The Pierre Auger Observatory status and the AugerPrime upgrade program

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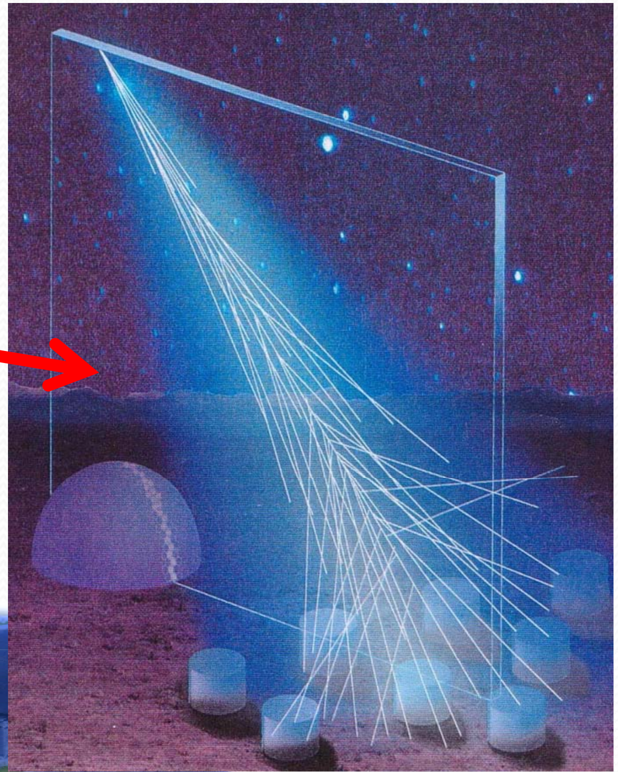
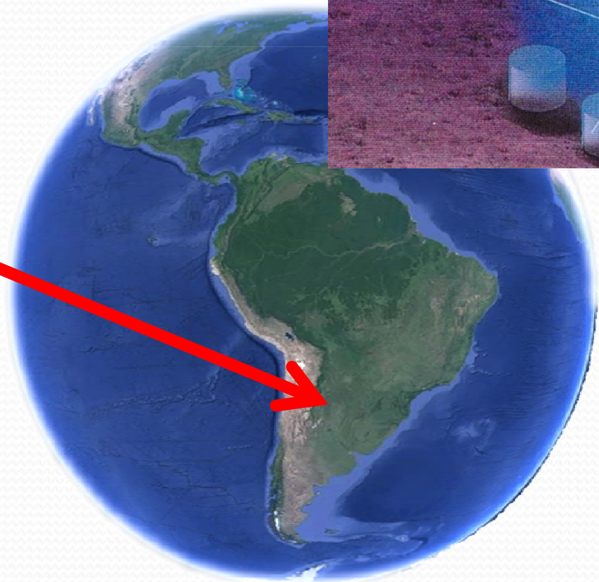
The Pierre Auger Observatory

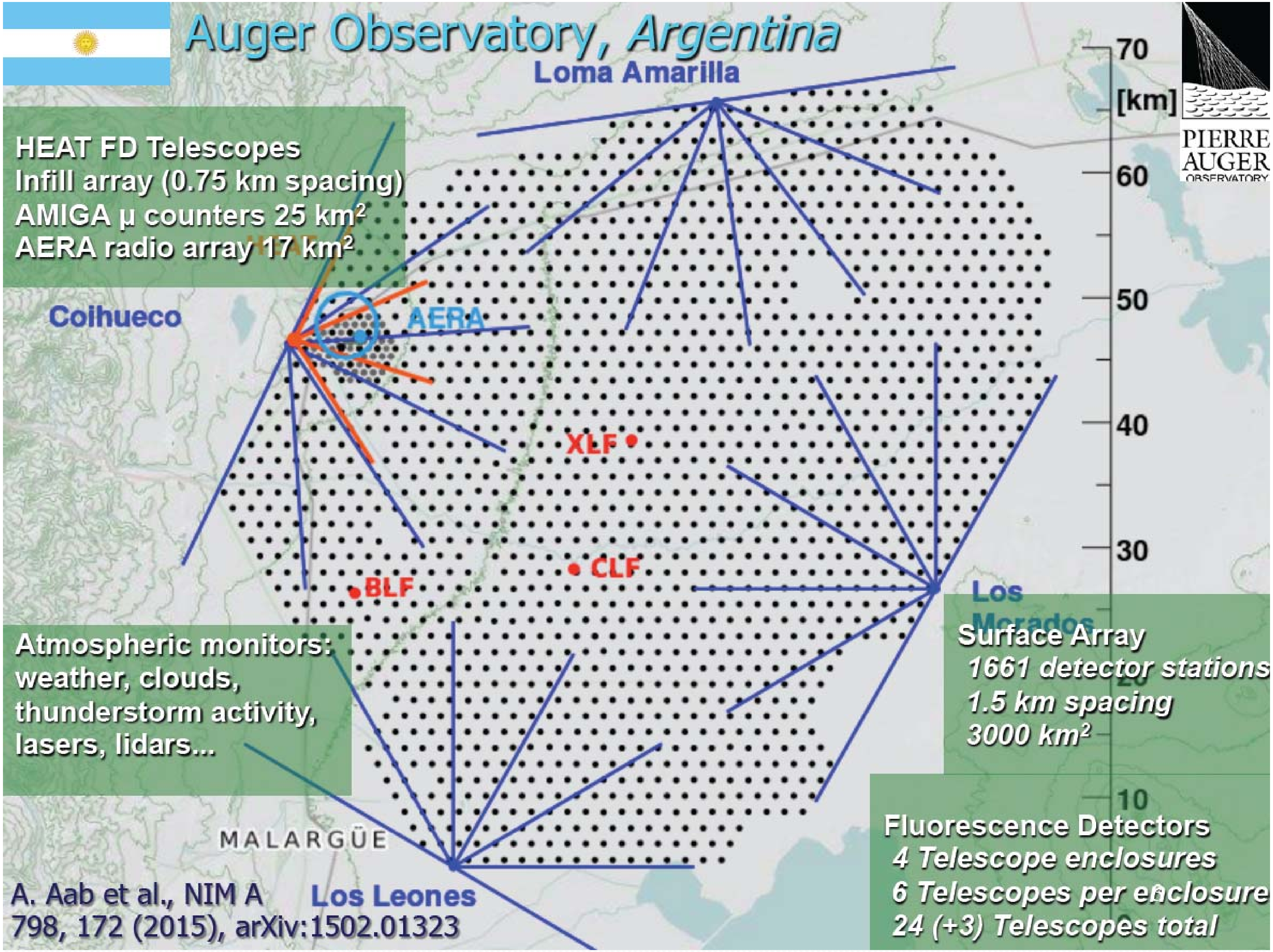
- Largest cosmic ray detector in the World, covering an area of **3000 km²**
- **Hybrid detector**: combination of two detection techniques allows for cross calibration and eliminates model dependences



- **International collaboration** of more than 450 scientists from 16 countries of the World
- Locates in the **southern hemisphere**, near the town of Malargue, Argentina



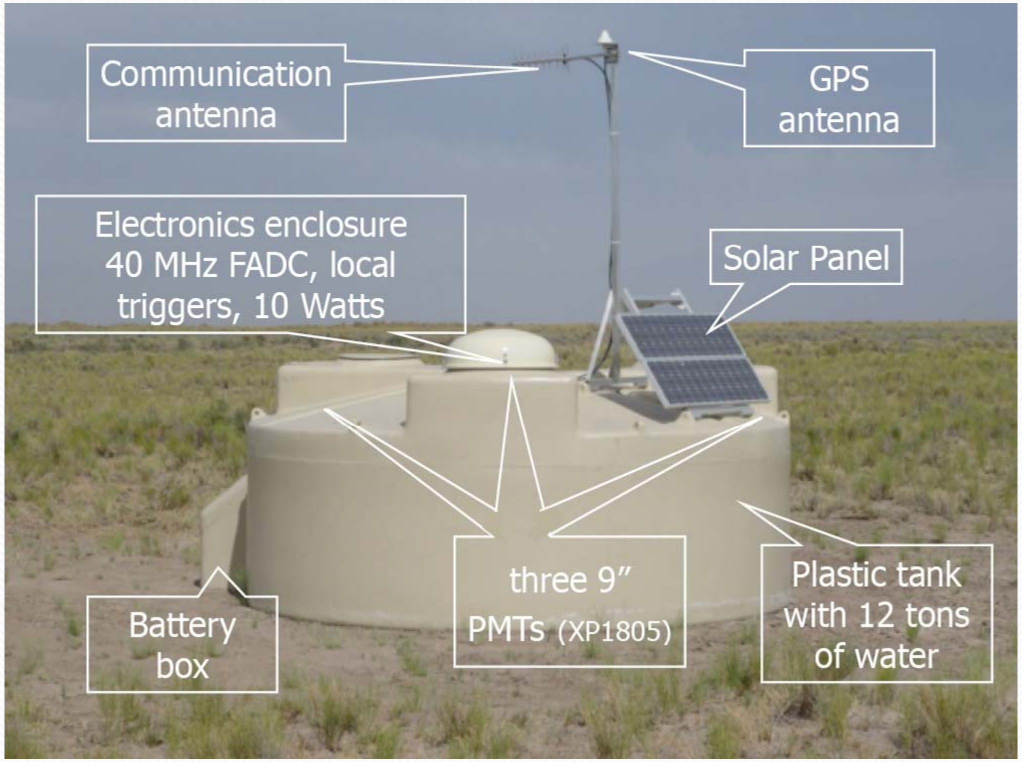
- In operation since 2004, **completed in 2008**

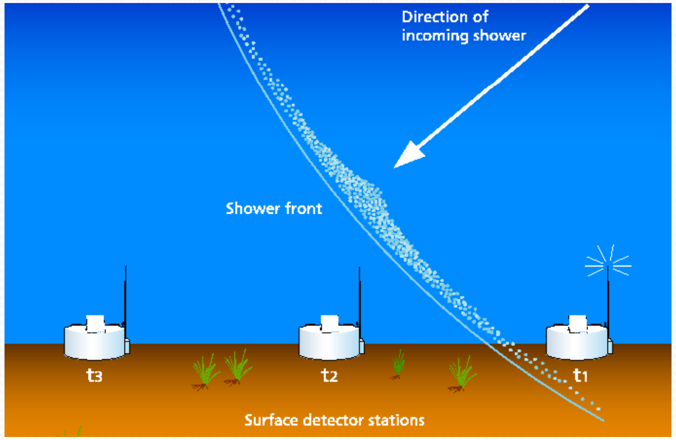

Auger Observatory, Argentina
Loma Amarilla
70
[km]
PIERRE AUGER OBSERVATORY
60
50
40
30
10
HEAT FD Telescopes
Infill array (0.75 km spacing)
AMIGA μ counters 25 km²
AERA radio array 17 km²
Coihueco
AERA
XLF
CLF
BLF
Los Morados
Surface Array
1661 detector stations
1.5 km spacing
3000 km²
Atmospheric monitors:
weather, clouds,
thunderstorm activity,
lasers, lidars...
MALARGÜE
Los Leones
Fluorescence Detectors
4 Telescope enclosures
6 Telescopes per enclosure
24 (+3) Telescopes total
A. Aab et al., NIM A 798, 172 (2015), arXiv:1502.01323

Hybrid Observation

The Surface Detector

- 12 tons of ultra pure water
- highly reflective liner
- the volume is observed from the top by three 8" photo-multipliers
- solar panel and accumulator cover the energy consumption of the station continuously
- communication antenna transmits the data into the control room
- placed in a grid 1.5 km apart, about 1660 stations in total



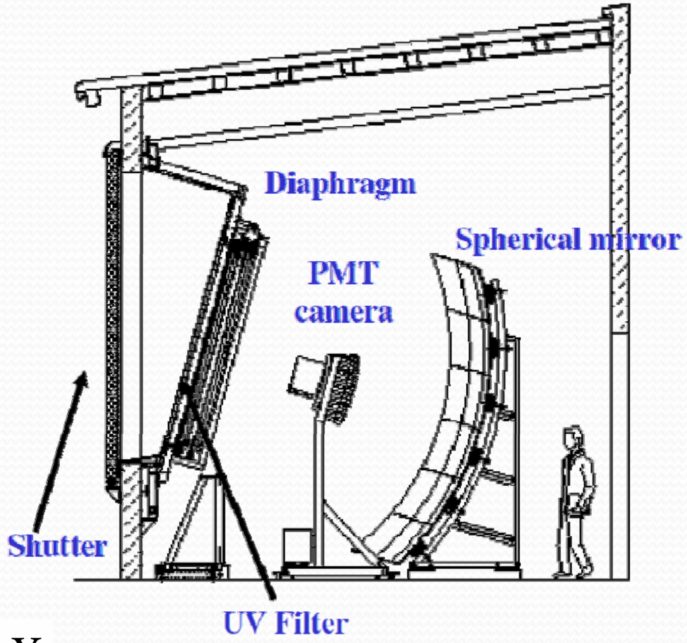


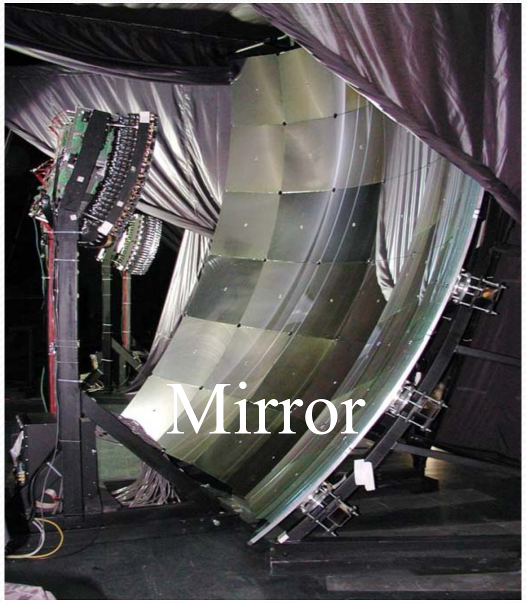
- Functions continuously (100% duty cycle)
- Observe the lateral profile of the shower
- Does not observe the longitudinal development of the shower

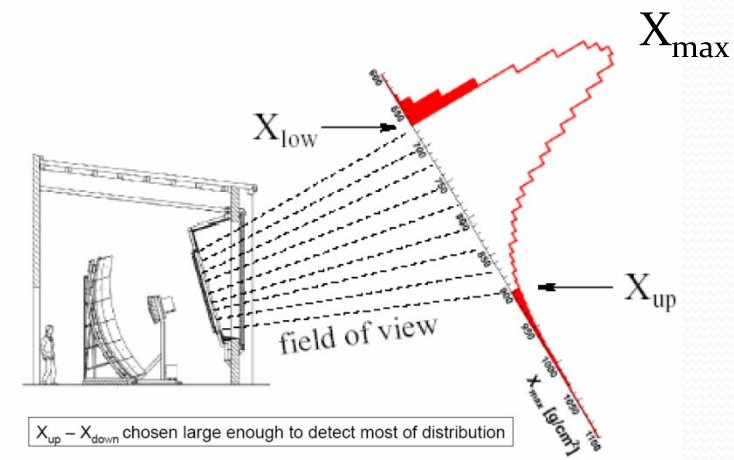
Hybrid Observation

The Fluorescence Detector

- Segmented spherical mirror (diameter 3.44 m)
- 30° by 30° filed of view, viewing up to 30° above the horizon
- 440 photo-multipliers in the focal plane
- 24 telescopes in 4 buildings



