PIERRE AUGER OBSERVATORY

AugerPrime upgrade of the Pierre Auger Observatory and some results

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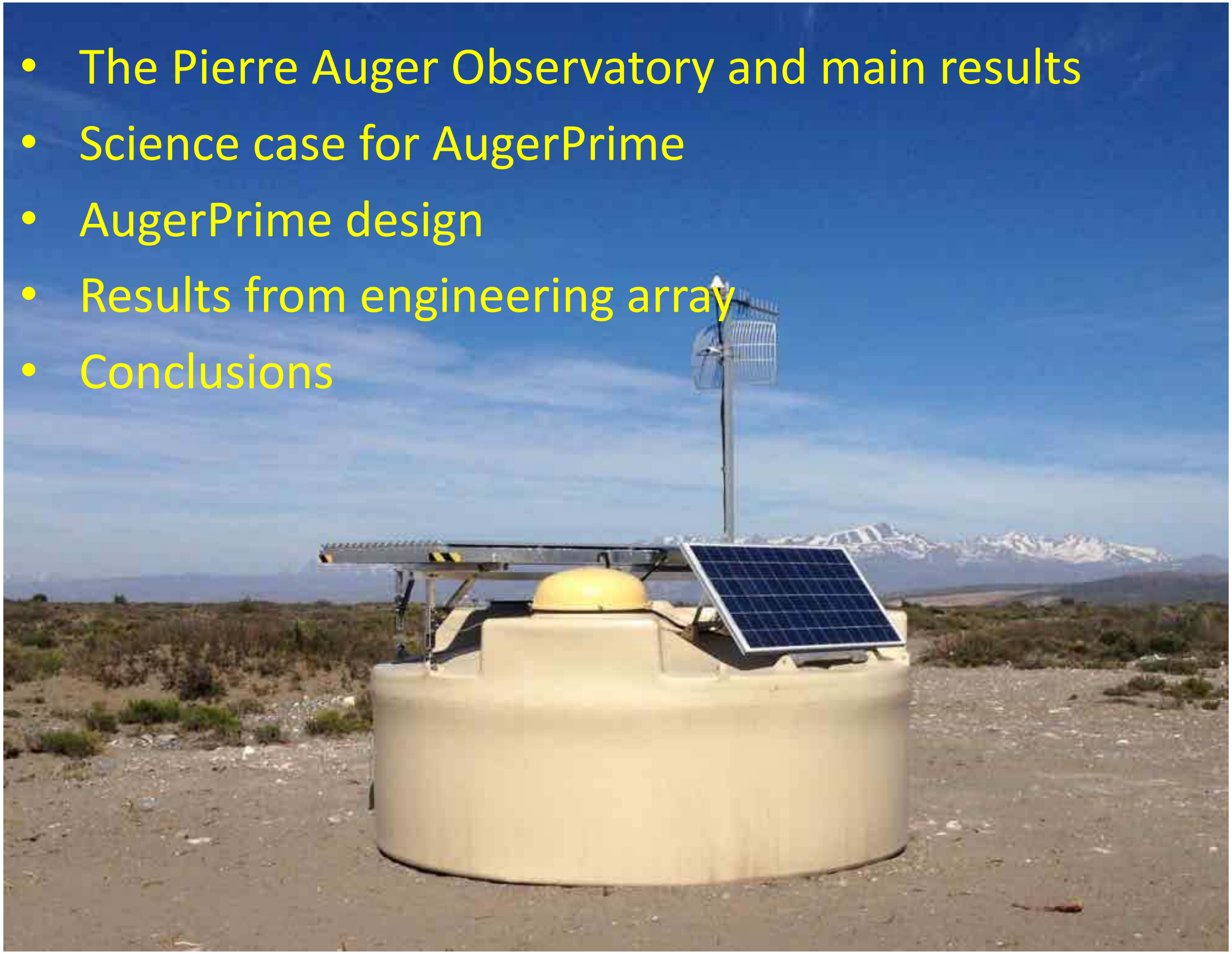
Moscow, 17-18 September 2018

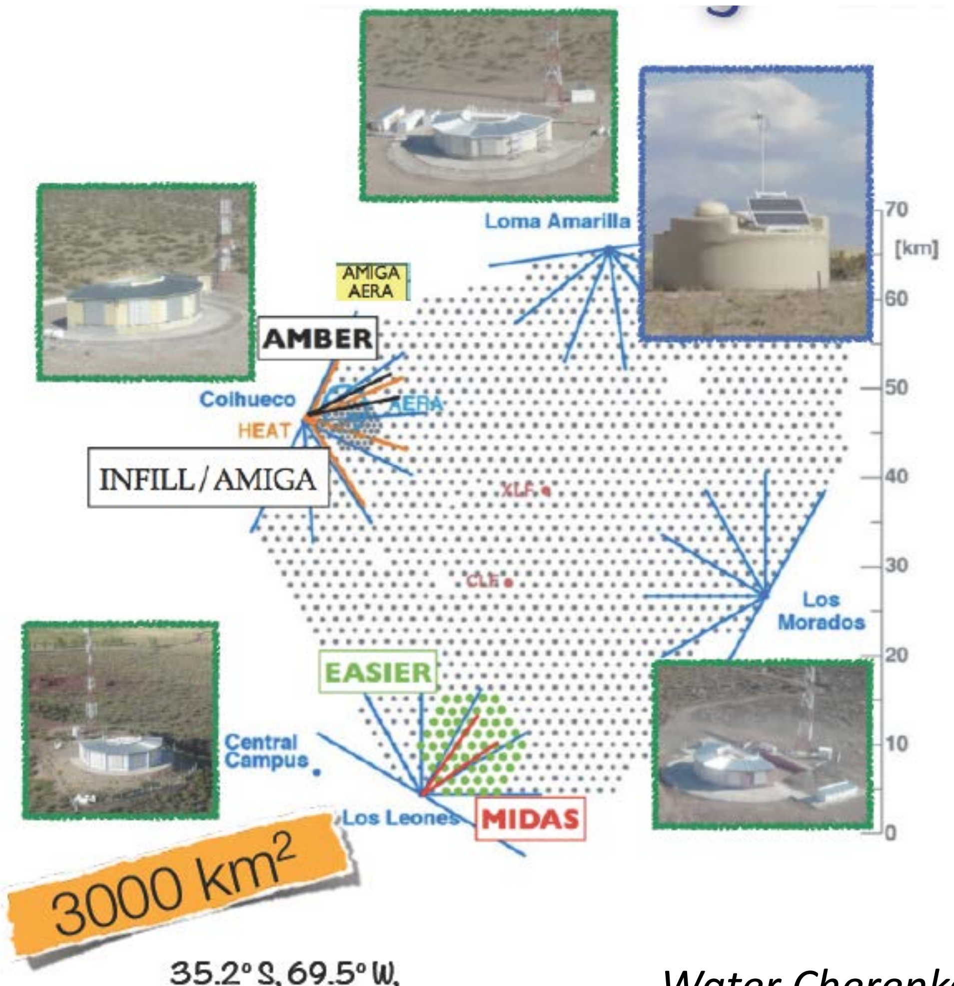
Outline

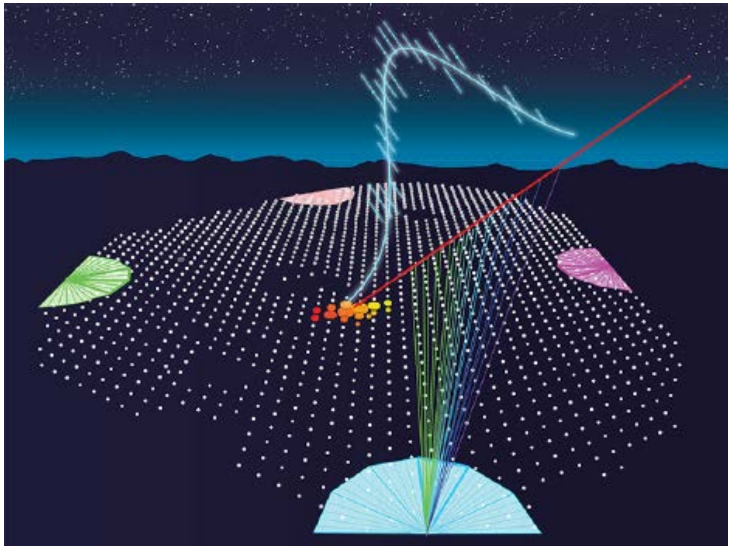


- The Pierre Auger Observatory and main results
- Science case for AugerPrime
- AugerPrime design
- Results from engineering array
- Conclusions

The Pierre Auger Observatory

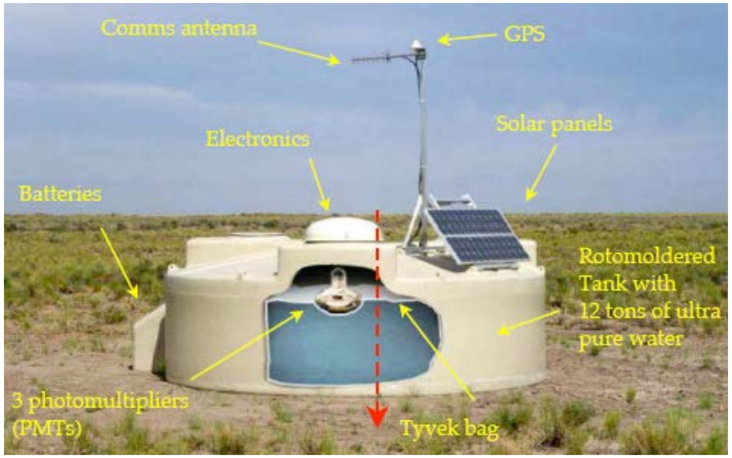
Pampa area at 1400m altitude in Argentina



