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AugerPrime Status and Prospects for the next decade

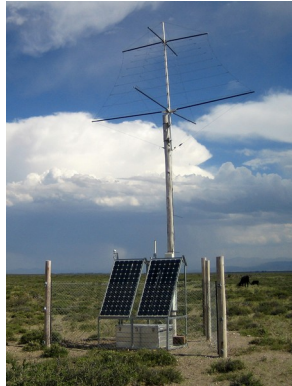


Martin Schimassek
for the Pierre Auger Collaboration

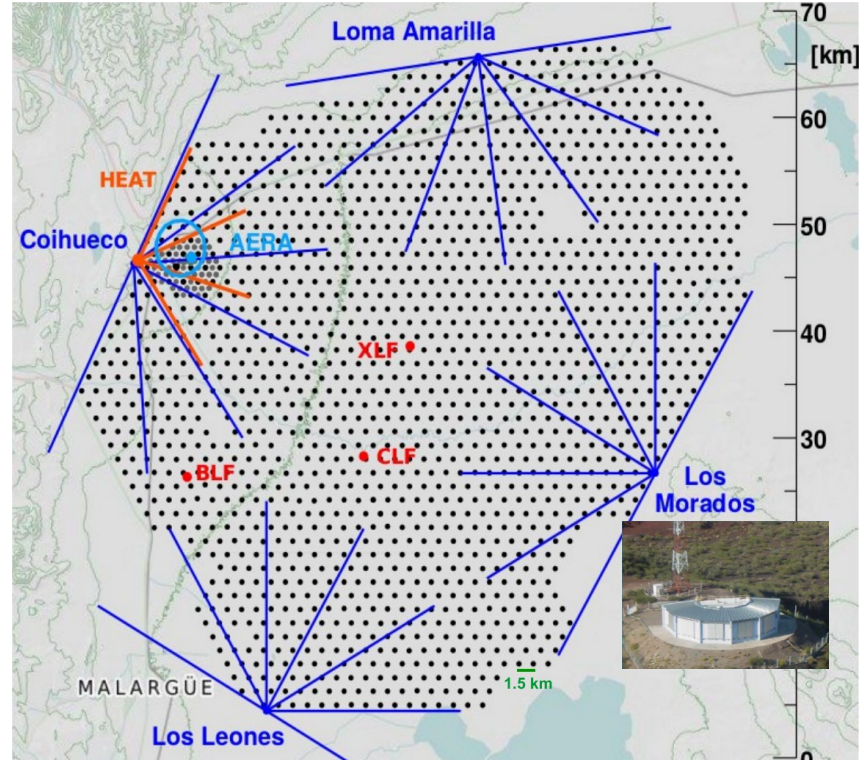


The Pierre Auger Observatory

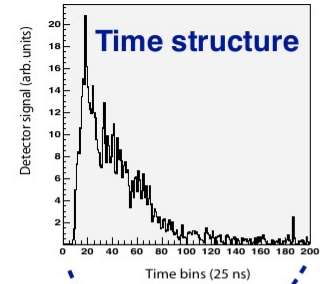
- largest cosmic-ray observatory in the world, operating since 2004



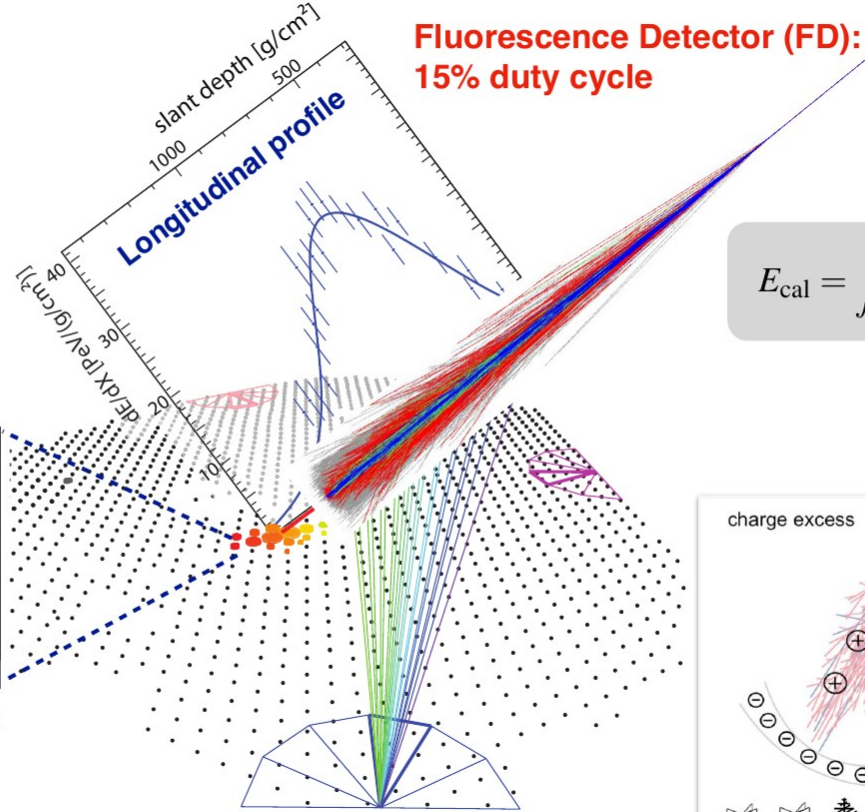
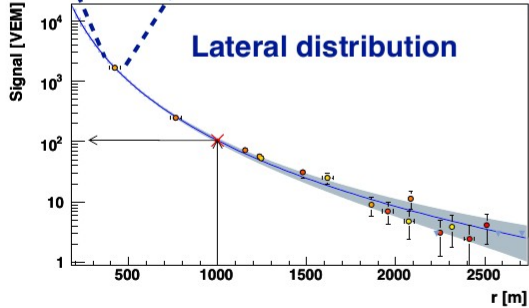
Pierre Auger Observatory
Province Mendoza, Argentina



