PIERRE AUGER OBSERVATORY

INFN Istituto Nazionale di Fisica Nucleare

Raggi Cosmici di Alta Energia L'Osservatorio Pierre Auger

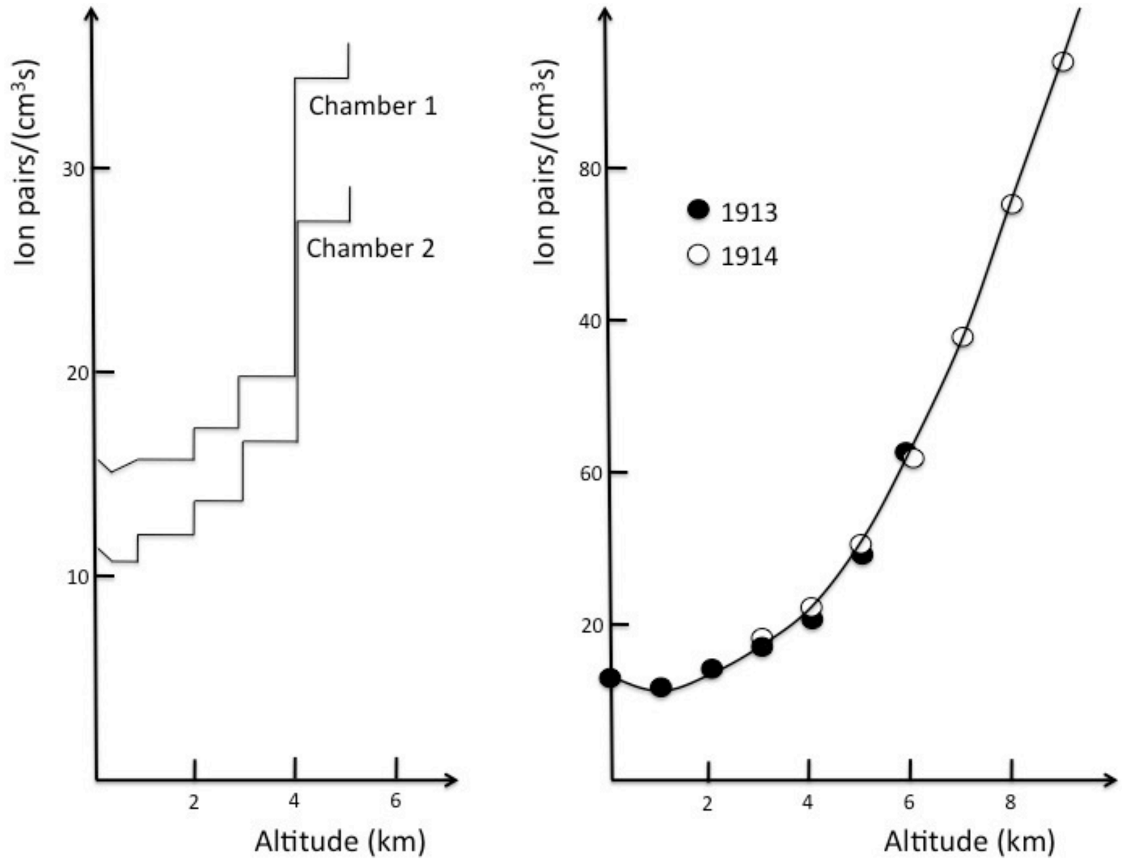
GONZALO RODRIGUEZ, INFN, Roma, Italia

For the Pierre Auger Collaboration

A little bit of History

PIERRE AUGER
OBSERVATORY

Victor Hess balloon flight (1912)



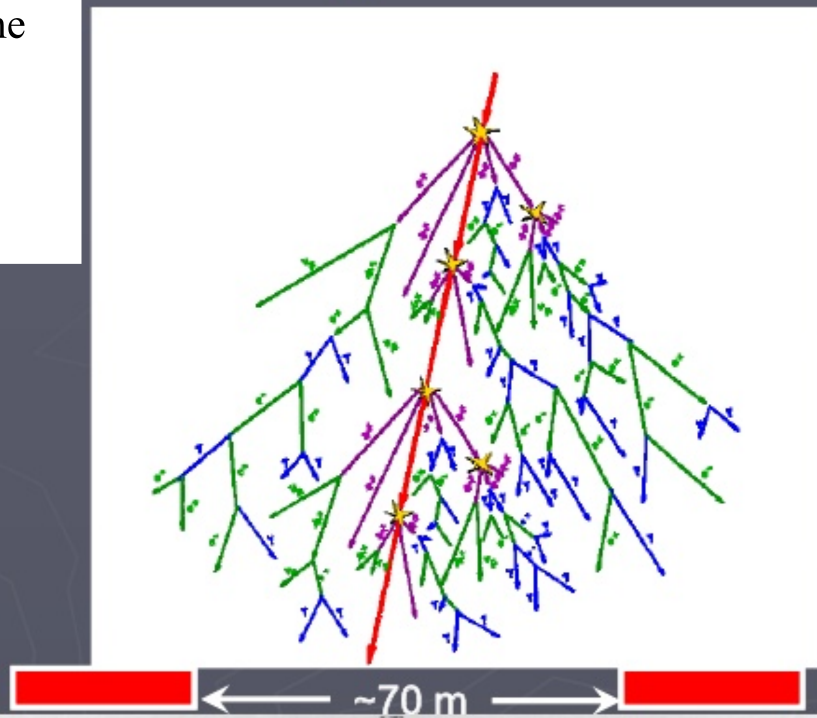
Increase of ionization with altitude as measured
Hess in 1912 (left) and by Kolhörster 1913-1914 (right)

A little bit of History

Pierre V. Auger

In 1938, Pierre Auger found that the cosmic radiation events were coincident in time meaning that they were associated with a single event, an air shower.

P. Auger (1899 – 1993)



PIERRE AUGER OBSERVATORY

New discoveries in fundamental physics from cosmic rays

PIERRE AUGER OBSERVATORY

- 1933: Antimatter, discover of the positron by Anderson using a cluod chamber
- 1937: The muon, or mu lepton, discovered by Neddermeyer+(mistaken for the pion until 1947: Conversi, Pancini, Piccioni)
- 1947: Pion (or p meson), the first meson, discovered by Lattes, Occhialini & Powell (predicted by Yukawa in 1935)
- 1947: Kaon (or K meson), the first strange particle, discovered by Rochester & Butler
- 1951: Λ, the first strange baryon, discovered by Armenteros+
- 1951-54: Parity violation (G-stack, the first European collaboration – mother of the modern HEP collaborations)

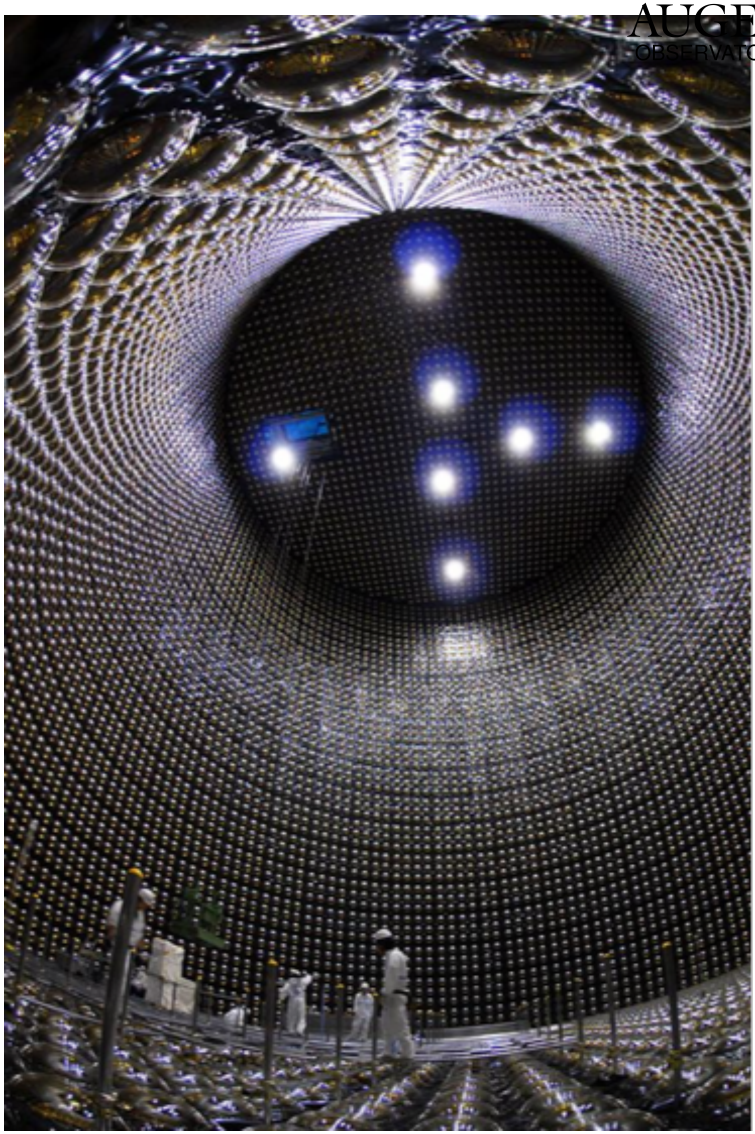
and CR continue to contribute to fundamental physics

PIERRE AUGER OBSERVATORY

- Cosmic rays and cosmological sources again move into the focus of VHE particle and gravitational physics

- One of the most important recent result on elementary particle physics came from cosmic rays: neutrino has a nonzero mass

  - Interplay between CR and accelerator physics, again
  - Solar neutrinos; KamLAND 2002 (reactor), Gran Sasso 2010 (accelerator), T2K 2011



Work in the field of cosmic rays

PIERRE
AUGER
OBSERVATORY

- CMB (1964)

- X-ray astrophysics
  – Rockets (1962) and satellites (Uhuru 1970, ...)

- VHE gamma-ray astrophysics
  – Many attempts in '60-'70; observation of Crab above 100 GeV, Weekes et al. 1989
  – Present large-scale IACTs HESS, MAGIC, VERITAS, CTA; Agile, Fermi satellites

- EHE cosmic detectors
  – Observation of a particle ~ 10^{20} eV in 1962 at Volcano Ranch (Linsley, Scarsi et al. 1962)
  – 1966: the GZK limit
  –...
  – Present large-scale detectors: the Pierre Auger laboratory

- Neutrino detectors
- ...

Work in the field of cosmic rays

PIERRE AUGER OBSERVATORY

- CMB (1964)
- X-ray astrophysics
  – Rockets (1962) and satellites (Uhuru 1970, ...)
- VHE gamma-ray astrophysics
  – Many attempts in '60-'70; observation of Crab above 100 GeV, Weekes et al. 1989
  – Present large-scale IACTs HESS, MAGIC, VERITAS, CTA; Agile, Fermi satellites
- EHE cosmic detectors
  – Observation of a particle ~ 10^{20} eV in 1962 at Volcano Ranch (Linsley, Scarsi et al. 1962)
  – 1966: the GZK limit
  –...
  – **Present large-scale detectors: the Pierre Auger laboratory**
- Neutrino detectors
- ...

Key Questions

PIERRE AUGER OBSERVATORY

- What is the origin of the flux suppression above $10^{19.6}$ eV?
  - Photodisintegration?
  - Maximum energy at sources?
- Is there a proton component at the highest energies?
  - Impact on neutrino spectrum
  - Particle astronomy
- Is new particle physics beyond the reach of LHC required?

Key Questions

PIERRE AUGER OBSERVATORY

- What is the origin of the flux suppression above $10^{19.6}$ eV?
  - Photodisintegration?
  - Maximum energy at sources?
- Is there a proton component at the highest energies?
  - Impact on neutrino spectrum
  - Particle astronomy
- Is new particle physics beyond the reach of LHC required?

Key Questions

PIERRE AUGER OBSERVATORY

- What is the origin of the flux suppression above $10^{19.6}$ eV?
  - Photodisintegration?
  - Maximum energy at sources?
- Is there a proton component at the highest energies?
  - Impact on neutrino spectrum
  - Particle astronomy
- Is new particle physics beyond the reach of LHC required?

Outline

- The Auger Observatory – close to the end of phase 1
  Events and analysis methods
  Vertical and inclined showers

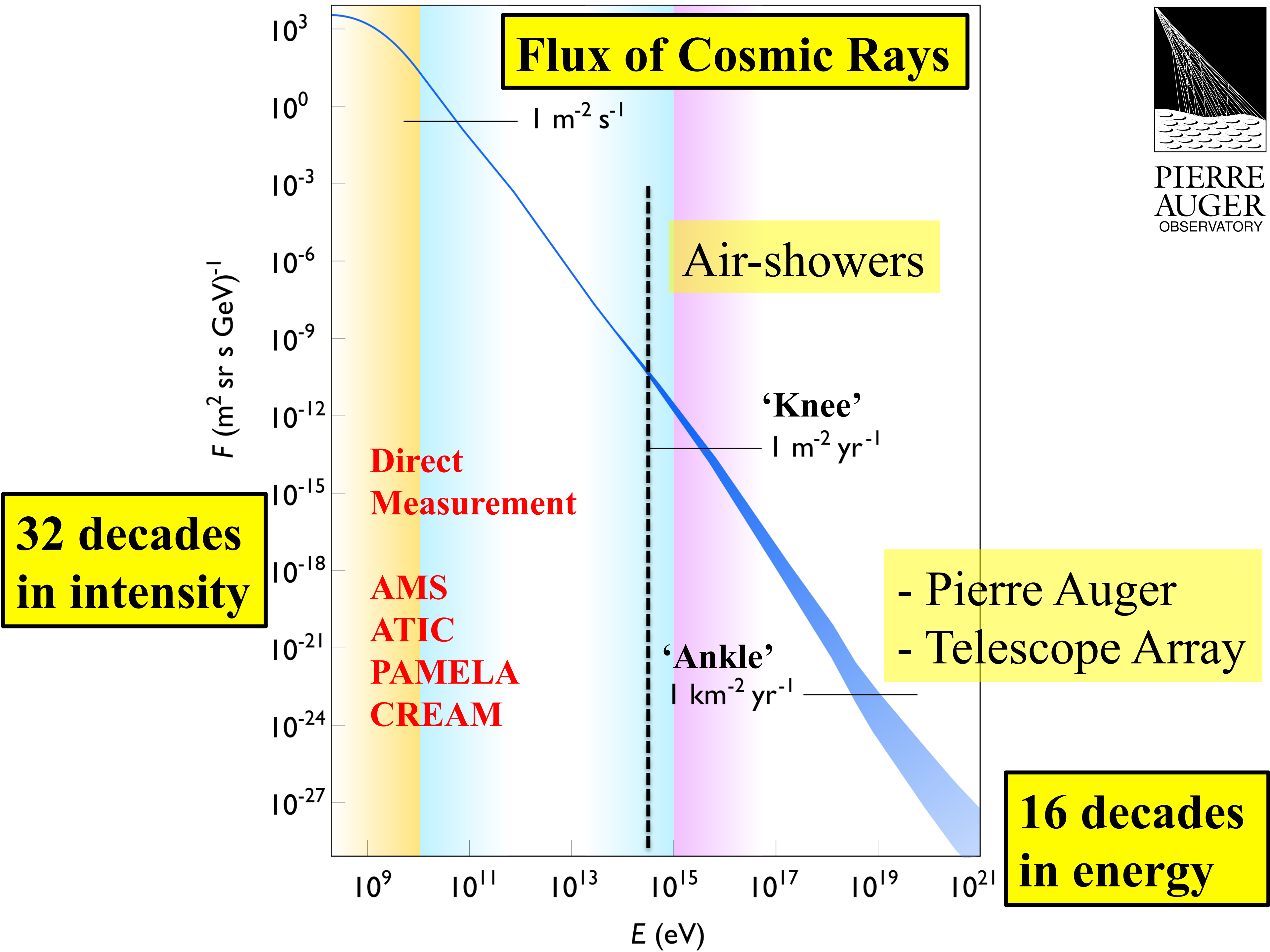
- Spectrum measurements

- Arrival directions

- Mass: Recent results on Nuclei
  Photon limit
  Neutrino limit

- Insights into hadronic interactions

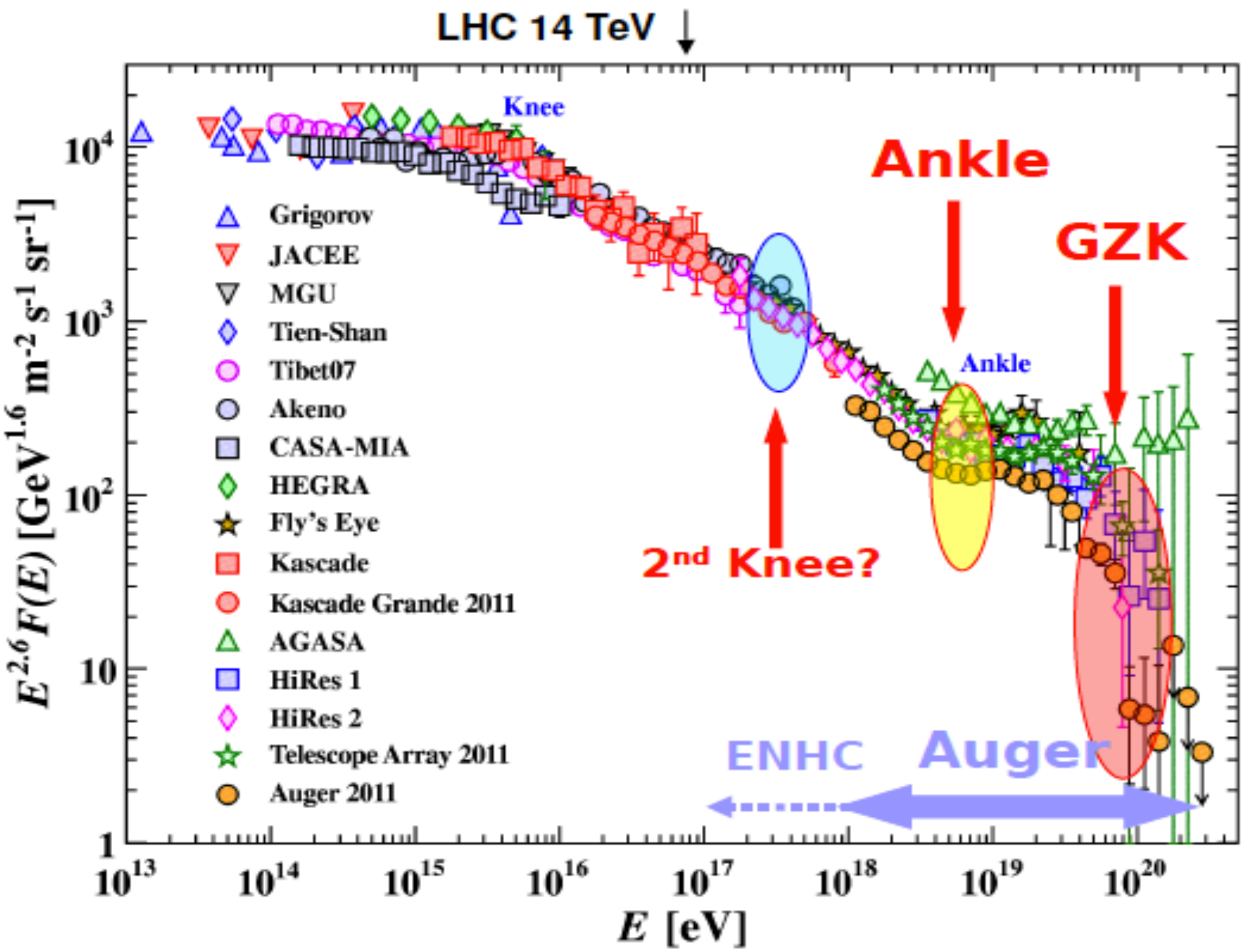
- Summary



Flux of Cosmic Rays
1 m-2 s-1
Air-showers
'Knee'
1 m-2 yr-1
'Ankle'
1 km-2 yr-1
Direct Measurement
AMS
ATIC
PAMELA
CREAM
- Pierre Auger
- Telescope Array
32 decades in intensity
16 decades in energy
F (m2 sr s GeV)-1
E (eV)
PIERRE AUGER OBSERVATORY

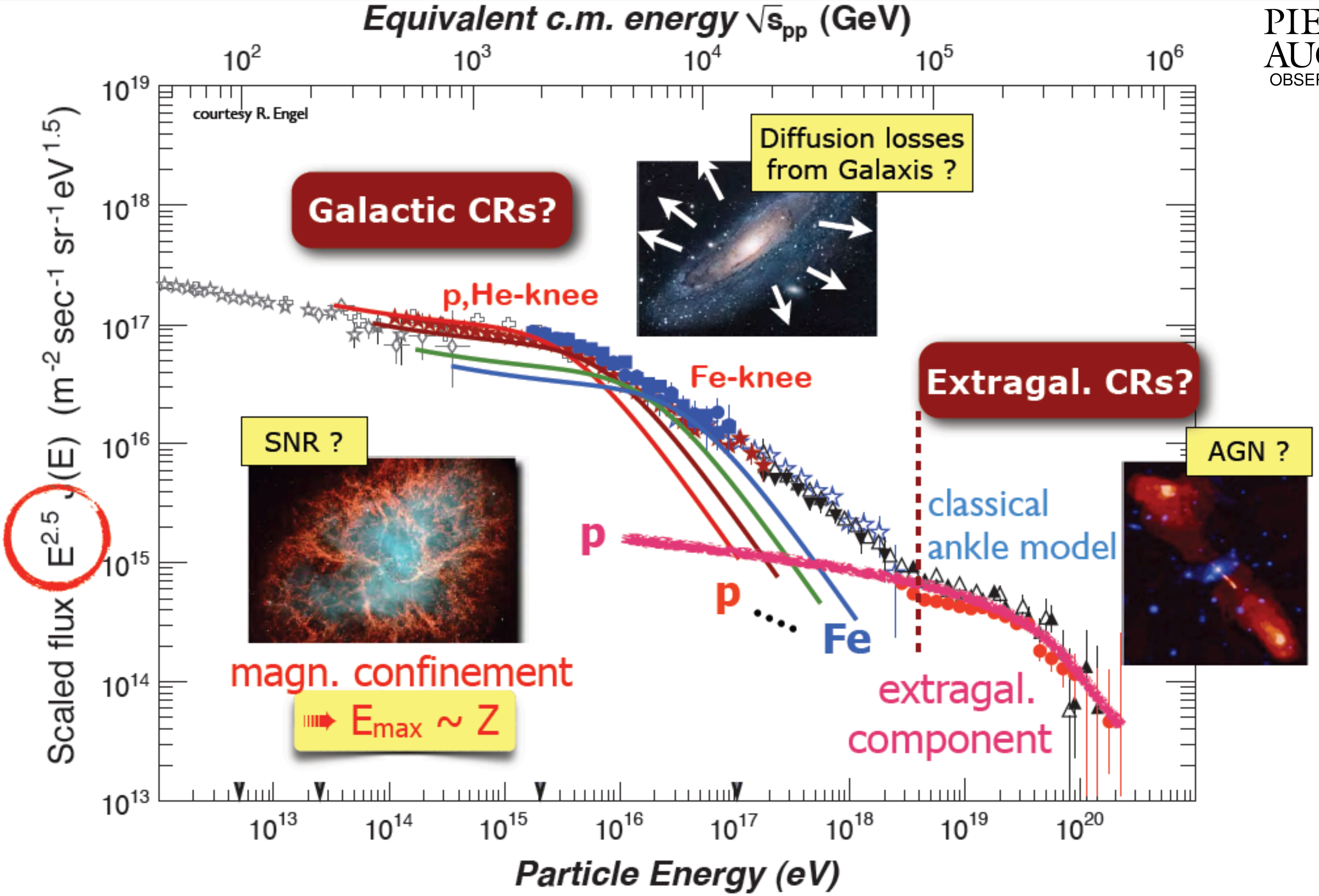
Cosmic Rays Data

PIERRE AUGER OBSERVATORY



Pierre Auger Observatory Energy > 10^{18} eV

Cosmic Rays Data
Sources and composition



PIERRE AUGER OBSERVATORY

Does the Cosmic Ray Energy Spectrum terminate

PIERRE AUGER OBSERVATORY

Greisen-Zatsepin-Kuz'min – GZK effect (1966)