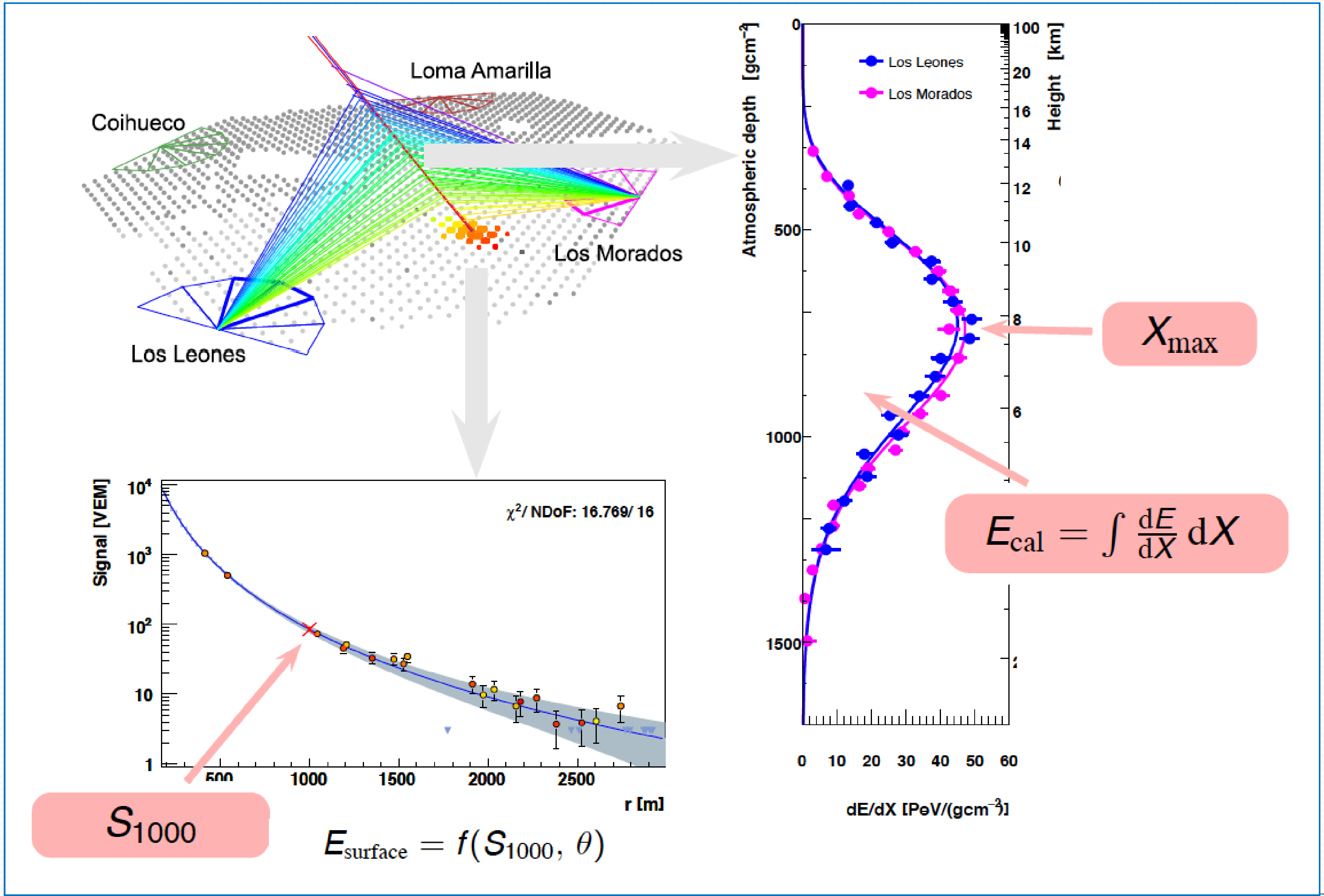




- Observes directly the location of the shower maximum (indicative of the primary mass)
- Nearly calorimetric measurement (model independent measure of the energy)
- Functions only during clear, moonless nights (about 15% of the total time)

Hybrid Observation

The Reconstruction

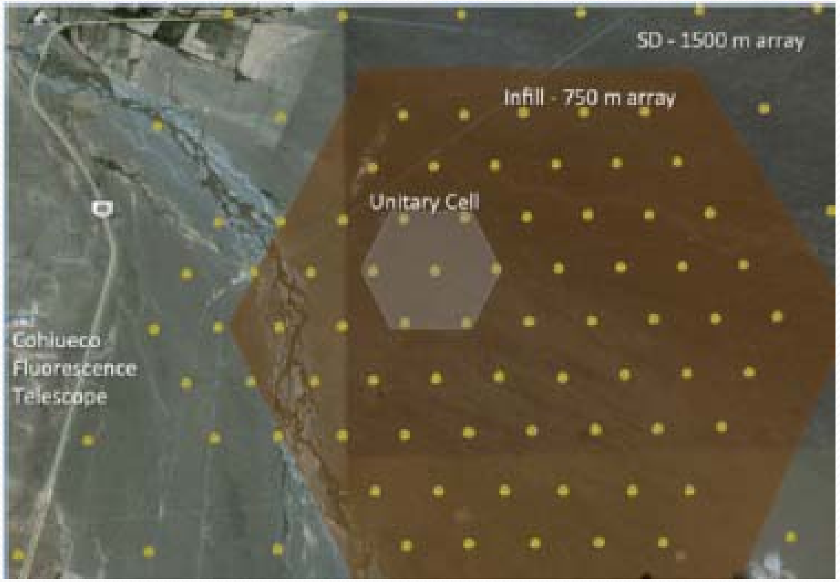


Observatory Enhancements
HEAT and INFILL

• Three additional telescope of the same design

• Pointing above FOV of the standard FD (30° to 60°)

• Lowering the energy threshold to 10^{17} eV



•61 WCD in half distance (750 m)

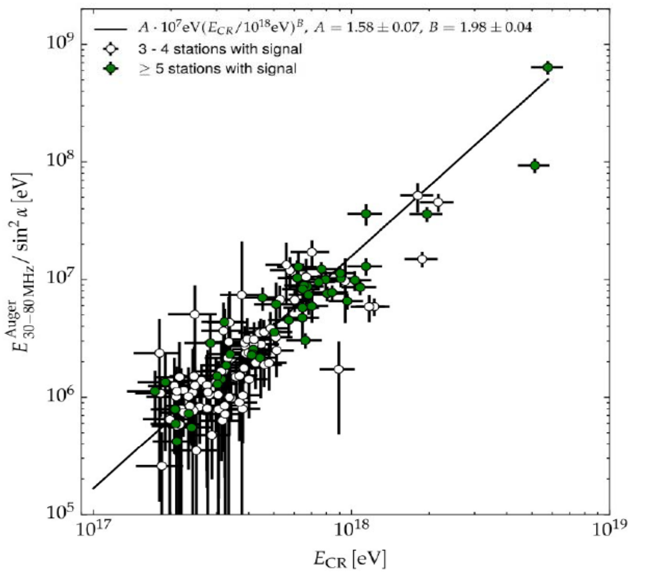
•Covering 23.5 km^2

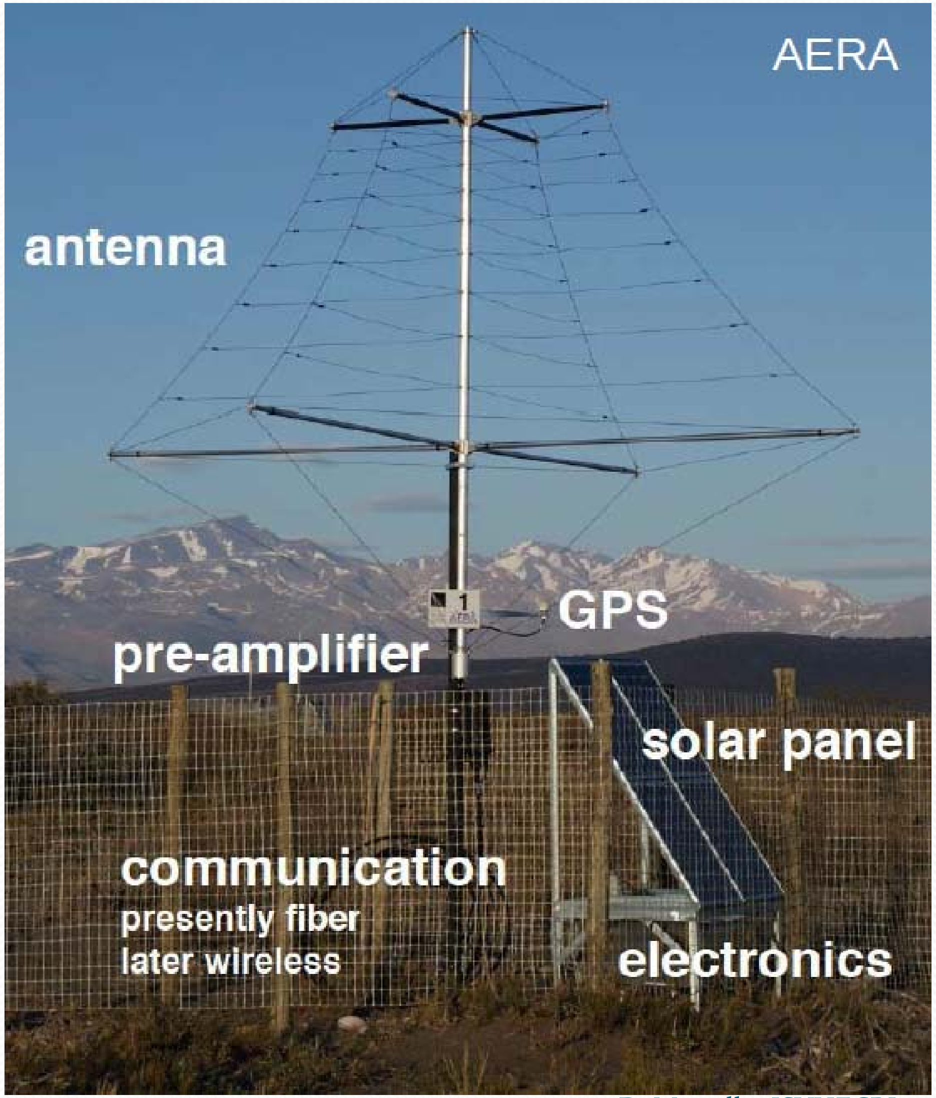
•Extends energy range of SD to $3x10^{17}$ eV

Observatory Enhancements

AERA Auger Engineering Radio Array

- 153 radio stations on 17 km²
- Coherent radiation of secondaries in 30-80 MHz
- Graded array 144 m to 750 m spacing
- Completed in 2015



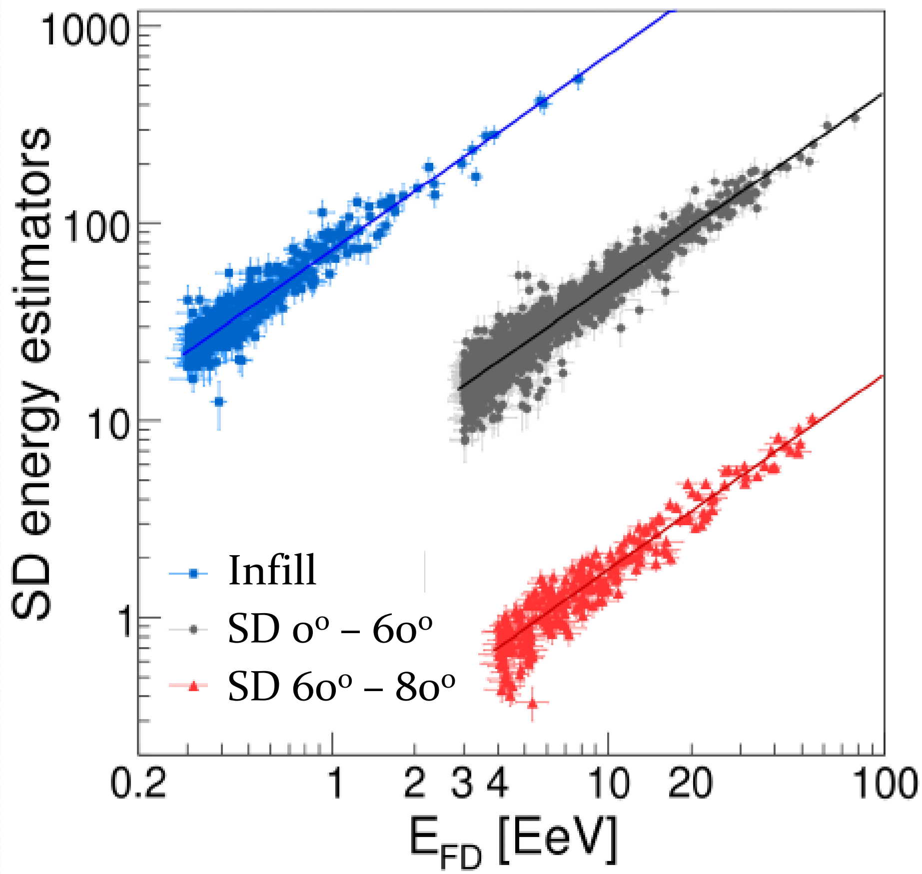


Auger Energy Scale

All the detectors are calibrate using the FD energy estimator. Three samples of events (different reconstruction approaches)

• Very inclined showers (60 to 80), only muons on the ground
• Full array with the standard spacing between the stations
• Infill array (750m spacing)

• all the three configurations can be described by a simple power law (no simulations needed)
• inherit the FD energy scale uncertainty of 14% (16% below 10^{18} eV)



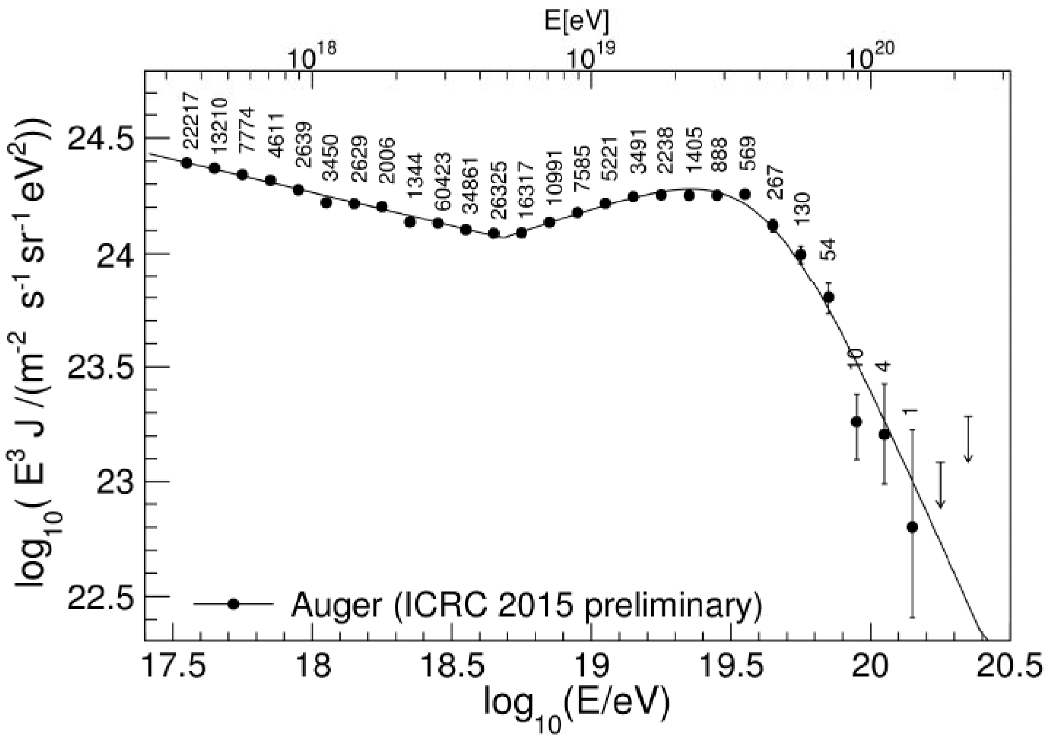
The Spectrum

Ankle region measured with high precision

Slope below ankle
γ = (3.29±0.02±0.05)
Slope above ankle
γ = (2.60±0.02±0.10)

Strong suppression above $10^{19.5}$ eV

Origin is not clear- GZK limit or end of the cosmic acceleration power?



The Spectrum

- Updated, combined Auger spectrum:
- 115,000 SD (>3 EeV) + 60,000 Infill (>0.3 EeV) + 10,000 hybrid events (>1 EeV);
- Exposure = 50,000 km2 sr yr .

