Highlights from the Pierre Auger Observatory

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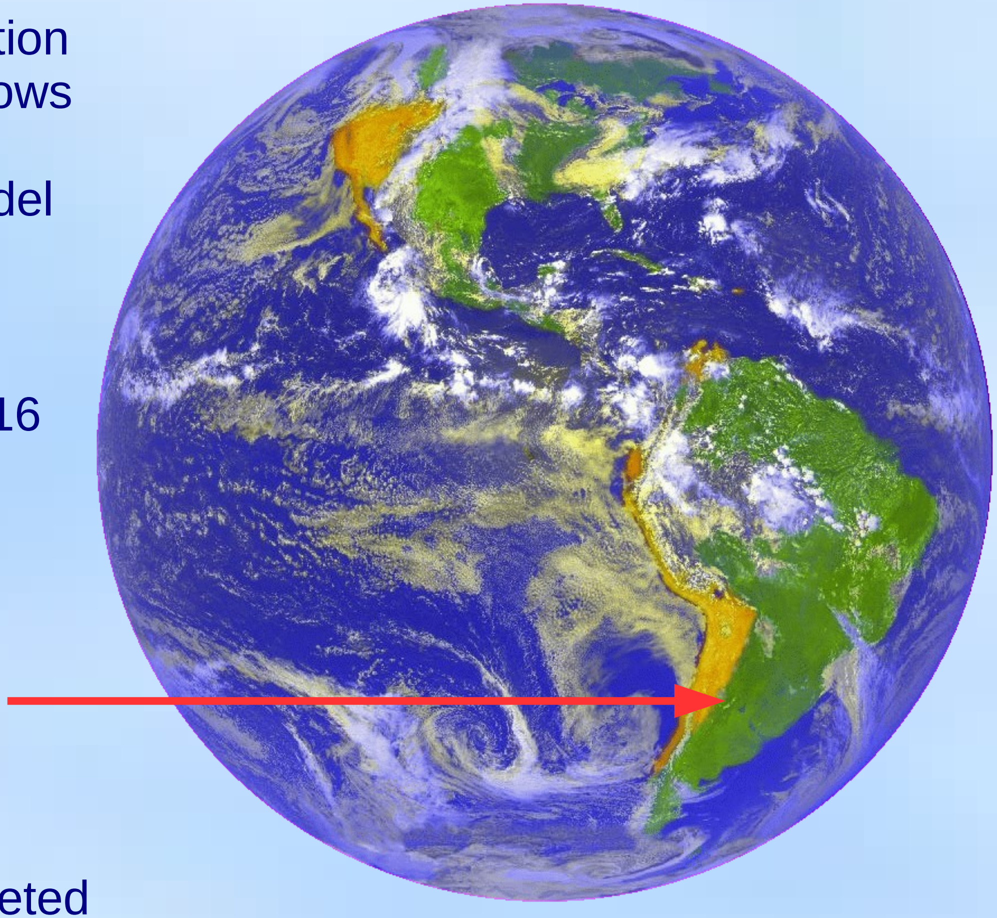
On behalf of the Pierre Auger Collaboration

Pierre Auger Observatory

PIERRE AUGER OBSERVATORY

- largest cosmic ray detector so far built, covering over **3000 km^2**
- **hybrid detector** – combination of two detection techniques allows for cross calibration of the two techniques and elliminates model dependence
- international collaboration of more than 450 scientists from 16 countries of the World
- located in the southern hemisphere, near the town of Malargue, Mendoza province, Argentina
- in operation since 2004, copleted in 2008



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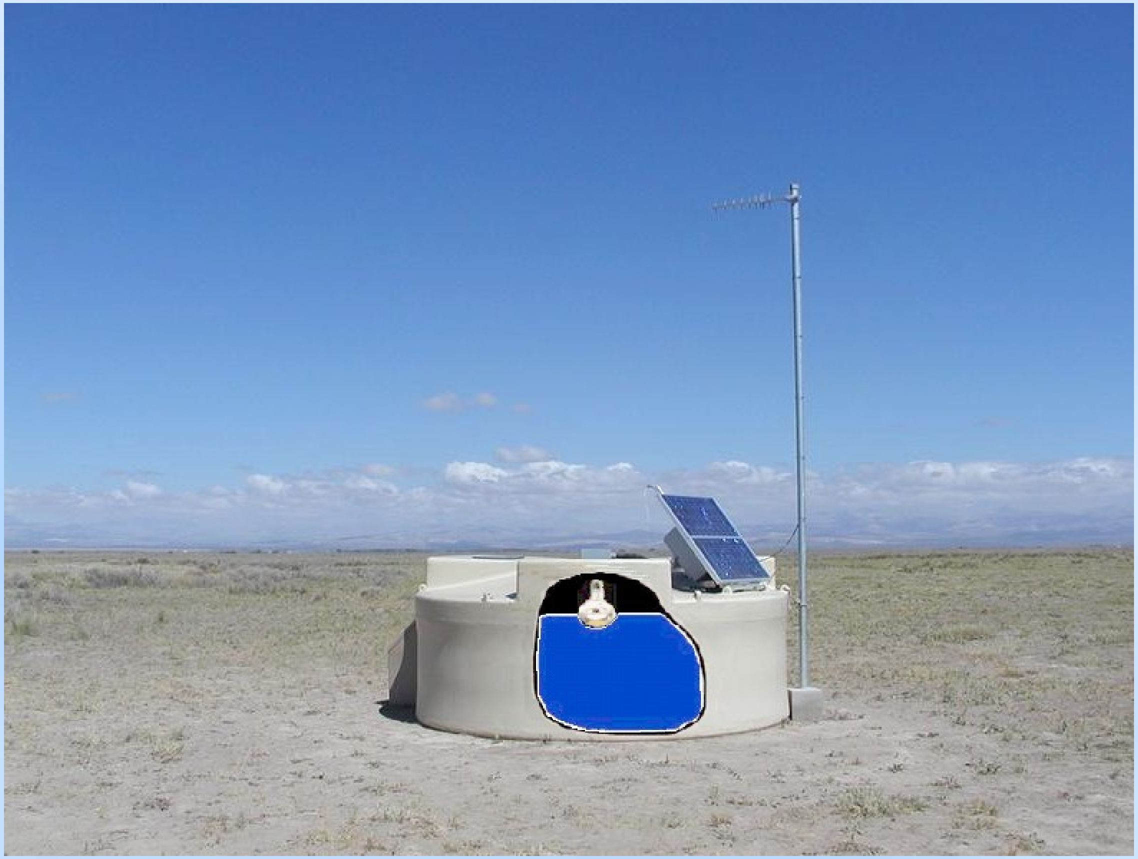
Hybrid observation

Surface detector

- 12 tons of ultra pure water
- highly reflective liner
- the volume is observed from the top by three 8 inch 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 ~ 1660 stations total

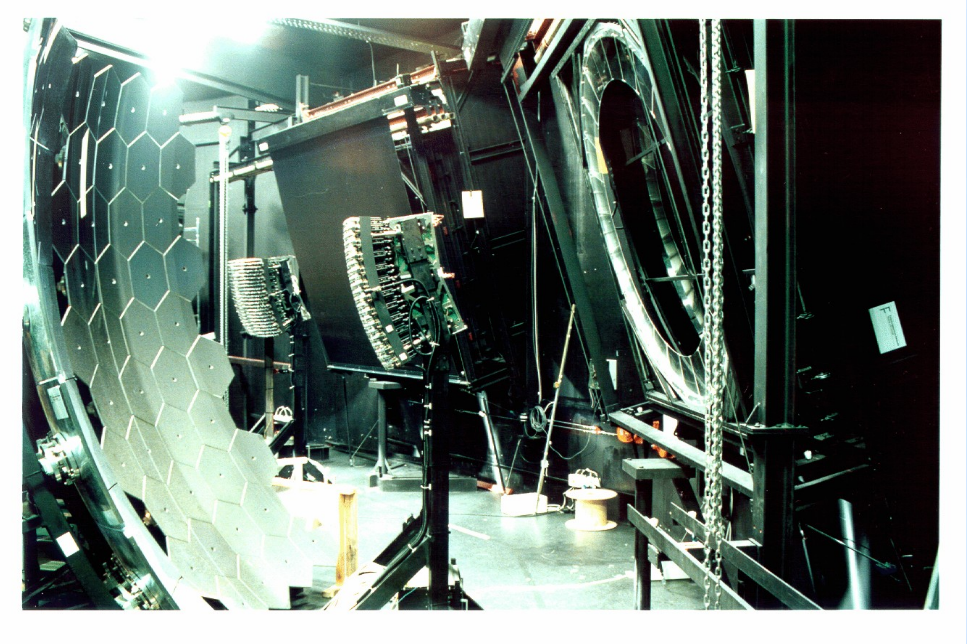


+ functions continuously (almost 100% of the time)
- does not observe the longitudinal development of the shower
- primary energy determination depends on simulations

Hybrid observation

Fluorescence detector

- segmented spherical mirror – diameter 3.44 m
- surface 3.6 by 3.6 m
- 30° by 30° field of view (Schmidt corrector ring), - viewing up to 30° above horizon
- 440 photomultipliers in the focal plane
- 24 telescopes in 4 buildings



\- functions only during clear, moonless nights (about 15% of the time)

\+ observes directly the location of the shower maximum (indicative of primary mass)

\+ nearly calorimetric measurement (model independent)

Observatory enhancements

High **E**levation **A**uger **T**elescopes

HEAT

- three additional telescopes of the same design
- pointing above FOV of the standard FD (30° to 60°)
- **lowering the energy threshold to 10^{17} eV**

- shower particles excite and ionise nitrogen in the atmosphere,deexitations produce light (300-400 nm)
- amount of the light emitted is proportional to the energy deposited in the atmosphere but it is affected by pressure, temperature and humidity

