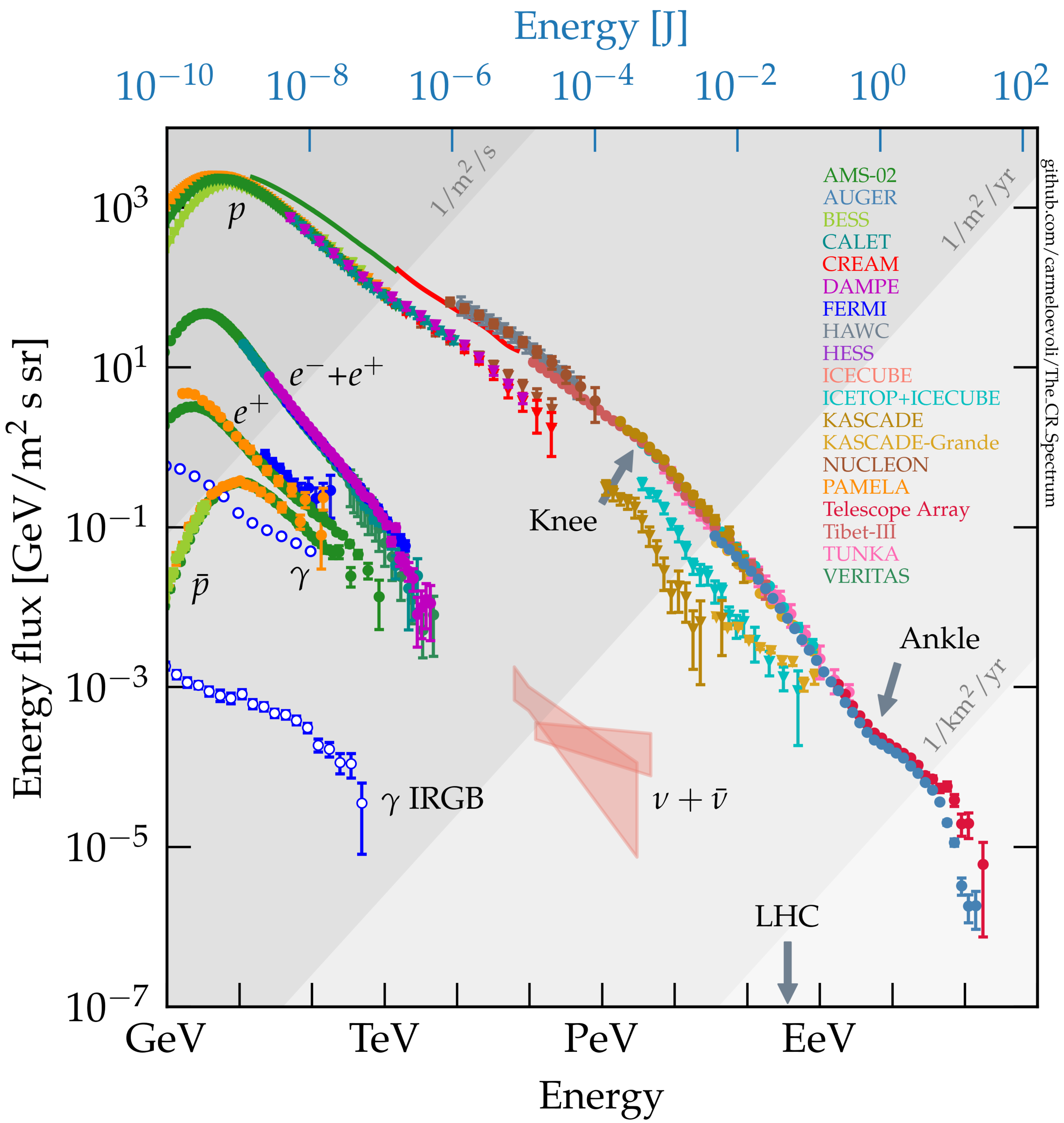
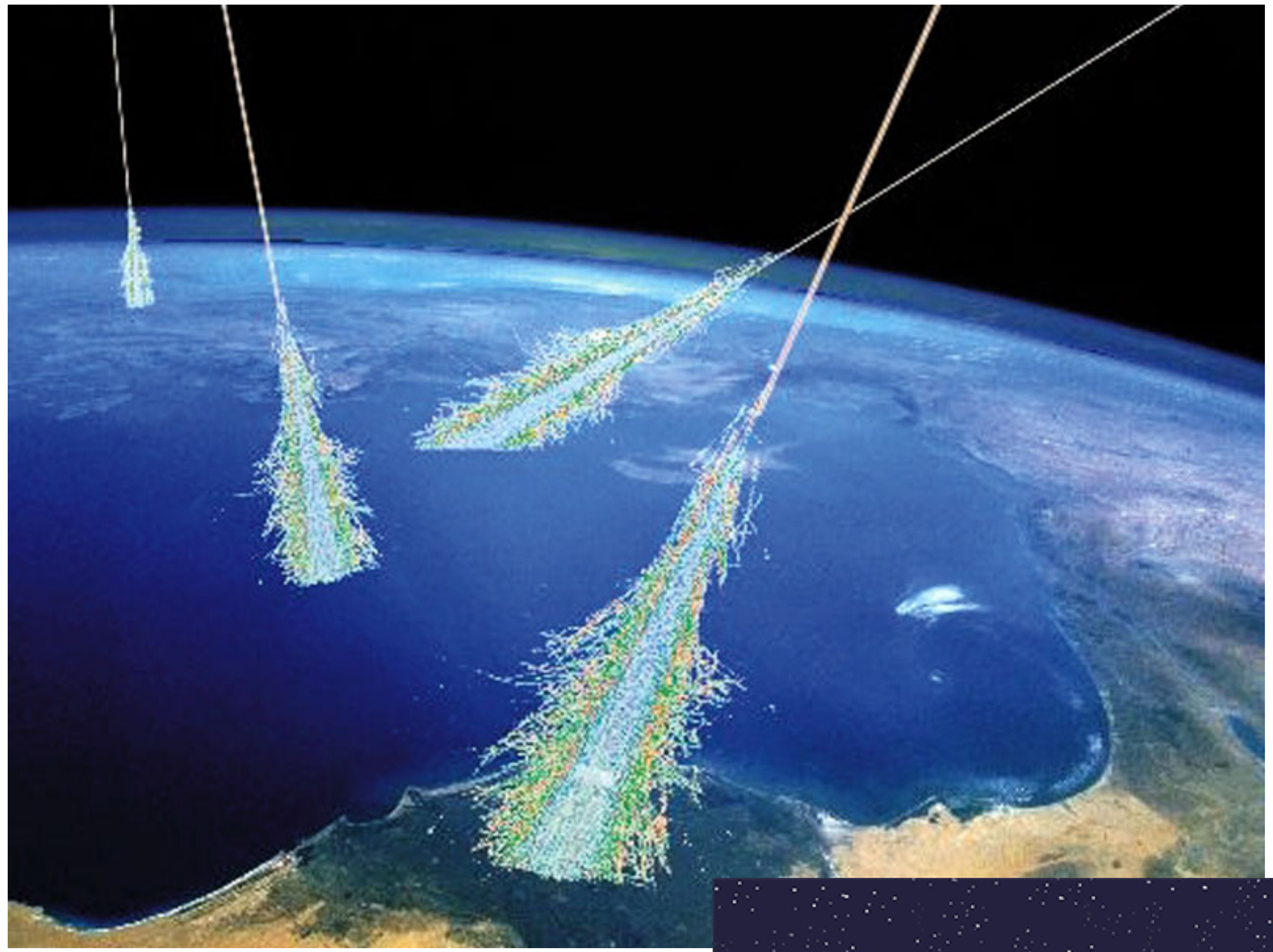
Latest Results on Ultra-High Energy Cosmic Rays from the Pierre Auger Observatory

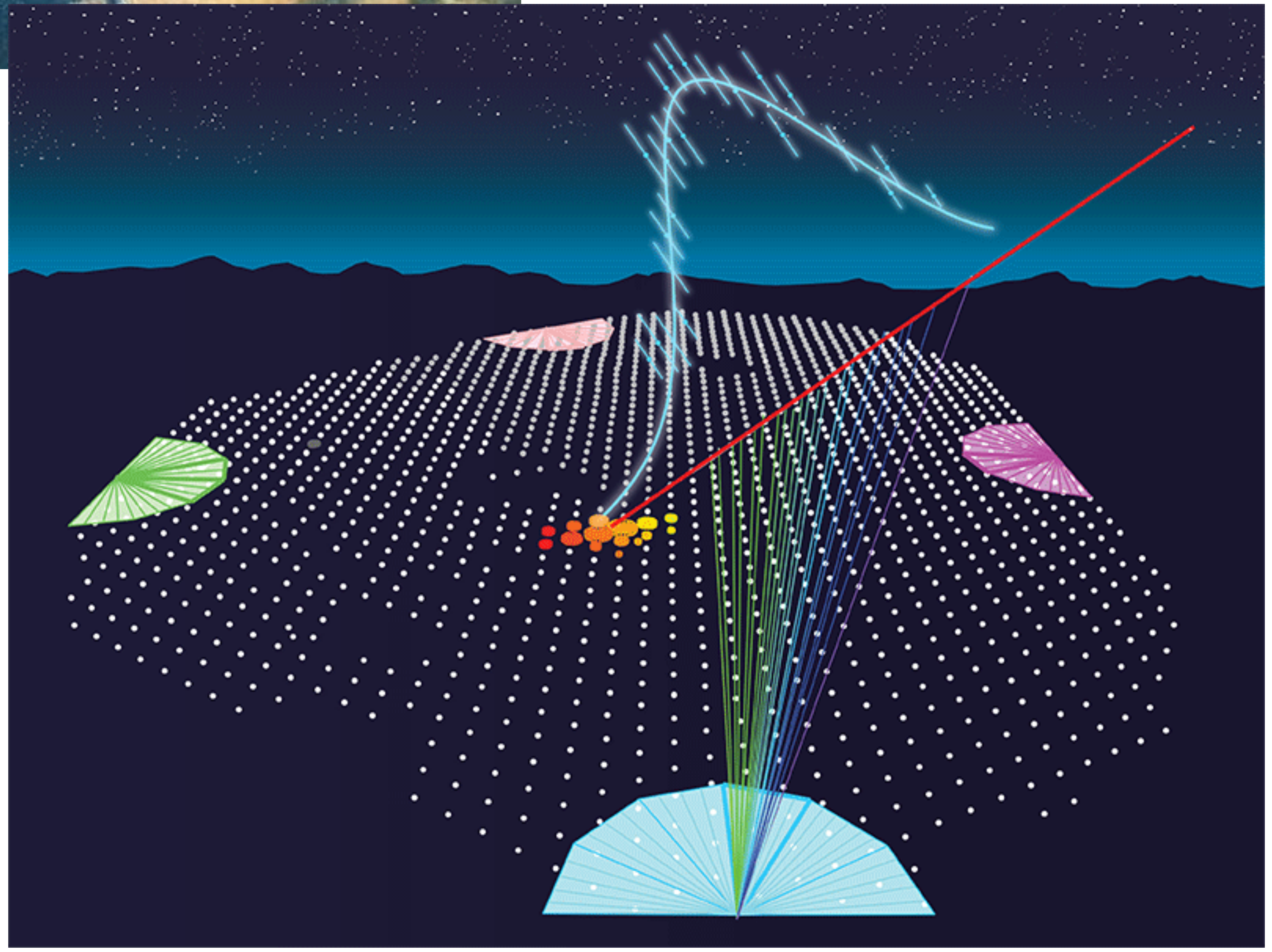
Bruce Dawson
The University of Adelaide
on behalf of the Pierre Auger Collaboration

Ultra-high energy cosmic rays



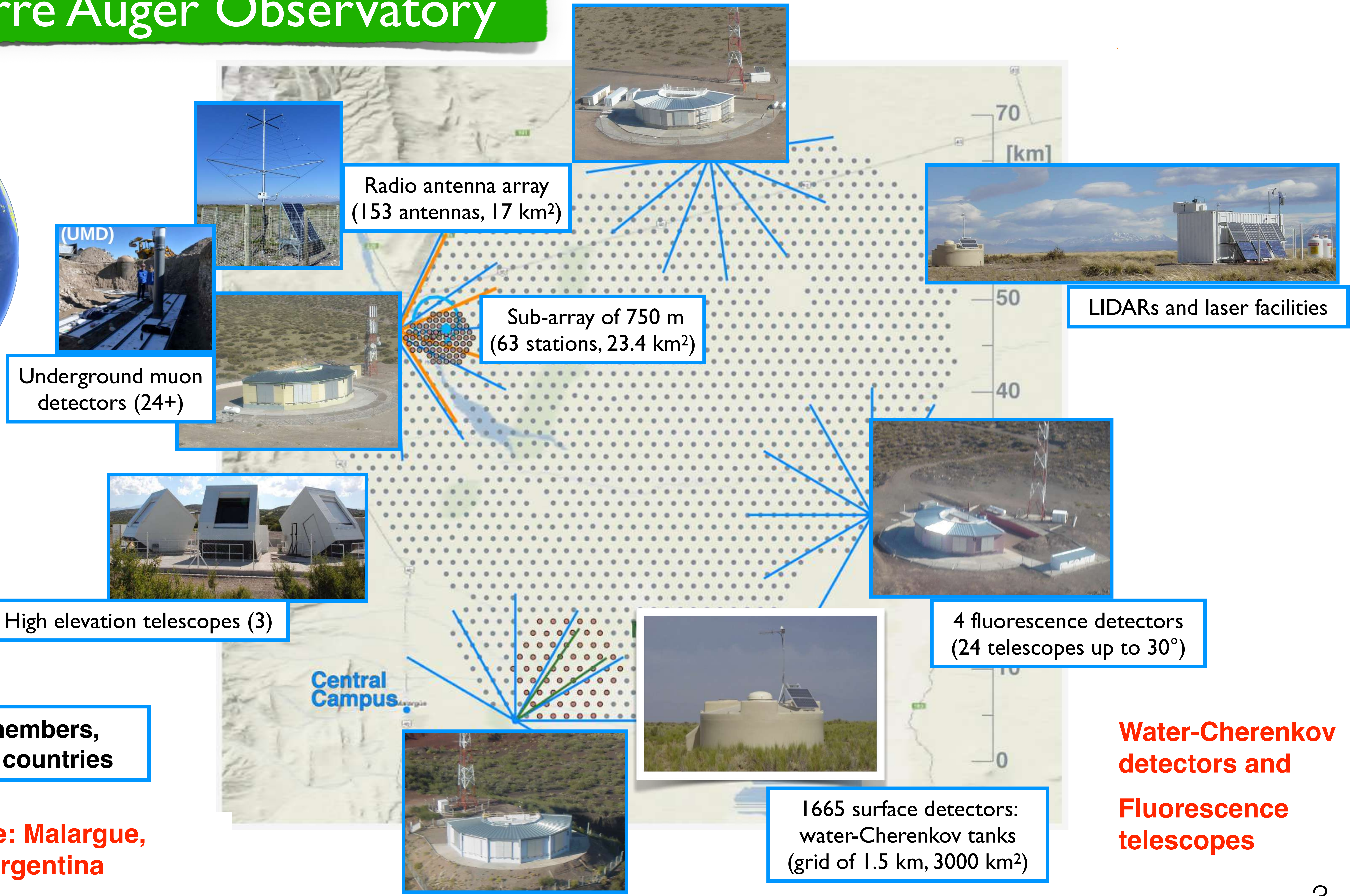


Pierre Auger Observatory



The Pierre Auger Observatory

Pierre Auger Observatory
Province Mendoza, Argentina



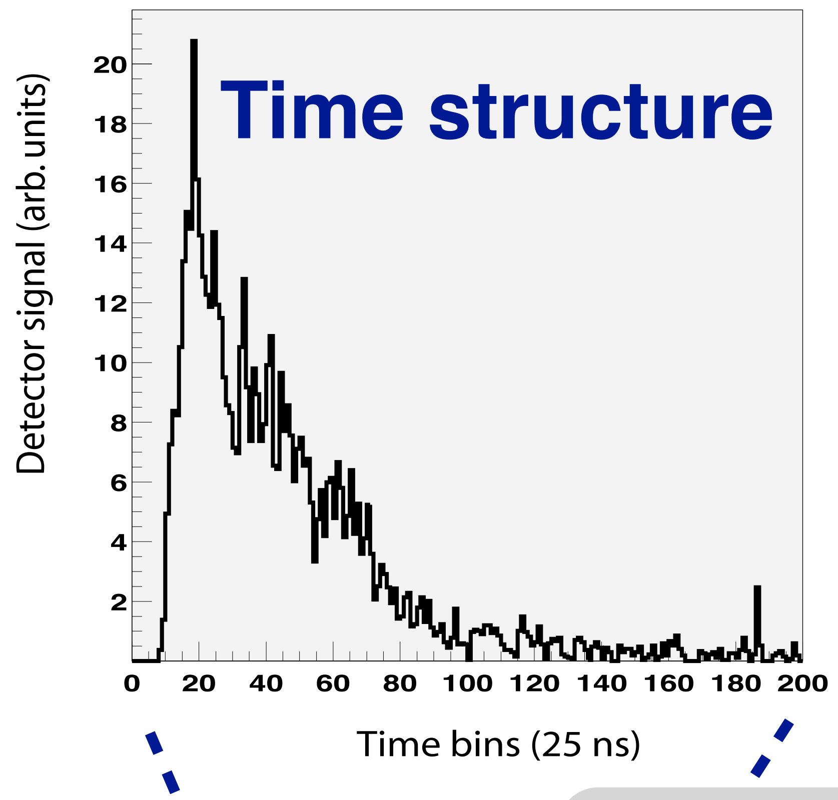
More than 400 members,
98 institutes, 17 countries

