AugerPrime - The upgrade of the Pierre Auger Observatory

Jarosław Stasielak (IFJ PAN, Kraków)

on behalf of the Pierre Auger Collaboration

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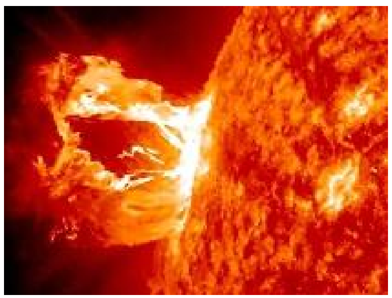
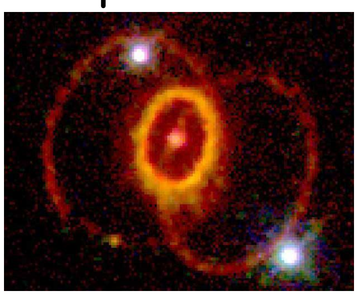
Cosmic rays (CRs) – high-energy particles coming from space
(protons, nuclei, neutrinos, photons, …)

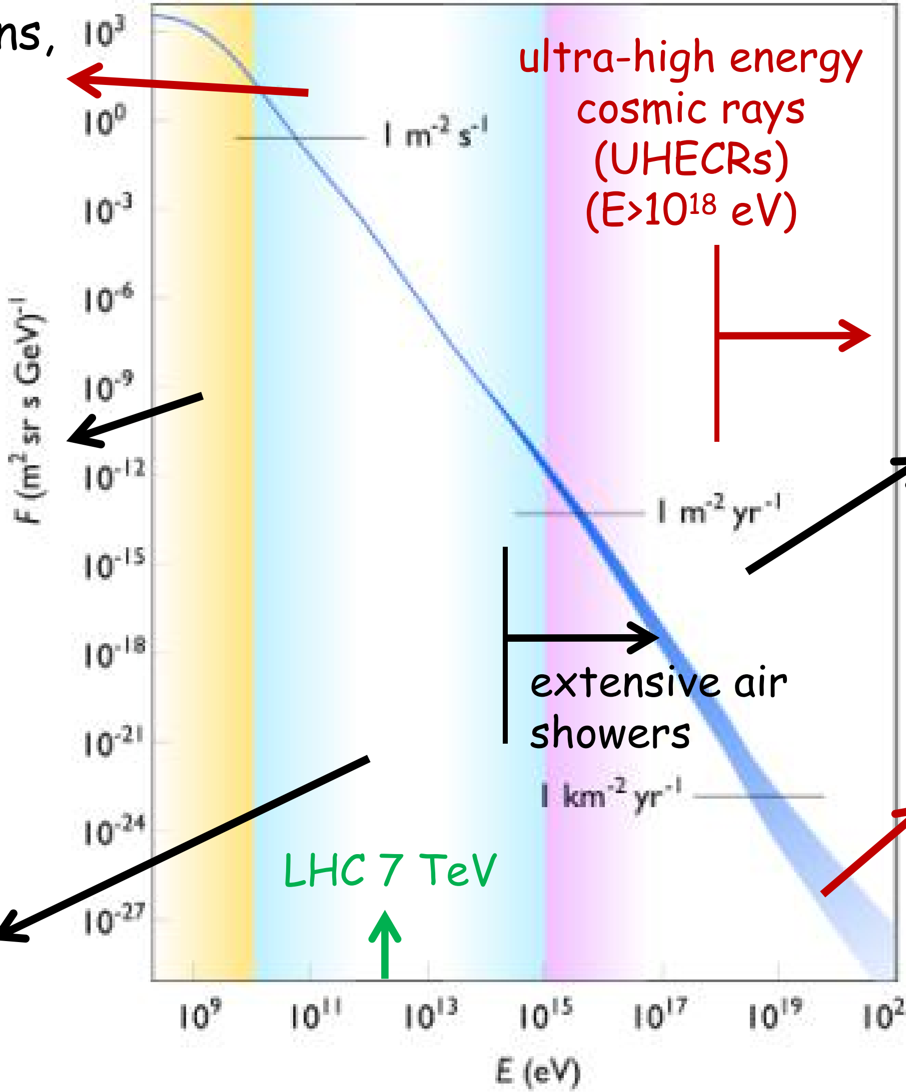
direct observations, satellites, balloon-borne experiments

Sun



Supernovae, pulsars



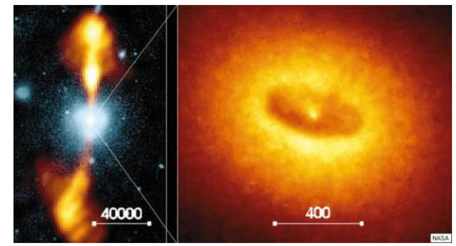


ultra-high energy cosmic rays (UHECRs) ($E>10^{18}$ eV)

extensive air showers

LHC 7 TeV

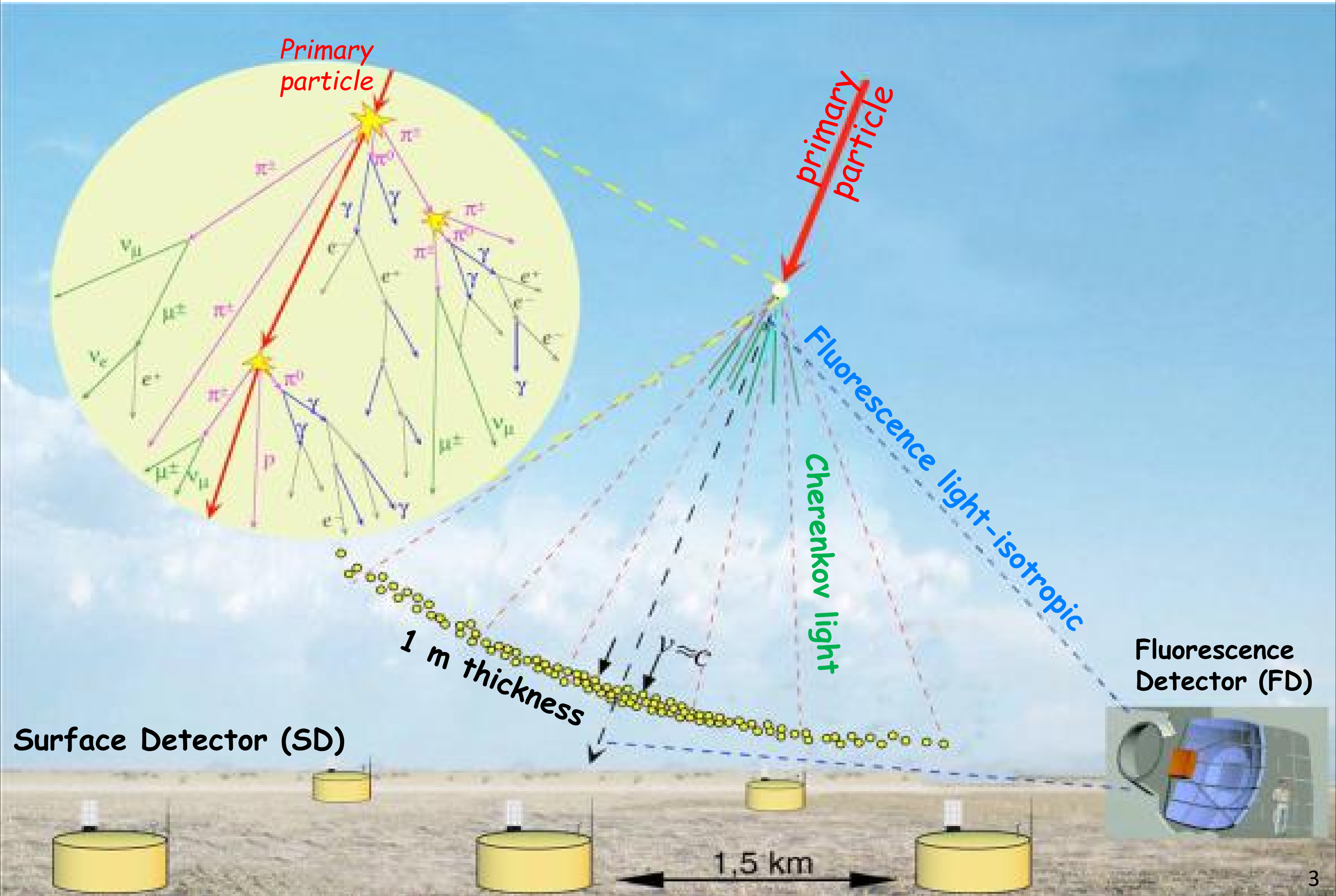
Sources unknown!
star burst galaxies, active galactic nuclei (AGNs) ???



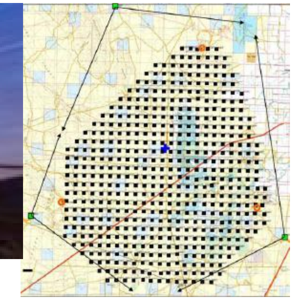
$E>10^{20}$ eV, very low flux: 1 particle/km^{2}/1000 yr (indirect observations, extensive air showers, detector arrays covering large area)

10^{20} eV in LHC technology → accelerator size of Mercury orbit

Ultra-high energy cosmic rays detection - extensive air showers



The largest ultra-high energy cosmic rays (UHECRs) observatories

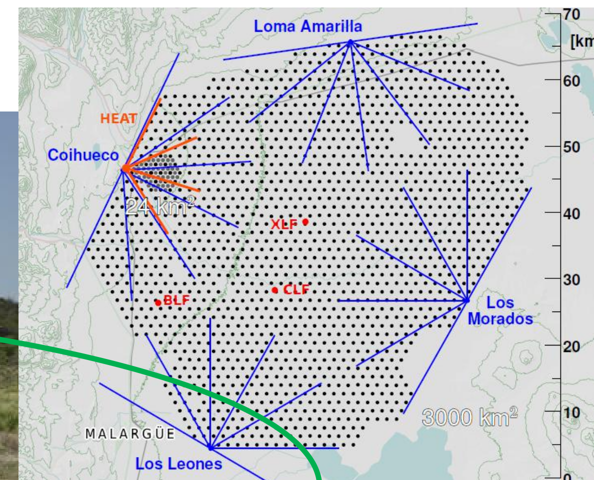


Northern hemisphere

Telescope Array (TA)
Location: USA
507 SD stations, area 680 km^2
36 FD telescopes overlooking the surface detector

Southern hemisphere

Pierre Auger Observatory (Auger)
Location: Argentina
1660 SD stations, area 3000 km^2
27 FD telescopes

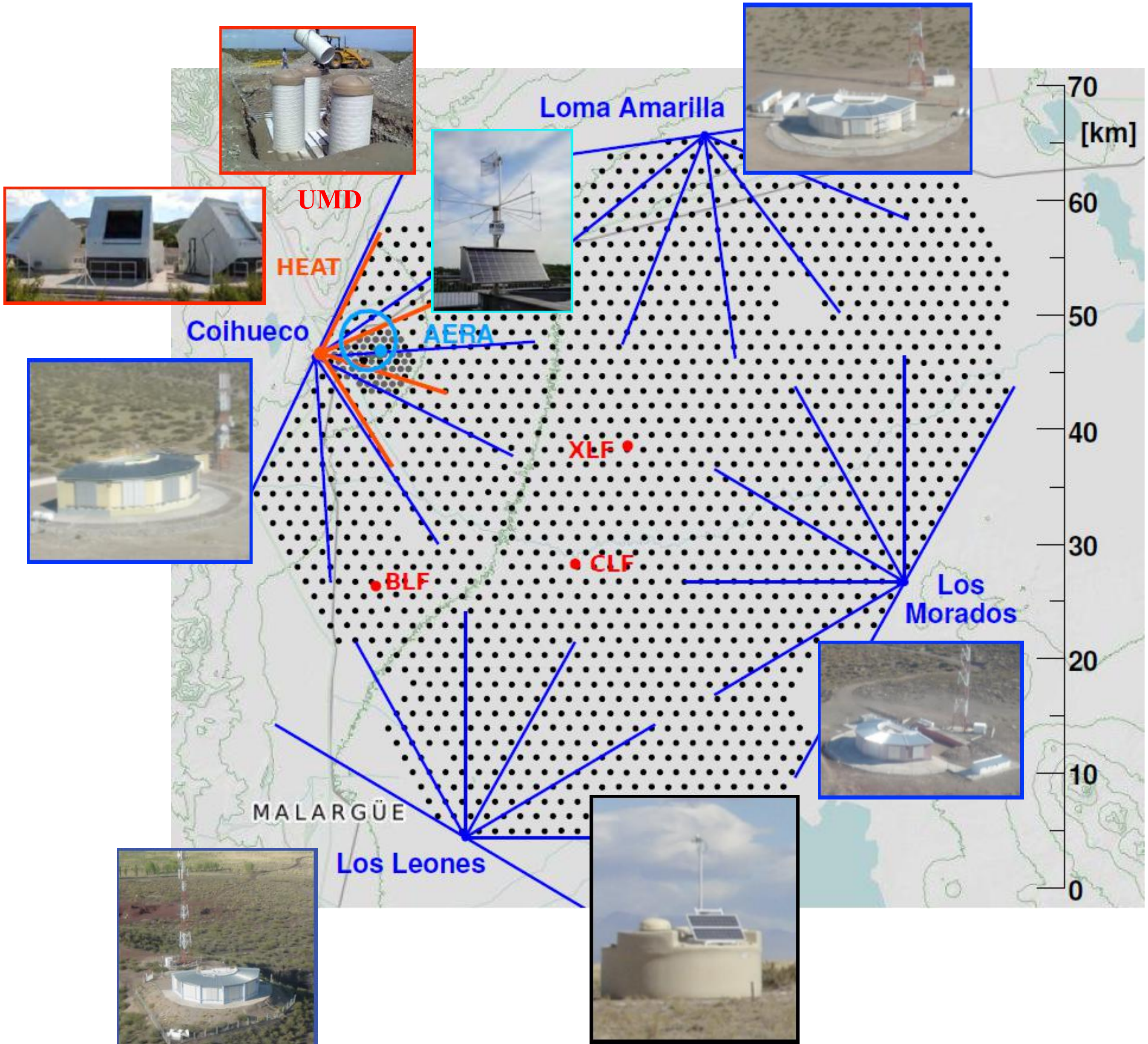


Key questions:

- Origin?
- Mass composition?
- Acceleration process?
- Is there an upper limit to the UHECRs energies?