=> extensive atmospheric monitoring needed

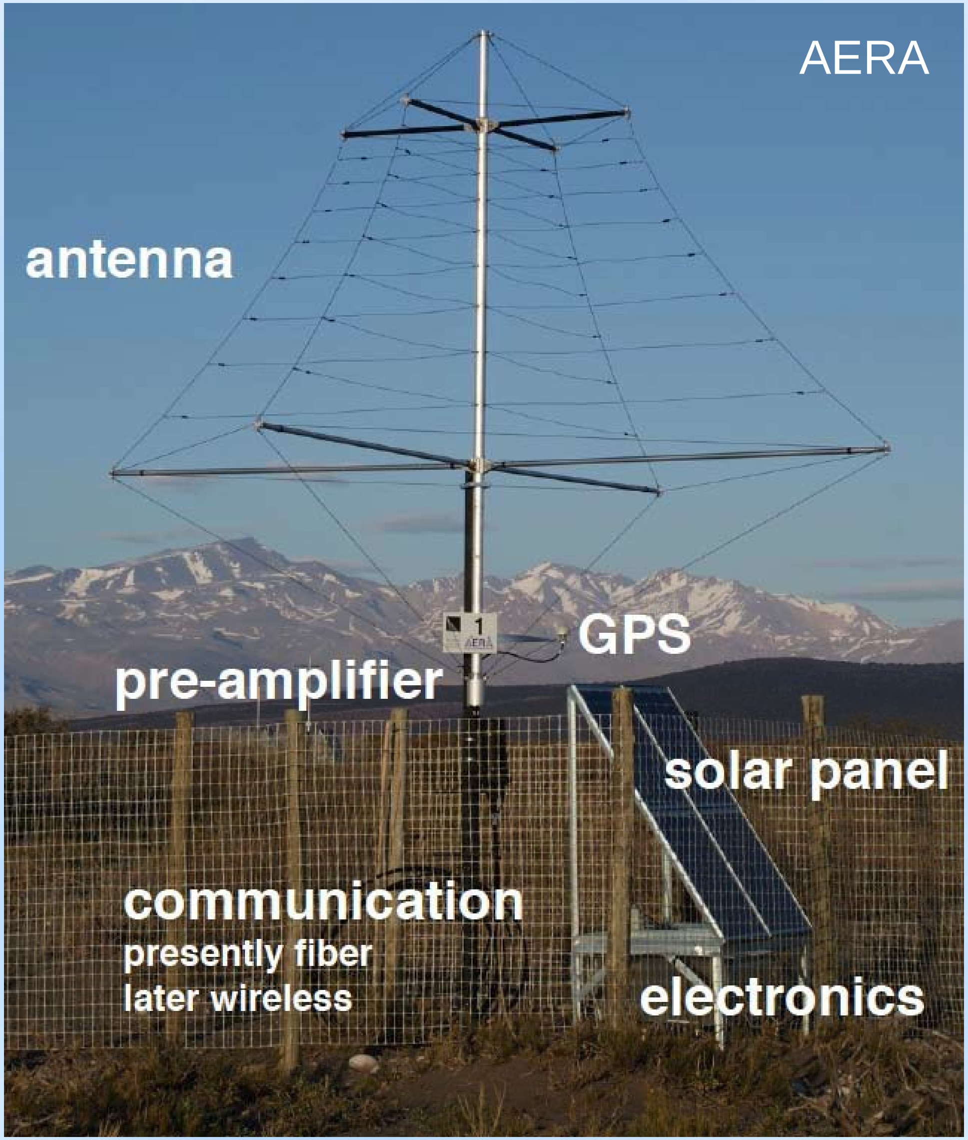
- Central Laser Facility (CLF), eXtreme Laser Facility (XLF), lidars, Raman laser, FRAM (Fotometrický robotický atmosferický monitor)

Observatory enhancements

Auger **E**ngineering **R**adio **A**rray

AERA

- 153 radio stations on 17 km^2
- coherent radiation of secondaries in 30-80 MHz band
- graded array 144m to 750m spacing
- completed in 2015



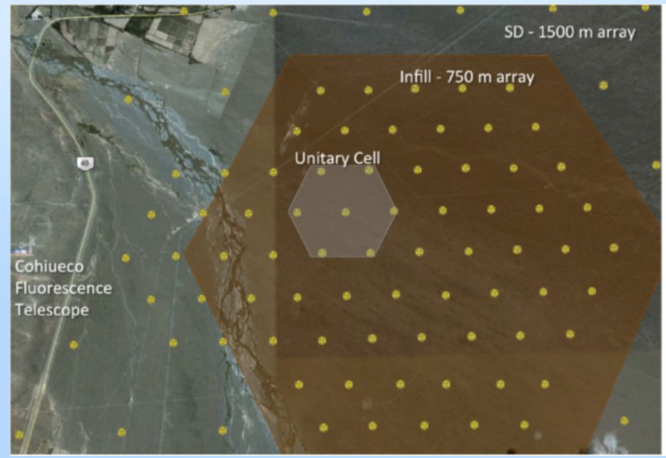
Observatory enhancements

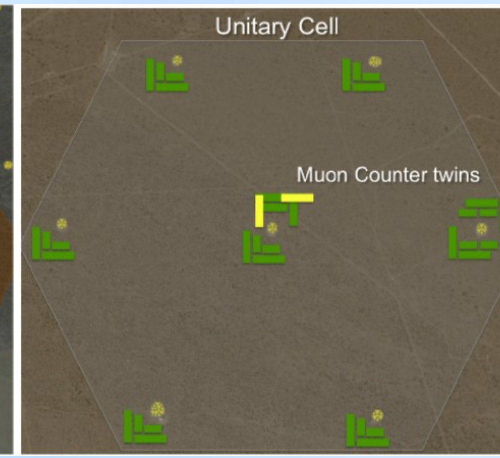
Auger **M**uon and **I**nfill for the **G**round **A**rray

AMIGA

Infill

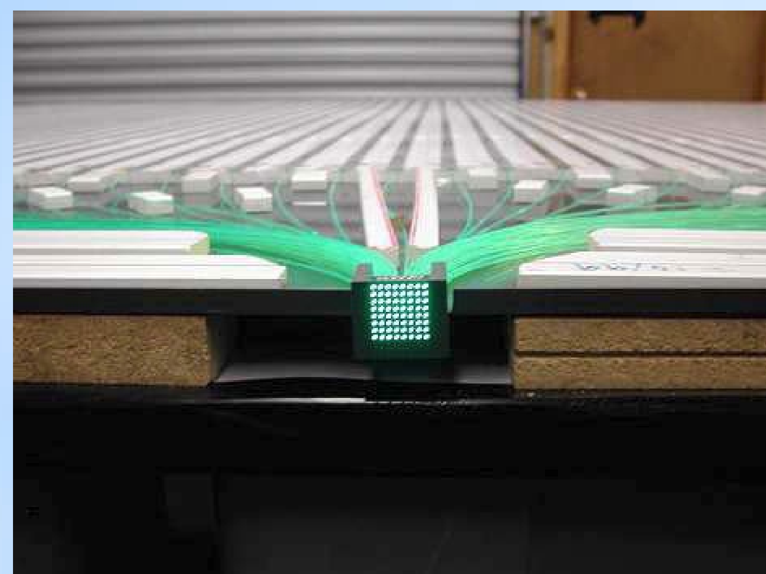
- 61 WCD in half distance (750 m)
- covering 23.5 km^2
- extends energy range of SD to $3x10^{17}$ eV (full efficiency)





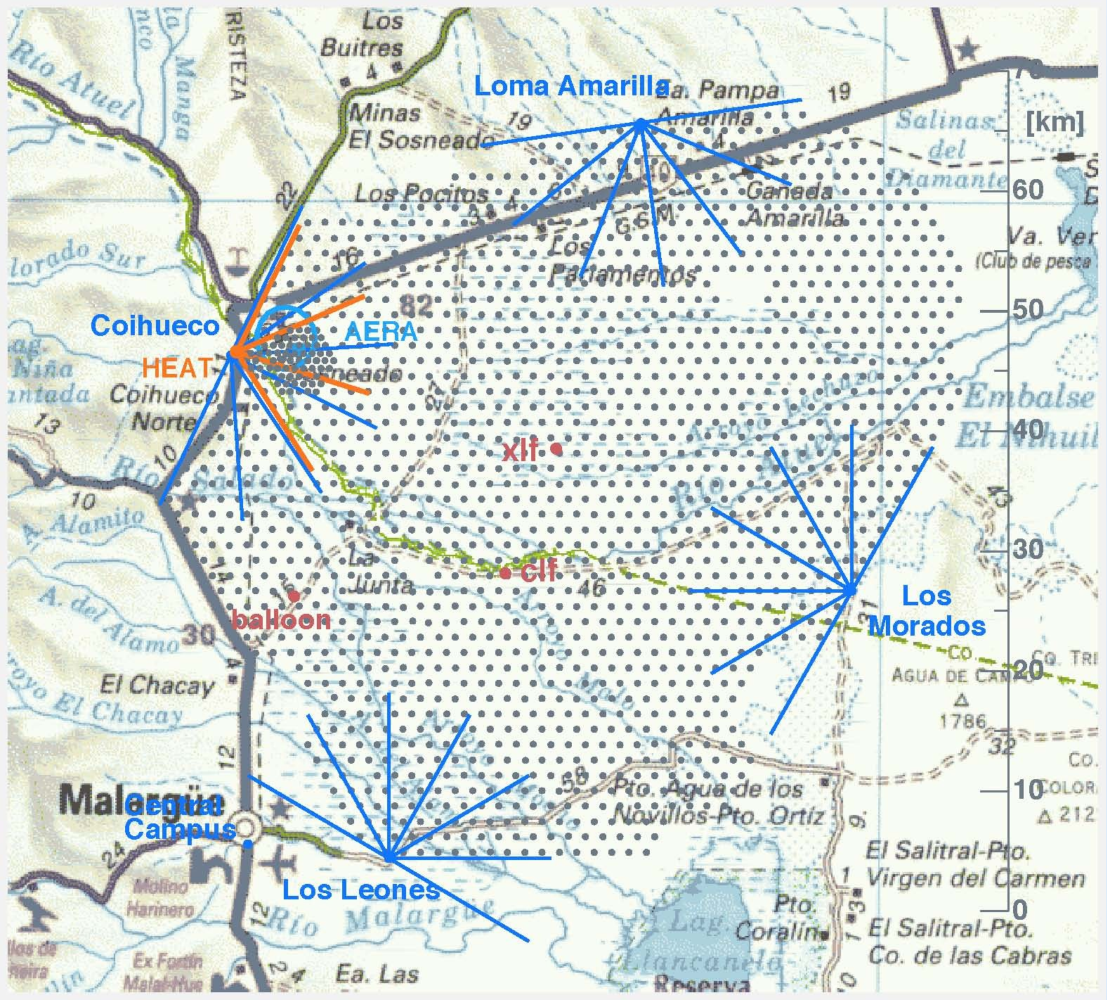
Underground muon counters

- 30 m^2 scintillator, 64 channel multianode PMT
- burried 2.25 m under ground level, aside the 61 Infill tanks
- study the composition sensitive observables, hadronic interactions



