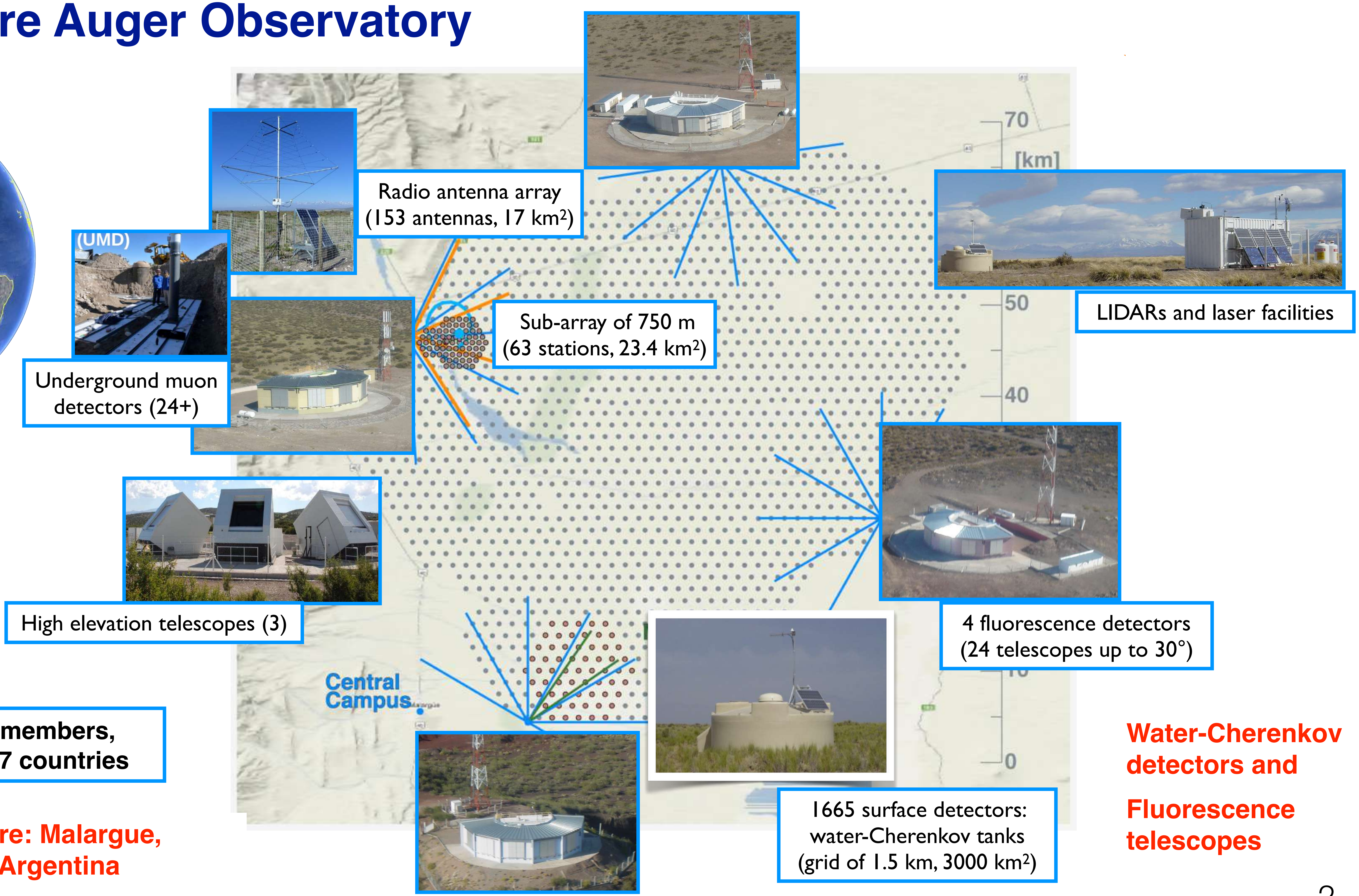
Latest Results from the Pierre Auger Observatory

Bruce Dawson
The University of Adelaide, Australia

TeVPA Chengdu, October 2021

The Pierre Auger Observatory

Pierre Auger Observatory
Province Mendoza, Argentina



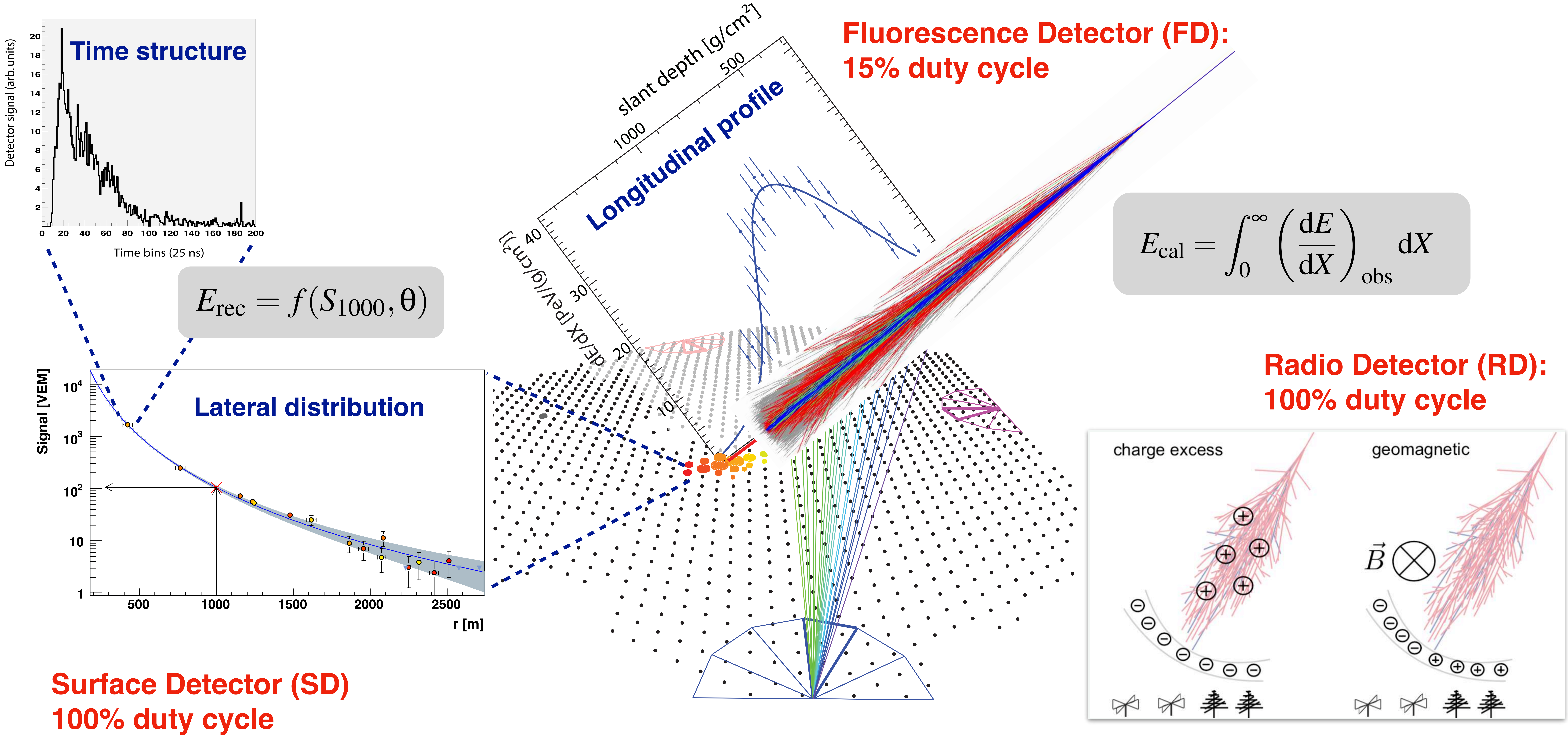
More than 400 members,
98 institutes, 17 countries

Southern hemisphere: Malargue, Province Mendoza, Argentina

Water-Cherenkov detectors and

Fluorescence telescopes

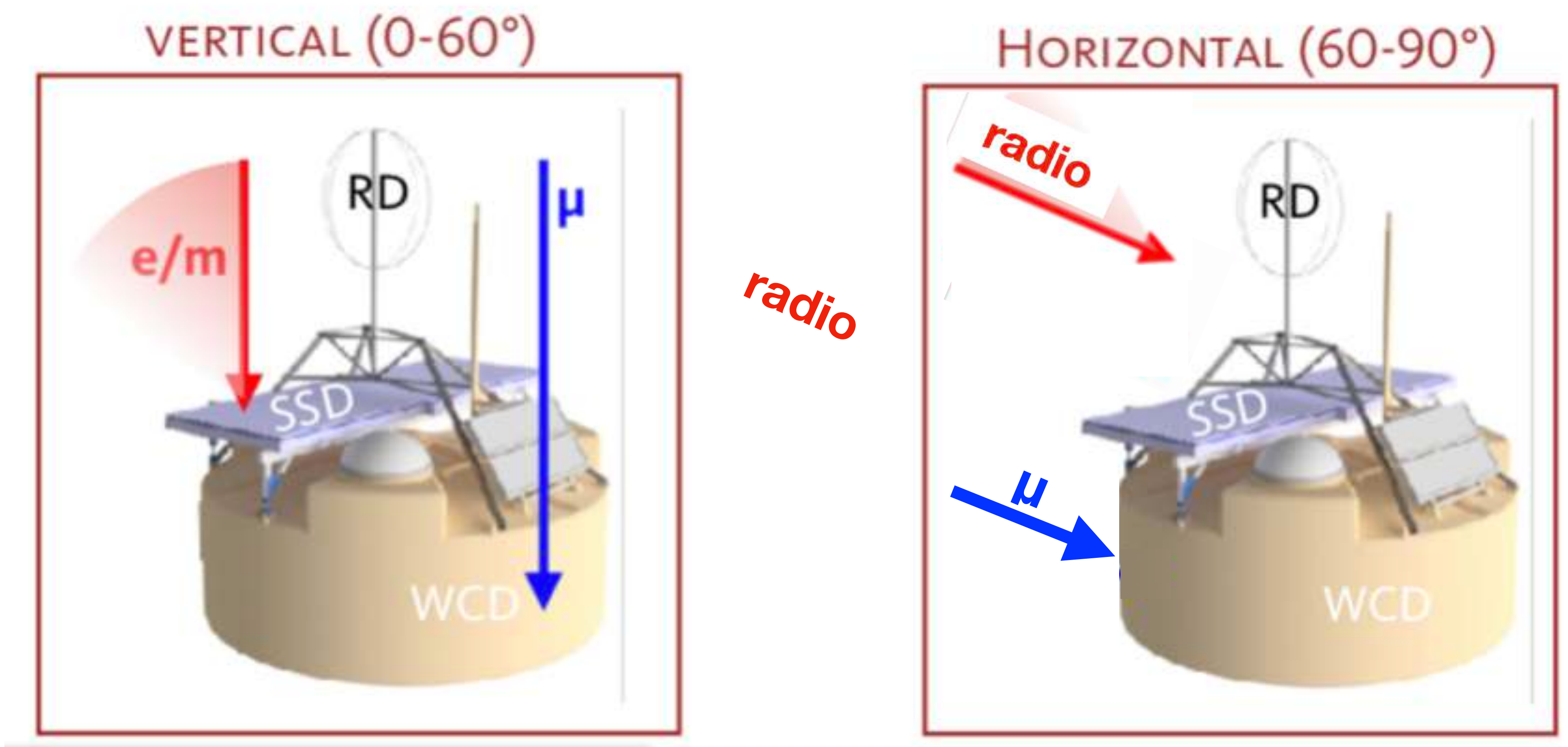
Auger is a Hybrid Observatory



$$E_{\rm rec} = f(S_{1000}, \theta)$$

$$E_{\rm cal} = \int_0^{\infty} \left(\frac{\mathrm{d}E}{\mathrm{d}X}\right)_{\rm obs} \mathrm{d}X$$

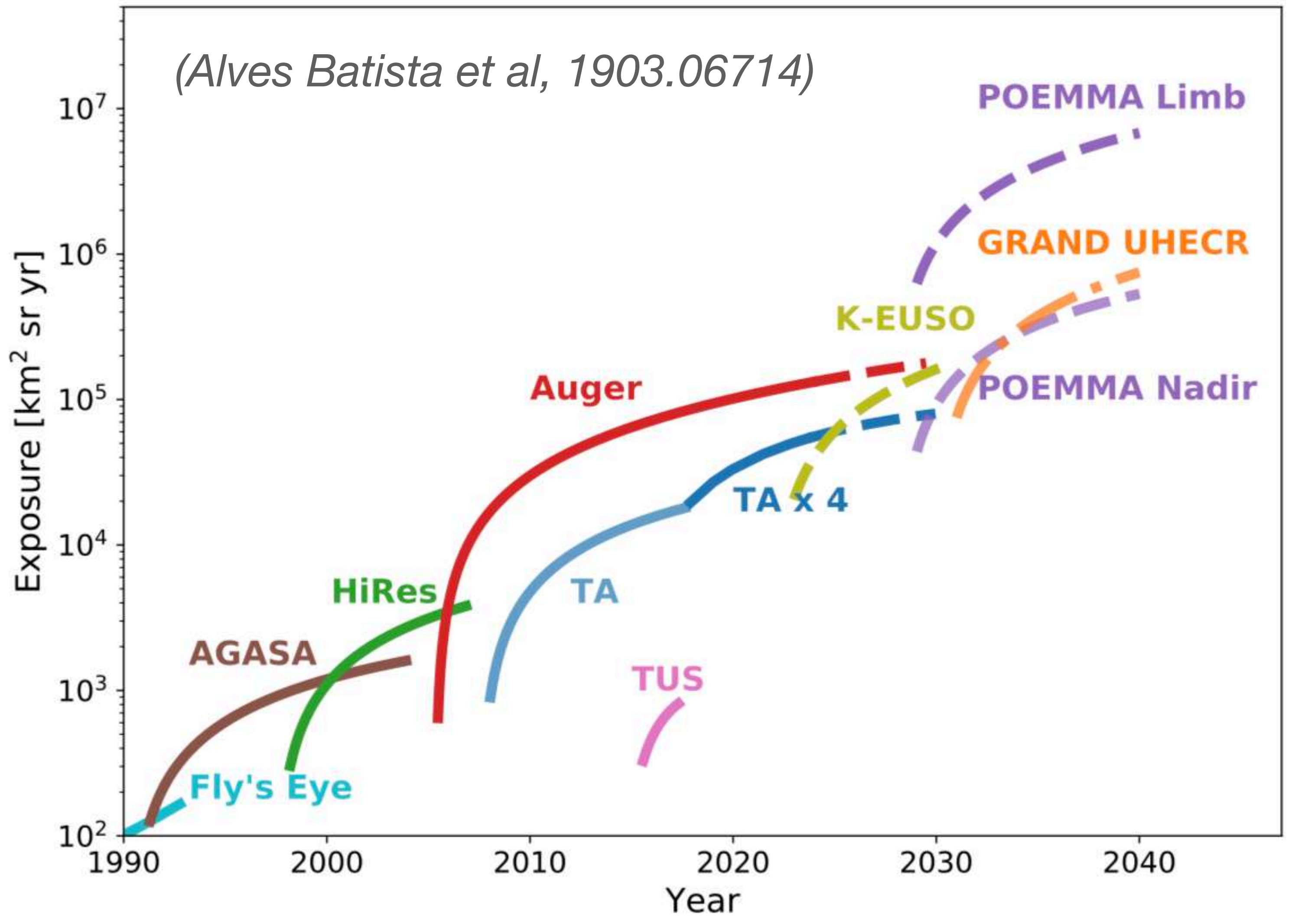
Moving to Phase II of the Observatory - AugerPrime



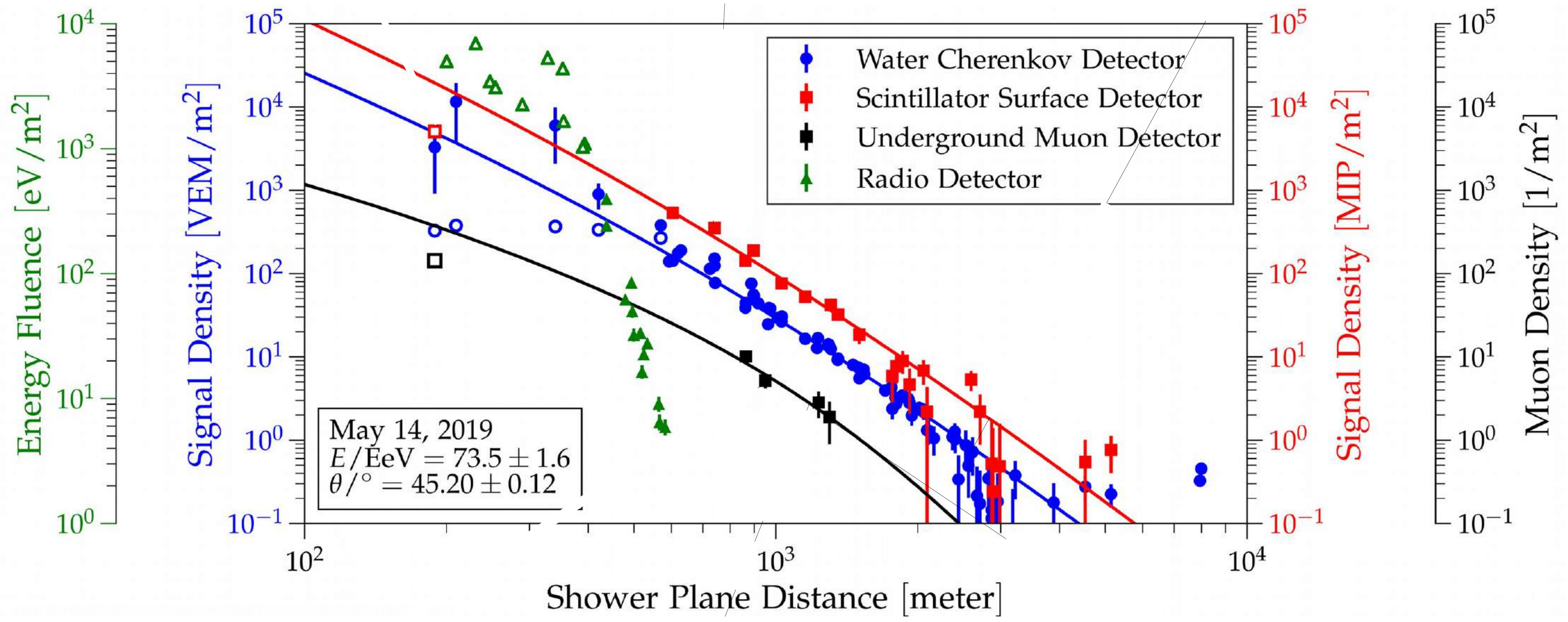
Phase I: exposure 80,000 km² sr y ($\theta < 60^\circ$)

Phase II

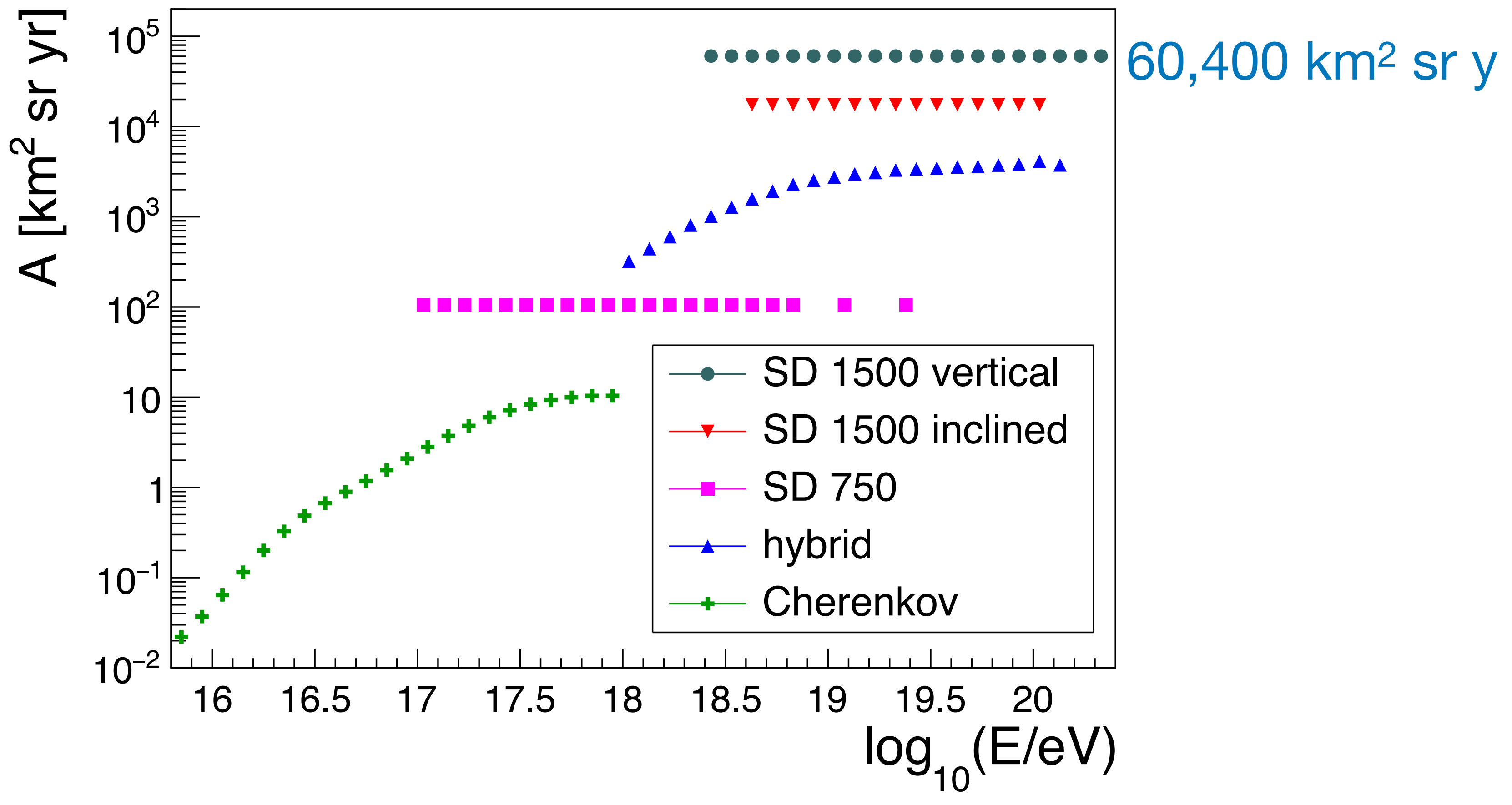
- 2022/23 - 2030
- mass composition info on all events
- scintillator detectors and radio
- expect new 40,000 km² sr y ($\theta < 60^\circ$)
- re-analysis of old data-set (deep learning)

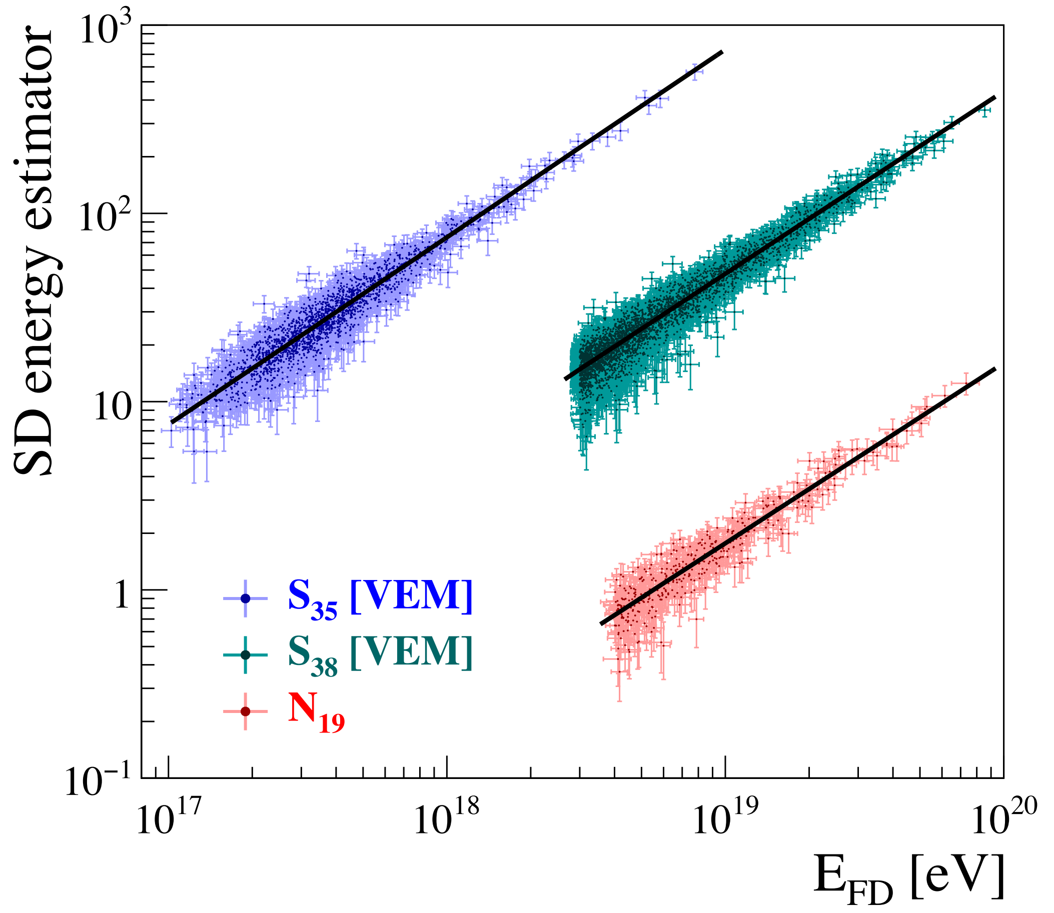


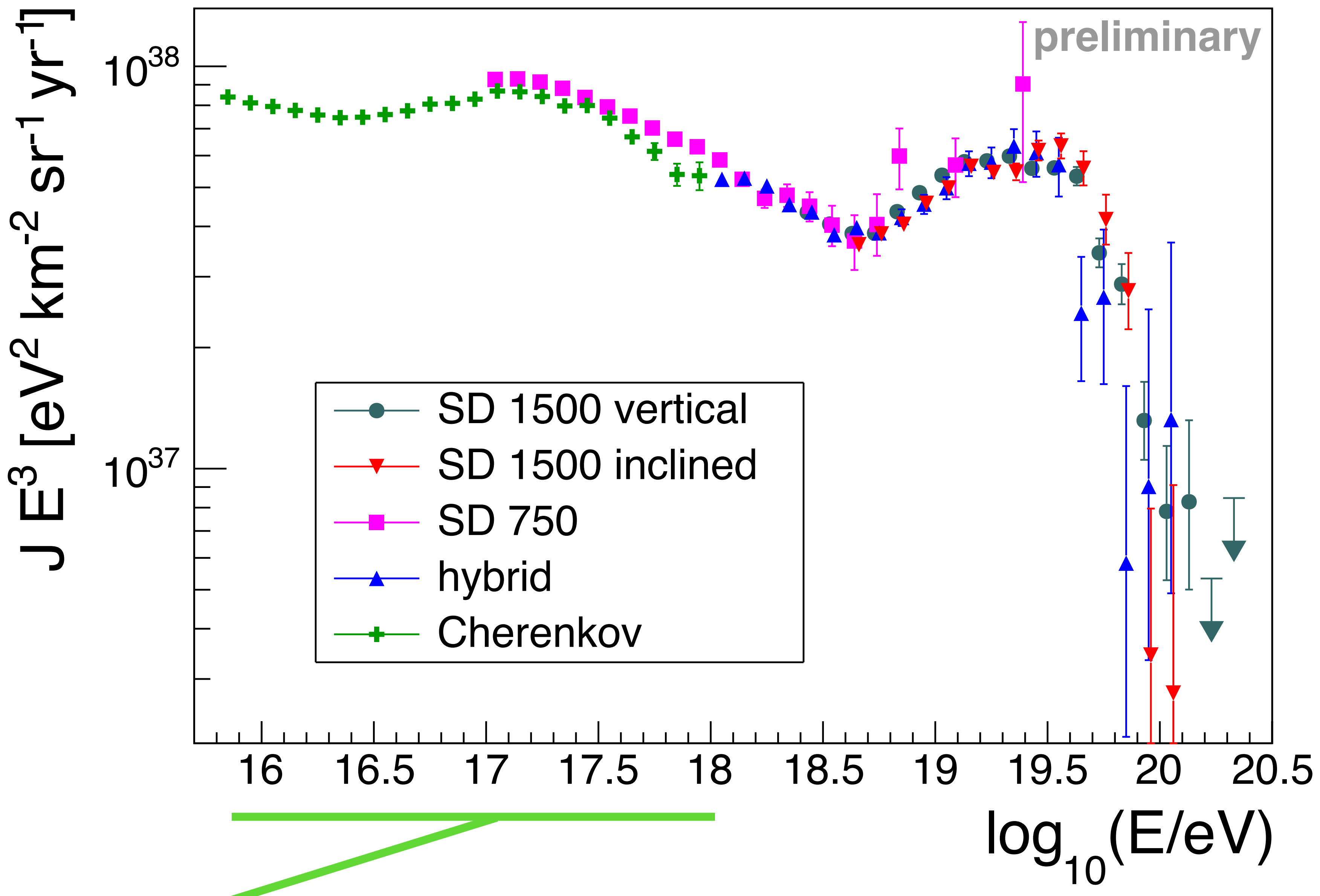
Example data from engineering array



The energy spectrum (including low-energy extensions)

