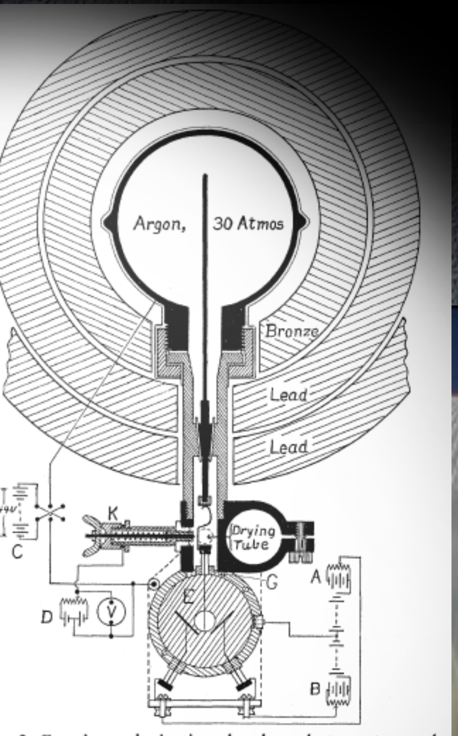
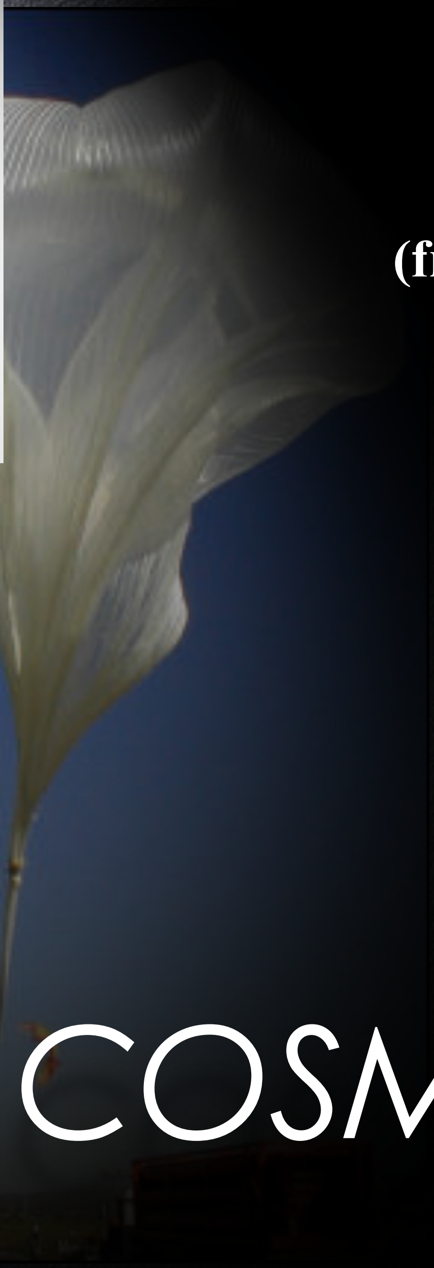
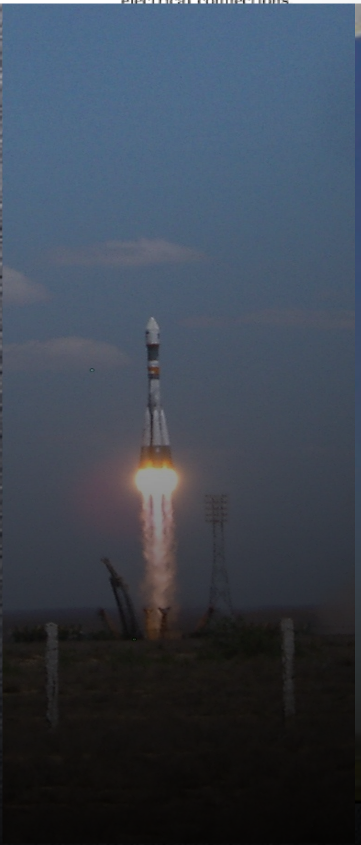
``The subject of cosmic rays is unique in modern physics for
the minuteness of the phenomena
the delicacy of the observations
the adventurous excursions of the observers
the subtlety of the analysis
the grandeur of the inferences”

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



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





COSMIC RAY DETECTION

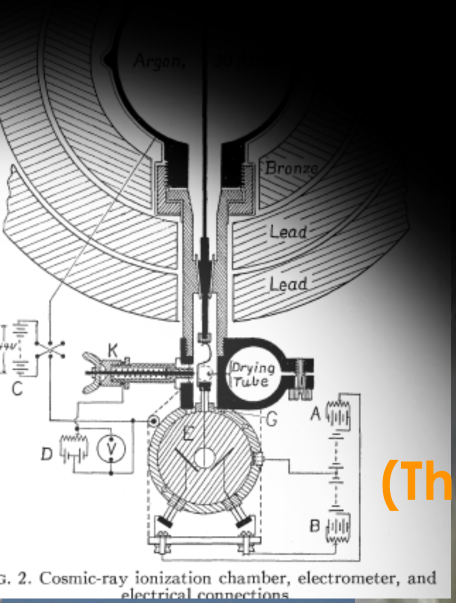
Piera L. Ghia (LPNHE-CNRS, Paris)

Outline

(The minuteness of the phenomena - The grandeur of the inferences)

Ia. Cosmic Rays: what do we know?

1b. Cosmic rays: how do we detect them?



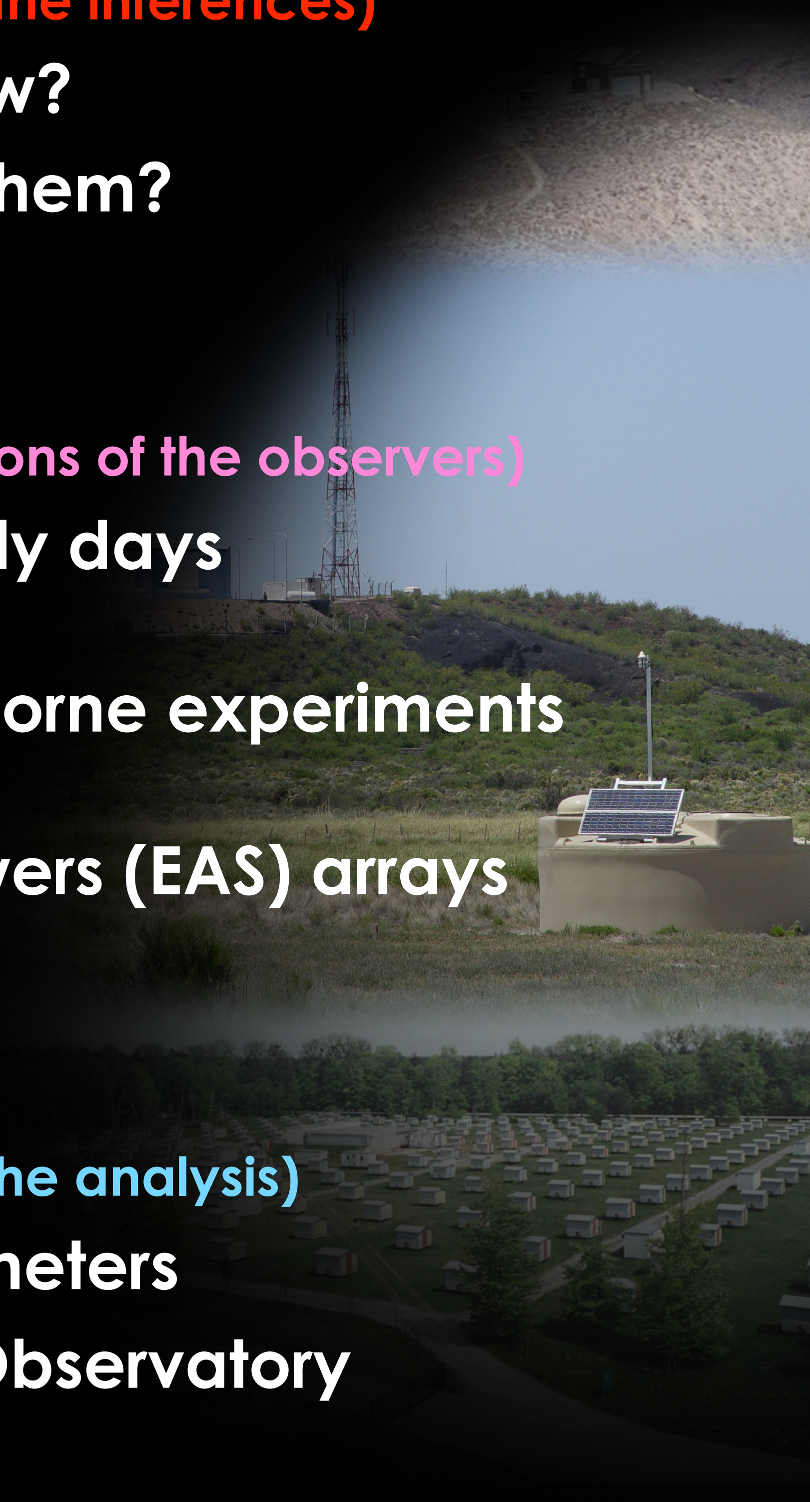
2. Cosmic-ray ionization chamber, electrometer, and electrical connections

(The delicacy of the observations - The adventurous excursions of the observers)

II. CR detection and detectors: the early days

III. Direct detection of CRs: balloon- and space-borne experiments

IV. Indirect detection of CRs: extensive-air showers (EAS) arrays



(The delicacy of the observations - The subtlety of the analysis)

V. From EAS observables to CR parameters

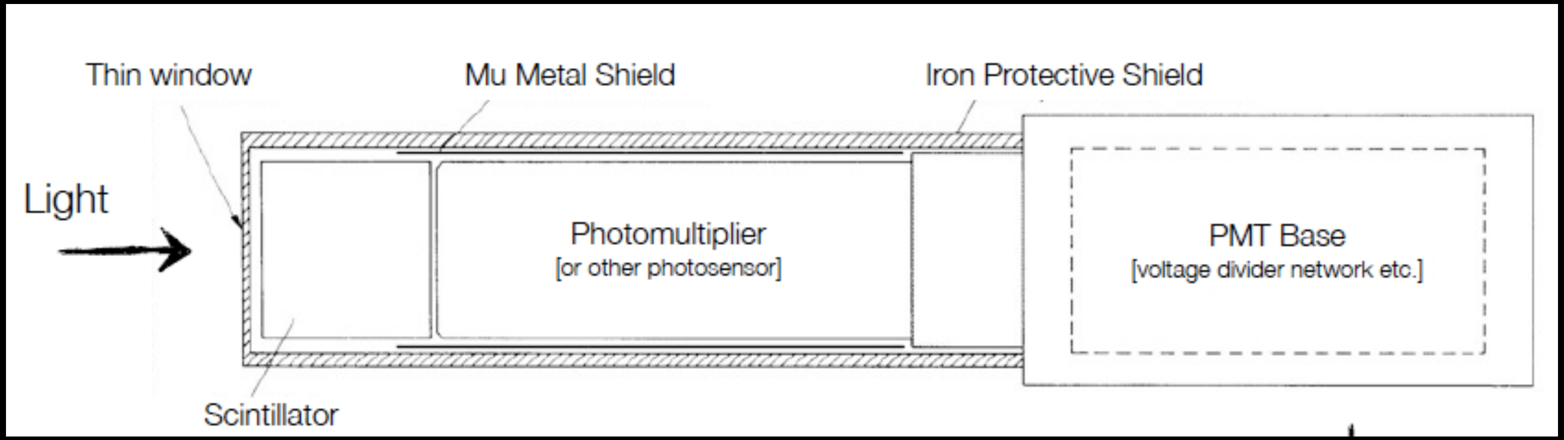
VI. An exemplary case: The Pierre Auger Observatory

A short recap

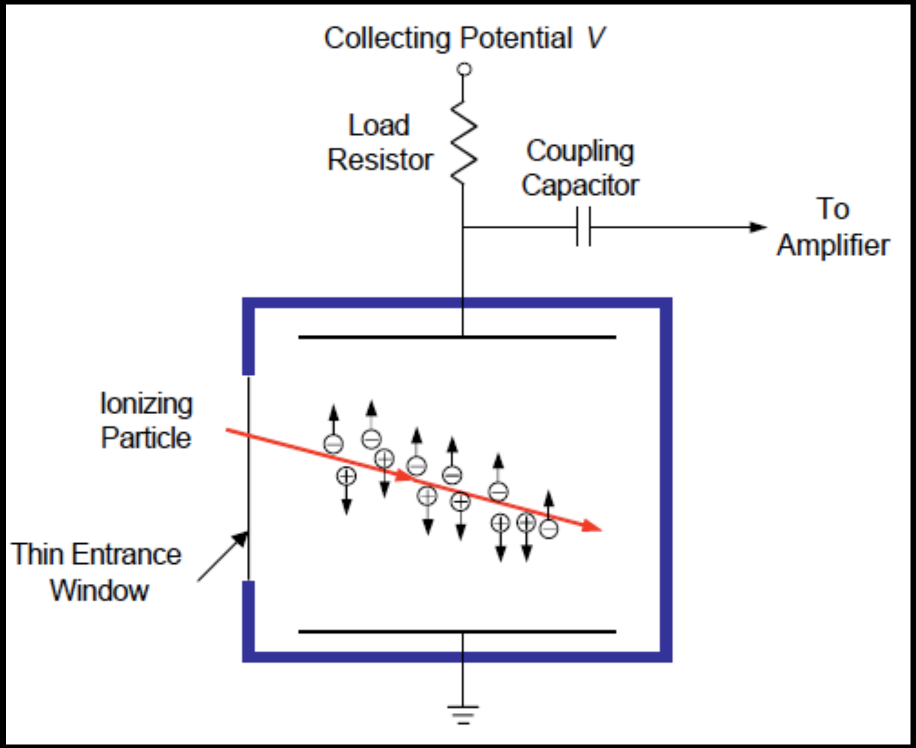
How do we study cosmic rays?

(by being a little bit adventurous
and by doing delicate measurements ;-)

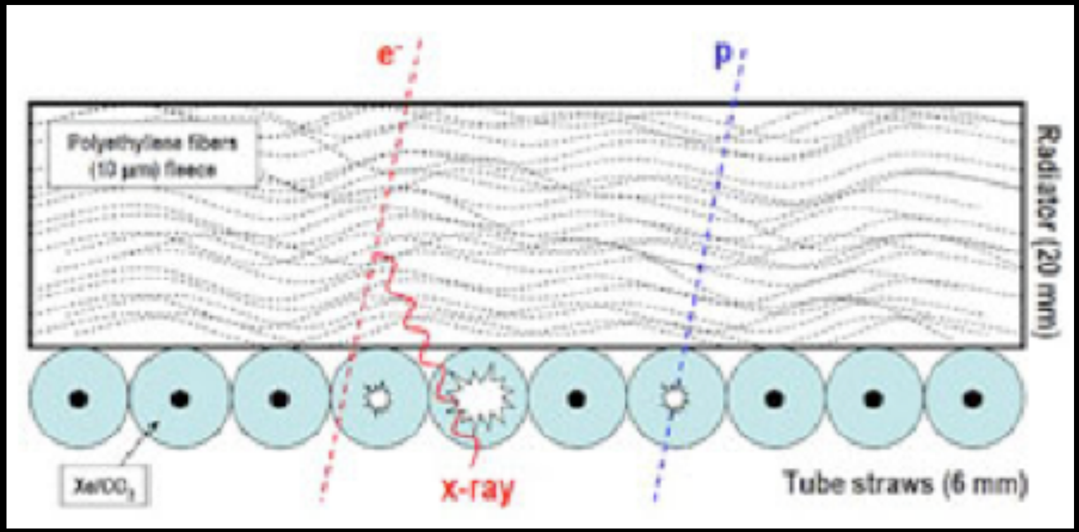
COSMIC RAY DETECTORS ARE PARTICLE DETECTORS...



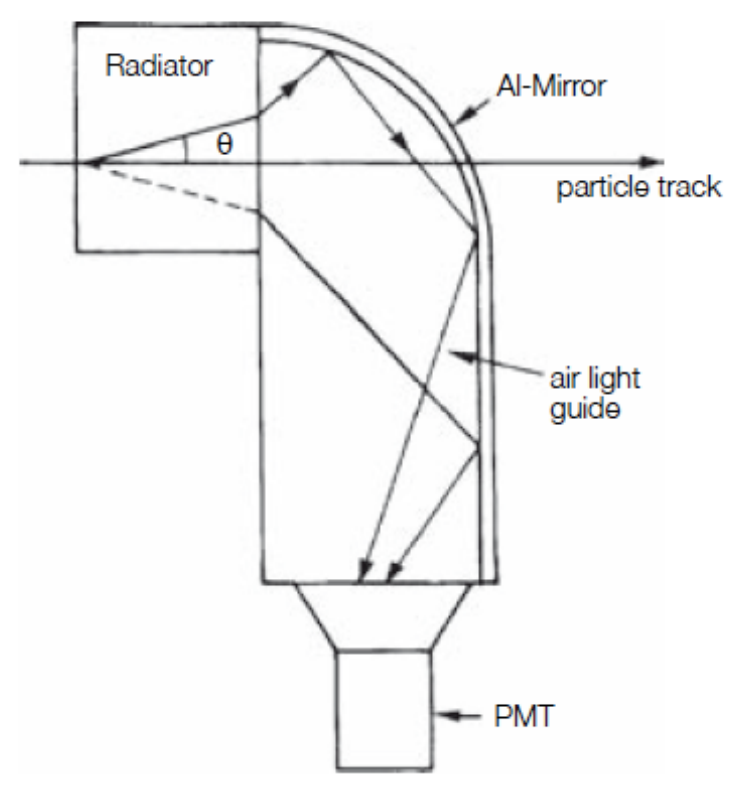
SCINTILLATORS+PMTS



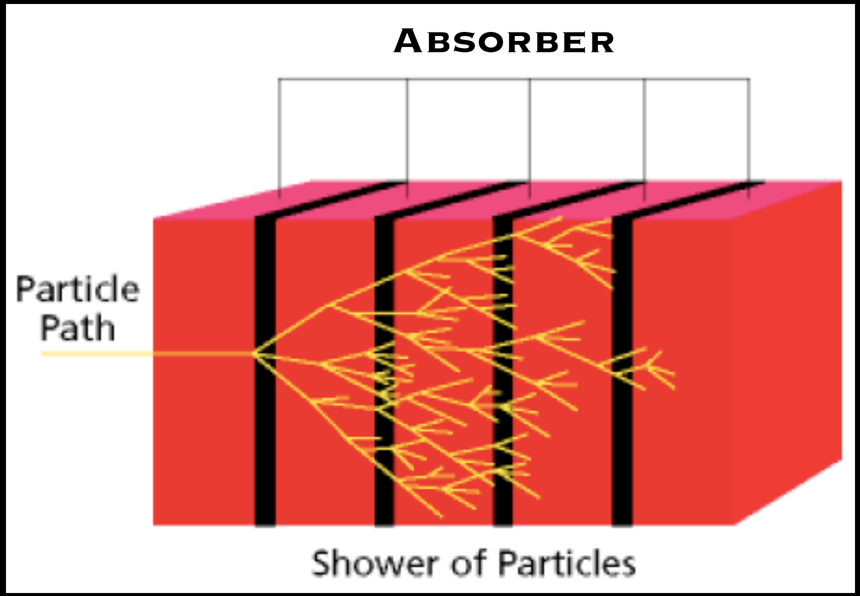
IONIZATION



TRANSITION RADIATION

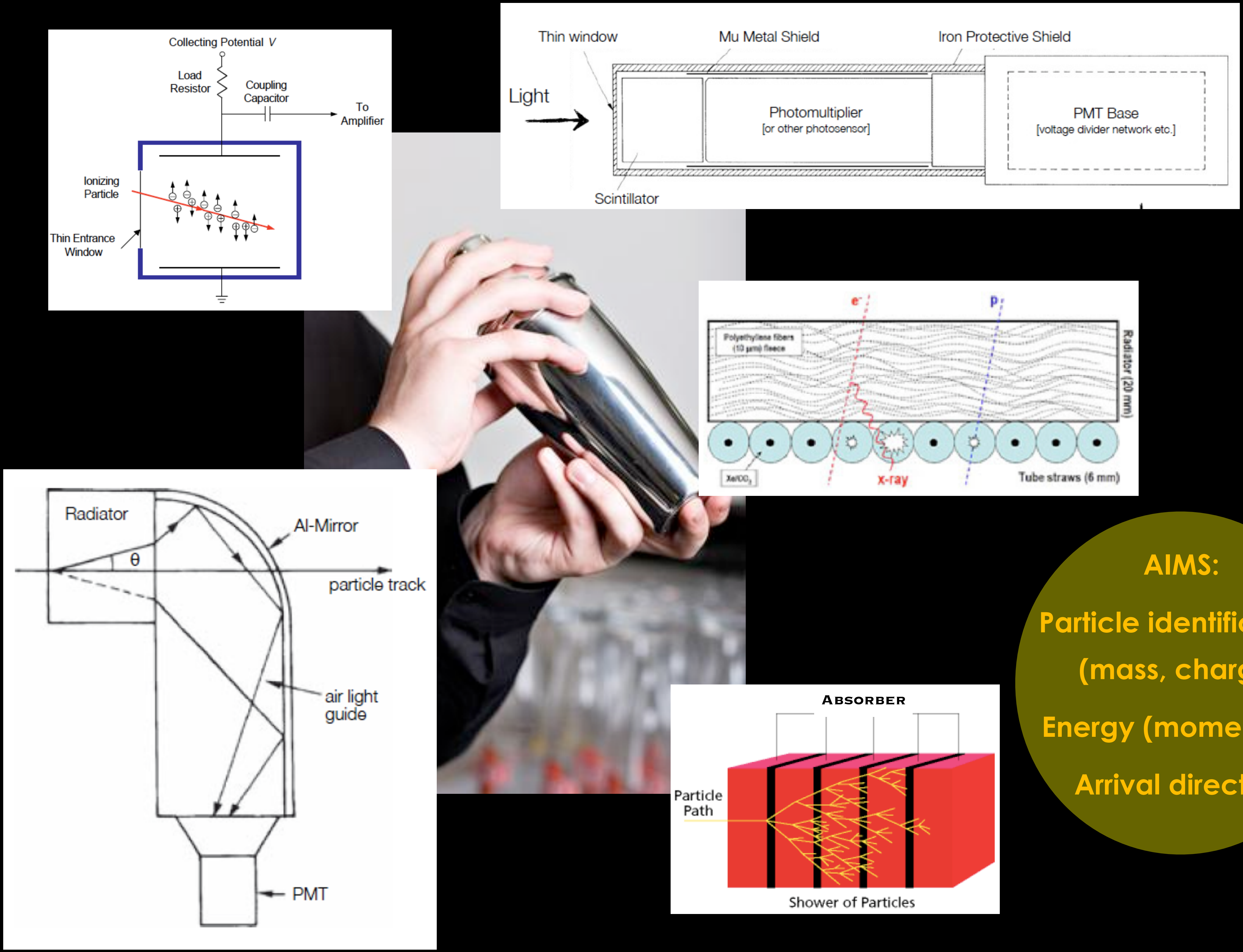


CHERENKOV



CALORIMETERS

...ASSEMBLED INTO COSMIC RAY TELESCOPES...