Detector locations

- surface array
- fluorescence telescopes
- HEAT
- AERA
- AMIGA



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Sellected science results include:

- energy spectrum
- arrival directions
- mass composition

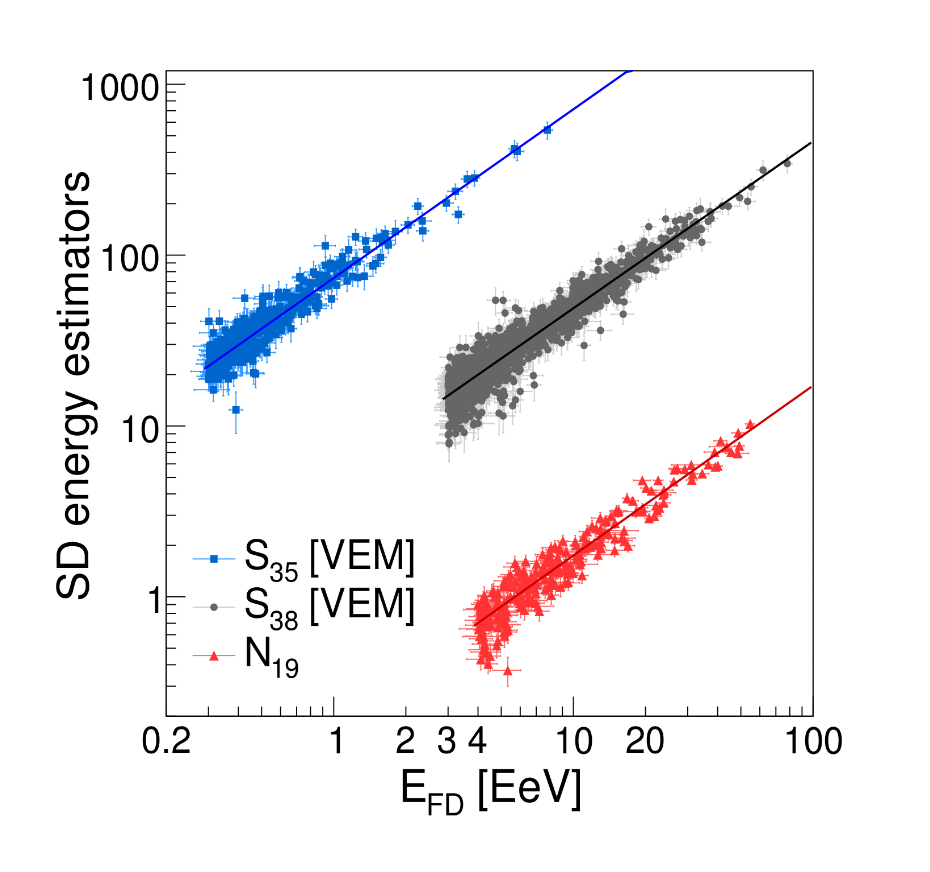
- limits on the presence of photons and neutrinos
- cross section of proton-air interaction
- verification of hadronic interaction models

Energy scale

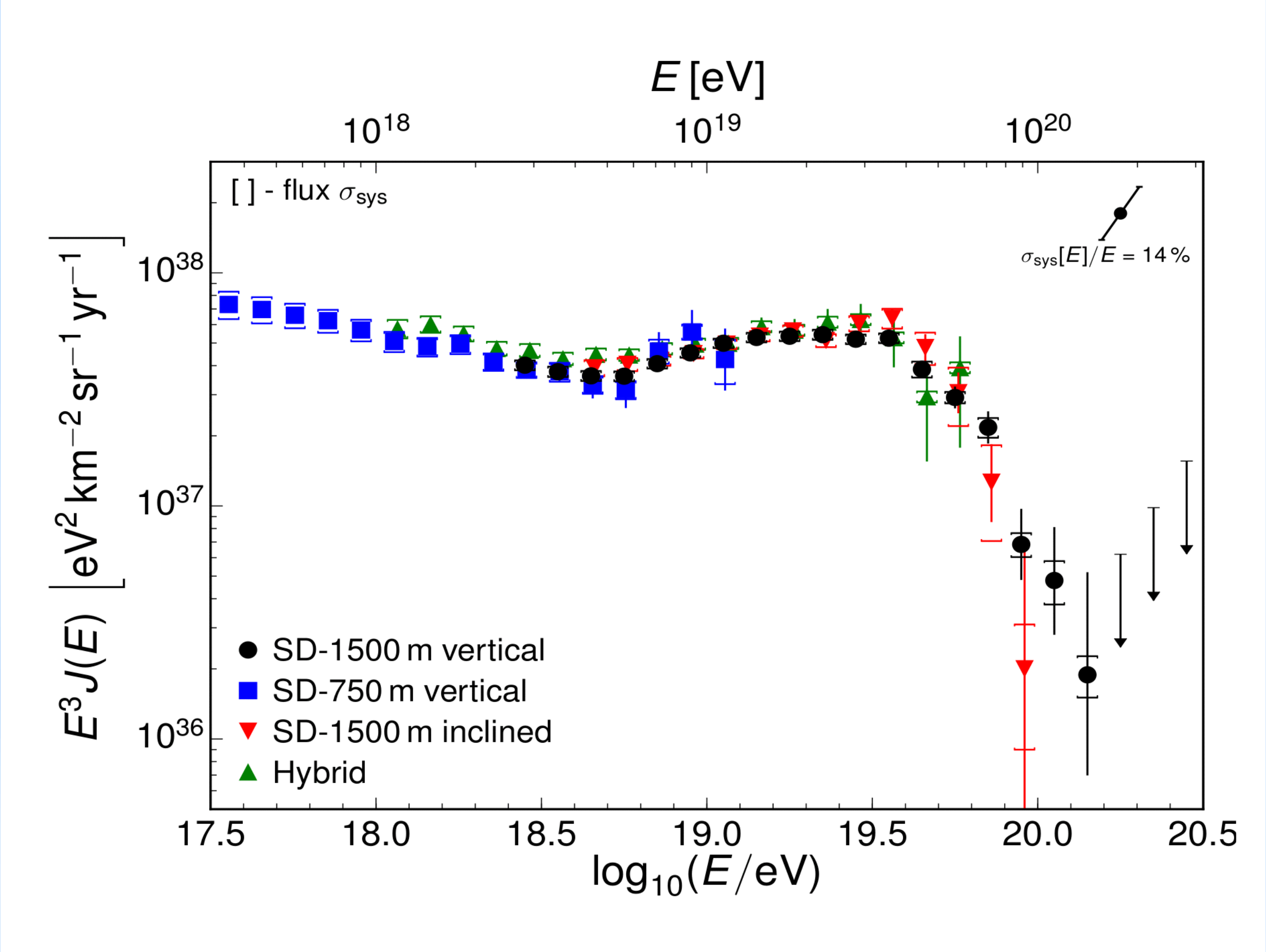
comparison of the energy derived from FD with energy estimators from surface arrays

- very inclined showers (60° to 80°)
  – only muons present on the ground
- full array with the standard spacing of the stations
- Infill array

- all three configurations show a good correlation with fluorescence telescopes
- can be described by simple power law
- used for calibration of surface arrays
  (no need to rely on simulations)
- inherit the FD energy scale uncertainty
  of 14% (16% below 10^{18} eV)