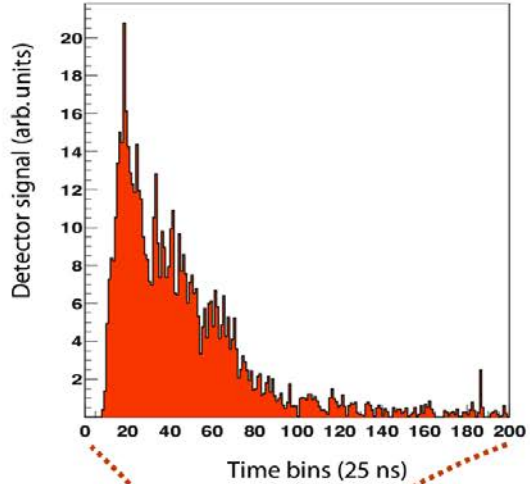


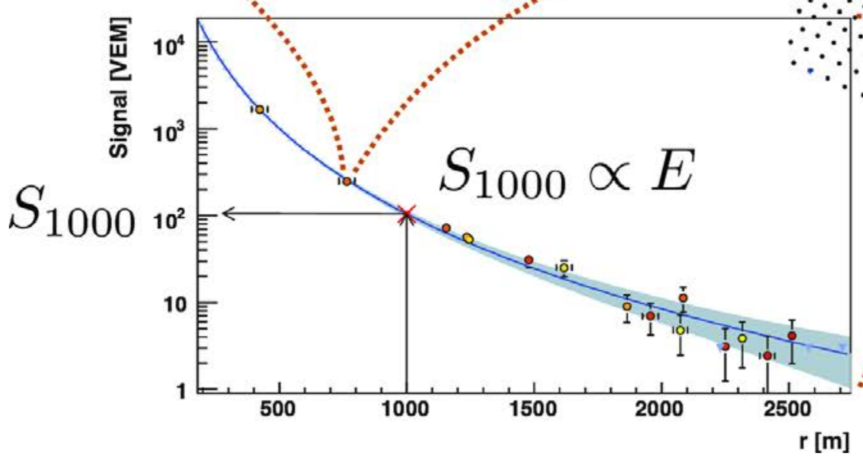
Hybrid observations.

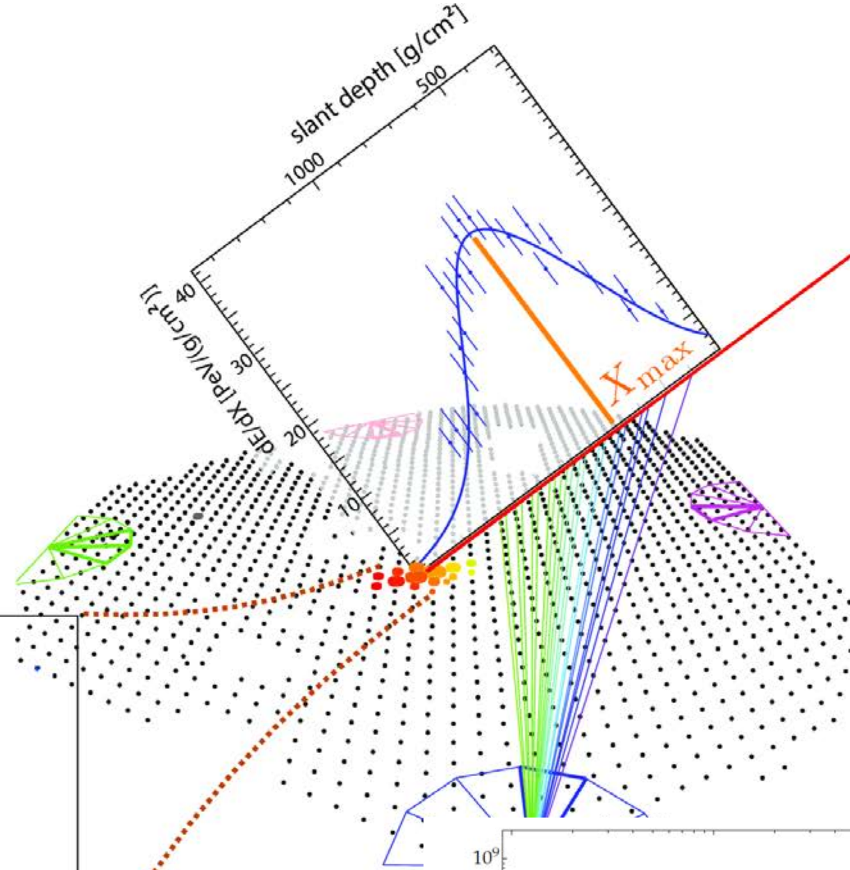
Water Cherenkov detectors (WCD).



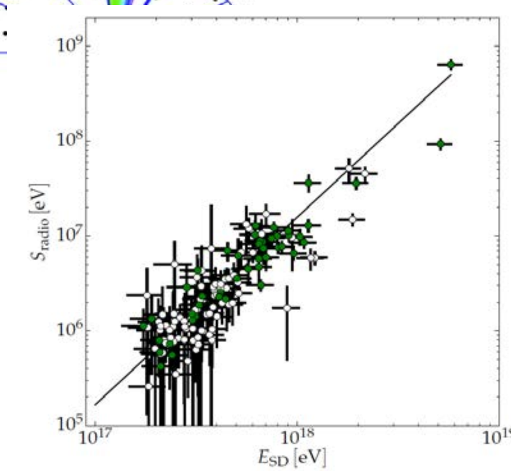
Shower observables



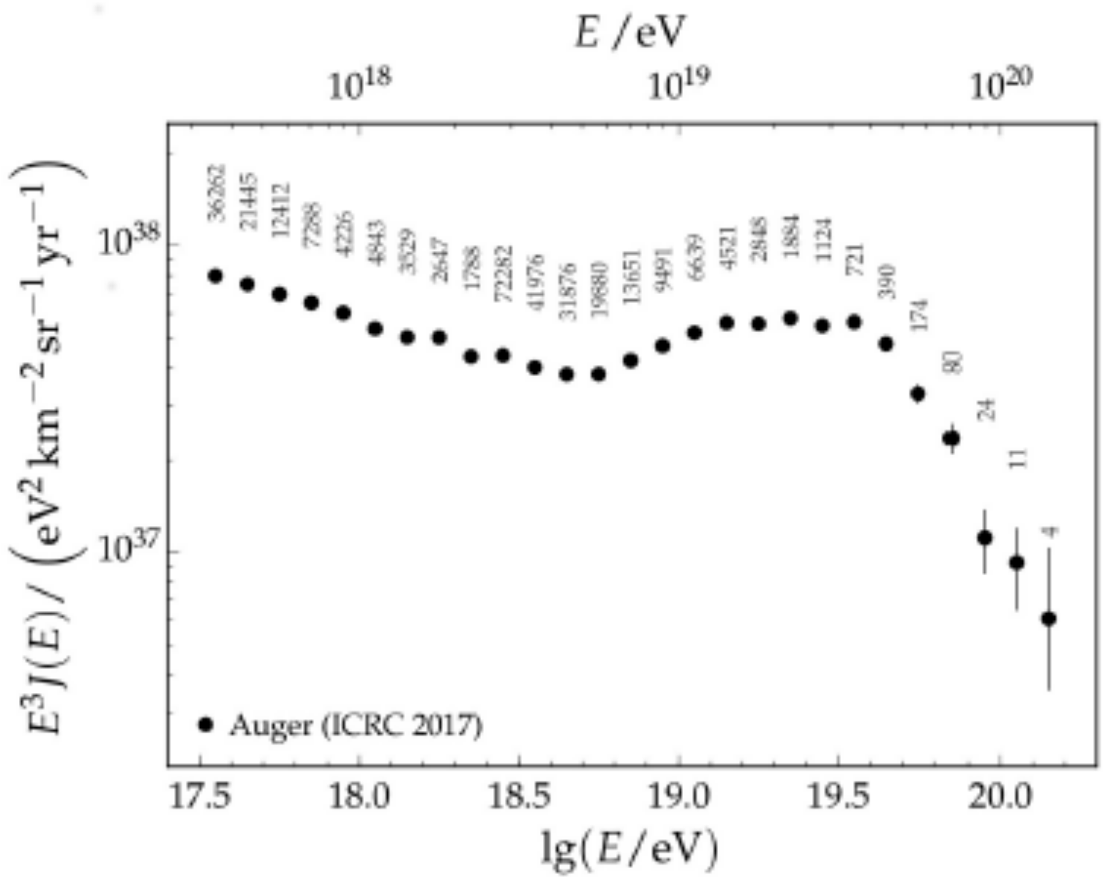




AERA is now integral part of Auger!



