This disagreement is plausibly due to the handling of X_{max} resolution due to varying aerosols at TA

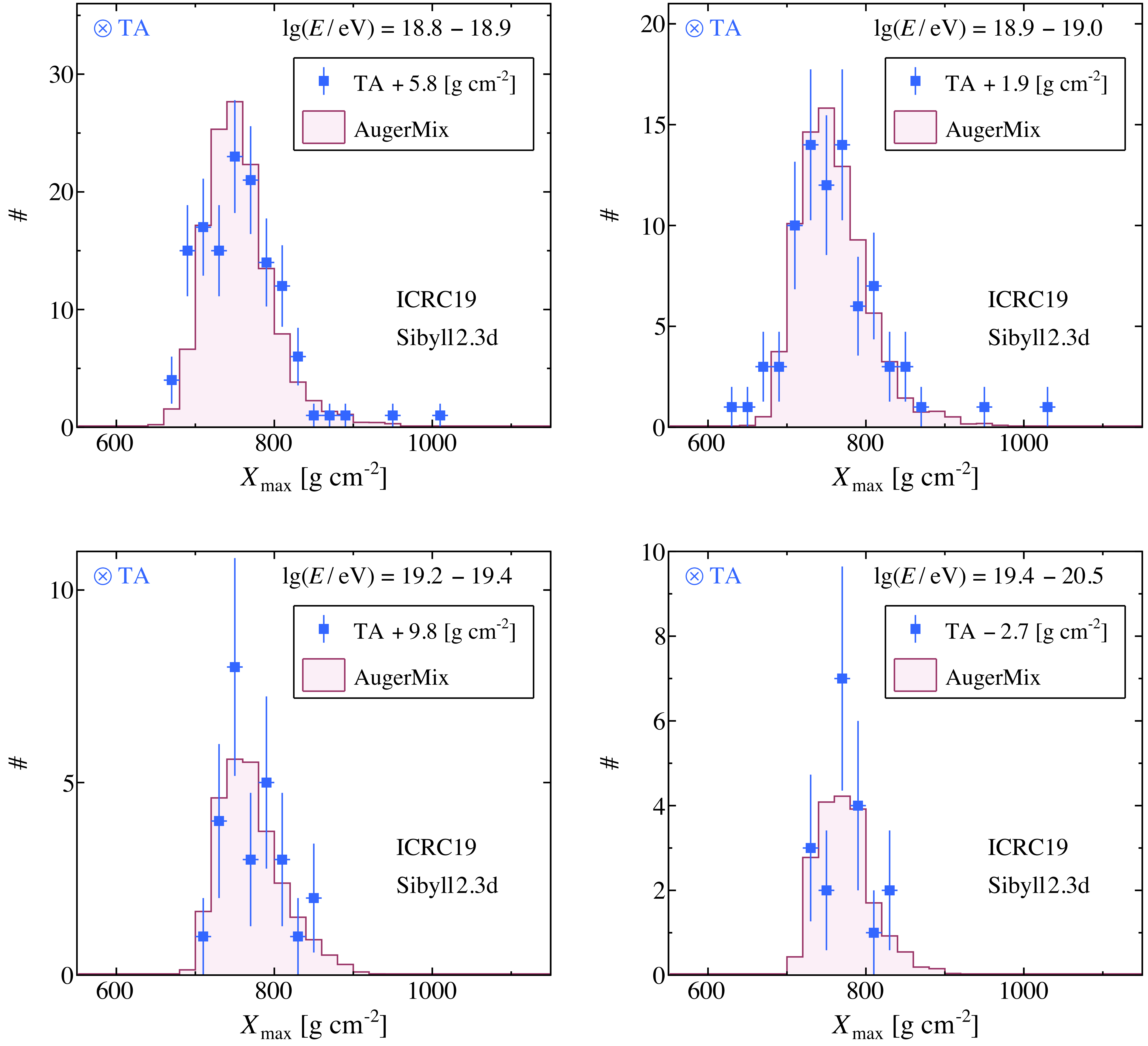
A robust difference between the Auger and TA X_{max} measurements **has not been found**

(UHECR 2022, D. Bergmann for the Auger-TA joint working group)

Auger-TA comparison of Xmax distributions (i)



Auger-TA comparison of Xmax distributions (i)

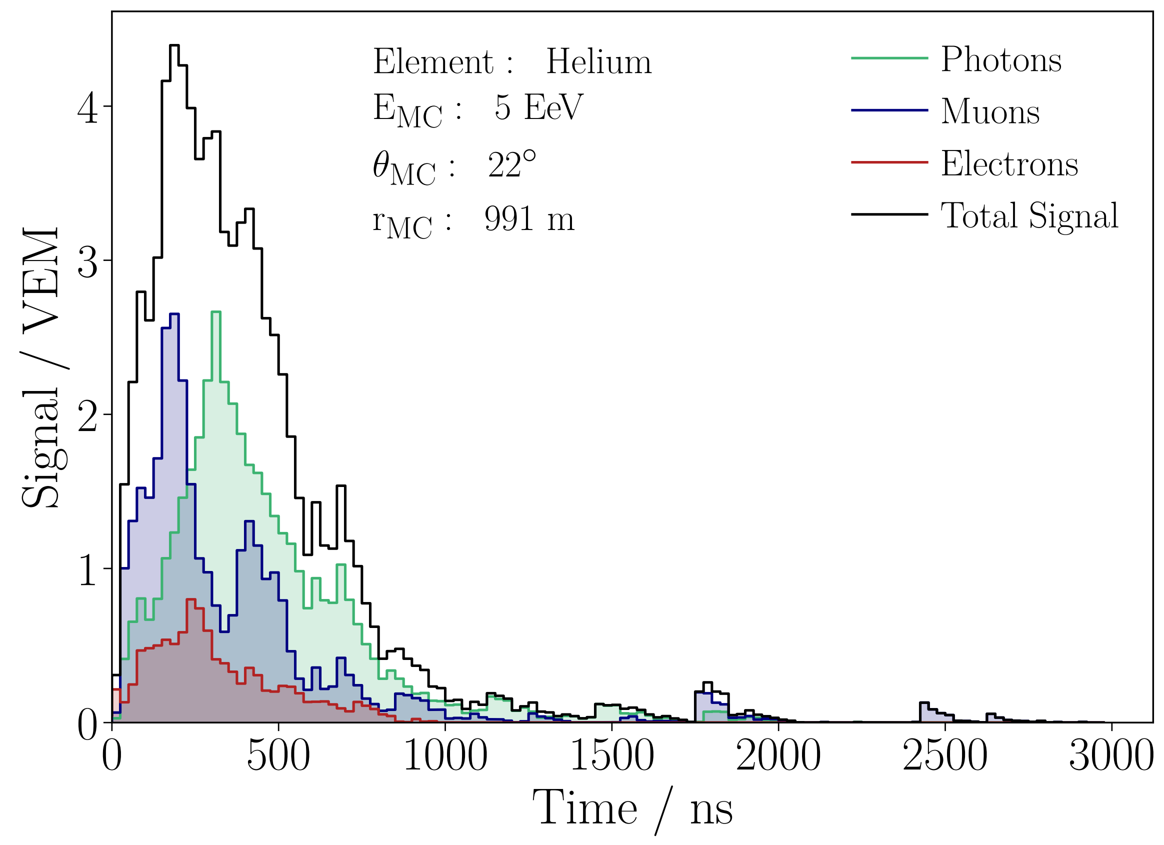


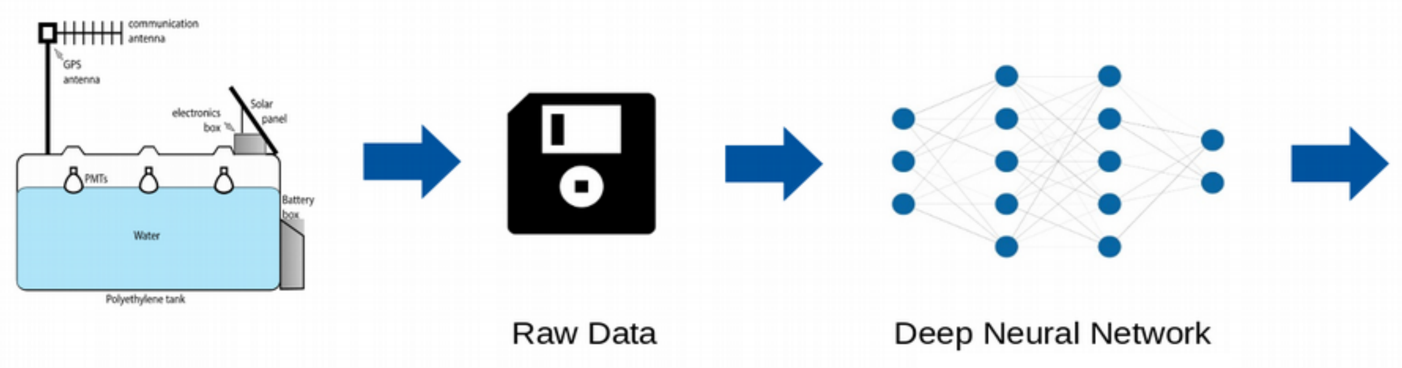
Mean Xmax shifted to agree between data sets for each energy bin

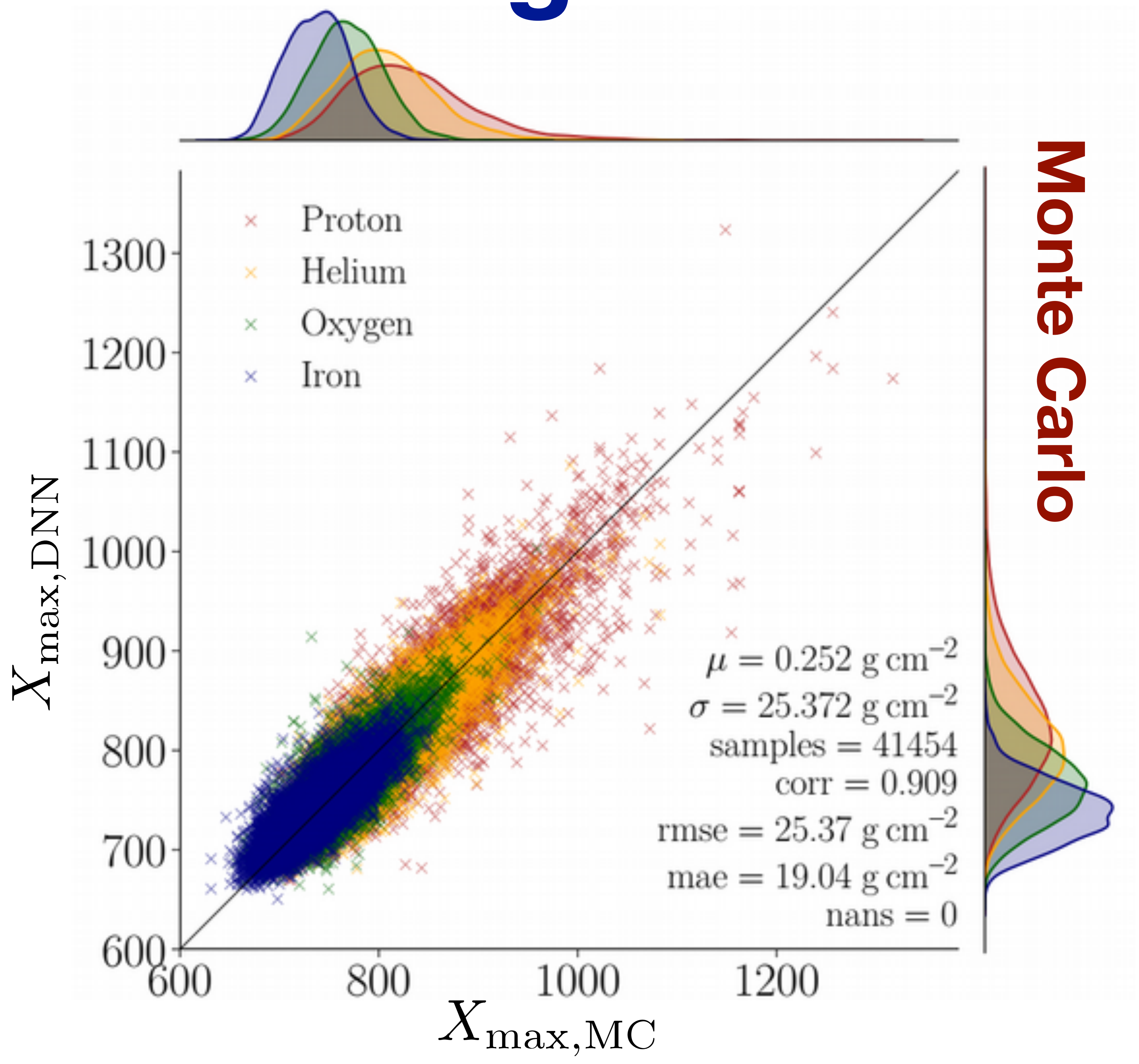
(UHECR 2022, D. Bergmann for the Auger-TA joint working group)

Surface detector data and machine learning

Simulated signal trace of one station



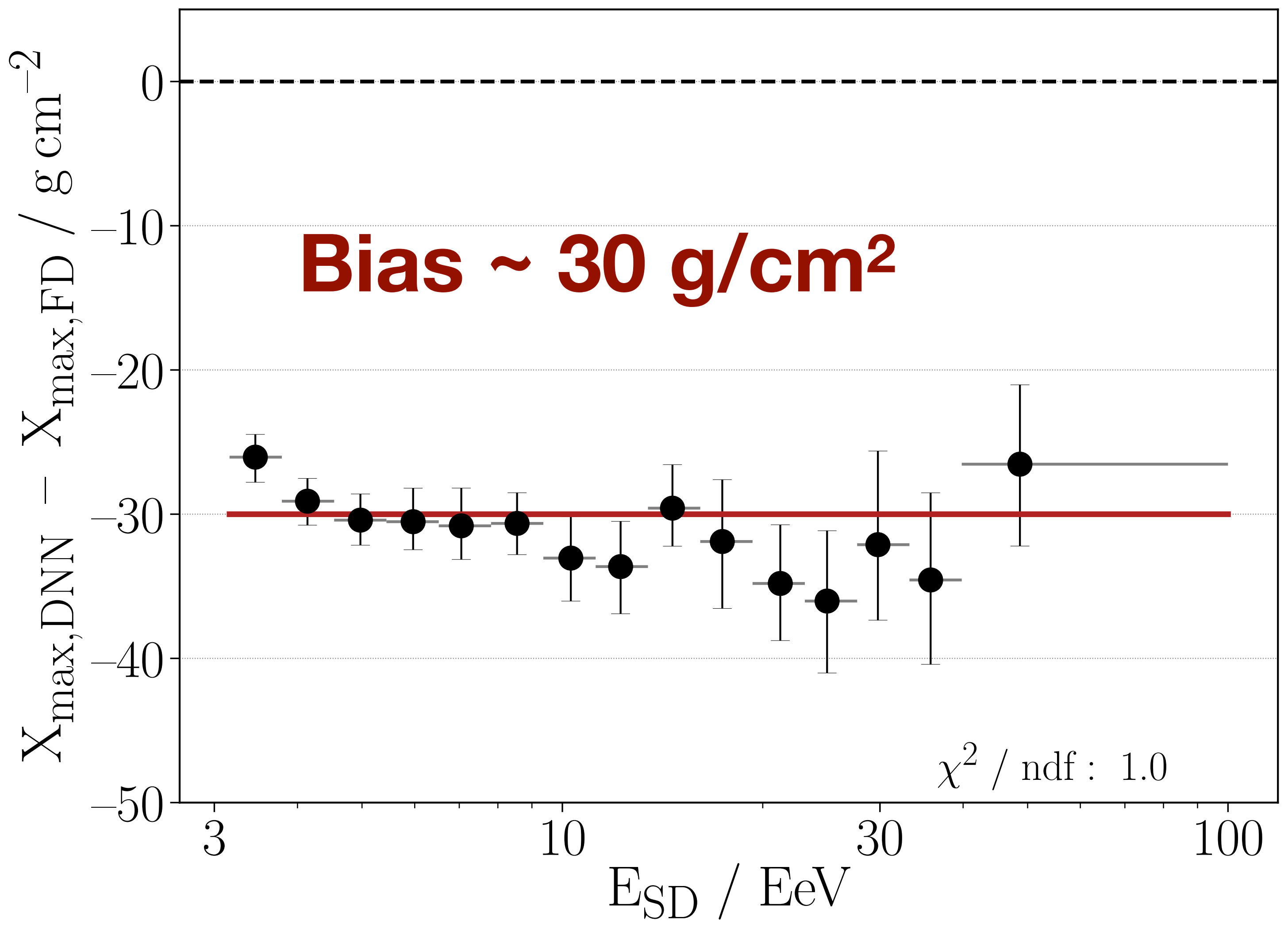




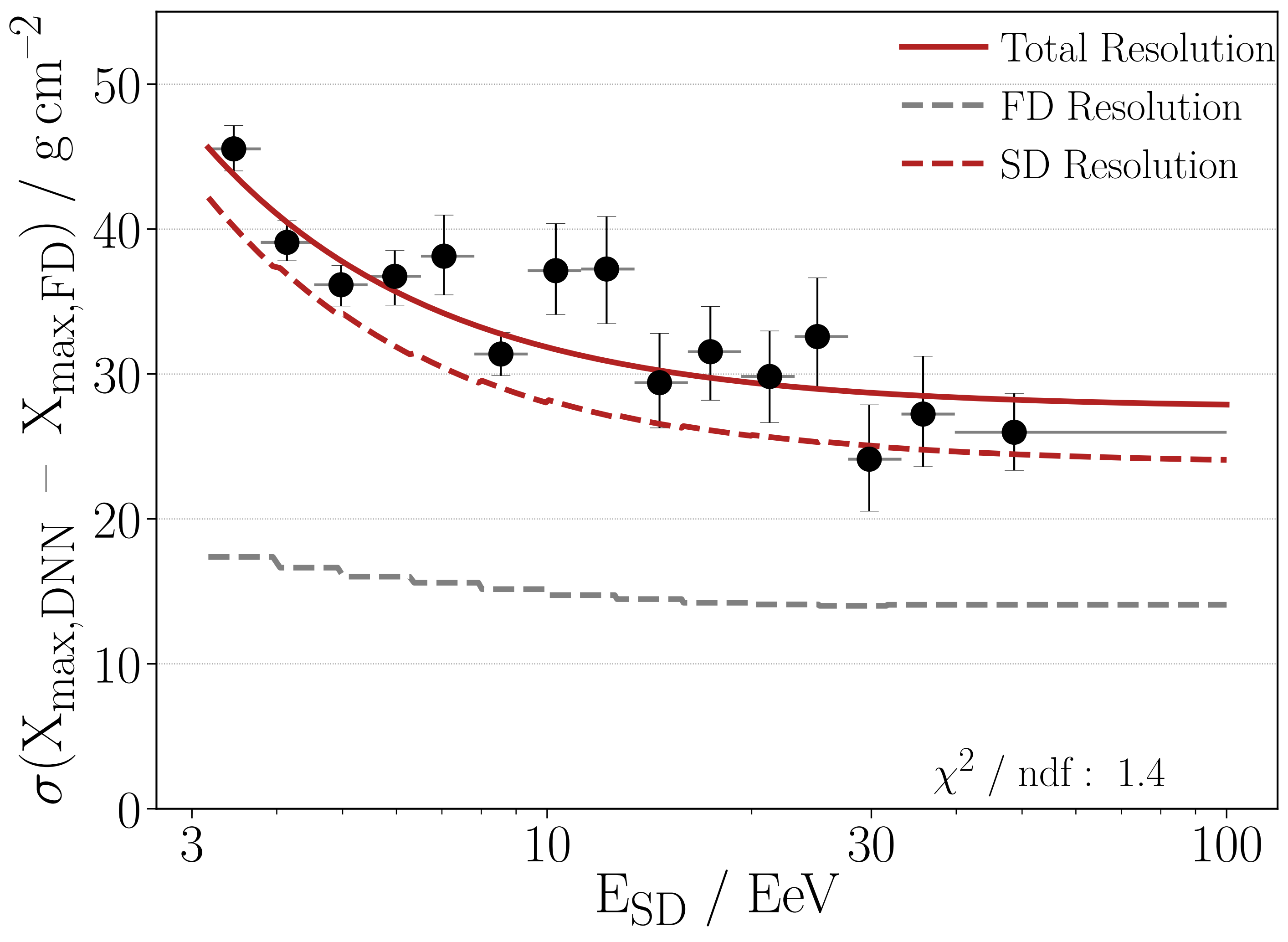
Monte Carlo

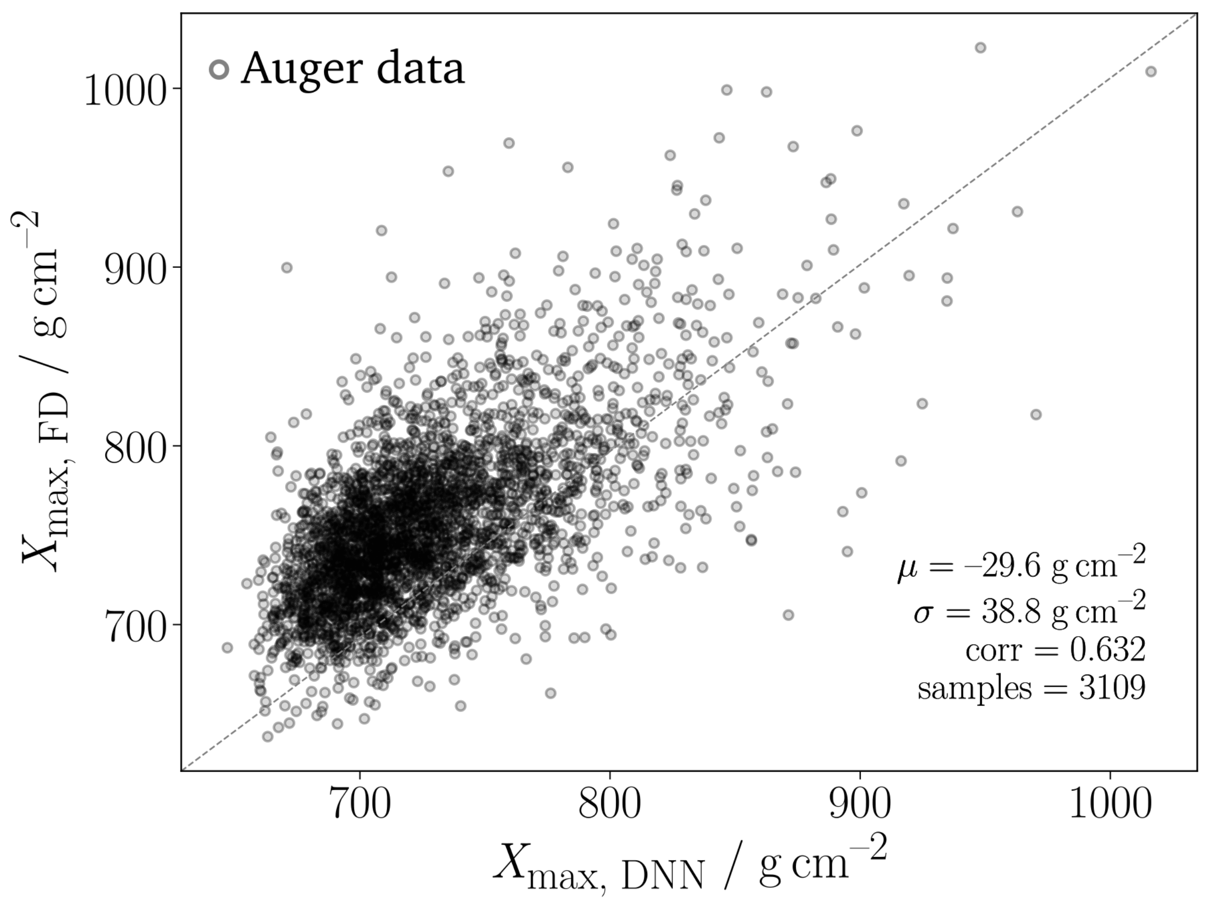
Reconstructing Xmax with DNNs: ultimate check with hybrid data

Mean Xmax (bias)



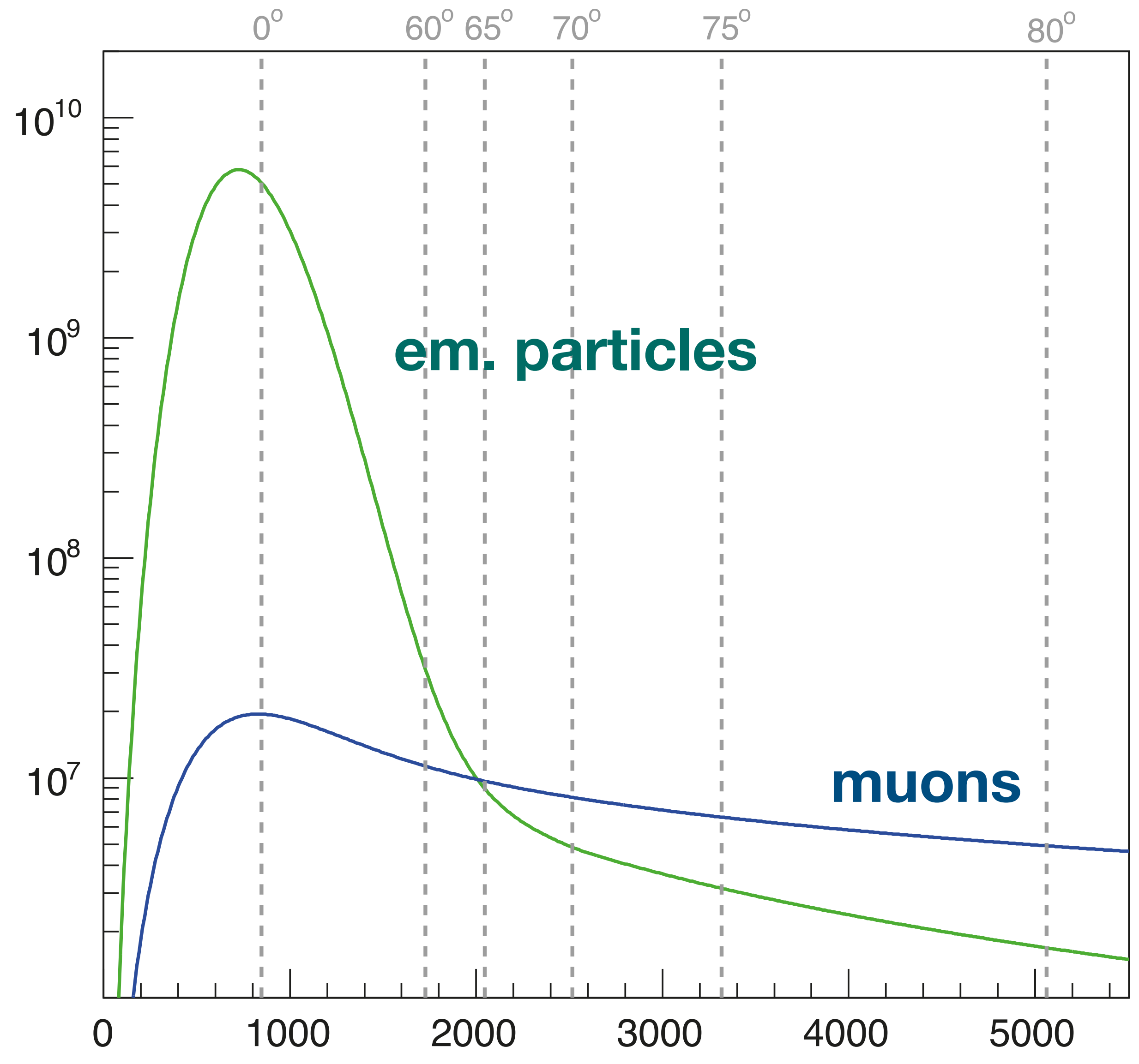
Shower-by shower Xmax resolution



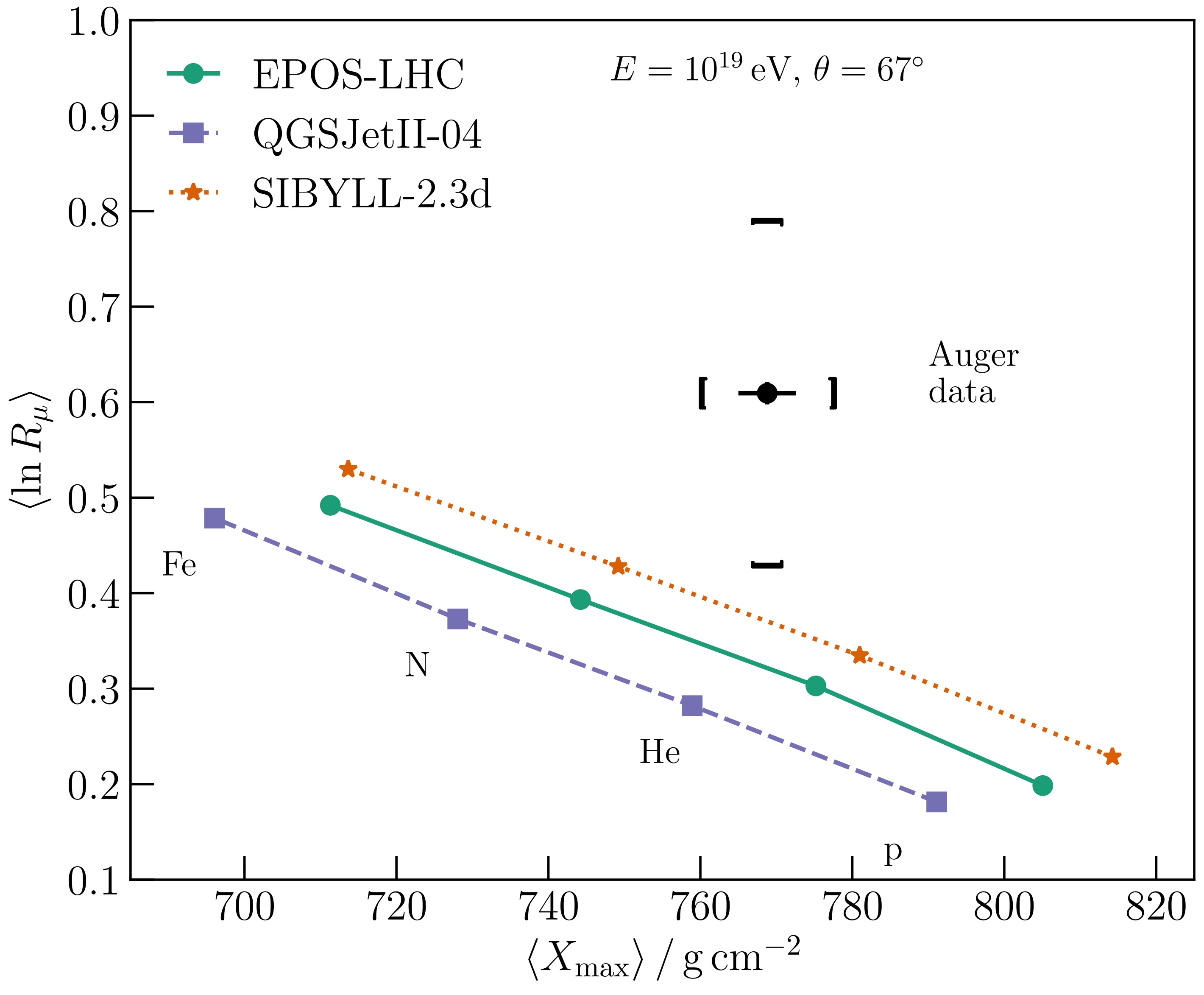


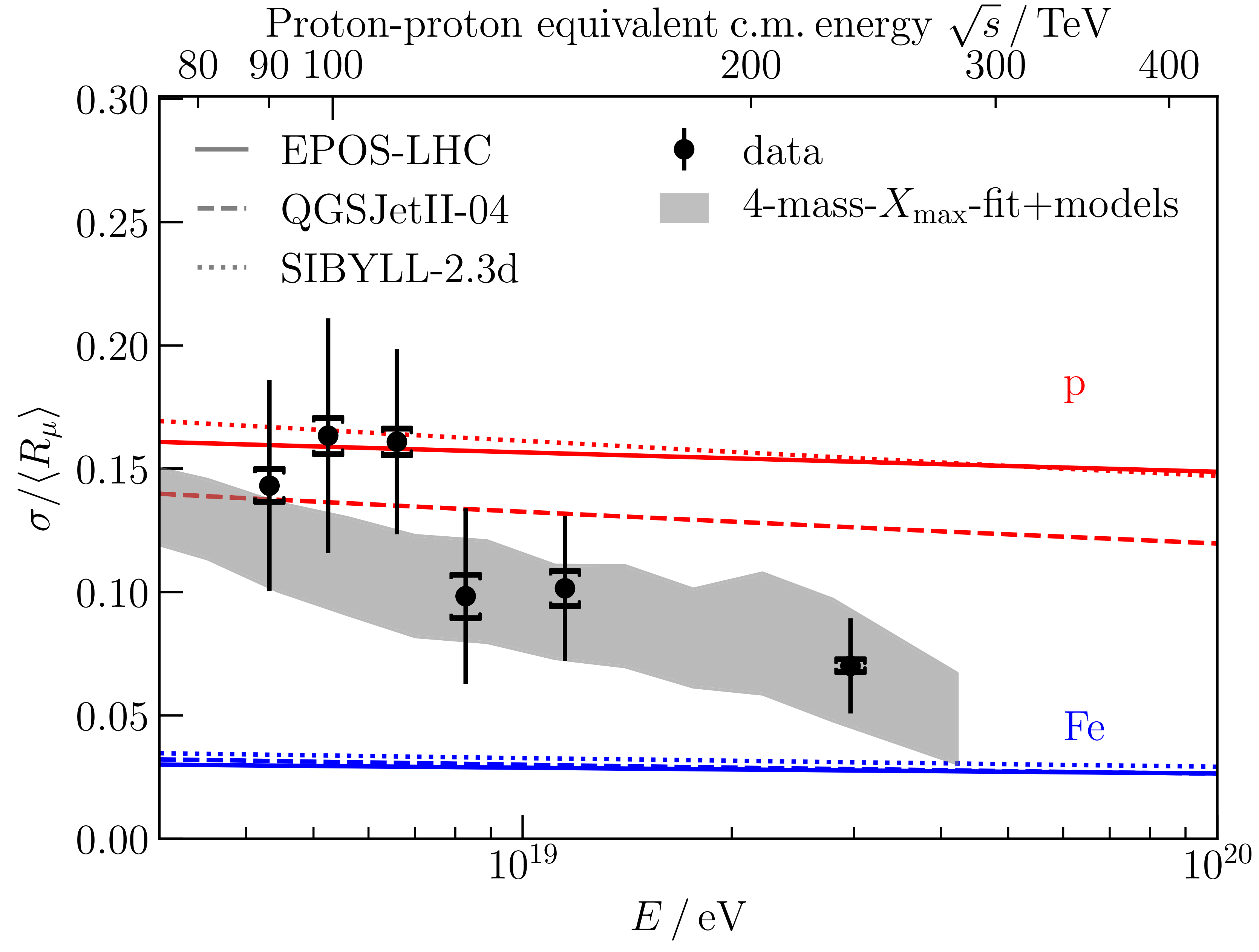
Hybrid data

What could be the origin of the problem?

