CRA2026

7th Cosmic Ray Anisotropy Workshop

3 - 6 November, 2026

Monterrey, Nuevo León, México

Cosmic-Ray Anisotropy Workshop 2026

Review of UHECR results

Karen Salomé Caballero Mora

Benemérita UNACH

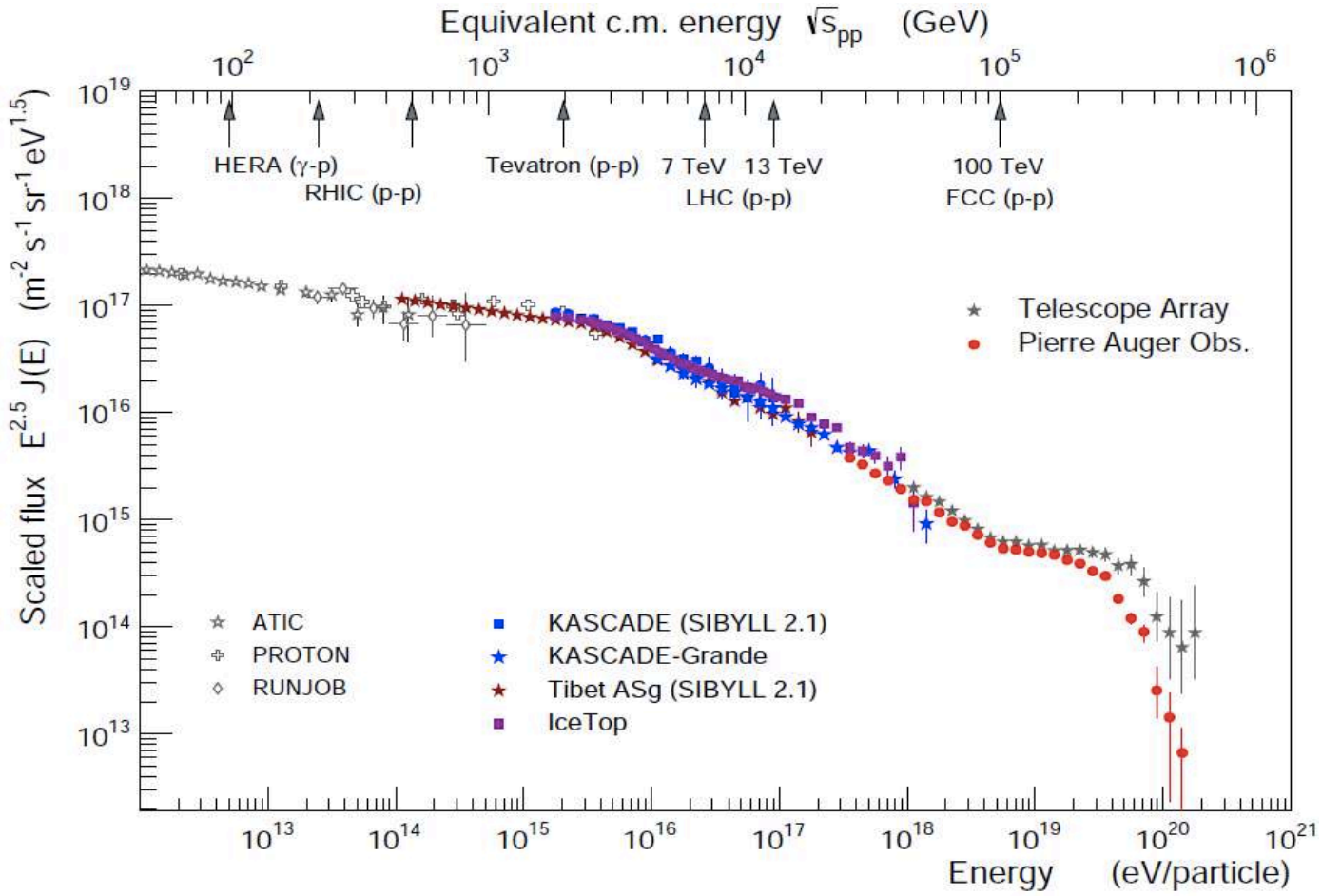
Session 5

4 November 2026



UHECR

Ultra-High-Energy-Cosmic-Rays
E> 10^{18} eV



Air -> Lab transformation

$$\sqrt{s} \cong \sqrt{2\ E_A\ m_B}$$

E_A = *Beam's energy*

m_B = *Particle's mass*

Example:
For an UHECR with
E_A= 1x10^{20}eV=1x10^{11} GeV=1x10^{8} TeV
A proton's beam mB=0.938 GeV

$$\sqrt{s} \cong 4.33x10^5\ GeV \sim 400\ TeV$$

With LHC Technology the size of Mercury's orbit to reach 10^{20} eV

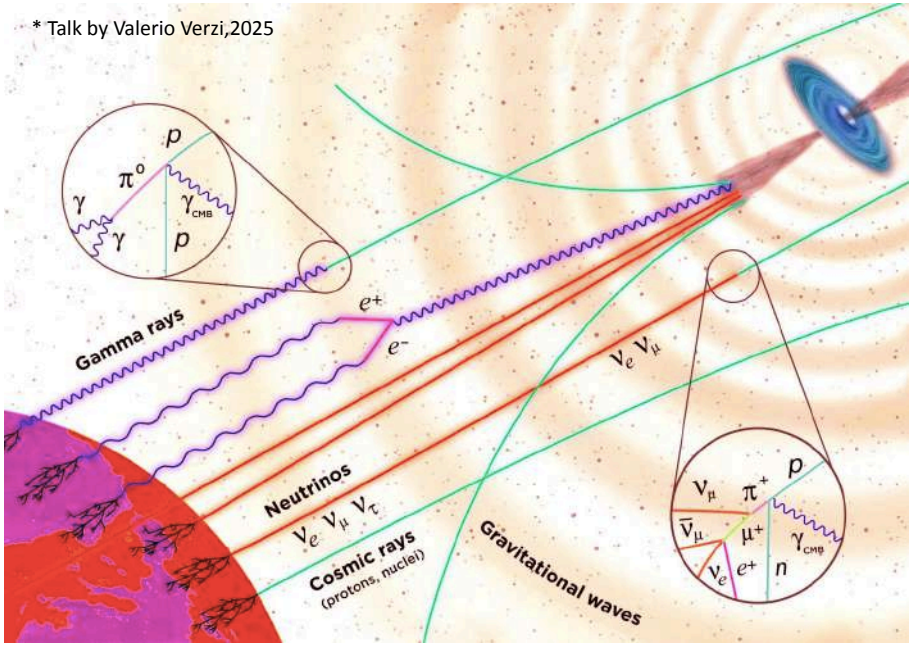
R. Engel (KIT) 2017

*Explanation's idea: Talk by Valerio Verzi,2025

Key questions for UHECR:

- The Origin
- Chemical mass composition
- The energy spectrum and its features
- Anisotropy and distribution of sources
- The muon puzzle in EAS

- The Hadronic Interaction Models (HIM)
- Inter-hemispheric collaboration: Auger@TA
- LHC as cosmic Lab
- Developing and applications of AI
- BSM Physics
- Multimessenger astroparticle physics



Main Facilities for UHECR detection:
Pierre Auger Observatory
Telescope Array

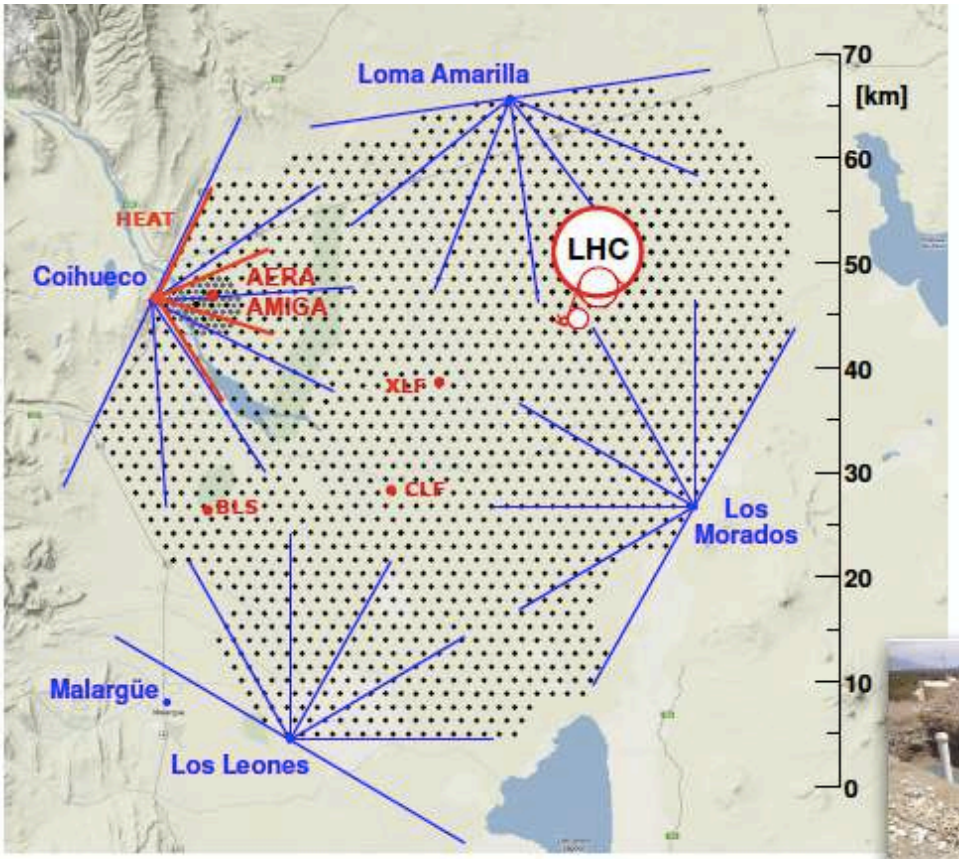
The Pierre Auger Observatory
Phase I

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 km^2 / 24 km^2 / 2 km^2
  - 1660 stations / 61 / 19
  - Thresholds:
    $10^{18.5}$ eV, $10^{17.5}$ eV, 6x10^{16} eV

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

Radio array (AERA)
- 153 stations
- 17 km^2





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*Based on Roth, M., ICRC2025

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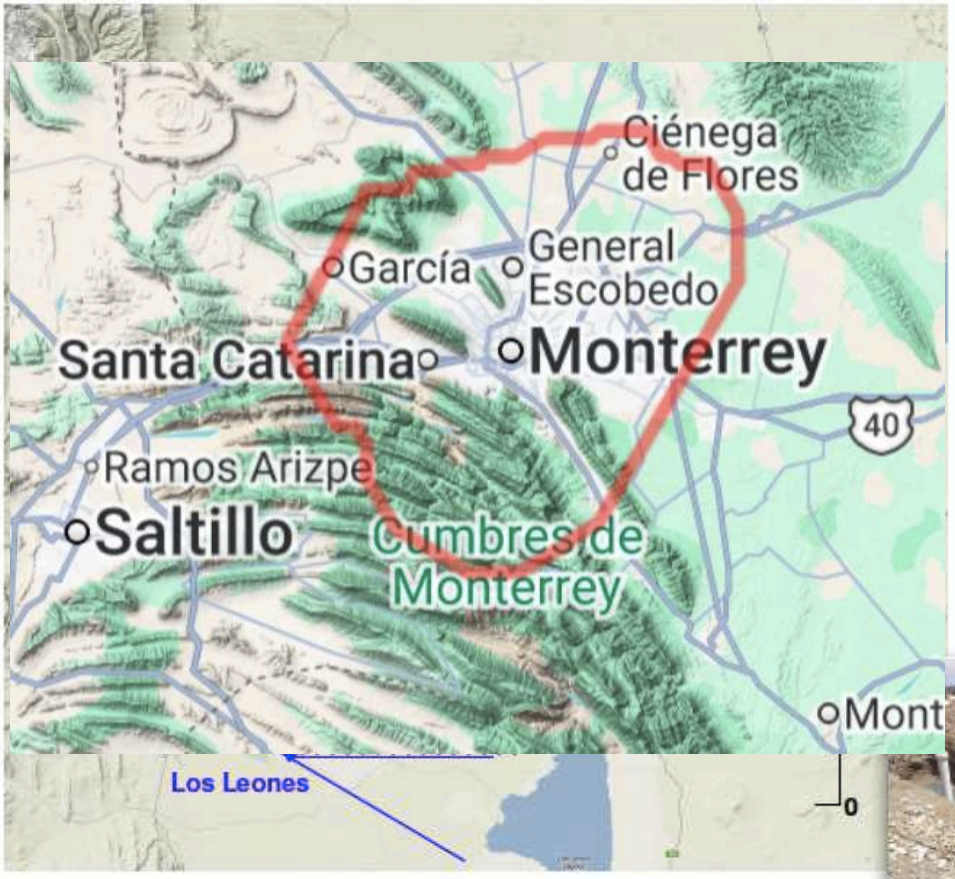
The Pierre Auger Observatory-Phase I

Fluorescence detector (FD)
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4

*Based on Roth, M., ICRC2025

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Hybrid detection

Fluorescence Detector (FD):

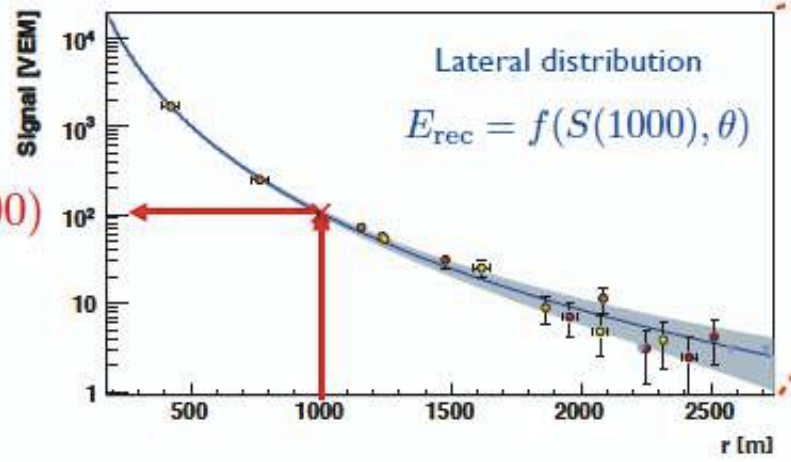
- calorimetric measurement of energy
- ca.15% duty cycle

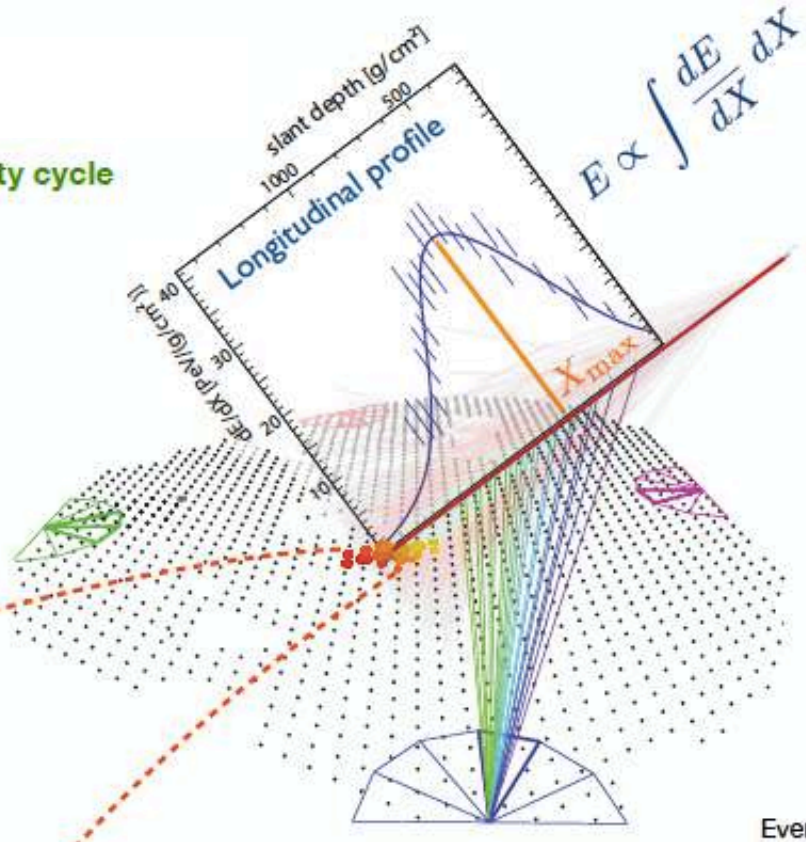
Surface Detector (SD):

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

15% duty cycle

100% duty cycle



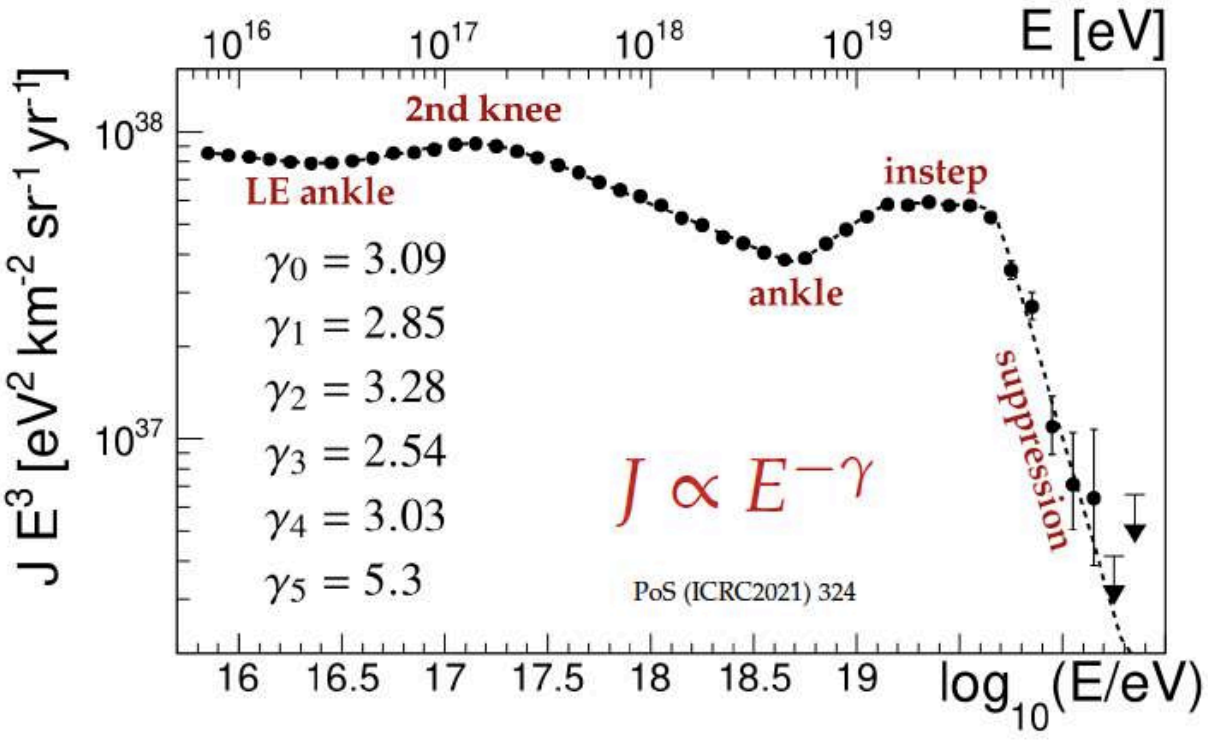


Event observed with Auger Observatory

*Based on Roth, M., ICRC2025

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Combined all-particle energy spectrum



