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

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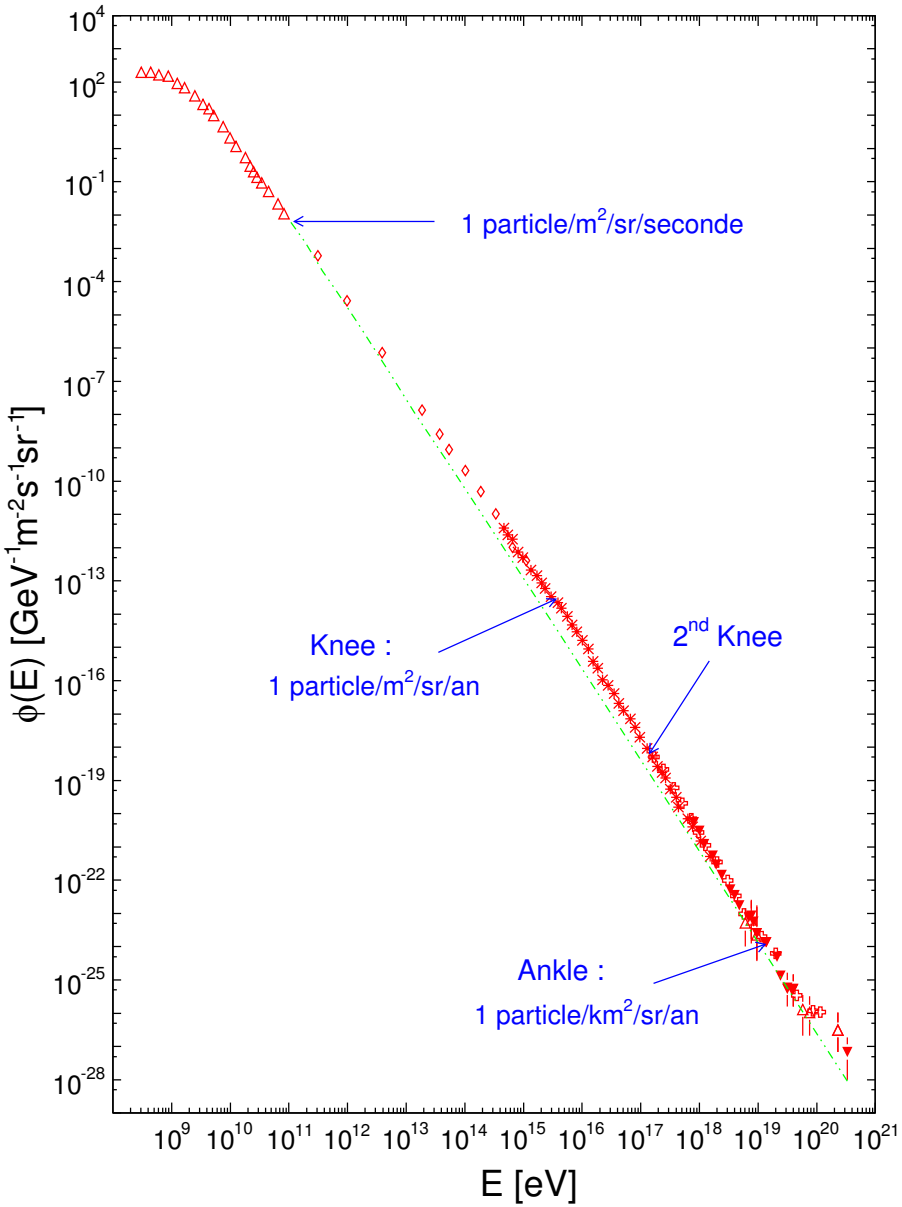
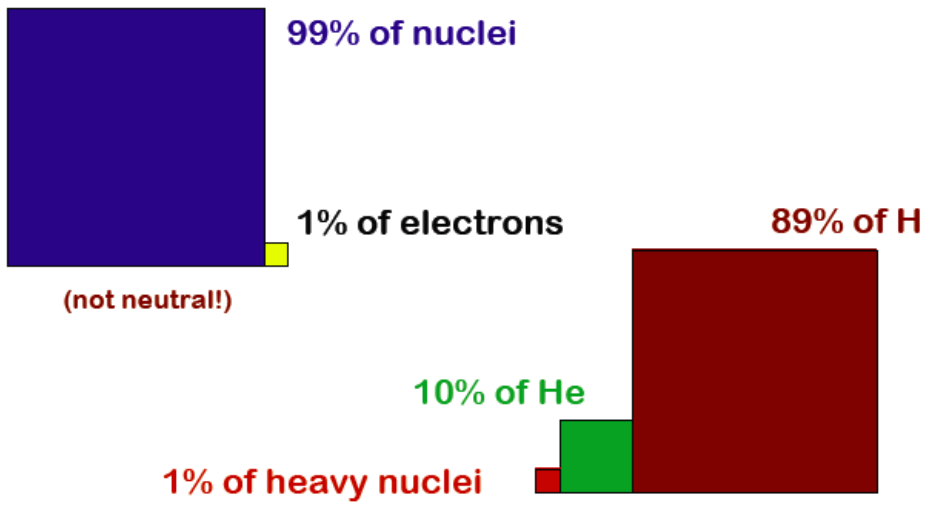
Cosmic ray energy spectrum



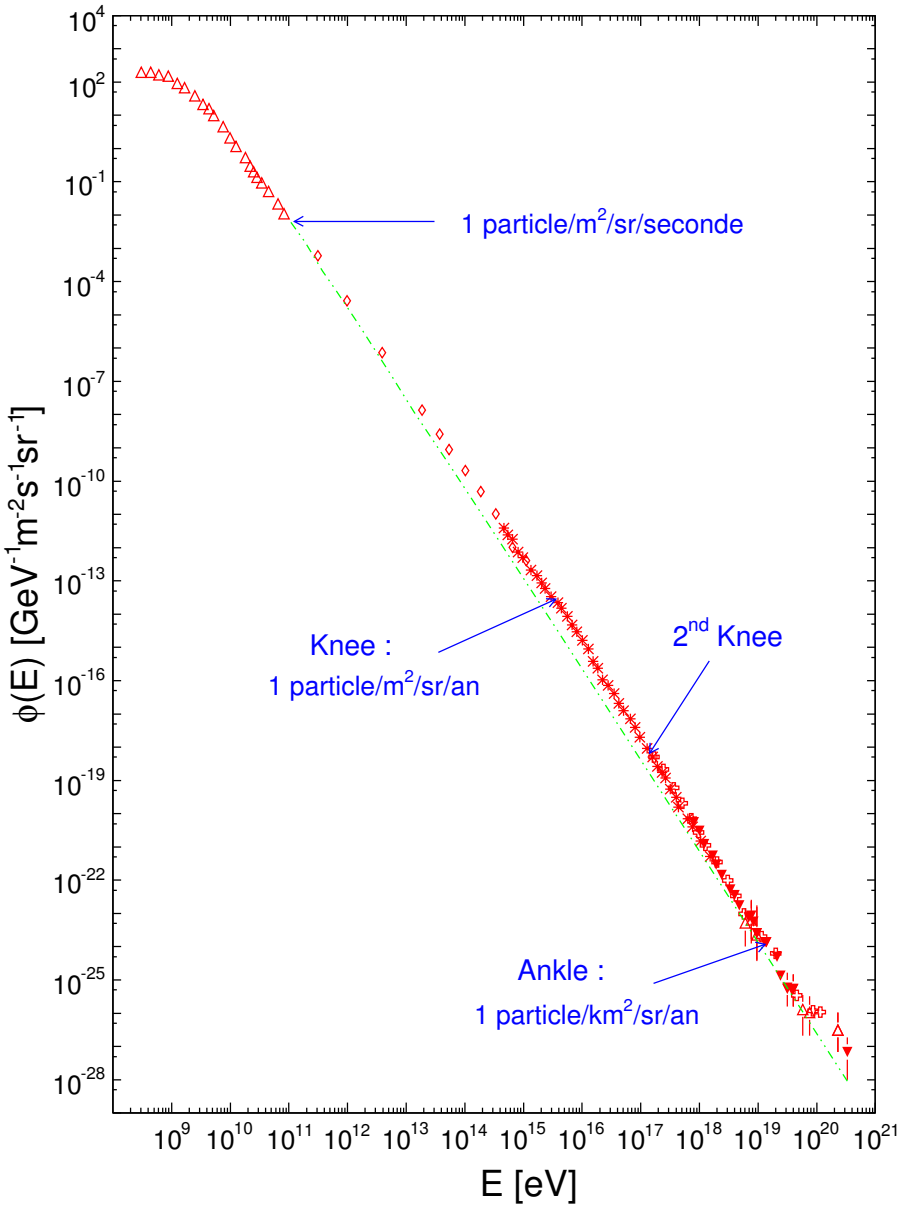
Origin of cosmic rays

- 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



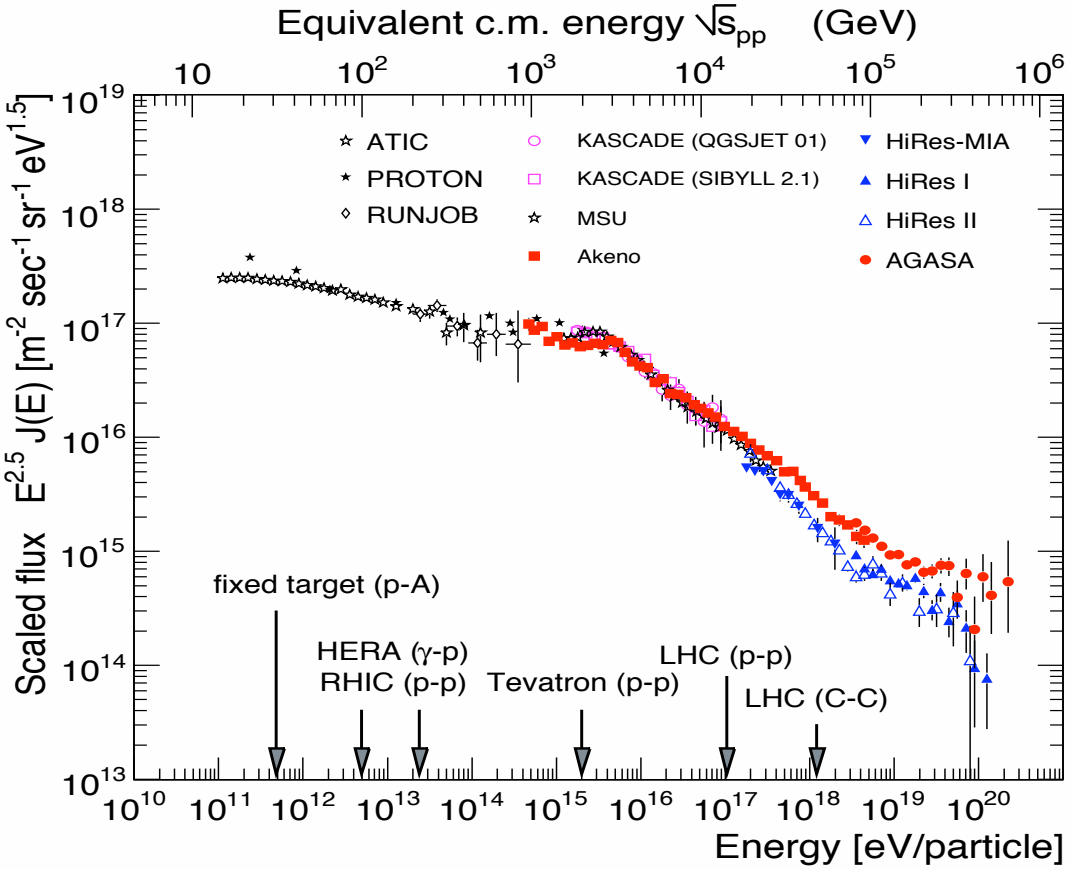
Up to the knee: direct detection

- 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



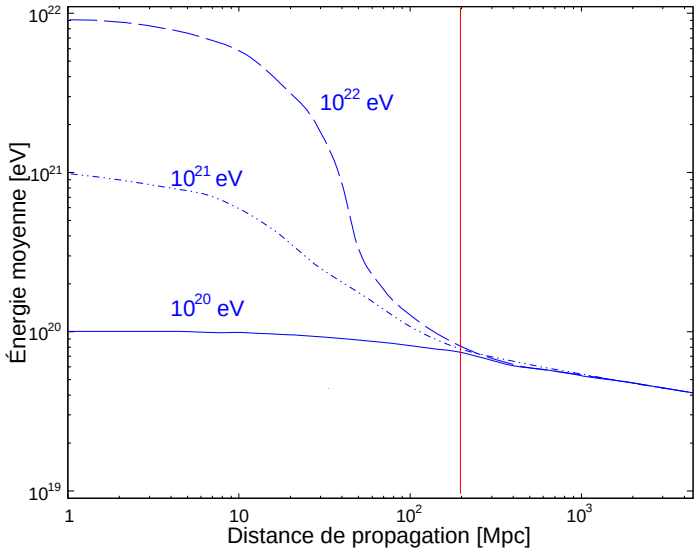
- low luminosity @ 10^{19} eV
  $\rightarrow$ 1 particle/km^2/century
- AGASA (Japan)
  $\rightarrow$ surface detector
- HiRes (Utah / USA)
  $\rightarrow$ fluorescence detector

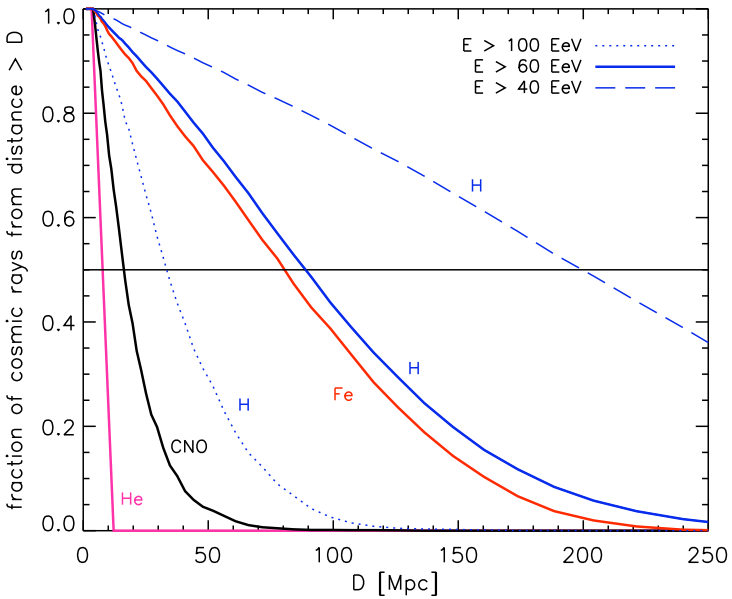
Acceleration – astrophysical shocks ($\rightarrow$ Hillas criterion)

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

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

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

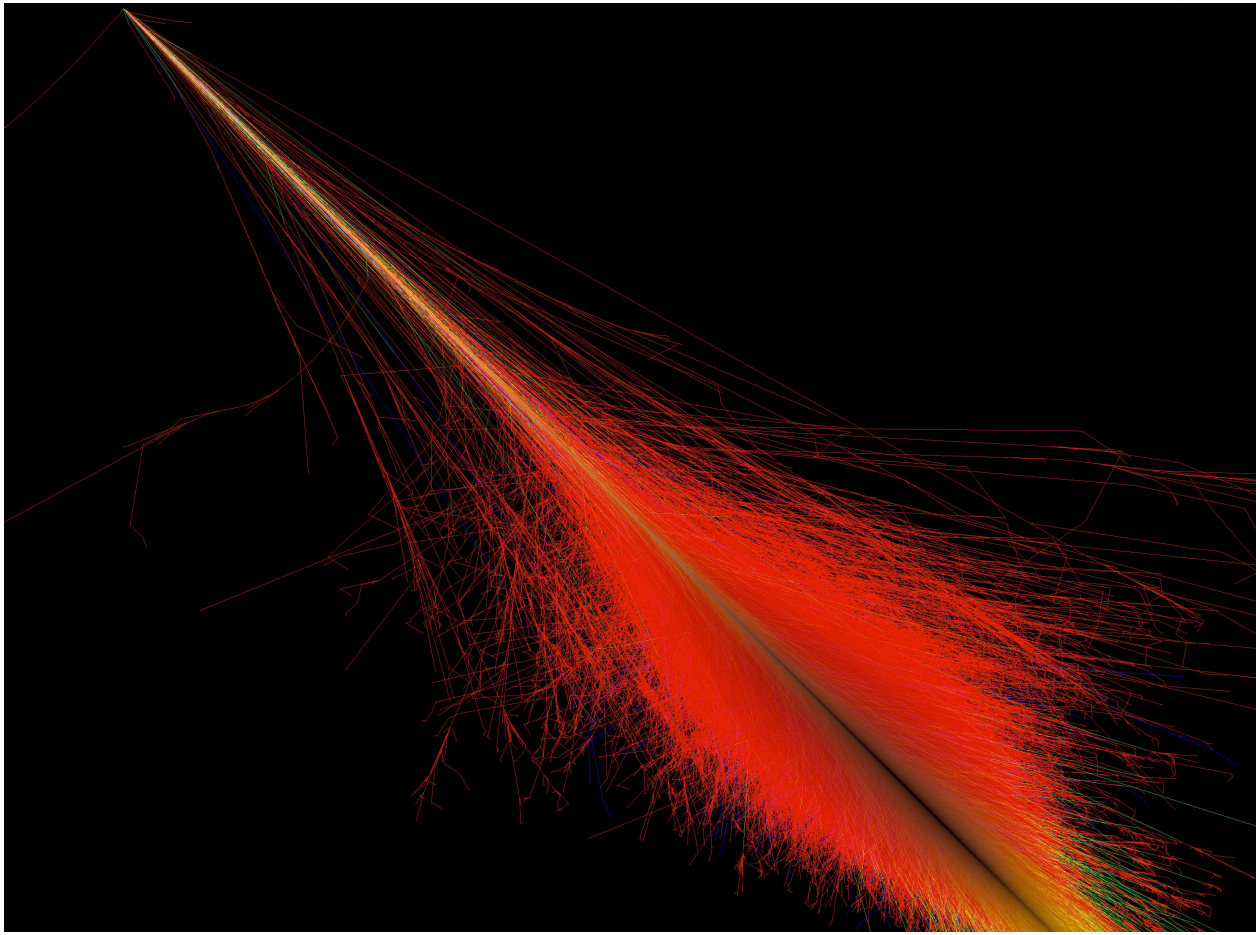
$$p + \gamma_{2.7\mathrm{K}} \rightarrow n + \pi^+ \rightarrow p + \pi^0$$

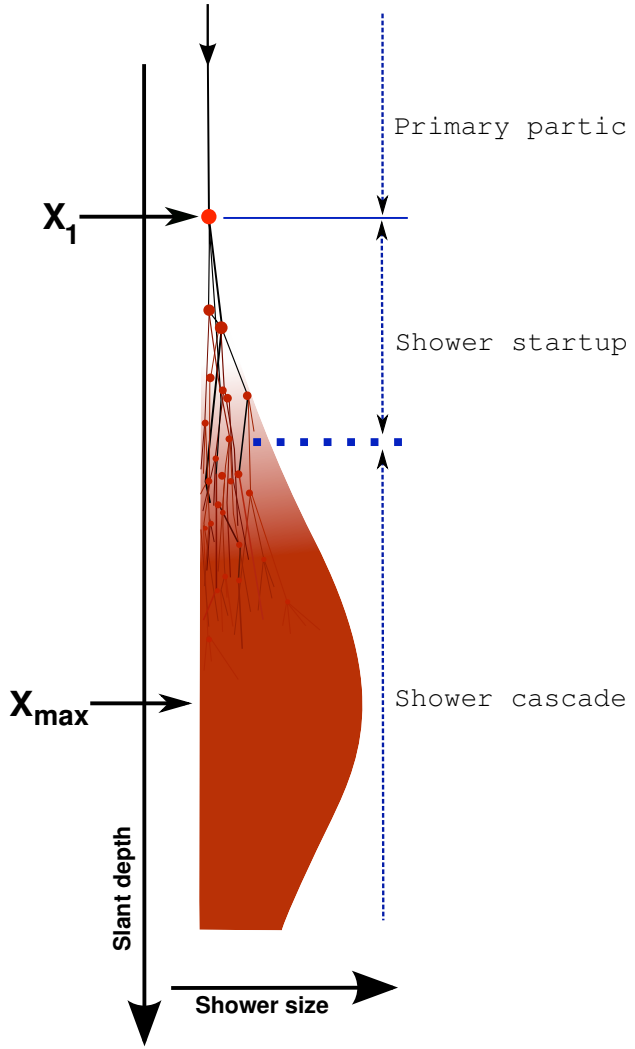
- energy threshold for the photo-pion production

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

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

Indirect detection – Extensive Air Showers





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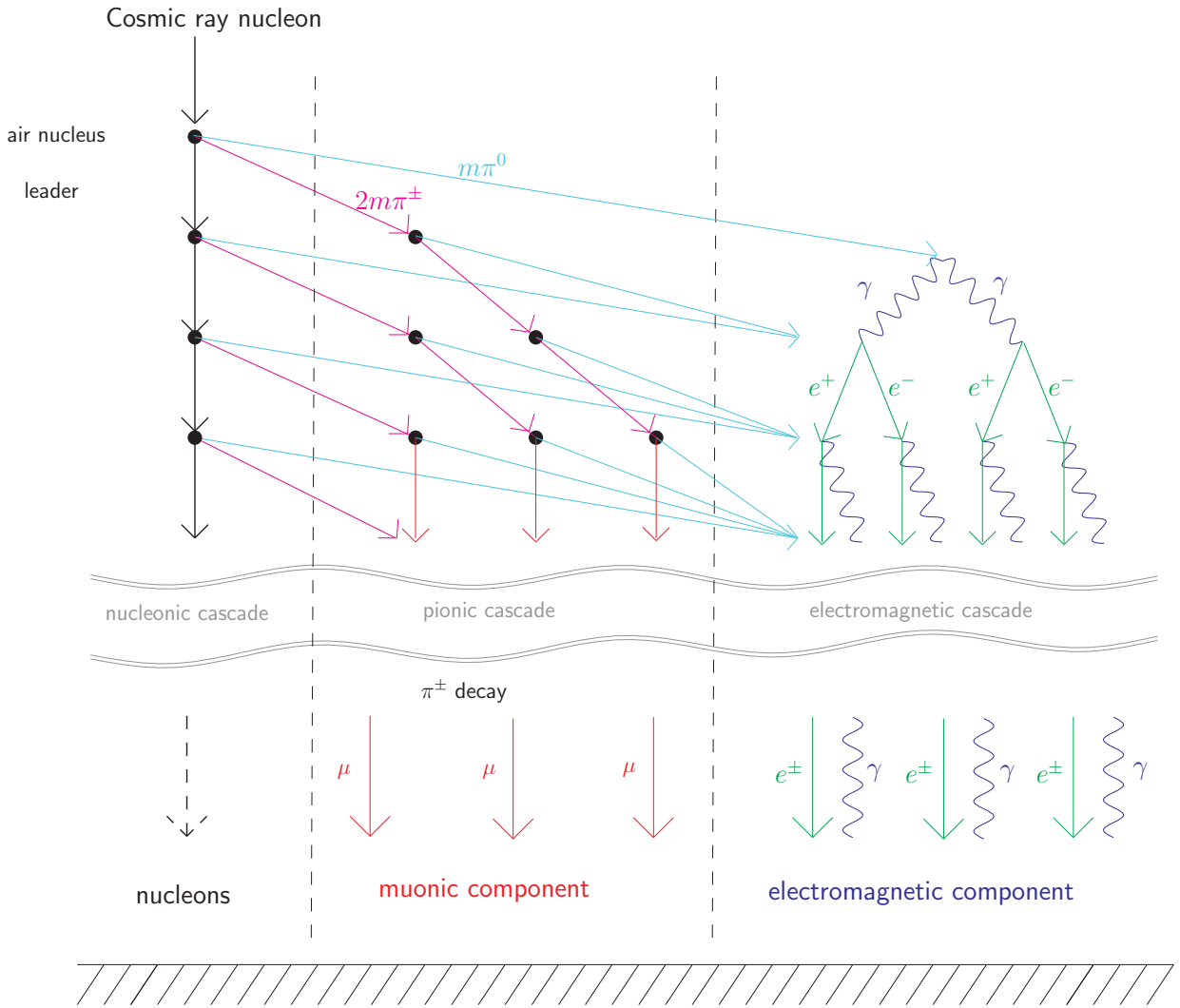
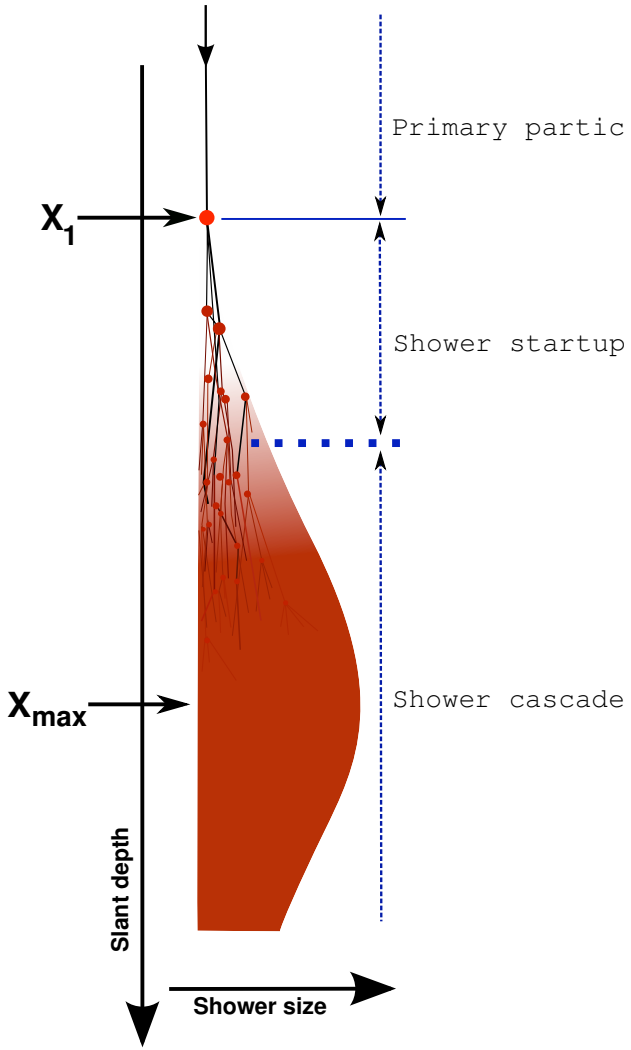
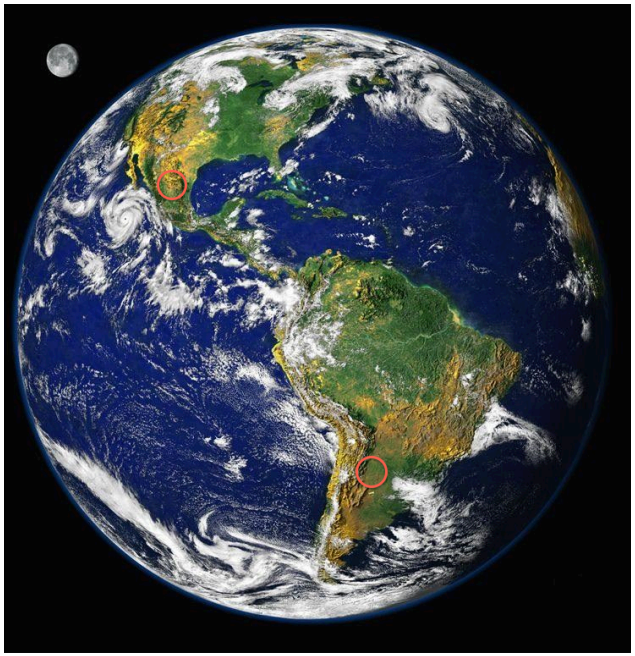




