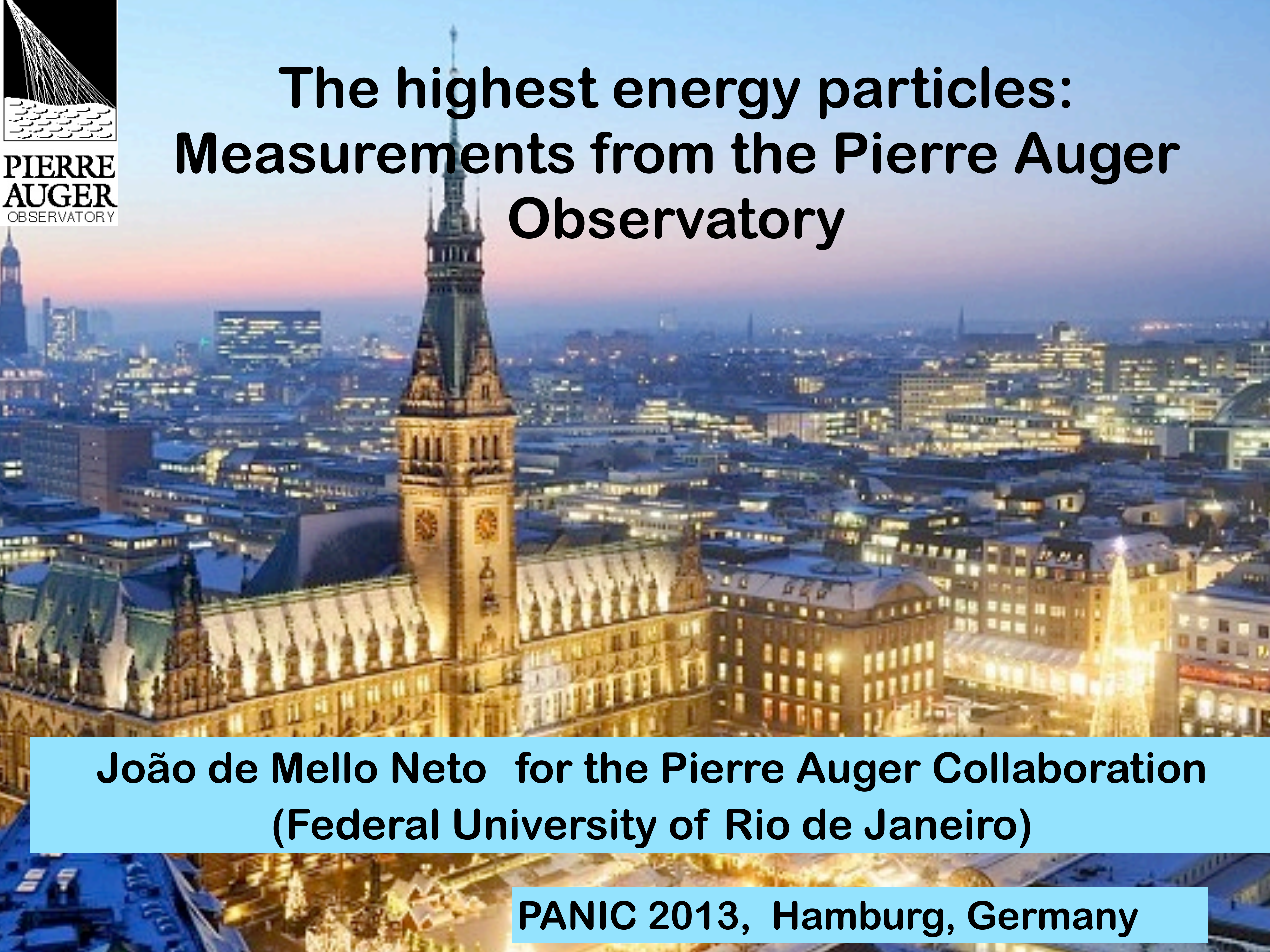


# The highest energy particles: Measurements from the Pierre Auger Observatory

João de Mello Neto for the Pierre Auger Collaboration
(Federal University of Rio de Janeiro)

PANIC 2013, Hamburg, Germany

# The highest energy particles

**Unanswered questions about UHECRs:**

★ What are those particles?
  **Mass composition**

★ Where do they come from?
  **Production sources**

★ How they reach $E > 10^{20}$ eV $= 100$ EeV ?
  **Acceleration mechanisms**

★ Can we extrapolate hadronic models orders of magnitude in energy?
  **Fundamental interactions**

**Their study has impact on**

★ Astrophysics

★ Particle Physics

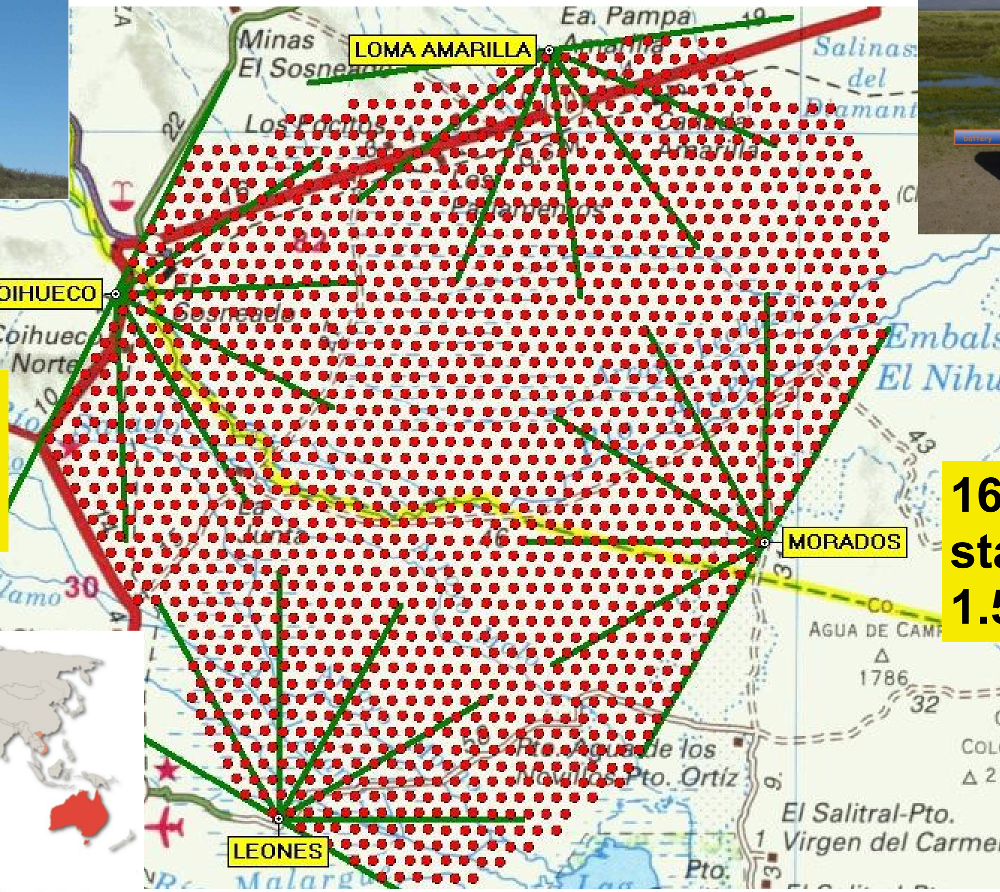
**The true high-energy frontier of physics!**

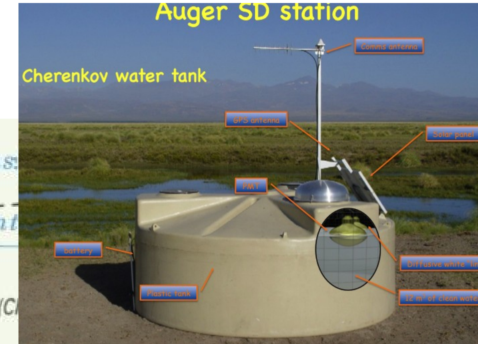
# Pierre Auger Observatory

**Fluorescence Detector**

**27 telescopes overlooking the array**

**3000 km$^2$**



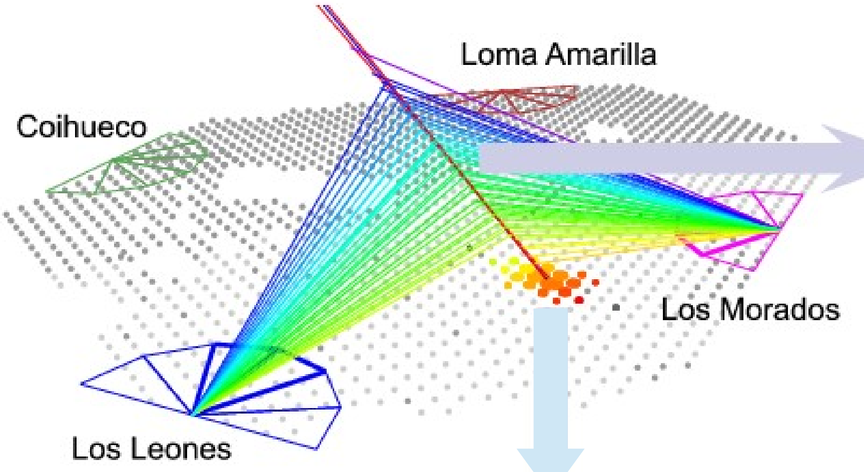

**Surface Detector**

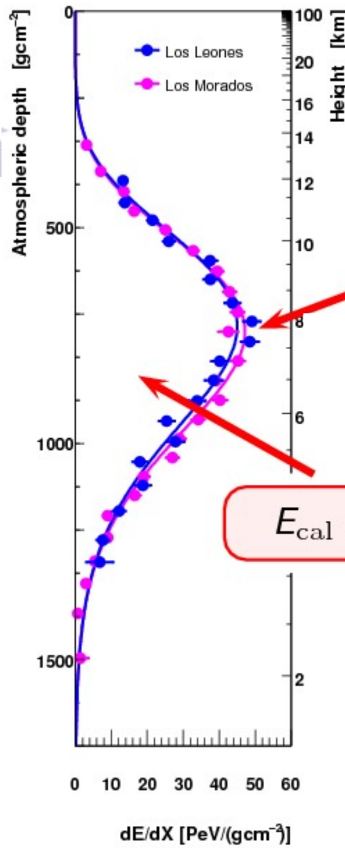
**1660 Cherenkov stations, in a grid of 1.5 km**