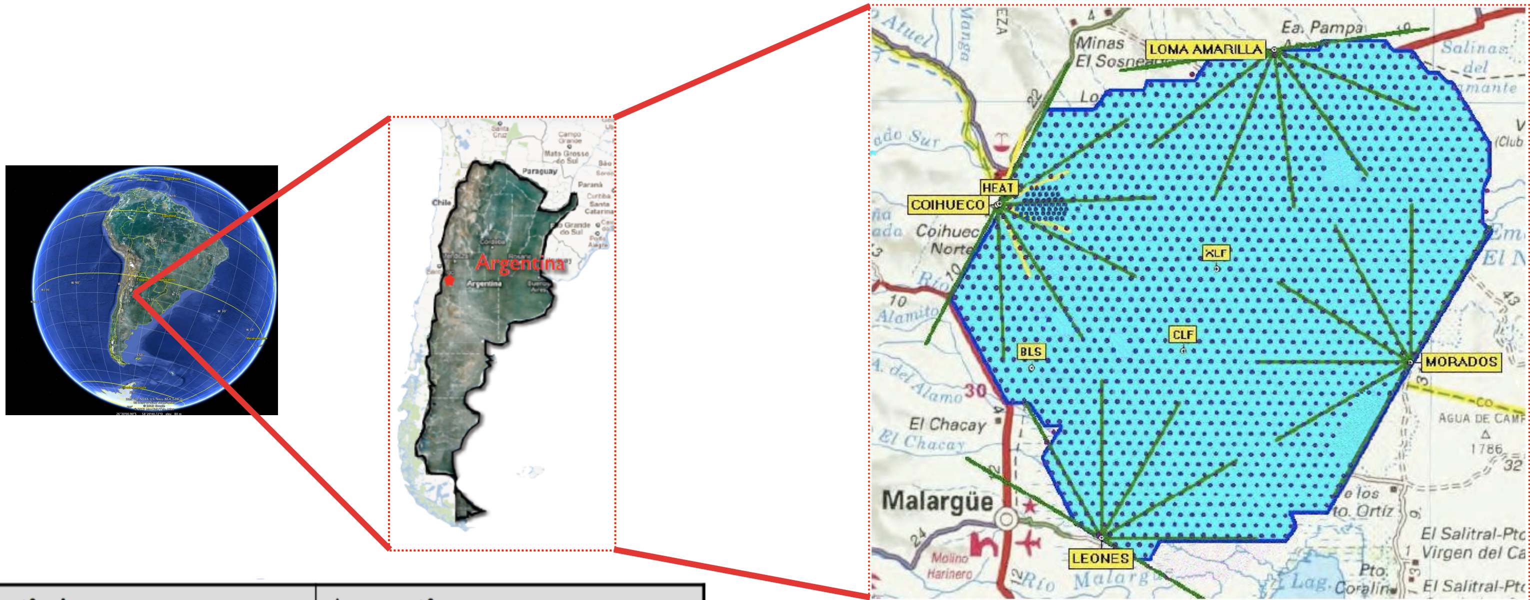
$$\gamma_{2.7\,K} + p \rightarrow \Delta^{+} \rightarrow n + \pi^{+} \text{ or } p + \pi^{o}$$

and

$$\gamma_{IR/2.7\,K} + A \rightarrow (A - 1) + n$$

- **Sources must lie within ~ 100 Mpc at 100 EeV**
  - **Note that neutrinos - of different energies – come from the decay of π^{+} and n**
  - **Photons from decay of π^{o}**

The Pierre Auger Observatory

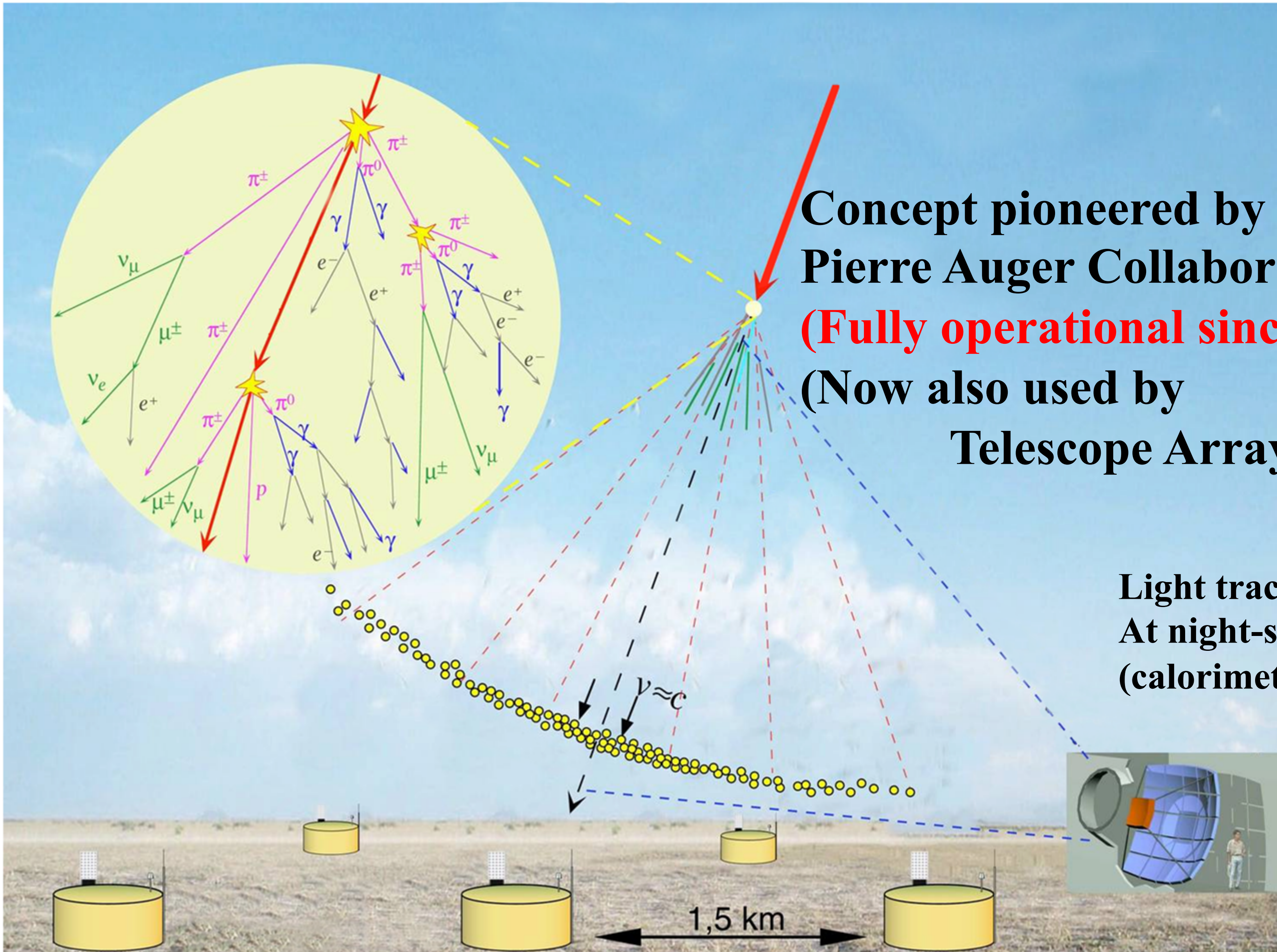


Croatia*	Argentina
Czech Republic	Australia
France	Brasil
Germany	Bolivia*
Italy	Colombia*
Netherlands	Mexico
Poland	USA
Portugal	Vietnam*
Rumania	
Slovenia	**Associate Countries*
Spain	~ 400 PhD scientists from
(United Kingdom)	~ 100 Institutions in 17

Aim: To measure properties of UHECR with unprecedented precision to discovery properties and origin of UHECR

Hybrid Observation of EAS

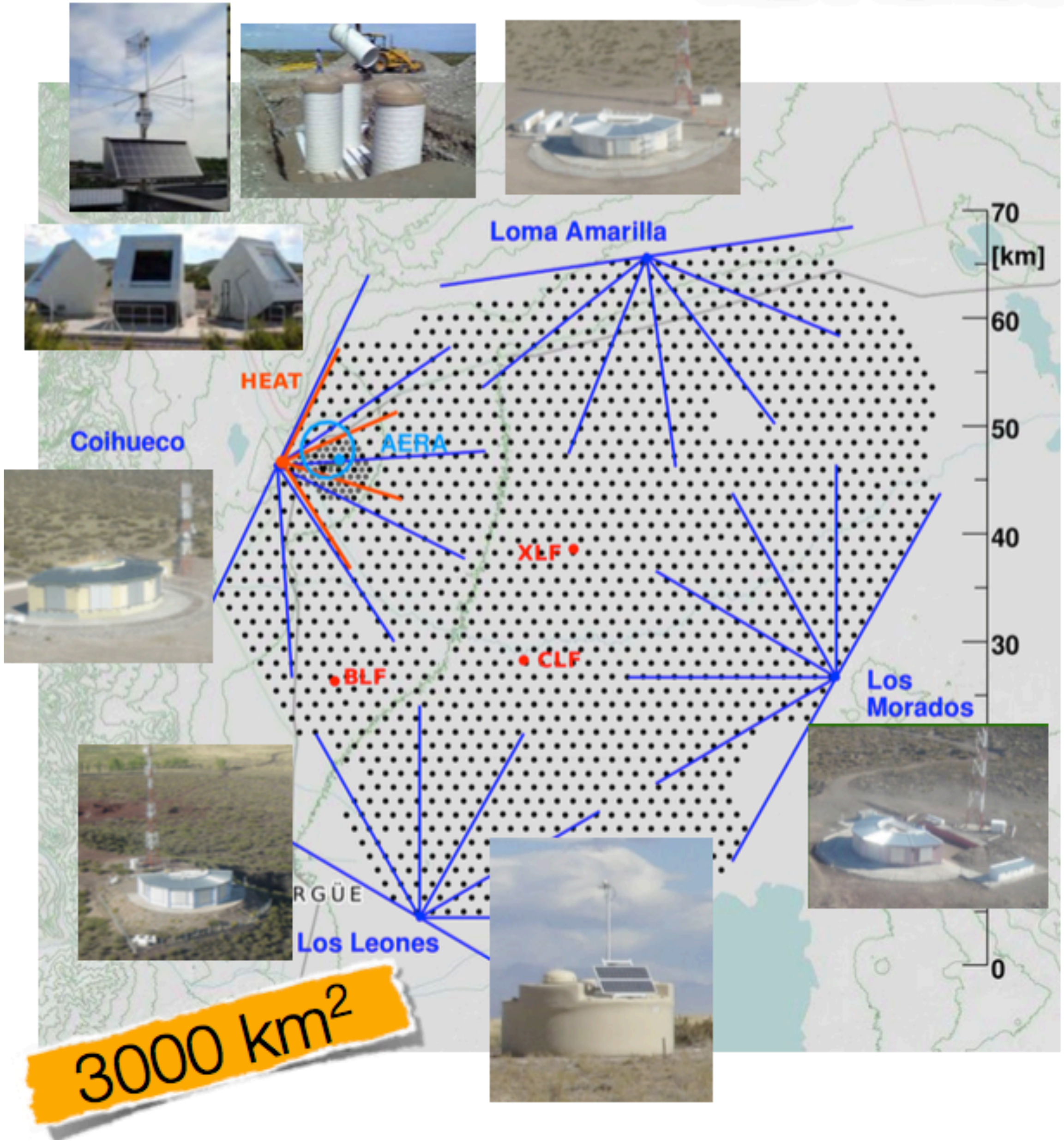
PIERRE AUGER OBSERVATORY



Concept pioneered by the Pierre Auger Collaboration
(Fully operational since 06/2008)
(Now also used by Telescope Array (TA))

Light trace
At night-sky
(calorimetric)

The Pierre Auger Observatory



PIERRE AUGER OBSERVATORY

Water-Cherenkov tanks

- 1660 in a 1.5 km standard grid
- 71 in 0.75 km infill grid (~30 km^2)

Fluorescence Telescopes

- 24 in 4 buildings overlooking SD
- 3 in 1 building overlooking the Infill

Underground Muon detectors

- engineering array phase - 61 aside the Infill stations

AERA radio antennas

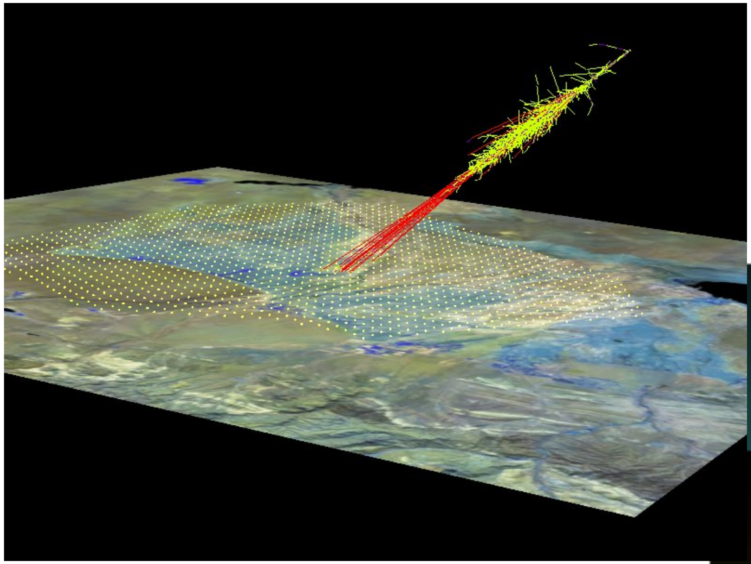
- 153 graded 17 km^2

Atmospheric monitoring stations

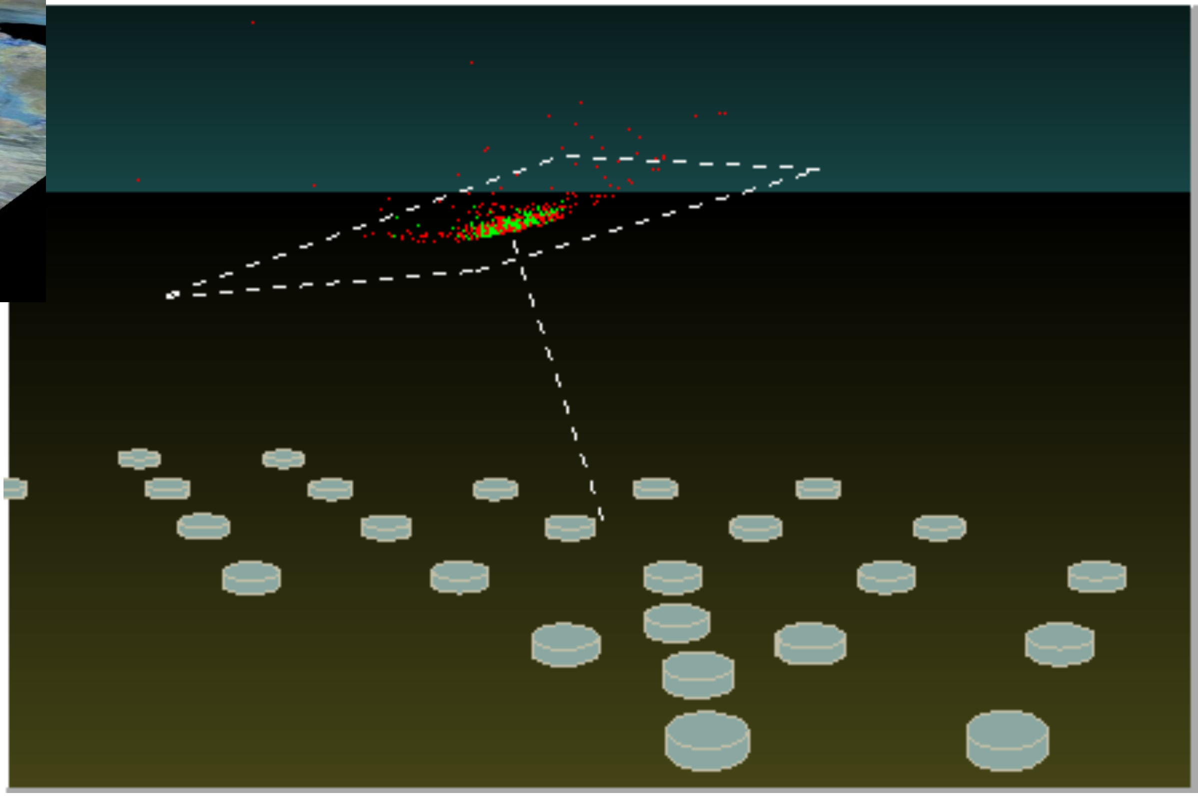
The Surface detector (SD)

Water Cherenkov Tank

PIERRE AUGER OBSERVATORY

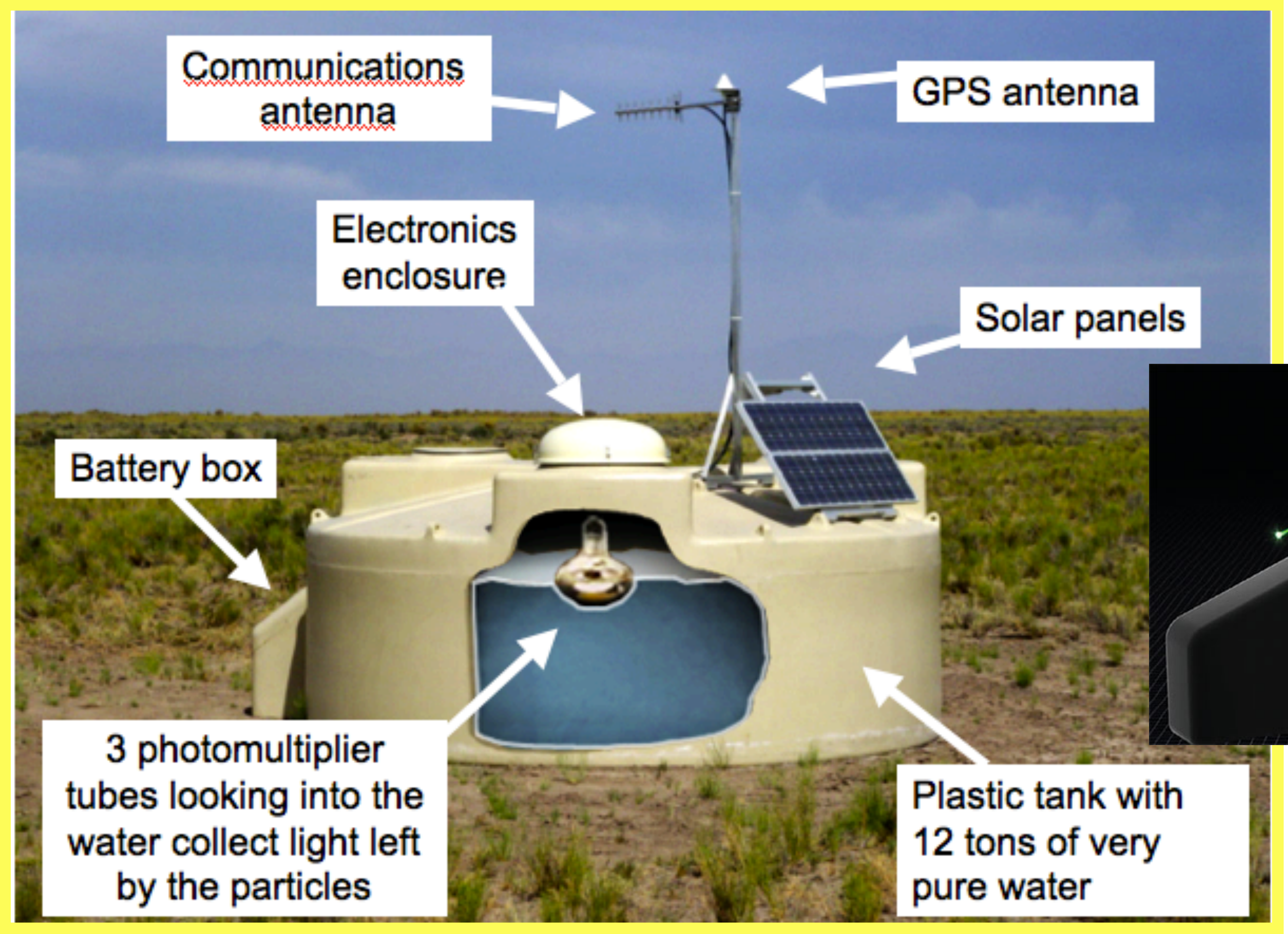


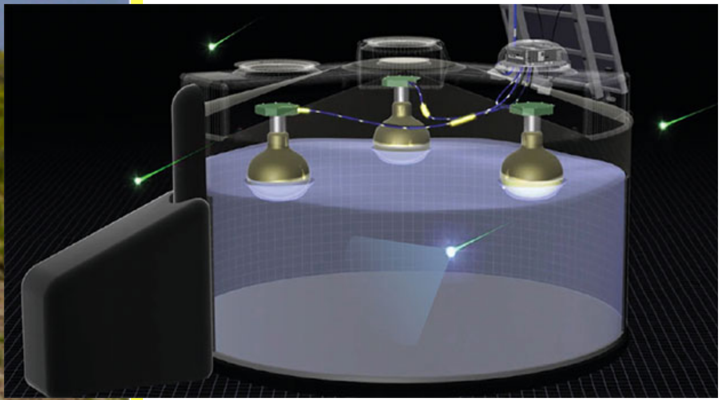
Millions of particles at ground:
SD detectors in coincidence sample the density of secondaries.



