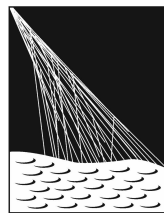
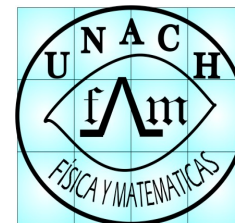




Credit: Steven Safir



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C.A. CIENCIAS FÍSICO-MATEMÁTICAS

Highlights of the Pierre Auger Observatory and current status

Karen Salomé CaballeroMora
On behalf of the Pierre Auger Observatory*
FCFM-UNACH

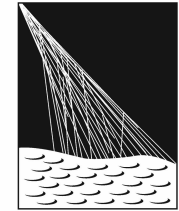
XIX Mexican Workshop on Particles and Fields, 2025
División de Ciencias e Ingenierías de la Universidad de Guanajuato, León
October 22nd 2025

*Based on Roth, M., on behalf of the Pierre Auger Observatory, *Exploring the Ultra-High-Energy Universe: Highlights from the Pierre Auger Observatory* at ICRC2025

Karen S. Caballero Mora UNACH karen.scm@gmail.com



A bit of history



OBSERVATORIO
PIERRE
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- Planned from 1992 on
- 1995 -> Study to know the viability and design of the experiment
- -> 1999 Agreement signed
- -> México from the beginning
- Inaugurated in 2008
- Conclusión 2009 (First stage)
- Next stage: Auger Prime 2015
- ~400 collaborators, ~17 countries
- In 2021, the first data were released to the scientific community



Mexican Group

Mexican researchers

Foreign researchers

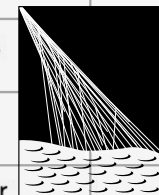
	Nombre	Institución
1	Enrique Varela Carlos	Benemérita Universidad Autónoma de Puebla (BUAP)
2	Humberto Antonio Salazar Ibarguen	BUAP
3	Rodrigo Pelayo Ramos	Instituto Politécnico Nacional (IPN)
4	Juan Carlos Arteaga Velázquez	Universidad Michoacana de San Nicolás de Hidalgo (UMICH)
5	Karen Salomé Caballero Mora (Responsable Técnica)	Universidad Autónoma de Chiapas (UNACH)
6	José Francisco Valdés Galicia	Instituto de Geofísica, Universidad Nacional Autónoma de México (IG-UNAM)
7	Lukas Nellen	Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México (ICN-UNAM)
8	Juan Carlos D'Olivo Saenz	ICN-UNAM
9	Gustavo Adolfo Medina Tanco	ICN-UNAM

	Nombre	Institución
1	Patricia María Hansen	Universidad Nacional de La Plata, Argentina
2	Beatriz García	Universidad Tecnológica Nacional, Argentina
3	Federico Andrés Sánchez	Universidad Nacional de San Martín, Argentina
4	Carla Bonifazi	Universidad Nacional de San Martín, Argentina

Mexican students



	Nombre	Institución
1	Marlon Steve García Mejía	BUAP
2	Victor Aldair Garmendia Fuentes	BUAP
3	Fidel Álvarez Azuara	BUAP
4	Andrea Corona Hernández	BUAP
5	Francisco Roberto Noverón Figueroa	IPN
6	Alely Medina Hernández	IPN
7	Daniel Alberto García Sánchez	UNACH
8	Juan Daniel Bonifaz Partida	UNACH
9	Juan Manuel Díaz Peña	UNACH
10	Ana Laura Colmenero César	UMICH
11	Diana Rodríguez Tzintzun	UMICH
13	Ernesto Noé López Guzmán	ICN-UNAM
14	Claudia Patricio Rodríguez	ICN-UNAM
15	Olaf De Jesús Enriquez Lizama	IG-UNAM
16	Oscar Batalla Cruz	IG-UNAM

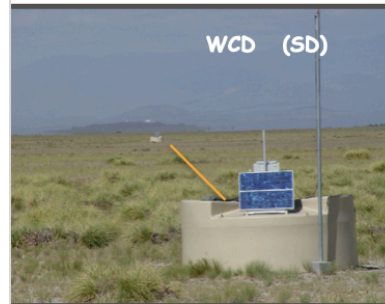


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OBSERVATORY

Mexican contributions

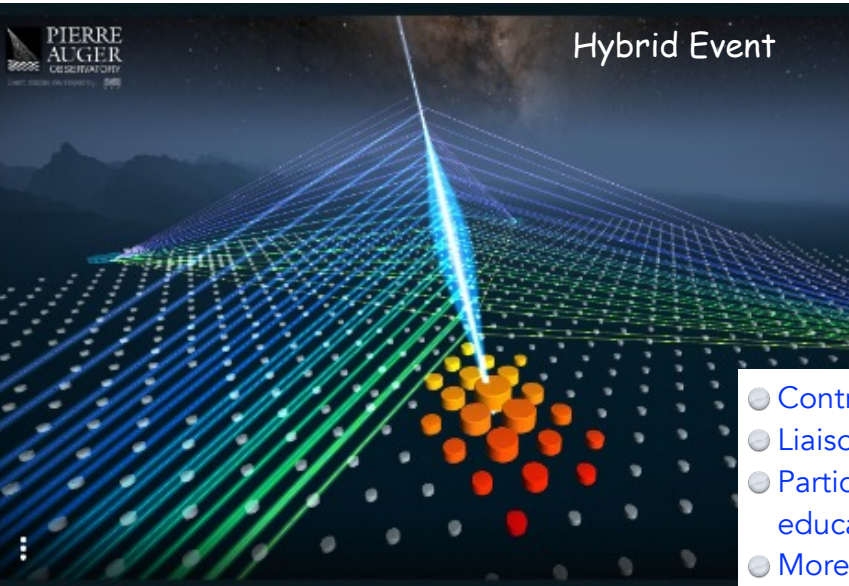
Goals:

- Study of Ultra-high Energy Cosmic Rays (UHECR)
- Origin, composition, acceleration and propagation mechanisms, existence of a cut-off in the flux.
- Extension to lower energies
- New measurement techniques
- Cosmogeophysics and space weather



Desarrollo de tecnología

- Contribution to data analysis
- Liaison with Mexican industry (Rotoplas built the first tanks)
- Participation in general decision-making positions (scientific board, leaders in outreach and education)
- More than 129 papers from the Collaboration, 26 bachelor theses, 13 master's degree theses, and 15 PhD theses
- On-site and remote measurement shifts
- Auger's international experience opened the door to other collaborations and experiments such as HAWC and the LHC



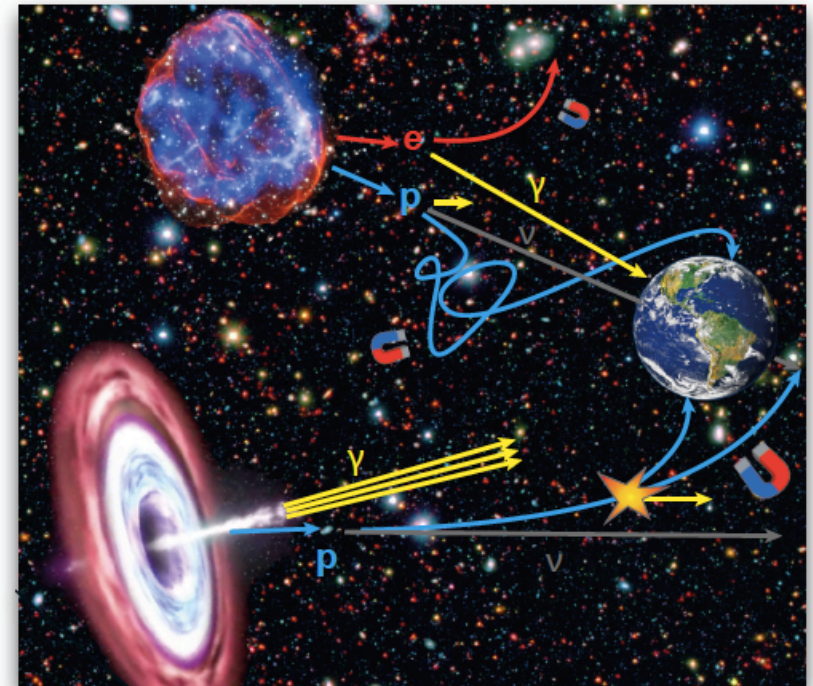
Mexican Group:

- Construction and design, leaders in several fields
- Leader in software development and simulation
- First large-scale neutrino and anisotropy studies

Ultra-high energy cosmic rays above 10^{18} eV

Pressing Physics questions:

- Gaining knowledge about Astrophysics, e.g.:
 - What and where are **the sources** of CRs?
 - How are CRs **accelerated**?
 - How do they **propagate** in which magnetized environments?
- Fundamental physics only possible with UHECRs, e.g.:
 - How do they **interact** in the atmosphere?
 - Are there hints for **BSM**?



Main measured quantities (but not only!):

- **Energy spectrum**
- **Mass composition**
- **Arrival direction**



The Pierre Auger Observatory

- East of Andes
- Province of Mendoza, Argentina *PoS(ICRC2025)1236; I. Alekotte*
- Area 3000 km²
- 2000: Engineering Array
- 2004: start...
- 2008: ... end of construction of Auger
- 2023: Start of Phase II data taking
- 2024: completion of AugerPrime
- Data taking till > 2035
- ≥ 2035

Phase I
Phase II



Local staff



Pierre Auger Collaboration

Argentina
Australia
Belgium
Brasil
Colombia*
Czech Republic
France
Germany
Italy
Mexico
Netherlands
Poland
Portugal
Romania
Slovenia
Spain
USA

*associated

*Based on Roth, M., ICRC2025

The Pierre Auger Observatory-Phase I

Fluorescence detector (FD)

- 4 sites
 - $E > 10^{18}$ eV
- HEAT
 - $E > 10^{17}$ eV

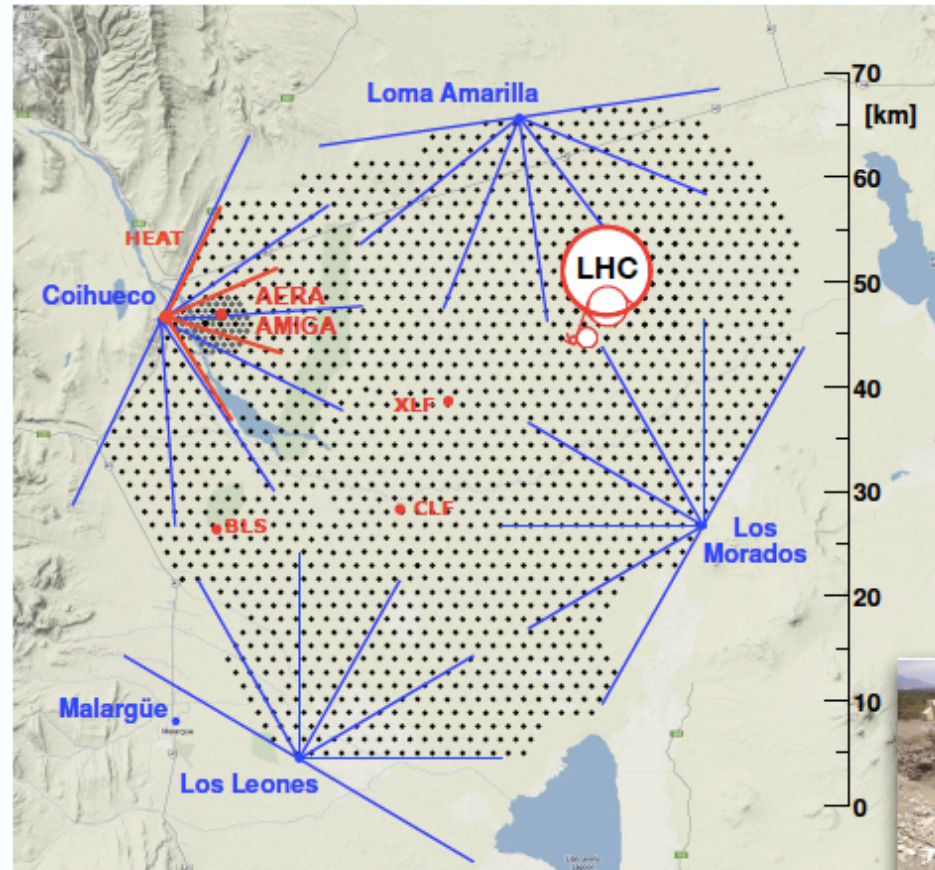
Surface detector array (SD)

- Water Cherenkov Tanks (WCD)
- Grid of 1500 m / 750 m / 433 m
 - 3000 km² / 24 km² / 2 km²
 - 1660 stations / 61 / 19
 - Thresholds:
 - $10^{18.5}$ eV, $10^{17.5}$ eV, 6×10^{16} eV

- Grid of 750 m and 433 m
 - Incl. underground muon counters
 - $E > 10^{17.5}$ eV

Radio array (AERA)

- 153 stations
- 17 km²



FD



HEAT



WCD



AERA



UMD

*Based on Roth, M., ICRC2025

The Pierre Auger Observatory

Fluorescence detector (FD)

- 4 sites
- $E > 10^{18}$ eV
- HEAT
- $E > 10^{17}$ eV

Surface detector array (SD)

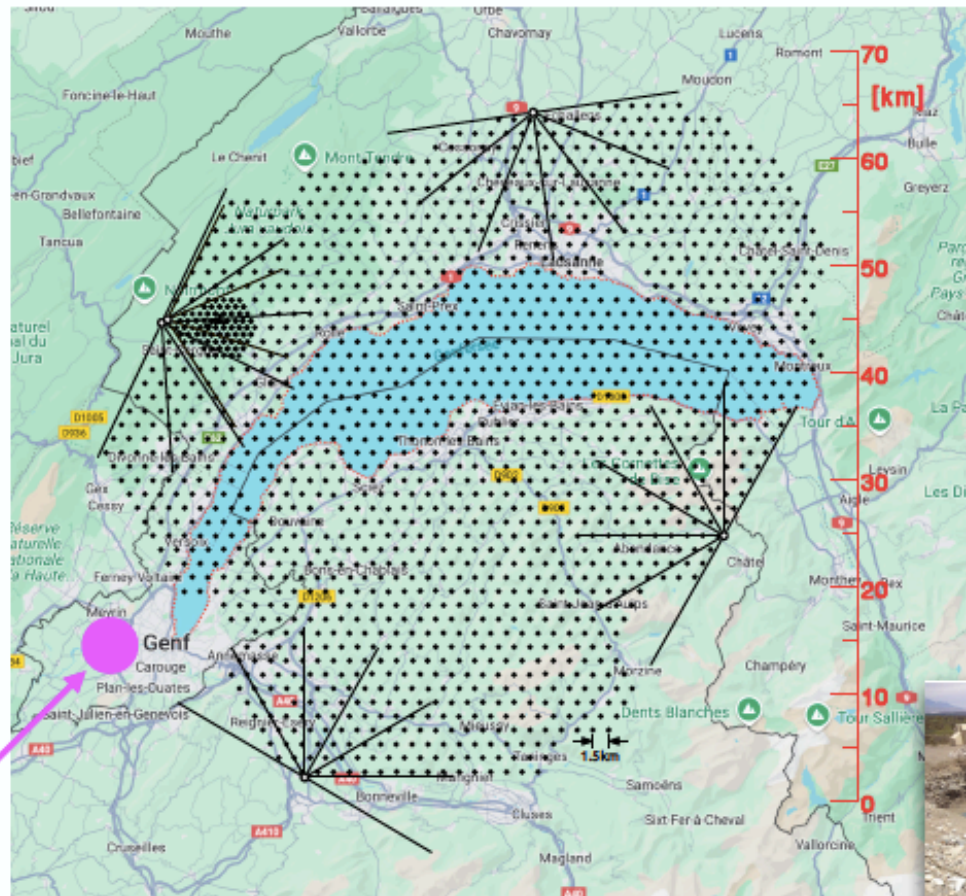
- Water Cherenkov Tanks (WCD)
- Grid of 1500 m / 750 m / 433 m
 - 3000 km² / 24 km²
 - 1660 stations / 61 / 19
 - Thresholds: 10^{18.5} eV, 10^{17.5} eV, 6x10¹⁶ eV

- Grid of 750 m and 433 m
 - Incl. underground muon counters
 - $E > 10^{17.5}$ eV

Radio array (AERA)

- 153 stations
- 17 km²

You are here



Hybrid detection

Fluorescence Detector (FD):

