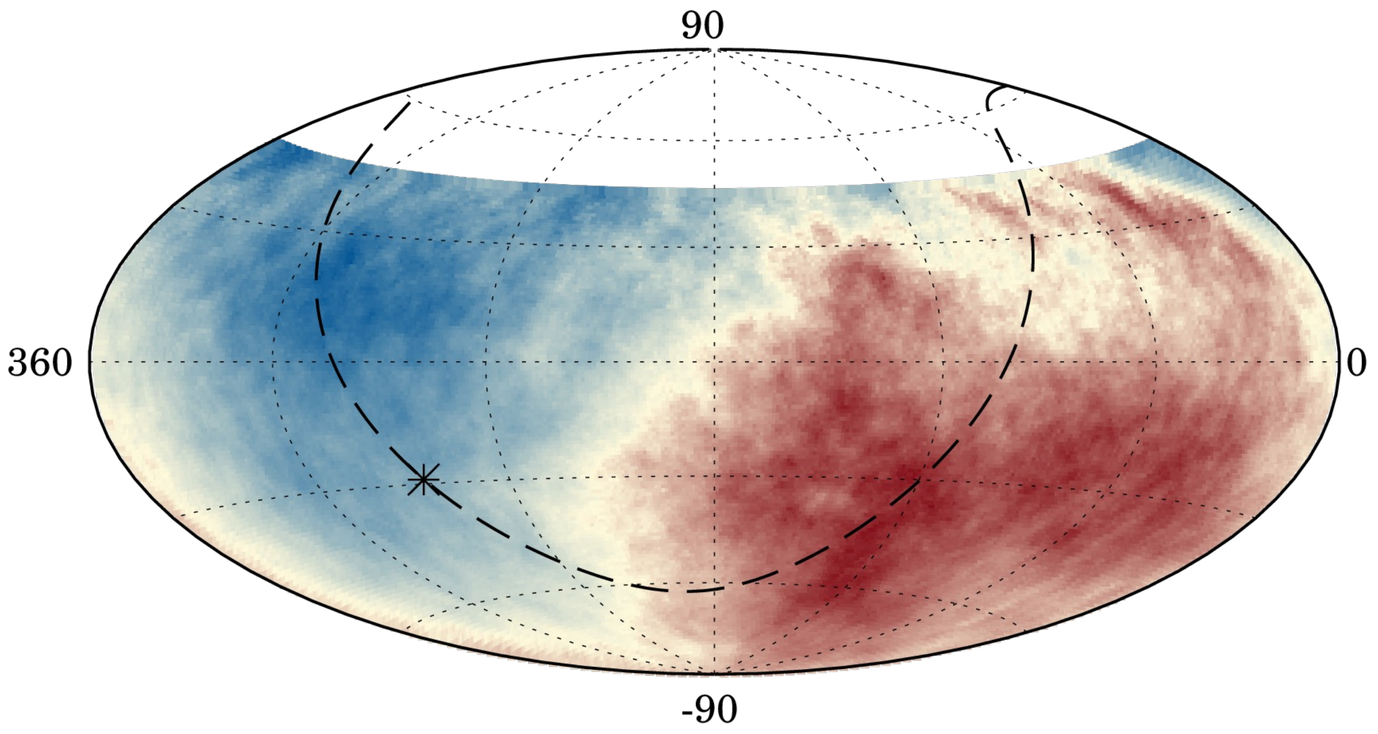
Recent results from the Pierre Auger Observatory



Particle astrophysics @ 10s M TeV

Radomír Šmída

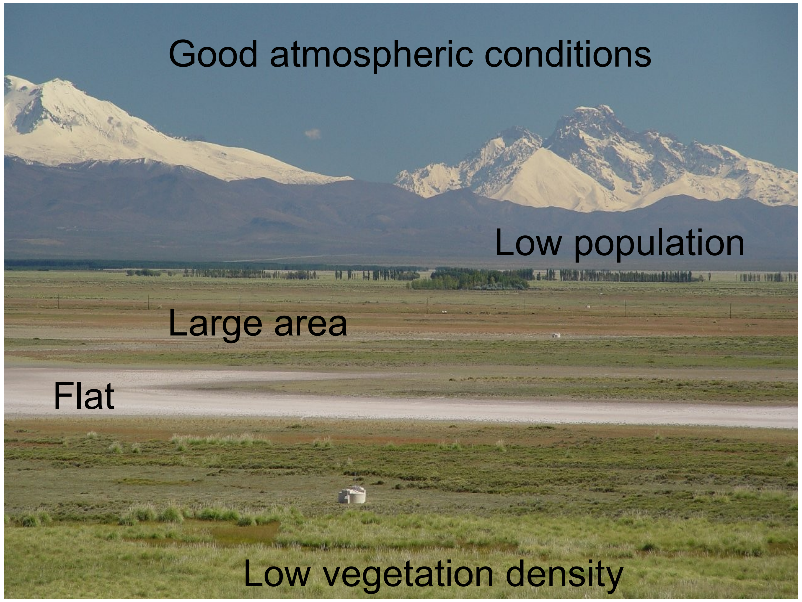
Karlsruher Institut für Technologie

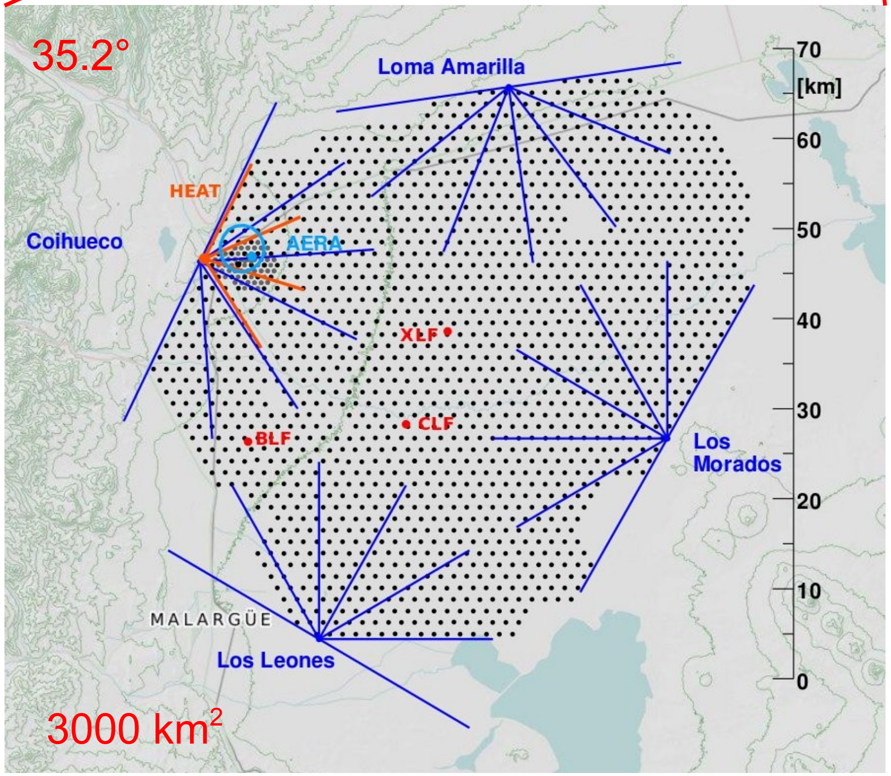
The Pierre Auger Observatory

The primary goal: study the most energetic cosmic rays (CRs)

Their flux is extraordinarily low: ca. 1 CR / km^2 yr @ 10^{19} eV

Pampa Amarilla
in Argentina

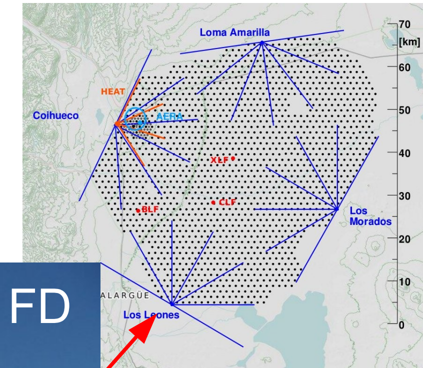




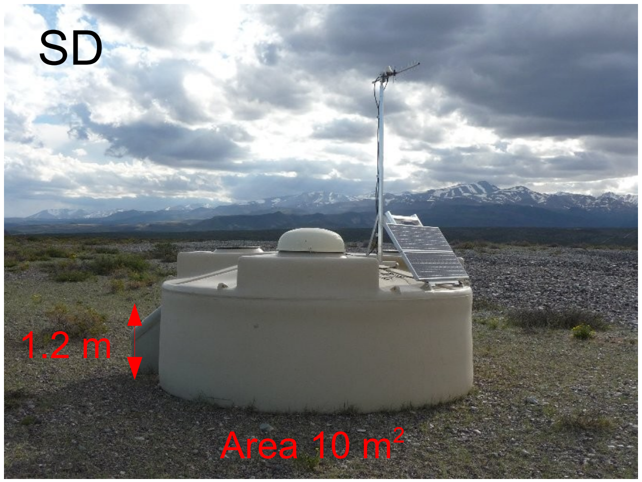
450 scientists, engineers, technicians & **students** from 16 countries

Construction between
2004 and 2008

The Pierre Auger Observatory



Hybrid detector w/ two complementary measurement techniques



Surface detector (SD):

1660 water Cherenkov stations

1.5 km (0.75 km) distance

3 PMTs / station

100% duty cycle

Geometrical exposure

Fluorescence detector (FD):

27 telescopes @ 4 sites

440 PMTs / telescope

FOV: 180° x 30° (60°)

Longitudinal shower development

→ model-independent energy

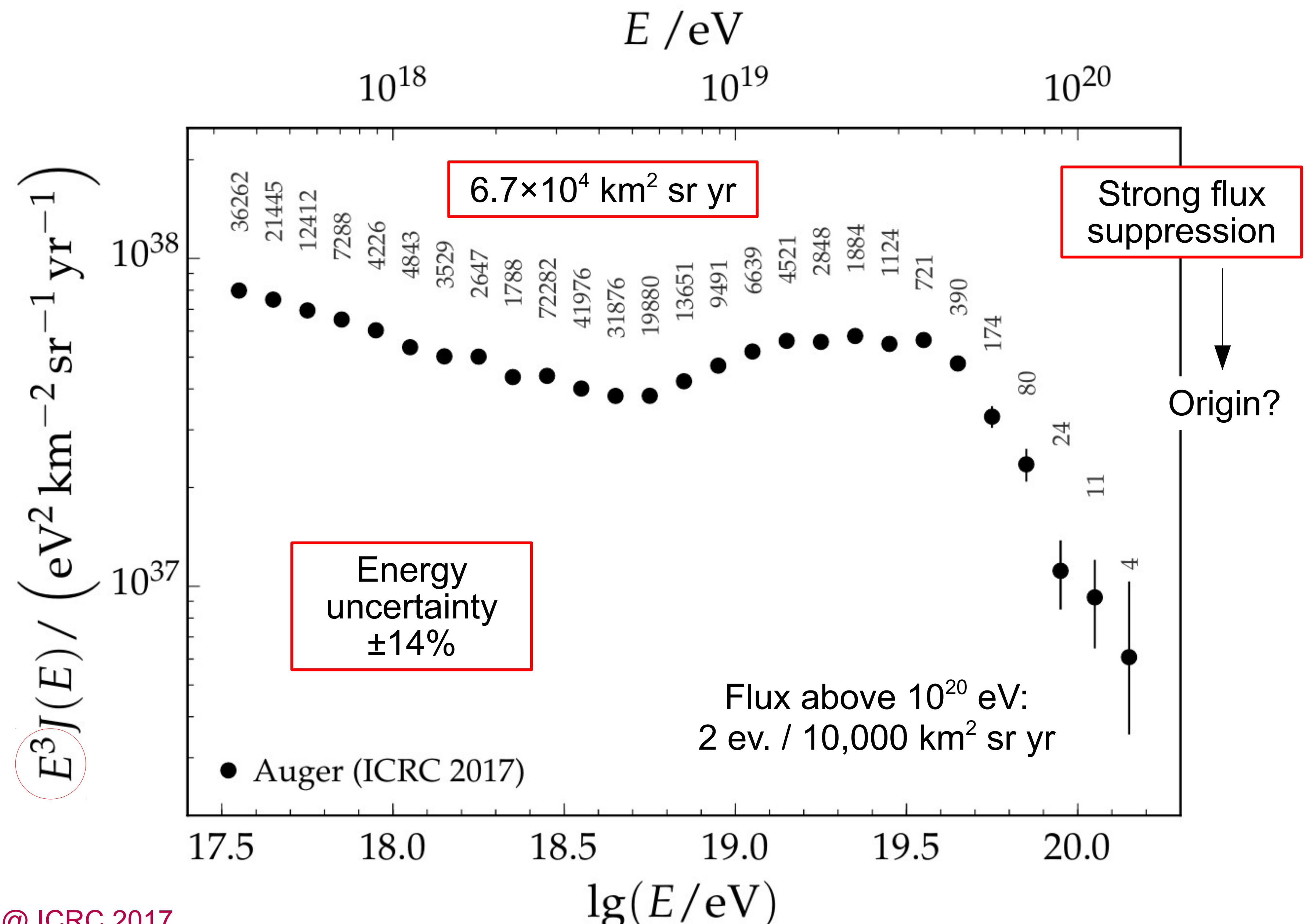
→ maximum of shower development X_{max}

Additional detectors and rich R&D program:
Underground muon detector (AMIGA)
Radio detector (AERA)
GHz antennas

Pierre Auger Coll., NIMA 798 (2015)

The energy spectrum

More details by Alan Coleman



F. Fenu @ ICRC 2017

The energy scale

Improvements of aerosol analysis technique M. Malacari @ ICRC 2017

Multiple scattering & shape of aerosol scat. phase function

Novel techniques:

