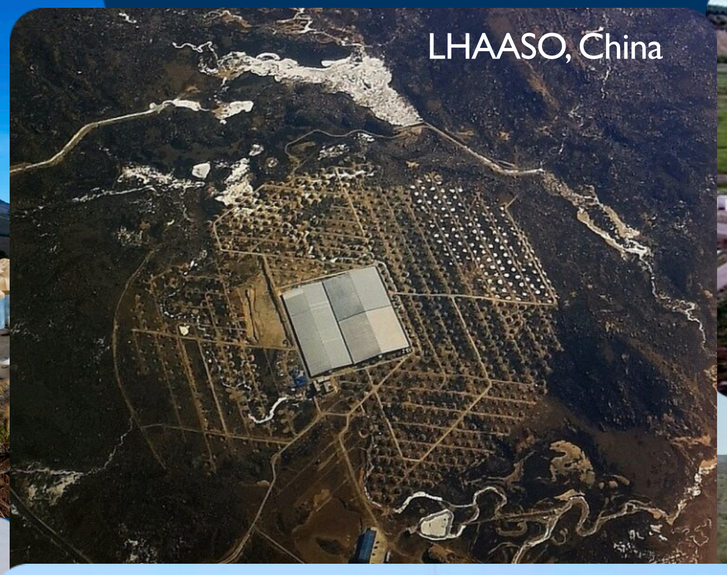
High-energy cosmic rays detection: extensive-air-shower (EAS) technique

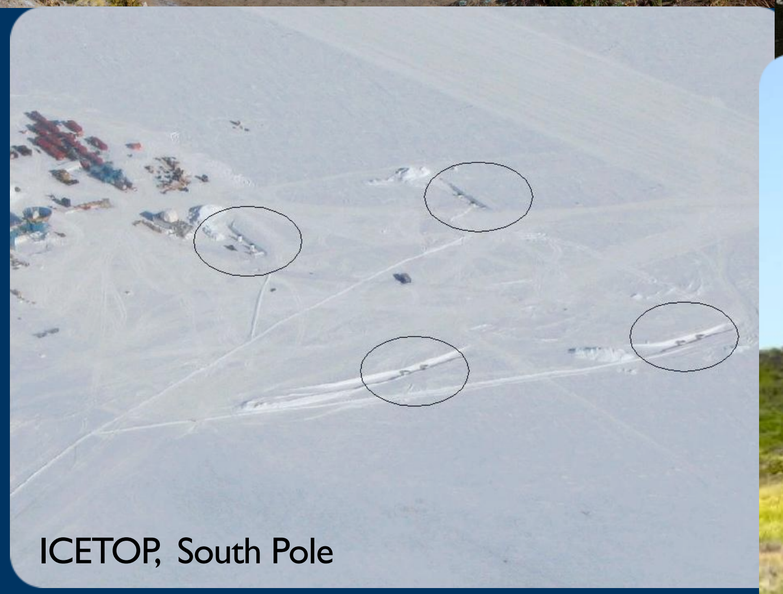
Piera L. Ghia (CNRS, IJCLab, Orsay)

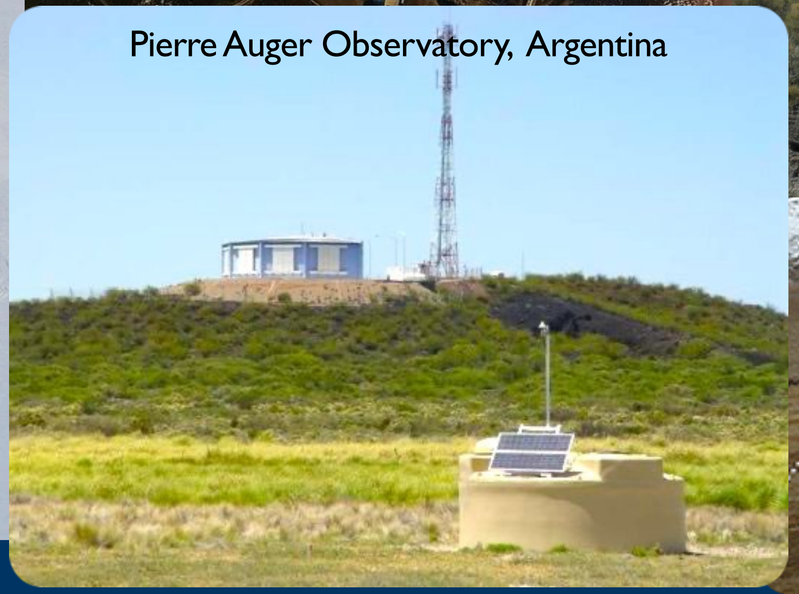


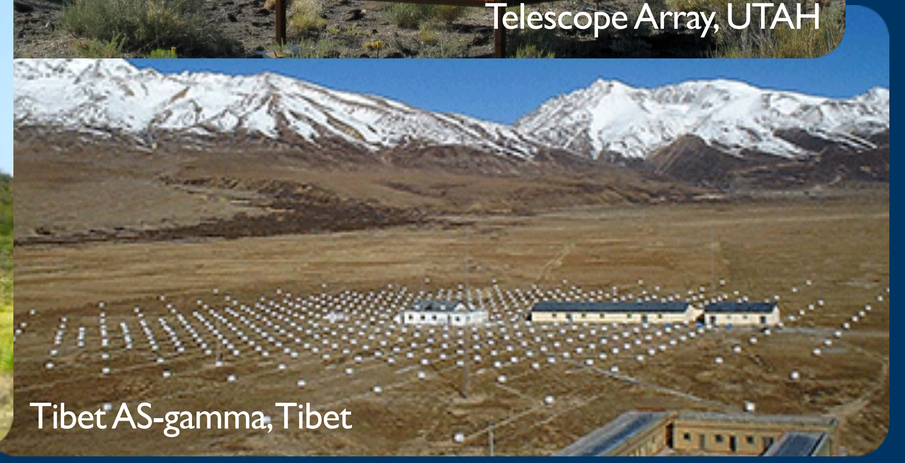












High-energy cosmic rays detection: extensive-air-shower (EAS) technique

``The subject of cosmic rays is unique in modern physics for
the minuteness of the phenomena
the delicacy of the observations
the adventurous excursions of the observers
the subtlety of the analysis
the grandeur of the inferences”

(from Bruno Rossi, “Cosmic Rays”, foreword)

High-energy cosmic rays detection: extensive-air-shower (EAS) technique

Outline (Part II)

PROLOGUE: why detecting Extensive Air Showers?

Extensive Air Shower detection: an historical perspective
(The minuteness of the phenomena -
The adventurous excursions of the observers)

Modern Extensive Air Shower detectors
(The minuteness of the phenomena -
The adventurous excursions of the observers)

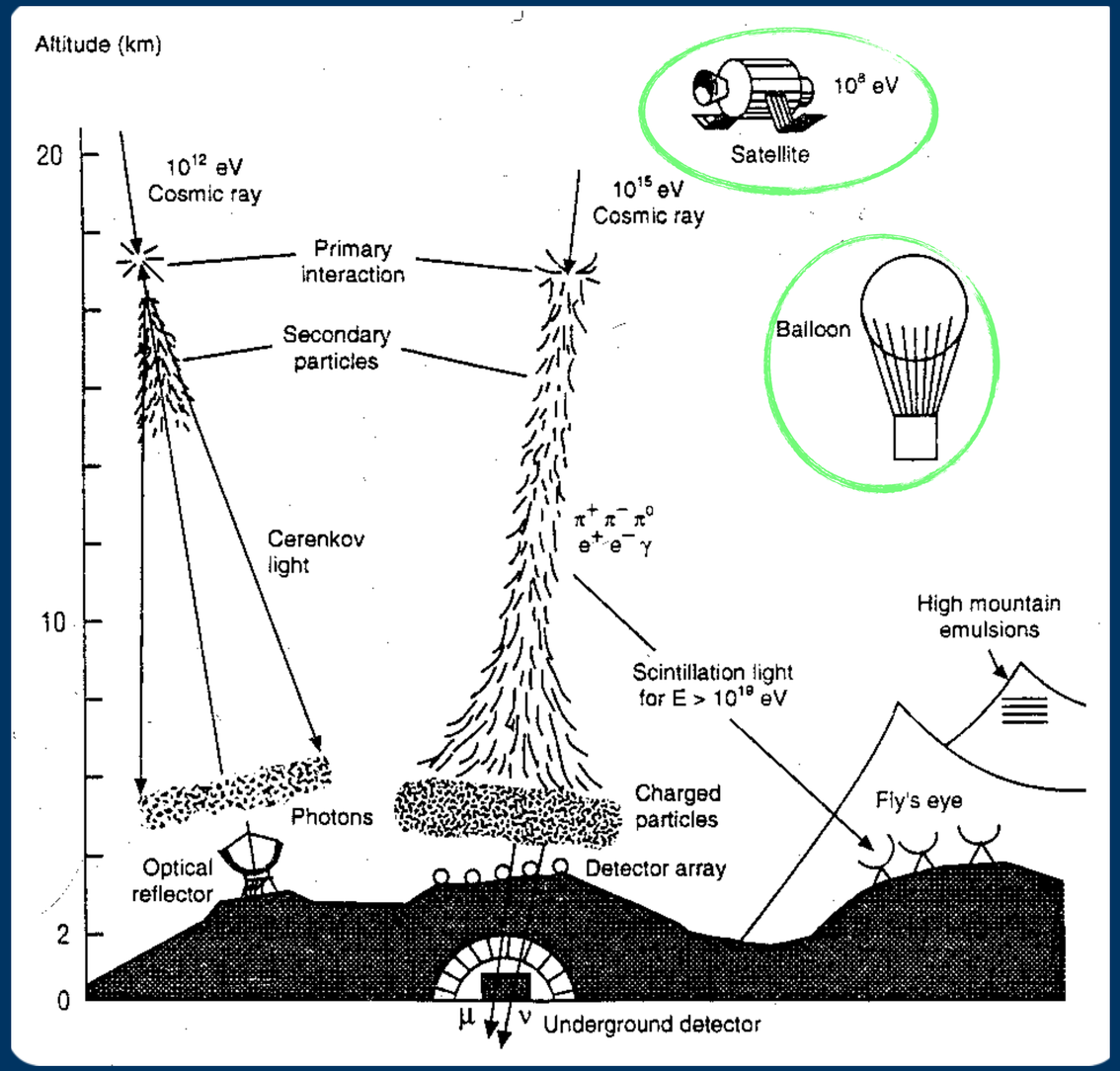
EAS observables: two exemplary instruments
(The delicacy of the observations)

From EAS observables to cosmic rays properties
(The subtlety of the analysis)

Short recap

Recap: cosmic ray flux (rate) vs detection

Different detection approaches depending on CR flux and energy



Low-energy CRs: rather high flux ($1/m^2/s$) but absorbed in the upper atmosphere.

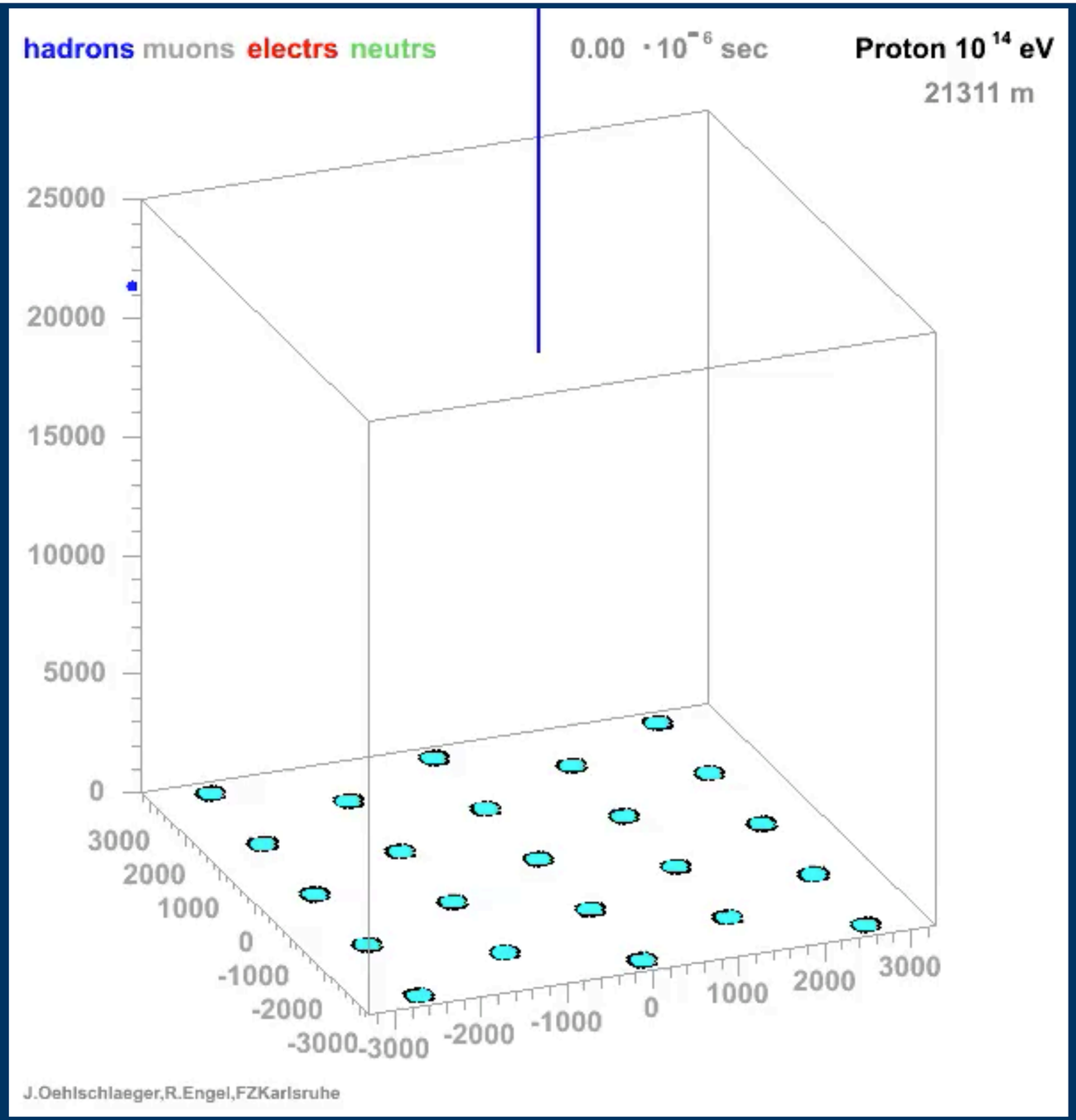
Direct detection (top of the atmosphere or in space): balloons, rockets, satellites

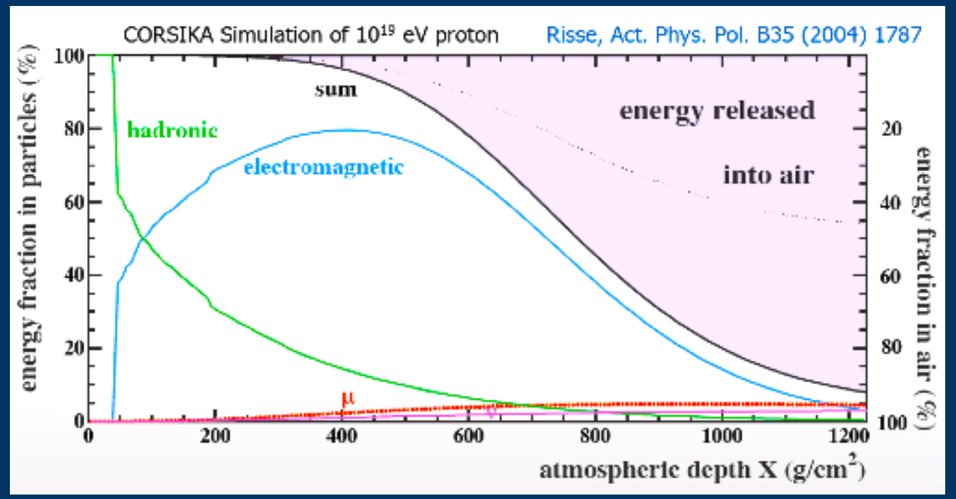
High energy CRs: rarer ($< 1/m^2/y$), but "penetrating" down to Earth via the creation of extensive air showers

Indirect detection (long-lived ground-level instruments): large telescopes, particle-detector arrays

NB. The distinction between low- and high-energy physics has evolved over time. Currently, long-duration experiments in space can reach up to 10^6 GeV, whilst telescopes or particle-detector arrays can reach as low as 10^4 GeV

Recap: relevance of extensive air showers (EAS)





90% of the primary energy of the cosmic ray is dissipated in the atmosphere via the creation of secondary cosmic rays while the shower develops around the **hadronic core**

The **electromagnetic component** is the most abundant, the **muonic** one the most penetrating

EAS particles radiate, in optical (Cherenkov and fluorescence light) or radio

Recap: characteristics of an extensive air shower

A (non) typical shower of 10^{19} eV:



Contains about 10^{10} particles at maximum development

Consists mostly of electromagnetic particles, with ≈ 10% muons. Hadronic particles are a very small fraction

Has the **maximum at few km (≈ 3-4) above sea level**

Has a **footprint at ground that can extend up to over 15 km**

Has a **thickness that can be a few hundreds meters** (depending on the distance from the core)

Recap: old ideas into new detectors

Particle detectors







Radiation detectors









Recap: building EAS detectors according to CR energy

















At 10^{11}-10^{13} eV:

Small and less penetrating showers:

Go for very high altitude: small spacing between detectors is necessary but “small” areas are sufficient

At 10^{14}-10^{16} eV:

Shower maximum still high in the atmosphere: mountain altitude still needed, but not very high

<100 m detector-spacing OK

Rather low fluxes: large-ish areas needed (0.1 km^2)

At 10^{17}-10^{18} eV:

Shower maximum deeper in atmosphere: sea level enough

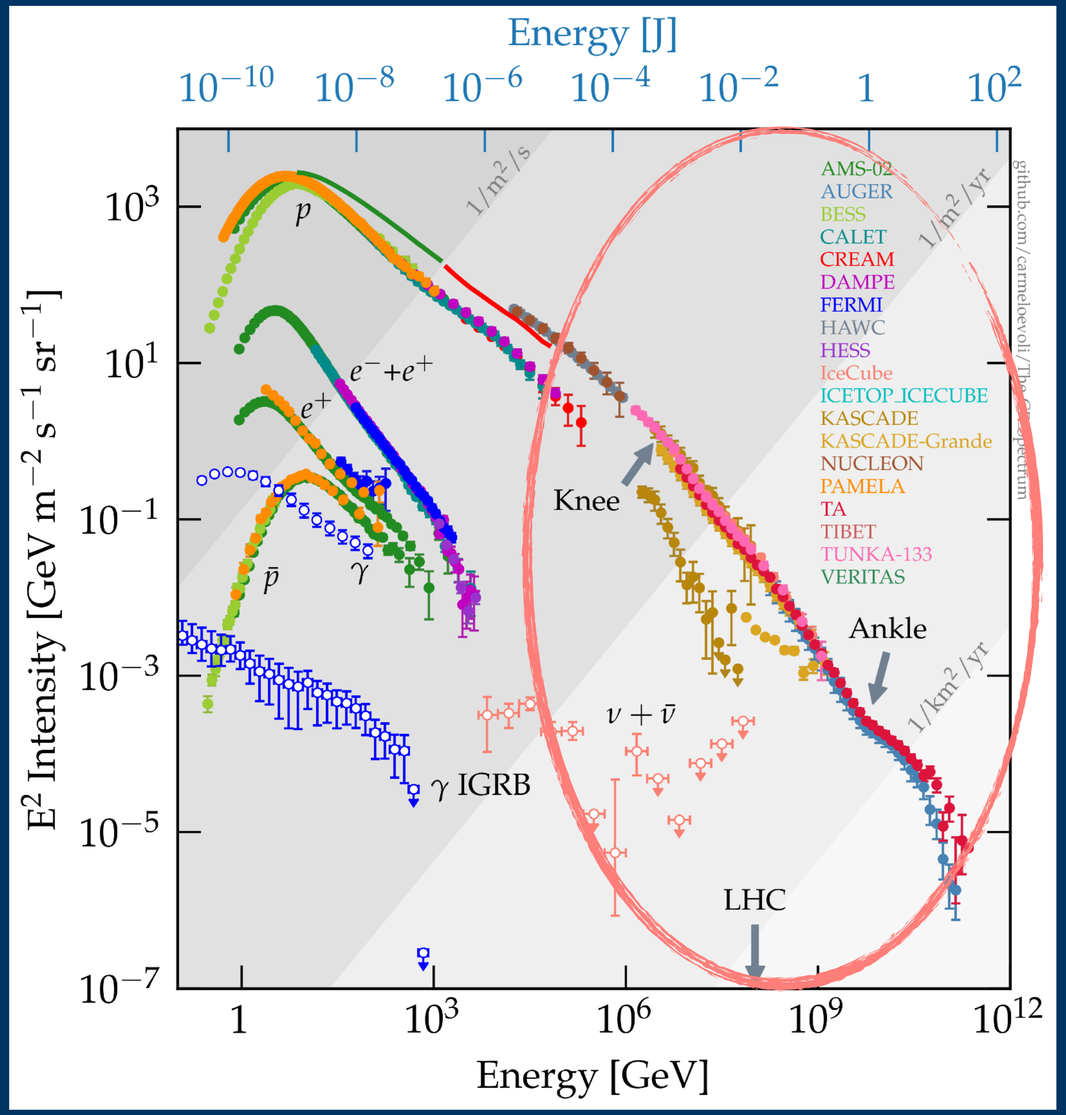
Low fluxes: areas ≈ 1 km^2 needed (spacing ≈ 150 m)

Above 10^{18} eV:

Extremely low fluxes: huge area needed (≈1000 km^2)

Giant showers: spacing ≈ 1000 m adequate

Recap: cosmic-ray energy spectra

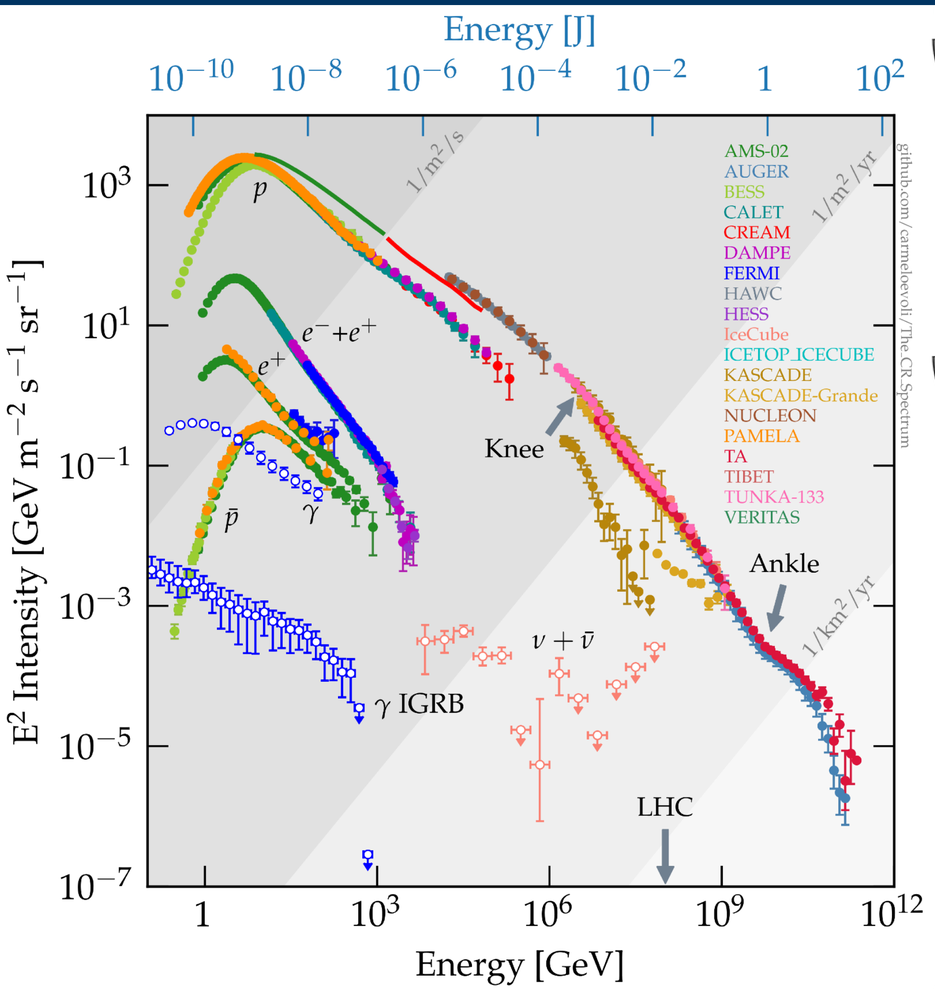


With **EAS detectors**, whether they are particle detector arrays or optical telescopes, the energy spectrum of cosmic rays is measured:

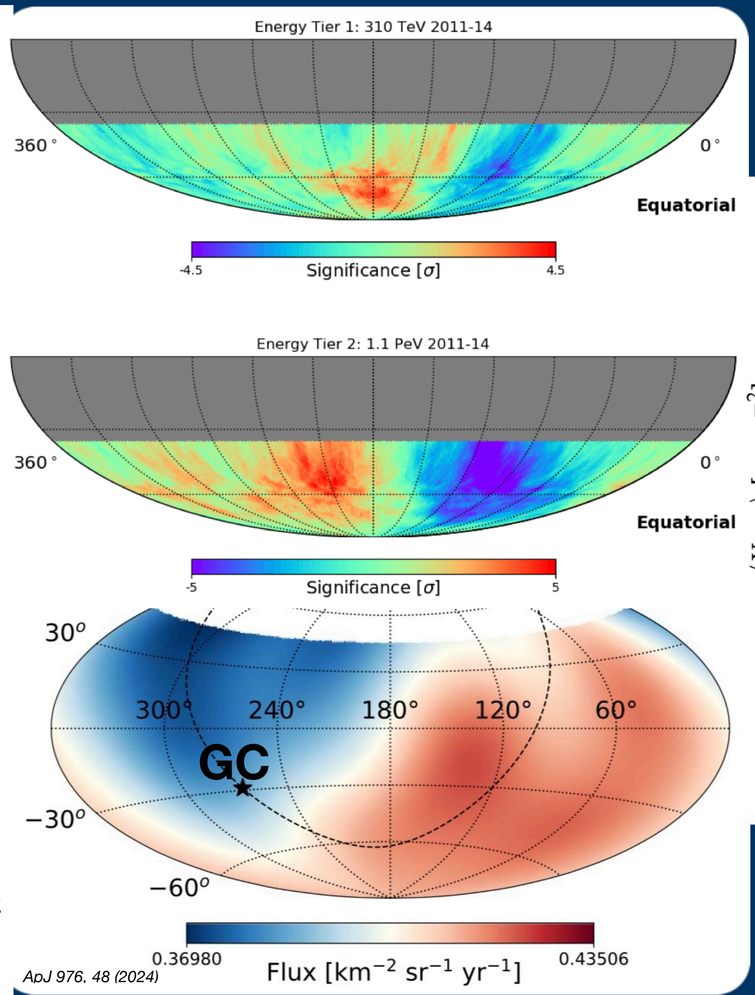
how is the primary particle's energy determined from the secondary particles or radiation?

