Ultra-high energy cosmic rays at the Pierre Auger Observatory

Karim Louedec

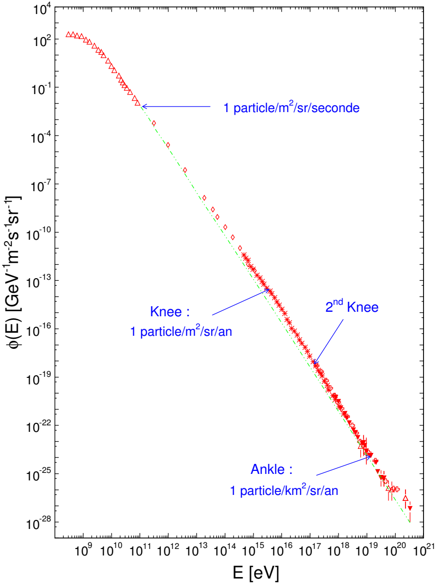
Laboratoire de Physique Subatomique et de Cosmologie
Université Joseph-Fourier, CNRS/IN2P3, Grenoble, France

Mardi 2 juillet 2013

cnrs dépasser les frontières
IN2P3
Les deux infinis

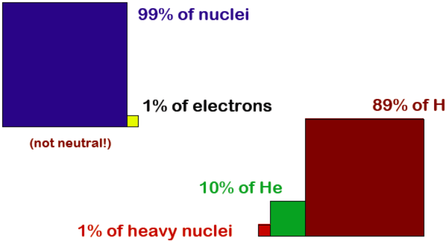
PIERRE AUGER OBSERVATORY

Cosmic ray energy spectrum



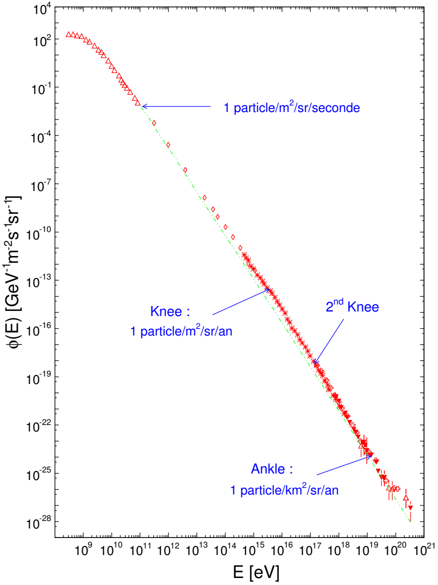
Origin of cosmic rays

- flux in power law $J \propto E^{-\gamma}$,
- up to a few 10^{17} eV : $\rightarrow$ galactic,
- beyond a few 10^{18} eV : $\rightarrow$ extragalactic.



(courtesy: E. Parizot)

Cosmic ray energy spectrum



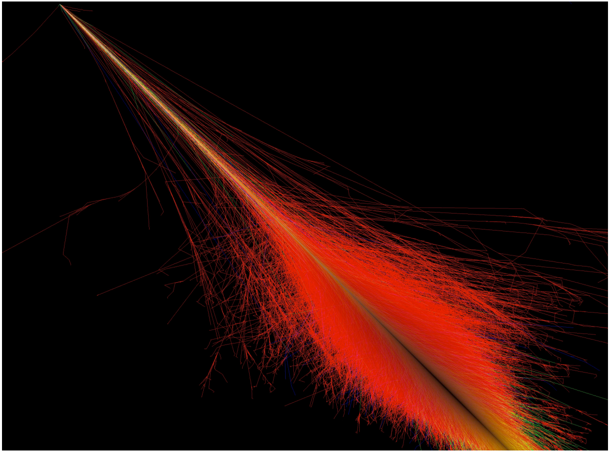
Up to the knee: direct detection

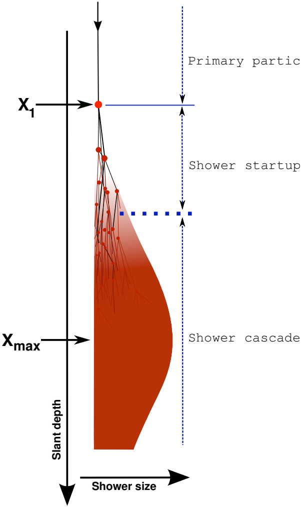
- outside atmosphere *(almost)*,
- :) → particle identification,
- :(→ only at low energies.