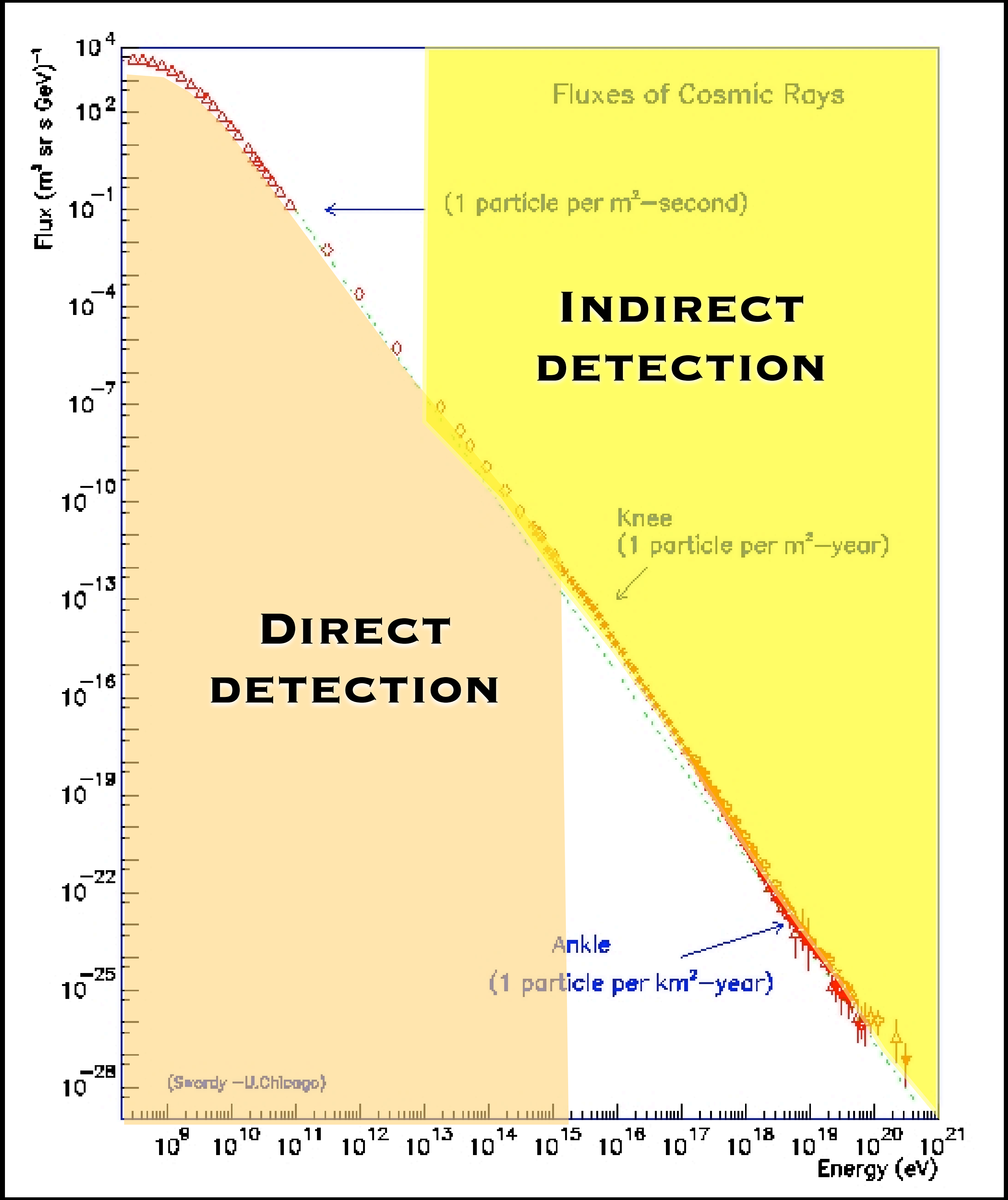
AIMS:

Particle identification (mass, charge)

Energy (momentum)

Arrival direction

...WHOSE LOCATION IS DICTATED BY THE CR FLUX



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

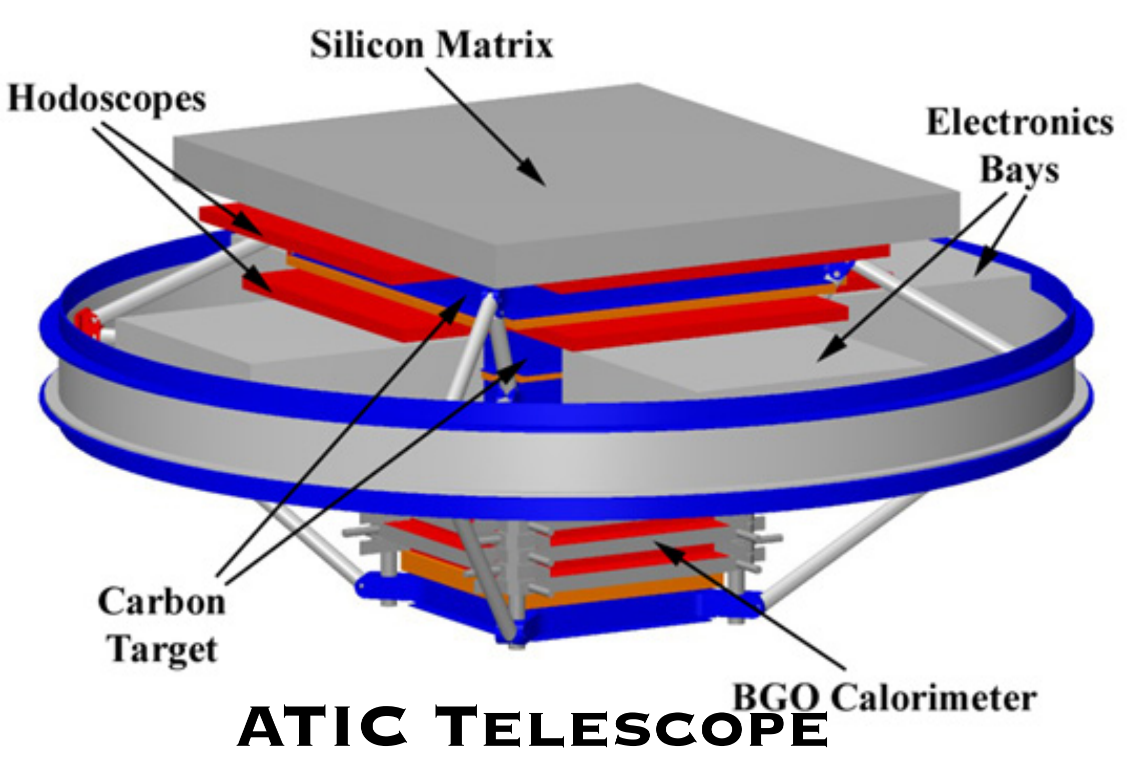
High energy cosmic rays: very rare (1/km^2 y), but “penetrating” up to ground (atmospheric air-showers).
Indirect detection: long-lived large arrays (ground level)

Large telescopes
Extensive Air showers arrays

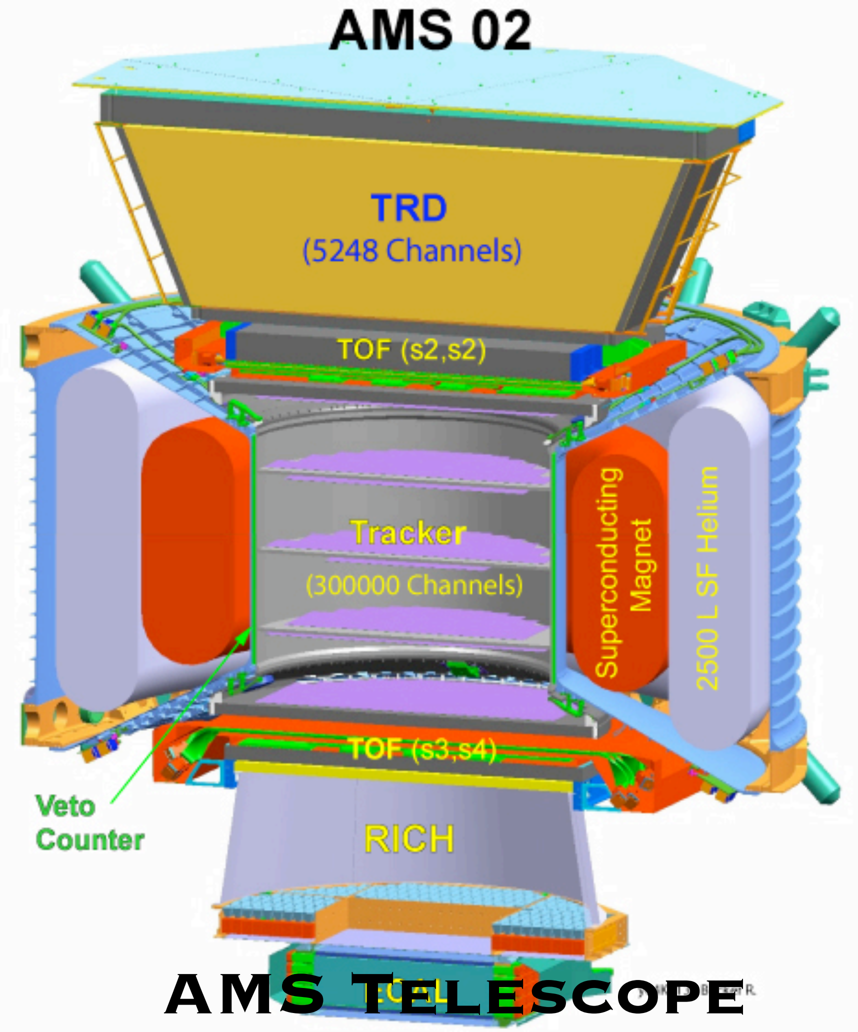
THEY CAN BE PLACED EITHER IN SPACE...


ATIC Balloon


AMS on the ISS



ATIC Telescope



AMS Telescope

...OR ON EARTH: TODAY'S LECTURE :-)

(The minuteness of the phenomena - The grandeur of the inferences)

Ia. Cosmic Rays: what do we know?

1b. Cosmic rays: how do we detect them?

(The delicacy of the observations - The adventurous excursions of the observers)

II. CR detection and detectors: the early days

III. Direct detection of CRs: balloon- and space-borne experiments

IV. Indirect detection of CRs: extensive-air showers (EAS) arrays

(The delicacy of the observations - The subtlety of the analysis)

V. From EAS observables to CR parameters

VI. An exemplary case: The Pierre Auger Observatory

The delicacy of the observations

The adventurous excursions of the observers

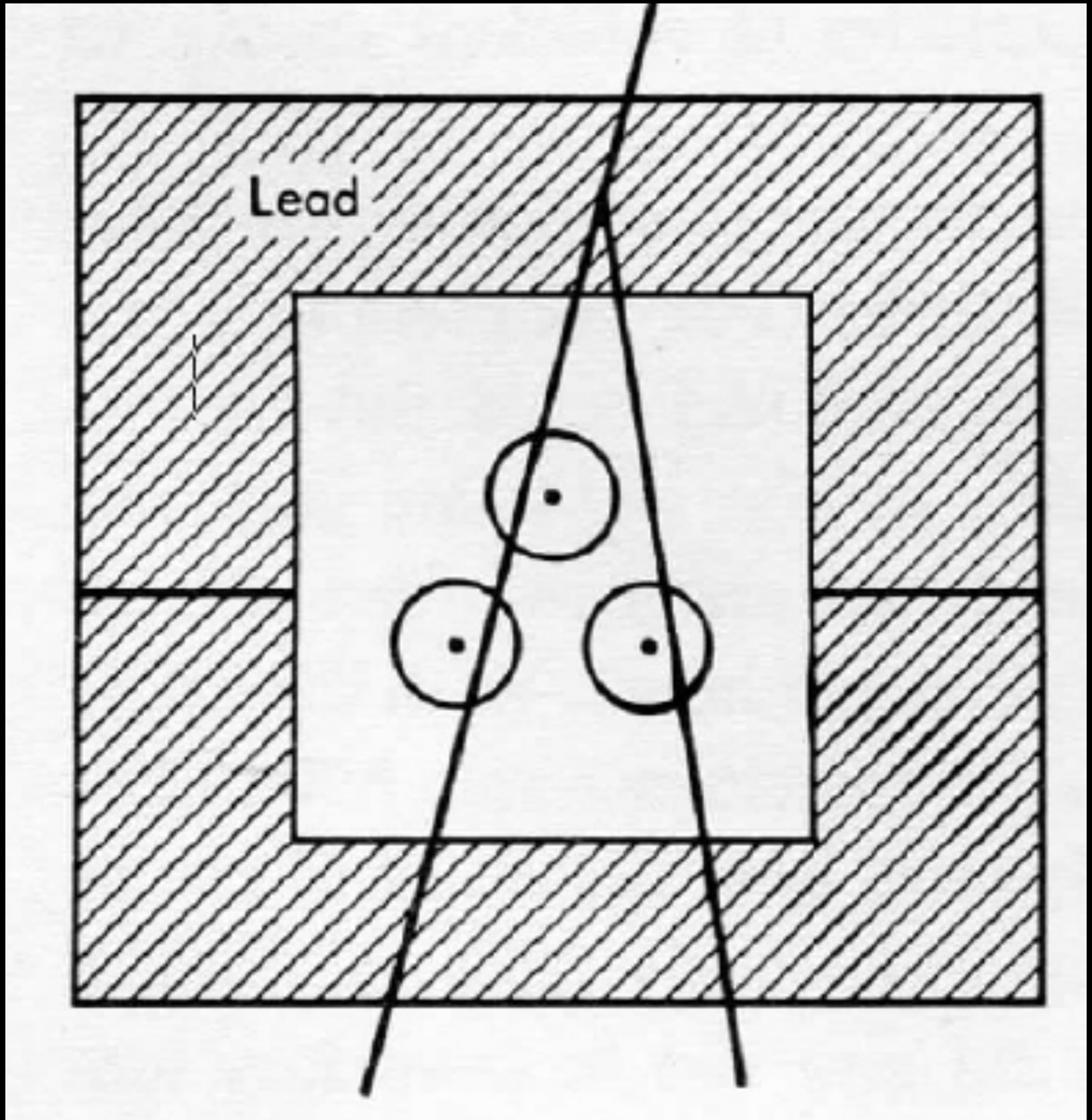
Indirect detection of cosmic rays: Extensive Air Showers (EAS) arrays

HOW DO WE DETECT RARE HIGH-ENERGY COSMIC RAYS?

As usual, a few steps back in time...

At the beginning of 1930s, Rossi already suspected the production of secondary particles by cosmic rays in matter, and saw the first hints of atmospheric showers

Rossi placed three G-M counters in a triangular array. The three counters could not be discharged by a single particle travelling in straight line. Yet, even when completely 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 ionizing particles emerging simultaneously from the lead. Coincidences were present also without lead: it later turned out that this effect was due to the production of secondary CRs in atmosphere



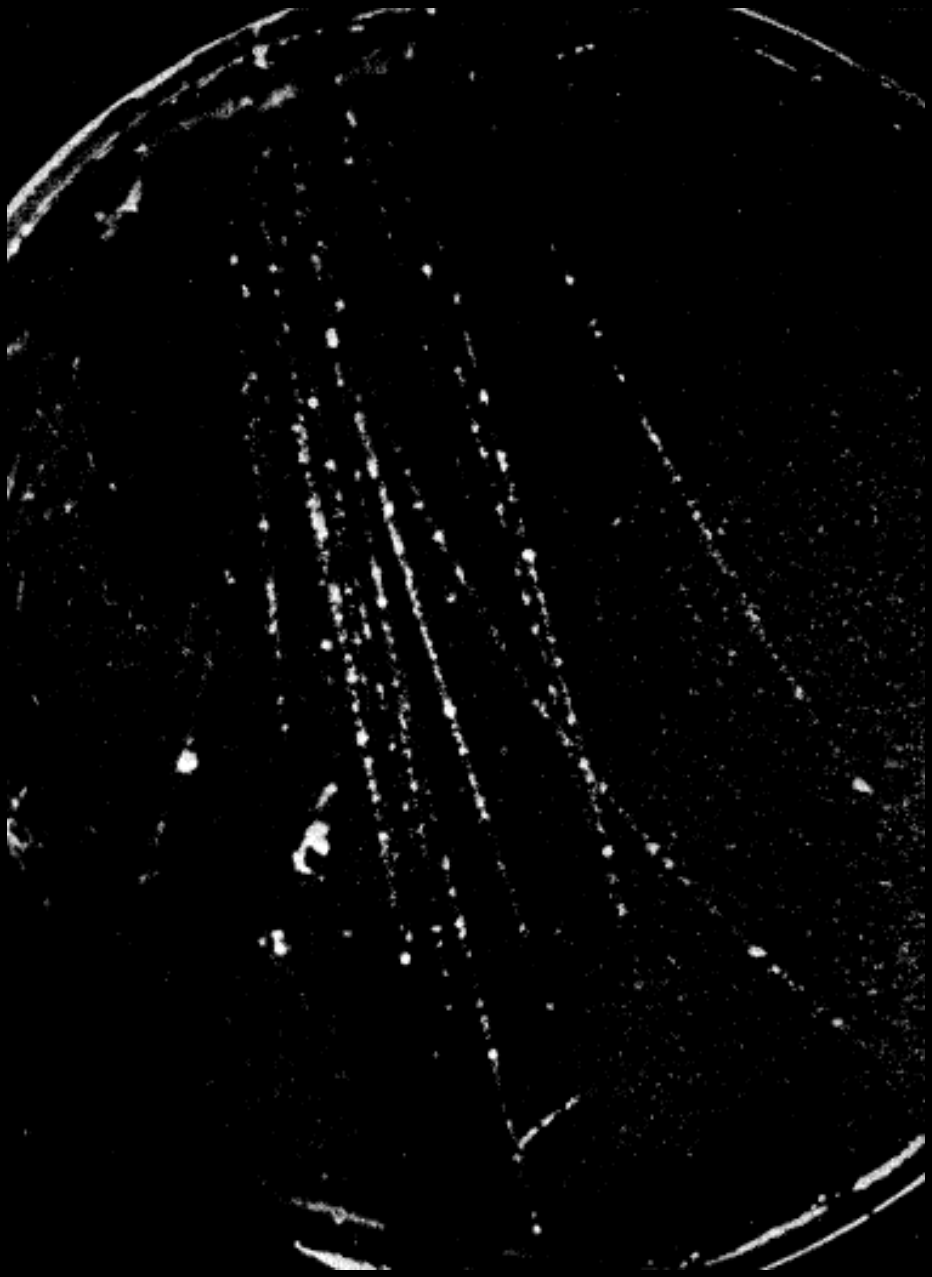
...REMINDER (FROM MONDAY)...

Counter-controlled cloud chamber

To be detected, particles must traverse the cloud chamber at some time during the expansion phase. If the particle enters the chamber too soon, the ions will diffuse away before the gas is cooled. If the particle enters too late, the gas will warm up before the ion trail is formed.

In many early experiments, cloud chambers were triggered randomly. It was a lucky accident when a cosmic ray happened to pass the chamber during the sensitive 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 somewhere near the chamber. The discovery of these "showers" marked another milestone in CR research.



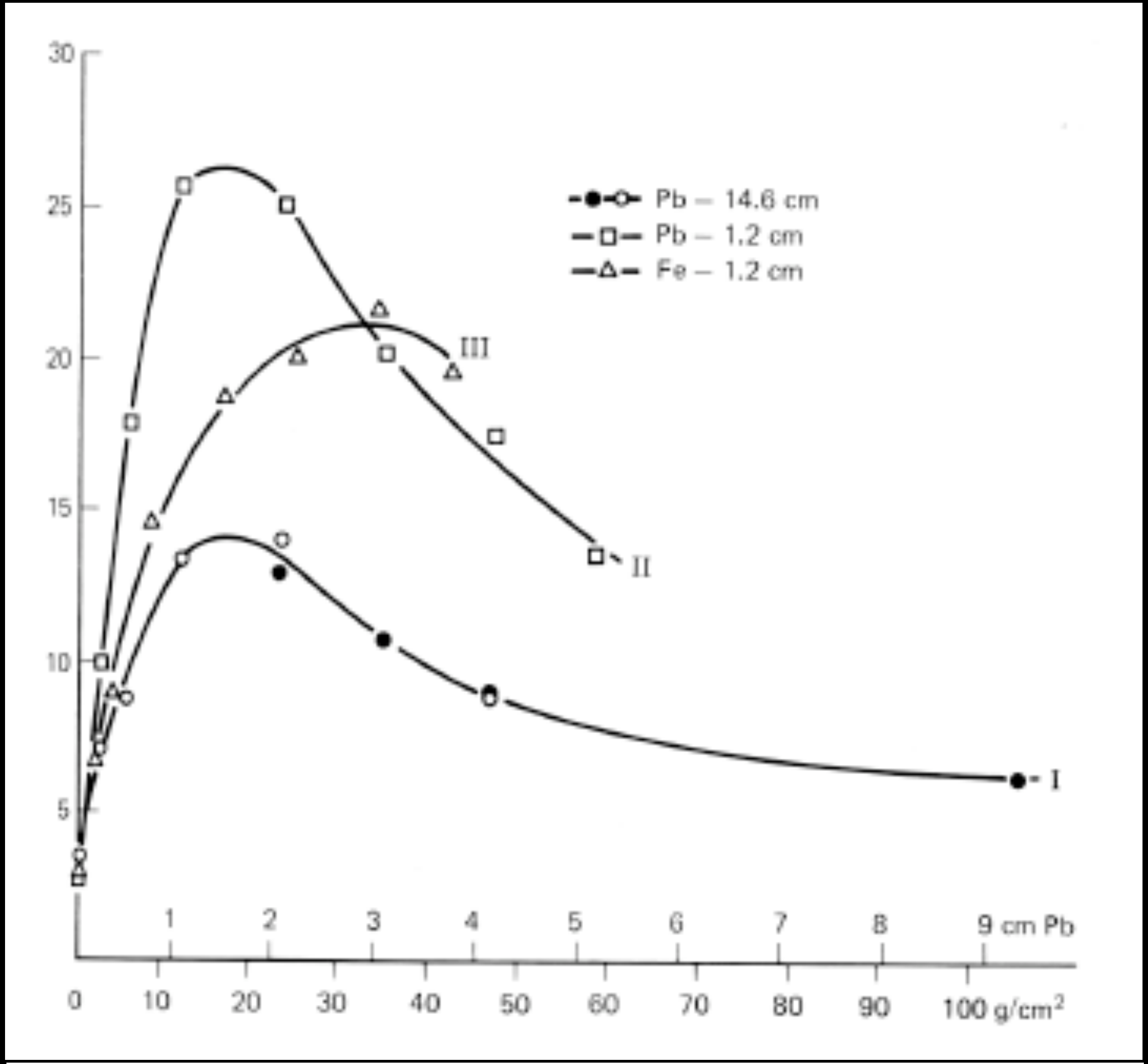
Sixteen separate tracks enter the chamber at the same time: they originate above the chamber. Positive and negative particles (differently curved by the magnet) are present (Blackett and Occhialini, 1933)

HOW DO WE DETECT RARE HIGH-ENERGY COSMIC RAYS?