Energy spectrum



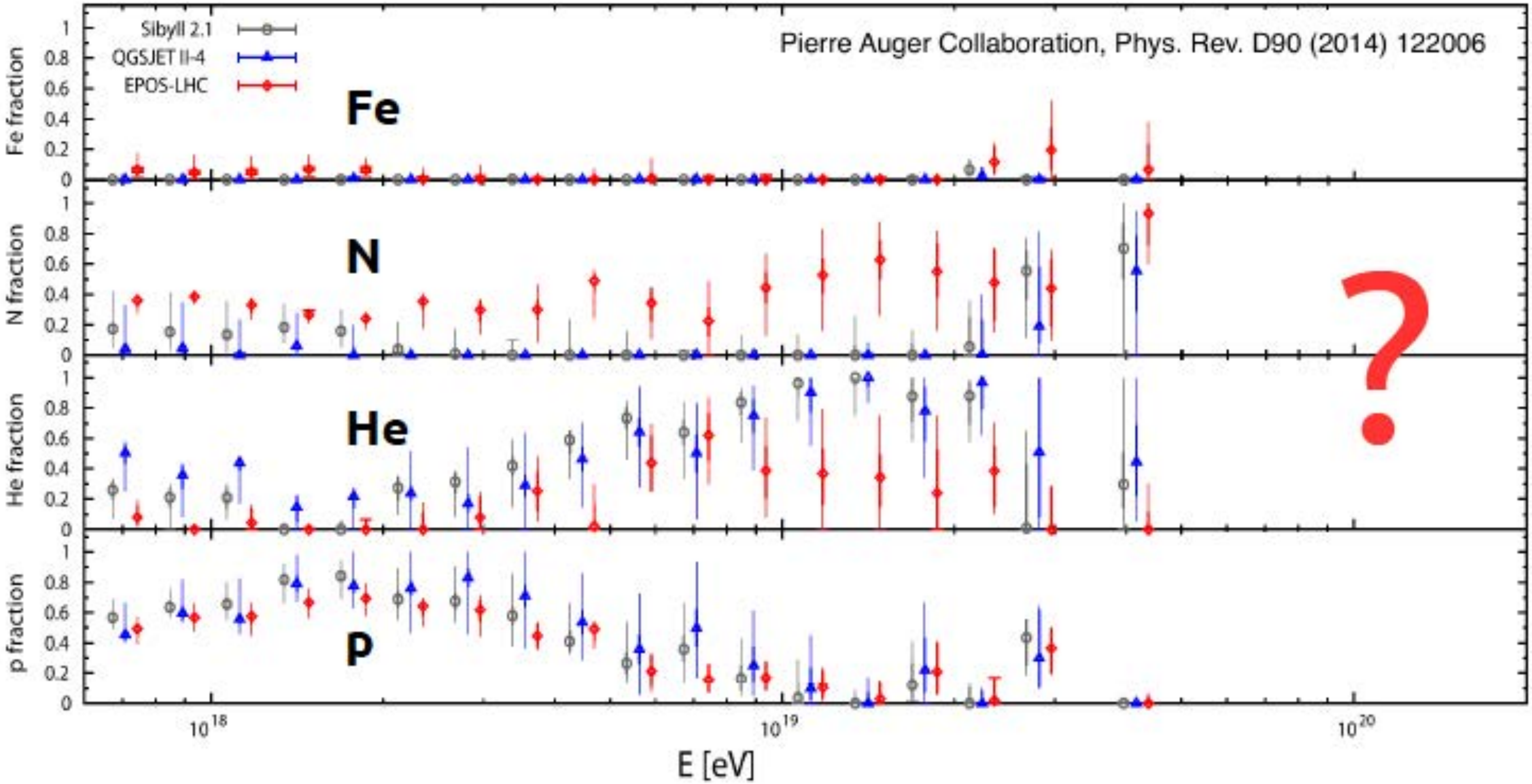
Energy spectrum (ICRC 2017).

Angle at 4.8 EeV

Strong suppression of the flux above $4\ 10^{19}$ eV

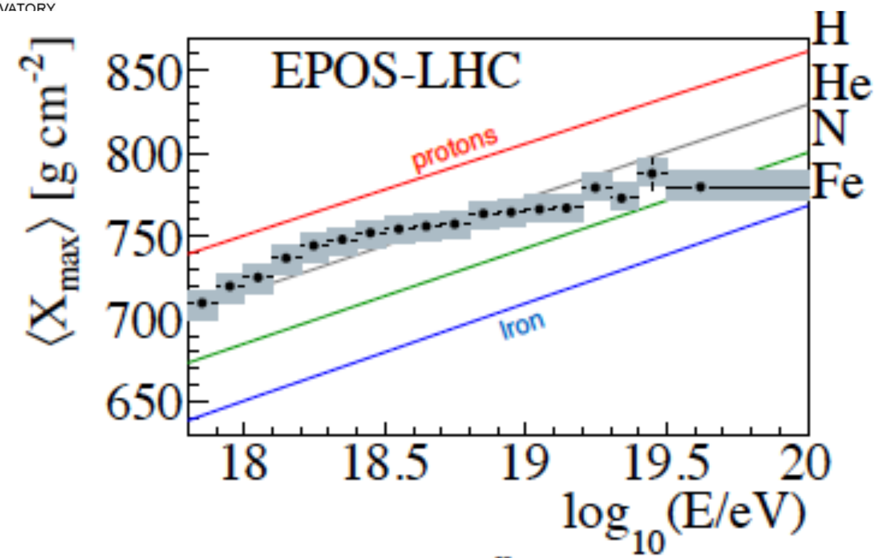
Composition

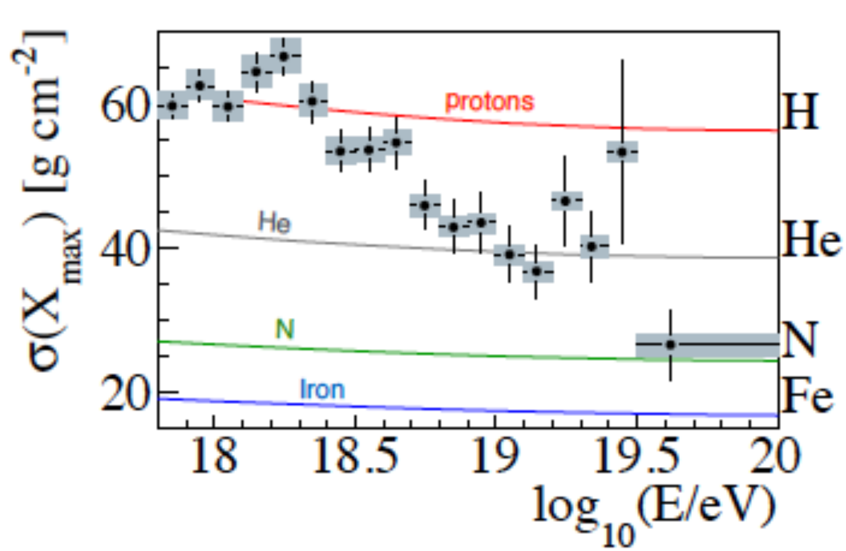
Fitting the data distributions with predictions from a variety of hadronic interaction models for variations in the composition of the primary cosmic rays and examining the quality of the fit.

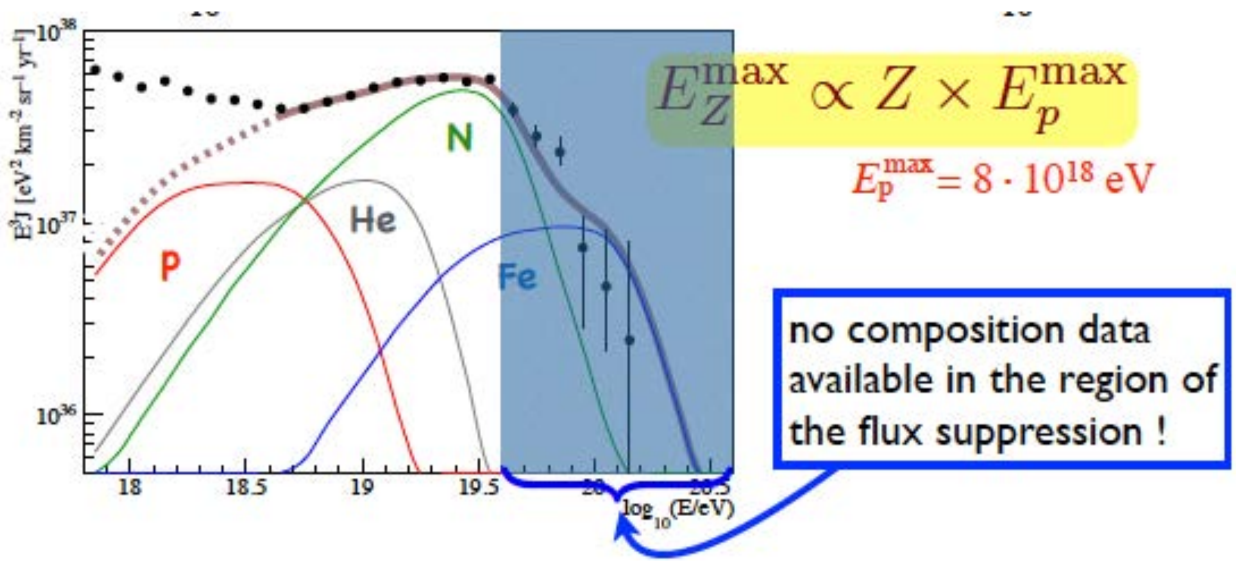


Composition gets heavier above $E > 3\ 10^{18}$ eV.