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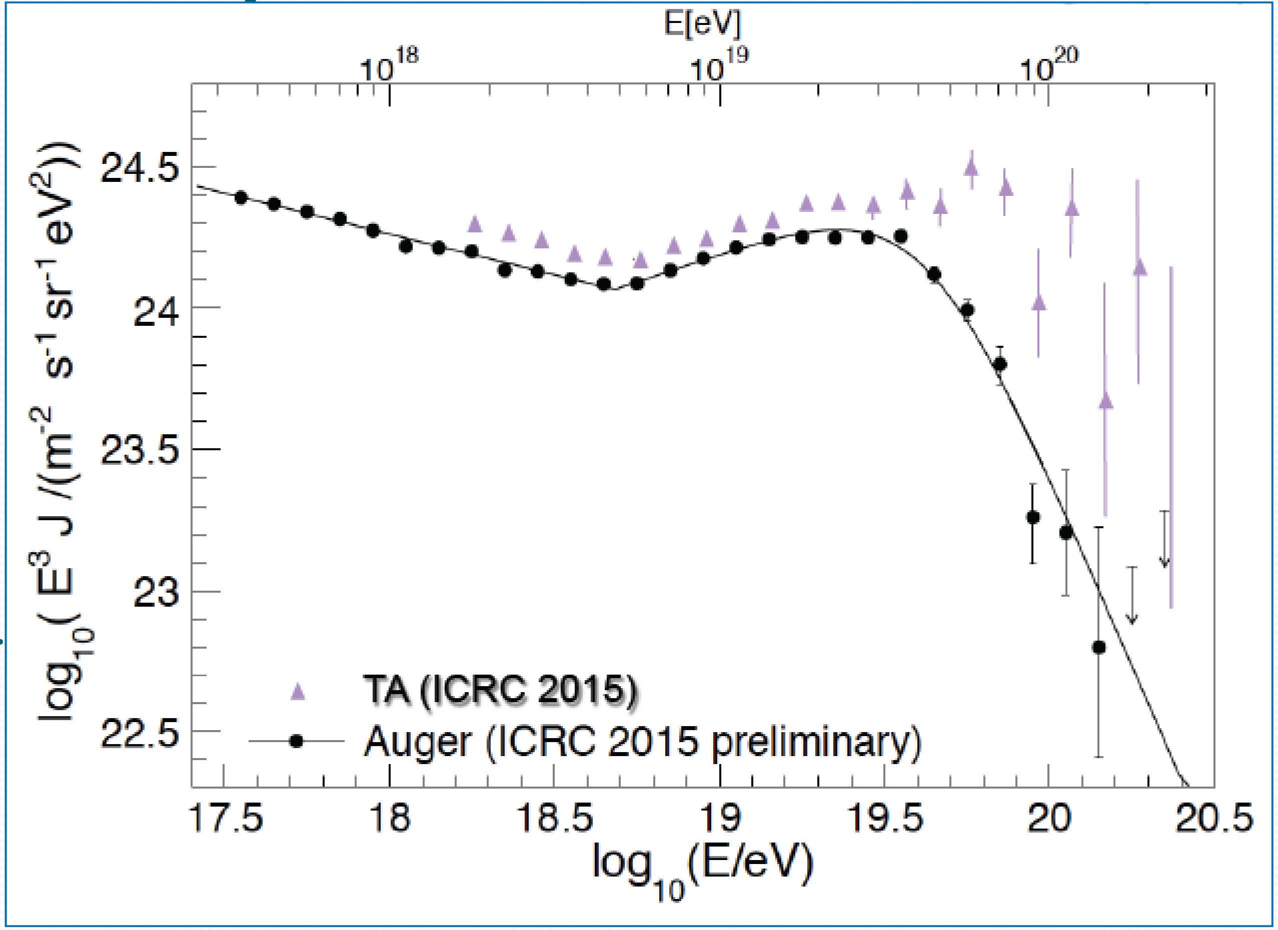

I. Valino et al., Proc. of 34th ICRC, The Hague (2015)
R.U. Abbasi et al., Astropart. Phys. 68, 27 (2015)

GZK-like suppression definitely seen (>20σ)

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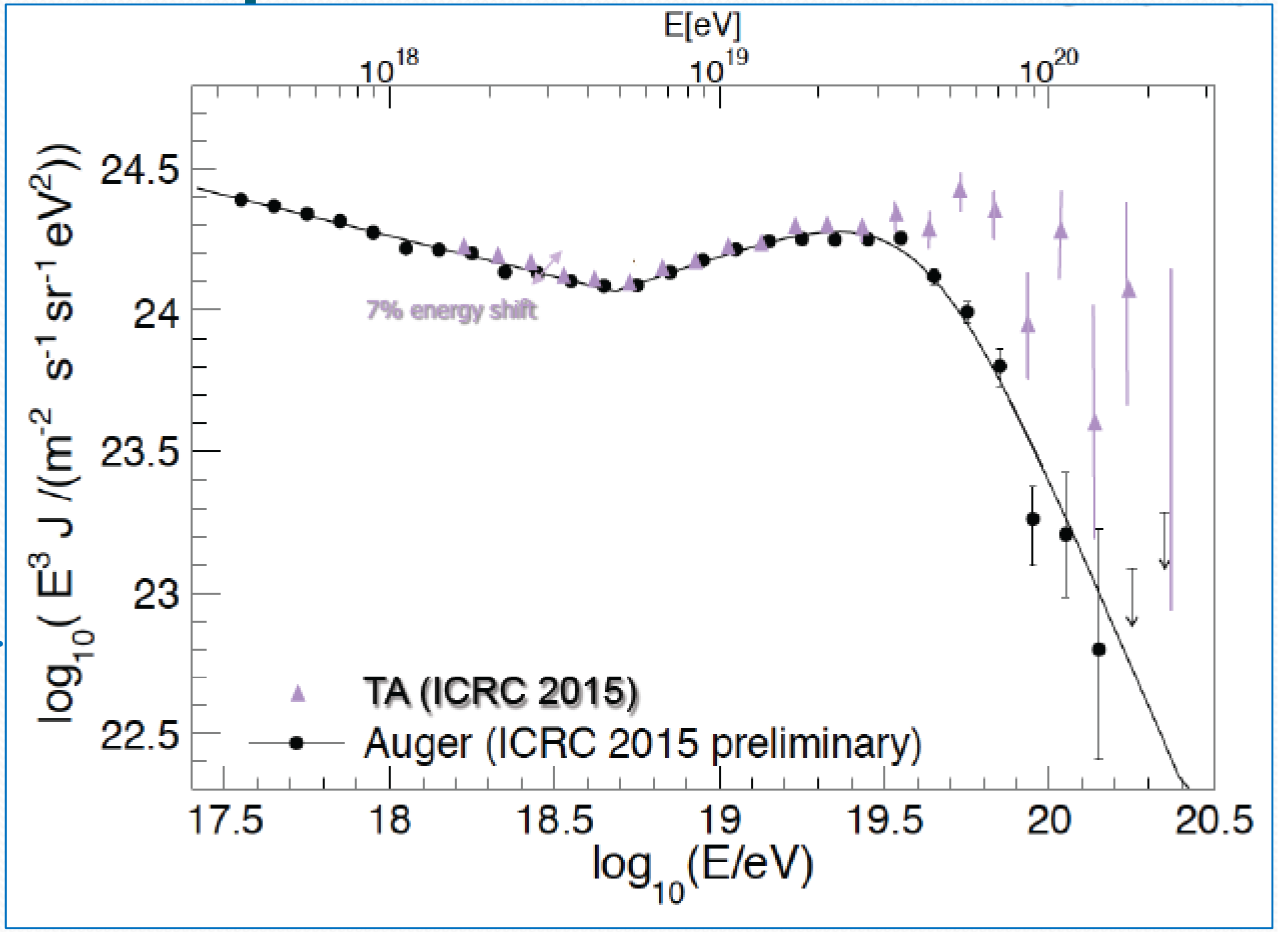

Differences between Auger and TA can be (mostly) accommodated within a systematic energy shift…
… but not easily at the highest energies.

I. Valino et al., Proc. of 34th ICRC, The Hague (2015)
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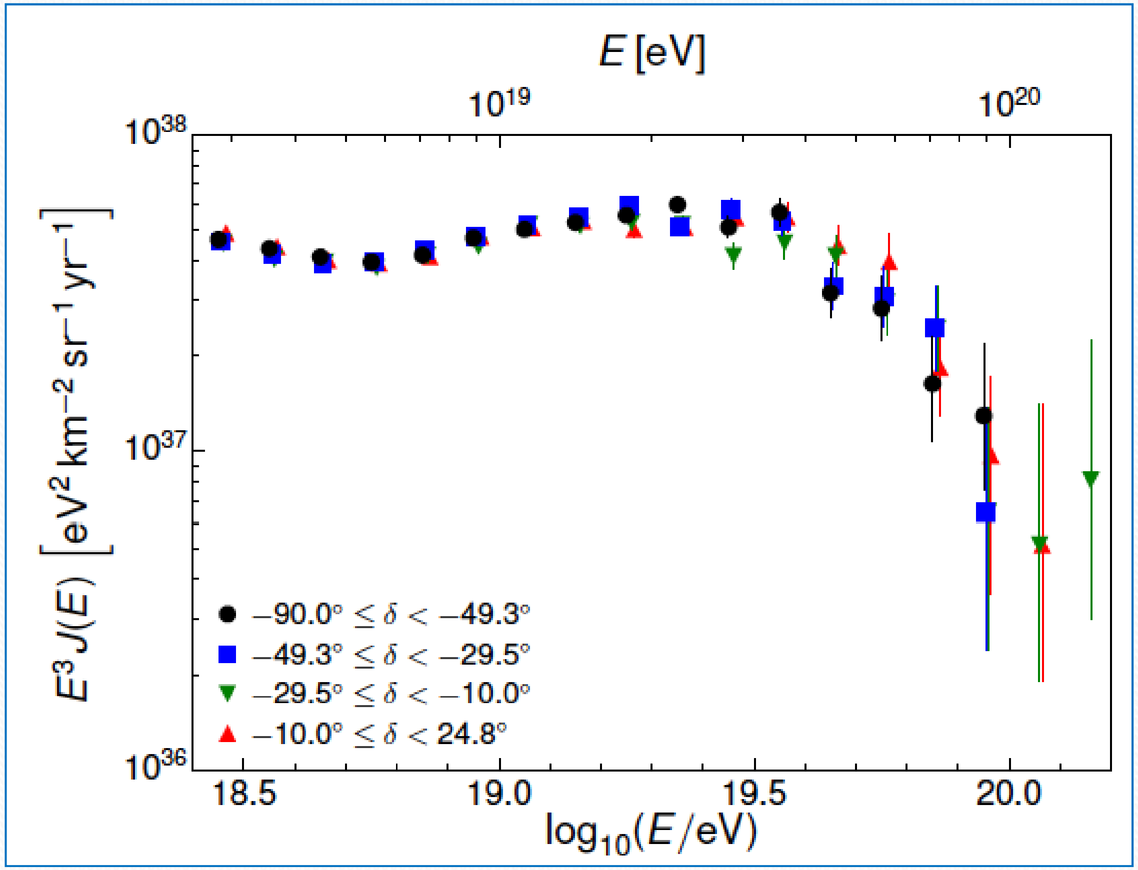
GZK-like suppression definitely seen (>20σ)

The Spectrum

Auger spectrum divided into 4 separate declination bands covering 71% of the sky;

No evidence for spectral dependence on source location.



I. Valino et al., Proc. of 34th ICRC, The Hague (2015)

What is the nature of the spectral suppression?

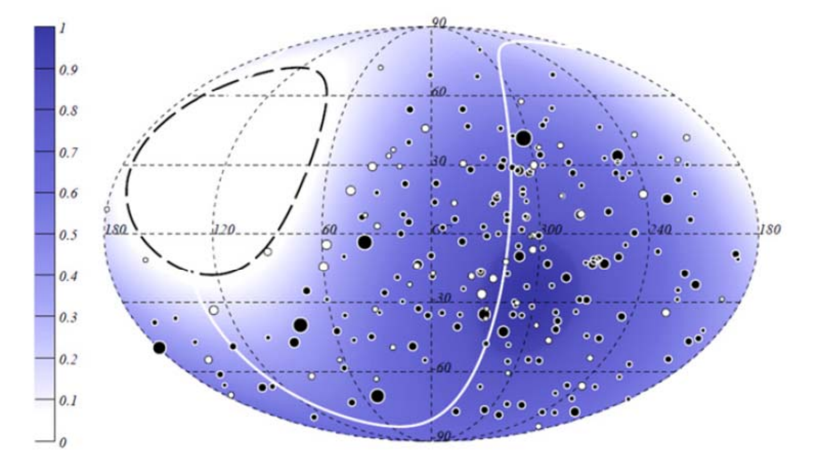
- GZK propagation effects (attenuation due to CMB interactions)?
- Intrinsic difficulty of producing 10^{20} eV particles in astrophysical sources?

1) Study mass composition and air shower development (UHE physics);

2) Look for sources in arrival direction distribution.

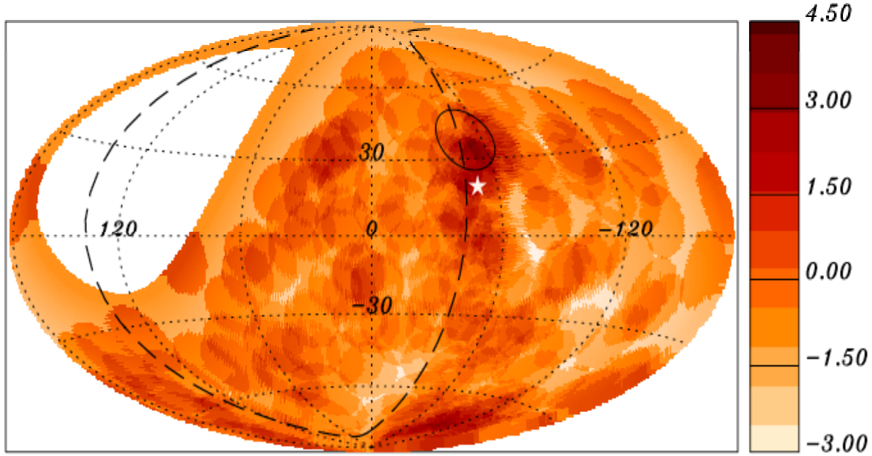
Anysotropy

231 Auger events with E ≥ 52 EeV and θ<80°;
• look for flux excesses, autocorrelations (scan in circles 1-30°, with E_{thresh} from 40 to 80 EeV);
• compare with catalogs of AGNs and other objects.



Li-Ma significance map in 12° circles;
largest excess 4.3σ, Ethresh = 54 EeV,
18° from CenA;
post-trial probability 69%, so compatible with isotropy. CenA

Note: 2007 69% AGN correlation has weakened to 28%, only 2σ above isotropy.



