The Pierre Auger Observatory: latest results and perspectives

Federico Sánchez
for the Pierre Auger Collaboration

ICHEP
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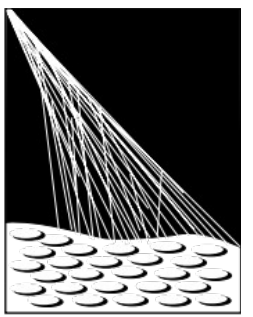
CNEA - CONICET - UNSAM



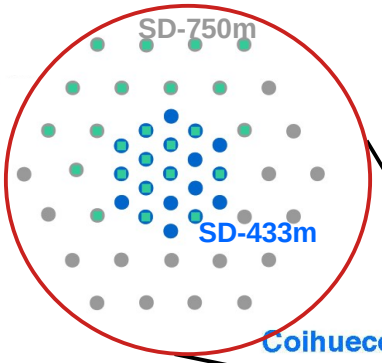
PIERRE AUGER OBSERVATORY

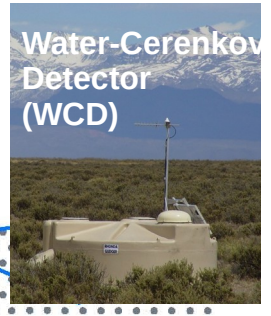
The Pierre Auger Observatory

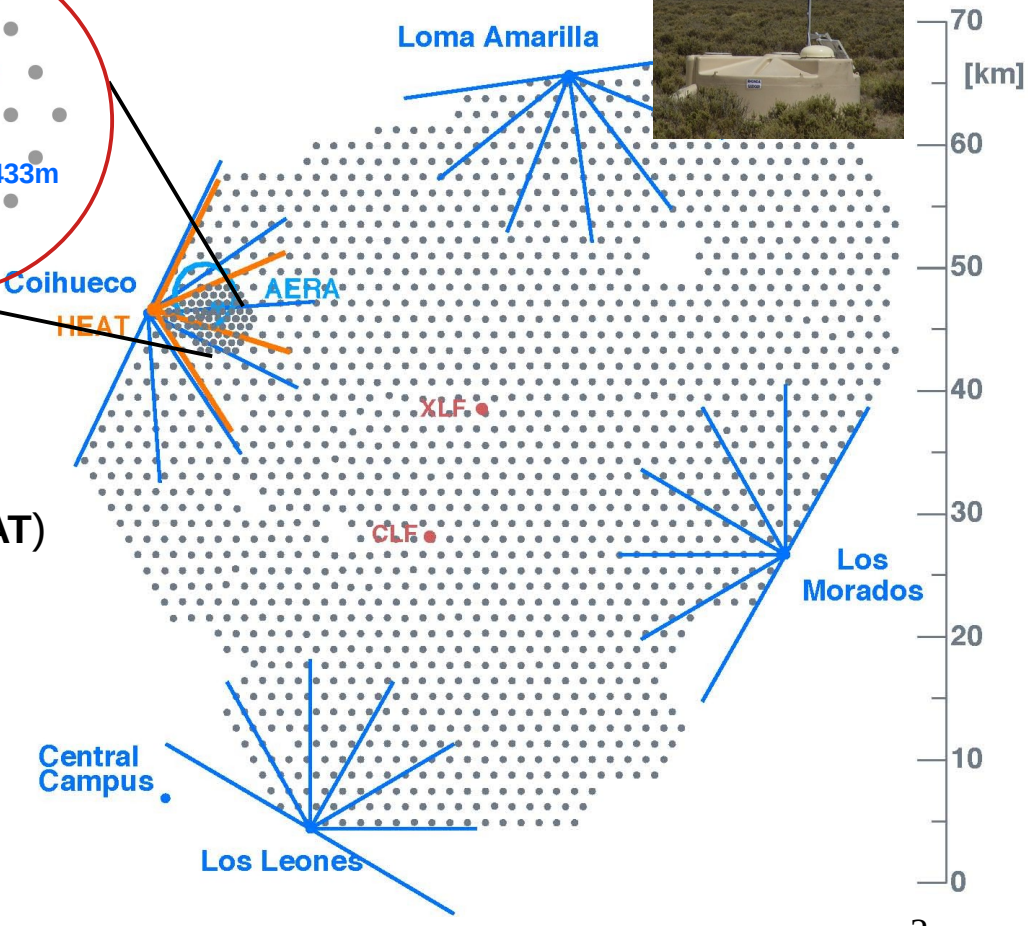
Surface detector (SD)

100% duty cycle

SD-1500m	SD-750m	SD-433m
3000 km^2	23.5 km^2	1.9 km^2
1600 WCDs	61 WCDs	19 WCDs
E^{v}_{thr} 2.5 EeV	E_{thr} 0.1 EeV	E_{thr} 0.03 EeV
E^{i}_{thr} 4.0 EeV		







Fluorescence detector (FD)

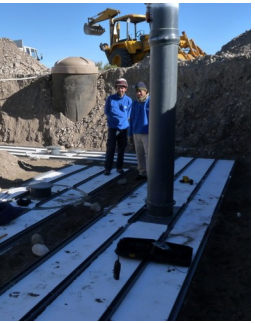
15% duty cycle

4 units x 6 telescopes
overlooking SD-1500m
FoV 30^o x 30^o
Minimum elevation 1.5^o

1 units x 3 telescopes (**HEAT**)
overlooking SD-750m
FoV 30^o x 30^o
Minimum elevation 30^o

The Pierre Auger Observatory

Underground Muon detector (UMD)



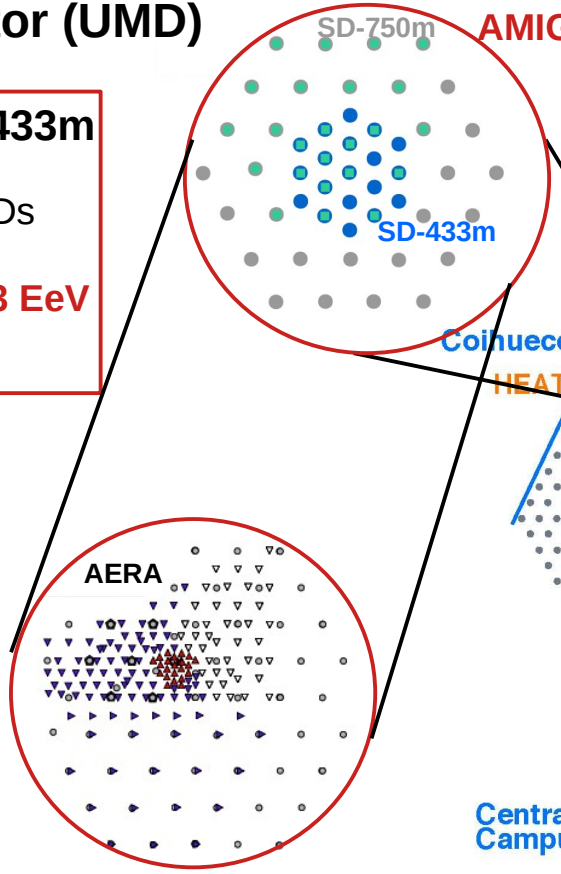
100% duty cycle

UMD-750m	UMD-433m
23.5 km^2	1.9 km^2
61 WCDs	19 WCDs
E_{thr} 0.1 EeV	E_{thr} 0.03 EeV

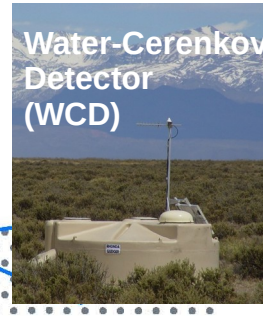
Radio detector (AERA)