Composition

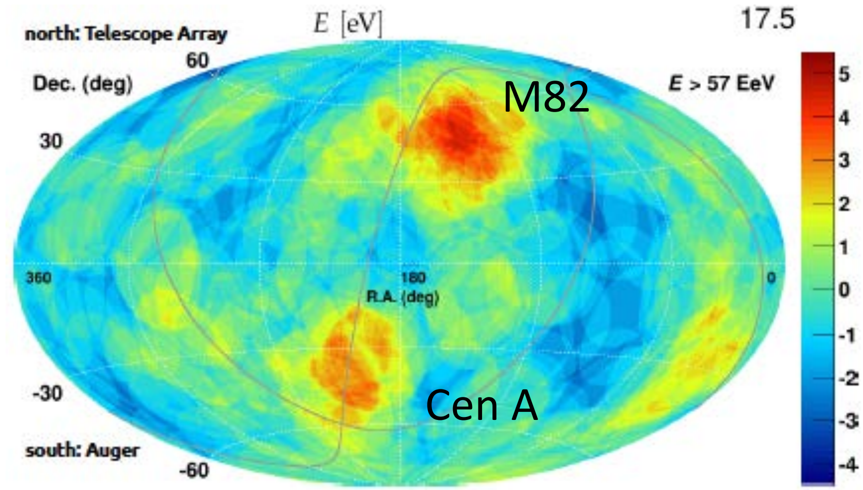




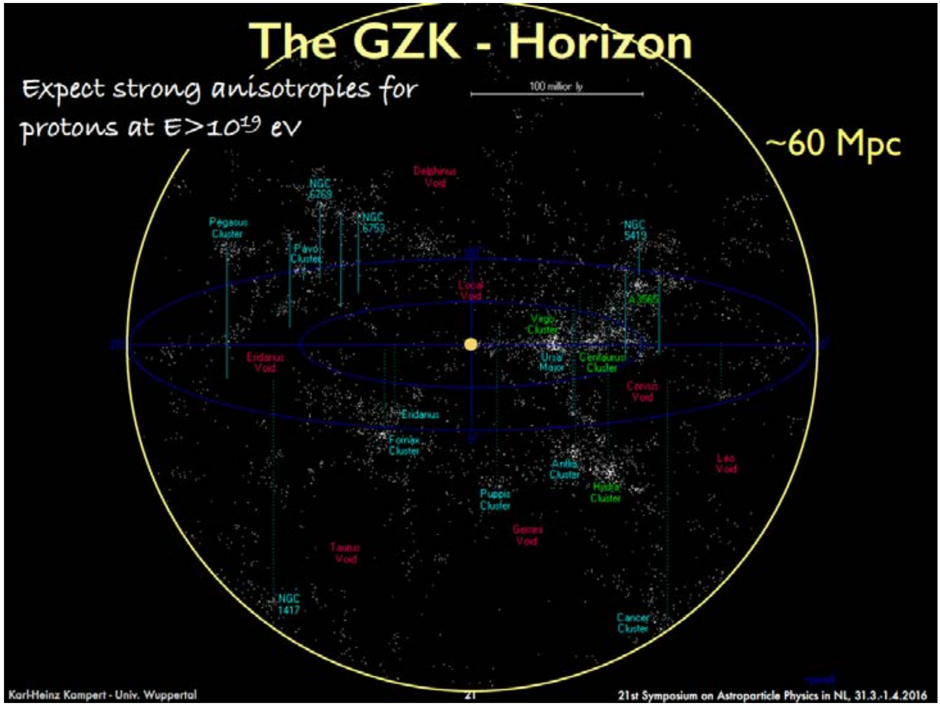


Anisotropies

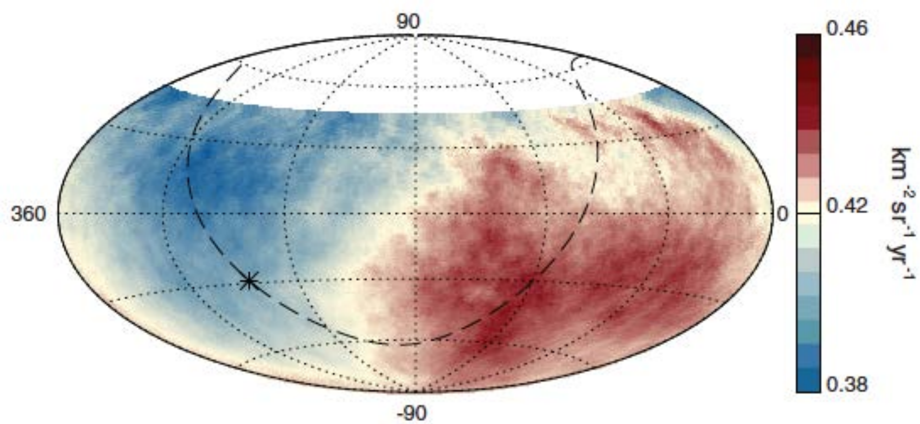
TA: ApJ 790:L21 (2014)



Auger: APP 34(2010)314



Challenging level of isotropy but significant dipole at E > 8×10^{18} eV.



Auger: Science 357, 1266–1270 (2017)

Science case for AugerPrime

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Elucidate the mass composition and the origin of the flux suppression at the highest energies.

Differentiate between the energy loss effects due to propagation and the maximum energy of particles injected by astrophysical sources.

Search for a flux contribution of protons up to the highest energies. We aim to reach a sensitivity to a contribution as small as 10% in the flux suppression region.

The evaluation of the proton fraction above a few times 10^{19} eV is important for estimating the physics potential of existing and future cosmic ray, neutrino, and γ -ray detectors.

Study extensive air showers and hadronic multiparticle production.

Direct measurements of the muon component of EAS will allow the study of hadronic interactions in an energy and kinematic region not reached by terrestrial accelerators.

Operate Auger until 2024 with improved detector and composition sensitivity for the Surface Detector.

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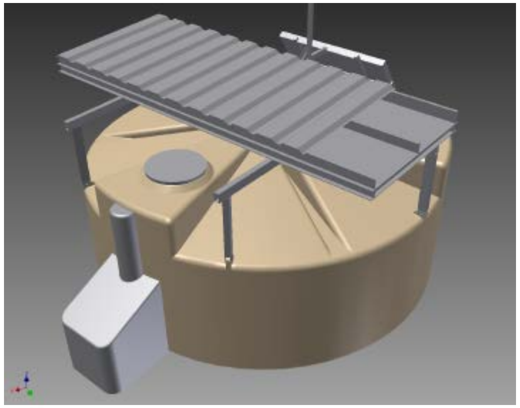
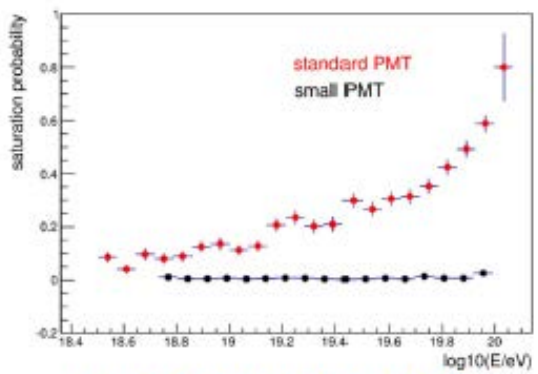
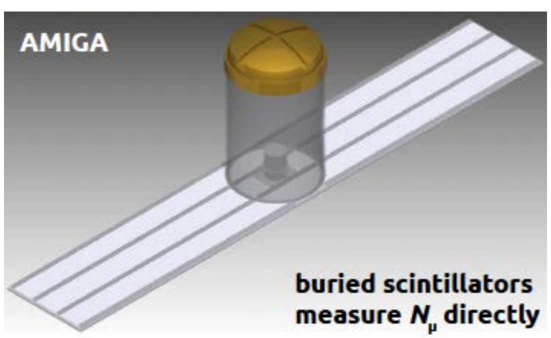
AugerPrime implementation



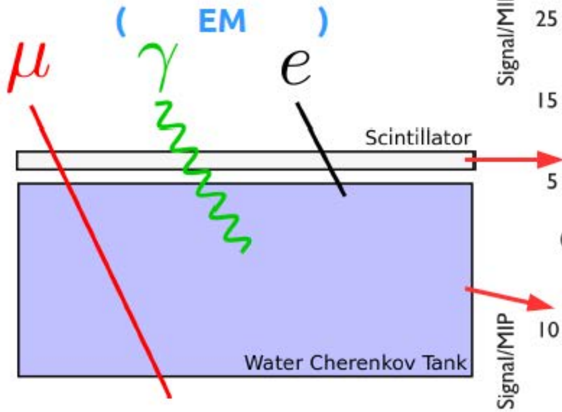


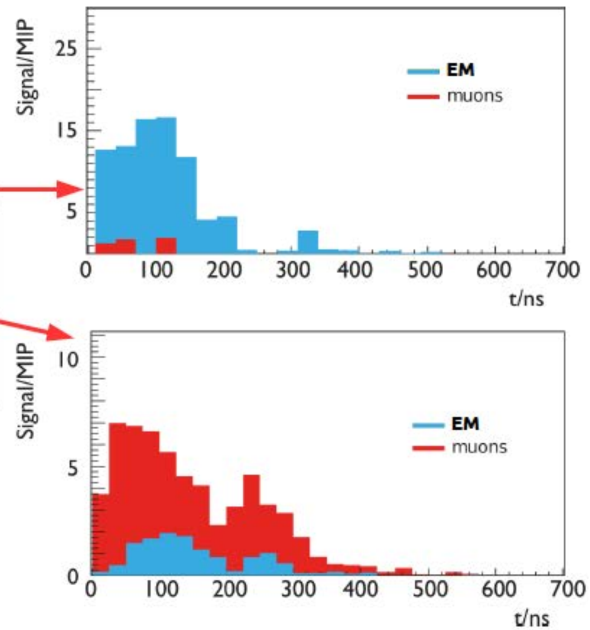
station closest to core



- A complementary measurement of the shower particles will be provided by a plastic scintillator plane (SSD) above the existing Water-Cherenkov Detectors (WCD).
- A small PMT will be added to WCD to increase the dynamic range.
- The surface detector stations will be upgraded with new electronics that will process both WCD and SSD signals.
- An Underground Muon Detector is built in the existing Surface Detector (SD) infill area of 23.5 km^2.
- The operation mode of the Fluorescence Detector (FD) will be changed to extend measurements into periods with higher night sky background.
  - This will allow an increase of about 50% in the current duty cycle of the FD.