Today: how from EAS we can infer the properties of the primary cosmic ray

ENERGY SPECTRUM

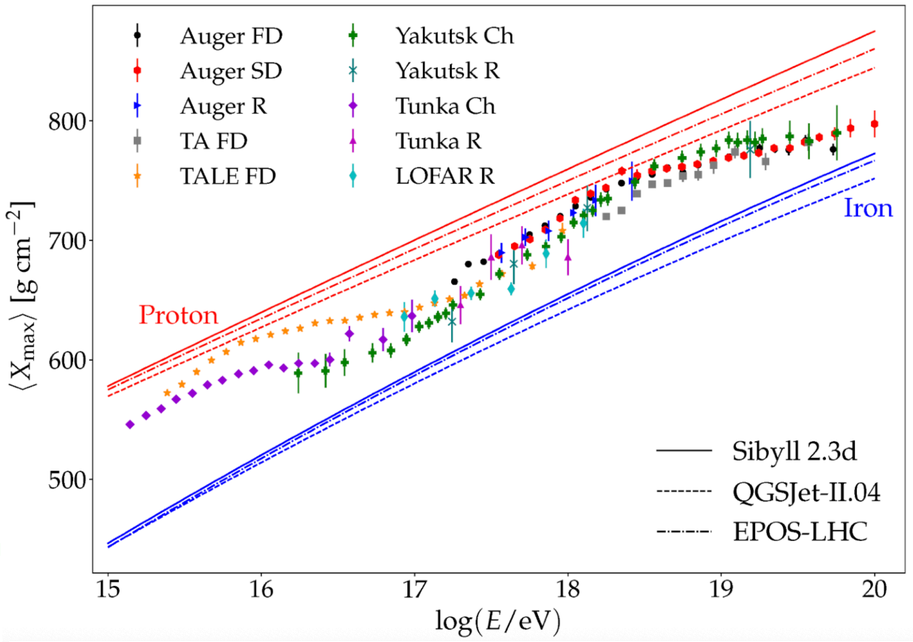


SKY MAPS



ApJ 976, 48 (2024)

MASS-COMPOSITION VS ENERGY

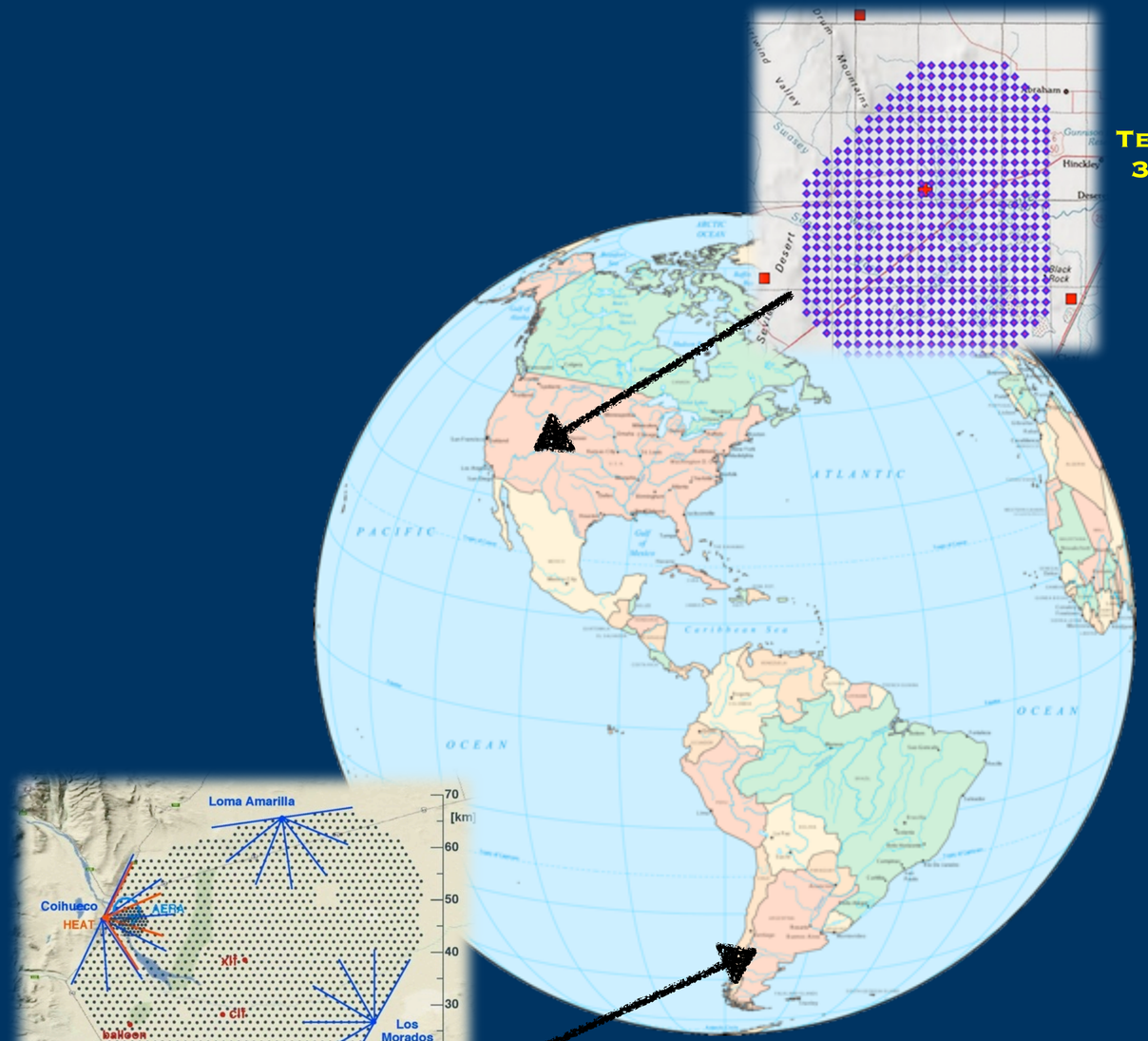


ENERGY **ARRIVAL DIRECTION** **MASS**

To infer the properties of the primary particle one needs not only to measure EAS (*detection*) but also to exploit as carefully as possible the "legacy" that their parents left to them *(analysis)*

EAS observables: two exemplary instruments

(The delicacy of the observations)



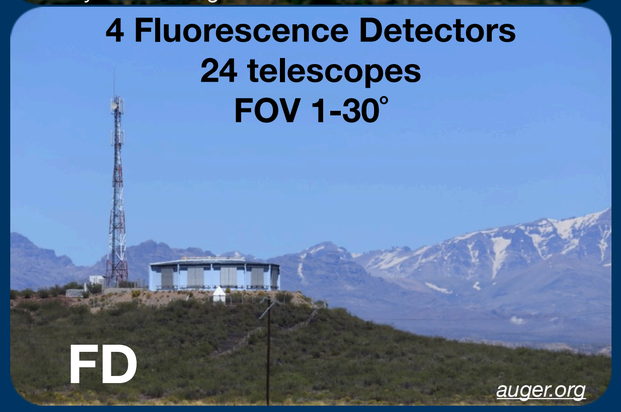
Telescope Array
39.3 N ,112.9 W

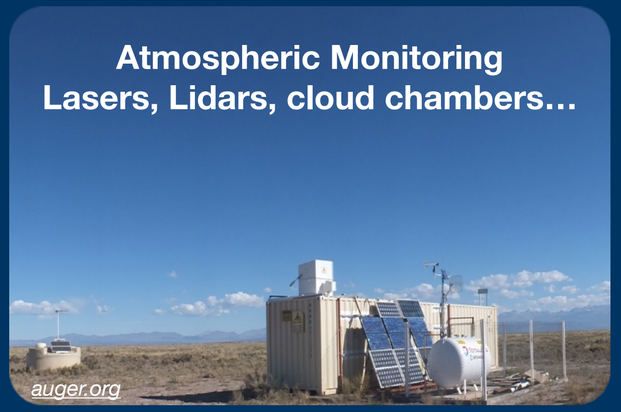
Pierre Auger Observatory
35.3 S, 69.3 W

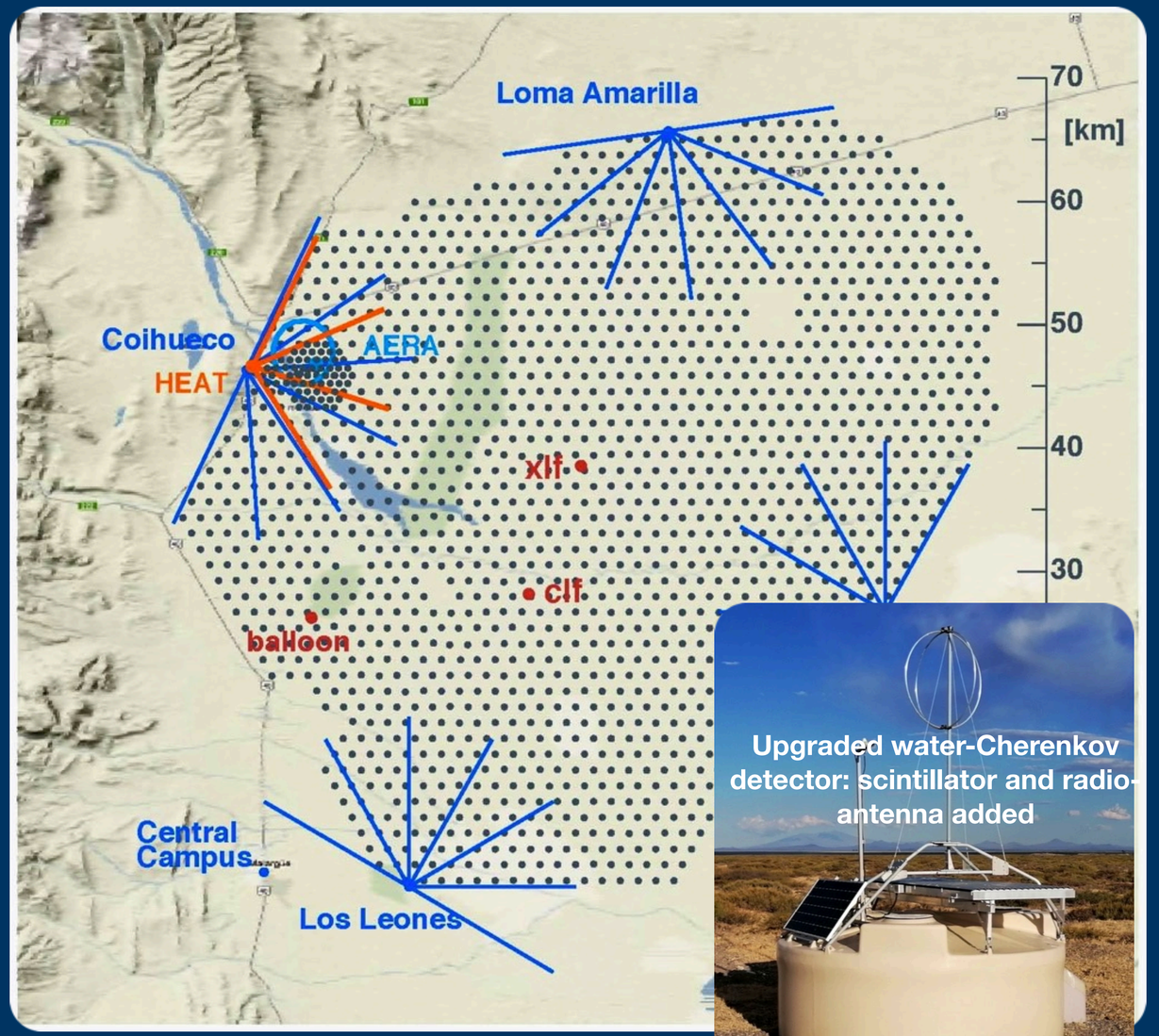
The Pierre Auger Observatory: overview

Multi-component (or "hybrid) EAS instrument











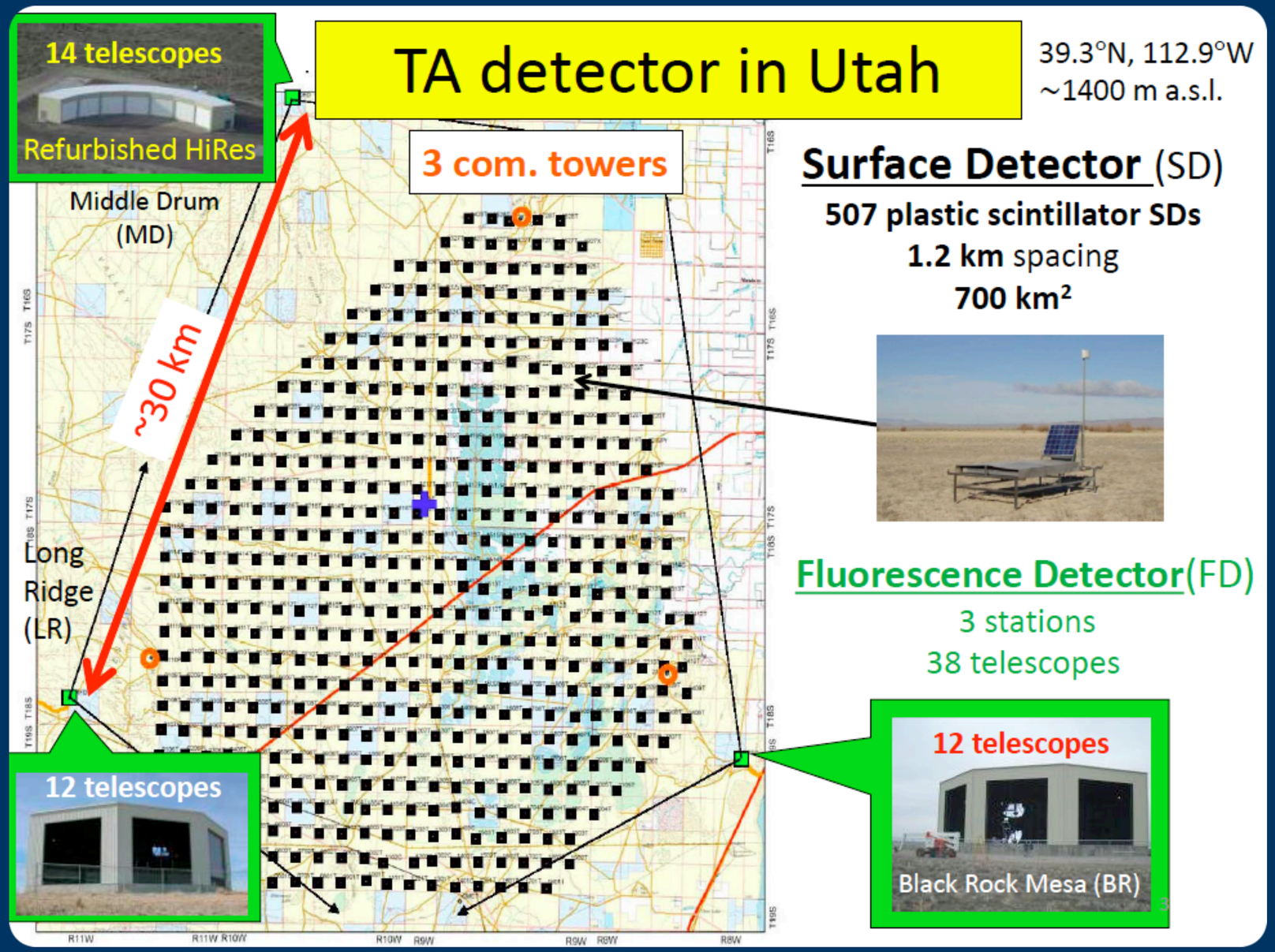


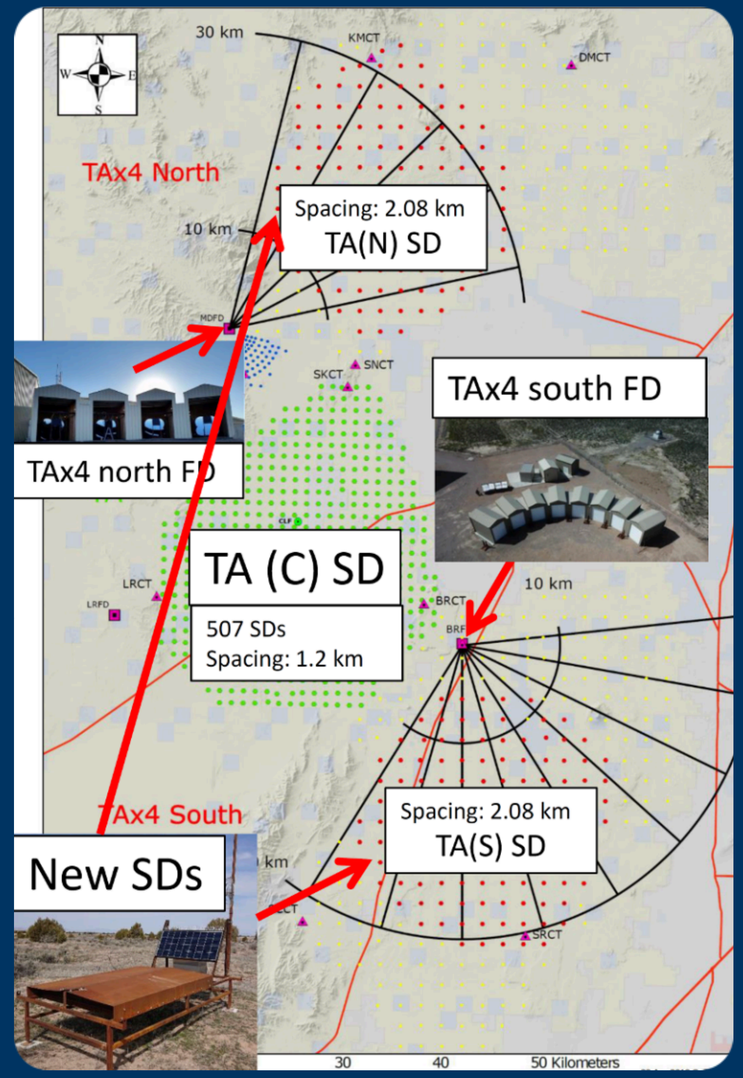




Telescope Array: overview

Multi-component (or "hybrid) EAS instrument

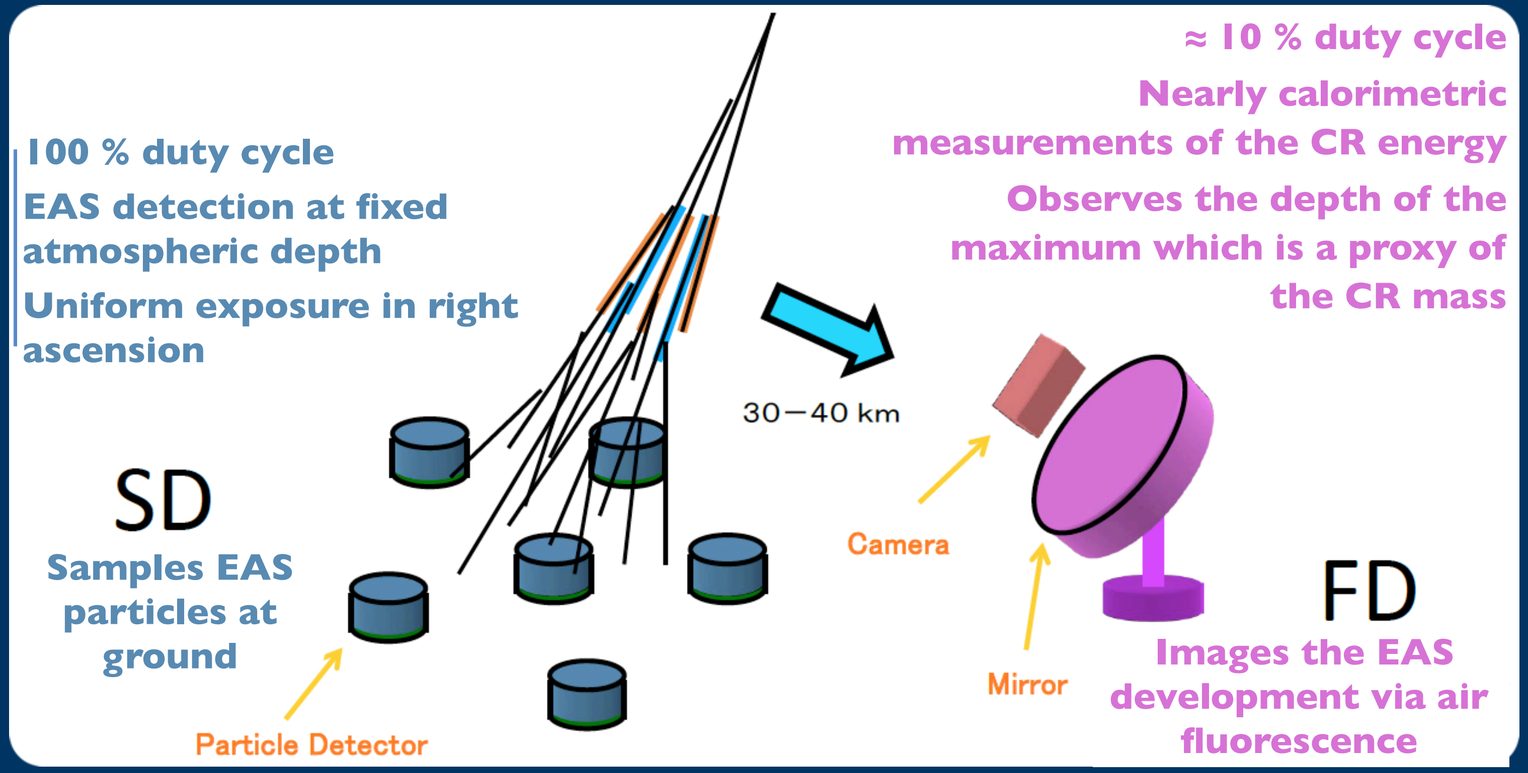




Upgrade: addition of scintillators (larger spacing) to extend the area to about 3000 km²

Why "hybrid" instruments?

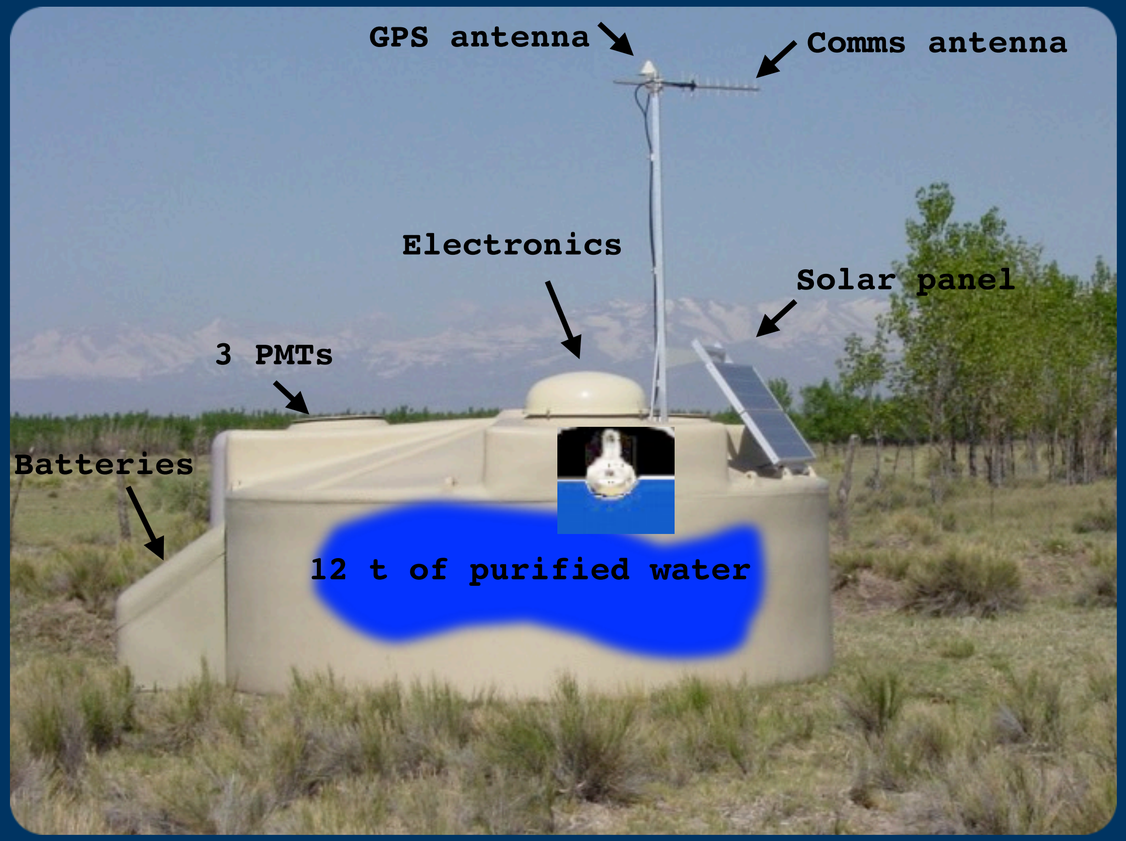
Marrying two complementary techniques



Technique	Surface detector array (SD)	Fluorescence detector (FD)
Duty cycle	100 %	15 %
Arrival direction	Direct $< 1^{\circ}$	Direct $< 1^{\circ}$
Energy	Indirect: Need for calibration	Direct: Calorimetric measurement
Mass	Indirect: Shower sampled at a unique depth	Direct: Shower development

Surface detector arrays: elemental piece

Auger



Water (12 t) Cherenkov detector

3 PMTs/detector

Area: 10 m²

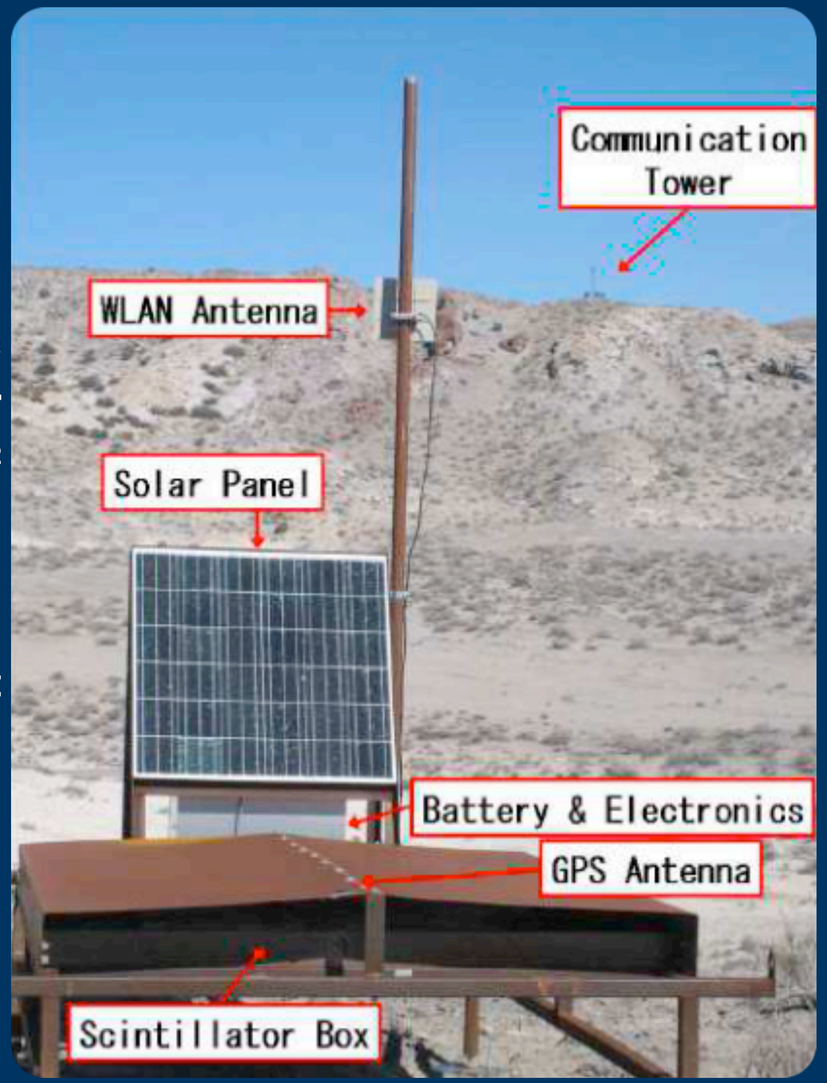
Thickness: 1.2 m

Acceptance up to 90 deg

Sensitive to em and mu component

(light signal larger for mu)

