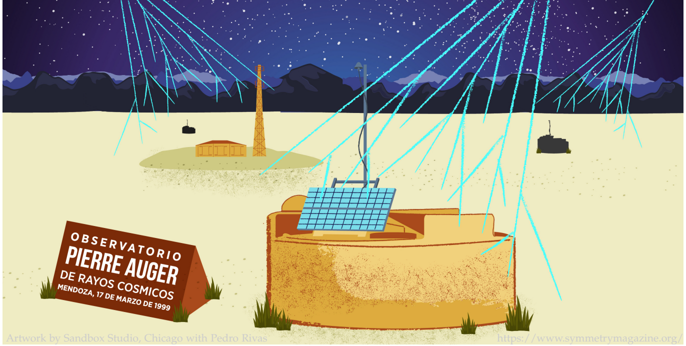
PIERRE AUGER OBSERVATORY



Artwork by Sandbox Studio, Chicago with Pedro Rivas https://www.symmetrymagazine.org/

Highlights from the Pierre Auger Observatory

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http://www.auger.org

FZU Fyzikální ústav Akademie věd České republiky

FZU Division seminar, 30/05/2024

Pierre Auger Collaboration

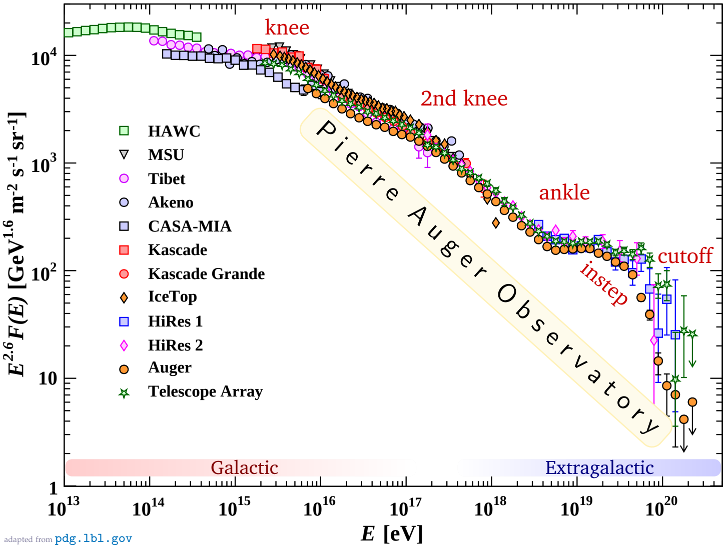
around 500 members from 18 countries

- Argentina
- Australia
- Belgium
- Brazil
- Colombia
- Czech Republic
- France
- Germany
- Italy
- Mexico
- Peru
- Poland
- Portugal
- Romania
- Slovenia
- Spain
- The Netherlands
- USA

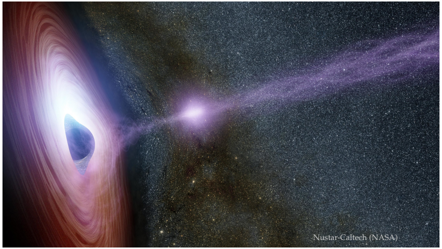
located near Malargüe, Argentina

Energy range of the Pierre Auger Observatory

The ultimate goal: discover cosmic-ray sources



adapted from pdg.lbl.gov

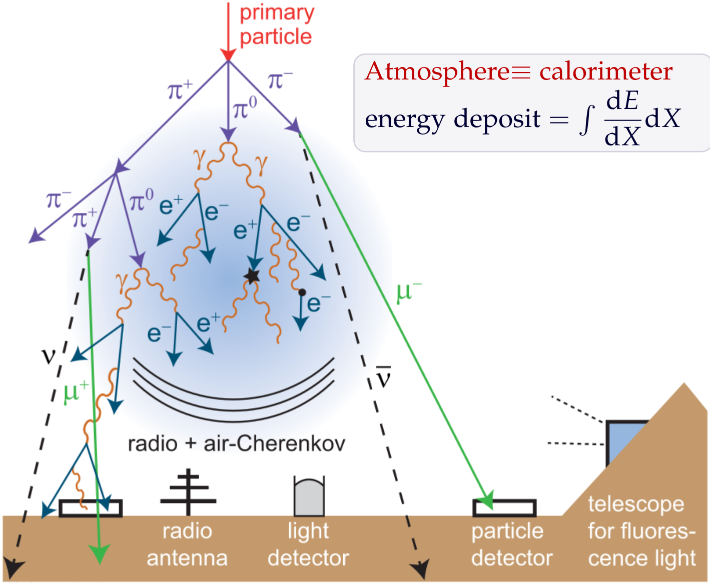


Essential inputs

- ◇ Arrival directions
- ◇ Energy spectrum
- ◇ Mass composition

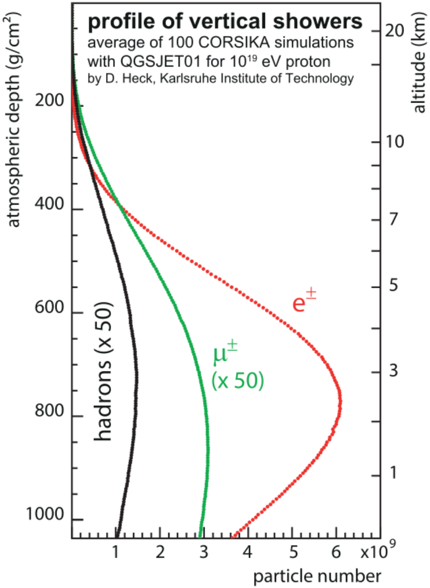
or detect photons and/or neutrinos!

Detection of extensive air showers: hybrid detector



Atmosphere≡ calorimeter

$$\text{energy deposit} = \int \frac{dE}{dX} dX$$



F. Schröder, PPNP 93 (2017) 1

Pierre Auger Observatory

Nucl. Instrum. Meth. A798 (2015) 172

Fluorescence detector (FD)

duty cycle 15 %

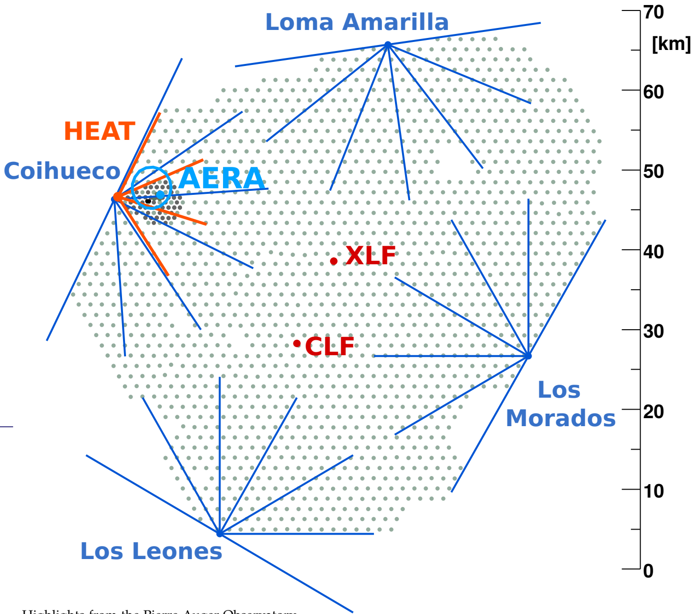
24 + 3 fluorescence telescopes

Surface detector (SD)

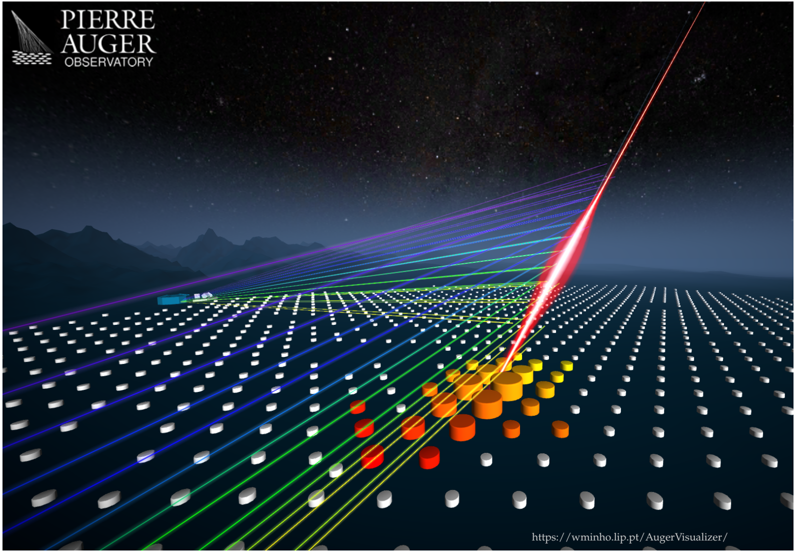
duty cycle 100 %

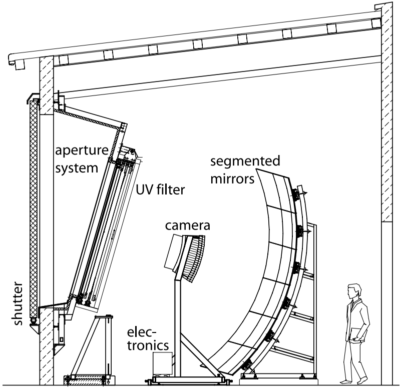
1660 water-Cherenkov detectors

grid	area	full efficiency lg(E/eV)
1500 m	3000 km^2	18.5
750 m	23.5 km^2	17.5
433 m	1.9 km^2	16.5



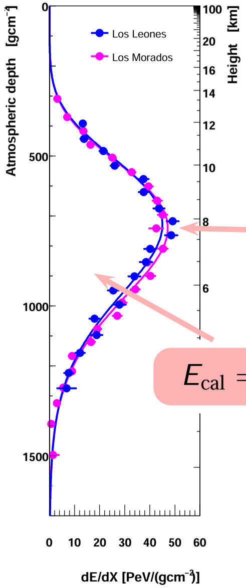
Energy estimation: atmosphere as a calorimeter





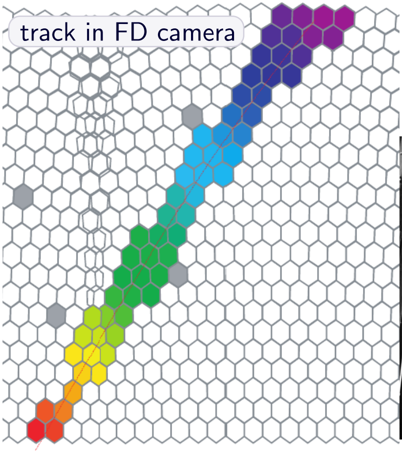
Fluorescence detector: direct observation of the longitudinal energy deposit

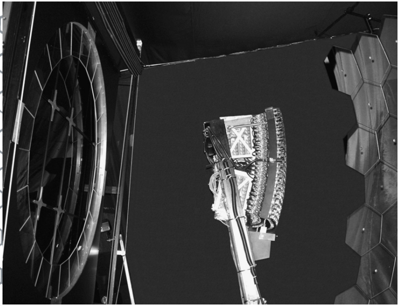
Energy estimation: atmosphere as a calorimeter