17 countries, ~ 500 physicists

**Hybrid detector: improve precision and reduce dependence on models**

# Detecting UHECRs




## Fluorescence Detector

**UV photons (4 ph/particle/m) emitted in the de-excitation of the atmospheric nitrogen**

$X_{\max}$

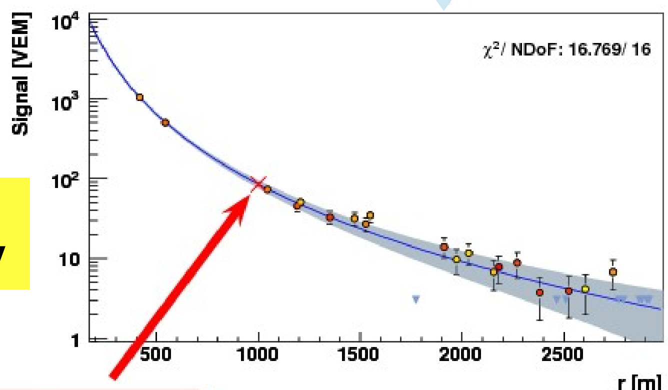
**Direct** measurement of $X_{max}$ (mass composition)

$E_{\rm cal} = \int dX \, \frac{dE}{dX}$

**longitudinal profile**

★ Calorimetric energy meas. (model independent)
★ lower energy threshold
★ 15% duty cicle (moonless)

**lateral density**




$S_{1000}$

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

## Surface Detector

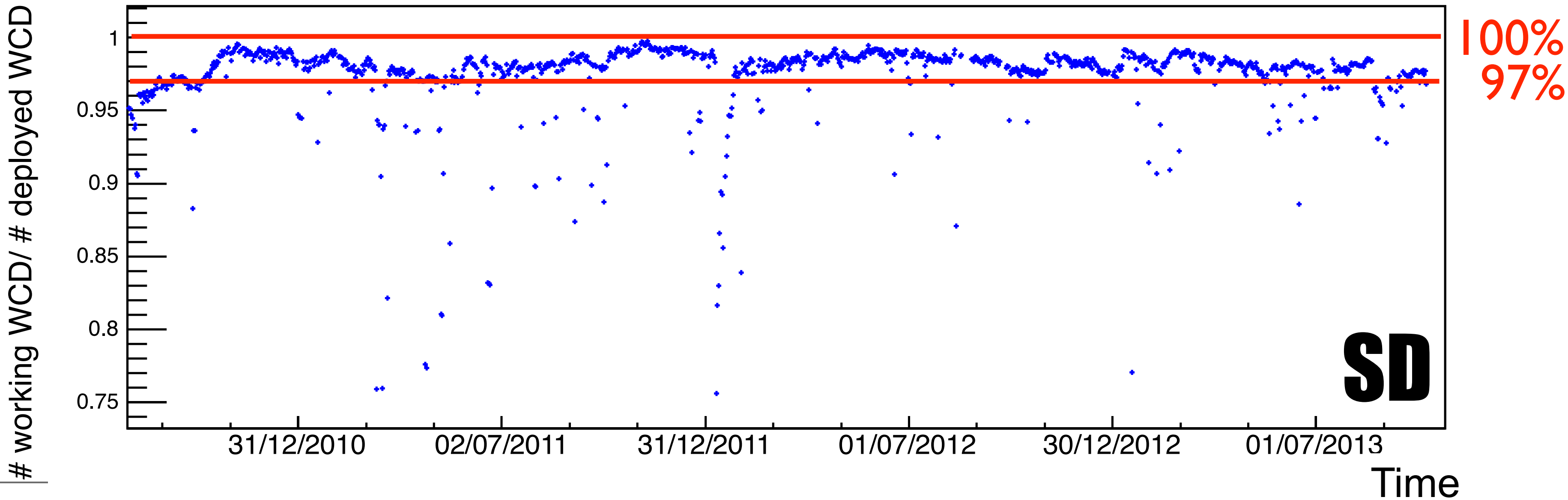
**Sample shower particles at ground**

★ 100% duty cycle (statistics)
★ Energy threshold (full eff.) 3 EeV
★ Geometrical aperture (no MC, no mod.)

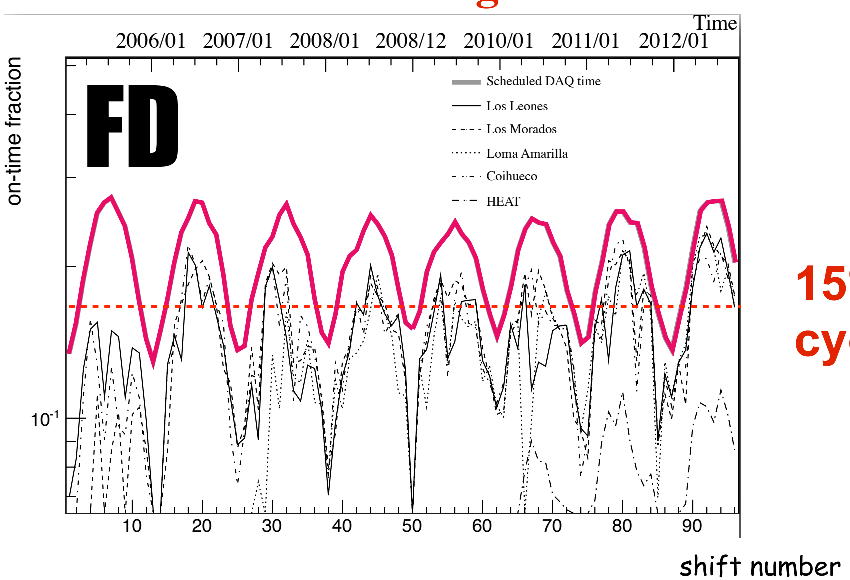
**"Golden hybrid" data sample:**

★ detector cross-calibration
★ systematics , cross-checks, etc

# Detector Performance




**Scheduled data-taking time fraction**



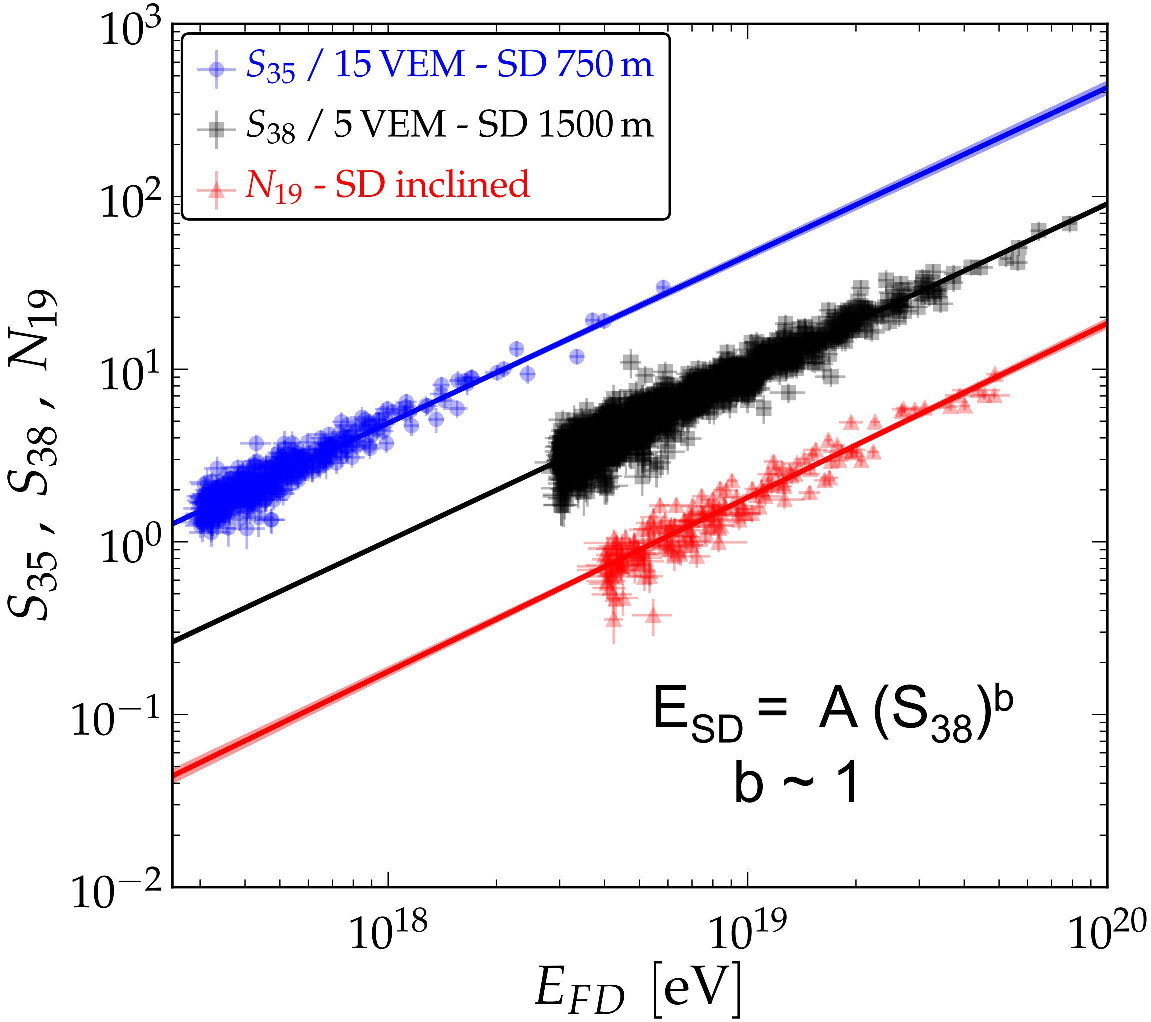

**15% duty cycle**

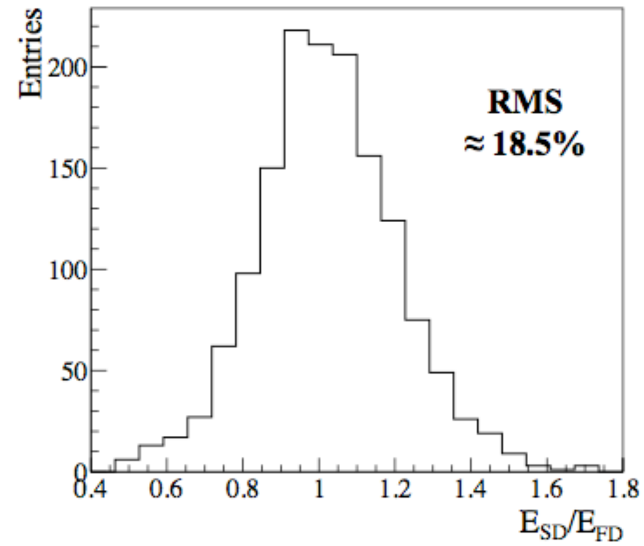
**Very effective atmospheric monitoring**