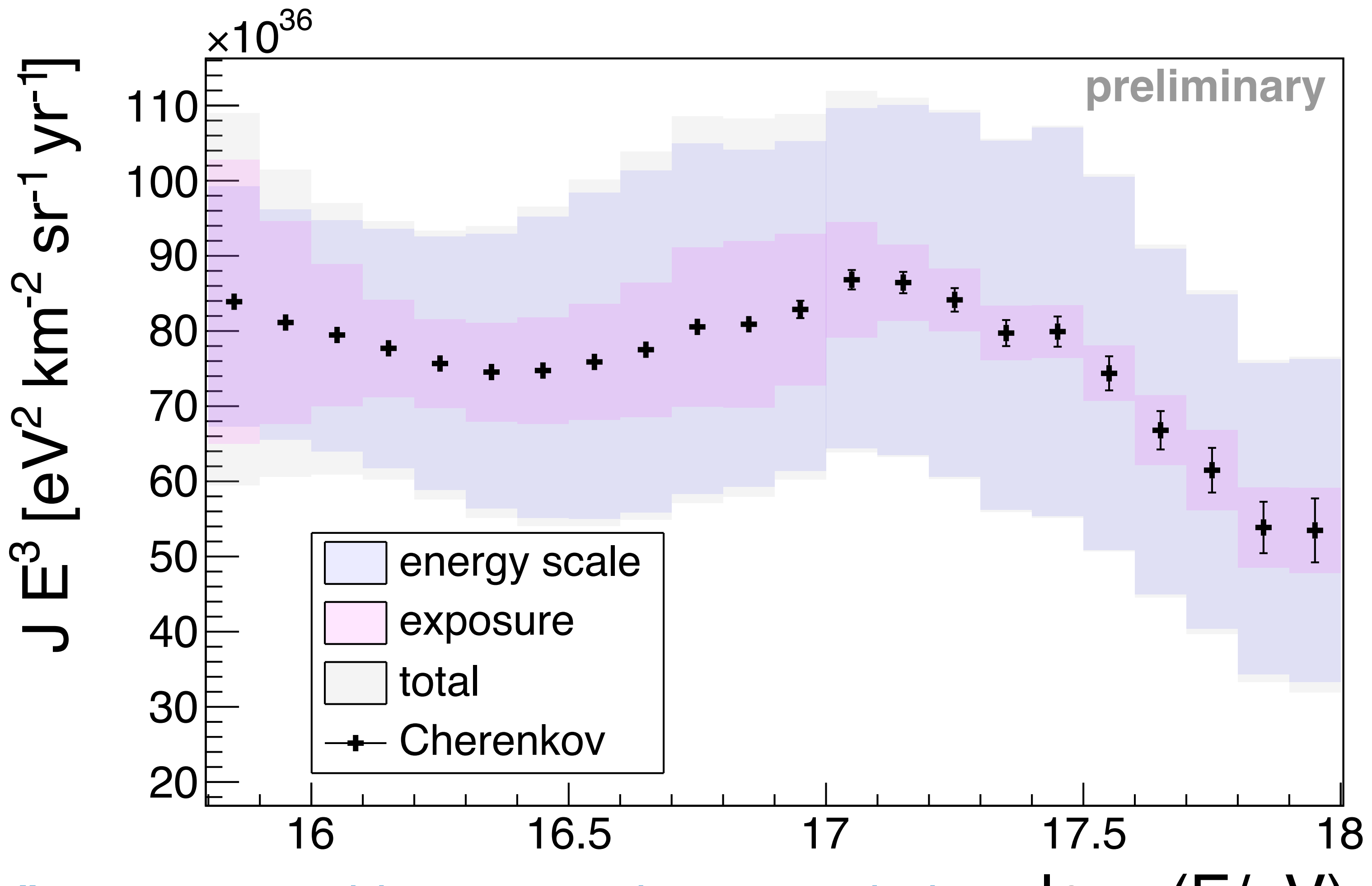




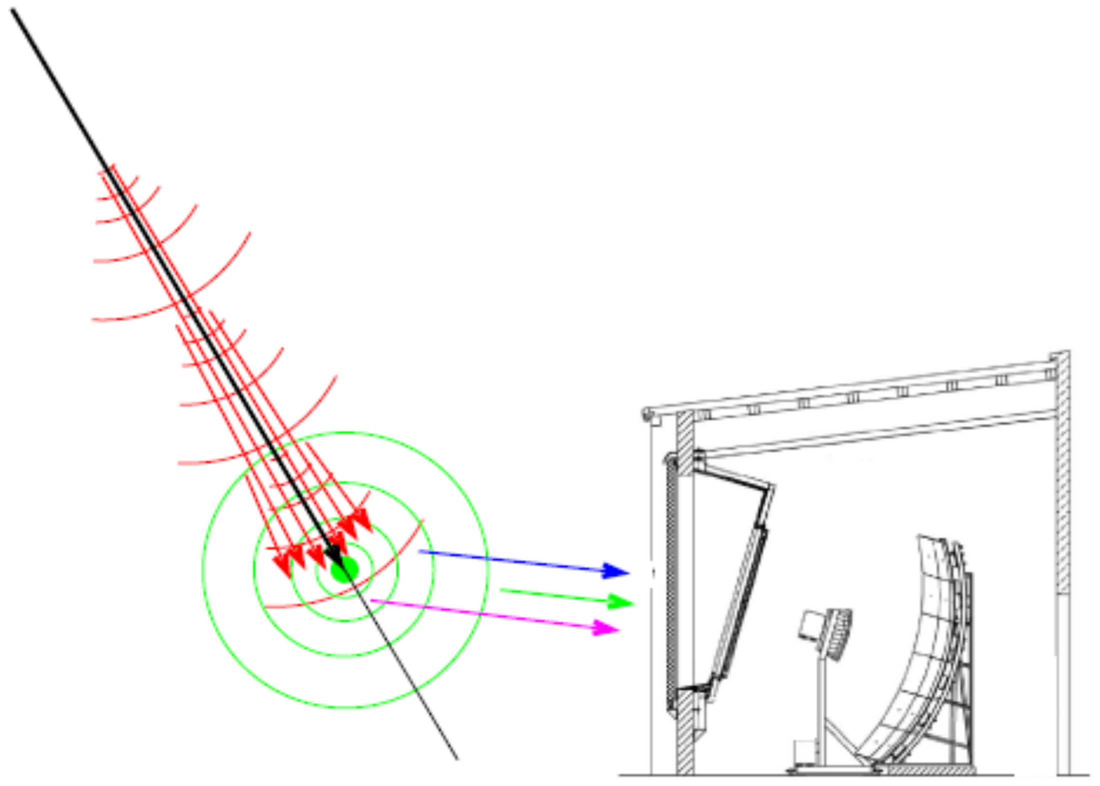


Five different measurements

- all have common energy scale (FD)
- four orders of magnitude in *E*
- spectra corrected for resolution effects
- "Cherenkov" spectrum, following example of TA (PCGF)



"Cherenkov" spectrum, with systematic uncertainties



Phys. Rev. Lett. 125 121106 (2020)
Phys. Rev. D102 062005 (2020)
ICRC21 324 (2021)

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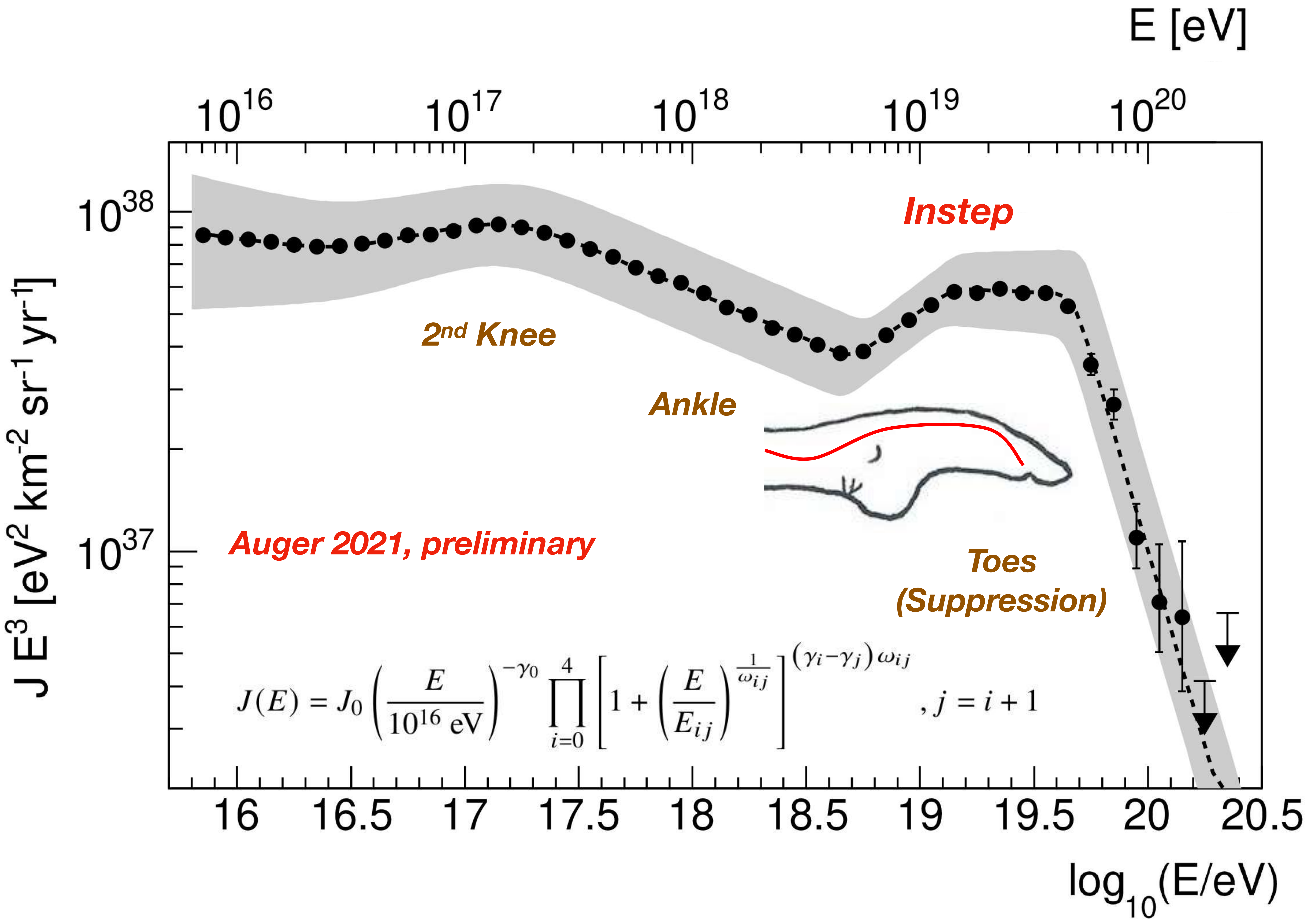
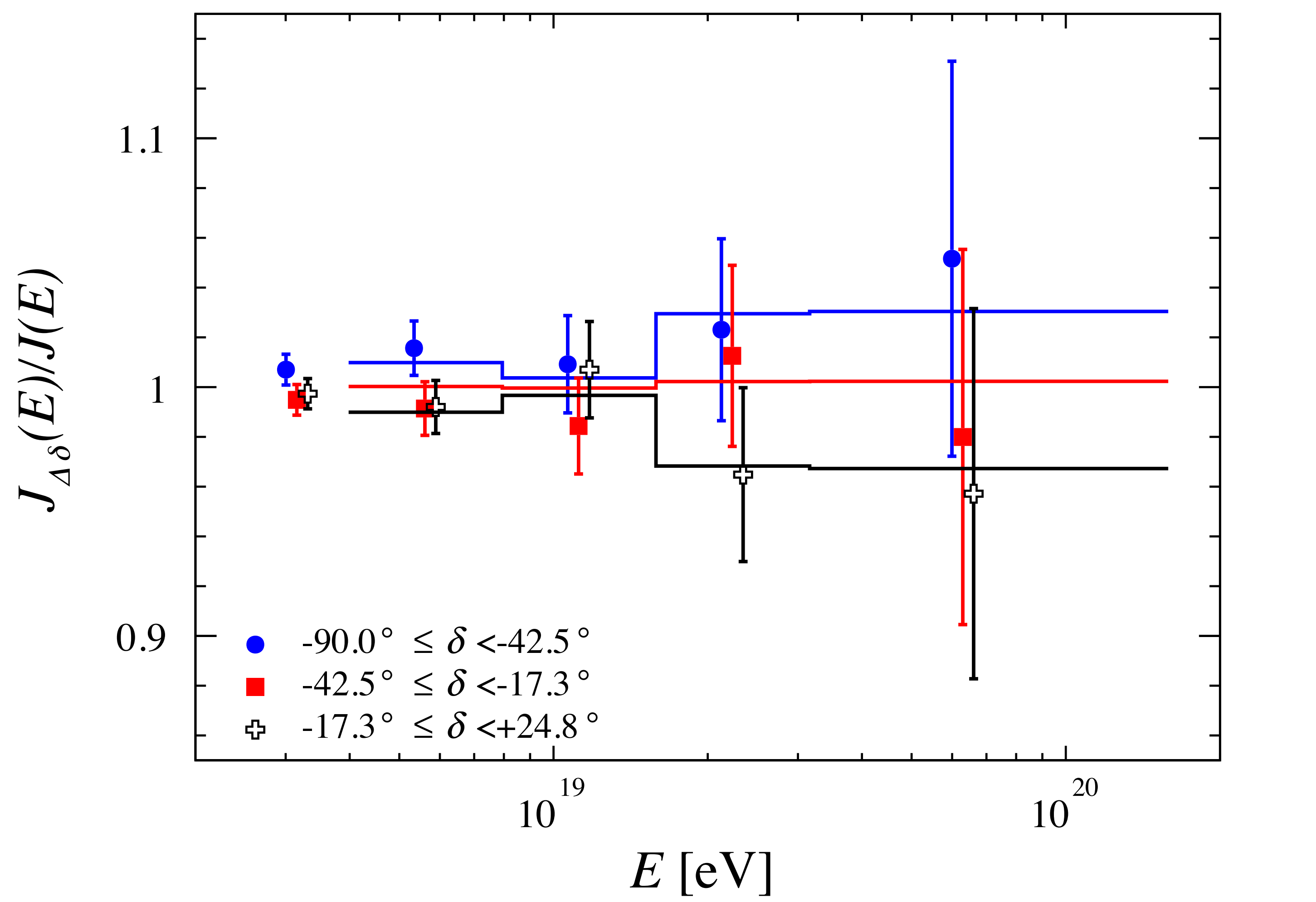
The energy spectrum - combined version

5 spectra combined
- small shifts allowed within uncertainties in exposure and energy calibration



Small declination dependence
(consistent with measured dipole anisotropy)



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

		$\gamma_0 = 3.09 \pm 0.01 \pm 0.10$
low energy ankle	$E_{01} = (2.8 \pm 0.3 \pm 0.4) \times 10^{16}$ eV	$\gamma_1 = 2.85 \pm 0.01 \pm 0.05$
2nd knee	$E_{12} = (1.58 \pm 0.05 \pm 0.2) \times 10^{17}$ eV	$\gamma_2 = 3.283 \pm 0.002 \pm 0.10$
ankle	$E_{23} = (5.0 \pm 0.1 \pm 0.8) \times 10^{18}$ eV	$\gamma_3 = 2.54 \pm 0.03 \pm 0.05$
instep	$E_{34} = (1.4 \pm 0.1 \pm 0.2) \times 10^{19}$ eV	$\gamma_4 = 3.03 \pm 0.05 \pm 0.10$
suppression	$E_{45} = (4.7 \pm 0.3 \pm 0.6) \times 10^{19}$ eV	$\gamma_5 = 5.3 \pm 0.3 \pm 0.1$

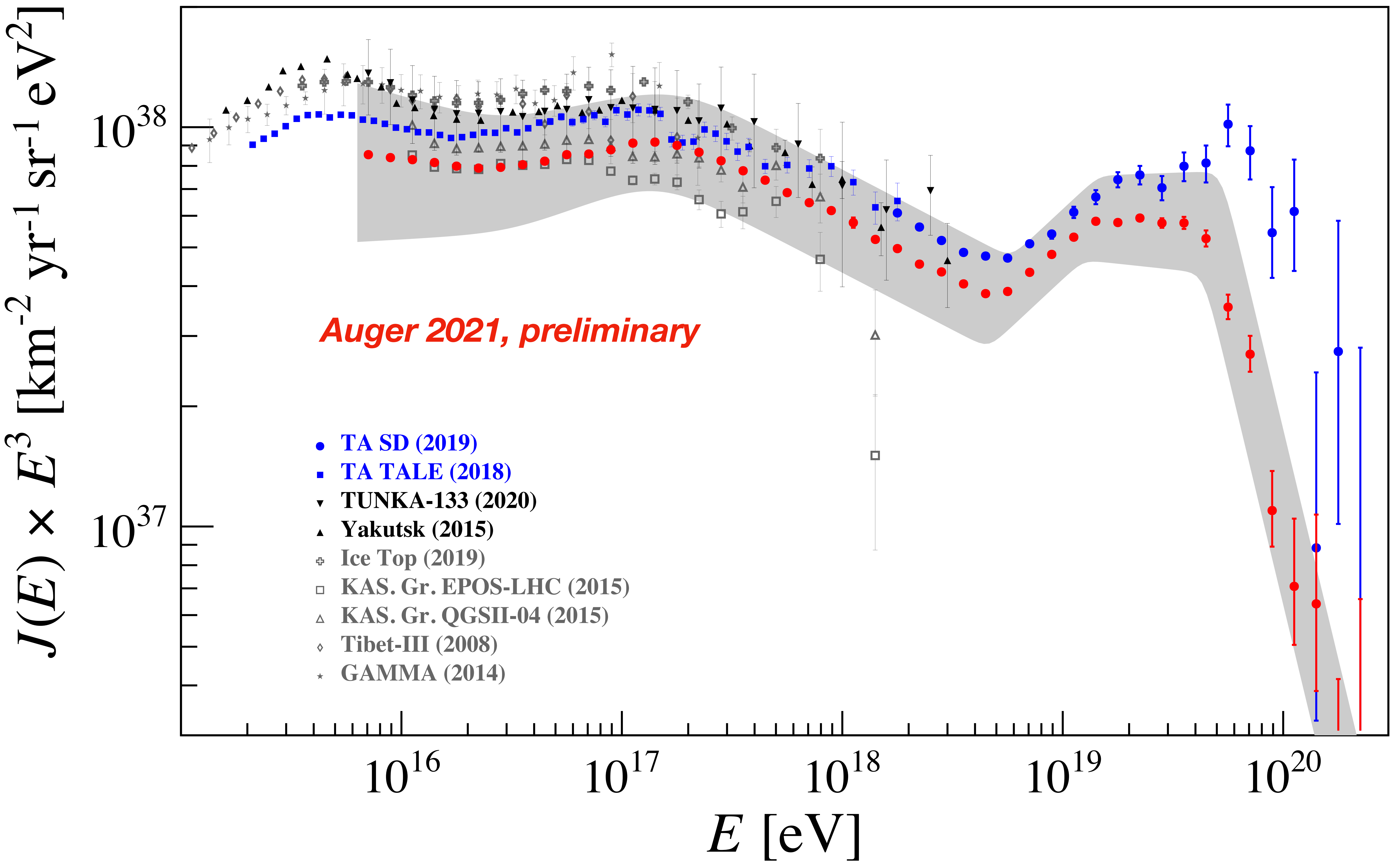
Origin of low-energy ankle and second knee likely related to mass evolution of Galactic CR.
New instep feature discovered - possible interpretation later

The energy spectrum - comparison with other measurements

No systematics shown for other experiments.

Auger's energy systematic (14%) is the smallest.

Energy-dependent shift required when comparing Auger and TA.



Phys. Rev. Lett. 125 121106 (2020)
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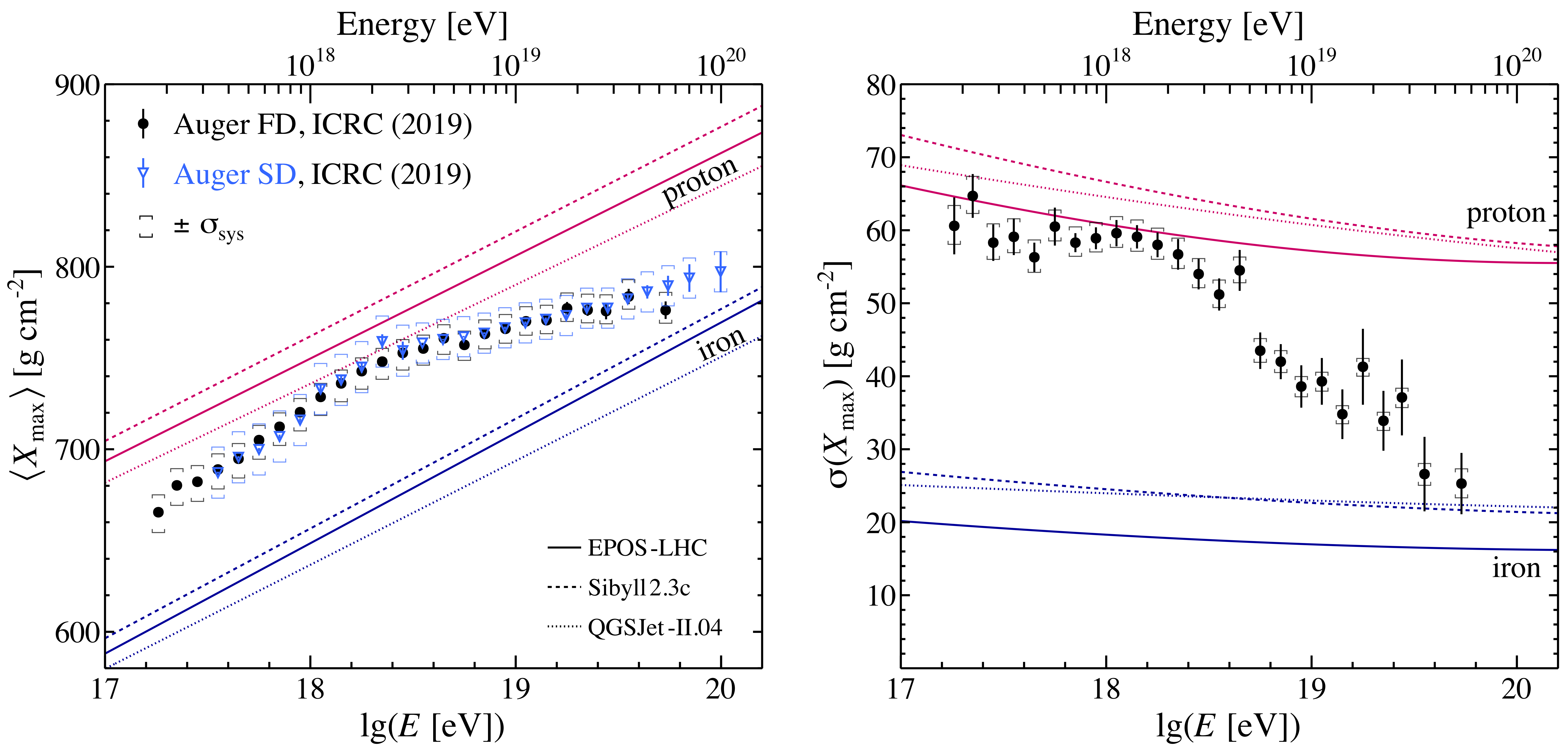
ICRC21 324 (2021)

Mass Composition



SD X_{max} from signal rise-time measurements, calibrated against FD X_{max}.

