Ultra-high energy cosmic rays: recent results and challenges for the next years

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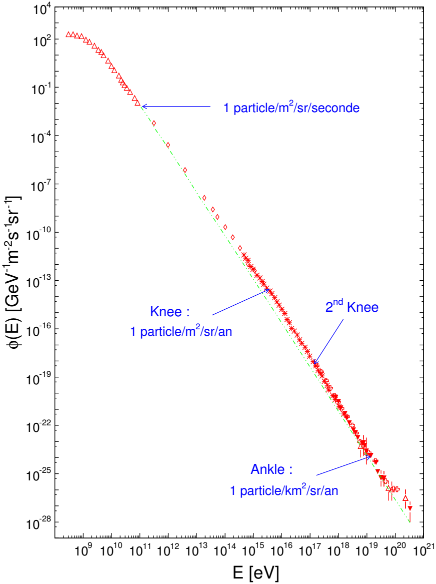
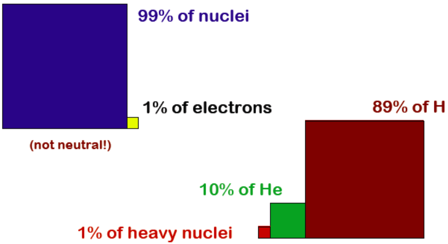
Lundi 28 avril 2014

Cosmic ray energy spectrum



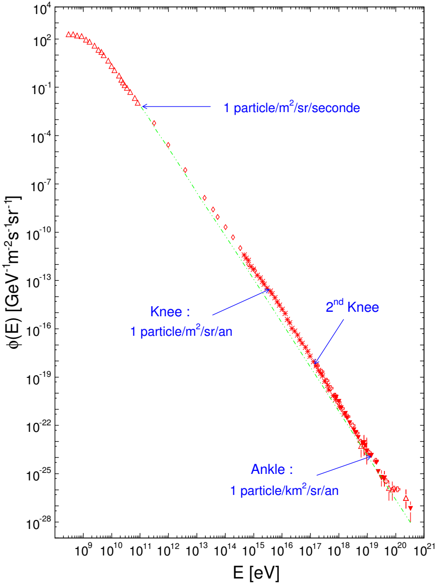
Origin of cosmic rays

- 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



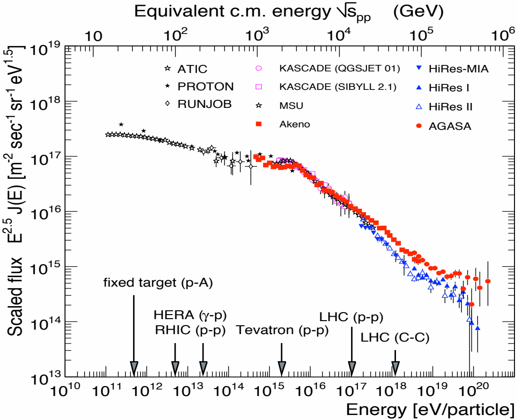
Up to the knee: direct detection

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

Beyond the knee: indirect detection

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

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



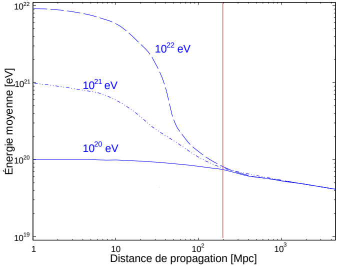
- low luminosity @ 10^{19} eV
  $\rightarrow$ 1 particle/km^2/century
- AGASA (Japan)
  $\rightarrow$ surface detector
- HiRes (Utah / USA)
  $\rightarrow$ fluorescence detector

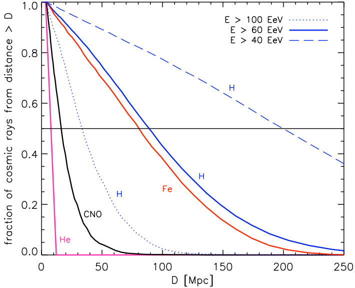
Acceleration – astrophysical shocks ($\rightarrow$ Hillas criterion)

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

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

UHECR propagation – the Greisen-Zatsepin-Kuz'min cutoff (1966)





END TO THE COSMIC-RAY SPECTRUM?

Kenneth Greisen

Cornell University, Ithaca, New York
(Received 1 April 1966)

- interaction of UHECRs with the CMB

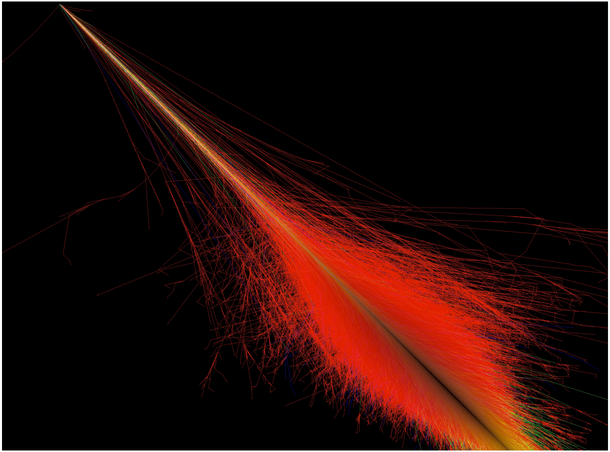
$$p + \gamma_{2.7\text{K}} \rightarrow n + \pi^+$$
$$\rightarrow p + \pi^0$$

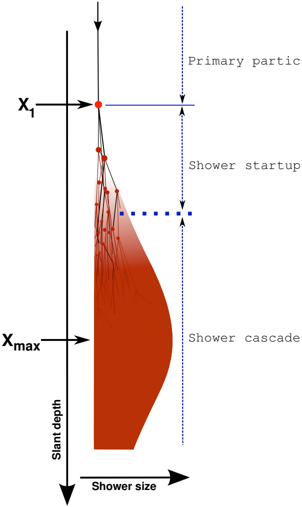
- energy threshold for the photo-pion production

$$E_\text{p} \geq 6.8 \times 10^{16} \left(\frac{1\text{ eV}}{E_{\gamma_{2.7\text{K}}}}\right)$$

only the *near* universe ($\lesssim 200$ Mpc) contributes to the cosmic ray flux → **GZK horizon**

Indirect detection – Extensive Air Showers





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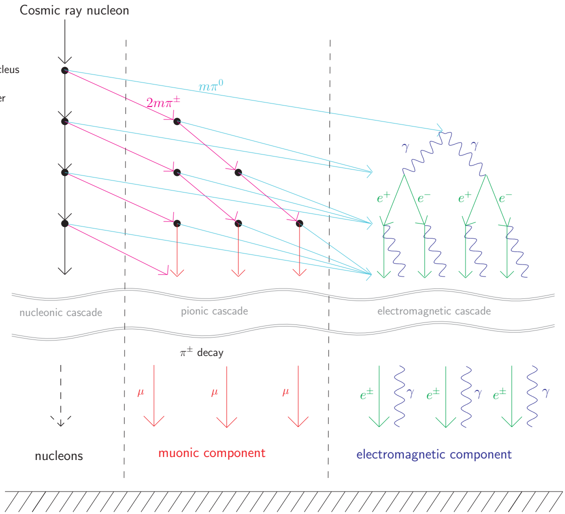
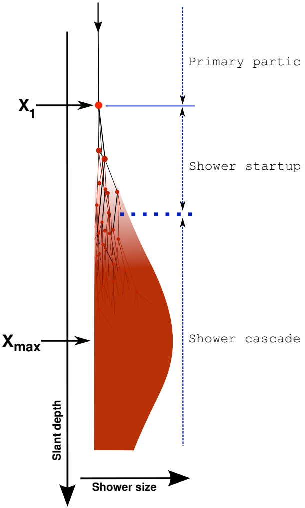
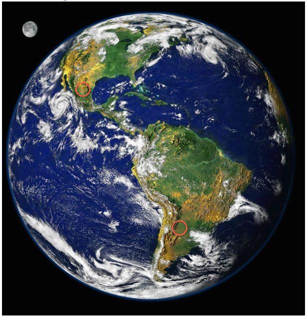
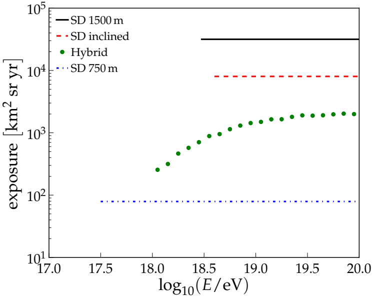




Currently, two main observatories all around the world





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

Telescope Array experiment / TA

Surface detector / SD

$\rightarrow$ 507 scintillator counters,

$\rightarrow$ 1.2 km spacing,

$\rightarrow$ 3 m^2 effective area / 2 layers,

$\rightarrow$ muon component: 15–20% of signal,

$\rightarrow$ SD expo: $3.7 \times 10^3\ \mathrm{km}^2\,\mathrm{sr\,yr}$.