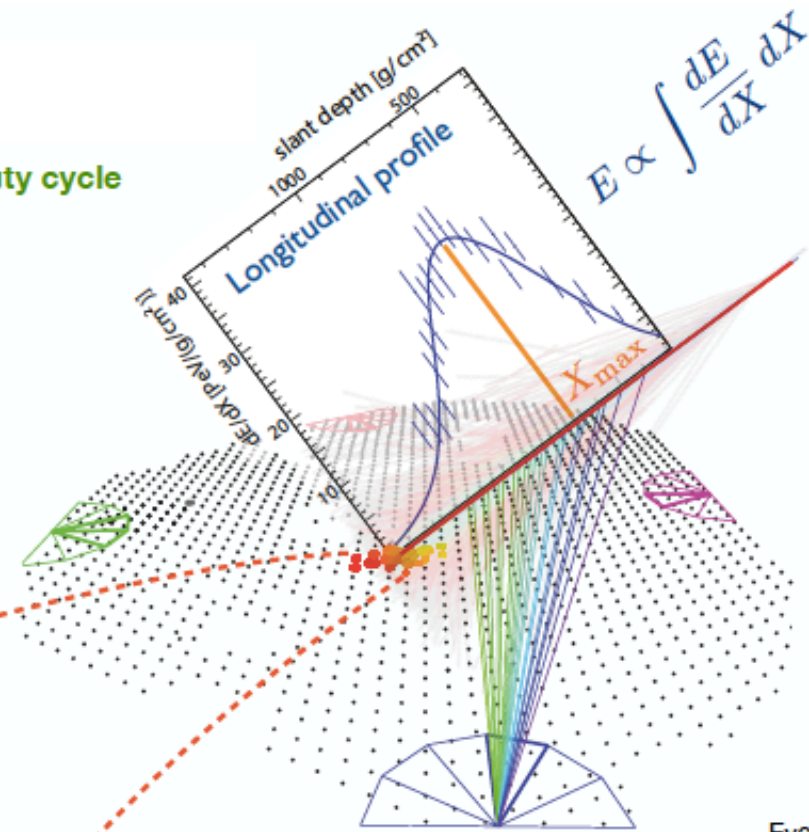
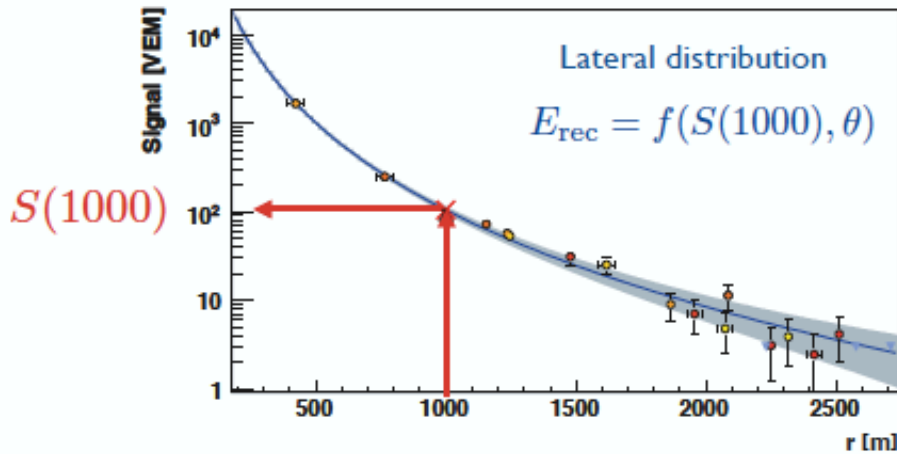
- calorimetric measurement of energy
- ca. 15% duty cycle

Surface Detector (SD):

- data driven shape of Lateral Distribution function (LDF)
- optimal distance at 1000 m
- ca. 100% duty cycle

15% duty cycle

100% duty cycle



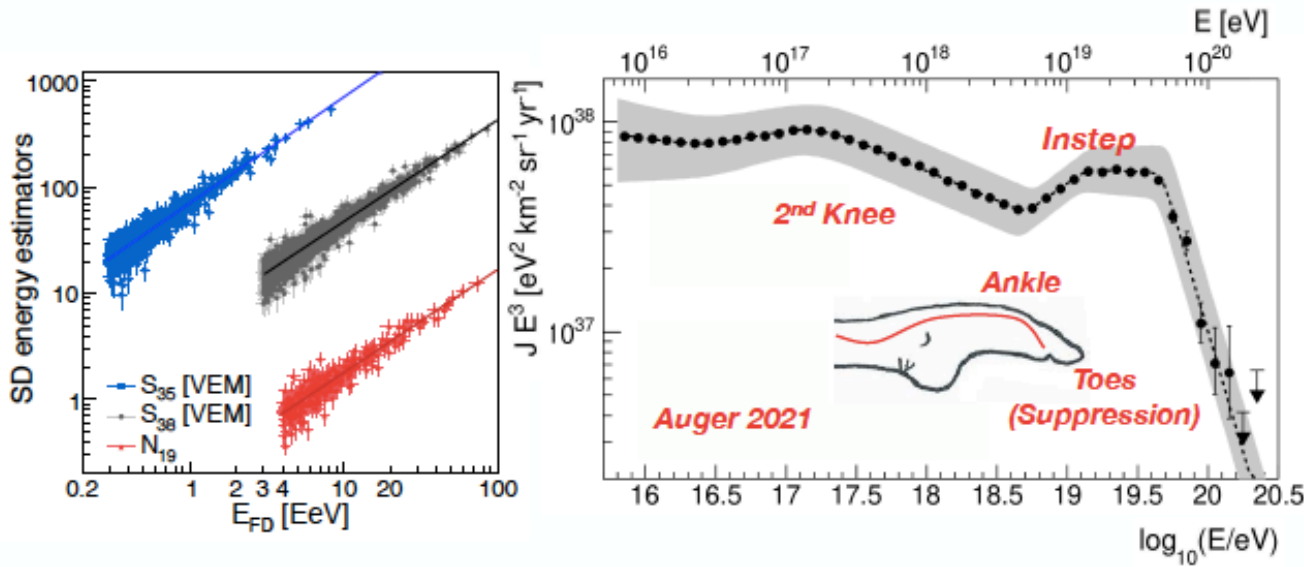
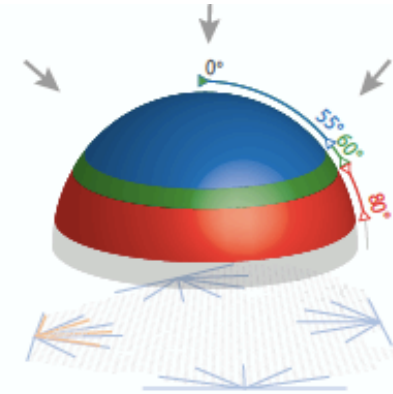
Event observed with Auger Observatory

Phase-I

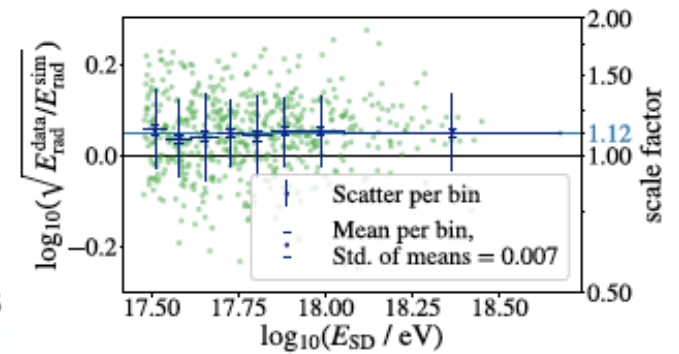
- Systematic uncertainty of energy scale $\Delta E/E = 14\%$
- Energy scale independently confirmed by Radio PoS(ICRC2025)292 T. Huege

All particle spectrum

Cherenkov:	$0^\circ < \theta < 60^\circ$	$E > 6 \times 10^{15}$ eV
750m:	$0^\circ < \theta < 55^\circ$	$E > 3 \times 10^{17}$ eV
Hybrid:	$0^\circ < \theta < 60^\circ$	$E > 3 \times 10^{18}$ eV
1500m:	$0^\circ < \theta < 60^\circ$	$E > 3 \times 10^{18}$ eV
1500m:	$60^\circ < \theta < 80^\circ$	$E > 4 \times 10^{18}$ eV



Radio energy scale wrt FD:
 1.120 ± 0.173 (sys) $^{+0.009}_{-0.008}$ (stat)



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

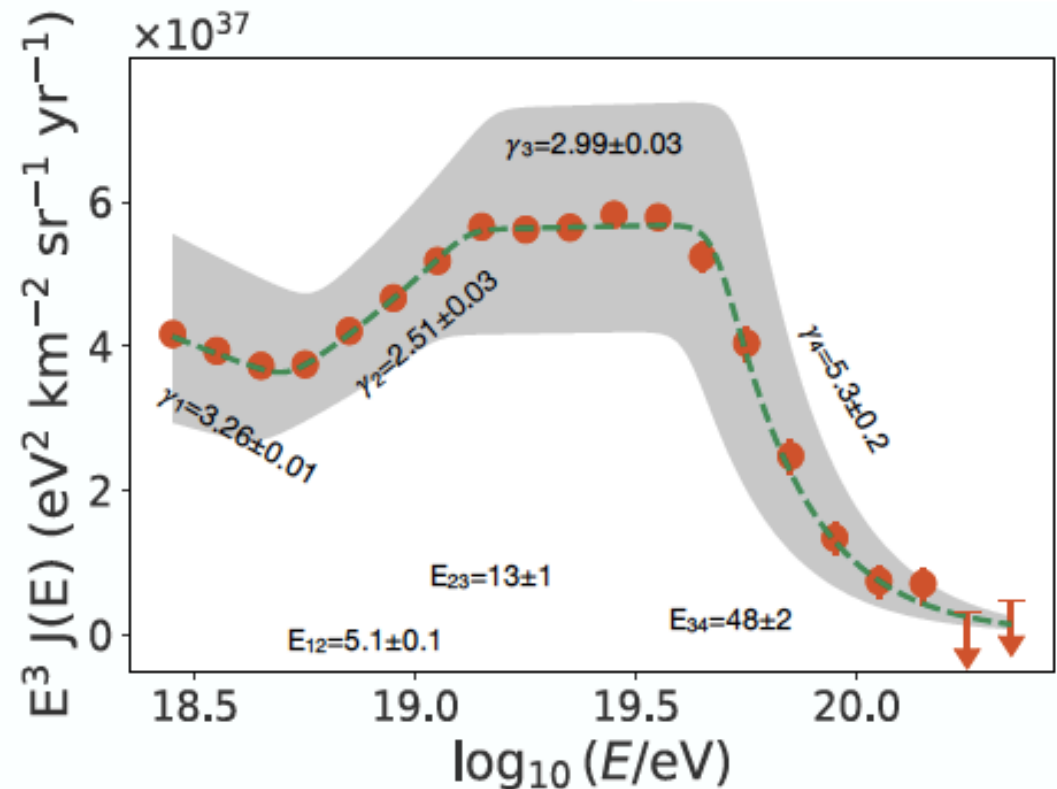
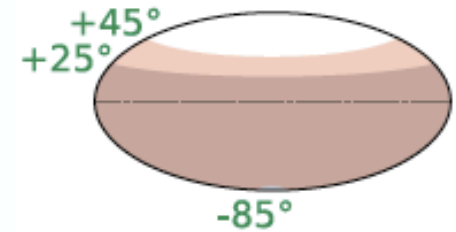
PoS(ICRC2025)292 Huege

*Based on Roth, M., ICRC2025

Combination of spectra

- Combination of data of 1500 m spacing
 $0^\circ < \theta < 60^\circ$ $E > 2.5 \times 10^{18}$ eV
 $60^\circ < \theta < 80^\circ$ $E > 4.0 \times 10^{18}$ eV
 performed in common declination band
 studying systematic effects
- 19 years of data
- Exposure $104\,900 \pm 3000$ km sr yr
- *Instep* feature significance above 5σ
- Is there a declination dependence?
- Potential imprint of dipole anisotropy?

Combined spectrum
for δ in $[-85^\circ, 45^\circ]$
Equatorial coordinates

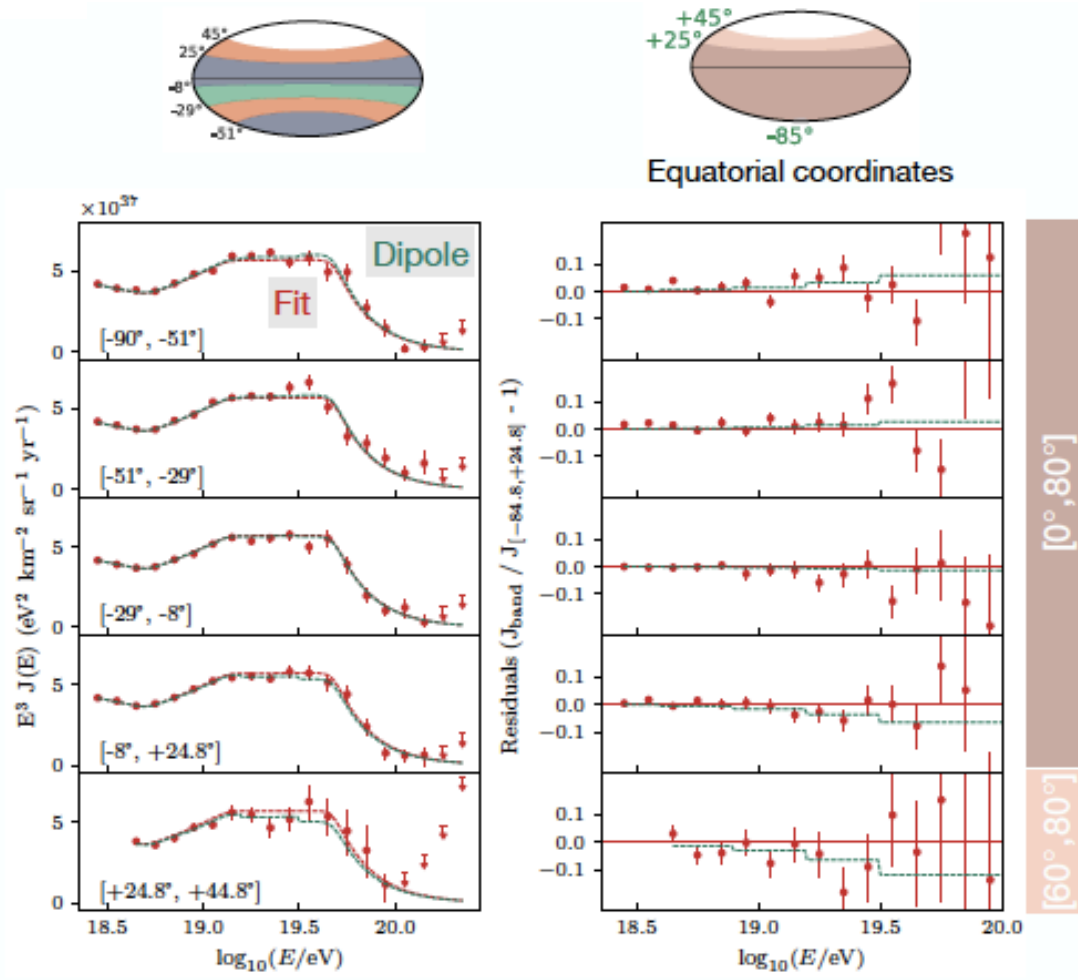
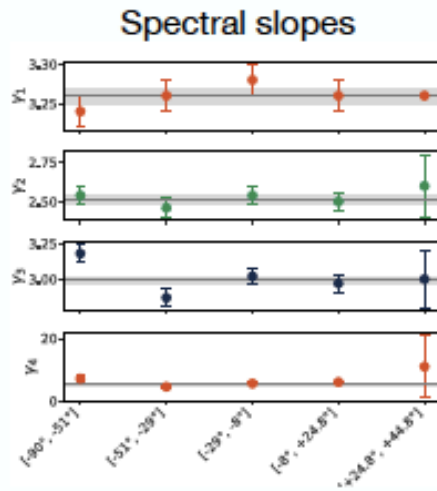


Declination dependent spectra

- Mild dipolar imprint; data follow expectations within stat. uncertainties
- No significant declination dependence up to $\delta = +45^\circ$
 - ➔ Disfavors origin of instep feature being attributed to distinctive spectrum of one/few foreground sources

Break energies

Ankle
Instep
Suppression



submitted to PRL
PoS(ICRC2025)370 D. Ravnani

*Based on Roth, M., ICRC2025

Karen S. Caballero Mora UNACH karen.scm@gmail.com

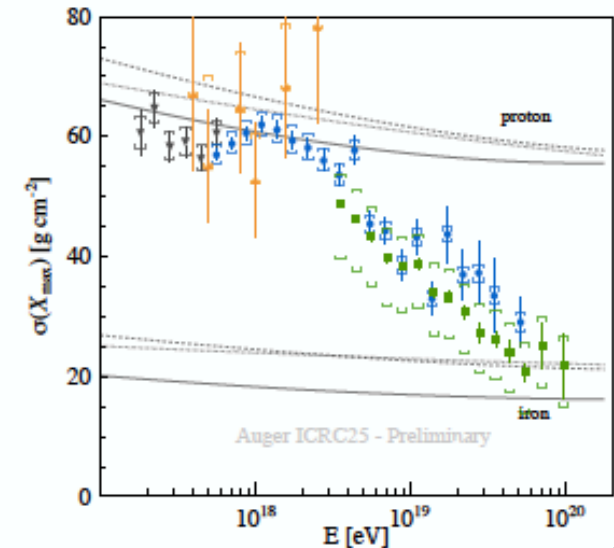
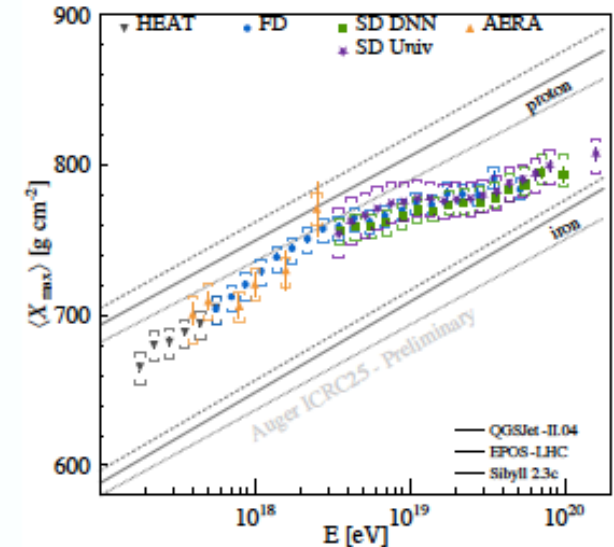
Phase-I Mass composition