Beyond the knee: indirect detection

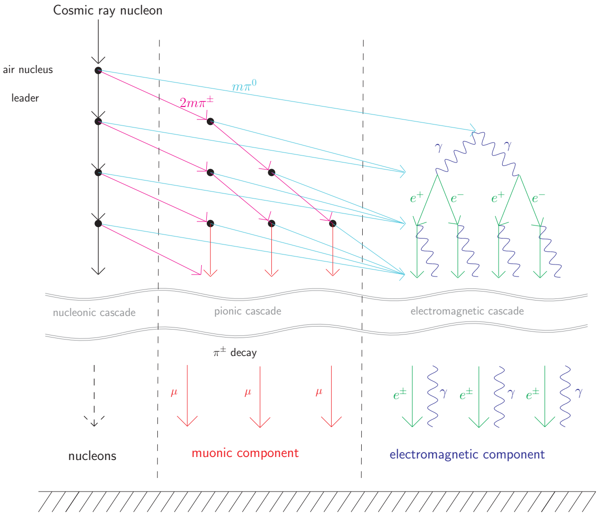
- atmospheric showers,
- :) → large collecting area,
- :(→ particle identification more difficult.

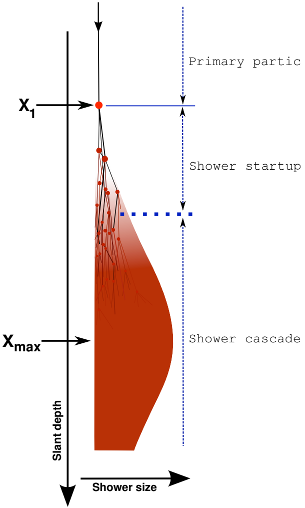
Indirect detection – Extensive Air Showers



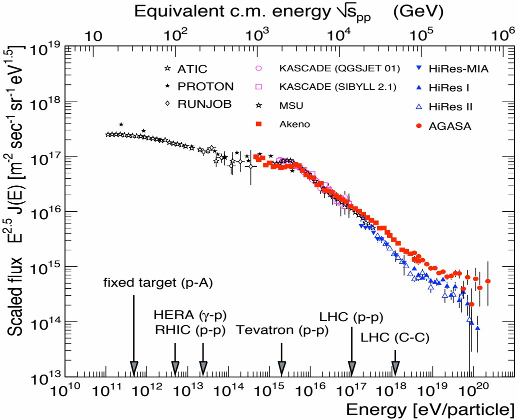


Indirect detection – Extensive Air Showers





Energy spectrum at Ultra-High Energy: status of some years ago



- low luminosity @ 10^{19} eV
  $\rightarrow$ 1 particle/km^2/century
- AGASA (Japan)
  $\rightarrow$ surface detector
- HiRes (Utah / USA)
  $\rightarrow$ fluorescence detector

Acceleration – astrophysical shocks ($\rightarrow$ Hillas criterion)

$$E_{\rm max} = Z \left(\frac{B}{1\ \mu{\rm G}}\right) \left(\frac{L}{1\ {\rm kpc}}\right) {\rm EeV}$$

Z: particle charge / L: size of acceleration region / B: magnetic field
$\rightarrow$ *candidates:* AGNs, GRBs, young pulsars, etc...

A plenty of questions...

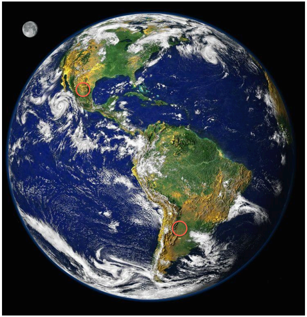
3 observables
arrival direction distribution / primary composition / energy spectrum

1. What is the source of ultra-high energy cosmic rays
   $\rightarrow$ what is the fundamental physics process for ultimate energies ?
   $\rightarrow$ how do they get their energy / acceleration mechanism ?