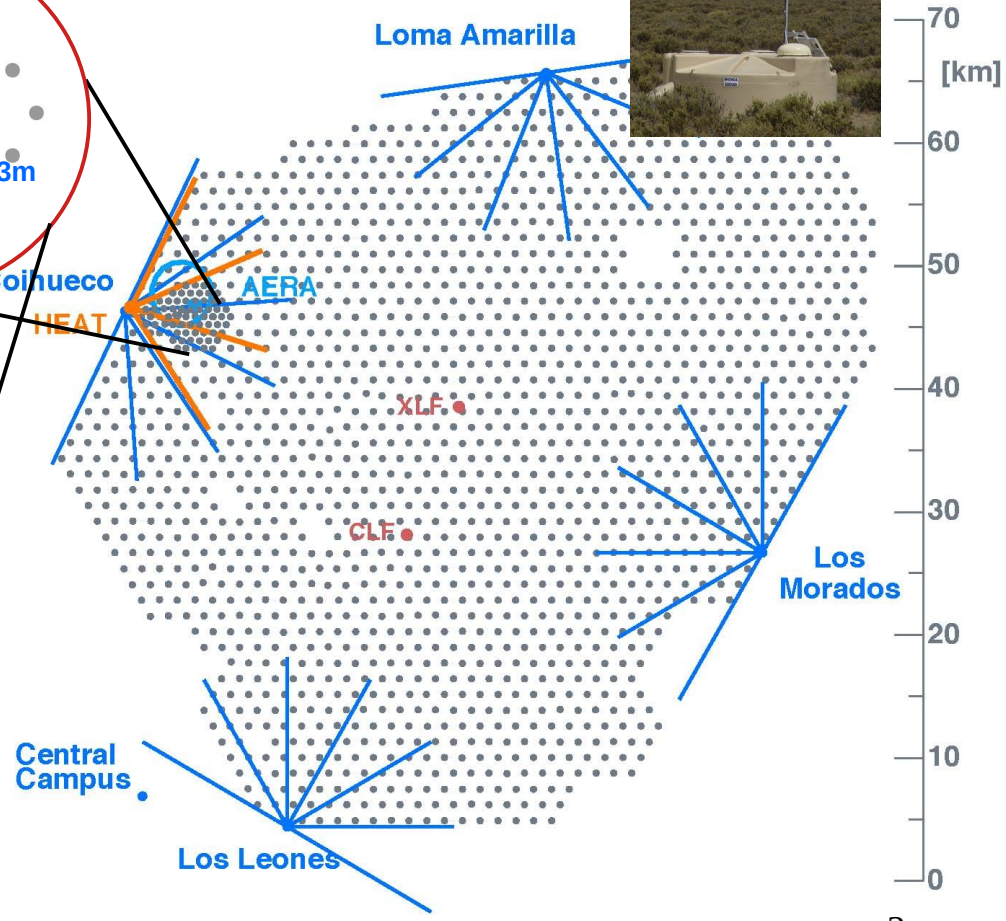
100% duty cycle

30-80 MHz
153 radio stations over 17 km^2
Spacing from 150m to 750m

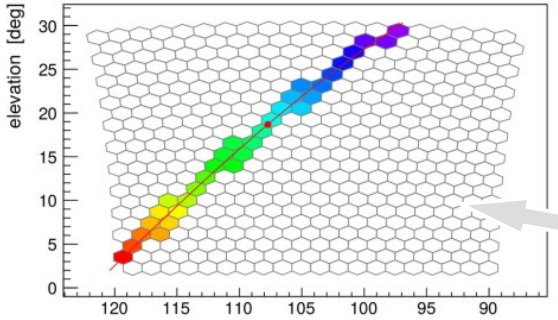


AMIGA: SD+UMD

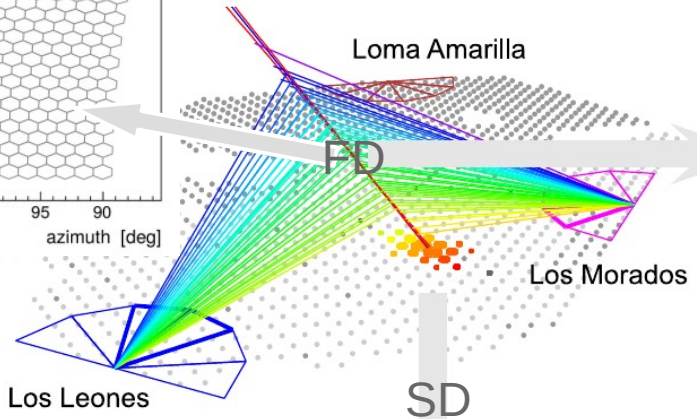


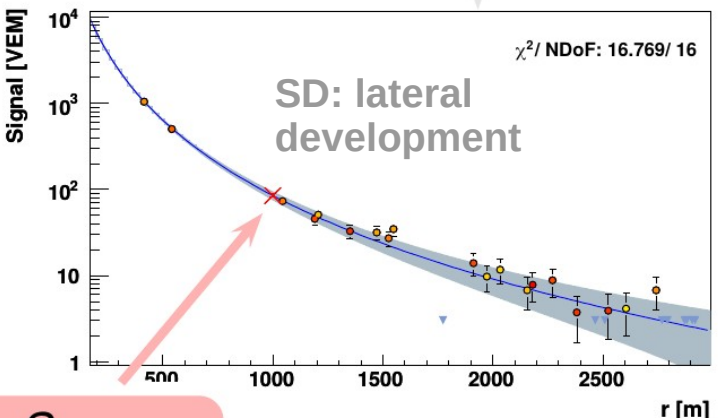


The hybrid technique

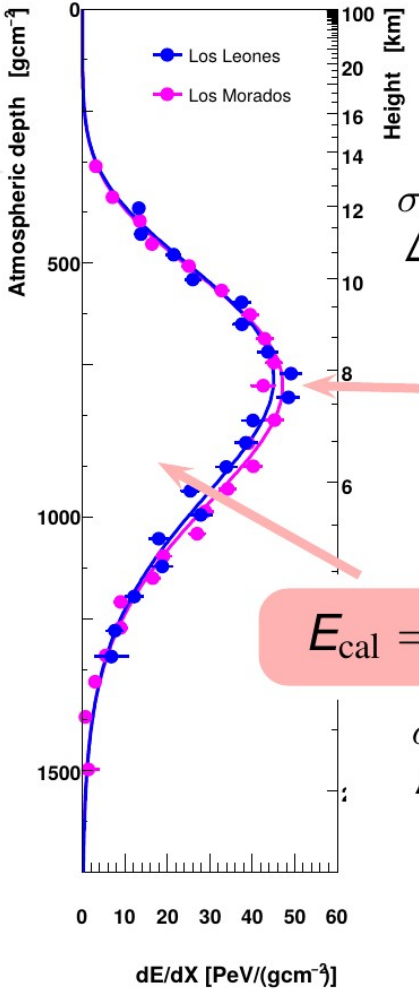


FD: longitudinal development





S_{1000}



$\sigma X_{\max} \leq 20\,\mathrm{g/cm^2}$
$\Delta_{\mathrm{sys}} \leq 10\,\mathrm{g/cm^2}$

Direct access to:

$X_{\max}$

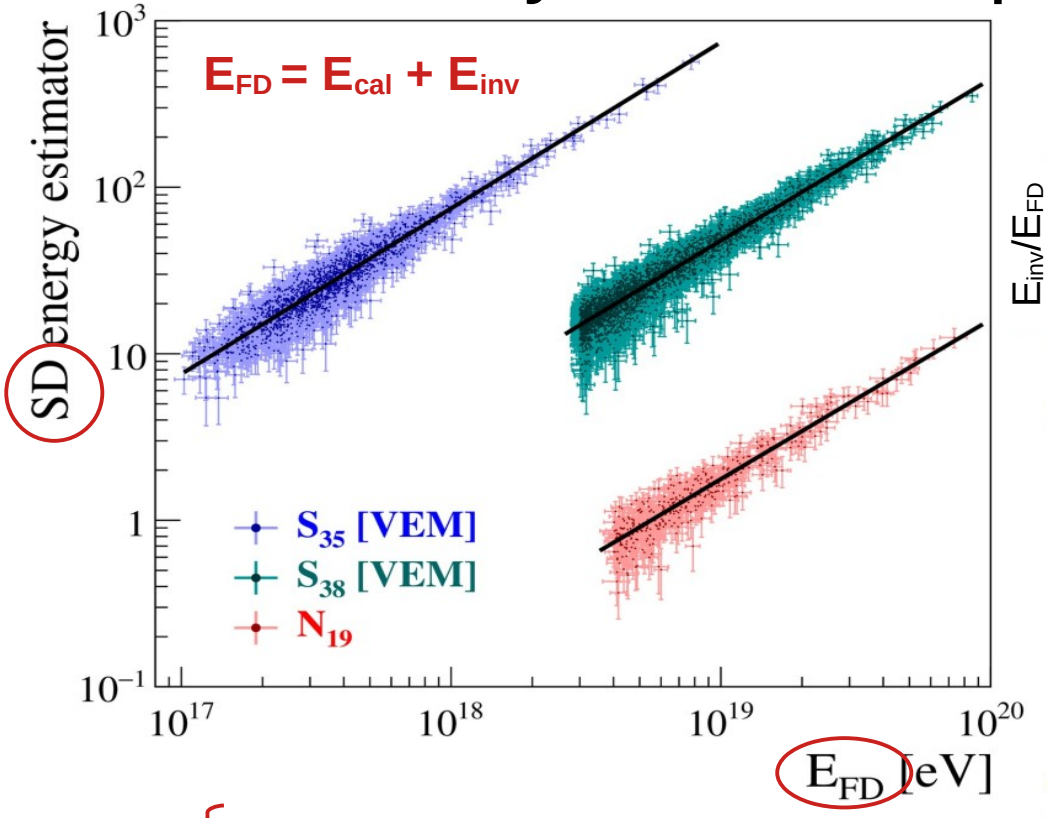
(and its fluctuations)

$E_{\mathrm{cal}} = \int \frac{\mathrm{d}E}{\mathrm{d}X}\,\mathrm{d}X$

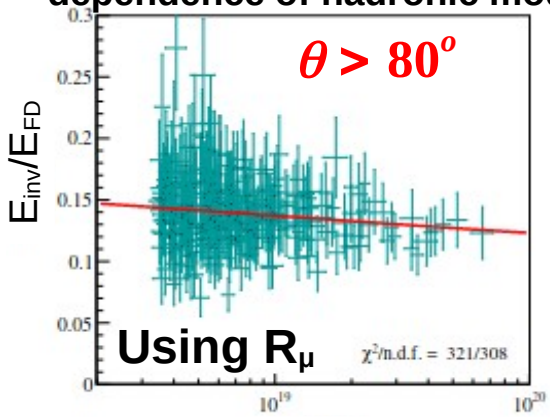
$\sigma_E/E \sim 8\,\%$
$\Delta_{\mathrm{sys}} \approx 15\,\%$

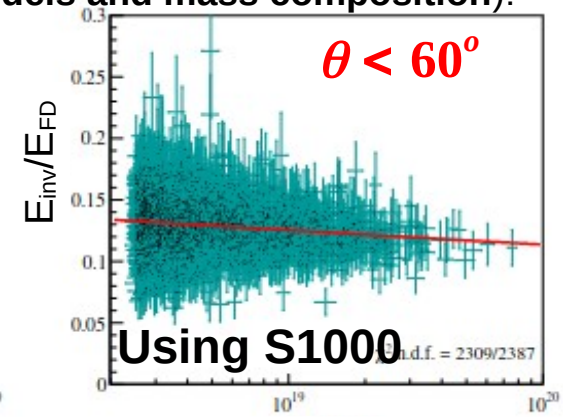
Signal size at fixed distance where fluctuations are minimized