Note: use of post-LHC hadronic models for comparison with data

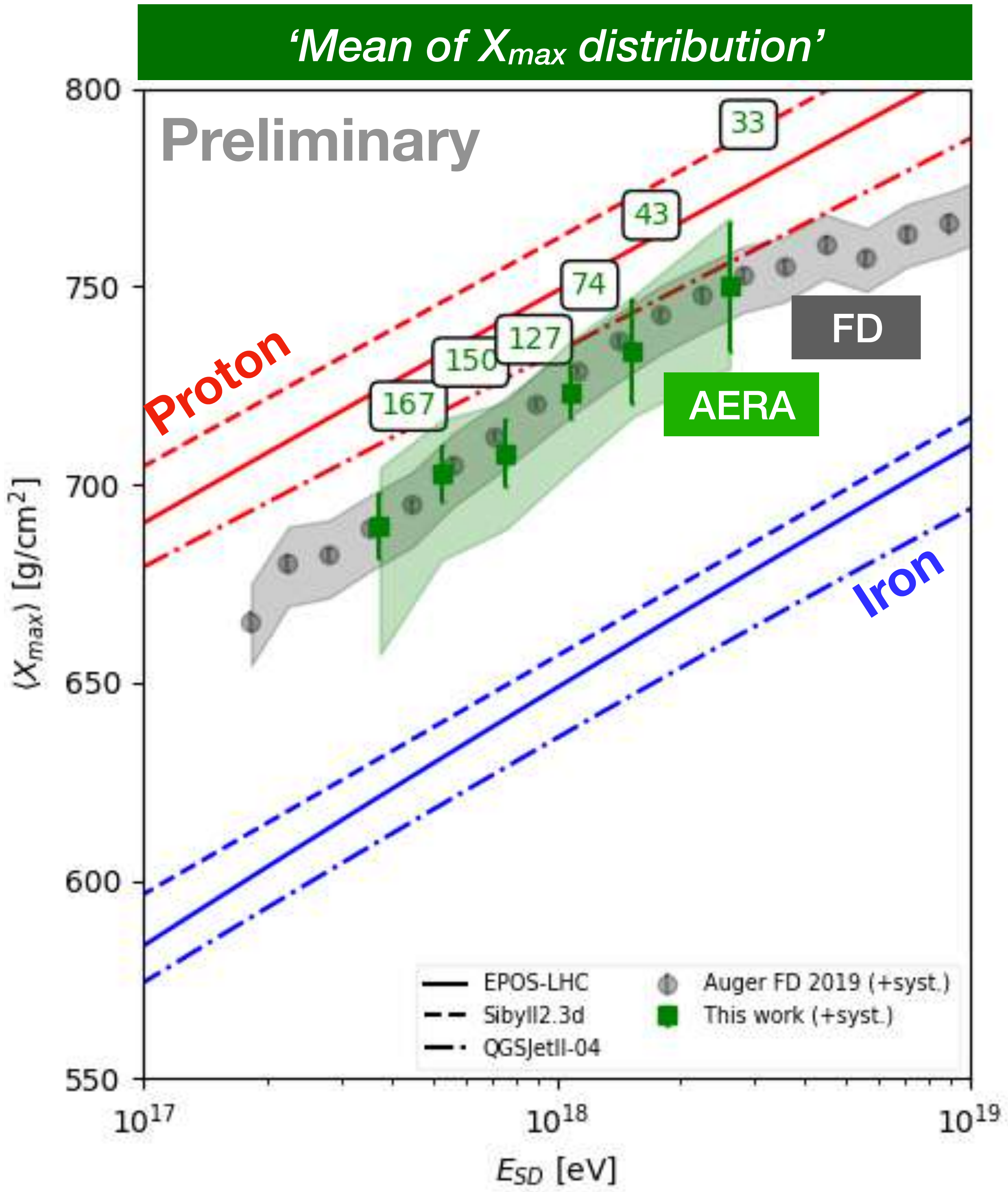
Phys. Rev. D90 122005 and 122006 (2014) + updates ICRC 2019

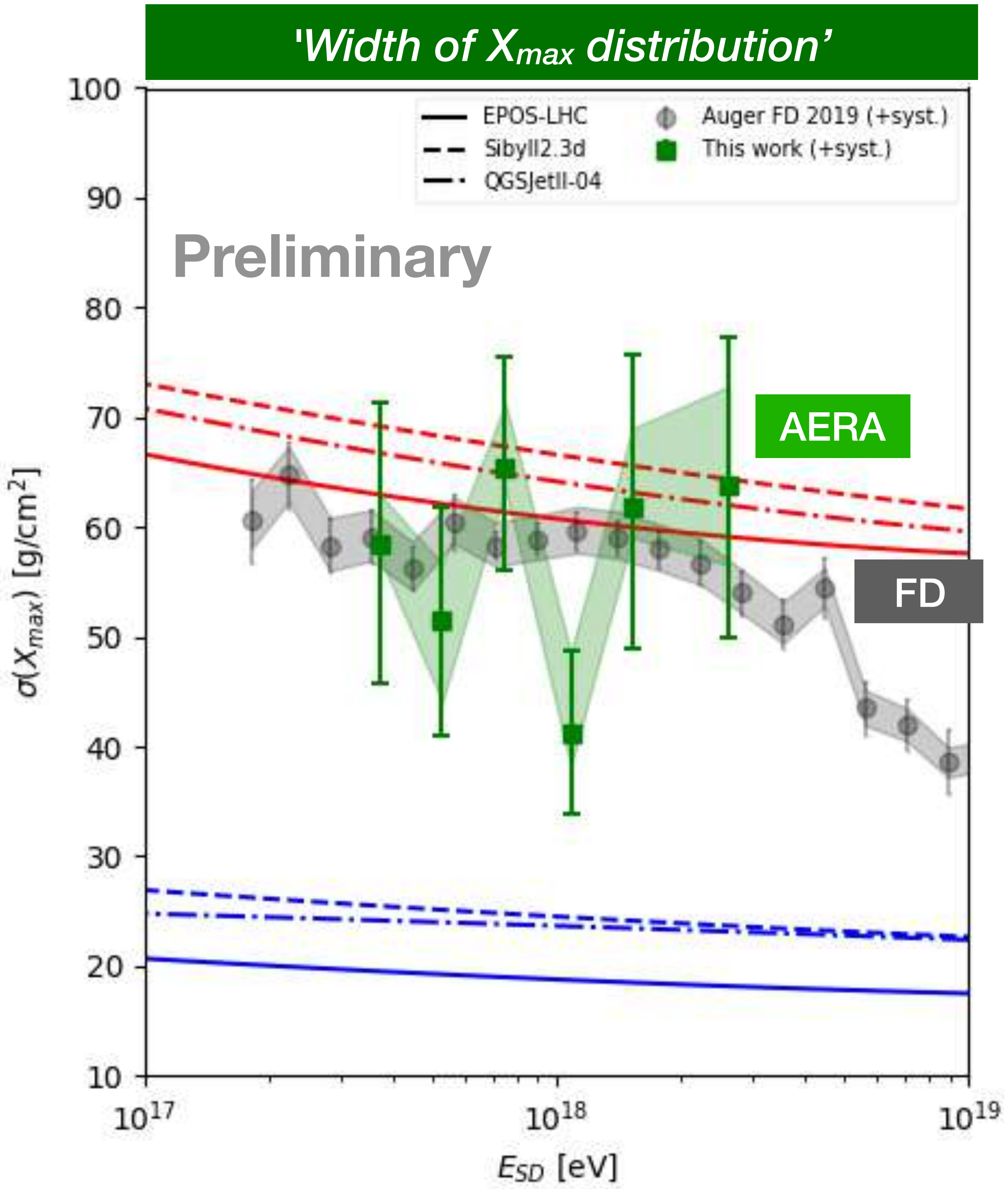
Mass Composition

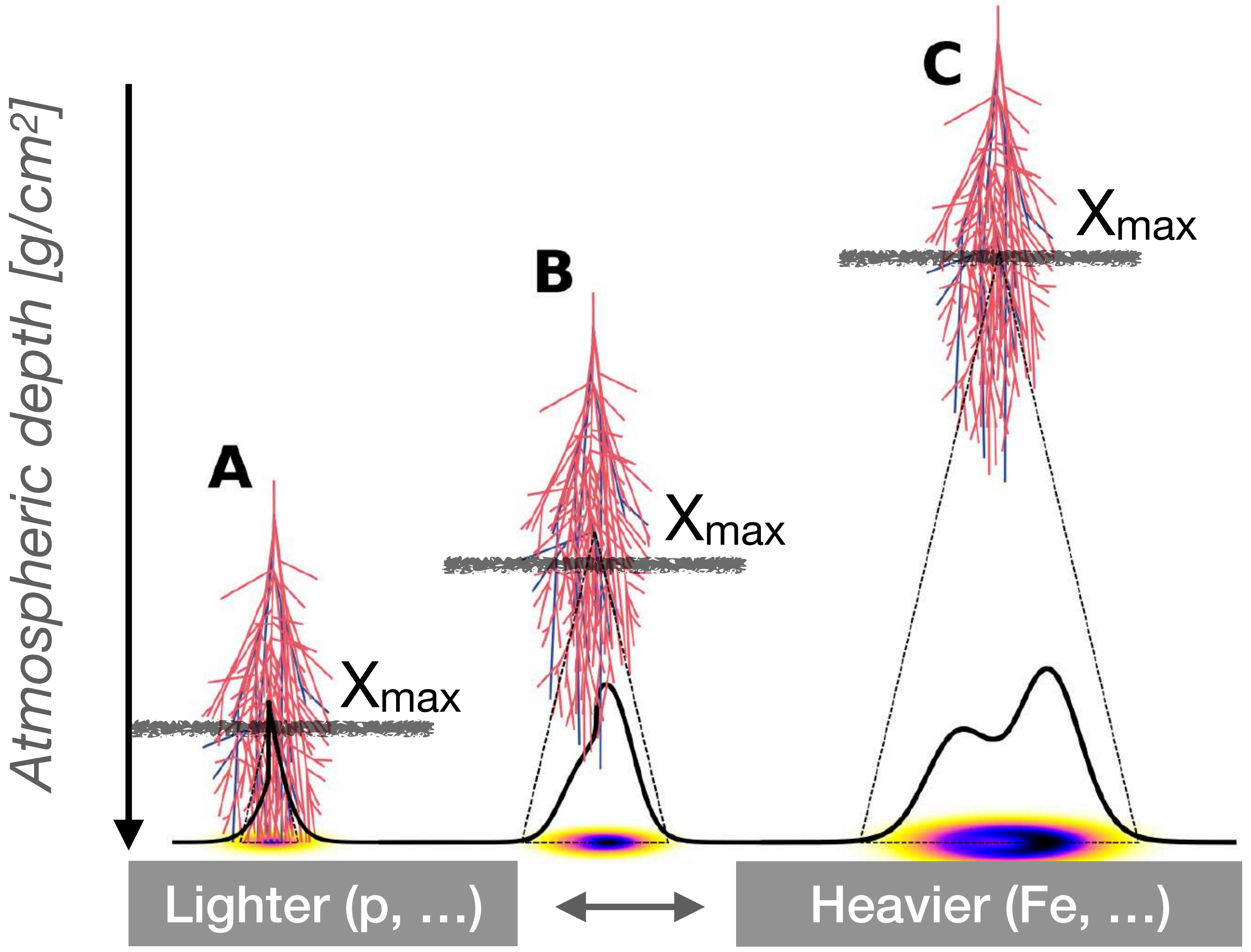
The maturing radio technique.

AERA: Auger Engineering Radio Array

Independent confirmation of Auger FD results (no cross-calibration involved)







Phase II
- radio will be key for studying mass composition in inclined showers, with 100% duty cycle

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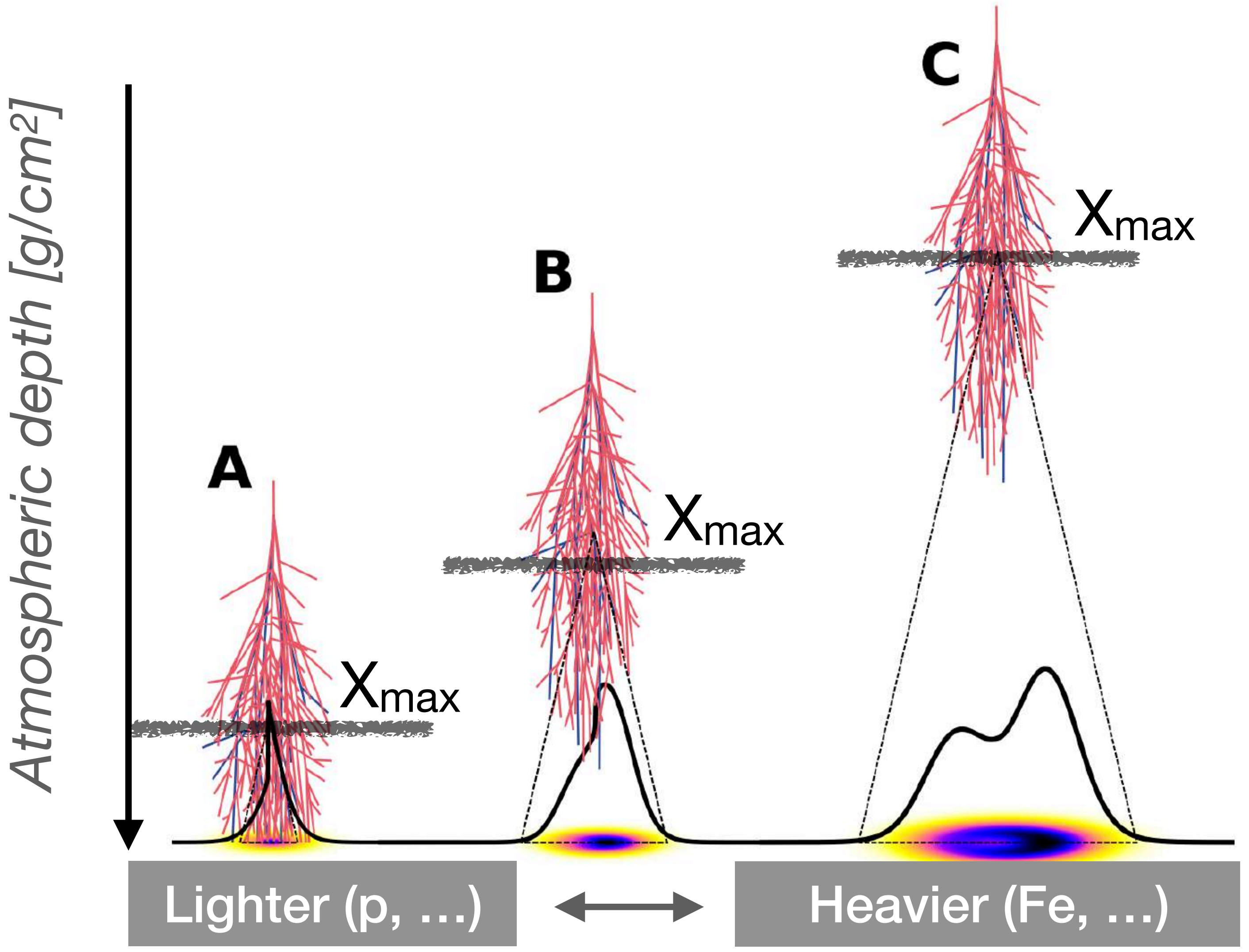
Mass Composition

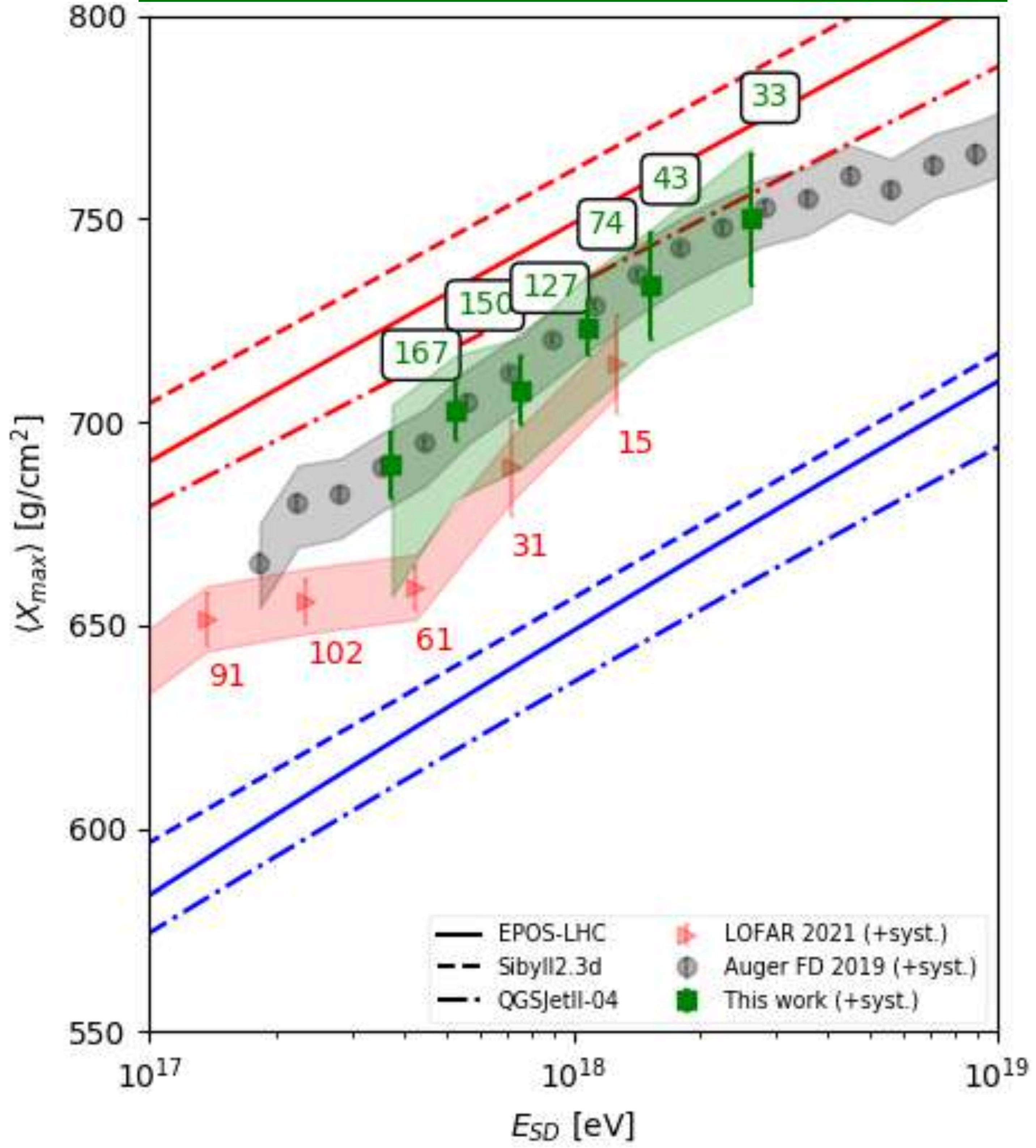
The maturing radio technique.

AERA: Auger Engineering Radio Array

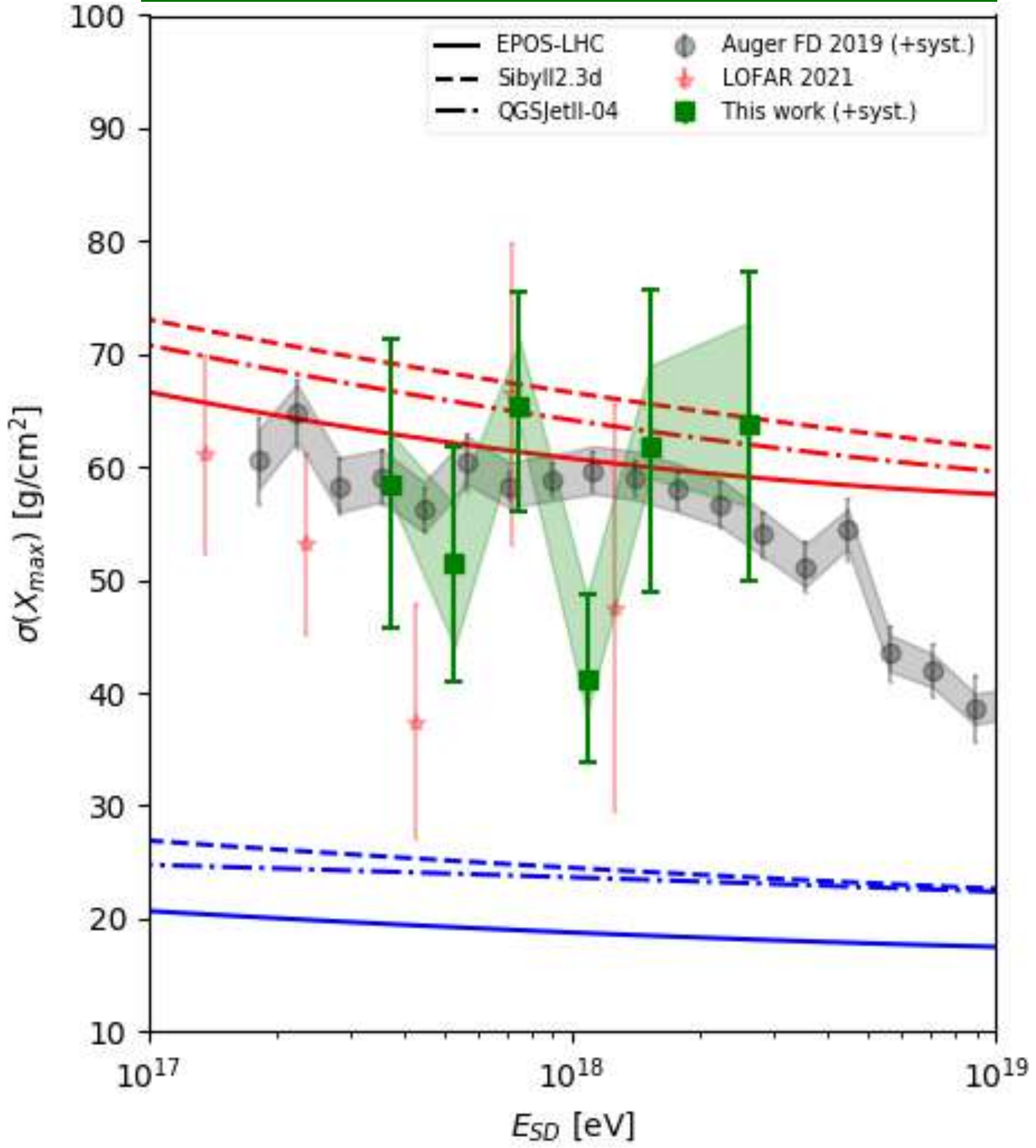


Agreement within systematics with LOFAR, but some systematics are common. Under investigation.

'Mean of X_{max} distribution'



'Width of X_{max} distribution'



Phase II
- radio will be key for studying mass composition in inclined showers, with 100% duty cycle

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An astrophysical interpretation

Global fit of a model to spectrum and mass measured at Earth
- now extended to below the ankle with two possible scenarios

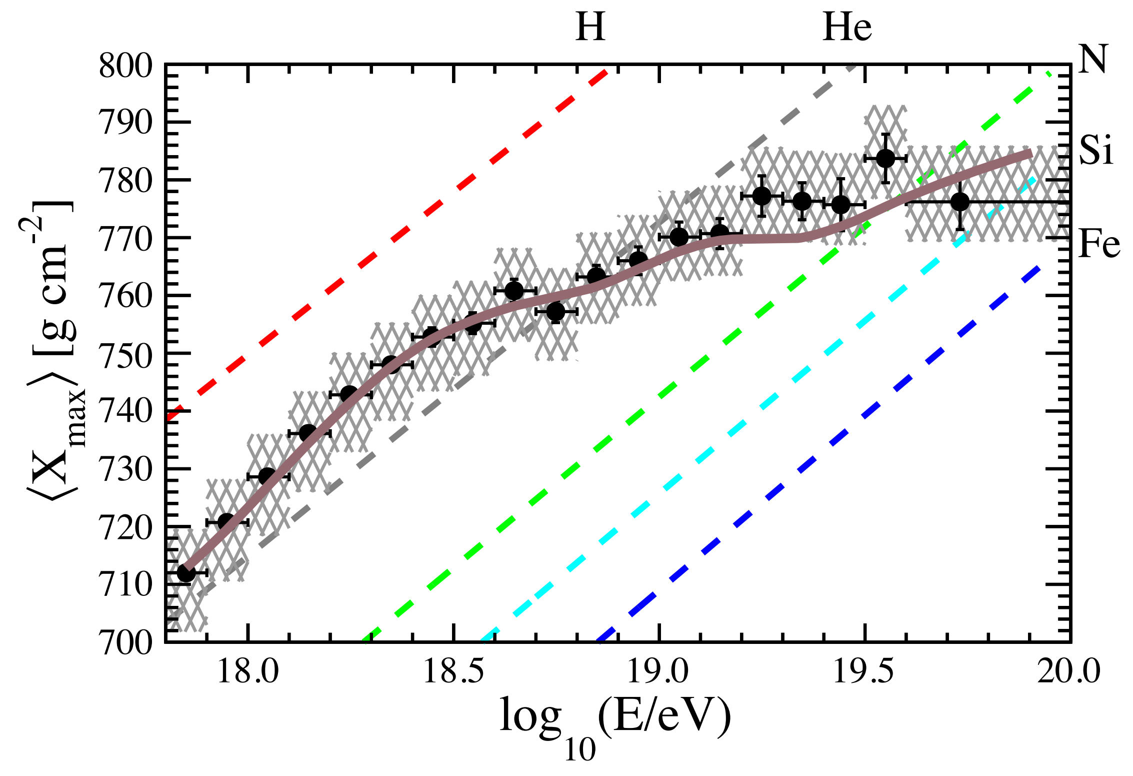
Extragalactic sources - assume rigidity-dependent cut-off at source

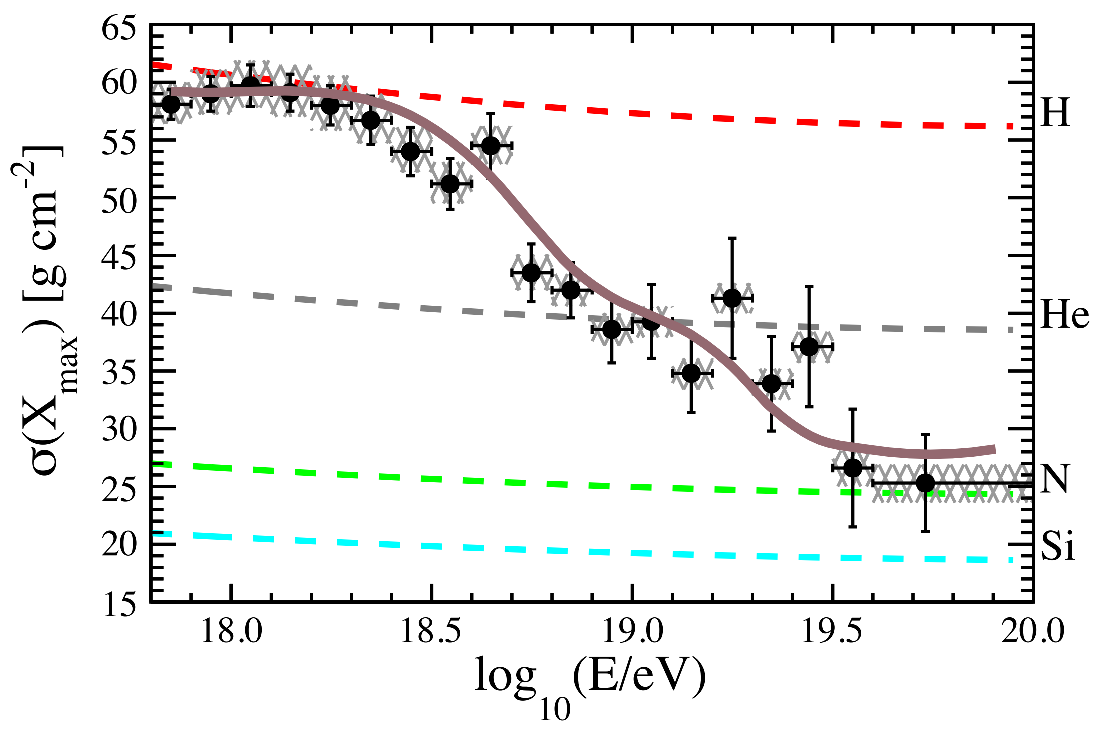
- uniformly distributed identical sources (except for local over-density $d < 30$ Mpc)
- Injected mass, five representative groups of A
- propagation energy losses included, source evolution dependence checked
- Fit for injected mass fractions f_A, spectral index γ and rigidity cutoff R_{cut}

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

Below the ankle

- two scenarios explored (incl. extragalactic contribution)
- Minimal difference in mass predictions from scenarios





