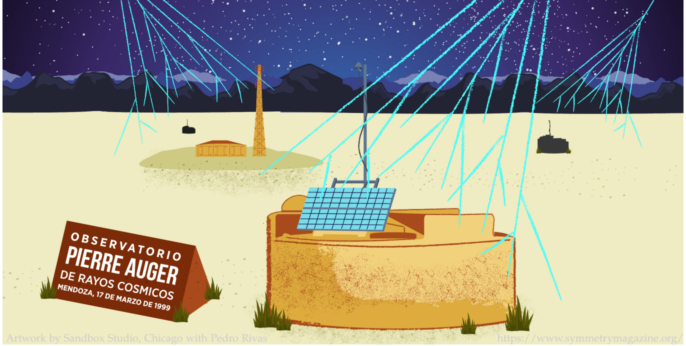
PIERRE AUGER OBSERVATORY

auger.org



The Pierre Auger Observatory: Latest results and prospects for the future

Co-funded by the European Union

MINISTRY OF EDUCATION, YOUTH AND SPORTS

Alexey Yushkov*

FZU Fyzikální ústav Akademie věd České republiky

*FZU — Institute of Physics of the Czech Academy of Sciences
The Pierre Auger Collaboration, Av. San Martín Norte 304, 5613 Malargüe, Argentina

FORTE

ICHEP 2024 PRAGUE

42nd ICHEP, Prague, 20/07/2024

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

Nucl. Instrum. Meth. A798 (2015) 172

Fluorescence detector (FD)

duty cycle 15 %

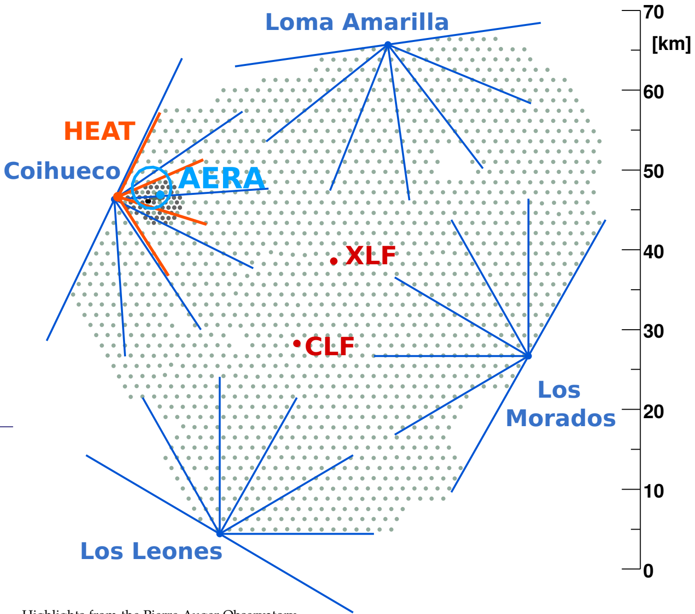
24 + 3 fluorescence telescopes

Surface detector (SD)

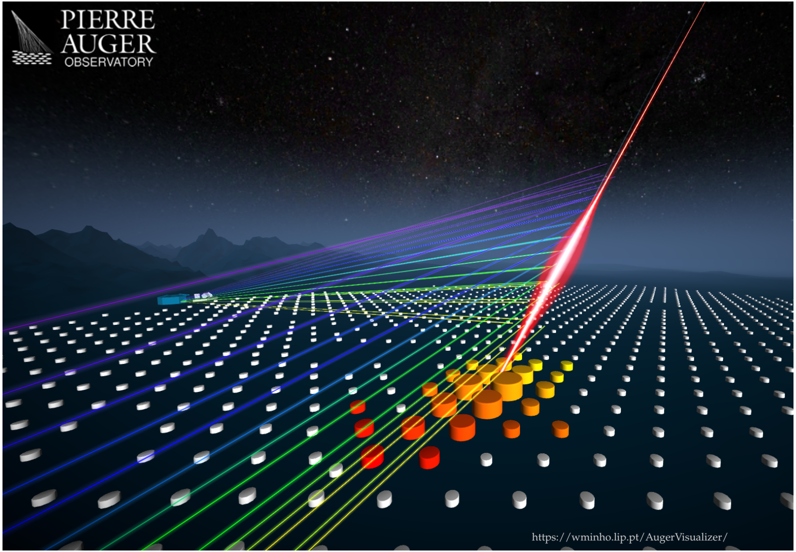
duty cycle 100 %

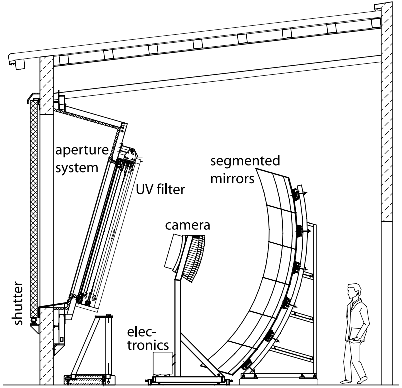
1660 water-Cherenkov detectors

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



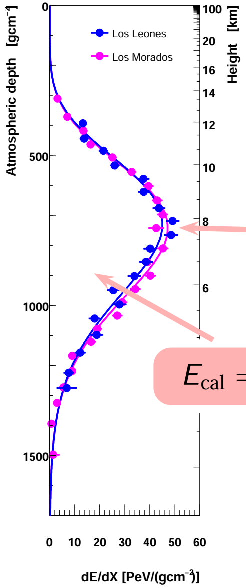
Energy estimation: atmosphere as a calorimeter