Measurement from the

- Longitudinal profile (FD, ~15% Duty Cycle)
- Temporal and lateral distributions (SD, ~100% DC)
 - DNN
 - Universality
- Radio footprint (RD, ~100% DC)

PoS(ICRC2025)331 E. Mayotte
PoS(ICRC2025)284 S. Hahn

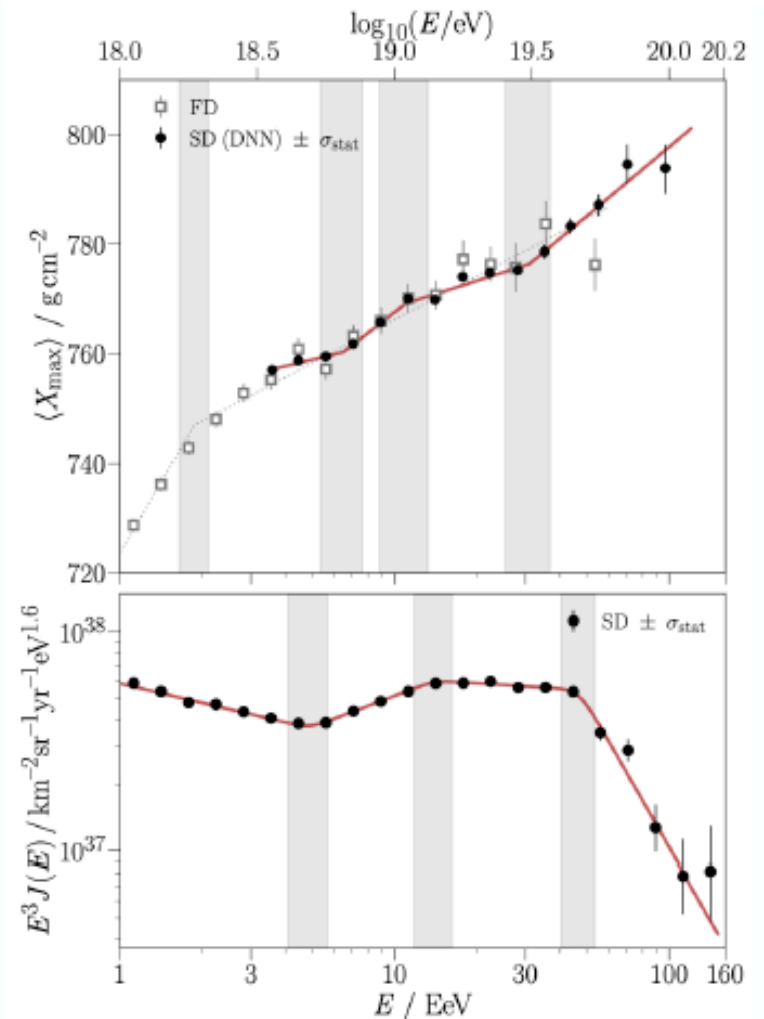
- $\langle X_{\max} \rangle$ gets lighter up to $\sim 2 \times 10^{18}$ eV and heavier above
- $\sigma(X_{\max})$ shows a trend towards heavier (and less mixed) composition above $10^{18.6}$ eV
- $\sigma(X_{\max})$ at highest energies
 - excludes large fraction of protons (DNN and FD) in agreement with IceCube *IceCube PRL 135 (2025)*
 - excludes the GZK as the dominant cause of spectral cutoff
 - X_{\max} shift needed in case of DNN analysis (~20%)



Xmax derived using DNNS

- Elongation rate agrees with FD when applying an offset of 31 g/cm²
- Clear evidence of structure in ER, best described with a three-break model
- Constant ER rejected at 4.6 σ
 - Incompatible with pure composition
- Kinks related to spectral features

parameter	3-break model	energy spectrum
val $\pm \sigma_{\text{stat}} \pm \sigma_{\text{sys}}$	val $\pm \sigma_{\text{stat}} \pm \sigma_{\text{sys}}$	val $\pm \sigma_{\text{stat}} \pm \sigma_{\text{sys}}$
$b / \text{g cm}^{-2}$	$750.5 \pm 3 \pm 13$	
$D_0 / \text{g cm}^{-2} \text{decade}^{-1}$	$12 \pm 5 \pm 6$	
E_1 / EeV	$6.5 \pm 0.6 \pm 1$	$4.9 \pm 0.1 \pm 0.8$
$D_1 / \text{g cm}^{-2} \text{decade}^{-1}$	$39 \pm 5 \pm 14$	
E_2 / EeV	$11 \pm 2 \pm 1$	$14 \pm 1 \pm 2$
$D_2 / \text{g cm}^{-2} \text{decade}^{-1}$	$16 \pm 3 \pm 6$	
E_3 / EeV	$31 \pm 5 \pm 3$	$47 \pm 3 \pm 6$
$D_3 / \text{g cm}^{-2} \text{decade}^{-1}$	$42 \pm 9 \pm 12$	



Phys. Rev. Lett. 134 (2025)
 Phys. Rev. D 111 (2025)
 PoS(ICRC2025)331 E. Mayotte

Mass composition of cosmic rays

- X_{\max} converted to average and variance of $\ln A$

Auger Collab. JCAP 02 (2013)
PoS(ICRC2025)331 E. Mayotte

- Inferring the mass composition depends on the hadronic interaction model

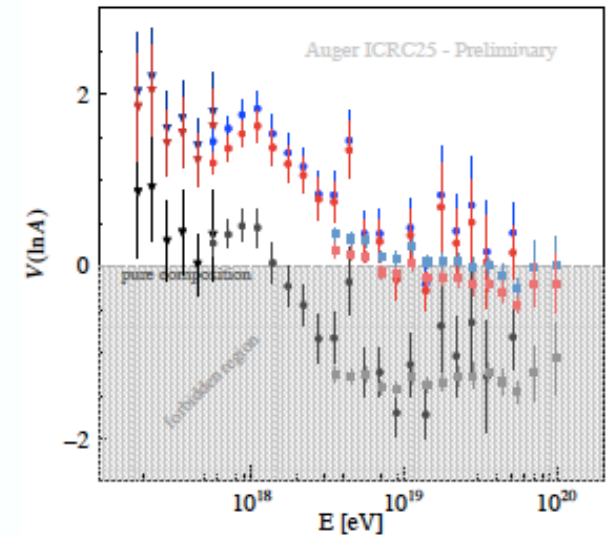
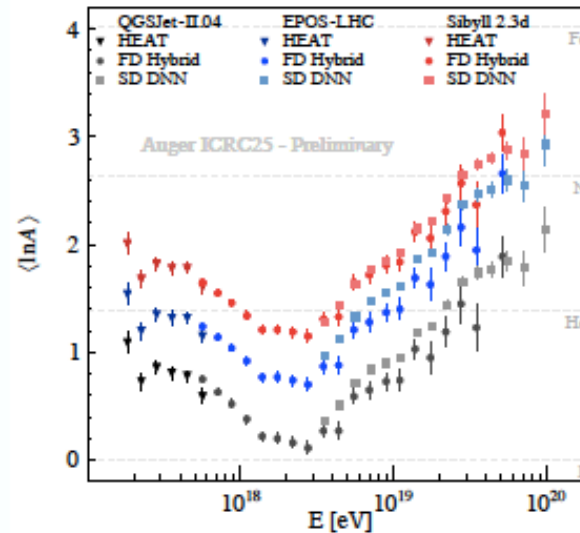
- $\sigma^2(\ln A) < 0$
Unphysical in case of QGSJet-II.04

- X_{\max} shift allowed by data, could alleviate the tension with QGSJet-II.04 (with additional cost of predicting heavier mass composition overall)

- Result challenges interpretation of observed flux features as purely proton-induced propagation effects

Phys. Rev. D 109 (2024)
PoS(ICRC2025)442 A. Yushkov

$$\langle \ln(A) \rangle = \ln(56) \frac{\langle X_{\max} \rangle - \langle X_{\max} \rangle_p}{\langle X_{\max} \rangle_{Fe} - \langle X_{\max} \rangle_p}$$



Phys. Rev. D 111 (2025)
Phys. Rev. Lett. 134 (2025)

Inelastic proton-proton Cross section at $\sqrt{s} \geq 40$ TeV

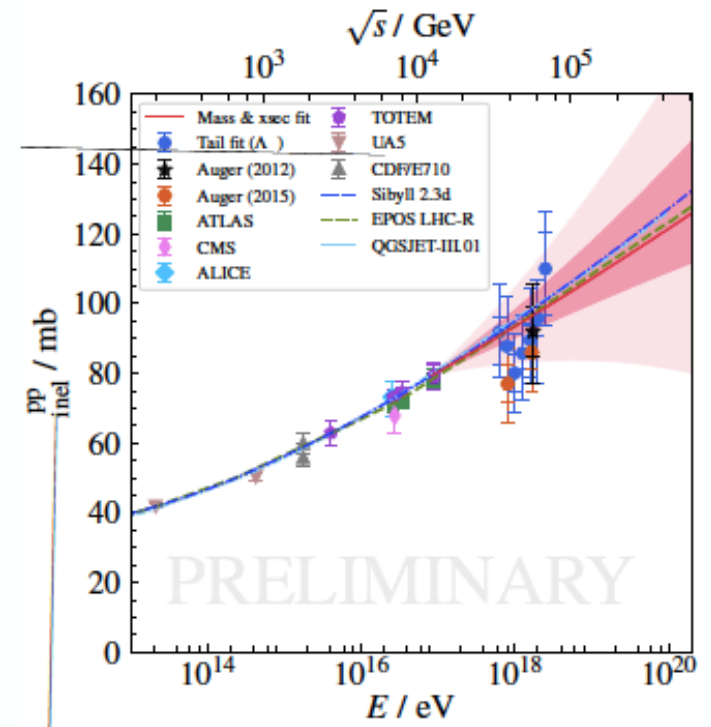
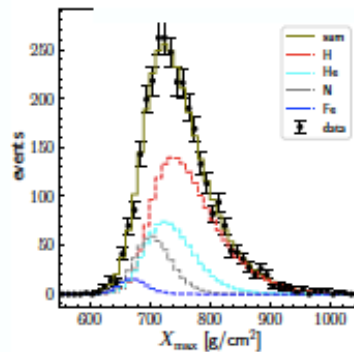
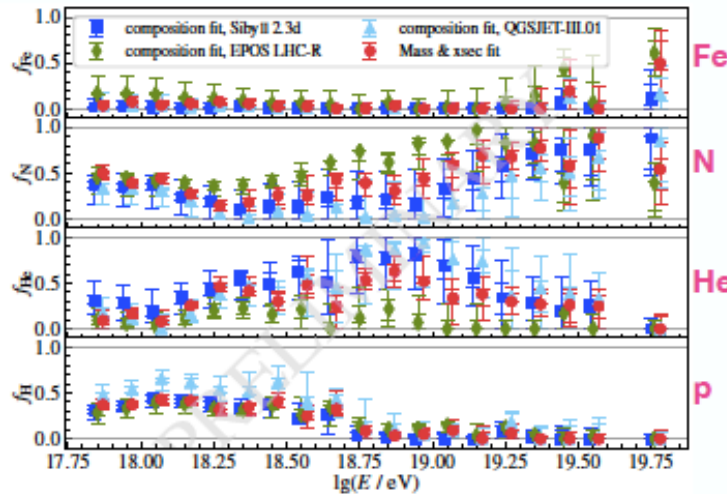
- Fits of the **fractional mass composition** of the derived from Hybrid data (full Phase I)

- **Simultaneous fit to X_{\max} distributions and x-section**

- X_{\max} scale included as free parameter addressing uncertainties in

- detector response and
- hadronic interaction models
- $\delta X_{\max} \sim 20$ g/cm²
- In agreement with SD analyses

Phys. Rev. D 109 (2024)
PoS(ICRC2025)431 J. Vicha

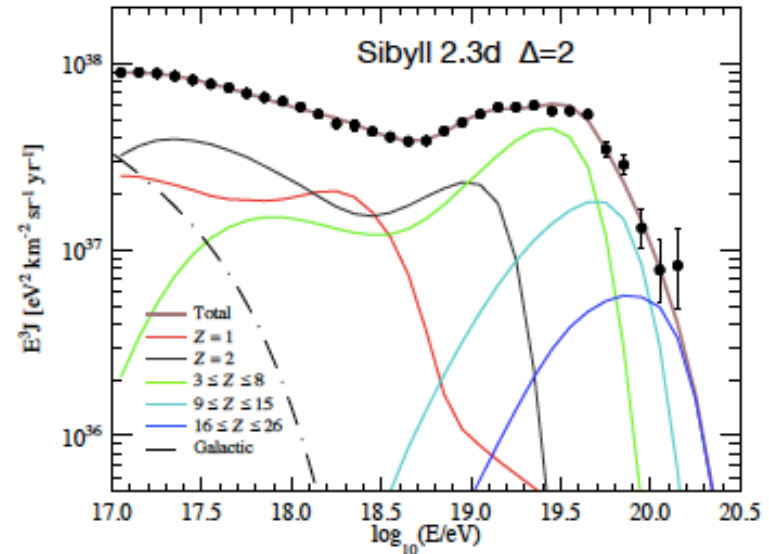


PoS(ICRC2025)416 O. Tkachenko

Mass Composition + Spectrum

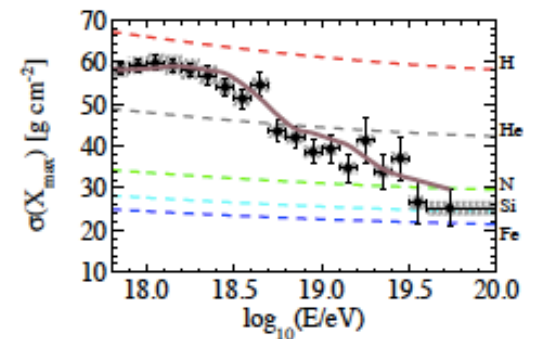
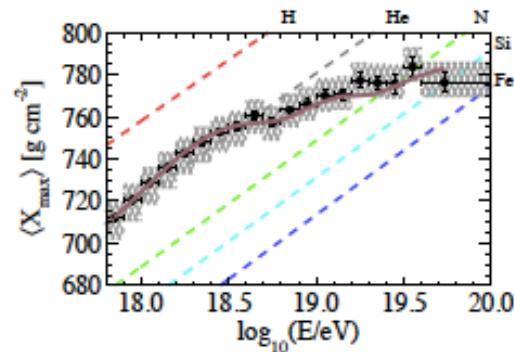
Combined fit above 0.1 EeV (energy and mass)

- Spectrum starting at $E=10^{17}$ eV
Composition starting at $E=10^{17.8}$ eV
- Extending fit below ankle requires
- Galactic component
Mollerach and Roulet JCAP 03 (2019) 017
- new low-energy extragalactic component (LE) consisting mostly of H, He and N with steep spectra



Need to suppress the steep
LE extragalactic component below few hundred PeV

→ Can naturally result from the expected
magnetic horizon suppression

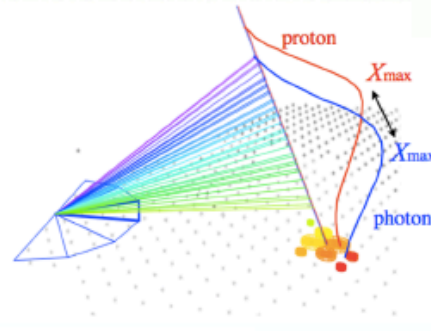


PoS(ICRC2025)373 E. Roulet

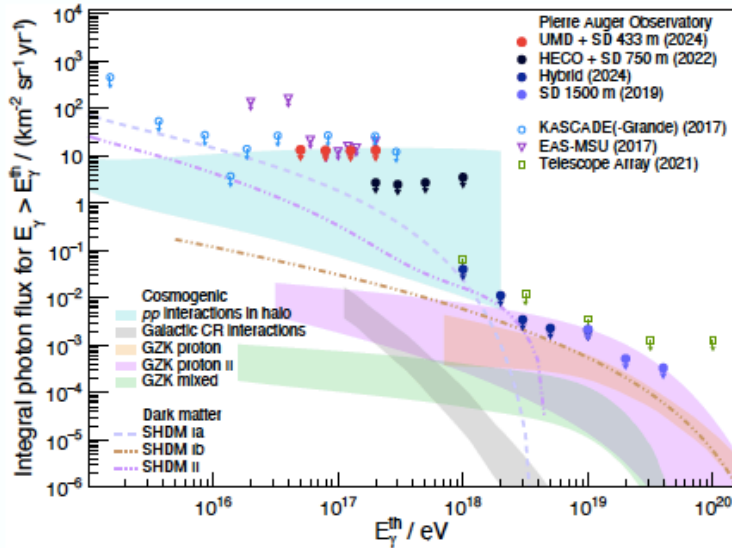
Multimessenger searches: Neutrinos and photons