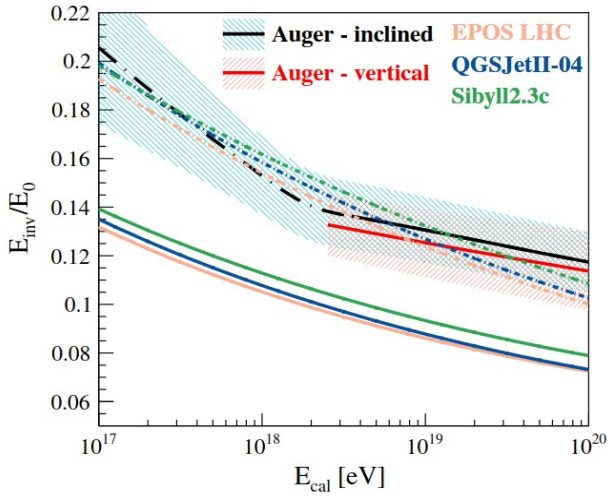
The hybrid technique: energy calibration



Data-driven parametrization at high energies (**reduced dependence of hadronic models and mass composition**):







10%-15% higher than purely Monte-Carlo predictions

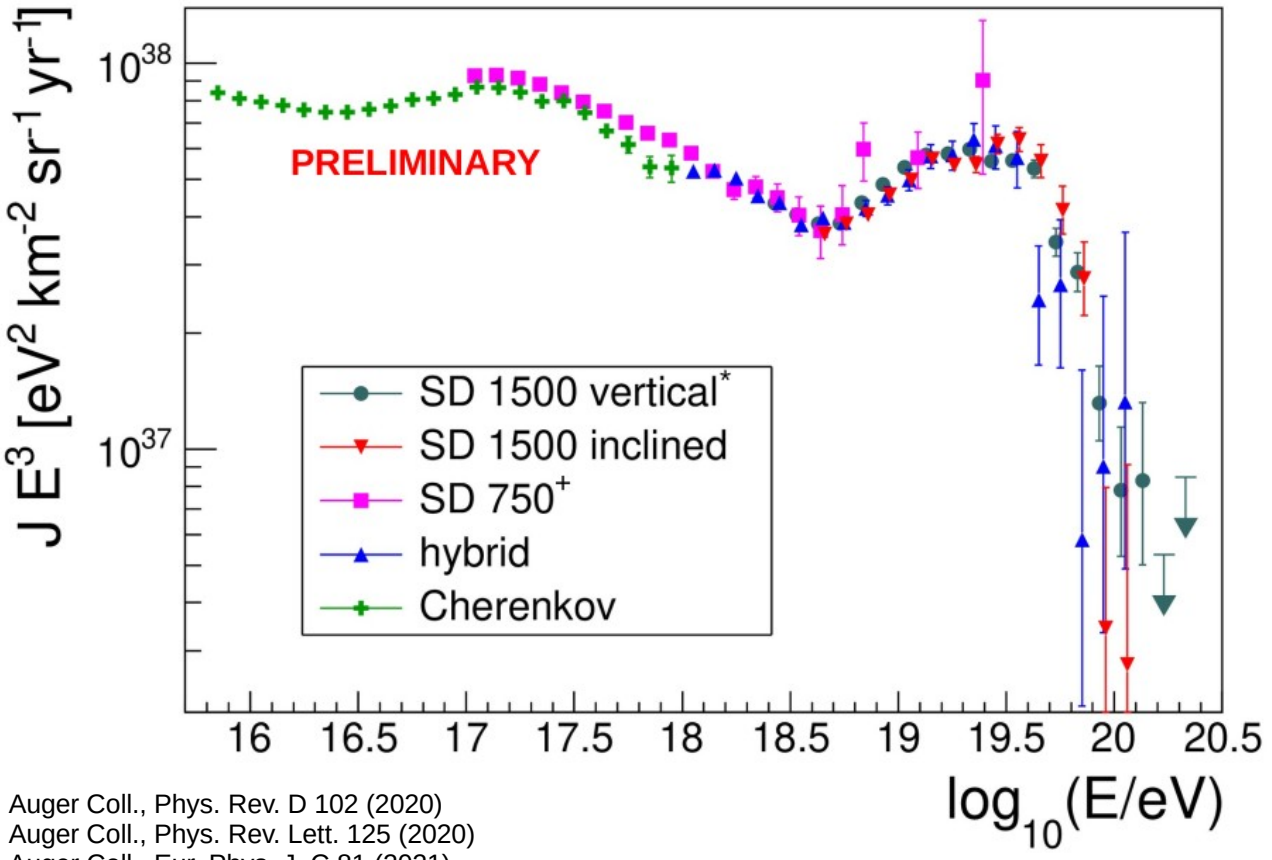
$\theta < 60^o$ { SD 1500 m vertical – S_{38}: threshold **2.5 EeV**
SD 750 m vertical – S_{35}: threshold **0.1 EeV**

$\theta > 80^o$ SD 1500 m inclined – N_{19}: threshold **4.0 EeV**

Auger Coll., Phys. Rev. D 100 (2019)
V. Novotny, PoS(ICRC2021) 324

Energy spectrum: all-particle flux

5 independent measurements (ICRC 2021)



Flux uncertainties:

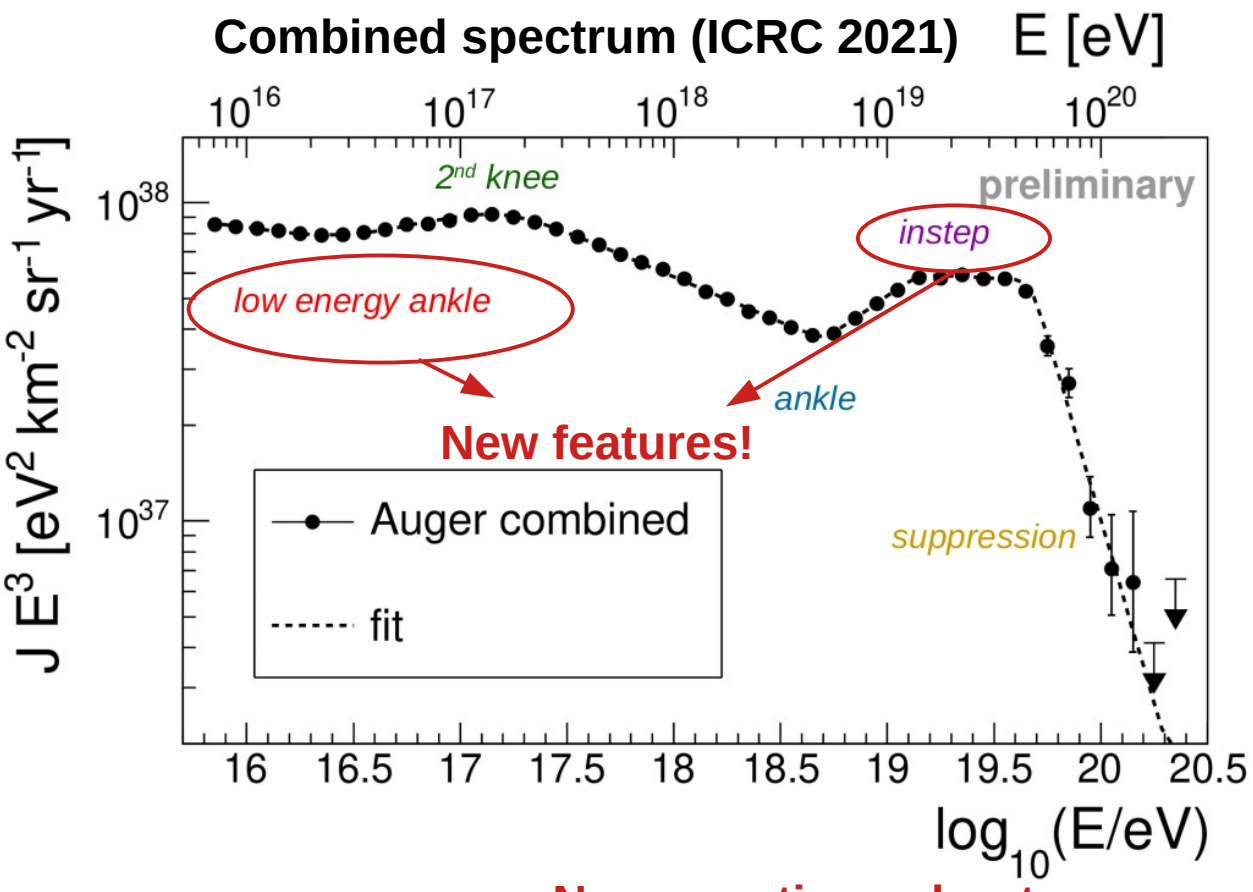
6% SD-1500 vertical
5% SD-1500 inclined
7-14% SD-750 vertical
10% Hybrid
15% Cherenkov

Energy resolution:

15% SD-1500 vertical
19% SD-1500 inclined
13% SD-750 vertical
10% Hybrid
18% Cherenkov

Auger Coll., Phys. Rev. D 102 (2020)
Auger Coll., Phys. Rev. Lett. 125 (2020)
Auger Coll., Eur. Phys. J. C 81 (2021)
V. Novotny, PoS(ICRC2021) 324

Energy spectrum: all-particle flux



Auger Coll., Phys. Rev. D 102 (2020)
Auger Coll., Phys. Rev. Lett. 125 (2020)
Auger Coll., Eur. Phys. J. C 81 (2021)
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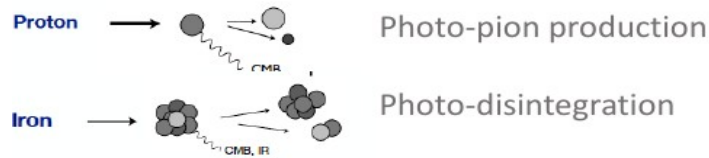
New questions about the origin of the new features

Traditional questions:

What is the origin of the flux suppression?