1. **airborne isotropic light source data**

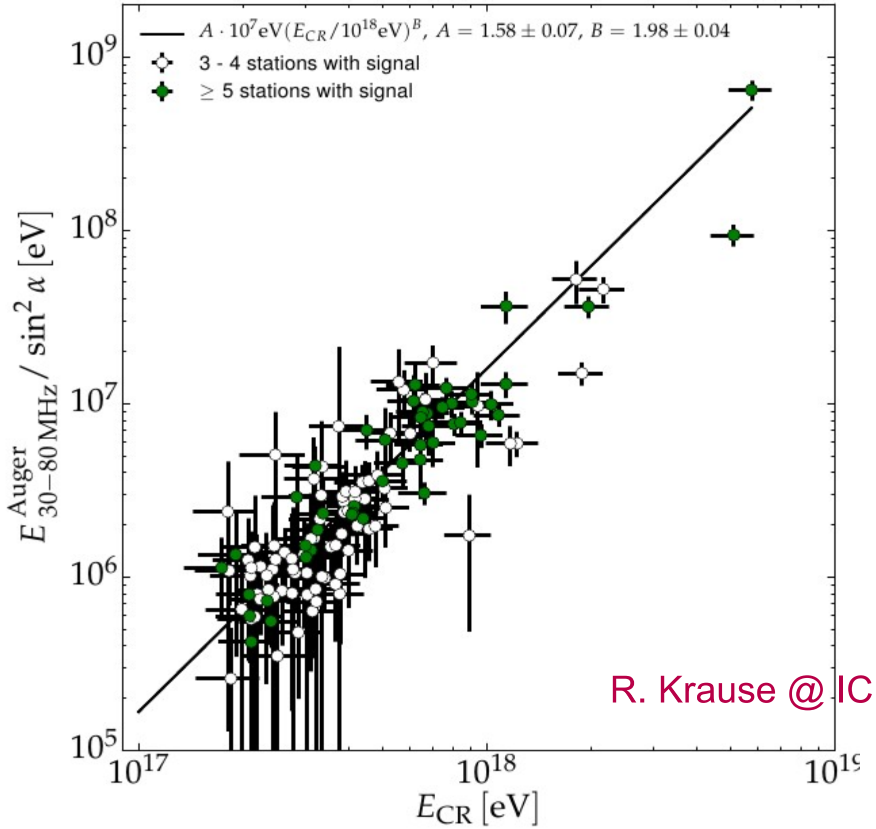
L. Tomankova, PhD (2016)

Autonomous drone

Can be calibrated in a laboratory

15 – 30 minutes flight

2. **radio signal measurement**



R. Krause @ ICRC 2017

Array of antennas (30 – 80 MHz)

CoREAS simulations

100% duty cycle

The composition

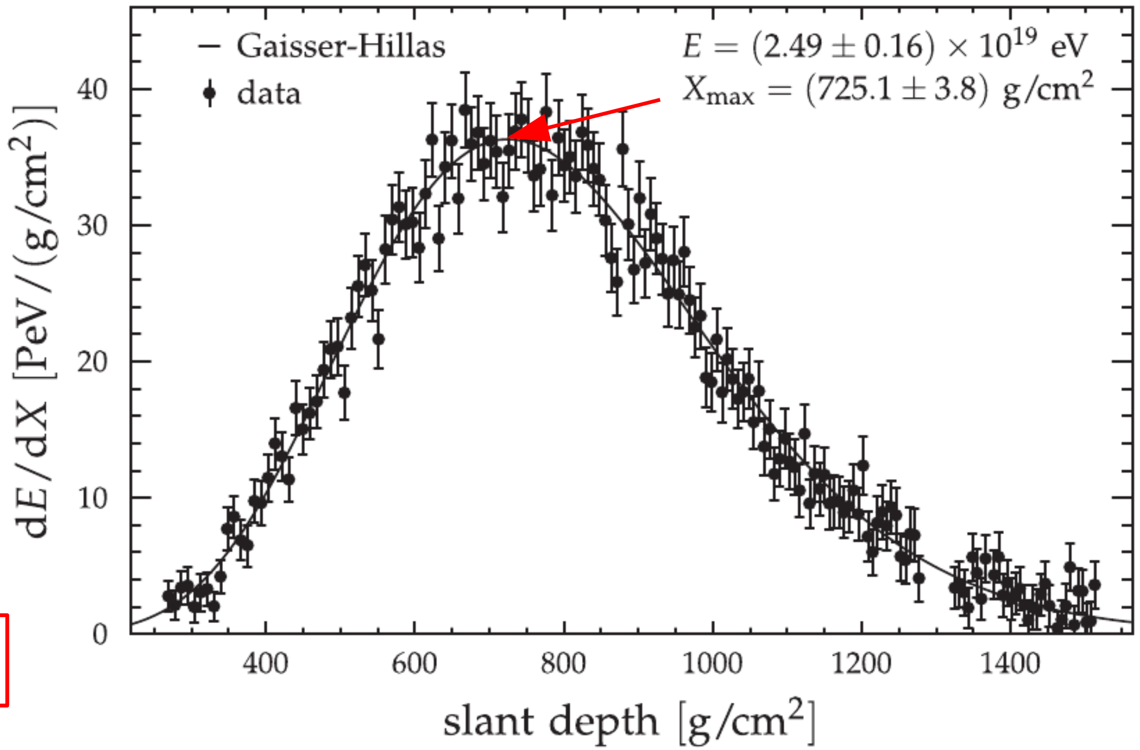
FD data → longitudinal profile

Quality and FOV selection cuts

only < 1% of triggered data survive

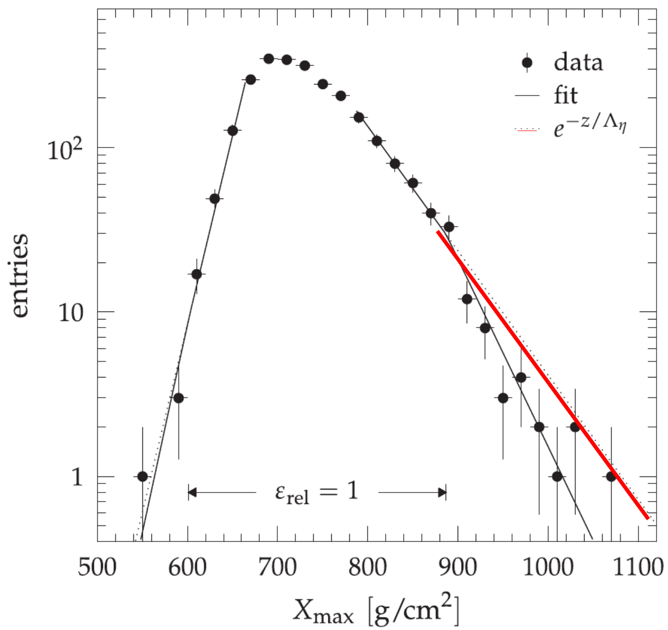
X_{max} systematics unc. ±10 g/cm^2

Difference between proton and Fe nucleon is on the level of 100 g/cm^2



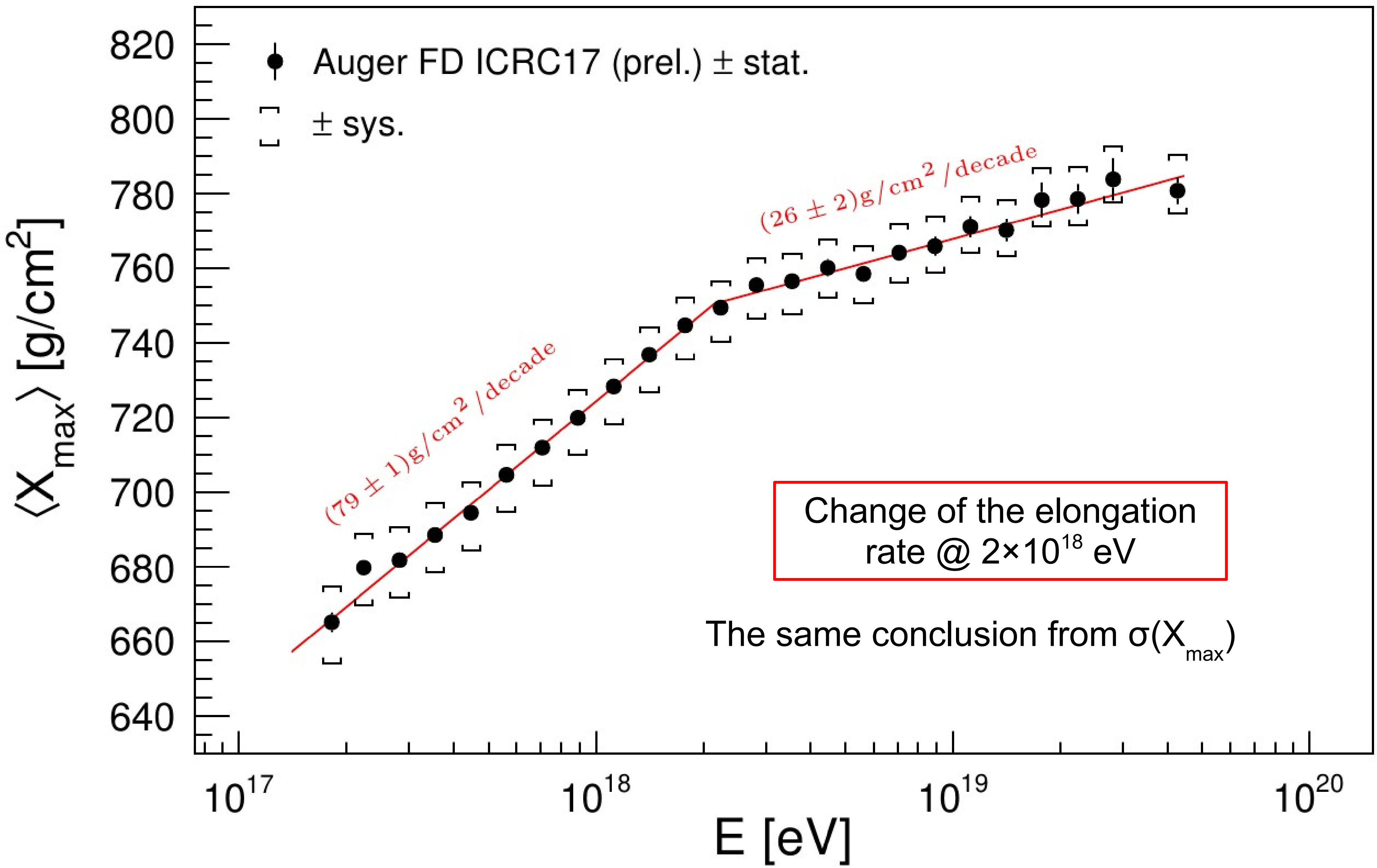
X_{max} acceptance is corrected for residual distortions

The shape of longitudinal energy-deposit profiles is universal, i.e. it does not depend on the primary particle or details of the first interaction.



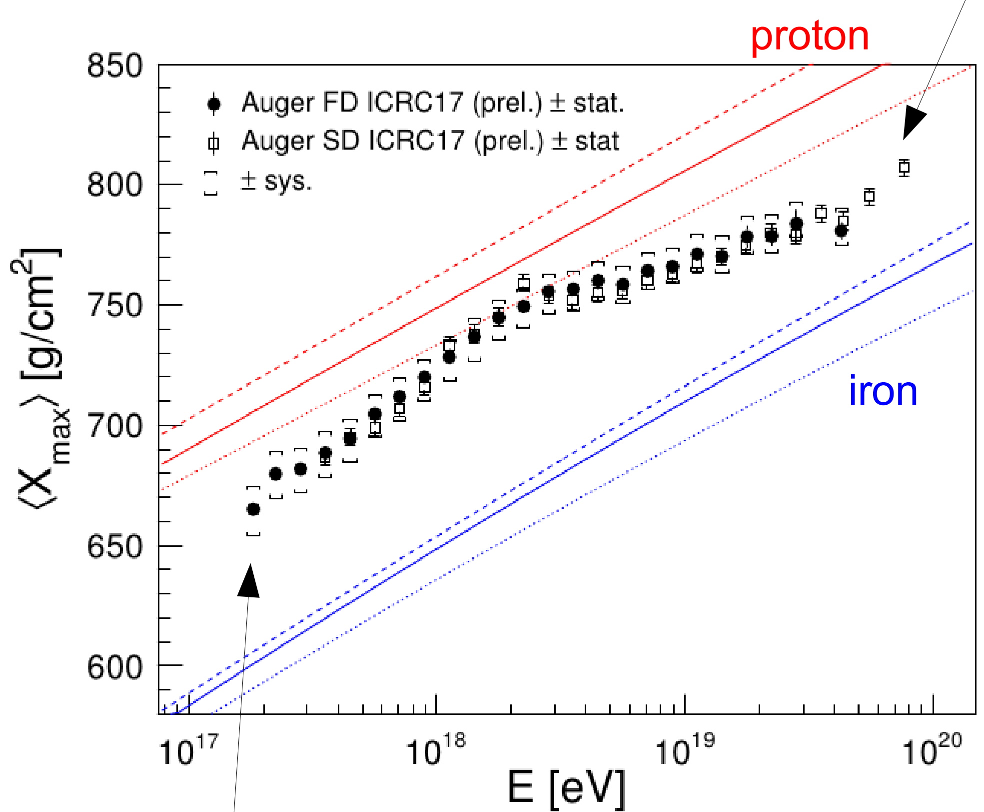
Pierre Auger Coll., PRD 90, 122005 (2014)