Water-Cherenkov detectors and

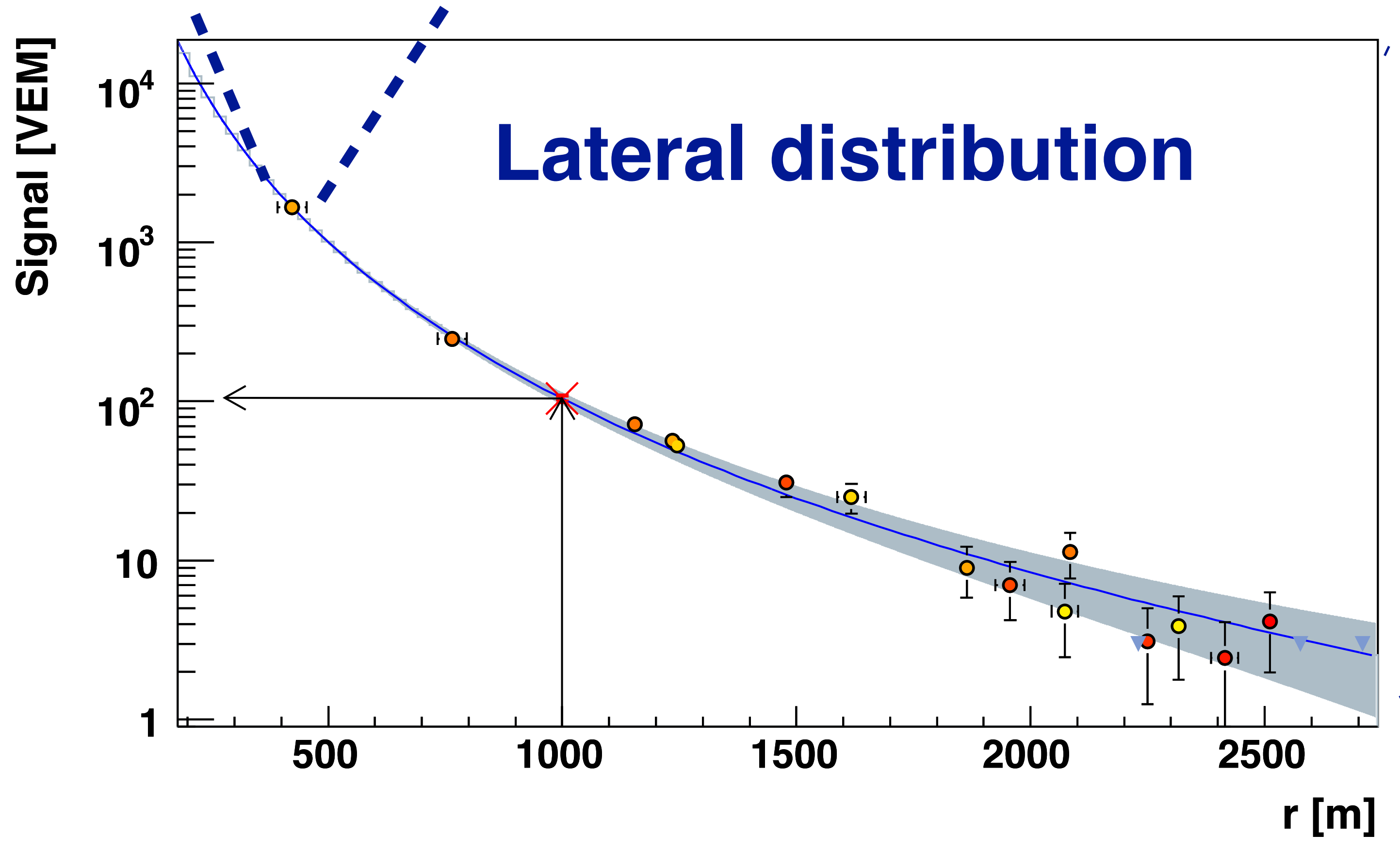
Fluorescence telescopes

Southern hemisphere: Malargue, Province Mendoza, Argentina

Auger is a Hybrid Observatory

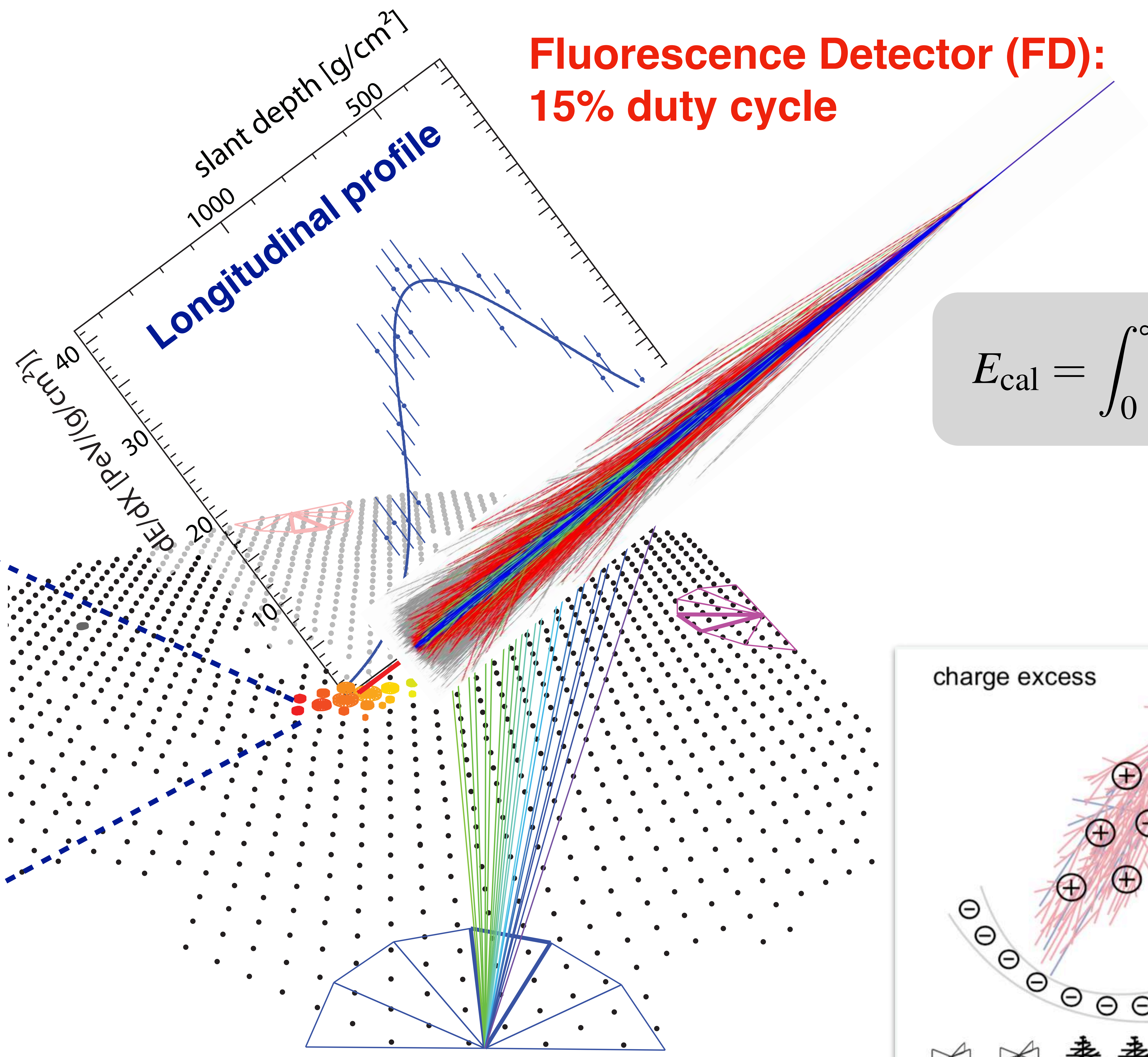


$$E_{\rm rec} = f(S_{1000}, \theta)$$



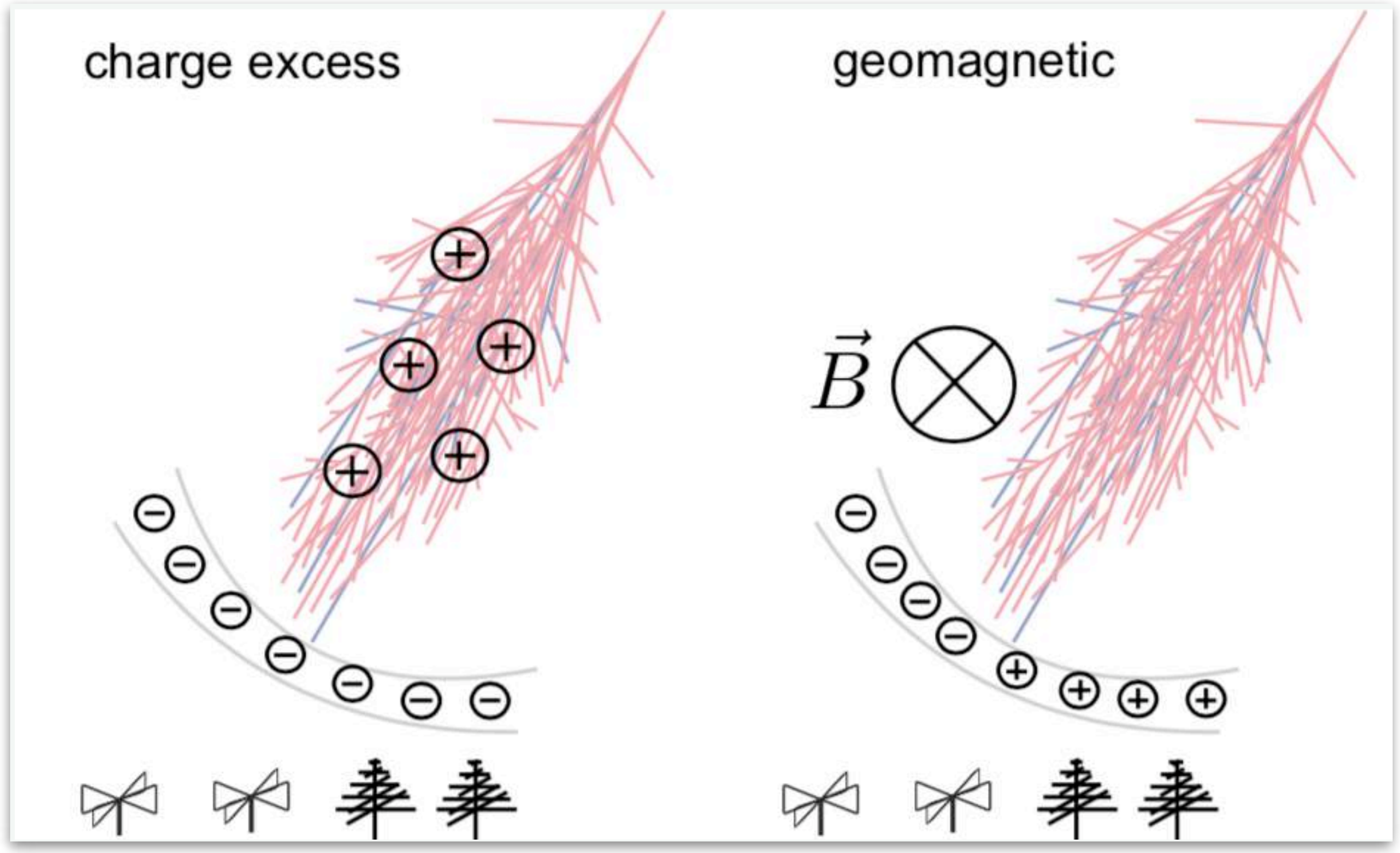
Surface Detector (SD)
100% duty cycle

Fluorescence Detector (FD):
15% duty cycle

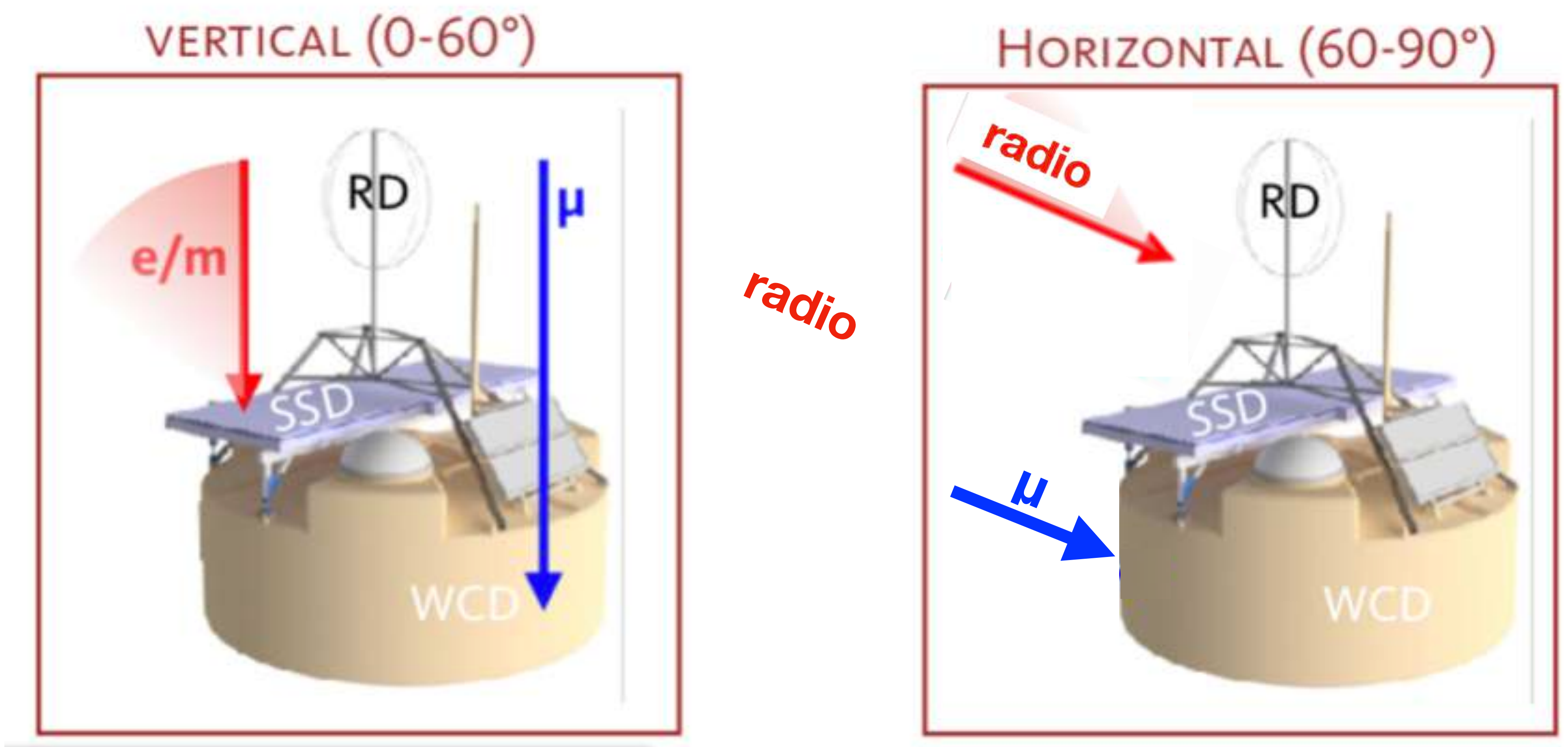


$$E_{\rm cal} = \int_0^\infty \left(\frac{dE}{dX}\right)_{\rm obs} dX$$

Radio Detector (RD):
100% duty cycle



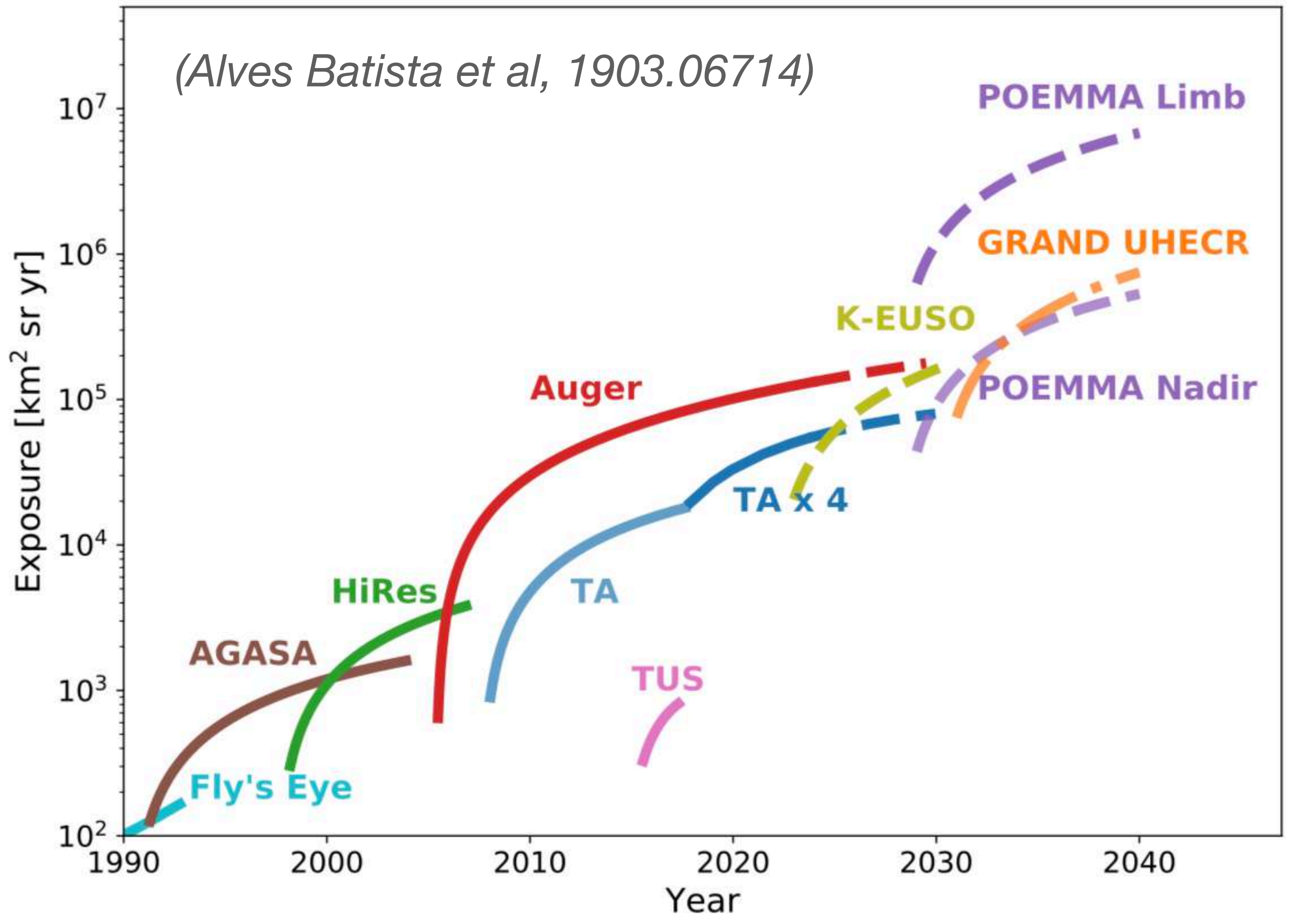
Moving to Phase II of the Observatory - AugerPrime



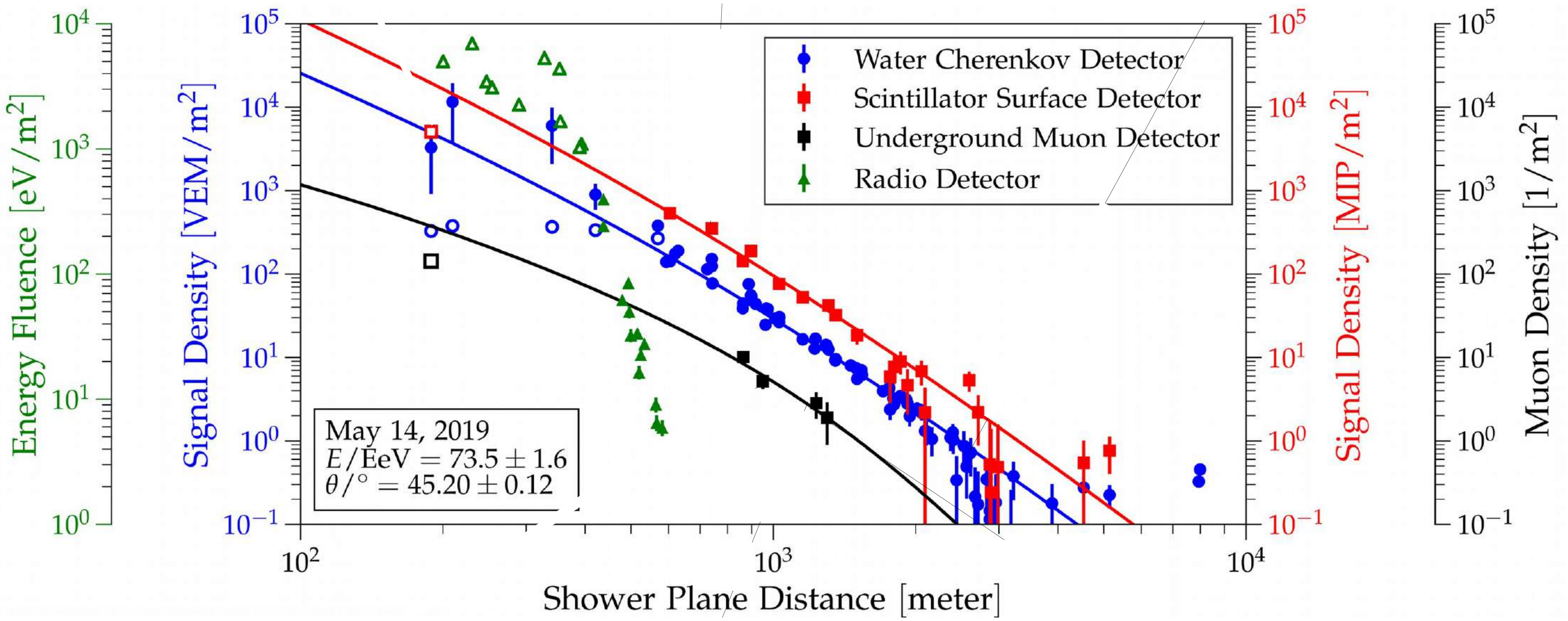
Phase I: exposure 80,000 km² sr y ($\theta < 60°$)

Phase II

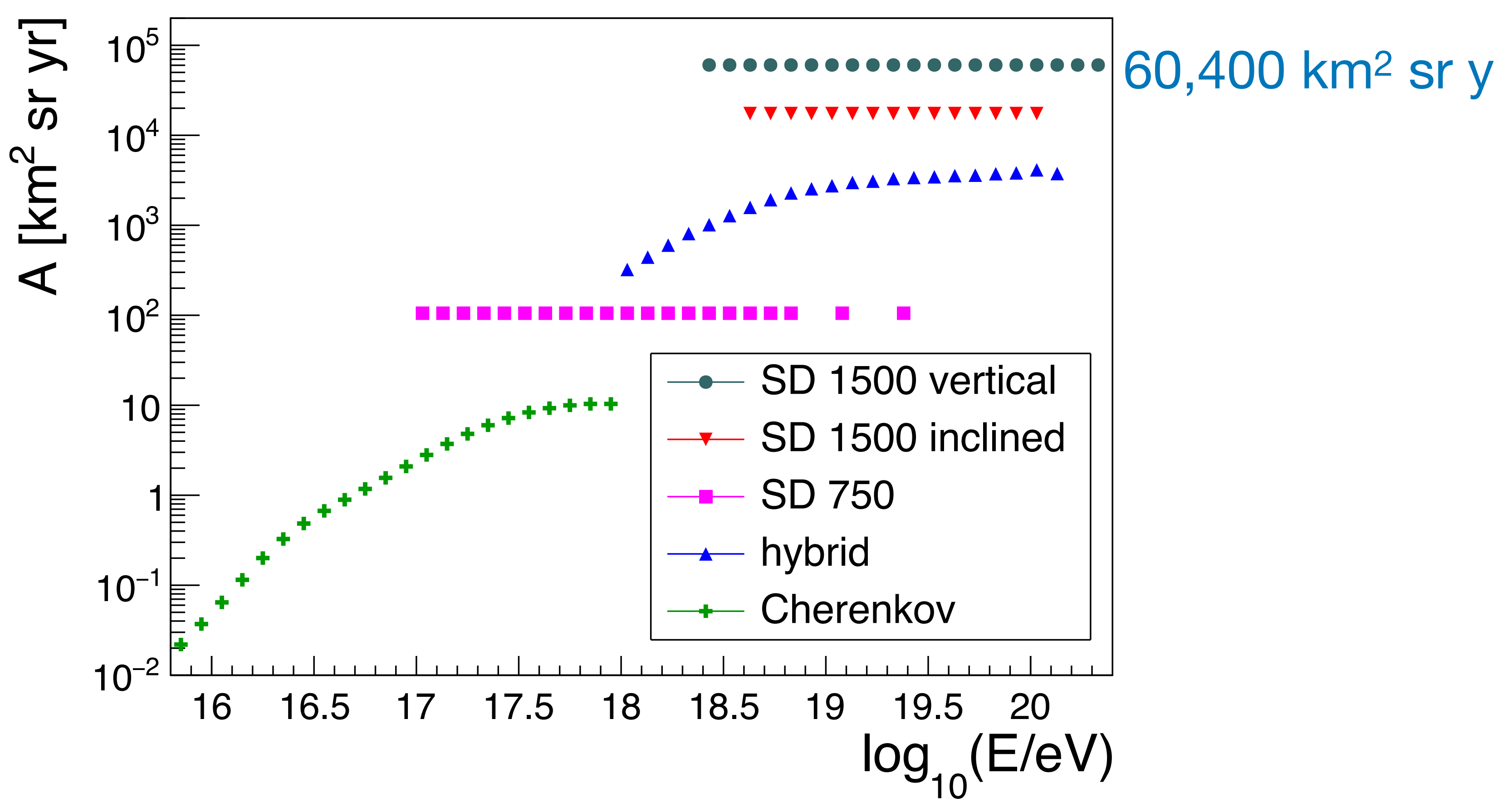
- 2022/23 - 2030
- mass composition info on all events
- scintillator detectors and radio
- expect new 40,000 km² sr y ($\theta < 60°$)
- re-analysis of old data-set (deep learning)

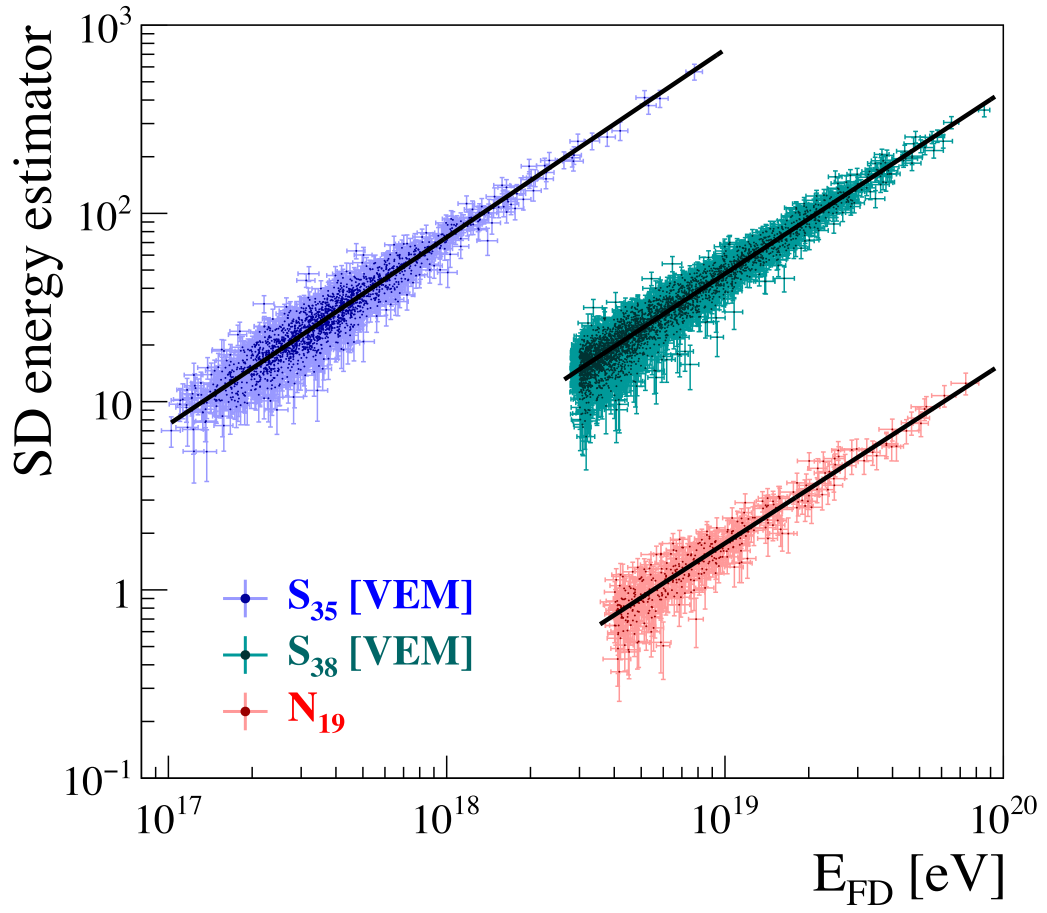


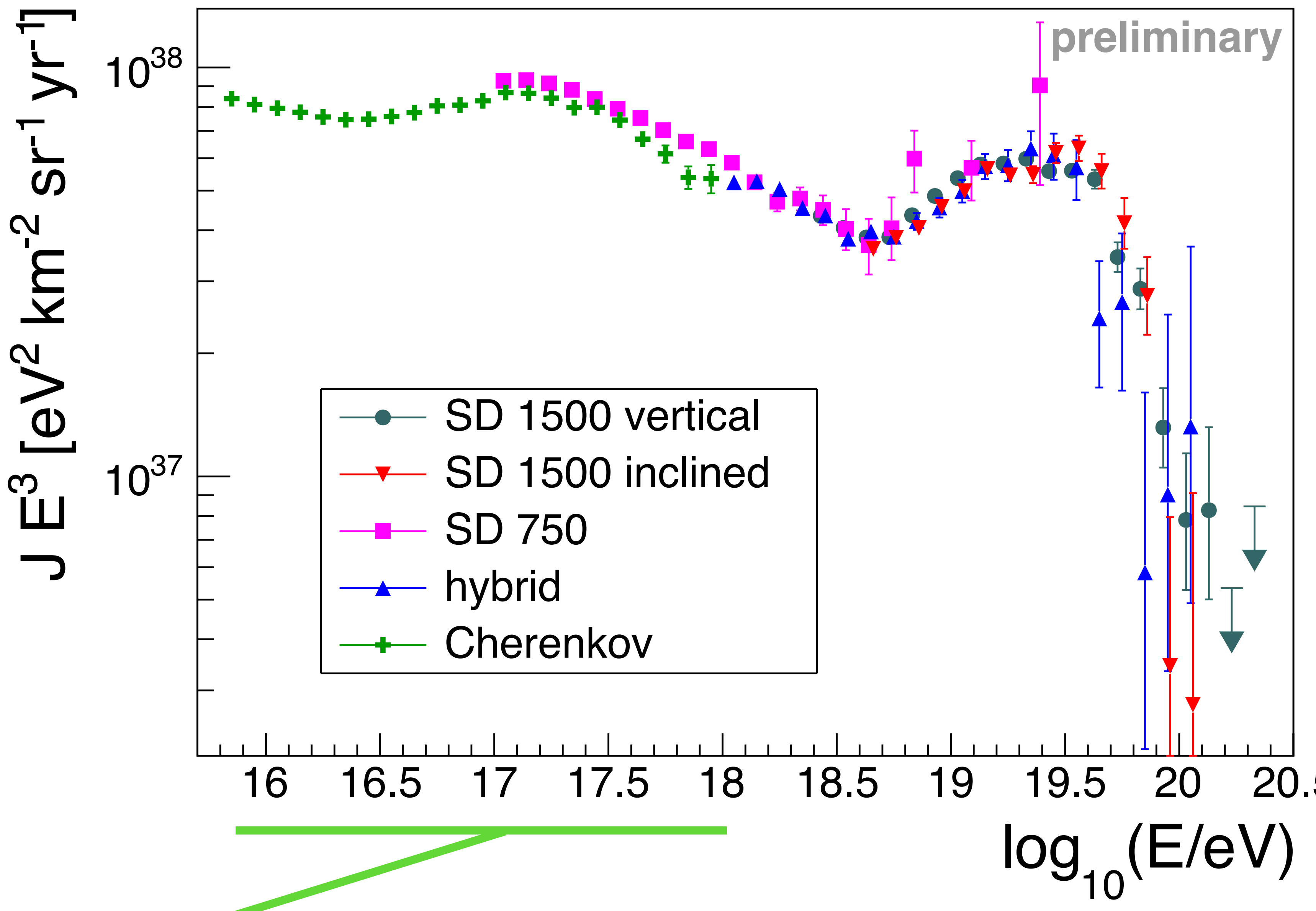
Example data from engineering array



The energy spectrum (including low-energy extensions)

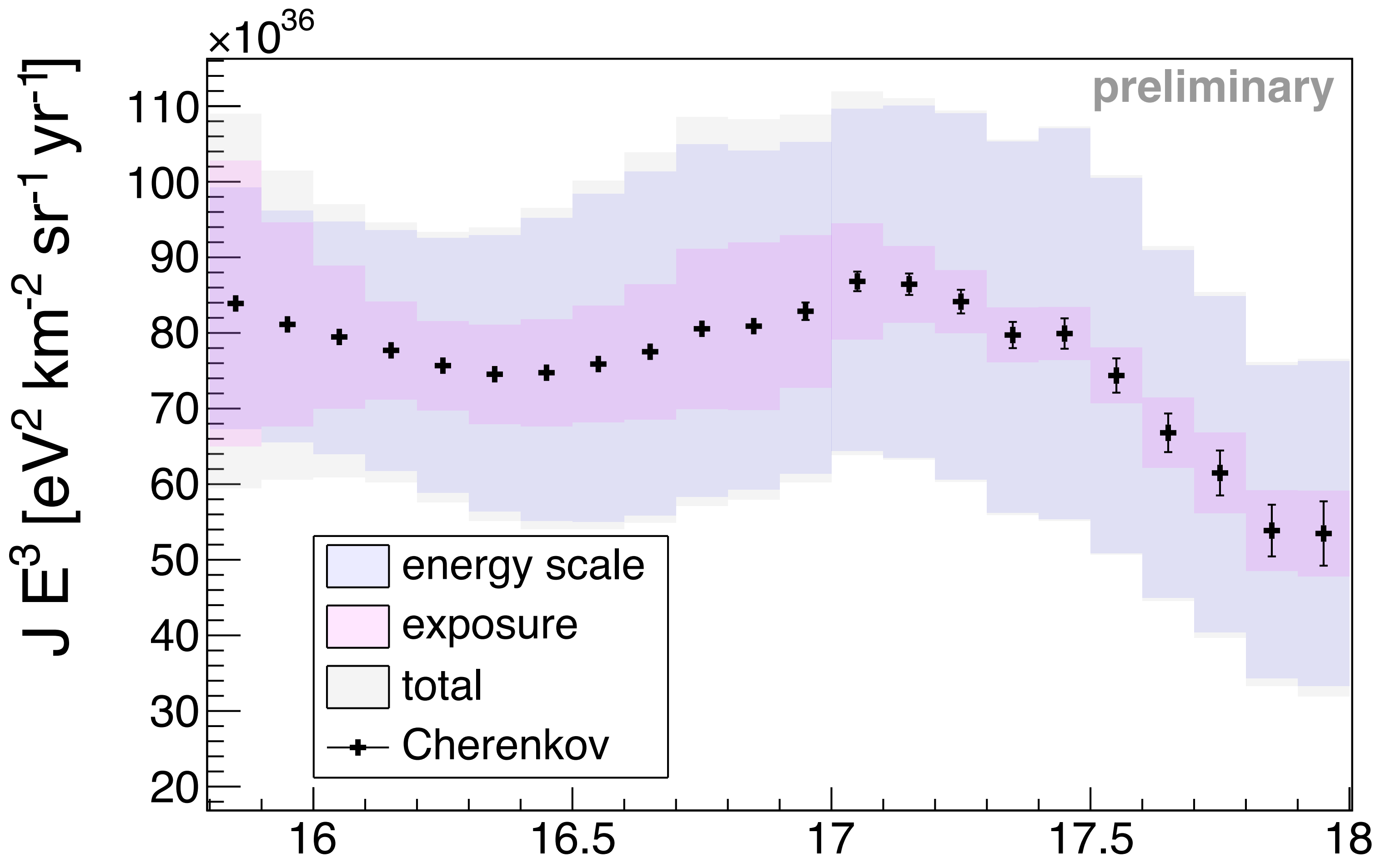




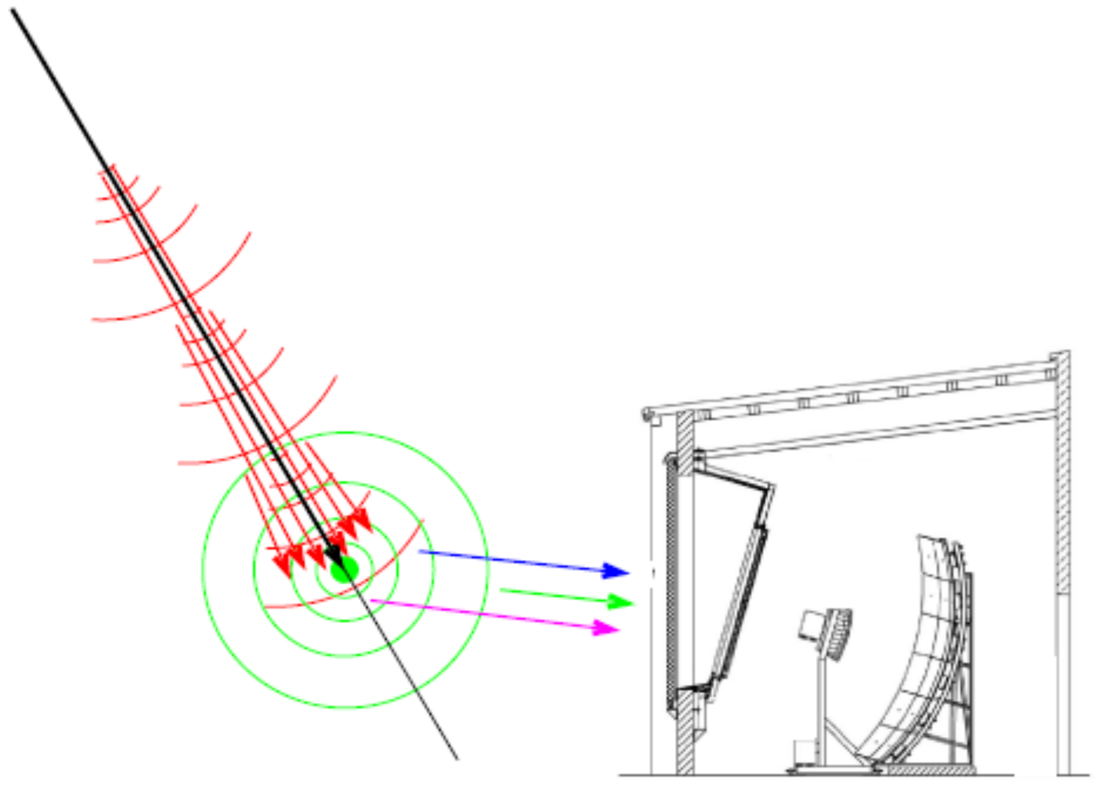


Five different measurements

- 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

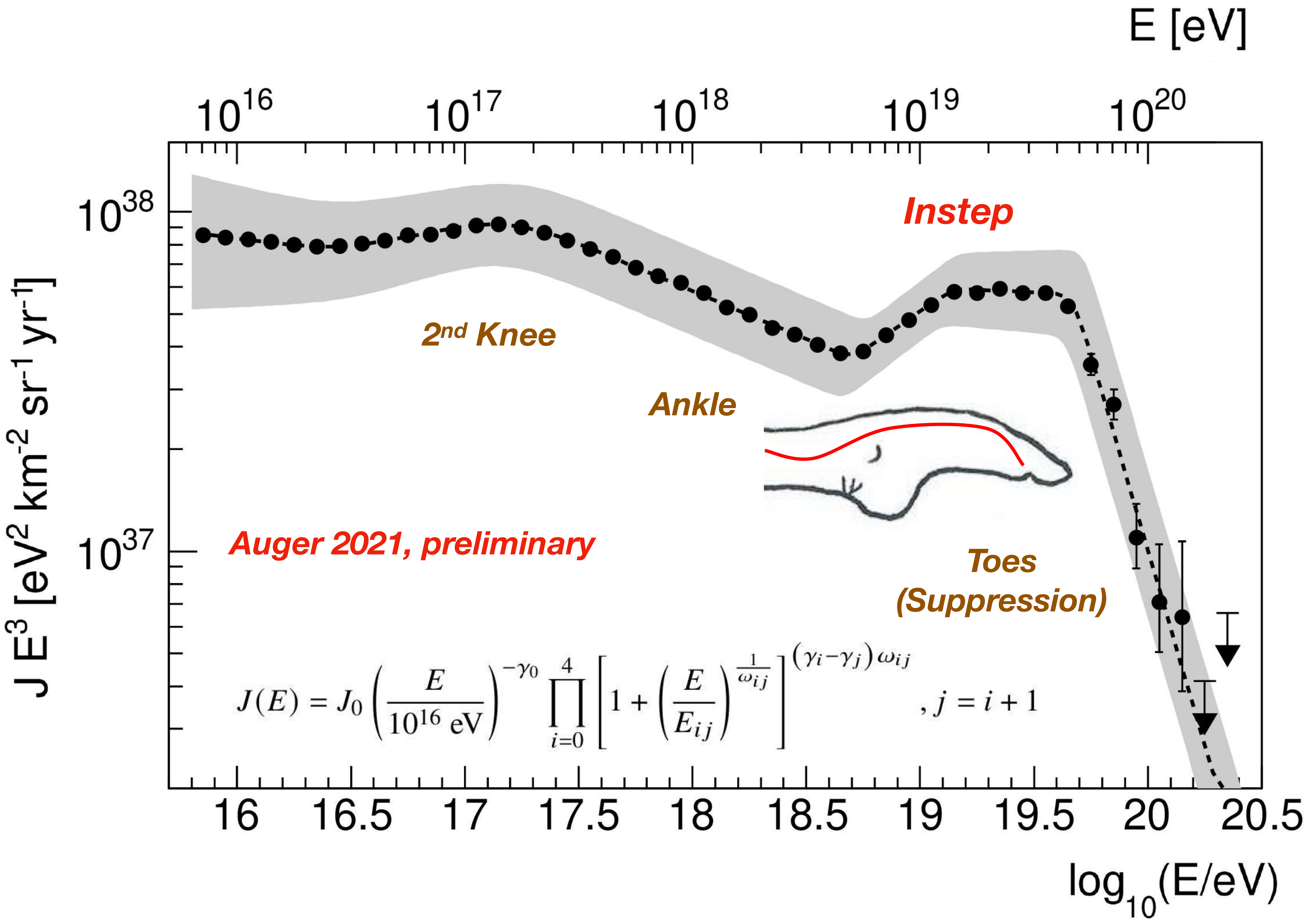


Phys. Rev. Lett. 125 121106 (2020)
Phys. Rev. D102 062005 (2020)
ICRC21 324 (2021)