2. What are ultra-high energy cosmic rays
   $\rightarrow$ which mass composition for primary cosmic rays ?
   $\rightarrow$ does their mass composition changes with the energy ?

Is it possible to identify the source(s) of ultra-high energy cosmic rays ?
–
charged astronomy: could they be used as astrophysical messengers ?

Currently, two main observatories all around the world



Pierre Auger Observatory (30 x AGASA)

→ Mendoza / Argentina,

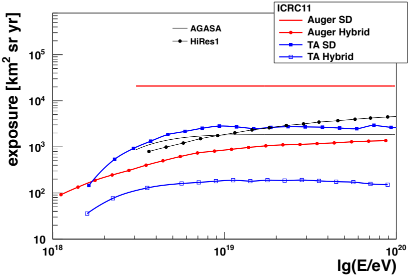
→ 3 000 km^2 array,

→ 500 collaborators / 19 countries,

→ collecting data since 2004,

→ annual expo: 6×10^3 km^2 sr yr.

PIERRE AUGER OBSERVATORY



Telescope Array (7 x AGASA)

→ Utah / USA,

→ 680 km^2 array,

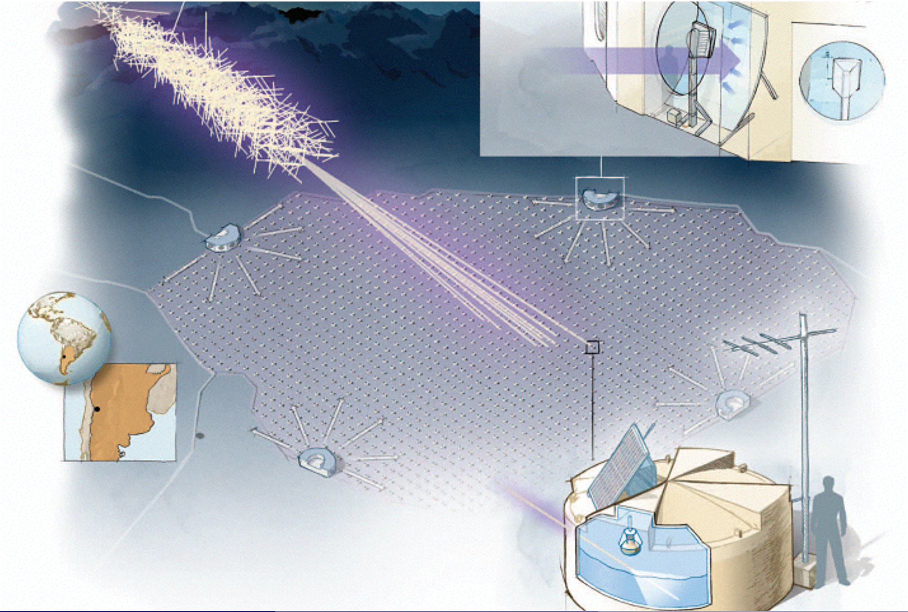
→ 140 collaborators / 5 countries,

→ collecting data since 2007,

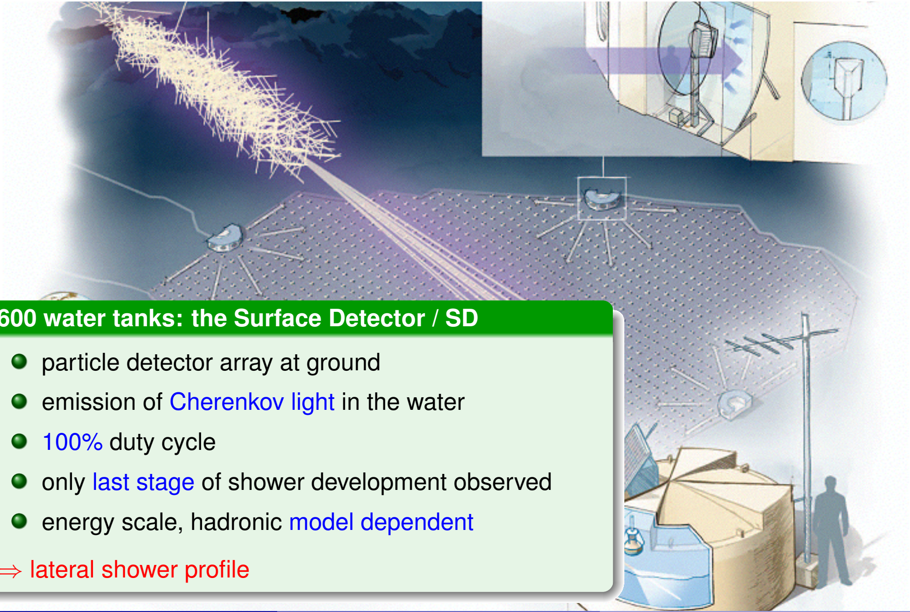
→ annual expo: 1.4×10^3 km^2 sr yr.