γ search

- No candidates found; best available limits across 4 decades of energy
- Closing gap to lower energies thanks to analysis using UMD data



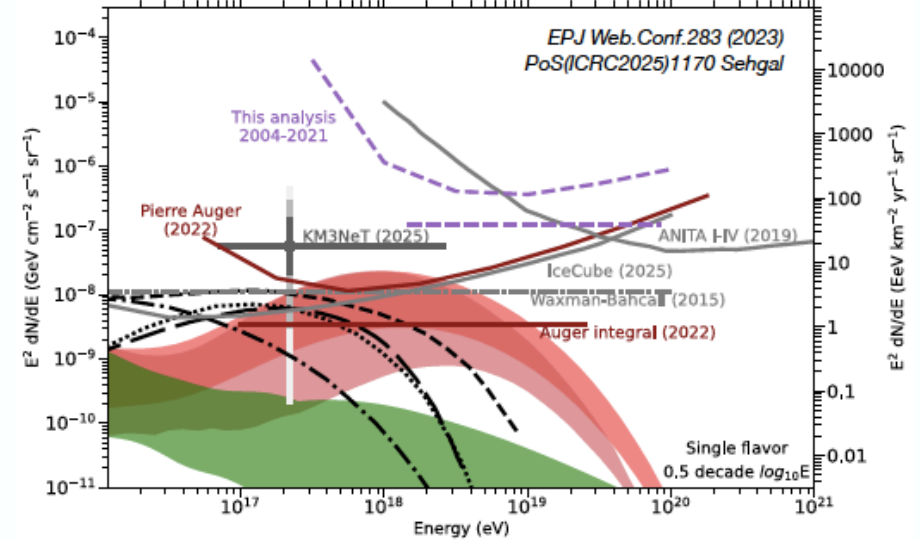
Phys. Rev. D 110 (2024)
JCAP 05 (2025)
PoS(ICRC2025)965 Savina



γ : Sensitivity reaches GZK predictions
Also used to constrain DM models

ν search

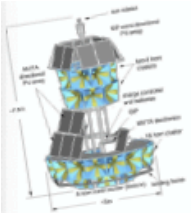
- No candidates found; best sensitivity slightly below 10^{18} eV
- Background very low, sensitivity limited by exposure
- Aperture comparable to that of IceCube if source direction is favourable



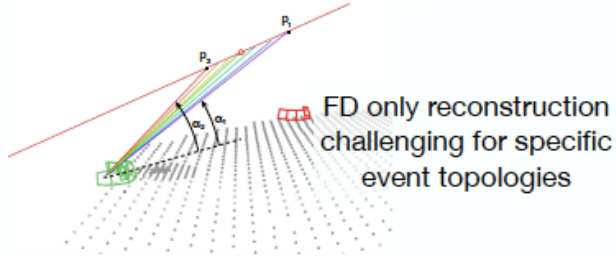
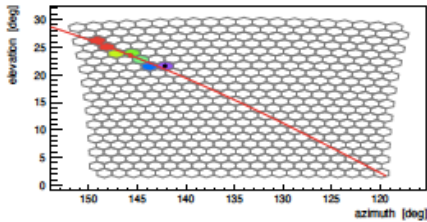
ν : Limits constrain GZK & astrophysical neutrino models

*Based on Roth, M., ICRC2025

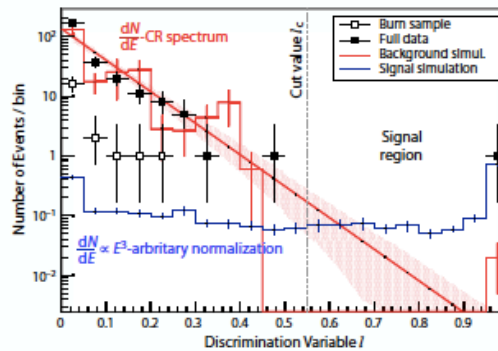
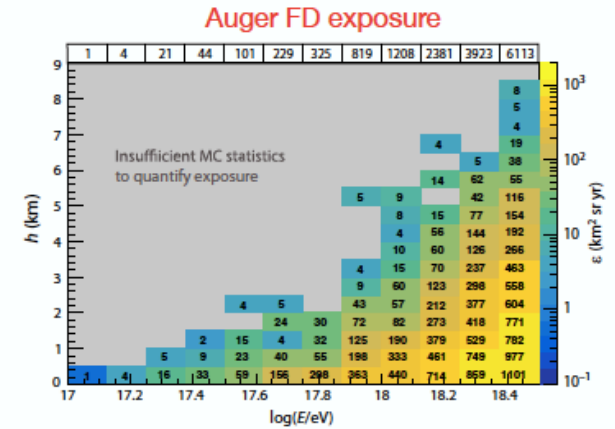
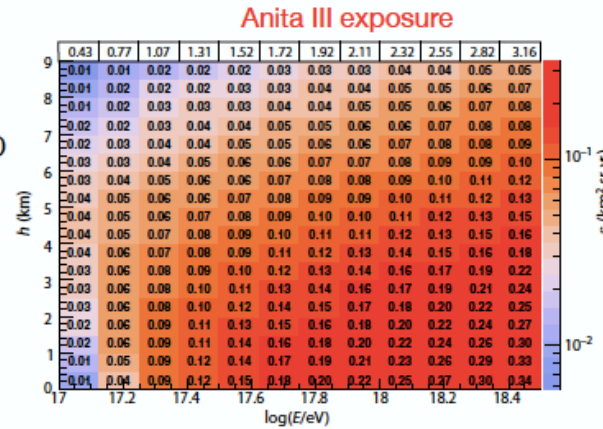
Search for upward-going air showers with Auger FD



- Two “anomalous” events detected by ANITA with non-inverted polarity:
 $E \sim 0,2 \text{ EeV}$; exit angle $\sim 30^\circ$
- Highly inclined events cannot be observed with SD
 \rightarrow Dedicated search using 14 years of FD data
- FD sensitivity depends on E and height of first interaction (factors larger wrt ANITA)



Exposure as function of E and height



1 candidate consistent with background of misreconstructed events (~ 0.3)

- Expected 59 (69) events for E^{-3} , flat in height
- Expected 12 (8) events for E^{-5} , flat in height
- Expected 18 (11) events for E^{-3} , tau-like decay
- With exposures of Anita I (Anita III)

Flux upper limits for E in $[0.1, 33] \text{ EeV}$

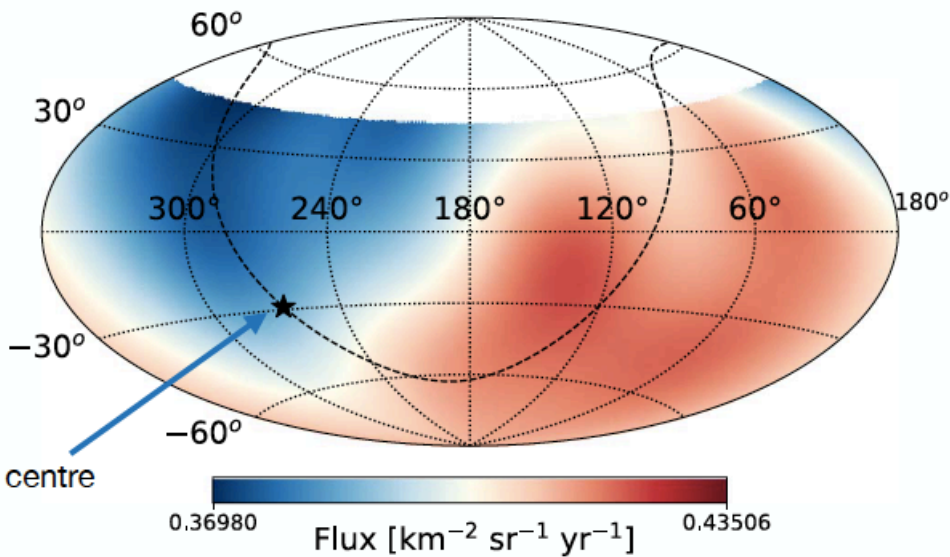
Auger results in strong tension with ANITA, even for very conservative assumptions

Phys. Rev. Lett. 134 (2025)

*Based on Roth, M., ICRC2025

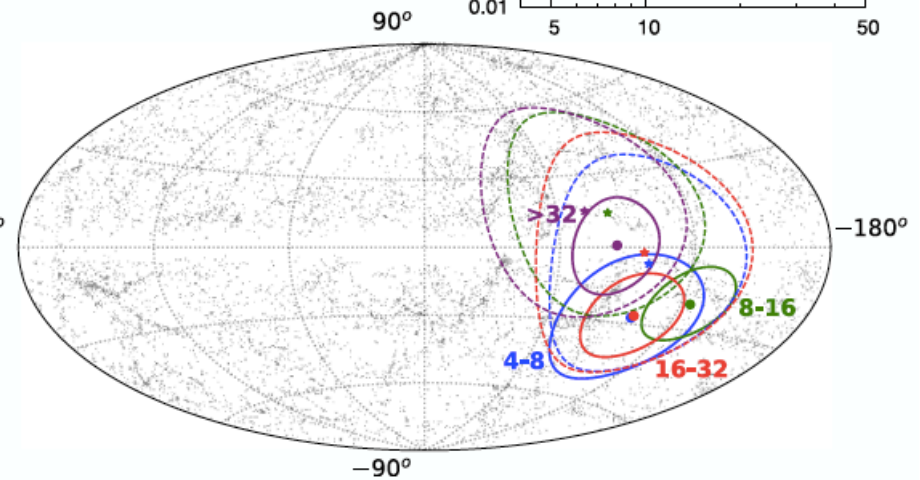
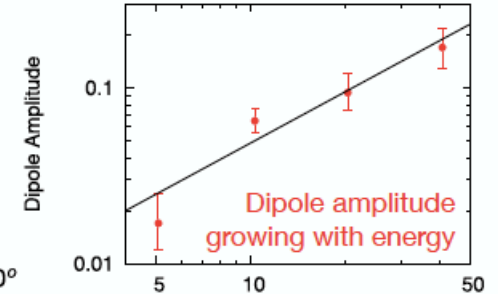
Large scale anisotropy

3D dipole above 8 EeV
in equatorial coordinates



- Significant modulation of $6.5^{+1.2}_{-0.9}\%$ at 6.8 σ level ($E > 8$ EeV)
- Direction 113° away from the Galactic center
 ➔ extragalactic origin of UHECRs above 8 EeV

Science 357 (2017)
ApJ 976 (2024)
PoS(ICRC2025)272 G. Golup



- Predictions for the direction of mean dipole (stars) and 68% CL contour regions (dashed lines) obtained for 103 realizations of source distribution (10^{-4} Mpc $^{-3}$)
- Data (solid lines)
- Gray dots: location of galaxies in IR catalog within 120 Mpc

Composition-driven anisotropy underway!

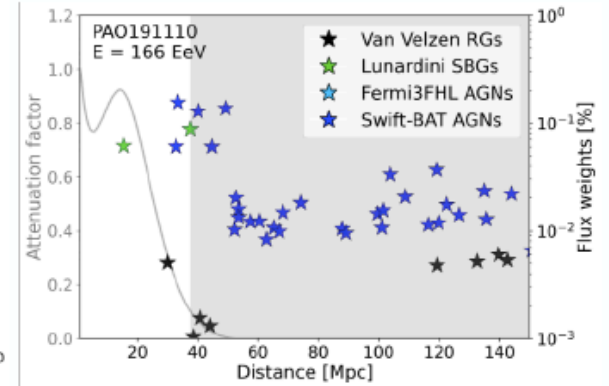
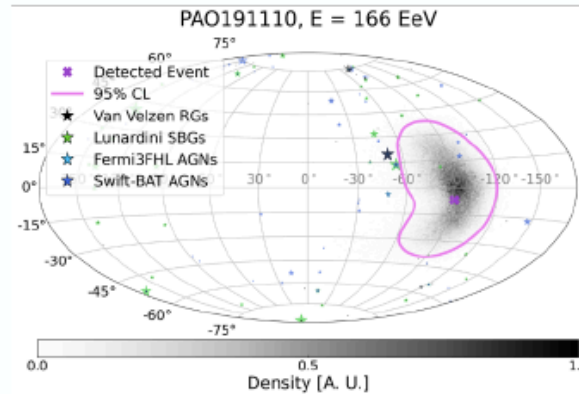
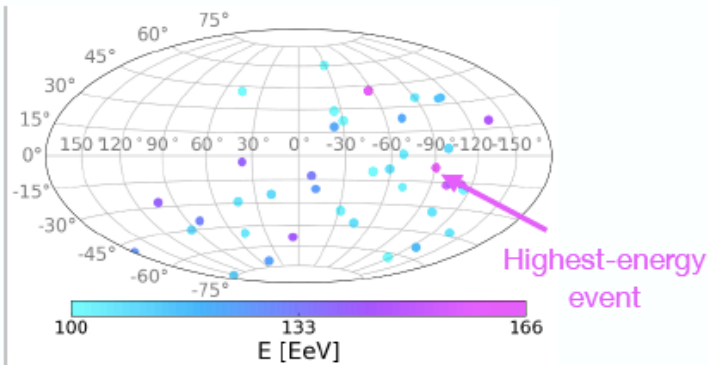
See T. Bister's highlight presentation on Monday: Probing UHECR sources

*Based on Roth, M., ICRC2025

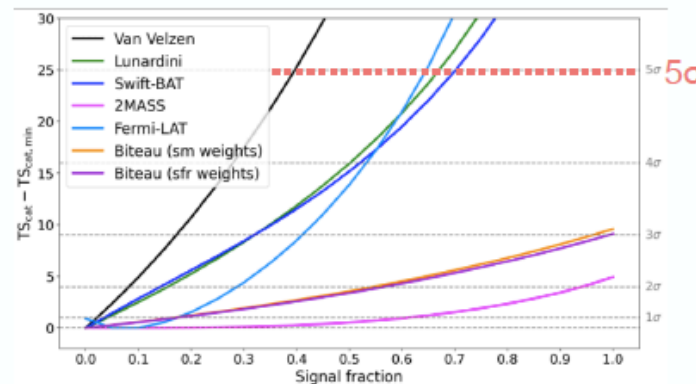
Constraining the origin of the highest-energy cosmic-ray events?

- 40 events above 100 EeV
Astrophys. J. Suppl. S. 264 (2023)
- 3D search using Galactic backtracking and accounting for limited horizon
- 6 classes of astrophysical sources
- 8 Galactic magnetic field models
- No EGMF

- 2 Methods applied:
 - event-by-event
 - likelihood-based analysis



Event-by-event: Backtracked positions of 39 of 40 events with $E \geq 100$ EeV are compatible with one or more sources

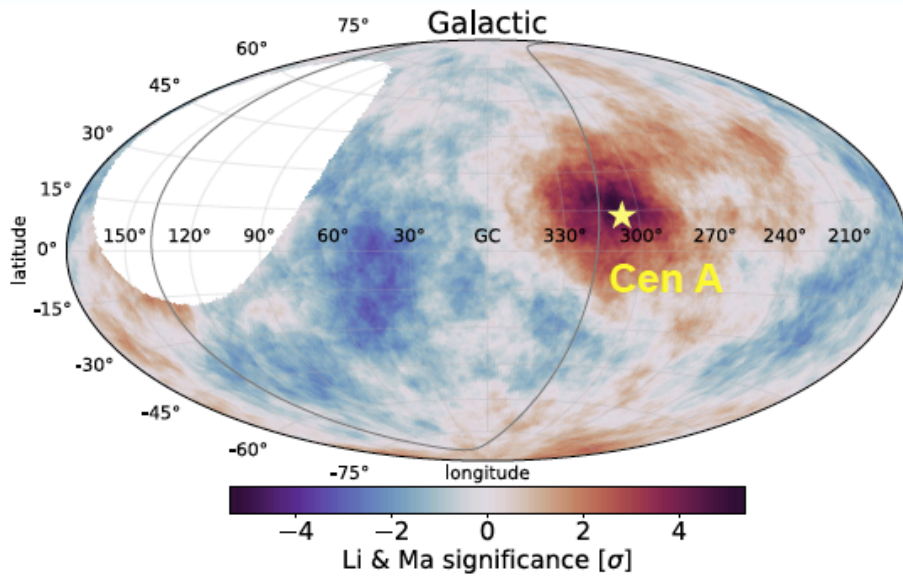


Likelihood-based analysis:

- Exclusion of fractions of signals for catalogs
- Only Fermi-LAT describes data better than isotropy for signal fractions $\leq 10\%$

*M. Unger, G. R. Farrar. Astrophys. J. 970 (2024)
PoS(ICRC2025)195 M. Bianciotto*

Arrival directions-high-energy anisotropy searches



Centaurus A region: $E > 38$ EeV, $\sim 27^\circ$ radius 4.0σ (post trial)

Starburst galaxies: $E > 38$ EeV, $\sim 25^\circ$ radius 3.8σ (post trial)