The Surface detector (SD)

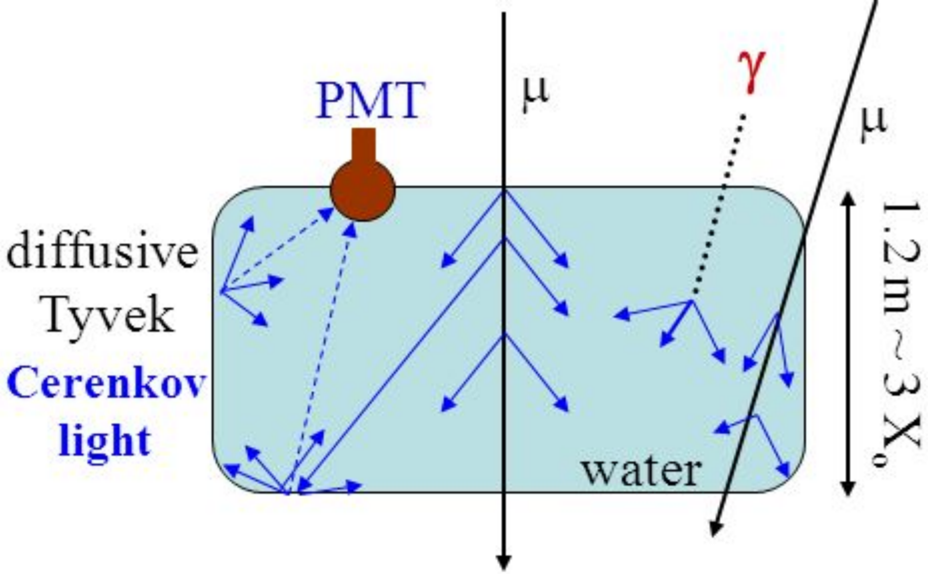
Water Cherenkov Station



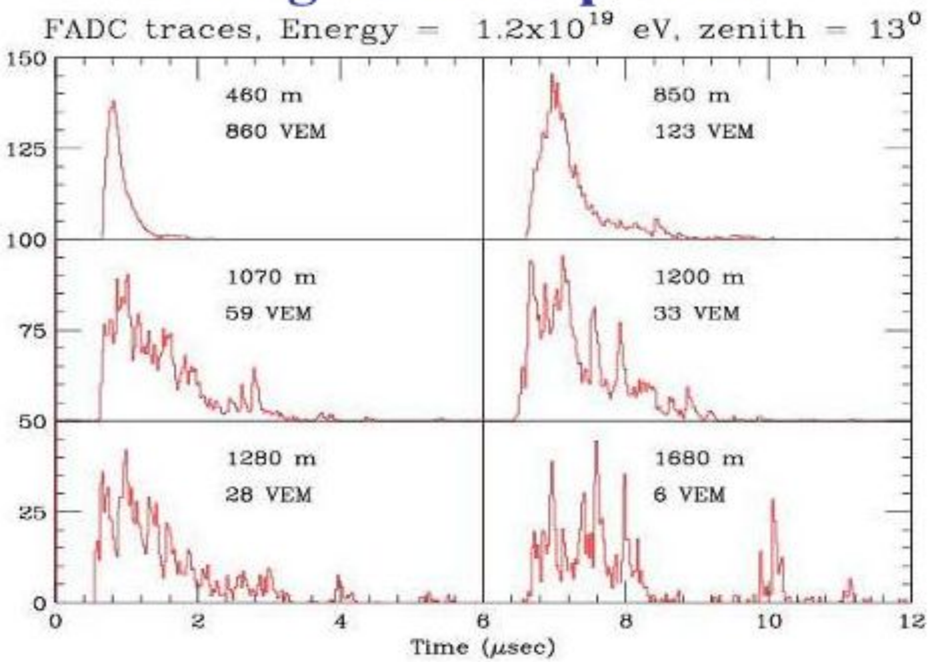


Tank Signal

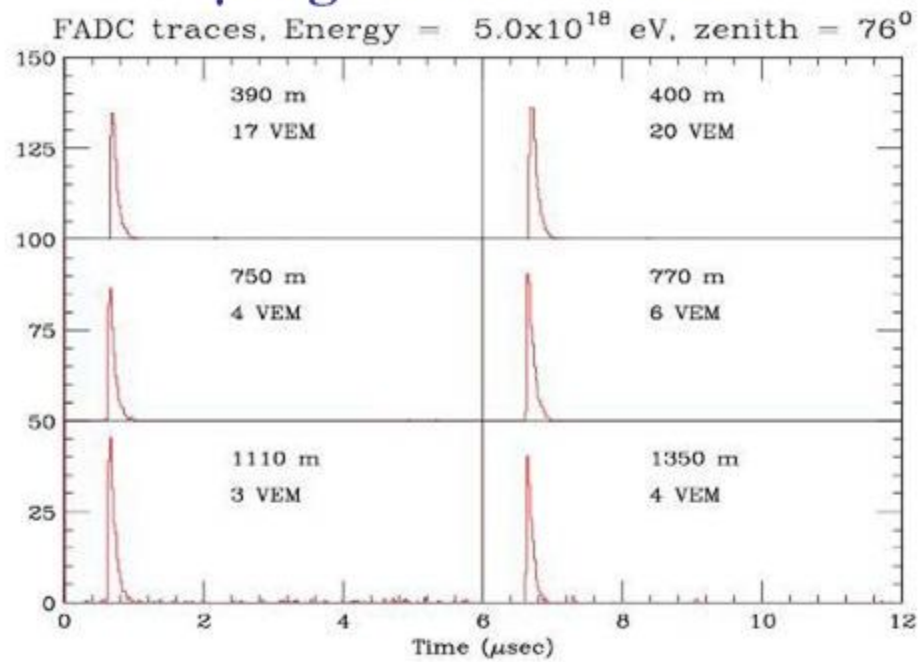
- μ-response ~ track
- e/γ-response ~ energy



'young' shower
strong e.m. component

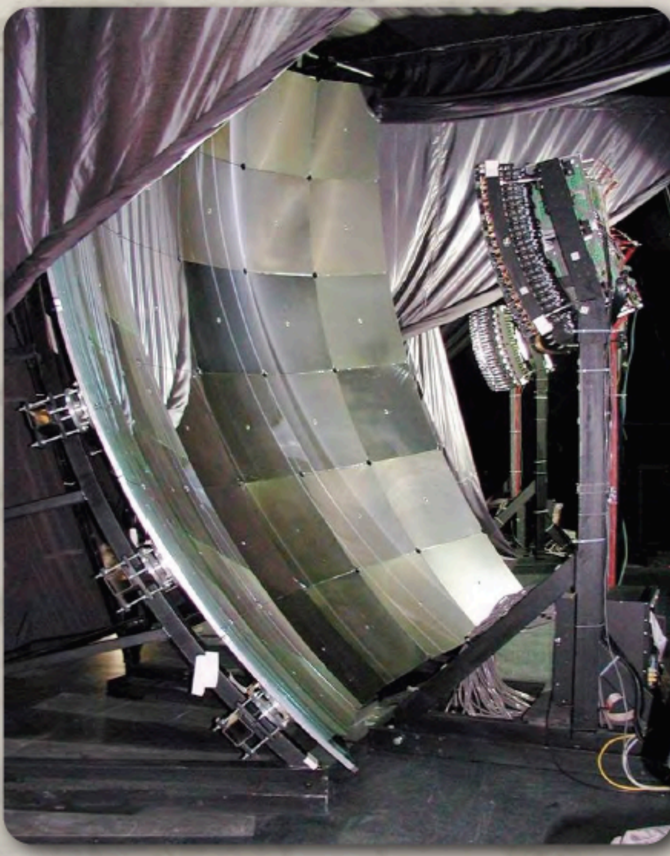


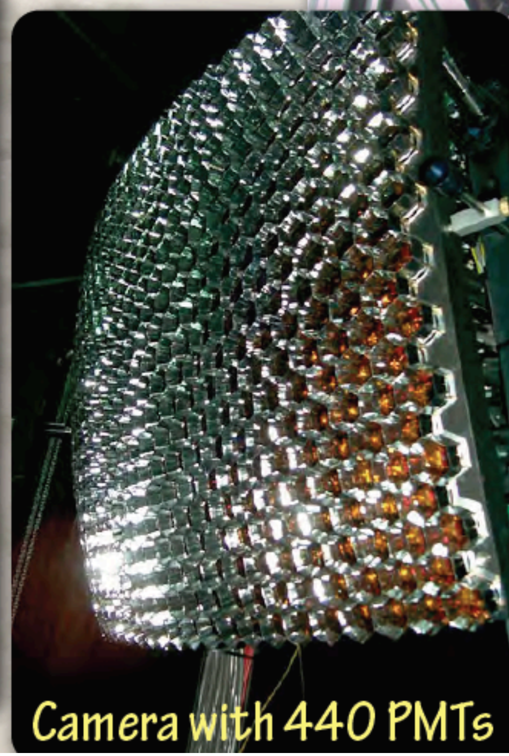
'old' shower
μ signal dominates

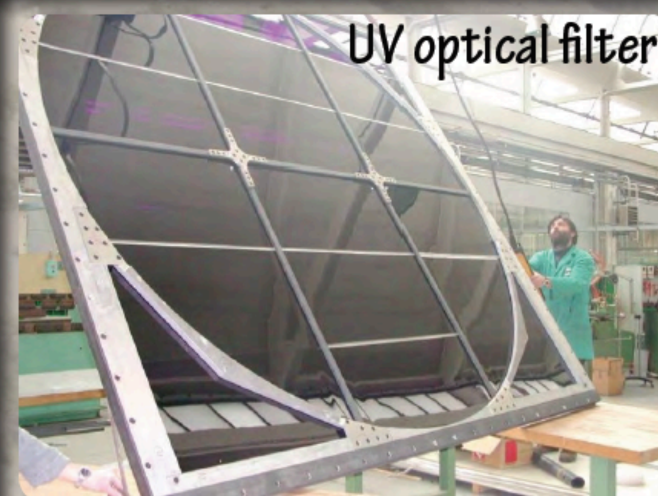


The Fluorescence detector (FD)

24 telescopes (6 per site)
12 m^2 mirrors, Schmidt optics
30°x30° deg field of view
440 PMTs/camera
10 MHz FADC readout



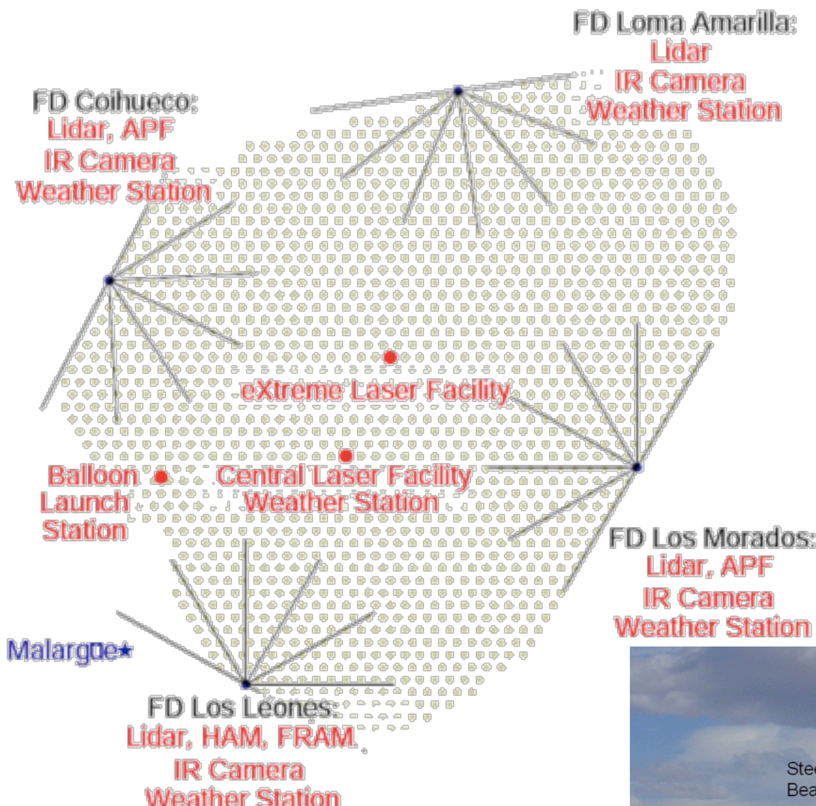




Atmospheric monitoring

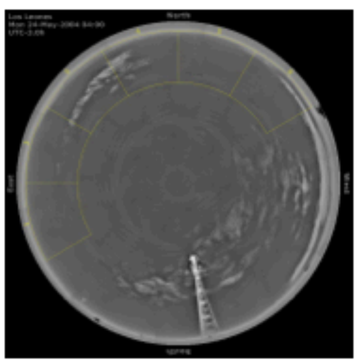
PIERRE AUGER OBSERVATORY

balloons

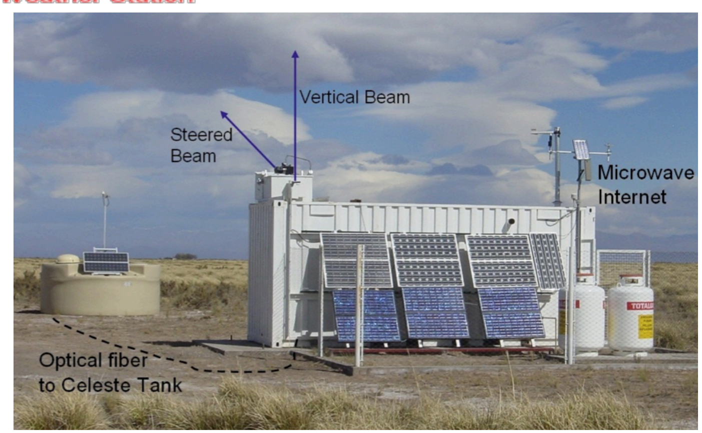


backscatter Lidar

IR cloud camera



Central Laser Facility

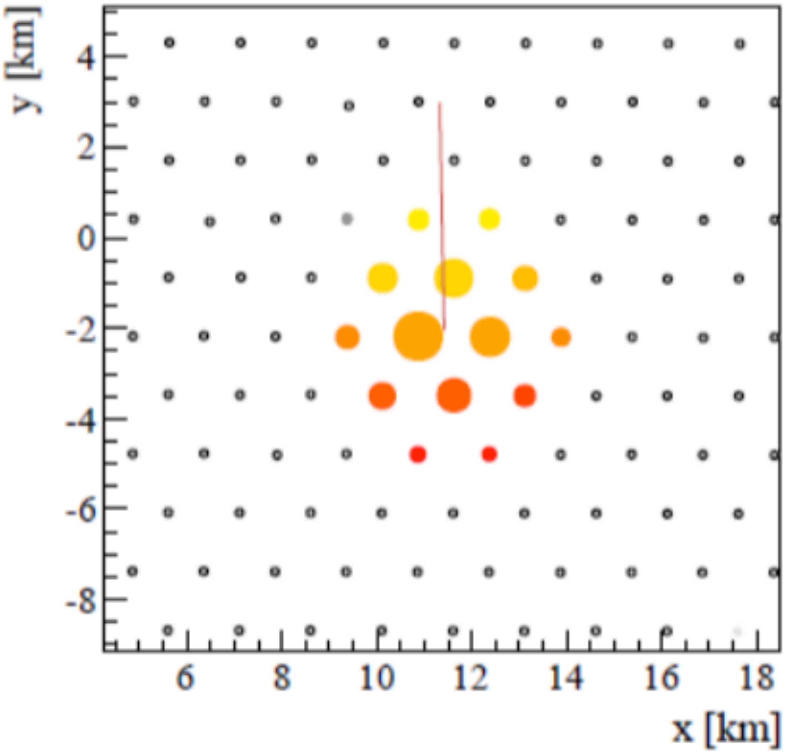


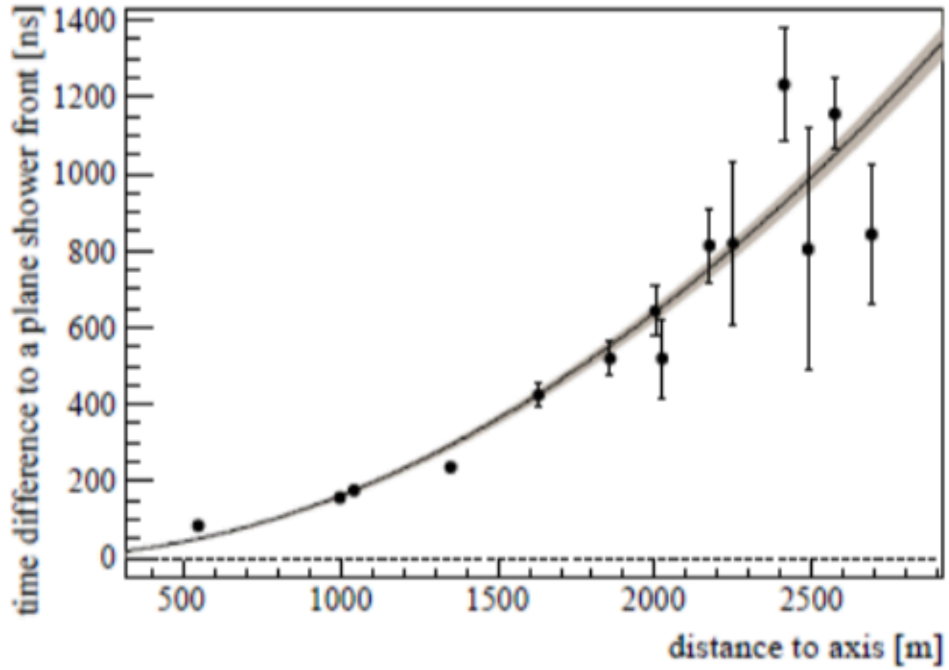
K. Louedec @ ICRC 2011

Reconstruction of an Event using Water-Cherenkov detectors

PIERRE AUGER OBSERVATORY

(i) Reconstruction of arrival direction





Angular accuracy: better than 0.9^0 for more than 6 station (arXiv 1502.01323)

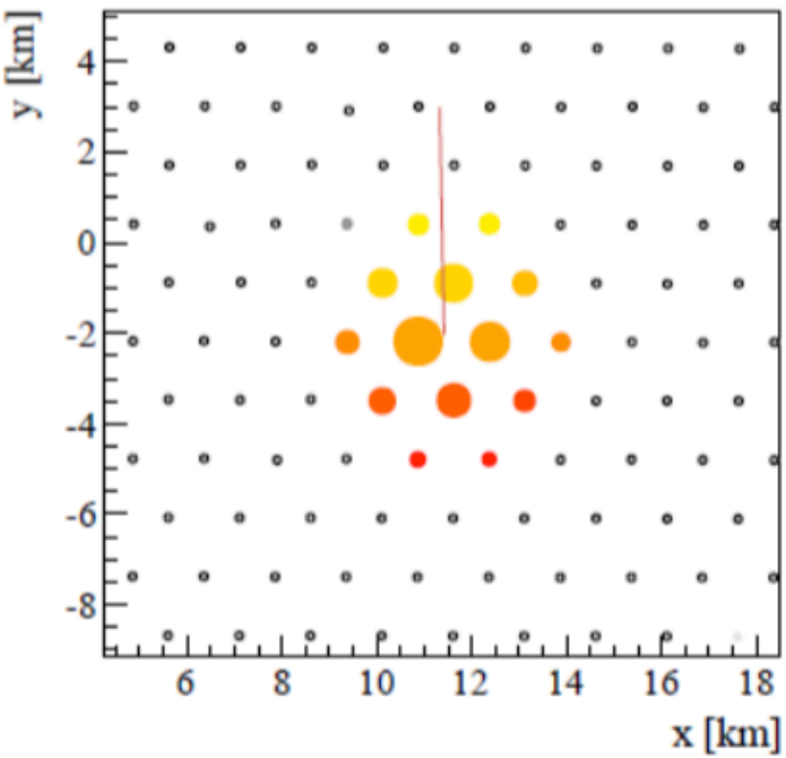
Reconstruction of an Event using Water-Cherenkov detectors

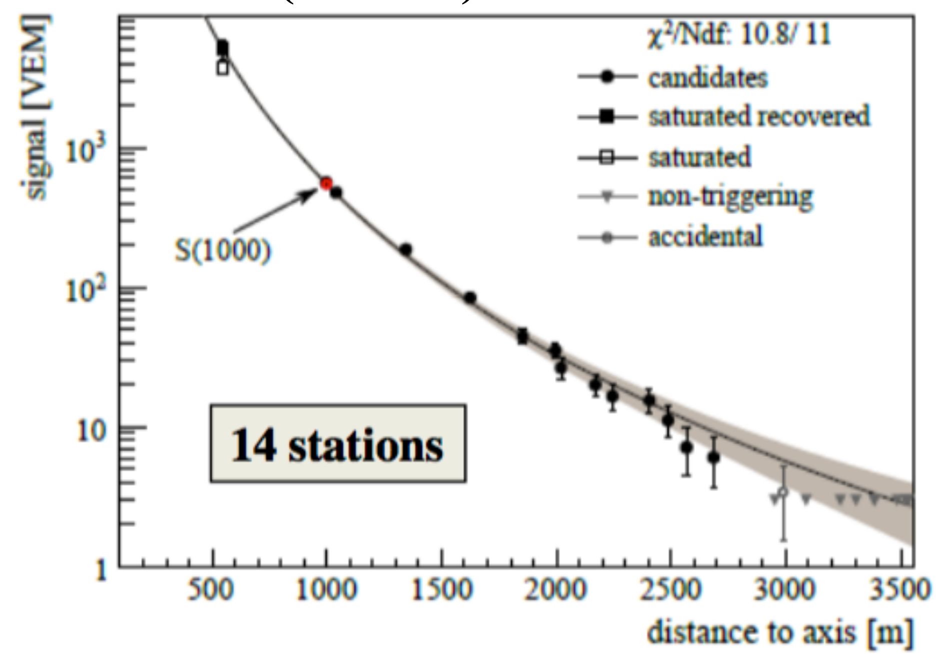
PIERRE AUGER OBSERVATORY

(ii) Reconstruction of shower size, S(1000)

Vertical shower: θ < 60°

E = (104 ± 11) eV and θ = 25.1°





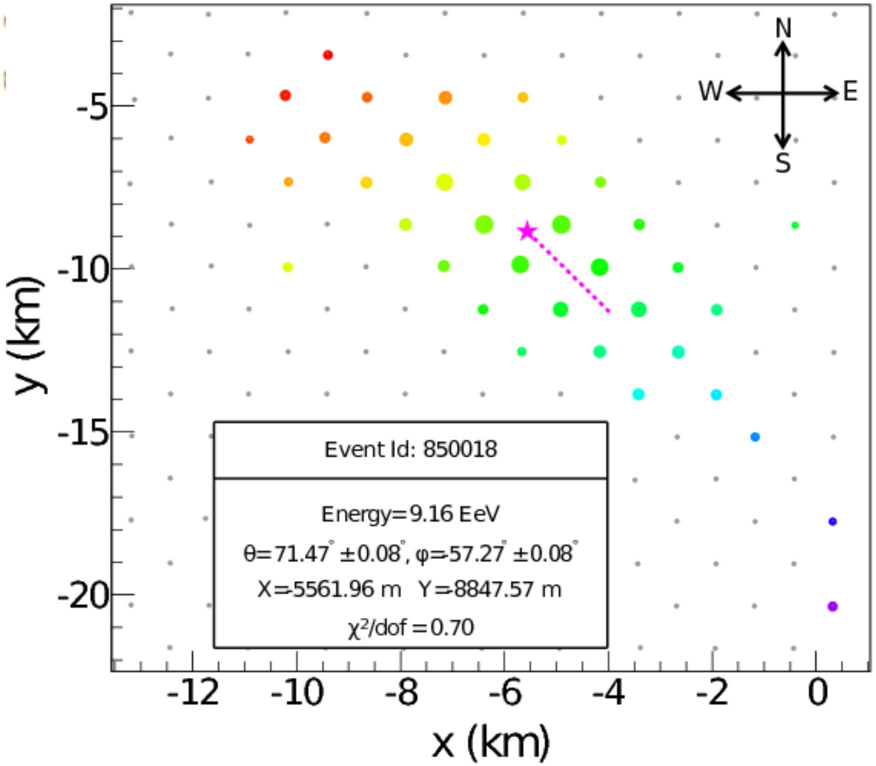
S(1000) distance at which signal has minimum spread for a range of lateral distributions
Accuracy of S(1000) ~ 10%. **(Details at arXiv 0709.2125 and 1502.01323)**

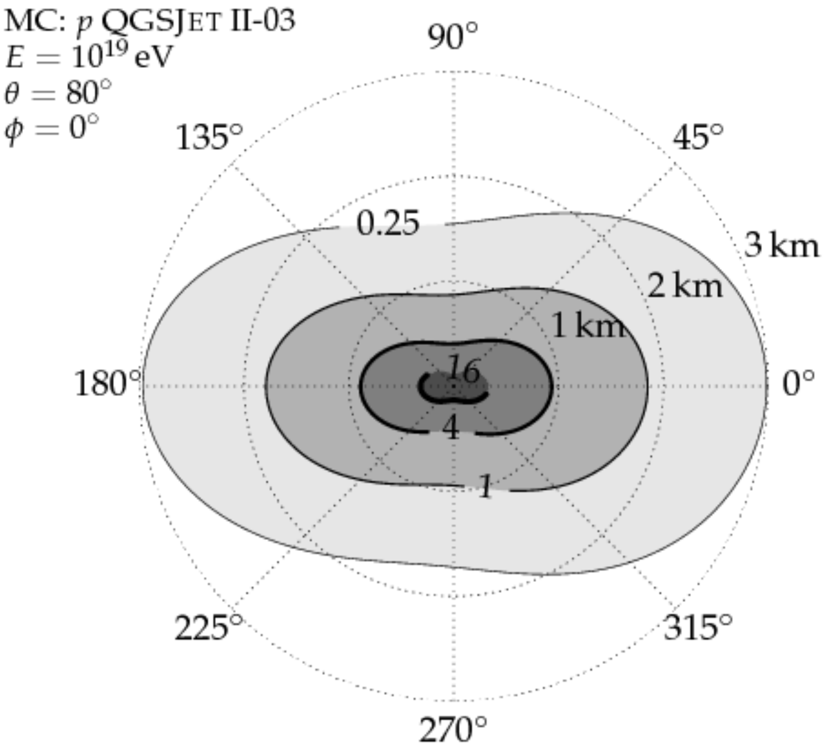
Reconstruction of an Event using Water-Cherenkov detectors

