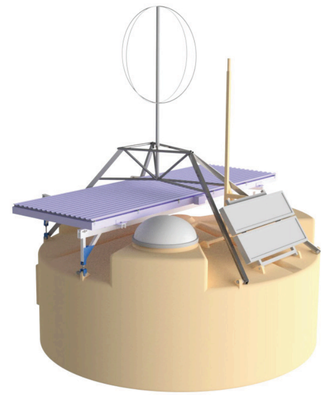
UHECR2022:
6th International Symposium on Ultra High Energy Cosmic Rays

AugerPrime: status and prospects

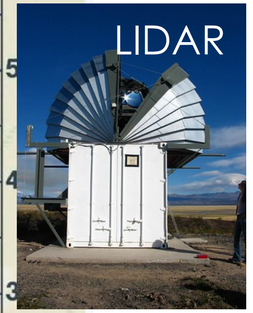
Corinne Berat [1] for the Pierre Auger Collaboration

(1) LPSC, Université Grenoble Alpes, CNRS/IN2P3.



Pierre Auger Observatory

- **The largest cosmic ray observatory, designed as an hybrid detector**
  - **surface detector (SD)** : water Cherenkov detectors (WCD)
    - 1600 on 3000 km^2, 1.5 km spacing
    - 61 additional SD stations « Infill »
      - on 27.56 km^2 with 750 m
      - on 1,95 km^2 with 433m spacing
  - **Fluorescence detector (FD)**: optical telescopes
    - 24 in 4 buildings overlooking SD
    - 3 in 1 building overlooking the denser array
  - **Engineering arrays (infill)**=> multi-hybrid
    - Auger Engineering Radio Array (AERA)
    - Buried muon detectors
  - **Atmosphere measurements** and monitoring



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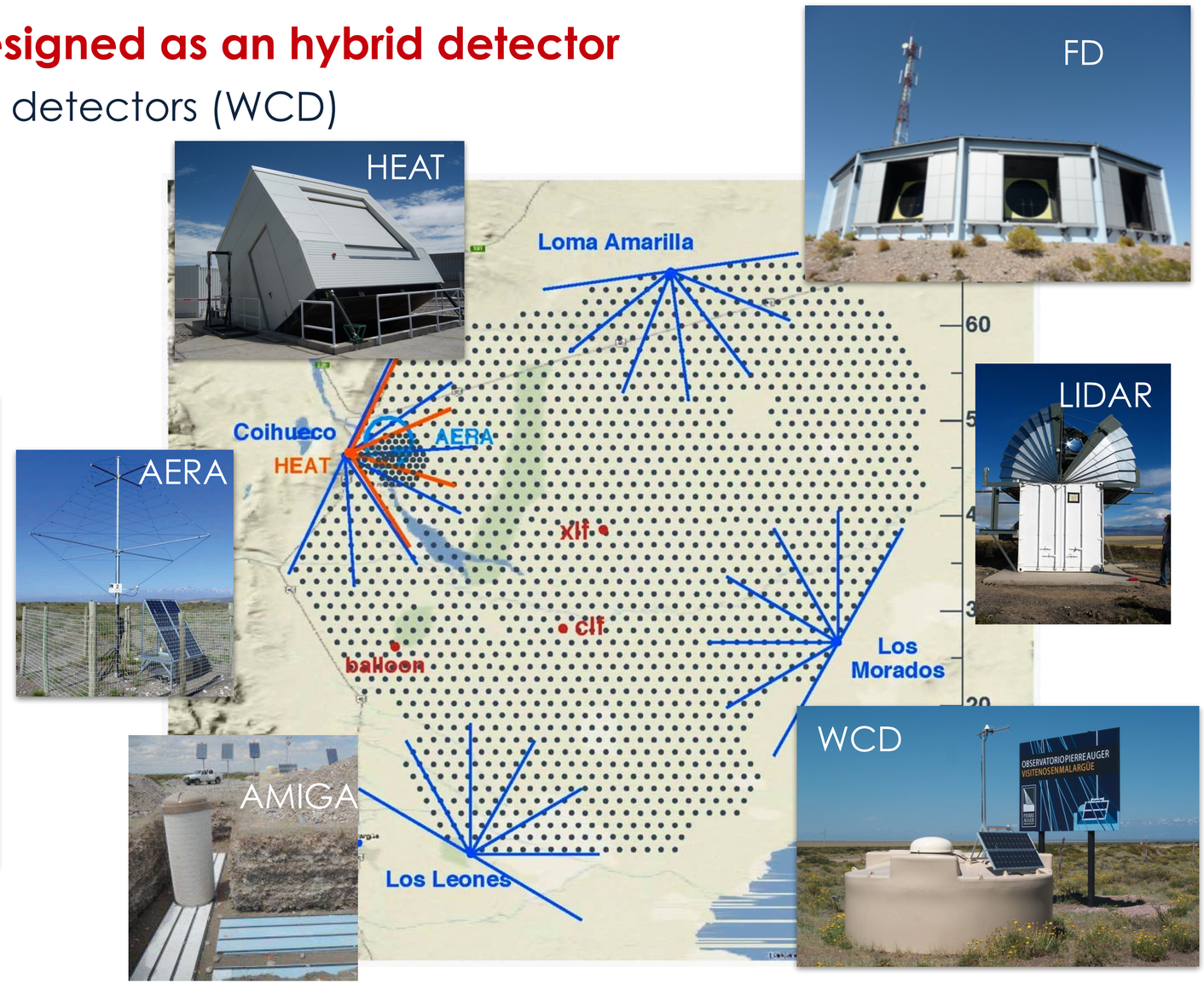
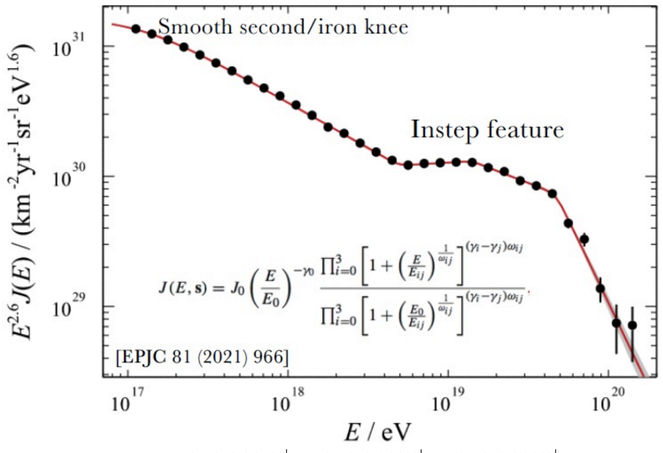
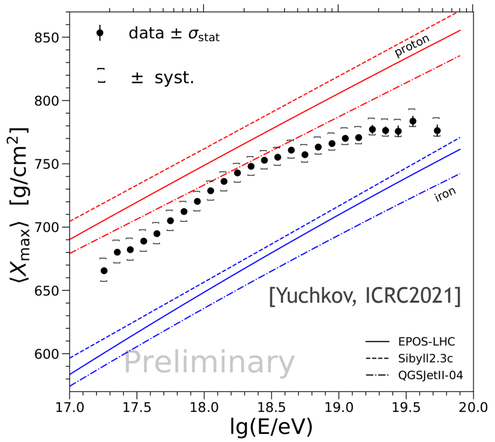
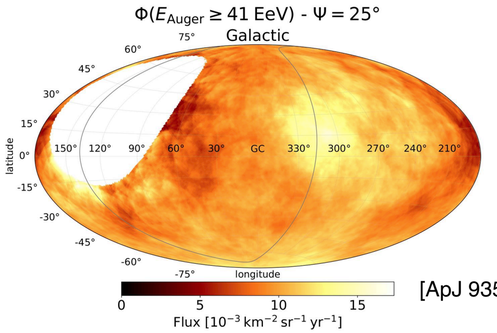
- **Surface Detector Calibration**
  - WCD signals measured in VEM units, 1 VEM = signal produced by a vertical muon traversing the WCD
  - **Conversion in VEM : provide a common reference level between WCD**
  - SD calibration : 1VEM <-> hardware units



Auger Phase I: harvest of results







[ApJ 935 (2022)170]

The largest exposure to UHECR
High quality measurements

- **Spectrum**
- **Composition**
- **Anisotropies**
- **Neutral searches and Multi-messenger physics**
- **Hadronic interactions**

and more …

Highest E events:
Mario Buscemi, talk 3/10

Spectrum:
Quentin Luce, Valerio Verzi, talks 3/10

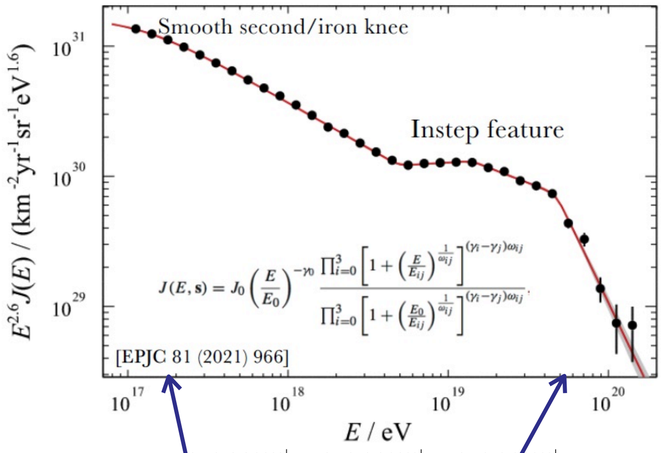
Composition and HI:
Jakob Vischa, talk 5/10,
Bjarni Pont, talk 3/10

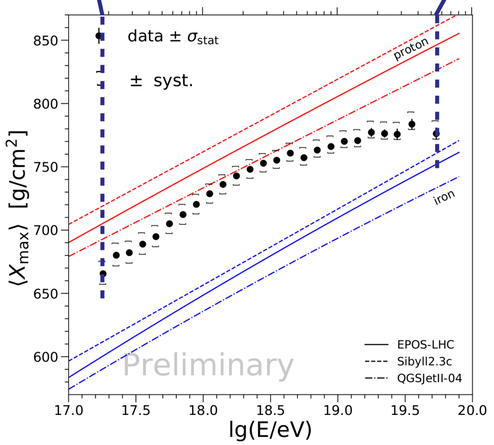
Anisotropies:
Ugo Giaccari, Eric Mayotte,
Federico Urban, talks 4/10

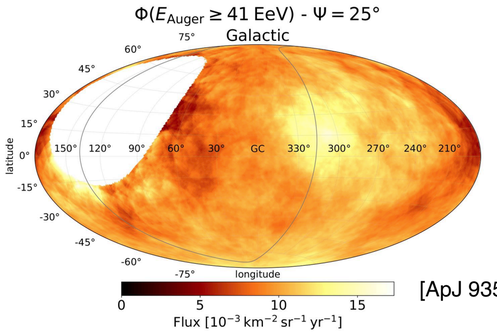
Neutrals:
Marcus Niechciol, talk 4/10
Multi-messengers: Lorenzo Perrone, talk 4/10, Vladimír Novotný, poster

⇒ **Open questions**

AugerPrime main goals







[ApJ 935 (2022)170]

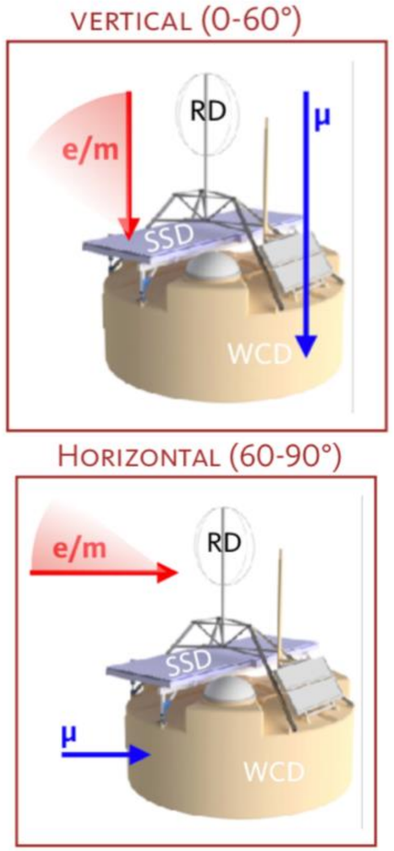
- **Composition measurement to the highest energies**
  - origin of the flux suppression
- **Event-by-event composition**
  - composition enhanced anisotropy studies
  - constraints on UHECR sources
  - particle astronomy?
- **Enhance sensitivity to γ-rays and ν fluxes**
  - exploring the potential of future experiments
- **Study of EAS and hadronic multiparticle production above √s=70 TeV**
  - address the inconsistencies in the muon content predicted/observed
  - particle physics beyond human-made accelerators
  - constraints on new physics phenomena

Number of muons: quantity that strongly correlates with primary mass.