Currently, two main observatories all around the world



Pierre Auger Observatory (30 x AGASA)

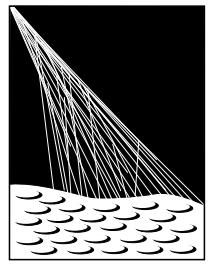
→ Mendoza / Argentina,

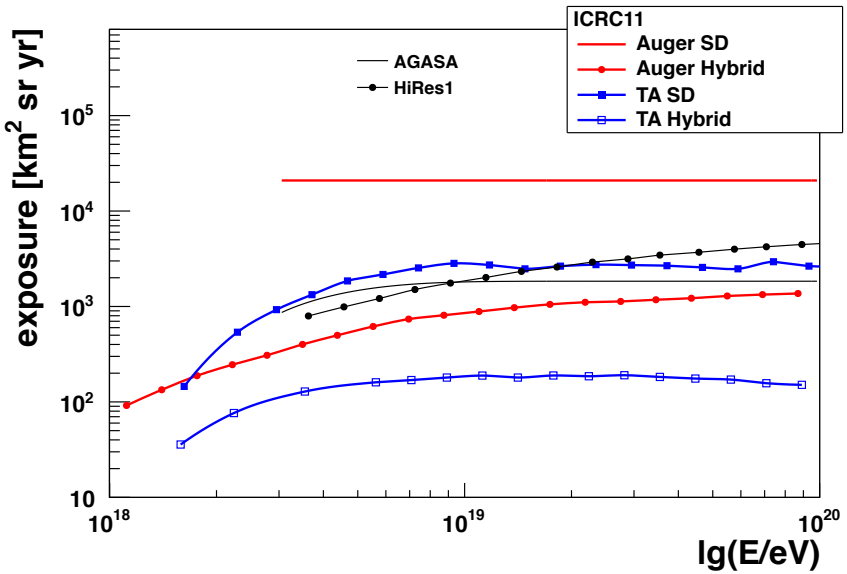
→ 3 000 km^2 array,

→ 500 collaborators / 19 countries,

→ collecting data since 2004,

→ annual expo: 6×10^3 km^2 sr yr.





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 experiment / TA

Surface detector / SD

→ 507 scintillator counters,

→ 1.2 km spacing,

→ 3 m^2 effective area / 2 layers,

→ muon component: 15–20% of signal,

→ SD expo: 1.4×10^3 km^2 sr yr.

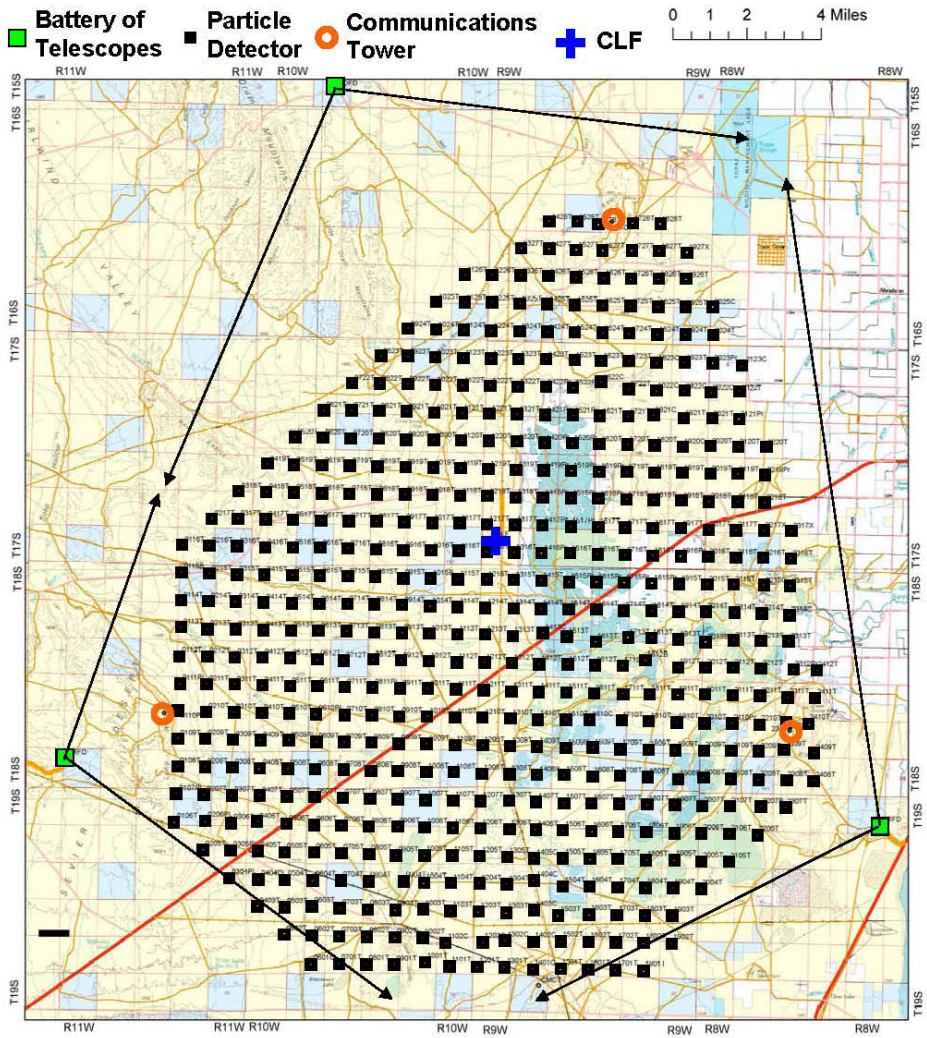
Fluorescence detector / FD

→ 3 fluorescence sites,

→ 12 + 12 + 14 telescopes,

→ HiRes technology,

→ hybrid expo: $\simeq 10^2$ km^2 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: 2.0×10^4 km^2 sr yr.

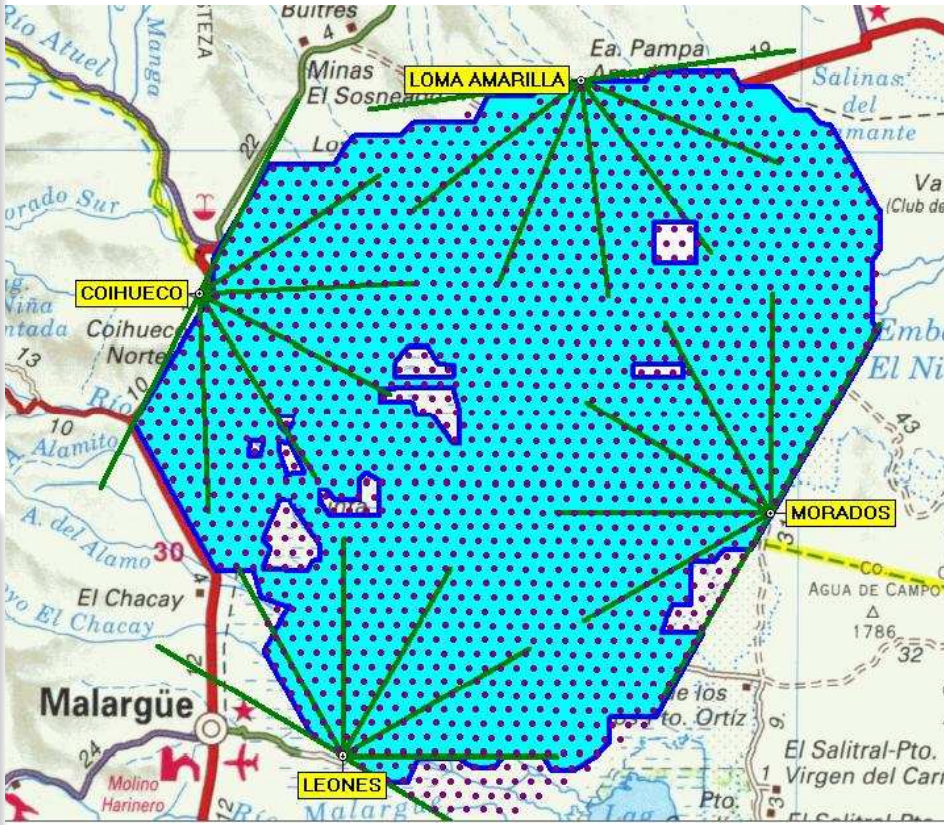
Fluorescence detector / FD

→ 4 fluorescence sites,

→ 4 x 6 telescopes / 30° x 180°,

→ 440 PMTs per telescope camera,

→ hybrid expo: $\leq 10^3$ km^2 sr yr.



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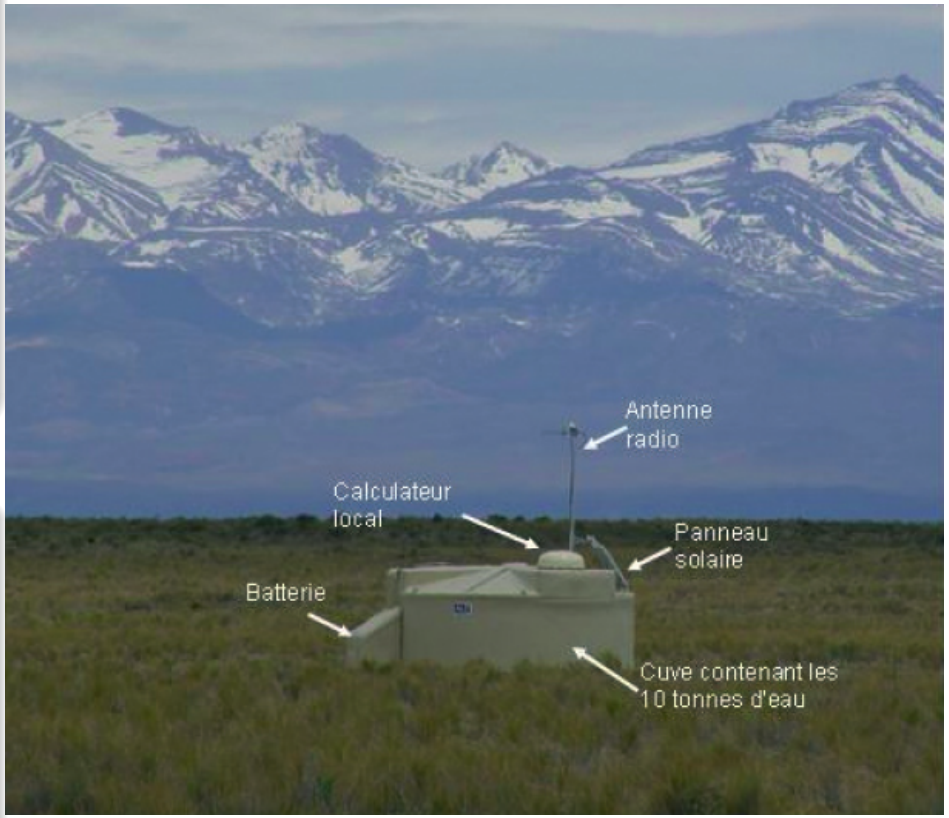

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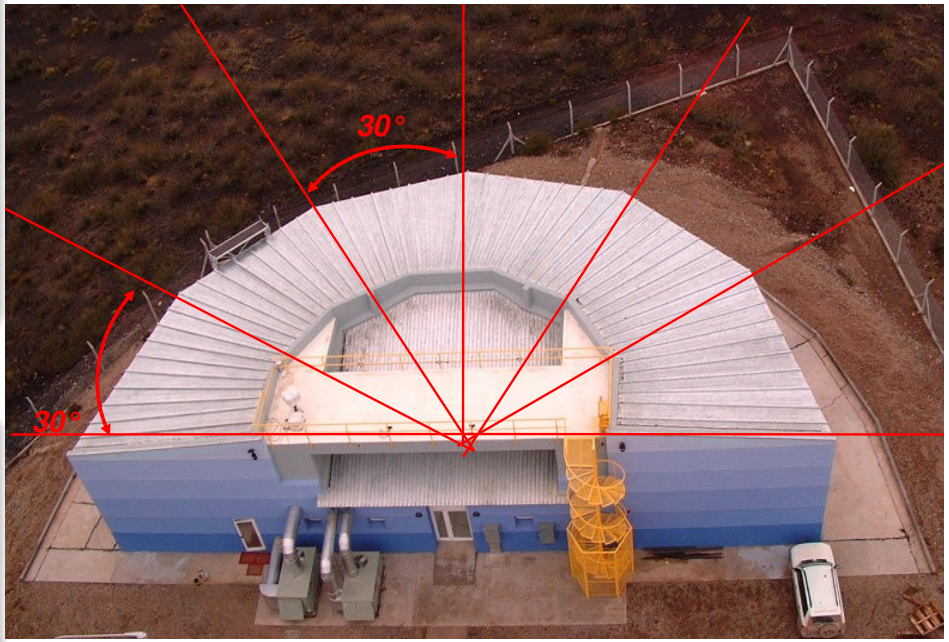

Similar design... and same problems sometimes !

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A plenty of questions...

3 observables
arrival direction distribution / primary composition / energy spectrum

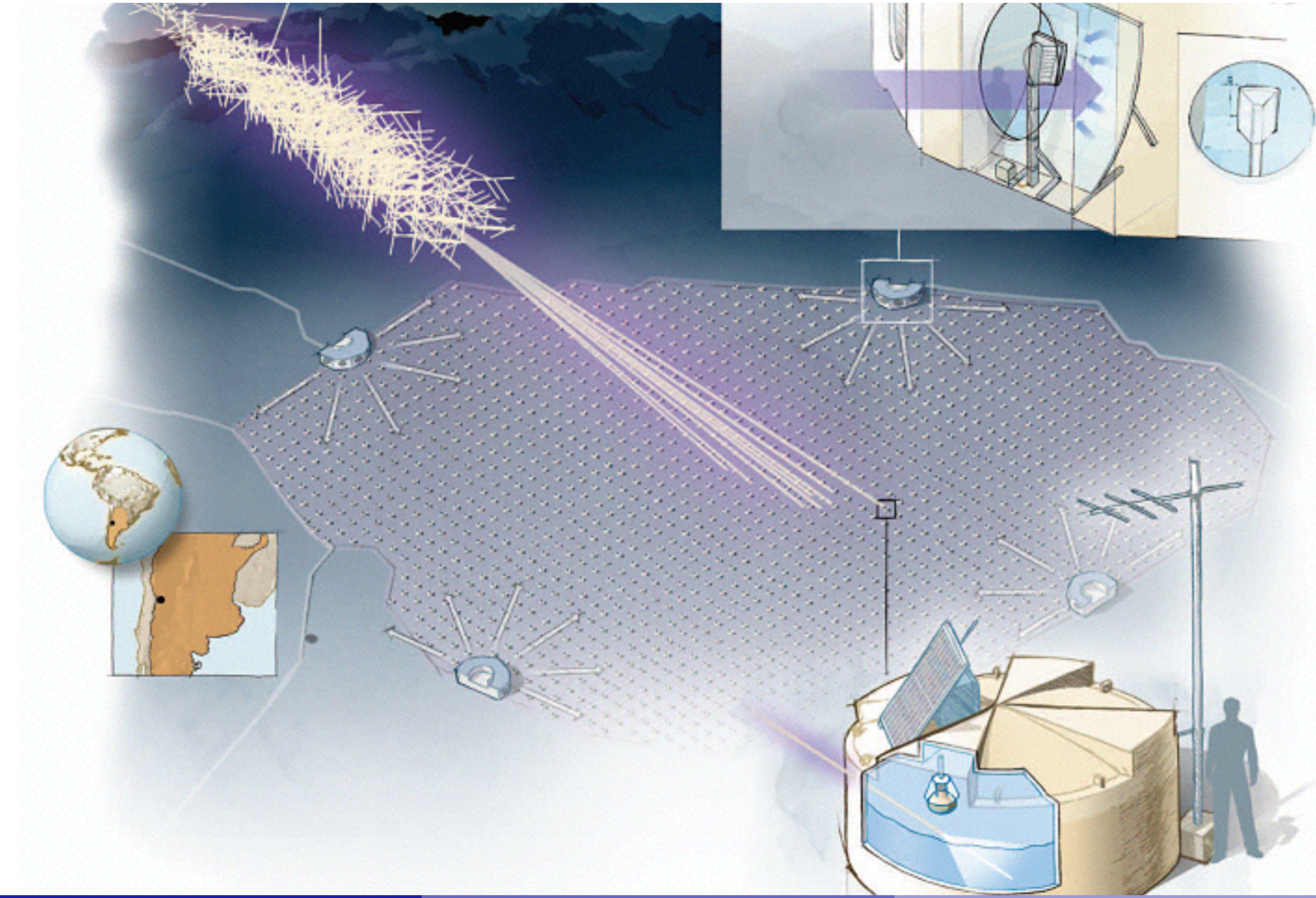
1. What is the source of ultra-high energy cosmic rays
   → what is the fundamental process for ultimate energies ?
   → how do they get their energy ?

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 ?

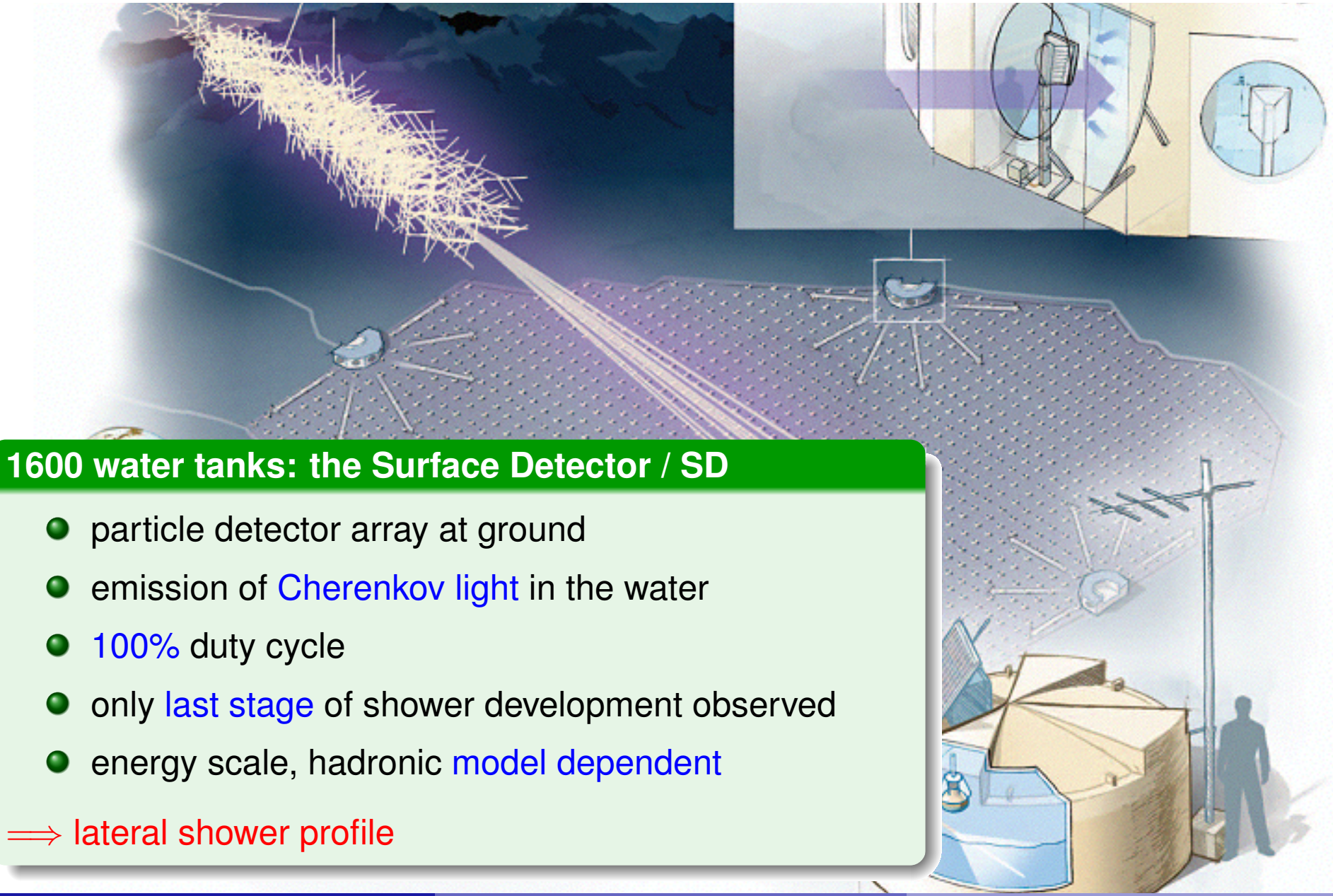
Is it possible to identify the source(s) of ultra-high energy cosmic rays ?
–
charged astronomy: could they be used as astrophysical messengers ?