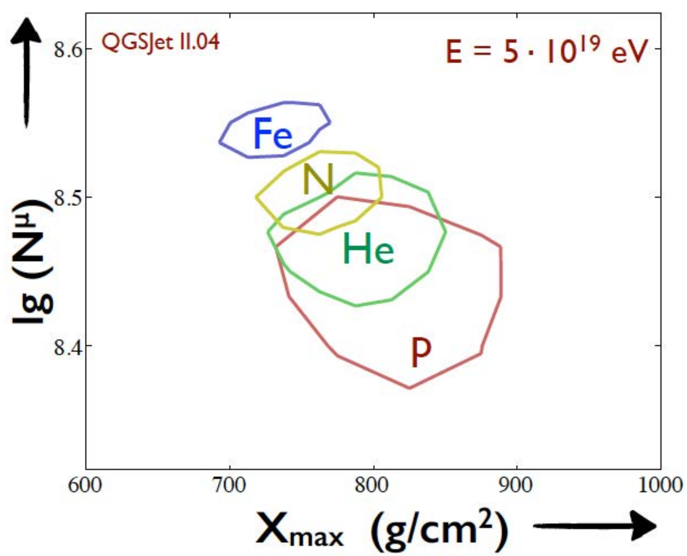
Enhanced composition sensitivity





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

Complementary response

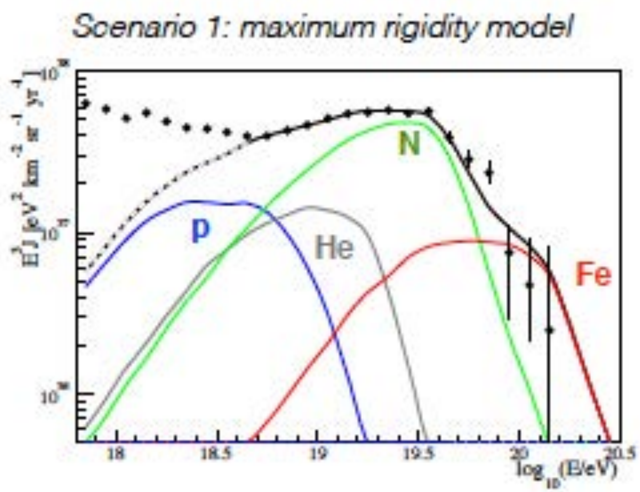


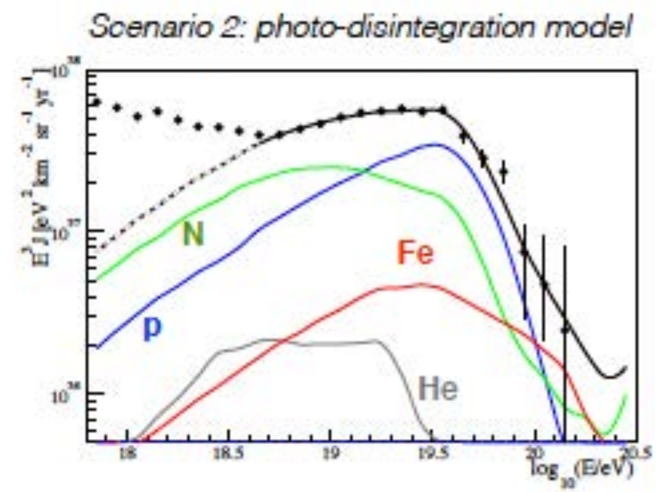
Muons may even outperform Xmax at highest energies !

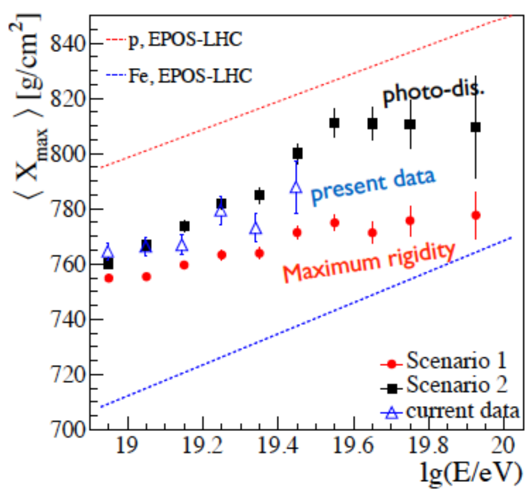
Benchmark scenarios

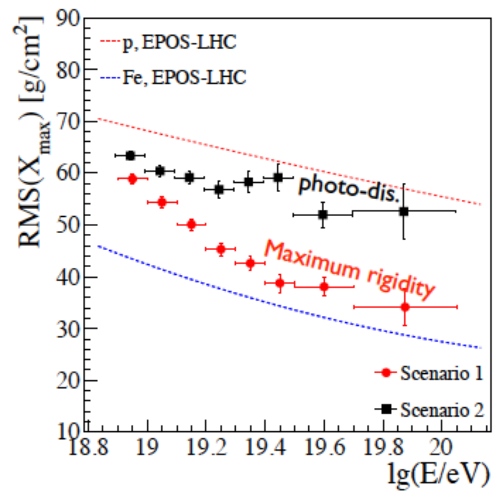
Illustration with two benchmark scenarios

ICRC2015









Reconstructed mean depth of shower maximum Xmax (left) and its fluctuations (right). Shower fluctuations and detector resolutions are included.

The two scenarios can be distinguished with high significance.

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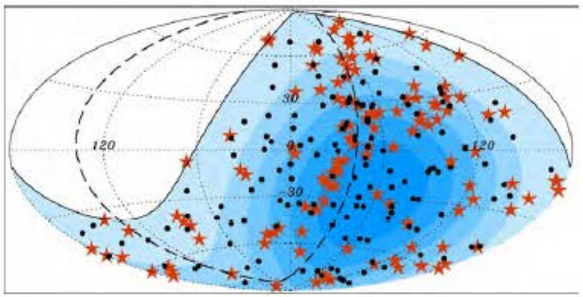
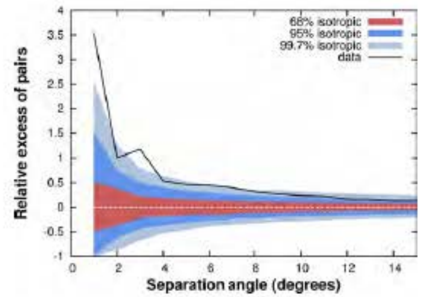
Composition enhanced anisotropy

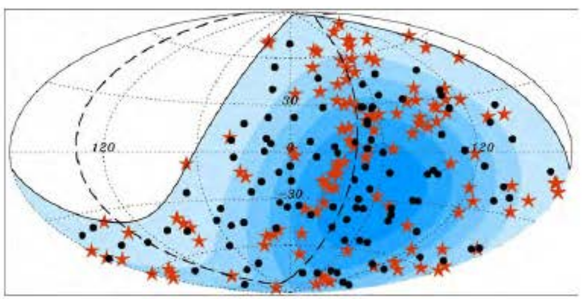
Use arrival directions of 141 measured events with $\theta < 60°$ and $E > 5.5 \cdot 10^{19}$ eV and randomly assign Xmax according to maximum rigidity model with 10% p-like at high E and let 50% of p-like events correlate with Swift-BAT sources

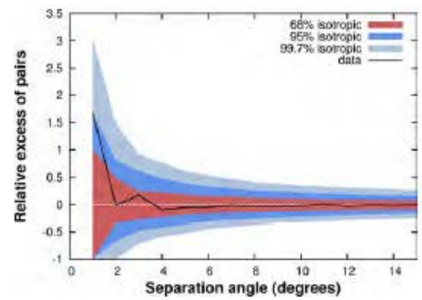




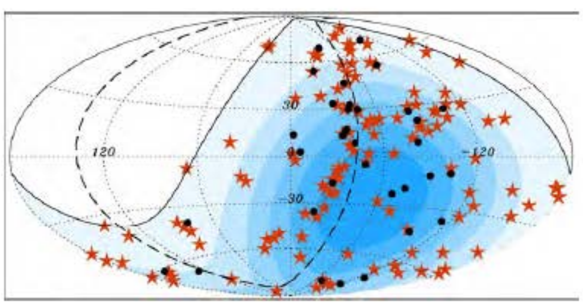
this reproduces well the present situation

