AugerPrime - the new Phase of the measurements at the Pierre Auger Observatory

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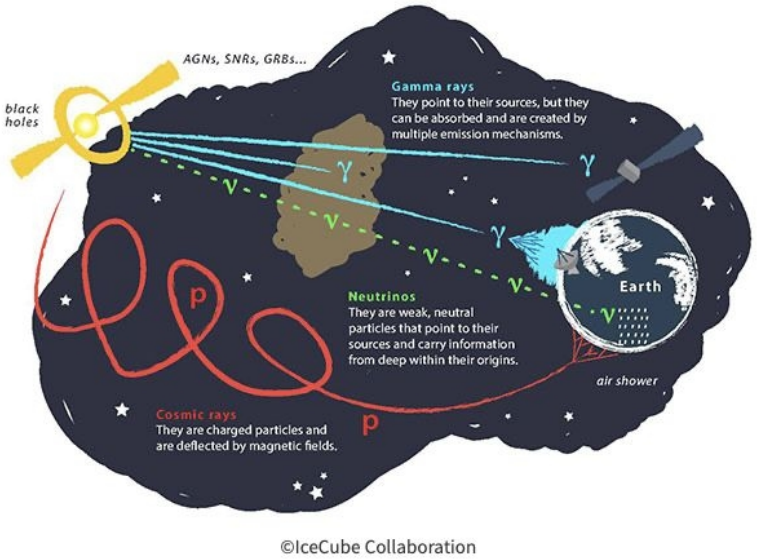
TeV Particle Astrophysics, Chicago 2024

Ultra-high energy cosmic rays



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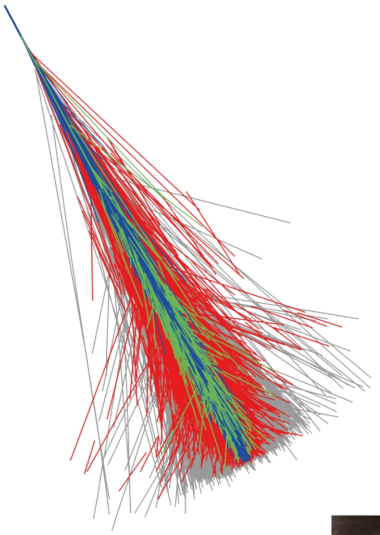
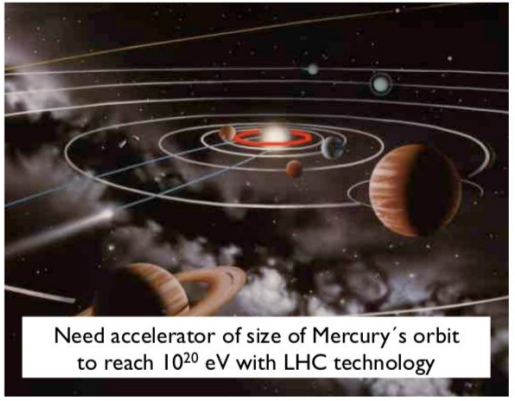


- **Open questions:**
  - What is their nature, origin, mechanisms of acceleration and propagation?
  - What is the origin of cosmic ray spectrum features?
  - What is their composition? Are there ultra-high energy photons and/or neutrinos?
  - Understanding the hadronic interactions at ultra-high energies…

- The most energetic (above 10^{18} eV), rare and mysterious particles in the Universe, probably of extragalactic origin. Their sources still remain unknown.

The highest ever observed particle's energy is ~ 320 EeV.

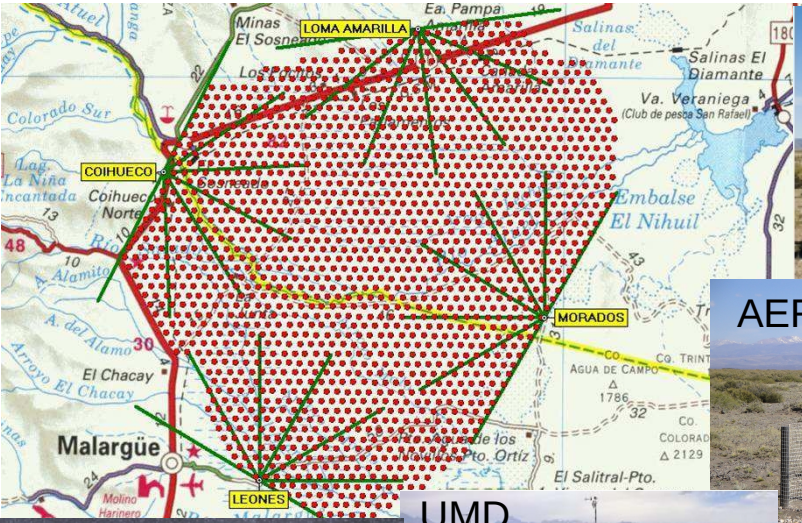
- Observation: indirectly, with large-sized observatories on the ground by registration of the extensive air showers induced in the Earth's atmosphere by the cosmic ray primary particles.

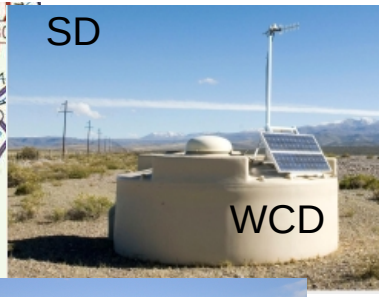


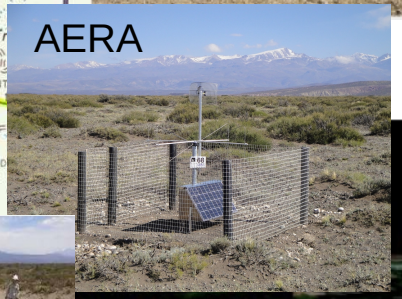
(Unger, 2006)

- **Key features investigated:**
  - primary particle energy and mass,
  - incoming shower direction,
  - identification of actual sources.