Bonifazi for Auger Collab, ICRC 2013

Chirinos for Auger Collab, ICRC 2013

# Auger energy measurements



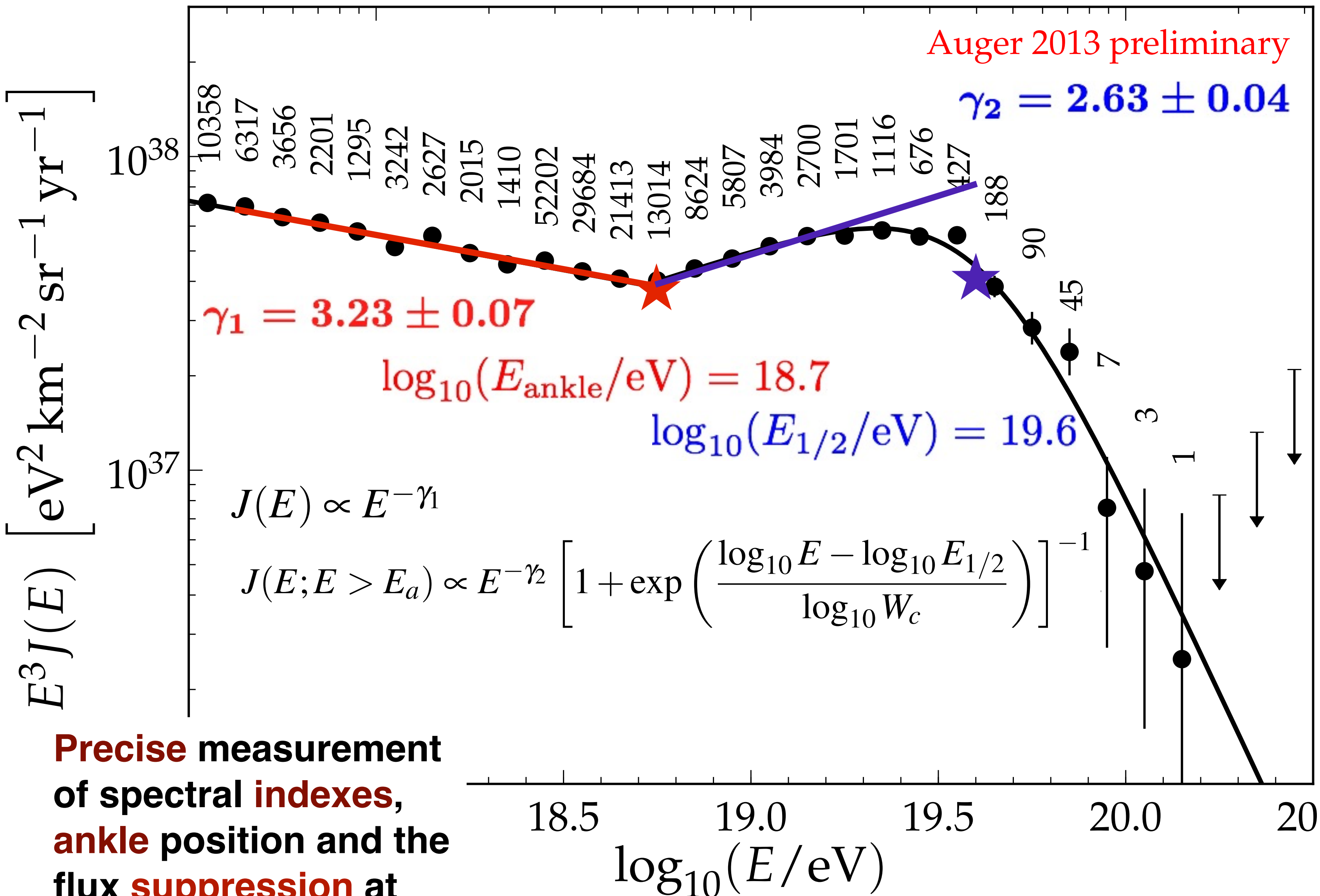

SD energy resolution < 12% above 10 EeV

SD angular resolution < 1° above 10 EeV

Schulz for Auger Collab, ICRC 2013

Energy calibrations to FD energies for all three SD measurements from the energy estimators