As usual, a few steps back in time...

At the beginning of 1930s, Rossi already suspected the production of secondary particles by cosmic rays in matter, and saw the first hints of atmospheric showers

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



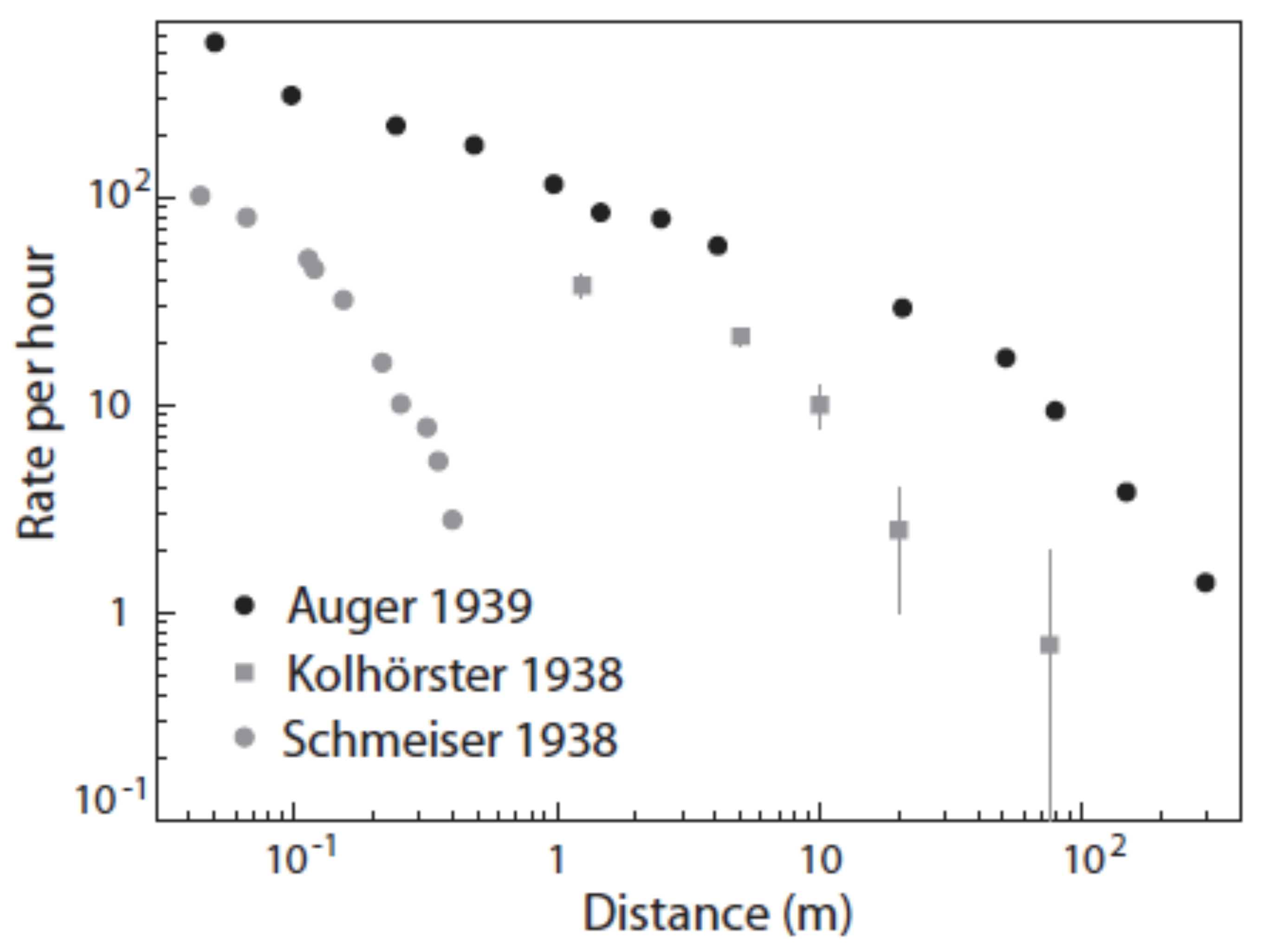
Rossi's transition curves. The curves I-III refer to measurements with Pb and Fe absorbers placed at distances above the counters

HOW DO WE DETECT RARE HIGH-ENERGY COSMIC RAYS?

As usual, a few steps back in time...

Schmeiser and Bothe pointed out that Rossi's transition curve implied the occurrence of showers in air and showed that particles in air showers had separations up to 40 cm. Independently, Kolhorster 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 (1938). 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.

HOW DO WE DETECT RARE HIGH-ENERGY COSMIC RAYS?

As usual, a few steps back in time...

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 arrays of Geiger counter allowed features of air showers to be understood relatively quickly. By the late 1930s it was known that air showers contained hadronic particles, muons and electrons and 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.

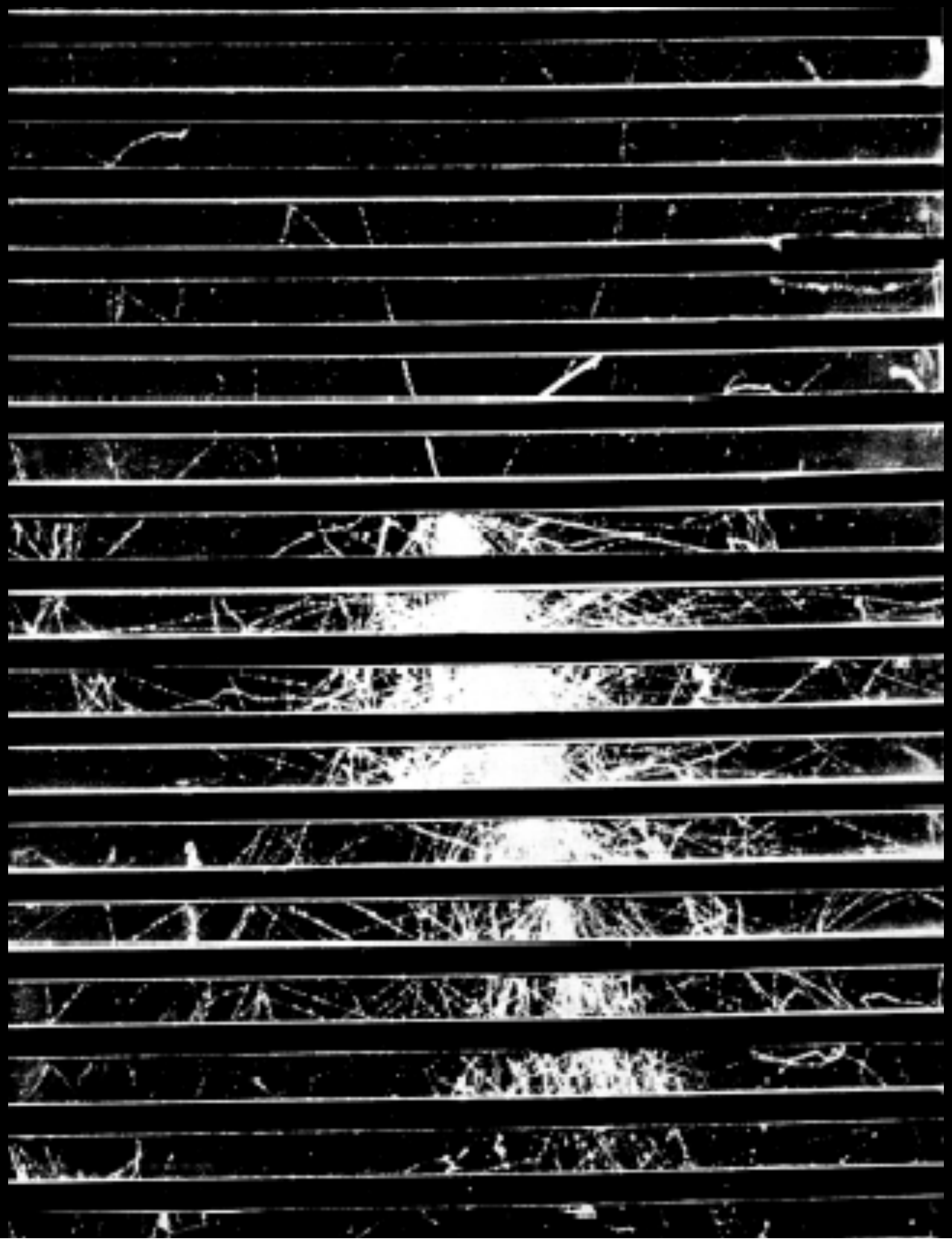
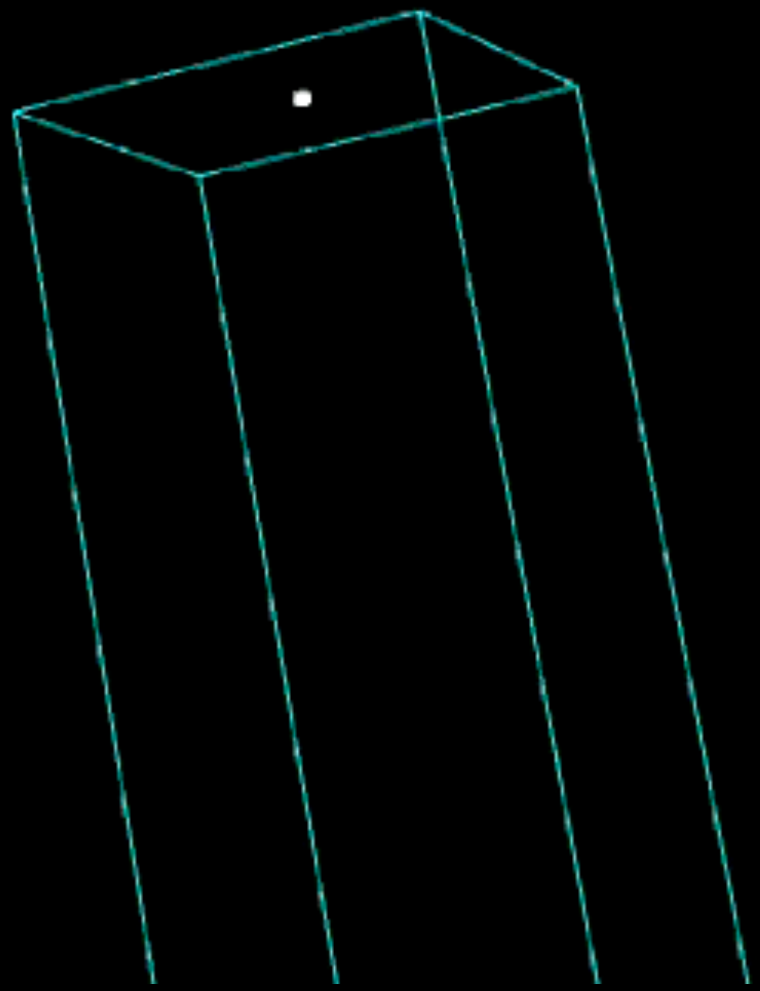


Image of a shower, as seen in a cloud chamber at 3027 m altitude, Fretter 1949 (primary proton of ≈ 10 GeV)

EXTENSIVE AIR SHOWERS

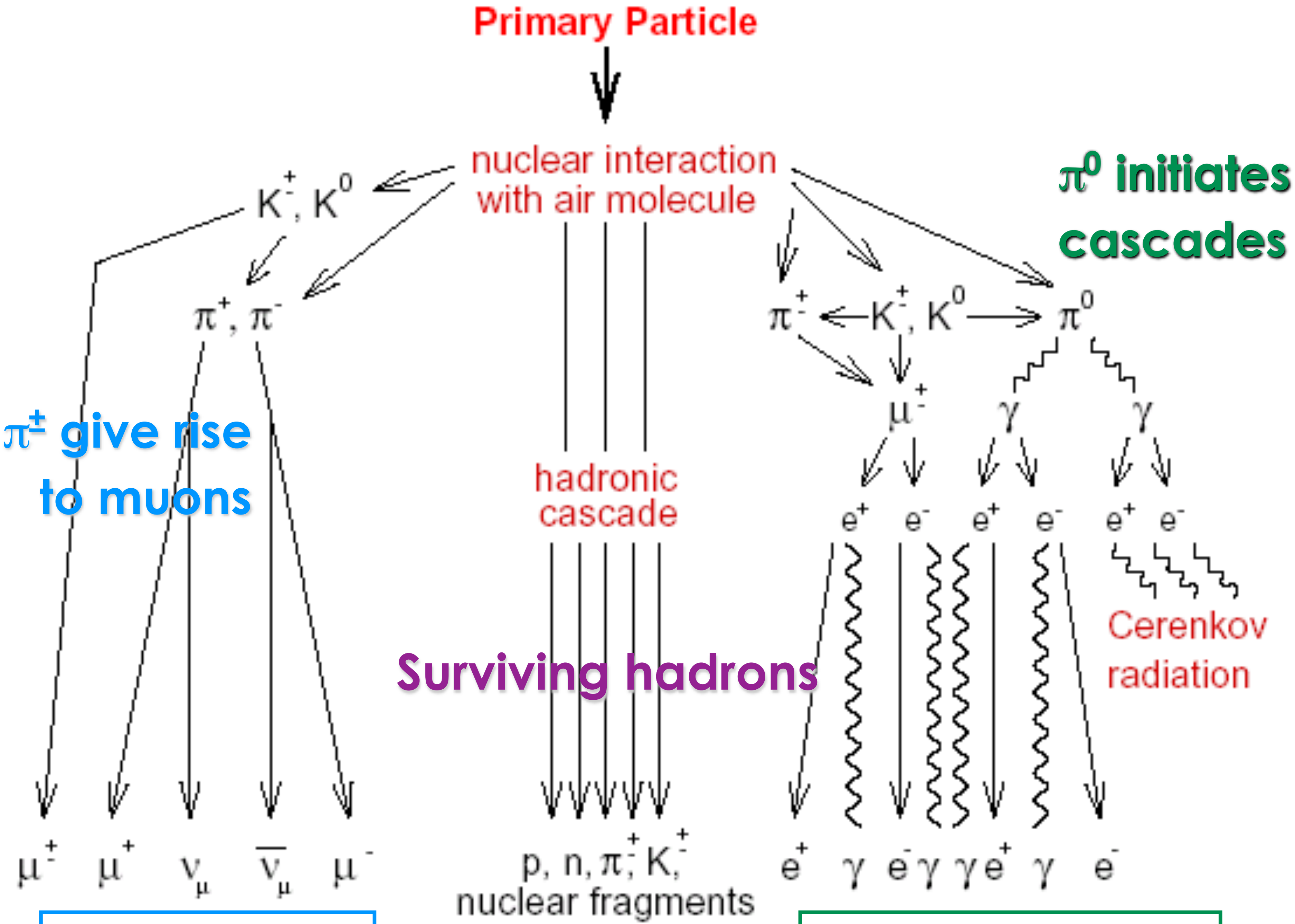


Credit Cosmos Group, Univ. Chicago

There is no way of studying the high-energy region of the cosmic-ray spectrum other than by observing air showers. The atmosphere is used as an inhomogeneous calorimeter. Extensive air showers can be detected over an extended area. Large effective area of detection compensates the smallness of flux

EXTENSIVE AIR SHOWERS

A high energy primary particle, upon entering the atmosphere, initiates a chain of nuclear interactions



