The Pierre Auger Observatory

Recent Results & Future Plans

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(with a little help from my friends)

February 22, 2024

The Pierre Auger Observatory

Pierre Auger Observatory
Province Mendoza, Argentina

Radio antenna array
(153 antennas, 17 km²)

Infill array of 750 m
(63 stations, 23.4 km²)

High elevation telescopes

LIDARs and laser facilities

4 fluorescence detectors
(24 telescopes in total)

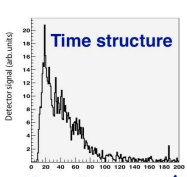
1665 surface detectors:
water-Cherenkov tanks
(grid of 1.5 km, 3000 km²)

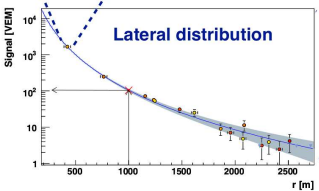
Central Campus

70 [km] 50 40 0

**More than 400 members,
95 institutes, 18 countries**

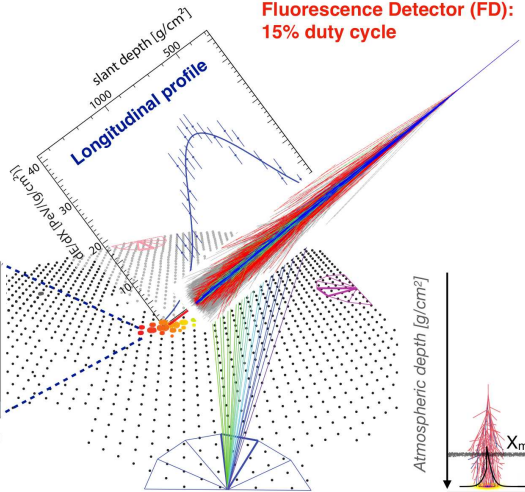
Air shower observables (hybrid observation)



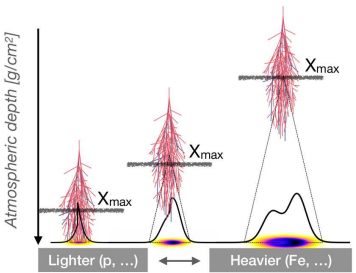


Surface Detector (SD)
100% duty cycle

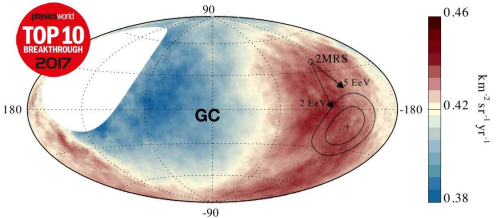
Fluorescence Detector (FD):
15% duty cycle



Radio Detector (RD):
100% duty cycle

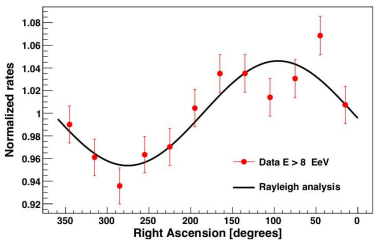


Medium Scale Anisotropy

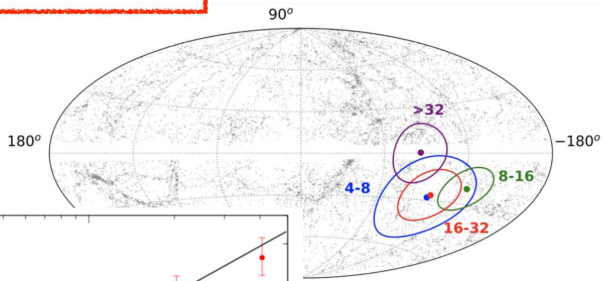


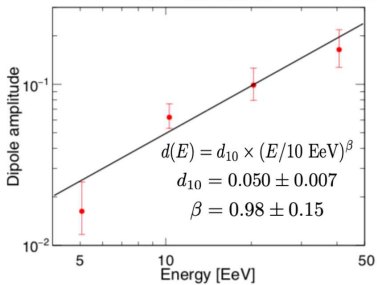
6.5% dipole at 6.9 σ (post rial)

(Science 357 (2017) 1266, update ICRC 2023)