These questions are related to each other!

Pierre Auger Observatory



Water-Cherenkov stations

- SD1500 : 1600 stations, 1.5 km grid, 3000 km^2
- SD750 : 61 stations, 0.75 km grid, 25 km^2

4 Fluorescence Sites

- 24 telescopes
- 3 high elevated telescopes (HEAT)

Underground Muon Detector

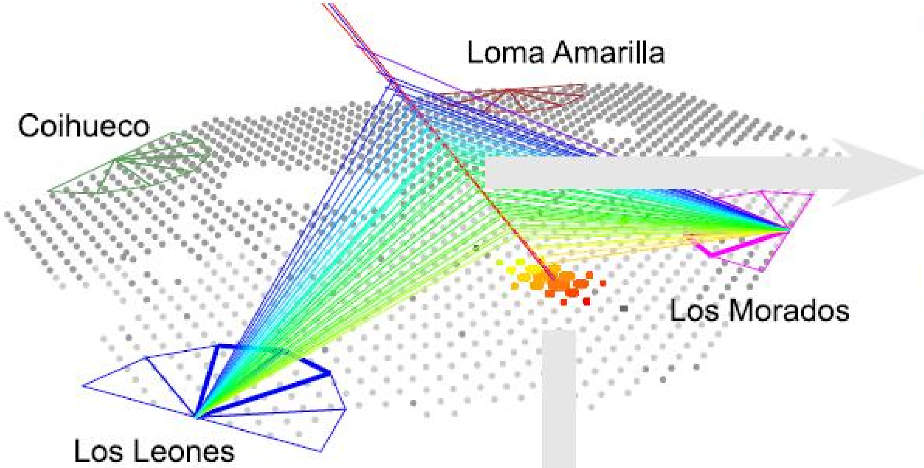
- 7 prototype stations

AERA radio antennas

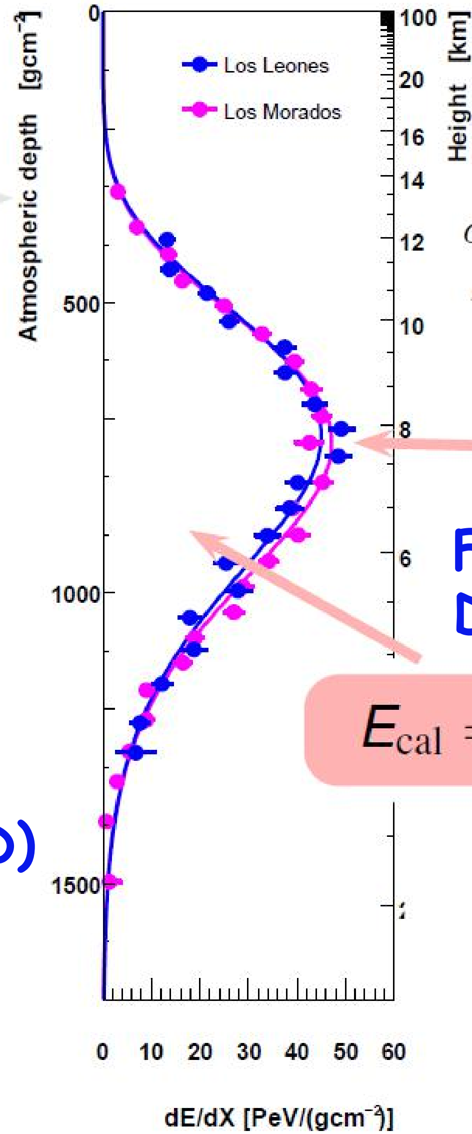
- 153 stations, 17 km^2

\+ Atmospheric monitoring devices

Detection of air showers



top of the atmosphere



duty cycle 13%
(clear, moonless night)

$\sigma X_{\max} \leq 20\,\mathrm{g/cm^2}$
$\Delta_{\mathrm{sys}} \leq 10\,\mathrm{g/cm^2}$

$X_{\max}$

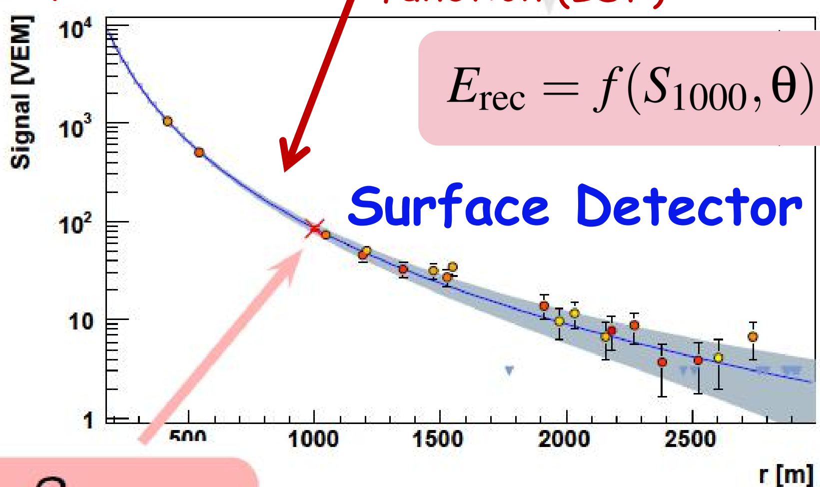
Fluorescence Detector (FD)

$E_{\mathrm{cal}} = \int \frac{\mathrm{d}E}{\mathrm{d}X}\,\mathrm{d}X$

$\sigma_E/E \sim 8\,\%$
$\Delta_{\mathrm{sys}} \approx 15\,\%$

duty cycle 100%

lateral distribution function (LDF)



$E_{\mathrm{rec}} = f(S_{1000}, \theta)$

Surface Detector (SD)

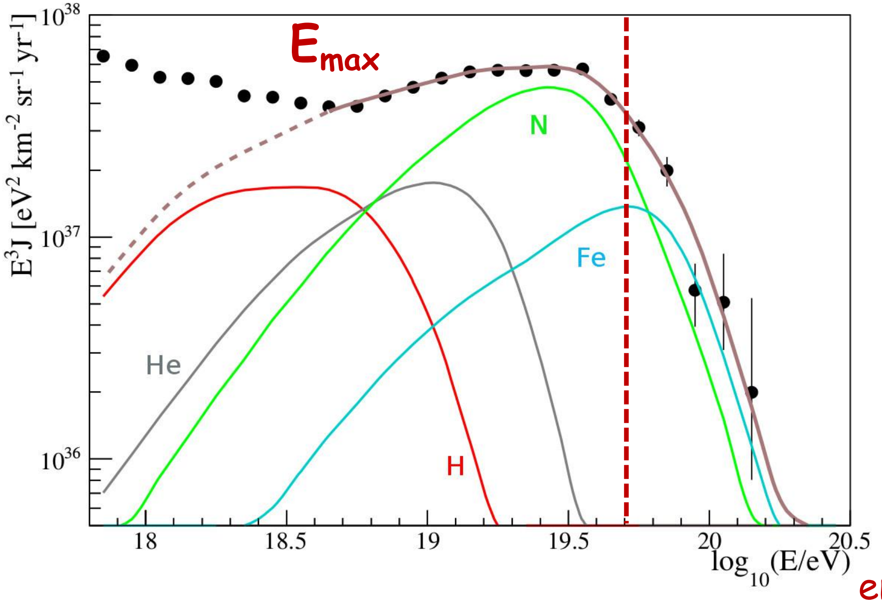
S_{1000}

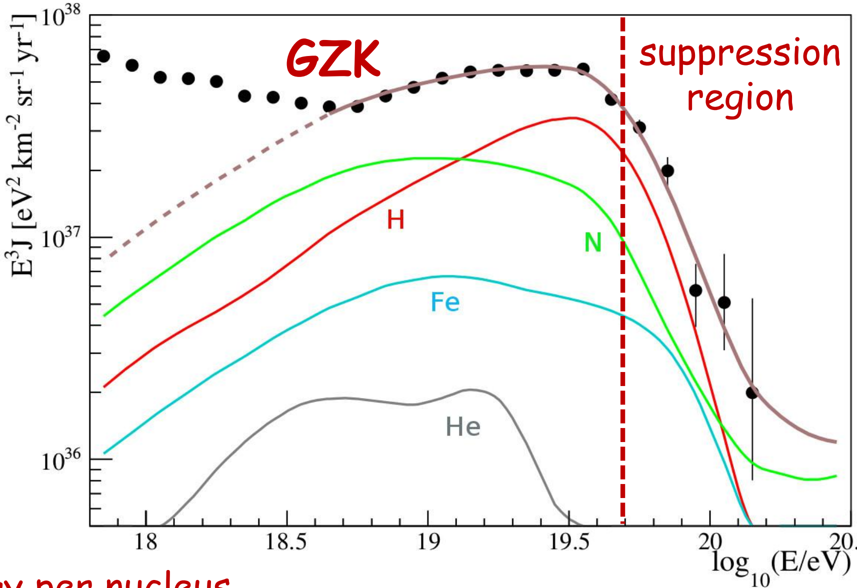
$E_{\mathrm{surface}} = f(S_{1000},\, \theta)$

Hybrid detection technique uses information from both SD and FD

Auger results (see the Highlight talk by Alexey Yushkov)

- Energy spectrum suppression above ~5 x 10^{19} eV confirmed unambiguously
- Origin of suppression: E_{max} or GZK?





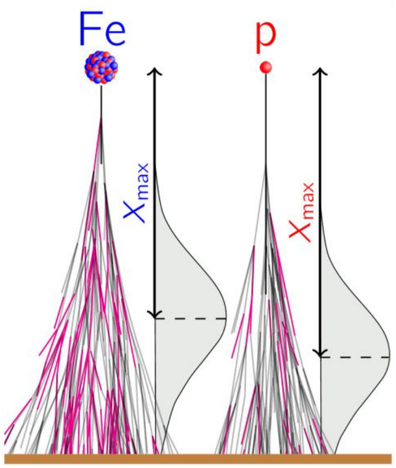
energy per nucleus

Maximum acceleration efficiency
$E_{max}(A) = Z\,E_{max}(p)$
(sources run out of steam, heavier nuclei dominate at the highest energies)

propagation effect
GZK/disintegration
(protons above the energy spectrum suppression?)

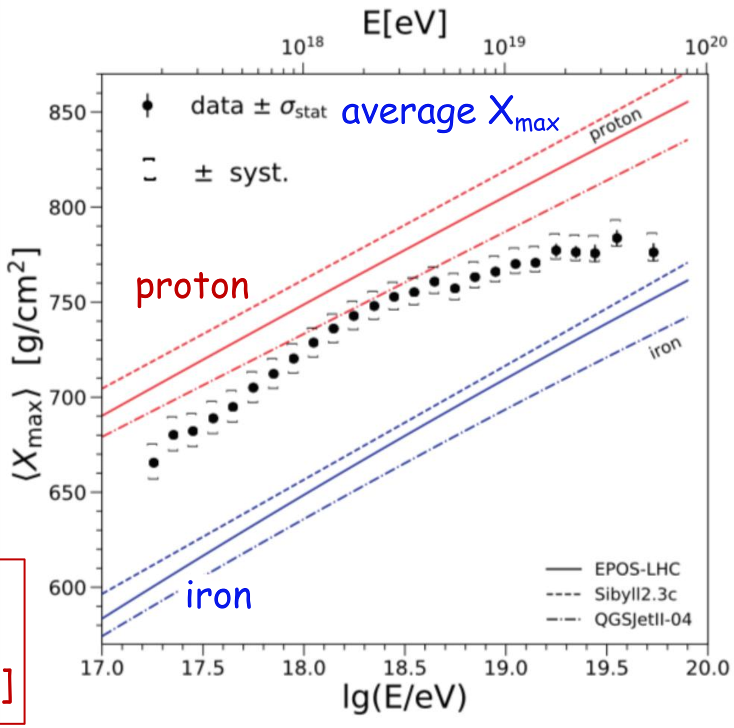
- The collected data not sufficient to discriminate between models
- Precise measurements of the mass composition needed

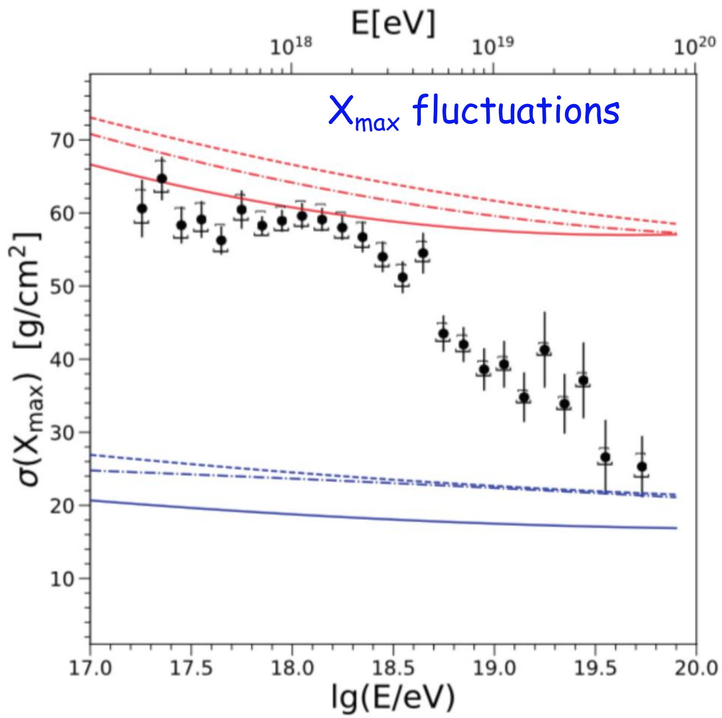
Mass composition measurements with FD - the best available method



$X_{max}(Fe) < X_{max}(p)$

$\sigma[X_{max}(Fe)] < \sigma[X_{max}(p)]$





- Mass composition NOT constant
- The inferred mass composition relies heavily on validity of hadronic interaction models **(see the talk by Dariusz Góra)**
- No X_{max} data above 3×10^{19} eV.
- Need composition from SD at the highest energies! (measurement of muon component)

Based on the available data it is still difficult to build a consistent picture of the origin of UHECRs and the nature of their energy spectrum suppression.