X_{max}

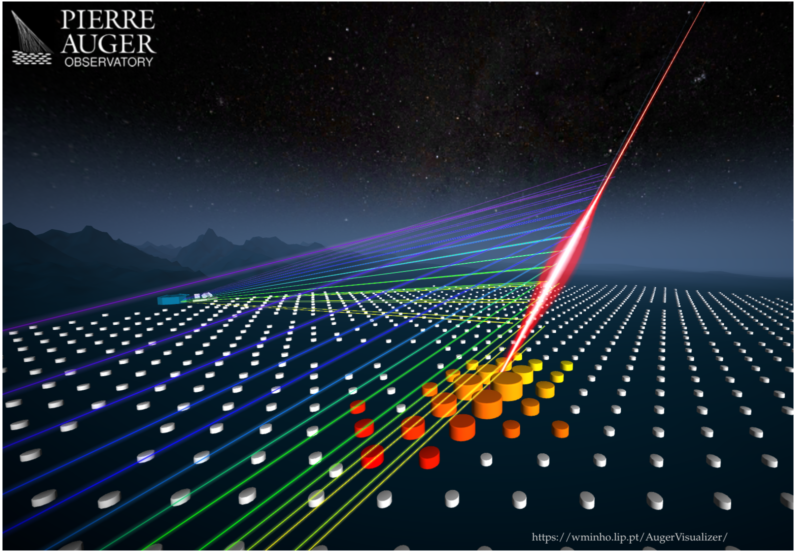
$$E_{cal} = \int \frac{dE}{dX} \, dX$$

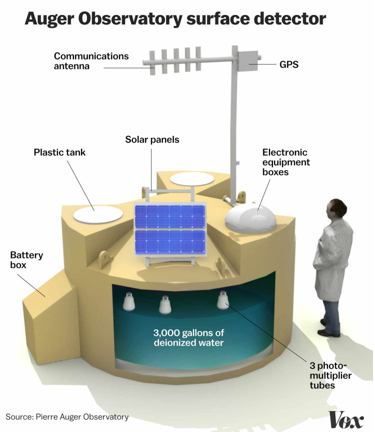




- ✓ Calorimetric energy
- ✓ Mass estimator X_{max}
- Caveat: uptime is only 15%

Energy estimation: sample particles reaching ground

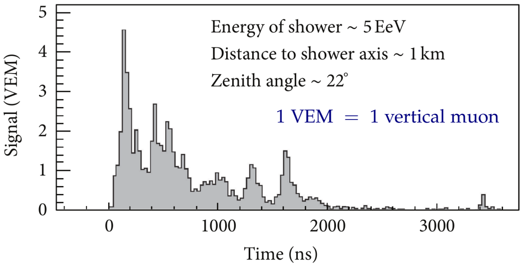




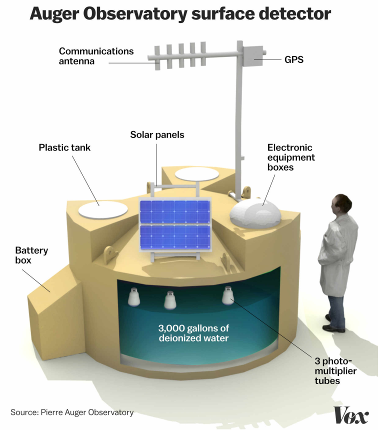
Surface water Cherenkov detectors (SD 'pixels'): lateral energy deposit

Signals from shower particles hitting SD station

$\sum S_i =$ total signal



light travels 300 m in 1000 ns: shower disk thickness here is few hundred meters (depends on E, θ, r)



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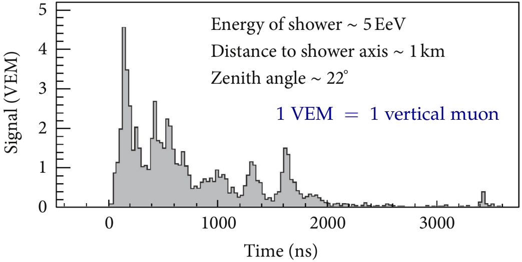
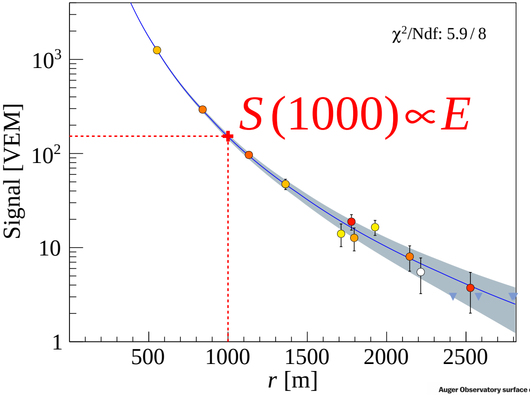
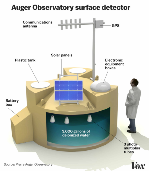


Fit to signals in all event stations





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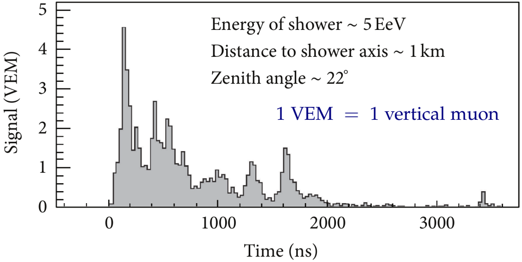

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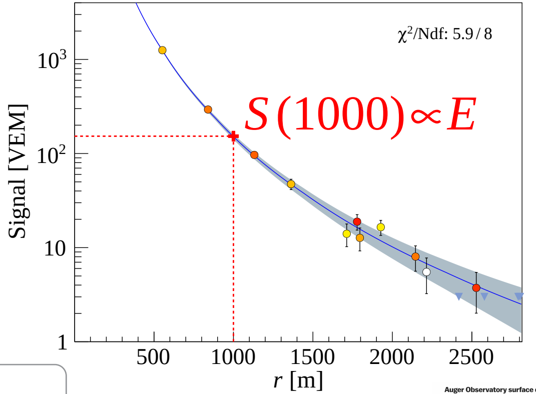
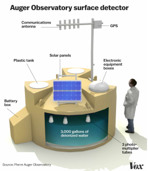
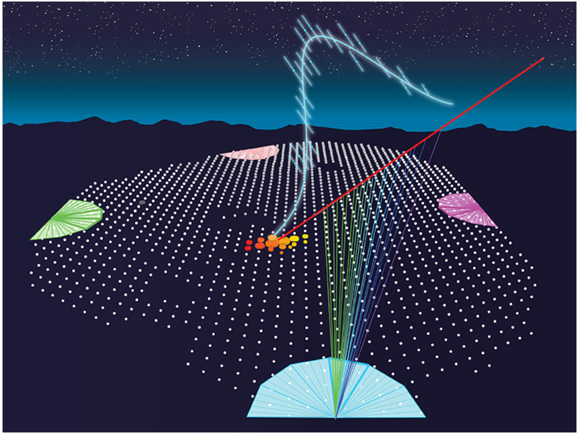


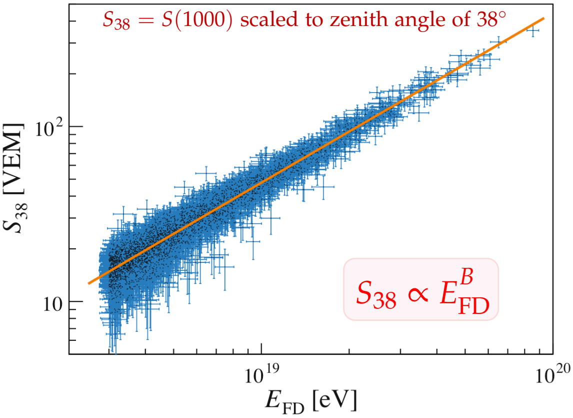
- ✓ Primary energy from $S(1000)$
- ✓ Mass estimator: SD signal (sensitive to muons)
- Caveat: both are hadronic-model-dependent



Hybrid events: SD energy calibration using FD



Subset of events with good SD and FD reconstructions



- ✓ Hadronic-model dependence of the SD energy is strongly reduced: energy spectrum is mostly data-driven
- ✗ Mass composition: X_{max} and [muon] signal in SD stations depend on the accuracy of air-shower simulations

Best mass composition parameters: number of muons and X_{max}

Difference proton – iron

in depth where the number of shower particles is at maximum

$$\langle X_{max}^{p} \rangle - \langle X_{max}^{Fe} \rangle \approx (80 - 100)\ \mathrm{g\,cm^{-2}}$$

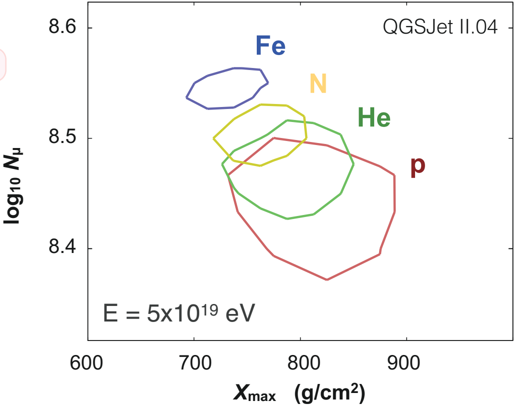
in number of muons reaching the ground

$$\langle N_{\mu}^{Fe} \rangle / \langle N_{\mu}^{p} \rangle \approx (1.3 - 1.4)$$

in fluctuations of both parameters

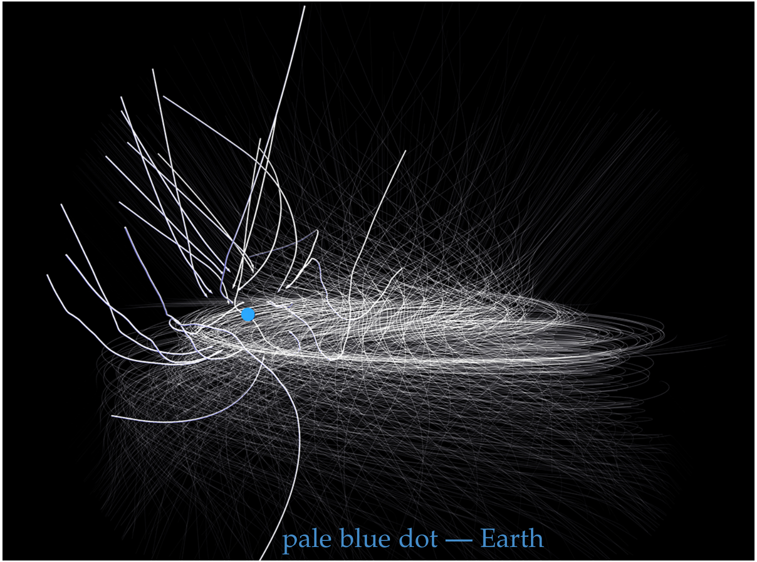
shower-to-shower fluctuations proton/iron ≈ 3

arXiv:1604.03637



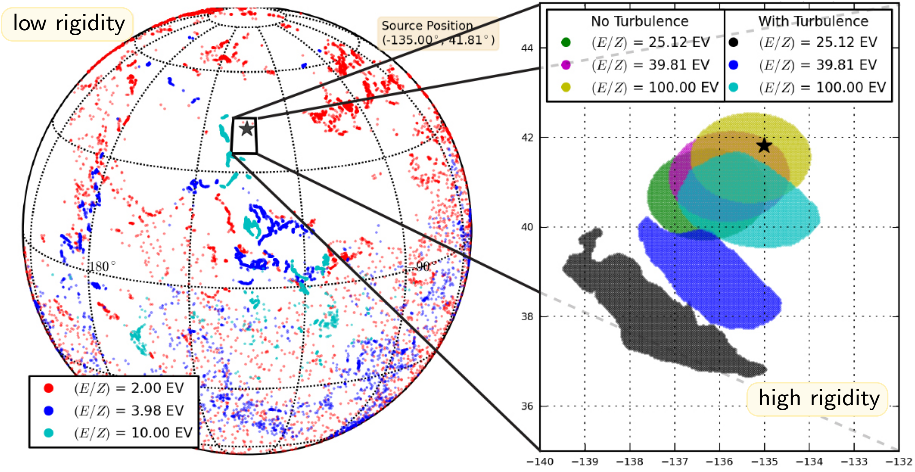
UHECR propagation: magnetic fields and charged-particle astronomy

Arrival directions of particles with low rigidity $R = E/Z$ are scrambled by galactic magnetic field



UHECR propagation: magnetic fields and charged-particle astronomy

arrival directions from a single source (★ mark)



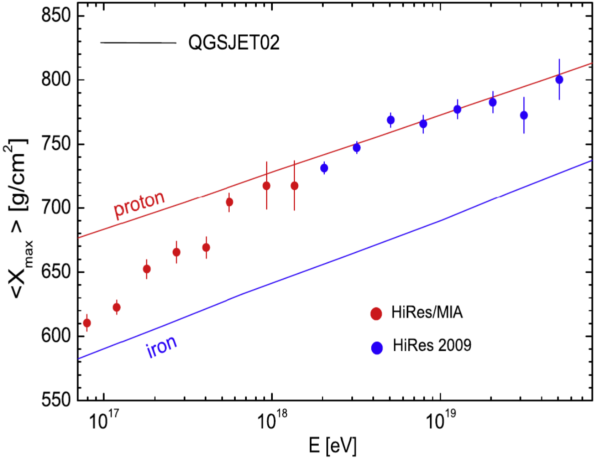
Backtracking to sources: do UHECR reach rigidities $R > 10$ EV?

https://www.nas.nasa.gov/SC14/demos/demo4.html

UHECR propagation: principal energy losses

Photonuclear reactions with extragalactic background light & cosmic microwave background

pion production	$p + \gamma \to \Delta^+ \to p + \pi^0$	horizon $\lesssim$ 200 Mpc: anisotropic matter distribution
	$p + \gamma \to \Delta^+ \to n + \pi^+$	Greisen–Zatsepin–Kuzmin cutoff $E_0 > 5 \times 10^{19}$ eV
photodisintegration	${}^{A}Z + \gamma \to {}^{A-1}Z + n$	Energy cutoff is similar to GZK
Gerasimova-Rozental cutoff (1961)		Secondary nucleon energies $\sim E_0/A$, below GZK
		Suppressed UHE photon and neutrino fluxes
pair production	$p + \gamma \to p + e^+ + e^-$	important above 2×10^{18} eV



The dip model (V. Berezinsky et al.)