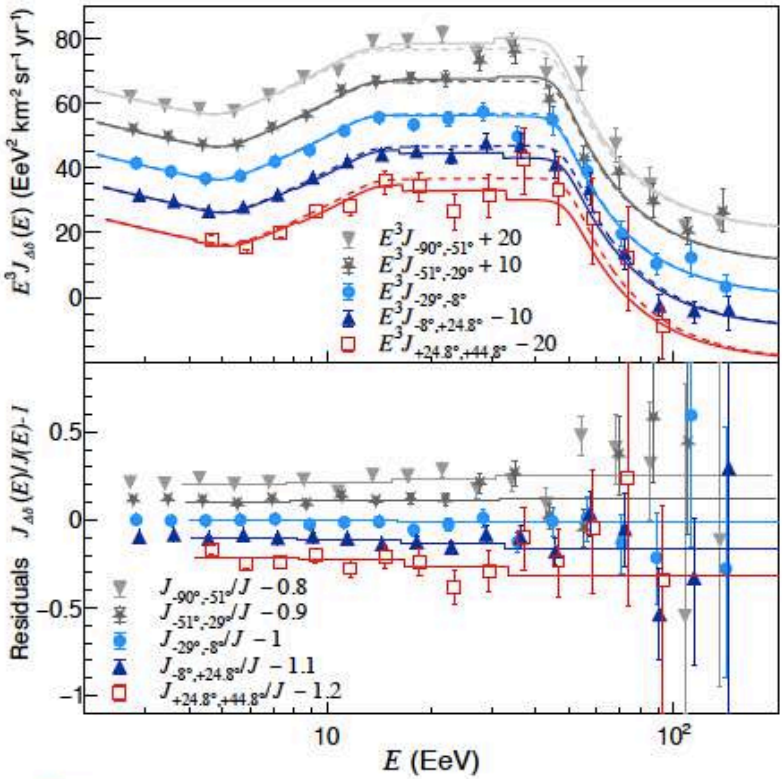
5 spectral features

$E_{01} = (2.8 \pm 0.3 \pm 0.4) \times 10^{16}$ eV
$E_{12} = (1.58 \pm 0.05 \pm 0.2) \times 10^{17}$ eV
$E_{23} = (5.0 \pm 0.1 \pm 0.8) \times 10^{18}$ eV
$E_{34} = (1.4 \pm 0.1 \pm 0.2) \times 10^{19}$ eV
$E_{45} = (4.7 \pm 0.3 \pm 0.6) \times 10^{19}$ eV

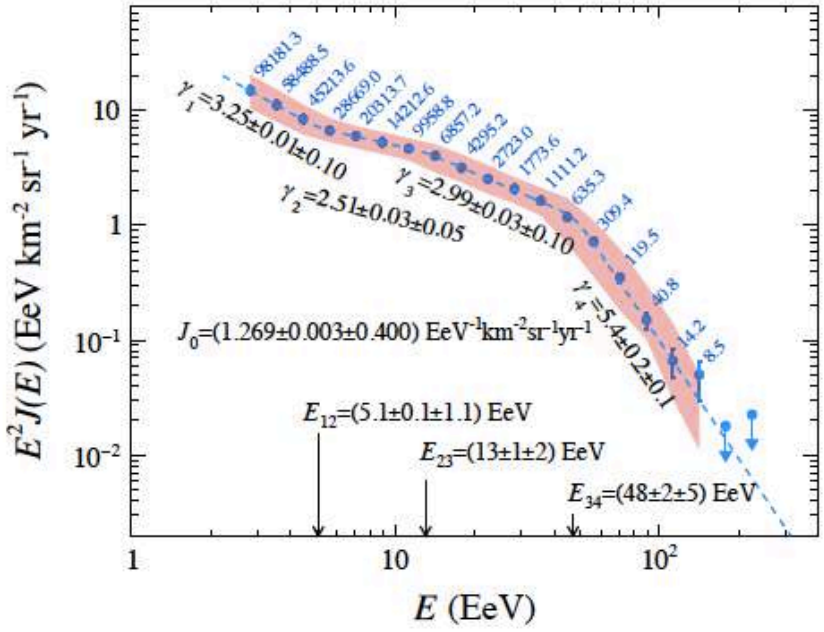
Mass composition is key to astrophysical interpretation

PRL 125 (2020) 121106, PRD 102 (2020) 062005, Eur. Phys. J. C 81 (2021) 966

All-particle spectrum across declination bands



- Five δ bands: $-90° \leq \delta \leq +44.8°$
- Exposure: $(104\,900 \pm 3\,100)$ km^2 sr yr, $\sim 310\,000$ events



- **Consistent spectra across bands: instep origin from few dominant sources disfavored**
- **Instep established at 5.5σ**

PRL 135 (2025) 241002

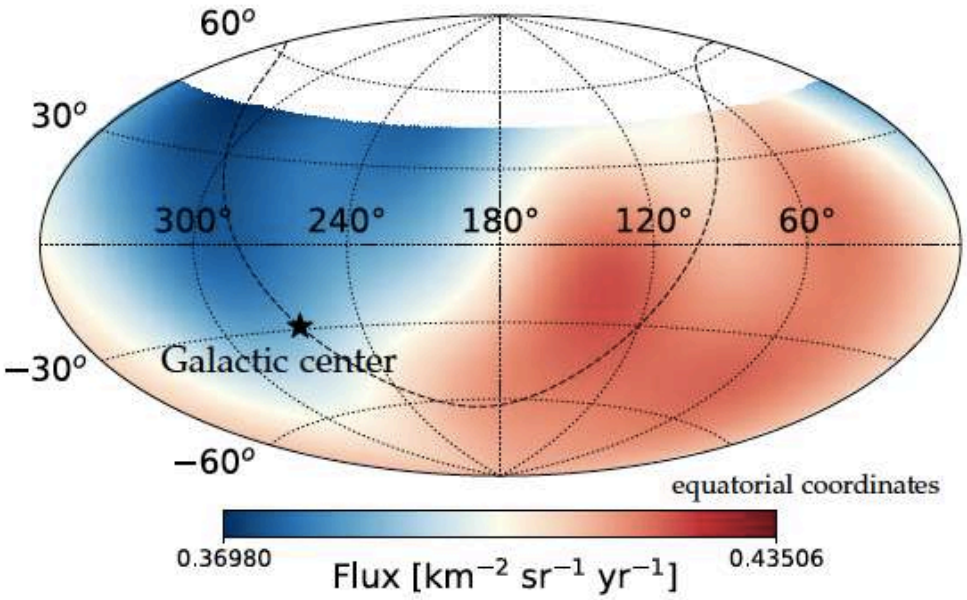
Extragalactic UHECR origin: dipole above 8 EeV

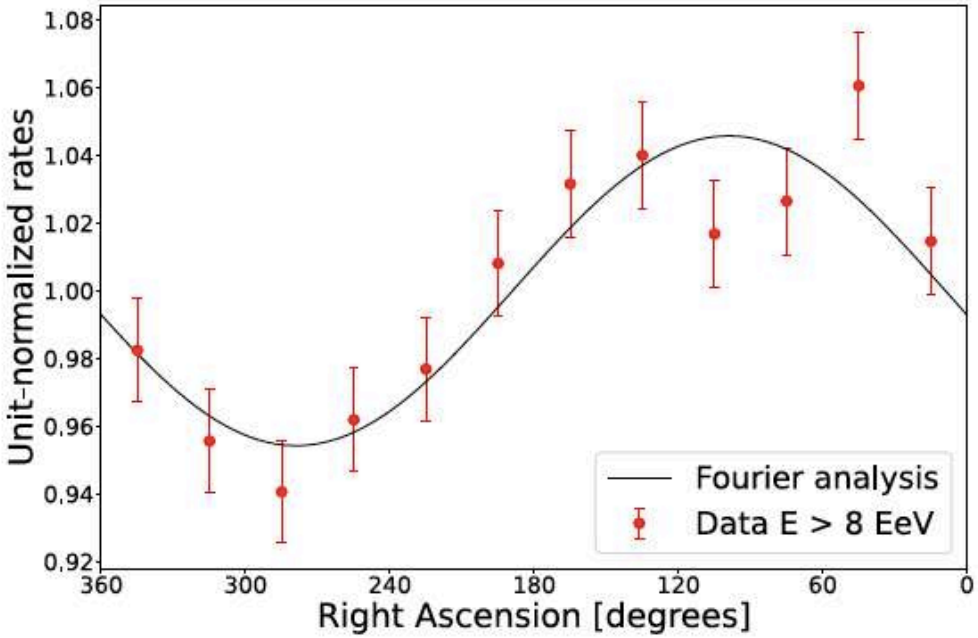
PIERRE AUGER OBSERVATORY

- Dipole for $E \geq 8$ EeV: amplitude $d = (7.4^{+1.0}_{-0.8})\%$, at 6.8σ from isotropy
- Phase in R.A. $\alpha_d = 97° \pm 8°$ is nearly opposite to the Galactic center $\alpha_{GC} = -94°$

Magnitude and direction of dipole support extragalactic origin of UHECRs with $E > 4$ EeV

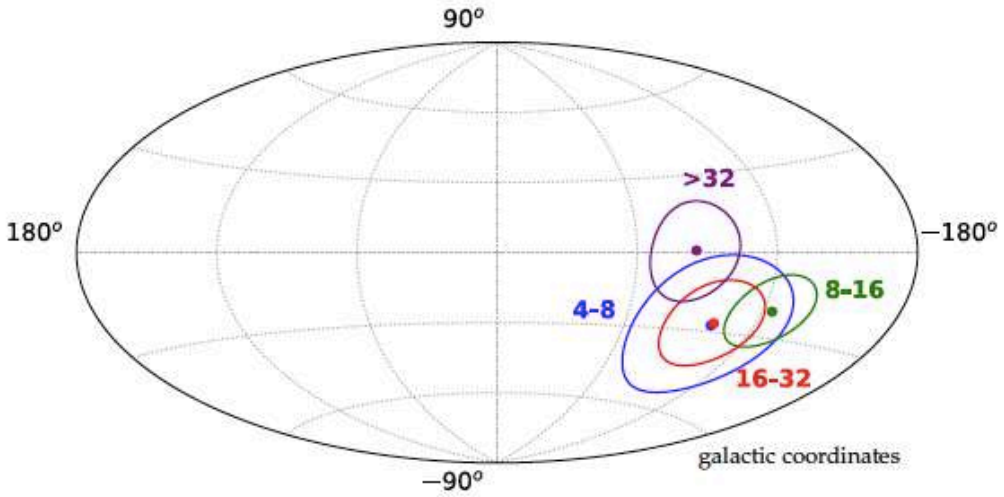
physics world TOP 10 BREAKTHROUGH 2017

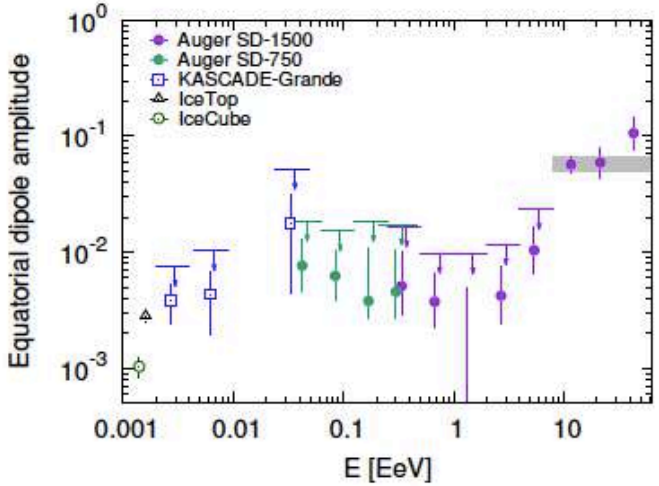


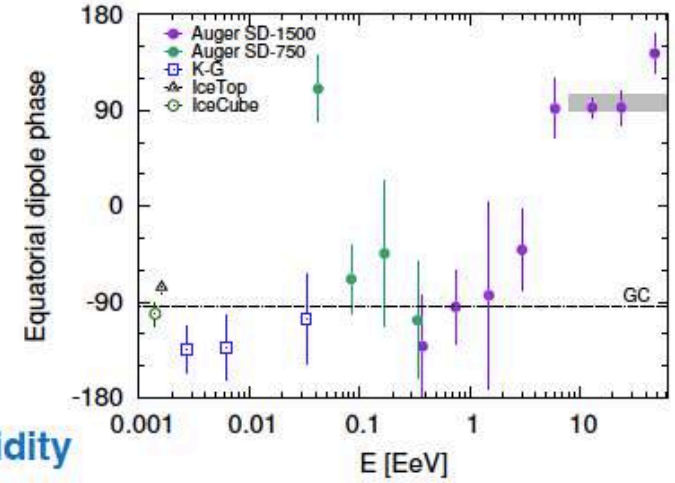


Science 57 (2017) 1266; Astrophys. J. 868 (2018) 4, 891 (2020) 142; Astrophys. J. 976 (2024) 48

Extragalactic UHECR origin: dipole above 8 EeV



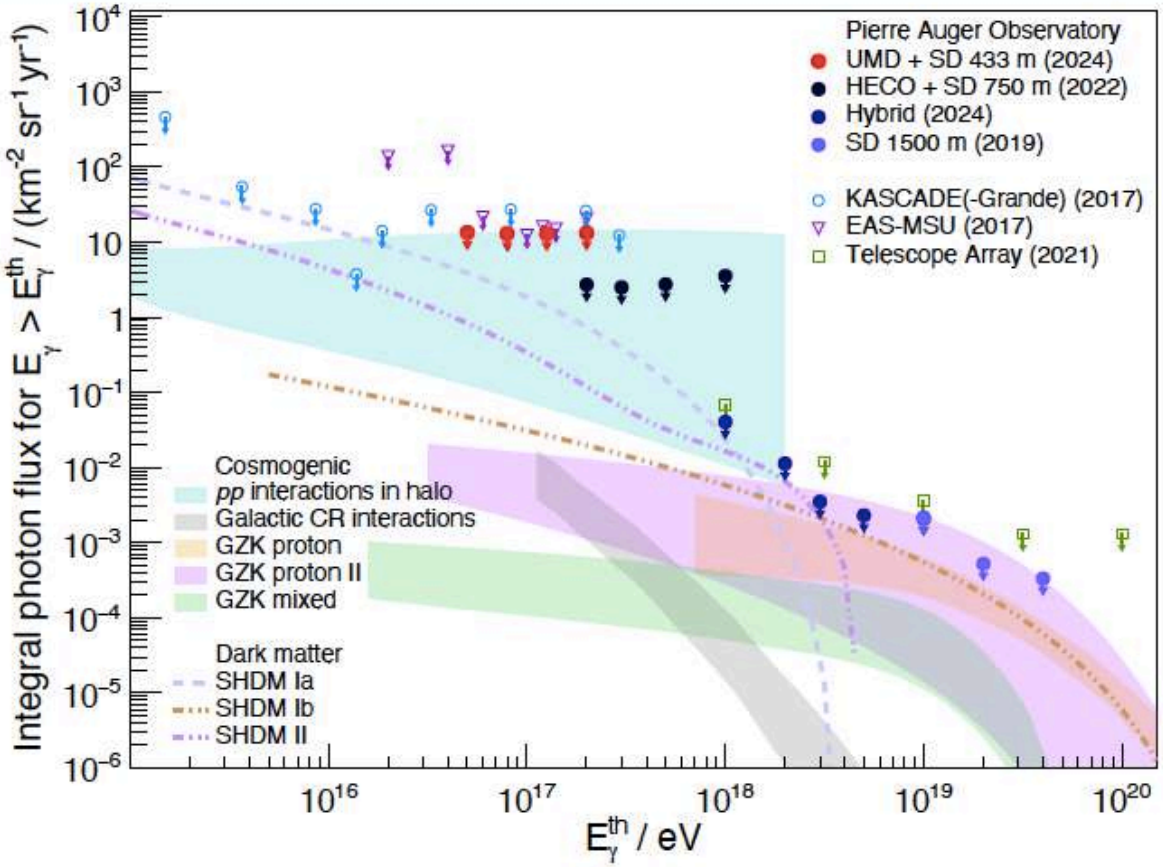




- **Below 4 EeV amplitudes consistent with isotropy**
- **Phase shifts from GC to nearly opposite above 4 EeV**
  GMF effect on extragalactic CR or Galactic CR origin
- **Evolution of direction and amplitude with energy**
  May reflect larger nearby-source contribution; possibly higher rigidity

Science 57 (2017) 1266; Astrophys. J. 868 (2018) 4, 891 (2020) 142; Astrophys. J. 976 (2024) 48

Photon searches



No unambiguous photon candidates identified

- **World-leading photon limits for E ≳ 10^{17} eV**
- **Earlier SHDM models are strongly constrained**
- **Significant increase of exposure needed to constrain GZK proton scenarios**

Search for photons E > 10^{19} eV from GW events

No candidates in coincidence with GW

Main limitations:

