AugerPrime,the upgrade of the Pierre Auger Observatory: current status and data taking

Parallel Session #6 "High Energy Astrophysics and Cosmic Rays"

TAUP 2025 – Wednesday August, 27th 2025

TAUP 2025

19TH INTERNATIONAL CONFERENCE ON TOPICS IN ASTROPARTICLE AND UNDERGROUND PHYSICS

TAUP XICHANG

PIERRE AUGER OBSERVATORY

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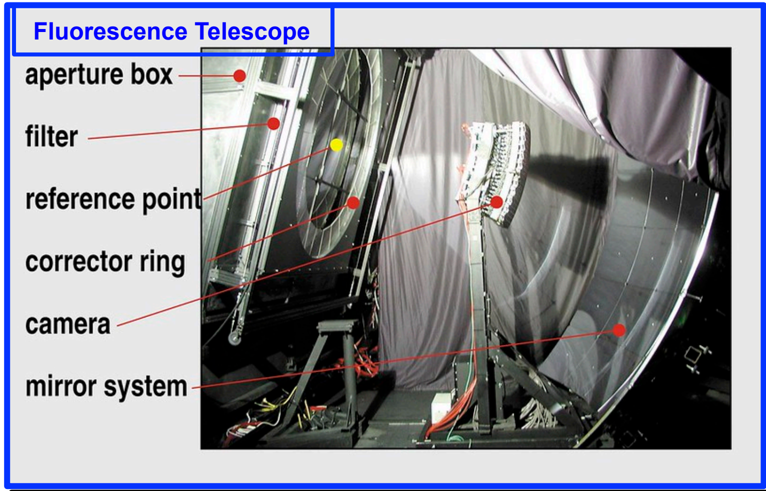
Uni ct FISICA E ASTRONC "ETTORE MAJORA

INFN CATANIA

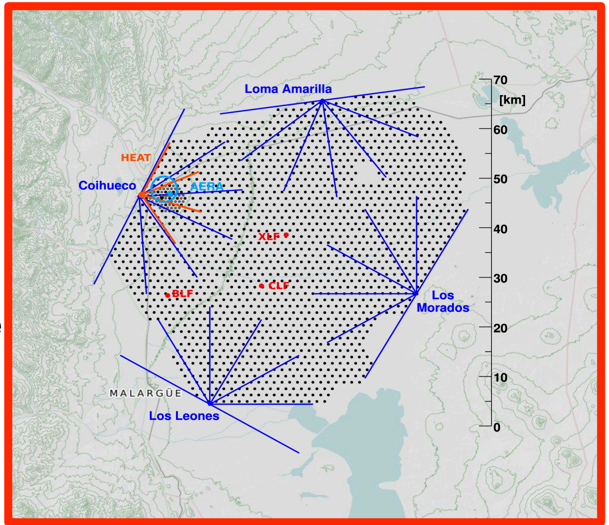
The Pierre Auger Observatory (http://www.auger.org)

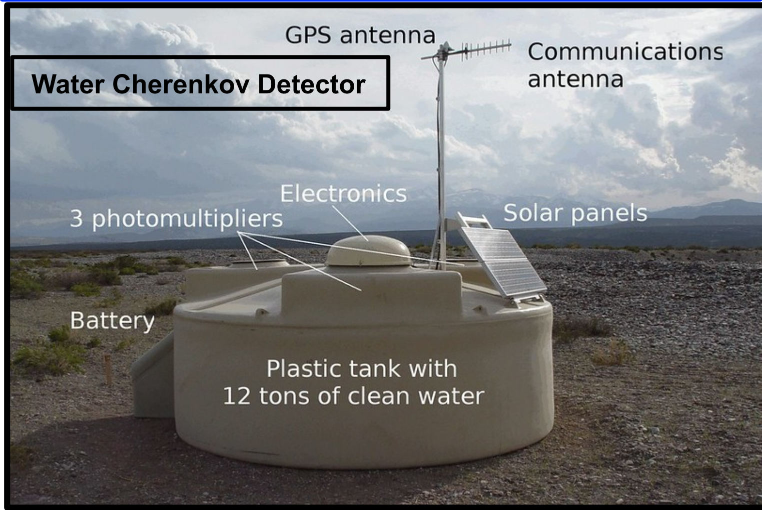
MAIN DETECTORS:

- FD (Fluorescence Detector):
  - 24 fluorescence telescopes (6/ site), (2÷30)° F.o.V in elevation,;
  - 3 fluorescence telescopes in Coihueco site, (30÷60)° F.o.V
- SD (Surface Detector): 1660 water-Cherenkov detectors (WCDs):
  - 1.5 km spacing (SD-1500)
  - 20 km^2, 750 m spacing (SD-750)
  - 3 km^2, 433 m spacing (SD-433)



- Area ≃ 3000 km^2
- 35.2° S lat, 69.5°W long
- ~1400 m a.s.l., <X> = 875 g/cm^2
- exposure > 10^5 km^2 sr yr
- low population density:0.1/ km^2
- special climate (dry atmosphere clear sky, low light pollution)

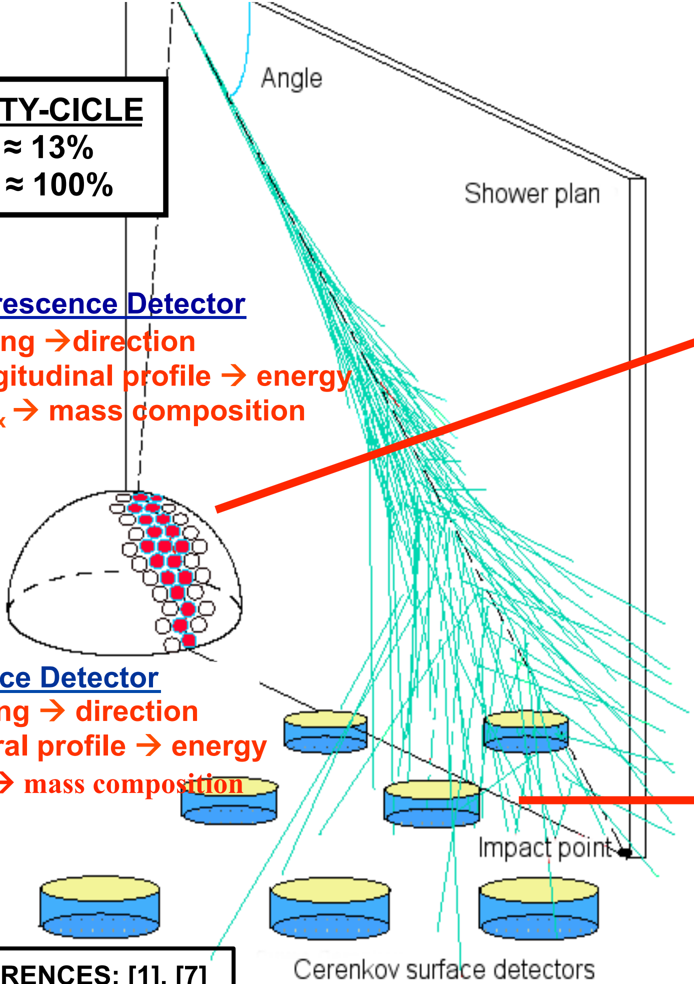




REFERENCES:
[1], [2], [3], [4], [5], [6]

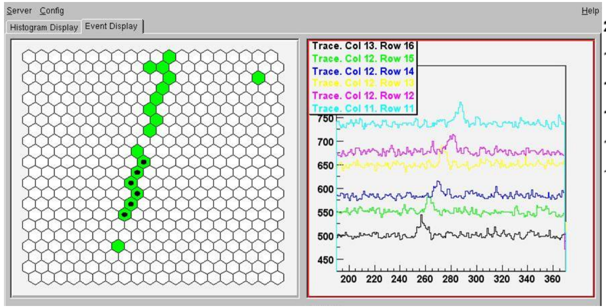
The Hybrid technique

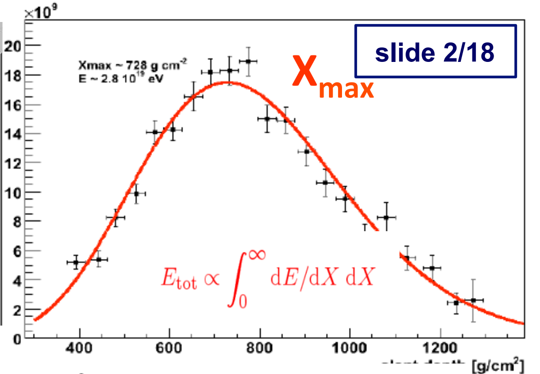
DUTY-CICLE
FD ≈ 13%
SD ≈ 100%

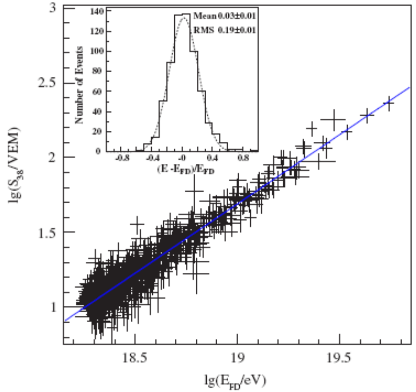


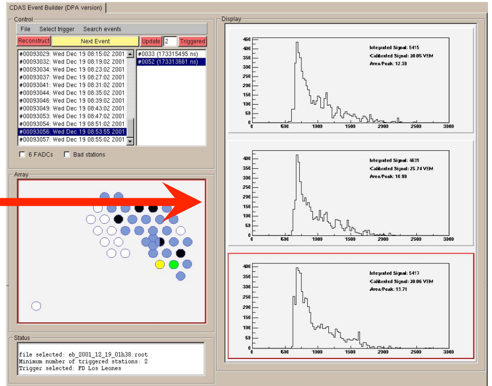
Fluorescence Detector
- timing → direction
- longitudinal profile → energy
- X_{max} → mass composition