Telescope Array



Double-layer scintillators

2 PMTs/detector

Area: 3 m²

Thickness: 1.2 cm

Acceptance up to 55 deg

More sensitive to em component

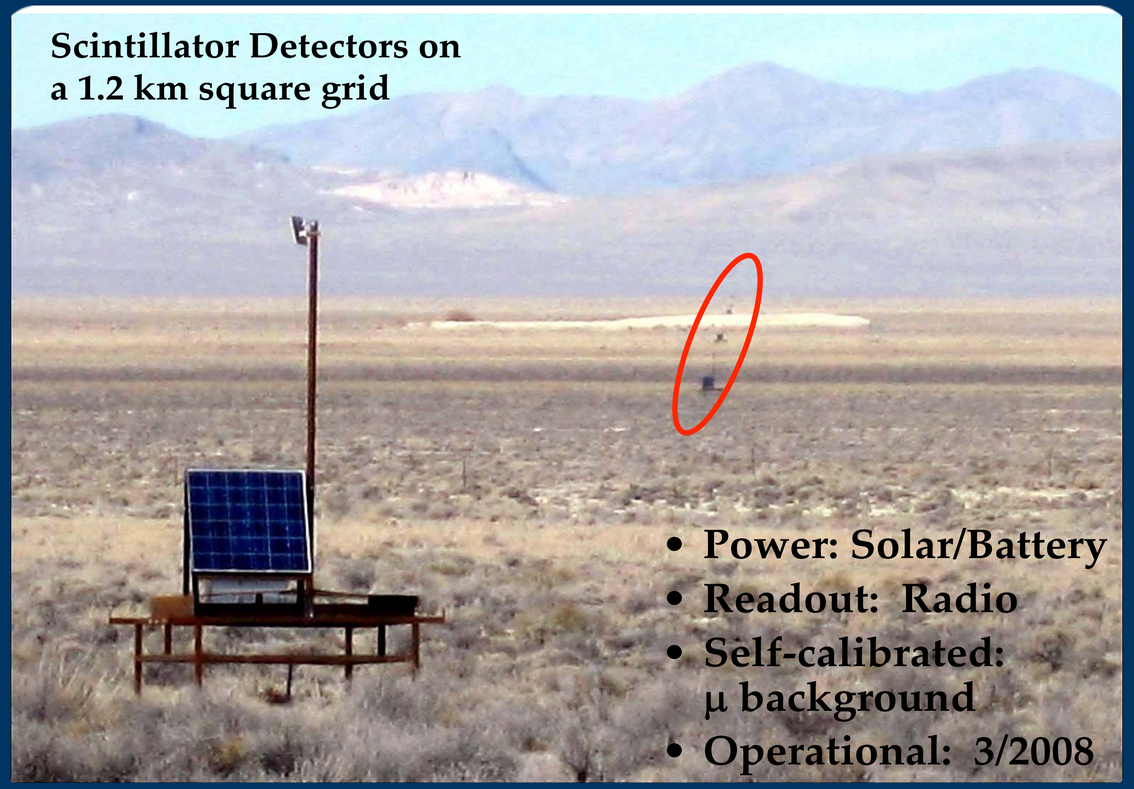
Surface detector arrays: (just) a glimpse

Auger



(Almost) perfectly aligned in the pampa, at a distance of 1.5 km one from another

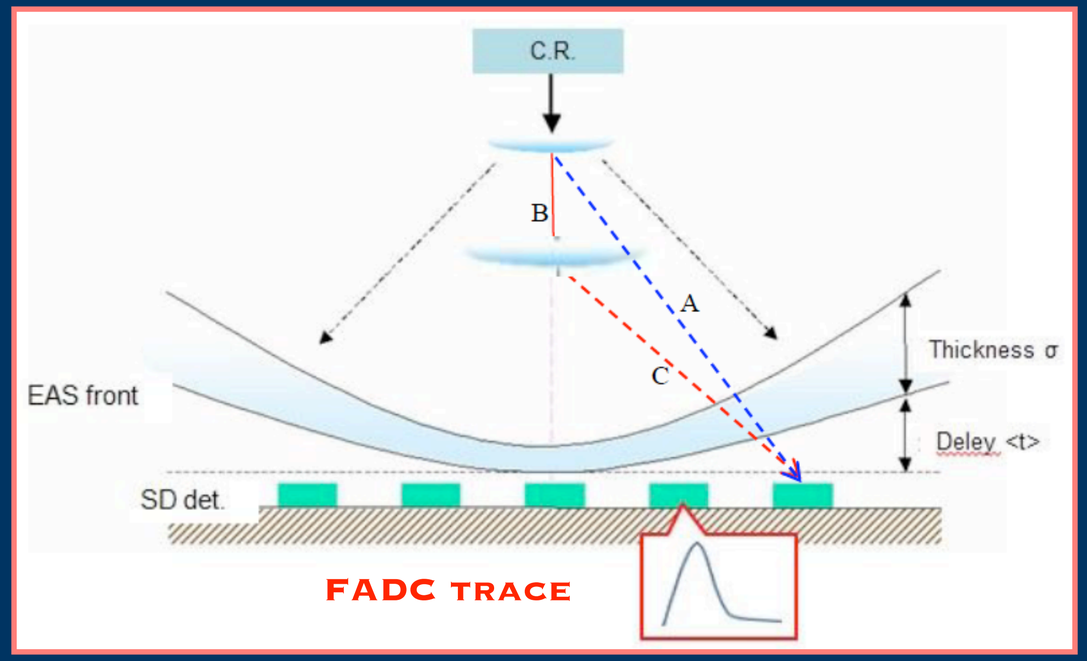
Telescope Array



(Almost) perfectly aligned in the desert, at a distance of 1.2 km one from another

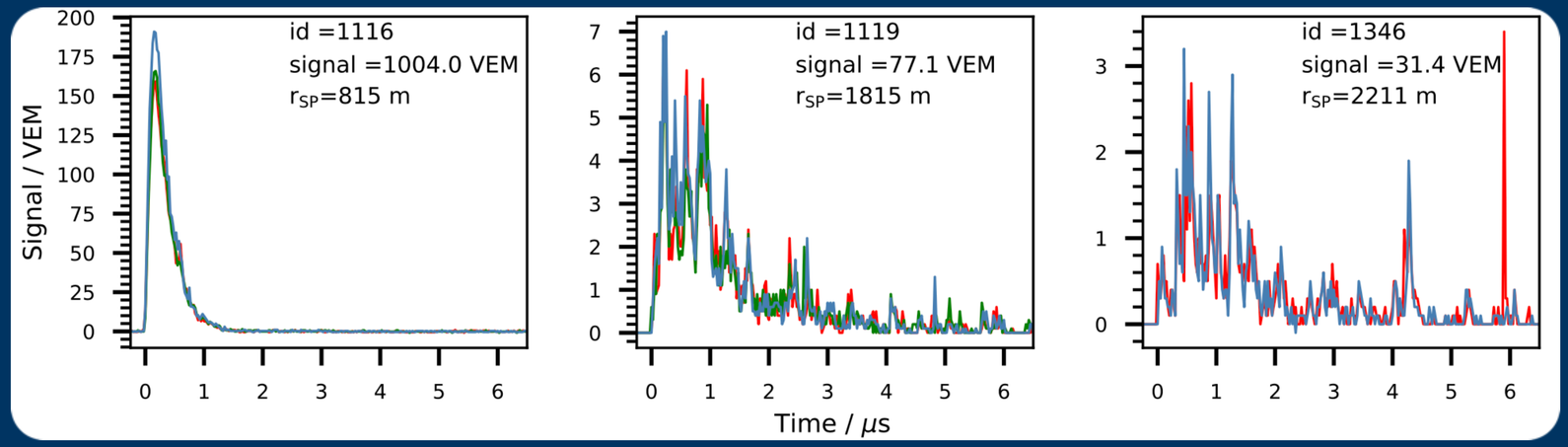
Pampa, desert:
The adventurous excursion of the observers :-)

EAS signals in particle detectors

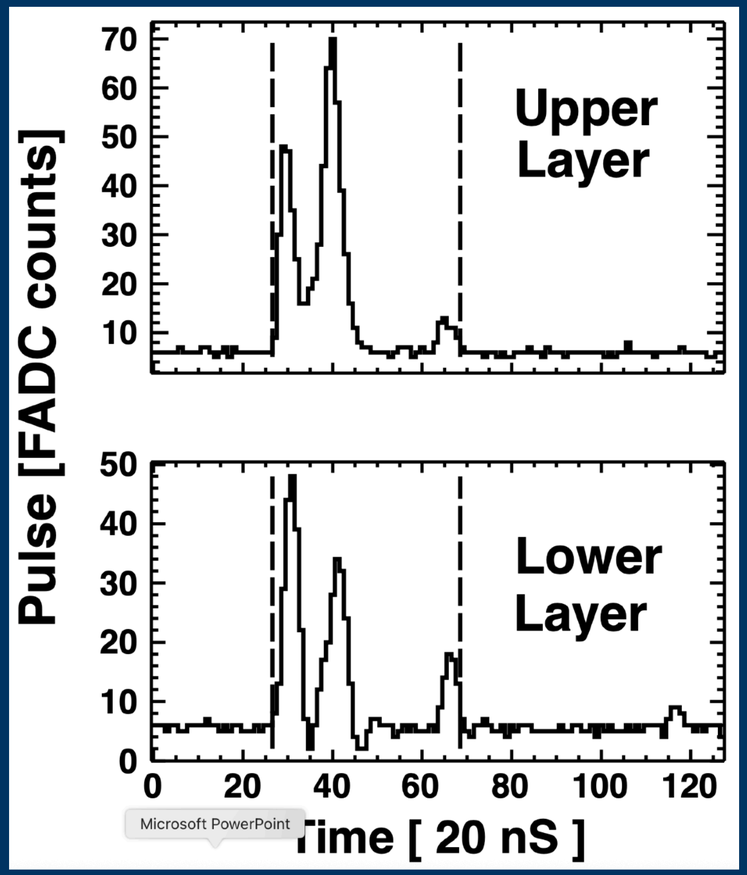


The PMTs signals are digitised by Fast Analog-to-Digital Converters (FADC), with a sampling time of 25 (20) ns

FADC traces @ Auger



FADC traces @ Telescope Array

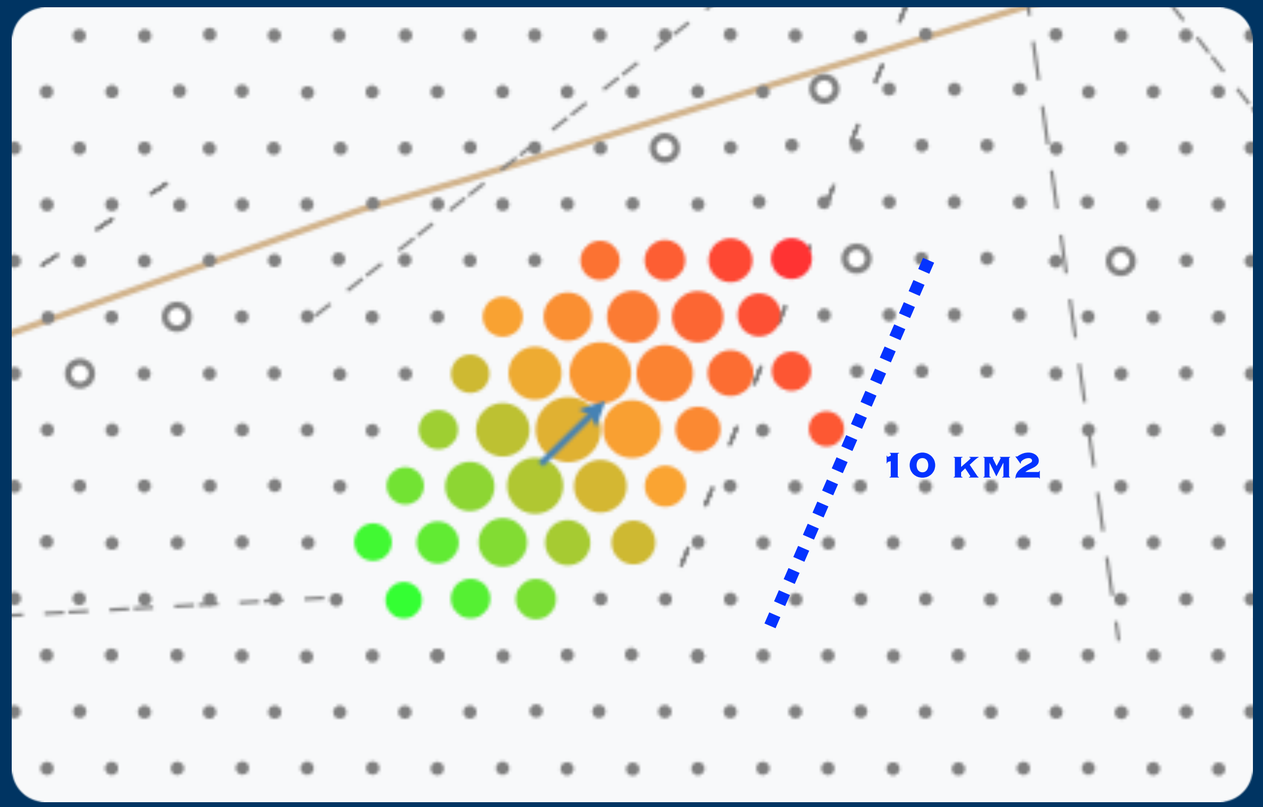


EAS image seen in the surface detector arrays

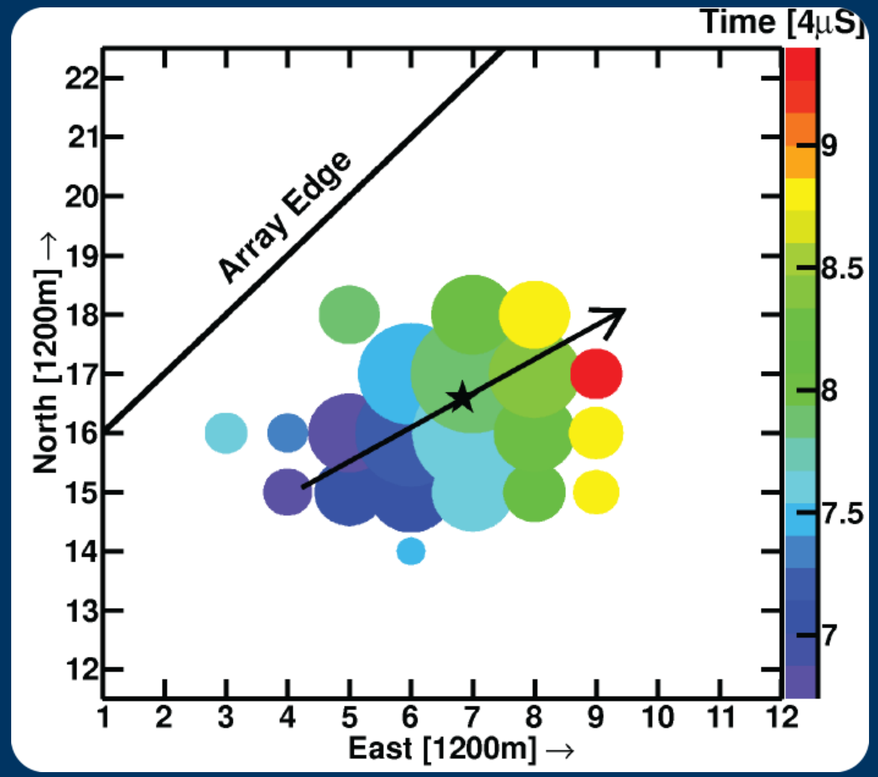
When the signals are above a certain threshold in at least 3 detectors within a certain time, the data acquisition starts

SD “photographs” the footprint of the shower at ground

Auger



Telescope Array



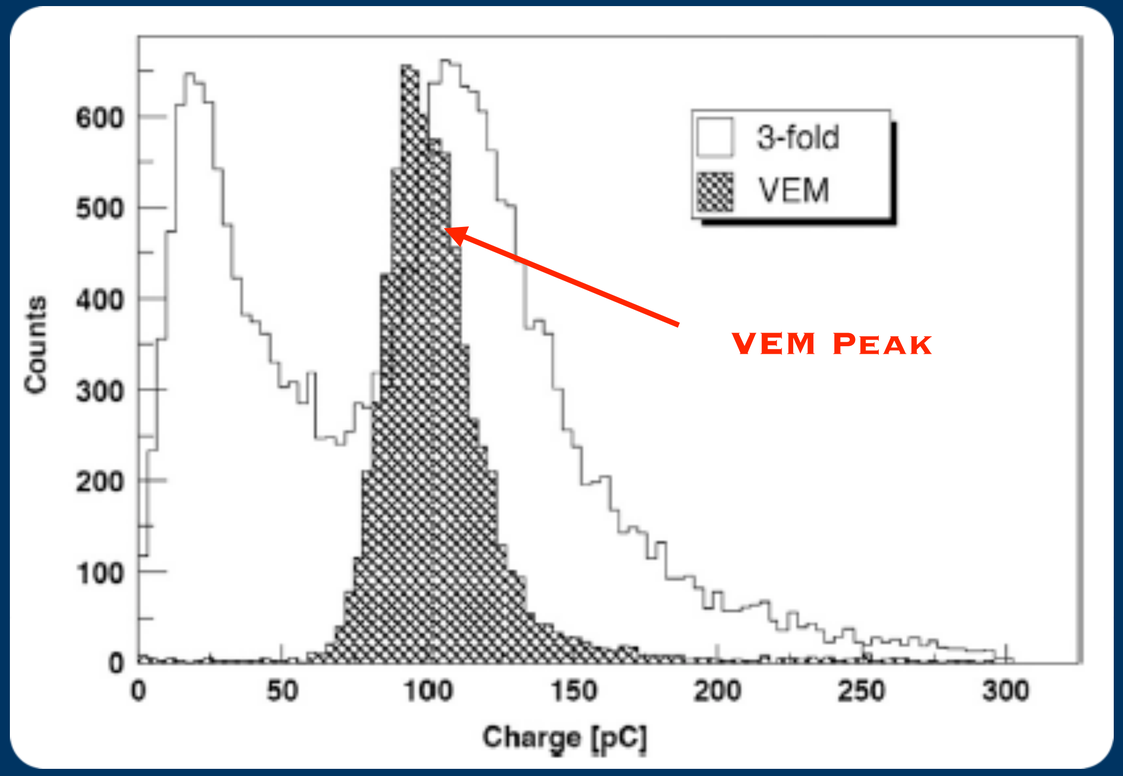
The dimension of the circles is proportional to the number of detected particles.
Colors represent the arrival time of the particles in the detectors

Calibration of surface detectors

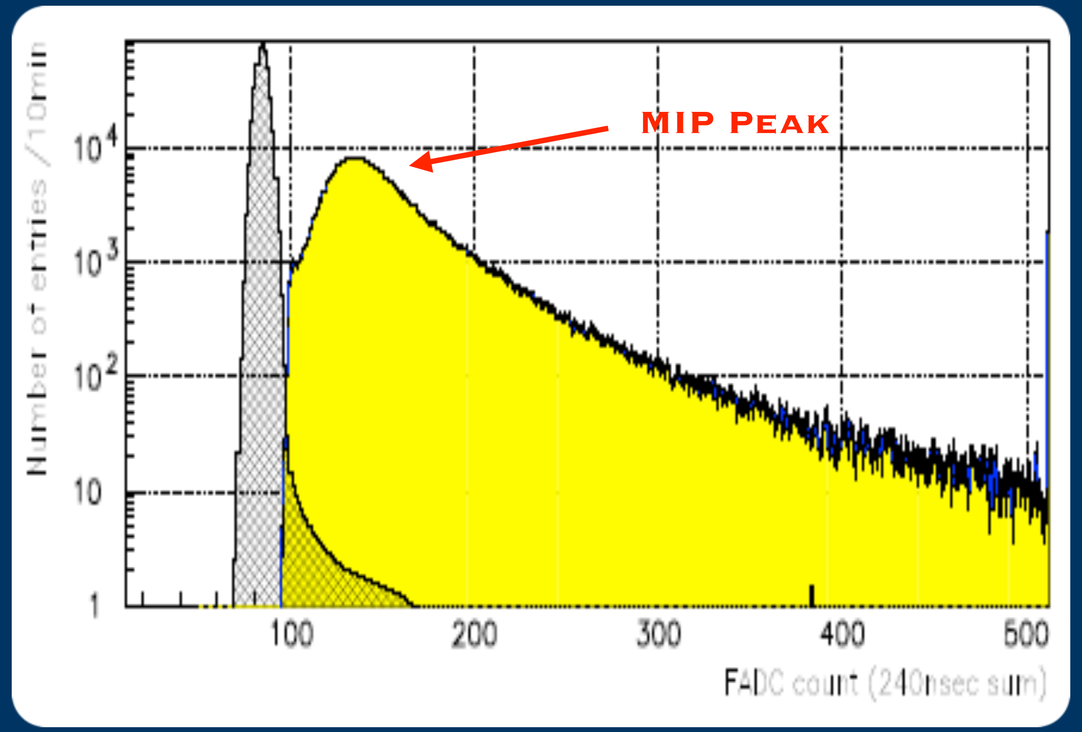
Based on secondary cosmic rays: atmospheric muons

The PMTs signals are converted to number of particles by using a “natural” phenomenon:
Atmospheric muons, remnant of low-energy showers absorbed high in the atmosphere: rate ≈ 200 Hz/m2

Auger



Telescope Array



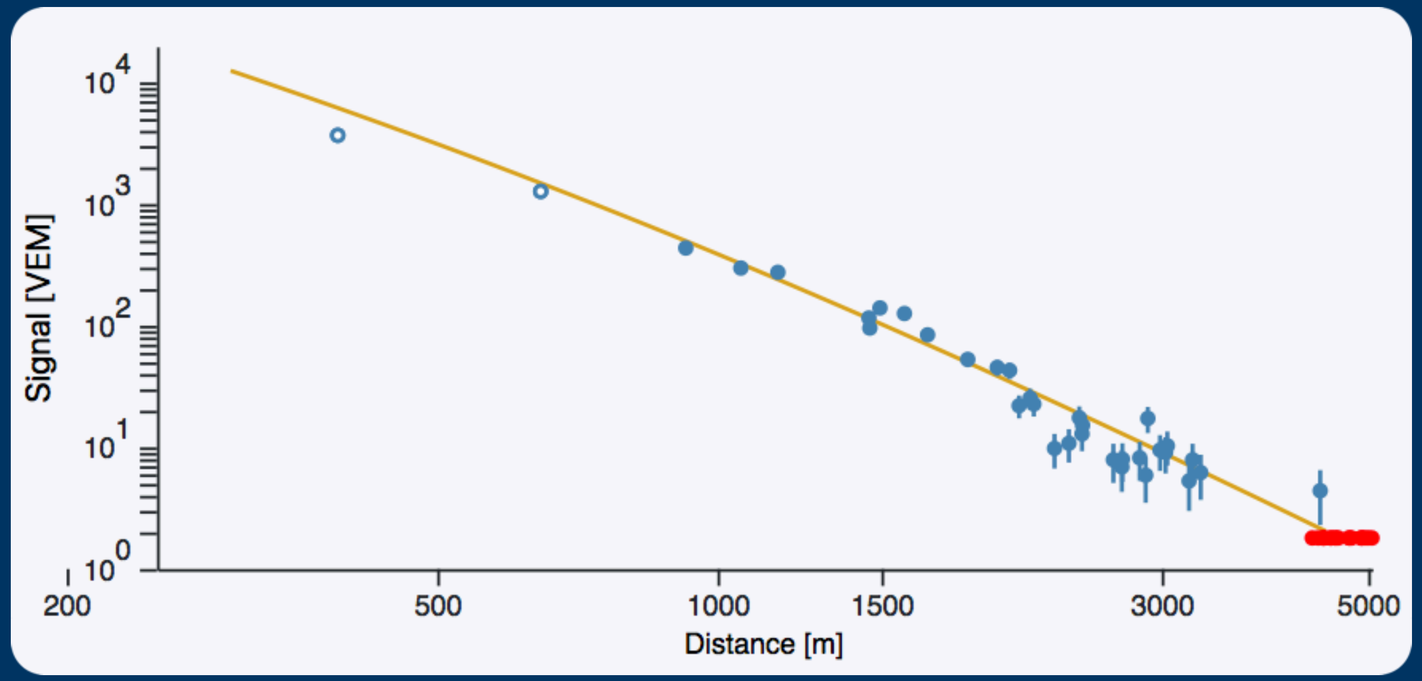
Charge spectrum obtained (every 10’) when a detector is triggered (at a low-threshold) by the coincidence among the PMTs

(VEM = Vertical Equivalent Muon; MIP = minimum ionising particle)

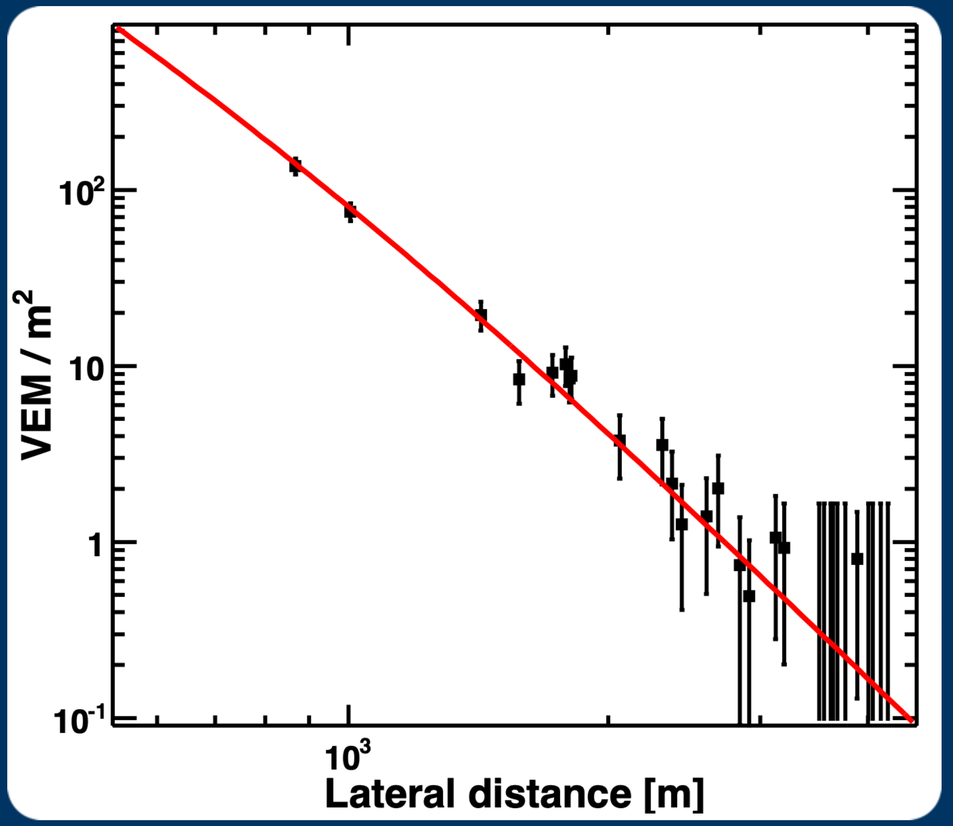
EAS particles seen by the surface detectors