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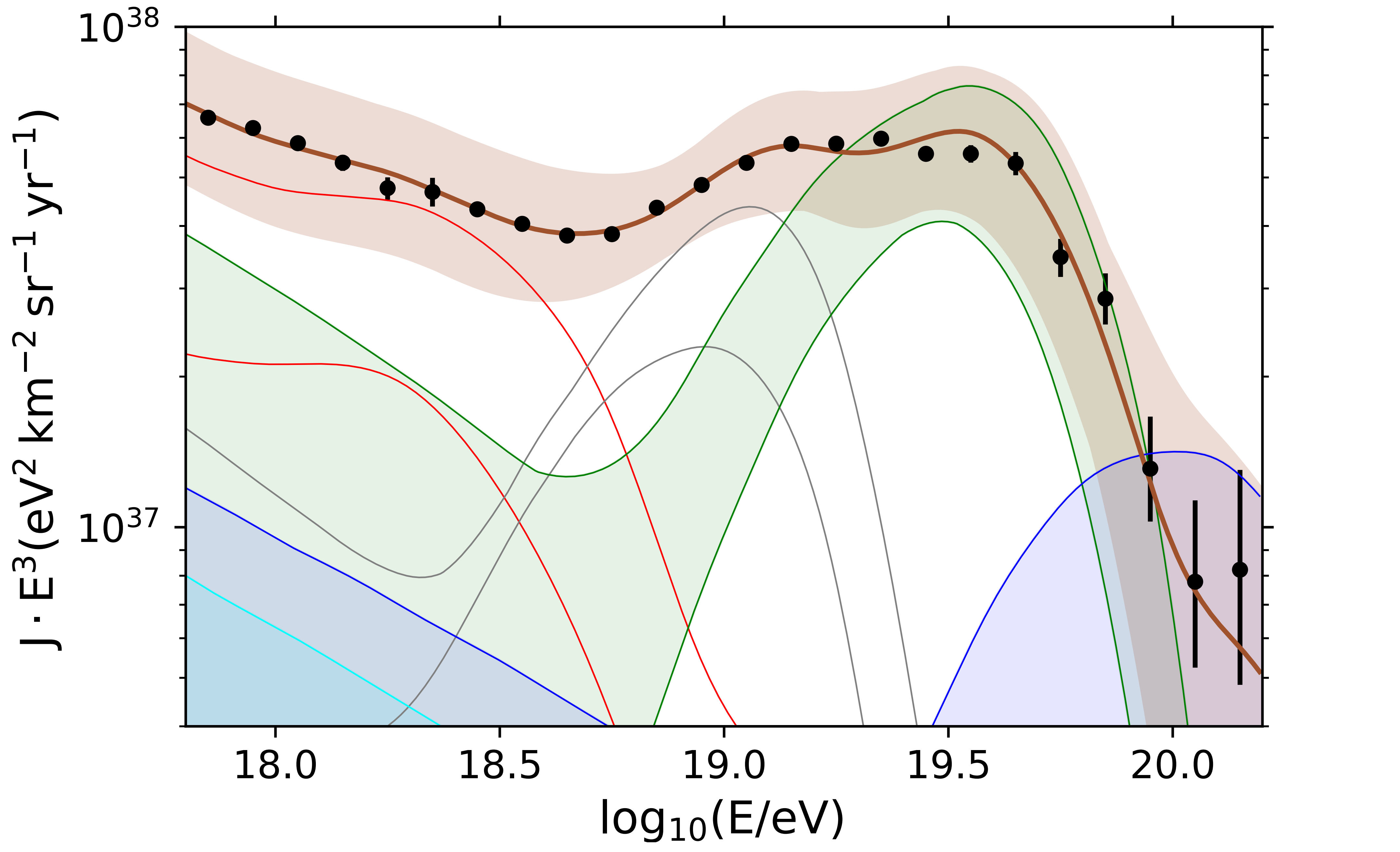
A = 1
1 < A < 5
4 < A < 23
22 < A < 39
38 < A < 57

Mass and spectrum at Earth



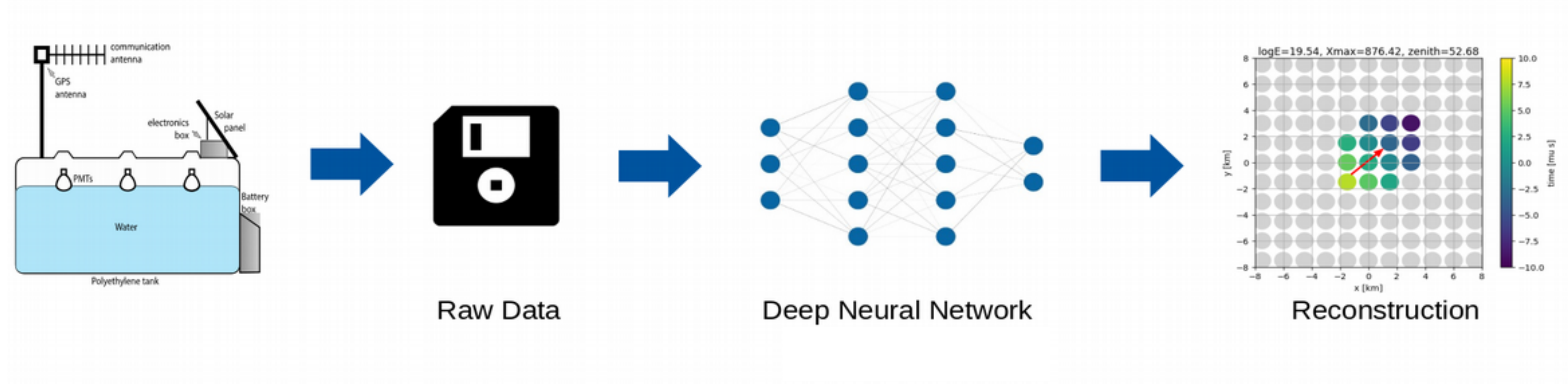
Bands describe experimental uncertainties (in E and Xmax), dominate over model systematics.

Result: $R_{\mathrm{cut}} \sim 1.5 \times 10^{18}$ V, with very hard source spectral index, $\gamma < 1$, not well constrained in the model. No strong dependence on source evolution m.

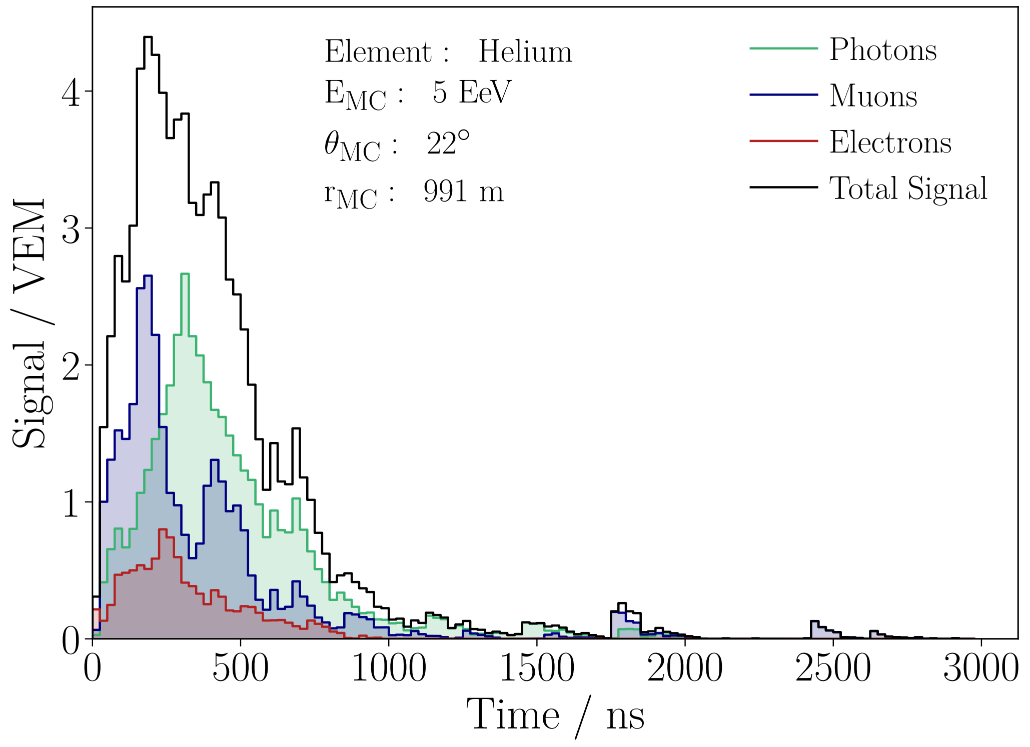
In this simple model, the spectral instep feature is associated with helium from nearer sources. The flux suppression is a superposition of source exhaustion and propagation energy losses.

A future direction - deep machine learning

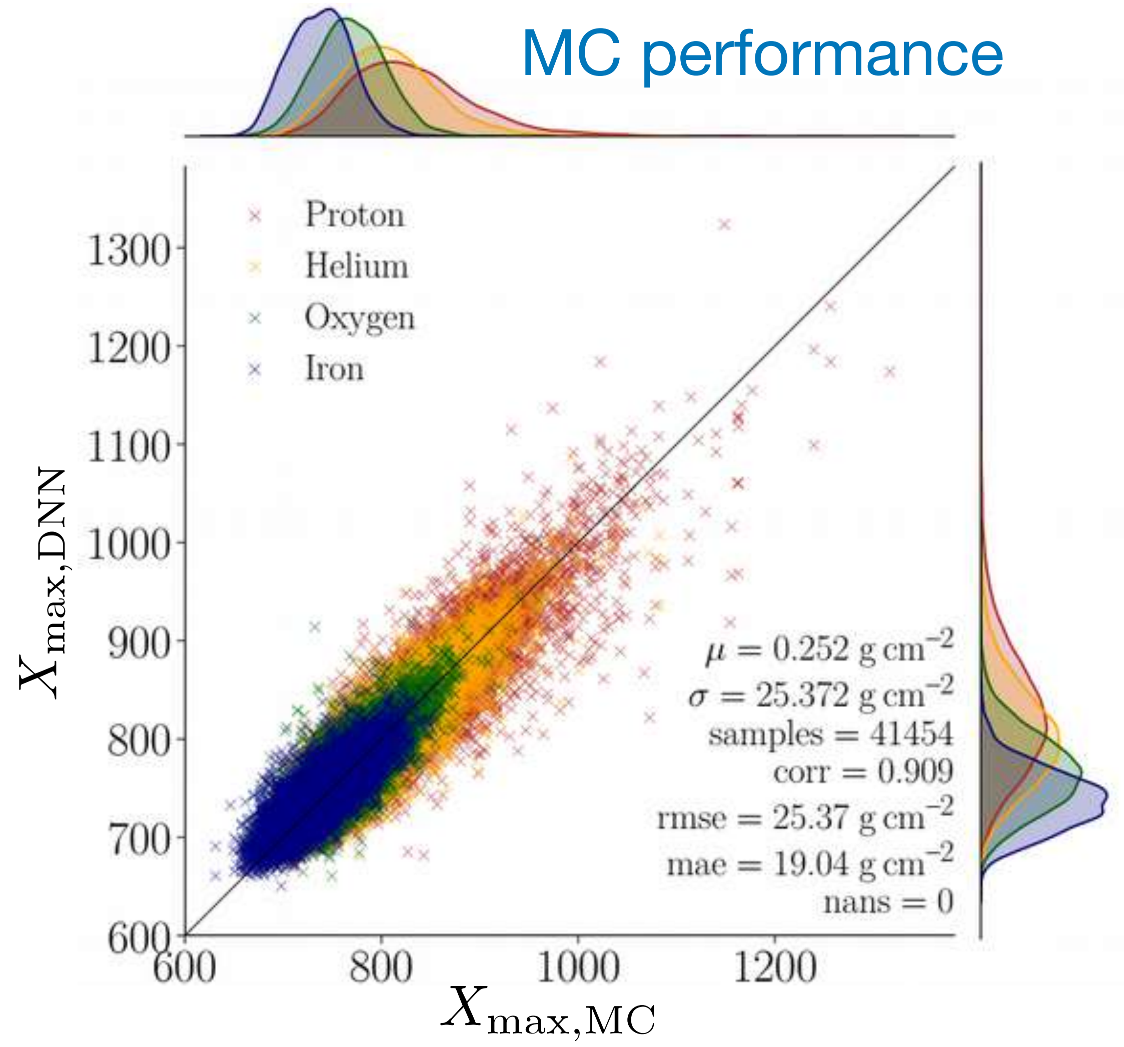
SD determination of $X_{\max}$ (MC studies, cross-check against FD data)



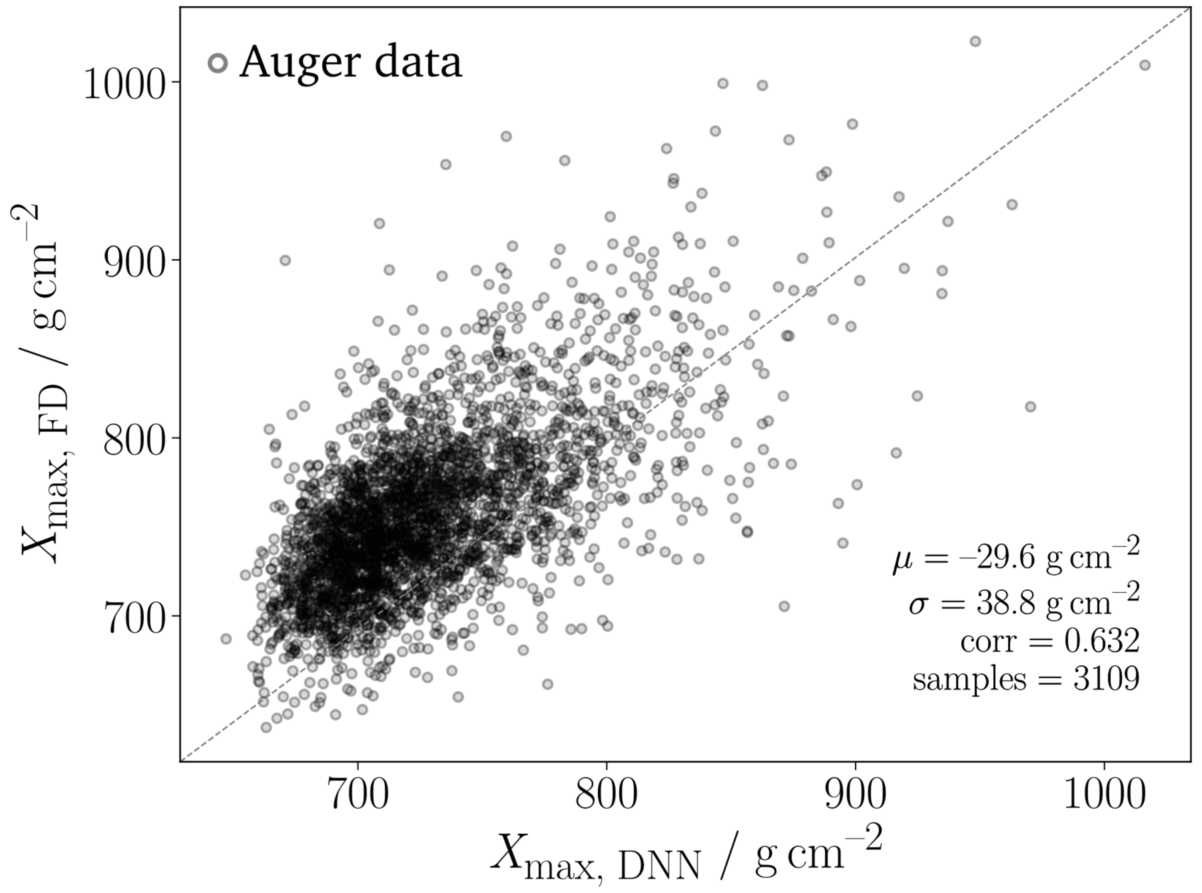
A simulated SD station trace

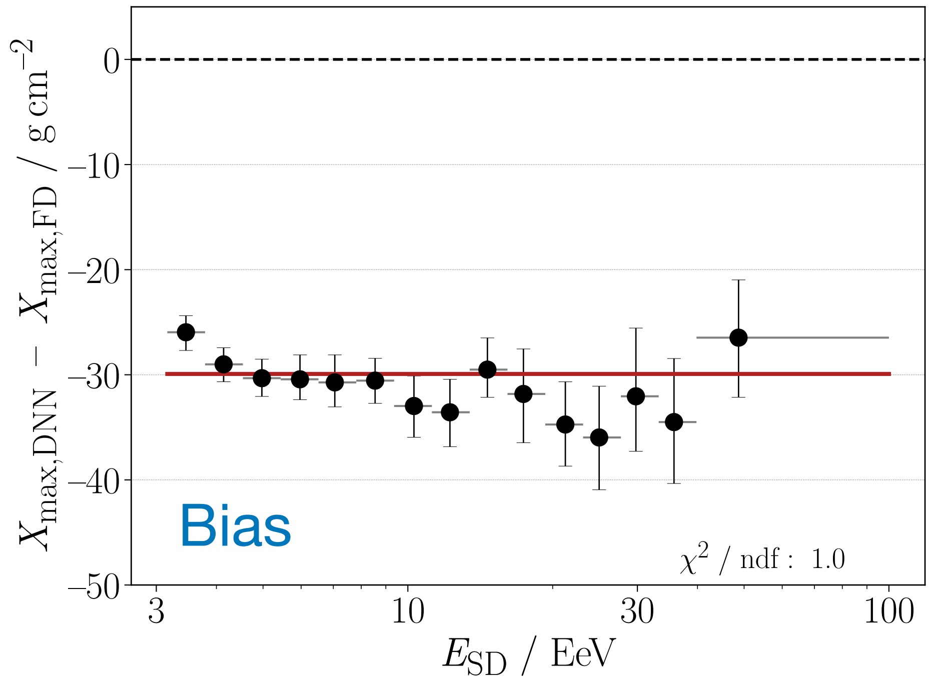


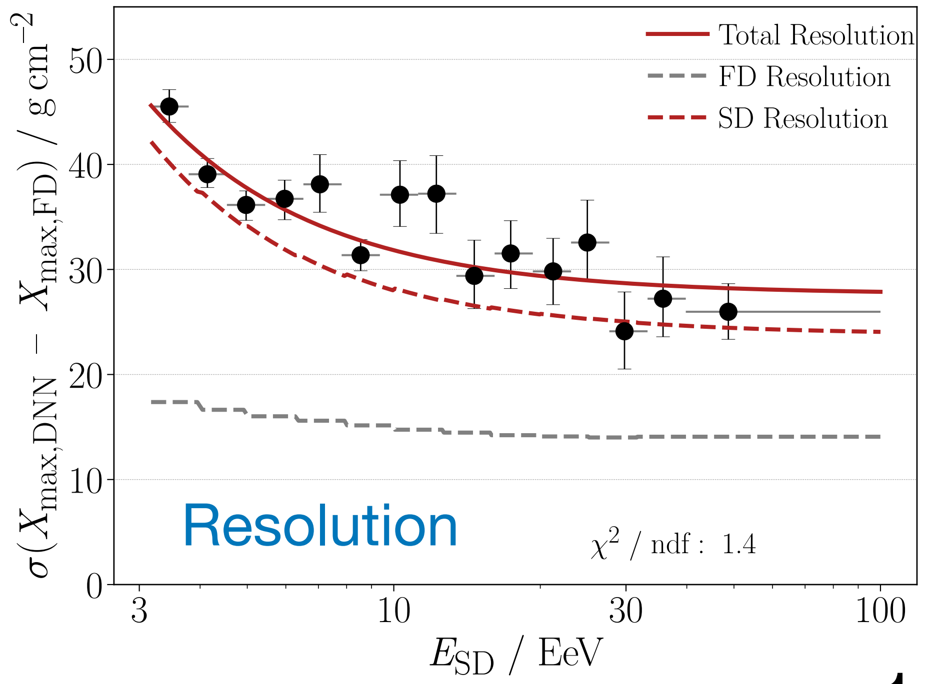
MC performance



Cross-check with real FD data







Promising results, with resolution (from real data) of ~ 30 g/cm^2.

However, a bias of -30 g/cm^2 suggests problems with simulations.

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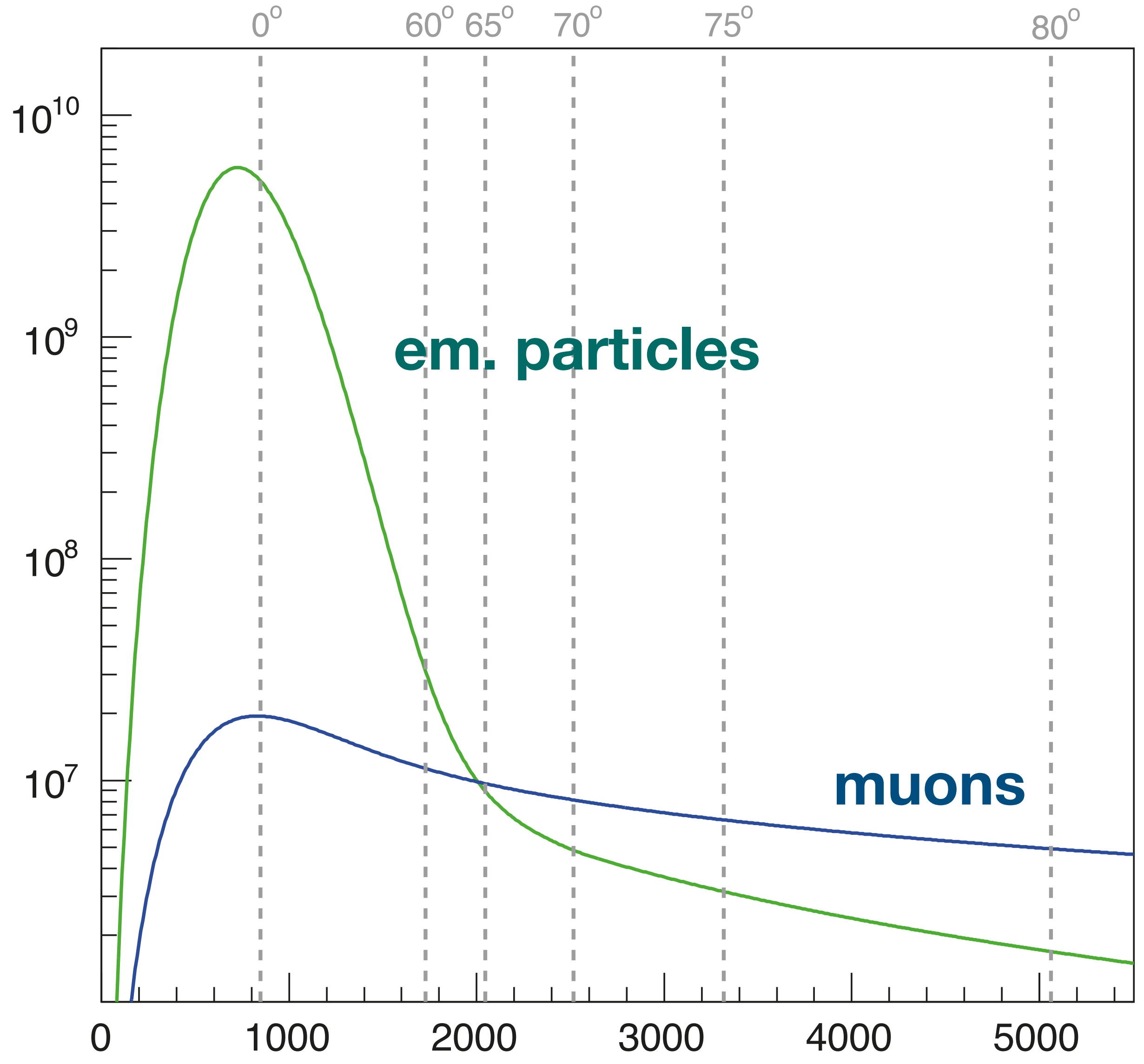
When perfected, can be applied to all historical Phase I data.

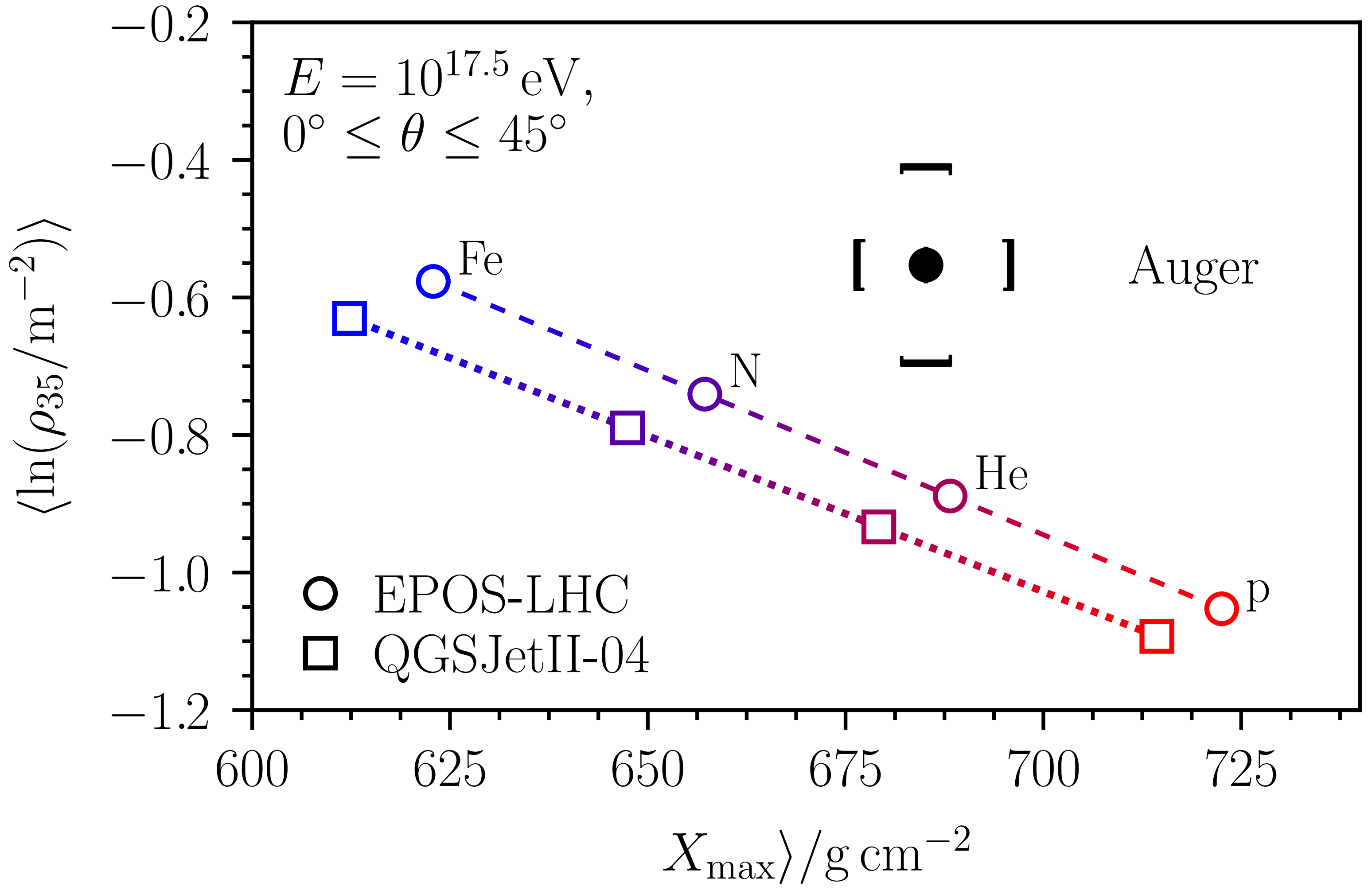
Hadronic interactions



Evidence of a deficit of muons in simulated air-showers.