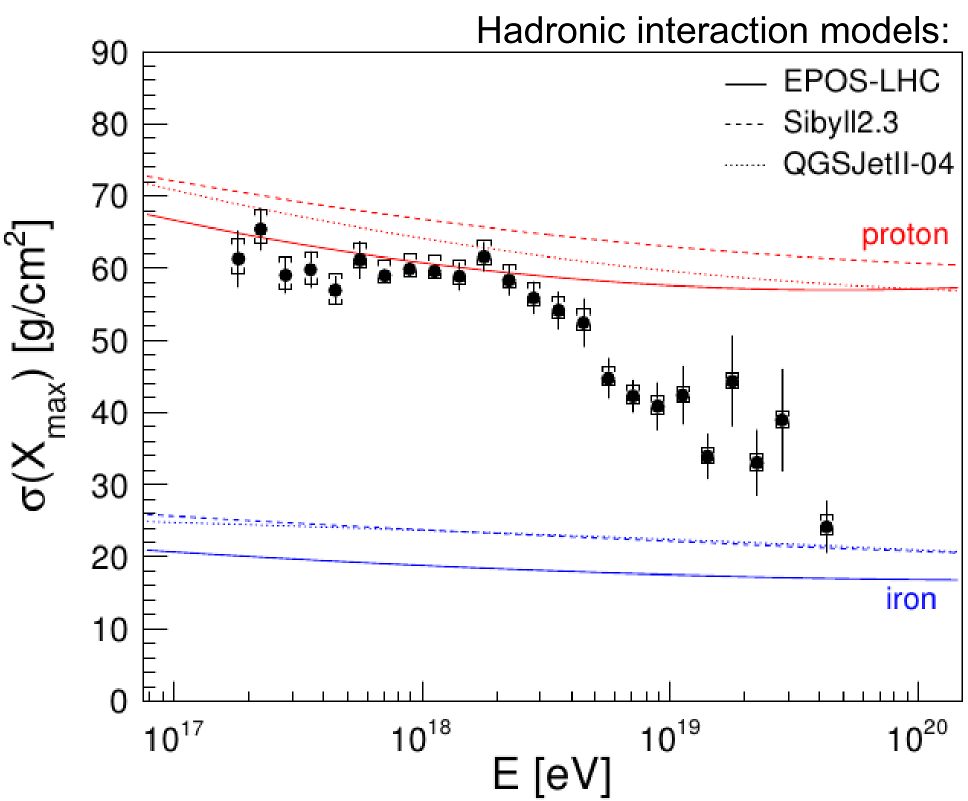
The composition



The composition

SD data (preliminary)





<E> = 2×10^{17} EeV => E_{cm} = 72 TeV (proton - nitrogen)

Hadronic interaction models extrapolated to only 5x higher energy than studied at the LHC.

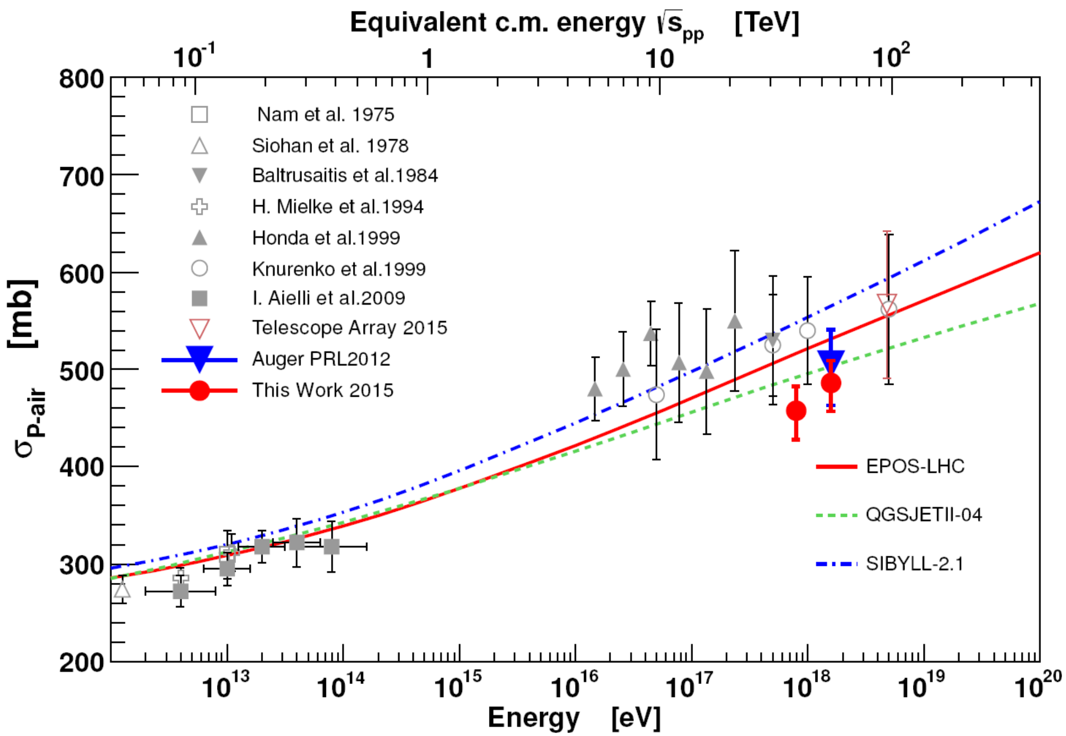
One of the highest energy FD events: E=8×10^{19} EeV, X_{max}=762 g/cm^2

J. Bellido @ ICRC 2017
P. Sanchez @ ICRC 2017

Particle physics

The proton-air cross section

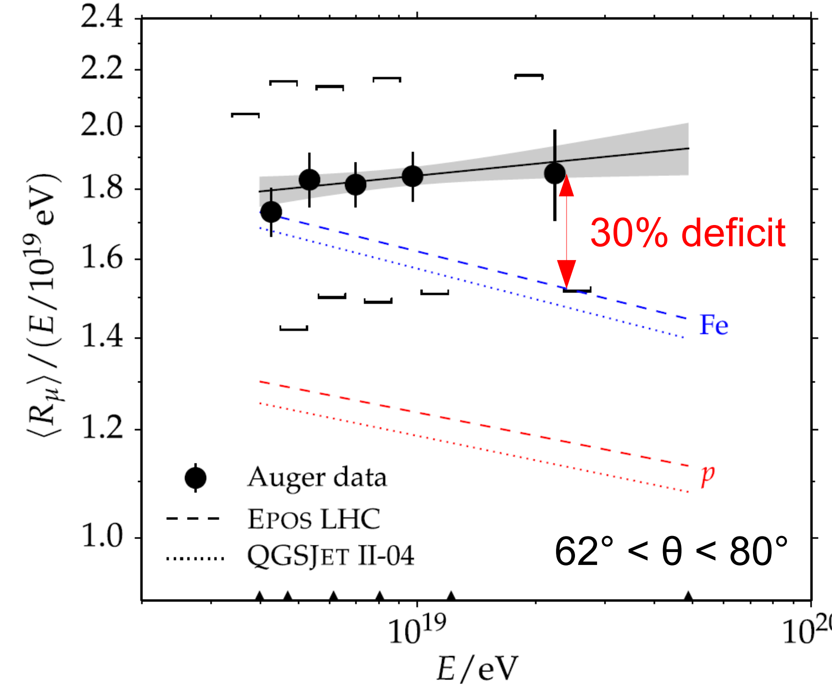
The 20% most deeply penetrating showers



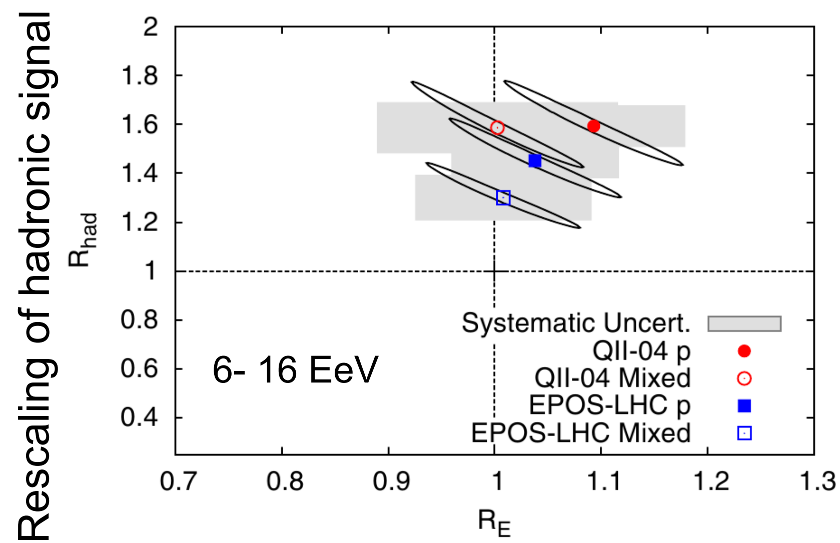
R. Ulrich @ ICRC 2015, arXiv:1509.03732

Valuable data for hadronic interaction models

Muon content in air showers

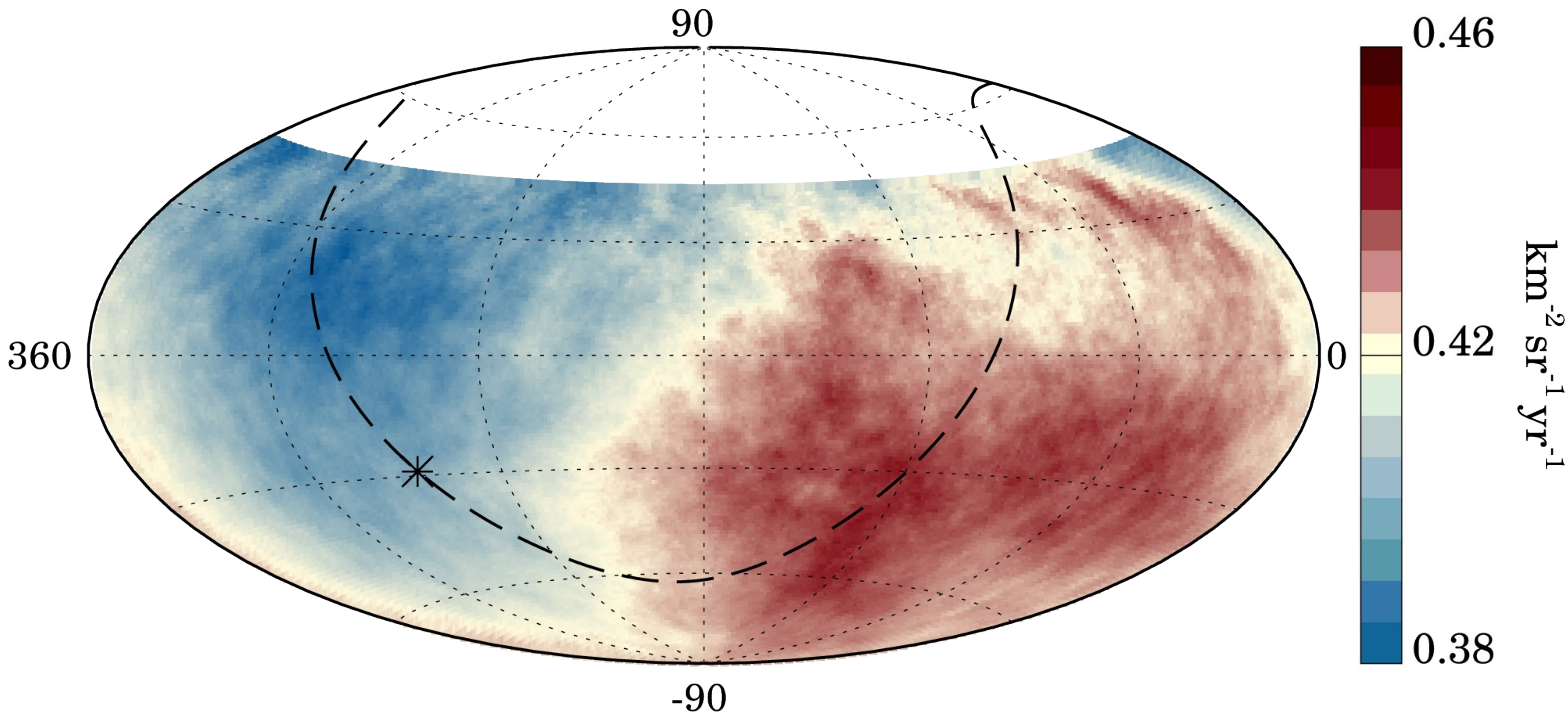


Pierre Auger Coll., PRD 91, 032003 (2015)



Pierre Auger Coll., PRL 117, 192001 (2016)