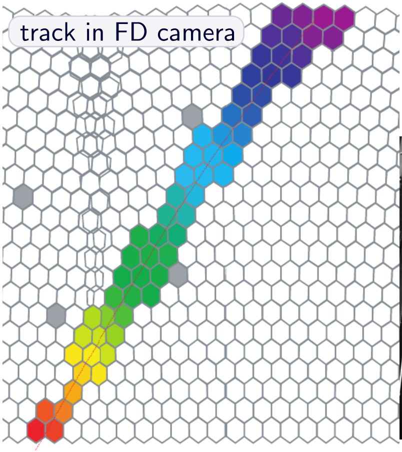
Fluorescence detector: direct observation of the longitudinal energy deposit

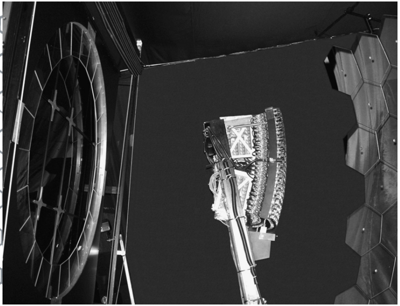
Energy estimation: atmosphere as a calorimeter



X_{max}

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





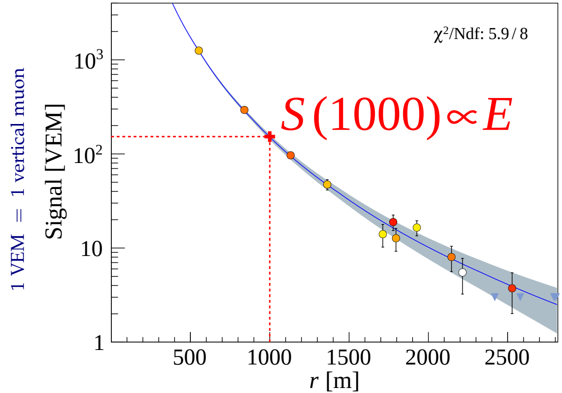
✓Calorimetric energy

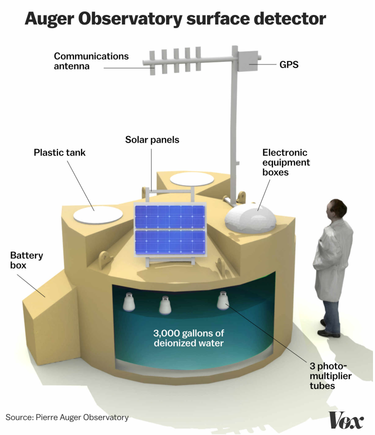
✓Mass estimator X_{max}

Caveat: uptime is only 15%

Energy estimation: sample particles reaching ground

Fit to signals in all event stations

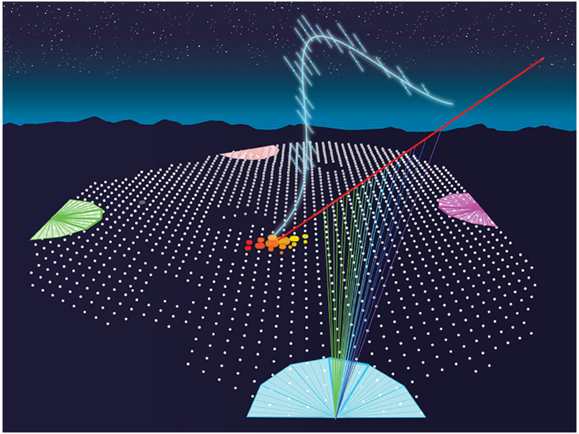




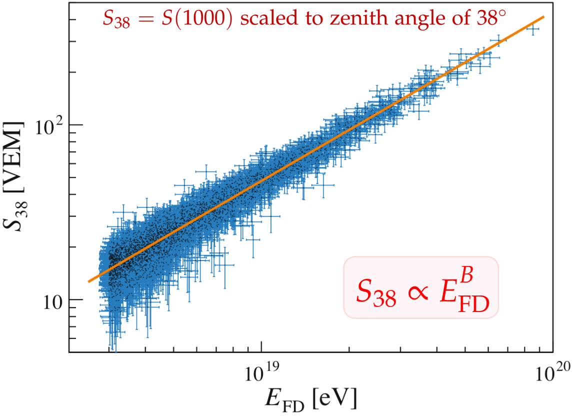
- ✓ Primary energy from $S(1000)$
- ✓ Mass estimator: SD signal (sensitive to muons)