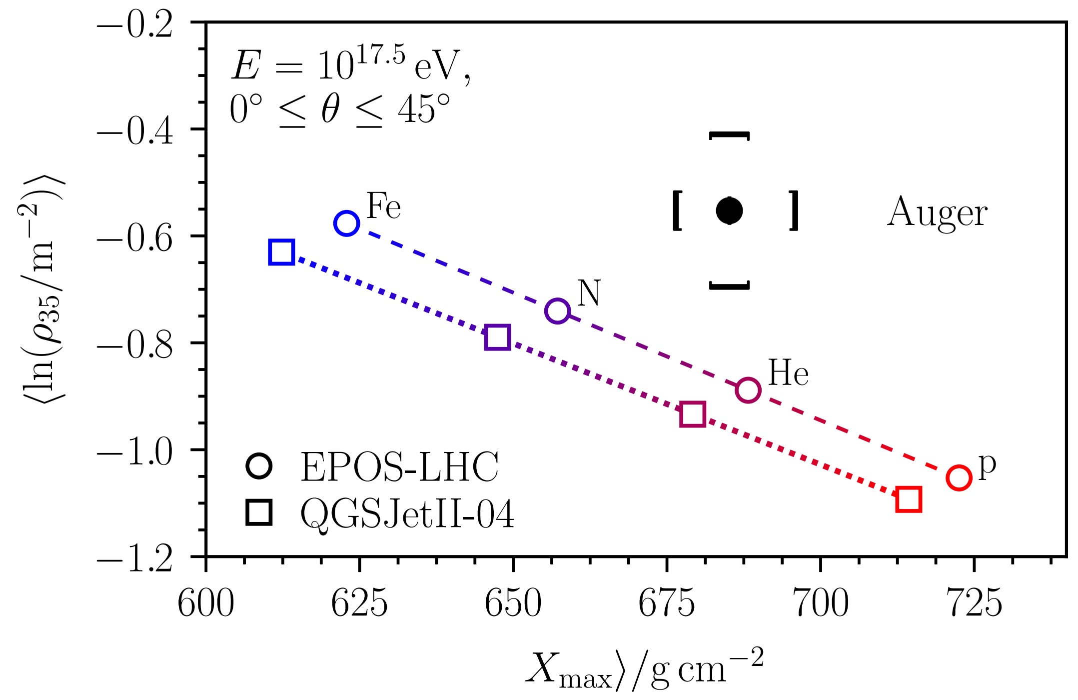


Hybrid events and inclined showers





Muon counters and vertical showers

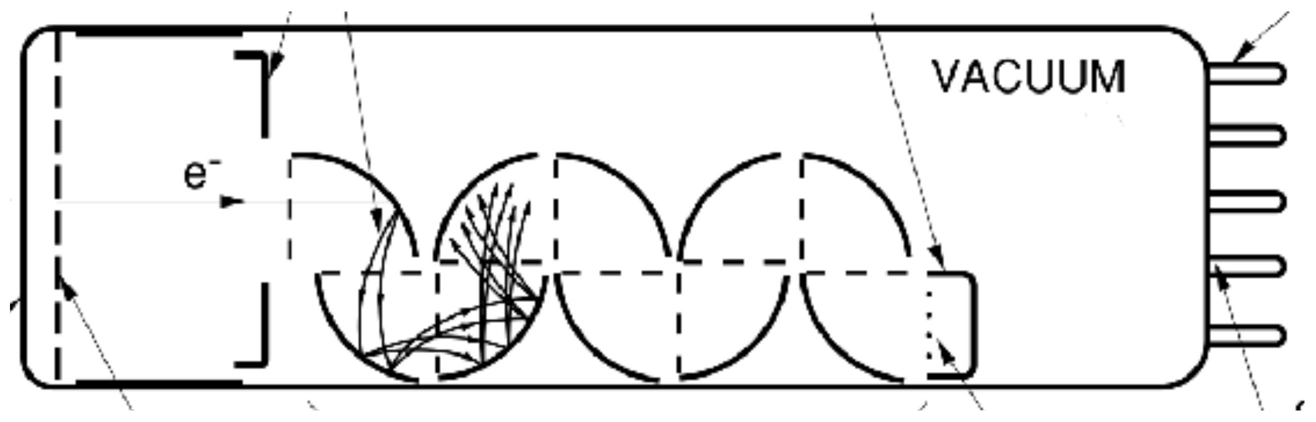


(Phys. Rev. Lett. 117 (2016) 192001,
Phys. Rev. D91 (2015) 032003)

Discrepancy in number of muons

Relative fluctuations in agreement

PMT analogy of air shower



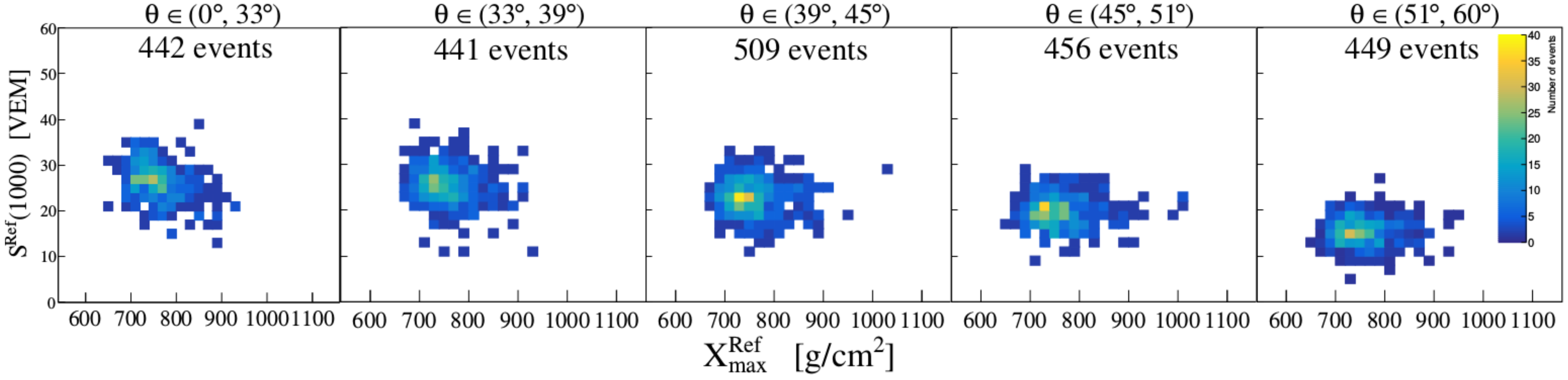
Muon fluctuations driven by first interactions

(Eur. Phys. J. C80 (2020) 751)

(Phys. Rev. Lett. 126 (2021) 152002)

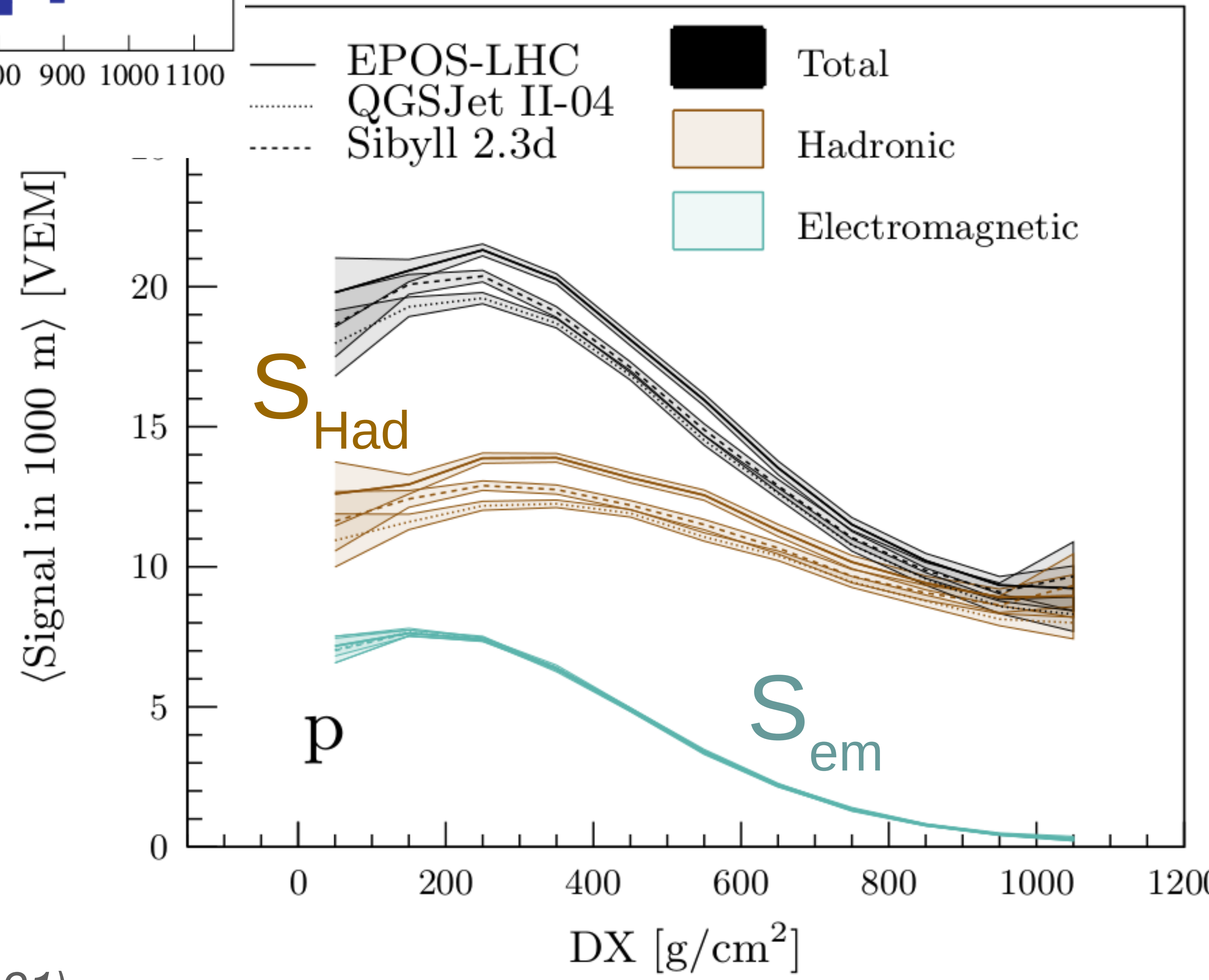
Test: modification of hadronic interaction models

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

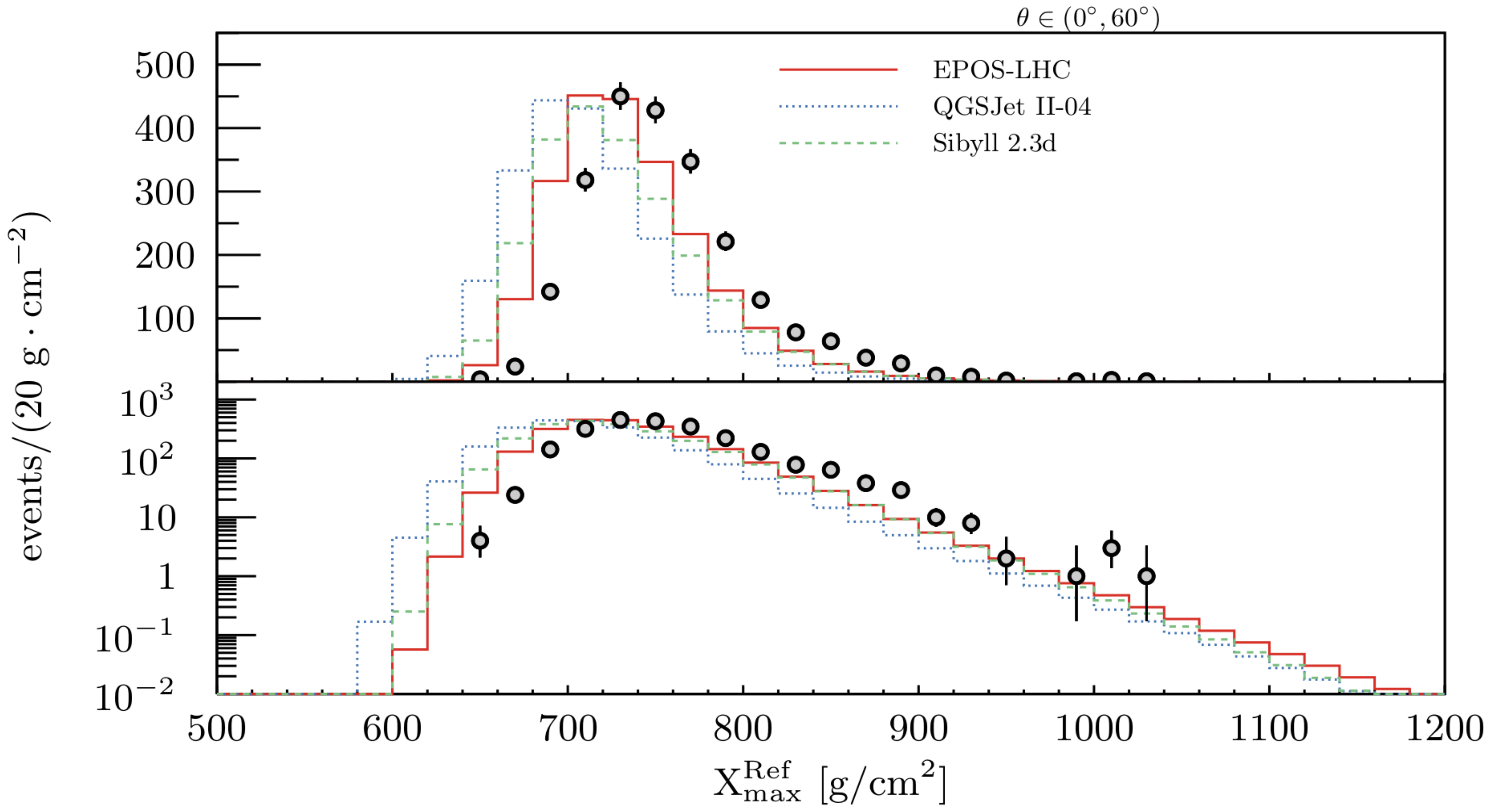
$$X_{max} \rightarrow X_{max} + \Delta X_{max}$$

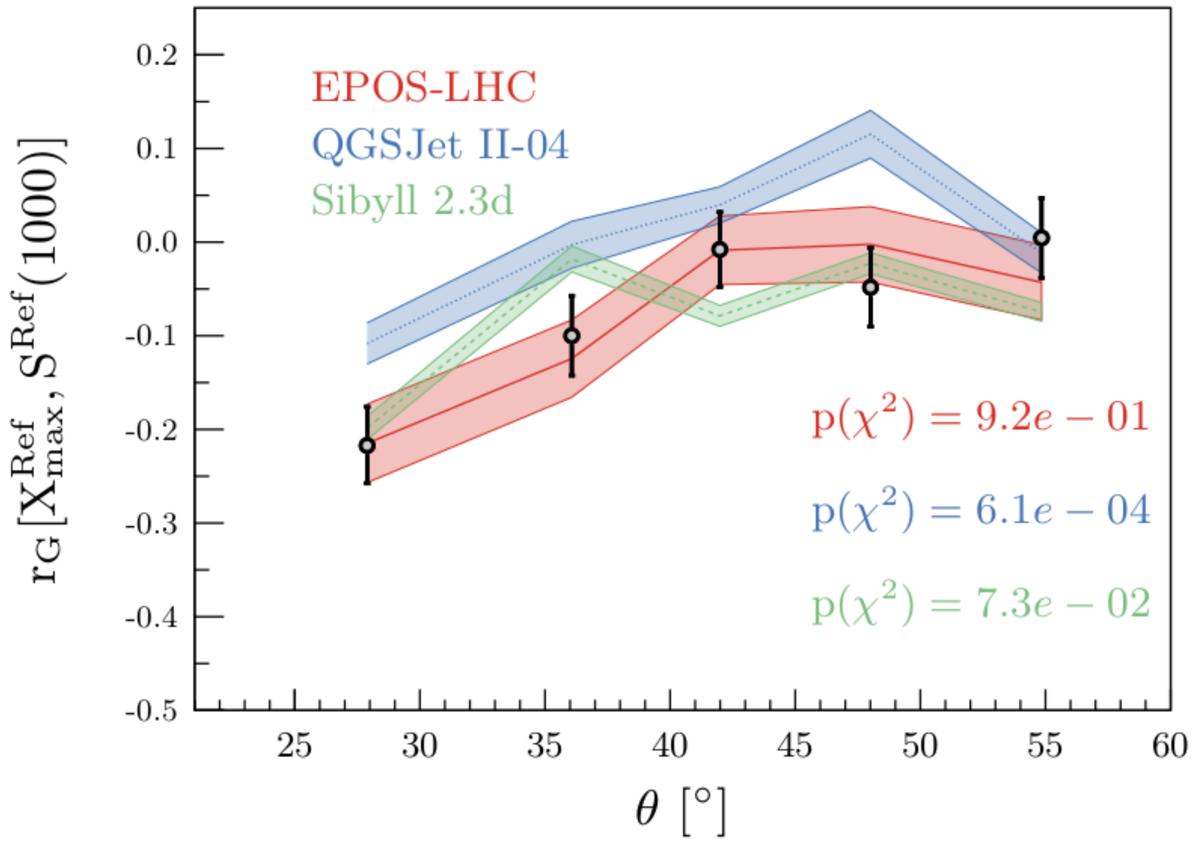
$$S_{Had}(\theta) \rightarrow S_{Had}(\theta) \cdot R_{Had}$$

New !

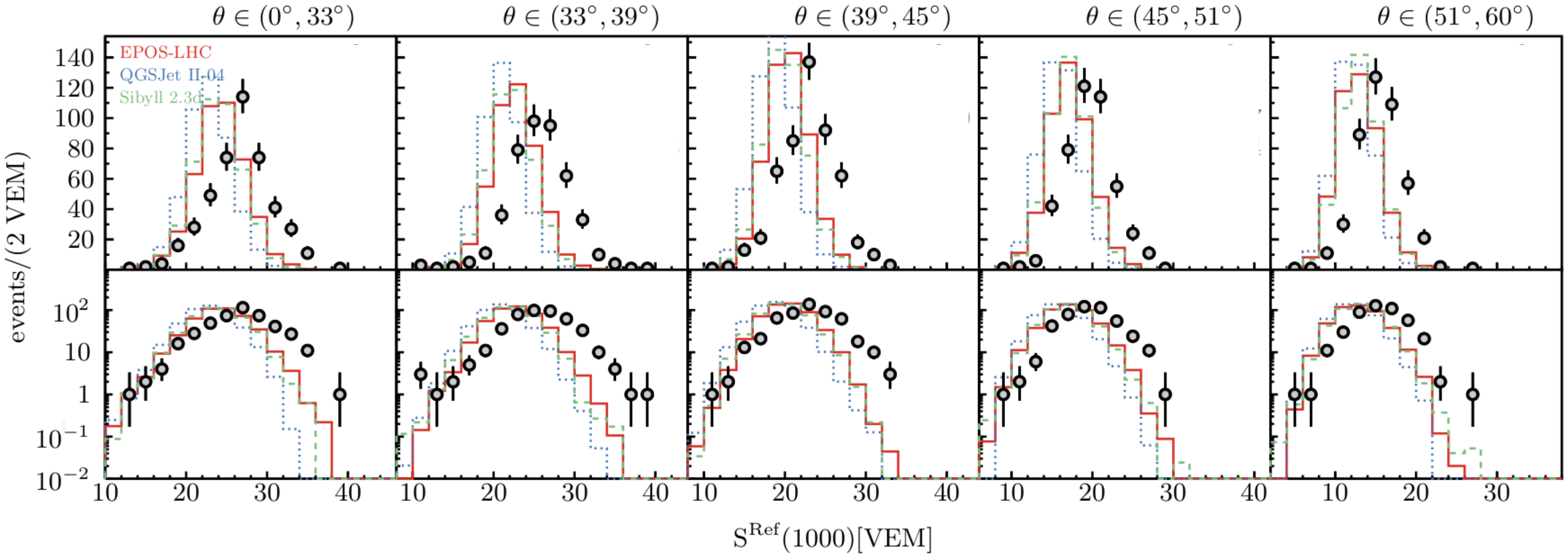
(Auger, UHECR 2022, ICRC 2021)

Test: 2D fit without any adjustments

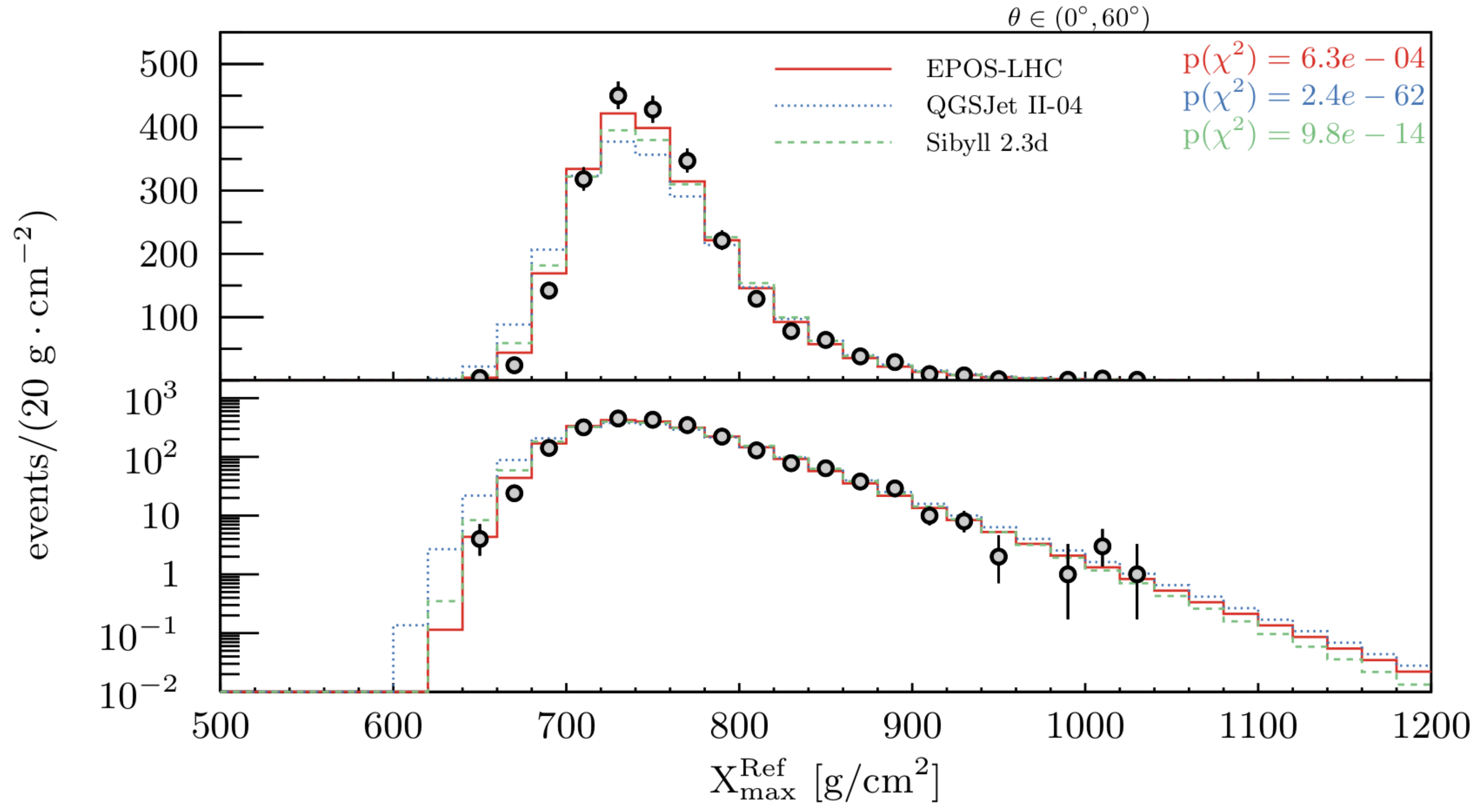


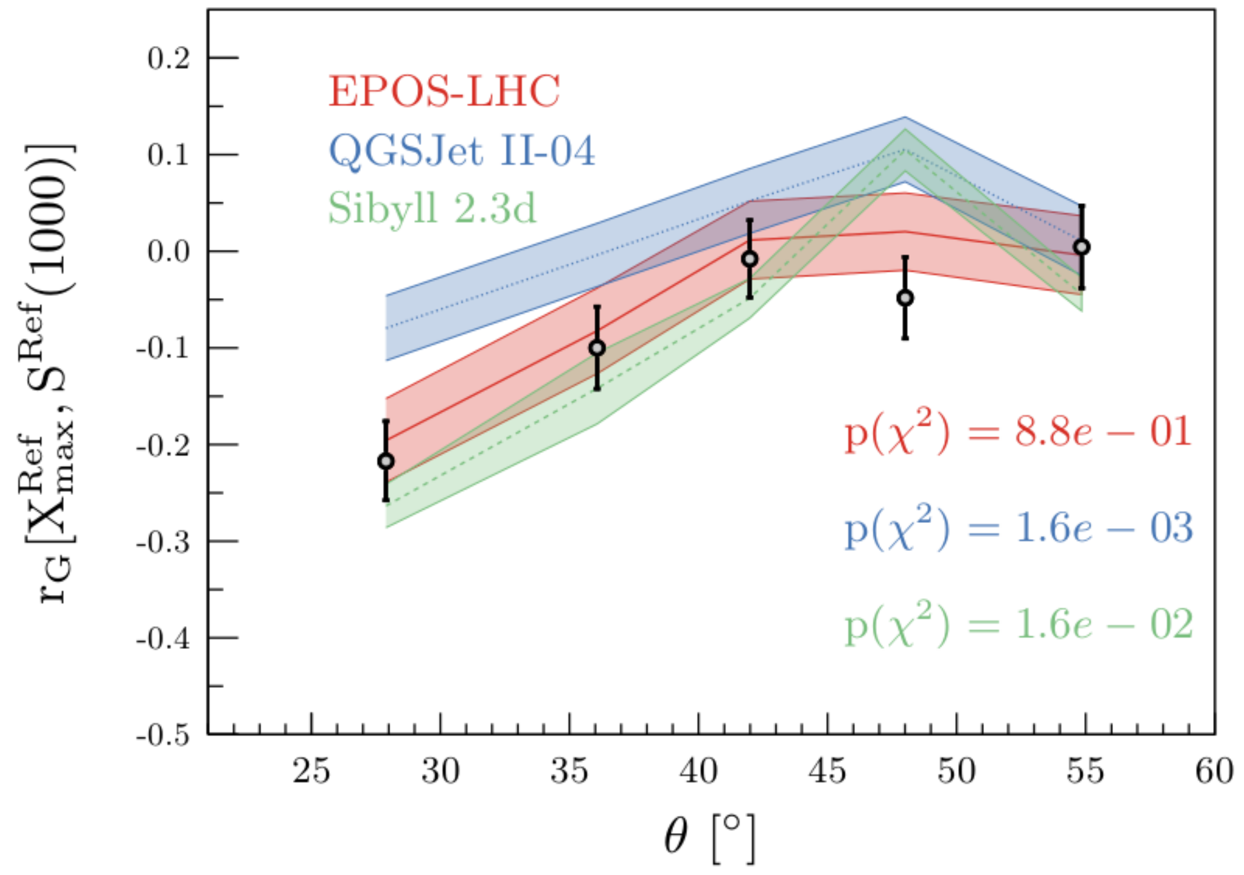


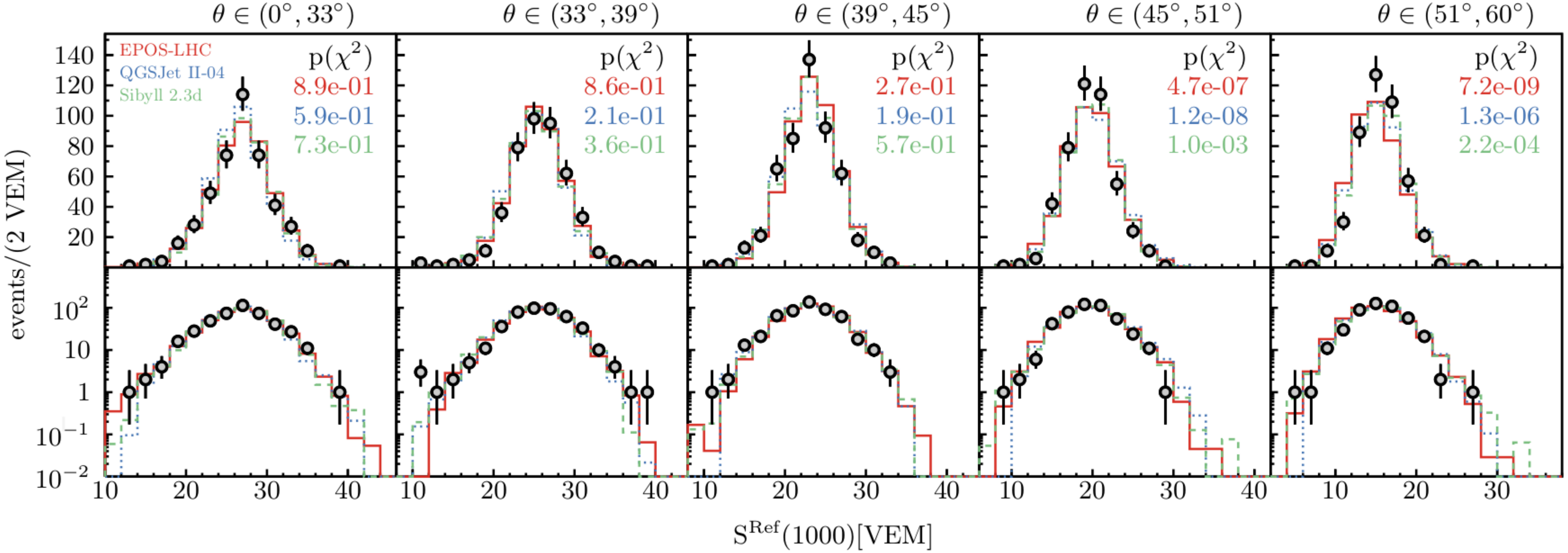
Gideon-Hollister correlation coeficient
[J. Am. Stat. Assoc. 82 (1987) 656]



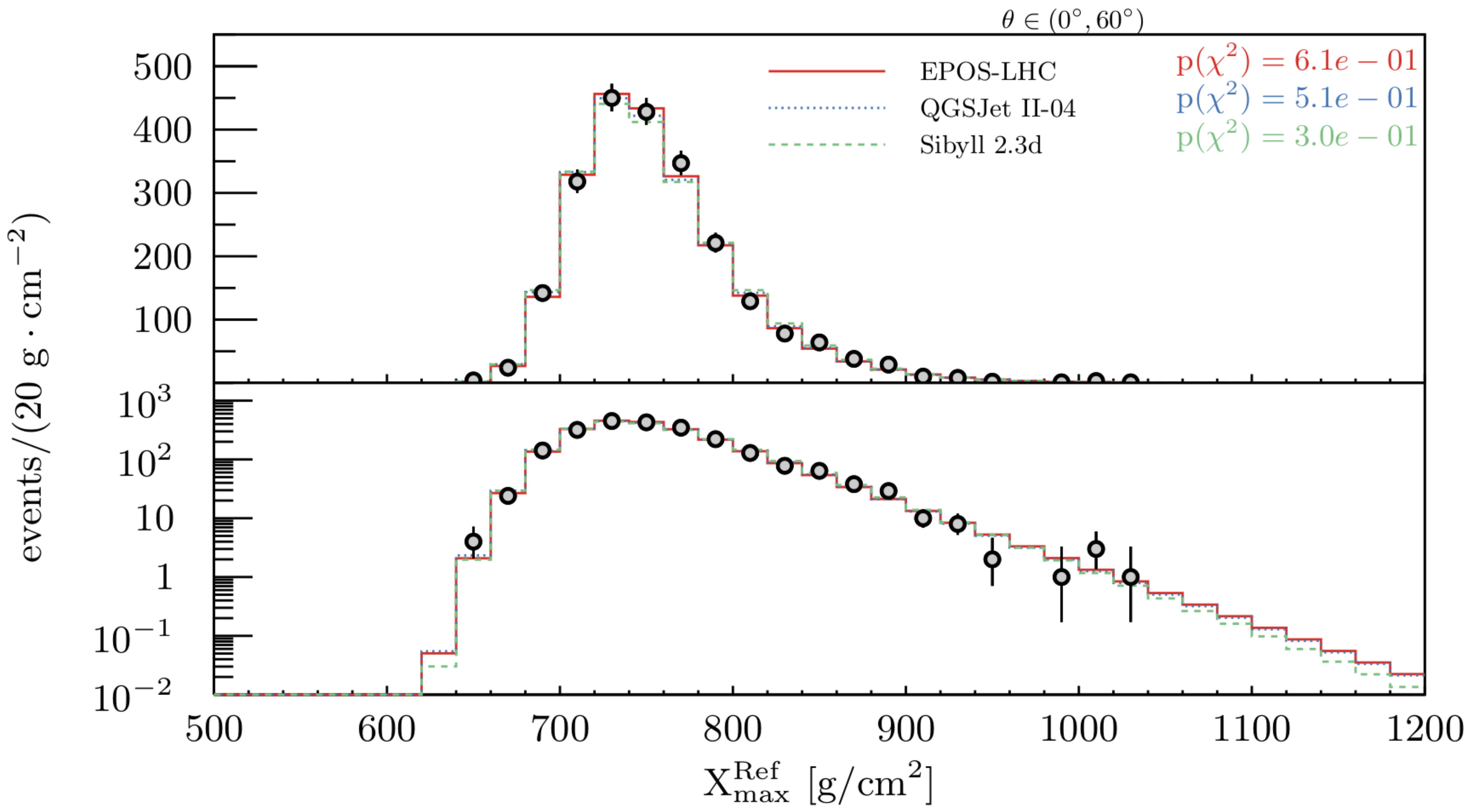
Test: 2D fit with rescaling hadronic component

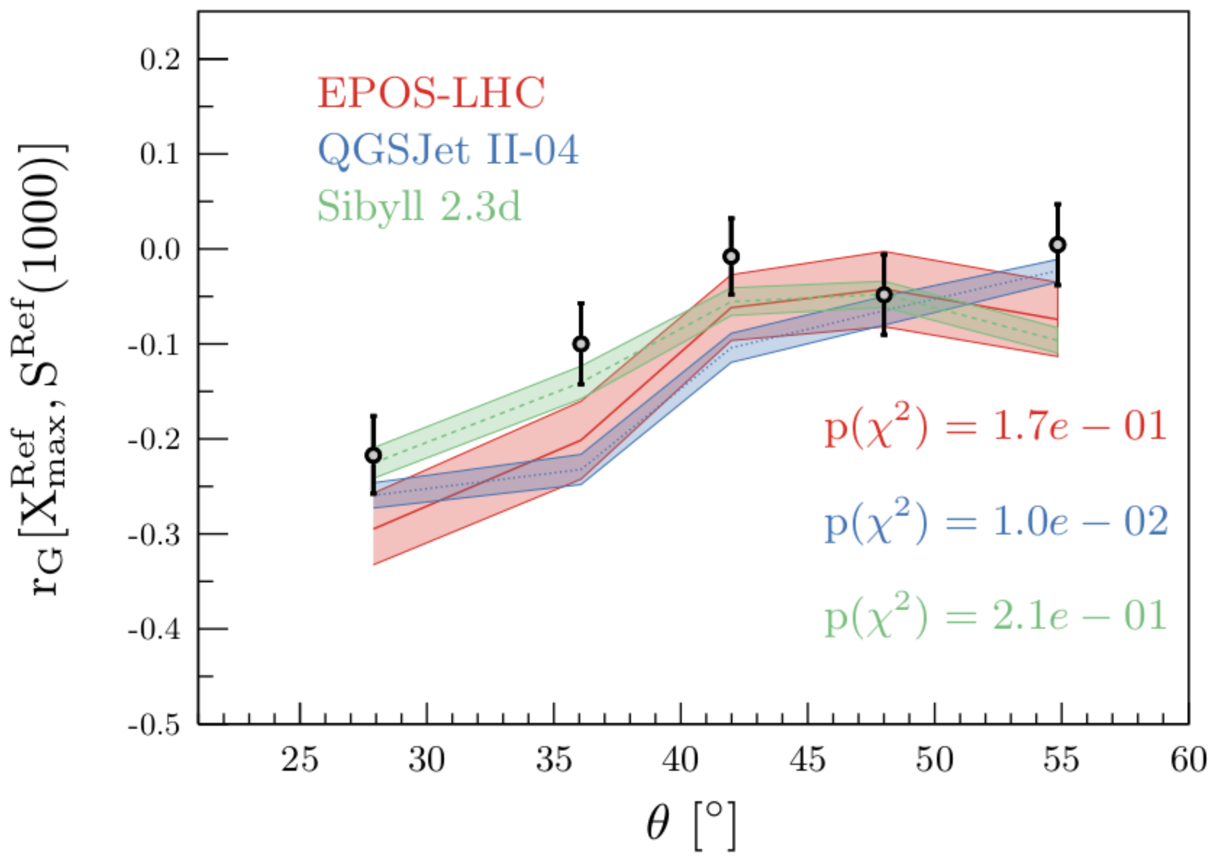


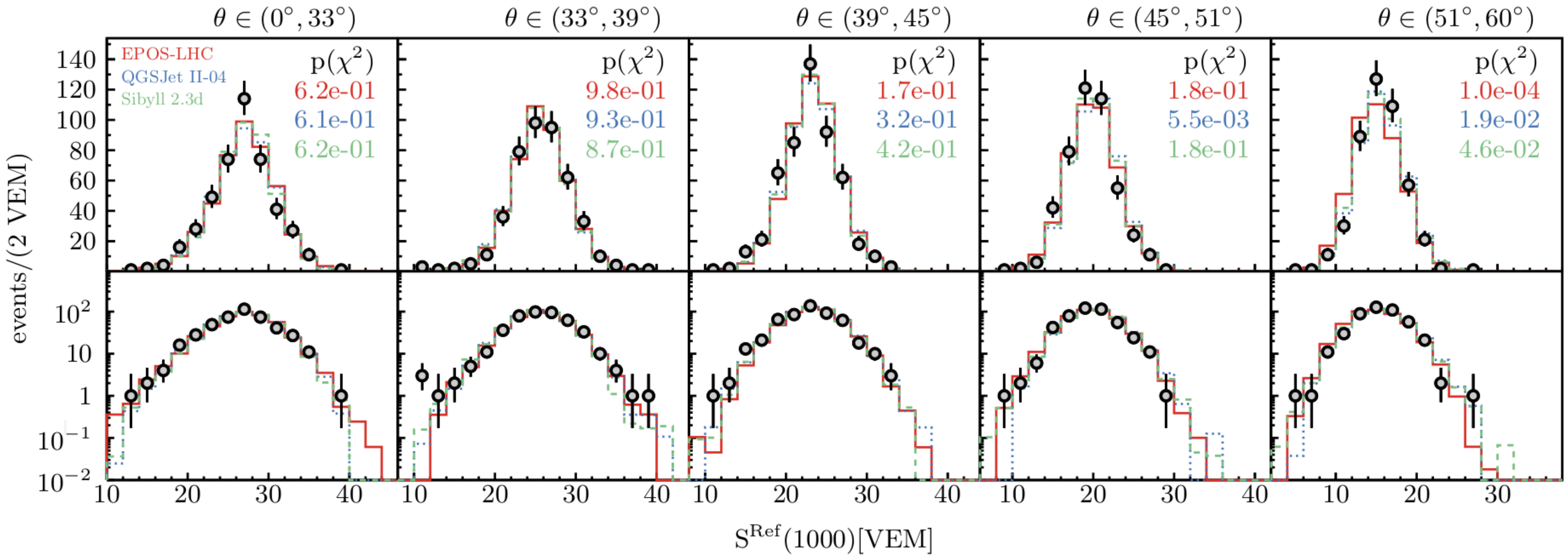




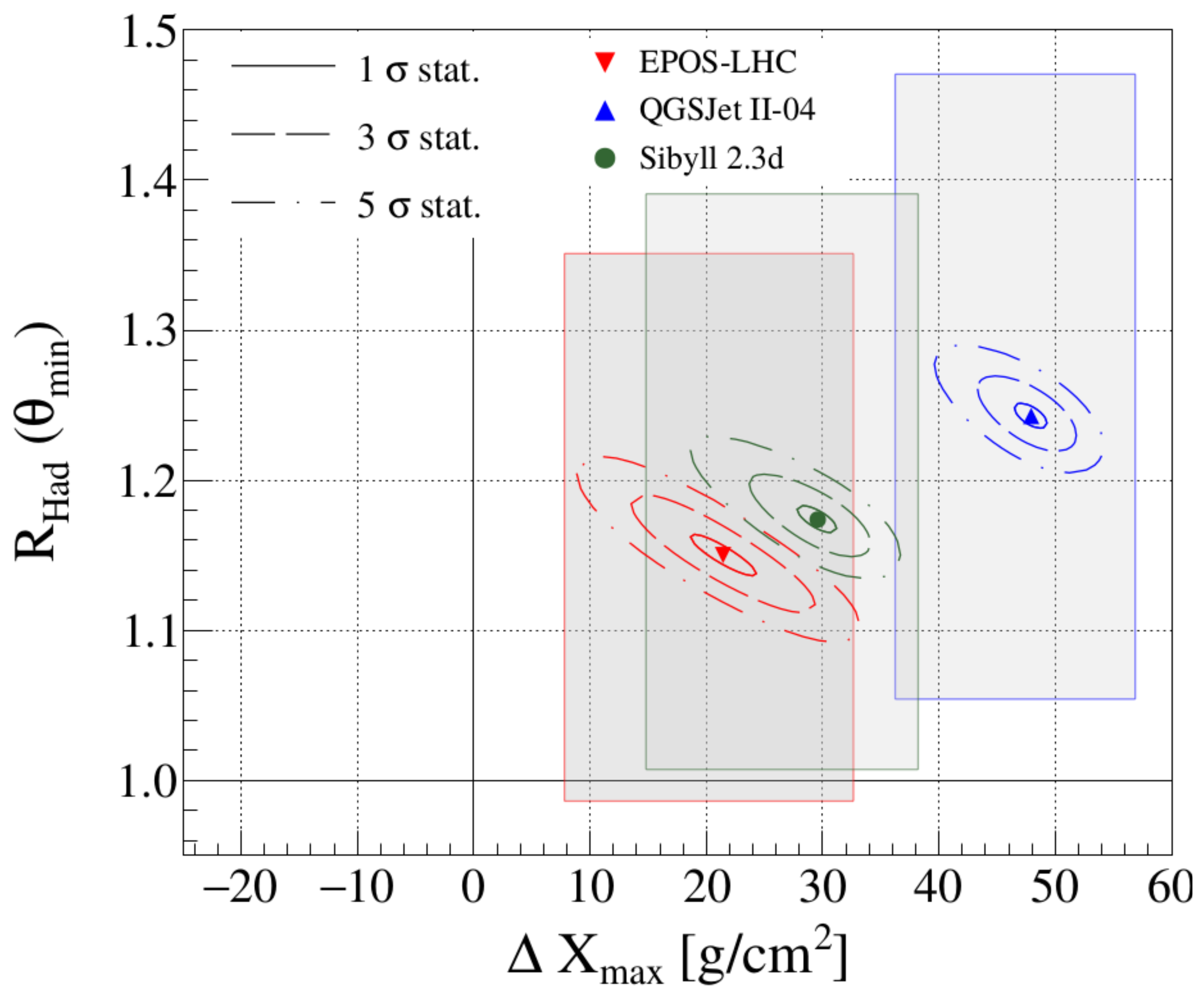
Test: 2D fit with rescaling had. component and shifting Xmax

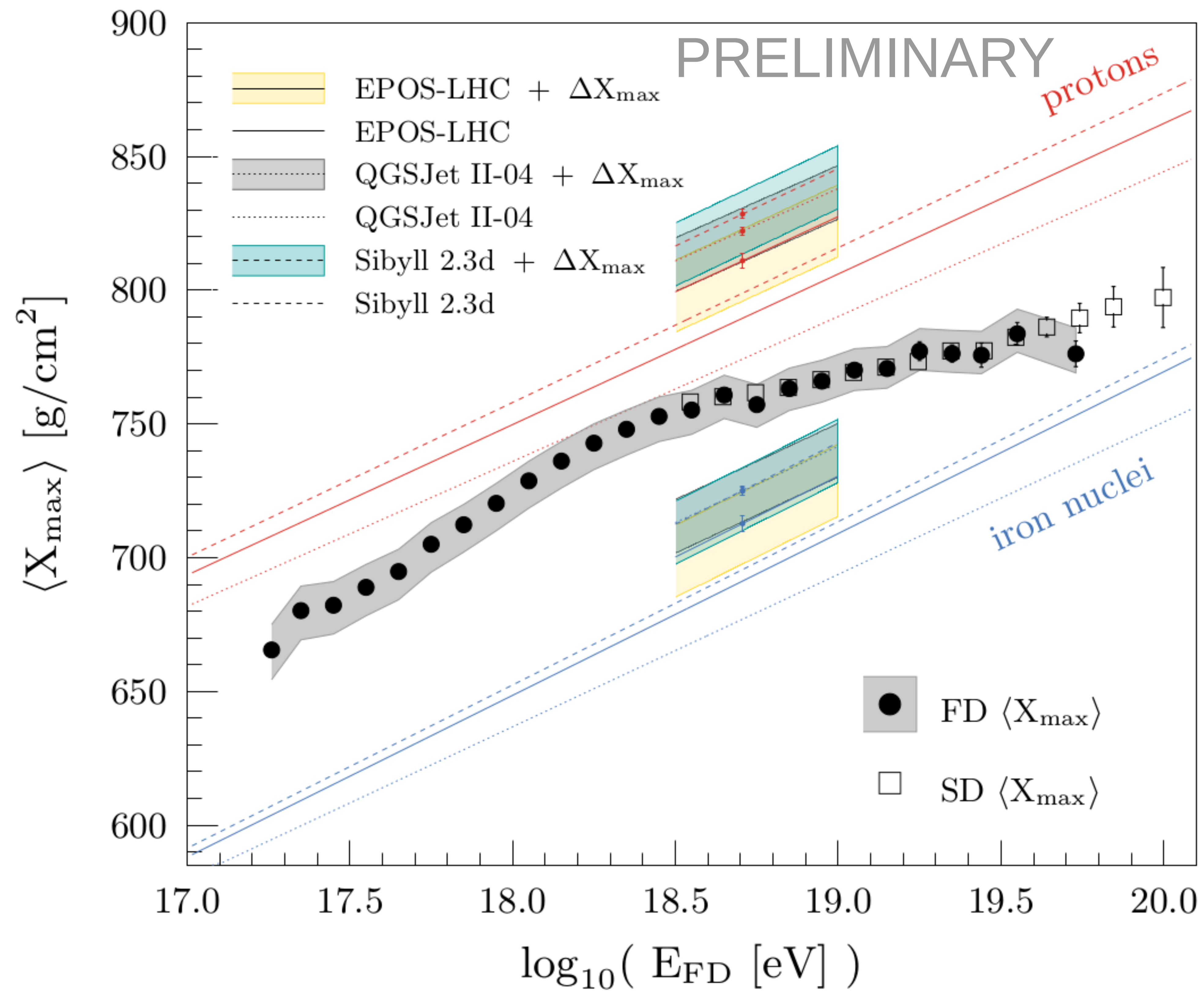






Test: modification of hadronic interaction models (ii)





