AugerPrime: the Pierre Auger Observatory upgrade

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on behalf of the Pierre Auger Collaboration

15th Pisa Meeting on Advanced Detectors
La Biodola, 22-28 May 2022

The Pierre Auger Observatory

Hybrid detection
of extensive air showers

Array of water-Cherenkov tanks

- 1600 in a 1.5 km grid of 3000 km^2
- 61 in a 750 m grid of 30 km^2 (*Infill*)

Fluorescence telescopes (FD)

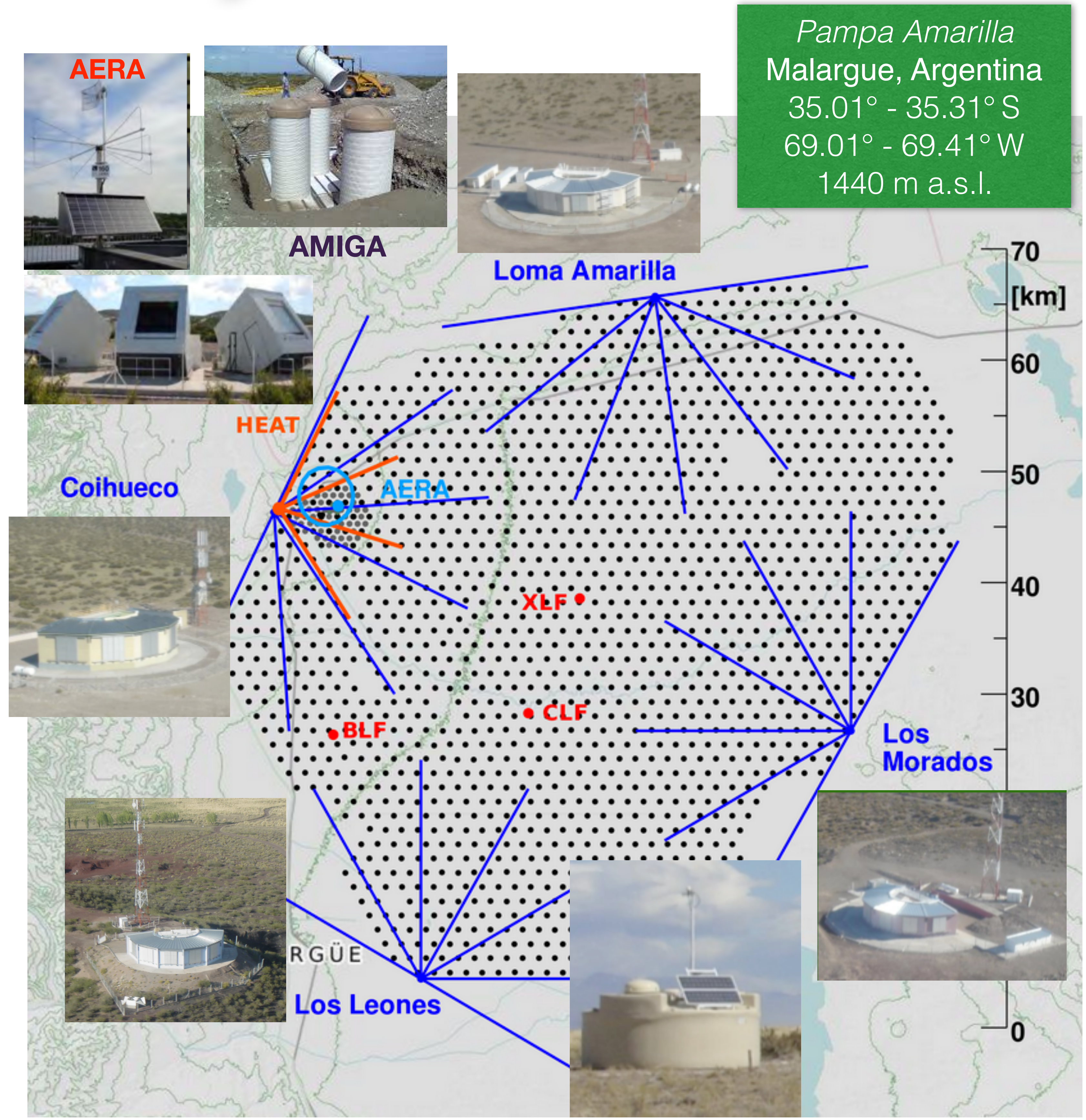
- 24 in 4 buildings overlooking the array - elevation 0°-30°
- 3 overlooking the Infill (*HEAT*) - elevation 30°-60°

Engineering array of underground muon detectors (*AMIGA*) in the Infill area.

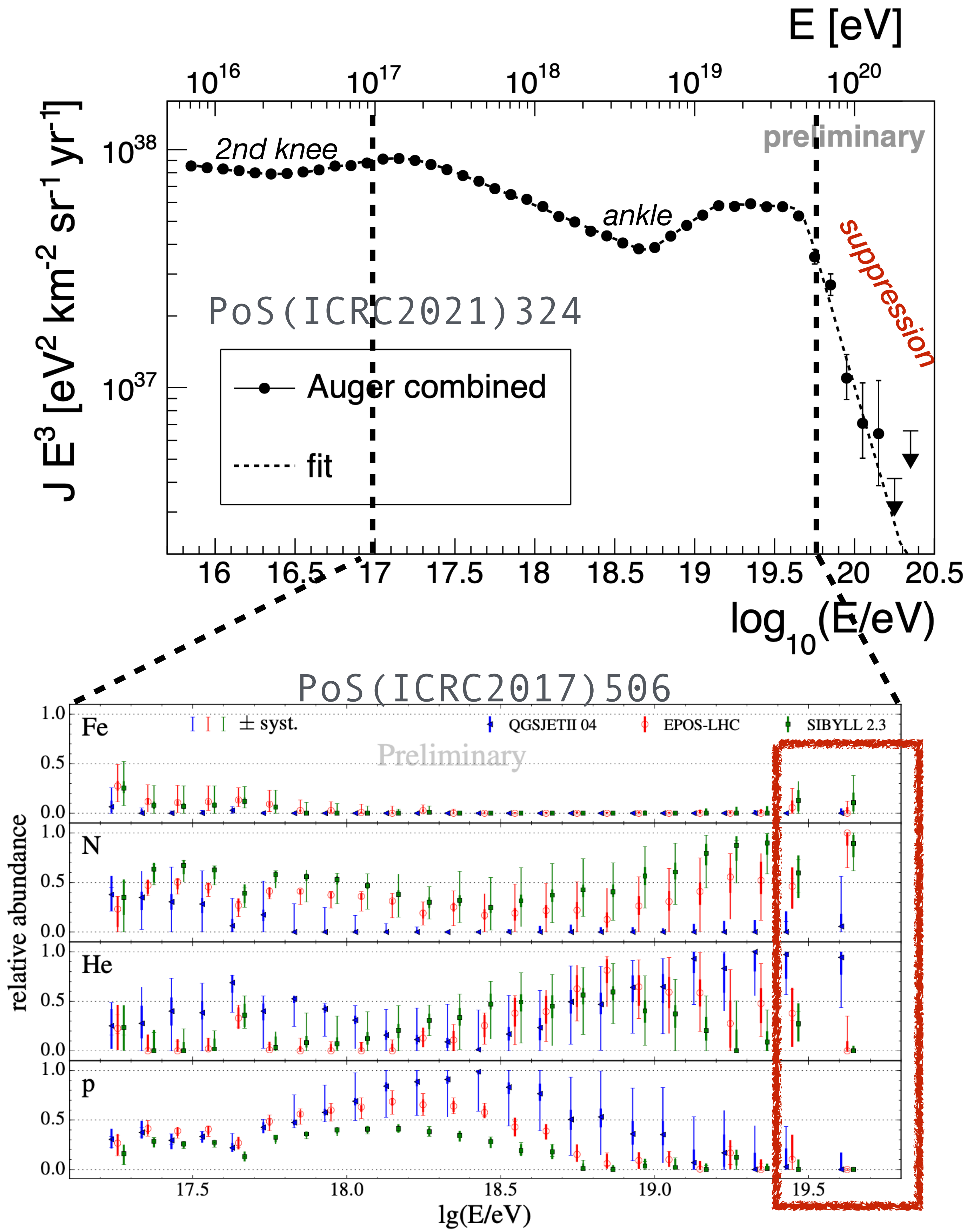
Array of radio antennas (*AERA*)

- 153 stations covering ~17 km^2

Around the center of the array :
monitoring & laser facilities



More than 15 years of data and results



- Flux suppression well established :
  effect of propagation (GZK effect) and/or maximum acceleration at sources ?

- Composition mixed and heavier above ~ 2×10^{18} eV from X_{max} measurements
  … but statistics too low above ~$10^{19.5}$ eV due to FD duty cycle ~15%.

- Large scale dipolar anisotropy (6.6 σ) : extragalactic origin for UHECR > 8 EeV

  +

  Hints of correlation with SBG/AGN directions for UHECR > 40 EeV
  ➟ Quest for sources still open.

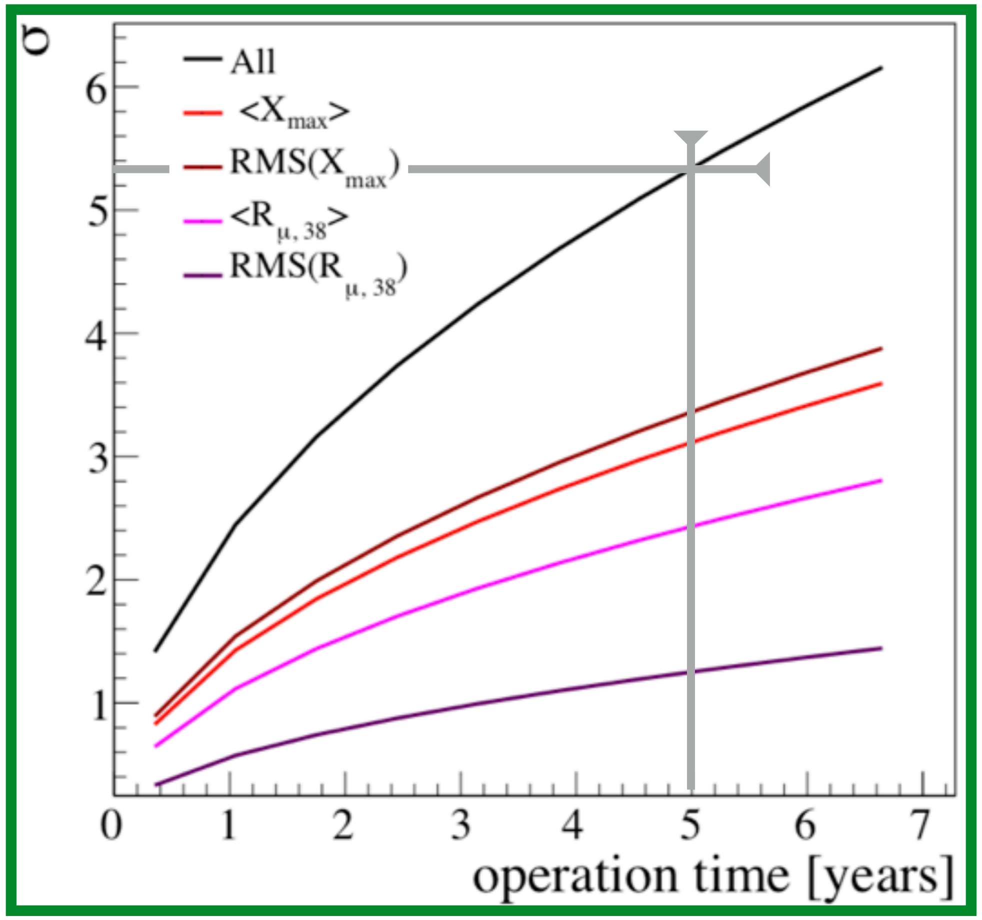
- Muon puzzle: muon content in simulations lower than in data
  Tension with all hadronic models.