Caveat: both are hadronic-model-dependent

Hybrid events: SD energy calibration using FD



Subset of events with good SD and FD reconstructions



✓ SD energy and energy spectrum measurements are mostly data-driven

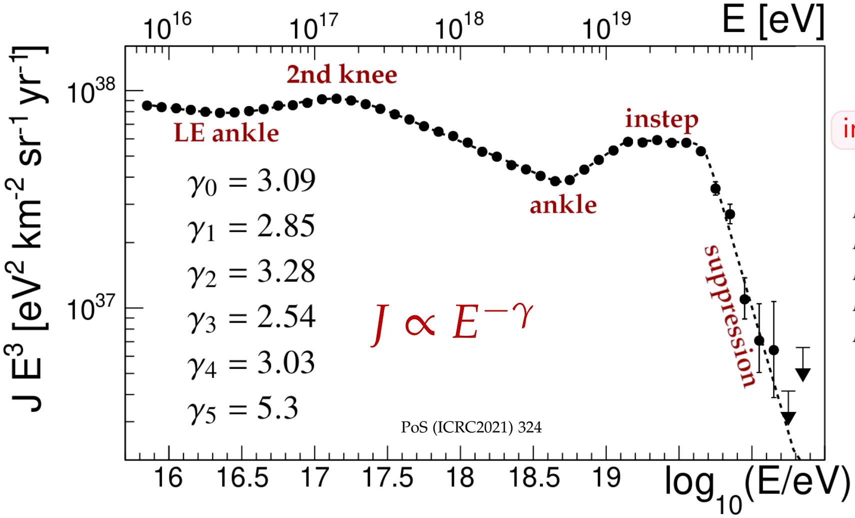
⚠ Mass composition: predictions on X_{max} and [muon] SD signal depend on air-shower simulations

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 (GZK) cutoff $E_0 > 5 \times 10^{19}$ eV
photodisintegration	${}^{A}Z + \gamma \to {}^{A-1}Z + n$	Energy cutoff is similar to GZK for protons
Gerasimova-Rozental cutoff (1961)		Secondary nucleon energies $\sim E_0/A$, below GZK cutoff
		Suppressed UHE photon and neutrino fluxes
pair production	$p + \gamma \to p + e^+ + e^-$	important above 2×10^{18} eV

All-particle 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

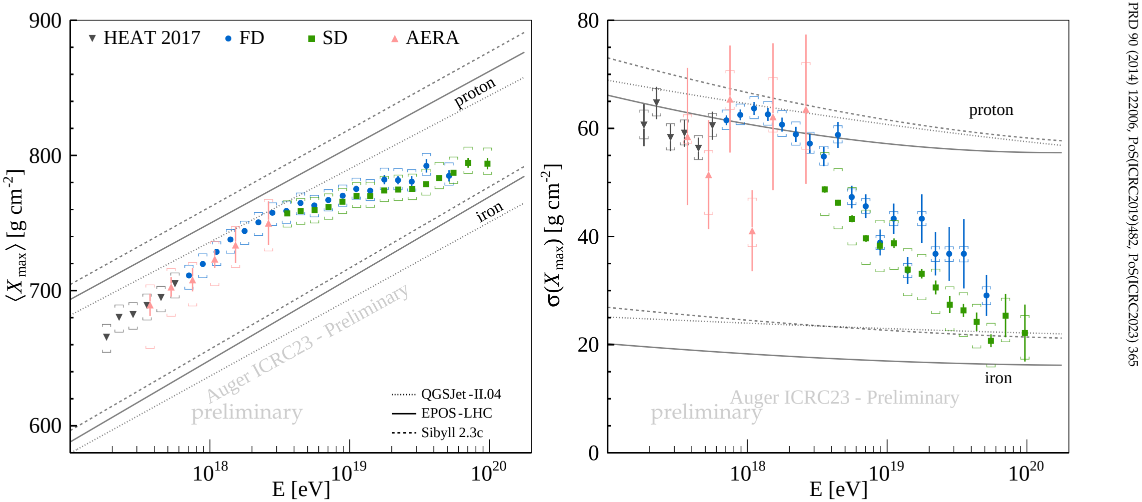
Elemental spectra (mass composition) is the key for astrophysical interpretation

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

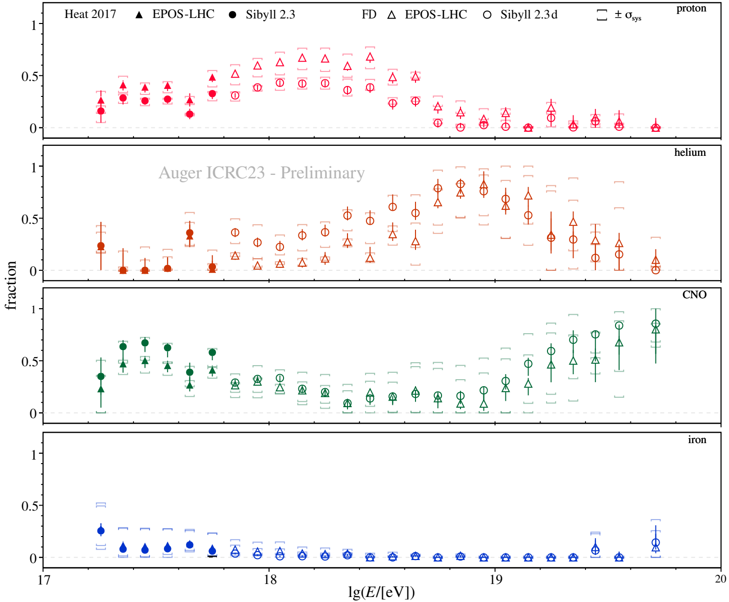
Mass composition: mean and standard deviation of X_{max}