PIERRE AUGER OBSERVATORY

(iii) Reconstruction of shower size, R_μ

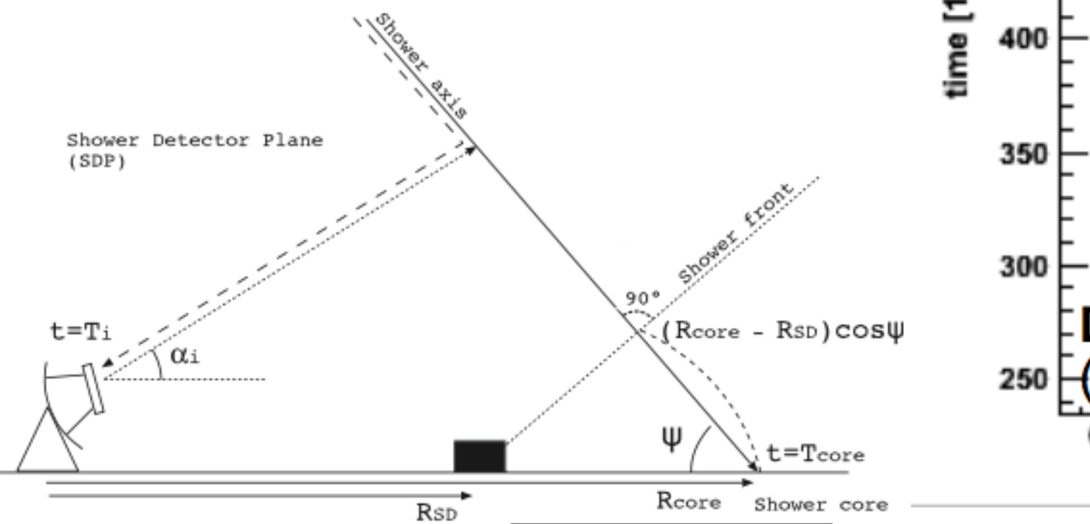
Inclined shower: θ > 62°

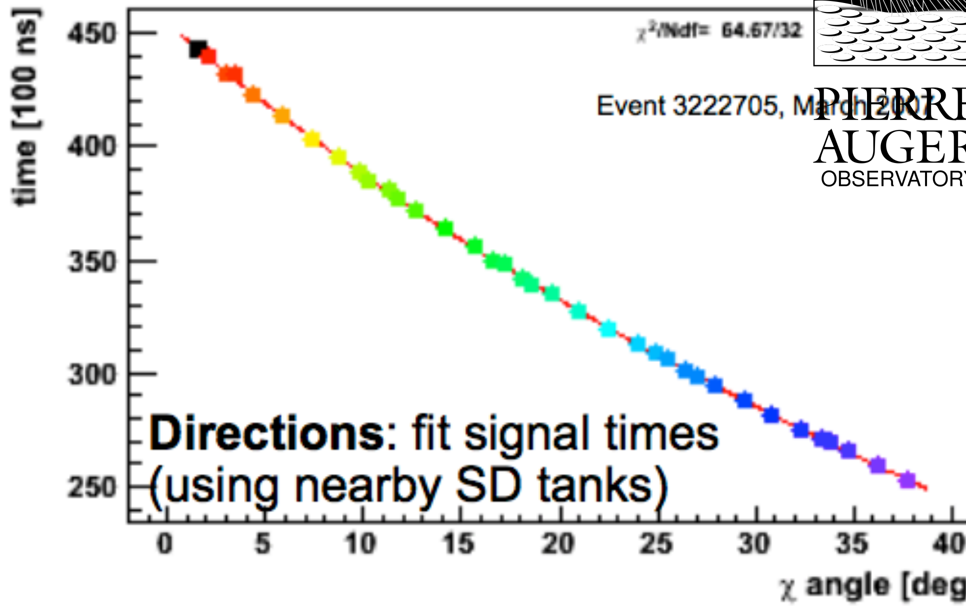


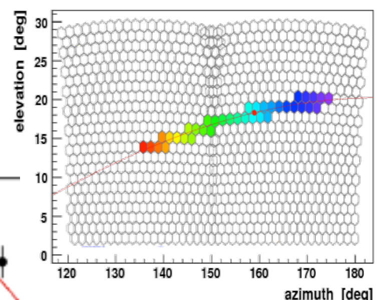


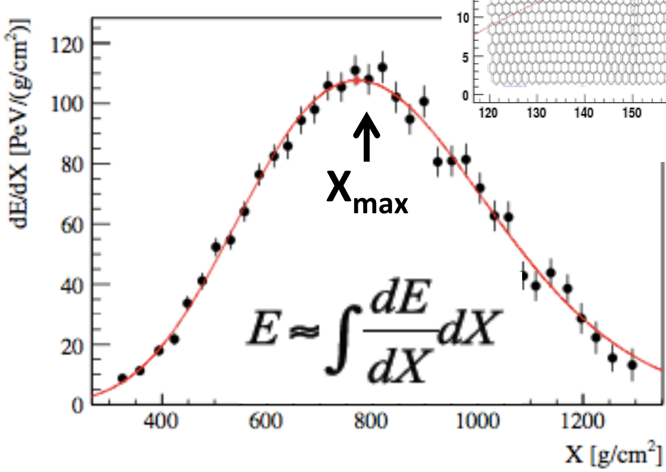
Particles must penetrate more atmosphere and at observation level the signals are almost entirely muons

Reconstruction of fluorescence event



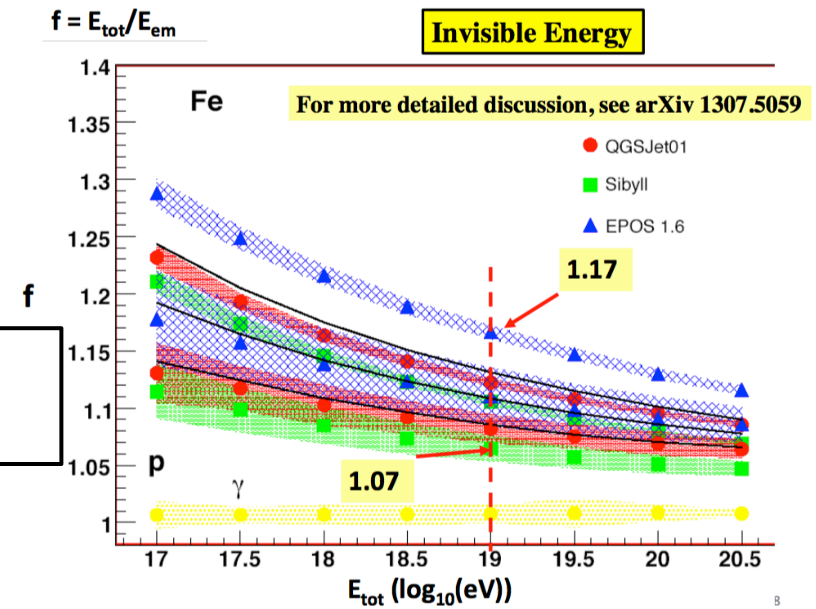




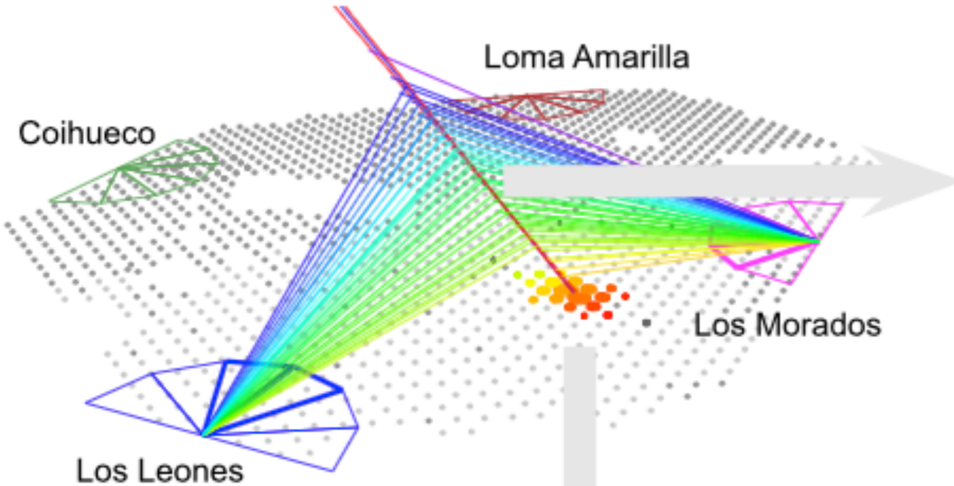


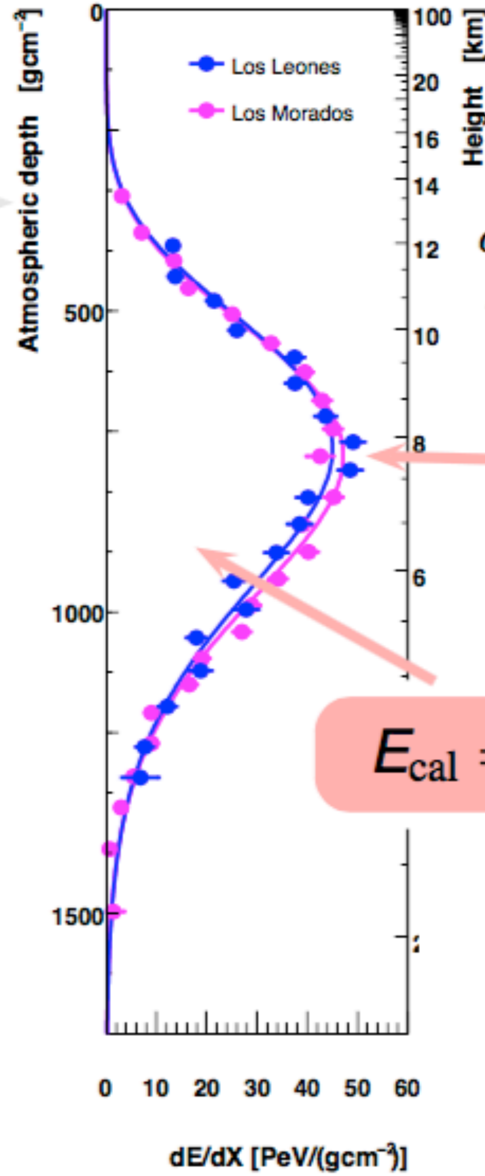
$$E \approx \int \frac{dE}{dX} dX$$

Must account for ‘invisible energy’



Hybrid detection of Air Showers



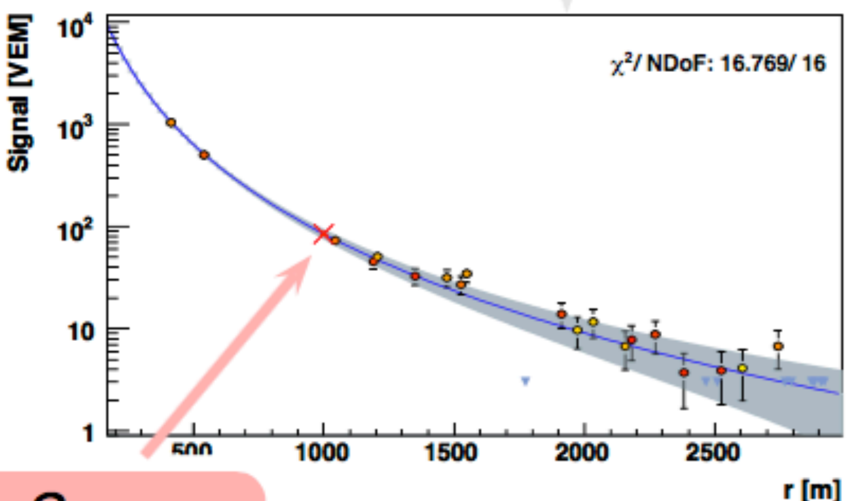


$\sigma_{X_{\max}} \leq 20\,\mathrm{g/cm^2}$
$\Delta_{\mathrm{sys}} \leq 10\,\mathrm{g/cm^2}$

$X_{\max}$

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

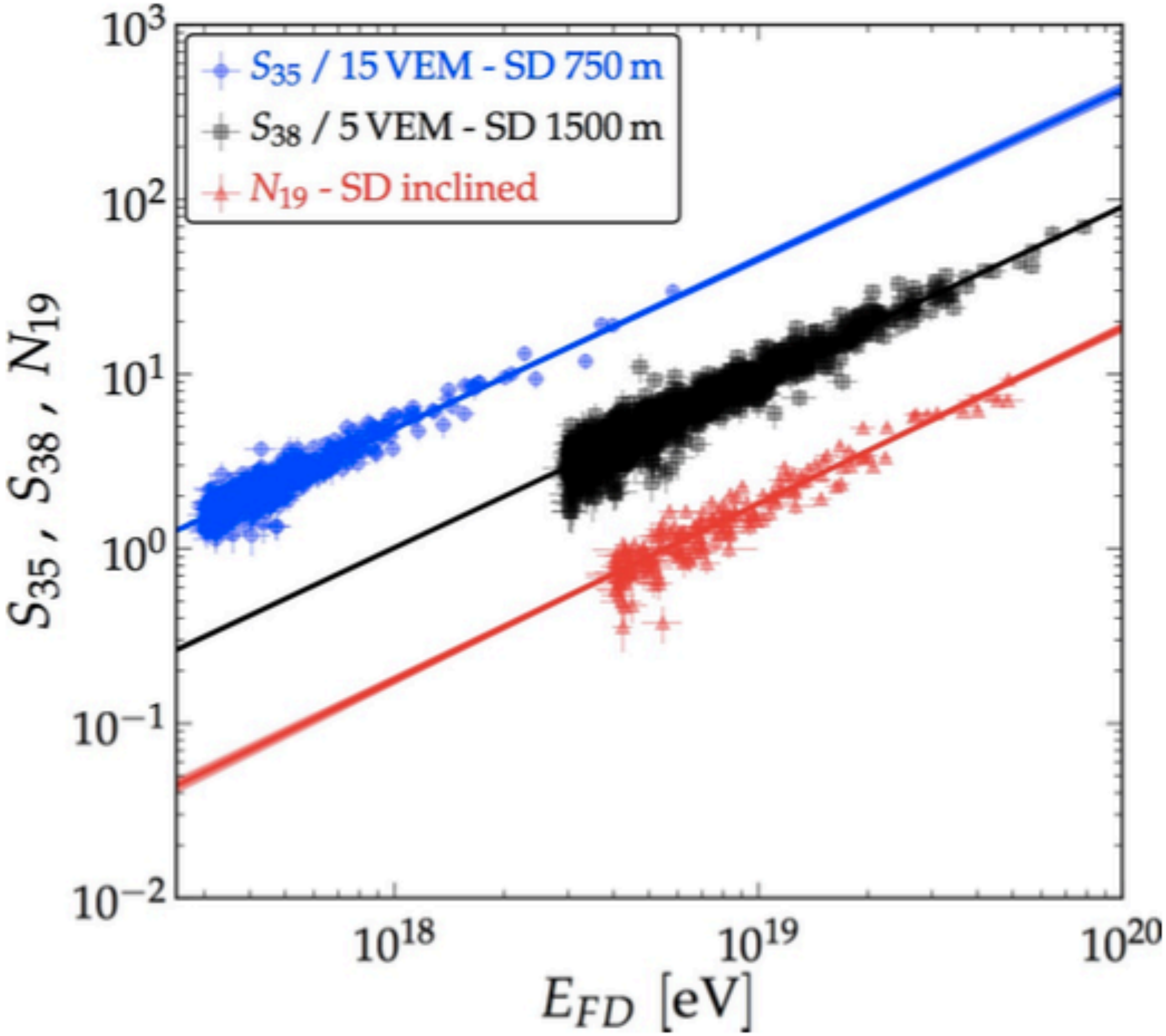
$\sigma_E/E \sim 8\,\%$
$\Delta_{\mathrm{sys}} \approx 15\,\%$



S_{1000}

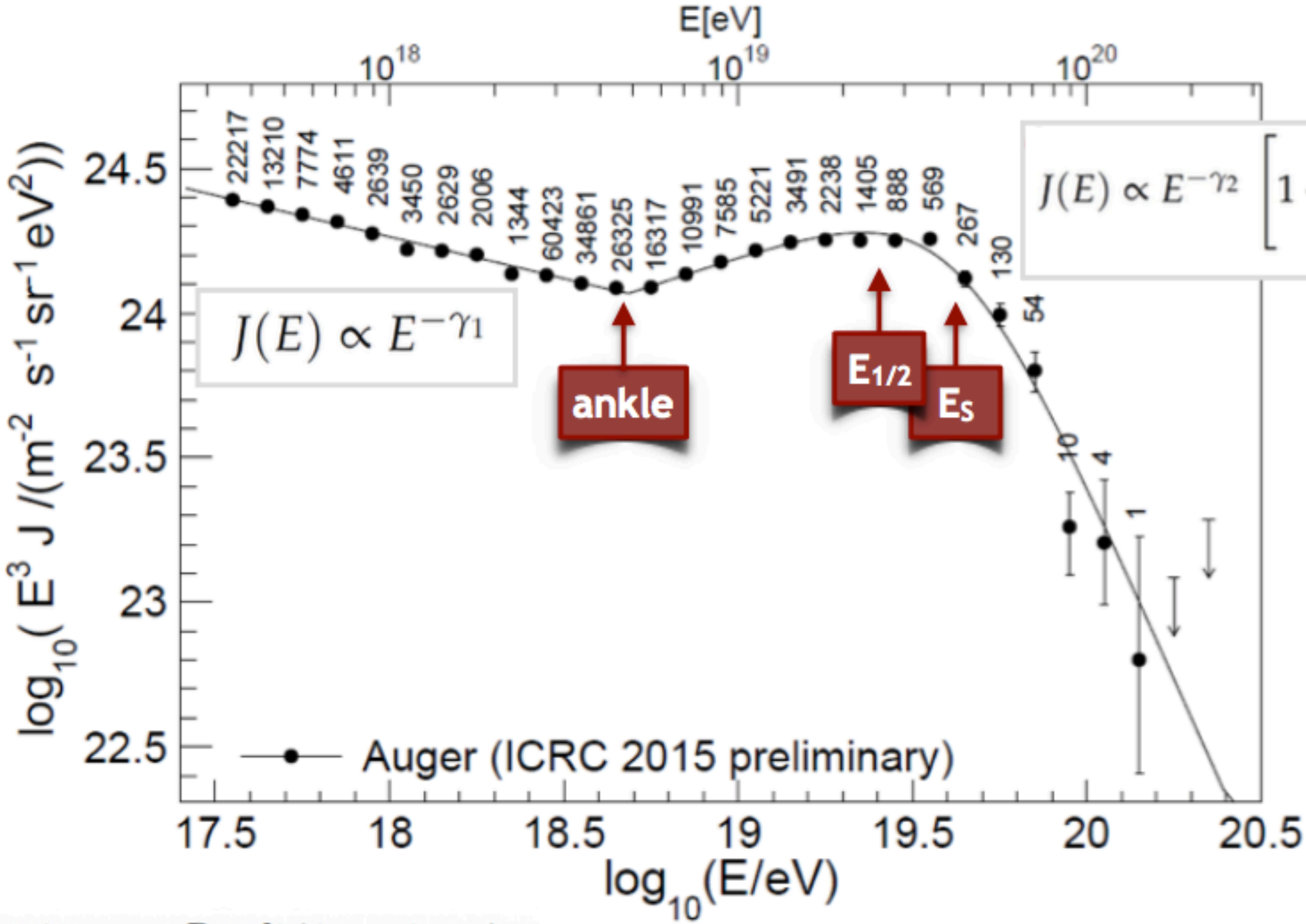
$E_{\mathrm{surface}} = f(S_{1000},\, \theta)$

Energy Calibration based on experimental data



Energy Spectrum of UHECRs

PIERRE
AUGER
OBSERVATORY



Parameter	Result ($\pm\sigma_{stat} \pm \sigma_{sys}$)
E_{ankle} [EeV]	$4.82 \pm 0.07 \pm 0.8$
γ_1	$3.29 \pm 0.02 \pm 0.05$
γ_2	$2.60 \pm 0.02 \pm 0.1$
E_s [EeV]	$42.09 \pm 1.7 \pm 7.61$
$\Delta\gamma$	$3.14 \pm 0.2 \pm 0.4$

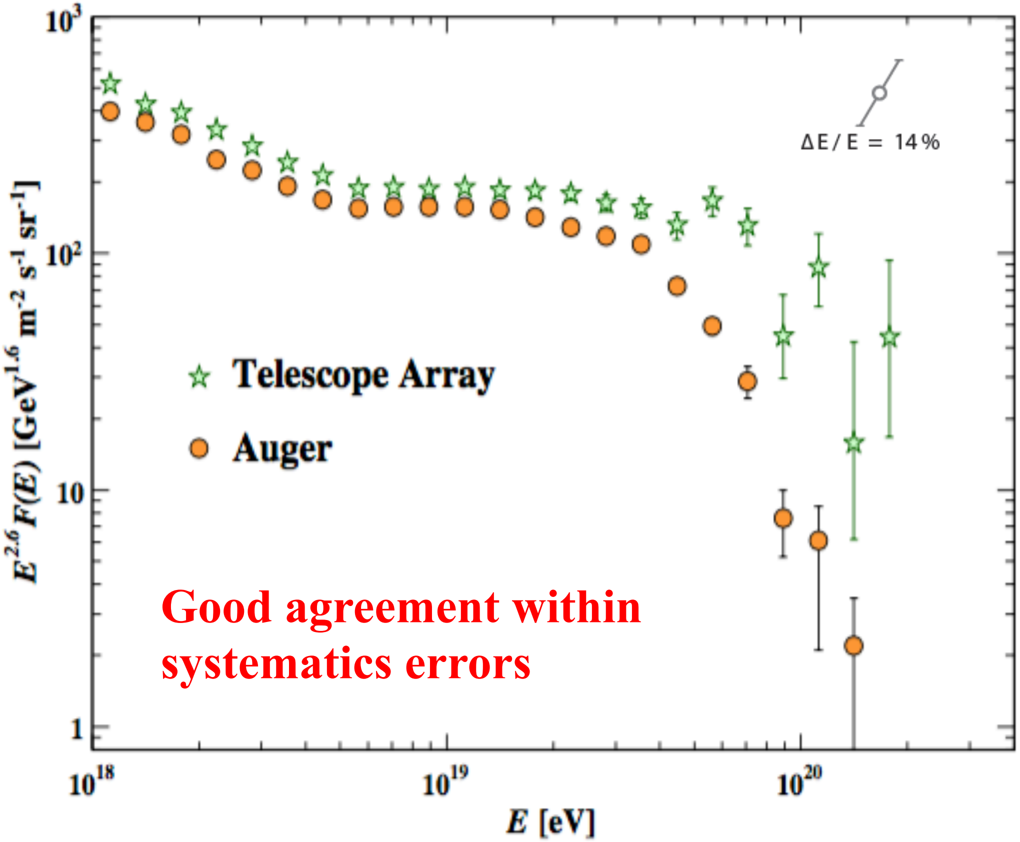
$E_{1/2} = (24.7 \pm 0.1\ ^{+8.2}_{-3.4})$ EeV

- **Ankle and cutoff clearly observed**
- **Fitting model:**
  - **Power law below the ankle**
  - **Power law with smooth suppression above**

Flux suppression for Pierre Auger & TA

PIERRE AUGER OBSERVATORY

- **Both Auger and TA see strong evidence for suppression of the spectrum near the expected GZK energy.**
- **Spectra differ in detail in the suppression region.**
  - **Differences in instruments/ analysis?**
  - **Different spectra in North vs. South?**



ICRC-2015 data, plot from RPP 2016

- **The well-established steepening of the spectrum itself is INSUFFICIENT for us to claim that we have seen the GZK effect**
  - **It might simply be that the sources cannot raise particles to energies as high as 10^{20}eV**
- **It would be enormously helpful if the arrival directions were Anisotropic and sources could be identified**

Deflections in magnetic fields:

at ~ 10^{19} eV: still ~ 10° in Galactic magnetic field - depending on the direction

Anisotropies

PIERRE
AUGER
OBSERVATORY

Arrival directions: affected by propagation in intervening magnetic fields → depends on energy and Z

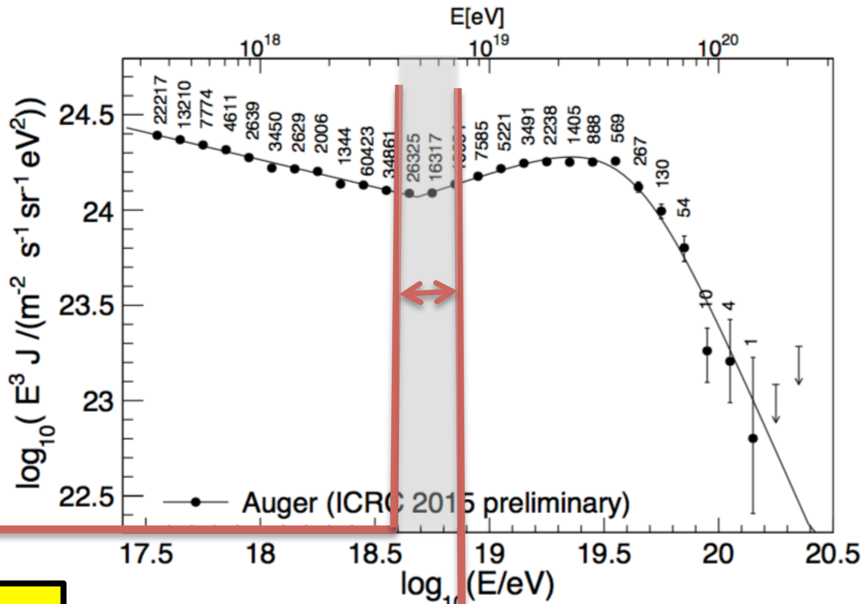
$r_L = E/ZeB$

Diffusive or quasirectilinear?