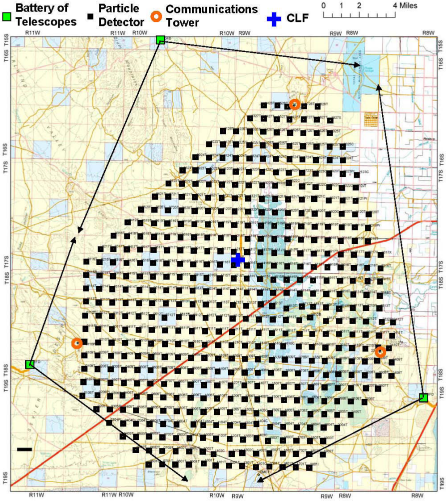
Fluorescence detector / FD

$\rightarrow$ 3 fluorescence sites,

$\rightarrow$ 12 + 12 + 14 telescopes,

$\rightarrow$ HiRes technology,

$\rightarrow$ hybrid expo: $\simeq$ a few $10^2\ \mathrm{km}^2\,\mathrm{sr\,yr}$.



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The Pierre Auger Observatory

Surface detector / SD

→ 1600 Cherenkov water tanks,

→ 1.5 km spacing,

→ 12 tons of water / 3 PMTs,

→ muon component: 30–80% of signal,

→ SD expo: $4.0 \times 10^{4}\ \mathrm{km}^{2}\,\mathrm{sr}\,\mathrm{yr}$.

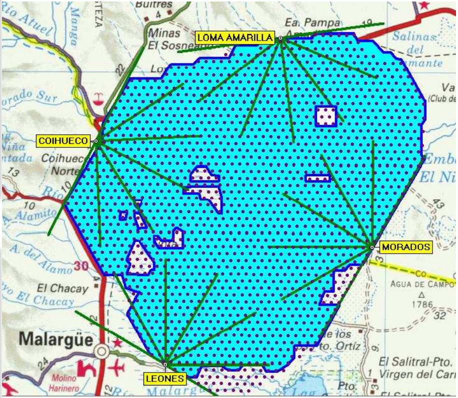
Fluorescence detector / FD

→ 4 fluorescence sites,

→ 4 x 6 telescopes / 30° x 180°,

→ 440 PMTs per telescope camera,

→ hybrid expo: $\leq 2.0 \times 10^{3}\ \mathrm{km}^{2}\,\mathrm{sr}\,\mathrm{yr}$.



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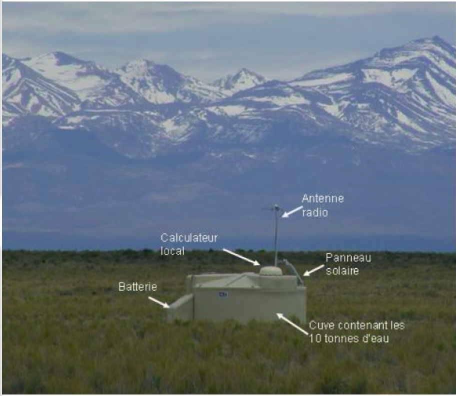

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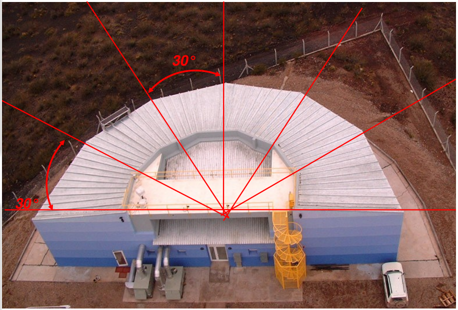


Similar design... and same problems sometimes !

Similar design... and same problems sometimes !

A plenty of questions...

3 observables
arrival direction distribution / primary composition / energy spectrum

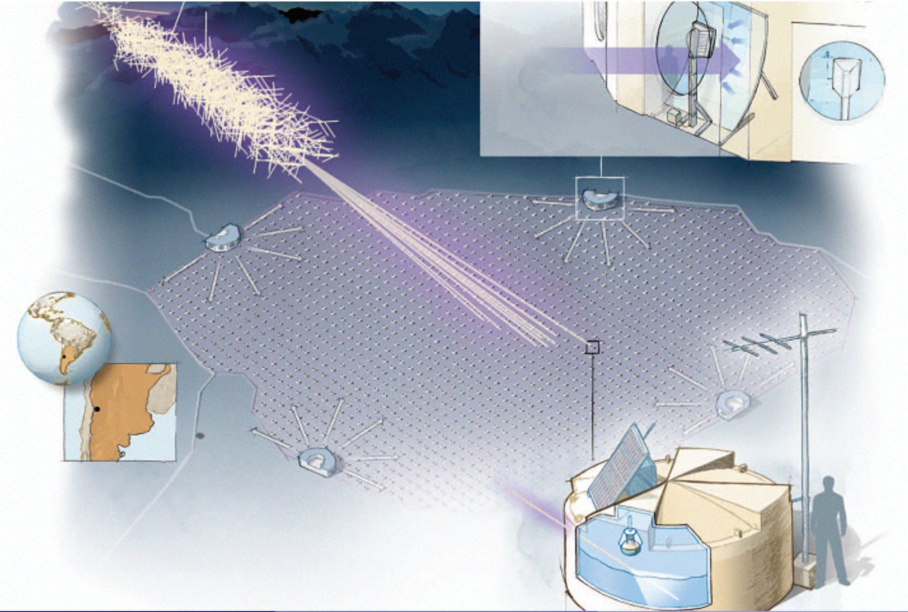
1. What is the source of ultra-high energy cosmic rays
   $\rightarrow$ what is the fundamental process for ultimate energies ?
   $\rightarrow$ how do they get their energy ?

2. What are ultra-high energy cosmic rays
   $\rightarrow$ which composition for primary cosmic rays ?
   $\rightarrow$ is there a change for hadronic interactions in the extensive air showers ?

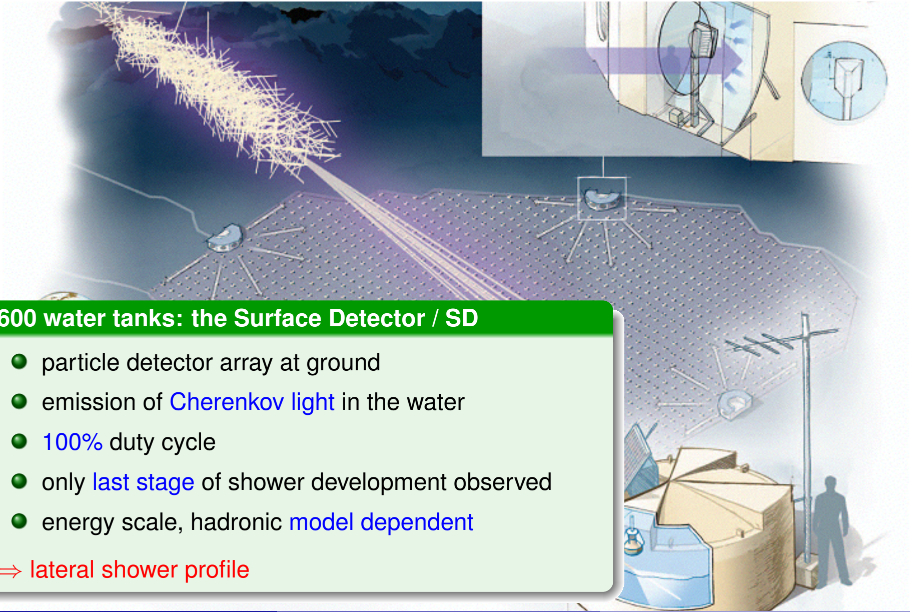
Is it possible to identify the source(s) of ultra-high energy cosmic rays ?
–
charged astronomy: could they be used as astrophysical messengers ?