TELESCOPE ARRAY PROJECT

The Pierre Auger Observatory



The Pierre Auger Observatory

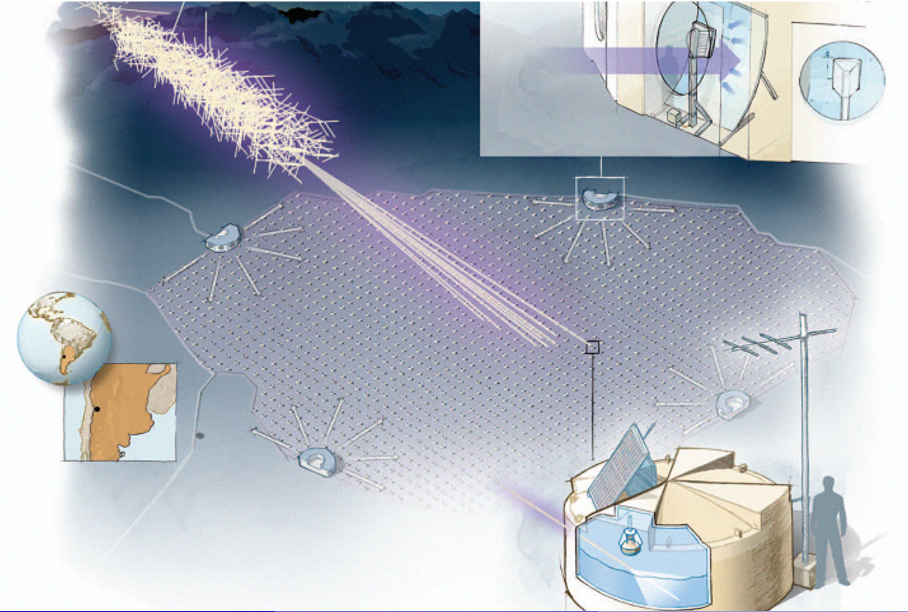


1600 water tanks: the Surface Detector / SD

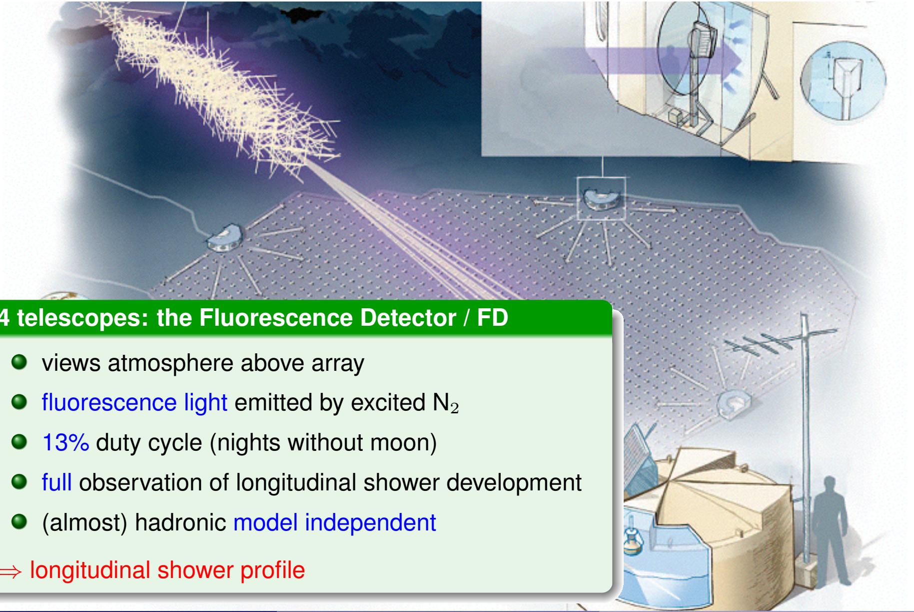
- particle detector array at ground
- emission of Cherenkov light in the water
- 100% duty cycle
- only last stage of shower development observed
- energy scale, hadronic model dependent