# Auger combined spectrum



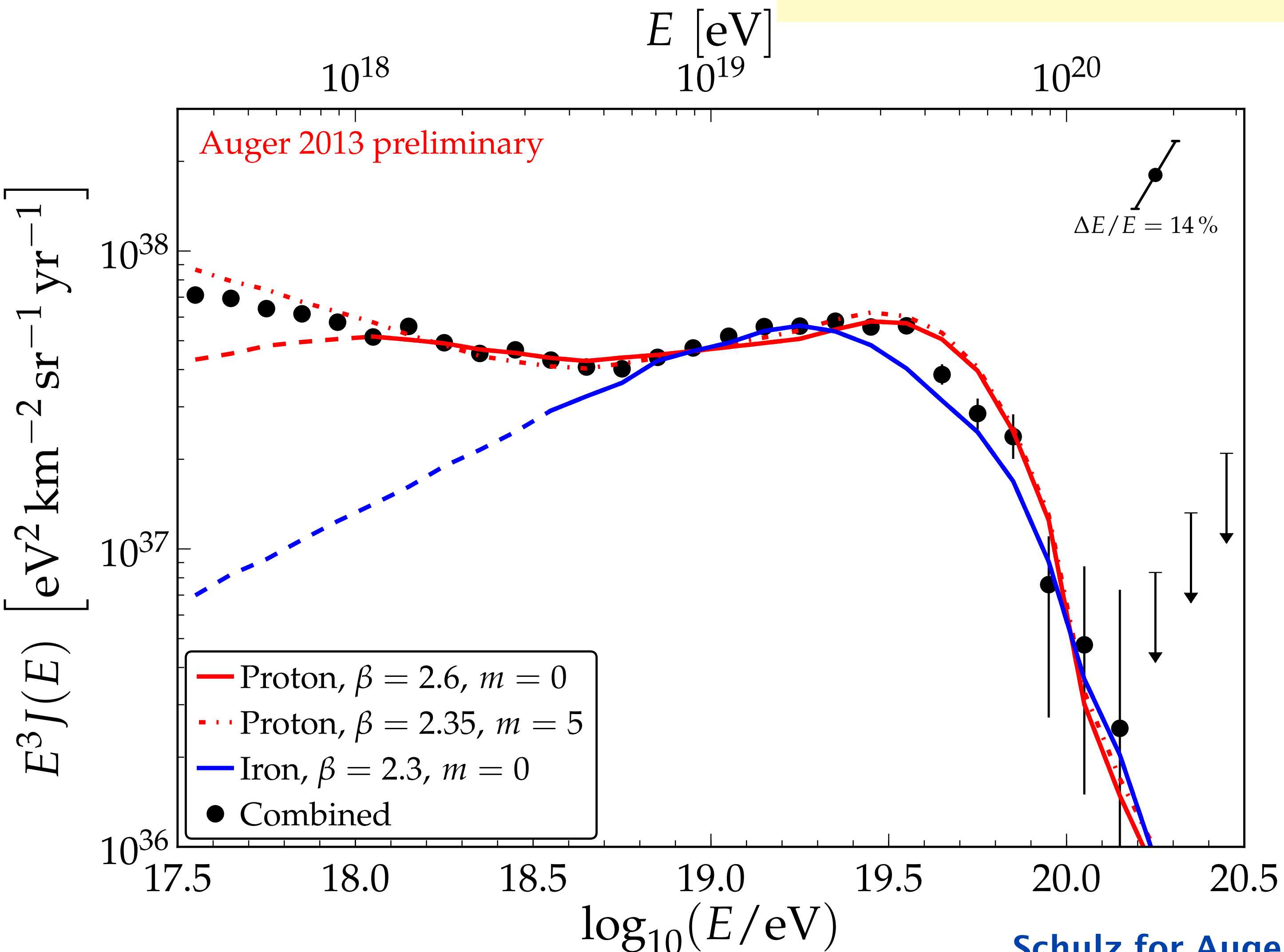

**Precise** measurement of spectral **indexes**, **ankle** position and the flux **suppression** at highest energies

Schulz for Auger Collab, ICRC 2013

# Auger combined spectrum

**GZK** or **sources** running out of **power**?

$$\phi(E) \propto E^{-\beta} \cdot (1+z)^m$$



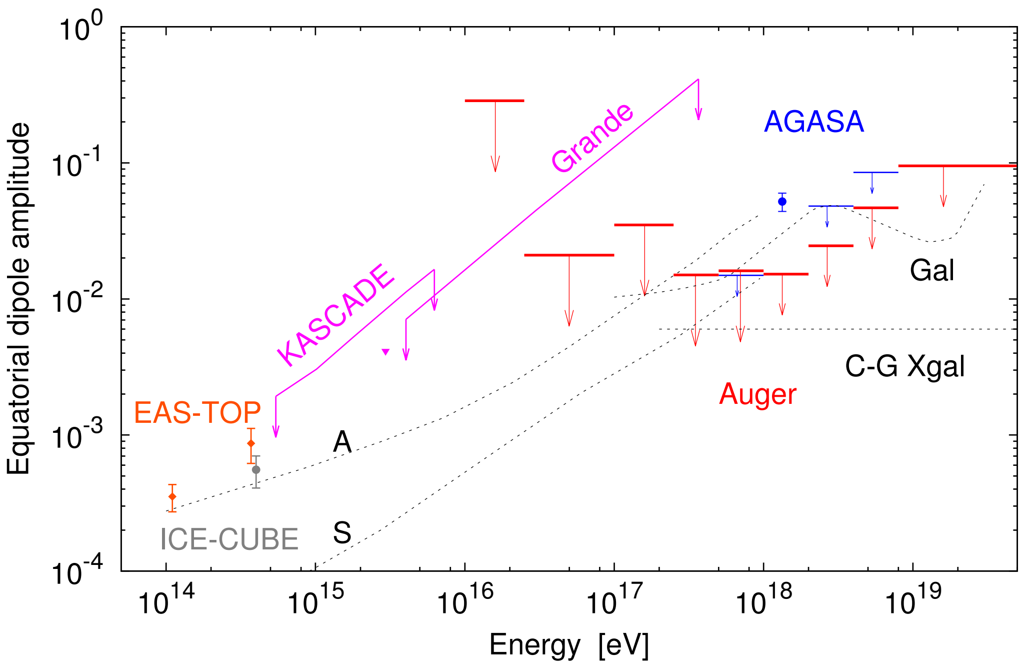

**Simple models: vary particle type, source injection spectrum index and source evolution fit the data surprisingly well.**

**Constraining models need composition measurement.**

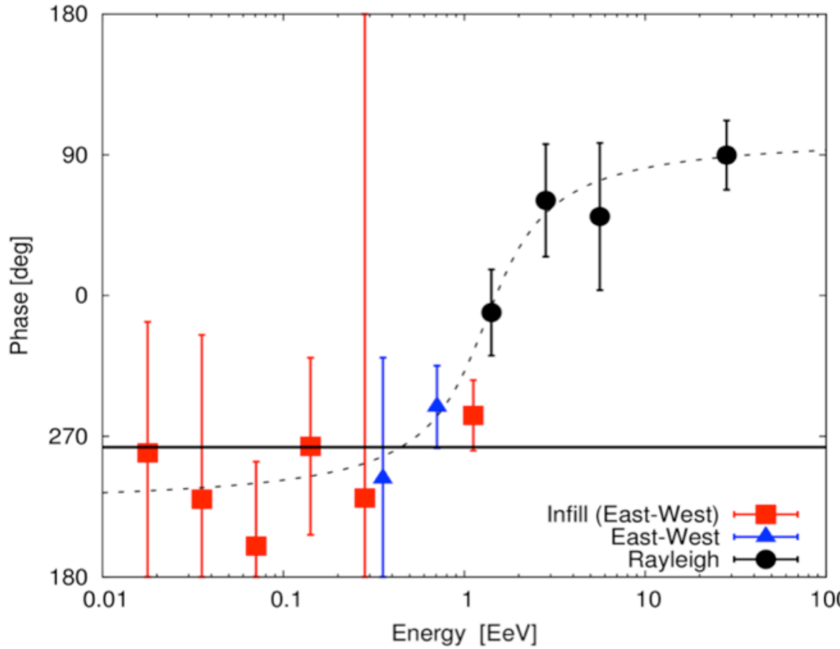
Schulz for Auger Collab, ICRC 2013

# Large scale anisotropy

## Amplitude




## Phase



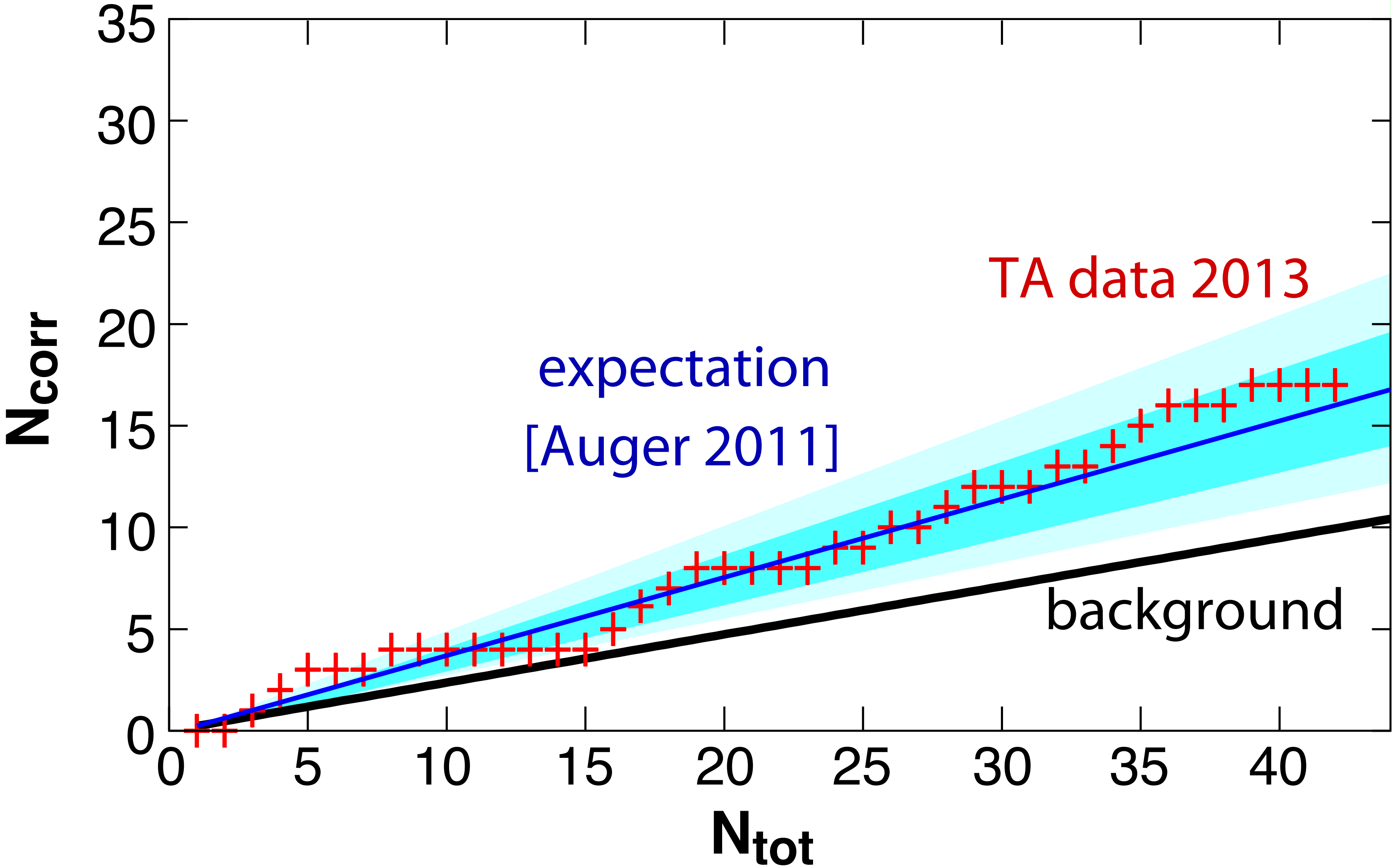

**Auger upper limits exclude some models.**
**Phase is more sensitive observable**
**Smooth change of phase away from GC at E > 1 EeV**

**For isotropic distribution, expect uniform distribution, uncorrelated in energy**

**Prescription to check with new data at 99% CL: constancy of phase at E<1 EeV with the Infill data, transition in phase at high energies**

