Extensive Air Shower (EAS) Detection

Piera L. Ghia (IPNO-CNRS, Orsay, France)

``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)

Malargüe, 7 March 2019

OUTLINE

PROLOGUE: the relevance of 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*)**

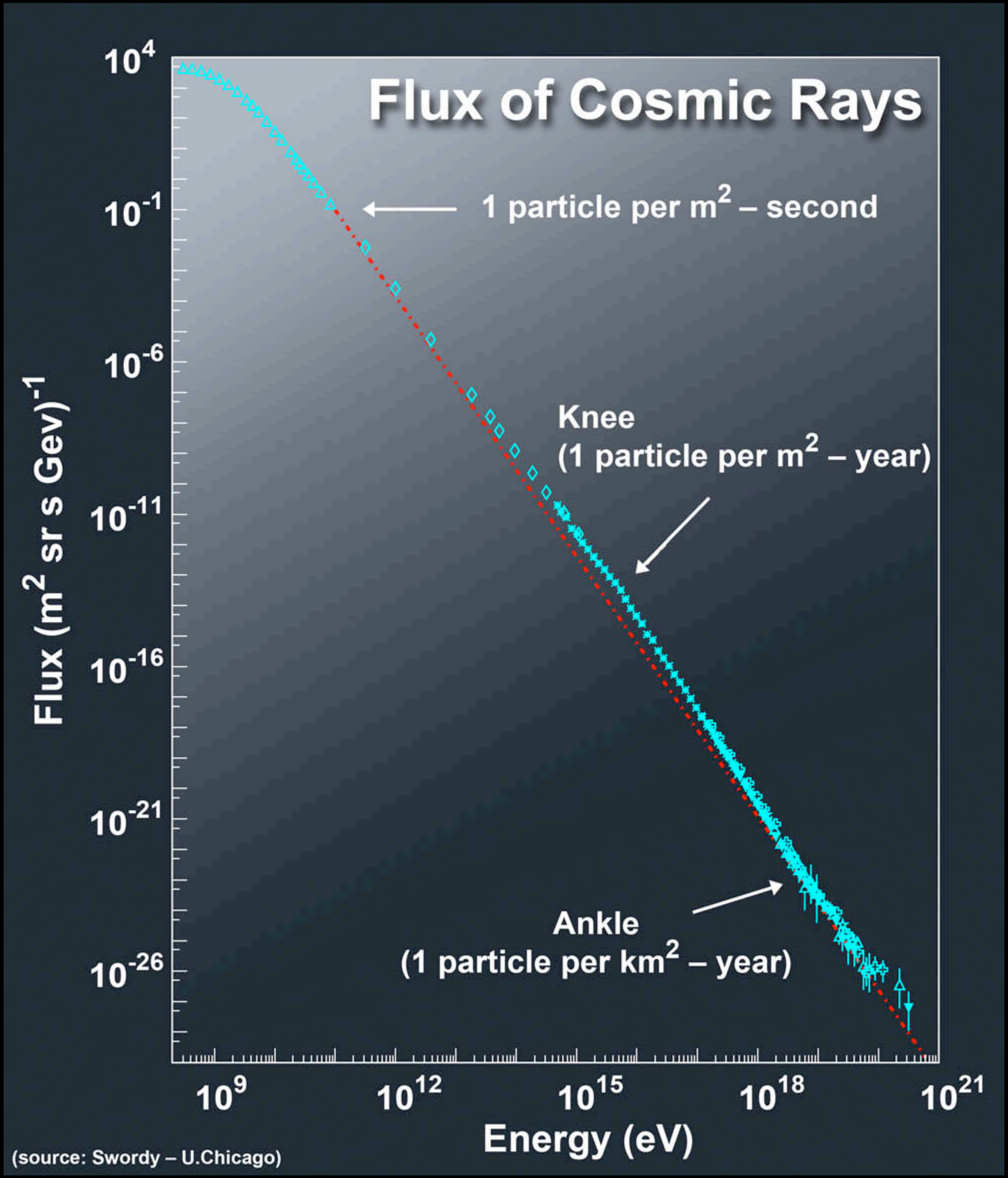
Two exemplary cases: the Auger Observatory and the Telescope Array

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

NB. For the grandeur of the inferences, don't miss Michael Unger' seminar !

The relevance of EAS detection

The energy spectrum of cosmic rays



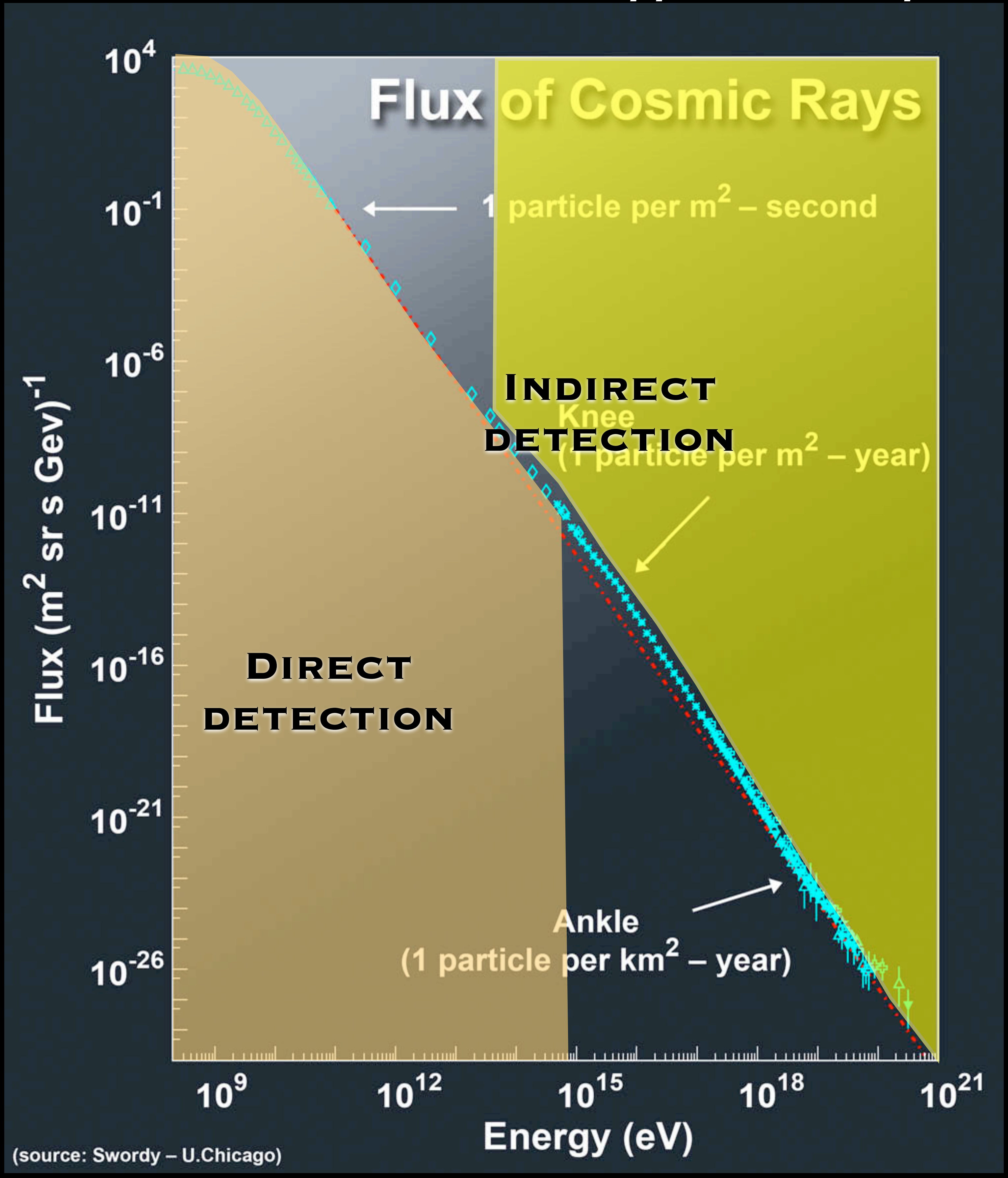
The most striking feature of cosmic rays is the fact that their energies span a very wide range

Their flux as a function of energy (the energy spectrum) is well represented by a power-law form : ($E^{-\gamma}$, $\gamma \approx 3$)

It is rather regular over ≈ 13 decades in energy, spanning ≈ 32 decades in flux!

The relevance of EAS detection

Different detection approaches depending on the CR energy



At lower energies (below tens of TeV): rather high flux ($1/m^2$ s-h) but CRs are absorbed in the upper atmosphere.
Direct detection is needed and feasible, on balloons, rockets or satellites

At higher energies (above tens of TeV): much rarer (< $1/m^2y$), but "penetrating" up to ground (via their extensive air-showers).
Indirect detection is needed and feasible with long-lived large instruments deployed at Earth

The relevance of EAS detection

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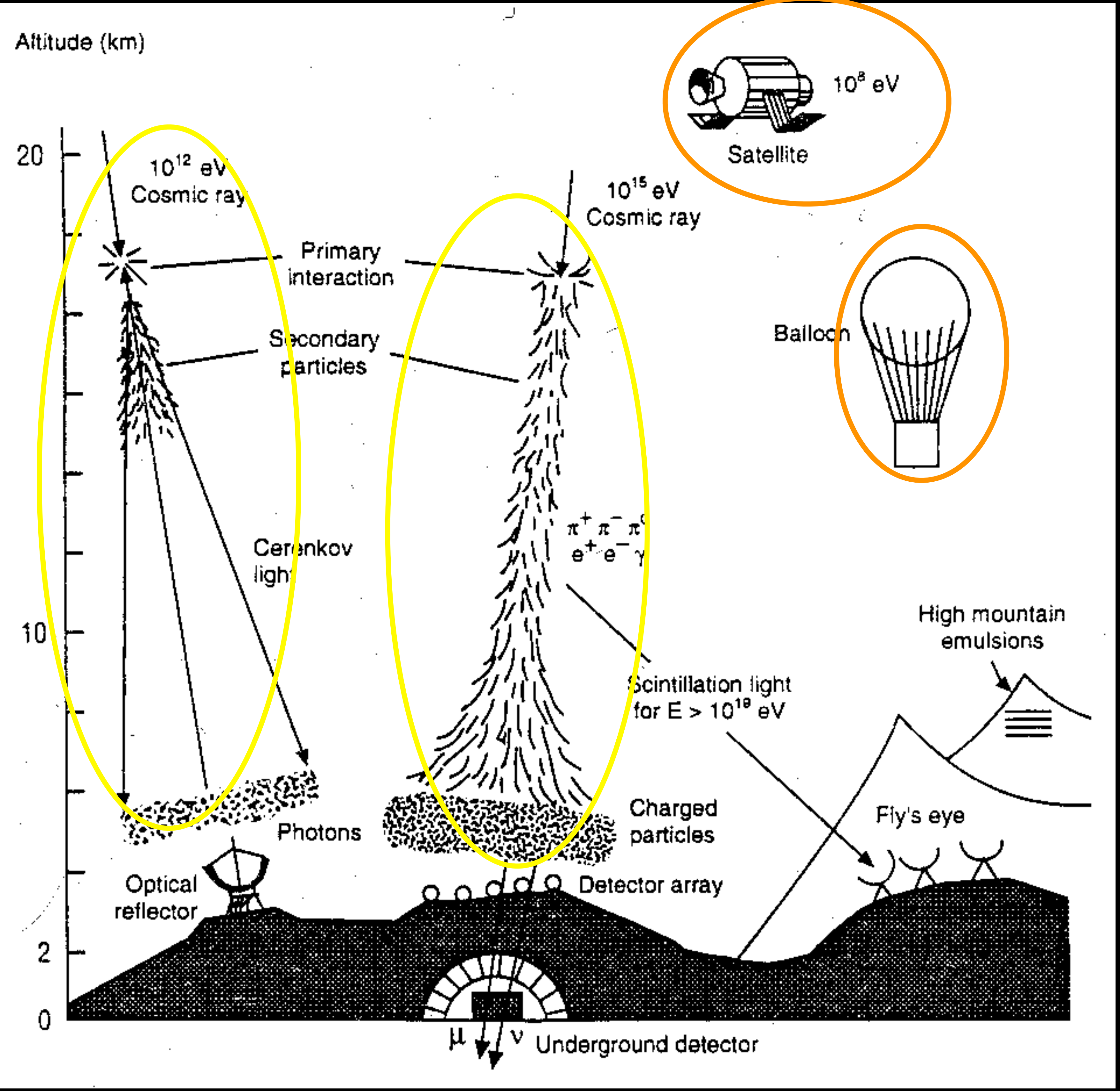

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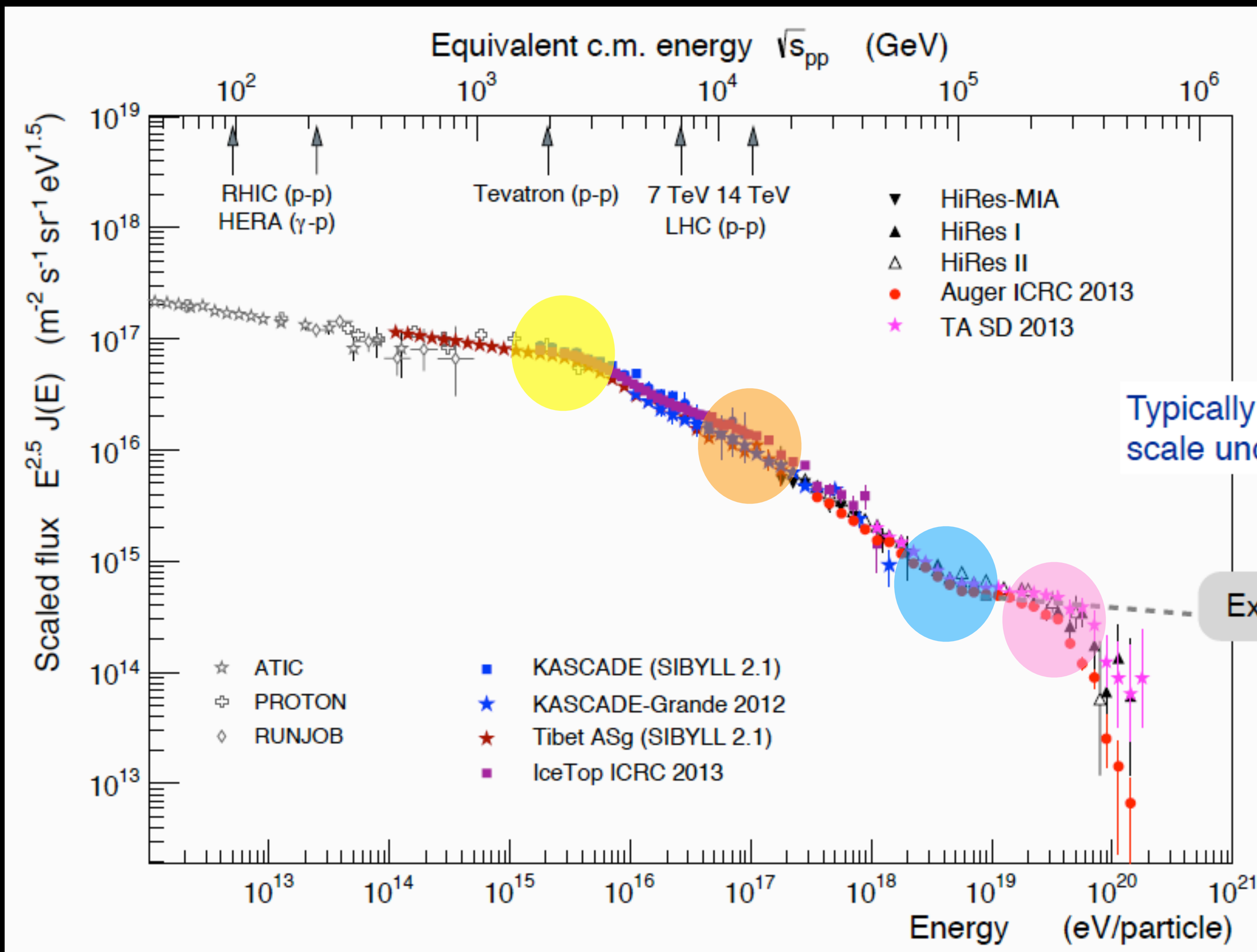
The relevance of EAS detection

The energy spectrum of high-energy cosmic rays shows in fact a few "irregularities"



All-particle primary energy spectrum measured by different EAS arrays. Spectrum scaled by $E^{2.5}$ to better evidence the "irregularities"

A softening ("knee") at ≈ 3 10^{15} eV

A softening ("II knee") at ≈ 10^{17} eV

A hardening ("ankle") at ≈ 4 10^{18} eV

A "suppression" at ≈ 5 10^{19} eV

These irregularities reflect changes in the CR behaviour, either in the acceleration mechanisms, or the sources, or the propagation to Earth.

The experimental study of CRs around these energies is key to understand their origin. **Different instruments for their (indirect) detection are required depending on the energy**

The challenge of EAS detection

The ultimate aim of EAS detection is the identification of the primary cosmic ray, in terms of

Mass/Charge

Energy

Arrival direction

We are dealing with an INDIRECT MEASUREMENT of CRs

To infer the properties of the primary particle one needs not only to detect EAS as precisely as possible but also to exploit as carefully as possible the "legacy" that their parents left into them

Extensive Air Shower detection:
An historical perspective

The minuteness of the phenomena
The adventurous excursions of the observers

Nani gigantum humeris insidentes

If I have seen further, it is by standing on the shoulders of giants

Chartres Cathedral
South Rose
St Matthew above Isaiah

"I make no apology for showing here and there a few historical notes about the history of cosmic ray detection.
This is much more than simply the recounting of some key events. Many of the present key ideas and experimental procedures have a long and distinguished history which reflects the insight and ingenuity of the great scientists of the past. These are our legacy and the foundation of the modern scientific experimental practice"

(inspired - and adapted - from Malcolm Longair)

Chartres Cathedral
South Rose
St Luke above Jeremiah

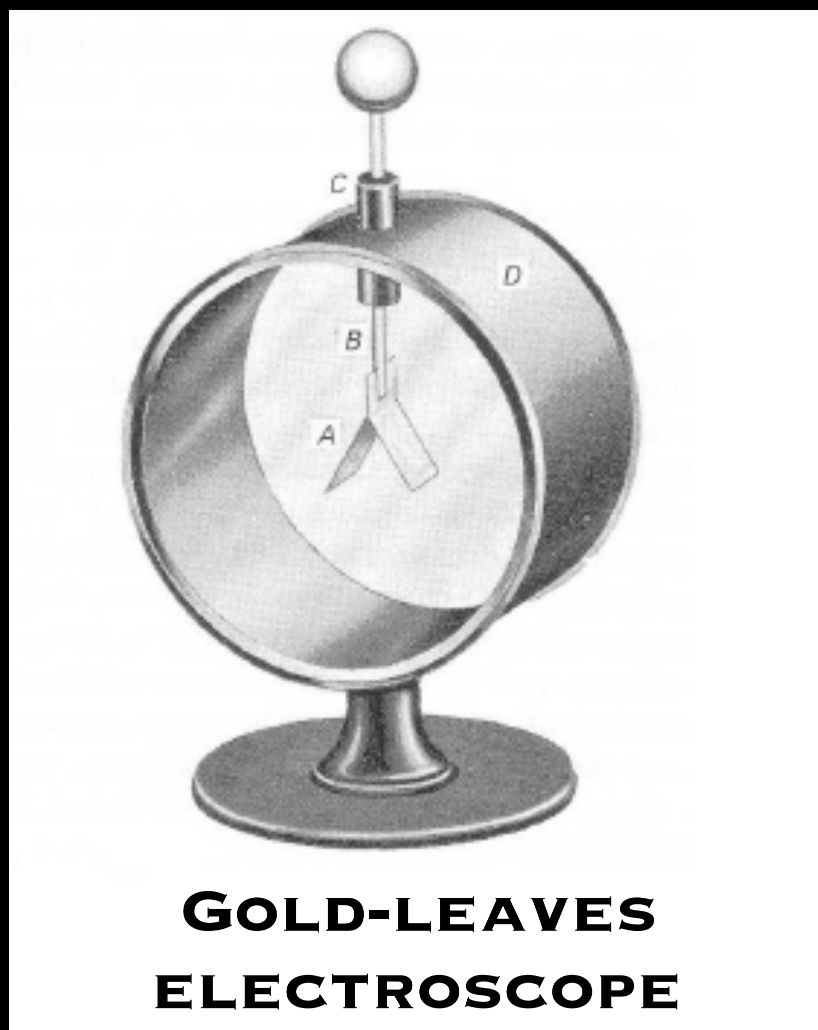
It is (quite) easy today to talk about the techniques used to detect and to exploit EAS to study cosmic rays

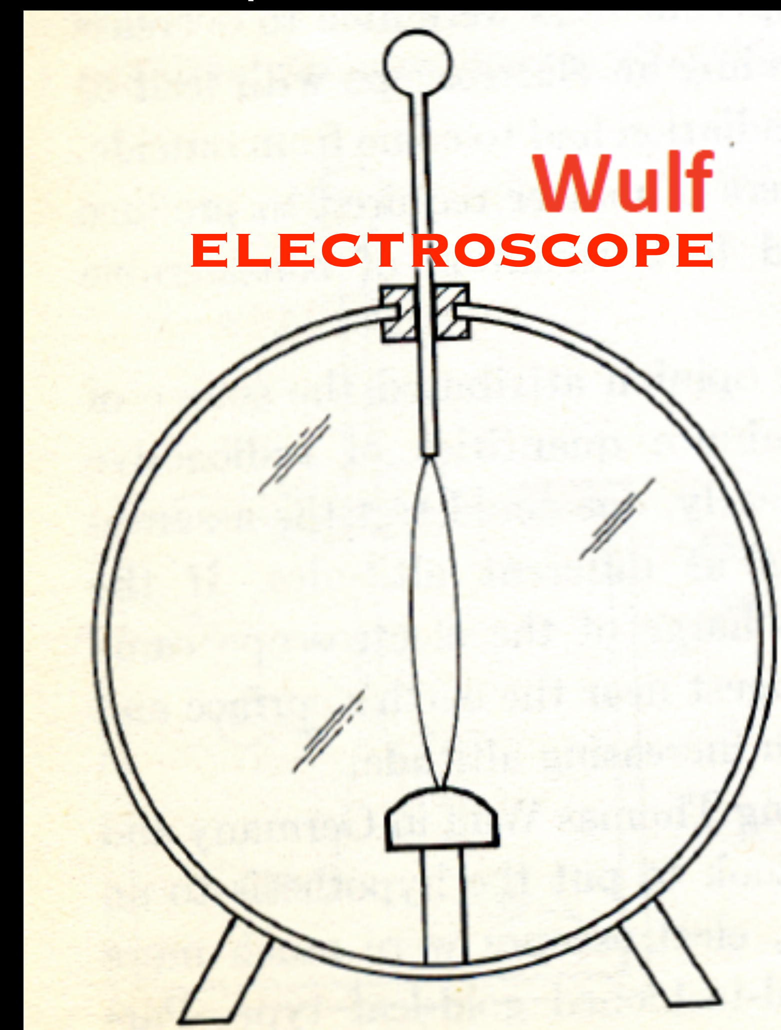
Yet, it took decades to consolidate the picture of EAS, both in terms of detection and of the physical processes involved

The very first steps towards the discovery of EAS

First of all: the discovery of cosmic rays!

First hints of the presence of cosmic rays came quite unexpectedly at the turn of 20th century, during the golden days of research into radioactivity. Radioactive elements ionise gases, enabling the gas to conduct electricity. Electroscopes were widely used to explore radioactive materials.





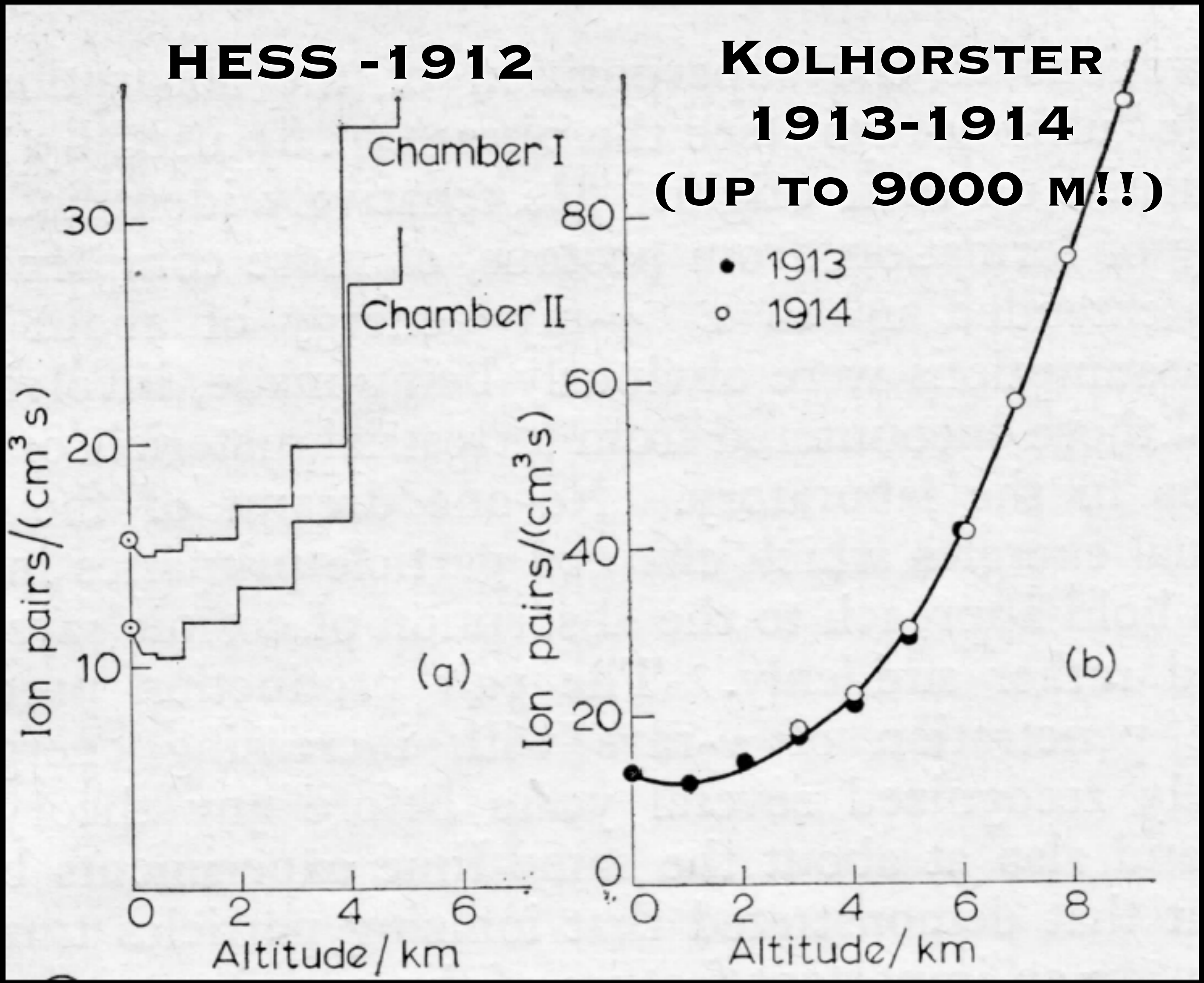
When an electroscope is given an electric charge, the leaves (or wires) repel each other and stand apart. Radiation can ionise the air in the electroscope and allow the charge to leak away: leaves or wires slowly come back together.

Puzzling inference: No matter how good the electroscopes, the electric charge continued to leak away even when there was no obvious nearby source of X-rays or radioactivity!

The very first steps towards the discovery of EAS

First of all: the discovery of cosmic rays!

To reduce possible effect of sources of radiation at ground, electroscopes were carried to the tops of tall buildings (Father Wulf, 1910, Eiffel Tower) or even to greater heights, using balloons (Victor Hess, 1912, Werner Kolhorster, 1913-1914). Experiments of great danger, great courage



Intensity of the ionizing radiation first decreased as the balloon went up and then increased

"The only possible way of interpret my findings was to conclude to the existence of a hitherto unknown and very penetrating radiation, coming from above and probably of extra-terrestrial origin" [V. Hess 1912]

The very first steps towards the discovery of EAS

Trying to infer the nature of cosmic rays

The discovery of cosmic rays was based on ionisation in an electroscope.

Pioneering experiments (Millikan 1920s, Compton 1930s) used also ionisation chambers to study the CR variation vs altitude and altitude

Compton's chamber was shielded by layers of lead (against local radioactivity). The central container (filled with argon) held a probe connected to high voltage)

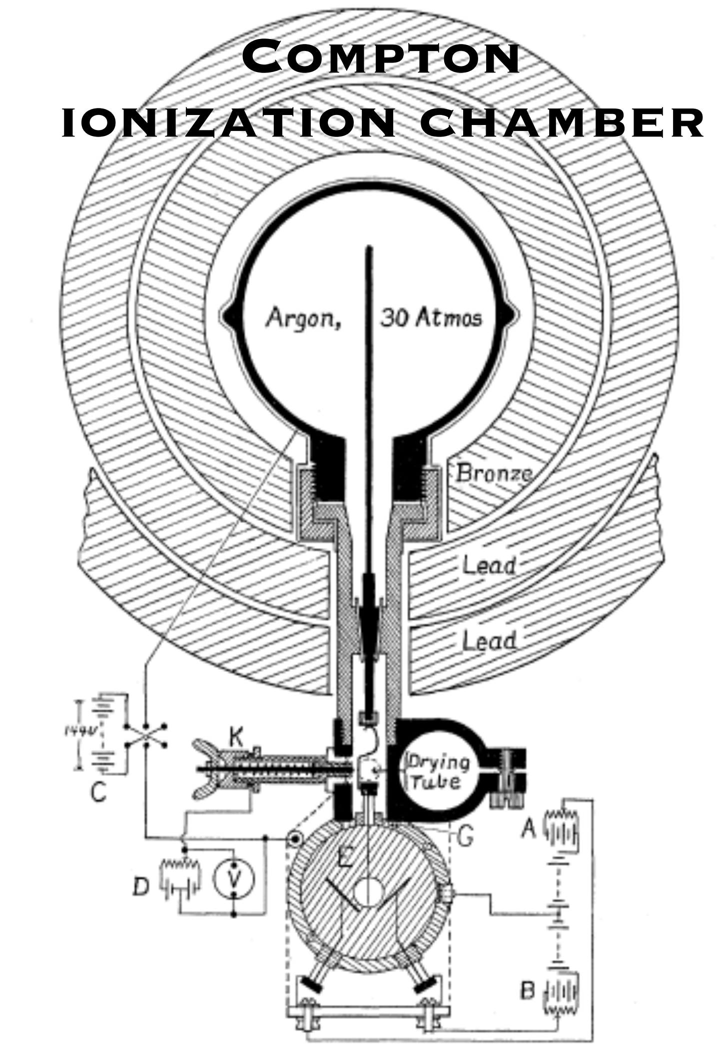


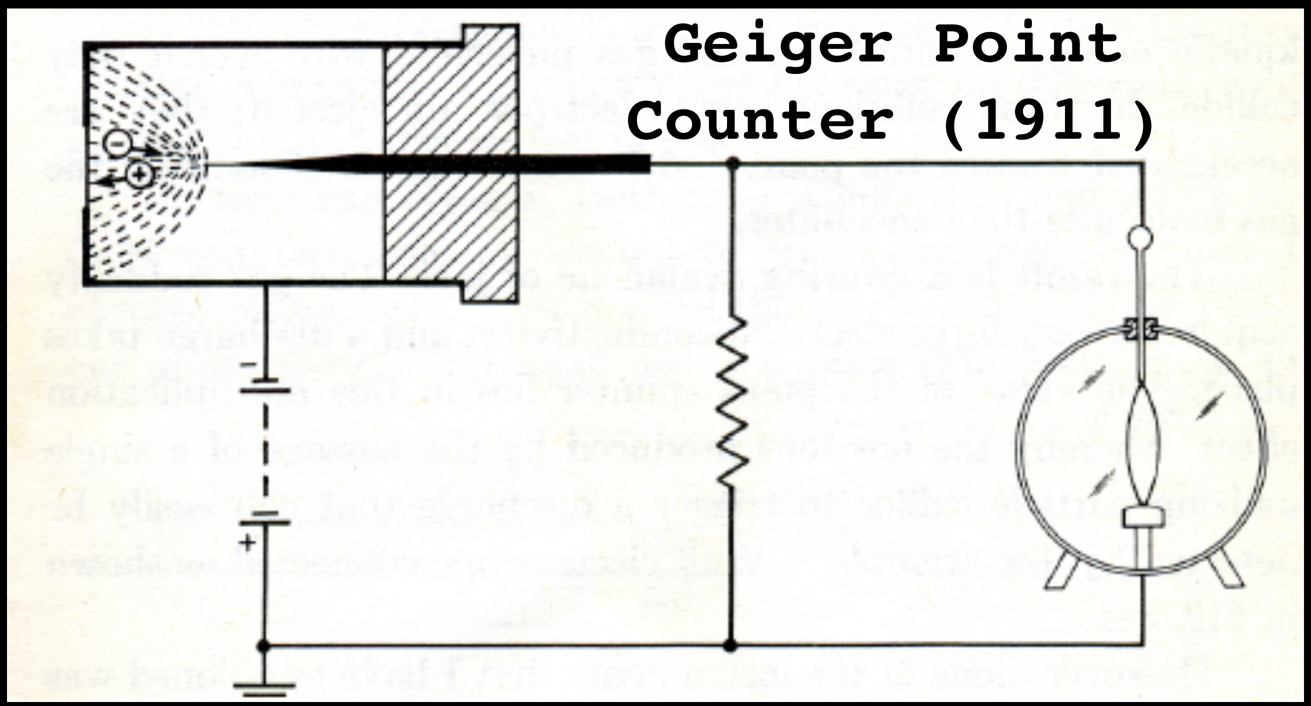
FIG. 2. Cosmic-ray ionization chamber, electrometer, and electrical connections

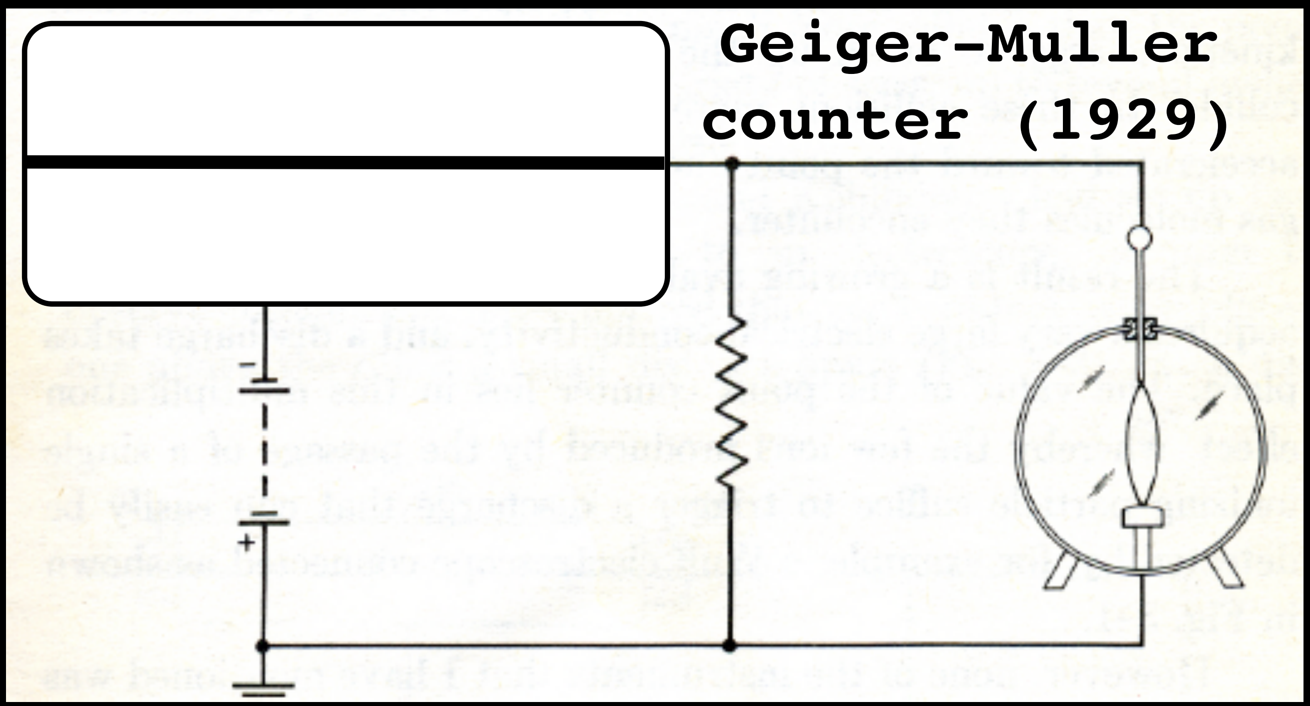
Electroscopes and ionisation chambers can only detect the combined ionising effect of many particles. They cannot access single particles

The very first steps towards the discovery of EAS

Trying to infer the nature of cosmic rays

The first detectors of single particles





A thin point rod in a metal box filled with gas. A battery maintains the rod at positive potential with respect to the box. Particles penetrating in the box produce ionisation. Ions and electrons are accelerated: an avalanche creates a brief electrical current: the electroscope wires undergo a sudden deflection

Not stable, not realisable in size large to counterpart the small intensity of CRs

1929: the invention by Geiger and his student Muller of the so-called Geiger-Muller counter.

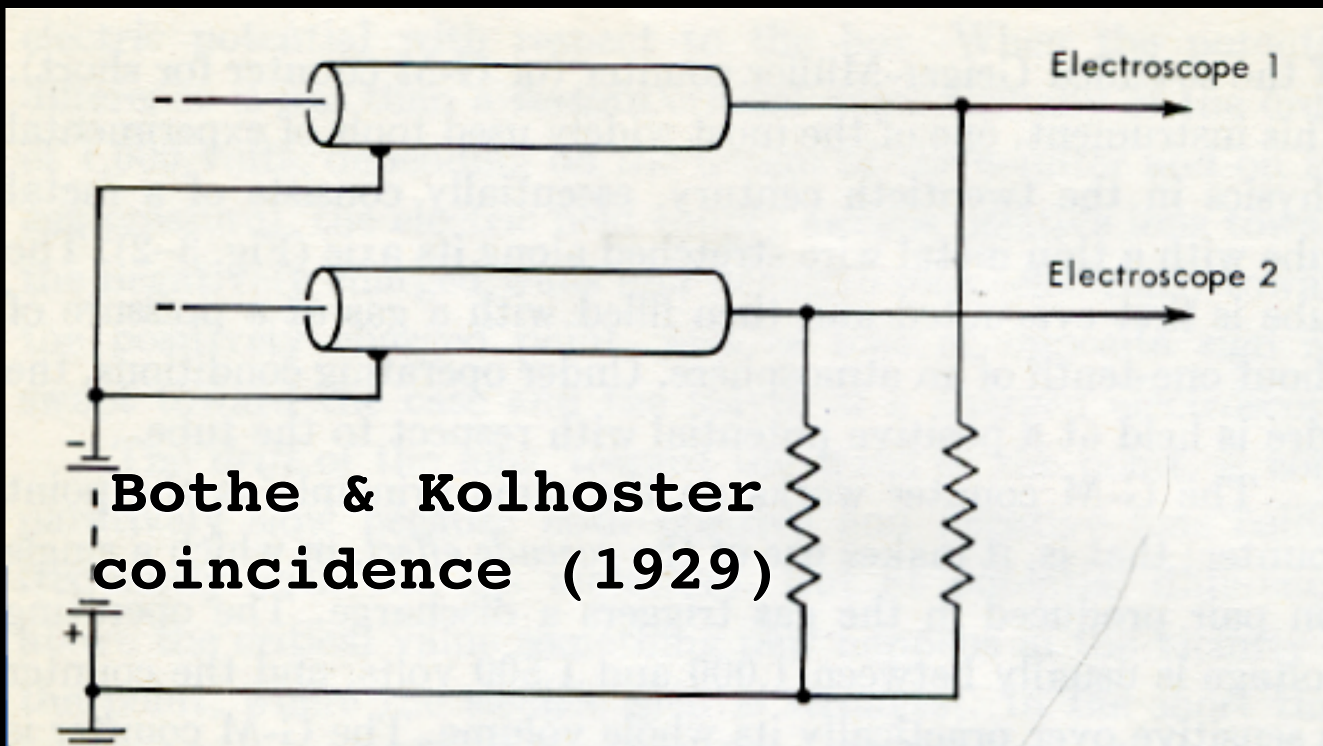
A metal tube filled with a gas with a thin metal wire stretched along its axis. Same principle as the point counter

Fast response time: not only individual events can be identified but also their arrival times

Easy to build, stable and realisable in different sizes. Very much used to study CRs

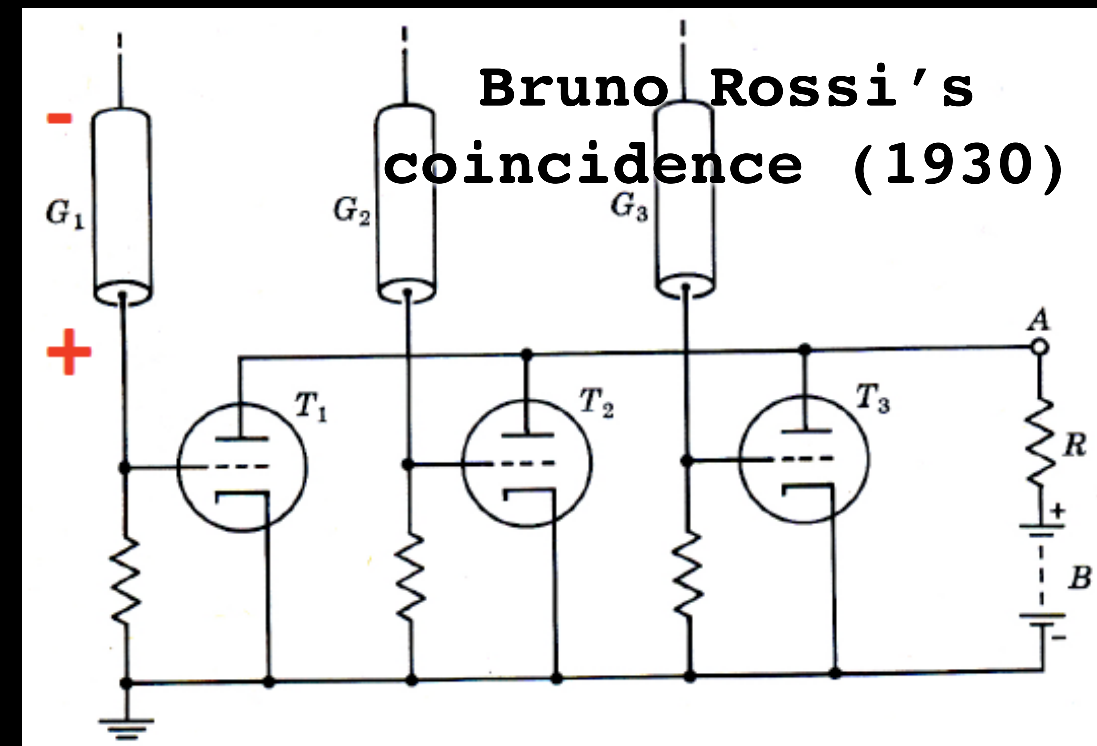
The very first steps towards the discovery of EAS

The invention of counting in coincidence



G-M counters (2 max) connected to electroscopes. When placed one above the other a small distance apart, often discharged simultaneously.

Coincidences were not by chance as they became less frequent when the distance increased. By inserting absorbers (lead, gold) between the counters (and still finding coincidences) **B&K concluded that "a corpuscolar radiation was detected...unlikely to be a gamma-radiation..."**



2 or more triodes coupled to G-M counters. When the grids were simultaneously driven to a negative potential by the coincident discharges of the 3 counters, a pulse appear at the plates.

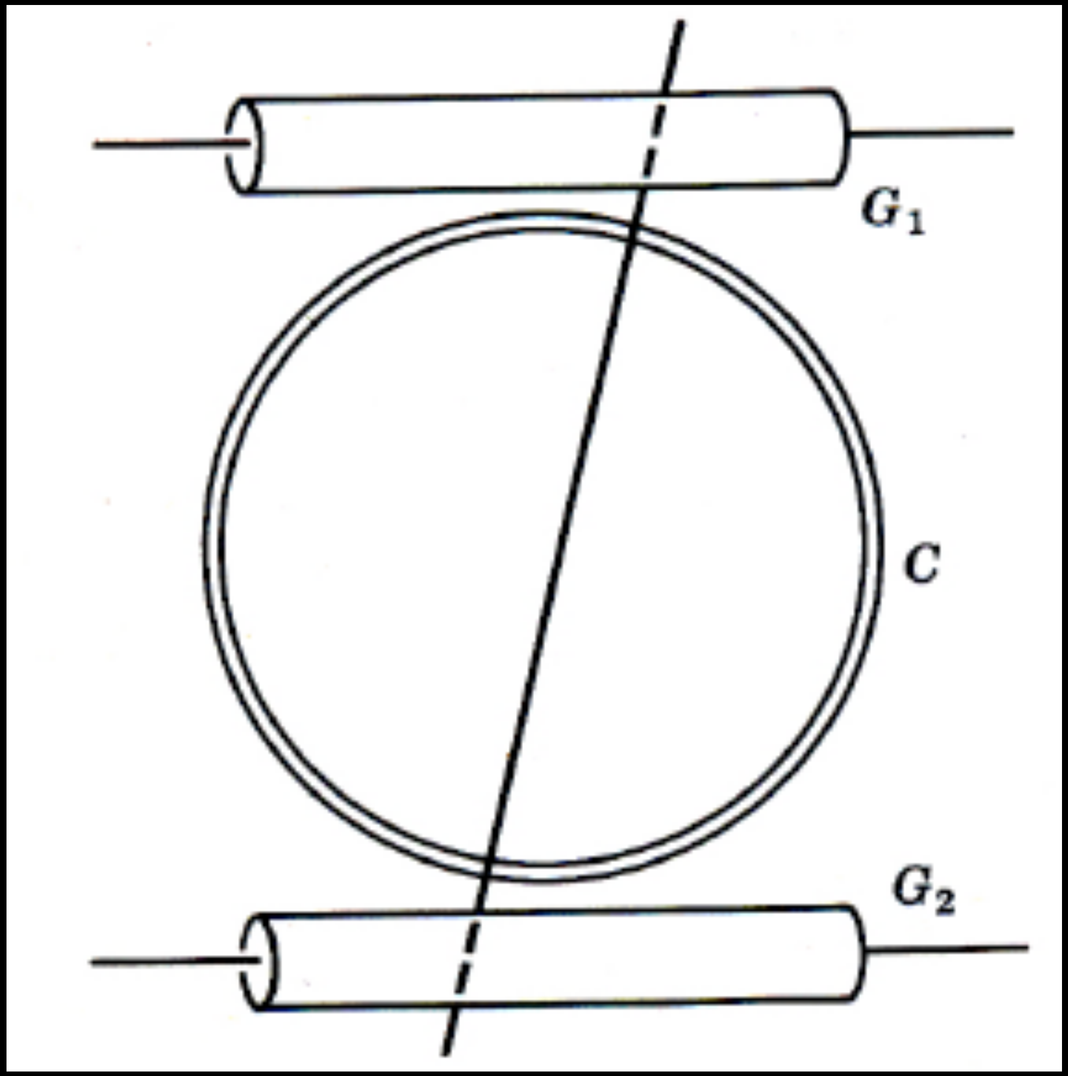
Bruno Rossi (1930) much improved the method by B&K obtaining a better time resolution, and extending the coincidence to more than 2 counters

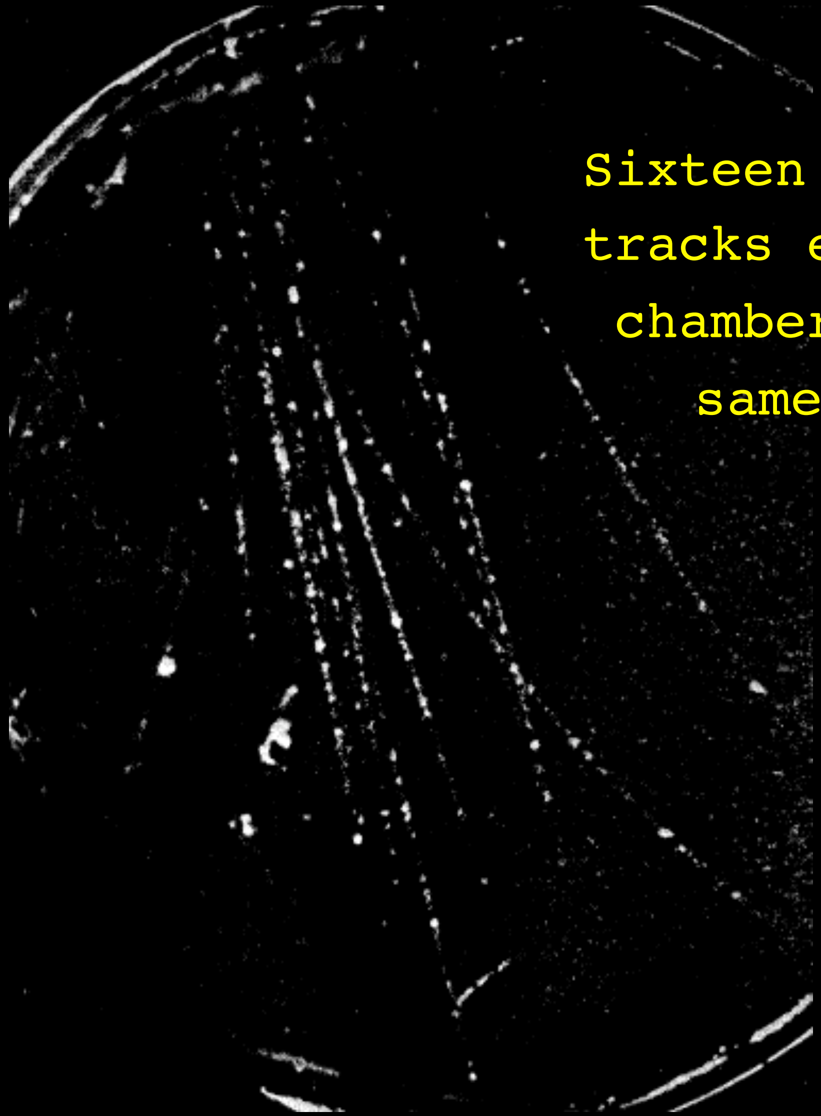
The very first steps towards the discovery of EAS

The invention of counting in coincidence and the very first hint of EAS

After working with Rossi, Occhialini joined Blackett in UK, where he applied Rossi's coincidence logic to Blackett's cloud chamber. The counter-controlled cloud chamber was born (1933)

A CR particle passing through two G-M counters (placed above and below the chamber) and the chamber produces a coincidence. The signal from the coincidence triggers the expansion of the chamber in time with the ions formation.