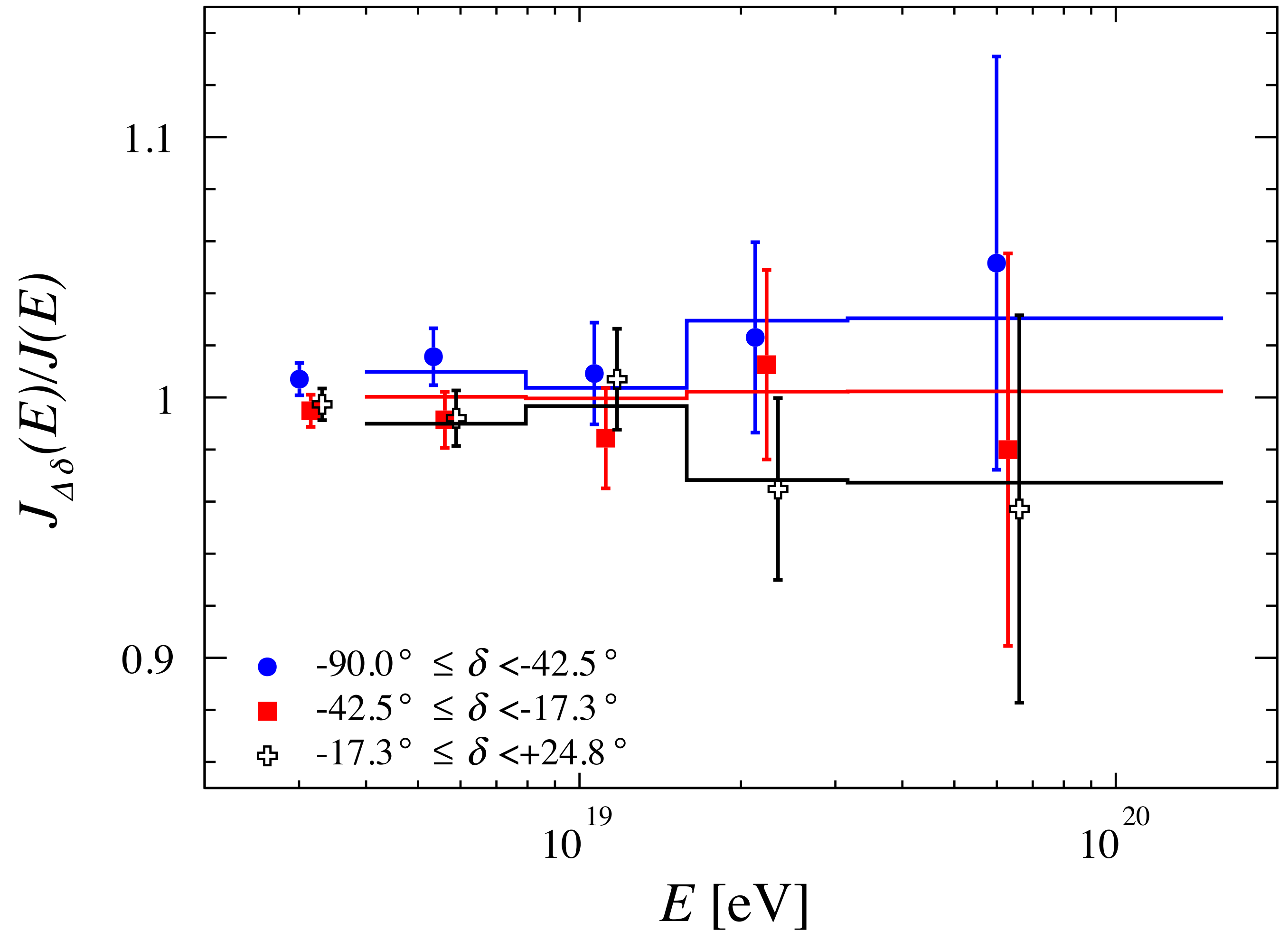
Phys. Rev. Lett. 125 121106 (2020)
Phys. Rev. D102 062005 (2020)
ICRC21 324 (2021)

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)

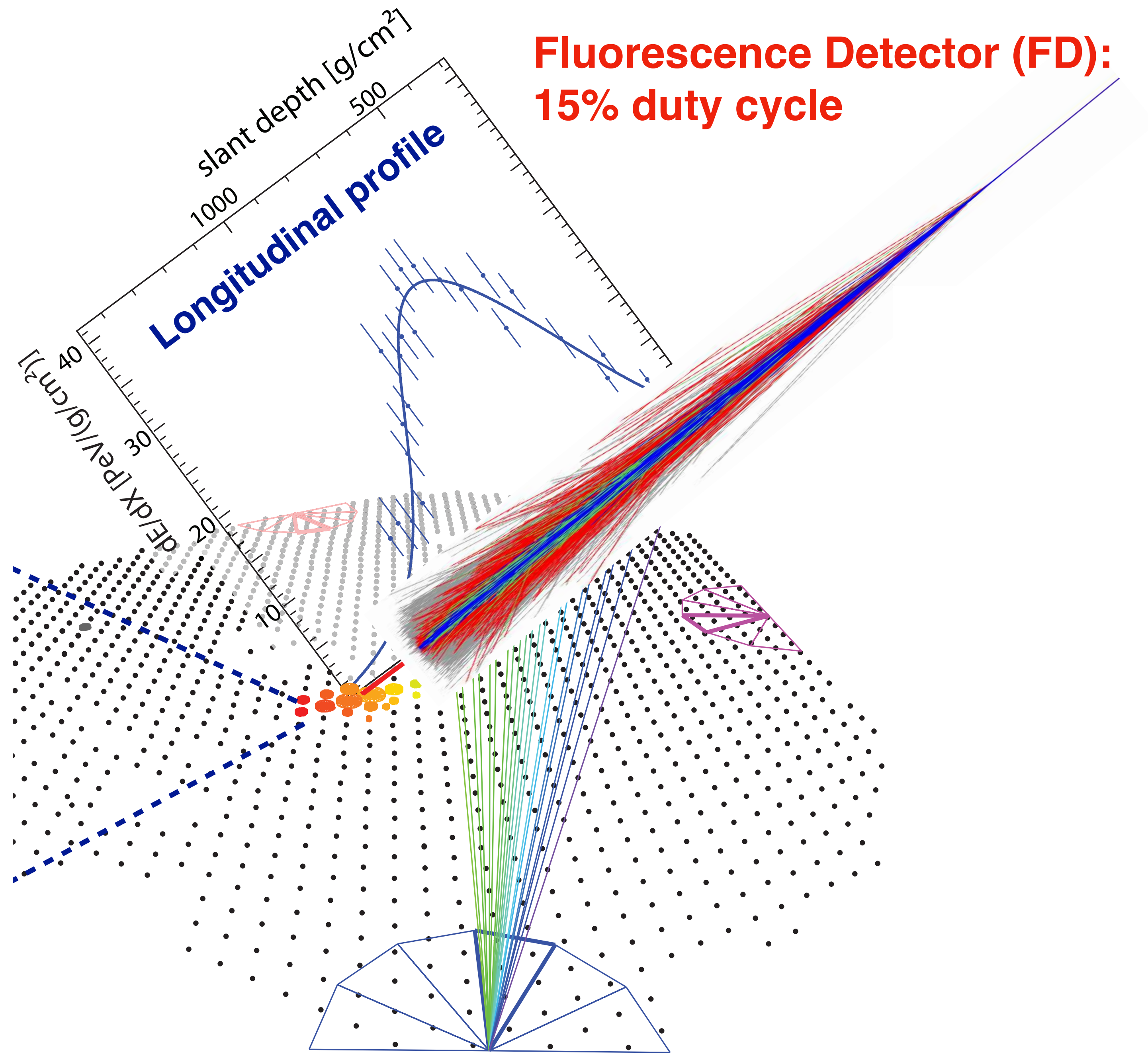


Origin of low-energy ankle and second knee likely related to mass evolution of Galactic CR.
New instep feature discovered - possible interpretation later

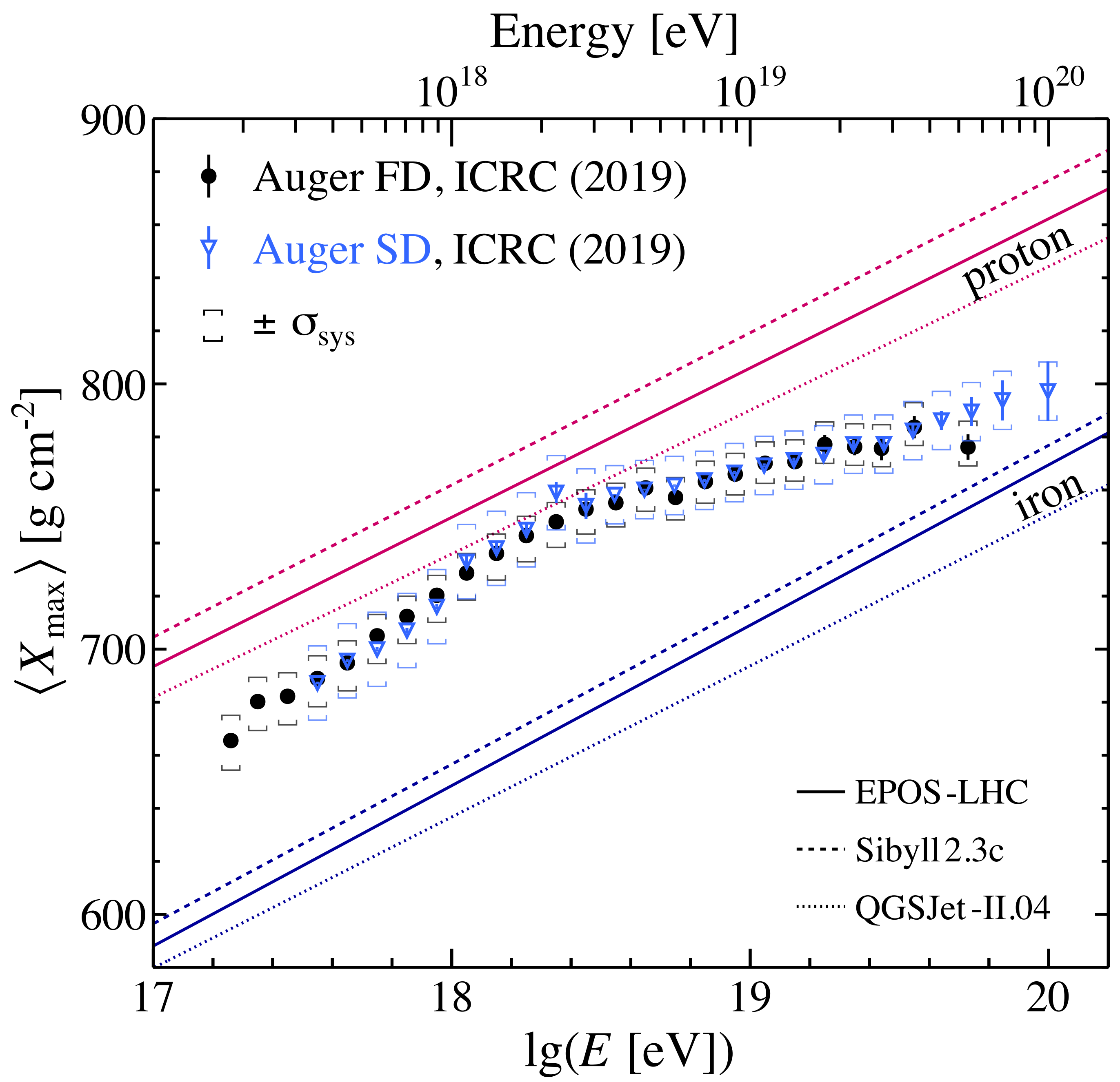
$J_0 = (8.34 \pm 0.04 \pm 3.40) \times 10^{-11}\ \mathrm{km^{-2} sr^{-1} yr^{-1} eV^{-1}}$

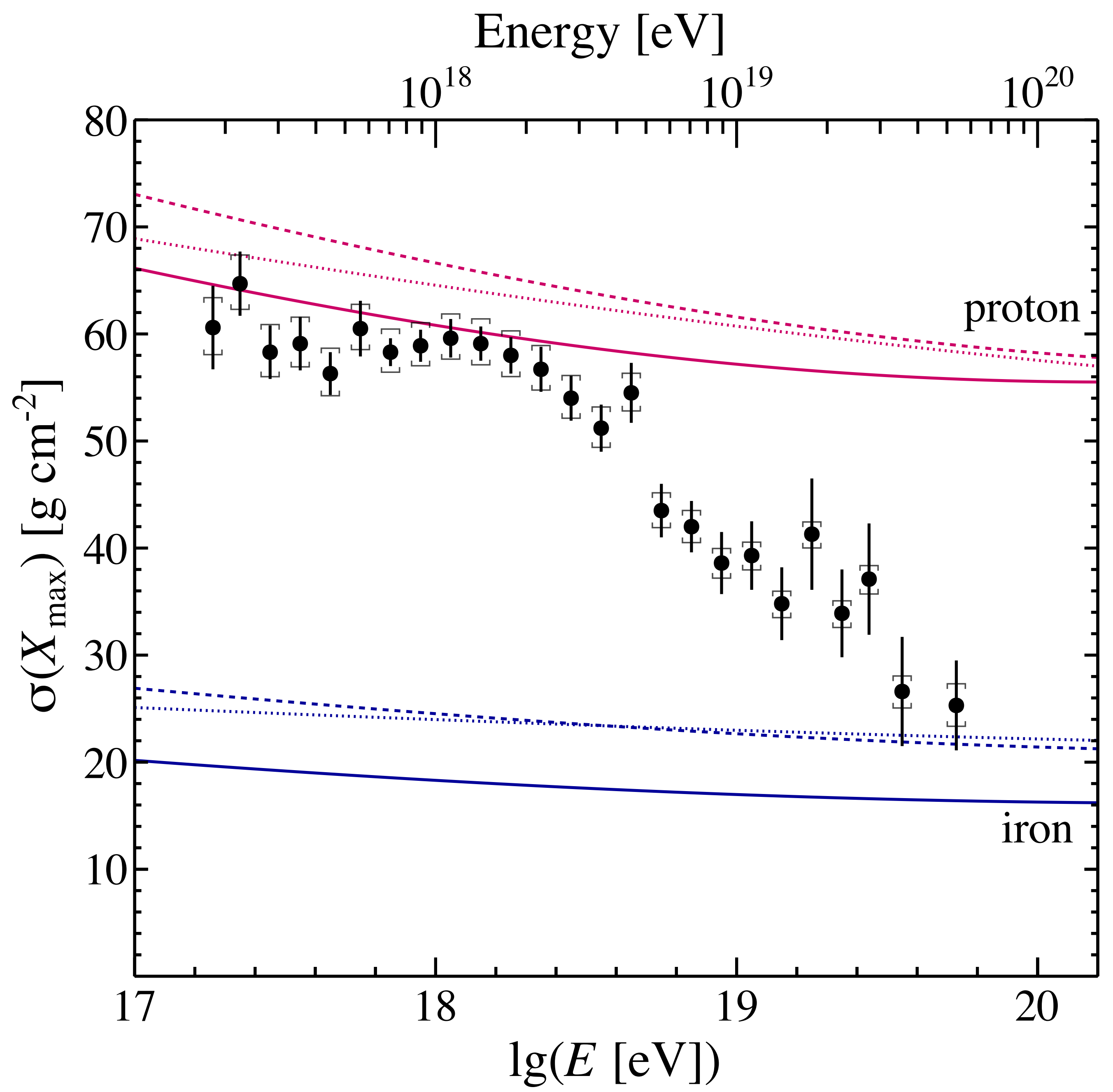
		$\gamma_0 = 3.09 \pm 0.01 \pm 0.10$
low energy ankle	$E_{01} = (2.8 \pm 0.3 \pm 0.4) \times 10^{16}$ eV	$\gamma_1 = 2.85 \pm 0.01 \pm 0.05$
2nd knee	$E_{12} = (1.58 \pm 0.05 \pm 0.2) \times 10^{17}$ eV	$\gamma_2 = 3.283 \pm 0.002 \pm 0.10$
ankle	$E_{23} = (5.0 \pm 0.1 \pm 0.8) \times 10^{18}$ eV	$\gamma_3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

Mass Composition



Depth of shower maximum, X_{max} can be viewed directly with fluorescence detectors.





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

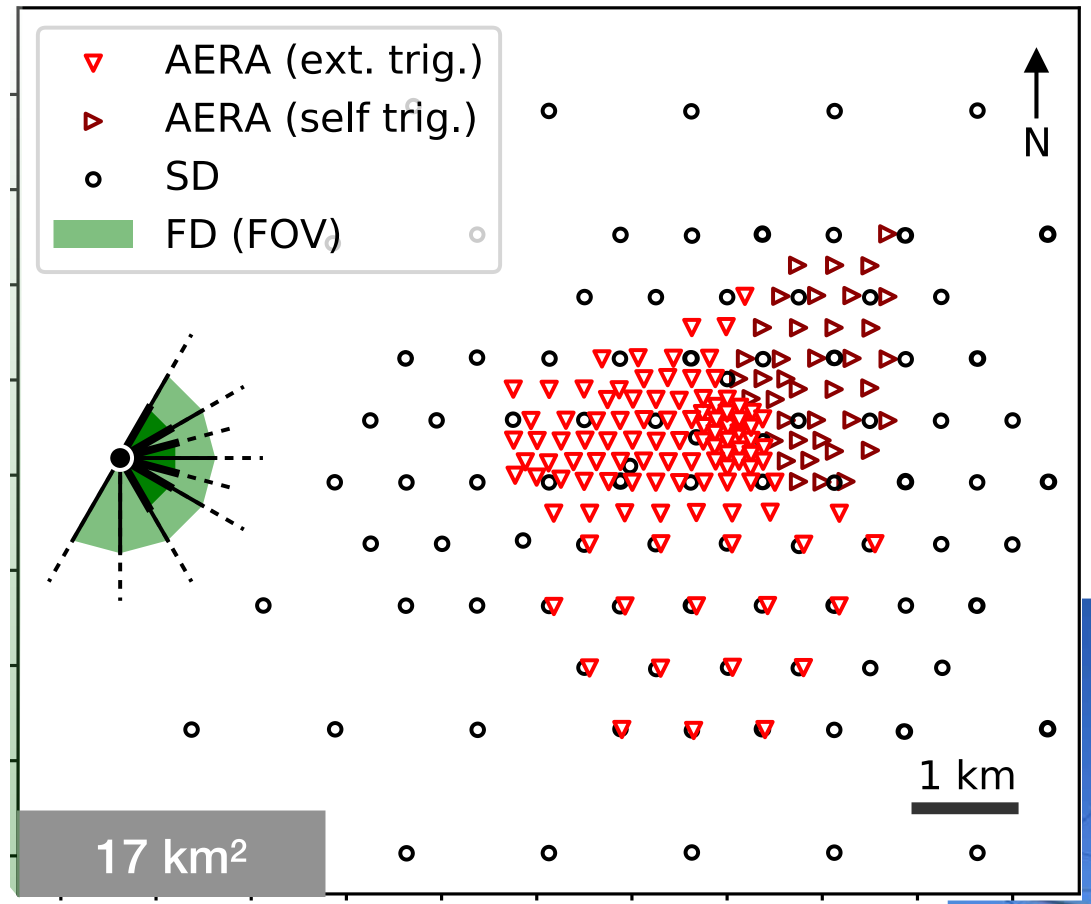
Note: use of post-LHC hadronic models for comparison with data

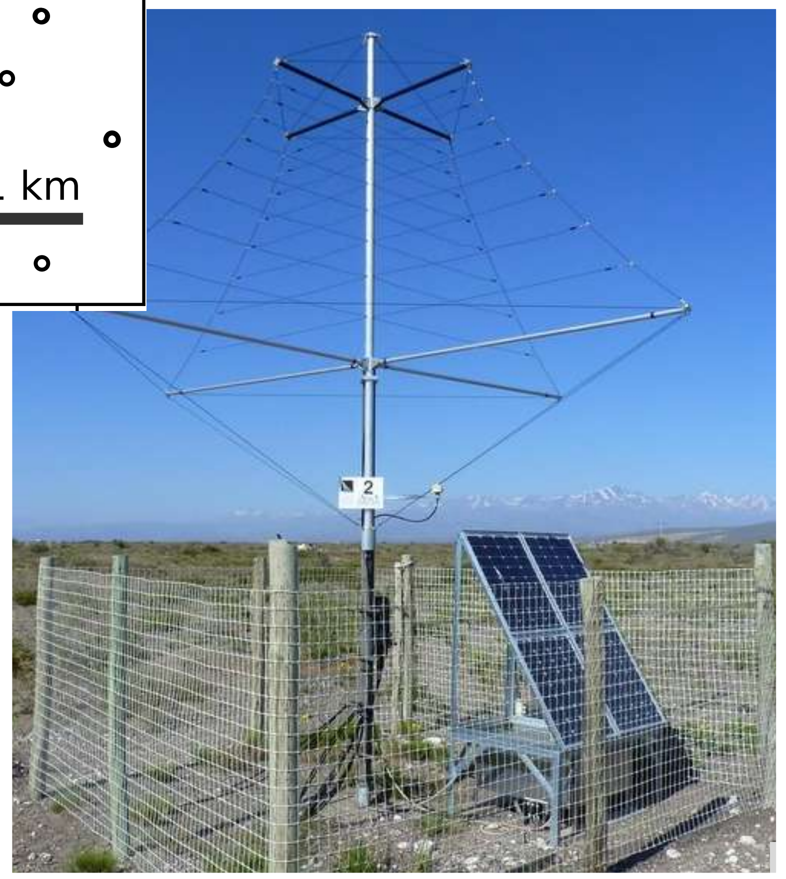
Phys. Rev. D90 122005 and 122006 (2014) + updates ICRC 2019

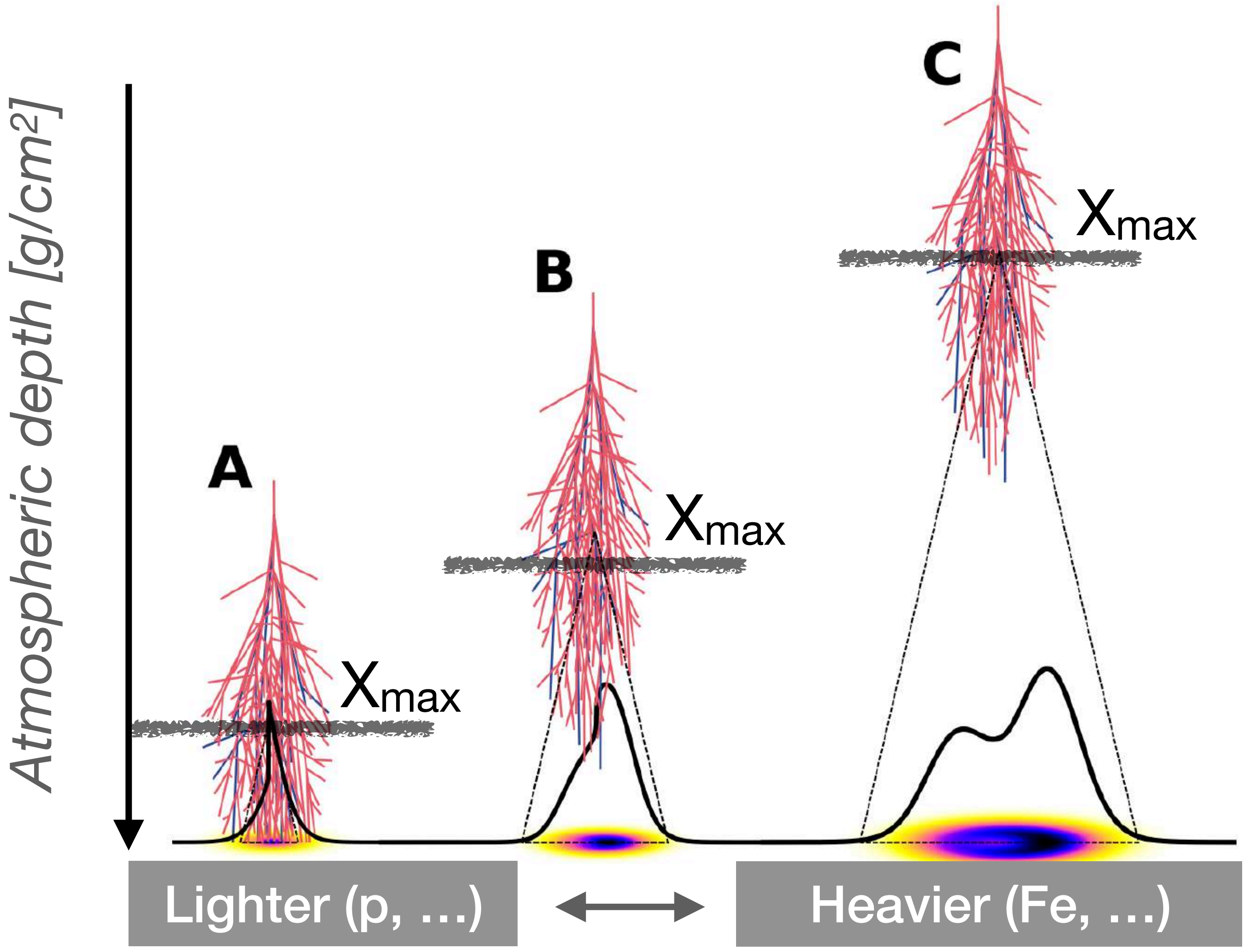
Mass Composition

The maturing radio technique.

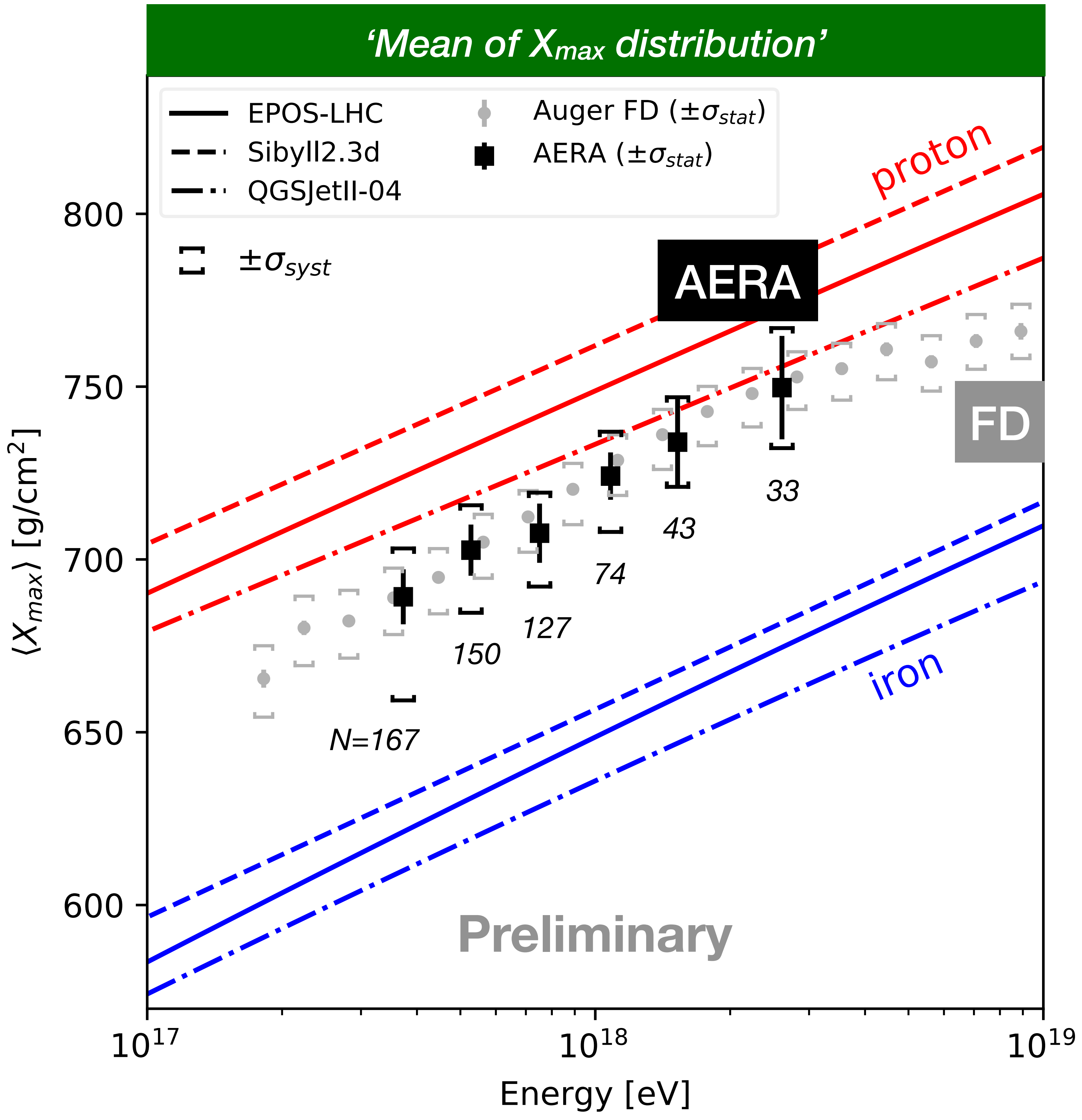
AERA: Auger Engineering Radio Array

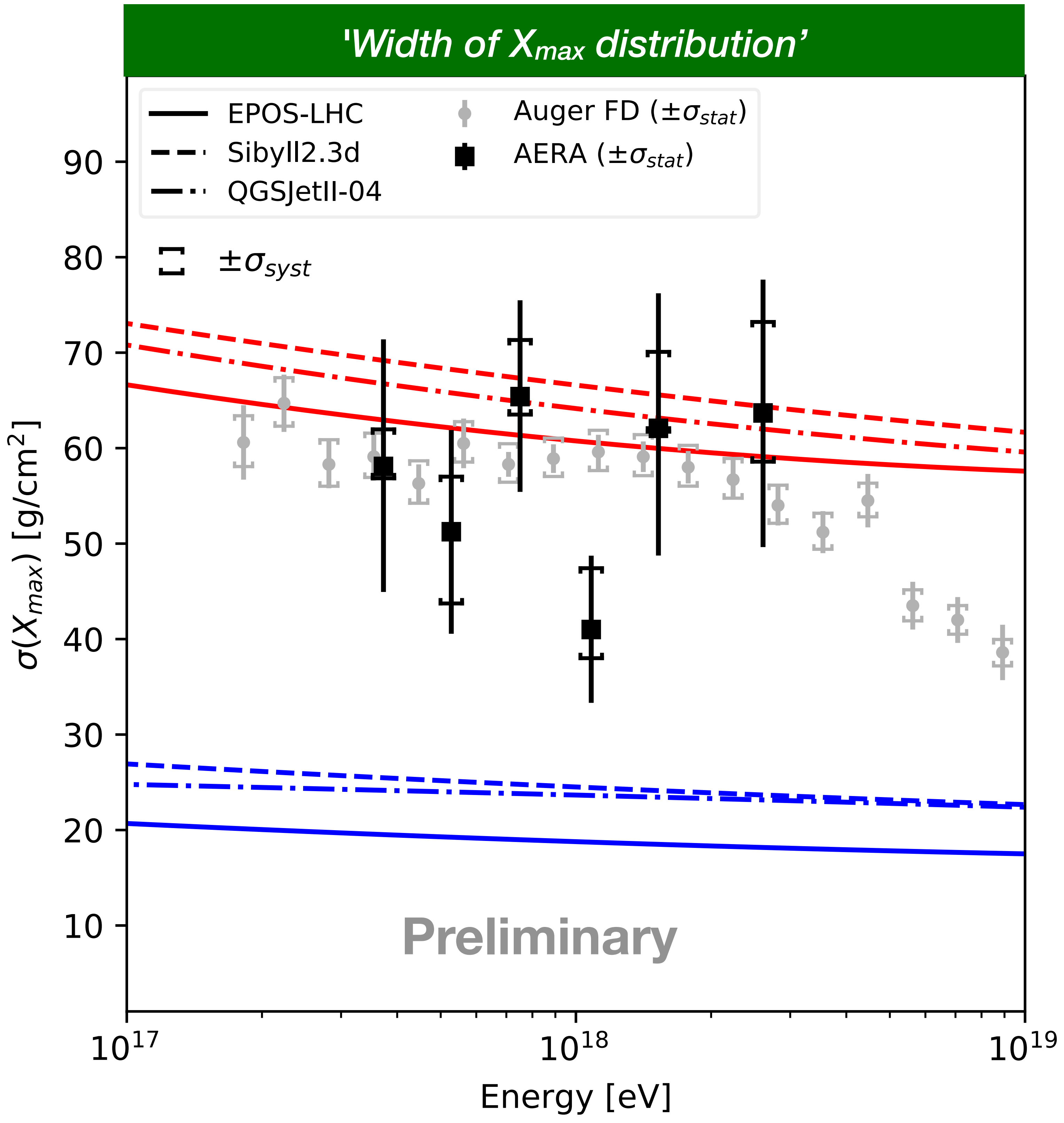






Independent confirmation of Auger FD results (no cross-calibration involved)