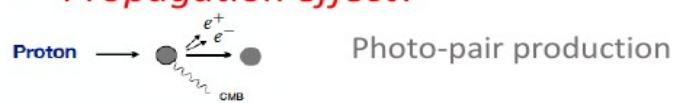
- *Propagation effect?*
  "Greisen-Zatsepin-Kuzmin"



- *Maximum injection energy?*

What is the origin of the ankle?

- *Propagation effect?*



- *Transition effect?*
- *Interactions in the source environment?*

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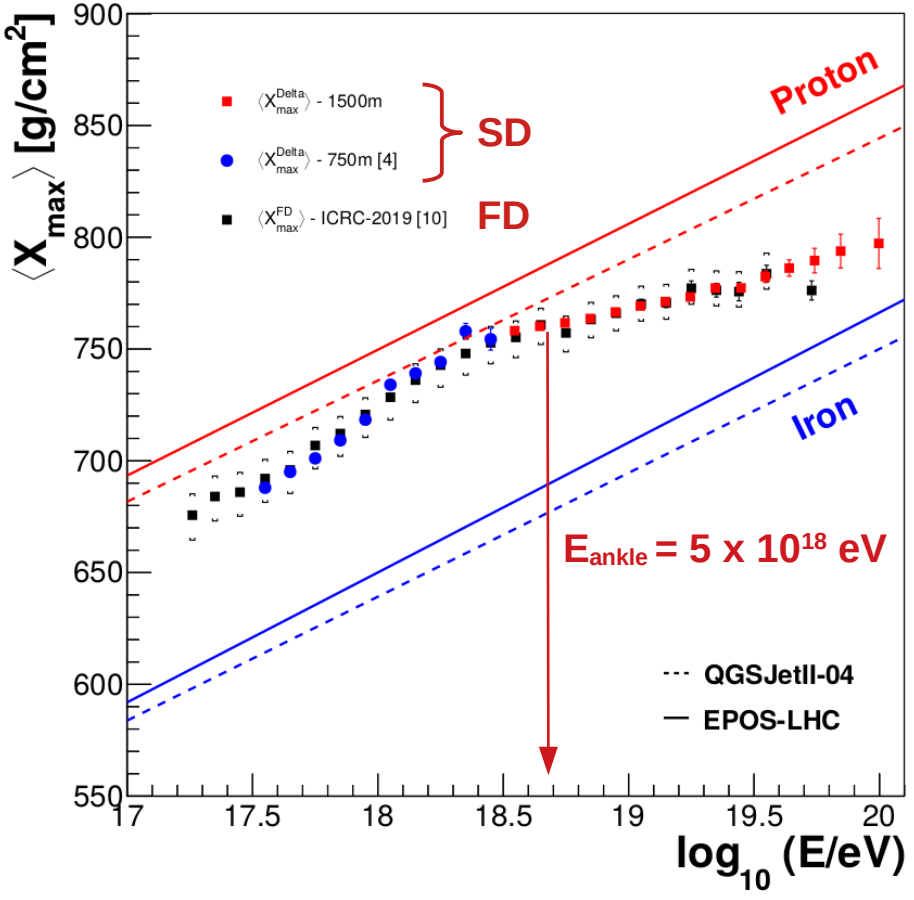
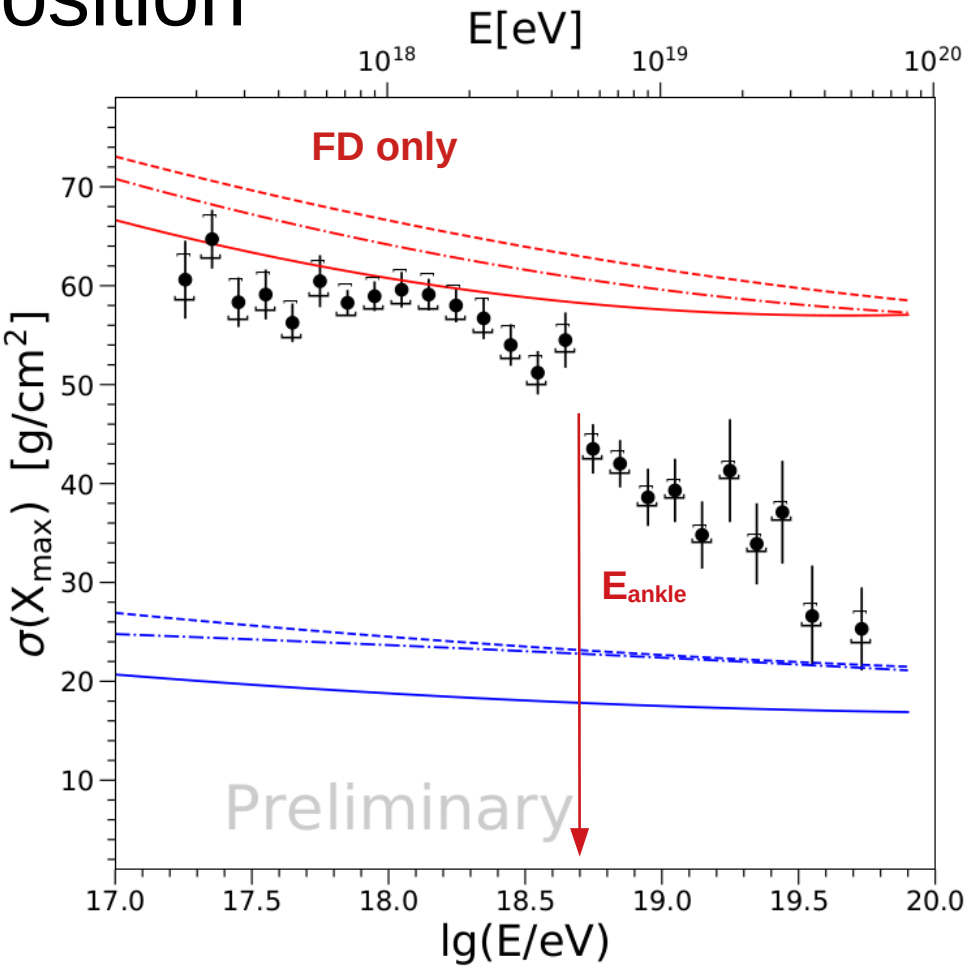
Auger Coll., Phys.Rev.D96 (2017) 122003

Composition

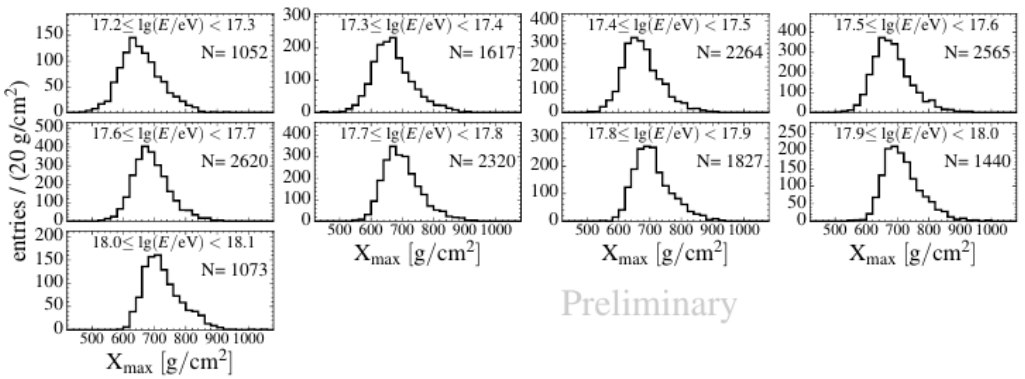




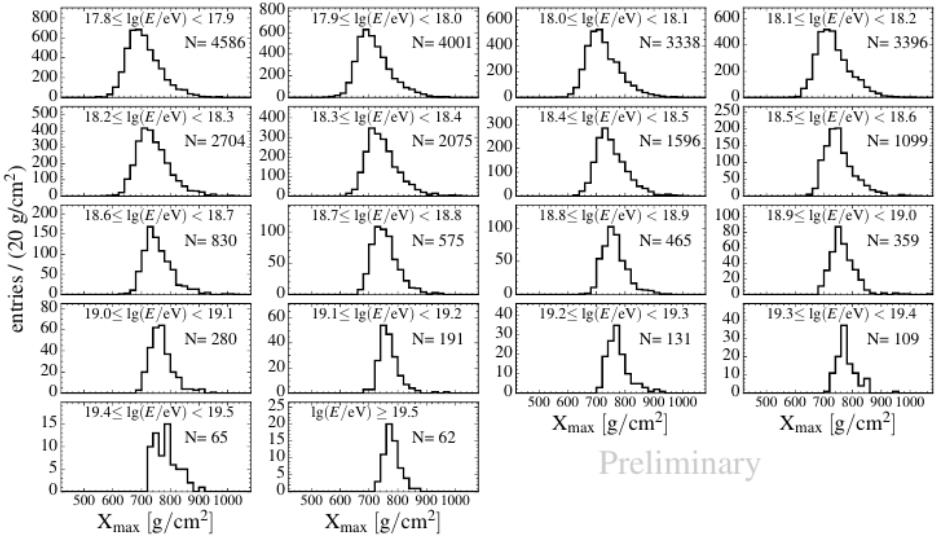
Break in elongation rate just below the energy of the ankle from 77 g/cm^2/decade to 26 g/cm^2/decade (composition constant above $10^{17.2}$ eV would have had ~60 g/cm^2/decade)