Sixteen separate tracks enter the chamber at the same time

With their new cloud chamber, in 1933 Blackett and Occhialini observed tracks of many particles that clearly resulted from the interaction of a single high-energy cosmic ray near the chamber. The discovery of these "showers" marked another milestone in CR research.

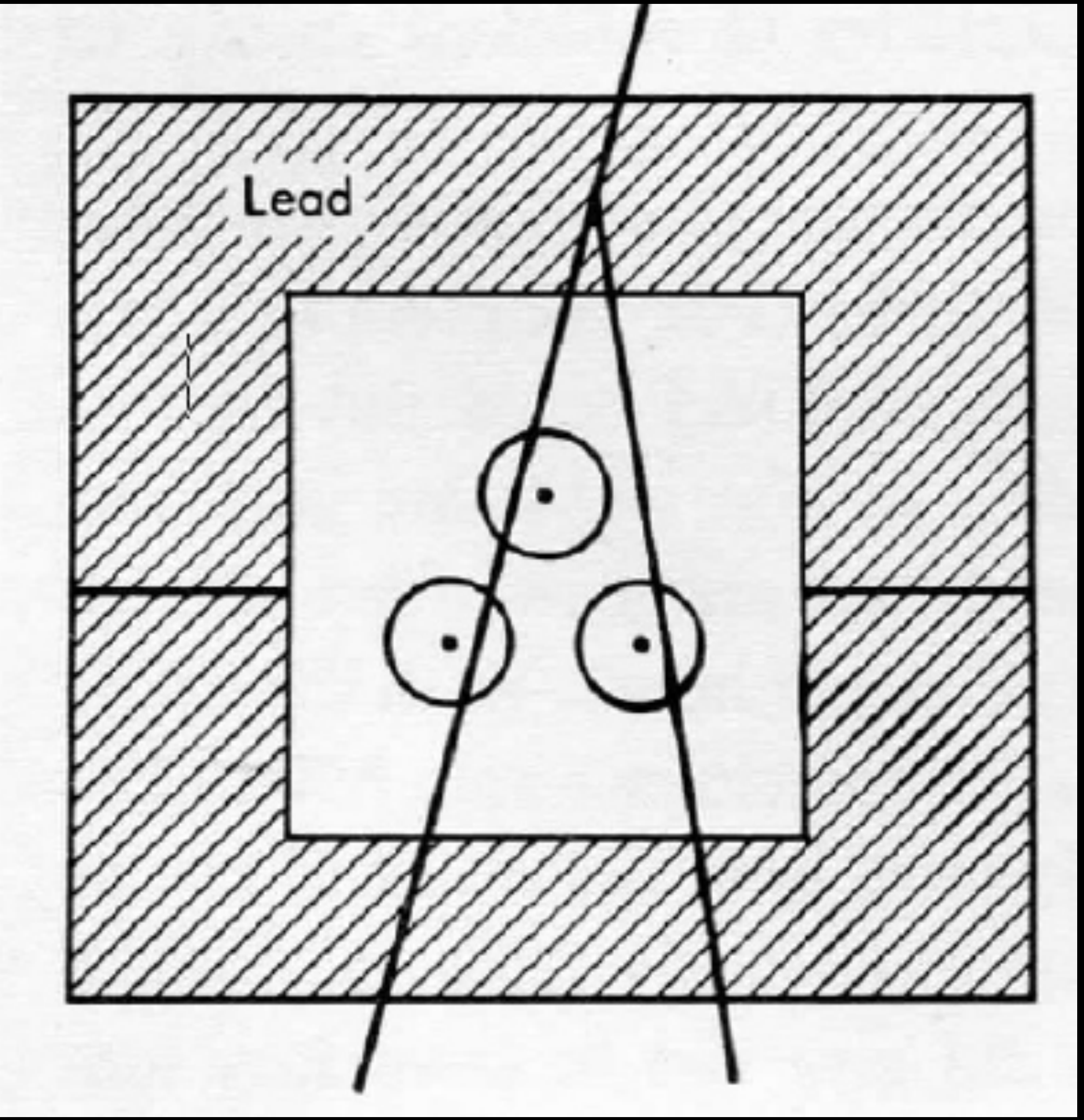
The serendipitous observation of “sciami estesi”

The first observation of “sciami estesi"

‘It would seem . . . that from time to time there arrives upon the equipment very extensive group of particles (‘sciami molto estesi di corpuscoli’) which produce coincidences between counters even rather distant from each other”

Bruno Rossi, 1934

Rossi placed three Geiger counters in a triangular array, i.e., they could not be discharged by a single particle traveling in straight line. Yet, even when surrounded by lead, the array recorded coincidences. The coincidence rate fell ALMOST to zero when the upper lead was removed. The coincidences could only have been the result of two or more ionising particles emerging simultaneously from the lead. Coincidences were present also WITHOUT lead: **Rossi correctly suspected that soft secondary particles were produced by cosmic particles either in the material or not.**



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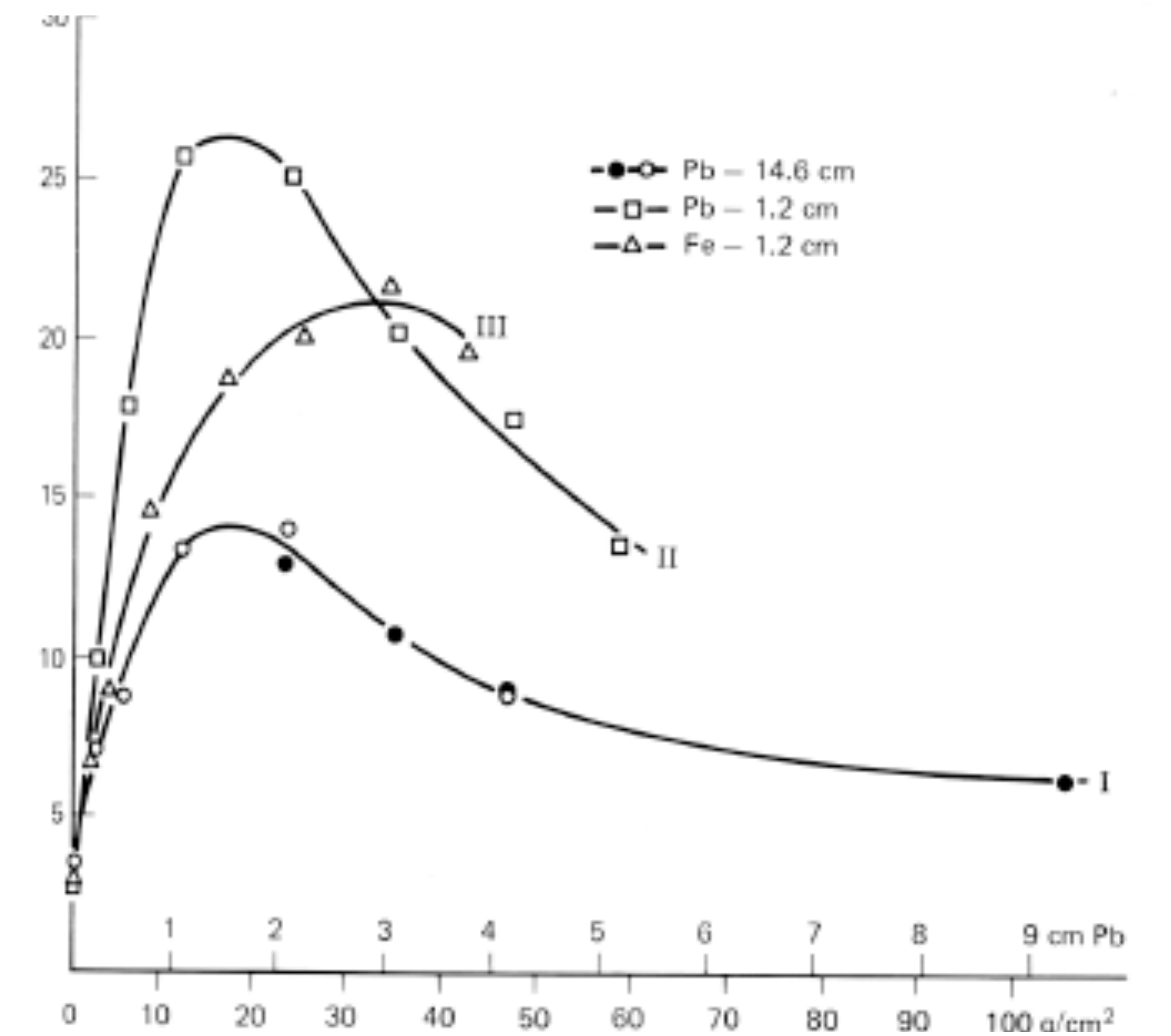
Rossi observed a rapid increase of triple coincidences in a triangular arrangement of Geiger counters when some centimetres of lead was placed above. Only with further increasing absorber thickness did the coincidence rate start to decline. Rossi correctly concluded that soft secondary particles were produced by cosmic particles entering the material. These secondary particles then suffer increasing absorption with increasing total thickness of the absorber.



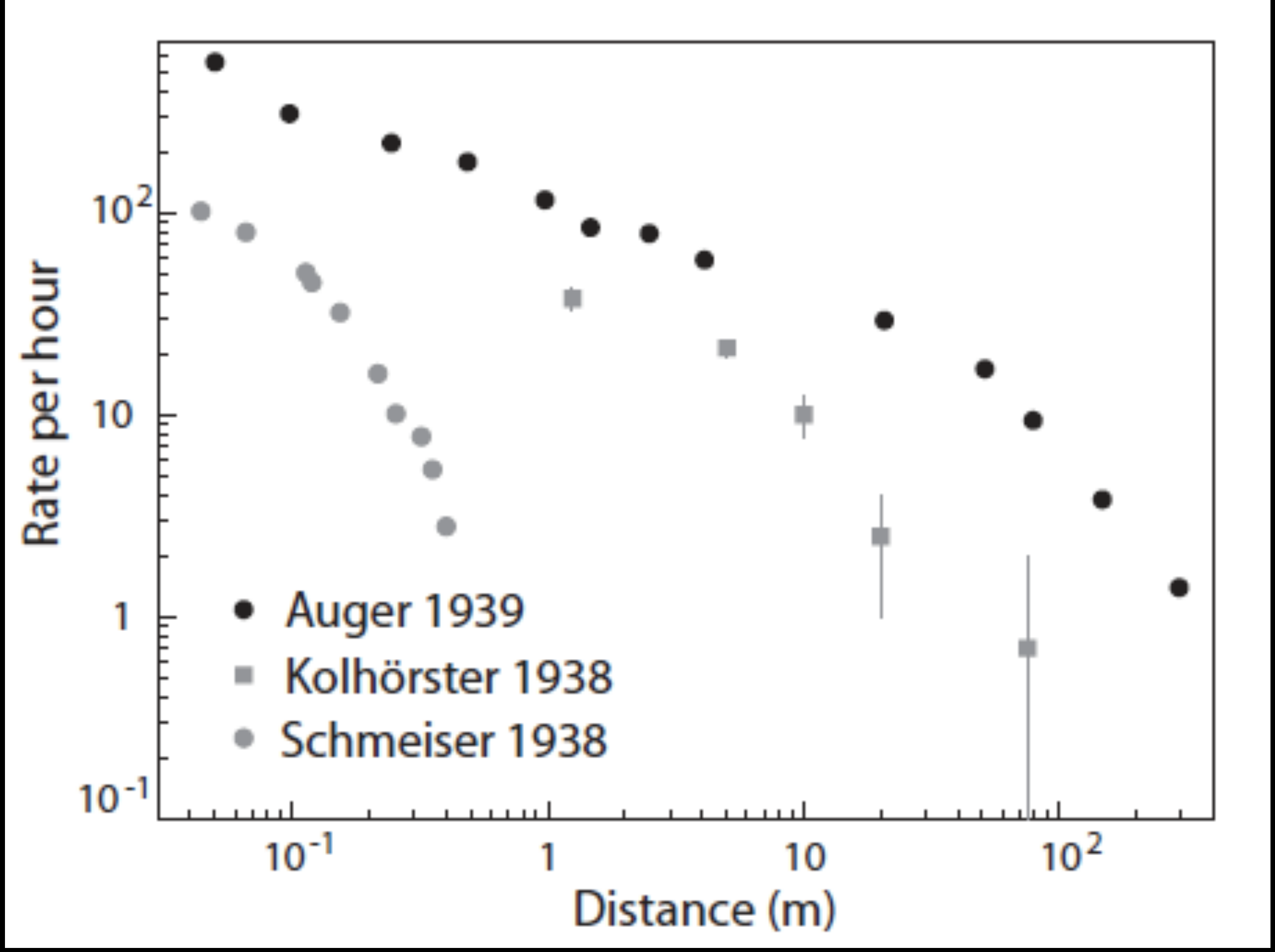
Rossi's transition curves. The curves I-III refer to measurements with Pb and Fe absorbers placed at distances above the counters

The discovery of Extensive Air Showers

Schmeiser & Bothe, Kolhörster, and PIERRE AUGER

Schmeiser and Bothe pointed out that Rossi's observations implied the occurrence of showers in air and showed that particles in air showers had separations up to 40 cm. Independently, Kolhörster et al. reported data on the rate at which coincidences between a pair of Geiger counters fell as a function of separation

Despite the work of Rossi and the two German groups, credit for the discovery of extensive air showers is usually given to Pierre Auger. His observation depended on the electronic developments by Roland Maze who improved the resolving time of coincidences. They found that the chance rate between two counters separated by some distance greatly exceeded the chance rate expected from the resolving time of the new circuit. **They estimated an energy of about ≈ 10^{15} eV for the primary particle!!!**



The discovery of extensive air showers: Decoherence curves measured with Geiger counters separated up to 300 m distance.

Towards understanding Extensive Air Showers

1940s - 1950s

Several groups, including Auger's, verified the inferences drawn from the Geiger counter observations using cloud chambers.

Work by Auger and his colleagues using cloud chambers triggered by Geiger counters allowed features of EAS to be understood relatively quickly.

By the late 1930s it was known that air showers contained hadronic particles, muons and electrons. Major advances in understanding took place in the late 1940s and early 1950s after the existence of two charged and one neutral pion was established and it was recognised that muons were secondary to charged pions.

The features visible in this photograph, except for scale, are extremely similar to those present when a high-energy particle enters the earth's atmosphere and creates a shower.

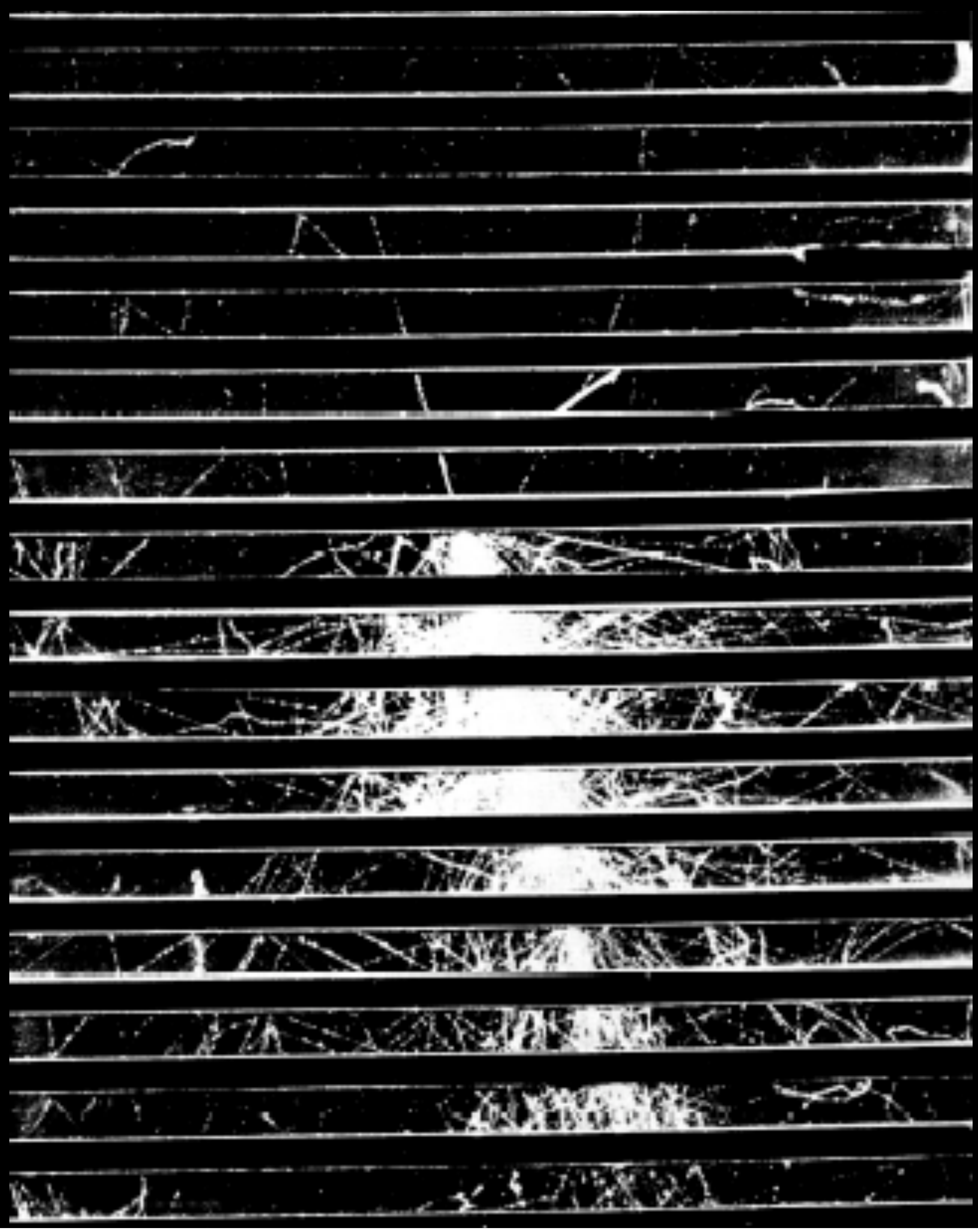


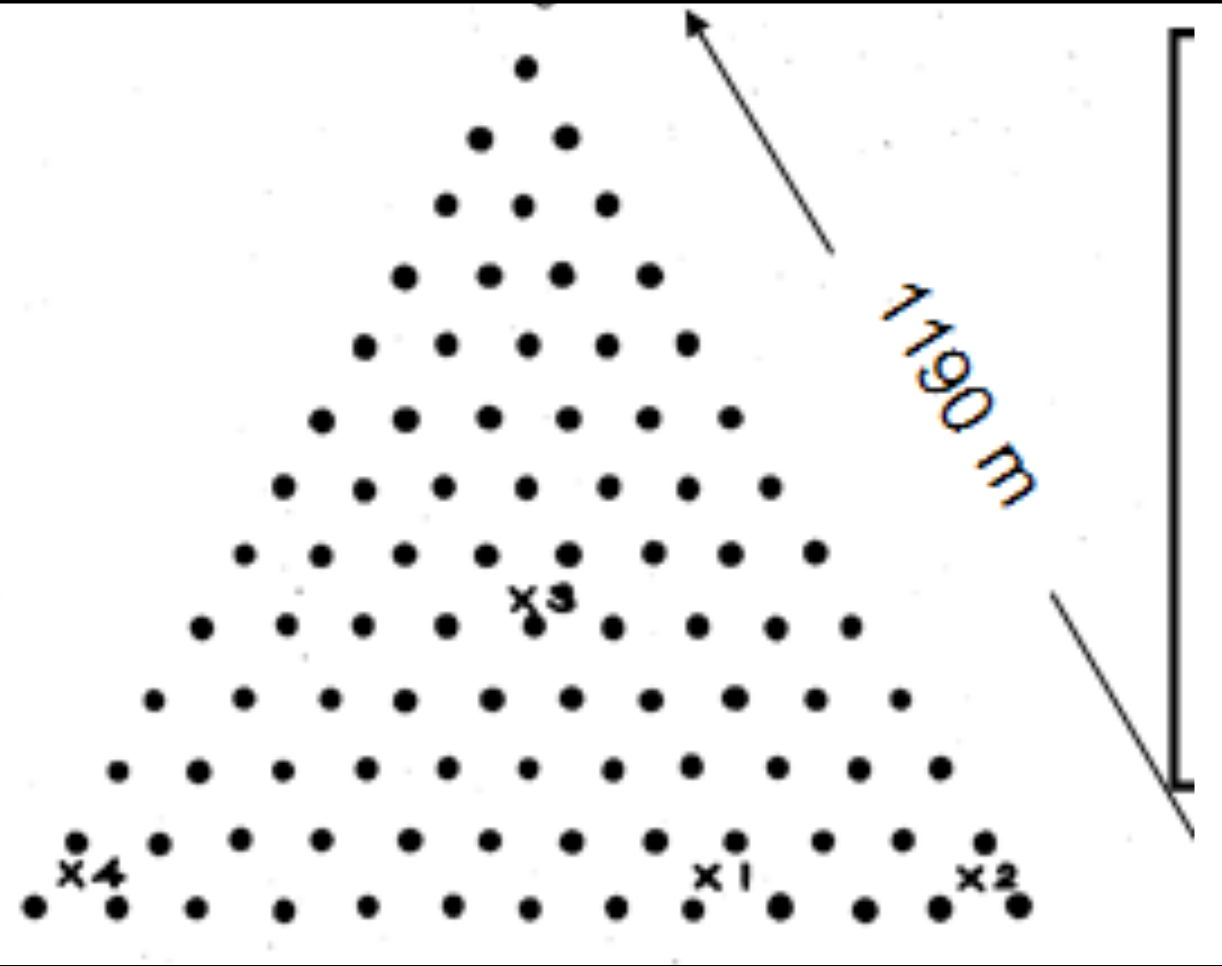
Image of a shower, as seen in a cloud chamber at 3027 m altitude, Fretter 1949 (primary proton of ≈ 10^{10} eV)

The very first EAS arrays

Skobeltsyn, Zatsepin, Miller (1947), Cranshaw & Galbraith (1954)

Up to the invention of PMTs and scintillators (after World War II, in the 1950s) progress in experimental EAS studies was done by using arrays of Geiger counters installed in the USSR and in UK

EAS array on the Pamir mountain (3860 m, USSR, 1947)
Geiger counters supplemented with ionisation chambers and cloud chambers. The birth of the very first "large" collaborations (20-30 people)



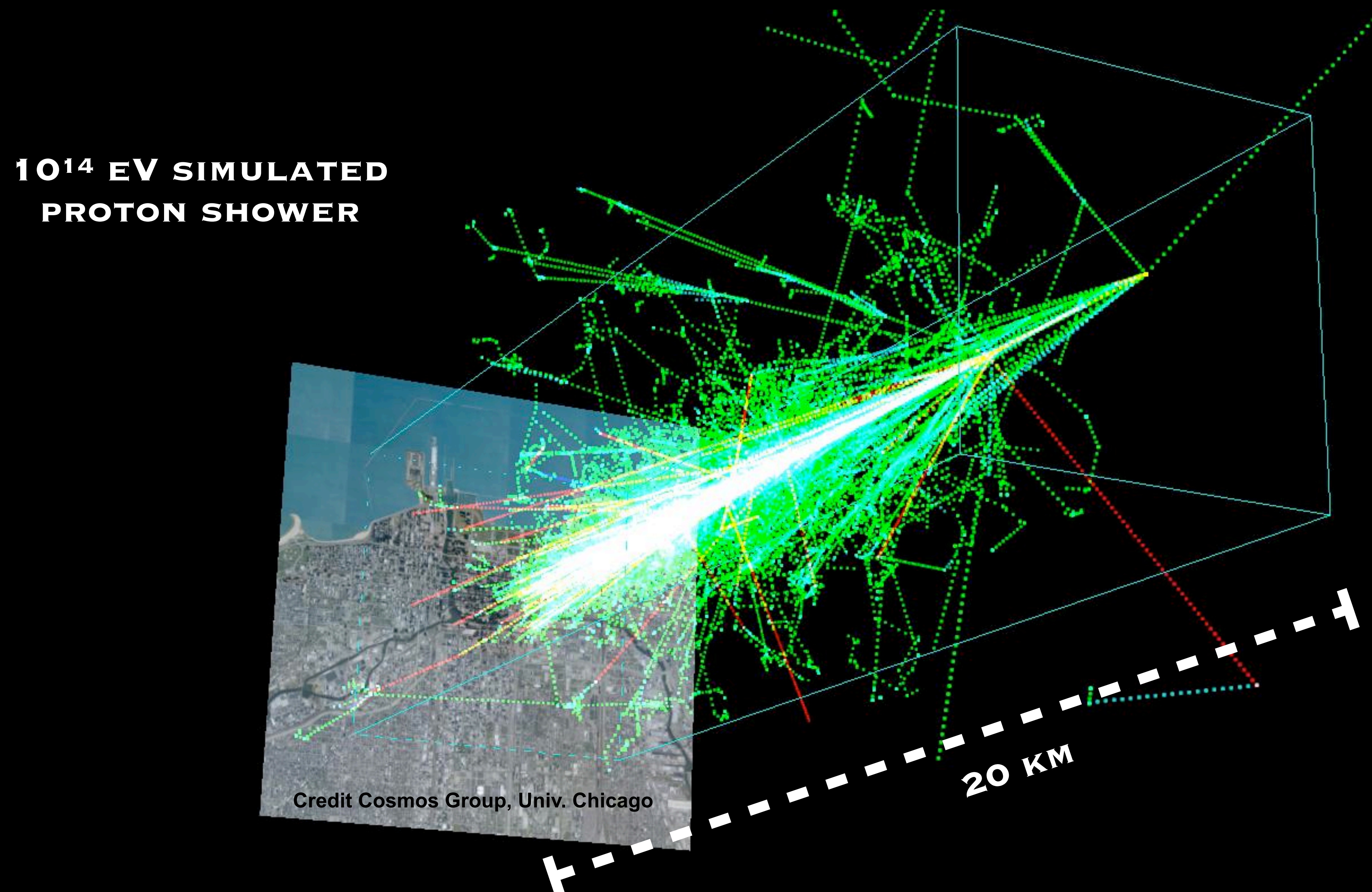
The first "large" array (0.6 km²) at Culham, UK (1954)
91 Geiger counters spaced by 99 m.
Hosted in a disused airfield at sea level

Modern Extensive Air Shower detectors

(The minuteness of the phenomena -
The adventurous excursions of the observers)

EAS are key to study high-energy cosmic rays

We now know much more on the EAS features (Ralph Engel's lecture)

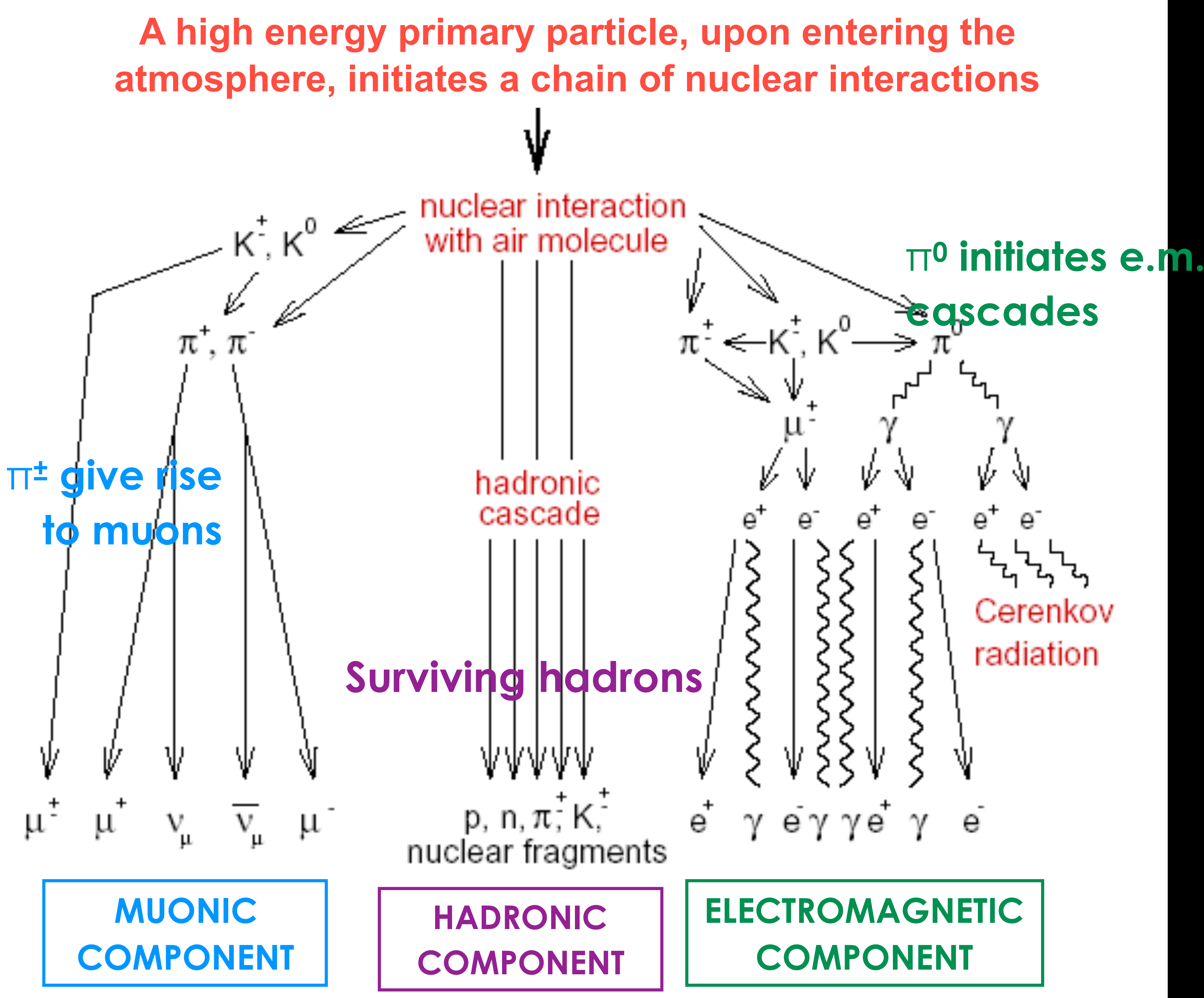


There is no way of studying high-energy cosmic-rays other than by observing air showers. The atmosphere is used as an inhomogeneous calorimeter.

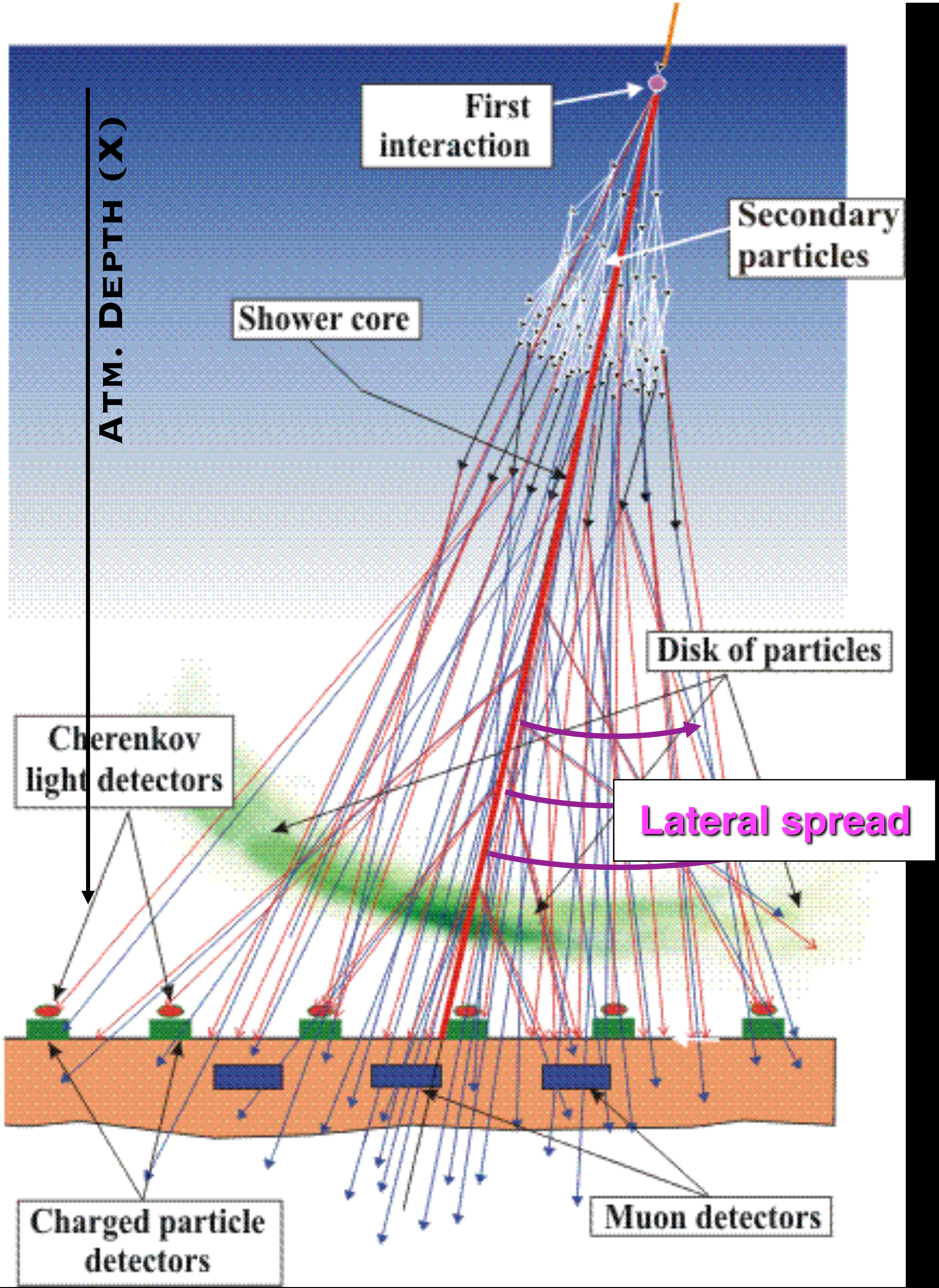
EAS can be detected over an extended area.

Large effective area of detection compensates the smallness of flux

EAS are key to study high-energy cosmic rays



Extensive air showers lateral development

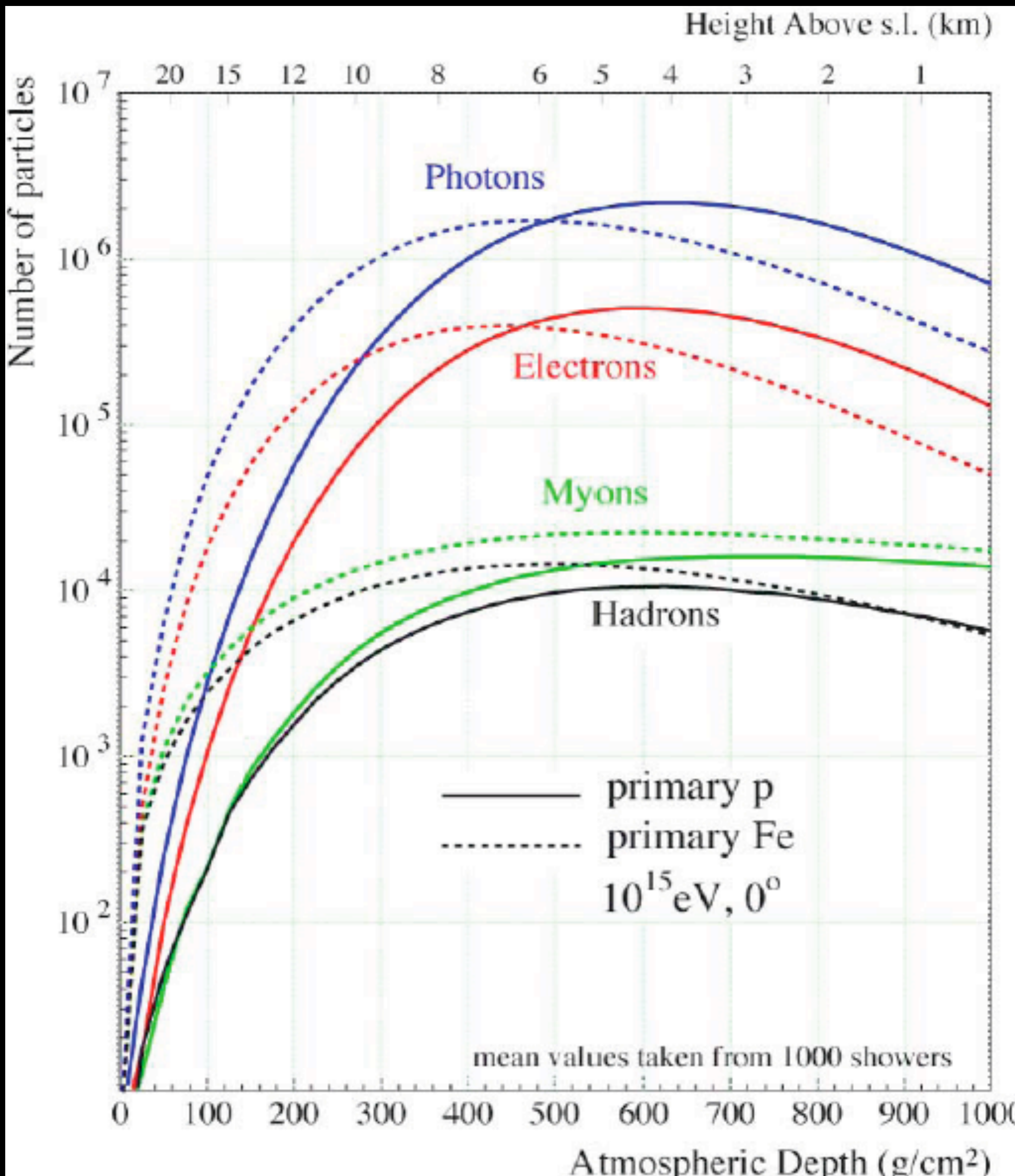


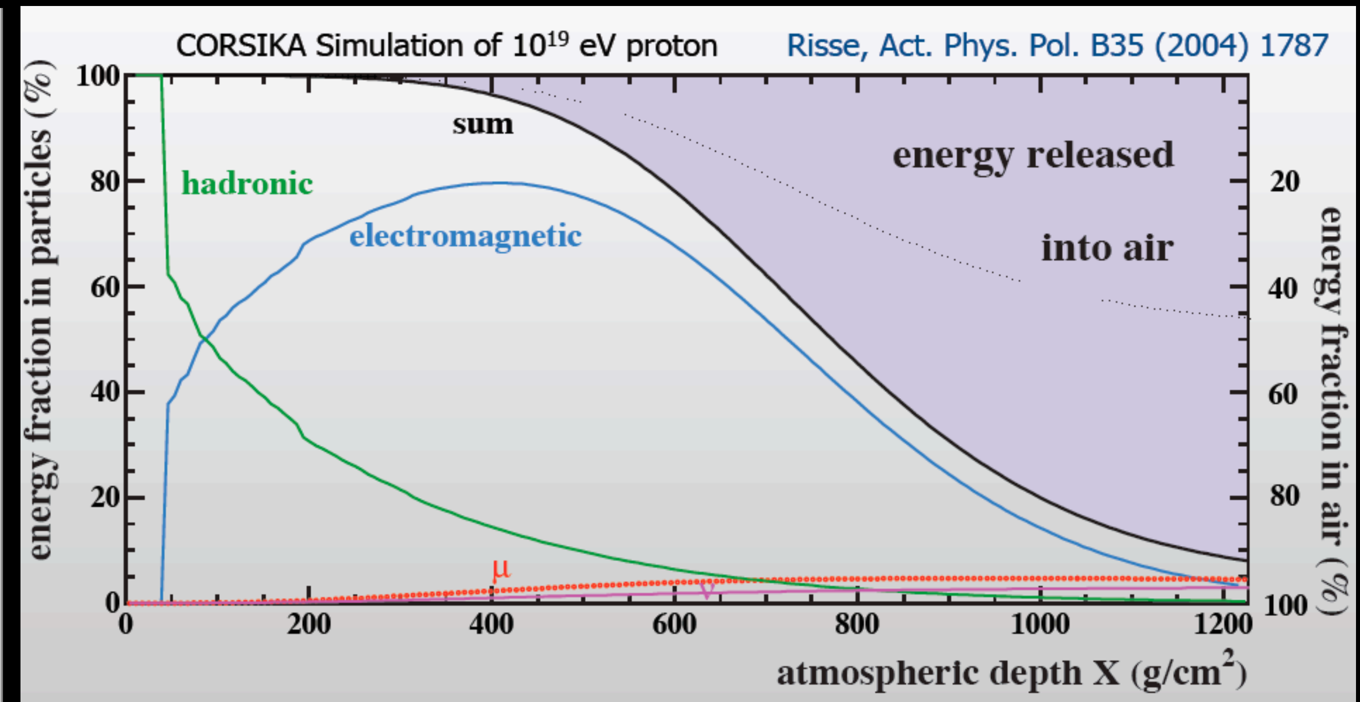
Secondary particles form a narrow “bundle”: the shower core

Initial transverse momentum and multiple scattering in atmosphere causes particles to spread out laterally from the core -> lateral distribution: particle density is greater in the core and it decreases with increasing distance from it

Due to different path lengths and velocities across the atmosphere shower particles are distributed over a wide area in a thin curved disk

Extensive air showers longitudinal development

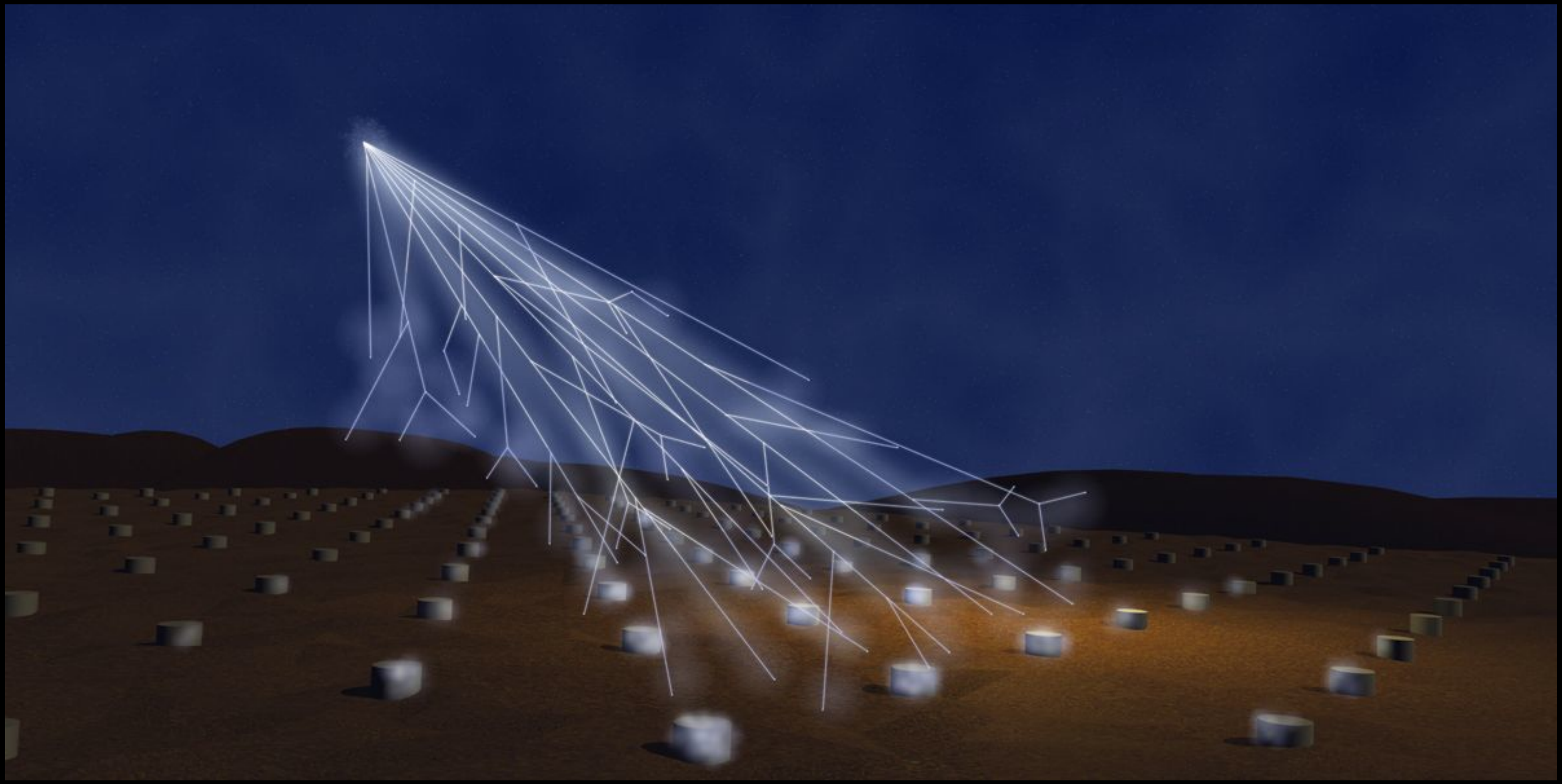




90% of the primary energy of the cosmic ray is dissipated in the atmosphere during shower development

The number of particles increases with atmospheric depth, reaches a maximum and then decreases (electrons attenuates more rapidly than muons)

For example: a shower produced by a CR of 10^{19} eV...