Outline

The Pierre Auger Observatory



The Pierre Auger Observatory

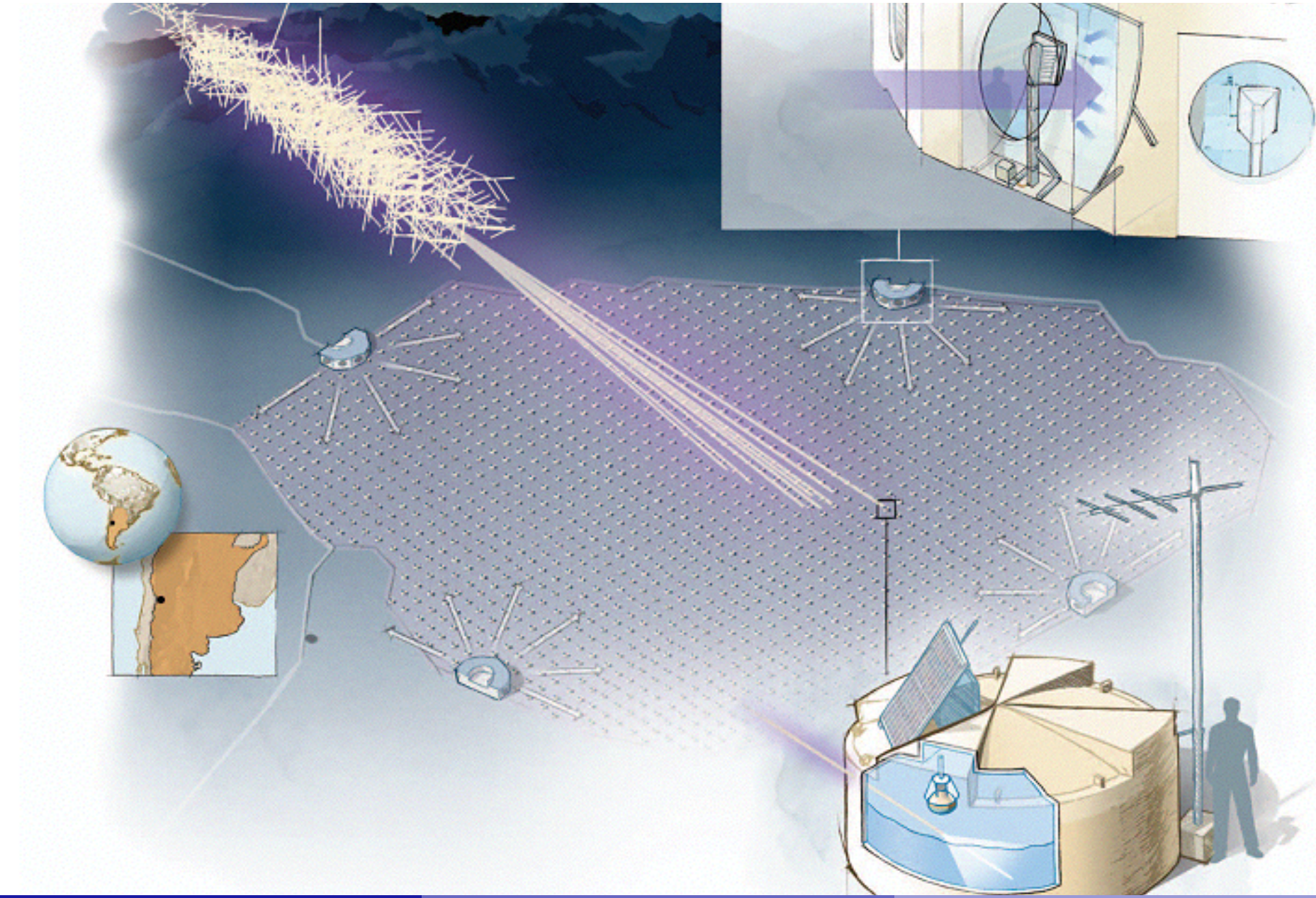


1600 water tanks: the Surface Detector / SD

- 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



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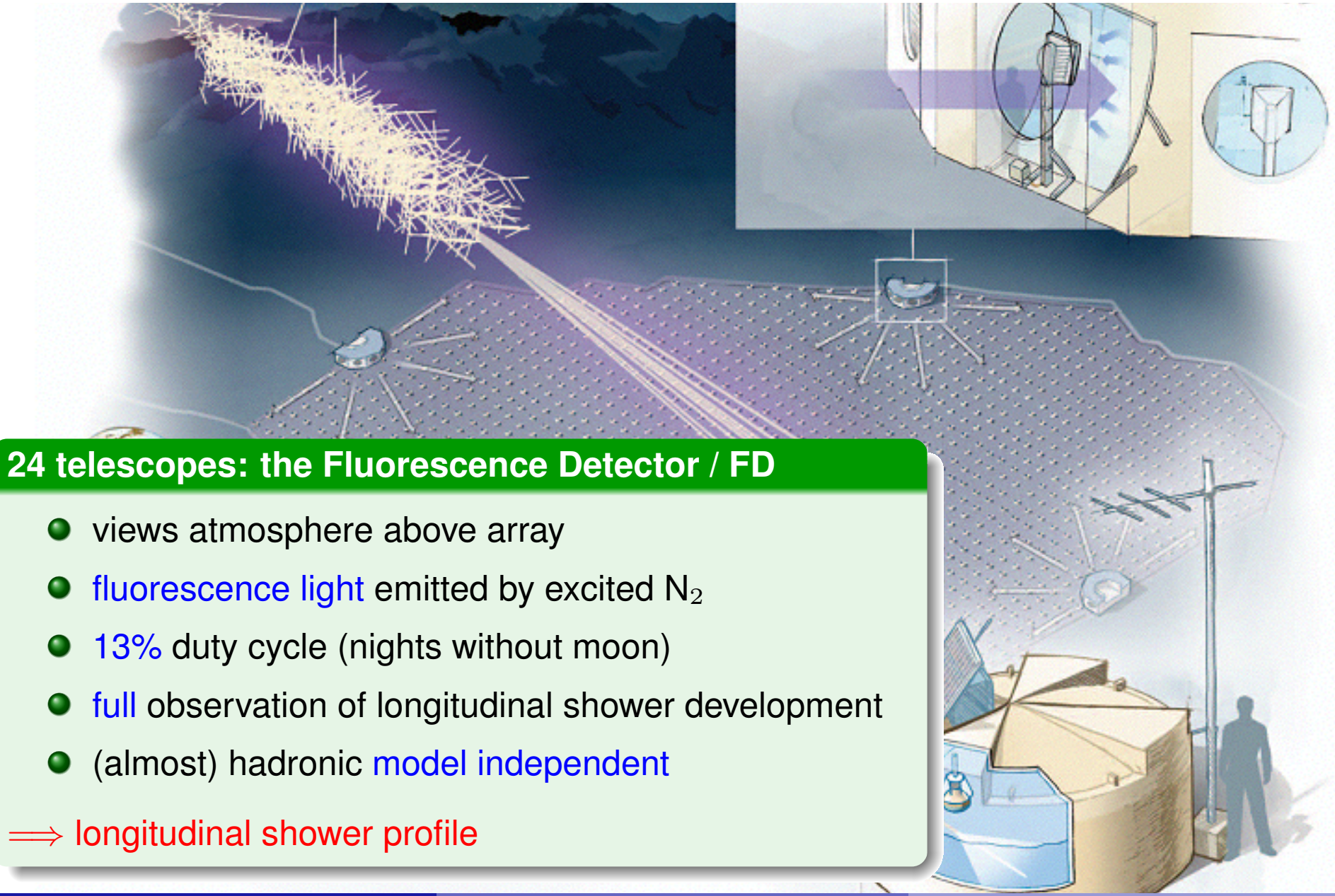
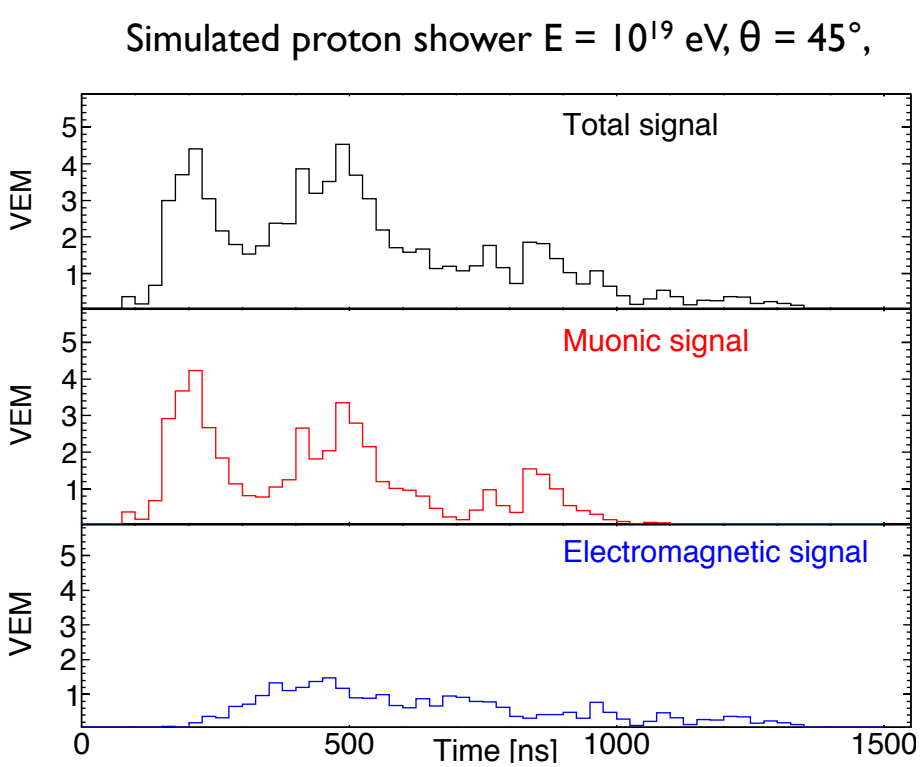


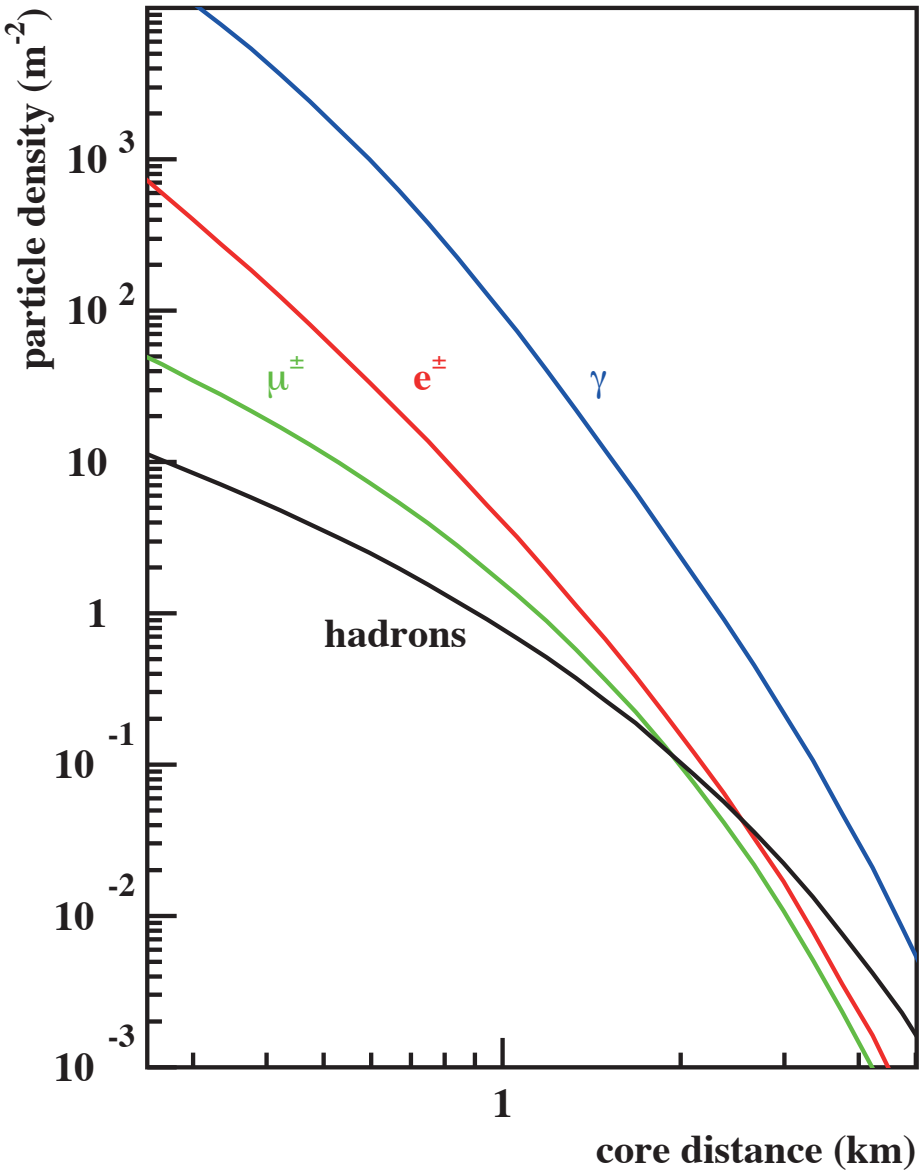
24 telescopes: the Fluorescence Detector / FD

- 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

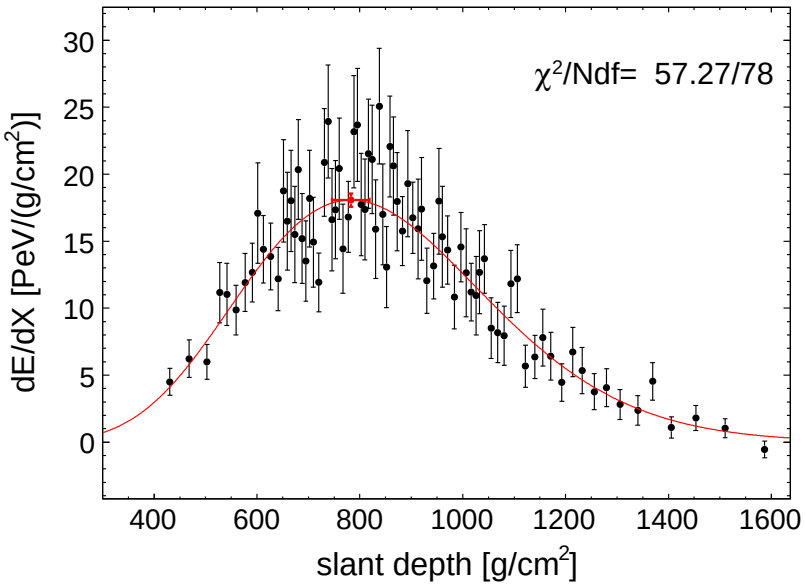


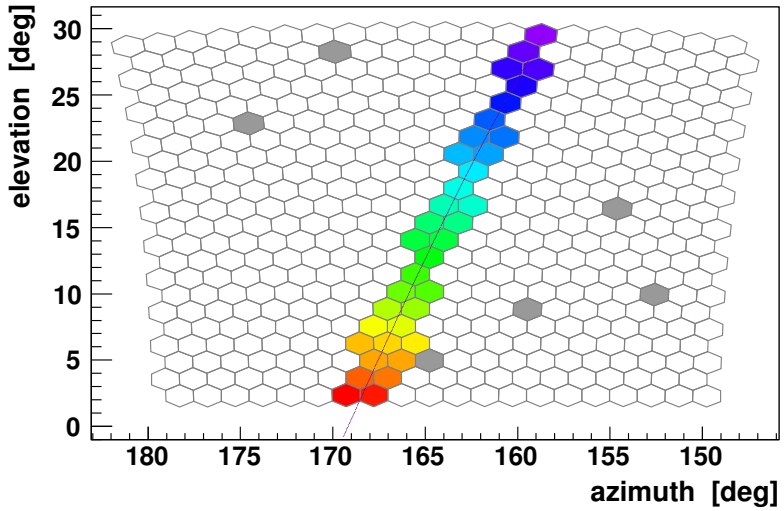


→ muonic signals are less dispersed in time, stronger in intensity,

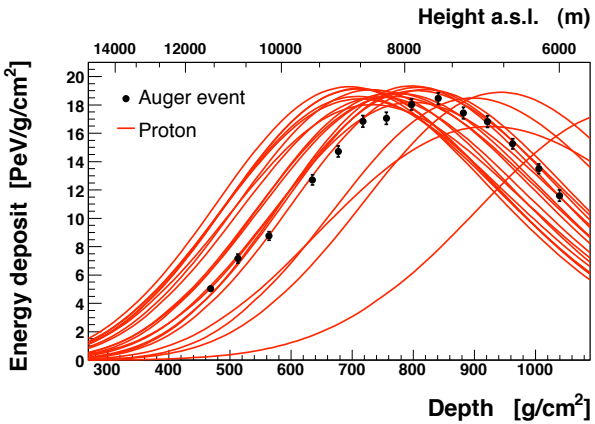
→ EM signal is seen as a diffusive background.

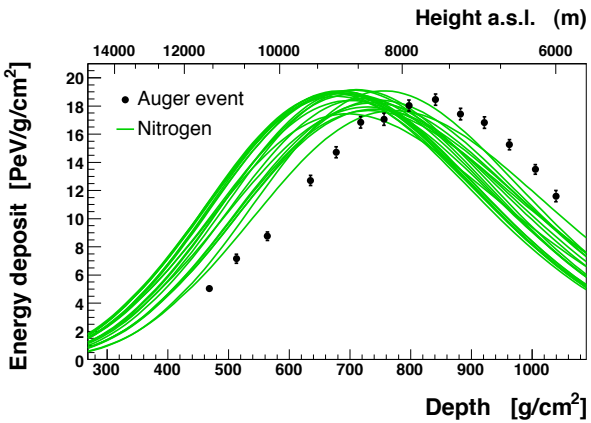
The Fluorescence Detector ⟶ Longitudinal profile

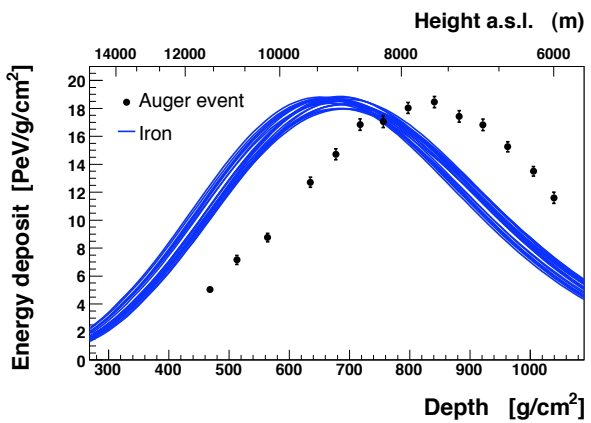




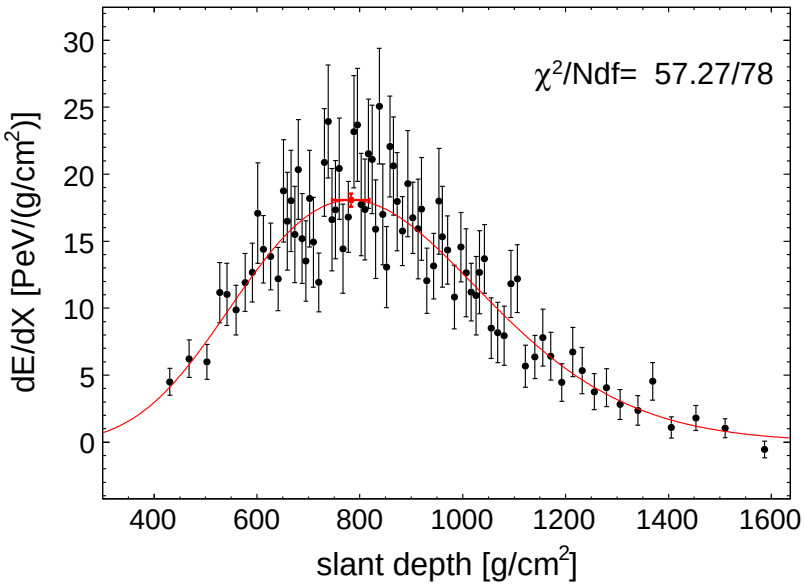
Longitudinal profile and mass composition

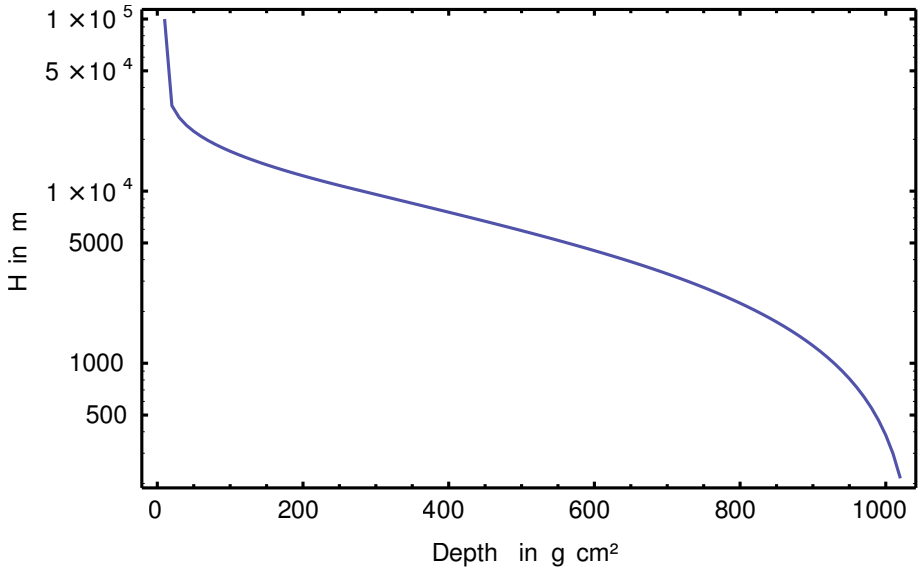






The Fluorescence Detector ⟶ Longitudinal profile





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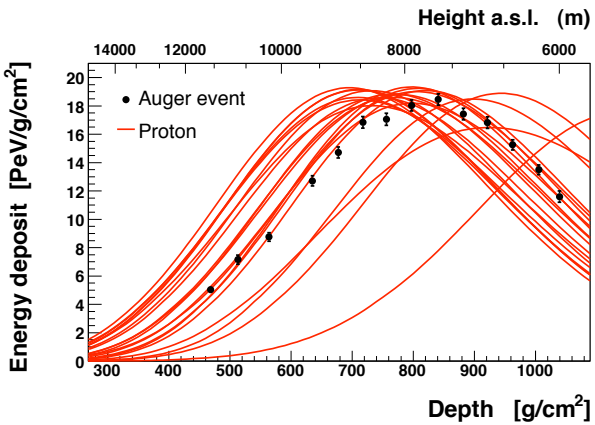
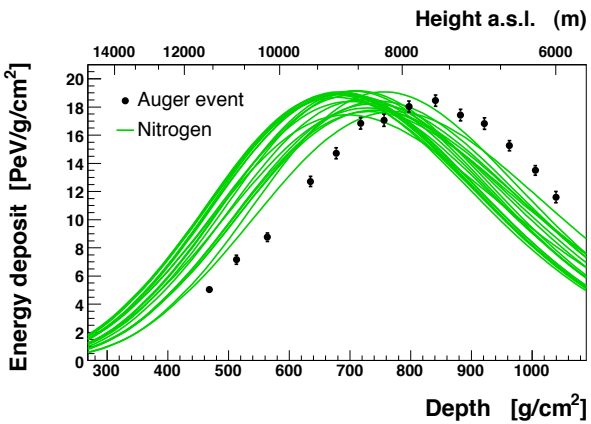
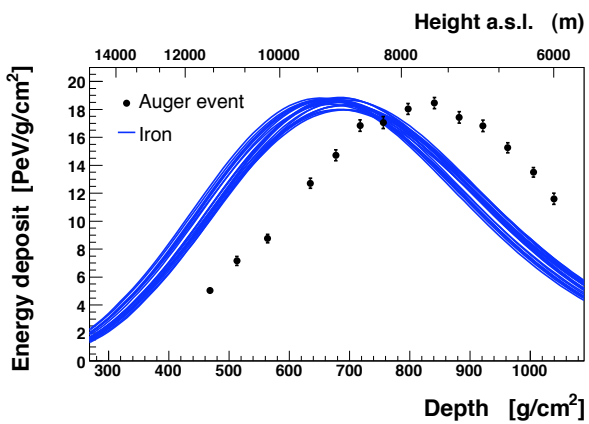
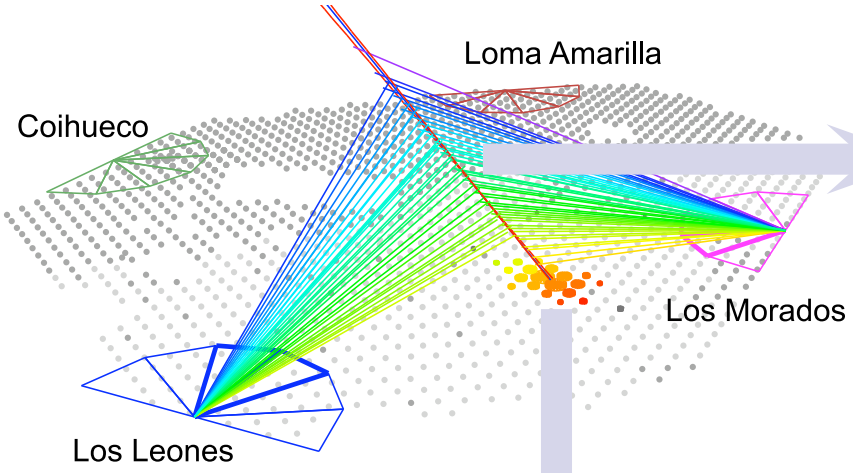
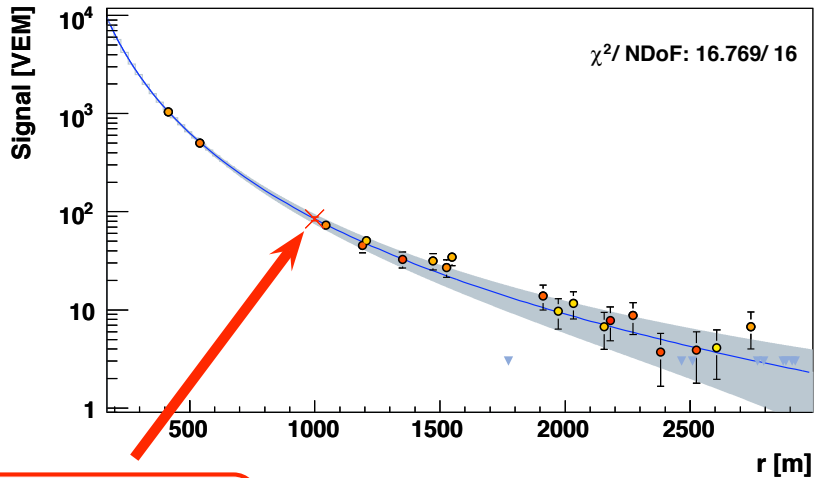