THE ASTROPHYSICAL JOURNAL, 804:15 (18pp), 2015 May 1

Anysotropy

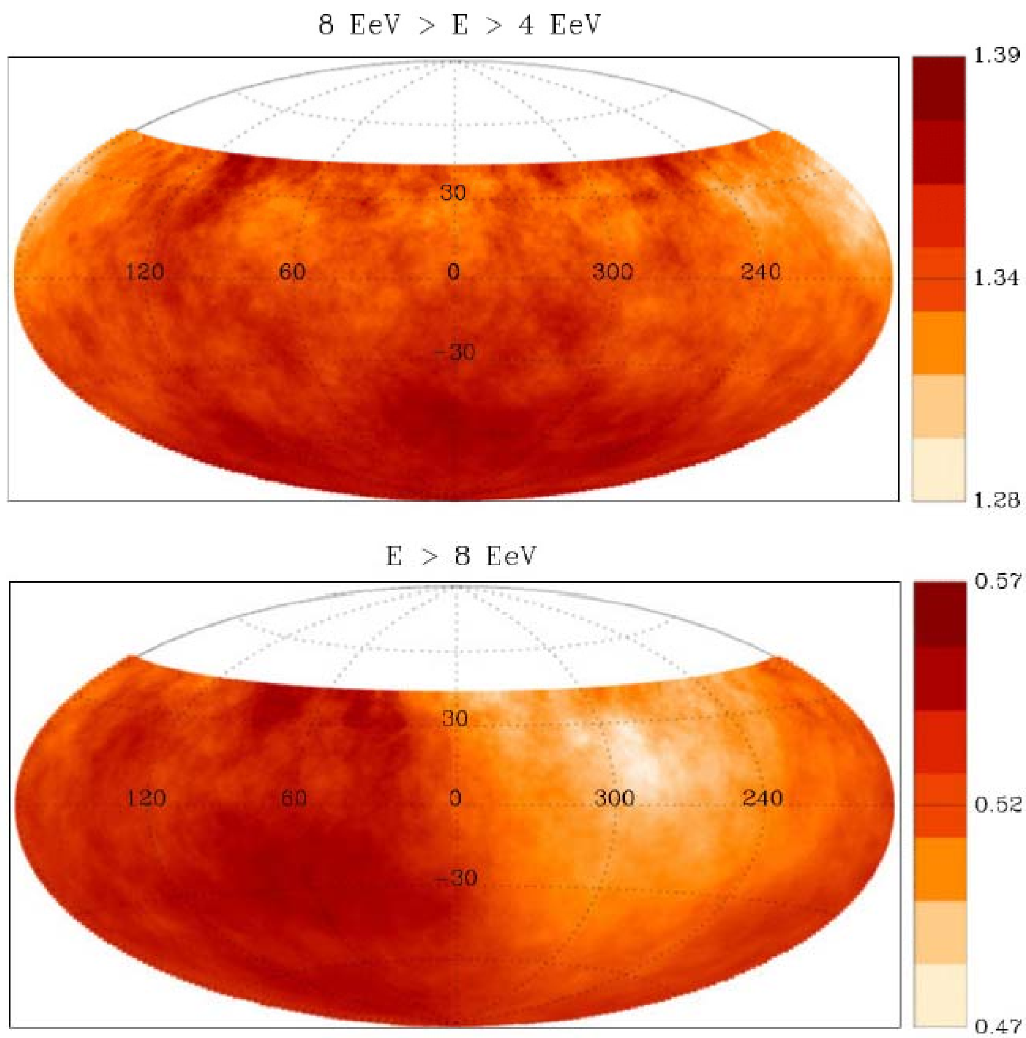
Large scale distribution

Inclined events up to 80° included
More than 70000 events with E>4 EeV
Covering about 85% of the sky
Divided in two bins of energy

4 EeV < E < 8 EeV
E> 8EeV

No significant anysotropy in the first bin
Dipole amplitude in the second bin

d=0.073 ± 0.015
pointing to
$(\alpha,\delta) = (95^{\circ} \pm 13^{\circ}, -39^{\circ} \pm 13^{\circ})$

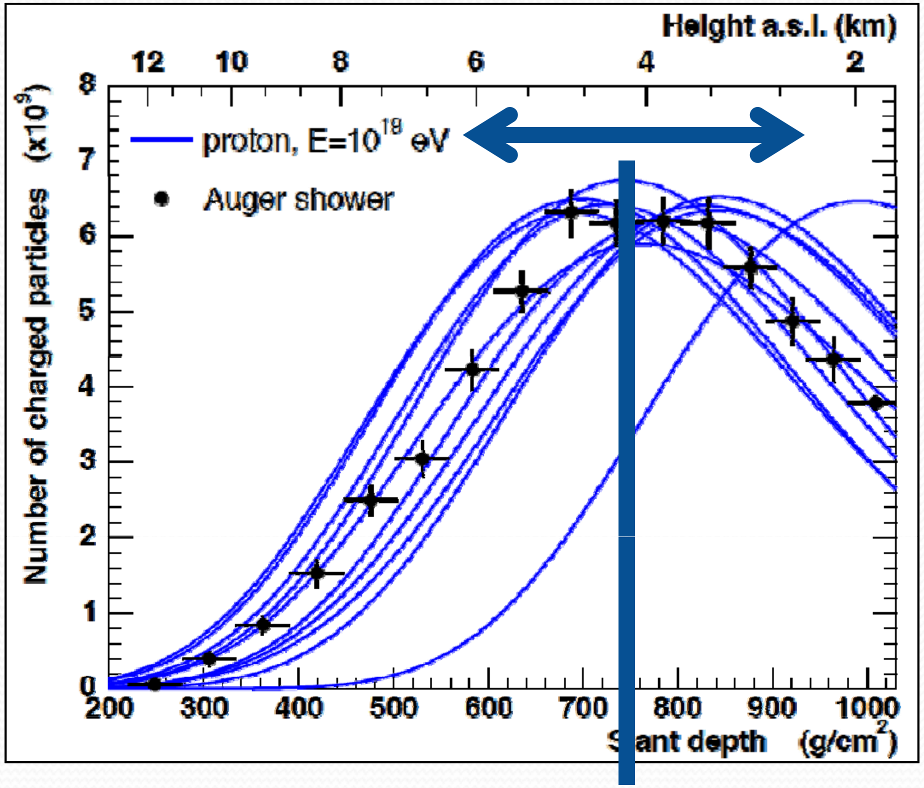


THE ASTROPHYSICAL JOURNAL, 802:111 (11pp), 2015 April 1

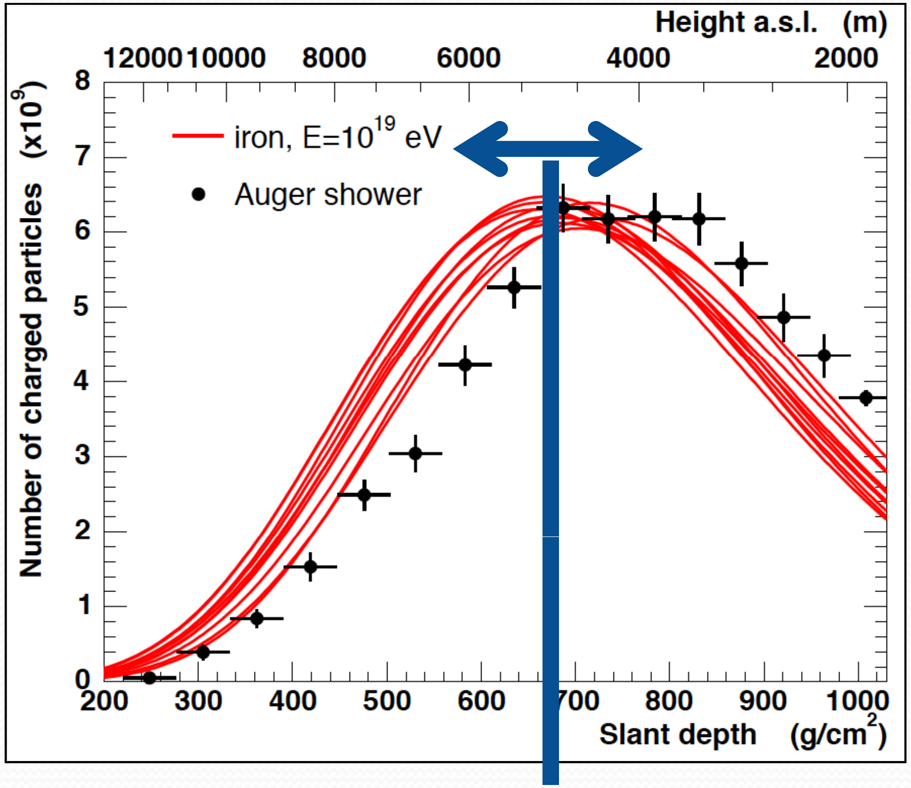
Mass Composition

Fluorescence data only

Hybrid measurements are sensitive to mass composition



X_{max} ~ 780 g/cm2



X_{max} ~ 680 g/cm2

p-induced showers develop deeper than Fe-induced ones and have greater fluctuations

Mass Composition

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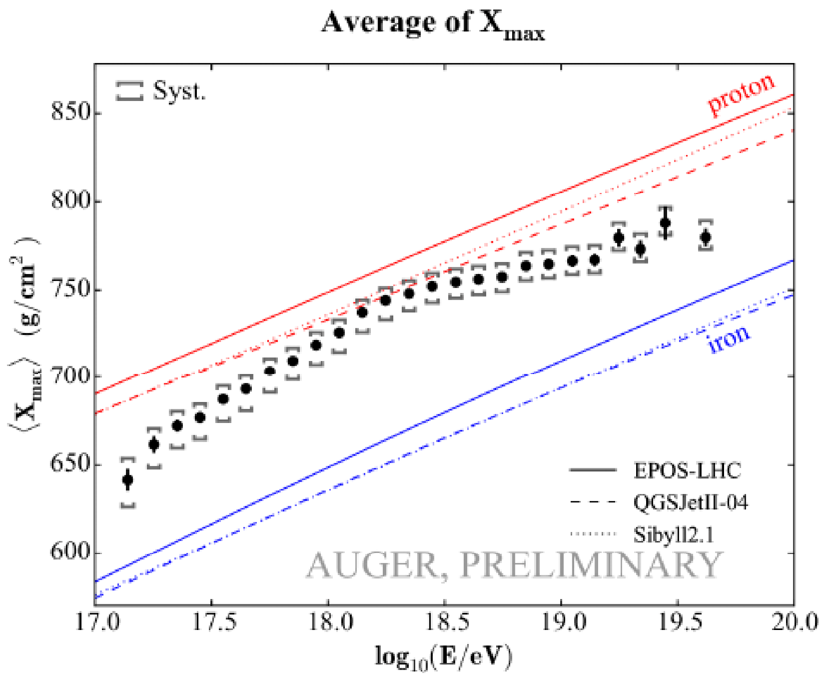
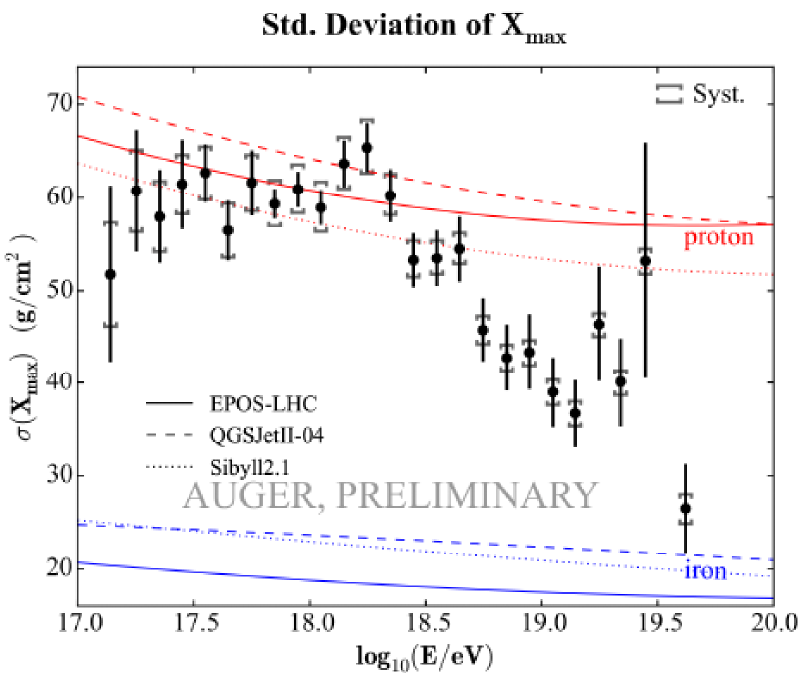




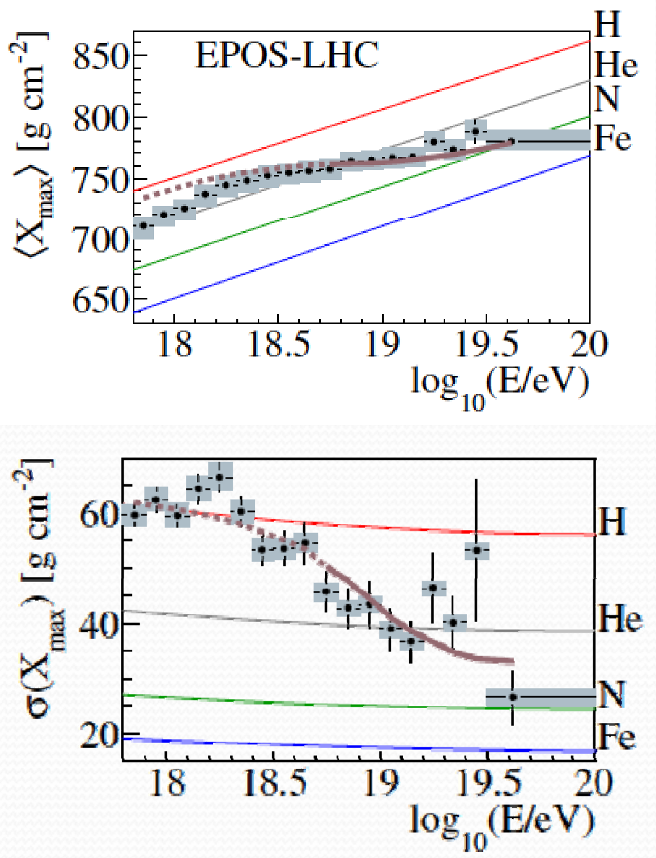
Both the estimators indicate a composition become lighter up to $10^{18.3}$ eV

.. then a transition from light to heavier primary above $10^{18.3}$ eV

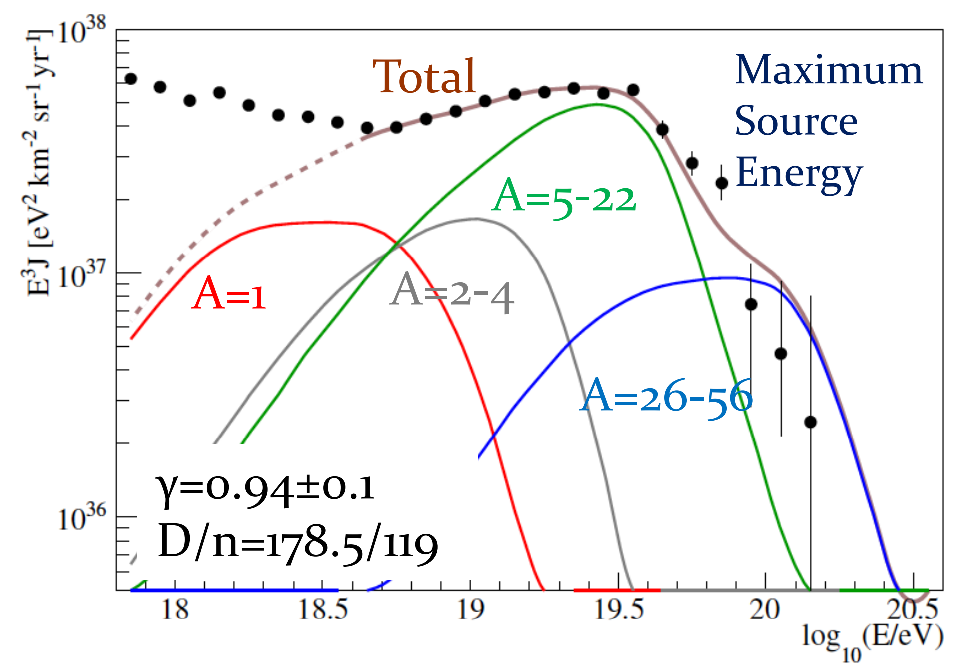
More details in the next talk by A. Yushkov

Combining X_{max} and spectrum

Homogeneous distribution of identical sources of p, He, N and Fe nuclei;
125 data points, 6 fit parameters: injection flux norm. and spec. index γ, cutoff rigidity Rcut, p/He/N/Fe fractions; best fit with very hard injection spectra (γ≤1).