Lateral distribution

Auger



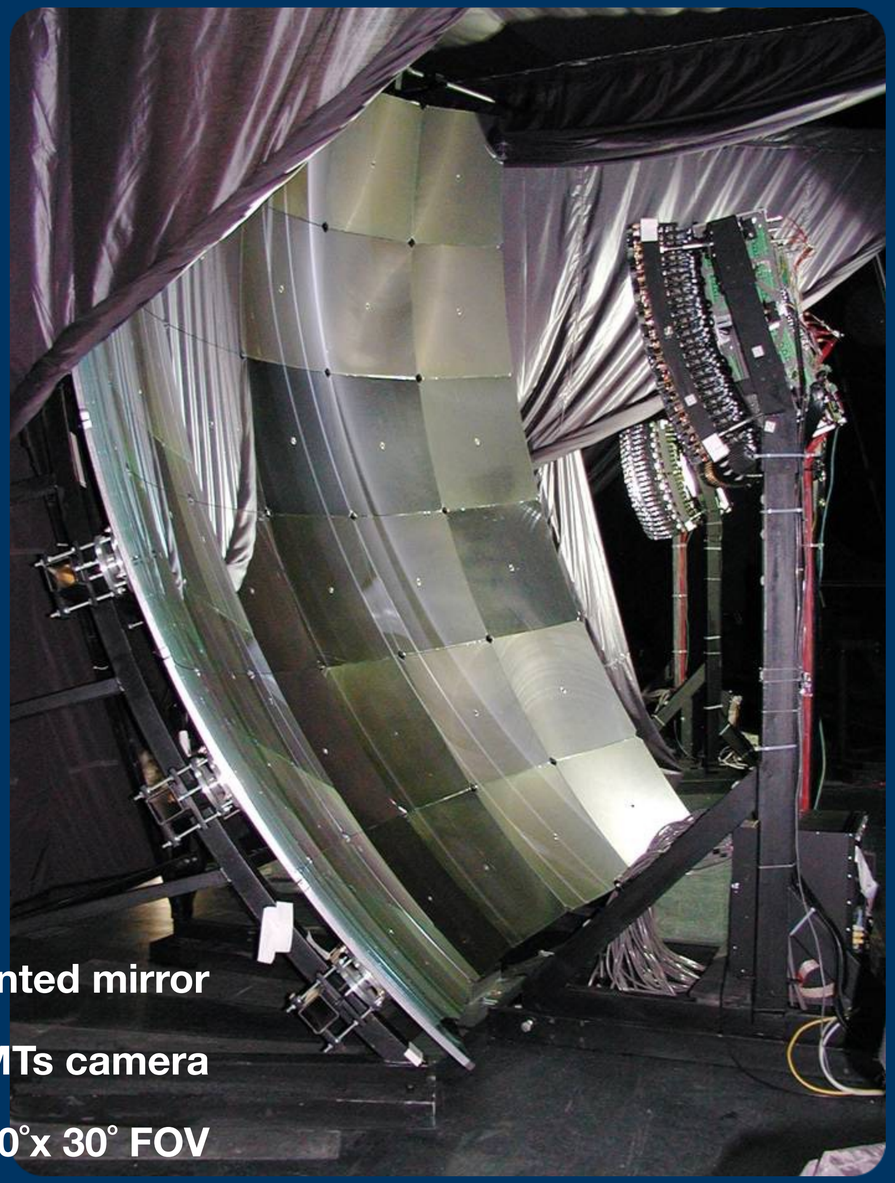
Telescope Array



Distribution of EAS particles as a function of the distance from the core

Fluorescence detectors: elemental piece

Auger

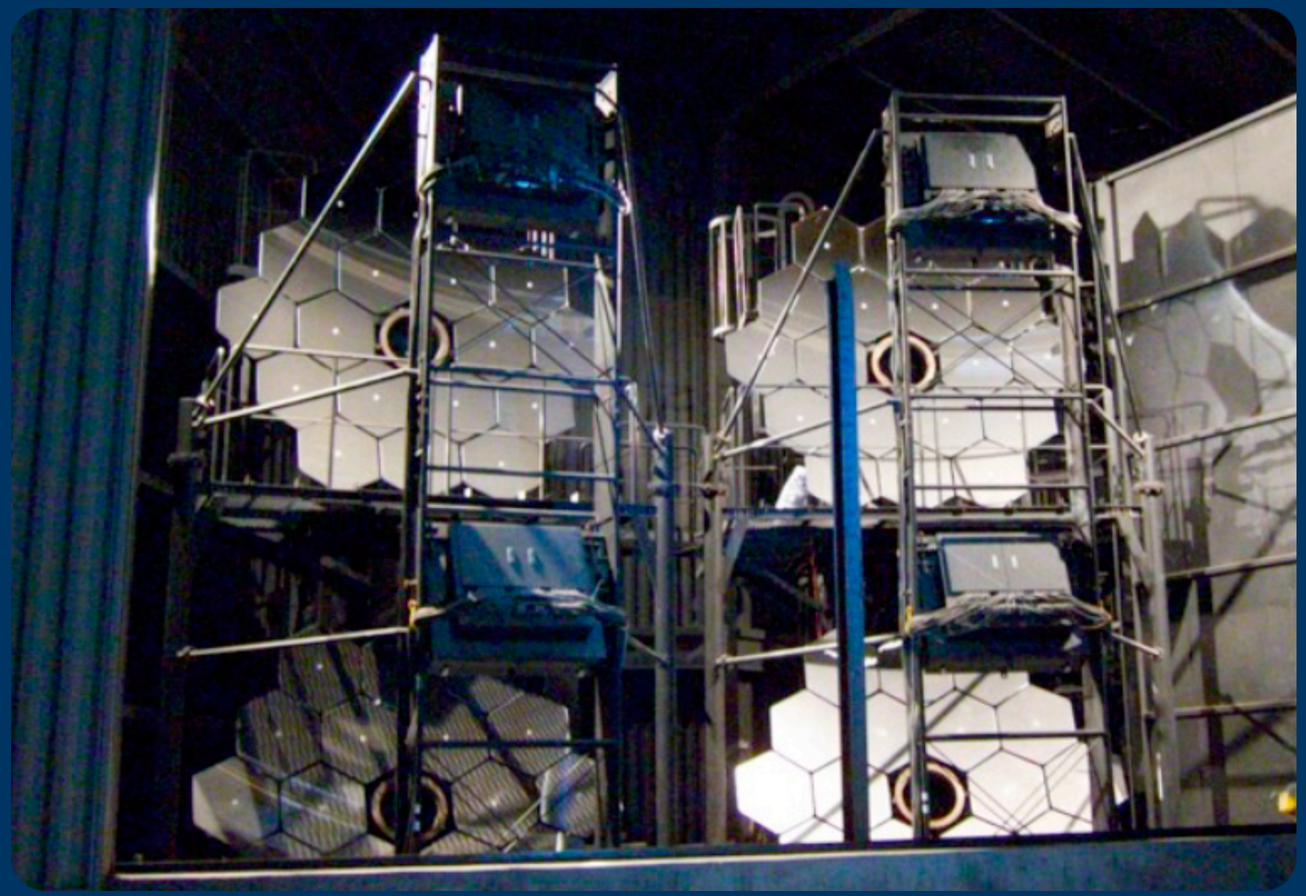


3.4 m^2 segmented mirror

440 PMTs camera

30°x 30° FOV

Telescope Array



3 m segmented mirror

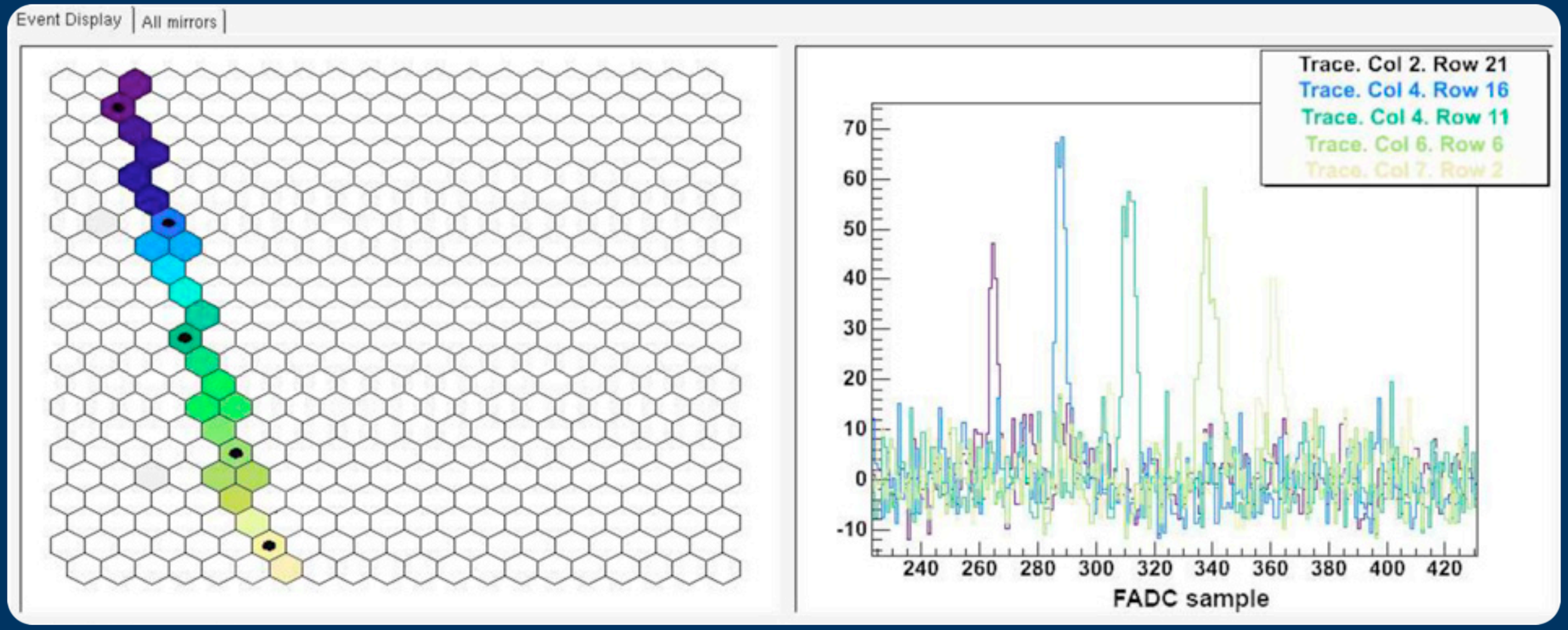
256 PMTs camera

15° x 18° FOV

EAS signals in fluorescence detectors

The PMTs signals are digitized by Fast Analog-to-Digital Converters (FADC), with a sampling time of 100 ns

NB. Only Auger traces here



Pattern of triggered pixels (color code: dark=earlier; light=later)

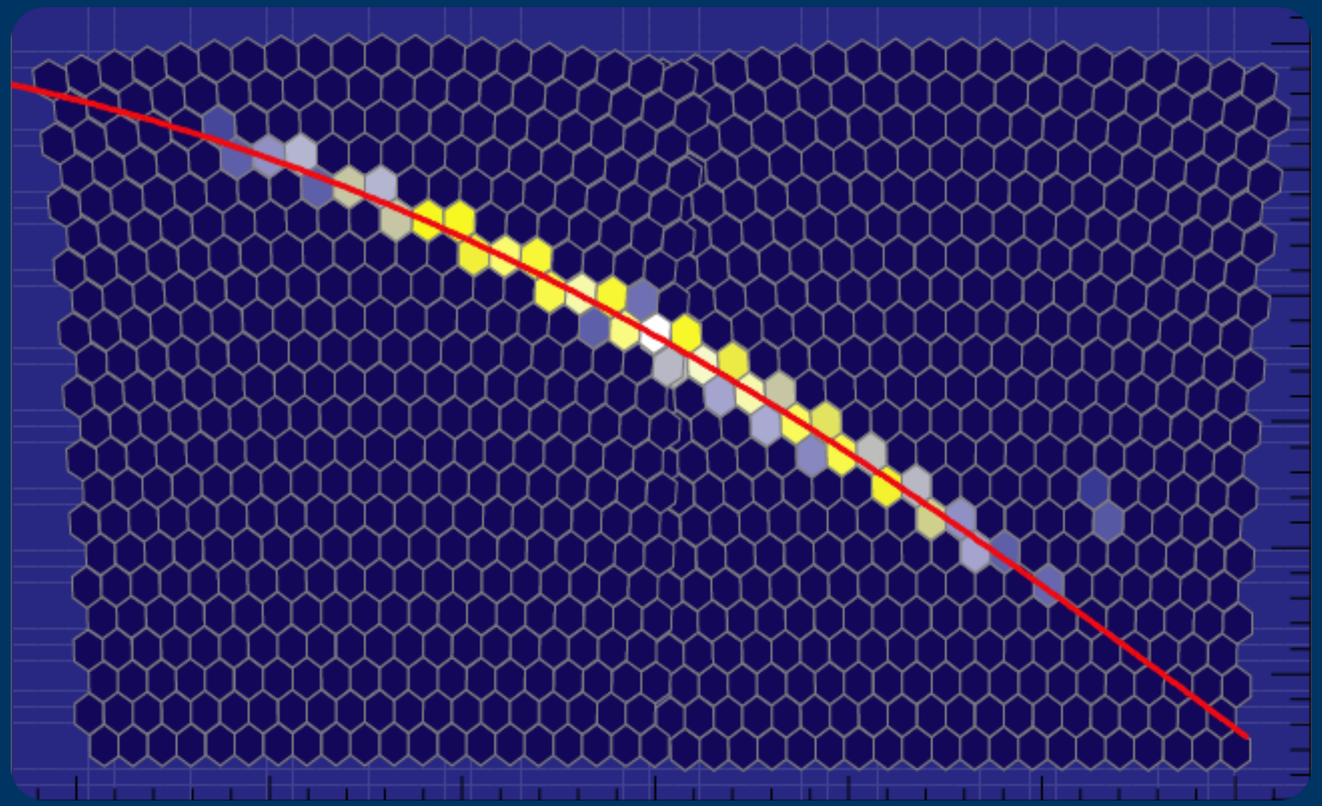
FADC traces of the triggered PMTs (black dots in the left panel)

EAS image seen in the fluorescence detectors

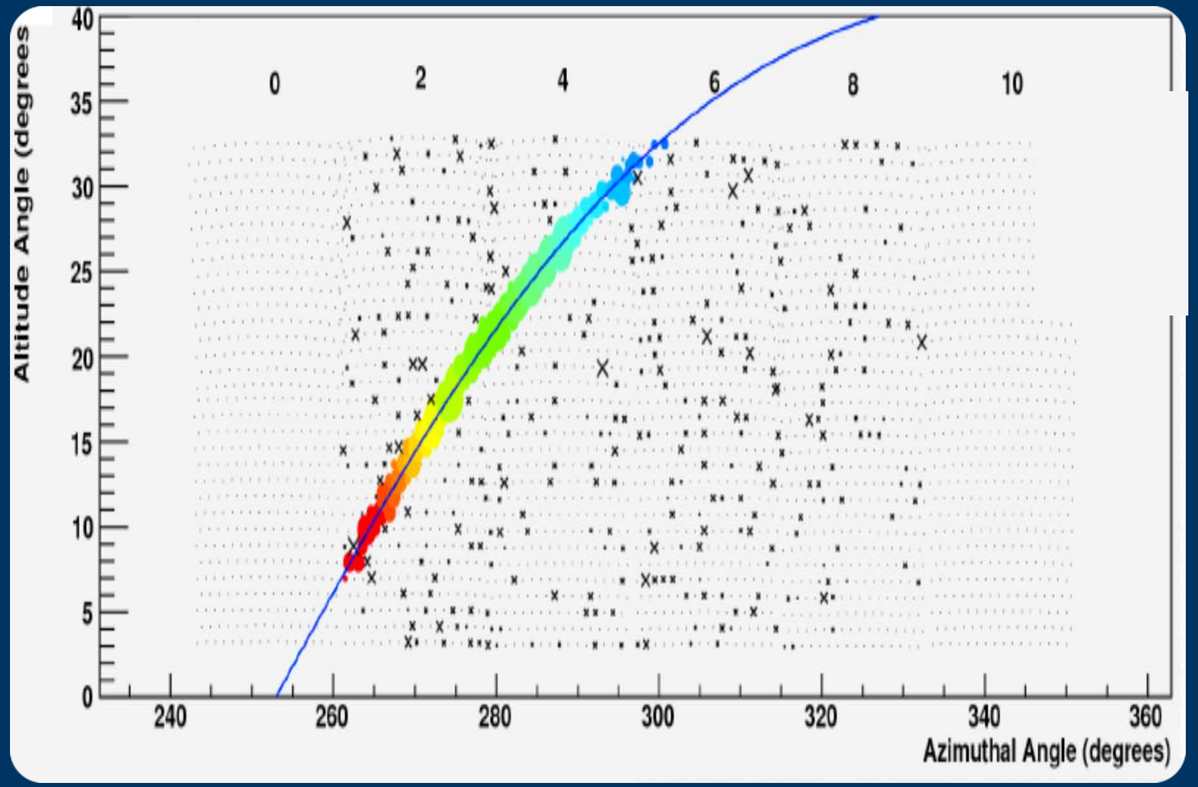
When signals are above a certain threshold in at least 5 pixels (PMTs) within a certain time, the DAQ starts

FD “photographs” the passage of the shower in atmosphere

Auger

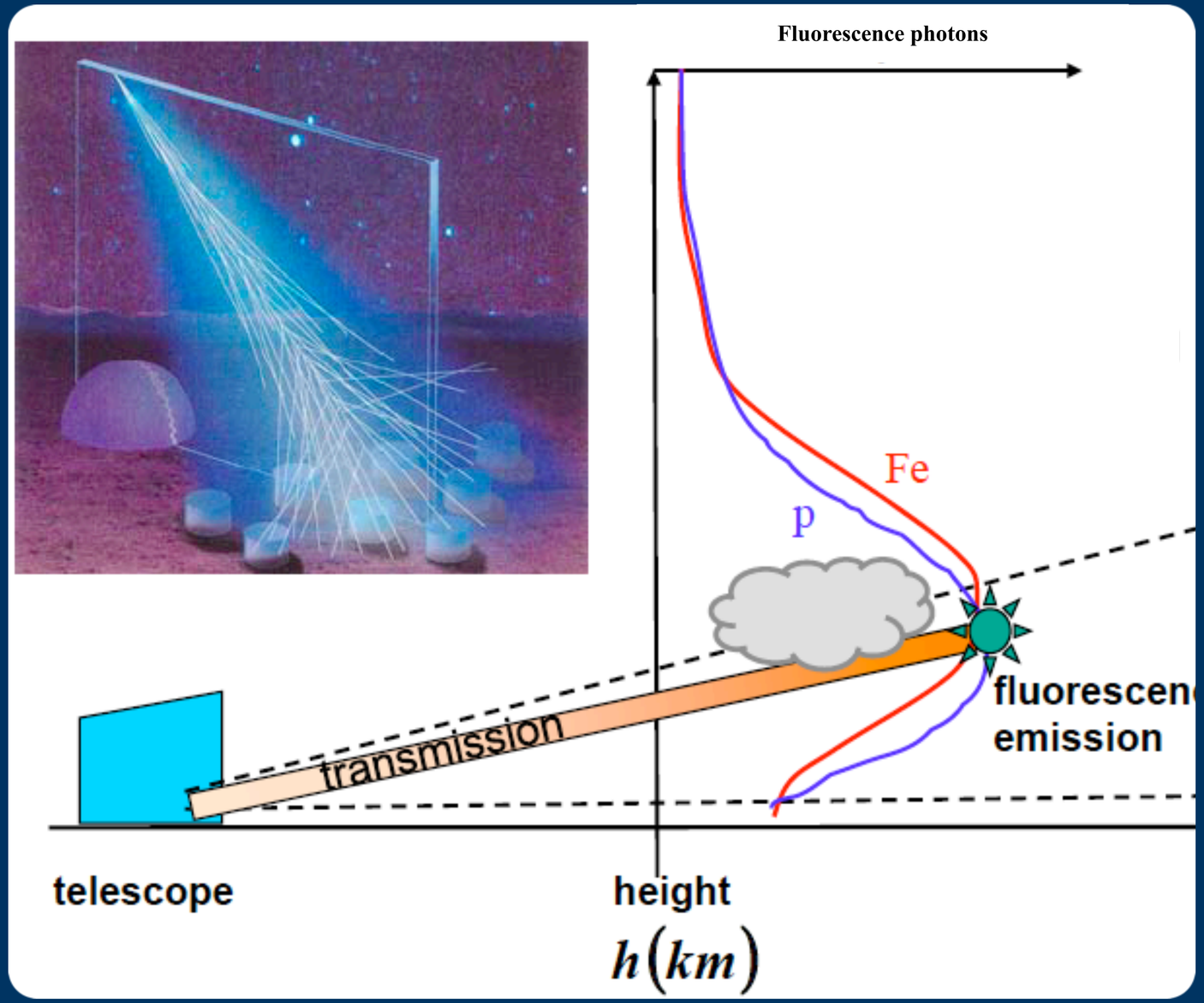


Telescope Array



Atmosphere monitoring and correction

Clouds and aerosols play a major role in the optical transmission

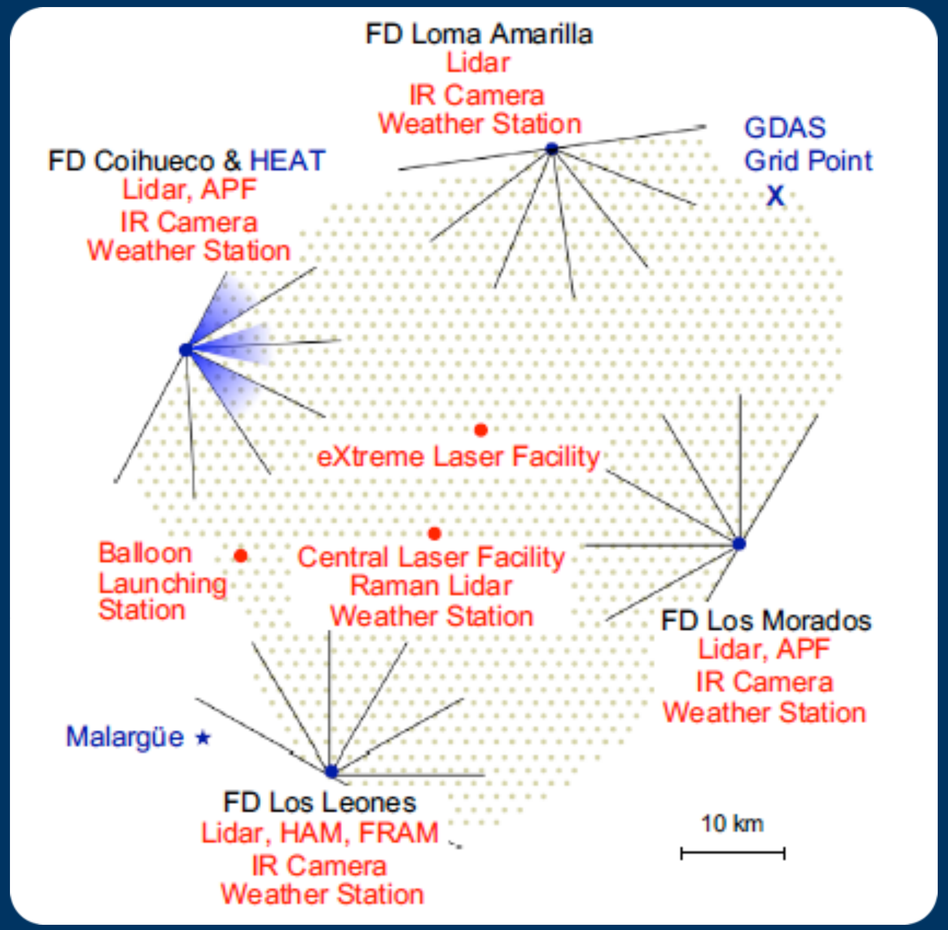


The **atmospheric transmission** between the air-shower and the FD must be taken into account to properly reconstruct the light generated along the shower axis from the light recorded at the telescope(s)

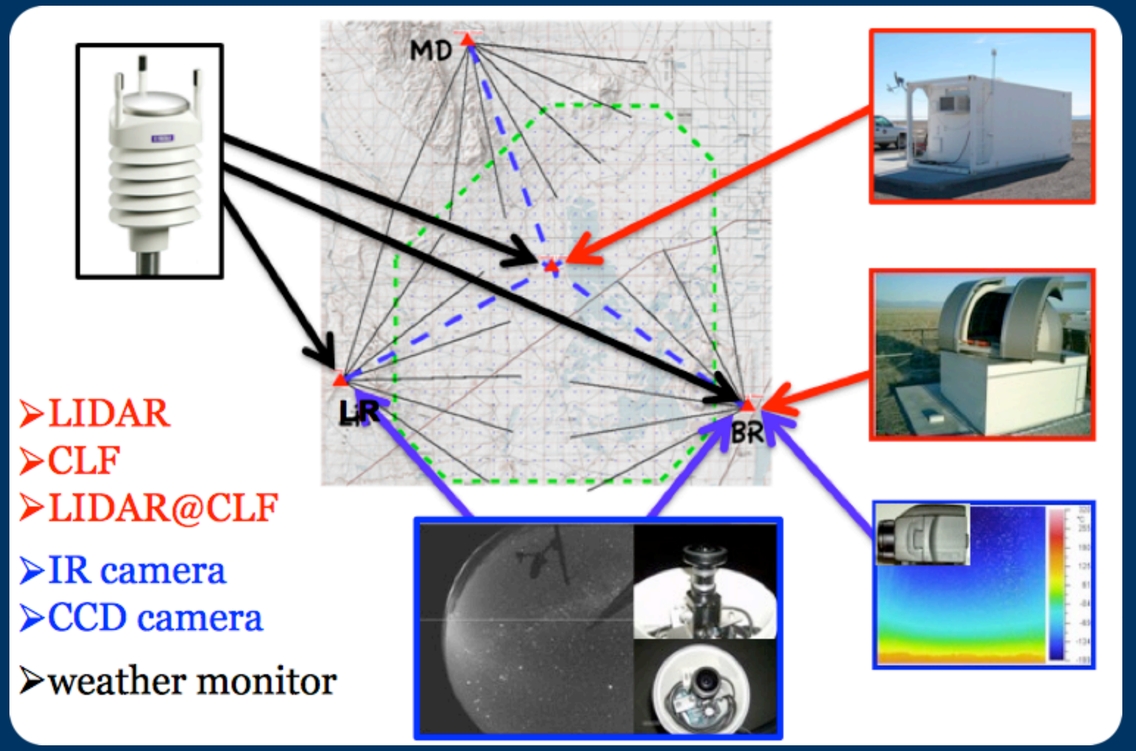
Atmosphere monitoring and correction

Clouds and aerosols play a major role in the optical transmission

Auger



Telescope Array



Weather stations measure P, T and humidity.