On astrophysical solution to UHECRs

Phys. Rev. D74 (2006) 043005

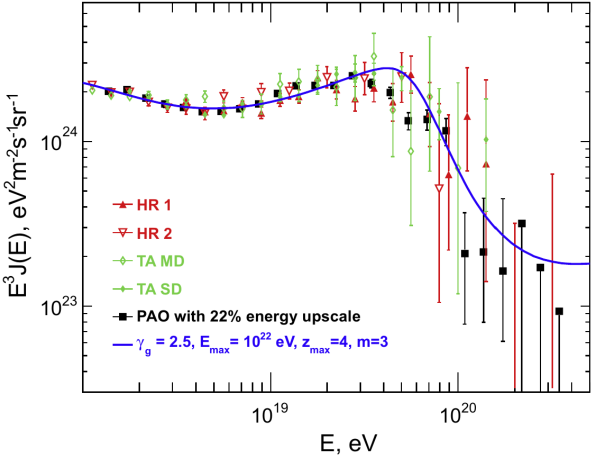
- ✓ Mass composition: proton-dominated
- ✓ Dip in spectrum: pair production
- ✓ Cutoff energy matches GZK

Predictions

- ◇ Detectable neutral particle fluxes
- ◇ Particle astronomy with $R \sim 100$ EV

Astropart. Physics 34 (2011) 620; 39–40 (2012) 129

Energy spectrum — mass composition around 2010: the encouraging model



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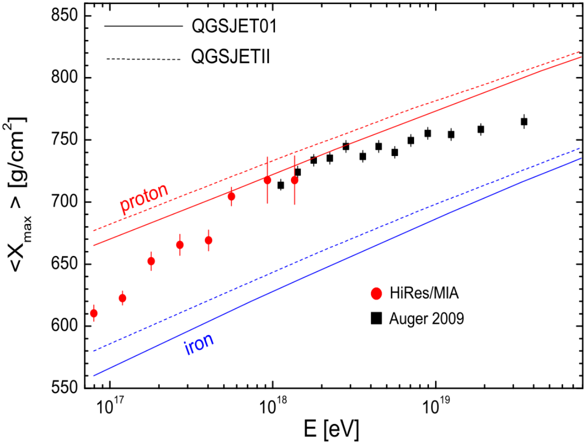

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Alert: "There is a dramatic conflict between recent observational data of two largest UHECR detectors: HiRes and Auger"

Astropart. Physics 34 (2011) 620; 39–40 (2012) 129

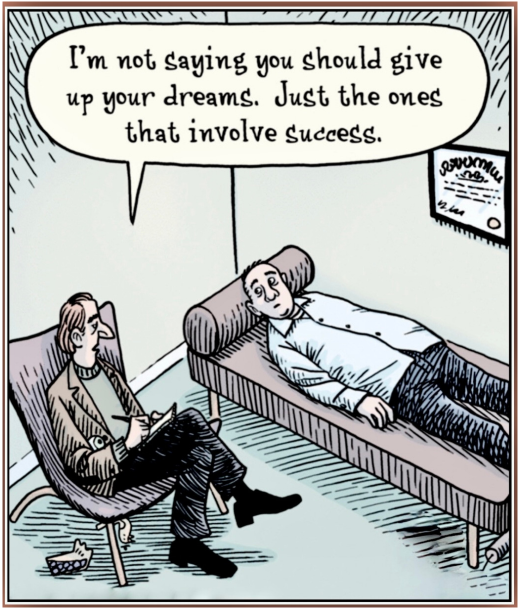
Auger as a game changer

The disappointing model (R. Aloisio, V. Berezinsky, A. Gazizov)

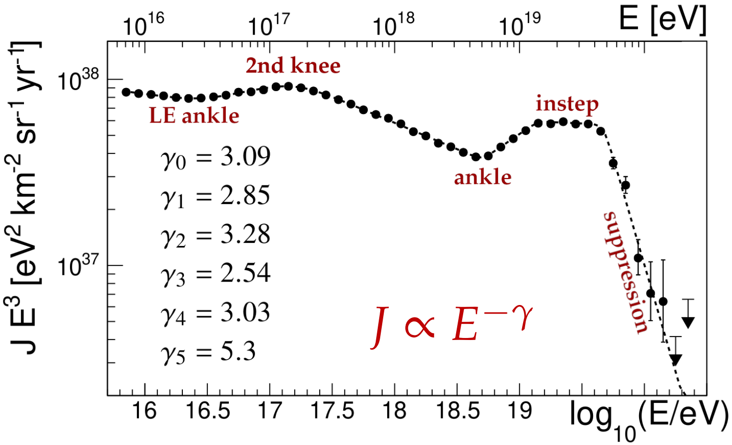
Astropart. Physics 34 (2011) 620

- ◇ Rigidity-dependent cutoff $(4 - 10) \times Z$ EeV
- ◇ Peters' cycle: successive domination of hydrogen, helium, CNO, iron at energies $\propto Z$
- ◇ Maximum energy for iron $(Z = 26)$ is $(100 - 300)$ EeV
- ◇ Energy per nucleon is $(2 - 5)$ EeV, almost no photonuclear reactions on CMB
- ◇ No GZK cutoff and cosmogenic neutrinos
- ◇ Spectrum suppression: maximum source energy and nuclei photodisintegration
- ◇ Around 100 EeV iron nuclei dominate, correlation to sources is poor (if any)

Auger as a game changer



Auger energy spectrum



instep — new and unexpected

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

PoS (ICRC2021) 324

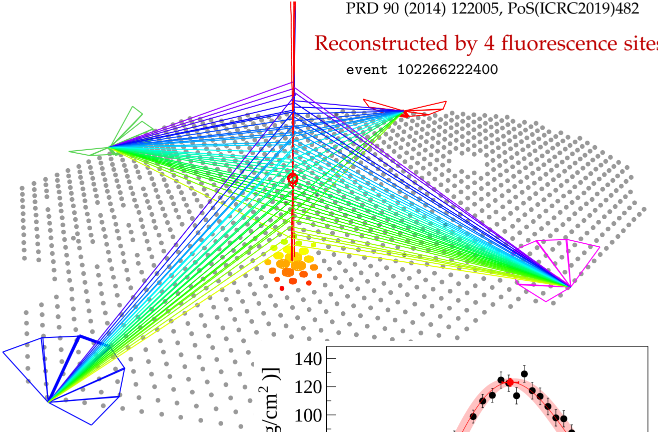
Mass composition is the key

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

Depth of the maximum of air-shower profiles X_{max}

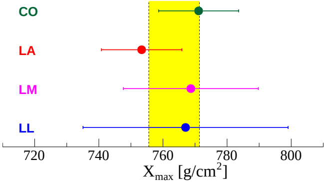
PRD 90 (2014) 122005, PoS(ICRC2019)482

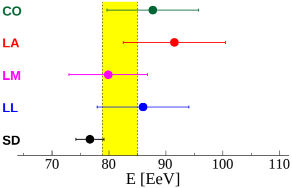
Reconstructed by 4 fluorescence sites

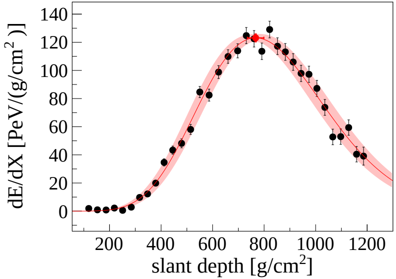


- ≈ 75210 high-quality events
- ≈ 1300 events with $E > 10$ EeV
- the highest energy ≈ 110 EeV

PoS(ICRC2023)319



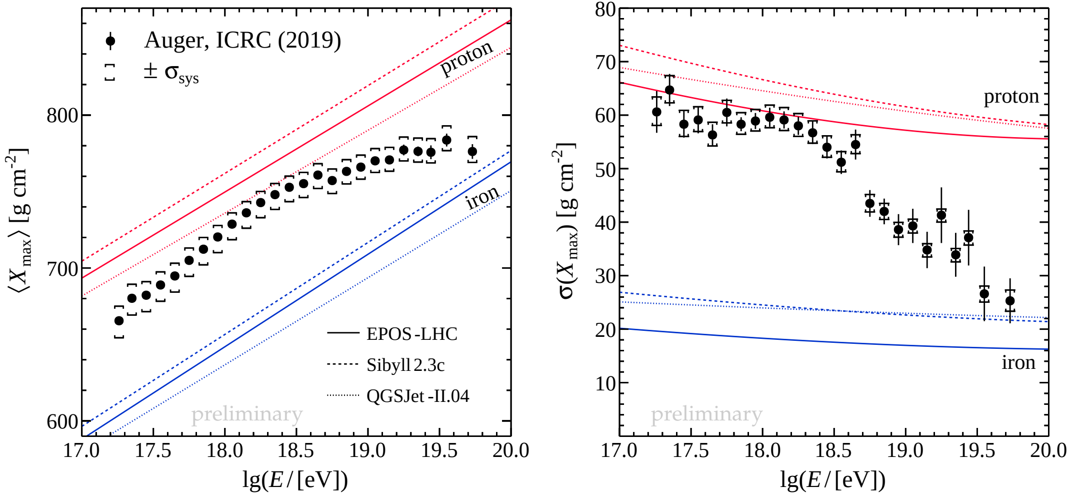




Energy evolution of mean and standard deviation of X_{max}

Break in $\langle X_{max} \rangle$, $\sigma(X_{max})$ at 2 EeV ($10^{18.3}$ eV): trend towards heavier masses

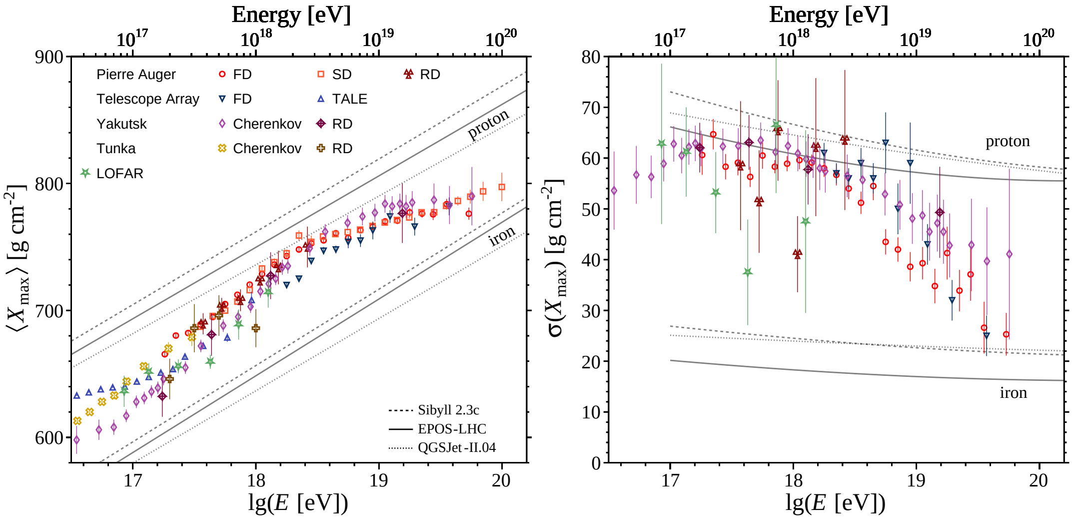
but hardening in the all-particle spectrum ('ankle') is at 5 EeV