Measurement Principle



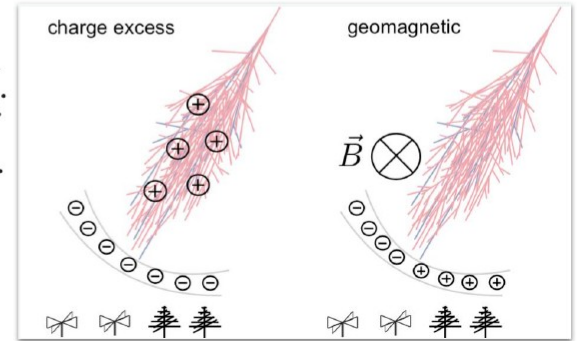
$$E_{\text{rec}} = f(S_{1000}, \theta)$$



**Fluorescence Detector (FD):
15% duty cycle**

$$E_{\text{cal}} = \int_0^{\infty} \left(\frac{dE}{dX} \right)_{\text{obs}} dX$$

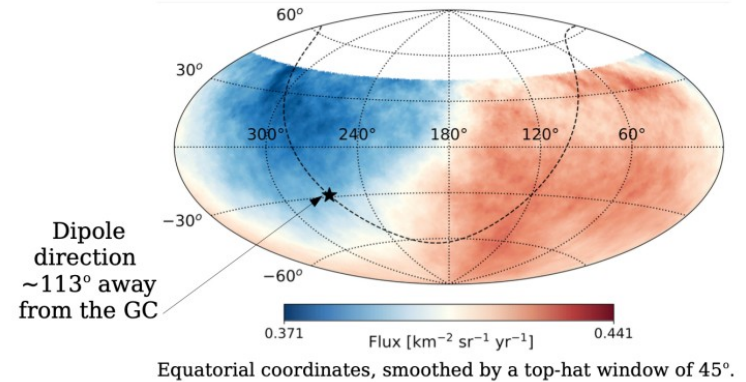
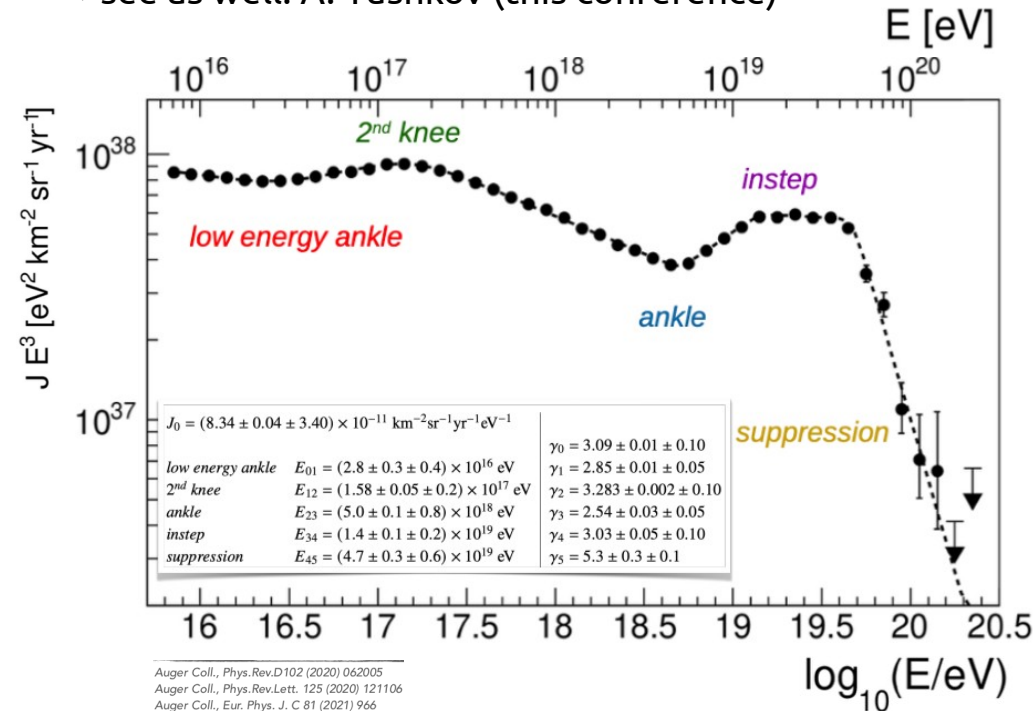
**Radio Detector (RD):
100% duty cycle**



**Surface Detector (SD)
100% duty cycle**

Results of Phase I

- largest ever exposure of >80 000 km² x sr x yr: spectrum over 4 decades in energy
- first >5sigma anisotropy result (dipole)
- see as well: A. Yushkov (this conference)



Auger Coll., *Science* 357 (2017) 1266
 Auger Coll., *Astrophys. J.* 868 (2018) 4
 G.Golup, *PoS(ICRC2023)* 252, *subm.ApJ*

Auger Coll., *Phys.Rev.D*102 (2020) 062005
 Auger Coll., *Phys.Rev.Lett.* 125 (2020) 121106
 Auger Coll., *Eur. Phys. J. C* 81 (2021) 966
 V.Novotny, *PoS(ICRC2021)* 324
 A.Brighetto, *PoS(ICRC2023)* 398