$E > 8 \times 10^{18}\,\mathrm{eV}$



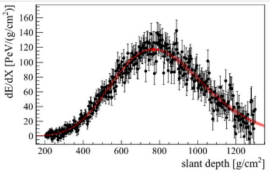


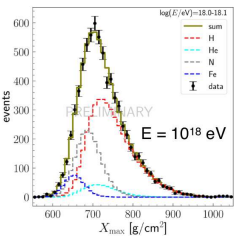
Points ~113° away from GC

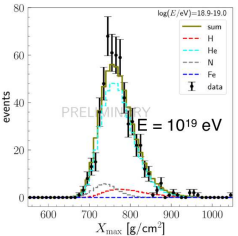
Dipole amplitude growing with energy

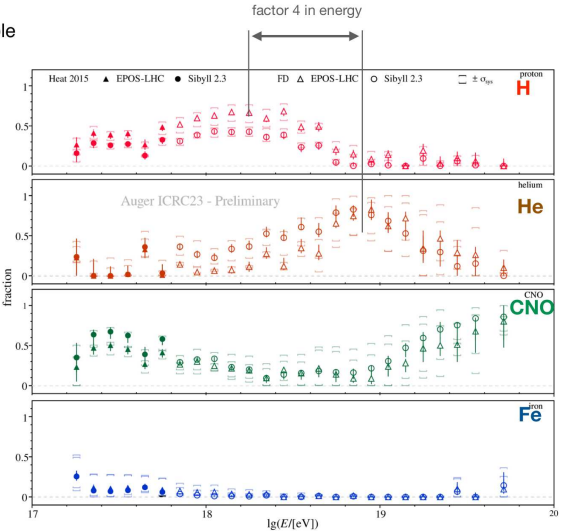
Composition from Full Xmax Distributions

Depth of shower maximum as composition-sensitive observable



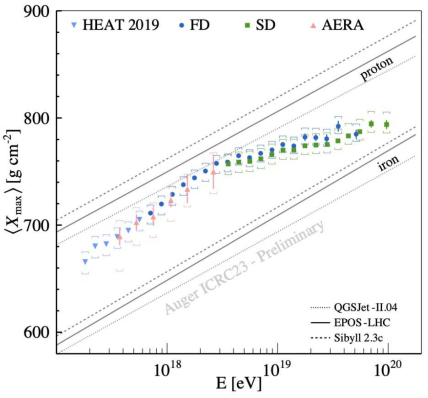


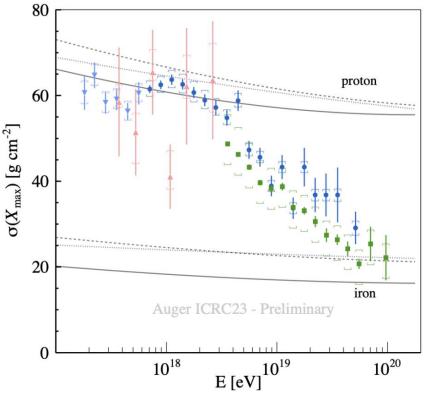


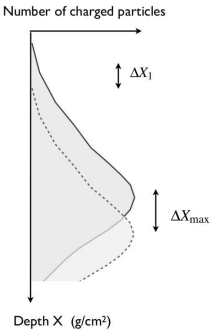


(Auger, Phys. Rev. D90 (2014), 122005 & 122005, ICRC 2023)

Composition (Xmax) including SD







$$\frac{\mathrm{d}P}{\mathrm{d}X_1} = \frac{1}{\lambda_{\mathrm{int}}} e^{-X_1/\lambda_{\mathrm{int}}}$$

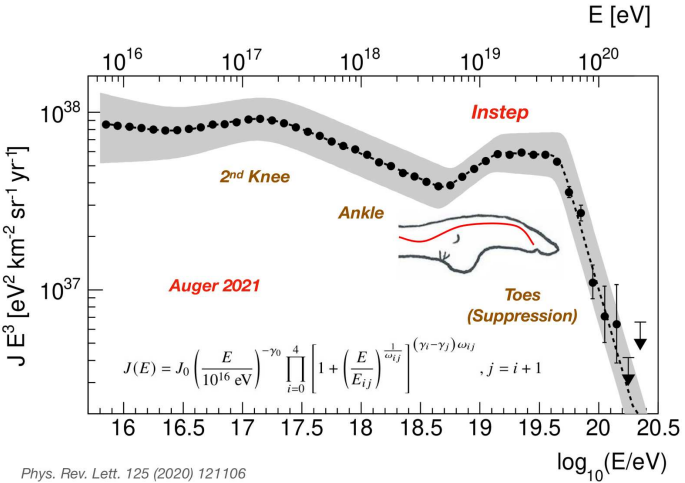
Important: LHC-tuned interaction models used for interpretation

$$\sigma_{X_1,\mathrm{p}} \sim 45 - 55\,\mathrm{g/cm^2}$$
$$\sigma_{X_1,\mathrm{Fe}} \sim 10\,\mathrm{g/cm^2}$$
$$(E \sim 10^{18}\,\mathrm{eV})$$