PRD 90 (2014) 122006, PoS(ICRC2019)482

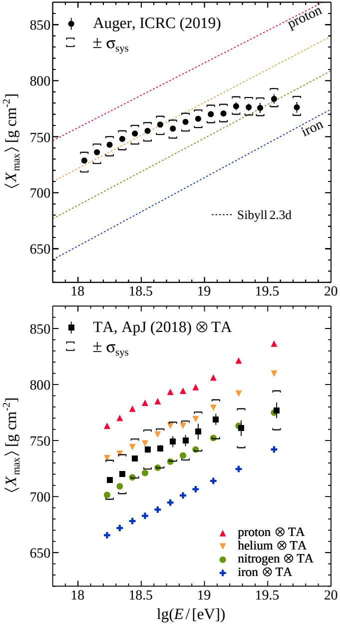
Energy evolution of mean and standard deviation of X_{max}

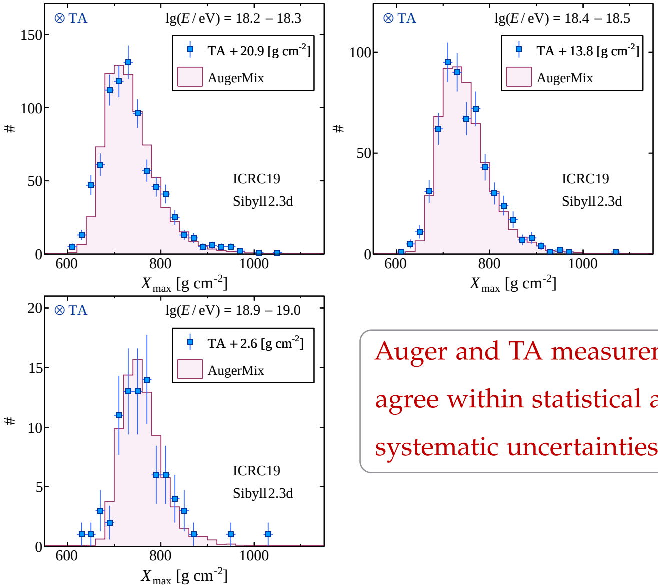
Similar trend for $E > 2$ EeV in other experimental data



Astropart. Phys. 149 (2023) 102819

X_{max} measurements at Auger and Telescope Array





Auger and TA measurements agree within statistical and systematic uncertainties

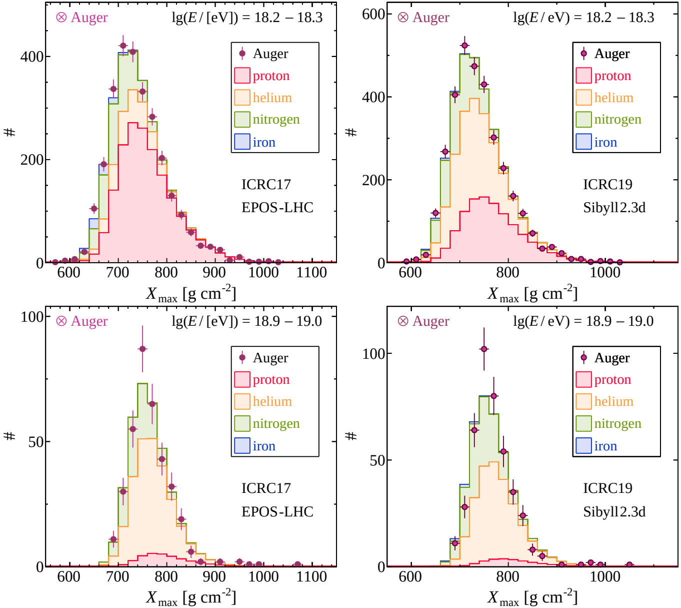
Individual nuclei: fits of X_{max} distributions with (p, He, N, Fe) templates

$\lg(E/\text{eV}) = 18.2 - 18.3$

p + He dominated

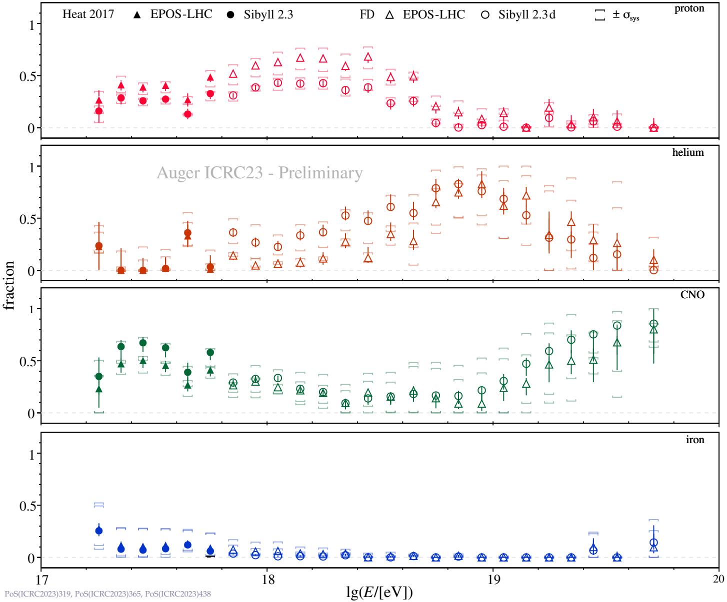
$\lg(E/\text{eV}) = 18.9 - 19.0$

few protons,
helium-dominated



PRD 90 (2014) 122006, PoS(ICRC2017)506, PoS(ICRC2019)482, PoS(ICRC2023)249

Fractions of primary nuclei: evolution with energy



PoS(ICRC2023)319, PoS(ICRC2023)365, PoS(ICRC2023)438

2nd knee ($\sim 10^{17}$ eV)

◇ decreasing iron contribution

◇ consistent with the 'iron knee'

ankle ($10^{18.7}$ eV)

◇ disappearance of protons

highest energies (cutoff)

◇ medium mass domination

maximum energy in sources?

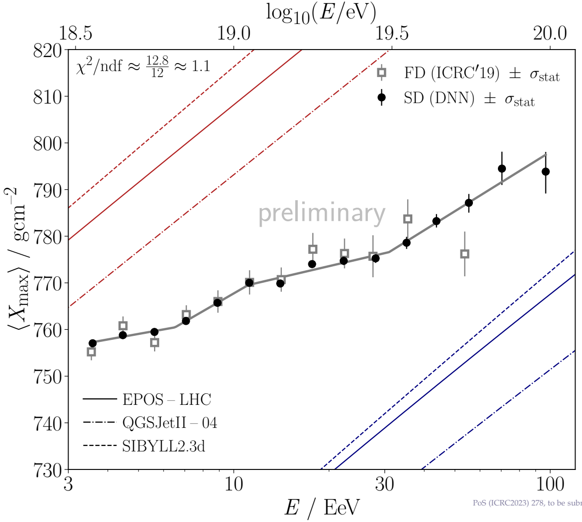
propagation effects?

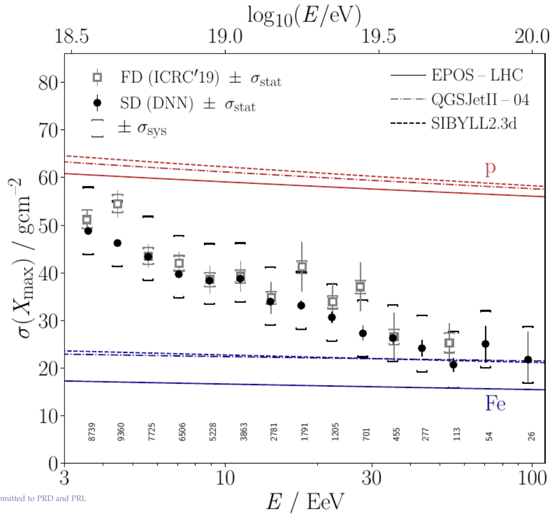
More data beyond cutoff are needed

X_{max} up to 10^{20} eV with machine learning and SD data

DNNs using SD traces and geometry: possible new breaks in $\langle X_{max} \rangle$

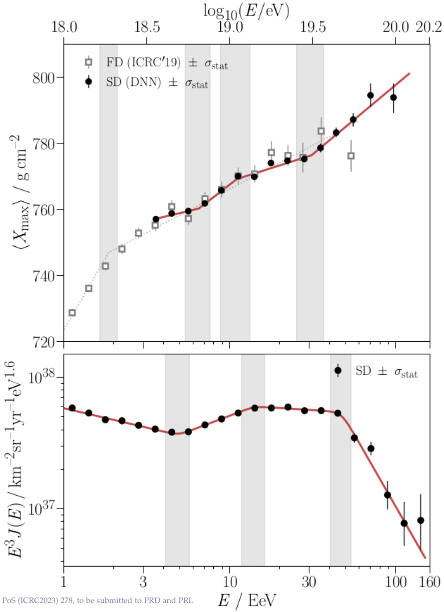
100 EeV: $\langle X_{max} \rangle$ evolution is compatible to $\langle \ln A \rangle = \text{const}$, $\sigma(X_{max})$ to a beam ~devoid of (H, He)





PoS (ICRC2023) 278, to be submitted to PRD and PRL

Breaks in $\langle X_{max} \rangle$ and energy spectrum



PoS (ICRC2023) 278, to be submitted to PRD and PRL

- ◇ three $\langle X_{max} \rangle$ breaks above 'ankle': significance $\approx 3\sigma$

  presence of all 3 breaks to be confirmed yet

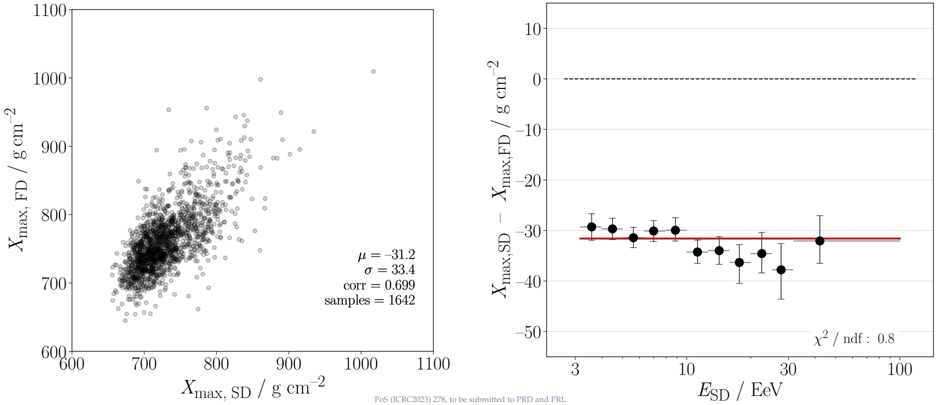
- ◇ breaks in $\langle X_{max} \rangle$ and spectrum do not need to coincide

  $\langle X_{max} \rangle$ break at 2 EeV can be associated with 'ankle' at 5 EeV

- ◇ proximity of features can be accidental due to their density

Uncertainties in the mass composition and hadronic models

Offset ≈ 30 $\mathrm{g\,cm^{-2}}$ between SD (DNN) and FD X_{max}

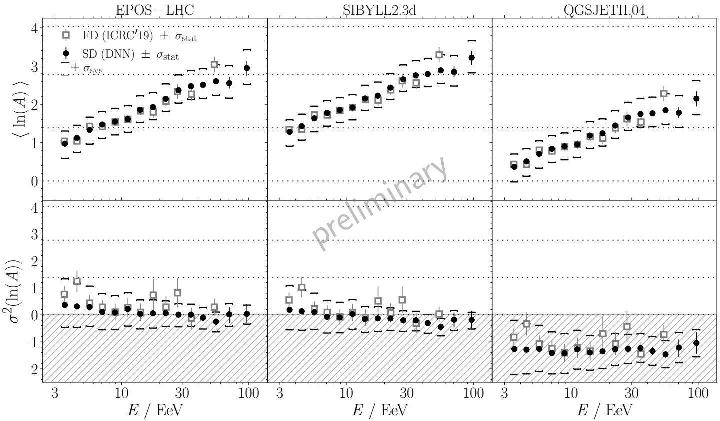


PoS (ICRC2023) 278, to be submitted to PRD and PRL

Might be caused by problems in simulations of the muon air-shower component

Uncertainties in the mass composition and hadronic models

DNN $X_{\rm max}$ converted to average and variance of $\ln A$ (zero for pure beams, max = 4 for proton-iron mix)



Negative $\ln A$ variation for QGSJet-II.04: predicted $\langle X_{\rm max} \rangle$ for this model is too shallow

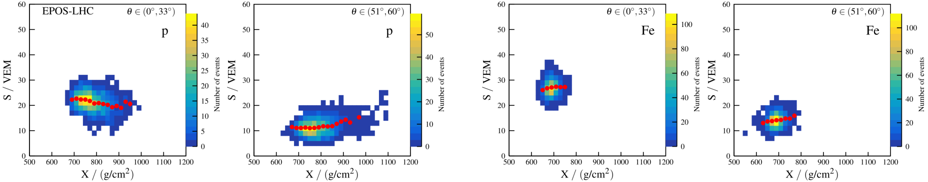
How good are other predictions? Can we find the scales of $X_{\rm max}$ and muon shower content using the data?