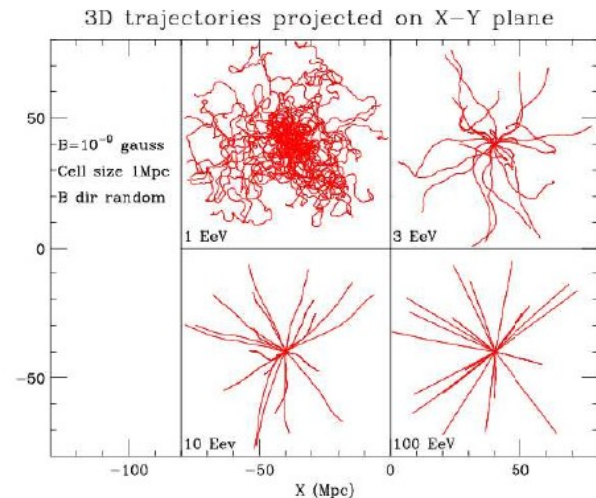
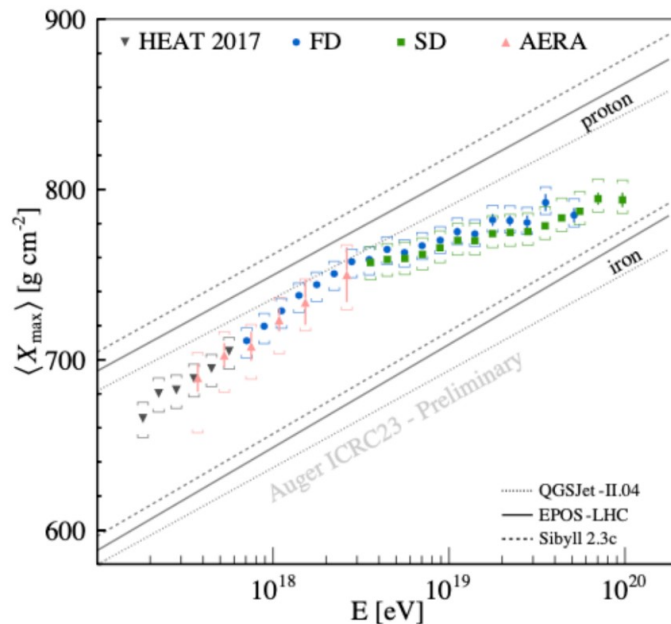
Motivation of AugerPrime

- cosmic-ray mass composition increasingly heavy (and mixed) with higher energies
→ selecting high rigidity events

- goals: event-by-event handle a mass-composition
→ particle astronomy?

- high resolution mass composition measurement to the highest energies

- insights into hadronic interactions
→ enable reanalysis of Phase I data

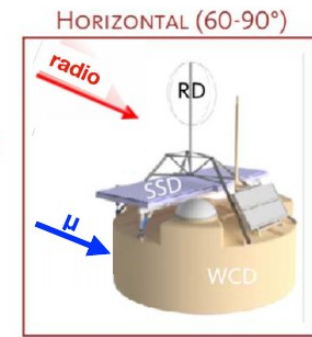
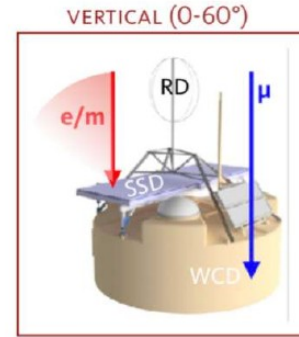


J. Cronin arXiv:astro-ph/0402487

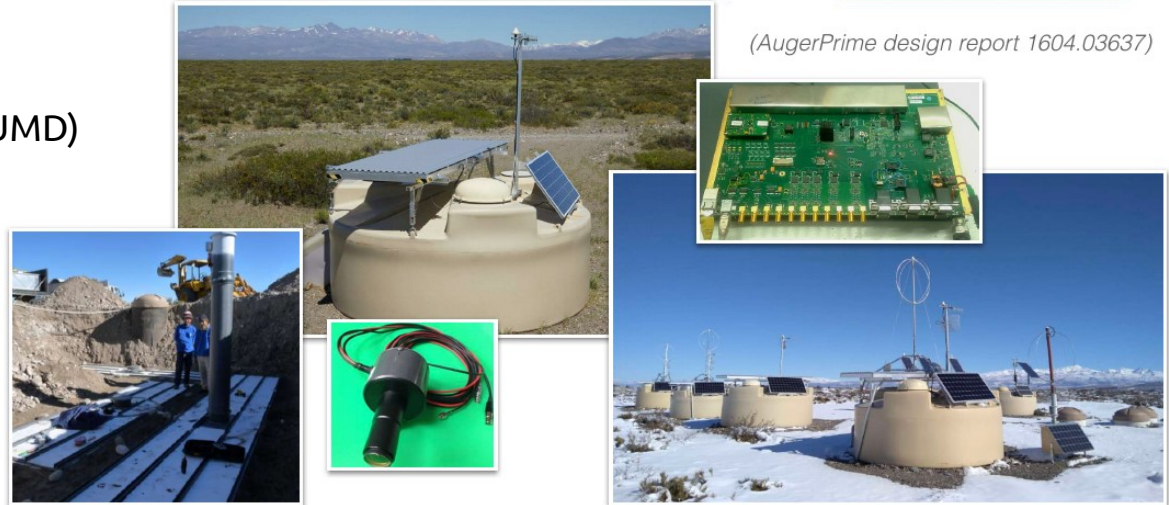
Introduction: AugerPrime

- New hardware:
 - additional scintillators (SSD)
 - a small PMT (sPMT)
 - radio antennas (RD)
 - underground muon counters (UMD)
 - new electronics

**Composition sensitivity
with 100% duty cycle**



(AugerPrime design report 1604.03637)