Increase in statistics with the currently working detectors is not sufficient:

Urgent need to upgrade cosmic ray observatories to enable more accurate mass composition determination.

AugerPrime: components

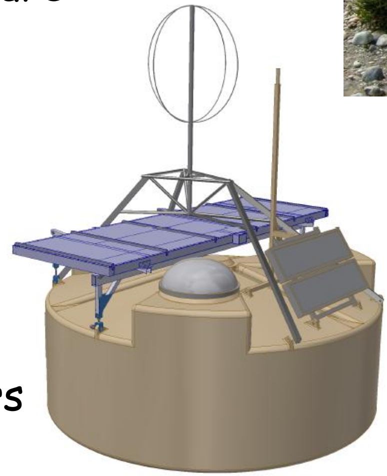
- New Surface Scintillator Detector (SSD) placed on top of ~1500 (almost all) of the existing SD stations (better measure shower components).

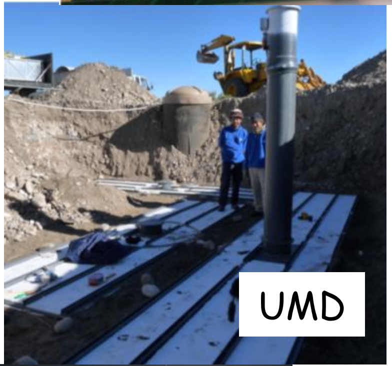
- Radio Detector (RD) at each SD station to measure the radio emission of air showers, 3000 km^2 radio array.

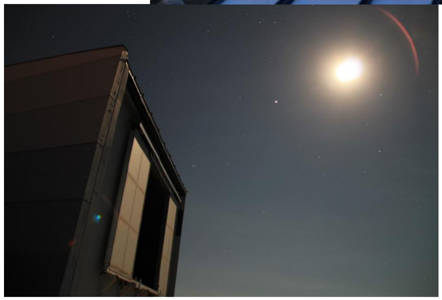
- SD electronics improvements:
  - faster sampling of ADC traces
  - better GPS timing accuracy
  - larger dynamic range
  - enhanced (more sophisticated) local triggers
  - process WCD, SSD, and RD signals.

- Upgrade of the Underground Muon Detector (UMD) (61 stations planned, 23.5 km^2 array).

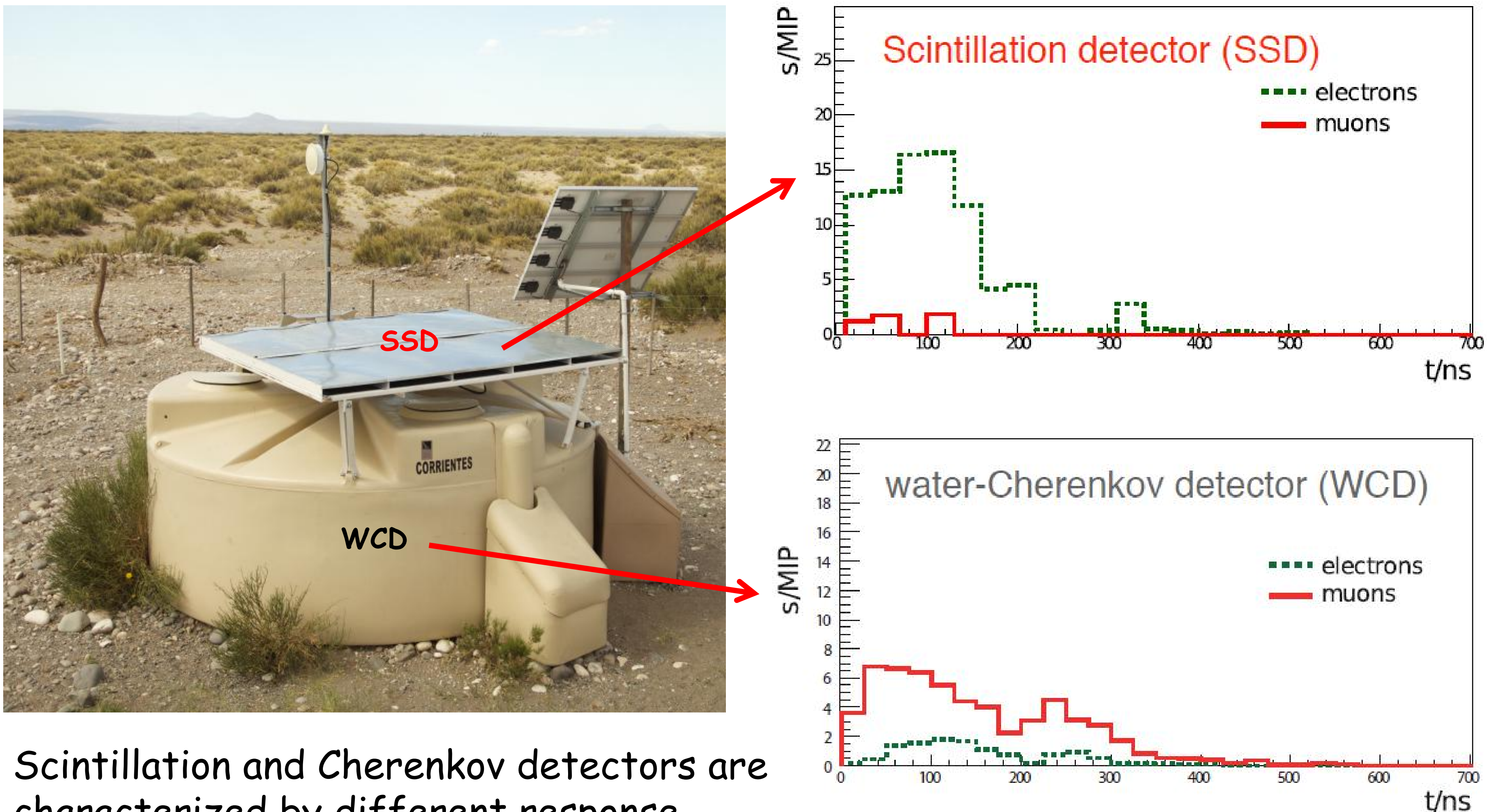
- Increase of the FD operation time (extend measurements into periods with higher night sky background and twilight). FD enables direct measurements of X_{max} - currently the best method of mass composition determination.







Surface Scintillator Detector (SSD)

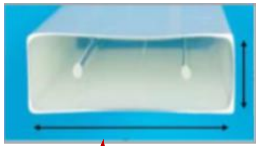


Scintillation and Cherenkov detectors are characterized by different response to muons and electrons

- ***disentangle muon and electromagnetic components***
- ***identification of the primary particles on event-by-event basis***

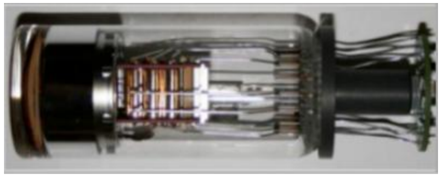
Surface Scintillator Detector (SSD)