X_{max} and muon scales: best fit of the Auger hybrid (SD + FD) data

Idea: fit simultaneously distributions of $S(1000)$ in five zenith angle bins and X_{max}

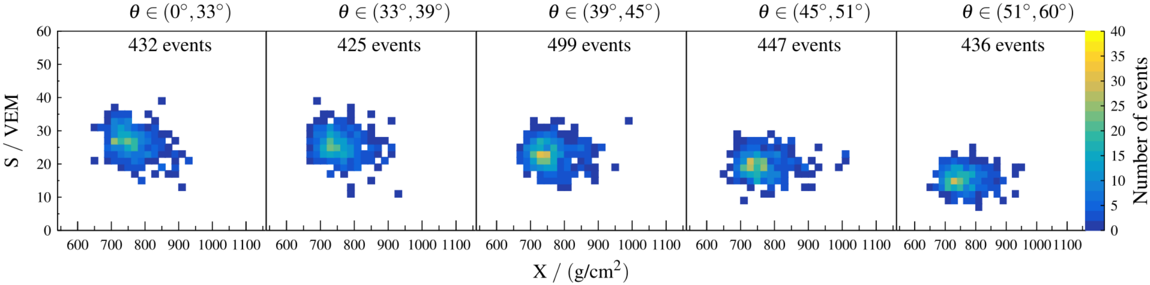
Shapes of simulated templates depend strongly on nuclei type and zenith angle

PRD 109 (2024) 102001



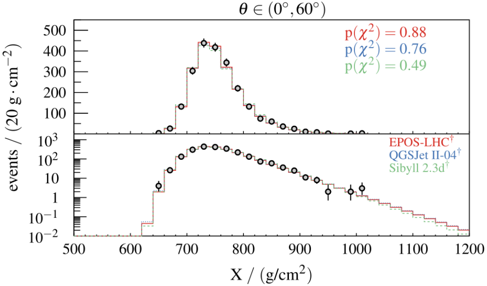
Free parameters: X_{max} and muon scales of hadronic models, fractions of (p, He, O, Fe)

Data, $\lg(E/\mathrm{eV}) = 18.5 - 19.0$



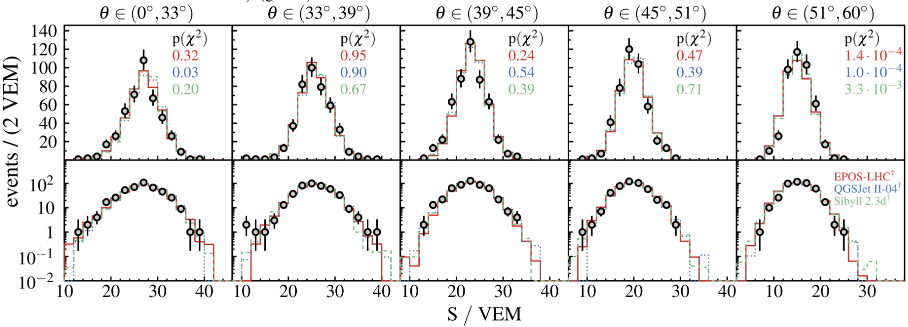
X_{max} and muon scales: best fit of the Auger hybrid (SD + FD) data

PRD 109 (2024) 102001

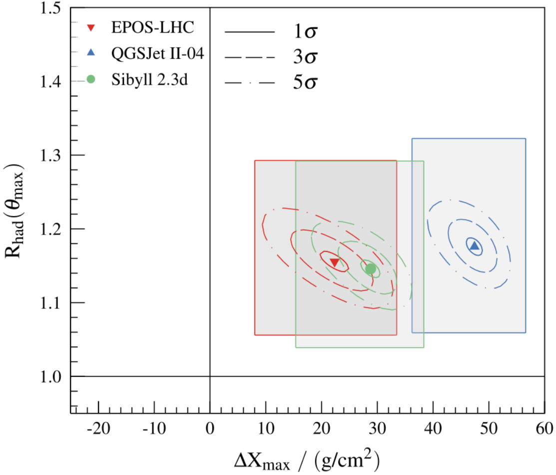


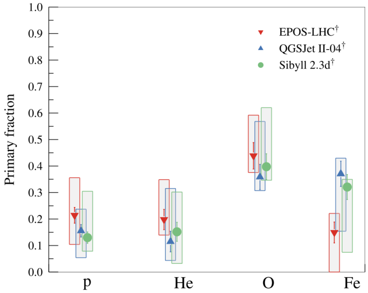
The fitting worked well!

Projected 1D distributions of X_{max} and $S(1000)$



X_{max} and muon scales of hadronic models for the best data fits





All hadronic models fit data best with

◇ X_{max} scales shifted 20 $\mathrm{g\,cm^{-2}}$ to 50 $\mathrm{g\,cm^{-2}}$ deeper

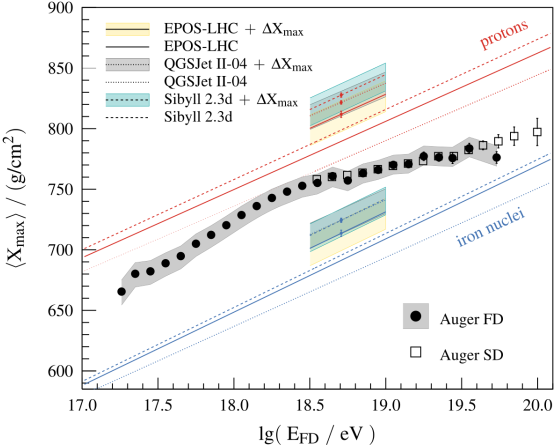
◇ Muon scales increased by 15% – 25%

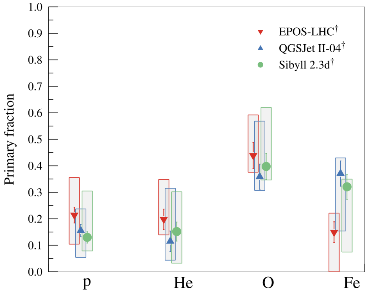
Time to face the consequence

Good: more consistent mass composition inferences

Not so good: heavy (∼iron) composition beyond 50 EeV

X_{max} and muon scales of hadronic models for the best data fits





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Auger as a game changer: continuing through the list

The disappointing model (R. Aloisio, V. Berezinsky, A. Gazizov)

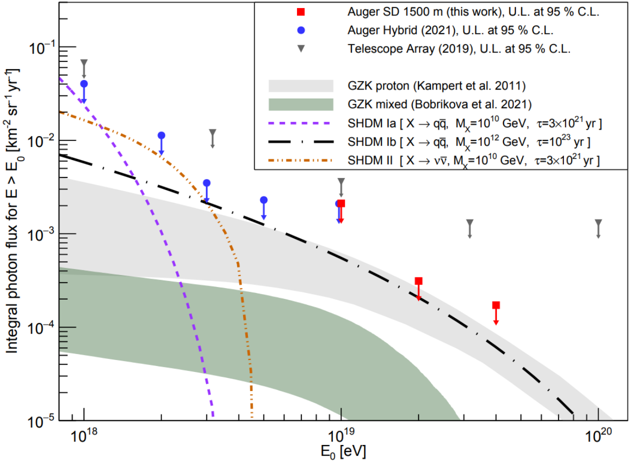
Astropart. Physics 34 (2011) 620

- ◇ Rigidity-dependent cutoff $(4 - 10) \times Z$ EeV
- ◇ Peters' cycle: successive domination of hydrogen, helium, CNO, iron at energies $\propto Z$
- ◇ Maximum energy for iron ($Z = 26$) is $(100 - 300)$ EeV
- ◇ Energy per nucleon is $(2 - 5)$ EeV, almost no photonuclear reactions on CMB
- ◇ No GZK cutoff and cosmogenic neutrinos
- ◇ Spectrum suppression: maximum source energy and nuclei photodisintegration
- ◇ Around 100 EeV iron nuclei dominate, correlation to sources is poor (if any)

SD observables

Lateral distribution of WCD signals

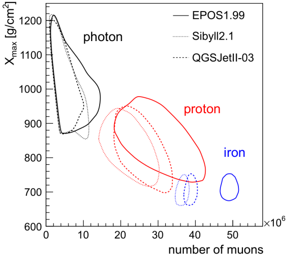
Spread in time of the shower front



JCAP 05 (2023) 021

γ-induced showers: deeper $X_{\max}$, lower muon content

Background: proton-induced showers



ApP 35 (2012) 660

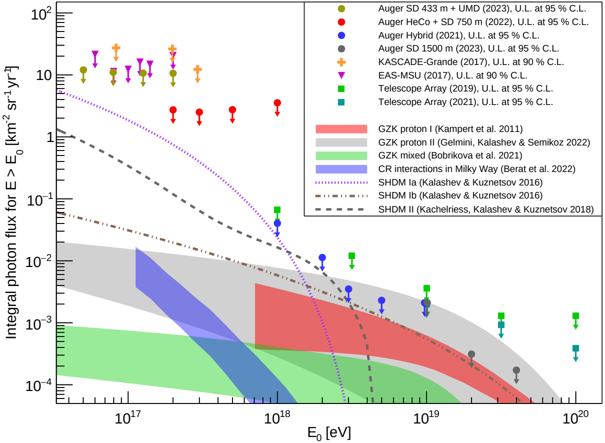
No photon excess with respect to background

Sensitivity is close to pure-proton scenarios

Summary of photon searches

No unambiguously identified photons

- Best photon limits for $E > 2 \times 10^{17}$ eV
- Earlier super-heavy dark matter models are strongly constrained by Auger limits
- 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 problems

Horizon of photons is few Mpc

Overwhelming hadronic background

ApJ 952 (2023) 91

photon searches at Auger: ApJ 789 (2014) 160; JCAP 04 (2017) 009; ApJL 837 (2017) L25; PoS (ICRC2021) 373; ApJ 933 (2022) 125; JCAP 05 (2023) 021, PoS (ICRC 2023) 1488

Dark matter

PHYSICAL REVIEW D **107,** 042002 (2023)

Cosmological implications of photon-flux upper limits at ultrahigh energies in scenarios of Planckian-interacting massive particles for dark matter

PHYSICAL REVIEW LETTERS **130,** 061001 (2023)

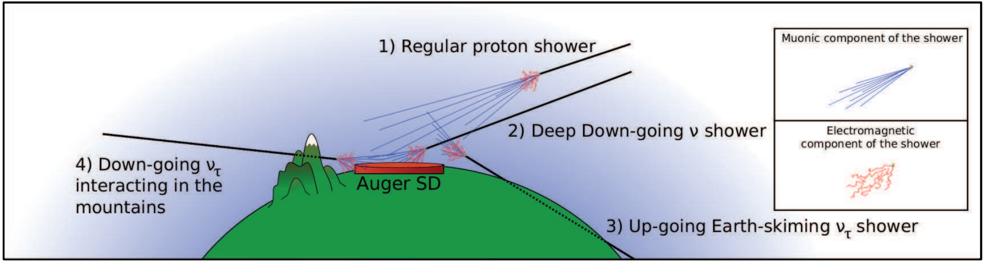
Limits to Gauge Coupling in the Dark Sector Set by the Nonobservation of Instanton-Induced Decay of Super-Heavy Dark Matter in the Pierre Auger Observatory Data