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

note that the 'ankle' in the spectrum is at 5 EeV



Fractions of primary nuclei from fits of the FD X_{max} distributions



2nd knee (~ 10^{17} eV)

- ◇ decreasing iron contribution
- ◇ consistent with the 'iron knee'

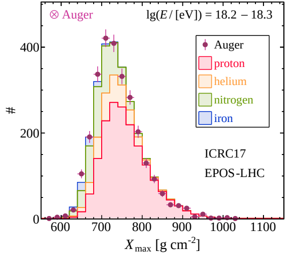
ankle ($10^{18.7}$ eV)

- ◇ disappearance of protons

highest energies (cutoff)

- ◇ medium mass domination

maximum energy in sources and propagation effects

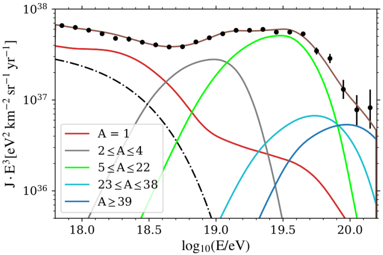


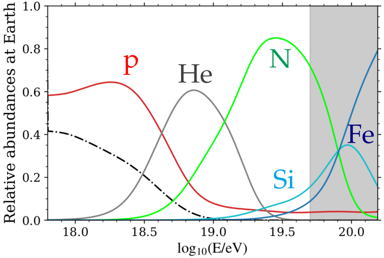
PoS(ICRC2023)319, PoS(ICRC2023)365, PoS(ICRC2023)438

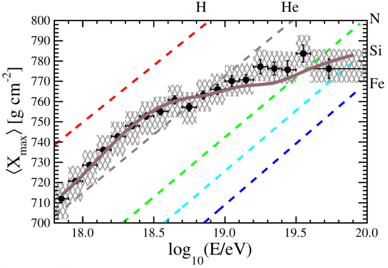
Astrophysical model for combined spectrum–composition fit

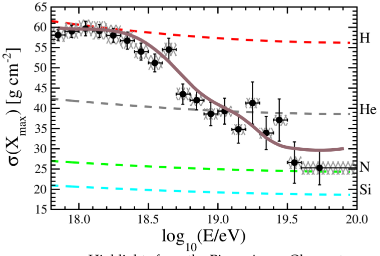
Example scenario: proton component with $\lg(R_{\mathrm{cut}}/\mathrm{V}) > 19.3$ plus

mixed component: $f_{\mathrm{He}} = 24.5\%$, $f_{\mathrm{N}} = 68\%$, $f_{\mathrm{Fe}} = 5\%$, $f_{\mathrm{Fe}} = 2.5\%$; $\lg(R/\mathrm{V}) = 18.19$; hard injection spectrum $\gamma = -1.47$









Instep

Combined effect from He and N

Galactic-extragalactic transition and cutoff nature

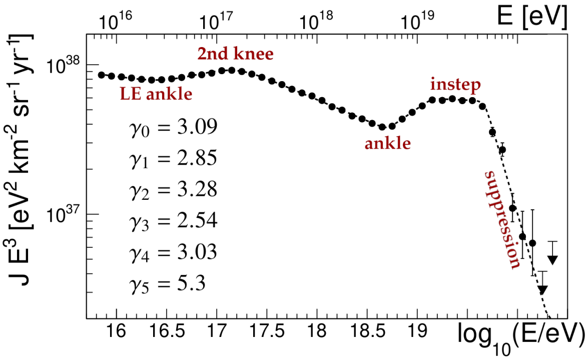
mass composition for respective energies should be included

Magnetic horizon effect

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

JCAP 04 (2017) 038, PoS (ICRC2021) 311, JCAP 05 (2023) 024, JCAP01(2024)022, arXiv:2404.03533

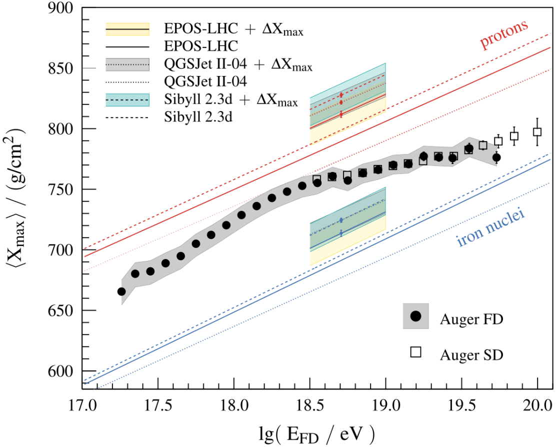
All-particle energy spectrum: plausible interpretations