$\Longrightarrow$ lateral shower profile

The Pierre Auger Observatory



The Pierre Auger Observatory

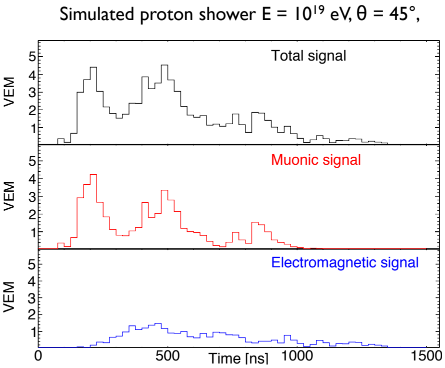


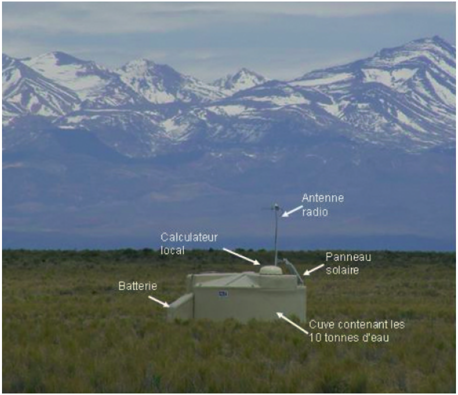
24 telescopes: the Fluorescence Detector / FD

- views atmosphere above array
- fluorescence light emitted by excited N_2
- 13% duty cycle (nights without moon)
- full observation of longitudinal shower development
- (almost) hadronic model independent

$\Longrightarrow$ longitudinal shower profile

The Surface Detector ⟶ Lateral profile

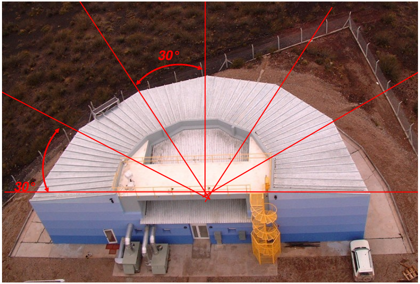


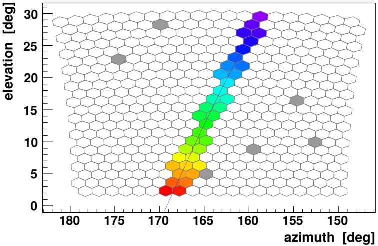


→ muonic signals are less dispersed in time, stronger in intensity,

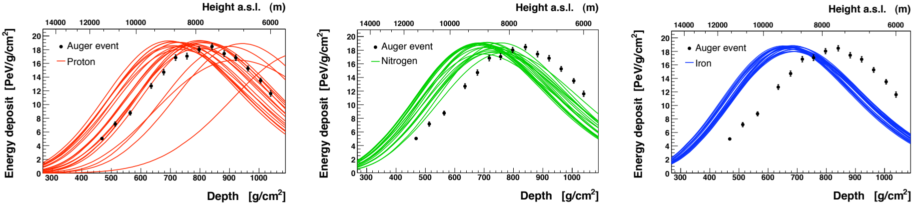
→ EM signal is seen as a diffusive background.