A. di Matteo et al., Proc. of 34th ICRC, The Hague (2015)



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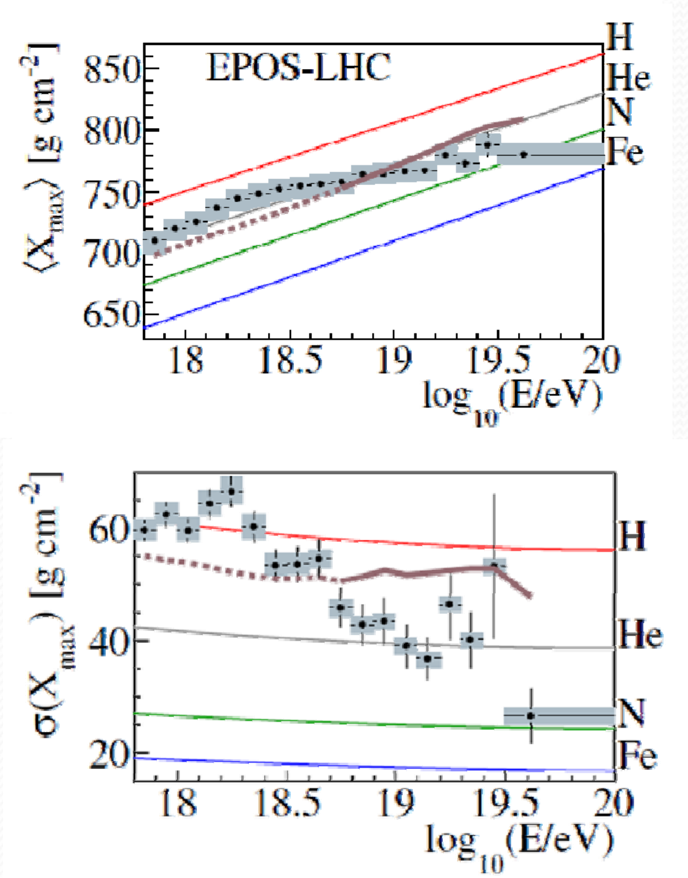

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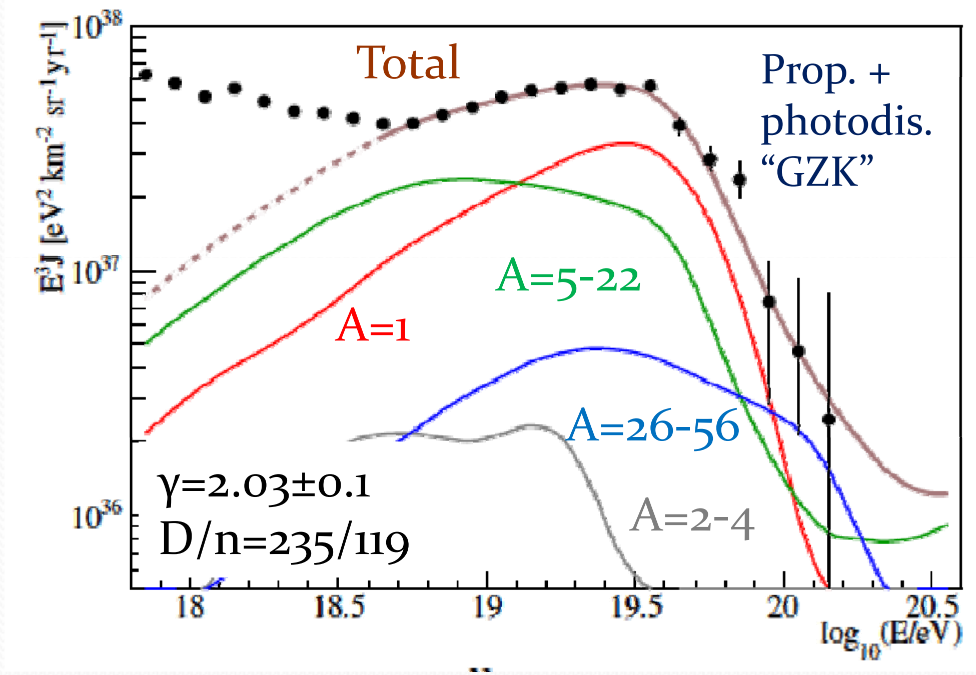


The upgrade Science Case

The data collected after 2017 must provide additional measurements to allow us to address the following key objective:

1. The mass composition and the origin of flux suppression at the highest energies
   - Understanding the origin of the flux suppression will provide fundamental constraints on the astrophysical sources and will allow a more reliable estimates of neutrino and gamma-ray fluxes at UHE.
2. Proton contribution in the flux suppression region ($E > 5x\ 10^{19}$ eV)
   - Estimate the physics potential of existing and future cosmic ray, neutrino and gamma-ray detectors; Search of proton astronomy
3. Fundamental particle physics at energies beyond reach of man-made accelerators. (see next talk)
   - Study extensive air showers and hadronic multiparticle production.

Mass composition measurement above 5 x 10^{19} eV with a sensitivity to the proton flux as small as 10%.

The strategy

Measure with the Pierre Auger Observatory until 2025.

(MOUs have been signed in Nov 2015)

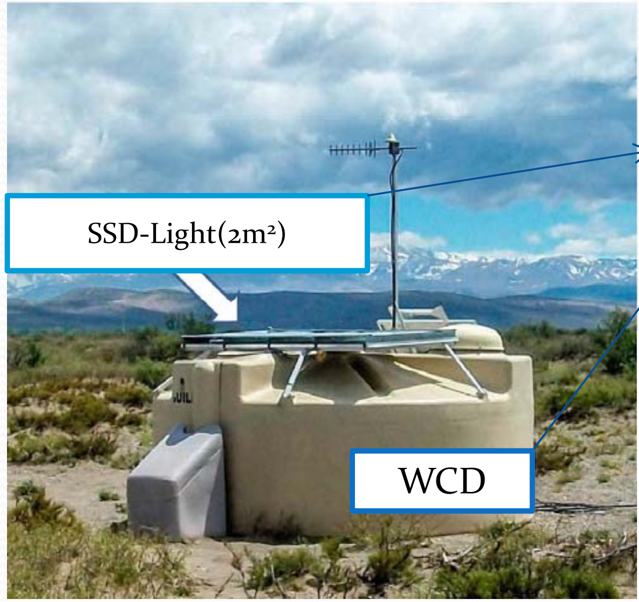
The upgrades:

1. Scintillator SD (SSD) to measure the mass composition with 100% duty cycle
2. Upgrade Surface Detector (SD) electronics and introduce a small PMT
3. Underground Muon Detector with AMIGA to have a direct muon measurement
4. Extended FD operation

Event statistics for the upgraded array in a data taking period from 2018-2024 (events up to zenith angle θ<60°) for both the 750 m array and the 1500 m array.

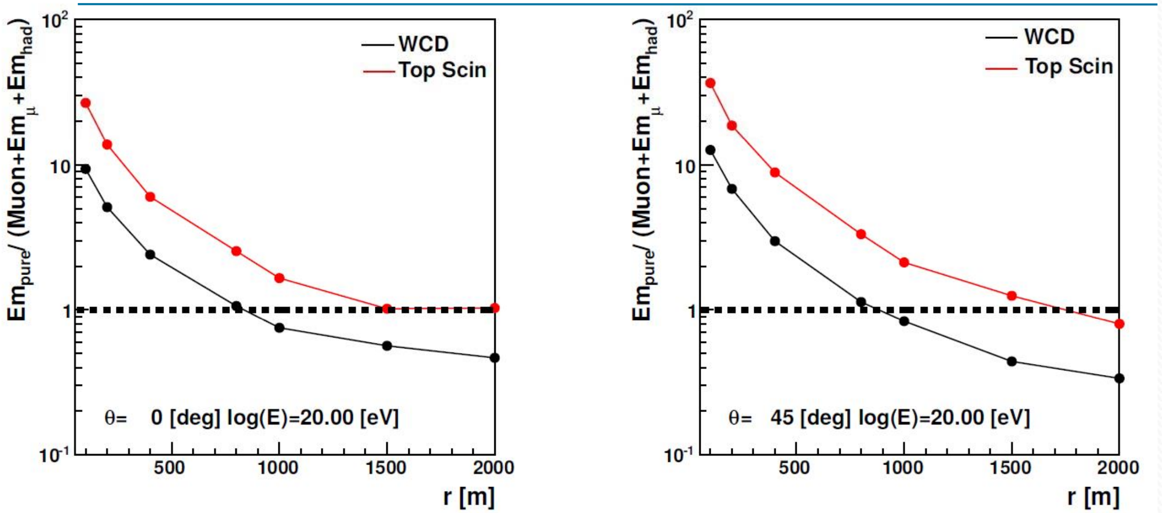
$\log_{10}(E/\mathrm{eV})$	$\mathrm{d}N/\mathrm{d}t\vert_{\mathbf{infill}}$ $[\mathrm{yr}^{-1}]$	$\mathrm{d}N/\mathrm{d}t\vert_{\mathbf{SD}}$ $[\mathrm{yr}^{-1}]$	$N\vert_{\mathbf{infill}}$ [2018-2024]	$N\vert_{\mathbf{SD}}$ [2018-2024]
17.5	11500	-	80700	-
18.0	900	-	6400	-
18.5	80	12000	530	83200
19.0	8	1500	50	10200
19.5	$\sim$1	100	7	700
19.8	-	9	-	60
20.0	-	$\sim$1	-	$\sim$9

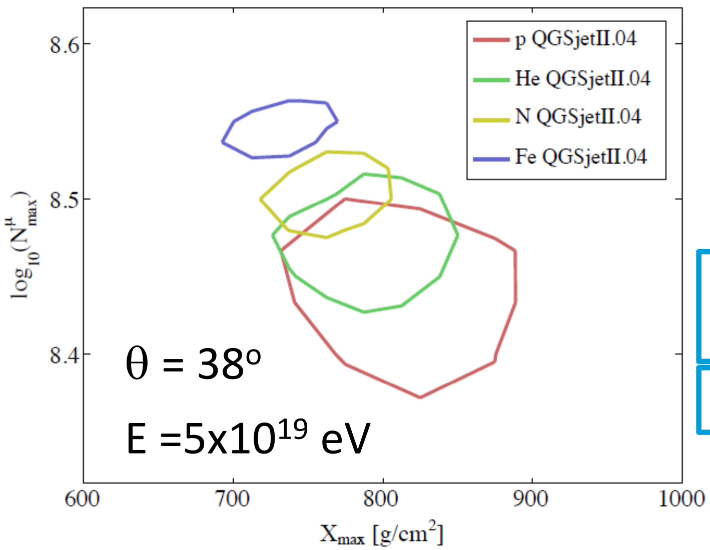
Scintillator Surface Detector Measurement



100% duty cycle

Complementarity of particle response used to discriminate electromagnetic and muonic components of air showers

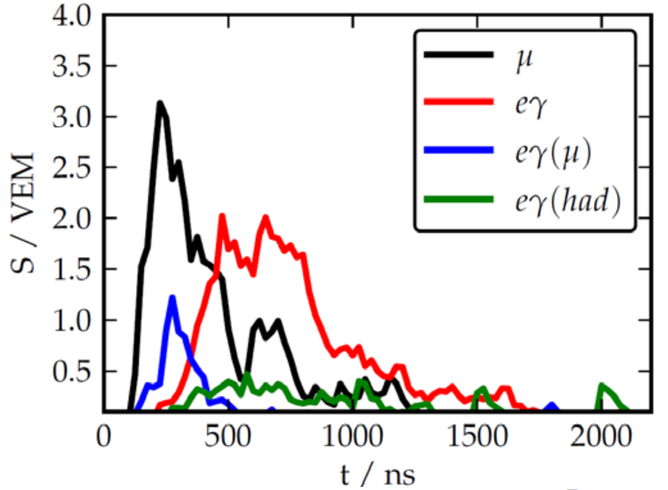




1σ contour of the number of muons at maximum of the muon shower development

Measure muon component for composition

SSD Measurement: Universality approach



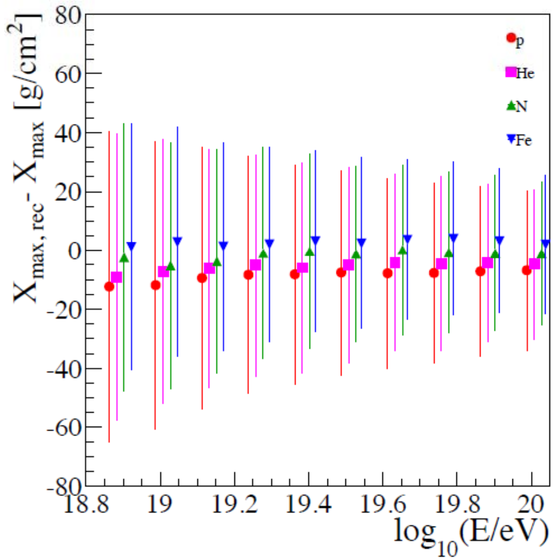
The shower universality method **predicts for the** entire range of **primary masses the air-shower** characteristics on the ground **using only three** parameters: ***E, Xmax and Nμ***

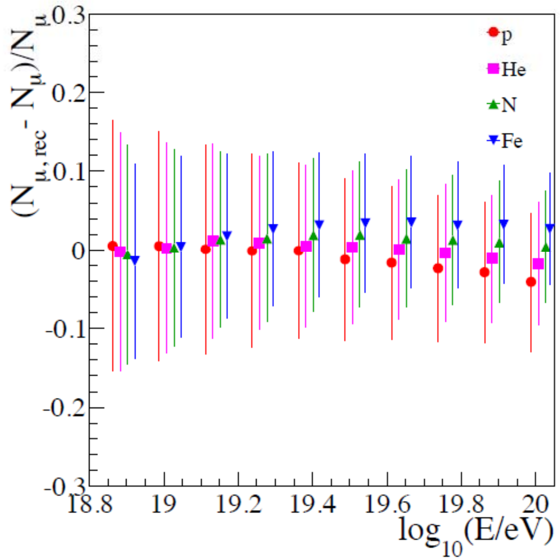
The parameter could be **estimated from the integrated signal and the temporal structure** of the signal measured in individual stations. Event by event basis

$$S_{\text{tot}} = S_{\text{em}}(r, DX, E) + N_{\mu}^{\text{rel}}\left[S_{\mu}^{\text{ref}}(r, DX, E) + S_{\text{em}}^{\mu}(r, DX, E)\right] + (N_{\mu}^{\text{rel}})^{\alpha} S_{\text{em}}^{\text{low-energy}}(r, DX, E)$$

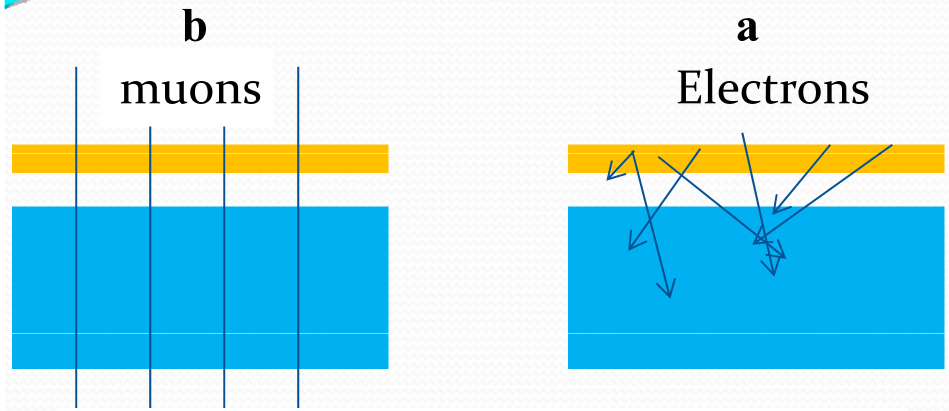
Applying the Universality method it is possible to take into account the **correlation between the WCD and the SSD. The parameters now are more** (Xμmax ,Xmax, Nμ) in the model.

This allows a measurement of the **number of muons on a event by event basis and the relation** between Xμmax ,Xmax and Nμrel can be calibrated.