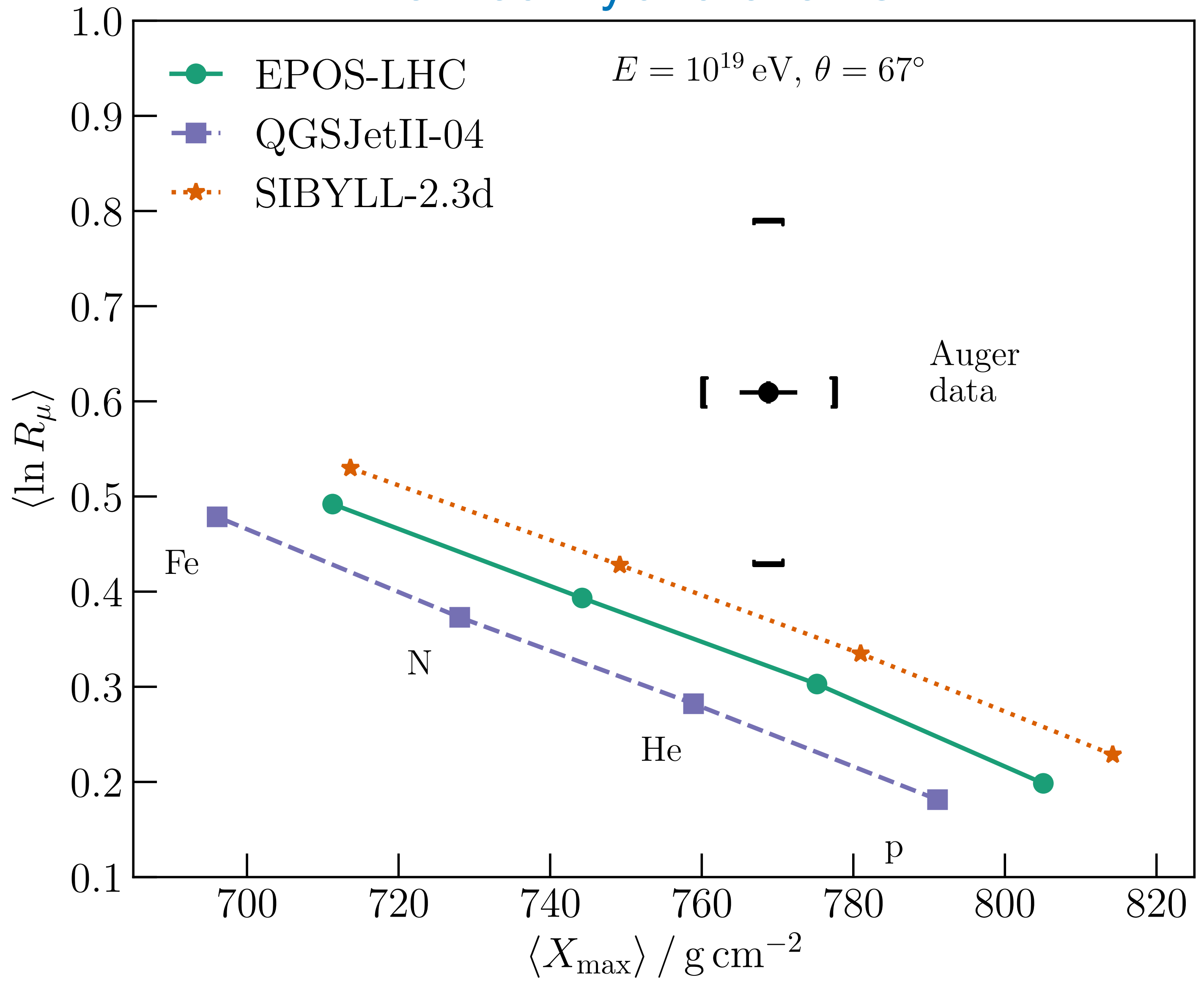
However, relative fluctuations in the muon number are consistent with data. (Fluctuations are driven by first interactions, PMT analogy)

Auger muon detectors and “vertical” hybrid events



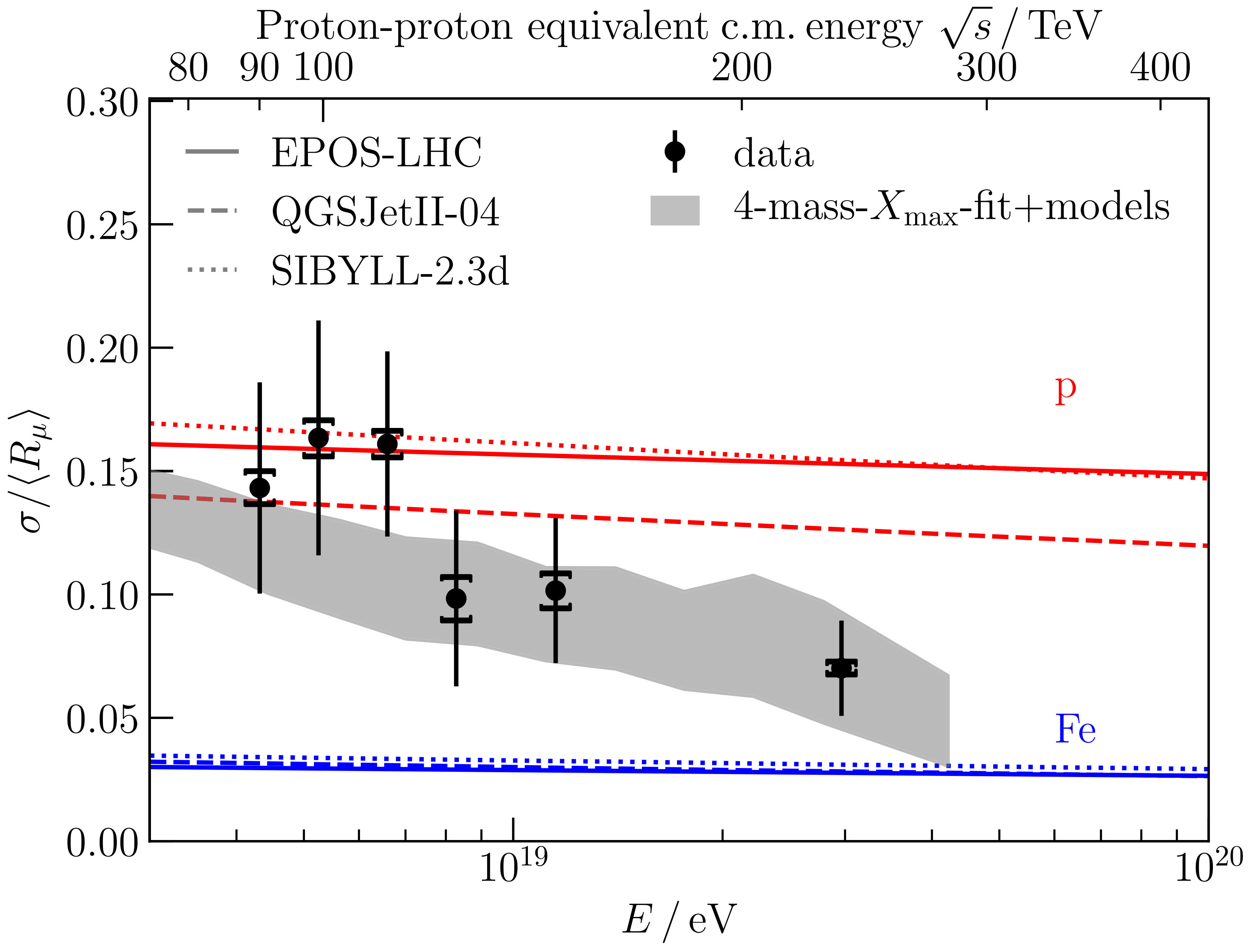
Eur. Phys. J. C80 751 (2020)

Inclined Hybrid events

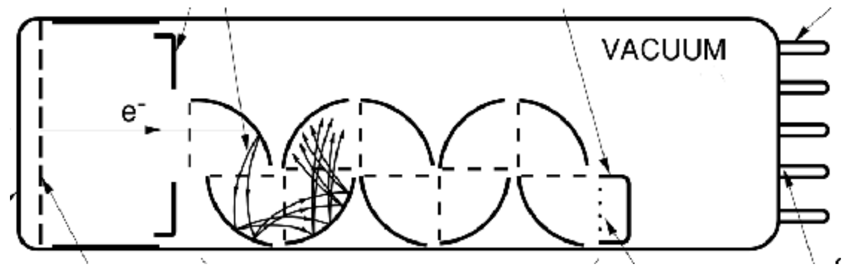


Phys. Rev. Lett. 117 192001 (2016)
Phys. Rev. D91 032003 (2015)

Inclined Hybrid events



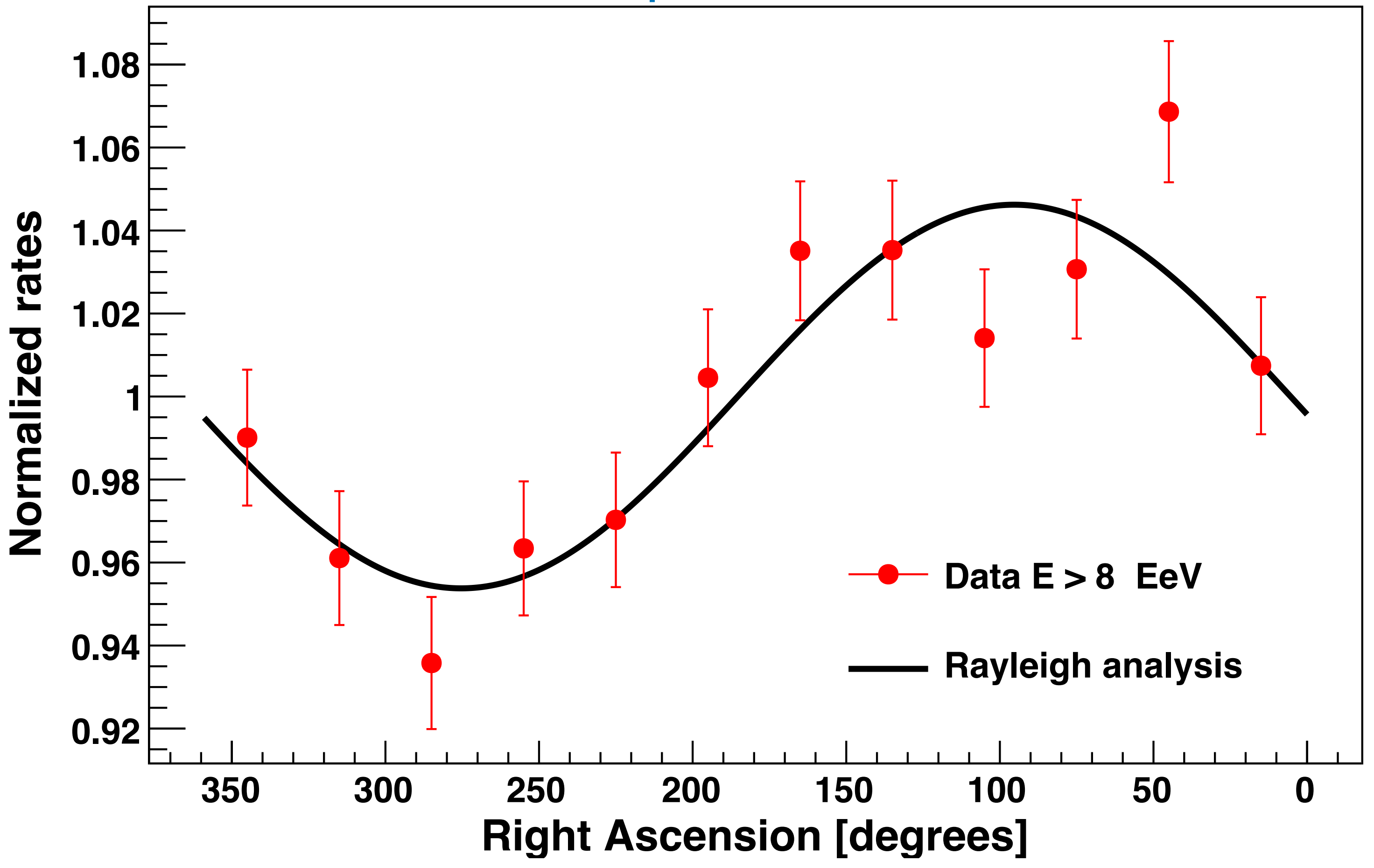
Phys. Rev. Lett. 126 152002 (2021)

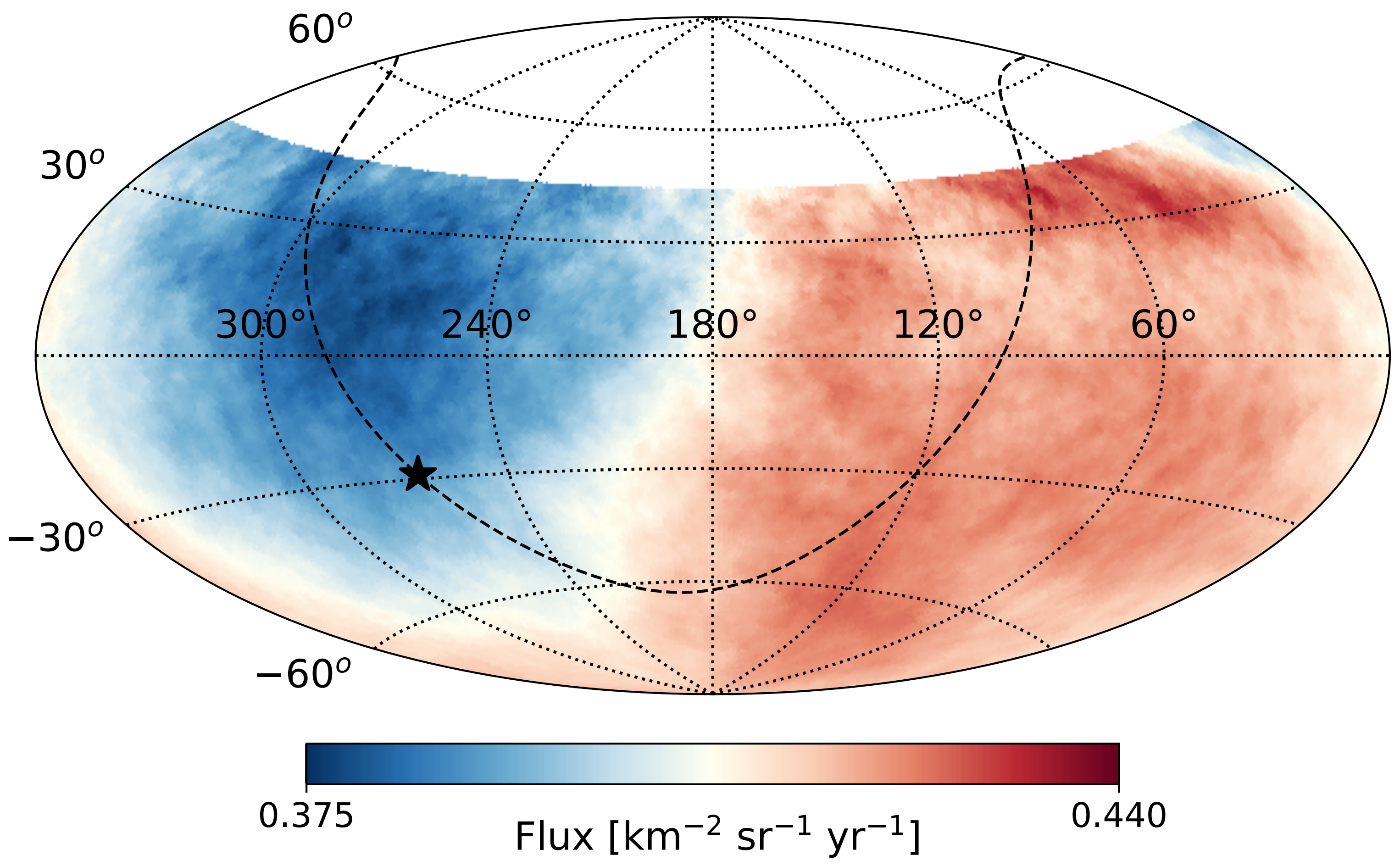


Anisotropy - large scale

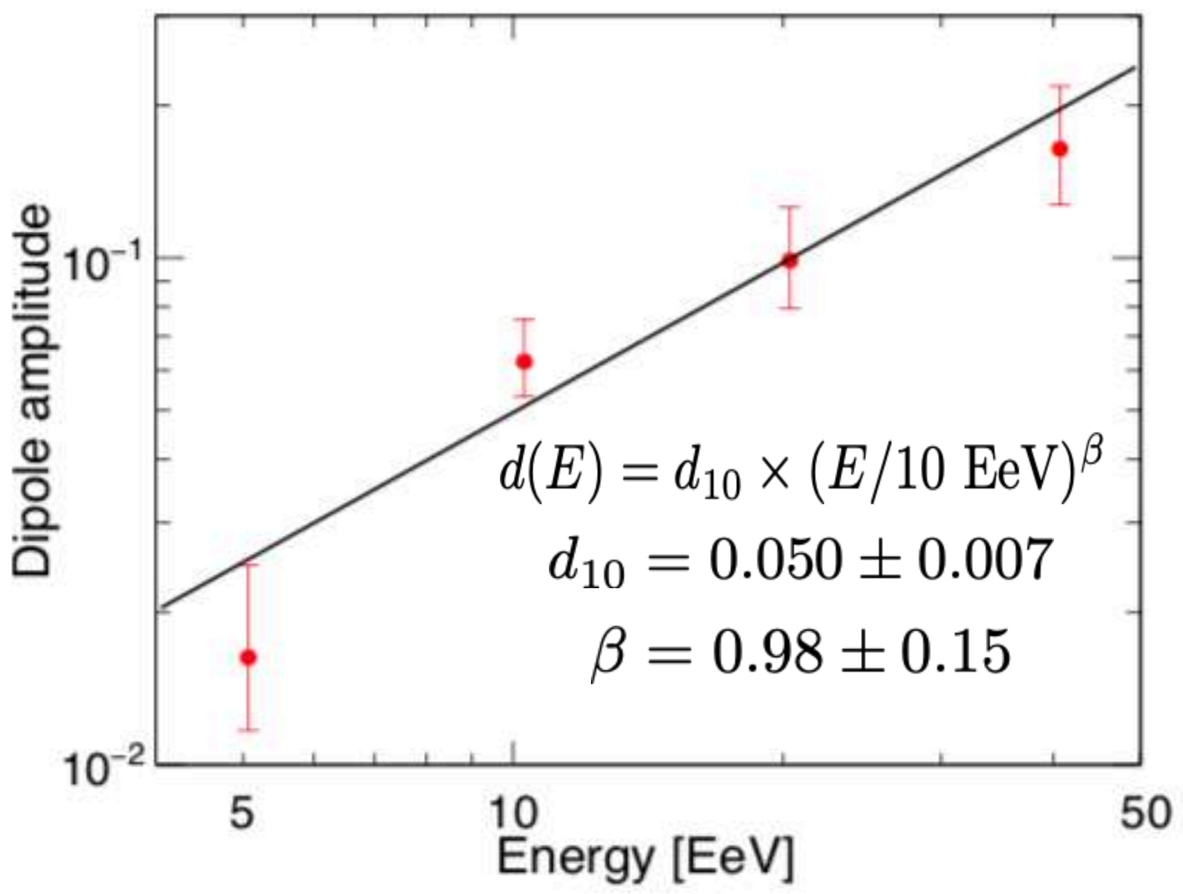
Exposure 110,000 km^2 sr yr
(Up to end of 2020, $\theta < 80^\circ$)

E > 8 EeV, amplitude 7.3%, 6.6σ

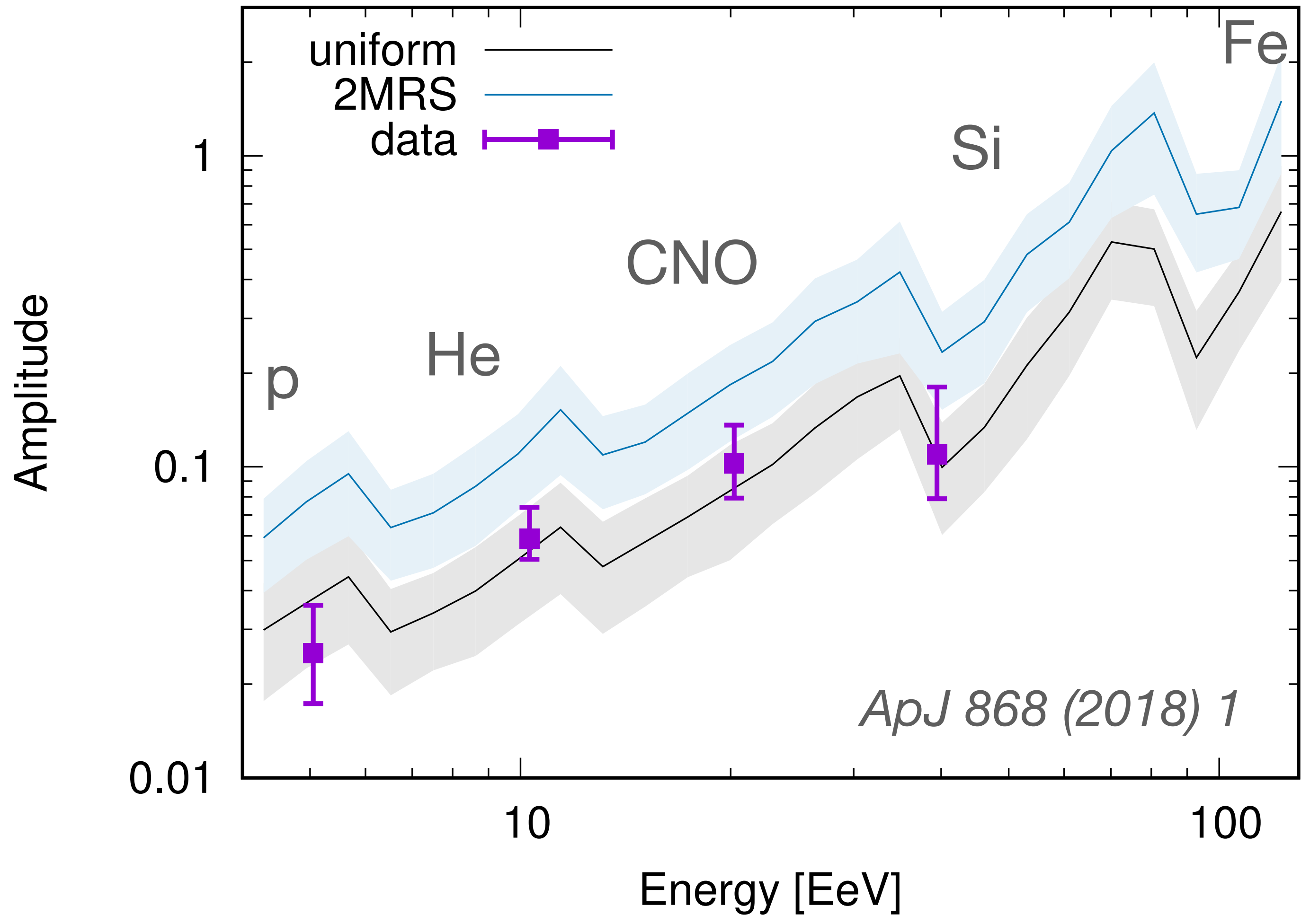




Differential bins



Mass scenario similar to Auger measurements:
(average rigidity still grows with energy, despite Z increasing)

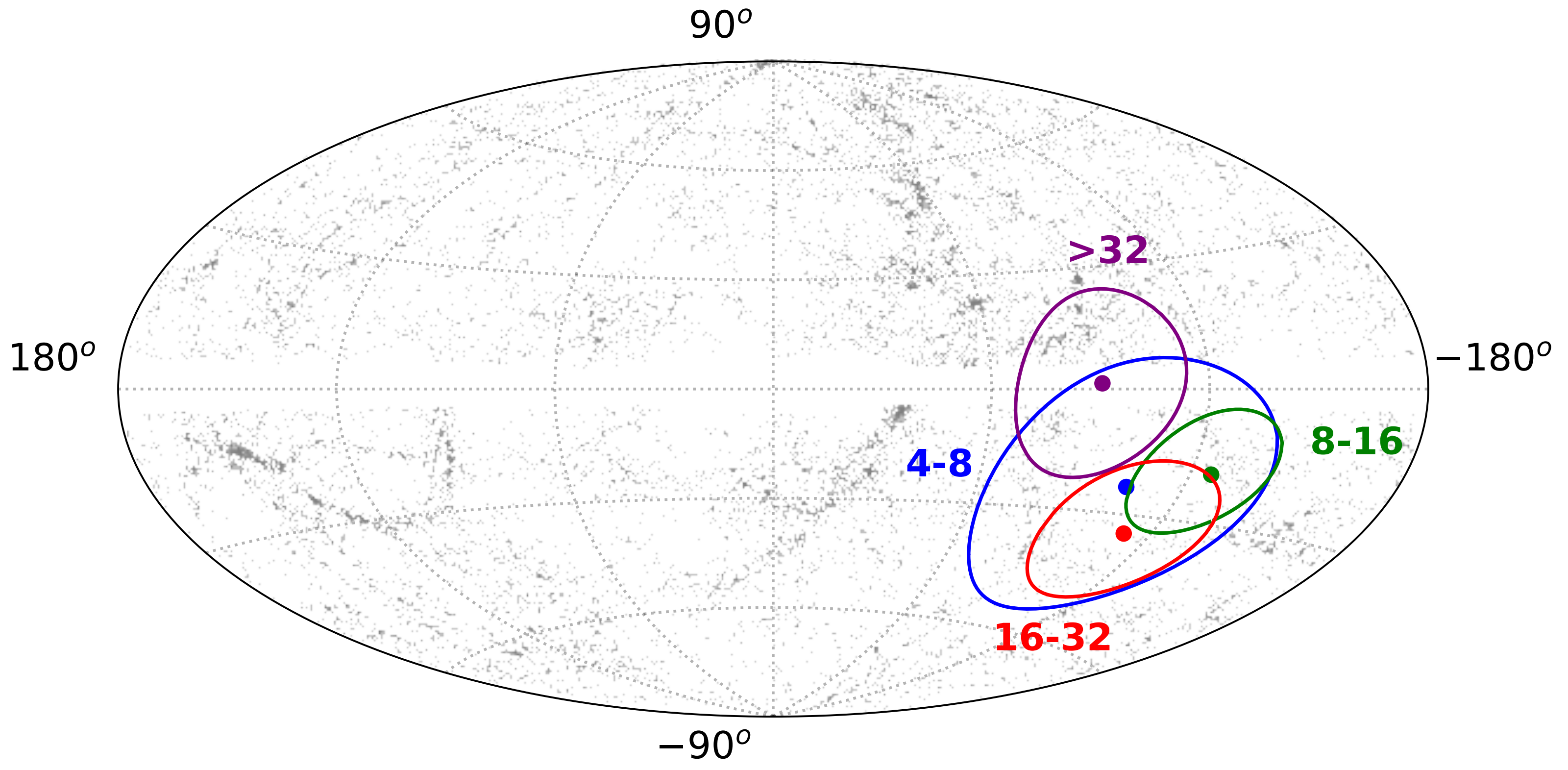


Dipole, and its energy dependence, must be the result of interplay between

- mass composition, and its energy dependence
- the local source distribution
- the magnetic horizon for cosmic ray of (E, A)
- the galactic magnetic field

e.g. Harari, Mollerach, Roulet PRD92 06314 (2015)
Ding, Globus, Farrar ApJ Lett. 913 L13 (2021)

Dipole directions, with 68% CL uncertainties



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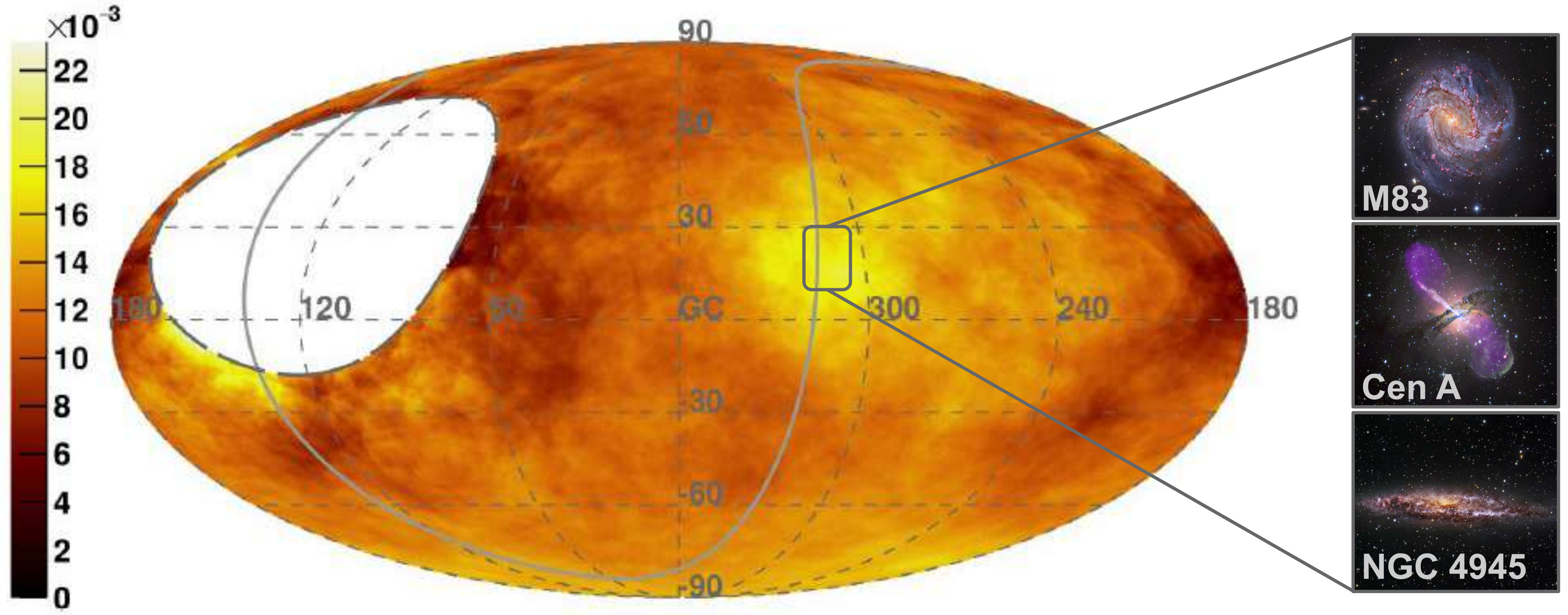
Anisotropy - at the highest energy