π^0 initiates e.m. cascades

$\pi^\pm$ give rise to muons

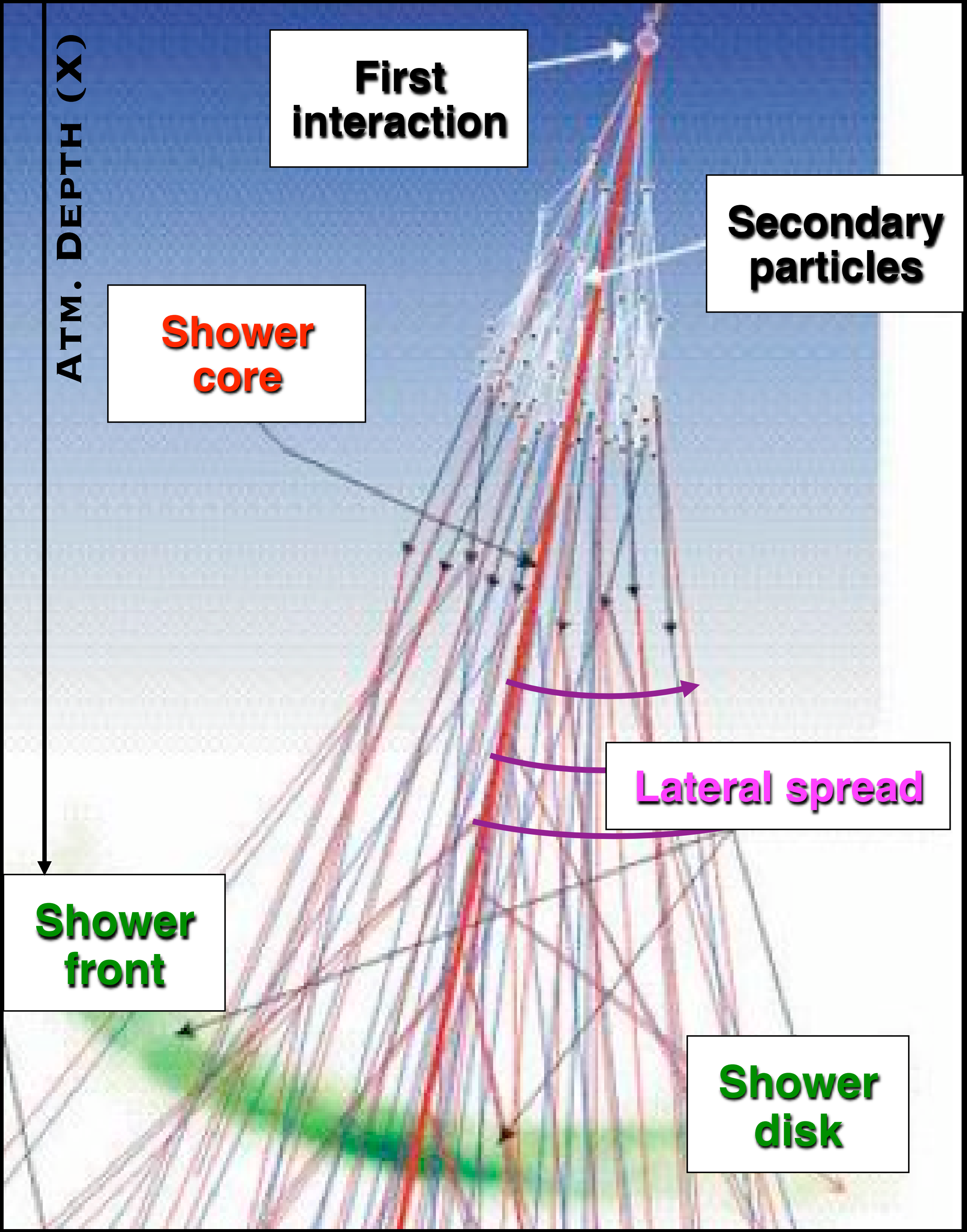
Surviving hadrons

MUONIC COMPONENT

HADRONIC COMPONENT

ELECTROMAGNETIC COMPONENT

EAS LATERAL DEVELOPMENT

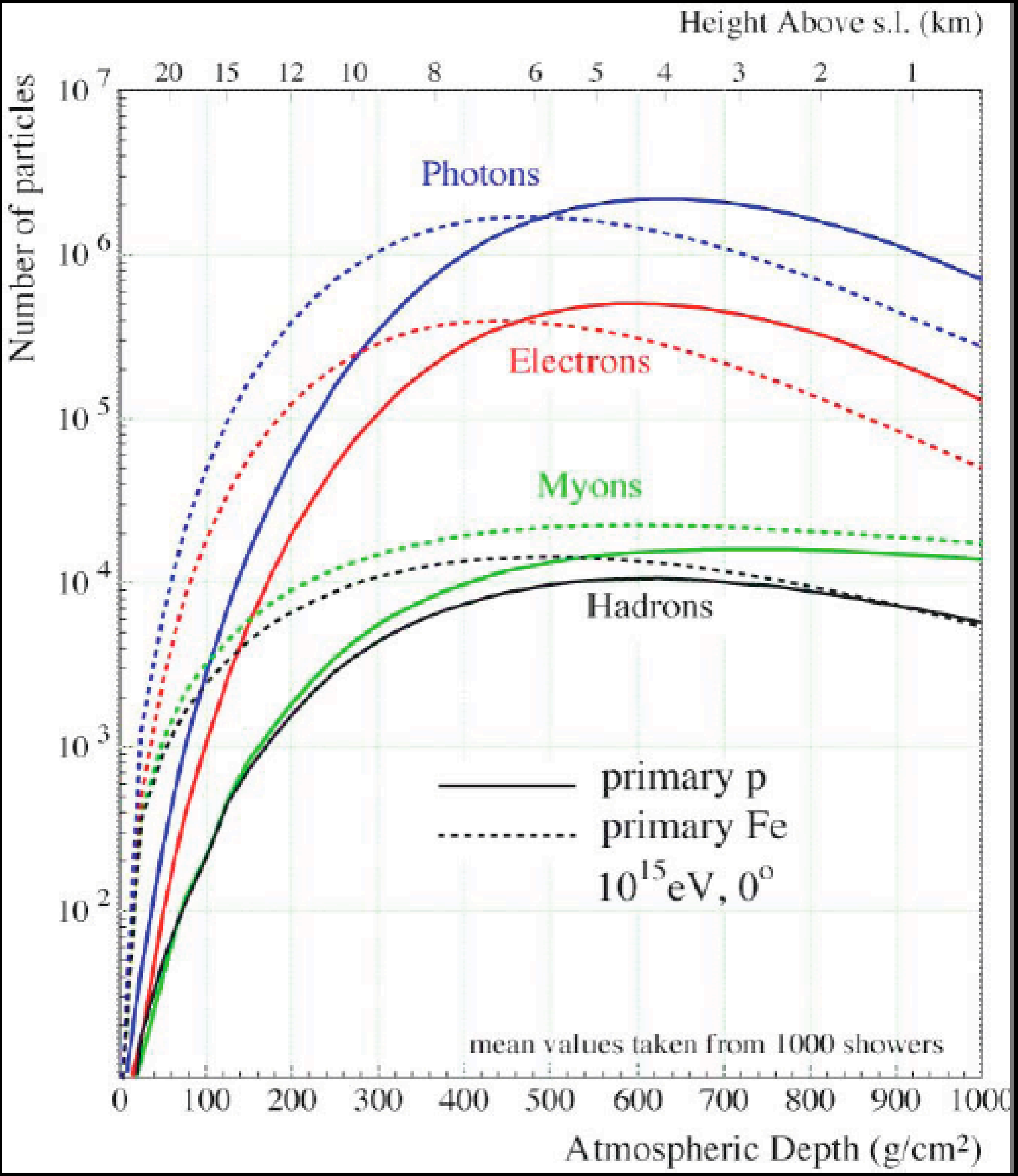


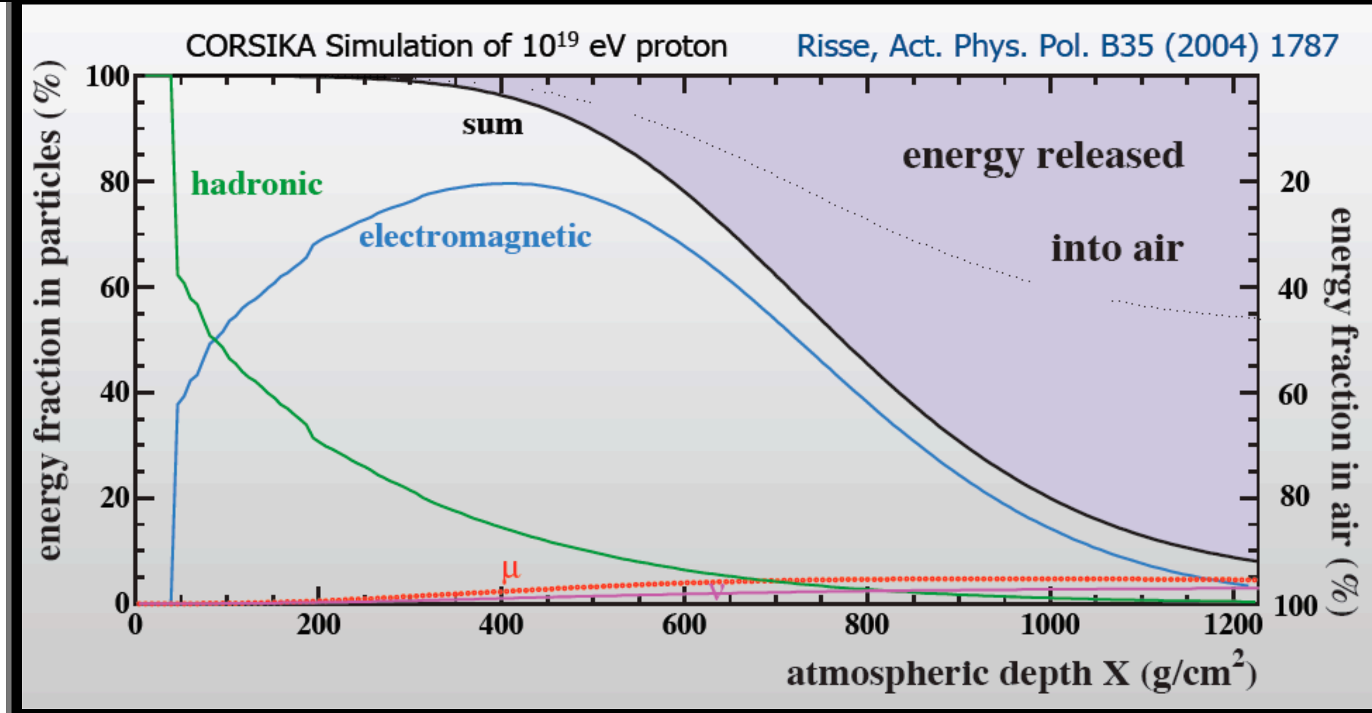
Secondary particles form a narrow “bundle”: the shower core

Initial transverse momentum and multiple scattering in atmosphere causes particles to spread out laterally from the core -> lateral distribution: particle density is greatest at 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

EAS LONGITUDINAL DEVELOPMENT

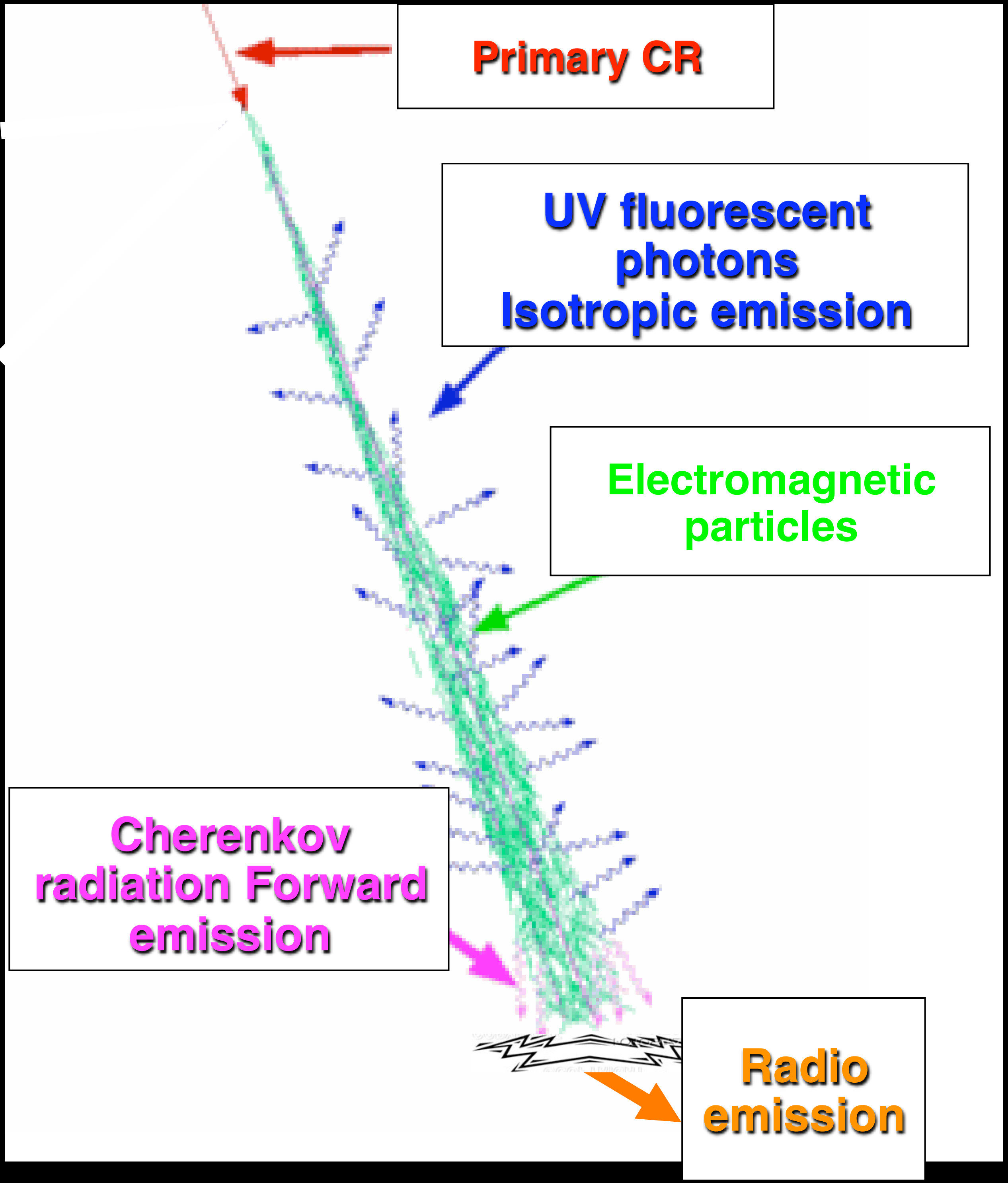




90% of the primary energy of the cosmic ray is dissipated in the atmosphere during shower development

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

RADIATION FROM SHOWER DEVELOPMENT



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 the gas molecules (mostly nitrogen). Some of this excitation energy is emitted in the form of isotropic visible and UV radiation.

Radio emission: Air shower electrons and positrons are deflected in the Earth's magnetic field. Because of their relativistic velocities, they emit synchrotron radiation, beamed very sharply downwards, at radio frequencies below 100 MHz. Many sparkles together produce a bright radio flash

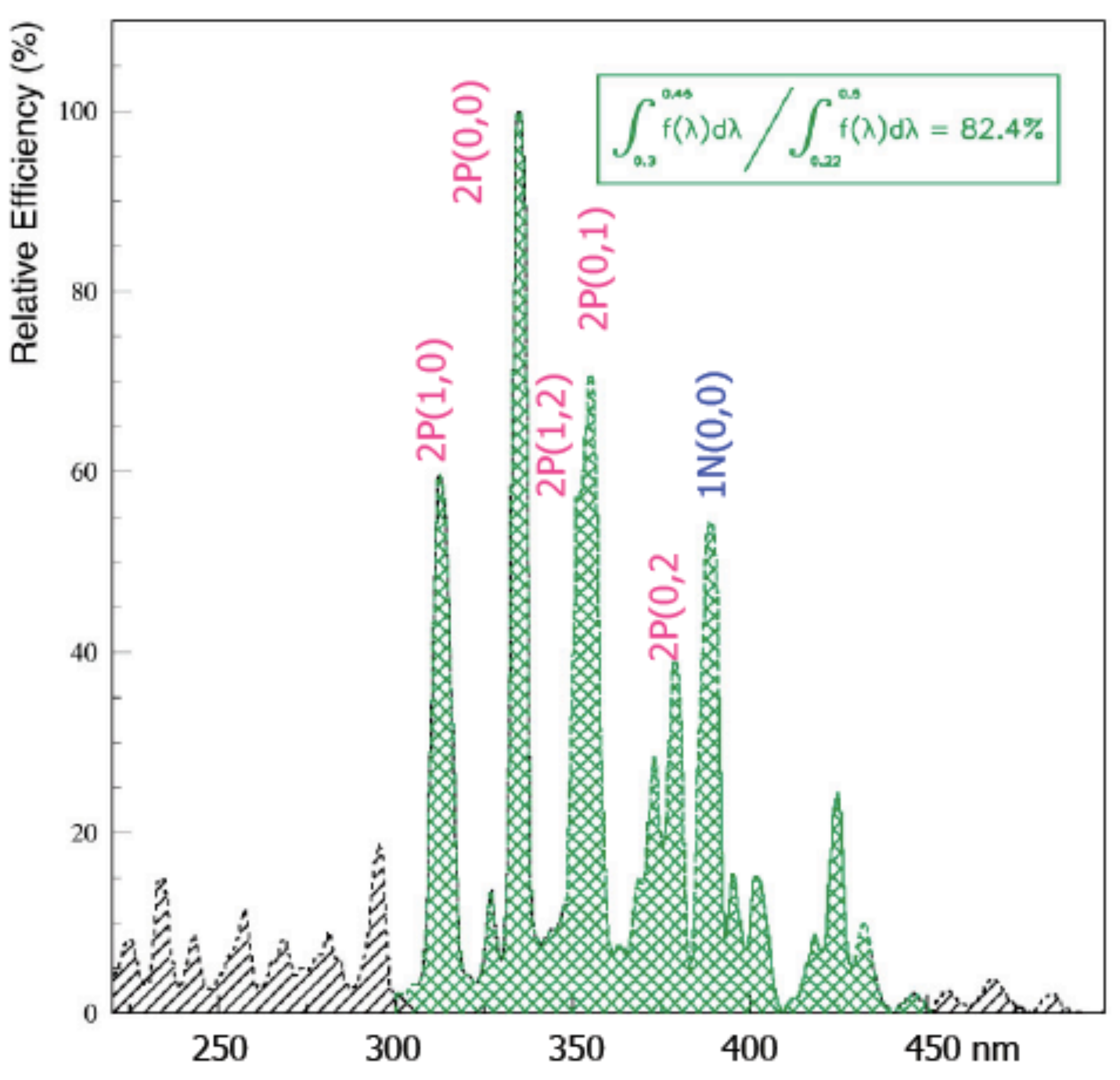
FLUORESCENCE RADIATION

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

The fluorescence yield between 300 and 400 nm is approx. 4 photons per shower particle per metre of track in the atmosphere.

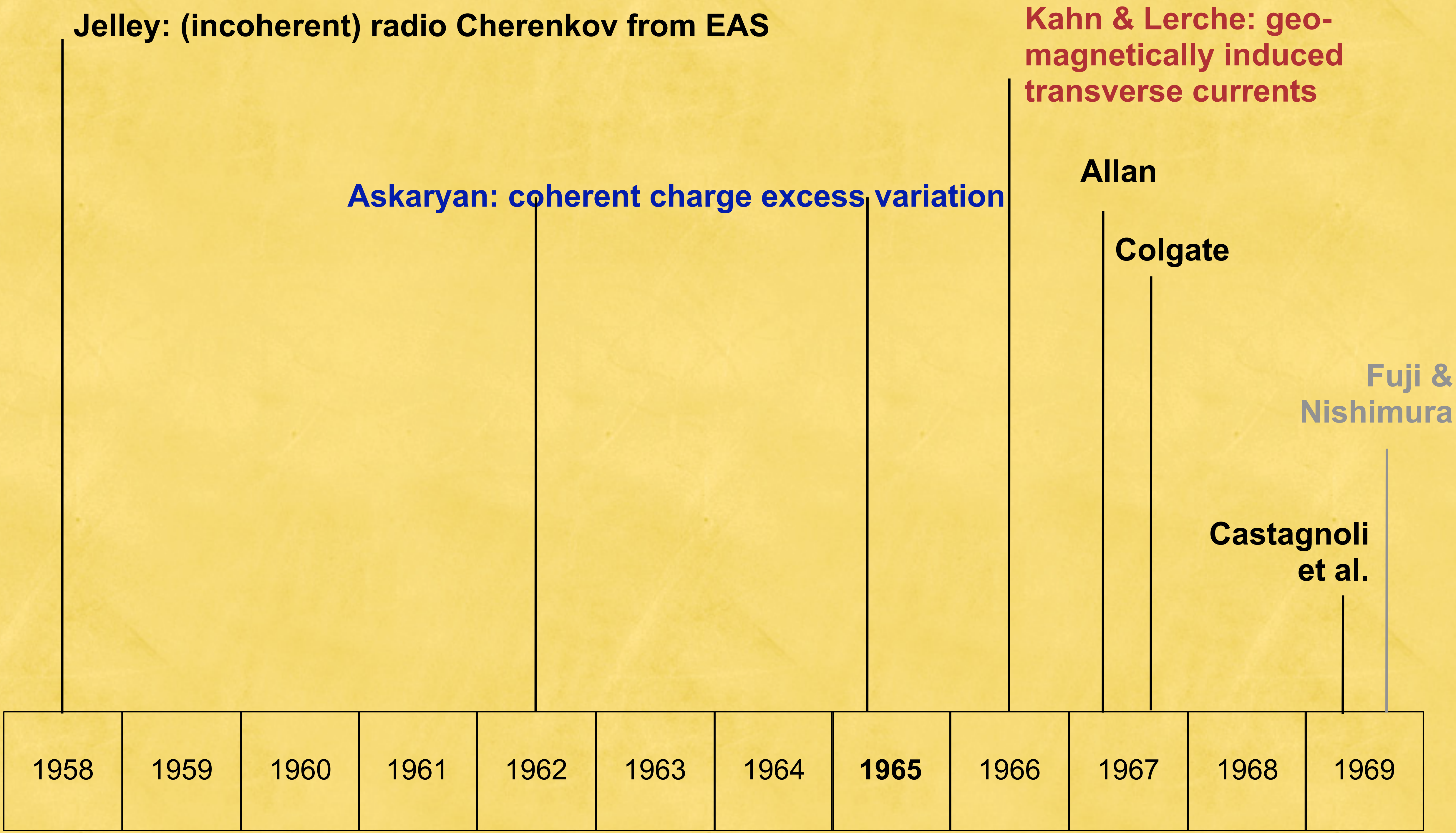
This radiation (commonly called fluorescence light) is emitted isotropically. It can travel several kilometers throught the atmosphere and detected by an optical telescope, i.e., mirrors and PMTs, typically, equipped with fast response electronics (fluorescence detectors).

Only 0.5% of dE/dX goes into fluorescence. This technique can be exploited only at very high energies (above 10^{17} eV). Like the Cherenkov one, it has a low duty cycle (cloudless, moonless nights)



Fluorescence spectrum

RADIO EMISSION FROM EAS



Jelley: (incoherent) radio Cherenkov from EAS

Askaryan: coherent charge excess variation

Kahn & Lerche: geo-magnetically induced transverse currents

Allan

Colgate

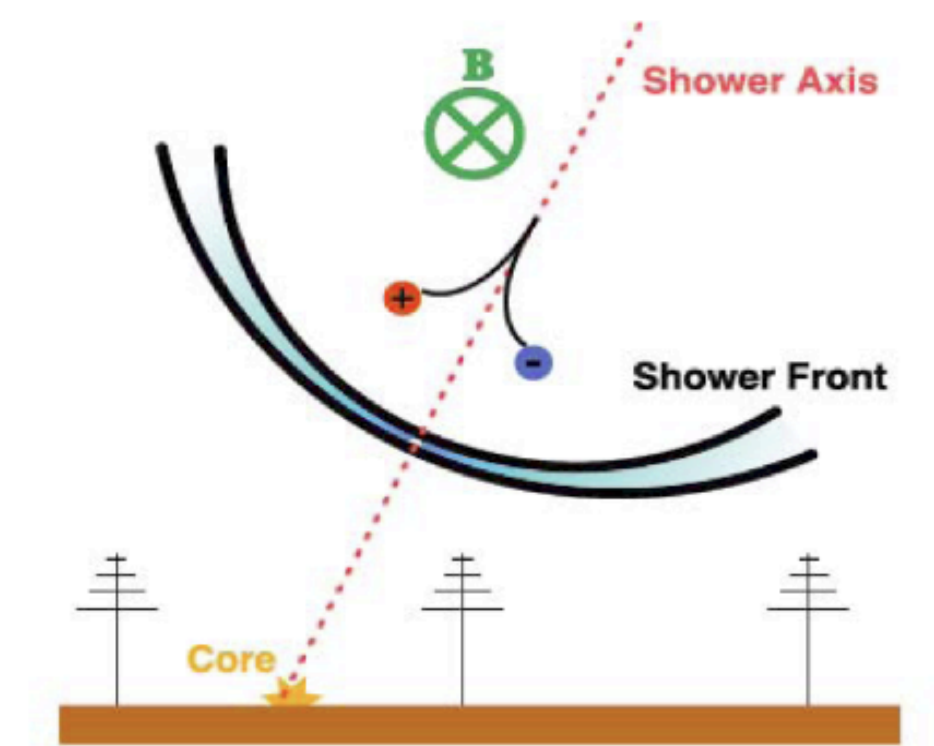
Fuji & Nishimura

Castagnoli et al.

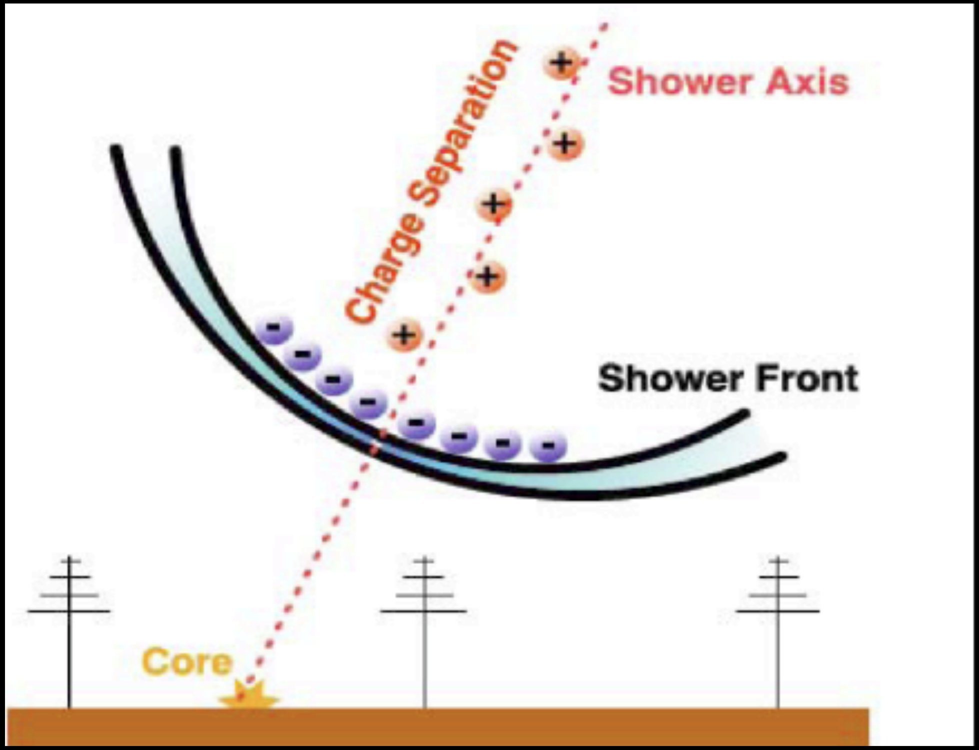
1958 1959 1960 1961 1962 1963 1964 **1965** 1966 1967 1968 1969

Jelley et al.: first experimental detection (1965)

RADIO EMISSION FROM EAS



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)

MICROWAVE EMISSION FROM EAS

Molecular Bremsstrahlung Emission

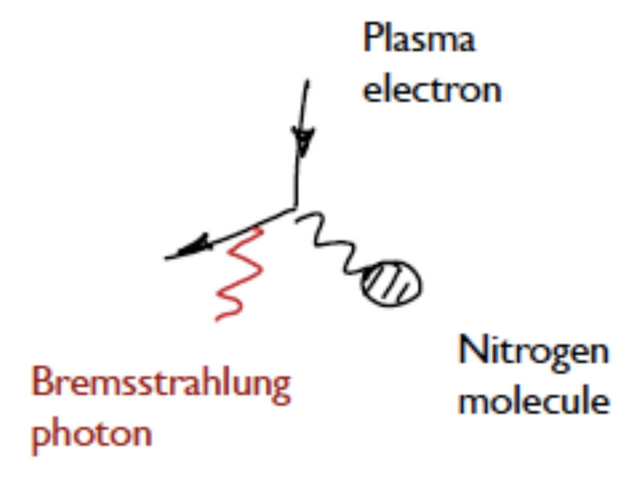
EAS particles dissipate energy through ionization. This produces a plasma with T(electrons) ~ 10^4-10^5K

The low energy tail of free electrons produce Bremsstrahlung emission in microwave regime from scattering interactions with neutral air molecules.