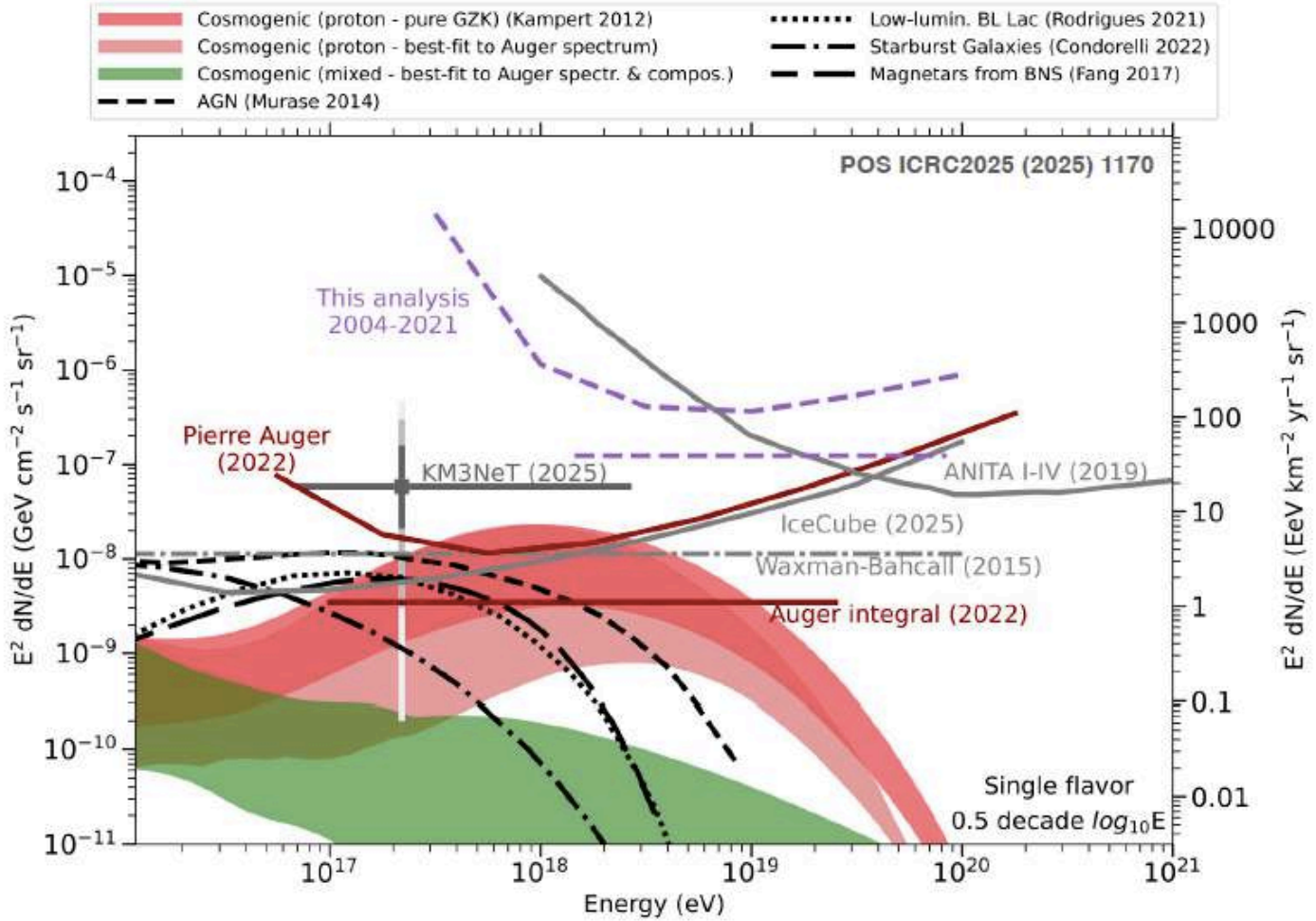
Photon horizon of only a few Mpc

Overwhelming hadronic background

ApJ 952 (2023) 91

ApJ 789 (2014) 160, JCAP 04 (2017) 009, ApJL 837 (2017) L25, ApJ 933 (2022) 125, JCAP 05 (2023) 021, PRD 110 (2024) 062005, JCAP 05 (2025) 061

Neutrino searches



No candidates: constraints on proton-dominated astrophysical models and source evolution

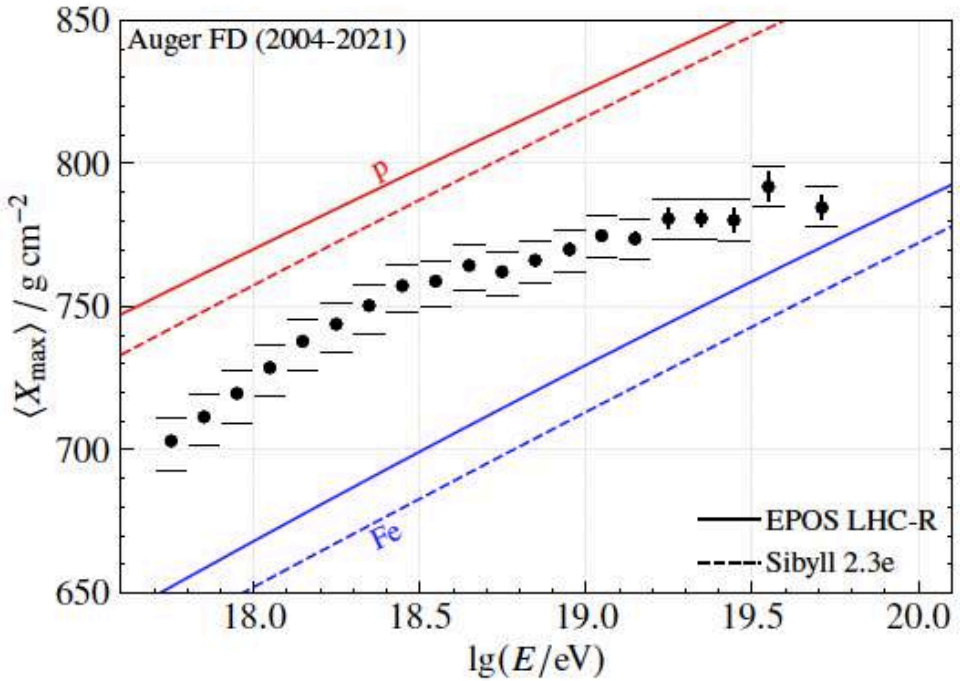
Search for neutrinos $E > 10^{19}$ eV from GW events

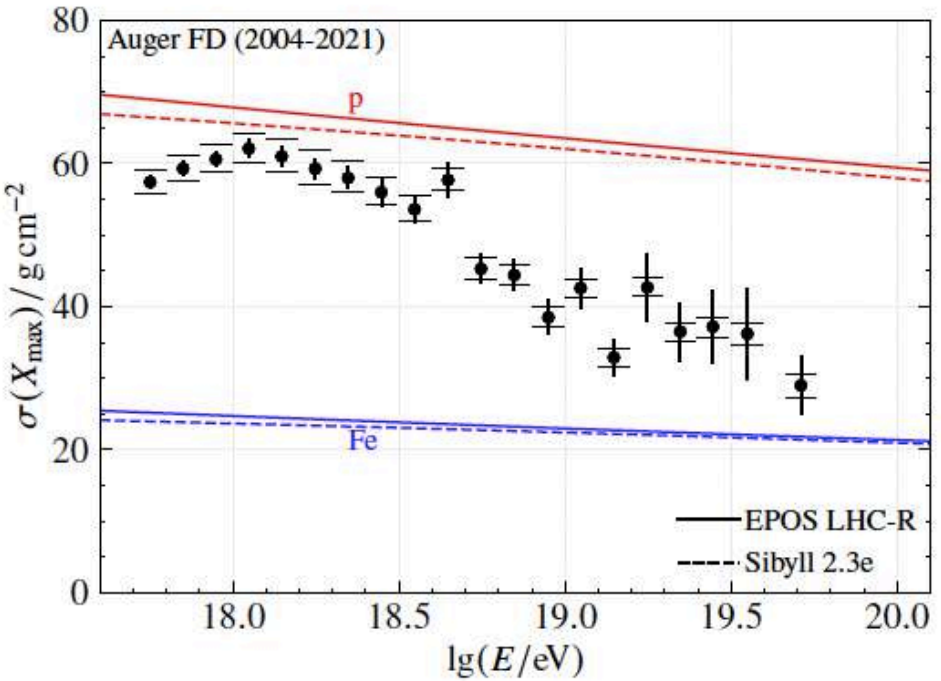
No candidates in coincidence with GW

ApJ L 850 (2017) L35

JCAP 01 (2016) 037, PRD 94 (2016) 122007, ApJ Lett. 850 (2017) L35, JCAP 10 (2019) 022, 11 (2019) 004; ApJ 902 (2020) 105

Mass measurements with the Fluorescence Detector



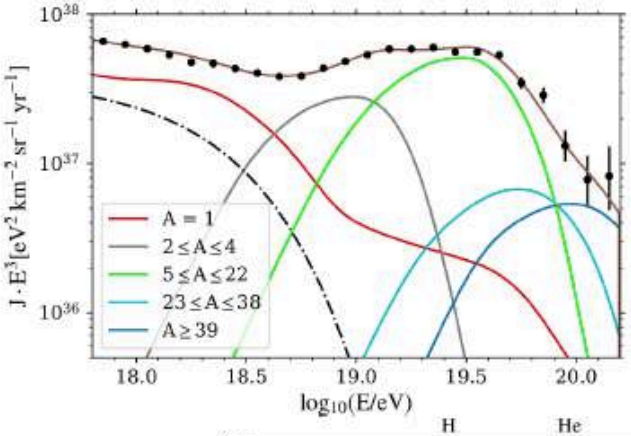


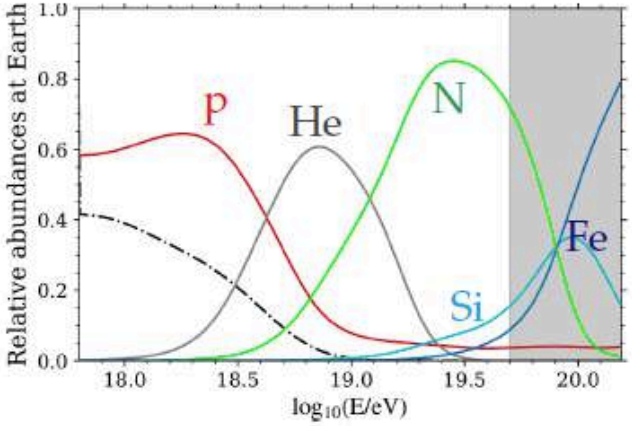
Evidence for a change in mass evolution as a function of energy (hardonic-interaction-model independent)

$\langle X_{\rm max}\rangle$ **composition lightens up to $10^{18.4}$ eV, then becomes heavier**

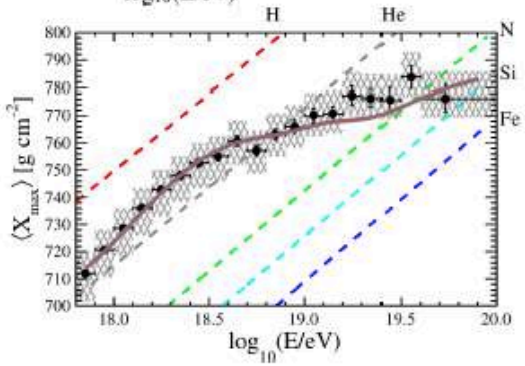
$\sigma(X_{\rm max})$ **growth up to $10^{18.1}$ eV, where trend changes towards heavier/less mixed composition**

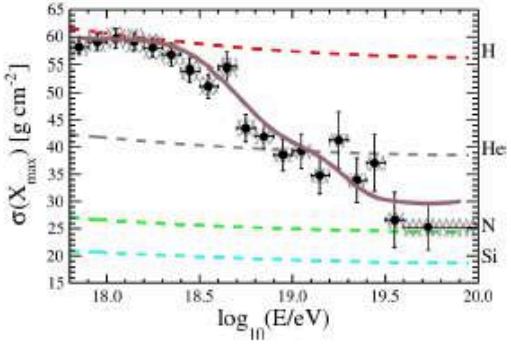
Astrophysical model for combined spectrum-composition fit





EPOS-LHC





Instep
Combined effect from He+N

Galactic-extragalactic transition need composition with SD statistics

Magnetic horizon effect

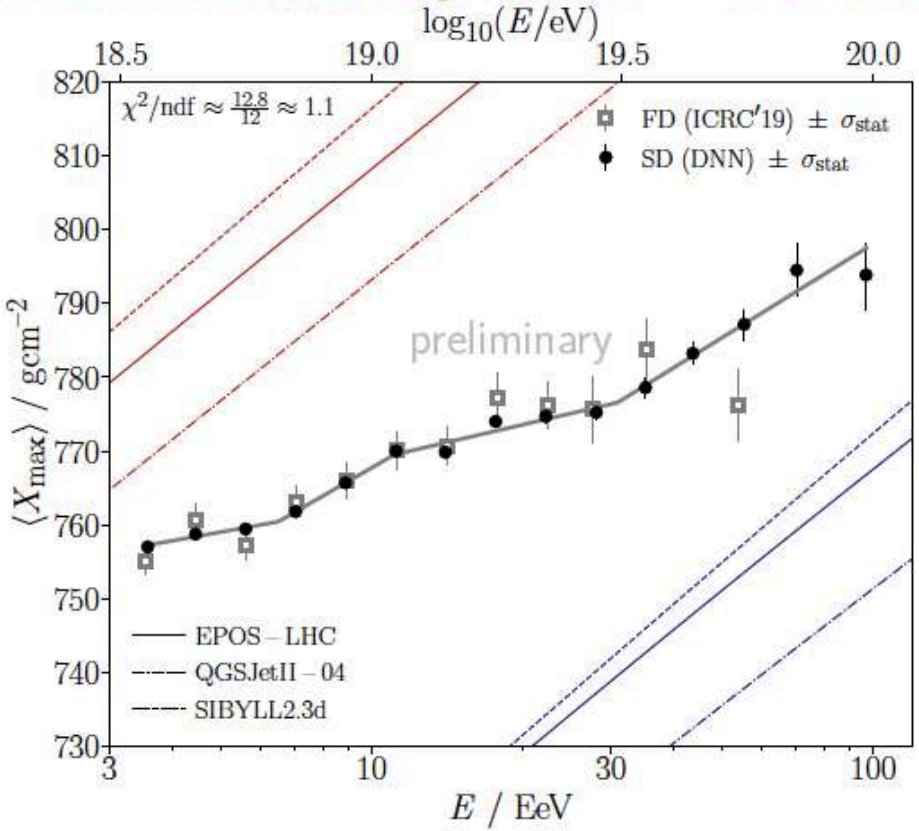
scenarios with injection spectrum $\gamma \approx -2$ (diffuse shock acceleration) are possible

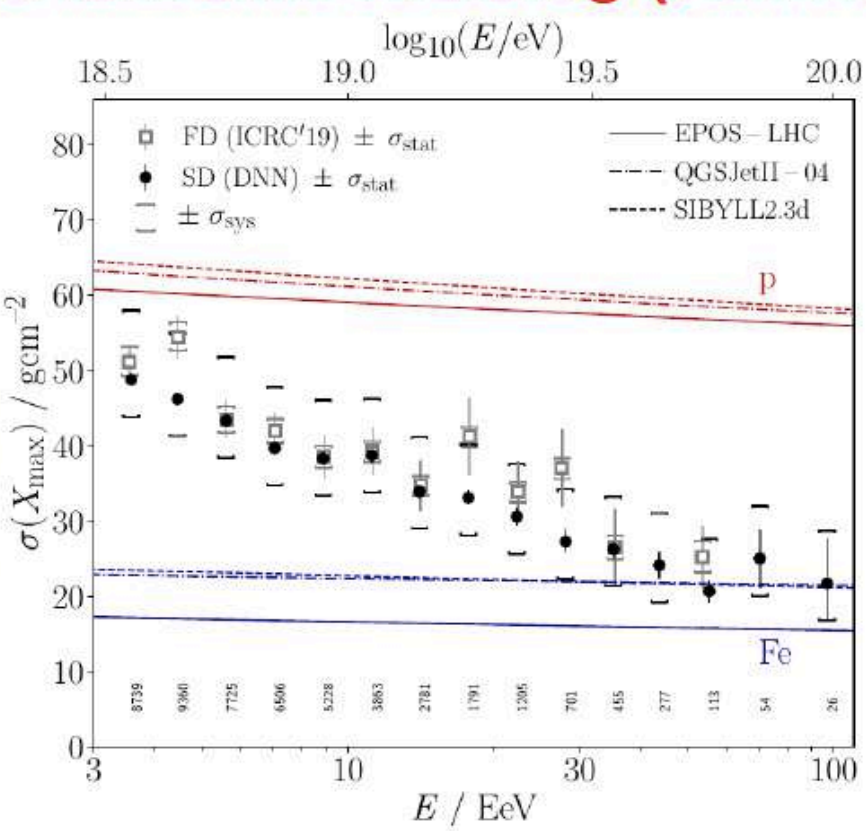
Example scenario: proton component with lg(R_{out}/V) > 19.3 plus mixed component: f_{He}=24.5%, f_N=68%, f_{Si}=5%, f_{Fe}=2.5% lg(R/V) = 18.19 hard injection spectrum $\gamma = -1.47$

14/42

JCAP 04 (2017) 038, PoS (ICRC2021) 311, JCAP 05 (2023) 024, JCAP 01 (2024) 022, JCAP 07 (2024) 094

SD data: X_{max} up to 10^{20} eV with machine learning (AixNet)