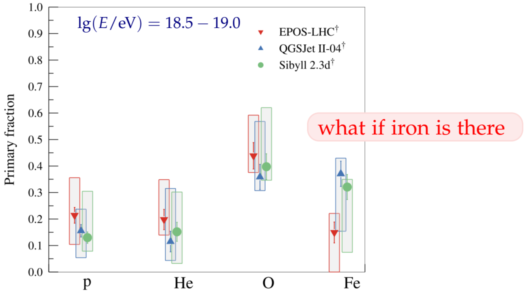
- ◇ Galactic-extragalactic transition ($\sim 10^{17}$ eV): vanishing Galactic iron; $E_{\max}(Z) \simeq Z E_{\max}^{\text{proton}}$
- ◇ Smooth behavior between 2nd knee and ankle: awaiting explanation
- ◇ Ankle: rigidity-dependent cutoff $\approx 5\text{Z} \times 10^{18}$ eV; vanishing protons
- ◇ Instep: interplay between helium and CNO
- ◇ Suppression: combination of maximum energy and nuclei photodisintegration

⚠ Mass composition: predictions on X_{max} and SD signal depend on air-shower simulations

Results from simultaneous fit of X_{max} and SD signal



More details in talk of Jakub Vícha in this session



PRD 109 (2024) 102001

All hadronic models fit data best with

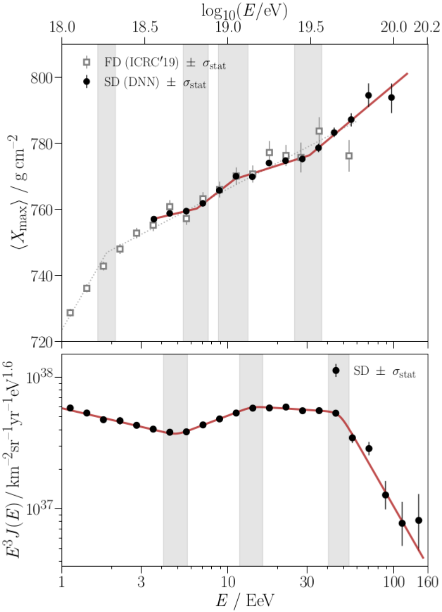
- ◇ X_{max} scales shifted $20\ \mathrm{g\,cm^{-2}}$ to $50\ \mathrm{g\,cm^{-2}}$ deeper
- ◇ Muon scales increased by 15% – 25%

Time to face the consequence

Good: more consistent mass composition inferences

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

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



New findings to incorporate in the astrophysical interpretations

- ◇ 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

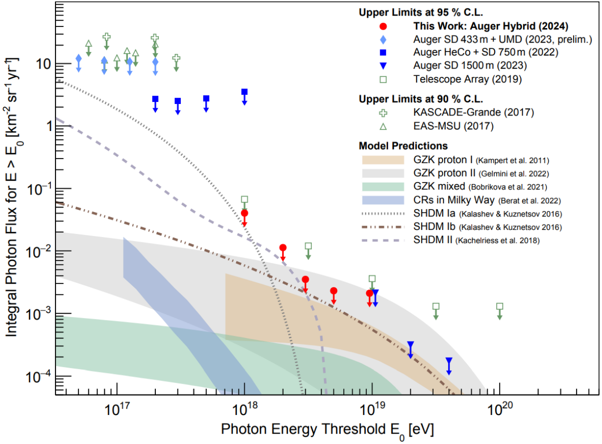
More details in talk of Thomas Fitoussi in this session

arXiv:2406.06319 & arXiv:2406.06315, submitted to PRD and PRL

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, arXiv:2406.07439

Dark matter

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

PRD 107 (2023) 042002

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)

PRL 130 (2023) 061001

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

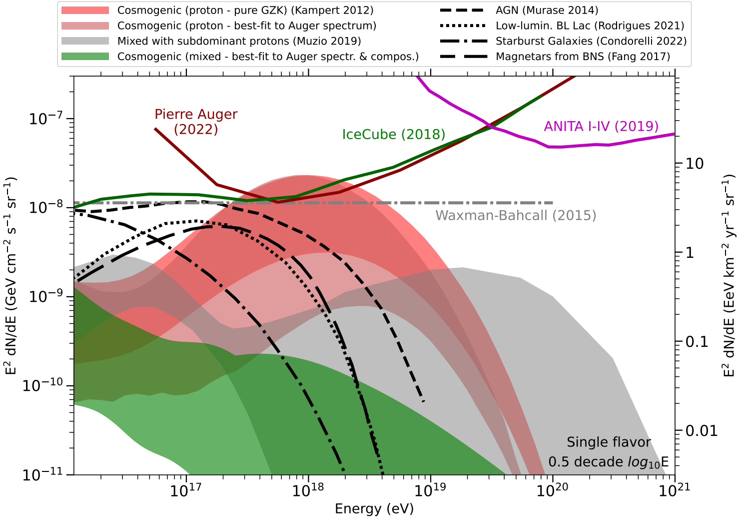
PHYSICAL REVIEW D **109,** L081101 (2024)