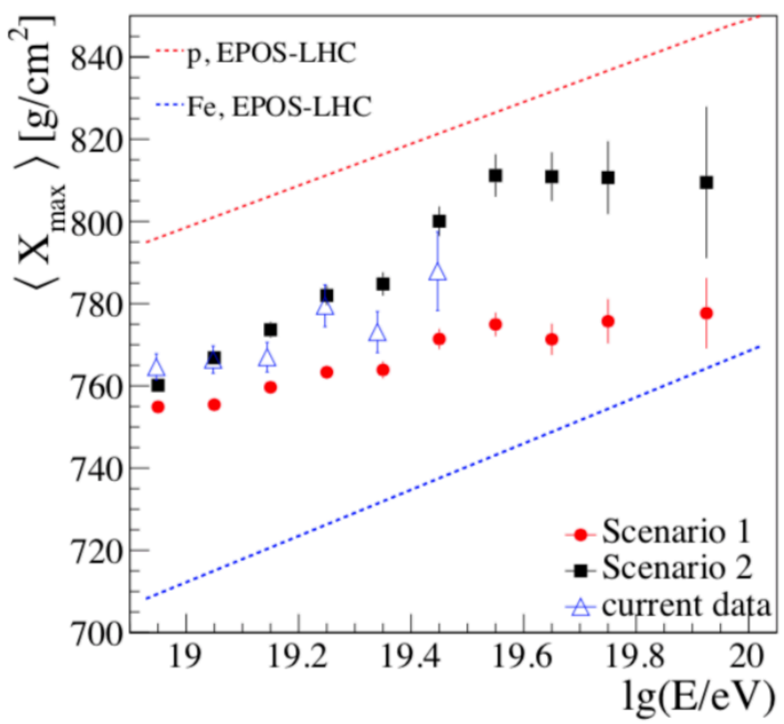
- … and many more

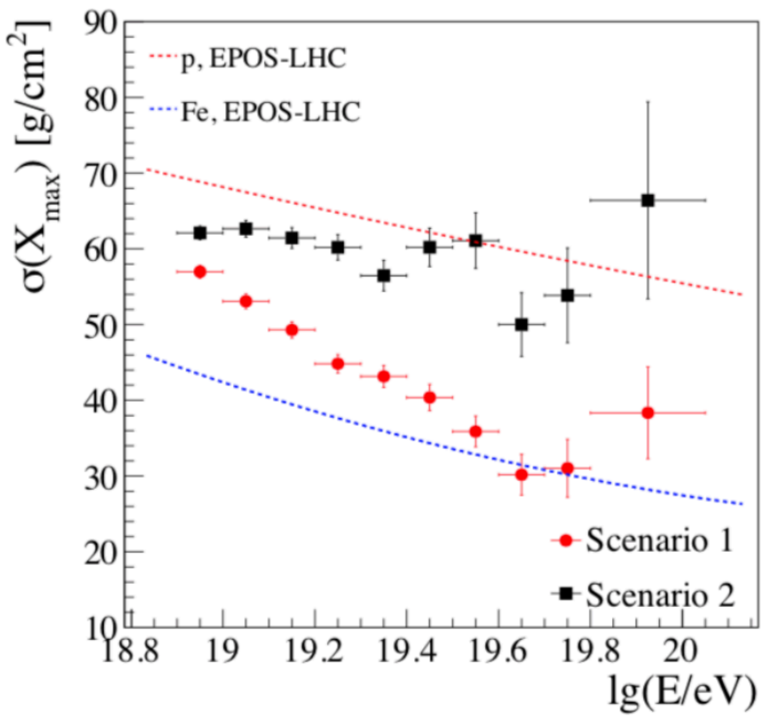
AugerPrime scientific case

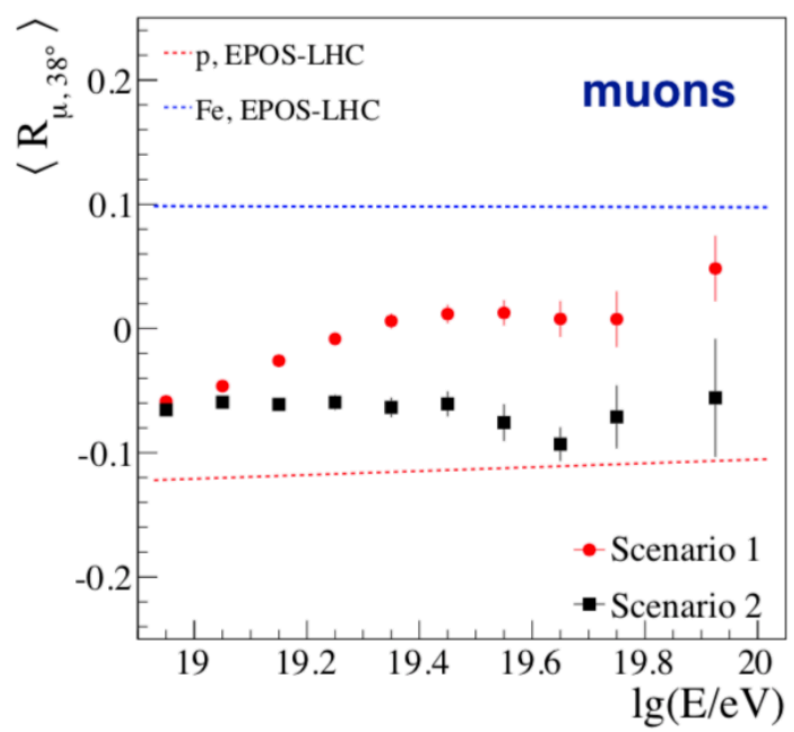
Primary goal : mass composition of UHE

- ➡ to study the origin of the suppression
- ➡ to accomplish composition-driven anisotropy analyses
  e.g. if 10% of protons at the highest energies
- ➡ to study the hadronic interactions at energy much larger than human made accelerators
  (hints of new physics ?)
- ➡ to provide better estimates of ɣ and ν flux
  (explore potential of future experiments)









Scenario 1 : maximum rigidity model   Scenario 2 : photo-disintegration model

The upgrade of the Observatory

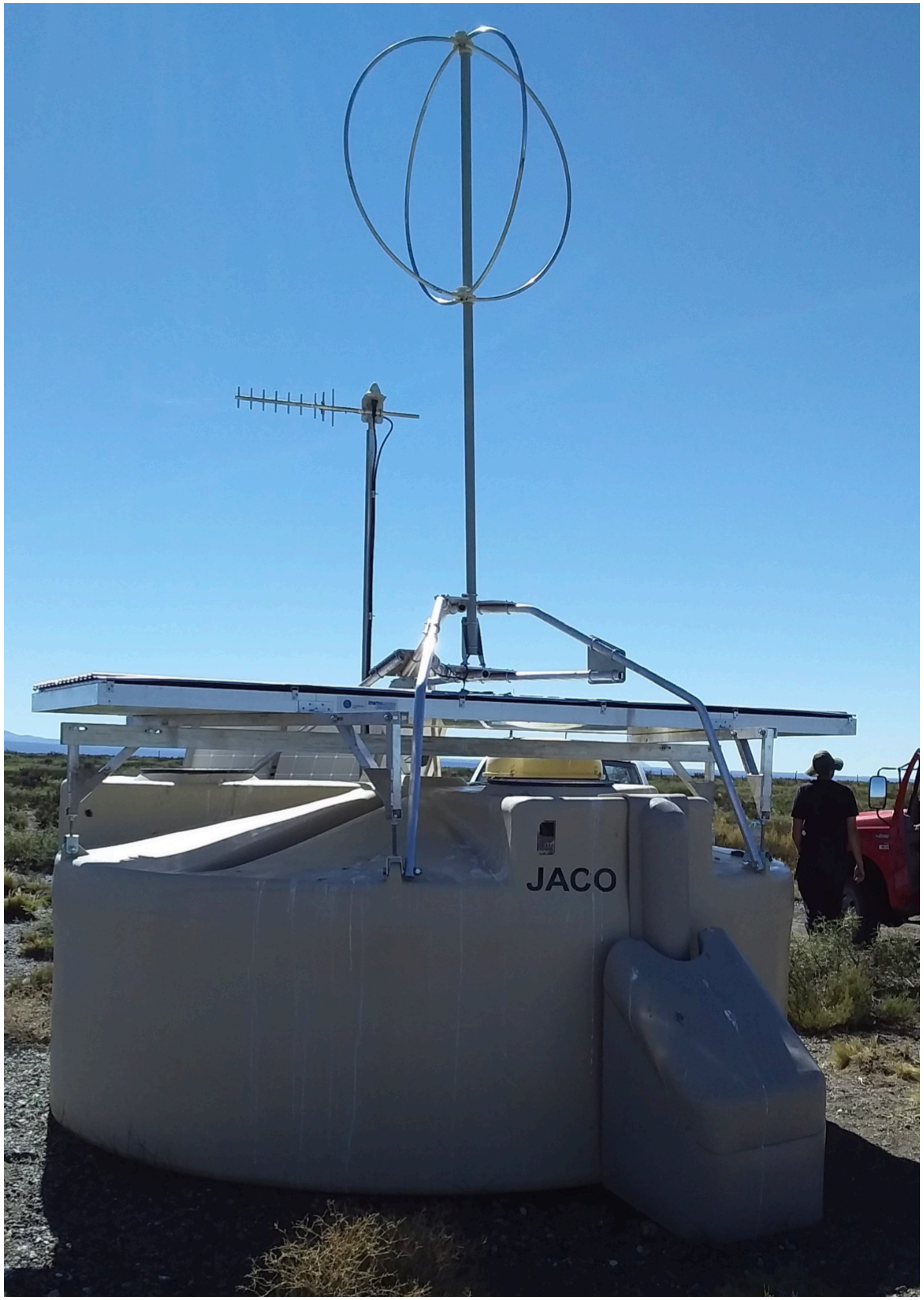
Surface Scintillator Detector (SSD)
different response to electromagnetic & muonic shower components w.r.t. WCD

Radio antenna
to measure the radio emission of showers in atmosphere (30-80 MHz)

Underground Muon Detector (UMD)
direct muon measurement and
cross-check of SSD-WCD combined analysis

Small PMT (SPMT)
increase of the dynamic range of WCD measurements

Upgraded Unified Electronics (UUB)
to process the signals from all the new detectors with improved performances

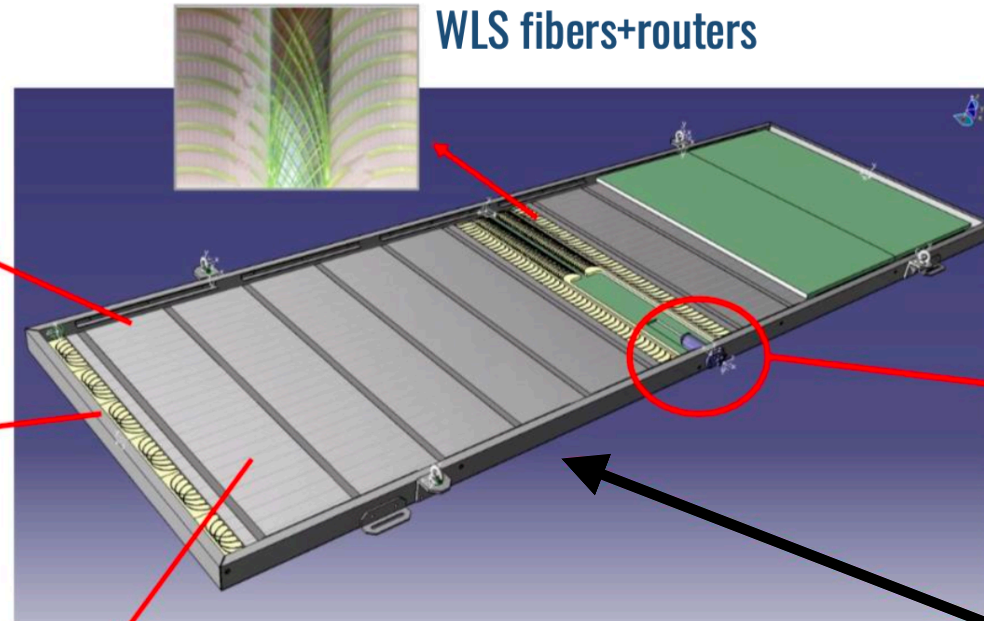


Auger Preliminary Design Report [arXiv:1604.03637]
A. Castellina, EPJ Web of Conf.210 (2019) 06002

The Scintillator Surface Detector (SSD)

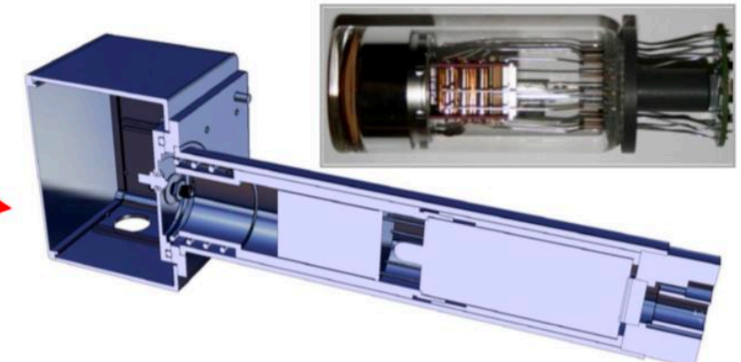
Extruded Scintillator
bars with 2 holes

WLS fibers+routers

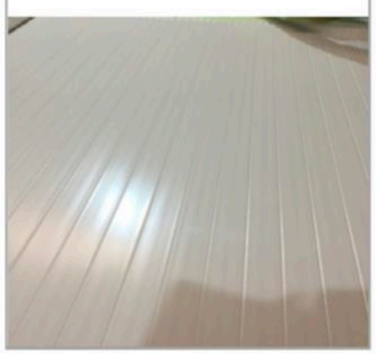


WLS fibers+routers

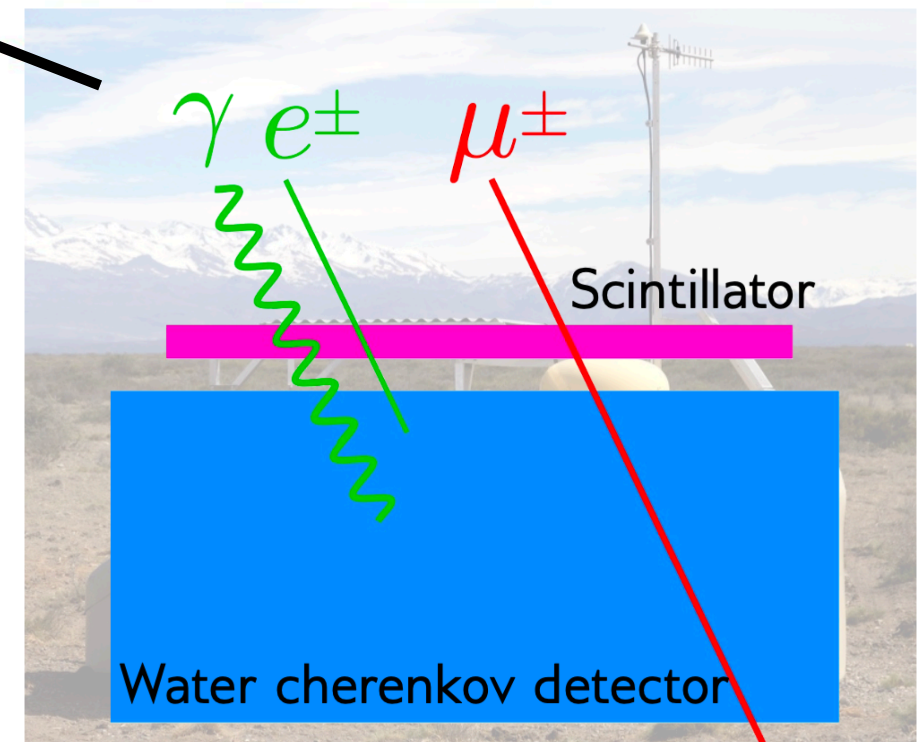
1.5-inch bi-alkali PMT
(Hamamatsu R9420)