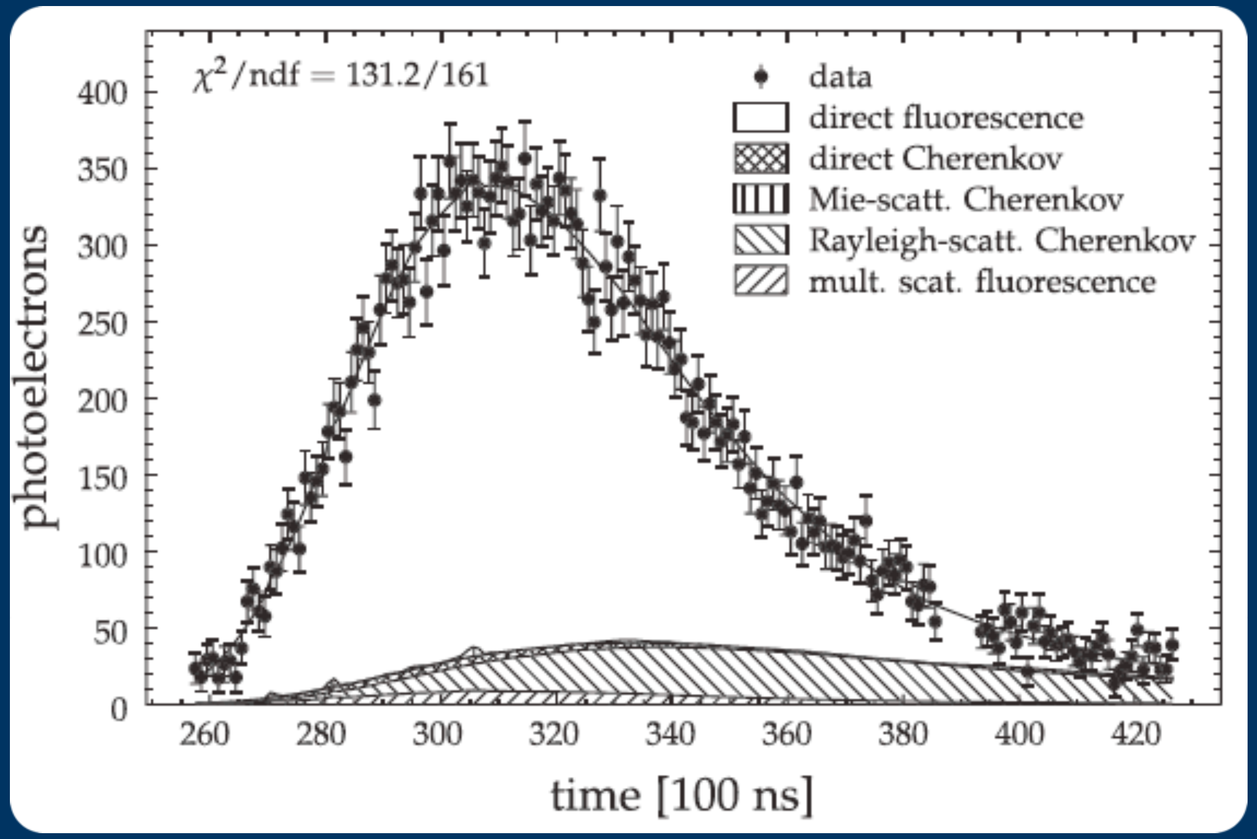
Infrared cameras and LIDARs monitor the cloud coverage.

Lasers and LIDARs allow to determine the aerosols optical-depth profile

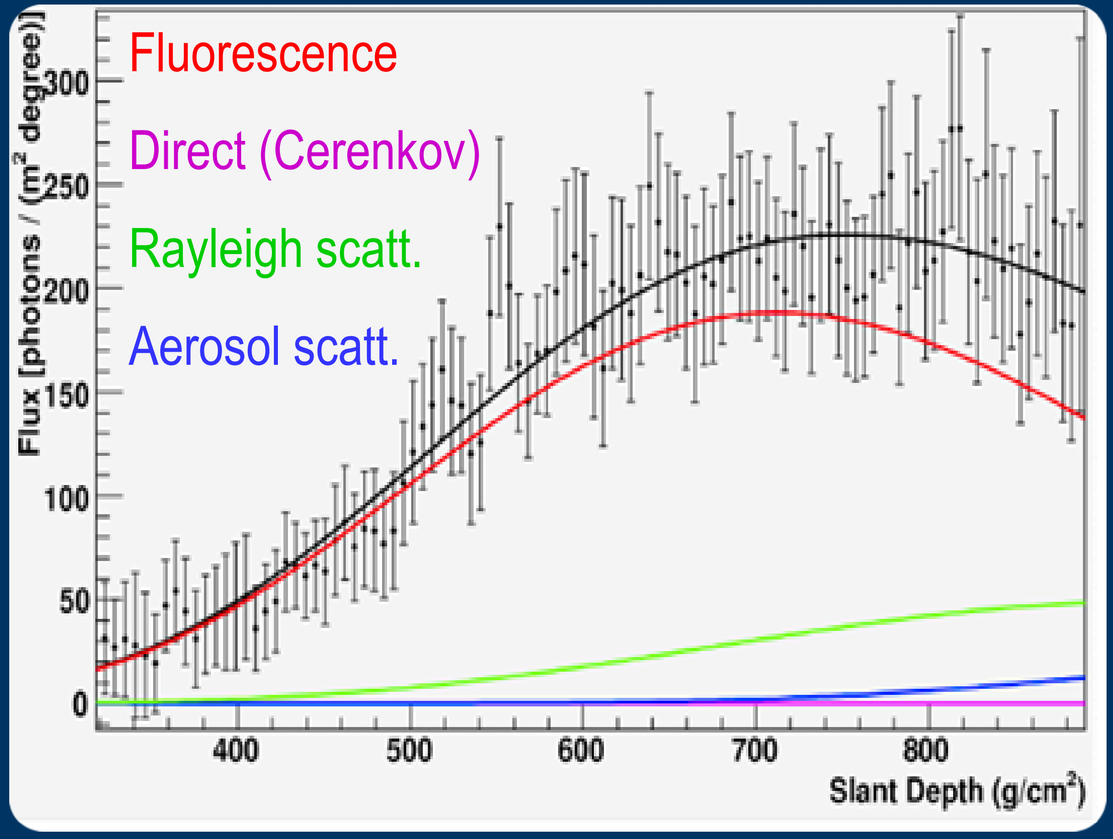
EAS light seen by the fluorescence detectors

Longitudinal development

Auger



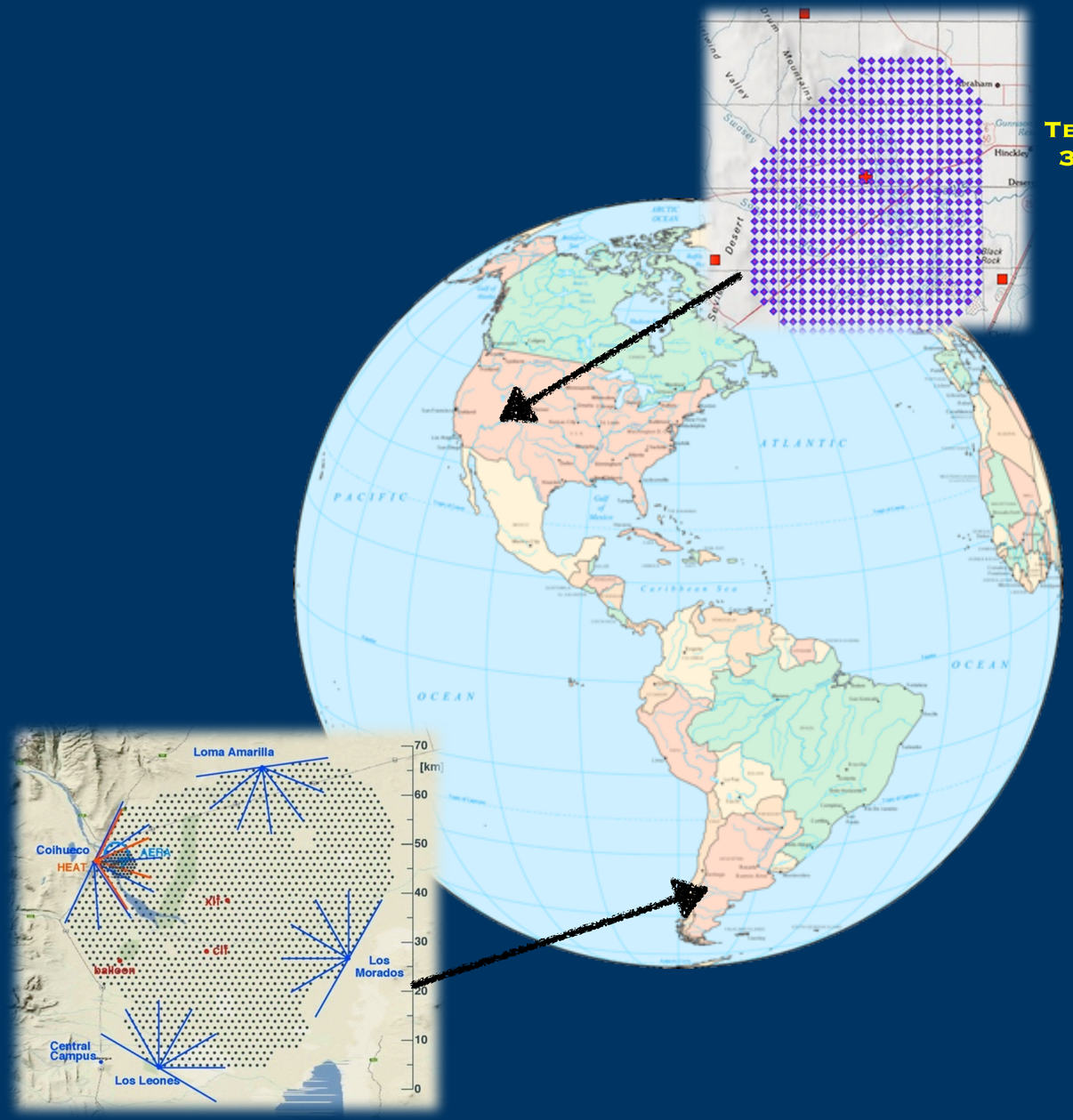
Telescope Array



Light-at-aperture measurements and reconstructed light sources

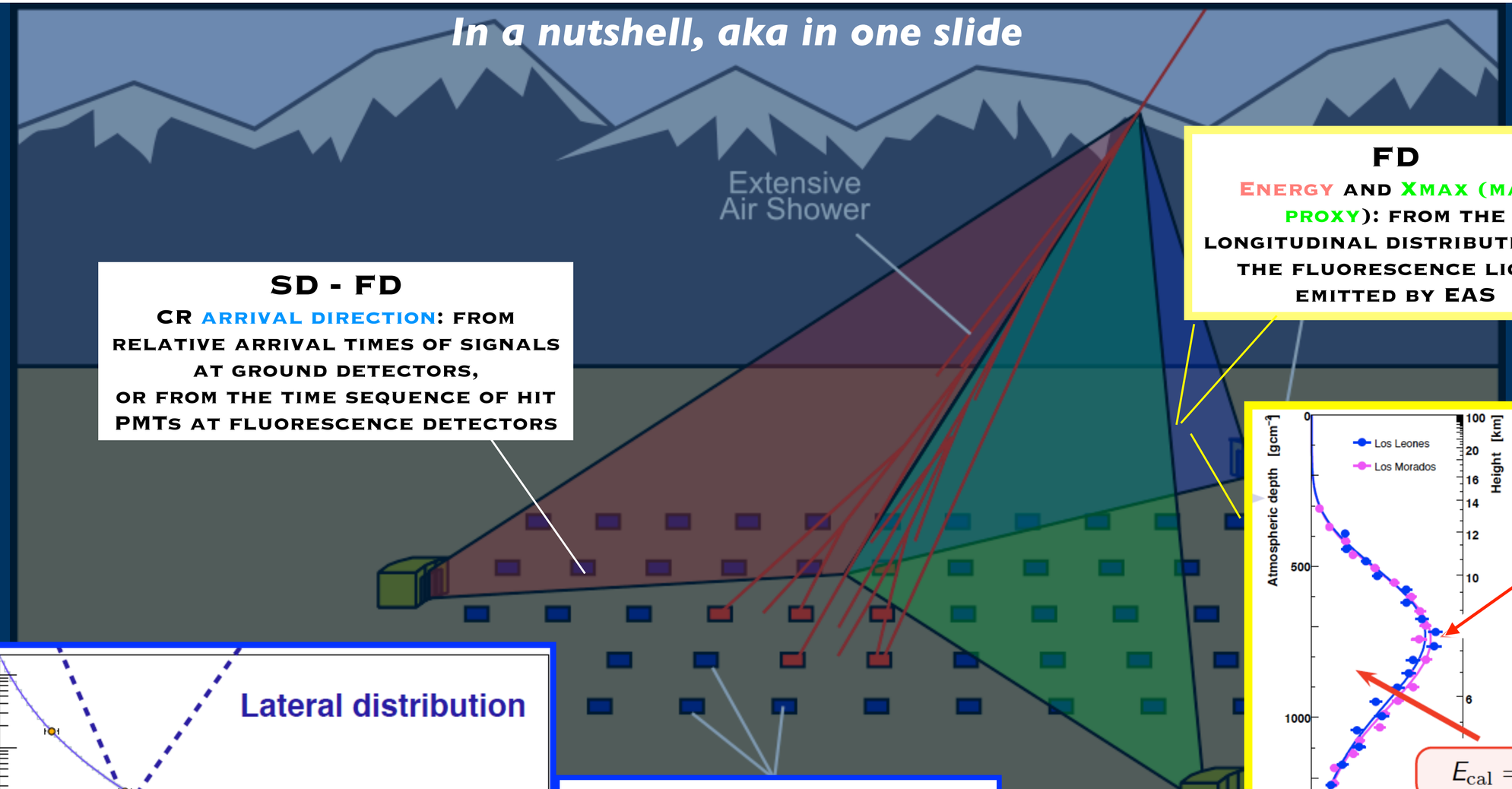
From EAS observables to cosmic rays properties

(The subtlety of the analysis)



How from EAS we can infer the properties of the primary cosmic ray

In a nutshell, aka in one slide

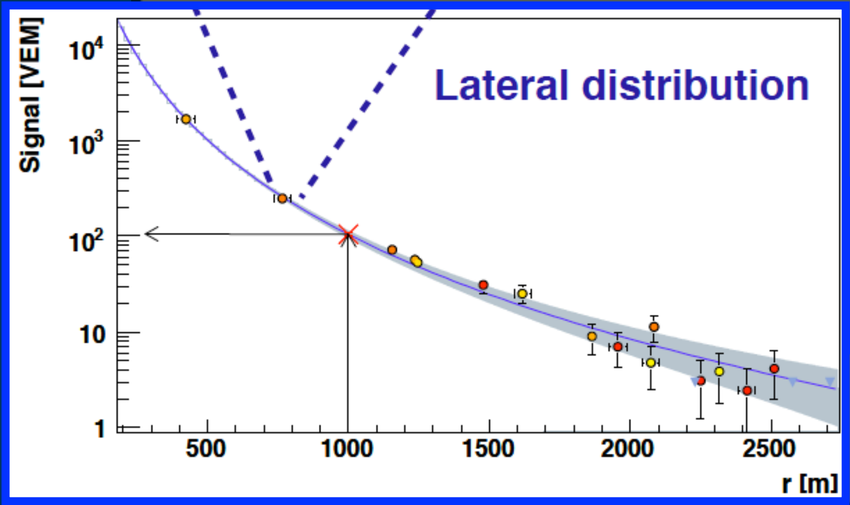


SD - FD

CR ARRIVAL DIRECTION: FROM RELATIVE ARRIVAL TIMES OF SIGNALS AT GROUND DETECTORS, OR FROM THE TIME SEQUENCE OF HIT PMTS AT FLUORESCENCE DETECTORS

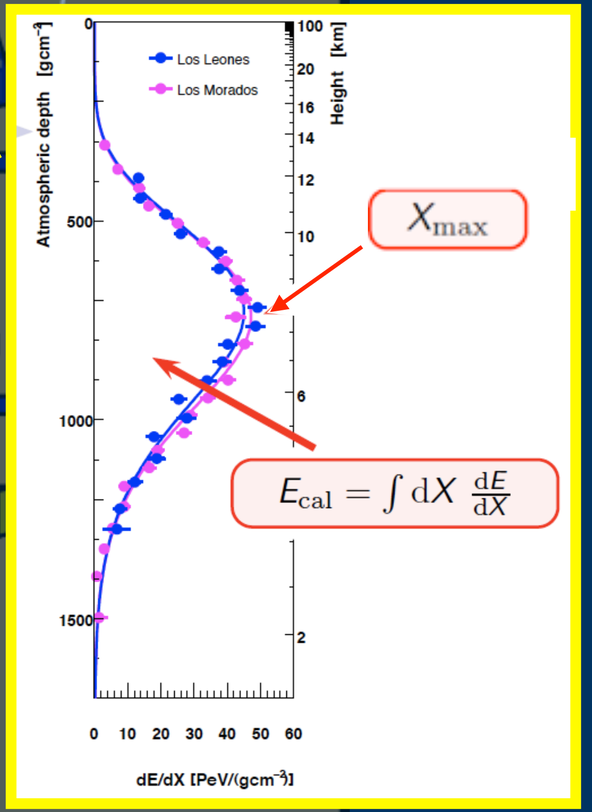
FD

ENERGY AND XMAX (MASS PROXY): FROM THE LONGITUDINAL DISTRIBUTION OF THE FLUORESCENCE LIGHT EMITTED BY EAS



SD

ENERGY PROXY: FROM THE DISTRIBUTION/NUMBER OF PARTICLES AT GROUND

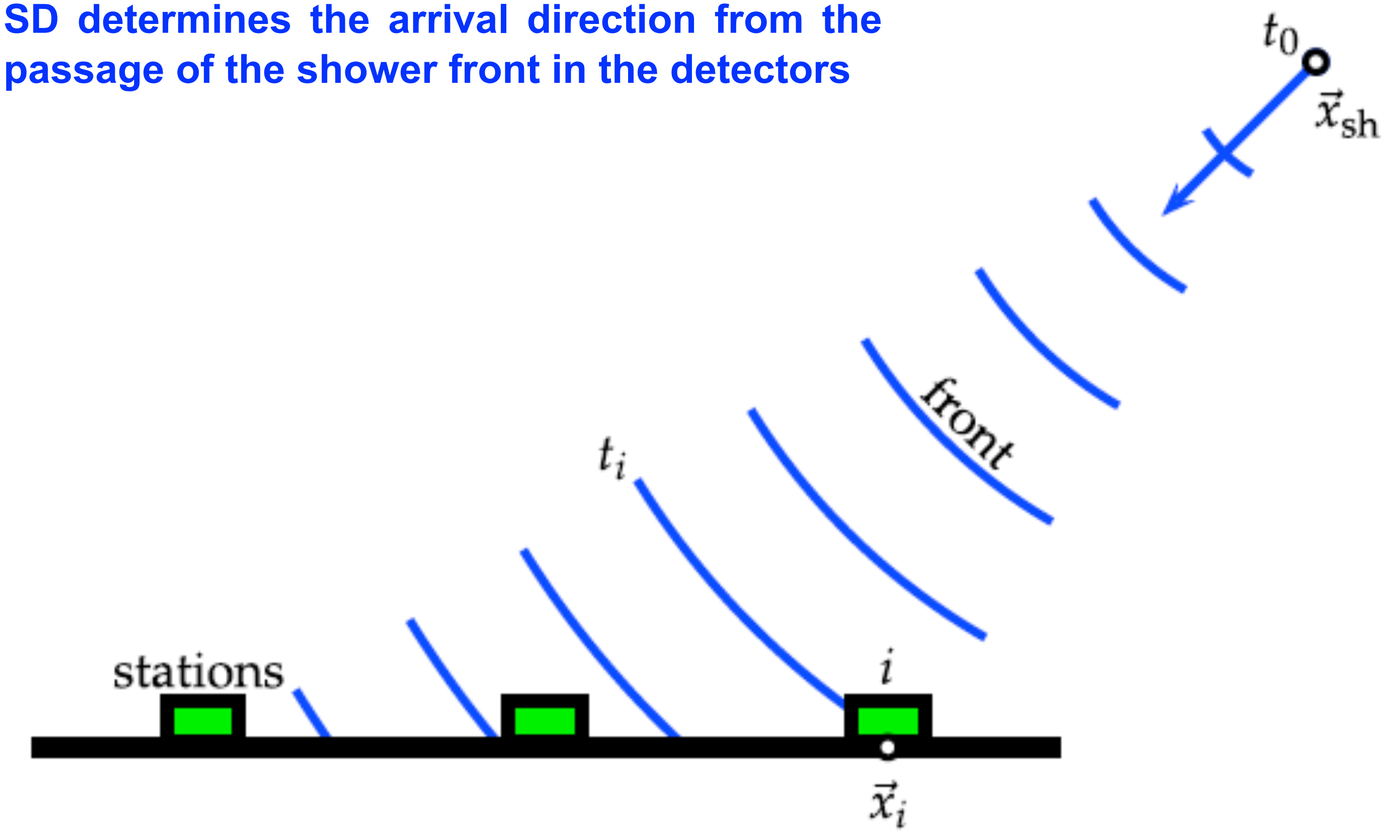


Let's start from the simplest one: arrival direction

Surface detectors

Most straightforward measurement: **the shower axis preserves the direction of the incoming particle**

SD determines the arrival direction from the passage of the shower front in the detectors



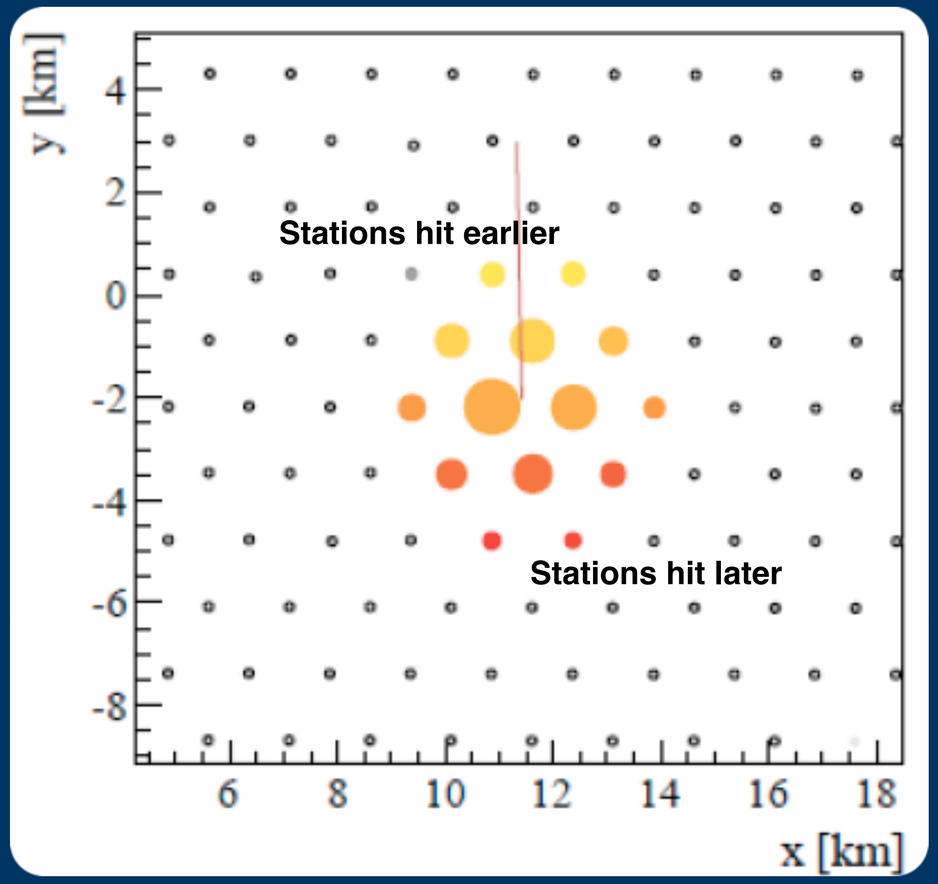
Time-of-flight technique:

Time differences among the arrival times t_i of shower particles in the different detectors give the arrival direction

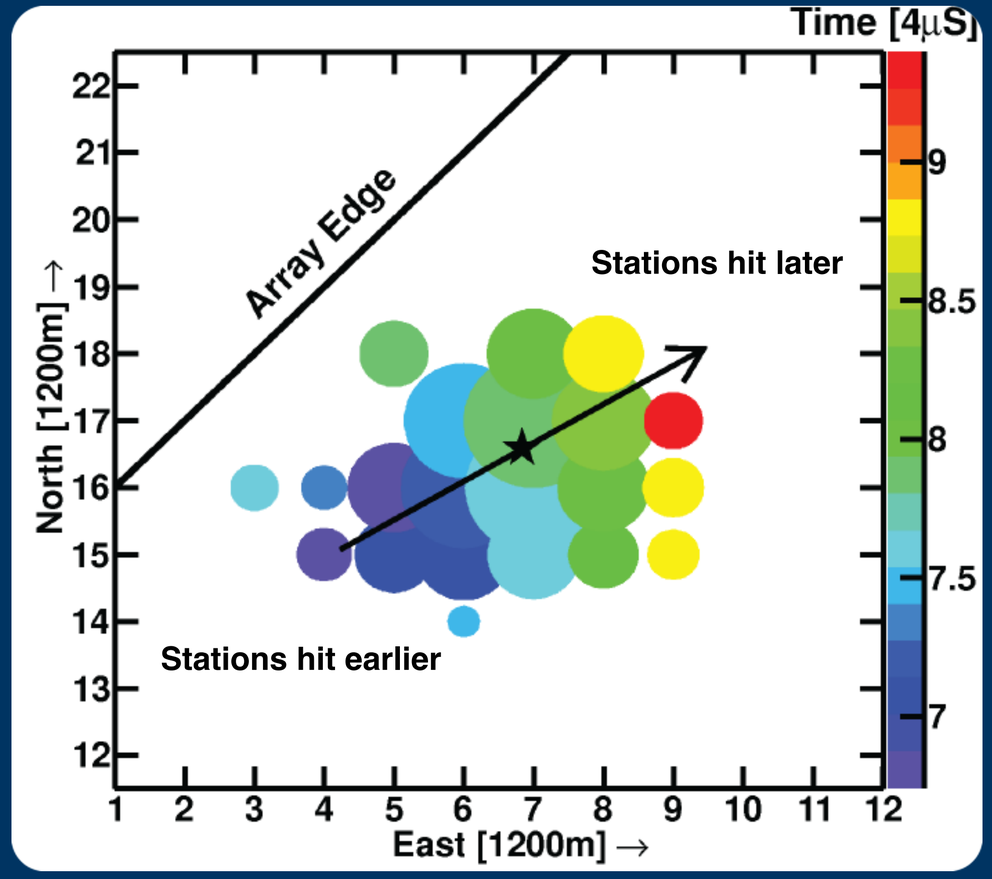
Measurement of the arrival direction

In practice

Auger



Telescope Array



Arrival direction: estimated by a fit of the shower front (moving at c)