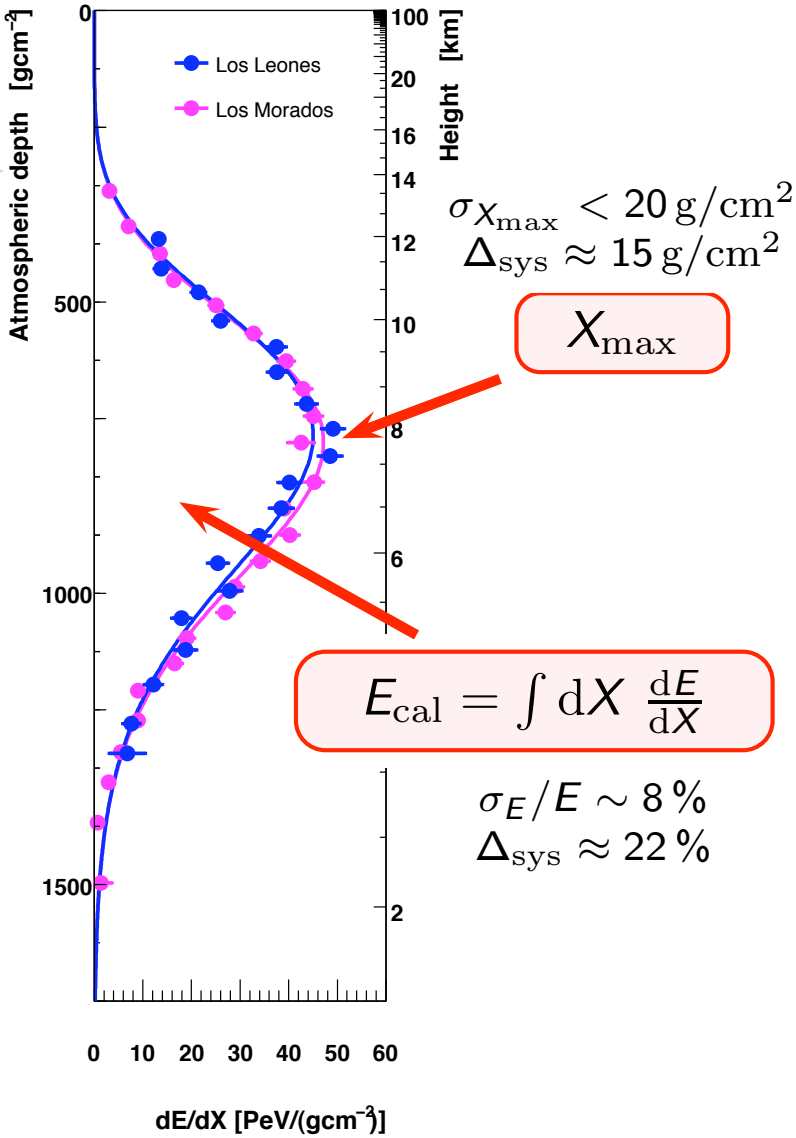
Auger hybrid detector – observables





S_{1000}

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



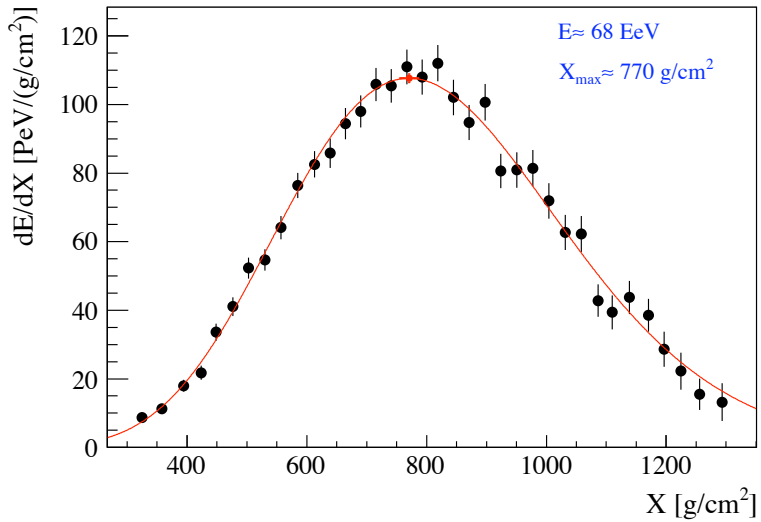
$\sigma_{X_{\mathrm{max}}} < 20\,\mathrm{g/cm^2}$
$\Delta_{\mathrm{sys}} \approx 15\,\mathrm{g/cm^2}$

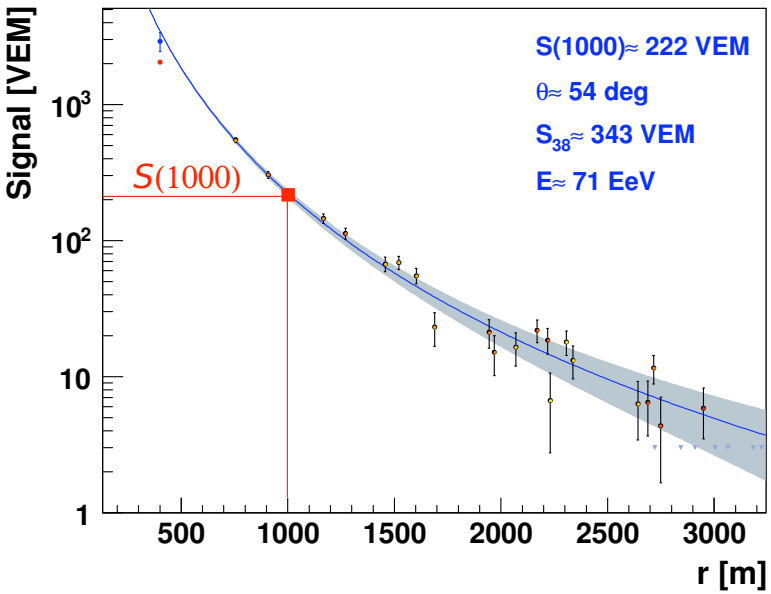
X_{max}

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

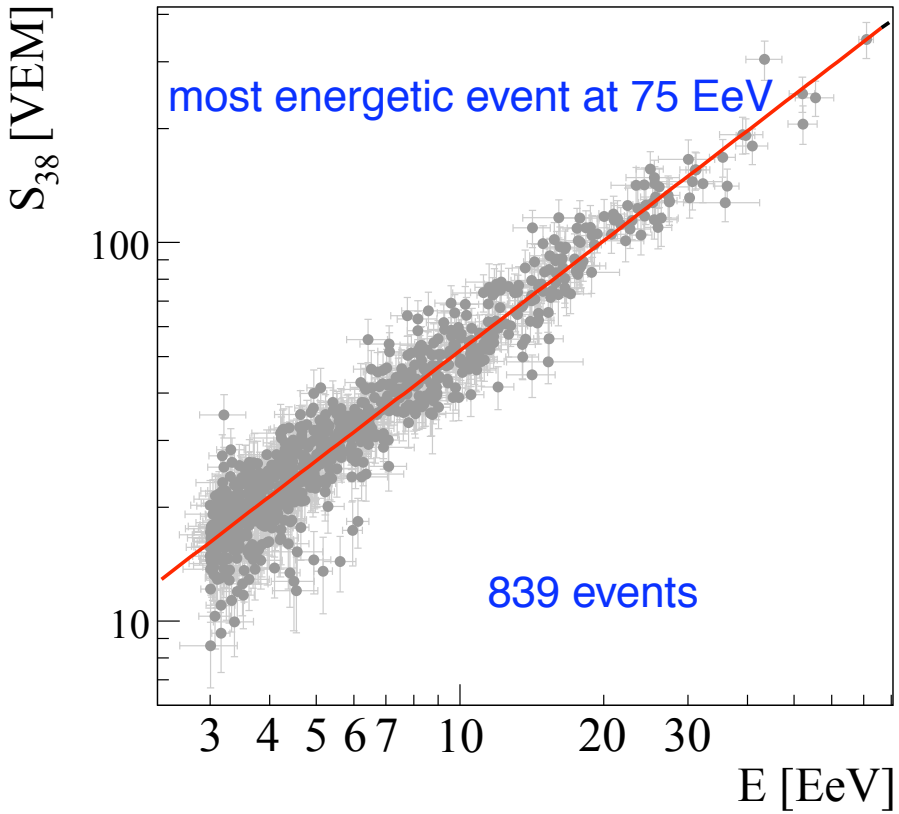
$\sigma_E/E \sim 8\,\%$
$\Delta_{\mathrm{sys}} \approx 22\,\%$

Auger hybrid detector – SD energy calibration by FD





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

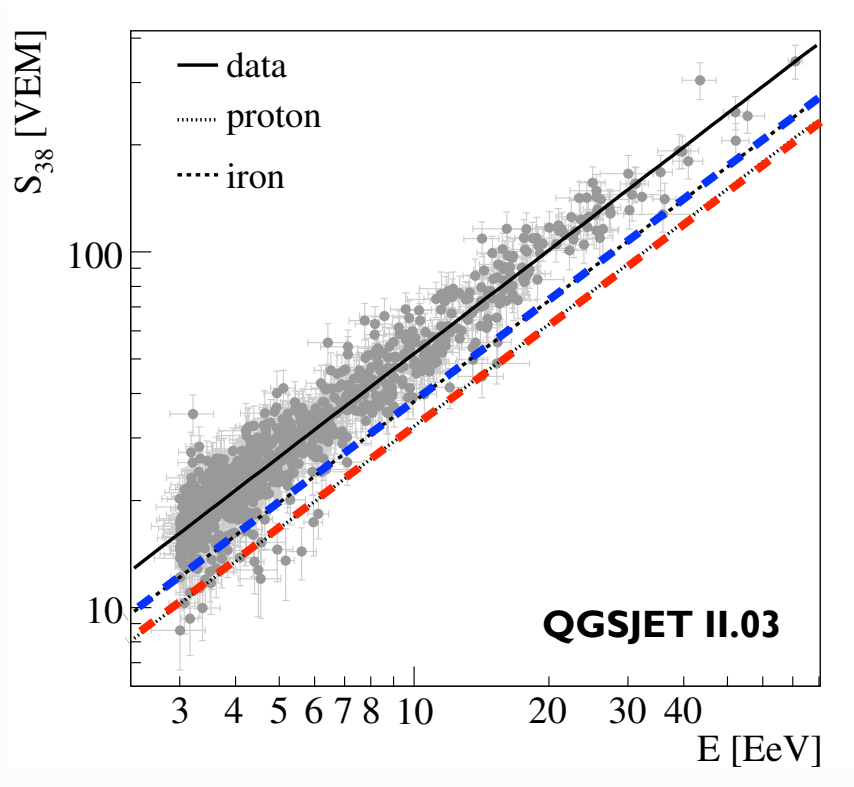


→ SD energy estimator calibrated using hybrid events (no Monte Carlo simulations),

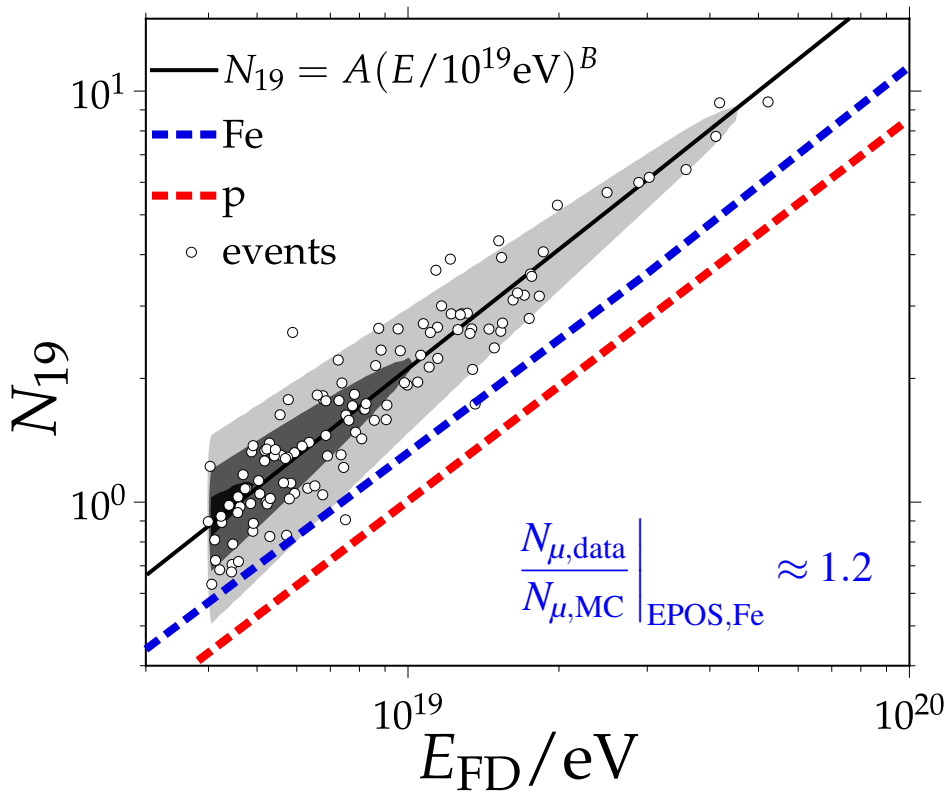
→ systematic uncertainties for the method:
7% @ 10^{19} eV *and* 15% @ 10^{20} eV

Advantage of the energy calibration by FD

Showers up to 60° zenith angle



Inclined showers (muon dominated)



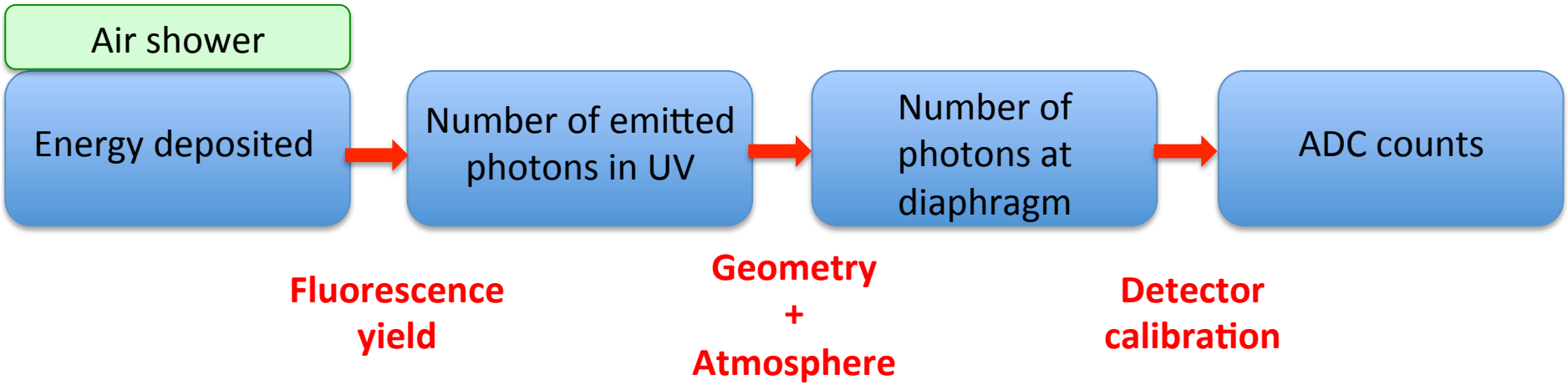
→ more signal than expected is recorded in the Cherenkov tanks,

→ the discrepancy is increased when looking at the muon component (?),

→ ... but it should be lower at Telescope Array (EM component mainly).

work still in progress, especially on the muon fraction vs energy

Energy systematics in fluorescence measurements



Pierre Auger Observatory	22%
calibration	9.5%
reconstruction	10.0%
atmospheric	8.0%
fluorescence yield	14.0%
invisible energy	4.0%

Telescope Array	21%
calibration	10.0%
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crucial when comparing energy spectrums or constraining UHECR sources

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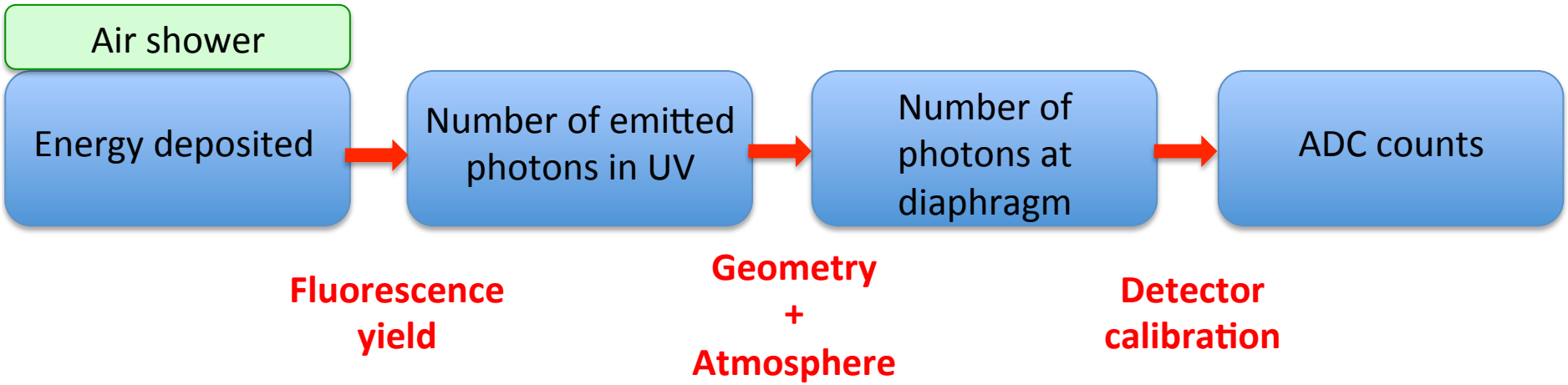

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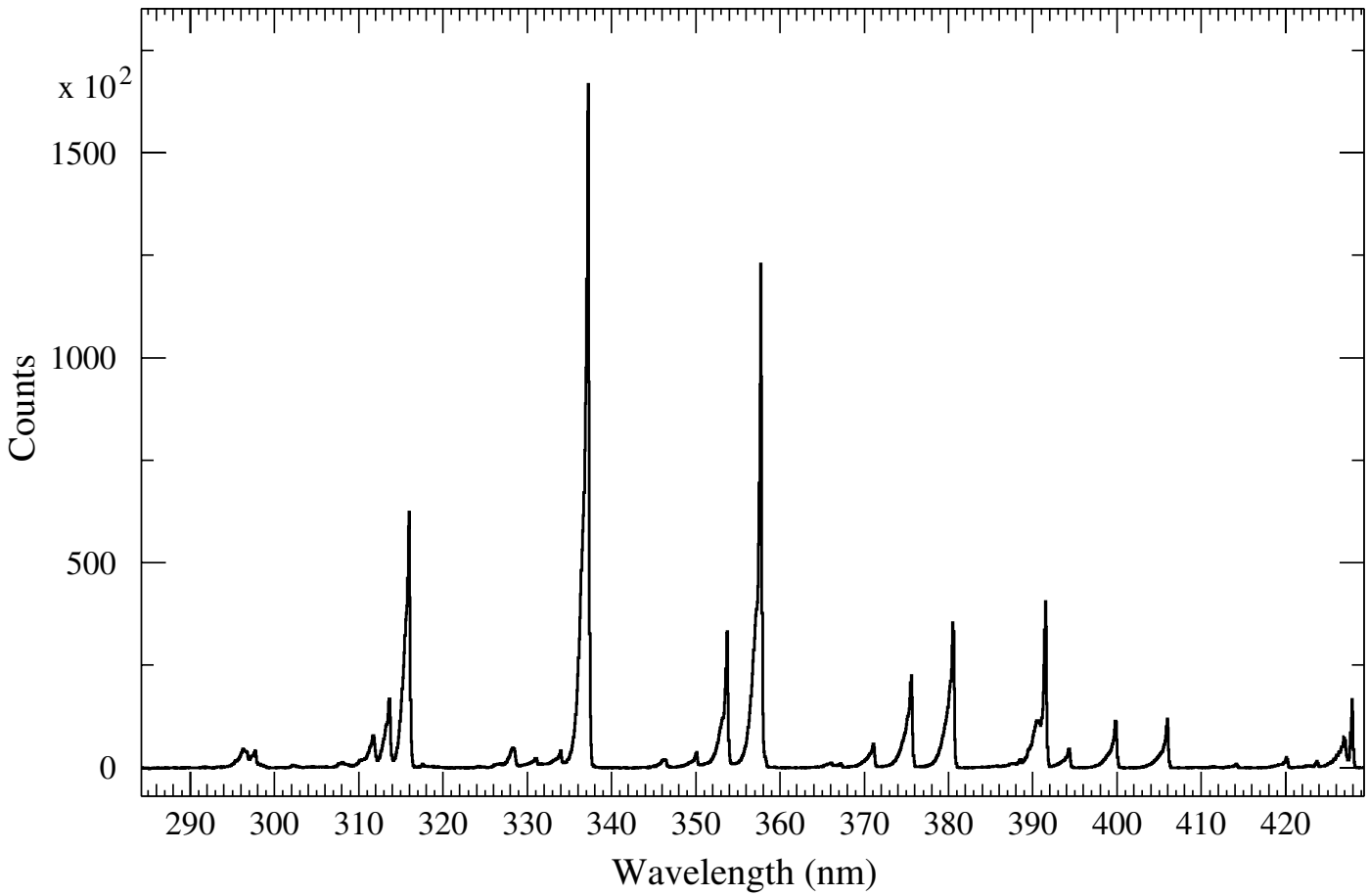
The fluorescence spectrum – up to recently, the largest uncertainty