Outline

The Pierre Auger Observatory



The Pierre Auger Observatory

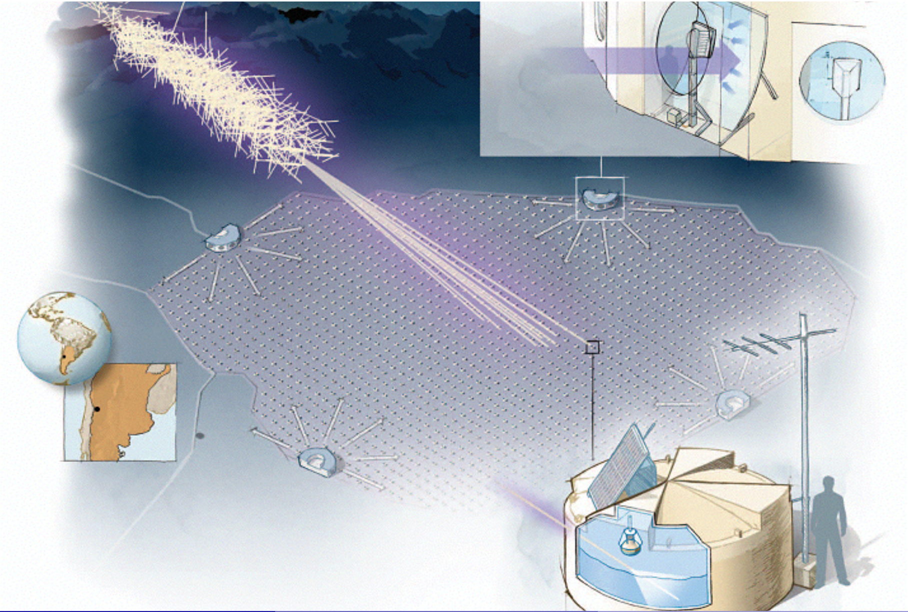


1600 water tanks: the Surface Detector / SD

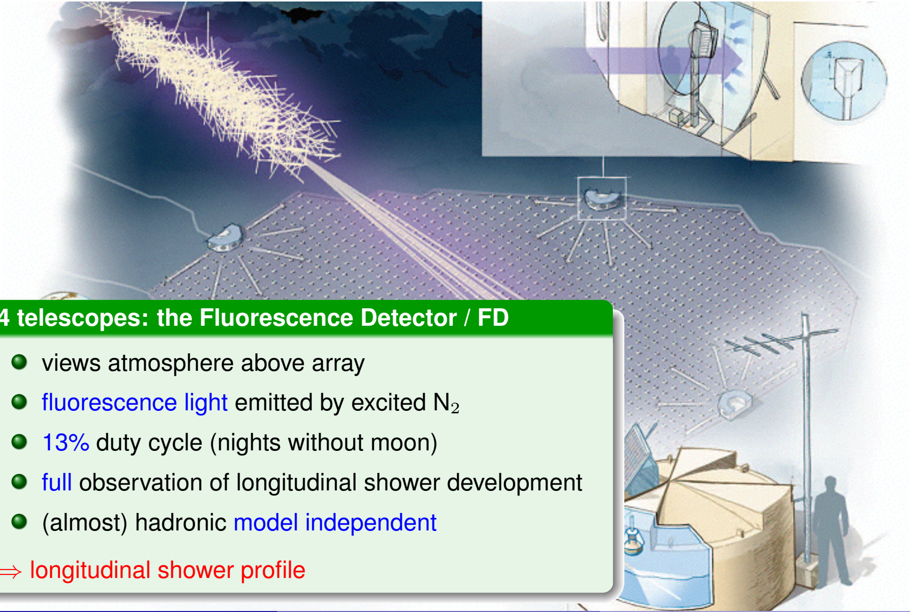
- particle detector array at ground
- emission of Cherenkov light in the water
- 100% duty cycle
- only last stage of shower development observed
- energy scale, hadronic model dependent

$\Longrightarrow$ lateral shower profile

The Pierre Auger Observatory



The Pierre Auger Observatory



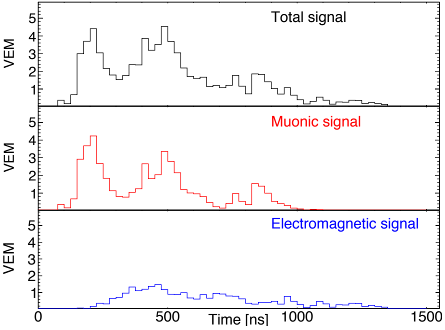
24 telescopes: the Fluorescence Detector / FD

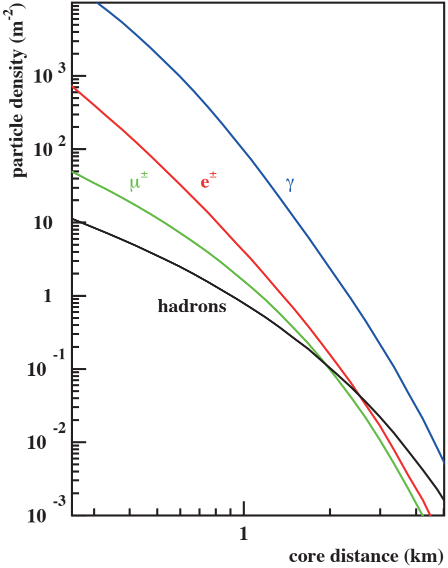
- views atmosphere above array
- fluorescence light emitted by excited N_2
- 13% duty cycle (nights without moon)
- full observation of longitudinal shower development
- (almost) hadronic model independent

$\Longrightarrow$ longitudinal shower profile

The Surface Detector $\longrightarrow$ Lateral profile

Simulated proton shower E = 10^{19} eV, θ = 45°,

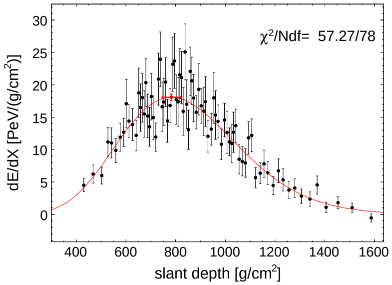


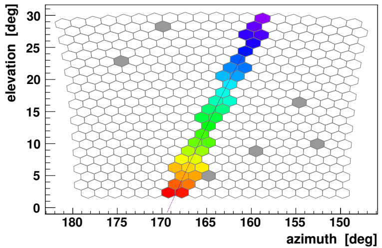


$\rightarrow$ muonic signals are less dispersed in time, stronger in intensity,

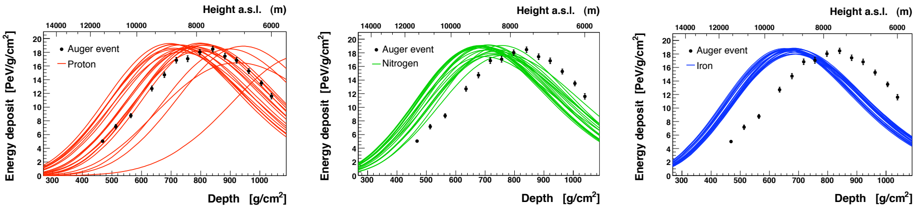
$\rightarrow$ EM signal is seen as a diffusive background.

The Fluorescence Detector $\longrightarrow$ Longitudinal profile

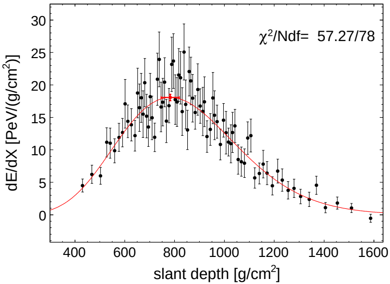


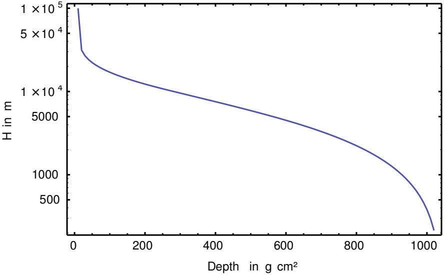


Longitudinal profile and mass composition



The Fluorescence Detector ⟶ Longitudinal profile





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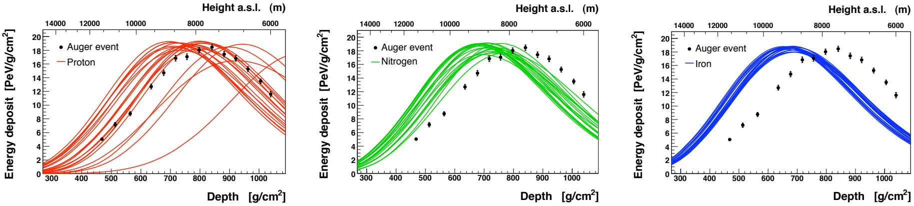
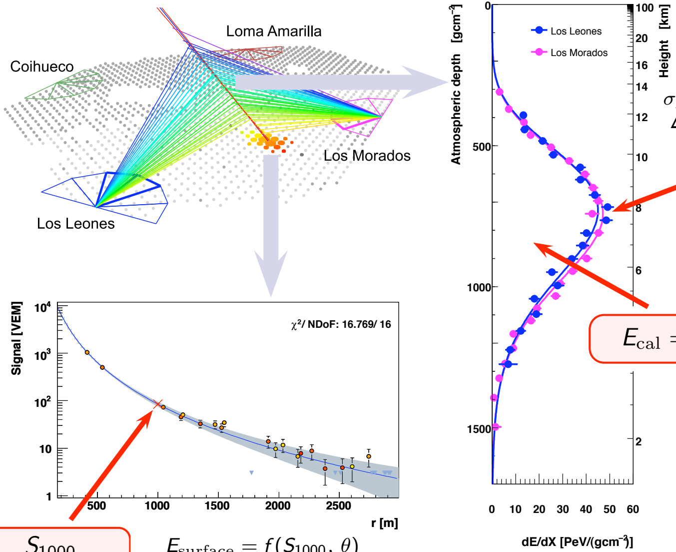