**Sidelnik for Auger Collab, ICRC 2013**

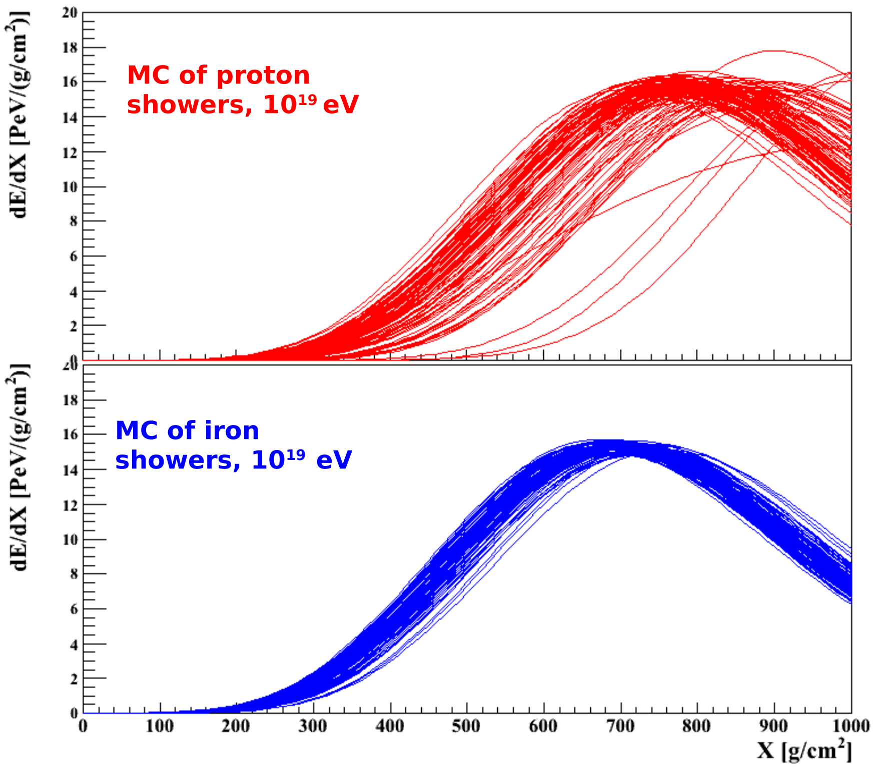
# AGN correlation: Auger and Tel. Array

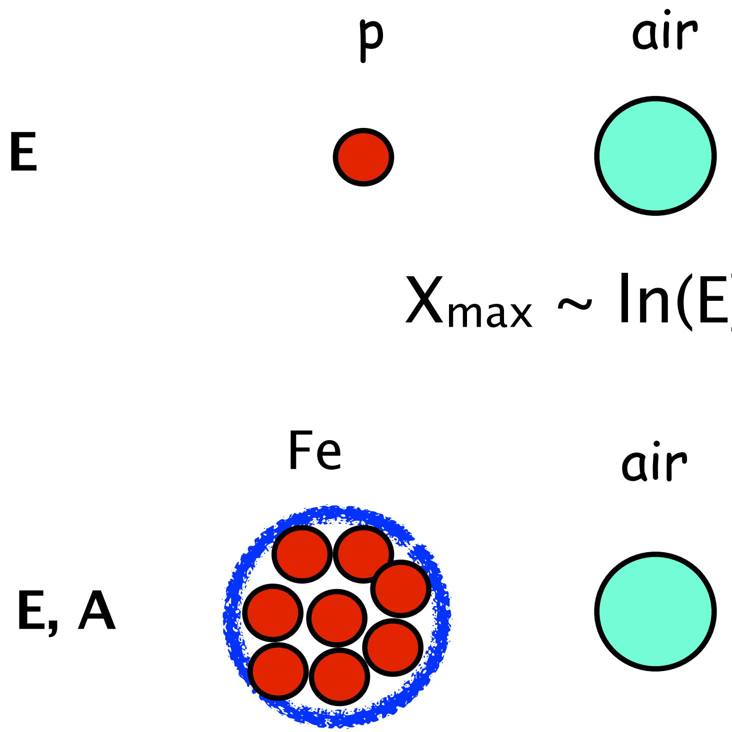



**A very good agreement between Auger and TA data**

Kampert, Tyniakov, ArXiv 1405.0575

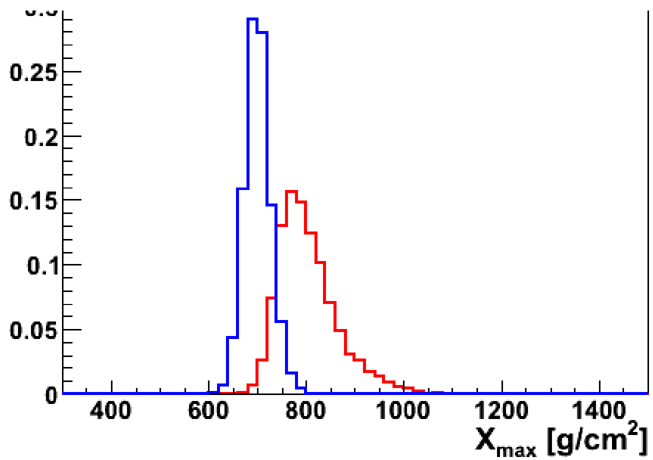
# Composition measurement



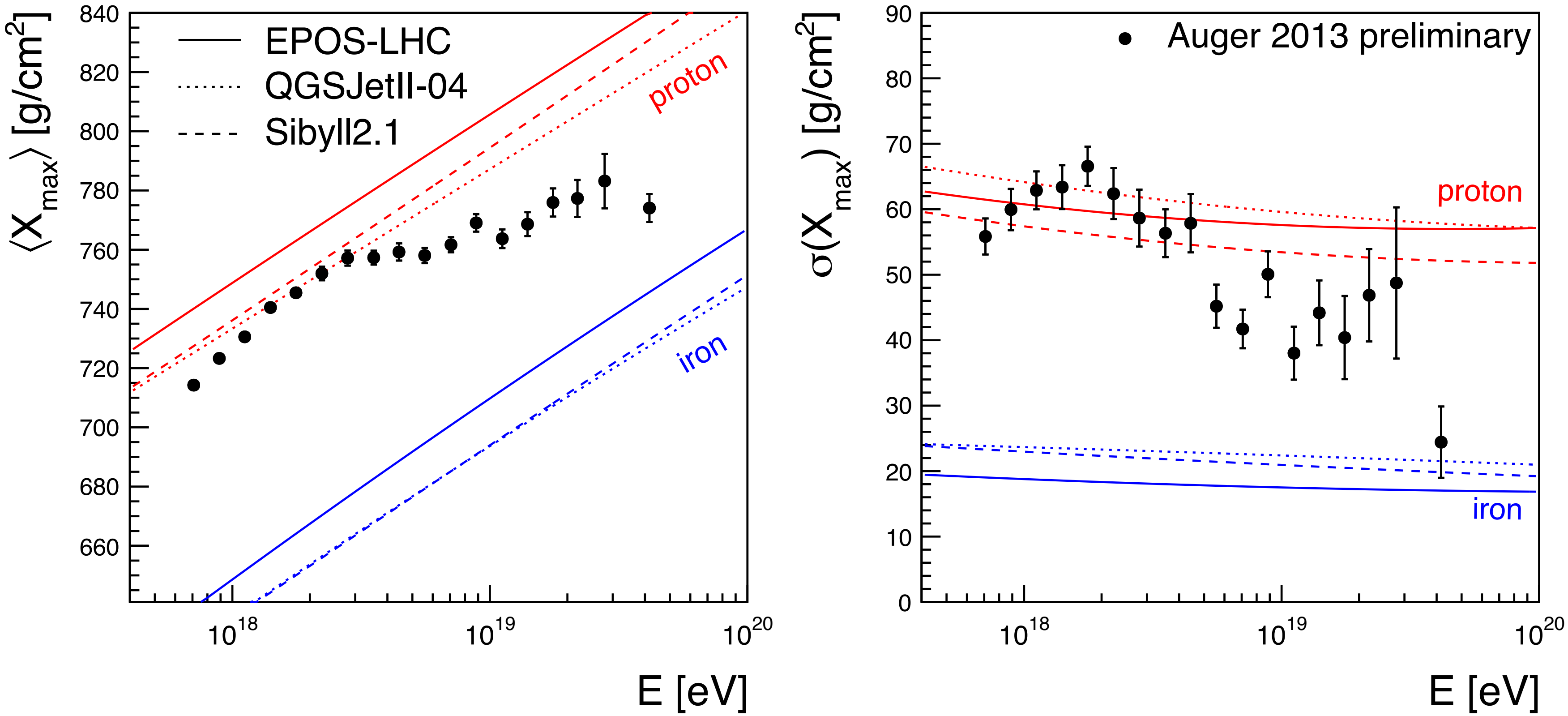

$X_{max} \sim \ln(E)$

$X_{max} \sim \ln(E/A)$




mean $X_{max}$ and RMS($X_{max}$) are sensitive to **composition**

# Composition measurement



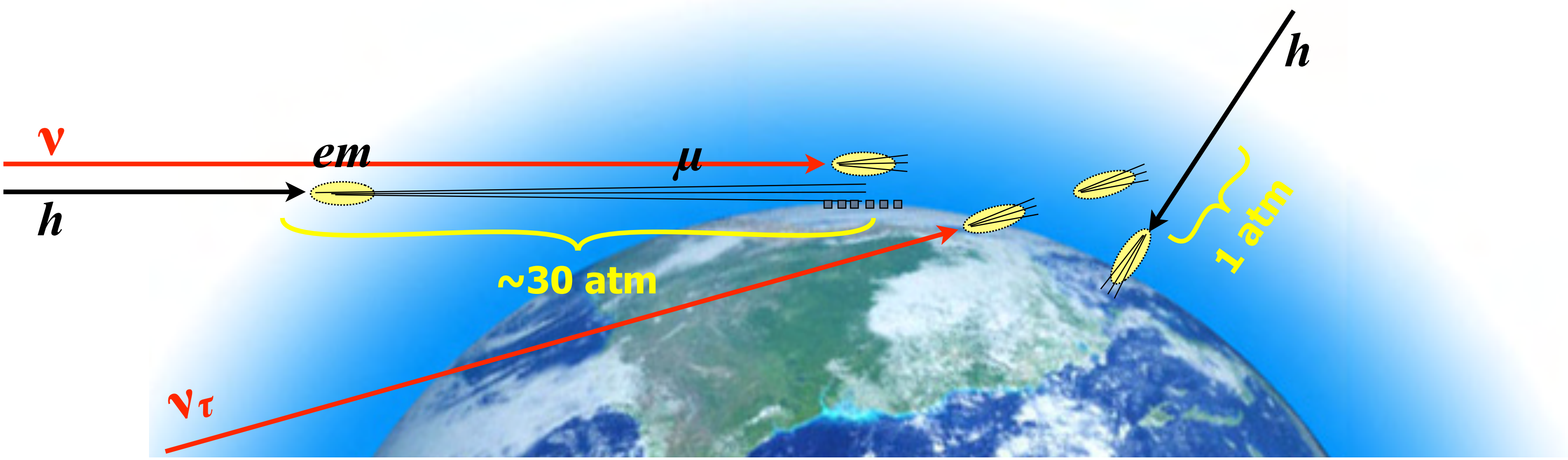

At the **highest energies** <$X_{max}$>, $\sigma(X_{max})$, **muon production depth** and **shower depth from asymmetry of risetimes** show **consistently** that our data better resemble the **simulations** of **heavier primaries** than pure protons.