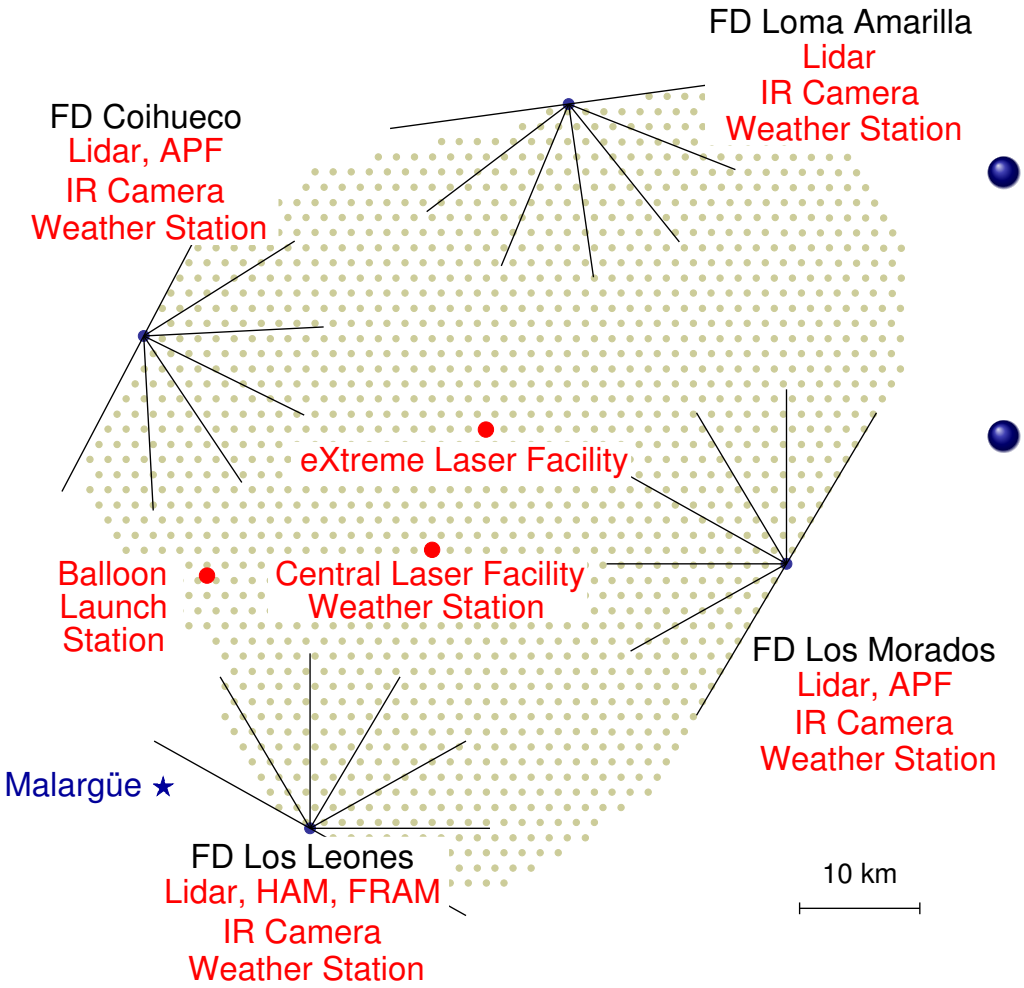


AIRFLY: $Y_{\rm air} = 5.67 \pm 0.07\,({\rm stat.}) \pm 0.21\,({\rm syst.})$ photons$_{337}$ / MeV $\rightarrow$ uncertainty of 4%

currently in Auger: $Y_{\rm air} = 5.05$ photons$_{337}$ / MeV $\rightarrow$ energy scale goes down by 10%

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

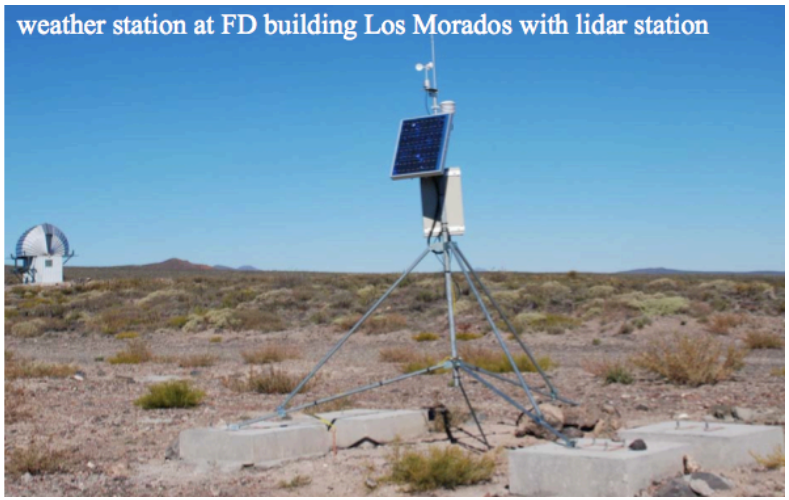
An extensive atmospheric monitoring

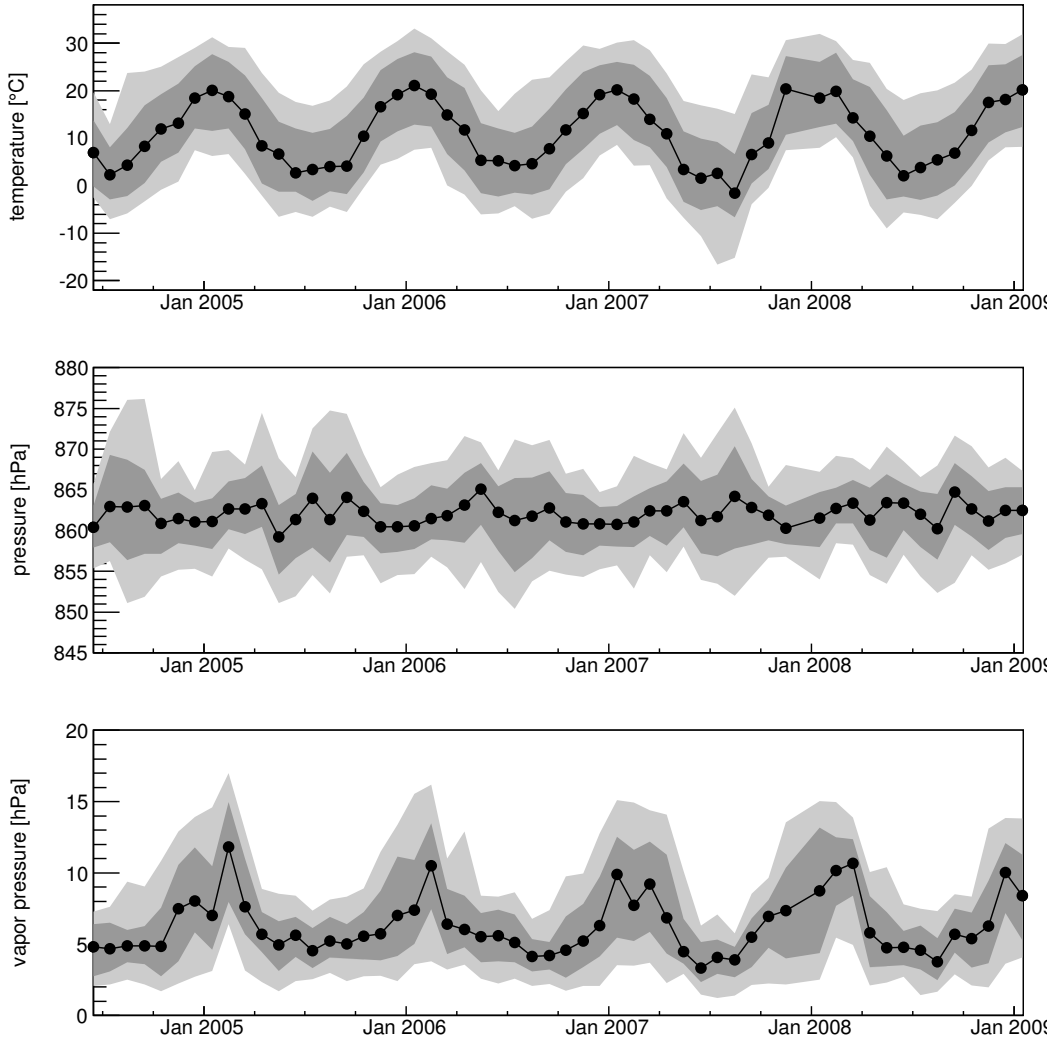


- Atmospheric state variables
  - → 5 ground-based weather stations,
  - → balloon lunches.
- Aerosol and cloud monitoring
  - → 4 ‘elastic’ lidars,
  - → 2 central lasers (CLF/XLF),
  - → 2 optical telescopes (HAM/FRAM),
  - → 2 aerosol phase functions (APF),
  - → 4 IR cameras,
  - → ... and soon,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

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

Atmospheric state variables – ground-based weather stations

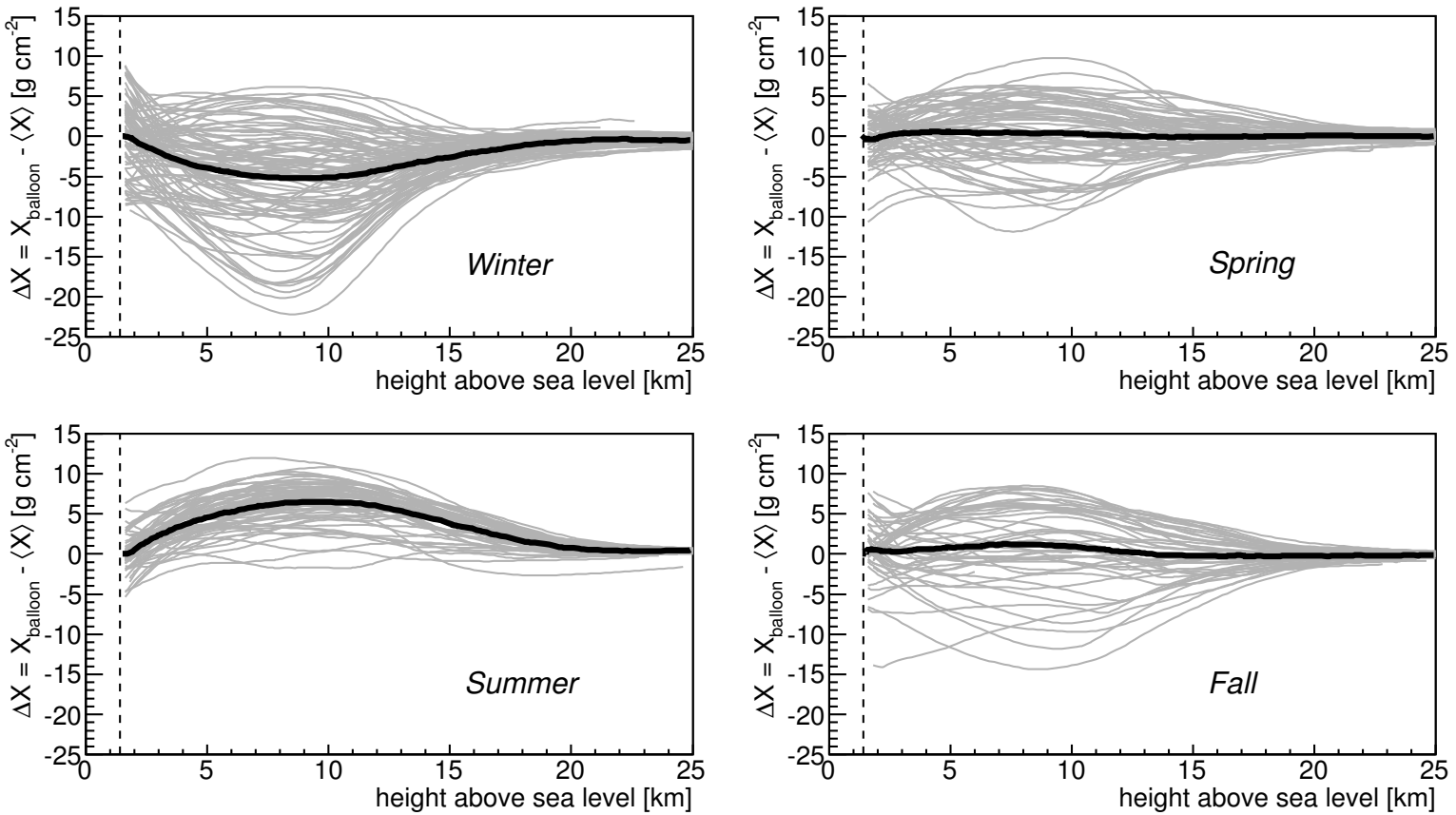




- temperature, pressure, humidity, wind speed
- data acquisition every 5 minutes,
- check of lateral homogeneity.

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

Atmospheric state variables – radio soundings

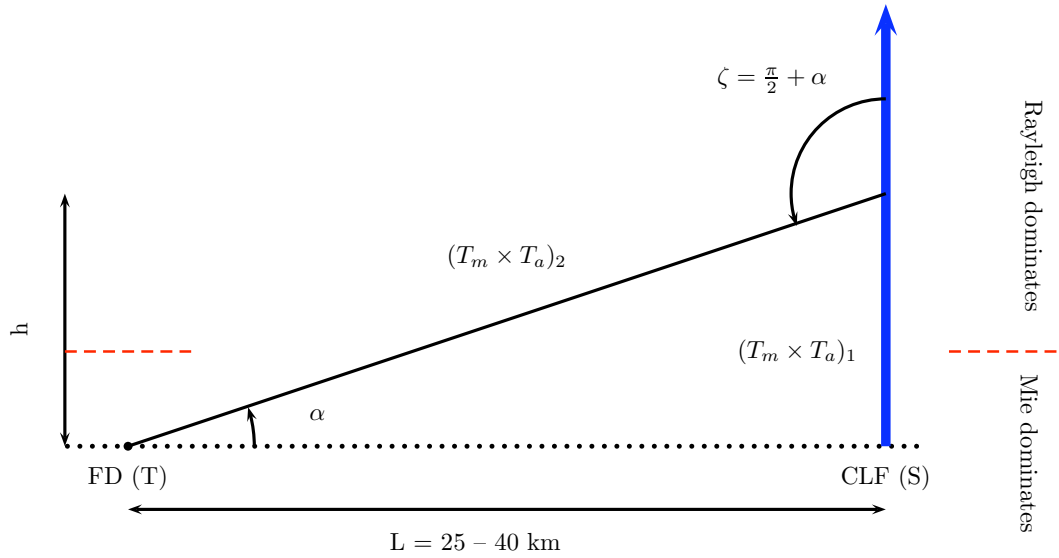


- temperature, pressure and humidity vertical profiles,
- around 350 balloon launches since August 2002,
- monthy models computed for molecular part.

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).



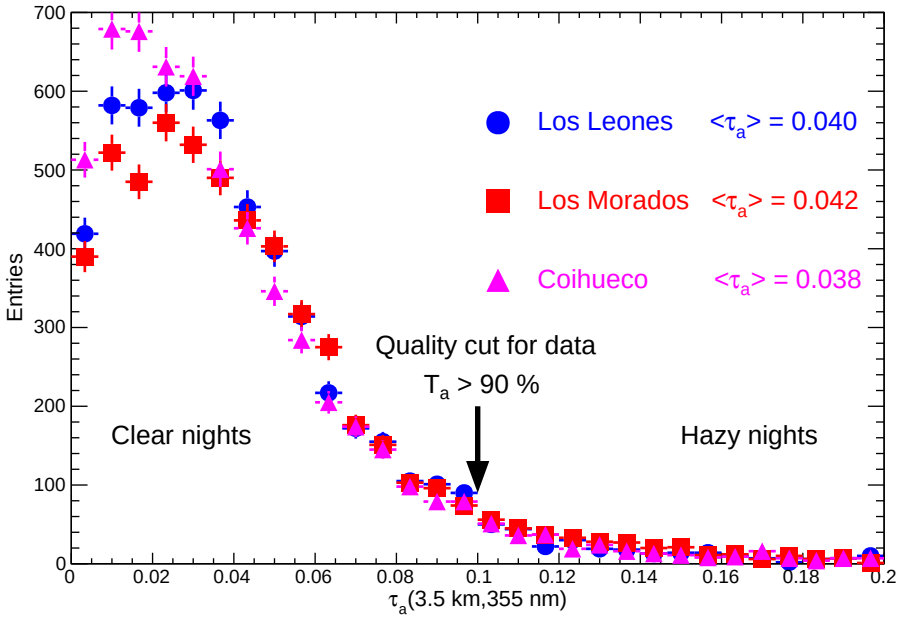
Aerosol optical depth $\tau_a(h, \lambda_0)$ – Aerosol attenuation

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

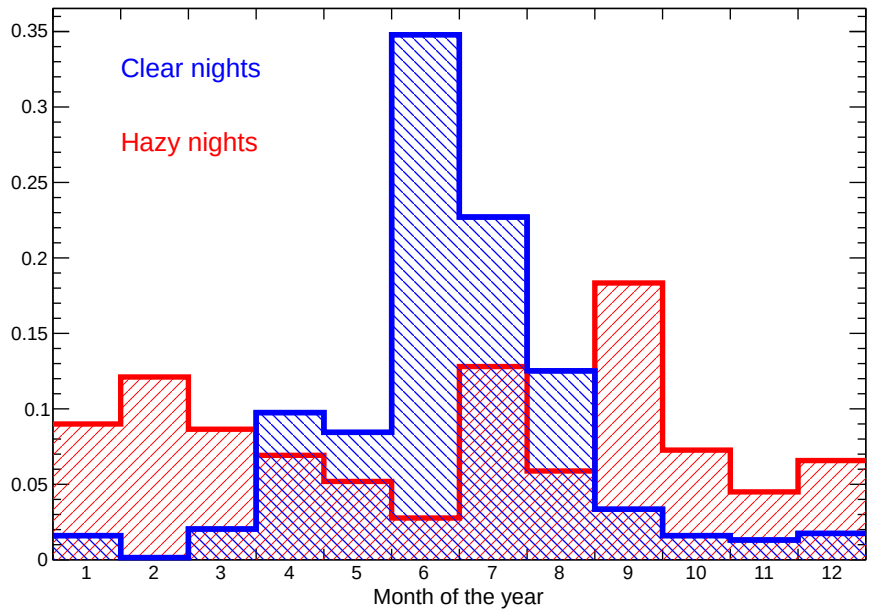
The Pierre Auger Collaboration, in press (JINST)

Aerosol optical depth measurements @ Auger

Aerosol optical depth at 3.5 km



Distribution in time of the Aerosol optical depth values



Let's divide the sample in three populations

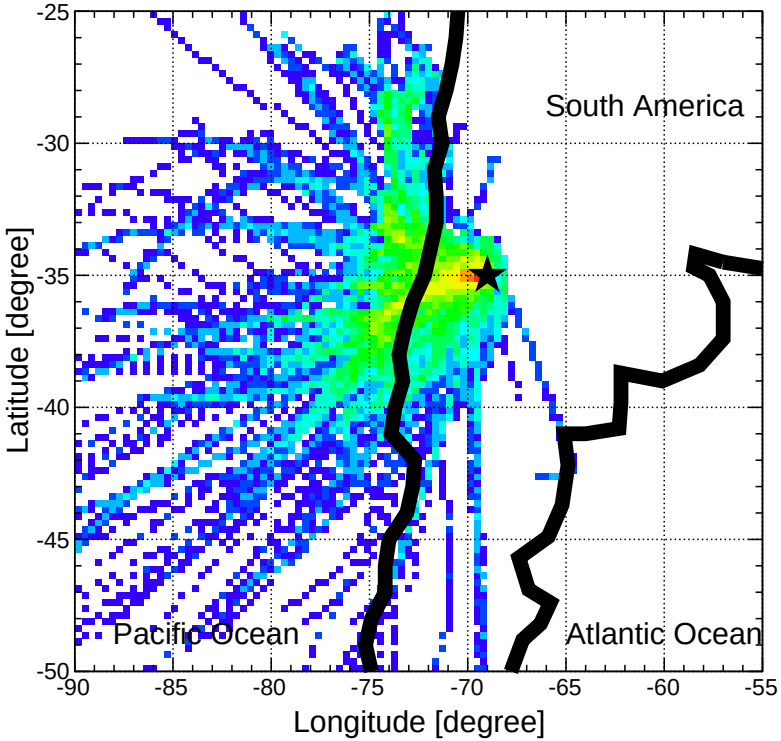
- **the clear nights** $\rightarrow$ the lowest aerosol concentrations: $\tau_a \leq 0.01$
- **the hazy nights** $\rightarrow$ the highest aerosol concentrations: $\tau_a \geq 0.10$
- the rest of the nights.

clear nights are more frequent during the Austral winter

Aerosol trajectories for clear/hazy nights @ Auger

Clear nights

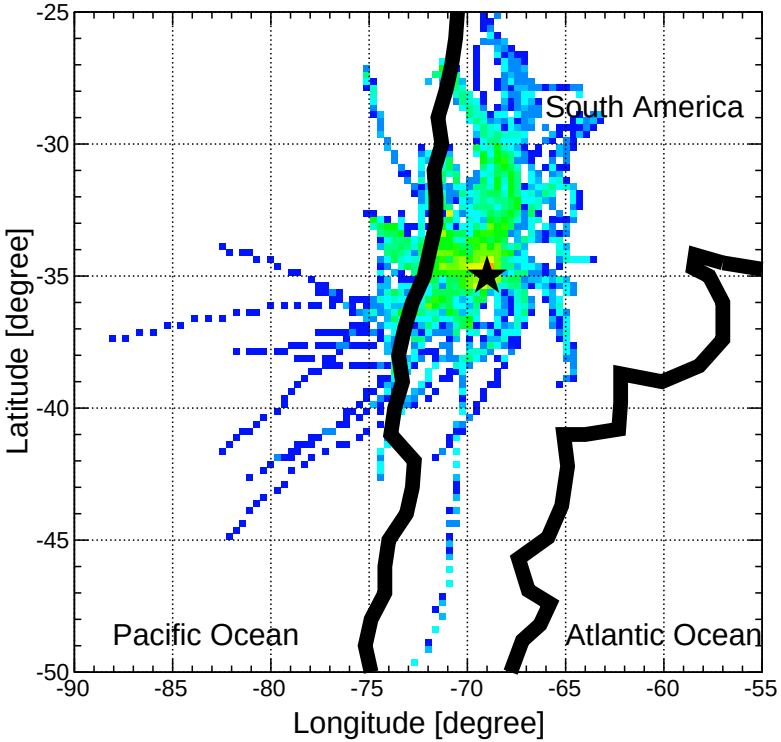
Distribution of trajectories: $0.00 \leq \tau_a(3.5\ \text{km}) \leq 0.01$



⇒ travel through the Pacific Ocean

Hazy nights

Distribution of trajectories: $0.10 \leq \tau_a(3.5\ \text{km}) \leq 0.30$



⇒ travel through continental areas

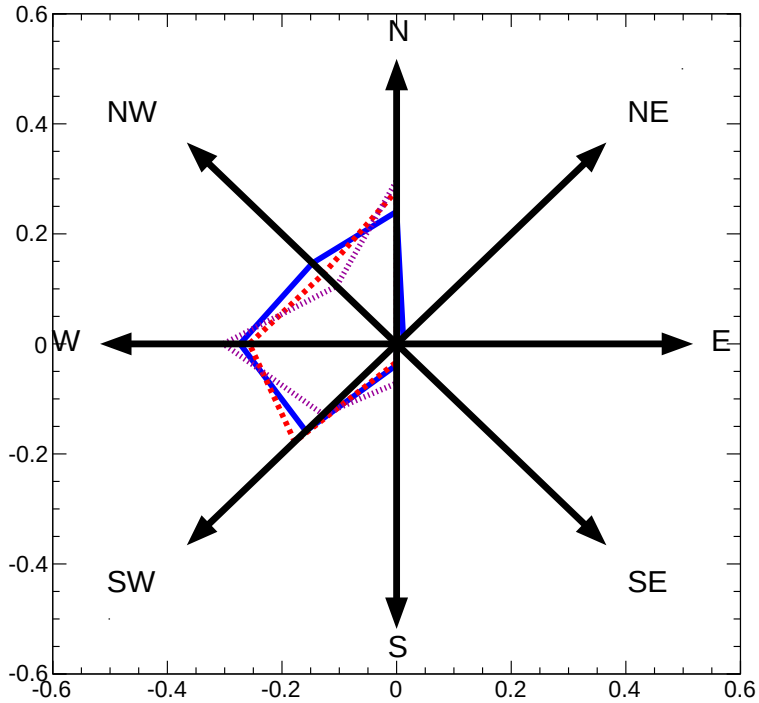
clear nights associated to air masses having traveled mainly above Pacific Ocean

K. Louedec, for the Pierre Auger Coll., 23rd ECRS, Moscow (2012)

Aerosol origins for clear/hazy nights @ Auger

Clear nights

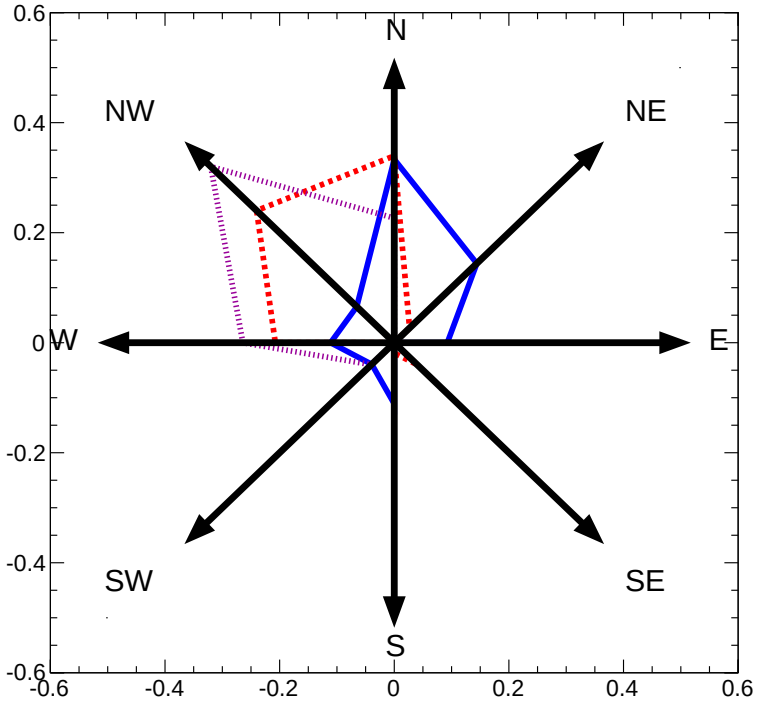
Air mass path directions: $0.00 \leq \tau_a(3.5\ \mathrm{km}) \leq 0.01$