Extruded scintillator bars
160cm long



Aluminum enclosure

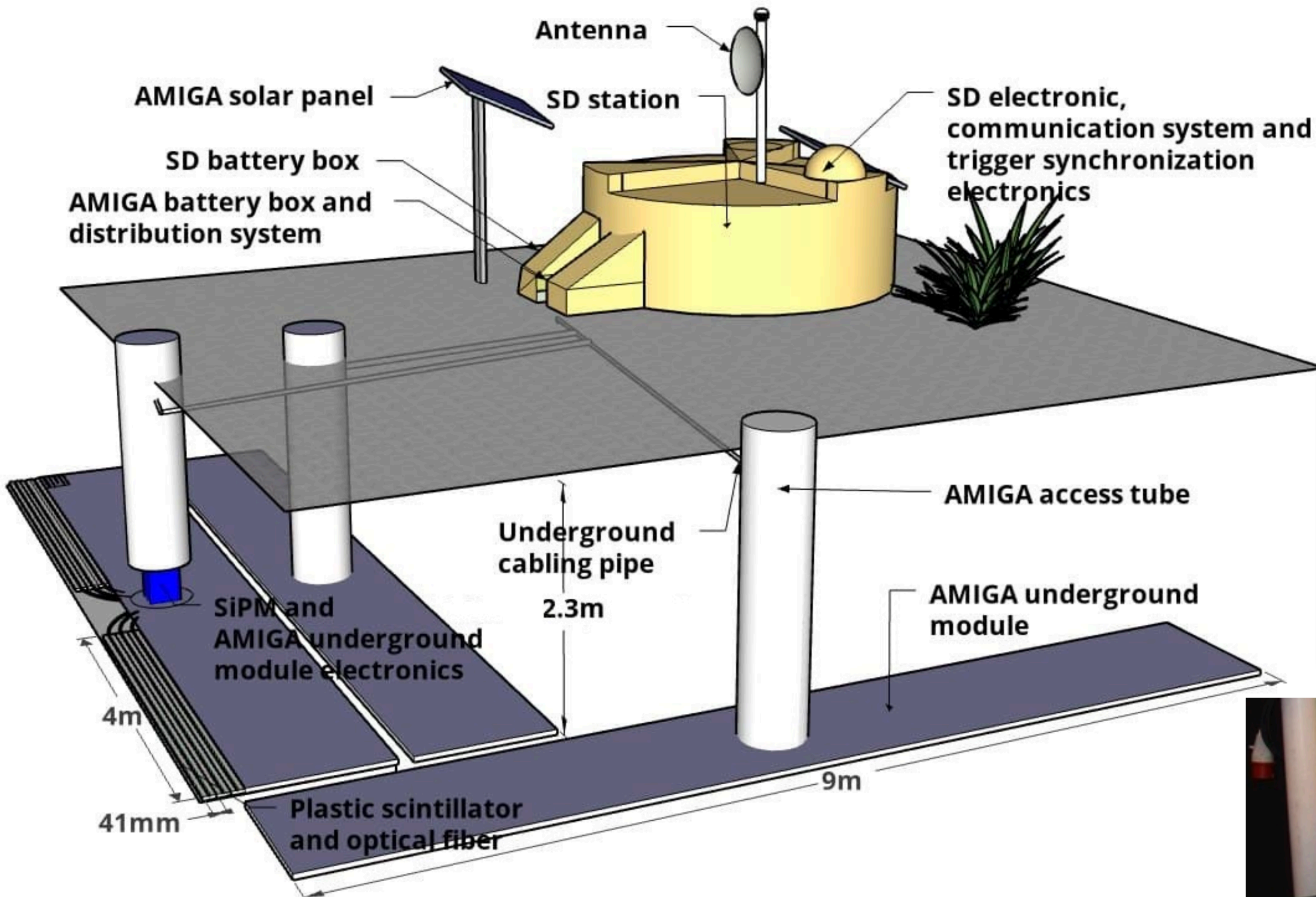


Large-scale production of >1500 SSDs and installation completed.

Preproduction array of 77 SSDs with PMTs running since March 2019 : long-term performances in G. Cataldi, PoS(ICRC2021)251

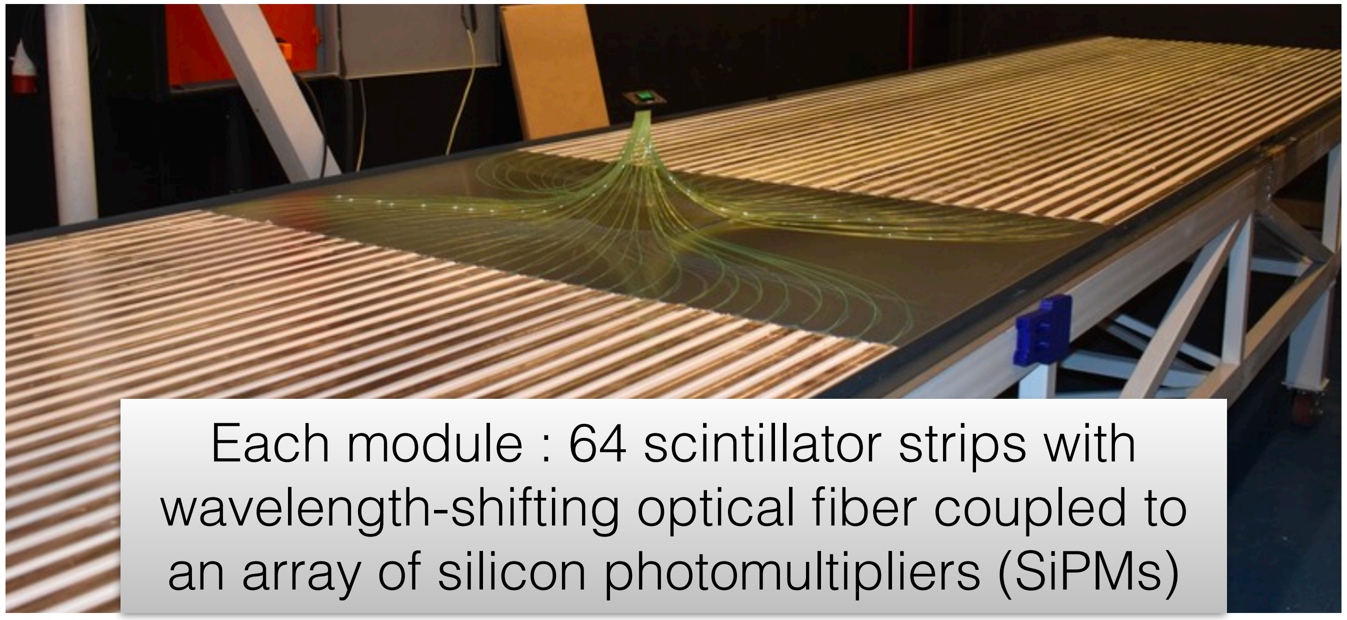
Each SSD is mounted above a WCD (in slave-trigger mode) to disentangle the muonic and e.m. components

The Underground Muon Detector (UMD)

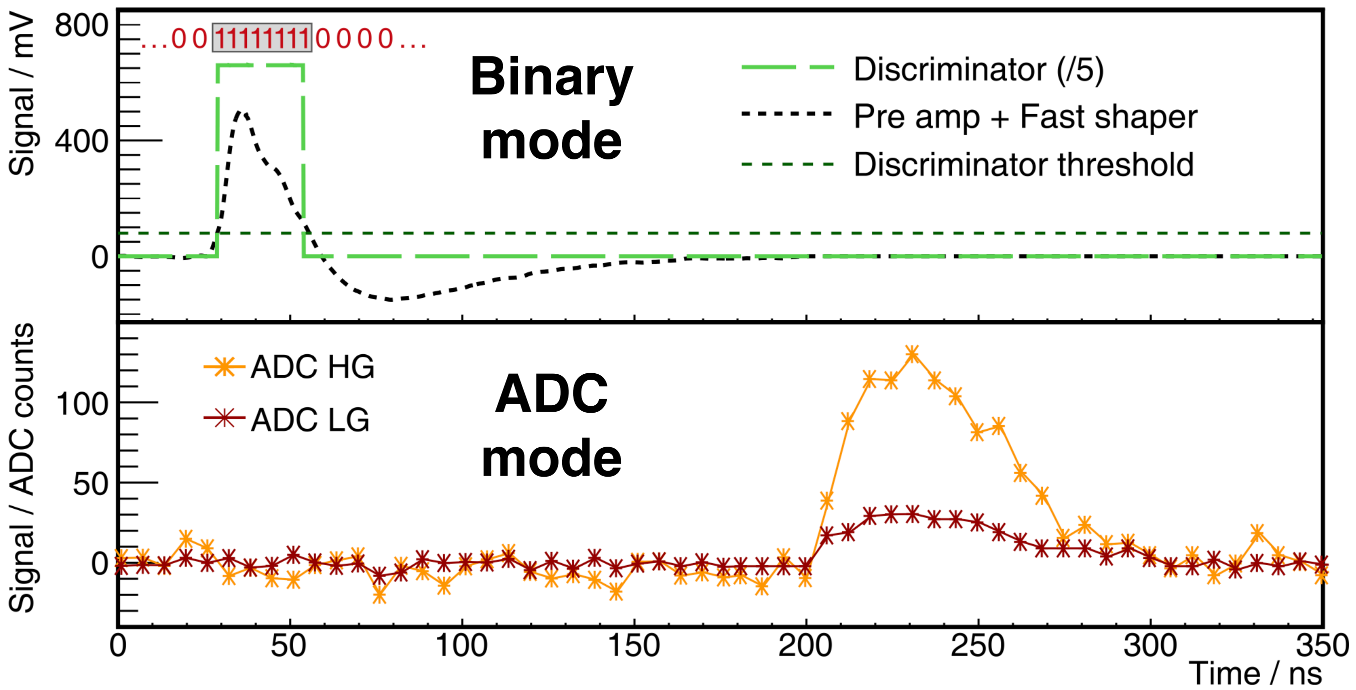


73 positions
in the Infill area, each with 3 modules of 10 m²

2.3 m underground
- e.m. component of the shower (e±, ɣ) absorbed
- direct measurement of muon density



Each module : 64 scintillator strips with wavelength-shifting optical fiber coupled to an array of silicon photomultipliers (SiPMs)



Two acquisition modes :

Binary mode (64 traces) to count single muons

ADC mode (64 SiPM signals summed) to measure a high number of muons in EAS

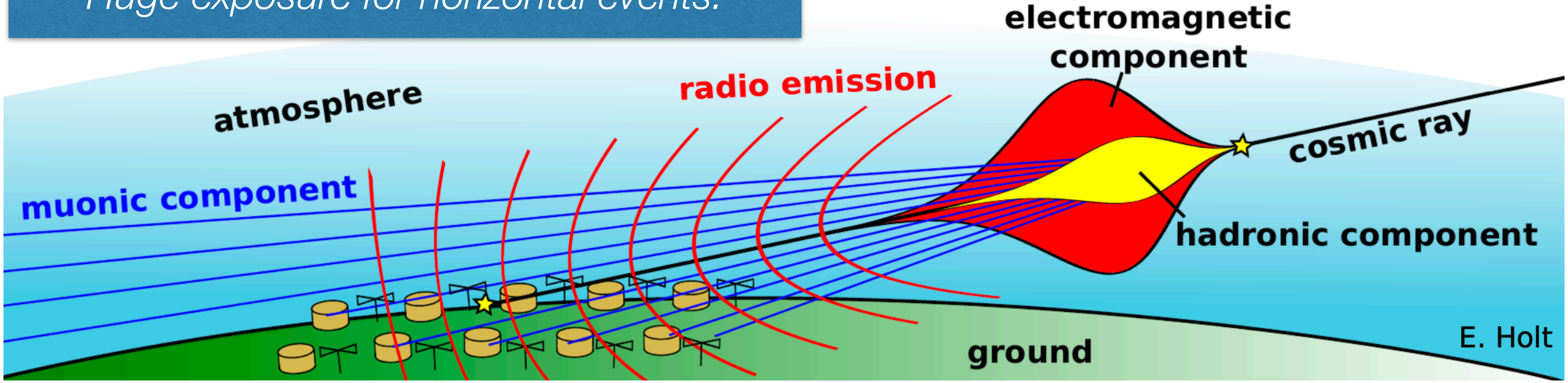
The Radio Detector array (RD)

- measurement of e.m. component in inclined showers (zenith > 60°) via radio emission
  - complementarity with SSD+WCD
  - complementarity with UMD (low energy region)
- ~300 km² of RD equals the yearly exposure of FD (duty cycle RD ≳ 95% vs FD ~ 15%)

For technical details and expected performances
Bjarni Pont, PoS(ICRC2019)395
Felix Schlüter, PoS(ICRC2021)262

1661 **dual-polarized Short Aperiodic Loaded Loop Antennas** (**SALLAs**)
1.2 m diameter, mounted on top of each WCD (slave-trigger mode).

World-largest radio detector for extensive air showers at UHE.
Huge exposure for horizontal events.