PHYSICAL REVIEW D **109,** L081101 (2024)

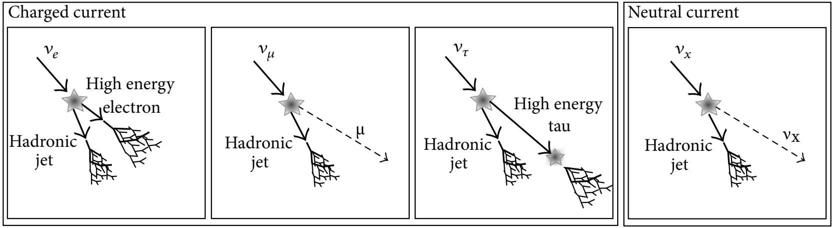
Constraints on metastable superheavy dark matter coupled to sterile neutrinos with the Pierre Auger Observatory

Neutrino searches

Earth-skimming ν_τ: (90°;95°) Down-going (60°;75°), (75°;90°)



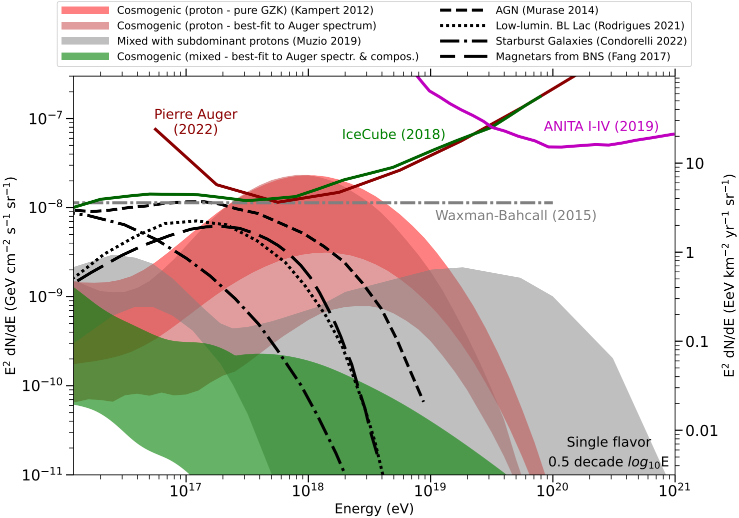
Search for young showers with a large EM contribution



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

Neutrino searches

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

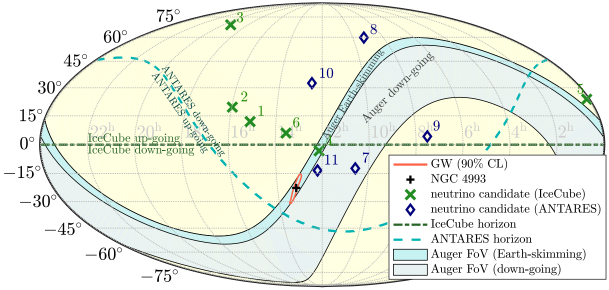


PoS (ICRC 2023) 1488

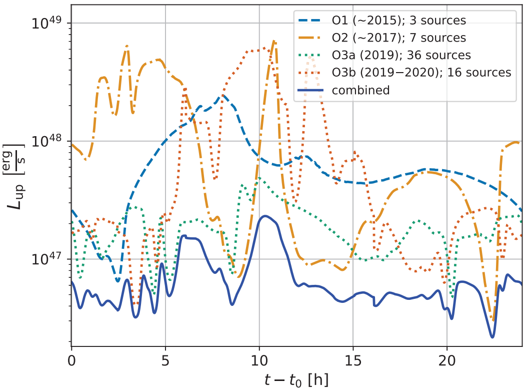
Energy range of Auger $E_\nu > 10^{17}$ eV

Zenith angle of optical counterpart within ± 500 s $(90.4°; 93.3°)$, Earth-skimming

Search results no candidates in time windows ± 500 s, $+14$ days



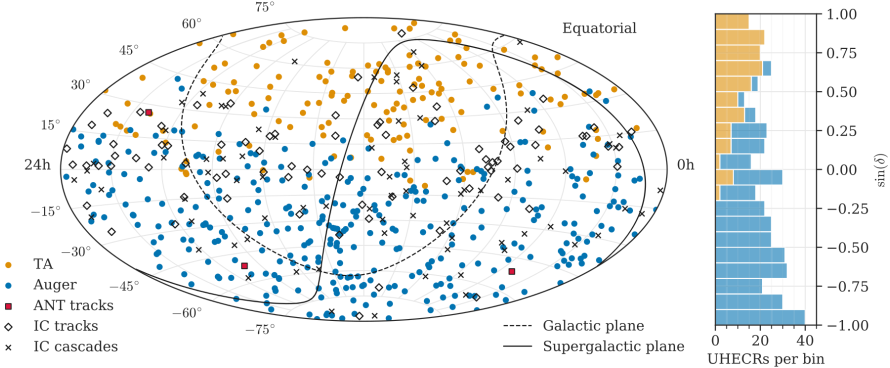
GW170817



no candidates from all LIGO-Virgo GWs: limits on isotropic neutrino luminosity (24h follow-ups)

GW follow-up searches: PoS (ICRC2021) 968, PoS (ICRC2023) 1488

UHECR correlation (Auger $E > 52$ EeV) with IceCube and ANTARES neutrinos



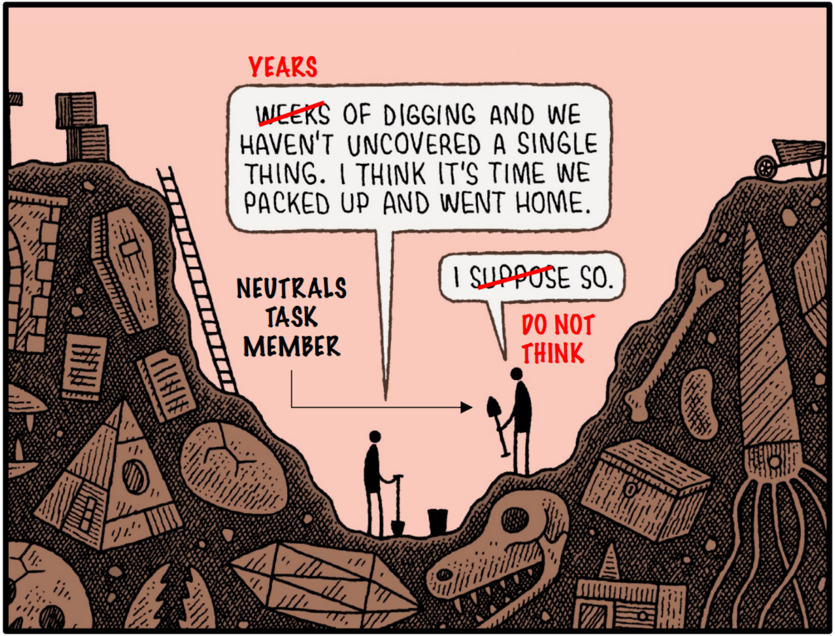
No significant correlation observed

UHECR horizon is limited (200 Mpc), unlike for neutrinos

If sources are transient: UHECR in 2 nG EGMF from 50 Mpc distance is delayed by 10^5 yr

Propagation in GMF can already cause a delay of two decades

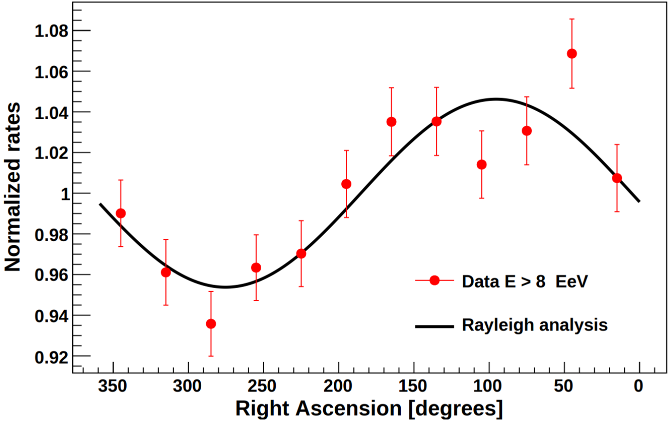
For heavy UHECR correlation to their sources is not preserved



[Tom Gauld, Department of mind-blowing theories, Canongate Books, 2020]

Modulation in flux of ultrahigh energy cosmic rays with $E \geq 8$ EeV

Nearly uniform exposure in right ascension → high sensitivity to flux modulations



Data set, 1/1/2004–31/12/2020

zenith $0° \leq \theta \leq 80°$
declination $-90° \leq \delta \leq 45°$
85% sky coverage

Exposure 110,000 km^2 sr year

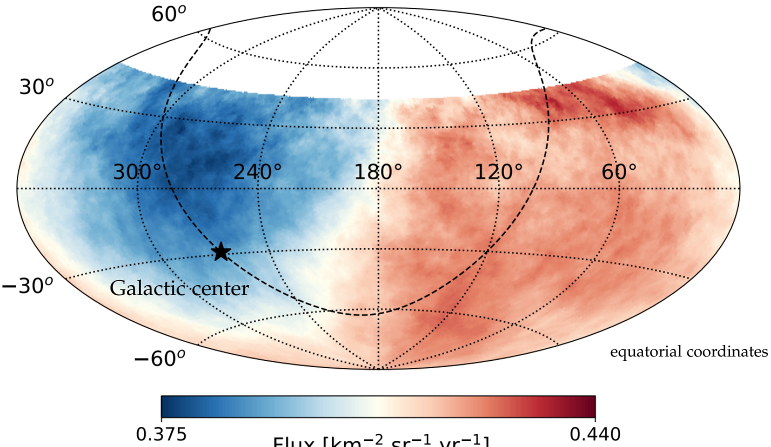
44,398 events with $E > 8$ EeV

Science 57 (2017) 1266; Astrophys. J. 868 (2018) 4, 891 (2020) 142; PoS(ICRC2021)335

Extragalactic origin of UHECRs: dipole for $E \geq 8$ EeV

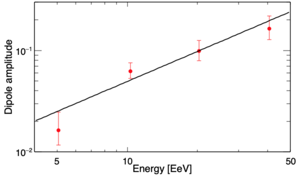
- ◇ Dipole for $E \geq 8$ EeV: amplitude $d = (7.3^{+1.1}_{-0.9})\%$, at 6.6σ from isotropy
- ◇ Phase in R.A. $\alpha_\mathrm{d} = 95° \pm 8°$ is nearly opposite to the Galactic center $\alpha_\mathrm{GC} = -94°$
- ◇ Magnitude and direction of dipole support extragalactic origin of UHECRs with $E > 4$ EeV

physicsworld TOP 10 BREAKTHROUGH 2017



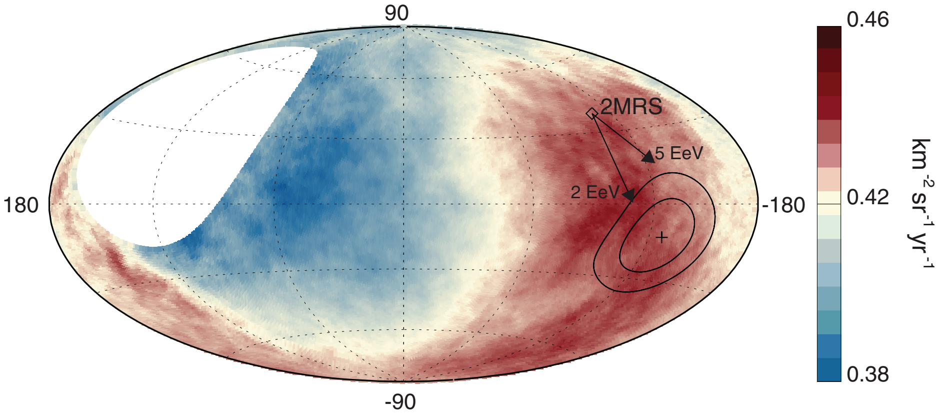
Observation of large-scale anisotropy for $E \geq 8$ EeV