Large-scale anisotropy



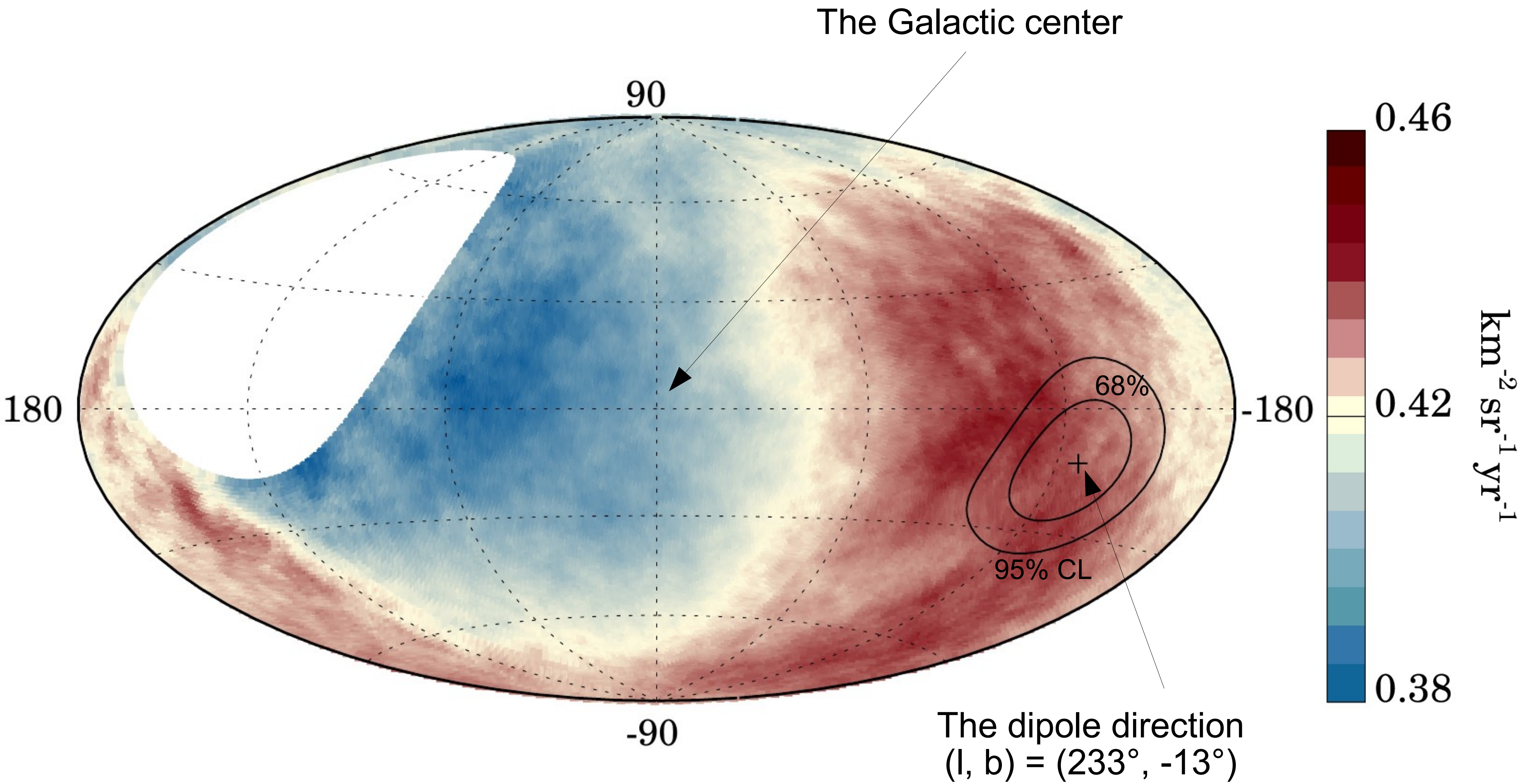
Equatorial coordinate system

Auger events: E ≥ 8×10^{18} eV, θ < 80°, 85% sky coverage

O. Taborda @ ICRC 2017

A dipole anisotropy with a significance of 5.4σ

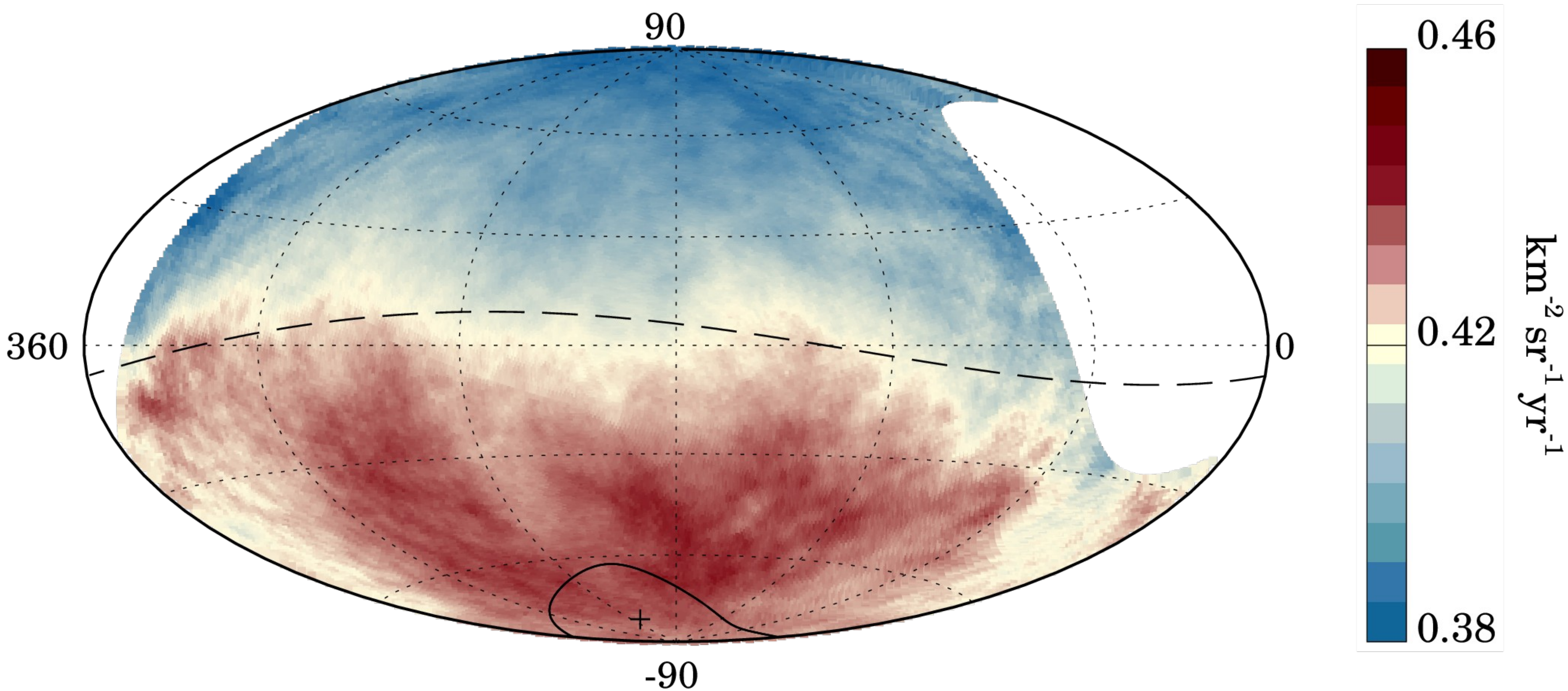
Large-scale anisotropy



Galactic coordinate system

A dipole of an amplitude $6.5^{+1.5}_{-0.9}$%

Large-scale anisotropy



Credit to S. Molerach

Supergalactic coordinate system

Intermediate-scale anisotropy

Active Galactic Nuclei

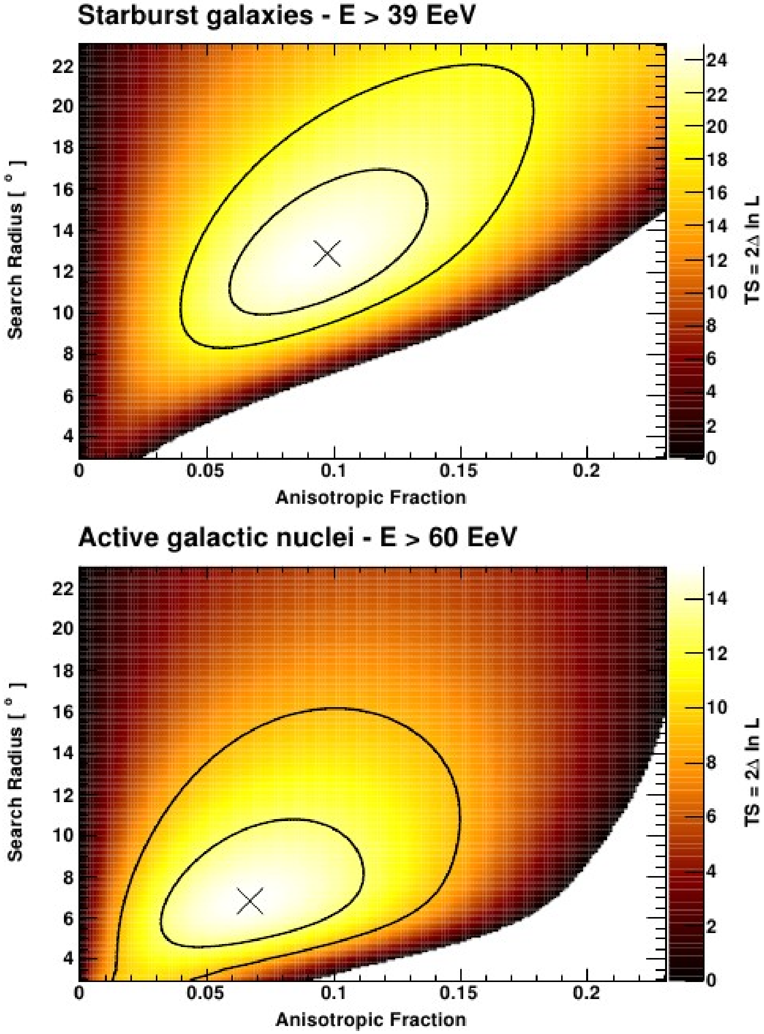
- 2FHL AGNs
- flux proxy: $\Phi(> 50\,\mathrm{GeV})$
- 17 objects within 250 Mpc

Star-forming of Starburst Galaxies

- Fermi-LAT search list (Ackermann+2016)
- $\Phi(> 1.54, \mathrm{GHz}) > 0.3$ Jy
- flux proxy: $\Phi(> 1.54, \mathrm{GHz})$
- 23 objects within 250 Mpc

Likelihood ratio analysis

- smearing angle ψ
- H_0: isotropy
- H_1: $(1 - f)\times$ isotropy + $f \times$ fluxMap(ψ)

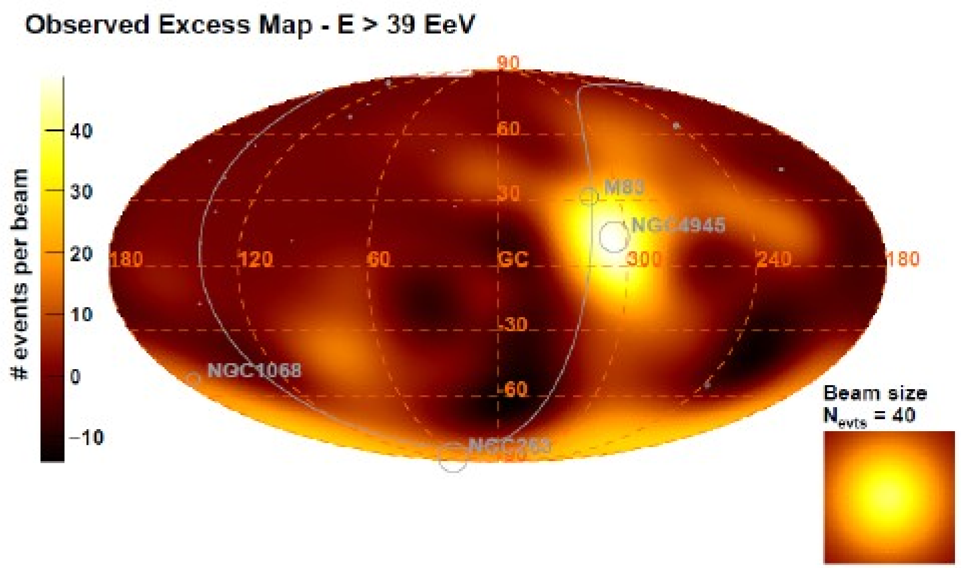


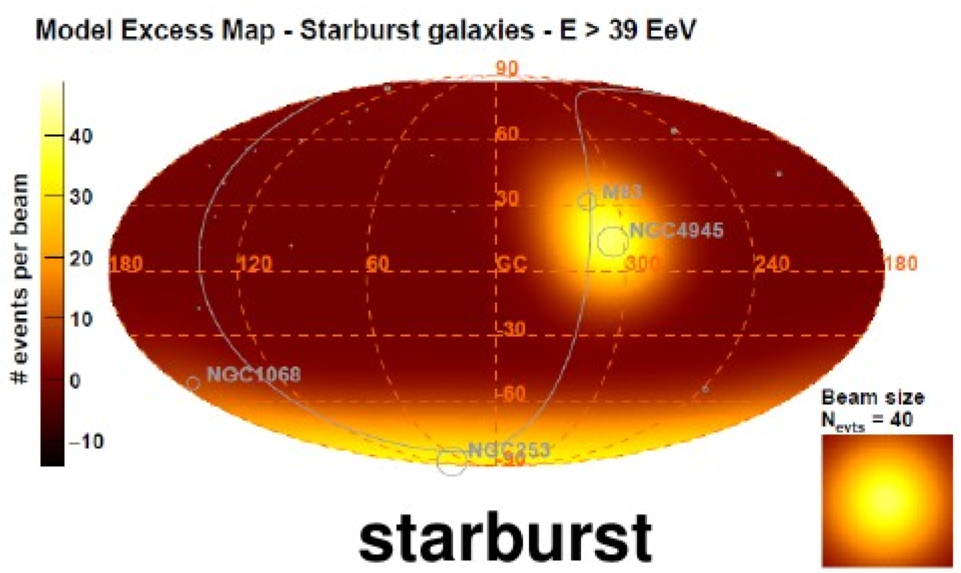
- $\mathrm{TS} = 2\log(H_1/H_0)$

U. Giaccari @ ICRC 2017
M. Unger @ ICRC 2017

Intermediate-scale anisotropy

preliminary





starburst

$$f = 10\%,\ \psi = 13^\circ$$

Parameters:
- the smearing angle,
- the anisotropy fraction,
- energy $(2 – 8)\times10^{19}$ eV.