The Small PMT (SPMT)

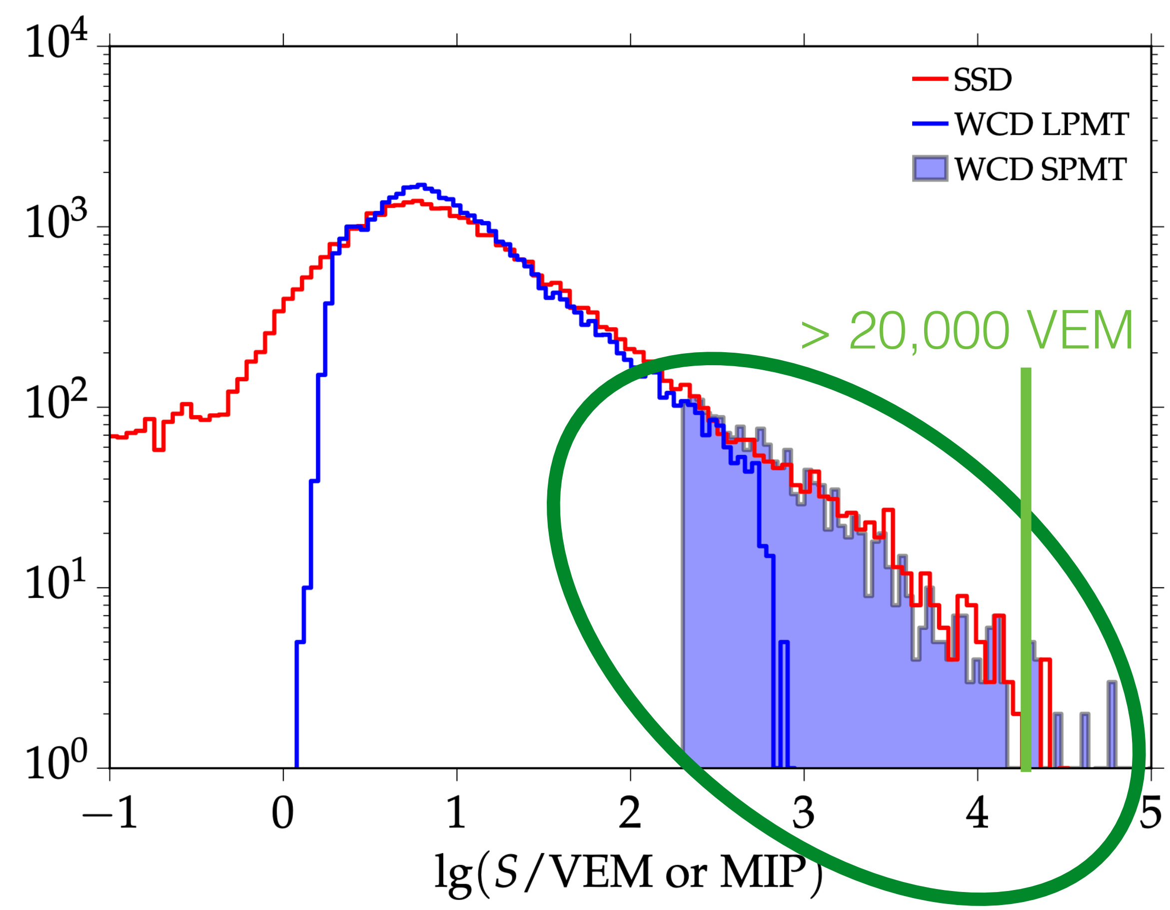
Hamamatsu R8619 1-inch diameter PMT

Linearity and gain curves of each SPMT carefully measured
(M. Buscemi et al., 2020 JINST **15** P07011)

[New HVPS module (A7501B)](#) developed by CAEN & INFN-Torino

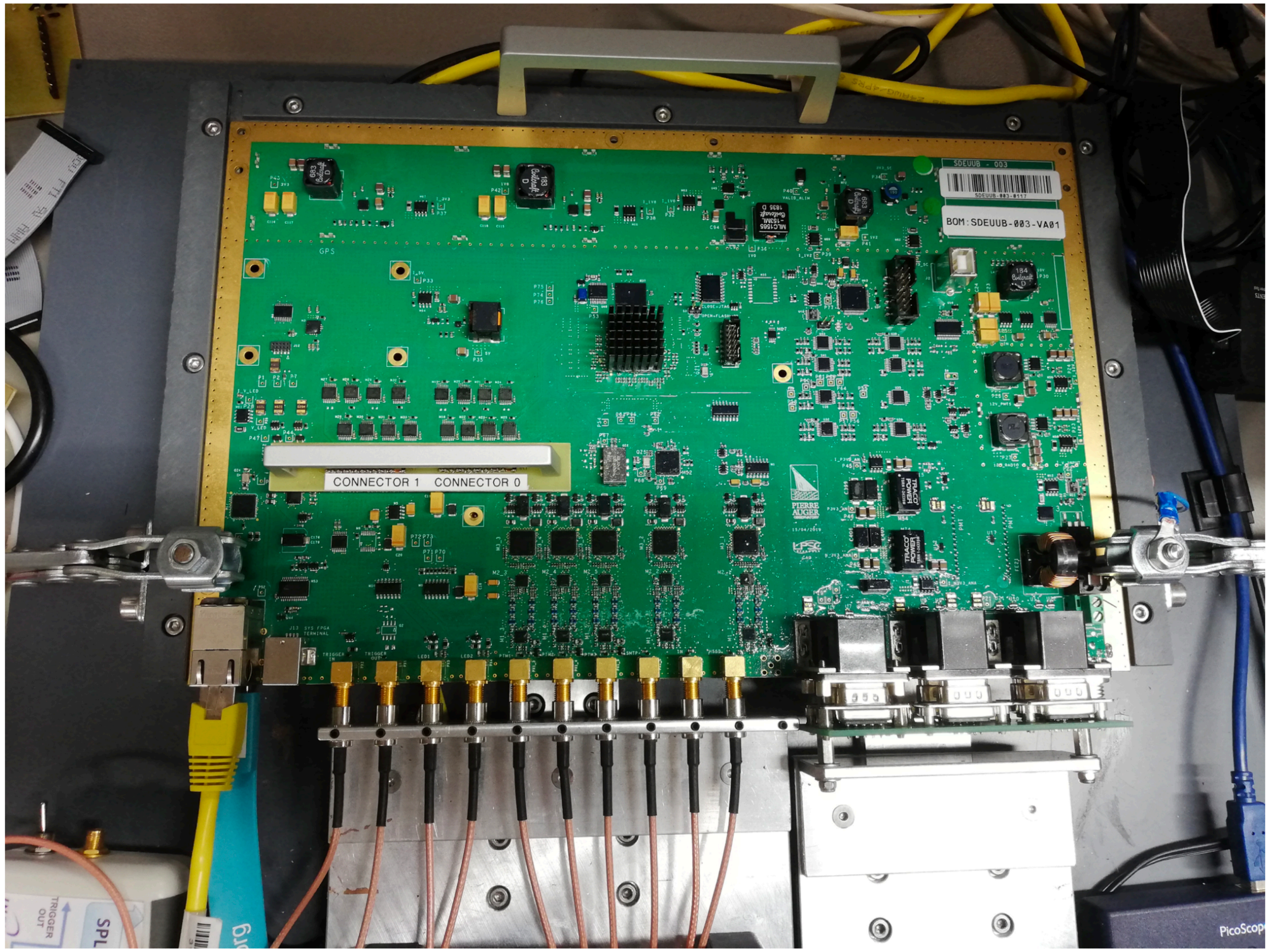
Validation of 1600+ unit
(G.A. Anastasi et al., 2022 JINST 17 T04003)

Active SPMT area ~1/100 of the 9-inch WCD PMTs
direct measurement of (very large) density of particles up 200-300 m from the shower core.



The Upgraded Unified Electronics (UUB)

On a single board :
analog signal processing, triggering, calibration (WCD + SSD PMTs), interface with UMD and RD systems, GPS time tagging, data 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 PMT, GPS antenna and communication cables)

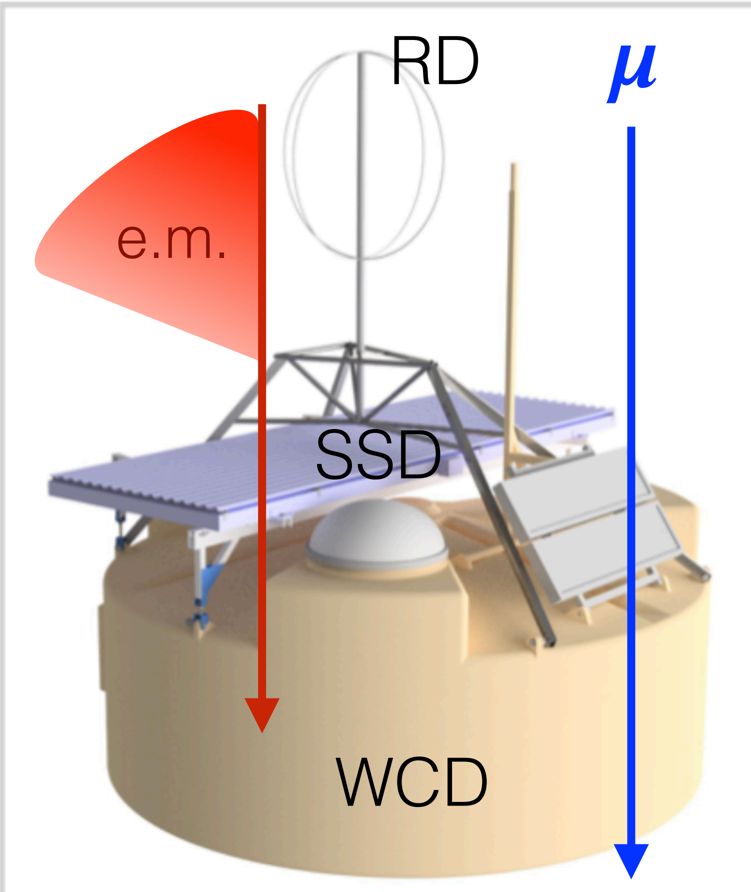
Technical details in
G. Marsella, PoS(ICRC2021)230

Manufacturer test (SITAEL company)
- automated optical inspection
- semi-automatic test bench
  (installation of operative system + full functionality test)

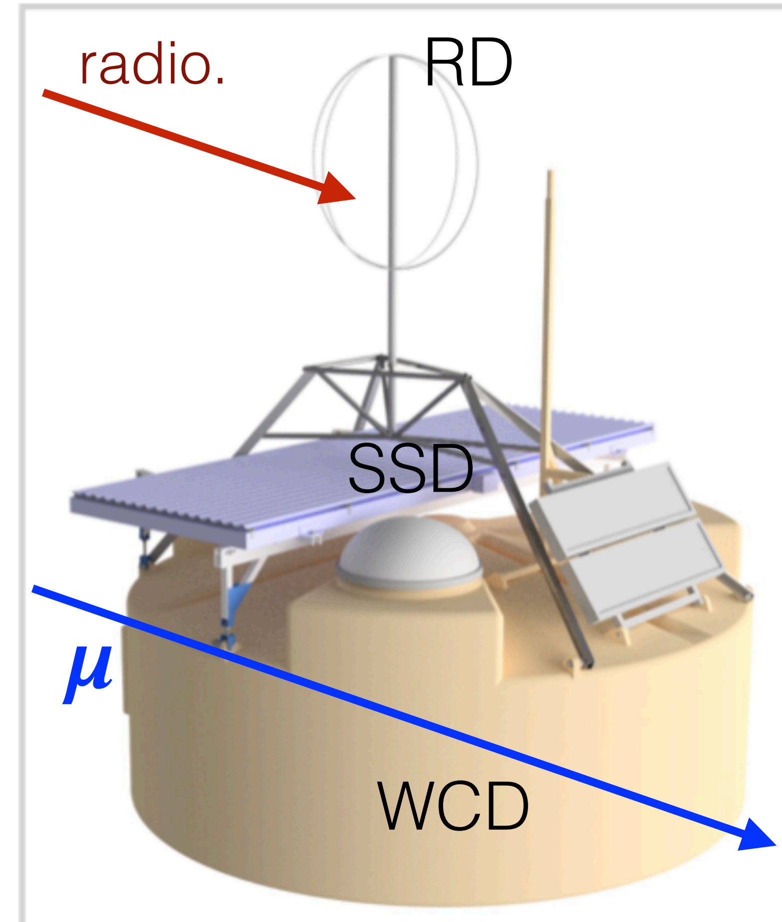
Environmental Stress Screening test @ Institute of Physics, Prague - details in M. Bohacova, PoS(ICRC 2019) 199

Measurements with AugerPrime

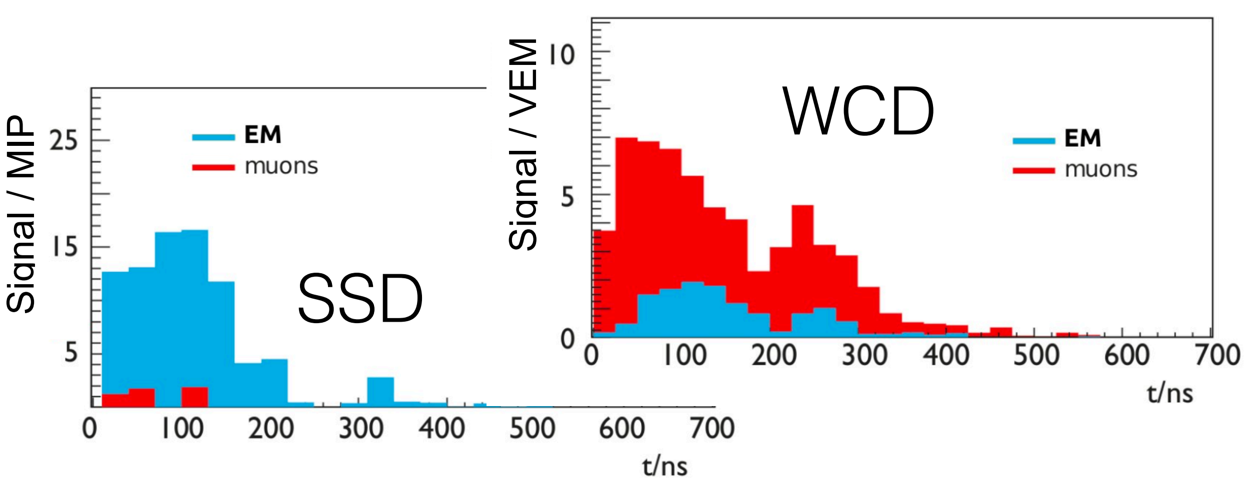
vertical events (0°- 60°)