- Contains about 10^{10} particles at the maximum

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

- Has the maximum at about 3 km above sea level

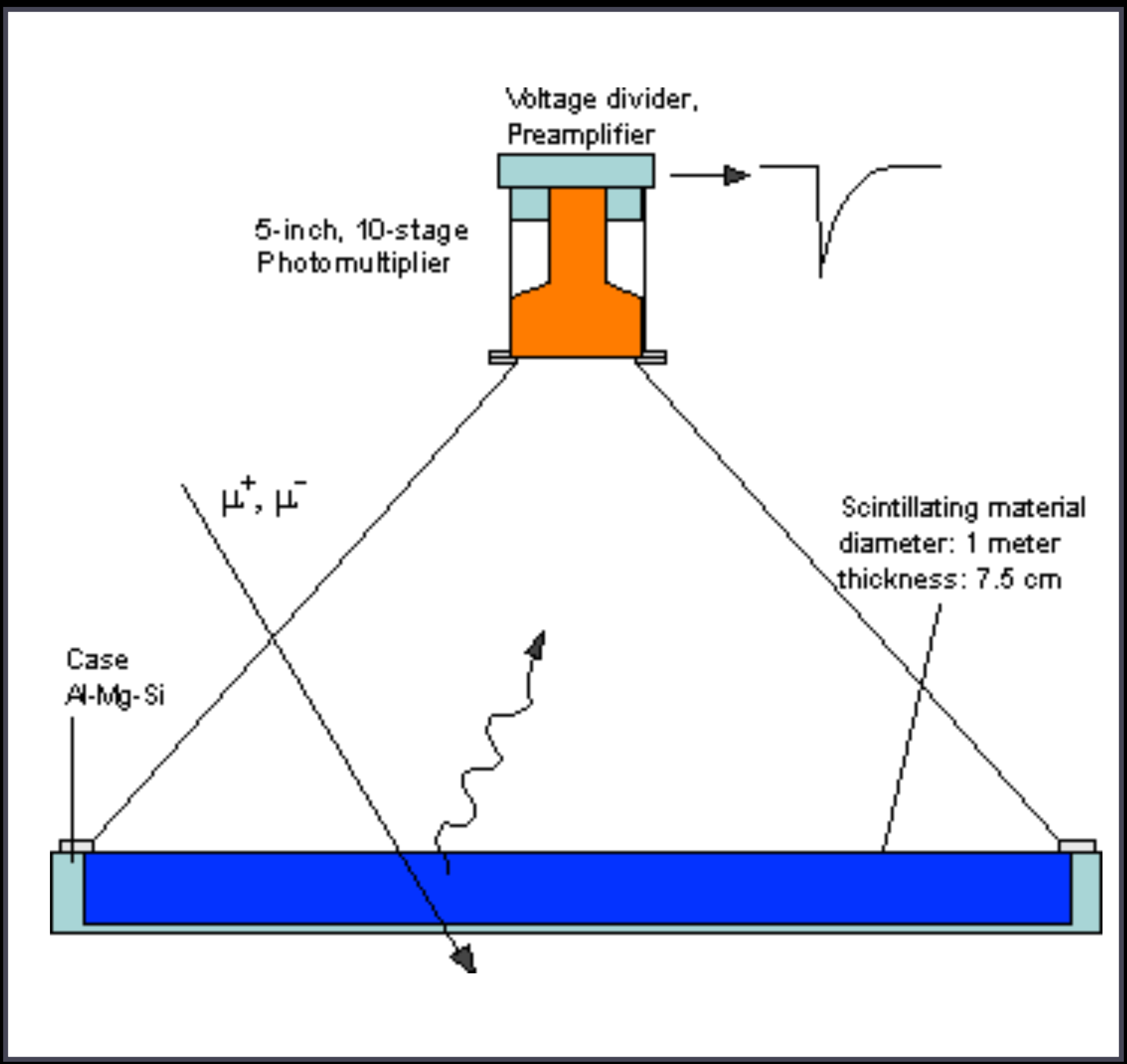
- Has a footprint at ground that can extend up to over 15 km

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

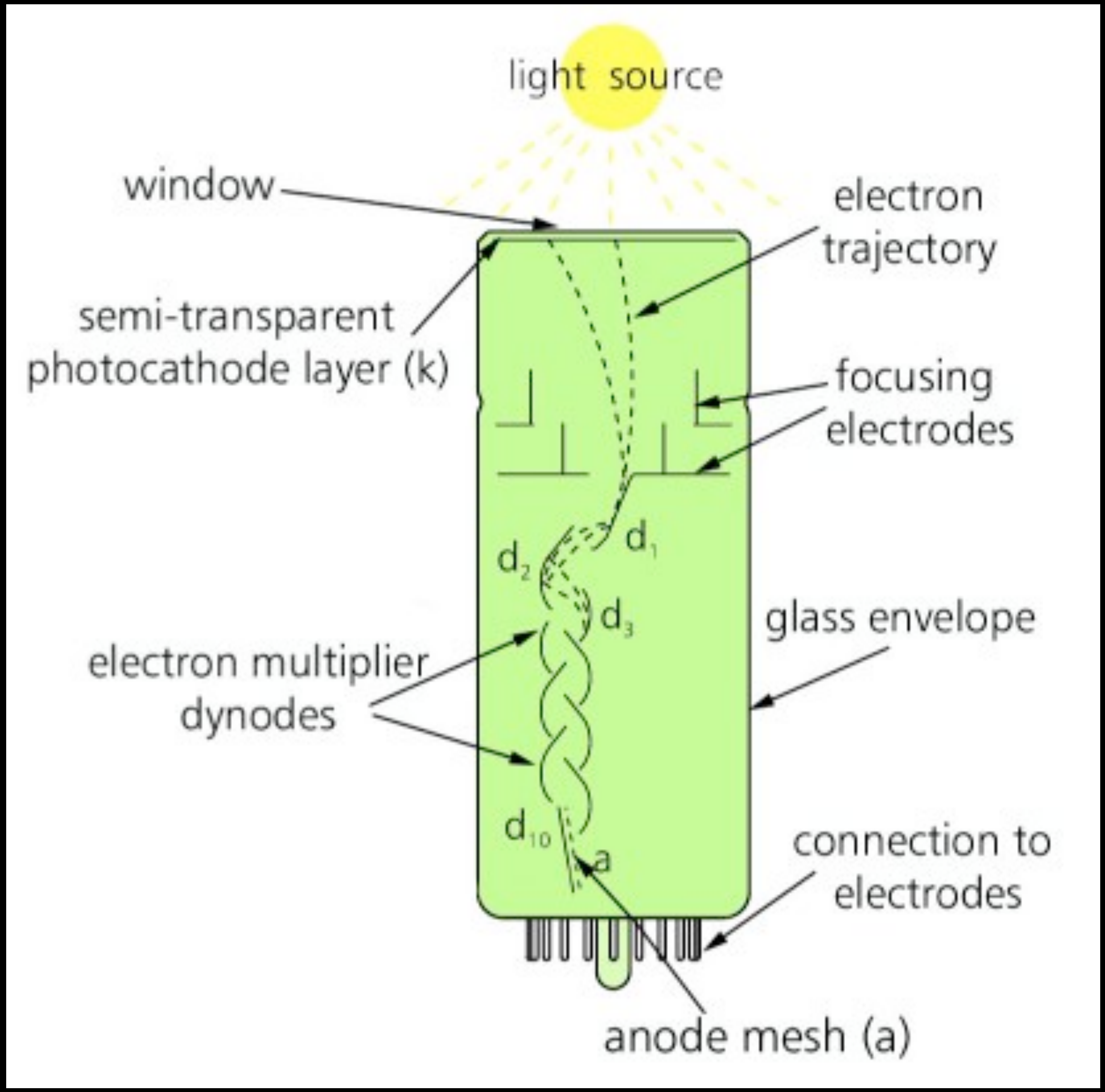
Particle detectors

Scintillators and photomultipliers (PMTs)

Scintillation detectors are historical devices. Rutherford used a scintillating zinc-sulphide screen to count alfa-particles (Crookes tubes). Photons were looked at by eye (by microscopes in darkened rooms). Their use was boosted by the invention of PMTs.



The first scintillator counter was invented in 1944 within the Manhattan Project



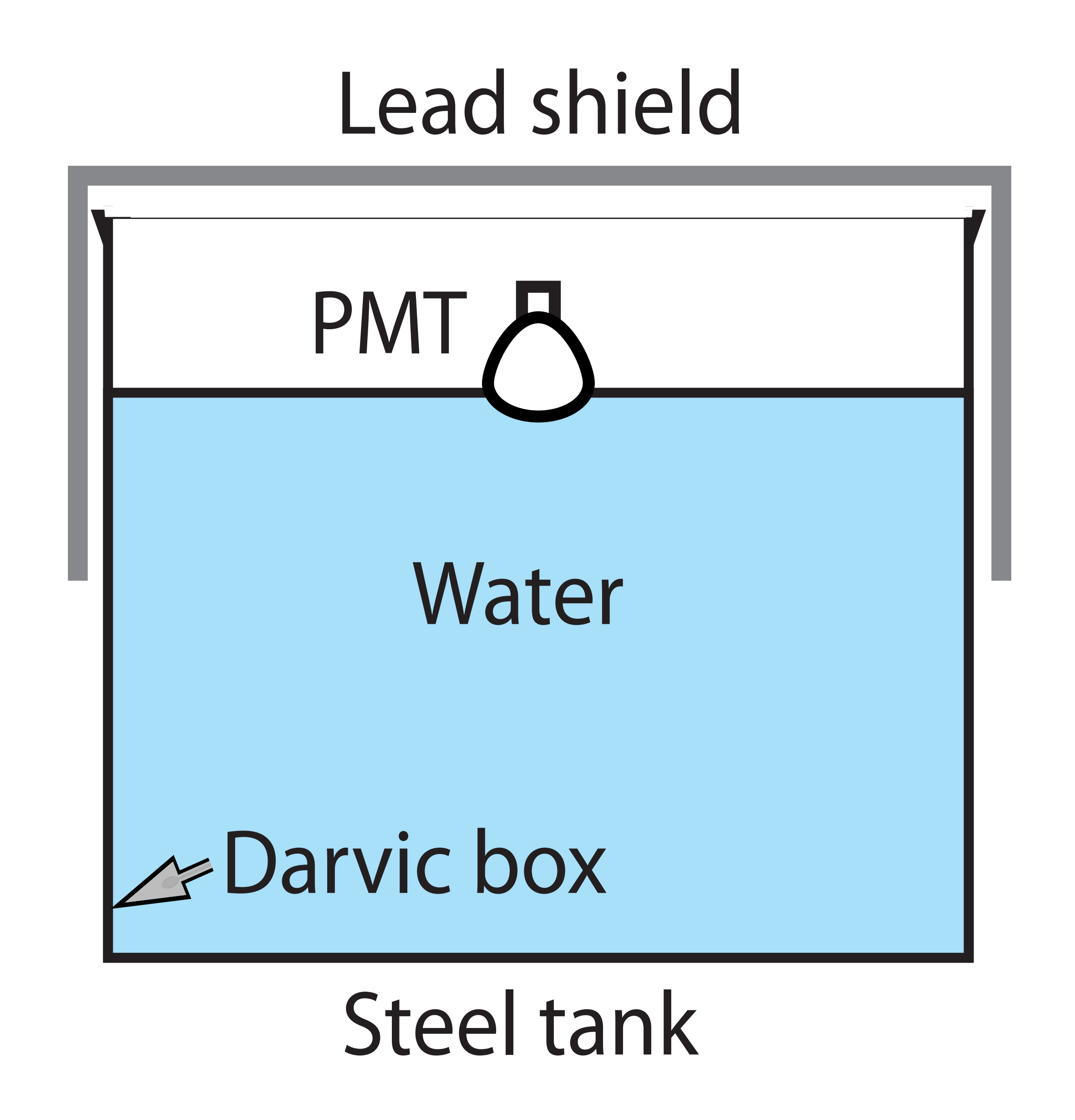
Photomultipliers tubes were developed in mid 40s (after World War II)

Particle detectors

Water Cherenkov detectors

When a particle moves through a medium at a velocity greater than c, it emits Cherenkov radiation (Cherenkov, Frank, Tamm, 1933).

[N.B. In Russia, the radiation is called Vavilov-Cherenkov radiation (Vavilov was Cherenkov's director)]

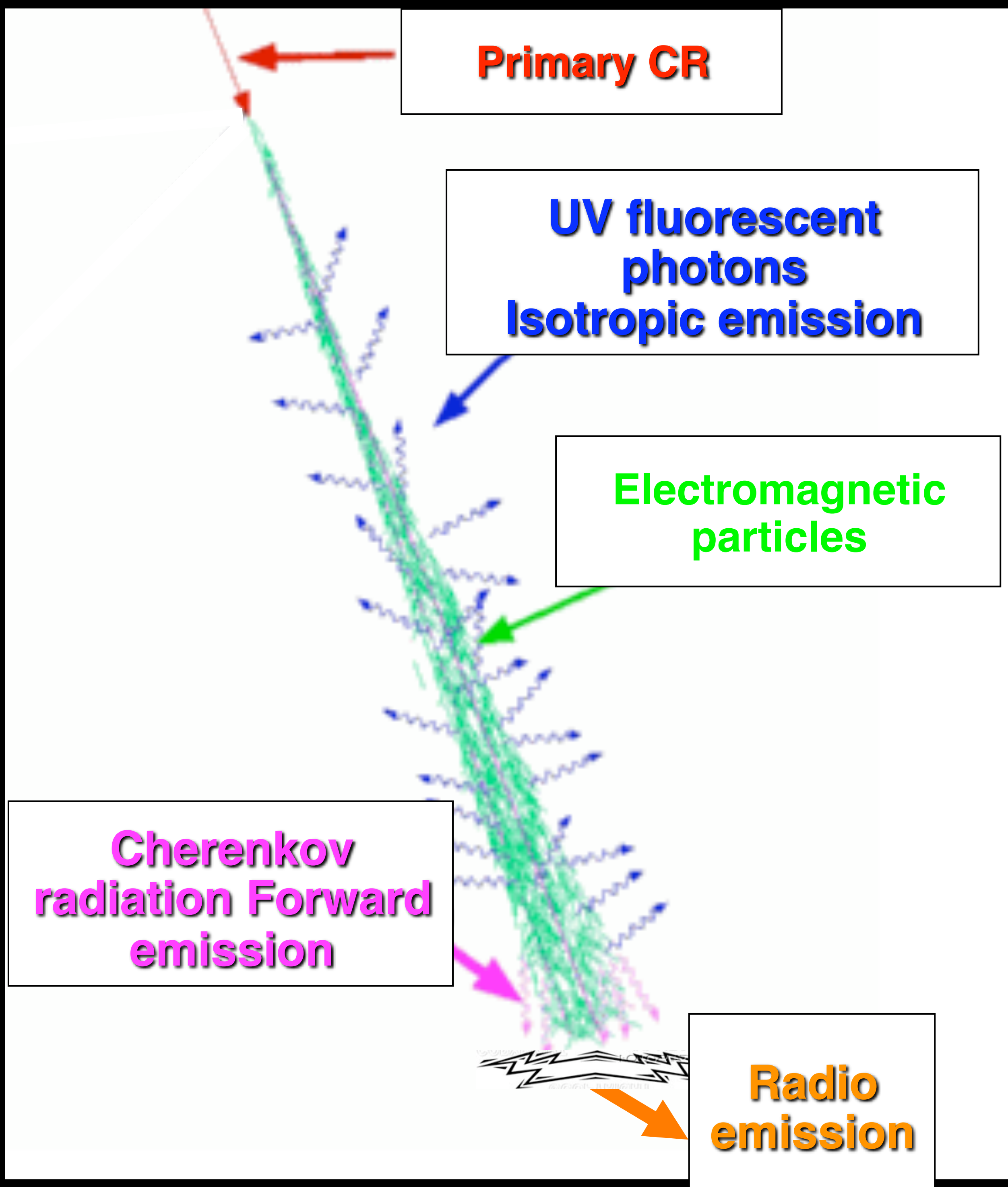


Scheme of the first WCD.
Depth water = 92 cm, area = 1.44 m²

Detectors of Cherenkov light produced in water.

First developed at Culham UK (Porter, 1958). It used a box of Darvic, a material used for sandwich boxes containing an inhibitor of bacterial growth. This allowed to prevent bacterial growth in unfiltered water and realise a stable detector.

EAS: not only particles but also radiation



Cherenkov radiation: Electrons and positrons in the shower travel faster than the speed of light in air and emit Cherenkov radiation, mostly in the forward direction

Fluorescence radiation: The passage of air shower e.m. particles in atmosphere results in the excitation of nitrogen molecules. Some of this excitation energy is emitted in the form of isotropic visible and UV radiation.

Radio emission: Main mechanisms: air shower electrons and positrons acceleration in the Earth's magnetic field. Also, radio-emission from the time-varying negative excess in the shower. Forward-beamed radiation.

Cherenkov radiation

Nani gigantum humeris insidentes (Blackett, Galbraith, Jelley)

When a particle moves through a medium at a velocity greater than c, it emits Cherenkov radiation (Cherenkov, Frank, Tamm, 1933).

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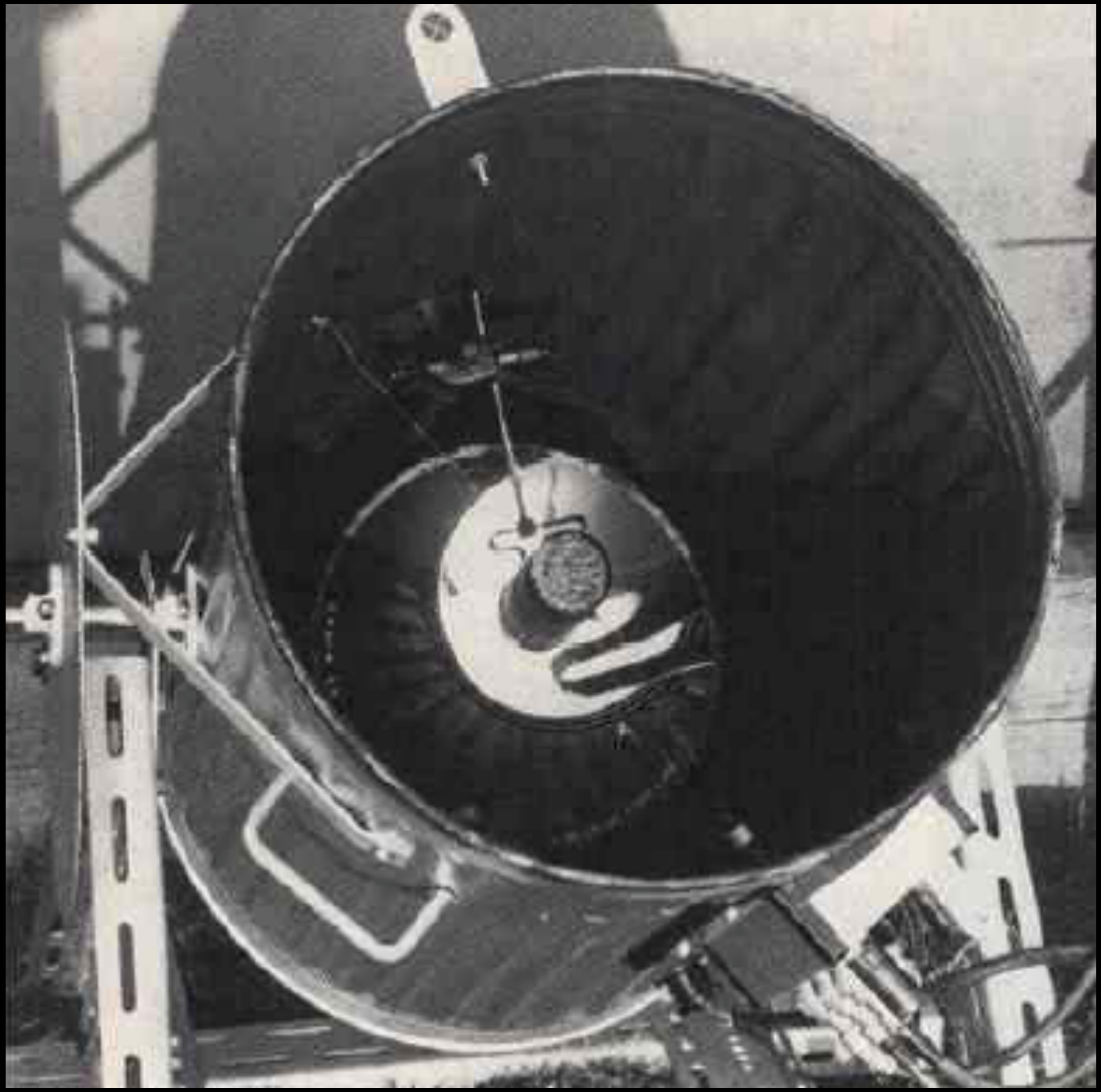
In 1948, Blackett was the first to discuss Cherenkov radiation in air concluding that CR showers should produce a flash of light that one should be able to see lying down and looking upwards under dark sky conditions, an investigation which Blackett carried out himself. The outcome of his "experiment" is unknown.

Soon after PMTs were invented, and used to detect Cherenkov light produced by showers (Galbraith and Kelley, 1952).

The technique has a low duty cycle (cloudless, moonless nights)



Galbraith, Kelley (1952): Cherenkov light experiment in a garbage can

Fluorescence radiation

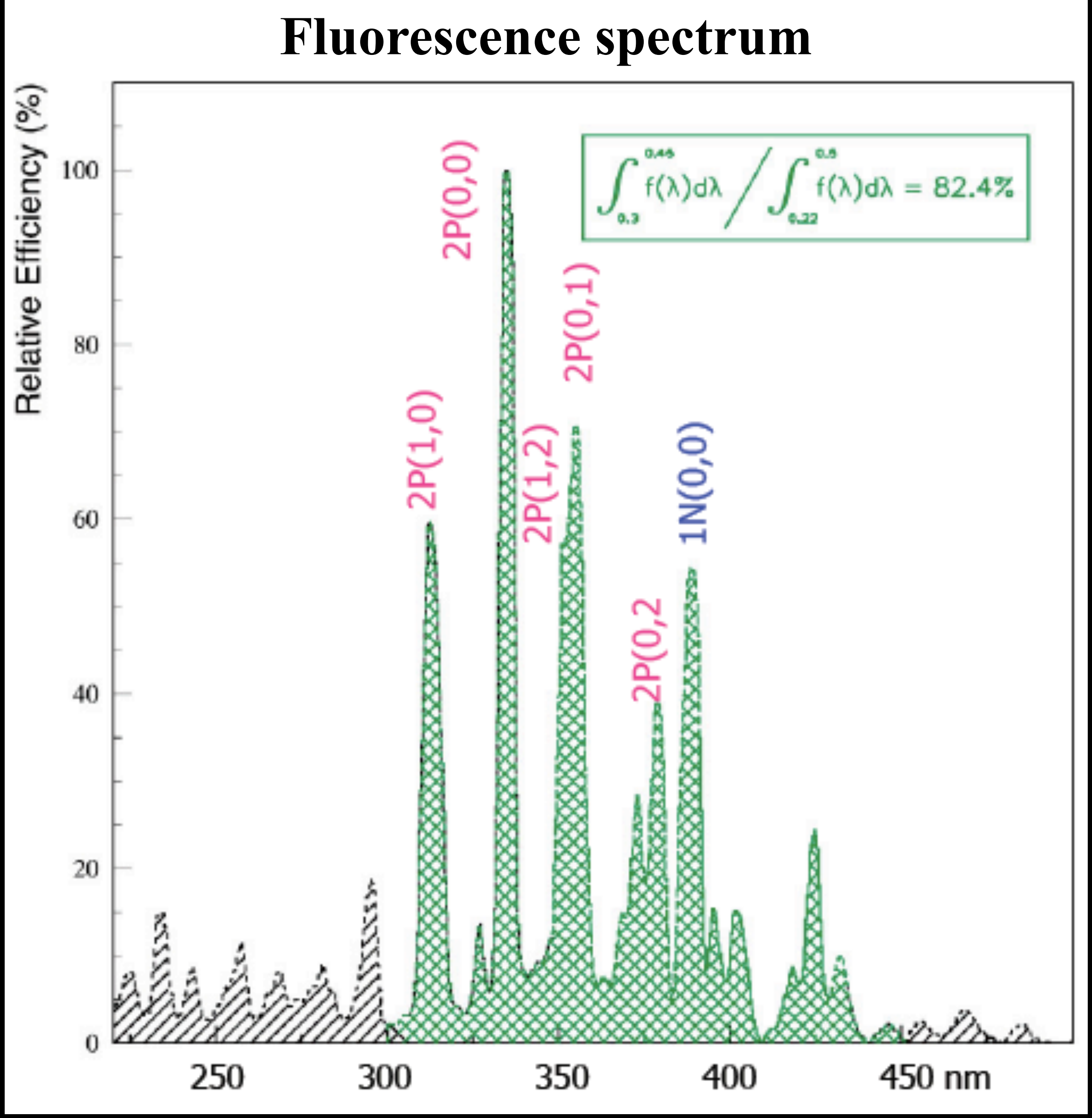
Nani gigantum humeris insidentes: Suga, Chudakov, Greisen (1960s)

Charged particles from EAS interact with Nitrogen molecules in air. Nitrogen molecules (1N and 2P bands) get excited and they emit (when returning to their ground state) a radiation in the wavelength range between 300 nm to 400 nm.

The fluorescence yield at 300-400 nm is approx. 4-5 photons per particle per meter of track in the atmosphere.

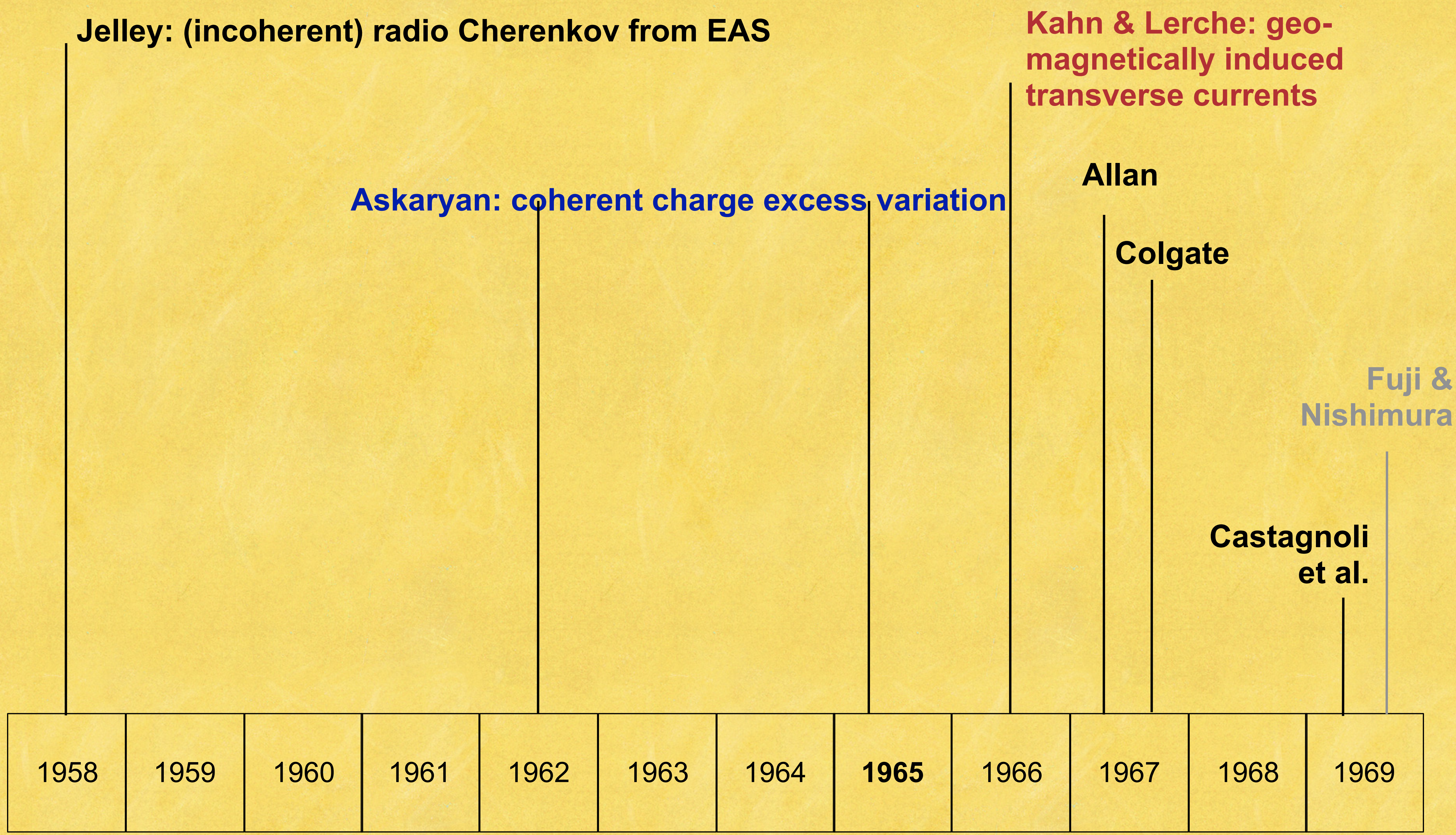
This fluorescence light is emitted isotropically. It can travel several km in atmosphere and be detected by optical telescopes, i.e., mirrors and PMTs equipped with fast electronics.

Only ≈0.5% of dE/dX goes into fluorescence. This technique can be exploited only at UHE (above 10^{17} eV). It has a low duty cycle (cloudless, moonless nights)



Radio emission

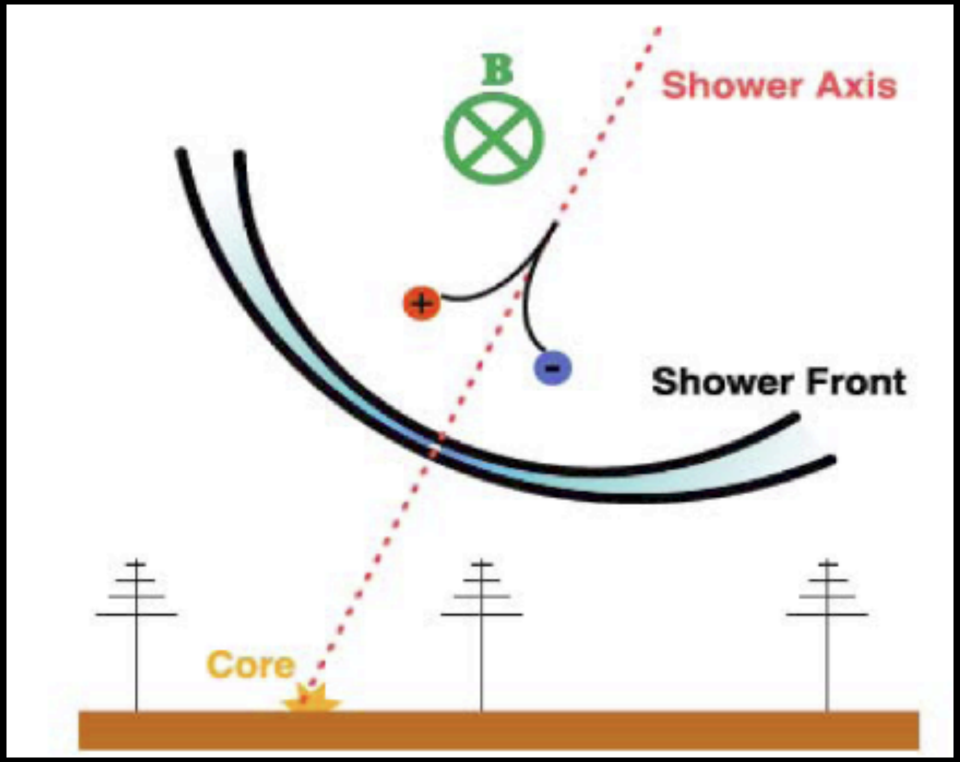
Nani gigantum humeris insidentes (1960s)

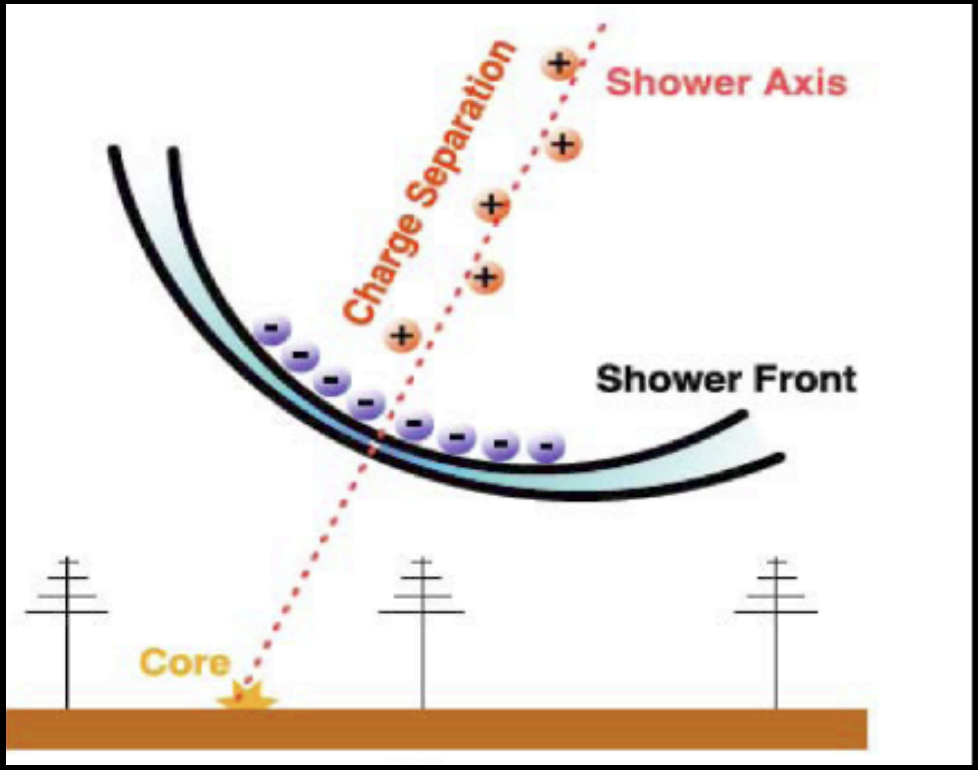


Jelley et al.: first experimental detection (1965)

Radio emission

Nani gigantum humeris insidentes (1960s)





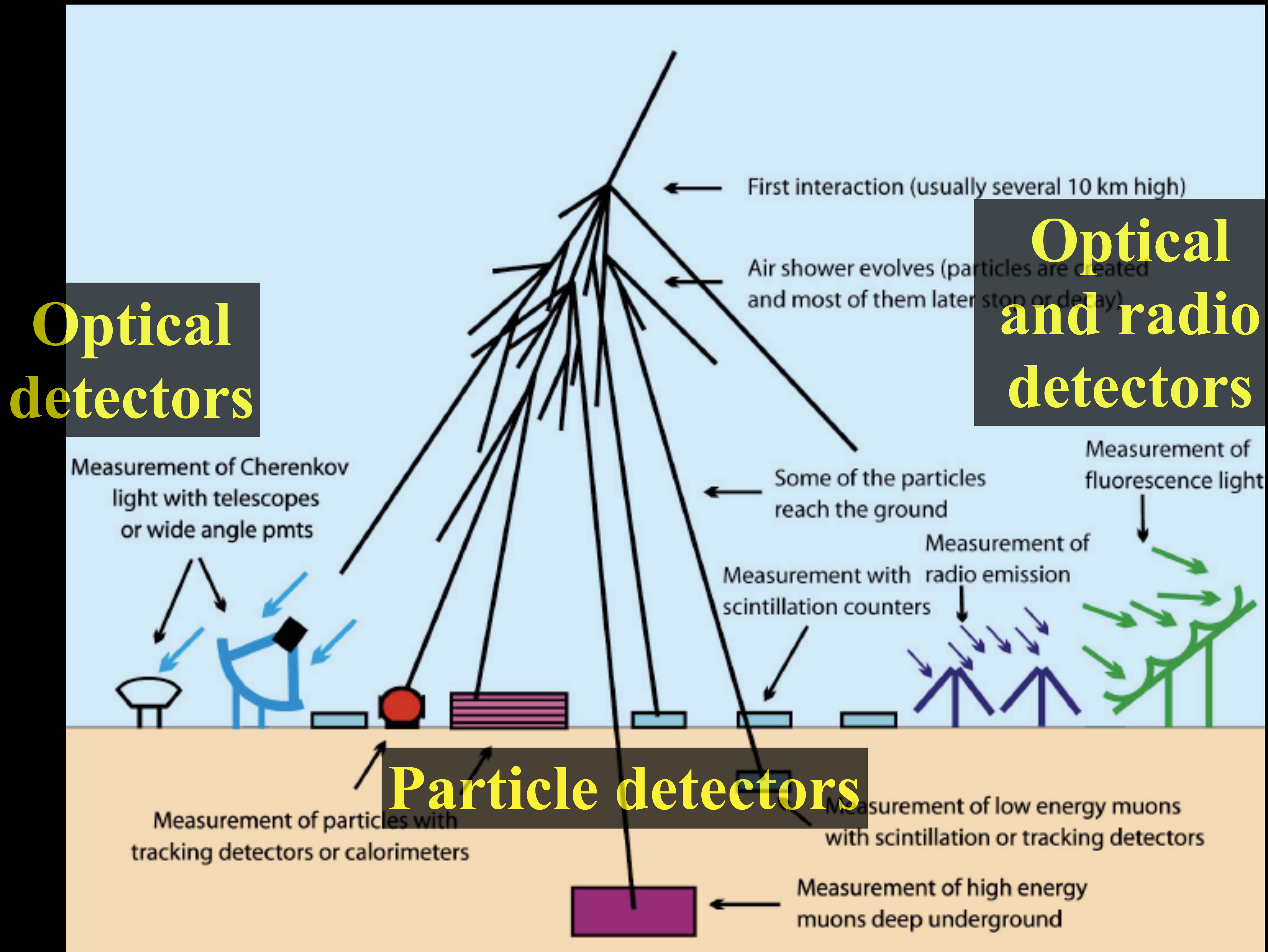
Geomagnetic effect*:*

deflection of charged particles in Earth's magnetic field (B). Electric current develops when the plasma moves through B. Radiation emitted by time varying electric current

Askarian effect:

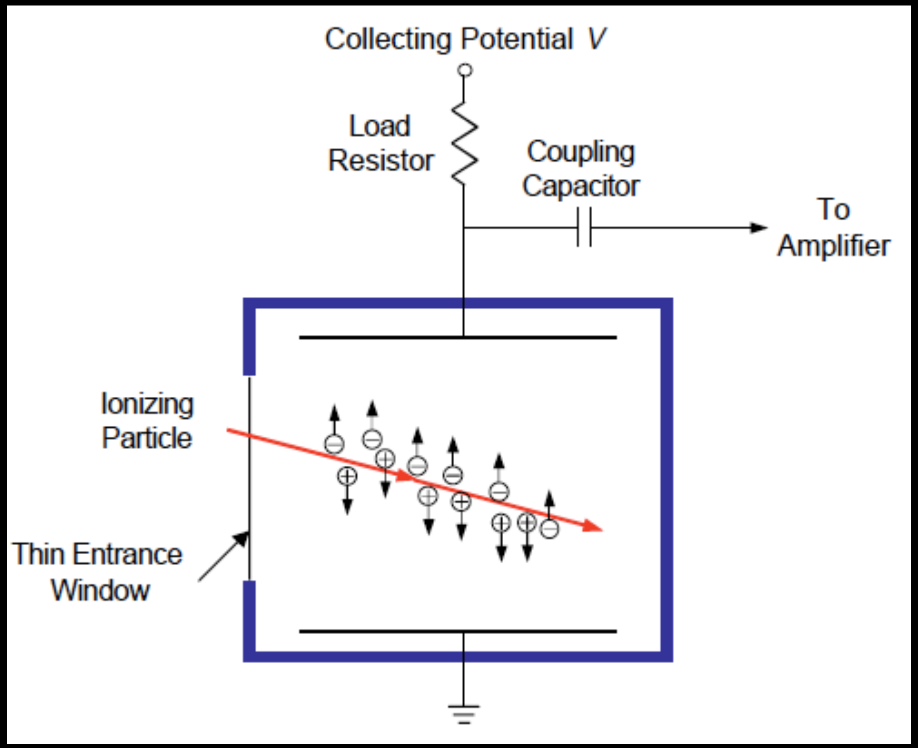
radio emission in the form of Cherenkov radiation. Due to the annihilation of positrons an excess of negative charge is created, producing Cherenkov radiation as it moves through the medium (air)

Different detectors for different observables

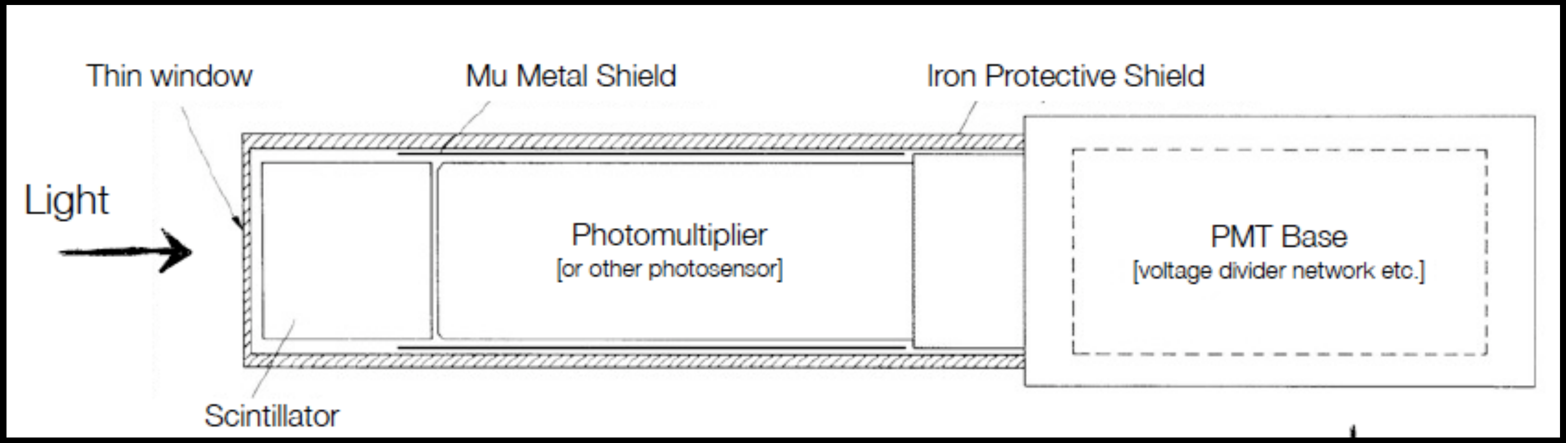


Different detectors for different observables

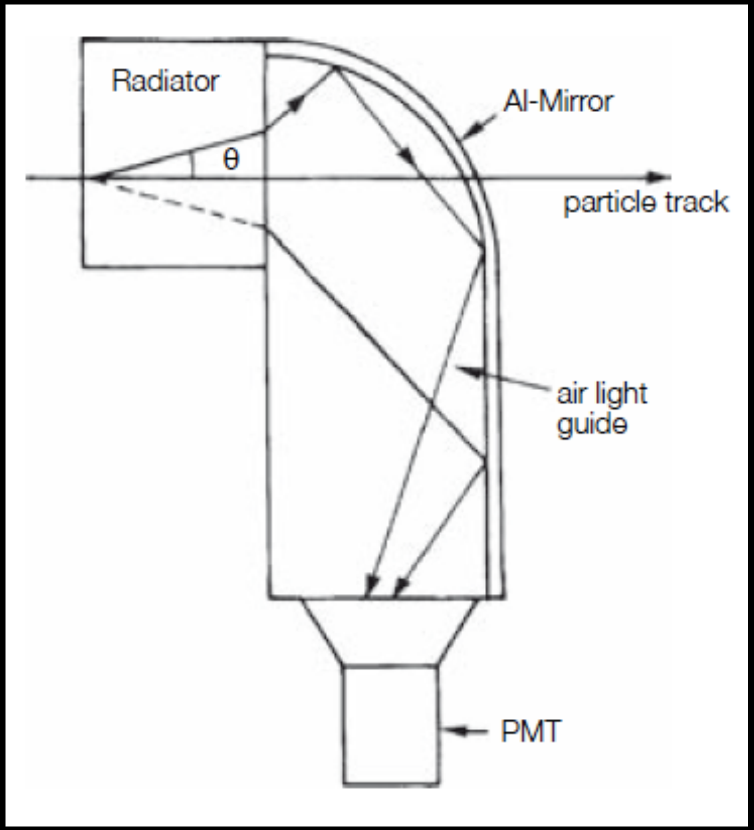
Particle detectors (100% duty cycle)



IONISATION



SCINTILLATORS+PMTS



CHERENKOV

Different detectors for different observables

Particle detectors (100% duty cycle)

Pros: ≈ 100% duty cycle

Cons: observation of the EAS at a unique fixed depth

*RPC = Resistive Plate Chambers

Different detectors for different observables

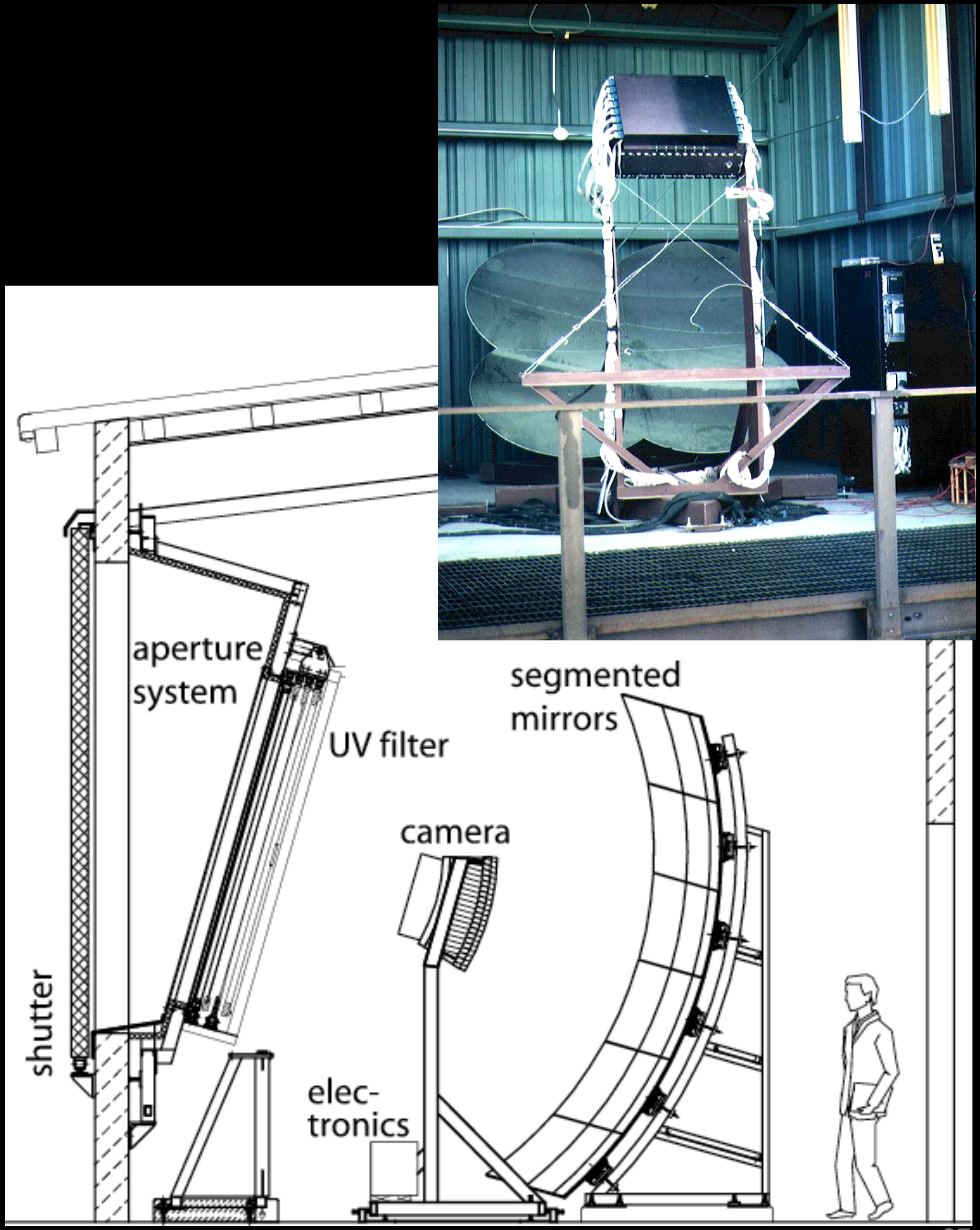
Optical detectors (limited duty cycle)

Cherenkov or fluorescence light is collected by a mirror and imaged onto a camera made by PMTs. Each PMT receives light coming from a specific region of the sky.

When an EAS crosses the field of view of the telescope, it triggers some of the PMTs. Each PMT records the trigger time and the intensity of the signal.

Pros: observation of the EAS longitudinal development, i.e., at various depths

Cons: ≈ 10% duty cycle

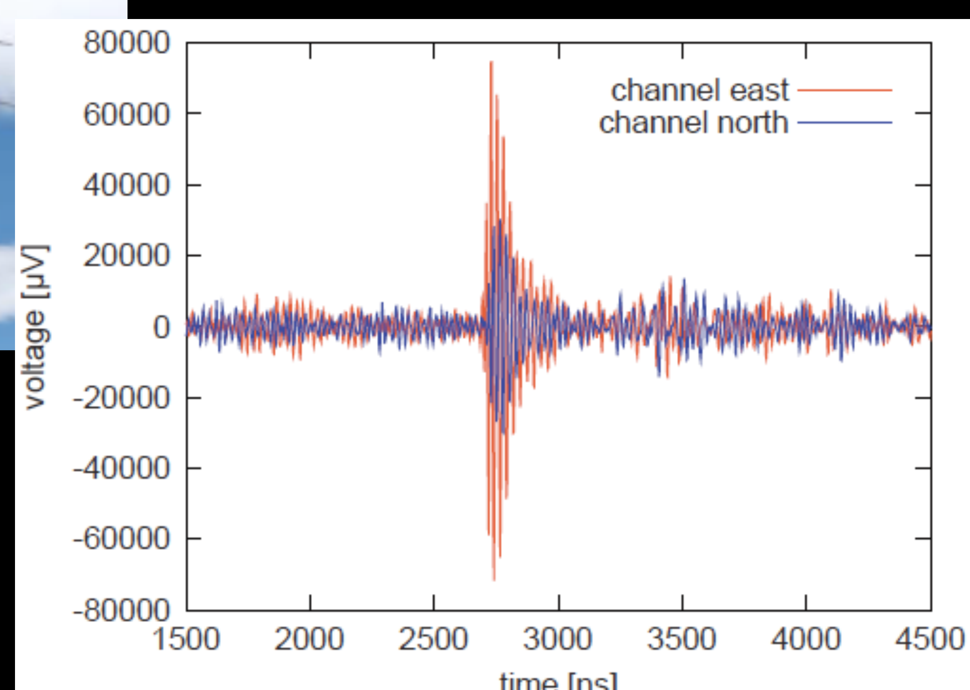


Different detectors for different observables

Radio detectors (100% duty cycle)

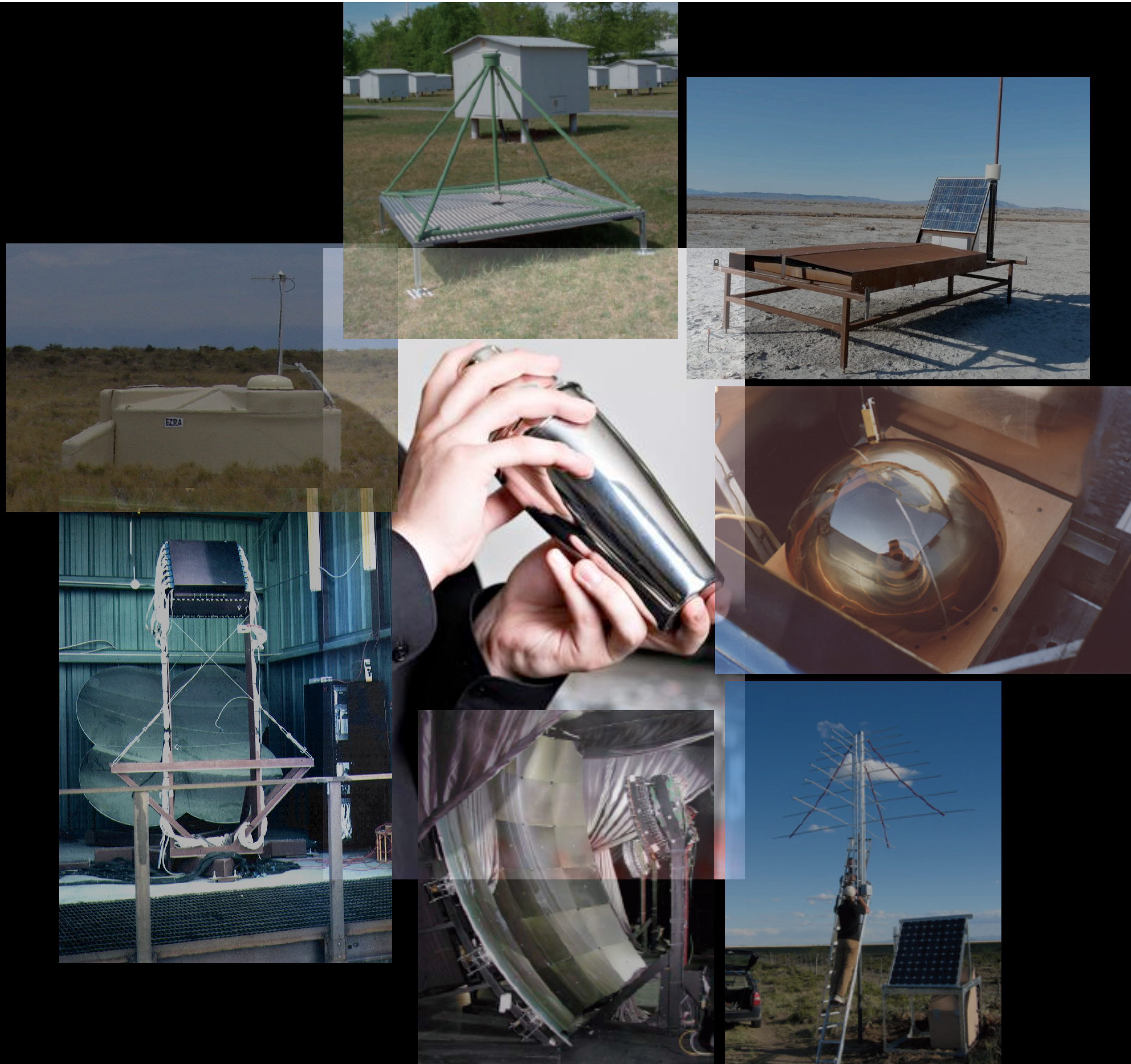
The measurement of the radio signal requires a radio antenna. Typically, one detector station consists of two antennas that are aligned perpendicular to each other, to allow for a measurement of the signal in two polarisation (EW-NS). Antennas can be triggered by traditional EAS arrays, or self-trigger.