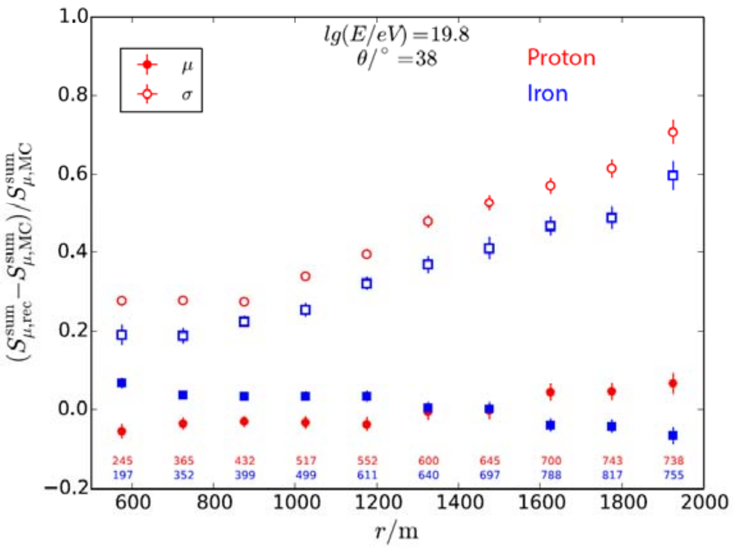


SSD: Matrix Inversion Method



$$\begin{pmatrix} S_{top} \\ S_{bot} \end{pmatrix} = \begin{pmatrix} a & b \\ 1-a & 1-b \end{pmatrix} \begin{pmatrix} S_{em} \\ S_{\mu} \end{pmatrix}$$

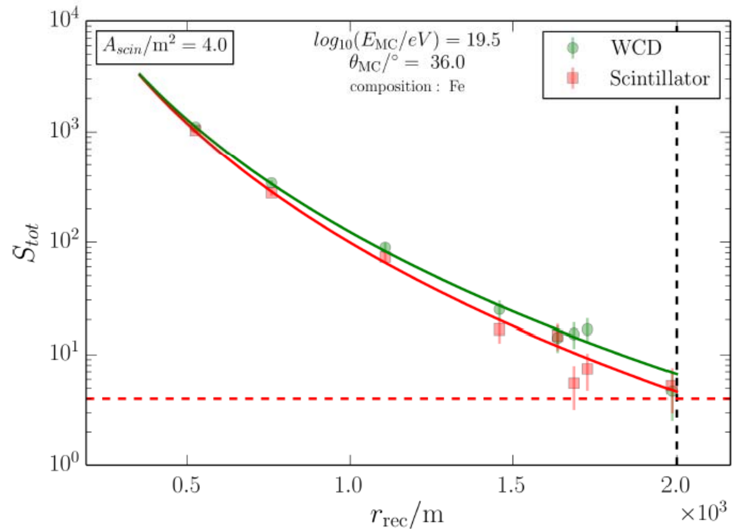
Single Station Analysis



Lateral Distribution Analysis

A **parameterization of the LDF for the SSD** was done using simulation.

Simulated Fe LDFs fit for WCD and SSD



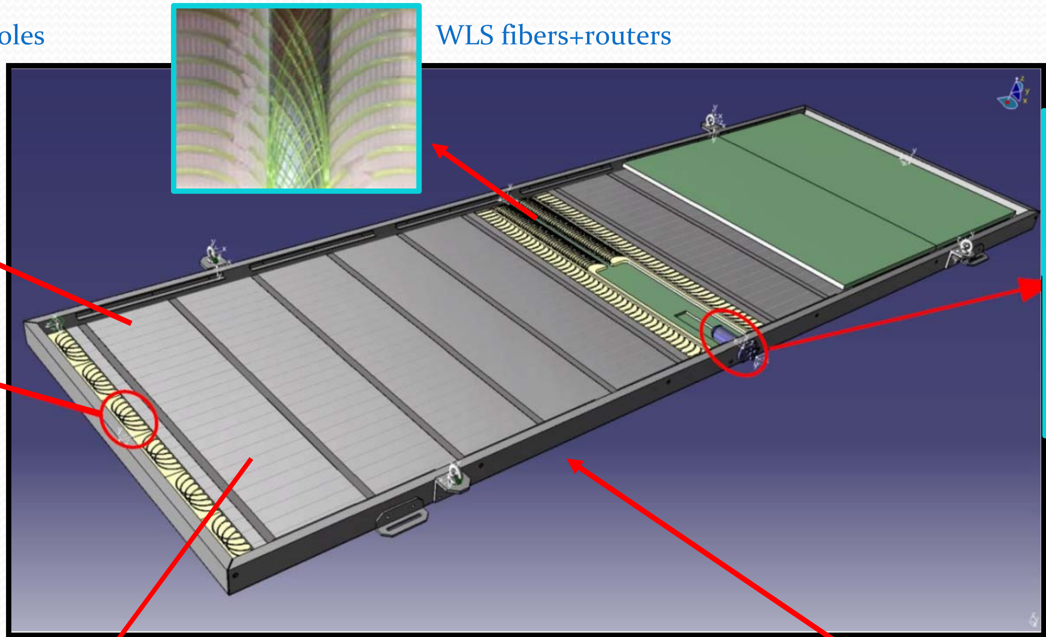
$$f_{p,Fe} = \frac{|\langle S_{Fe} \rangle - \langle S_p \rangle|}{\sqrt{\sigma(S_{Fe})^2 + \sigma(S_p)^2}} \sim 1.5$$

Figure of merit

SSD:The detector

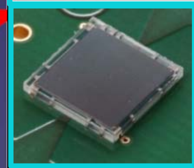
Extruded Scintillator bars with 2 holes

WLS fibers+routers



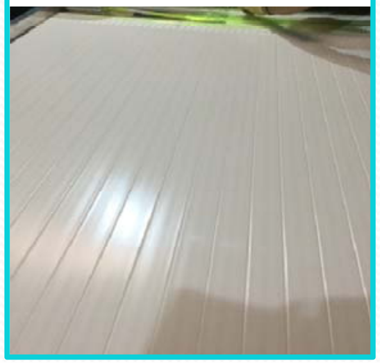
WLS fibers+routers

PMT



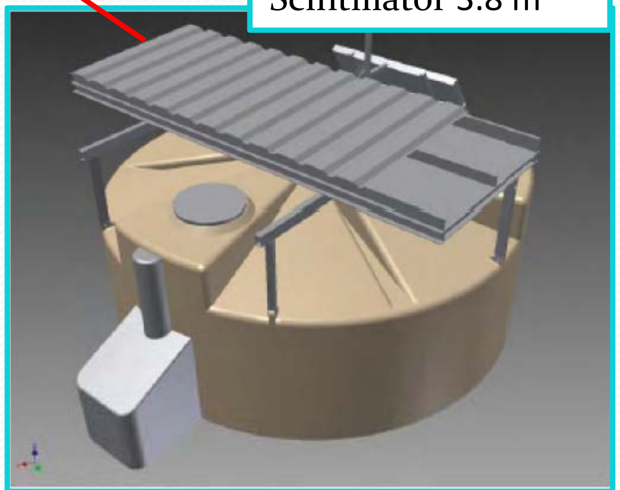
SiPM

Extruded scintillator bars 160cm long

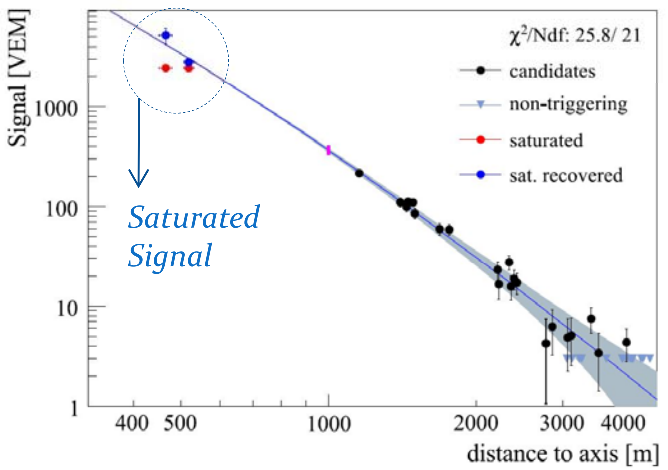


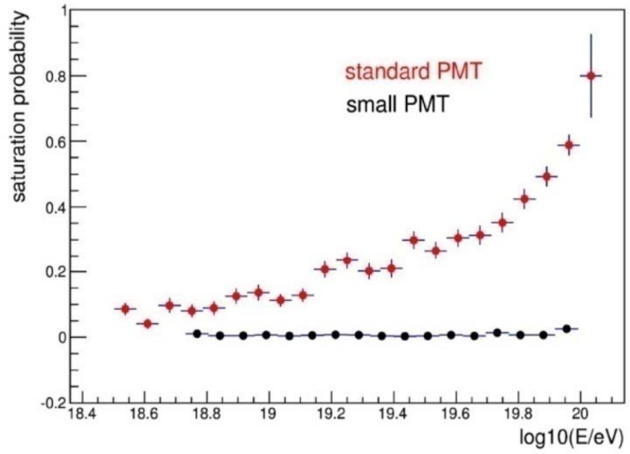
Alu Enclosure

Scintillator 3.8 m^2



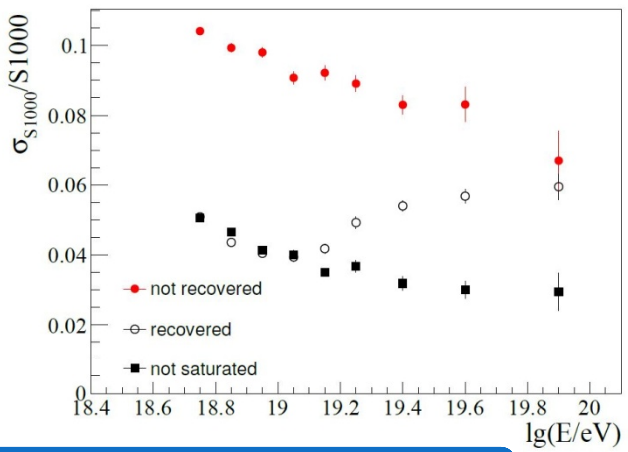
SD Electronics: small PMT

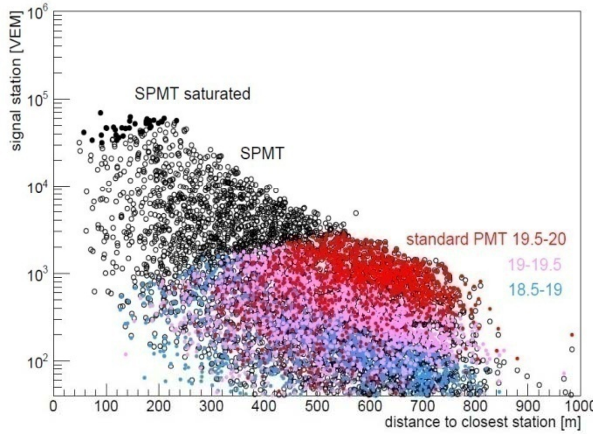




Probability of having at least one saturated station in an event as function of energy, obtained from simulation for standard and small PMT

Lateral Distribution of the signal sizes recorded in SD detectors





The distribution of the expected signals as a function of the distance between the shower axis and the closest SD station

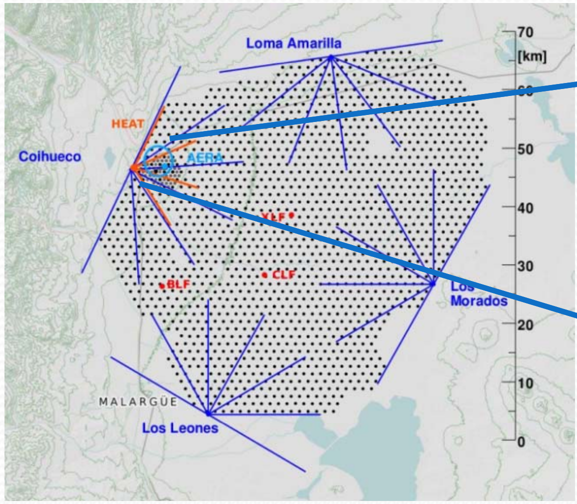
Resolution of the Reconstructed S(1000)

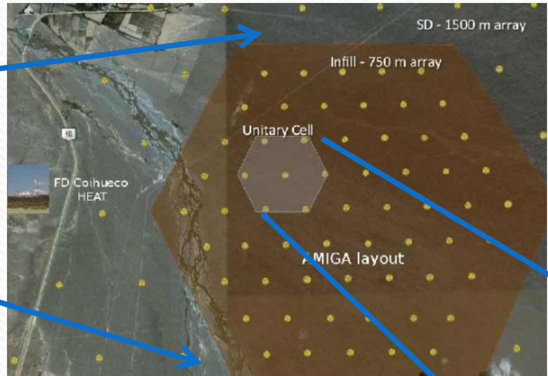
The Underground Muon Detector

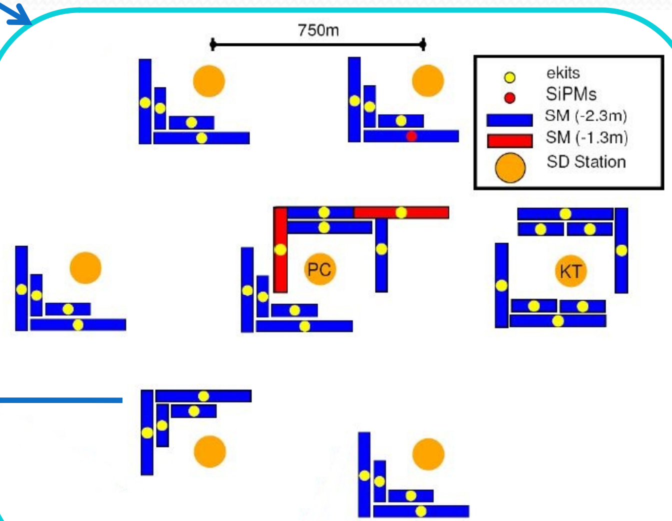
The UMD is required in the existing SD infill area of 23.5 km² in order to provide important direct measurements of the shower muon content and its time structure while serve as verification and fine-tuning of the methods used to extract muon information with the SSD and WCD measurements.

61 AMIGA muon detectors (30 m²) are planned to be deployed on a 750m grid (a total area of 23.5 km²)

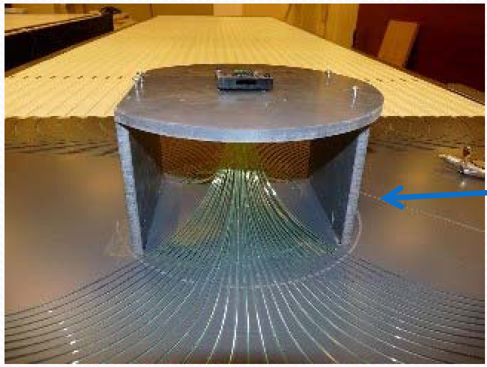
AMIGA layout: an infill of surface stations with an inter-detector spacing of 750 m. Plastic scintillators of 30m² are buried under 280 g/cm² of vertical mass to measure the muon component of the showers. The Unitary Cell indicates the prototype area of the muon detector.