PRD 109 (2024) L081101

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

Neutrino searches

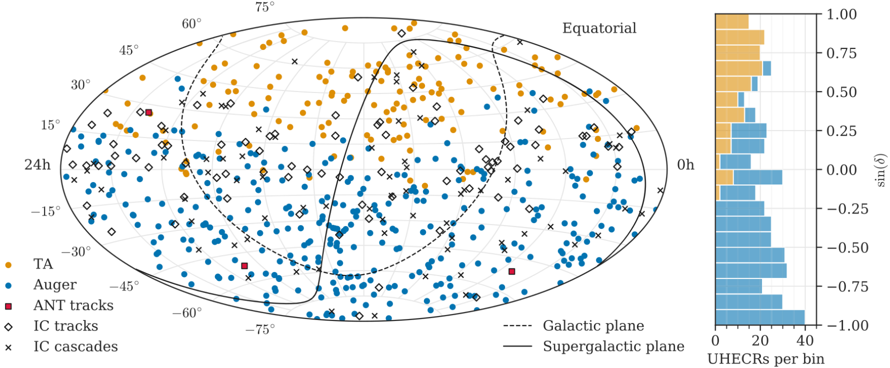
No candidates: constraints on proton-dominated astrophysical models and source evolution



More details & multimessenger physics connection:
talk of Denise Boncioli
Neutrino Physics, July 19

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, PoS (ICRC 2023) 1488

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



Astrophys. J. 934 (2022) 164

No significant correlation observed

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

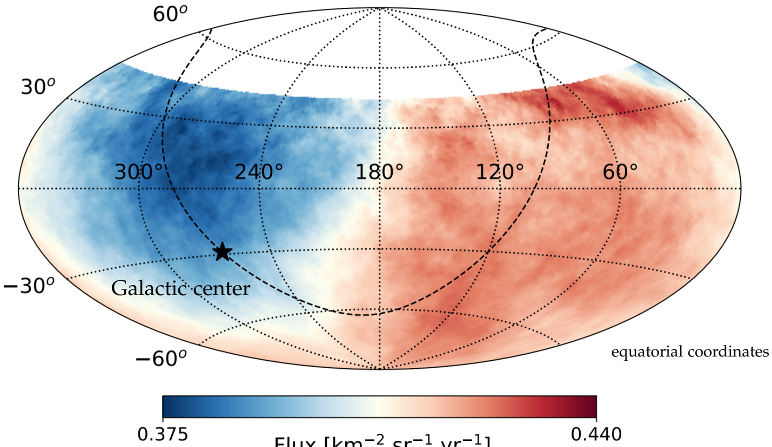
If sources are transient: UHECR in 2 nG EGMF from 50 Mpc distance is delayed by 10^5 yr

Propagation in GMF can already cause a delay of two decades

For heavy UHECR correlation to their sources is not preserved

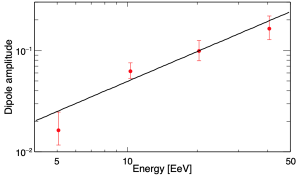
Extragalactic origin of UHECRs: dipole for $E \geq 8$ EeV

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



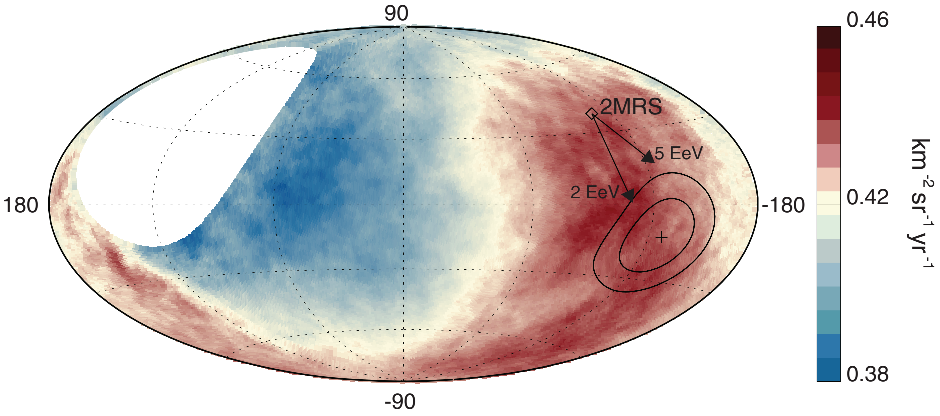
Observation of large-scale anisotropy for $E \geq 8$ EeV

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

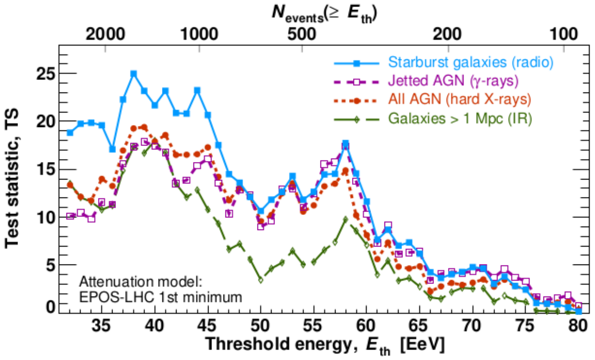
Anisotropies tested against catalogues of astrophysical objects