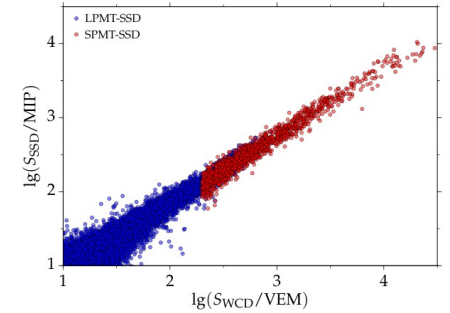
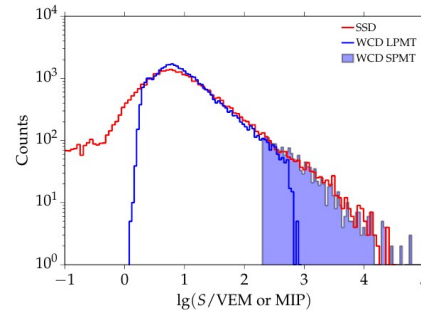
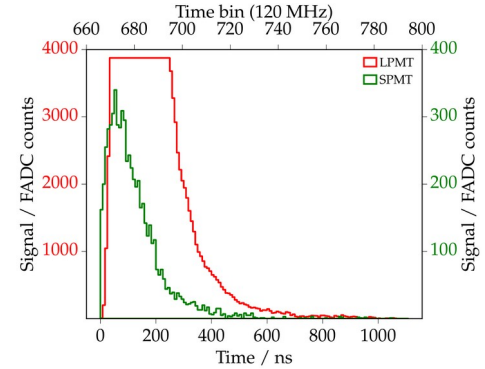
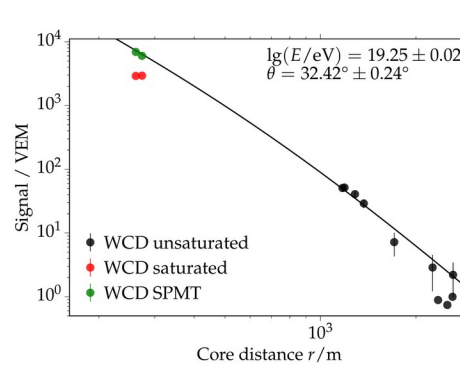
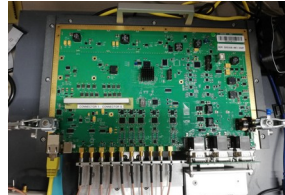


AugerPrime: Upgraded WCD

- upgraded WCD: higher dynamic range + higher bandwidth electronics, more CPU-power

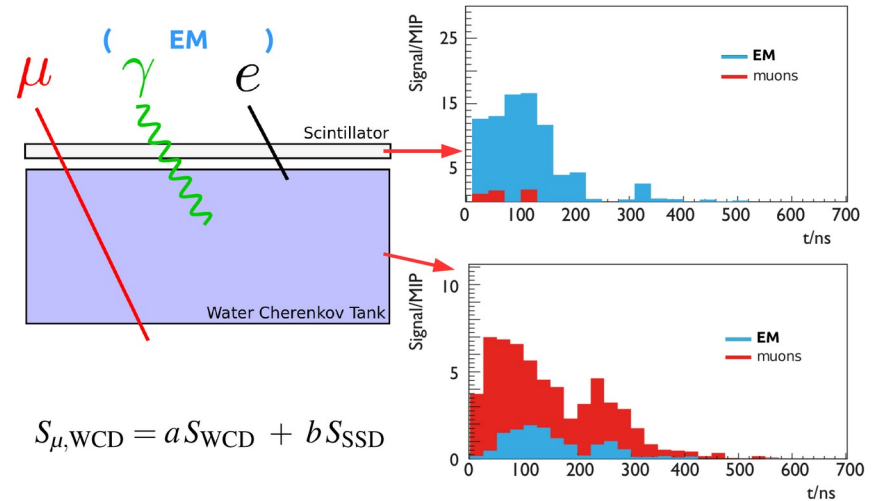
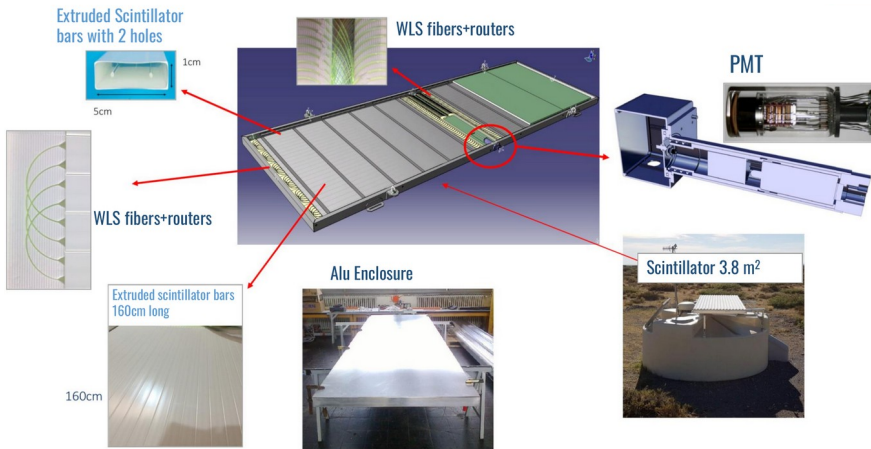
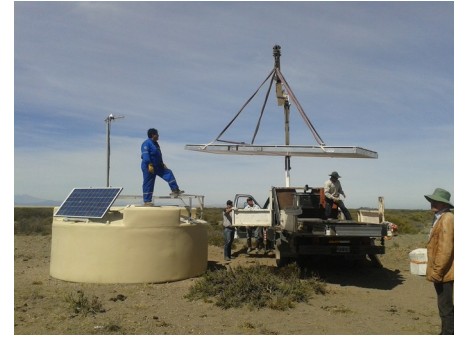