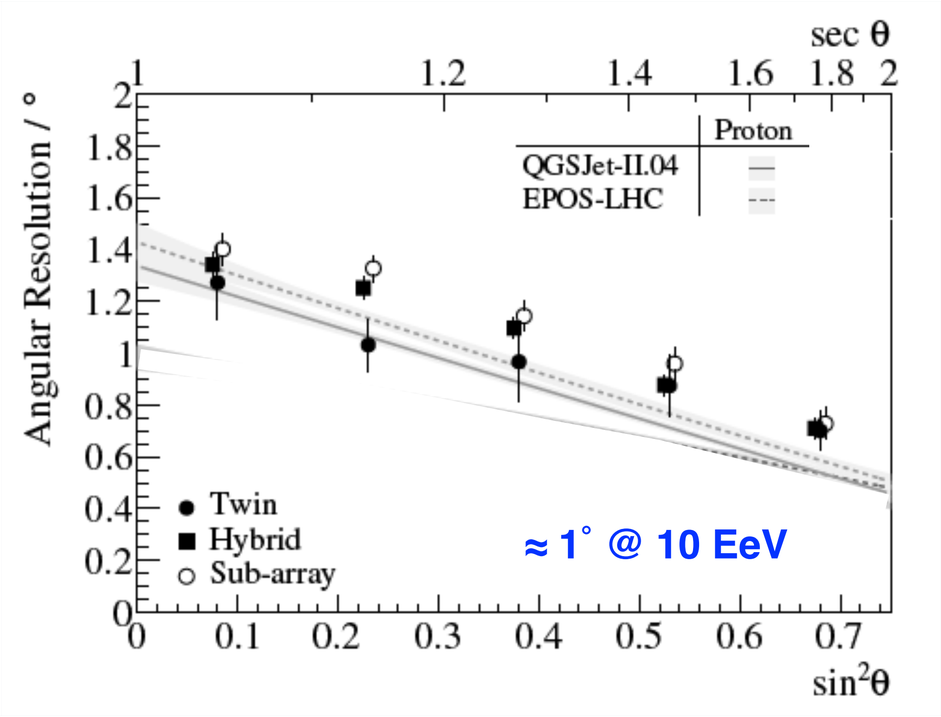
If only 3 detectors are triggered: fit to a plane front

If more: fit to a spherical front

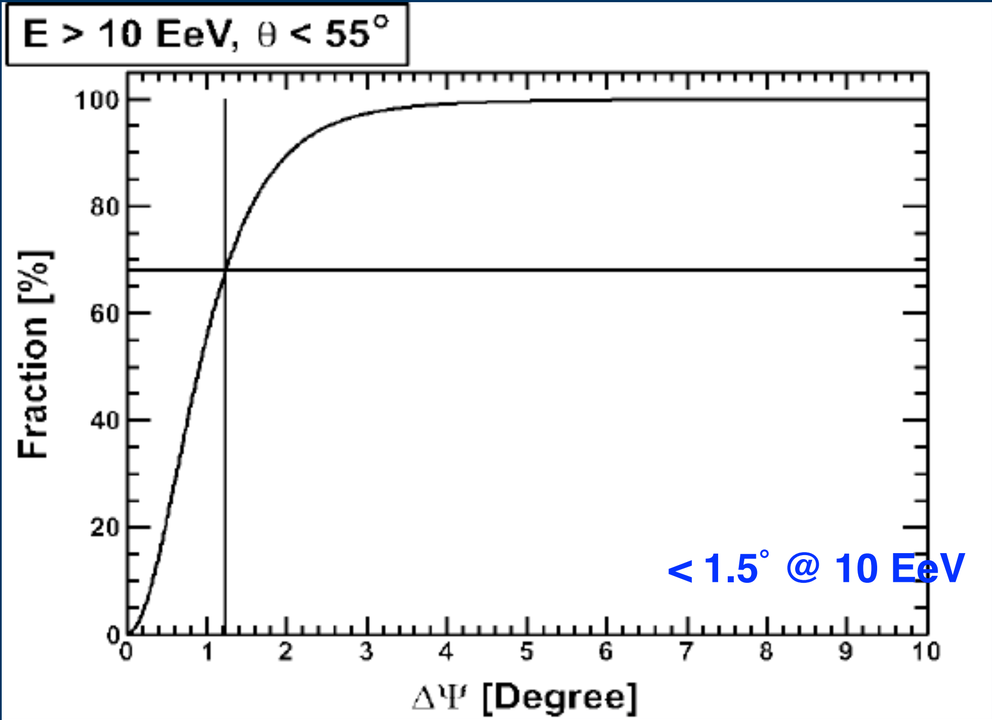
Arrival direction (angular) resolution

SD angular resolution

Auger



Telescope Array



Angular resolution: determined via simulations

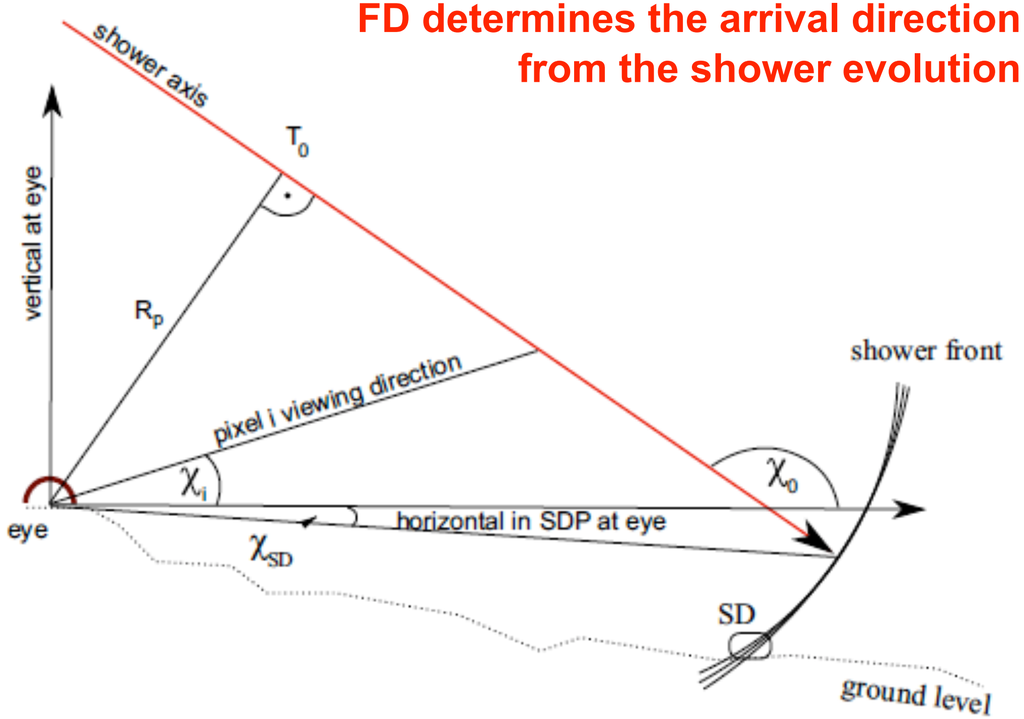
The reconstructed arrival direction is compared with the injected one (for Auger, cross-check with data too)

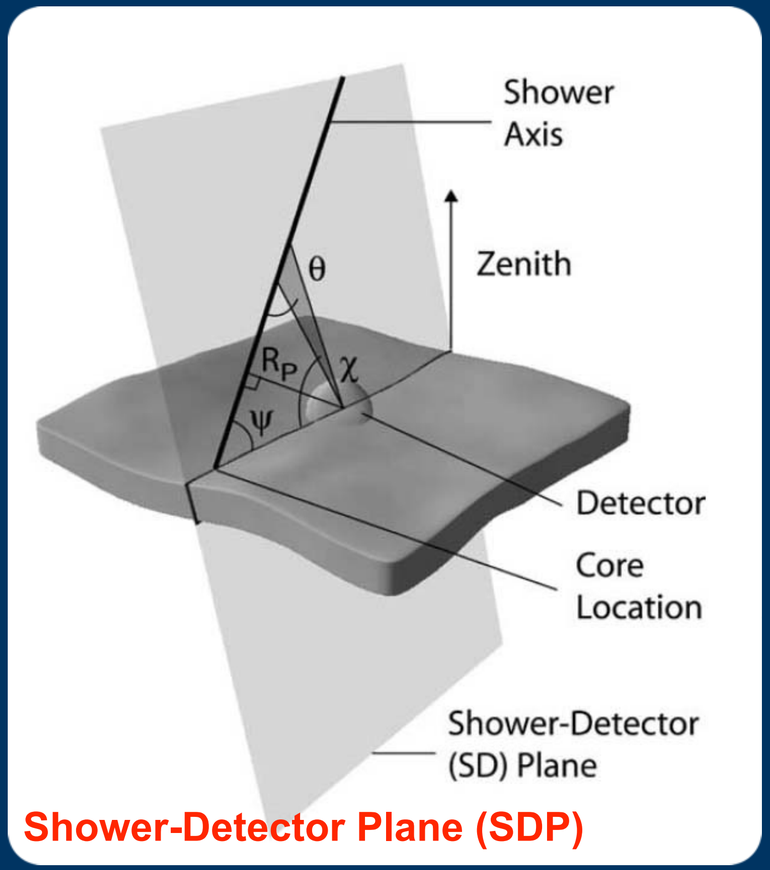
It depends on the timing resolution and on the number of triggered detectors

Measurement of the arrival direction

Fluorescence detectors

FD determines the arrival direction from the shower evolution





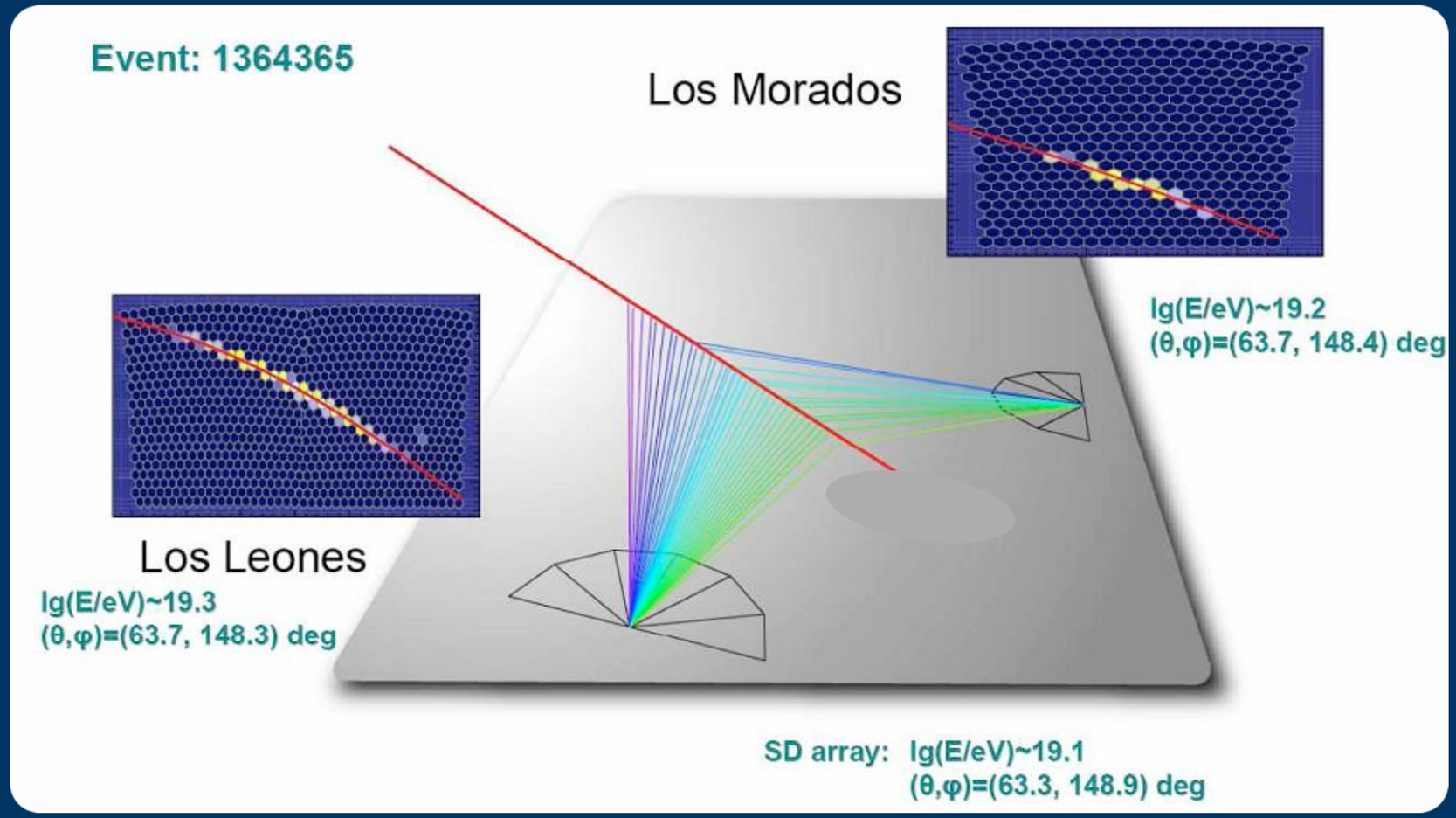
Shower-Detector Plane (SDP)

The arrival direction is obtained in two steps:

1. The viewing directions of the triggered pixels and the detector itself define the so-called Shower Detector Plane
2. The SDP contains the shower axis. The position of the shower axis within the SDP is obtained using the trigger times from the PMTs.

Measurement of the arrival direction

"Stereo" events, i.e., observed by two or more FDs

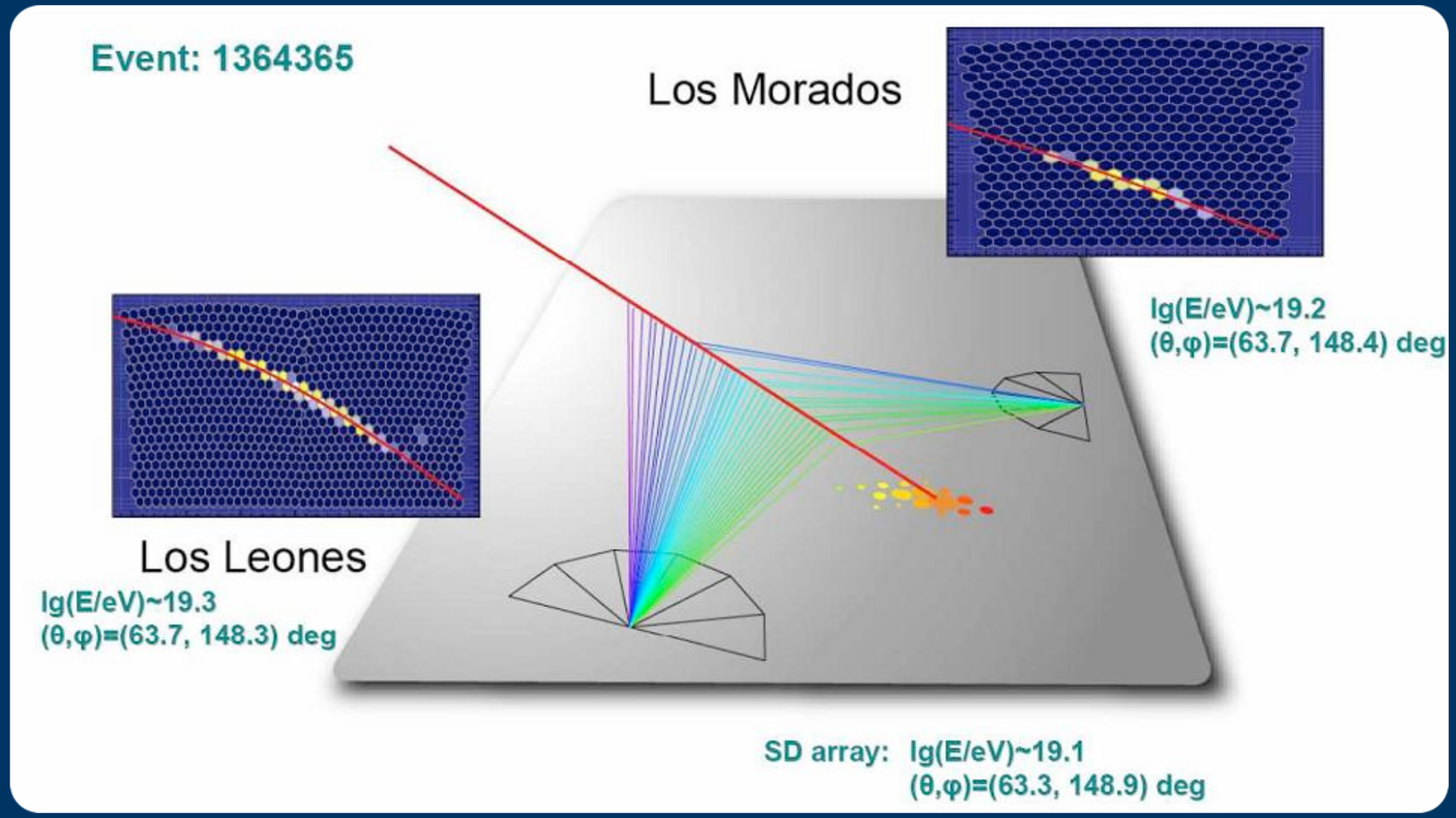


When an EAS is observed in "stereo", the arrival direction is defined by the intersection of two (or more) SDPs.

Higher precision, check of the geometry

Measurement of the arrival direction

"Hybrid" events, i.e., observed by SD and FD simultaneously



When an EAS is observed in "hybrid" mode, the geometry of the shower is fixed by SD (core position).

The angular resolution improves to ≈ 0.5 deg

Arrival direction: a glance at the past

Nani gigantum humeris insidentes: Bassi, Clark, Rossi (again!), (1953)

The idea of constructing large-area detectors, in which fast timing of the arrival of the shower particles would be possible, is due to the MIT group, led by Rossi.

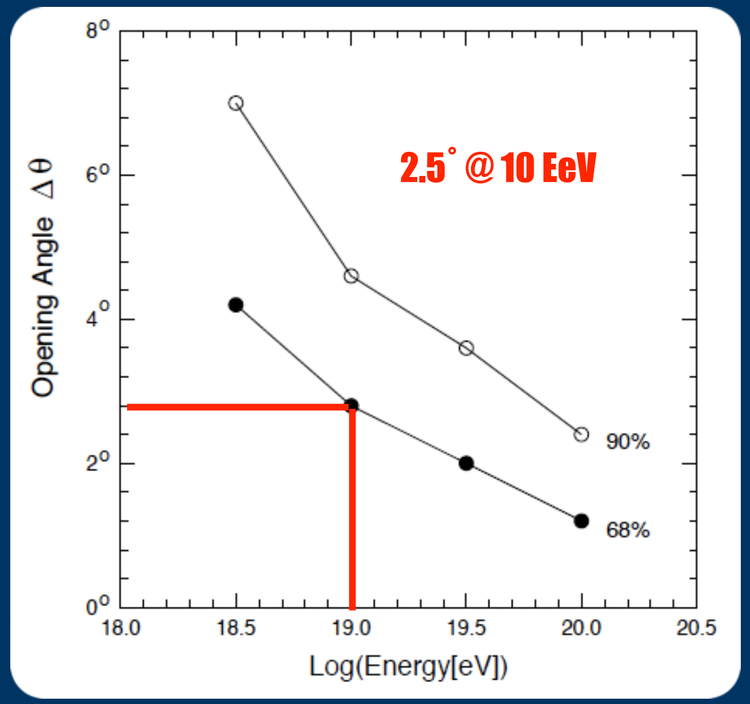
They predicted that the shower directions could be determined within 2 degrees.

EARLIER EAS INSTRUMENTS

where.[1] An array of scintillation detectors is used to find the direction (from pulse times) and size (from pulse amplitudes) of shower events which satisfy a triggering requirement. In the present case, the direction of the shower was nearly vertical (zenith angle $10 \pm 5^\circ$). The values

Volcano Ranch (1960s)

AGASA (1990s)



The predictions were not so wrong after all, even for "old" instruments (old electronics)

Slightly more difficult: energy

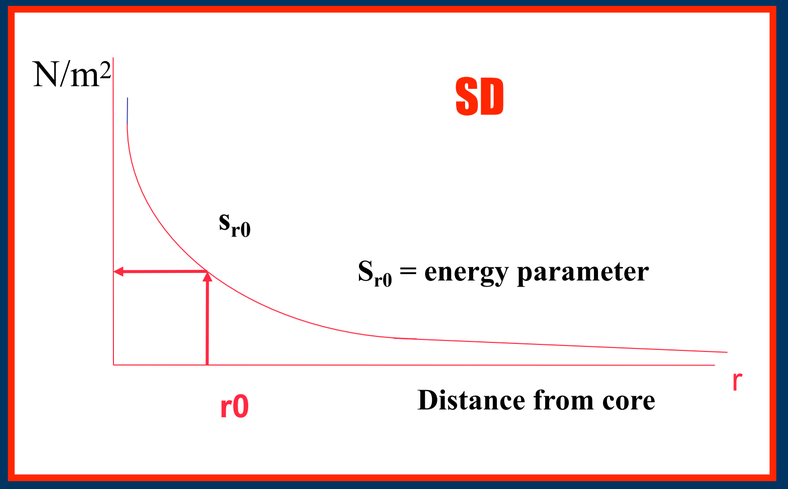
Different energy estimators

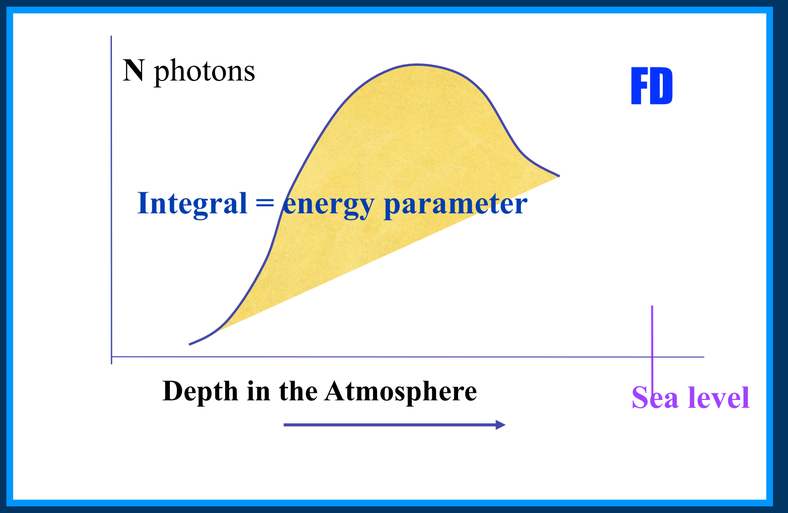
Number of electrons Ne (shower size): at shower maximum Ne is proportional to primary energy (**need MC to convert**)

Lateral distribution of particles: there is a distance, r0, at which density fluctuations are minimal with respect to primary energy/ mass: S (r0) is the energy estimator (**need MC to convert**)

Number of muons Nμ : less absorbed, “flatter” longitudinal development, less fluctuations. Less numerous than electrons, but ≈ independent of mass (**need MC to convert**)

Cherenkov and fluorescence photons: direct measurement of shower energy deposited in atmosphere (total number of Cherenkov photons; longitudinal shower profile). **No need for MC**





Slightly more difficult: energy

Surface detectors

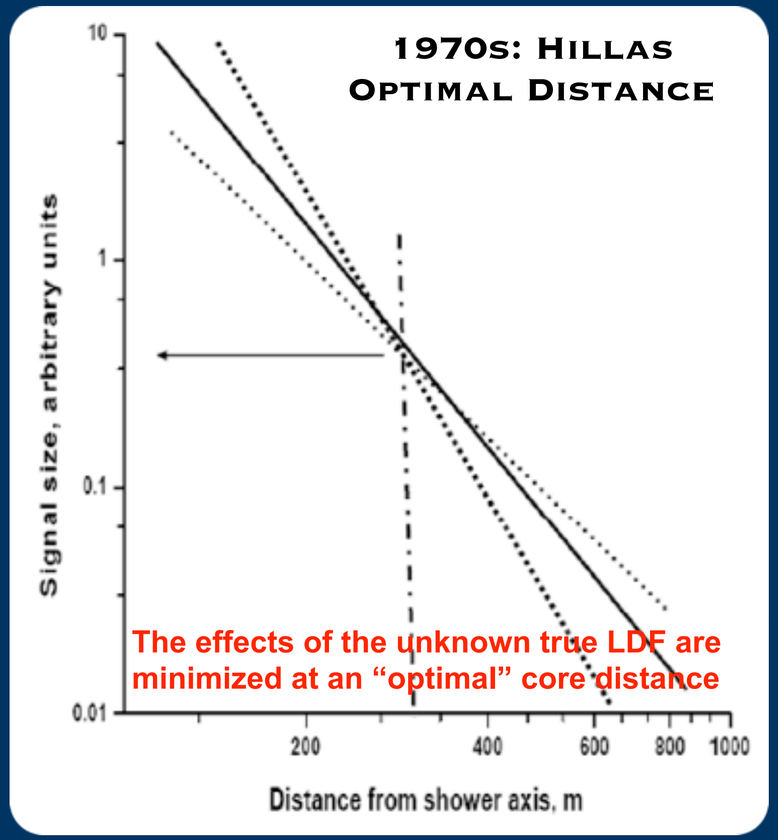
SD measures a “slice” of the energy deposited from the shower:

the best one can do is extracting from the “slice” an energy estimator

The **shower size** is an energy estimator. But, because of fluctuations in the shower development, the association is not simple. A lower-energy cosmic ray interacting deep in atmosphere can create a cascade with the same size at ground as the one produced by a more energetic particle interacting higher in atmosphere.

Measuring the shower size at the depth of the shower maximum reduces the impact of the fluctuations; but, observations at the shower maximum are only possible at high altitudes and for relatively low-energy events.

For depths lower than that of the shower maximum, and for a large spacing between detectors, determining the fall-off of the signal vs distance from the axis is difficult, and it cannot be determined with precision on an event-by-event basis.