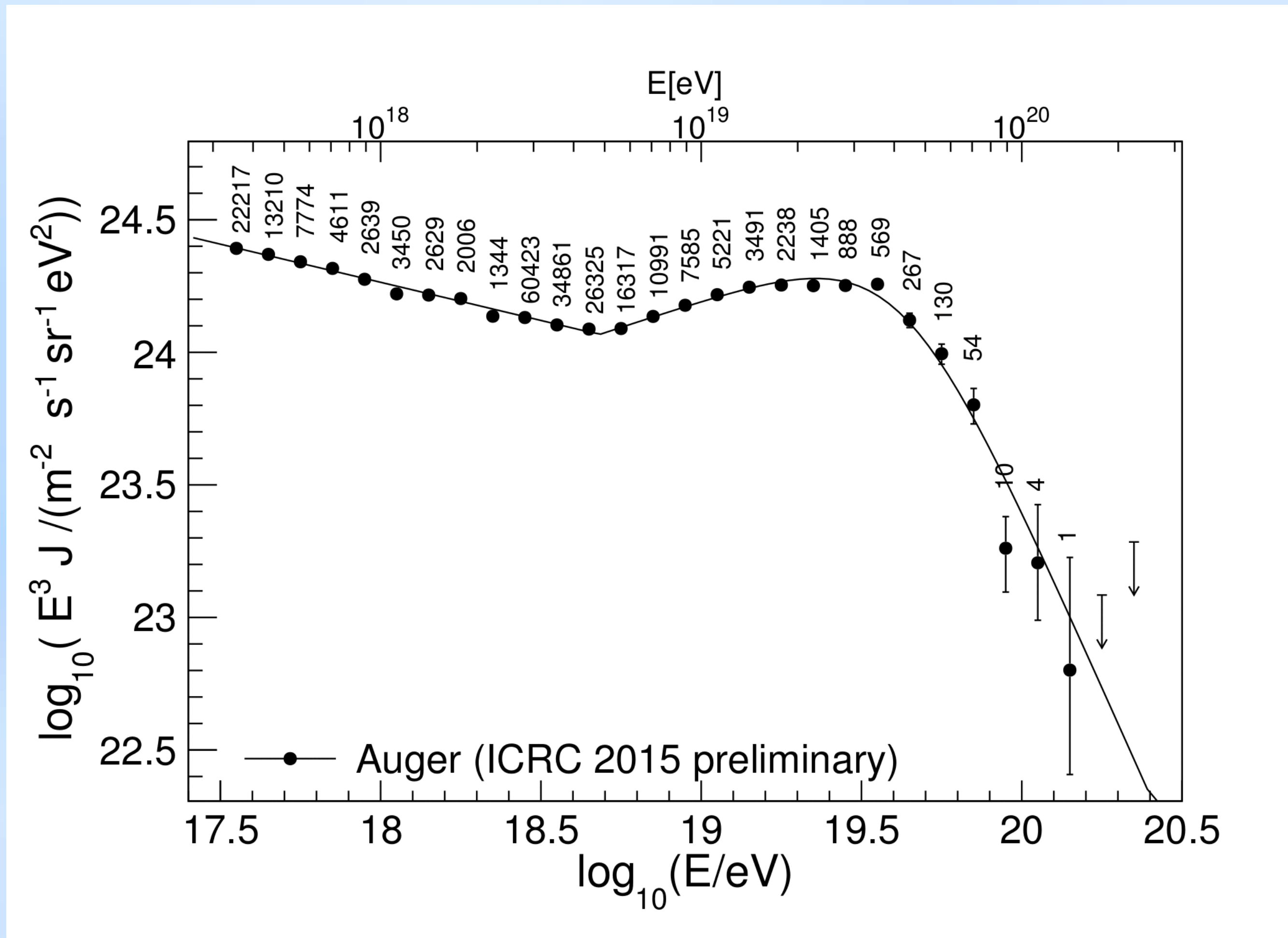


Energy spectrum

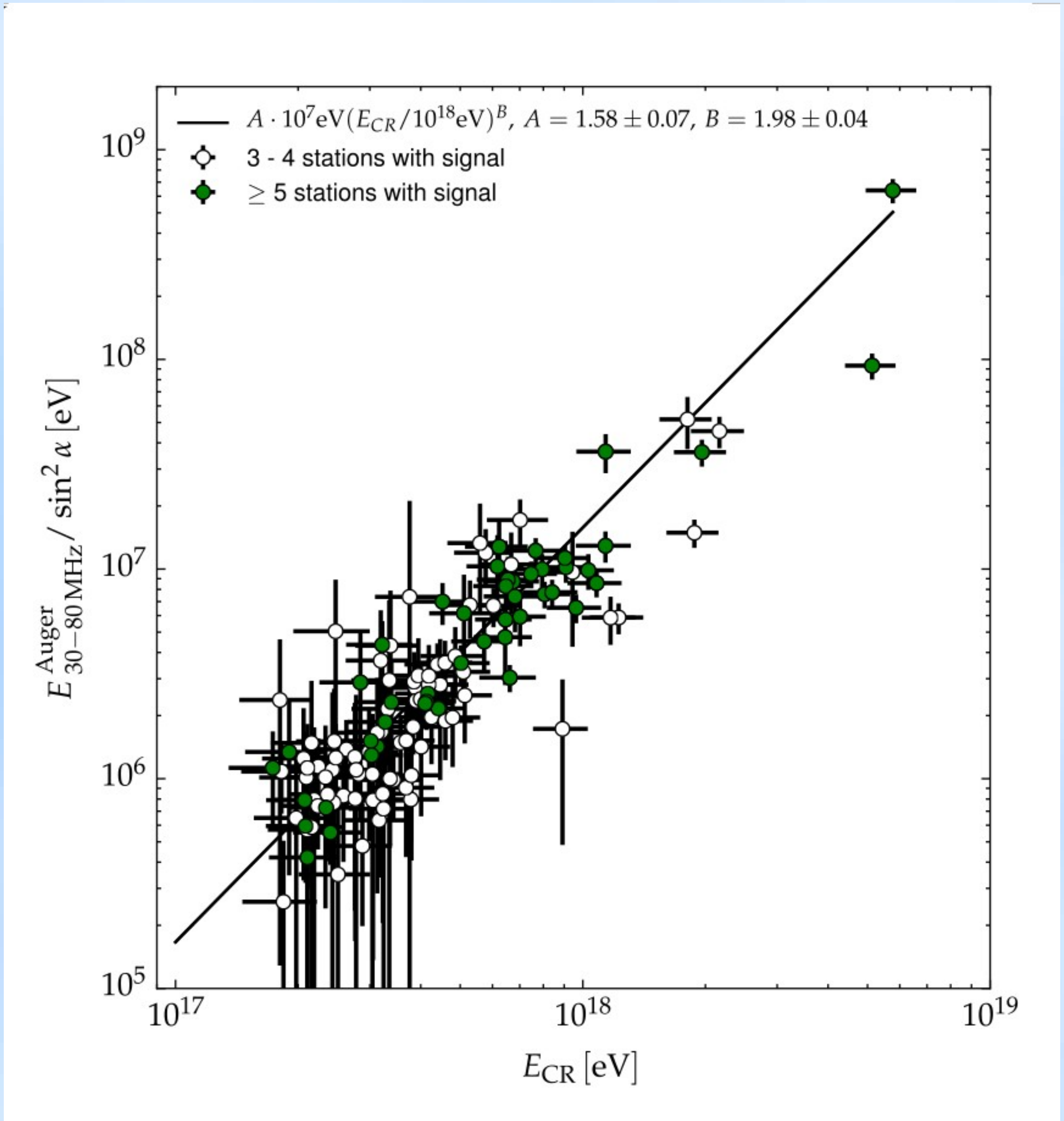


Energy spectrum

- ankle region measured with high precision
  $E_{ankle} = (4.8 \pm 0.1 \pm 0.8) \times 10^{18}$ eV
- Slope below ankle
  $\gamma_1 = (3.29 \pm 0.02 \pm 0.05)$
  above ankle
  $\gamma_2 = (2.60 \pm 0.02 \pm 0.10)$
- strong suppression above $10^{19.5}$ eV
- origin is not clear – GZK limit or end of the cosmic accelerator power
  (composition dependent)



AERA energy scale



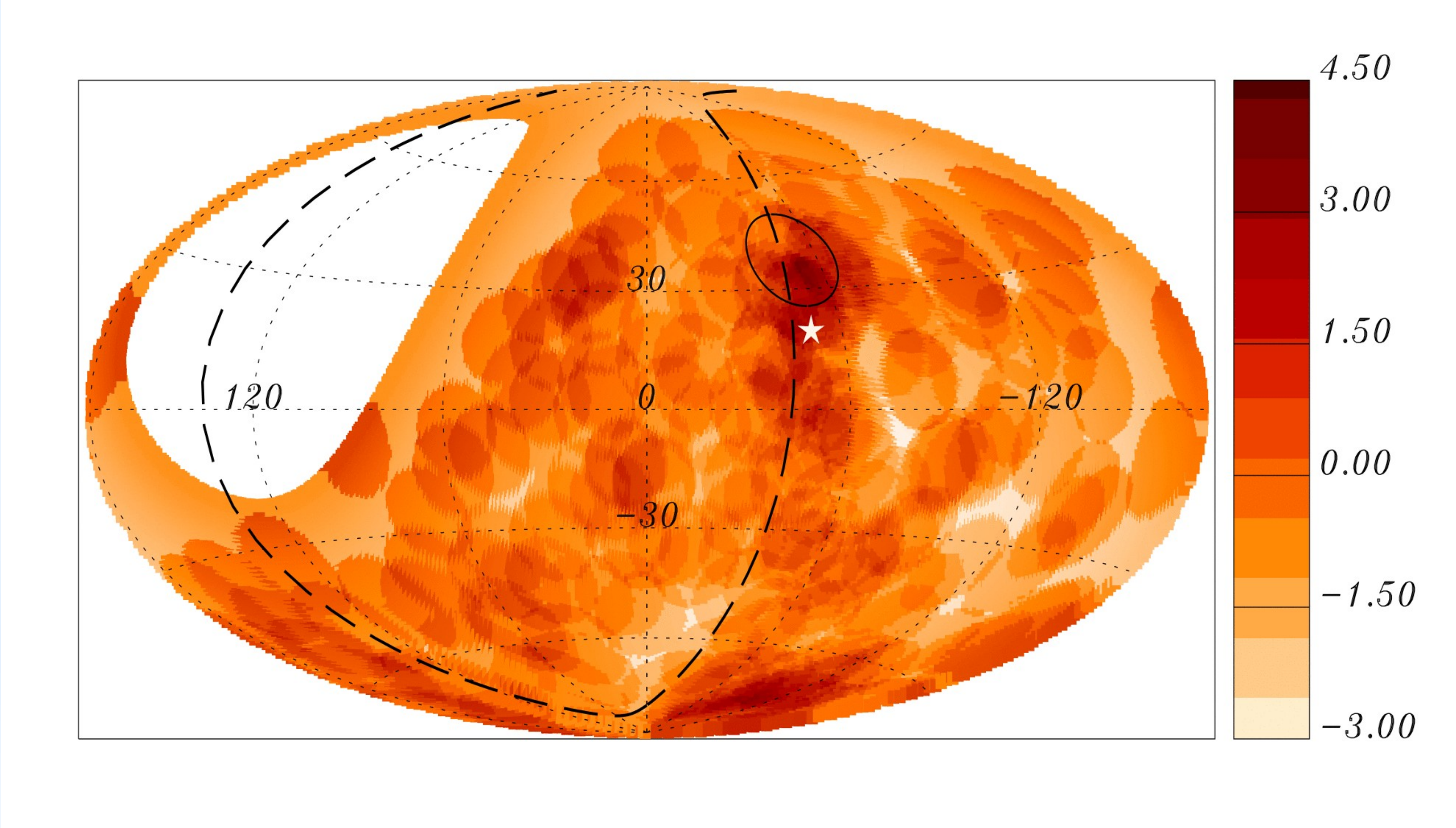
- 5500 showers measured in coincidence with SD (300 with FD)