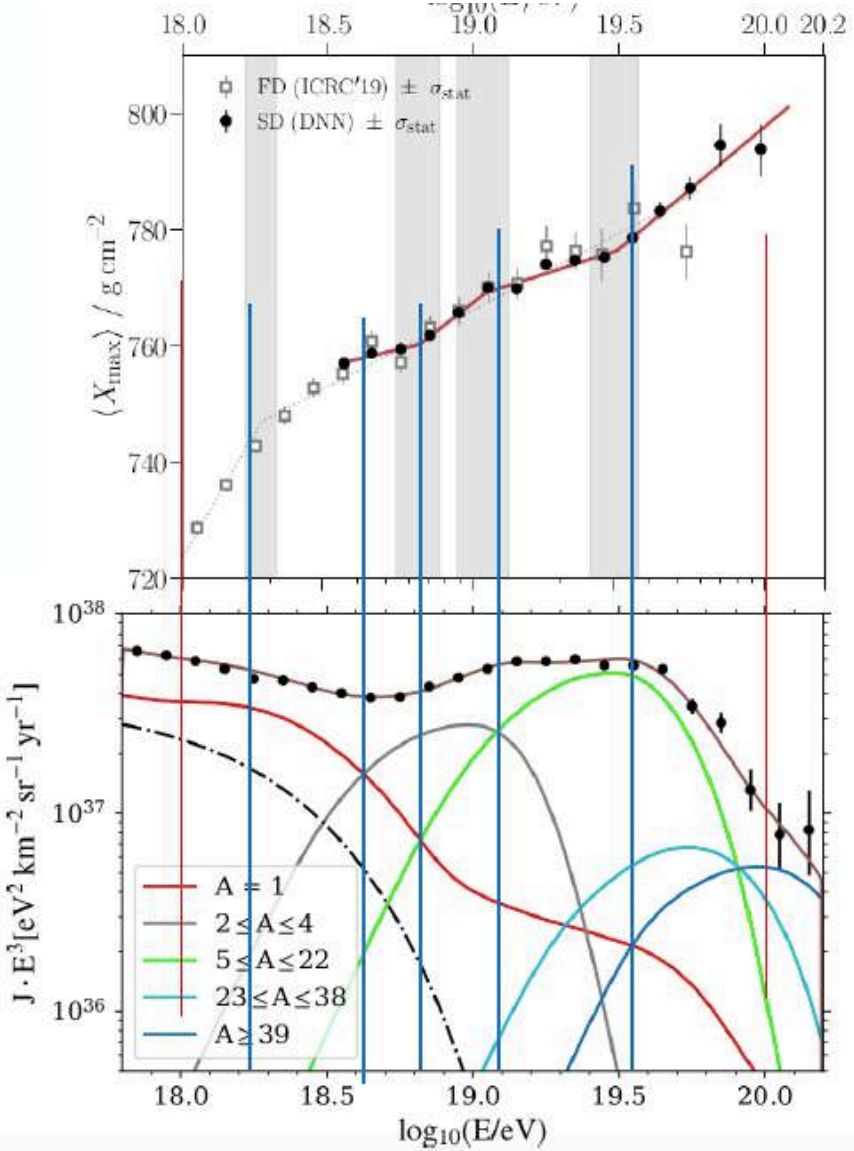




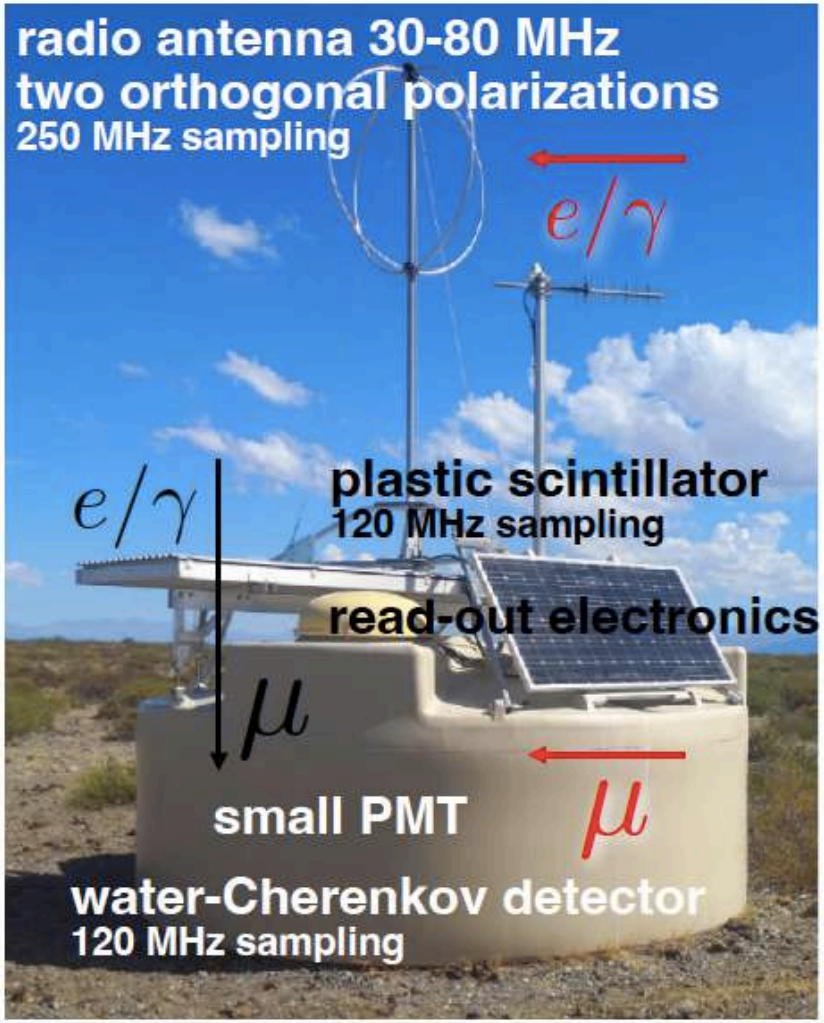
100 EeV: $\langle X_{\mathrm{max}} \rangle$ evolution is compatible to ln A=const
$\sigma(X_{\mathrm{max}})$ to a beam nearly devoid of protons and helium nuclei

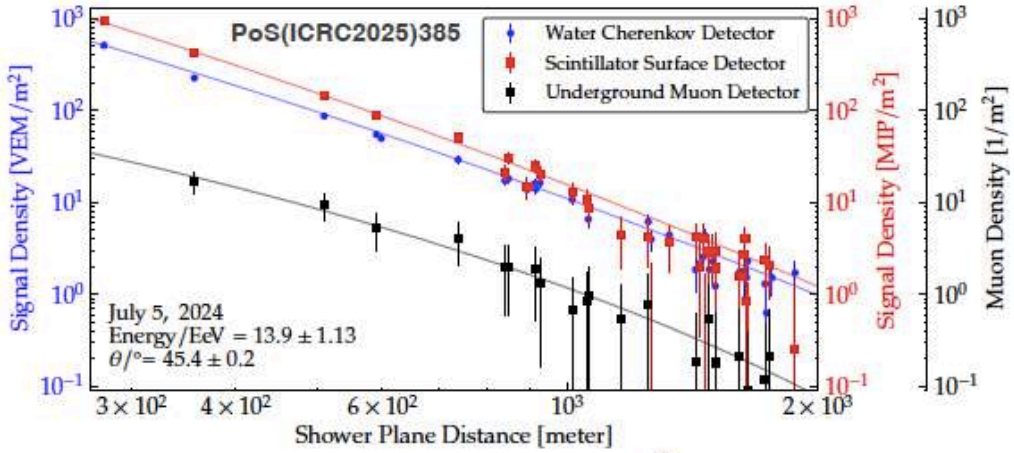
PRD 111 (2025) 022003, PRL 134 (2025) 021001

Alignment of features

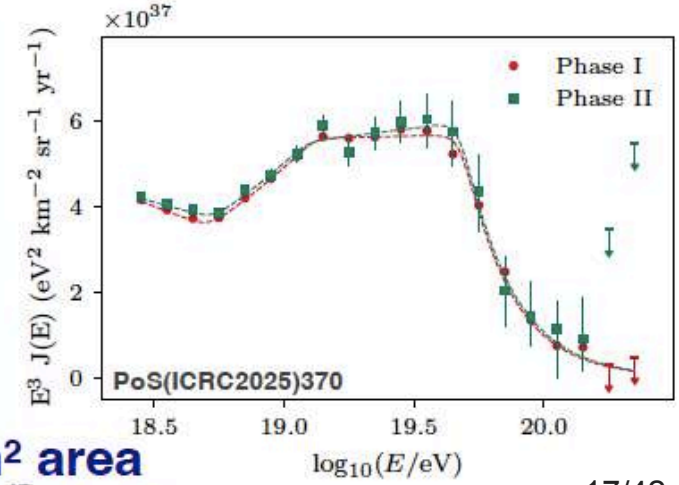


Upgrade of Observatory - taking data until 2035 (and beyond)



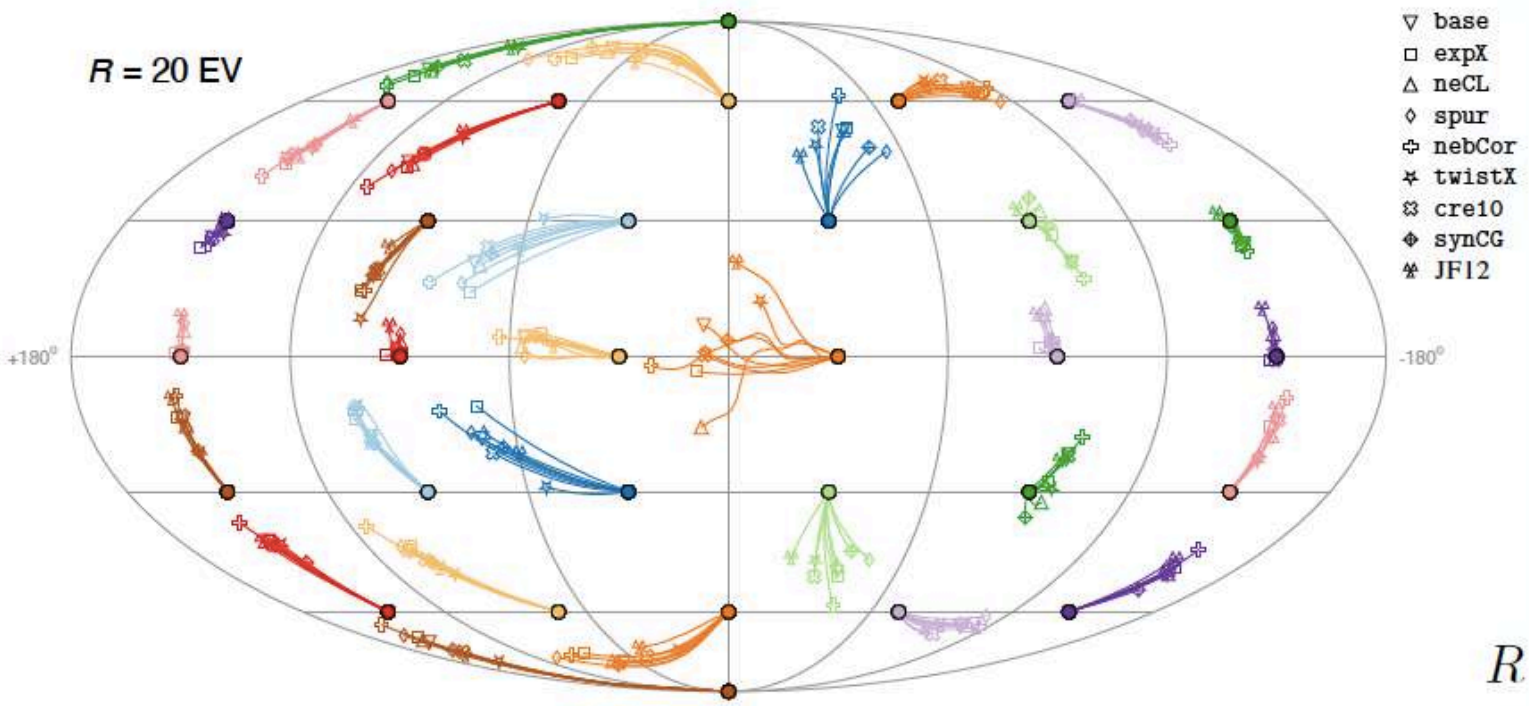






SD (750 m) of 23.5 km² area
+ underground muon detectors

Deflection of cosmic rays in magnetic fields



$$R = \frac{E}{Z} \approx \frac{E}{A/2}$$

Figure 19. Angular deflections of ultrahigh-energy cosmic rays in the eight model variations derived in this paper and JF12. The cosmic-ray rigidity is 20 EV (2×10^{19} V). Filled circles denote a grid of arrival directions and the open symbols are the back-tracked directions at the edge of the Galaxy.

The Coherent Magnetic Field of the Milky Way

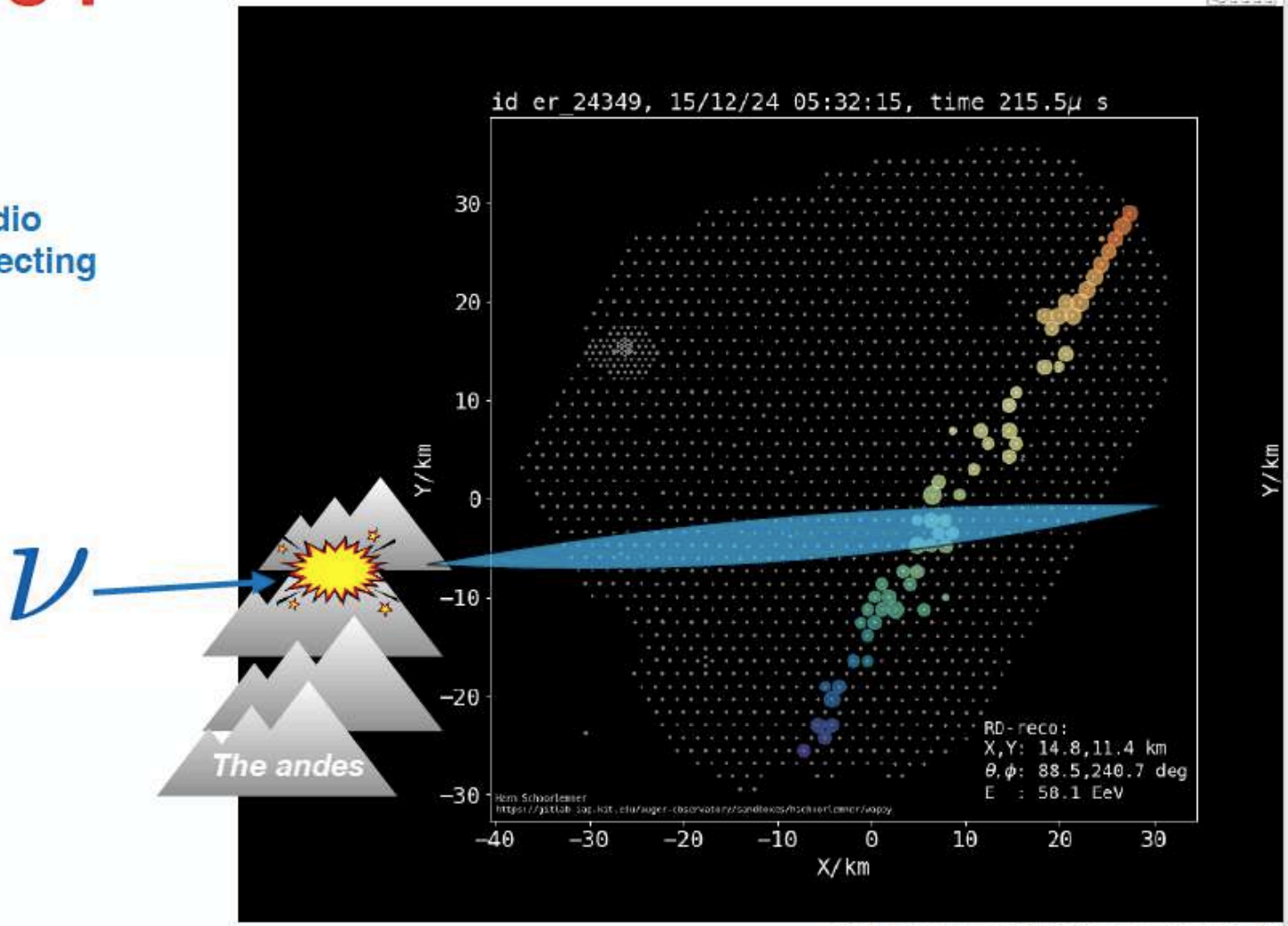
MICHAEL UNGER [1,2] AND GLENNYS R. FARRAR [3]

arXiv:2311.12120v3

need to know rigidity (mass) of incoming cosmic rays

Earth-skimming potential

- 65 km footprint (WCD + RD)
- Nearly from the horizon: 89°
- around 2×10^{19} eV
- completely new domain for radio
  —> illustrates the case for detecting Earth-skimming neutrinos
  (e.g. hitting the Andes)

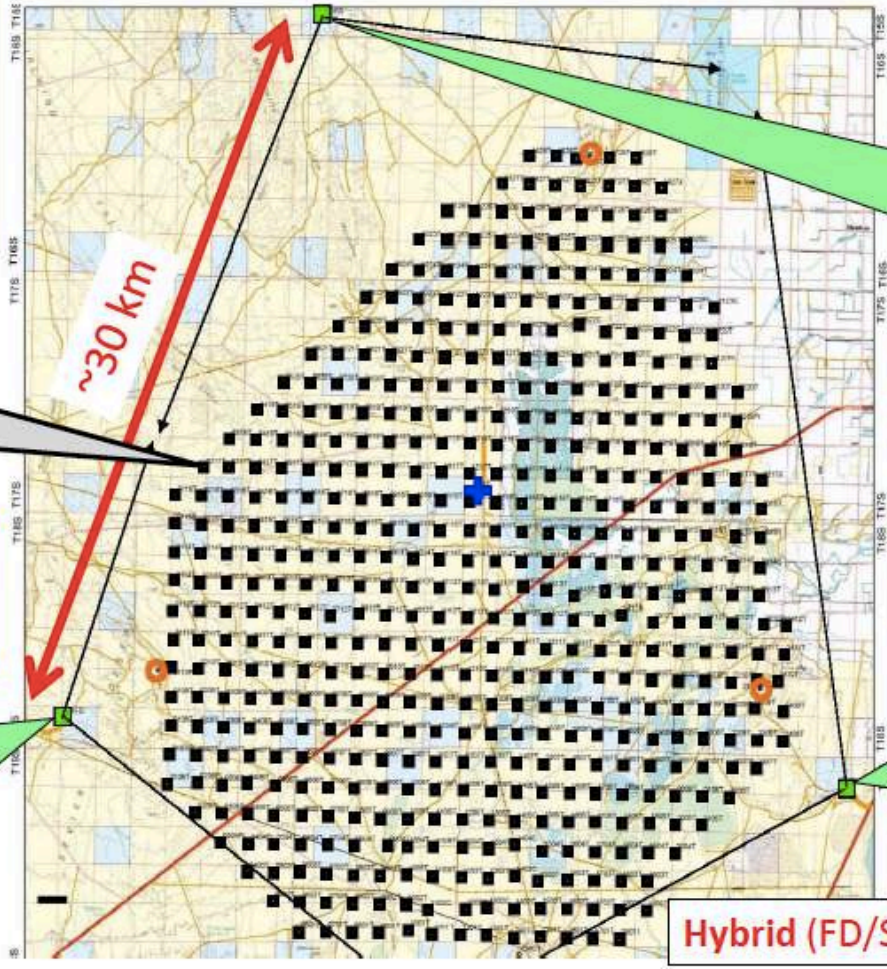


Telescope Array (TA) Detector

Utah, USA
39.3°N, 112.9°W
~1400 m a.s.l.