Composition

$\lg(E/\mathrm{eV}) = 17.2 \ldots 18.1$

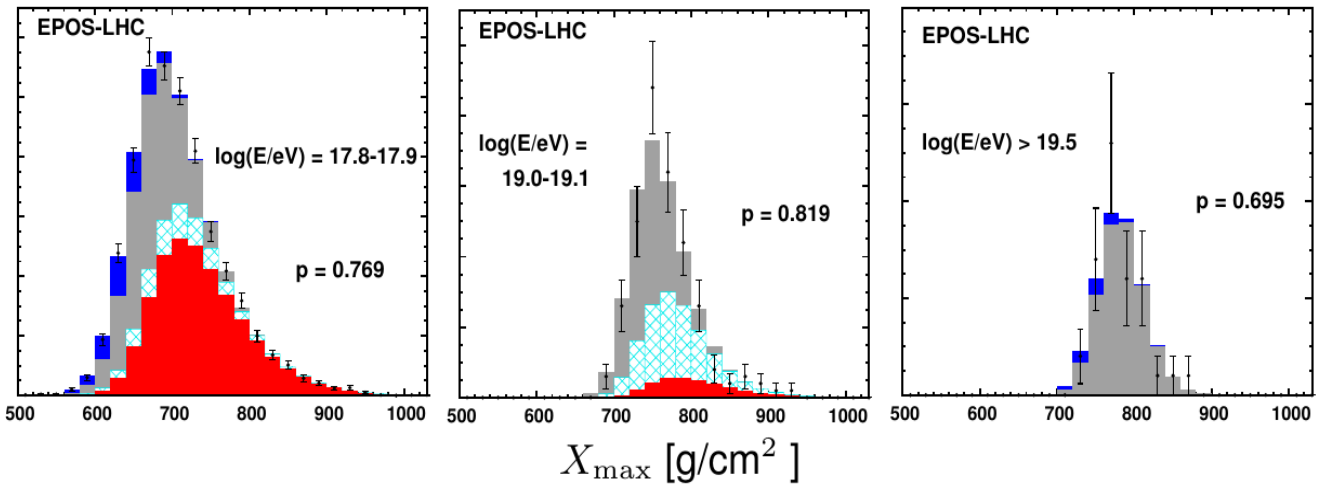


$\lg(E/\mathrm{eV}) = 17.8 \ldots > 19.5$



Example of 4-component fit

p
He
N
Fe



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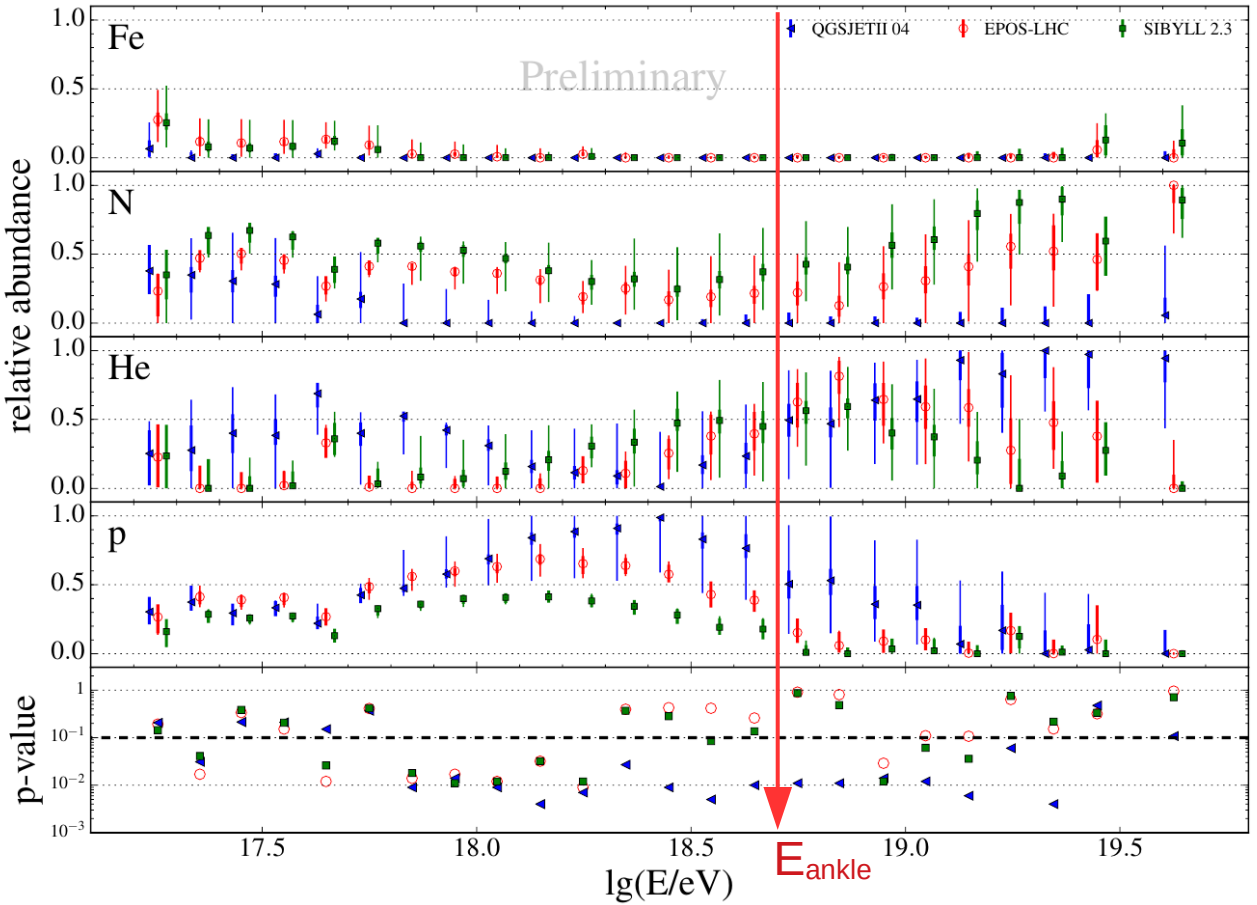
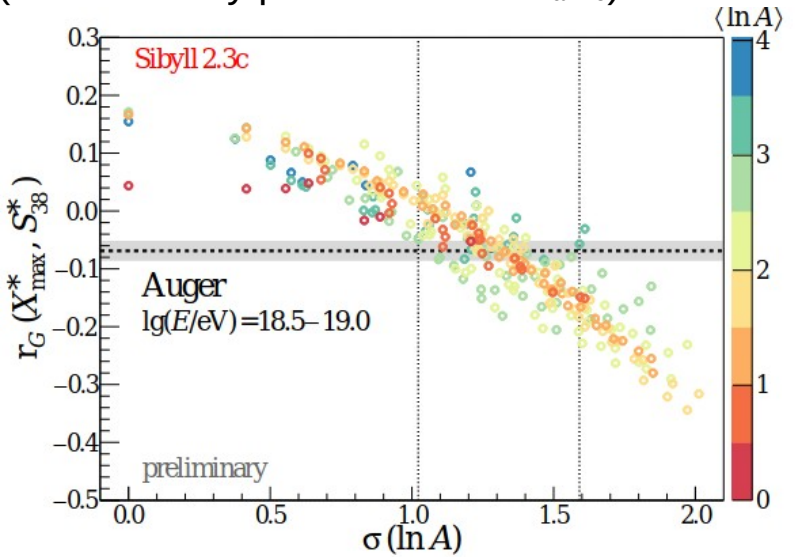
J. Bellido, PoS(ICRC2017) 506

Composition

Ankle feature as a propagation effect is highly disfavored (needs mainly protons above E_{ankle})





Negative correlation in data :

- cannot be reproduced using any pure composition
- only explained by mixed compositions containing primary nuclei **heavier than helium**

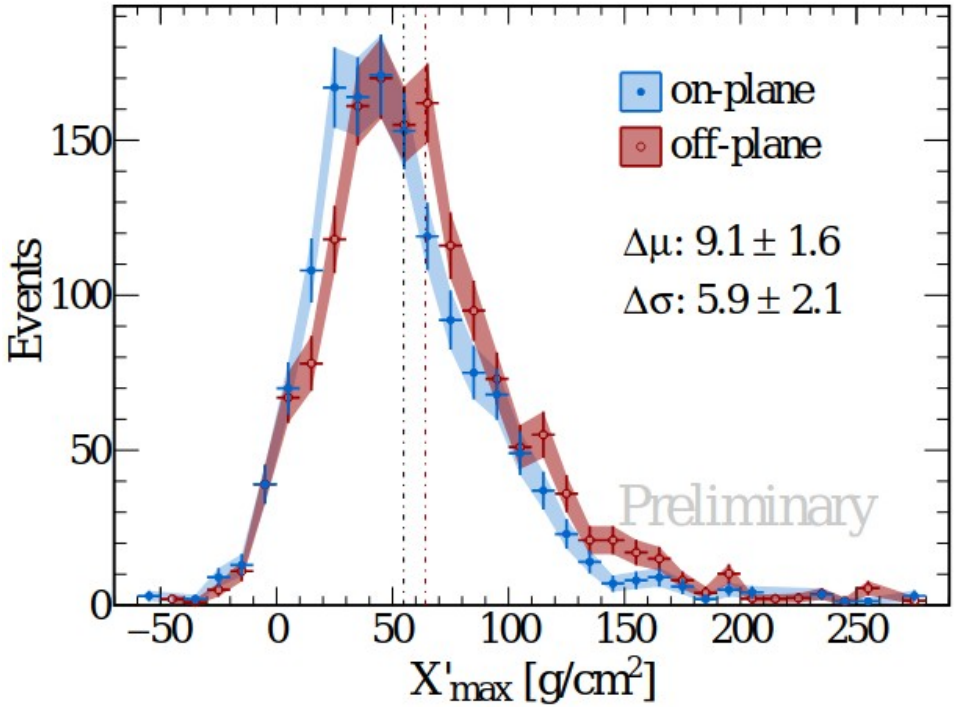
What is the **composition at the sources?** What is the **injected flux?**