PRL 116, 241101 (2016)

- **detailes in the next talk by Benedikt Zimmermann**

Arrival directions

excess significances in 12° radius, E > 54 EeV,
10 years of data, zenith angles up to 80°



- excess of events within 15° of the Centaurus A position – not signifficant

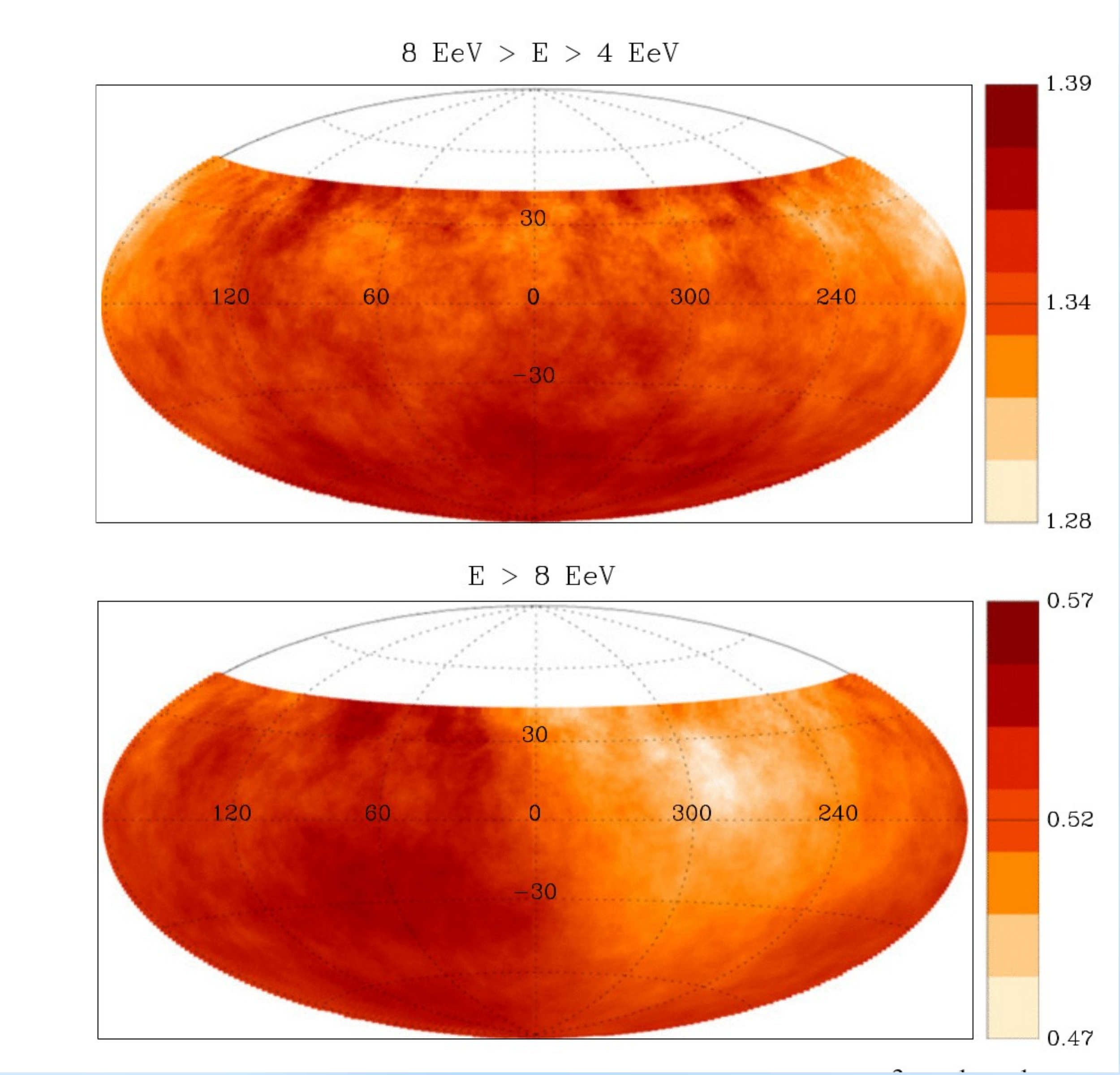
Arrival directions
Large scale distribution

- inclined events 60° to 80° included in the analysis
- ~70 000 events, E > 4 EeV, (full efficiency for inclined)
- covering ~ 85% of the sky

- divided into two energy bins:
  4 EeV < E < 8 EeV
  E > 8 EeV

- no signifficant departure from isotropy in the first bin

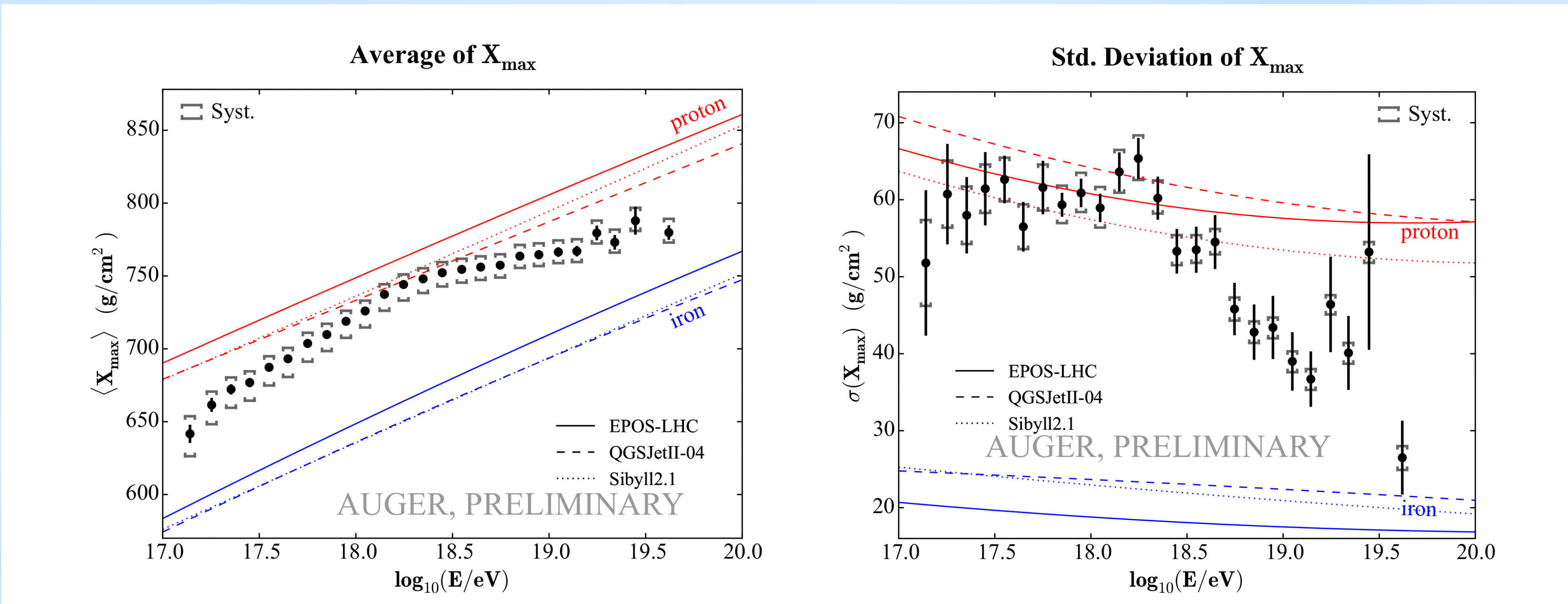
- In higher energy bin – dipol amplitude
  d = 0.073 ± 0.015
  pointing to
  (α,δ) = (95°± 13°, -39°± 13°)



Mass composition

fluorescence data only

(FD ~ 18000 events, HEAT ~ 5500)