Surface Detectors (SD)
507 SDs
3m² plastic scintillator
1.2 km spacing
~700 km²





Middle Drum (MD)



14 telescopes

Fluorescence Detectors (FD)
3 FD stations
Totally 38 telescopes

Long Ridge (LR)



12 telescopes

Black Rock Mesa (BR)



12 telescopes

Hybrid (FD/SD) observation started in 2008

TAx4 Experiment

Aim

- Quadruple TA
- Four-times-faster highest-energy cosmic-ray collection

TAx4 SD

Goal

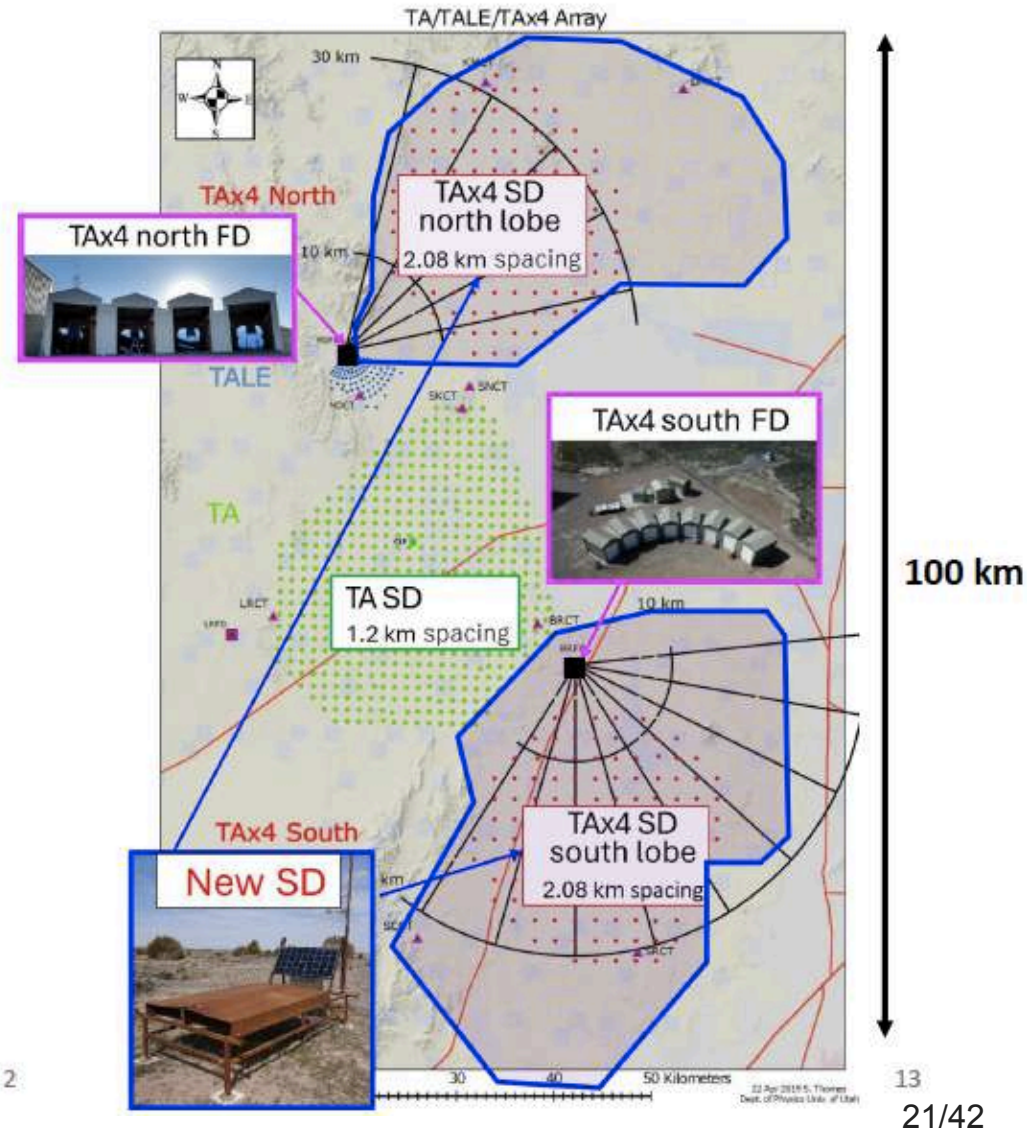
- Deploy 500 SDs with 2.08 km spacing
- Expand the array to ~3,000 km² (TA SD + new SD)

Current Status

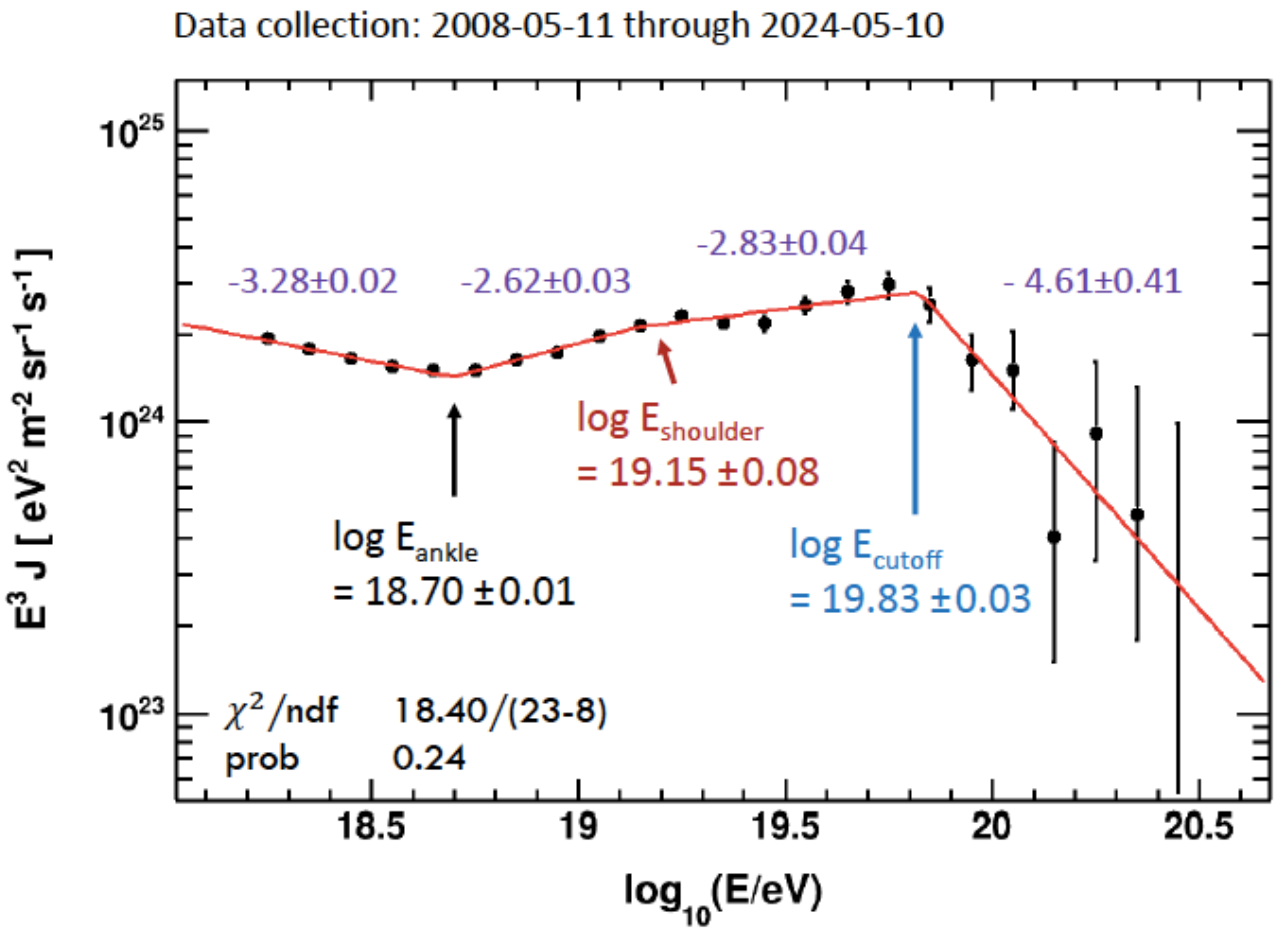
- 257 SDs deployed in 2019 (current size: TAx2.5)

TAx4 FD Stations

- HiRes telescopes refurbished (4+8)
- Constructed and operating



Spectral Features from 16 years of TA SD Data



- **Cutoff feature at $10^{19.83}$ eV**
  N_{exp}: 173.7
  N_{obs}: 97
  Chance probability: 1.6×10^{-10} (~6.3σ)
- **Shoulder feature at $10^{19.15}$ eV**
  N_{exp}: 2156.4
  N_{obs}: 1921
  Chance probability: 1.3×10^{-7} (~5.2σ)
  – Softening observed at $10^{19.15\pm0.08}$ eV
  – Significance: a 5.2σ
  – Auger observed it at $10^{19.15\pm0.03}$ eV
  (with +9% energy rescaling)
  – TA agrees with Auger

Hotspot: Intermediate-scale Anisotropy (E ≥ 57 EeV)

Analysis method

ApJL **790**, L21 (2014)

- Oversample UHECR events within a fixed-radius circle around each arrival direction
- Evaluate the Li-Ma significance relative to isotropy

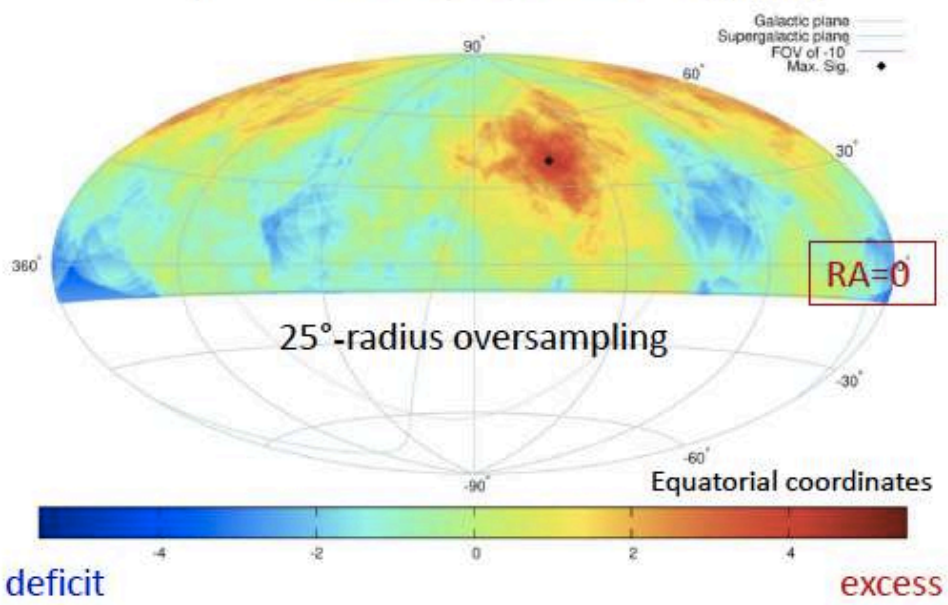
Initial analysis (first 5-year TA SD data)

- 72 events
- Max. local significance: 5.1σ
- Global significance: 3.4σ

Update (16-year TA SD data)

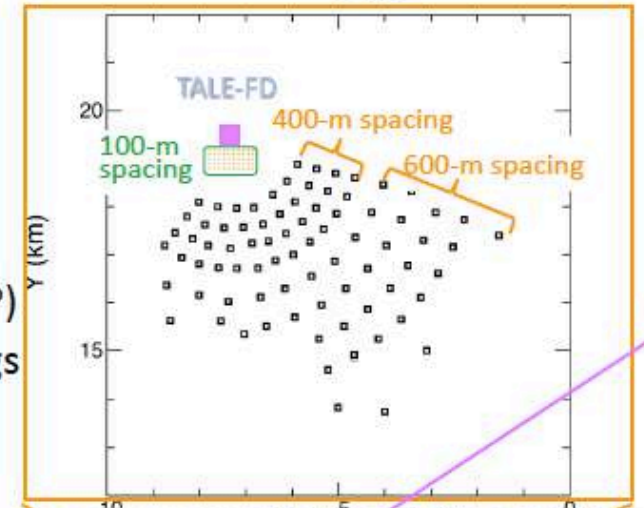
J. Kim, PoS(ICRC2025)302

- 228 events
- max. local significance: 4.9σ at (144.0°, 40.5°)
- global significance: **2.9σ**

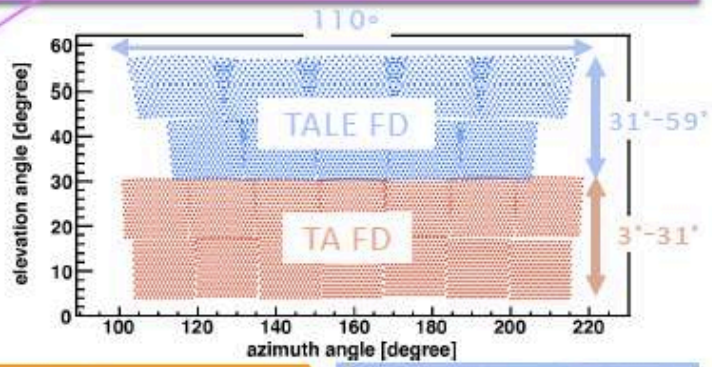


Telescope Array Low-energy Extension (TALE) + Infill

- **Low-energy extension down to ~10^{15} eV**
- **Hybrid measurement**
  - 10 FDs: higher elevations (31°-59°)
  - 80 SDs: 400-m and 600-m spacings
  - 50 infill SDs: 100-m spacing
- **Precise measurement of the composition**
- **Operation**
  - FDs: Sep. 2013 ~
  - SDs: Nov. 2017 ~
  - Infill SDs:Nov. 2023 ~







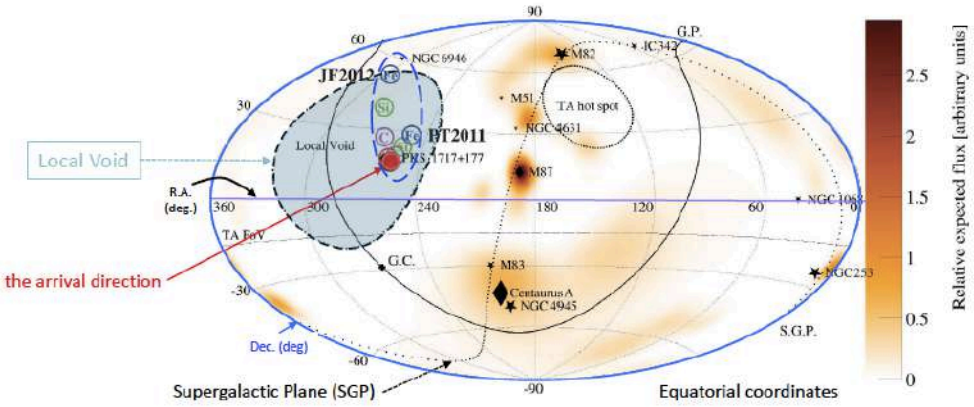




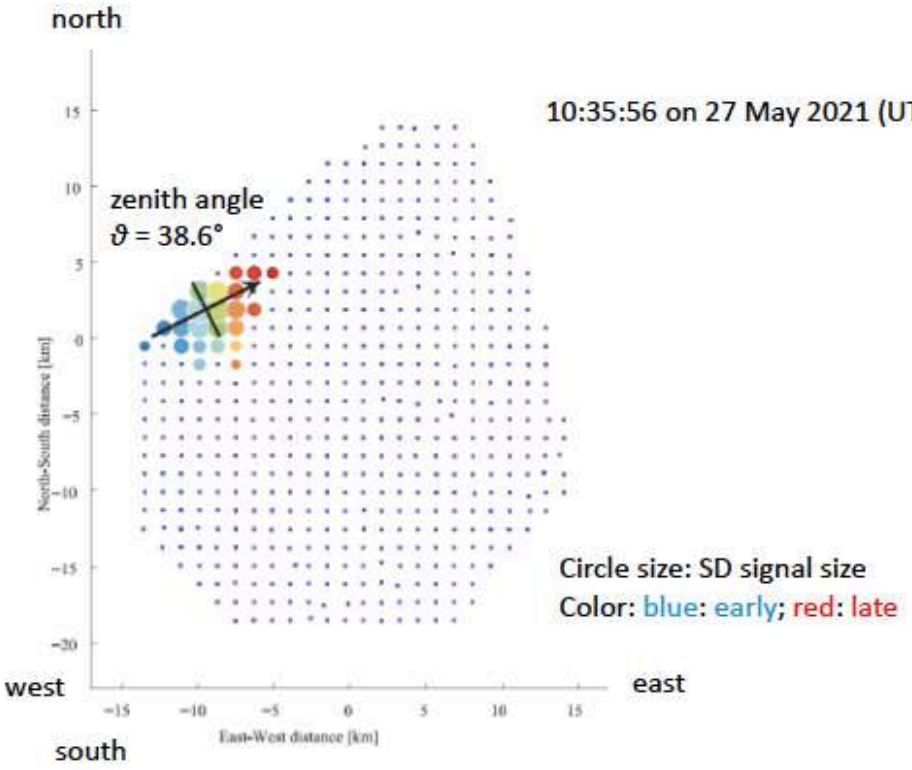
Extremely Energetic TA SD Event

TA SD maximum-energy event

- Observed in 2021
- $E_{\rm max}^{\rm TA}$ = **244** ± 29(stat.) ± 51(syst.) EeV
- Science 382, 903 (2023)
- Comparable to the Fly's Eye (FD) "Oh-My-God particle"
  - **320 EeV** (1991)



Shower footprint



Arrival direction: inside the Local Void

- No prominent source candidates

→ Possible unknown astrophysical or new physical origin?