side view of an extruded scintillator bar with 2 holes



1 cm

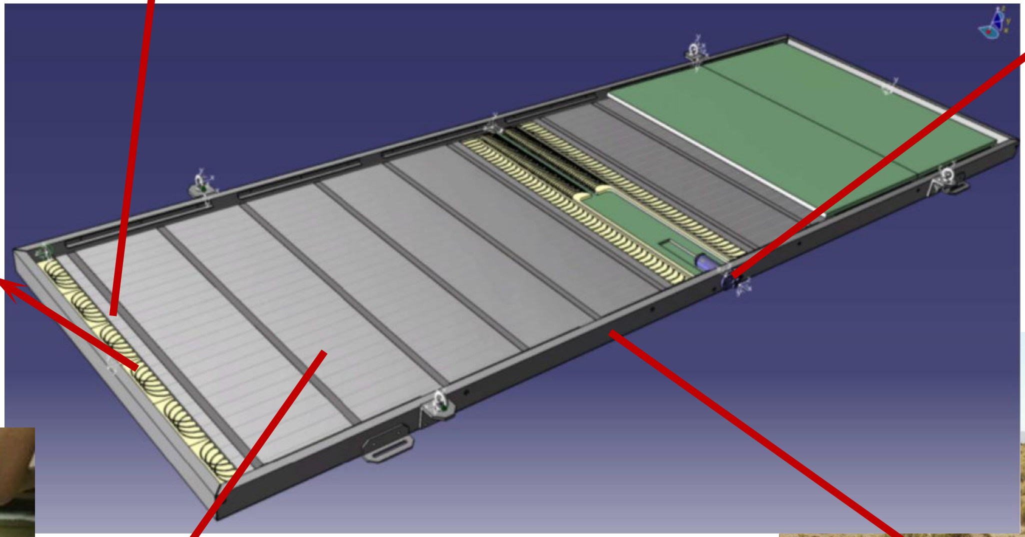
5 cm

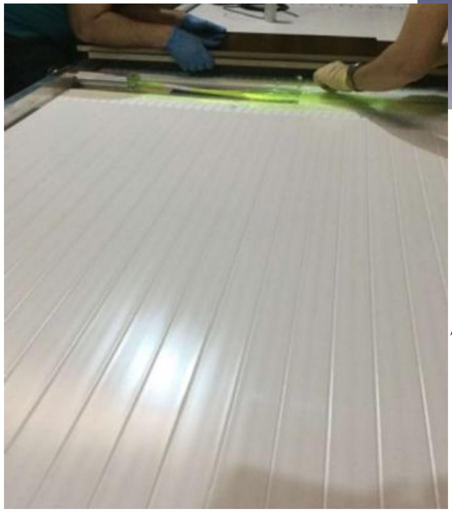


PMT

WLS fibers and fiber routers

SSD

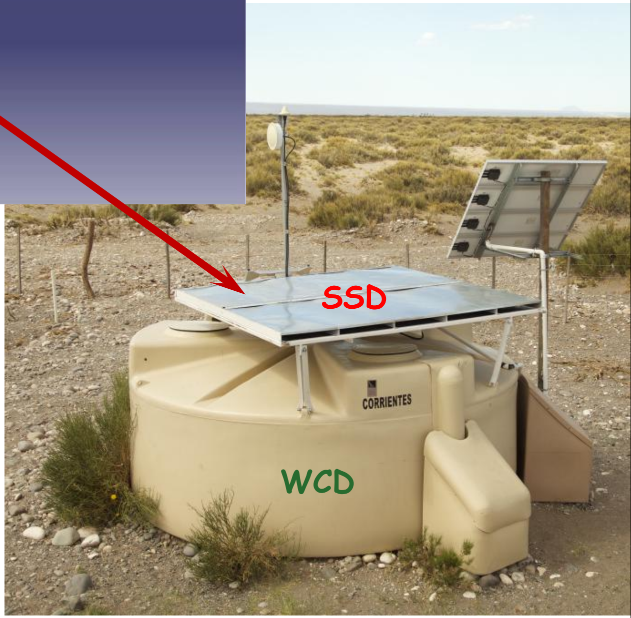




Scintillator bars 160x5x1 cm

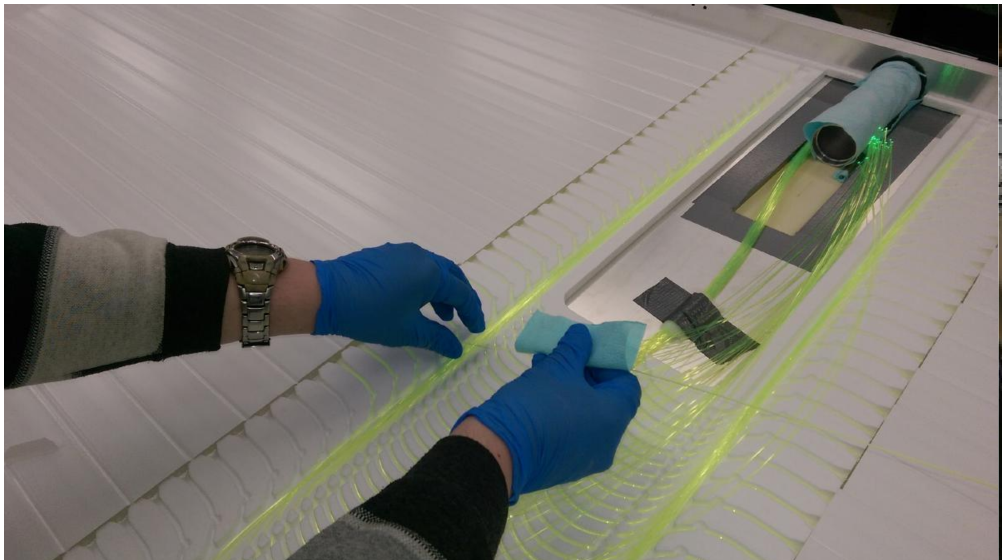
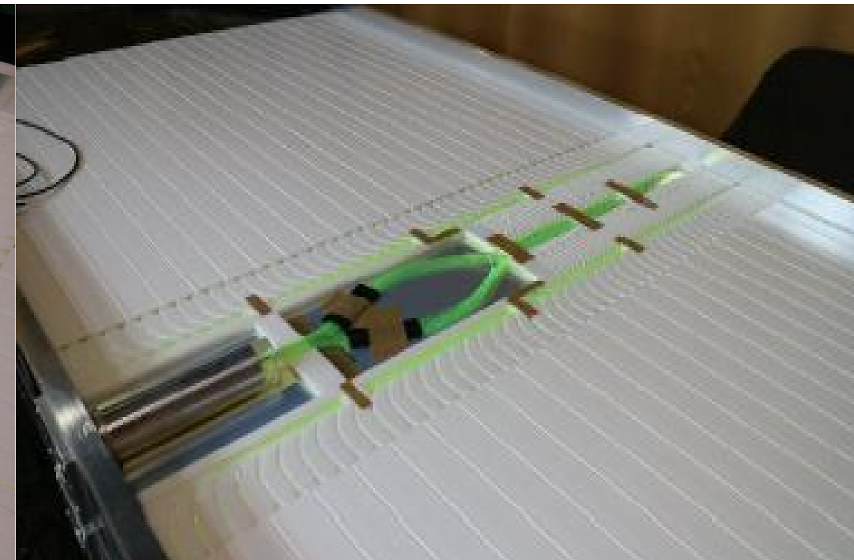
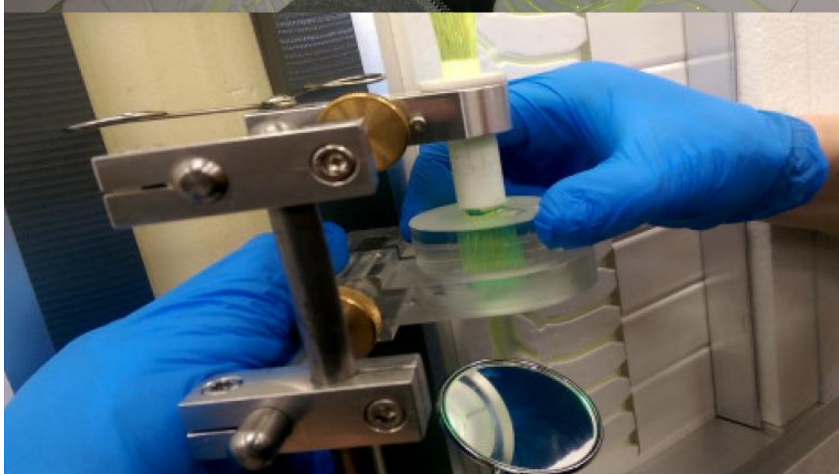
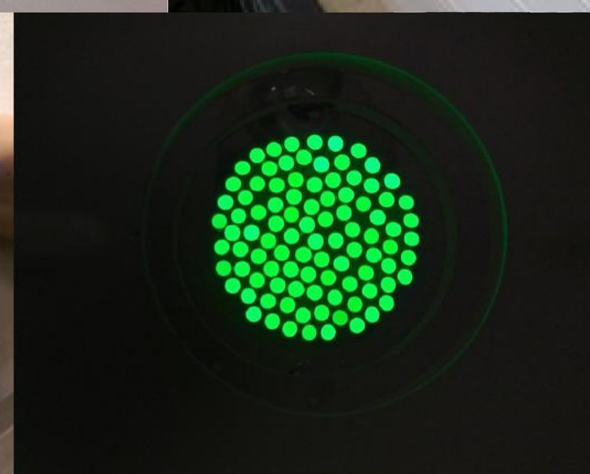
48 scintillator bars, total area 3.8 m²

Aluminium enclosure



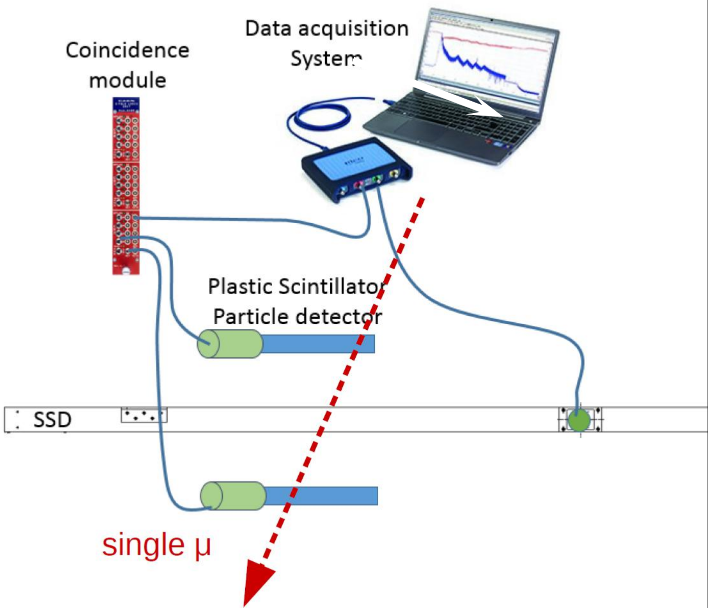
Surface Scintillator Detector (SSD)

- SSD assembly distributed among six institutions: RWTH Aachen, LPSC Grenoble, Karlsruhe Institute of Technology, IFJ PAN Kraków, INFN Lecce and NIKHEF Nijmegen.
- PMTs tests in Bergische Universität Wuppertal and INFN Napoli.

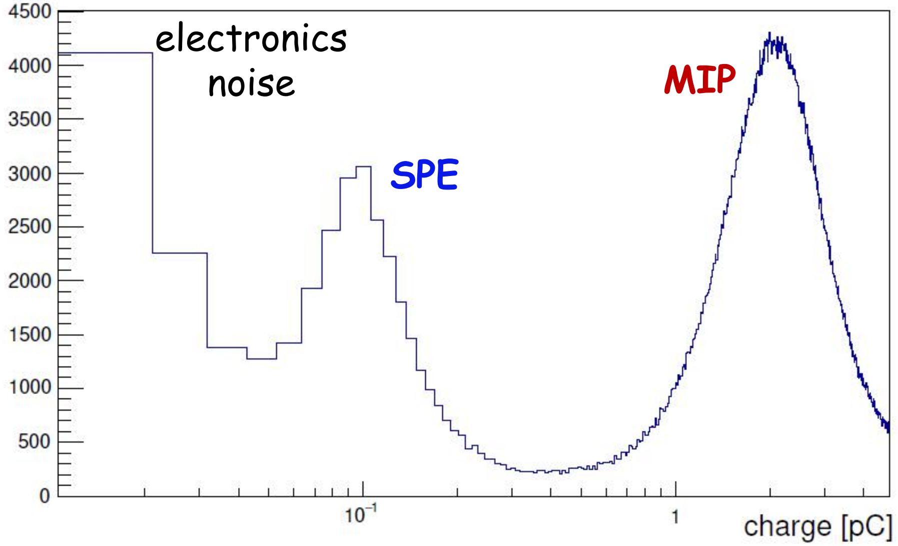

SSD tests carried out at the assembly sites

- Tests with cosmic-ray muons
  - ✓ two small particle detectors working in coincidence provide a trigger for SSD read out.
  - ✓ determination of SSD response to a reference MIP.

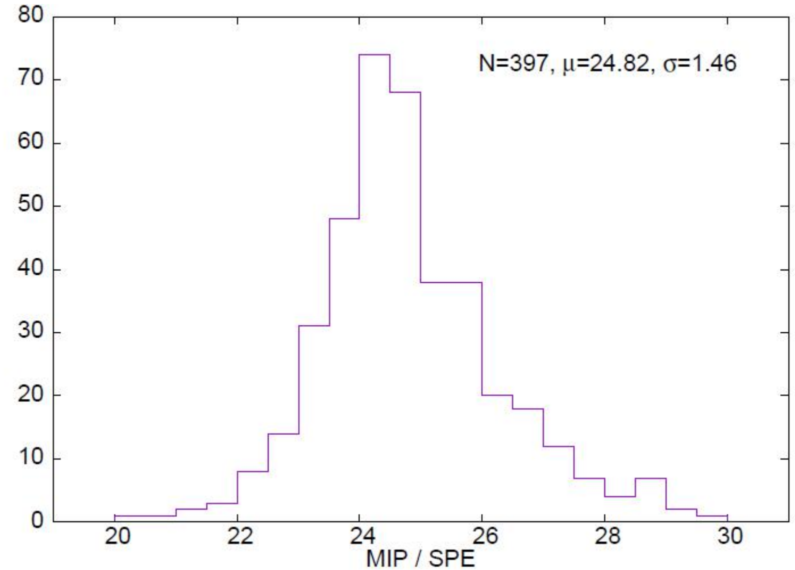


- The ratio MIP/SPE check the quality of SSD. It reflects the efficiency of the key detector components at generating (scintillators), collecting (fibers) and transmitting (cookie) the light.

- The shape of the MIP peak tests the uniformity of response over the active area of the detector.



Measurements of the **MIPs** (**Minimum Ionizing Particle**) with respect to **SPEs** (**Single Photoelectron**).



MIP/SPE distribution

Electronics upgrade

The new electronics will process WCD, SSD, RD, and UMD signals and will increase the data quality by providing

- faster sampling of ADC traces (40 MHz -> 120 MHz), better suited for counting muons
- more precise absolute timing accuracy from new GPS receivers (12 ns -> 4 ns)
- faster data processing and more sophisticated local trigger (more powerful processor and FPGA)
- larger dynamic range (10 bits -> 12 bits)
- more FADC channels (6 -> 10)
- improve calibration and monitoring capabilities
- backwards-compatibility with the old design (similar power consumption, hardware interfaces...).

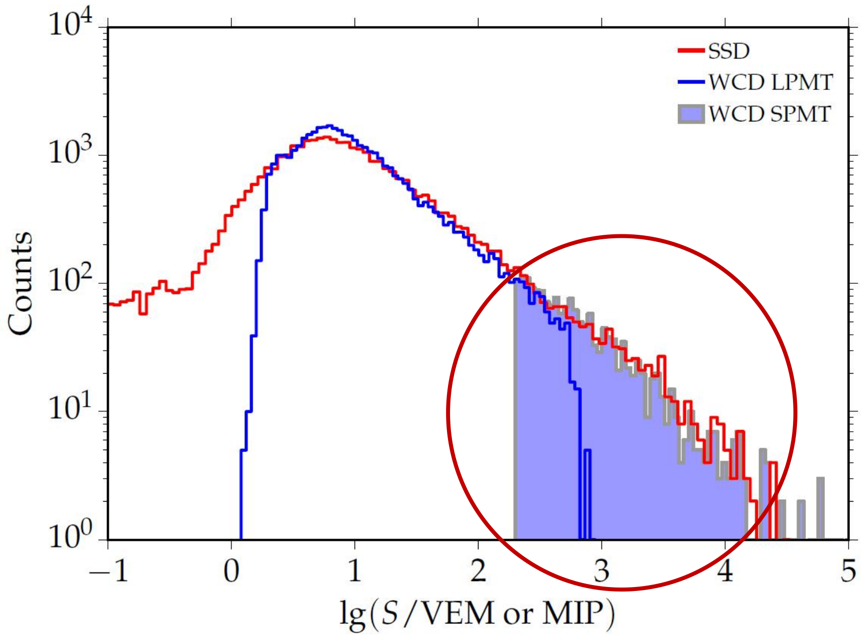
Electronics upgrade - small PMT

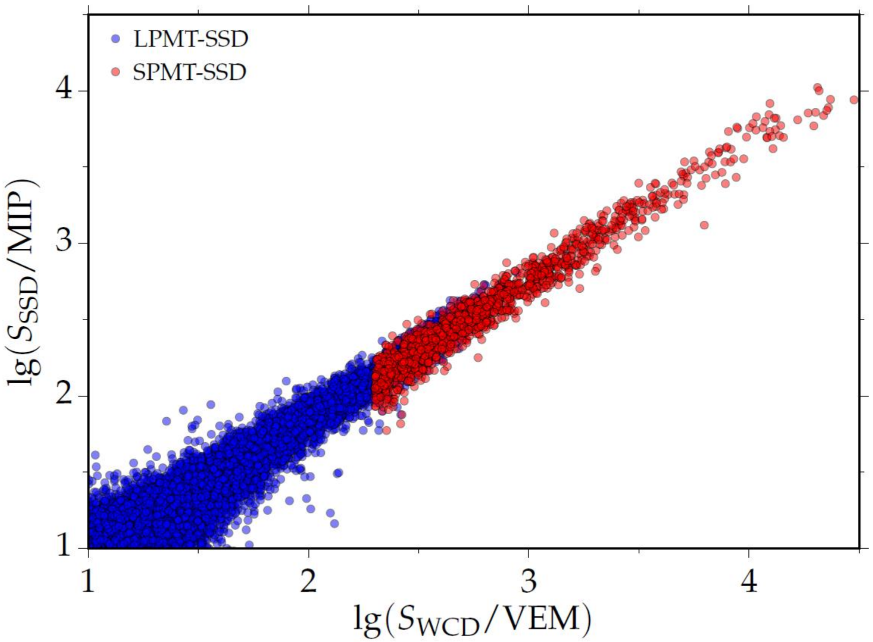
In addition, each WCD will be equipped with a small low-gain PMT (SPMT) in the center of the detector to register large pulses from very close showers that saturate the signal of the currently working large PMTs (LPMT).