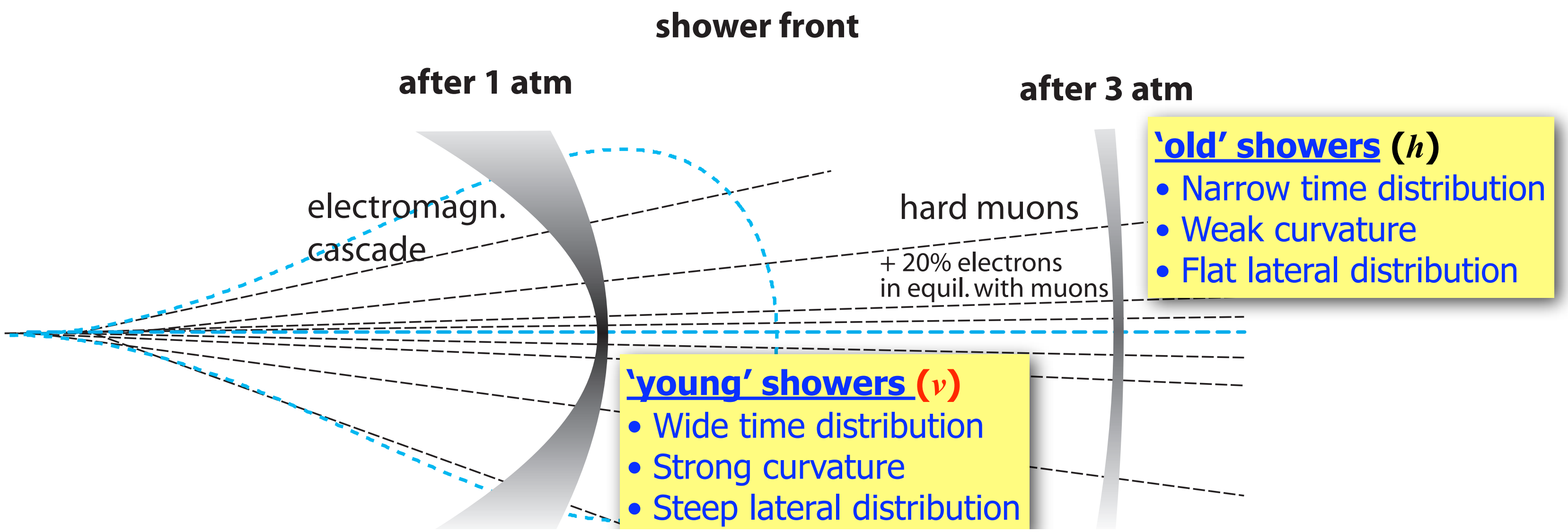
**V. de Souza, Auger Collab, ICRC 2013**

**Auger Collab., PRL 104 091101, 2010**

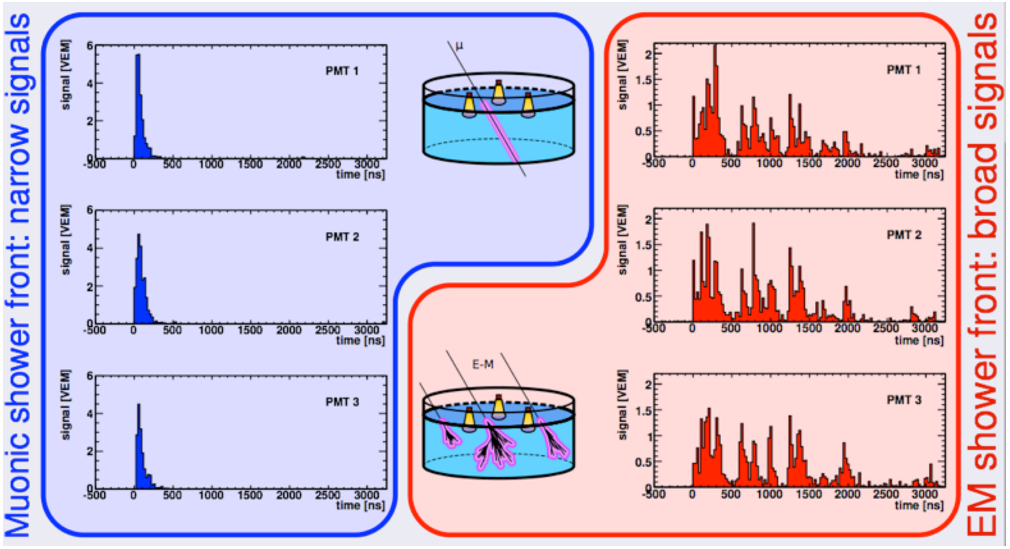
# Neutrino induced showers

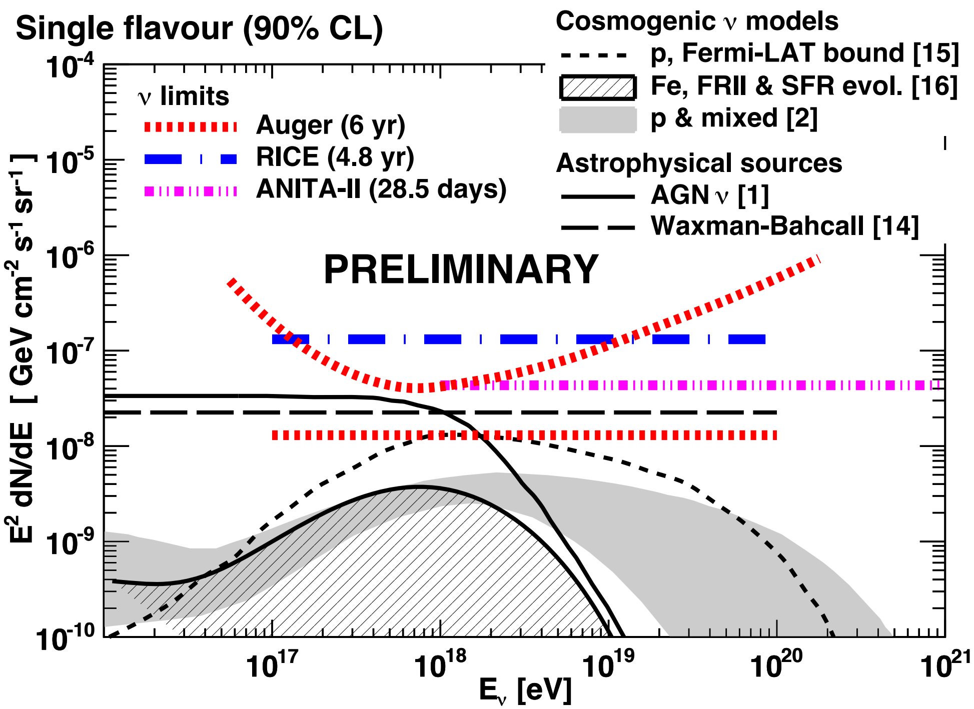
## Only a neutrino can induce a young horizontal shower !



# Auger neutrino limits




**young ν induced showers**

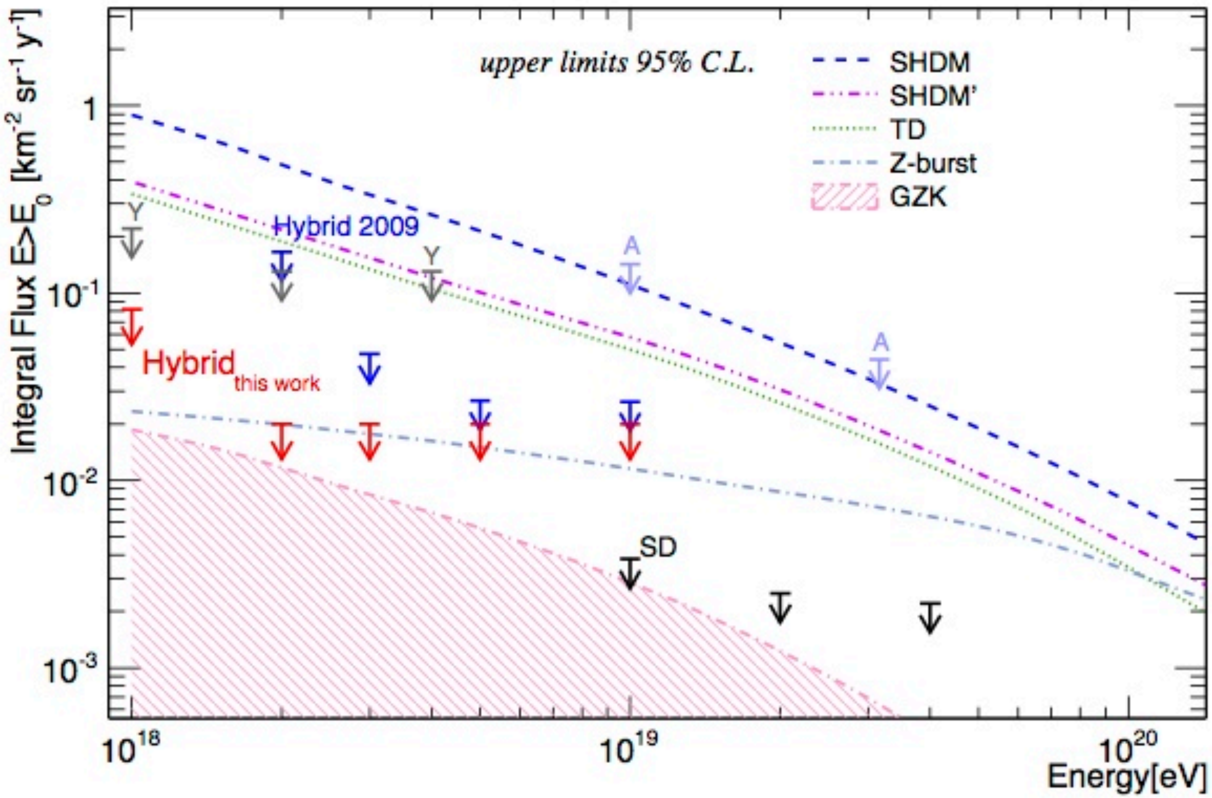
- ★ wide time distribution in surface stations
- ★ elongated footprint of inclined shower
- ★ propagation speed of shower front at ground