Mass Composition from Correlations with Nearby LSS

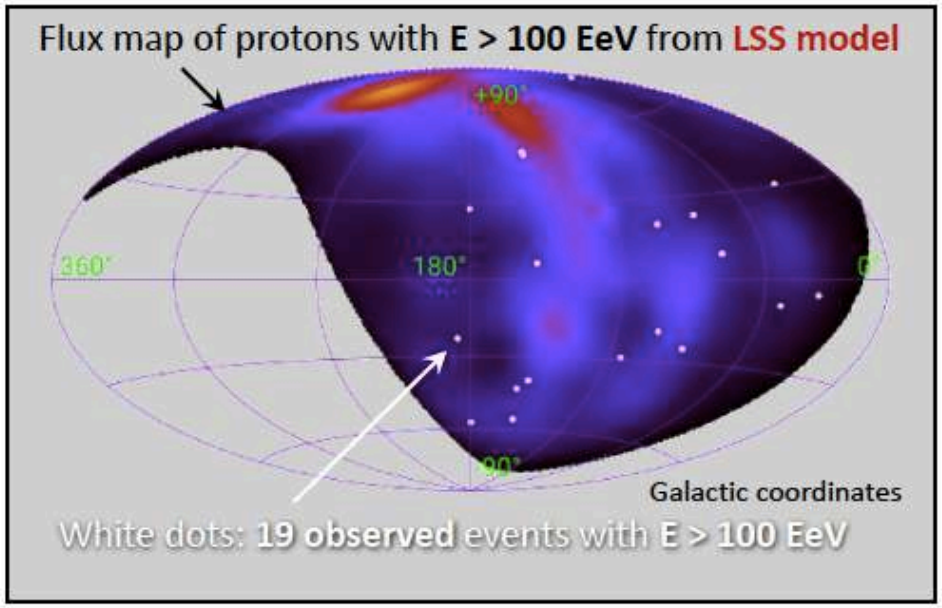
PRL **133**, 041001 (2024)
PRD **110**, 022006 (2024)

LSS (Large-scale Structure) model

- **Sources:** 2Mass Redshift Survey (<250 Mpc)
- **UHECRs:** protons, O, Si, Fe
- **Propagation:** simulated UHECR propagation
  - **GMF:** Galactic magnetic field models are included
  - **EGMF:** Extragalactic magnetic fields are modeled via smearing angles
    - Smearing angle: 10° at 100 EeV

The 19 observed events with E > 100 EeV

- Data are compatible with isotropy



Comparison:
LSS model with 19 observed events with E > 100 EeV

To match the data within 2σ
very heavy mass composition (> Fe), or
strong EGMF (> 20 nG, λ=1 Mpc) for proton

Mass-Number (lnA) Comparison with Other Experiments

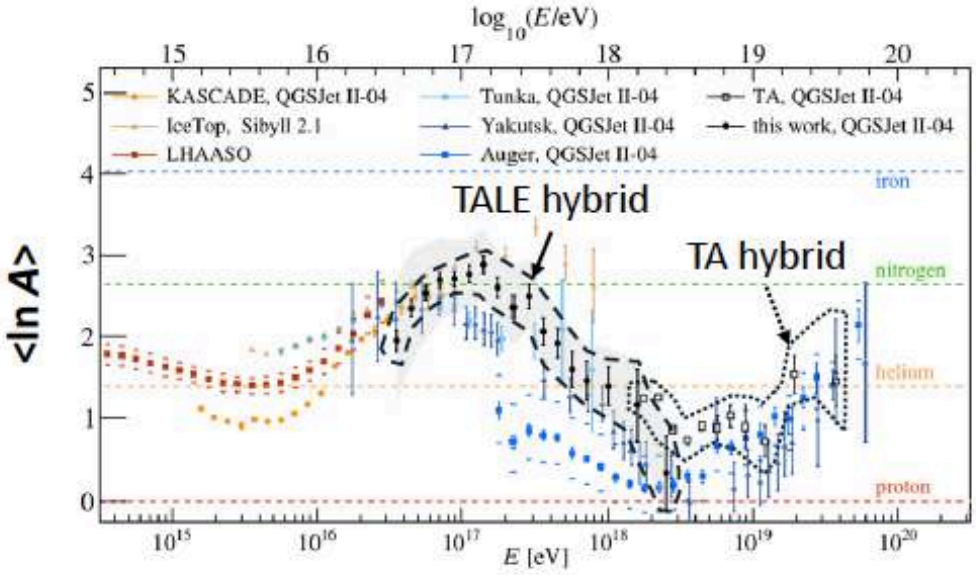
PRD 113, 062003 (2026)

- **Logarithmic mass number**

  $\langle \ln A \rangle = \sum_i (f_i \times \ln A_i)$

  - i: p, He, N, or Fe
  - f_i: best fit fraction
- **TALE hybrid** ($10^{16.5}$ – $10^{18.5}$ eV)
  - intermediate → heavier → light
- **TA hybrid** ($10^{18.2}$ – $10^{19.5}$ eV)
  - light → intermediate
- **Comparison with other experiments**
  - Overall trend consistent
  - Auger slightly smaller in 2x10^{17} – 2x10^{18} eV

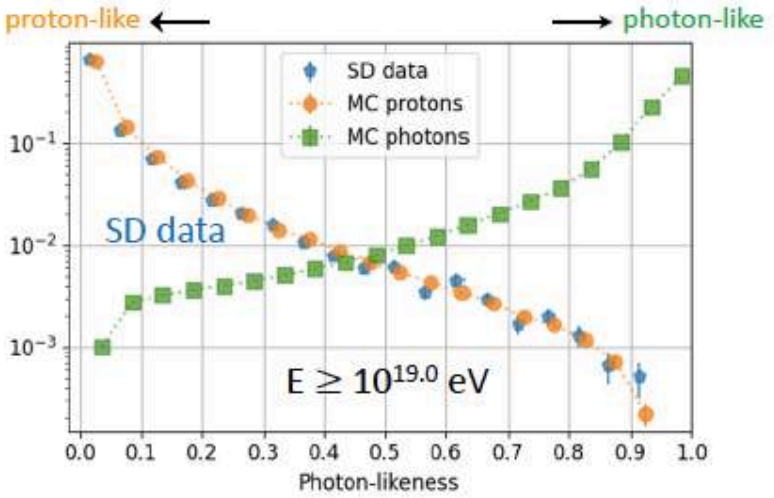
0.3x10^{15} ~ 8x10^{19} eV

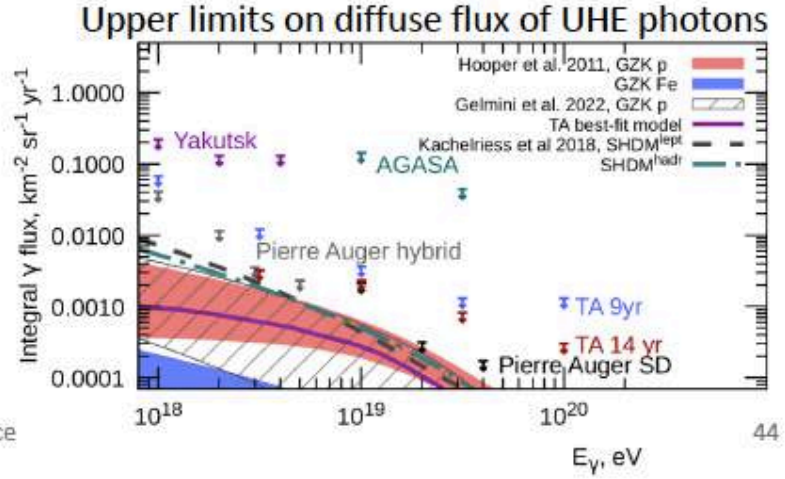


TA SD UHE Photon Search

- NN classifier trained on photon/proton MC
- Uses composition-sensitive SD observables and waveforms
- Fine-tuned with high-confidence non-photon data:
  - to remove lightning events
- Photon-likeness parameter separates photon-like and proton-like events
- Observed candidates match hadronic background

JCAP06 (206) 052





TA SD UHE Neutrino Search

K. Takahashi, PoS(ICRC2025)1192
Dissertation

Scope & Data

- **Goal:** Explore UHECR origin with EeV neutrinos
- **Dataset:** 16 years of TA SD data
- **Sky coverage:** Northern sky, high-energy regime

Event selection

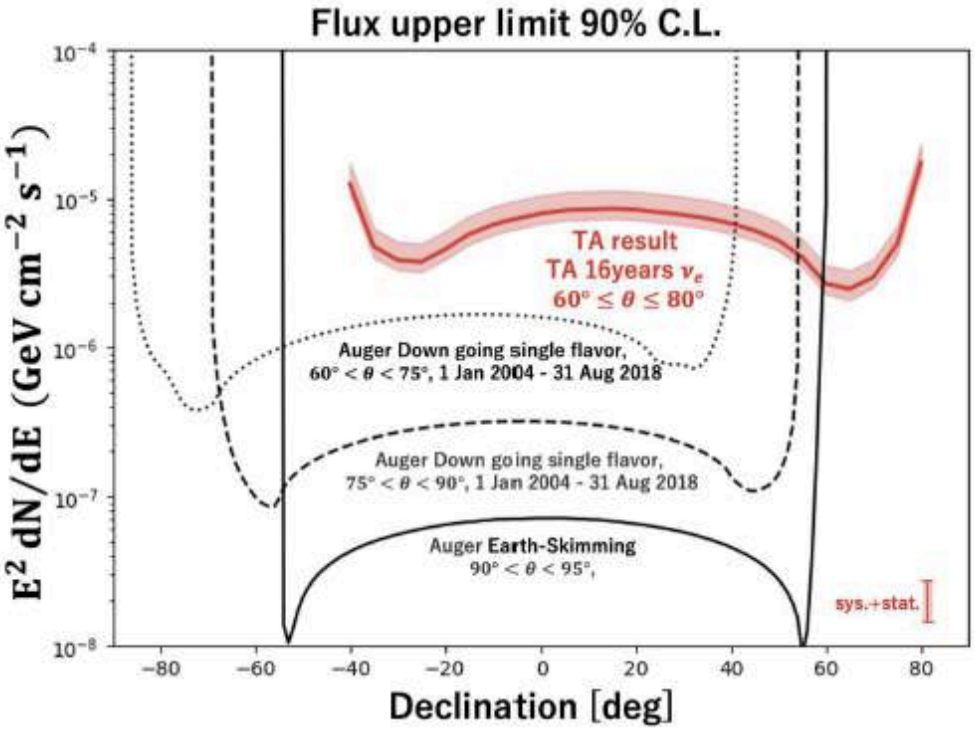
- Inclined shower events: **60°< θ <80°**

Discrimination parameters

- **AoP:** Area over Peak
- **Arrival Time Curvature**

Results

- No neutrino event observed
- Expected background N_{exp} = **2.44**
- Flux upper limits obtained (90% C.L.)



Machine-Learning Approach to TA SD Data

A. Prosekin

Background

- **Expected: better** energy/angular resolution
- **Xmax analysis:** so far **FD** has been used

  FD: observes longitudinal shower profile

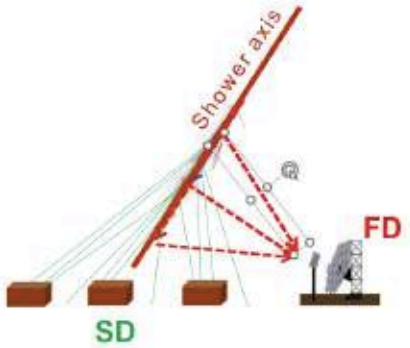
  → Duty cycle: **~10%** → **low statistics**

  SD: ~100% duty cycle

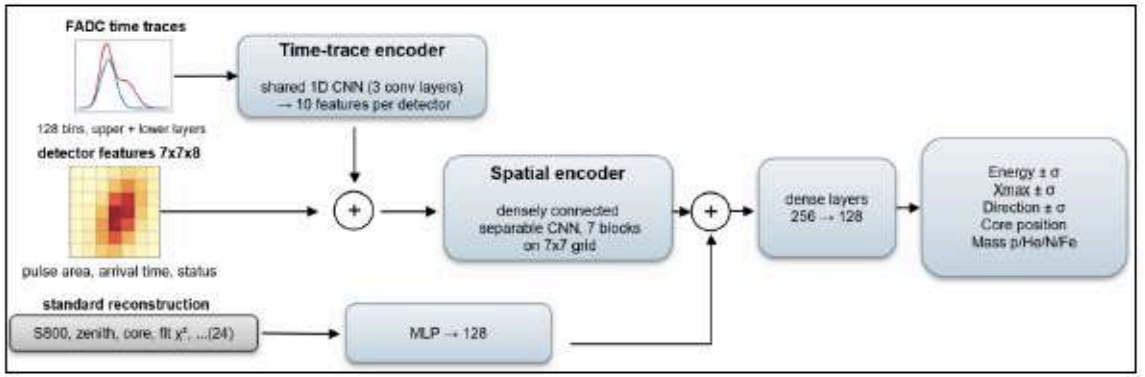
  → **10 times** statistics → **statistically more precise analysis possible**

Training / Method

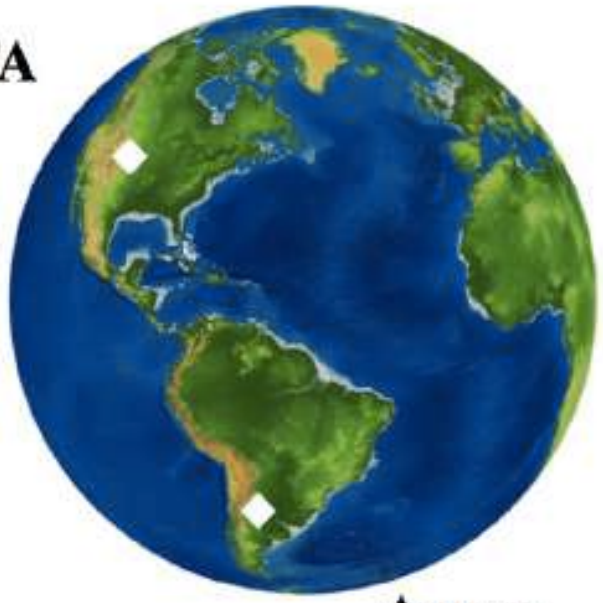
- **Inputs:** SD waveforms + detector positions
- 5M MC events, equal p/He/N/Fe mix
- Hadronic models: **QGSJetII-04 / EPOS-LHC**
- **CNN outputs:** energy, Xmax, direction, core position, mass (p/He/N/Fe)



CNN scheme:
time-trace encoder + **spatial encoder** → unified features



Pierre Auger vsTelescope Array

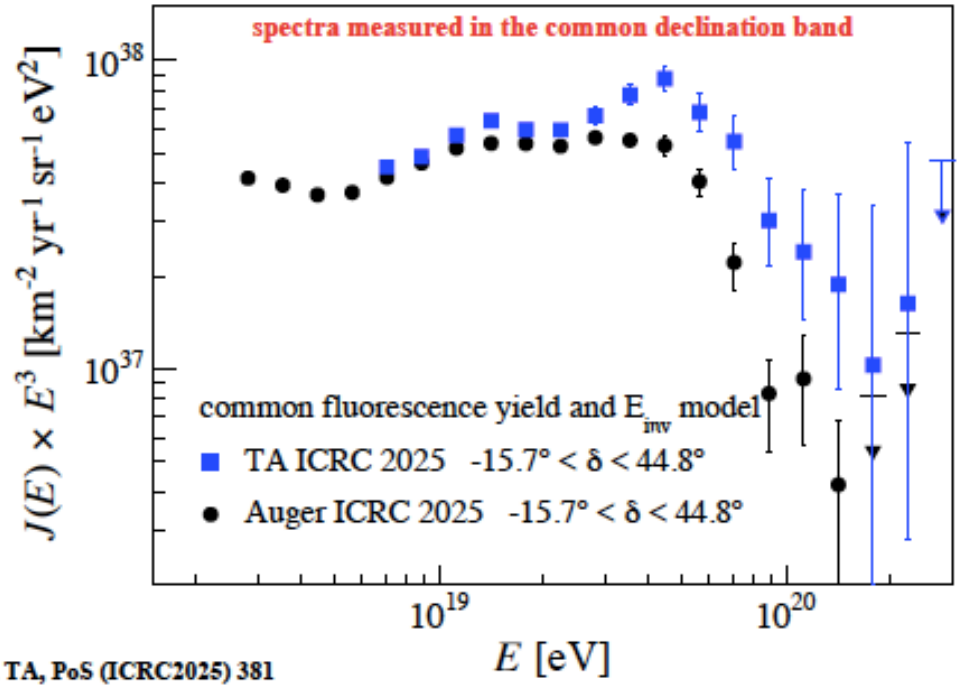


both:
Surface Detector (SD)
Fluorescence Detector (FD)

fully operative since 2008

differences in the energy estimations may affect the anisotropy signals

discrepancy at highest energies in the flux not understood
(cross calibration factor in energy ~ 20%/decade)



Auger and TA, PoS (ICRC2025) 381

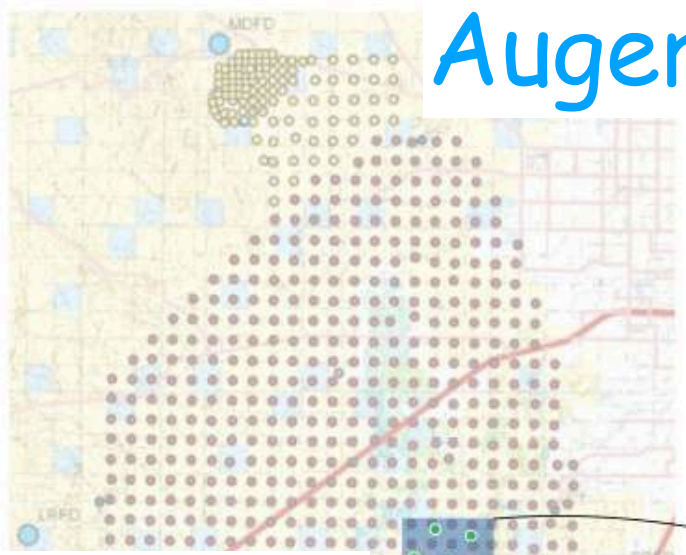
*Talk by Valerio Verzi,2025

Auger@TA

Goal: To address the discrepancy
Strategy: Cross-calibration with self-triggering micro-Auger array within the TA array.