1 inch in diameter
1/9th of the WCD LPMT

SPMT

- extends the dynamic range of the WCD signals by a factor of 30 (up to ~20000 VEM)
- allows determination of the particle densities down to ~300 m from the shower core.
- reduce number of saturated event at the highest energies below 2%



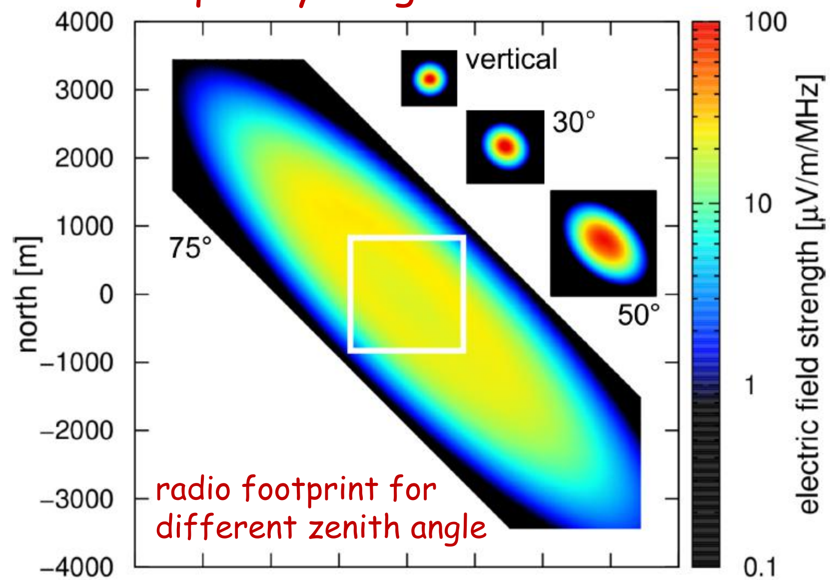


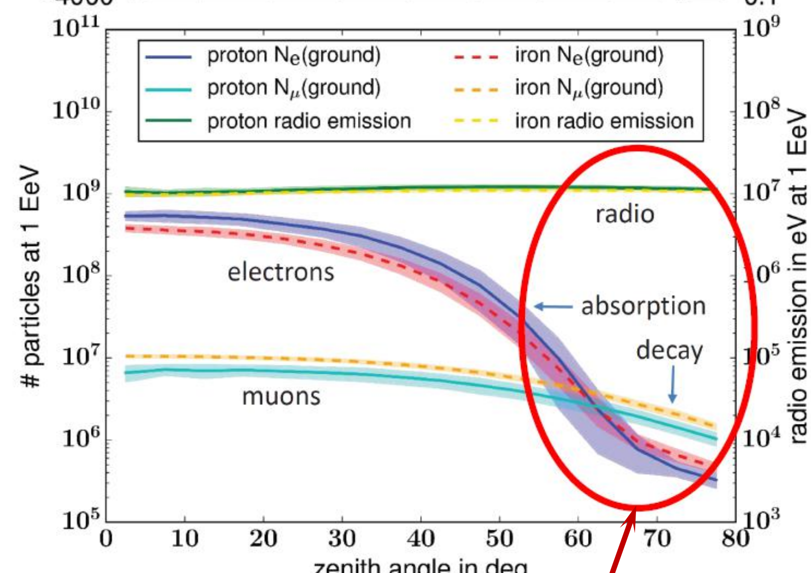
Radio Detector (RD) - 3000 km² array

- Combination of WCD, SSD and RD will be used to measure the ratio of the EM energy and the number of muons for inclined showers.
- Radio signal does not depend on the shower inclination angle.

short aperiodic loaded loop antenna (SALLA)

Frequency range 30 to 80 MHz

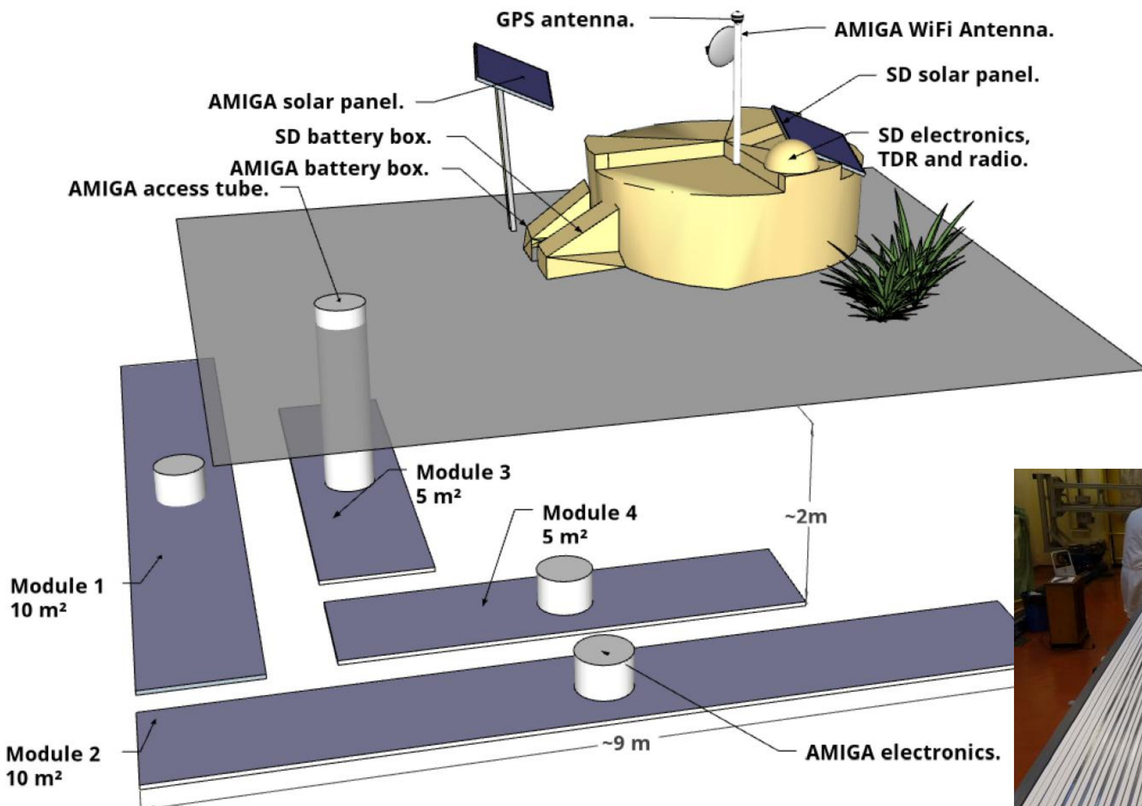


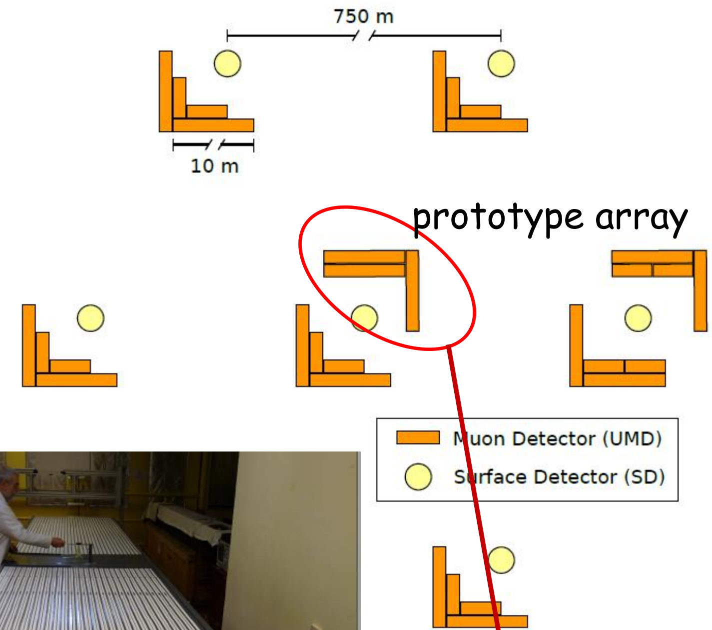


inclined showers

Underground Muon Detector (UMD)

- UMD will provide important direct measurements of the shower muon content and its time structure
- It will be used for verification and fine-tuning of the methods used to extract muon information from the SSD and WCD measurements.



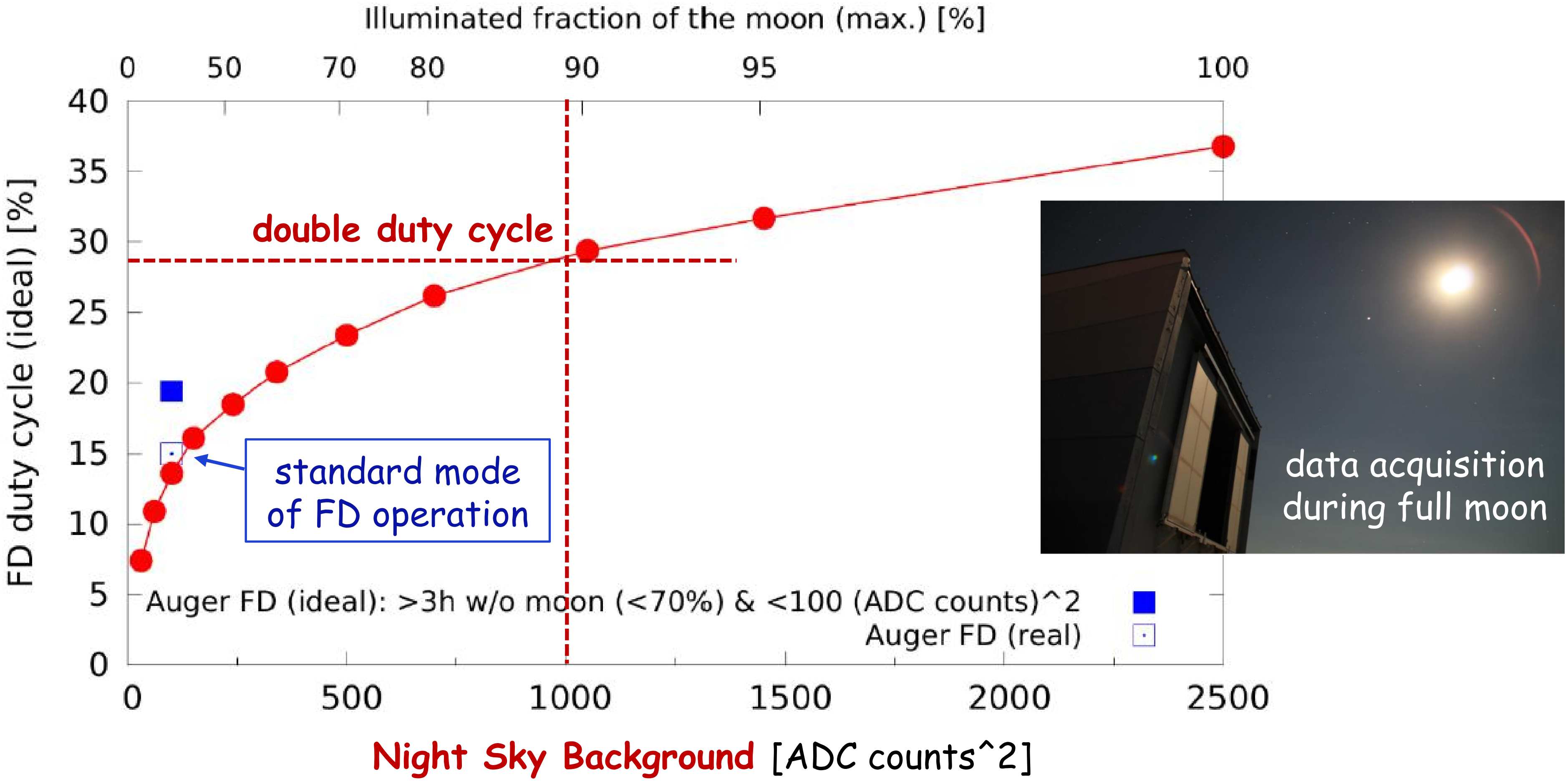


final design:
3x10 m² modules

planned 61 stations buried ~2 m underground,
23.5 km2 array with 750 m spacing

Extended FD operation mode - increase of the duty cycle

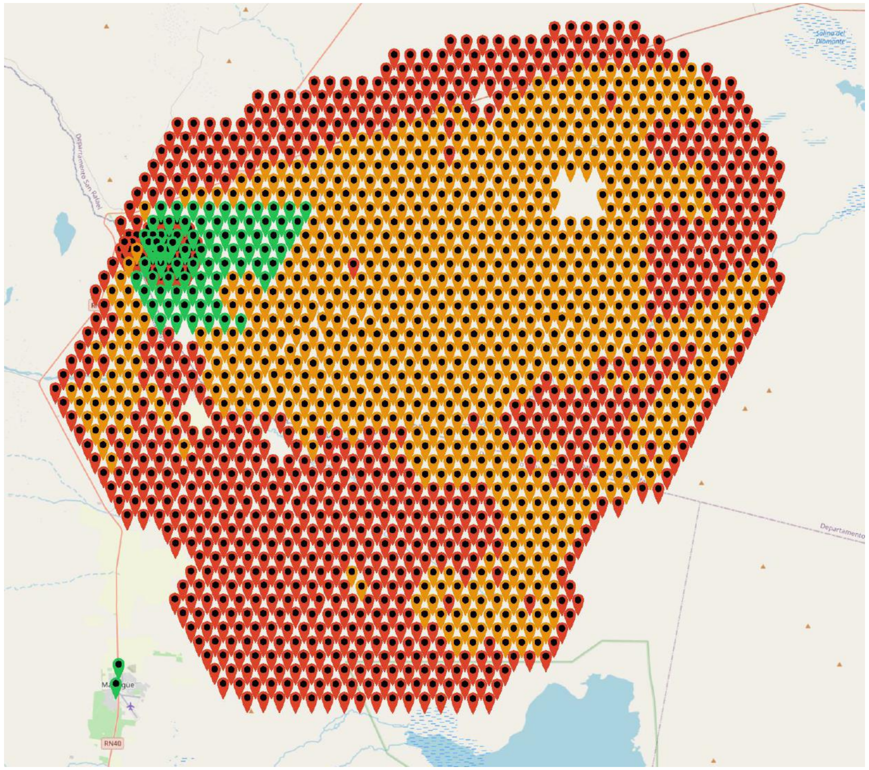
- Allow FD operation during nights with the increased night sky background (NSB), i.e. during nights with moonlight.
- It will require reduction of the PMT gain (G) in FD cameras to prevent them from aging.