The Pierre Auger Observatory, Phase I





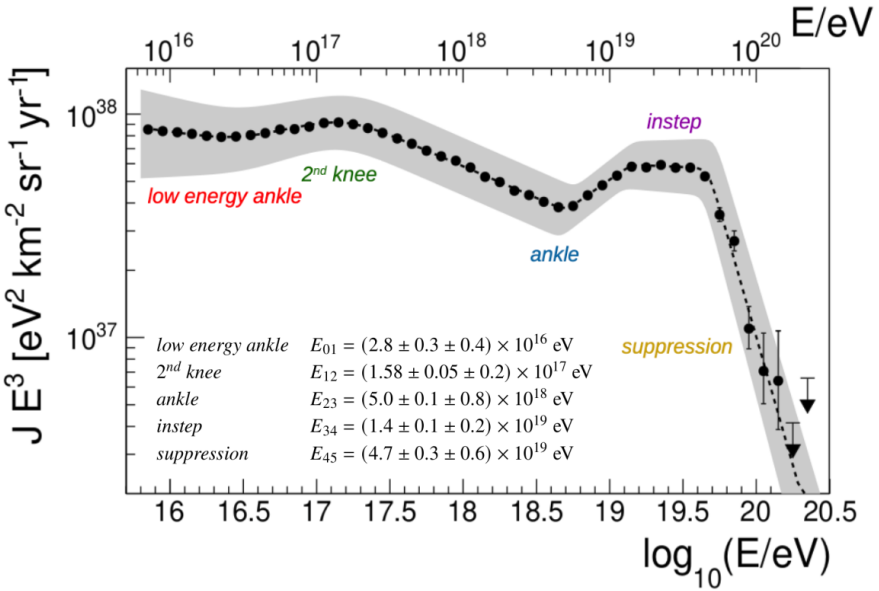


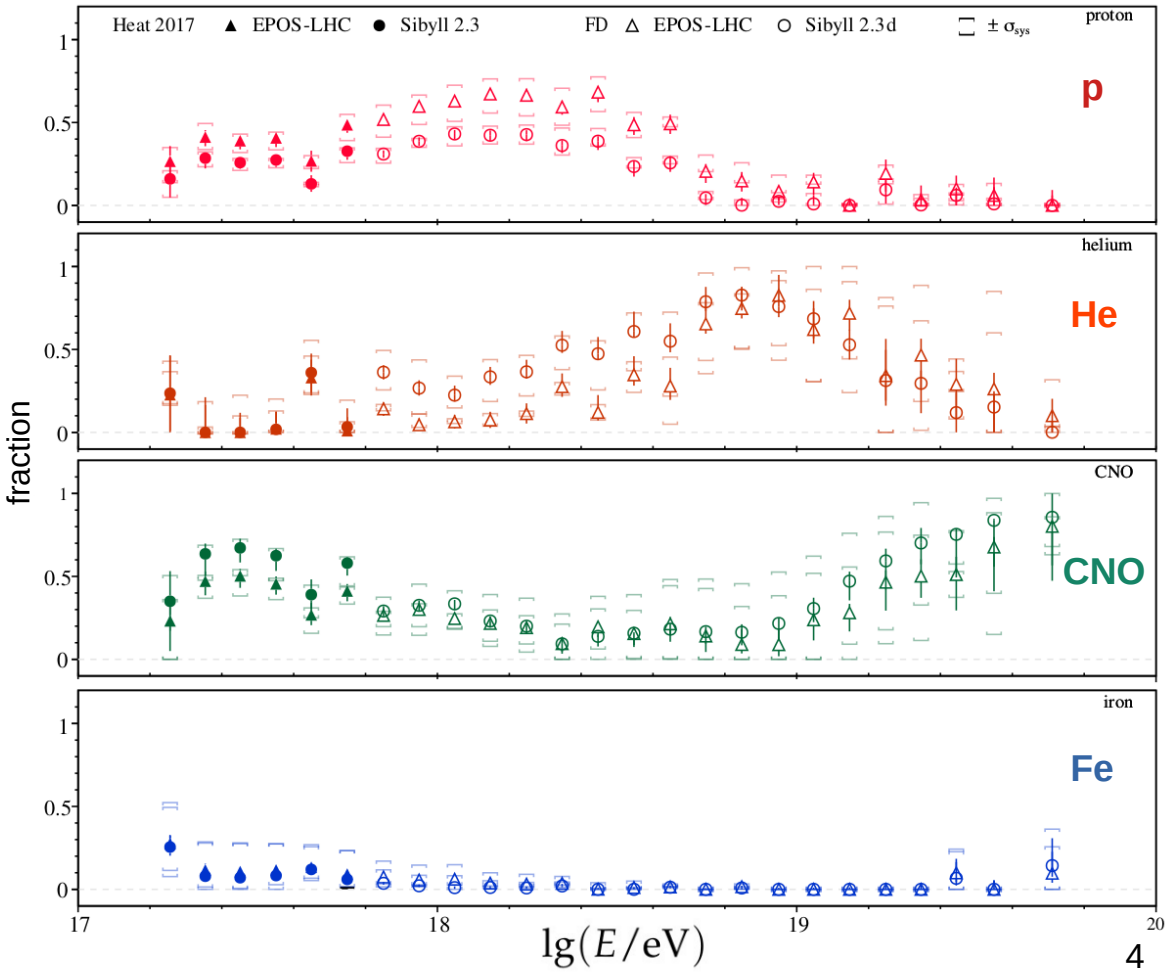
- Situated at foothills of Andes, province of Mendoza, Argentina. The area is **3000 km²**
- **Hybrid detector**:
  Surface detector (SD) array - 1660 water-Cherenkov detectors (WCD)
  + Air fluorescence detectors (FD) - 27 telescopes
- Engineering arrays:
  - AERA: 153 radio antennas
  - UMD: 24 underground muon detectors
- **Phase I**:

  ✓ almost 20 years of data taking – from 2004
- ✓ Exposure 80 000 km² sr yr (θ<60º)