Upgrade Key point : disentangling the muonic and electromagnetic components of the Extensive Air Showers

The AugerPrime components

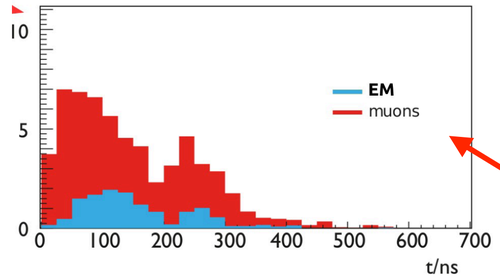
➤ Complementary measurement of the shower particles

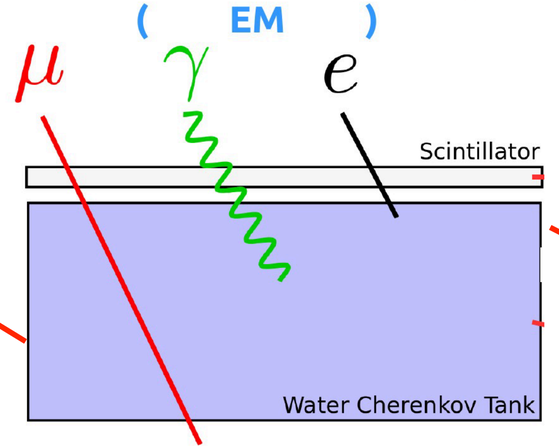


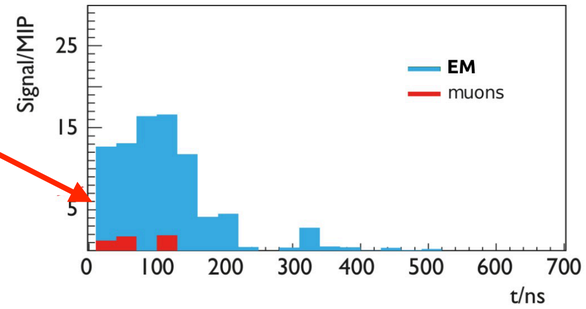
➡ Adding mass sensitivity to the SD : new detectors above WCD

➤ Plastic Surface Scintillator Detectors (SSD)

Significantly more sensitive to muons.







➤ Radio antenna

- to measure the radio emission (30-80 MHz) of inclined showers

➤ Additional small PMT in the WCD

- to increase the dynamic range

➤ Underground Muon Detector (UMD)

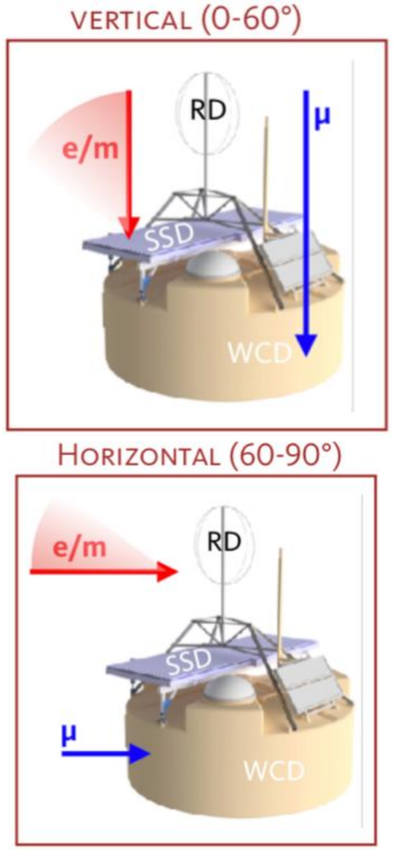
- to measure N_μ in low energy shower (denser array)

➤ New electronics

- to process / interface signals from all detectors

The AugerPrime components

- **Complementary measurement of the shower particles**



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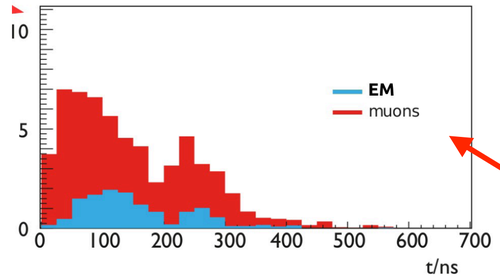
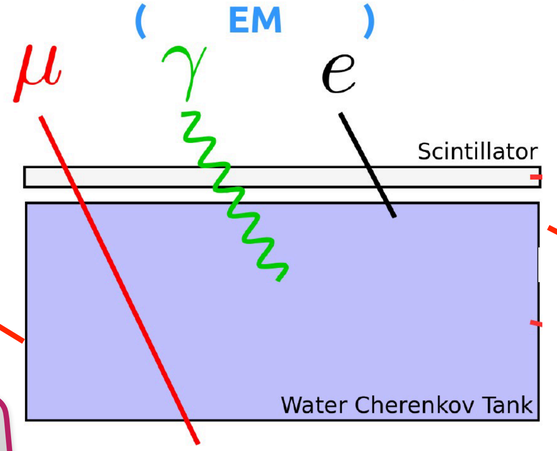
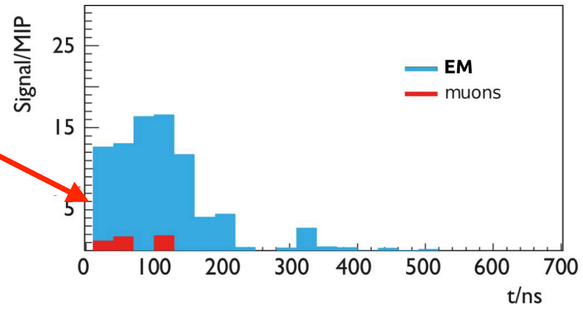
- **Plastic Surface Scintillator Detectors (SSD)**

Significantly more sensitive to muons.







- **Radi**
  - to m sion (30-80 MHz) of inclined showers

Tim Hugue's talk, Friday 7/10

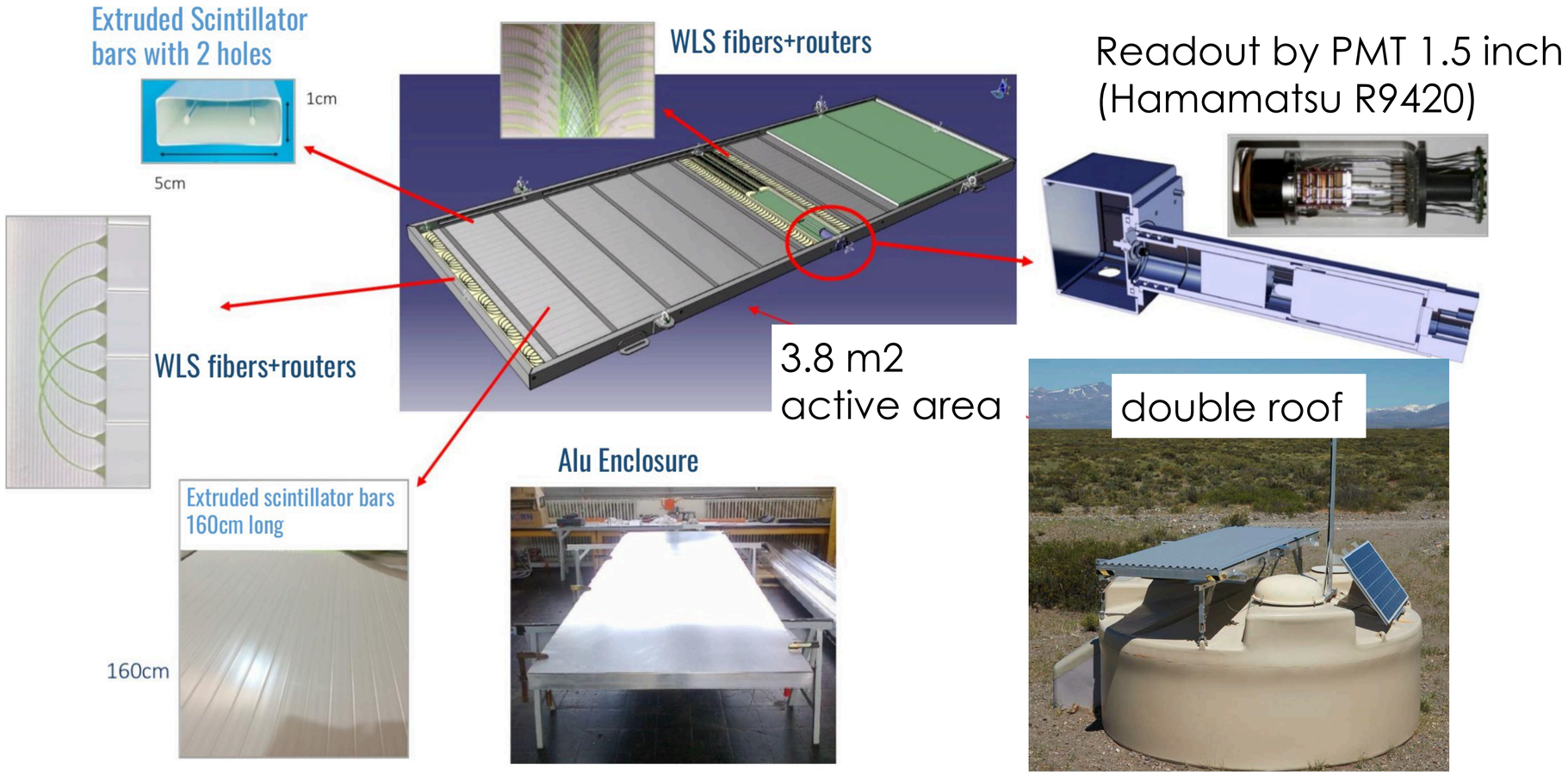
- **Additional small PMT in the WCD**
  - to increase the dynamic range
- **Unde MD)**
  - to m ergy shower (denser array)