+



AugerPrime: SSD

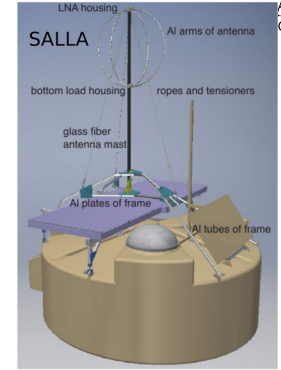
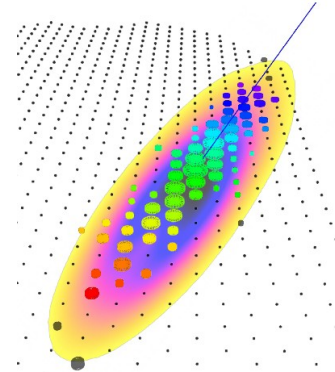
- add 3.8 m² Scintillator (SSD) on top of the existing SD-station
- different response to EM / muons allows estimation of mass on event-by-event basis



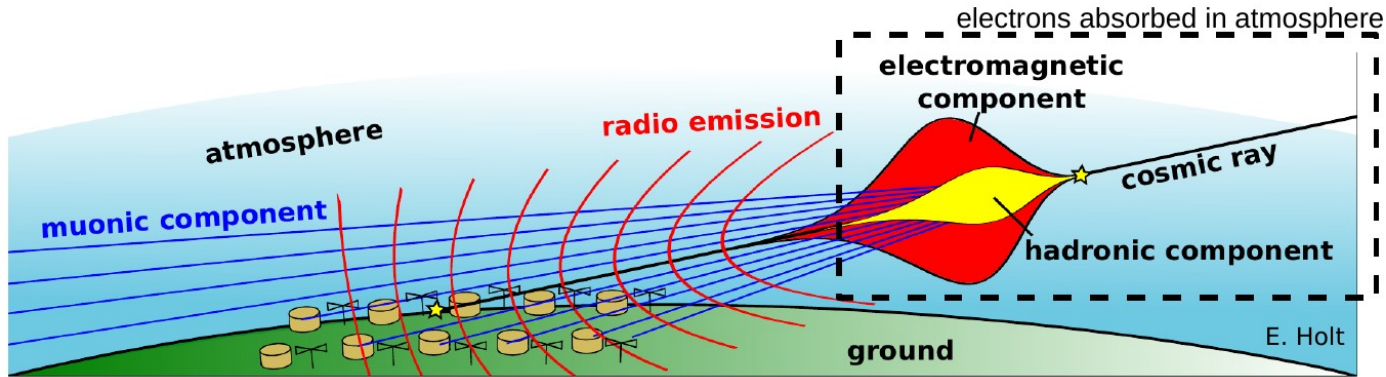
$$S_{\mu, \text{WCD}} = a S_{\text{WCD}} + b S_{\text{SSD}}$$

AugerPrime: RD

- deploy SALLA antennas on every SD-station
- measurement possible for very inclined showers
- extinction of EM-component allows muon-measurement
With the SD → EM + muons with RD + WCD

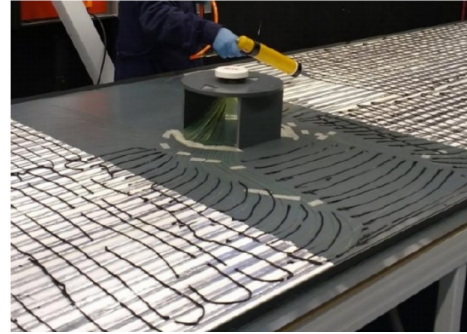
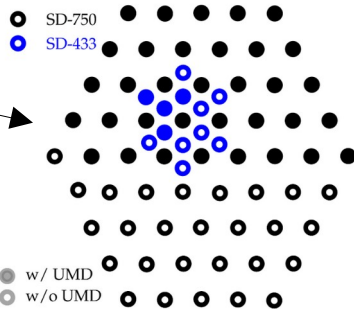
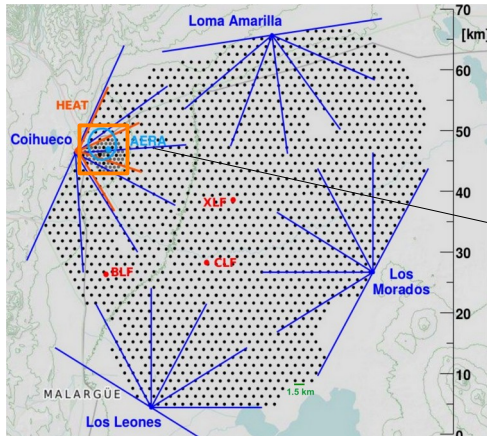


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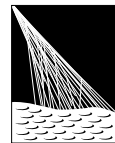


AugerPrime: UMD

- in infilled region (750 m / 433 m spacing): deploy under ground muon detectors
- 30 m² of scintillators buried 2.3 m
→ shield EM-components
- direct measurement of muon component at
~ 10¹⁸ eV