The Pierre Auger Collaboration:
- 18 countries
- ~400 authors

Some results from the Phase I data



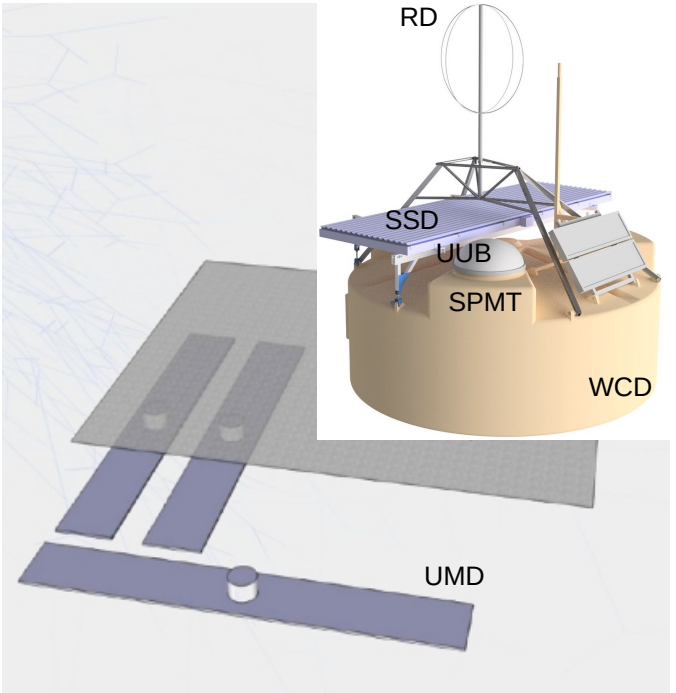


- **Combined Auger energy spectrum, with its features** - the most precise estimate of the energy spectrum of ultra-high energy cosmic rays yet available (PoS(ICRC2021)324)
  (See the presentation by Fiona Ellwanger)
- **Fractions of primary mass** groups are derived by fitting model predictions to the FD-measured X_{max} distributions in energy bins (PoS(ICRC2023)365)
  (See the presentation by Miguel Martins)

The AugerPrime Upgrade

Main goals for Auger Phase II

- Study of nature and origin of the most energetic cosmic rays
- Determine mass composition up to the highest energies
- Unravel origin of the flux suppression at the highest energies
- Search for the ultra-high energy neutrinos and photons
- Study of hadronic interactions at ultra-high energies
- Search for the new physics at the ultra-high energy frontier



Idea: Use detectors with different responses to the **electromagnetic** and **muonic** air shower components.

***New Components*:**

- Radio Detector (RD)
- Scintillator Surface Detector (SSD)
- New SD electronics (UUB)
- Small photomultiplier (SPMT)
- Underground Muon Detectors (UMD)

Phase II:

✓ data taking – from 2019 to > 2035

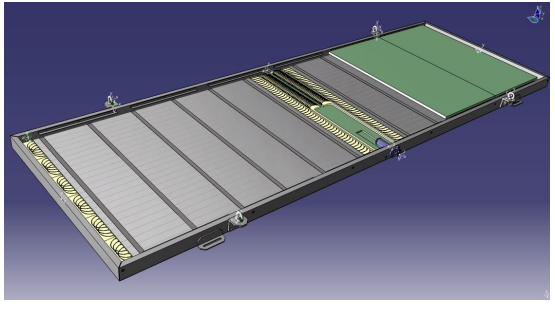
✓ + 40 000 km^2 sr yr (θ<60º)

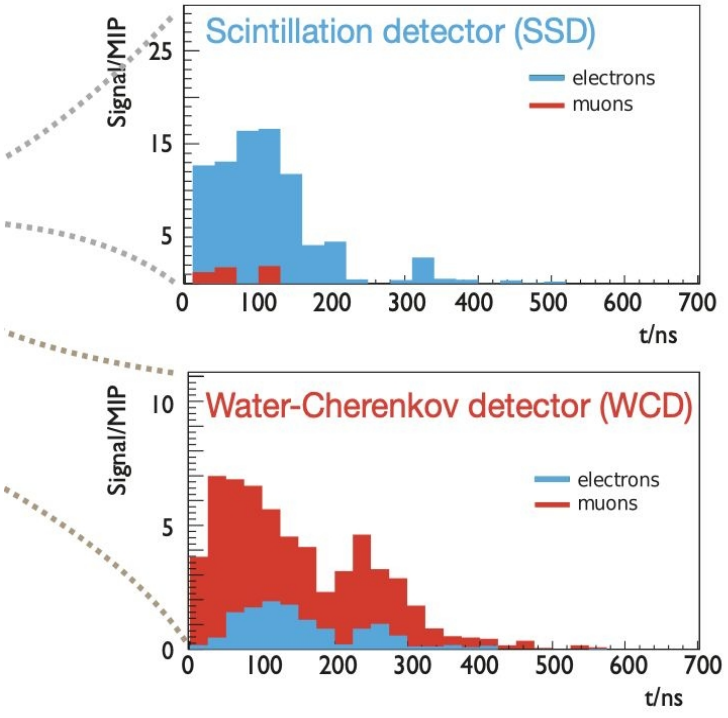
✓ Multi-hybrid events : FD, WCD, SSD, RD, UMD

Phase II: Surface Scintillator Detector (SSD)

- **Measurement of mass composition in combination with the WCD at the highest energies**
- Sensitive to charged particle density
- SSD components:
  - Extruded scintillator bars (1600x50x10 mm)
  - WLS optical fibers (Kuraray 1 mm), two per scintillator bar
  - Readout by 1.5” PMT (Hamamatsu R9420)
  - Two scintillator panels per station

Scintillator 3.8 m²





SSD and WCD - complementary detectors to discriminate EM and muonic shower components