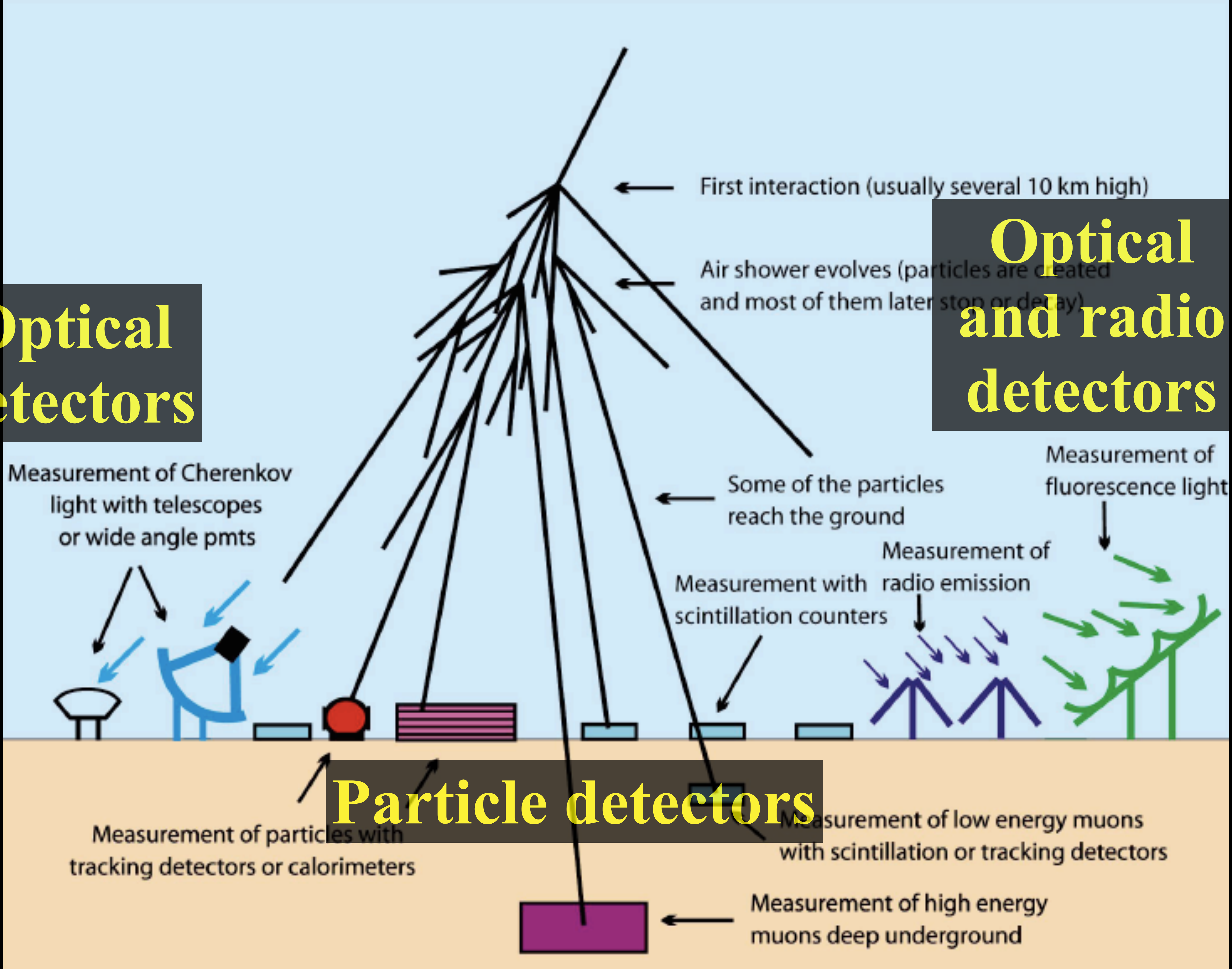
The emission is unpolarized and isotropic.

Potential exists for an FD-like detection technique capable of measuring the shower's longitudinal development with nearly 100% duty cycle, limited atmospheric effects and low cost (ability to cover large area)

Observed in laboratory. First observation from showers too (2011)



DIFFERENT DETECTORS FOR DIFFERENT EAS OBSERVABLES



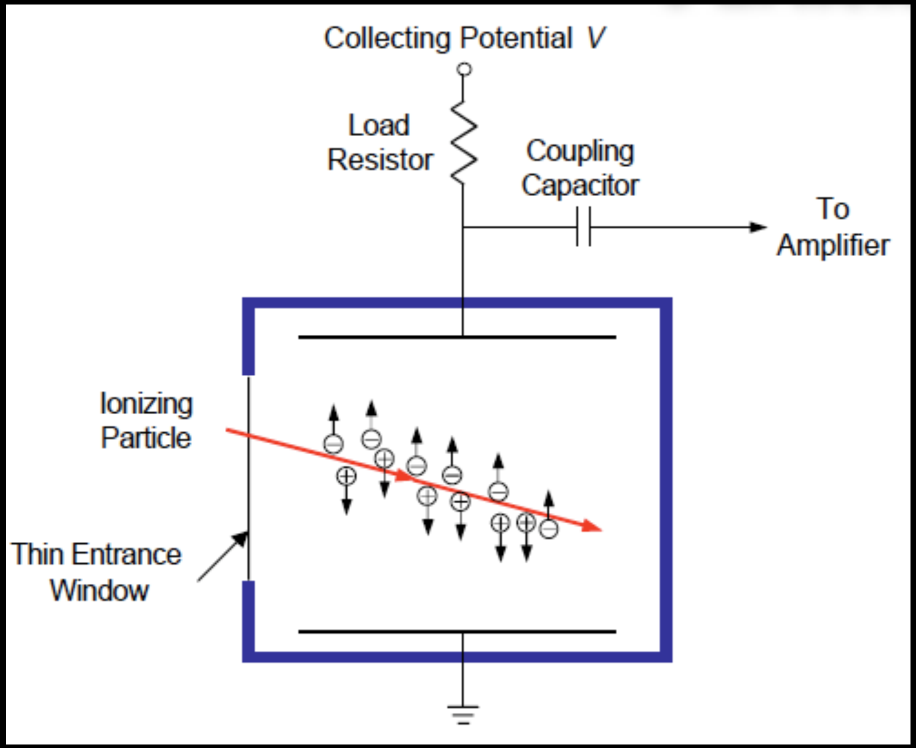
Optical detectors

Optical and radio detectors

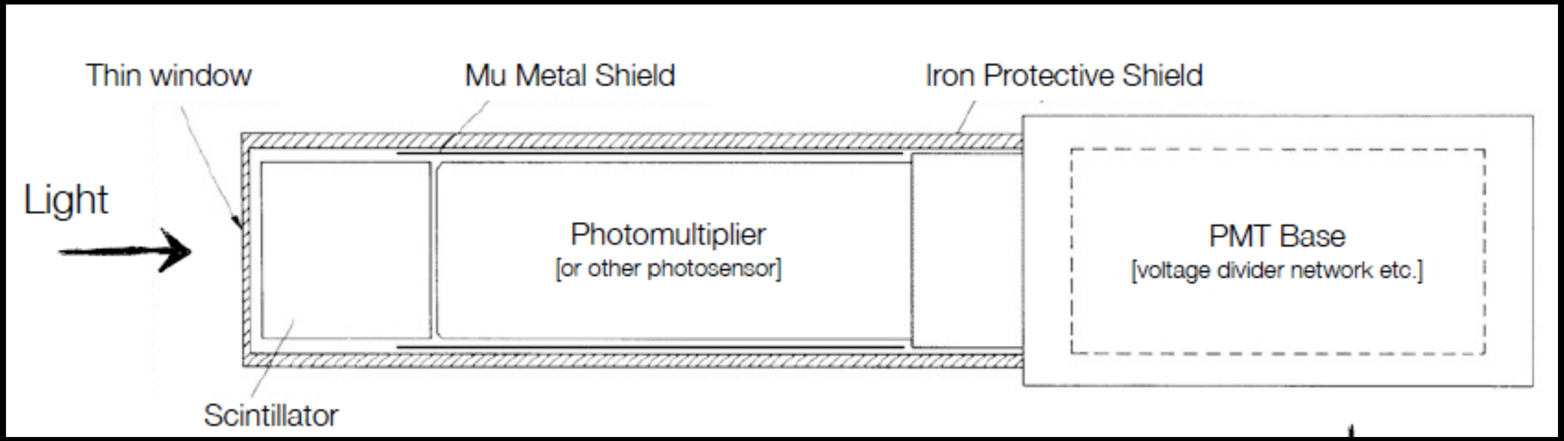
Particle detectors

DIFFERENT DETECTORS FOR DIFFERENT EAS OBSERVABLES

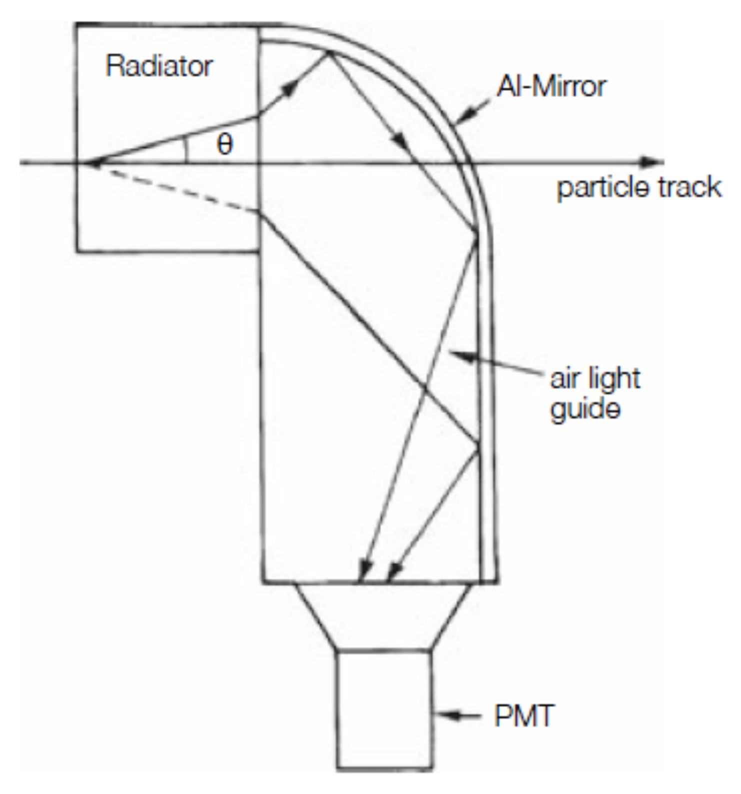
Particle detectors (100% duty cycle)



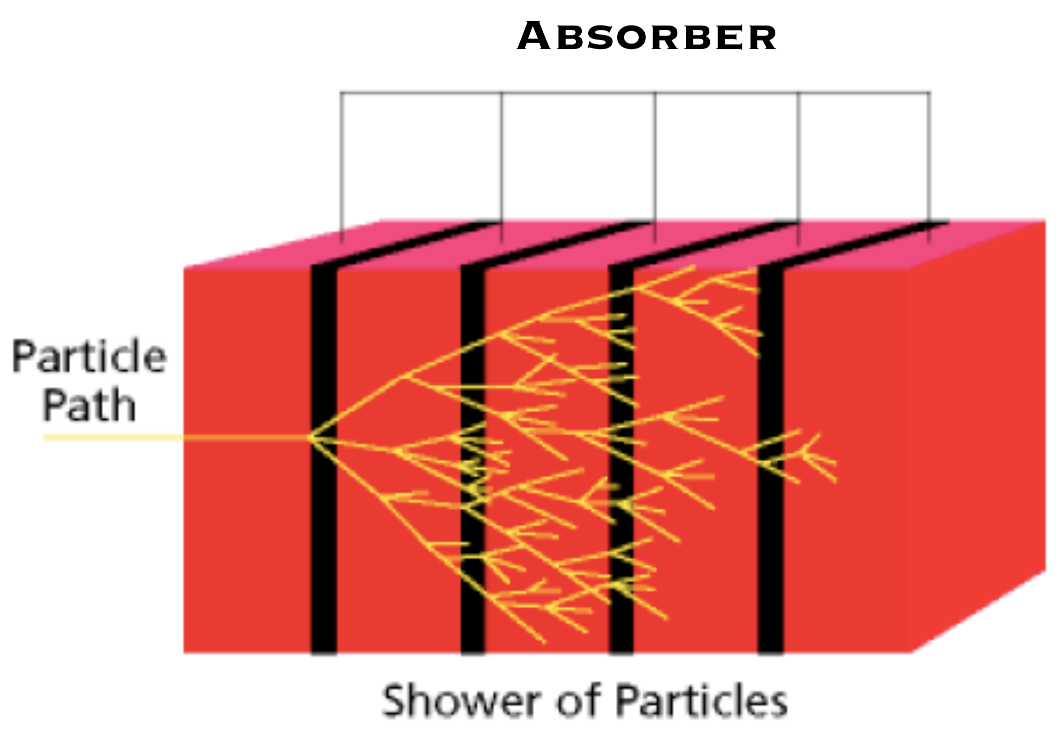
Ionization



Scintillators+PMTs



Cherenkov



Calorimeters

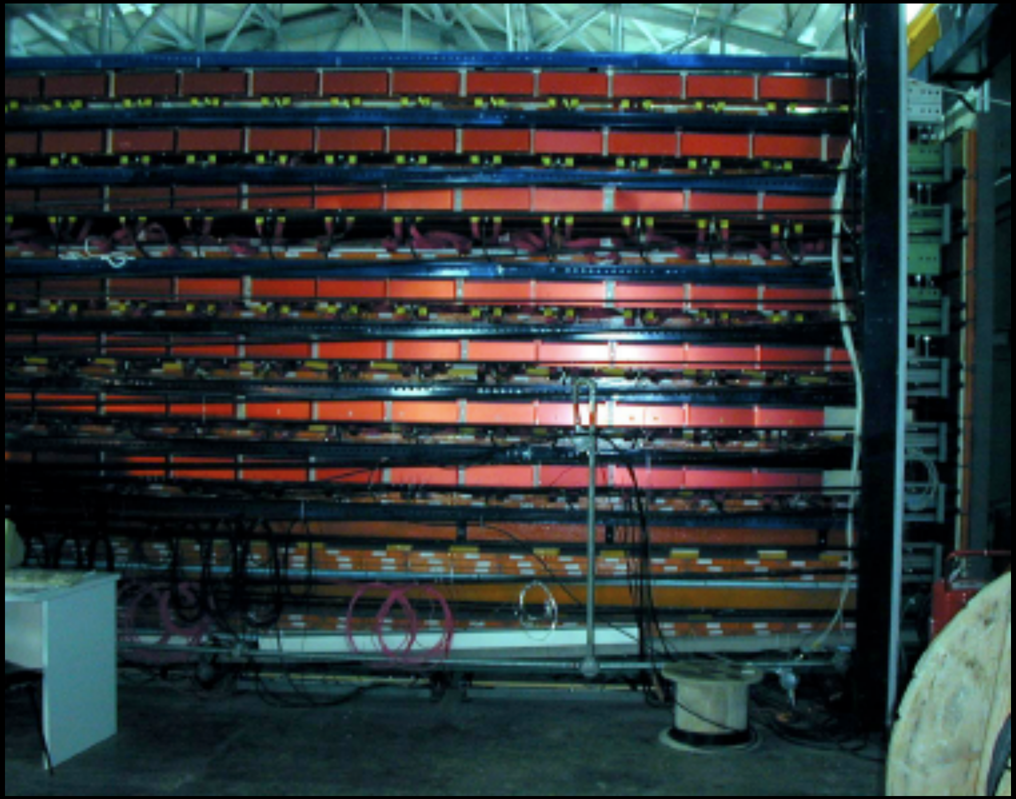
DIFFERENT DETECTORS FOR DIFFERENT EAS OBSERVABLES

Particle detectors (100% duty cycle)

Ionization (RPC)
For electrons/photons and muons

Scintillators+PMTs
(for electrons/photons and muons)

Cherenkov (in water)
For electrons/photons and muons



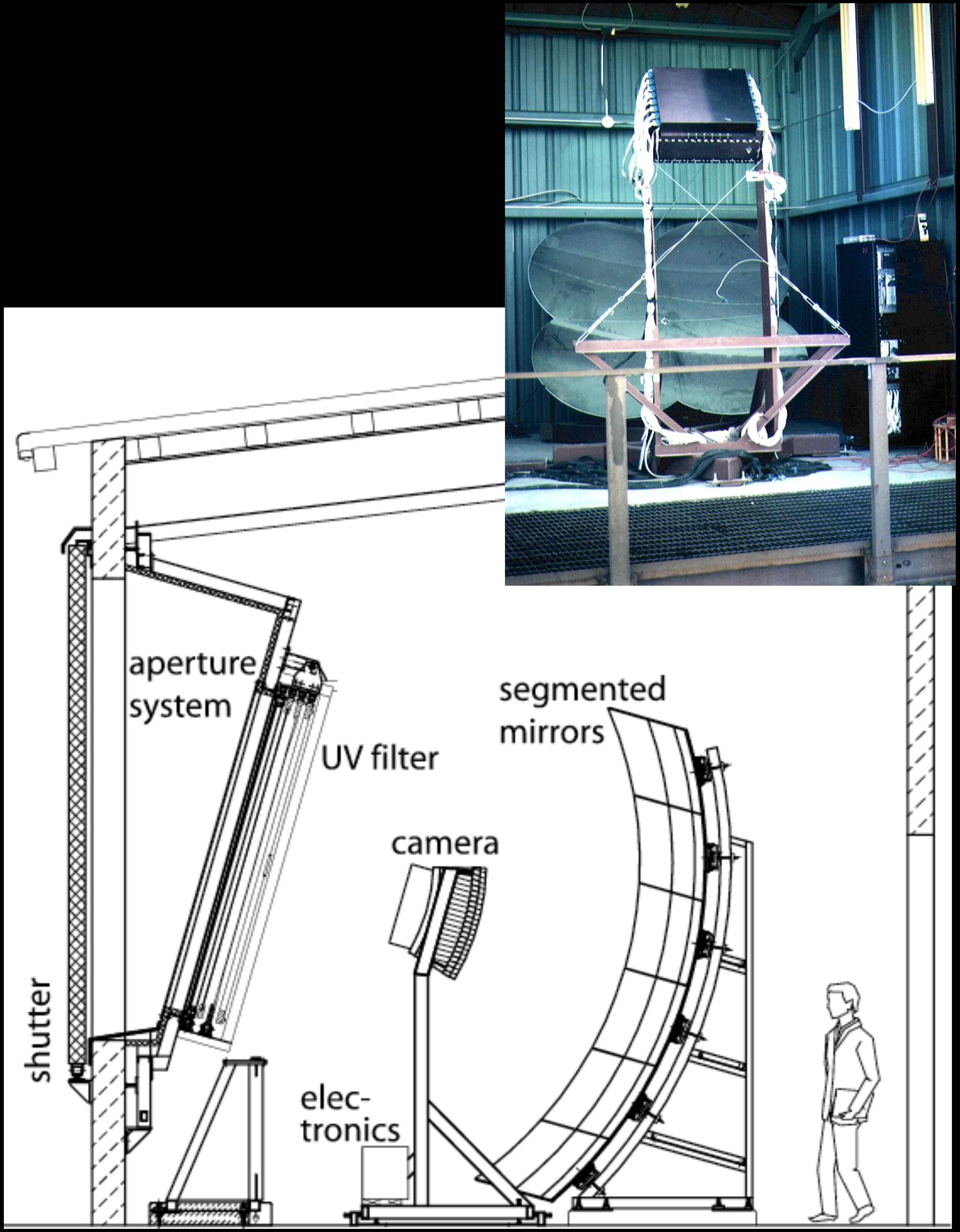
Calorimeters (for muons & hadrons)

DIFFERENT DETECTORS FOR DIFFERENT EAS OBSERVABLES

Optical detectors (10% duty cycle)

The light from Cherenkov or fluorescence emission is collected by a mirror or a lens and imaged on to a camera made by photosensors (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 triggered PMT records the trigger time and the intensity of the signal.