Astrophys. J., 935:170, 2022

PoS(ICRC2023) 252 G. Golup

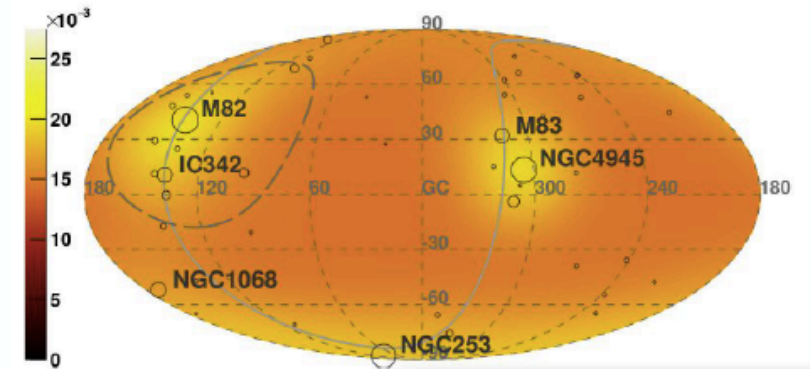
PoS(ICRC2025)177 L. Apollonio

Confirmed by common TA& Auger analysis

PoS(ICRC2025)282 A. Gálvez Ureña

Discovery level of 5σ expected only after 2025

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



Scanning the super galactic plane

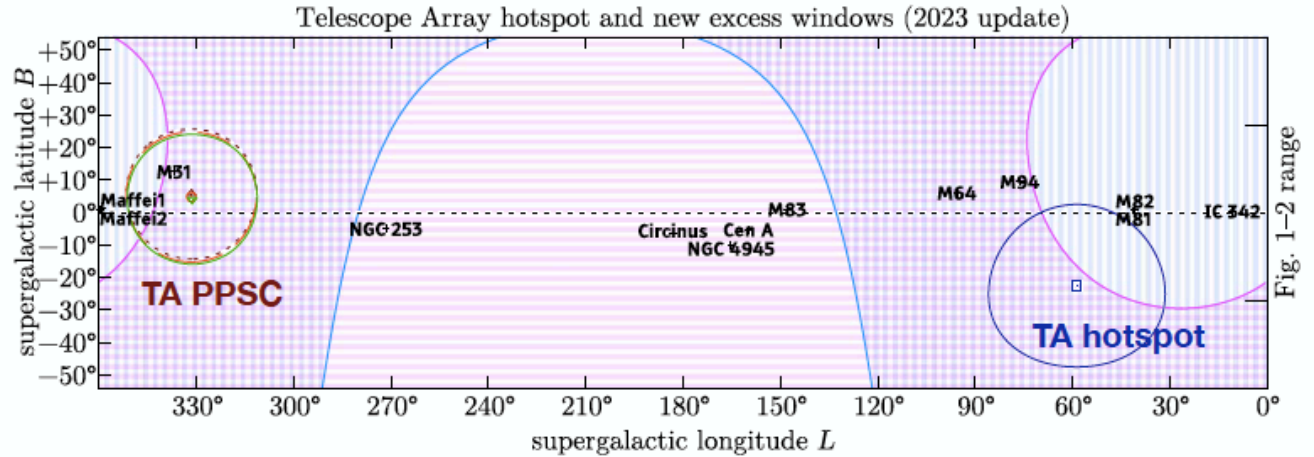
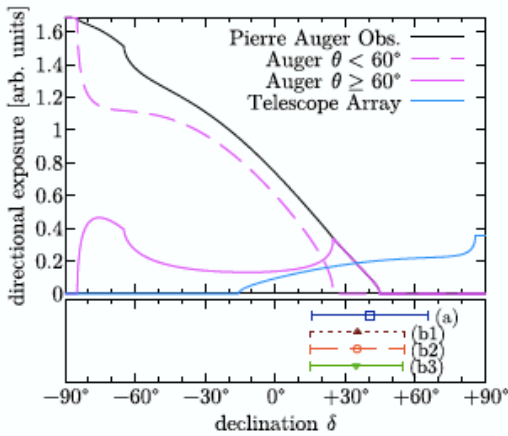


Fig. 1-2 range

	TA (Telescope Array Collaboration 2023)									Pierre Auger Observatory (This Work)								
	E_{min}	N_{tot}	$\frac{\epsilon_{in}}{\epsilon_{tot}}$	N_{bg}	N_{in}	$\frac{\Phi_{in}}{\Phi_{out}}$	Z_{LM}	99% L.L.	post-trial	E_{min}	N_{tot}	$\frac{\epsilon_{in}}{\epsilon_{tot}}$	N_{bg}	N_{in}	$\frac{\Phi_{in}}{\Phi_{out}}$	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	

No hint for excesses in TA "spots" with data of comparable size

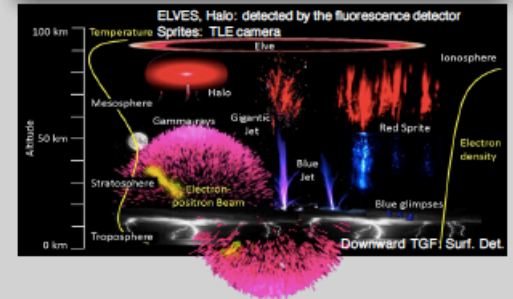
At variance with claim of TA that declination dependent spectrum due to presence of excesses in particular regions of the Northern sky

Astrophys. J., 984 123, 2025
 PoS(ICRC2025)177 L. Apollonio

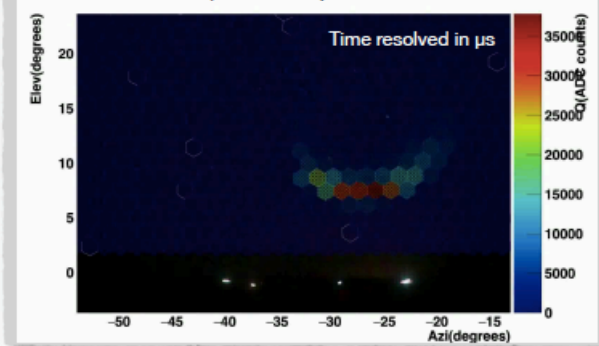
*Based on Roth, M., ICRC2025

Auger as a cosmo-geophysics laboratory

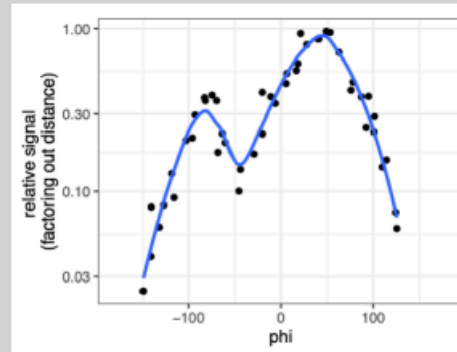
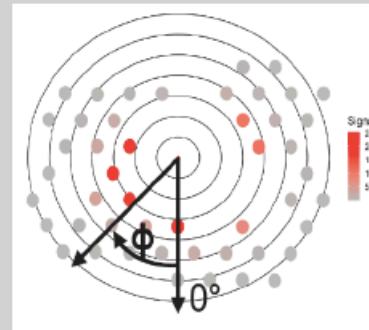
Zoo of atmospheric phenomena powered by sun and thunderstorms



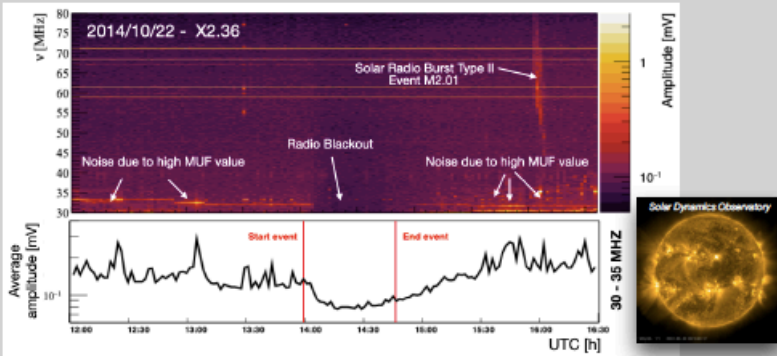
Simultaneous FD observations of multiple ELVES and SPRITES
PoS(ICRC2025)342, Mussa



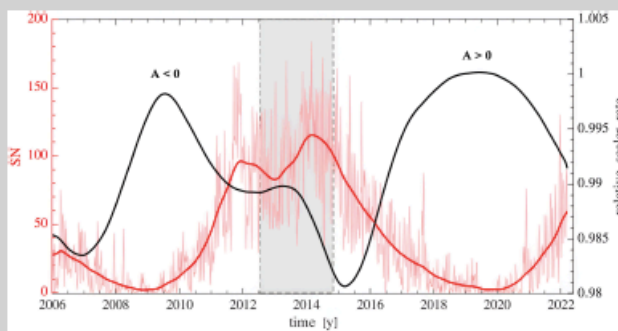
Characterization of downward Terrestrial Gamma-ray Flashes
PoS(ICRC2025)223 R. Colalillo



Study of solar activity with AERA
Radio blackouts PoS(ICRC2025)1332 R. de Almeida



Scaler data as proxy of solar activity
PoS(ICRC2025)1370, C. Taricco



*Based on Roth, M., ICRC2025

AugerPrime

Radio upgrade
➔ Independent energy scale



Scintillator ➔ Composition



New electronics ➔ New triggers



Underground muon detector
➔ Direct muon measurements



High-dynamic range PMTs
➔ High precision data

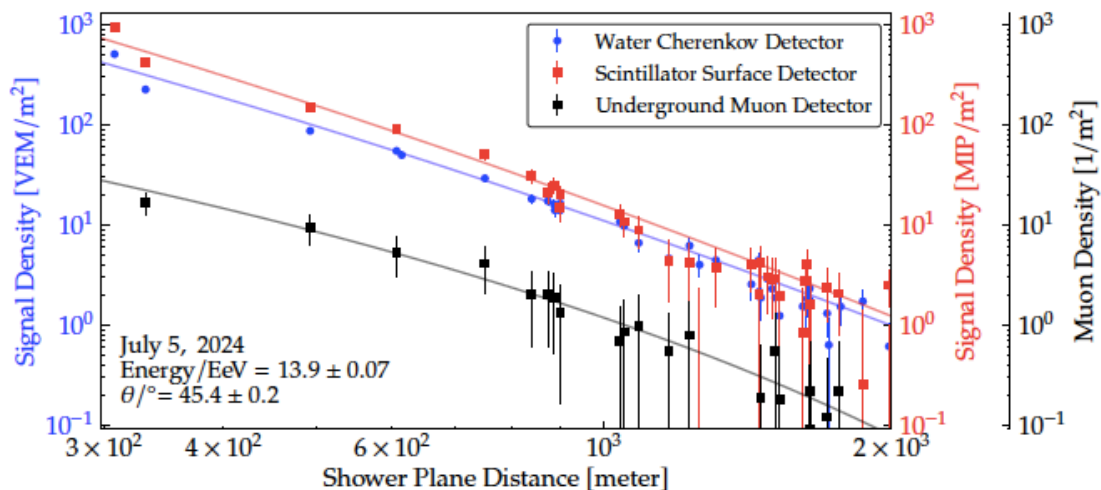
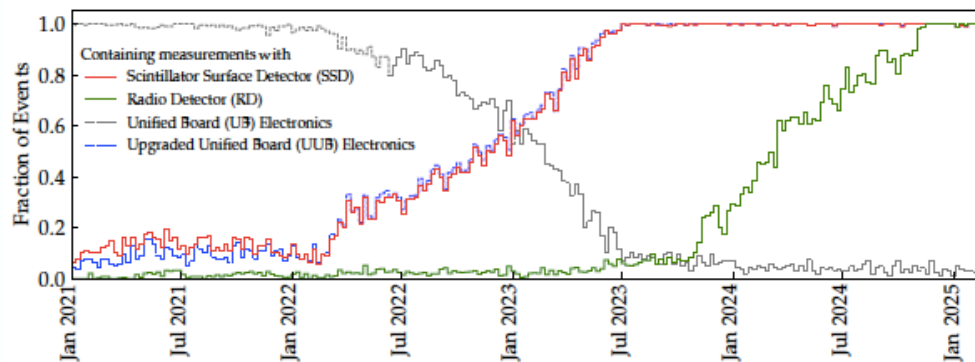
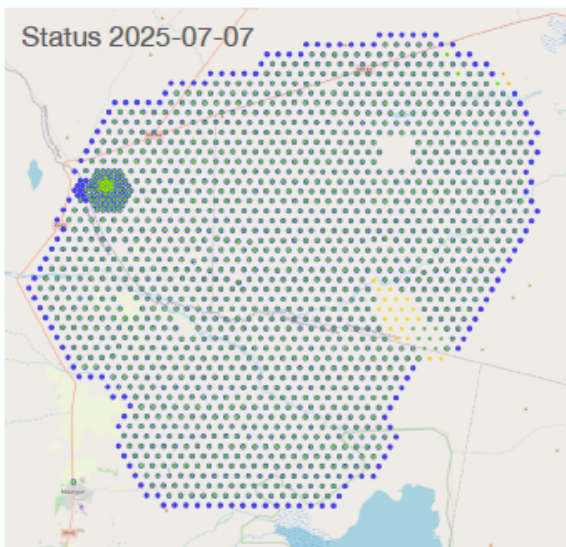


Towards multi-hybrid observations of extensive air showers

Successful multihybrid data acquisition by AugerPrime

AugerPrime (7/2025)

- 1479 scintillators installed
- 1529 with new electronics (incl. rim)
- 1584 radio antennas



PoS(ICRC2025)385 D. Schmidt

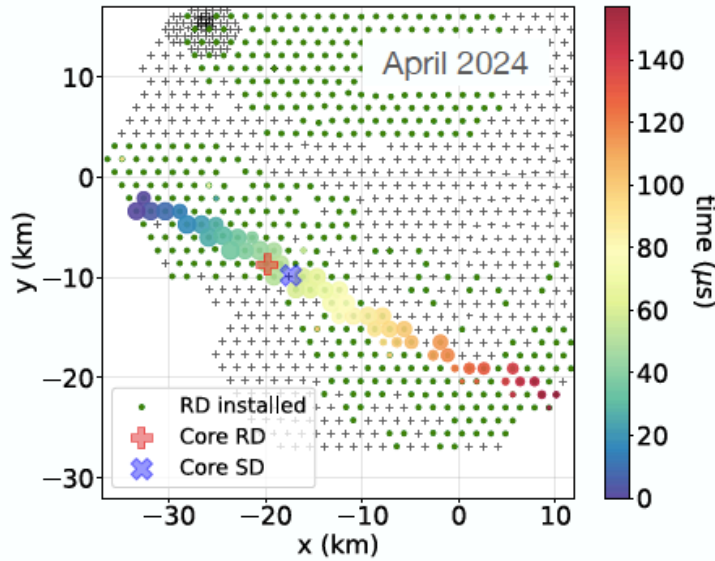
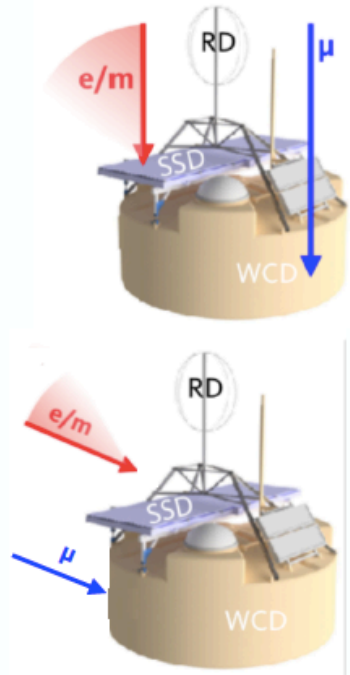
*Based on Roth, M., ICRC2025

Advent of AugerPrime: data start flowing in

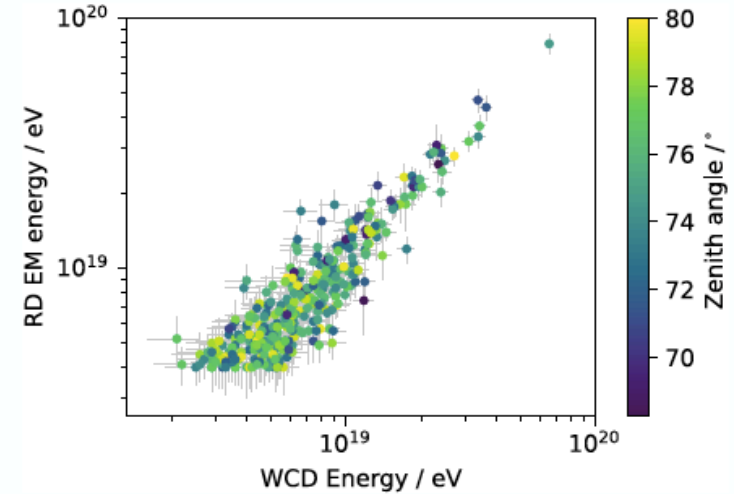
RD: most extended radio event detected so far

Sensitivity:

- WCD & RD: inclined events
- WCD & SSD: vertical events



	RD	SD
Azimuth (deg)	156.9±0.1	156.8±0.1
Zenith (deg)	84.8±0.1	84.7±0.1
Energy (EeV)	32±4	29±2