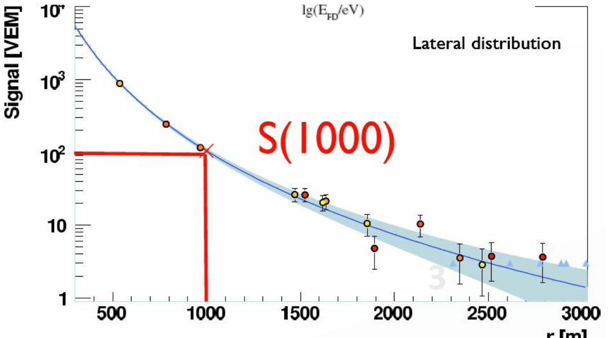
Surface Detector
- timing → direction
- lateral profile → energy
- μ/e → mass composition





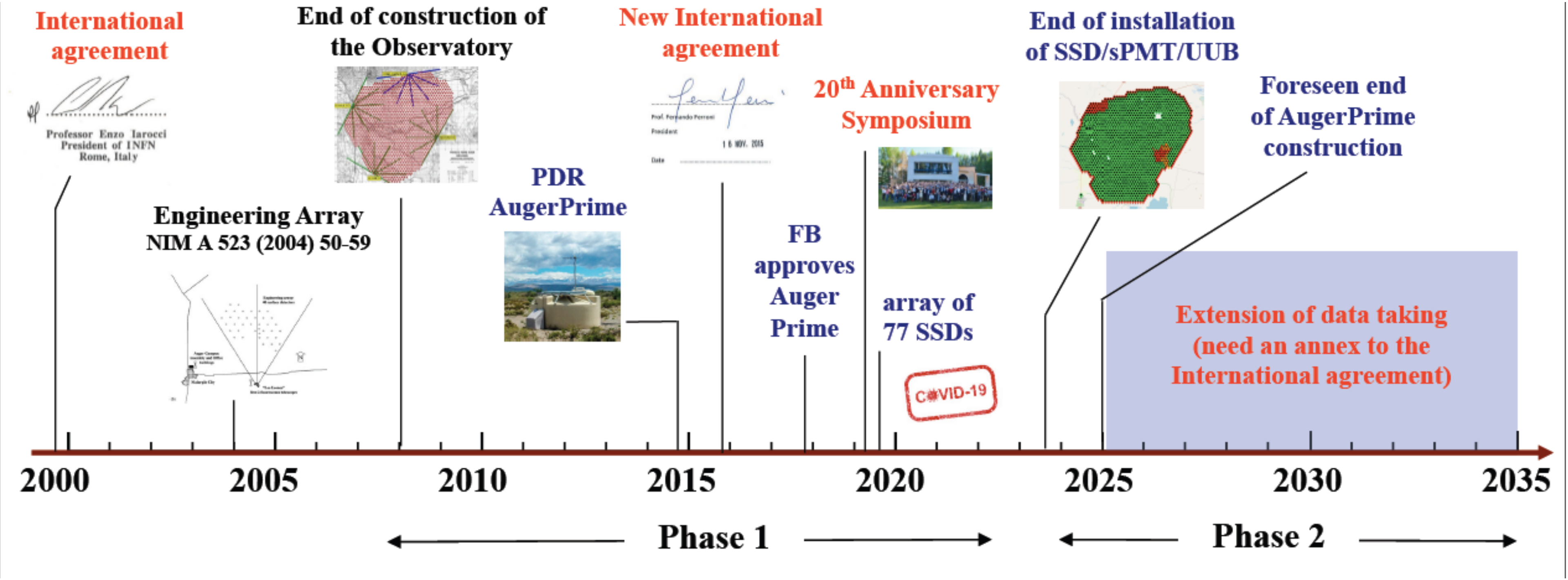






REFERENCES: [1], [7]

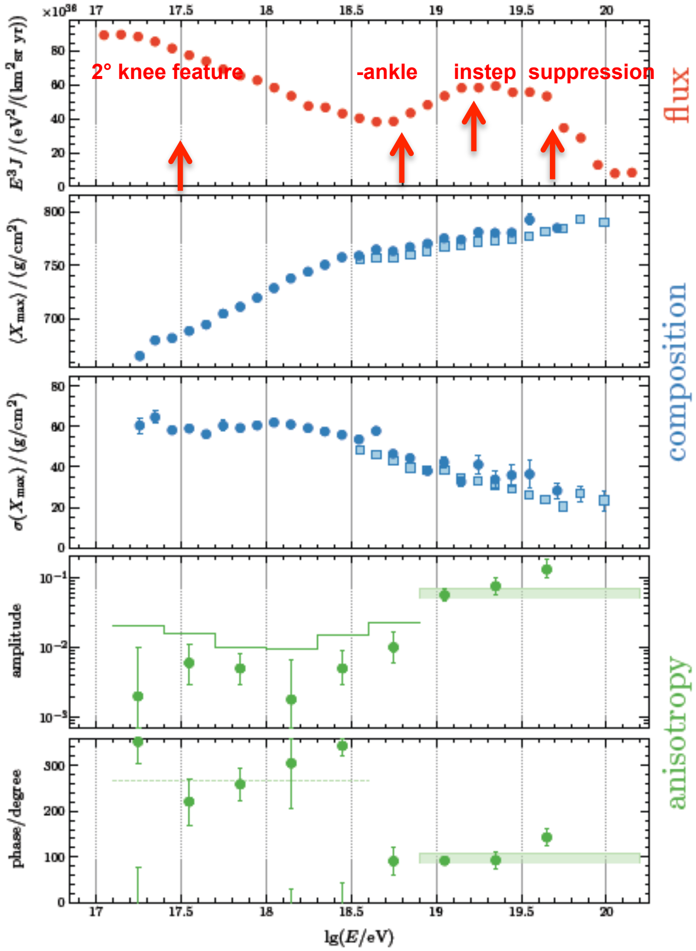
The Times's Arrow of the Pierre Auger Observatory



- **Engeneering Phase (1999-2002)** = installation of 27 water-Cherenkov detectors + 1 fluorescence telescope (**1999-2002**);
- **Preliminary Phase (2002-2004)**= first stage of the Observatory under construction (**2002-2004**);

- <u>Phase I (2004-2021)</u>= data taking period prior the Upgrade (AugerPrime) of the Observatory (**A≈ 1.2x10^5 km^2 sr yr = 15.6 years**);
- **Commissioning Phase(2022-2023) =** ongoing commissioning phase of the upgraded detectors;
- <u>Phase II (2024-2035)</u> = data taking period with the Upgrade of the Observatory (AugerPrime)

Summary of main scientific results - PHASE1 - Pierre Auger Observatory



main OBSERVABLES: → INFORMATION>10^{17}eV:

1) Energy Spectrum → **source energetics**

REFERENCES:
[8], [9], [10], [11]

2) Longitudinal profiles of air showers: mean (above) & fluctuations (below) of the depth of the shower maximum X_{max} → **elemental abundances in source environments**

REFERENCES:
[12], [13], [14], [15], [16]

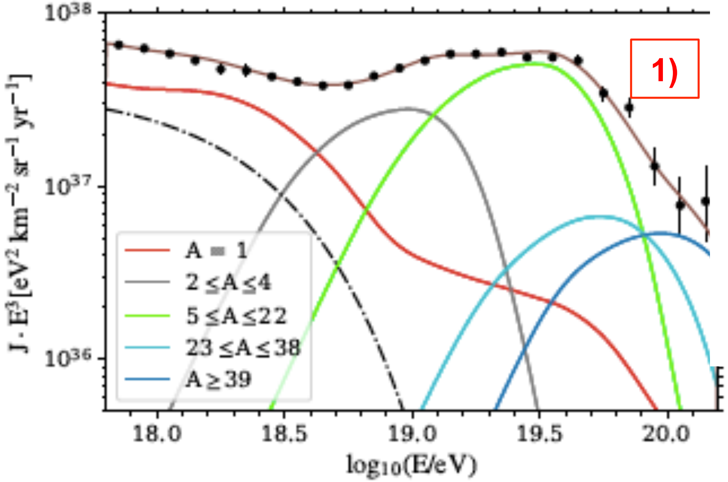
3) Large-scale anisotropy contrasts in right ascension: amplitude (above) & phase (below) → **hot sky regions**

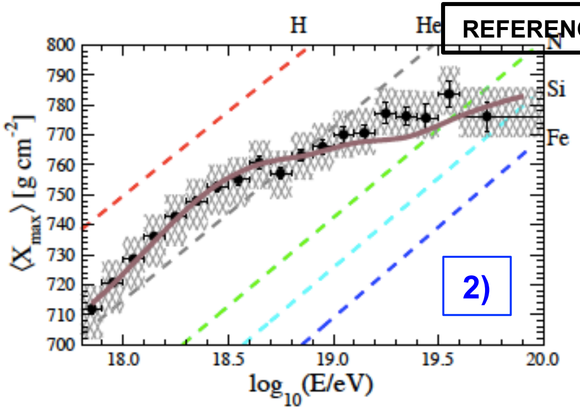
REFERENCES:
[17], [18], [19], [20]

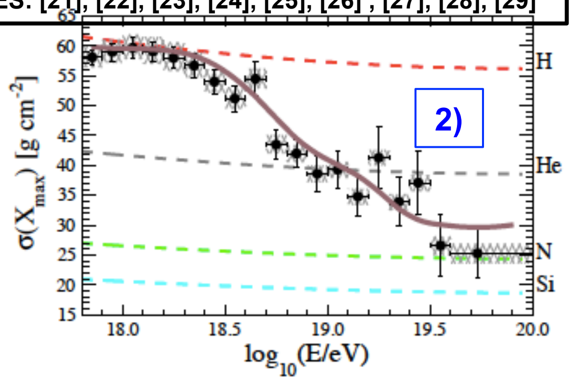
Significant changes in each observable in a common energy range (a few EeV) suggesting that (at least) two different underlying emission phenomena are at play!