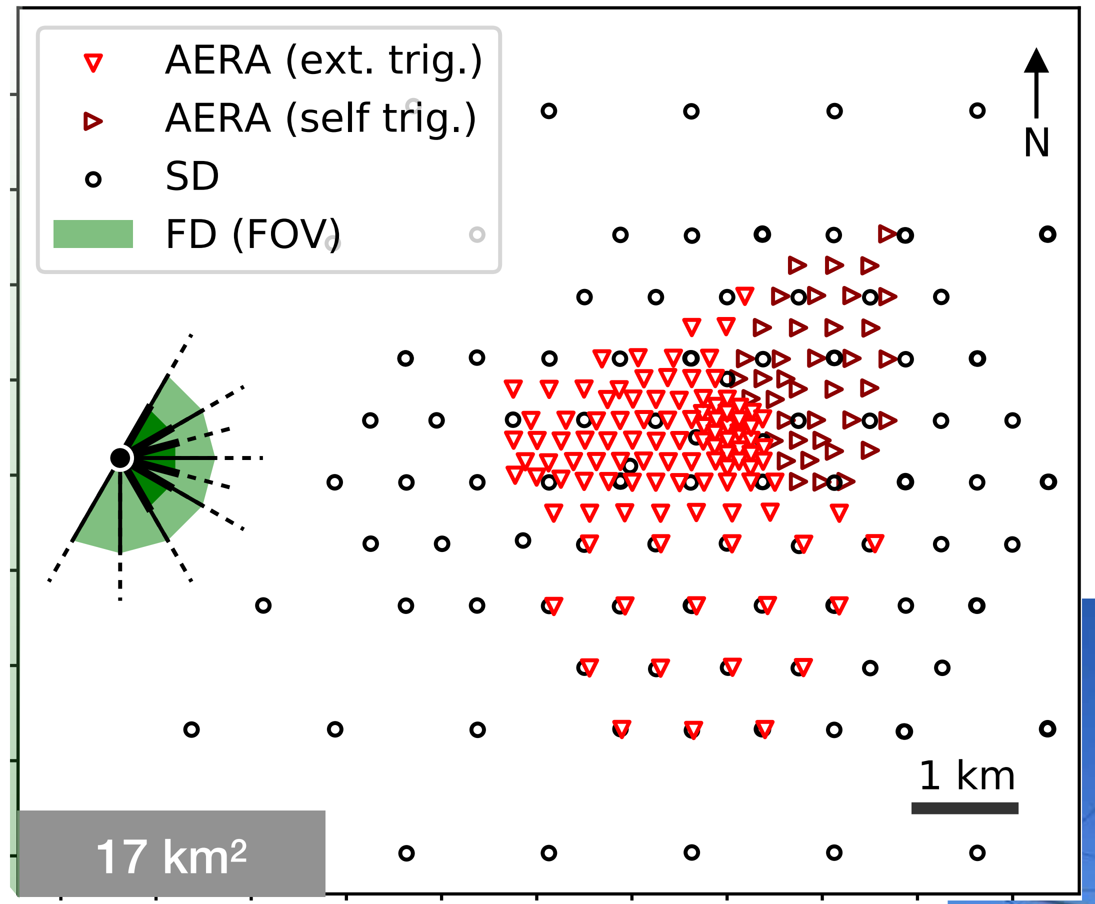
Phase II
- radio will be key for studying mass composition in inclined showers, with 100% duty cycle

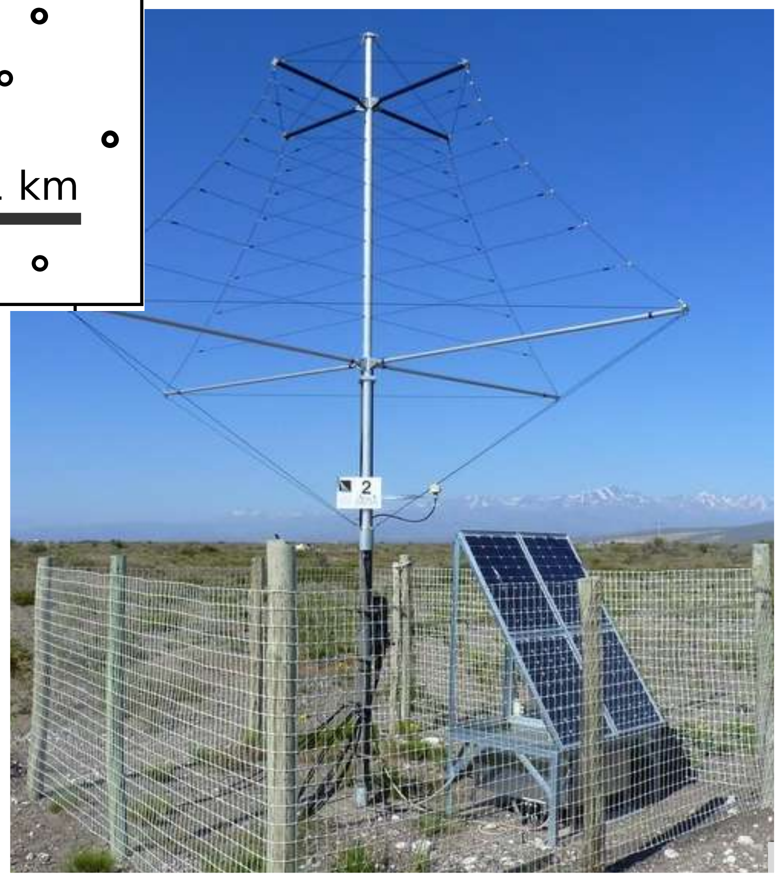
ICRC21 387 (2021), PRD (in preparation)

Mass Composition

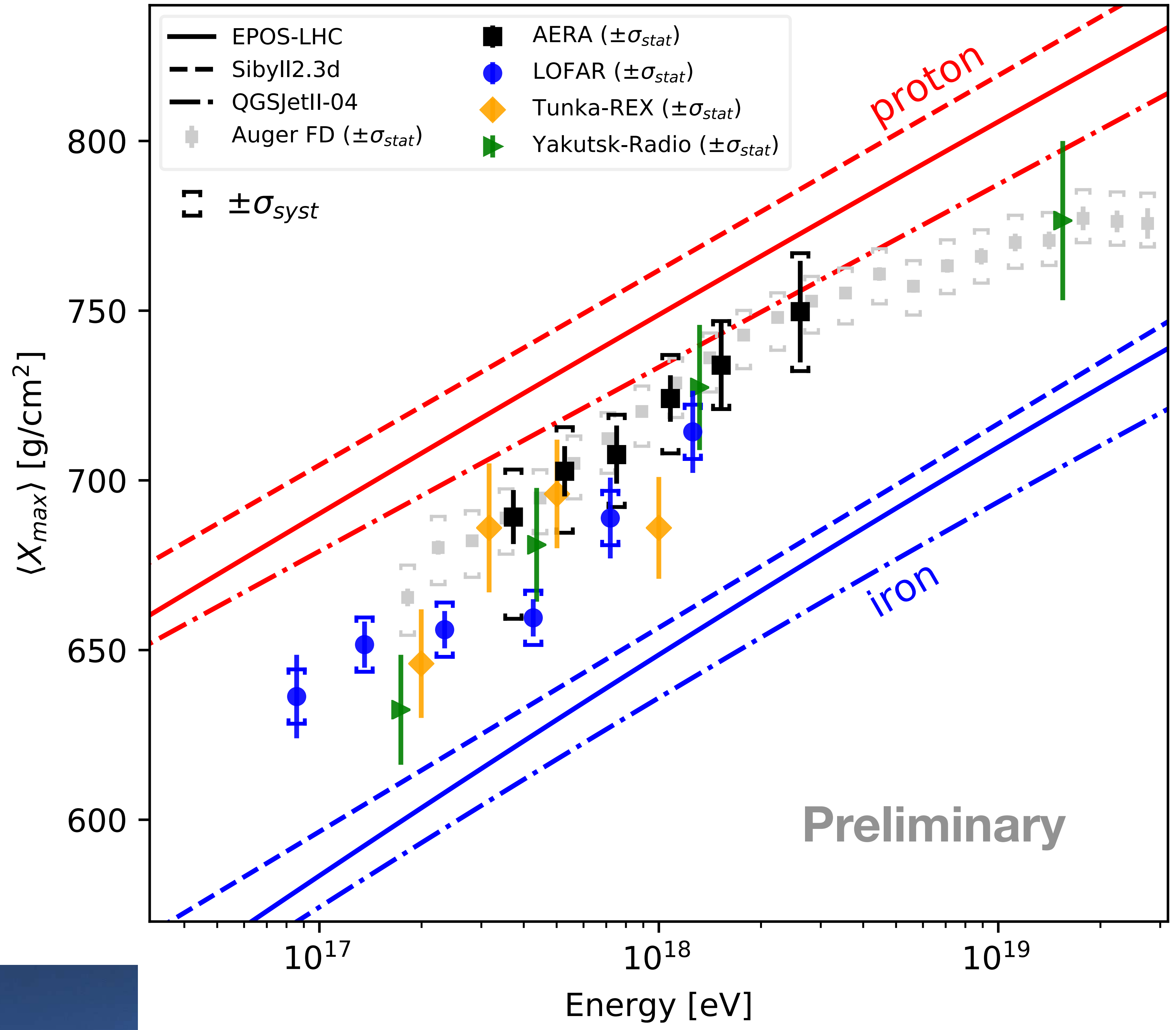
The maturing radio technique.

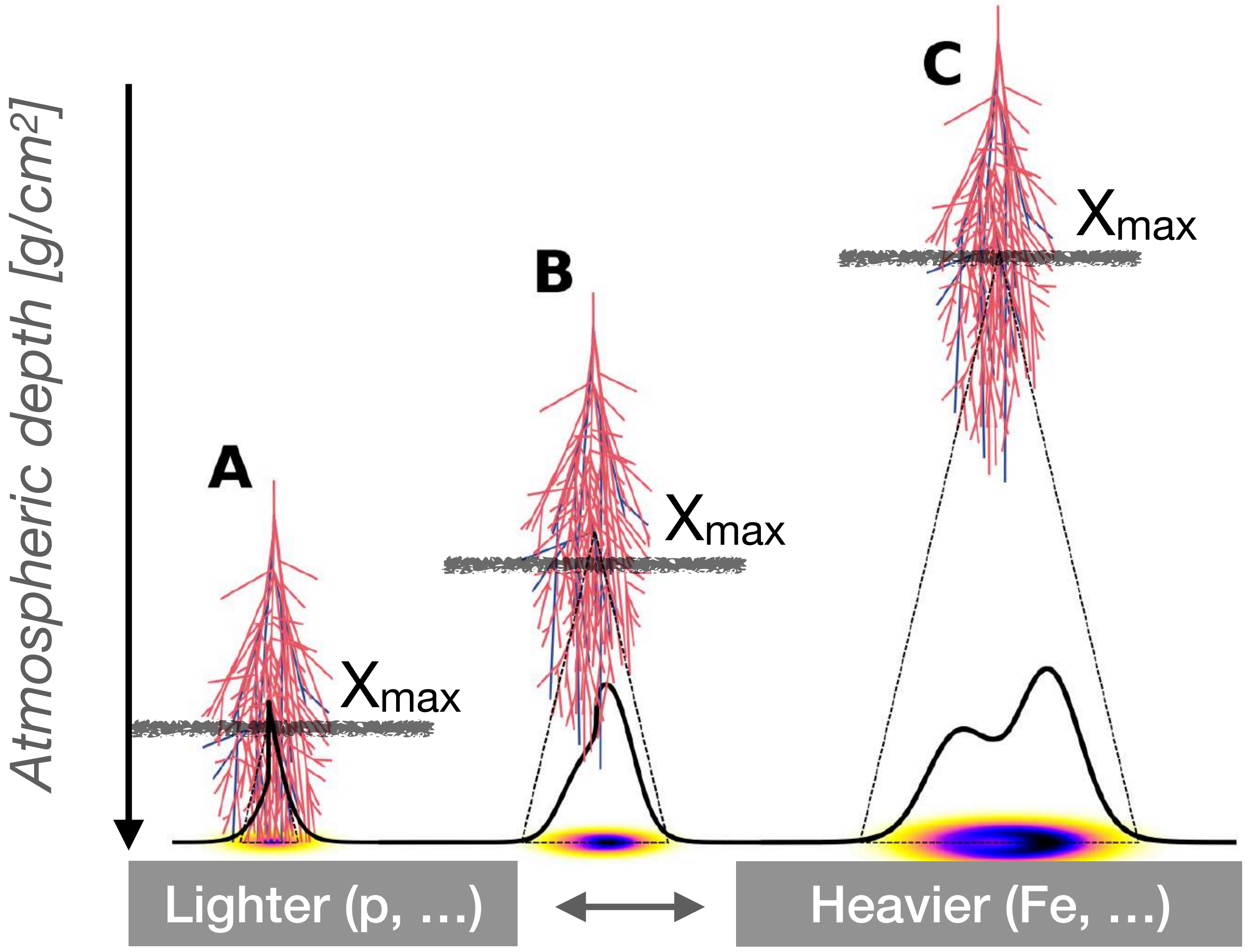
AERA: Auger Engineering Radio Array





Agreement within systematics with LOFAR, but some systematics are common.
Under investigation in a joint working group.



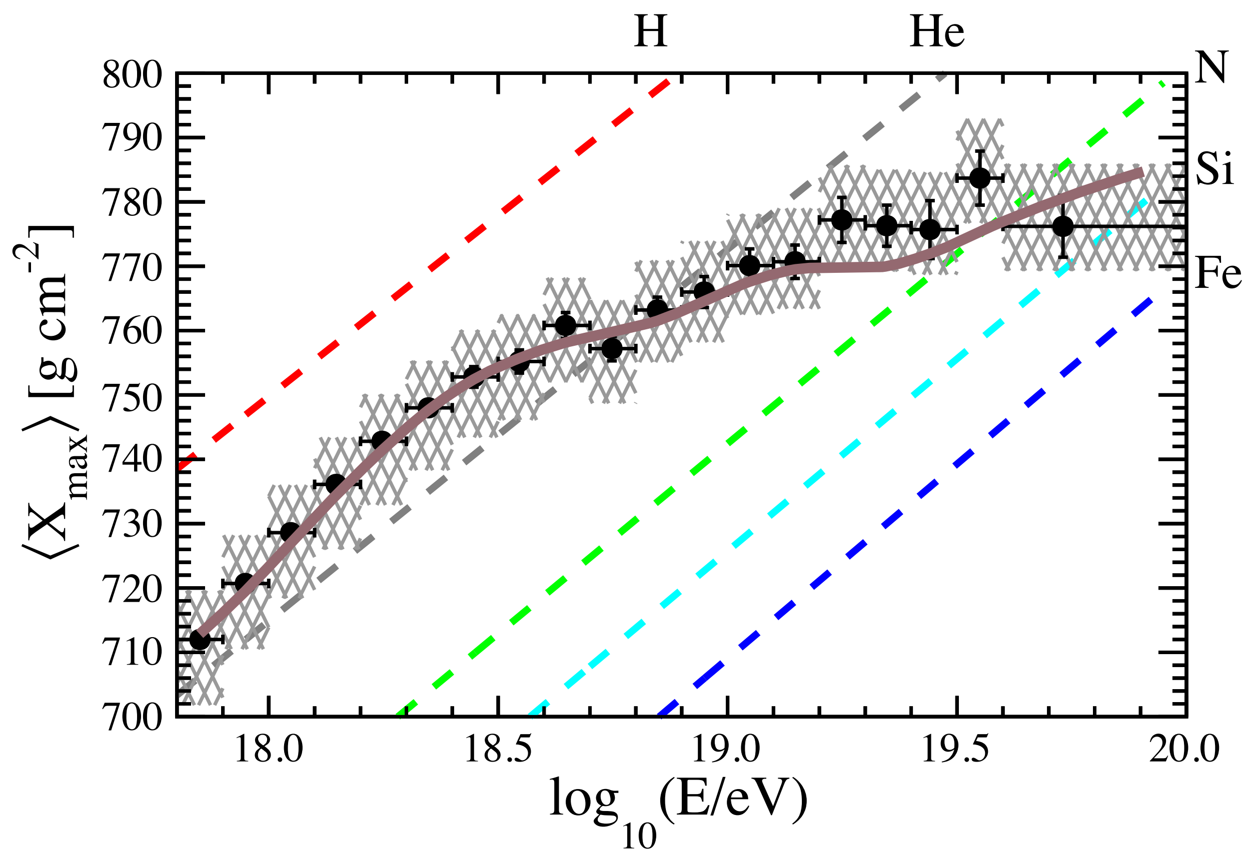


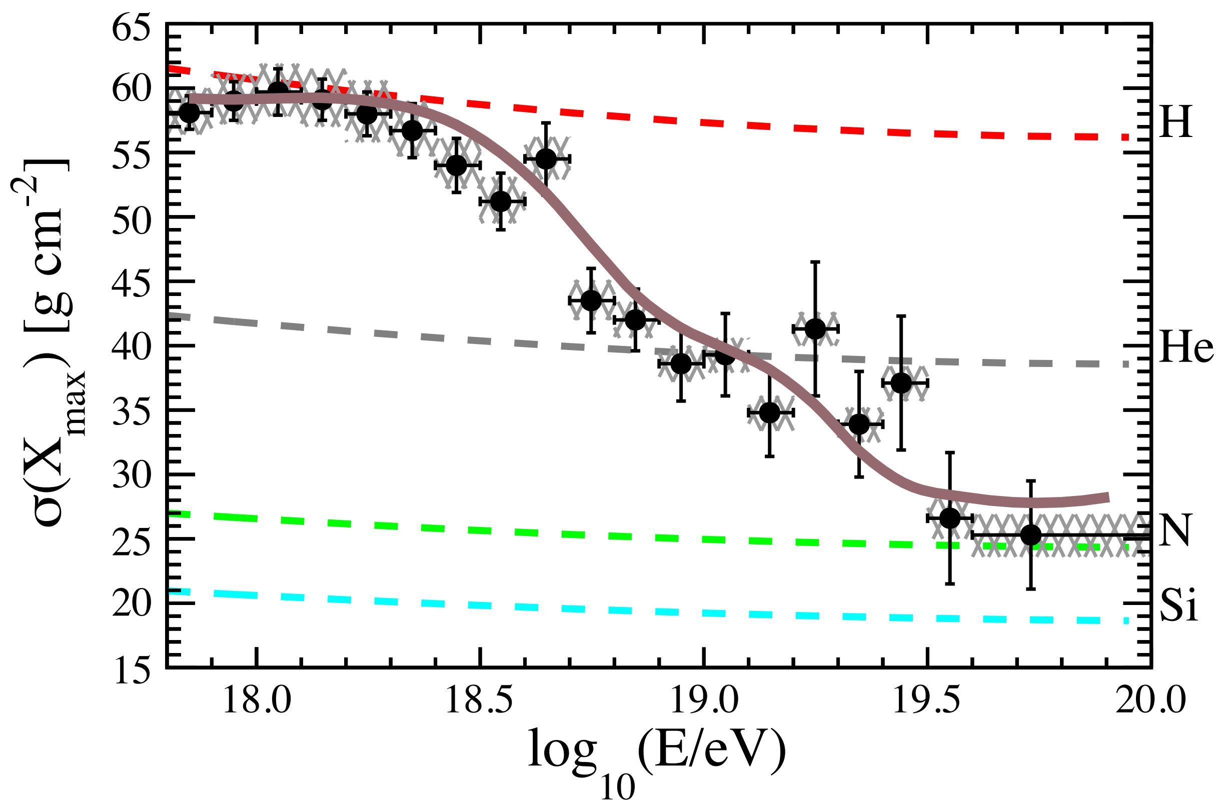
Phase II
- radio will be key for studying mass composition in inclined showers, with 100% duty cycle

ICRC21 387 (2021), Phys. Rev. D (in preparation)

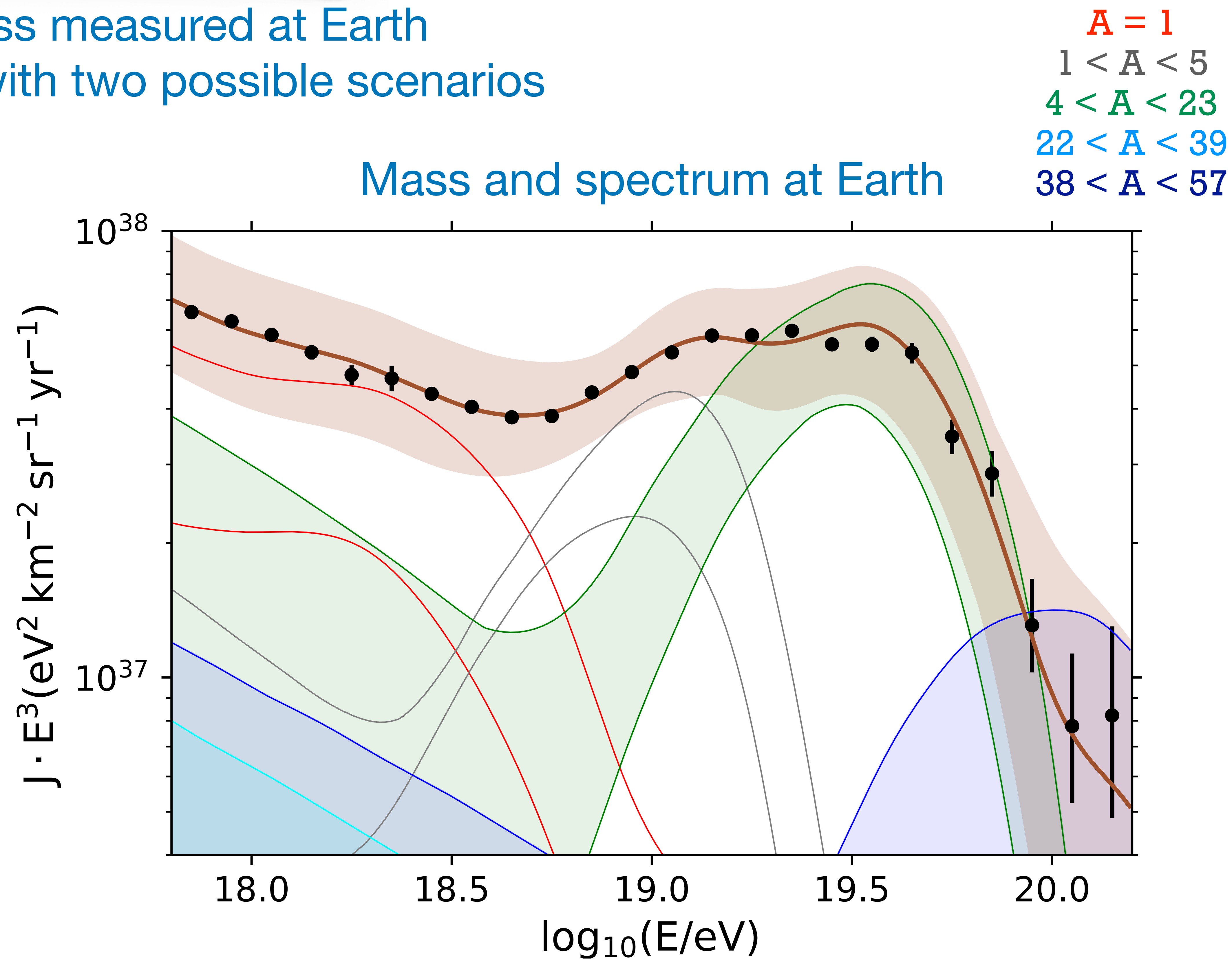
An astrophysical interpretation

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





Mass and spectrum at Earth



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

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}

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

Below the ankle

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

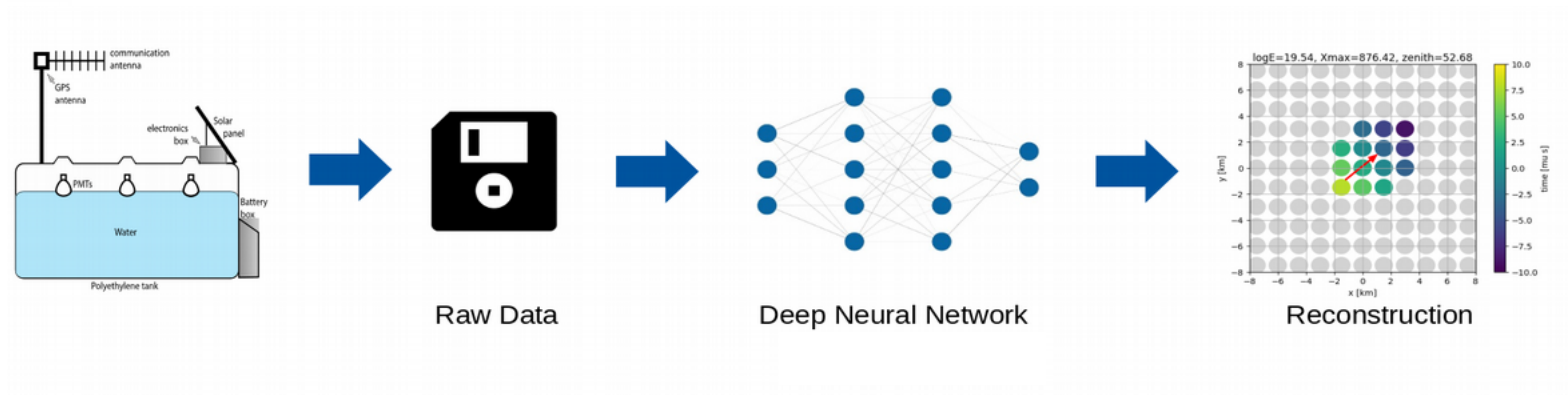
Result: $R_{cut} \sim 1.5 \times 10^{18}$ V, with very hard source spectral index, $\gamma < 1$, not well constrained in the model. No strong dependence on source evolution m.

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.