Marina Scornavacche's Poster

- **New electronics**
  - to process / interface signals from all detectors

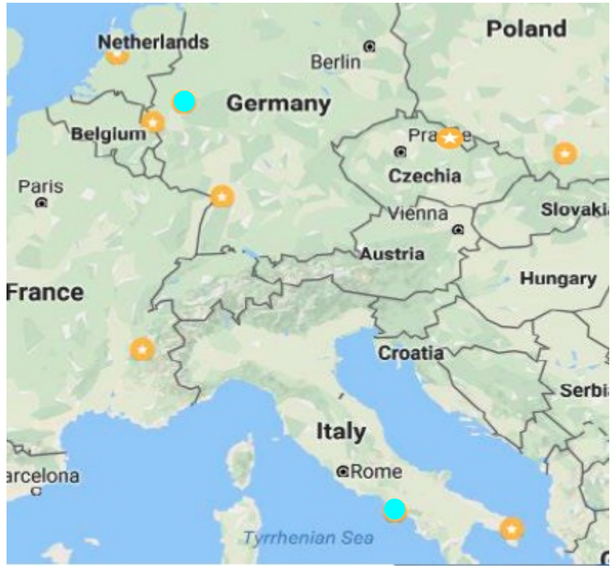
The Surface Scintillator Detector

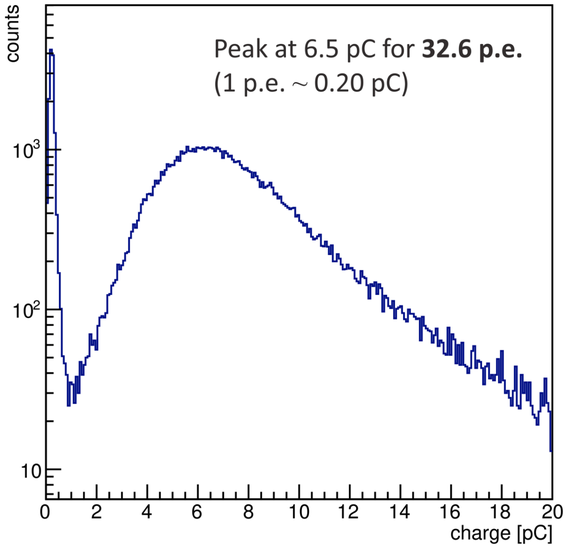
- **Components**
  - Extruded scintillator bars (1600x50x10 mm), 2 x 24 per detector
  - WLS fibers (Kuraray 1 mm)



The Surface Scintillator Detector

- **Production and tests of SSD modules**
  - 1518 SSDs produced and tested in 7 European research institutes
- **Tests using atmospheric muons**
  - Light tightness
  - Minimum Ionizing Particles (MIP) unit for the signal calibration MIP/SPE to check the quality of SSD modules





30 ± 2 pe. per MIP

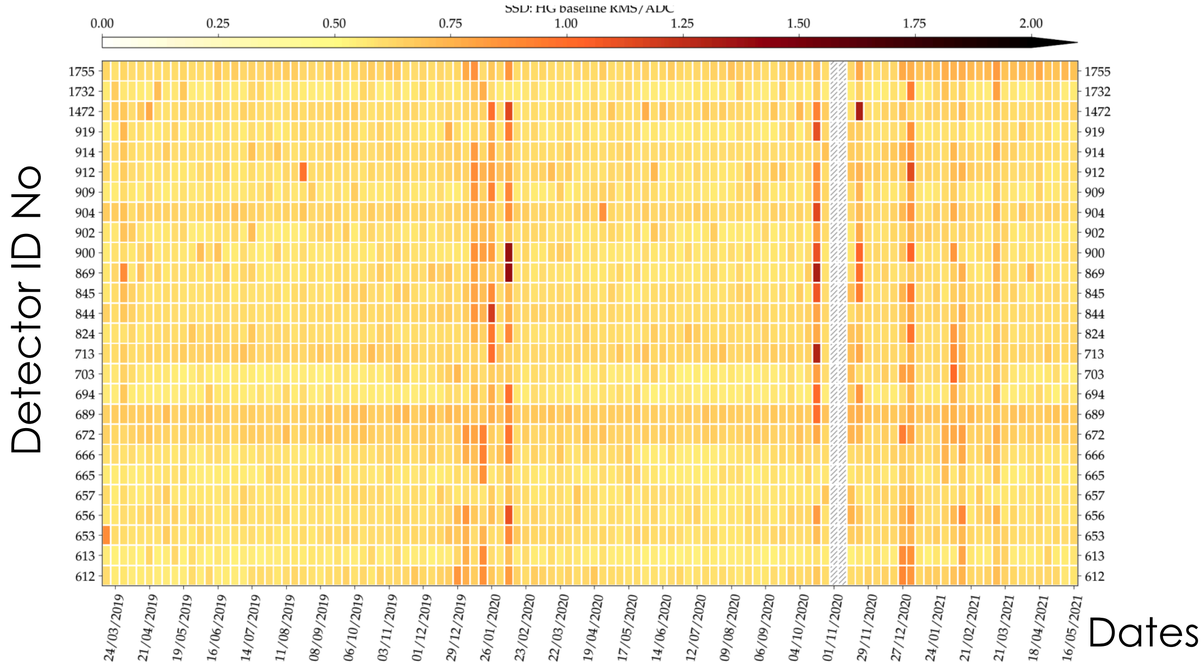
- **Tests and validation of all SSD PMTs**
  - performed in 2 European research institutes
  - Linear response in a wide range

➡ **Shipment to Argentina**

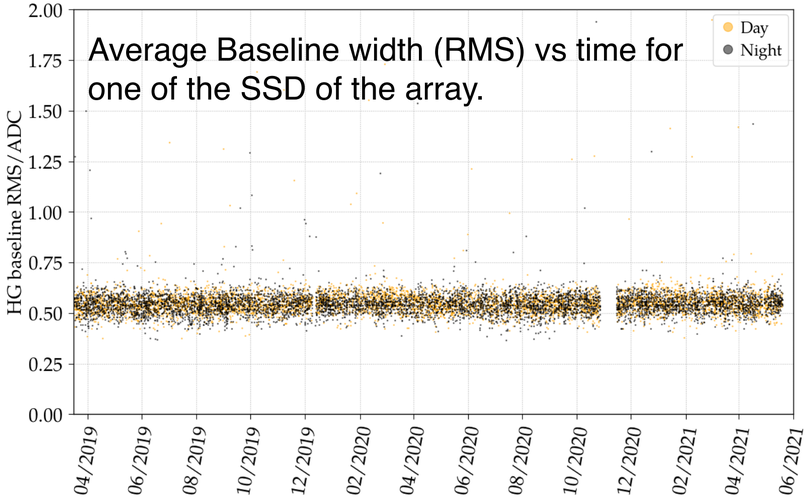
SSD Preproduction array

- **Check SSD performance on site**
  - 77 SSD installed in March 2019
  - adapted version of non-upgraded electronics
    (1 LPMT of the WDC disconnected, to connect the SSD PMT)
  - Monitoring of the SSD during several months

Evolution of the RMS (in ADC counts) for the PMTs trace (HG channel) for a subsample of SSD of the preproduction array



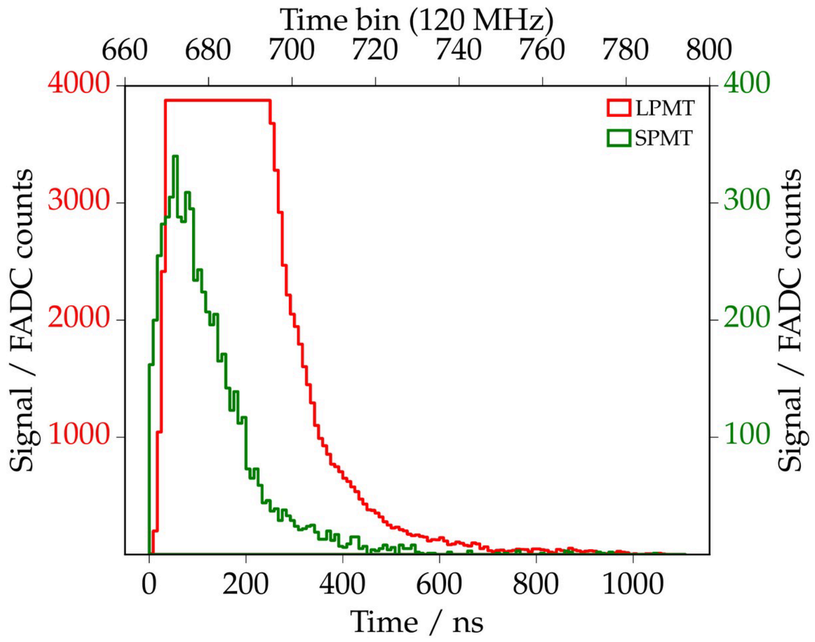
Light tightness



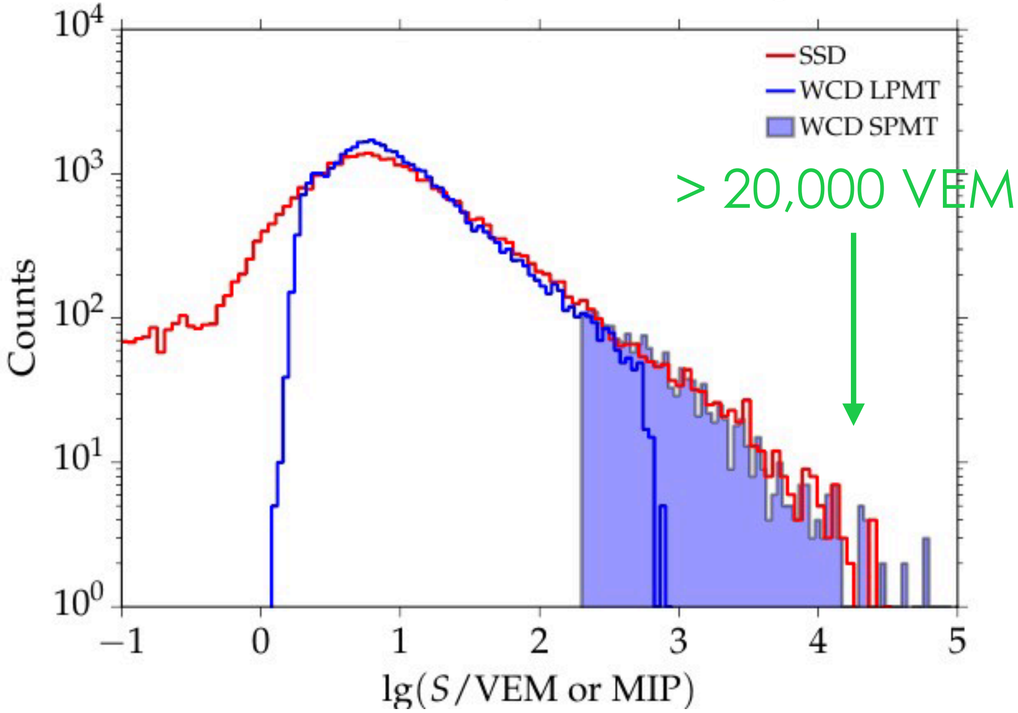
PoS(ICRC2021)251

The Small PMT

- **4th PMT installed in each WCD**
  - Hamamatsu R8619 1-inch diameter PMT
  - passive base, power supply in a separate box (G.A. Anastasi et al., 2022 JINST 17 T04003)
  - Linearity and gain curves of each SPMT carefully measured (M. Buscemi et al., 2020 JINST 15 P
  - active area ~100 times smaller, gain optimisation =>as close as 250 m from the shower core
  -