Hillas’ technique:

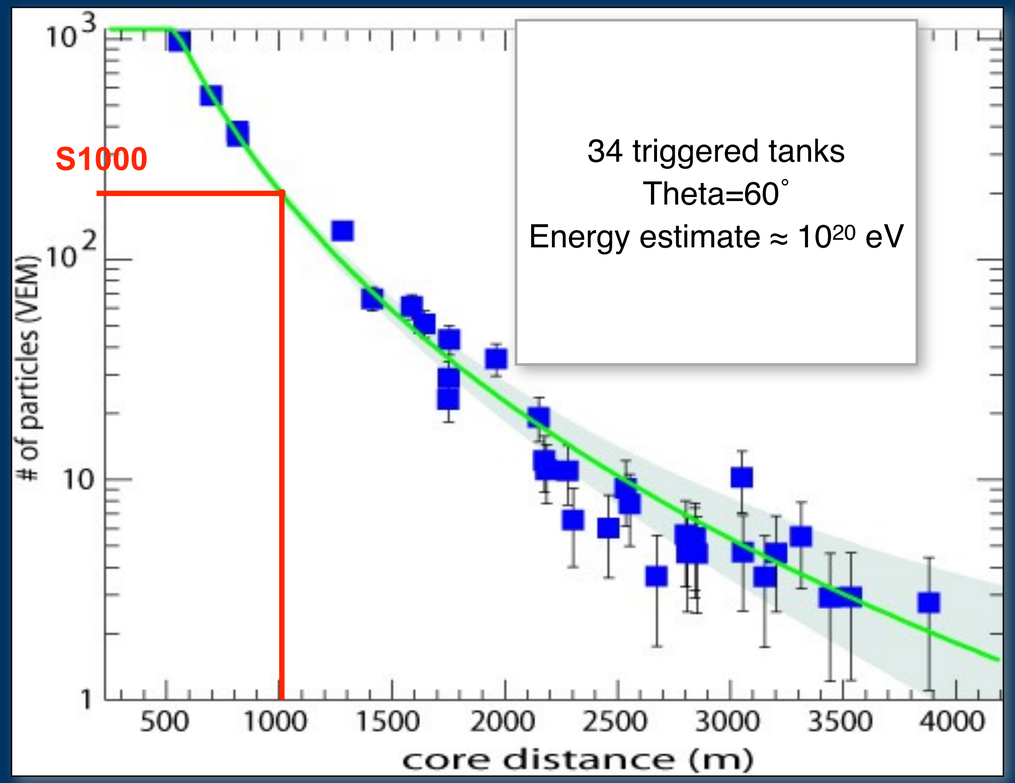
Use the signal at a distance appropriate for the separation of the detectors (**Optimal distance**) at which the uncertainty in the determination of this signal is least susceptible to the lack of knowledge of lateral distribution function

Not only the signal at the “optimal” distance minimally depends on the chosen LDF, but also the fluctuations of the particle density far from the core are quite small.

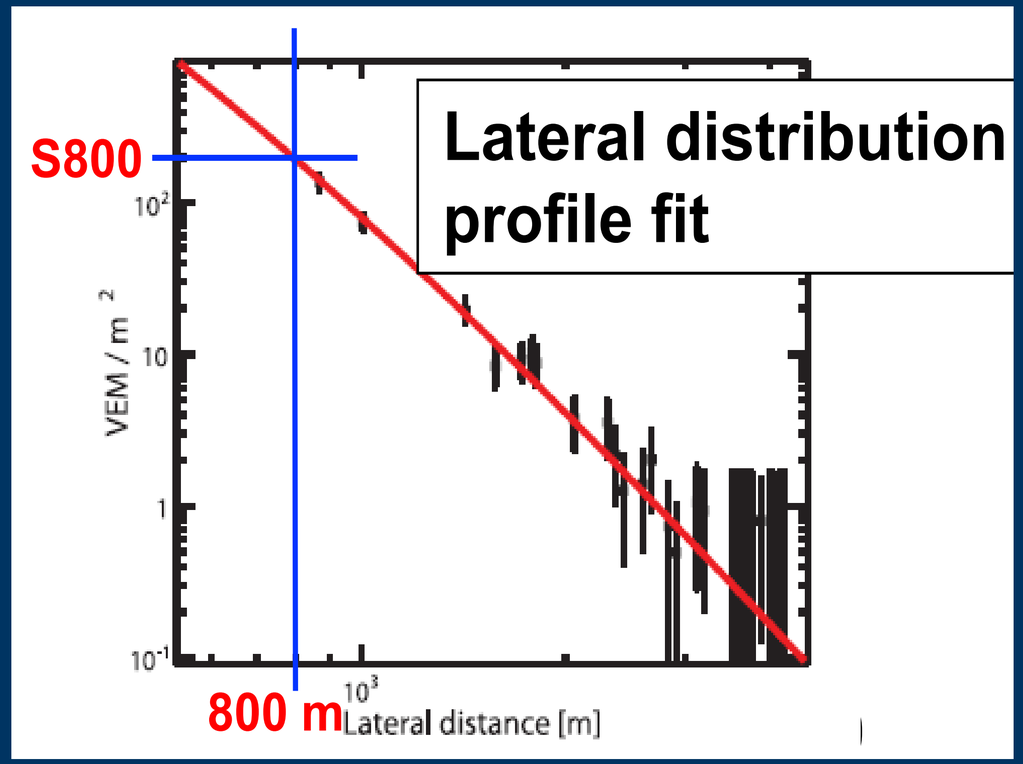
Energy determination with Auger and TA surface detectors

In practice: how to get the energy estimator

Auger



Telescope Array



Reconstruct geometry (arrival direction & impact point)

Fit signals vs distance from the core **to a lateral distribution function** (LDF)

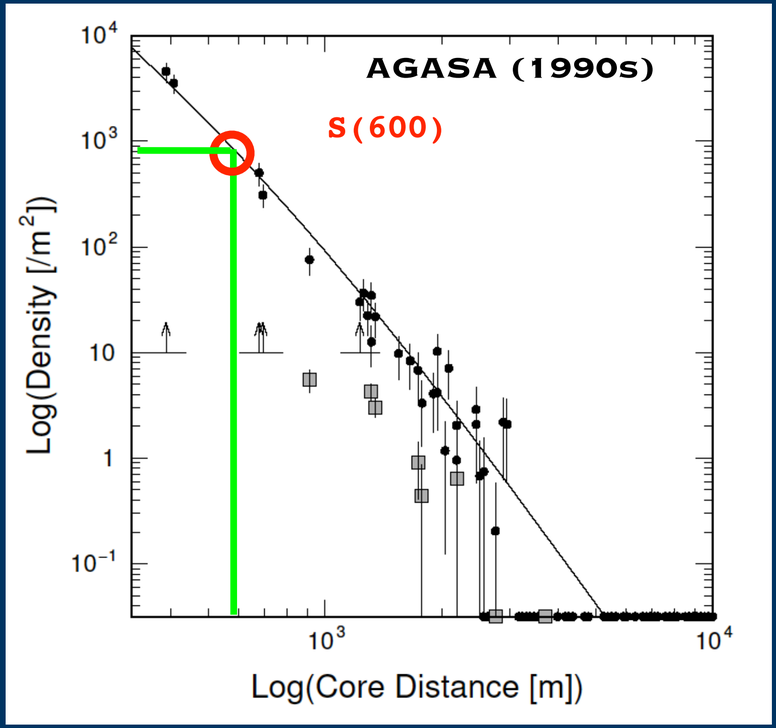
Extract the signal at the "optimal" distance

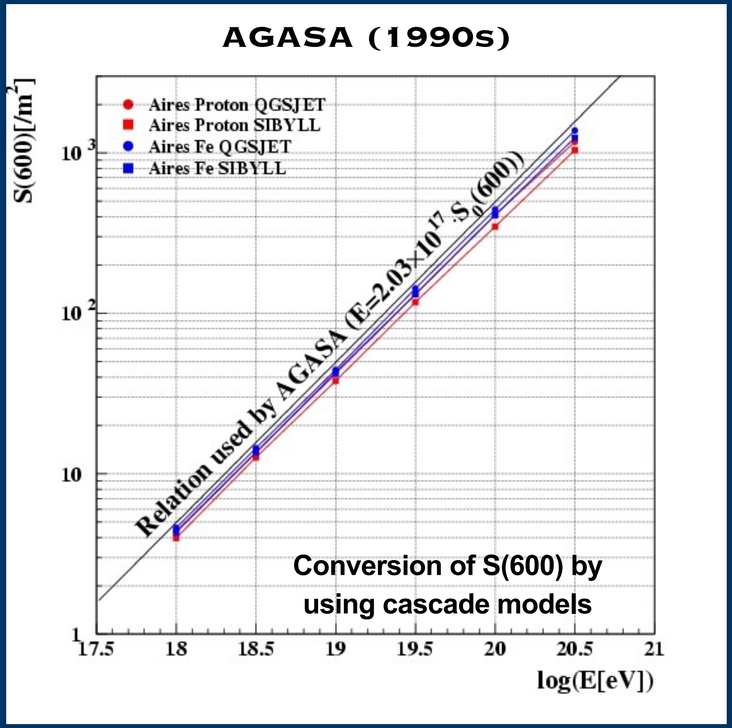
The "optimal" distance depends on detectors spacing, (ropt=1000/800 m for Auger/TA)

How to pass from energy estimator to primary energy?

Earlier: full Monte Carlo simulations were used

EARLIER EAS INSTRUMENTS





To convert the energy estimator into energy, predictions from calculations/simulations of shower development: look-up tables

However, model predictions draw on extrapolations of the properties of interactions studied at accelerators. Large (if not unknown) systematics, even after LHC

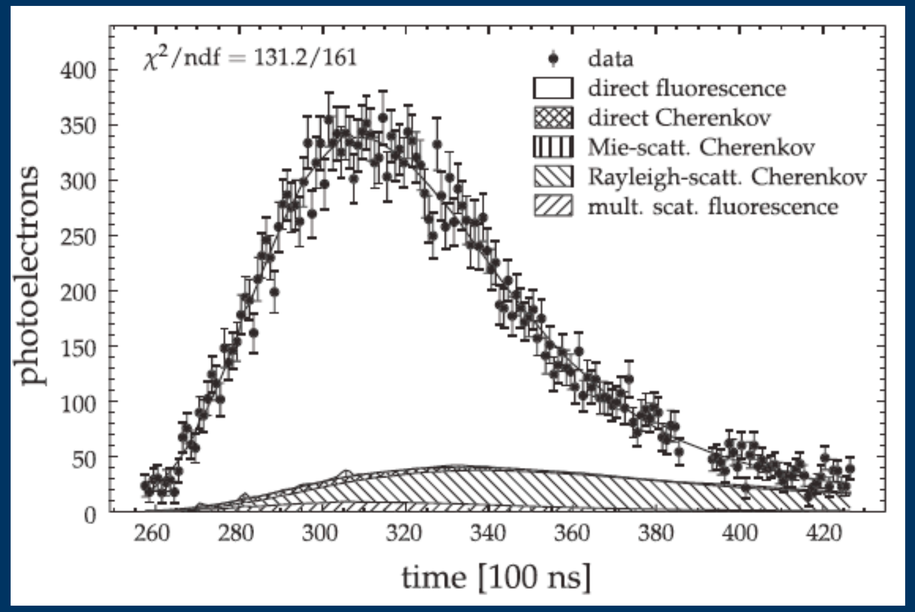
Also, models require a mass-composition, that must be assumed. Large (if not unknown) systematics

Primary energy from fluorescence detectors

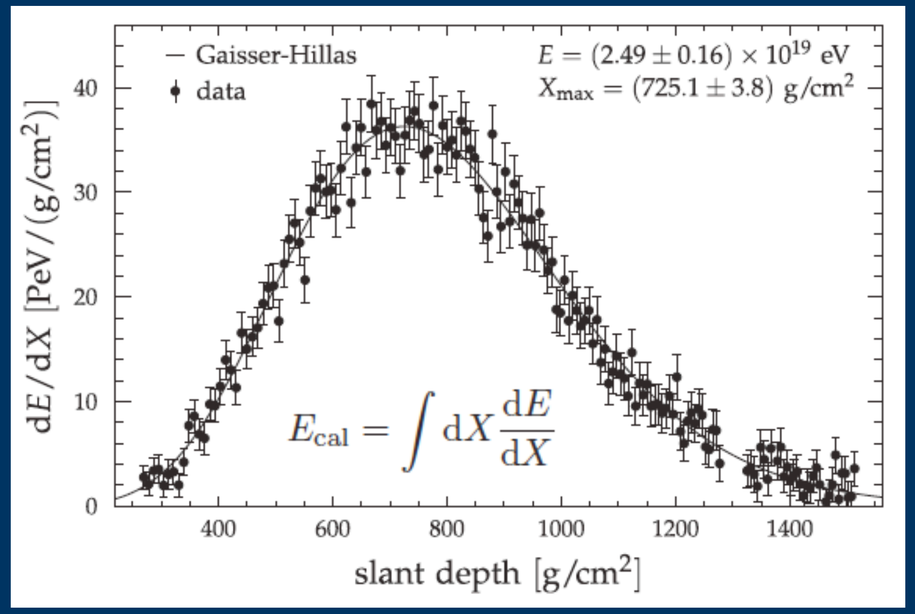
Data-driven calibration

The cosmic ray energy is deposited in atmosphere like in a giant calorimeter. Fluorescence detectors see the full development, thus allowing for a **direct measurement of the shower energy** deposited in atmosphere.
Model predictions do not enter the game!

Photons vs time



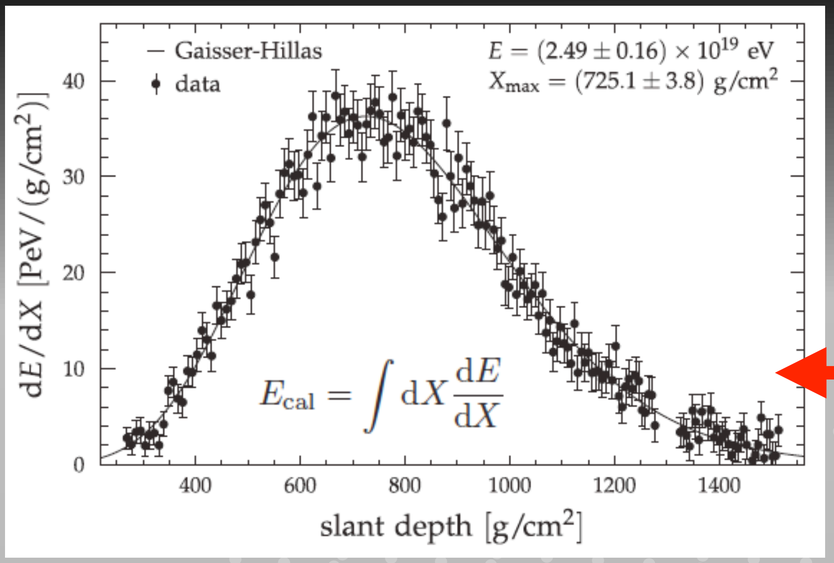
Energy deposit vs slant depth



Reconstruct geometry (shower detector plane - SDP - and shower axis in SDP)
Fit the number of photons detected in the PMTs to a longitudinal shower profile (usually the Gaisser-Hillas function)
The number of detected **photons is folded with the fluorescence yield, and the atmospheric transmission**
The energy is derived after **correcting for the "invisible" energy, carried away by neutrinos and muons.**

Primary energy: calibrate SD energy estimator with FD energy

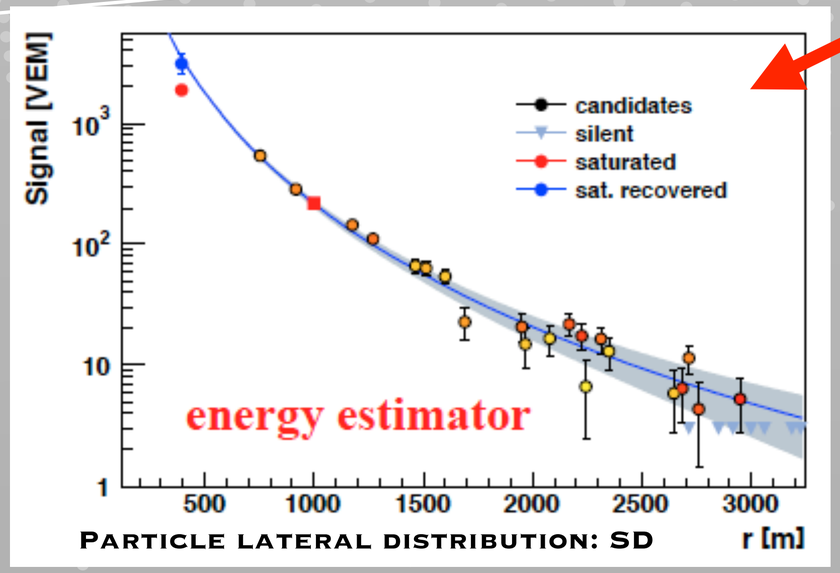
The smartness of the hybrid detection



LONGITUDINAL PROFILE RECONSTRUCTION: FD

FD

SD

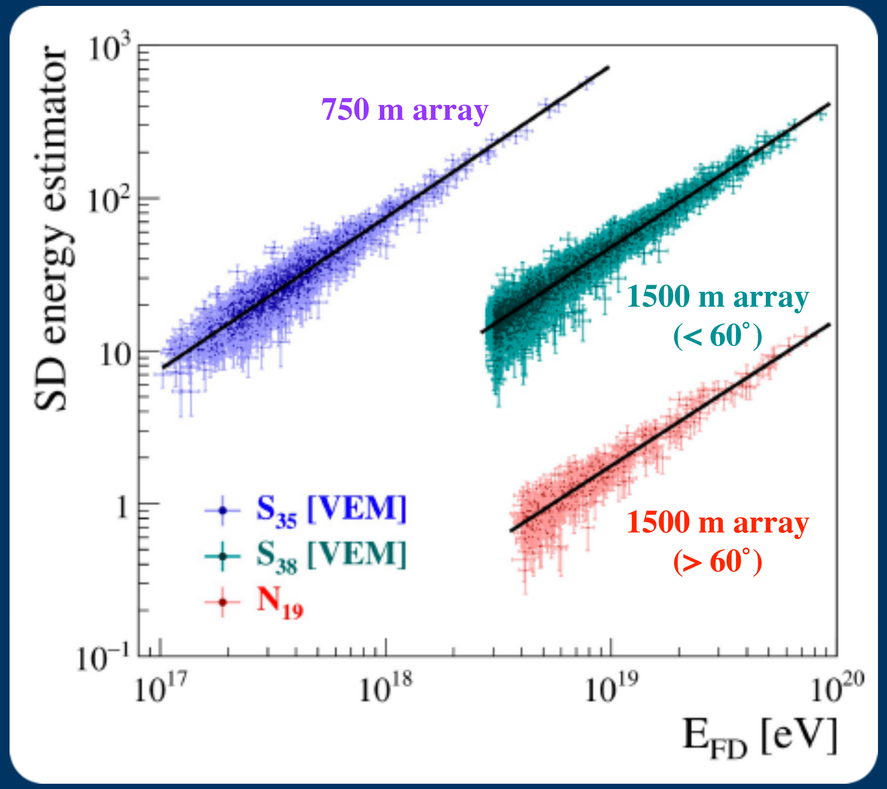


PARTICLE LATERAL DISTRIBUTION: SD

Primary energy: calibrate SD energy estimator with FD energy

Energy calibration in practice

AUGER

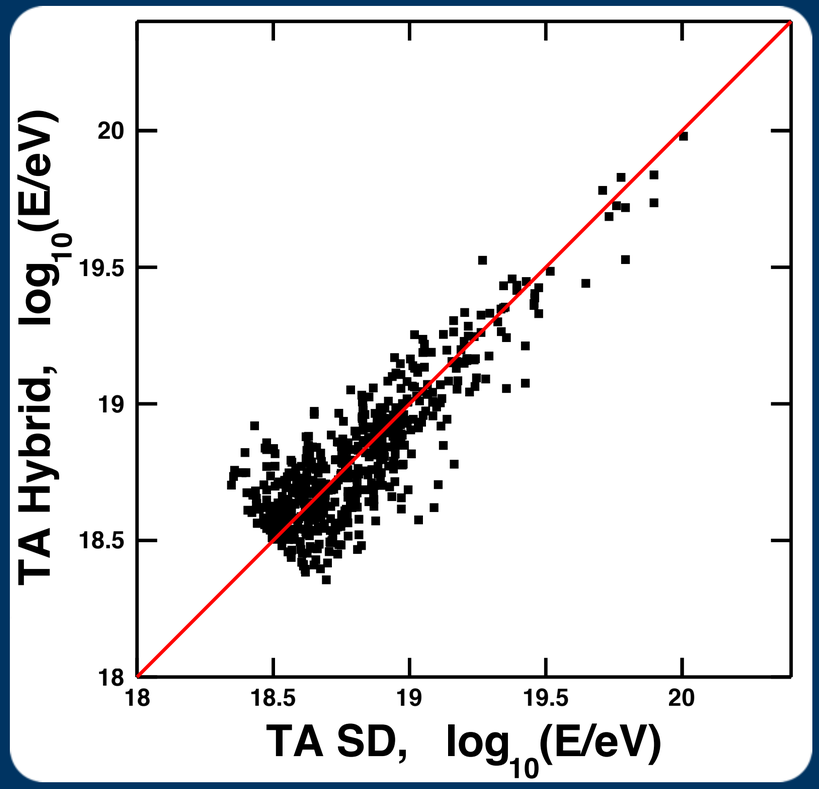


Purely data-driven calibration

S(1000) is corrected for attenuation/ theta (Constant Intensity Cut) -> S38

S38 is calibrated versus EFD

TELESCOPE ARRAY



Calibration through a MC look-up table

The model dependence is removed via the calibration with EFD

Primary energy: the smartness of the hybrid technique

Energy resolution

Auger

Systematic uncertainties on the energy scale	
Fluorescence yield	3,6 %
Atmosphere	3.4%-6.2%
FD calibration	9,9 %
FD reconstruction	6.5%-5.6%
Invisible energy	3%-1.5%
Stat. error of the cal. fit	0.7%-1.8%
Stability of the E scale	5 %
TOTAL	**14 %**

SD energy statistical uncertainty (@10 EeV) ≈ 12%

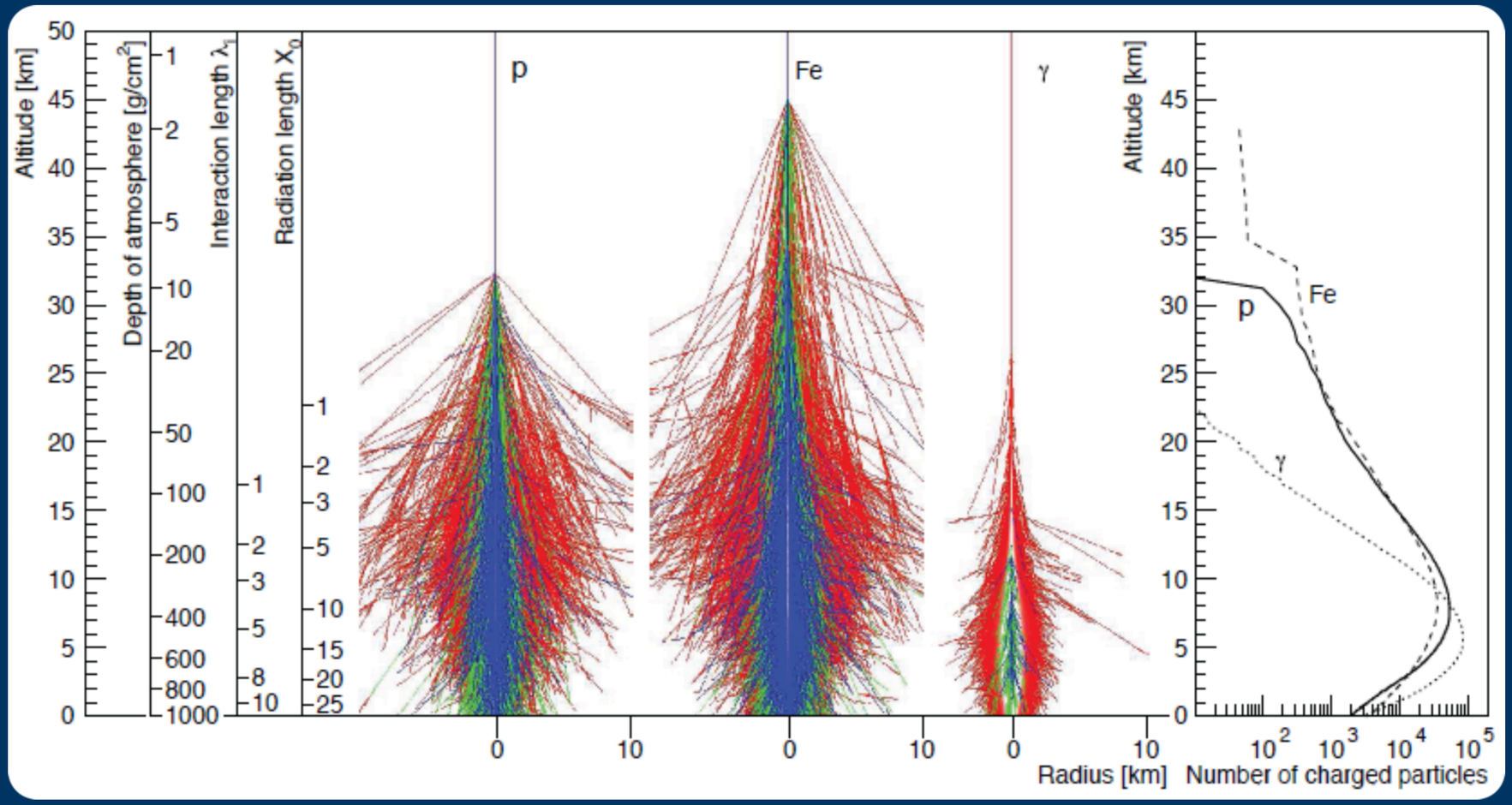
Telescope Array

Systematic uncertainty in energy determination	
Fluorescence yeild	11%
Atmospheric attenuation	11%
Absolute detector calib.	10%
reconstruction	10%
total	21%

SD energy statistical uncertainty (@10 EeV) ≈ 20%

The most difficult: mass/charge

The mass of a cosmic ray can only be inferred from comparisons of observables with shower simulations, subject to uncertainties of models of hadronic interactions at energies barely or not accessible to accelerators



Observables sensitive to mass:

Depth of shower maximum (at fixed energy, a nucleus-shower develops faster than a proton-shower)

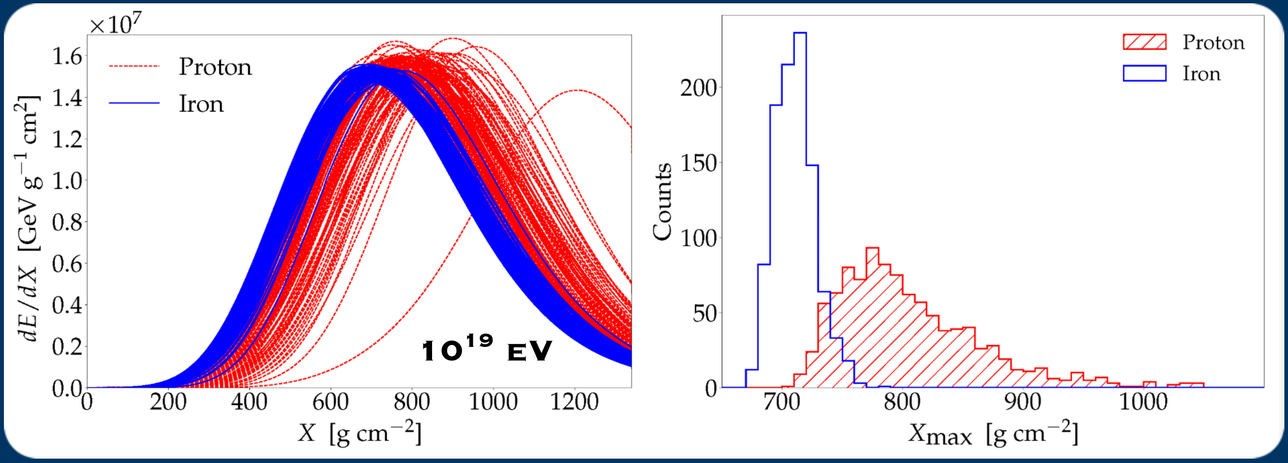
Number of muons (primary nucleus produces more muons than a primary proton)