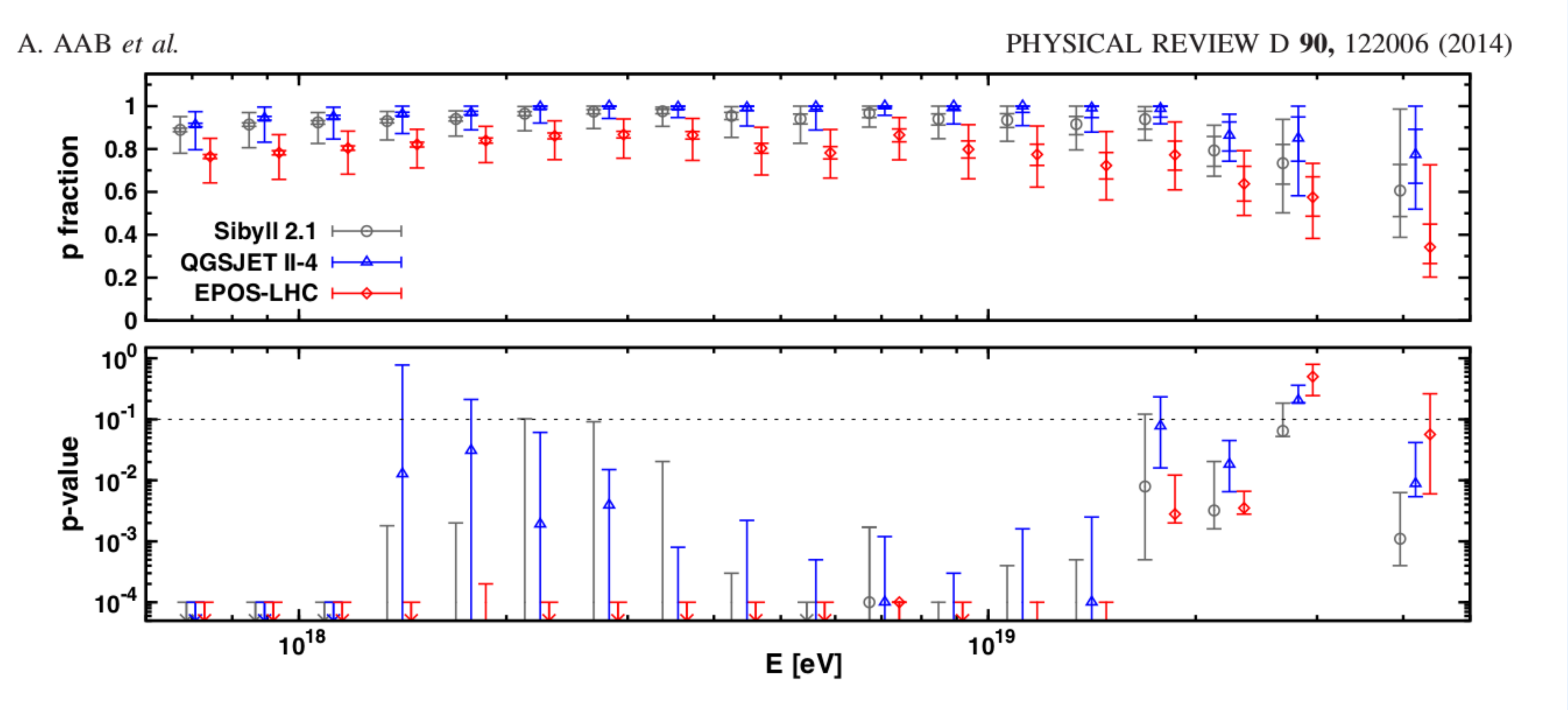


- mean of the shower maxima as well as their fluctuations indicate a composition becoming lighter up to $10^{18.3}$ eV

- transition from light to heavier primaries above $10^{18.3}$ eV

Mass composition

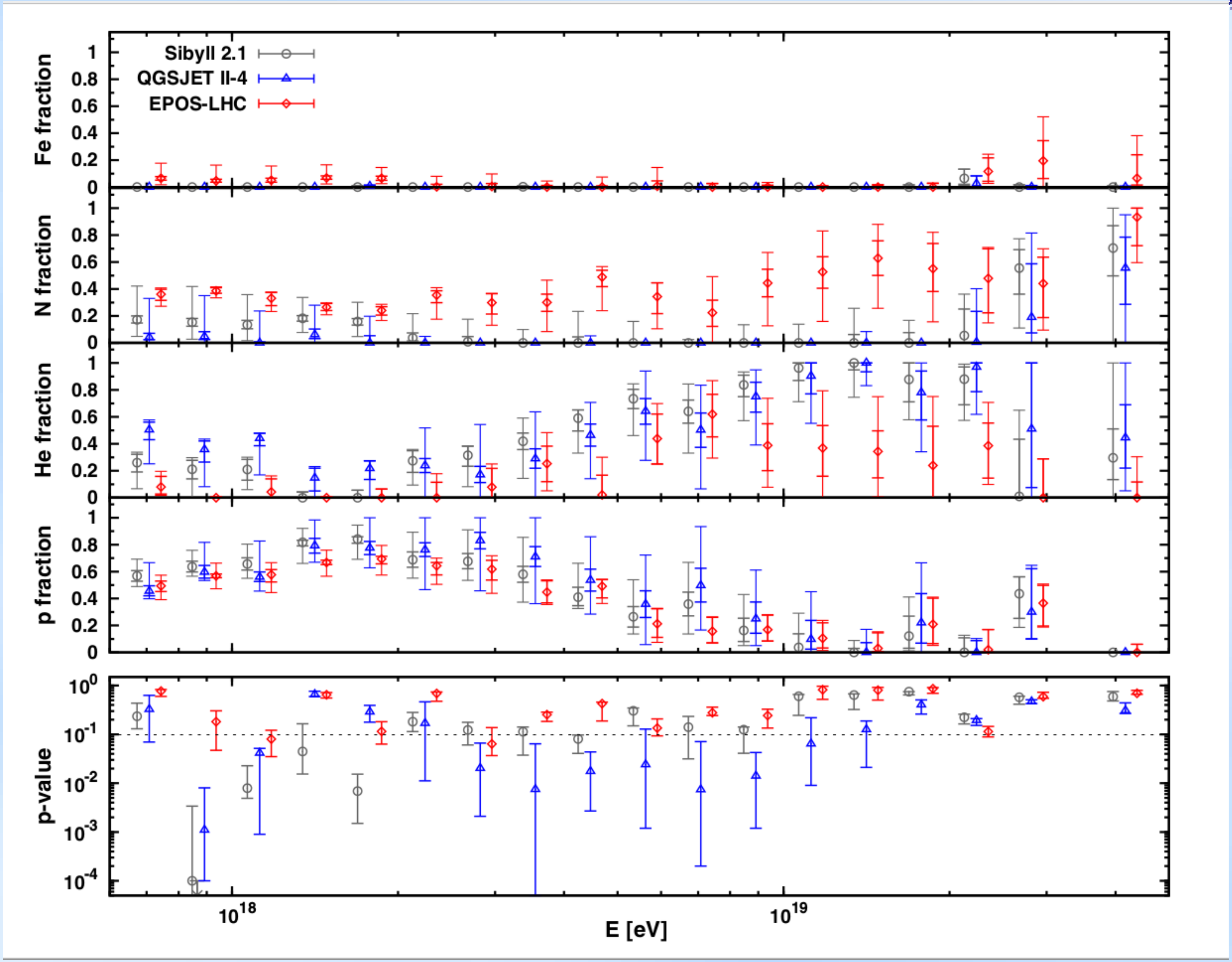
Xmax distribution fitted by simulated mixtures of different components



- mixture of protons and iron nuclei only does not give a good quality fit for any of the models considered

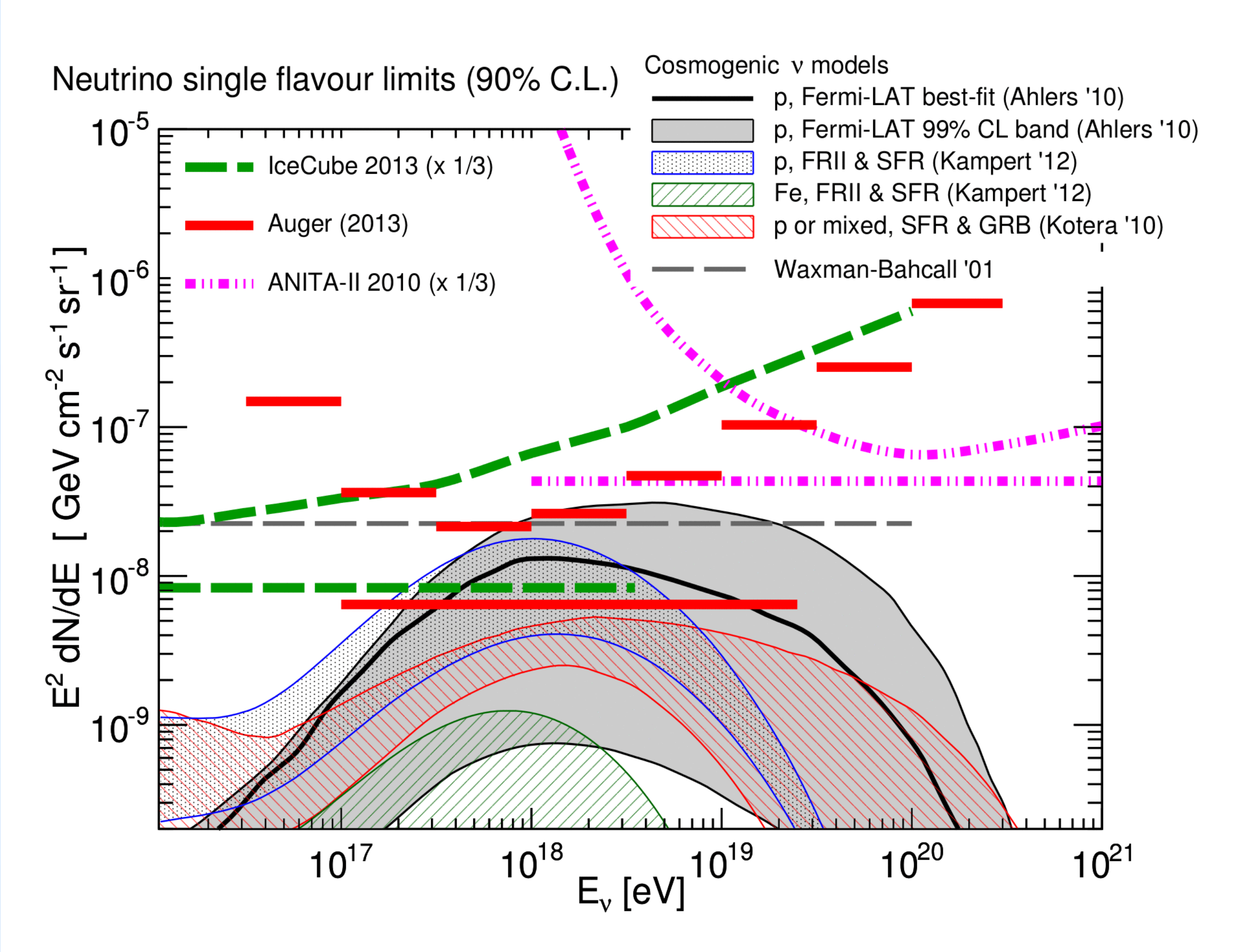
- 4 component mixture (p, He, N, Fe) gives a satisfactory fit quality (best description by EPOS-LHC)