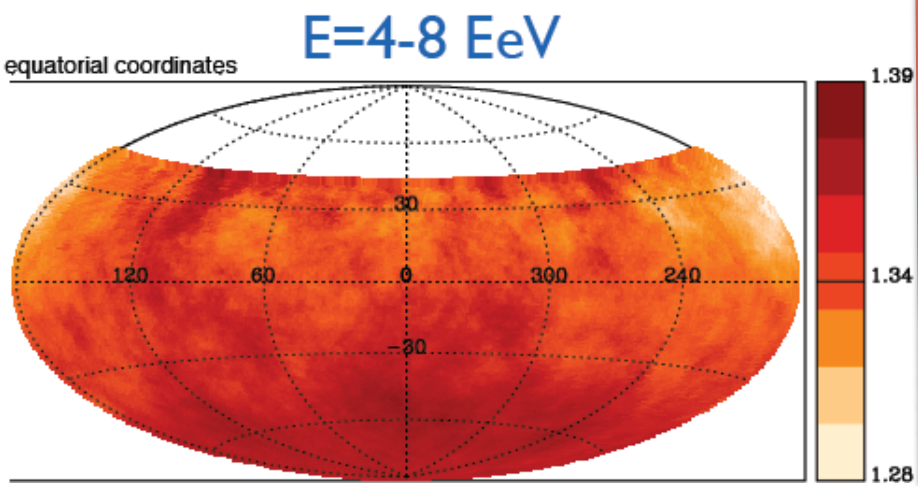
- **spectrum**
- **arrival directions distribution**

UHECR Sky surprisingly isotropic

PIERRE AUGER OBSERVATORY



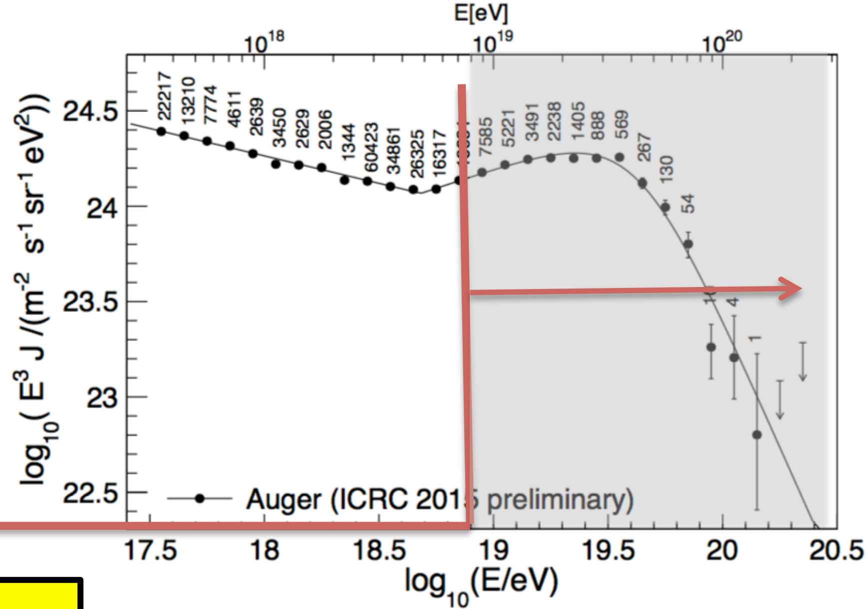
Isotropic distribution



Auger Collaboration ApJ 802:111 (2015)

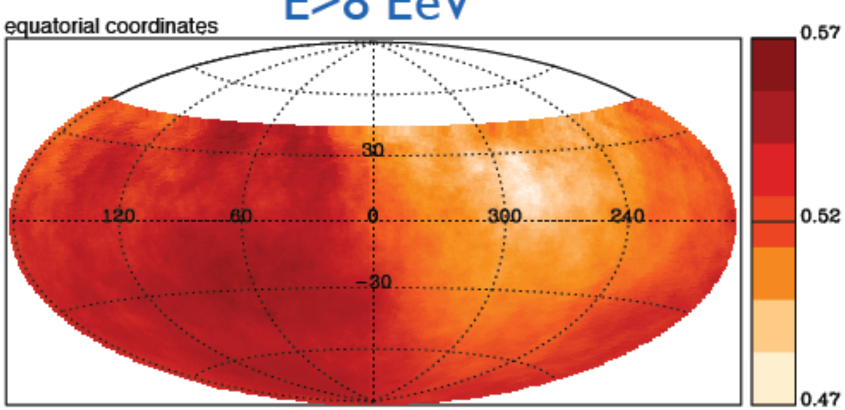
UHECR Sky surprisingly isotropic

PIERRE AUGER OBSERVATORY



Dipole like anisotropy

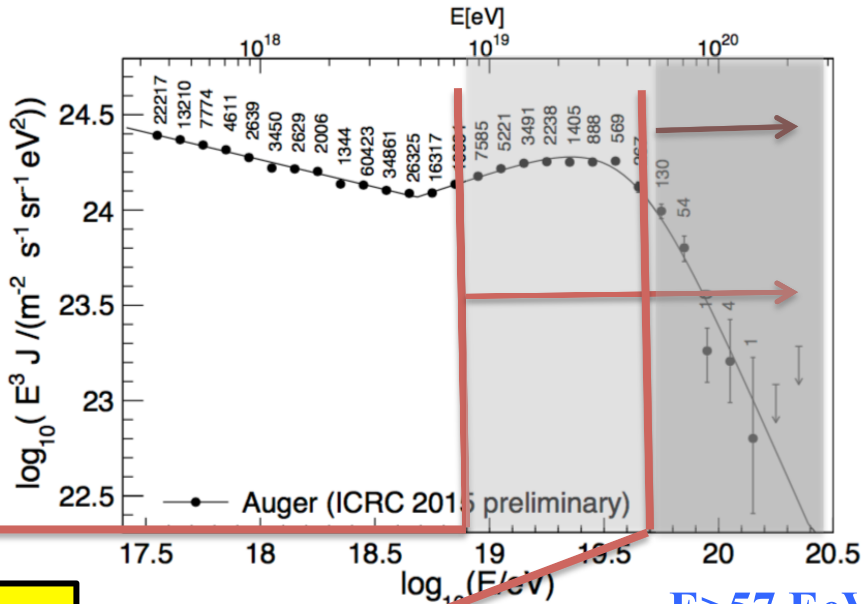
E>8 EeV



Auger Collaboration ApJ 802:111 (2015)

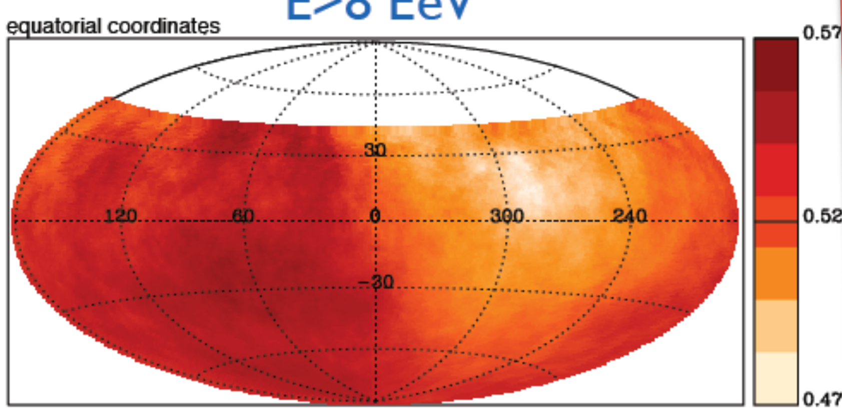
Amplitude: (4.4±1.0)%; $p=6.4\cdot10^{-5}$

UHECR Sky surprisingly isotropic



Dipole like anisotropy

E>8 EeV



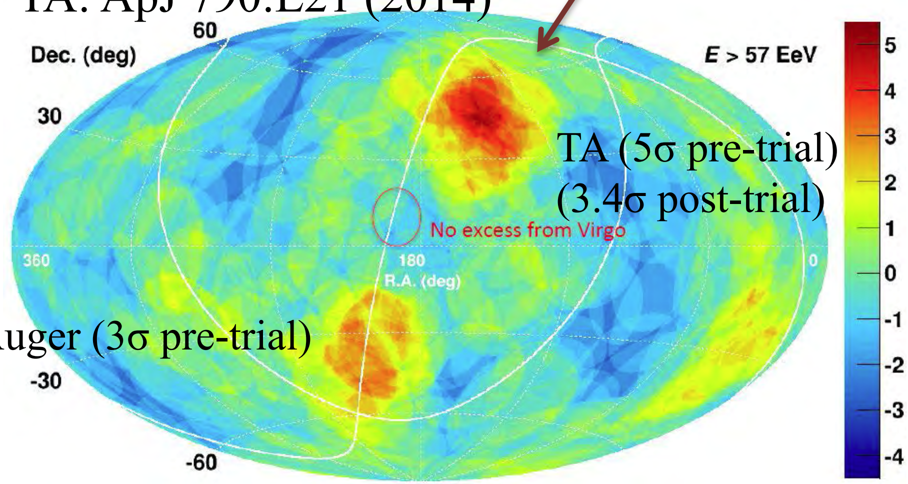
Auger Collaboration ApJ 802:111 (2015)

Amplitude: (4.4±1.0)%; p=6.4·10^{-5}

Hot/warm spot

E>57 EeV

TA: ApJ 790:L21 (2014)



Auger: APP 34(2010) 314

PIERRE AUGER OBSERVATORY

To interpret the arrival direction data a crucial question is

"What is the mass of the cosmic ray primaries at the highest energies?"

Answer is:

- **dependent on unknown hadronic interaction physics at energies up to ~ 30 times CM energy at LHC4**
- **In particular, cross-section, inelasticity and multiplicity and, in addition , pion-nucleus and nucleus- nucleus interactions**
- **Here is an important link between particle physics and astroparticle physics**

PIERRE AUGER OBSERVATORY

To interpret the arrival direction data a crucial question is

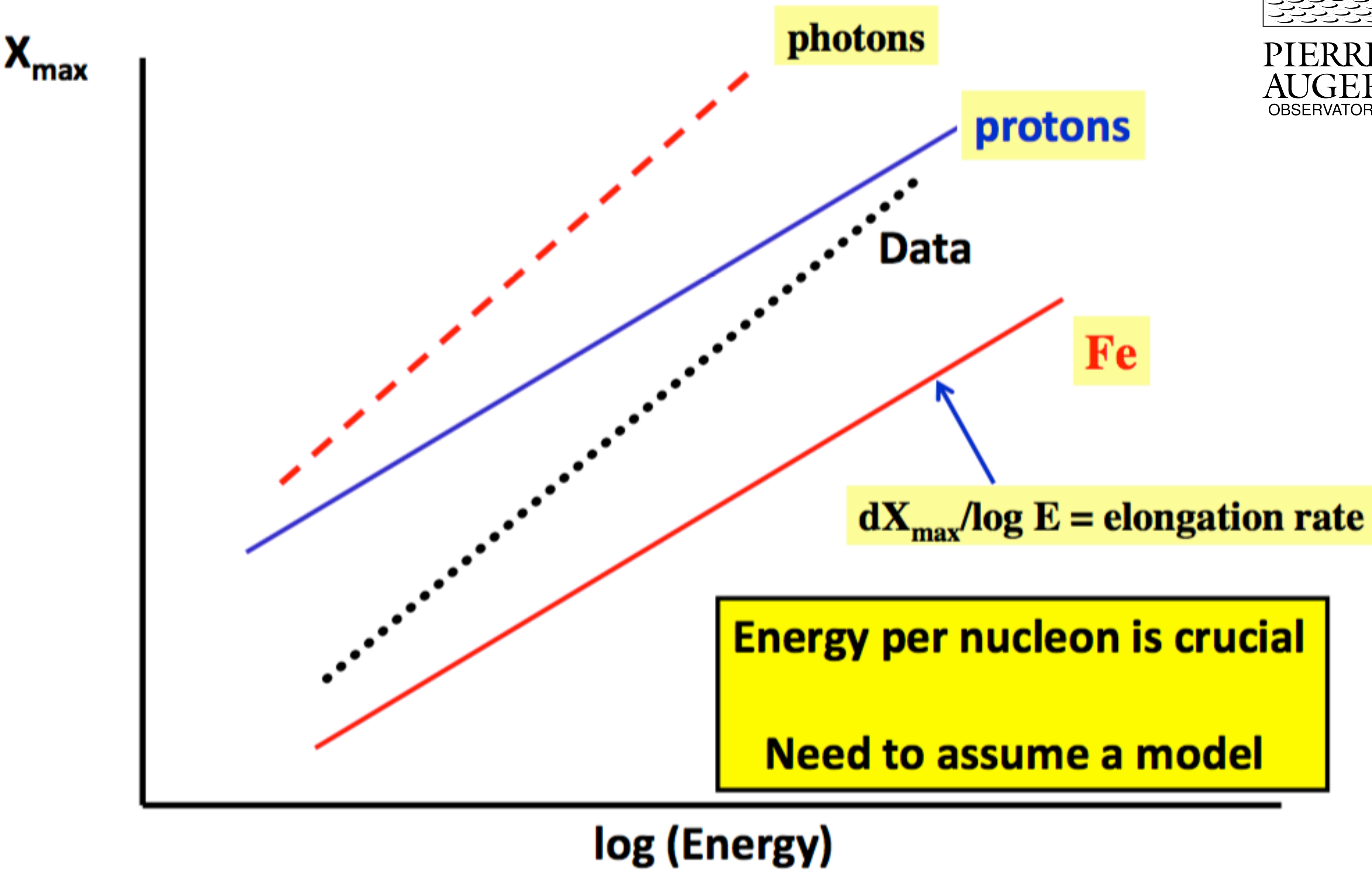
"What is the mass of the cosmic ray primaries at the highest energies?"

Answer is:

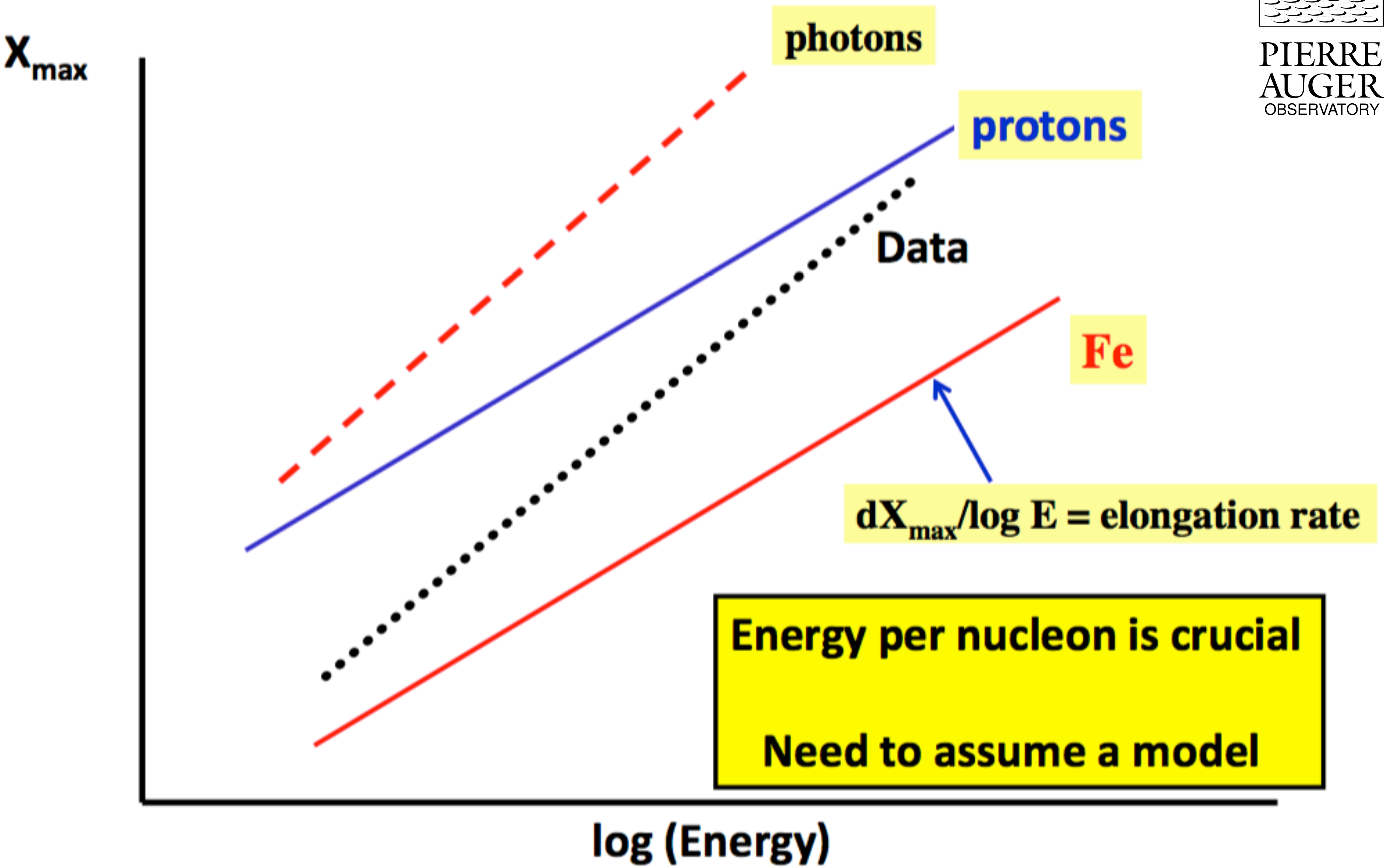
- dependent on unknown hadronic interaction physics at energies up to ~ 30 times CM energy at LHC
- In particular, cross-section, inelasticity and multiplicity and, in addition , pion-nucleus and nucleus- nucleus interactions
- Here is an important link between particle physics and astroparticle physics

Composition

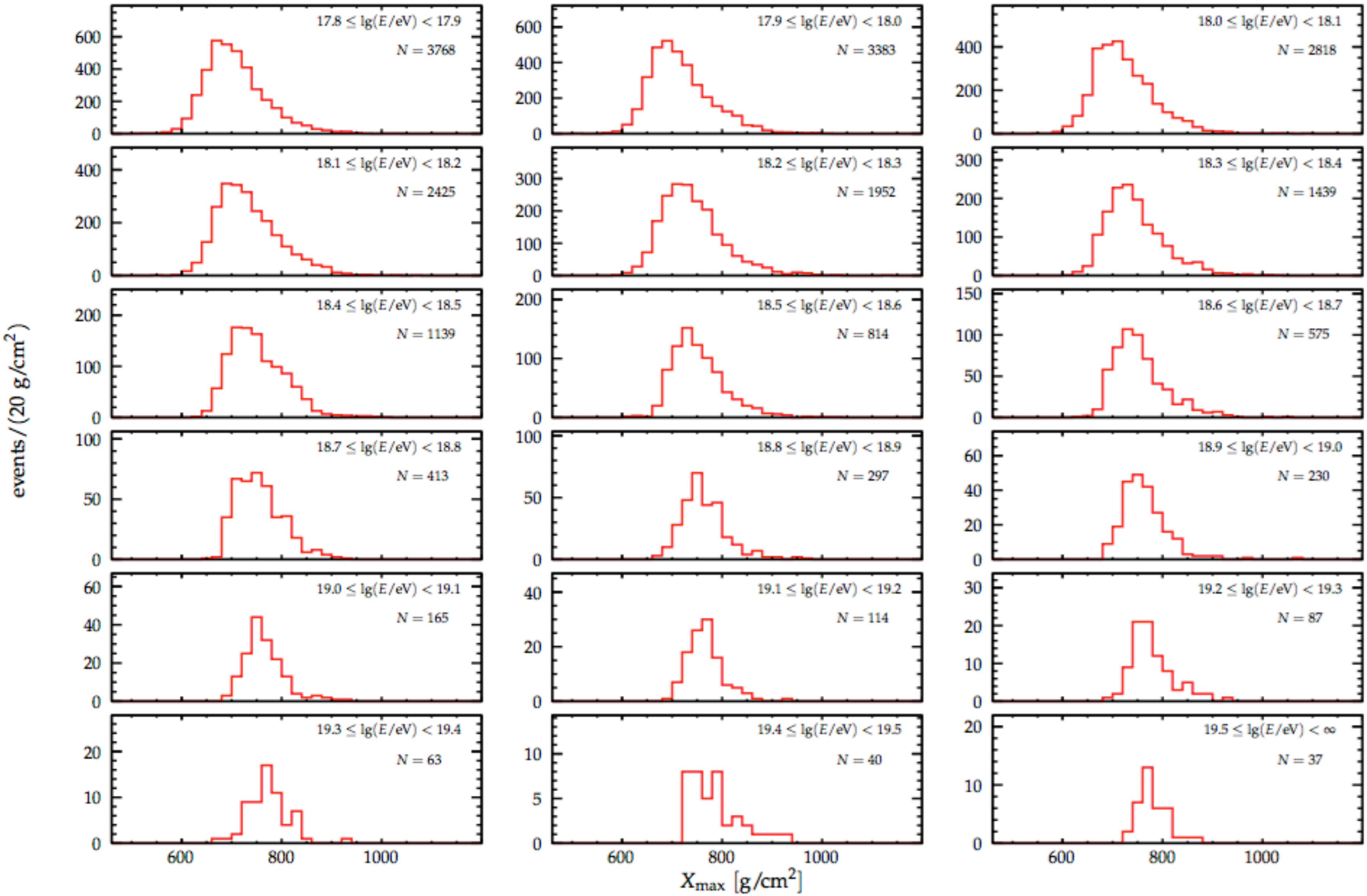
How we infer the variation of mass with energy