Exposure 120,000 km² sr yr
optimised quality cuts, up to end of 2020

a priori region around Cen A (crowded region)
(first flagged with 7% of current exposure)

$\Phi(E_{Auger} > 41$ EeV) [km^{-2} sr^{-1} yr^{-1}] - Galactic coordinates - $\Psi = 24°$

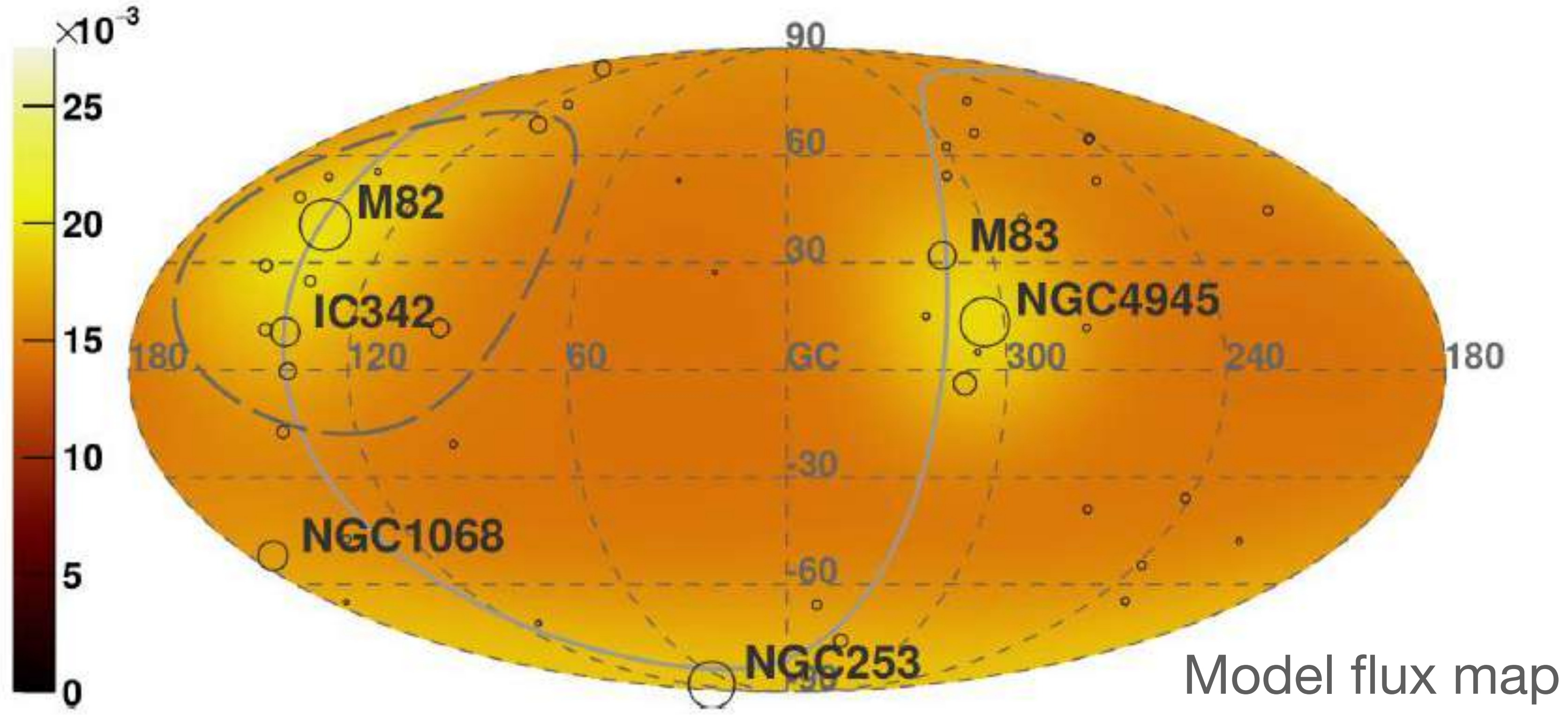


Direction fixed to that of Cen A, free E_{th} and Ψ

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

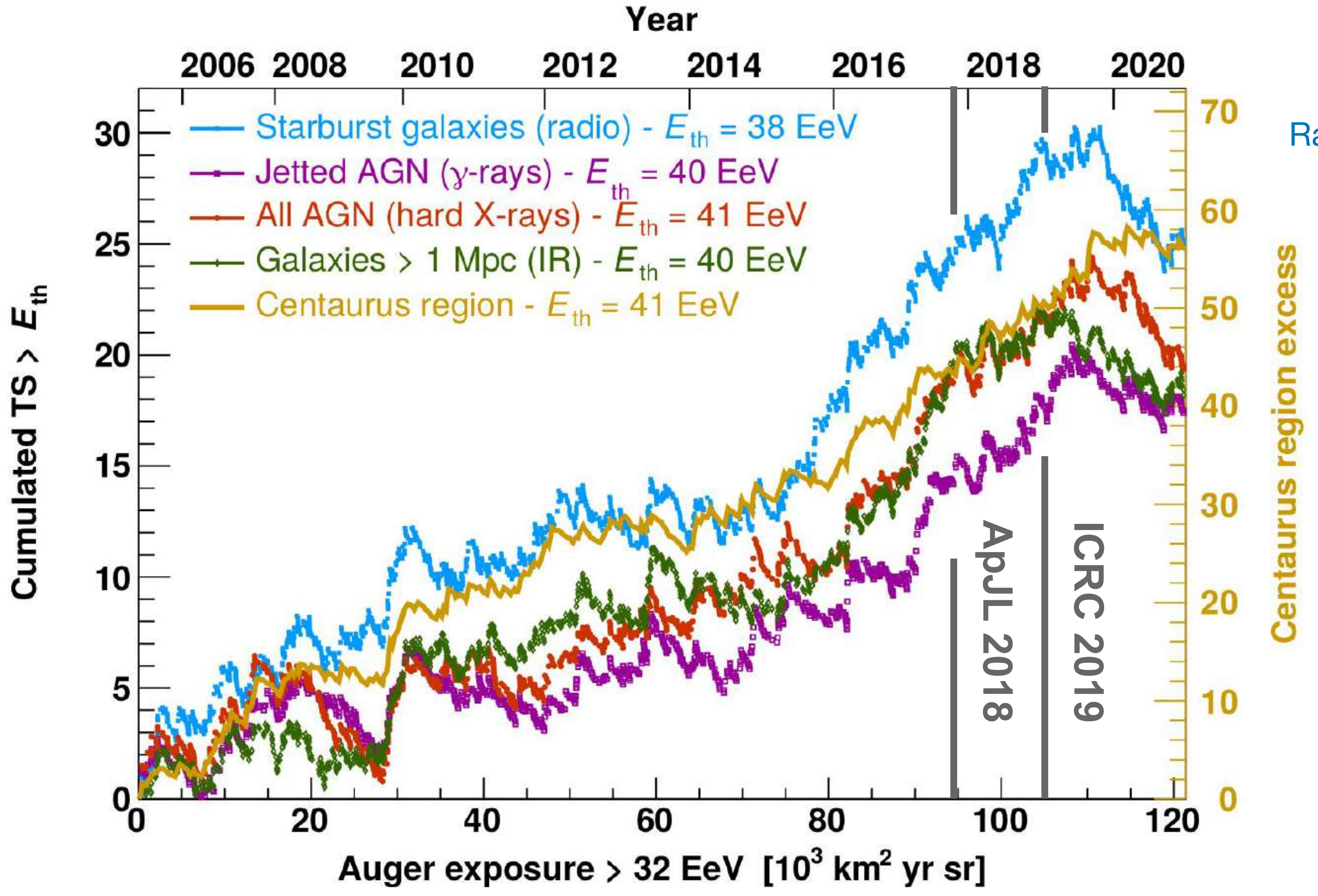
Example of catalog search (expected flux map)

Starburst galaxies (radio) - expected $\Phi(E_{Auger} > 38$ EeV) [km^{-2} sr^{-1} yr^{-1}]



Model flux map

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}



Range of post-trial excesses

4.0σ

3.1σ

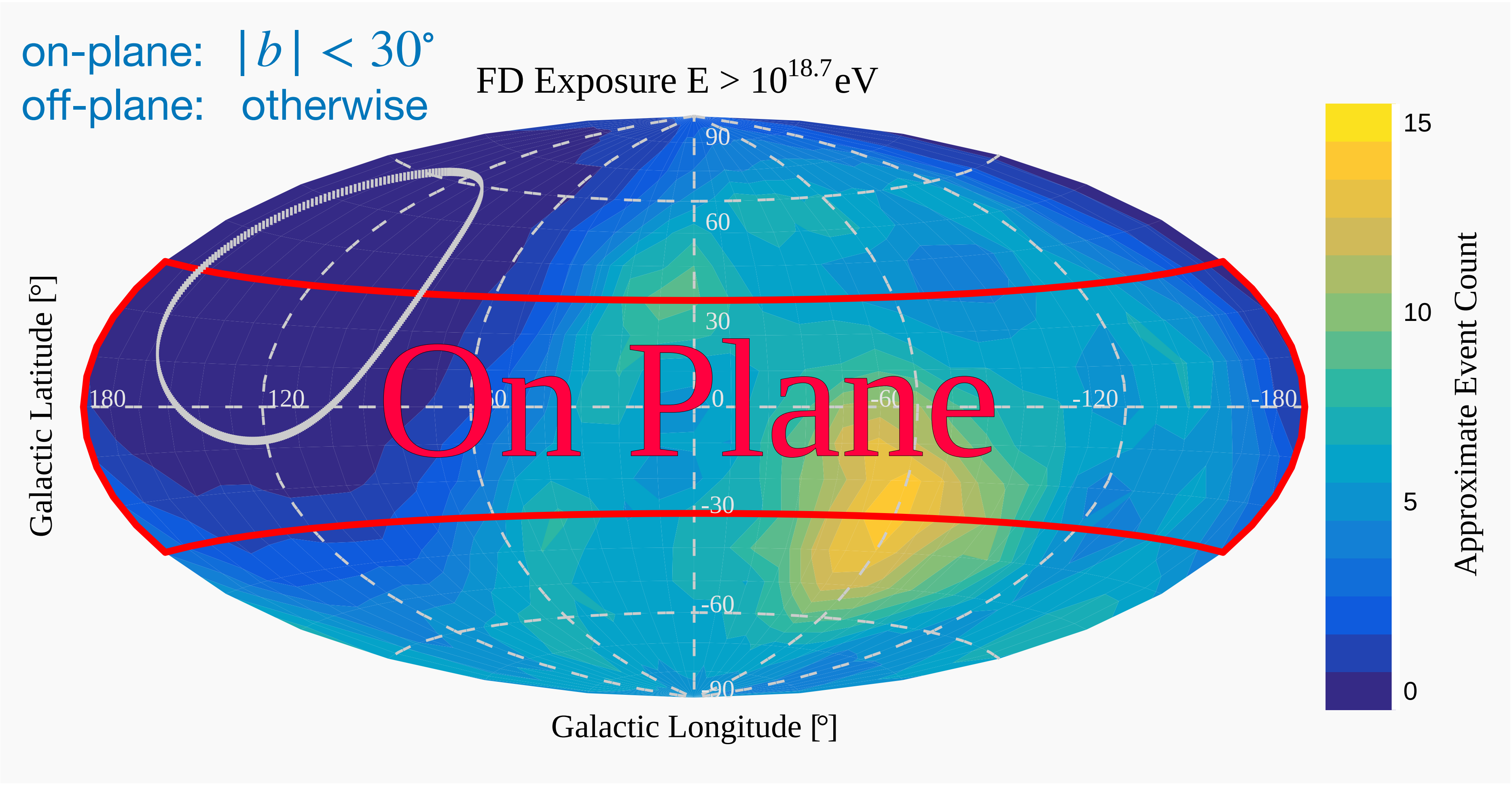
Growth of test-statistic (TS) compatible with a linear increase, with a 5σ result expected in 2025-2030 with the same analysis.

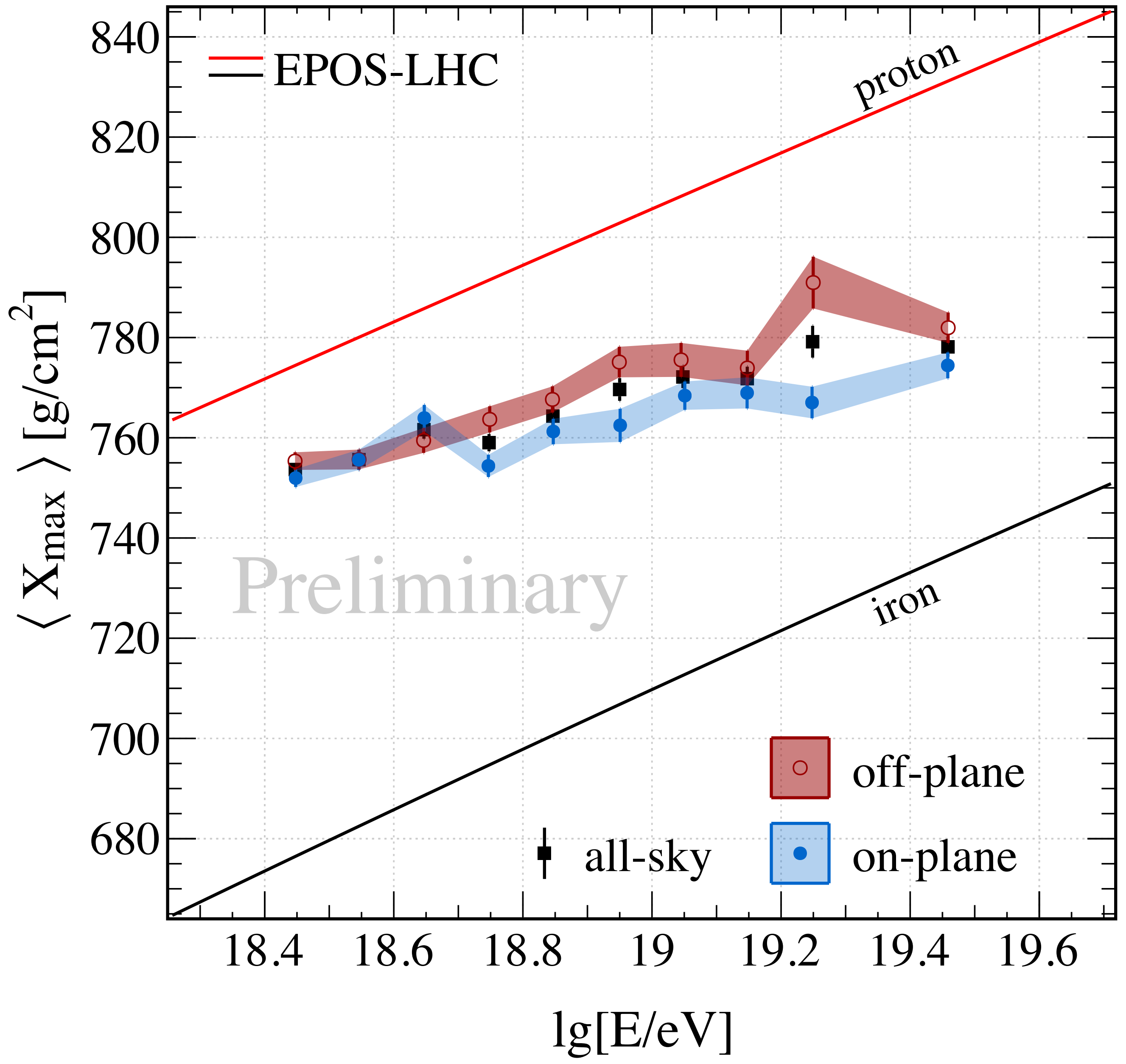
Phase II sensitivity improvements include:
- 100% duty cycle for mass information (AugerPrime)
- including more than 85% of the sky (collaboration with TA and TAx4)

ICRC21 307 (2021)
Ap. J. Lett 853 L29 (2018)

Hints of a mass-dependent anisotropy

Difference between mean X_{max} on and off the galactic plane?



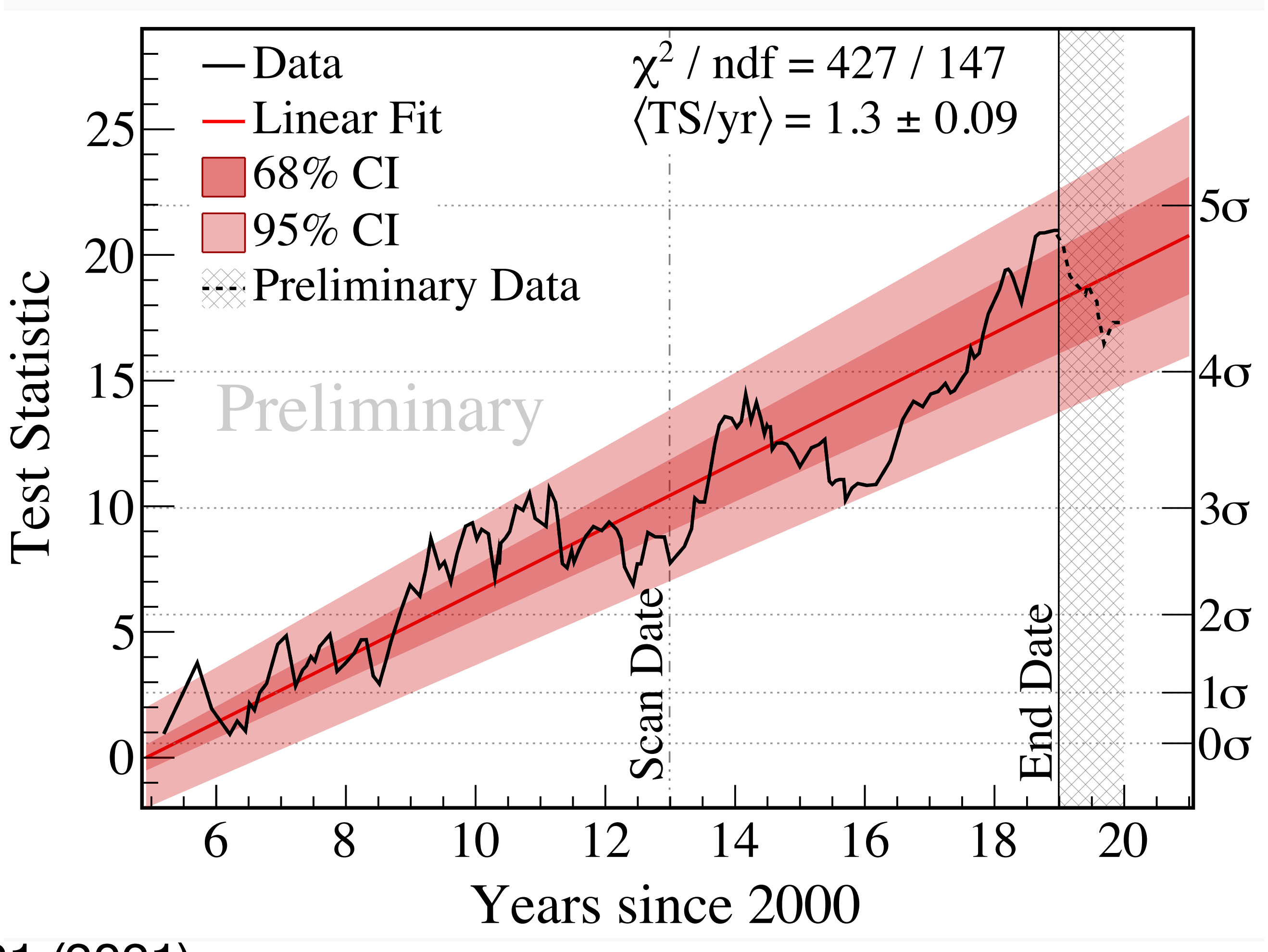


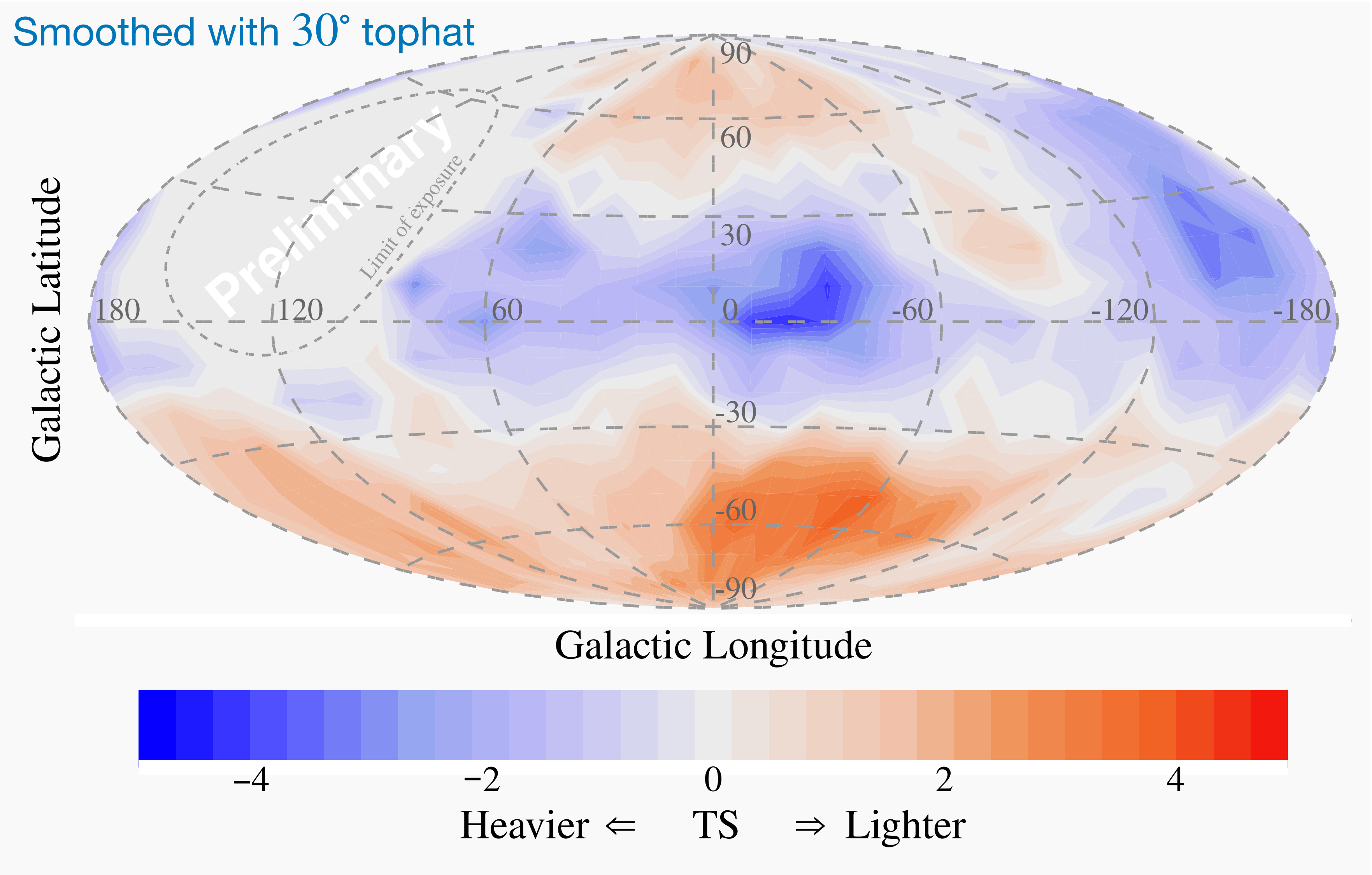
X_{max} from fluorescence detector

Significance 3.3σ ($E > 10^{18.7}$ eV) after accounting for:

- penalties for trials (choice of b-cut, energy threshold)
- possible systematics

Growth of “signal” consistent with linear





If real, it doesn’t imply galactic sources.

It might be the result of the interplay of source directions, the mass-dependent horizon, and the GMF.