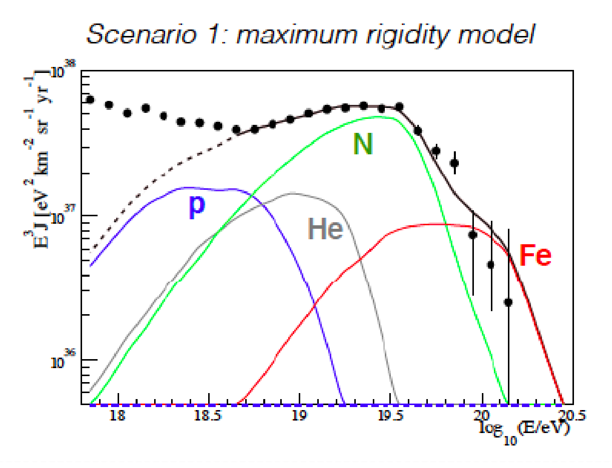


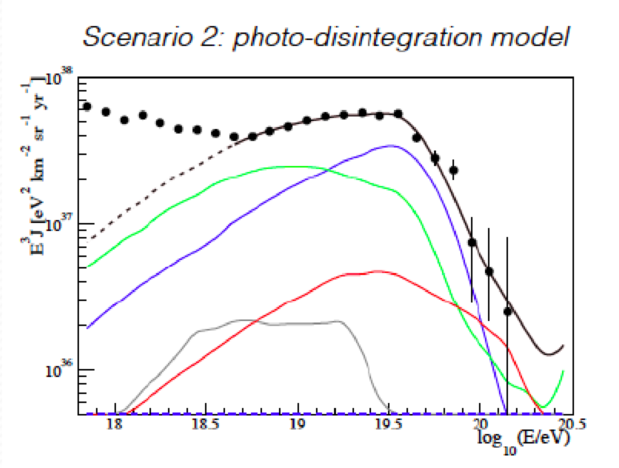


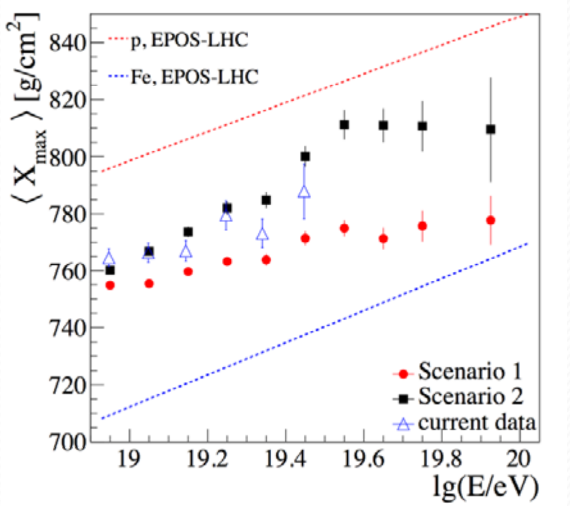
AMIGA-Unitary cell

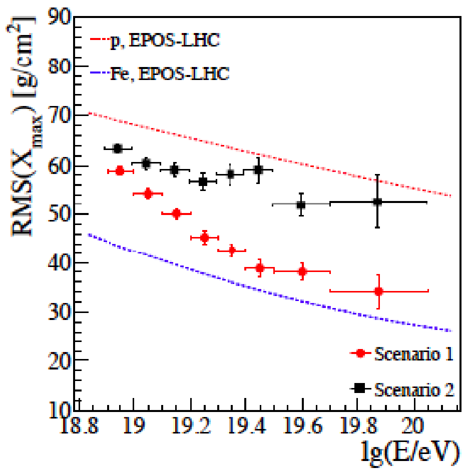


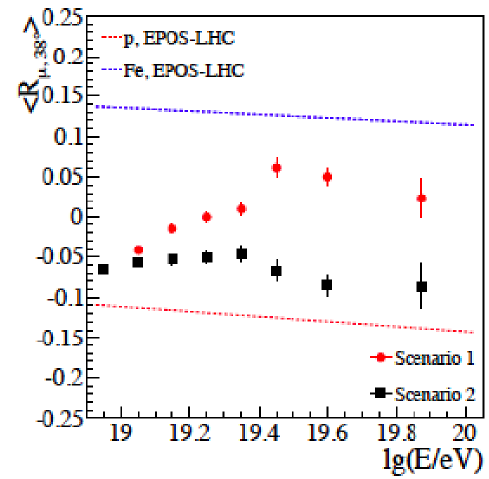
Science Impact of upgrade





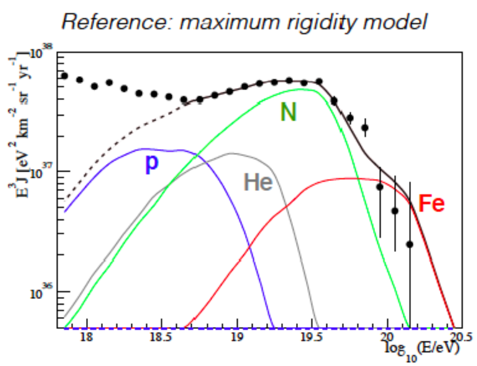


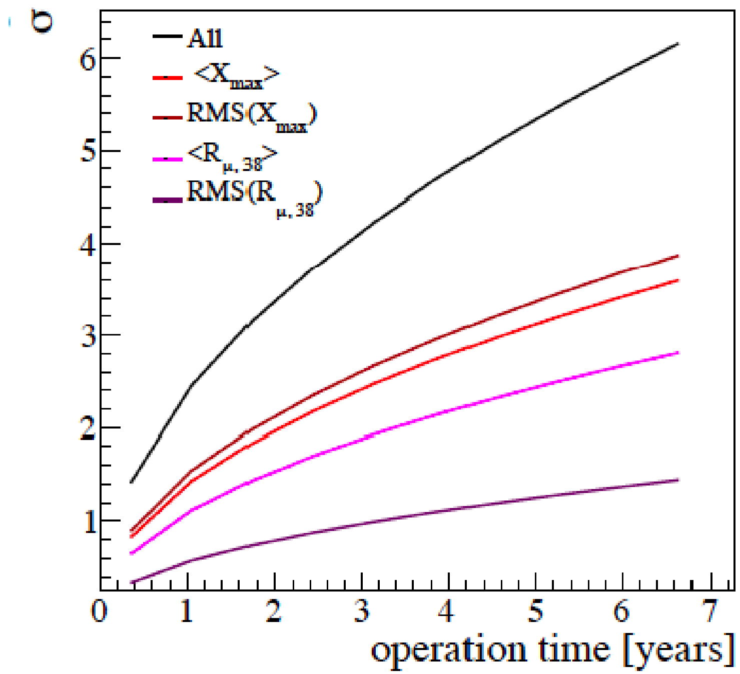




Science Impact of upgrade

- Physics reach: detection of 10 % proton contribution
- Significance of distinguishing scenarios with and without 10% of protons





•Standard scenario 1 (almost no protons)
• Scenario 1 with 10 % protons added

Timeline for new SDE and SSD

- July 2016: Engineering Array (12 stations) ready!
- Nov 2016: Evaluation of detectors
- 2017-2018: Deployment
- Till 2025: Data taking (up to 40,000 km^2 sr yr)
- Similar event statistics as collected so far will be reached with upgraded detectors.

Summary and Outlook

- Flux suppression above ~40 EeV; GZK effect? source exhaustion?
- Flux is disappointingly isotropic above 40 EeV, particle astronomy is hard !
- Magnetic fields (Galactic, extragalactic) play a huge role;
- Xmax (and its RMS) evolution with energy suggest mass becomes heavier at the highest energies;
- Hadronic interaction issues? (see next talk)
- Improved knowledge of mass composition is needed:
- AugerPrime will allow a study of mass composition above

  5×10^{19} eV and address:
  - Origin of the flux suppression (GZK energy loss Vs. maximum energy of sources)
  - Proton contribution of more than 10% above 5×10^{19} eV?
    (particle astronomy, GZK γ and ν fluxes → future experiments)
  - New particle physics beyond the reach of LHC?

Thanks!

Backup slides

Fluorescence Detector Operation

- The FD provides exceptional information about extensive air showers (model-independent energy reconstruction and direct measurement of the longitudinal development profiles)
- The main limitation of the FD is the duty cycle, currently at the level of 15%.

Increase the exposure for cosmic ray events above 10^{19} eV by extending the FD measurement into hours with high night sky background (NSB)

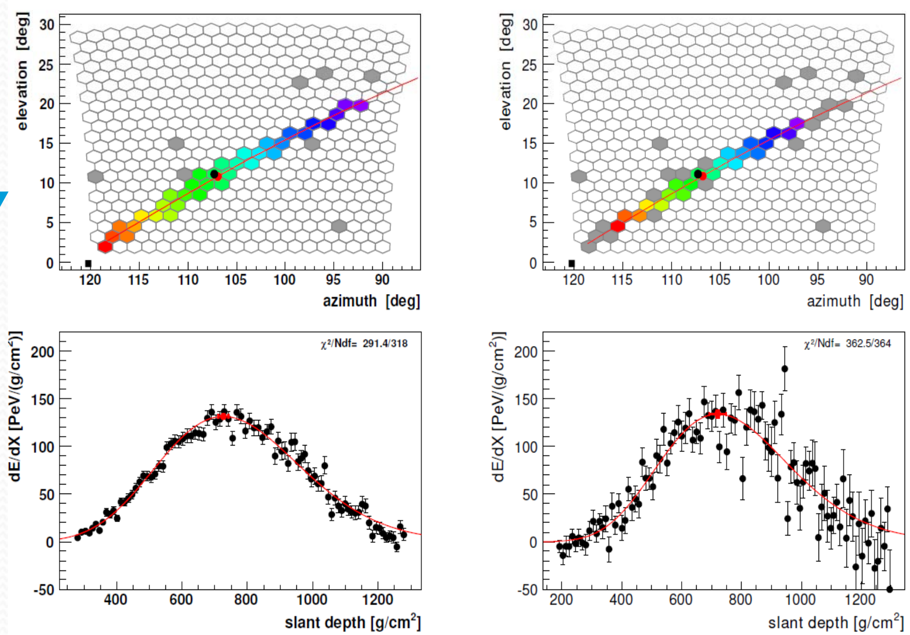
A significant increase of the duty cycle is possible by the extension of the FD operation to times at which a large fraction of the moon in the sky is illuminated. During such operations the PMT gain must be reduced (lower HV) to avoid an excessively high anode current.

10x reduced PMT gain by reducing supplied HV

satisfy linearity, stability and lifetime

Existing measured air showers have been analyzed with the standard reconstruction chain after adding random noise to the ADC traces.

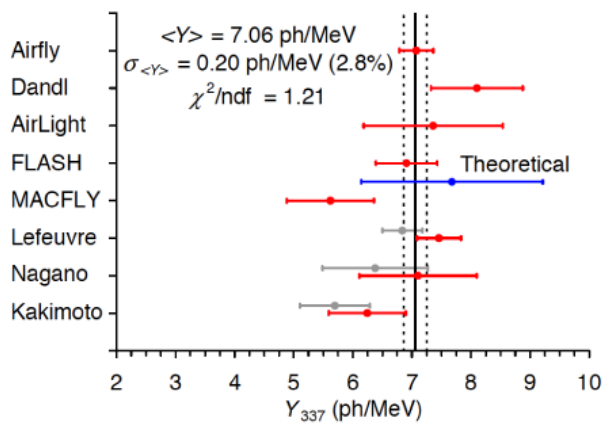
keep very high selection efficiency and reconstruction.

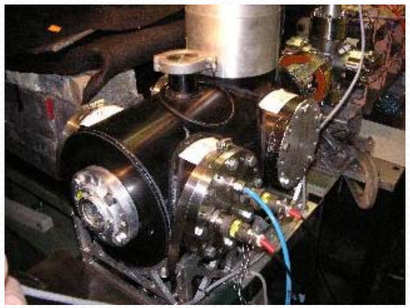


The FD Energy Scale

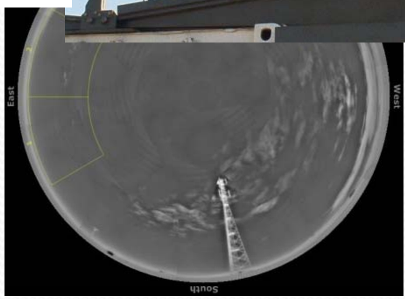
E_{dep} → $N_\gamma(\lambda)$ → **Photons in FD FOV** → **Photons at diaphragm** → **ADC counts**

Fluorescence yield

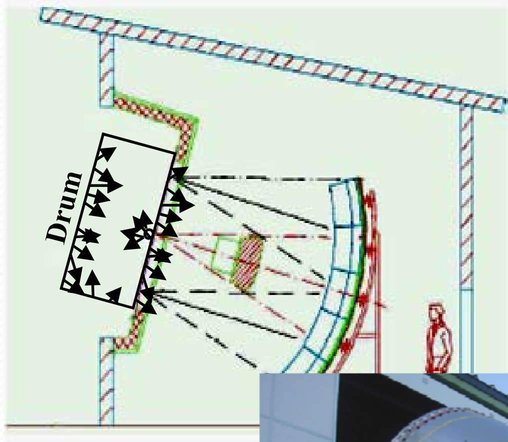


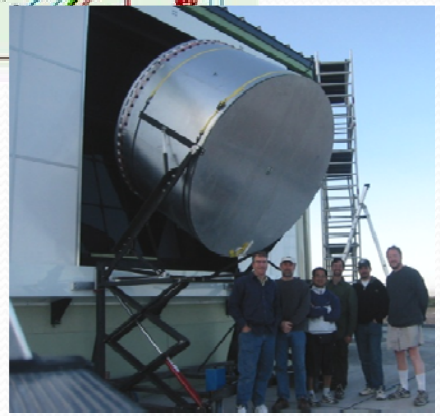


Atmosphere monitoring



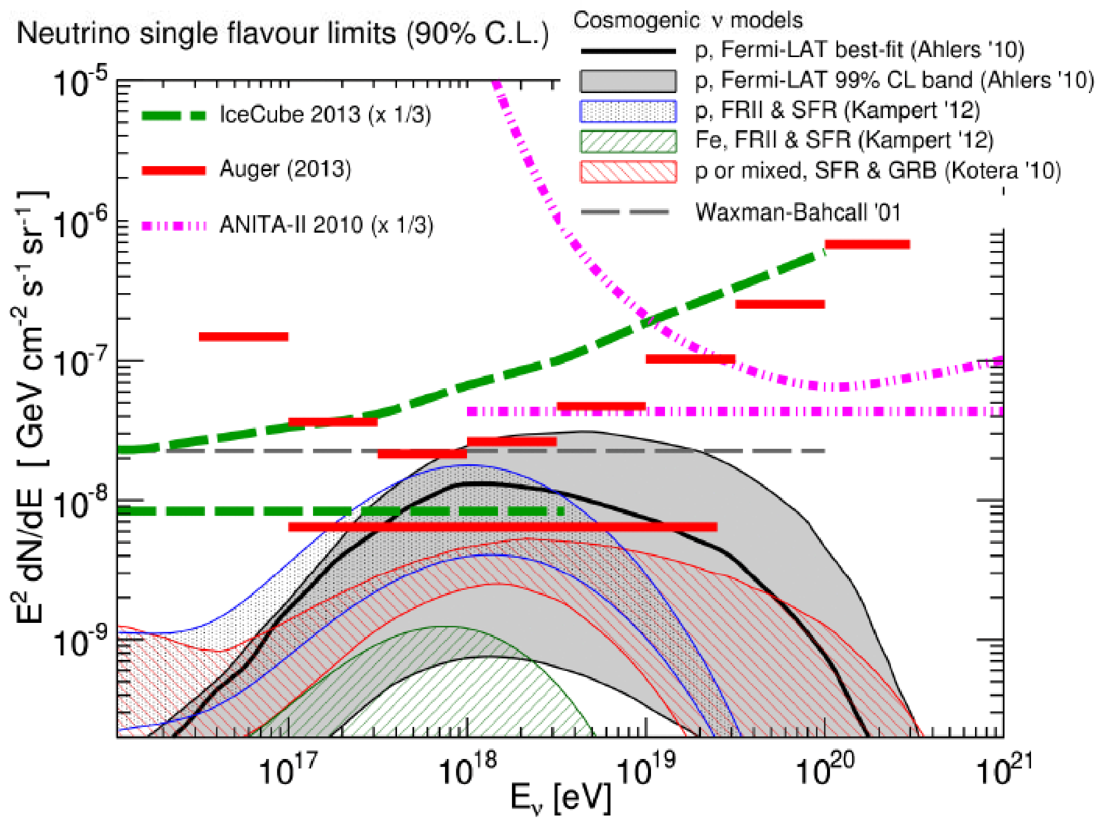
Detector calibration





Systematic uncertainly 14 %

Neutrino Detection



Inclined downward going events (60° to 90°) or Earth-skimming events (90° to 95°) ν_τ

No neutrino candidate found

Challeinging the Waxman-Bahcall limit

SD Electronics

Auger electronics based on a 15 years old design

1. Increase of 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 1” PMT (SD PMTs are 9”) small PMT
2. Faster data processing and more sophisticated local triggers
   a) more powerful processor and FPGA
3. Improved calibration and monitoring capabilities
4. New components:
   1. Connection to the SSD and any additional (R&D) detectors
   2. Prolong lifetime and reduce failure rate