Antenna triggered by particle detectors



Self-triggered antennas

Detectors are assembled into EAS telescopes/arrays



…In a way that depends on the energy of interest…

Choice of detectors spacing and array altitude impacts on energy threshold
Total area of the array limits the maximum energy

At 10^{11}-10^{13} eV (superposition with DIRECT MEASUREMENTS)

Air showers are re-absorbed high in the atmosphere: very high altitude needed

Air shower are "small": small spacing needed or full ground coverage (to go down to ≈ 10^{11} eV)

High fluxes: "small" areas sufficient

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

Shower maximum still high in the atmosphere: moderate mountain altitude needed

Moderate detector spacing needed (<100 m)

Rather low fluxes: moderately large 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 (detector spacing ≈ 150 m)

Above 10^{18} eV

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

N. B. Ideal detector: all (or many) of the shower components (multi-component, or hybrid, detector)

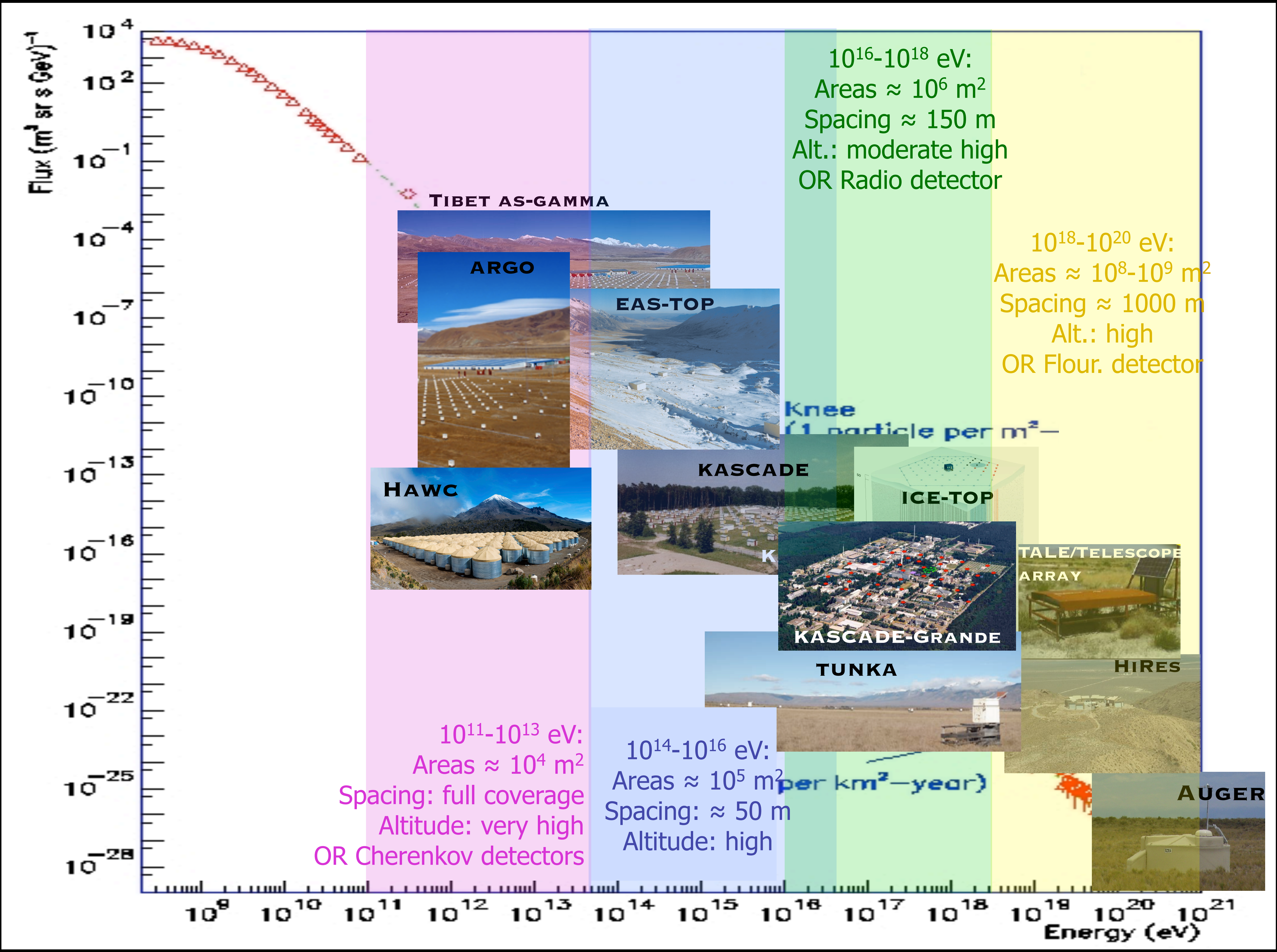
Recent and current EAS particle experiments

AGASA [Akeno Giant Air Shower Array] (Japan)
ARGO-YBJ: in Tibet
BAKSAN (Mt. Caucasus, Russia)
Buckland Park Extensive Air Shower Array (Australia) (operational 1971-1998)
CASA [Chicago Air Shower Array] (operational 1990-1998, USA)
EAS-TOP (Italy, above the Gran Sasso laboratory, 1990-2000)
Haverah Park (Leeds University, operational until 1993) (UK)
GRAPES, India
HAWC, Mexico
HEGRA (operational 1988-2002) (Spain)
ICETOP (South Pole, over ICECUBE)
KASCADE [KArlsruhe Shower Core and Array DEtector] (Germany)
KASCADE-GRANDE (Germany)
MILAGRO (Water Cherenkov experiment near Los Alamos) (USA)
Pierre Auger Observatory (Argentina)
SPASE 2 [South Pole Air Shower Array]
SUGAR [Sydney University Giant Air shower Recorder] (operational from 1968 to 1979)
Telescope Array (USA)
Tian-Shan Mountain Cosmic Ray Station
Tibet AS-gamma experiment: scintillation counter array (Tibet)
Yakutsk (Russia)
Volcano Ranch (USA)

Recent and current EAS radiation experiments

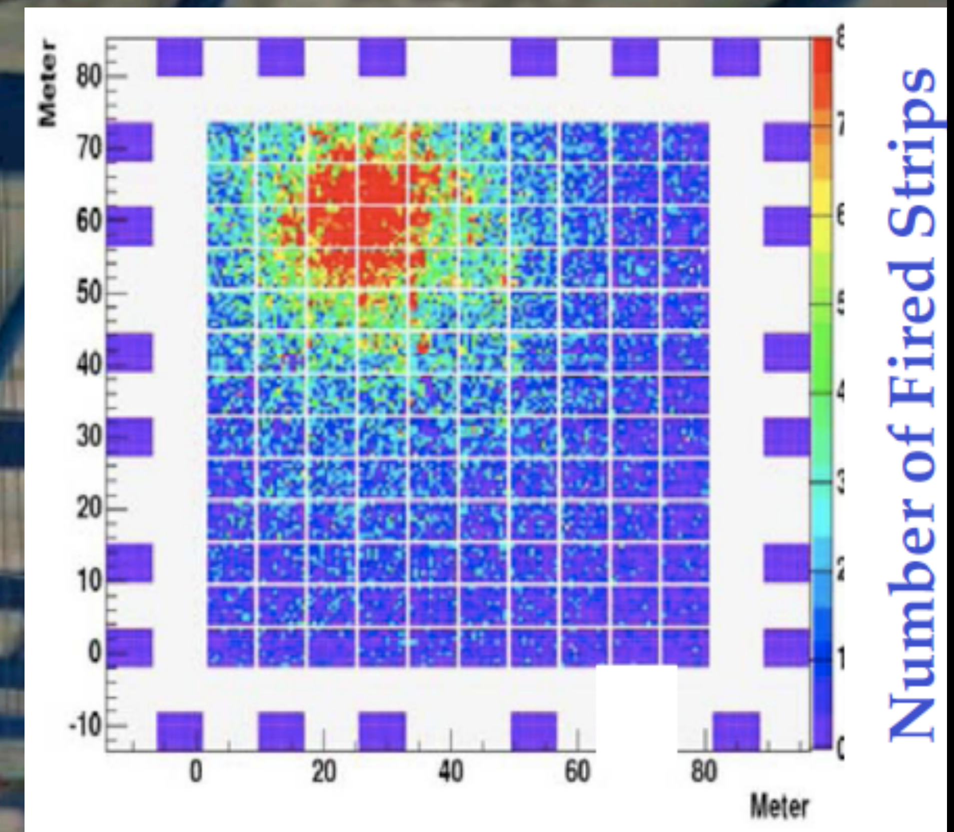
AIROBICC (non-imaging counters in the HEGRA array)
BLANCA [Broad LAteral Non-imaging C(h)erenkov Array] (at CASA))
TUNKA (array of non-imaging counters near Lake Baikal)

ASHRA [All-sky Survey High Resolution Air-shower detector]
PIERRE AUGER OBSERVATORY
EUSO [Extreme Universe Space Observatory] (proposed)
HiRes The High Resolution Fly's Eye Cosmic Ray Detector
Telescope Array [TA]



Flux (m² sr s GeV)⁻¹
Energy (eV)
Tibet AS-gamma
ARGO
EAS-TOP
Hawc
KASCADE
ICE-TOP
KASCADE-Grande
TUNKA
TALE/Telescope Array
HiRes
Auger
Knee
(1 particle per m²–
per km²–year)
10¹¹-10¹³ eV:
Areas ≈ 10⁴ m²
Spacing: full coverage
Altitude: very high
OR Cherenkov detectors
10¹⁴-10¹⁶ eV:
Areas ≈ 10⁵ m²
Spacing: ≈ 50 m
Altitude: high
10¹⁶-10¹⁸ eV:
Areas ≈ 10⁶ m²
Spacing ≈ 150 m
Alt.: moderate high
OR Radio detector
10¹⁸-10²⁰ eV:
Areas ≈ 10⁸-10⁹ m²
Spacing ≈ 1000 m
Alt.: high
OR Flour. detector

TO MEASURE COSMIC RAYS AT 10^{11}-10^{13} EV: ARGO



4300 m a.s.l (Tibet)
"Full coverage" detection surface
RPCs (small space-time "pixels")
Area ≈ 10^4 m^2
In operation
Energy range: 10^{11}-10^{13} eV
Main physics aims: γ-ray astronomy, cosmic ray studies overlapping direct measurements

Resistive Plate Chambers carpet

TO MEASURE COSMIC RAYS AT ≈ 10^{11}-10^{14} EV: HAWC

4100 m a.s.l (Mexico)
300 adjacent water-Cherenkov
Area ≈ 2.2×10^4 m^2
In operation
Energy range: 5 10^{11}-10^{14} eV
Main physics aims: γ-ray astronomy, cosmic ray studies overlapping direct measurements

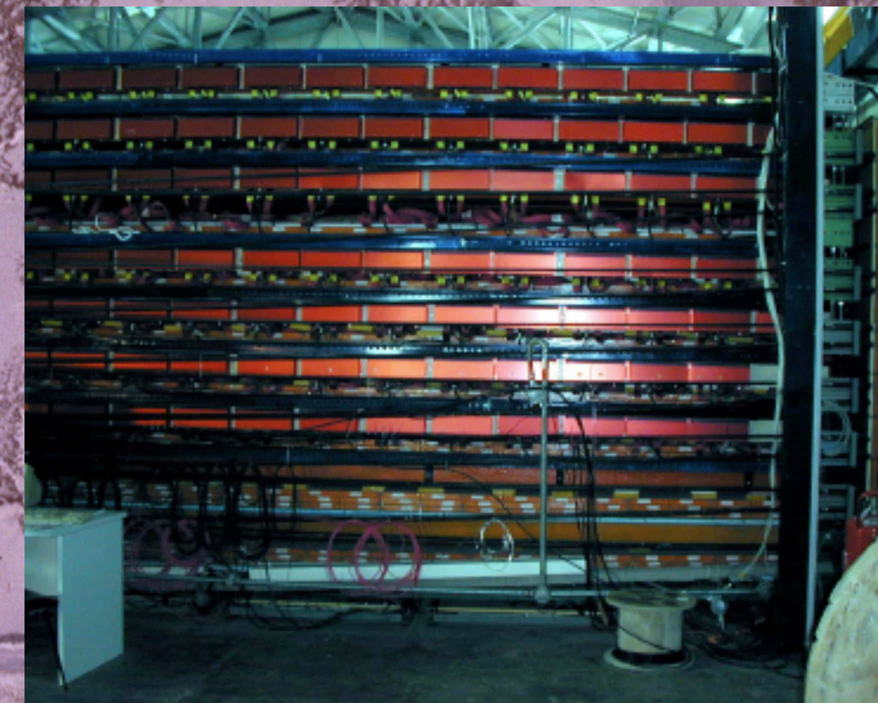
TO MEASURE COSMIC RAYS AT ≈ 10^{13}-10^{15} EV: TIBET AS-GAMMA

4300 m a.s.l (Tibet)
697 scintillators @ 7.5 m

36 scintillators @ 15 m
Area ≈ 4×10^4 m^2
In operation
Energy range: 10^{12}-10^{15} eV
Main physics aims: γ-ray astronomy, cosmic ray studies overlapping direct measurements

TO MEASURE COSMIC RAYS AT ≈ 10^{14}-10^{16} EV: EAS-TOP

2000 m a.s.l (Gran Sasso, Italy)
MULTI-COMPONENT ARRAY:
35 scintillator modules 80 m spacing
Central muon/hadron calorimeter
8 Cherenkov telescopes
3 Radio antennas
In operation in the 90s
Area 10^5 m^2
Energy range: 10^{14}-10^{16} eV



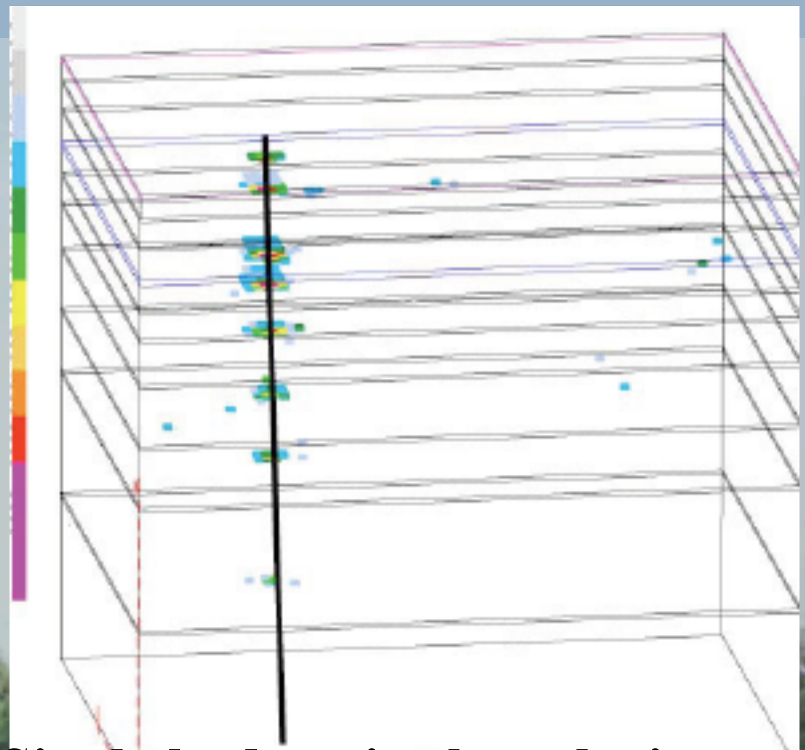
Calorimeter at the center: muon tracking, hadron measurement

Main physics aims: γ-ray astronomy, cosmic ray spectrum and composition at the “knee”, cosmic ray anisotropies

F.Arneodo

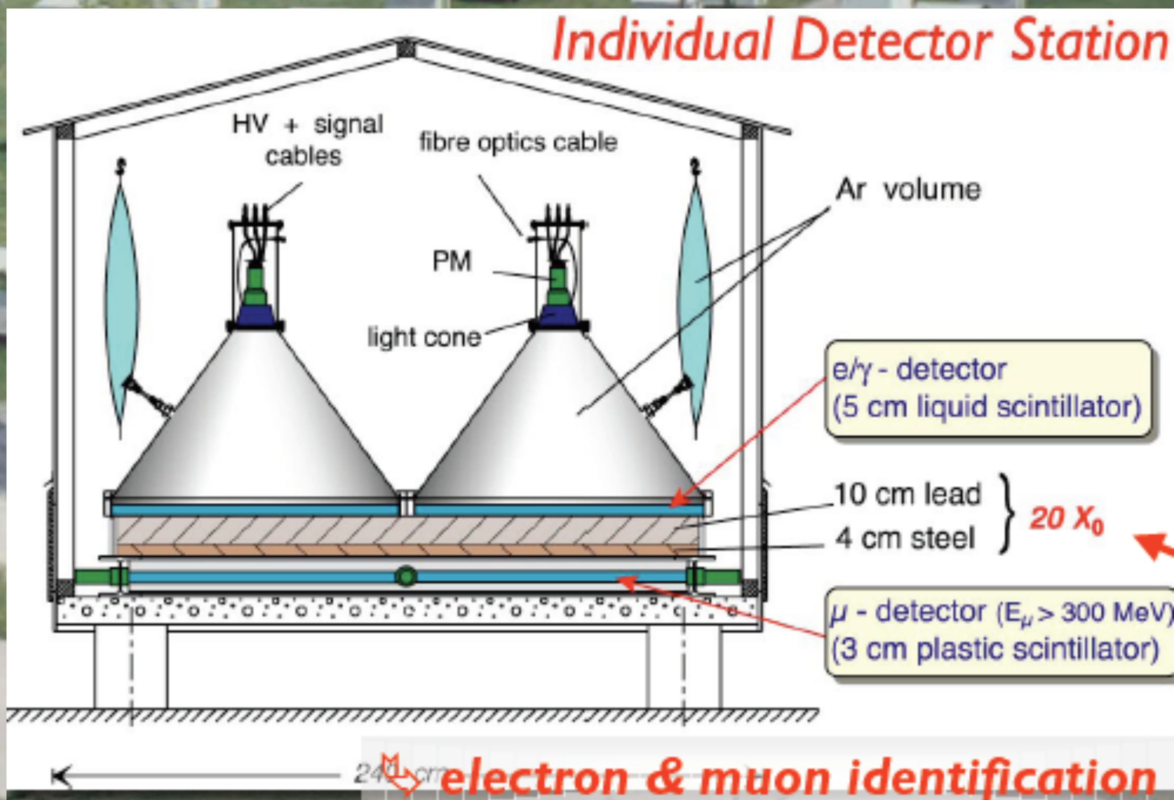
TO MEASURE COSMIC RAYS AT ≈ 10^{14}-10^{16} EV: KASCADE

Sea level (Karlsrhue, Germany)
MULTI-COMPONENT ARRAY:
252 scintillator modules (electrons/muons)
Central calorimeter
In operation in the 90s
15 m spacing, area 4×10^4 m^2
Energy range: 5×10^{14}-5×10^{16} eV



Single hadron in the calorimeter

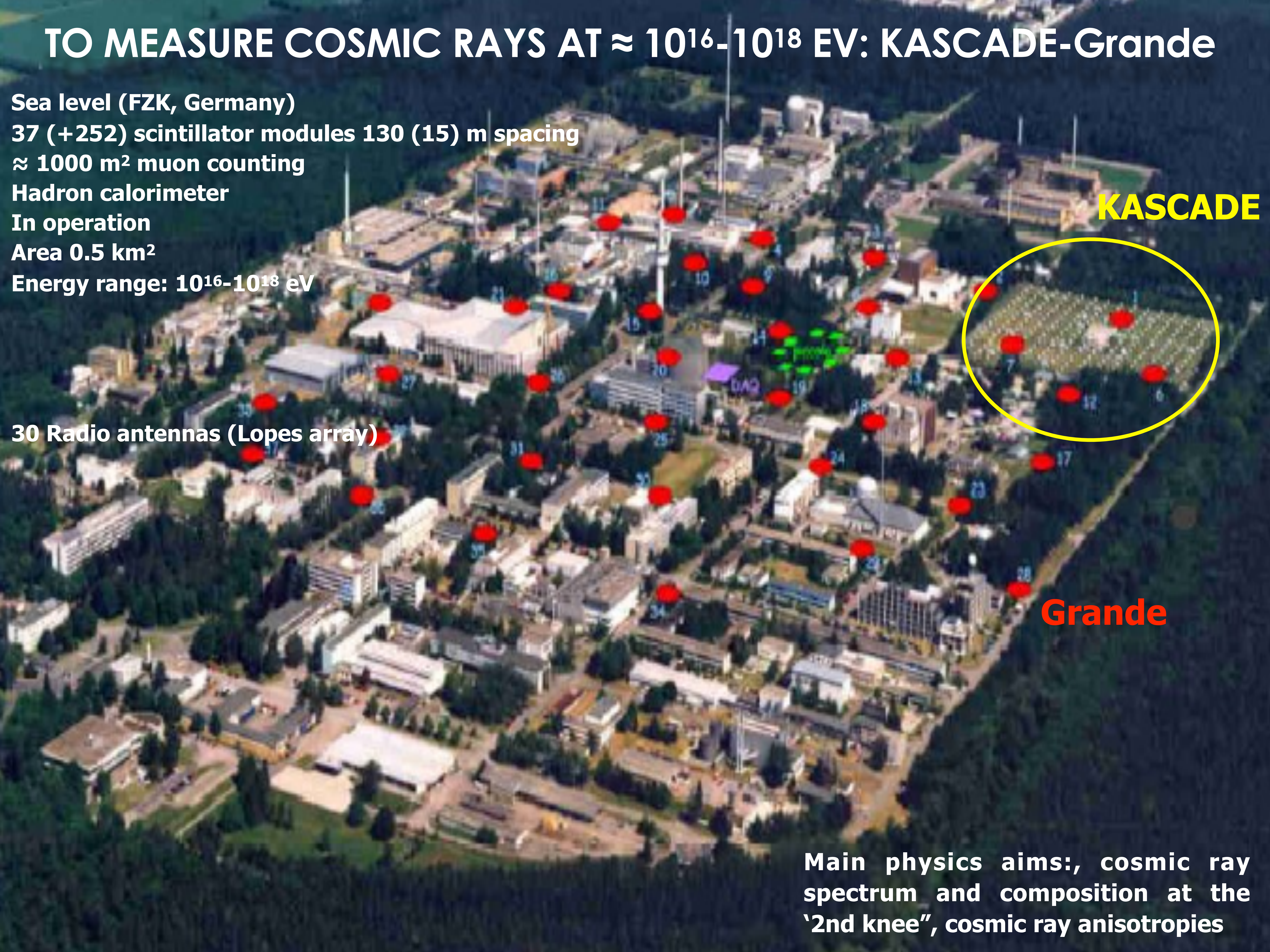
Area ~ 0.04 km^2,
252 surface detectors



TO MEASURE COSMIC RAYS AT ≈ 10^{16}-10^{18} EV: KASCADE-Grande

Sea level (FZK, Germany)
37 (+252) scintillator modules 130 (15) m spacing
≈ 1000 m^2 muon counting
Hadron calorimeter
In operation
Area 0.5 km^2
Energy range: 10^{16}-10^{18} eV

30 Radio antennas (Lopes array)



Main physics aims:, cosmic ray spectrum and composition at the ‘2nd knee”, cosmic ray anisotropies

TO MEASURE COSMIC RAYS AT ≈ 10^{14}-10^{17} EV: ICETOP

Freezing PMT domes

Installation of a detector

South Pole (on top of IceCube)

80 stations: 160 ice Cherenkov detectors

In operation

125 m spacing, area ≈ 10^6 m^2

Energy range: 10^{14}-10^{17} eV

Credit Desy Zeuthen

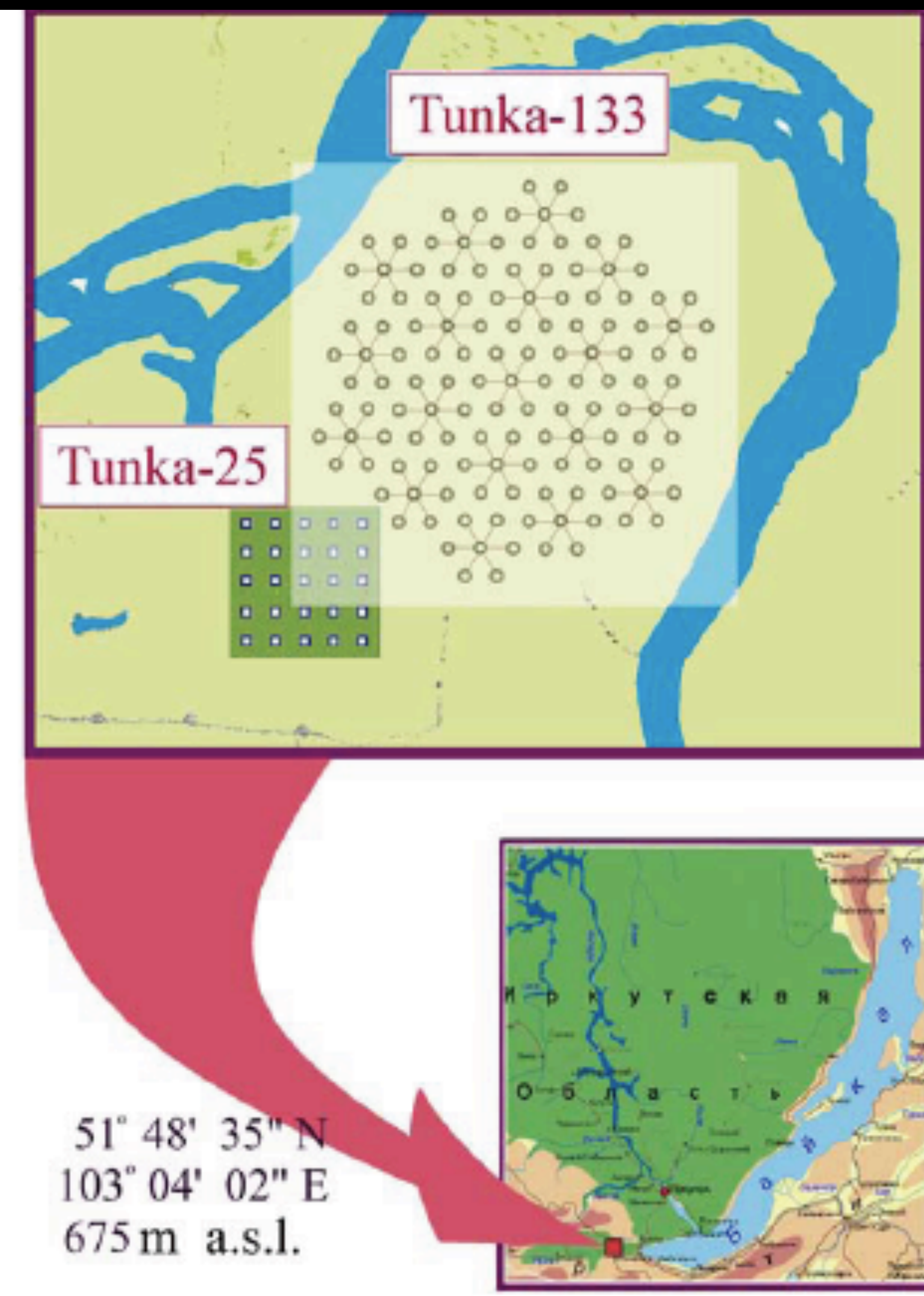
TO MEASURE COSMIC RAYS AT ≈ 10^{15}-10^{18} EV: TUNKA

Tunka Valley (Russia), 700 m a.s.l.

133 open-air Cherenkov detectors; 19 clusters of 7 detectors each

In operation

Area 1 km^2; Energy range: 10^{15}-5×10^{18} eV



TO MEASURE COSMIC RAYS AT > 10^{18}: FLY'S EYE


16 pixels PMT camera

Early 80s-1995
USA, Utah, 100 m a.s.l.
2 fluorescence telescopes (67 mirrors & 880 PMTs + 36 mirrors & 464 PMTs)
Spacing ≈ 3.4 km

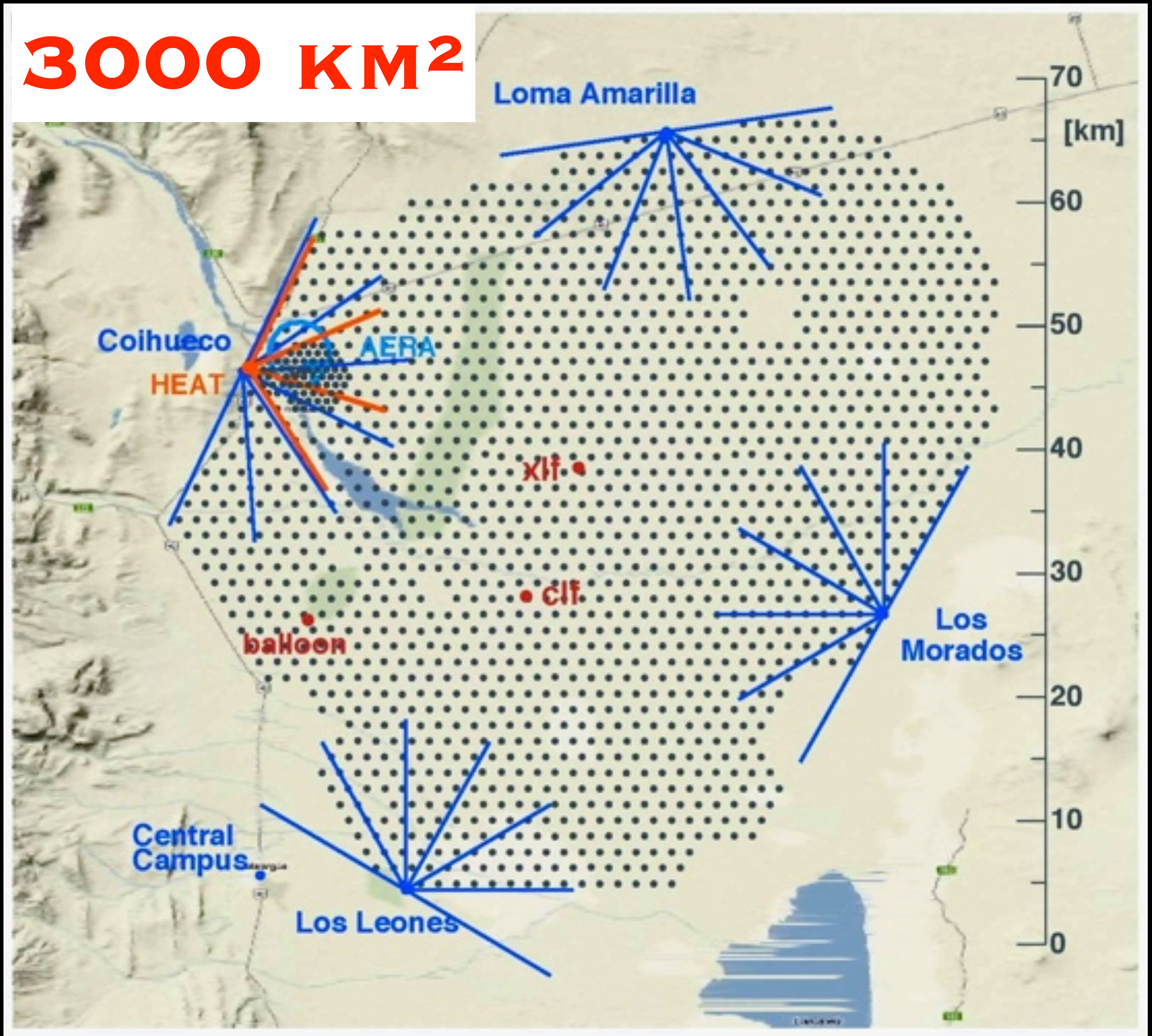
TO MEASURE COSMIC RAYS AT > 10^{18}: HiRES

- USA, Utah, 100 m a.s.l. (up to end 2000s)
- 2 fluorescence telescopes (HiRES 1 & 2)
- Larger spacing wrt Fly's Eye ≈ 12.6 km
- HiRes 1: 21 mirrors (alt. 3-17 deg): higher statistics, higher energy threshold
- HiRes 2: 42 mirrors (alt. 3-31 deg). Lower energy threshold
- High precision stereo measurements

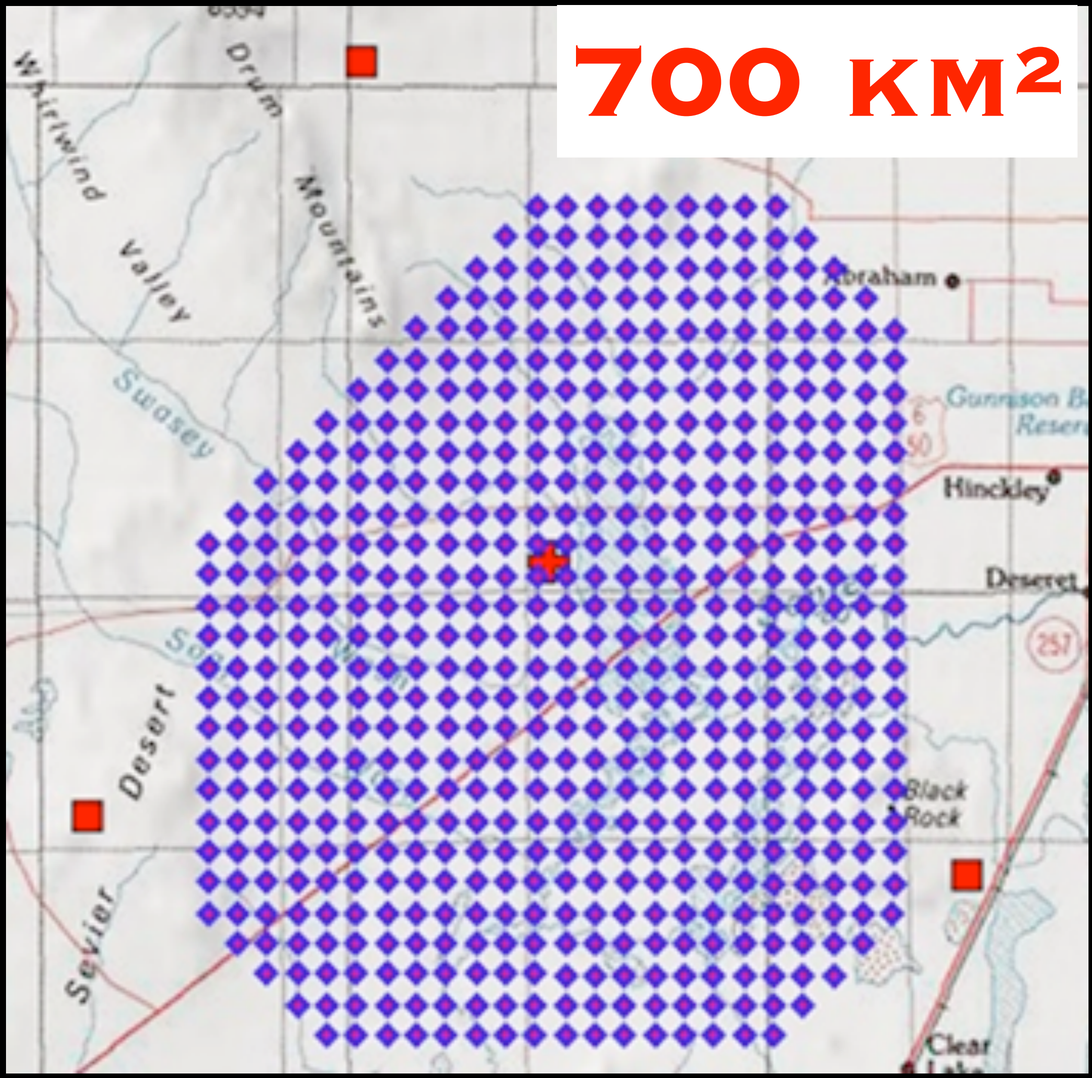
To measure cosmic rays at E > 10^{18} eV

The two giants!

2004:
Pierre Auger Observatory
Malargüe, Argentina
1660 surface detectors,
4 fluorescence detectors



2008:
Telescope Array,
Utah, USA
507 surface detectors
3 fluorescence detectors



Two exemplary cases: the Pierre Auger Observatory and the Telescope Array:
EAS observables

The delicacy of the observations

The Pierre Auger Observatory

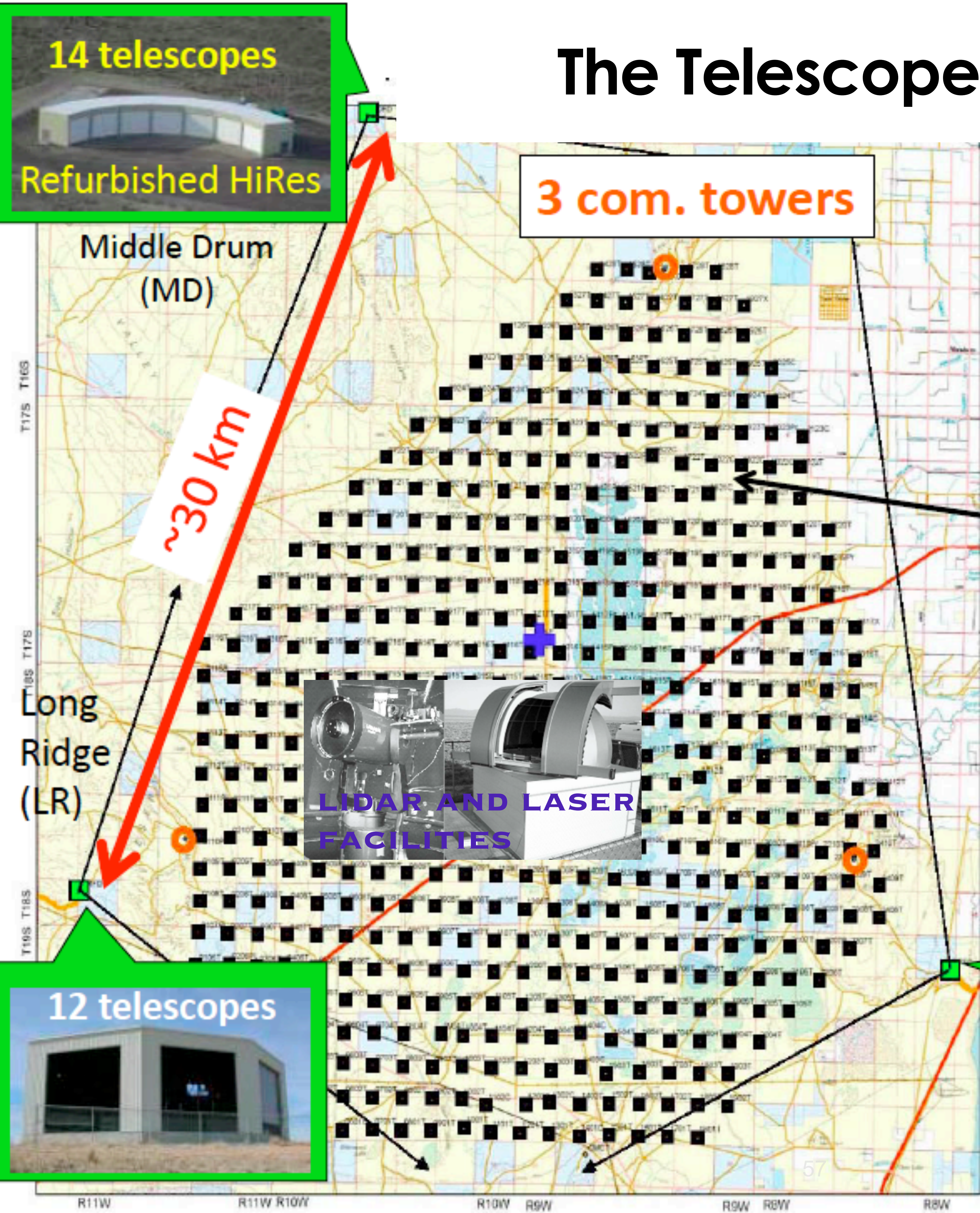
Surface Array:
1600 water Cherenkov stations, 1500 m spacing, A≈3000 km2

Lidar and laser facilities

4 Fluorescence detectors:
24 telescopes in total

The Telescope Array

39.3°N, 112.9°W
~1400 m a.s.l.



Surface Detector (SD)

507 plastic scintillator SDs
1.2 km spacing
700 km^2

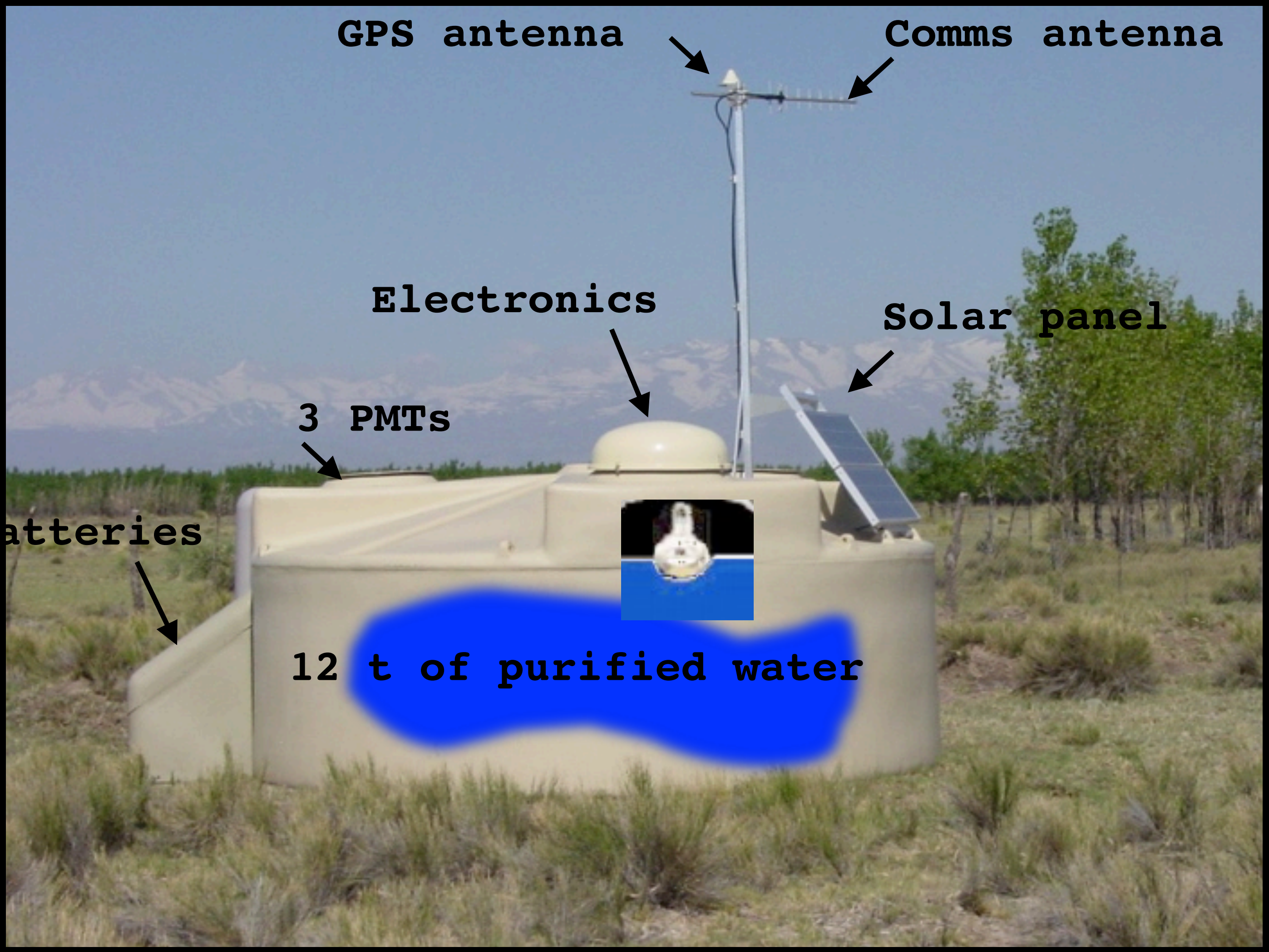
Fluorescence Detector(FD)

3 stations
38 telescopes

From H. Sagawa, ICRC 2013

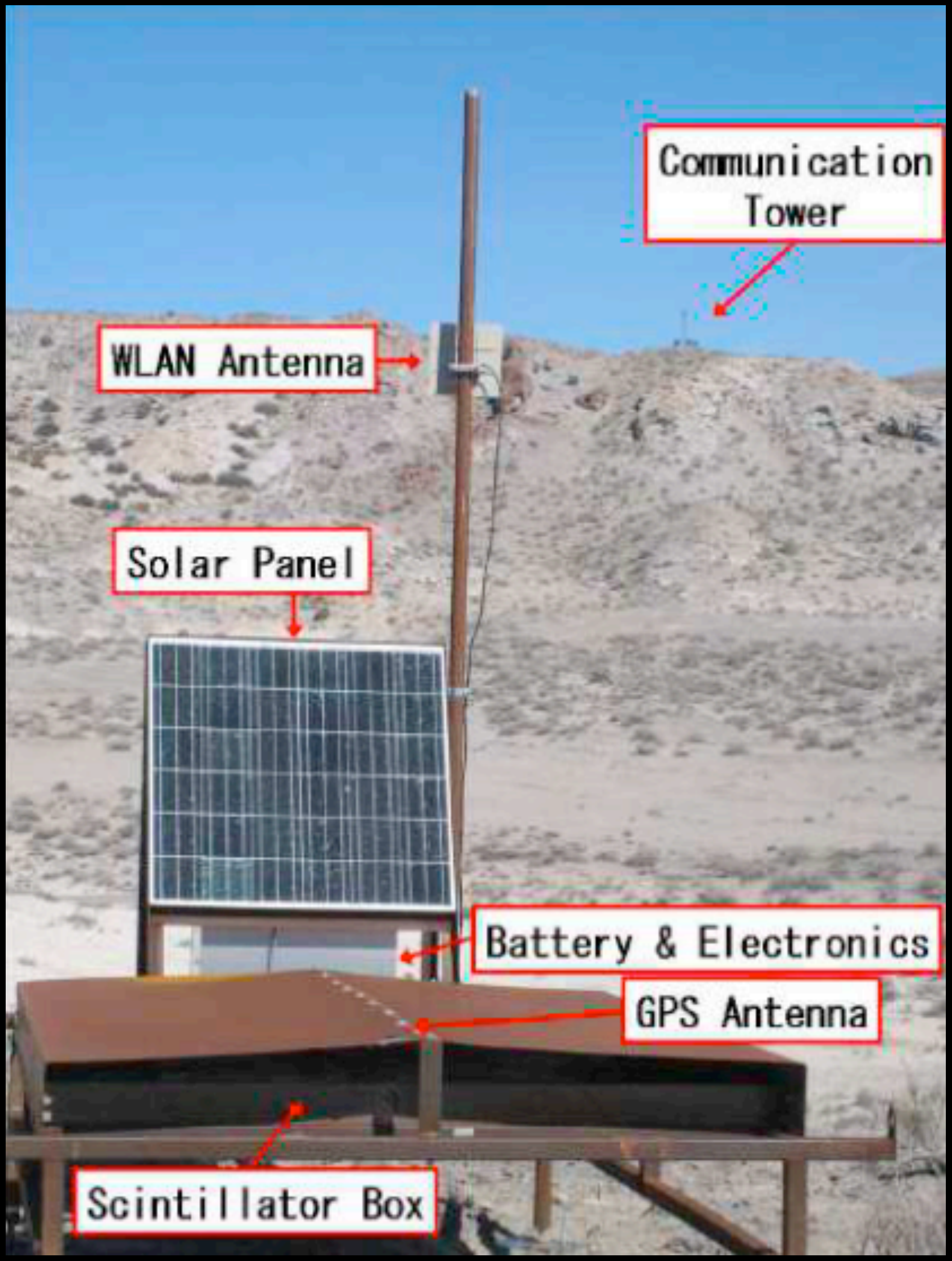
Auger and TA surface detectors

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



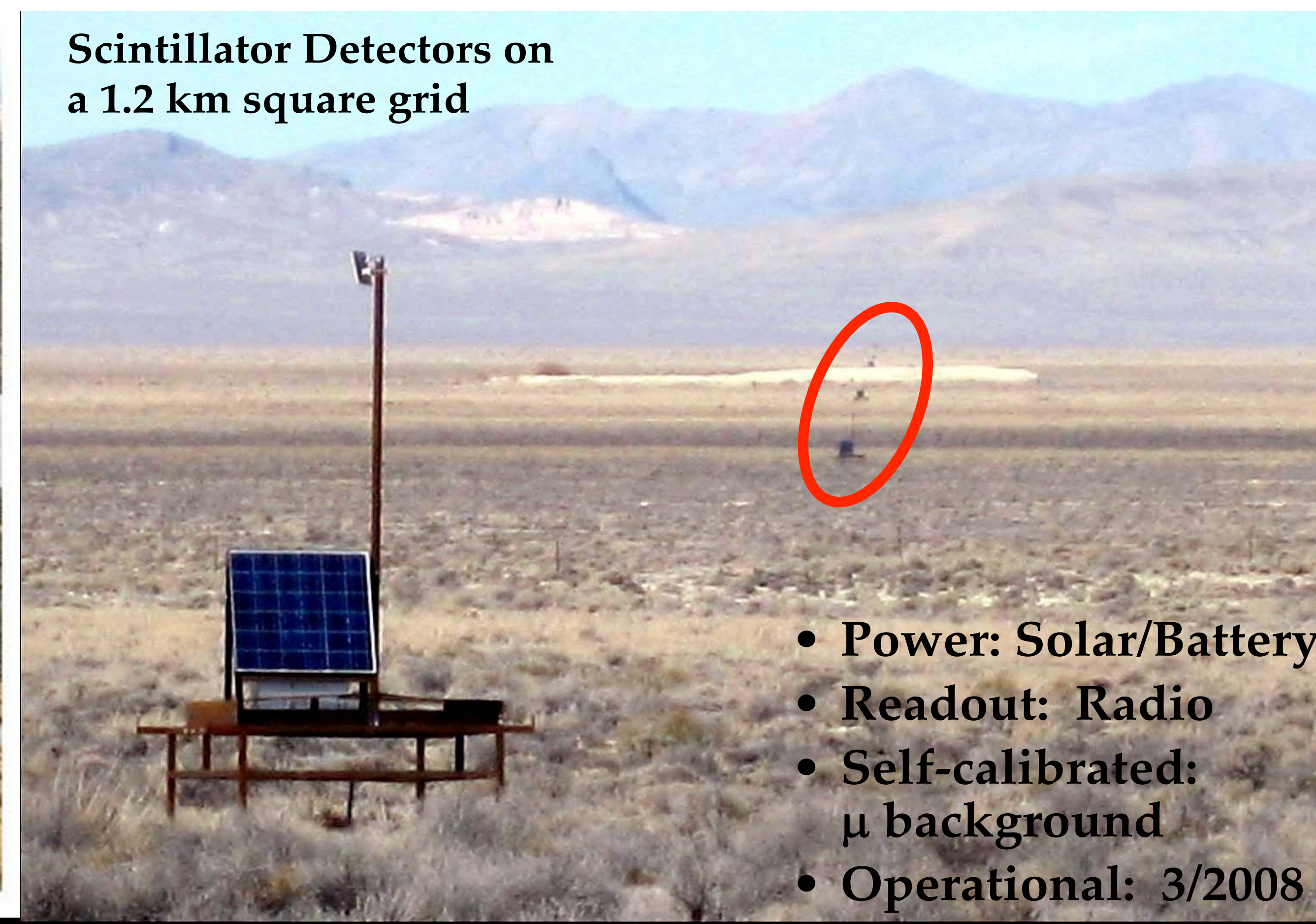
Scintillators
2 PMTs/detector
Area: 3 m²
Thickness: 1.2 cm
Acceptance up to 55 deg
More sensitive to em component