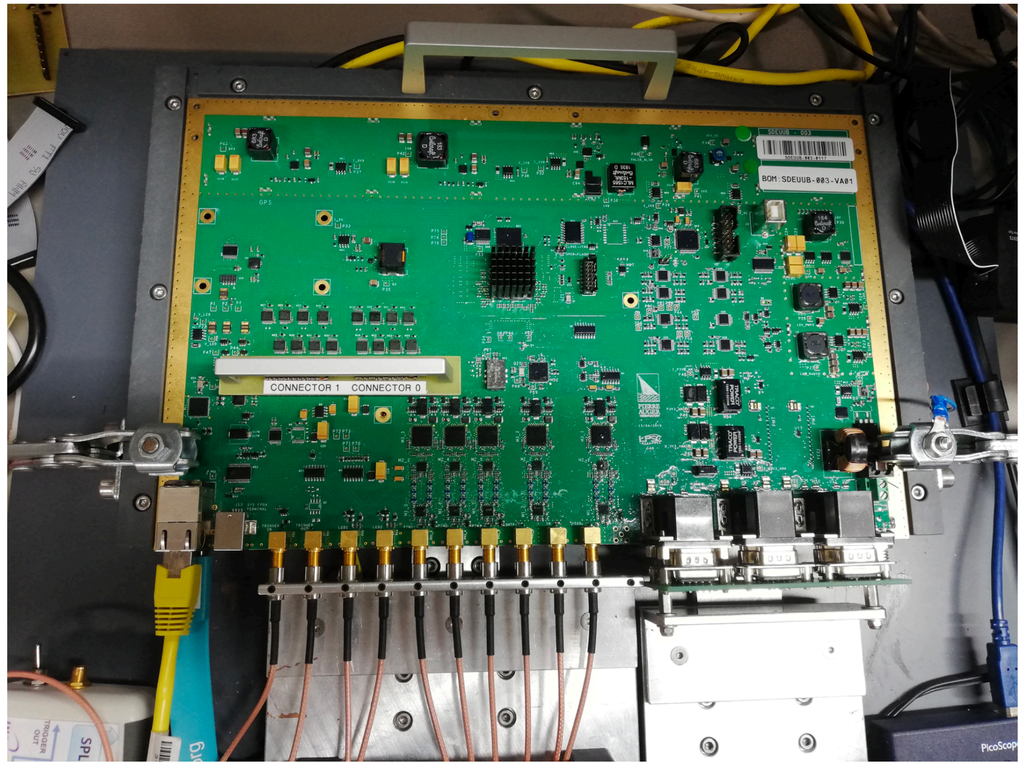
Extension of the dynamic range



The Upgraded Unified Electronics (UUB)

- **onboard**
  - analog signal processing
  - triggering, calibration (WCD + SSD PMTs)
  - GPS time tagging, data acquisition
  - interface with UMD and RD systems
  - acquisition and communications via radio transmitter

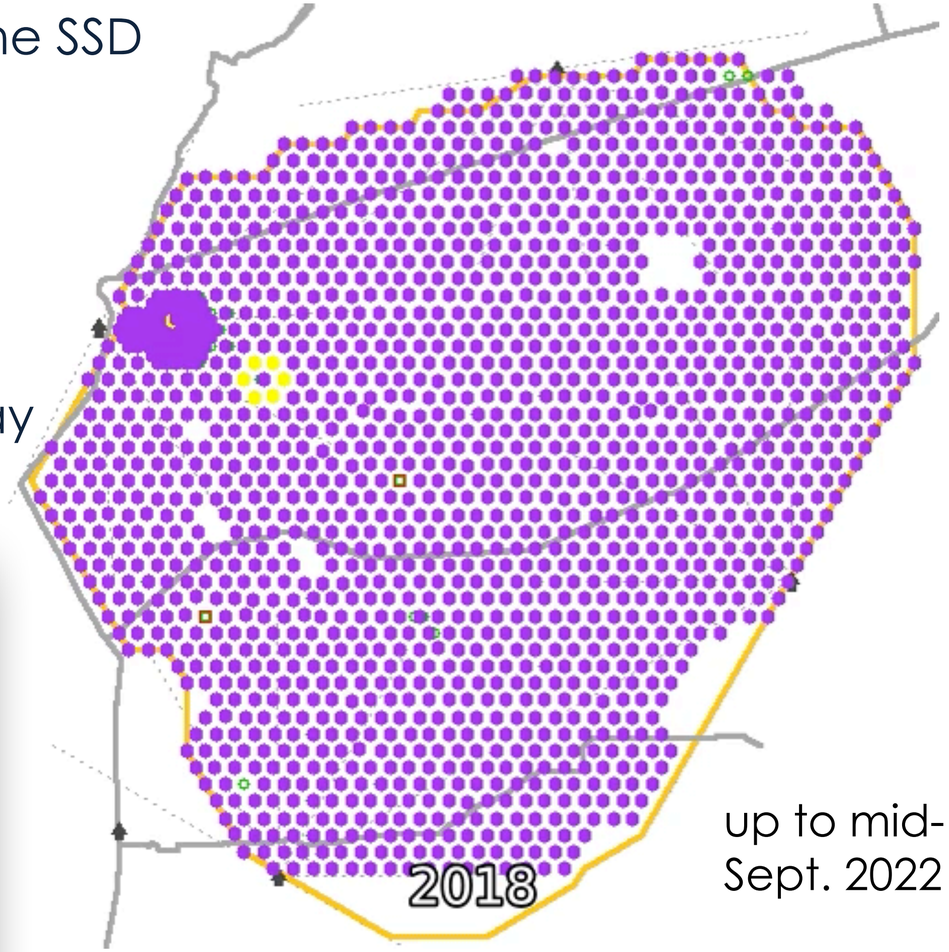
- **With respect to old electronics :**
  - faster ADCs (40 —> 120 MHz)
  - larger dynamic range (10 —>12 bits)
  - significantly more powerful FPGA
  - upgraded CPU (> 10 times faster)
  - backwards-compatibility
    - fit the enclosure of current electronics
    - accept the existing connection cables



- Production started on March 21
- Manufacturing: SITAEL SpA company
- tests after production
- Environmental Stress Screening tests in one European research institute

Deployment status

- **SSD**
  - In spite of the Covid-19 pandemic, the deployment of the SSD was completed (except on the boarder)
  - end of deployment: march 2022
- **UUB and sPMT**
  - Since 12/2020
  - now ~560 detector stations upgraded - $\gtrsim$ 30% of the array



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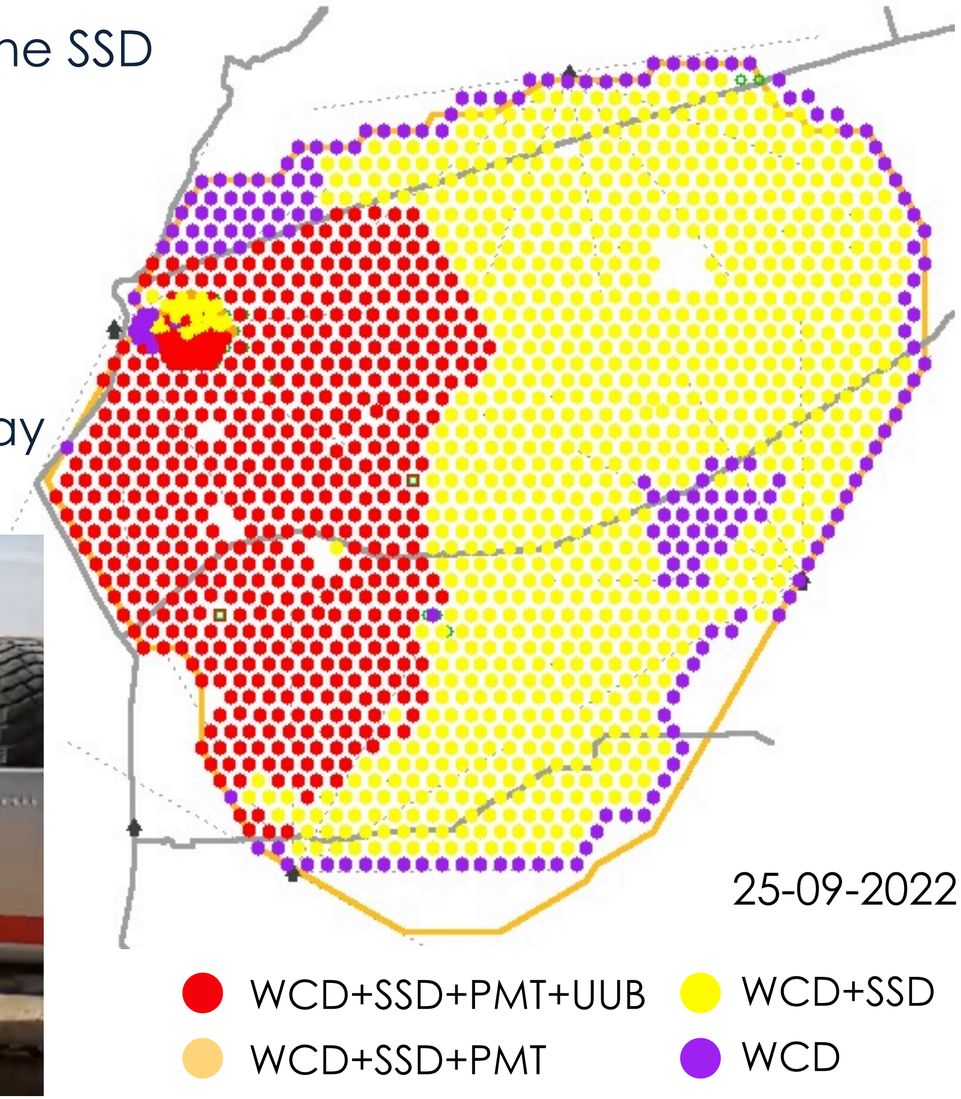
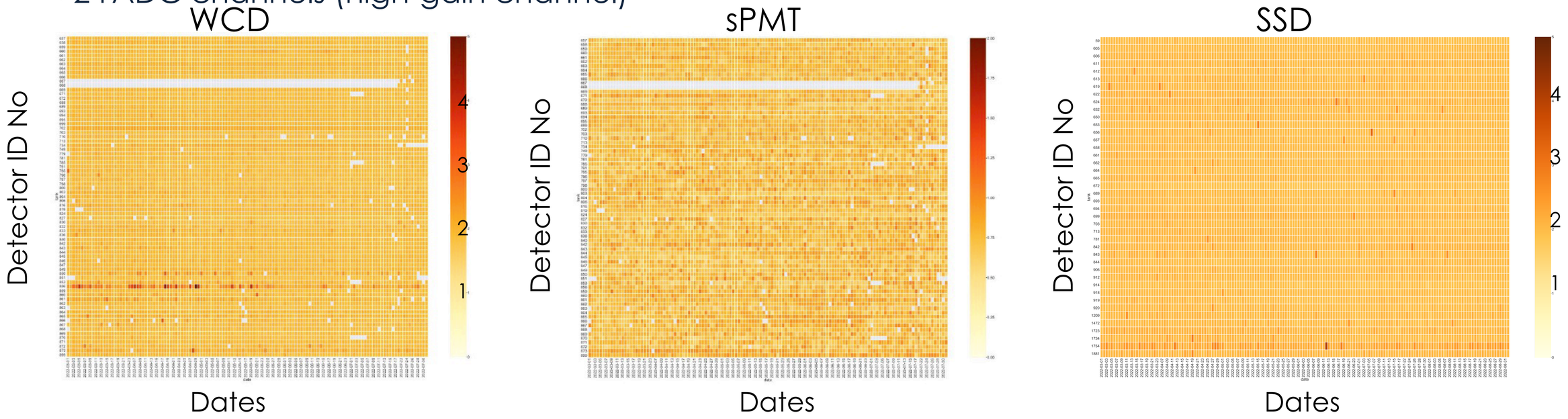
Thanks to the strong commitment and effort from the staff in Malargüe



AugerPrime detector commissioning

- **DAQ running without major interruption**
- **Level of noise as expected**
  - monitoring of the baselines for LPMT and sPMT during 5 months
  - < 2 FADC channels (high-gain channel)