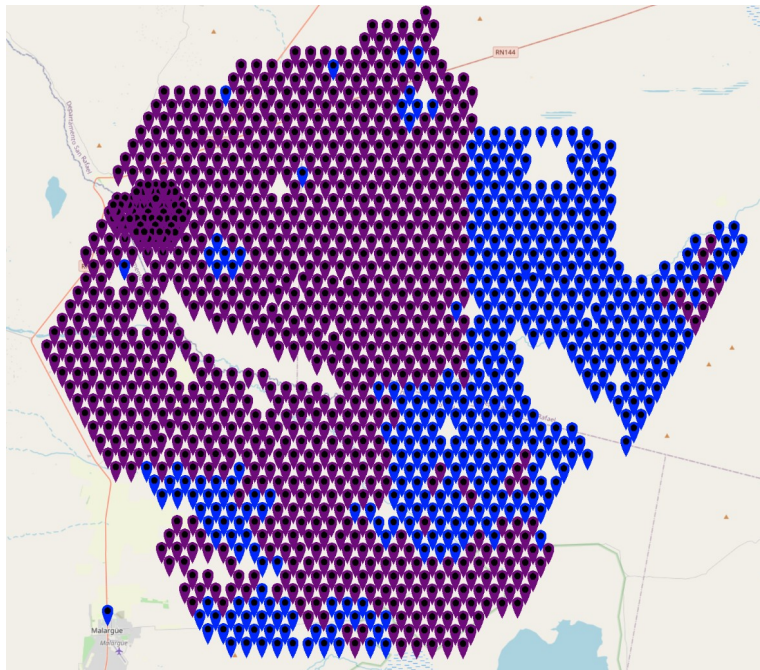
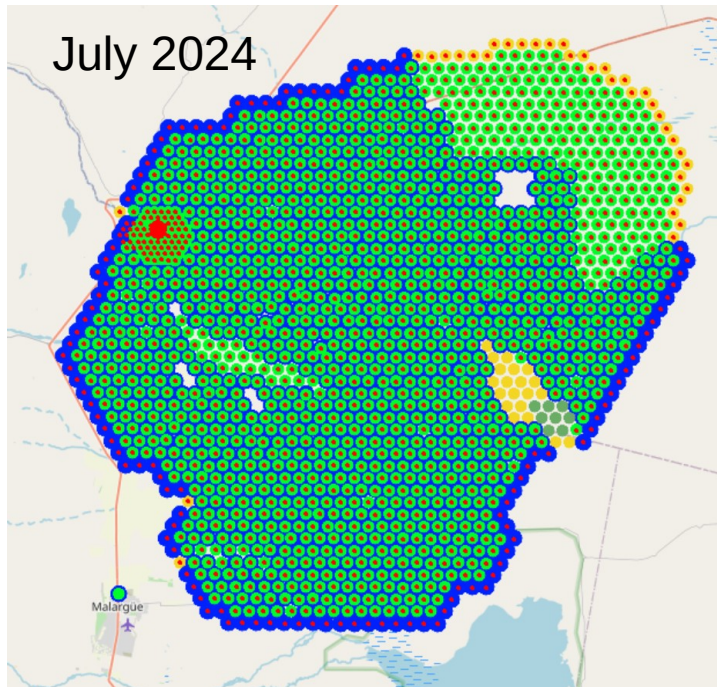


AugerPrime: Deployment Status



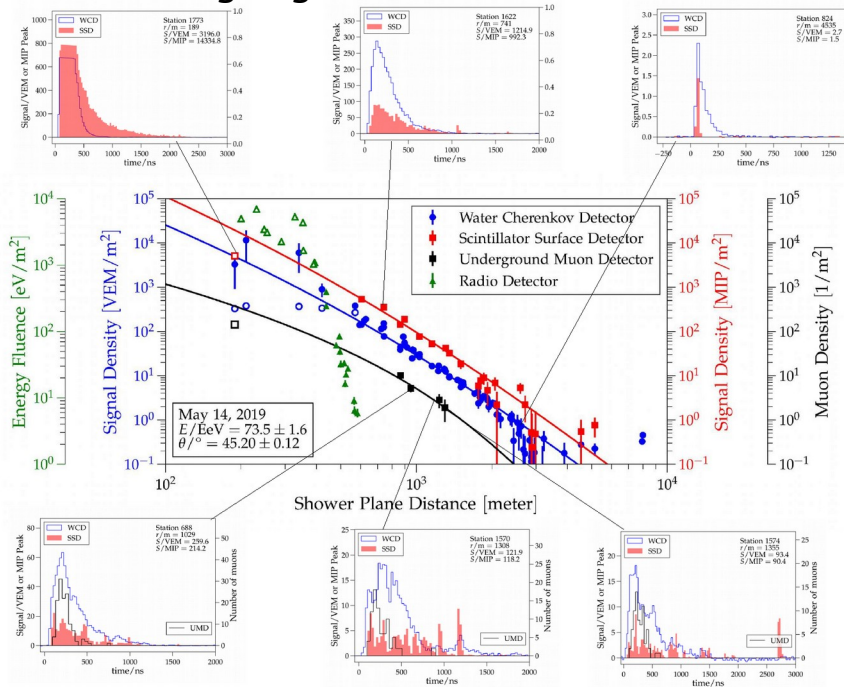
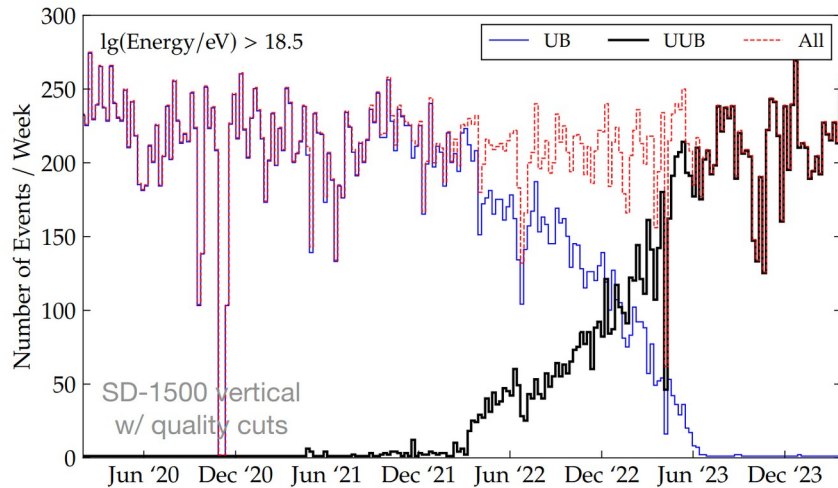
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- SSD (green) and electronics (red dot): deployment where accessible finished July 2023
- RD-deployment in two steps: antenna-hardware (blue) and electronics (purple)