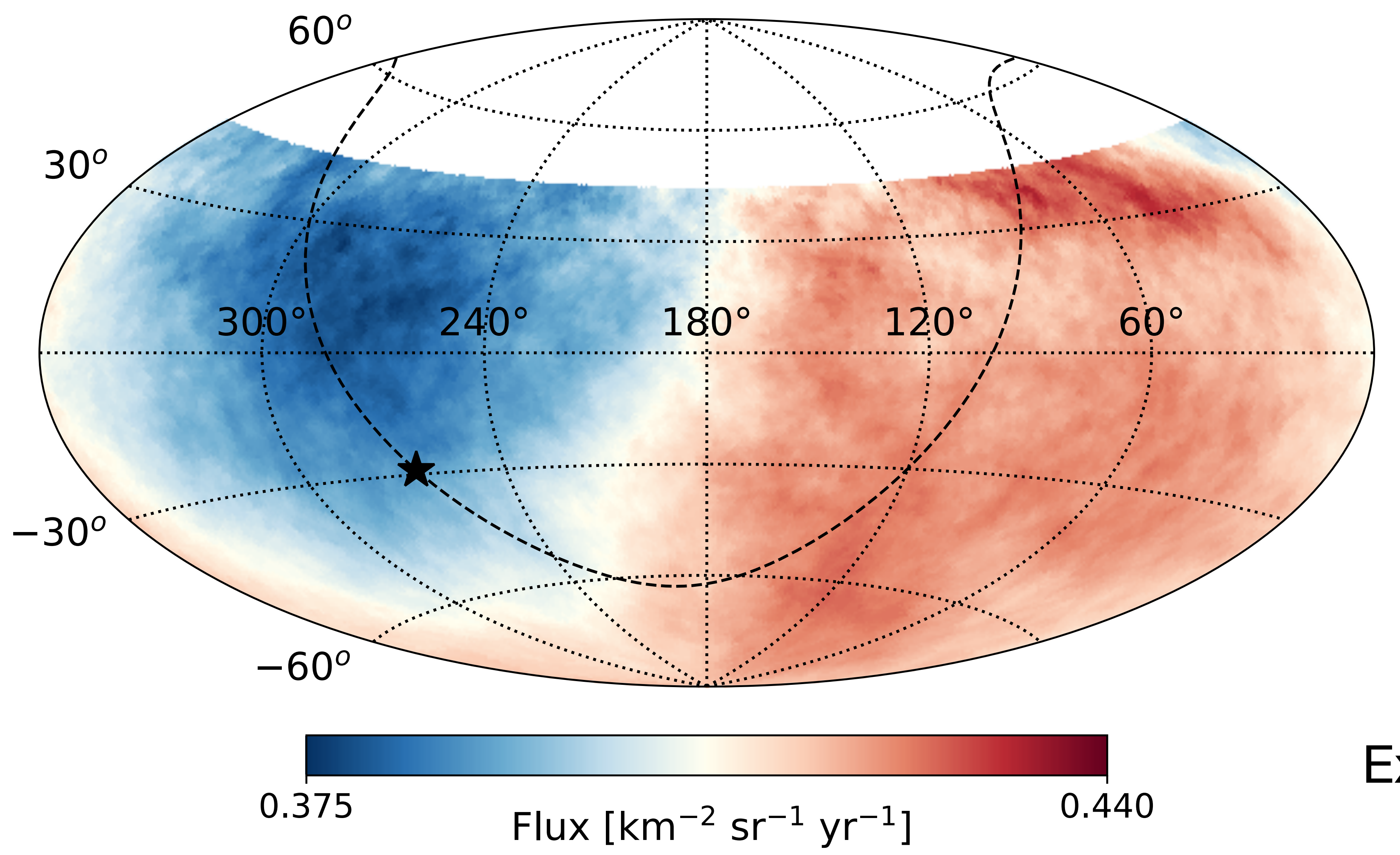
(Auger, UHECR 2022)

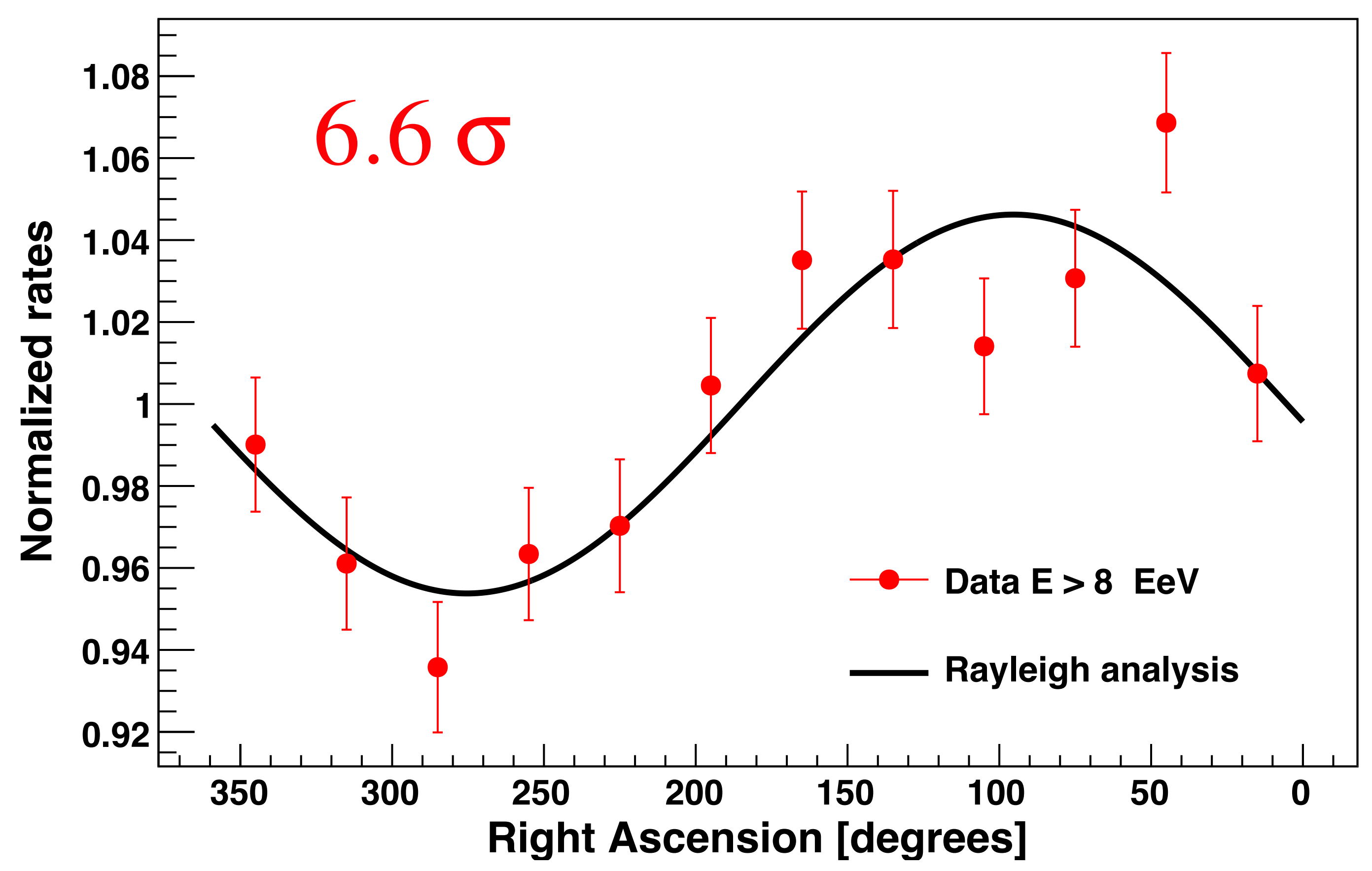
Assumption: relative fluctuations not changed

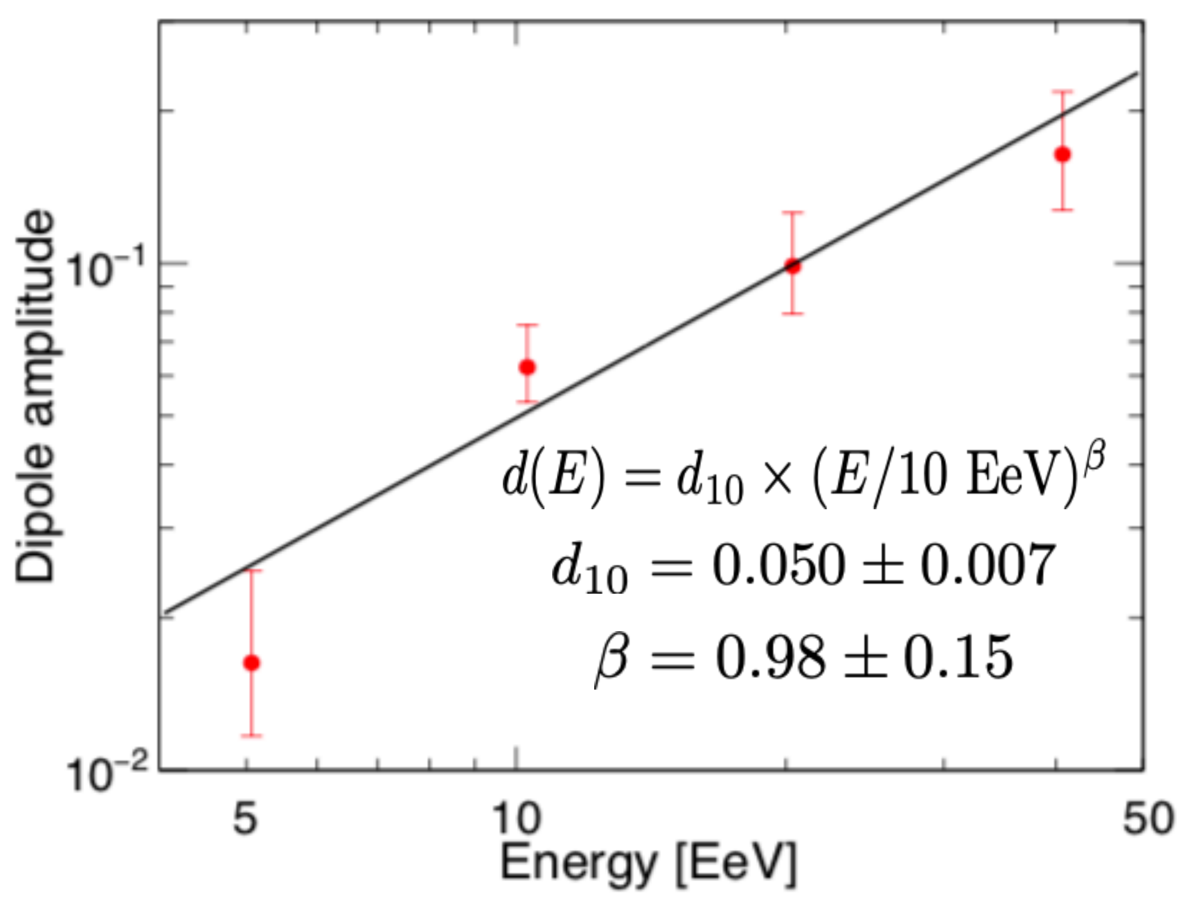
Main improvement by re-scaling muon component (attenuation, more muons at ground)

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

Anisotropy on large angular scales – dipole

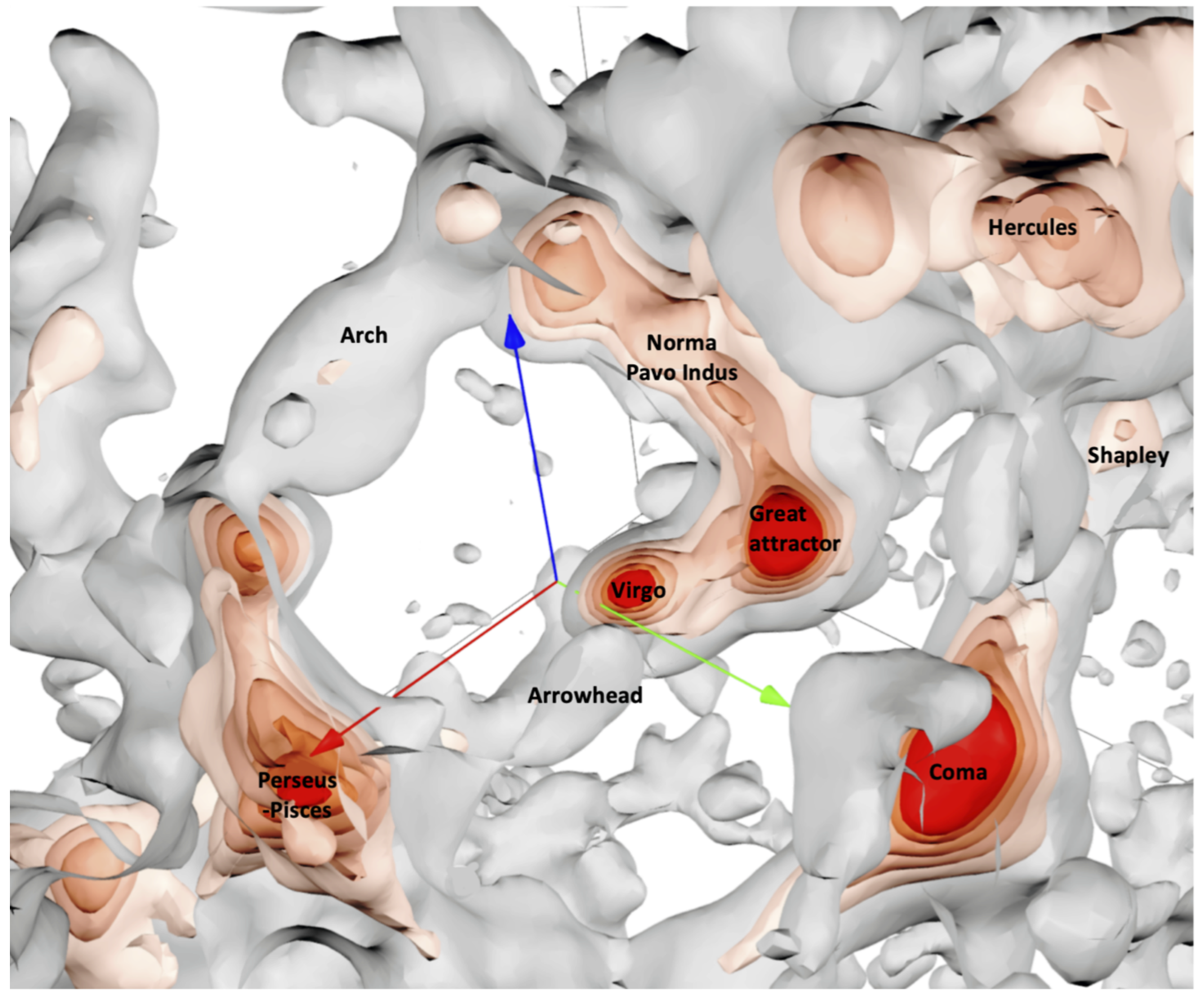






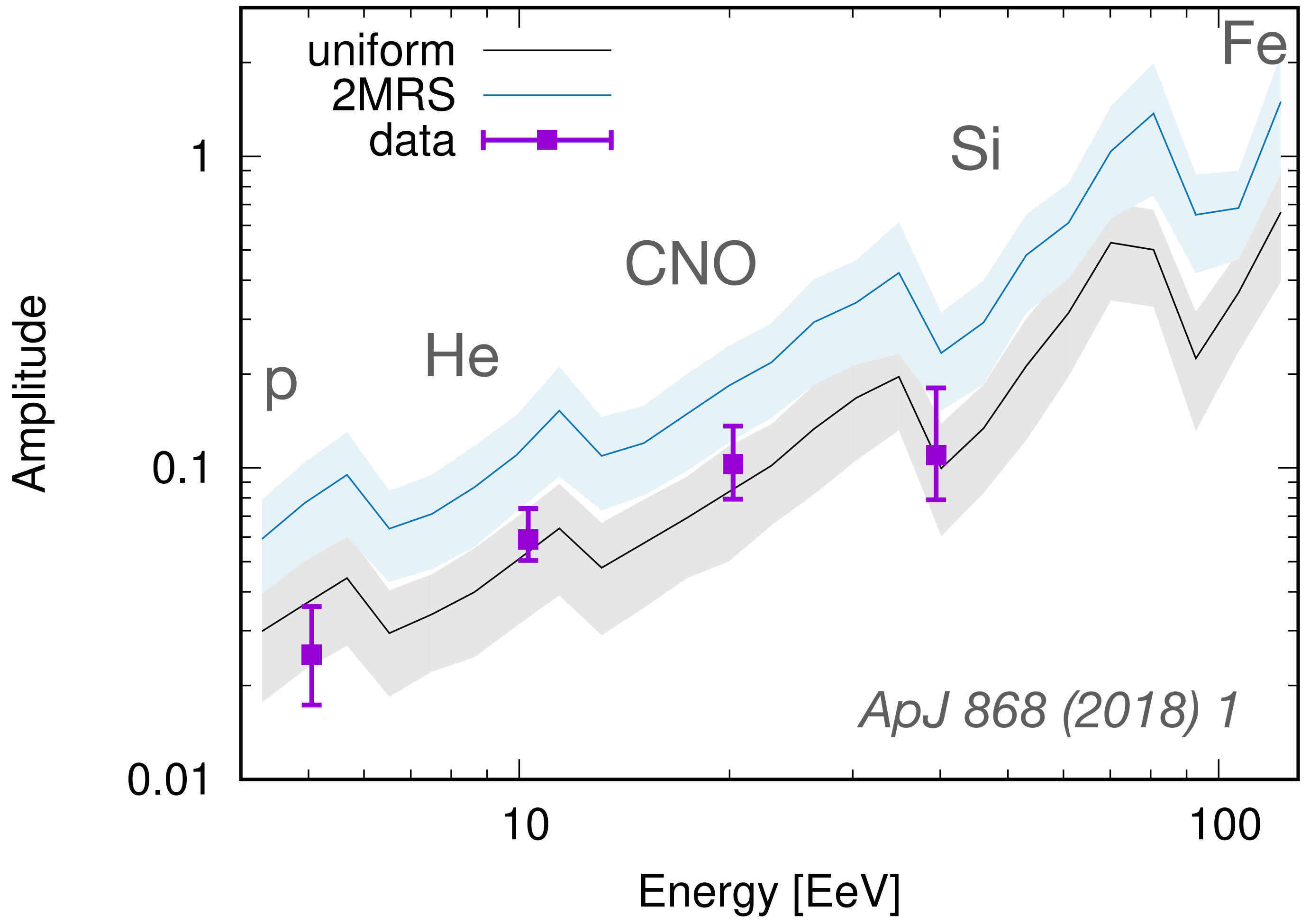
Exposure until end of 2020 (θ < 80°): 110,000 km^2 sr yr

$$p \sim 5 \times 10^{-11}$$



Fundamental observation: non-trivial interplay of

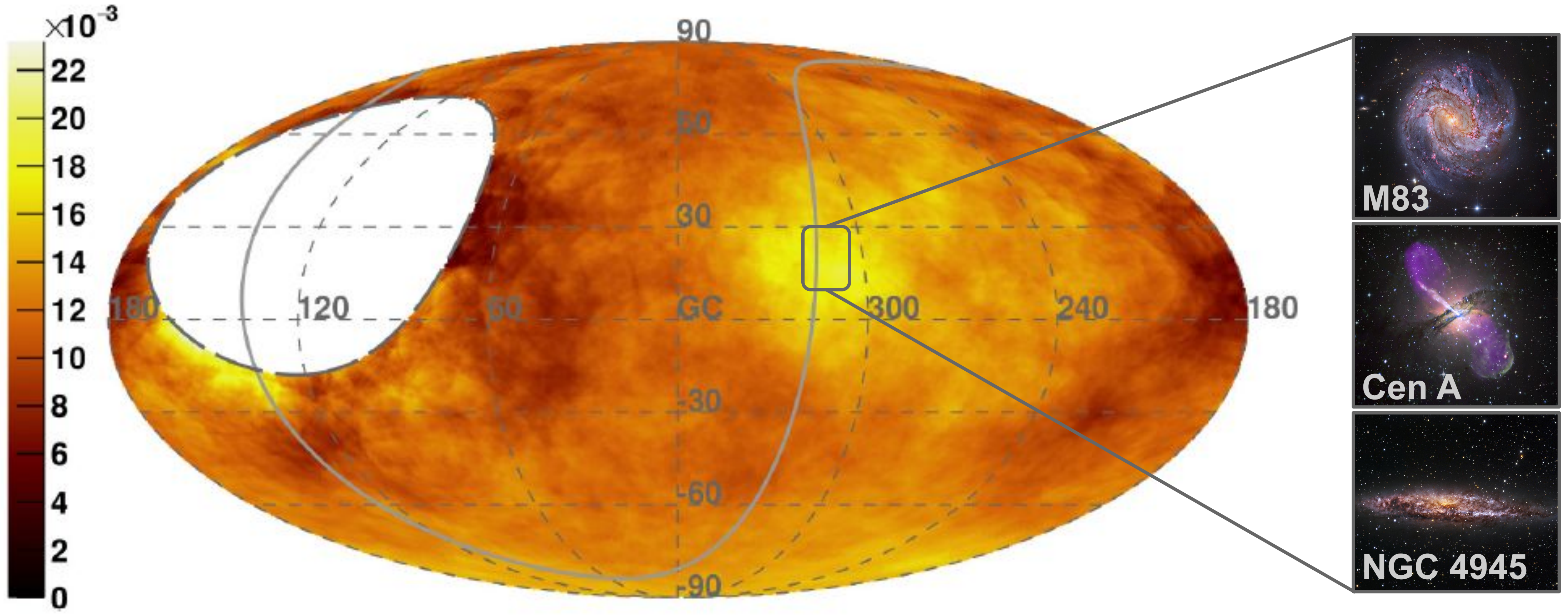
- **mass composition,**
- **magnetic horizon and**
- **local source distribution**



(Ding, Globus & Farrar 2101.04564)

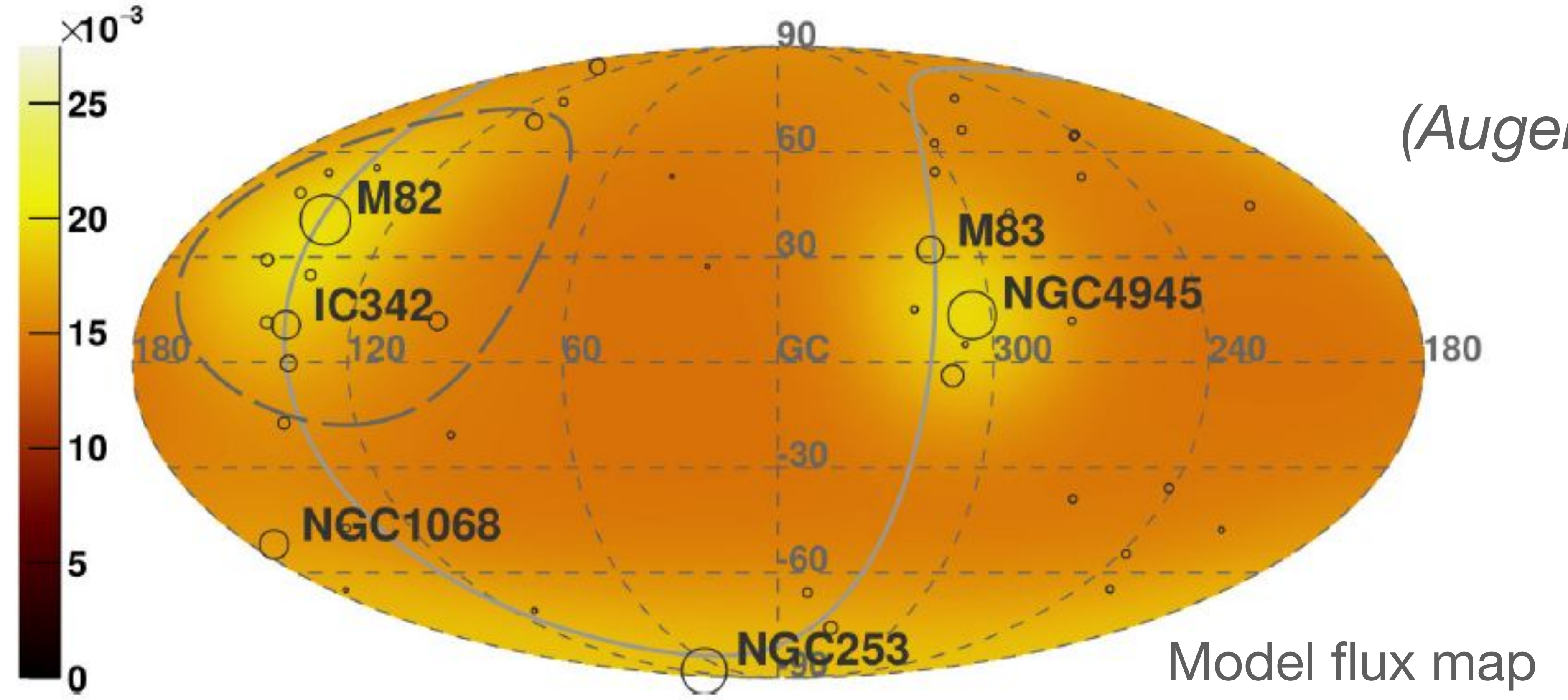
(Harari, Mollerach, Roulet PRD92 (2015) 06314)

Anisotropy searches at highest energies – catalogs



Direction fixed to that of Cen A, free E_{th} and Ψ

E_{th} > 41 EeV, Ψ = 27°: **3.9σ post-trial** deviation from isotropy (5% excess)

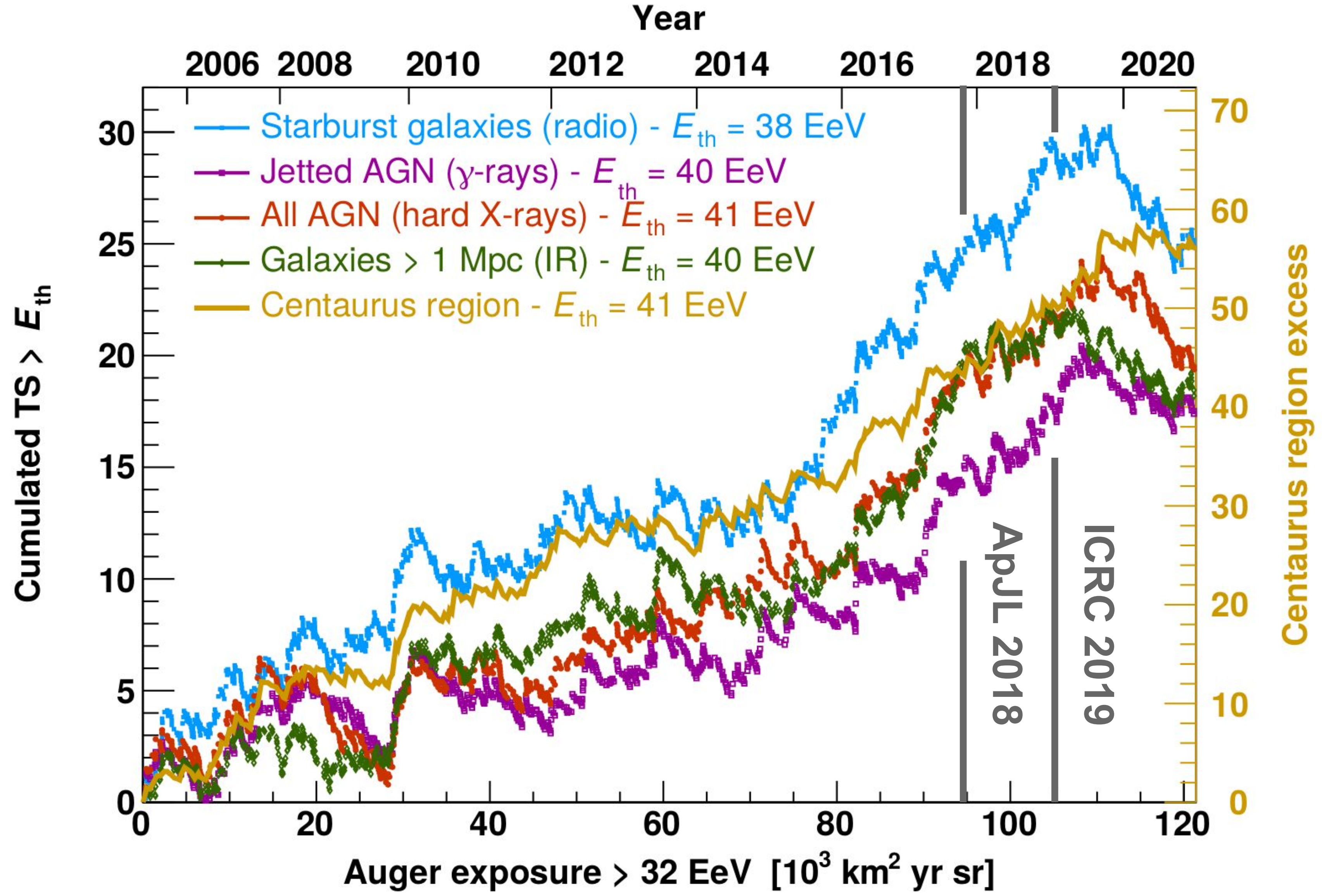


(Auger, ApJ 935 (2022) 170)

Model flux map

All data until end of 2020, optimized quality cuts: 120,000 km² sr yr

Catalog	E_{th} [EeV]	Ψ [deg]	α [%]	TS	Post-trial p-value
All galaxies (IR)	40	24^{+16}_{-8}	15^{+10}_{-6}	18.2	6.7×10^{-4}
Starbursts (radio)	38	25^{+11}_{-7}	9^{+6}_{-4}	24.8	3.1×10^{-5}
All AGNs (X-rays)	41	27^{+14}_{-9}	8^{+5}_{-4}	19.3	4.0×10^{-4}
Jetted AGNs (γ-rays)	40	23^{+9}_{-8}	6^{+4}_{-3}	17.3	1.0×10^{-3}



4.0σ

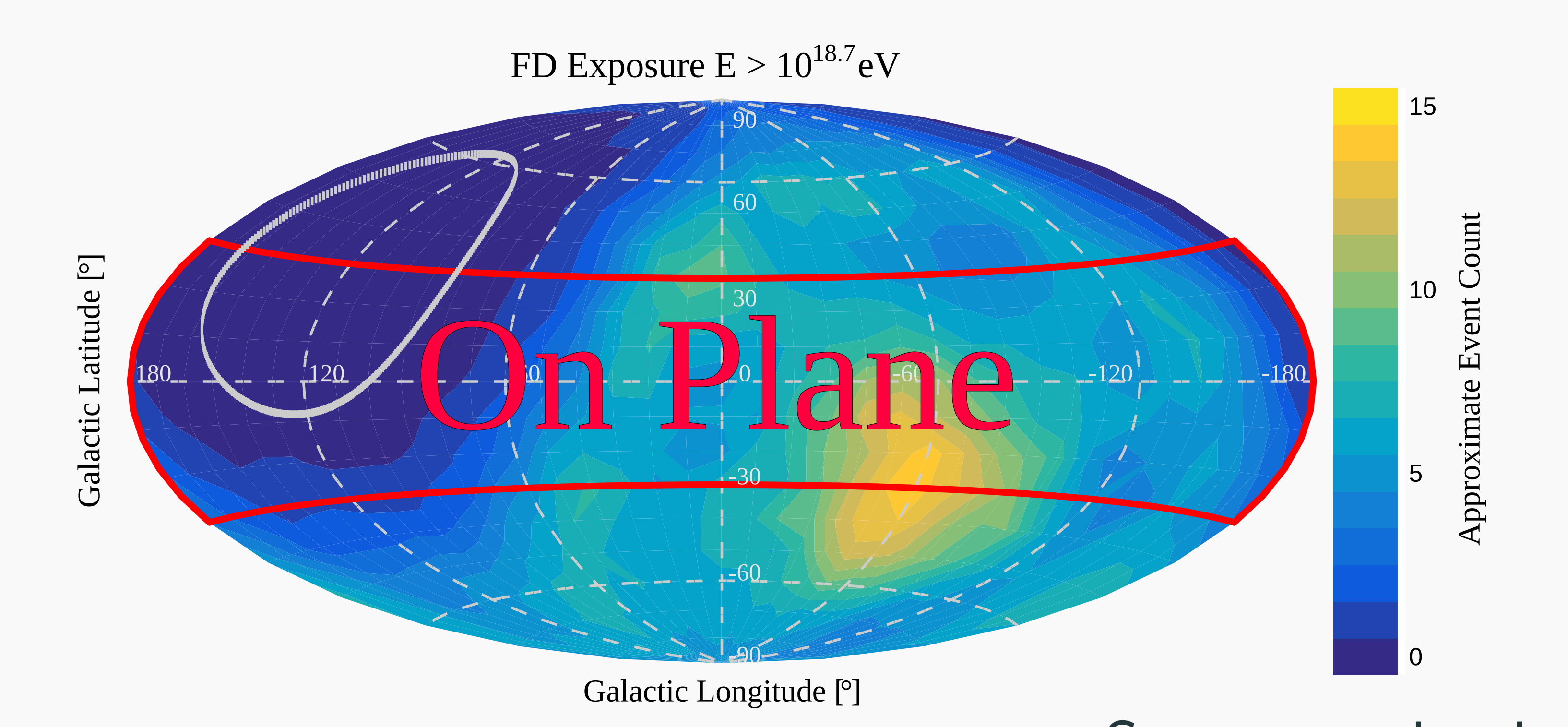
3.1σ

Growth of test statistic (TS) compatible with linear increase

Discovery threshold of 5σ expected in 2025 – 2030 (Phase II)

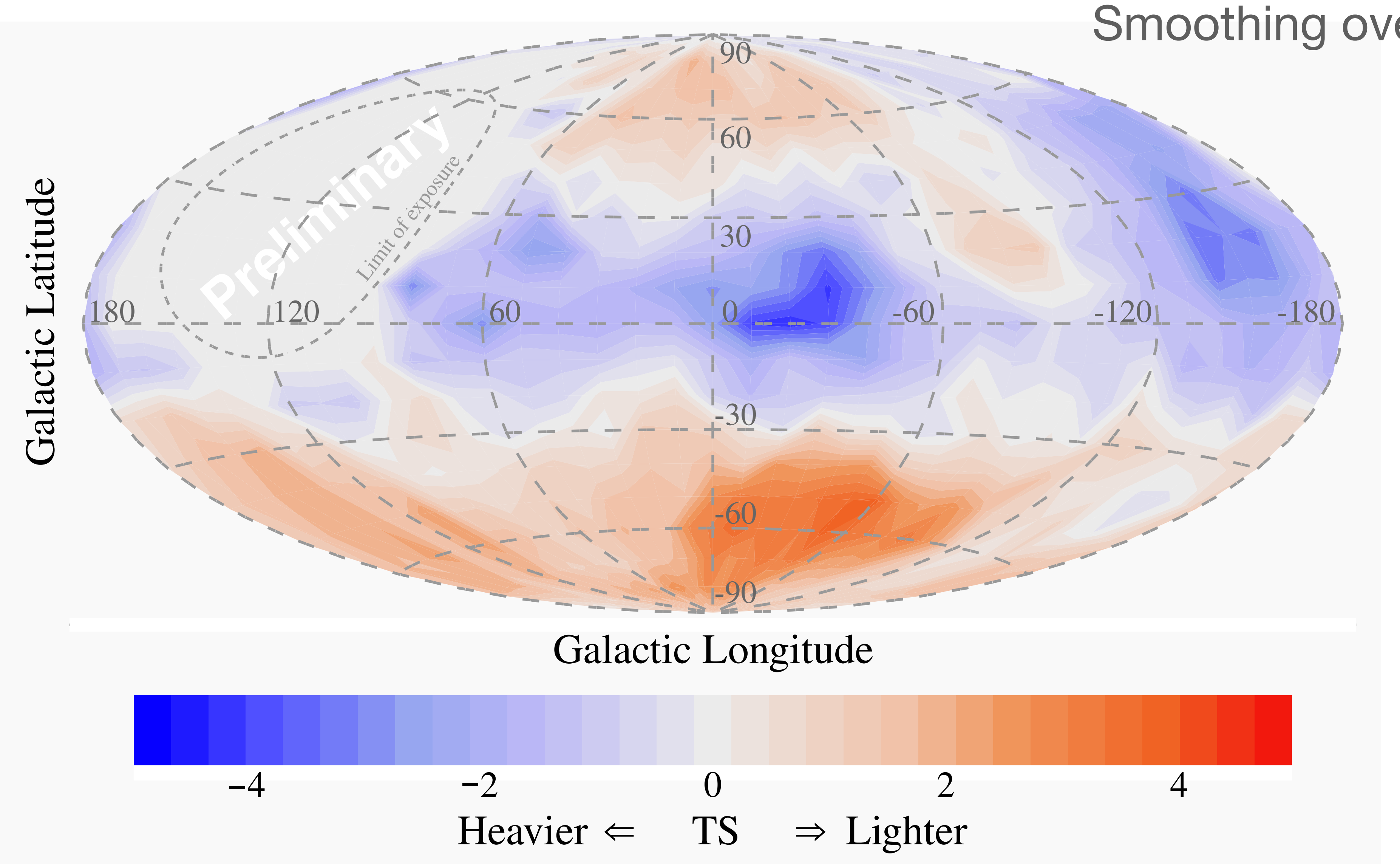
Other means to increase sensitivity (Auger 85% sky coverage)

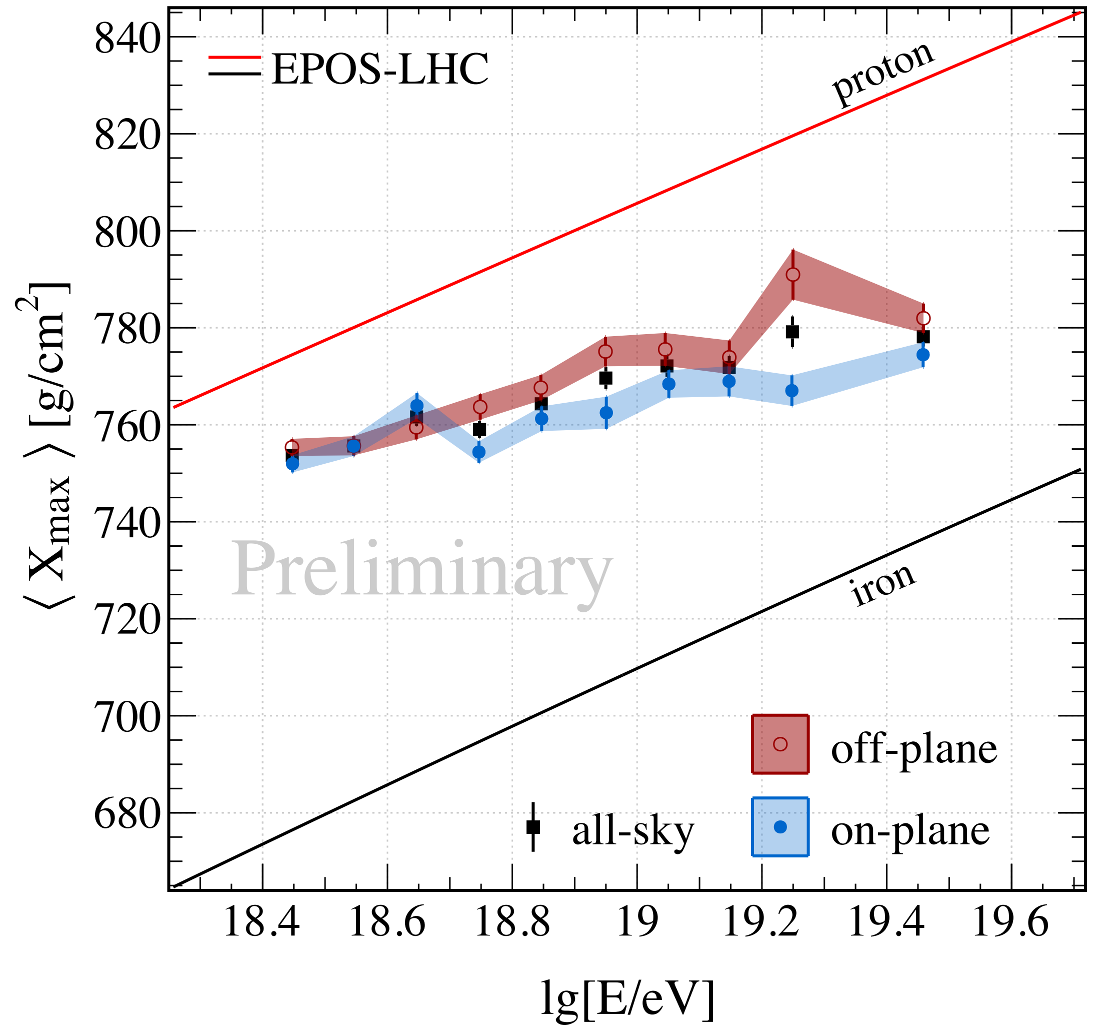
First look at composition and anisotropy