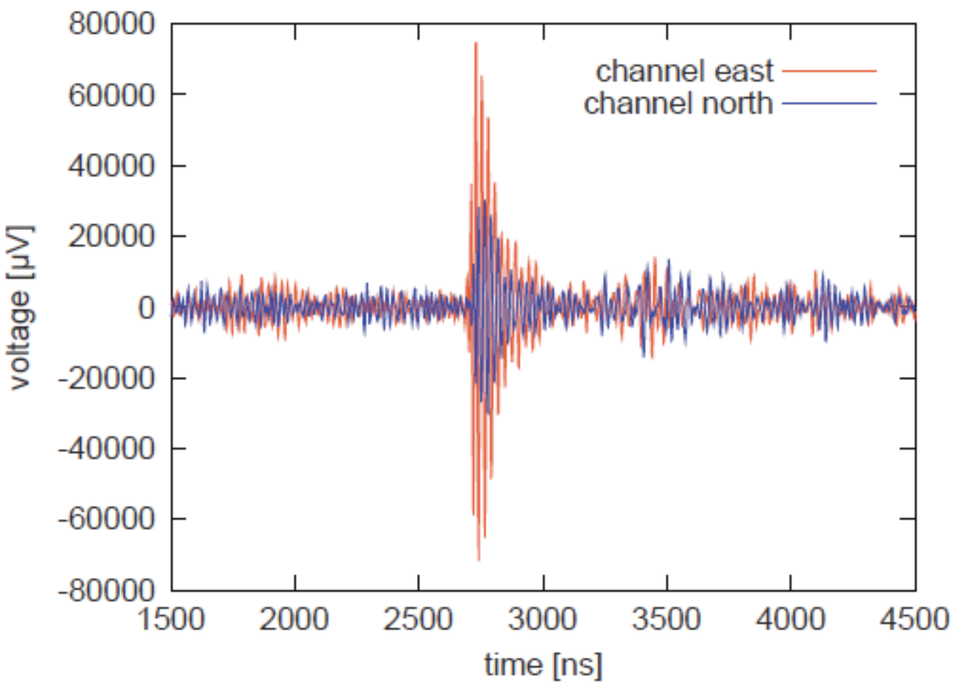


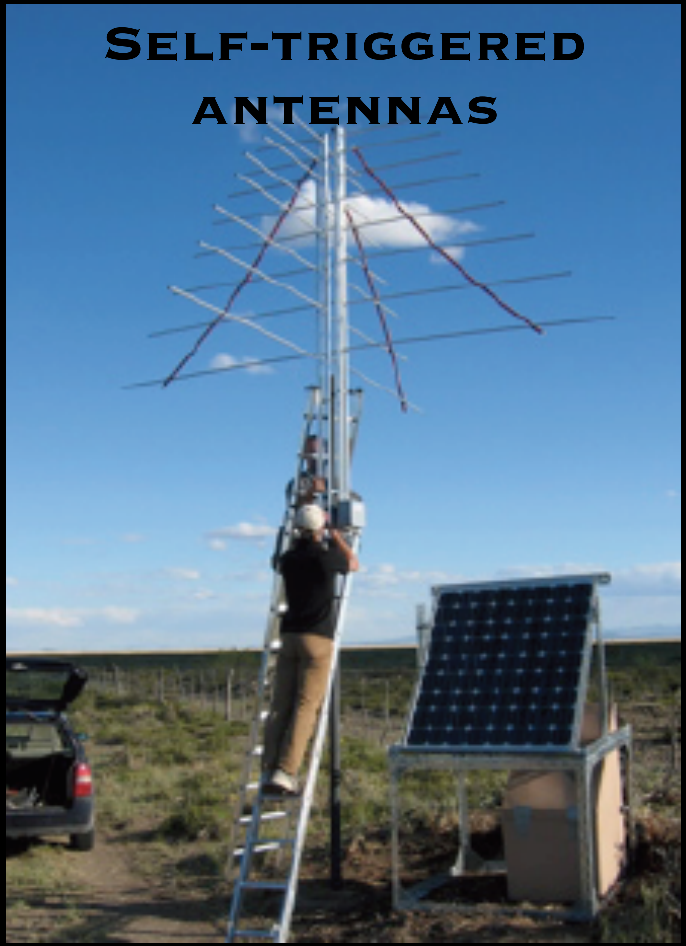
DIFFERENT DETECTORS FOR DIFFERENT EAS OBSERVABLES

Radio detectors (100% duty cycle)

The measurement of the radio signal requires a detection device, i.e, 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 polarisations (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)

Giant showers: spacing ≈ 1000 m adequate

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

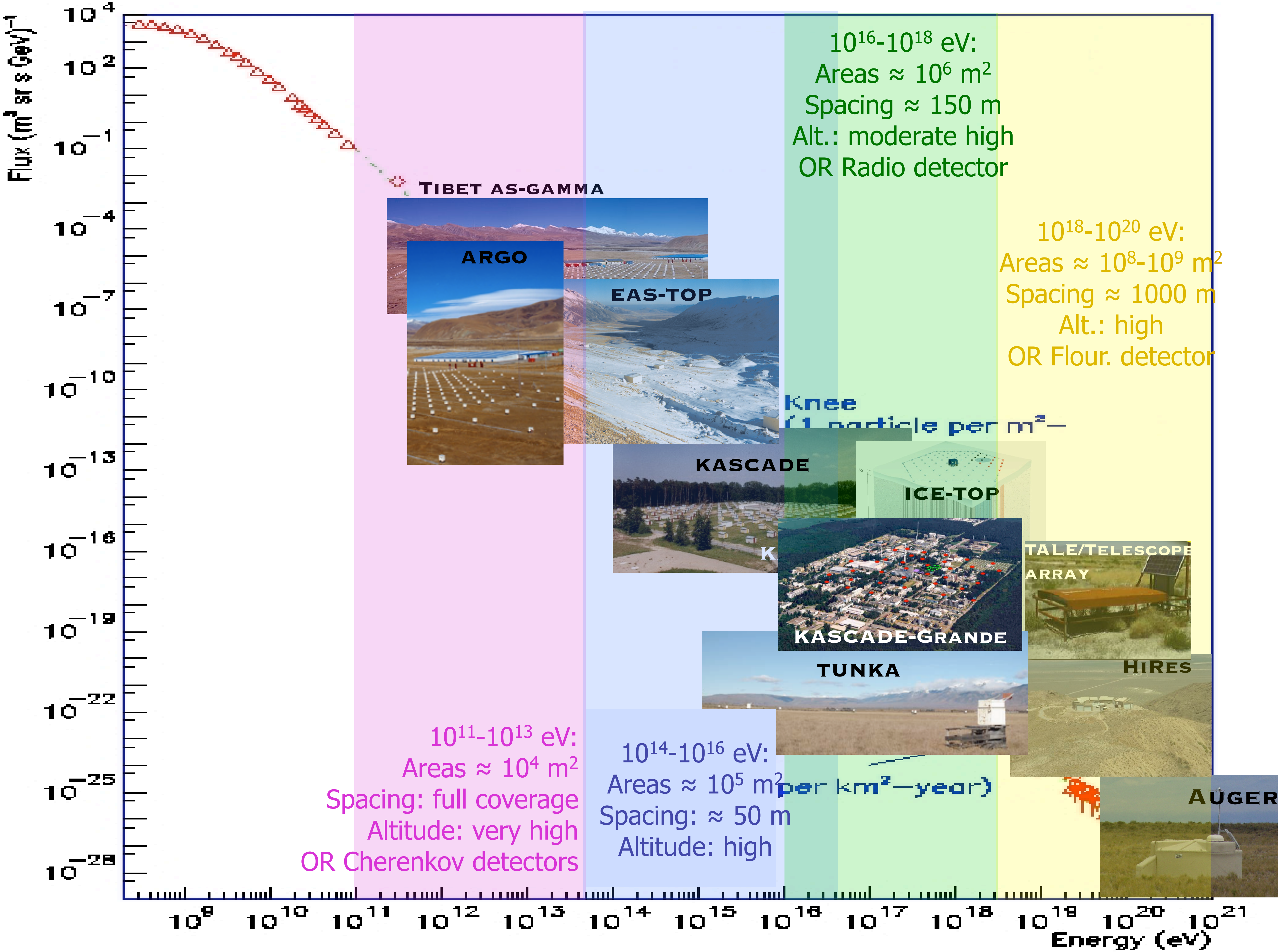
RECENT AND CURRENT EAS PARTICLE DETECTORS

AGASA [Akeno Giant Air Shower Array]
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)
EAS-TOP (Italy, above the Gran Sasso laboratory, 1990-2000)
Haverah Park (Leeds University, operational until 1993)
GRAND [Gamma Ray Astrophysics at Notre Dame] (an array of tracking detectors)
GRAPES, India
HEGRA (operational 1988-2002)
ICETOP (South Pole, over ICECUBE)
KASCADE [KArlsruhe Shower Core and Array DEtector].
KASCADE-GRANDE.
MILAGRO (Water Cherenkov experiment near Los Alamos).
Mt. Norikura Observatory in Japan
Pierre Auger Observatory.
SPASE 2 [South Pole Air Shower Array]
SUGAR [Sydney University Giant Air shower Recorder] (operational from 1968 to 1979)
Telescope Array
Tian-Shan Mountain Cosmic Ray Station
Tibet AS-gamma experiment: scintillation counter array
Yakutsk (Russia)

RECENT AND CURRENT “LIGHT” EAS DETECTORS

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 for ISS).
HiRes The High Resolution Fly's Eye Cosmic Ray Detector
Telescope Array [TA]



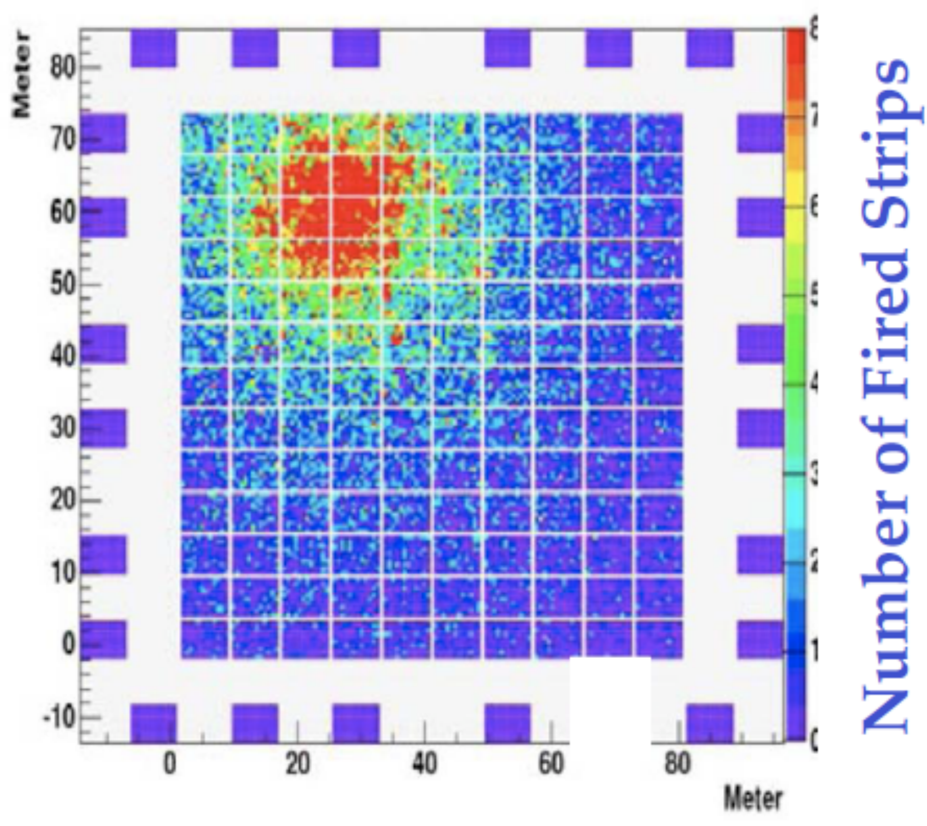
10^{11}-10^{13} eV:
Areas ≈ 10^4 m^2
Spacing: full coverage
Altitude: very high
OR Cherenkov detectors

10^{14}-10^{16} eV:
Areas ≈ 10^5 m^2
Spacing: ≈ 50 m
Altitude: high

10^{16}-10^{18} eV:
Areas ≈ 10^6 m^2
Spacing ≈ 150 m
Alt.: moderate high
OR Radio detector

10^{18}-10^{20} eV:
Areas ≈ 10^8-10^9 m^2
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

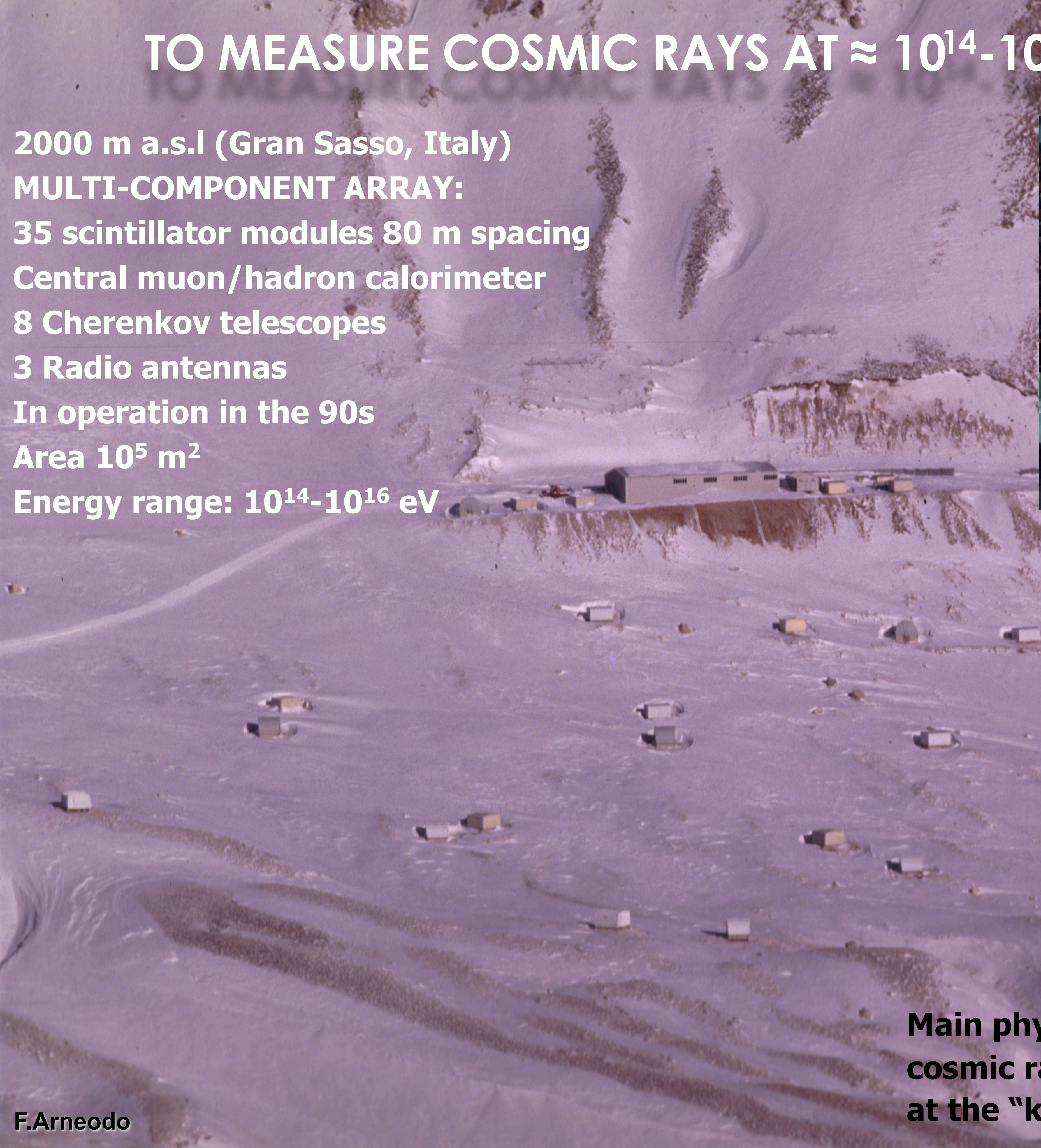
Resistive Plate Chambers carpet

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

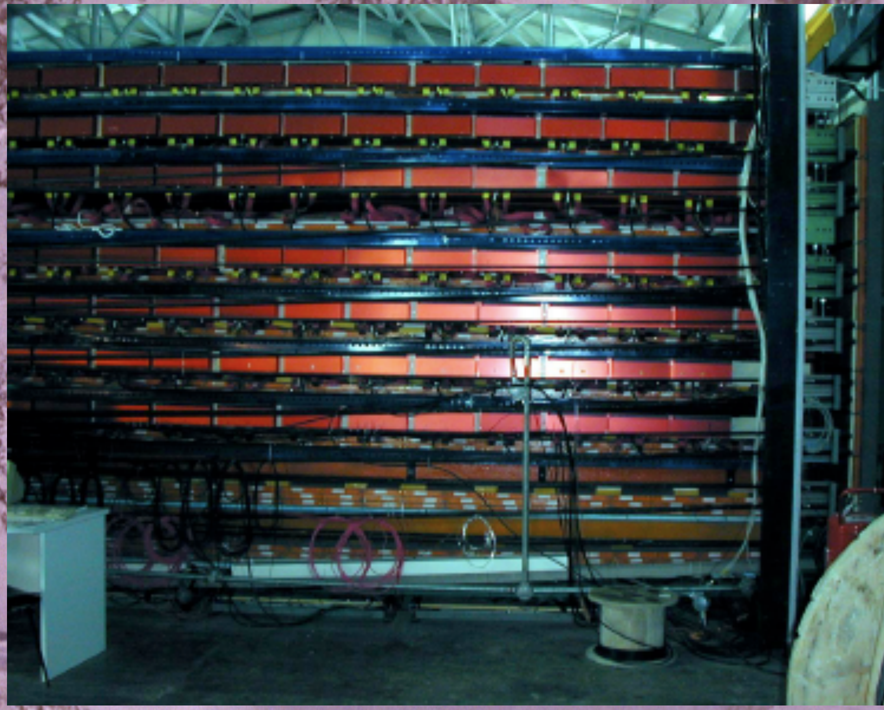
4300 m a.s.l (Tibet)
697 scintillators @ 7.5 m

36 scintillators @ 15 m
Area ≈ $4x10^4$ 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



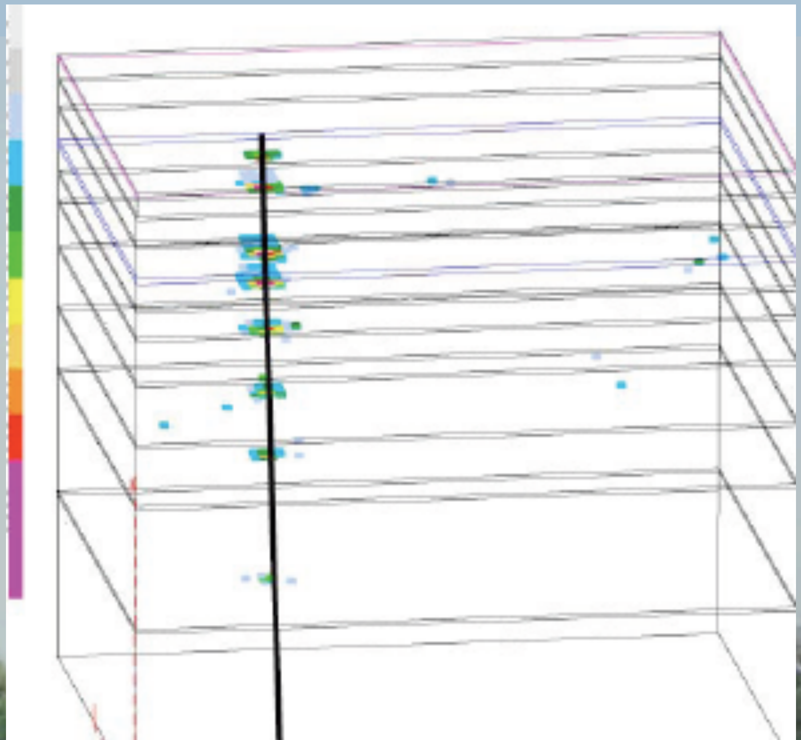
Calorimeter at the center: muon tracking, hadron measurement

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

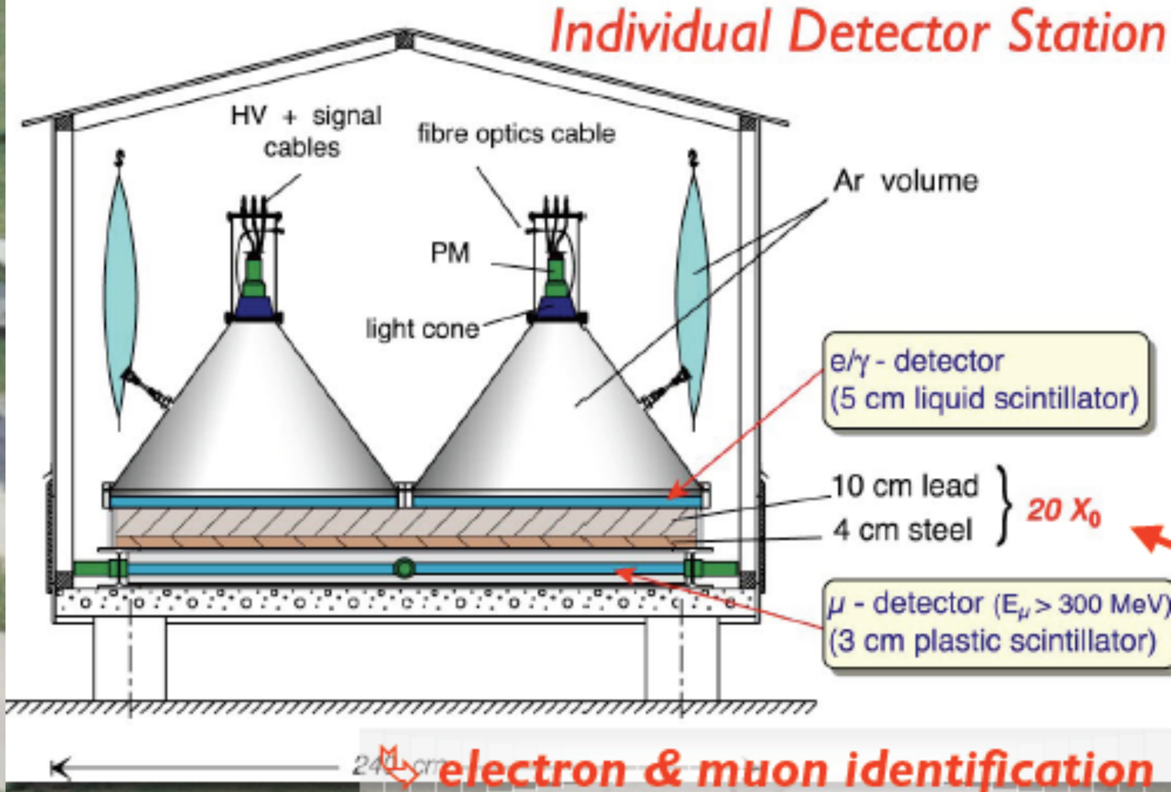
F.Arneodo

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 $4x10^4$ m^2
Energy range: $5x10^{14}$-$5x10^{16}$ eV