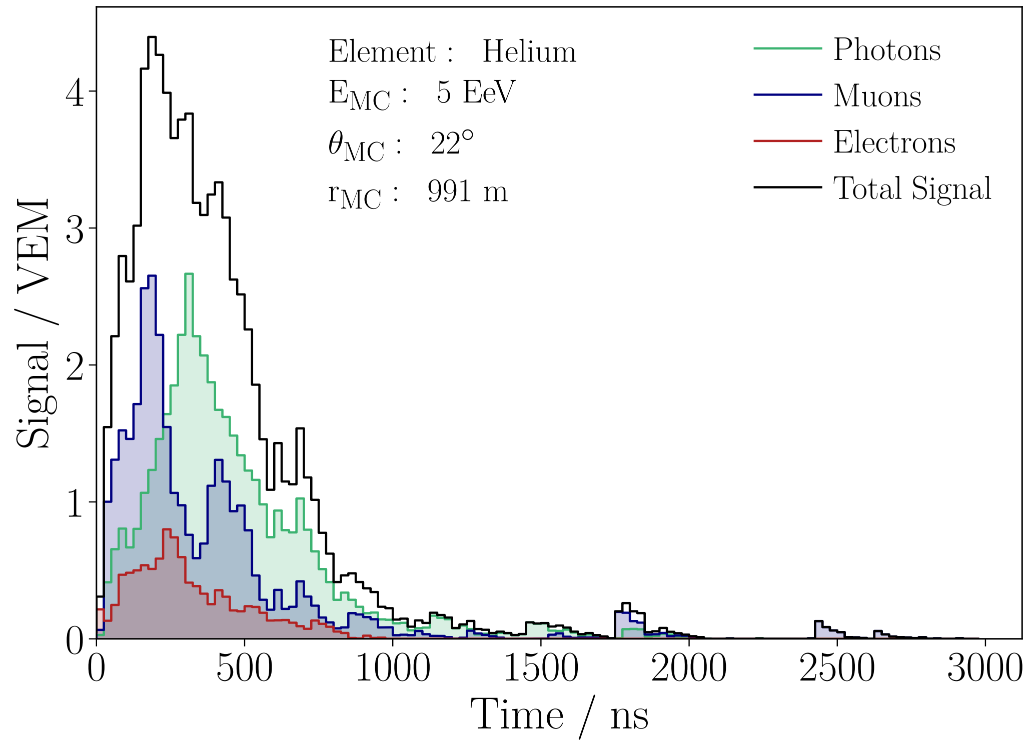
ICRC21 311 (2021), JCAP (submitted 2022)

A future direction - machine learning

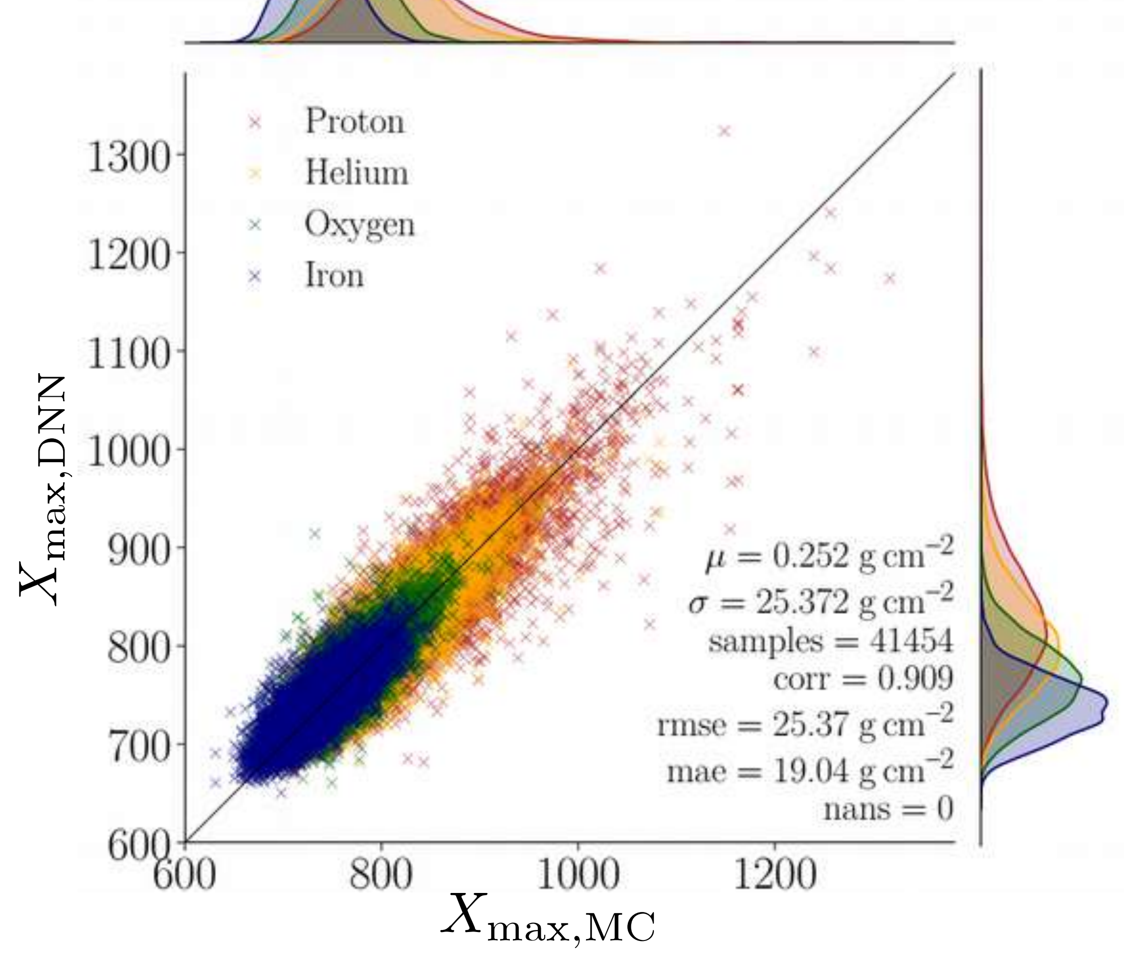
SD determination of X_{max} (MC studies, cross-check against FD data)



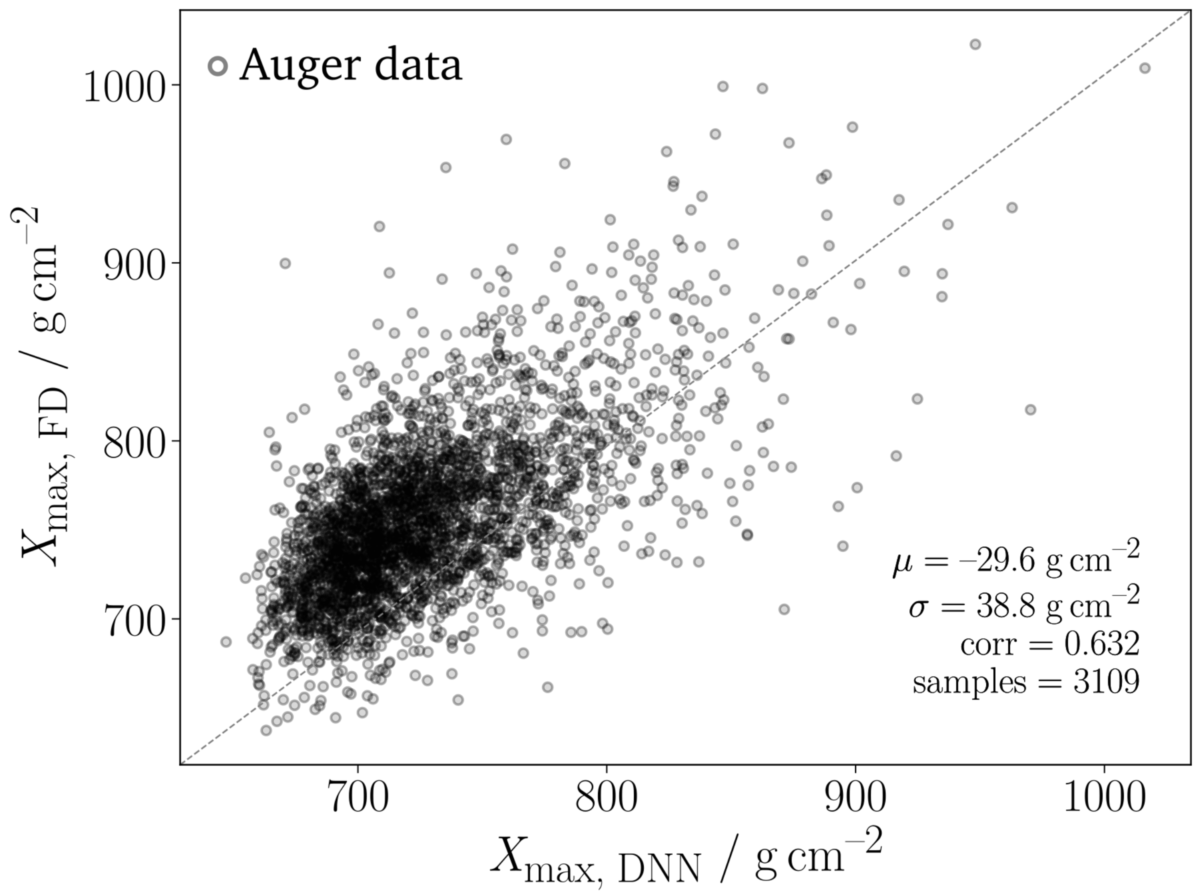
A simulated SD station trace

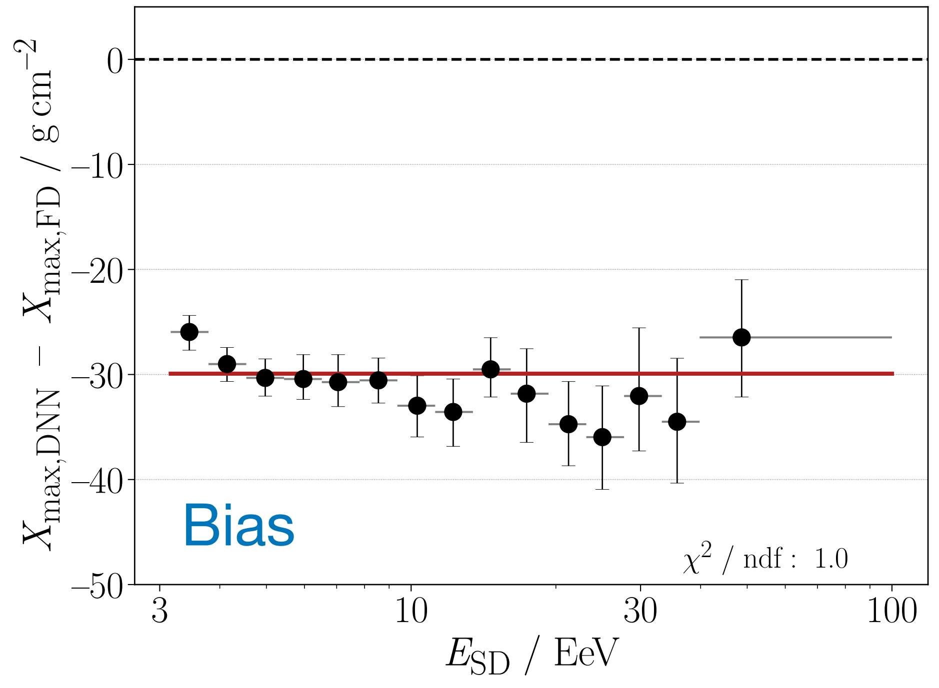


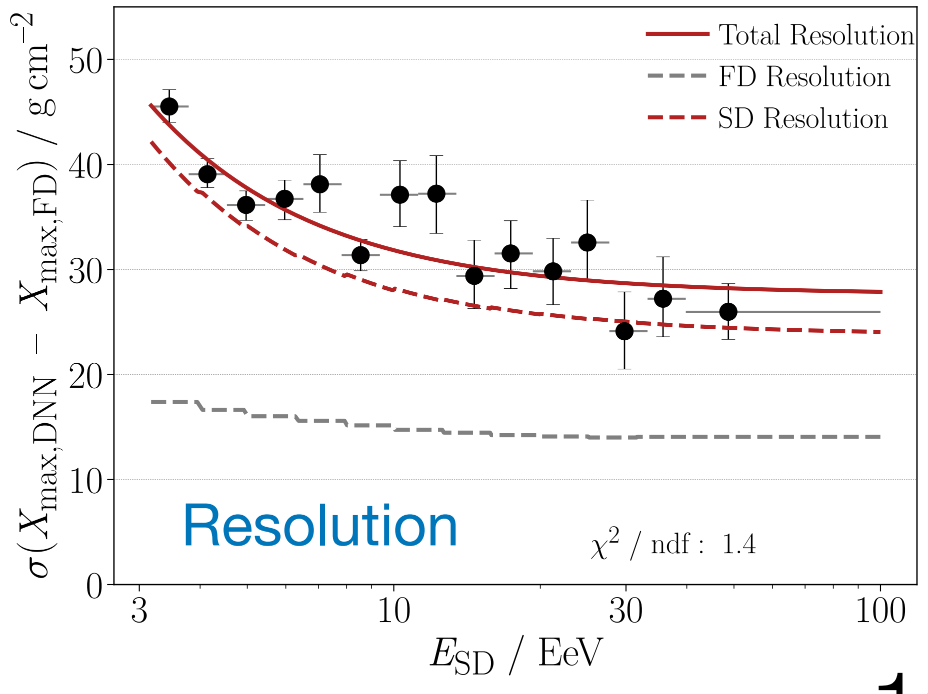
MC performance



Cross-check with real FD data







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

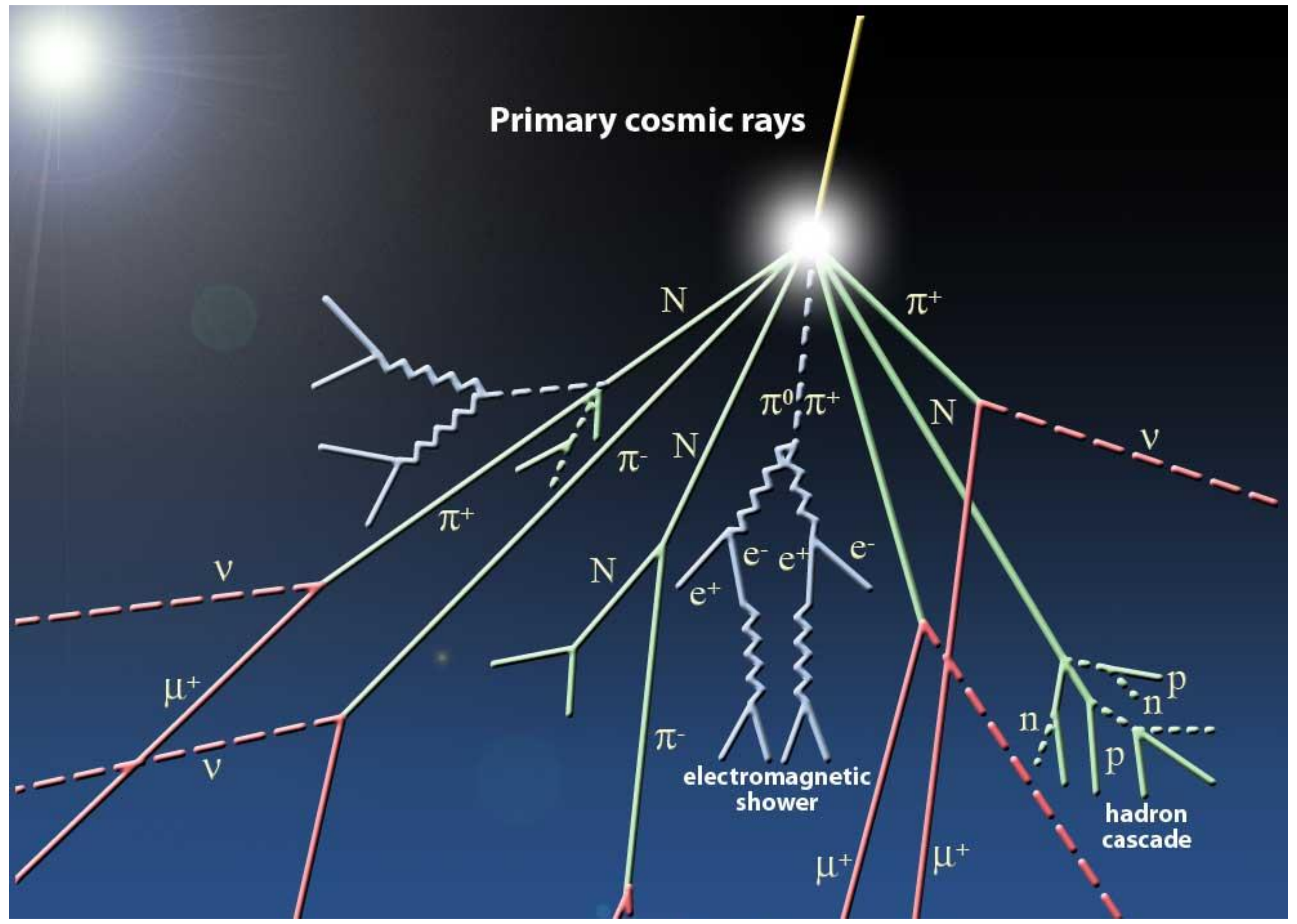
However, a bias of -30 g/cm^2 suggests problems with simulations.

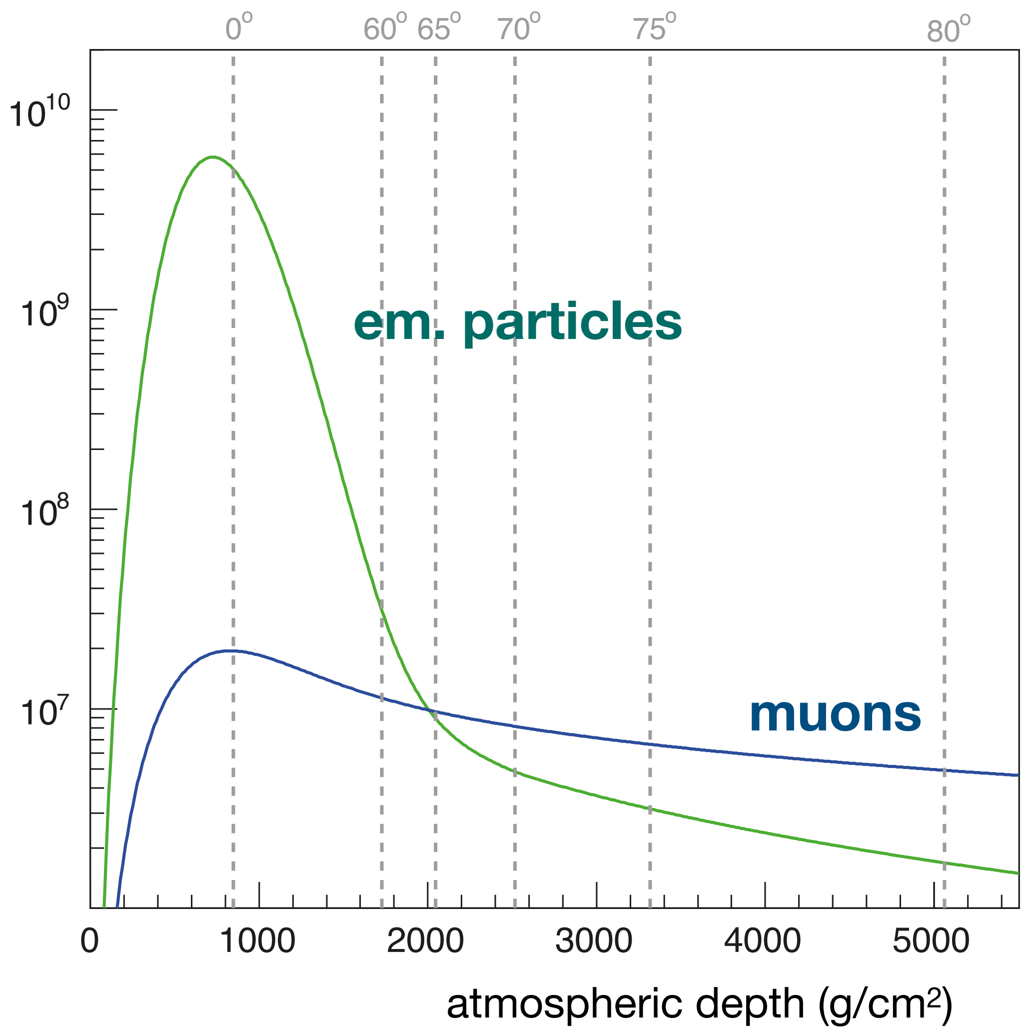
JINST 16 (2021) P07019

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

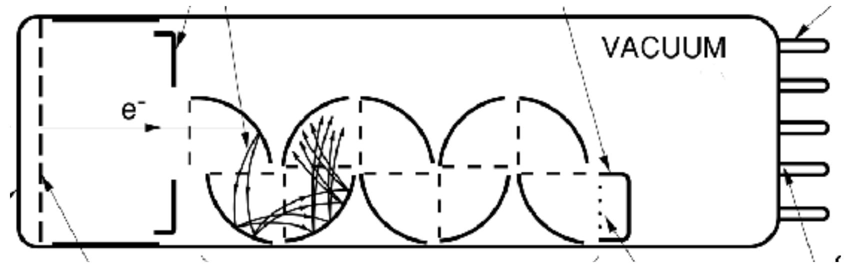
Hadronic interactions

Collisions well beyond LHC energy



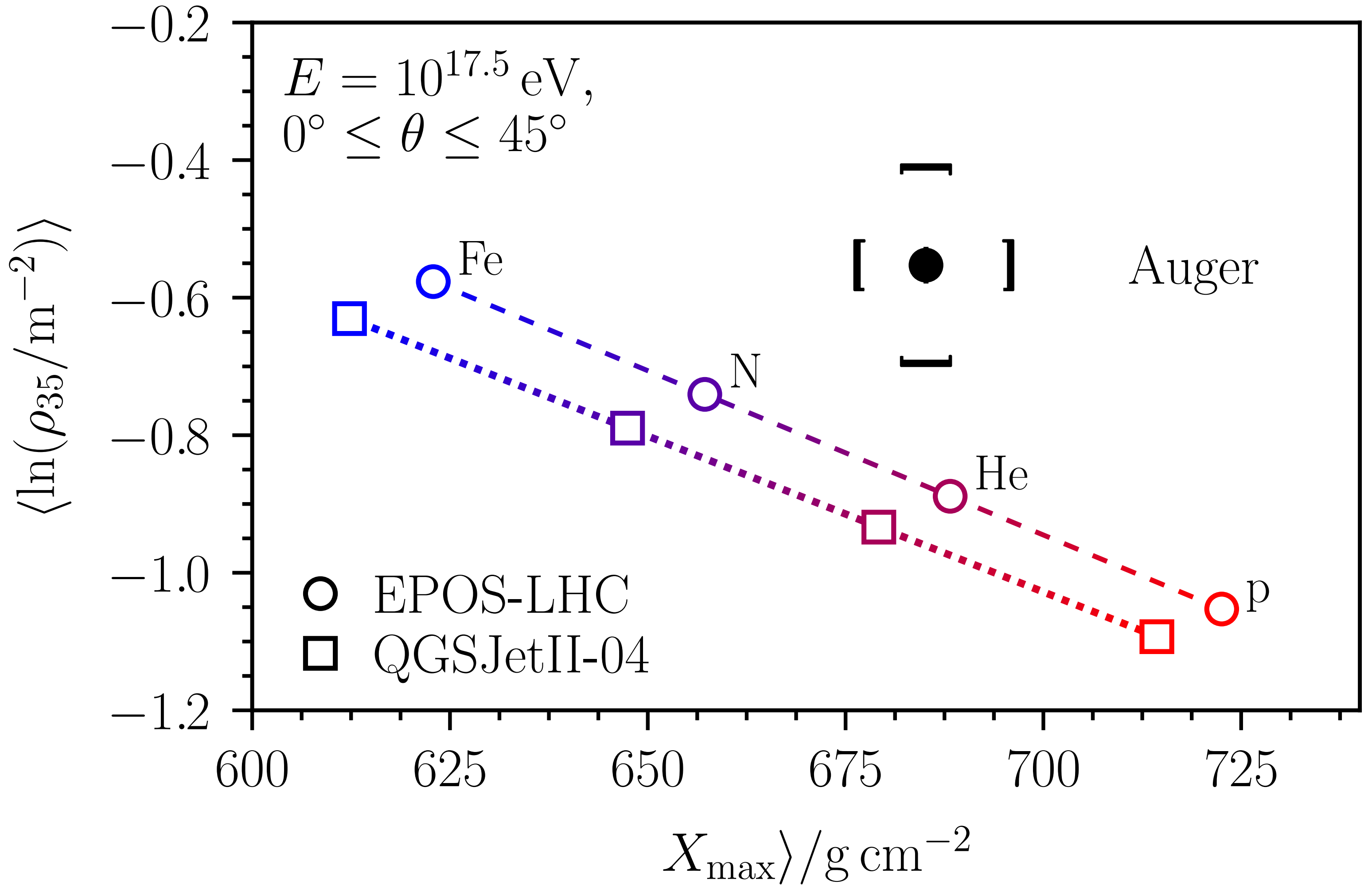


However, relative fluctuations in the muon number are consistent with data.
(Fluctuations are driven by first interactions, PMT analogy)



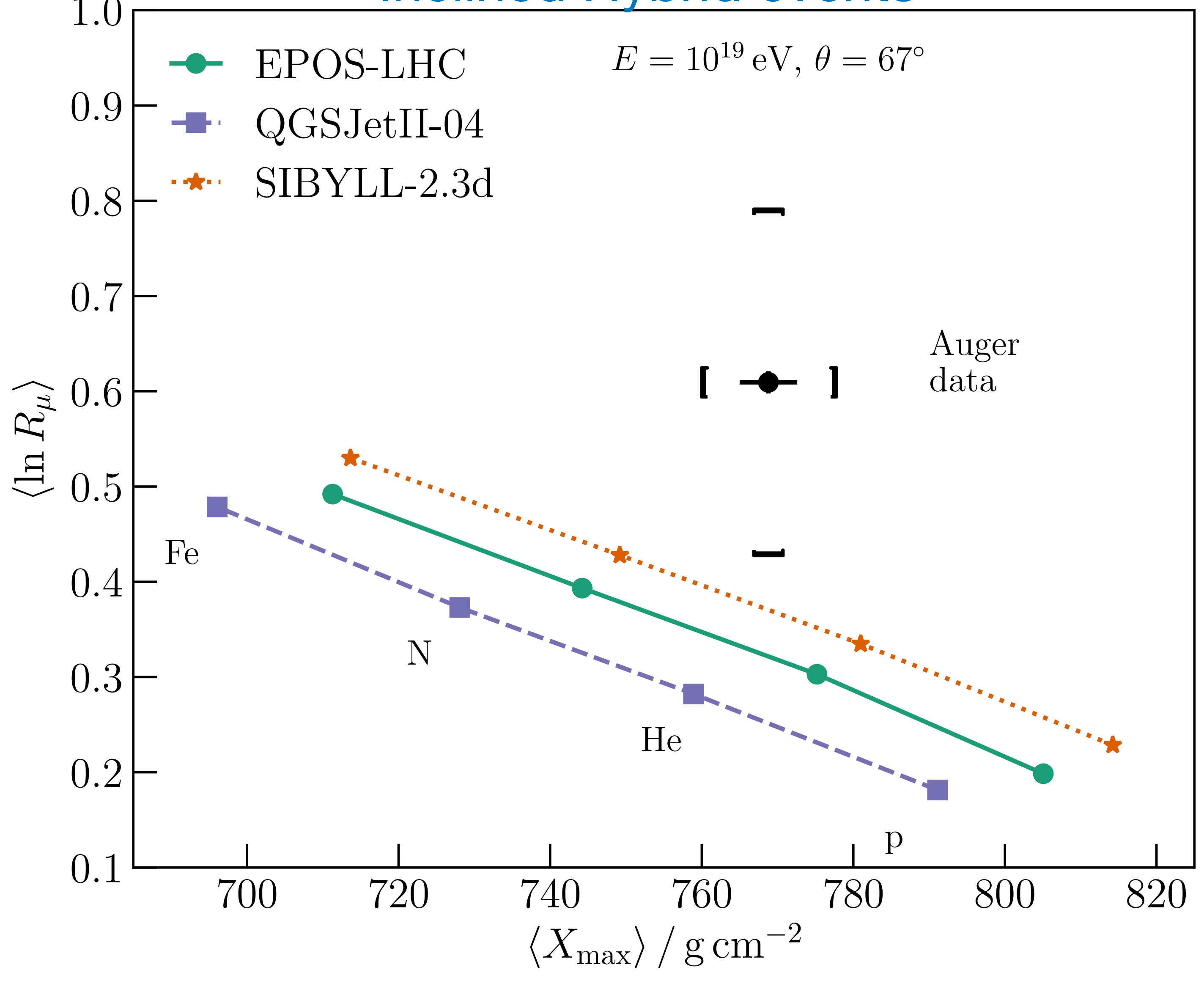
Evidence of a deficit of muons in simulated air-showers.

Auger muon detectors and “vertical” hybrid events



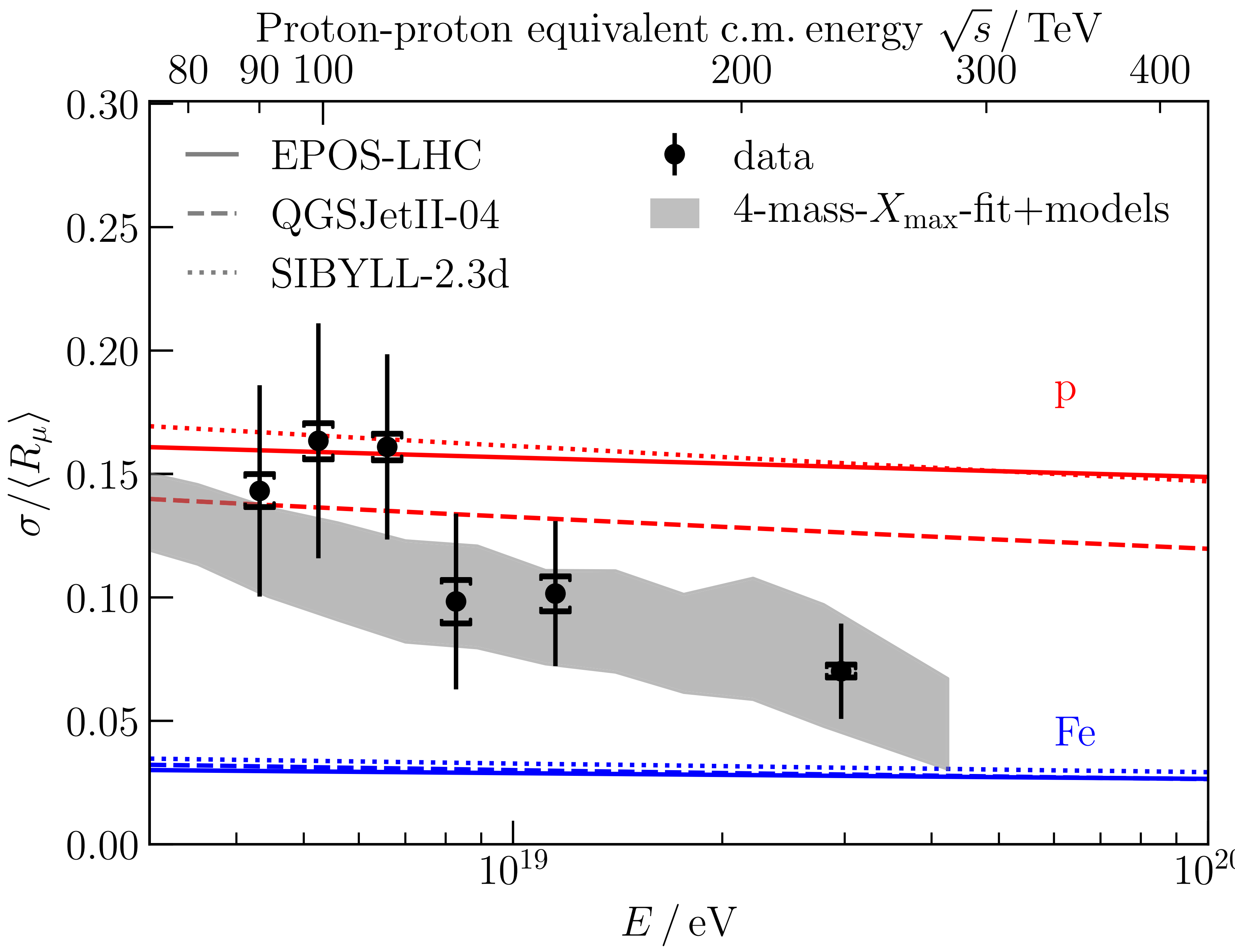
Eur. Phys. J. C80 751 (2020)