Mass composition



PRD 90, 122006 (2014)

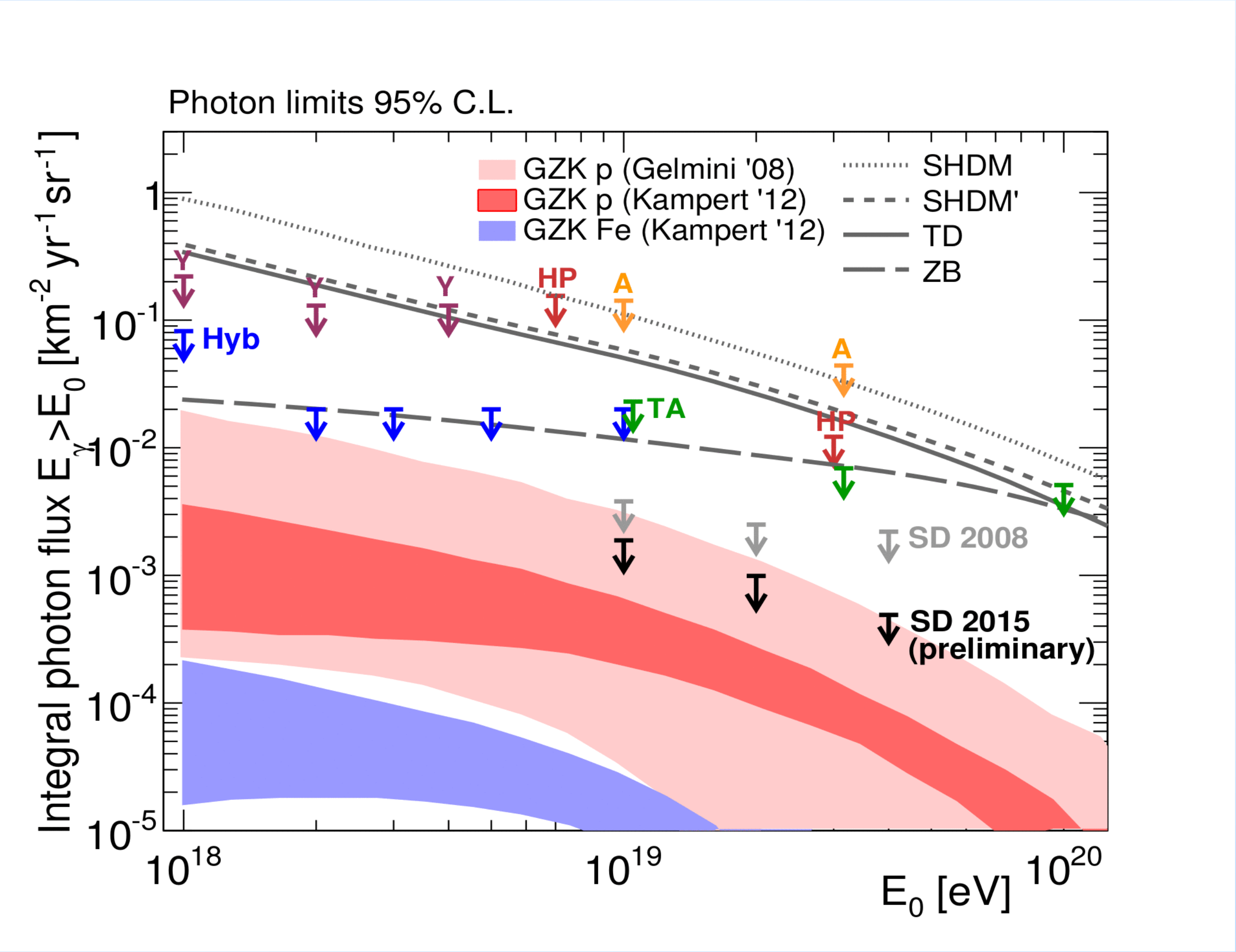
Neutrino detection



- inclined downward going (60°to 90°) or Earth-skimming (90° to 95°) ν_τ
- no neutrino candidate found
- challenging the Waxman-Bahcall limit

PRD 91, 092008 (2015)

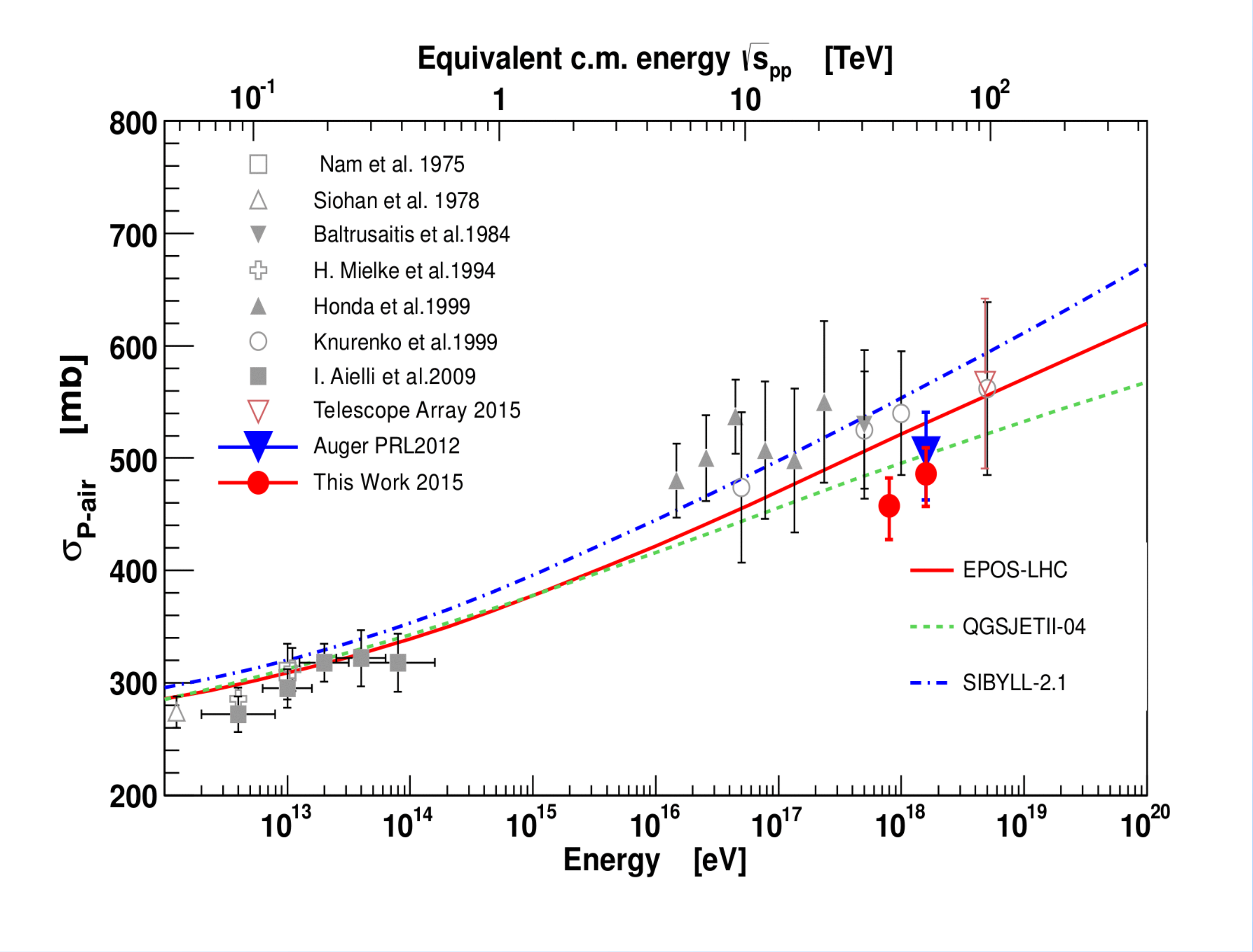
Photon limit



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

Proton-air cross-section

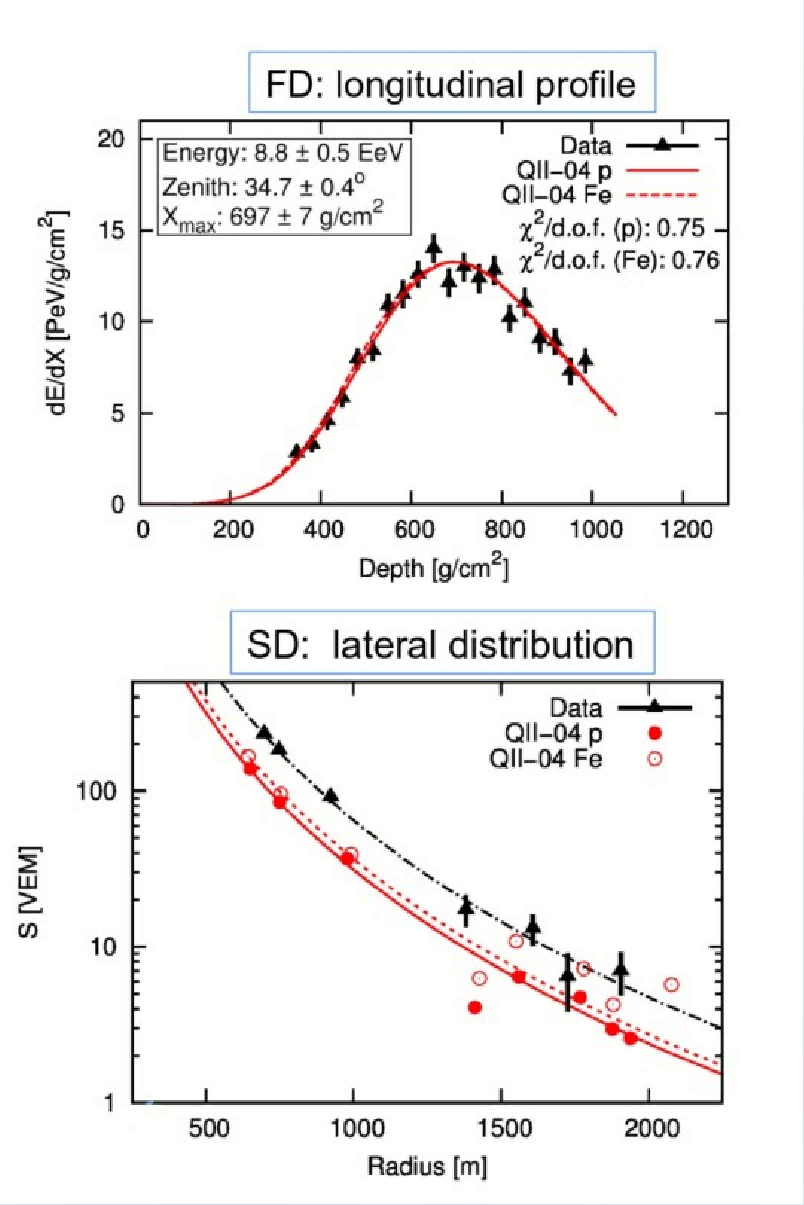
in two energy bins **17.8 < lg(E/eV) < 18** and **18 < lg(E/eV) < 18.5**
where the flux is expected to be dominated by protons