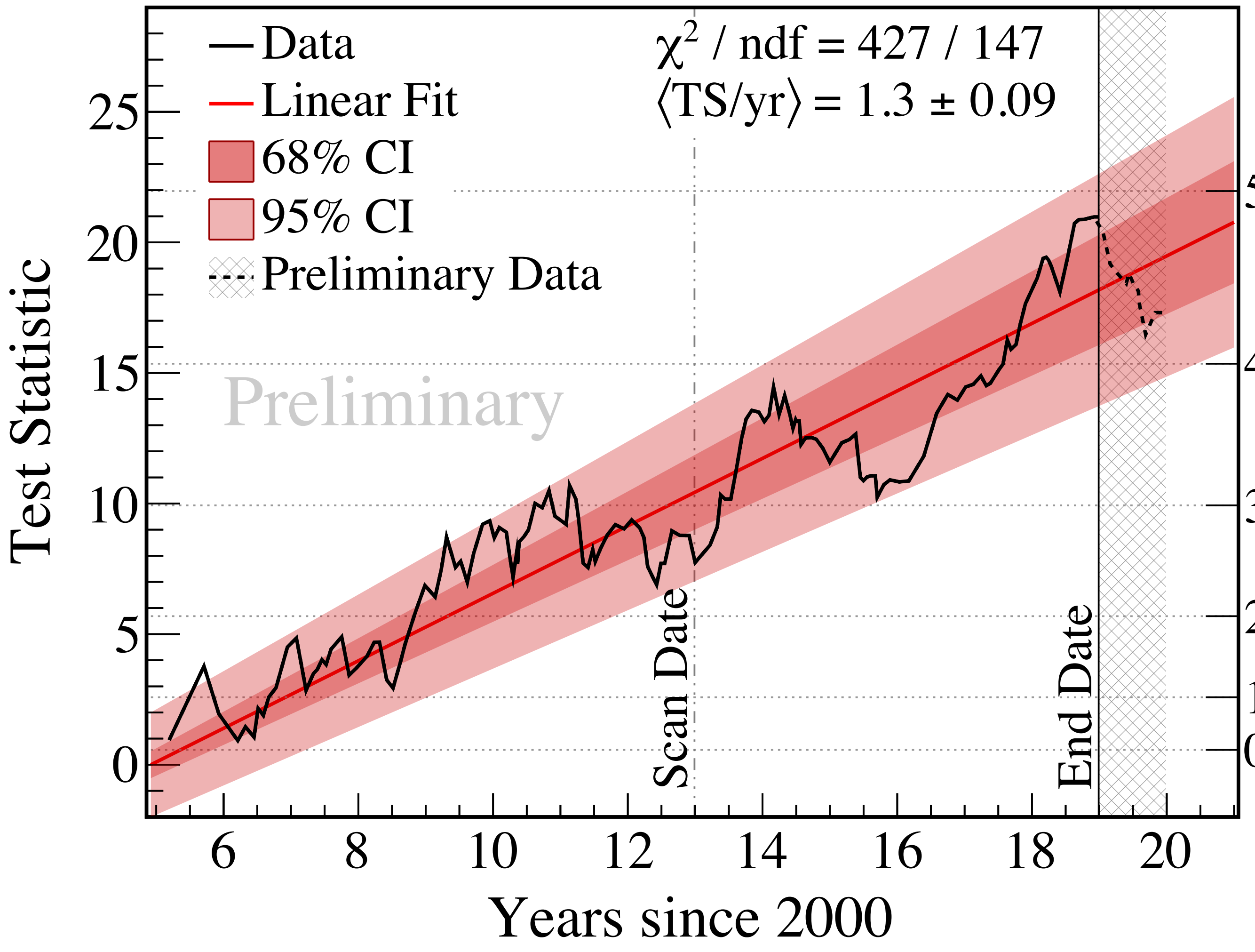


- Scan over the data recorded before 01.01.2013 (54 %)
- 5° steps in b and 0.1 $\lg(E/\text{eV})$ steps in energy
- Highest TS of 8.35 for: $\rightarrow E_{\text{min}} = 10^{18.7}$ eV
  $\rightarrow b_{\text{split}} = 30°$

Smoothing over 30° bins







Not necessarily related to Galaxy

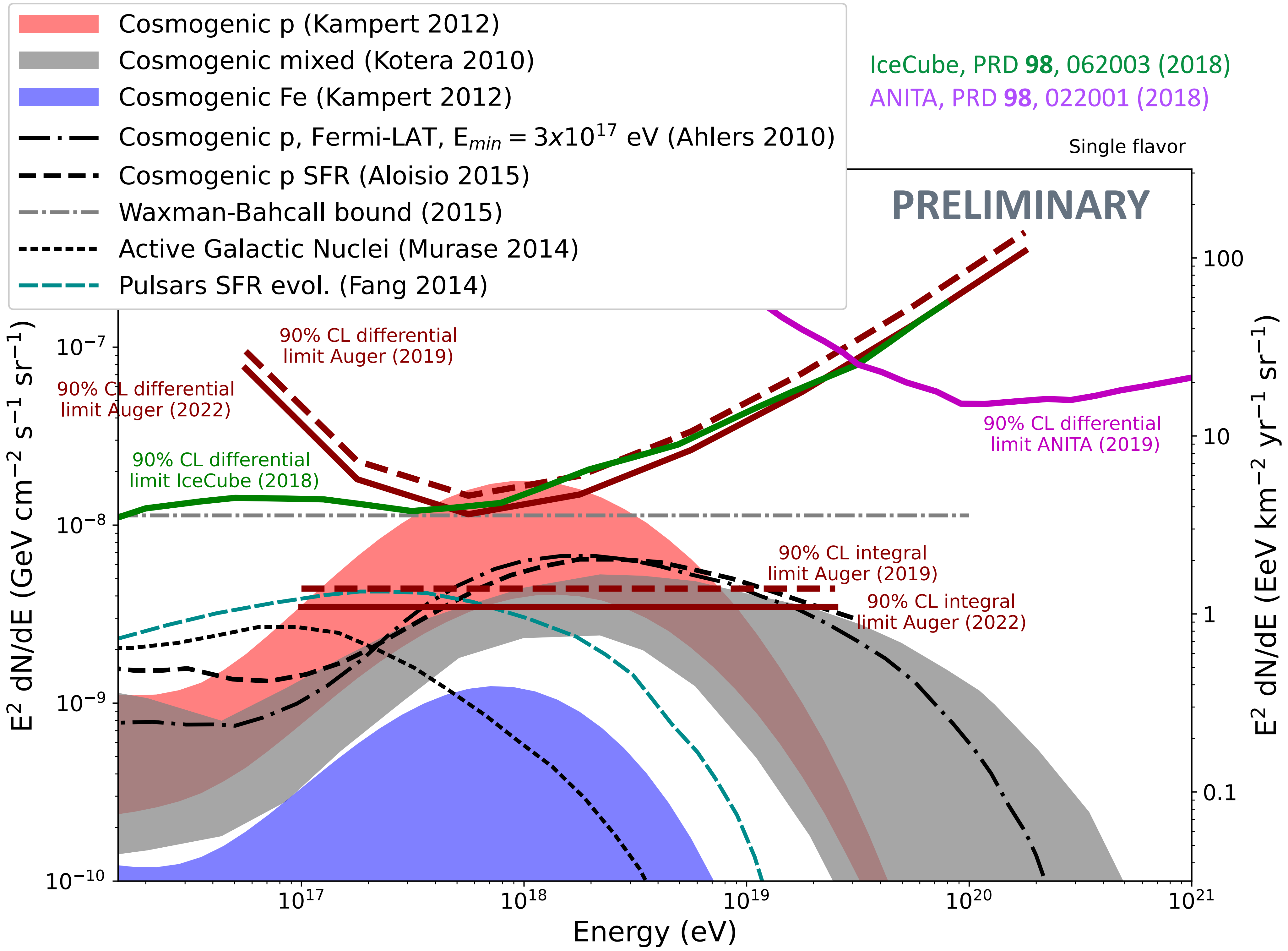
Local source distribution and mass-dependent horizon effect?

No independent confirmation from other data

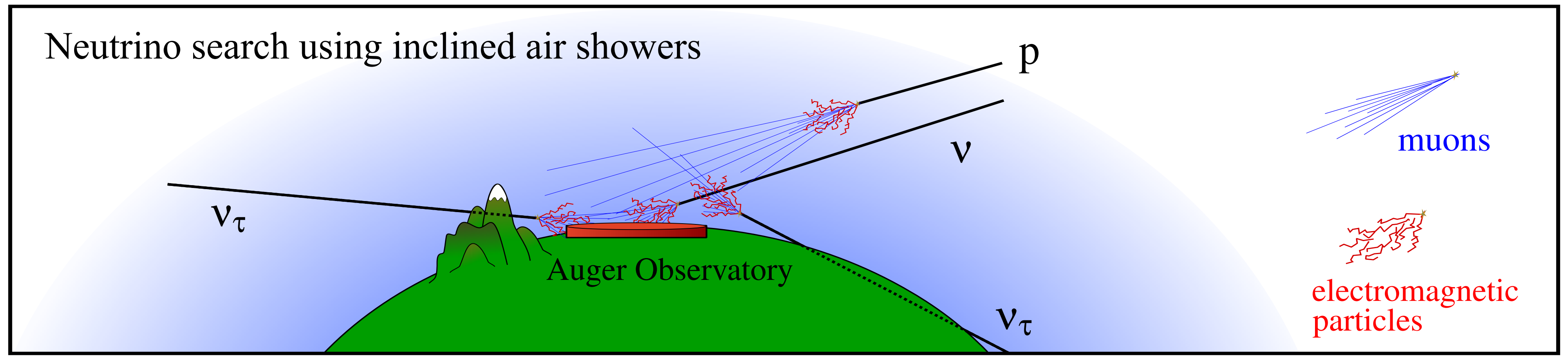
Phase II data and more statistics really important to make progress

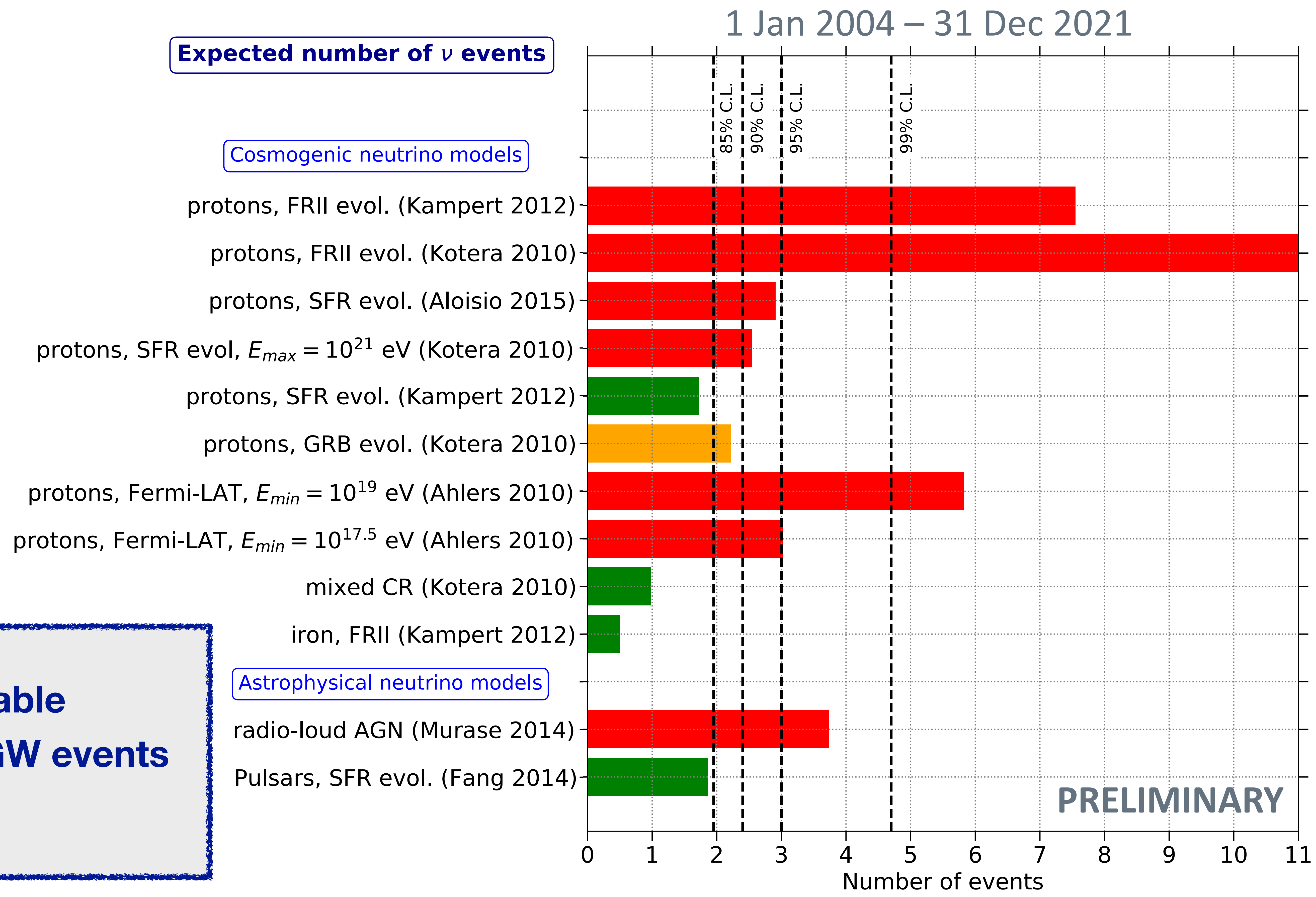
(Auger, UHECR 2022 & ICRC 2021)

Neutrinos and multi-messenger observations



(Auger, UHECR 2022 & ICRC 2021)





Aperture comparable to IceCube if direction of source is favorable

Multi-messenger: searches for neutrinos in coincidence with GW events

Phase II: lowering of detection threshold (new electronics)

Phase II: upgrade of the Observatory – AugerPrime

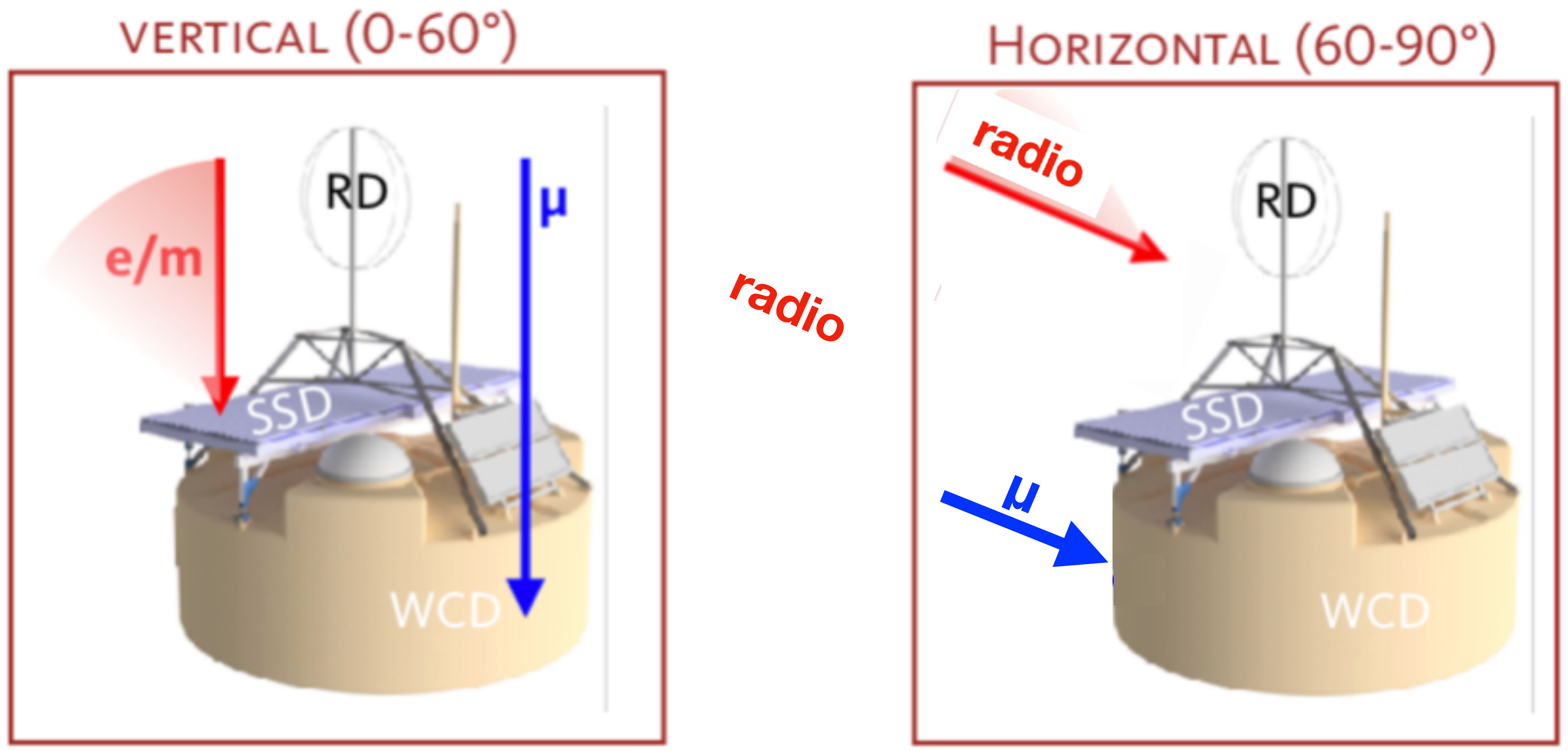
Physics motivation

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

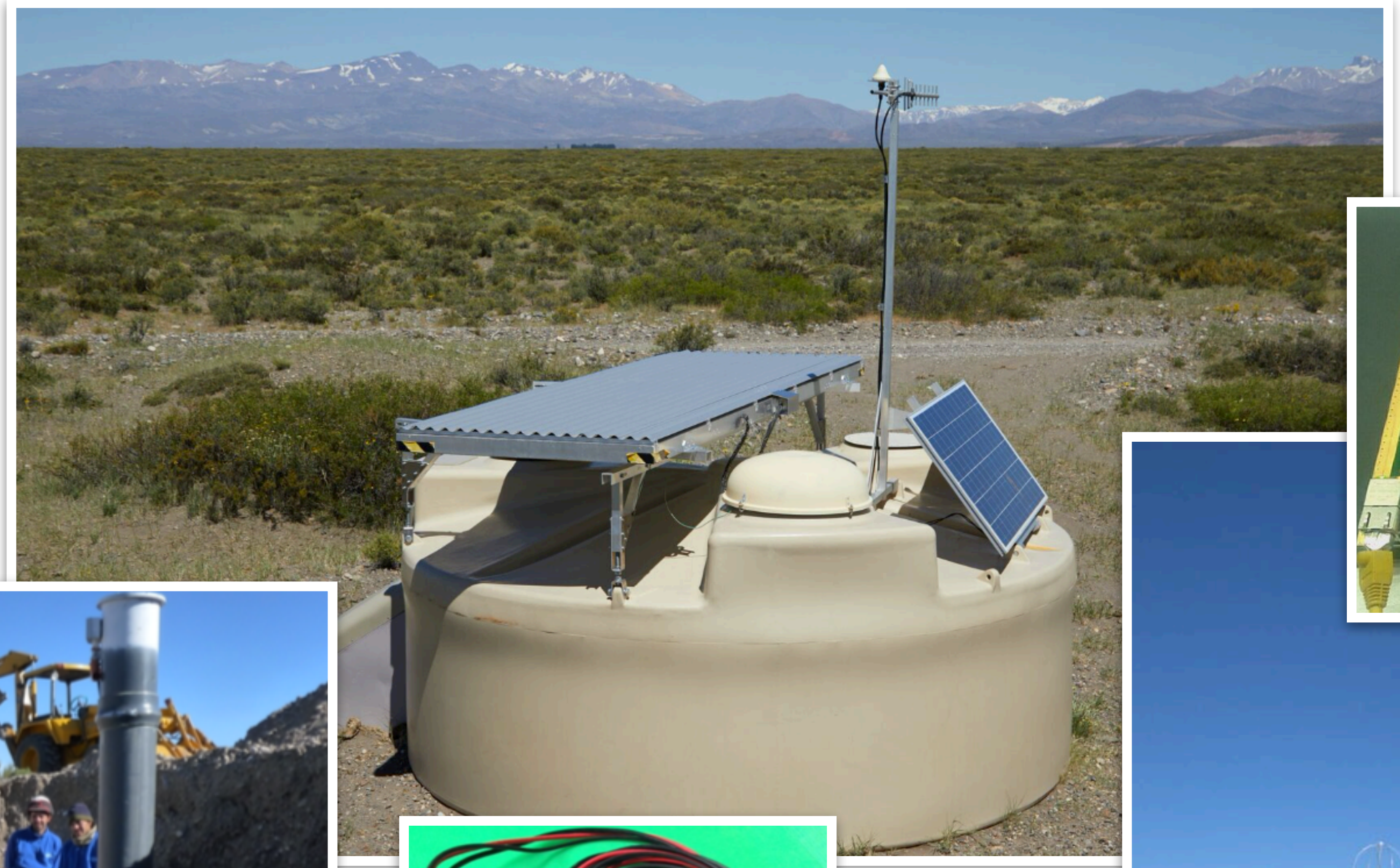
Components of AugerPrime

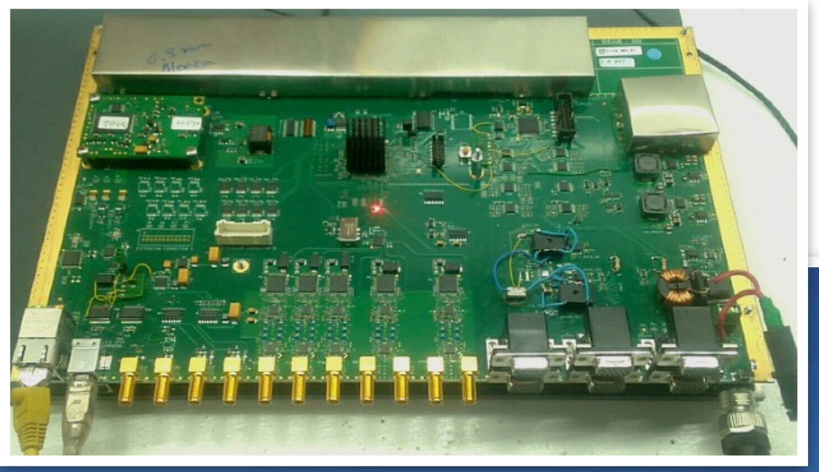
- 3.8 m^2 scintillator panels (SSD)
- New electronics (40 MHz -> 120 MHz)
- Small PMT (dynamic range WCD)
- Radio antennas for inclined showers
- Underground muon counters (750 m array, 433 m array)
- Enhanced duty cycle of fluorescence tel.

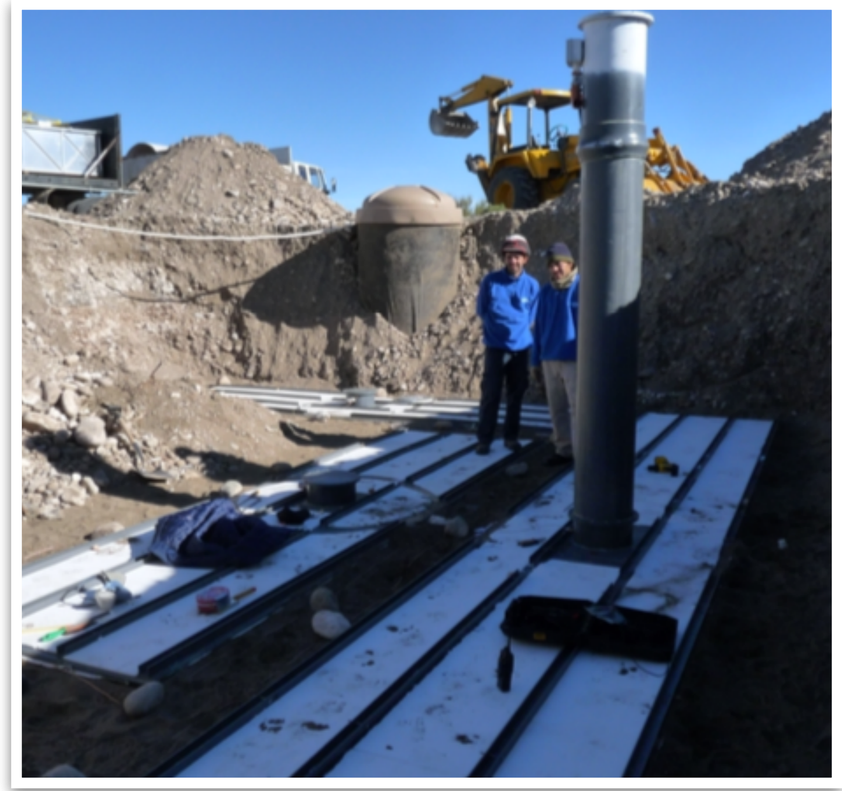
Composition sensitivity with 100% duty cycle



(AugerPrime design report 1604.03637)





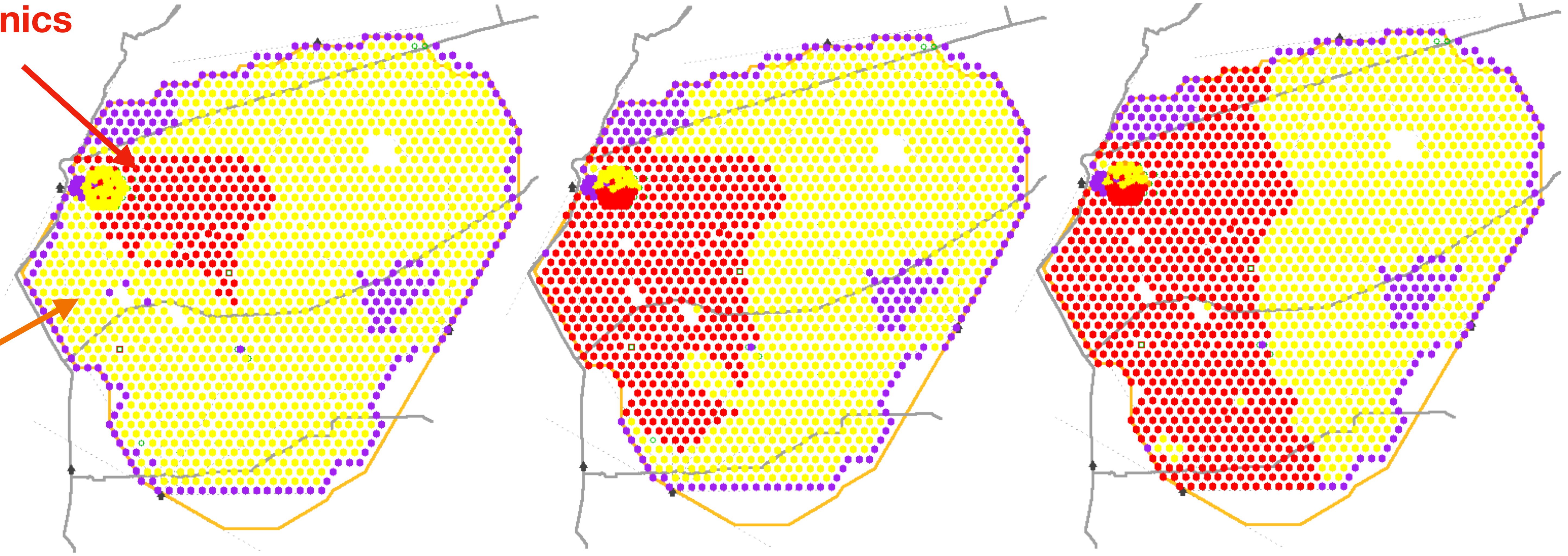


Transition to Phase II of the Observatory

Nov 2021 July 2022 Nov 2022

New electronics

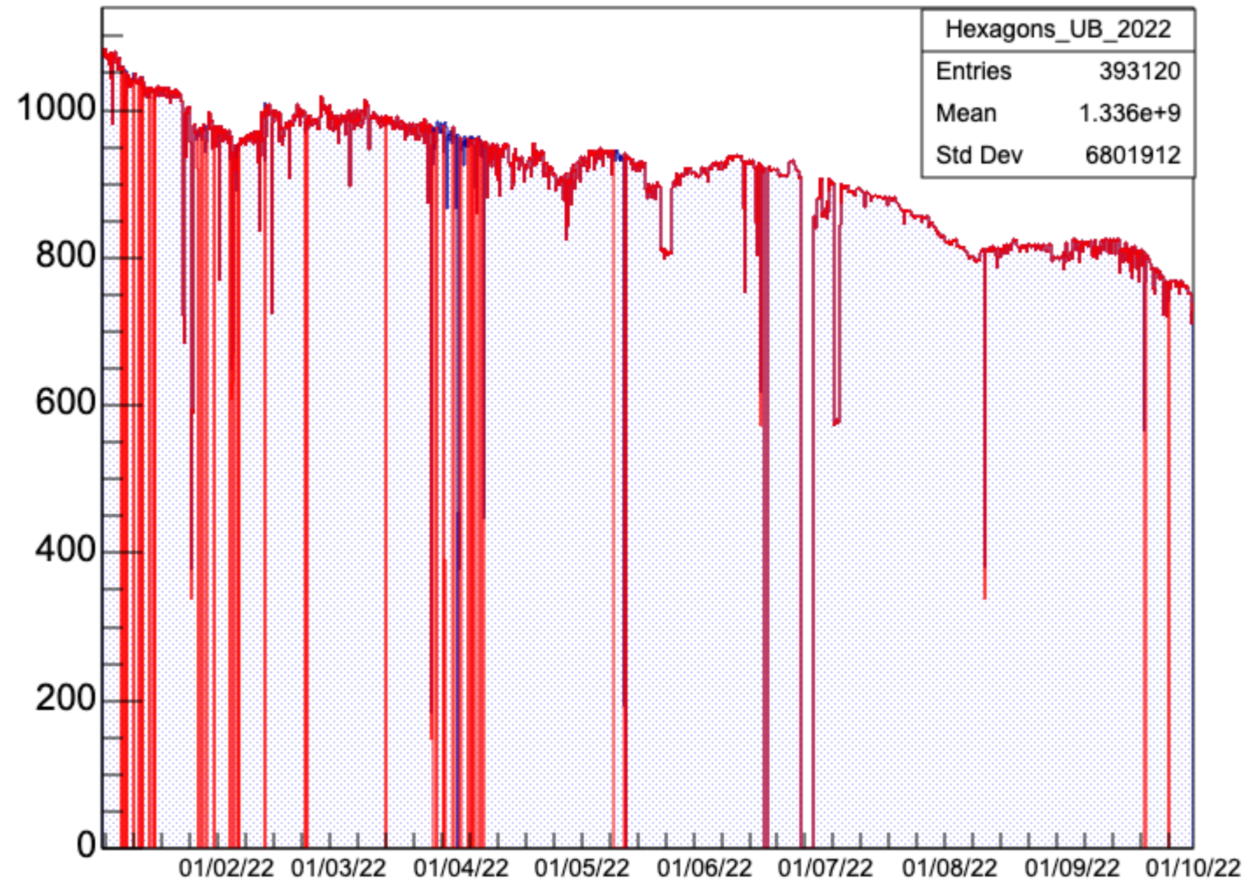
Scintillators



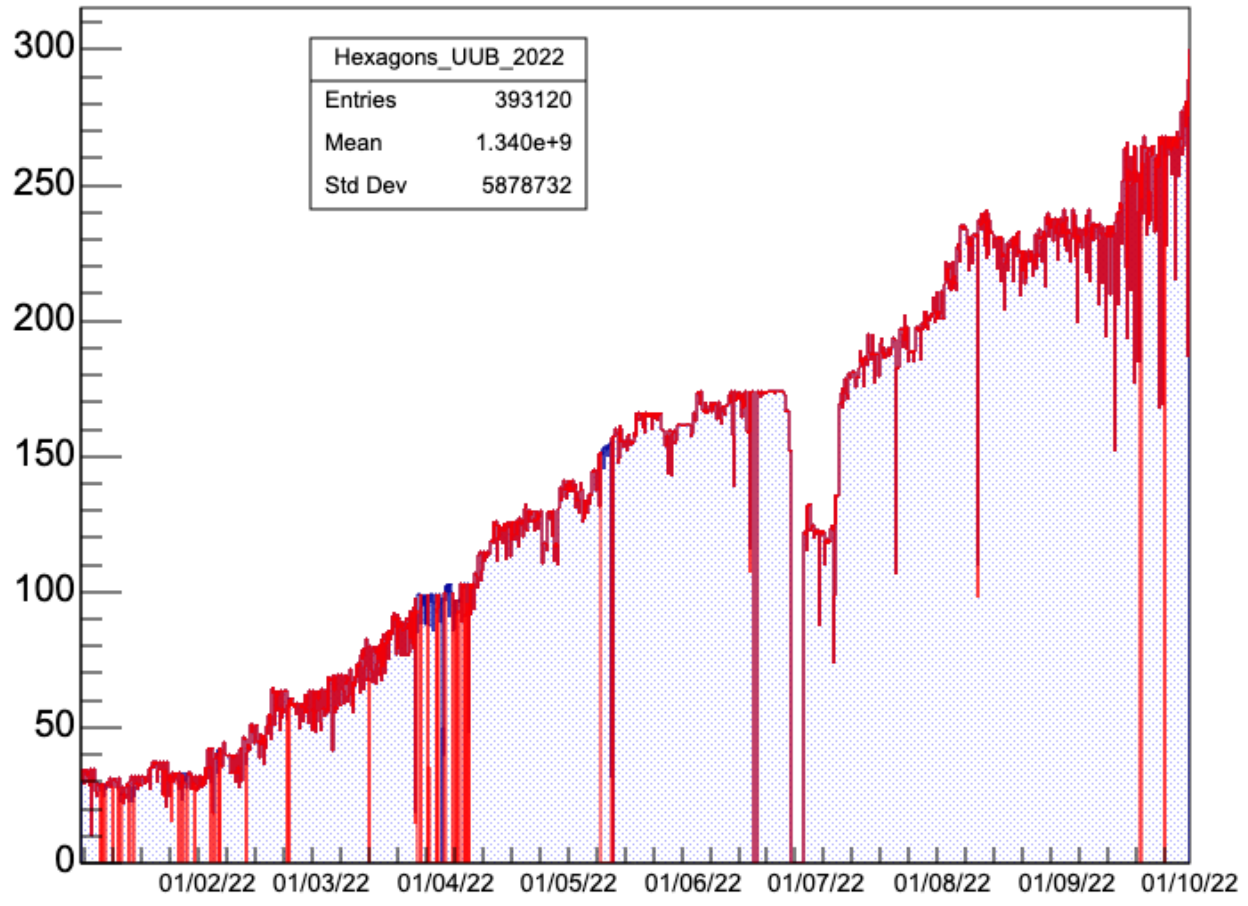
Very stable data taking while upgrading array

Shutdown of array: very cloudy period

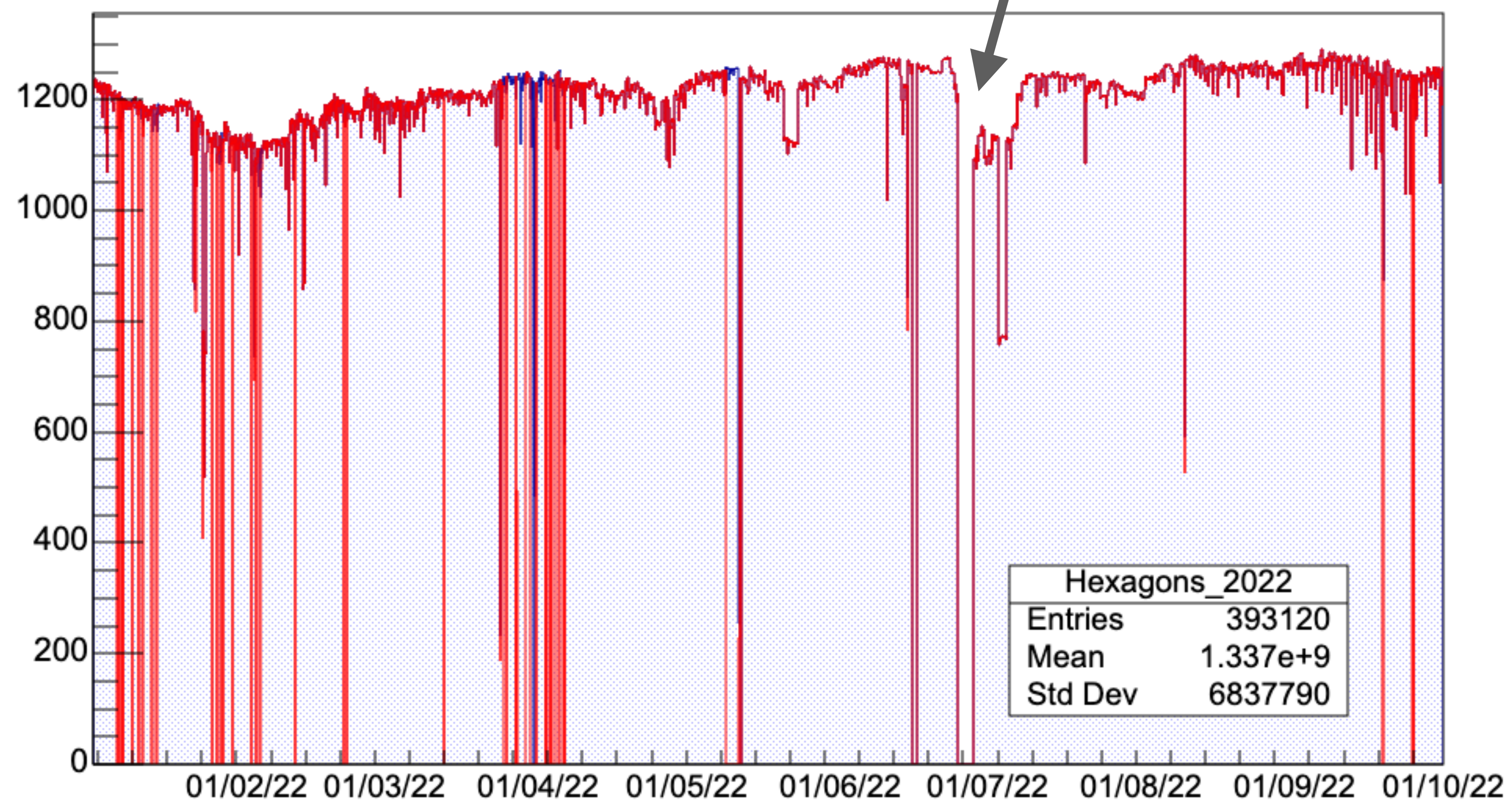
Hexagons with old electronics (UB)