(FD telescopes: PRD 90 (2014), 122005 & 122005, updated ICRC 2023)
(SD risetime: Phys. Rev. D96 (2017), 122003)

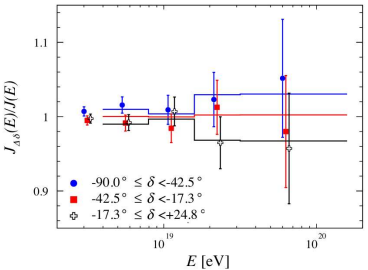
(AERA/radio: PRL & PRD 2023)
(SD DNN: ICRC 2023, to be published)

The Cosmic Ray Spectrum



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

Declination dependence of spectrum



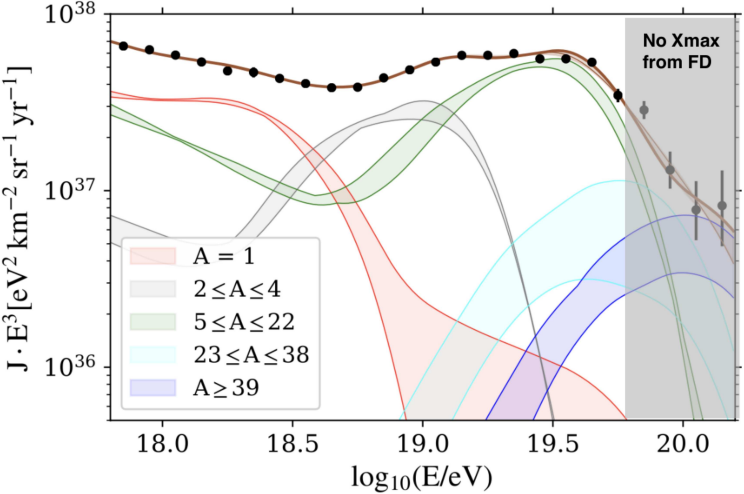
Lines: Expectation from observed dipole

Uncertainty dominated by 14% sys. energy scale

Instep not compatible with source models dominated by single mass group (p, …, Fe)

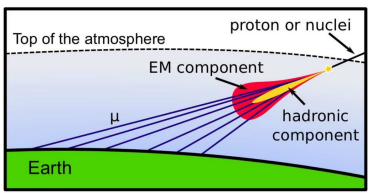
Example Fit to Spectrum with Composition

(Auger, JCAP 05 (2023) 024)

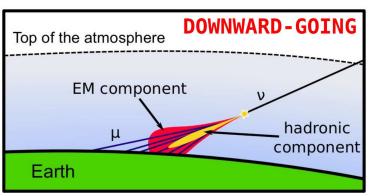


Source injection spectra universal in rigidity (scaling with charge Z)

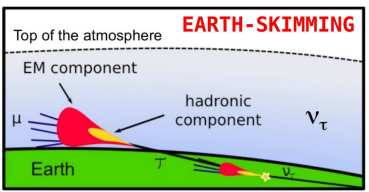
Neutrino Detection in a Surface Detector



Development of an extensive air shower cascade initiated by a hadronic primary.