Resulting Astrophysical Scenario – PHASE1 Pierre Auger Observatory

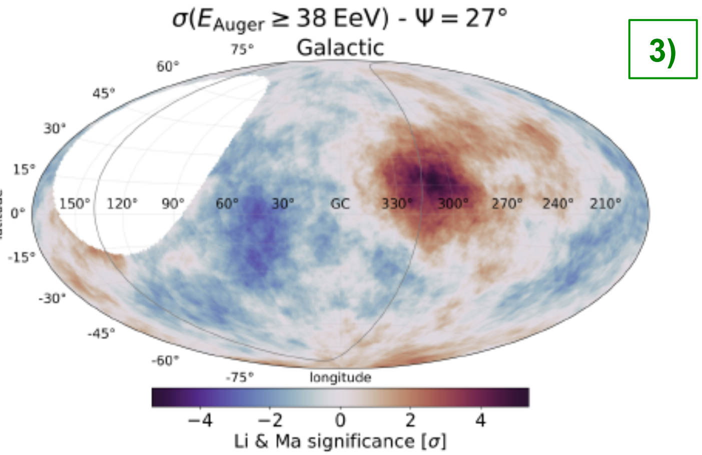
REFERENCES: [21], [22], [23], [24], [25], [26] , [27], [28], [29]







1) Energy Spectrum + 2) Mass Composition + 3) Anisotropy



New Paradigma of the UHECRs scenario (not pure-proton)!

- at Earth, the steepening above ≅ 5×10^{19} eV reflects the combined effects of the maximum energy (E_{max}) acceleration of the heaviest nuclei at the sources and the GZK effect;

- several nuclear components contribute to the total intensity > the ankle energy;
- abundance of nuclear elements at the sources is dominated by intermediate -mass (He-Si) nuclei accelerated to E_{max} = 5 EeV Z;

- some evidence of anisotropies >≅ 3.8×10^{19}eV that mirror the inhomogeneous distribution of nearby extra-galactic matter;
- the signal strength of correlation is < 10-15% in the case of Starburst Galaxies.

AugerPrime Science Case

OPEN QUESTIONS:

- What is the nature and the origin of the UHECRs?
- What is the origin of the observed flux suppression?
- Do UHE neutrinos and photons exist?
- What is the origin of the "muon puzzle"? Are there unexpected features of hadronic interactions at the highest energies?
- Is physics Beyond Standard Model (BSM) hiding at the energy frontier?

The AUGERPRIME makings in Phase 2:

Composition sensitive information, on event-by-event basis, plus overall data-quality improvement

- perform power data analysis based on new, multi-hybrid measurements;
- improve our understanding of already data taken;
- increase statistical sensitivity on ongoing searches;
- constrain production on UHE photons and neutrinos
- train, verify, apply modern Machine Learning techniques

Ultimate goals: discovery of UHECRs'sources & study of Particle Physics at energies beyond the human-made accelerators. **The AugerPrime is the only UHECR detector that allow us this before at least 2035!**

AUGERPRIME: the Upgrade of the Pierre Auger Observatory
A Multi-Hybrid complementary system

REFERENCES: [30], [31], [32], [33]

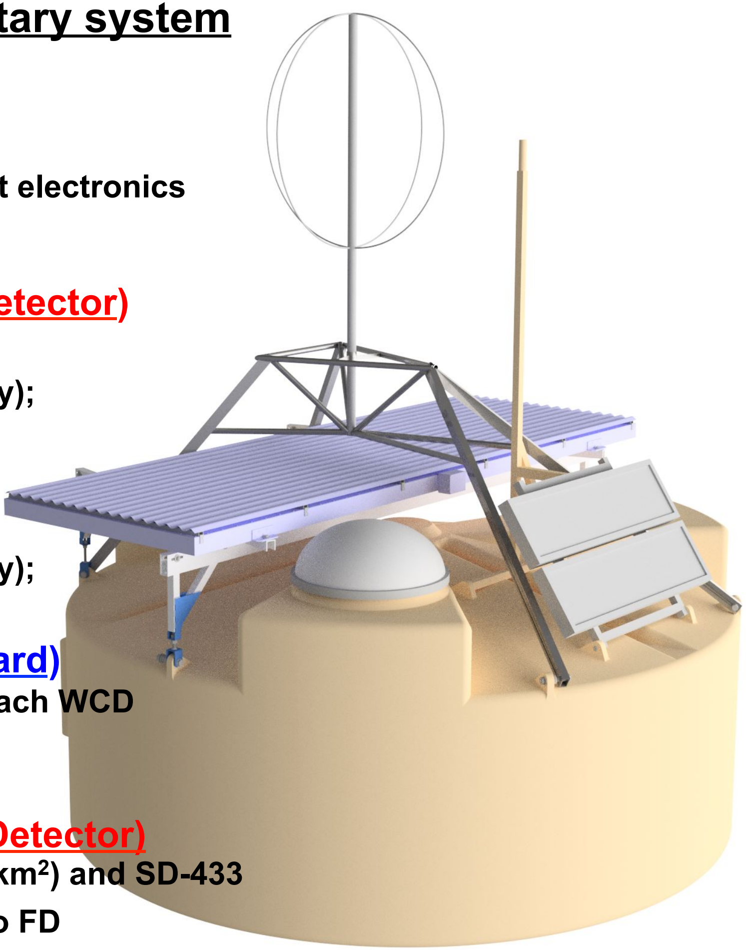
- **RD (Radio Detector)**
  a radio antenna and its read-out electronics
  on top of each WCD

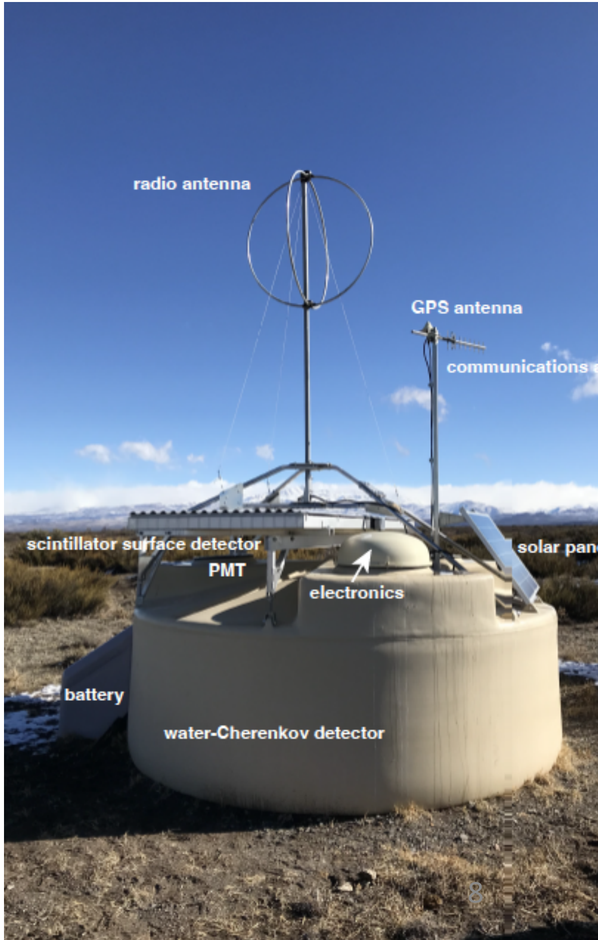
- **SSD (Scintillator Surface Detector)**
  mounted on top of each WCD
  (excluding outer ring of the SD Array);

- **sPMT (smallPMT)**
  a small added PMT for each WCD
  (excluding outer ring of the SD Array);