- **Experimental test successful:** PMT gain reduced from the standard G = 50k to G = 5k, showers recorded at near full moon

AugerPrime: status

Deployment of SSD, RD, UMD ongoing



Water-Cherenkov station with new scintillator detector (SSD) and new radio antenna (RD)

SSD array:

- Engineering array (12 stations) since 2016 and
- Pre-production SSD array (77 stations) since March 2019
  are taking data
- 845 SSD stations already deployed out of ~1500 (Aug 2020)

Summary

- The results obtained by the Pierre Auger Observatory indicate that further advances in the understanding of UHECRs require an improvement of the measuring capabilities of the existing detectors. The key feature is a better separation of the muonic and electromagnetic components of air showers.

- **AugerPrime**, the ongoing upgrade of the Pierre Auger Observatory has been designed for this task.

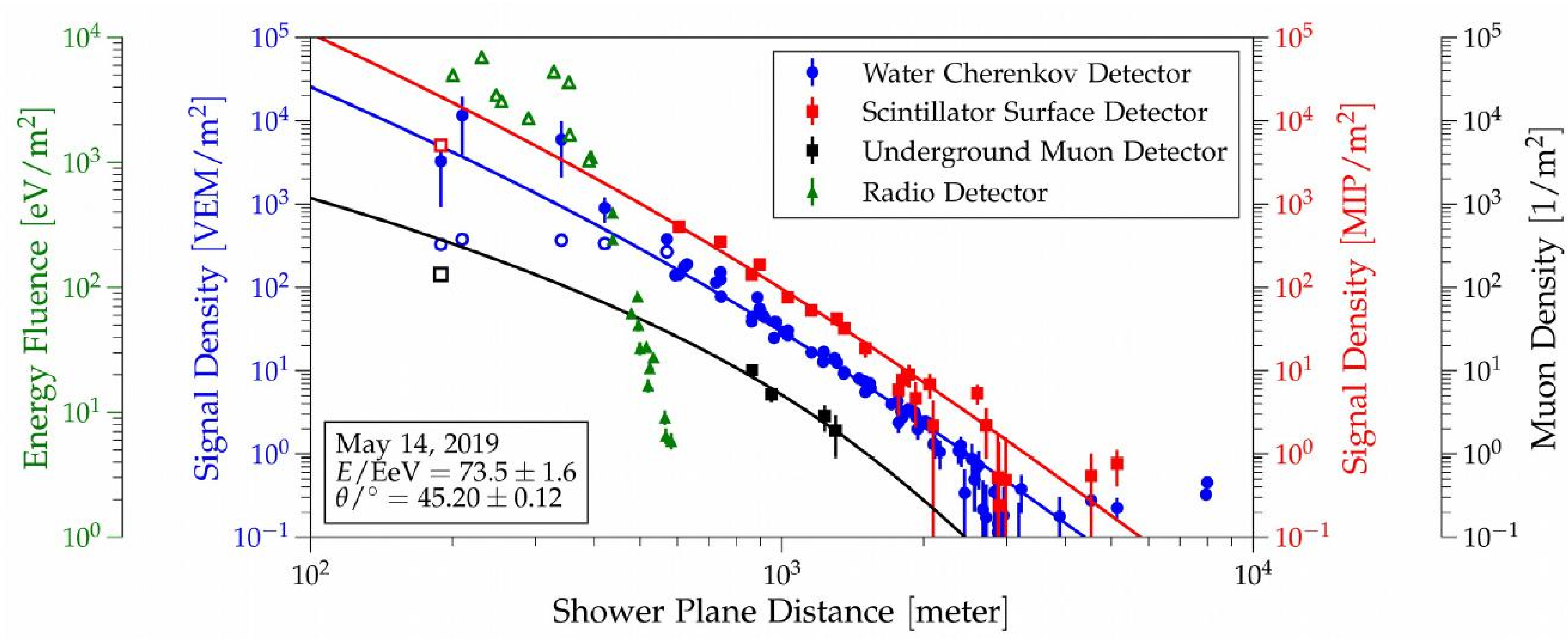
- AugerPrime will help us to
  - ✓ understand the origin of flux suppression and astrophysical scenarios of UHECR production/propagation.
  - ✓ get information on primary mass composition on an event-by-event basis.
  - ✓ determine the proton flux contribution (as small as 10%) at the highest energies, and achieve more accurate particle astronomy.
  - ✓ provide better estimates for ultra-high energy neutrino and photon fluxes
  - ✓ understand origin of the muon excess in the data
  - ✓ search for new physics at energies beyond the reach of the LHC.

- AugerPrime Engineering Array (12 stations) and Pre-production SSD array (77 stations) are already operational.

- Construction of the world-largest radio detector (3000 km^2) has started.

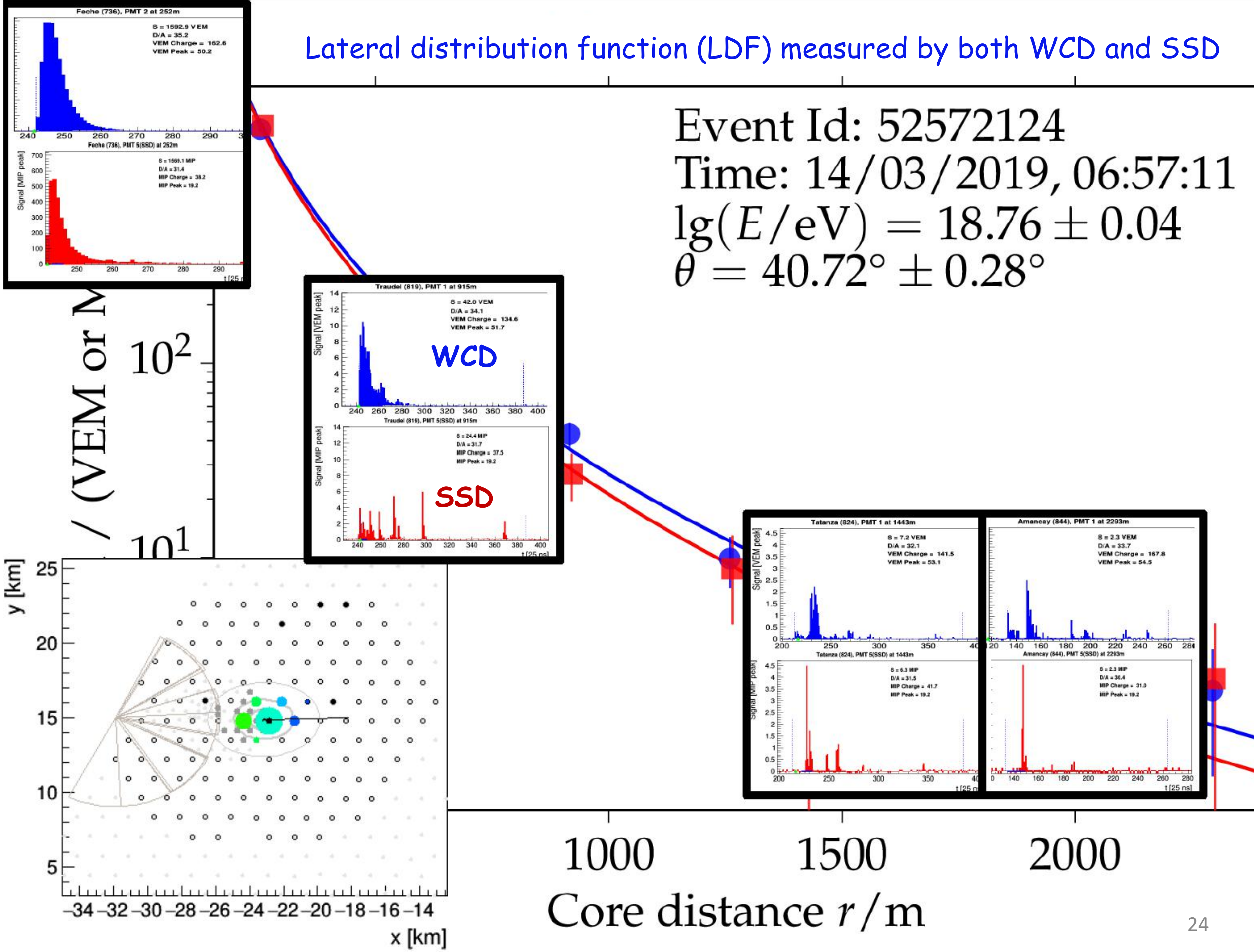
Backup slides

AugerPrime will provide a multi-hybrid cosmic ray detector, that will allow simultaneous measurement of a shower with WCD, SSD, RD, UMD (muon counters) and fluorescence detectors.

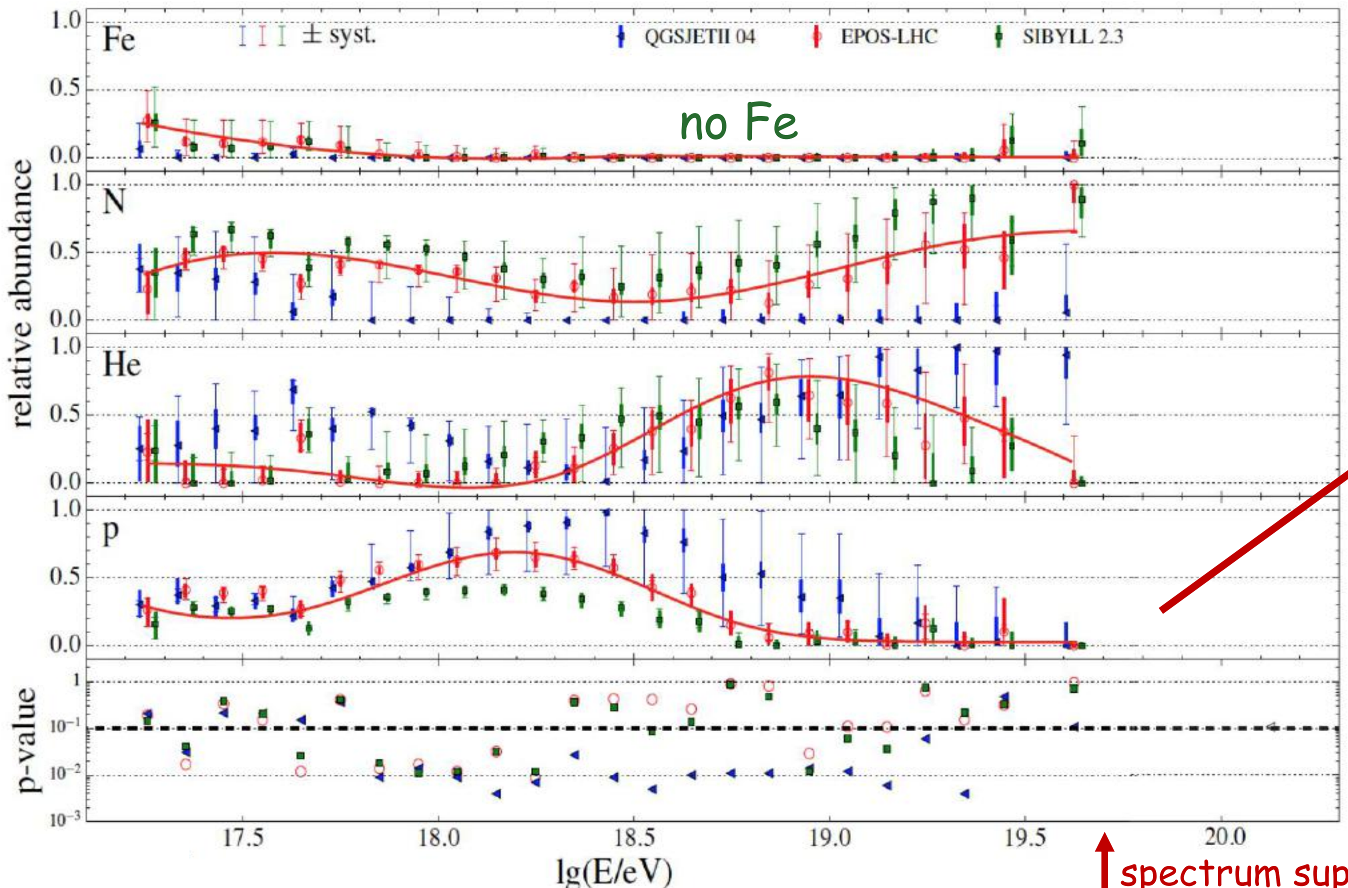


Lateral distribution of signals measured by different detectors of a real event, as a function of the distance to the shower core

Lateral distribution function (LDF) measured by both WCD and SSD



Fractions of different nuclei in cosmic ray spectrum - fits to X_{max} data



Small fraction of **p** ~10% to explain dipole anisotropy ?

spectrum suppression, no direct X_{max} measurements (small duty cycle of FD)

- No protons at the highest energies?
- **The hadronic interaction models have difficulties to fit the data** (large uncertainties and large differences between models). A more accurate determination of mass composition is required.
- Alternative methods: measurements of muon component?