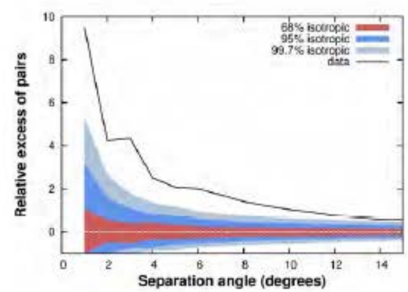
~ 3σ effect





p-like events are removed

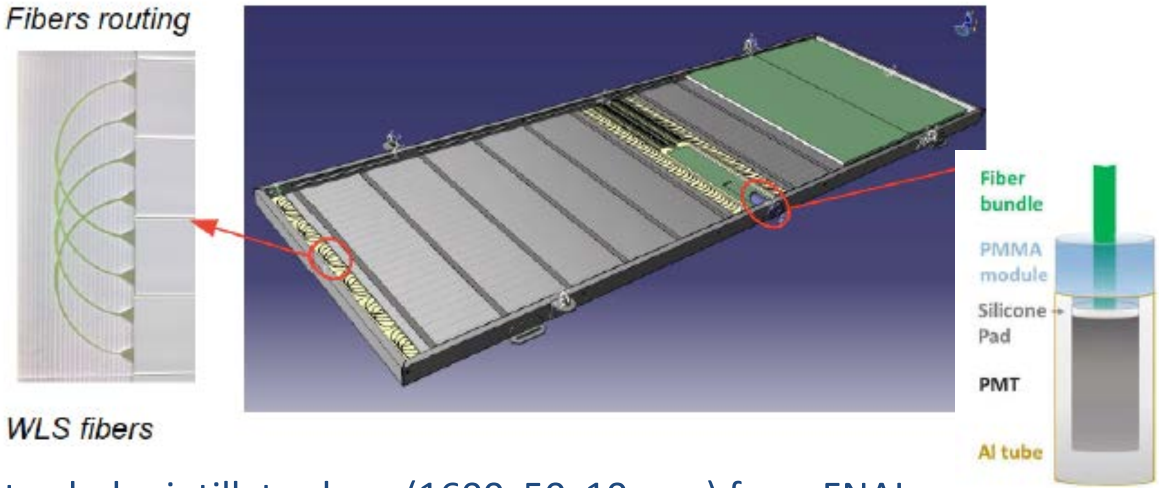




only p-like events included

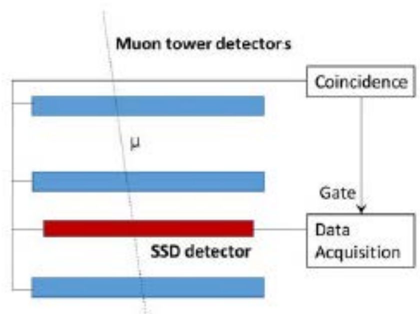
~ 5σ effect

Scintillator detectors (SSD)

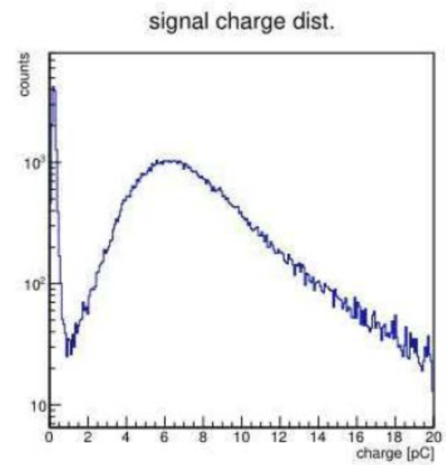


- Extruded scintillator bars (1600x50x10 mm) from FNAL.
- WLS fibers (Kuraray 1 mm), two per scintillator bar.
- Two modules in one box per station, area about 4 m^2.
- Readout by PMT (R9420).
- Dynamic range from fractions of MIP to >20000 MIP (about 250 m from the shower core).
- Simple and robust construction with double roof for thermal insulation.

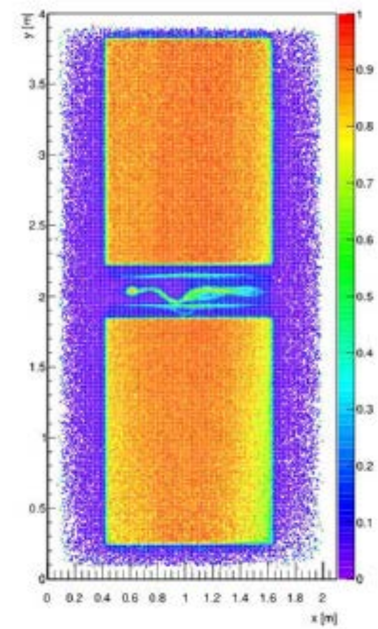
Production has started.



SSD test bench.

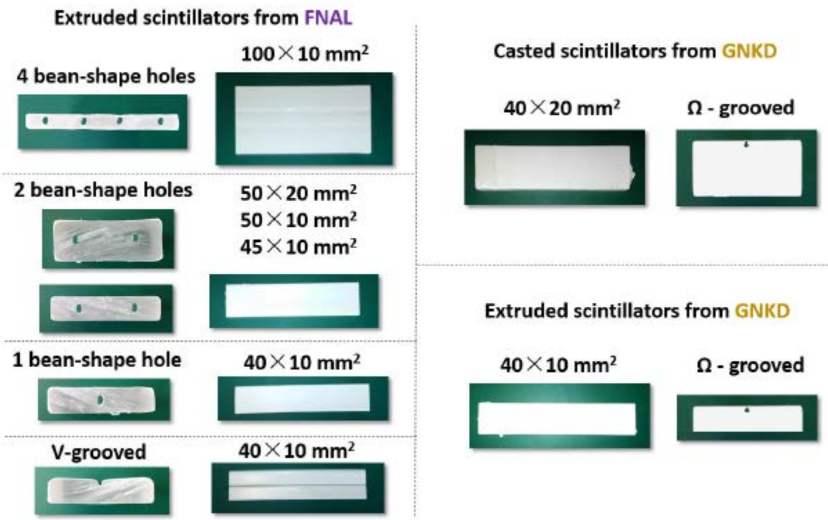


Charge distribution measured for atmospheric muons, MIP = 30 p.e.



SSD efficiency.

Test results on scintillators and fibers



No.	Scintillator profile (mm)	Fiber end & glue in groove	Results (p.e.)
1	FNAL 100×10, 4 holes	cut	26.7 ± 1.4
2	FNAL 50×20, 2 holes	cut	42.3 ± 1.9
3	FNAL 50×10, 2 holes	U-route	43.7 ± 1.9
4		cut	26.6 ± 0.6
5	FNAL 40×10, 1 hole	cut	18.0 ± 0.4
6	FNAL 40×10, 1 Groove	cut	18.8 ± 0.5
7		cut, D.C.3145	26.0 ± 0.2
8		cut, BC600	30.9 ± 0.9
9	GNKD 40×10, 1 Groove	cut	16.6 ± 0.4
10	GNKD* 40×20, 1 Groove	cut	50.4 ± 2.0

Several scintillator and WLS fiber configurations were tested.

- Saint-Gobain BCF-91-A 1.2 mm
- Saint-Gobain BCF-99-29-AMC 1.2 mm
- Kuraray Y11(200)-MSJ 1.0 mm
- Kuraray Y11(300)-MSJ 1.0 mm

Results in p.e. number:
S(K.Y11(300)-MSJ) = 24.8 +/- 0.4 p.e.
S(K.Y11(200)-MSJ) = 21.9 +/- 0.3 p.e.
S(S.G.BCF-91-A) = 19.7 +/- 0.4 p.e.
S(S.G.BCF-99-29-AMC) = 17.1 +/- 0.2 p.e.

K.Y11(300)-MSJ 1.0mm was chosen for SSD.