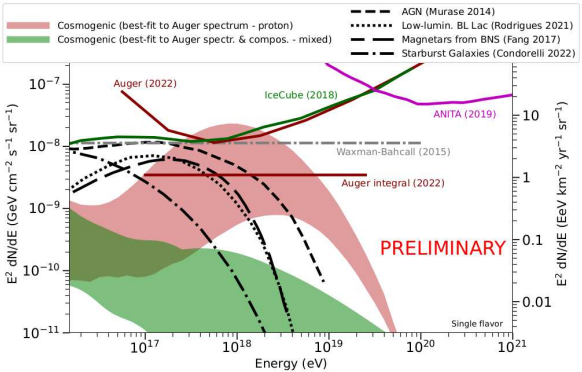


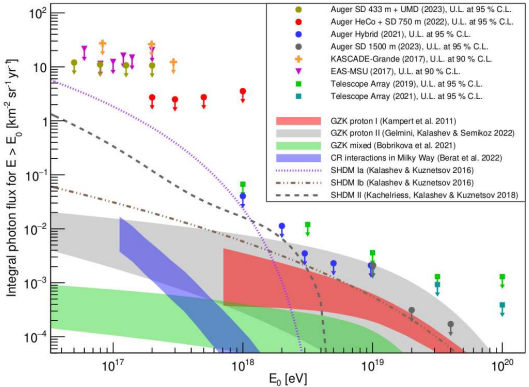
Development of an extensive air shower initiated by downward-going neutrino.



Development of an extensive air shower initiated by an earth-skimming τ neutrino.

Current Neutrino and Photon Limits (ICRC 2023)

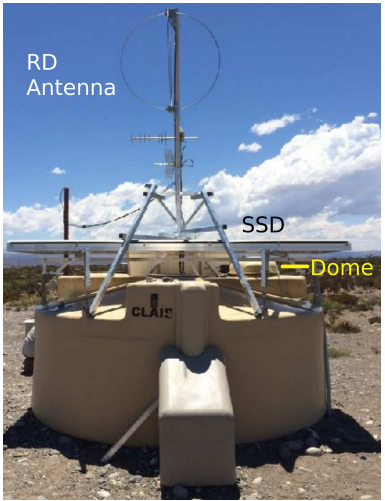




AugerPrime $\Longrightarrow$ Auger Phase 2

- Primary goals for Auger Phase 2
  - What is the nature and origin of UHECRs?
  - Purity of mass composition
  - UHE neutrinos and photons
  - New physics at the UHE frontier?
  - (Geophysics, UHE Test Facility,...)

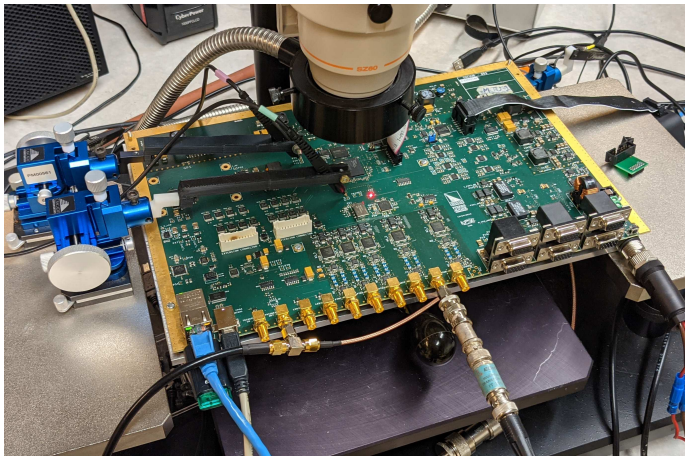
AugerPrime



The AugerPrime upgrade of the Auger Observatory Surface Detector contains

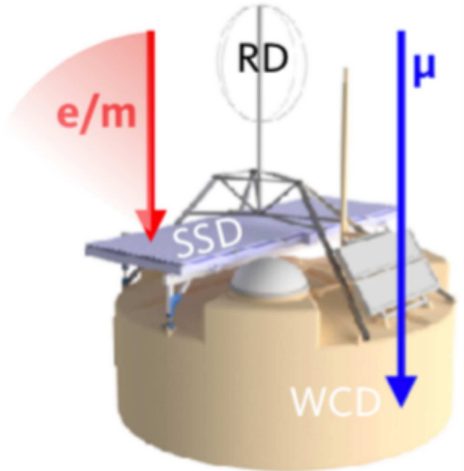
1. Scintillator-based Surface Detector (SSD) atop the Water Cherenkov Detector (WCD) (black annotation).
2. Radio Detector (RD) atop the Water Cherenkov Detector (WCD) (large circular antenna at highest point with white annotation).
3. New station electronics board (UUB). The UUB is hidden underneath the dome (yellow annotation) visible between the top of the WCD and bottom of the SSD on the right side of the top of the tank.
4. Addition of a 4th (smaller) PMT to increase the dynamic range
5. Underground muon detector in infill region (UMD)