Auger hybrid detector – observables



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

$X_{\max}$

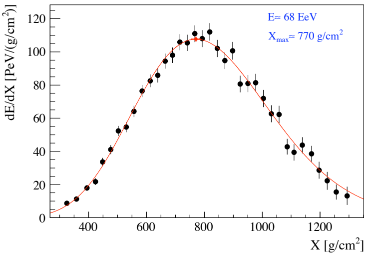
$E_{\mathrm{cal}} = \int \mathrm{d}X \, \frac{\mathrm{d}E}{\mathrm{d}X}$

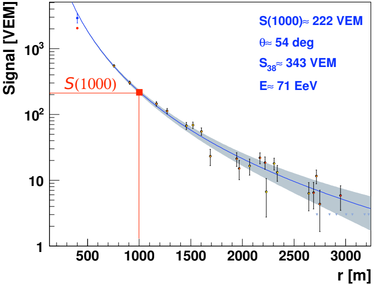
$\sigma_E/E \sim 8\,\%$
$\Delta_{\mathrm{sys}} \approx 22\,\%$

S_{1000}

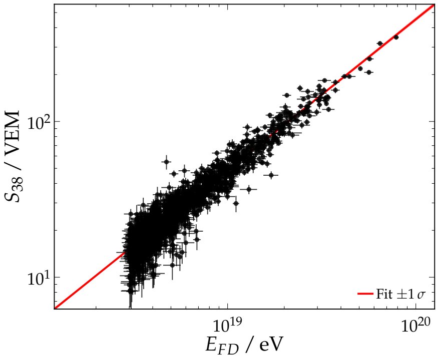
$E_{\mathrm{surface}} = f(S_{1000},\, \theta)$

Auger hybrid detector – SD energy calibration by FD





$$E = A\,(S_{38^\circ})^B$$

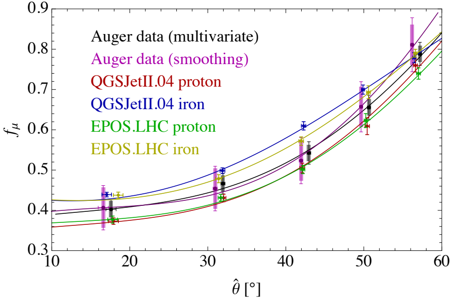


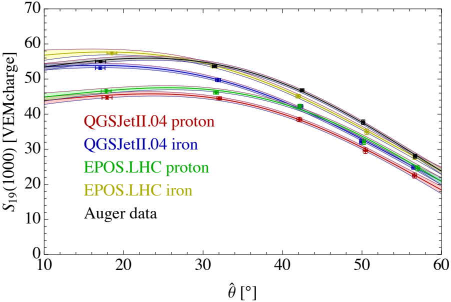
→ SD energy estimator calibrated using hybrid events (no Monte Carlo simulations),

→ rescaling: 1.24 (avg.)$\times E_{\mathrm{SD}}^{\mathrm{MC}}$,

→ systematic uncertainties for the method: 7% @ 10^{19} eV *and* 15% @ 10^{20} eV

Advantage of the energy calibration by FD





→ more signal than expected is recorded in the Cherenkov tanks,

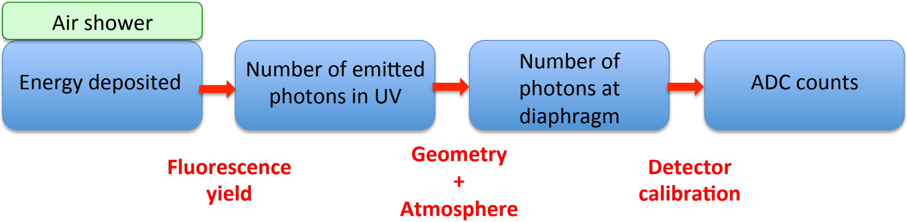
→ however, muon fraction is well bracketed by hadronic interaction models,

→ same analysis at Telescope Array would be interesting for cross-checks.

fluorescence technique seems to be **essential** in UHECR observatories

B. Kégl, for the Pierre Auger Coll., 33rd ICRC, Rio de Janeiro (2013)

Energy systematics in fluorescence measurements

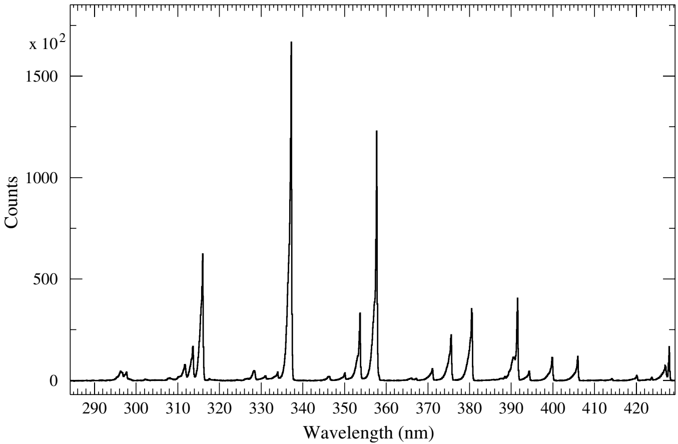


Pierre Auger Observatory	14%
calibration	9.9%
reconstruction	6.5% – 5.6%
atmospheric	3.4% – 6.2%
fluorescence yield	3.6%
invisible energy	3.0% – 1.5%
stability energy scale	5.0%

Telescope Array	21%
calibration	10.0%
reconstruction	10.0%
atmospheric	11.0%
fluorescence yield	11.0%
invisible energy	√
stability energy scale	√

crucial when comparing energy spectra or constraining UHECR sources

The fluorescence spectrum – up to recently, the largest uncertainty

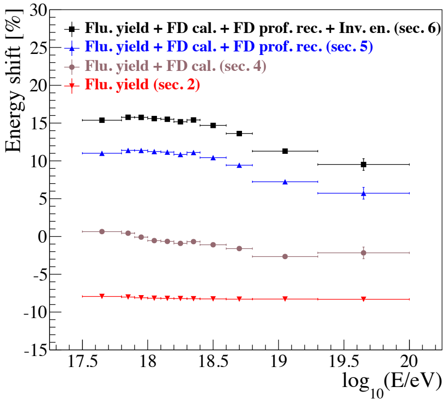


AIRFLY: $Y_{\mathrm{air}} = 5.67 \pm 0.07\,(\mathrm{stat.}) \pm 0.21\,(\mathrm{syst.})$ photons$_{337}$ / MeV $\rightarrow$ uncertainty of 4%

previously in Auger: $Y_{\mathrm{air}} = 5.05$ photons$_{337}$ / MeV $\rightarrow$ energy scale went down by 8%

M. Ave et al [AIRFLY], Astropart. Phys. **28** *(2007) 41–57*

The new energy scale @ Auger: +15.6%



Changes in FD energies at 10^{18} eV	
Absolute fluorescence yield (sec. 2)	**-8.2%**
New optical efficiency	4.3%
Calibr. database update	3.5%
Sub total (FD calibration - sec. 4)	**7.8%**
Likelihood fit of the profile	2.2%
Folding with the point spread function	9.4%
Sub total (FD profile reconstruc. - sec. 5)	**11.6%**
New invisible energy (sec. 6)	**4.4%**
Total	**15.6%**

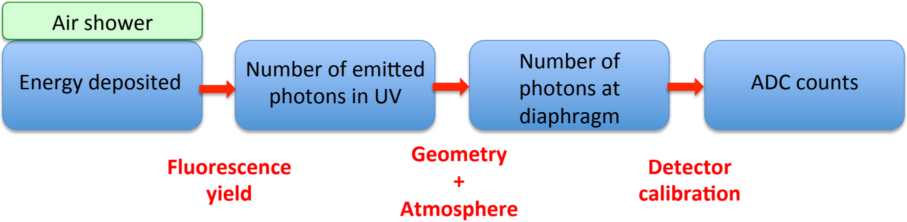
→ new fluorescence yield measured by the AIRFLY collaboration,

→ telescope optical properties studied using a point source with an octocoptere,

→ new invisible energy correction based on data themselves.