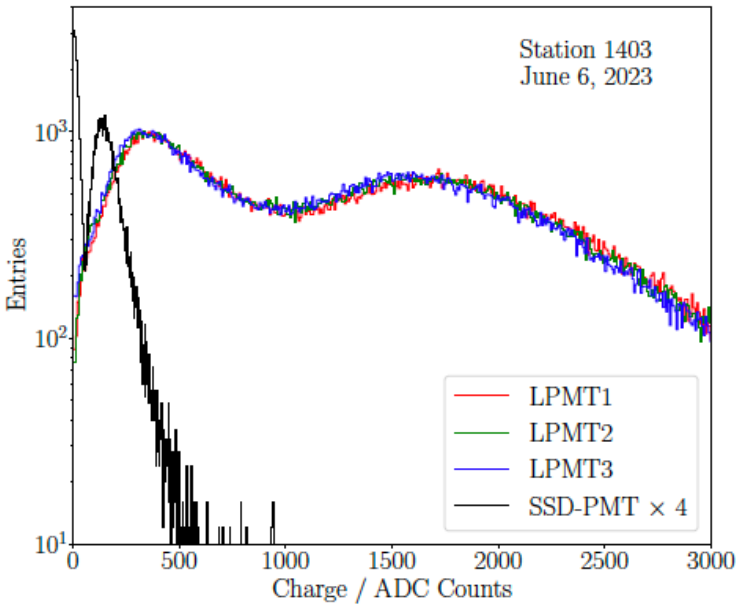
Disentangling different components is possible with multi-parametric analyses

$$S_{\mu,\mathrm{WCD}} = a\,S_{\mathrm{WCD}} + b\,S_{\mathrm{SSD}}$$
$$S_{\mathrm{em},\mathrm{WCD}} = c\,S_{\mathrm{WCD}} + d\,S_{\mathrm{SSD}}$$

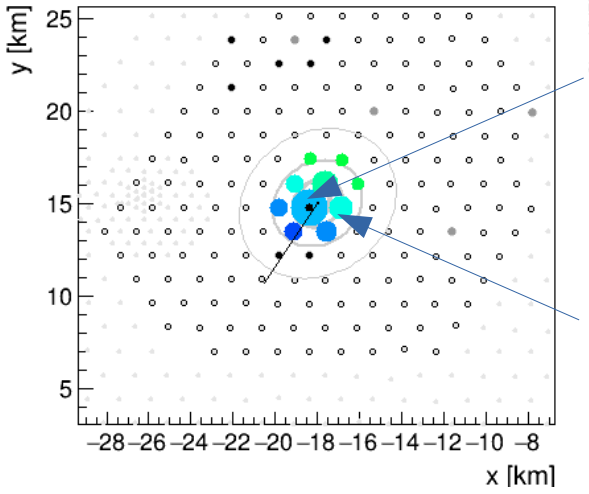
Calibration and events

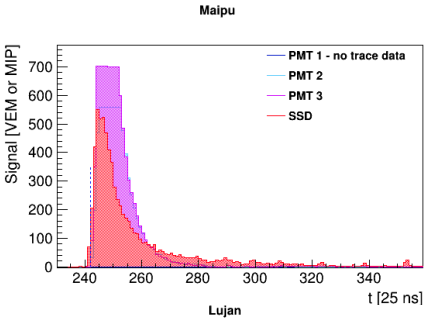
WCD and SSD are calibrated by atmospheric muons:

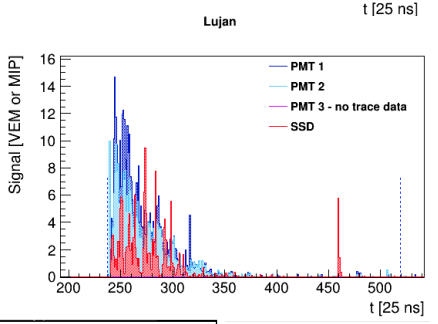
- *Vertical Equivalent Muons (VEM)*
- *Minimum Ionizing Particle (MIP)*

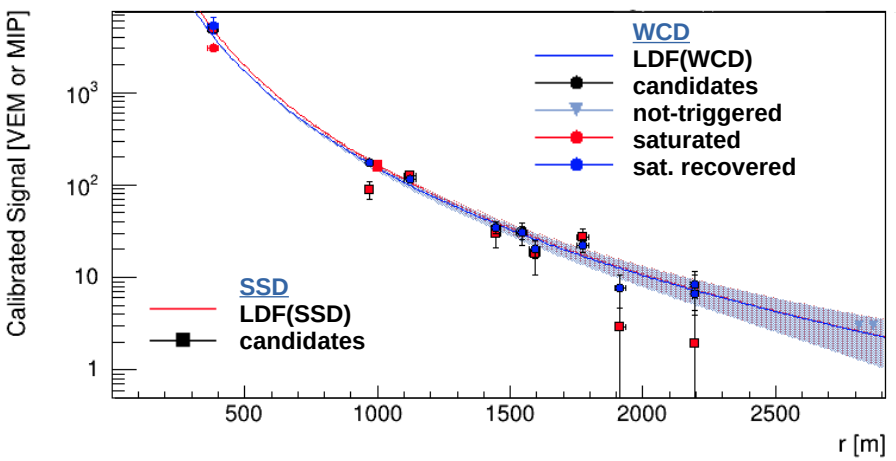


Calibration histograms of VEM and MIP integrated charges, collected in 60 seconds.









Event 53661662

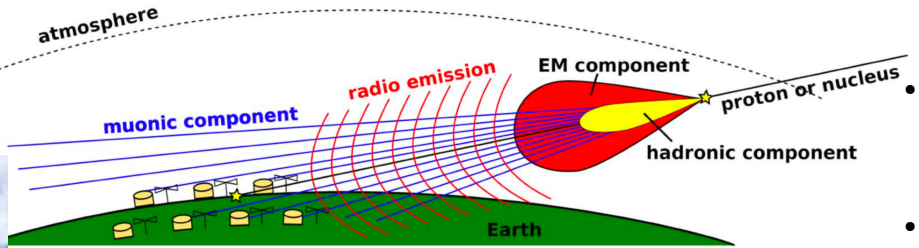
E = 3.12 x 10^{19} eV

θ = 32.9 deg

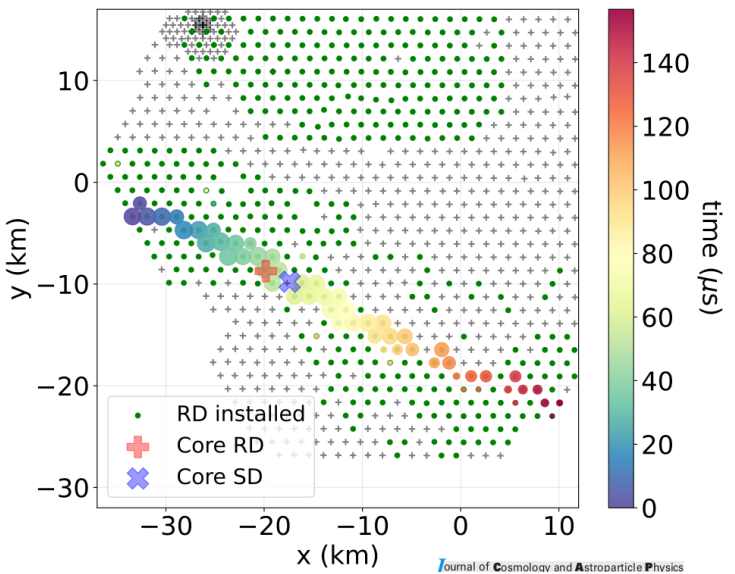
φ = 240.0 deg

Phase II: The Auger Radio Detector (RD)