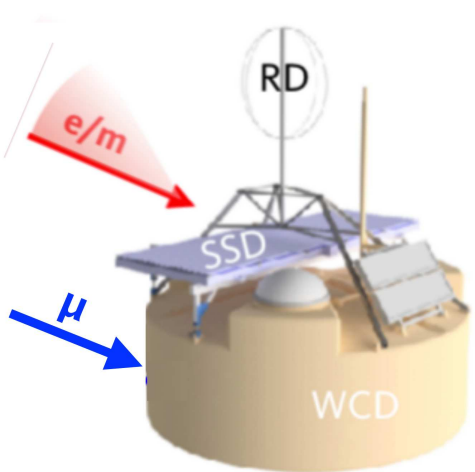
AugerPrime UUB



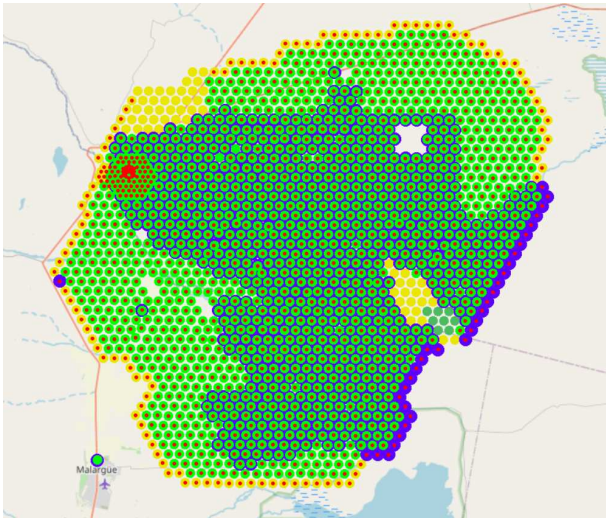
1. Faster ADC (40MHz $\Longrightarrow$ 120 MHz)
2. More dynamic range (10 bits $\Longrightarrow$ 12 bits, additional small PMT)
3. Additional channels for SSD, SPMT, RD
4. More powerful processor and FPGA (Resources to implement targeted triggers)

SSD and RD Complementarity



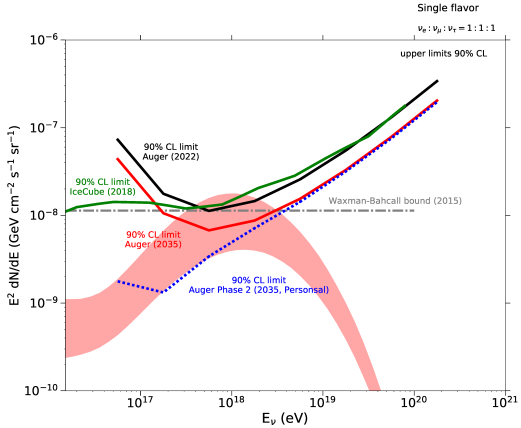


Status of AugerPrime Deployment (21-Feb-2024)

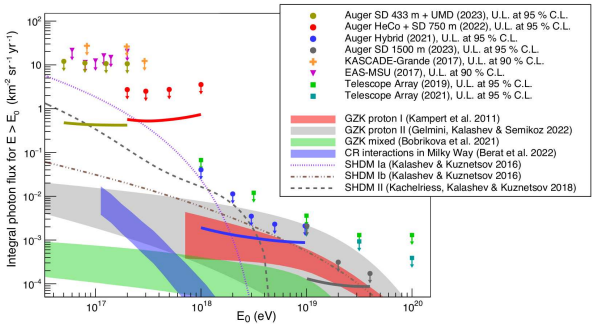


- stations with a UUB installed (+SSD-PMT and SPMT)
- stations with a SSD
- stations with a RD antenna

Anticipated ν and γ Limits in Phase 2



Simplified ν limit slide with future outlook. Red: expected limits in 2035 due just to more running time. Blue: Personal estimate, based on work in progress, of limits when AugerPrime enhancements are fully leveraged.



Solid lines: Estimated limits after 10 years of running Auger Phase 2.

Take Away

- Successful Phase 1 operation completed
  - Established clear evidence for complex composition
  - Dipole anisotropy established
  - More than 100 papers published
- Phase 2 operation starting 2025
  - Even better composition determination
    - Event by event composition measures
  - Improved UHE ν and γ detection limits (or possibly detection)