- **UUB (Upgraded Unified Board)**
  upgraded read-out electronics for each WCD

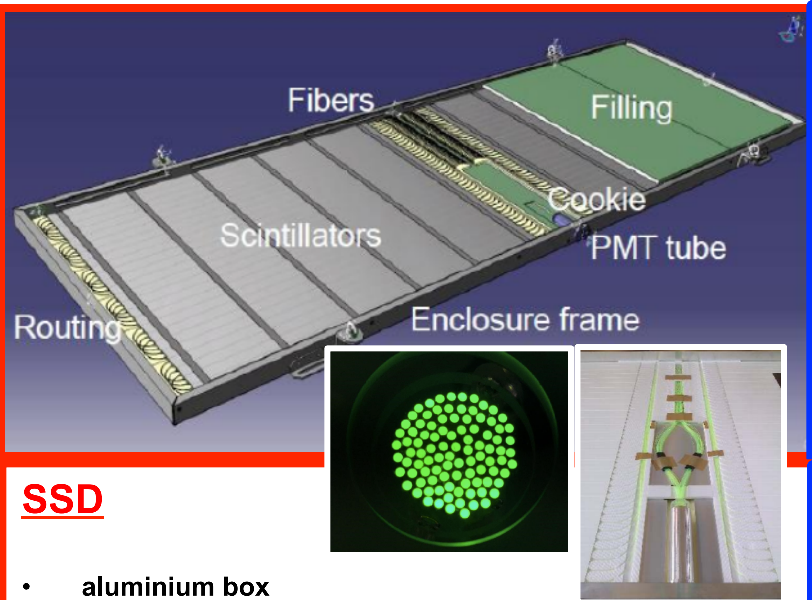
- **UMD (Underground Muon Detector)**
  μ detectors buried in SD-750 (23.5 km^2) and SD-433
  infilled arrays, nearby the Coihueco FD

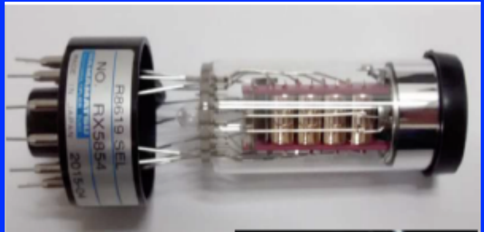


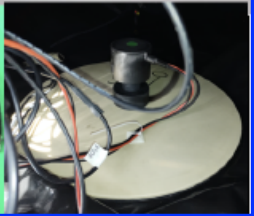


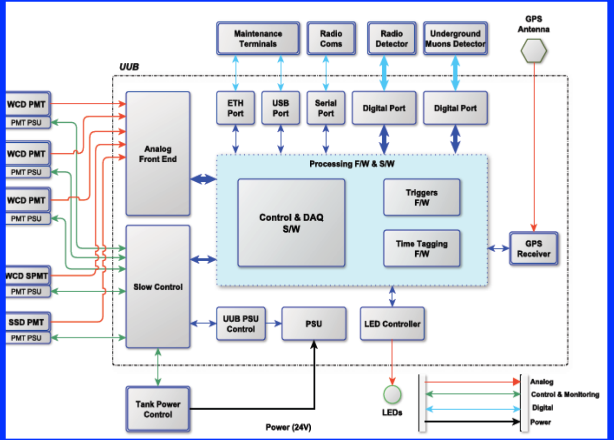
The AUGERPRIME Detector & components: SSD + sPMT + UUB

REFERENCES: [34], [35], [36], [37], [38]









SSD

- aluminium box
- **2 plastic scintillators panels** A ≈ 2 m^2 = (3.8x1.3x 0.1) m^3
- **24 scintillator bars** (1.6x0.05x0.01)m^3 STYRON PS, doped 1% PPO + 10% POPOP, produced @FNAL, co-extruded with TiO_2 reflective layers;
- **2 WLS** fibers (Kuraray) in U configuration, forming 96 (2x48) fiber ends;
- "cookie": PMMA cylinder for optical coupling with PMT;
- **1 PMT** (bi-alkaly HAMAMATSU R9420, d=1.5') in an aluminium tube;
- HV base (by ISEG);

modules assembled and tested in 6 different Auger sites

sPMT

- **PMT** (HAMAMATSU R8619, d=1.0');
- 30 mm window in the Tyvek liner bag containing ultra-pure H_20;
- PVC flange (≈ 40 cm) around window;
- passive base
- **external custom-made power supply** (HVPS) A7510B CAEN)

sPMTs tested in a dedicate facility;

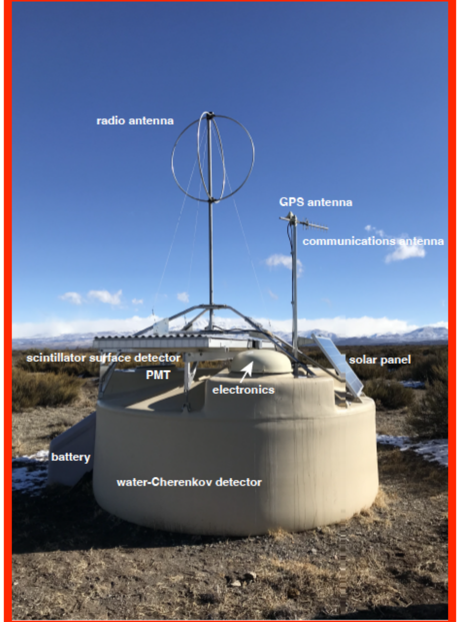
UUB

- **Single board** (340x215) mm^3 by A4F (SITAEL);
- Xilinx Zynq-7020 All Programmable SoC FPGA;
- 7° order-Bessel low-pass filter (60 MHz cut-off frequency);
- commercial digitizers **12 bit, 120 MHz dual channel FADC** (AD9628);
- 16 bit RISC CPU micro-controller (MSP430);
- Synergy SSR-6TF (**5 ns**) timing GPS receiver;

UUBs tested (ESS) in Auger Laboratory + tested on Pierre Auger Observatory;

The AUGERPRIME detectors: RD + UMD

REFERENCES: [39], [40], [41], [42], [43], [44]



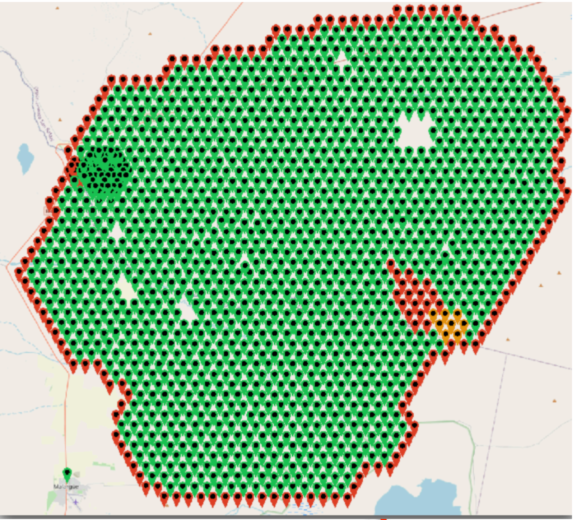
RD

- 1 Short Aperiodic Loaded Loop Antenna (SALLA), revised and improved design of the developed antenna for the AERA enhancement;
- diameter of 122 cm i.e. (30-80) MHz frequency region
- 2 aluminum rings, forming a dual-polarized antenna: one aligned parallel to the orientation of the Earth's magnetic field, the other one perpendicular to it;
- a fiberglass mask;
- a pre-amplifier at the top and a load resistor (392 Ω) at the bottom of antenna;
- 2 coaxial cables to connect pre-amplifier with electronics inside WCD;
- read-out of 2 channels by means a 12 bit 250 MHz FADC;
- a FPGA coordinates data exchange with the UUB

UMD

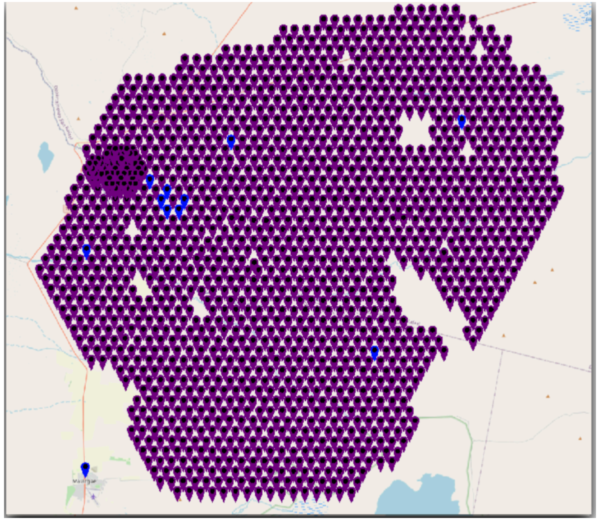
- 3 scintillator modules (produced @FNAL), each with detection Area ≈ 10 m^2, buried at 2.3 m depth (540 g/cm^2) at a 7 m distance from WCD;
- segmented in 64 plastic-scintillation strips, each (400 x 1 x 4) cm^3 ;
- embedded WLS optical fibers;
- array of 64 SiPMs (HAMAMATSU S13361-2050, 1584 micro-cells);
- PVC water-tight casing with a PVC inspection tube for installation & maintenance
- indipendent power-supply via photo-voltaic panels;
- indipendent telecommunication system for WCD-UUB-UMD in SD-750 infill;
- operation in *slave-mode,* receiving trigger signal by the corresponding WCD;
- operation in *binary-mode*, 320 MHz read-out, i.e. digital "1" when signal over threshold.

AUGERPRIME – Current (August 2025) Status of the detector installation



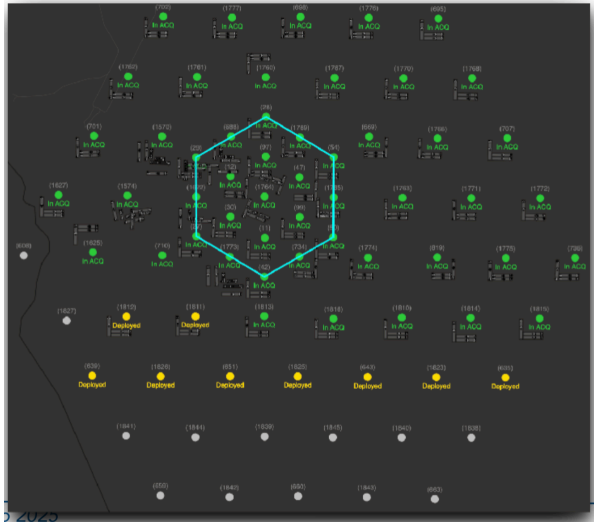
Upgraded WCDs

without SSD



WCD + RD

WCD + antenna



WCD + UMD (67%) SD750

without UMD

Upgraded WCD =
WCD + SSD + sPMT + UUB
concluded in June 2023!