Limits start to dig into potential sources and cosmogenic “GZK” neutrinos

Auger Collab. Astrop. J. Lett, 2012

Pieroni, Auger Collab. ICRC, 2013

# Upper limits on flux of photons




**Photons characterized by:**

- ★ deep Xmax in FD
- ★ small signal in SD

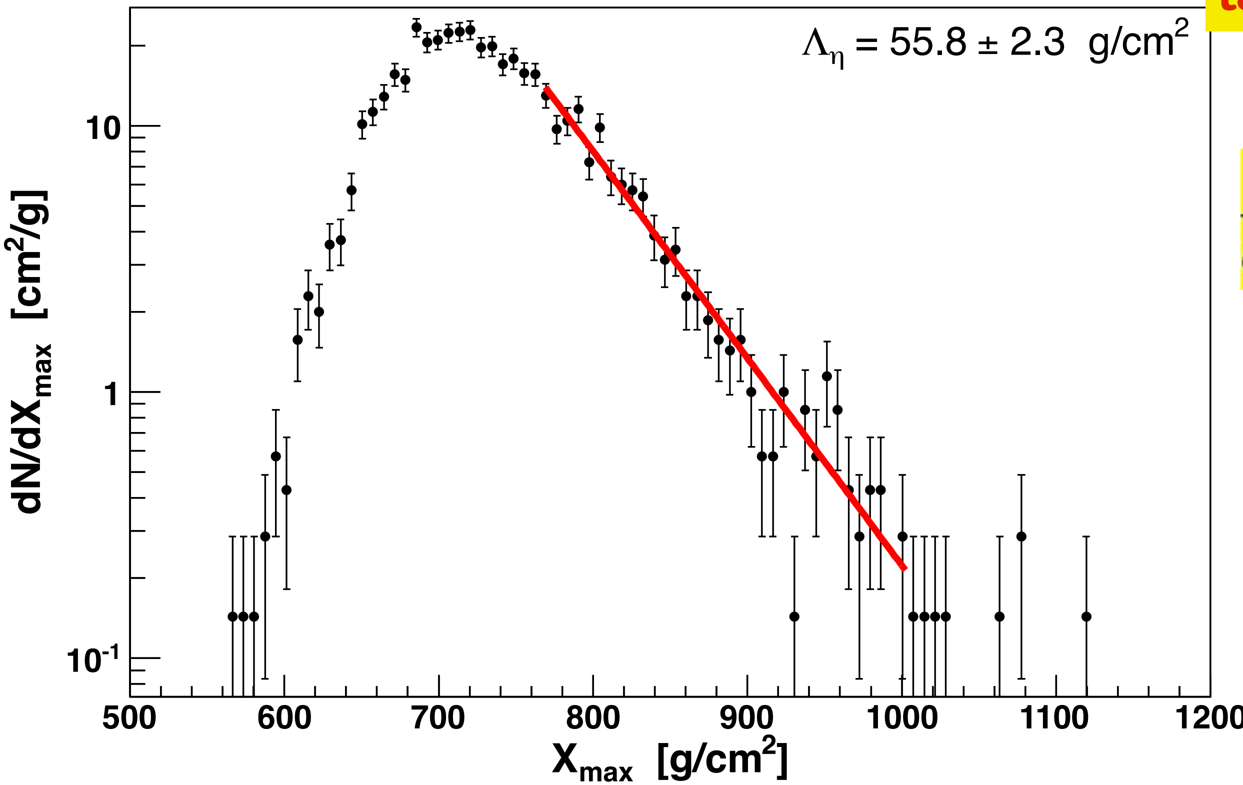
The **observation** of a photon flux **compatible** with the cosmogenic prediction could provide an **independent proof** of the GZK process

**disfavour exotic "particle physics" origin of UHECR**

- ★ **Models disfavoured down to 1 EeV**
- ★ (optimistic) **GZK in reach**

Auger Collab, Astrop. Phys (2009)
M. Settimo, Auger Col., ICRC 2011

# p-Air & pp Cross-Section at 57 TeV




$10^{18}$ eV < E < $10^{18.5}$ eV

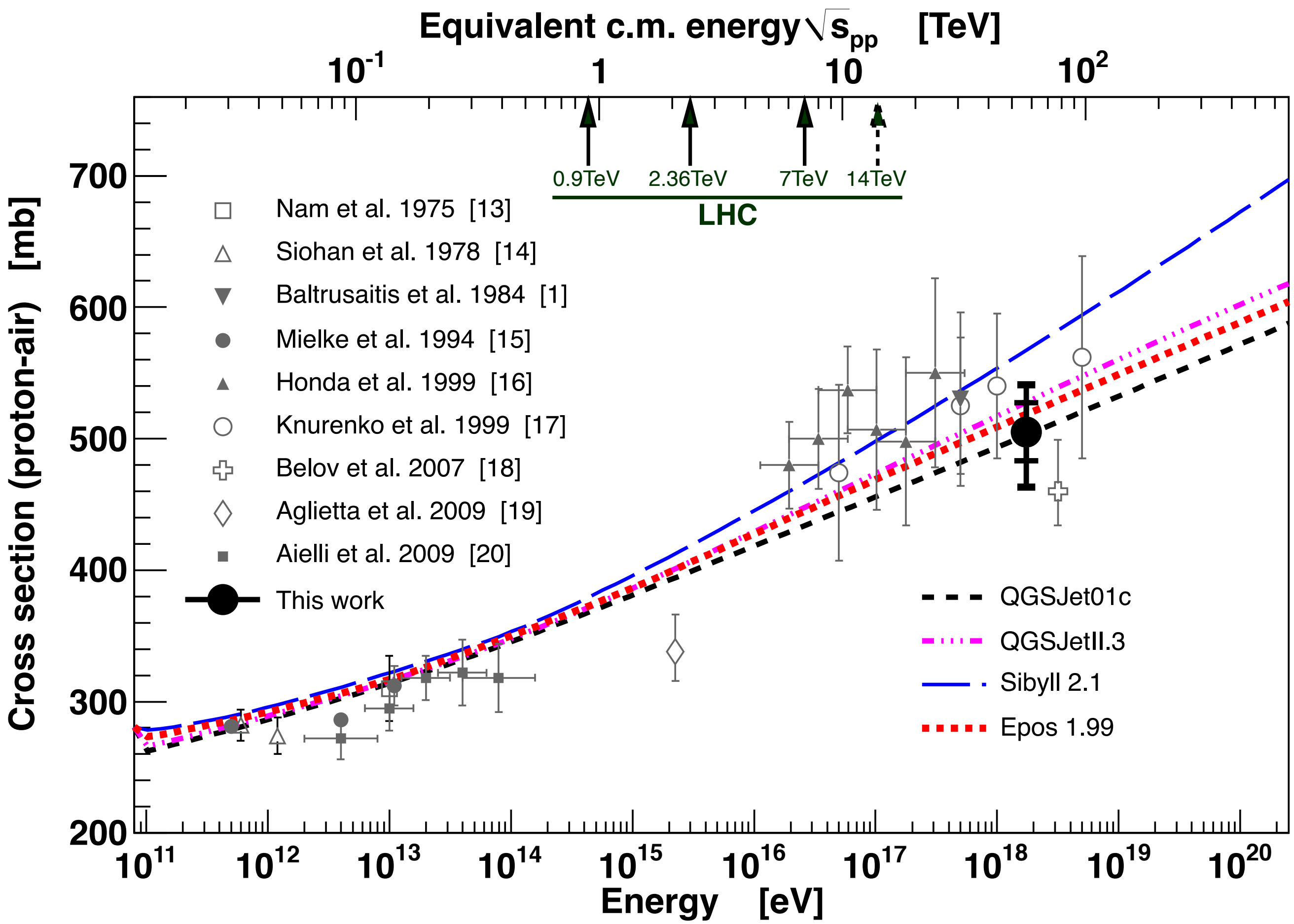
**tail dominated by protons**

$$\frac{dN}{dX_{max}} \sim \exp\left(-\frac{X_{max}}{\Lambda_\eta}\right)$$

$\Lambda_\eta \rightarrow \sigma_{p\rightarrow Air}$
by tuning models
to reproduce tail
seen in data

Auger Collab. Phys. Rev. Lett, 2012

# p-Air Cross-Section



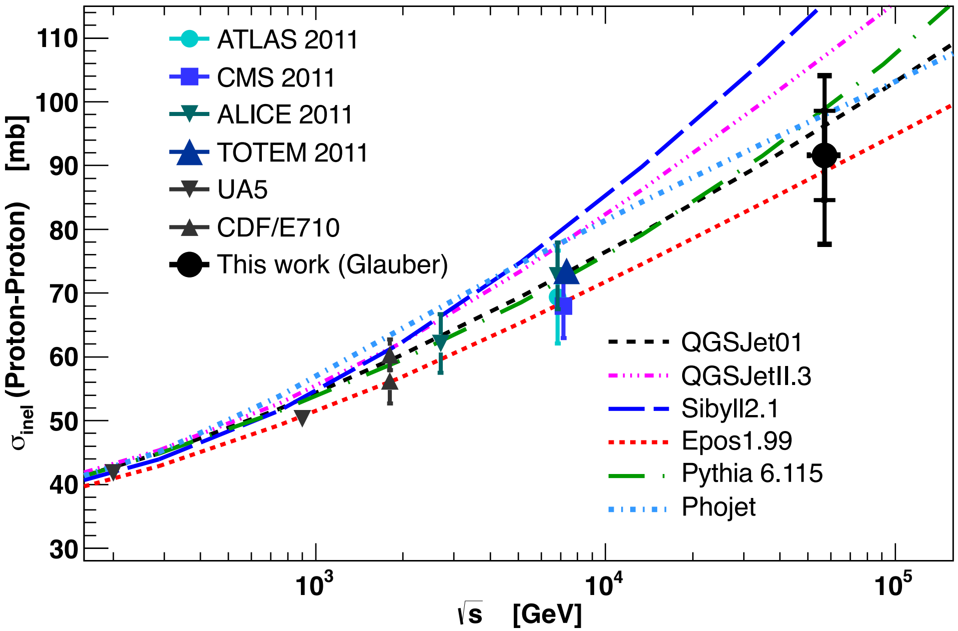

systematic uncertainties
< 0.5% photons
< 25% He

$$\sigma_{p\text{-air}}^{\text{prod}} = [505 \pm 22(\text{stat}) {}^{+28}_{-36}(\text{sys})] \text{ mb}$$