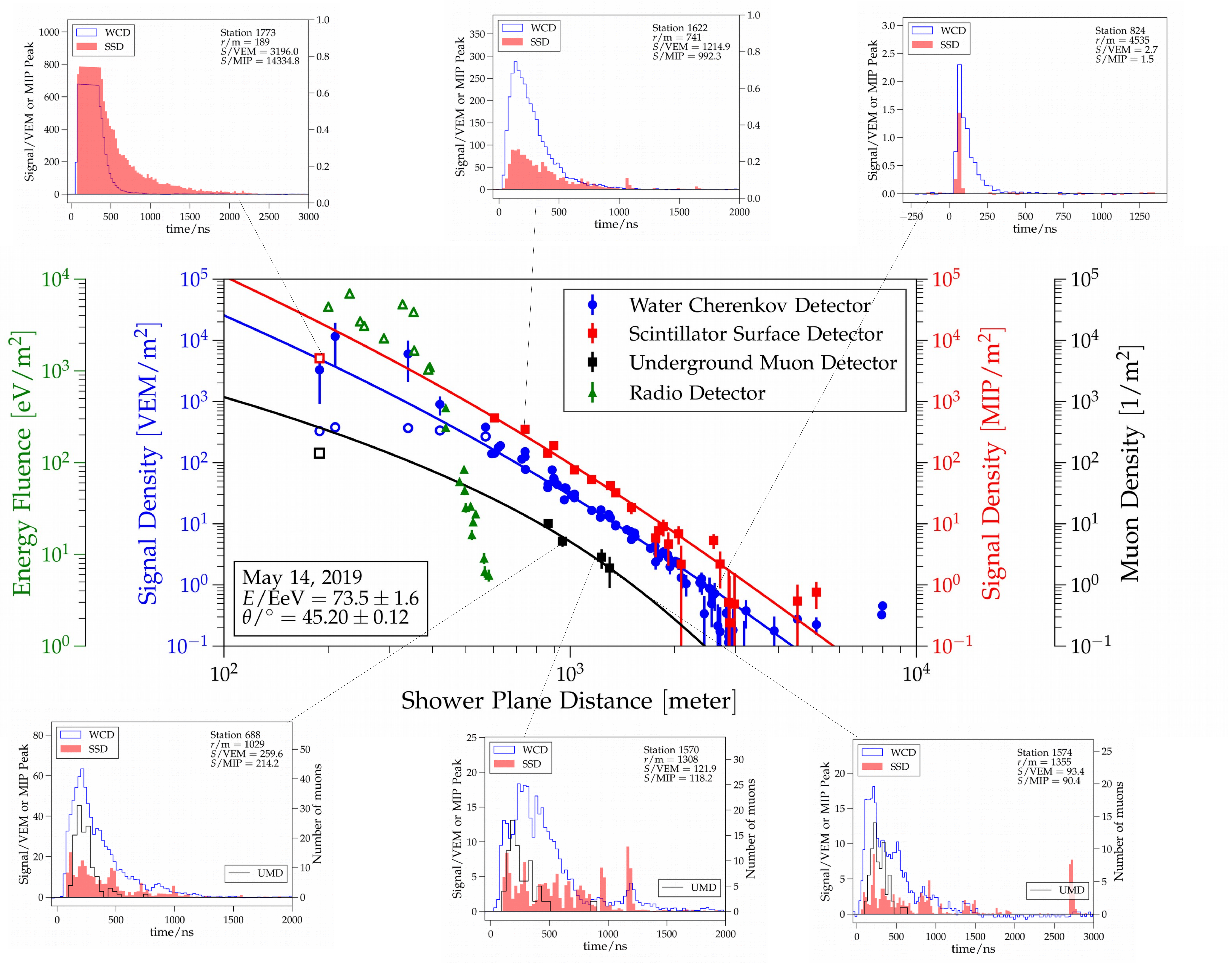
Hexagons with new electronics (UUB)



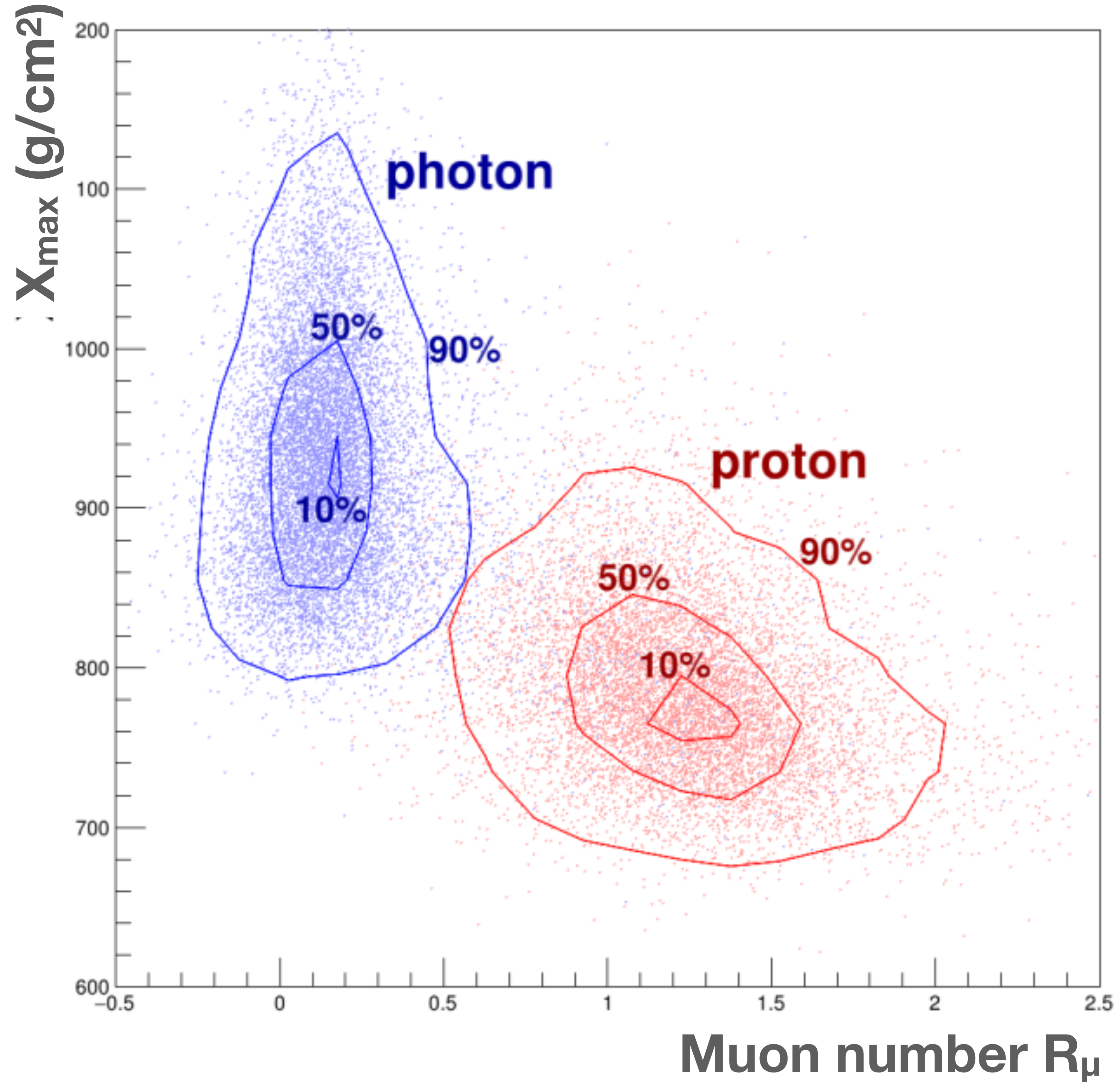
Hexagons taking data in total



Example of rich information in data of Phase II



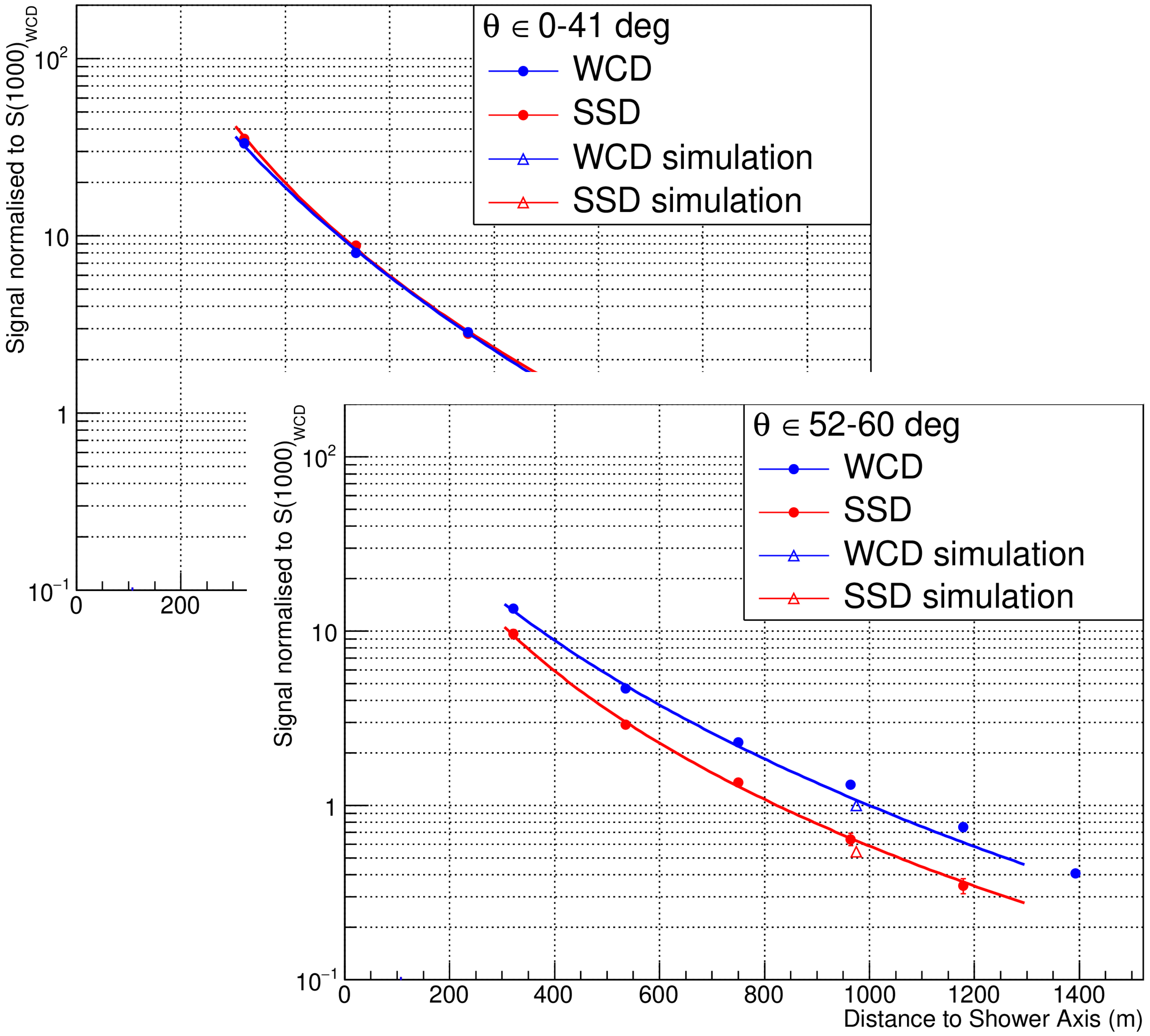
Great physics potential in muons



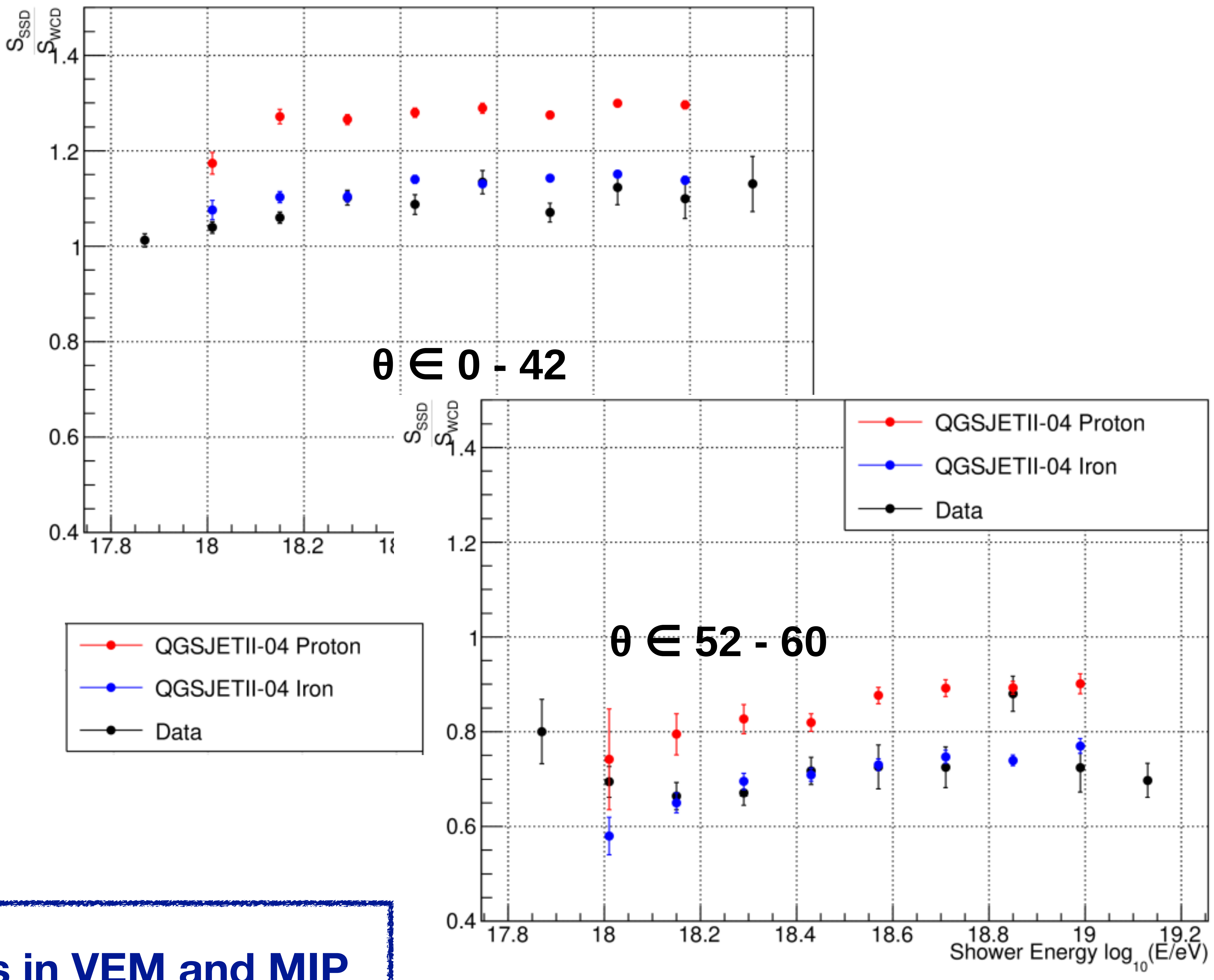
(Auger, Universe 2022)

A first look – data of pre-production array (preliminary)

Average lateral profiles

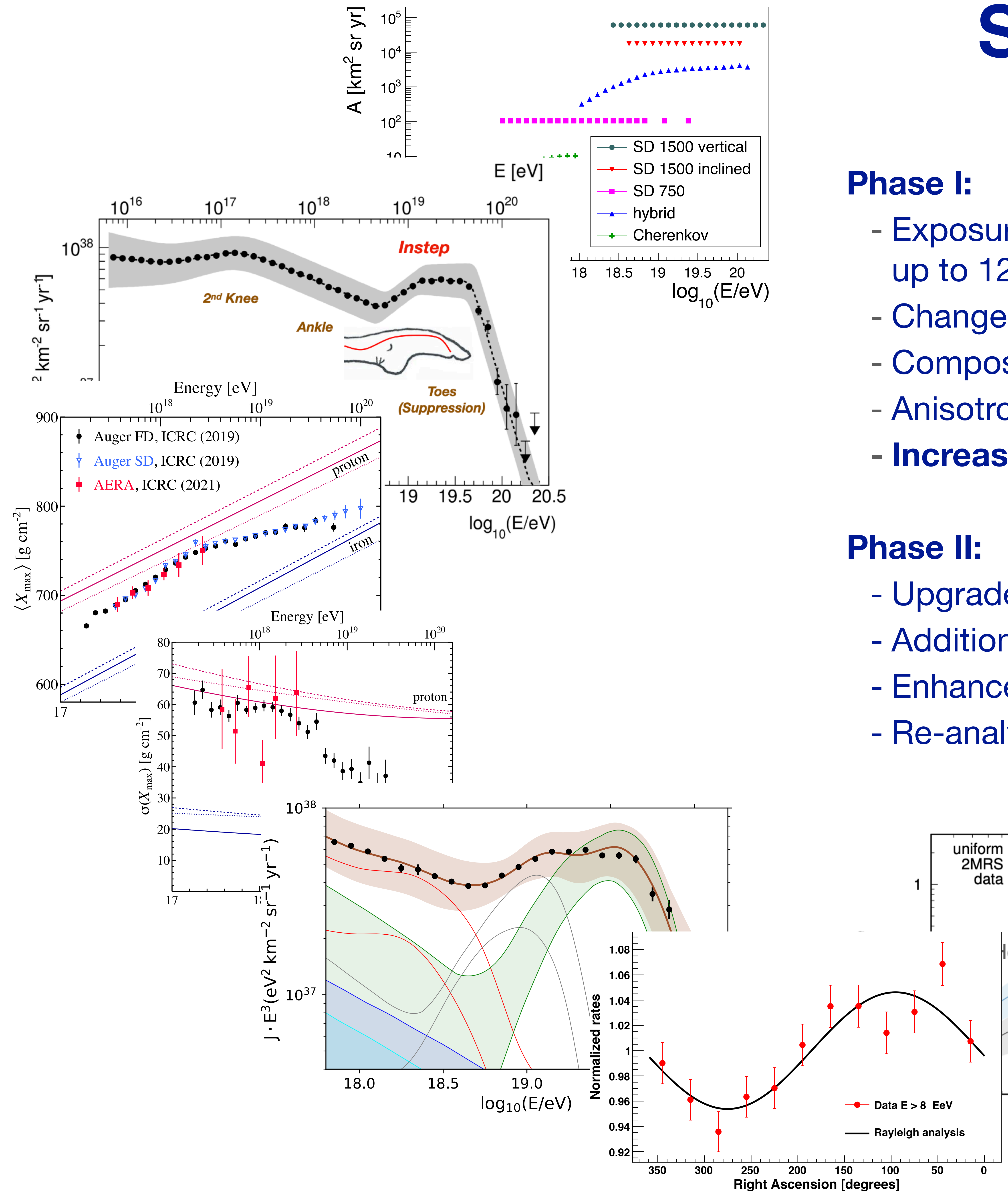


Ratio S_{SSD}/S_{WCD} encodes physics



Size of scintillator chosen to have similar signals in VEM and MIP

Summary

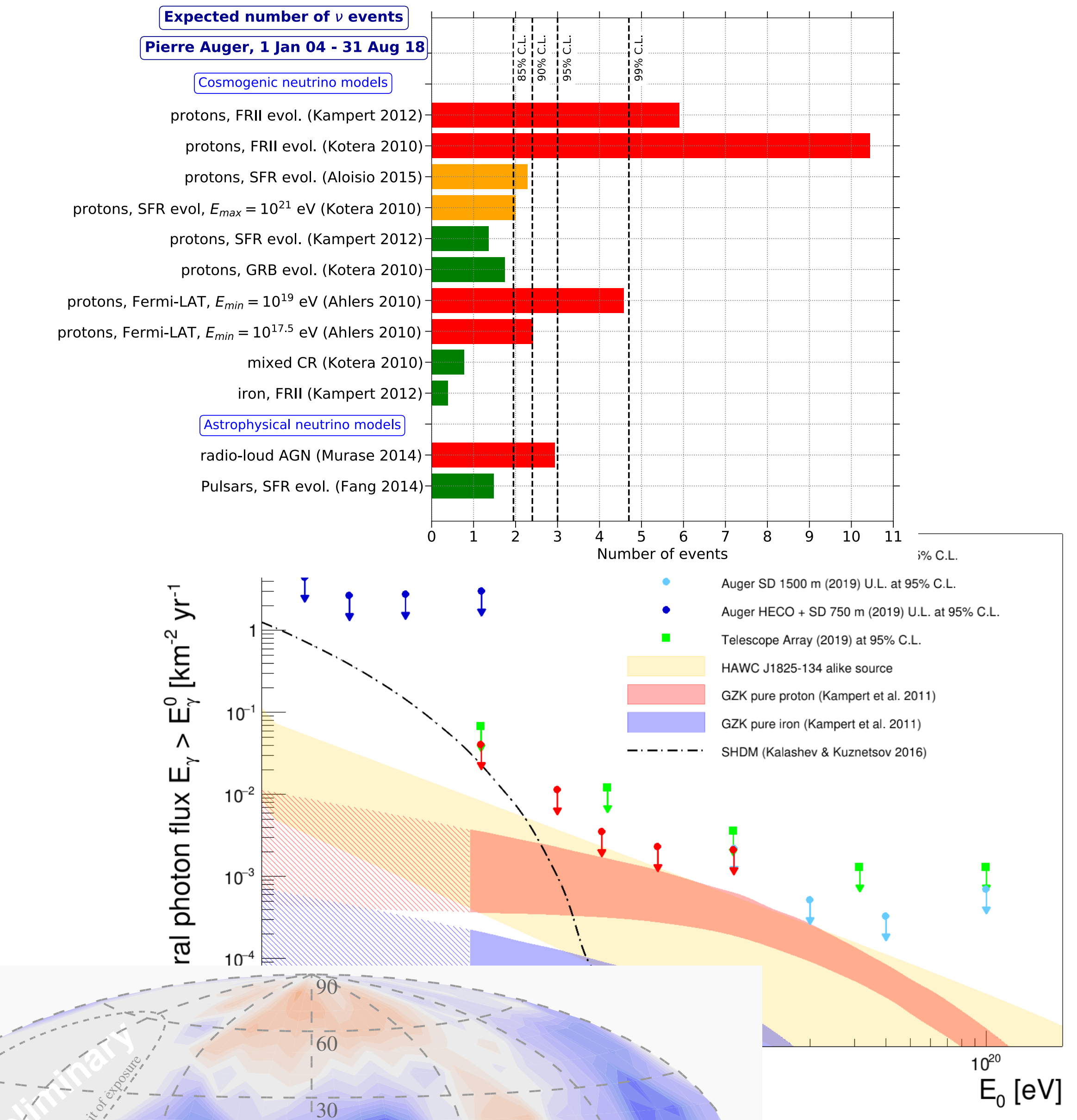


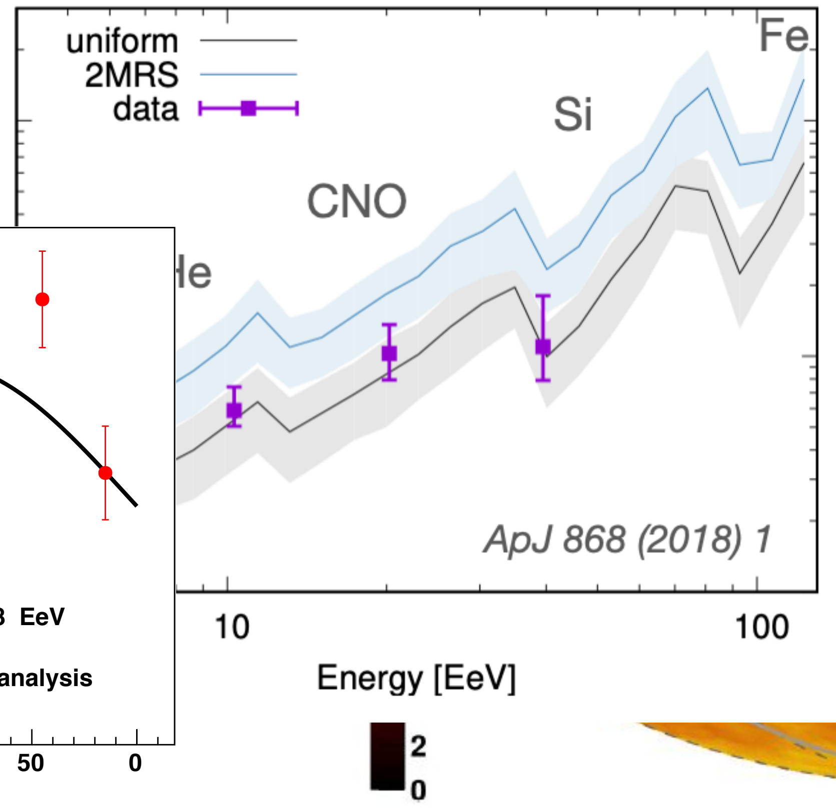
Phase I:

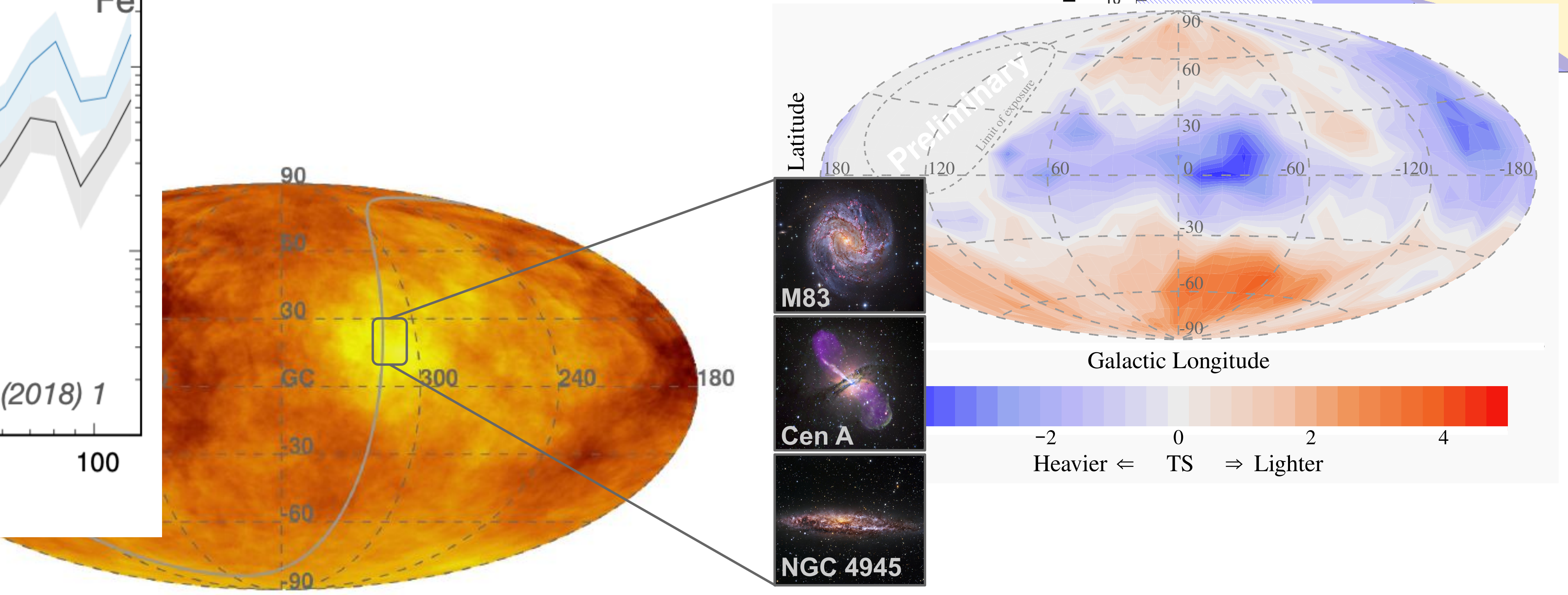
- Exposure 80,000 km² sr yr (vertical, highest quality), up to 120,000 km² sr yr (loose cuts, combined)
- Change of composition established
- Composition tightly linked to hadronic interactions
- Anisotropy observations very challenging
- **Increasingly consistent picture is emerging**

Phase II:

- Upgrade AugerPrime in progress
- Additional exposure 40,000 km² sr yr (vertical) expected
- Enhanced composition and hybrid information
- Re-analysis of all data planned

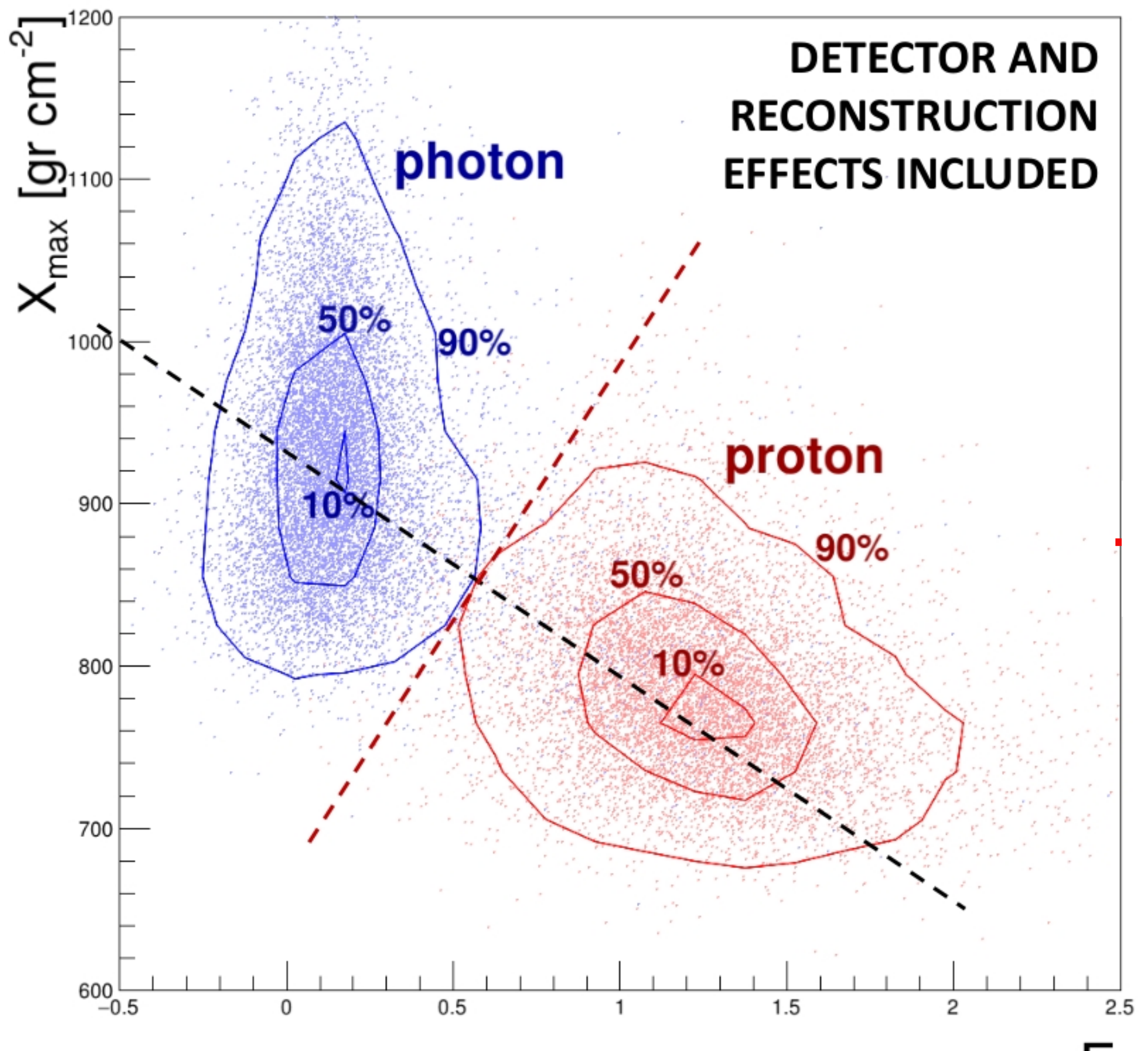






Backup slides

Searches: Ultra-high energy photons



Muon signal by shower universality

Cut at 50% photon efficiency (median)

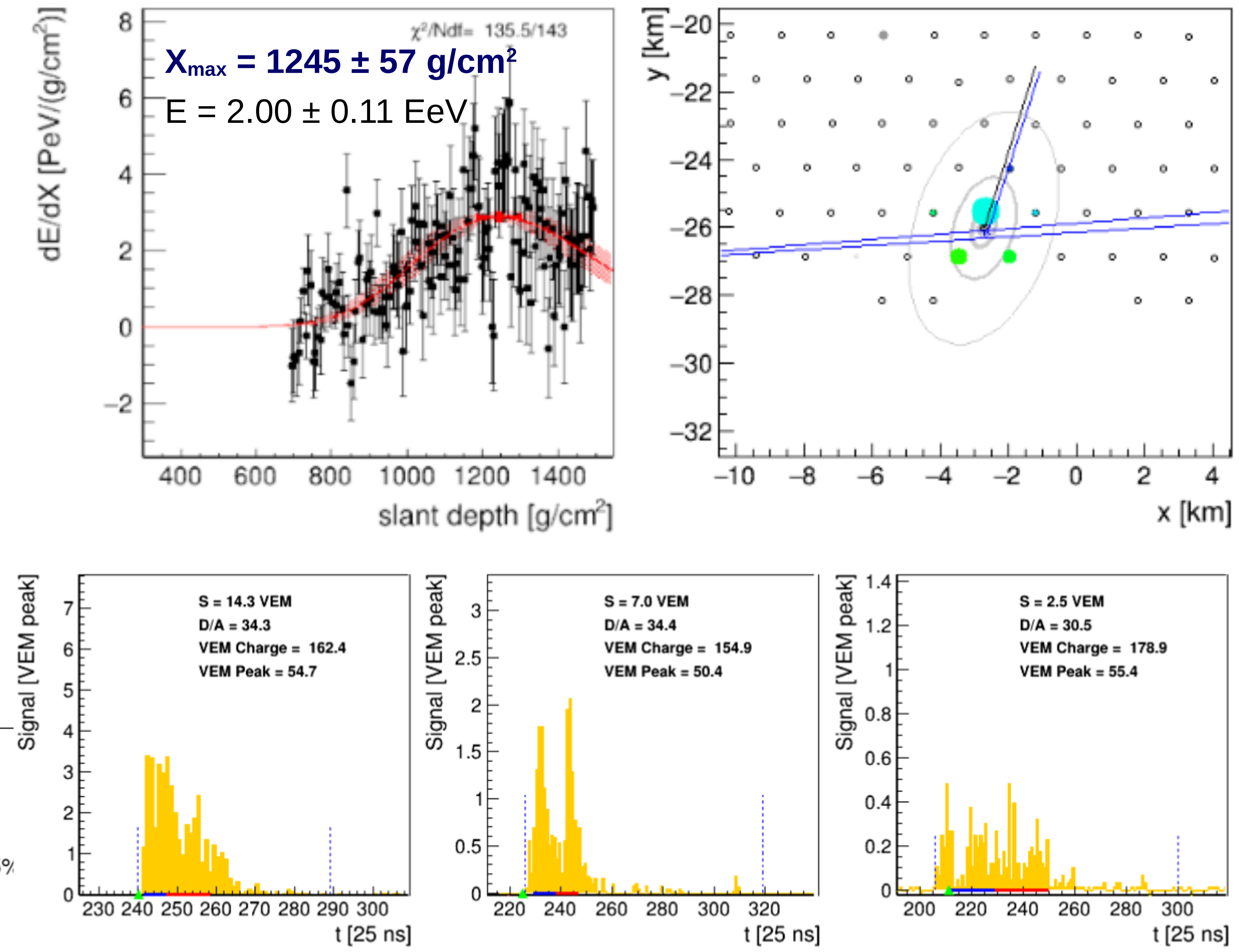
Background compatible with stat. expectation (burn sample of data)

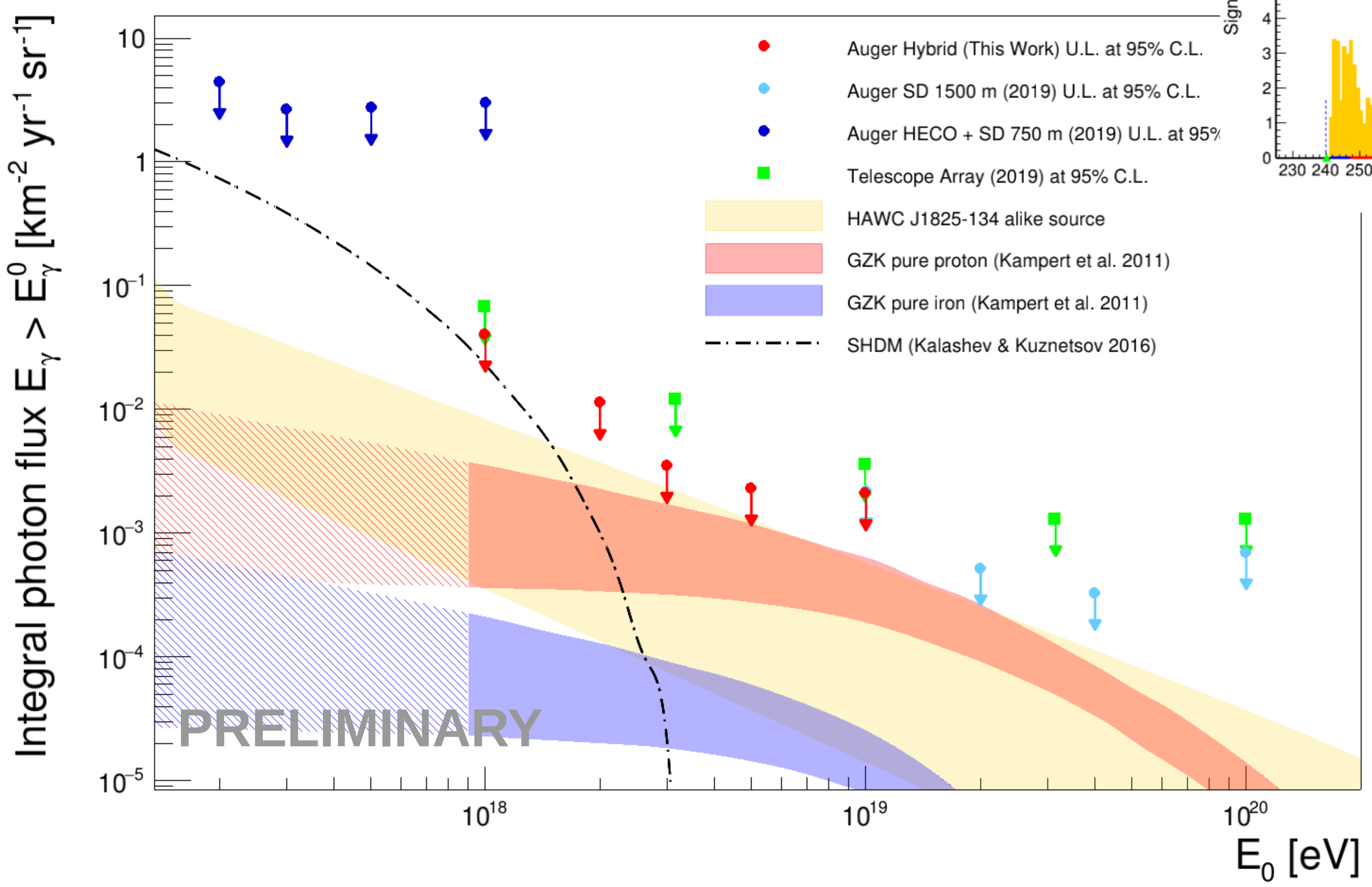
Multi-messenger: searches for photons in coincidence with GW events