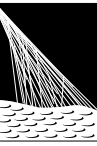


Commissioning Status

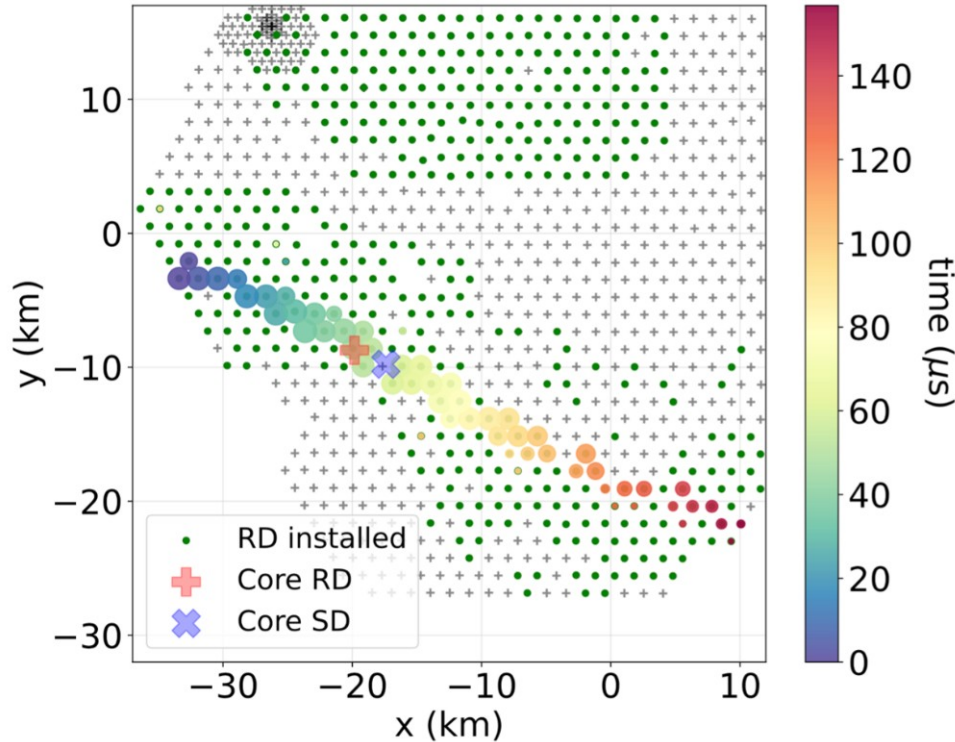
- data collection with AugerPrime for commissioning started with deployment
- currently last steps in commissioning the new components are on-going
- physics data taking to commence at latest beginning 2025



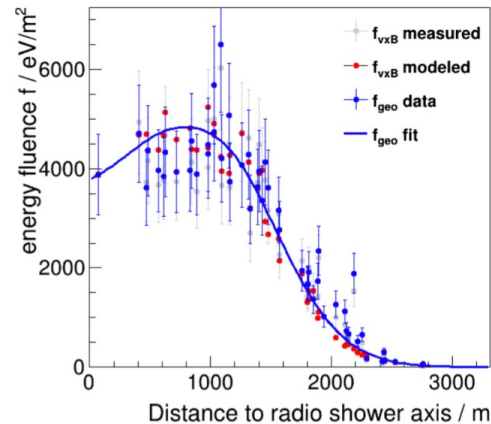
A first glimpse: RD-data



- also RD-data taking is on-going: first events for commissioning are there

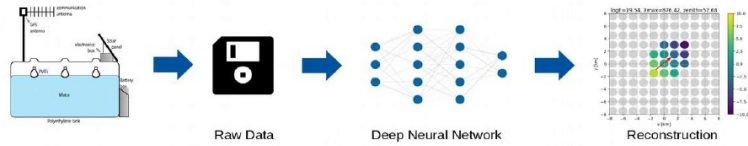


Event at 84.7 degree
 $36 \pm 3 \text{ EeV}$



Prospects

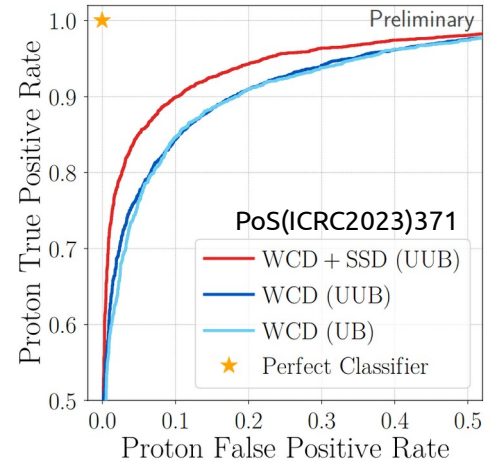
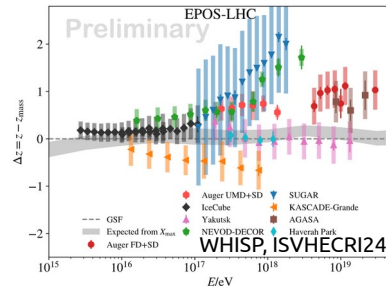
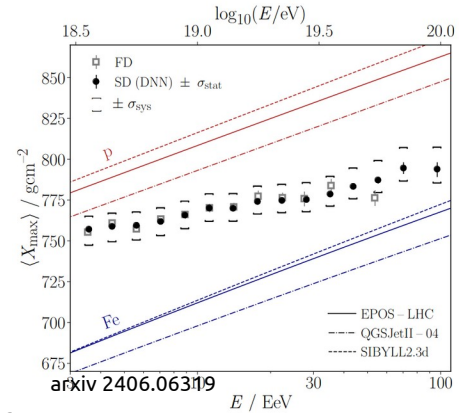
- Deep learning applications can profit from additional data:
Phase I: depth of shower maximum from WCD alone