Auger and TA surface detectors

Auger

Perfectly aligned in the pampa, at a distance of 1.5 km one from another

Telescope Array

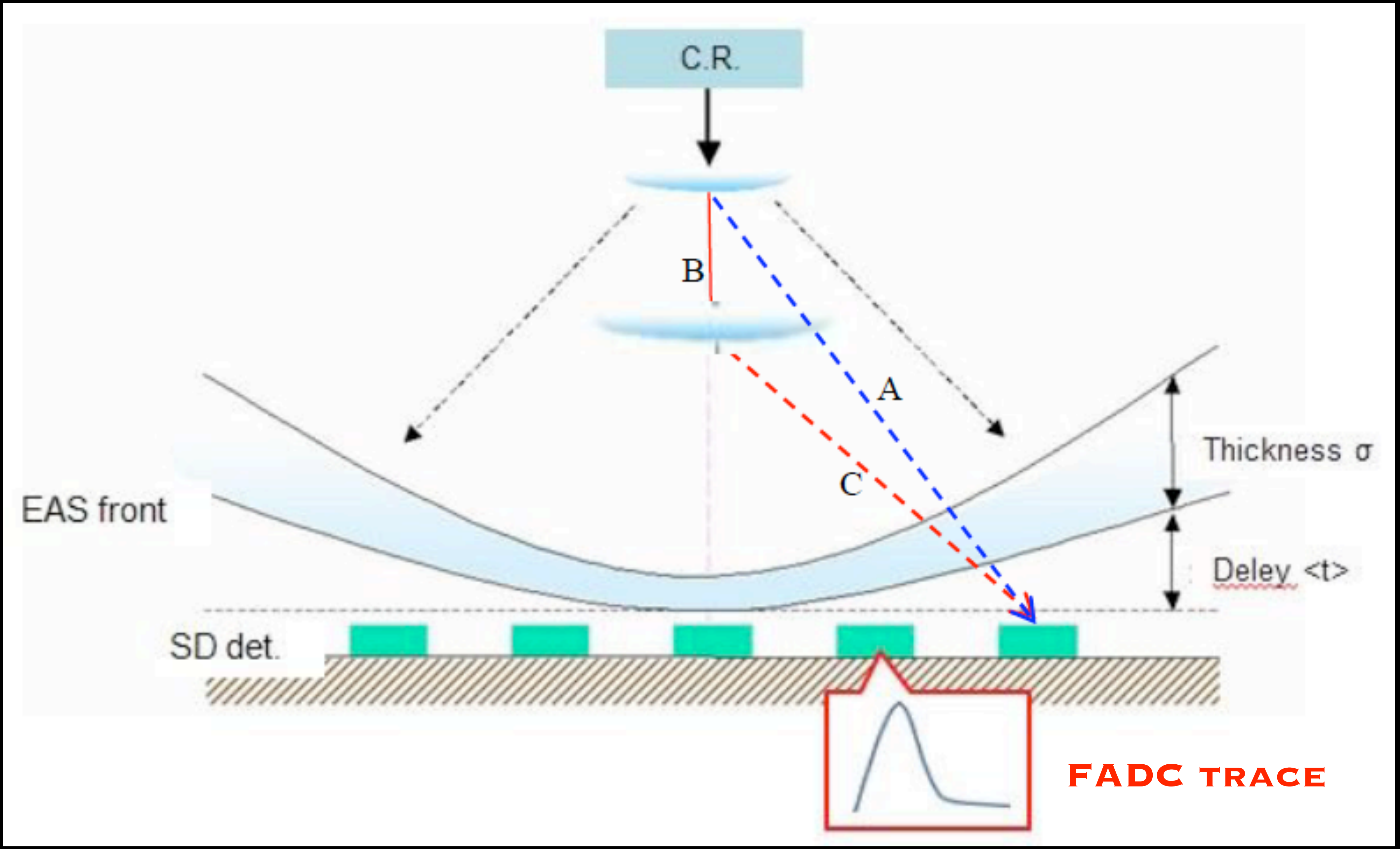


Perfectly aligned in the desert, at a distance of 1.2 km one from another

Pampa, desert:

The adventurous excursion of the observers :-)

EAS signals in surface detectors



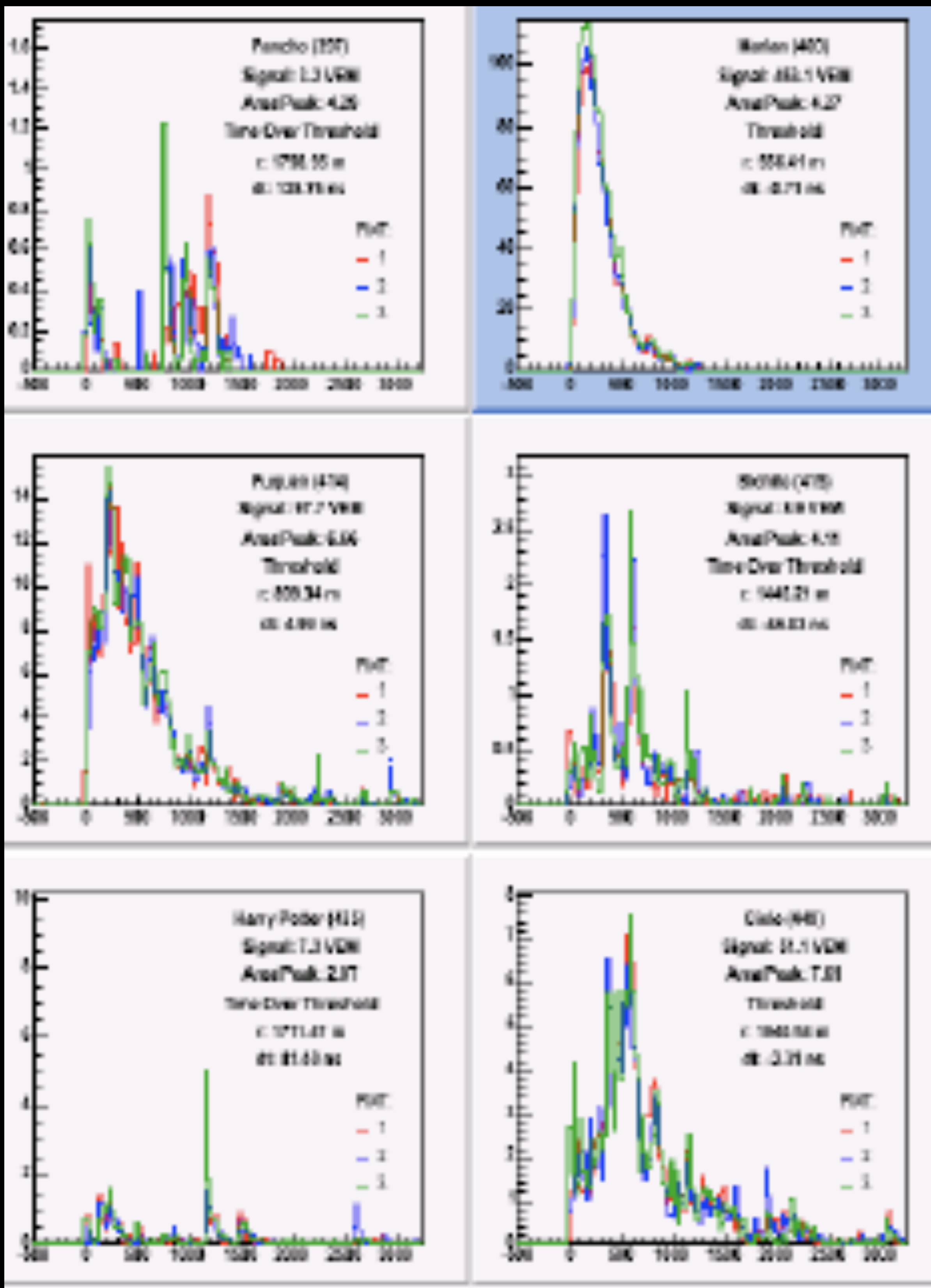
The PMTs signals are digitized by Fast Analog-to-Digital Converters (FADC), with a sampling time of 25 (20) ns.

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

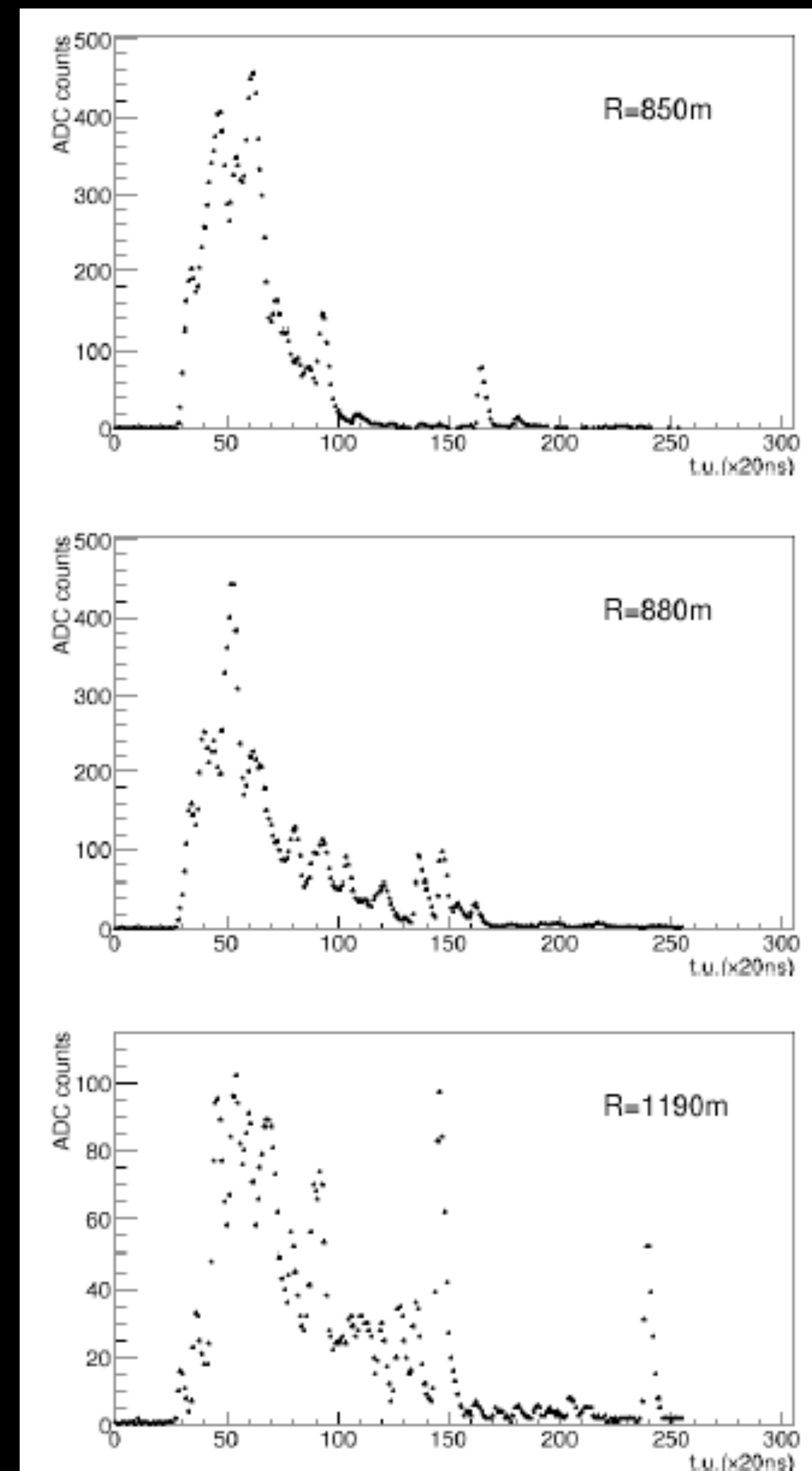
EAS signals in surface detectors

Examples of real FADC traces

Auger

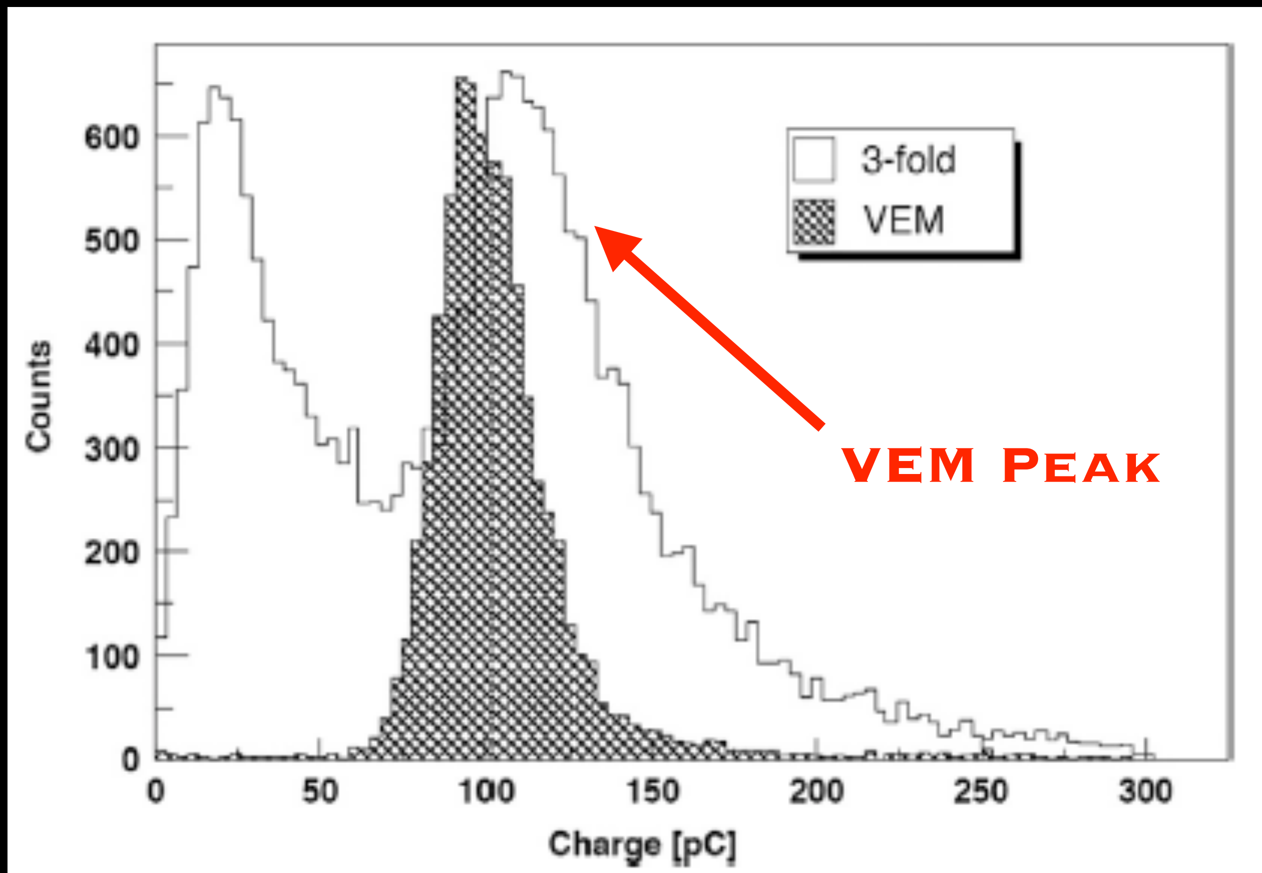


Telescope Array

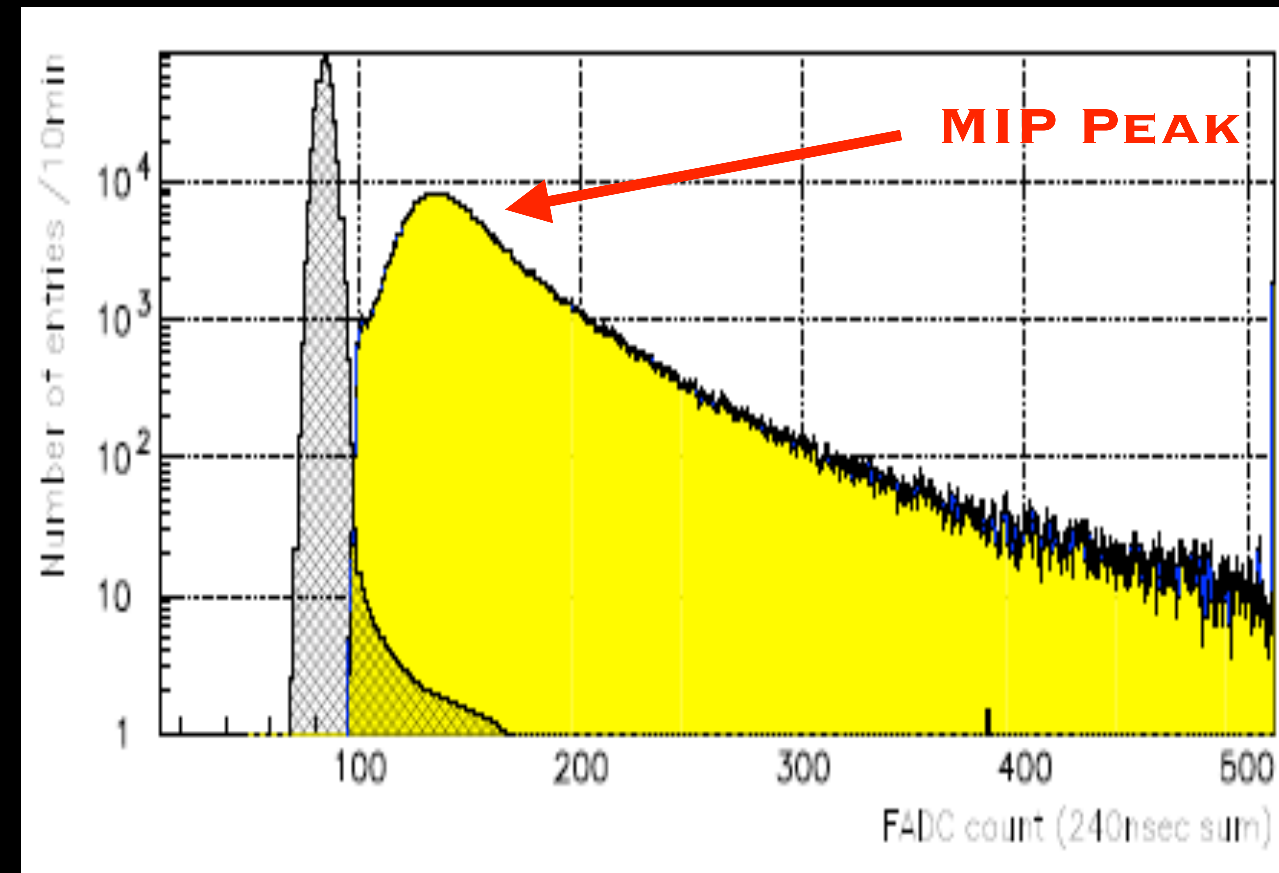


Calibration of surface detectors

Auger



Telescope Array

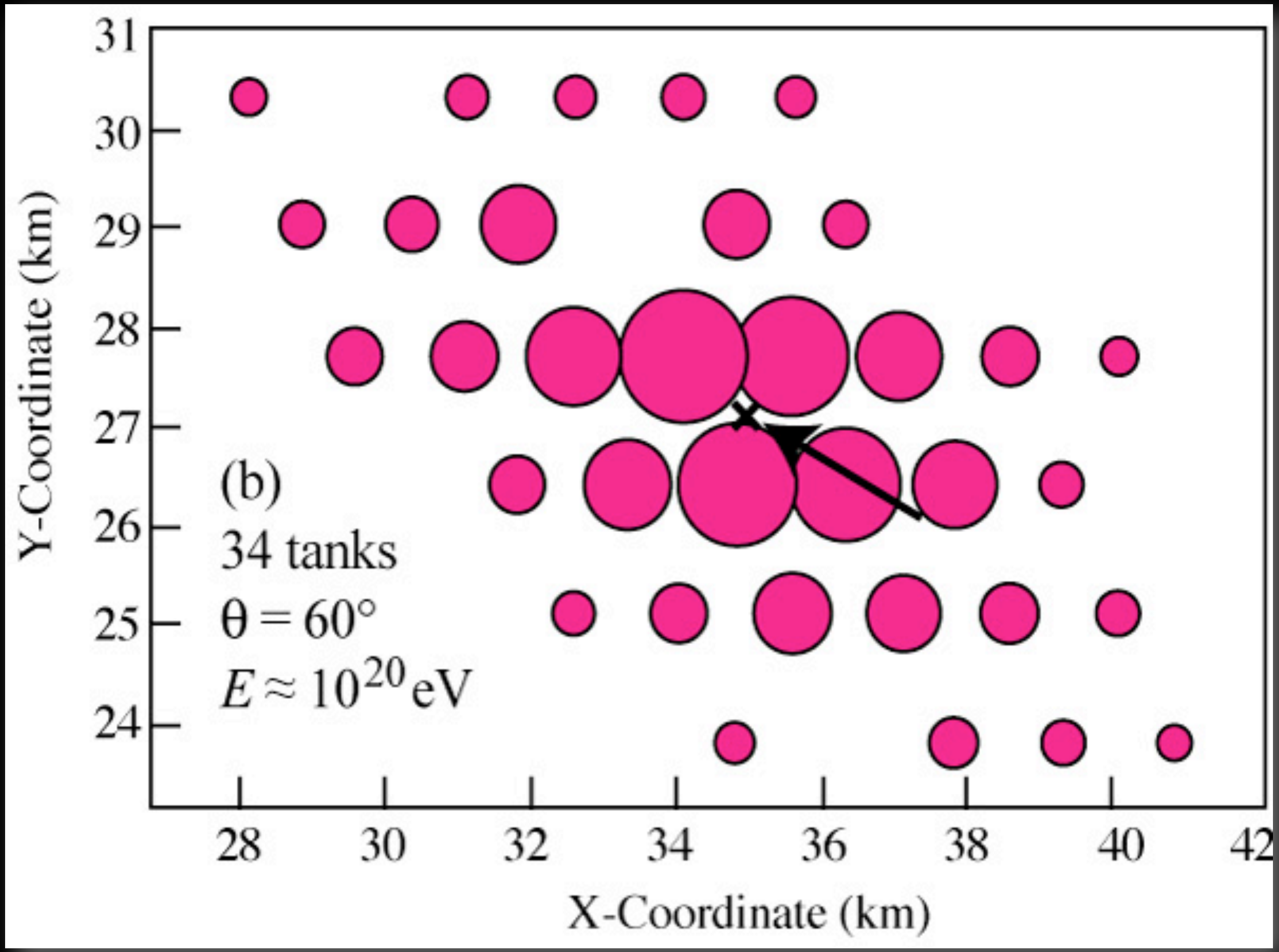


Charge spectrum obtained (every 10 minutes) when a detector is triggered (at a low-threshold) by the coincidence among the PMTs
(VEM = Vertical Equivalent Muon; MIP = minimum ionizing particle)

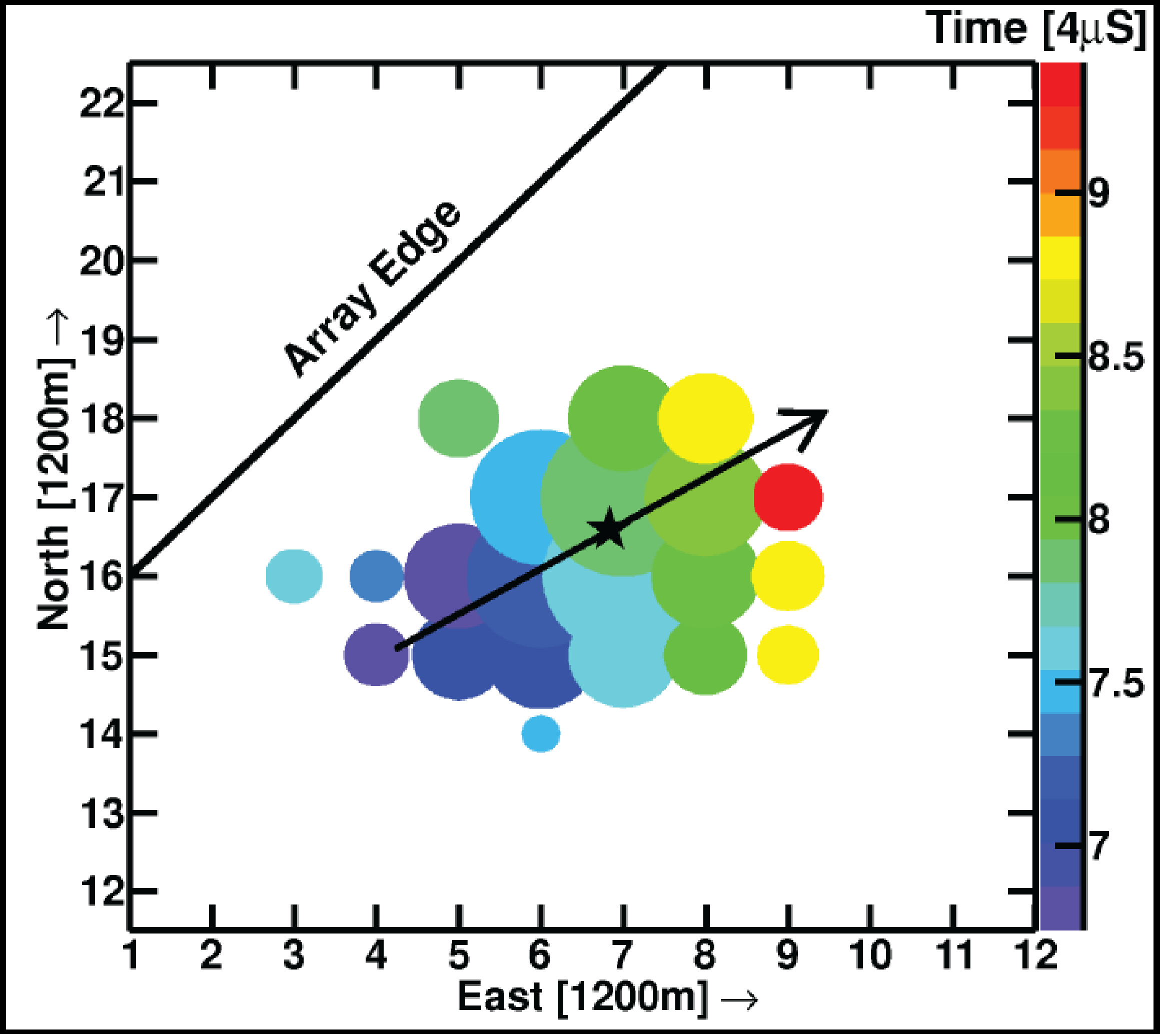
The PMTs signals are converted to number of particles by using “natural” muons (residual of low-energy showers absorbed high in the atmosphere: rate ≈ 200 Hz/m^2)

Finally: EAS seen by the surface detectors

Auger



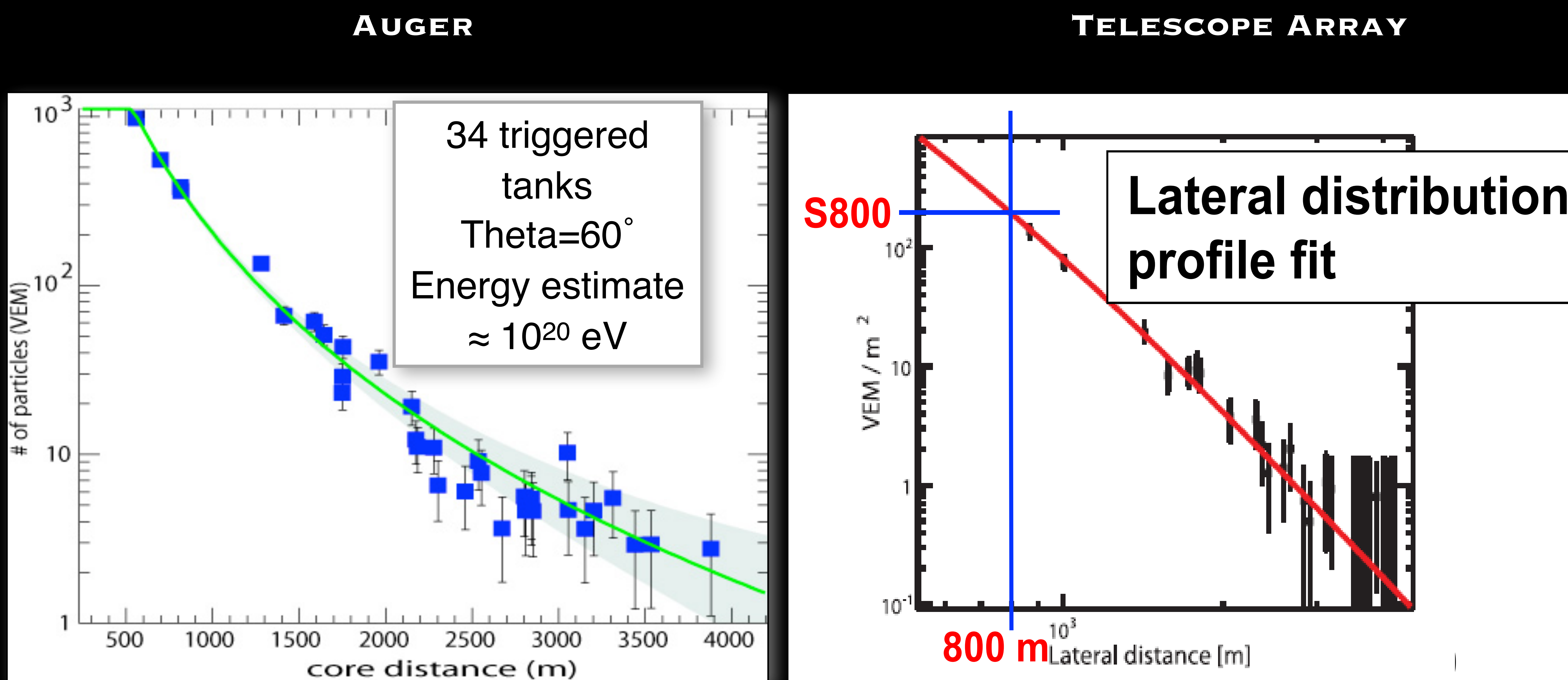
Telescope Array



The dimension of the circles is proportional to the number of detected particles

SD "photographs" the footprint of the shower at ground

Finally: EAS seen by the surface detectors

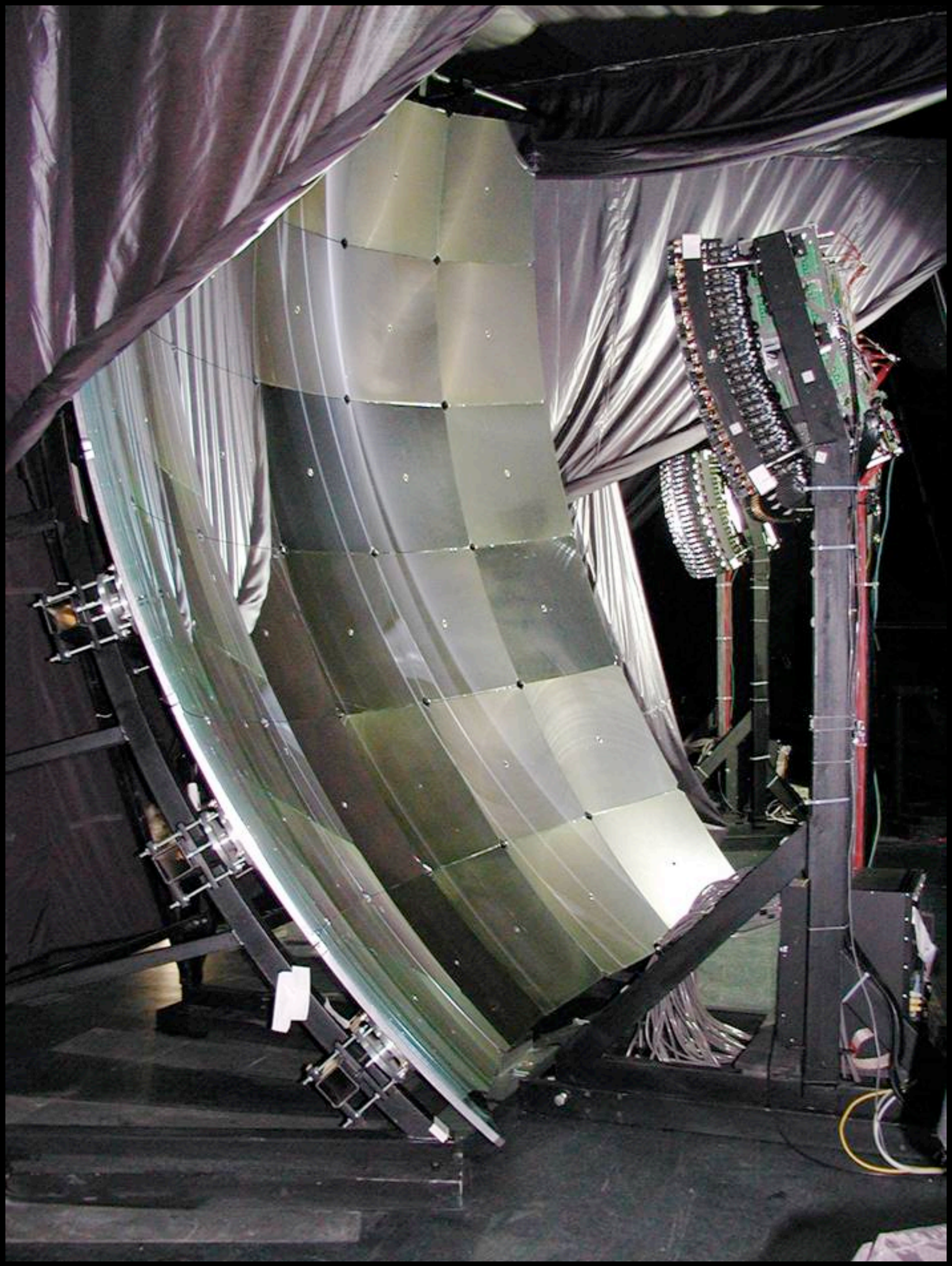


Distribution of EAS particles as a function of the distance from the core

SD measures the lateral distribution of particles

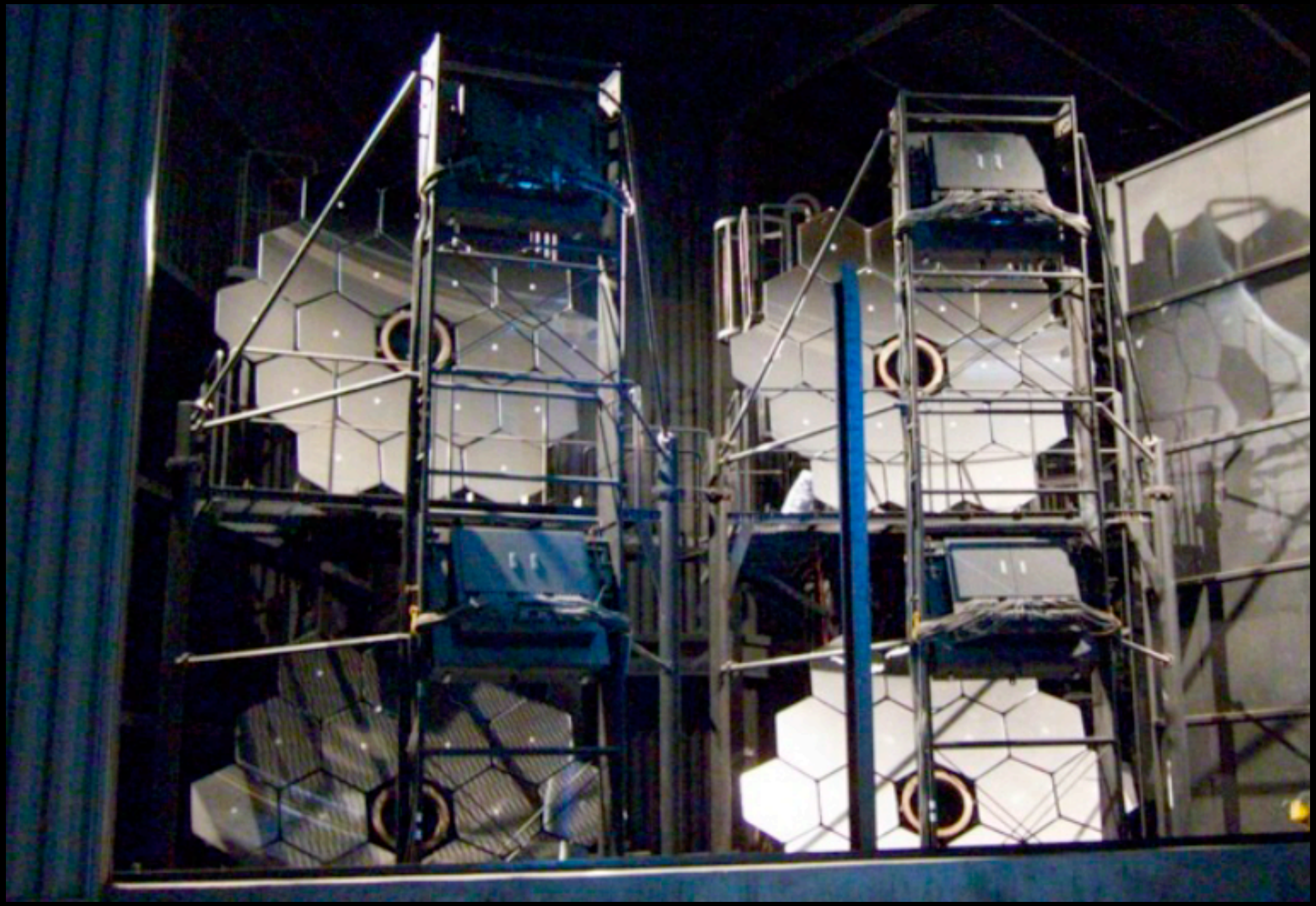
Auger and TA fluorescence detectors

Auger



3.4 m segmented mirror
440 PMTs camera
30°x 30° FOV

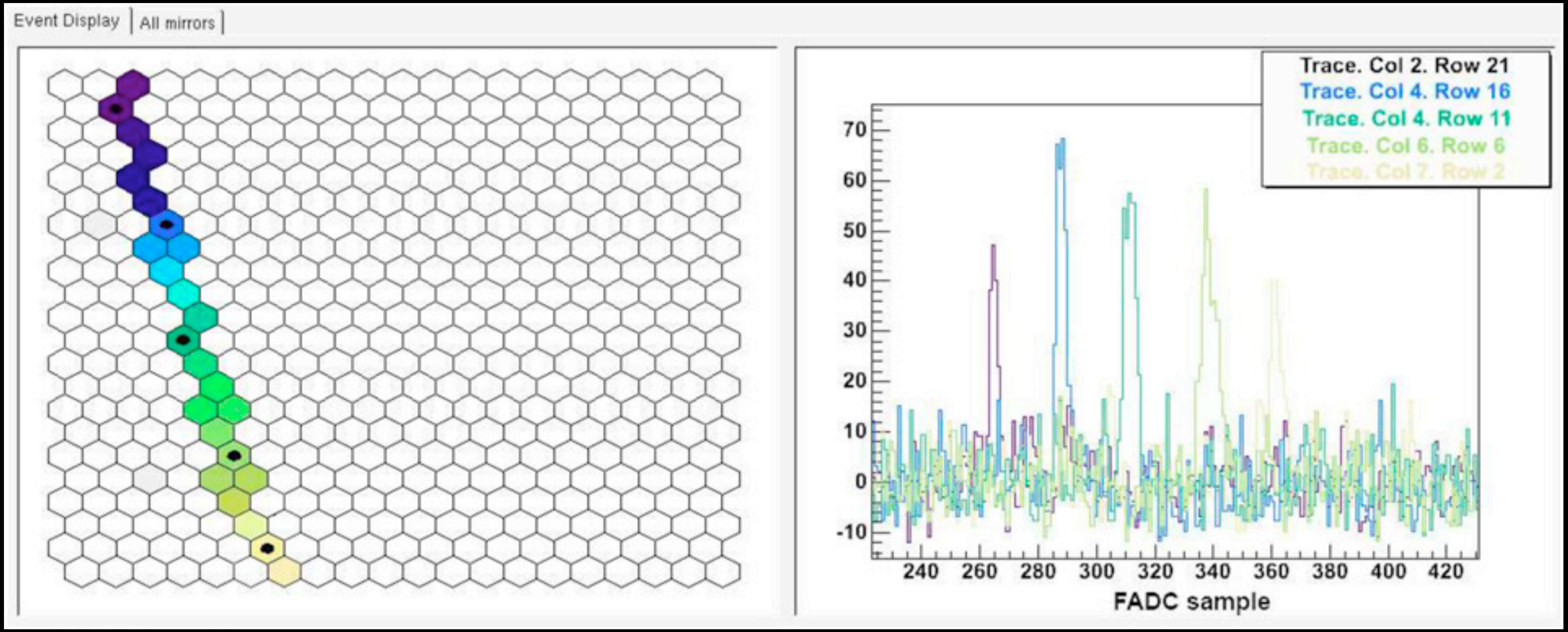
Telescope Array



3 m segmented mirror
256 PMTs camera
15° x 18° FOV

EAS signals in fluorescence detectors

Examples of real FADC traces (sorry: Auger only ;-)



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

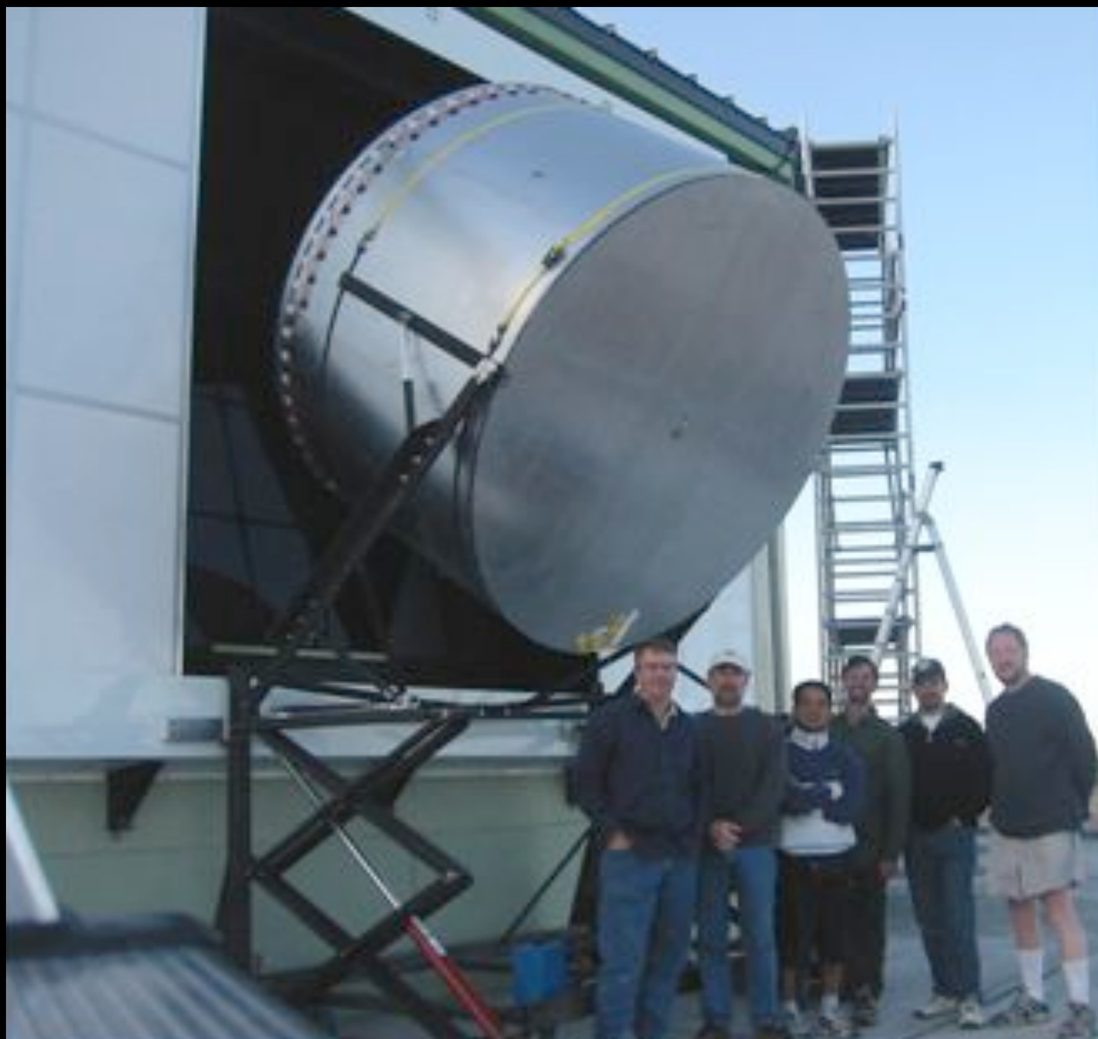
FADC traces of the triggered PMTs (black dots in the left panel)

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

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

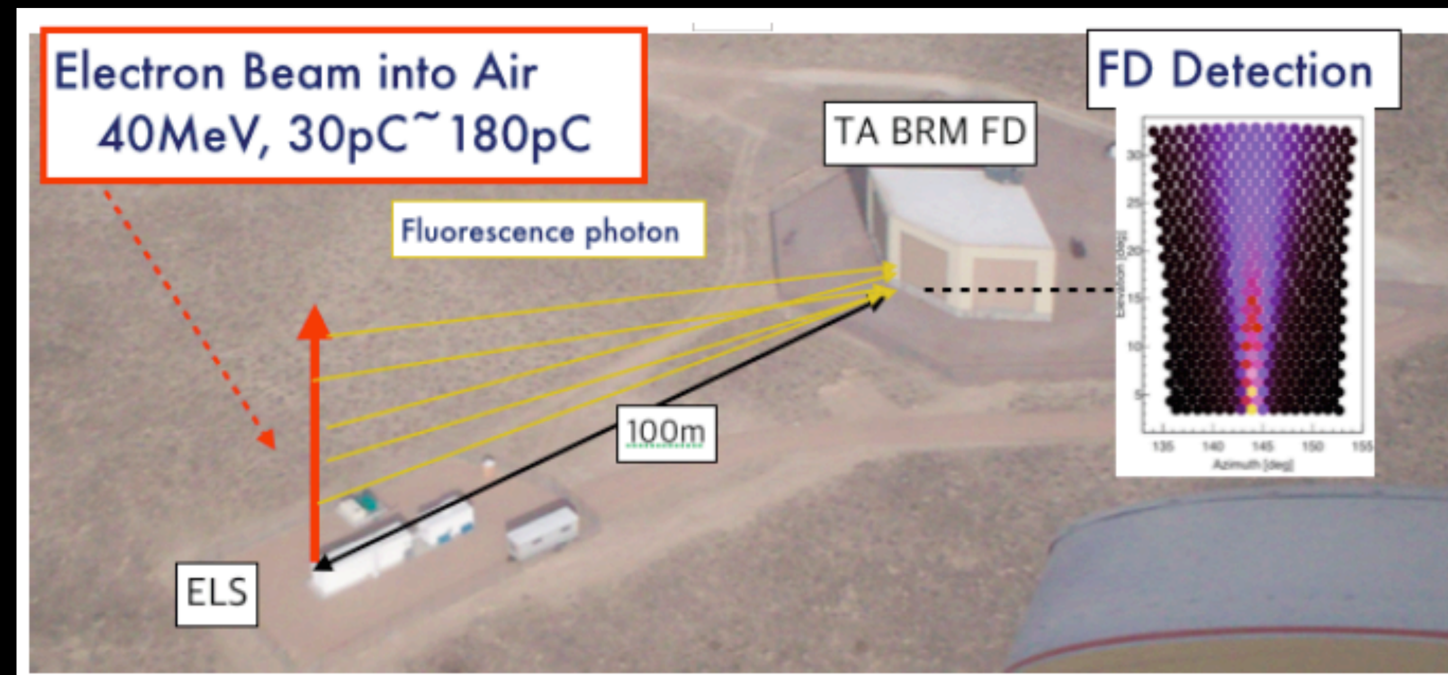
Calibration of fluorescence detectors

Auger



A calibrated large-diameter, drum-shaped, light source provides an absolute, end-to-end calibration

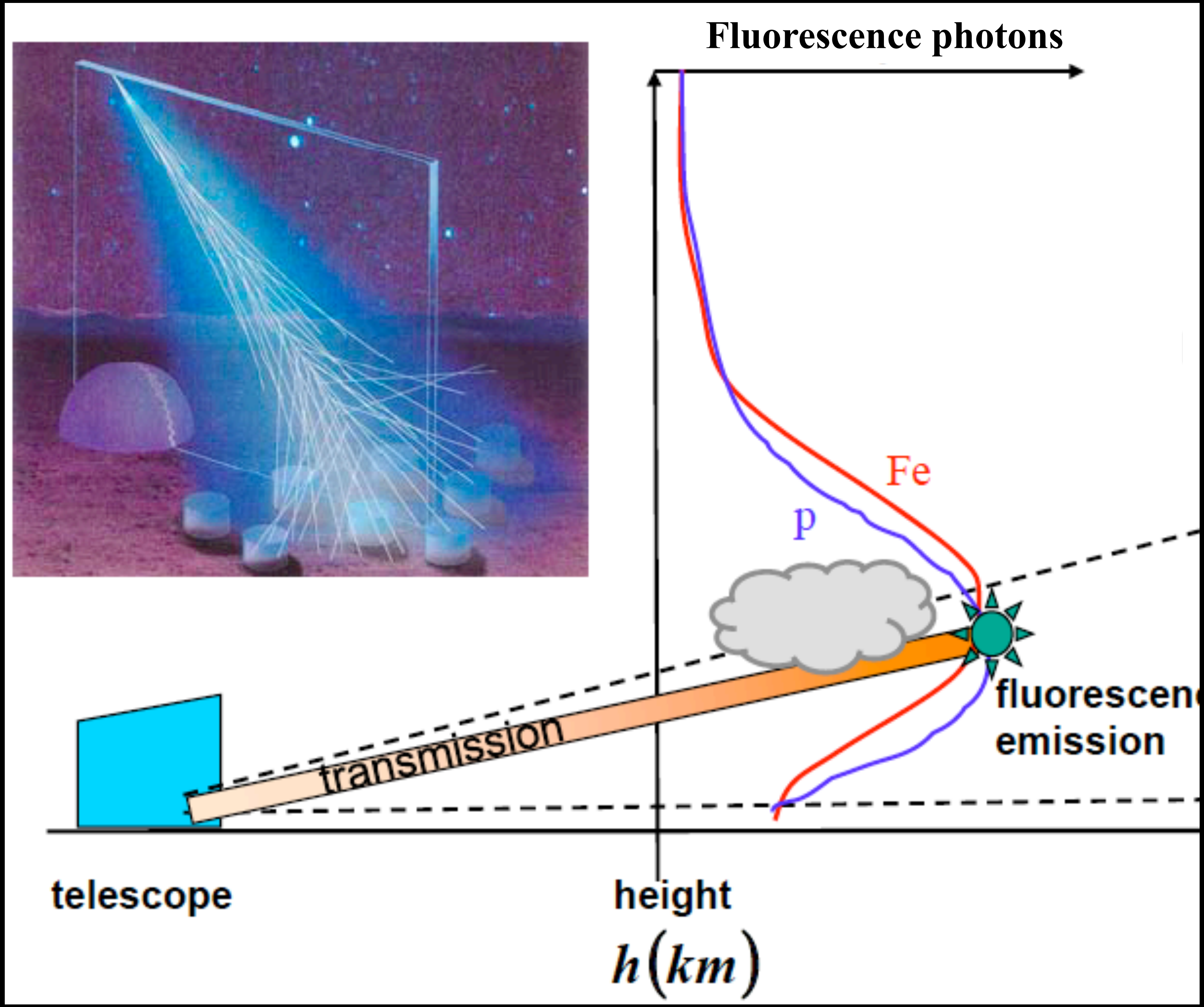
Telescope Array



The Electron Light Source is an electron linear accelerator serving as an absolute calibration. The ELS fires a vertical 40 MeV electron-beam of duration 1 μs at a repetition rate of 0.5 Hz.