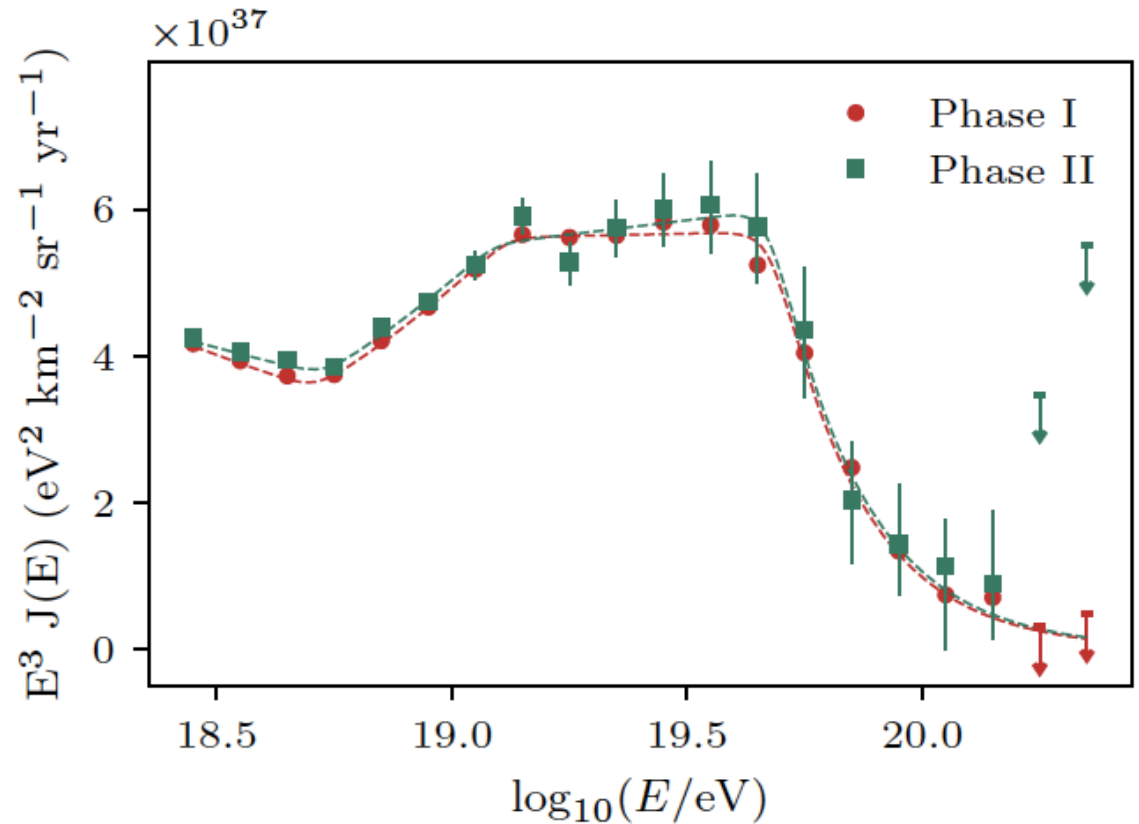
SD and RD data well in agreement

PoS(ICRC2025)385 D. Schmidt
 PoS(ICRC2025)294 J. Hörandel

*Based on Roth, M., ICRC2025

Phase II – Physics data look very promising

- Reusing analysis chain of Phase I as WCD data backward compatible
- Exposure: $9200 \pm 300 \text{ km}^2 \text{ sr yr}$
~10% Phase I
- Consistent spectra of Phase I and II
- High confidence in incoming data



Shaping the future

— Observatory as testbed for next generation arrays

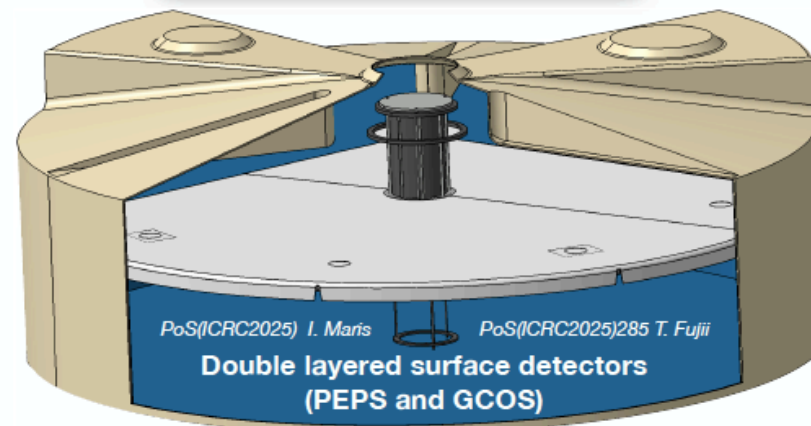
PoS(ICRC2023)303 F. Bradfield



PoS(ICRC2025)1024 B. de Errico



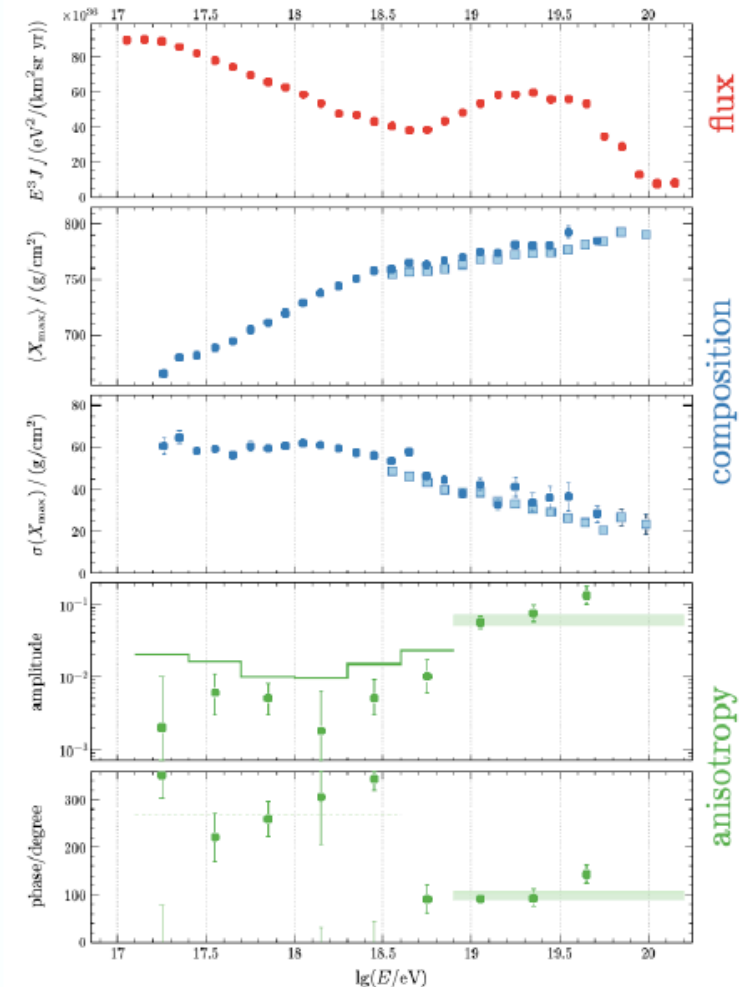
PoS(ICRC2025)387 F. Schröder



Summary

- Auger data contribute to **increasingly consistent picture** of UHECR challenging basic scenarios, such as UHECR-proton paradigm, but... this is not the end of the story!
- Upgrade **AugerPrime implemented**, Phase II started
- Towards a 100% duty cycle collection of multi-hybrid events
 - ➔ AugerPrime will push understanding of **UHECR source characteristics, particle physics aspects and fundamental physics**

- Many aspects **not addressed** in this presentation, e.g. limits for **BSM physics, muon deficit, testing air-shower modeling, calibration, outreach, ...**
- **Auger open data**, see <https://opendata.auger.org/>



utz
Bukux-awulú
Tioj-bätyix
iGRACIAS!
Miac tlazocamatic
NIB ÓOLA
Diosí meyamu
Hocolawal
Ts'akatal
Tak'
dyos bo'otik

Back up slides

Hybrid detection

Fluorescence Detector (FD):

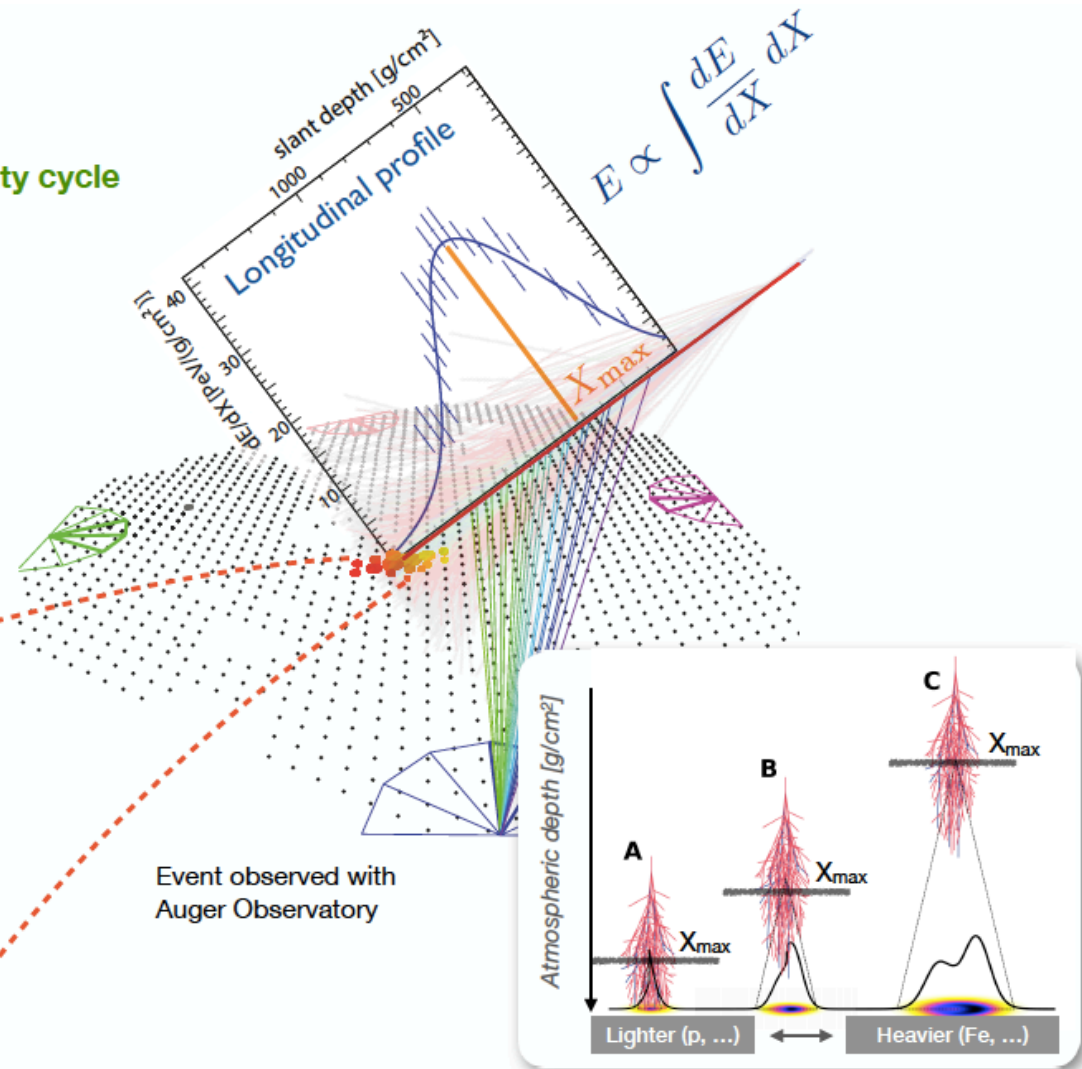
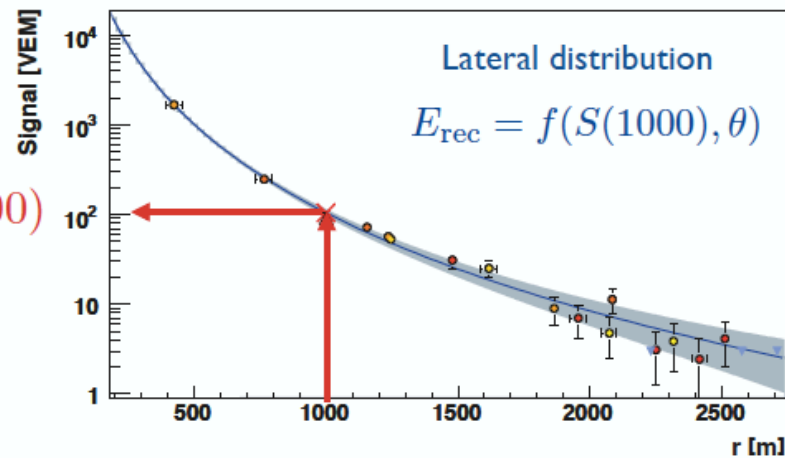
- calorimetric measurement of energy
- ca. 15% duty cycle

Surface Detector (SD):

- data driven shape of Lateral Distribution function (LDF)
- optimal distance at 1000 m
- ca. 100% duty cycle

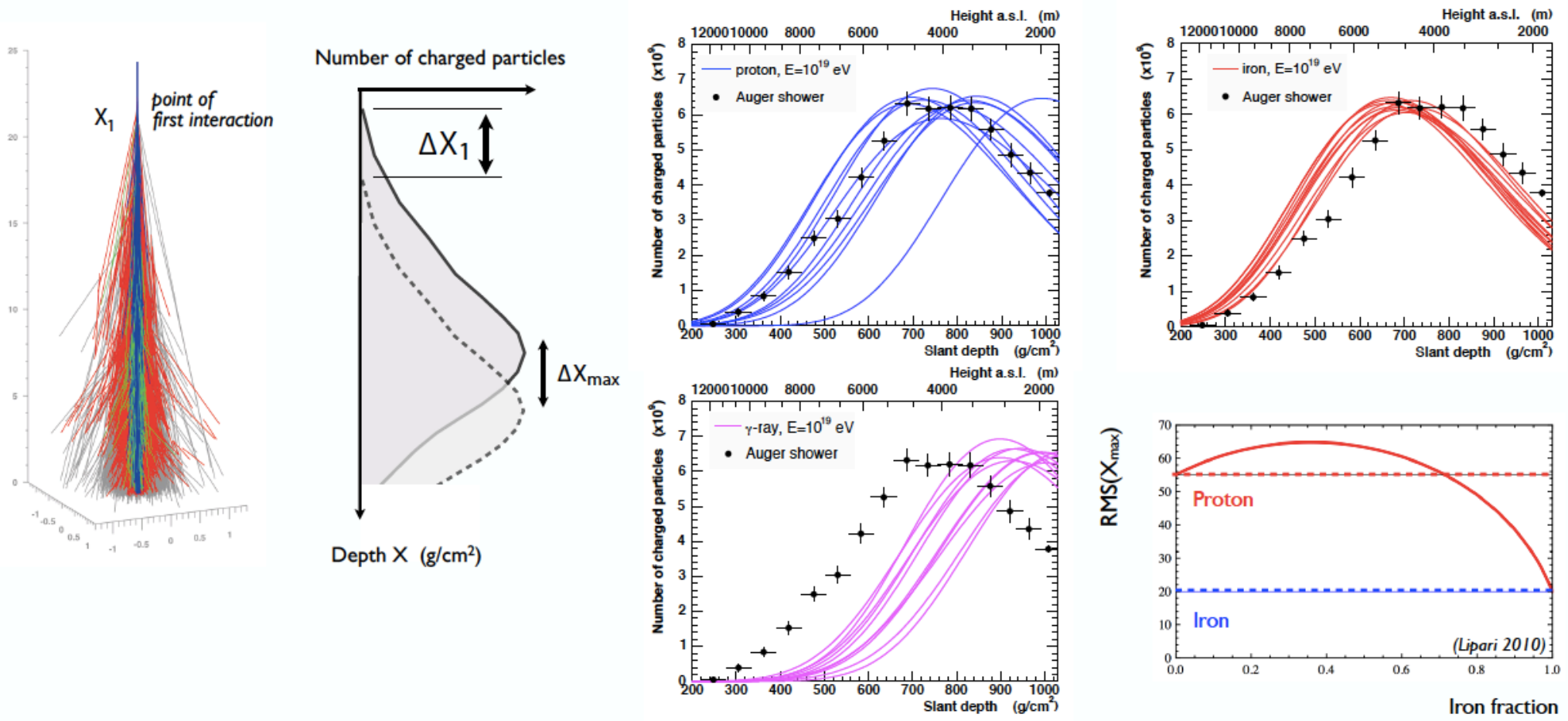
15% duty cycle

100% duty cycle



*Based on Roth, M., ICRC2025

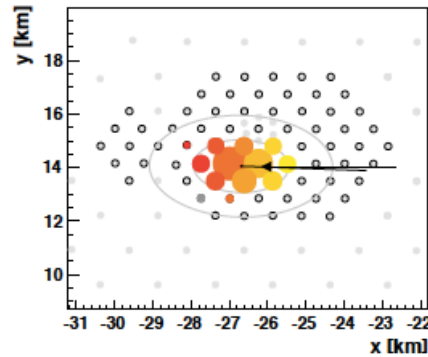
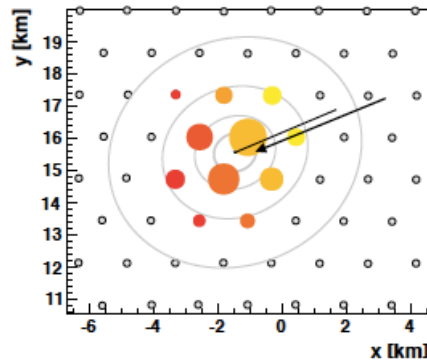
Mass composition: Depth of shower maximum