(Auger, UHECR 2022 & ICRC 2021)

estimated events above median:
$N_{exp}(E > 10^{18.0}$ eV) = 30 ± 16

Candidates found:
N_{obs}(E > 18.0 eV) = 22

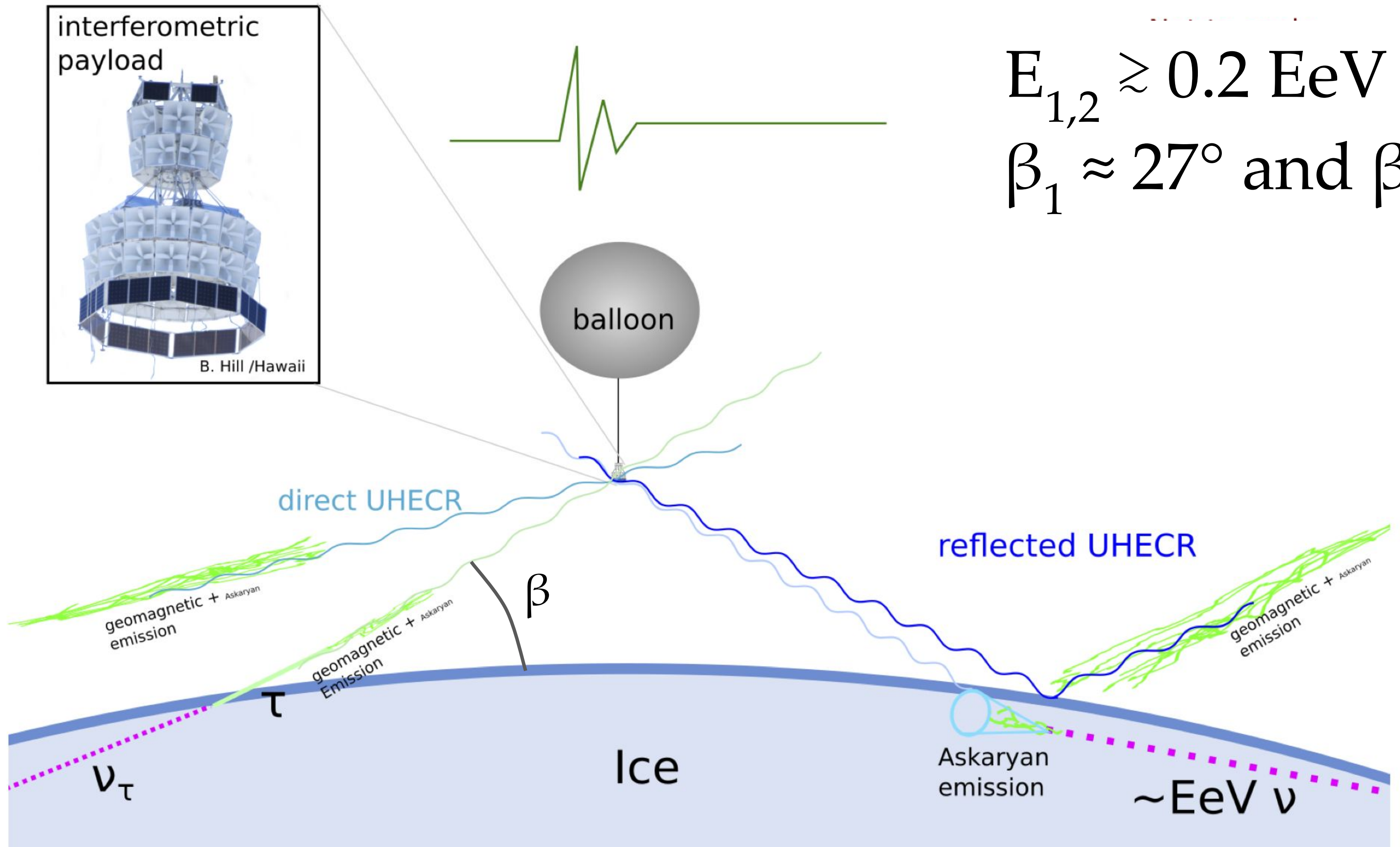




Limits begin being background-dominated

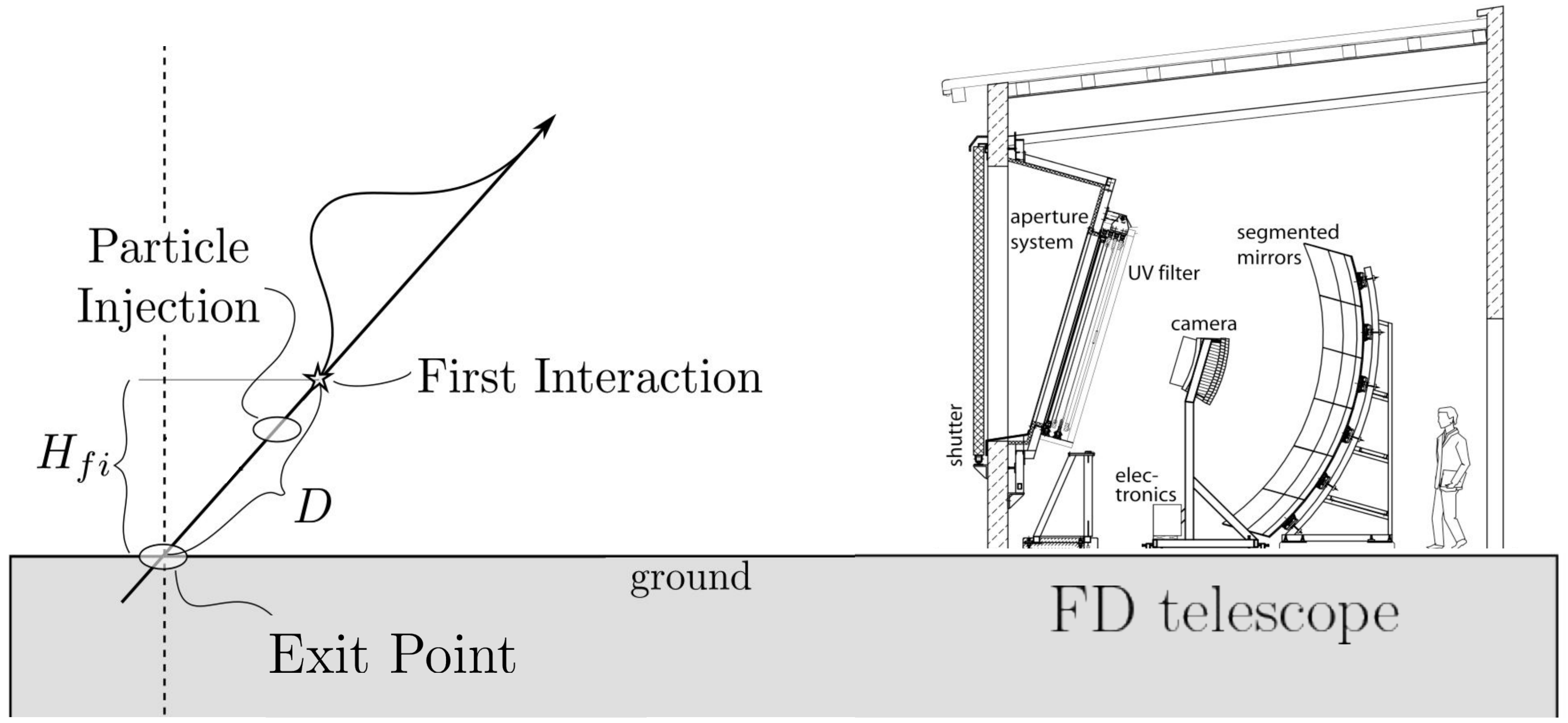
Phase II: additional data for photon/hadron separation or photon discovery

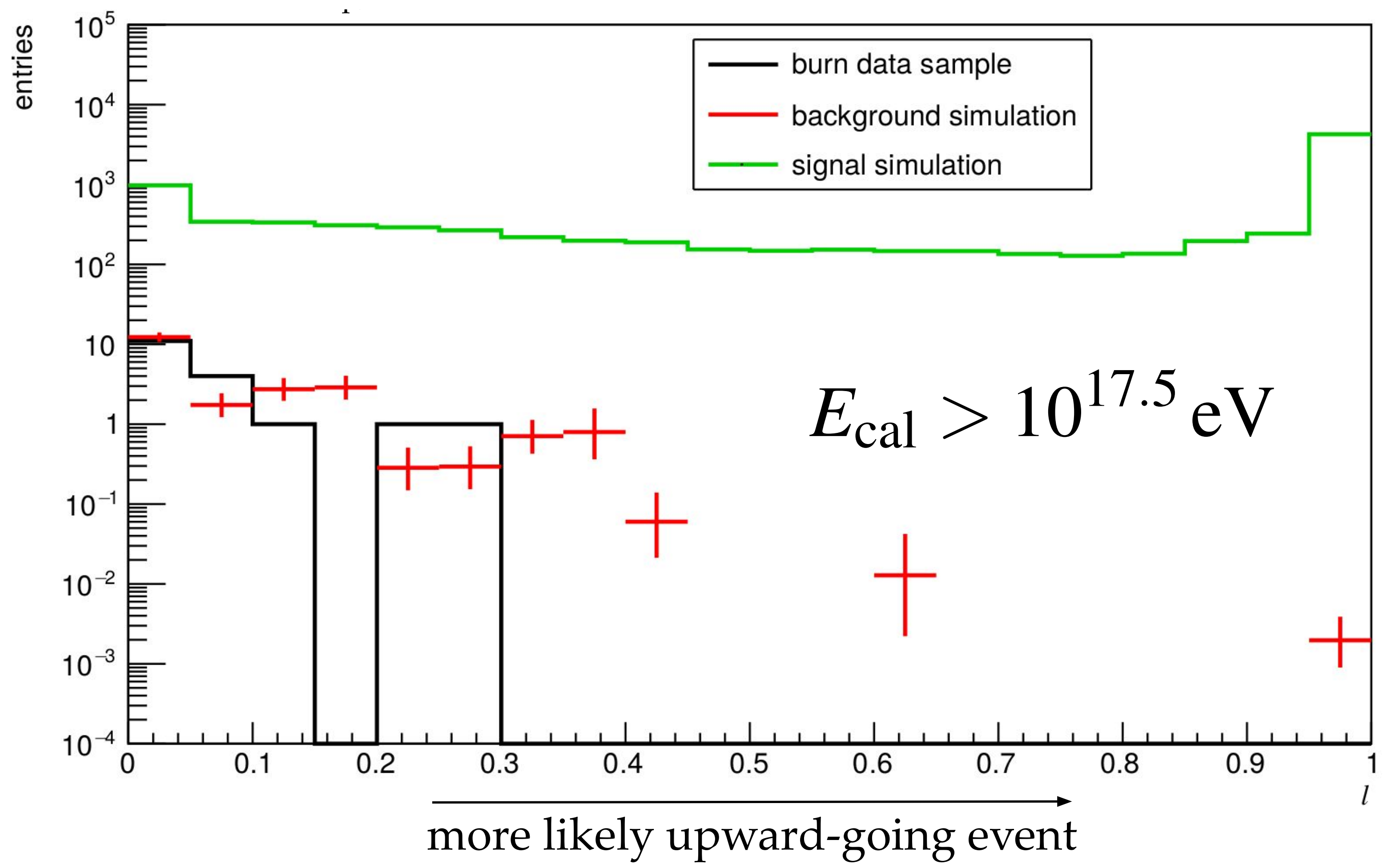
Searches: Upward-going events motivated by ANITA



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

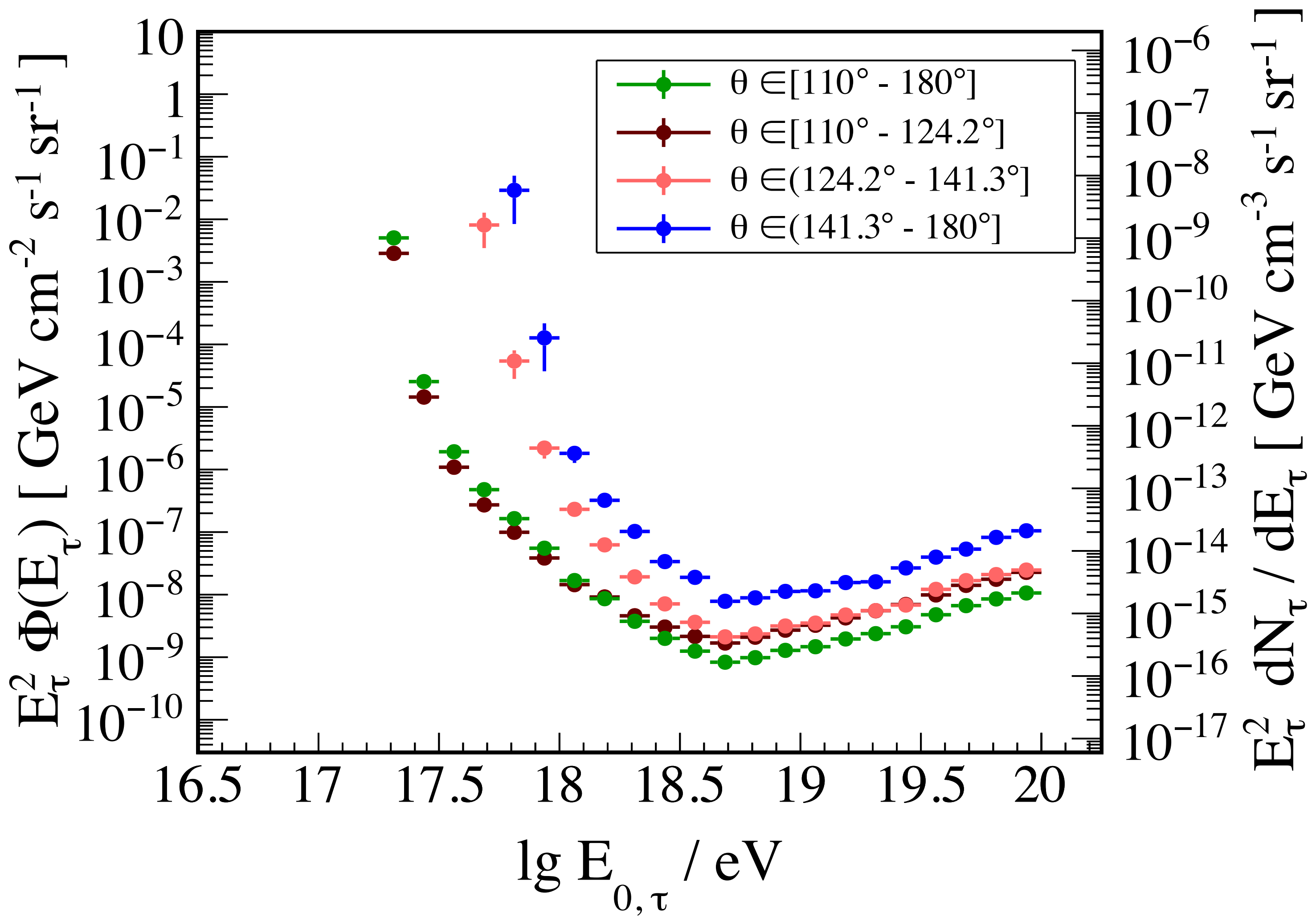
$E_{1,2} \gtrsim 0.2$ EeV $\approx 10^{17.8}$ eV
$\beta_1 \approx 27°$ and $\beta_2 \approx 35°$





(Eva Santos)

Tau scenario



Auger results:

Background 0.45 ± 0.18 expected

One event observed

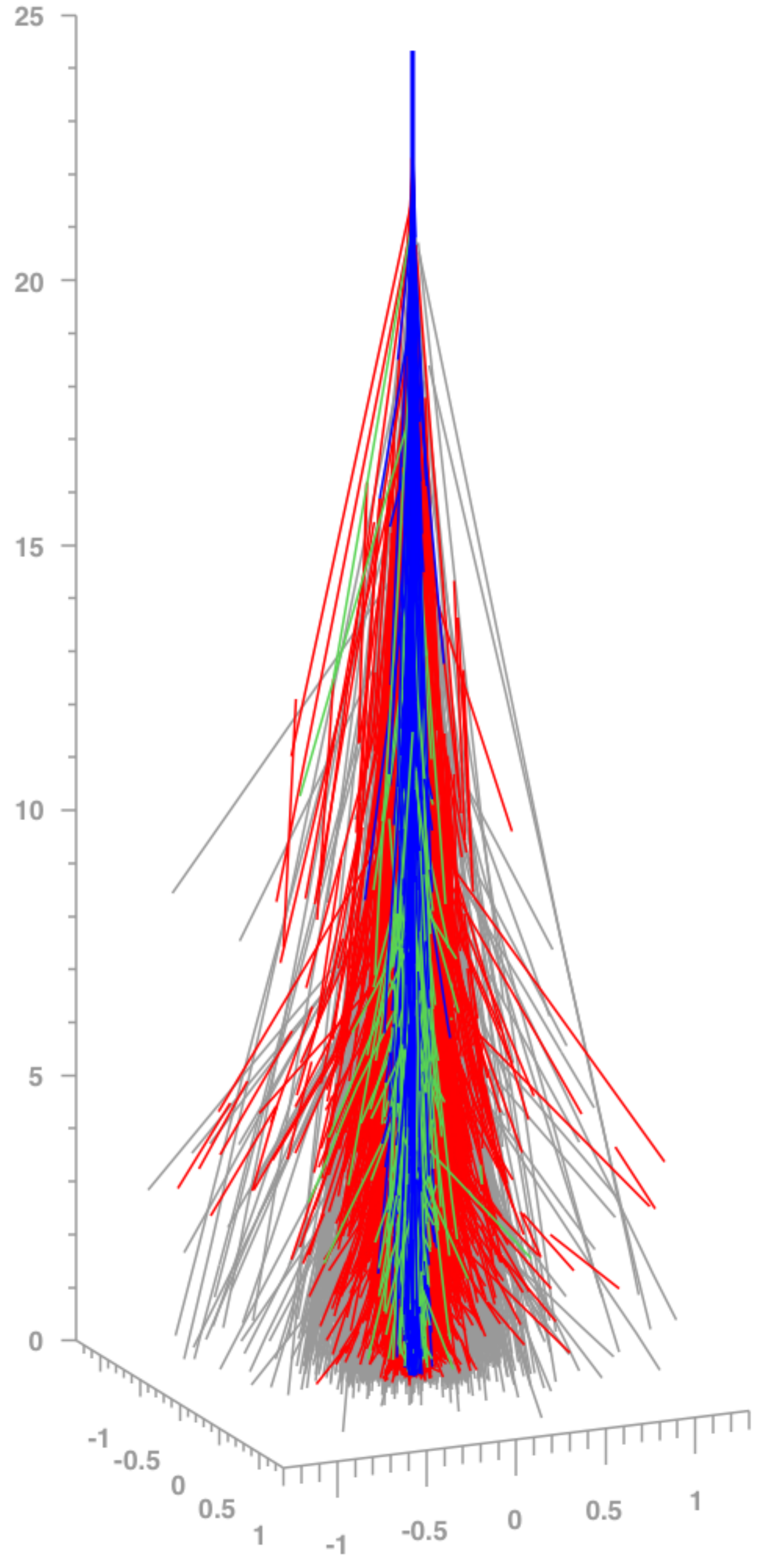
Flux limits on anomalous events

Uniform distribution

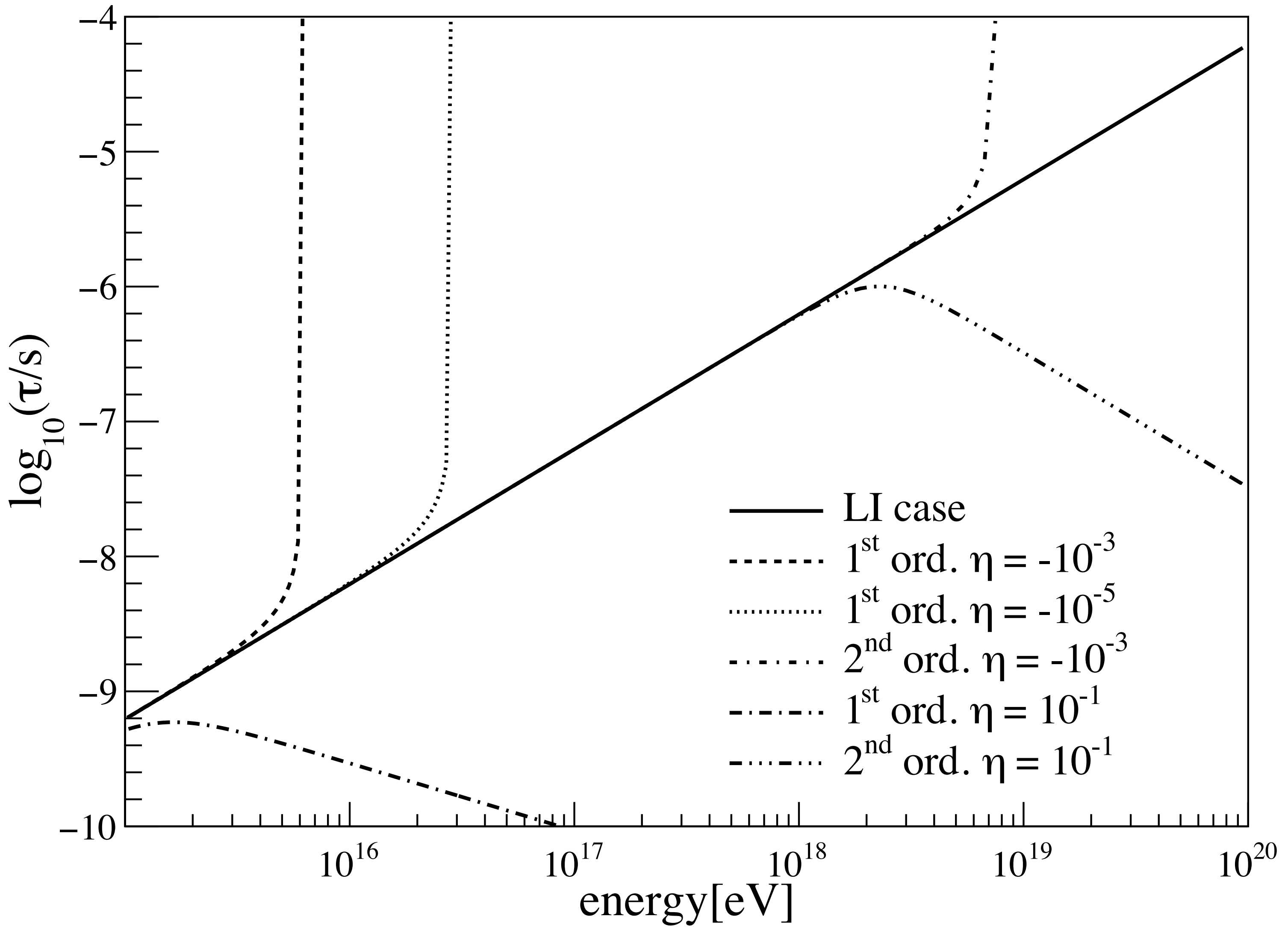
3.6×10^{-20} cm^{-2} sr^{-1} yr^{-1} if exposure is weighted with **E^{-1}**

8.5×10^{-20} cm^{-2} sr^{-1} yr^{-1} if exposure is weighted with **E^{-2}**

Searches: Lorentz invariance violation (LIV)



Lorentz-dilated lifetime of neutral pions



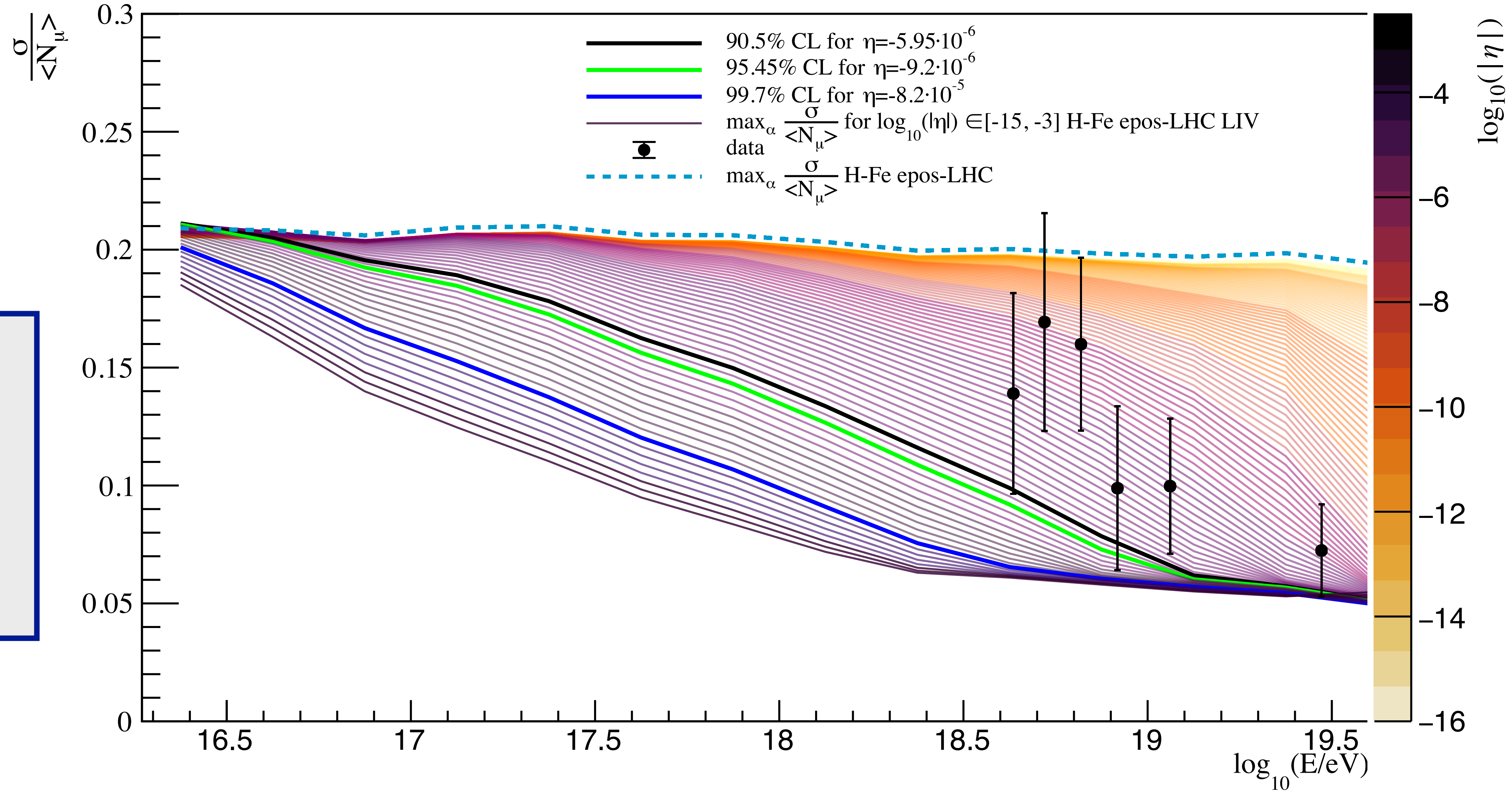
$$E^2 - p^2 = m^2 + \eta^{(n)} \frac{p^{n+2}}{M_{\rm Pl}^n}$$

$$\gamma_{\rm LIV} = E/m_{\rm LIV}$$

$$m_{\rm LIV}^2 = m^2 + \eta^{(n)} \frac{p^{n+2}}{M_{\rm Pl}^n}$$

Comparison of model simulations with data on muon number fluctuations

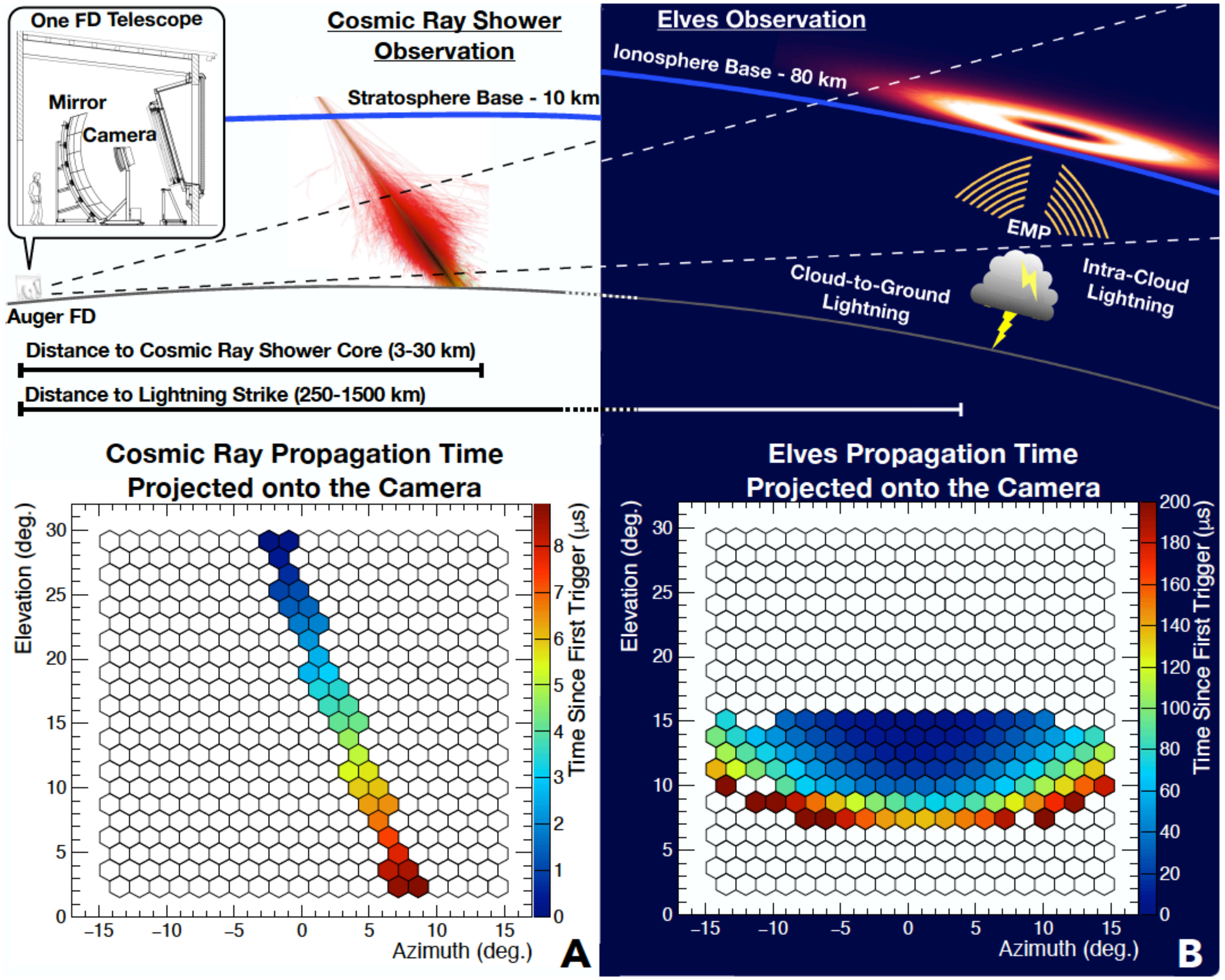
New limits on LIV parameter η



(Caterina Trimarelli)

Atmospheric phenomena – Elves and other beasts

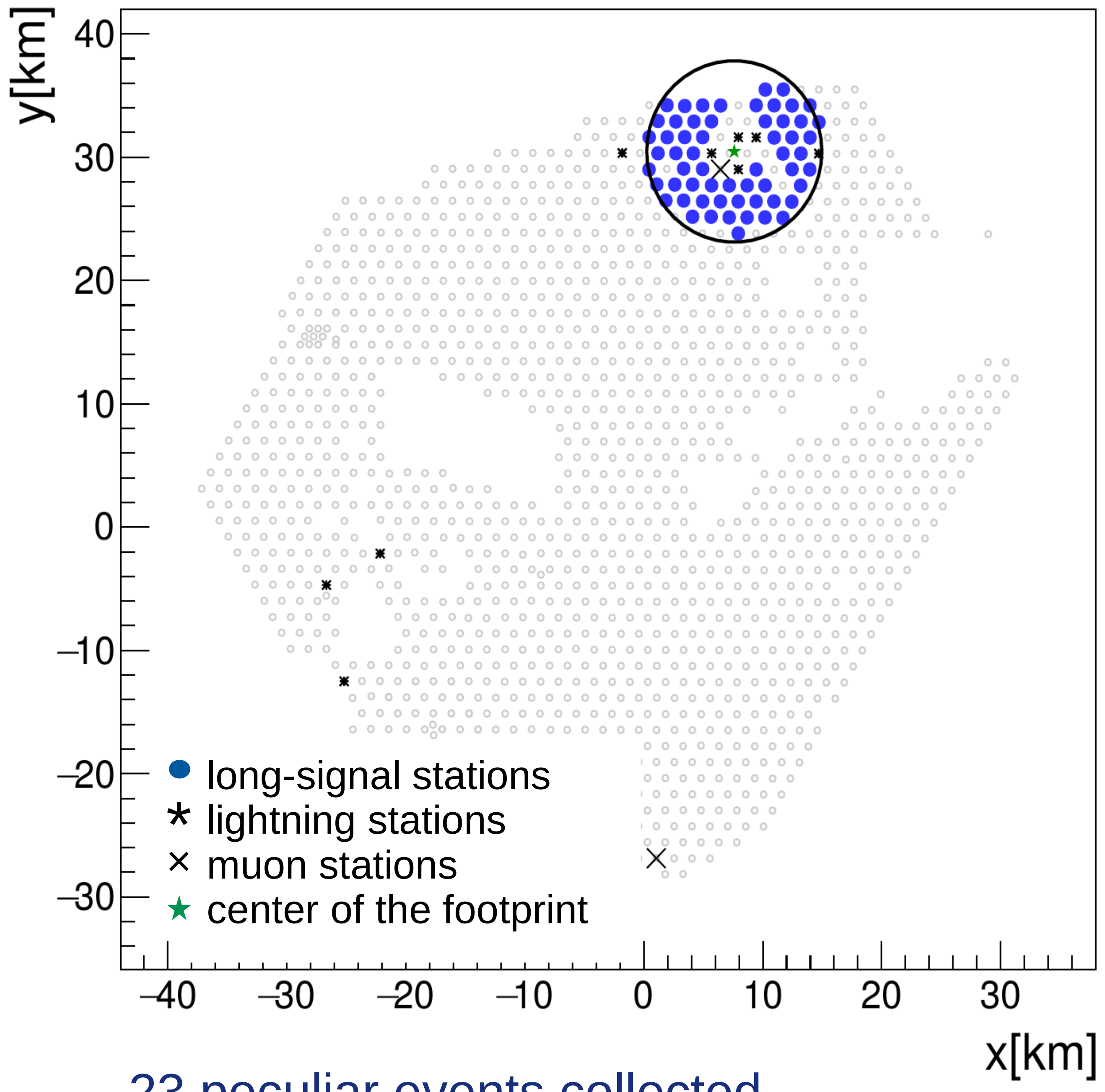
1600 Elves observed with fluorescence telescopes



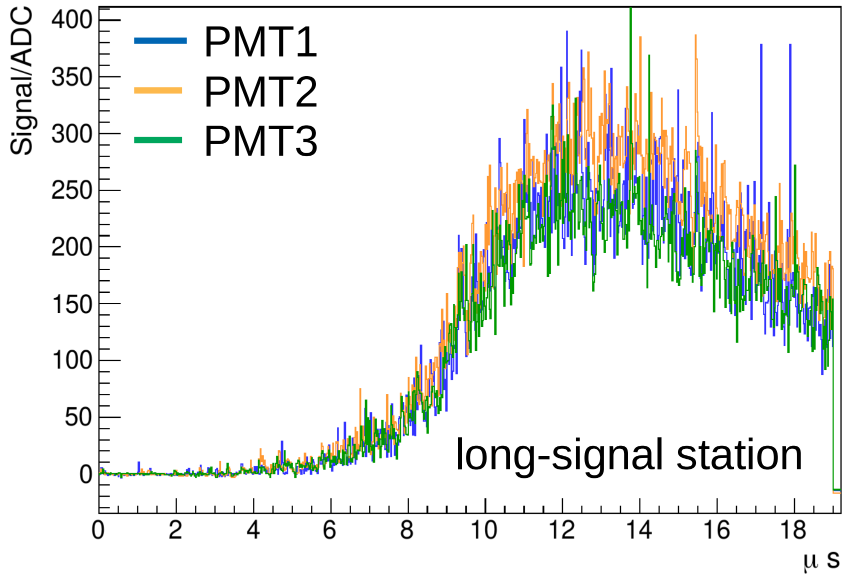
CRs ~ 8 µs

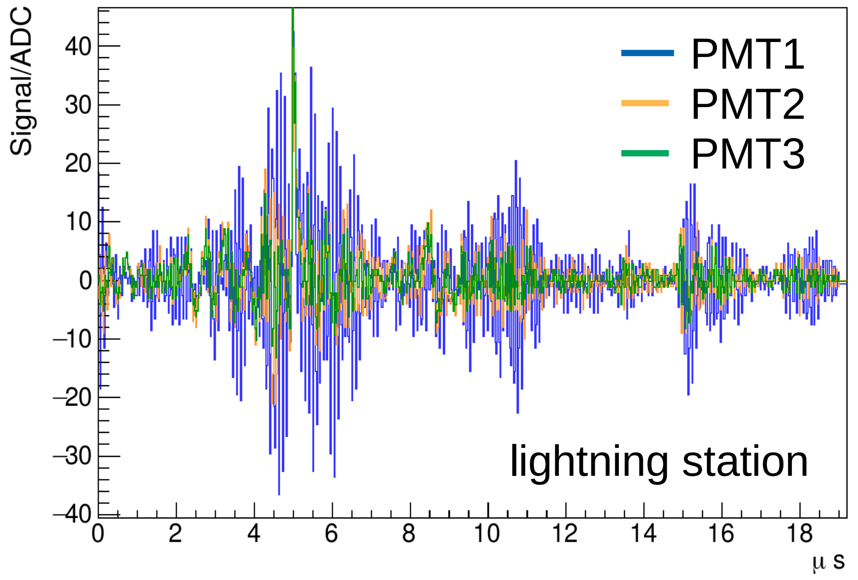
ELVES ~ 200 µs

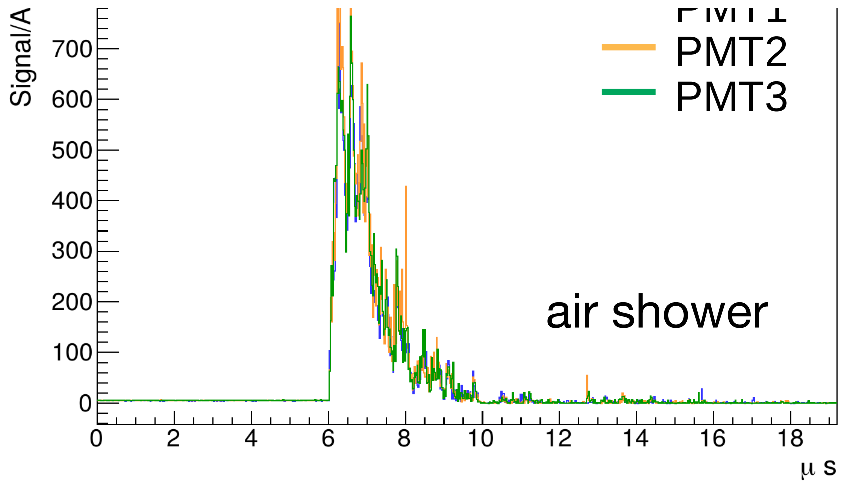
Downward-going Terrestrial Gamma Ray Flashes (TGFs) ?



23 peculiar events collected.