The PMTs signals are converted to number of photons by illuminating the cameras with well-calibrated light sources

Auger and TA atmospheric monitoring

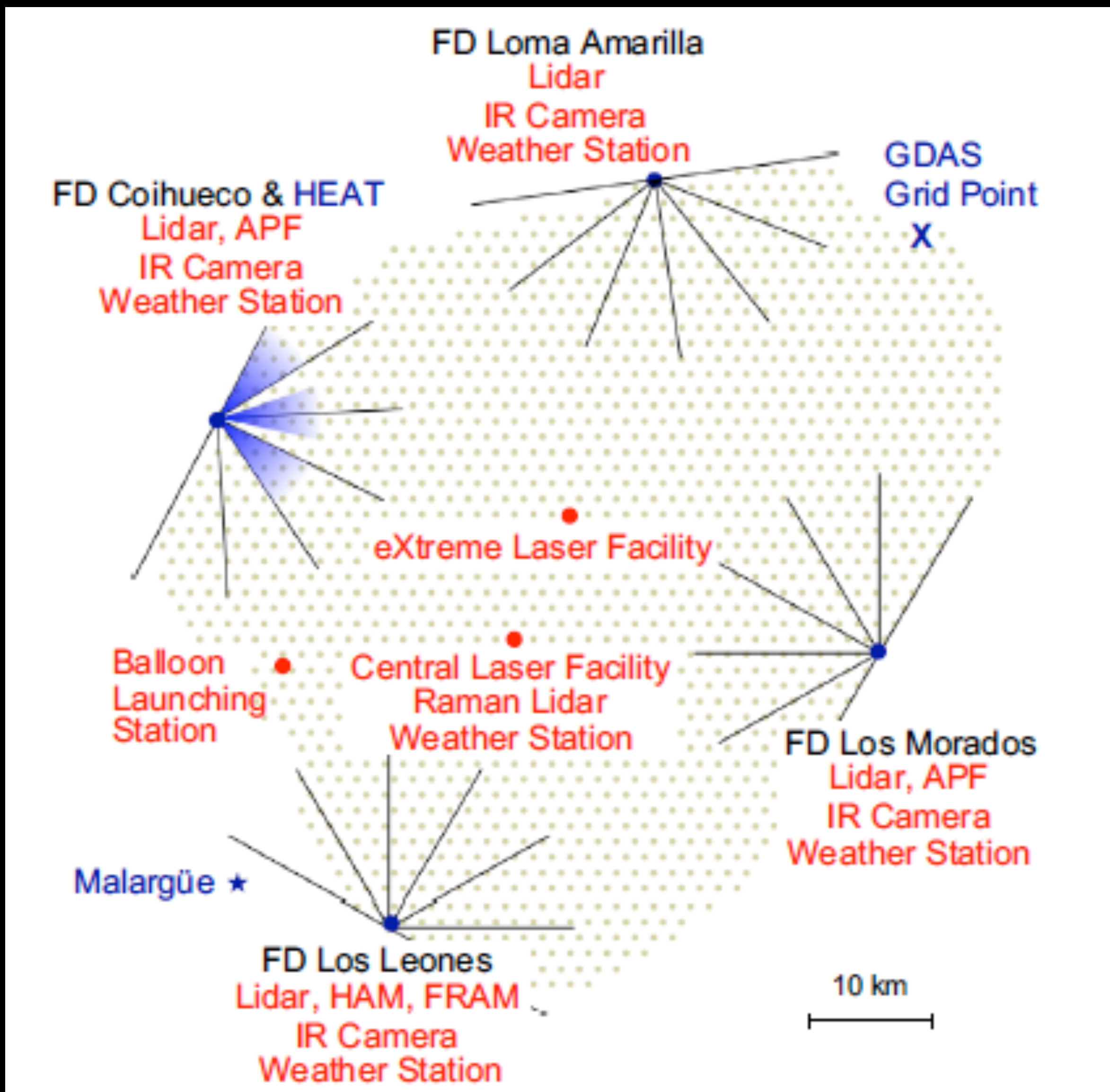


Also, the atmospheric transmission between the air-shower and the FD must be taken into account to properly reconstruct the light generated along the shower axis from the light recorded at the telescope(s)

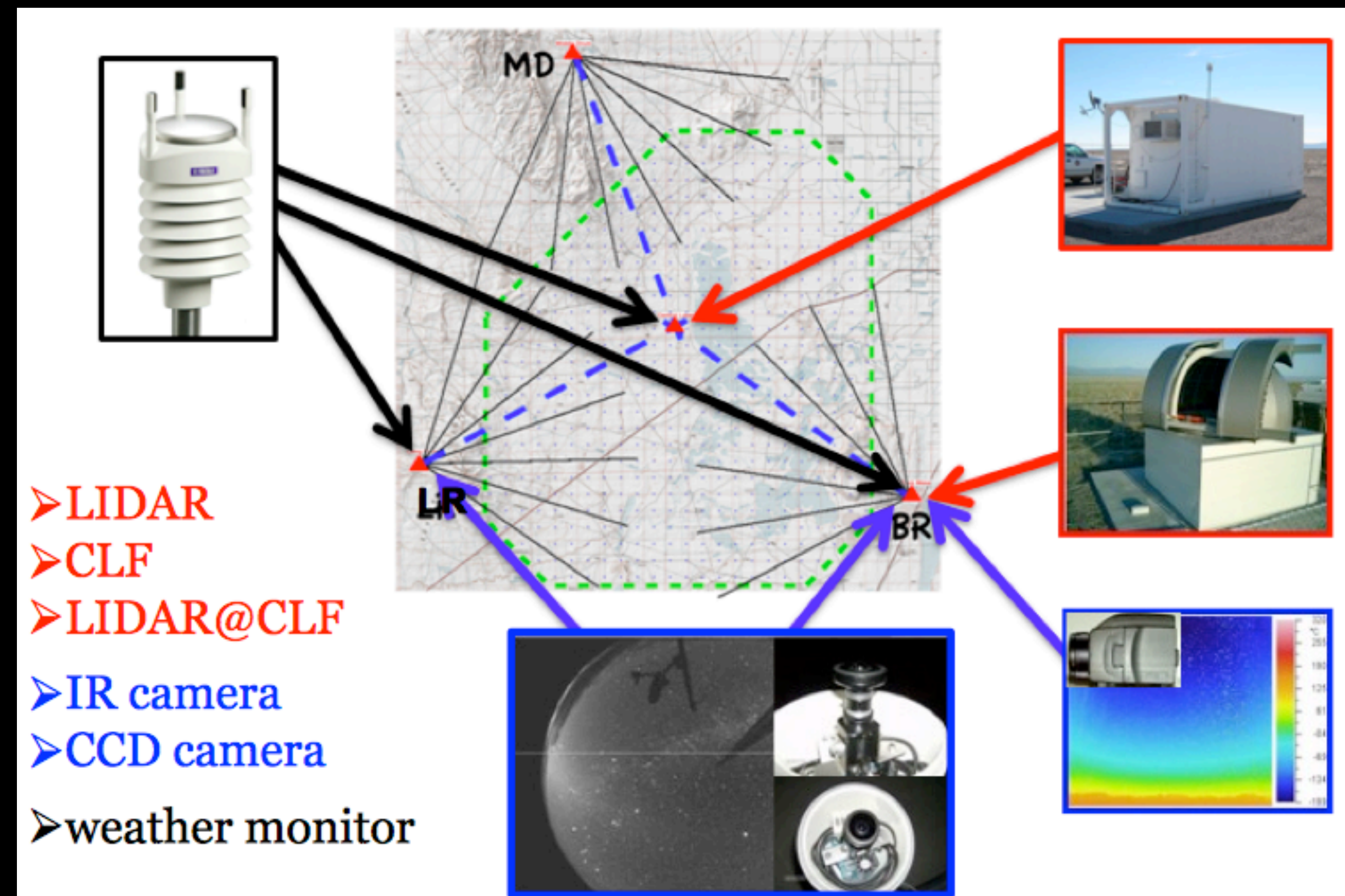
Auger and TA atmospheric monitoring

Clouds and aerosols play a major role in the optical transmission

Auger



Telescope Array



Weather stations measure P, T and humidity.

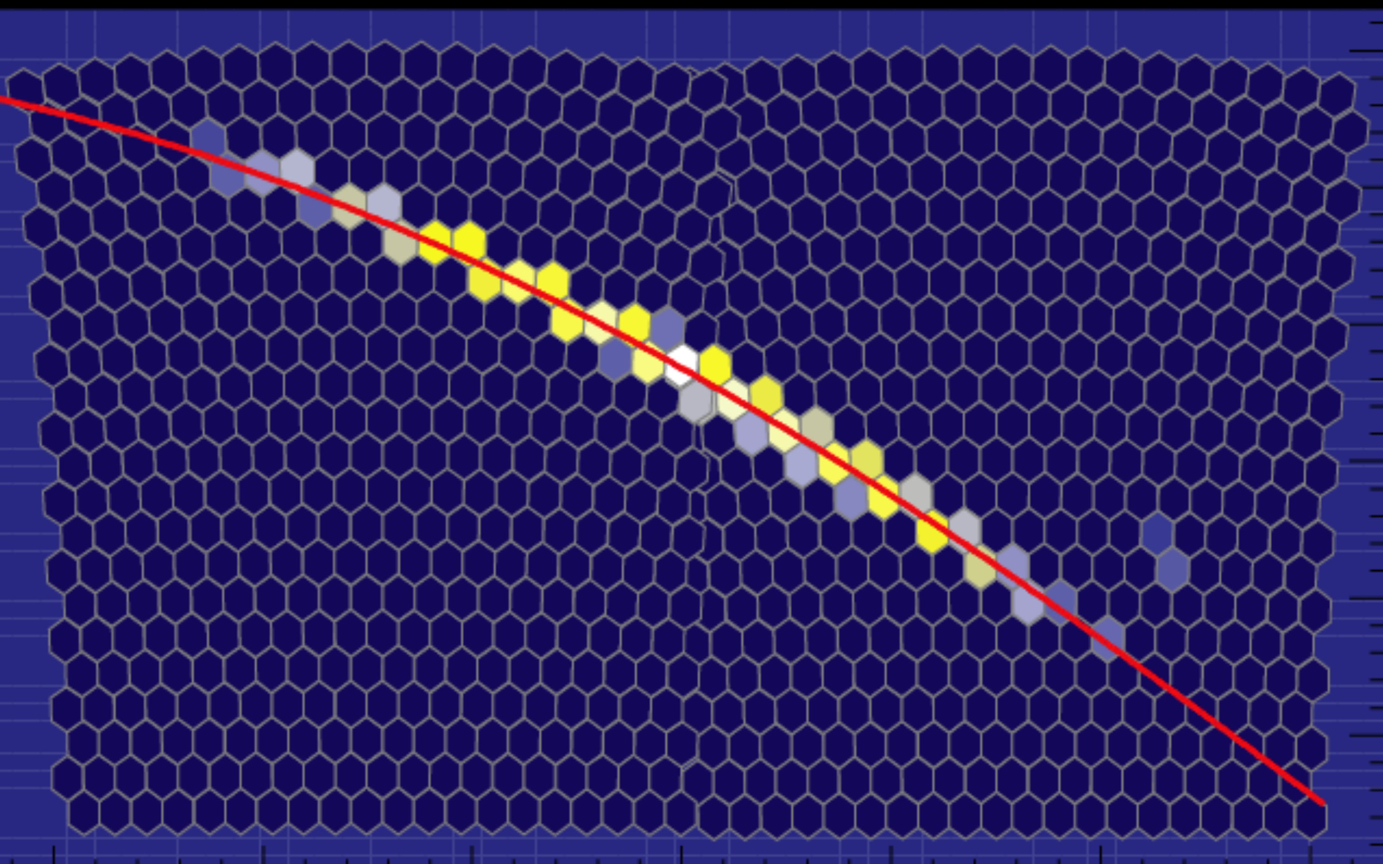
Infrared cameras and LIDARs monitor the cloud coverage.

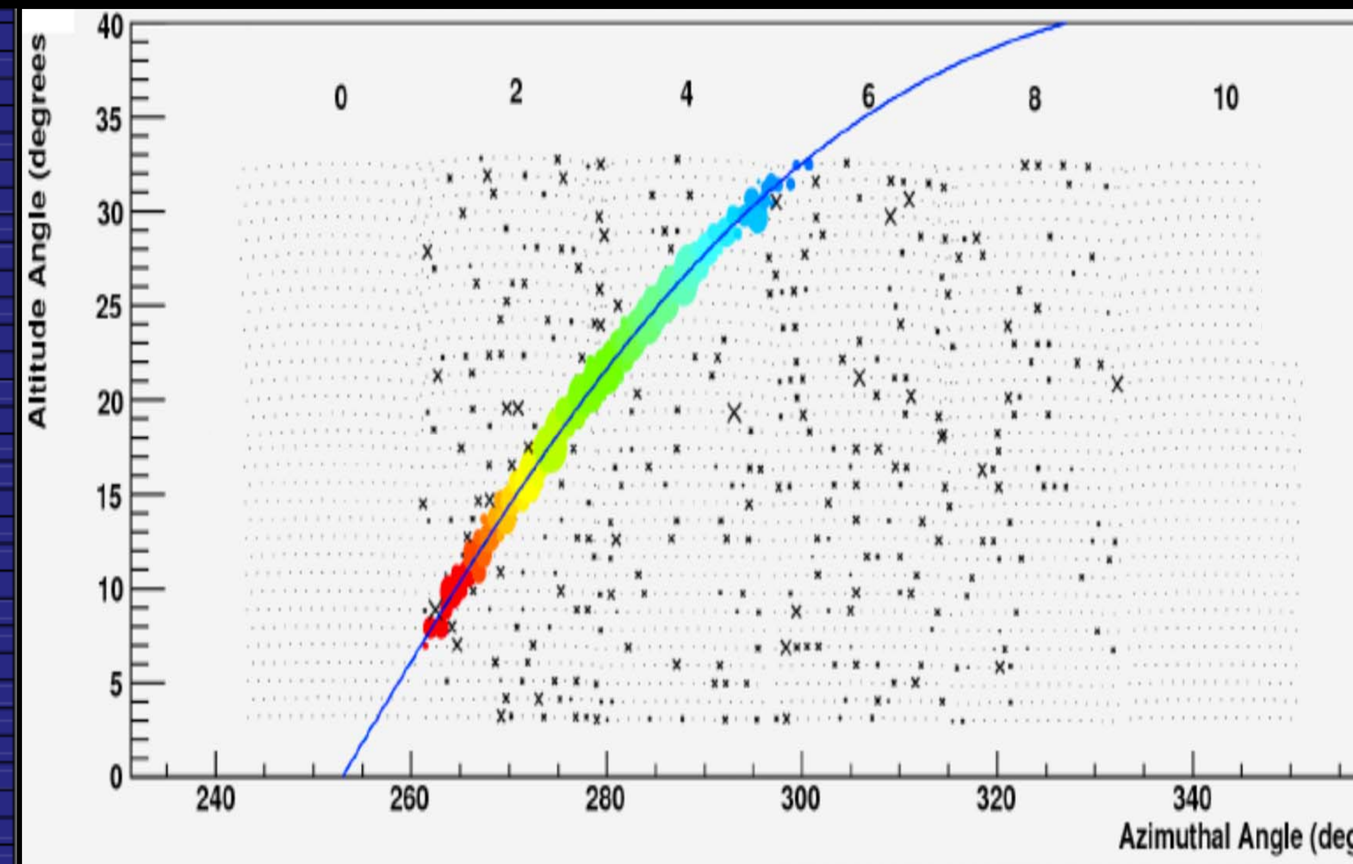
Lasers and LIDARs allow to determine the aerosols optical-depth profile

Finally: EAS seen by the fluorescence detectors

AUGER

TELESCOPE ARRAY

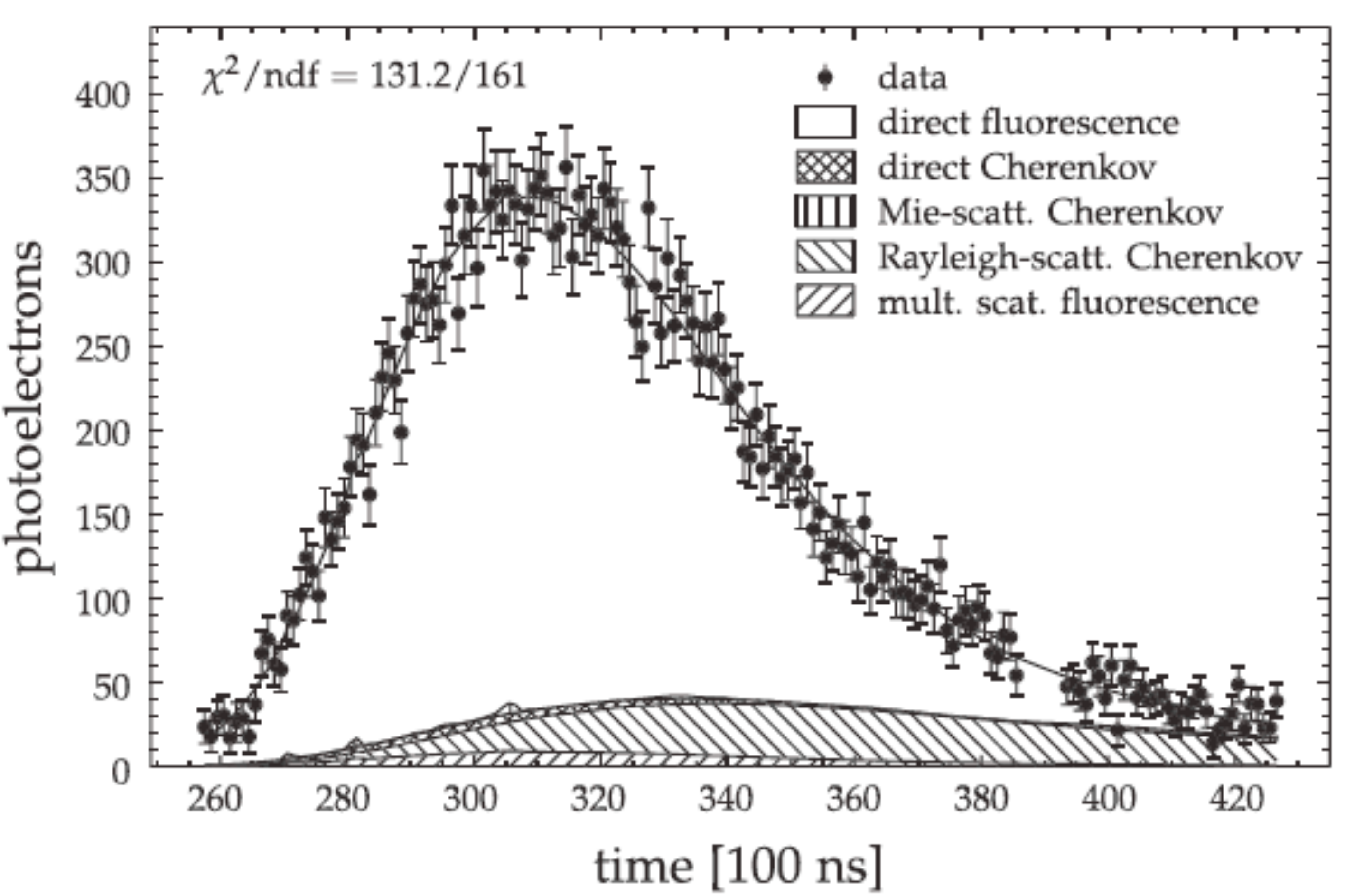




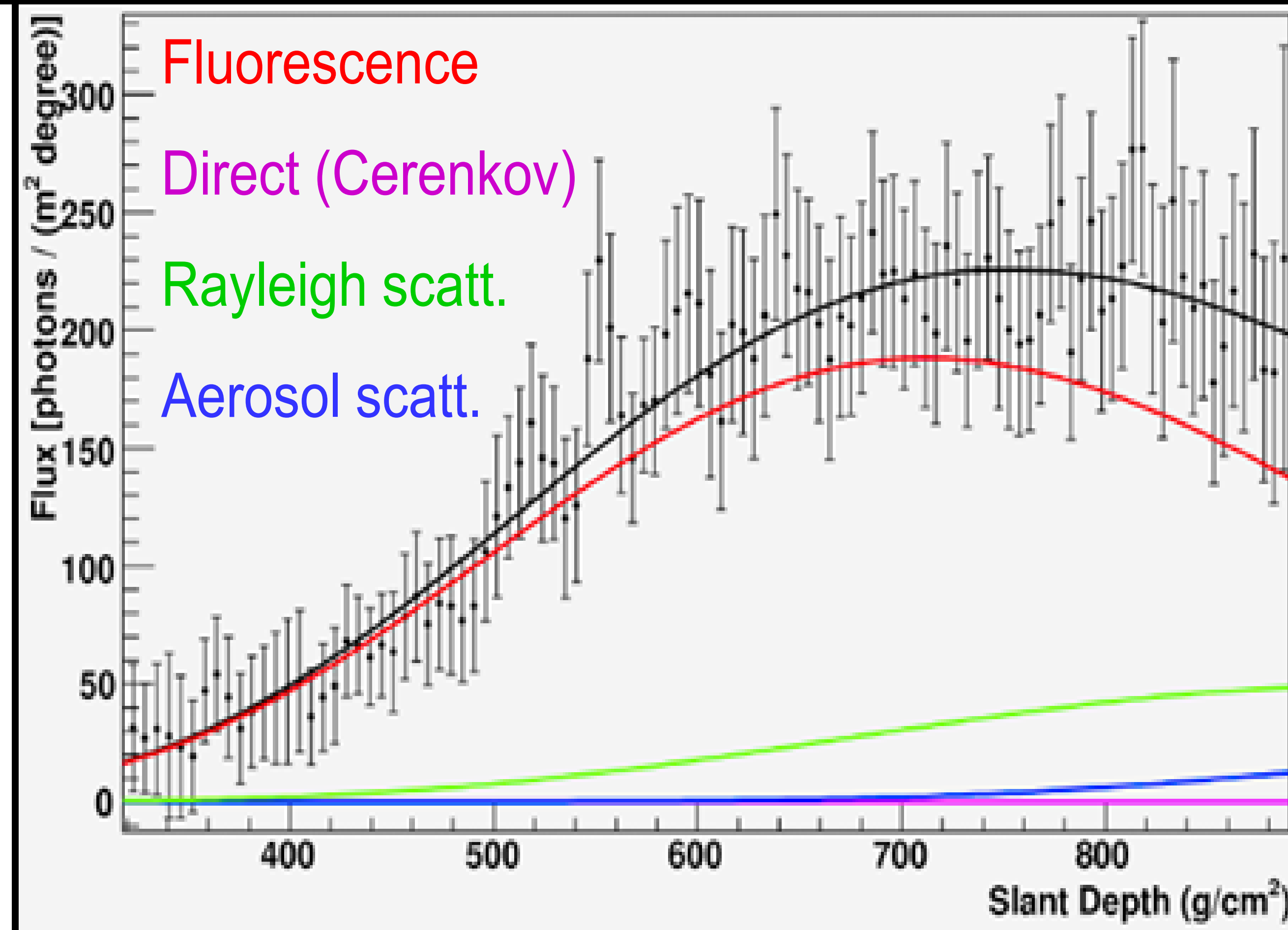
FD “photographs” the passage of the shower in atmosphere

Finally: EAS seen by the fluorescence detectors

AUGER



TELESCOPE ARRAY



Light-at-aperture measurements and reconstructed light sources

FD measures the longitudinal development in atmosphere

Two exemplary cases: the Pierre Auger Observatory and the Telescope Array:
From EAS observables to CR properties

The subtlety of the analysis

Which information on CRs must we extract from EAS?

The ultimate aim of EAS detection is the identification of the primary cosmic ray, in terms of

Mass/Charge

Energy

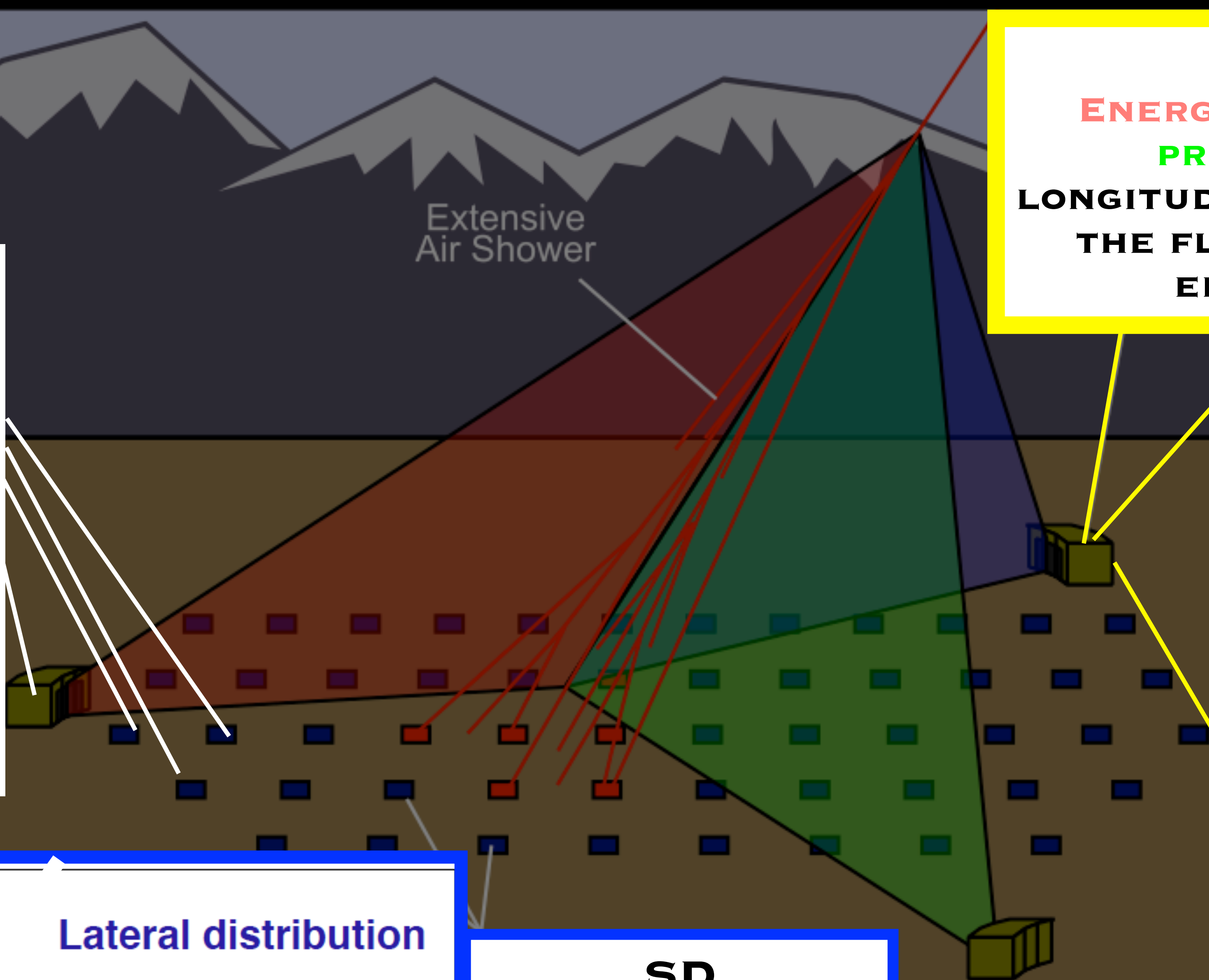
Arrival direction

We are dealing with an INDIRECT MEASUREMENT of CRs

To infer the properties of the primary particle one needs not only to detect EAS as precisely as possible but also to exploit as carefully as possible the "legacy" that their parents left into them

How do we pass from the observed EAS to the CR?

In a nutshell, aka in one slide

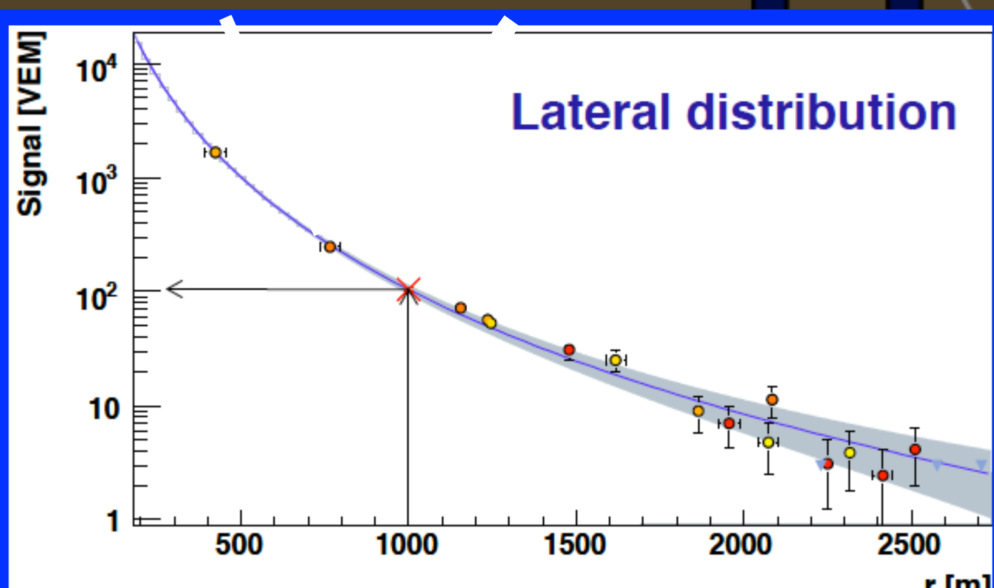


FD

ENERGY and XMAX (mass proxy): from the longitudinal distribution of the fluorescence light emitted by EAS

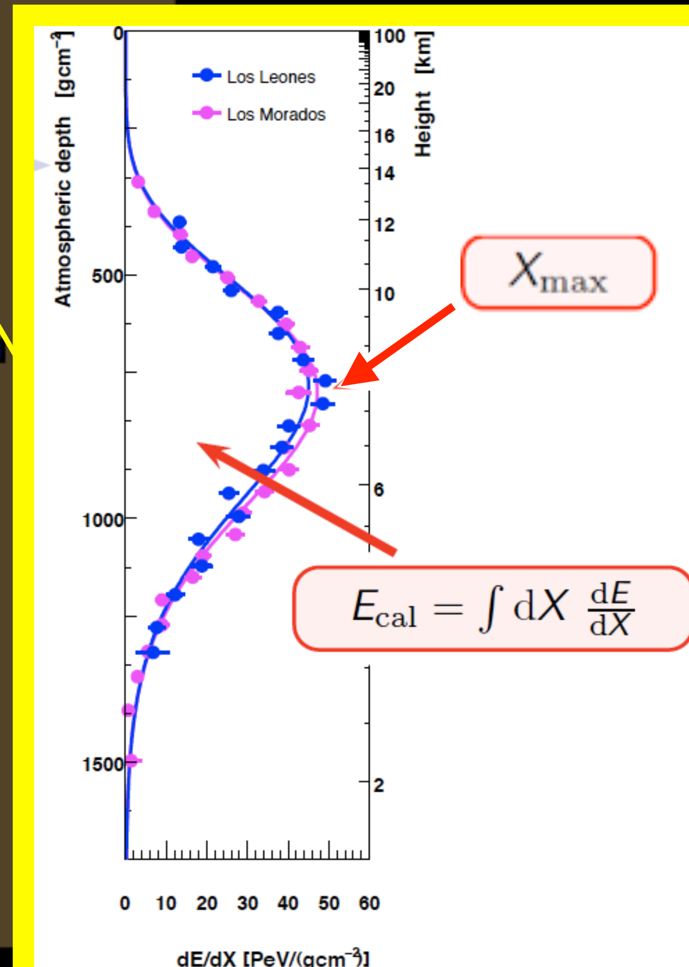
SD - FD

CR ARRIVAL DIRECTION: from relative arrival times of signals at ground detectors, or from the time sequence of hit PMTs at fluorescence detectors



SD

ENERGY PROXY: from the distribution/ Number of particles at ground

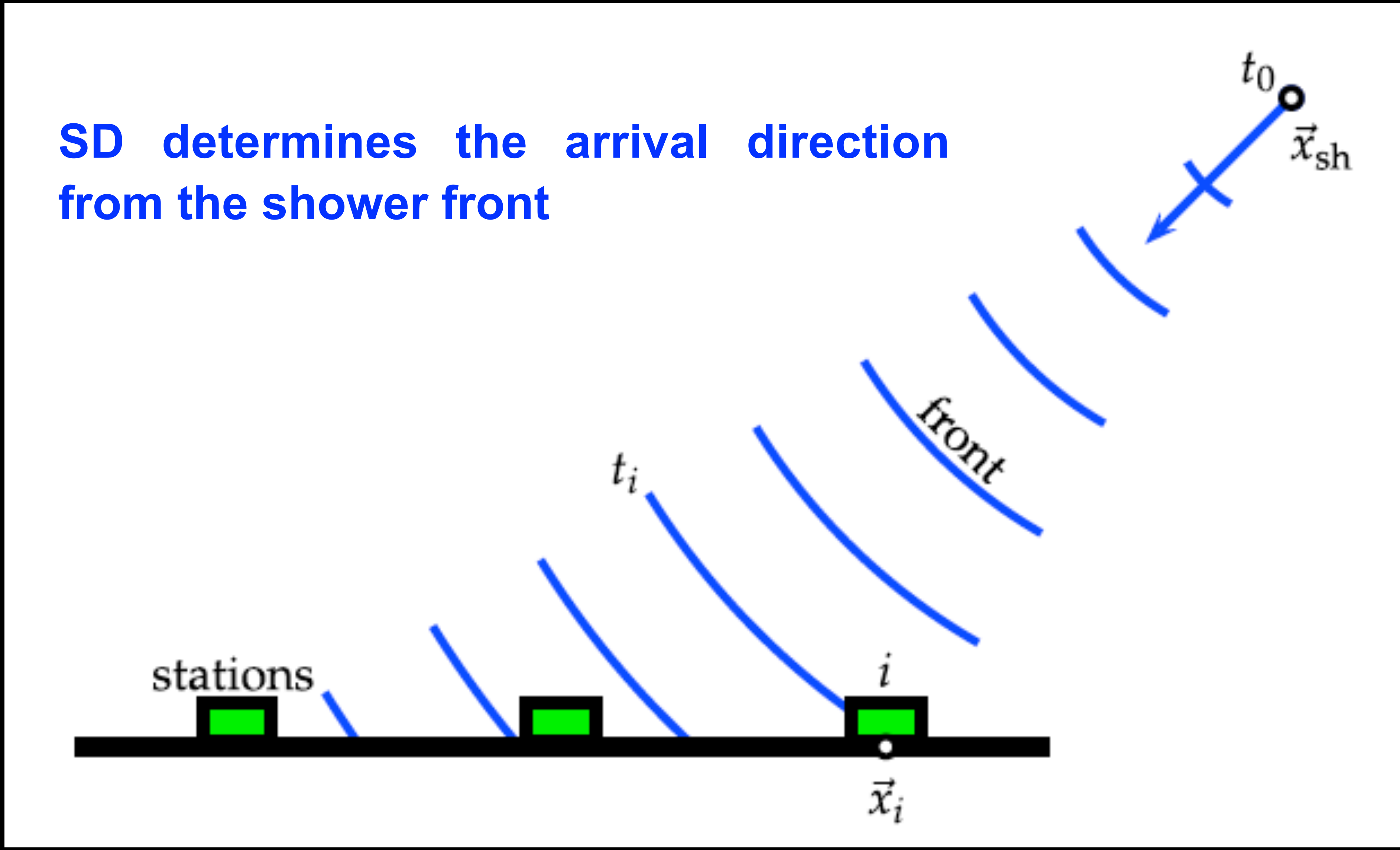


Let's start from the simplest one: arrival direction

Surface detectors

Most straightforward measurement

The shower axis preserves the direction of the incoming particle



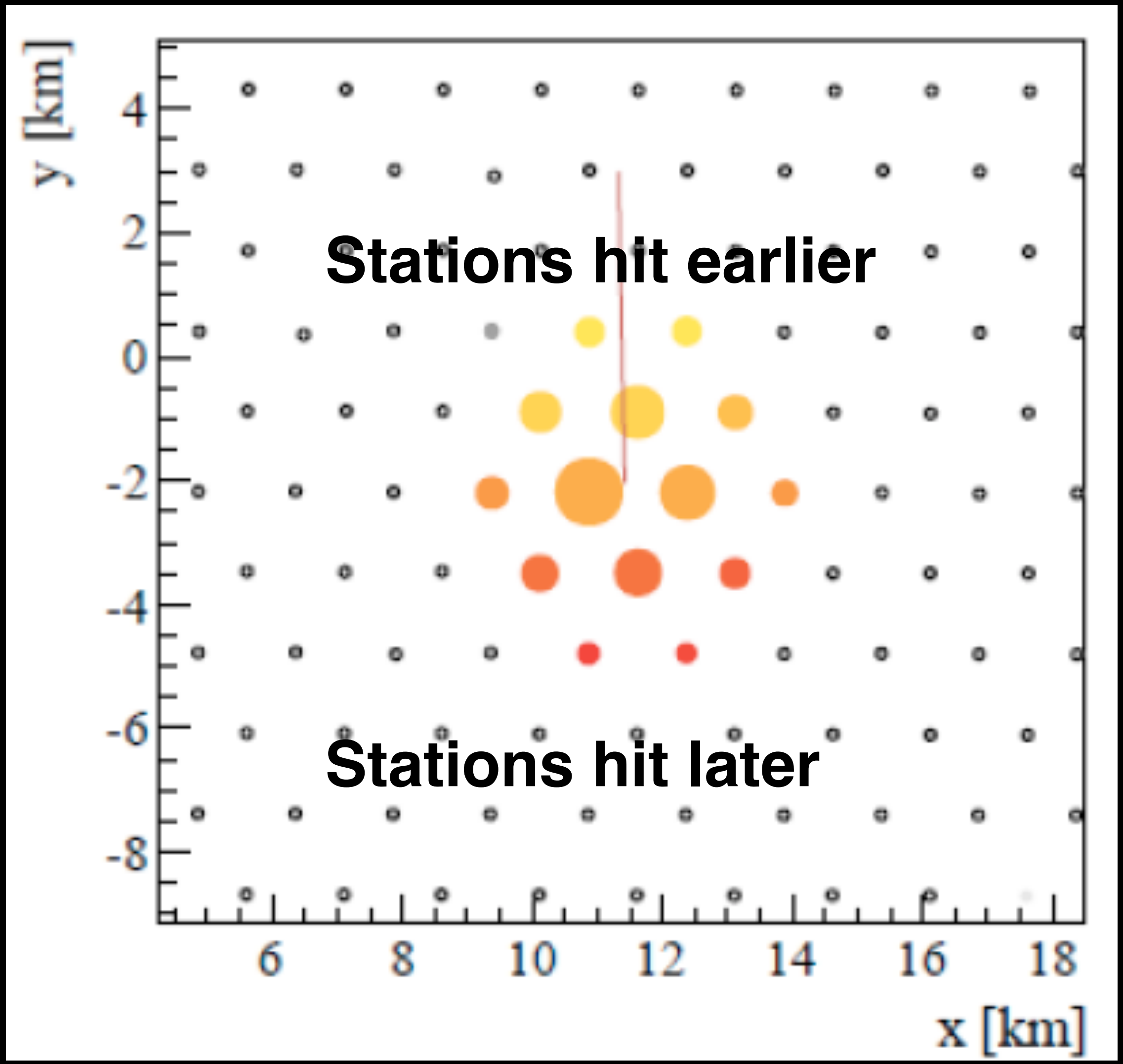
Time-of-flight technique:

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

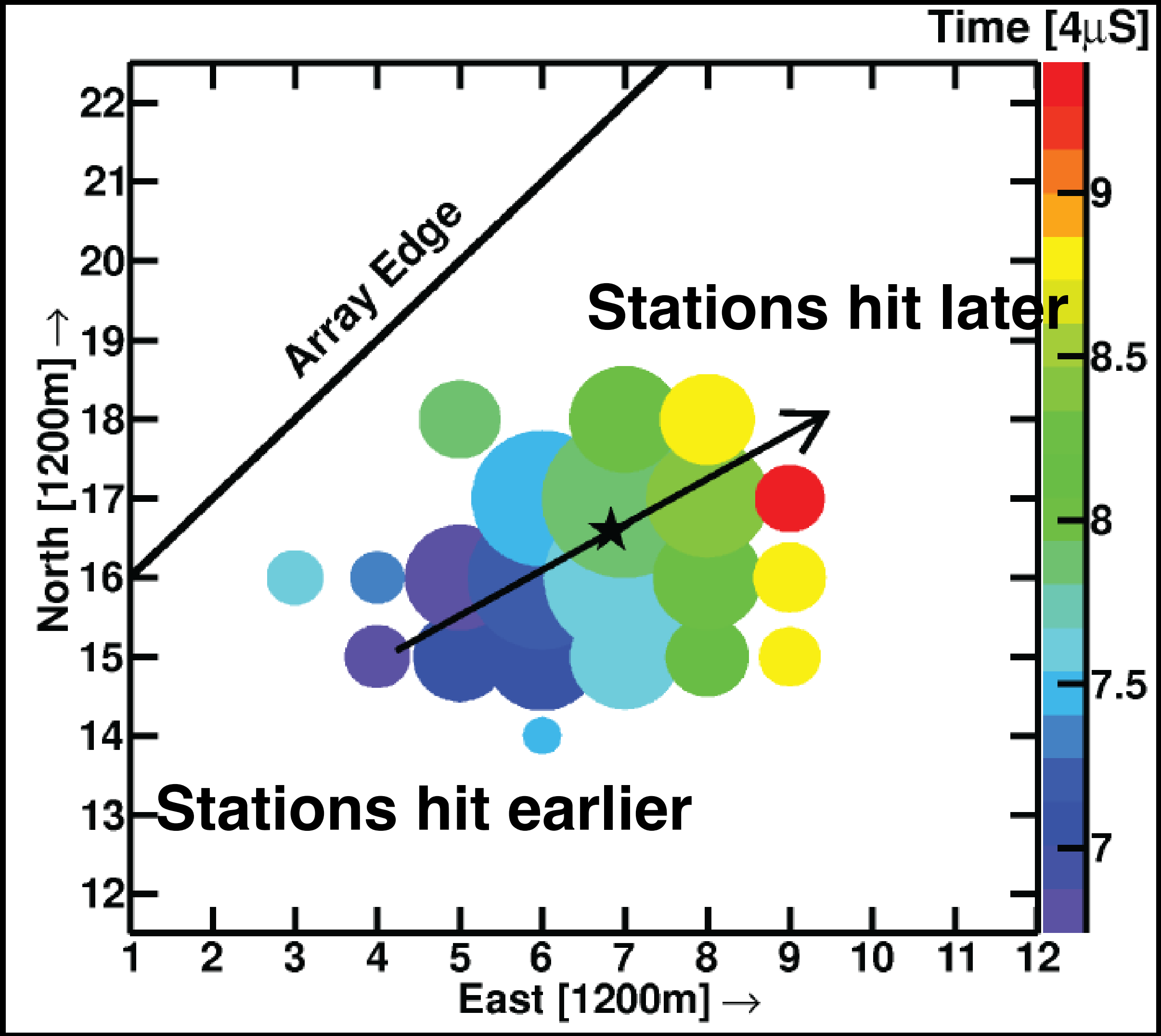
Measurement of the arrival direction

In practice

Auger



Telescope Array



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

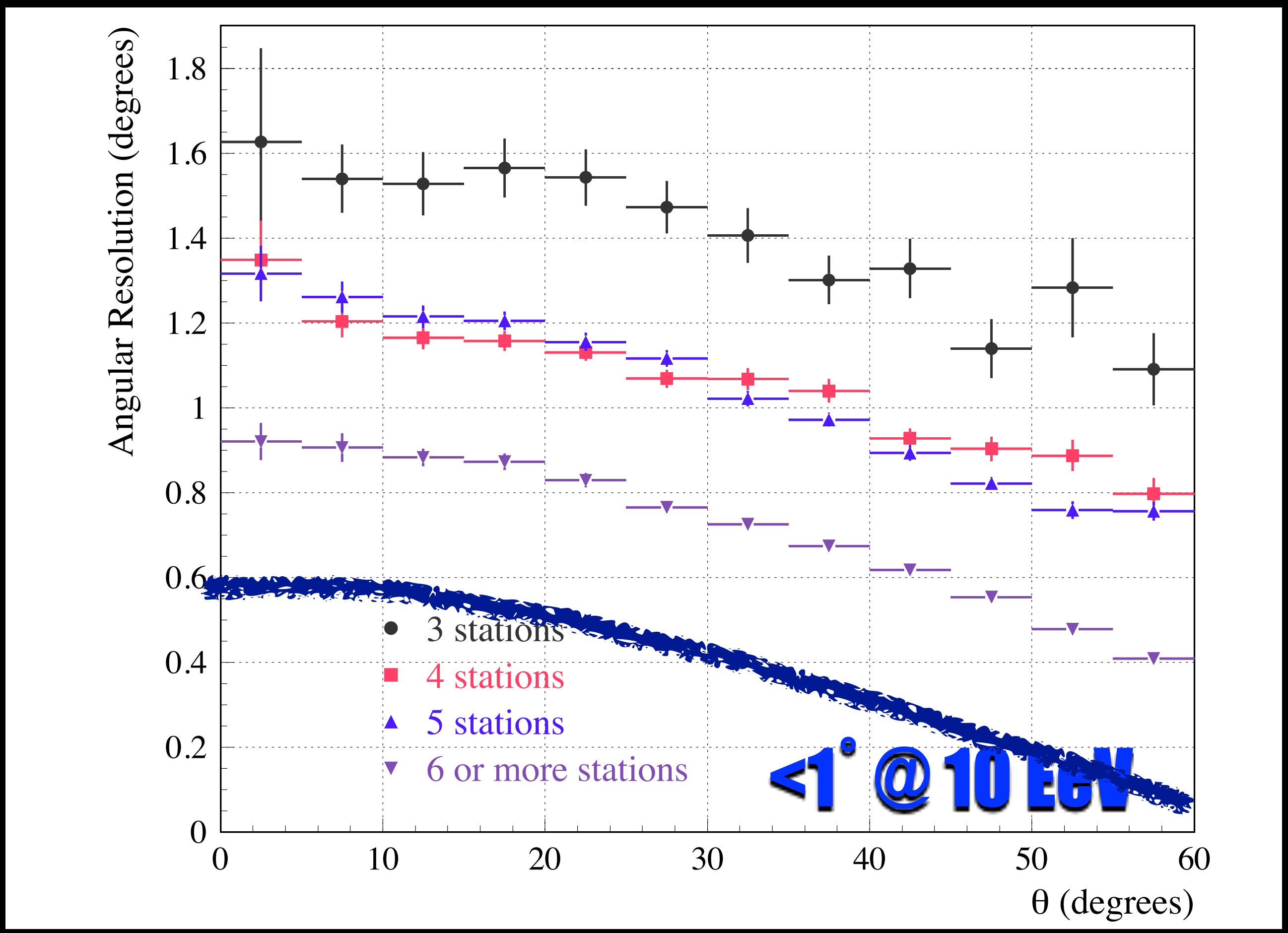
If only 3 detectors are triggered: fit to a plane front