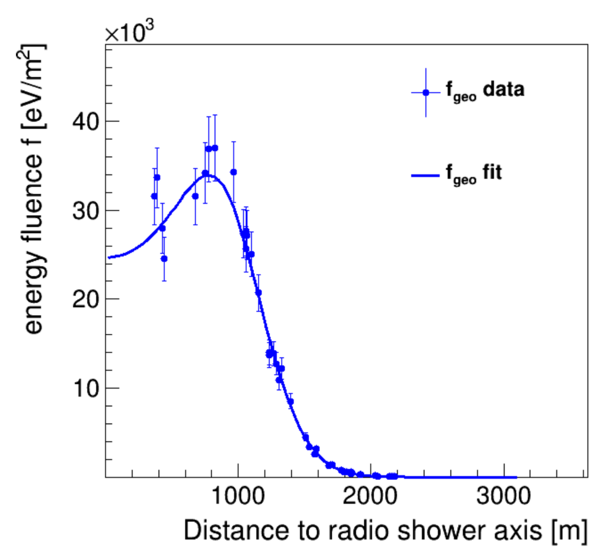
Simultaneous measurement of a shower with WCD, SSD, RD, UMD (& fluorescence telescopes)



inclined events (60°- 95°)



density of muons at ground (WCD) ⟶



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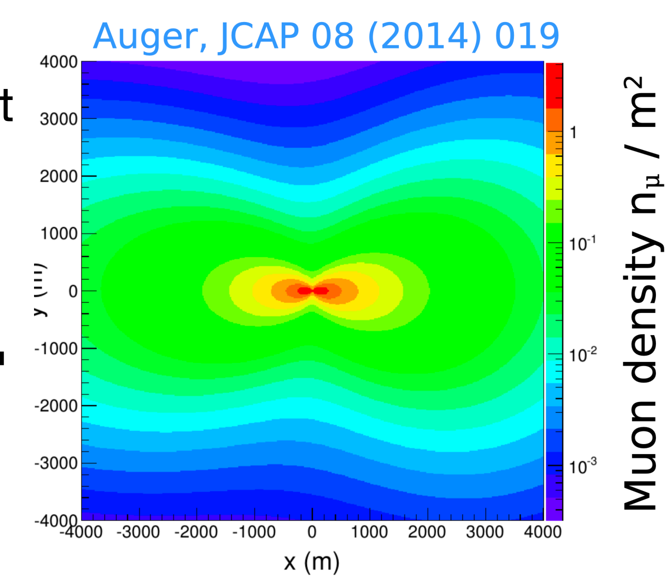


⟵ radiation at ground from e.m. component (RD)

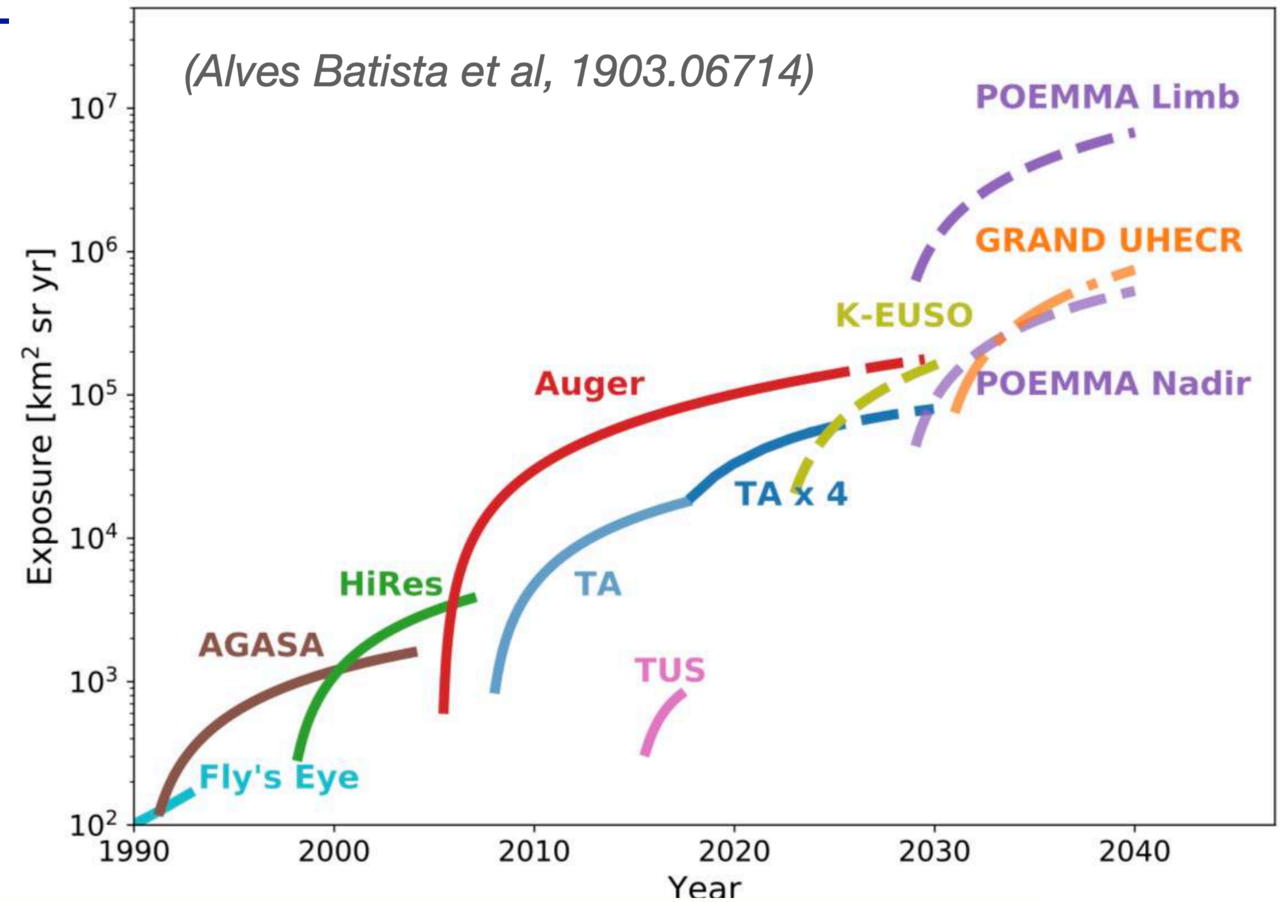
+ RADIO

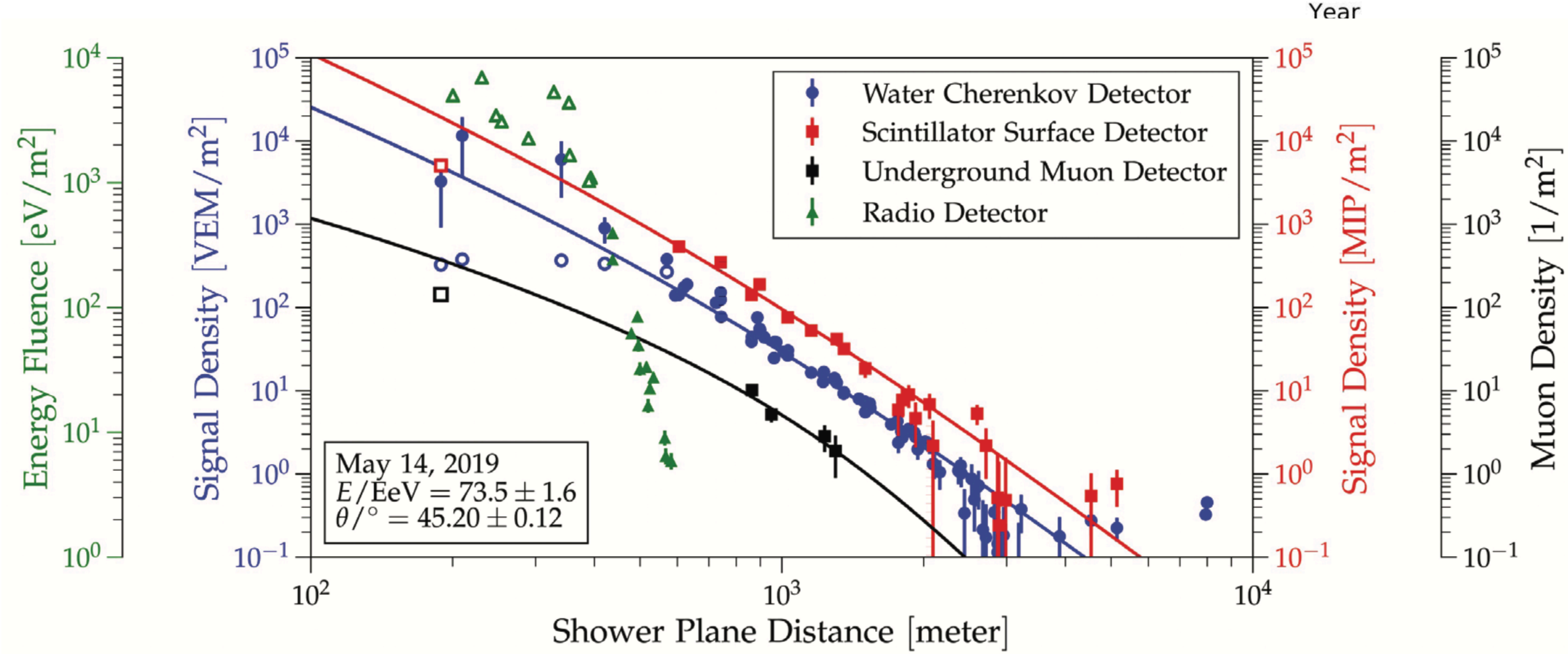
- top-down method (i.e. comparison with MC)
- radio observables (e.g. LDF slope, wavefront shape)
- comparison with muon density from UMD (lower energies)

Conclusions

AugerPrime :
largest exposure detector for UHECR with composition sensitivity above 4 x 10^{19} eV

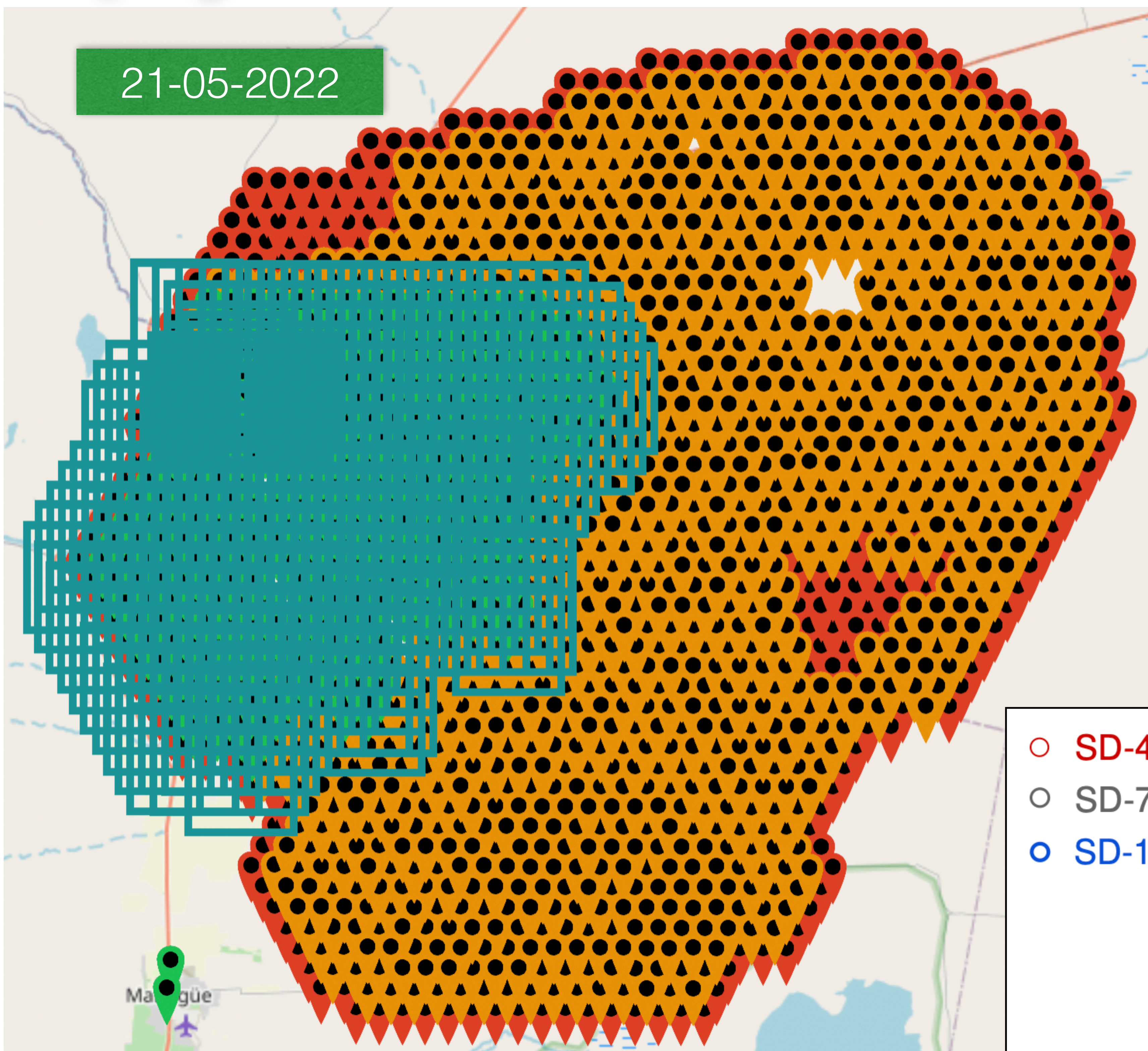
- ★ Deployment and commissioning to be completed by mid 2023.
- ★ Data taking foreseen up to 2030.
- ★ Fundamental input for future experiments.