- **Dual-polarised radio antenna** installed to SD stations to detect EM component mainly of inclined (θ > 60º) air showers



A cosmic ray measured using RD

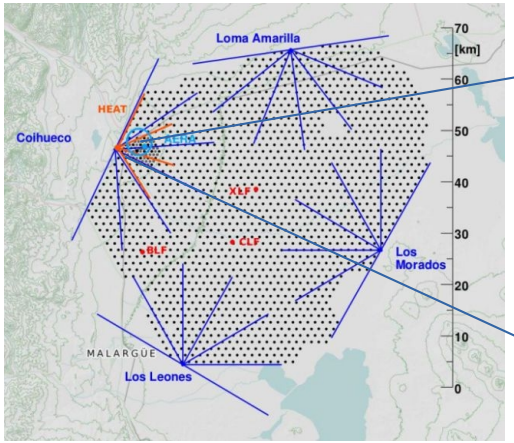


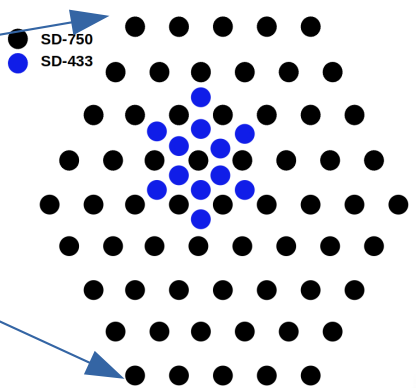
- Atmosphere is transparent to radio emission in the 30-80 MHz range
- RD antennas use digitizers, which are able to record the events in coincidence with the SD stations
- More than 3000 showers are expected to be registered by RD with energies >10 EeV in 10 years

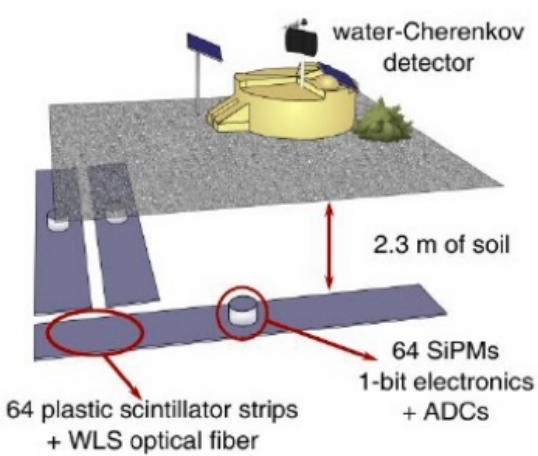
Benefits of RD measurements:

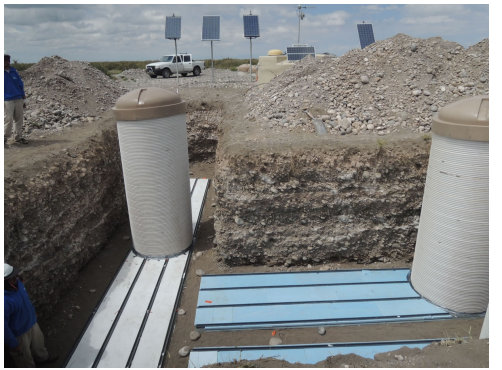
- increased **mass sensitivity for inclined air showers** produced by cosmic rays - as RD measures EM component, WCD measures muons
- increased **sensitivity to neutral particles - photons and neutrinos** - they have negligible particle footprint, but produce strong radio signal which can be measured with the RD

Phase II: Underground Muon Detector (UMD)

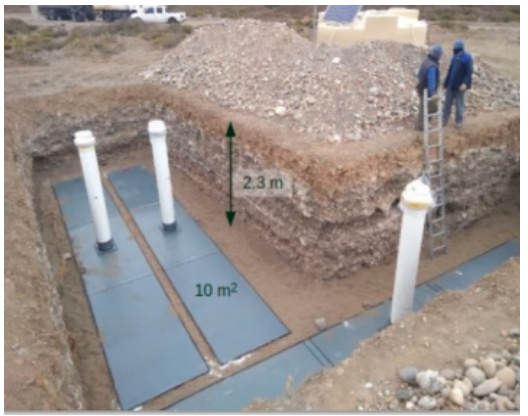


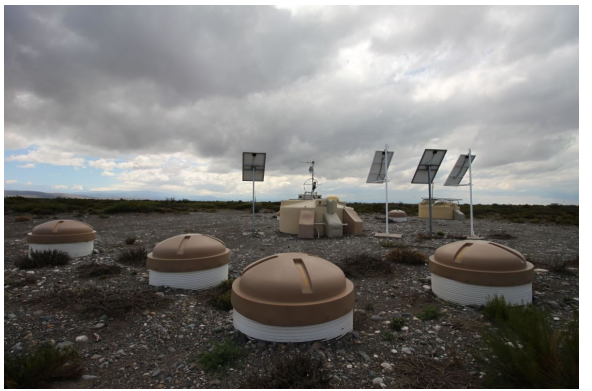






- **The UMD is designed to**
  - directly measure the muon content within the air-showers
  - cross-check muon evaluation with SD
  - enhance photon/hadron discrimination
- **Each UMD**:
  - 3 x 10m^2 module, buried at 2.3 m underground
  - each module has 64 plastic scintillator strips, equiped with WLS optical fibers, and 64 Silicon Photo Multipliers (SiPMs)
- **Expected**: UMD array will be fully operational by the end of 2024