If more: fit to a spherical front

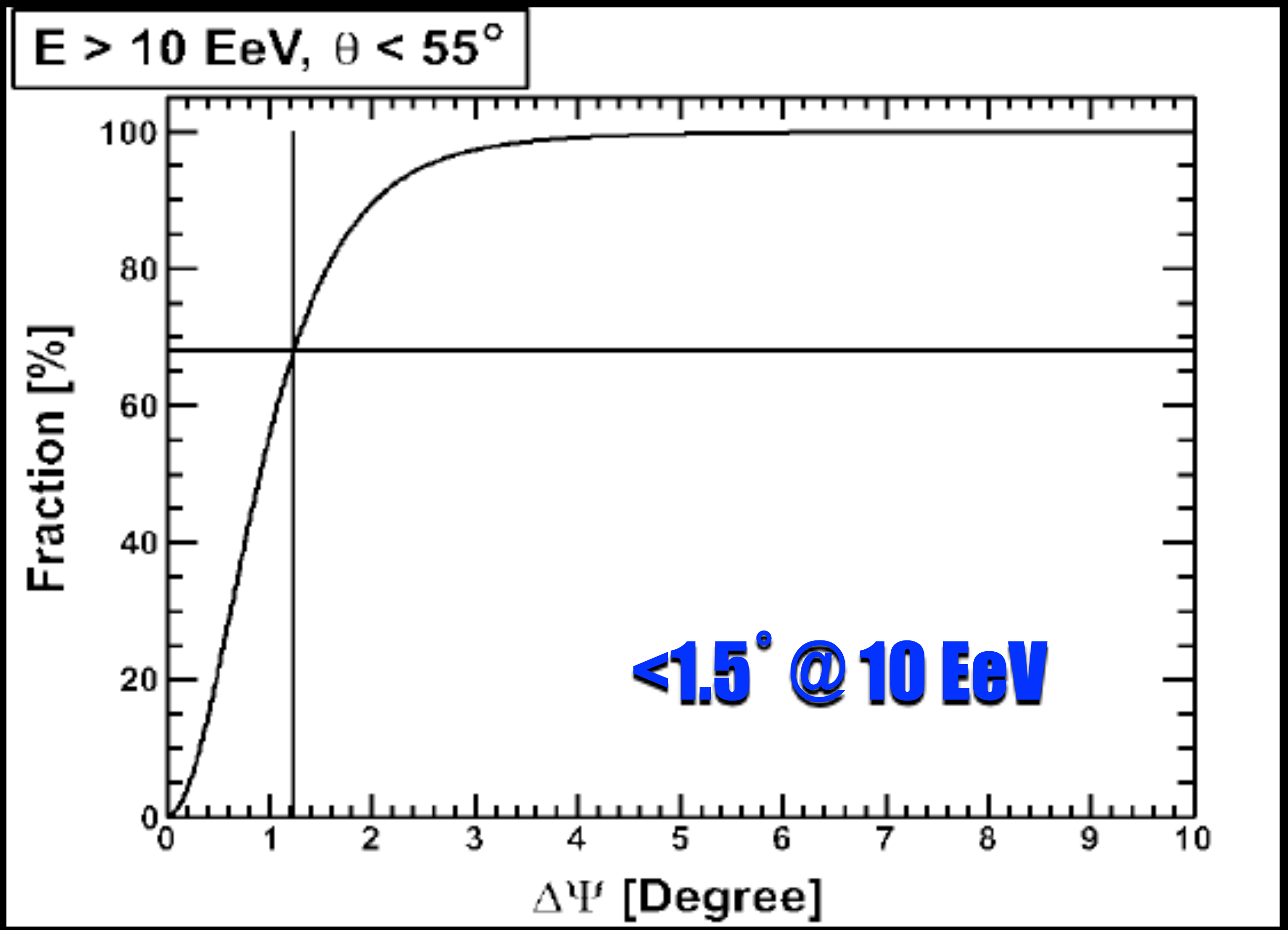
Arrival direction (angular) resolution

SD angular resolution

Auger



Telescope Array

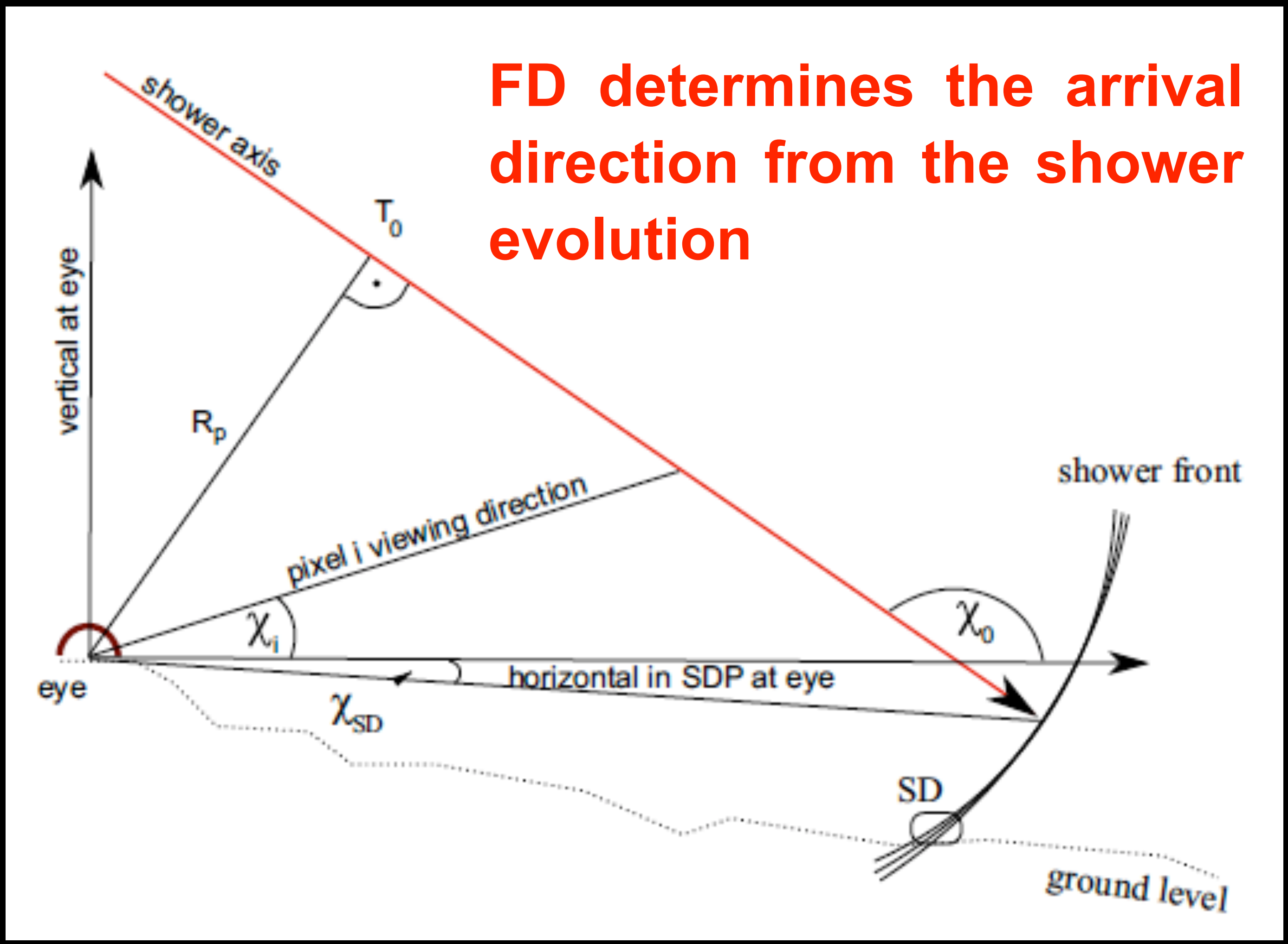


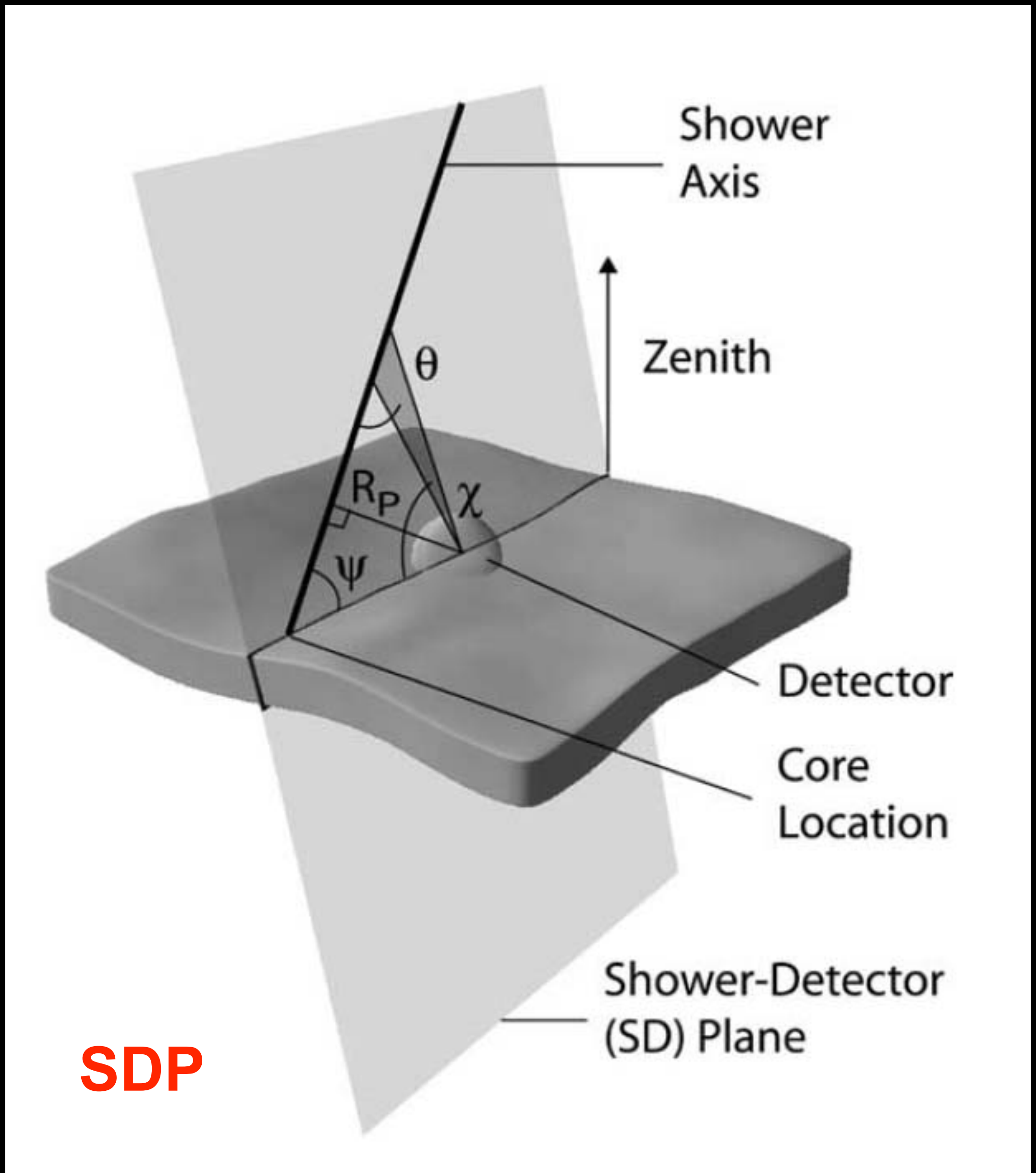
Angular resolution: determined by the shower-front fit, on an event-by event basis.

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

Measurement of the arrival direction

Fluorescence detectors





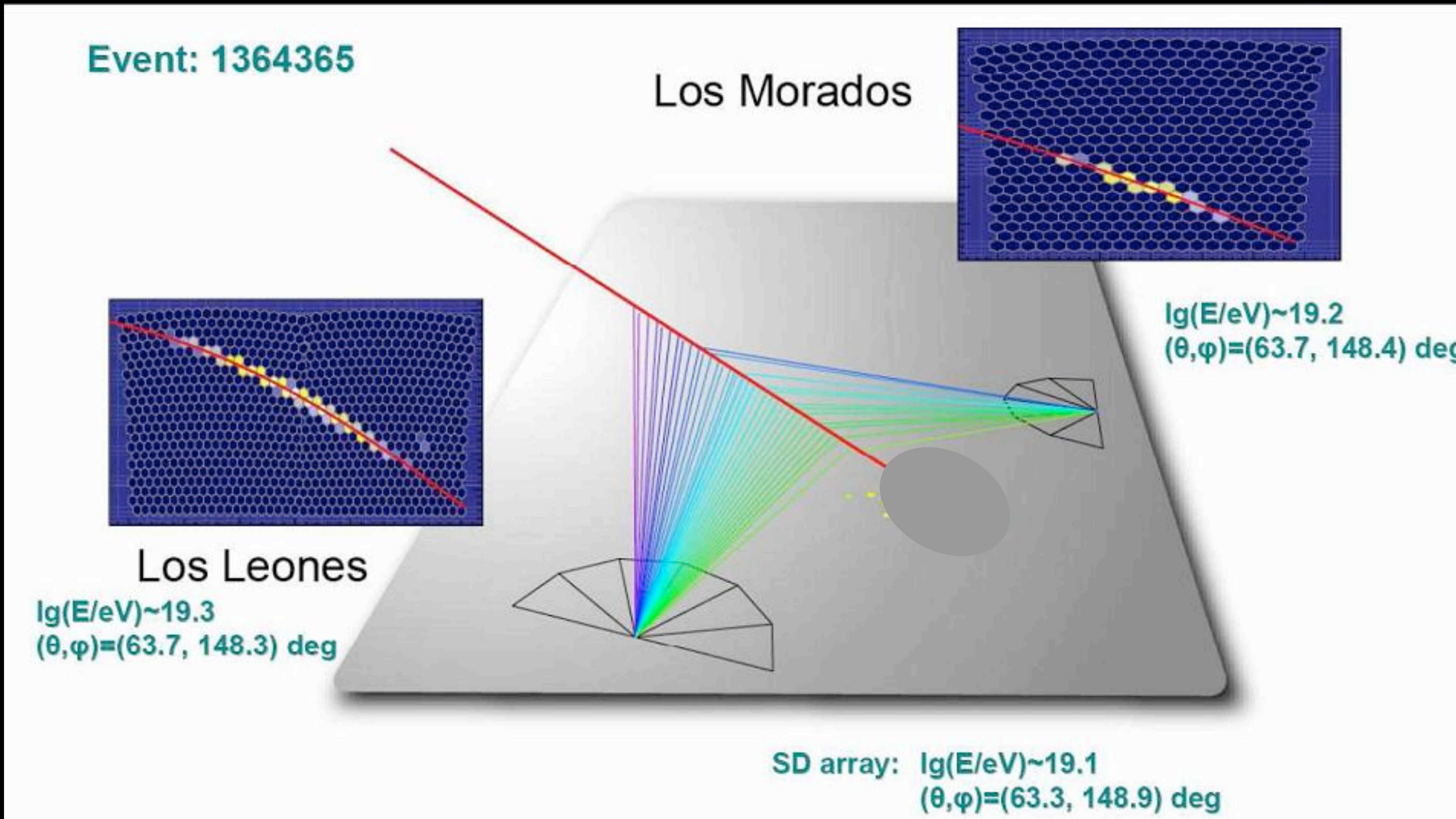
The arrival direction is obtained in two steps:

1. The observing directions of the triggered pixels and the detector itself define a plane that is called Shower Detector Plane (SDP).

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

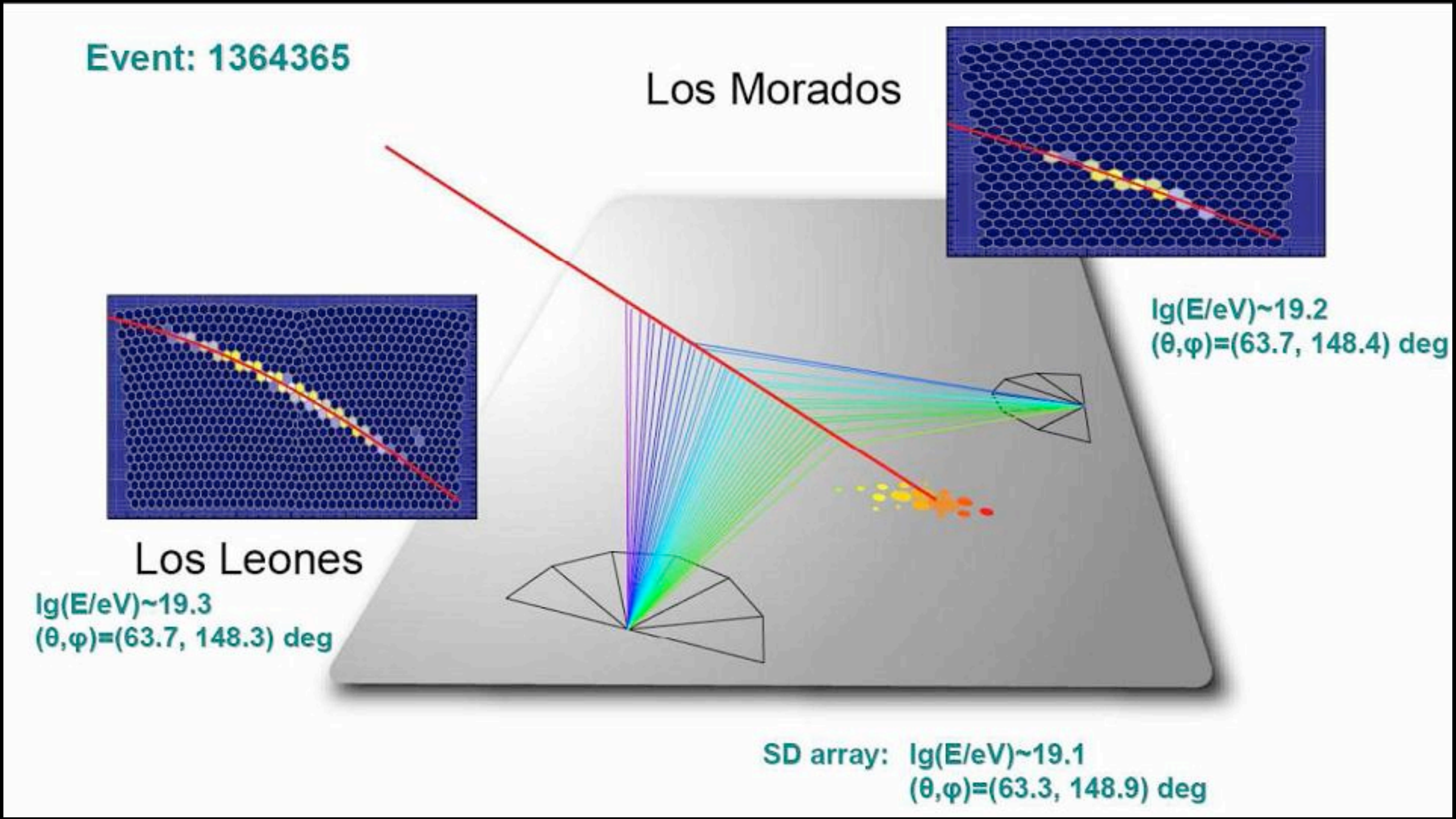


When an EAS is observed in "stereo", the arrival direction is defined by the intersection of the two (or more) SDPs.

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

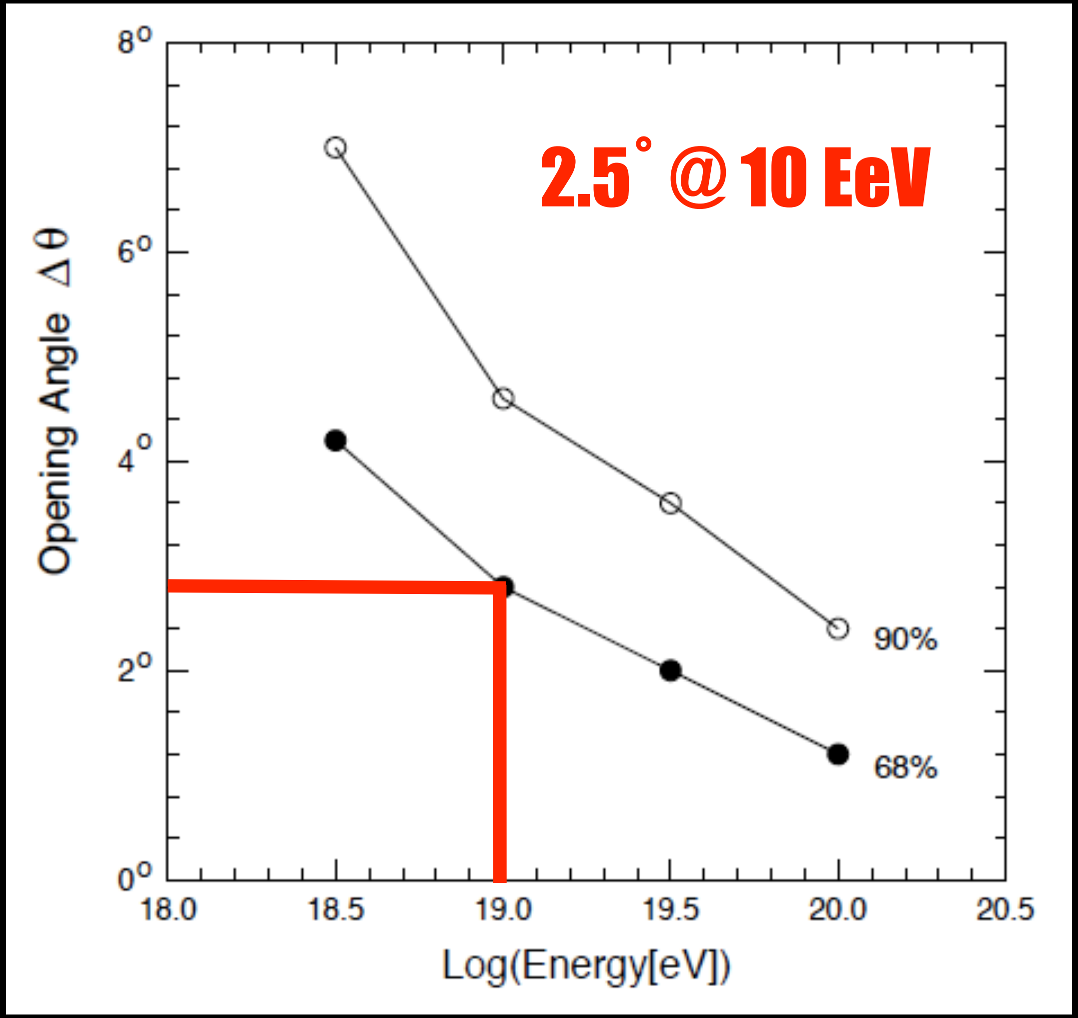
Nani gigantum humeris insidentes: Bassi, Clark, Rossi (again!), (1953)

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.

Volcano Ranch (1960s)

> 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 $10 \pm 5°$). The values

AGASA (1990s)



Bassi et al were not so wrong after all!!!!

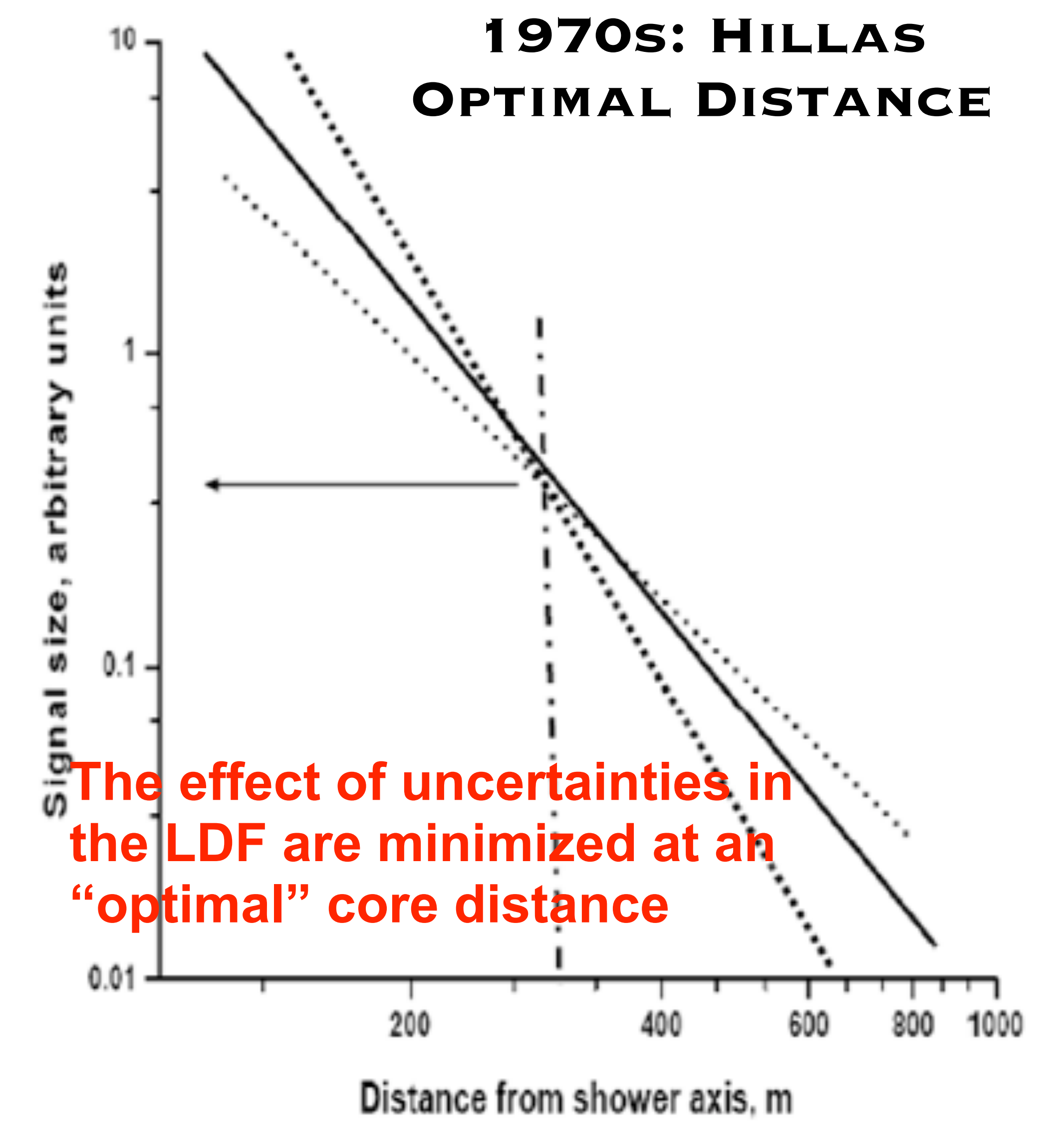
Slightly more difficult: energy

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

Early times

- Showers contain nucleons, pions and muons in addition to the more abundant electrons and photons.
- Yet, well described under the assumption that the primaries were photons or electrons.
- Early practice: infer the primary energy from the total number of e.m. particles.
- Large uncertainty due to the lack of knowledge of the "true" LDF
- Large fluctuations

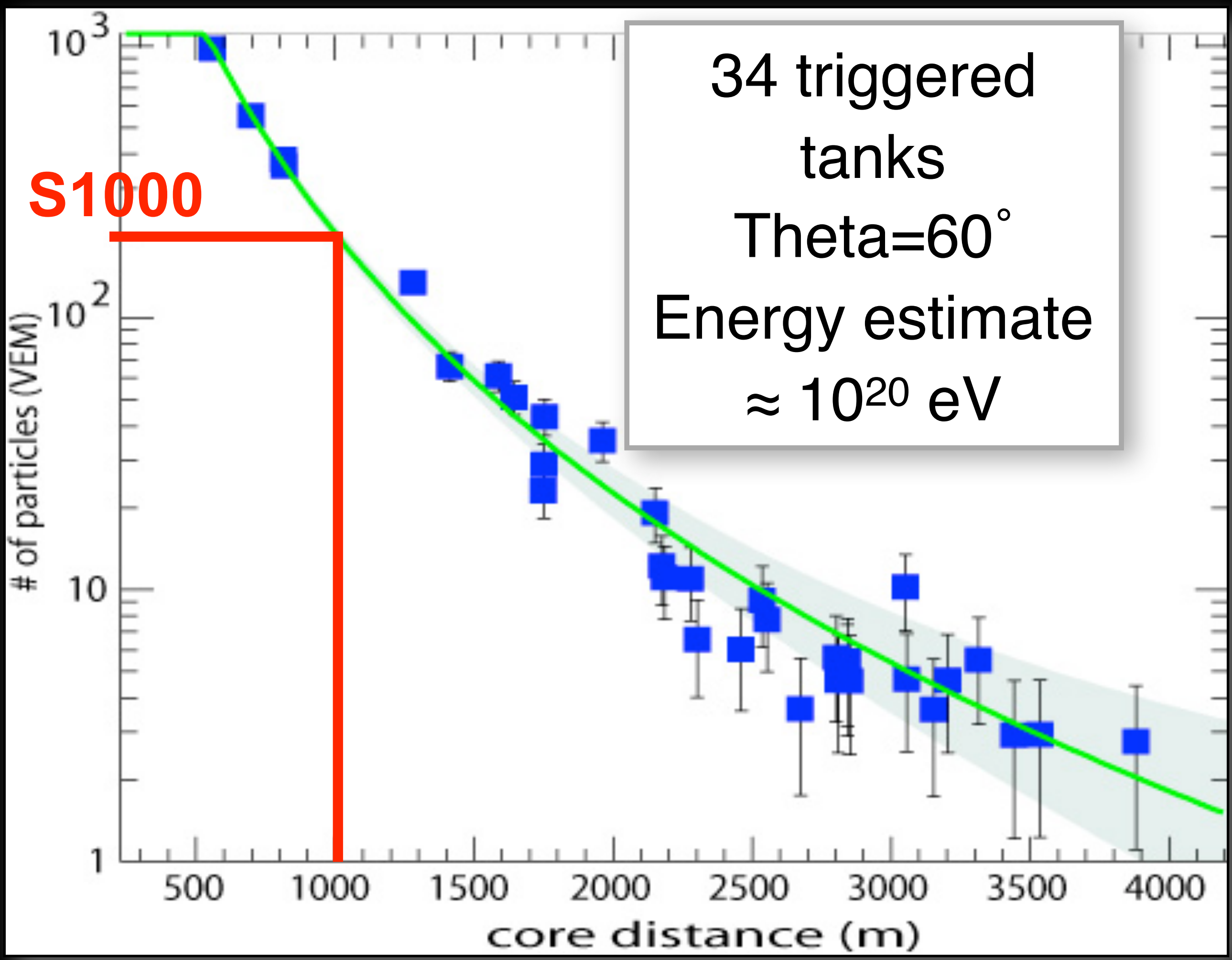


Not only the signal at the "optimal" distance minimally depends on the chosen LDF, but also the fluctuations of the particle density far from the core are quite small.

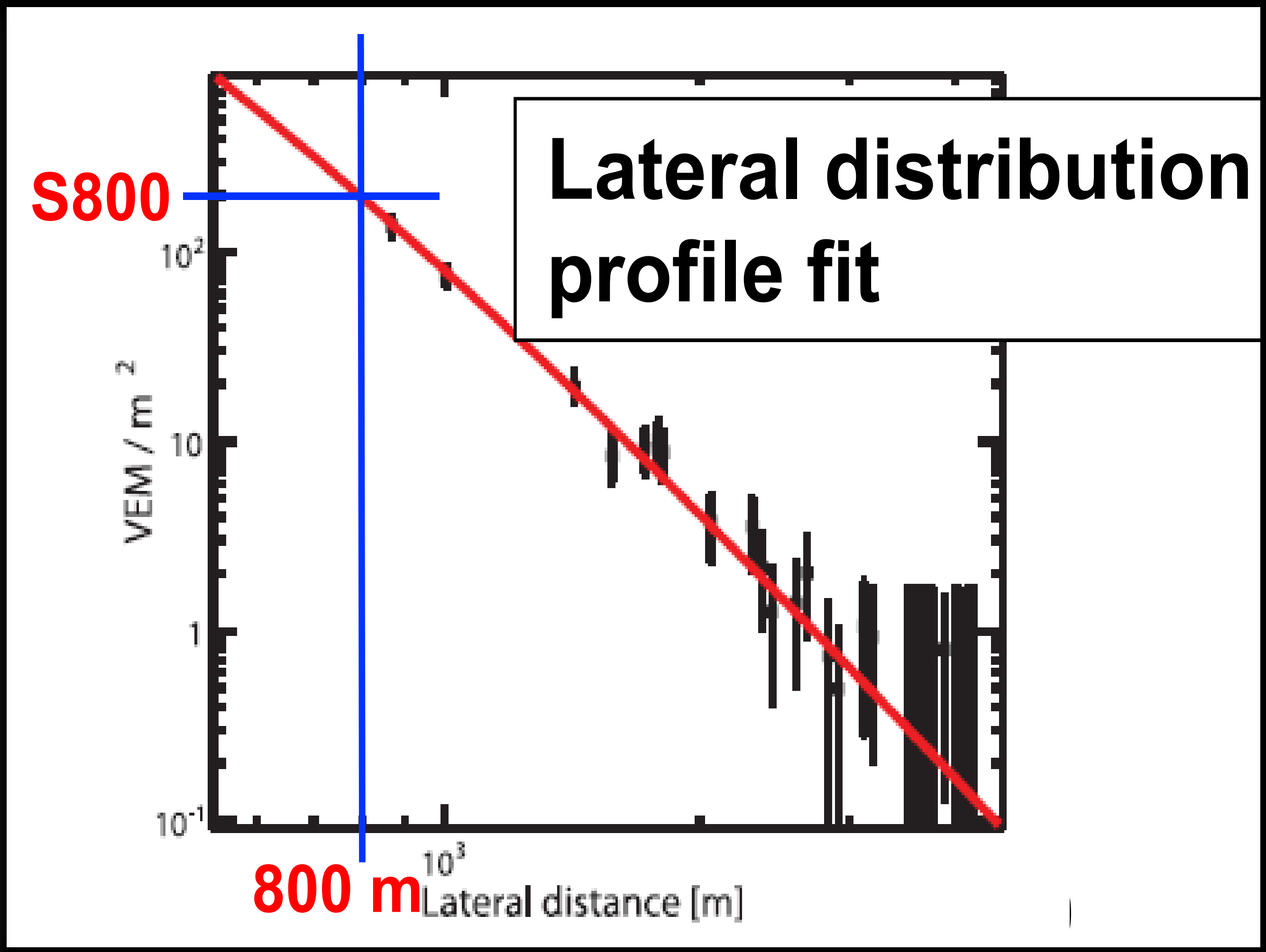
Energy estimator from the surface detectors

In practice

Auger



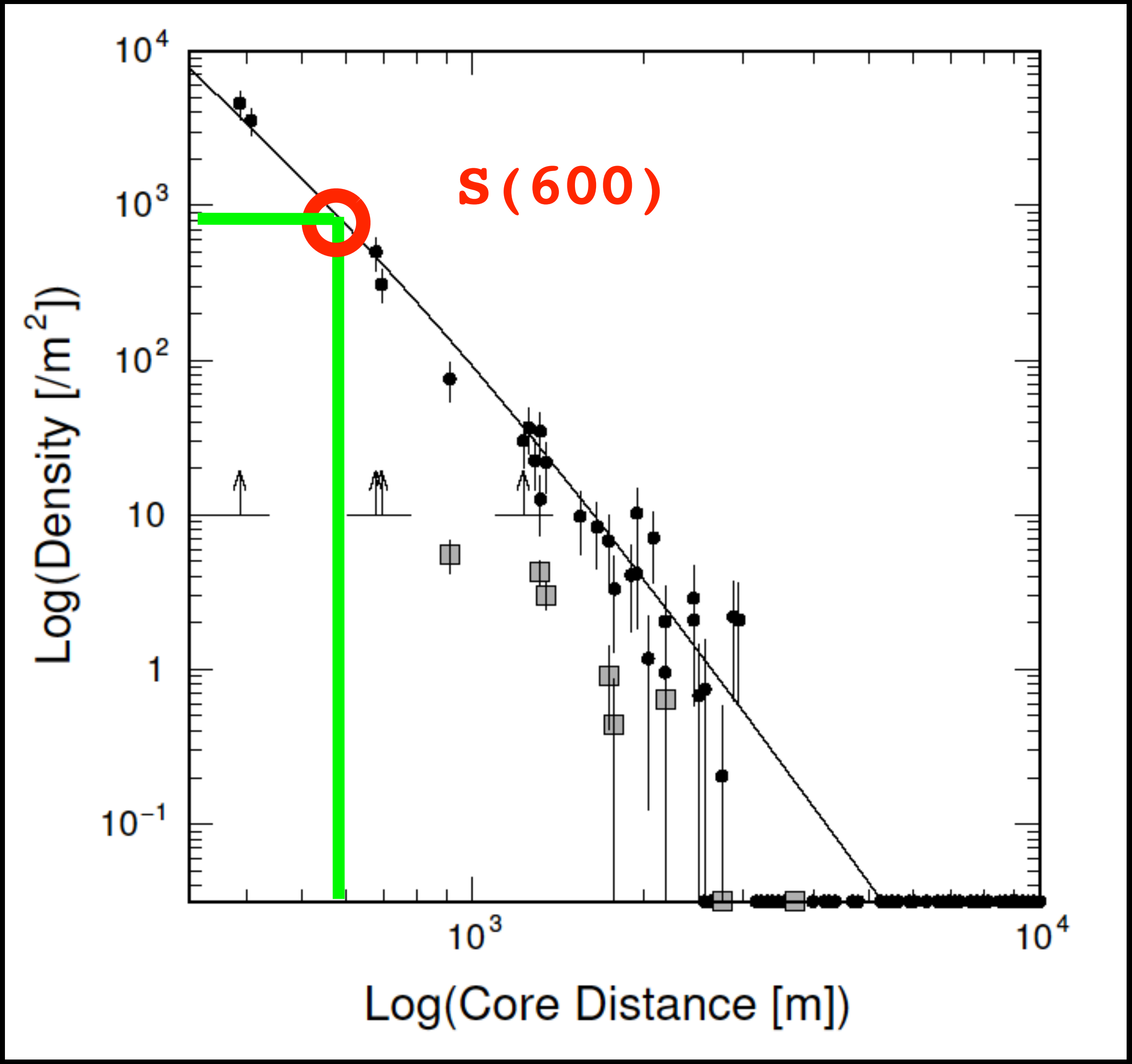
Telescope Array

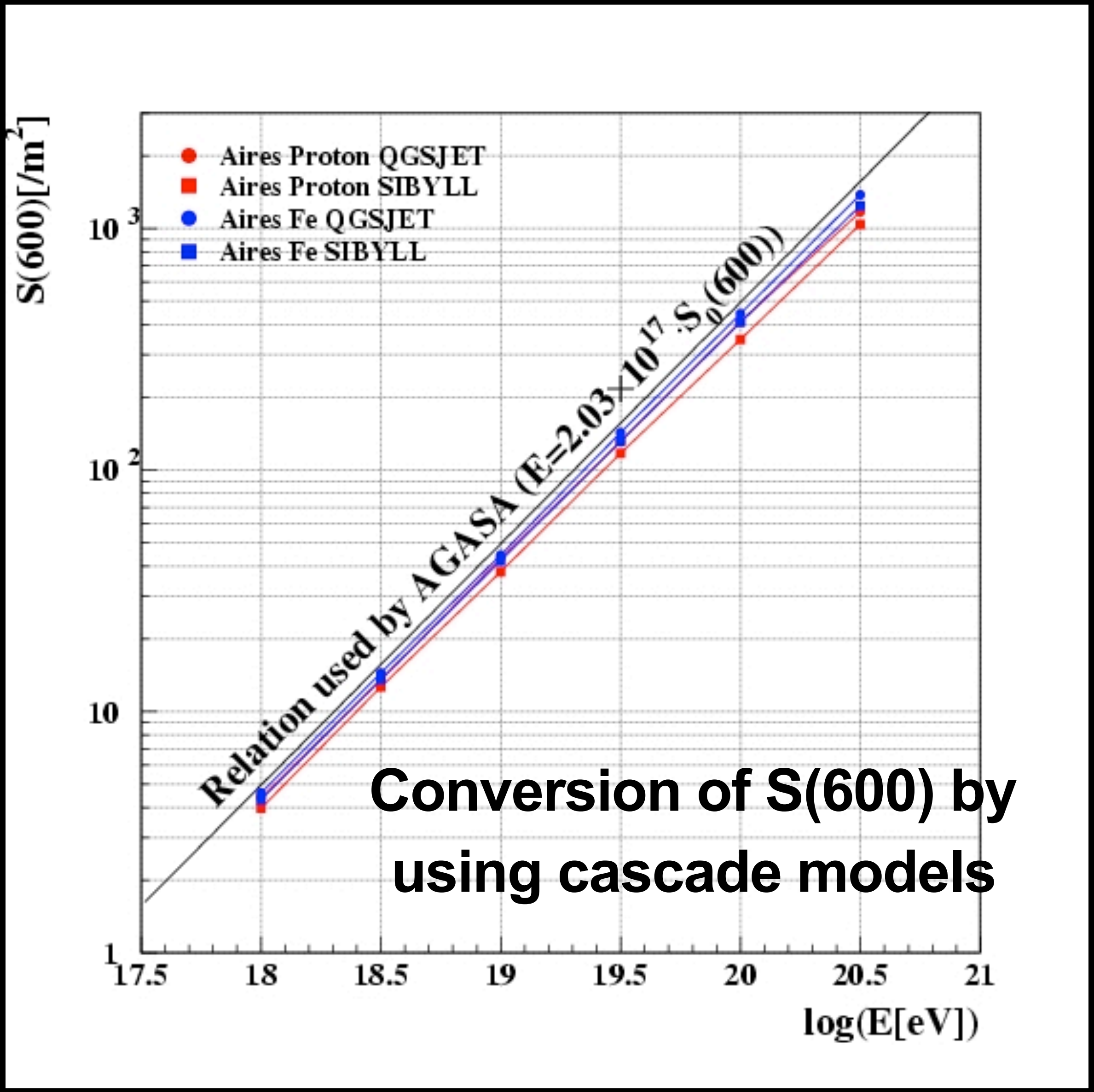


- Reconstruct geometry (arrival direction & impact point)
- Fit particle lateral distribution (LDF)
- Extract the signal at the "optimal" distance
- The "optimal" distance depends on detectors spacing, r_{opt}=1000/800 m for Auger/TA)

How to pass from energy estimator to primary energy?

Usually full Monte Carlo simulations are used





To determine the primary energy from measurements with a surface array one one has to use predictions from calculations of shower development

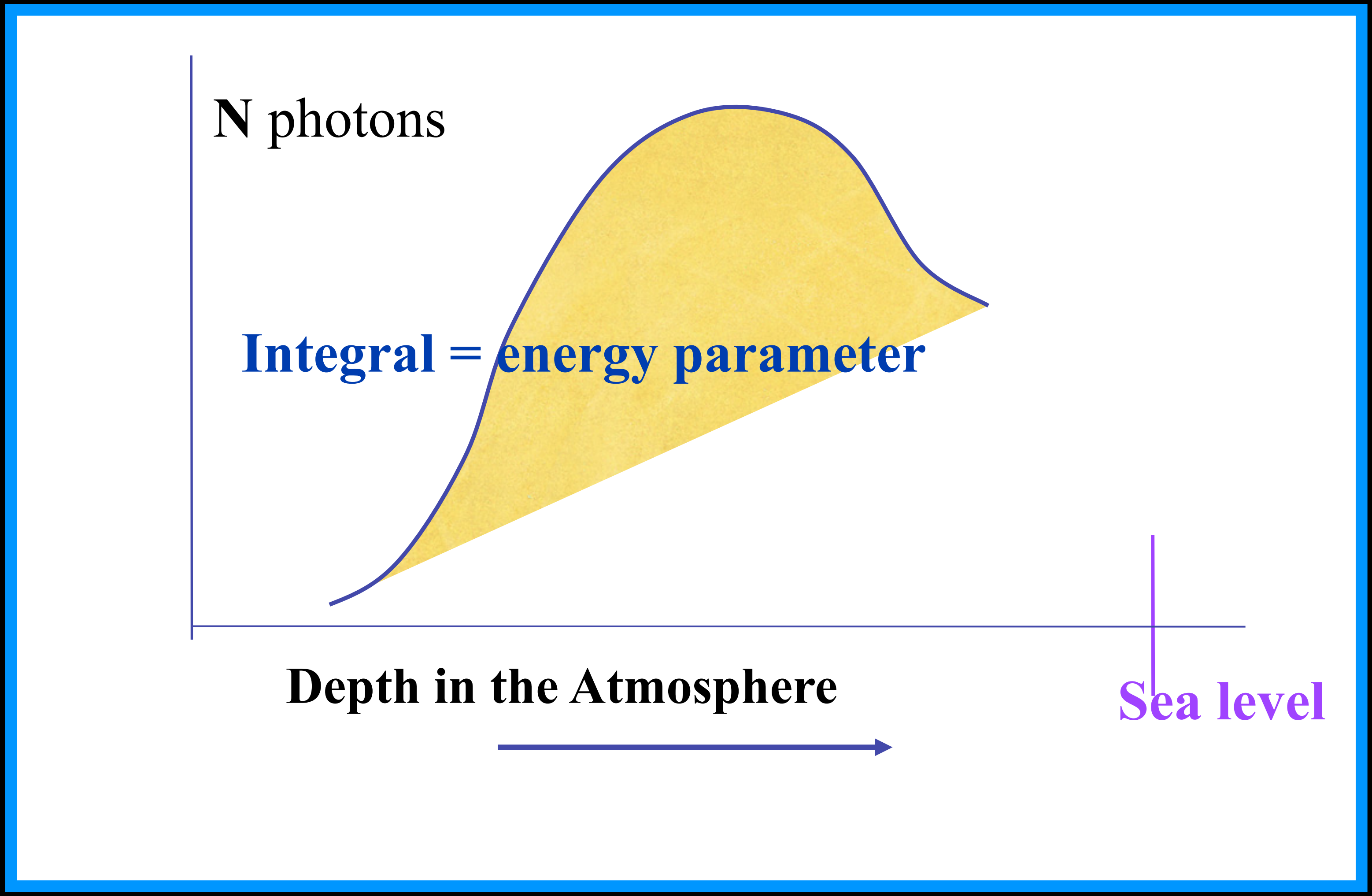
MEMENTO: UHECR energies are well-above those produced in accelerators!!!