Auger Coll., Phys.Rev.D90 (2014) 122005
Auger Coll., Phys.Rev.D96 (2017) 122003
J. Bellido, PoS(ICRC2017) 506
A. Yushkov (ICRC2019) 482

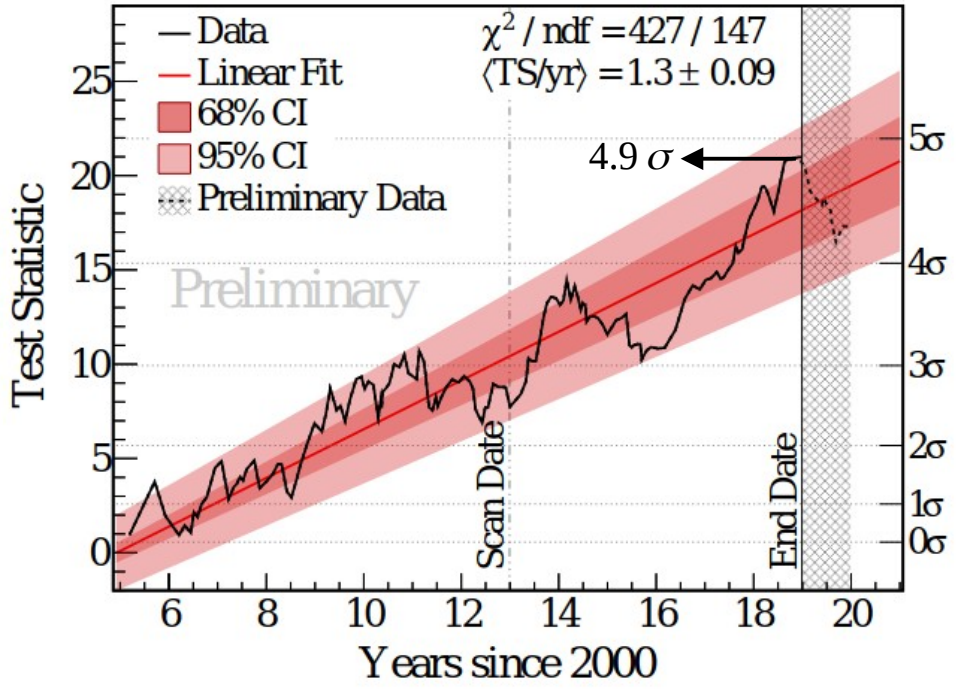
Composition

Auger Coll., Phys.Rev.D90 (2014) 122005
Auger Coll., Phys.Rev.D96 (2017) 122003
E. Mayotte, PoS(ICRC2021) 321

Data-driven scan for optimal thresholds *(on/off galactic plane)* $|b| \leqslant 30^0$ $10^{18.7}\,eV$



TS time evolution



- **Primaries from the on-plane region having on average a heavier mass**
- **TS of 21.0 arising by chance is 5.96 × 10−7 (corresponding to a significance of 4.9σ)**

Composition

Auger Coll., Phys.Rev.D90 (2014) 122005
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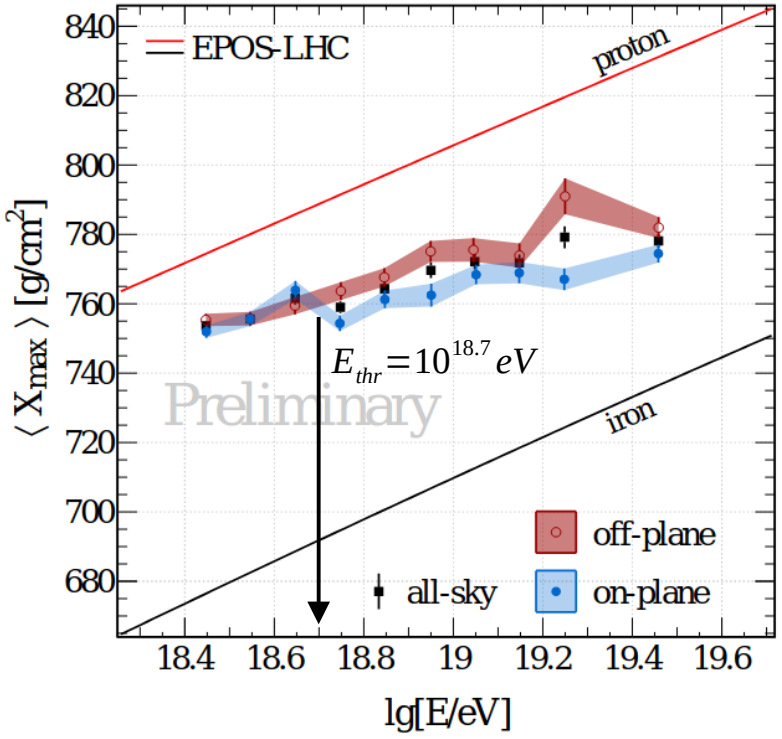
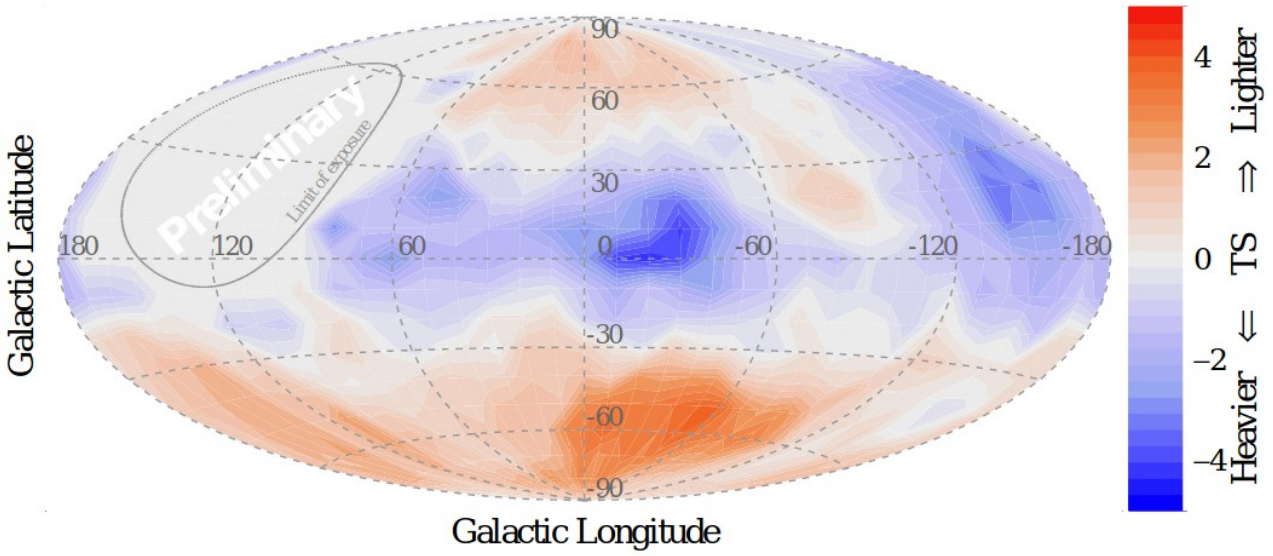
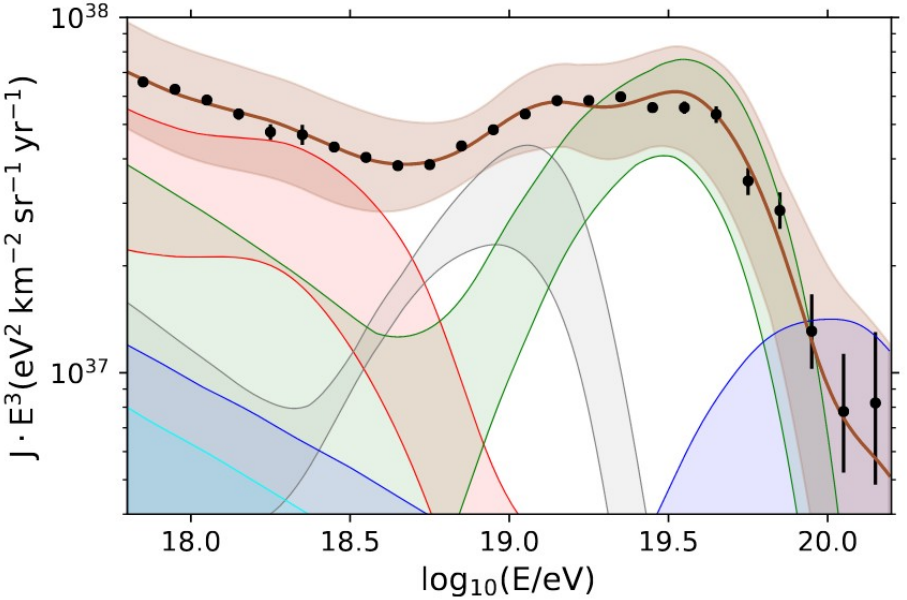
E. Mayotte, PoS(ICRC2021) 321

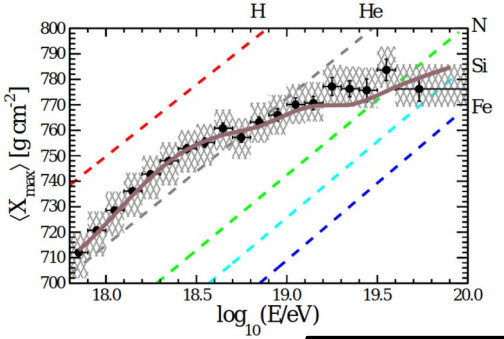


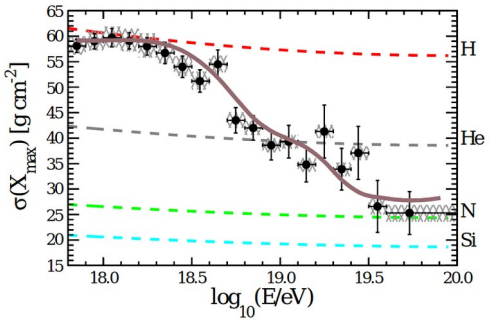


- **A model independent verification of a mixed composition above the ankle.**
- **Might be an indication of galactic magnetic field influence**
- **Local source distribution or mass dependent horizons?**