Phase II

- study will benefit from more data, including re-analysed existing SD data

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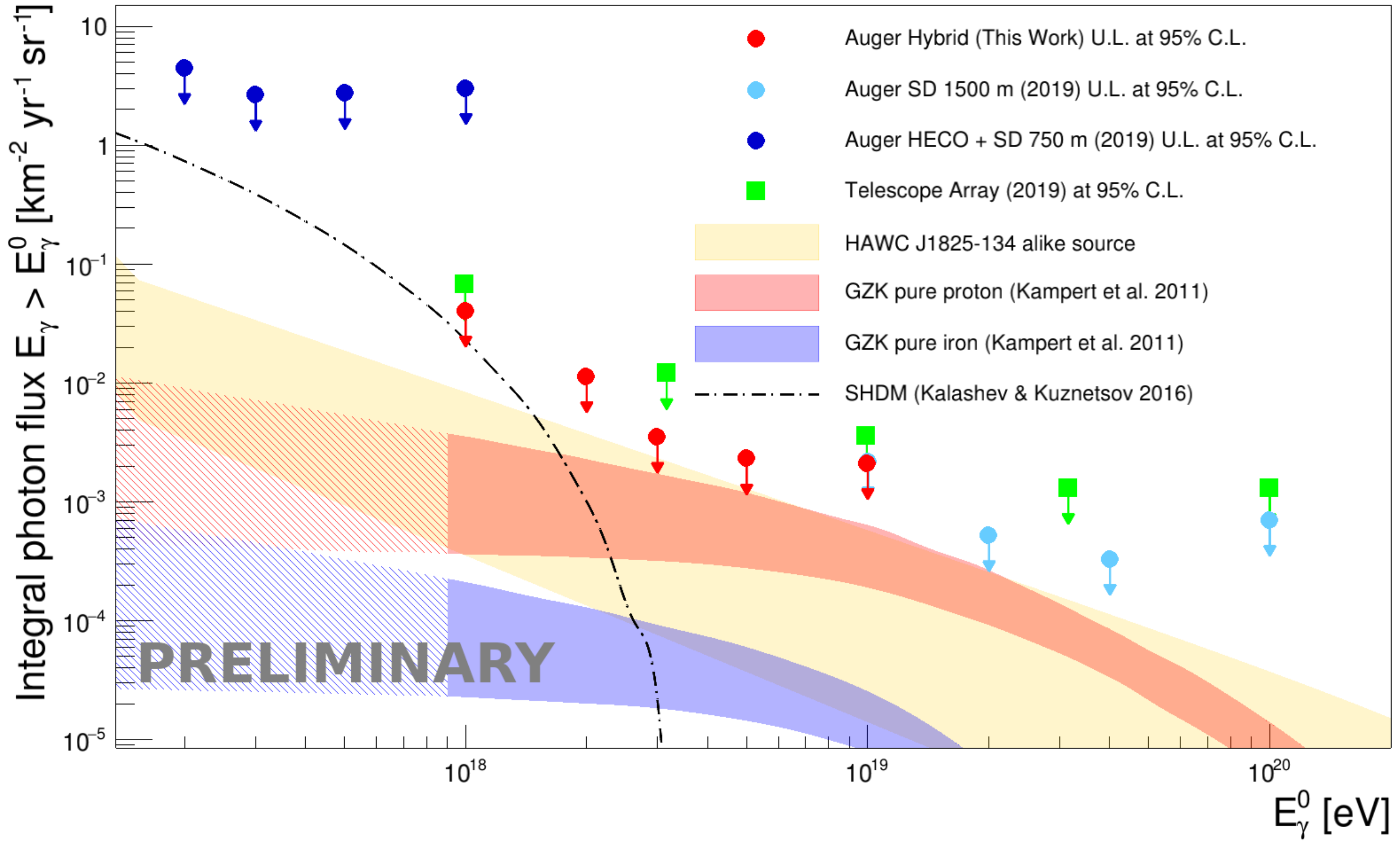
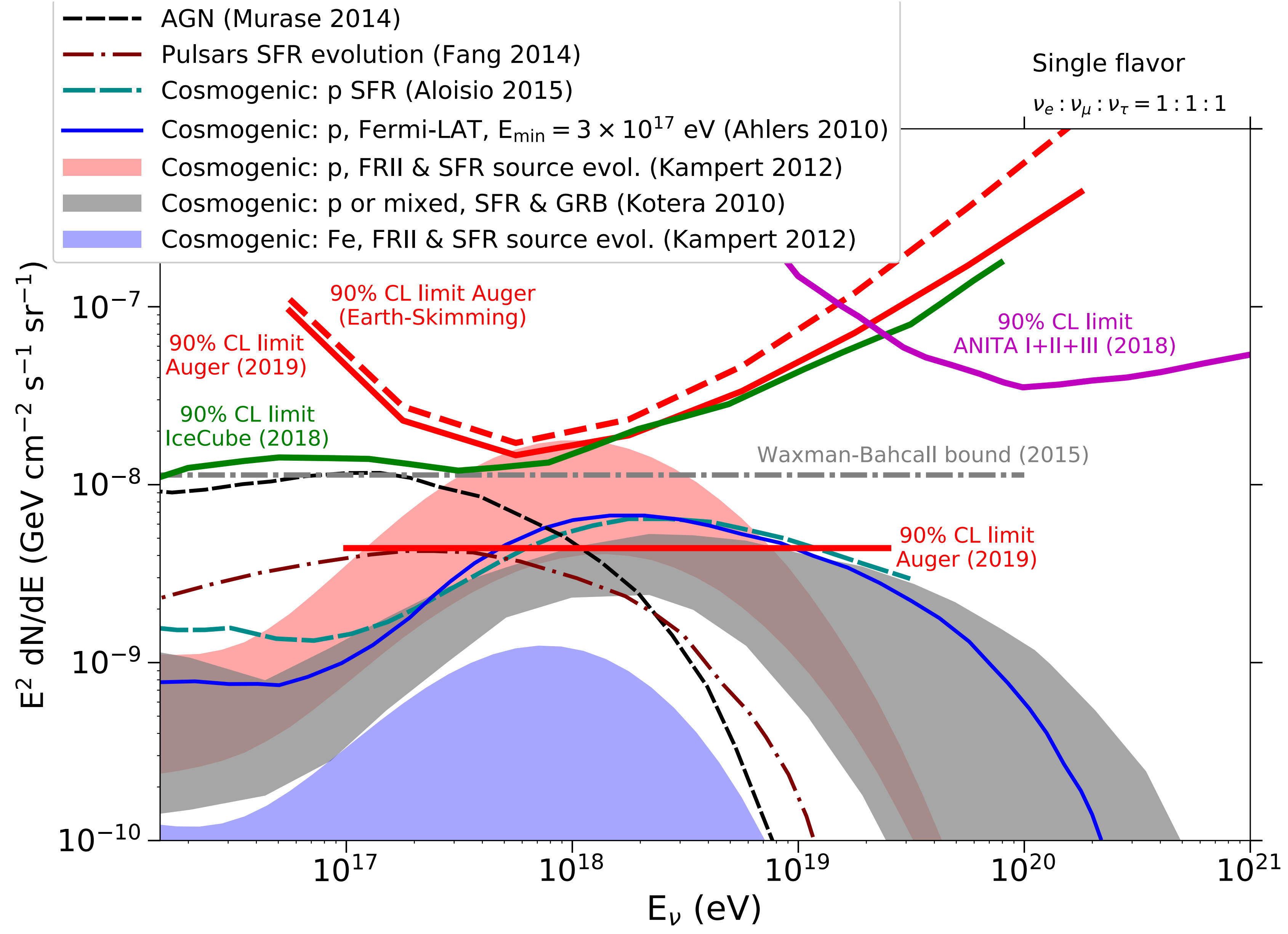
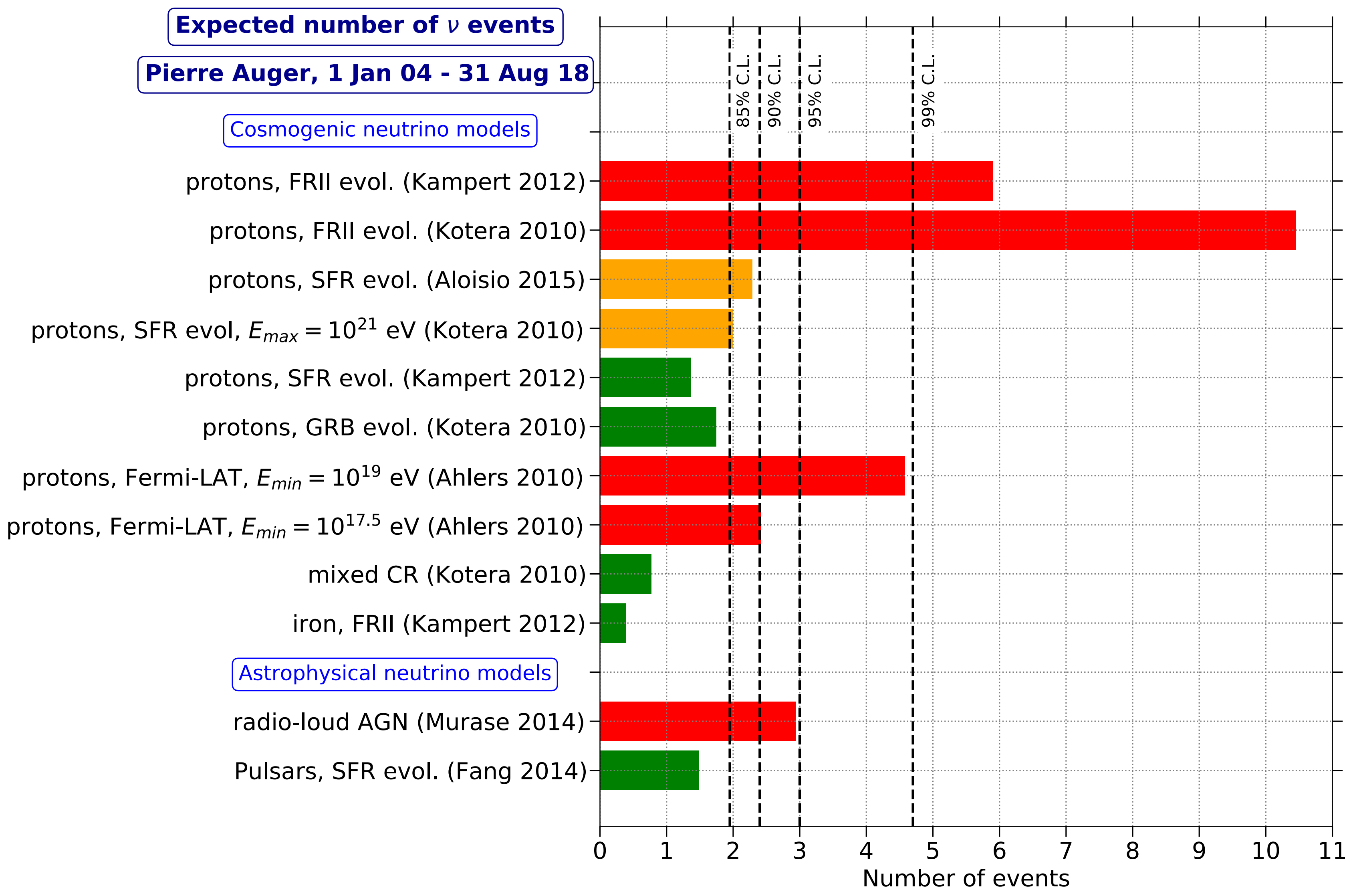
Neutrino and Photon searches

Cosmogenic photons and neutrinos
- pure proton model at UHE challenged, some variants ruled out

Multi-messenger physics
- searches for photons/neutrinos in coincidence with GW events
- Auger's neutrino aperture comparable to IceCube if direction favourable

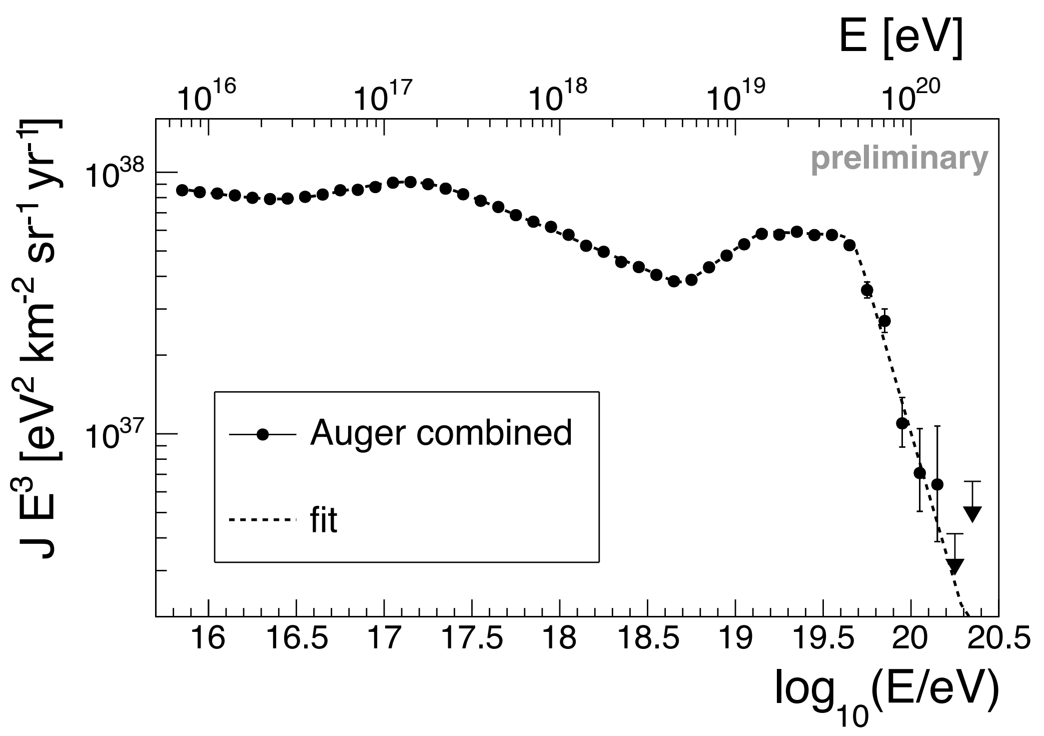


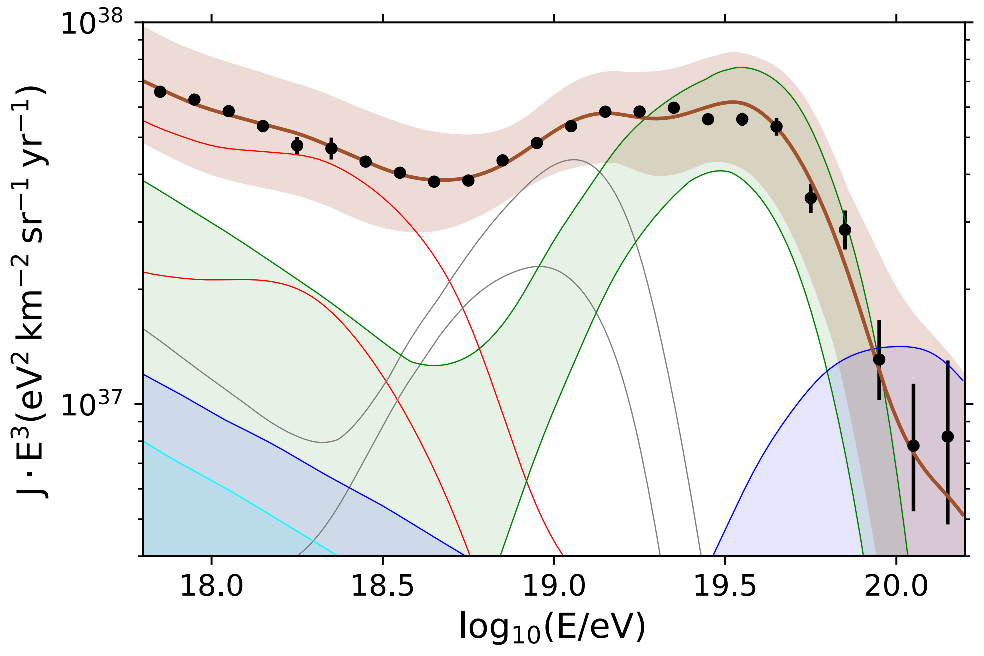


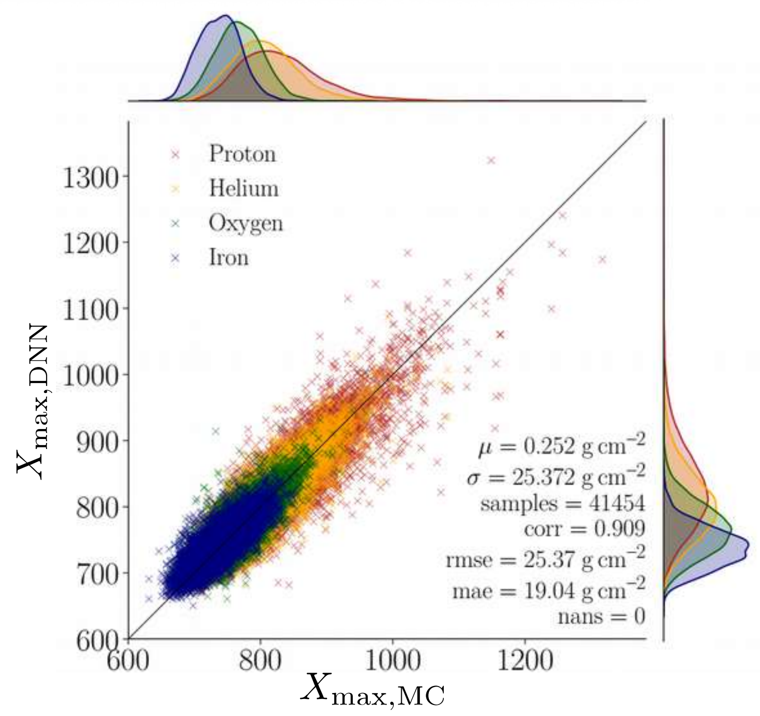


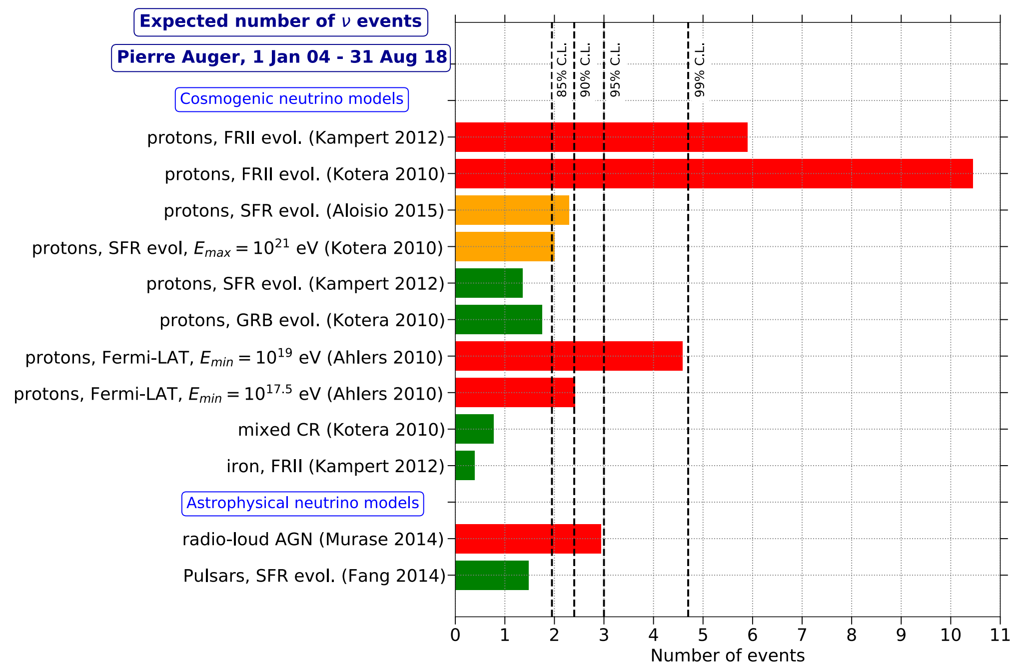
Phase II
- photon searches enhanced with new methods for photon/hadron discrimination
- neutrino searches enhanced with more sensitive triggers (new SD electronics)

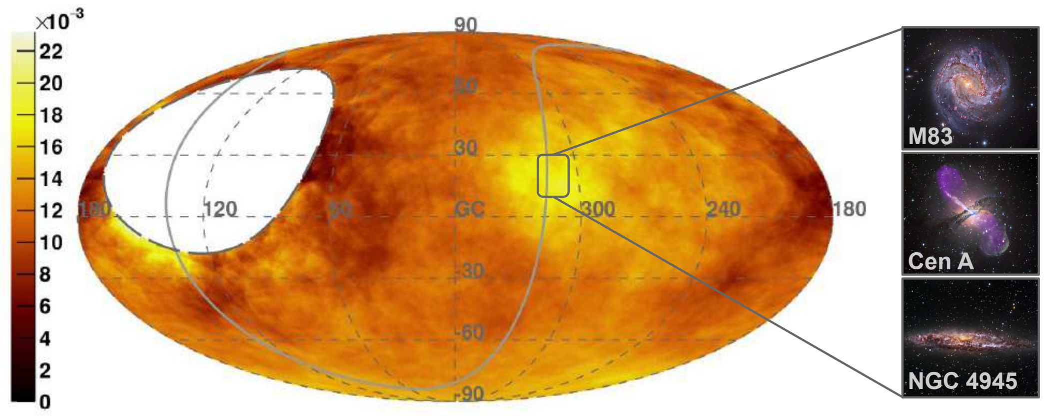
Conclusions and Outlook



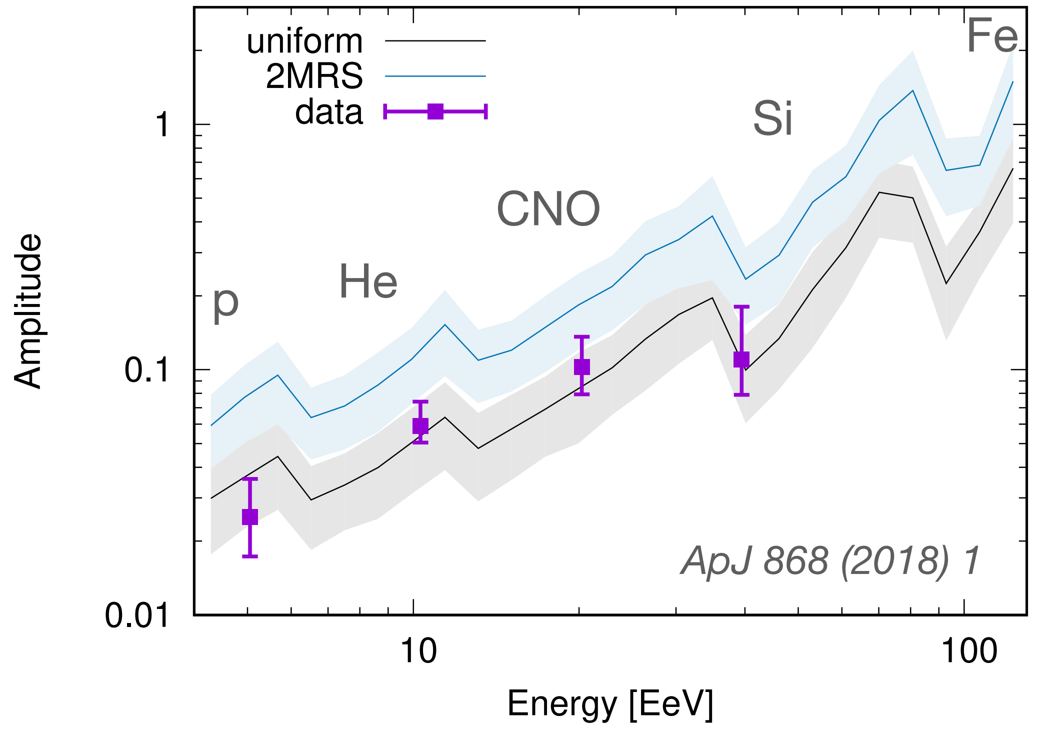




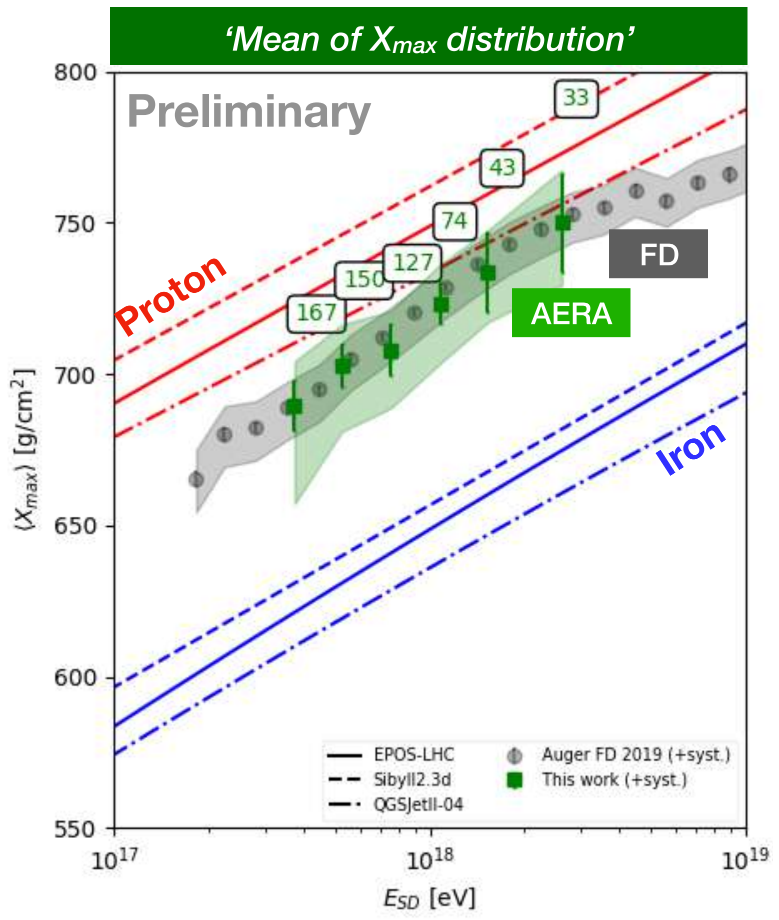




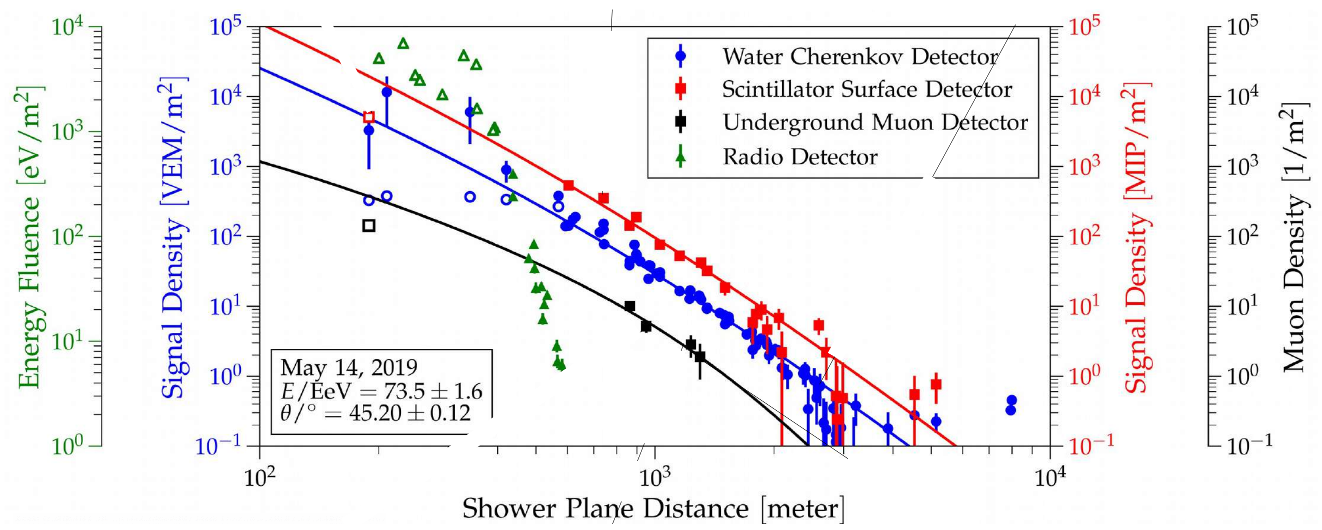
- Auger continues to explore the origin of UHECR with a rich range of results



- Phase I has produced results that appear to be telling a consistent story (e.g. change of mass confirmed, challenging anisotropy studies, neutrino limits …)



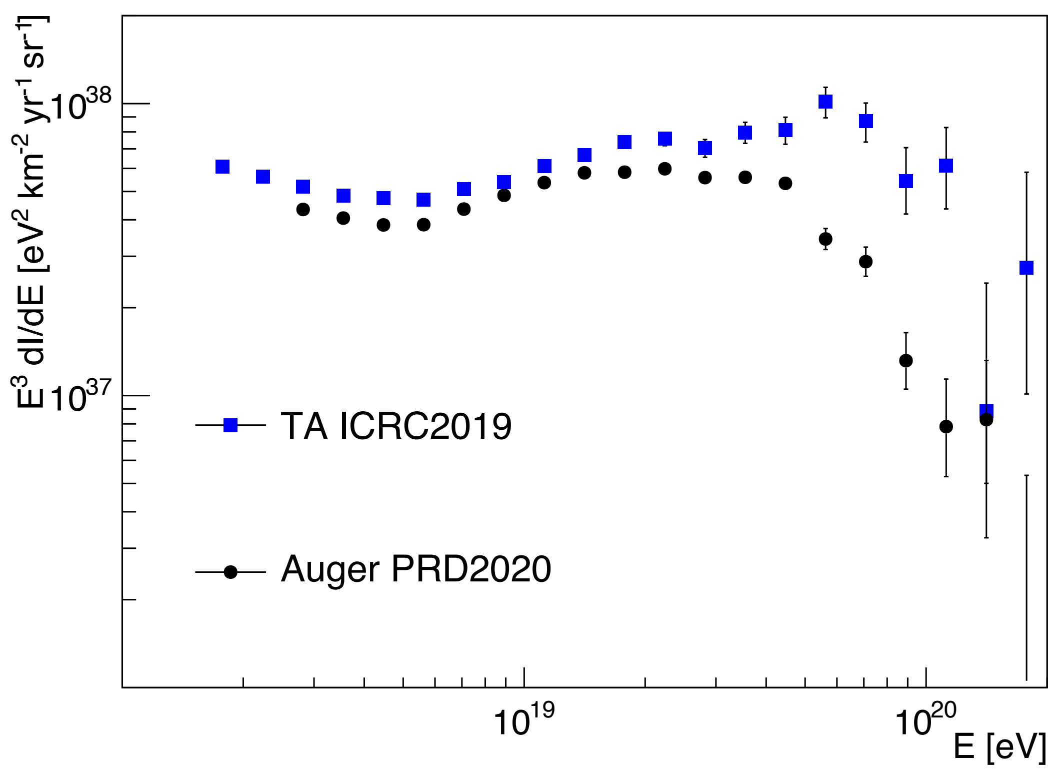
- Phase II soon to be underway, with enhanced mass information and more hybrid measurements. (And re-analysis of old data with the benefit of new knowledge!)