Model predictions draw on extrapolations of the properties of interactions studied at accelerators. Large (if not unknown) systematics

The smartness of the hybrid technique

Use fluorescence detectors to calibrate surface detectors

The UHECR energy is deposited in atmosphere like in a giant calorimeter. Fluorescence detectors see the full development

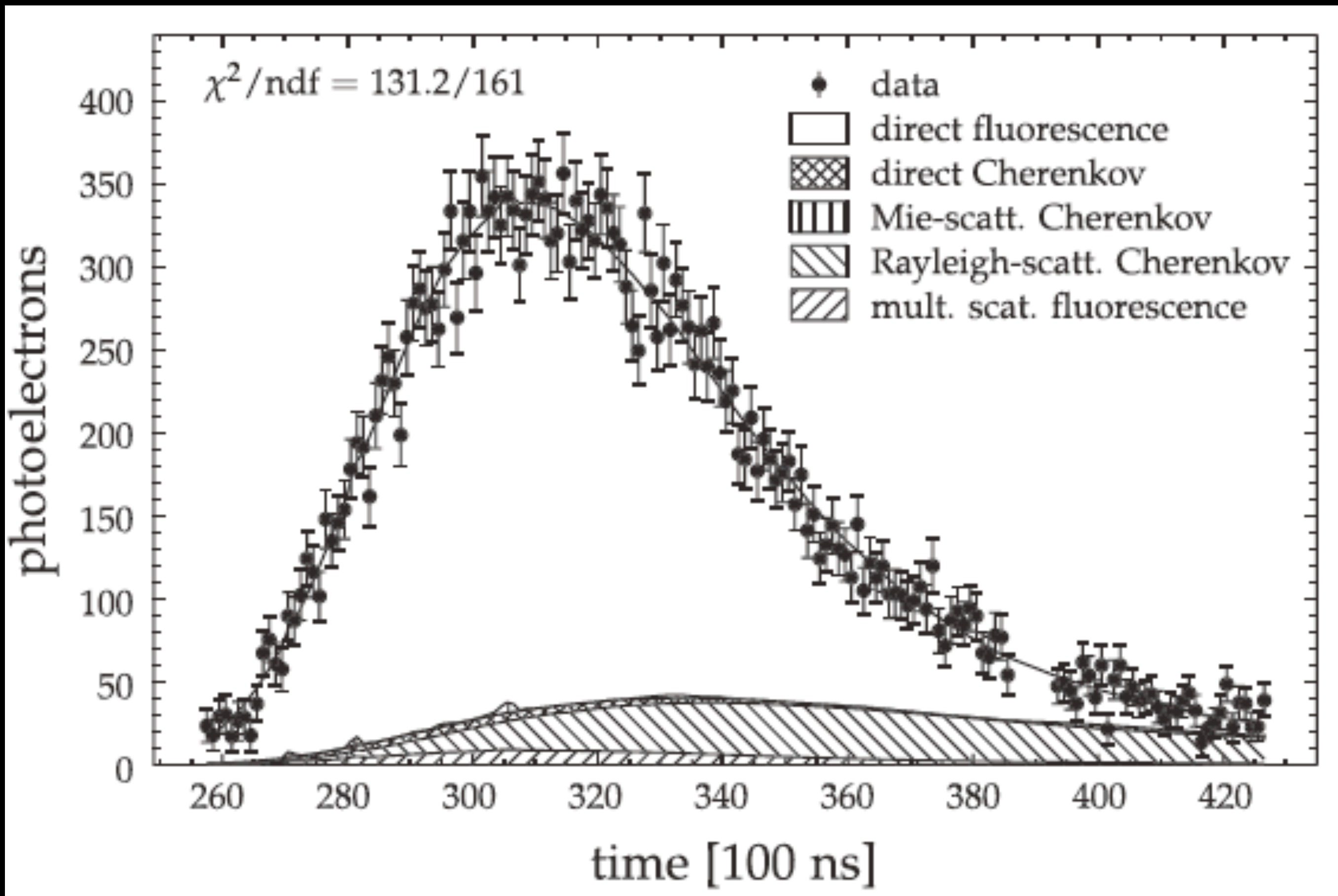


Fluorescence detectors allow for a direct measurement of the shower energy deposited in atmosphere.

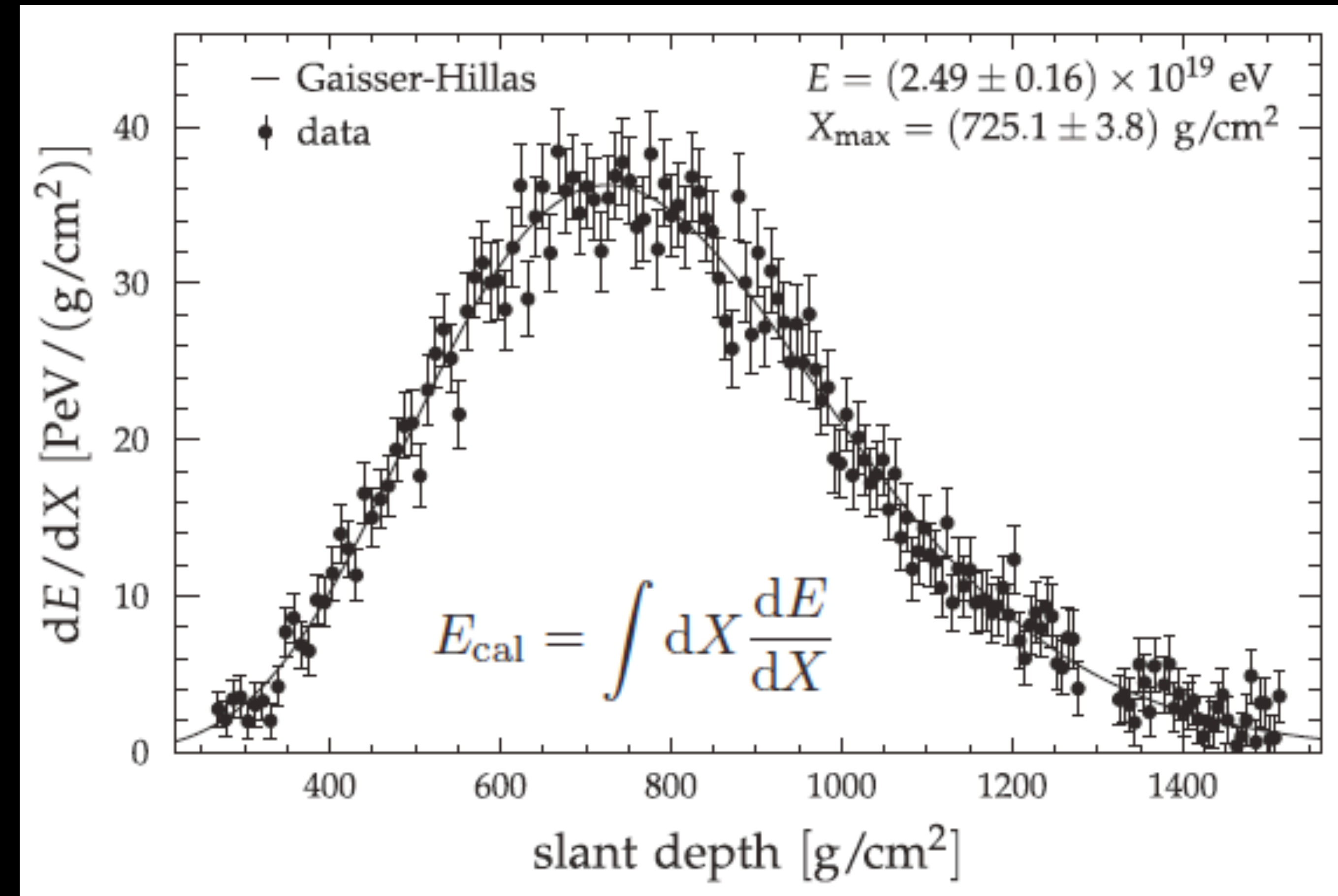
Model predictions do not enter the game!

UHECR energy from fluorescence detectors

In practice



Photons vs time

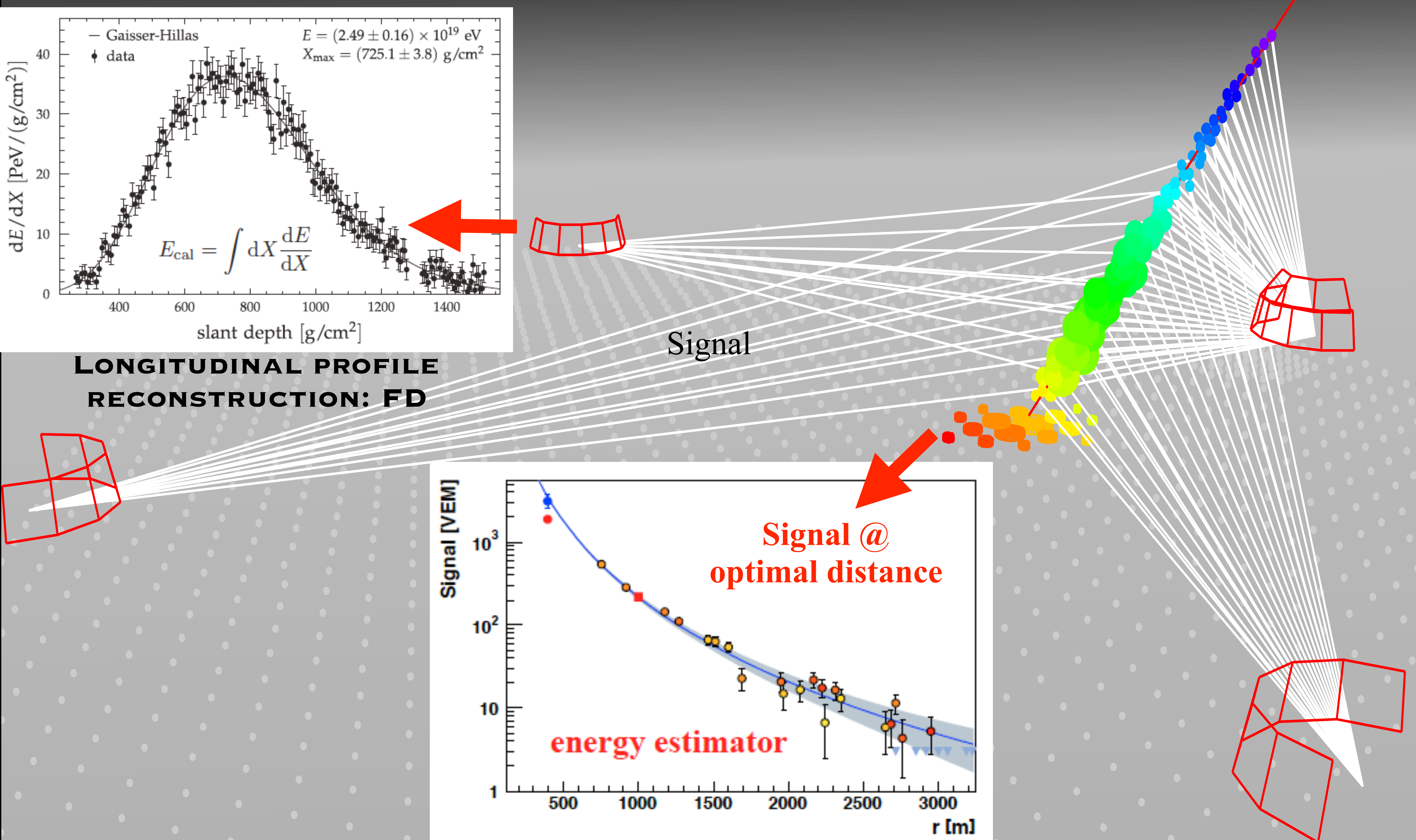


Energy deposit vs slant depth

- **Reconstruct geometry (shower detector plane - SDP - and shower axis in SDP)**
- **Fit longitudinal shower profile: a log-likelihood fit of the number of photons detected in the PMTs using 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.**

The smartness of the hybrid technique

Use hybrid events for the calibration of the SD energy estimator with the FD calorimetric energy



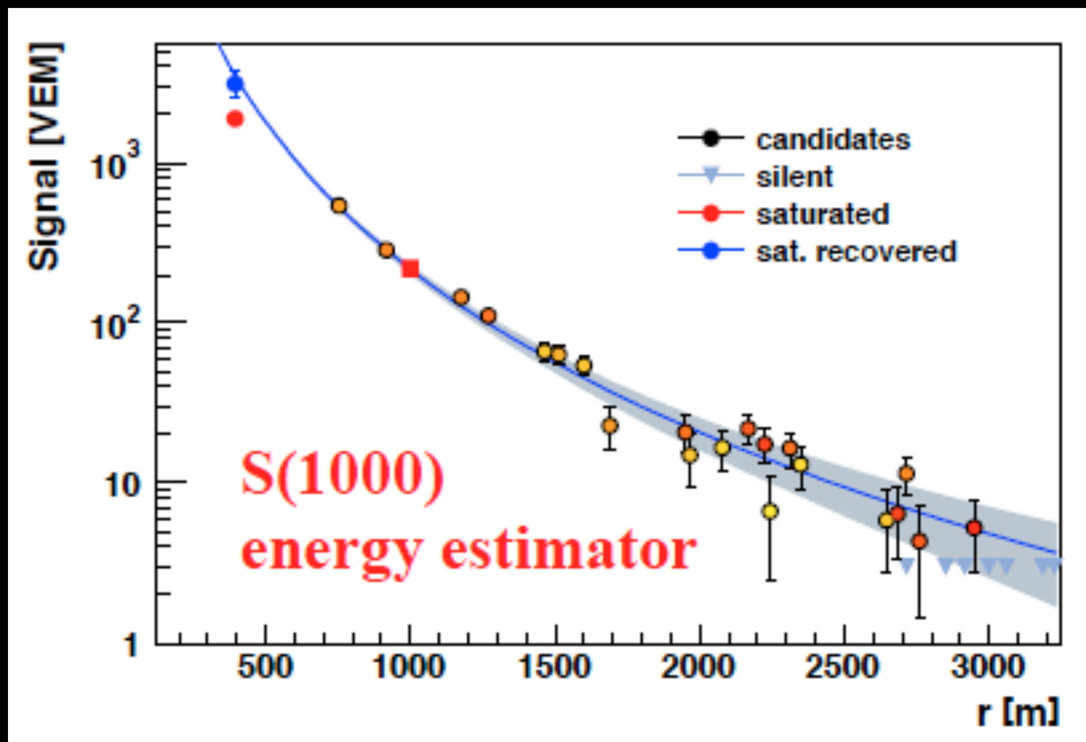
Longitudinal profile reconstruction: FD

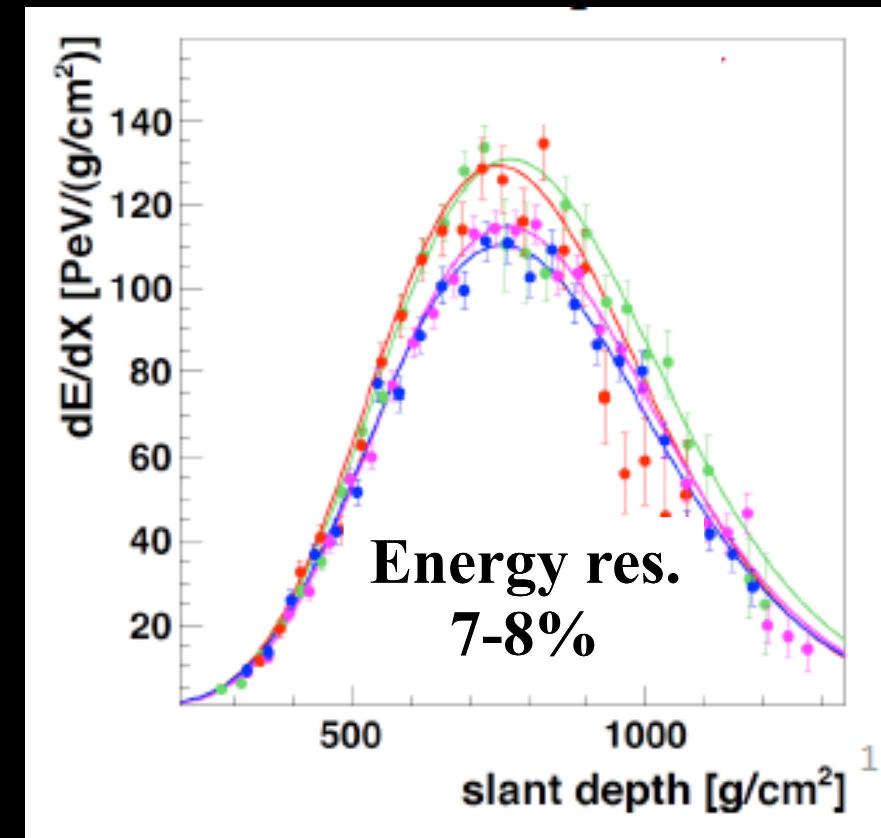
Particle lateral distribution: SD

The smartness of the hybrid technique

In practice

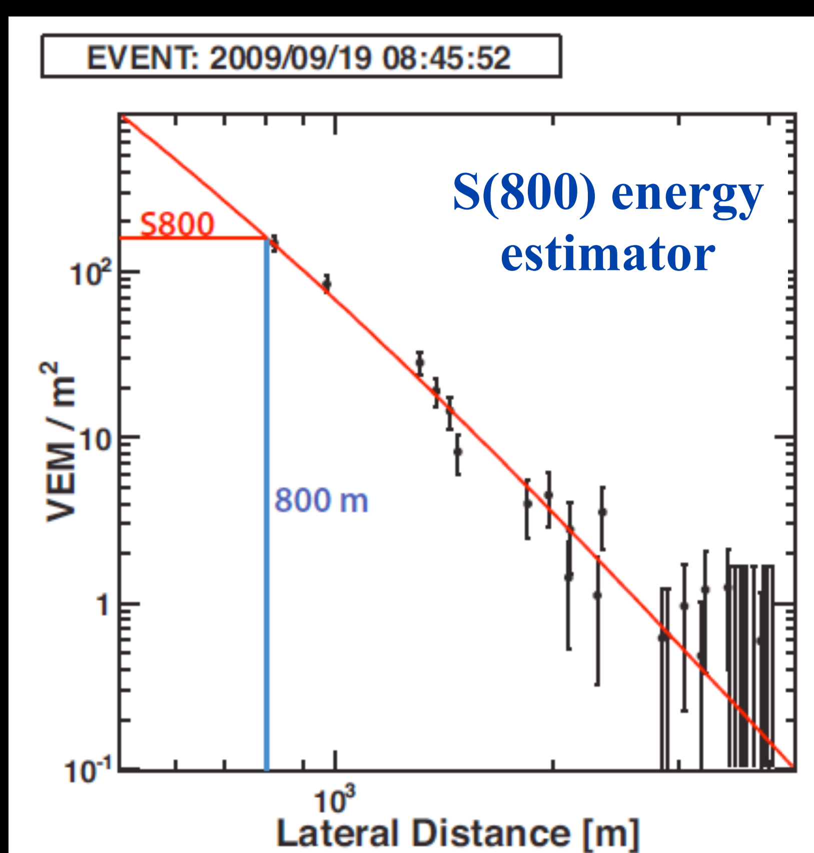
AUGER

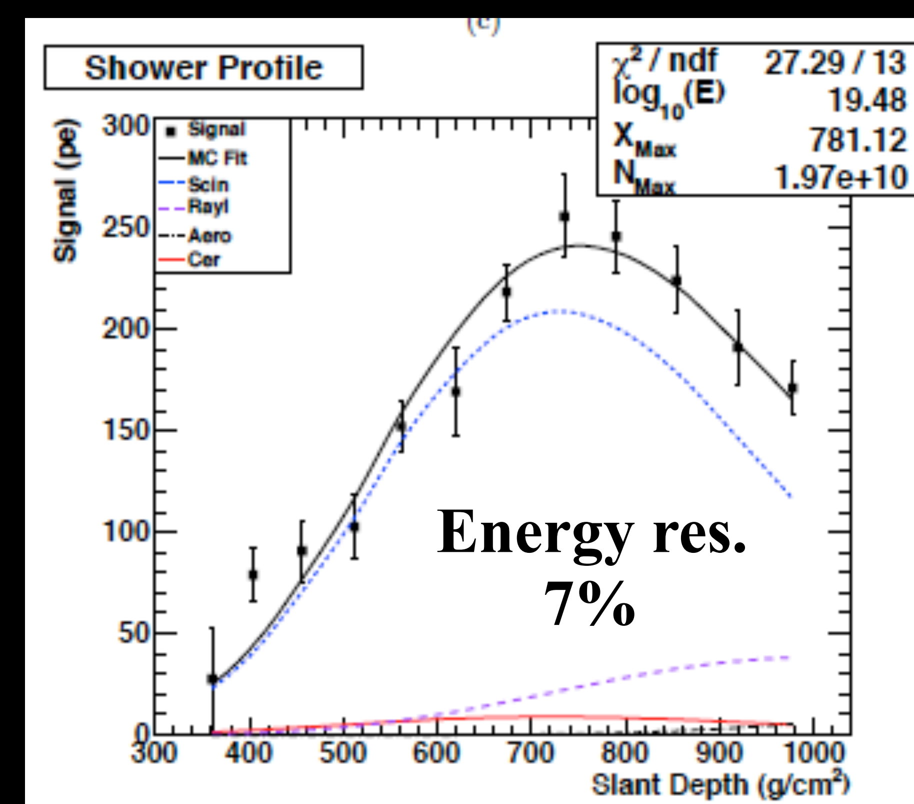




HYBRID EVENTS: CALIBRATION OF SD ENERGY ESTIMATOR WITH FD CALORIMETRIC ENERGY

TELESCOPE ARRAY

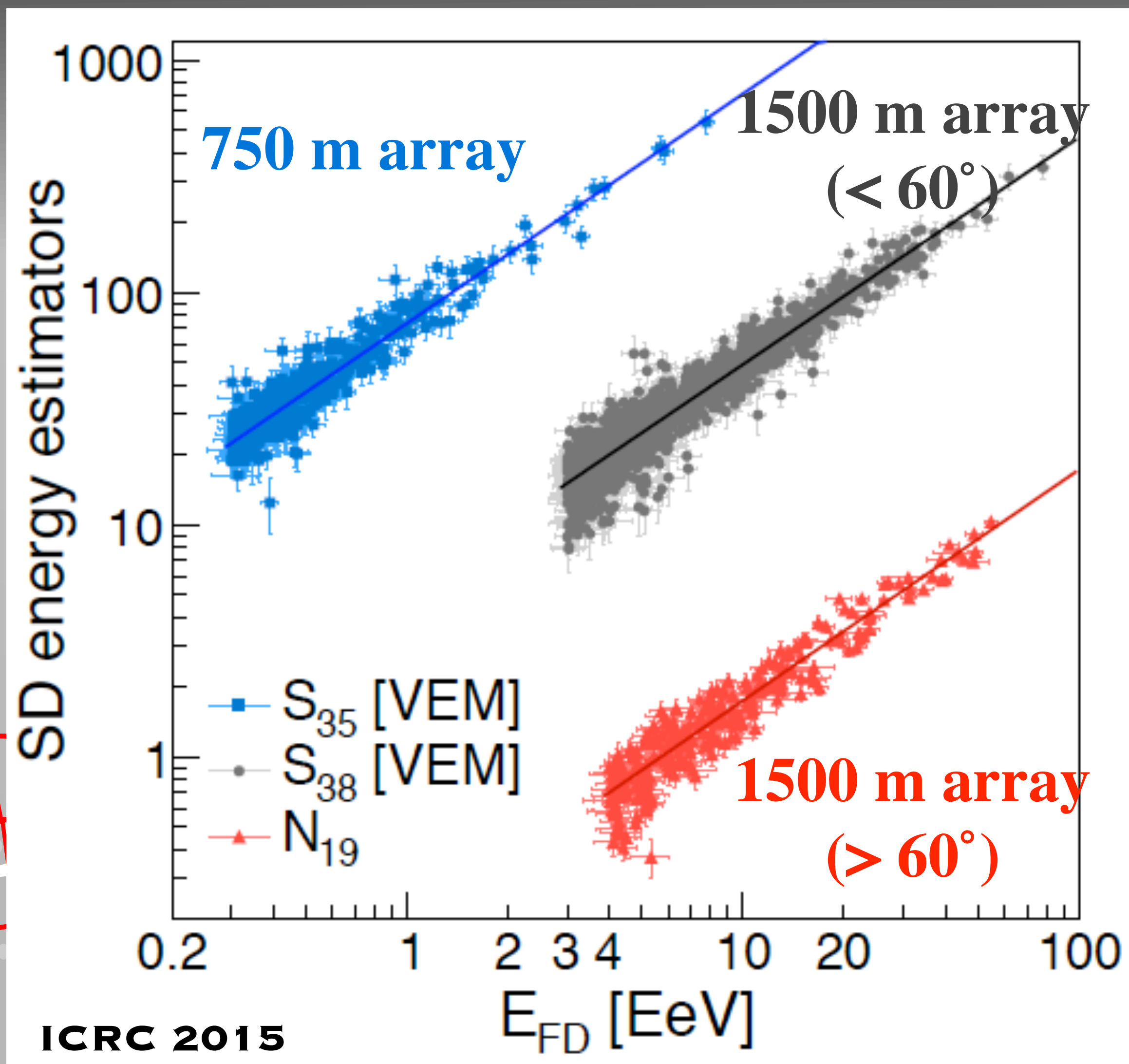




Energy calibration

In practice

Auger

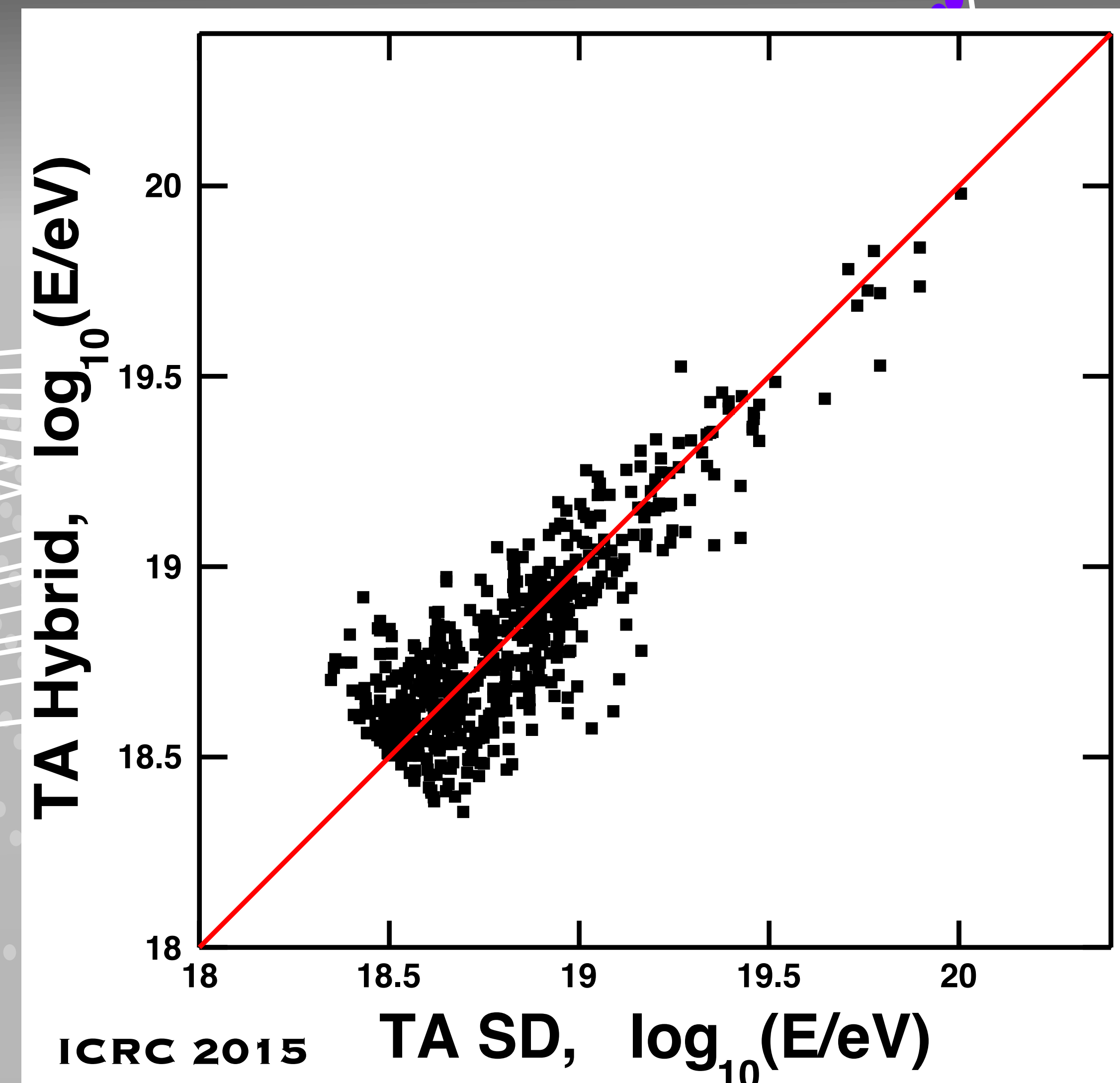


Purely data-driven calibration

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

S38 is calibrated versus EFD

Telescope Array



S(800) is converted to energy E(S800,theta) through a MC look-up table

The model dependence is removed via the calibration with EFD

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%

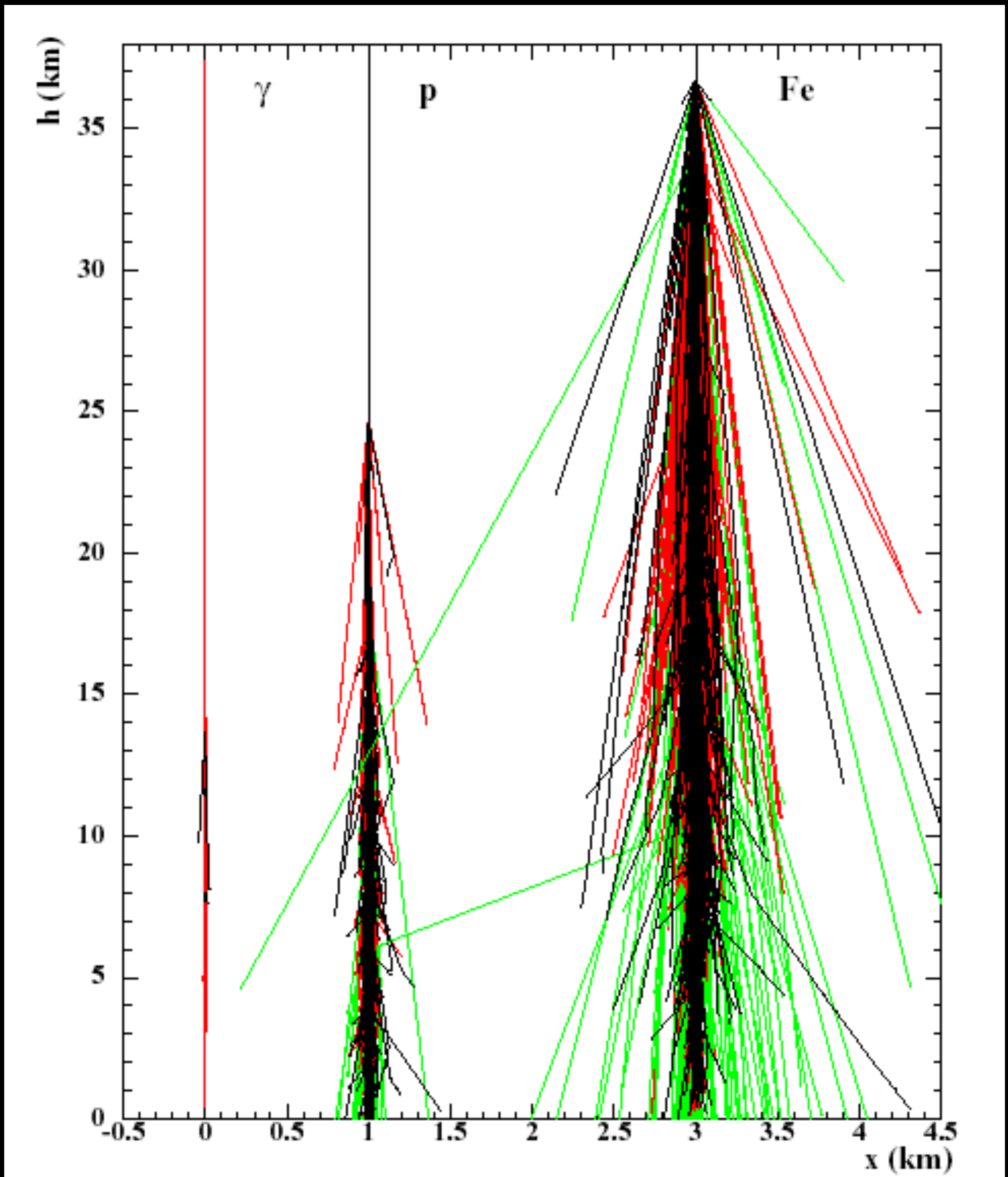
Telescope Array

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 one: mass

The mass of an UHECR can only be inferred from comparisons of observables with shower simulations, subject to uncertainties of models of hadronic interactions at energies not accessible to accelerators

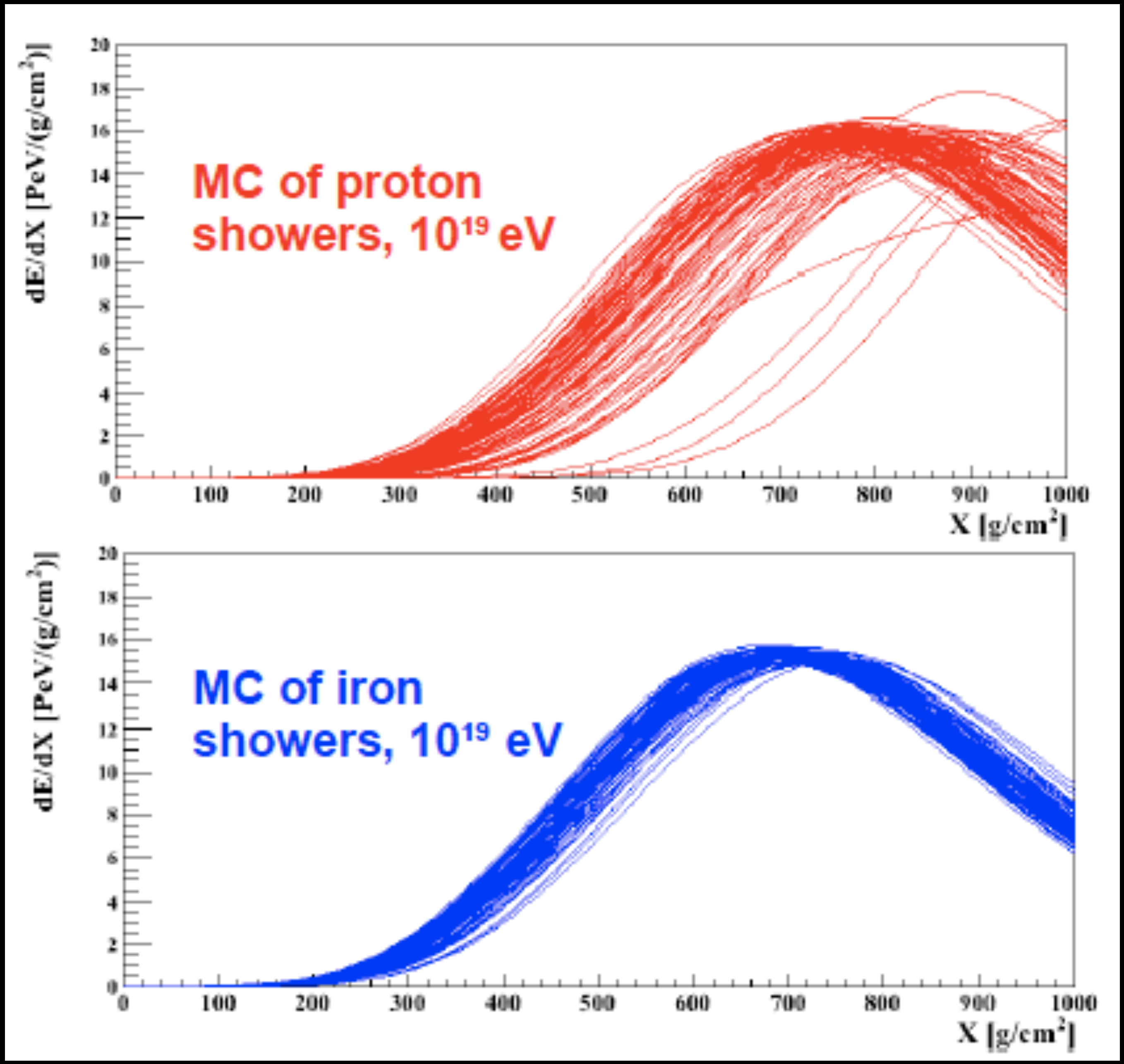


Observables sensitive to composition:

- **Depth of shower maximum (at fixed energy, a nucleus-shower develops faster than a proton-shower)**
- Relative number of electrons and muons (primary nucleus produces more muons than a primary proton)
- Shower front curvature (the higher the first interaction, the flatter the front)

The most difficult one: mass

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

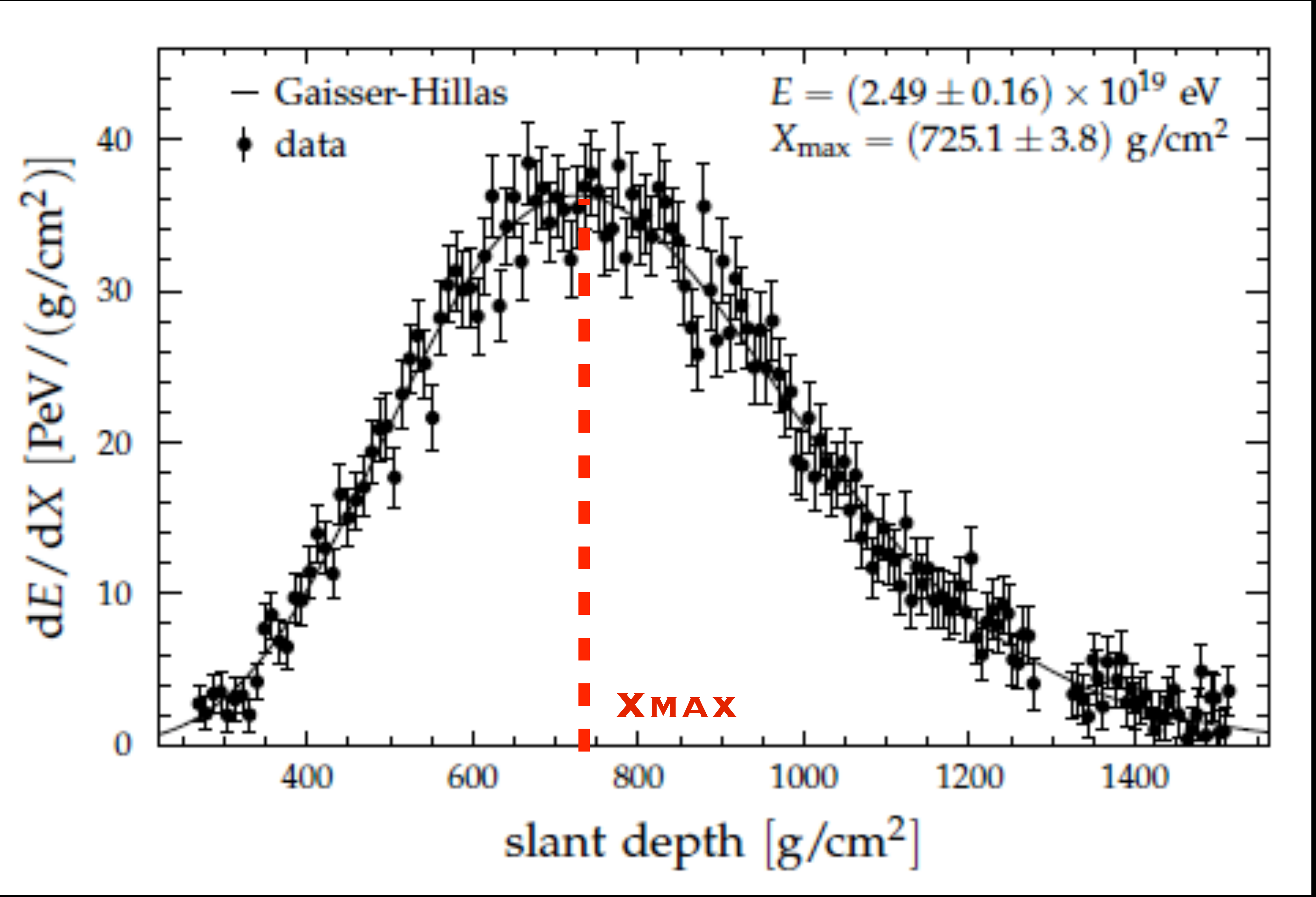


First interaction of heavier primaries is shallower and fluctuates less. Sigma of the Xmax distribution is mass sensitive too

Xmax measurement

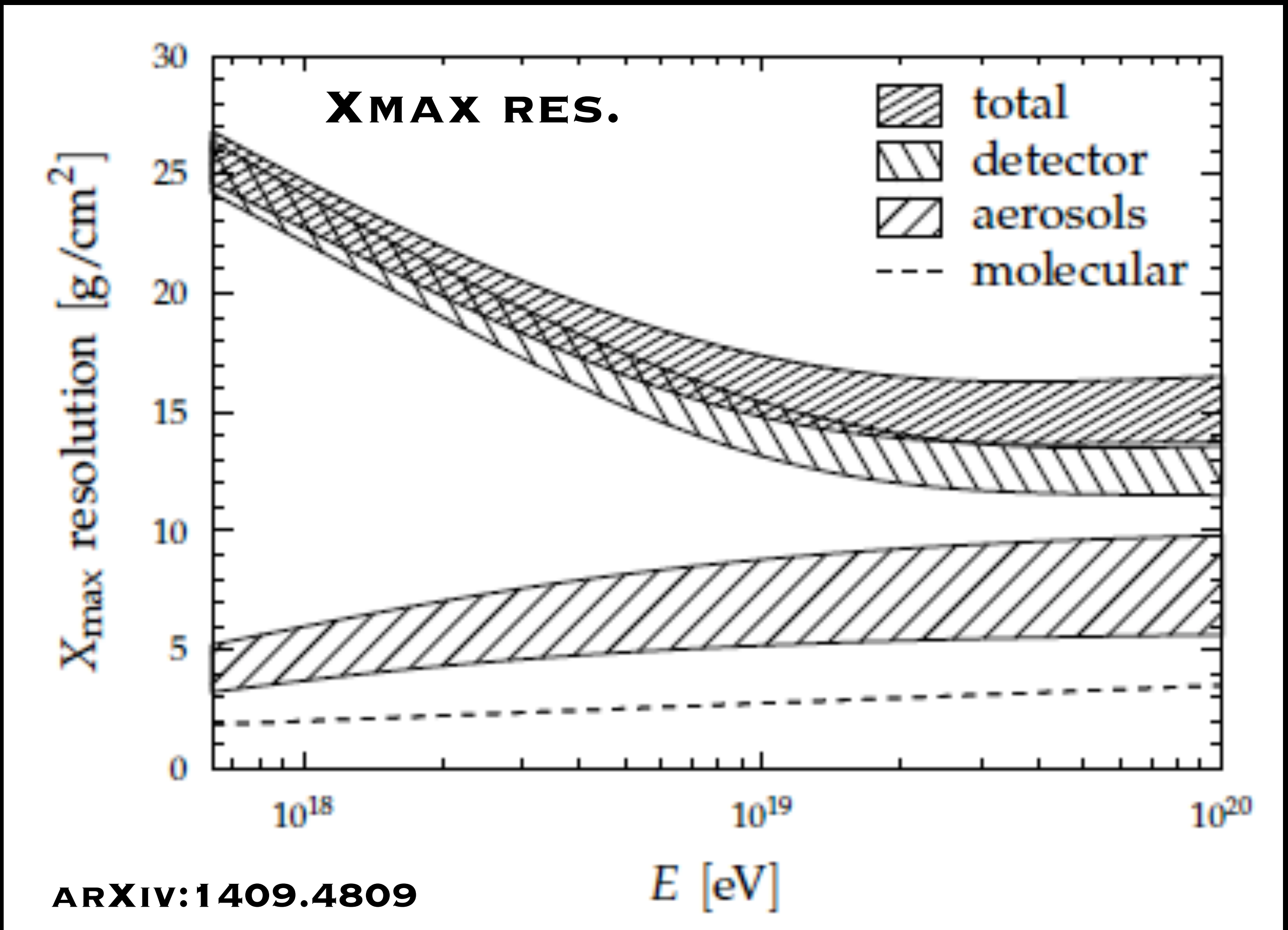
In practice

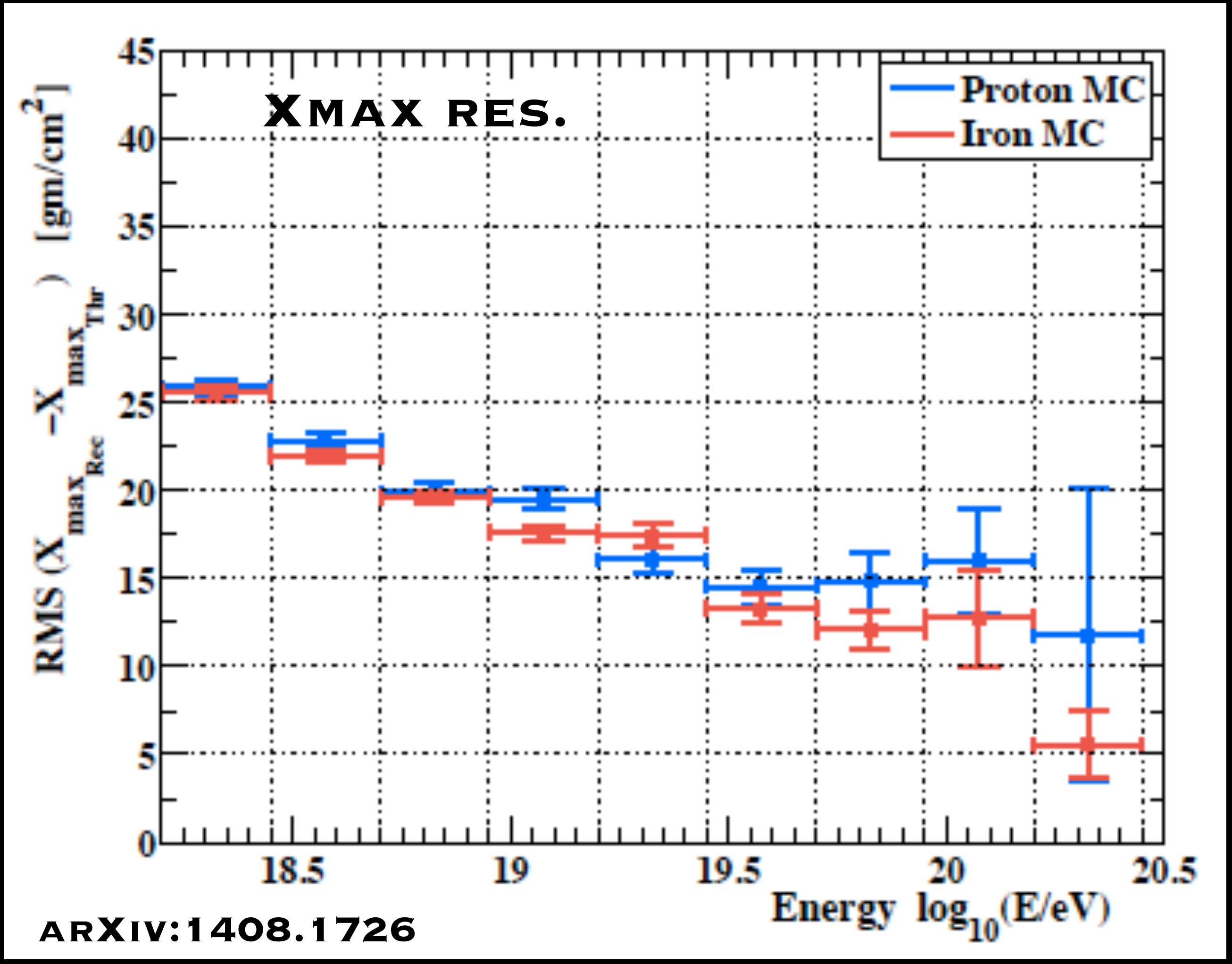
Xmax can be directly measured by fluorescence detectors



Xmax resolution

Auger | **Telescope Array**





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

Systematic uncertainty ≈ 10%

Systematic uncertainty ≈ 16%

Finally ready to go to UHECR inferences!

Once we know...	We can study...
Energy	Flux vs energy [Energy spectrum]
UHECR mass	Origin of spectral feature(s)
UHECR arrival direction	Distribution of arrival directions

It's time to pass the torch to Michael Unger…

Credits

It is hard to keep track of the original source of material contained in a lecture. My apologies to those who originally created the plots and graphs collected here and are not properly quoted.

Innumerable papers have served to this lecture, more or less modern.

It has been a pleasure to take profit of a few historical books which made me feel humble:

Bruno Rossi, Cosmic Rays, Mc Graw-Hill 1964

Michael W. Friedlander, Cosmic Rays, Harvard University Press 1989

Yataro Sekido and Harry Elliot, Early History of Cosmic Ray Studies, Reidel Publishing Company 1985

Malcolm S. Longair, High Energy Astrophysics, Cambridge University Press

And finally I am in debt with countless colleagues with whom I share the passion for Extensive Air Showers and cosmic rays. In particular I invite you to read the review of KH Kampert and AA Watson, Eur. Phys. J. H 37, 359–412 (2012), which I had the honour to proof-reading before publication.

Finally, the foundation of all what I know about EAS and detectors has been taught to me by Carlo Castagnoli and Gianni Navarra, now gone, but always alive in me.

Thanks for your attention!

I hope that you won’t think like Enrico Fermi did once:

“Before I came here I was confused about this subject. Having listened to your lecture I am still confused. But on a higher level.”