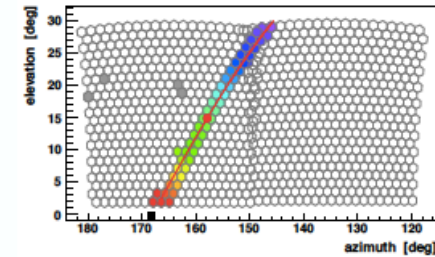
*Based on Roth, M., ICRC2025

Phase I data: Footprint on ground depends on geometry and energy

1500 m
 $\theta < 60^\circ$
 100% eff.
 @ 3 EeV
 $E = A S_{38}^B$

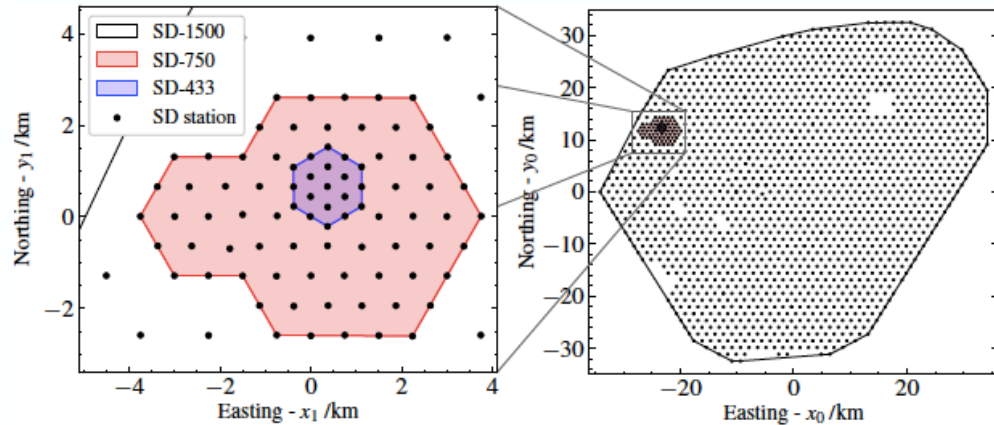
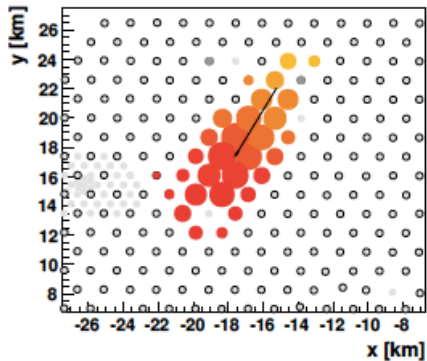


• 750 m
 • $\theta < 55^\circ$
 • 100% eff.
 @ 0.3 EeV
 • $E = A S_{35}^B$



• FD + 1 SD station
 • $\theta < 60^\circ$
 • 100% eff.
 @ 1 EeV
 • $E = E_{FD}$

1500 m
 $60^\circ < \theta < 80^\circ$
 100% eff.
 @ 4 EeV
 $E = A N_{19}^B$
 N_{19} by definition independent of θ



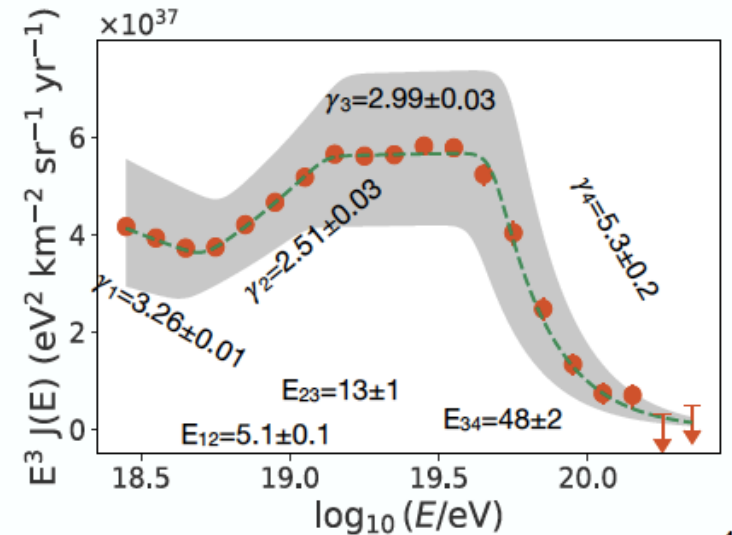
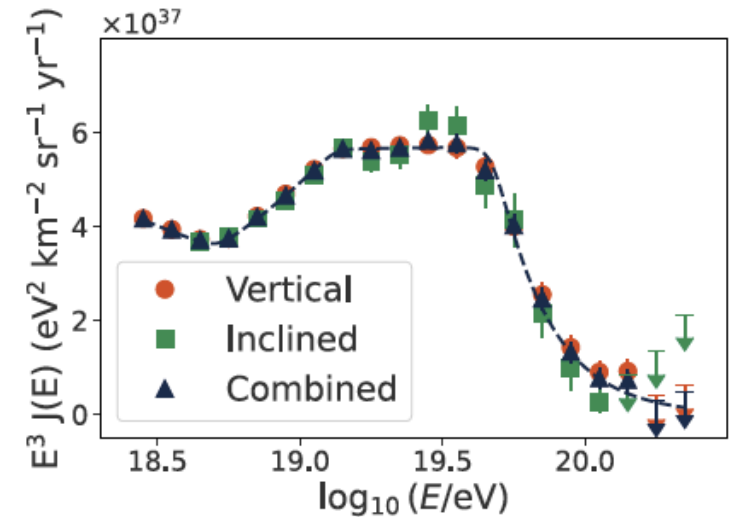
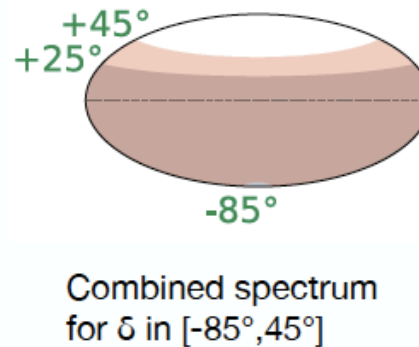
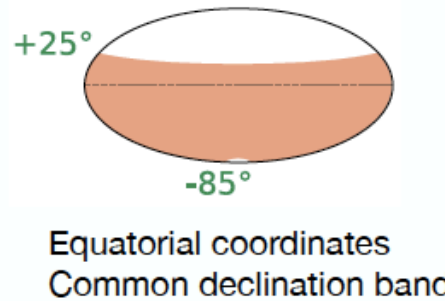
*Based on Roth, M., ICRC2025

Combination of spectra

- Combination of data of 1500 m spacing
 - $0^\circ < \theta < 60^\circ$ $E > 2.5 \times 10^{18}$ eV
 - $60^\circ < \theta < 80^\circ$ $E > 4.0 \times 10^{18}$ eV
 performed in common declination band studying systematic effects

- 19 years of data
- Exposure $104\,900 \pm 3000$ km sr yr
- Instep feature significance above 5σ

- Is there a declination dependence?
- Potential imprint of dipole anisotropy?

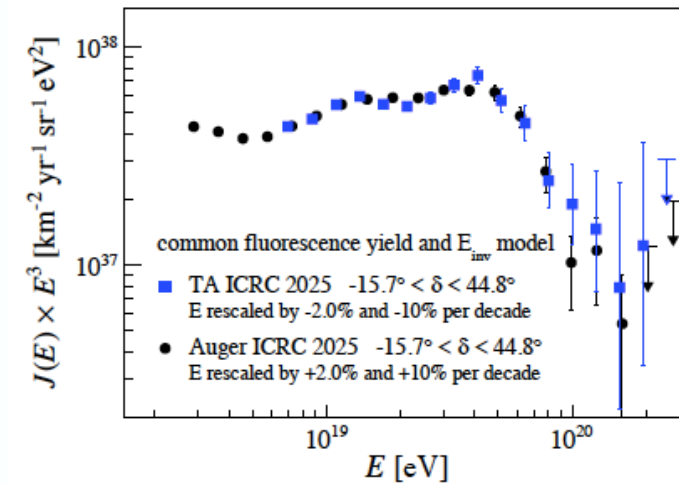
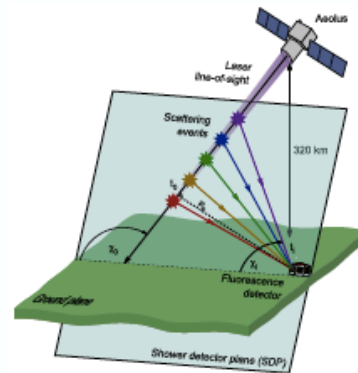
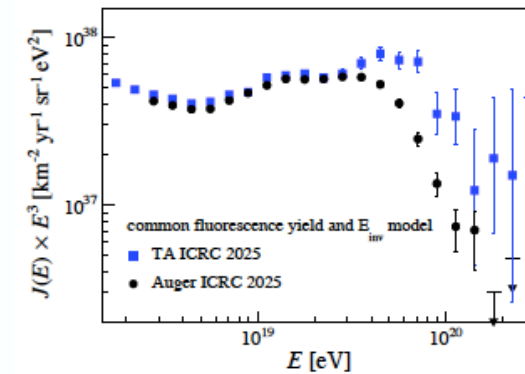
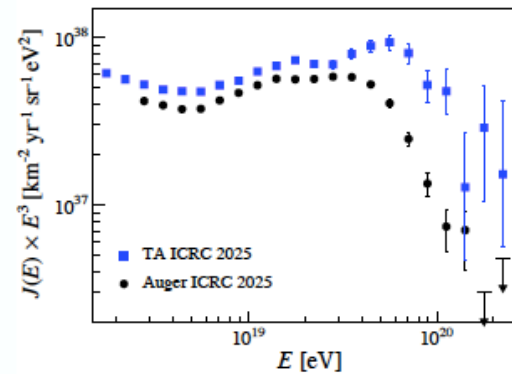


submitted to PRL
PoS(ICRC2025)370 D. Ravnani

*Based on Roth, M., ICRC2025

Declination dependent spectra: TA & Auger

- Tension of Auger and TA spectra at highest energies
- Usage of same fluorescence yield
 - ➔ agreement below suppression region within 4%; well within systematic uncertainty of 14%
- In common declination band using same E_{inv} model
 - Rescaling by 2% each
 - In addition energy rescaling of $\pm 10\%$ /decade
 - ➔ Tension resolved; evolving mass composition may explain the difference
- Controlling systematic uncertainties related to detector response of utmost importance
- Ways forward:
 - Scintillator detectors (SSDs) (PoS 385; Schmidt)
 - Auger@TA installation (PoS 182; Bartz Mocellin)
 - EarthCARE (PoS 422; Unger)



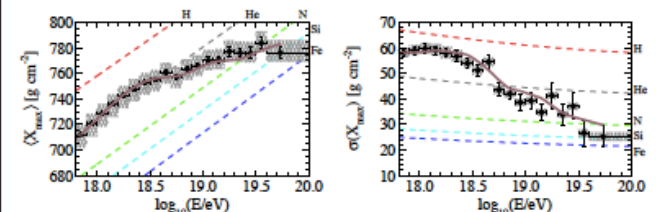
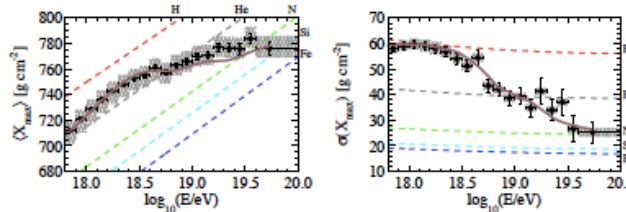
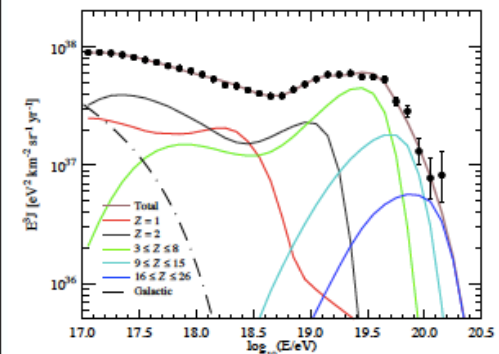
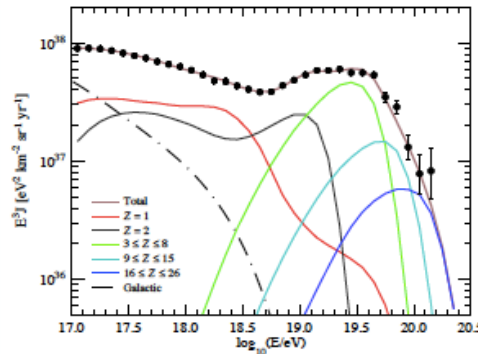
(PoS XXX; Salamida)

*Based on Roth, M., ICRC2025

Combined fit above 0.1 EeV (energy and mass)

- Previous analyses:
 - Fit with one population above ankle $E > 10^{18.7}$ eV (JCAP 04 (2017) 038)
 - Fit with two populations across ankle $E > 10^{17.8}$ eV (JCAP 05 (2023) 024)

- NOW: (PoS 840; Roulet)
 - Extending fit below ankle requires new low-energy extragalactic low energy component (LE) consisting mostly of H, He and N with steep spectra
 - H dominated for EPOS
 - He dominated for Sibyll



Need to suppress the steep LE extragalactic component below few hundred PeV
 → Can naturally result from the expected magnetic horizon suppression

(PoS 373; Roulet)

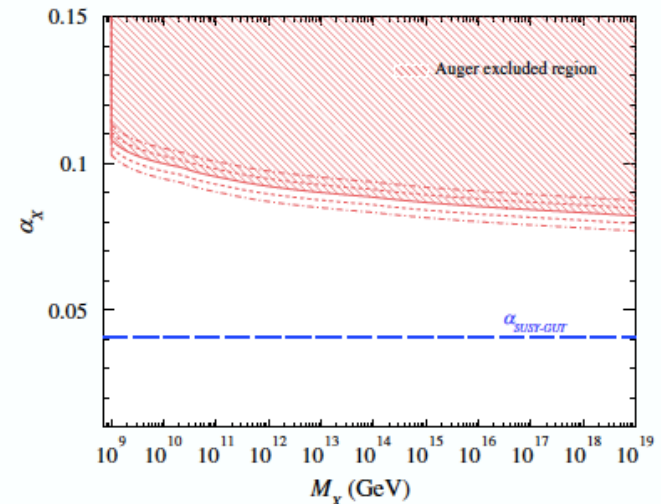
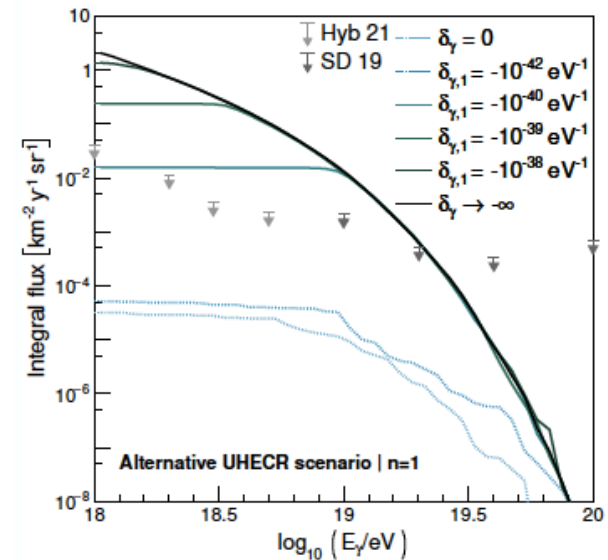
*Based on Roth, M., ICRC2025

Non-standard physics

- Violations of Lorentz invariance could modify cross section and threshold of interactions of UHECRs and secondary particles *JCAP01 (2022)*
- Decay products of super-heavy dark matter particles constrained with UHECR measurements (non-observation of cosmogenic particles) *PRL 130 (2023)*

Current sensitivity to several aspects of non-standard physics strongly affected by determination of proton fraction

➔ AugerPrime will contribute significantly to improve these constraints



*Based on Roth, M., ICRC2025

Composition informed dipole

- Assuming composition model reproducing Auger measurements (FD; EPOS-LHC)