Auger Collab. Phys. Rev. Lett, 2012

# UHECRs and LHC

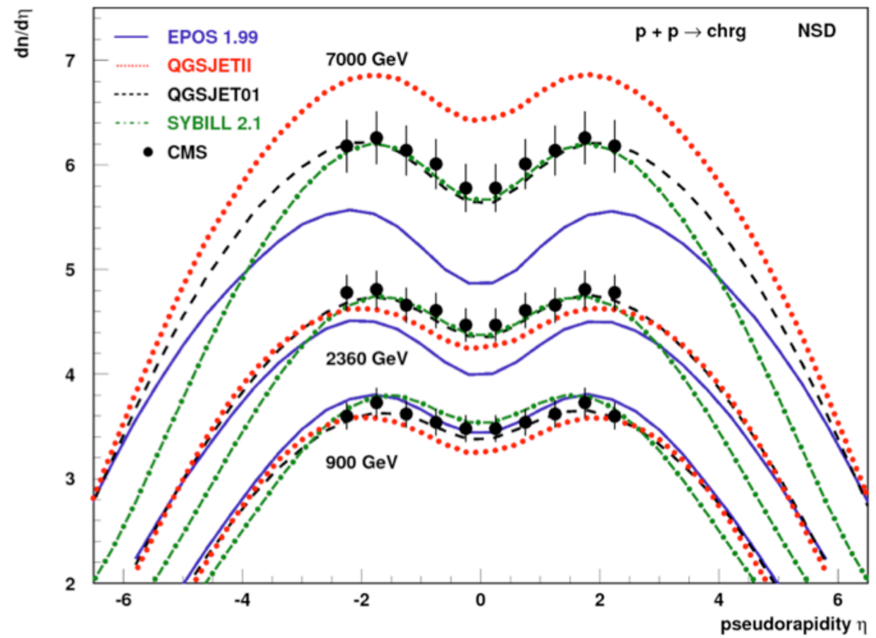
**Inelastic pp Xsec at 57 TeV: standard Glauber theory + propagation of modeling uncertainties**




$$\sigma_{pp}^{\mathrm{inel}} = \left[92 \ \pm 7(\mathrm{stat}) \ ^{+9}_{-11}(\mathrm{sys}) \ \pm 7(\mathrm{Glauber})\right] \ \mathrm{mb}$$

$$\sigma_{pp}^{\mathrm{tot}} = \left[133 \ \pm 13(\mathrm{stat}) \ ^{+17}_{-20}(\mathrm{sys}) \ \pm 16(\mathrm{Glauber})\right] \ \mathrm{mb}$$

**Pseudo-rapidity distributions at LHC and Monte Carlo simulations**




★ central distributions well **bracketed** by the model predictions,

★ **true predictions** as the models were tuned years before LHC data became available

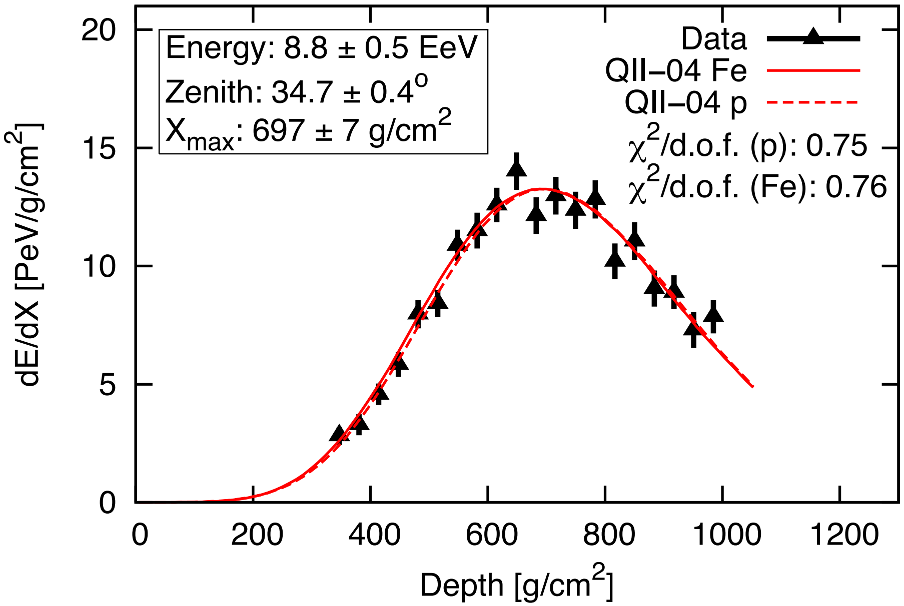
Auger Collab. Phys. Rev. Lett, 2012

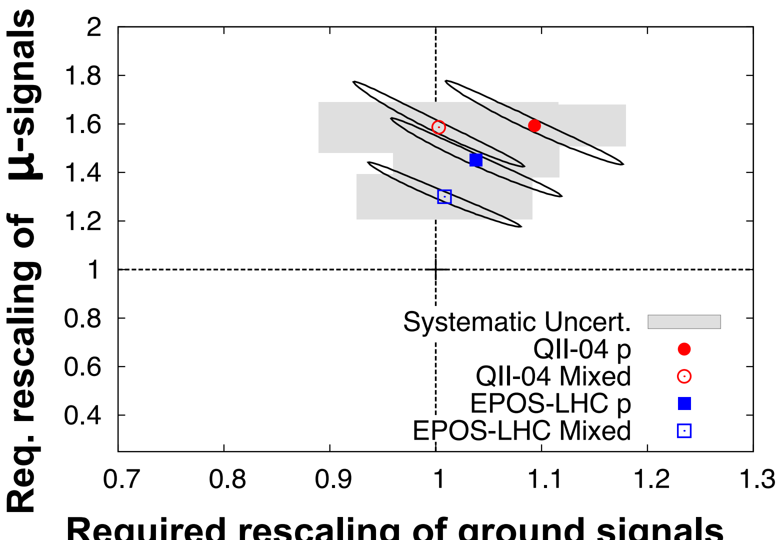
UHECRS 2012 Hadronic Interactions report

# hadronic models underestimate muons

**Measured event**

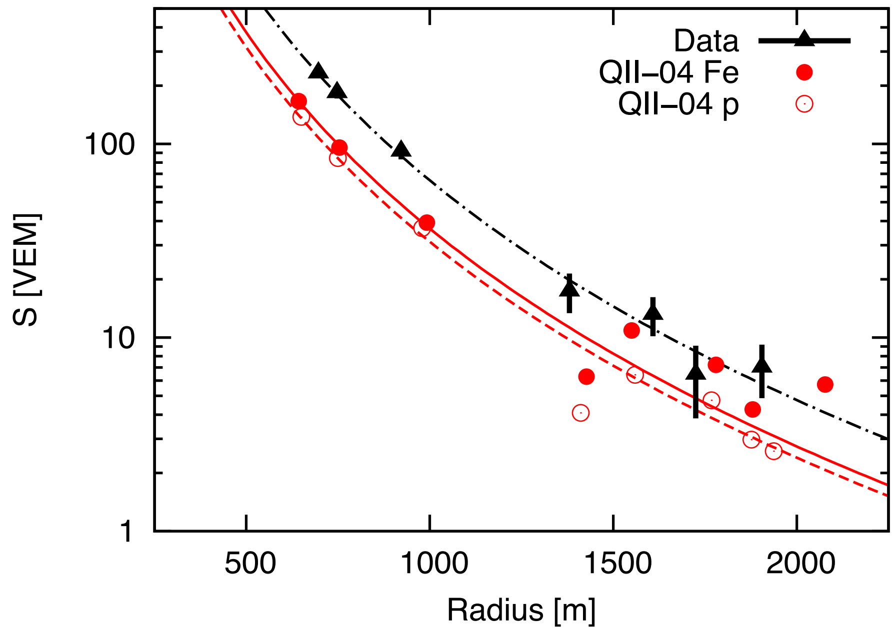
**with matching p and Fe-simulations**




**Same measured event**

**with predicted p signals for p and Fe**




**Models underestimate muon content of EAS by 30-60%**

Farrar for Auger Collab, ICRC 2013

# Major achievements - first six years

- ★ Clear observation of **flux suppression**
- ★ Strongest existing **bounds** on EeV ν and ϒ
- ★ Strongest existing bounds on **large scale anisotropies**
- ★ First hints on directional **correlations** to nearby matter
- ★ Increasingly **heavier** composition above ankle
- ★ pp **cross section** at ~10*$E_{LHC}$, LIV–bounds
- ★ **muon deficit** in models at highest energies
- ★ **geophysics** (elves, solar physics, aerosols...)

**Auger upgrade: improve muon counting in surface detector array**

# Science goals of Auger upgrade

- ★ **Elucidate the origin of the flux suppression, GZK vs. maximum energy scenario**
  - fundamental constraints on UHECR sources
  - galactic vs extragalactic origin
  - reliable prediction of GZK $\nu$ and $\Upsilon$
- ★ **Search for a flux contribution of protons up to the highest energies at a level of ~ 10%**
  - proton astronomy up to the highest energies
  - propects of future UHECR experiments
- ★ **Study of extensive air showers and hadronic multiparticle production above ~70 TeV**
  - particle physics beyond man-made accelerators
  - derivation of constraints on new physics phenomena

# Conclusion

- ★ The Pierre Auger experiment is complete since 2008 and it is taking data since 2004
- ★ Very robust hybrid technique to detect CRs at the highest energies

  Many interesting results on astrophysics and particle physics

- ● Measurement of the spectrum suppression: GZK or maximum energy scenario?
- ● Large scale anisotropy:
  - ★Most stringent upper limits at present on the amplitudes
  - ★Phase does not follow a random distribution
  - ★With higher statistics the galactic/extragalactic transition may be stablished
- ● Weak correlation with VCV catalogue
  - ★Correlation is stabilizing
- ● Very competitive neutrino limits
- ● Stringent limits on photon primaries and top-down models
- ● Measurement of p-air cross section at 57 TeV
- ● Working on upgrades - muon detectors

# Thank you