A posteriori significance of 3.9σ

Penalized for energy scan only. (Does not include a selection of catalogues, previous searches and hidden trials.)

Interesting hint of an anisotropy, which will be studied with new data.

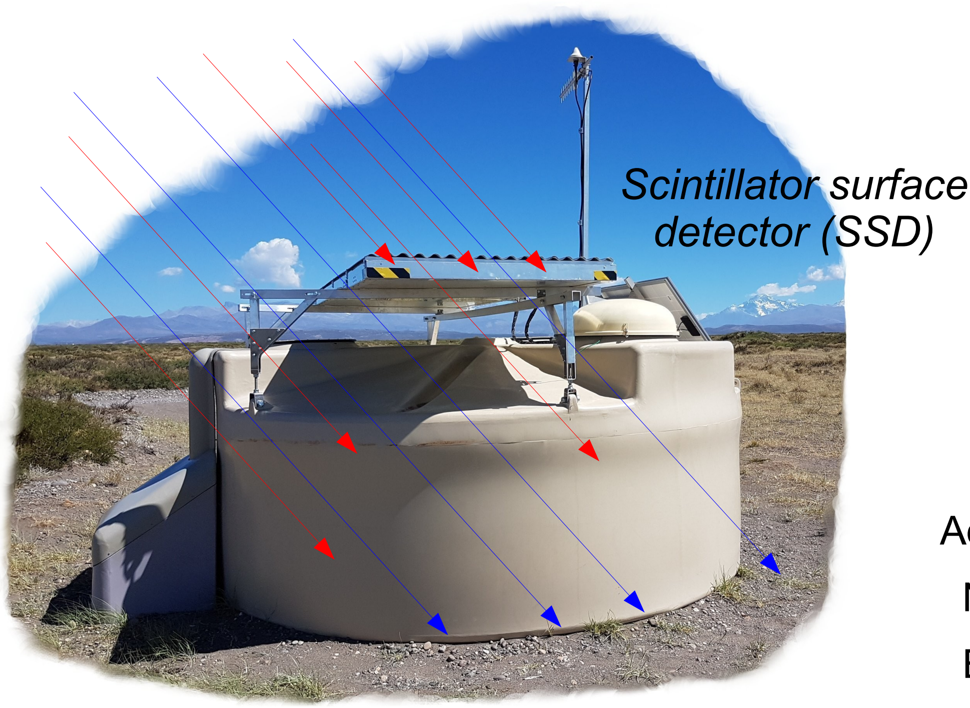
AugerPrime – upgrade of the Observatory

Preliminary Design Report,
arXiv:1509.03732

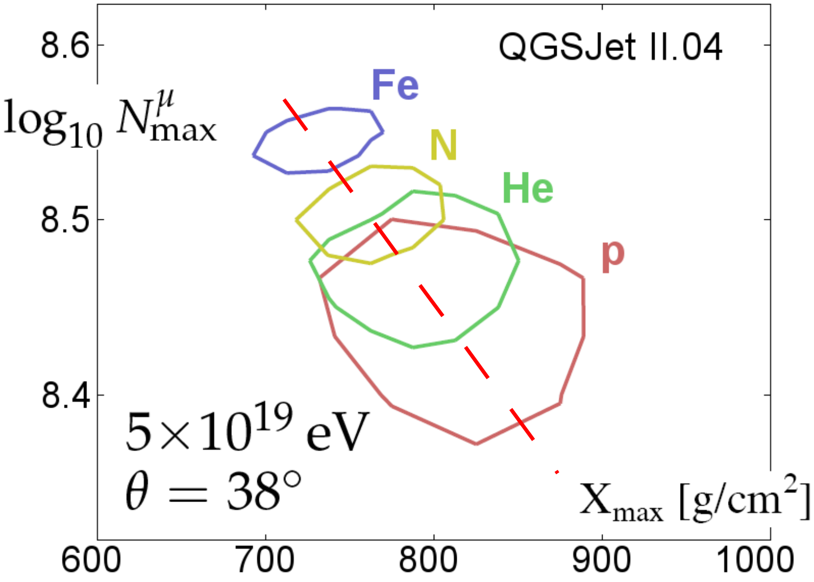
The composition at the highest energies → This is the key to understanding the origin and properties of the most energetic cosmic rays.

Idea: Use two detectors with different responses to the electromagnetic and muonic (air shower) component.

Both, N_μ and X_{max}, can be reconstructed from WCD and SSD.



Water Cherenkov detector (WCD)



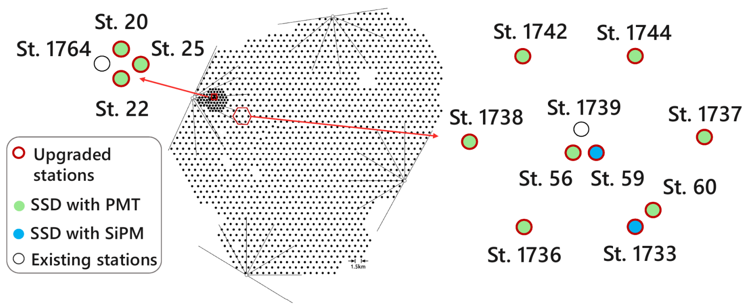
Additional upgrades:

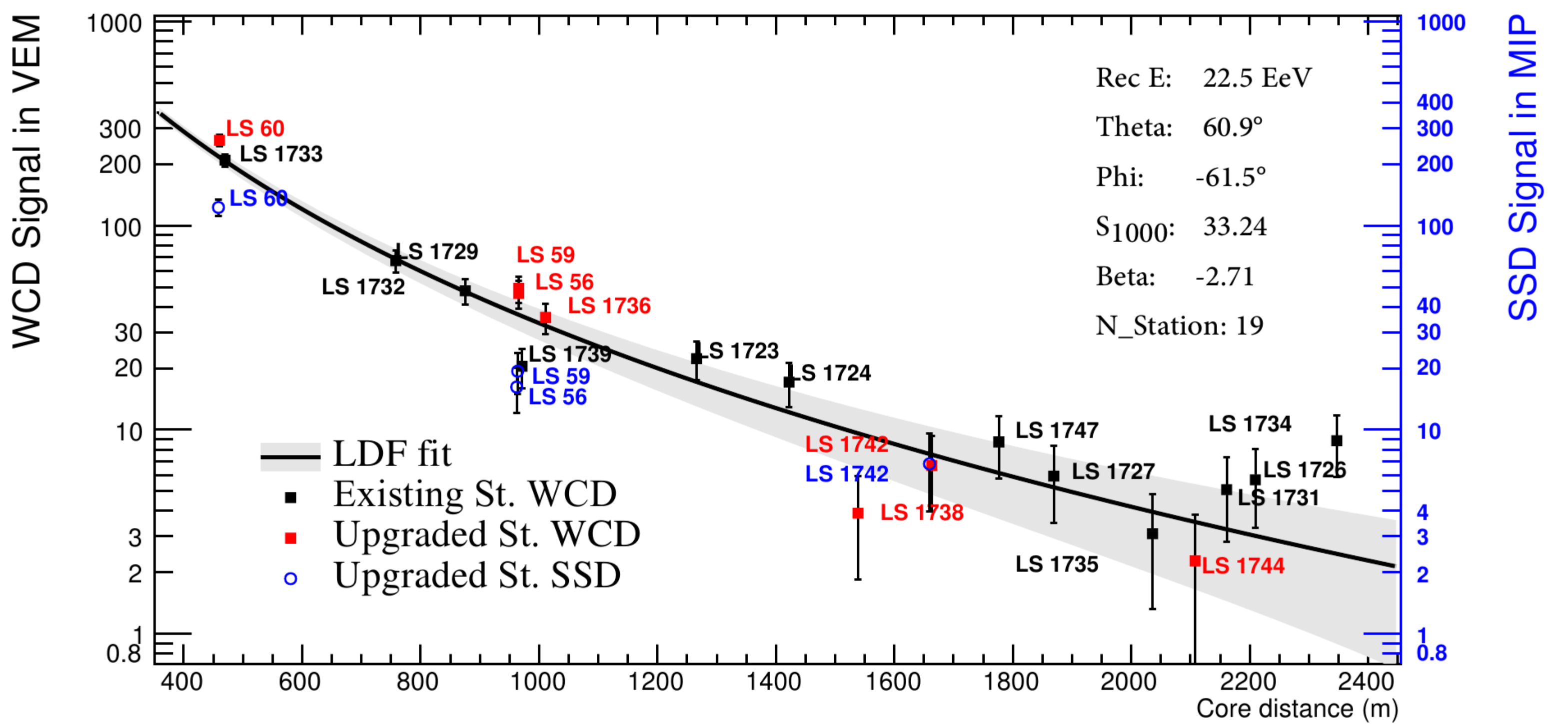
- New electronics & extended dynamic range
- Extended FD-observation by 50%
- Bigger AMIGA array

A. Castellina, D. Martello, D. Schmidt, R. Smida, T. Suomijarvi @ ICRC 2017

AugerPrime – first results

First detectors since mid Sep 2016





Z. Zong @ ICRC 2017

Conclusions

The experiment is performing very well and collects valuable data about air showers

Important results:

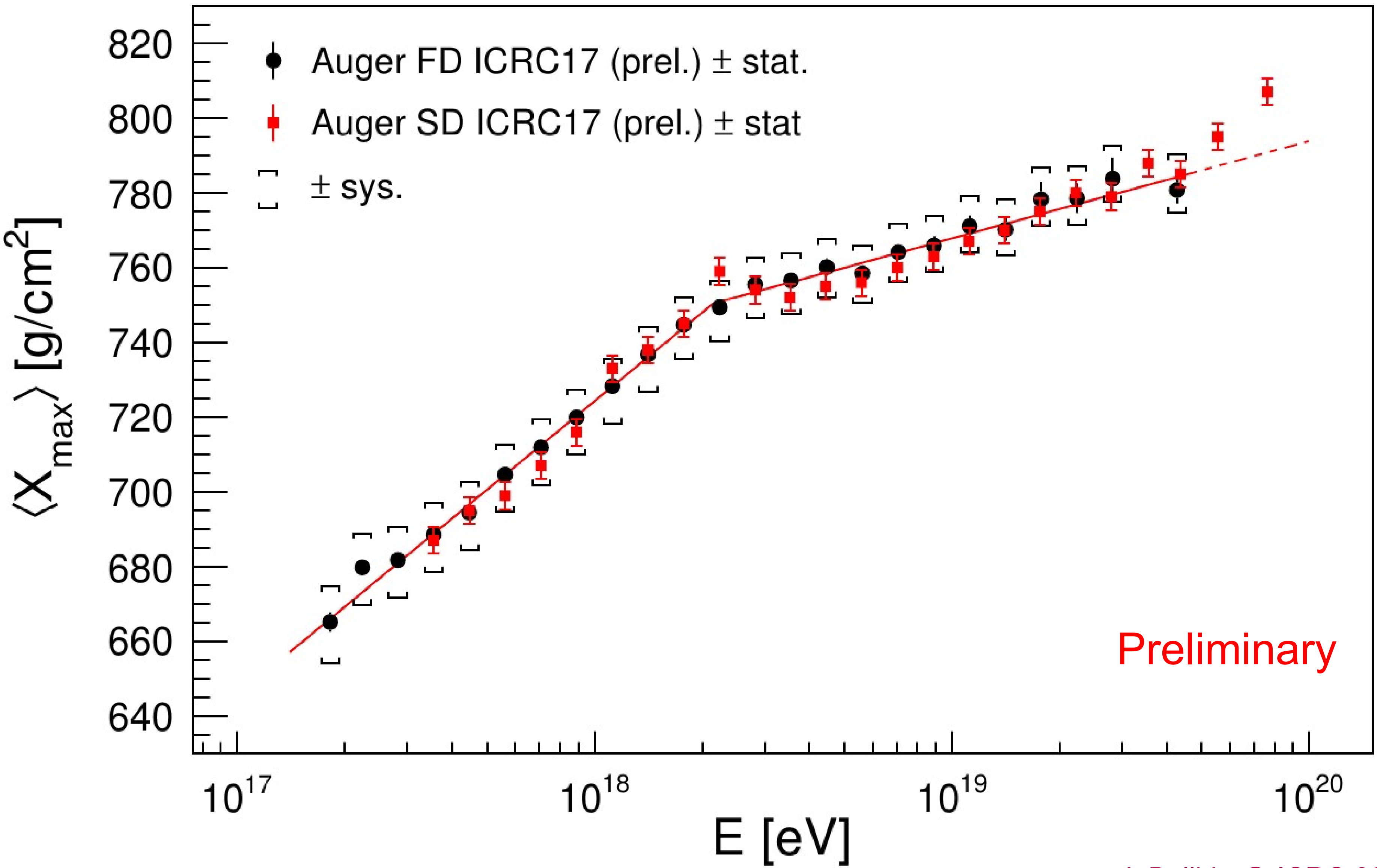
- The energy spectrum has strong suppression above 4×10^{19} eV of unknown origin
- The composition changes at 2×10^{18} eV, missing data at the highest energies
- Interesting particle physics with air showers: proton-air cross section & excess of muons
- Large-scale anisotropy: a dipole above 8×10^{18} eV
- A hint of an anisotropy on intermediate-scale above 3.9×10^{19} eV