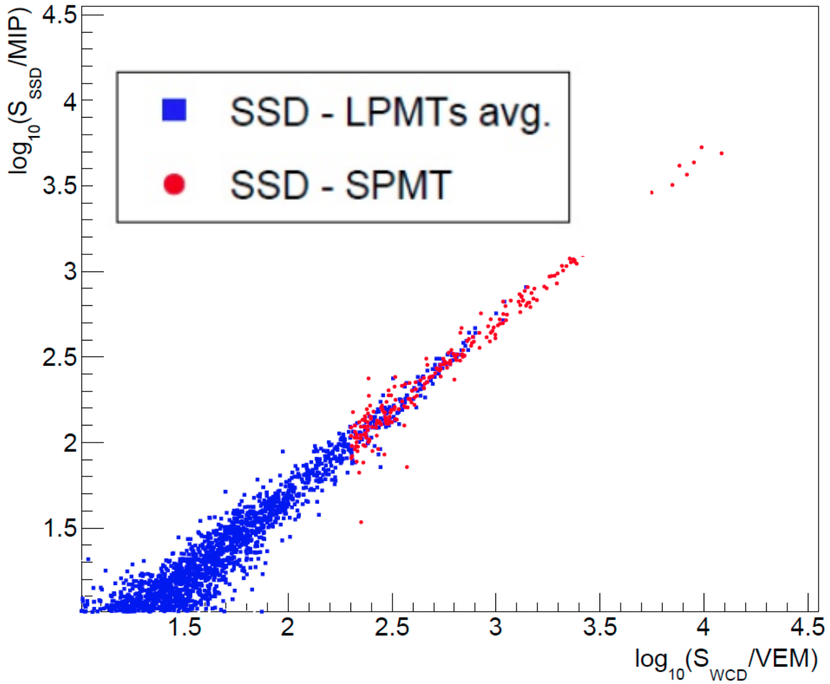
- **Timing & trigger rates**
  - time resolution ~5ns (measured using showers triggering 2 nearby stations)
  - some issues solved, other under detailed studies

- All triggers running at 40 MHz (backwards compatible)

AugerPrime detector calibration

Calibration and cross-calibration

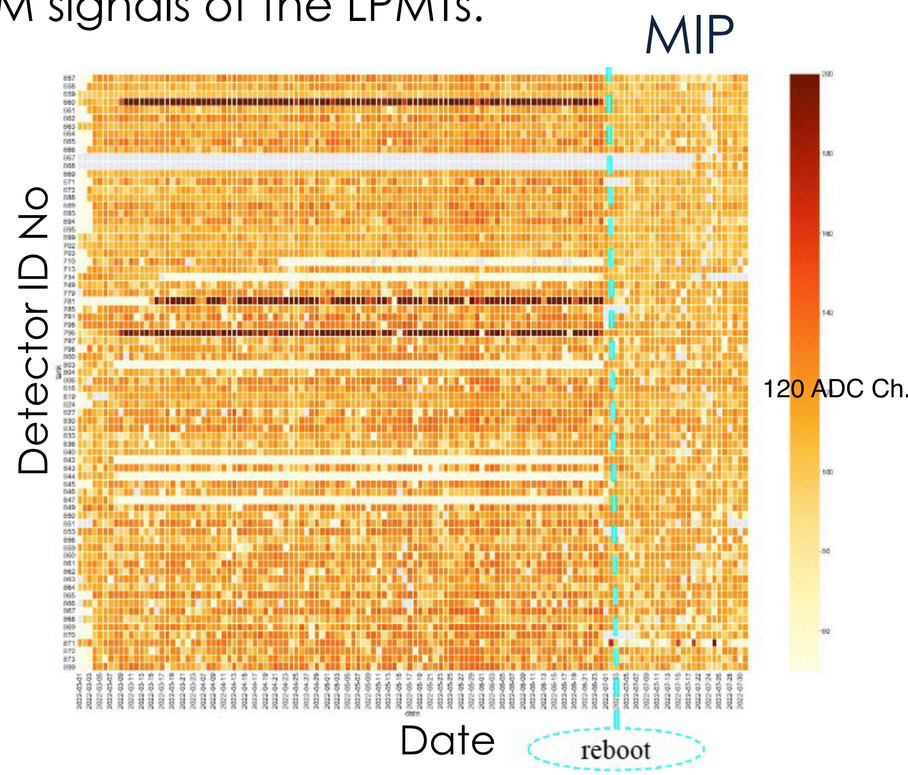
- done using atmospheric muon signals acquired by dedicated triggers for LPMT and SSD PMT
  - WCD PMTs unit : VEM - SSD PMT unit : MIP
  - About 40% of WCD calibration triggers produce a MIP in the SSD.
- small local showers selected to cross-calibrate sPMT using the VEM signals of the LPMTs.



➡Very good correlation between the calibrated signals of the WCD and SSD

➡Stability of calibration

VEM and MIP monitored



On-going: use SSD data to perform better WCD calibrations

Reconstruction of events

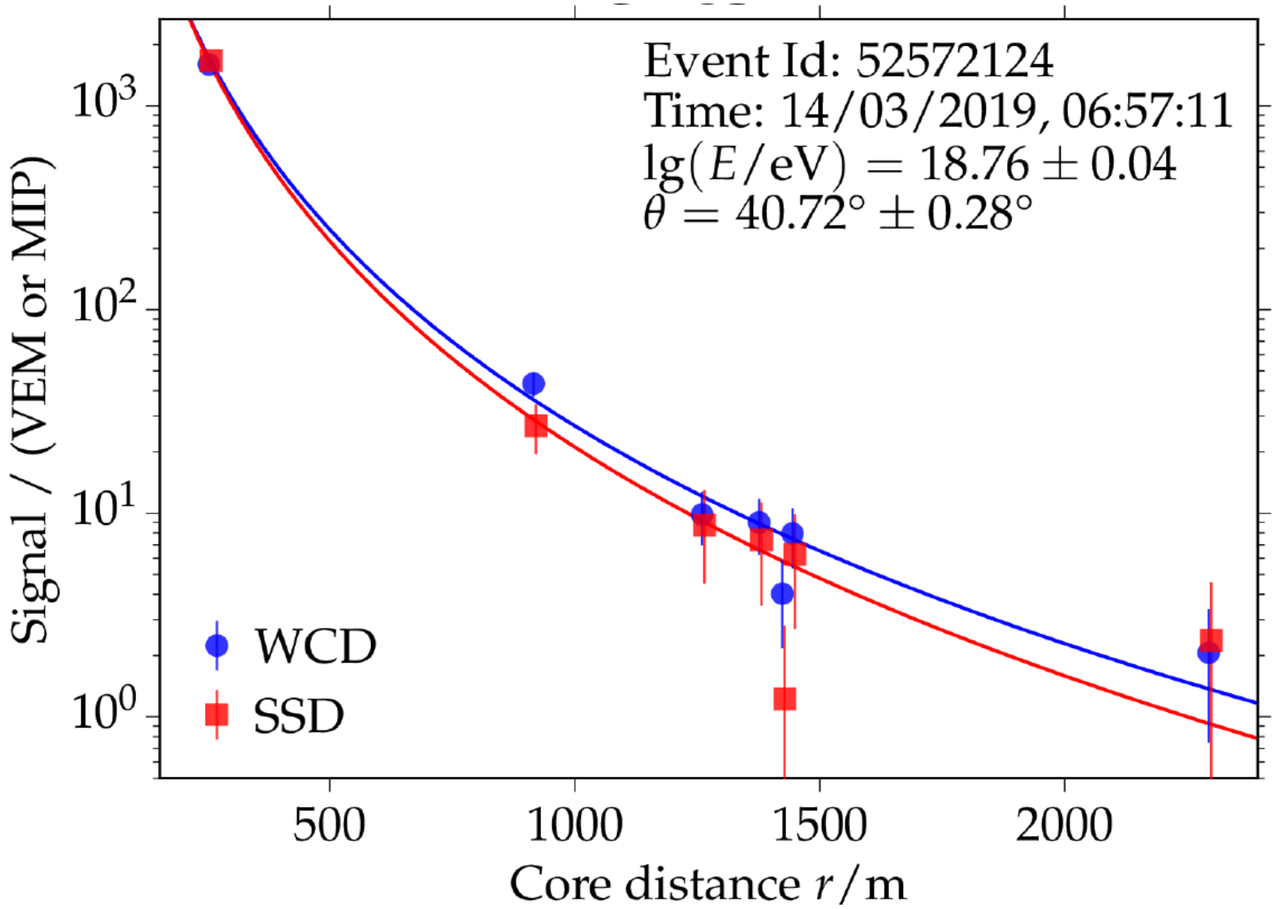
- **LDF reconstruction**
  - Modified NKG-like function

$$S(r) = S(r_{\mathrm{opt}}) f_{\mathrm{NKG}}(r)$$

$$f_{\mathrm{NKG}}(r) = \left(\frac{r}{r_{\mathrm{opt}}}\right)^{\beta} \left(\frac{r + r_{\mathrm{s}}}{r_{\mathrm{opt}} + r_{\mathrm{s}}}\right)^{\beta+\gamma}$$

    - r_{opt} = 1000m

  - lateral distribution measured with both SSD and WCD
  - different slopes clearly visible

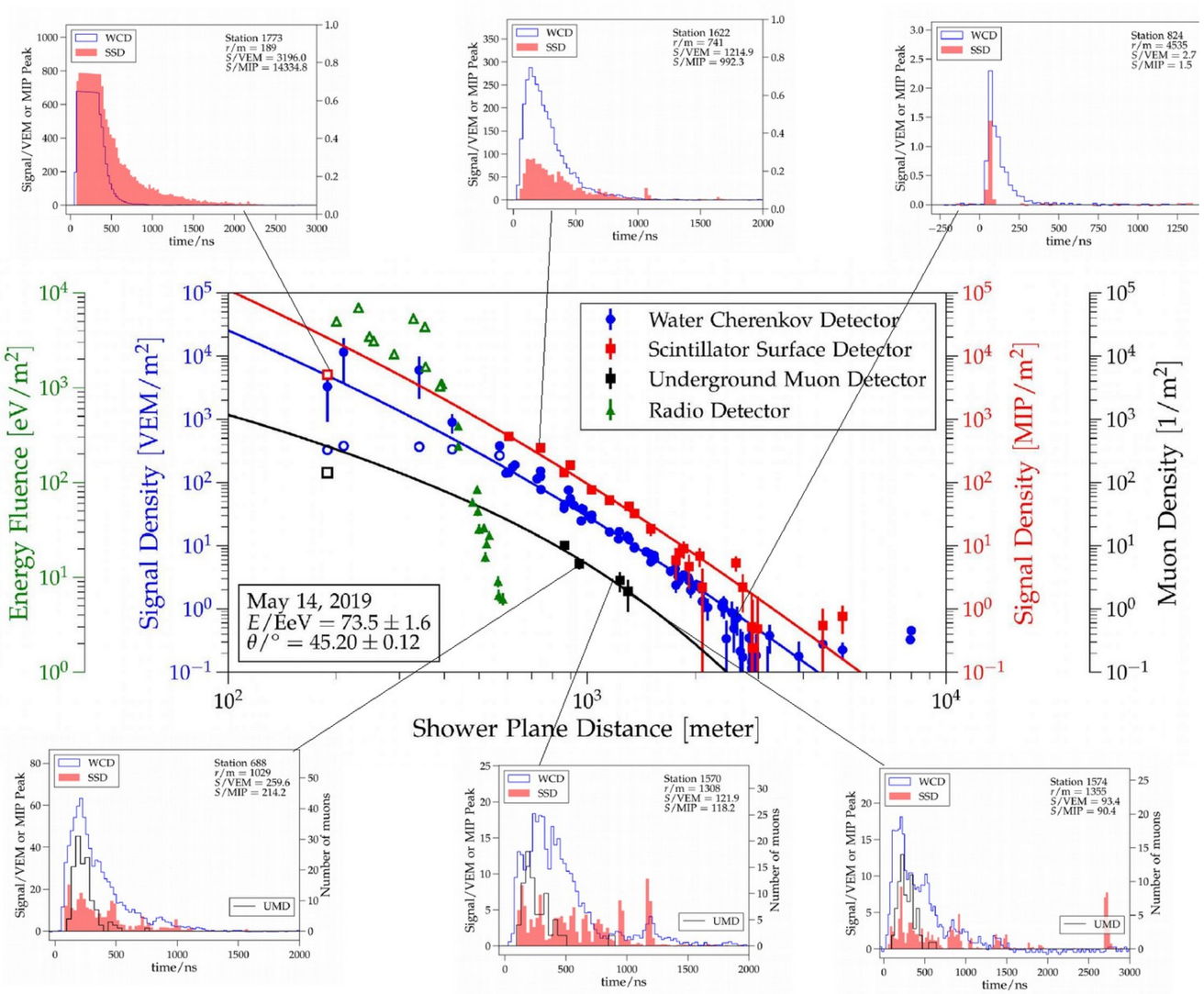


Prospects

- **Deployment**
  - Production of electronics boards should be completed on November 2022
  - Deployment will continue up to mid-2023.