- 8 Auger SD stations with WCD and AugerPrime Scintillator Detectors
- A simple CDAS software

- A functional triangular array is fully operational (July 2025)
- Deployment ongoing



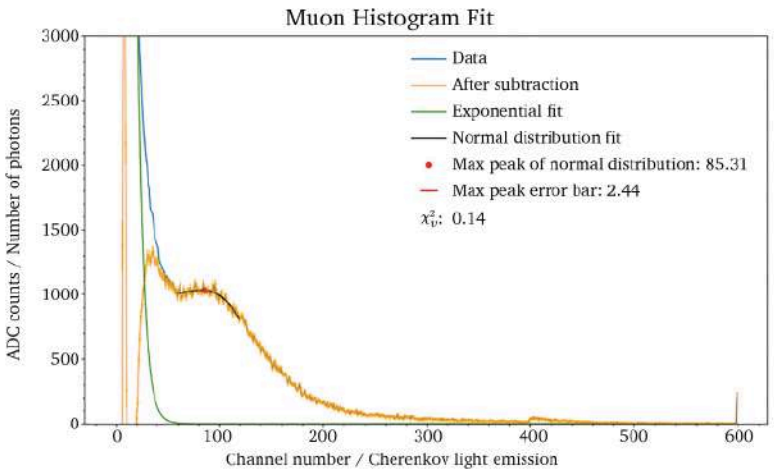
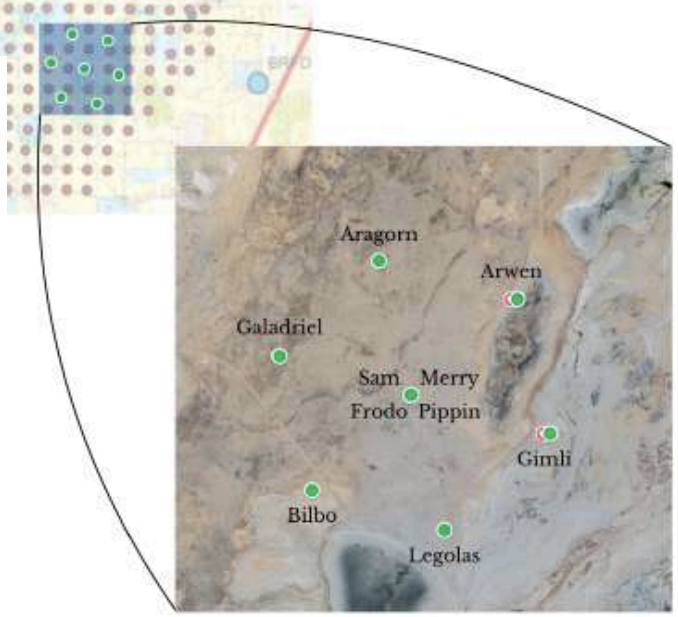


Figure 5: An obtained muon charge histogram for station *Sam*.

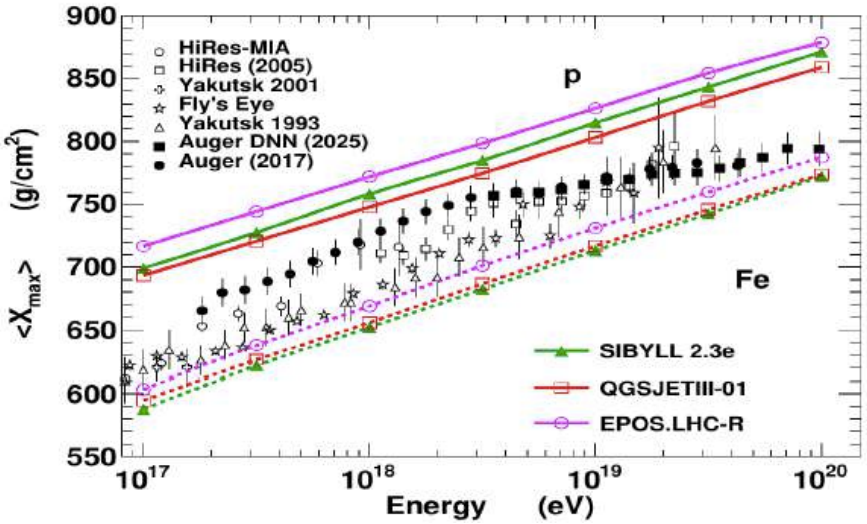


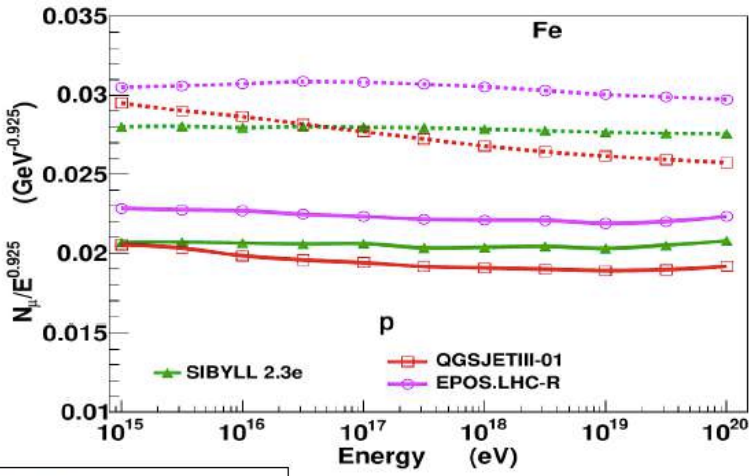
ICRC 2025, 182

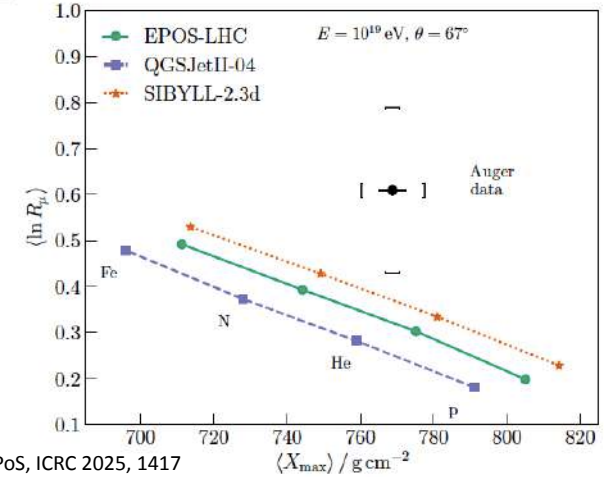
The muon puzzle

Hadronic interaction models
- Interactions
- Energy losses of secondary particles in the atmosphere

Do not predict measurements:
- Muon deficit for Auger



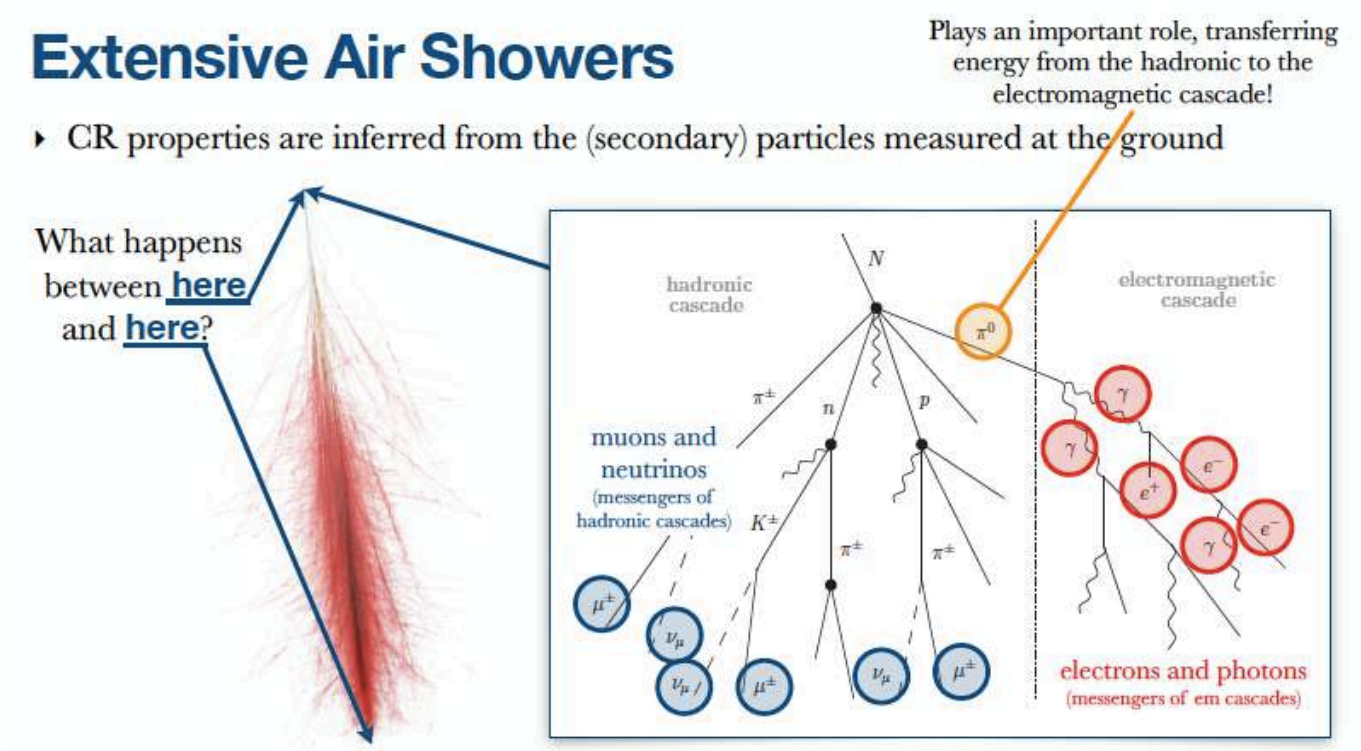




Auger: Phys. Rev. Lett. 126 (2021) 152002, Eur. Phys. J. C 80 (2020) 751, PRL 117 (2017) 192001, Phys. Rev. D 91 (2015) 032003

*Talk by Valerio Verzi,2025, T. Pierog PoS, ICRC 2025, 1417

The muon puzzle



- e.m. cascade well understood (QED)
- Large uncertainties in hadronic interactions (non perturbative QCD)

Possible explanations:

- Muon fluctuations and high-energy muons disfavor origin in the first interactions
- Favored:Soft QCD effect cumulating during shower development (neutral pion fraction)
- Small shift in X_{max} needed

What is needed:

- Further model tuning with EAS
  - Muon fluctuations
  - Muon energy spectra
  - Muon production depth
  - Muon lateral distribution

LHC p-O interactions needed

*Talk by Dennis Soldin,ISVHECRI 2026,Talk by Valerio Verzi,2025

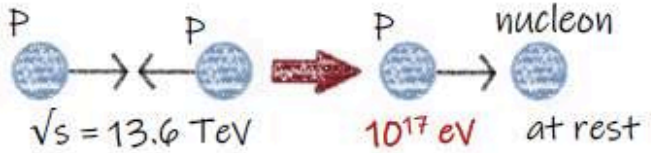
LHC as cosmic lab

Motivation:
To improve the hadronic interaction models

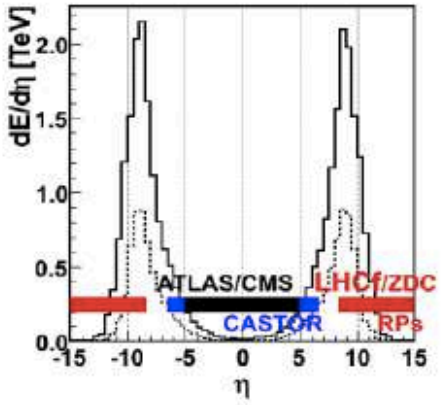
- **Hadronic collisions** that best reproduce CR-atmosphere interaction

p or light nucleus + O or N

- **Center of mass energy as high as possible** to approach UHECR energies (>10^{18} eV) → Large Hadron Collider (LHC)



- **Very forward region** to probe the region of interest for the EAS development, where the largest fraction of energy is focused



High pseudorapidity η

small θ

$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$



*Talk by Helena Gensini, LHCf collaboration, CRIS-MAC 2026

LHC as cosmic lab

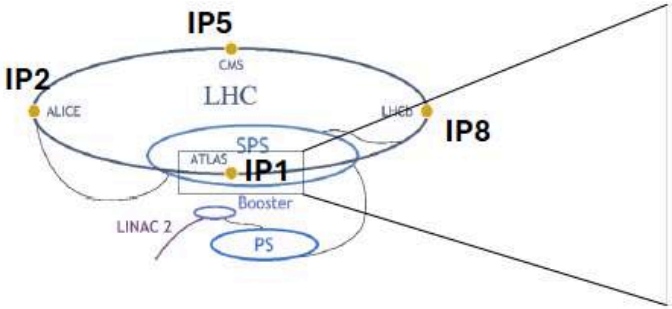
Measured quantities at LHC with an impact on the development of EAS originated by UHECRs

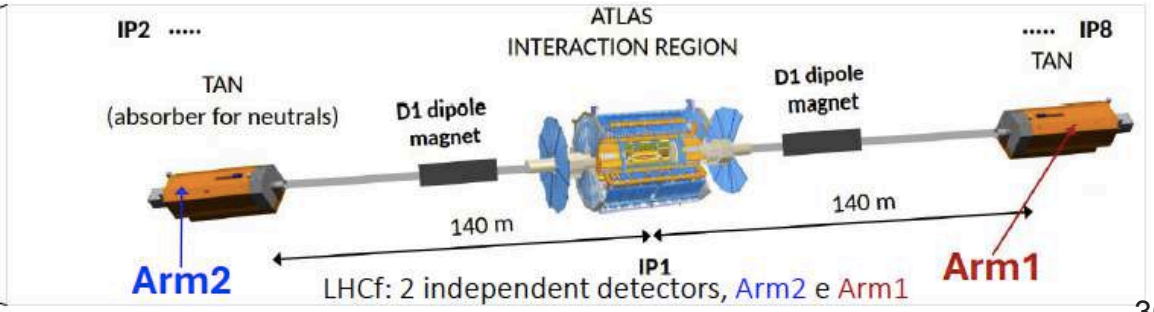
Input parameters of hadronic interaction models

- Hadronic inelastic cross section, σ_{inel}
- Particle multiplicity, m
- Ratio E/H $\rightarrow R = E_\gamma / E_h$
- Inelasticity $1 - k$, where $k = p_{lead}/p_{beam}$
  - Forward energy spectrum
  - Test of scaling laws
    $\rightarrow$ for extrapolation at $E > 10^{17}$ eV
  - Nuclear effects

4 LHC large experiments + TOTEM

LHCf in the very forward region of the collision





*Talk by Helena Gensini, LHCf collaboration, CRIS-MAC 2026

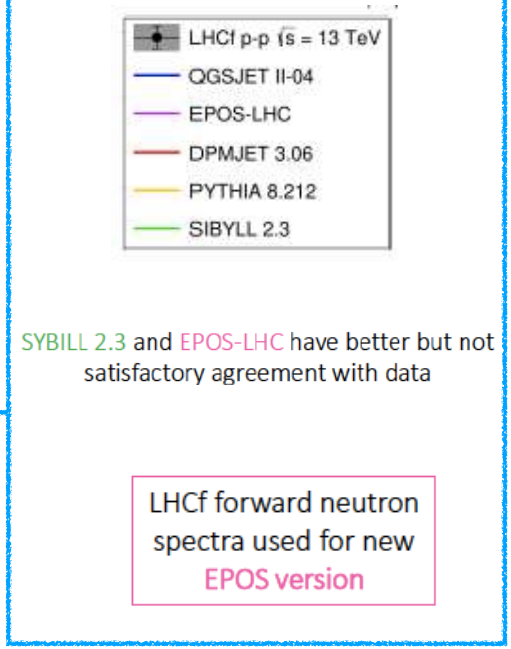
LHC as cosmic lab

The LHCf Experiment Operations:

		$\sqrt{s}$ or $\sqrt{s_{NN}}$	E_{lab} (eV)	year	note
LHC Run I	p+p	$\sqrt{s}$=0.9 TeV	4.3×10^{14}	2009-2010	
	p+p	$\sqrt{s}$=7 TeV	2.6×10^{16}	2010	
	p+Pb	$\sqrt{s_{NN}}$=5.02 TeV	1.4×10^{16}	2013	Arm2 only
	p+p	$\sqrt{s}$=2.76 TeV	4.1×10^{15}	2013	Arm2 only
LHC Run II	p+p	$\sqrt{s}$=13 TeV	9.0×10^{16}	2015	
	p+Pb	$\sqrt{s_{NN}}$=8.16 TeV	3.6×10^{16}	2016	Arm2 only
RHIC	p+p (RHICf)	$\sqrt{s}$=510 GeV	1.4×10^{14}	2017	Arm1 only
LHC Run III	p+p	$\sqrt{s}$=13.6 TeV	9.0×10^{16}	2022	
	p+O	$\sqrt{s_{NN}}$=9.6 TeV	5.0×10^{16}	2025	Arm2 only

Focus of this presentation

- Some results from Run II p+p
- Run III p+p and p+O ongoing analyses



*Talk by Helena Gensini, LHCf collaboration, CRIS-MAC 2026

LHC as cosmic lab

Run II p+p at $\sqrt{s} = 13$ TeV → $E_{lab} = \mathbf{9.0 \times 10^{16}}$ eV

- **Neutron** production cross section
- LHCf – ATLAS joint analysis: **diffractive processes** contribution in photon production
- **η** production rate

*Info on **leading baryon** and **average inelasticity***

*Info on **electromagnetic component***

Run III p+p at $\sqrt{s} = 13.6$ TeV → 8 times statistics wrt Run II (many ongoing analyses)

- **η** meson spectra
- Development of deep learning techniques for $\boldsymbol{K_S^0}$ reconstruction → *It will be the first measurement of **strangeness** production in the very forward region!*

Run III p+O at $\sqrt{s_{NN}} = 9.6$ TeV → $E_{lab} = \mathbf{5 \times 10^{16}}$ eV