V. Verzi, for the Pierre Auger Coll., 33rd ICRC, Rio de Janeiro (2013)

Energy systematics in fluorescence measurements



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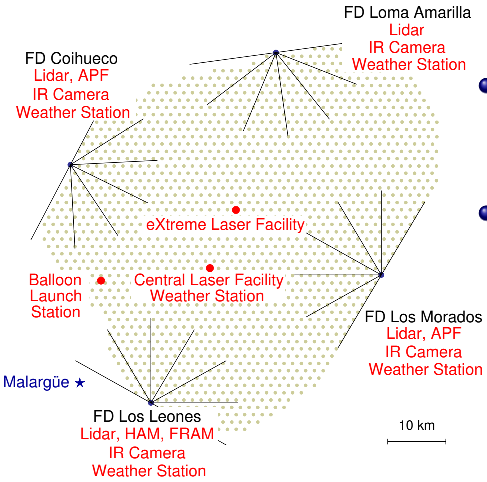
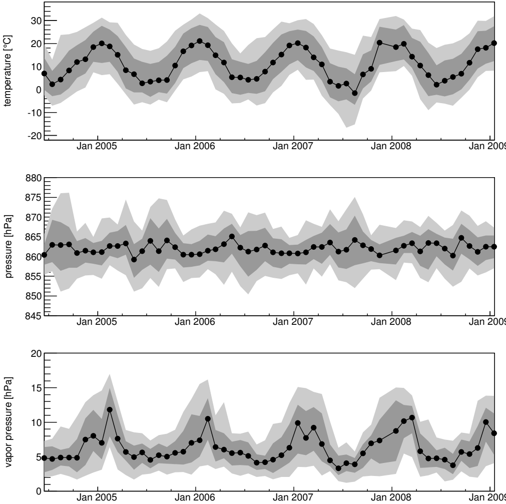
An extensive atmospheric monitoring



- 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 since 2013, a Raman lidar.

K. Louedec, for the Pierre Auger Coll., 32$^{\mathrm{nd}}$ ICRC, Beijing (2011)

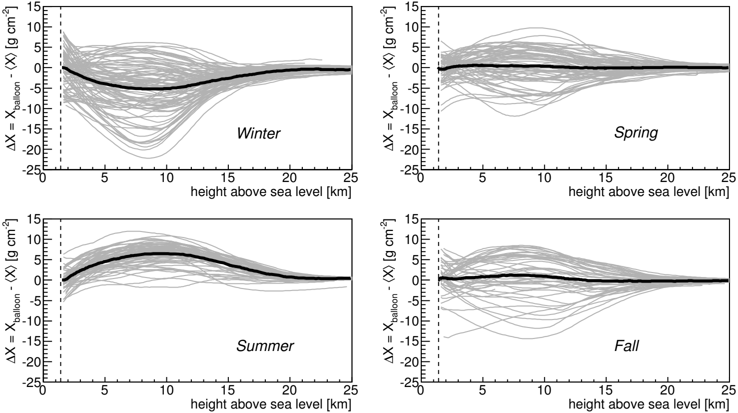
Atmospheric state variables – ground-based weather stations



- temperature, pressure, humidity, wind speed
- data acquisition every 5 minutes,
- check of lateral homogeneity.

The Pierre Auger Collaboration, Astropart. Phys. **33** *(2010) 108–129*

Atmospheric state variables – radio soundings

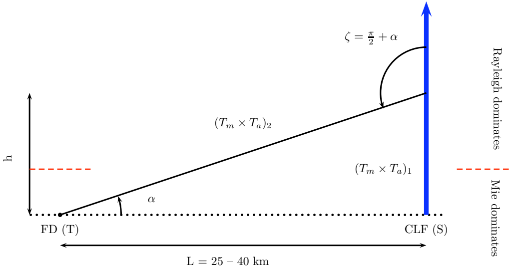


- temperature, pressure and humidity vertical profiles,
- around 350 balloon launches since August 2002,
- monthy models computed for molecular part.

The Pierre Auger Collaboration, Astropart. Phys. **33** *(2010) 108–129*

Aerosol component – Central Laser Facility

- laser wavelength fixed @ 355 nm (fluorescence band),
- uses the aerosol-free nights as references,
- aerosol optical depth profiles averaged hourly (200 shots).

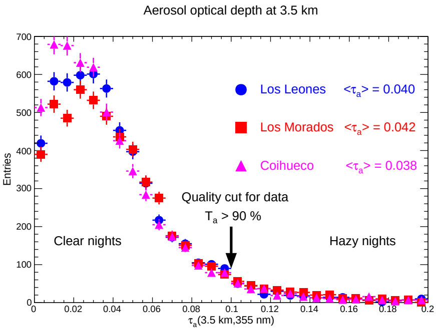


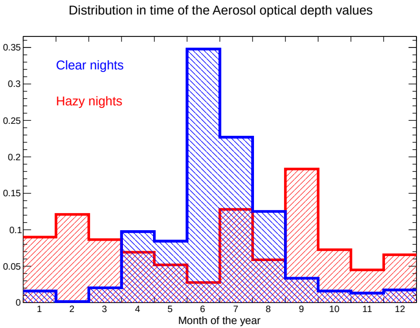
Aerosol optical depth $\tau_a(h, \lambda_0)$ – Aerosol attenuation

$$\tau_a(h, \lambda_0) = -\frac{\sin\alpha(h)}{1 + \sin\alpha(h)} \log\left(\frac{N_{\mathrm{obs}}[\alpha(h)]}{N_{\mathrm{aerosol-free}}[\alpha(h)]}\right)$$

The Pierre Auger Collaboration, JINST **8** *(2013) P04009*

Aerosol optical depth measurements @ Auger





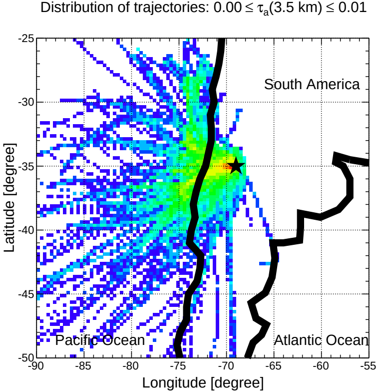
Let's divide the sample in three populations

- **the clear nights** → the lowest aerosol concentrations: $\tau_a \leq 0.01$
- **the hazy nights** → the highest aerosol concentrations: $\tau_a \geq 0.10$
- the rest of the nights.

clear nights are more frequent during the Austral winter

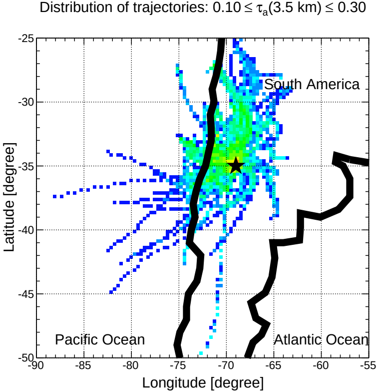
Aerosol trajectories for clear/hazy nights @ Auger

Clear nights



⇒ travel through the Pacific Ocean

Hazy nights



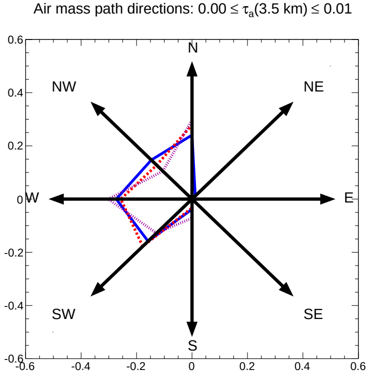
⇒ travel through continental areas

clear nights associated to air masses having traveled mainly above Pacific Ocean

The Pierre Auger Collaboration, Atmos. Res., accepted (2014)

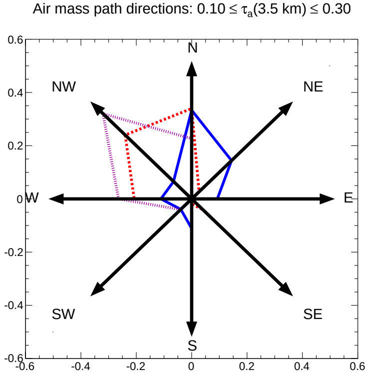
Aerosol origins for clear/hazy nights @ Auger

Clear nights



⇒ very good agreement

Hazy nights



⇒ North to North-West

500m AGL — 1000m AGL — 3000m AGL

Interdisciplinary sciences at the Pierre Auger Observatory

EPJ Plus

1. Editorial: Introductory remarks by Alan Watson
   → by A. Watson
2. The Pierre Auger Observatory and interdisciplinary science
   → by L. Wiencke
3. Atmospheric aerosols at the Pierre Auger Observatory and environmental implications
   → by K. Louedec and R. Losno
4. Description of atmospheric conditions at the Pierre Auger Observatory using meteorological measurements and models
   → by B. Keilhauer and M. Will