Starburst galaxies

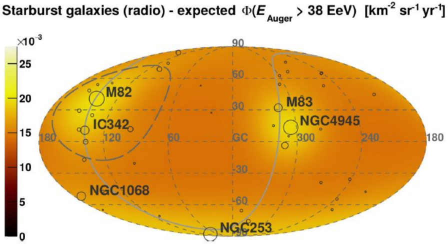
Significance 4.2σ, $E > 38$ EeV

γAGNs

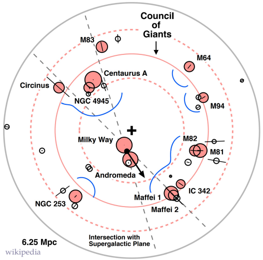
Significance 3.3σ, $E > 39$ EeV



starburst galaxies



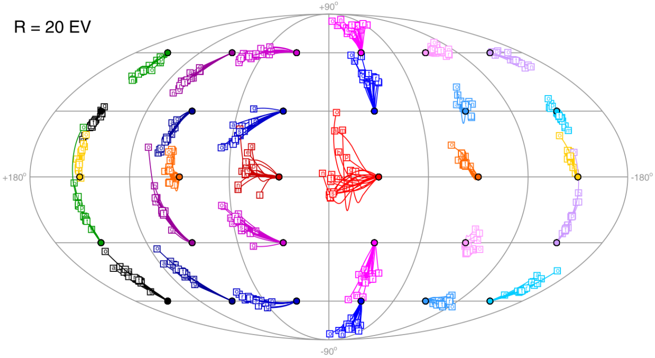
Cen A (jetted AGN, $\approx$ 4 Mpc) hotspot drives deviation from isotropy for all catalogues



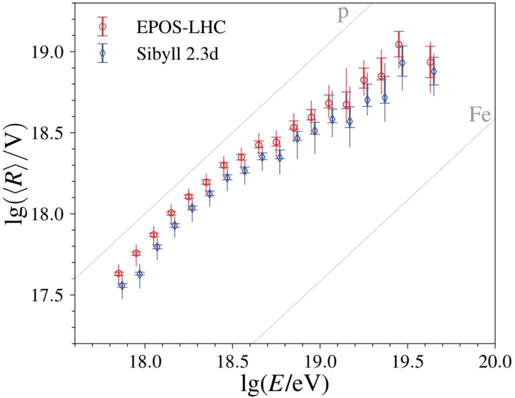
ApJL 853 (2018) L29; PoS (ICRC2021) 307; ApJ 935 (2022) 170

Future: Particle astronomy for mixed composition?

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



UHECR rigidities from the FD 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

More details: talks of Martin Schimassek (today in Upgrade session) & Lukas Nellen (Computing, July 19)

For each WCD

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

SD (750 m) of 23.5 km^2 area

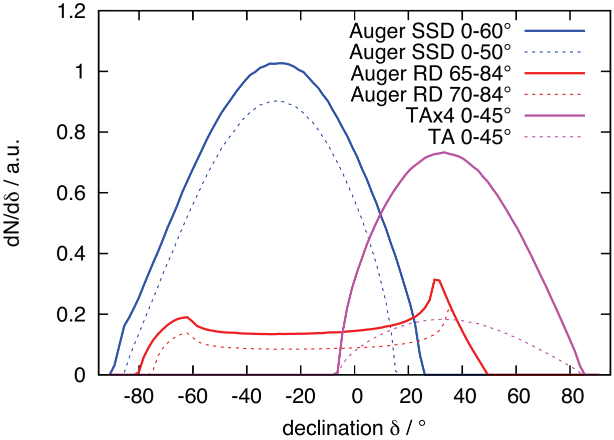
+ underground muon detectors

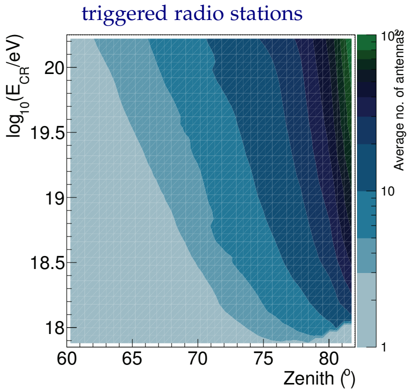
AugerPrime: EPJ Web Conf., 210 (2019) 06002; PoS(ICRC2023)343, 344, 392

Radio Detector

- ◇ zenith angles > 65 degrees: complementary to scintillator detectors
- ◇ full separation of EM (RD) and muon (WCD) components

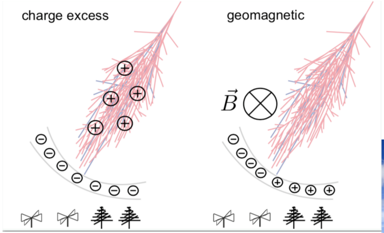
Composition and hadronic interactions physics, enlarged declination range

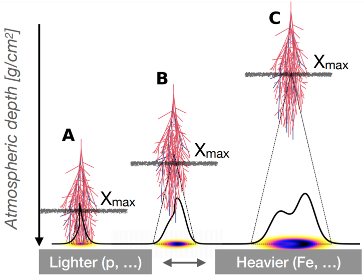


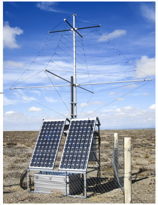


X_{max} measurements with radio detector AERA

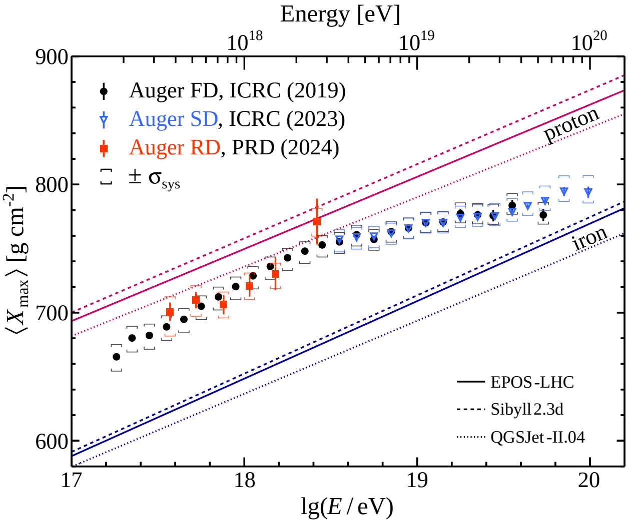
Largest radio array for cosmic-ray detection