- Phase II: more information available → better reconstructions possible

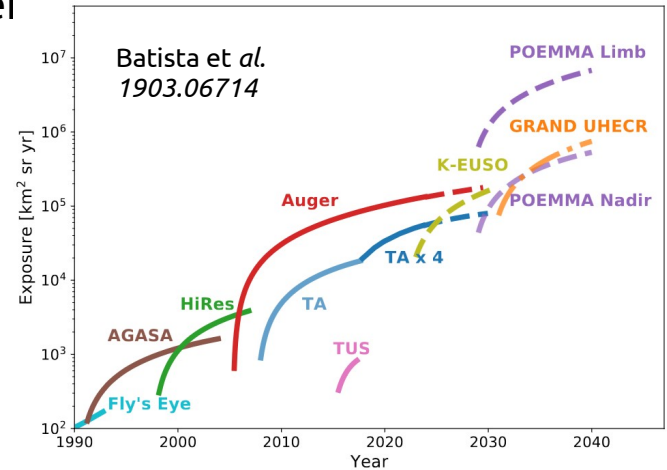
→ e.g. training directly on mass composition rather than X_{\max}

→ better control of systematics: compare with non-DL methods (muon deficit)



Summary

- AugerPrime: continue and enhance the successful operation of the Pierre Auger Observatory > 2030
- new possibilities of primary mass measurements at ultra-high energies
- deployment almost finished for all new detector components
- AugerPrime will remain the largest observatory for the next decade: now with mass sensitivity!



Back Up

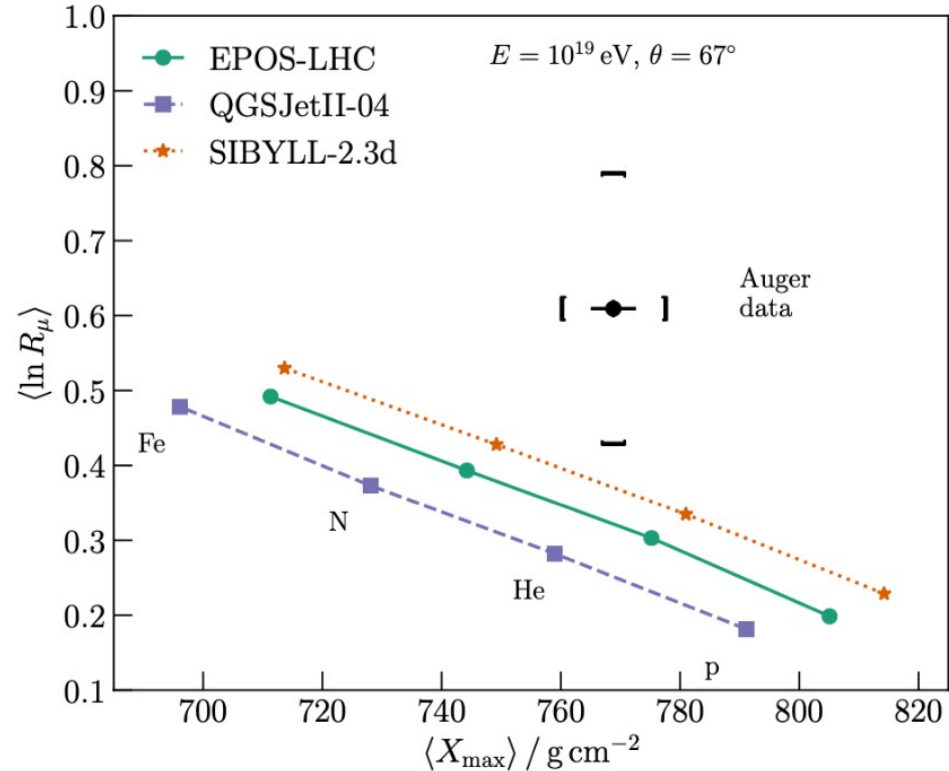


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Hadronic Interactions



- rely on simulations for interpretation of air-shower measurements
- need high-energy hadronic interaction models
- tests of these models:
 - Should describe Energy, X_{\max} , and number of muons at the same time
- use hybrid measurements: FD → E, X_{\max}
SD → muons
- see as well: J. Vicha (this conference)



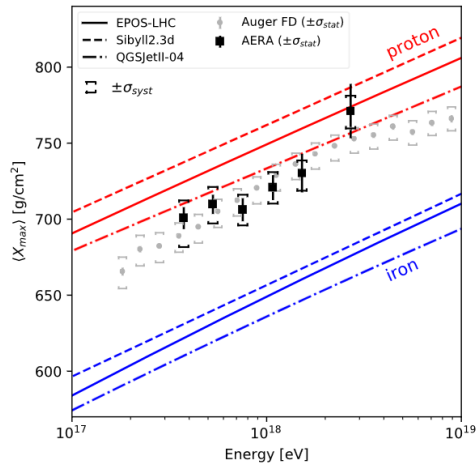
Auger Coll., PRD91 (2015) 032003+059901

AugerPrime: RD



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- existing radio detector (since 2010)
Auger Engineering Radio Array (AERA)
- 153 stations, 17 km²
- demonstration of measurements: basis for AugerPrime RD



PRD 109, 022002 (2024)