Interdisciplinary sciences at the Pierre Auger Observatory

5. A beginning investigation into the possible role of cosmic rays in the initiation of lightning discharges at the Pierre Auger Observatory
   → by W. C. Brown, J. R. Dywer, A. Huangs, P. R. Krehbiel et al.
6. Observation of ELVES at the Pierre Auger Observatory
   → by R. Mussa and G. Ciaccio
7. Ground-truthing a satellite-based night-time cloud identification technique at the Pierre Auger Observatory
   → by J. Chirinos
8. Atmospheric monitoring with LiDARs at the Pierre Auger Observatory
   → by V. Rizi, A. Tonachini, M. Iarlori and G. Visconti

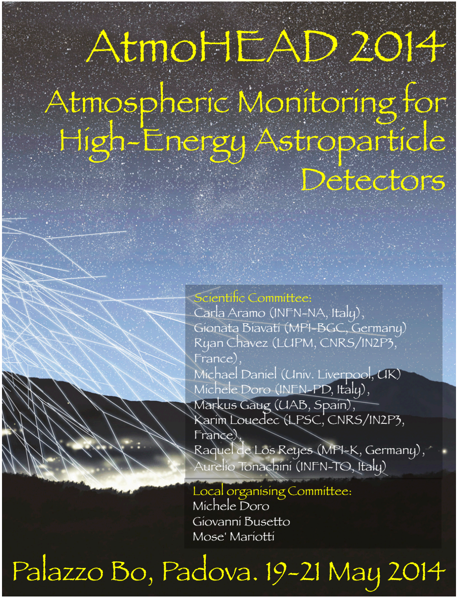
Interdisciplinarity in astroparticle experiments

Concept

- optimise the monitoring of the environment (atmosphere, Earth, oceans)
  → improve the accuracy of measurements in astroparticle physics,
  → a wide variety for locations of facilities,
  → *papers in Astroparticle physics*
- design an interdisciplinary platform
  → host scientists from other fields, with their expertise,
  → access to facilities unique in the world,
  → *papers in Earth sciences*

Promote the exchange between the two communities to better **understand** the current measurements and better **design** the next detectors

AtmoHEAD'14 workshop



International workshop about atmospheric monitoring in astroparticle experiments

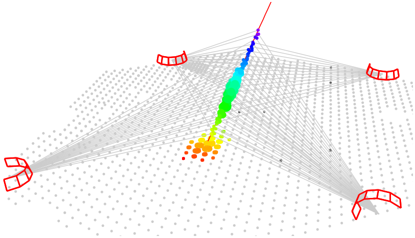
→ opened to all experiments in astroparticle physics,

→ organised *mainly* for the next generation of Cherenkov telescope arrays,

→ registrations still opened.

Outline

FD $\rightarrow$ maximum of the shower longitudinal profile

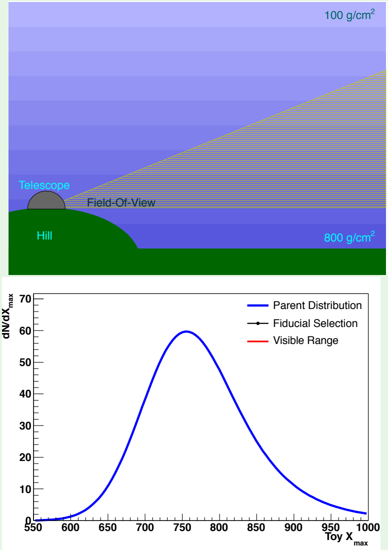


$\rightarrow$ longitudinal development: $X_{\max} \propto \log A$

$X_{\max}$ measurement strategies

- Pierre Auger Observatory
  $\rightarrow$ apply fiducial cuts
  $\rightarrow$ compare unbiased data to simus
- Telescope Array
  $\rightarrow$ apply same cuts in data/simus
  $\rightarrow$ compare biased data to biased simus

Illustration of acceptance bias



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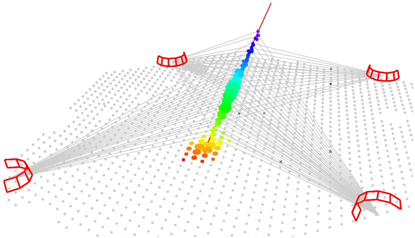

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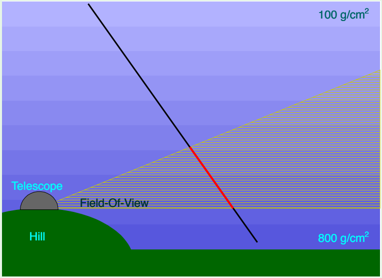

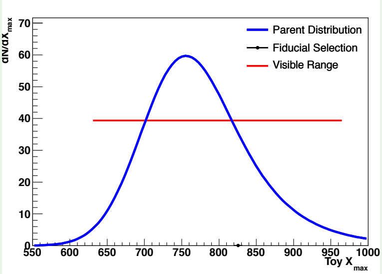

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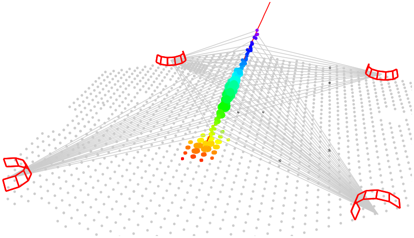

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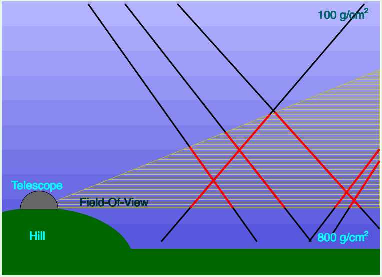

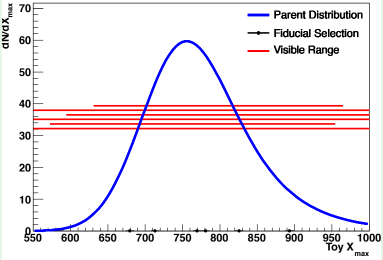

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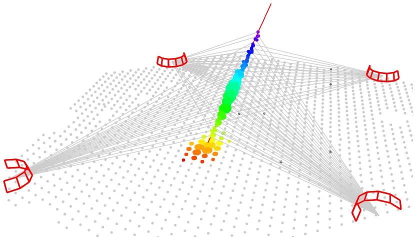

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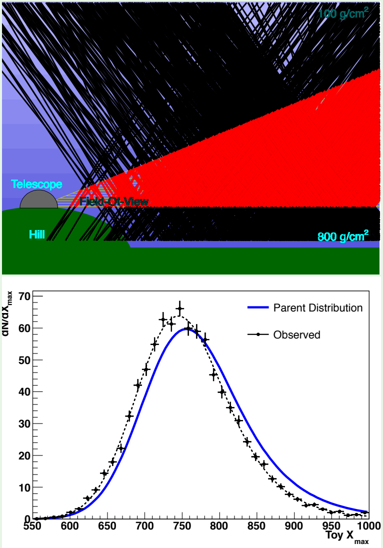
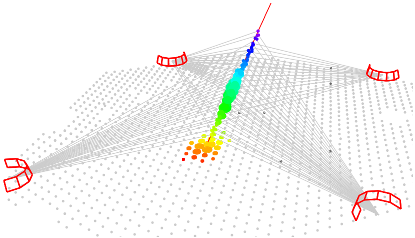


FD → maximum of the shower longitudinal profile



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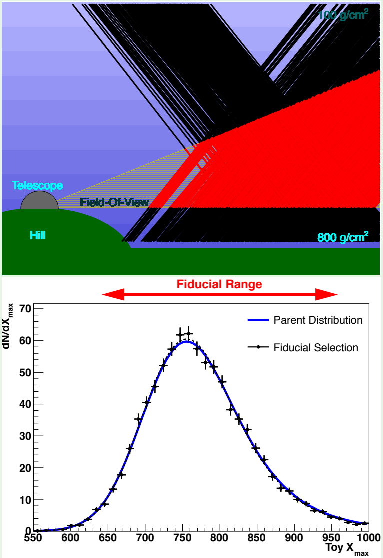