Inclined Hybrid events



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

Inclined Hybrid events

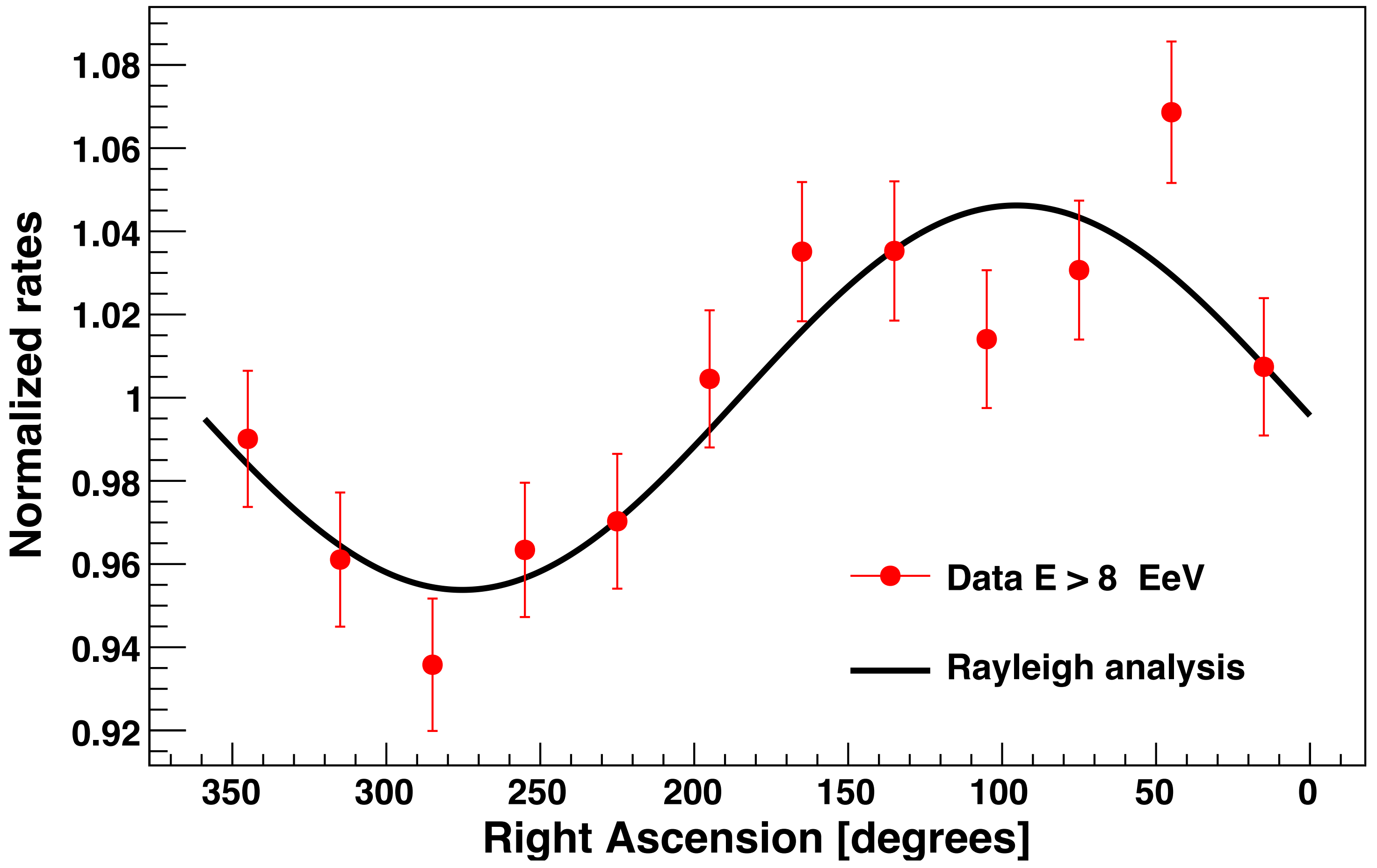


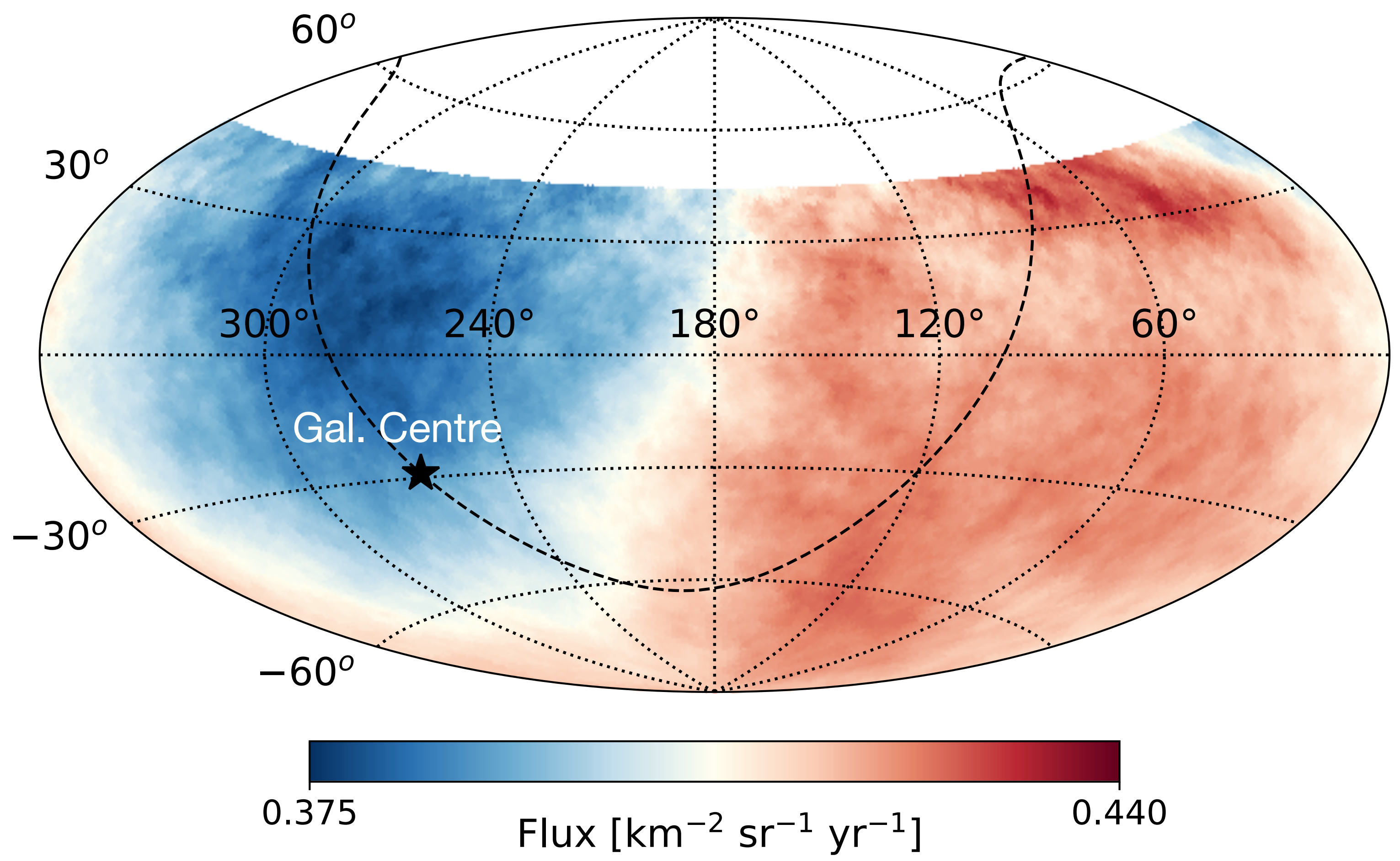
Phys. Rev. Lett. 126 152002 (2021)

Anisotropy - large scale

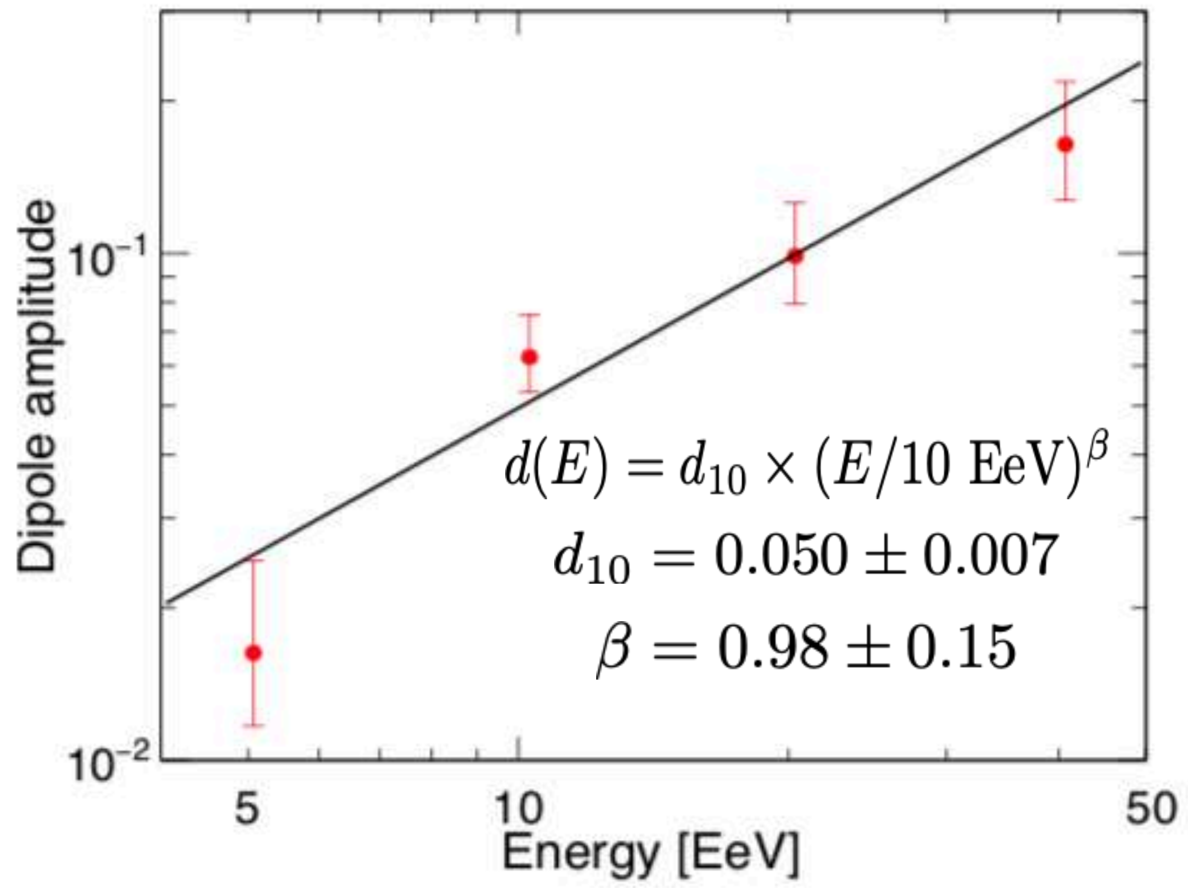
Above ~ 4×10^{18}eV

Exposure 110,000 km² sr yr
(Up to end of 2020, $\theta < 80^\circ$)





Differential bins



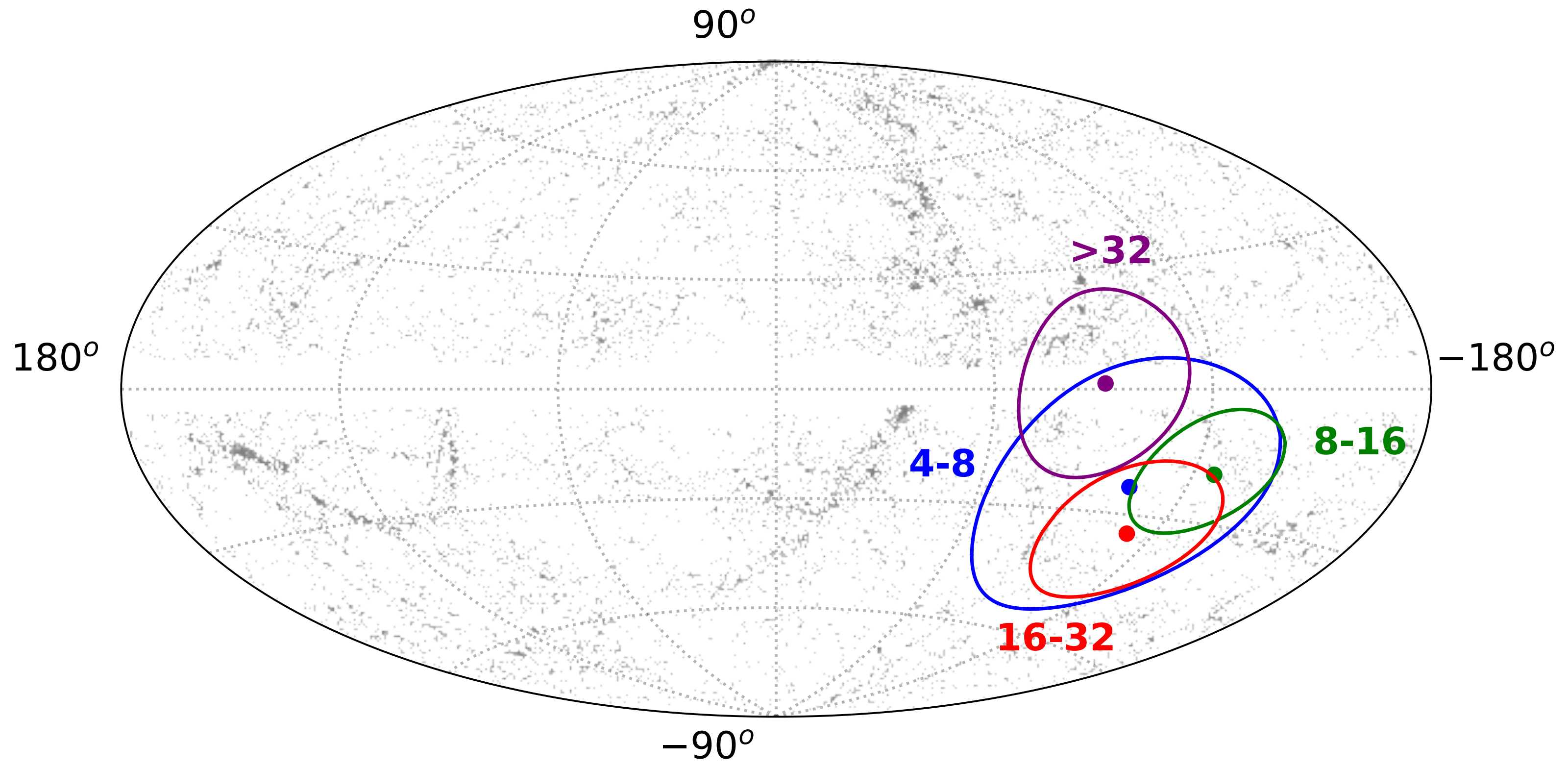
Mass scenario similar to Auger measurements:
(average rigidity still grows with energy, despite Z increasing)

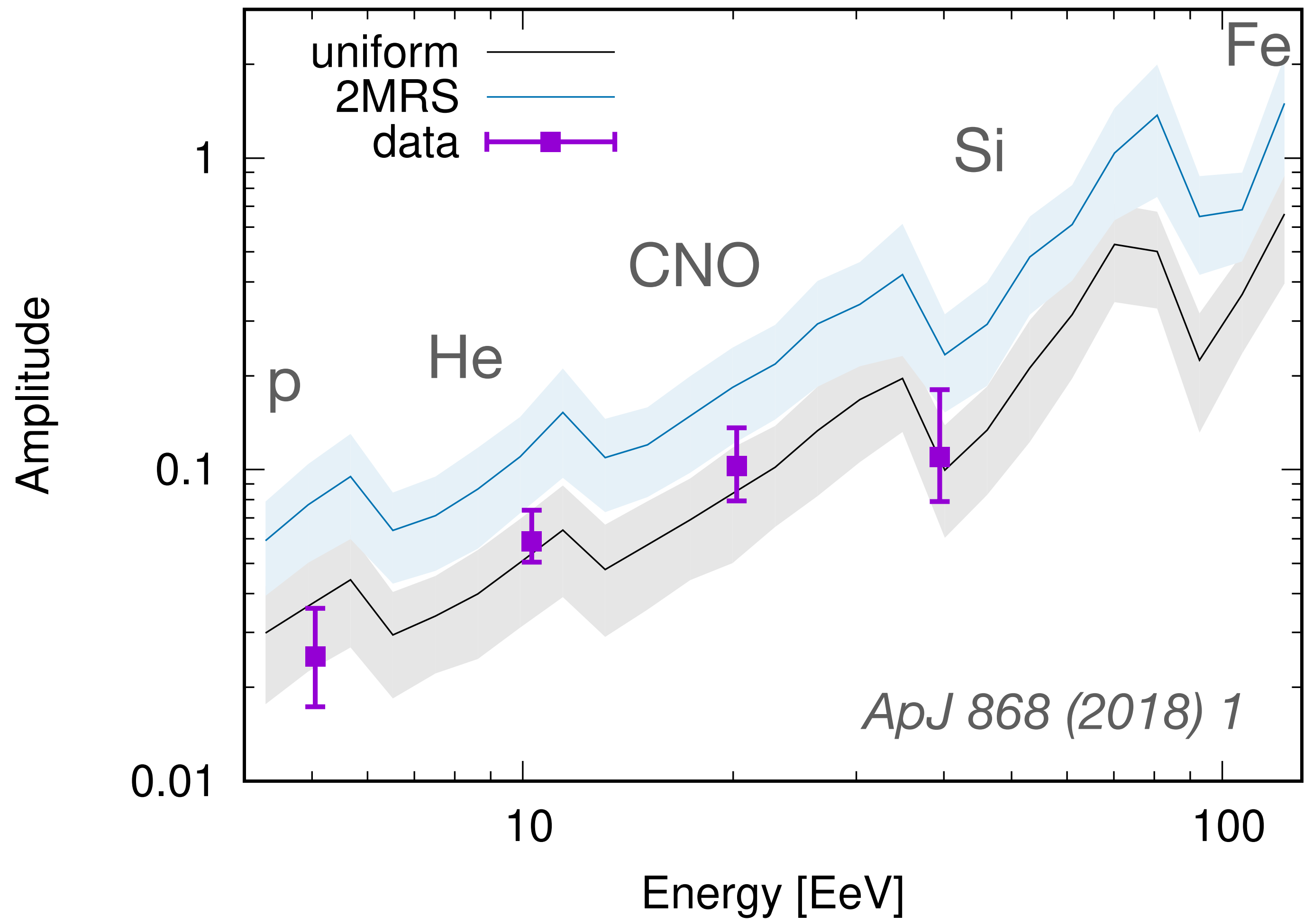
Dipole, and its energy dependence, must be the result of interplay between

- 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





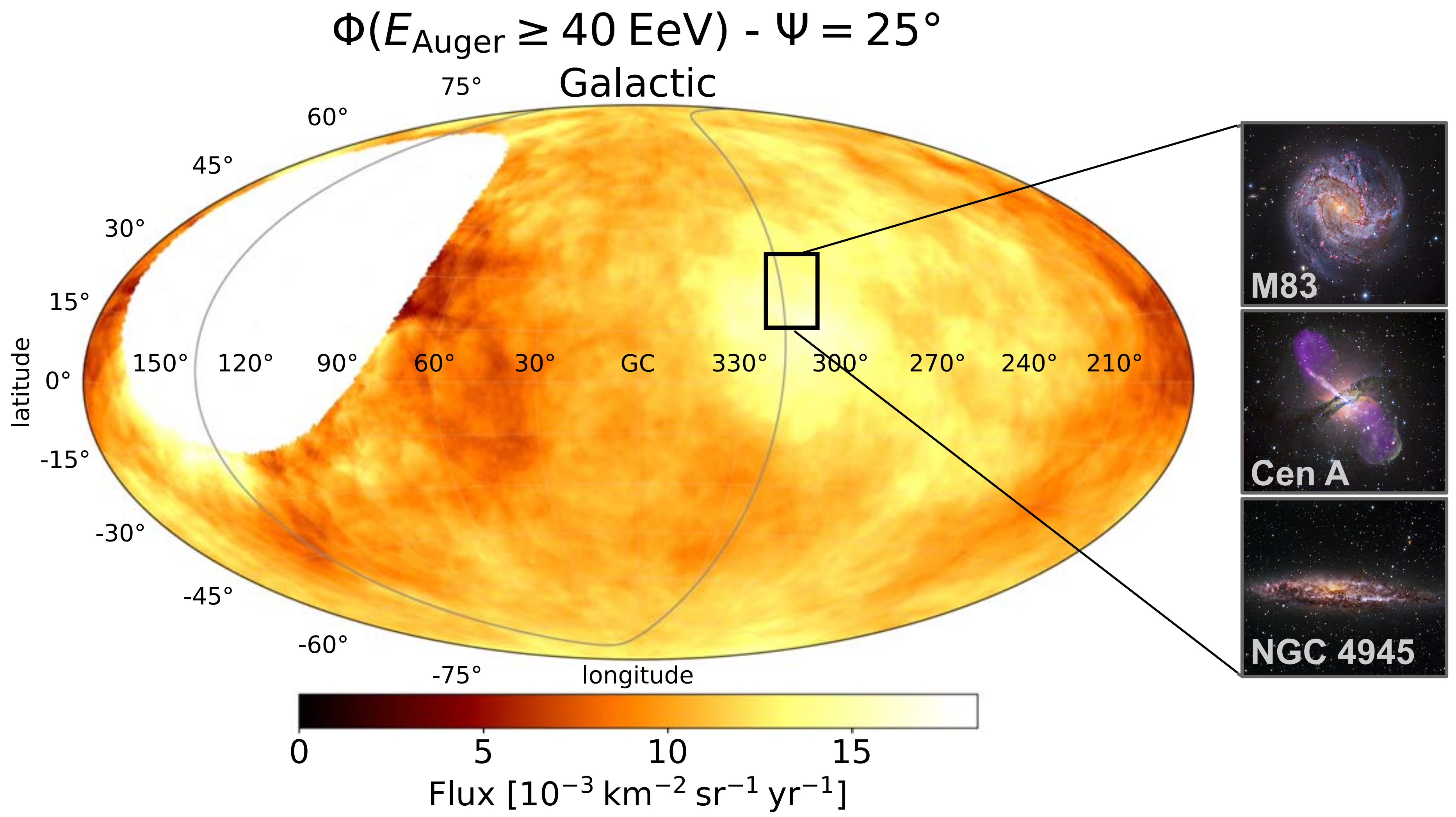
Science, 357 1266 (2017)
ICRC21 335 (2021)

Anisotropy - at the highest energy

Above ~ 4×10^{19}eV

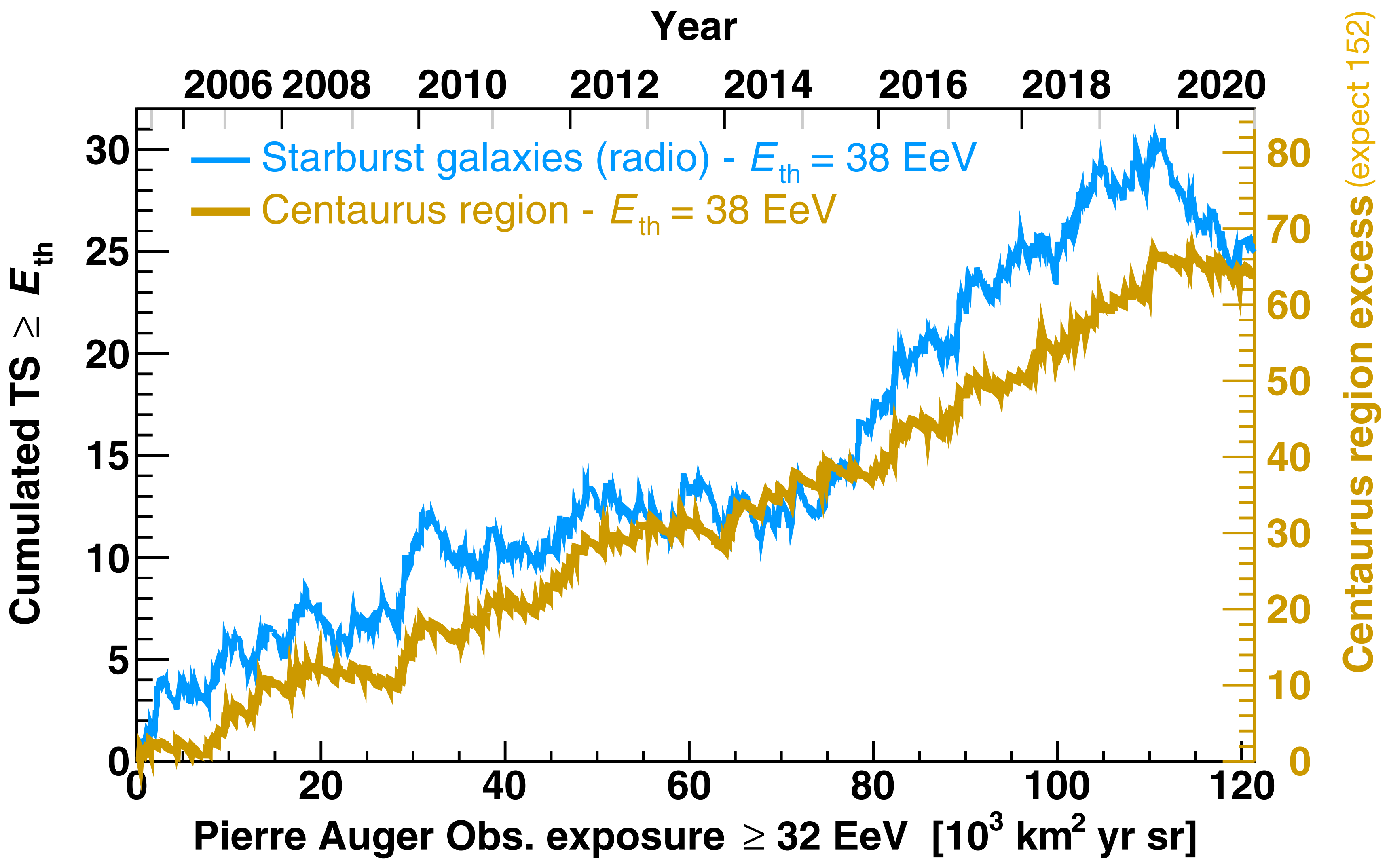
Exposure 122,000 km² sr yr
optimised quality cuts, up to end of 2020

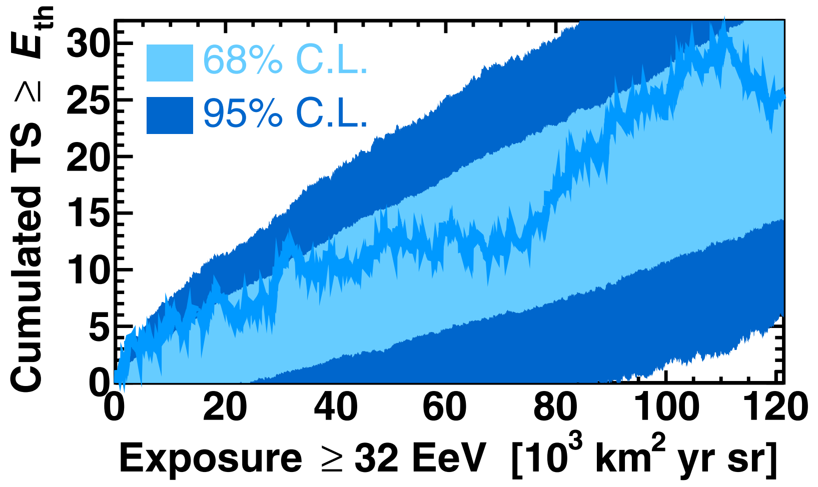
a priori region around Centaurus (crowded region)
(first flagged with 7% of current exposure)
$E_{th} = 38$ EeV, top-hat radius $27°$, post-trial deviation from isotropy: 3.9σ

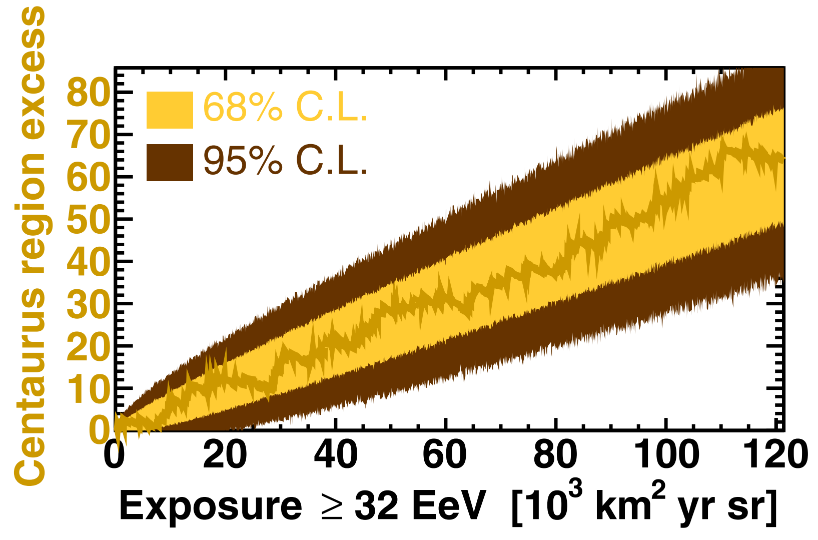


Catalog	Eth [EeV]	Signal fraction %	Test statistic	Post trial p-value
All galaxies (IR)	40	16	18.0	7.9 x 10^{-4}
Starbursts (radio)	38	9	25.0	3.2 x 10^{-5}
All AGN (X-ray)	39	7	19.4	4.2 x 10^{-4}
Jetted AGN (gamma-ray)	39	6	17.9	8.3 x 10^{-4}

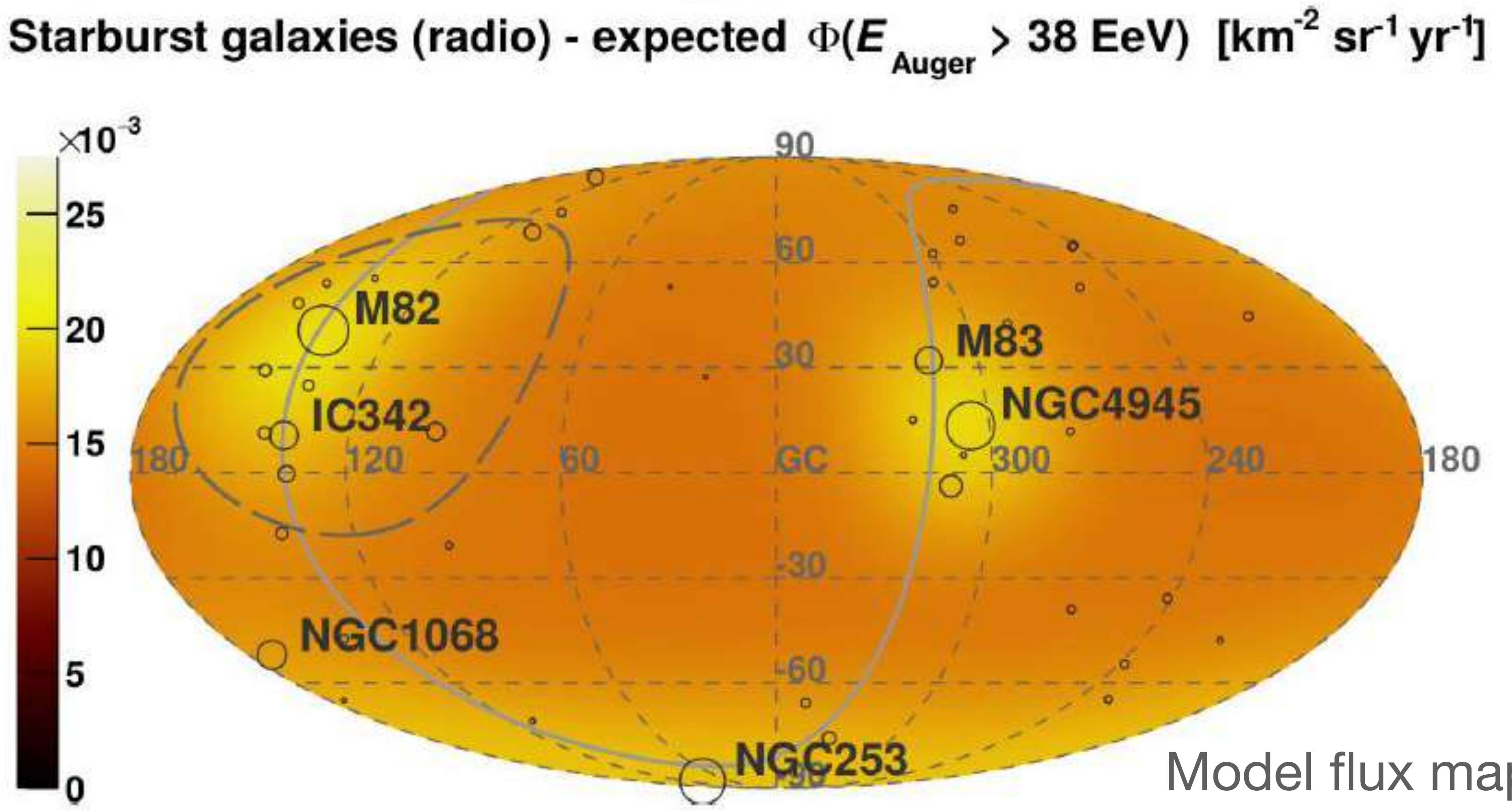
4.0σ







Example of catalog search (expected flux map)