FNAL 50 10mm^2 2-hole scintillator was chosen for SSD.
(A balance between cost, performance, and availability)

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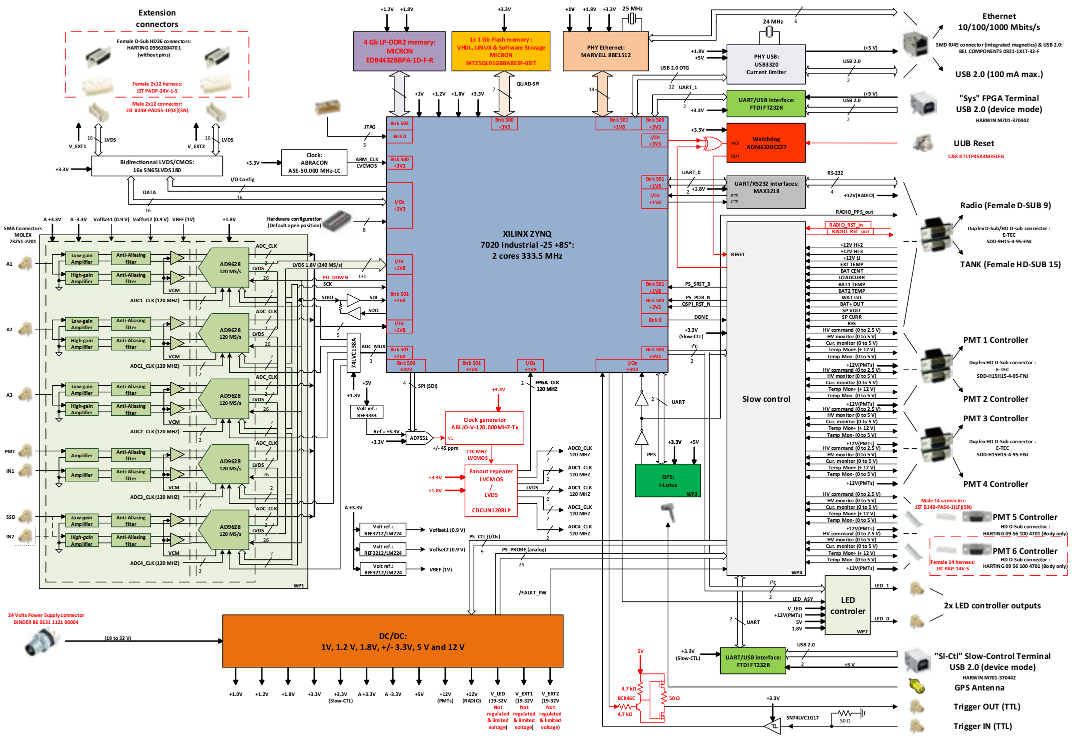
*Results on light yield of plastic scintillator samples (*casted plastic scintillators).*

Electronics upgrade



UUB block diagram (V2).

- Processes signals from WCD and SSD.
- Increased the data quality:
  - Faster sampling of ADC traces, 120 MHz;
  - Better timing accuracy, 4ns;
  - Increased dynamic range.
- Enhanced local trigger and processing capabilities (with a more powerful local station processor, FPGA Xilinx Zynq 7020).
- All functionalities on a single board, UUB (upgraded unified board).
- Improved calibration and monitoring capabilities.
- Power consumption < 12 W.

UUB (V1).

To implement some minor design changes, a new main board was fabricated and is being installed to engineering array. The production is planned to start end of this year.

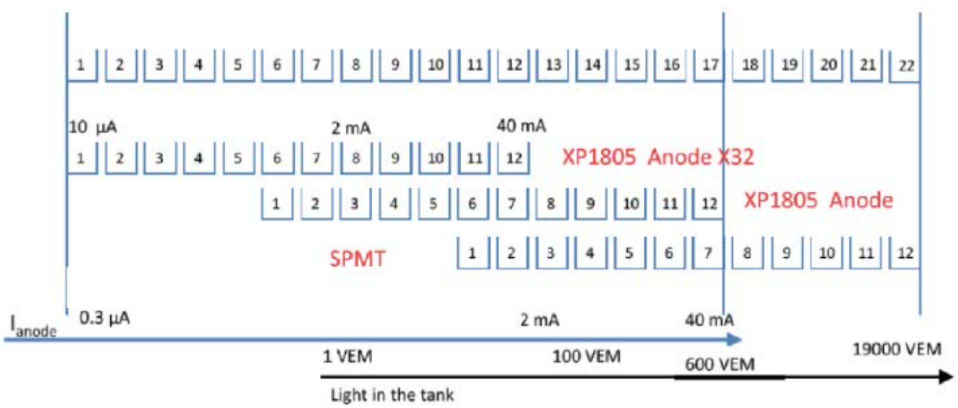
Increased WCD dynamic range

Add 1'' PMT (SPMT) to the three 9" PMTs (LPMT) of the WCD.

CAEN HV module

SPMT, Hamamatsu R8619

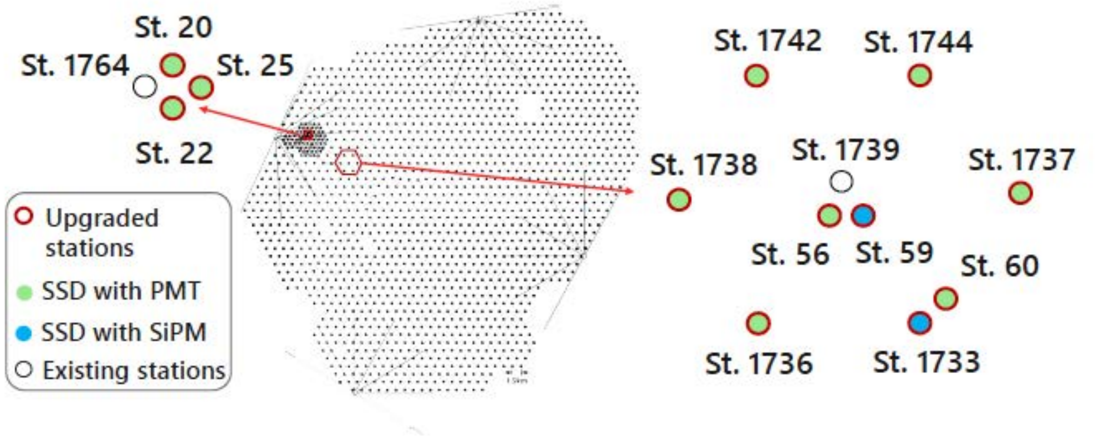
LPMT, 9'' XP1805



Scheme for the WCD dynamic range.

- Dynamic range from fractions of VEM to >20000 VEM.
- Less than 2% saturated events at the higher energies.
- Unambiguous determination of the particle density down to about 250 m from the shower core.

Engineering array



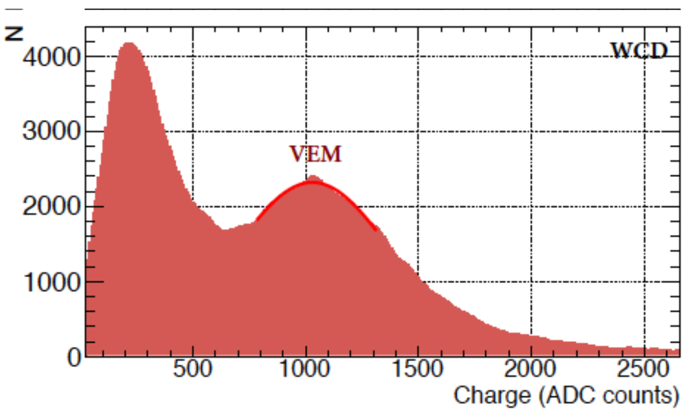
AugerPrime engineering array layout.

The AugerPrime engineering array (EA) of 12 upgraded detectors (WCD+SSD+UUB) is in operation since October 2016.

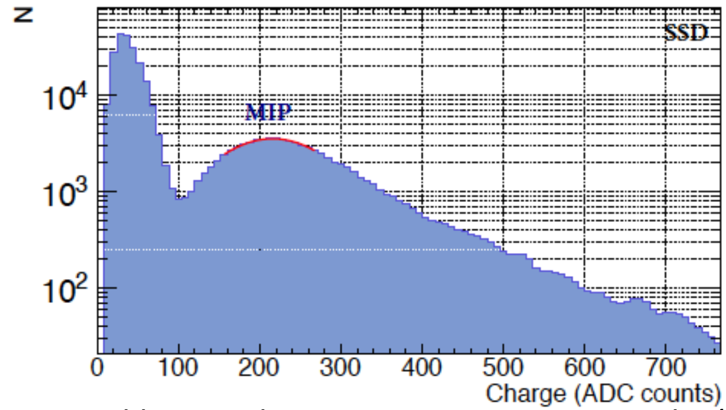
<u>Goal:</u>

- Verify hardware and firmware/software performances;
- Develop and verify calibration and monitoring routines;
- Develop and verify trigger and data acquisition routines;
- Verify communication and power consumption.

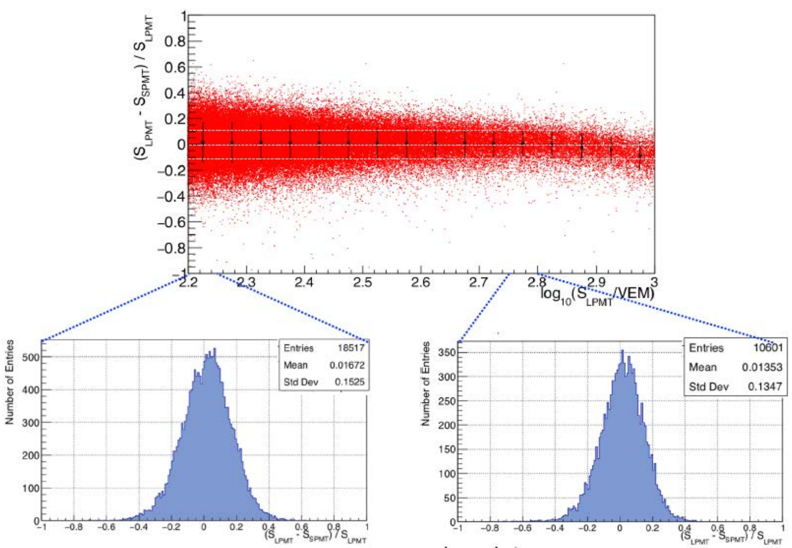
Calibration and dynamic range

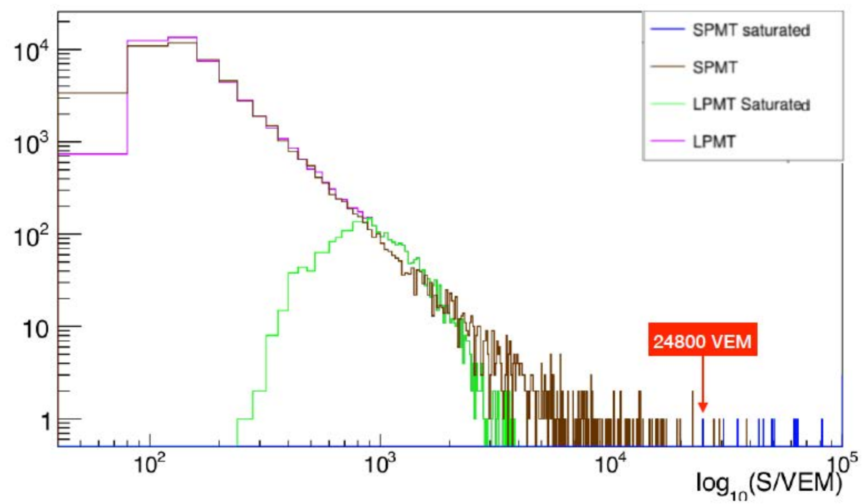


WCD calibration by vertical equivalent muon (VEM) charge.