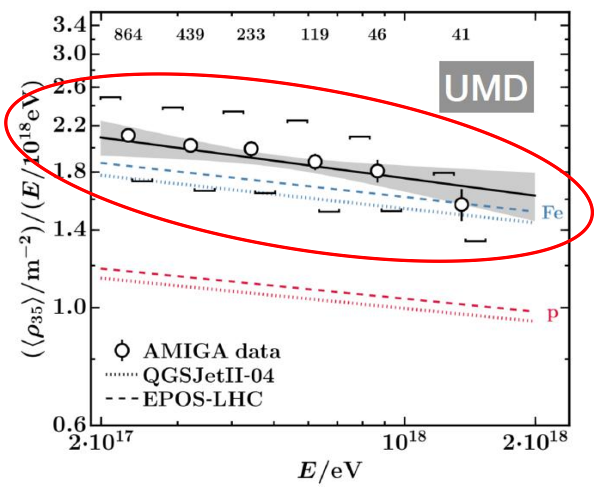
Hadronic interaction models have problem

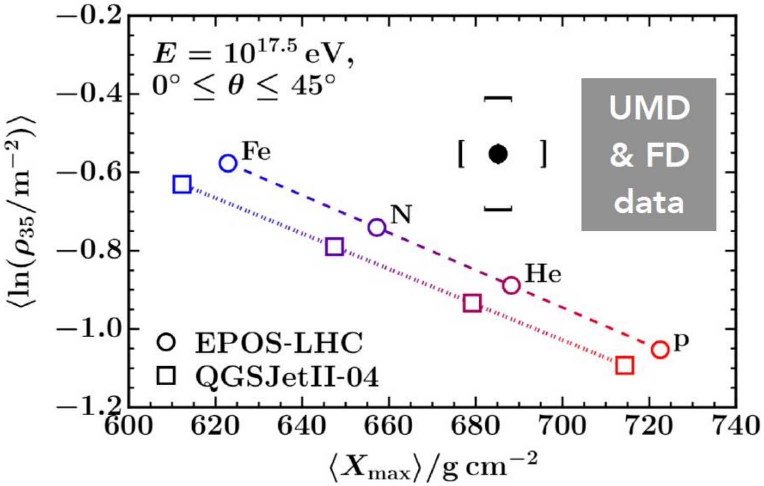
data from Underground Muon Detector and Fluorescence Detector

not compatible with X_{max} data

discrepancy between data and models predictions

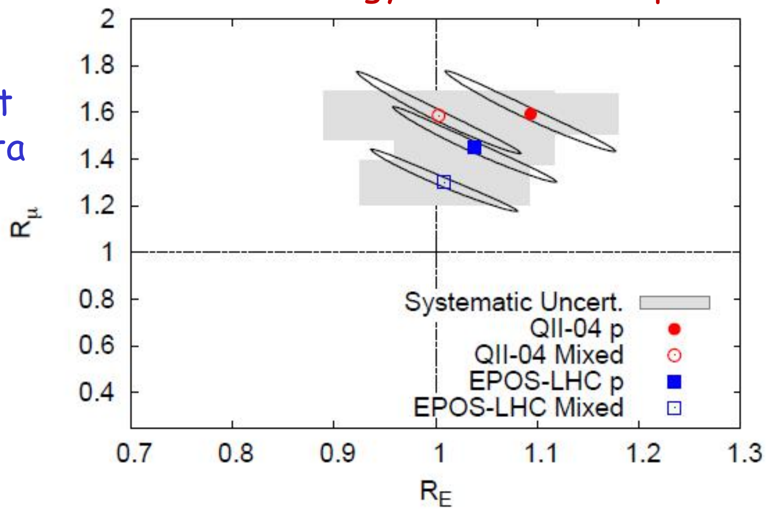
muon density





Let's fit models with rescaled energy and muon component (by factors R_E and R_μ) to hybrid data

R_E, R_μ values best matching the data



Muon deficit in simulations: 30-60 %

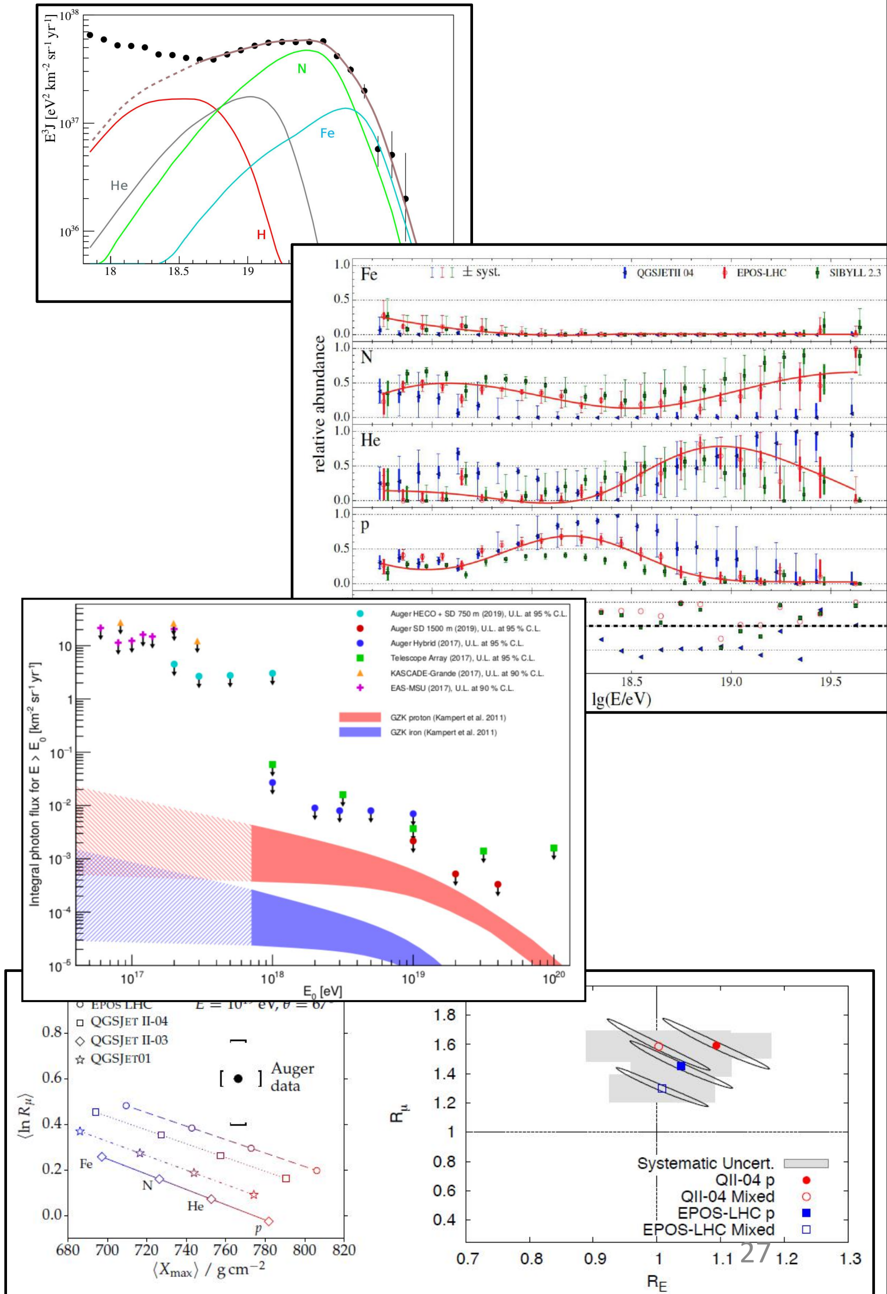
Energy ~ OK (within systematics)

Hadronic models do not reproduce muon numbers!

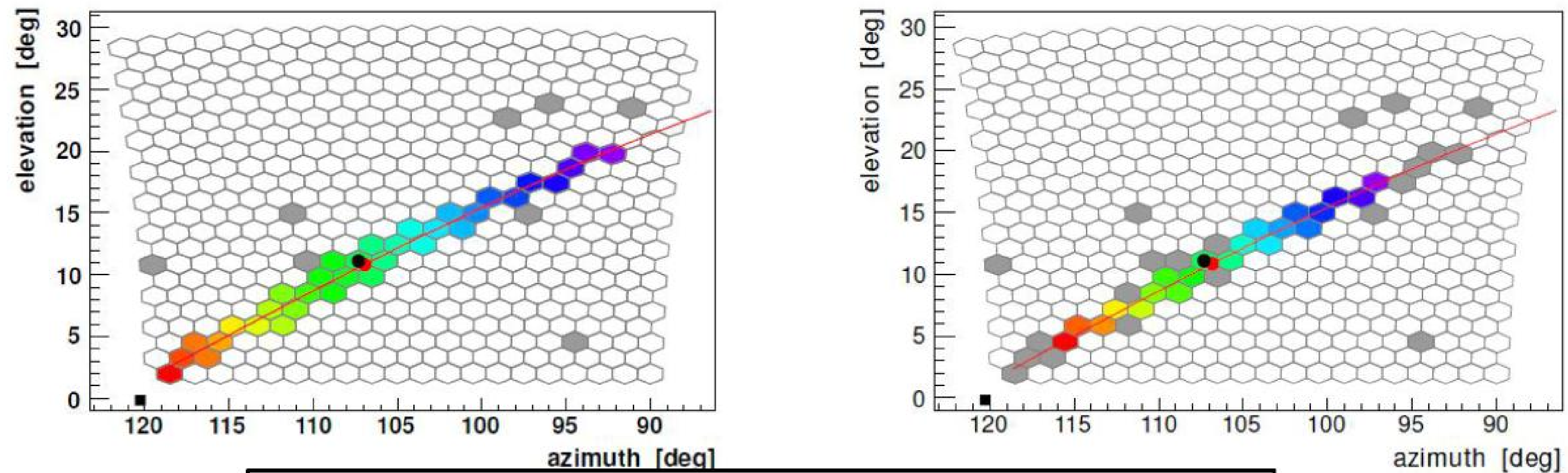
AugerPrime: science case for the upgrade of the Auger Observatory

Upgrade is necessary to ensure that the new data will provide additional information to allow us to address the following:

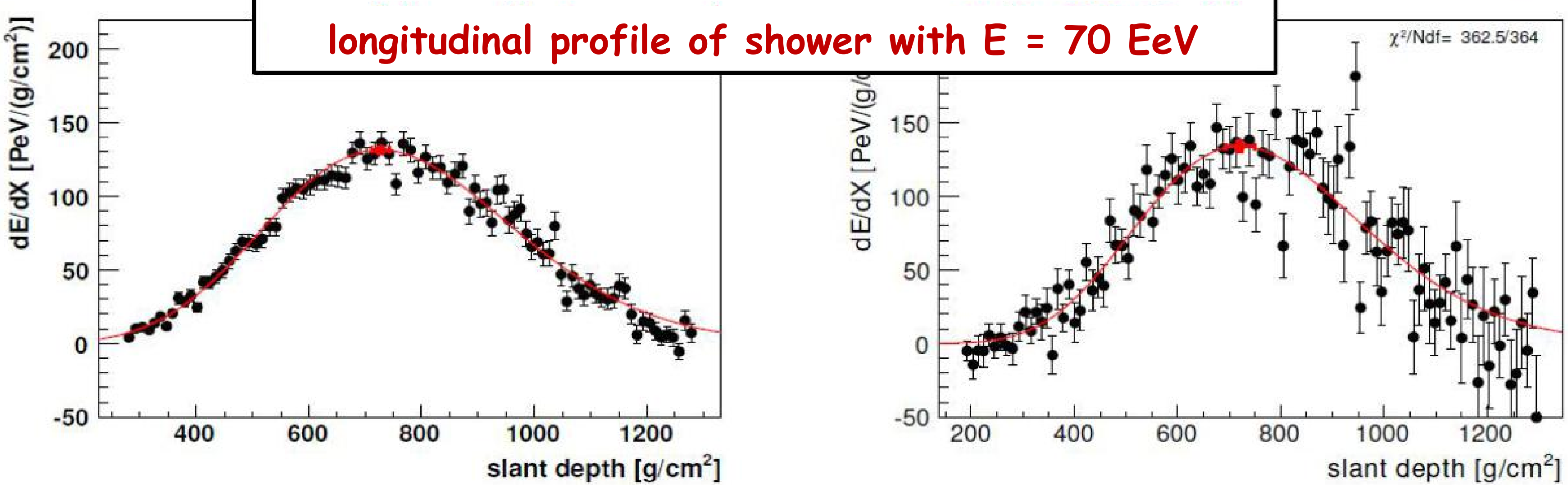
- Mass composition study at the highest energies on event-by-event basis
  - ✓ explain the origin of UHECRs and its flux suppression
  - ✓ charged particle astronomy? (10% sensitivity for protons at the highest energies)
- Provide better estimates for ultra-high energy neutrino and photon fluxes
  - ✓ establish potential for future experiments
- Better measure shower components
  - ✓ study hadronic interactions at ultra-high energy **beyond those accessible at LHC**
    - understand the muon deficit in shower simulations
    - test our understanding of hadronic interactions
  - ✓ set limits on non-standard physics



- Increased background noise lead to degradation of the quality of collected data. However, for the highest energies it is not so severe... and for lower energies we already have enough statistics.