⇒ very good agreement

Hazy nights

Air mass path directions: $0.10 \leq \tau_a(3.5\ \mathrm{km}) \leq 0.30$



⇒ North to North-West

500m AGL — 1000m AGL — 3000m AGL

Interdisciplinary sciences at the Pierre Auger Observatory

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*

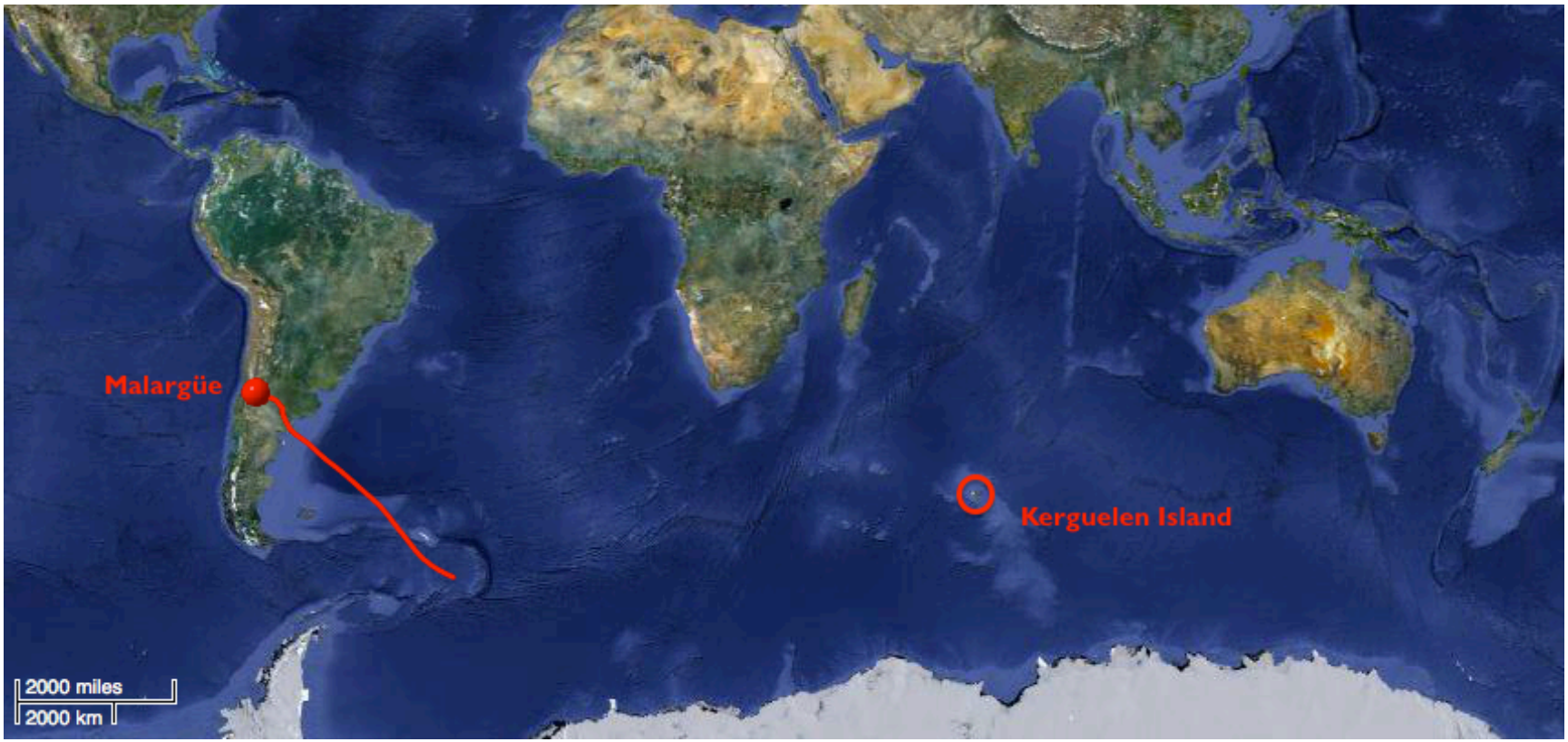
Promote the exchange between the two communities to better **understand** the current measurements and better **design** the next detectors

Example: modelling of the evolution of aerosols in South America

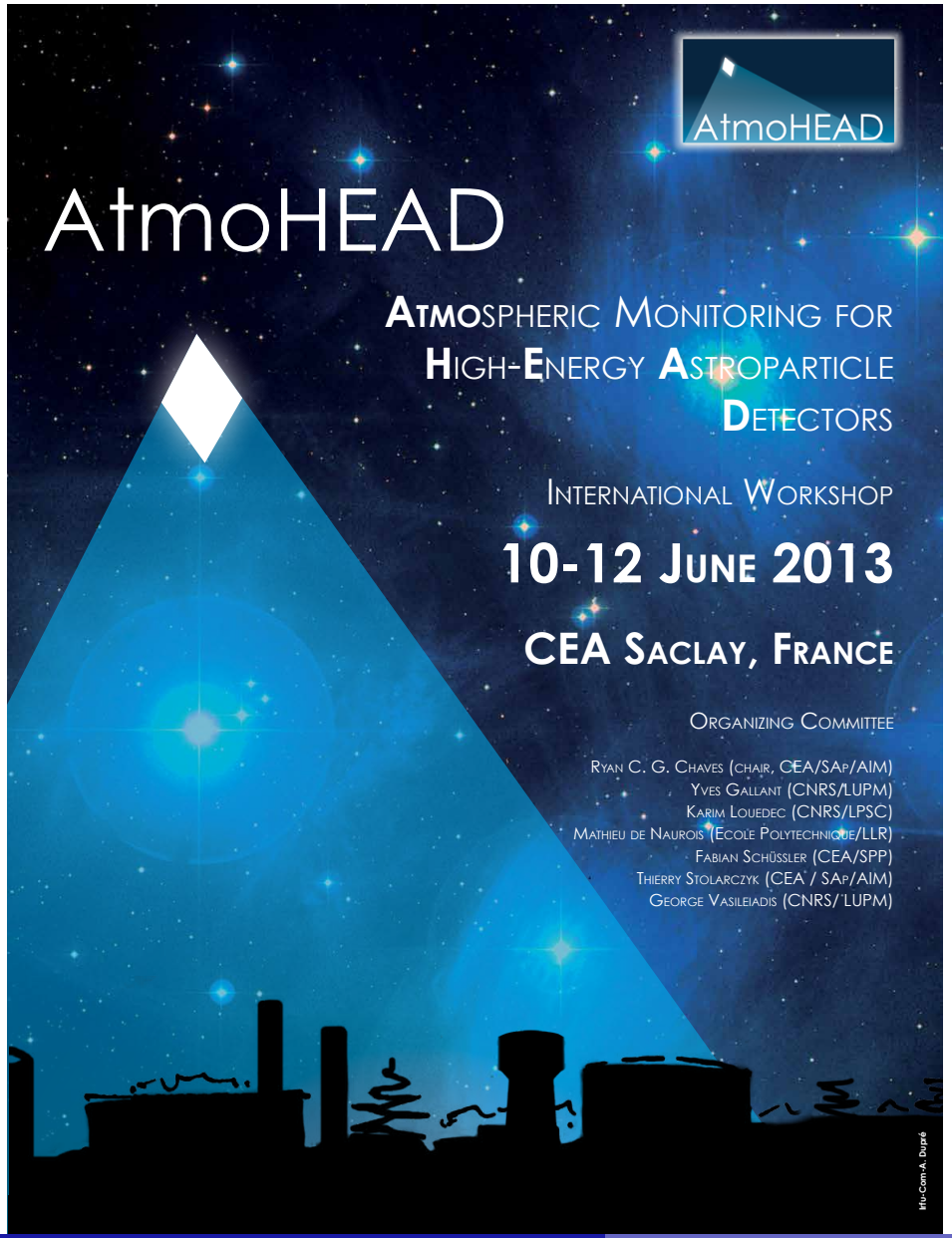
- Austral region from 40° to 65° South is one of the major CO_2 sink,
- trace metals (aerosols) $\rightarrow$ growth of phytoplankton $\rightarrow$ trap CO_2,

$\rightarrow$ characterize chemical properties of aerosols (dust) in Argentina.

collaboration with one french atmospheric lab from INSU (LISA, Créteil)



The AtmoHEAD workshop: soon @ CEA Saclay...



International workshop about atmospheric monitoring in astroparticle experiments

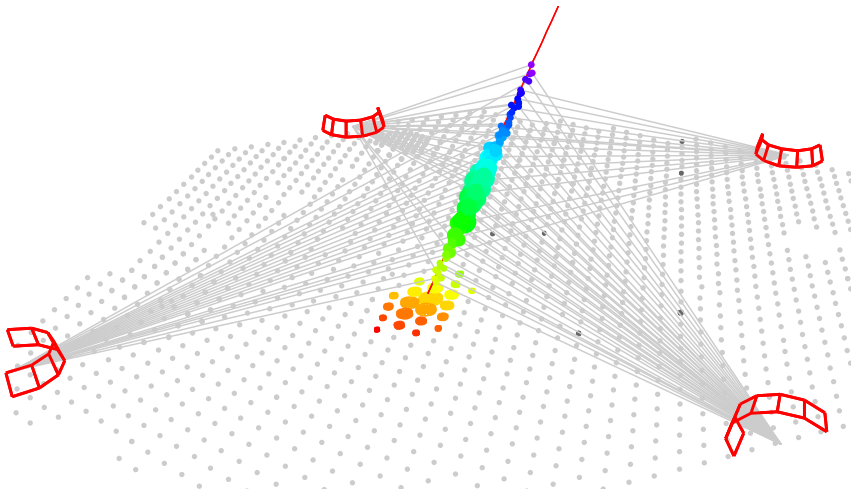
→ opened to all experiments in astroparticle physics,

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

→ public announcement very soon...

Outline

FD → maximum of the shower longitudinal profile

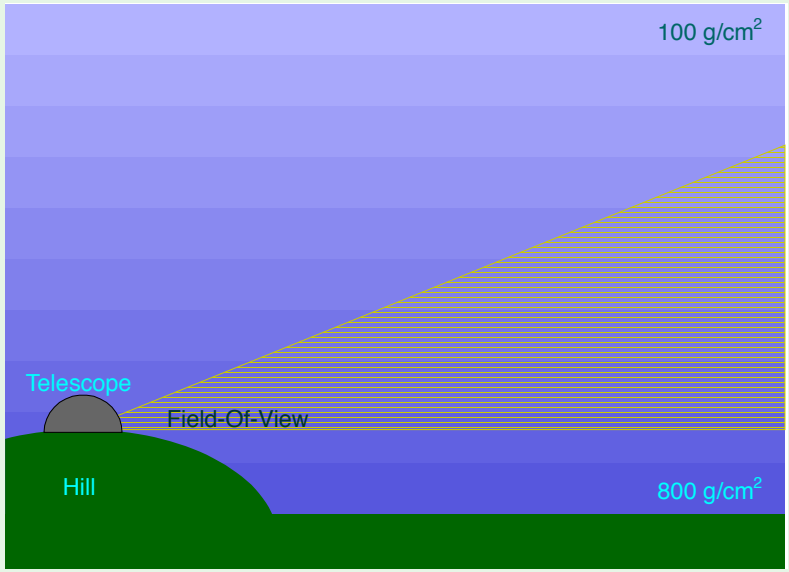


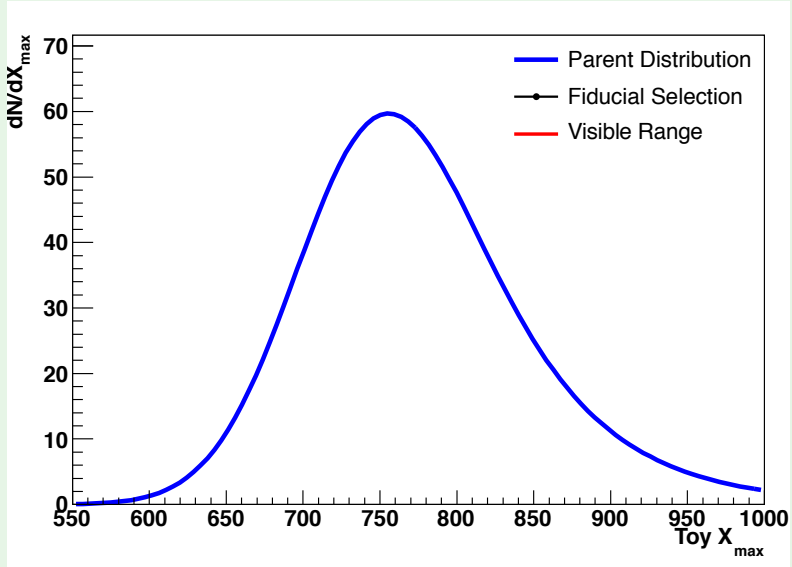
→ longitudinal development: $X_{max} \propto \log A$

X_{max} measurement strategies

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

Illustration of acceptance bias





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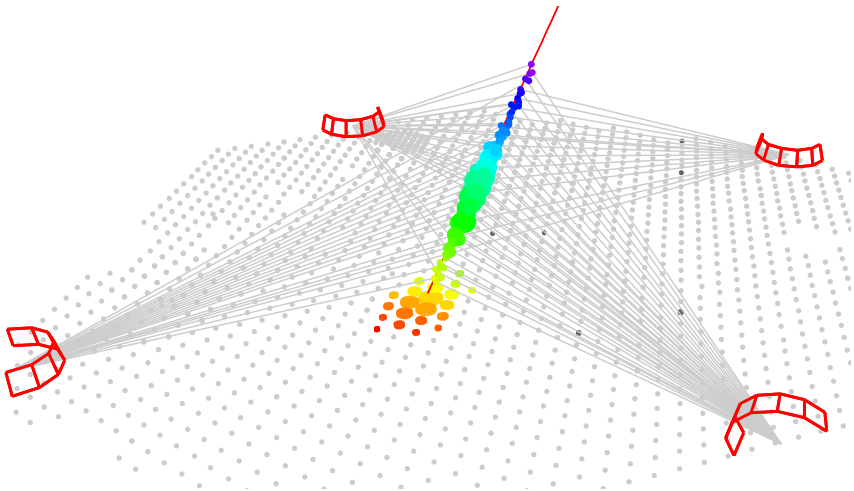

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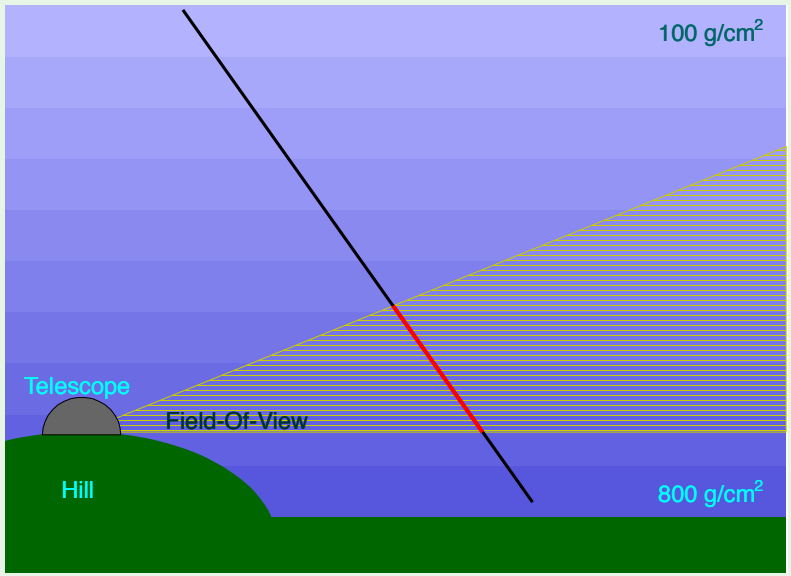

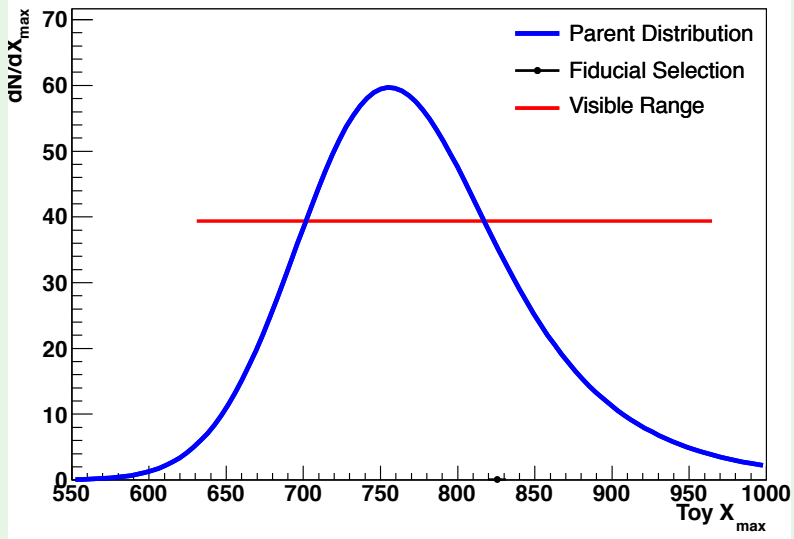

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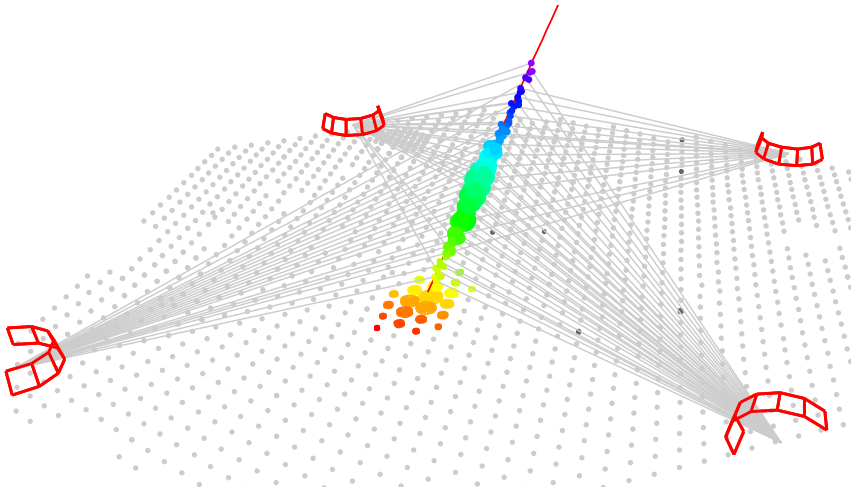

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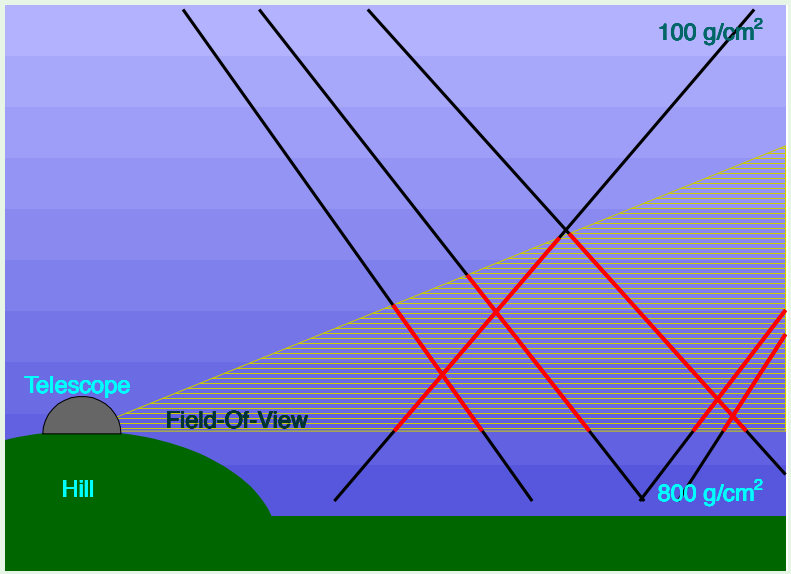

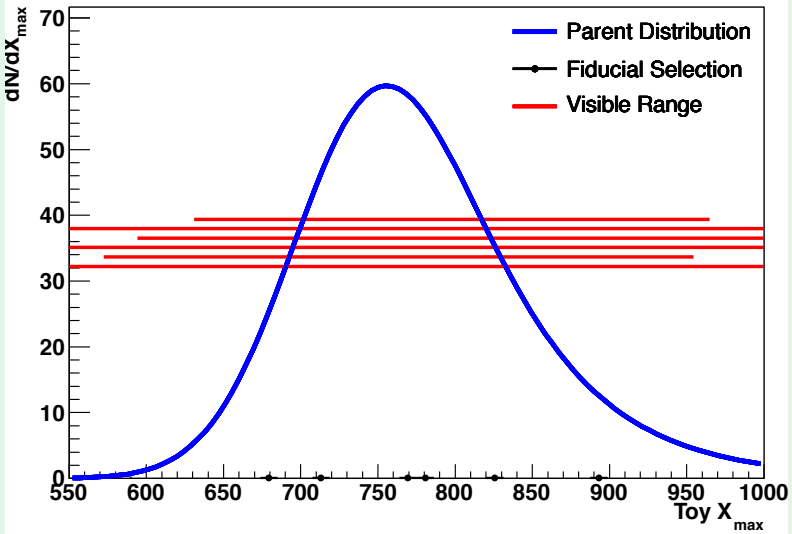

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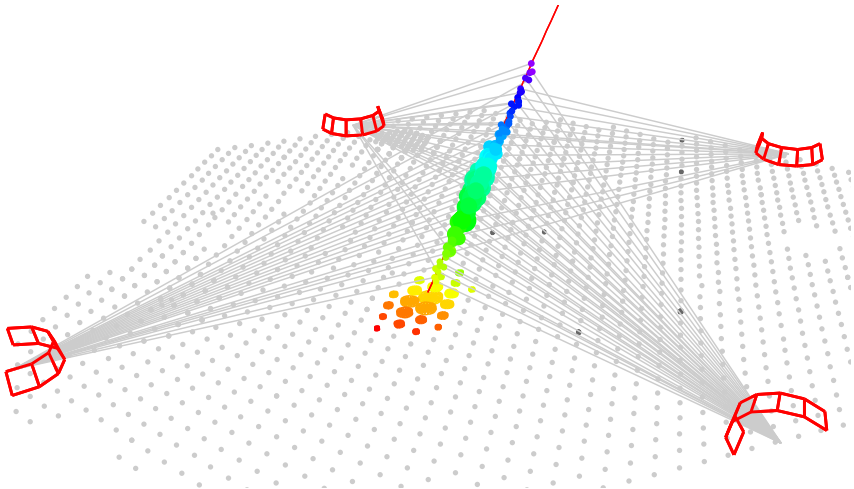

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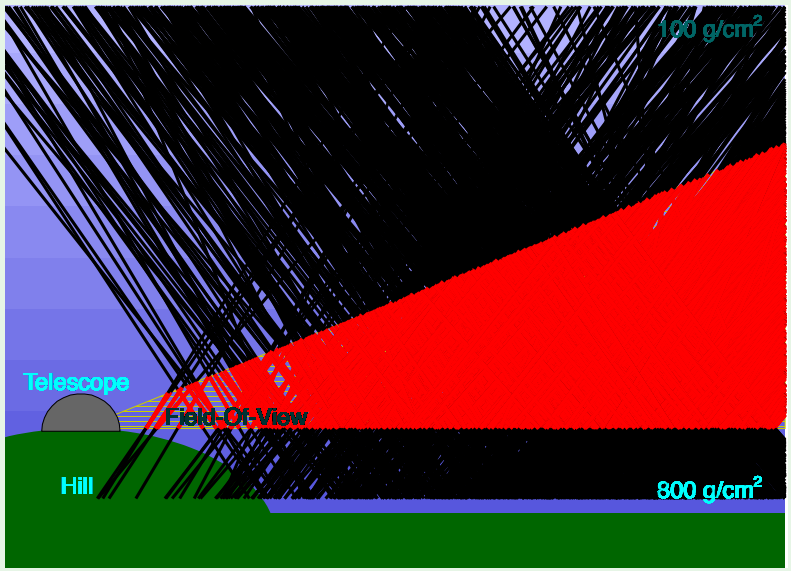