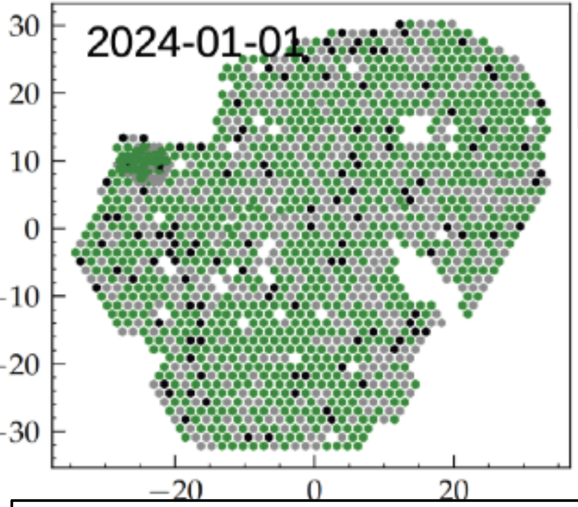
The total deployment will be completed at the end of 2025!

AugerPrime	Start depl.	Installation	Completion	Data -taking
UUB	during 2020	1939	OK (June 2023)	YES
sPMT	during 2020	1480 (excl. 31 outer side)	OK (June 2023)	YES
SSD	end 2018	1478 (excl. 31 outer side)	OK (end 2021)	YES
RD	Aug 2023	1605	OK (end 2024)	YES
UMD	2019	41/61 (SD750) 100% (SD433)	expected end 2025	YES (partially)

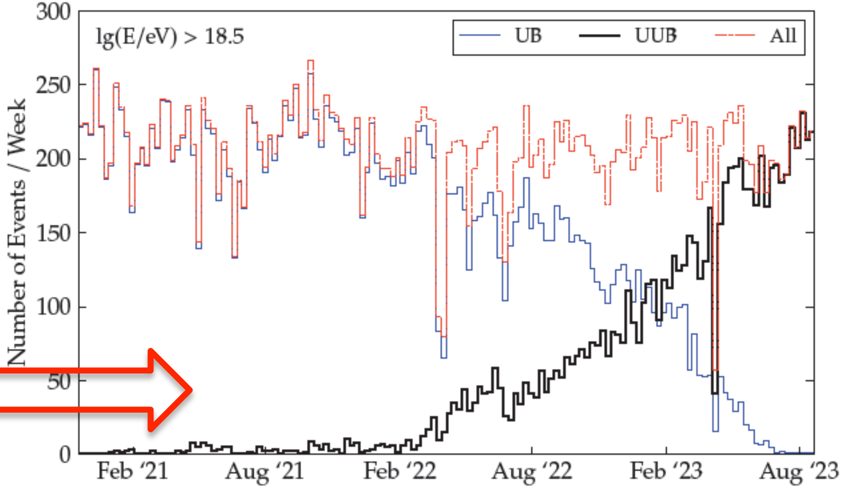
AUGERPRIME Commissioning

Commissioning i.e. "*bringing (something newly produced) into work conditions*"

Regular maintenance of ≈5000 Large PMT of SD-1500 is crucial for the AugerPrime Commissioning!



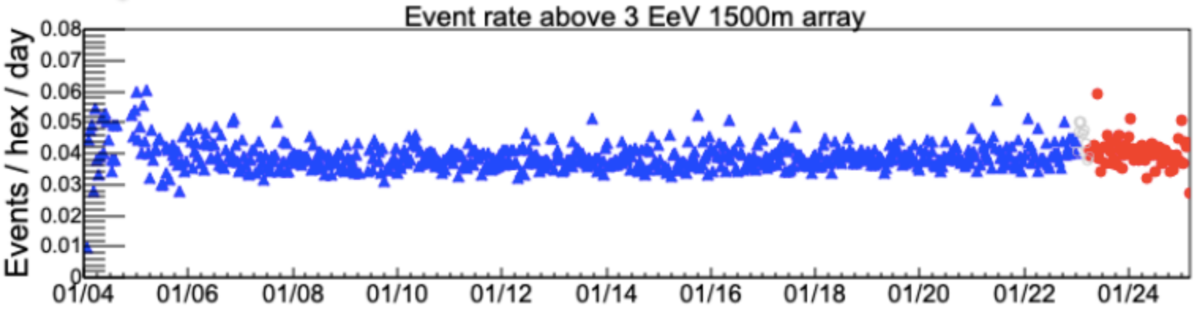
- • = SD OK (n. 911)
- •= SD with >1 PMT OK
- •= not usable



Good compatibility!
Phase 1-Phase 2 data

REFERENCE: [46], [47]

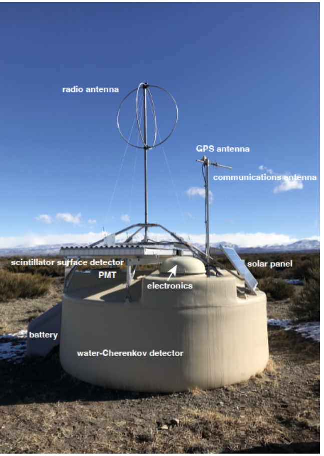
- **methods used for Phase1-daily commissioning adapted to Phase2 monitoring data;**
- **sensible parameters (VME peak, charge, ToT,...) used for checking anomalies;.**
- **preliminary criteria for alarms;**
- **tools ready to be used.**



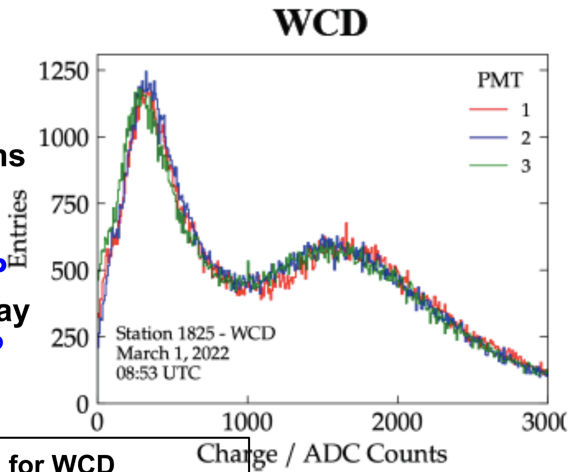
AUGERPRIME – Calibration WCD+SSD+sPMT

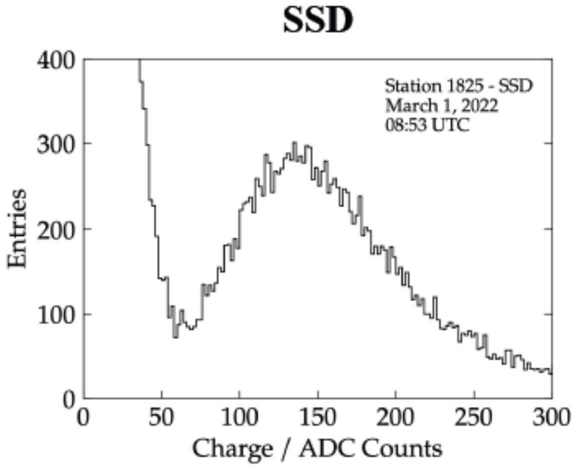
- **SSD**

calibration every minute using atmospheric μ's



- stability
  - day/night fluctuations
    3% in VEM 15% in MIP
    seasonal modulation
    3% in VEM 4-5% in MIP
- uniformity across the Array
  13% in VEM, 6% in MIP





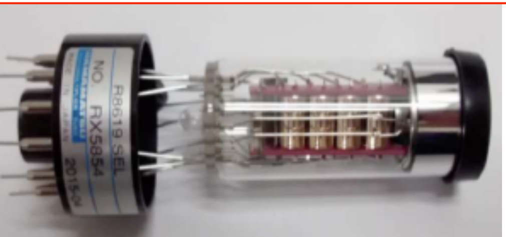
- Vertical Equivalent Muon (VEM) for WCD
- Minimum Ionizing Particle (MIP) ≈ 30 phe for SSD

- **sPMT**

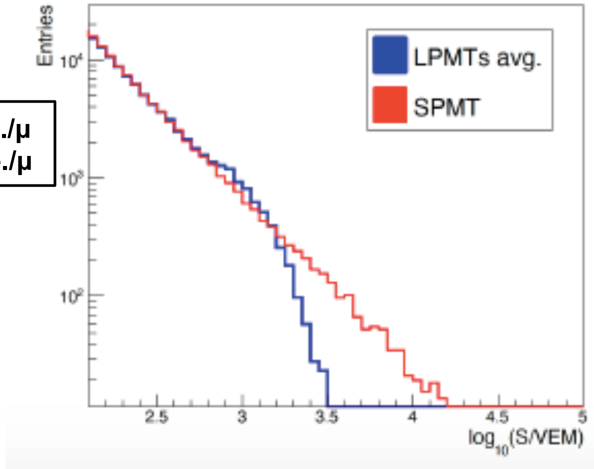
calibration against LPTM using local small showers (≈200/hour)

$$S_{SPMT}[VEM] = \beta\, Q_{SPMT}[FADC\ counts]$$

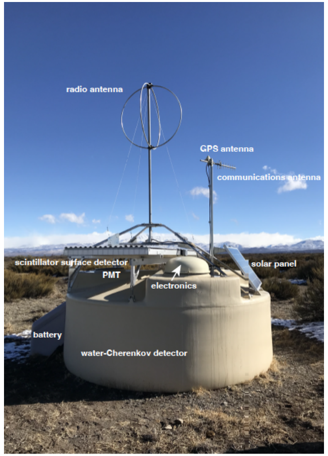
sPMT (1-inch) 1 p.e./μ
LPMT (9-inch) 9 p.e./μ