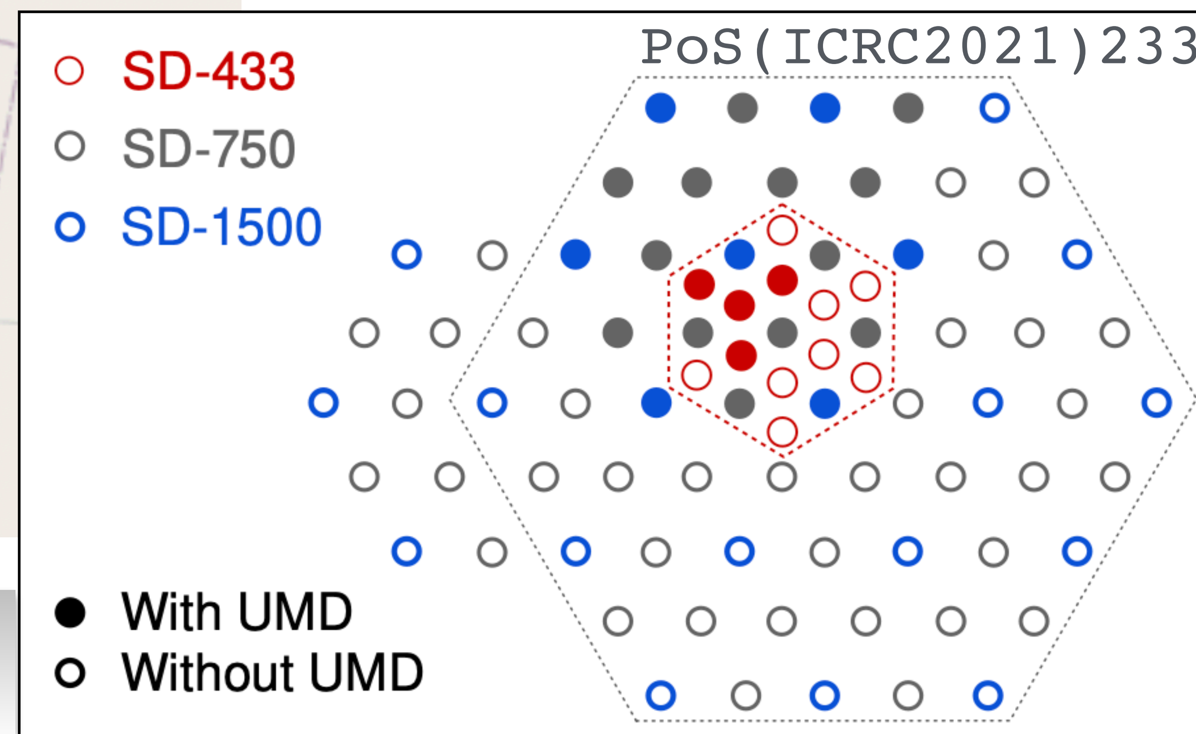




Backup

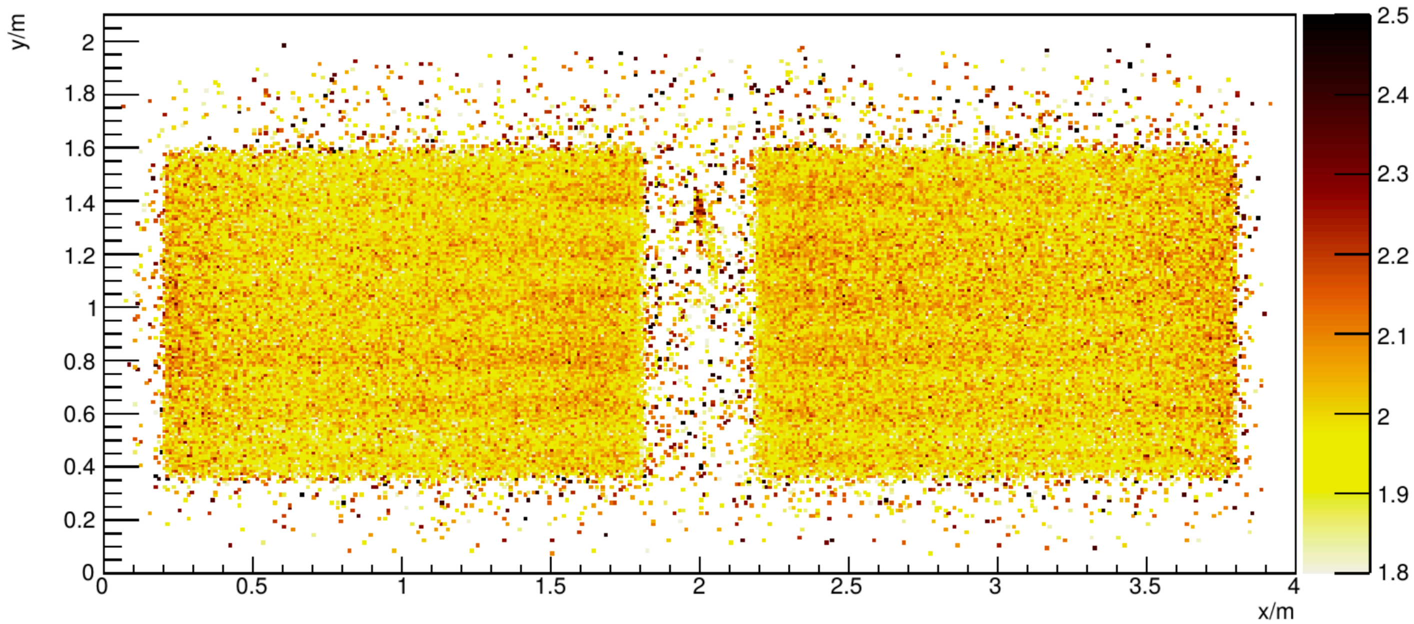
Deployment status





UMD deployment and commissioning currently on-going
at a pace of 2 stations per month

SSD



All SSD tested with cosmic-ray muons :
(i) to check the light tightness;
(ii) to determine the response to a reference minimum-ionizing particle

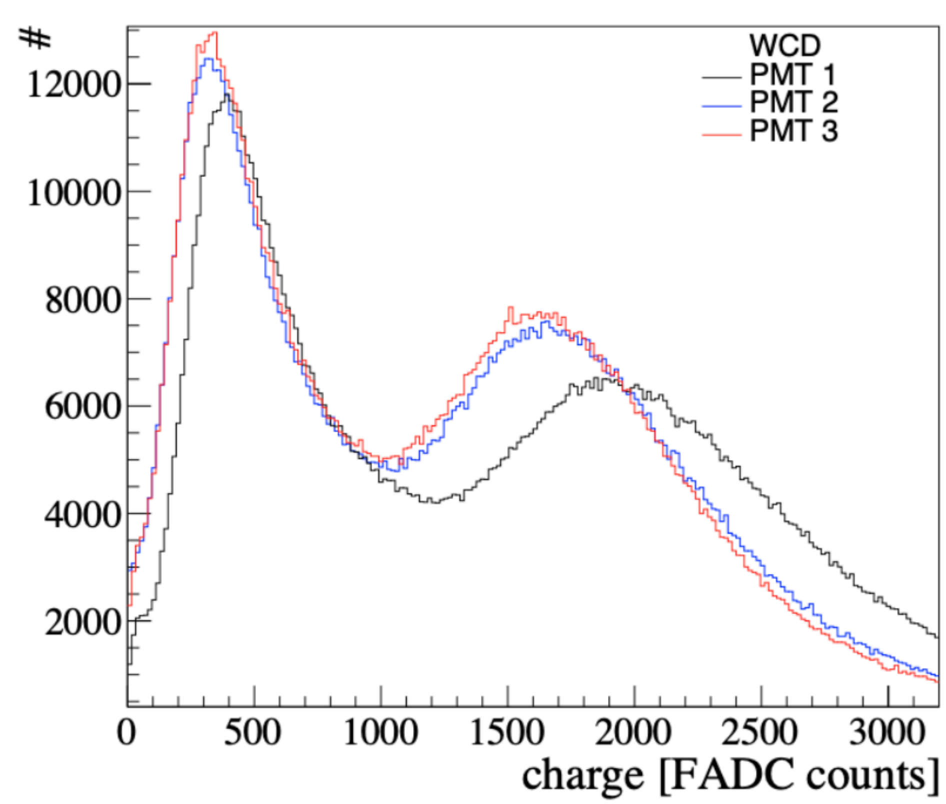
Left: average logarithm of the deposited charges in 1 cm × 1 cm bins for one SSD as measured in a muon tower.

Calibration performed using atmospheric muon signals acquired by dedicated triggers.

WCD PMTs unit : VEM
Vertical Equivalent Muon

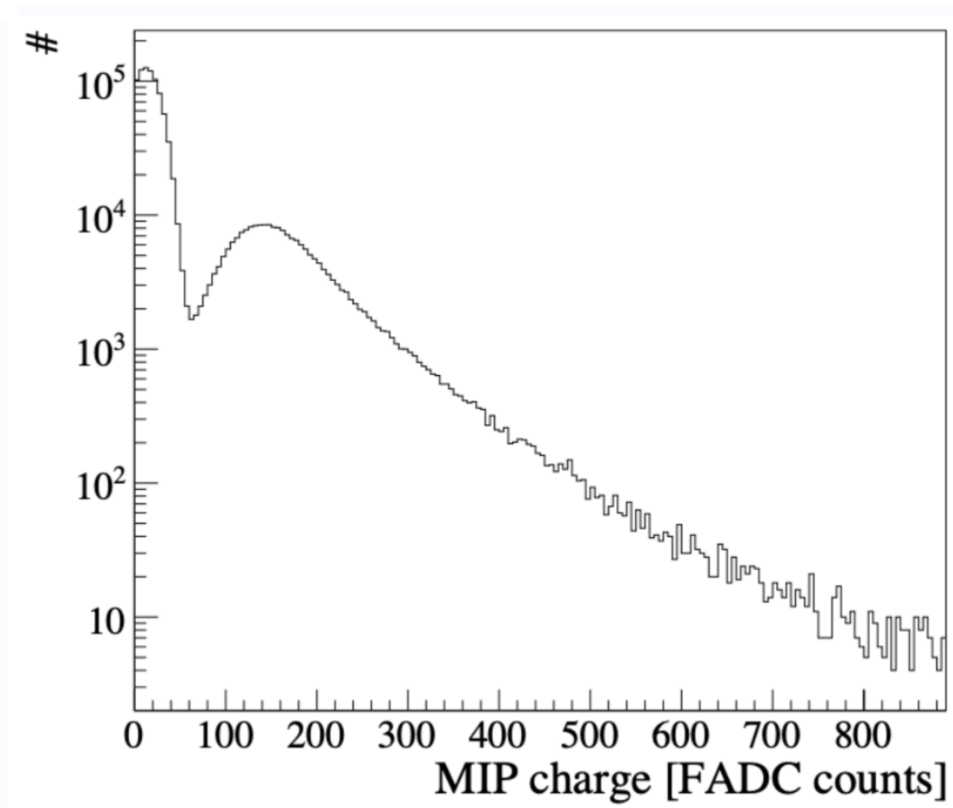
SSD PMT unit : MIP
Minimum-Ionizing Particle

About 40% of WCD calibration triggers produce a MIP in the SSD.