Consistency with isotropy for 4 EeV $< E <$ 8 EeV disfavors dominant galactic CR origin



Comparing to dipole of 2MASS Redshift Survey catalog of galaxies $(l, b) = (251°, 38°)$

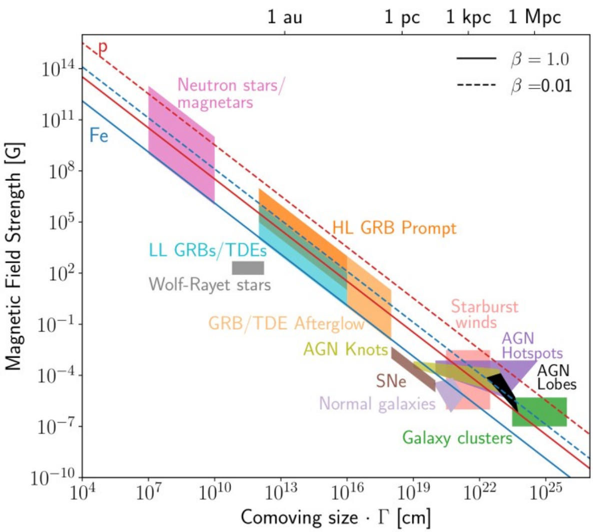
GMFs change position of 2MRS dipole (as shown for $E/Z = 2$ EeV or 5 EeV)
and reduce its amplitude (might explain lower amplitude for 4 EeV $< E <$ 8 EeV)



galactic coordinates, Galactic center is at the origin, measured dipole direction is marked with a cross

Source candidates

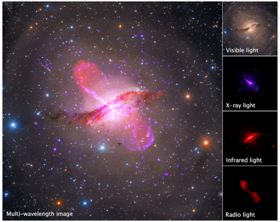
Hillas plot: characteristic sizes and magnetic field strength of various classes of sources



plot: Front. Astron. Space Sci. 6 (2019) 23

NGC 4151 (Eye of Sauron)
non-jetted AGN

Cen A, jetted AGN



M82, starburst galaxy

Anisotropies tested against catalogues of astrophysical objects

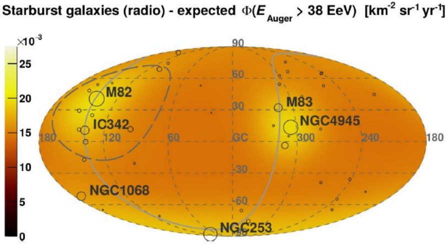
Starburst galaxies

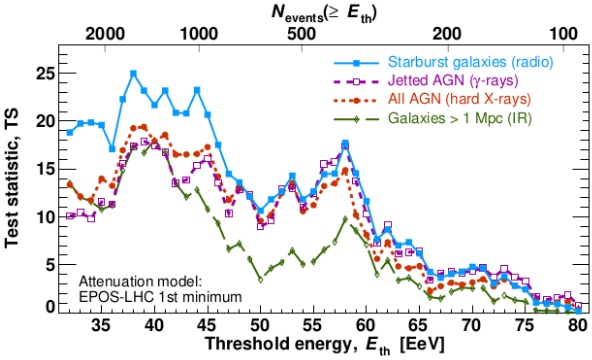
Significance 4.2σ, $E > 38$ EeV

γAGNs

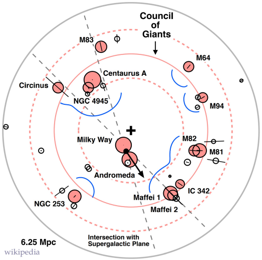
Significance 3.3σ, $E > 39$ EeV

starburst galaxies





Cen A hotspot drives deviation from isotropy for all catalogues



ApJL 853 (2018) L29; PoS (ICRC2021) 307; ApJ 935 (2022) 170

Astrophysical model for combined spectrum – mass composition fit

sources: low & high energy extragalactic populations, identical in each population, no evolution

distribution: uniform, except for local overdensity < 30 Mpc

injected nuclei: ^{1}H, ^{4}He, ^{14}N, ^{28}Si, ^{56}Fe

cutoff: rigidity ($R = E/Z$) dependent

cosmic photon background: CMB, extragalactic background light

energy losses: adiabatic, $e^{+} - e^{-}$ and photo-meson production, photo-disintegration

extragalactic magnetic fields: no interaction (1D propagation)

propagation software: SimProp

energy range: $E > 10^{17.8}$ eV

interactions in atmosphere: EPOS-LHC, QGSJetII-04, Sybill 2.3d

data to fit: SD spectrum, FD $X_{\max}$ distributions

fit results are very sensitive to variations in input assumptions and experimental uncertainties

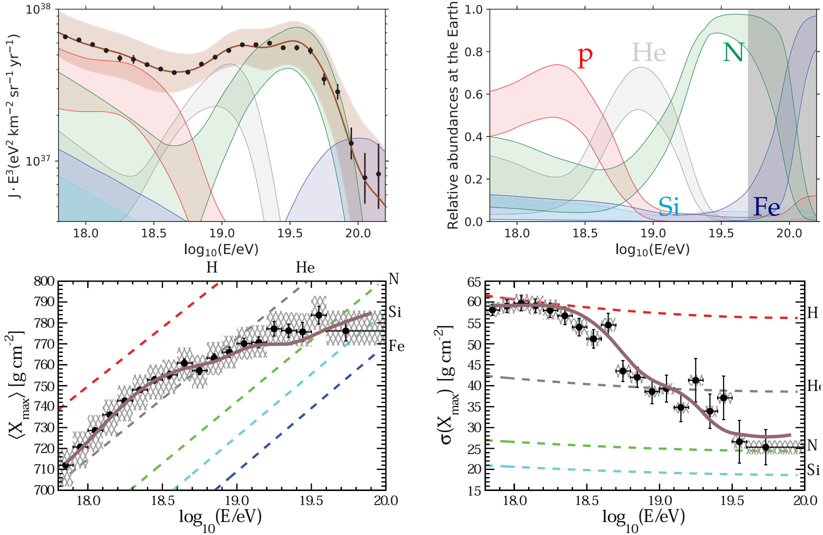
JCAP 04 (2017) 038, PoS (ICRC2021) 311, JCAP 05 (2023) 024

Astrophysical model for combined spectrum–composition fit

composition at source (example): $f_{\mathrm{He}} = 29\%,\ f_{\mathrm{N}} = 69\%,\ f_{\mathrm{Fe}} = 2\%$

hard injection spectrum $\gamma = -1.98 \pm 0.10$

low rigidity cutoff $\lg(R/\mathrm{V}) = 18.16 \pm 0.01$



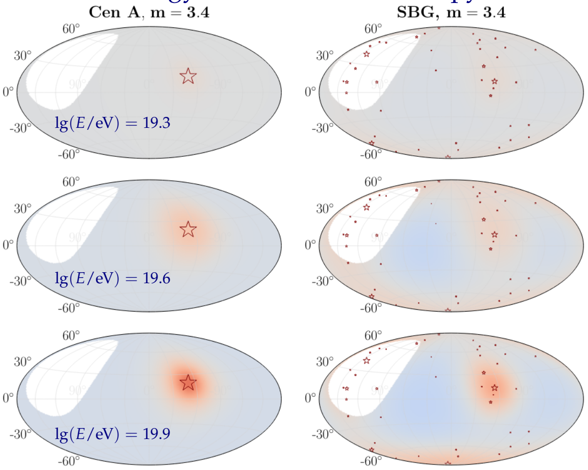
Instep

Combined effect from He and N

Galactic-extragalactic transition and cutoff nature

mass composition for respective energies should be added

energy evolution of anisotropy



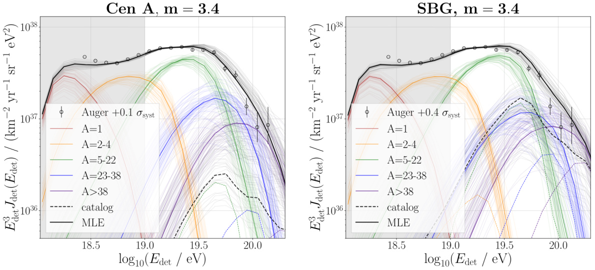
Tested catalogs: 26 γAGN 44 SBG Cen A

Using: distance, flux weight, direction, signal fraction

SBGs and Cen A describe data well

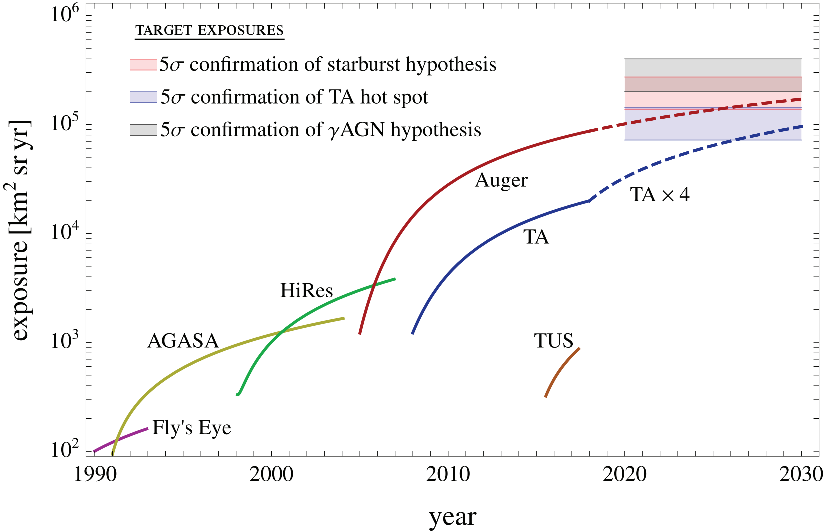
Caveat

coherent magnetic deflections are not accounted



Future: is charged-particle astronomy still possible?

Composition enhanced anisotropy: SD exposure and SD mass tagging required



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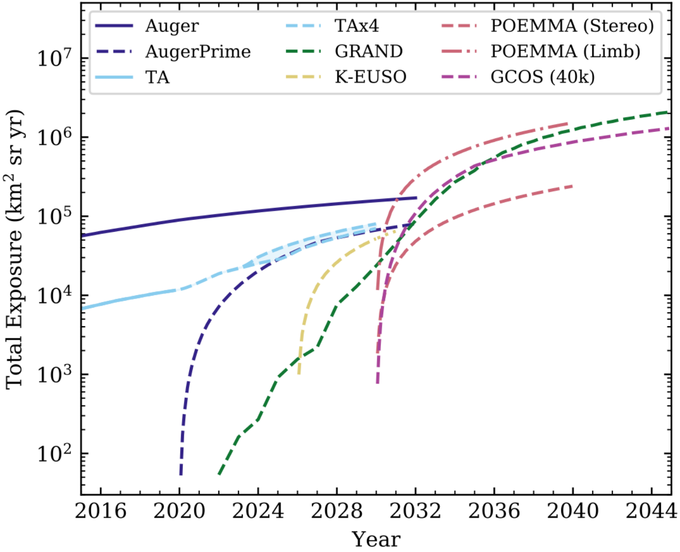
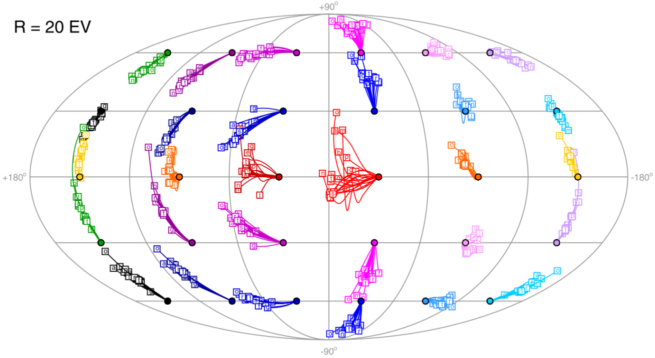
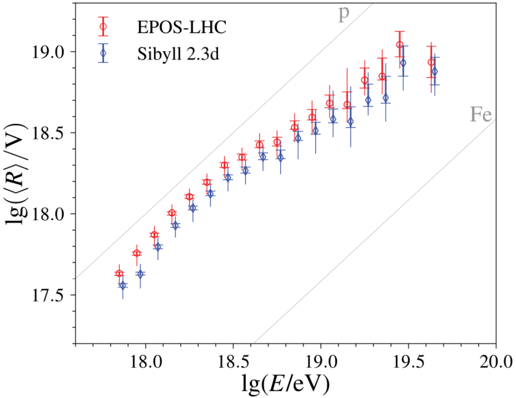


Particle astronomy for mixed composition?