Model flux map

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

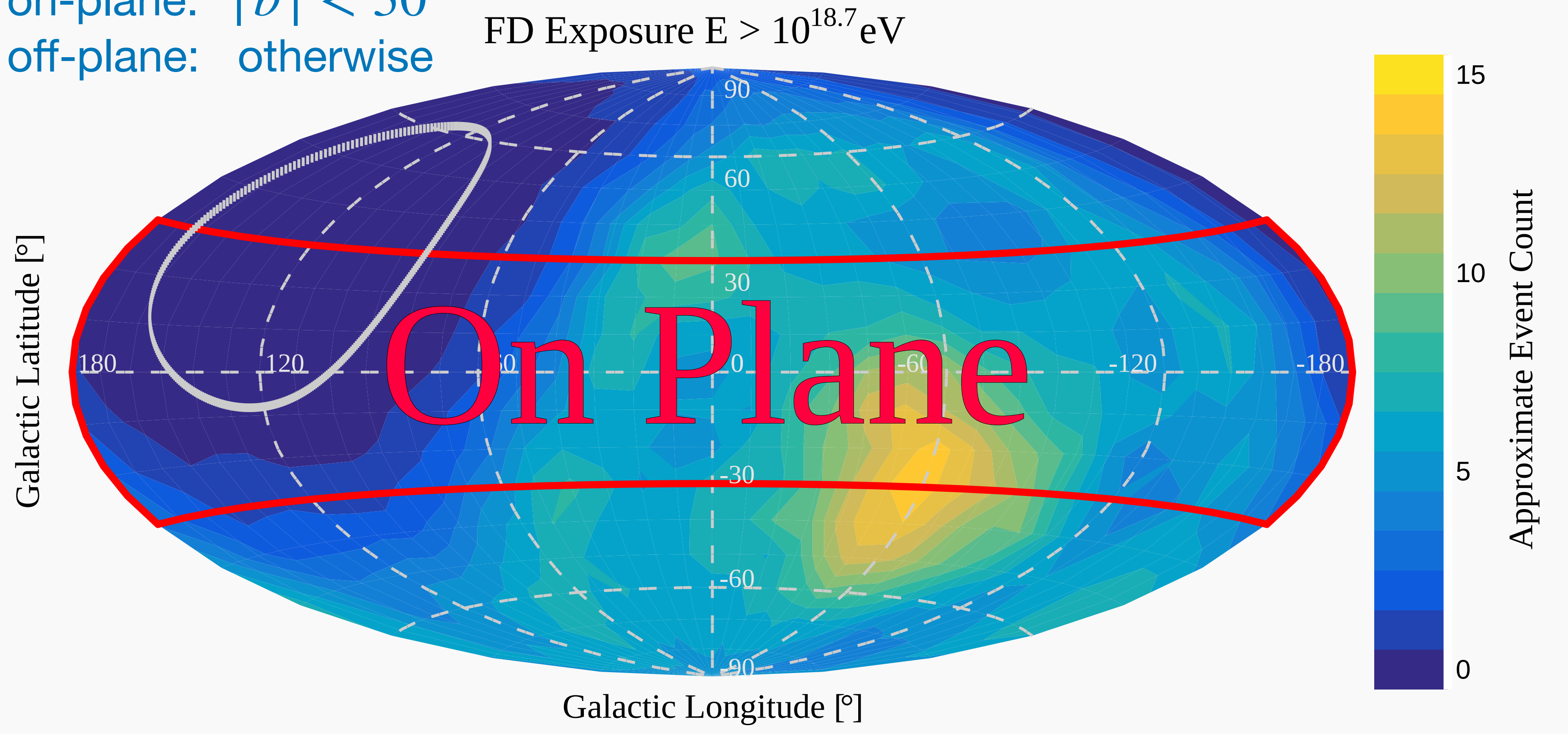
Phase II sensitivity improvements include:
- 100% duty cycle for mass information (AugerPrime)
- including more than 85% of the sky (collaboration with Telescope Array)

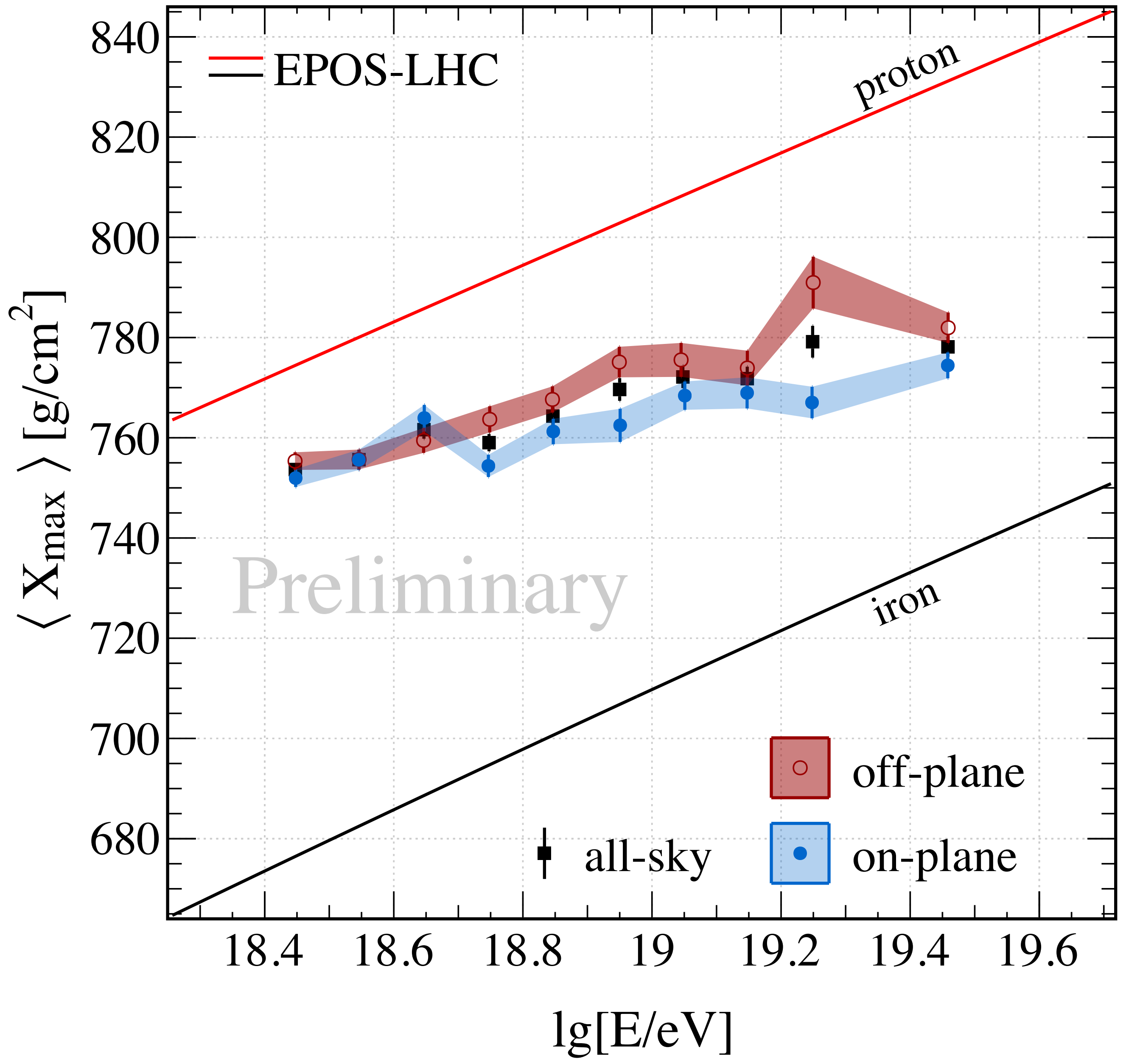
ICRC21 307 (2021)
Ap. J. Lett 853 L29 (2018), Ap. J. 935 170 (2022)

Hints of a mass-dependent anisotropy

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

on-plane: $|b| < 30^{\circ}$
off-plane: otherwise

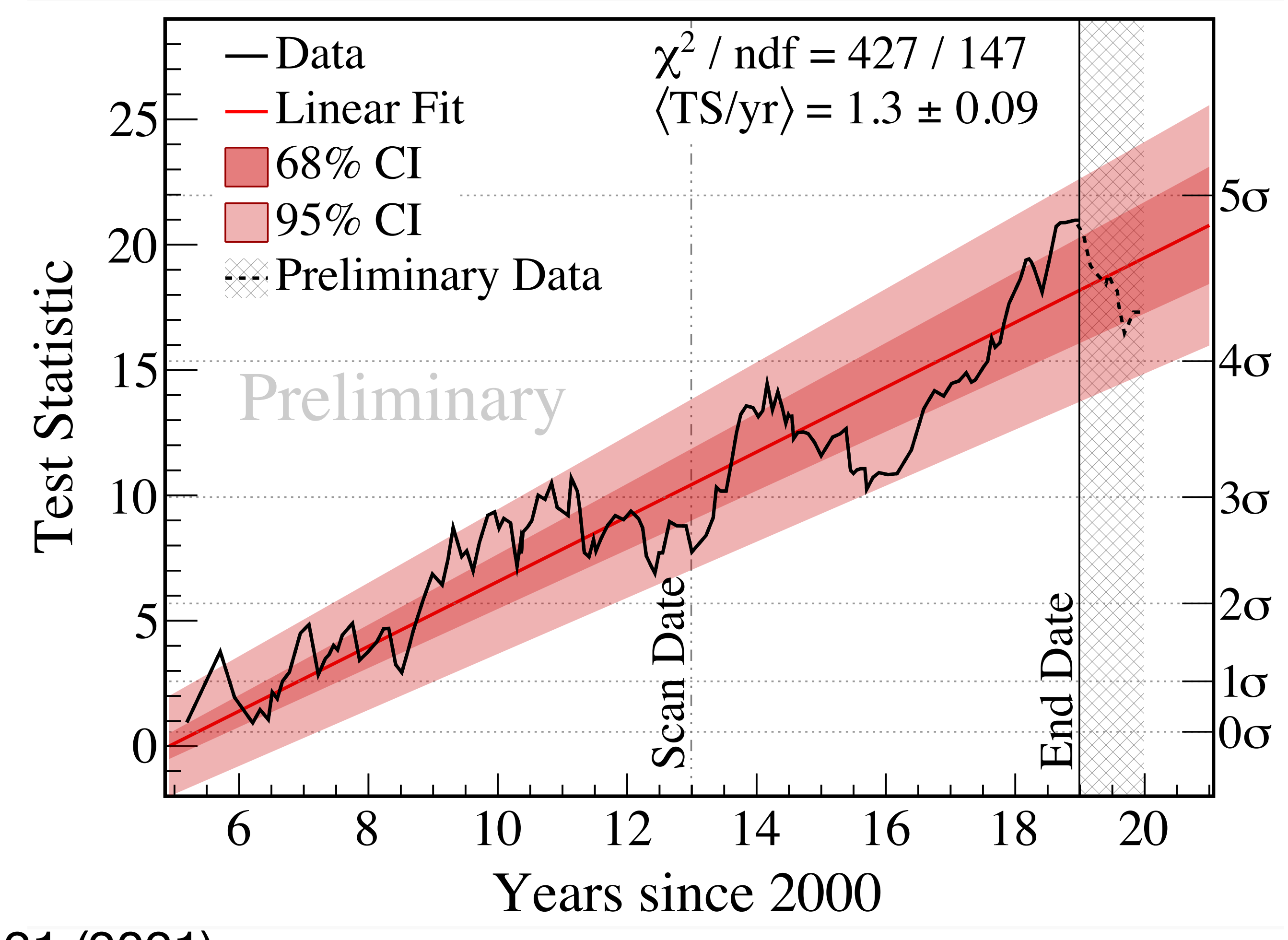




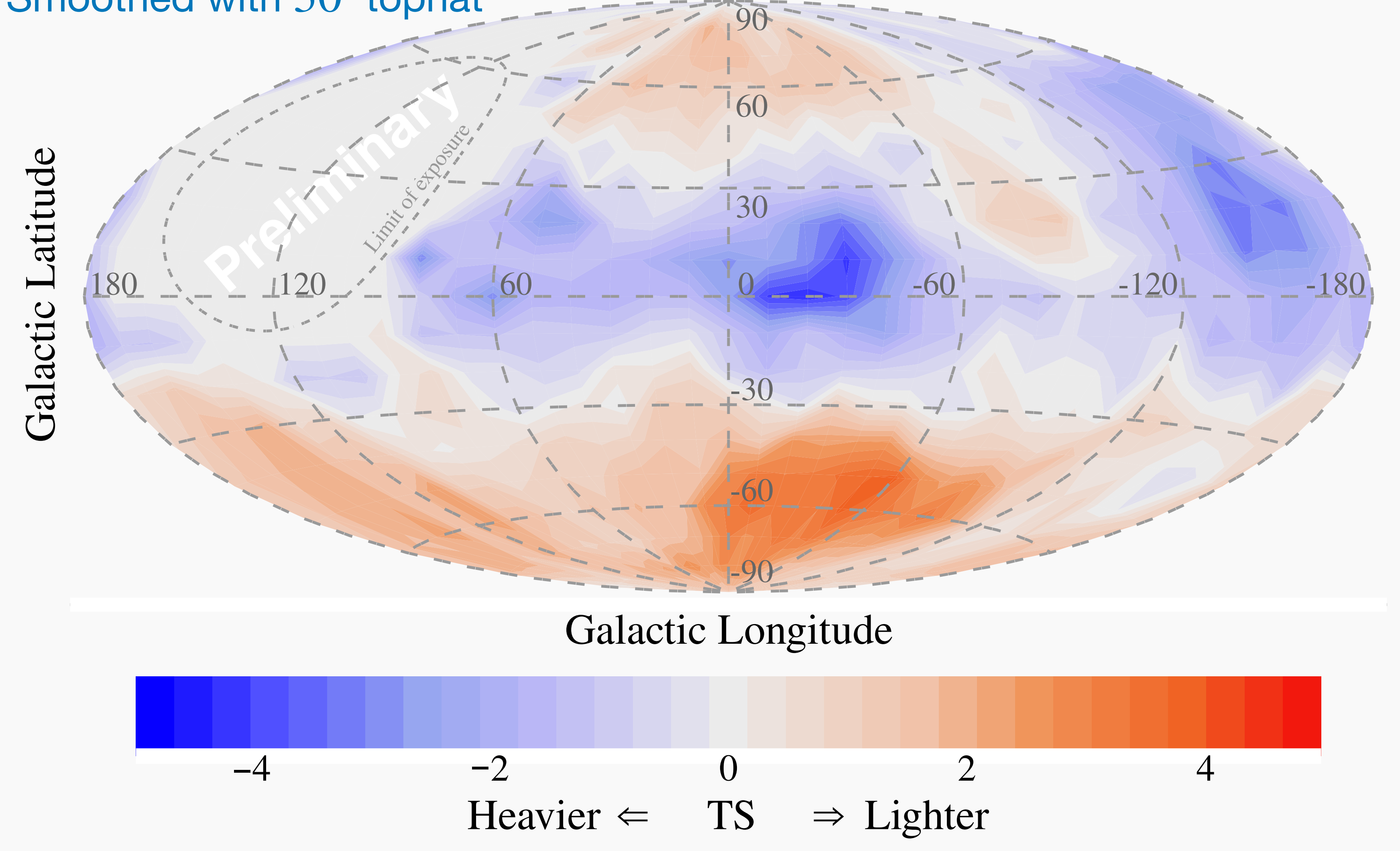
X_{max} from fluorescence detector

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



Smoothed with 30° tophat



If real, it doesn't imply galactic sources.

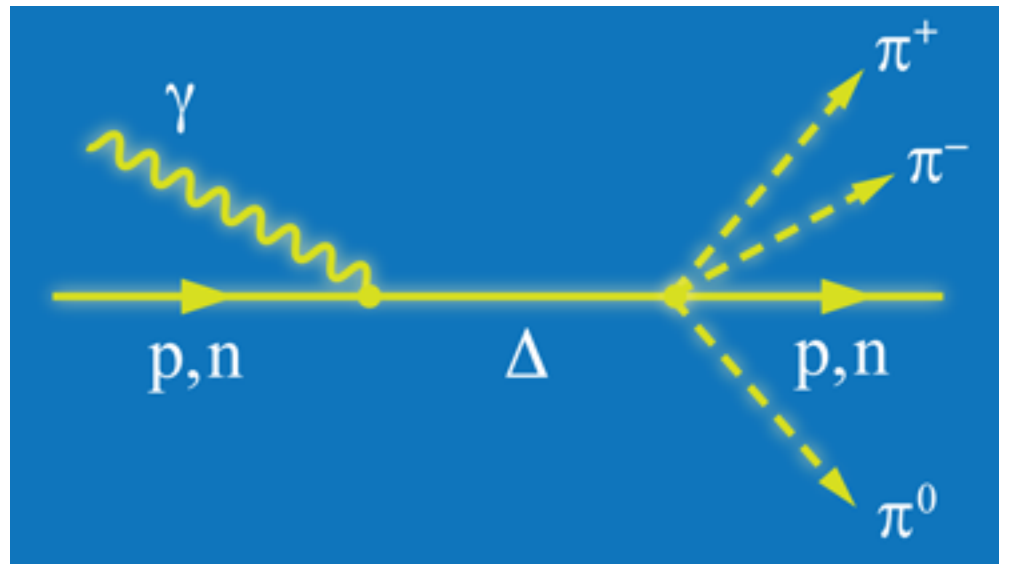
It might be the result of the interplay of source directions, the mass-dependent horizon, and the GMF.

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

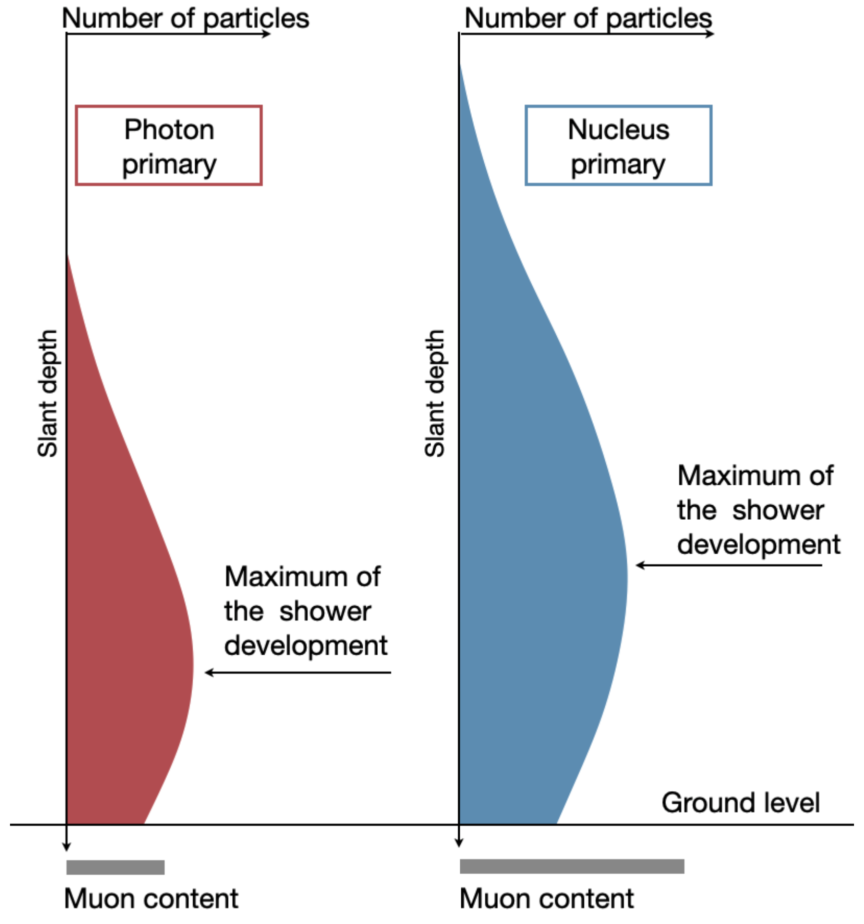
ICRC21 321 (2021)

Neutrino and Photon searches

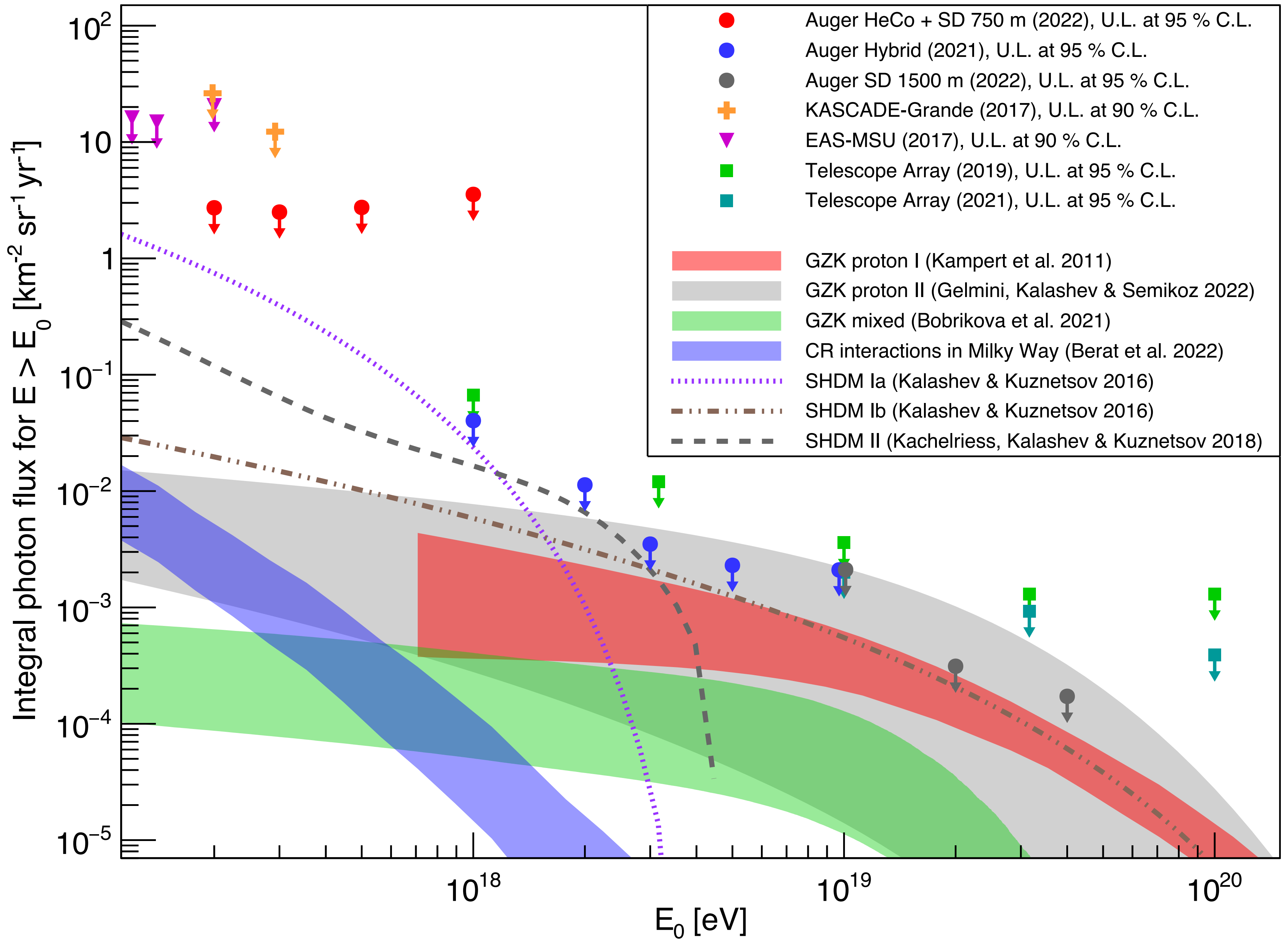
“GZK” interaction - protons + CMB



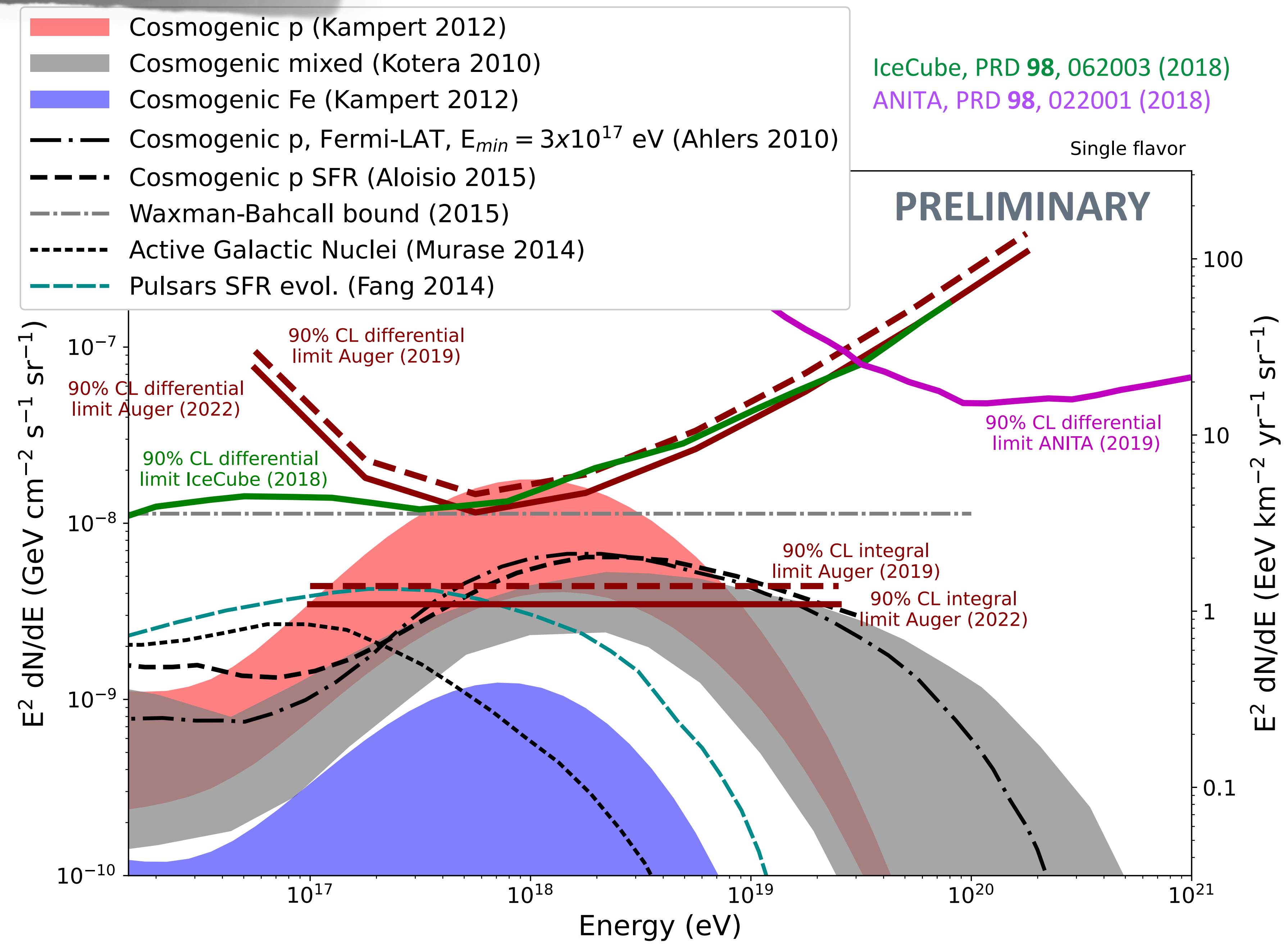
Cosmogenic photons and neutrinos
- pure proton model at UHE challenged, some variants ruled out

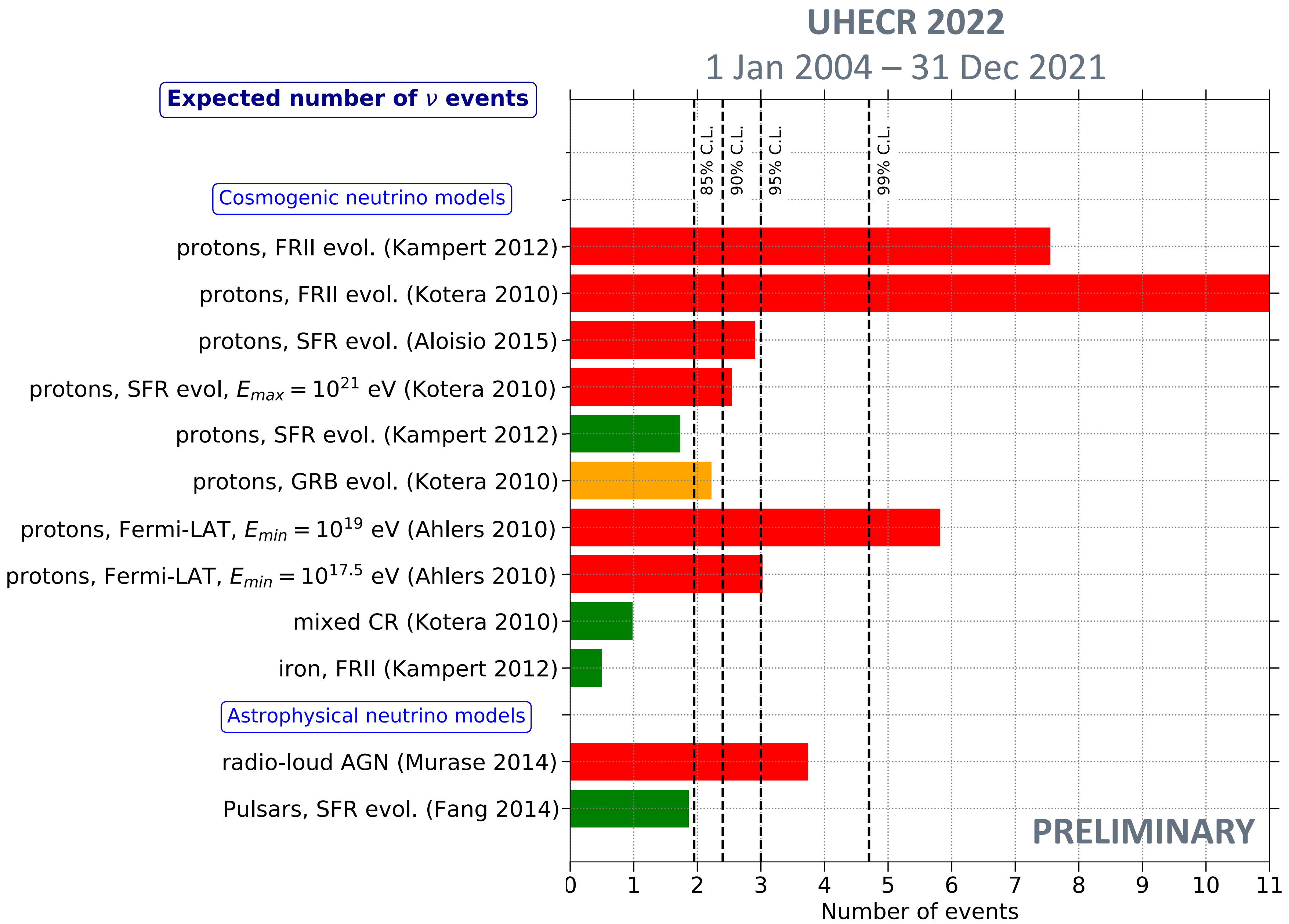


PHOTONS



NEUTRINOS





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)