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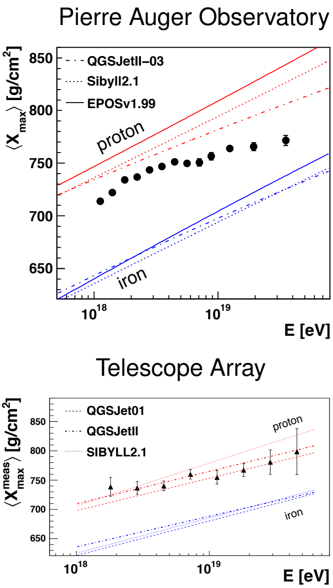
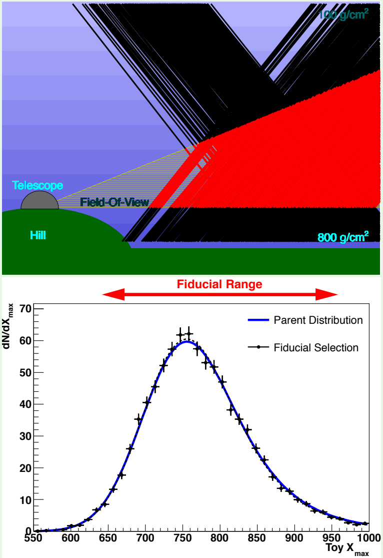
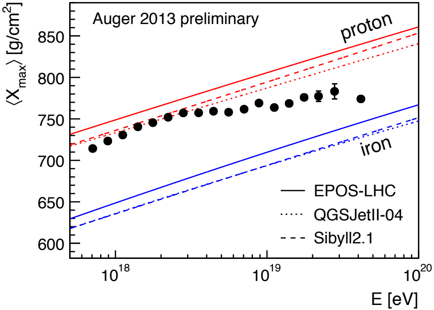
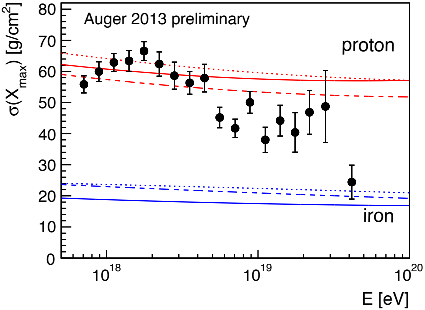


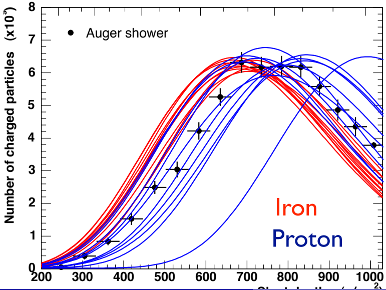
Illustration of acceptance bias



FD → maximum of the shower longitudinal profile @ Auger





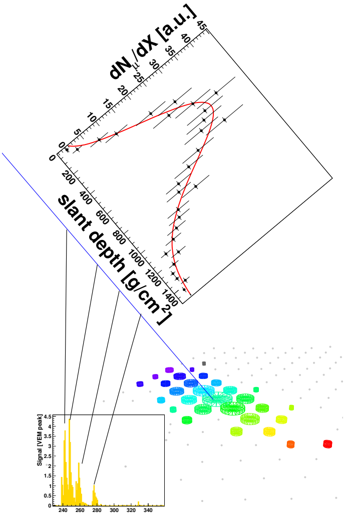


→ only hybrid data (13% of the whole Auger data set),

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

A. Letessier-Selvon, for the Pierre Auger Coll., 33rd ICRC, Rio de Janeiro (2013)

SD → muon production depth @ Auger

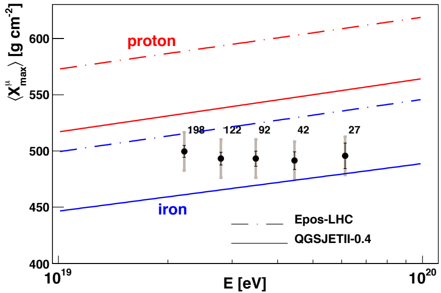


→ selection of muon-rich stations only,

→ projection of signal time traces to axis,

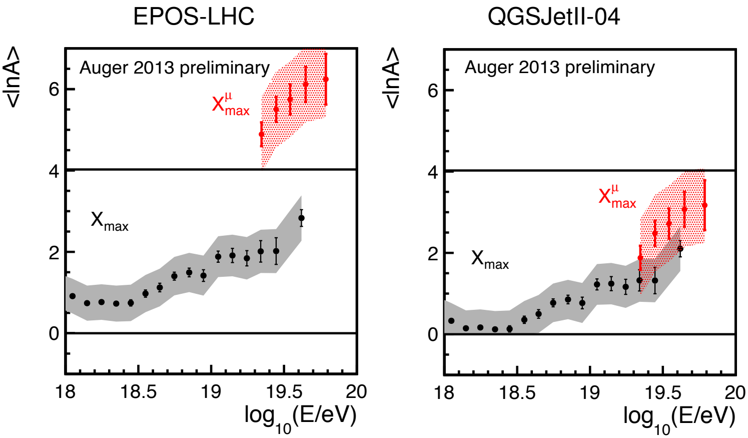
→ sum up stations, and fit with Gaisser-Hillas,

→ estimation of the maximum altitude (i.e. depth) of muon production



D. Garcia-Gamez, for the Pierre Auger Coll., 33$^{\mathrm{rd}}$ ICRC, Rio de Janeiro (2013)

SD / FD $\rightarrow$ understanding of hadronic interactions @ Auger

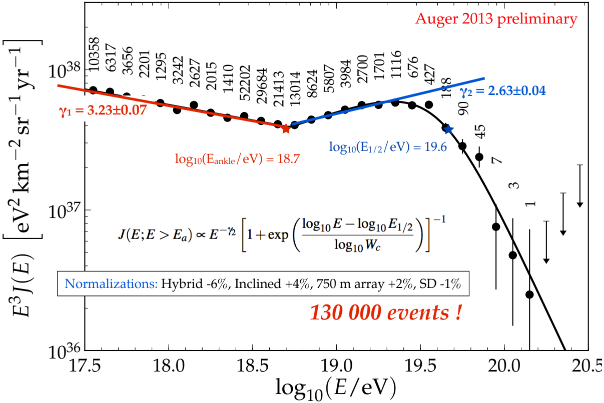


$\rightarrow$ $\langle$ln A$\rangle$ can be derived from $X_{\max}$ and $X^{\mu}_{\max}$ measurements,

$\rightarrow$ test of the consistency of hadronic models for EM and muonic components.

A. Letessier-Selvon, for the Pierre Auger Coll., 33$^{\mathrm{rd}}$ ICRC, Rio de Janeiro (2013)

Energy spectrum – spectral features

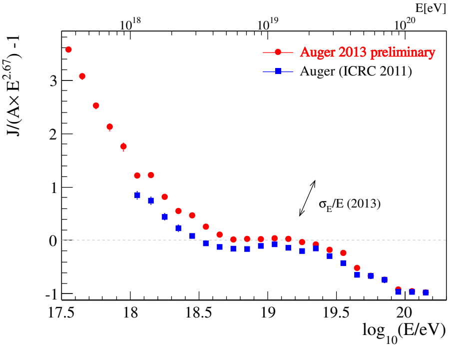


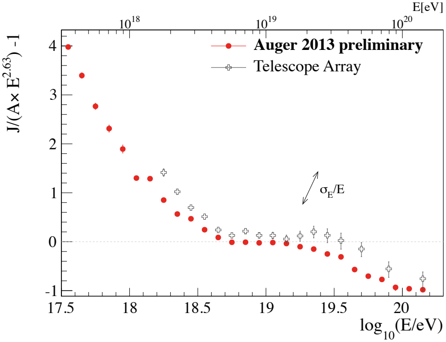
→ spectra combined with a total of 130 000 events,

→ a cut-off is clearly observed at highest energies (AGASA was wrong).

A. Letessier-Selvon, for the Pierre Auger Coll., 33rd ICRC, Rio de Janeiro (2013)

Energy spectrum – spectral features





→ Auger 2011 to Auger 2013: the ankle moves from $10^{18.6}$ eV to $10^{18.7}$ eV,

→ Auger and TA: spectra in agreement within stat. and syst. uncertainties,

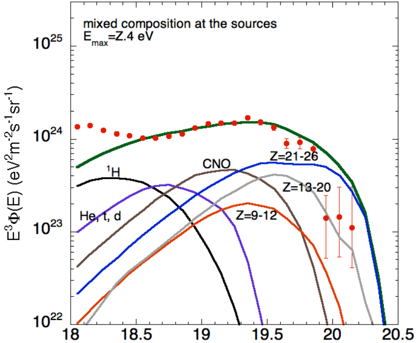
→ high energy fluxes drop at different energies.

+ keep in mind the different fluorescence yield values used in both experiments

A. Schulz, for the Pierre Auger Coll., 33$^{\rm rd}$ ICRC, Rio de Janeiro (2013)

Energy spectrum – possible astrophysics scenarios

Upper end of source energy spectrum ?



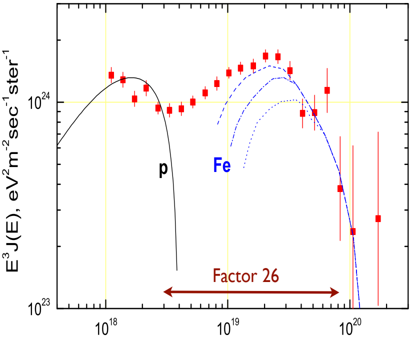
→ mixed composition similar to galactic,

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

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

→ superposition of upper energy limit and GZK suppression *(Allard)*

Single local source without GZK ?