First peak : low energy e±, γ

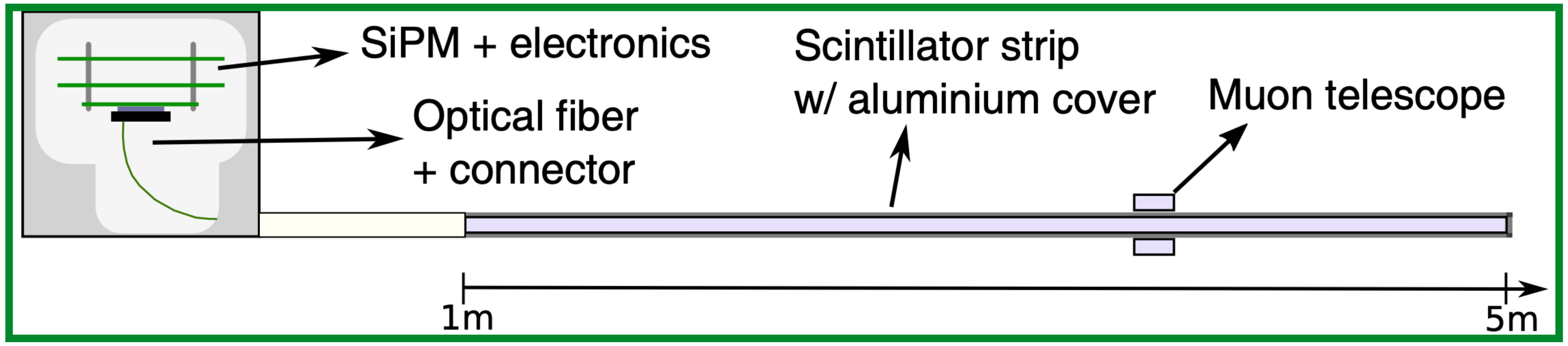
Second peak : VEM estimate

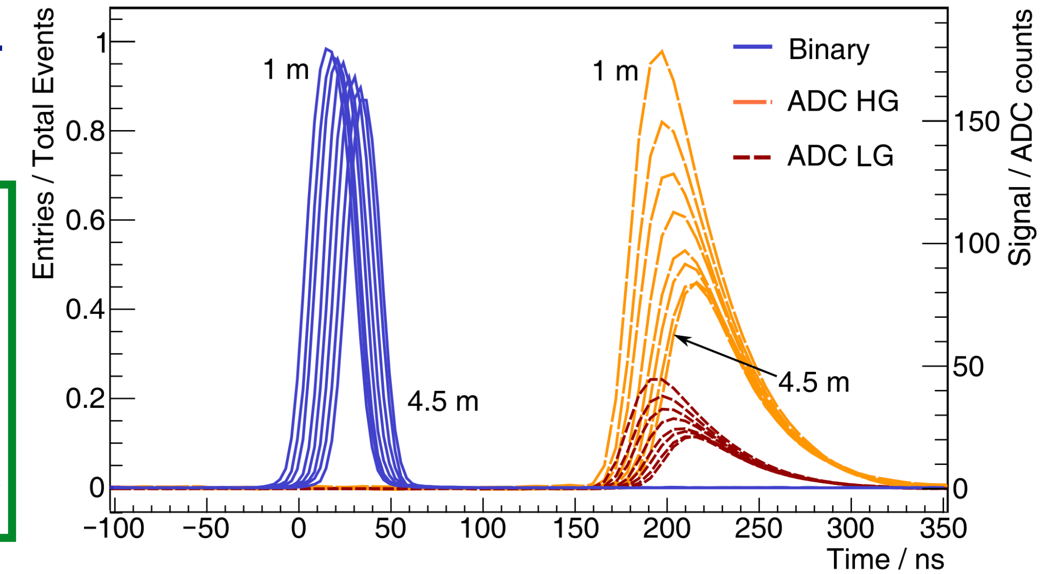


First peak : pedestal (integral of baseline)

Second peak : MIP estimate

UMD

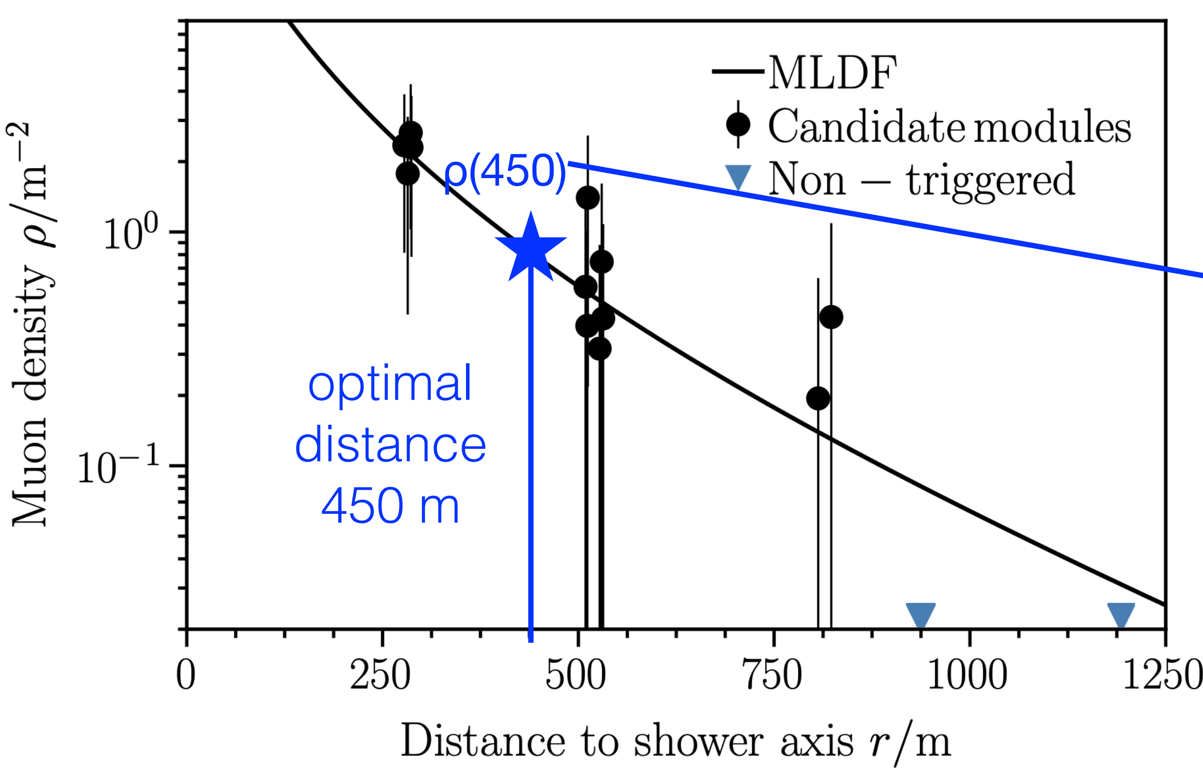




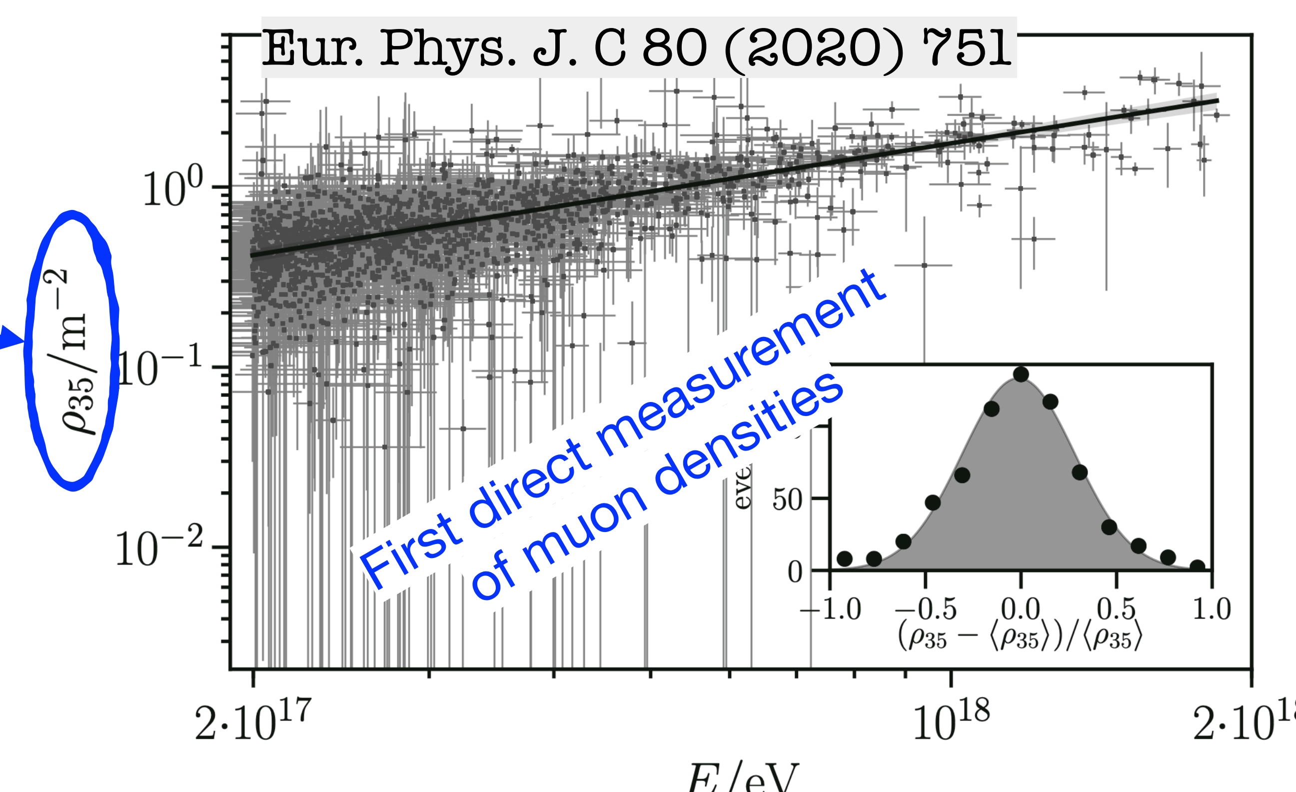
Schematics of the laboratory setup (left) used to characterize the UMD traces and average traces (right) for the binary and ADC modes, measured at different optical-fiber lengths

Muon lateral distribution function (MLDF)

ρ(*r*, *E*,θ) = ρ(450) *f* (*r*,θ)



Reconstructed muon densities ρ_{35} VS energy E (estimated using the WCD data alone)