The Fluorescence Detector ⟶ Longitudinal profile

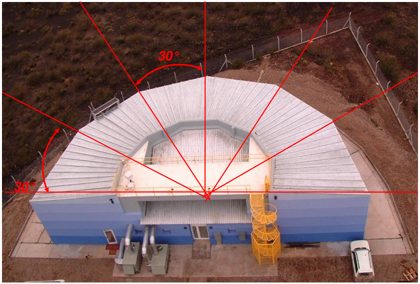


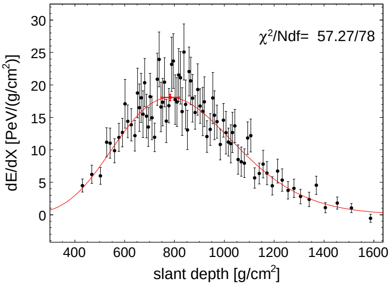


Longitudinal profile and mass composition

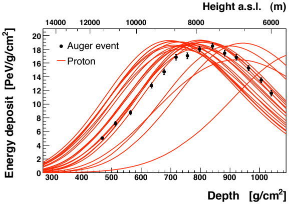


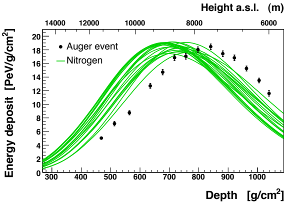
The Fluorescence Detector ⟶ Longitudinal profile

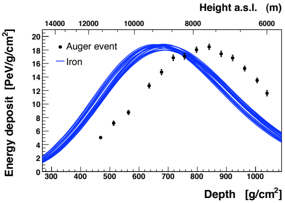




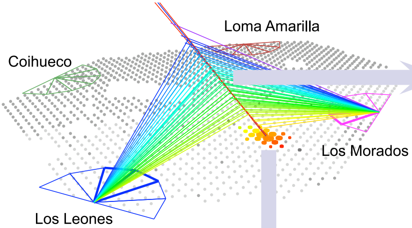
Longitudinal profile and mass composition

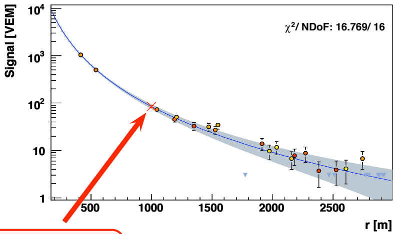






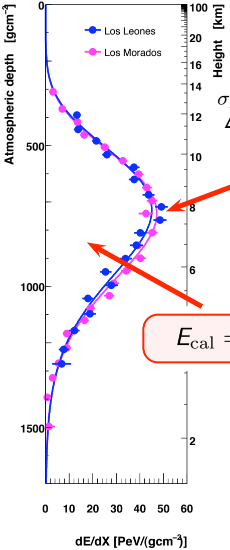
Auger hybrid detector – observables





S_{1000}

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



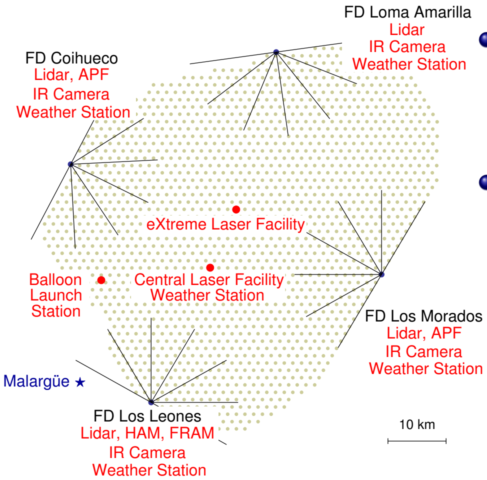
$\sigma_{X_{\rm max}} < 20\,{\rm g/cm^2}$
$\Delta_{\rm sys} \approx 15\,{\rm g/cm^2}$

$X_{\rm max}$

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

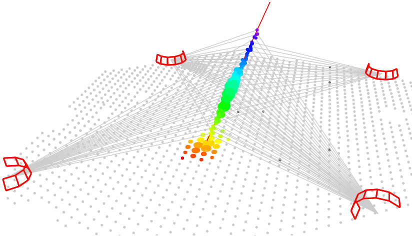
$\sigma_E/E \sim 8\,\%$
$\Delta_{\rm sys} \approx 22\,\%$