How we infer the variation of mass with energy



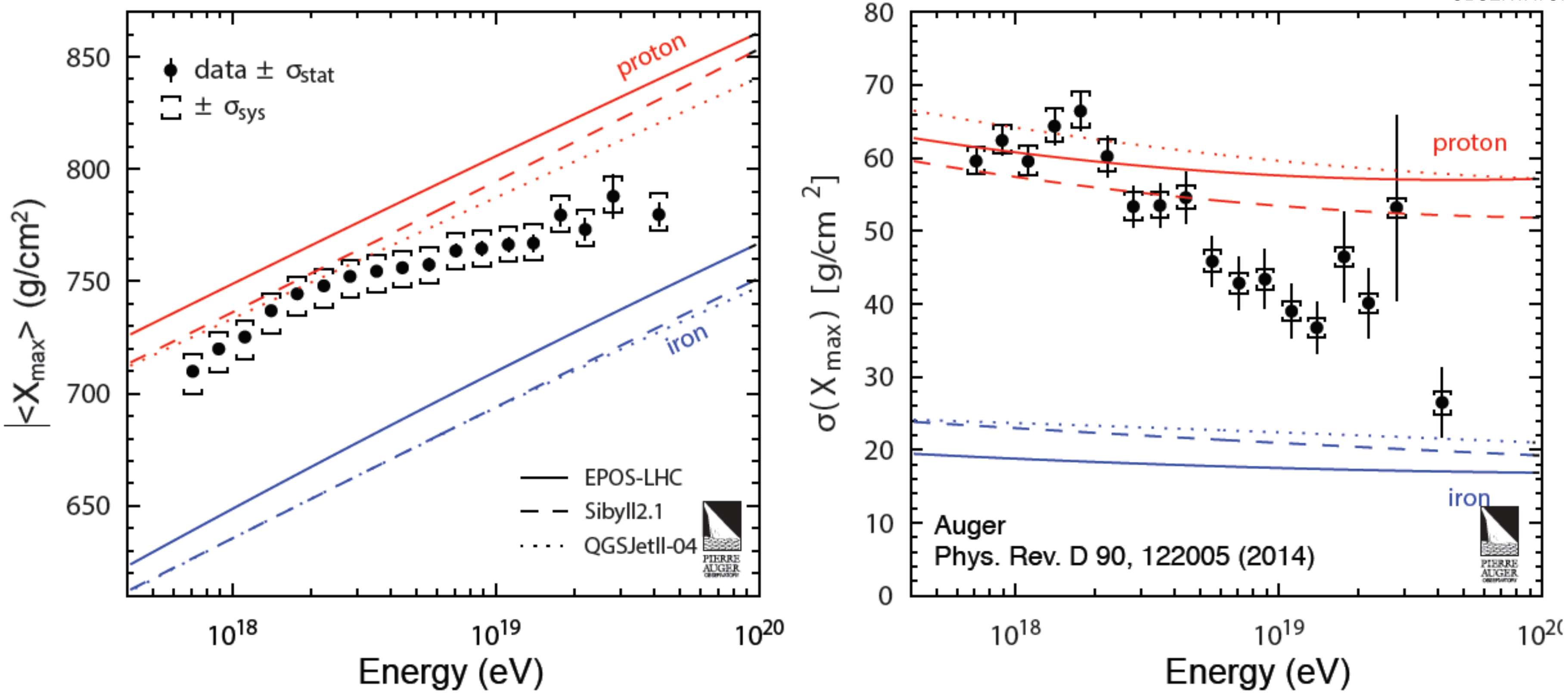
X_{max} Distributions



The Pierre Auger Collaboration, PRD **90** (2014) 12, 122005

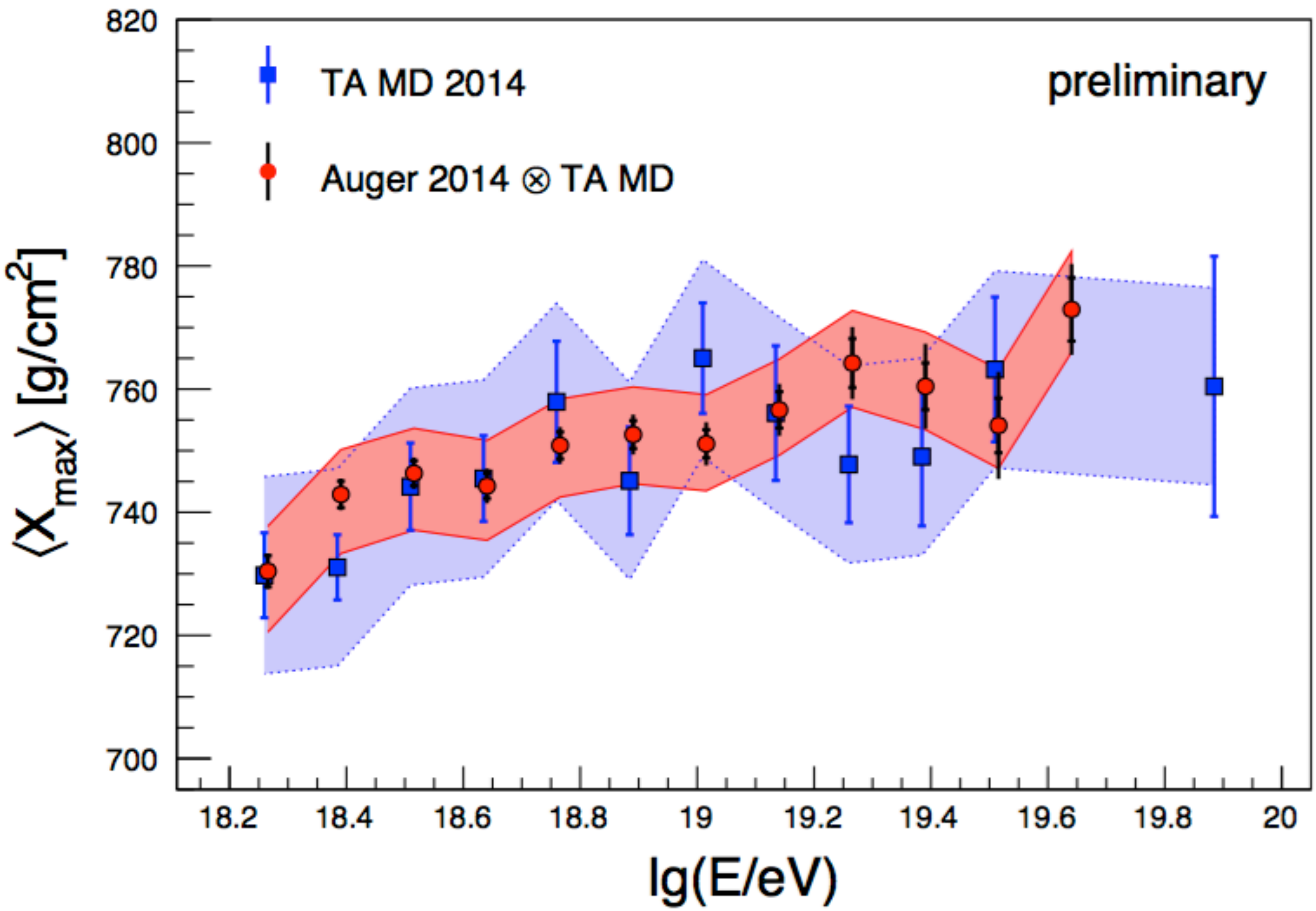
X_{max} & RMS(X_{max}) as function of E

Auger; Phys. Rev. D 90, 122005 (2014)



Auger data show a smooth change to a heavier composition above 5 EeV

Average Shower Maximum: Comparison to TA



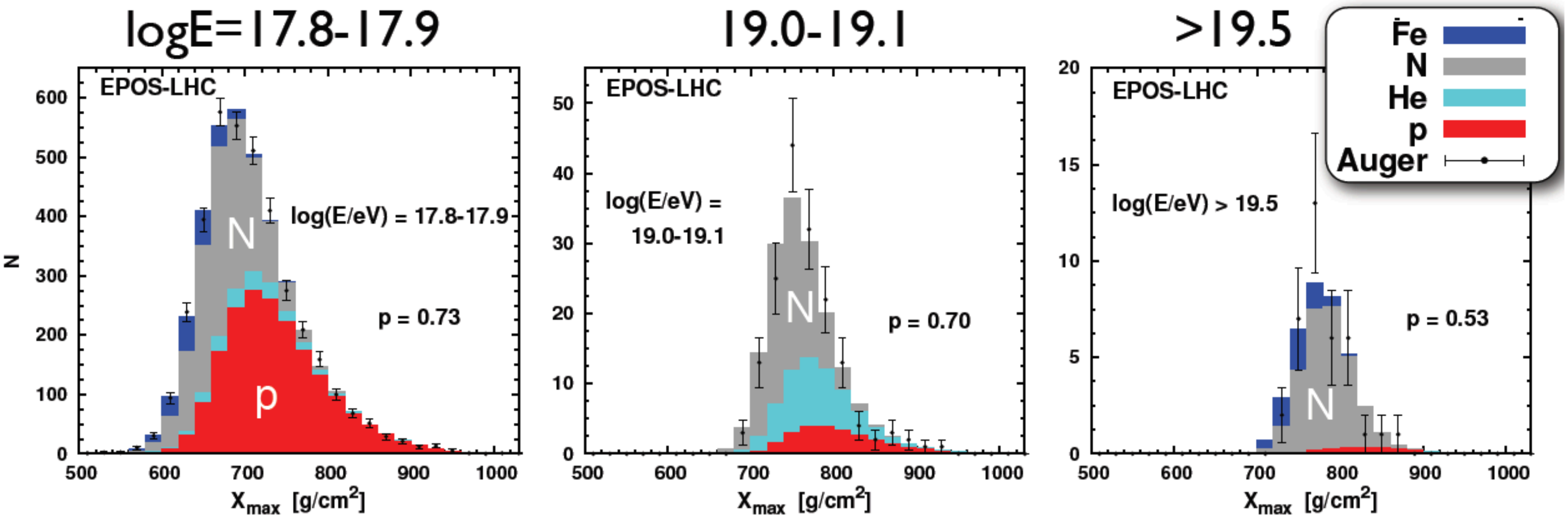
$\langle\Delta\rangle = (2.9 \pm 2.7 \text{ (stat.)} \pm 18 \text{ (syst.)}) \text{ g/cm}^2$

MU for the Pierre Auger and TA Collaborations, Proc. 34th ICRC, arXiv:1511.02103

PIERRE AUGER OBSERVATORY

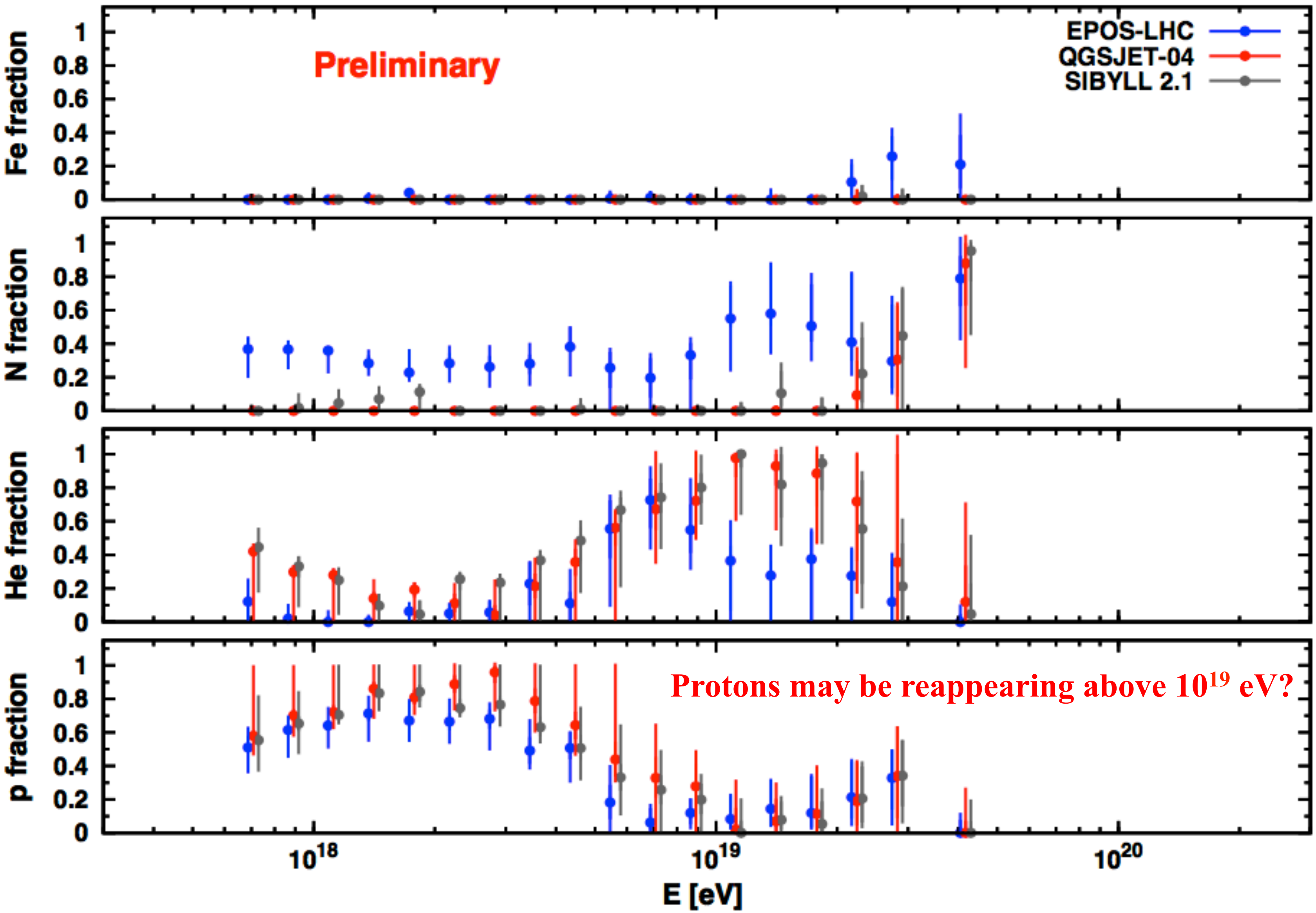
Fits to X_{max} Distributions

Here shown for EPOS-LHC

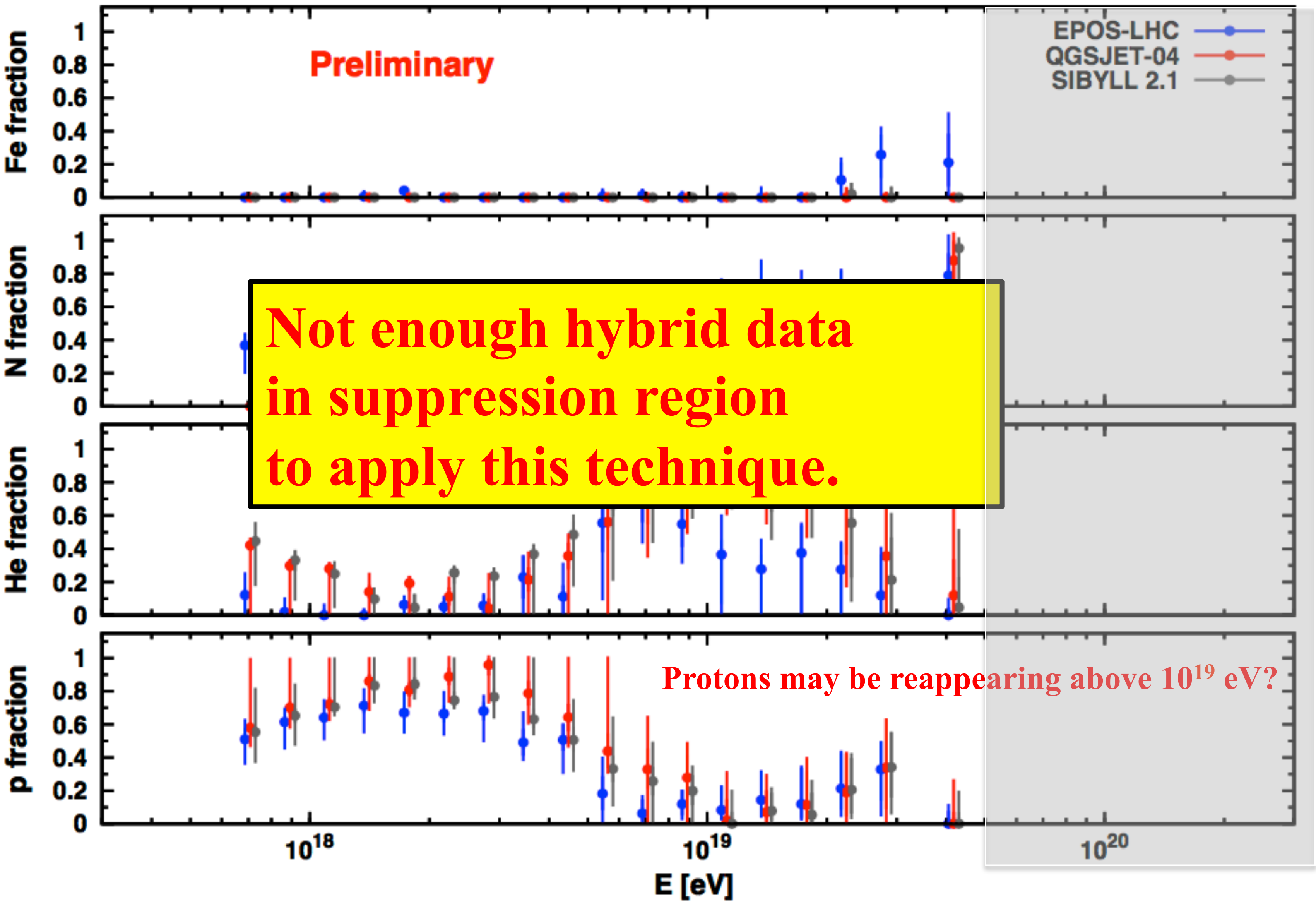


above 10^{19} eV p,He components diminish for N, Fe to take over

Fits to X_{max} Distributions



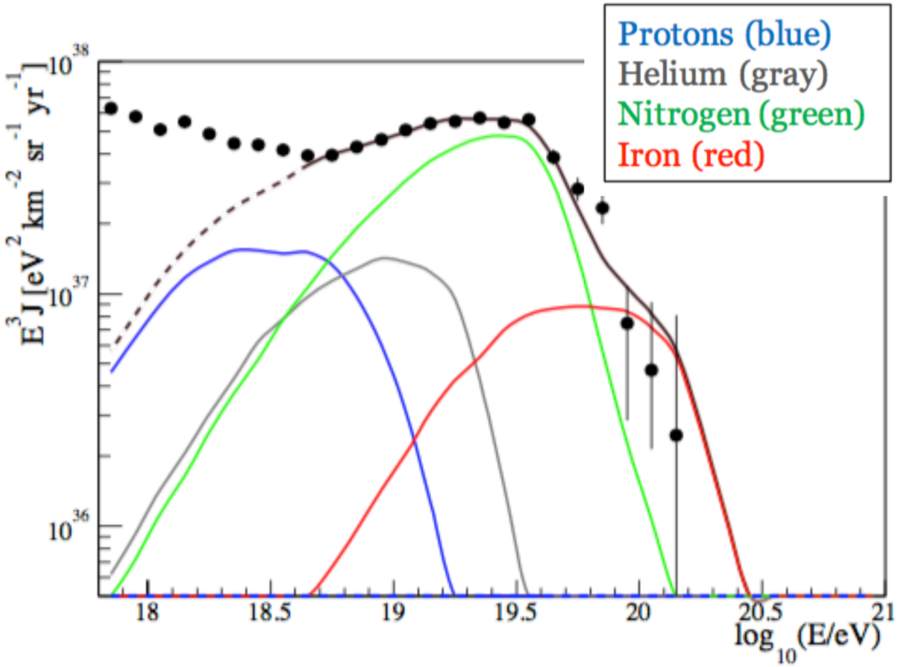
Fits to X_{max} Distributions



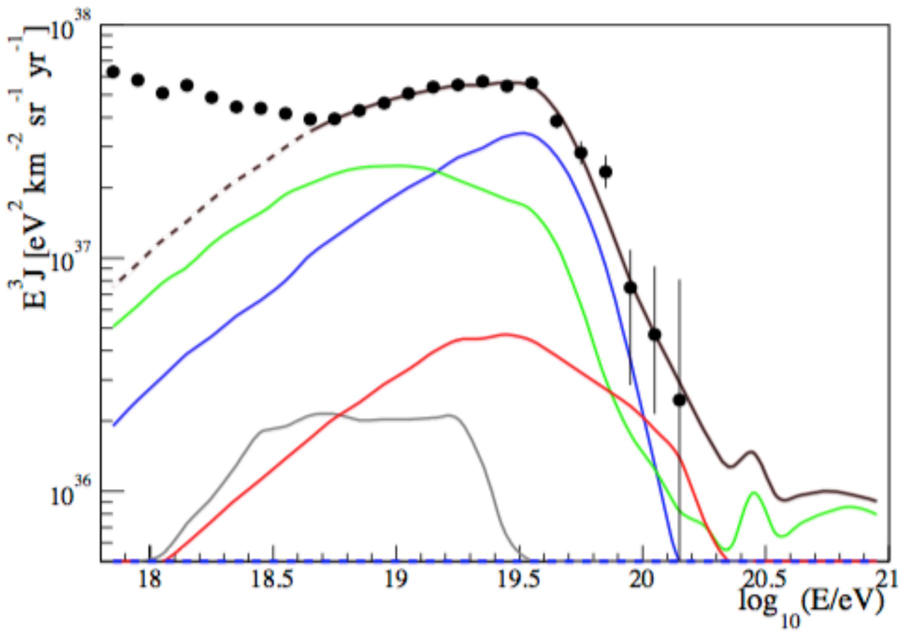
Composition Scenarios

PIERRE AUGER OBSERVATORY

"Maximum Energy" (A)



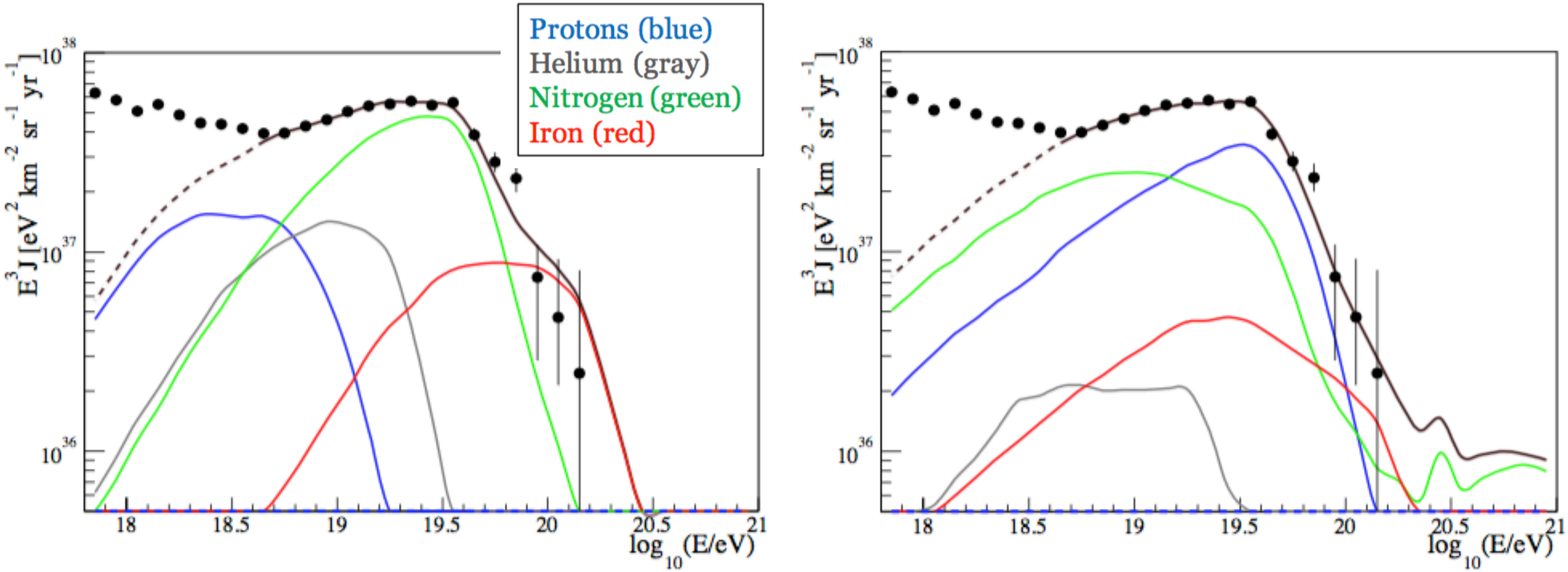
"Photodisintegration" (B)



Composition Scenarios

PIERRE AUGER OBSERVATORY

"Maximum Energy" (A) "Photodisintegration" (B)



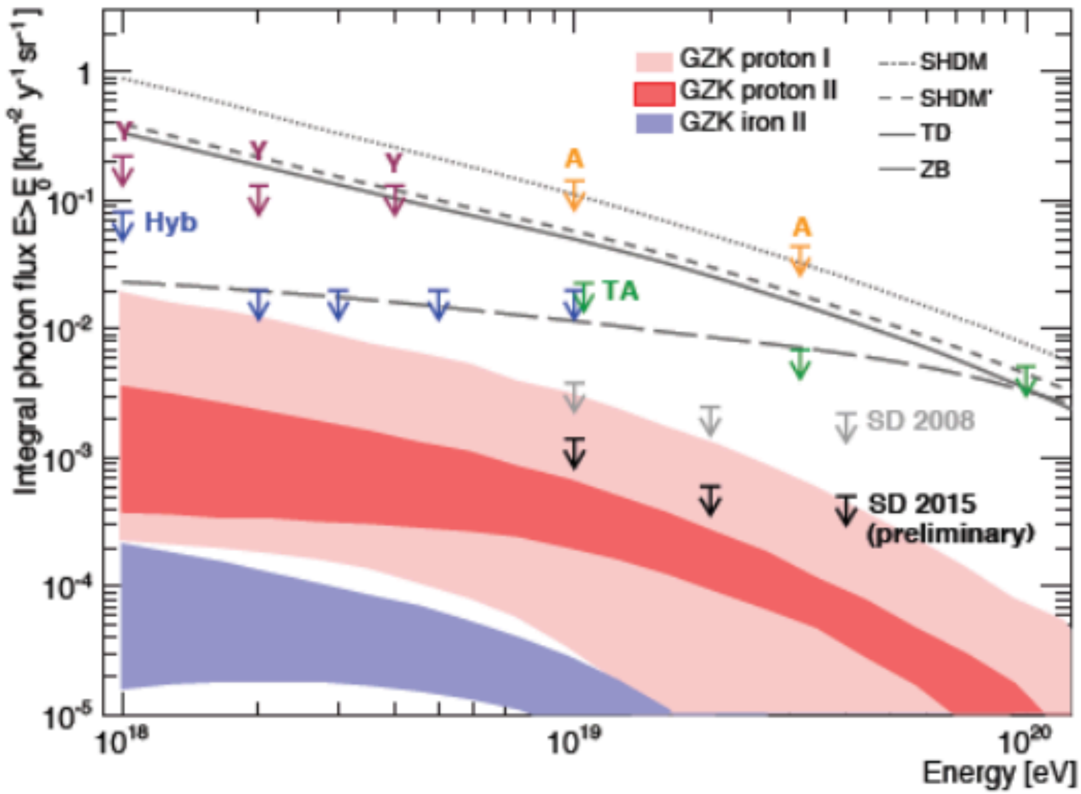
Is suppression GZK or Emax?
We need more events in the suppression region!