- precision in β: 2.2%
- seasonal modulation in β: (8-10)%
- stability day/night fluctuations: 5%
- uniformity across the Array: 10%



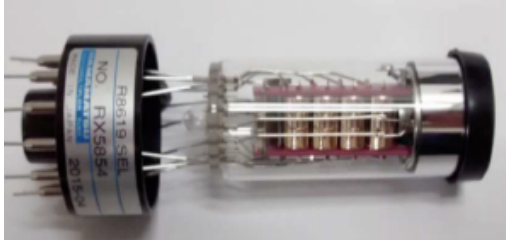
AUGERPRIME Monitoring WCD+SSD+sPMT

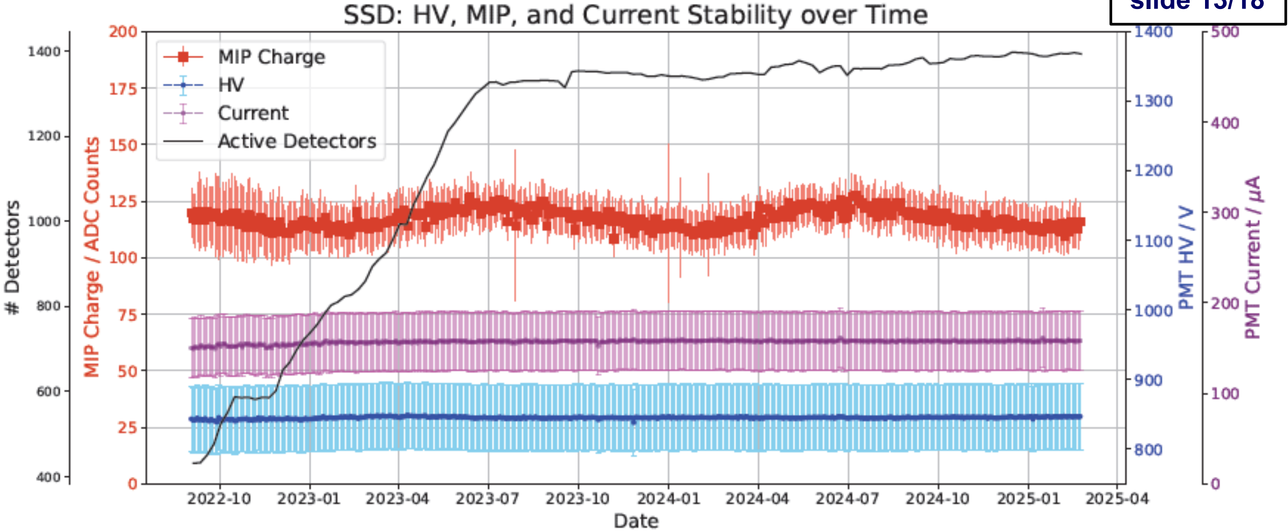


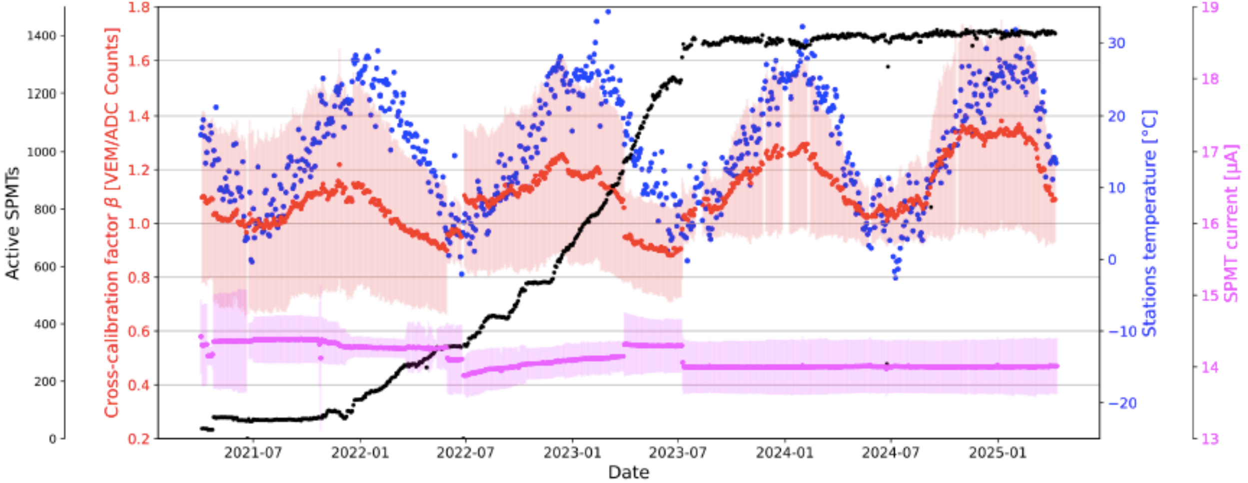
- **SSD**

REFERENCE: [46]