An extensive atmospheric monitoring

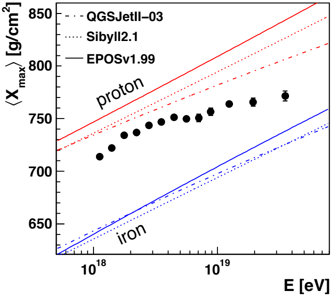


- Atmospheric state variables
  - → 5 ground-based weather stations,
  - → balloon lunches.
- Aerosol and cloud monitoring
  - → 4 'elastic' lidars,
  - → 2 central lasers (CLF/XLF),
  - → 2 optical telescopes (HAM/FRAM),
  - → 2 aerosol phase functions (APF),
  - → 4 IR cameras,
  - → ... and soon, a Raman lidar.

Mass composition – evolution with the energy



Pierre Auger Observatory



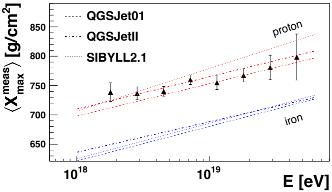
→ longitudinal development: $X_{\max} \propto \log A$

→ only hybrid data (13% of the whole Auger data set),

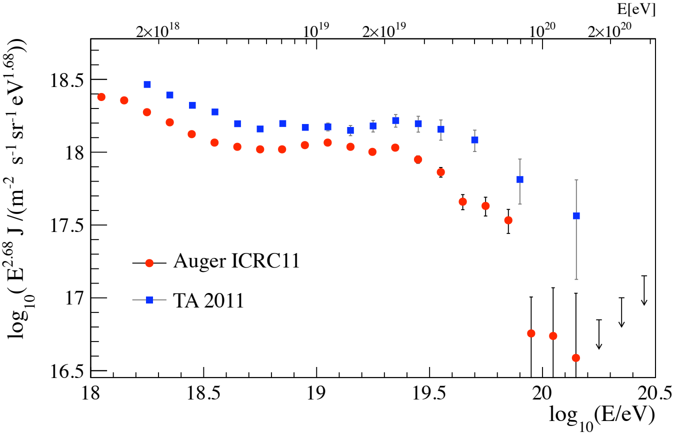
→ transition from a mixed or light to a heavy composition at highest energies.

P Facal, for the Pierre Auger Coll., 32$^{\text{nd}}$ ICRC, Beijing (2011)

Telescope Array



Energy spectrum – spectral features



→ cutoff in the flux observed around 6×10^{19} eV with a high significance,

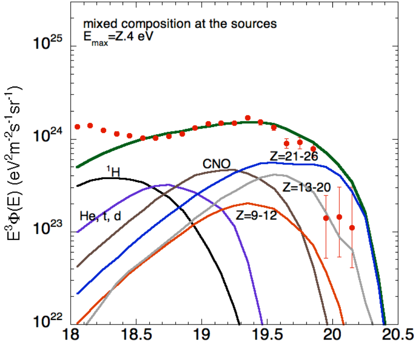
→ high energy flux drops at different energies,

→ Auger and Telescope Array: northern sky and southern sky events different ?

→ *origin of this cutoff:* does it come mainly from the source or from the propagation ?

Energy spectrum – possible astrophysics scenarios

Upper end of source energy spectrum ?



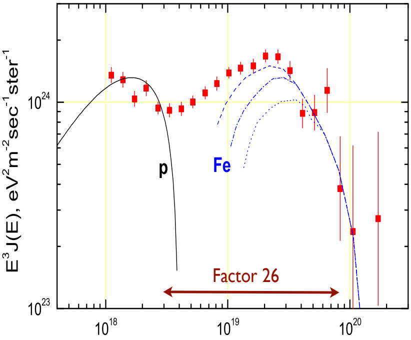
$\rightarrow$ mixed composition similar to galactic,

$\rightarrow E_{\rm max} = Z \times 4 \times 10^{18}$ eV,

$\rightarrow$ hard spectral index at sources ($\gamma = 1.6$),

$\rightarrow$ superposition of upper energy limit and GZK suppression *(Allard)*

Single local source without GZK ?