Spectrum and composition combined fit







Both scenarios compatible within systematics (dominated by experimental systematics rather than models)

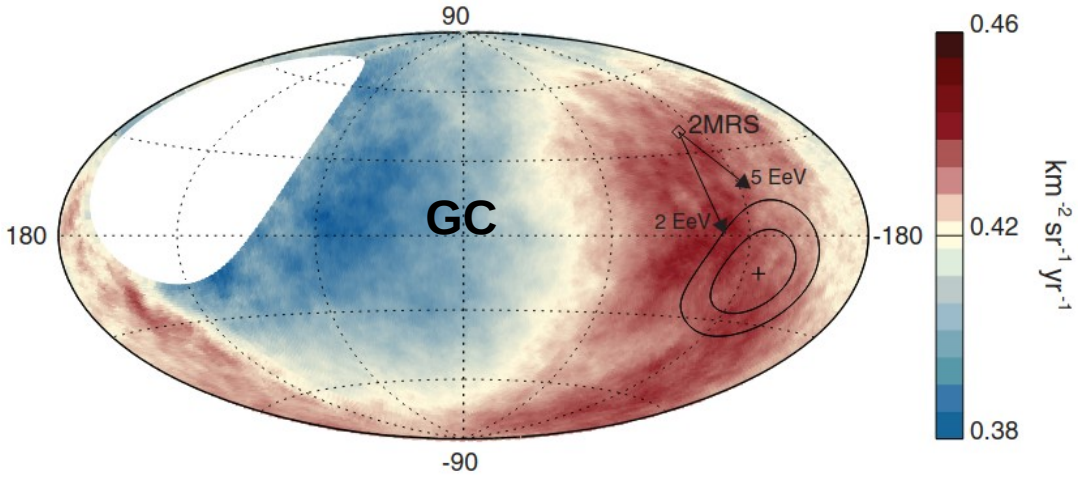
Best fit results:

1) **Soft Low + Hard High extra-Galactic component**
2) **Possible Galactic component (medium mass elements)**

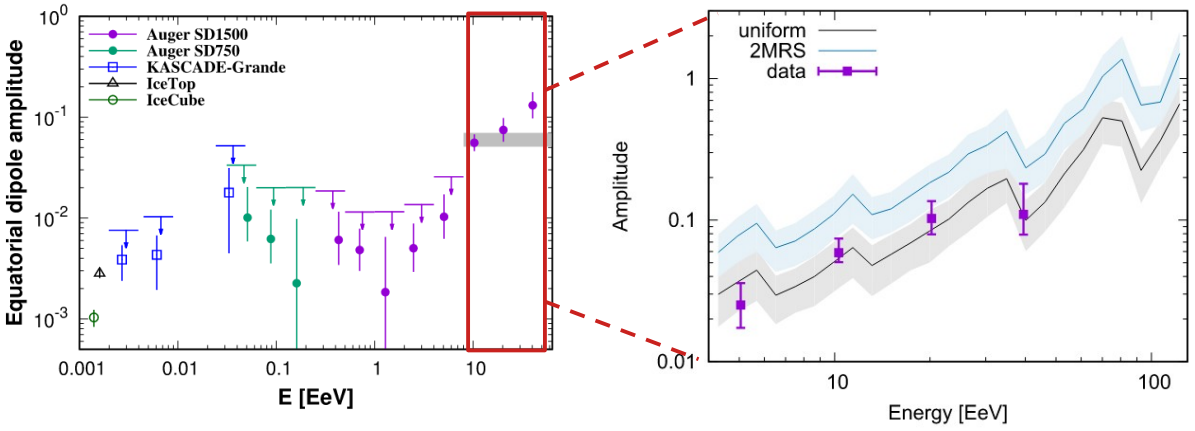
E. Guido, PoS(ICRC2021) 311

	Scenario A		Scenario B	
Galactic contribution (at Earth)	N+Si		-	
J_0^{gal} [eV^{-1} km^{-2} sr^{-1} yr^{-1}]	$(1.07 \pm 0.06) \cdot 10^{-13}$		-	
$\log_{10}(R_{cut}^{gal}/V)$	17.48 ± 0.02		-	
f_N (%)	93.0		-	
EG components (at the sources)	Low energy	High energy	Low energy	High energy
$\mathcal{L}_0$ [erg Mpc^{-3} yr^{-1}]	$7.28 \cdot 10^{45}$	$4.4 \cdot 10^{44}$	$1.7 \cdot 10^{46}$	$4.5 \cdot 10^{44}$
γ	3.30 ± 0.05	-1.47 ± 0.12	3.49 ± 0.02	-1.98 ± 0.10
$\log_{10}(R_{cut}/V)$	24 (lim.)	18.19 ± 0.02	24 (lim.)	18.16 ± 0.01
I_H (%)	100 (fixed)	0.0	49.87	0.0
I_{He} (%)	-	27.17	10.92	28.60
I_N (%)	-	69.86	36.25	69.05
I_{Si} (%)	-	0.0	0.0	0.0
I_{Fe} (%)	-	2.97	2.96	2.35
D_J (N_J)	49.5 (24)		60.1 (24)	
$D_{X_{max}}$ ($N_{X_{max}}$)	593.8 (329)		554.8 (329)	
D (N)	643.3 (353)		614.9 (353)	

Arrival directions: large scale and moderate energy



- **Dipole at (ℓ, b) = (233°, -13°)** observed with **6.6σ** significance and 15° uncertainty **above 8 EeV**
- Around **125° away from Galactic Center** (suggesting extra-Galactic origin)
- **Increasing amplitude with increasing energies** above 8 EeV
- Quadrupole component not significant



Complex interplay of mass composition, source distributions & magnetic fields

(next steps is spectrum+composition+anisotropy combined fit)

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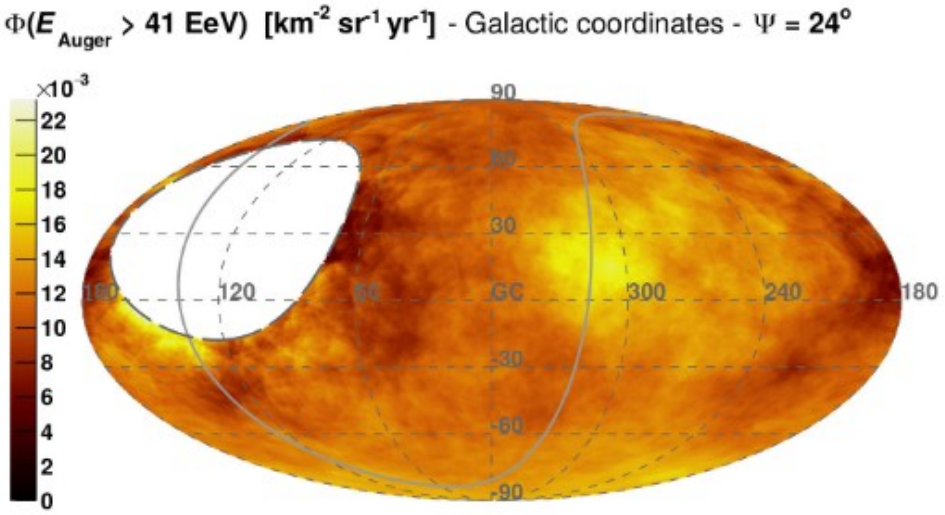
Auger Coll., ApJ. 868 (2018)
Auger Coll., ApJ. 891 (2020)
R. De Almeida, PoS(ICRC2021) 335

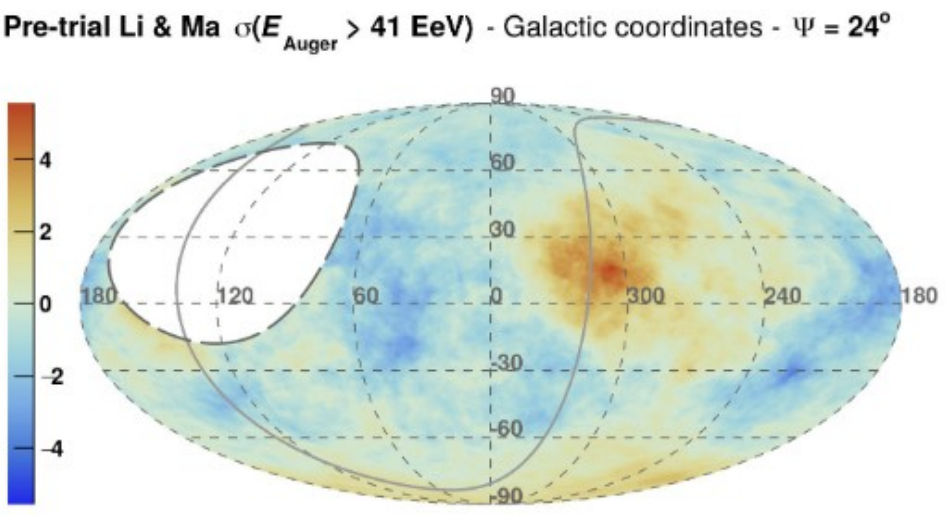
Arrival directions: intermediate scale and high energy

Blind and astrophysically-motivated searches for energies above 32 EeV using 17 years of data (2004/01 − 2020/12) and 122000 km^2 exposure