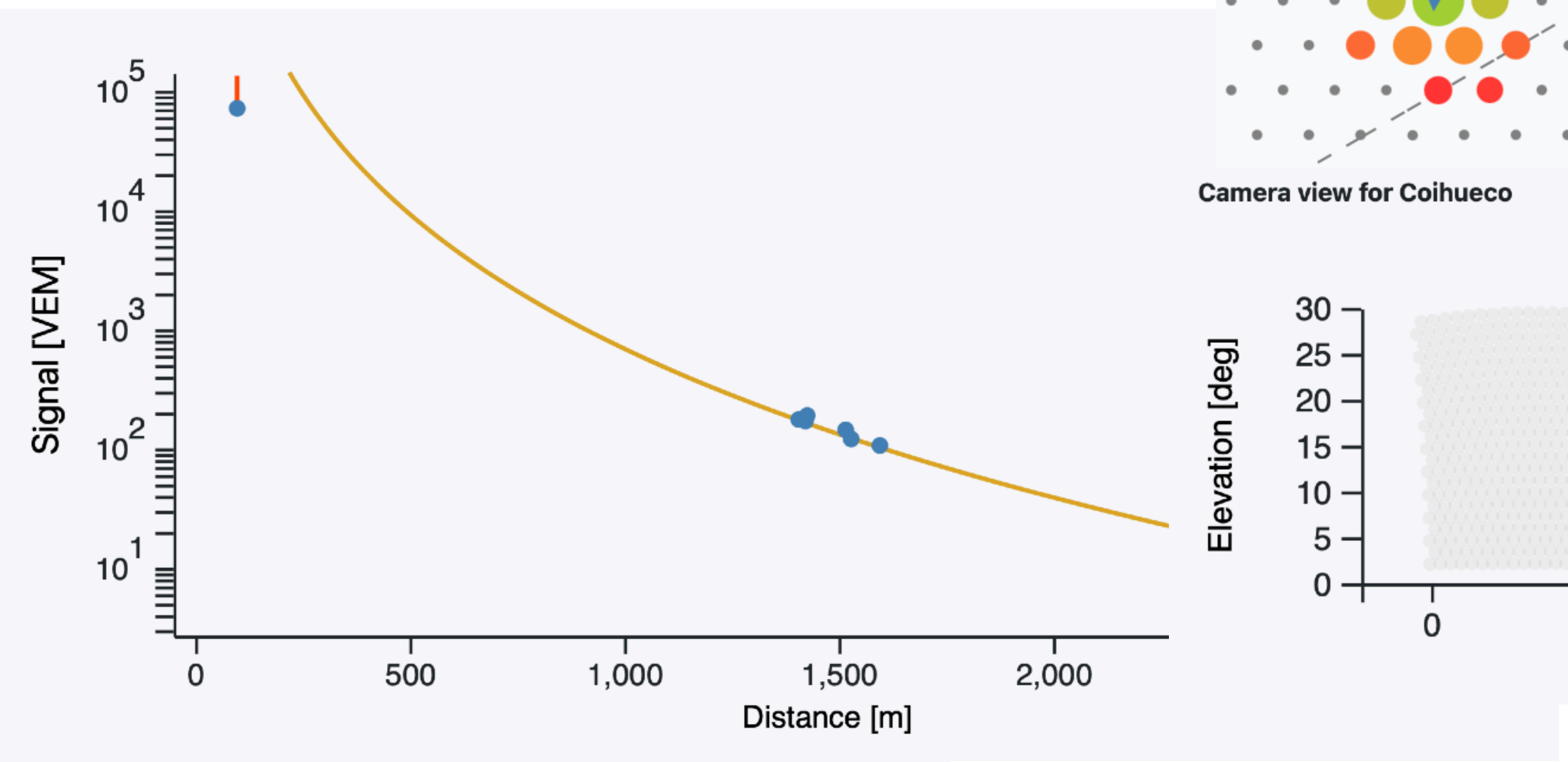
Rich physics of additional phenomena still at the beginning of exploration

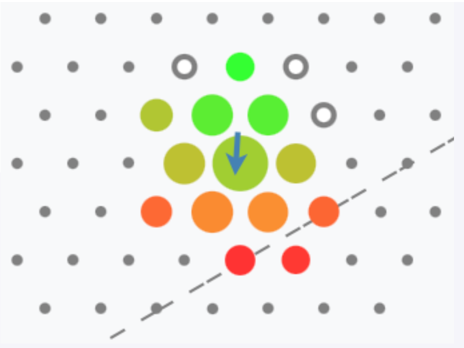
(Adriana Vazquez) *(Earth Space Sci. 7 (2020) 4)* (Roberta Colalillo)

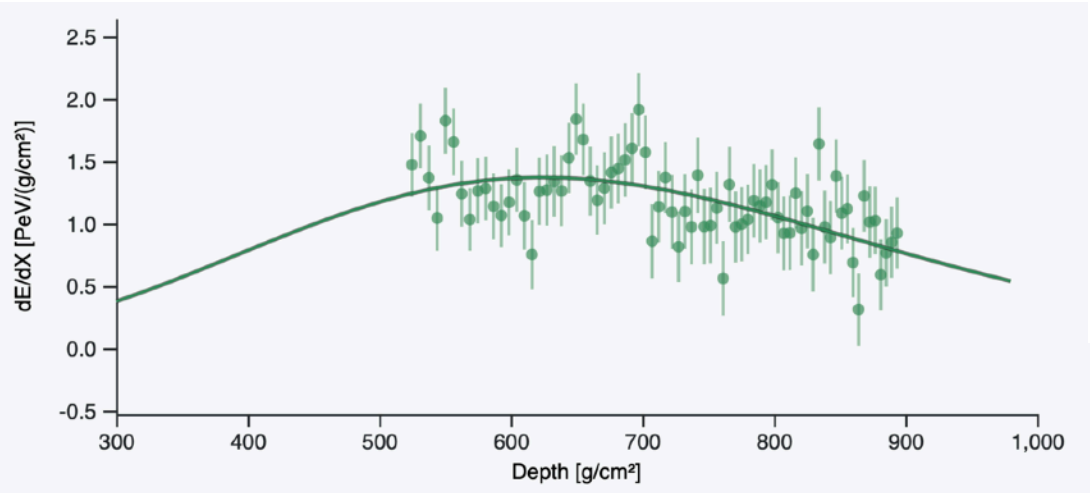
An invitation: Auger open data

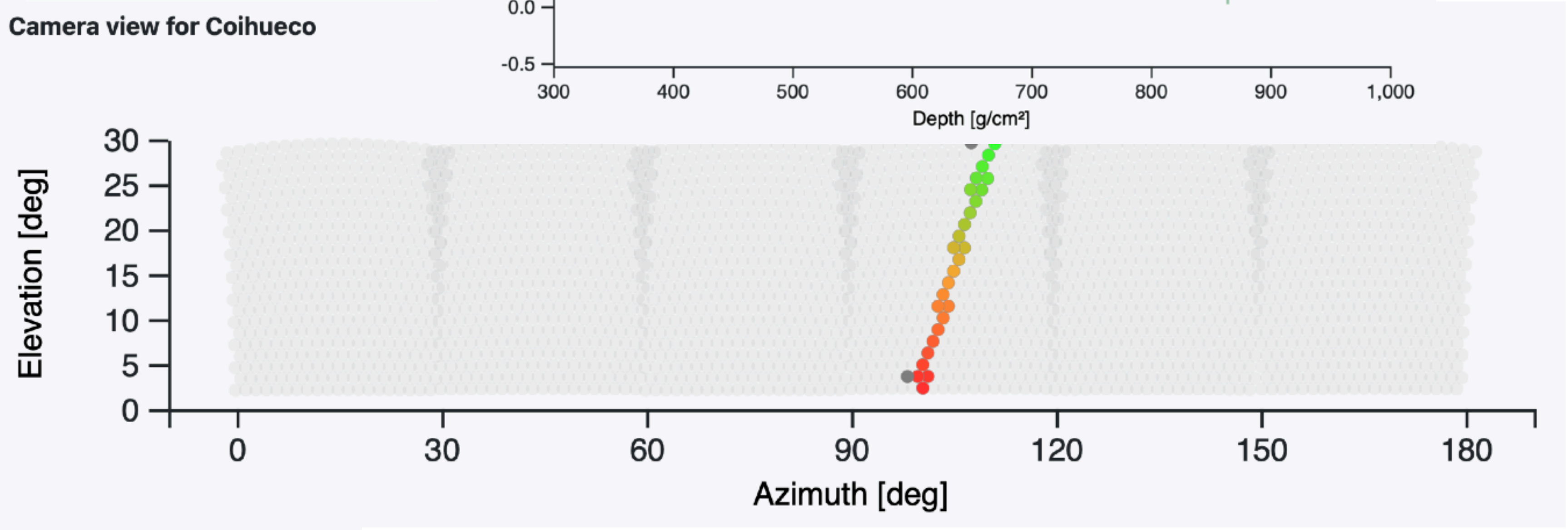
opendata.auger.org

DOI:10.5281/zenodo.4487613

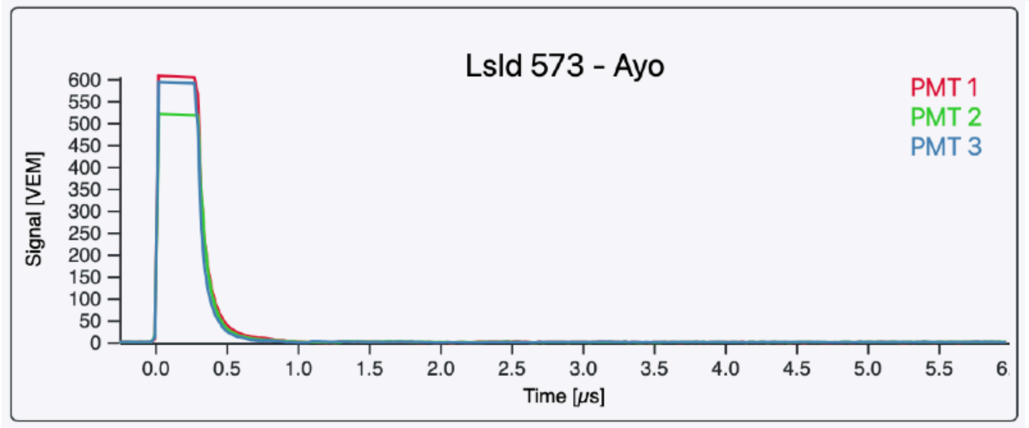


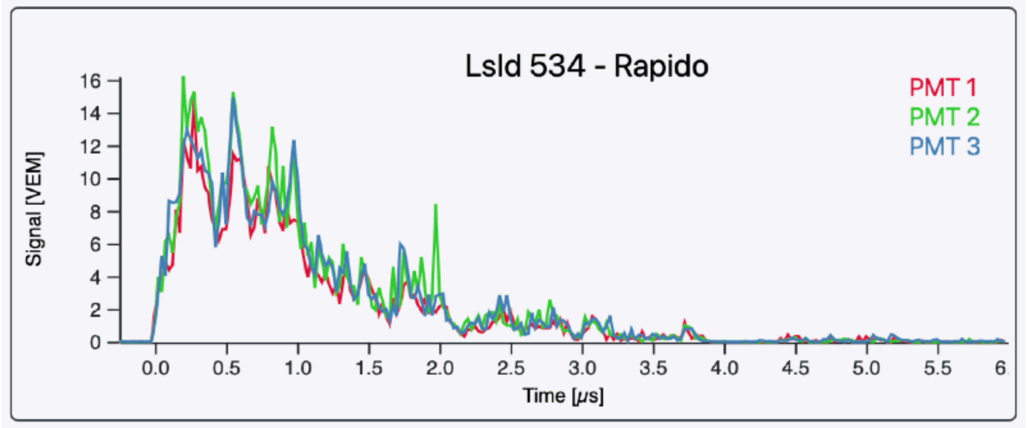


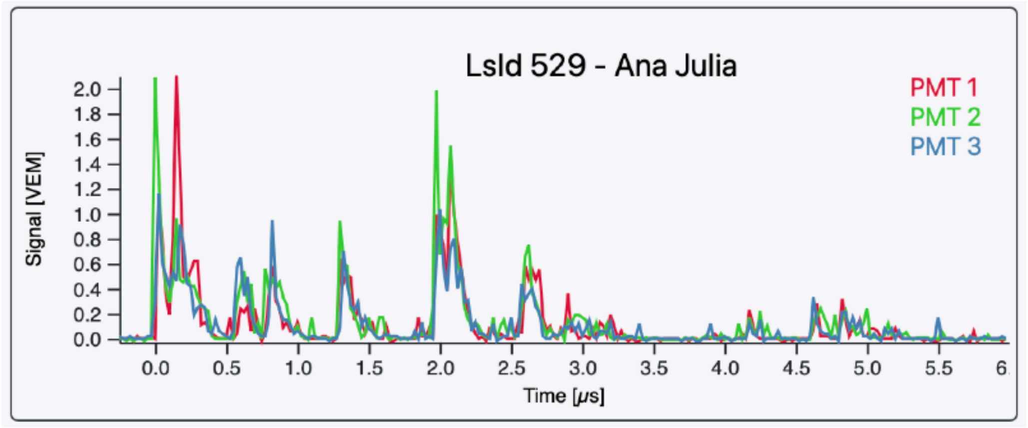





```
In [19]:
Y_0val = FC_CL * 0.9

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')
```



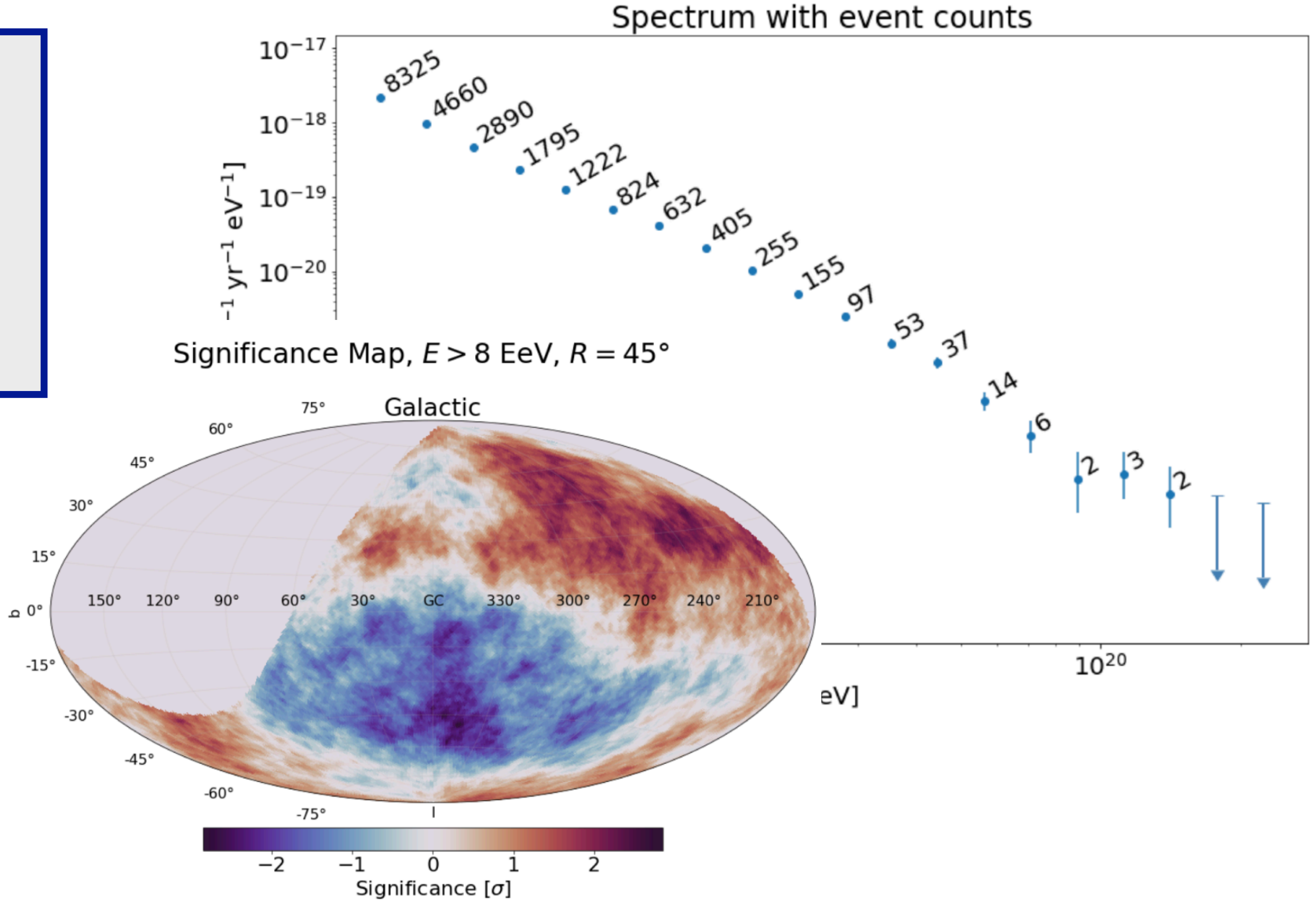




Currently 10% of Auger vertical data
Research-level data in JSON format
Online visualization of events
Data analysis scripts for science plots

You are welcome to use this data

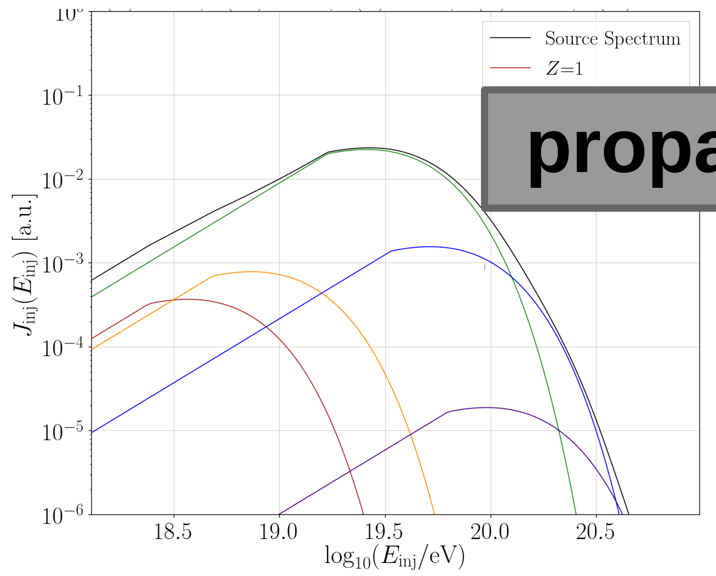
If you have a great idea what to look for we can work with you to apply your analysis also to the full data set



Outlook: How to gain sensitivity to distinguish source scenarios

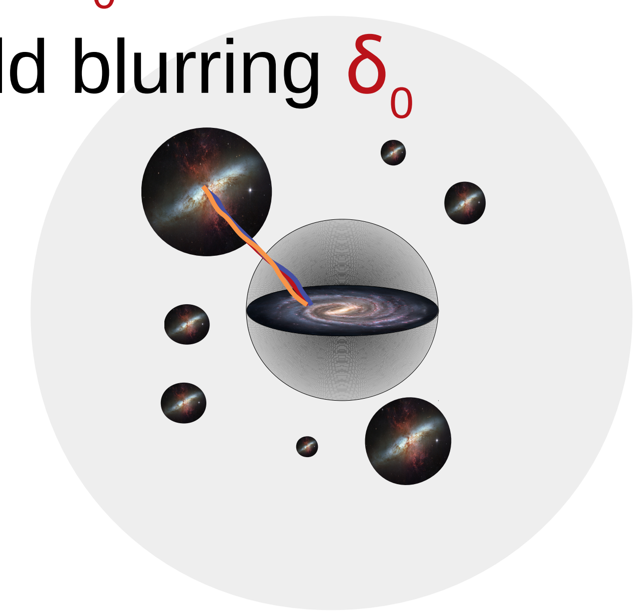
Universe model setup:

injected spectrum:
γ, R_{cut}, a_i

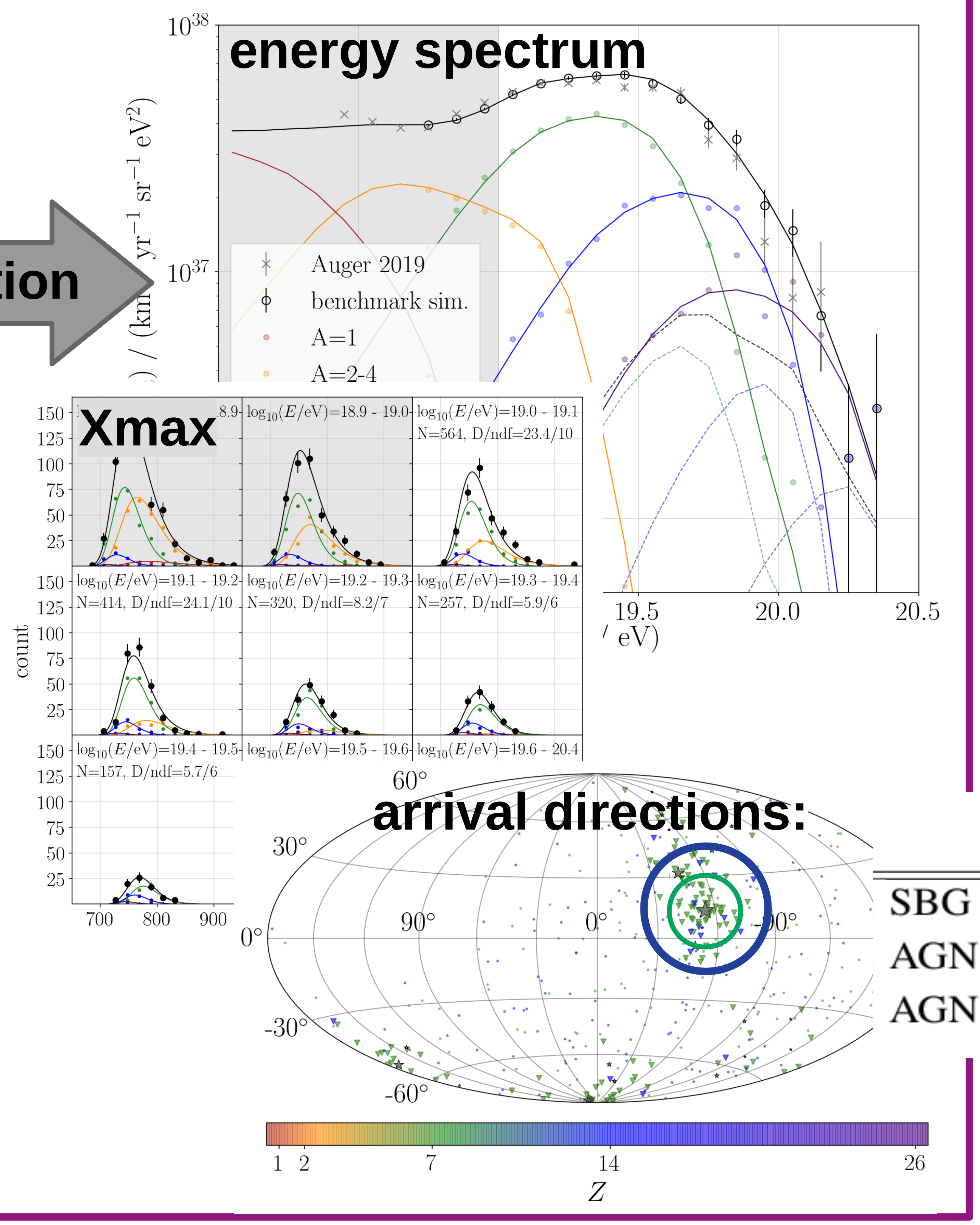


propagation

3d setup:
signal fraction f_0,
magnetic field blurring δ_0



Simulated observables:



Fit of model parameters to

- energy spectrum,
- Xmax distribution
- arrival direction distribution

Flux and Xmax data:
fluxes of different mass groups at Earth

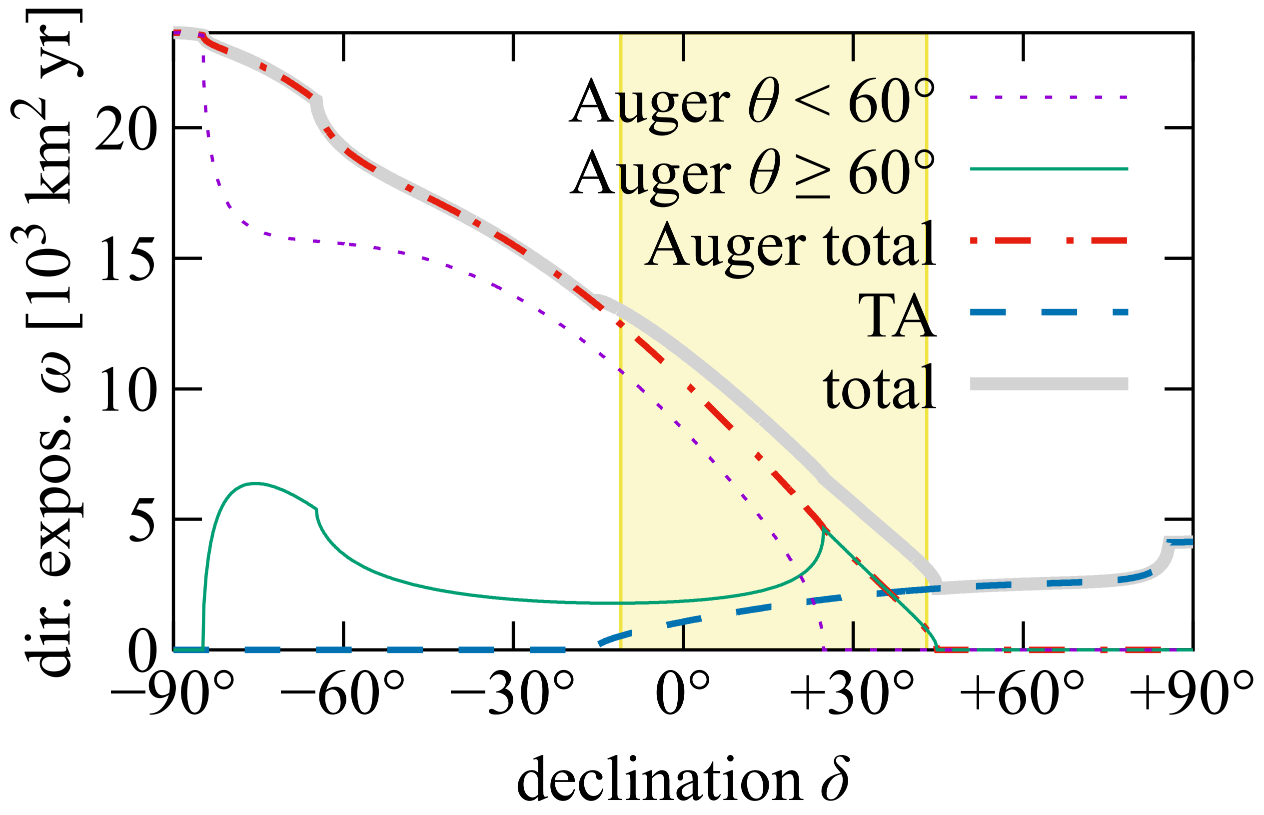
Arrival direction distribution:
distance sensitivity (deflection, production of secondaries)

	Deviance			Likelihood	
	D_E	$D_{X_{max}}$	D_{total}	$2\log\frac{\mathcal{L}_{AD}}{\mathcal{L}_{AD}^{ref,m=3.4}}$	$2\log\frac{\mathcal{L}_{sum}}{\mathcal{L}_{sum}^{ref,m=3.4}}$
SBG model ($m = 3.4$) $\rightarrow$ *sim. truth*	5.5	80.2	85.7	30.6	32.4
AGN model ($m = 3.4$)	6.0	81.8	87.8	11.2	10.8
AGN model ($m = 5.0$)	5.6	84.1	89.9	1.4	−1.0

Monte Carlo study: Scenarios with similar catalog correlations can be clearly distinguished

Joint Auger-TA anisotropy working group

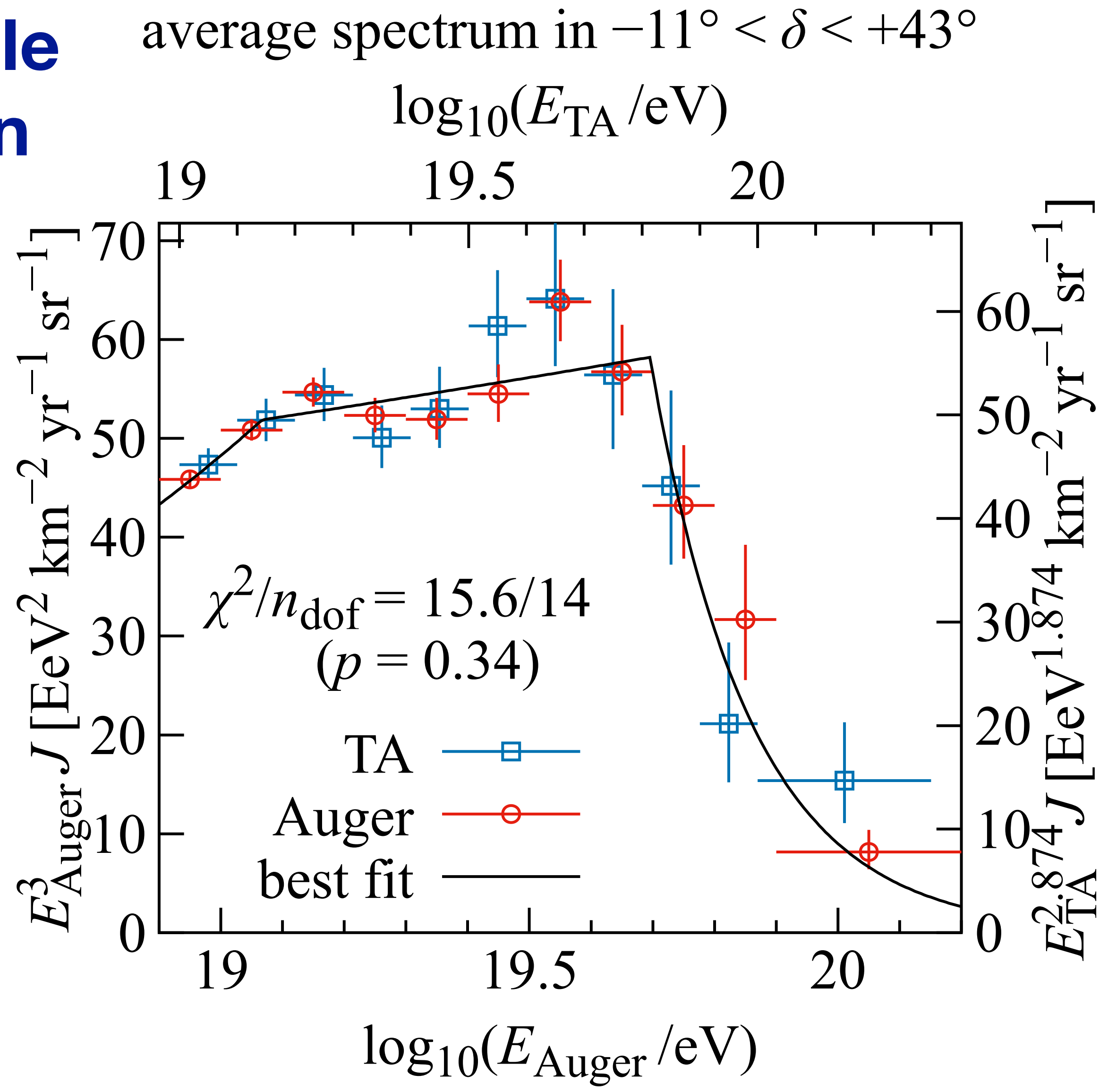
Sky coverage



Auger (θ < 80°): 120,000 km² sr yr

TA (θ < 55°): 14,000 km² sr yr

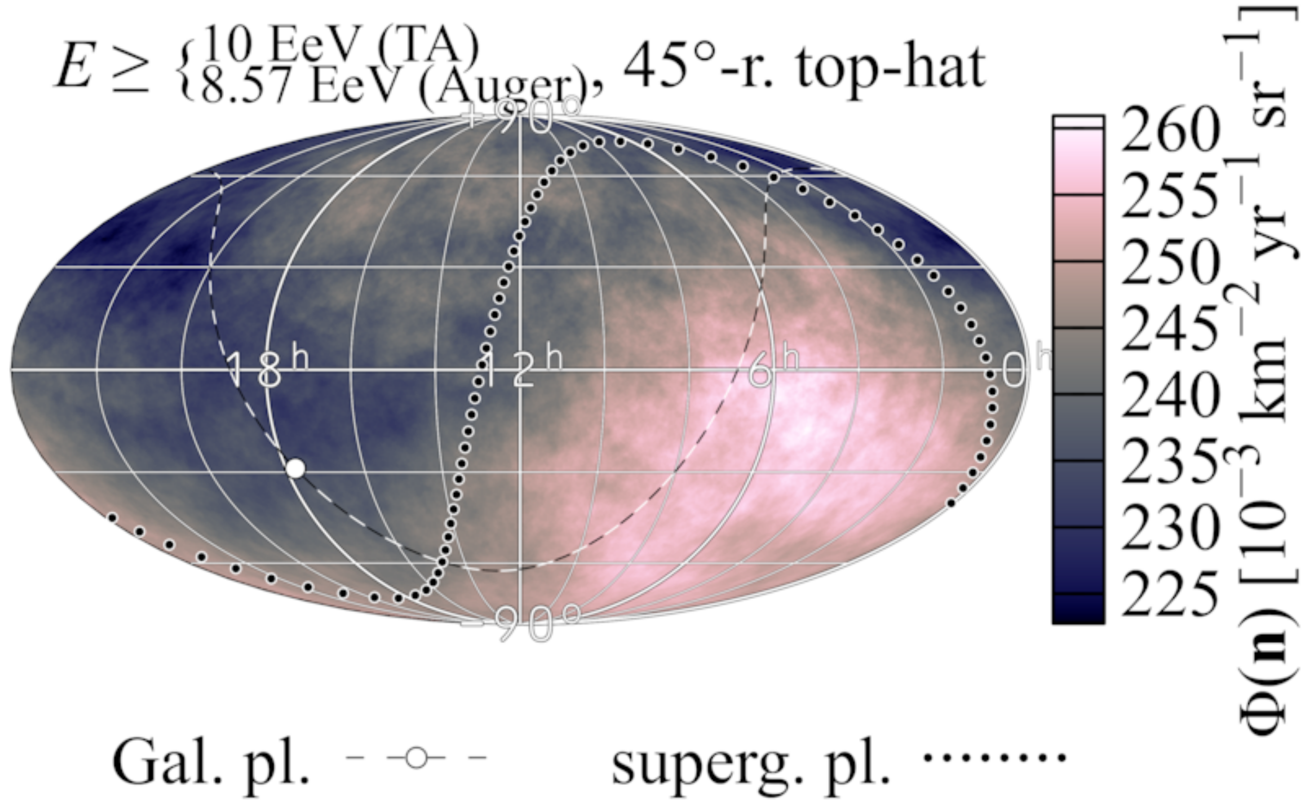
Energy scale conversion



$$\frac{E_{Auger}}{10\ \text{EeV}} = 0.857 \left(\frac{E_{TA}}{10\ \text{EeV}}\right)^{0.937}$$

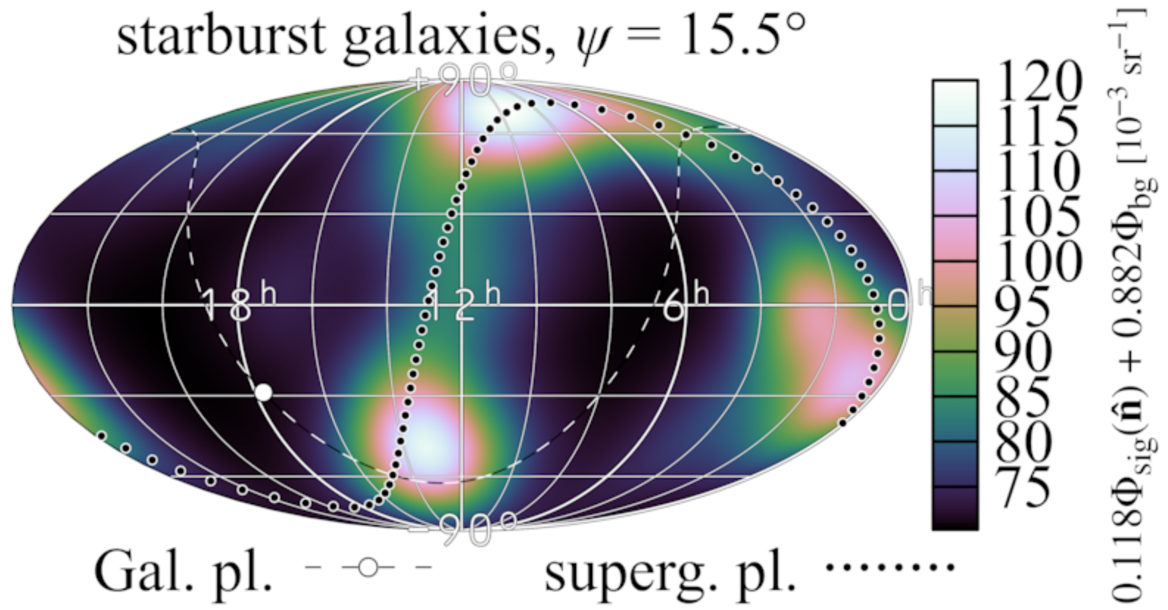
$$\frac{E_{TA}}{10\ \text{EeV}} = 1.179 \left(\frac{E_{Auger}}{10\ \text{EeV}}\right)^{1.067}$$

Large angular scales



Dipole direction better constrained, compatible with Auger-only result

Catalog correlation searches

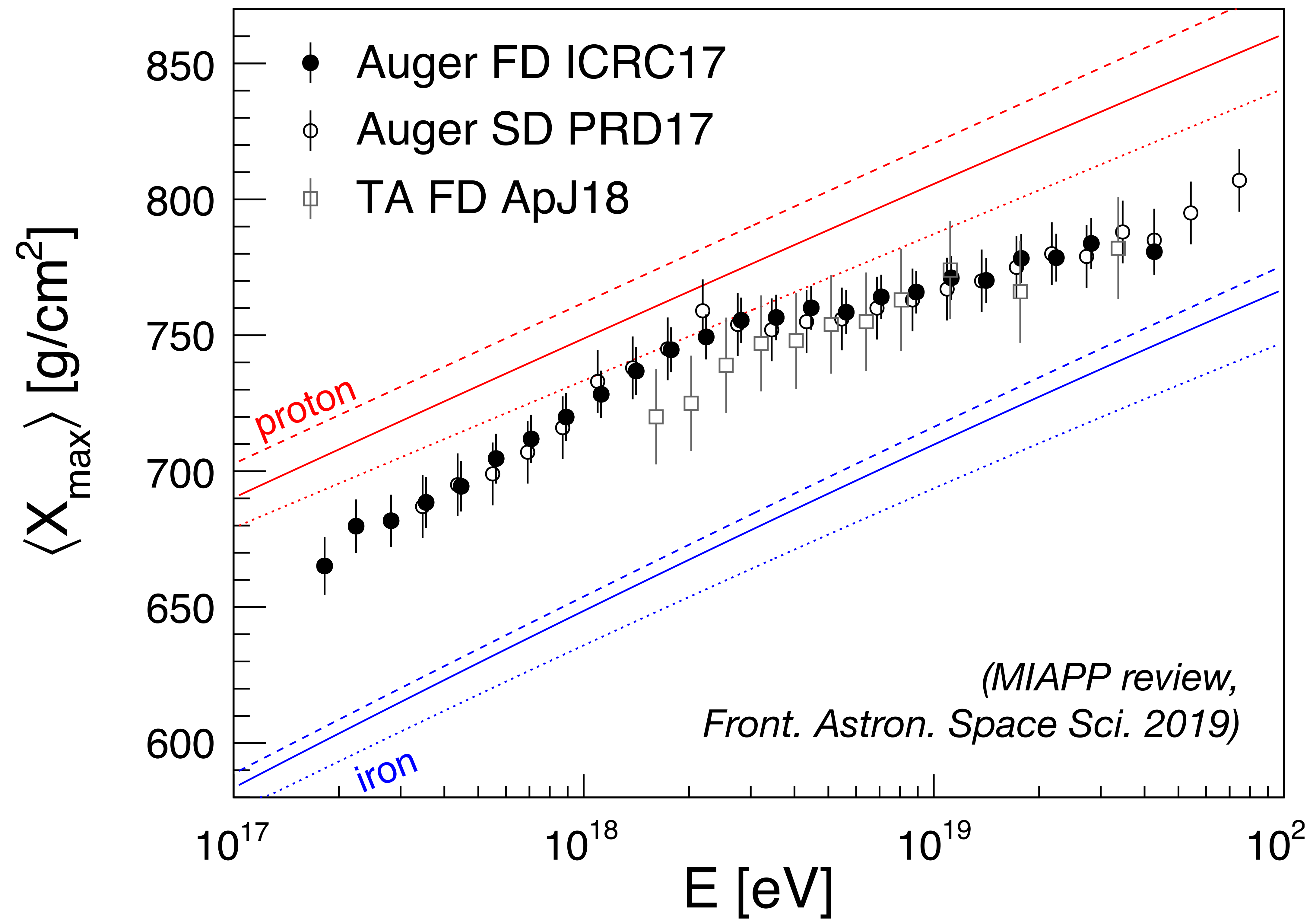


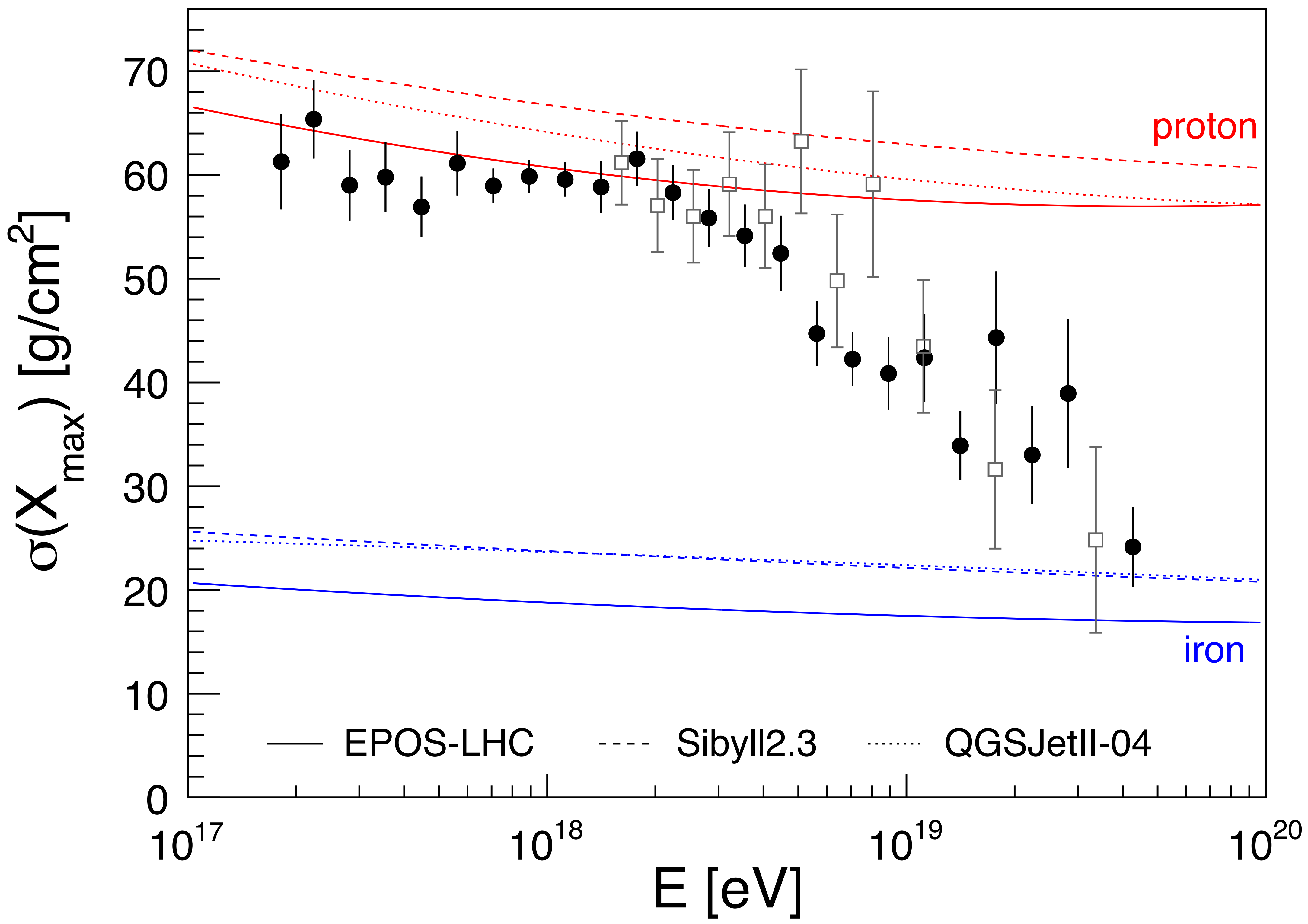
(Auger-TA,ICRC 2021)