Single hadron in the calorimeter

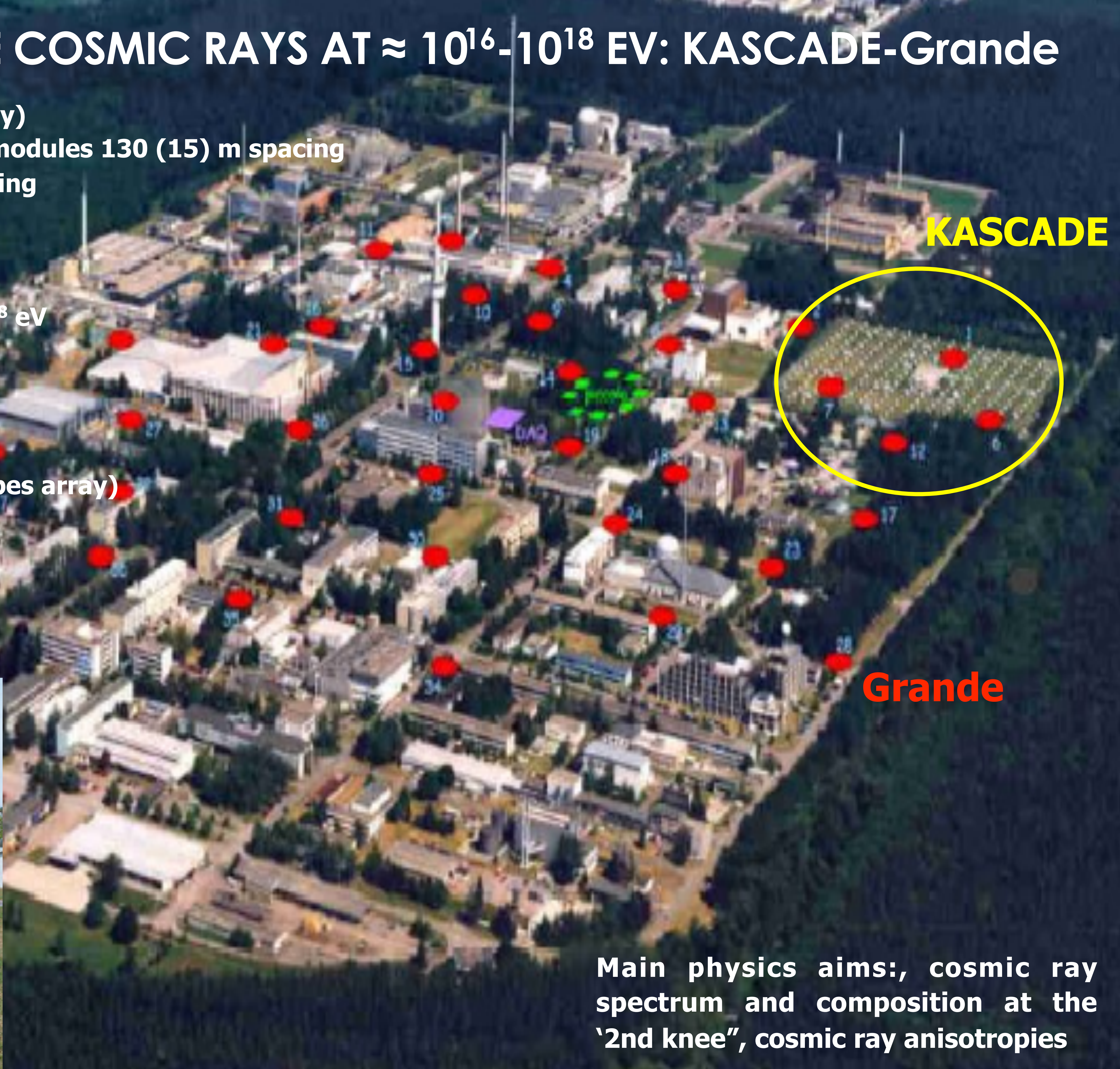

Area ~ 0.04 km^2,
252 surface detectors



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

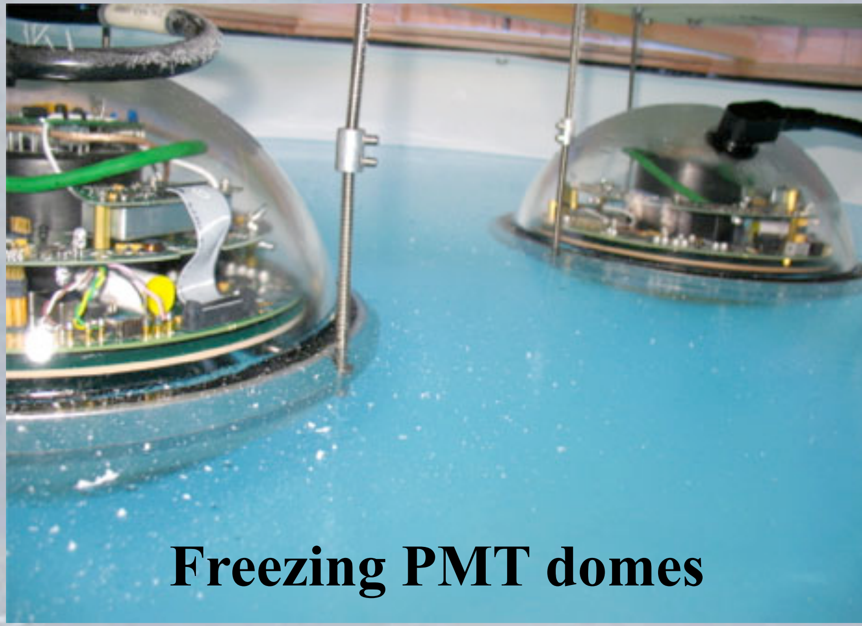
Sea level (FZK, Germany)
37 (+252) scintillator modules 130 (15) m spacing
≈ 1000 m^2 muon counting
Hadron calorimeter
In operation
Area 0.5 km^2
Energy range: 10^{16}-10^{18} eV

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

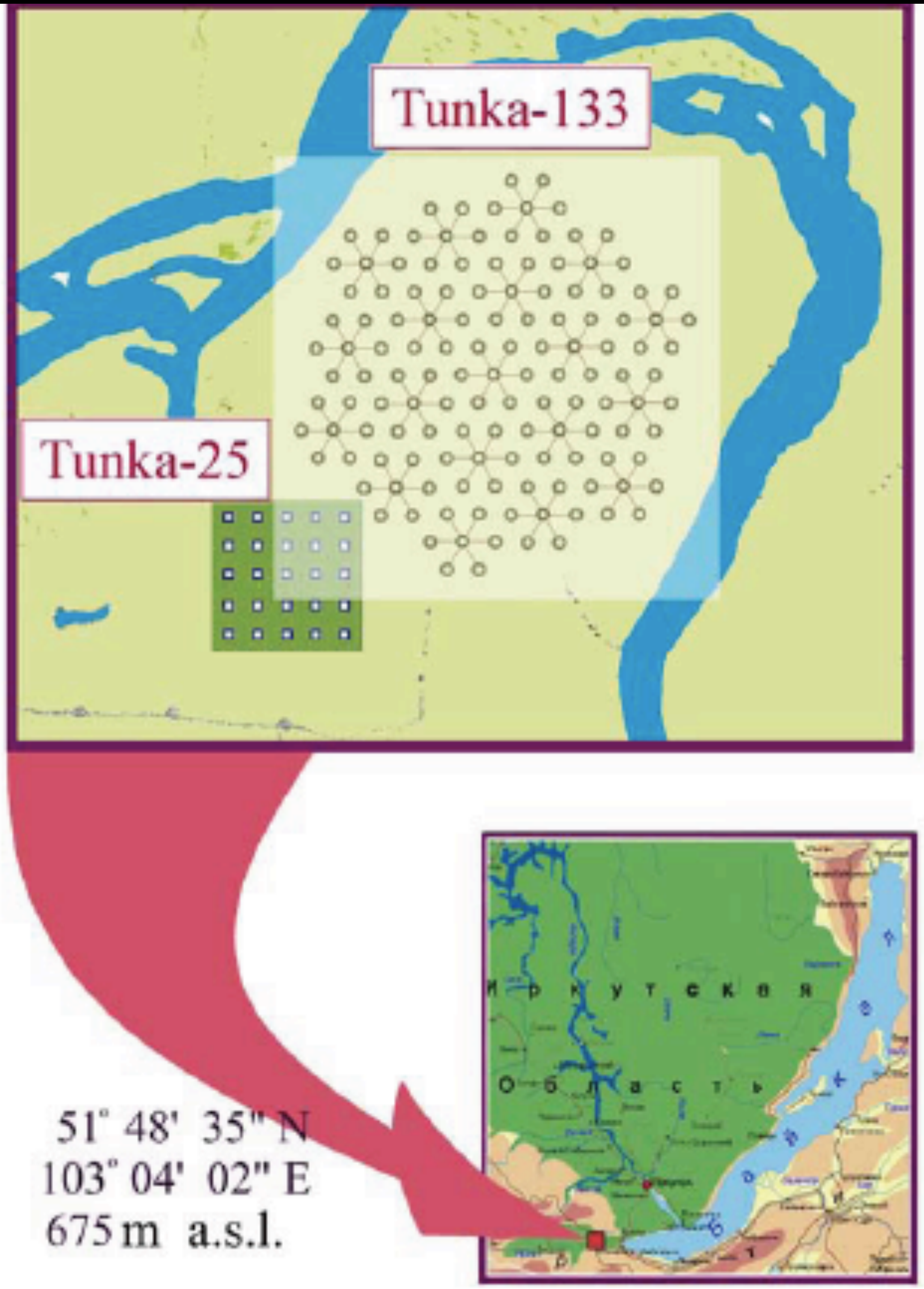
125 m spacing, area ≈ 10^6 m^2

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}-$5x10^{18}$ 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.

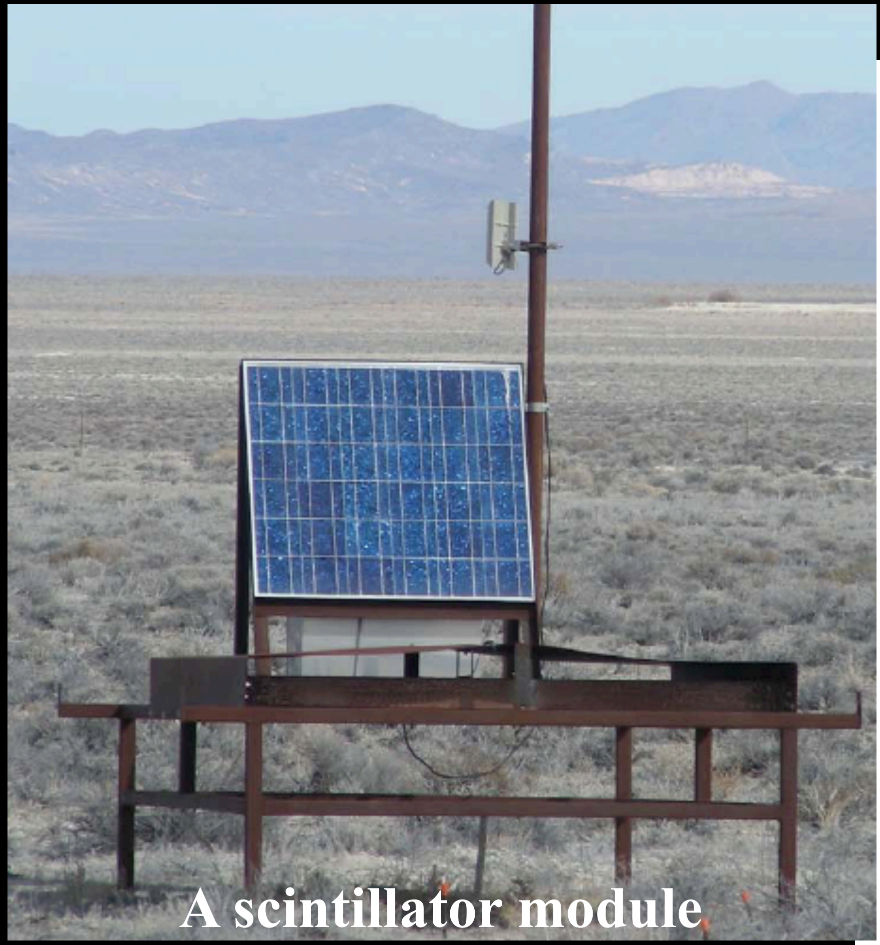
2 fluorescence telescopes (67 mirrors & 880 PMTs + 36 mirrors & 464 PMTs)

Spacing ≈ 3.4 km

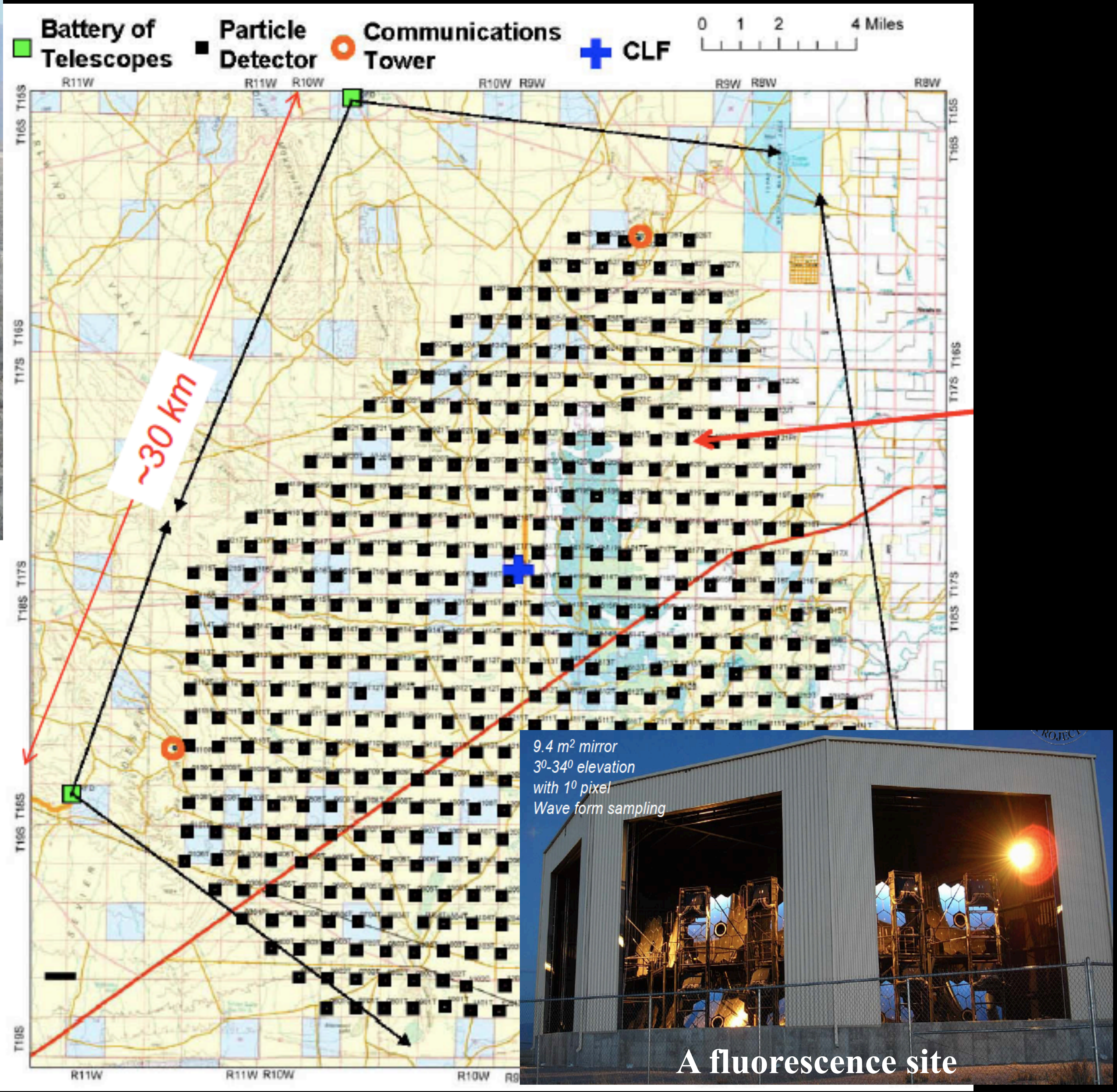
TO MEASURE COSMIC RAYS AT > 10^{18}: HiRES

- 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 > 10^{18}: TELESCOPE ARRAY



A scintillator module



A fluorescence site

USA, Utah, 1400 m a.s.l.

Hybrid detector: 507 scintillators SD array+ 3 fluorescence sites

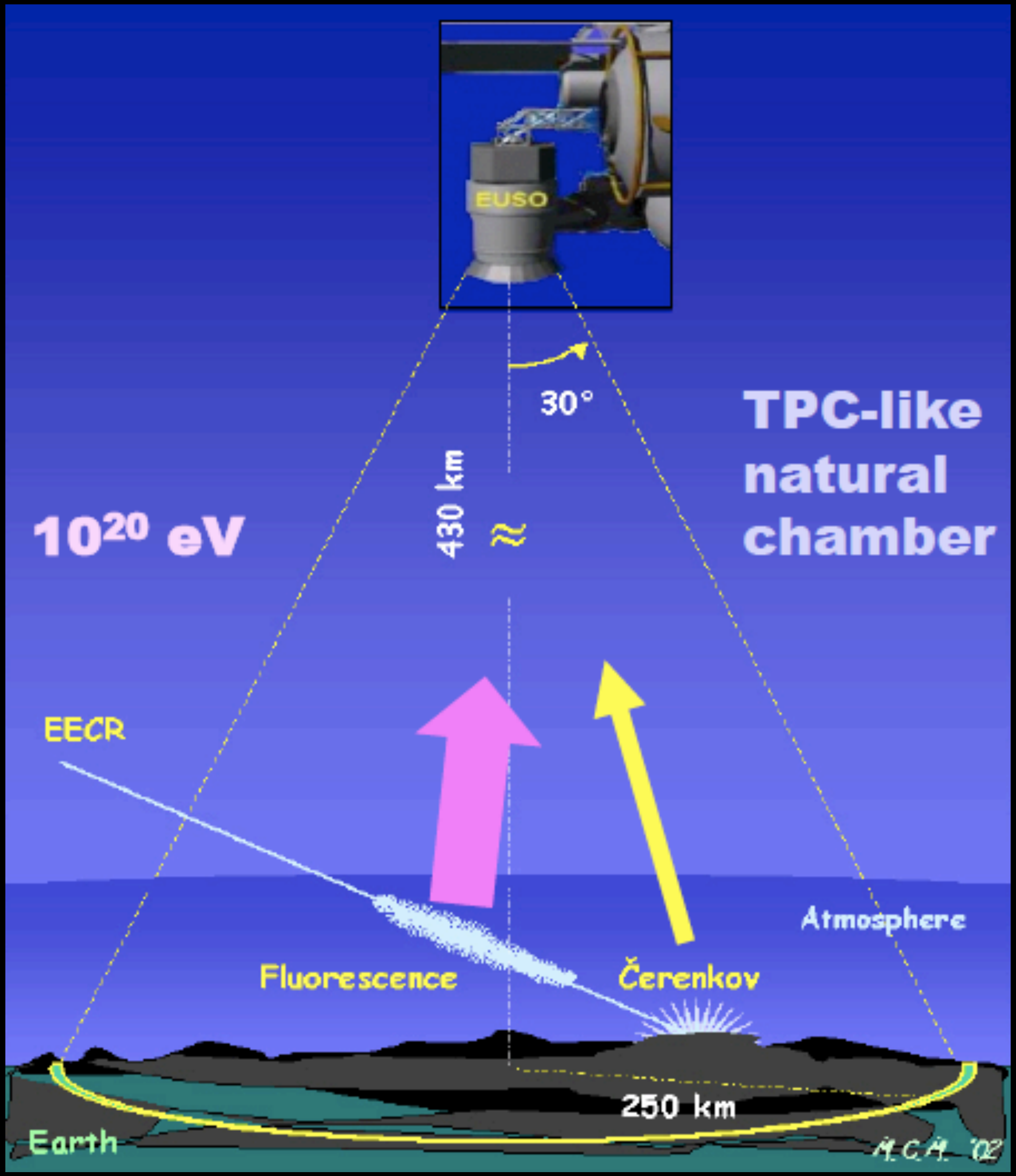
SD Spacing ≈ 1200 m

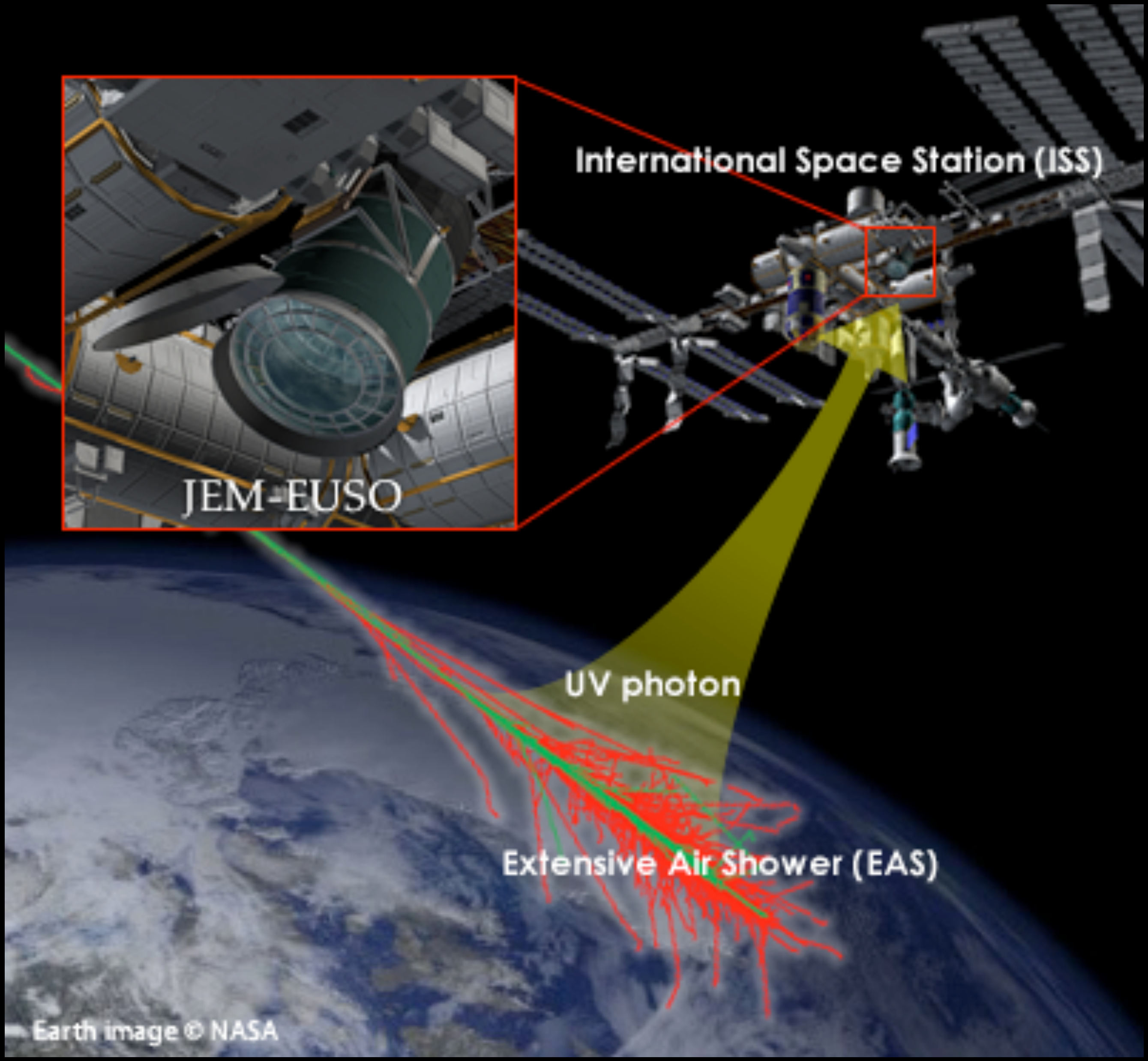
Enclosed area: 700 km^2

Fully efficient above 0.1 EeV

In operation

TO MEASURE COSMIC RAYS AT > 10^{20}: JEM-EUSO





In space: to be installed on ISS (altitude ≈ 400 km)
Fluorescence detector
6000 PMTs for a 2.25 m focal surface
Fresnel lenses
Aperture: 10^5-10^6 km2 sr; Energy range: >10^{20} eV

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

Argentina, Malargue, 1500 m a.s.l.