- **Event reconstruction**
  - several studies to improve reconstruction
  - Sophisticated algorithms using time structure of traces also in development.
    - principles of air shower universality
    - machine learning techniques

- Multi hybrid measurements with AugerPrime



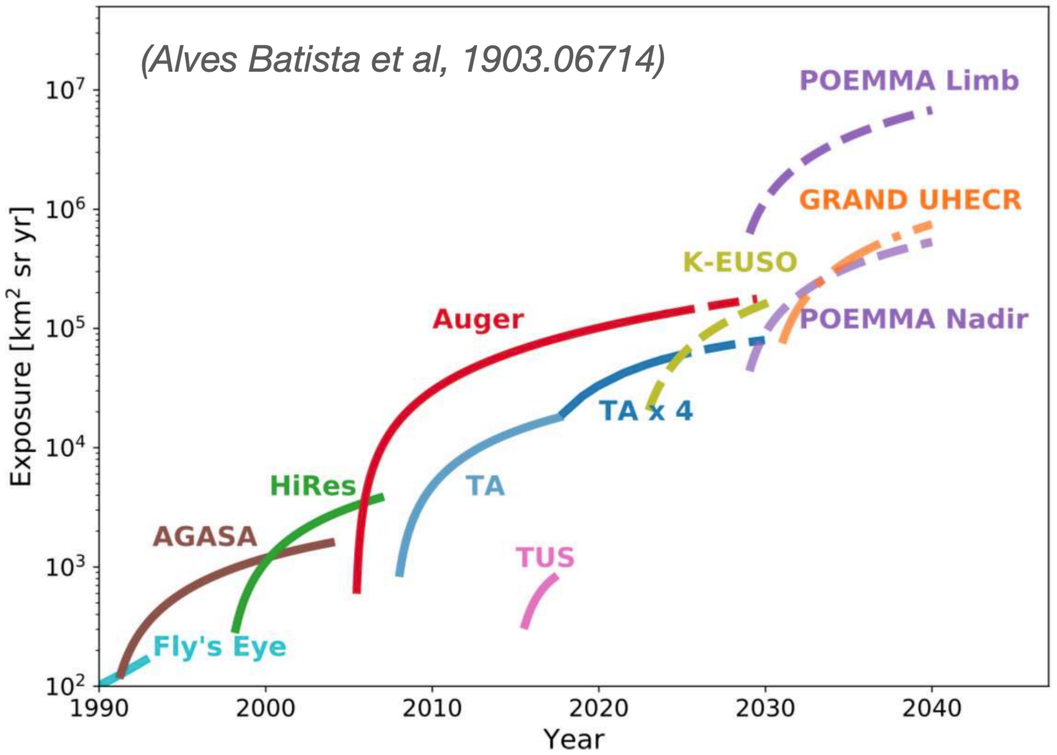
Lateral distribution of signals from WCD, SSD, UMD and RD of a real event, including a fit (solid red, blue and black lines) to the measured data.

Prospects

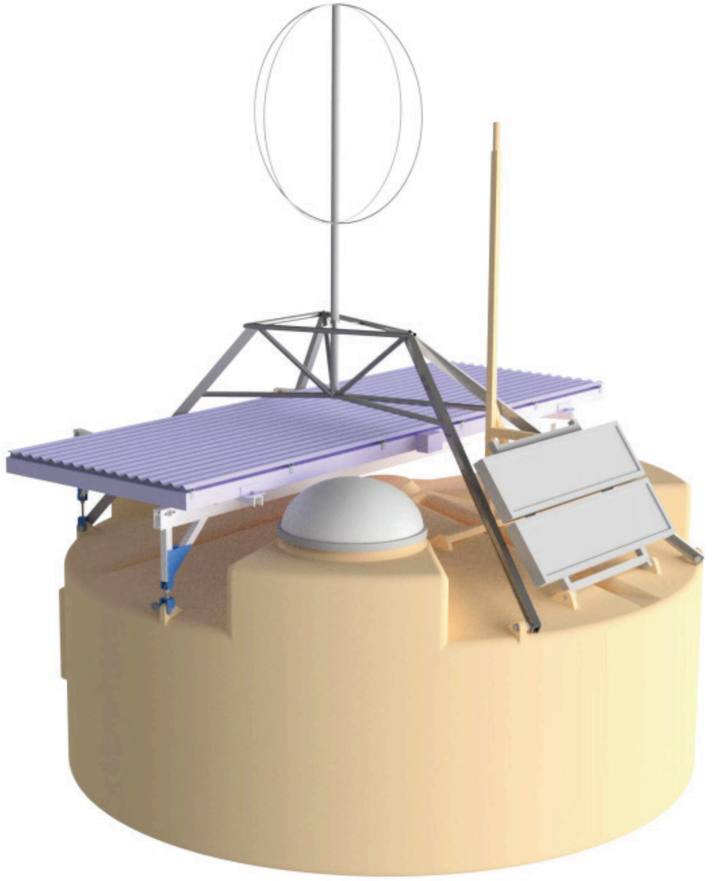
- **Moving towards primary mass**
  - on-going work on deconvolution of the contributions of the electromagnetic and muonic shower components
  - Physics analysis coming soon !

- **Auger Phase II**

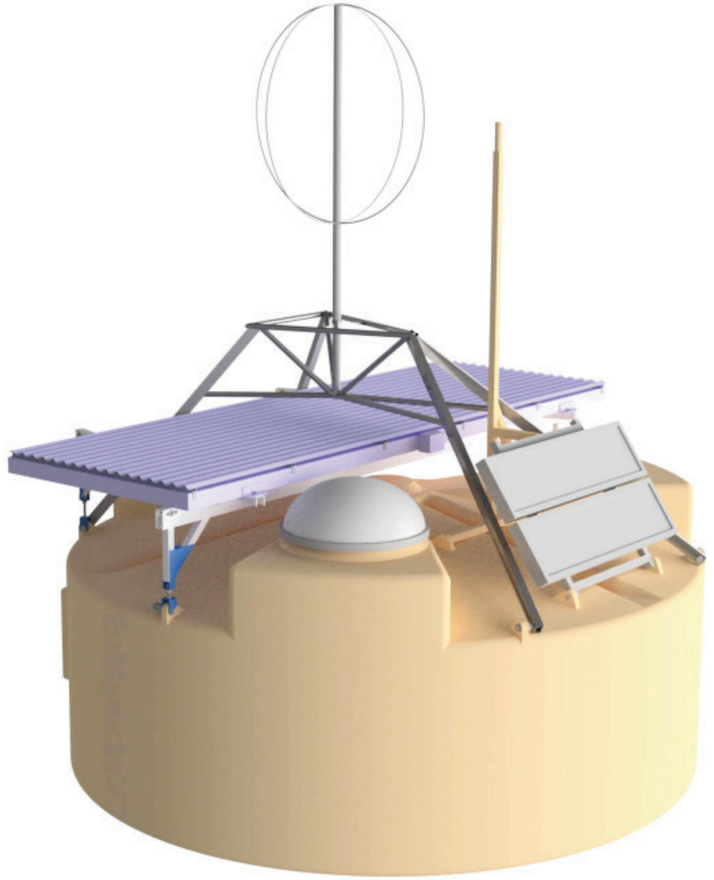
- Data taking 2022/23 – 2030
- ~40 000 km^2 sr yr $\theta < 60°$
- Re-analysis of Phase I data set (machine learning techniques)



Thank you !