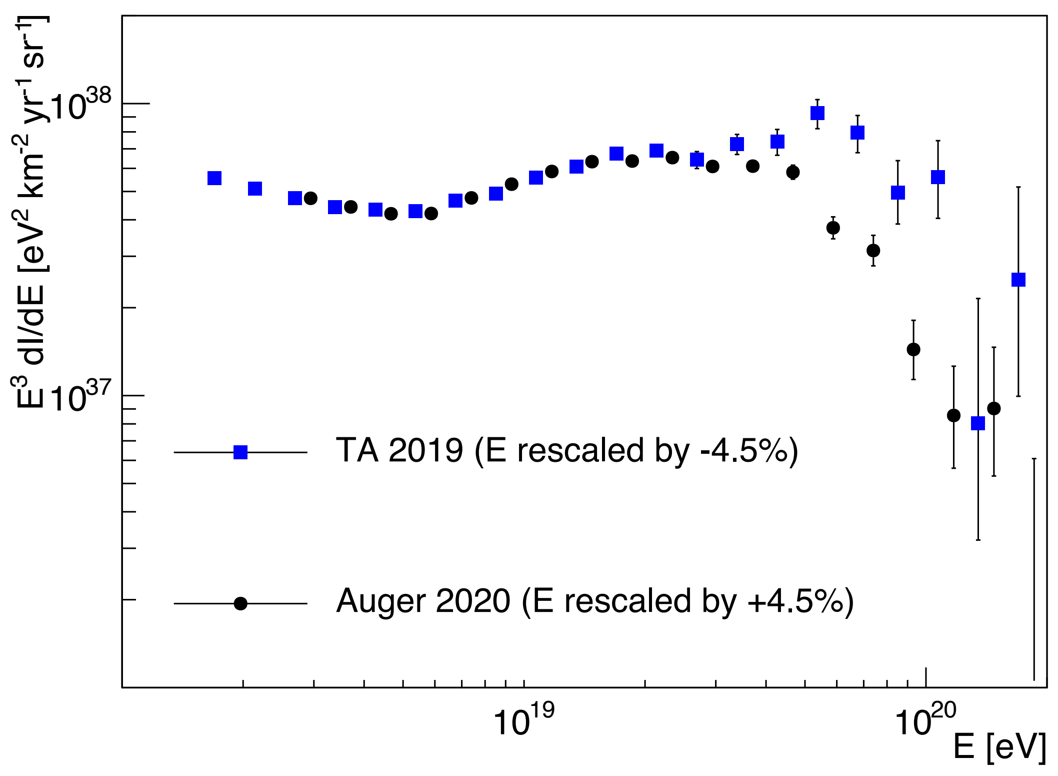


Backup

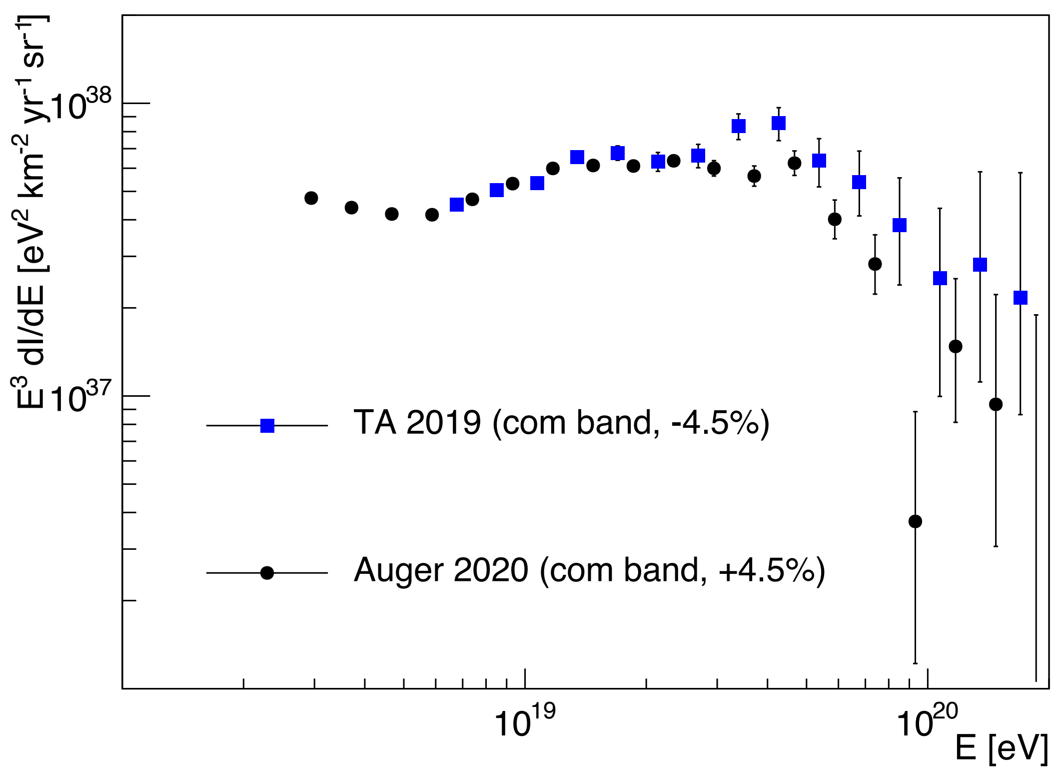
Spectrum - Joint Working Group with TA

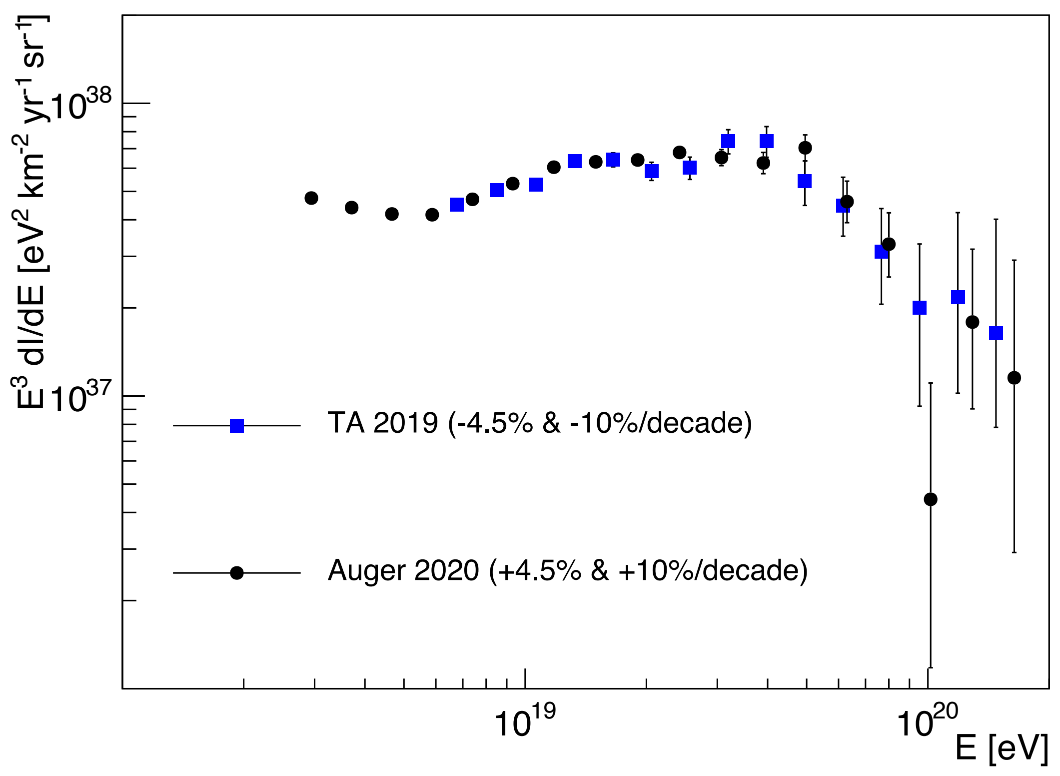
All data - shifts of ± 4.5% is not satisfactory for all energies



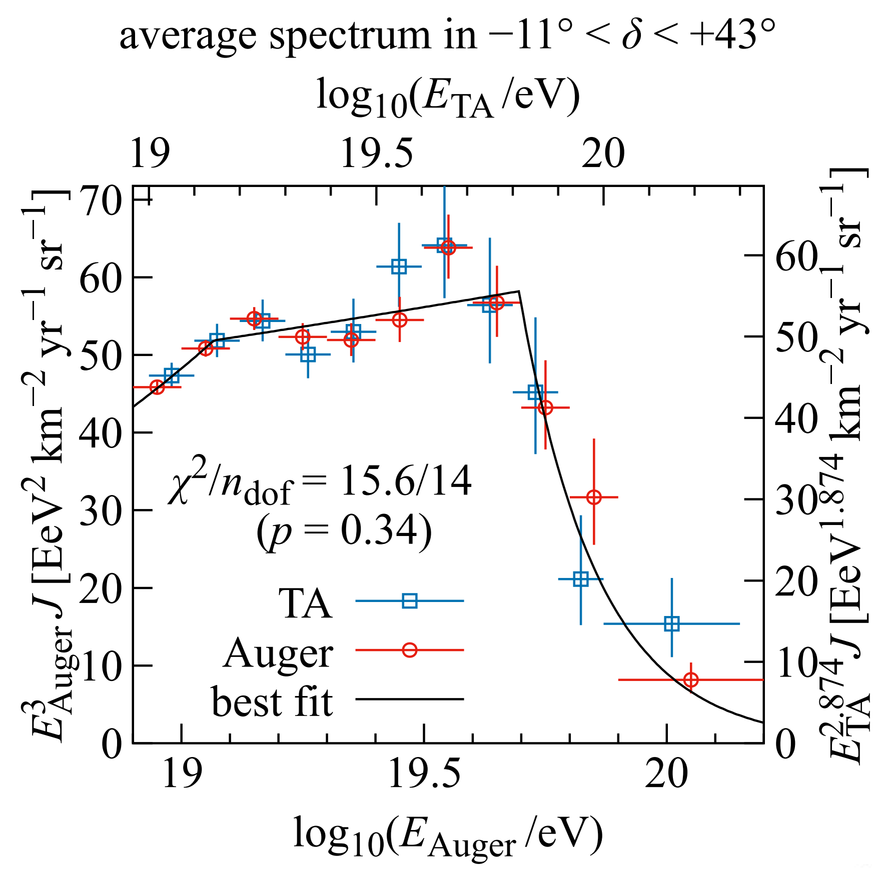


Common declination band - an energy-dependent shift is required





An active joint working group exists
- energy systematics Auger (14%), TA (21%)
- disagreements (even in the common declination band)
- differences in some assumptions (fluorescence yield, invisible energy) cannot explain disagreement
- collaboration on this issue continues
- corrections are made for joint physics analyses (e.g. anisotropy)



From anisotropy joint WG

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

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

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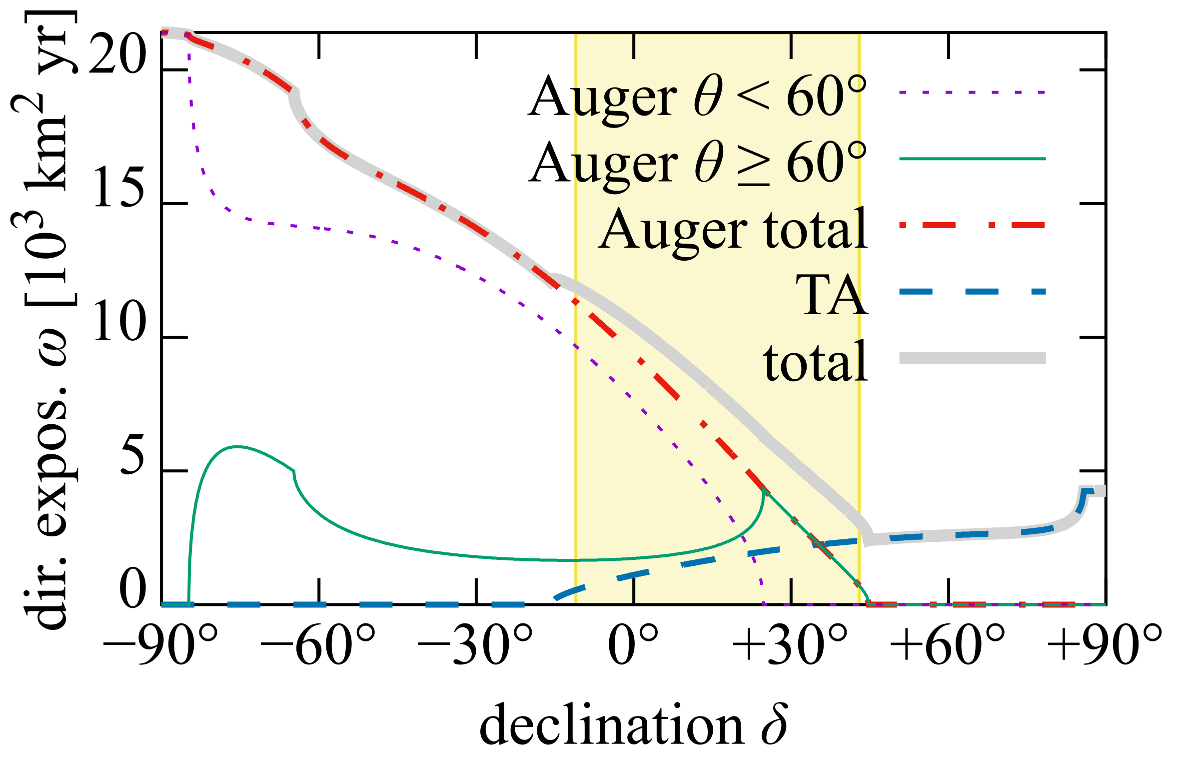
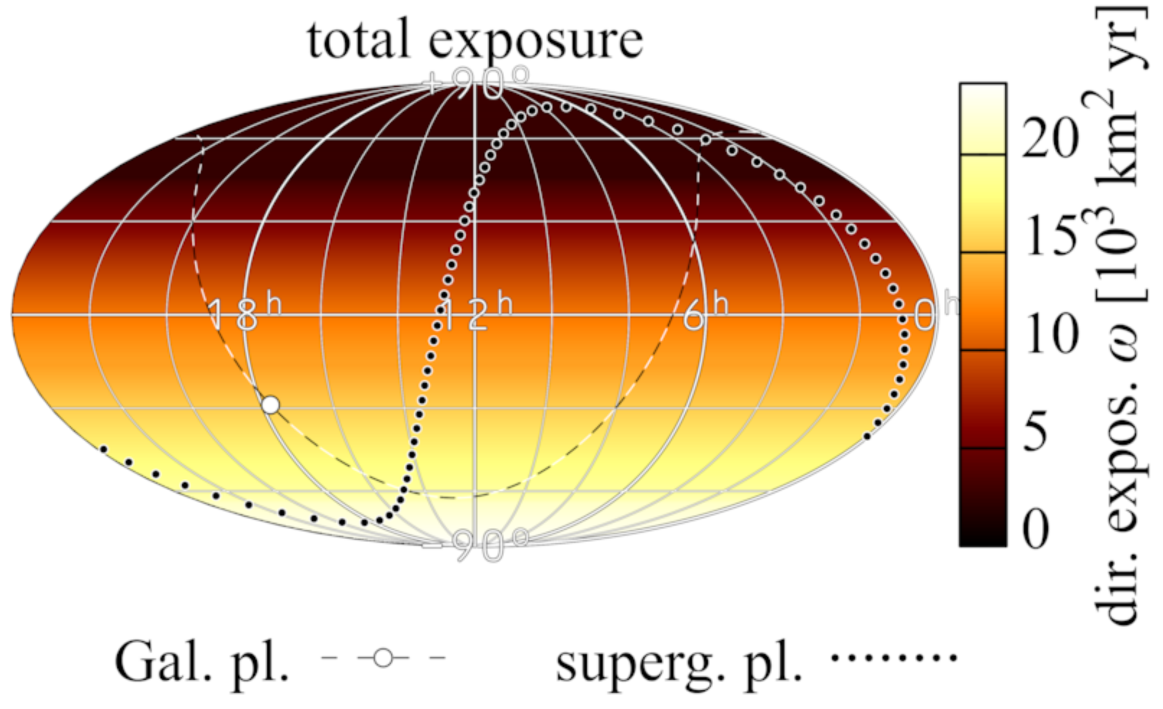
Anisotropy - Joint Working Group with TA

(All plots in equatorial coords)

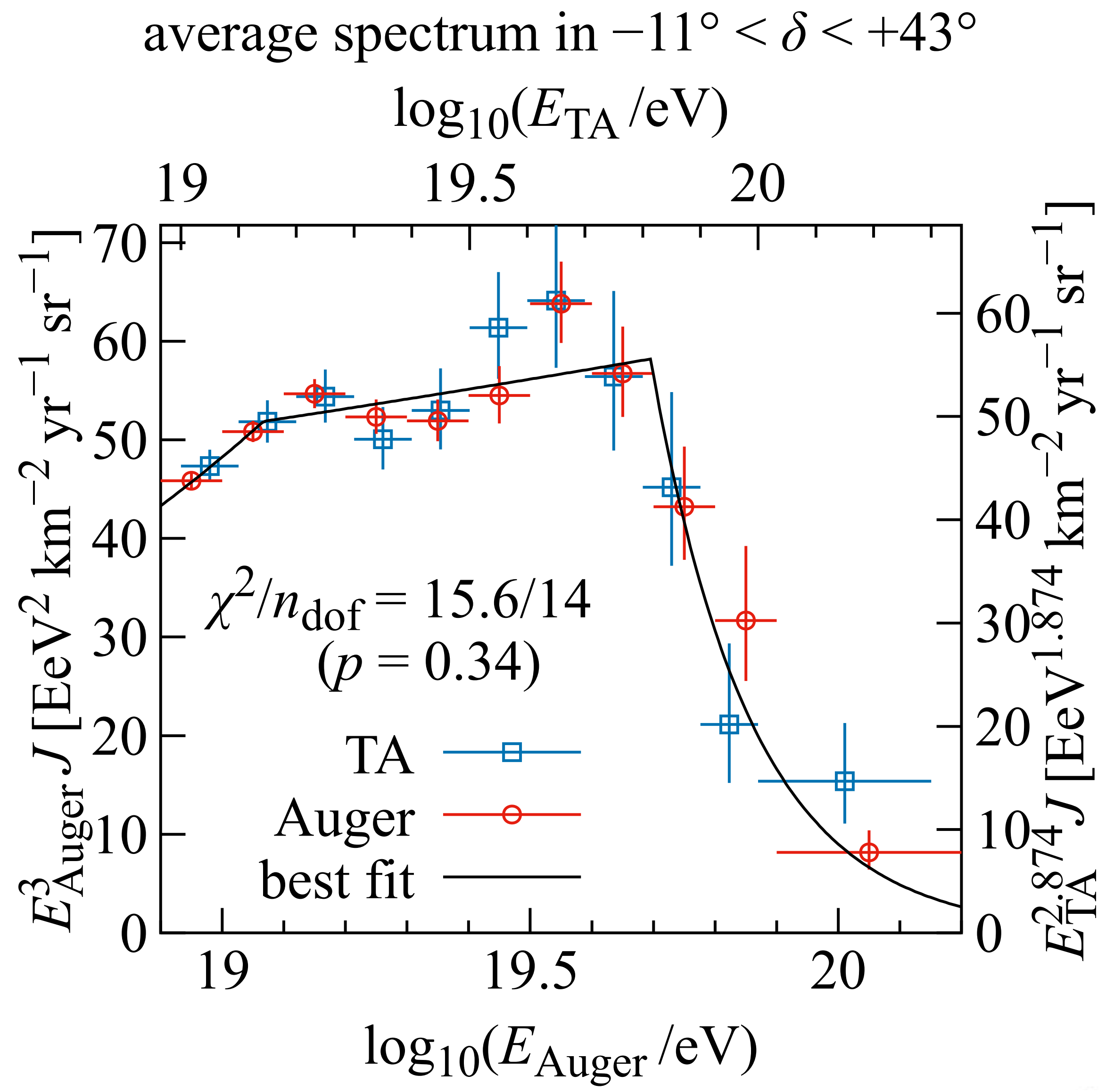
Auger and TA exposures





Auger ($\theta < 80^\circ$): 120,000 km² sr yr

TA ($\theta < 55^\circ$): 14,000 km² sr yr

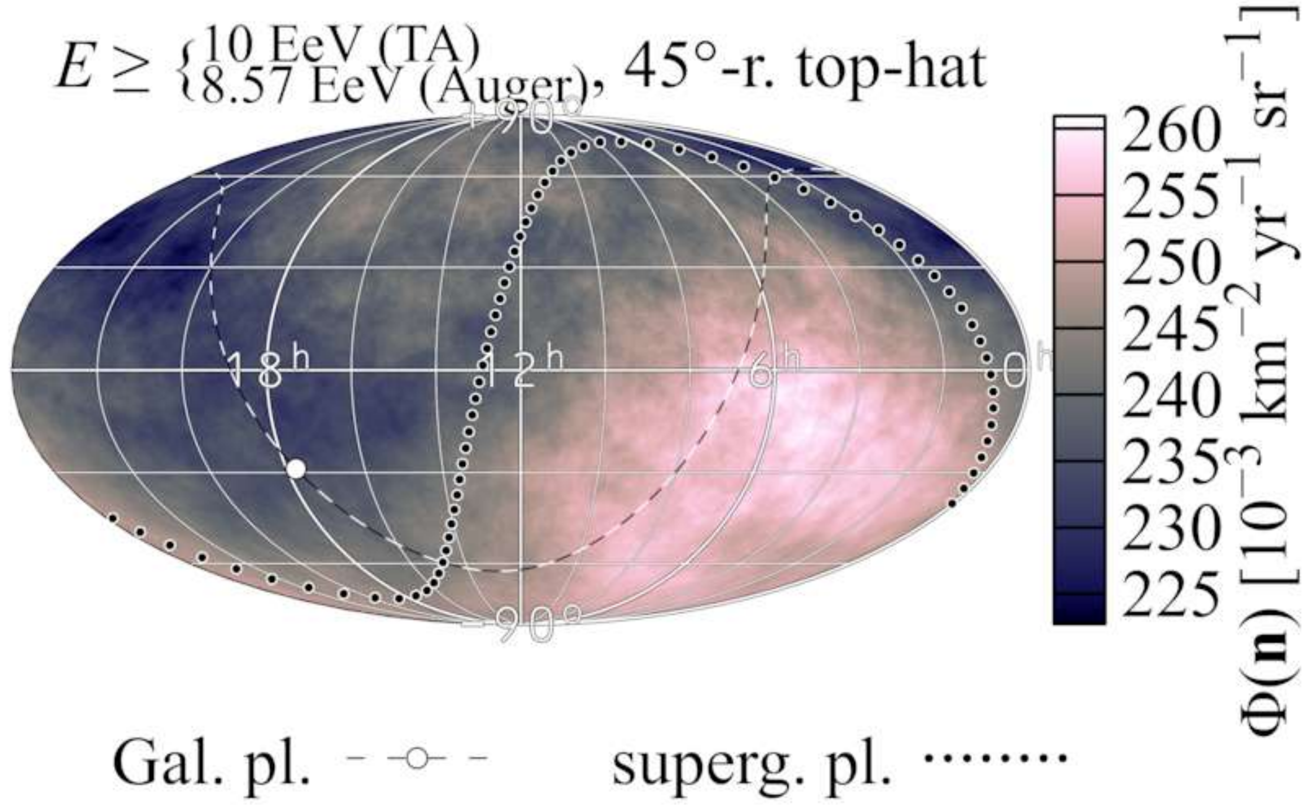


Energy conversion recipe

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

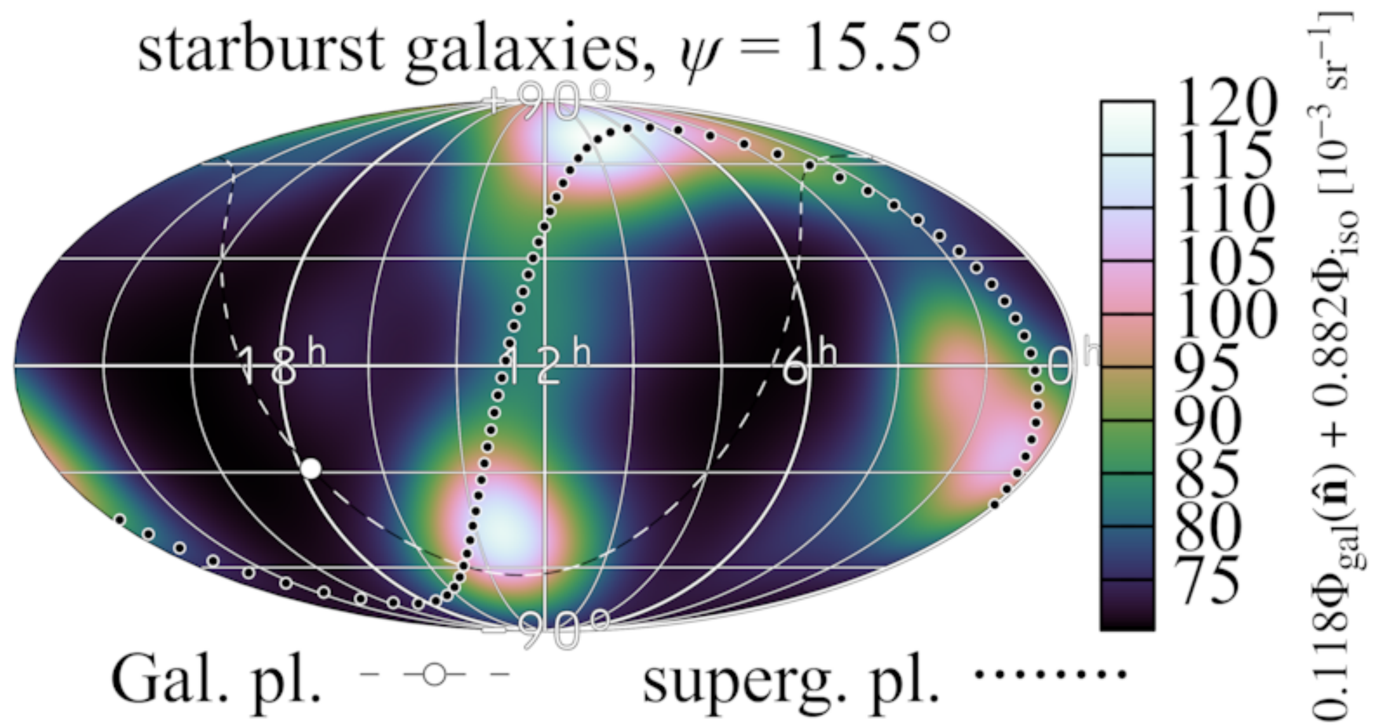
$$\frac{E_{\text{TA}}}{10\ \text{EeV}} = 1.179\left(\frac{E_{\text{Auger}}}{10\ \text{EeV}}\right)^{1.067}$$

Large angular scales



Direction of dipole better determined, compatible with Auger-only.

Catalog searches



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

4.2σ for starburst galaxy search.

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