Still many open questions → strong motivation for AugerPrime

AugerPrime is under way, first SSDs are taking data since Oct 2016

Back-up

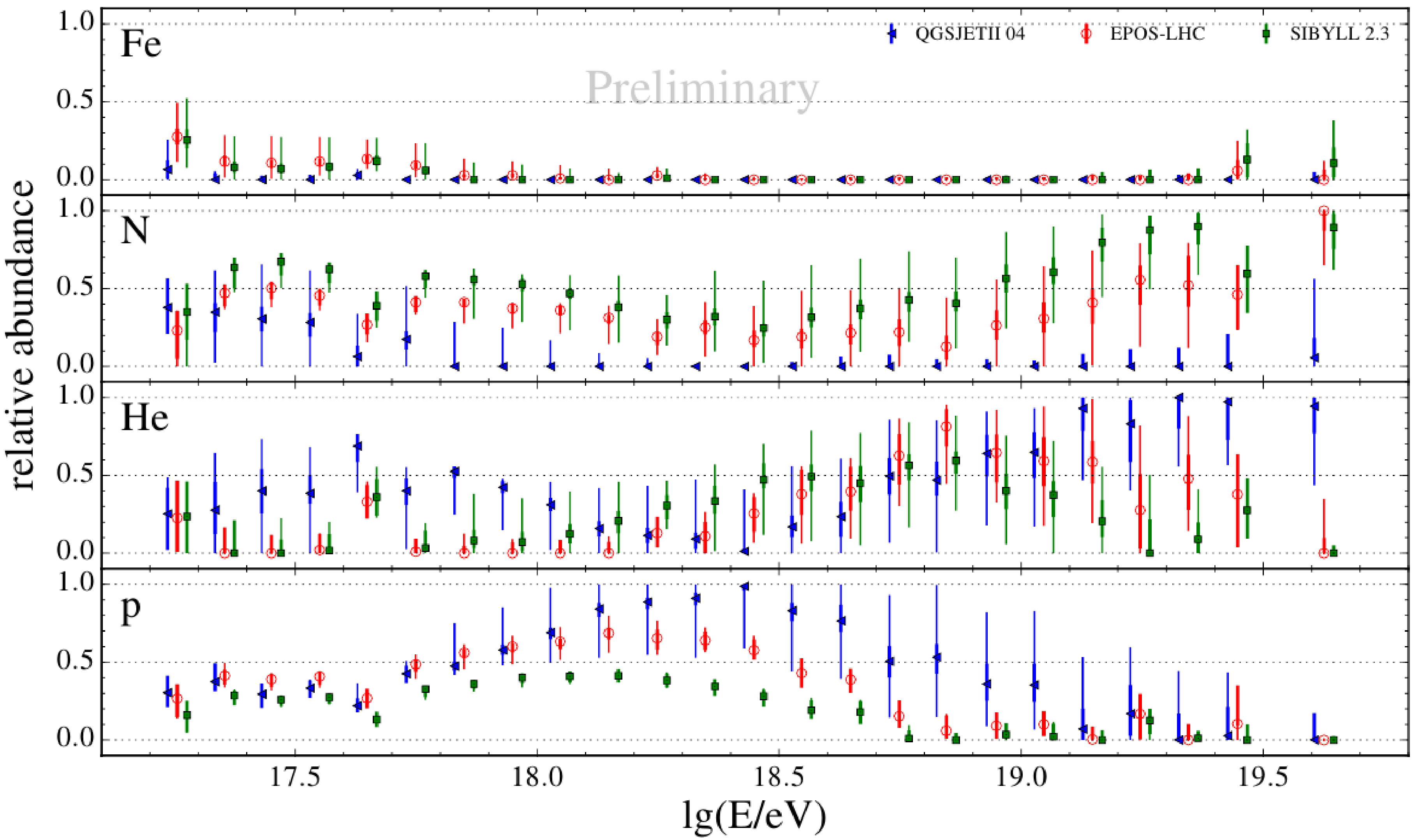
The composition



J. Bellido @ ICRC 2017
P. Sanchez @ ICRC 2017
M. Unger @ ICRC 2017

The composition fractions

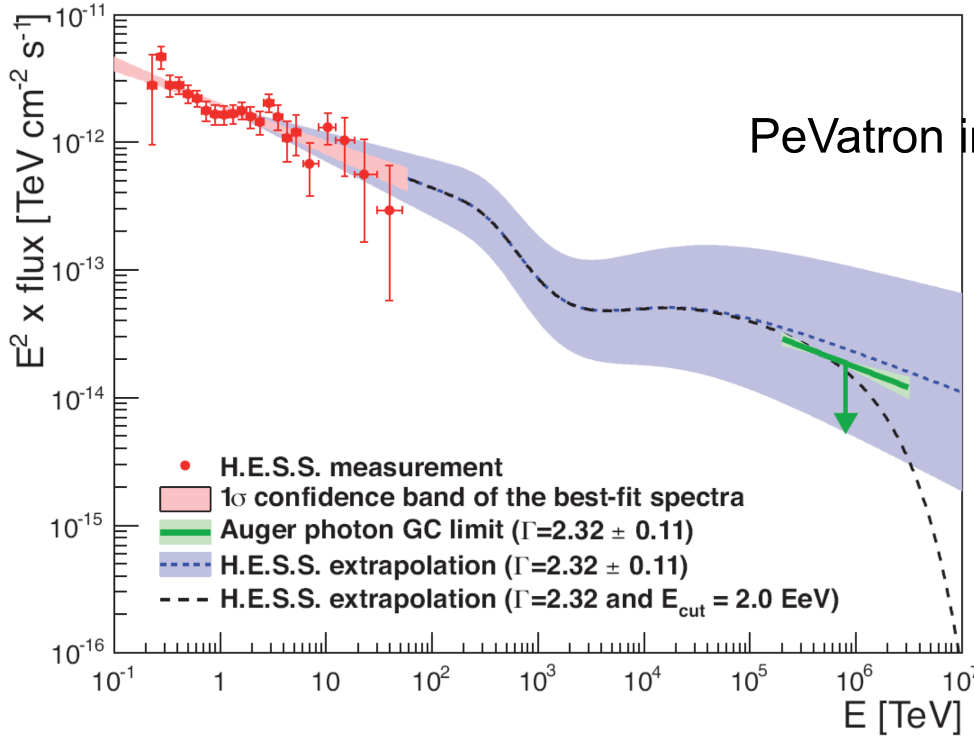
4-component fit of Xmax distribution



10^6 TeV photons, neutrinos and ...

Diffuse and targeted searches for photons and neutrinos → reaching GZK predictions for optimistic models

M. Niechciol @ ICRC 2017   E. Zas @ ICRC 2017

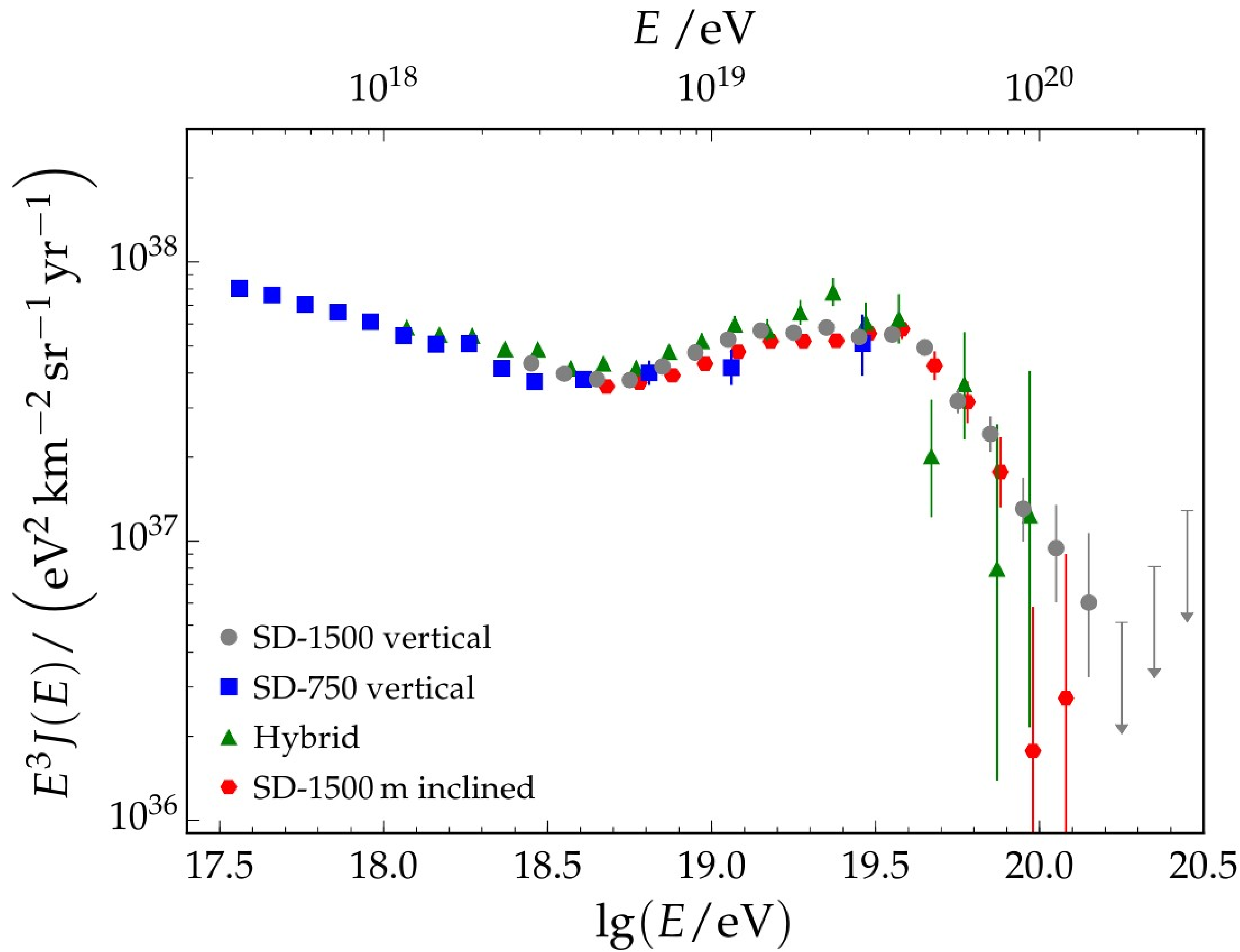


PeVatron in the Galactic centre

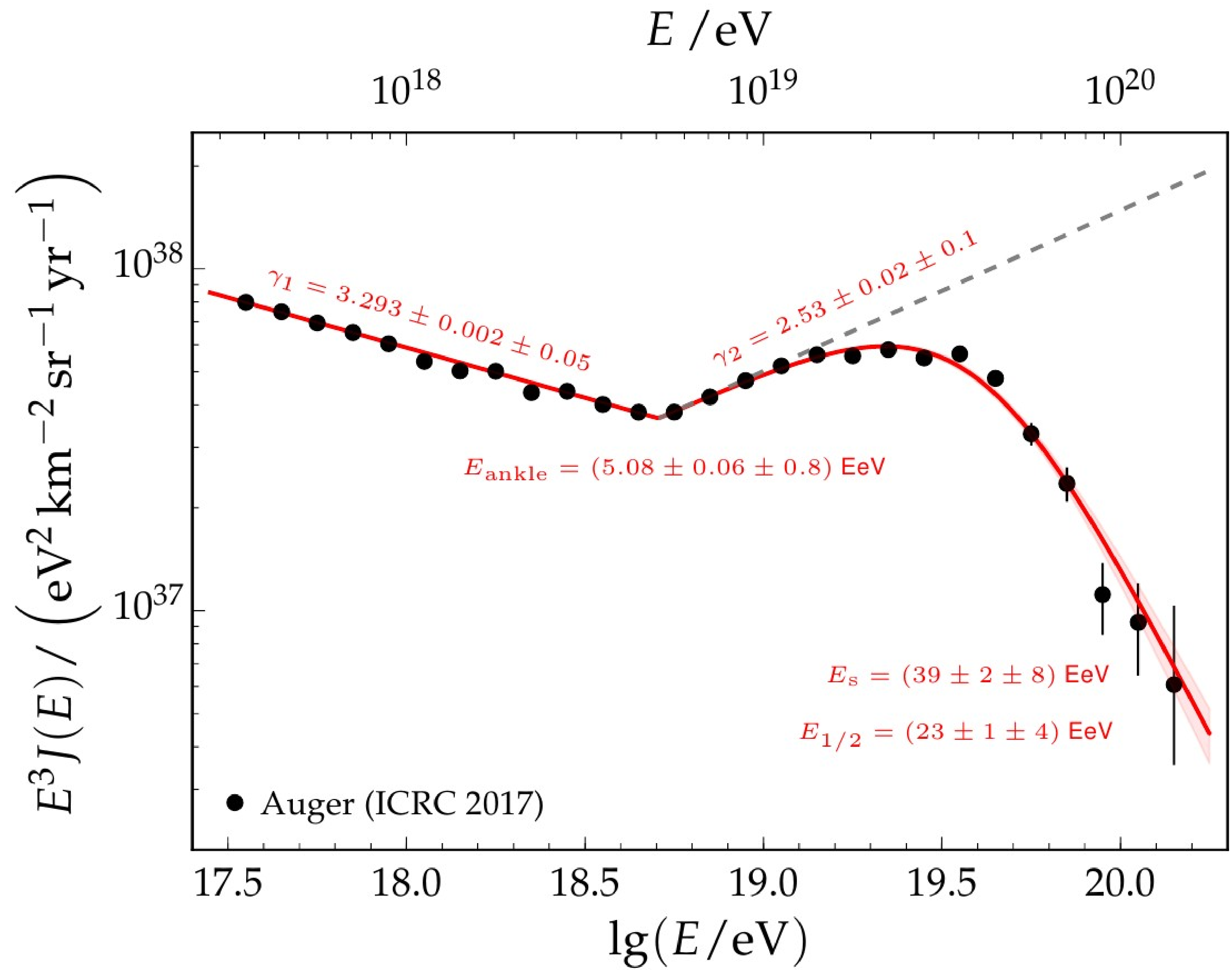
Neutrons   Pierre Auger Coll., ApJ 789, L34 (2014)

Ultrarelativistic monopoles   Pierre Auger Coll., PRD 94, 082002 (2016)

UHE neutrinos from LIGO GW   Pierre Auger Coll., PRD 94, 122007 (2016)



E /eV
10^{18}
10^{19}
10^{20}
10^{38}
10^{37}
10^{36}
$E^3 J(E) / \left(\mathrm{eV^2\,km^{-2}\,sr^{-1}\,yr^{-1}}\right)$
SD-1500 vertical
SD-750 vertical
Hybrid
SD-1500 m inclined
17.5
18.0
18.5
19.0
19.5
20.0
20.5
$\lg(E/\mathrm{eV})$



E /eV
10^{18}
10^{19}
10^{20}
$E^3 J(E)$ / $\left(\mathrm{eV^2\,km^{-2}\,sr^{-1}\,yr^{-1}}\right)$
10^{38}
10^{37}
$\gamma_1 = 3.293 \pm 0.002 \pm 0.05$
$\gamma_2 = 2.53 \pm 0.02 \pm 0.1$
$E_{\mathrm{ankle}} = (5.08 \pm 0.06 \pm 0.8)$ EeV
$E_{\mathrm{s}} = (39 \pm 2 \pm 8)$ EeV
$E_{1/2} = (23 \pm 1 \pm 4)$ EeV
Auger (ICRC 2017)
17.5
18.0
18.5
19.0
19.5
20.0
$\lg(E/\mathrm{eV})$

Motivation for the upgrade

To provide additional measurements to allow us to address the following questions:

1. The origin of the flux suppression at the highest energies

   Measurement of the mass composition beyond the reach of the FD.