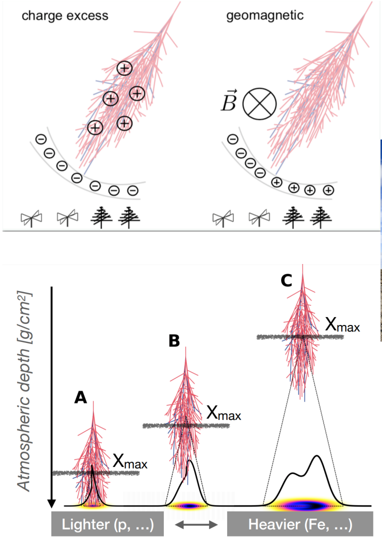
good agreement with other measurements

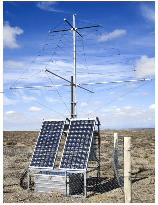


PoS(ICRC2021)387, PRD 109 (2024) 022002, PRL 132 (2024) 021001

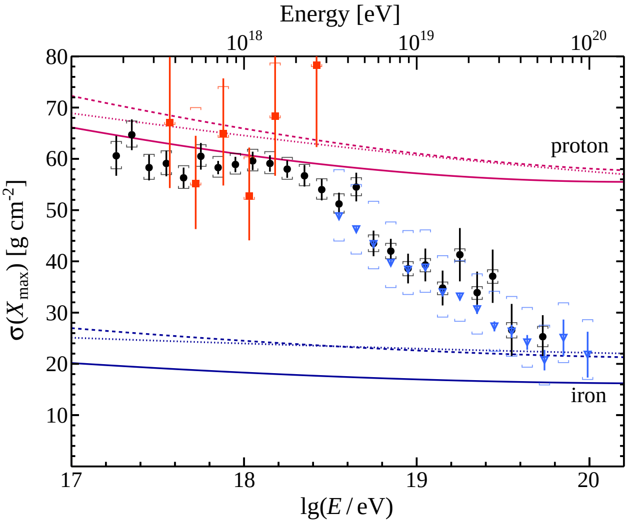
X_{max} measurements with radio detector AERA

Largest radio array for cosmic-ray detection





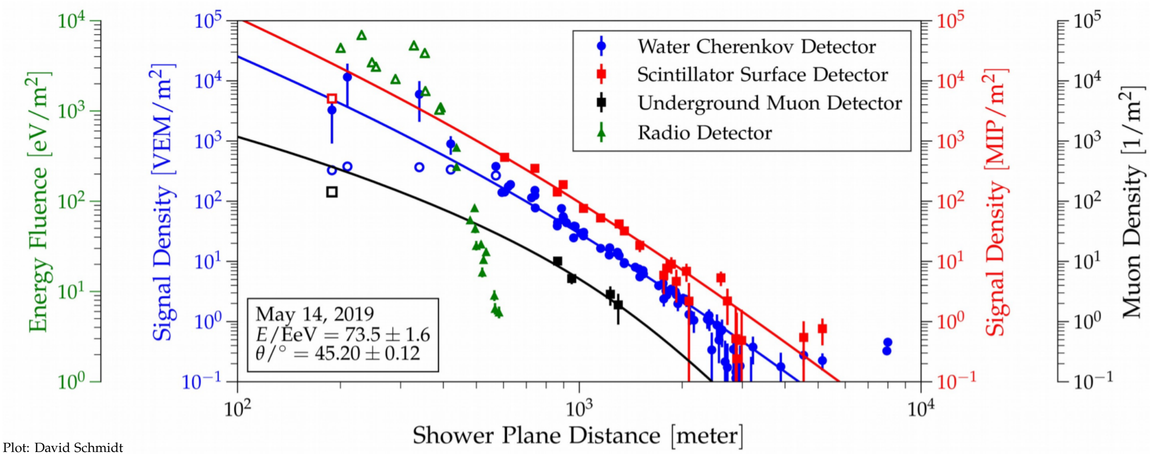
good agreement with other measurements



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

Scientific data: next decade

Multihybrid data from AugerPrime



Plot: David Schmidt

Scientific data: next decade

+ Reduced systematics in hadronic interaction models
+ Mass composition with AugerPrime 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

Stay tuned: our refereed journal papers

Scientific data: next decade

+ Reduced systematics in hadronic interaction models
+ Mass composition with AugerPrime 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

Don't miss:
talk of Viviana Scherini,
Outreach, July 19

Stay tuned: our refereed journal papers