→ protons at 10^{18} eV already X-gal,

→ ankle would be transition p to He/CNO,

→ 2nd knee as transition gal to X-gal,

→ single local source dominating, GZK unimportant *(Aloisio et al.)*

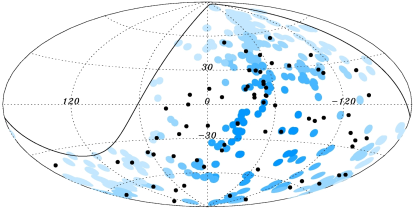
Anisotropy – arrival directions of highest energy events

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

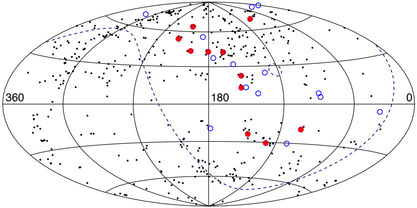
→ AGNs trace the nearby extragalactic matter,

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

Pierre Auger Observatory



Telescope Array



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

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

$\rightarrow$ search for anisotropy using nearby AGN (Veron-Cetty Veron catalog),

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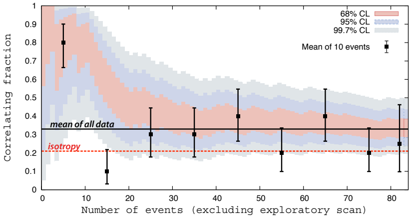
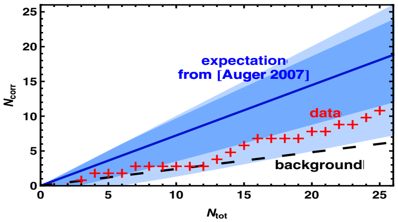


$$f = 33 \pm 5\%$$

Telescope Array



$$f = 44 \pm \%$$

$\rightarrow$ weaker (but still significant) AGN correlation than previously published,

$\rightarrow$ excess around the Centaurus A vicinity.

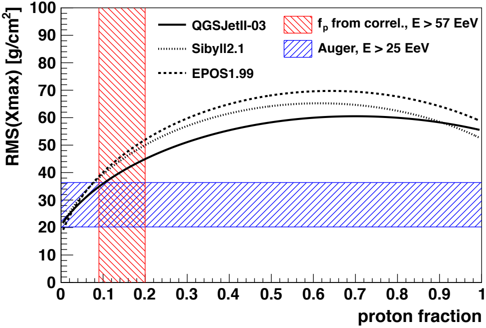
The Pierre Auger Collaboration, Astropart. Phys. ***34*** *(2010) 314–326*

Anisotropy – proton astronomy at highest energies ?

$\rightarrow$ *simplistic interpretation of correlation and composiiton*,

$\rightarrow$ f_p: fraction of correlating protons / $(1 - f_p)$: fraction of isotropised iron,

$\rightarrow$ no intermediate nuclei are considered – too small mean free paths,



$\rightarrow$ Auger Observatory: $f_p = 12^{+7}_{-6}\%$

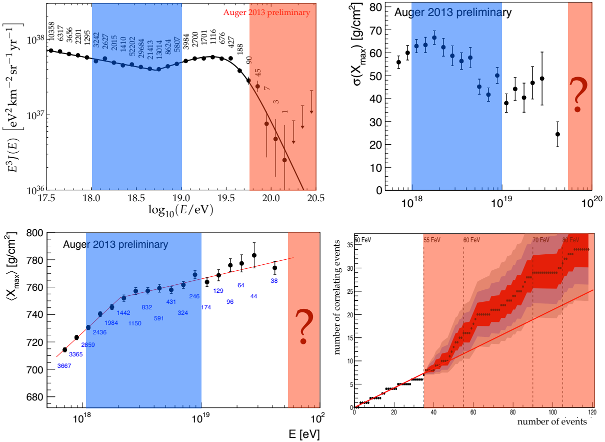
$\rightarrow$ Telescope Array: $f_p = 20^{+15}_{-12}\%$

$\rightarrow$ combined arrays: $f_p = 14^{+6}_{-5}\%$

M. Unger, CTA link 2012

consistency of Auger data estimating **composition** and **anisotropy**

All together – coherence of Auger observations



ankle region:

→ propagation effect ? signature of a transition between two types of sources ?

cut-off region:

→ source maximal acceleration ? propagation effect ? change in the hadronic interactions ?

A plenty of questions... (still)

1. What is the source of ultra-high energy cosmic rays
   → what is the fundamental process for ultimate energies : :-(
   → how do they get their energy: :-(
   ... but suppression in the energy spectrum and no photons/neutrinos at UHE !
2. What are ultra-high energy cosmic rays
   → which composition for primary cosmic rays: :-)
   → is there a change for hadronic interactions in the extensive air showers: ○

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

–

proton astronomy ?

Outline

The Pierre Auger Observatory – beyond 2015 (ground-based)

improve cosmic ray composition measurement seems to be the key

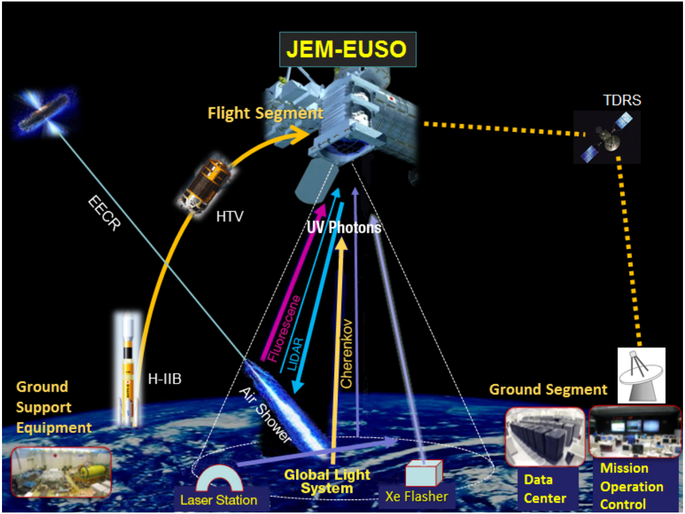
- composition at low energies – 10^{17} to a few 10^{18} eV
  $\rightarrow$ search cutoff of proton spectrum,
  $\rightarrow$ investigate the signal deficit in Monte Carlo simulations,
  $\rightarrow$ improve sensitivity to photons from GZK effect,
  $\rightarrow$ fluorescence telescopes and surface detectors for lower energies

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

search protons and study their anisotropy at highest energies

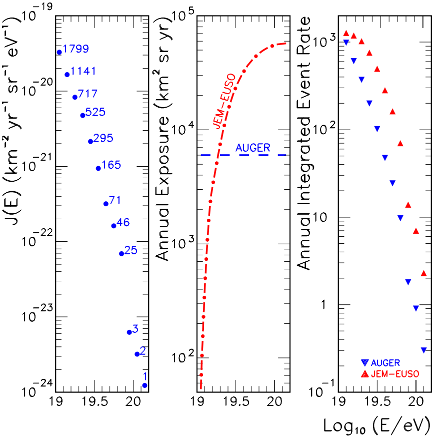
The JEM-EUSO telescope – a new era (on the ISS)

identify the first astrophysical source of ultra-high energy cosmic rays



The JEM-EUSO telescope – a new era (on the ISS)

provide a **full** and **uniform** coverage of the sky



Nominal performances expected @ 10^{20} eV

→ energy resolution: $\Delta E/E \leq 30\%$,

→ uncertainty of the maximum of the shower: $\Delta X_{\max} \leq 120$ g/cm^2,

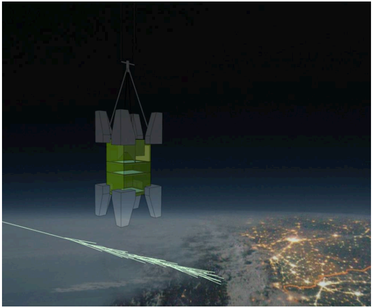
→ angular resolution better than $2.5°$,

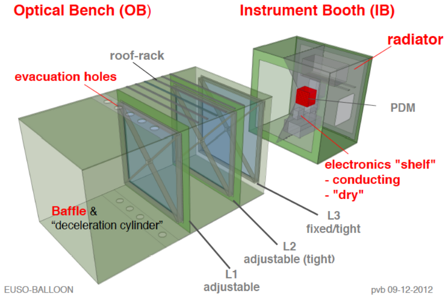
→ integrated exposure reaching 10^6 km^2 sr yr, i.e. 1MLinsley,

at higher energies, the GZK horizon is reduced → number of astrophysical sources reduced and angular separations increased

EUSO-BALLOON – a pathfinder (stratospheric balloon)

validate the concept of UHECR detection from space – here at 40 km above ground





→ first flight planned for 2014 in Canada, with active support from french collaborators

→ several flights should be planned to characterise completely the detector *(using laser shots)*

→ ... and if they are lucky, record the first air shower from space !

Thanks for your attention !