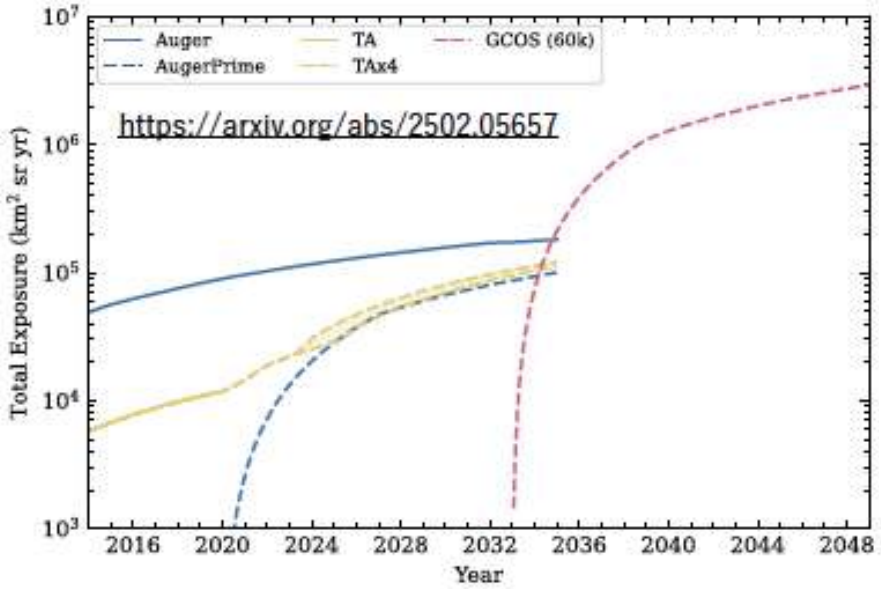
- Most important LHCf operation successfully completed in July 1-3, 2025 → *Most representative of CR-atmosphere collisions*
- Preliminary **photon** spectra → ***pO nuclear modification factor***

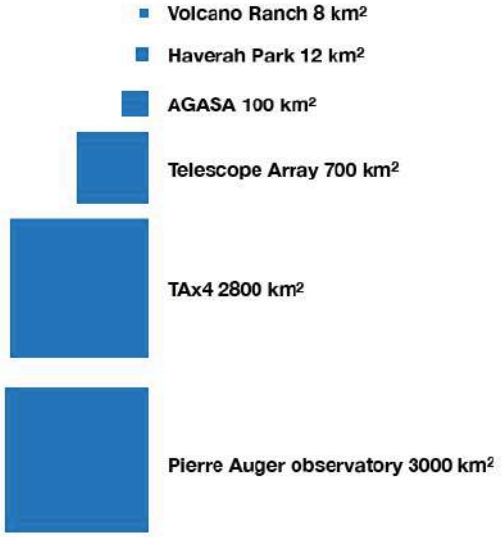
*Talk by Helena Gensini, LHCf collaboration, CRIS-MAC 2026

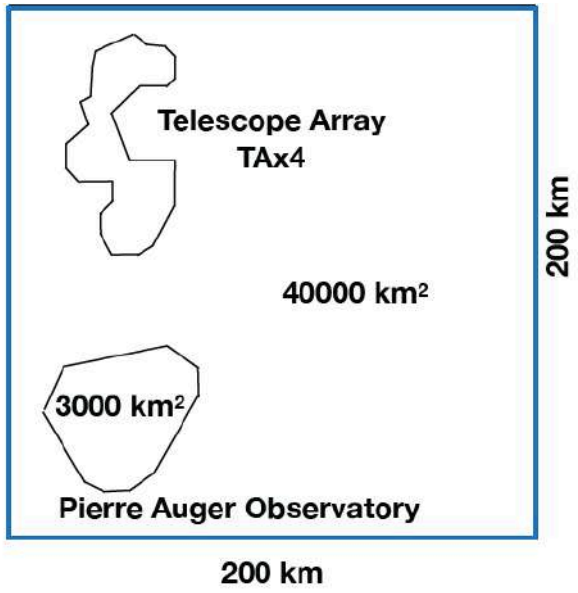
Future experiments

Global Cosmic Rays Observatory - GCOS

20 times Auger





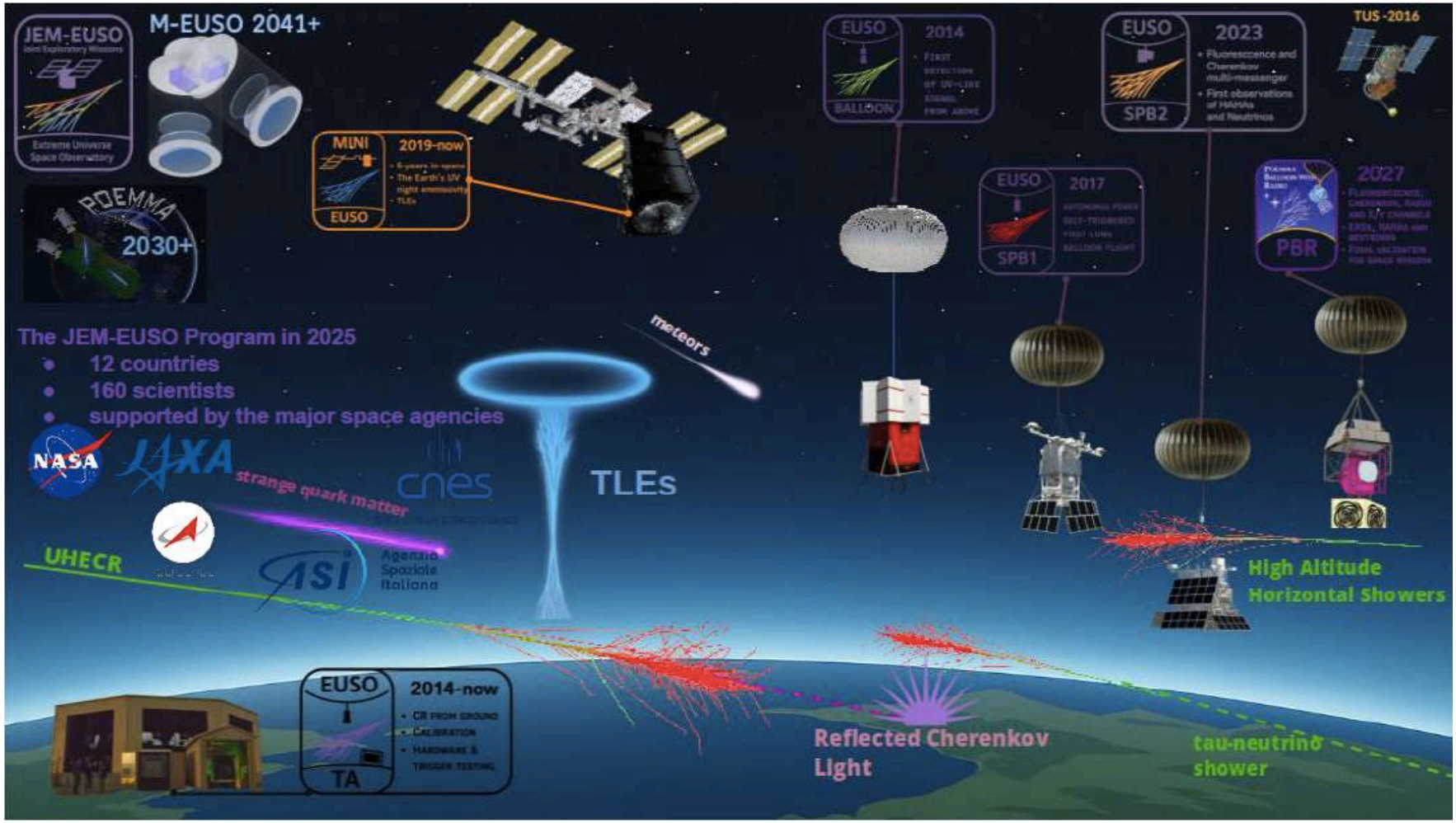


Multi-messenger Astronomy proposal-->2030

workshop in Sept 2025
https://indico.cern.ch/event/1525785/overview

*Talk by Valerio Verzi,2025, J. Hörandel, PoS ICRC 2021, arXiv:2203.01127v1

Future experiments from space



*Talk by Valerio Verzi,2025,Z. Plebaniak, J.Eser, ICRC 2025

Summary

- Current Observatories have provided unprecedented information for improving our understanding of UHECRs
- A better understanding of the hadronic interactions is expected from p-O collisions at LHC
- The estimation of mass composition will be improved
- Multi-Messenger searches with photons and neutrinos can be done for the highest energies
- Strong scientific case for future experiments: CGOS, GRAND, JEM-EUSO



CRA2026
7th Cosmic Ray Anisotropy Workshop

Backup Slides

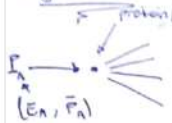
TRANSFORMACIÓN MARCO AIRE-LAB

(EJE SUPERIOR DEL ESPECTRO)

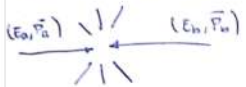
Relación entre experimentos de laboratorio y Rayos Cósmicos en CMS

$(P-P)$

Rayos Cósmicos



En el laboratorio



Aquí notemos que $\vec{P}_a = -\vec{P}_b$

$\Rightarrow \vec{P}_c = 0$

CMS-Lab

$\vec{P}_a + \vec{P}_b = \vec{P}_c = 0$ y $E_a + E_b = E_c$ $\quad E_c = E_a + E_b$

También $\vec{P}_c \cdot \vec{P}_c = \vec{P}_c^2 = E_c^2 - P_c^2 = M^2 \Rightarrow E_c^2 = M^2$

$\Rightarrow s = (E_a + E_b)^2 = M^2 \Rightarrow \sqrt{s} = E_a + E_b$

CMS-Aire

Considerando el sistema en el centro de masa de la colisión

$M^2 = P_c^2$ → es porque la partícula incidente es la que aporta al sistema la colisión

$M^2 = (P_A + P_B)^2 = P_A^2 + 2\vec{P}_A \cdot \vec{P}_B + P_B^2 = P_A^2 + 2(E_A E_B - P_A P_B) + P_B^2$

Pero $P_B = 0 \Rightarrow E_B^2 - P_B^2 = m_B^2 \Rightarrow E_B^2 = m_B^2 \Rightarrow M^2 = m_A^2 + 2(E_A m_B) + m_B^2$

Usando ambas relaciones

$s = (E_a + E_b)^2 = M^2 = m_A^2 + 2(E_A m_B) + m_B^2$

Pero $m_A = m_B = .938\,GeV \Rightarrow s = 2(E_A m_B) + 2m_B^2$

$\Rightarrow \sqrt{s} = \sqrt{2(E_A m_B) + 2m_B^2} = \sqrt{2m_B(E_a + m_B)}$

En la práctica m_B es despreciable

nos queda $\sqrt{s} = \sqrt{2E_A m_B}$

Ejemplo:

$E_A = 1 \times 10^{20}\,eV = 1 \times 10^{11}\,GeV \Rightarrow$

$\sqrt{s} = \sqrt{2(1\times10^{11})0.938}\,GeV = 4.33 \times 10^5\,GeV$

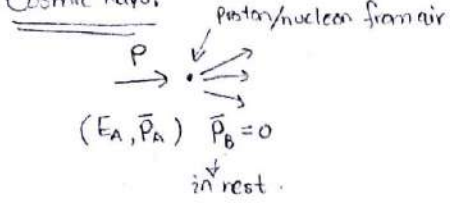
Scanned by CamScanner

TRANSFORMACIÓN MARCO AIRE-LAB

B going from $\sqrt{s} \rightarrow E_{lab}$

We consider:

Cosmic Rays:



We need to know: Scalar product of four-vectors

$\sum g_{\mu\nu} A_\mu B_\nu = A_0 B_0 - \vec{A}\cdot\vec{B}$ $\quad g_{00}=1$ $\quad g_{11}=g_{22}=g_{33}=-1$ $\quad g_{\mu\nu}=0$ for $\mu \neq \nu$

four momenta: $P_\mu = (E, P_x, P_y, P_z) = (E, \vec{P})$

$\boxed{M^2 = P^2}$ because P is a Lorentz scalar

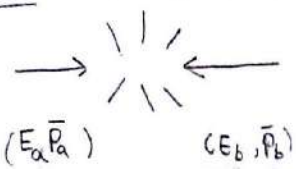
↓ is the rest-mass and is invariant under Lorentz transformation

$E^2 - c^2 p^2 = \frac{m^2 c^4 - m^2 v^2 c^2}{1 - v^2/c^2} = m^2 c^4 \quad c=1 \Rightarrow$

$\boxed{E^2 - p^2 = m^2}$

Lorentz invariant

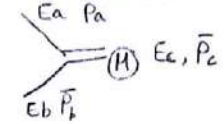
CMS Center of mass System



in CMS: $\vec{P}_a = -\vec{P}_b$

in CMS $\vec{P}_c = 0$

Feym_diag



In CMS:

$\vec{P}_a + \vec{P}_b = \vec{P}_c = 0$

$E_a + E_b = E_c$

$\vec{P}_c^2 = E_c^2 - P_c^2 = M^2$ but $P_c = 0 \Rightarrow E_c^2 = M^2$

$S = (E_a + E_b)^2 = M^2 \Rightarrow E_a + E_b = M$

In air:

$M^2 = \vec{P}_c^2 \rightarrow$ considering the CMS from the collision

$M^2 = (P_A + P_B)^2$

$= P_A^2 + 2 P_A P_B + P_B^2$

$= P_A^2 + 2(E_A E_B - \vec{P}_A \vec{P}_B) + P_B^2$

$= m_A^2 + 2(E_A E_B - \vec{P}_A \vec{P}_B) + m_B^2$ but $P_B = 0$

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In CMS: $\vec{P}_a + \vec{P}_b = \vec{P}_c = 0$

$E_a + E_b = E_c$

$\vec{P}_c^2 = E_c^2 - P_c^2 = M^2$ but $P_c = 0 \Rightarrow E_c^2 = M^2$

$S = (E_a + E_b)^2 = M^2 \Rightarrow E_a + E_b = M$

Center of mass energy $\sqrt{s} = E_a + E_b$

In air: $M^2 = \vec{P}_c^2$ → considering the CMS from the collision

$M^2 = (P_A + P_B)^2$

$= P_A^2 + 2P_AP_B + P_B^2$

$= P_A^2 + 2(E_AE_B - P_AP_B) + P_B^2$

$= m_A^2 + 2(E_AE_B - P_AP_B) + m_B^2$ but $P_B = 0$

$= m_A^2 + 2(E_AE_B) + m_B^2$ but $E_B^2 - p_B^2 = m_B^2 \Rightarrow E_B^2 = m_B^2$

$\Rightarrow M^2 = m_A^2 + 2(E_Am_B) + m_B^2$

Using the M:

$S = (E_a + E_b)^2 = m_A^2 + 2(E_Am_B^2) + m_B^2$

$\Rightarrow S = m_A^2 + 2(E_Am_B^2) + m_B^2$

but $m_A = m_B = 0.938$ GeV → negligabel

$\Rightarrow S = 2(E_Am_B) \Rightarrow \sqrt{s} = \sqrt{2E_Am_B}$

E_{beam}

$\Rightarrow \sqrt{s} = \sqrt{2E_A\,0.938}$ GeV

Example: $E_{beam} = 1\times10^{20}$ eV $= 1\times10^{11}$ GeV

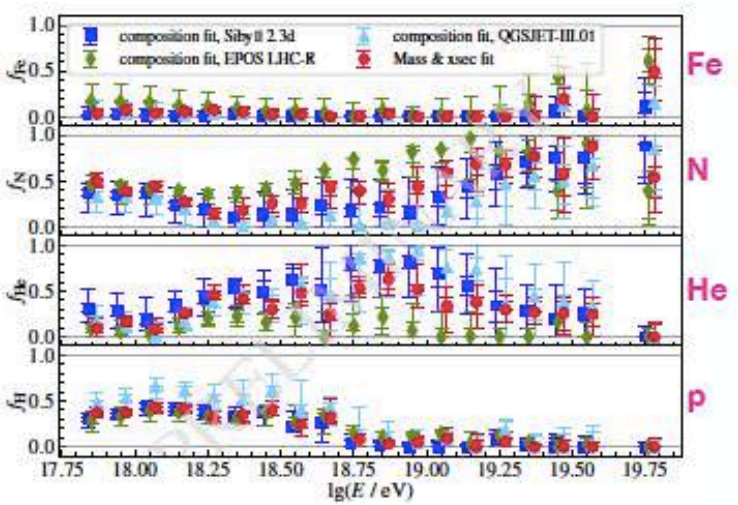
$\Rightarrow \sqrt{s} = \sqrt{2(1\times10^{11})0.938} = 4.33\times10^5$ GeV

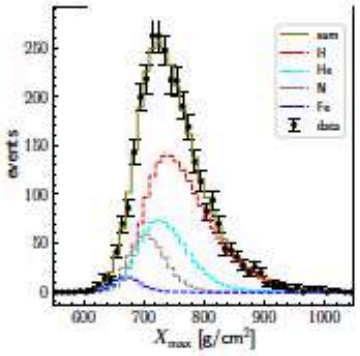
Generated by CamScanner from intsig.com

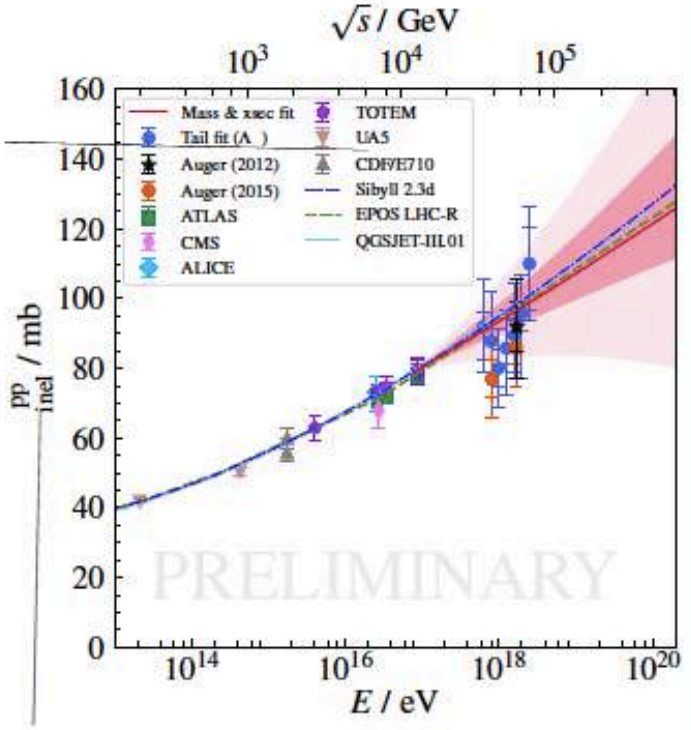
Inelastic proton-proton Cross section at $\sqrt{s}$ ≥40 TeV

- 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
  - δX_{max} ~ 20 g/cm²
  - In agreement with SD analyses

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*Based on Roth, M., ICRC2025

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