Shower front structure: curvature and timing (the higher the first interaction, the flatter the front)

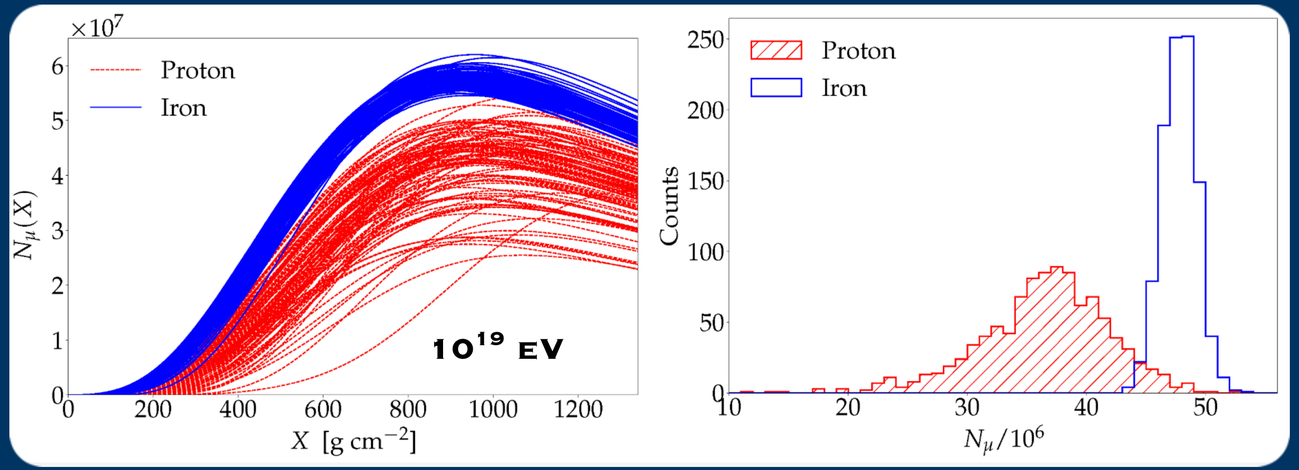
The two most mass-sensible observables

Depth of shower maximum and number of muons

Depth of the maximum



Number of muons



Observables sensitive to mass:

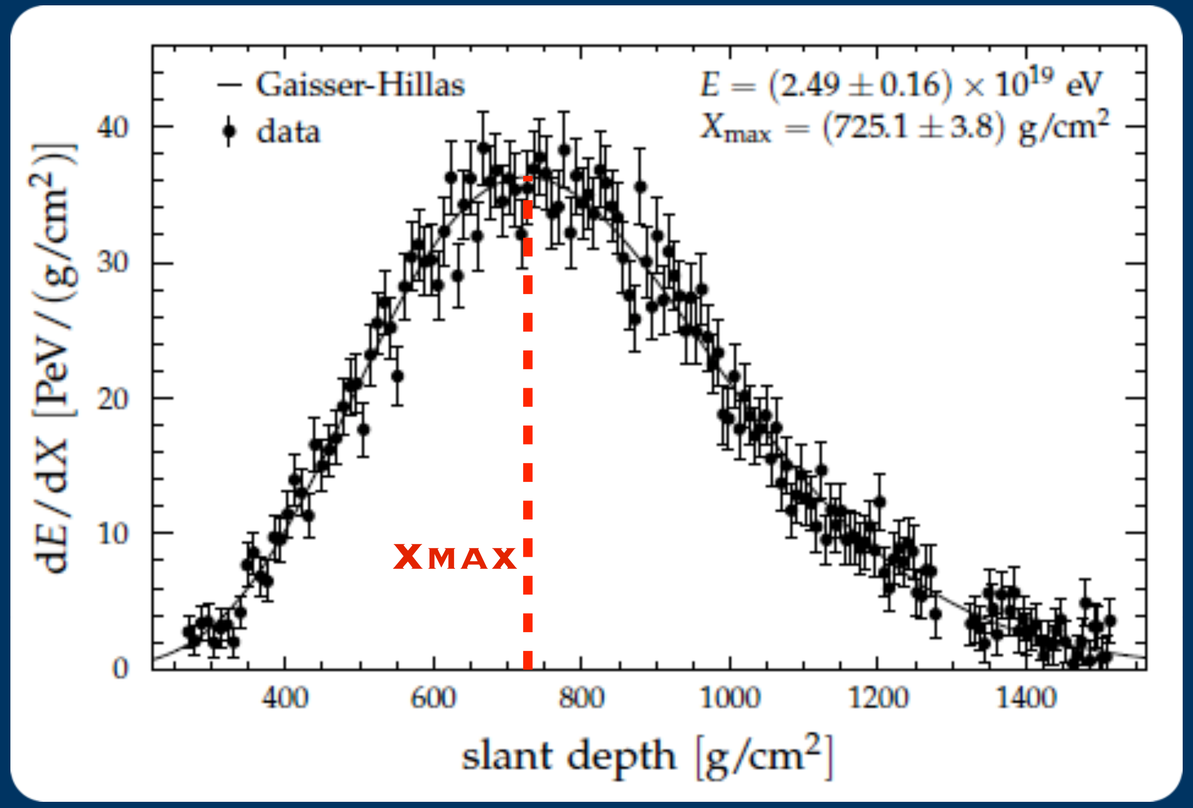
Depth of shower maximum (at fixed energy, a nucleus-shower develops faster than a proton-shower)

Number of muons (primary nucleus produces more muons than a primary proton)

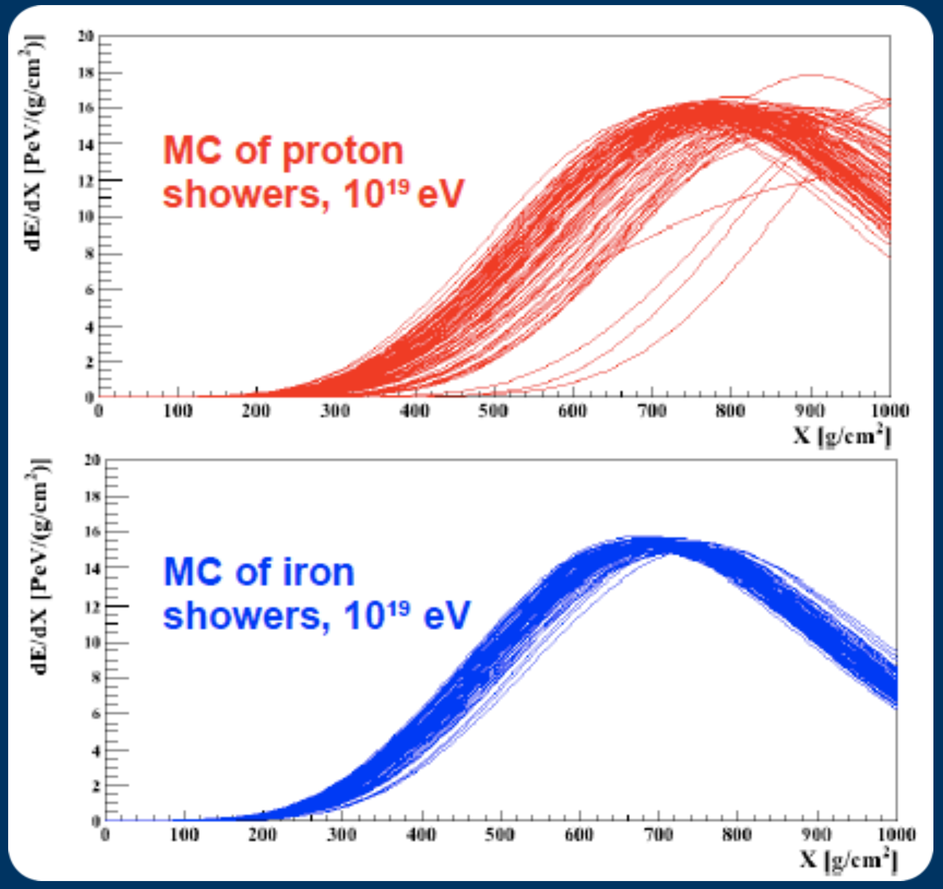
The depth of the shower maximum

Fluorescence detector

Xmax, the depth of the shower maximum, is the main EAS observable sensitive to CR mass



Xmax can be directly measured by fluorescence detectors



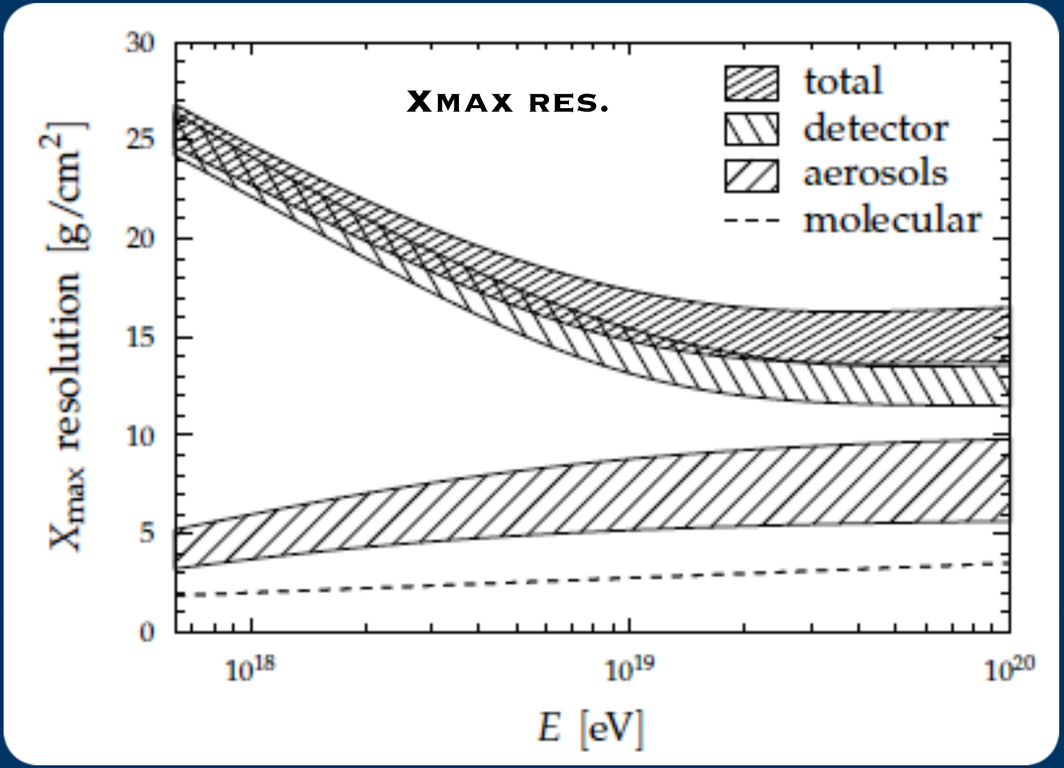
First interaction of heavier primaries is shallower and fluctuates less.

Sigma of the Xmax distribution is mass sensitive too

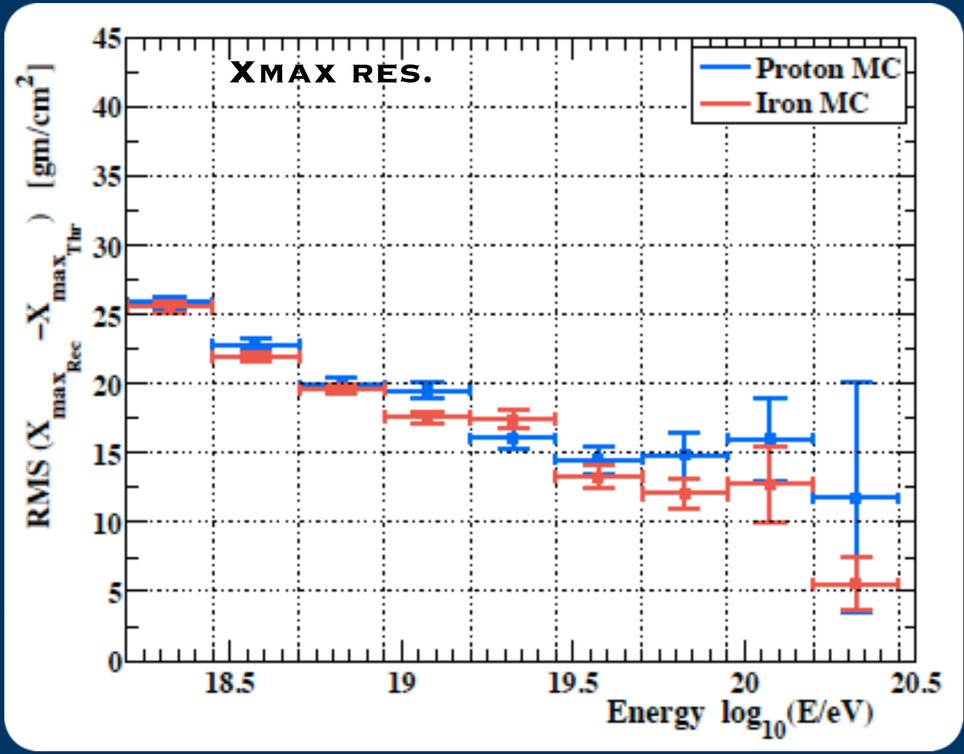
The depth of the shower maximum

Xmax resolution

Auger



Telescope Array



Between 25 and 15 g/cm2, getting better with increasing energy

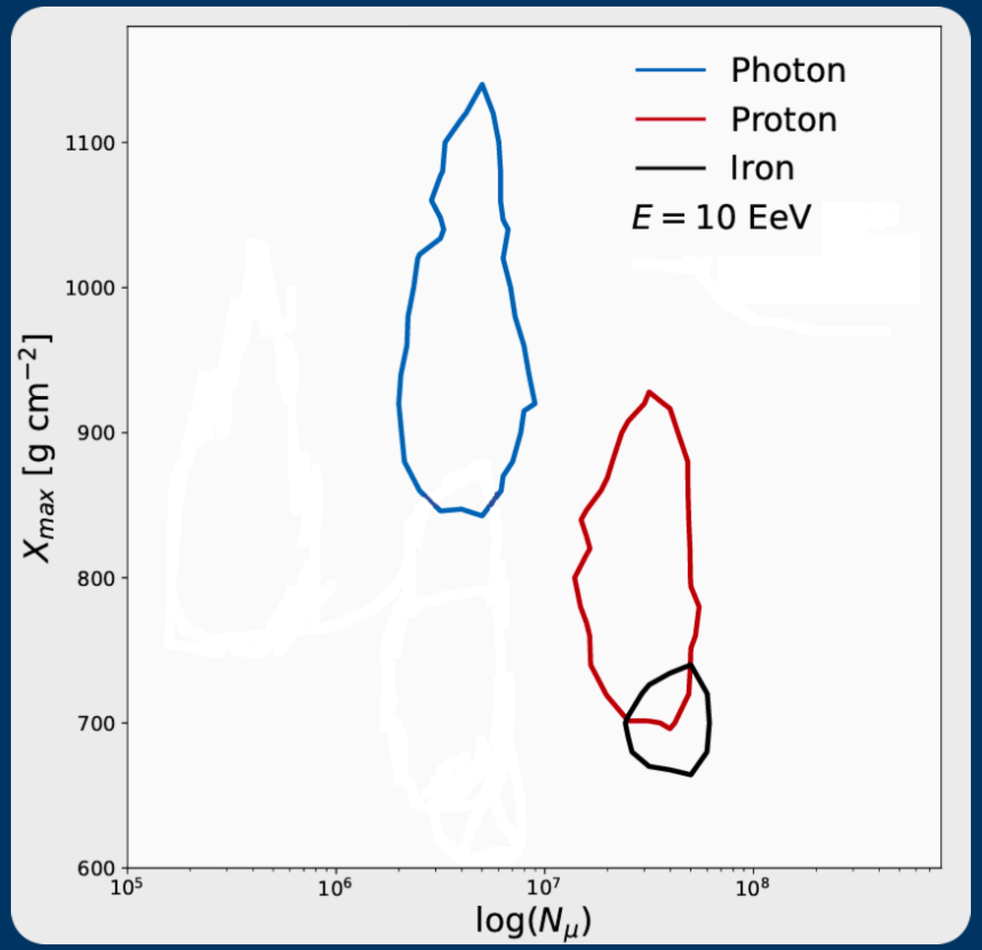
Systematic uncertainty ≈ 10%

Systematic uncertainty ≈ 16%

Not only nuclei…

Gamma-rays vs nuclei (same principles as nuclei-nuclei ;-)

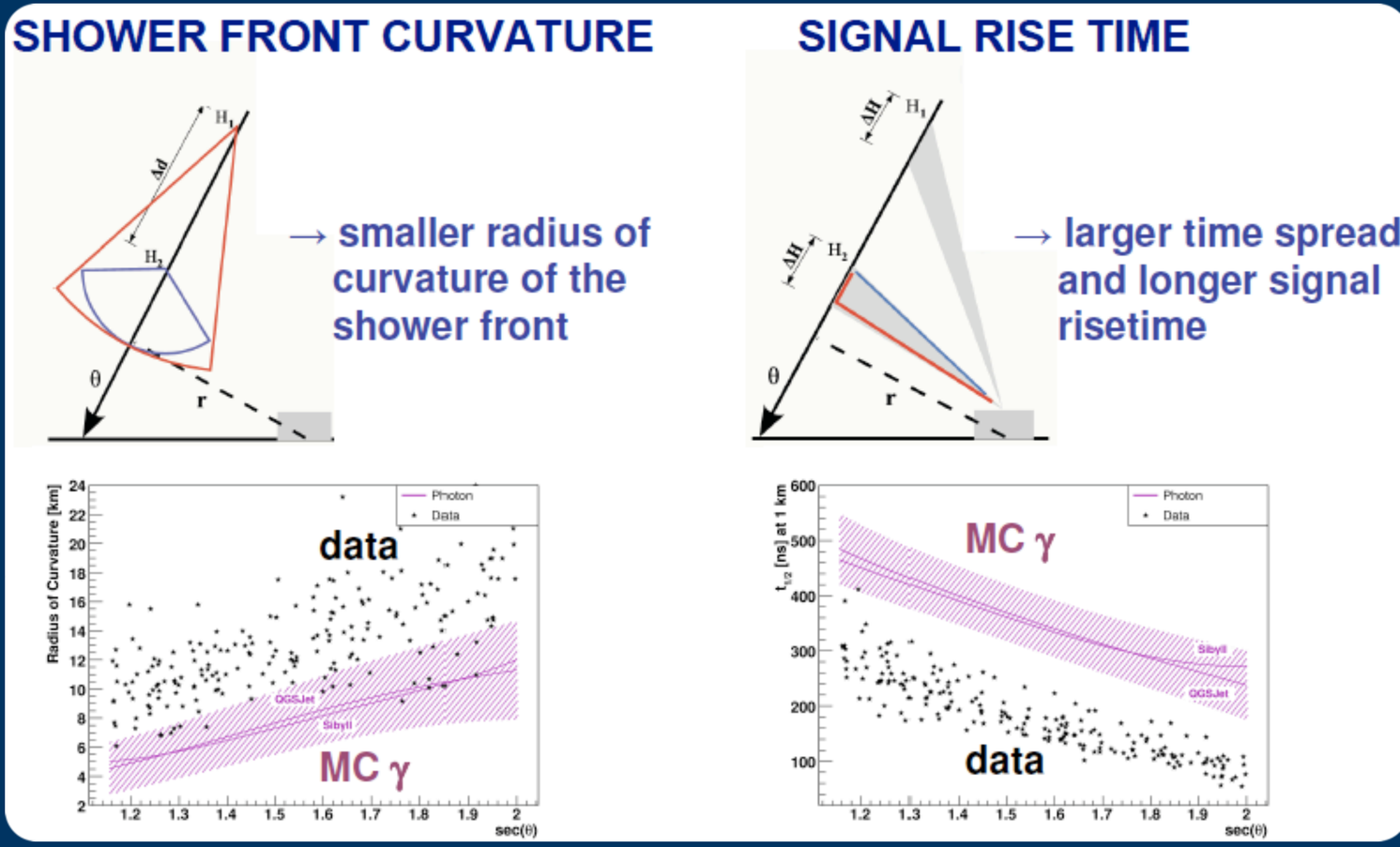
Shower development: Xmax & number of muons



Deeper maximum

Smaller number of muons

Shower-front structure



Smaller radius curvature (“younger” showers)

Longer rise time (lack of muons)

And to finish: back to the beginning…

Indirect CR detection What we measure and what we don't

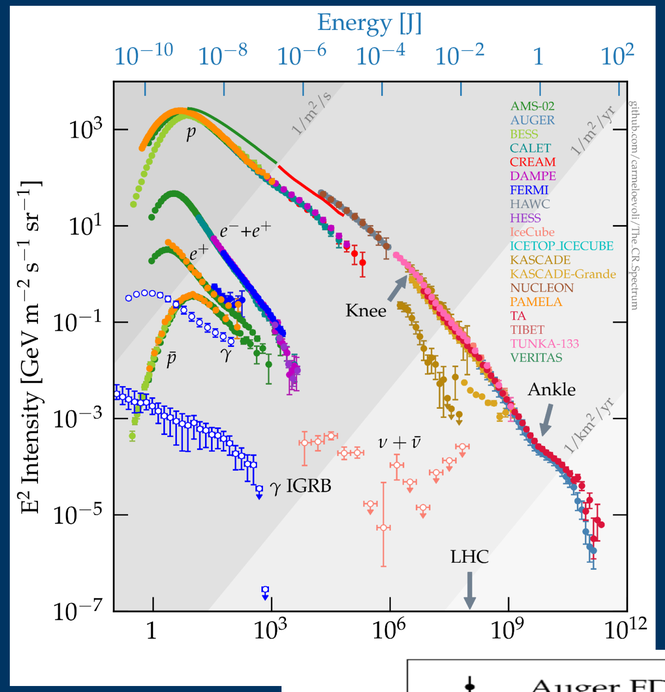
We measure

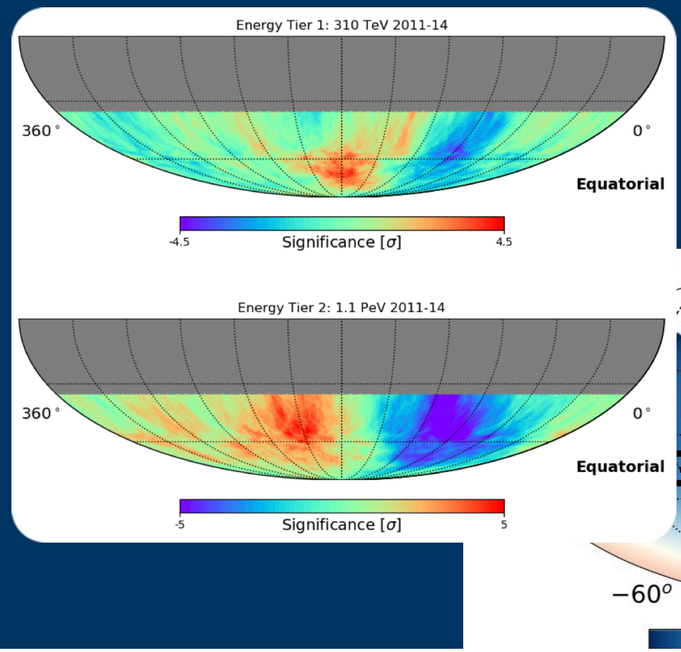
CR Energy

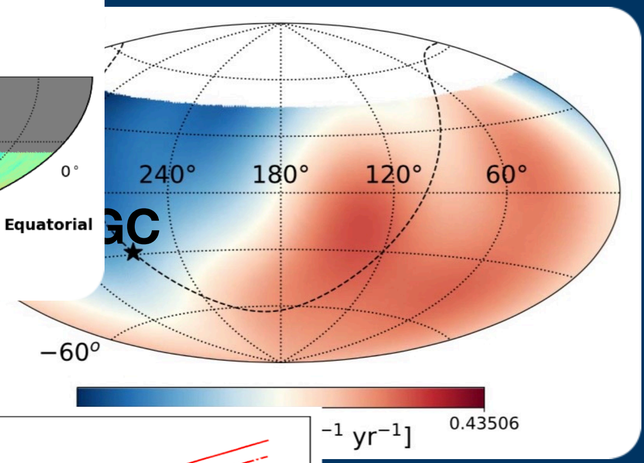
CR arrival direction

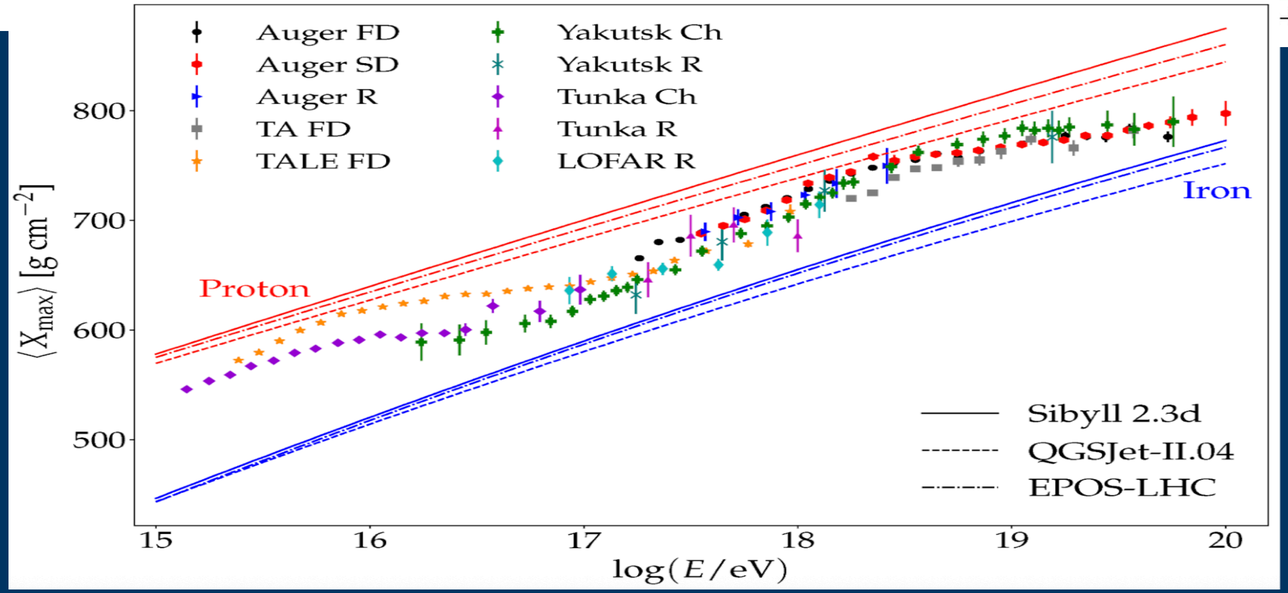
We do not measure, we infer

CR mass









Thanks for your attention have a nice school!