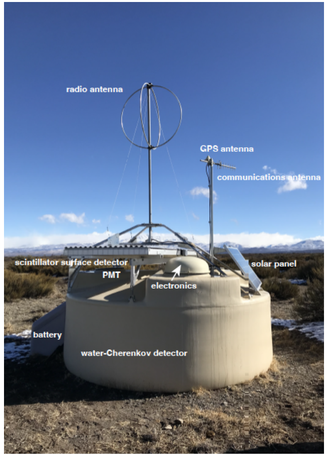
- **sPMT**

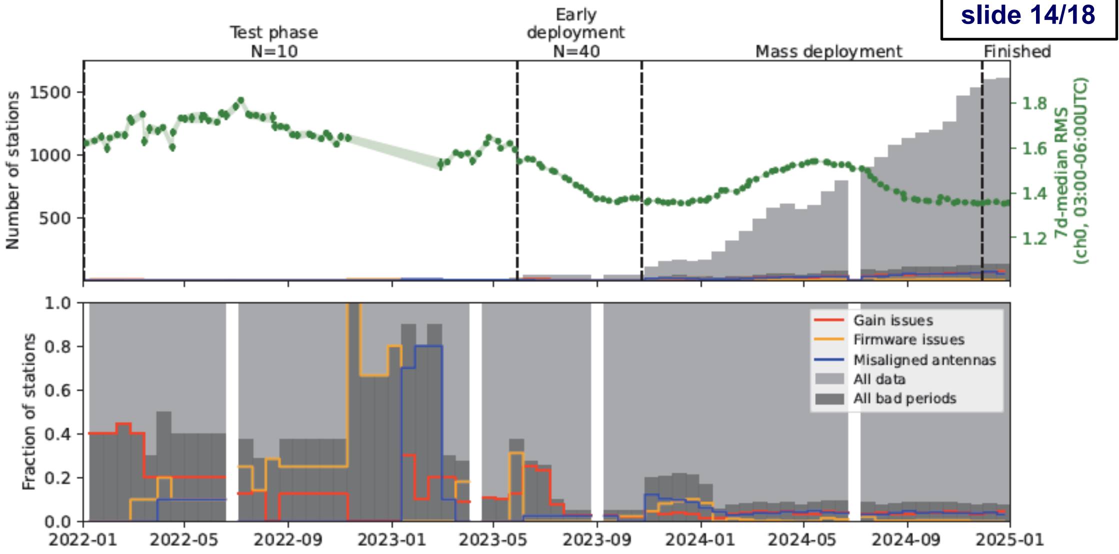






AUGERPRIME Monitoring RD & UMD

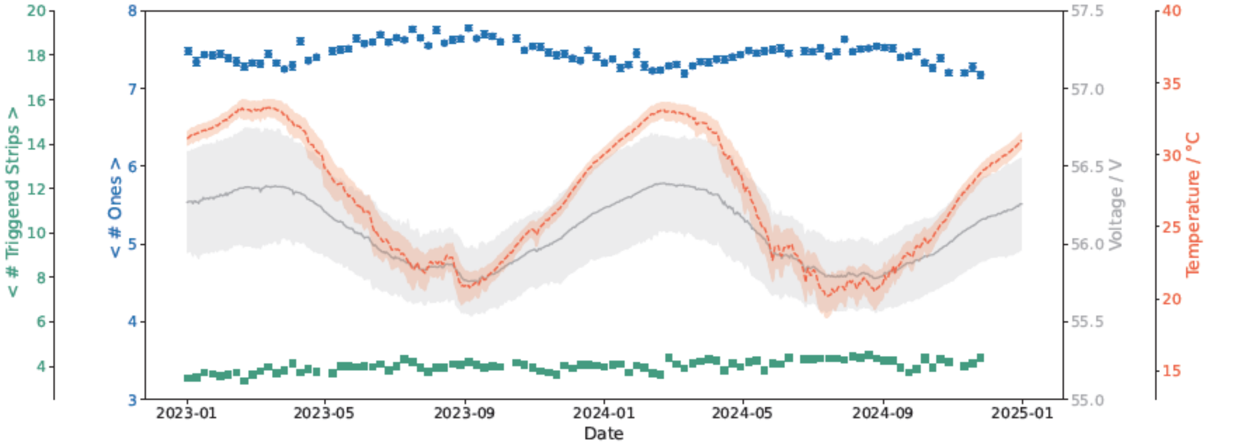




- RD

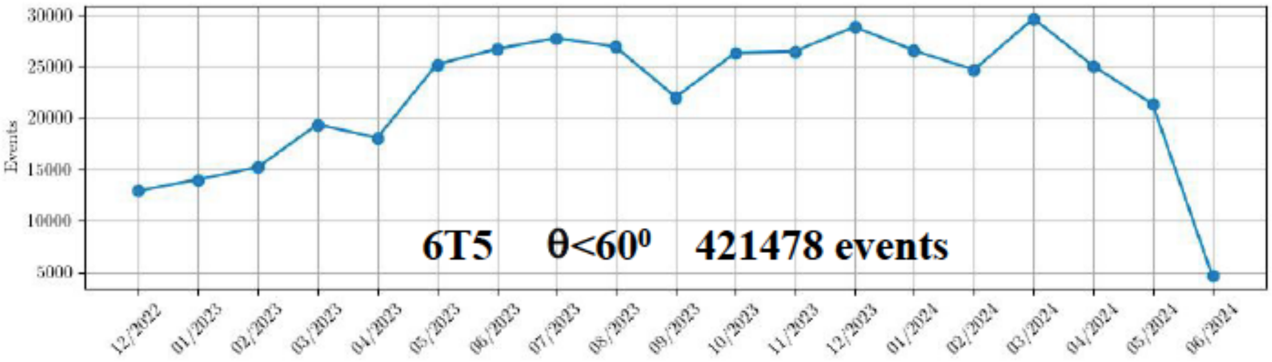
REFERENCE: [46]

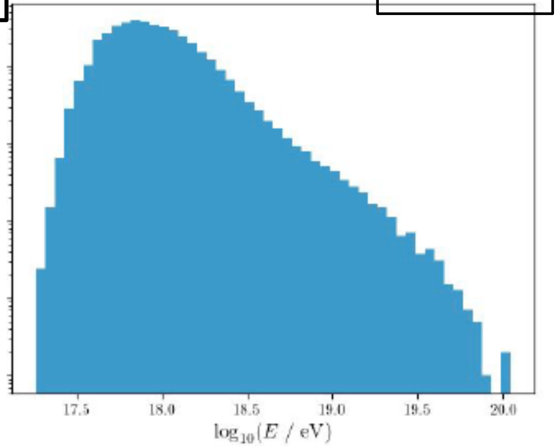
- UMD



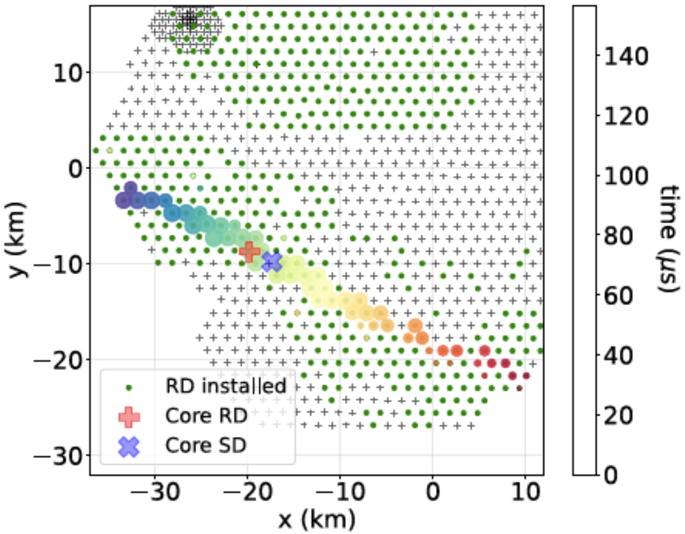
AUGERPRIME – Data Taking

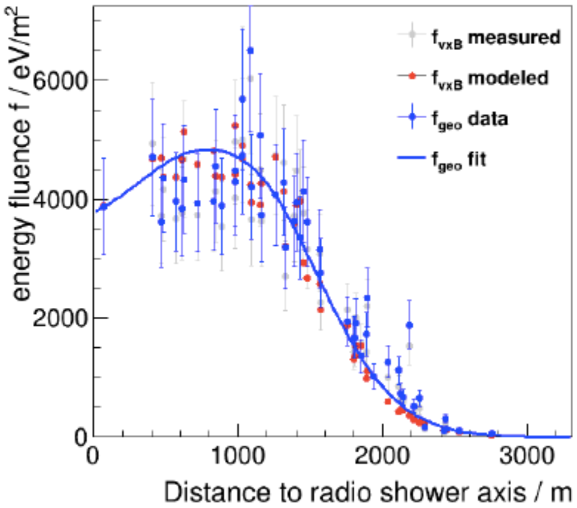
REFERENCES: [33], [45], [47]





First AugerPrime Data Production: 12/2022 – 06/2024



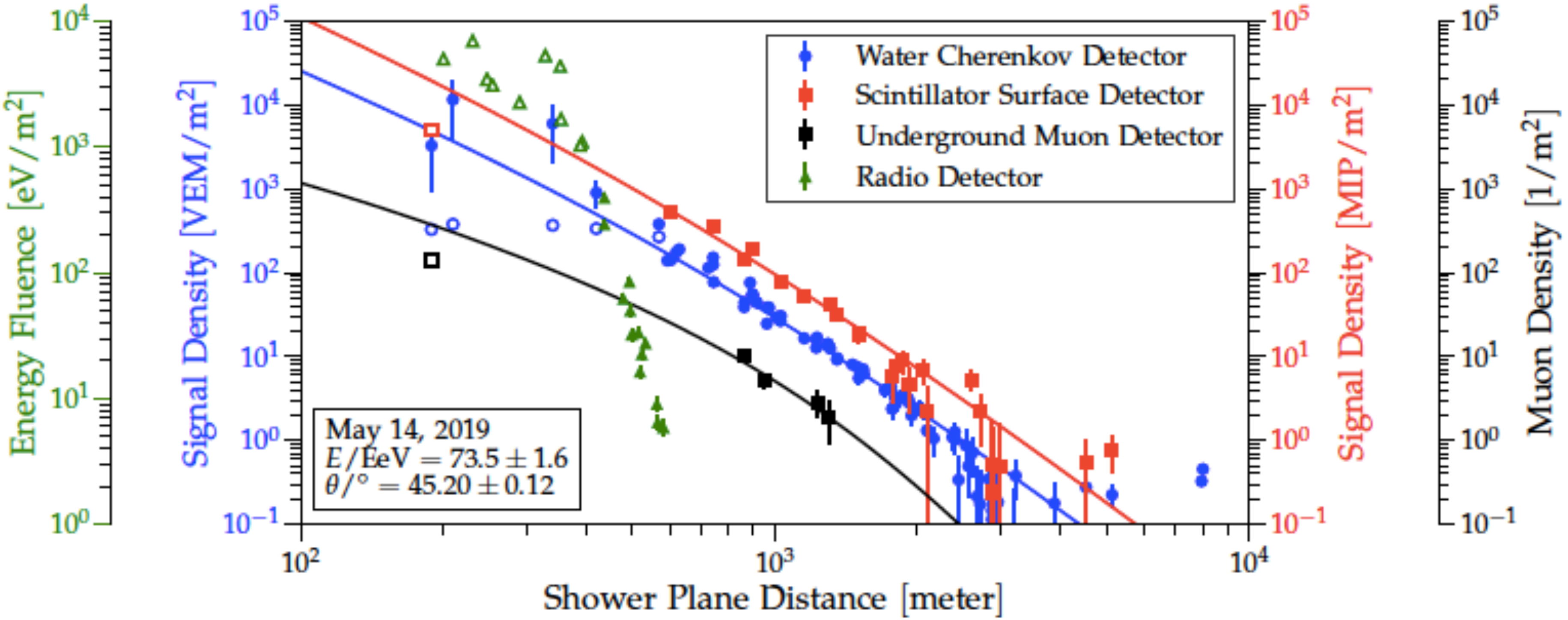


Event Inclined in RD

Event	RD	SD
Azimuth (deg)	156.99 ± 0.01	157.0 ± 0.1
Zenith (deg)	84.7 ± 0.01	84.7 ± 0.1
Energy (EeV)	36.23 ± 3.34	38.55 ± 2.92
Core X (km)	-19.8	-17.40 ± 0.88
Core Y (km)	-8.73	-9.78 ± 0.45

REFERENCES: [47]

A well-reconstructed multi-hybrid event!



AUGERPRIME – Benefits

1. Composition sensitive information, on event-by-event basis

Mass composition (& hadronic interaction)

Measurements of e/m and μ components in air shower:
- 2 π coverage with WCD + SSD/RD;
- direct measurements of μ's at low energies (≈ 1 GeV) with UMD.