Analysis	E_{th} [EeV]	Ψ [deg]	$N_{observed}$	$N_{expected}$	Post-trial p-value
Overdensity	41	24	156	98	1.4×10^{-2}
Autocorrelation	41	11	11,709	11,023	0.21
Supergalactic plane	44	20	395	351	0.16
Galactic plane	58	20	154	132	0.41
Galactic center	64	18	17	10	0.54

← Largest post-trial **significance of 2.2σ**





Most significant excess at (ℓ, b) = (307°, 16°) close to the intersection of the Galactic and super-Galactic planes and Centaurus A region → significance of **3.9σ if direction fixed**

Auger Coll., Science 357 (2017)
Auger Coll., ApJ. 868 (2018)
Auger Coll., ApJ. 891 (2020)
J. Biteau, PoS(ICRC2021) 307

Arrival directions: intermediate scale and high energy

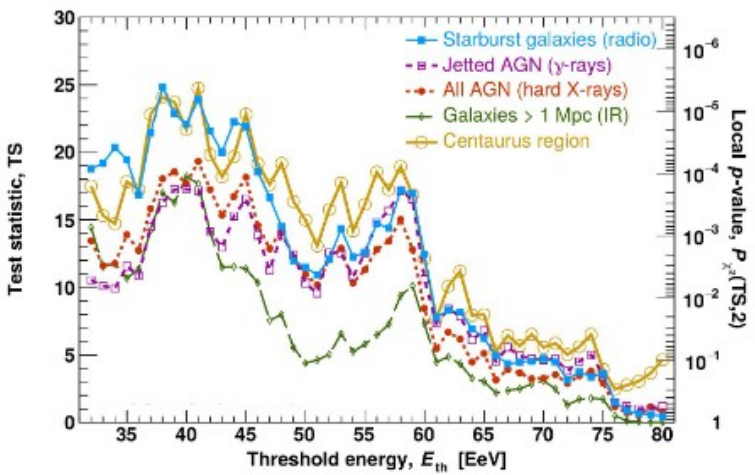
Blind and **astrophysically-motivated** searches for energies above 32 EeV using 17 years of data (2004/01 − 2020/12) and 122000 km^2 exposure

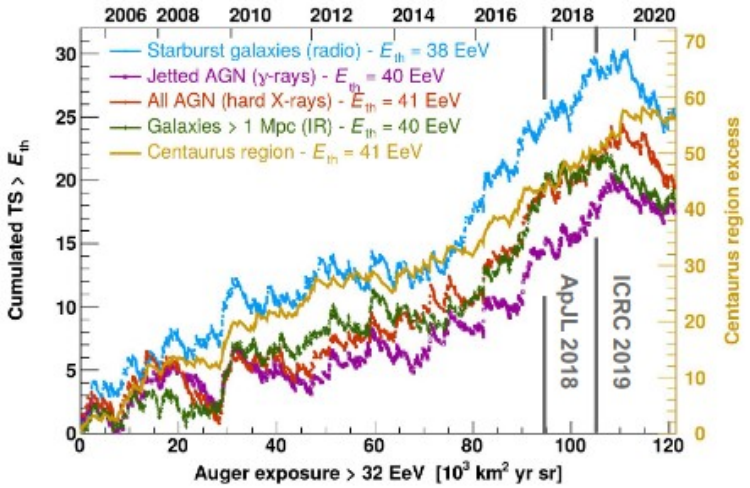
Four catalogs investigated

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

Likelihood ratio analysis

- smearing angle ψ
- H_0: isotropy
- H_1: $(1-f)\times$ isotropy + $f\times$ fluxMap(ψ)
- $\mathrm{TS} = 2\log(H_1/H_0)$





Free parameters are:

- ✔ **the threshold energy**
- ✔ **the smearing angle**
- ✔ **the fraction of anisotropy**

The anisotropy suggested with all four catalogs is driven by a hotspot in the Centaurus region.

The **TS profiles** of the catalogs display:

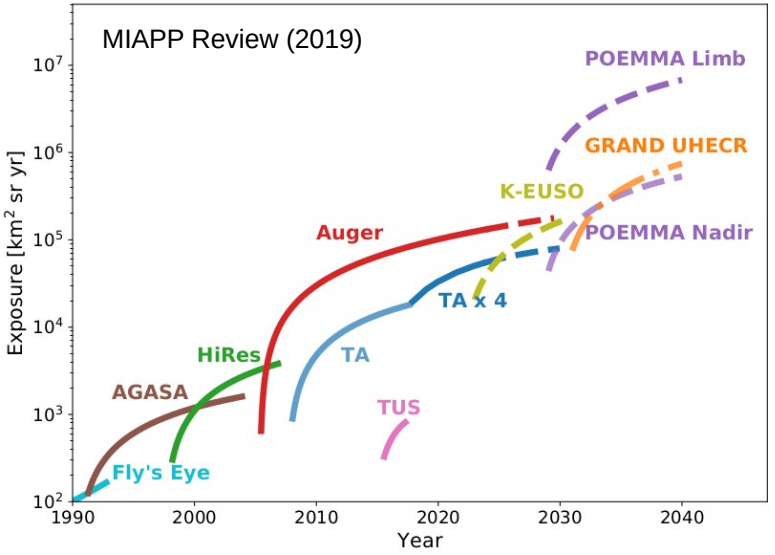
- **An energy dependence similar to that observed in the Centaurus region**
- **Maximum above 40 EeV**
- **Significance ranging from 3.1σ to 4.0σ**
- **Growth at a rate of ~ 2 units / year (full array), with TS(5σ) ~ 35**

Auger Coll., Science 357 (2017)
Auger Coll., ApJ. 868 (2018)
Auger Coll., ApJ. 891 (2020)
J. Biteau, PoS(ICRC2021) 307

AugerPrime: a multi-hybrid observatory

Motivations

1. Elucidate the origin of the flux suppression
2. Search for a flux contribution of protons up to the highest energies at the level of ~ 10% (charge particle astronomy)
3. Study of extensive air shower physics and hadronic interactions above √s=70 TeV



On each Water-Cherenkov station (WCD) over 3000 km²

1. Additional **surface scintillators** (**SSD**) on top of WCD
2. 3x **faster electronics** (**UUB**)
3. Additional **small-area PMT** (**sPMT**) for WCD
4. Addiotinal **radio antennas** (**RD**)

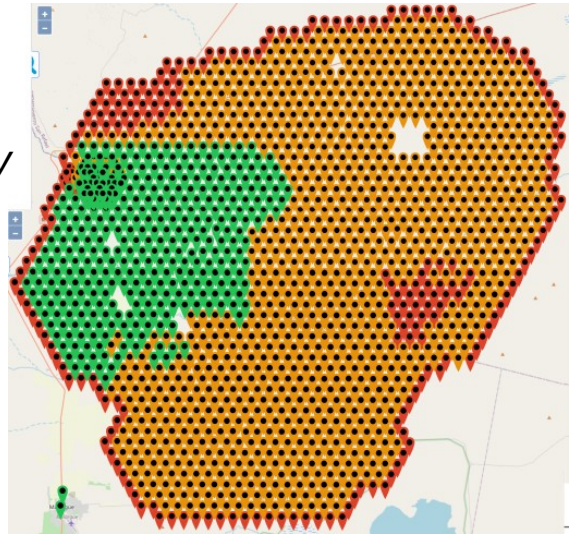
In the Infill region (23.1 km²)

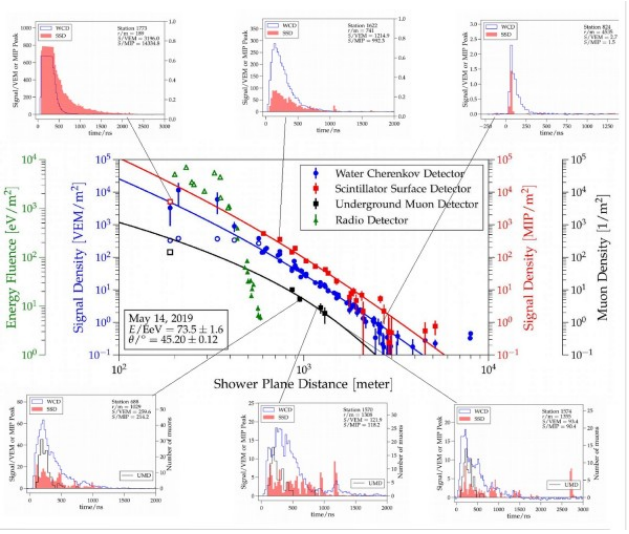
5. The **Underground Muon Detector** (**UMD**)

Provide the largest exposure detector so far operative with unprecedented composition sensitivity above 4×10^{19} eV

AugerPrime: a multi-hybrid observatory

Current deployment status *(end of construction by mid 2023)*





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⇨

1. To measure signal components in combination with WCD
2. To better measure signal timings
3. To increase dynamic range to more than 20,000 VEM
4. To measure radio emission (sensitive to longitudinal development of showers)

In the Infill region (23.1 km²)

5. The **Underground Muon Detector** (**UMD**)

5. To have a direct measurement of the muon component

Conclusions

From phase-I data:

Spectrum → has a well defined change in spectral index at ~ 5 EeV (ankle)
→ has a strong suppression above ~ 40 EeV
→ new features appeared (high-energy instep & low-energy ankle)

Composition → light (but mixed) dominated below the ankle
→ heavier nuclei towards the highest energies

Anisotropy → 6.6σ evidence at large angular scale and energy greater than 8 EeV favoring extragalactic origin above this energy
→ 3.1σ - 4.0σ evidence at intermediate angular scale and energy above 40 EeV dominated by Centaurus region

Source models & propagation → difficult to interpret data because of interplay of mass composition, source distributions & magnetic fields
→ need to add anisotropy to the combined fits

Open data → 10% released at *https://opendata.auger.org*