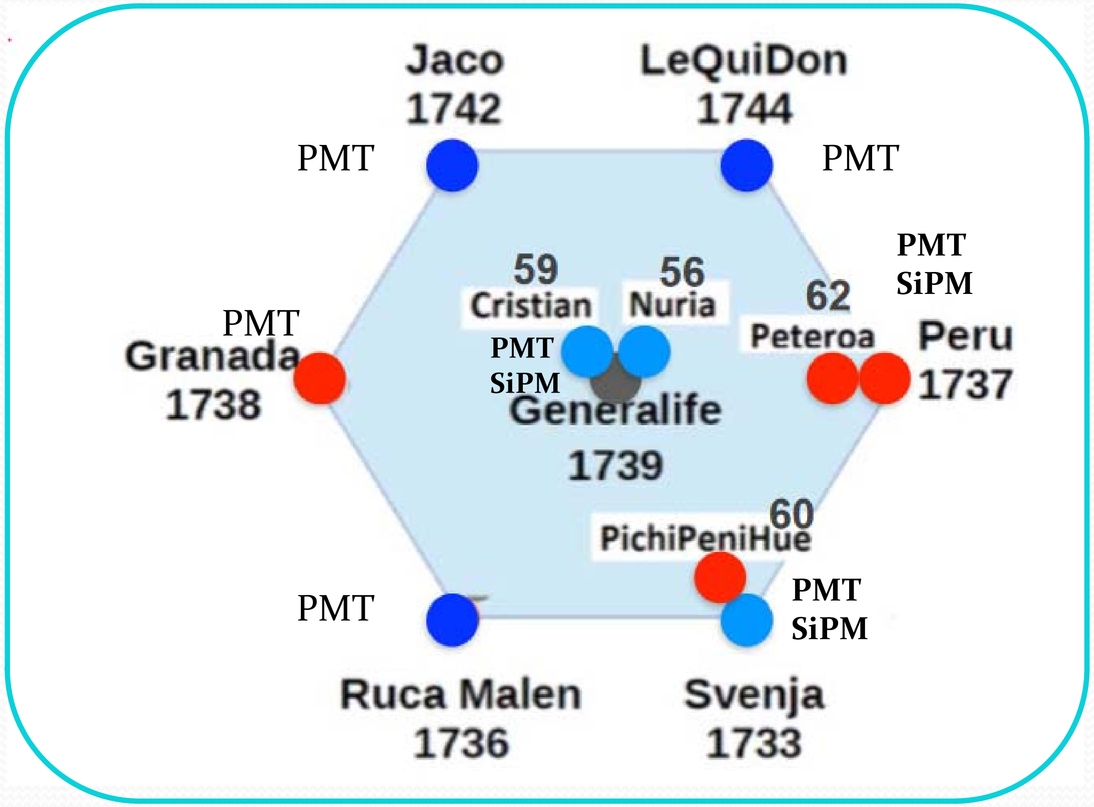
Can be swapped in place with old design
(same power communications, hardware interfaces…)

The Upgrade Unified Board (prototype)

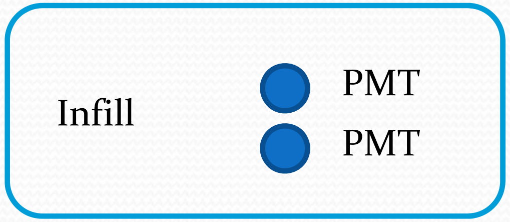
SSD:The Engineering Array

12 SSD EA Module ready!
On their way to PAO.

Located in standard array

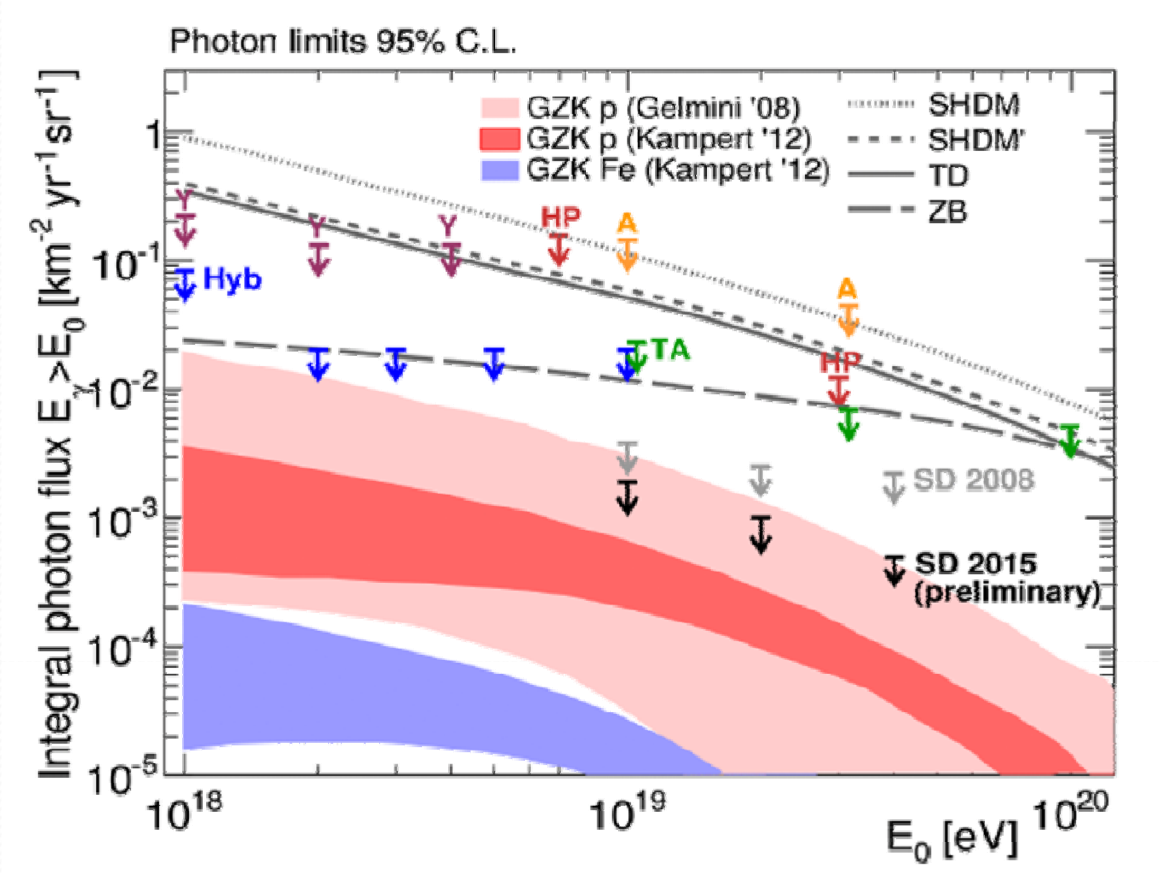


Located in infill array



Twin stations will allow to verify particle number resolution

Photon Limit



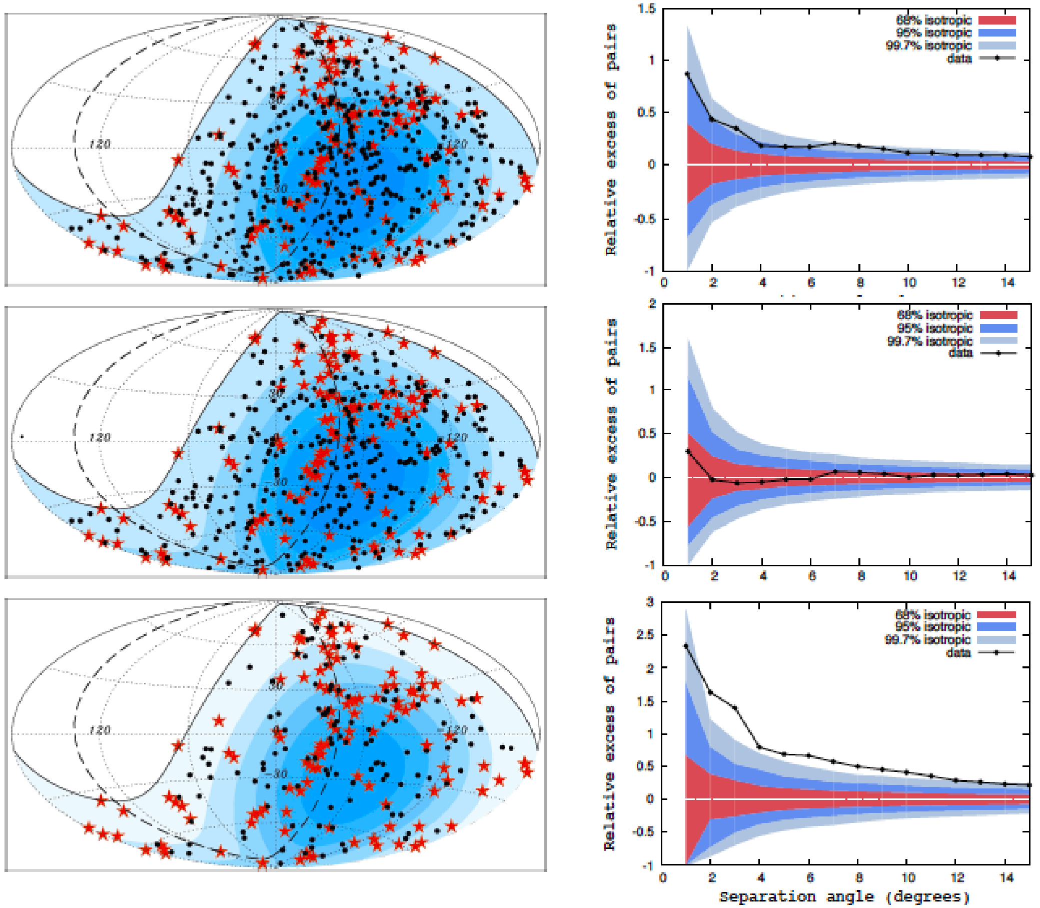
• larger depth of maximum, steeper lateral distribution at ground compared to nucleonic showers
• events with inclination 30 to 60 selected
• 4 events survive the photon cuts, which is compatible with background

Science Impact of upgrade: composition-enhanced anisotropy

Modified Auger data set
(E > 4×10^{19} eV, 454 events)

X_{max} assignment according to maximum rigidity scenario

10% protons added, half of which from within 3° of AGNs



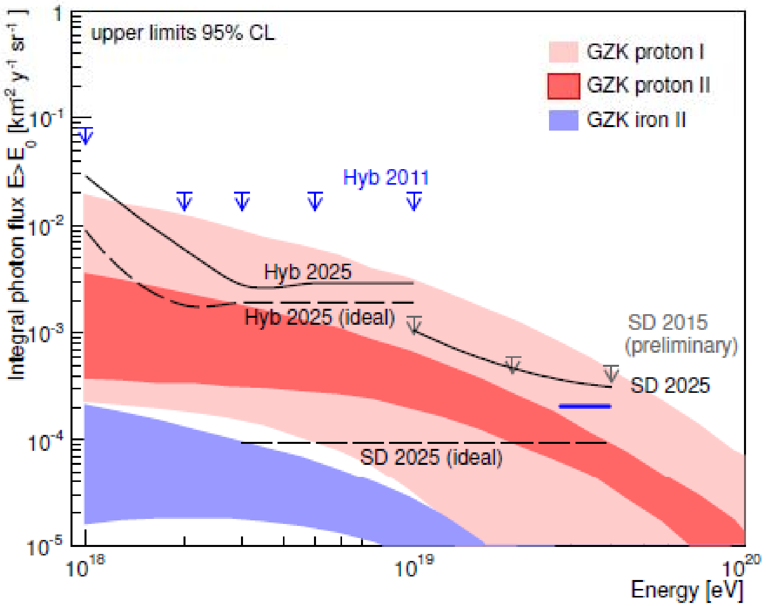
all 454 events

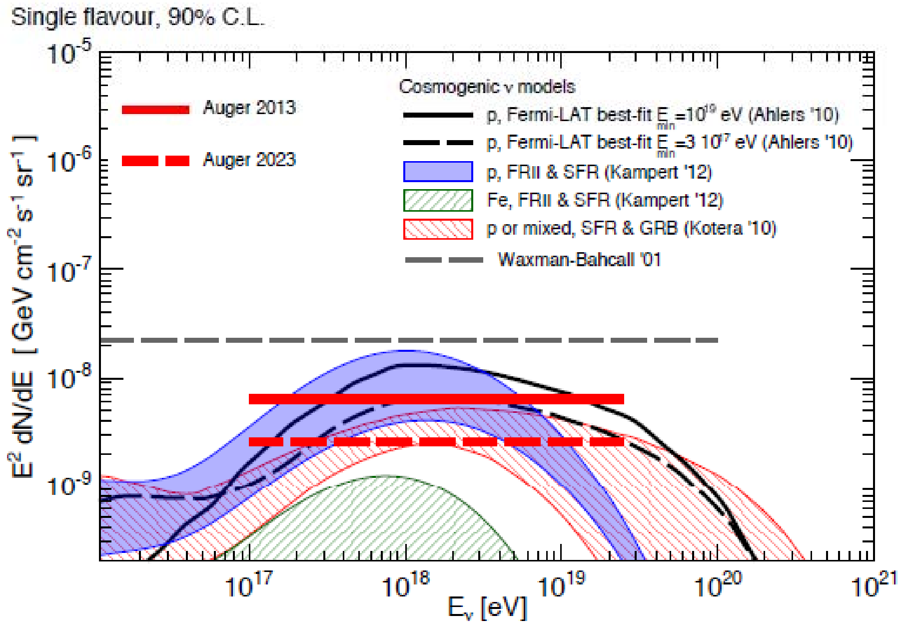
proton depleted data set (326)

proton enhanced data set (128)

Science impact of upgrade: photon and neutrino flux limits

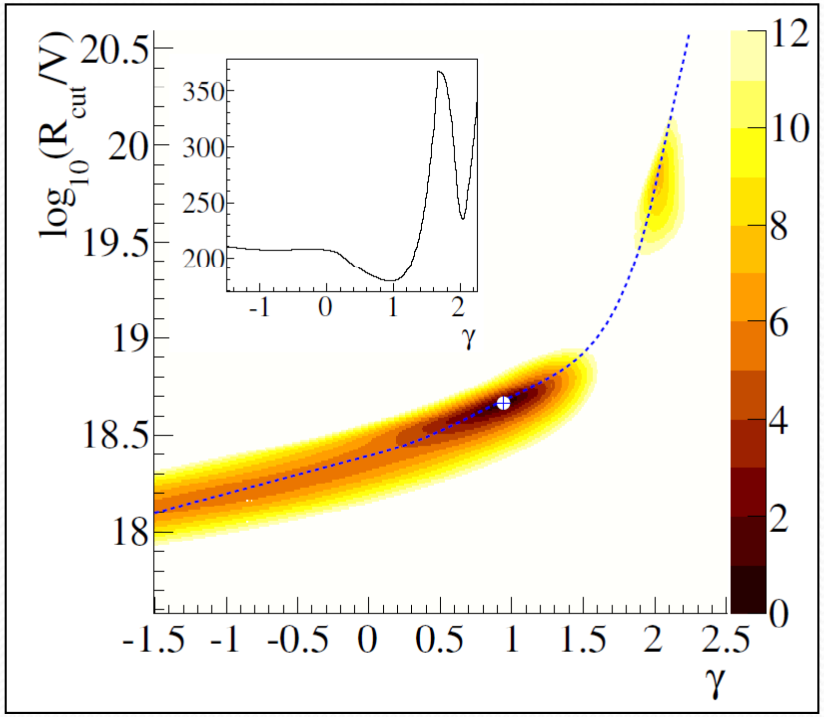
Expected sensitivity on the flux of photons and neutrinos.
In addition to the conservative estimates based on the increase of statistics, also the projected photon sensitivity for the ideal case of being able to reject any hadronic background due to the upgraded surface detector array is shown.





Combining X_{max} and spectrum

A. di Matteo et al., Proc. of 34th ICRC, The Hague (2015)



model SPG	best fit	2nd local min
J_0 [eV^{-1} Mpc^{-3} yr^{-1}]	7.17×10^{18}	4.53×10^{19}
γ	$0.94^{+0.09}_{-0.10}$	2.03
$\log_{10}(R_{cut}/V)$	18.67 ± 0.03	19.84
p_H	$0.0^{+29.9}\%$	0.0%
p_{He}	$62.0^{+3.5}_{-22.2}\%$	0.0%
p_N	$37.2^{+4.2}_{-12.6}\%$	94.2%
p_{Fe}	$0.8^{+0.2}_{-0.3}\%$	5.8%
D/n	178.5/119	235.0/119
$D(J)$, $D(X_{max})$	18.8, 159.8	14.5, 220.5
p	2.6%	5×10^{-4}

$$\frac{dN_{inj,i}}{dE} = \begin{cases} J_0 p_i (E/E_0)^{-\gamma}, & E/Z_i < R_{cut} \\ J_0 p_i (E/E_0)^{-\gamma} \exp(1 - E/Z_i R_{cut}), & E/Z_i > R_{cut} \end{cases}$$