$\rightarrow$ protons at 10^{18} eV already X-gal,

$\rightarrow$ ankle would be transition p to He/CNO,

$\rightarrow$ 2nd knee as transition gal to X-gal,

$\rightarrow$ single local source dominating, GZK unimportant *(Aloisio et al.)*

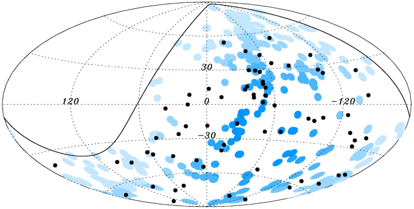
Anisotropy – arrival directions of highest energy events

→ search for anisotropy using nearby AGN (Veron-Cetty Veron catalog),

→ AGNs trace the nearby extragalactic matter,

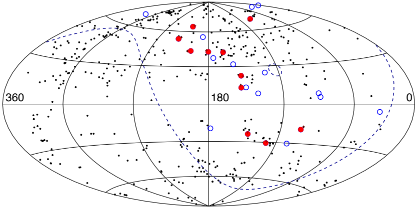
→ scan over a three dimensional parameter space: $E \geq 57$ EeV, $z \leq 0.018$, $\psi \leq 3.1^\circ$

Pierre Auger Observatory



28 out of 84 correlate, $\mathrm{P}_{\mathrm{chance}} = 1\%$

Telescope Array



11 out of 25 correlate, $\mathrm{P}_{\mathrm{chance}} = 2\%$

→ weaker (but still significant) AGN correlation than previously published,

→ excess around the Centaurus A vicinity.

The Pierre Auger Collaboration, Astropart. Phys. **34** *(2010) 314–326*

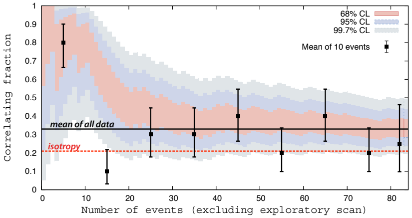
Anisotropy – arrival directions of highest energy events

→ search for anisotropy using nearby AGN (Veron-Cetty Veron catalog),

→ AGNs trace the nearby extragalactic matter,

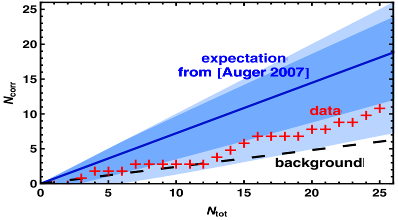
→ scan over a three dimensional parameter space: $E \geq 57$ EeV, $z \leq 0.018$, $\psi \leq 3.1°$

Pierre Auger Observatory



$$f = 33 \pm 5\%$$

Telescope Array



$$f = 44 \pm \%$$

→ weaker (but still significant) AGN correlation than previously published,

→ excess around the Centaurus A vicinity.

The Pierre Auger Collaboration, Astropart. Phys. **34** *(2010) 314–326*

Summary

→ a cutoff is clearly observed in the energy spectrum at 6×10^{19} eV,

→ transition from a mixed or light to a heavy composition at highest energies,

→ ... and no photons/neutrinos detected at ultra-high energies (upper limits),

→ an anisotropy is still observed at UHE, but the sources are not yet identified.

A plenty of questions... (still)

→ what is the source of ultra-high energy cosmic rays ?

→ how do they get their energy ?

→ what are the processes involved in the cutoff in flux ?

Is it possible to identify the source(s) of ultra-high energy cosmic rays ?

–

proton astronomy ?

The Pierre Auger Observatory – beyond 2015

improve cosmic ray composition measurement seems to be the key

- composition at low energies – 10^{17} to a few 10^{18} eV
  → search cutoff of proton spectrum,
  → improve sensitivity to photons from GZK effect,
  → fluorescence telescopes and surface detectors for lower energies

- composition at highest energies – need a composition estimation event-by-event
  → search for small proton fraction at higher energies – proton astronomy ?,
  → investigate the end of the spectrum and compatibility with iron primaries,
  → particle physics and proton–air cross section,
  → several possibilities: modified SD, scintillator array, radio antenna MHz/GHz, etc...

search protons and study their anisotropy at highest energies

Thanks for your attention !