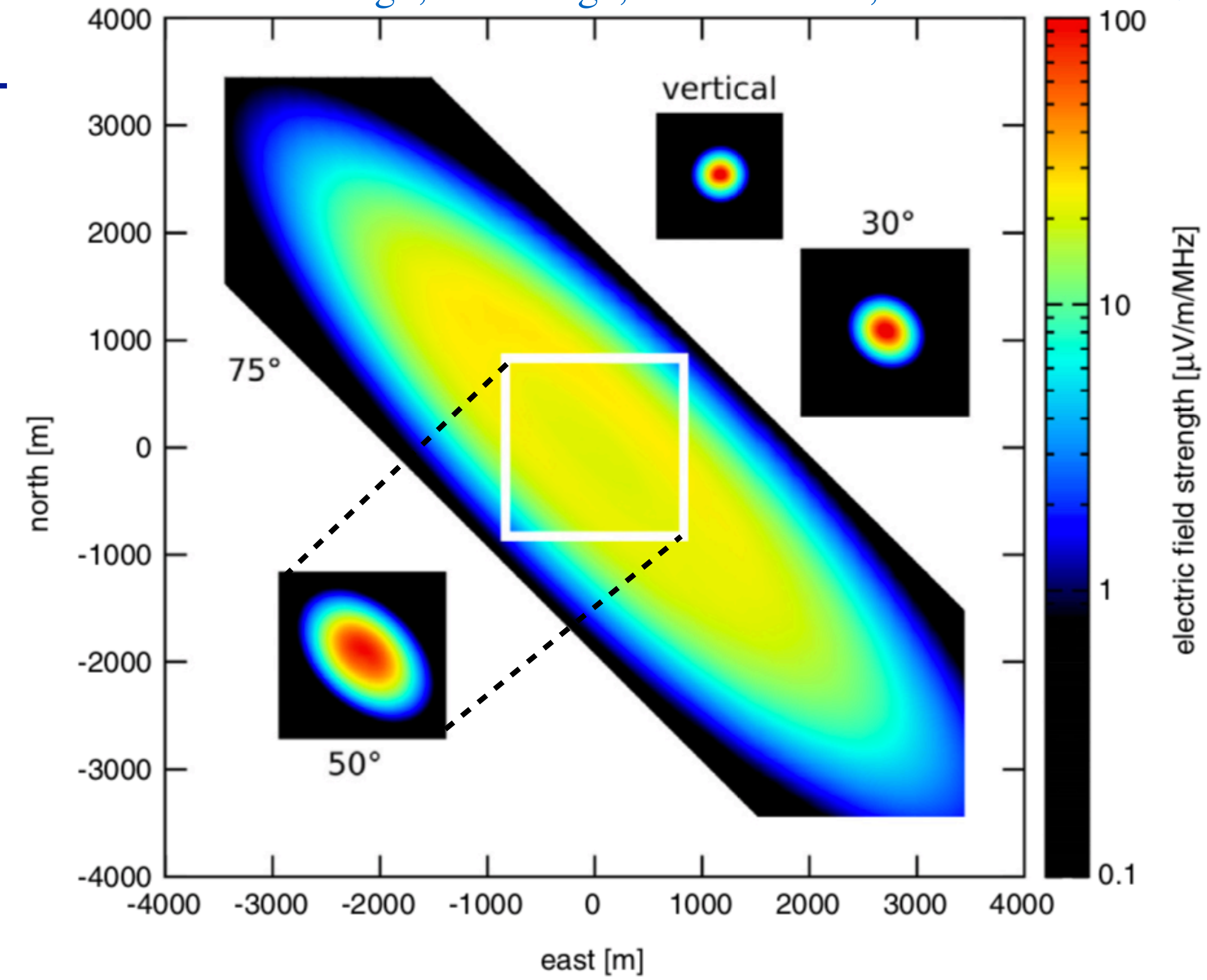
RD

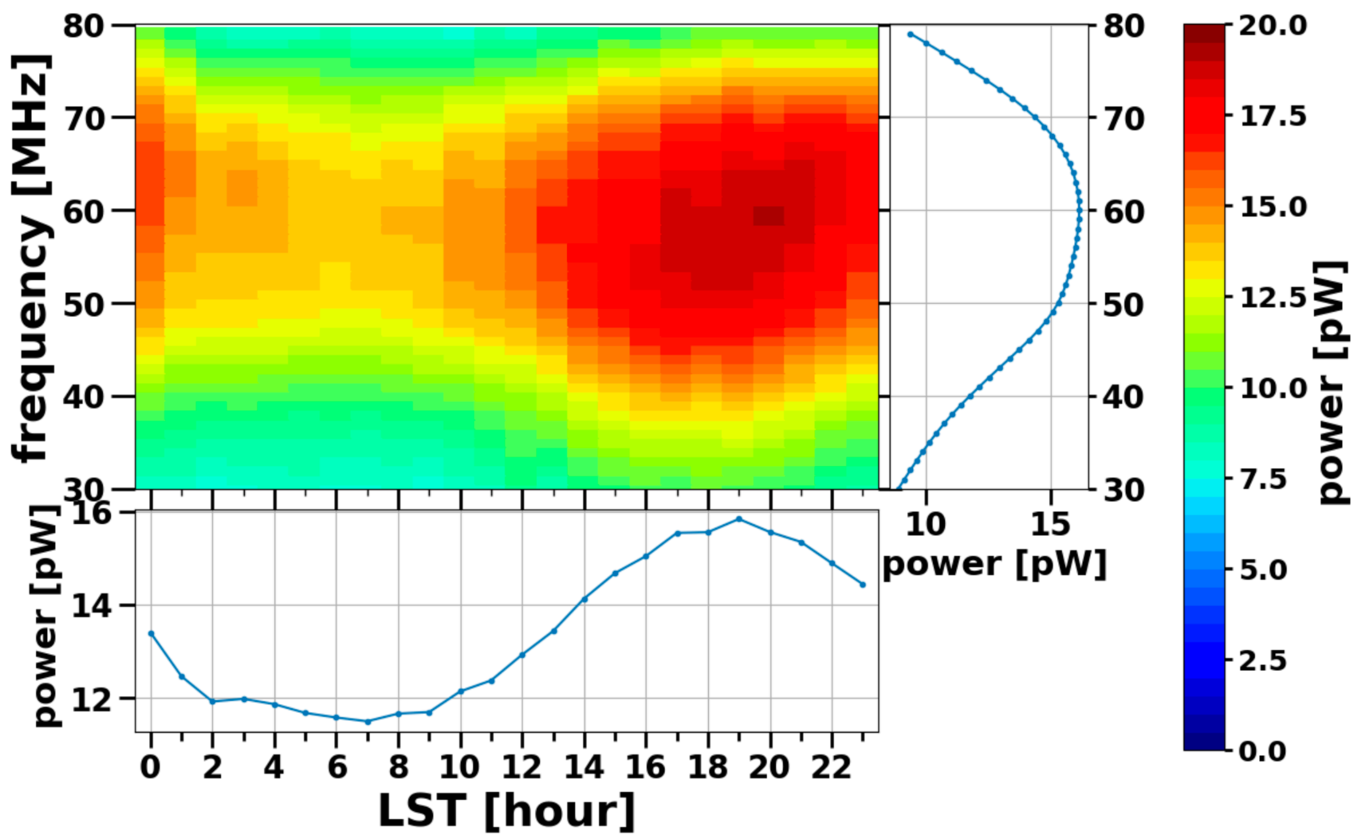
➡ Radio emission not absorbed in atmosphere
- signals depends on the source distance and not on the amount of traversed matter

➡ Radiation strongly forward-beamed into a cone of few degrees :
- vertical shower: small footprint, strong signals
- inclined shower: large footprint, weaker signals

✓ Nearly full efficiency for $\theta \gtrsim 70°$ at high energies

T. Huege, A. Haungs, UHECR2014, arXiv:1507.07769

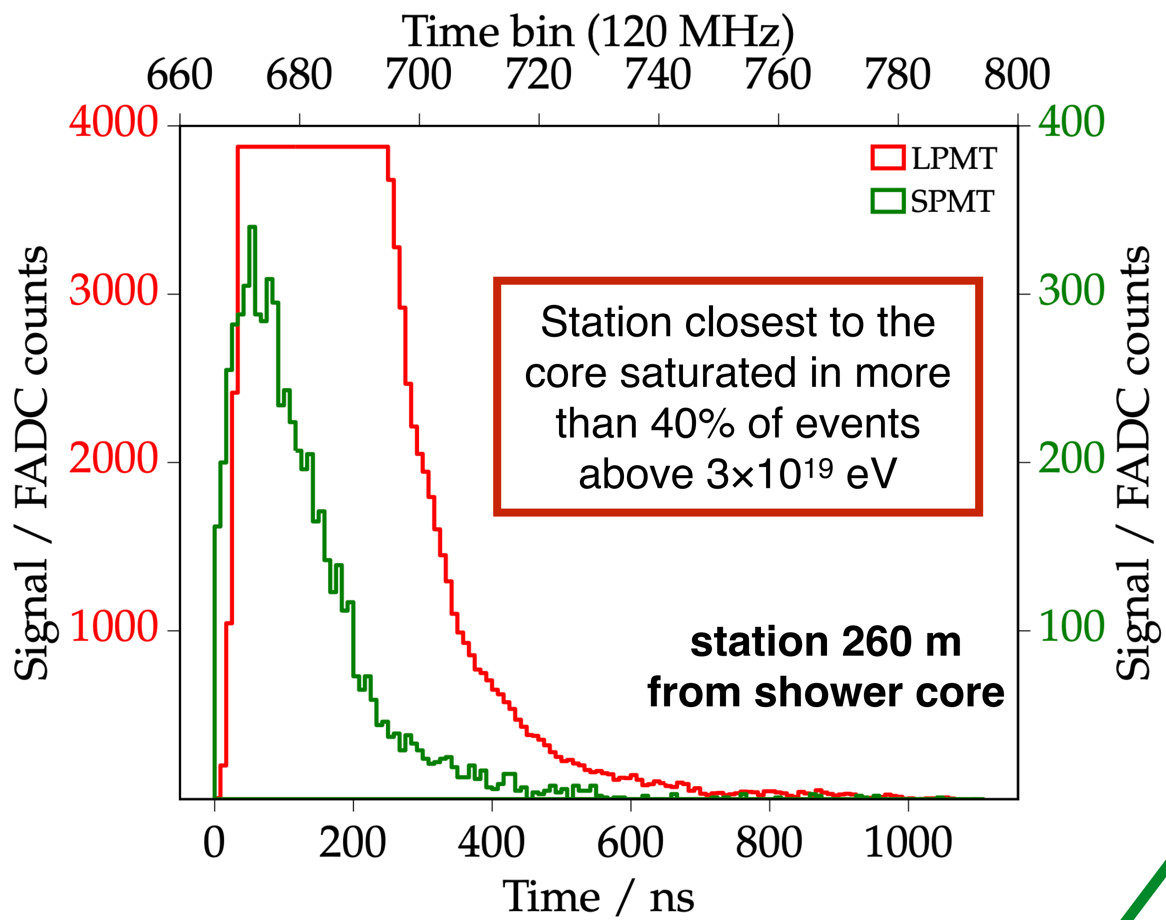




End-to-end pilot calibration using the Galactic radio emission
(Tomáš Fodran, PoS(ICRC2021)270)

Target : absolute calibration of the Radio Detector
- Measurement of power as a function of frequency and local sidereal time (LST), separately for the EW and NS channels.
- Simulations using different sky temperature map models and different antenna models.
- Comparison to estimate calibration constant and background noise.

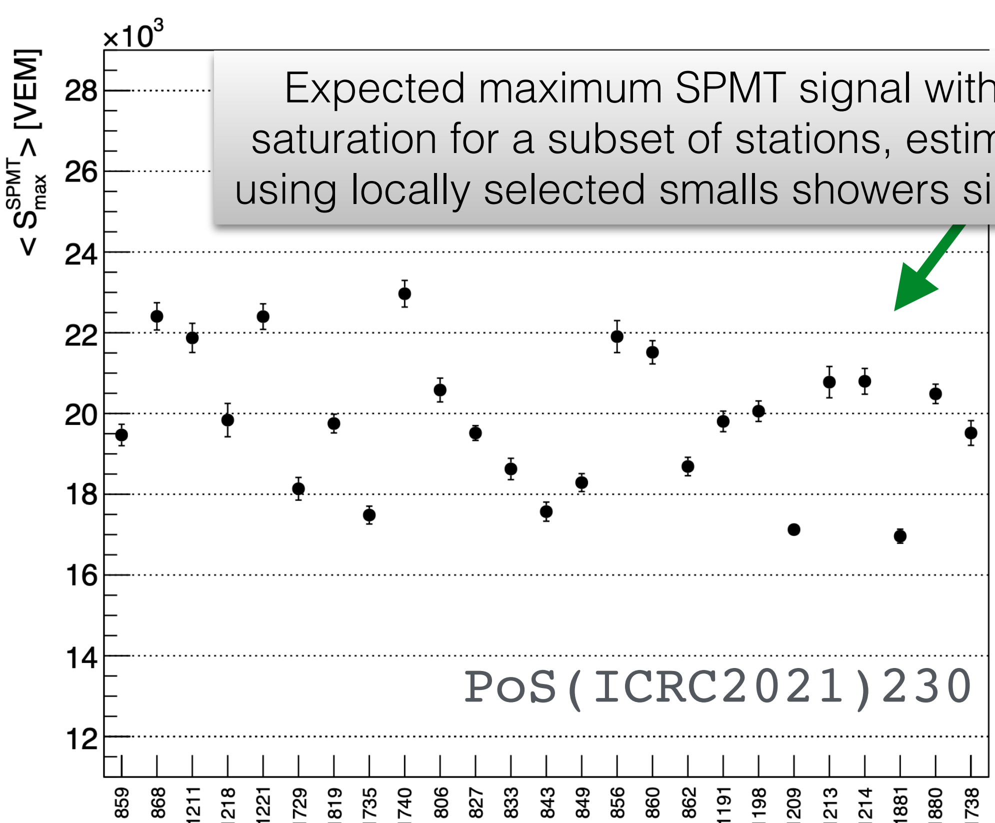
SPMT



Measurements with the WCD 9-inch PMTs limited by **electronics saturation** : overflow of the anode FADC dynamic range of 4095 channels, occurring for integrated signals ≳ 700 VEM

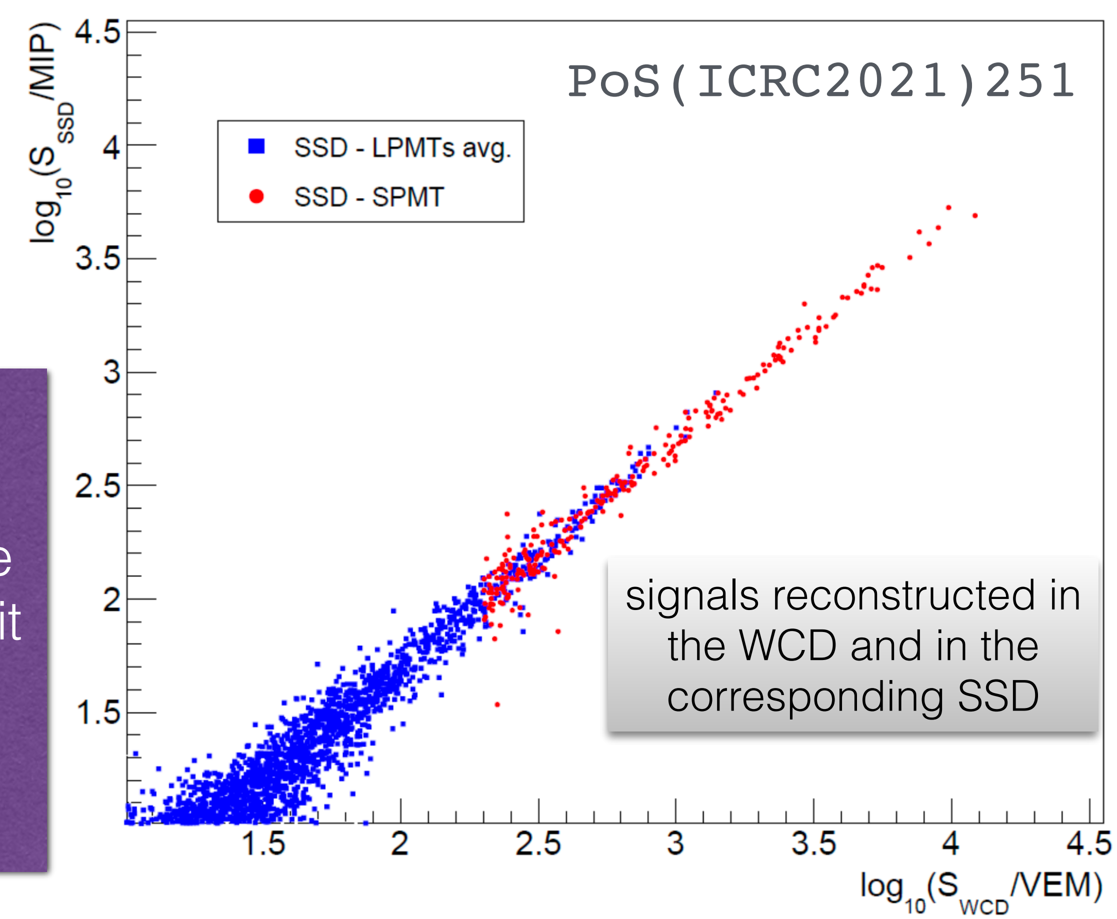
SPMT extends the dynamic range of WCD up to > 20,000 VEM

Only stations < 300 m from the core (and at very high energies) are expected to saturate



Expected maximum SPMT signal without saturation for a subset of stations, estimated using locally selected smalls showers signals.

The WCD and SSD dynamic ranges must be similar to benefit the most from the combined information.



signals reconstructed in the WCD and in the corresponding SSD

Radio emission mechanism

The 30–80 MHz band is used by most experiments.
Due to coherence effects, the cosmic-ray-induced radio emission is strongest below 100 MHz.
Atmospheric noise and short-wave band transmitters make measurements below 30 MHz unfeasible.
From 85 to 110 MHz the FM band interferes with measurements.

Geomagnetic emission

- geomagnetic field deflects e- and e+ in opposite directions —>
  transverse current varying over time
- linear polarisation of the radiation (E aligned along the Lorentz force)
- propagation along the shower axis

Askaryan effect

- ionisation of ambient medium by EAS particles:
  e+ annihilation —> excess of e- along the longitudinal development
- linear polarisation of the radiation (E radially oriented wrt EAS axis)
- sub-dominant in EAS