SSD calibration by minimum ionizing particle (MIP).

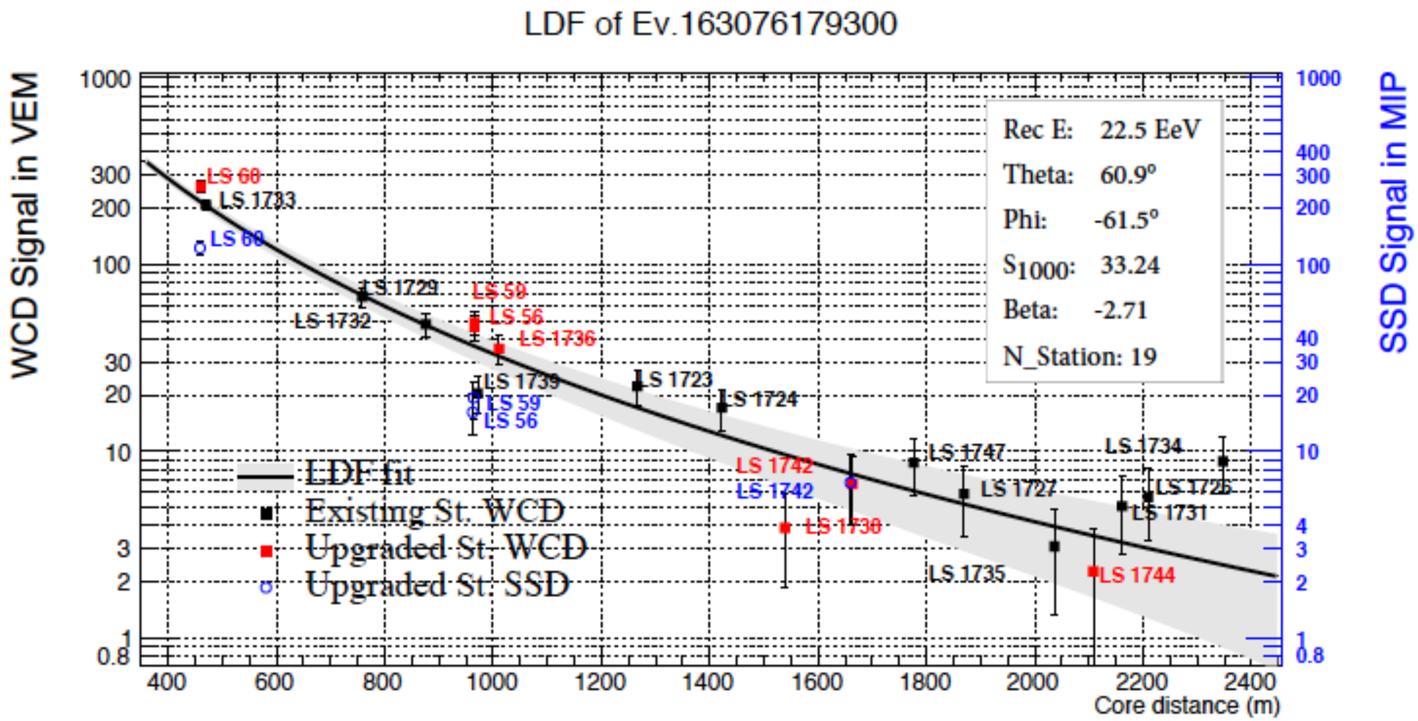




WCD dynamic range.

- **SSD dynamic range > 10 kMIP.**
- **WCD dynamic range > 20 kVEM.**

Shower measurements by EA

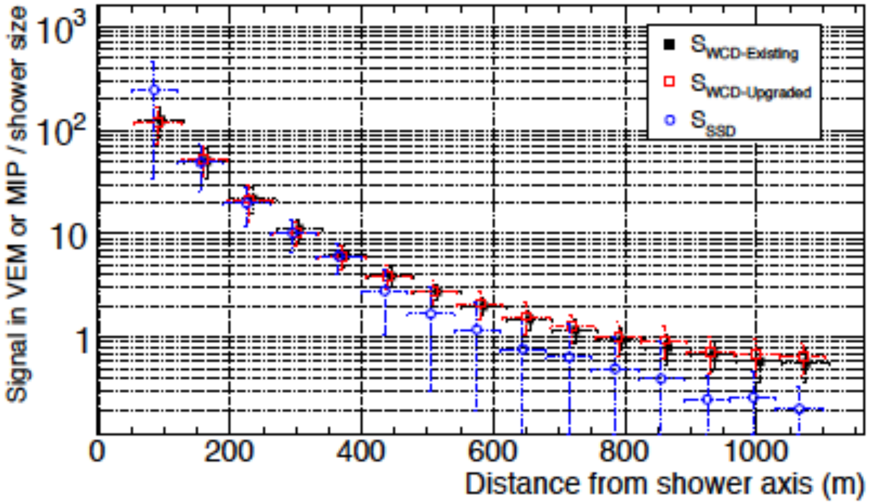


The LDF of a shower can be described as a modified NKG function (K. Greisen, 1956; K. Kamata and J. Nishimura, 1958)

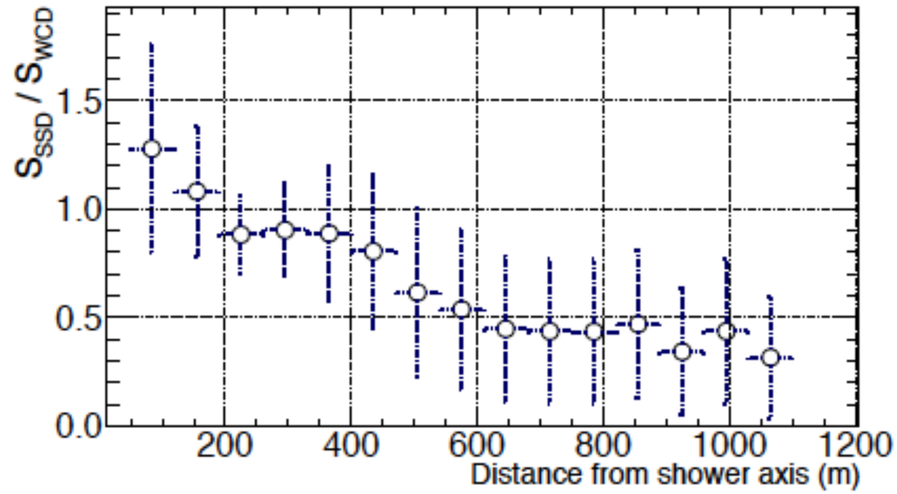
$$S(r) = S(r_{opt}) \left(\frac{r}{r_{opt}}\right)^{\beta} \left(\frac{r + r_1}{r_{opt}}\right)^{\beta+\gamma}$$

Signals from upgraded stations (in red) compared to the LDF reconstructed by the existing stations (in black). The measured SSD signals are shown in blue.

Global LDF



The global LDF of the signals from upgraded stations and existing stations. Signals are normalized by the shower size.



The ratio of S_{SSD}/S_{WCD} as a function of distance from the shower axis.

- **$S_{SSD} > S_{WCD}$ in the area close to the shower core since the EM component has a higher proportion than the muonic component.**
- **$S_{WCD} > S_{SSD}$ in the region further away from the core, since the muonic component turns to be dominant in the proportion compared to the EM component.**
- **S_{SSD}/S_{WCD} larger than 1 for the region near the shower axis and tending to the ratio of the detector areas (A_{SSD} : A_{WCD} = 0:4) at large distances (>700 m).**

Timeline

- Design has been validated by Engineering Array.
- Construction is now starting.
- Data taking is currently planned until 2024 (40 000 km^2 sr year).
- Similar event statistics will be reached with AugerPrime as with observatory so far.

Conclusions

- The Auger observatory has yielded important results however the origin of the flux suppression is still unknown.
- AugerPrime aims to identify primary particles at the highest energies:
  - Distinguish between propagation and source effects;
  - Search for proton flux at the highest energies;
  - Study hadron interactions at the highest energies.
- Engineering Array is taking data since October 2016 with good performance.
- Construction has started and will and take about 2 years.
- Data taking until 2024 will yield similar statistics as with the current observatory.