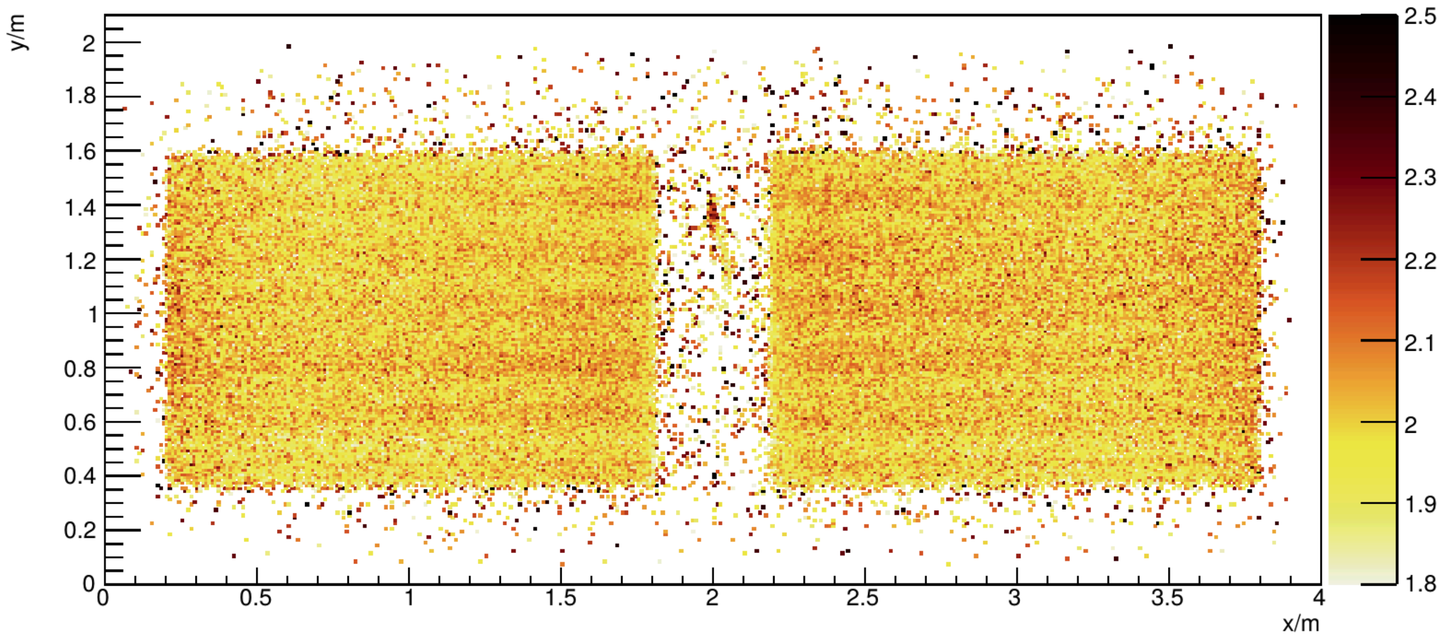


Backup



The Surface Scintillator Detector

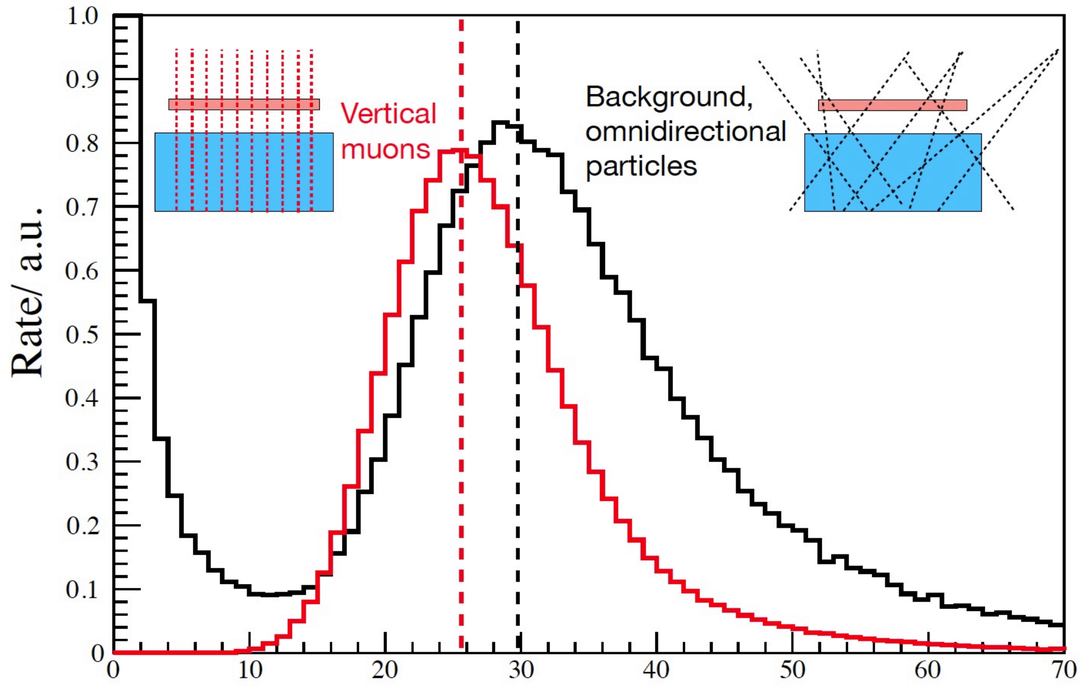
- **Test procedure during production**
  - Using atmospheric muons
    - The uniformity in the response of the SSD detectors can be measured via external trackers (e.g. planes of limited streamer tubes) on a muon tower setup.



    - ± 5 % along the bars, ± 10 % between bars

SSD Calibration

From Multidirectional muons to MIP



MIP defined as peak of charge distribution produced by uniformly incident, vertical muons

Stable relationship with peak of charge from omnidirectional background

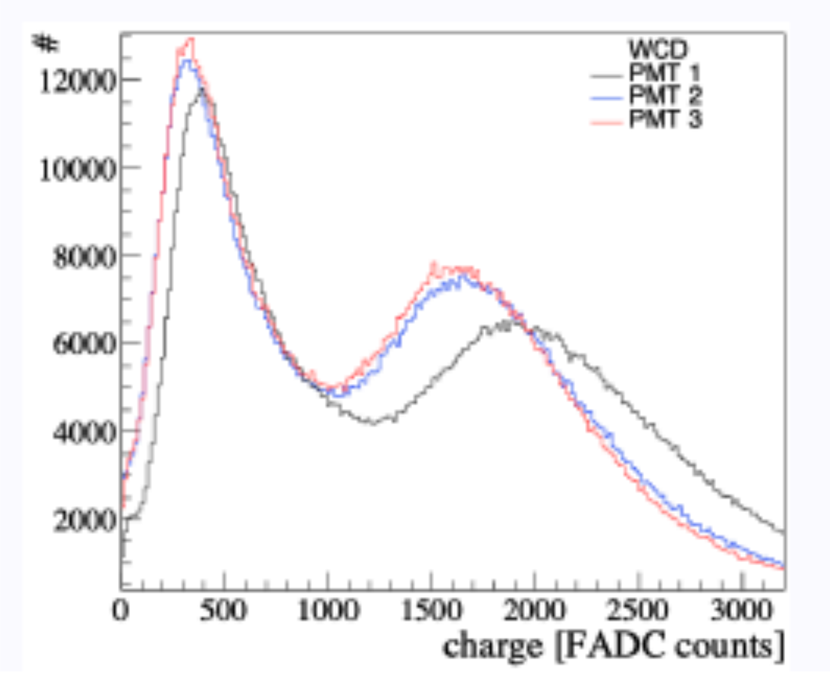
Estimated ratio of 1.16 ± 0.02 from simulations

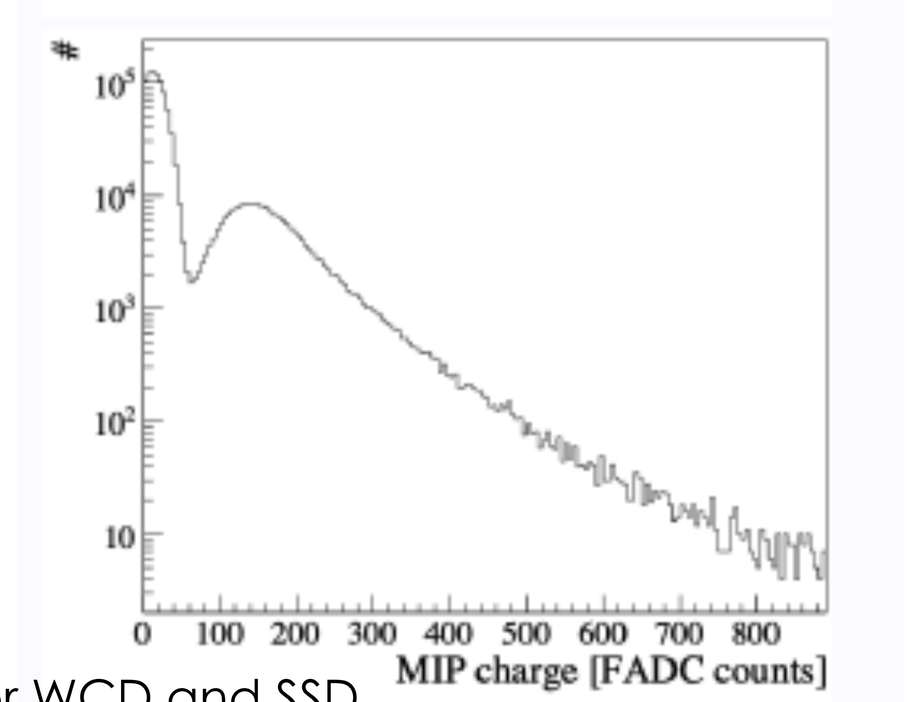
In situ measurement planned

AugerPrime detector calibration

Calibration and cross-calibration

- done using atmospheric muon signals acquired by dedicated triggers for LPMT and SSD PMT
  - WCD PMTs unit : VEM - SSD PMT unit : MIP
  - About 40% of WCD calibration triggers produce a MIP in the SSD.