Phase II: SD electronics and small PMT

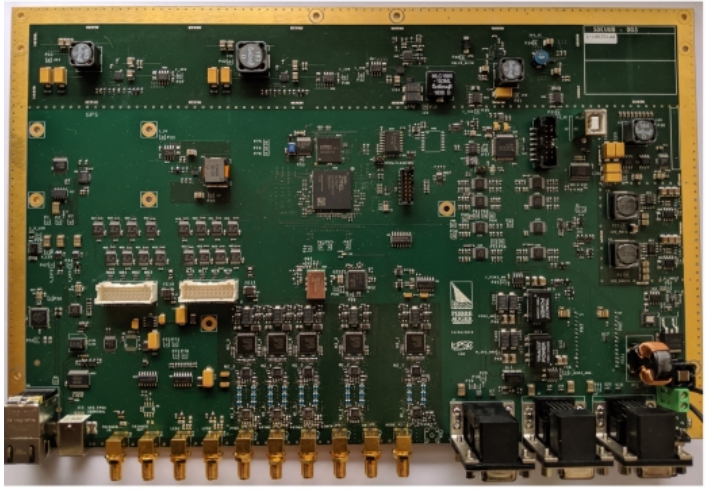
1. Increased the data quality (better timing, dynamic range and μ identification):
   a) faster sampling of ADC traces (40 → 120 MHz)
   b) more precise absolute timing accuracy - new GPS receiver
   c) increase the dynamic range by adding a small 1” PMT (large LPMTs are 9”)
2. Faster data processing and more sophisticated local triggers - with a more powerful local station processor and FPGA (Xilinx Zync-7020)
3. Improved calibration and monitoring capabilities
4. New components:
   a) Connection to the SSD and any additional (R&D) detectors
   b) Additional Small PMT

Totally compatible with the old design

Upgraded Unified Board (UUB):

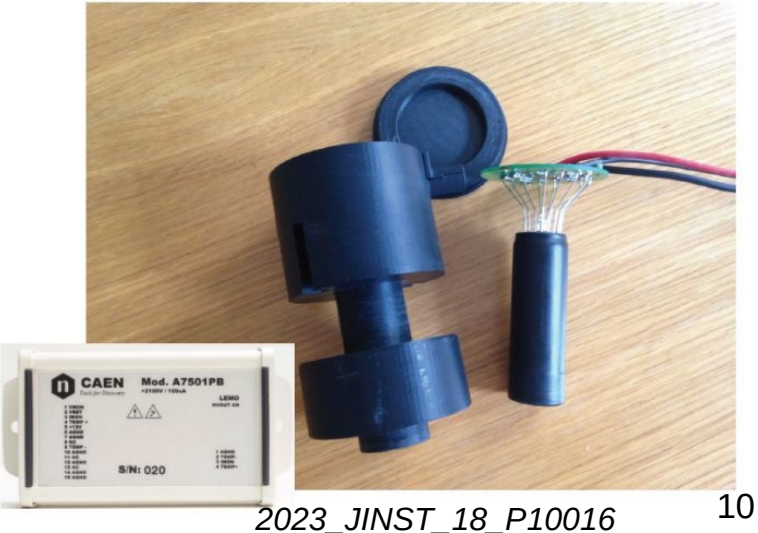
→ Processes signals of WCD, SSD and RD detectors and increases resolutions and data processing capabilities

→ With UUB we will enhance the sensitivity of triggers to electromagnetic signals

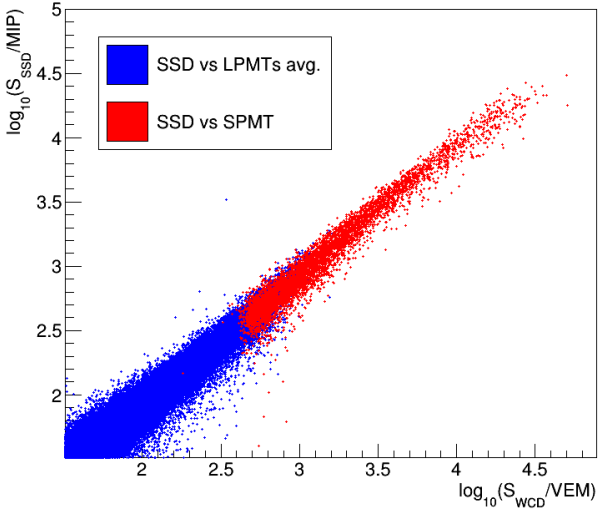


Small PMT (SPMT):

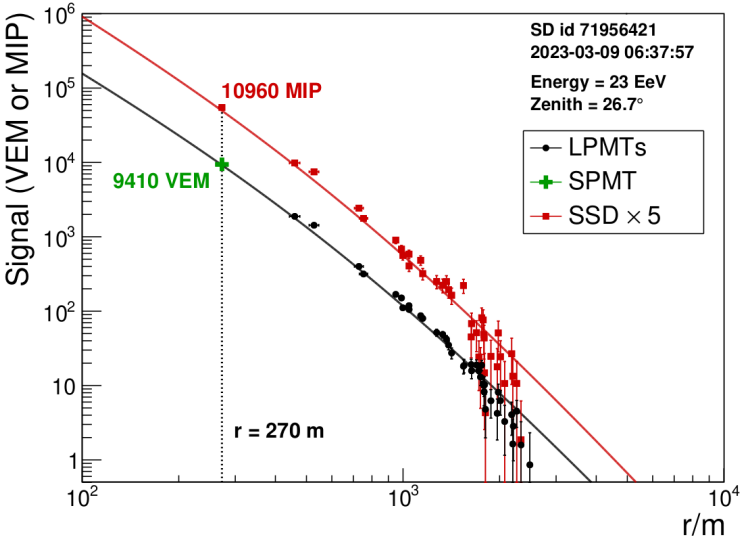
→ Extend the Dynamic Range of the WCD:
- a smaller low-gain PMT installed in SD stations
- measures large pulses that saturate the signal of the large PMTs (LPMT)



The dynamic range and Event reconstruction



Good correlation between SSD and WCD (LPMT) signals:
- LPMTs are used up to the saturation region (blue dots)
- SPMT (red dots) extend further the measurements



Lateral Distribution (LDF) of the signal sizes recorded in SD detectors with the help of an additional Small PMT

- The fit of LDF can be effectively constrained at least down to distances of ~ 250 m from the shower core even at the highest energies.