Backtracking (circles — initial directions) for different models of galactic magnetic fields



UHECR rigidities from Auger X_{max} data



Select low-Z component if there is any. Correct deflections? Restrict analysis to certain sky regions?

arXiv:2311.12120; ApP 149 (2023) 102819

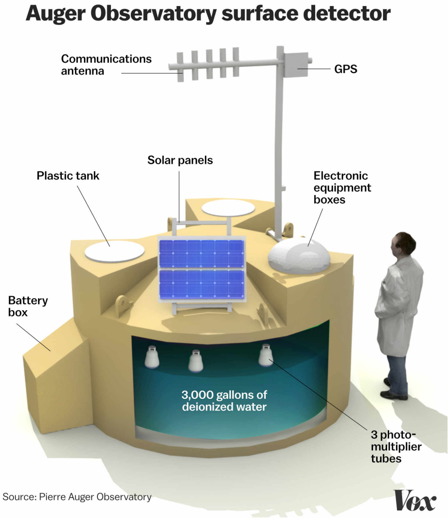
AugerPrime upgrade: to run until 2035

For each WCD

+ new electronics
+ small PMT
+ 3.8 m^2 scintillator detectors
+ radio antenna

SD (750 m) of 23.5 km^2 area

+ underground muon detectors



AugerPrime: EPJ Web Conf., 210 (2019) 06002; for Telescope Array TA × 4 upgrade see PoS(ICRC2021)012

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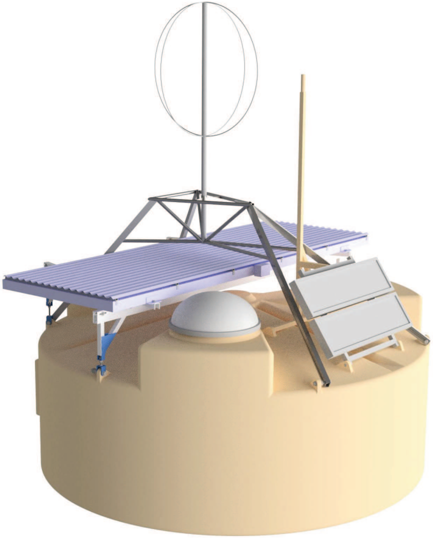

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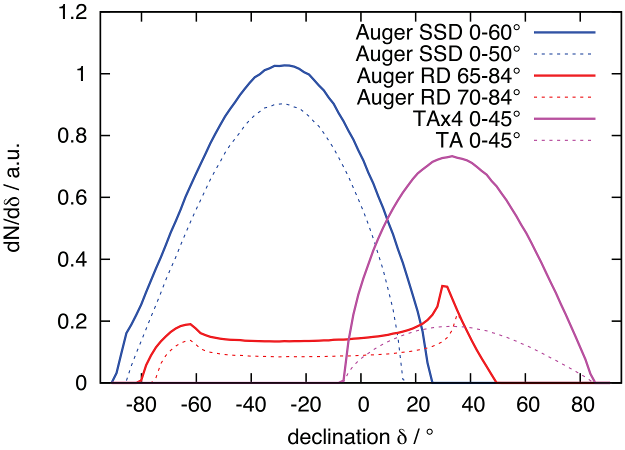
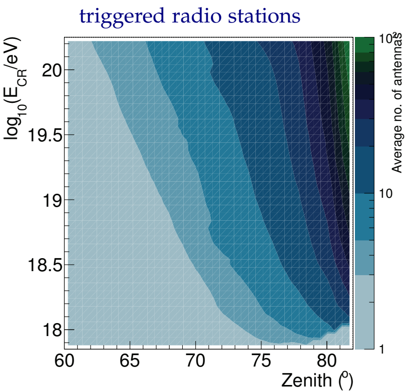
Radio Detector

◇ zenith angles > 65 degrees: complementary to scintillator detectors

◇ full separation of EM (RD) and muon (WCD) components

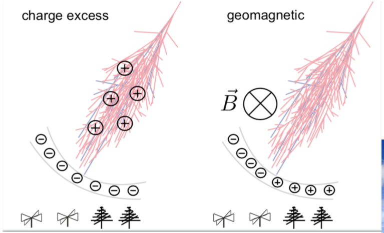
Composition and hadronic interactions physics, enlarged declination range

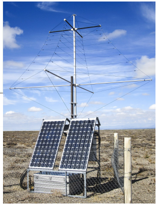


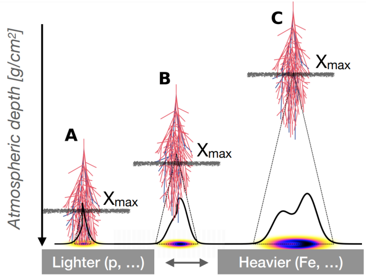


X_{max} measurements with radio detector AERA

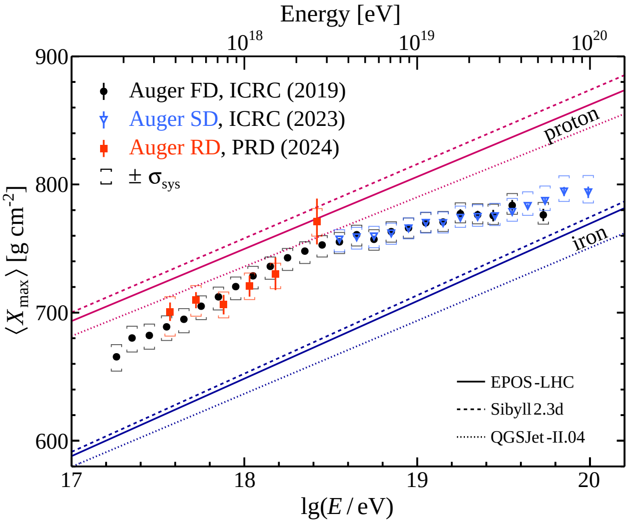
Largest radio array for cosmic-ray detection







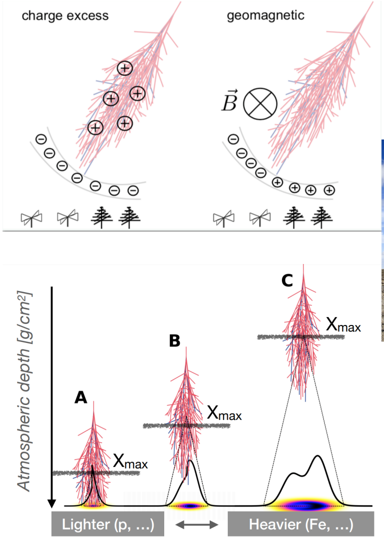
good agreement with other measurements

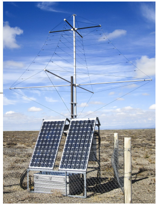


PoS(ICRC2021)387, PRD 109 (2024) 022002, PRL 132 (2024) 021001

X_{max} measurements with radio detector AERA

Largest radio array for cosmic-ray detection





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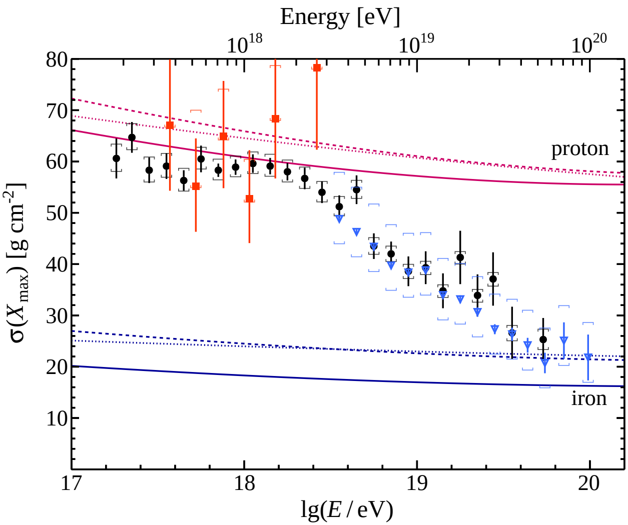
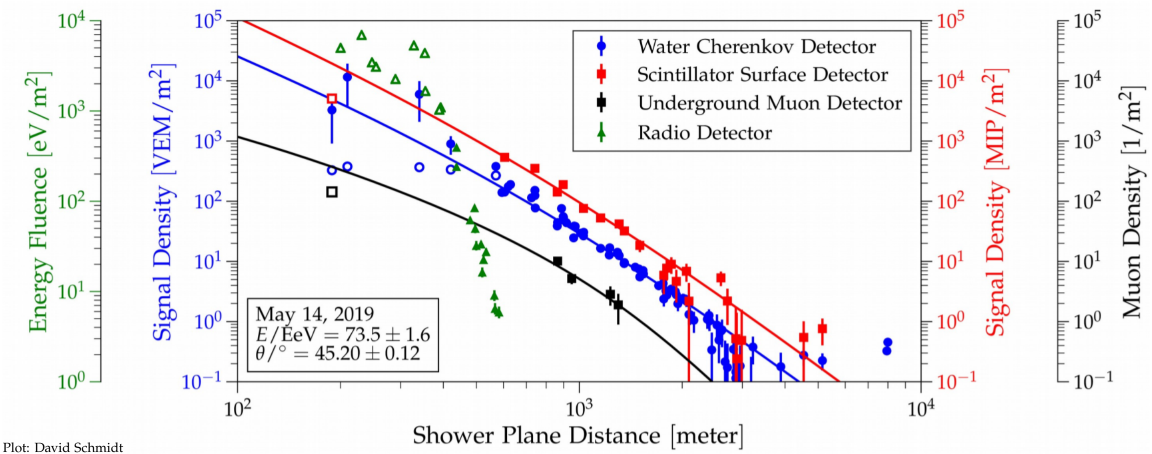


PoS(ICRC2021)387, PRD 109 (2024) 022002, PRL 132 (2024) 021001

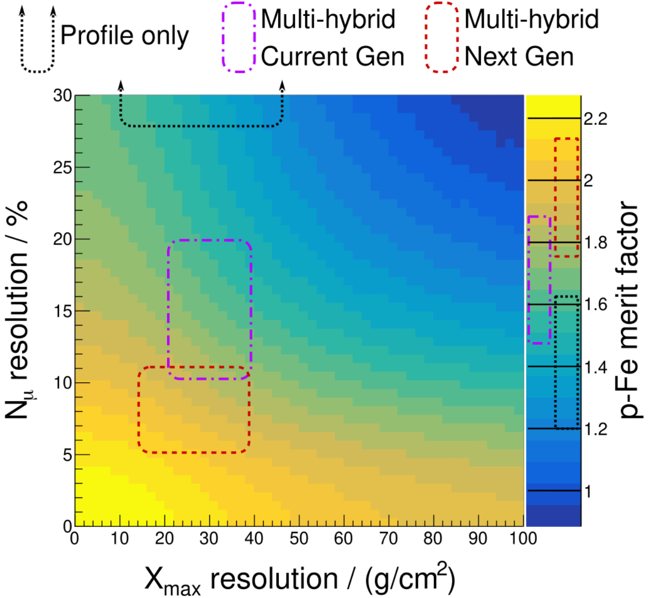
Multihybrid data from AugerPrime



Plot: David Schmidt

Scientific data: next decade

Better mass composition sensitivity with next generation multihybrid observations



ApP 149 (2023) 102819

Scientific data: next decade

- Reduced systematics in hadronic interaction models
- Mass composition with SD/SSD and machine learning
- Composition sensitivity in the flux suppression region
- Sensitivity to 10% proton fraction in this region
  (important for GZK photon and neutrino fluxes)
- Composition enhanced anisotropy studies
- Search for new phenomena in hadronic interactions
- Experience and data for the design of the next generation observatories