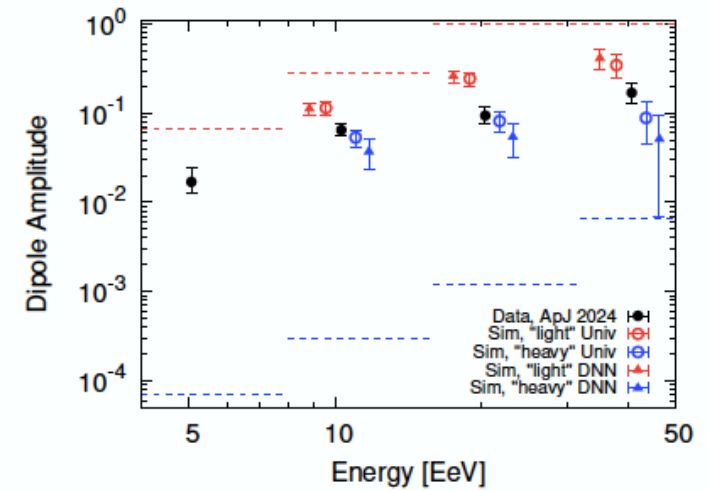
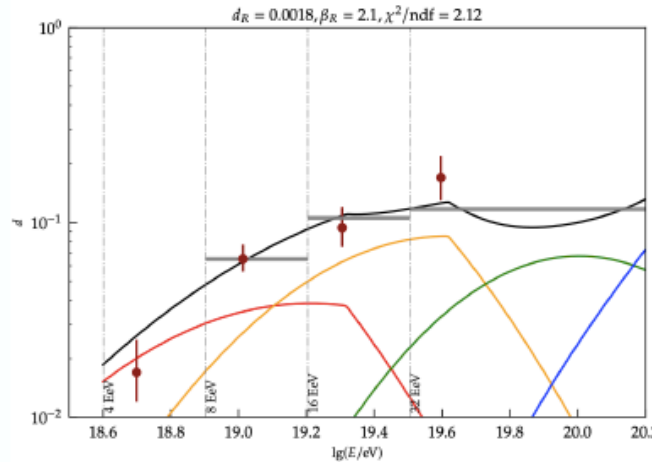
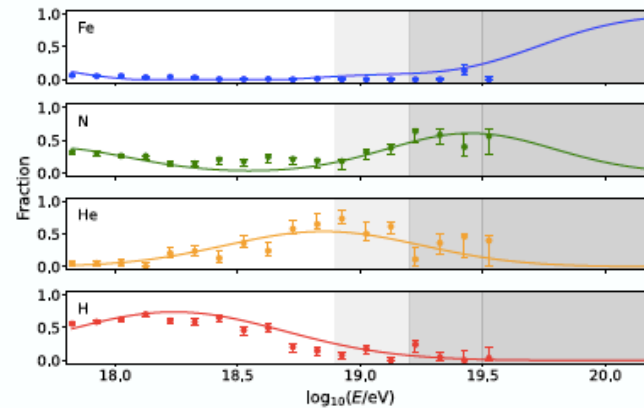
- Dipole amplitude as function of rigidity (E/Z):

$$d(E, Z) = d_R \left(\frac{E/E\text{eV}}{Ze} \right)^{\beta_R}$$

- Tested with 2 different reconstruction methods (Universality & DNNs)

- Separation of light and heavy by standardized mean difference

$$\text{SMD} = \frac{|d_{\text{light}} - d_{\text{heavy}}|}{\sqrt{\sigma_{\text{light}}^2 + \sigma_{\text{heavy}}^2}}$$



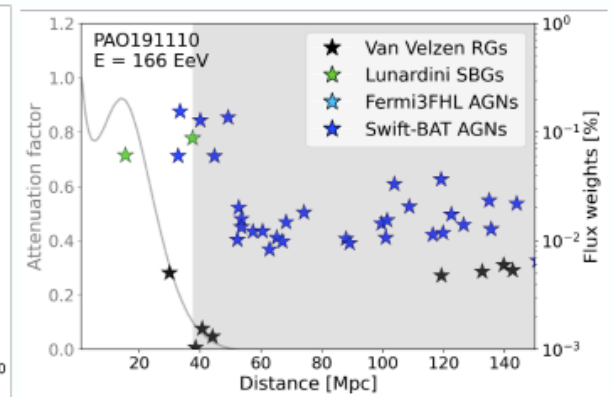
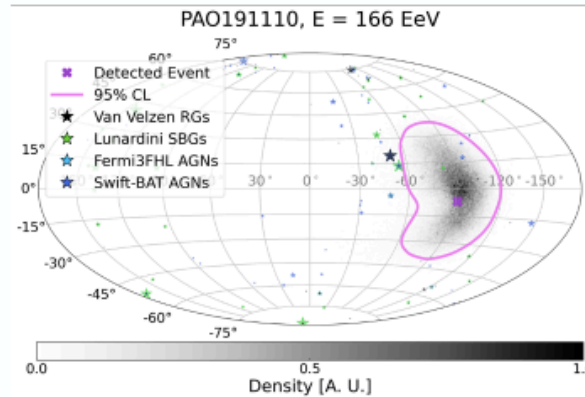
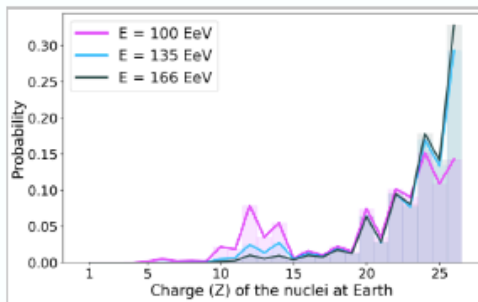
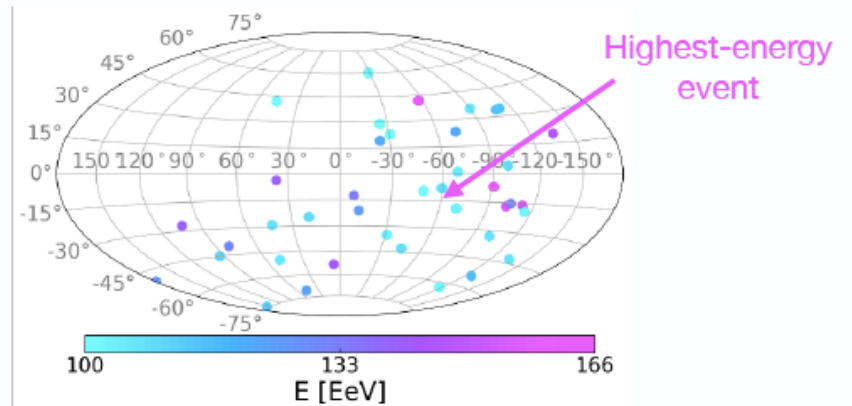
Analysis in progress

(PoS 272; Golup)

*Based on Roth, M., ICRC2025

Constraining the origin of the highest-energy cosmic-ray events?

- 40 events above 100 EeV (*Astrophys. J. Suppl. S. 264 (2023)*)
- Simulations:
 - Uniform source distribution in $D \in (1, 200)$ Mpc
 - Spectrum and composition from data
Auger Collab. JCAP, 05:024, 2023
- 6 classes of astrophysical sources
Local Group ($D < 1$ Mpc) excluded from source catalogs
- Galactic backtracking and accounting for limited horizon
- Magnetic field setup:
 - UF23 ensemble (regular field) + JF12 Planck-tune (random field)
 - No EGMF



Backtracked positions of 39 of 40 events with $E \geq 100$ EeV are compatible with one or more sources

M. Unger, G. R.Farrar. Astrophys. J. 970 (2024), (PoS 195; Bianciotto)

*Based on Roth, M., ICRC2025

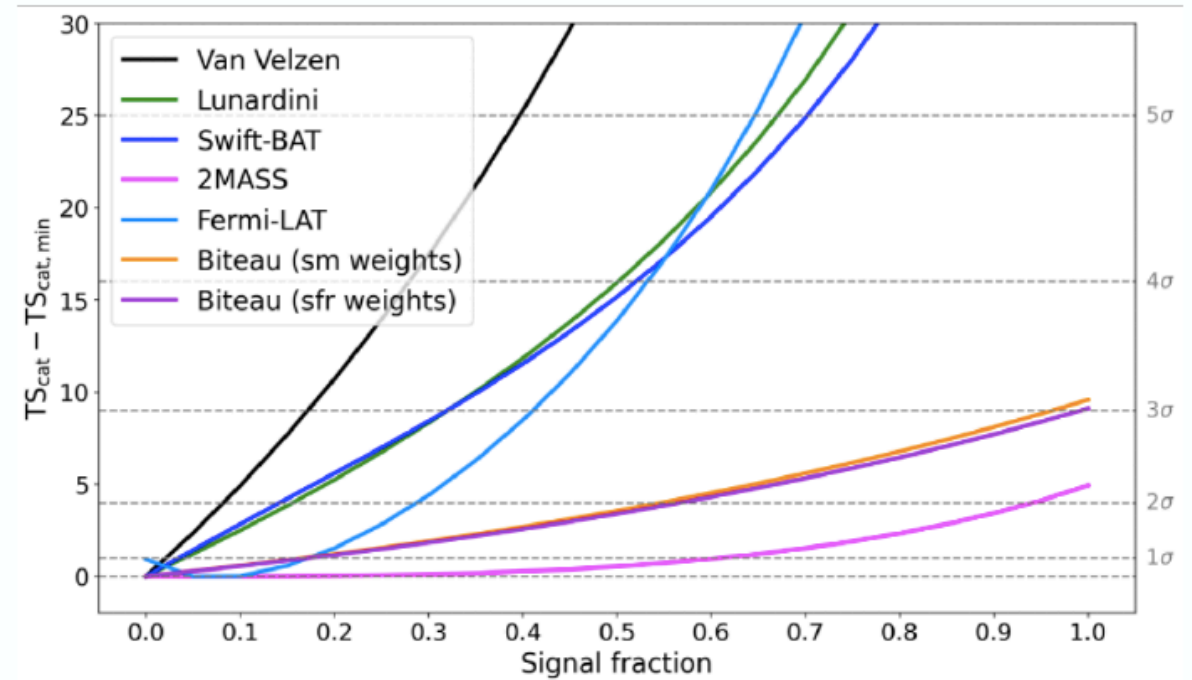
Constraining the origin of the highest-energy cosmic-ray events?

- Likelihood-based analysis
- Marginalization over 8 GMF models, considered equally probable

$$\mathcal{L}_{\text{cat}} = \frac{1}{8} \sum_{\text{model}=1}^8 \mathcal{L}_{\text{cat,model}}$$

$$TS_{\text{cat}} = -2 \ln \mathcal{L}_{\text{cat}}$$

- Contributions of:
 - > 40% Van Velzen
 - > 65% Fermi-LAT
 - > 67% Lunardini
 - > 70% Swift-BAT



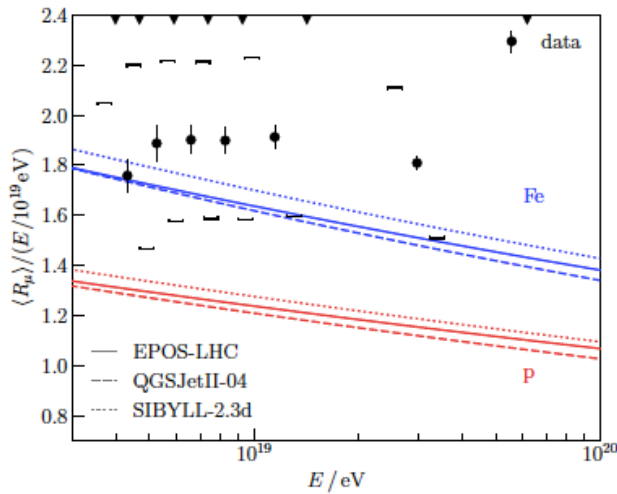
are excluded at the 5σ level under assumption of

- Auger 2023 best-fit injection model,
- negligible EGMF,
- nominal energy

*Based on Roth, M., ICRC2025

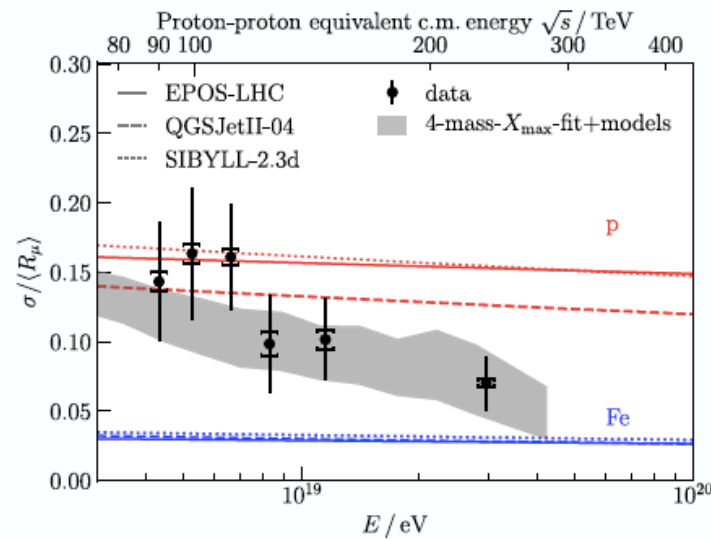
Muon measurement – inclined showers

Number of muons in showers with $\theta > 65^\circ$

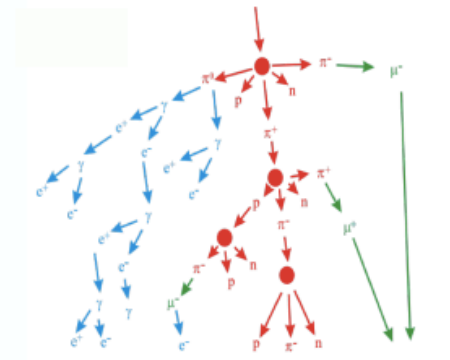
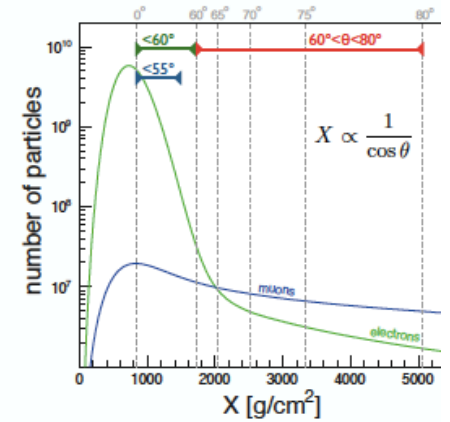


(Auger PRD 2015, PRL 2021)

Shower-to-shower fluctuations



70% of fluctuations from first interaction



Lorenzo Cazon et al.
Astropart. Phys. 36 (2012) 211
Phys. Lett. B 784 (2018) 68
Phys. Rev. D 103 (2021) 022001

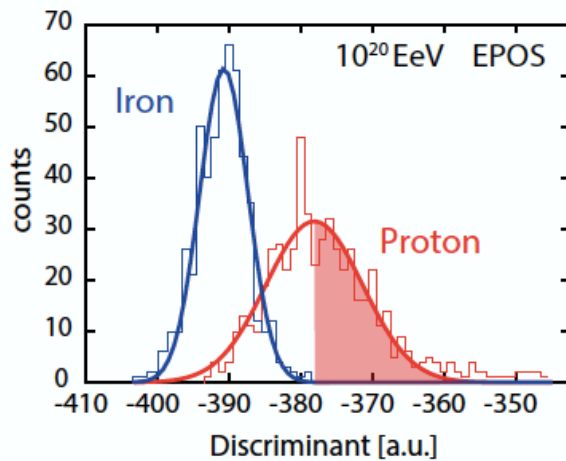
Discrepancy of muon number (20–30%),
 but non in relative shower-to-shower fluctuations

*Based on Roth, M., ICRC2025

Upgrade of Auger Observatory: AugerPrime

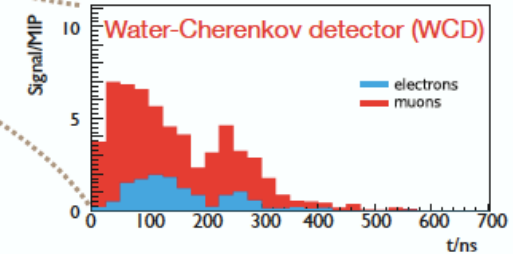
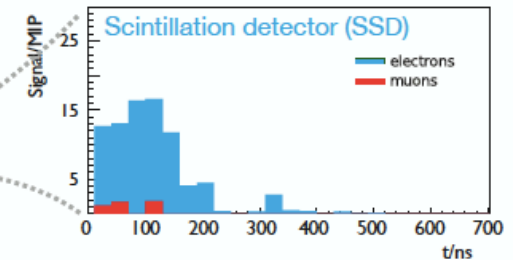
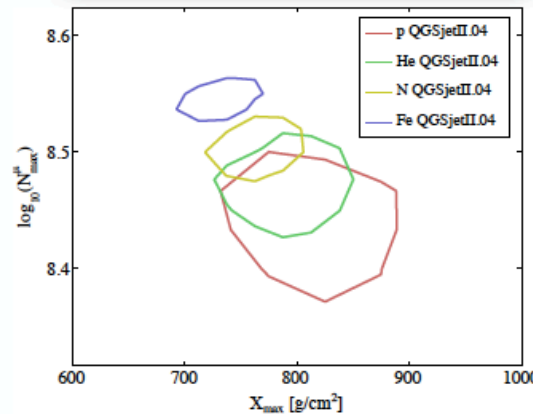
To increase exposure with composition sensitive data Surface array needed!

Duty cycle: 100% (SD) vs 15% (FD)



(AugerPrime design report 1604.03637)

Complementarity of particle response used to discriminate em. and muonic components



$$S_{\mu, \text{WCD}} = a S_{\text{WCD}} + b S_{\text{SSD}}$$

$$S_{\text{em}, \text{WCD}} = c S_{\text{WCD}} + d S_{\text{SSD}}$$

*Based on Roth, M., ICRC2025