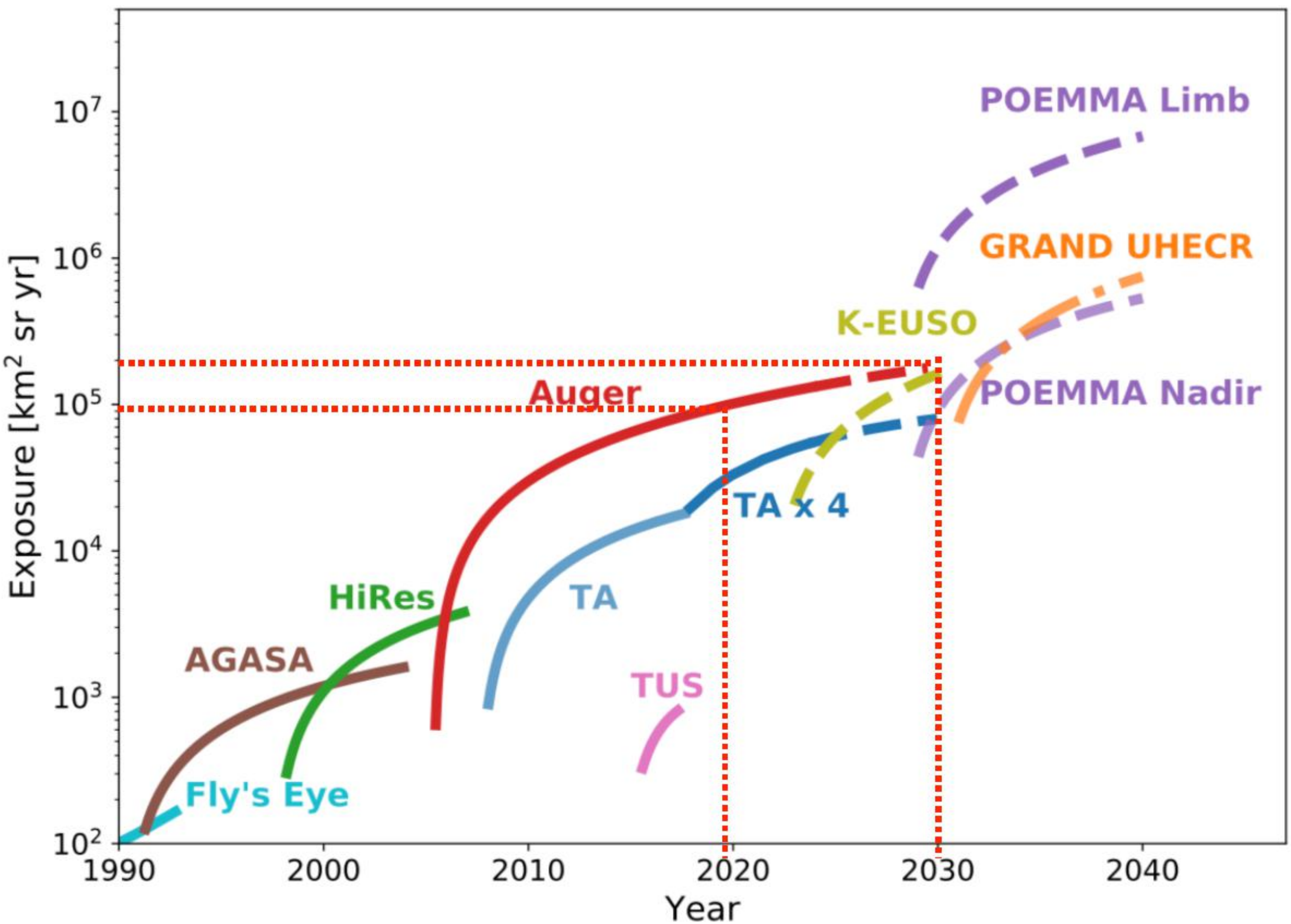
longitudinal profile of shower with E = 70 EeV



standard night sky background

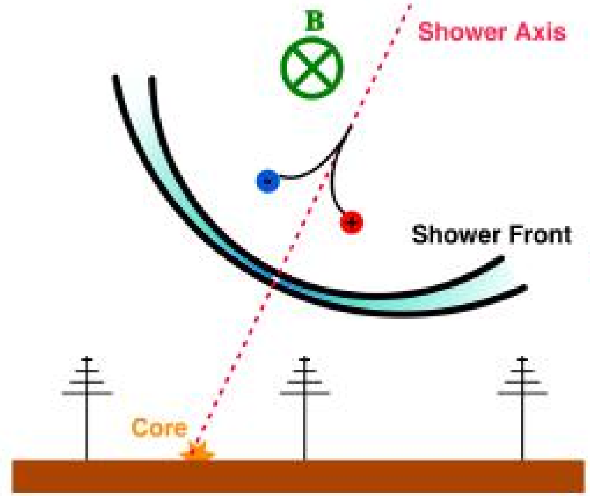
illuminated fraction of the moon 90%

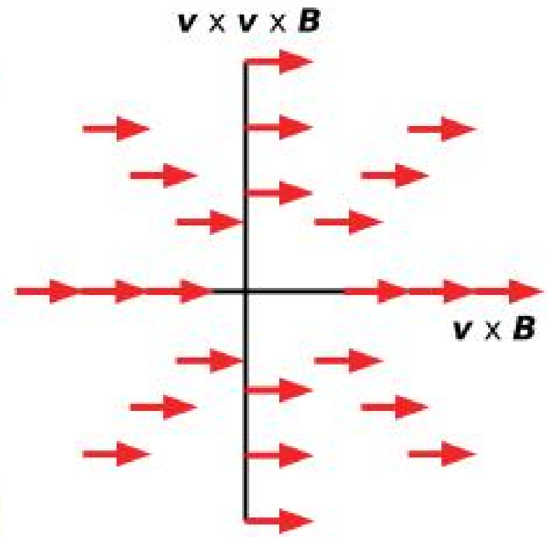
Auger will double our exposure in the next 10 years, before any future observatory takes over!



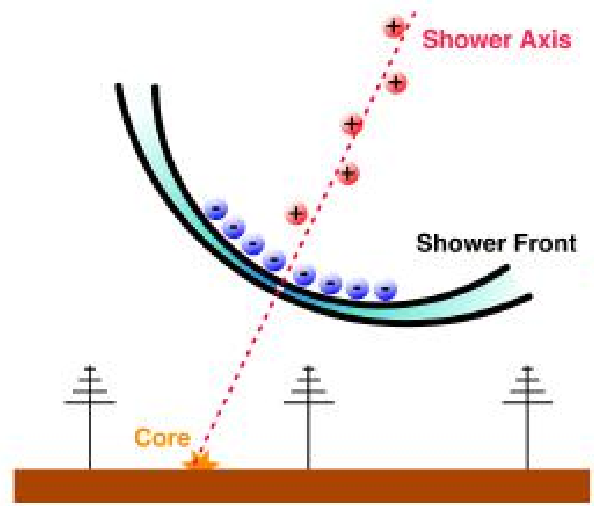
Mechanisms of air shower radio emission

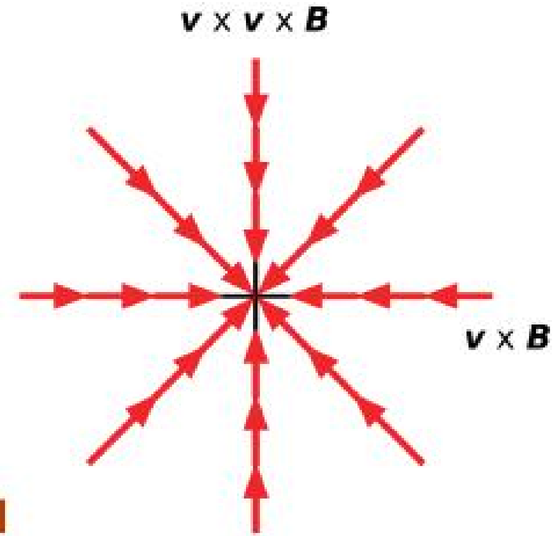
- Geomagnetic effect (main contribution, linearly polarized)
  geomagnetic field deflects e^- and e^+ in the opposite directions
  ⬇
  transverse current varying over time





- Askaryan effect (typical contribution ~10%, radially polarized):
  e^+ annihilation in the shower front
  ⬇
  time variation of e^- excess





Radio signal is a short pulse (~ 100ns). Signal compression in time (geometric effect) leads to its amplification in the forward direction.

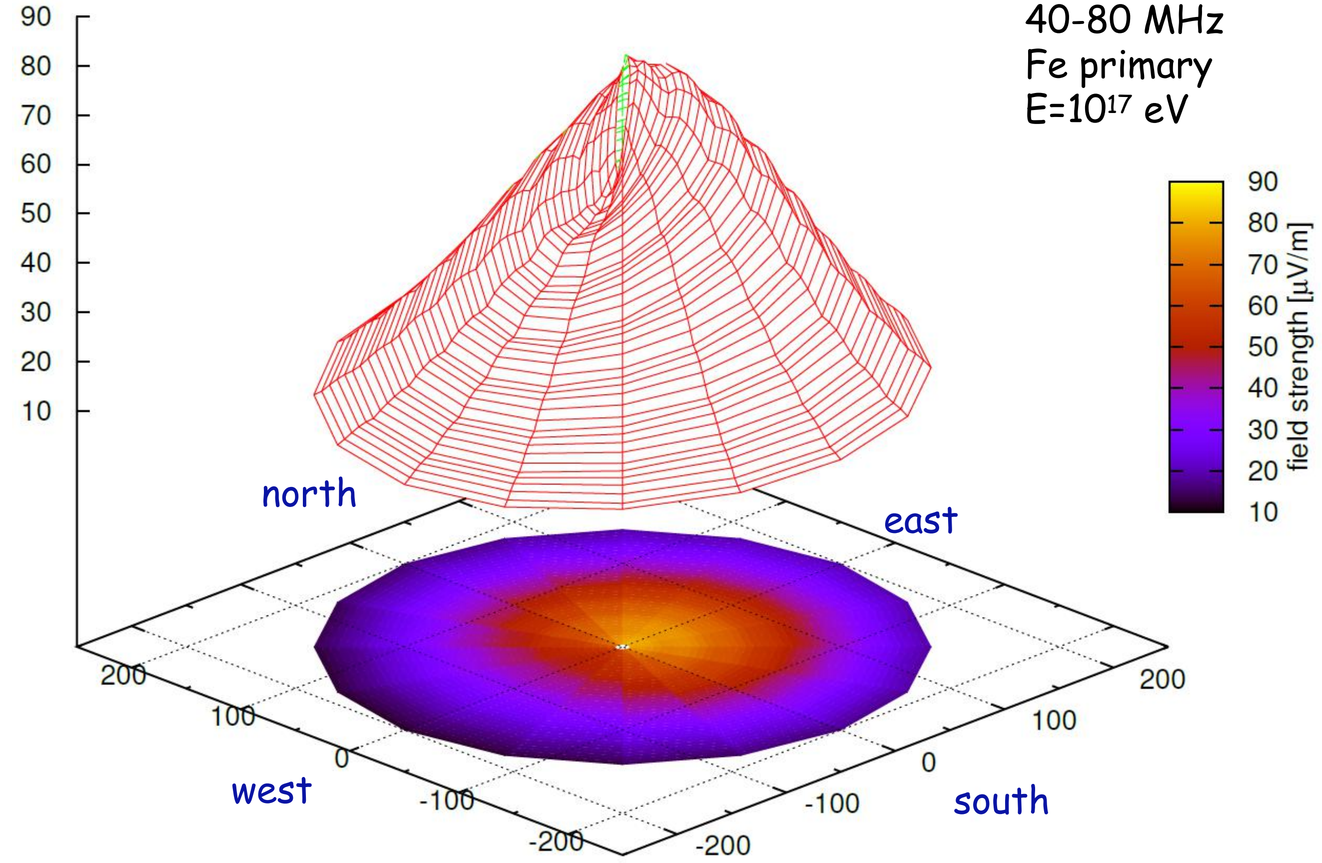
polarization in the plane perpendicular to the shower axis

Typical radio footprint of the vertical shower

superposition of
geomagnetic and
Askaryan emission
(different polarizations)

⬇

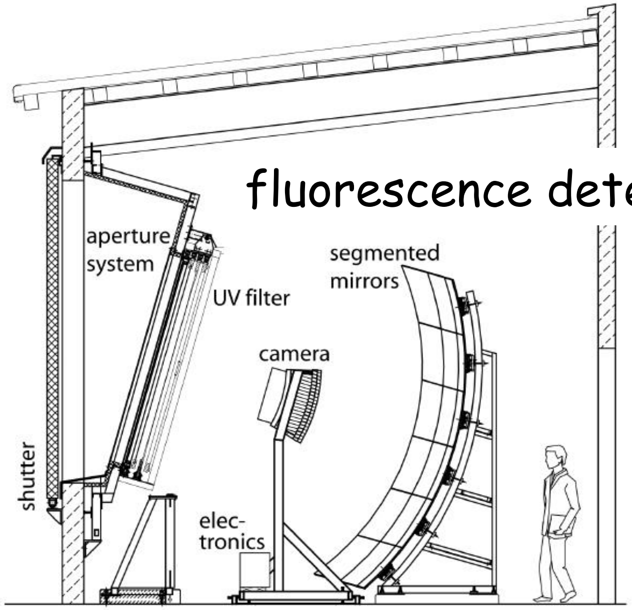
east-west asymmetry

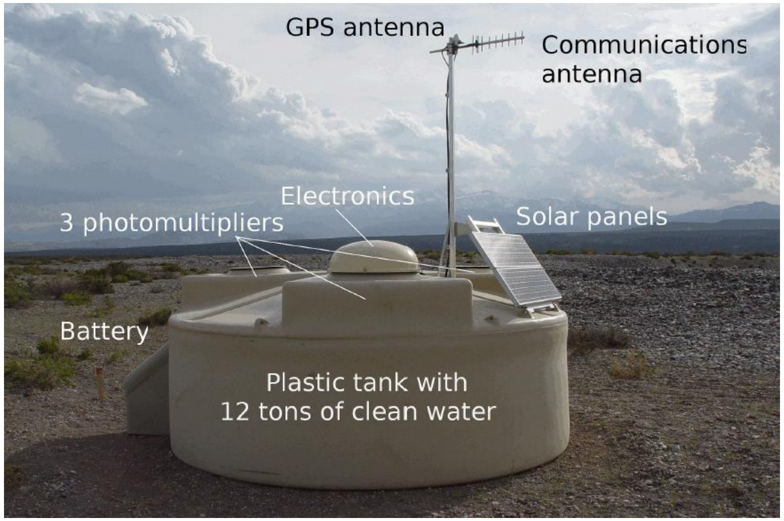


The radio detector array allows:

- calorimetric energy measurement (integration of the radio signal on ground)
- determination of the (geometric) distance to the shower maximum and thus X_{max}
- precise measurement of the shower geometry
- 100% duty cycle

Classic methods of UHECRs detection - summary





water-Cherenkov detector

Fluorescence detector (observation of air showers at various stages of their development in the atmosphere):

- calorimetric energy measurement
- direct observation of the shower maximum X_{max}
- duty cycle of only ~13% (limited to cloudless, moonless nights)

Surface detector (observation of air showers only at the ground):

- high accuracy of air shower geometry reconstruction
- continuous work (100% duty cycle)

Hybrid detection: shower observation with two independent detectors provides more information, increases accuracy of energy and geometry determination