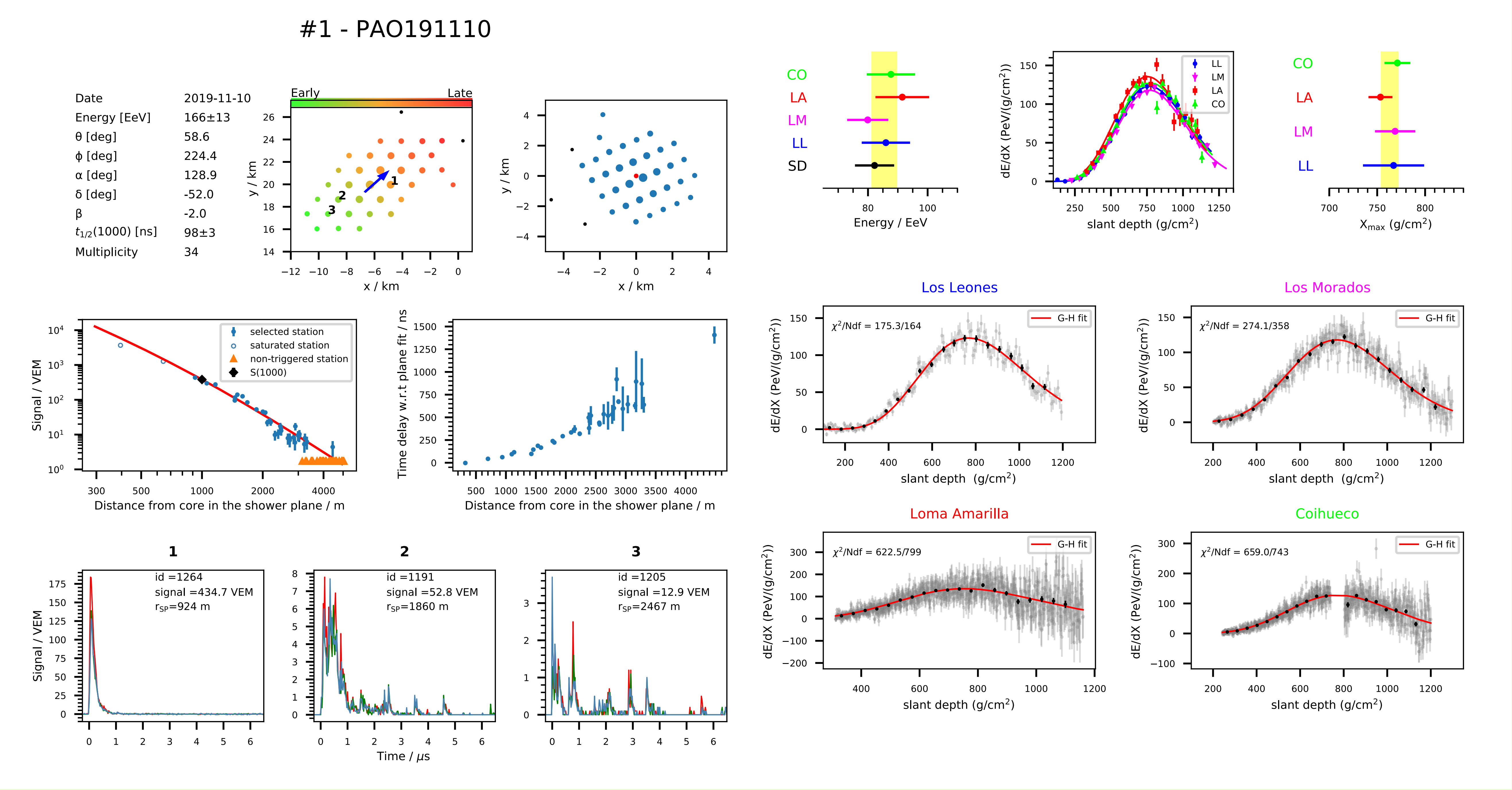
Universe 8, 579 (2022); UHECR2022 L’Aquila (2022)

Examples of other recent studies

Ap. J. Suppl. (in press 2022)

A Catalog of the Highest-Energy Cosmic Rays Recorded During Phase I of Operation of the Pierre Auger Observatory

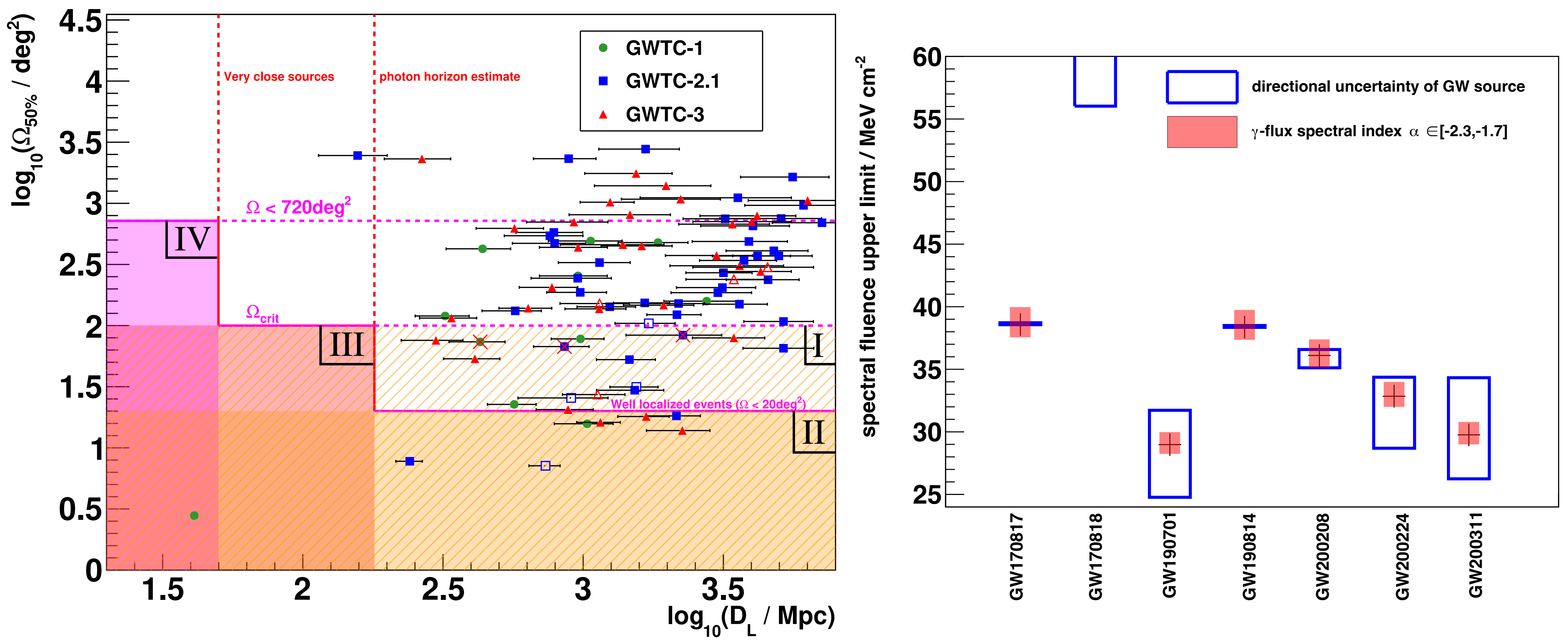
The Pierre Auger Collaboration



Ap. J. (submitted 2022)

Search for UHE Photons from Gravitational Wave Sources with the Pierre Auger Observatory

The Pierre Auger Collaboration



JCAP 01 (2022) 023

Journal of Cosmology and Astroparticle Physics

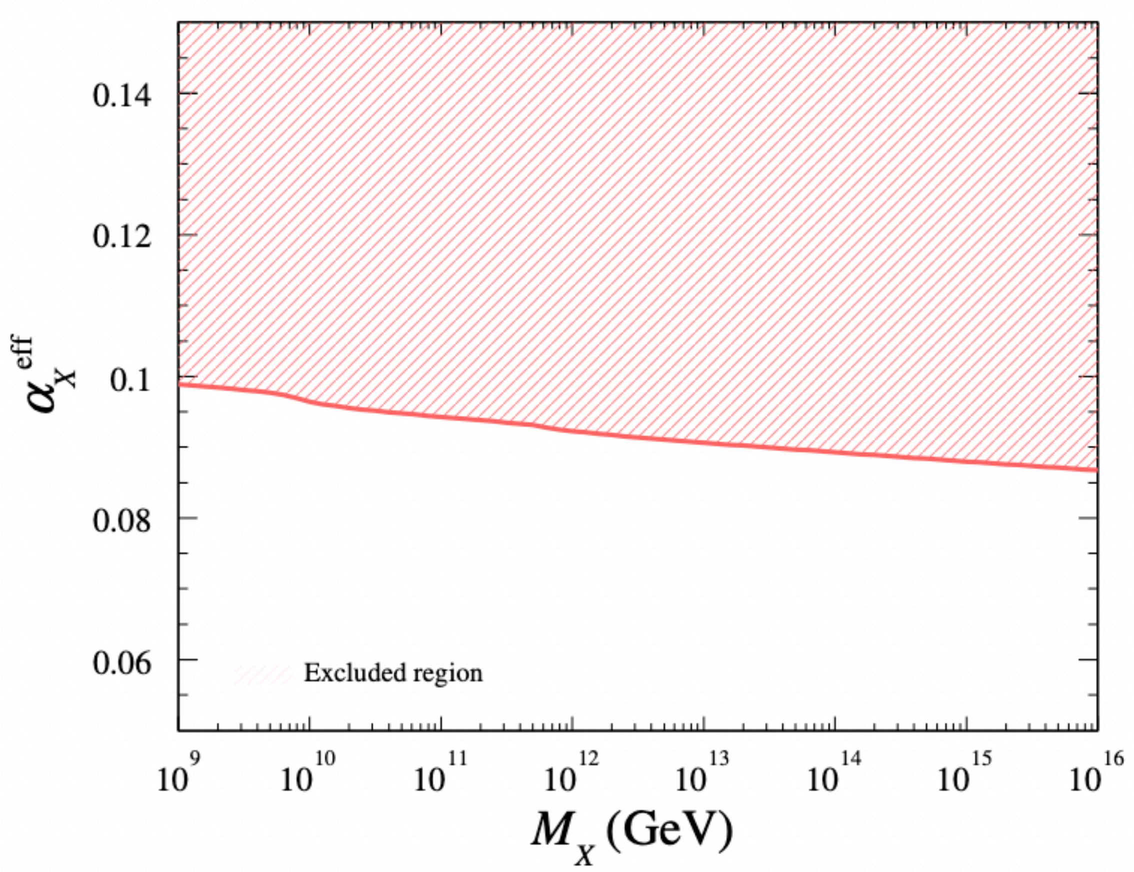
An IOP and SISSA journal

Testing effects of Lorentz invariance violation in the propagation of astroparticles with the Pierre Auger Observatory

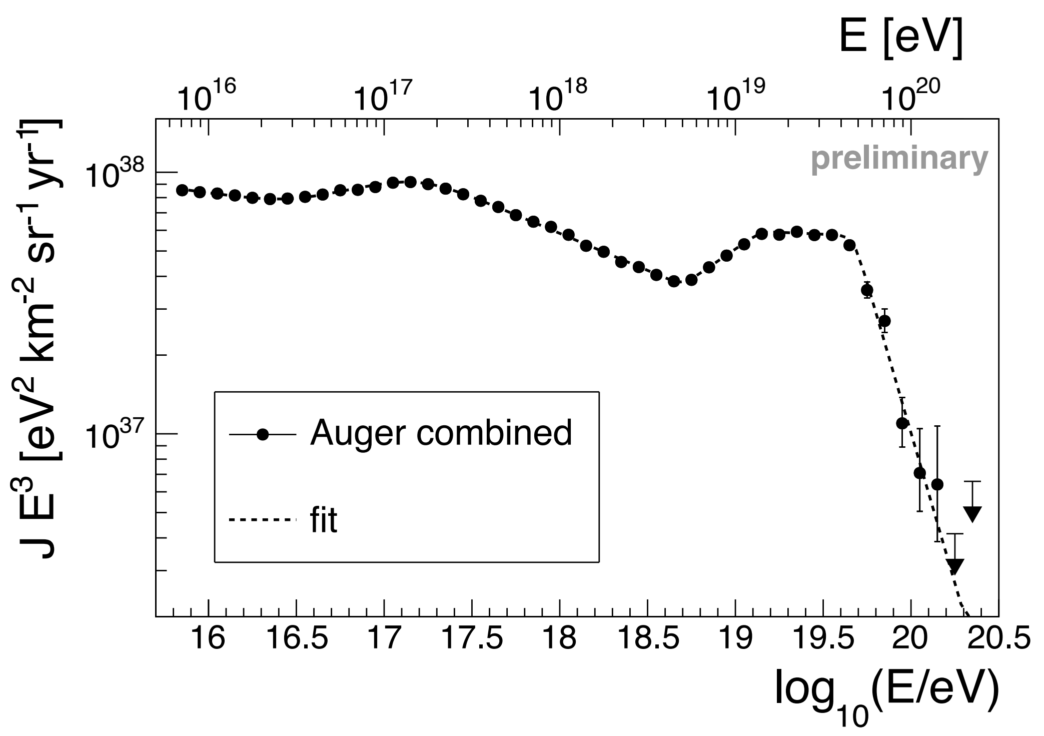
Phys. Rev. Lett. (submitted 2022)

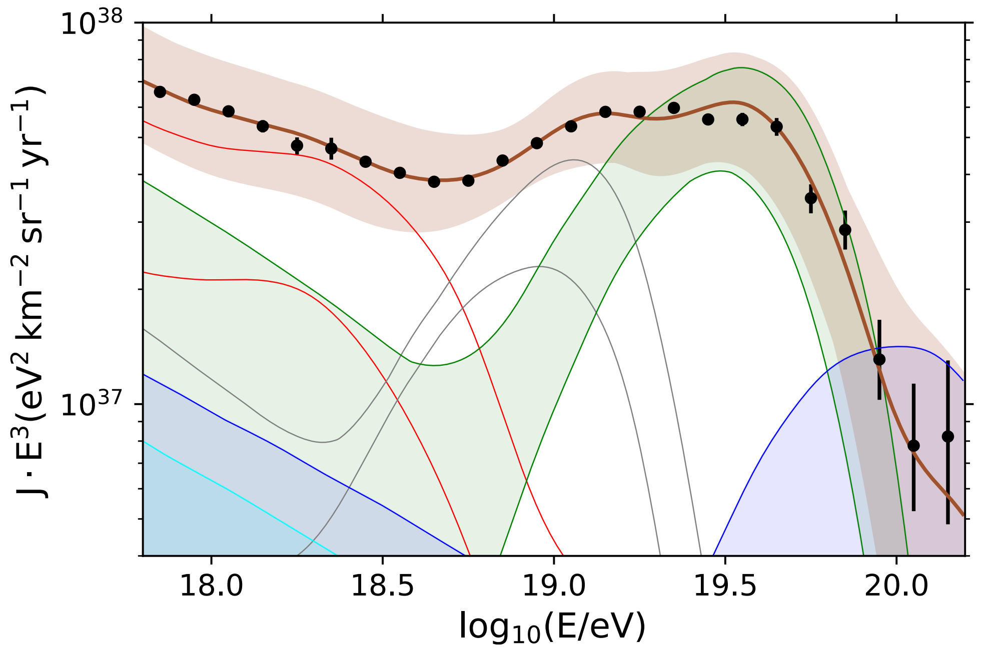
Limits on dark-sector gauge coupling from non-observation of instanton-induced decay of super-heavy particles in the data of the Pierre Auger Observatory

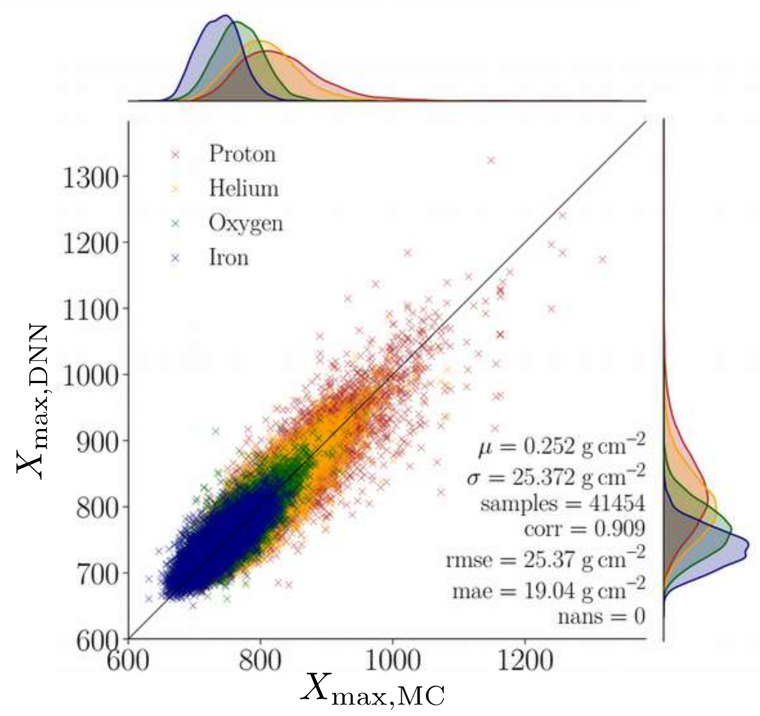
The Pierre Auger Collaboration

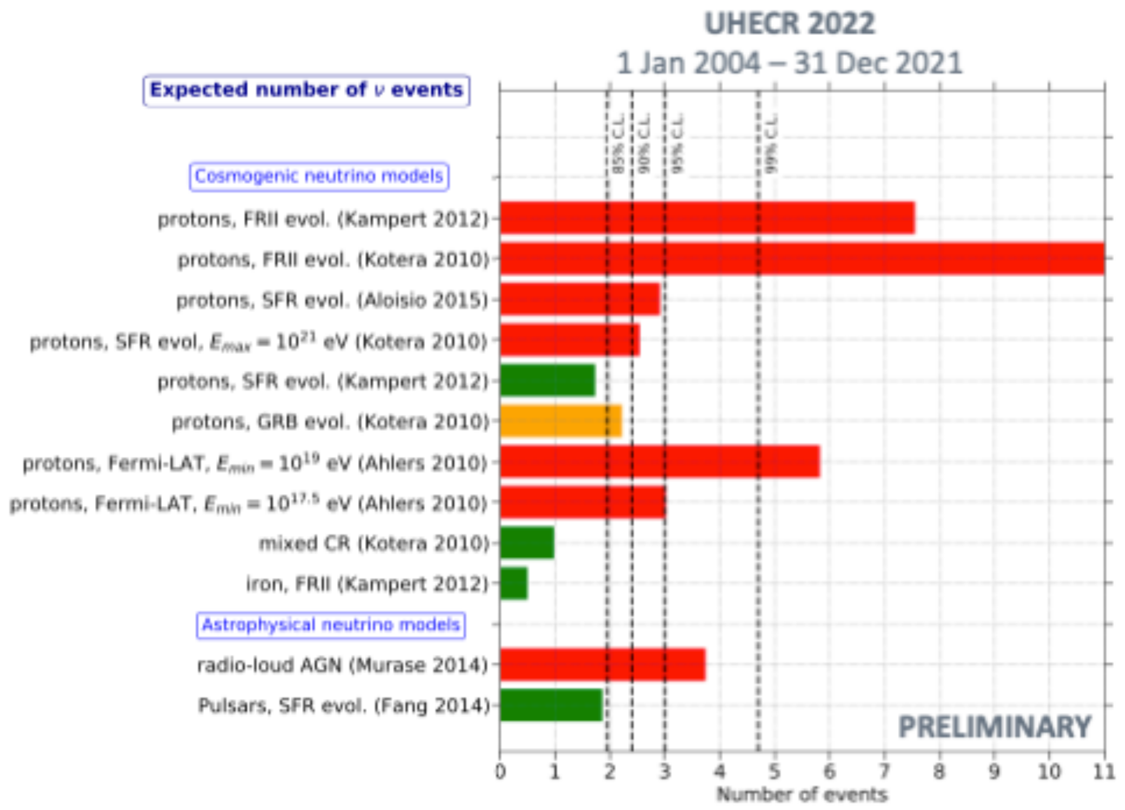


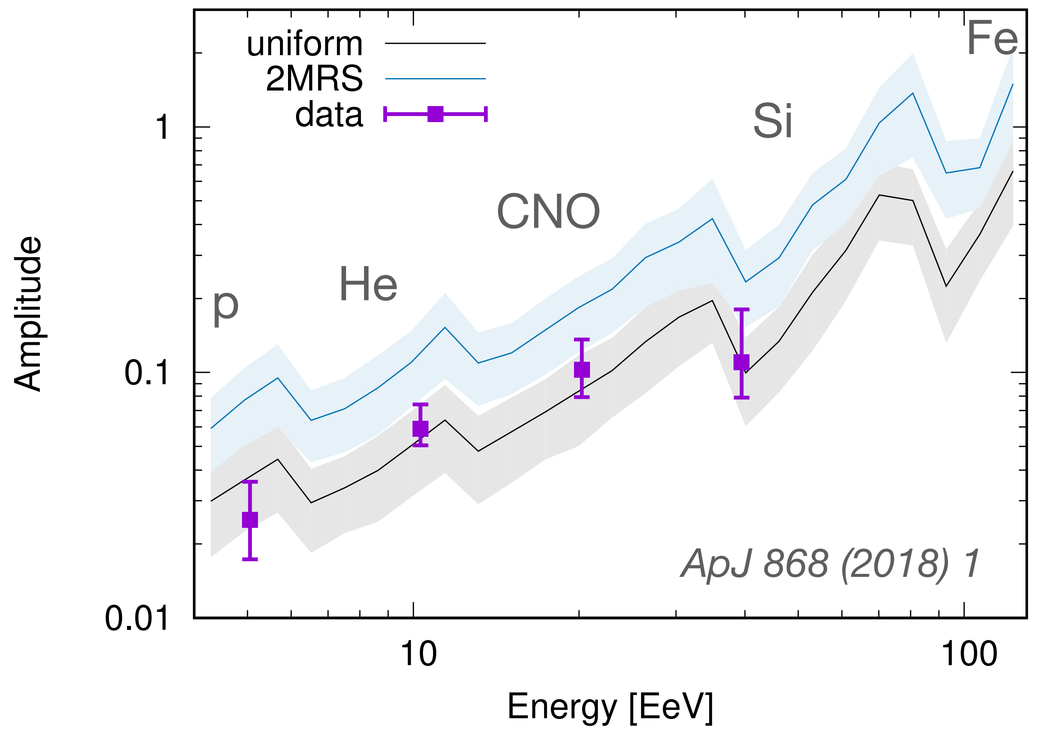
Conclusions and Outlook

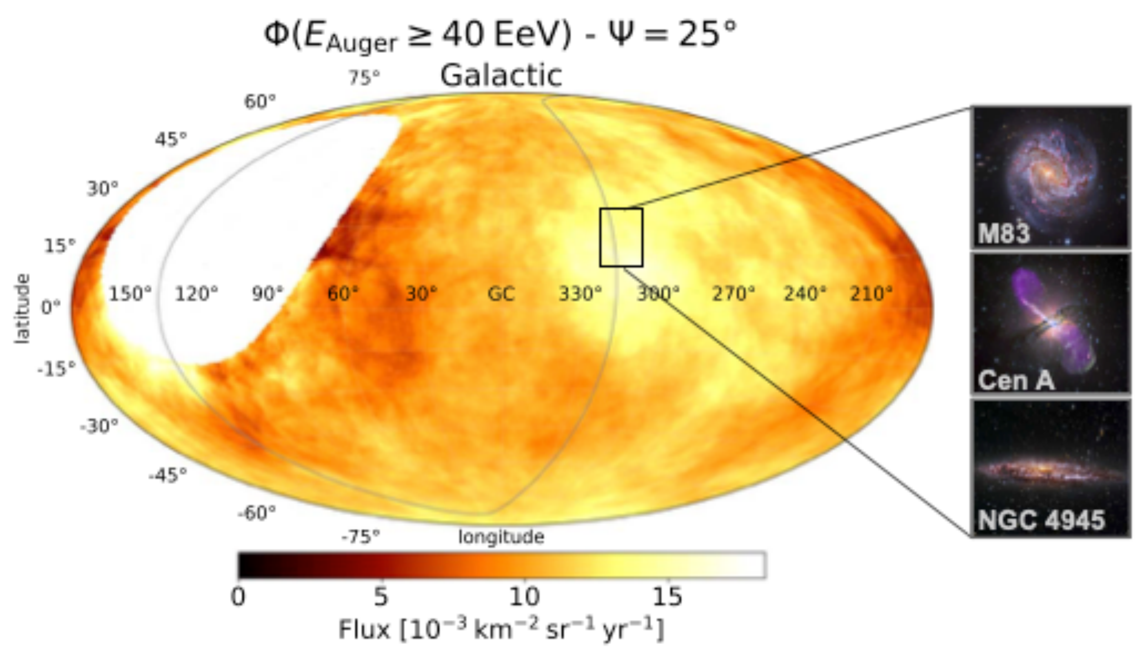


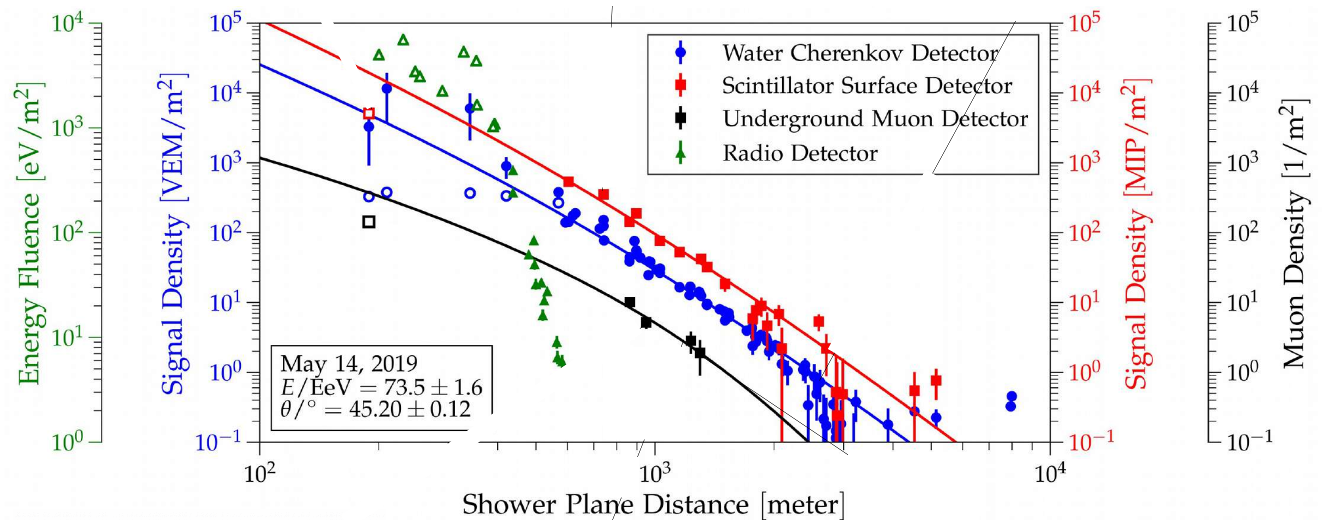


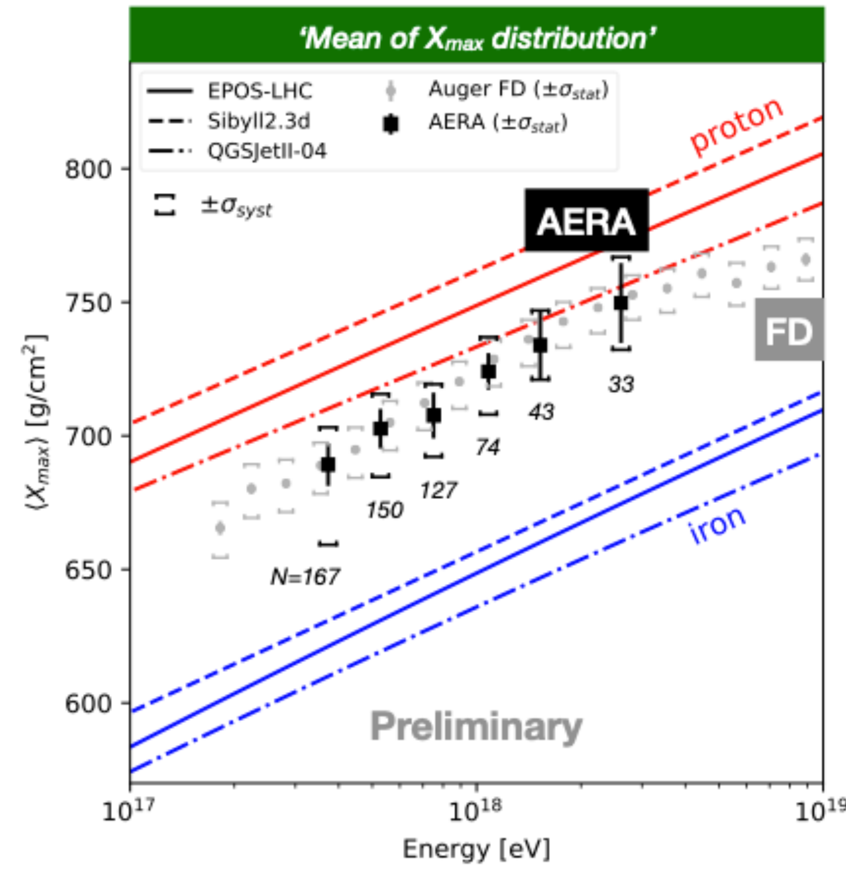












- Auger continues to explore the origin of UHECR with a rich range of results
- Phase I has produced results that appear to be telling a consistent story (e.g. change of mass confirmed, challenging anisotropy studies, neutrino limits …)
- Phase II soon to be underway, with enhanced mass information and more hybrid measurements. (And re-analysis of old data with the benefit of new knowledge!)