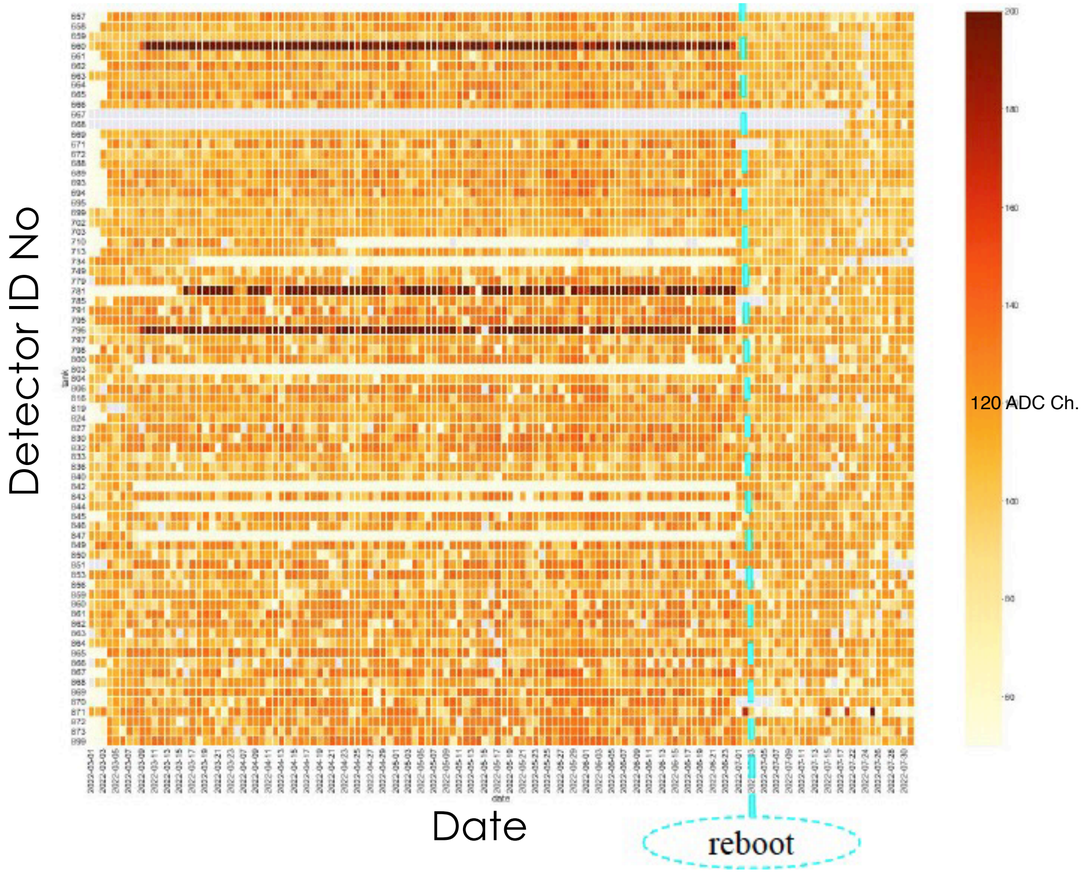


Calibration histograms for WCD and SSD

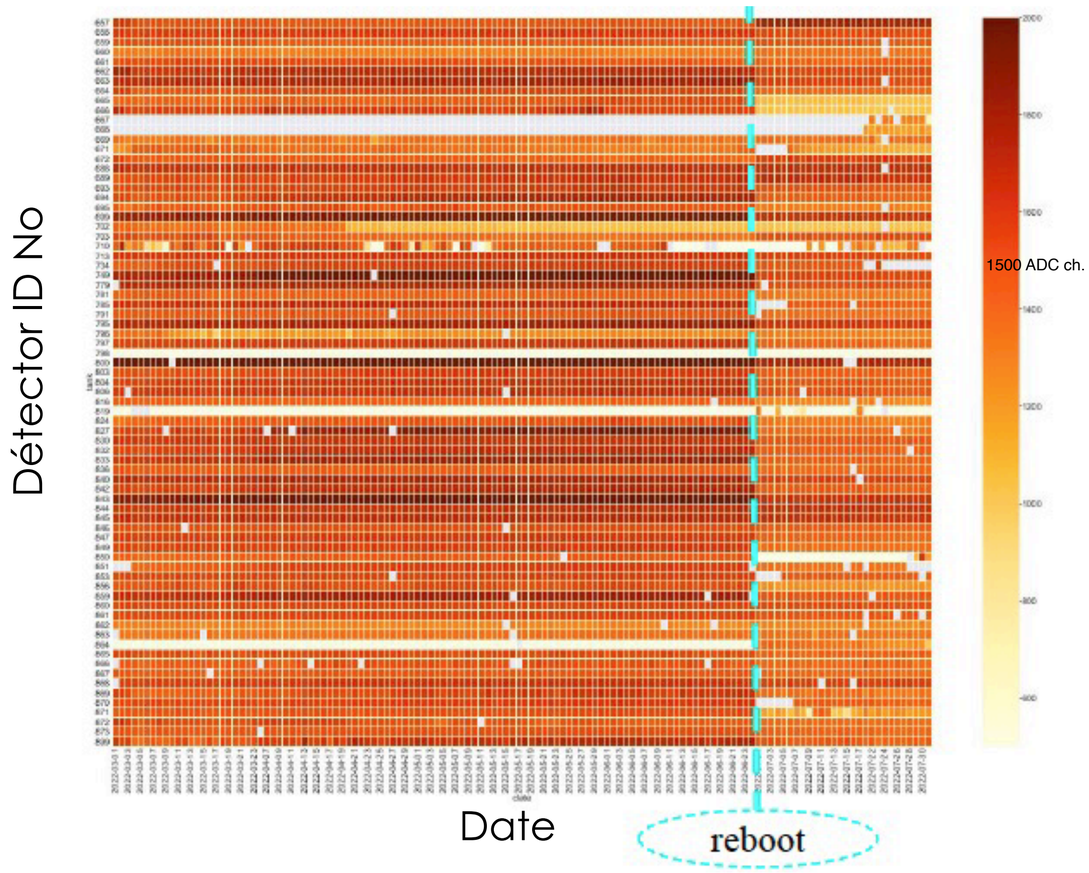
AugerPrime detector calibration

- **Stability of calibration parameters**

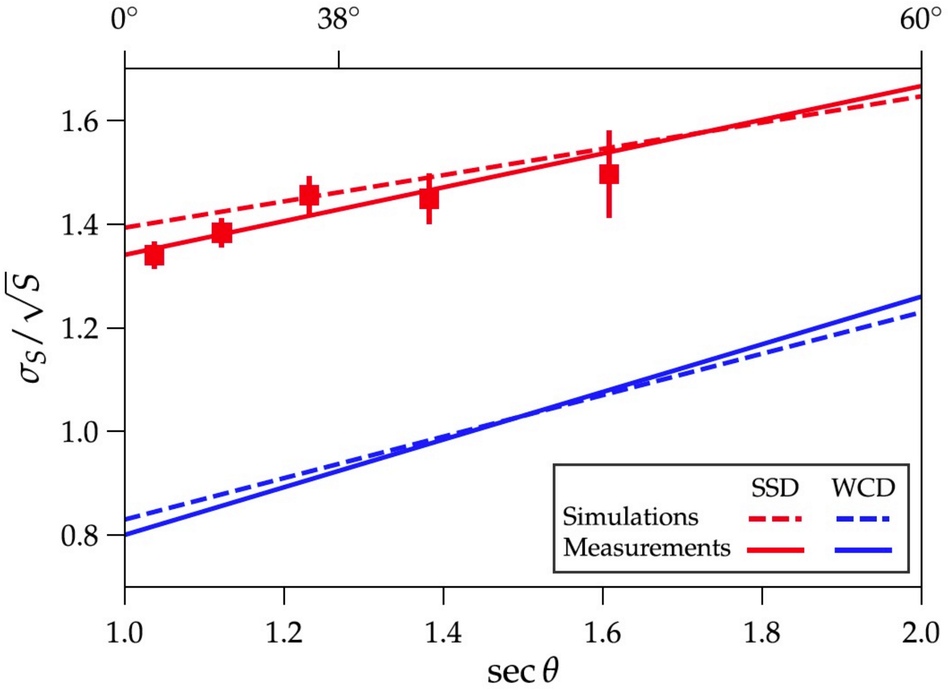
MIP



VEM

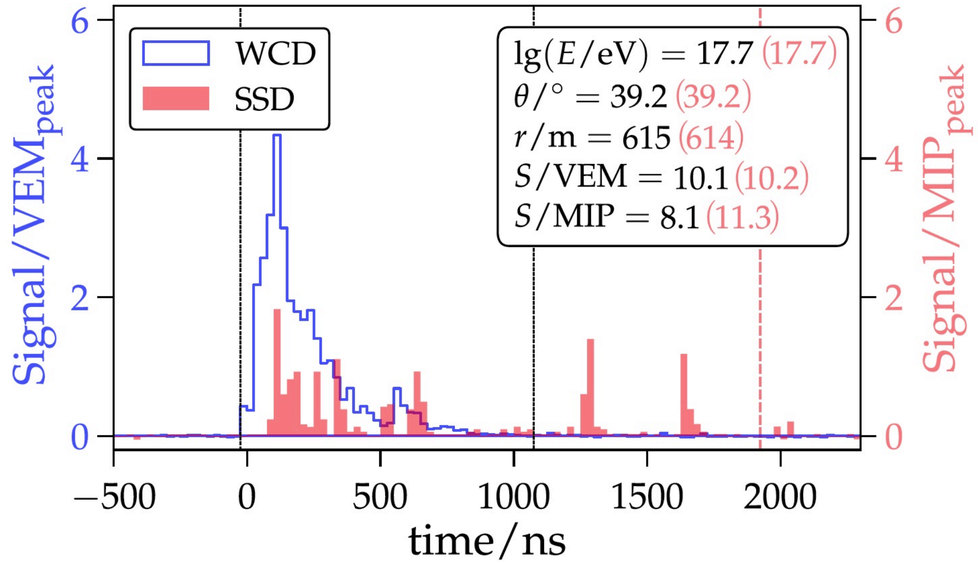


Signal Uncertainties



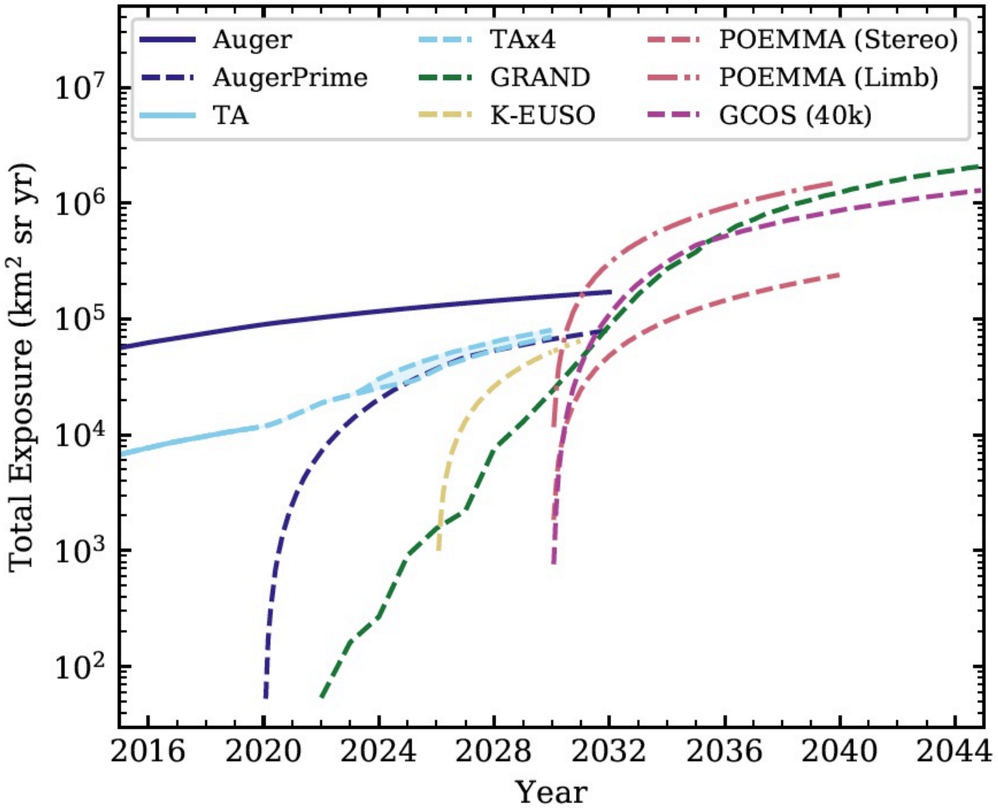
- Sampling fluctuations…
  - measured with multiplet stations
  - simulated with pseudo-doublets •
- Results comparable for both WCD and SSD

Integration Window



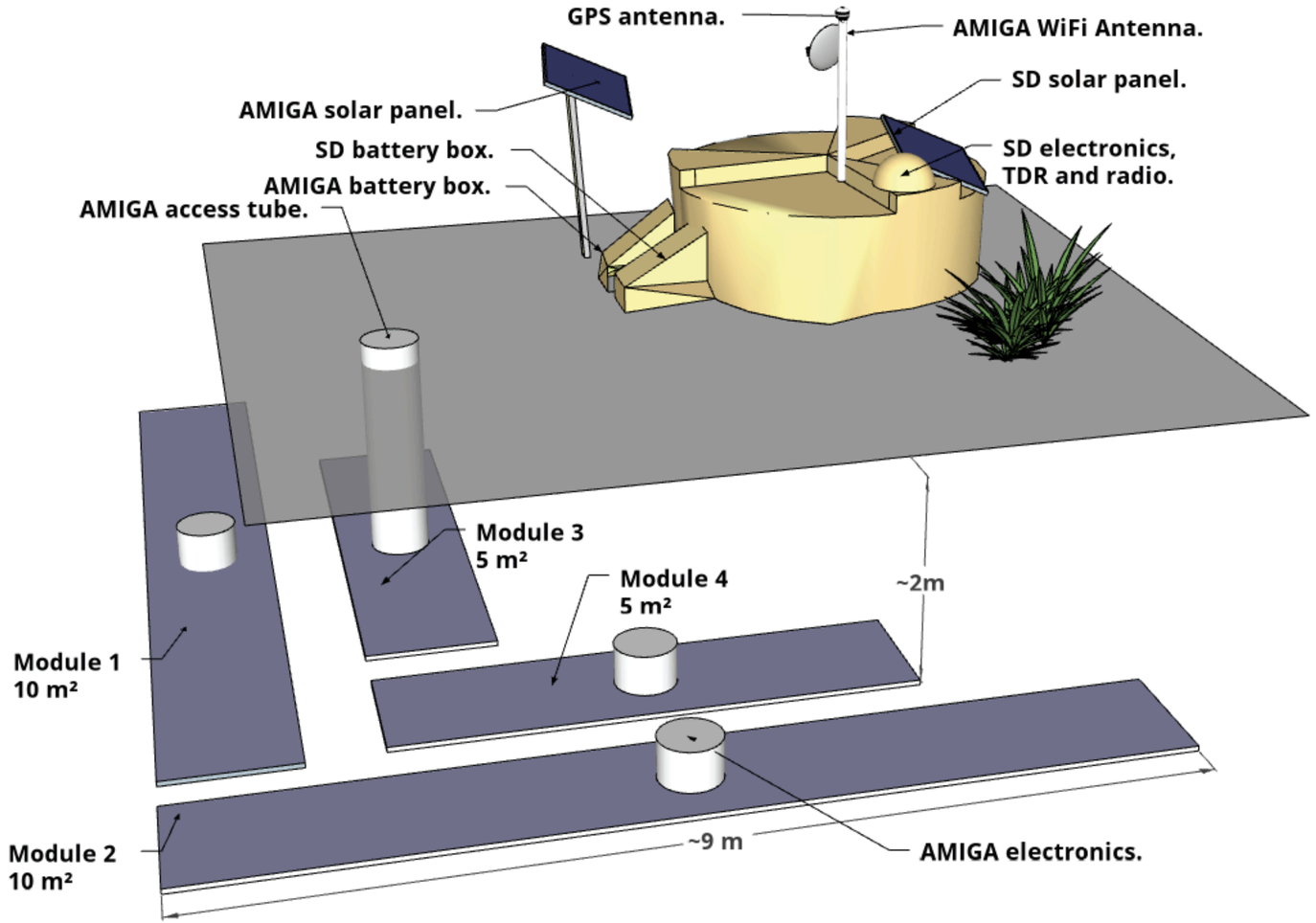
• Algorithm developed forWCD to determine whether adjacent signal segments are causally connected applied to SSD trace
• Integration window is expanded taking into account the SSD traces
• 10% (1%) increase in SSD signal for WCD signals < 10 VEM (60 VEM), primarily due to late SSD signals.

Exposure for CR with E>50 EeV



Underground Muon Detector

- **station general overview**



Underground Muon Detector

- **Muon lateral distribution function (MLDF)**