2. Proton contribution in the flux suppression region ($E > 5 \times 10^{19}$ eV)

   Search of point sources and estimate the physics potential of existing and future cosmic ray, neutrino, and gamma-ray detectors.

3. Fundamental particle physics at energies beyond reach of man-made accelerators

   Study extensive air showers and hadronic multiparticle production.

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

How to do it?

Preliminary Design Report, arXiv:1509.03732

Measure with the Pierre Auger Observatory (designed 15 yrs ago) until the end of 2024.
MOUs have been signed in Nov 2015.

Proposed upgrades:

1) Upgrade surface detector electronics & a small PMT

2) Scintillator SD (SSD) to measure the mass composition with 100% duty cycle

3) Finish AMIGA to have a direct muon measurement

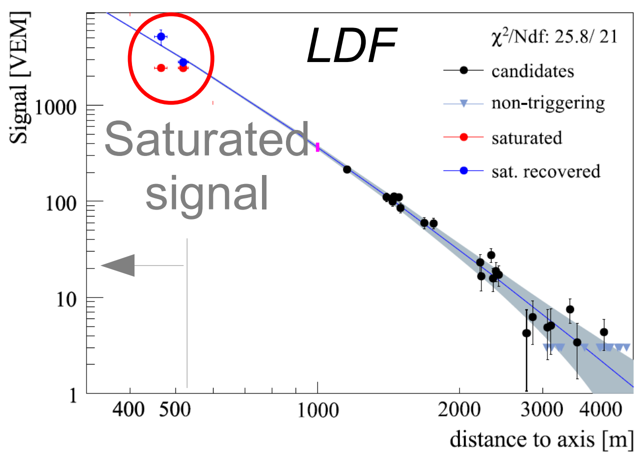
4) Extended FD operation

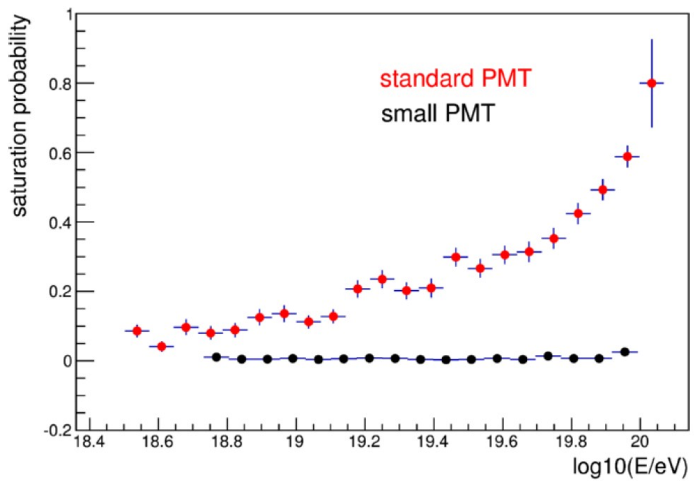
Event statistics will more than double compared with the existing data set, with the critical added advantage that every event will now have mass information.

$\log_{10}(E/\mathrm{eV})$	$\mathrm{d}N/\mathrm{d}t\vert_{\mathbf{infill}}$ [yr^{-1}]	$\mathrm{d}N/\mathrm{d}t\vert_{\mathbf{SD}}$ [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

SD electronics and small PMT

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”)





Improved LDF fit

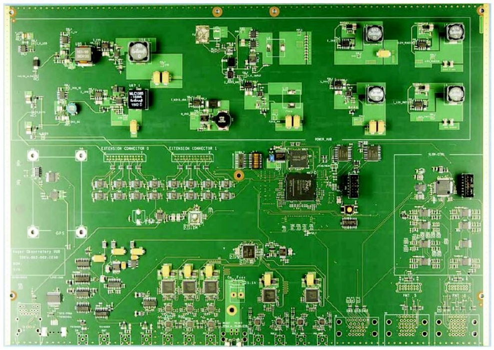
↓

Better SD-only X_{max} resolution

2. Faster data processing and more sophisticated local triggers (more powerful processor and FPGA)

3. Improved calibration and monitoring capabilities

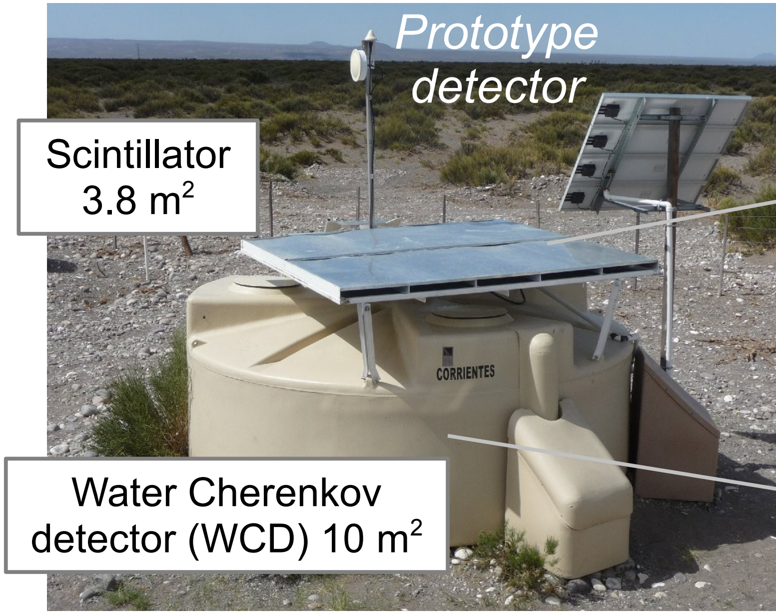
4. New components:
    a) Connection to the SSD and any additional (R&D) detectors
    b) Prolong lifetime and reduce failure rate

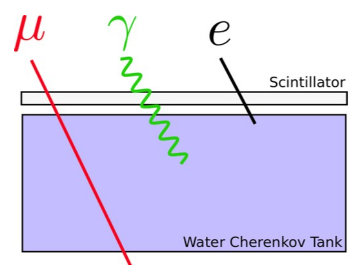


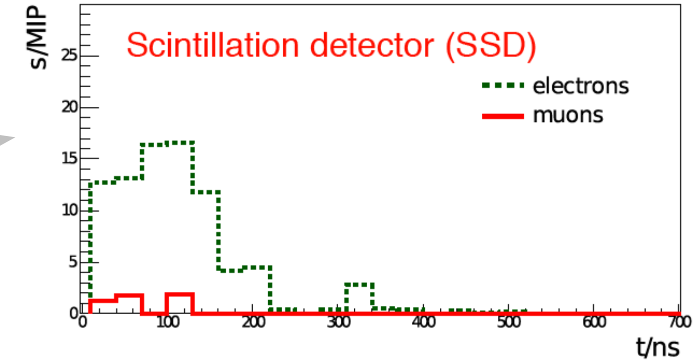
Prototype is being tested.

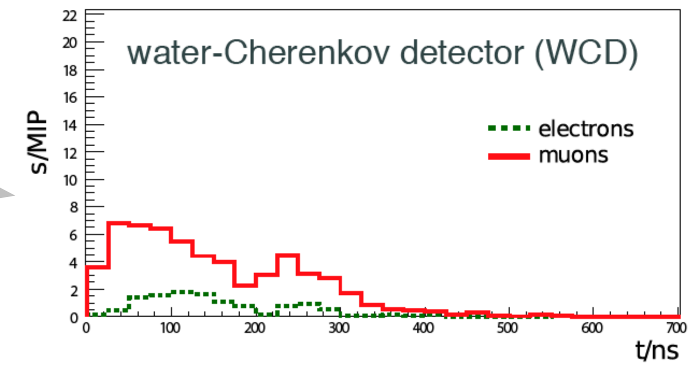
SSD measurement

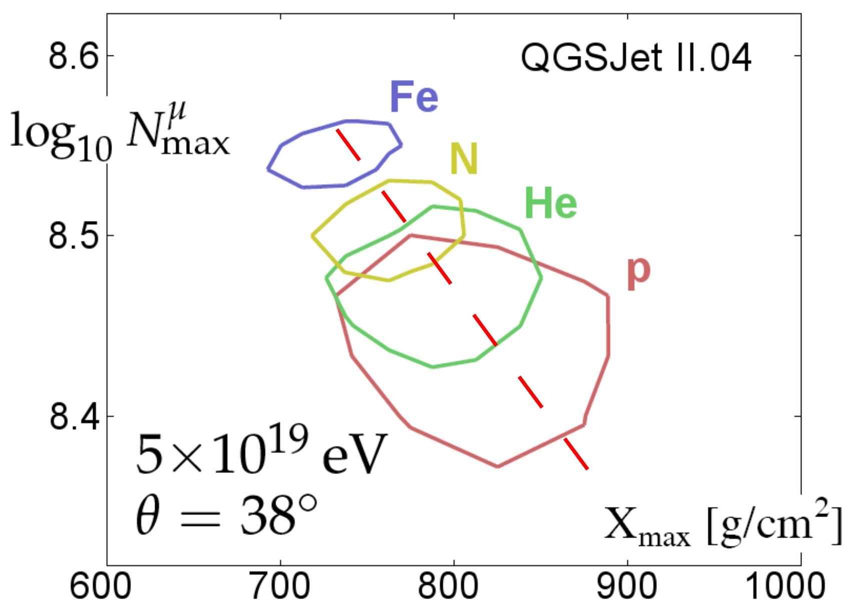
100% duty cycle











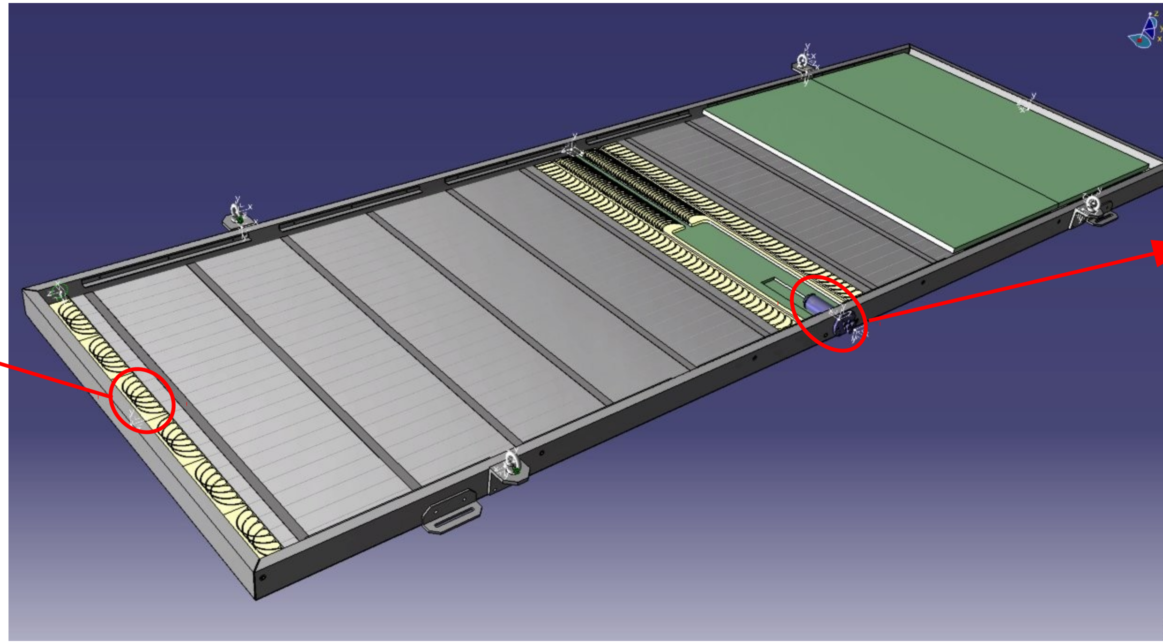
Complementarity of particle response used to discriminate electromagnetic and muonic components of air showers.

Both, N_μ and X_{max}, can be reconstructed from WCD and SSD.