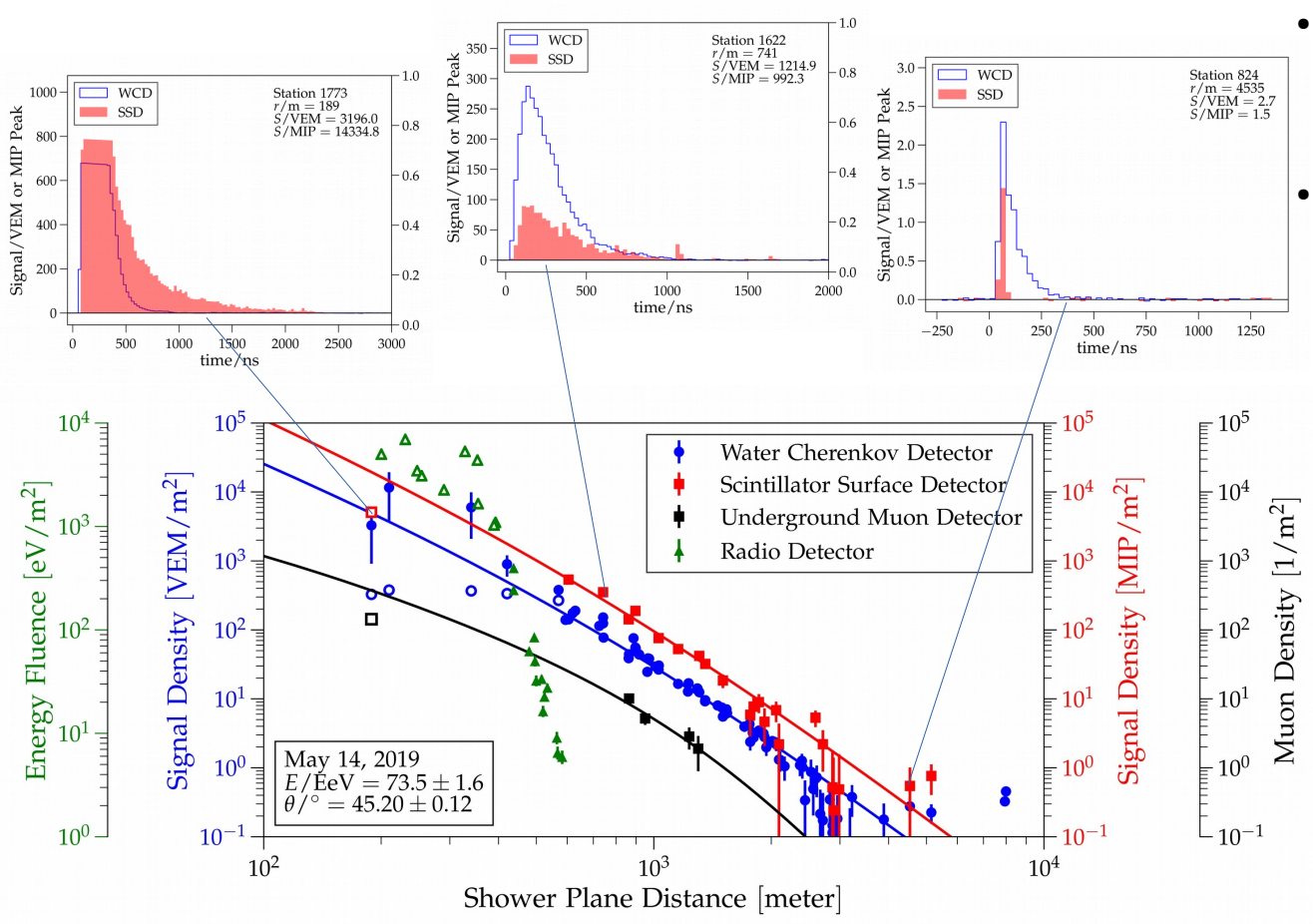
- **Phase I**: the reconstruction of the shower geometry is performed using only *the information from the WCD LPMTs*

- **Phase II**: the dynamic range of acquisition of WCDs has been extended by SPMT, which allows for the measurement of signals without saturation in the vast majority of the observed extensive air shower events.

- Events collected with the array of upgraded stations confirm the effectiveness of this design, allowing the measurement of signals up to at least 20,000 VEM and correspondingly 20,000 MIP without saturation in the digitized traces.