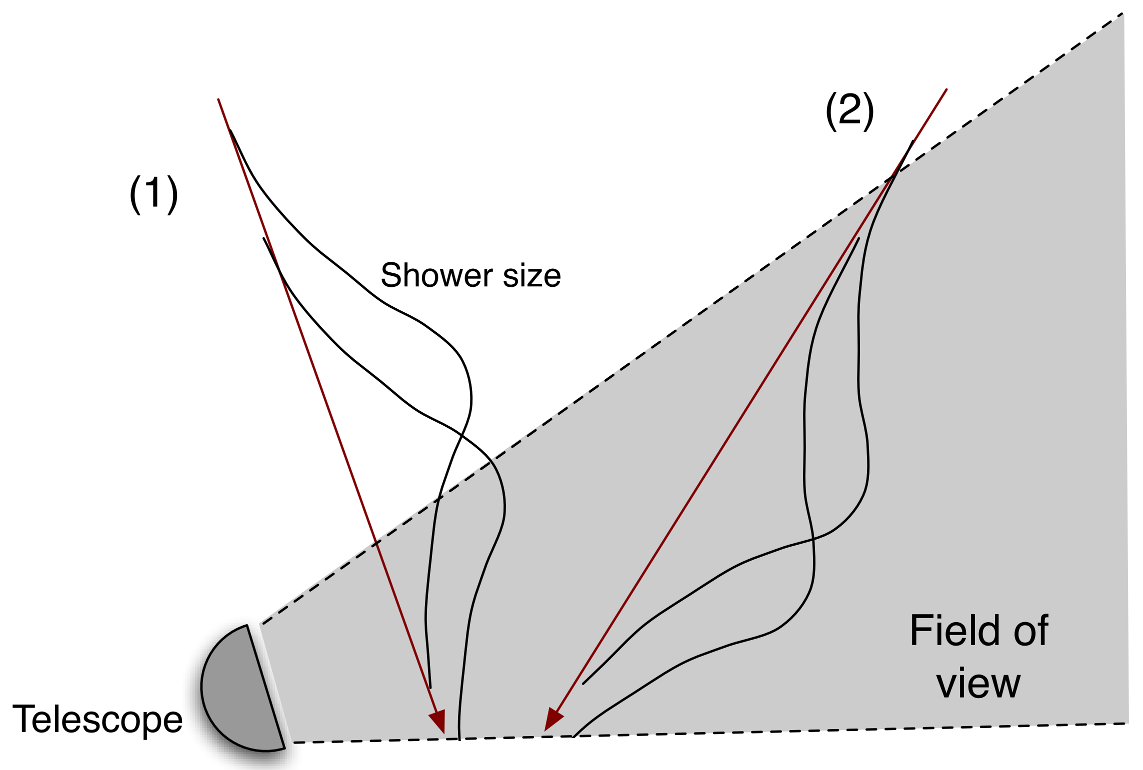
catalog	E_{min} (Auger)	E_{min} (TA)	ψ	equiv. top-hat radius	f	TS
all galaxies	41 EeV	53 EeV	$24°^{+13°}_{-8°}$	$38°^{+21°}_{-13°}$	$38\%^{+28\%}_{-14\%}$	16.2
starburst galaxies	38 EeV	49 EeV	$15.5°^{+5.3°}_{-3.2°}$	$24.6°^{+8.4°}_{-5.1°}$	$11.8\%^{+5.0\%}_{-3.1\%}$	27.2

4.2σ for the starburst galaxy catalog 2.9σ for the all-galaxy catalog

Comparison of Xmax data of Auger and TA





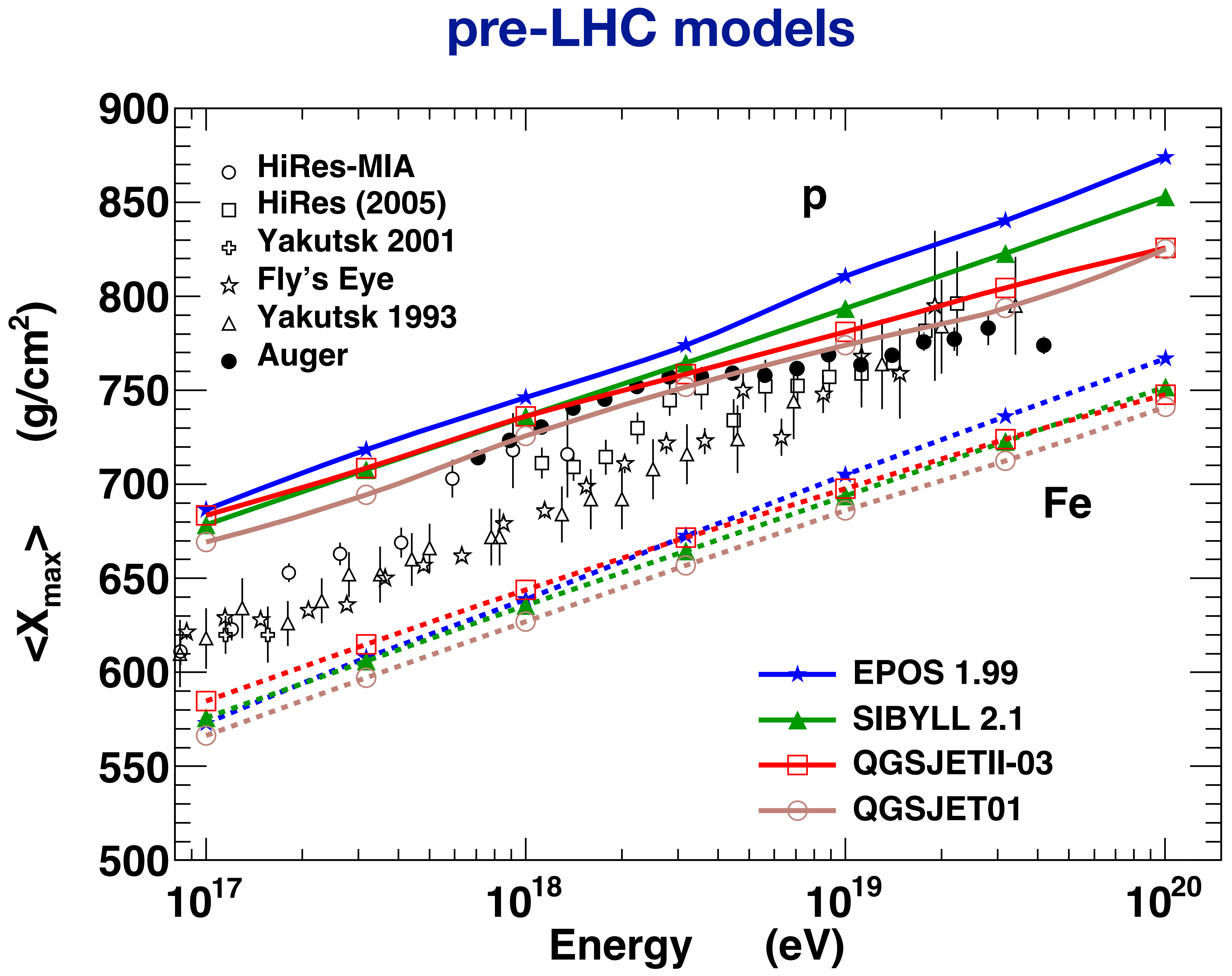


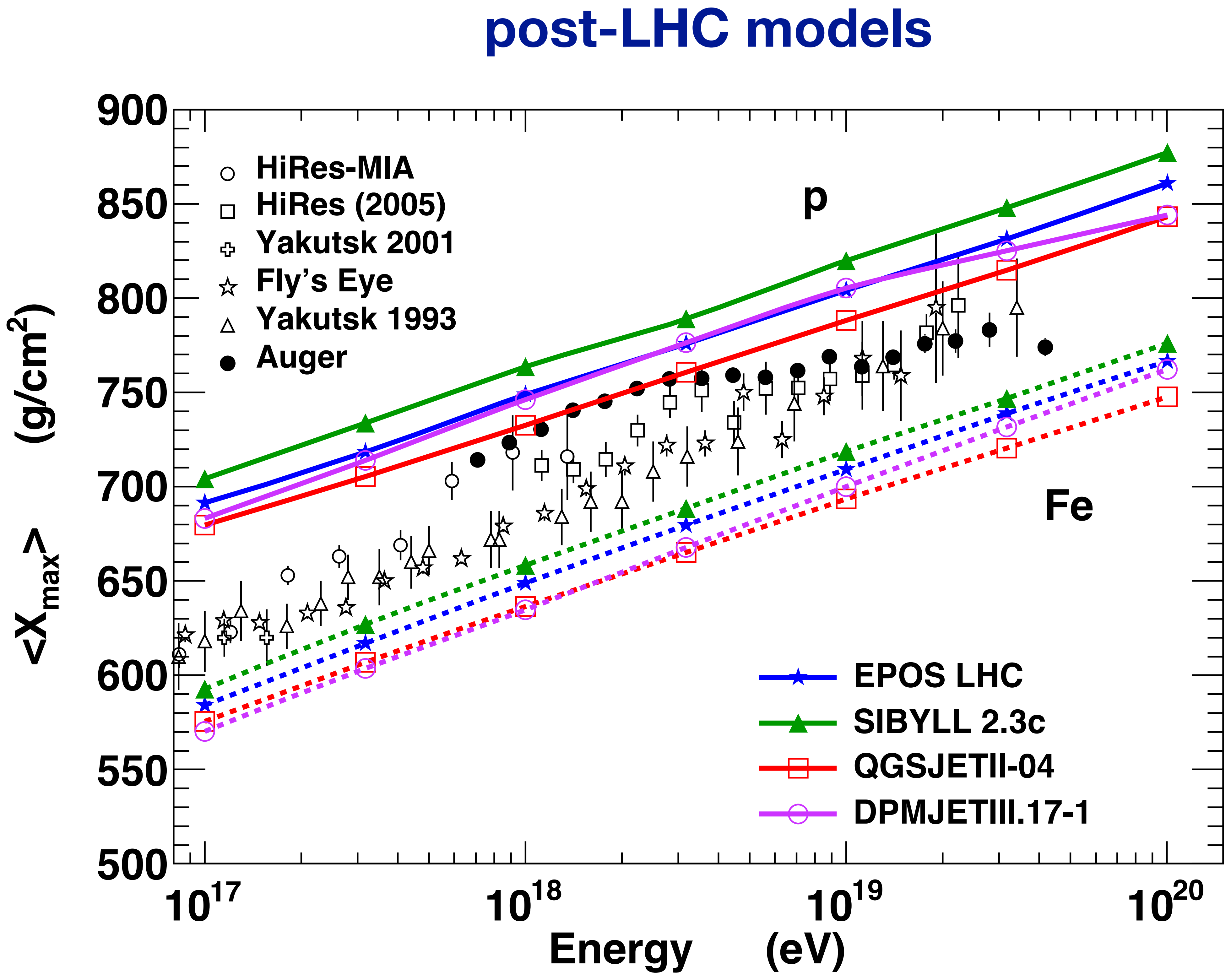
Work in progress:

data consistent in energy range with sufficient statistics

(Auger-TA Xmax Working Group, UHECR 2018)

Change of model predictions thanks to LHC data





(Pierog, ICRC 2017)

Sys. X_{max} uncertainty Auger: $\Delta X_{\max} = -10\,\mathrm{g/cm^2} \; +8\,\mathrm{g/cm^2}$

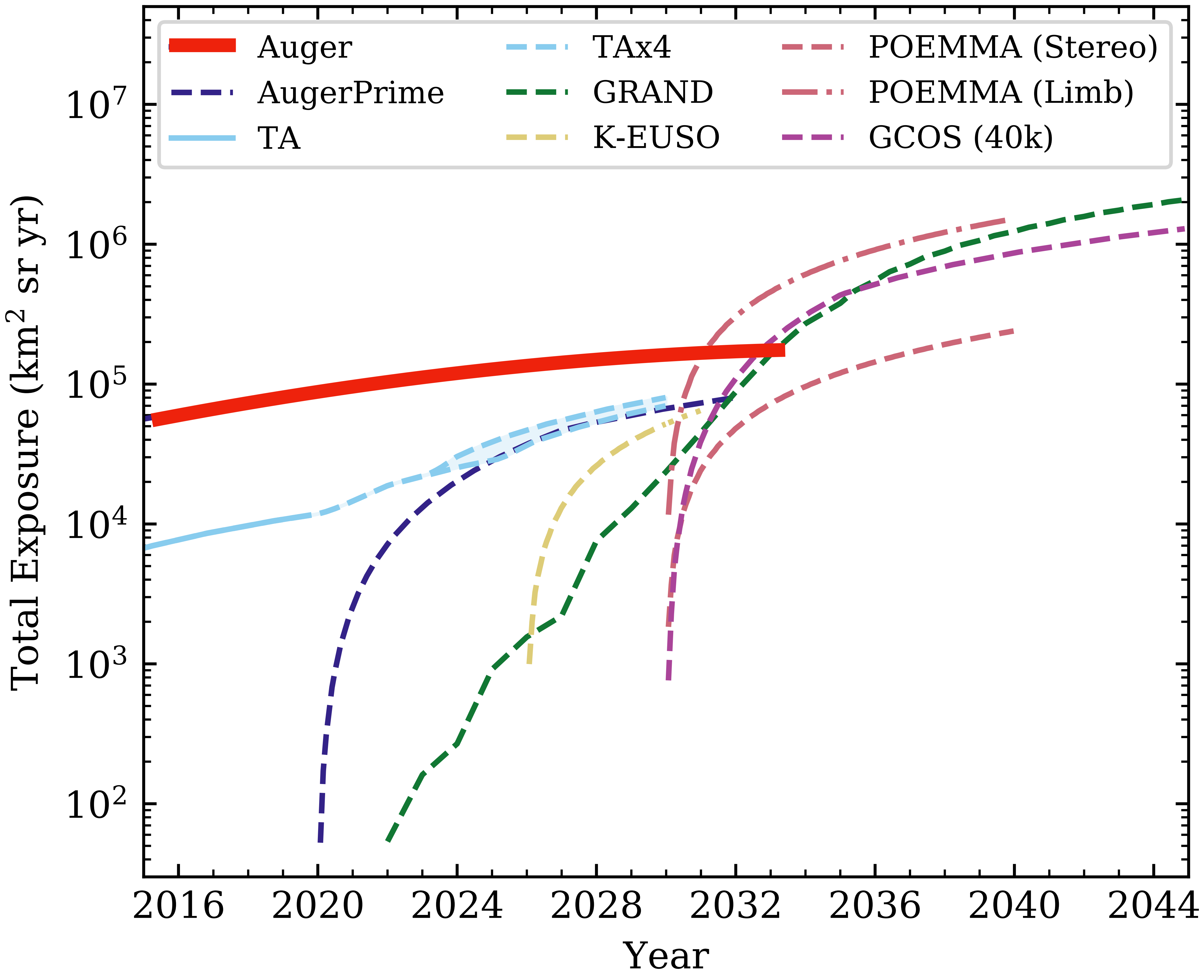
TA: $\Delta X_{\max} = \pm 20\,\mathrm{g/cm^2}$

LHC-tuned models should be used for data interpretation

(see also discussion Lipari, Phys.Rev.D 103 (2021) 103009)

Snowmass P5 strategy process

Solid lines: existing instruments, broken lines: planned instruments



(Snowmass UHECR White Paper, 2205.05845)

Several changes of paradigms

Measurement of composition-sensitive observables

- Mass composition and source / propagation physics
- Mass-enhanced anisotropy studies
- Hadronic interactions and particle physics
- Fundamental physics (LIV)
- Astrophysical magnetic fields

Multi-messenger observations

- Ultra-high energy photon and neutrino fluxes
- Transient source observation

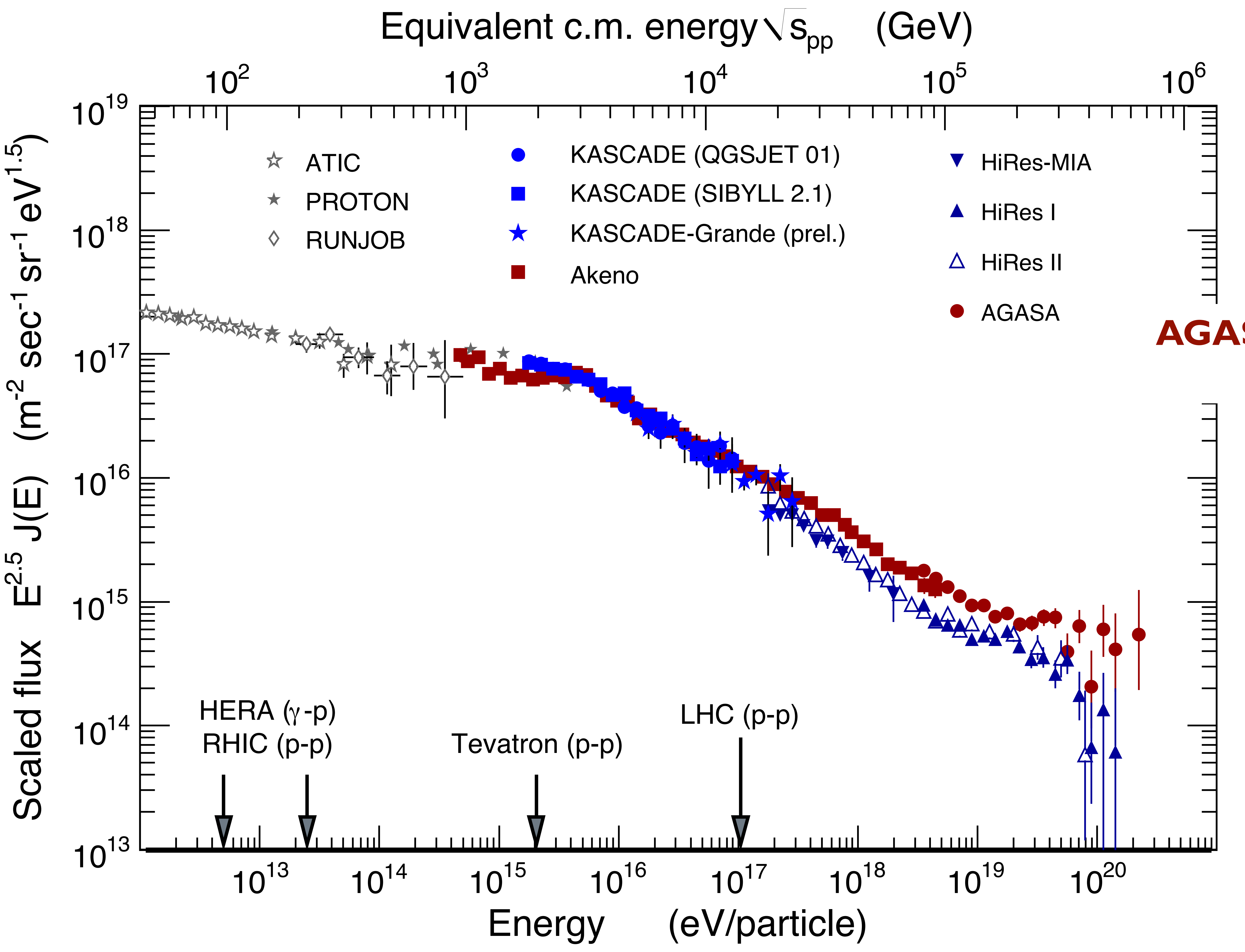
Extension of sensitivity to lower energy

- Transition from galactic to extragalactic cosmic rays
- Multi-messenger observations at lower energy

Test facility and multi-disciplinary measurements

- Multi-hybrid detection technologies
- Calibrated environment, link to new instruments
- Atmospheric phenomena and transients

History: energy spectrum and mass composition

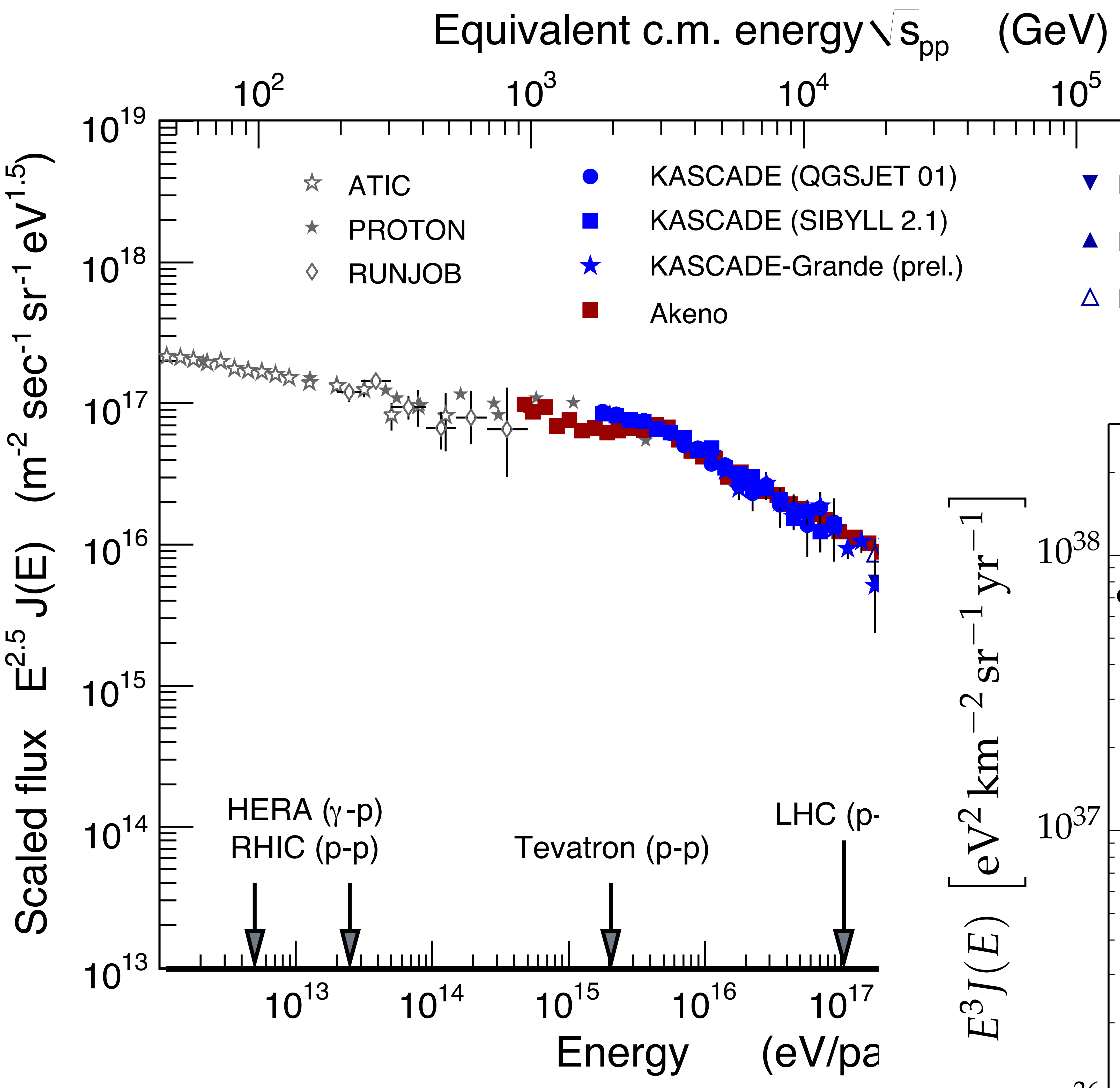


AGASA: particles at ground
(scintillator array)

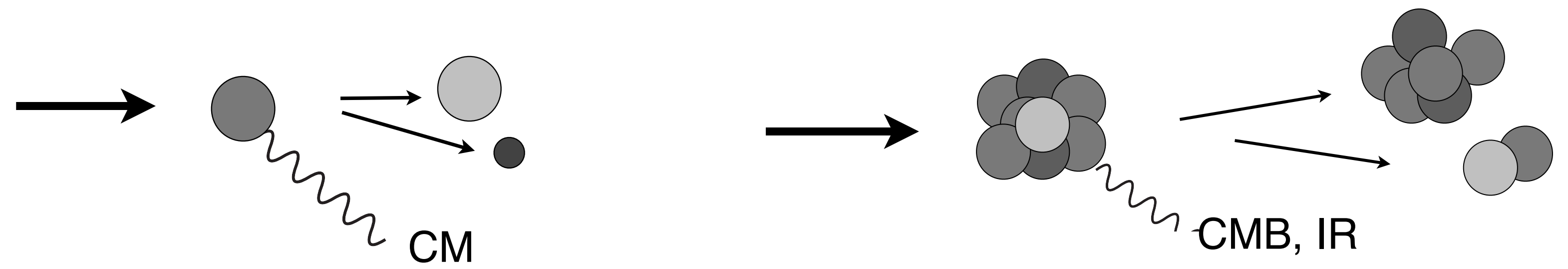
HiRes Fly´s Eye: longitudinal shower profile
(fluorescence telescopes)

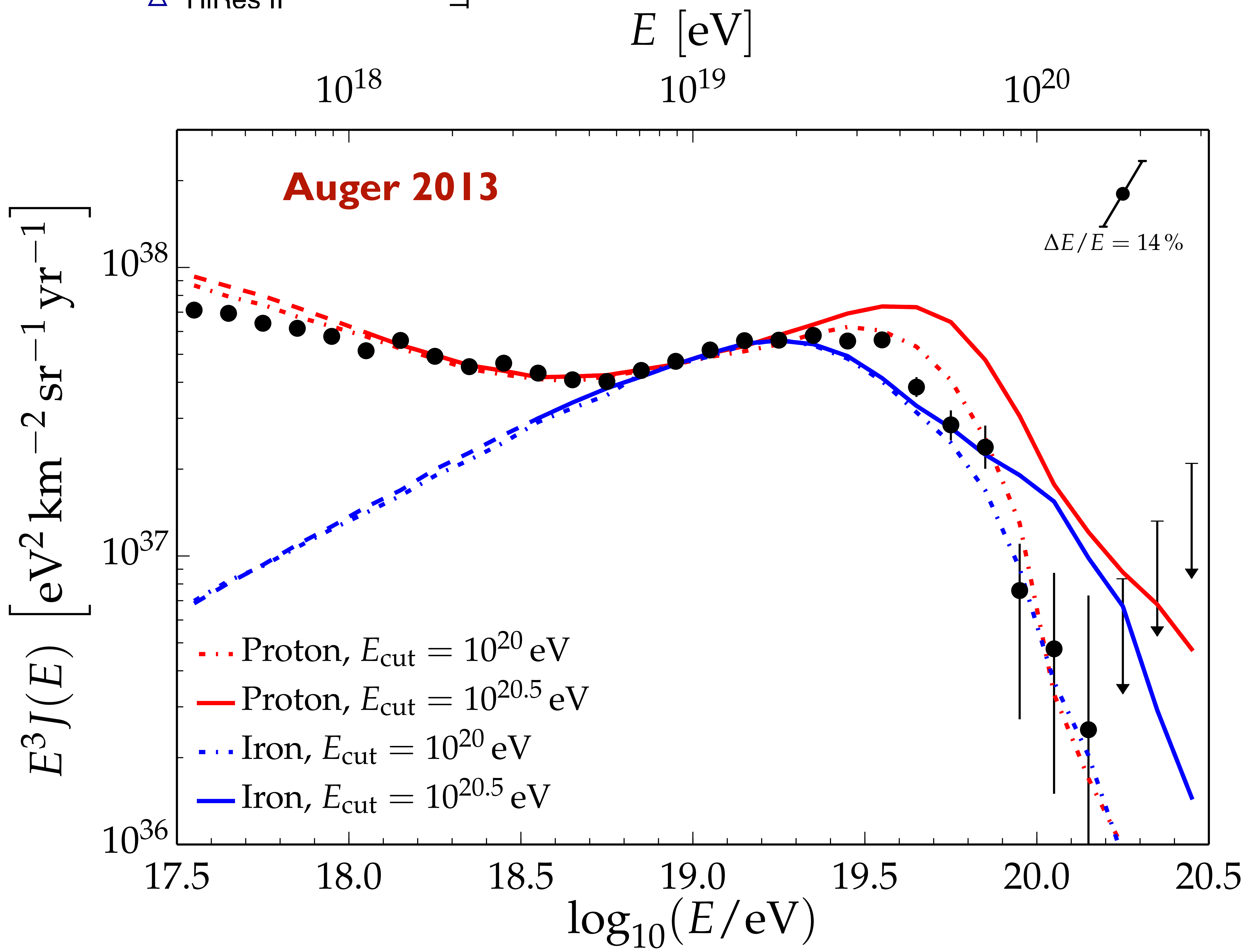
(RE, Nijmegen Summer School, 2006)

History: energy spectrum and mass composition

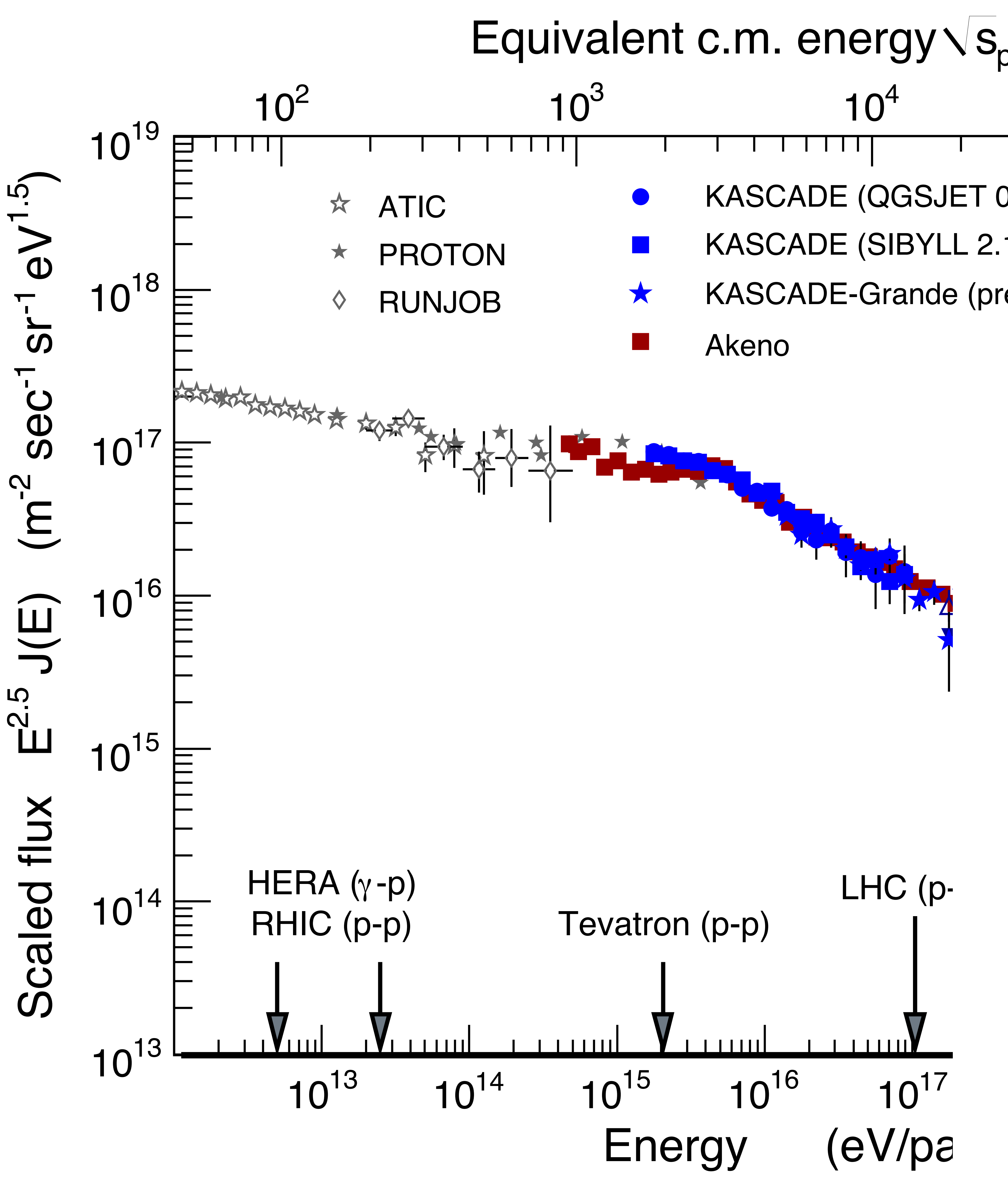


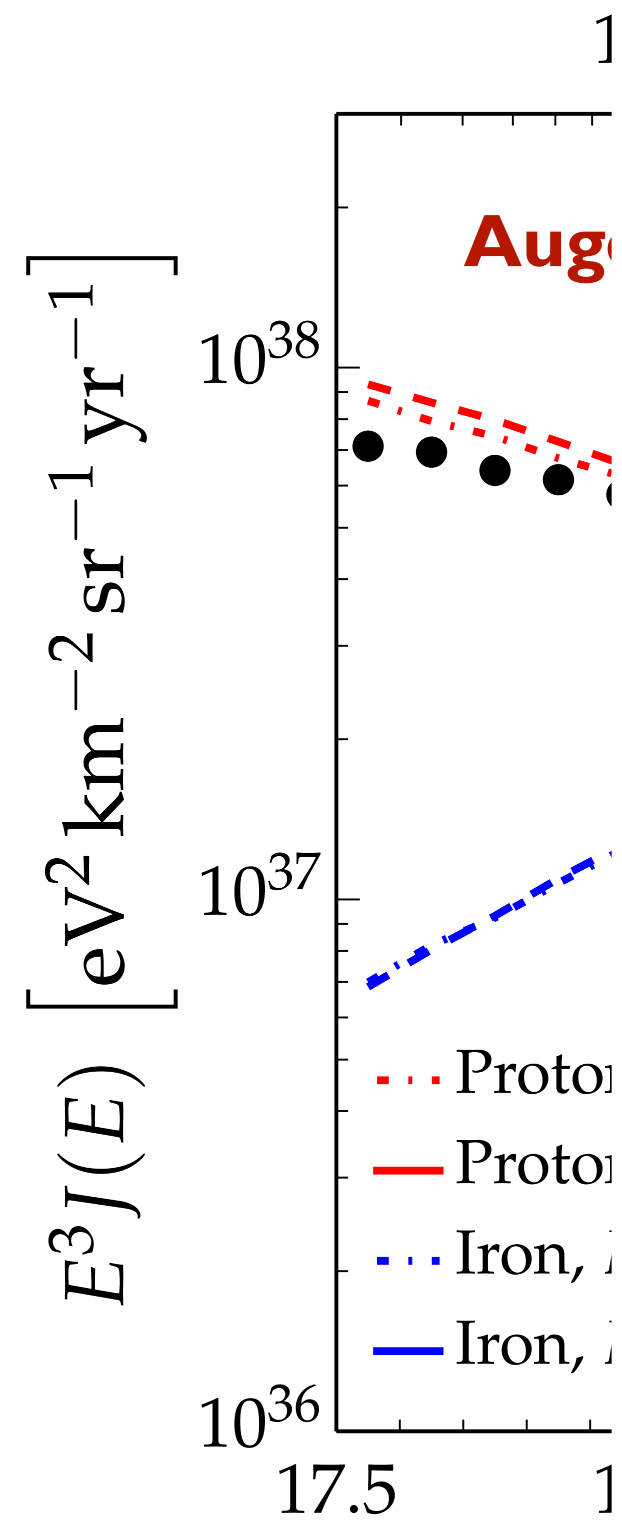
Greisen-Zatsepin-Kuzmin (GZK) effect

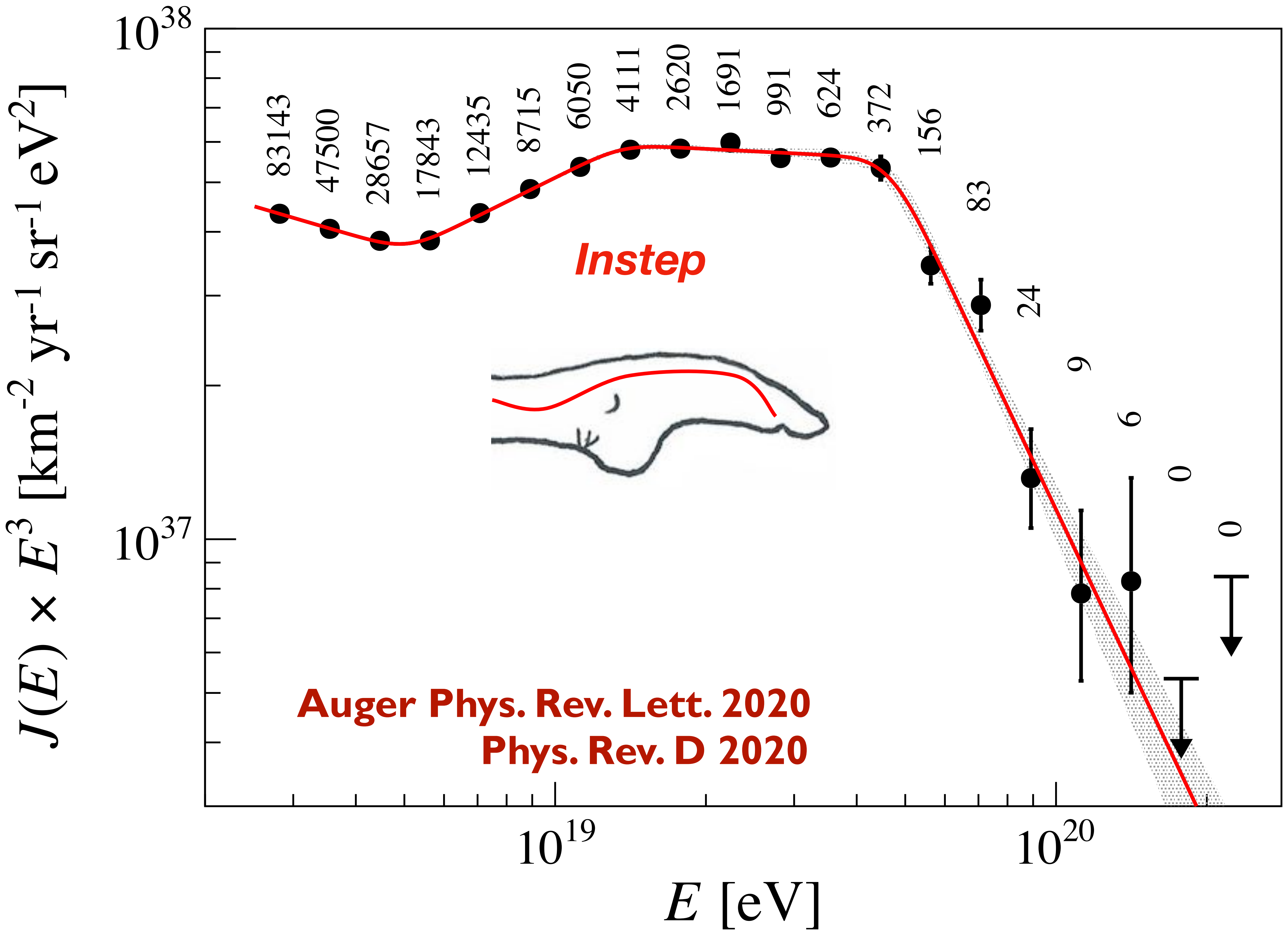




History: energy spectrum and mass composition







History: energy spectrum and mass composition

$$R_{\text{cut}} = 1.4 \ldots 1.6 \times 10^{18}\,\text{V}$$