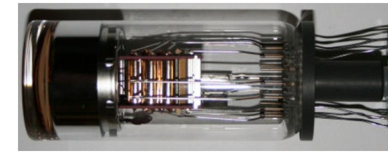
Scintillator detector

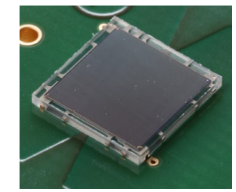
Fibers routing

WLS fibers



PMT/SiPM

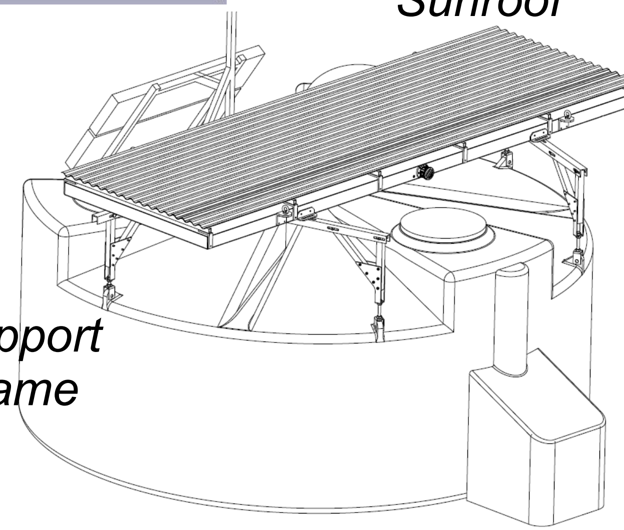




Extruded scintillator bars
(1600 x 50 x 10 mm)

Alu enclosure

Sunroof



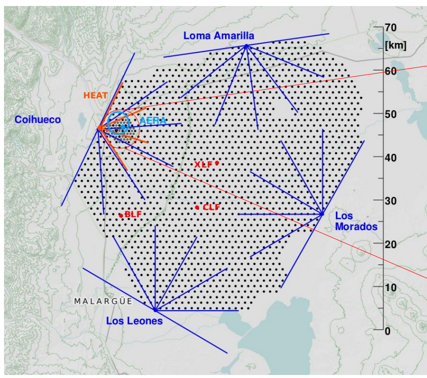
Support frame

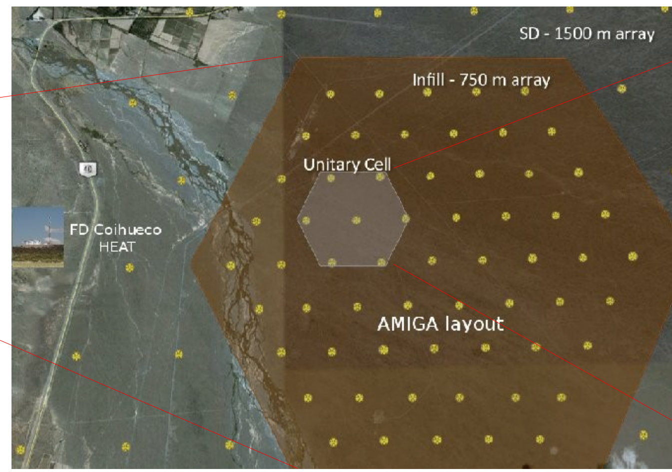
AMIGA

The underground muon detector

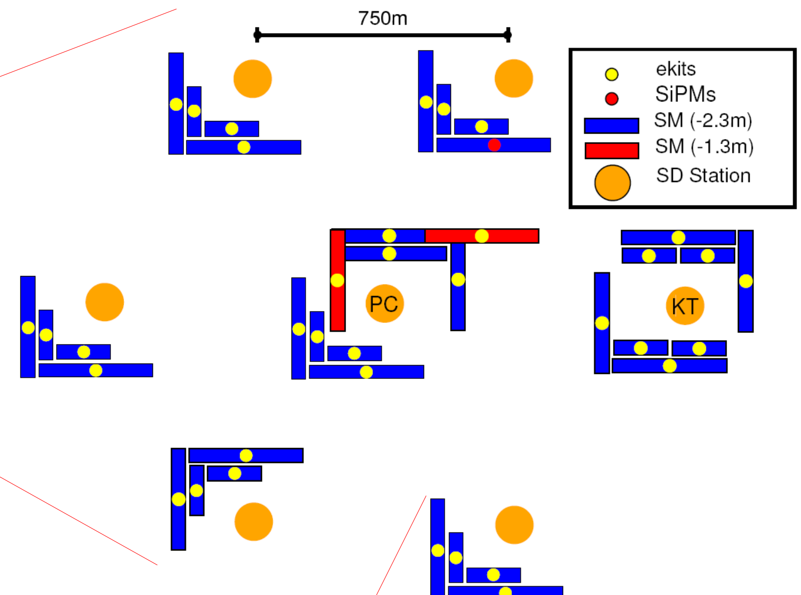
61 AMIGA muon detectors (30 m^2) are planned

Will be deployed on a 750m grid (a total area of 23.5 km^2)

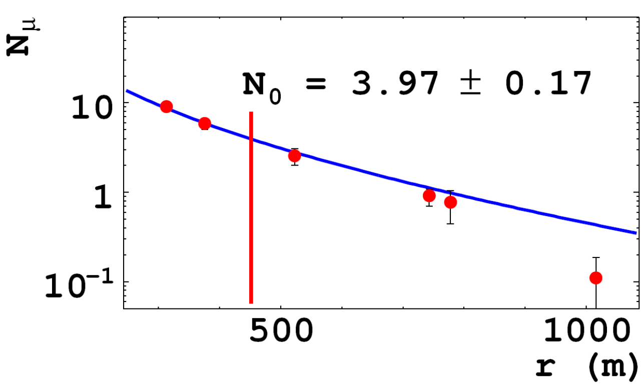


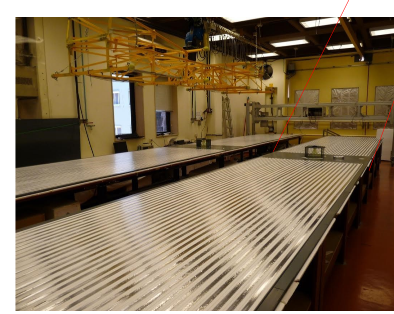


AMIGA Unitary cell (Feb 2015)



LDF, E = 2 x 10^{18} eV





Standard FD operation

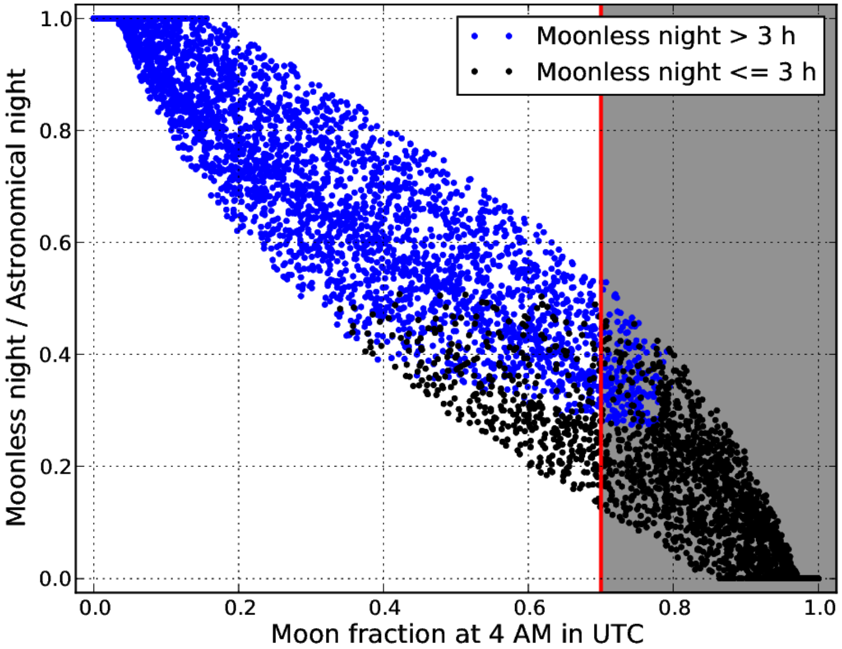
FD provides exceptional information (e.g. model-independent energy reconstruction & mass composition measurement).

The main limitation of the FD is its duty cycle (15% nowadays).

The current criteria for FD measurement:

1. *The sun more than 18° below the horizon*
2. *The moon remains below horizon for longer than 3 hours*
3. *The illuminated fraction of the moon must be below 70%*

Pierre Auger Coll., NIMA 798 (2015)



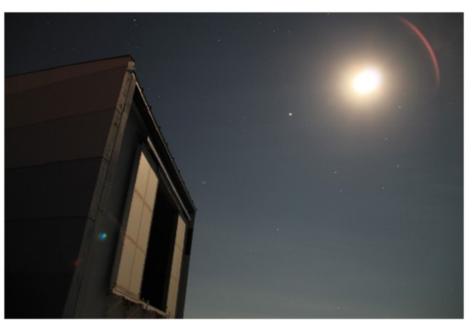
Measurement periods (~17 nights long), limit on the PMT illumination (i.e. no rapid aging), and the PMT response stays linear.

By relaxing criteria #2 and #3 the FD duty cycle can be increased by 50%, while keeping very high selection efficiency and reconstruction.

Extended FD operation

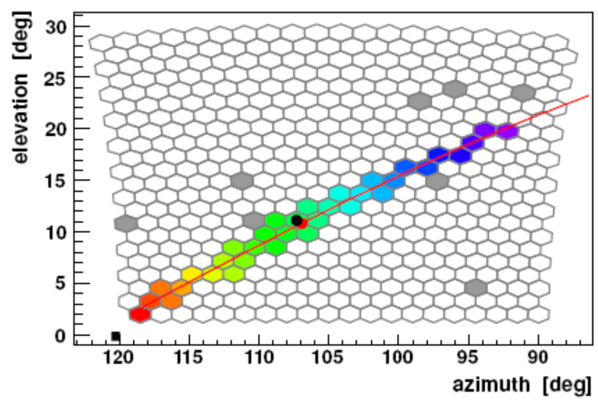
15% duty cycle

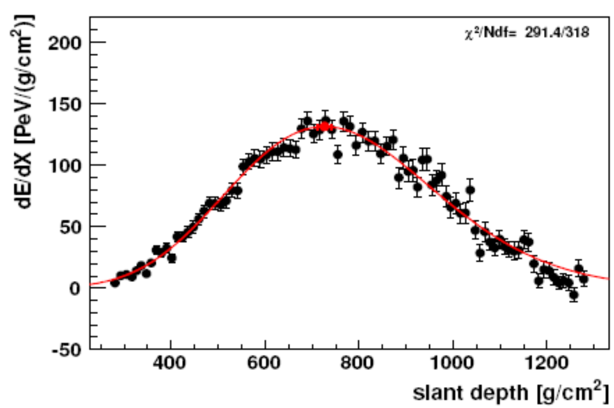
Increase by 50% by measurement during high night sky background



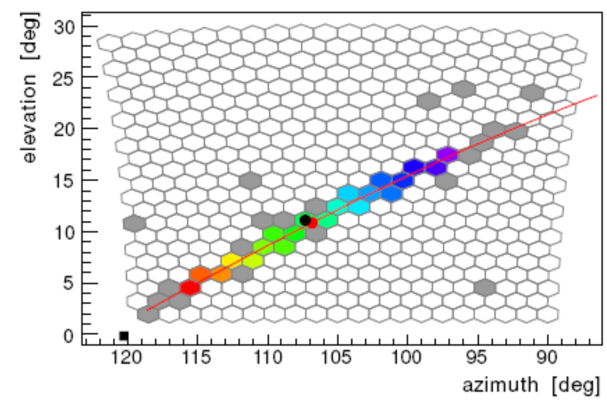
The moon and Jupiter above Los Leones in the morning on 4 Mar, 2015.

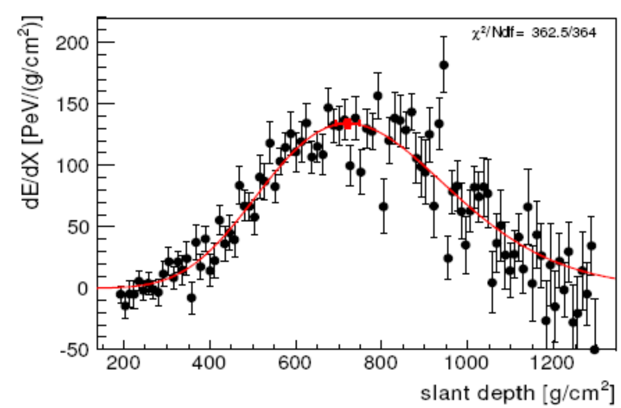
Clear sky, no moonlight



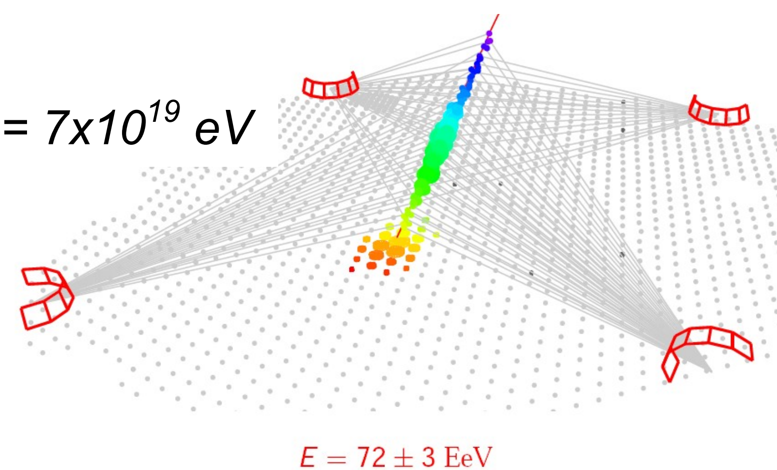


40 times higher NSB (90% moon)





E = 7x10^{19} eV



10x reduced PMT gain by reducing supplied HV.

Successful test has been done last year.