What about photons?

PIERRE AUGER OBSERVATORY

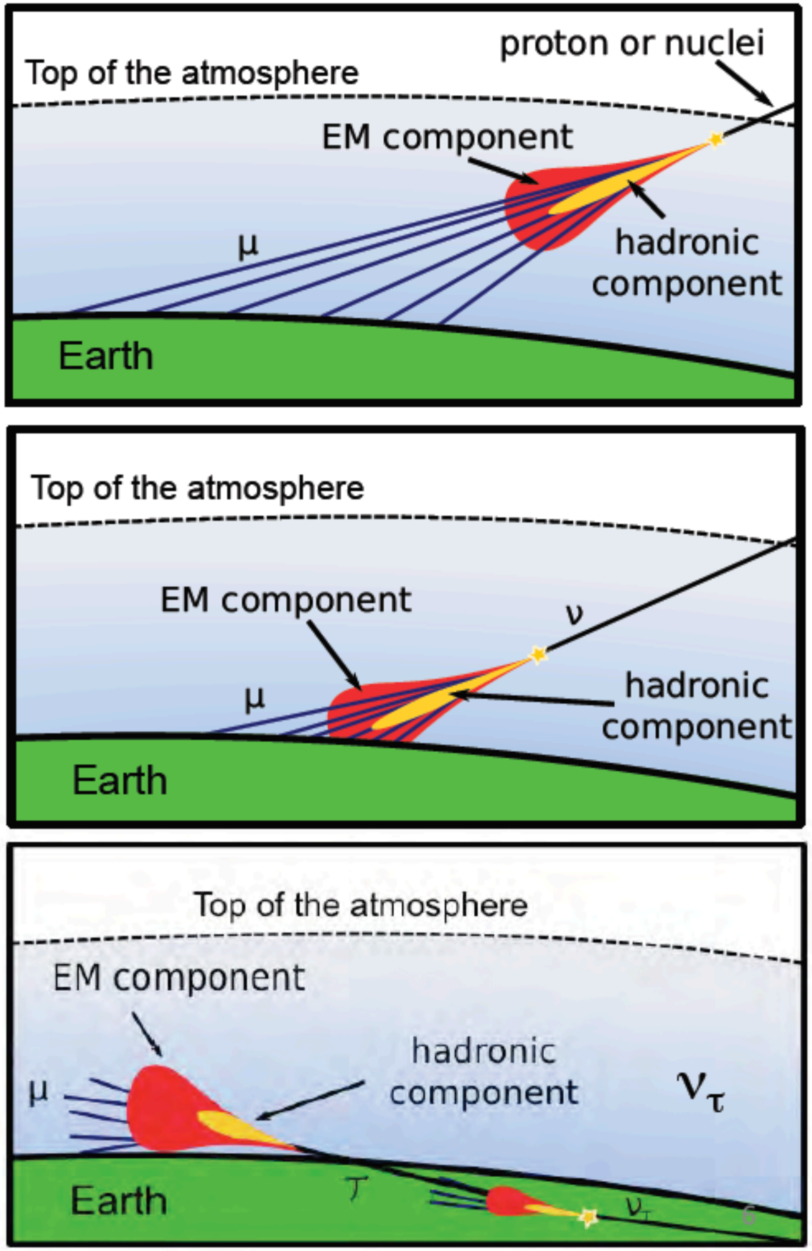
Searches for photons make use of anticipated differences in showers arising from:

- the steeper fall-off of signal with distance
- the slower risetime of the signals in the water-Cherenkov detectors
- the larger curvature of the shower front
- the deeper development in the atmosphere resulting in greater X_{max}



The limits rule out exotic, super-heavy relic models

What about neutrinos?



PIERRE AUGER OBSERVATORY

Search for EeV Neutrinos in inclined showers:

- **Protons & nuclei initiate showers high in the atmosphere.**
  - Shower front at ground:
    - mainly composed of muons
    - electromagnetic component absorbed in atmosphere.
- **Neutrinos can initiate "deep" showers close to ground.**
  - Shower fromt at ground: electromagnetic + muonic component

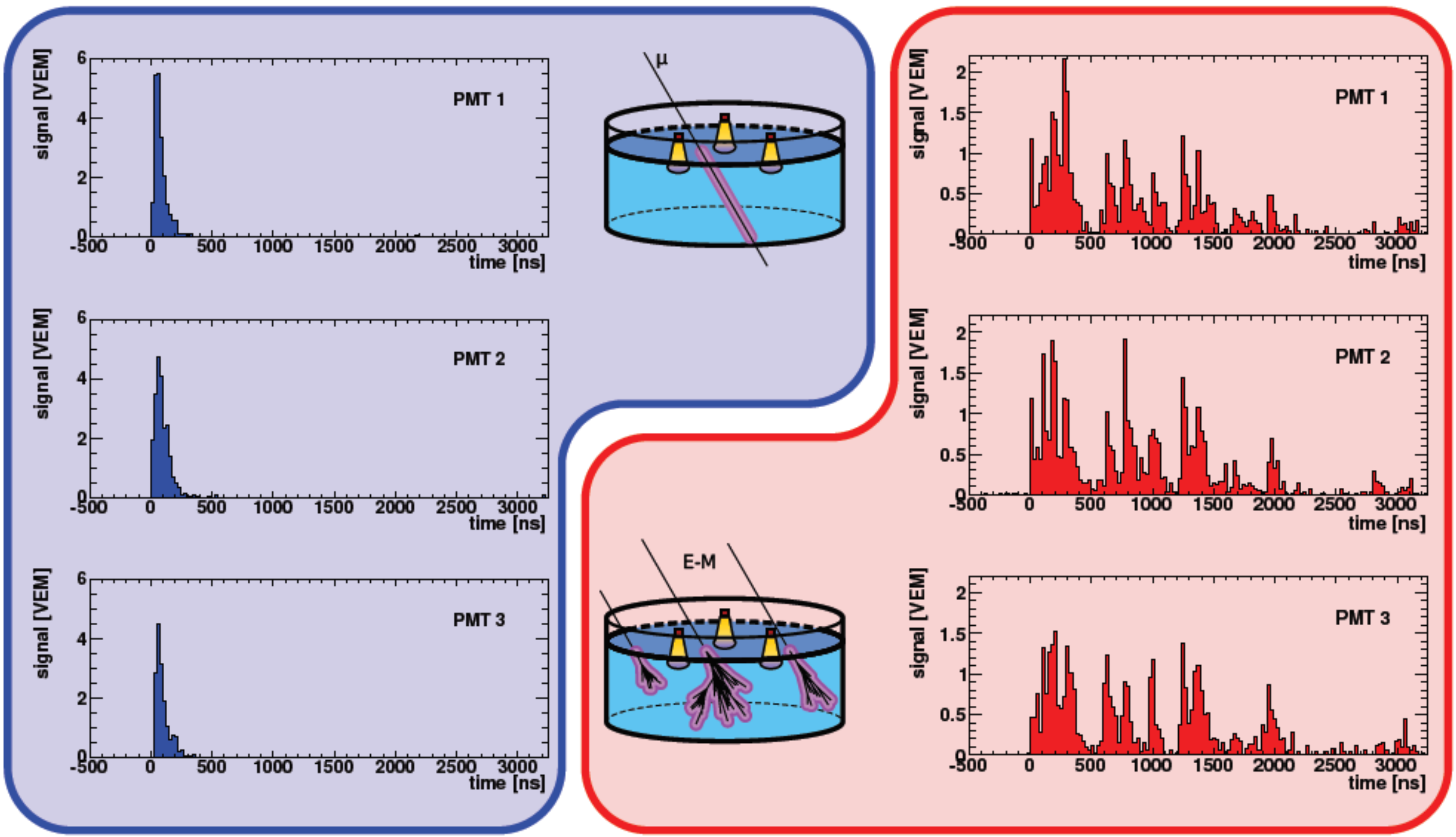
Searching for neutrinos: searching for inclined showers with electromagnetic component

What about neutrinos?

With the SD, we can distinguish muonic from electromagnetic shower fronts (using the time structure of the signal in the water Cherenkov stations)

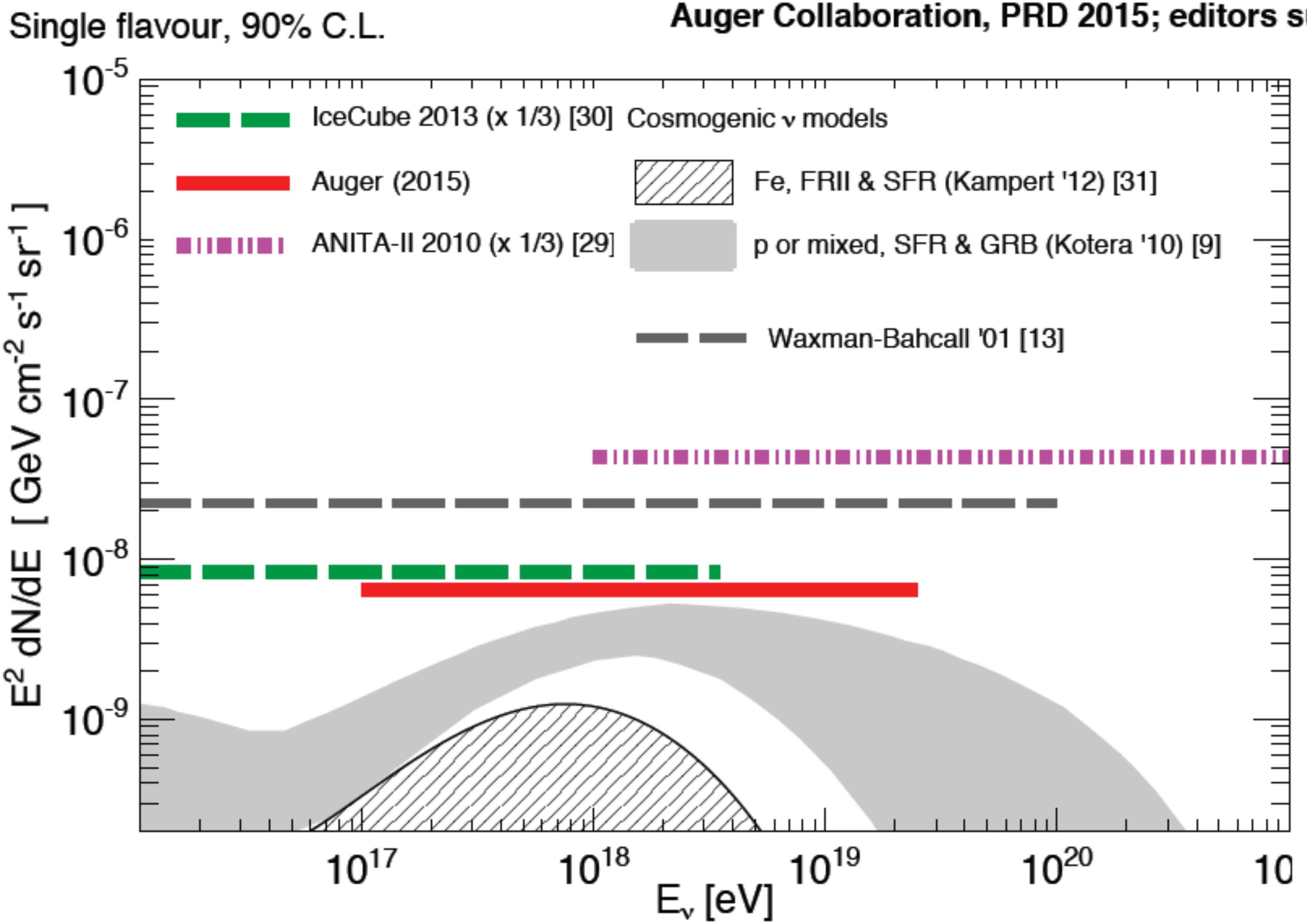
PIERRE AUGER OBSERVATORY

Muonic shower front: narrow signals



EM shower front: broad signals

What about neutrinos?

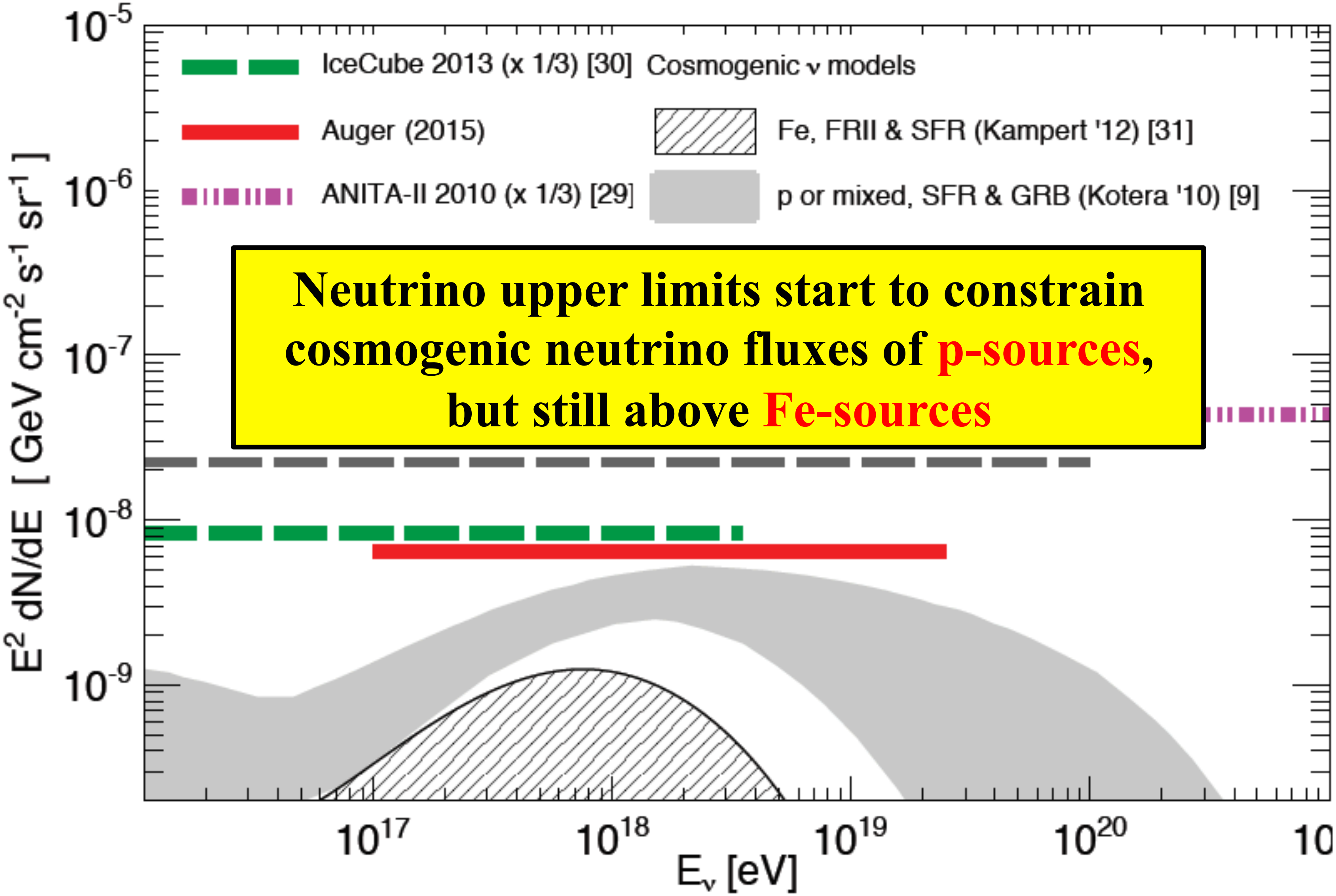


PIERRE AUGER OBSERVATORY

What about neutrinos?

Single flavour, 90% C.L.

Auger Collaboration, PRD 2015; editors su



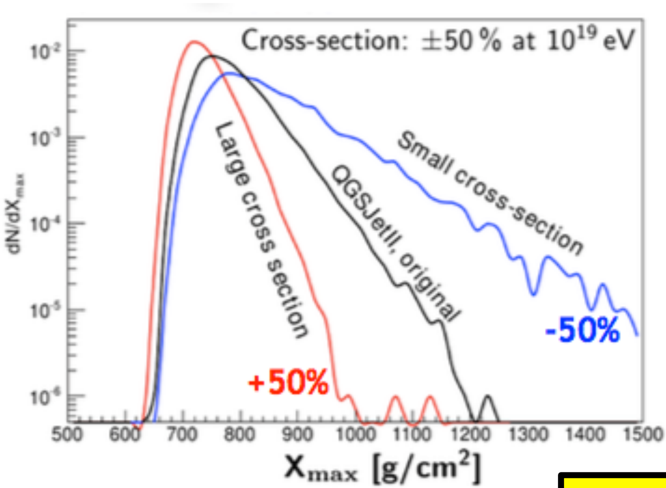
Neutrino upper limits start to constrain cosmogenic neutrino fluxes of p-sources, but still above Fe-sources

PIERRE AUGER OBSERVATORY

Hadronic models

PIERRE AUGER OBSERVATORY

The p-Air cross section

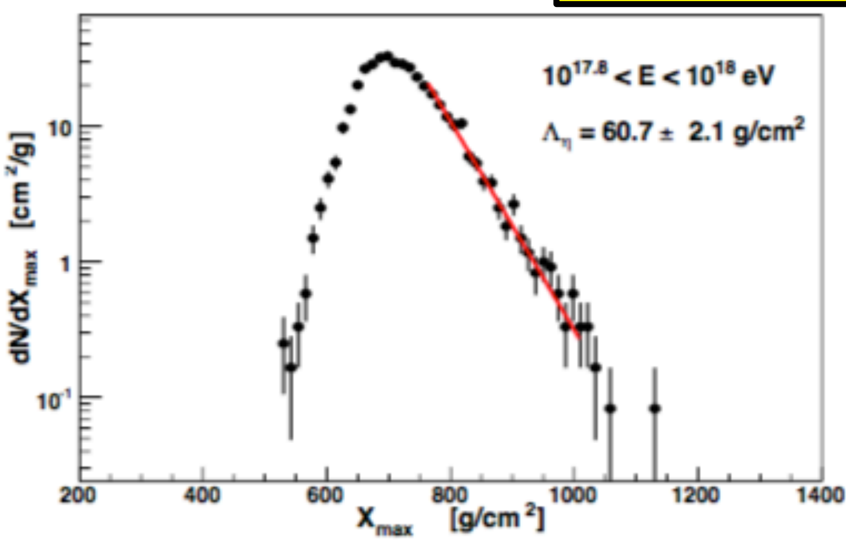


The tail of the longitudinal distribution is sensitive to the $\sigma^{inel}_{p\text{-}Air}$

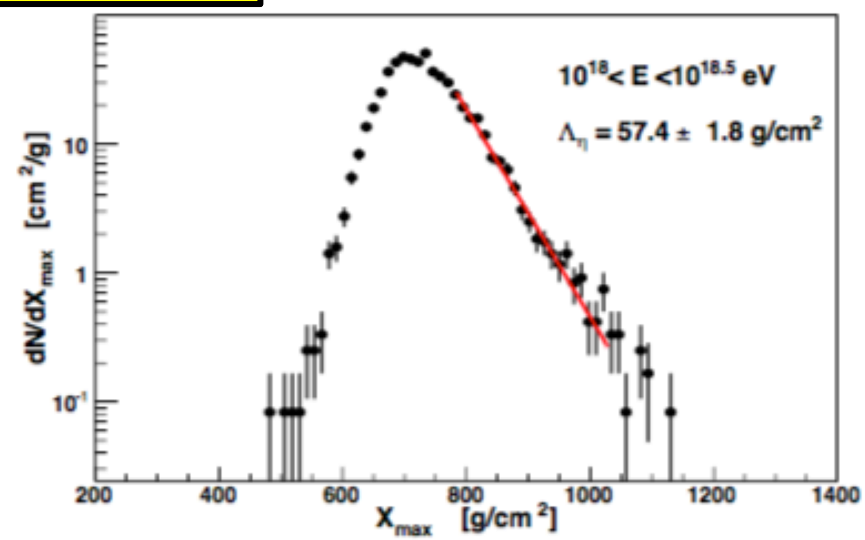
$$\frac{dN_{EAS}}{dX_{max}} \propto e^{-X_{max}/\Lambda_X}$$

$$\Lambda_X \propto \lambda_{int}$$

tail of X_{max} distribution:



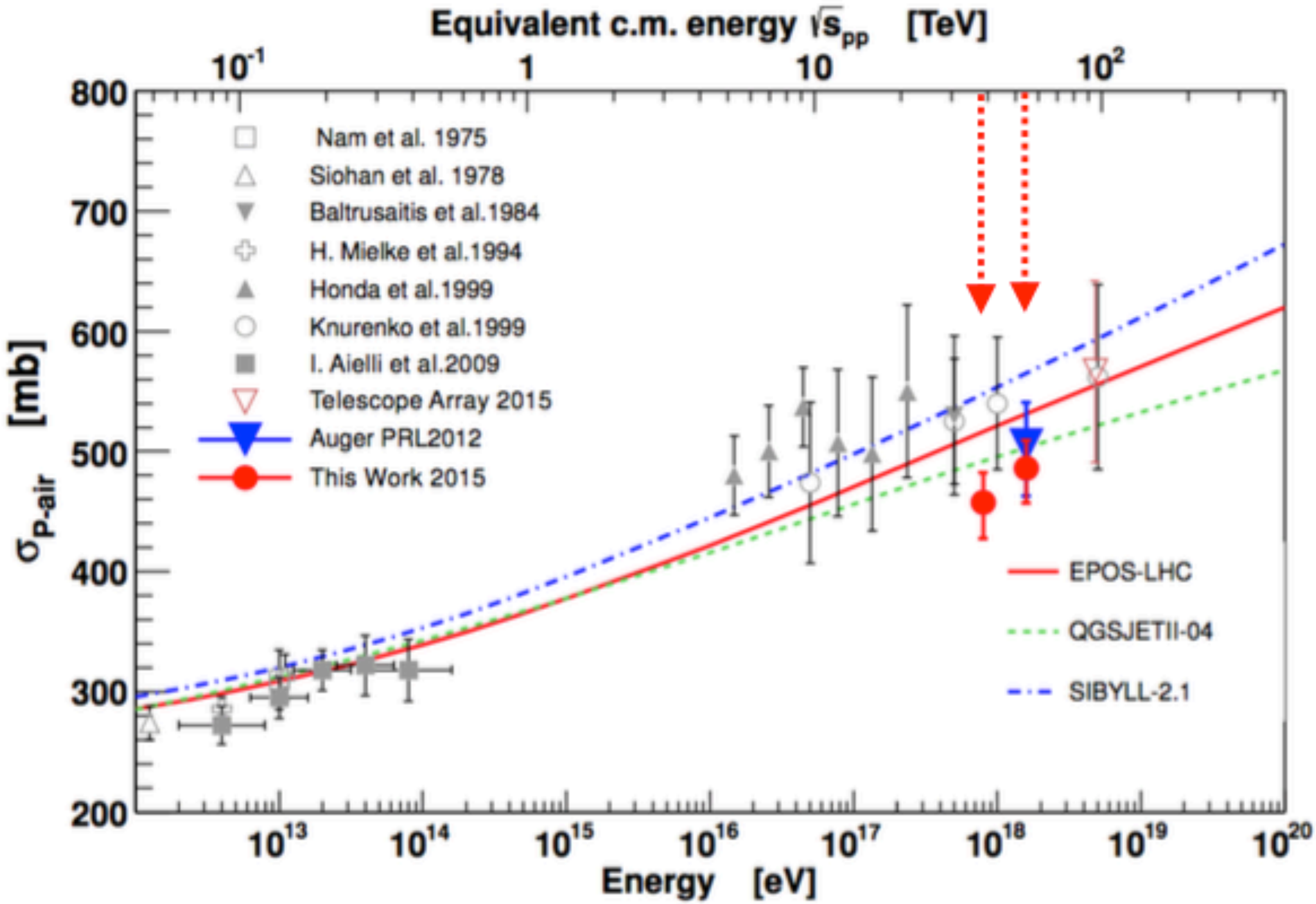
$\langle E \rangle = 10^{17.90}$ eV



$\langle E \rangle = 10^{18.22}$ eV

PIERRE AUGER OBSERVATORY

The p-Air cross section



Muons to test the hadronic interaction models

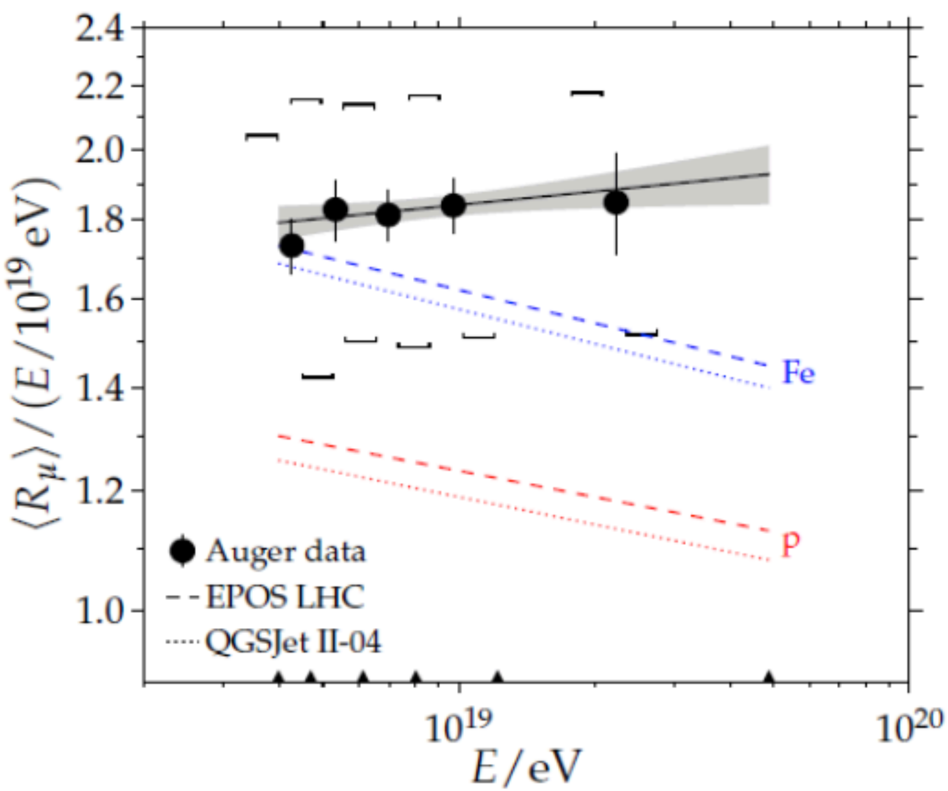
PIERRE AUGER OBSERVATORY

We find that there are problems with models at high energies and large angles where muon number in showers can be studied cleanly

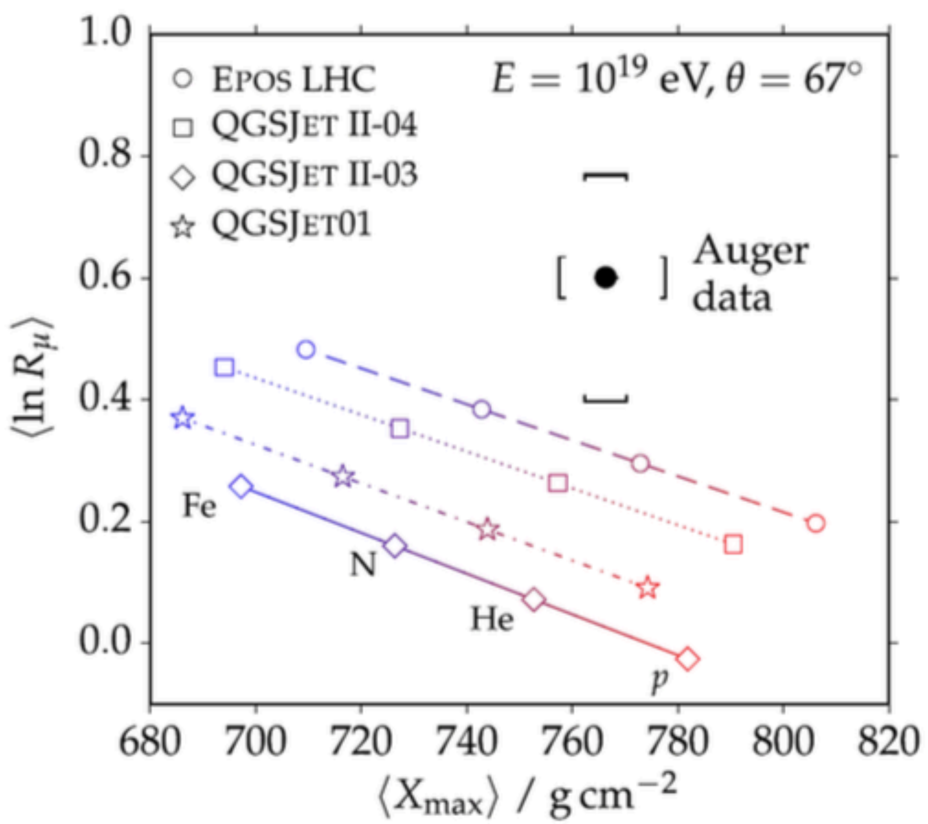
- Muons in inclined showers
  - PRD91 (2015) 032003; PRD91 (2015) 059991
- Muon content in hybrid events
  - L. Collica, ICRC2015, arXiv:1509.03732v1
- Muon production depth
  - PRD90 (2014) 012012; PRD92 (2015) 019903

Muon content in inclined events

<R$_\mu$> higher than MC-Fe expectations



clear tension between muon and X_{max} measurements

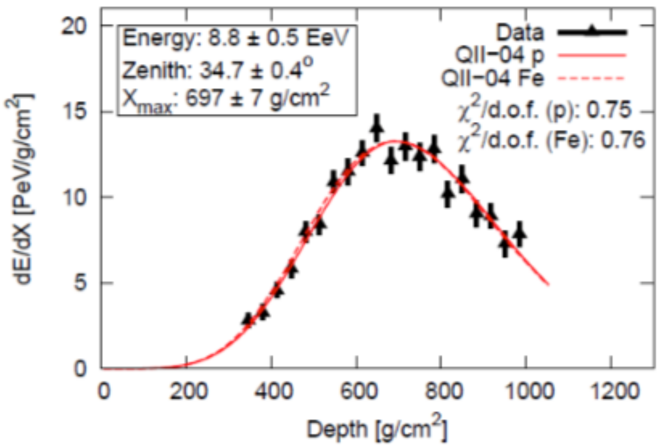


Muon numbers predicted by models are under-estimated by 30 to 80% (20% systematic)

Muon content from hybrid events

Data vs Simulation

example:



ratio of S(1000) data/MC:

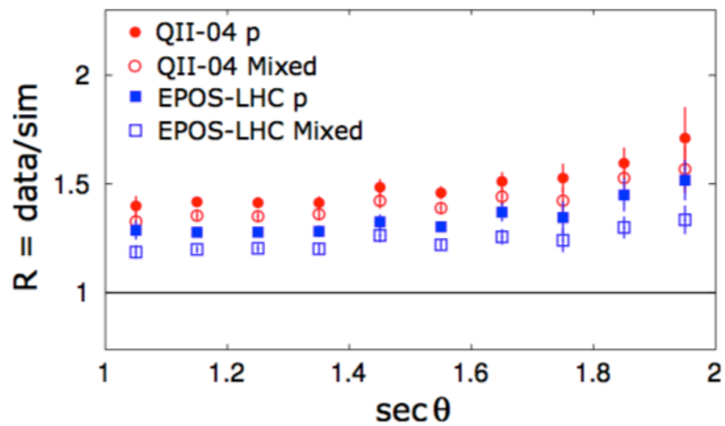
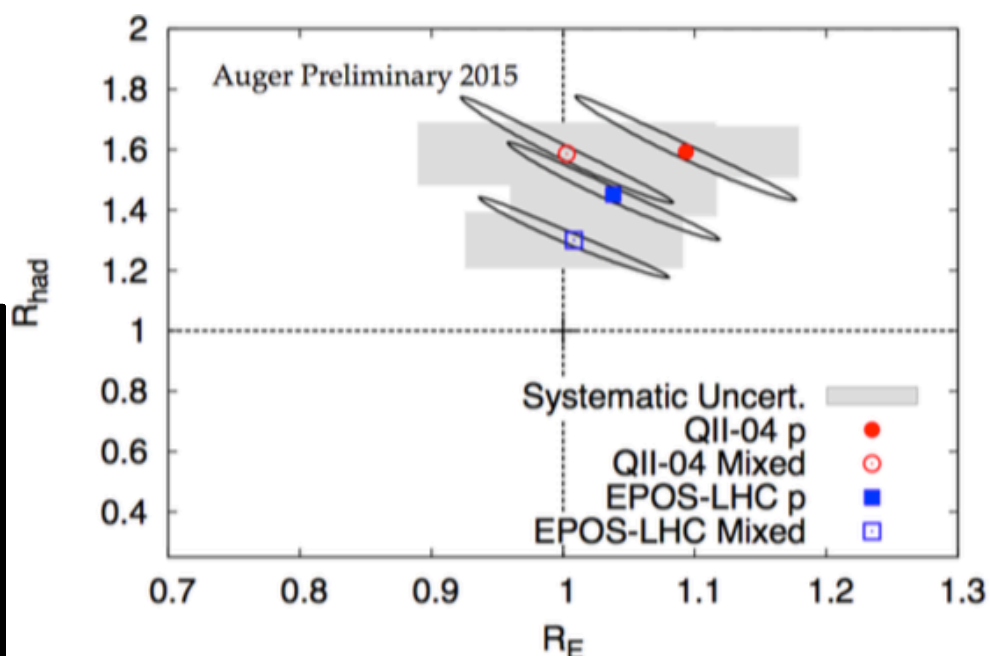


TABLE I. R_E and $R_{\rm had}$ with statistical and systematic uncertainties, for QGSJET-II-04 and EPOS-LHC.

Model	R_E	$R_{\rm had}$
QII-04 p	$1.09 \pm 0.08 \pm 0.09$	$1.59 \pm 0.17 \pm 0.09$
QII-04 Mixed	$1.00 \pm 0.08 \pm 0.11$	$1.61 \pm 0.18 \pm 0.11$
EPOS p	$1.04 \pm 0.08 \pm 0.08$	$1.45 \pm 0.16 \pm 0.08$
EPOS Mixed	$1.00 \pm 0.07 \pm 0.08$	$1.33 \pm 0.13 \pm 0.09$

$$S_{\rm resc}(R_E, R_{\rm had})_{i,j} \equiv R_E \, S_{EM,i,j} + R_{\rm had} \, R_E^{\alpha} \, S_{{\rm had},i,j}$$

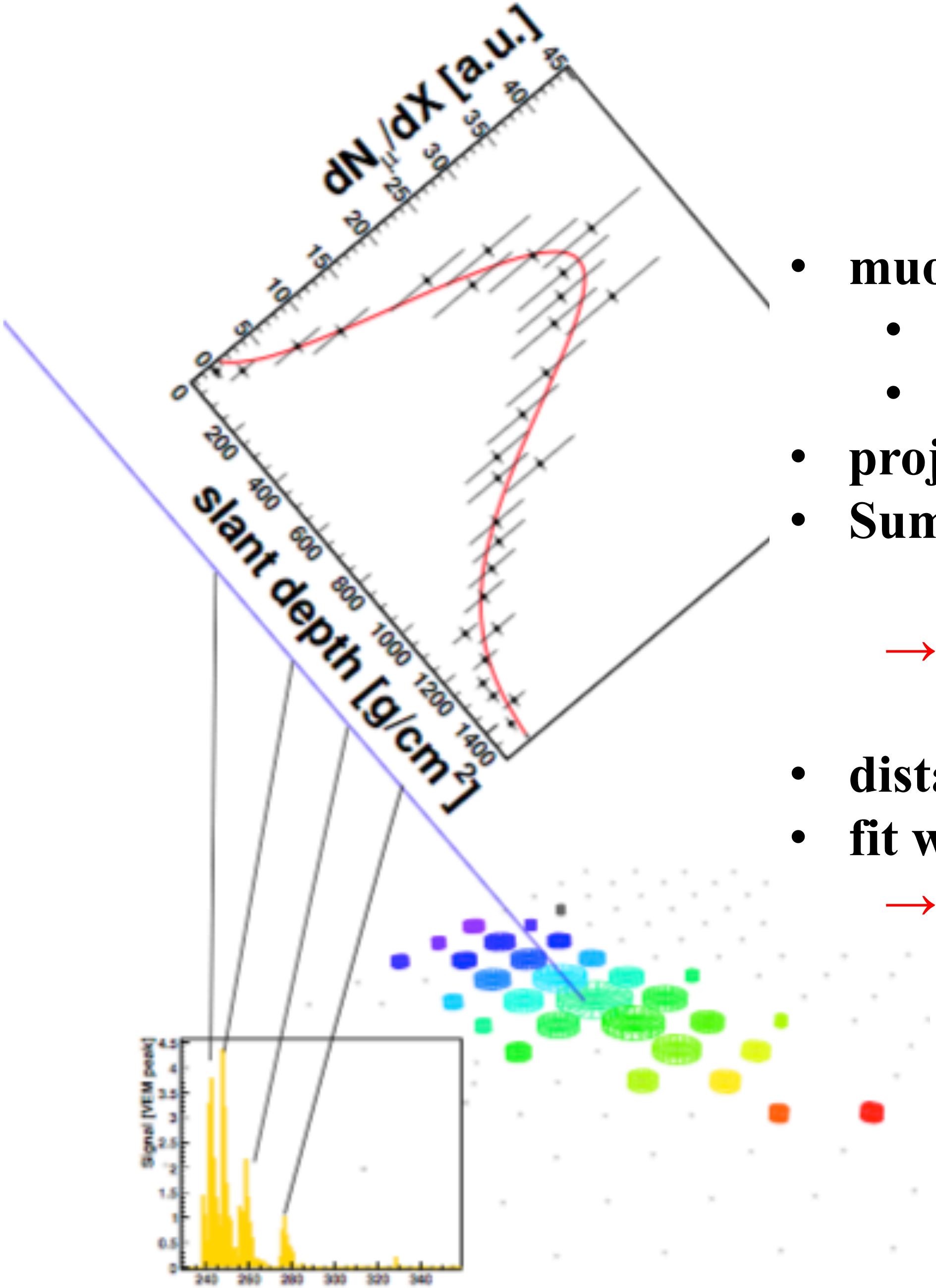


- **observed muon signal 1.3-1.6 times larger than expected**
- **smallest discrepancy with prediction of EPOS-LHC for mixed composition (1.9σ level)**

PIERRE AUGER OBSERVATORY

Muon Production Depth

PIERRE AUGER OBSERVATORY



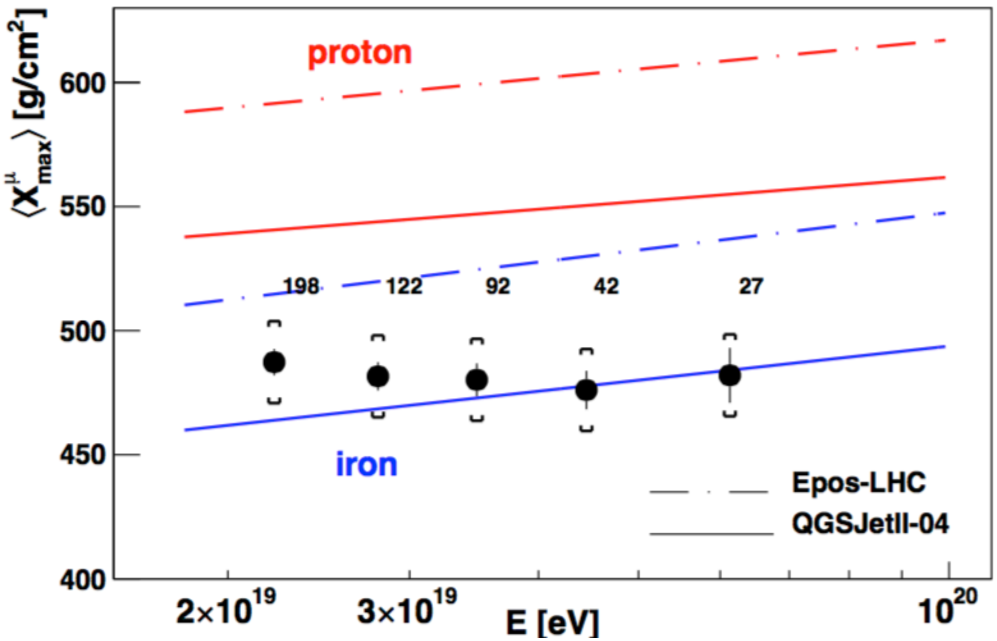
- **muon-rich stations:**
  - **events with zenith angle 55-65 deg.**
  - **stations with core distance >1.7 km**
- **projection of time traces to axis**
- **Sum up stations**

→ distribution of muon production heights

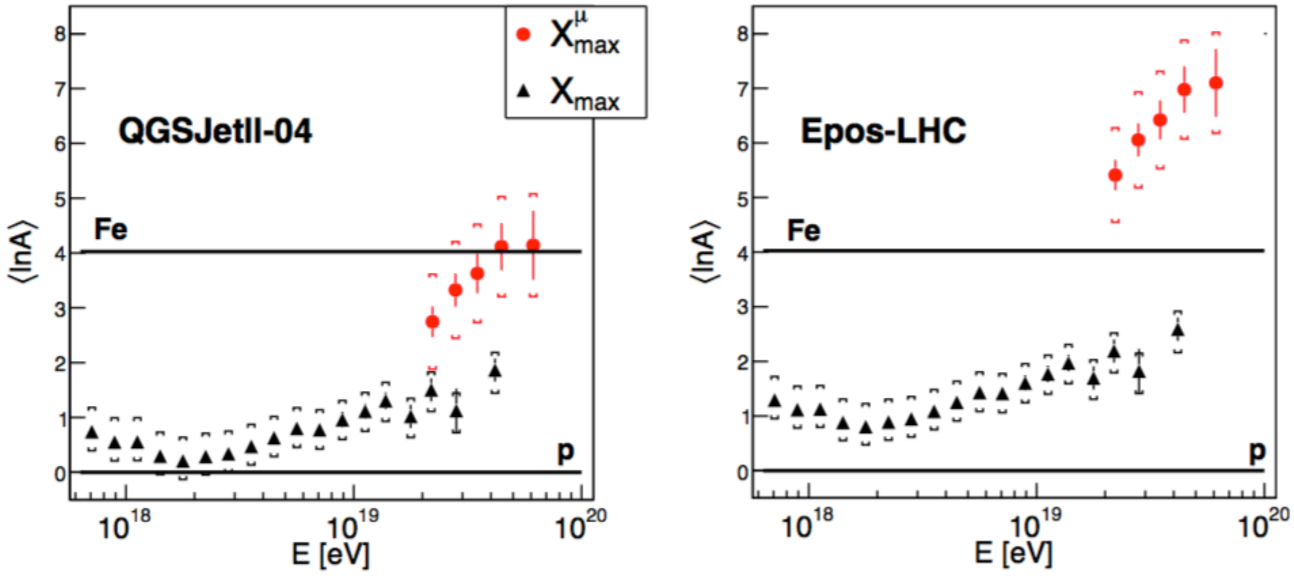
- **distance to slant depth conversion**
- **fit with Gaisser-Hillas**

→ maximum at X^{μ}_{max}

Muon Production Depth



- **Data bracketed by models only for QGSJetII-04**
- **Composition is not constant, ER~-25 g cm-2/ decade**
- **QGSJETII-04 compatible with data within 1.5σ, EPOS-LHC incompatible at 6σ level**



The best model for the muon content EPOS-LHC) fails in describing the MPD

[a small change in π-Air inelasticity can induce a cumulative effect in MPD and N_{μ}^{tot}]

Summary of main results from Auger Observatory

From Auger…

- ✓ all particle flux suppression above 4x10^{19} EeV
- ✓ the sources of UHECRs are astrophysical
- ✓ trend towards heavier composition above 10$^{18.5}$ eV
- ✓ high level of isotropy, but 7% dipole above 8x10^{18} eV
- ✓ hadr.int.models unable to reproduce measurements in a consistent way

…to AugerPrime

- ✓ extension of the composition measurements into the extreme energy range above 5 x 10^{19} eV
- ✓ increase of data quality (timing, dynamic range…)

Timeline

Summer 2016: engineering array
Fall 2016-17 : deployment
2018-24 : data taking