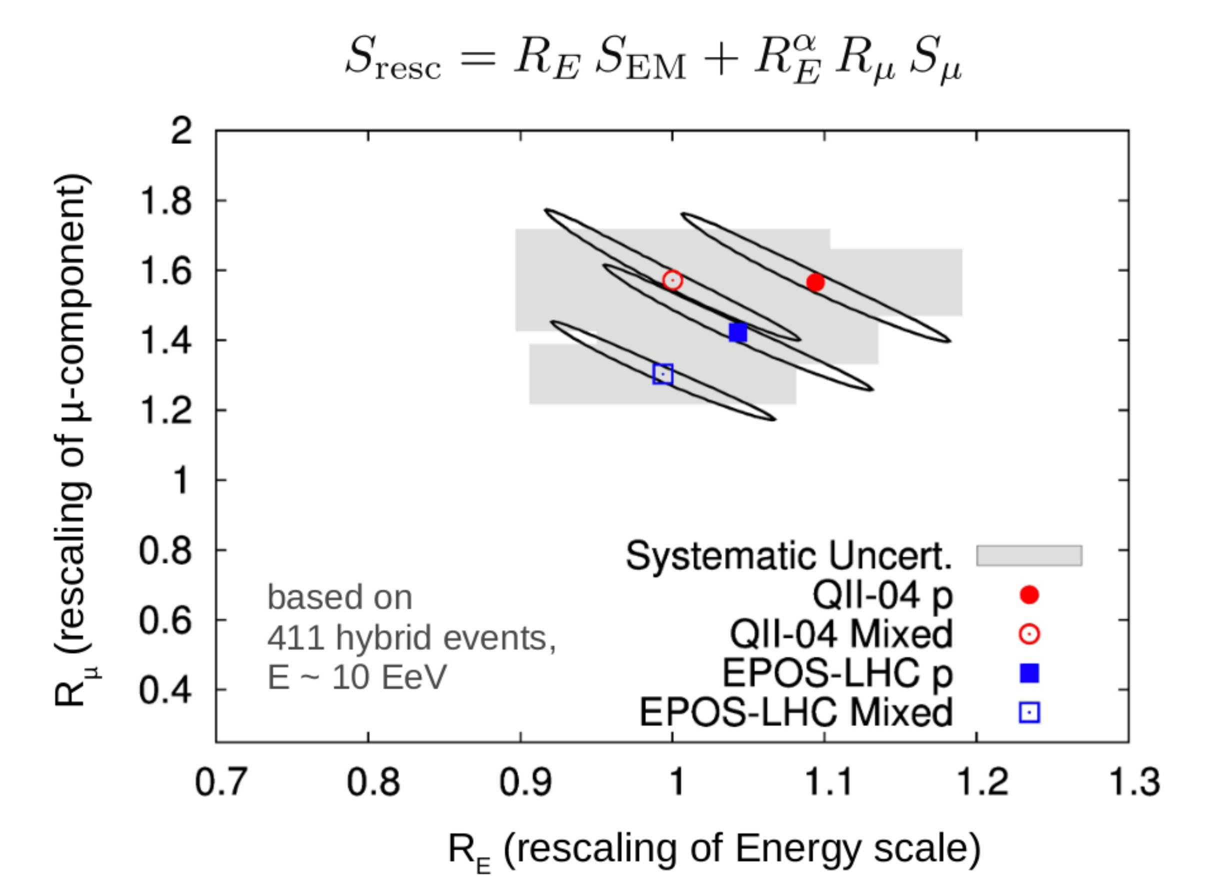
tail of the Xmax distribution is related to the distribution of the first interaction point
← inversely proportional to p-air cross section

Probing hadronic interaction models

- set of hybrid events used
- event reconstructed by fluorescence detector only
- the corresponding parameters used to simulate the surface detector response
- the simulations underestimate the signal with respect to the measured one for all events
- discrepancy is growing with larger zenith angles



Probing hadronic interaction models



- the number of muons in hadronic interaction models is too low by at least 30%

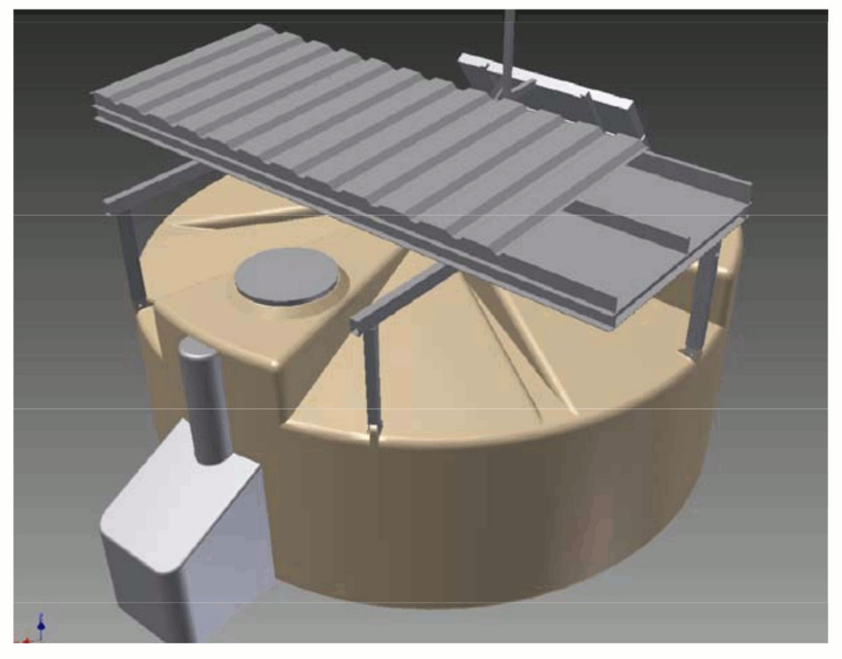
- more on hadronic interactions a dedicated talk by Francisco Diogo on Friday

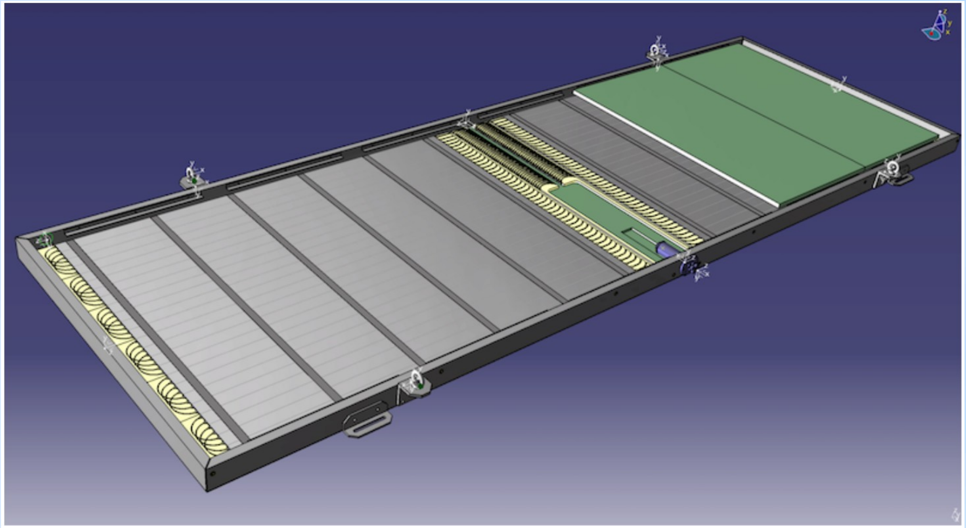
Upgrade motivation

- gain a mass composition information in the flux suppresion region - distinguish between propagation effect and maximum energy from astrophysical sources
- search for a proton flux at highest energies – reach sensitivity to a contribution as low as 10%
- air shower physics and hadronic multiparticle production studies at energies unreachable by man-made accelerators

Upgraded observatory

- add a scintillation panel above each SD station
- faster and more powerfull electronics
- complete AMIGA muon counter array
- small PMT in the tank to encrease the dynamic range
- extend the FD operation to periods with higher night sky background





- More in a dedicated talk by Gabriella Cataldi

Summary

- many more interesting analyses can be found in astro-ph.HE:1509.03732v1
- joint analyses with TA and IceCube: astro-ph.HE: 1511.02103 and 1511.02109

- observed a clear suppression of the flux of cosmic particles above $10^{19.5}$ eV
- observed a shift from lighter to heavier particles above 10^{19} eV
- capability to do particle physics at energies far beyond man-made accelerators

- plan is to collect data until 2025
- with upgraded detector: scintillator above each tank, faster electronics, improved dynamic range, ...