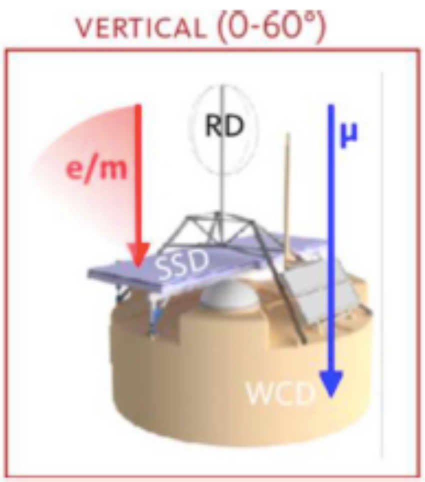
2. Overall data-quality improvement

Better performances
- increased dynamic range (>20000 VME) with sPMT
- increased sampling rate (120 MHz) with UUB

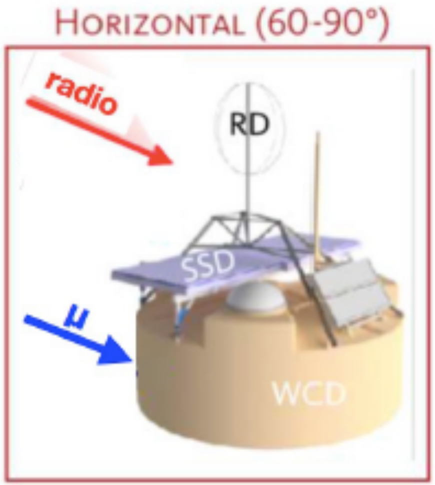
3. Increasing of statistics

- extention of data taking over 10 years

WCD+SSD



WCD+RD



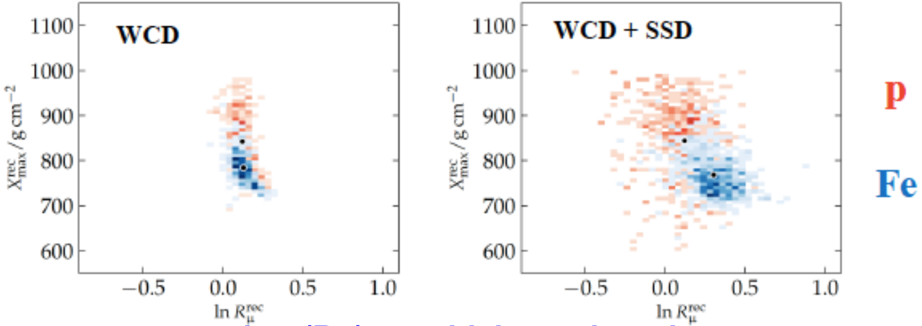
N events 10 years odata-taking (2035)

Lg(E/eV)	SD-433	SD-735	SD-1500	FD-Hybr.	FD-Cher.	RD
16.8	118000				48000	
17.5	3700	81000			4400	
18.0	270	5600		13000		
18.5	24	460	106000	3000		
19.0	5	88	13400	650		3000
19.5			1000	50		310
19.8			100	≈5		23
20.0			12	≈1		≈3

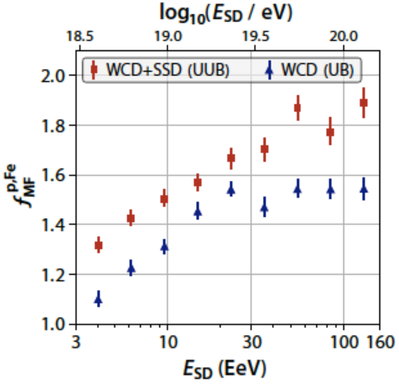
AUGERPRIME – Perspectives

REFERENCES: [33]

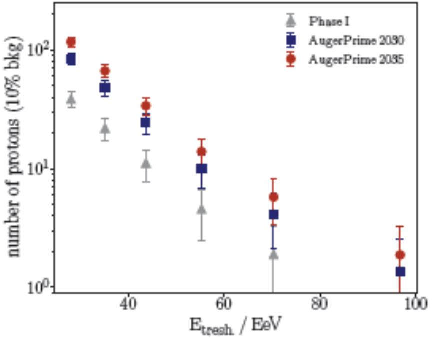
A) MASS COMPOSITION



Merit Factor MF: difference in units of std-dev



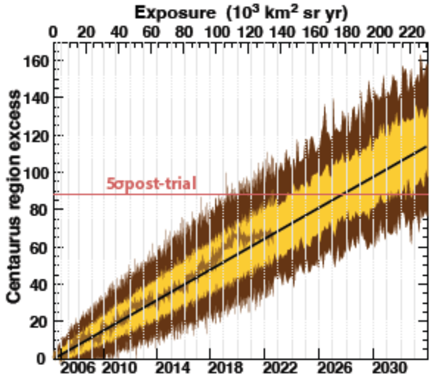
Mixture of 5% p – 95% Fe

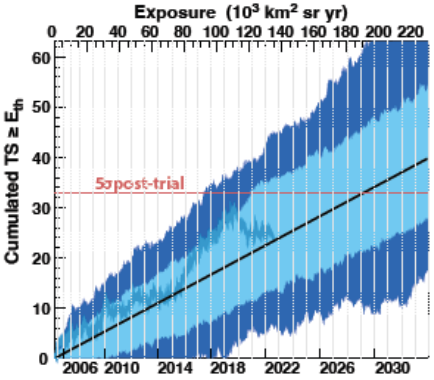


- muon number (Rμ) sensitivity to the primary mass
- better sensitivity to Rμ combining WCD + SSD
- better sensitivity to primary mass reconstructing Rμ, X_{max} and E

B) ANISOTROPY

- 5 σ discovery expected in the next few years
- searches done selecting lighter primaries will boost the significance





C) MULTI-MESSENGER ASTRONOMY

- Photon limit will benefit from the increased exposure and the better photon-hadron discrimination
- AugerPrime sensitivity to UHE photons and neutrinos will be improved!

AugerPrime,the upgrade of the Pierre Auger Observatory: current status and data taking

Parallel Session #6 "High Energy Astrophysics and Cosmic Rays"
TAUP 2025 – Wednesday August, 27th 2025

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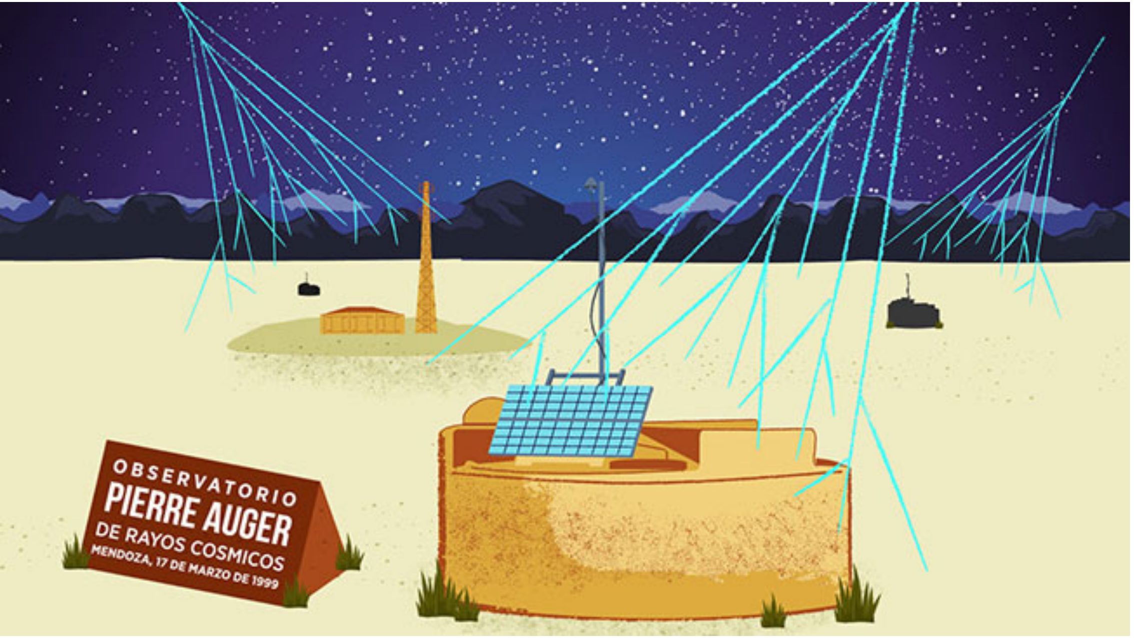
Observatorio Pierre Auger, Av.San Martìn Norte 304, 5613 Malargue, Argentina

THANK YOU very much for your kind attention!



For more details, plase, see also ***Talks at this Conference*** presented on behalf of the Pierre Auger Collaboration:

- ***Eva dos Santos: "Probing hadronic interactions at the 100 TeV scake with the Pierre Auger Observatory"*** **CR#1 August 25th 2025;**
- ***Piera Lusa Ghia: "25 Years of the Pierre Auger Observatory: a constantly evolving instrument yielding a rich and varied harvest"*** **CR#2 August 25th 2025;**
- ***Teresa Bister: "Astrophysical interpretation of ultra-high-energy cosmic ray meausurements at the Pierre Auger Observatory"*** **CR#2 August 25th 2025;**
- ***Fiona Ellwanger: " Probing the flux of Ultra-High-Energy neutral particles at the Pierre Auger Observatory"*** **CR#1 August 25th 2025**

Lastly, a big thanksgiving to all the fantastic guys of the TAUP2025 LOC (in particular, CHANG CAI) for helping me successfully in recovering my laptop and allowing me to present this Talk !!!!

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