PoS (ICRC2023)343

Multi-Hybrid measurements of Air Showers

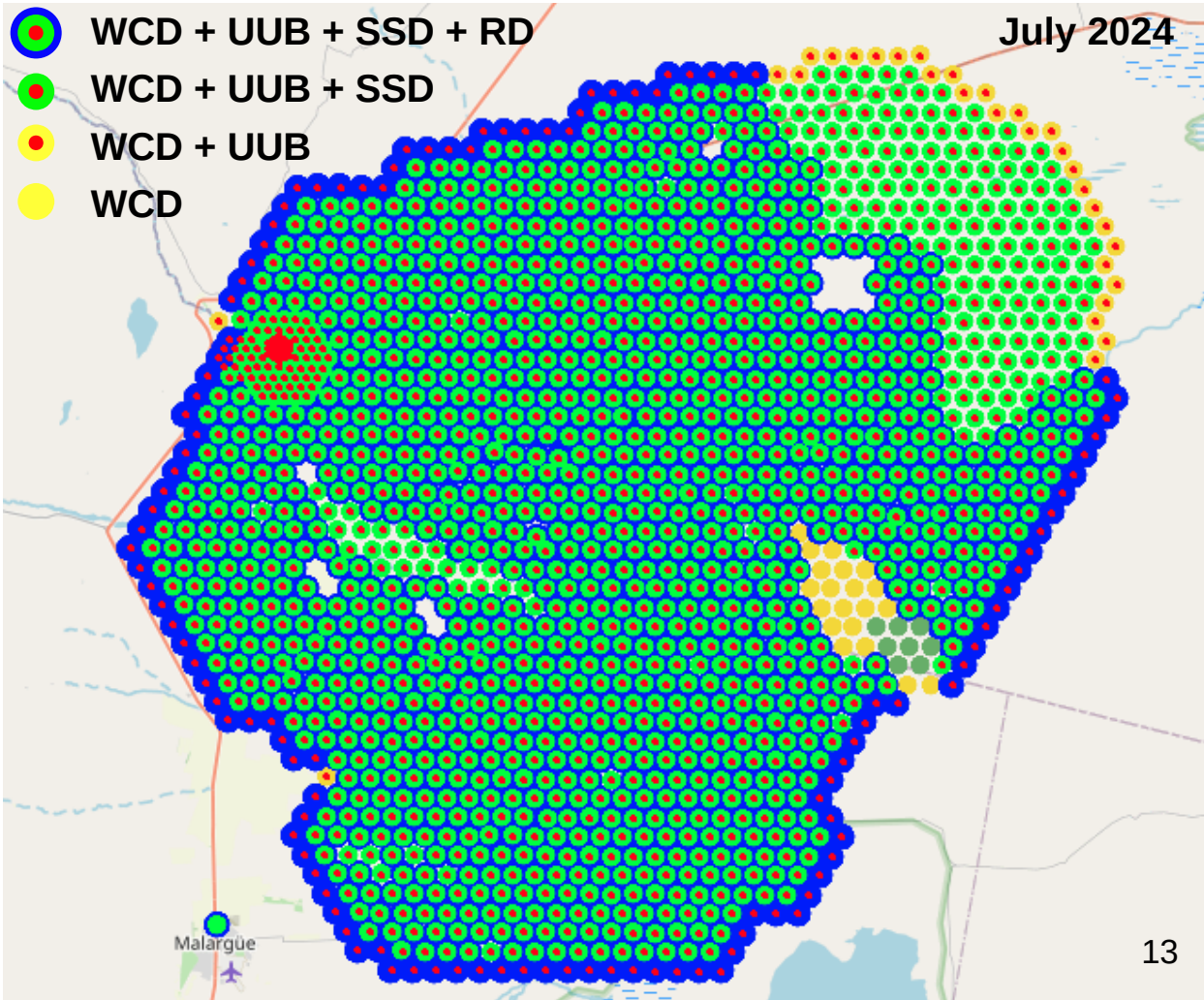


- WCD/SSD/RD/UMD can collect multi-hybrid events with a 100% duty cycle, FD duty cycle 15%
- Separation of shower components can be obtained:
  - ➔ by WCD/SSD for events with θ = 0º - 60º up to the highest energies
  - ➔ by WCD/RD for inclined events with θ = 60º - 90º up to the highest energies
  - ➔ by WCD/SSD/UMD extending the mass sensitivity to the lower energies and improving the photons/hadrons discrimination

AugerPrime status

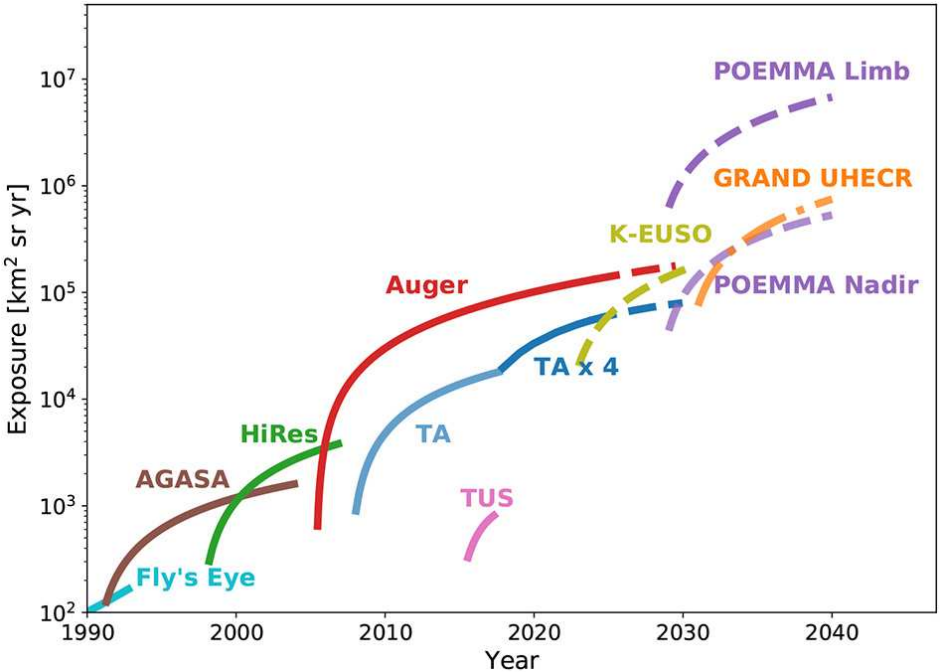
- Stations with SSD, SPMT, and UUB – completed:
  - ✔ 1475 SSD installed
  - ✔ 1465 SPMT installed
  - ✔ 1624 UUBs installed
- Stations with RD, expected to be completed in August 2024
  - ✔ 1367 RD antennas installed until July
  - ✔ 970 RD digitizers installed
- Over 60% UMD installed

Phase II installation is expected to be completed in 2024



Conclusions

- Phase I - demonstrated the need for AugerPrime upgrade
- Multi-Hybrid detection (WCD + SSD + RD + UMD + FD)
- Phase II installation nearly completed - finish by the end of 2024
- AugerPrime will offer cosmic ray particle mass estimates event-by-event
- Expected to run until > 2035, increase exposure by ~40 000 km^2 sr yr
- AugerPrime will offer new unique data for cosmic ray science, and contribute to global multi-messenger observations
- Auger is an ideal platform for testing new instruments



Exposure of the ultra-high energy cosmic ray experiments as a function of time for ground-based and space experiments (Front.Astron.Space Sci. 6 (2019)23)