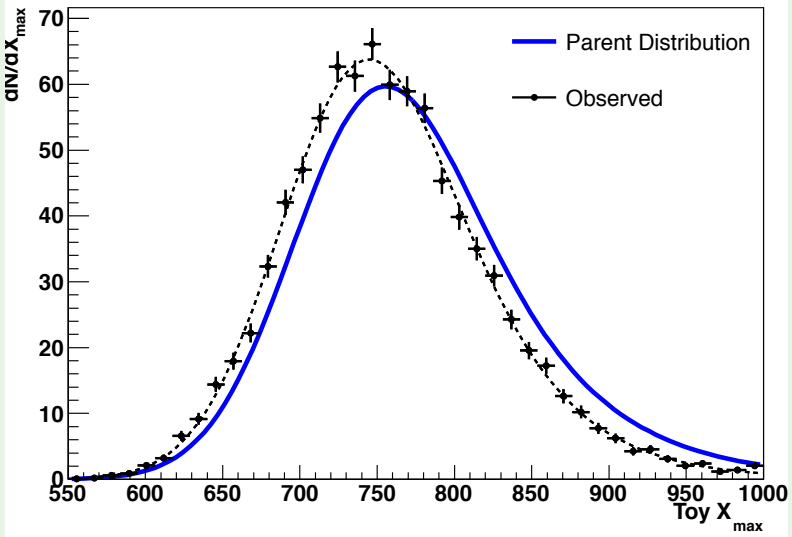

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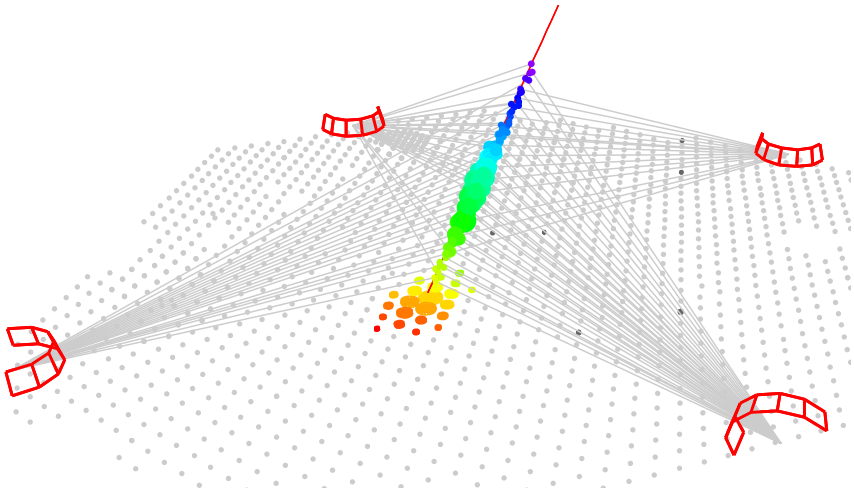

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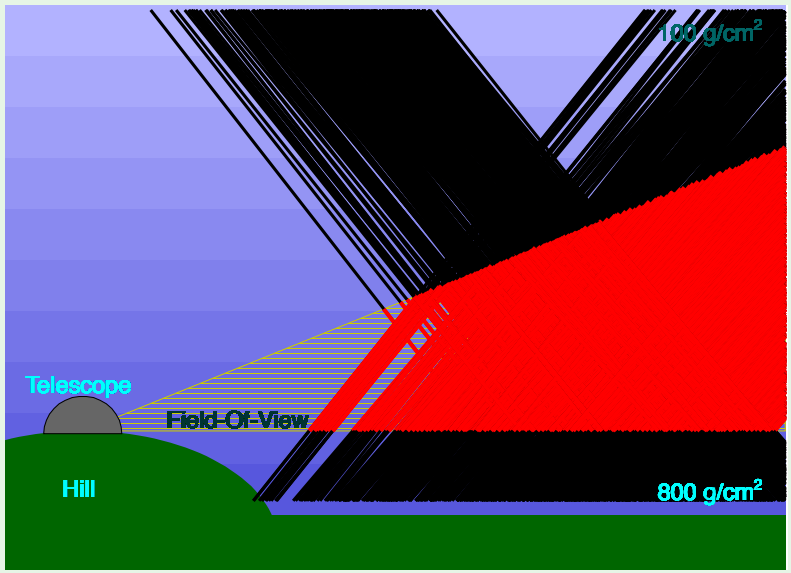

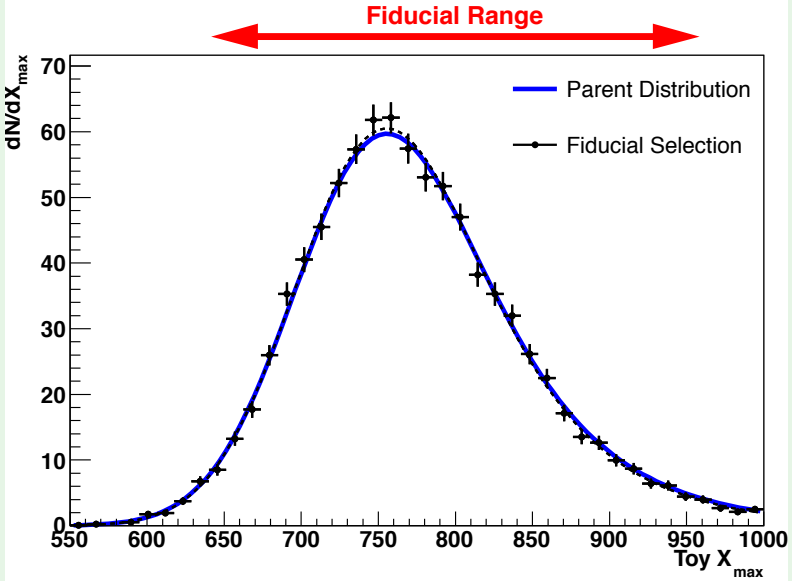

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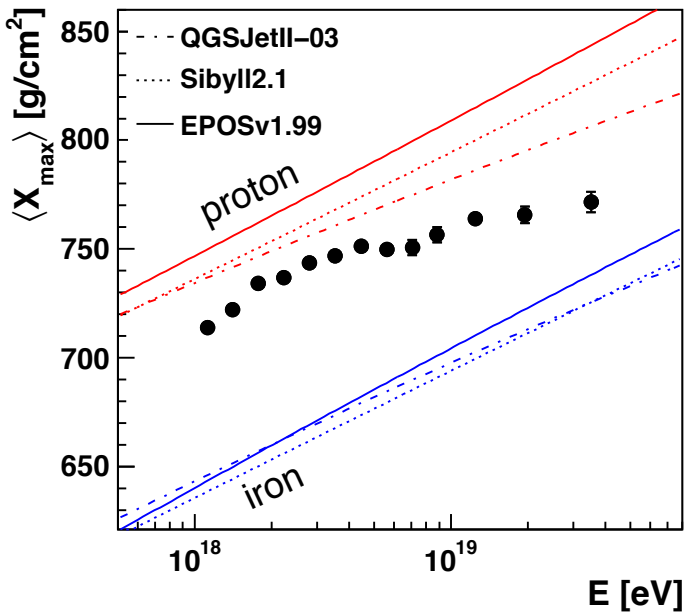
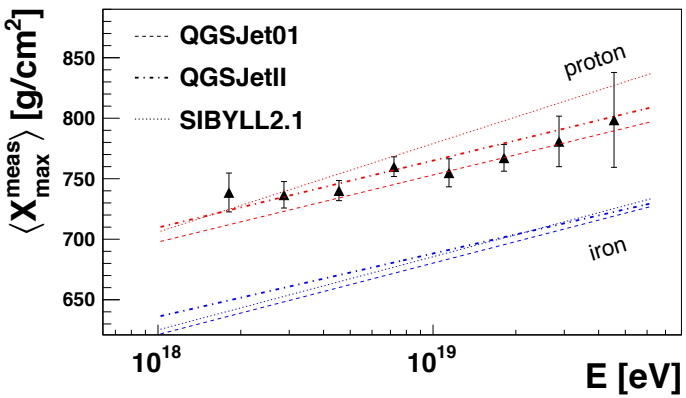


Telescope Array



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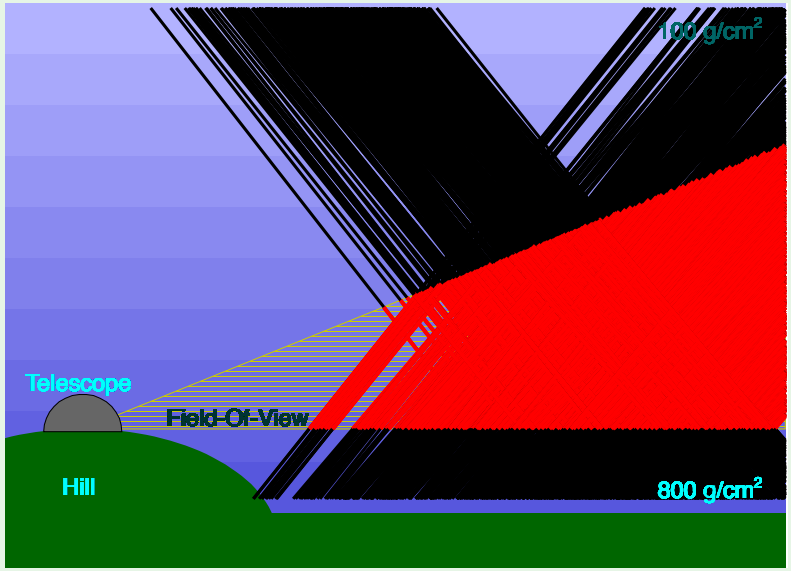
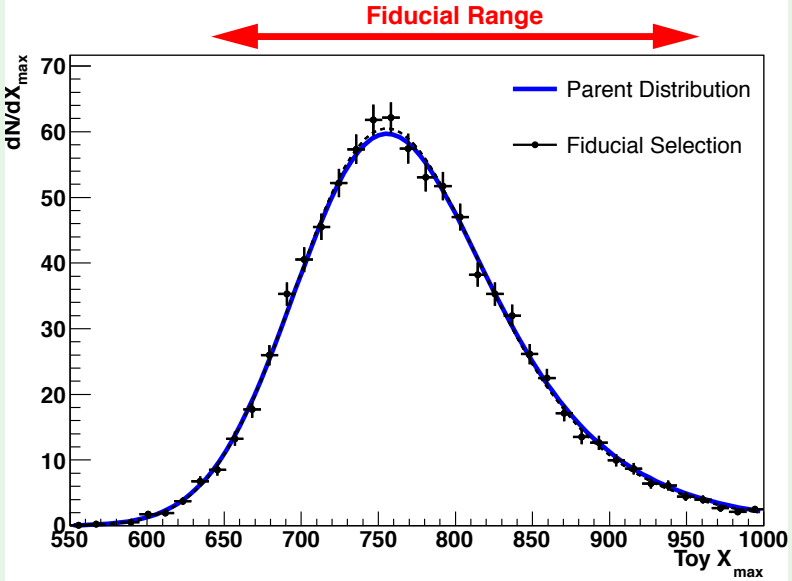
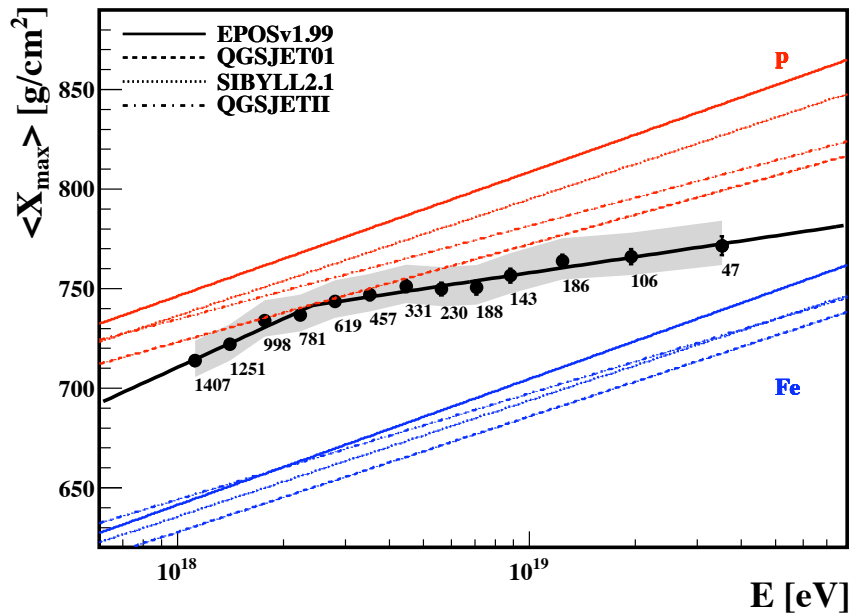
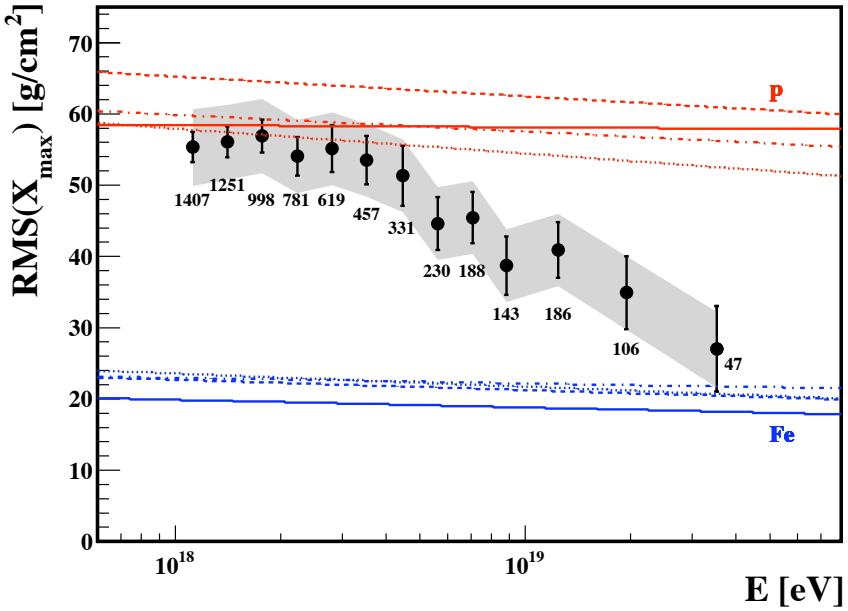
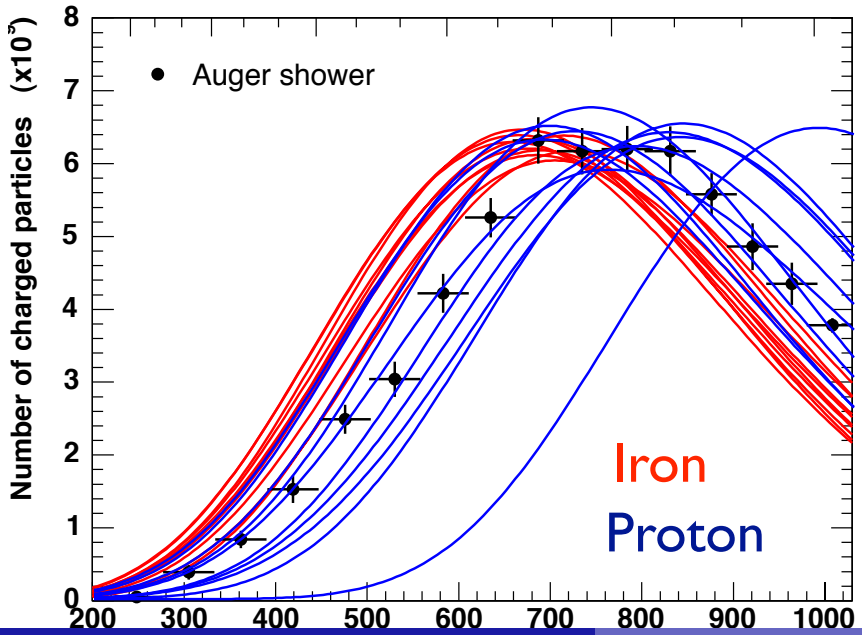




FD → maximum of the shower longitudinal profile @ Auger





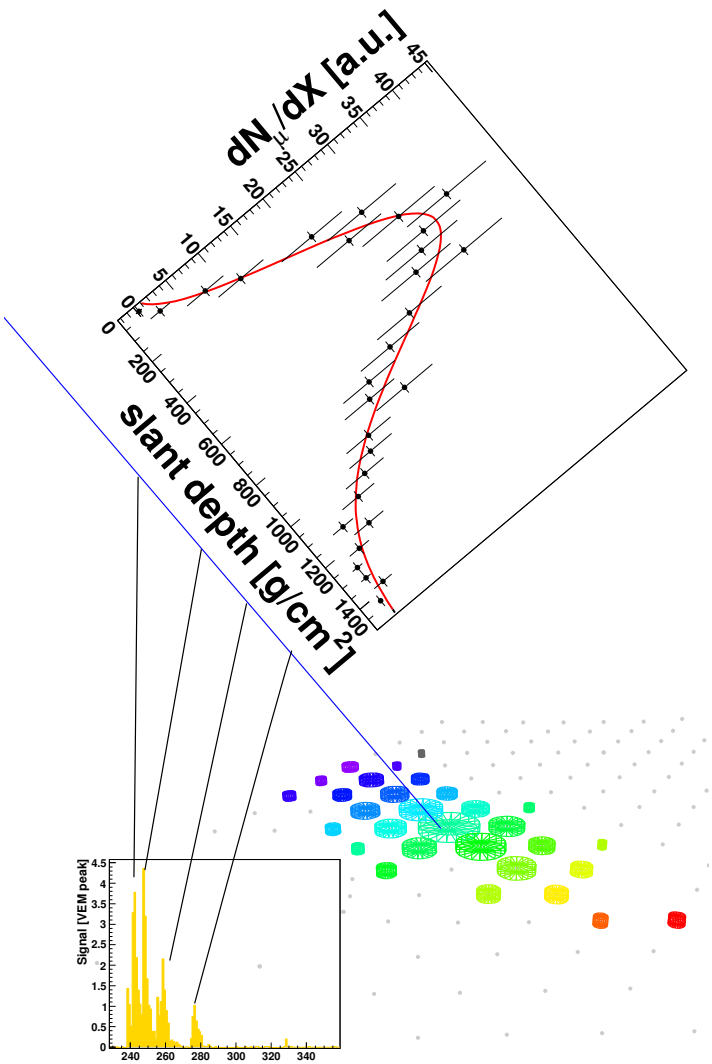


→ only hybrid data (13% of the whole Auger data set),

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

P Facal, for the Pierre Auger Coll., 32nd ICRC, Beijing (2011)

SD → muon production depth @ Auger

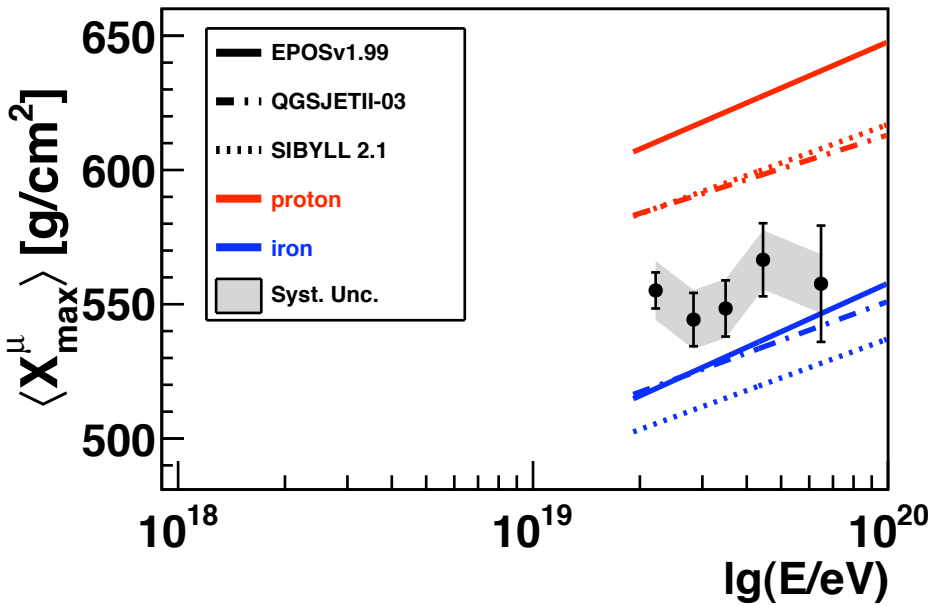


→ selection of muon-rich stations only,

→ projection of signal time traces to axis,

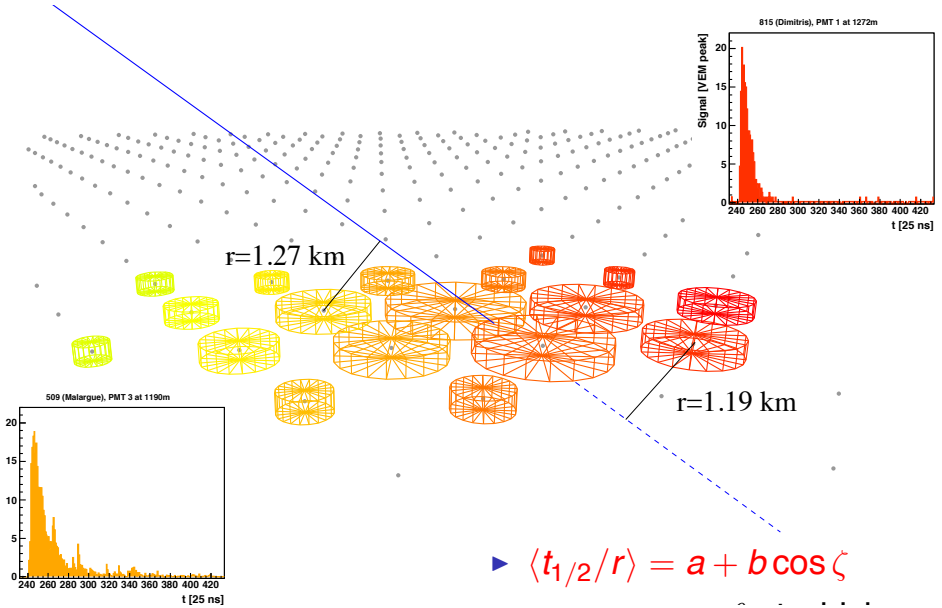
→ sum up stations, and fit with Gaisser-Hillas,

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

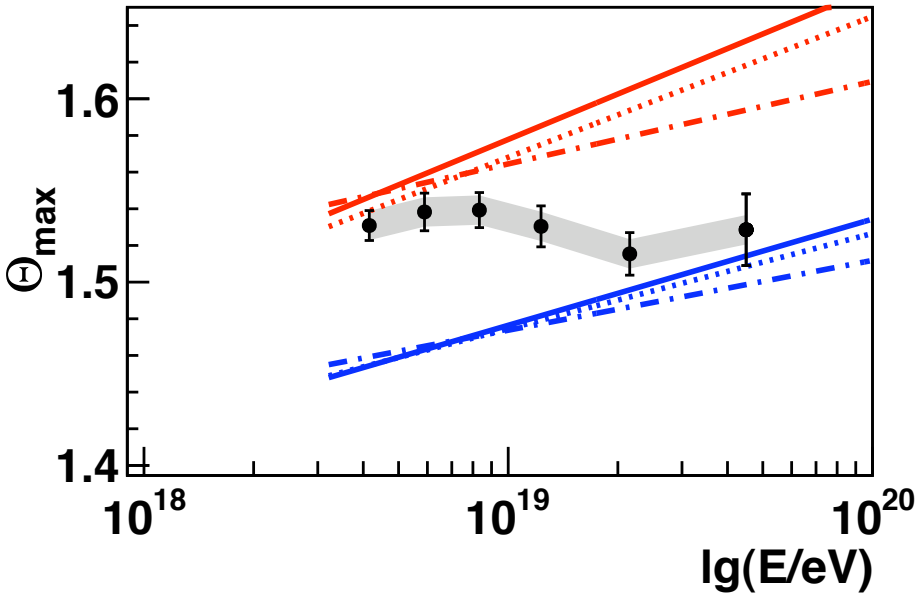


D Garcia-Gamez, for the Pierre Auger Coll., 32nd ICRC, Beijing

SD → rise time asymmetry @ Auger



- $\langle t_{1/2}/r \rangle = a + b \cos\zeta$

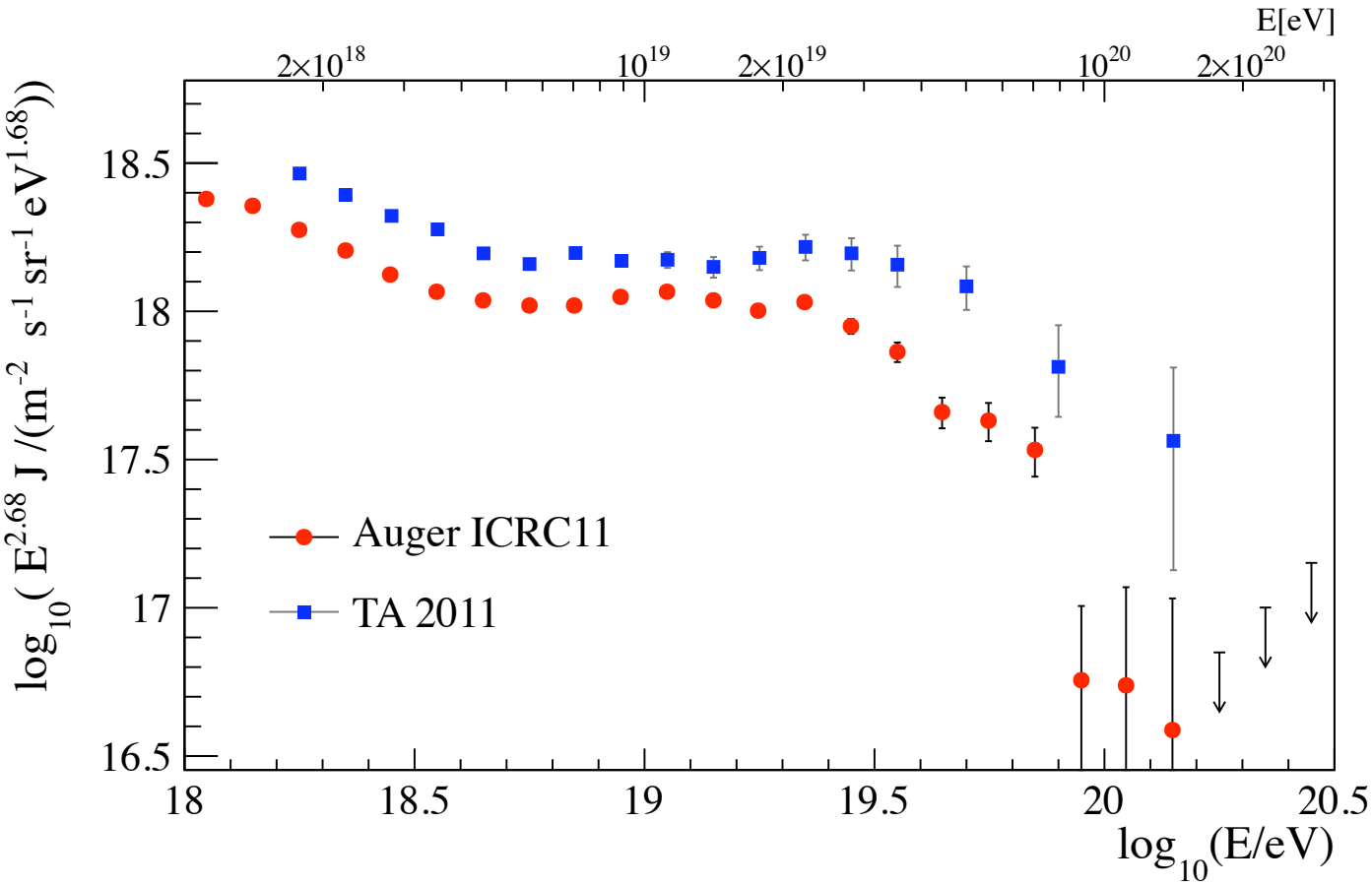


→ estimation of the longitudinal air shower development by SD,

→ statistics could be much higher than for fluorescence measurements !

D Garcia-Pinto, for the Pierre Auger Coll., 32nd ICRC, Beijing

Energy spectrum – spectral features



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

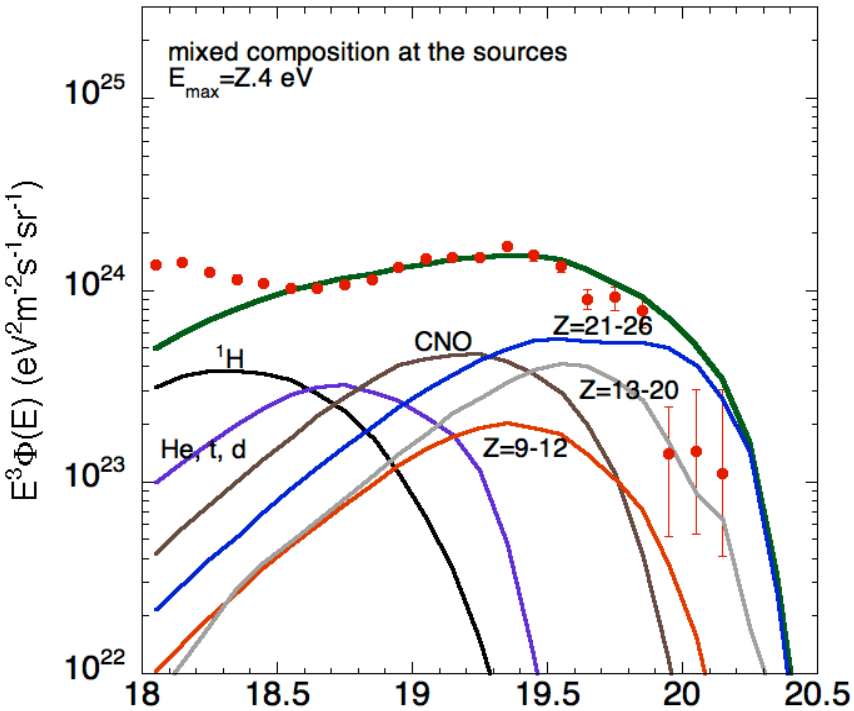
→ high energy flux drops at different energies,

→ $\simeq 20\%$ energy rescaling needed to provide overlap.

+ keep in mind the 10% coming from the new fluorescence yield value.

Energy spectrum – possible astrophysics scenarios

Upper end of source energy spectrum ?



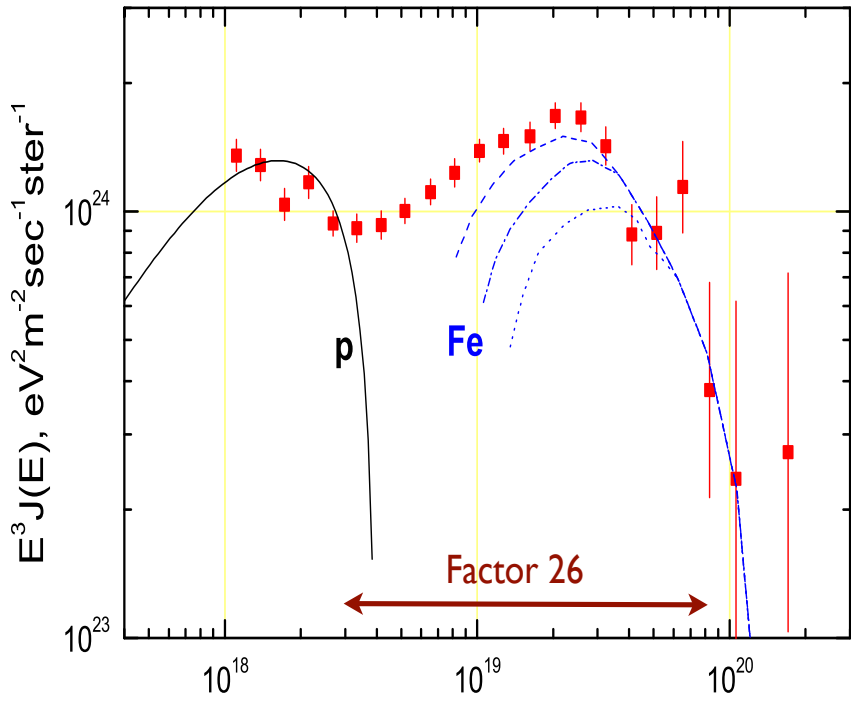
→ mixed composition similar to galactic,

→ $E_{\max} = Z \times 4 \times 10^{18}$ 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.)*

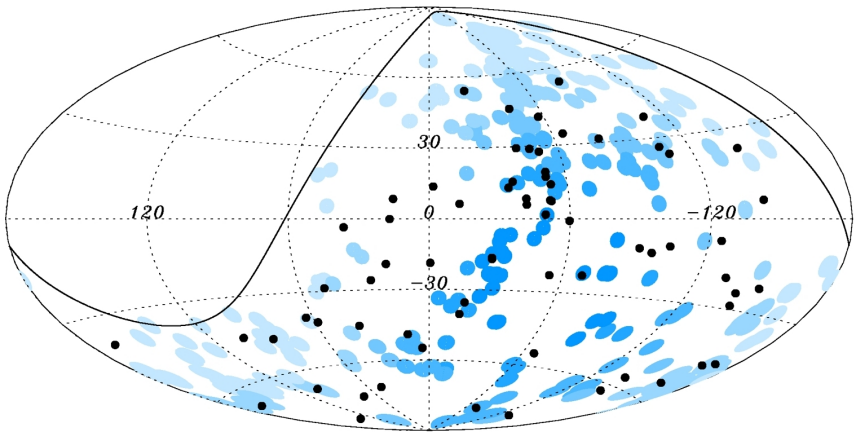
Anisotropy – arrival directions of highest energy events

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

→ AGNs trace the nearby extragalactic matter,

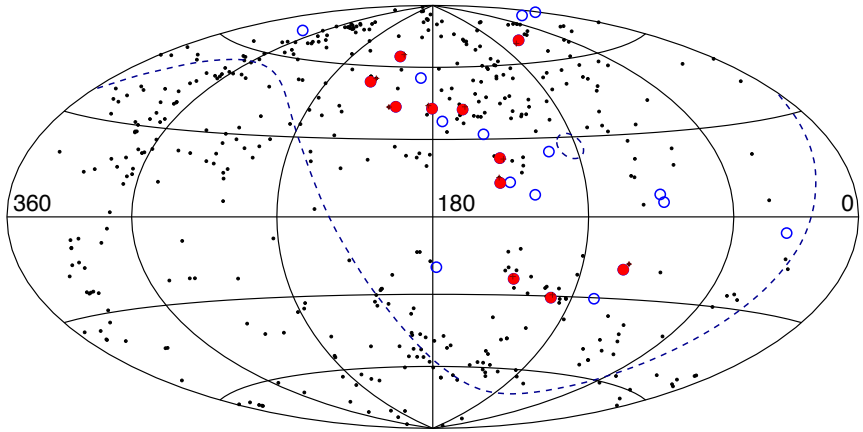
→ scan over a three dimensional parameter space: $E \geq 57$ EeV, $z \leq 0.018$, $\psi \leq 3.1^\circ$

Pierre Auger Observatory



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*

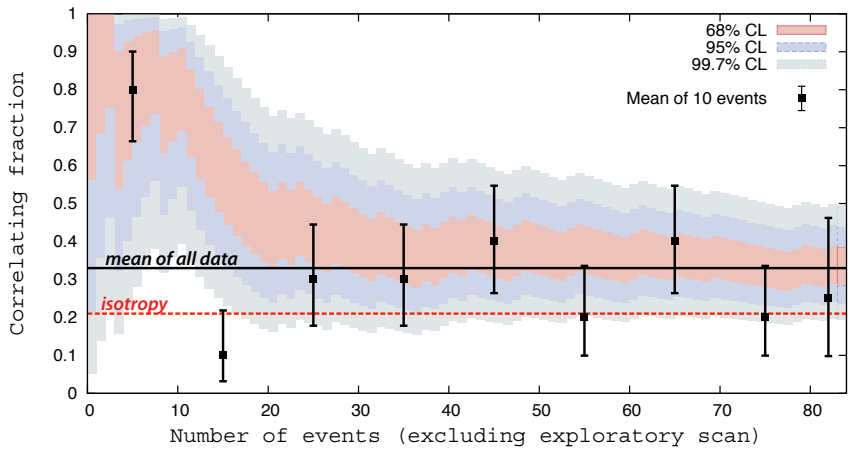
Anisotropy – arrival directions of highest energy events

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

→ AGNs trace the nearby extragalactic matter,

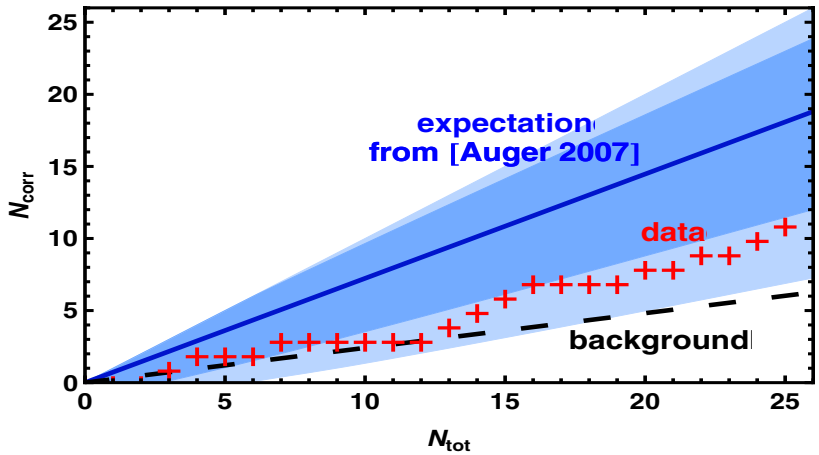
→ scan over a three dimensional parameter space: $E \geq 57$ EeV, $z \leq 0.018$, $\psi \leq 3.1^\circ$

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.

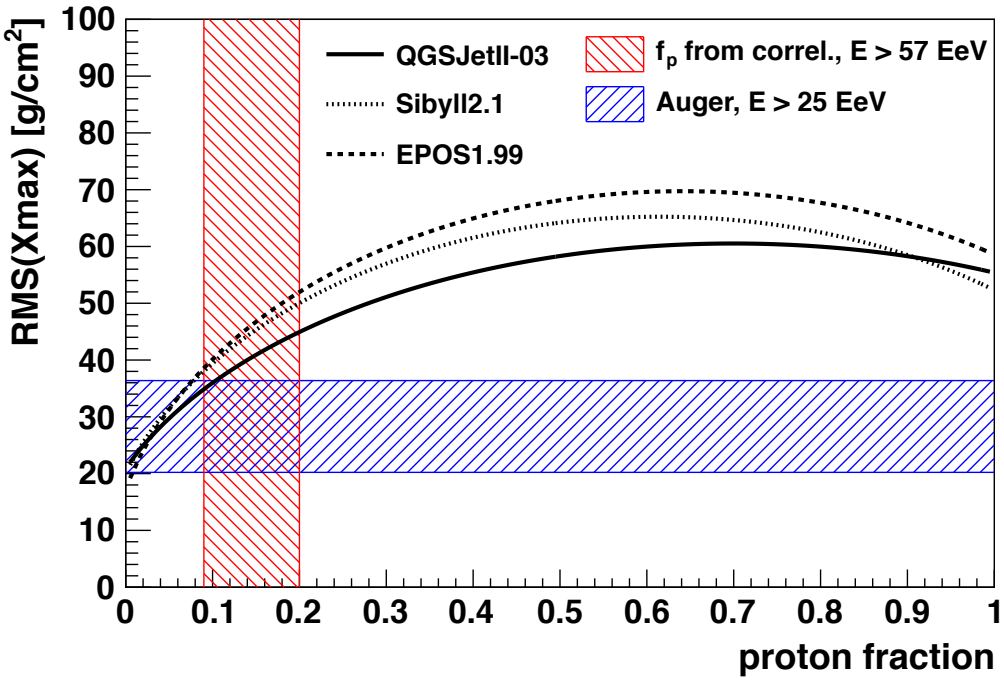
The Pierre Auger Collaboration, Astropart. Phys. **34** *(2010) 314–326*

Anisotropy – proton astronomy at highest energies ?

→ *simplistic interpretation of correlation and composiiton*,

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

→ no intermediate nuclei are considered – too small mean free paths,



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

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

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

M Unger, CTA link 2012

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

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 ?

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

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

improve cosmic ray composition measurement seems to be the key

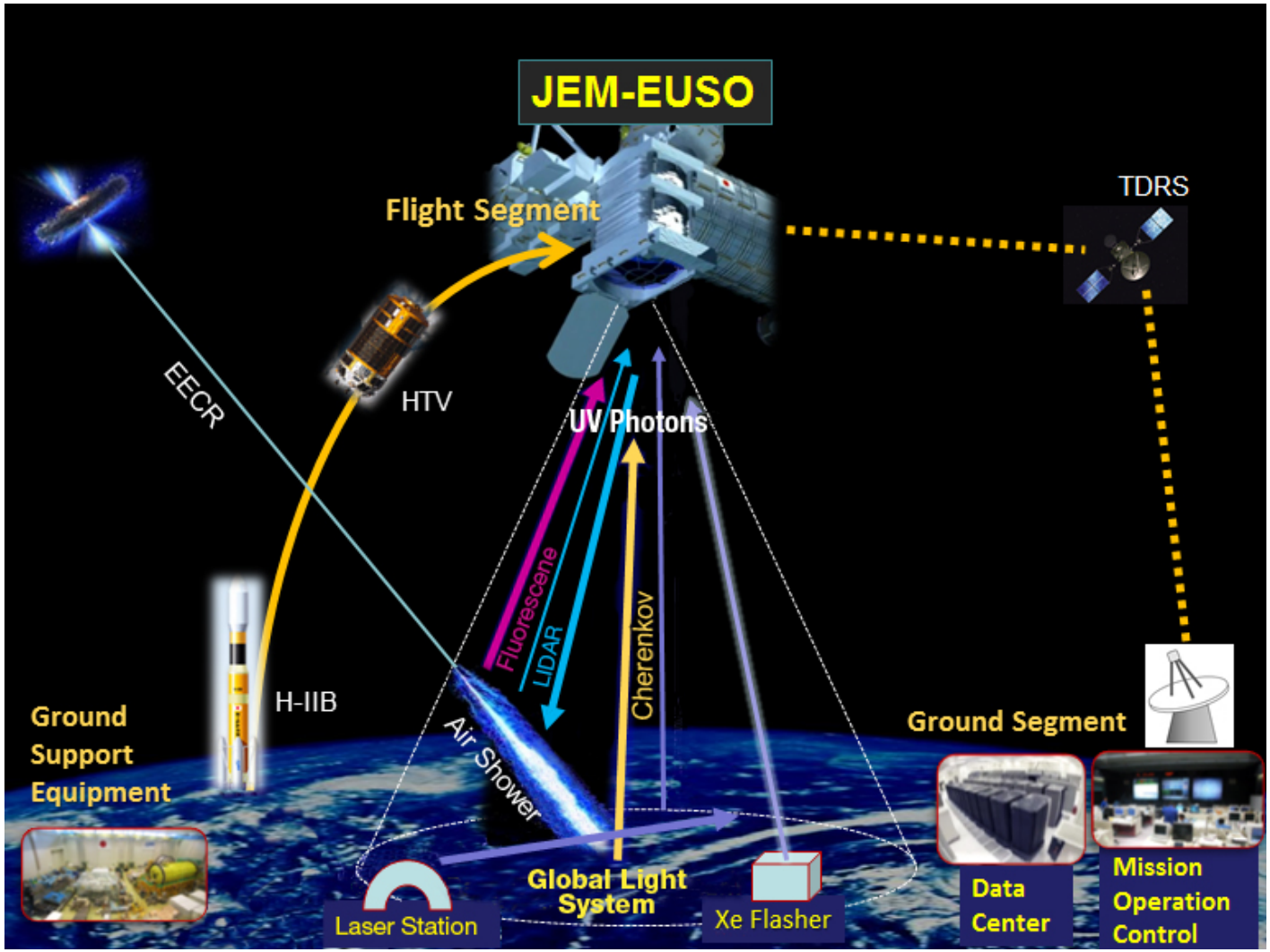
- composition at low energies – 10^{17} to a few 10^{18} eV
  → search cutoff of proton spectrum,
  → investigate the muon deficit in Monte Carlo simulations,
  → improve sensitivity to photons from GZK effect,
  → fluorescence telescopes and surface detectors for lower energies

- 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

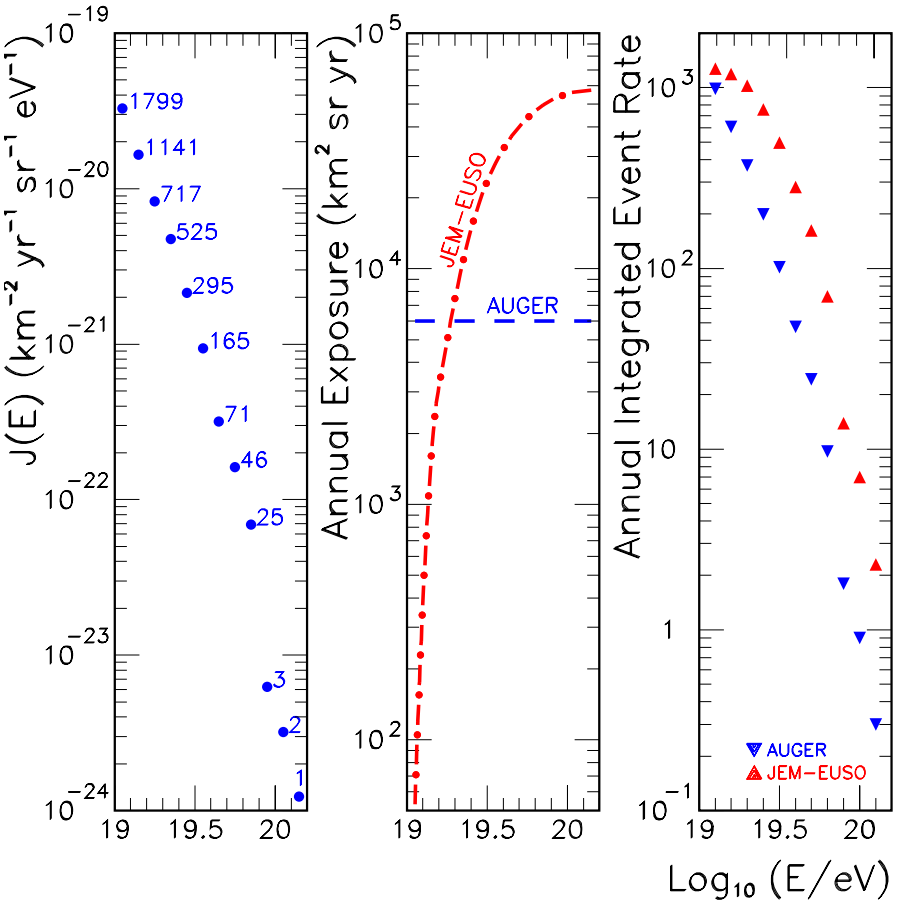
The JEM-EUSO telescope – a new era (on the ISS)

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

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

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

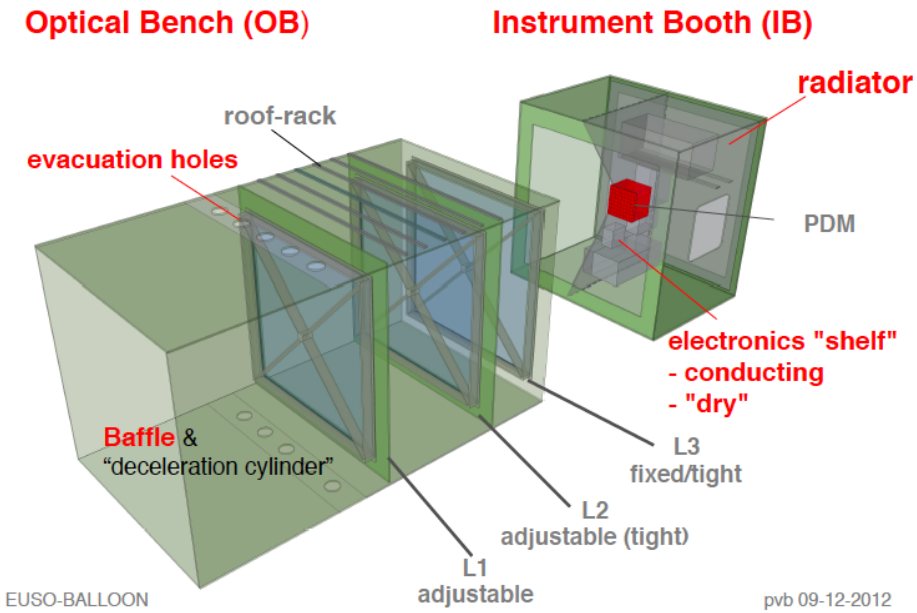
$\rightarrow$ angular resolution better than 2.5°,

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

at higher energies, the GZK horizon is reduced $\rightarrow$ 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 !