“Hybrid” detector: 1600 water Cherenkov SD + 4x6 fluorescence detectors

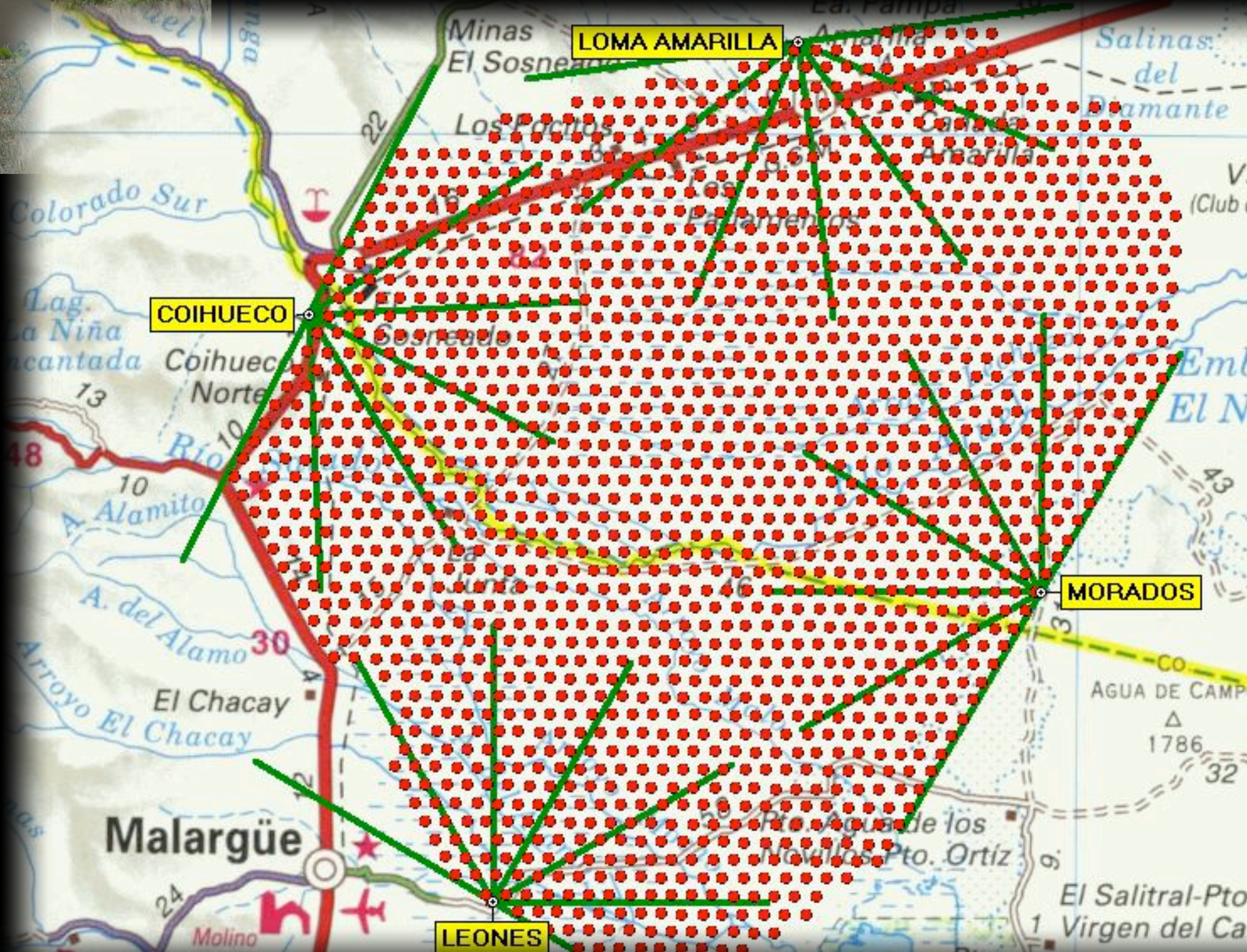
High precision hybrid measurement

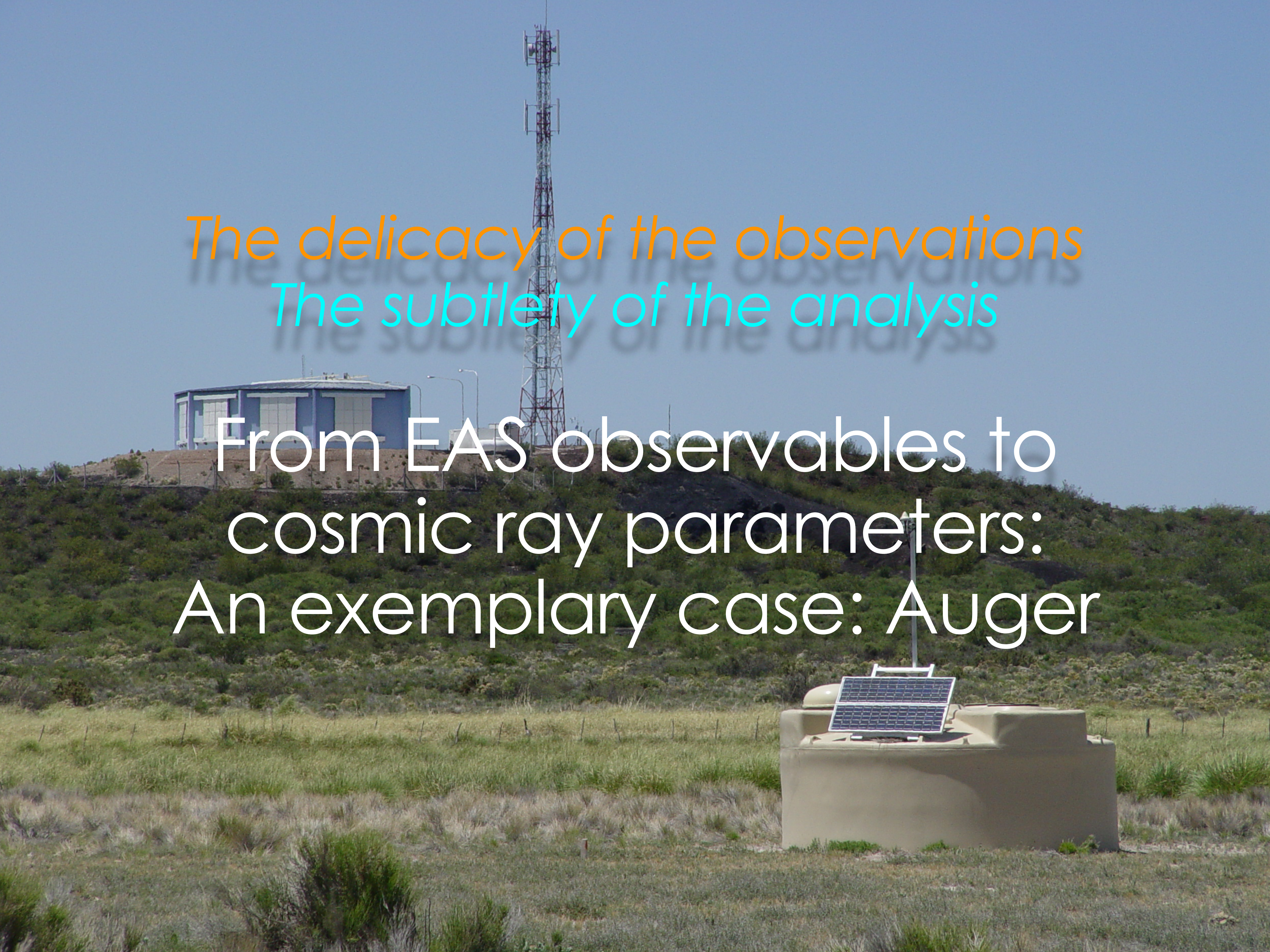
SD spacing ≈ 1500 m

Enclosed area: 3000 km2

Fully efficient above 1 EeV

In operation



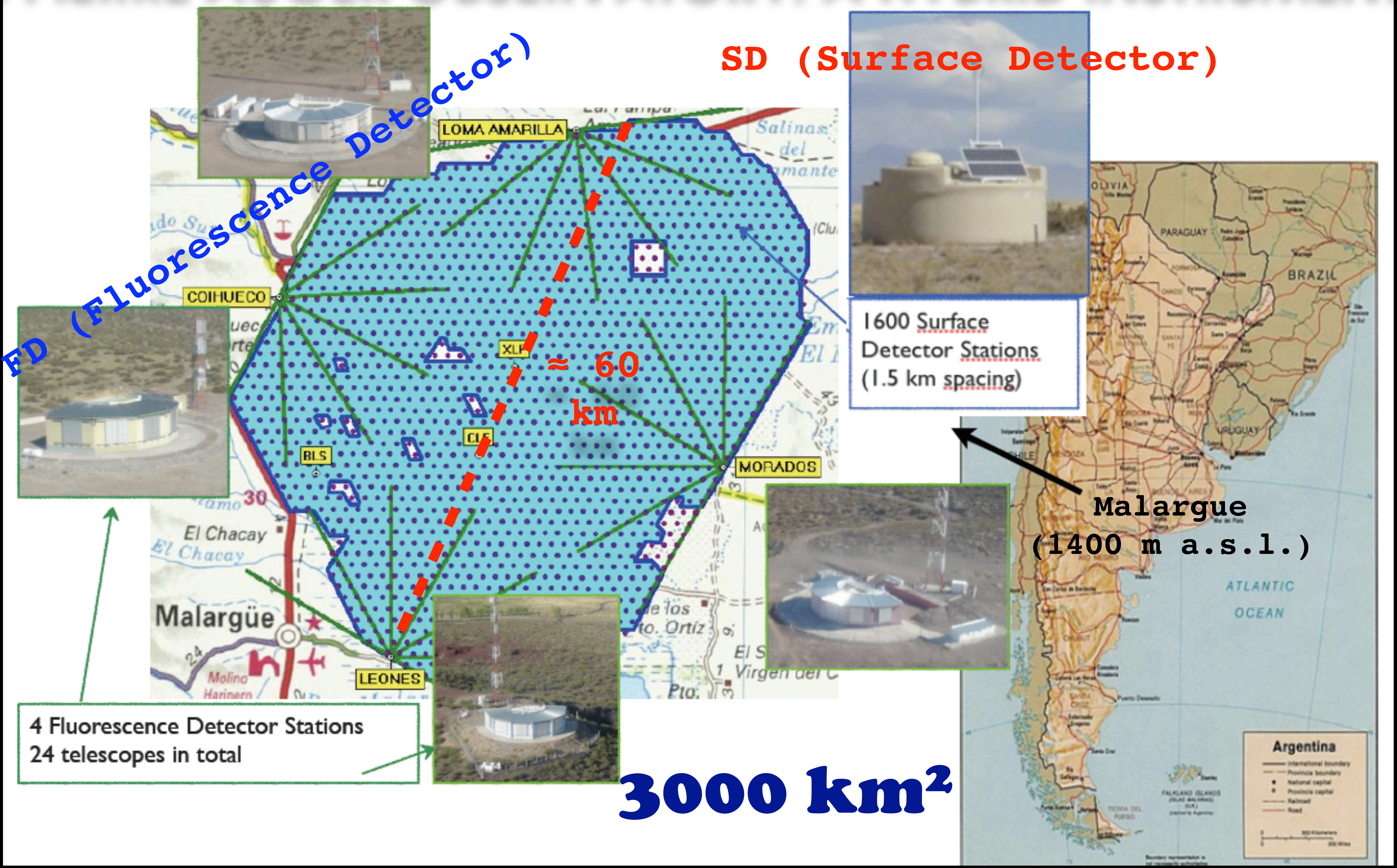


The delicacy of the observations

The subtlety of the analysis

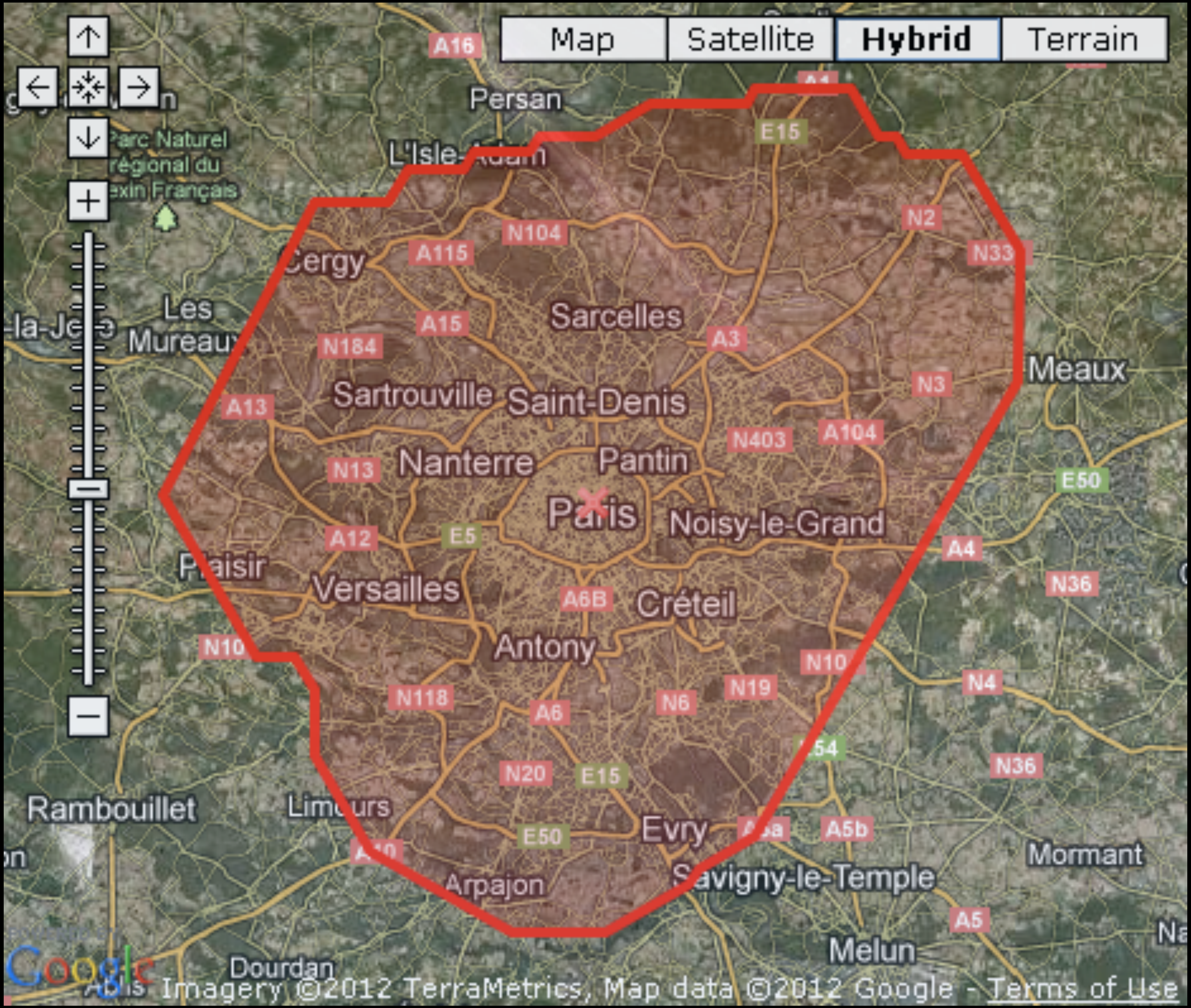
From EAS observables to cosmic ray parameters: An exemplary case: Auger

THE PIERRE AUGER OBSERVATORY: A HYBRID INSTRUMENT



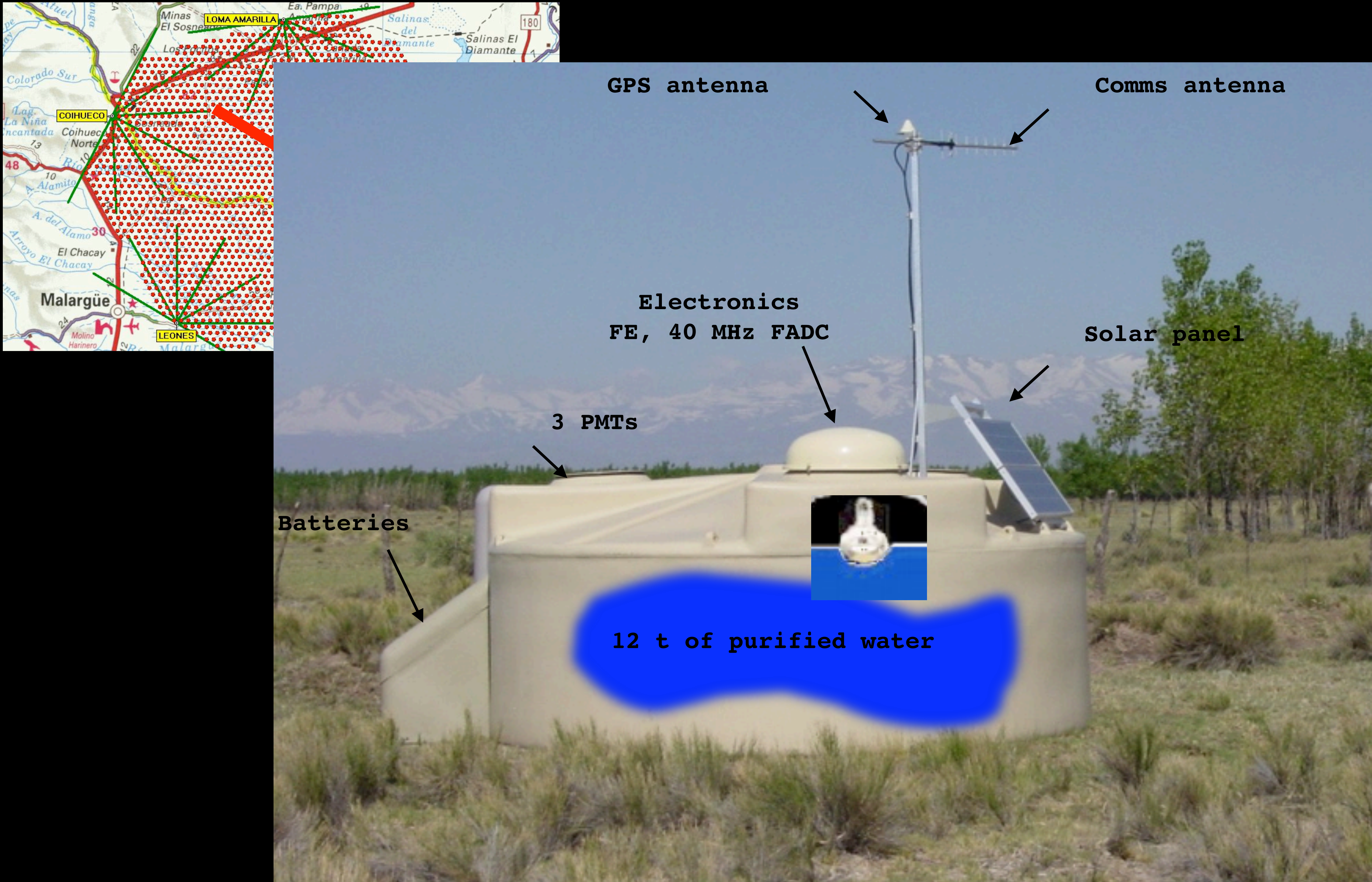
- “Hybrid” detector: 1600 water Cherenkov (SD) + 4x6 fluorescence detectors (FD)
- SD fully efficient above 3 EeV (100% d.c), FD&&SD above 1 EeV (but ≈ 13% d.c.)
- In operation from 2004 (completed in 2008)
- Full Auger: ≈ 1500 (100) (2) events/month above 3x 10^{18} (10^{19}) (5x 10^{19}) eV

THE SIZE OF THE PIERRE AUGER OBSERVATORY :-)



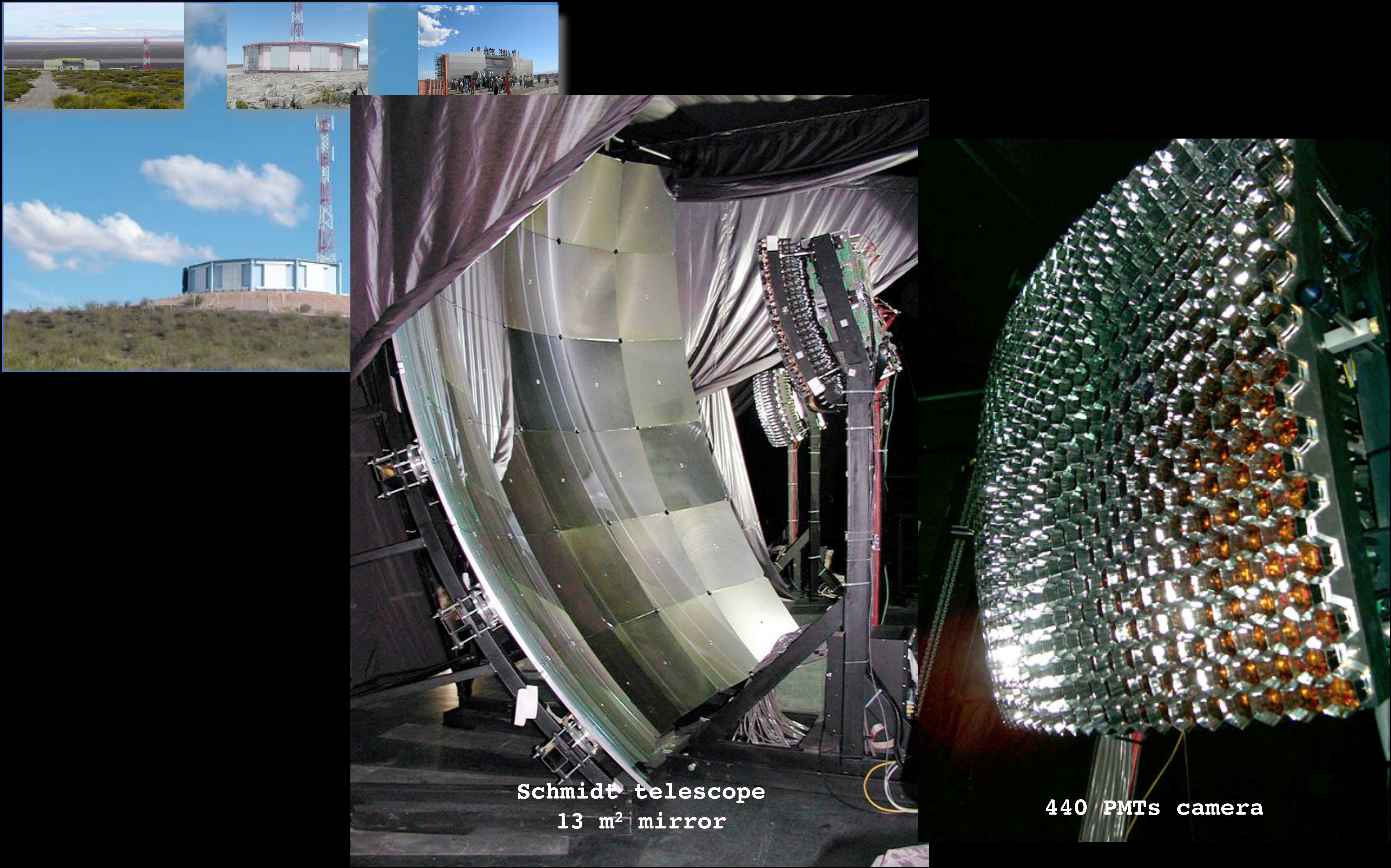
THE SURFACE DETECTOR ARRAY

Surface Detector (SD): 1600 water Cherenkov tanks, 100% duty cycle



THE FLUORESCENCE DETECTOR

Fluorescence Detector (FD): 4 x 6 telescopes
10% duty cycle

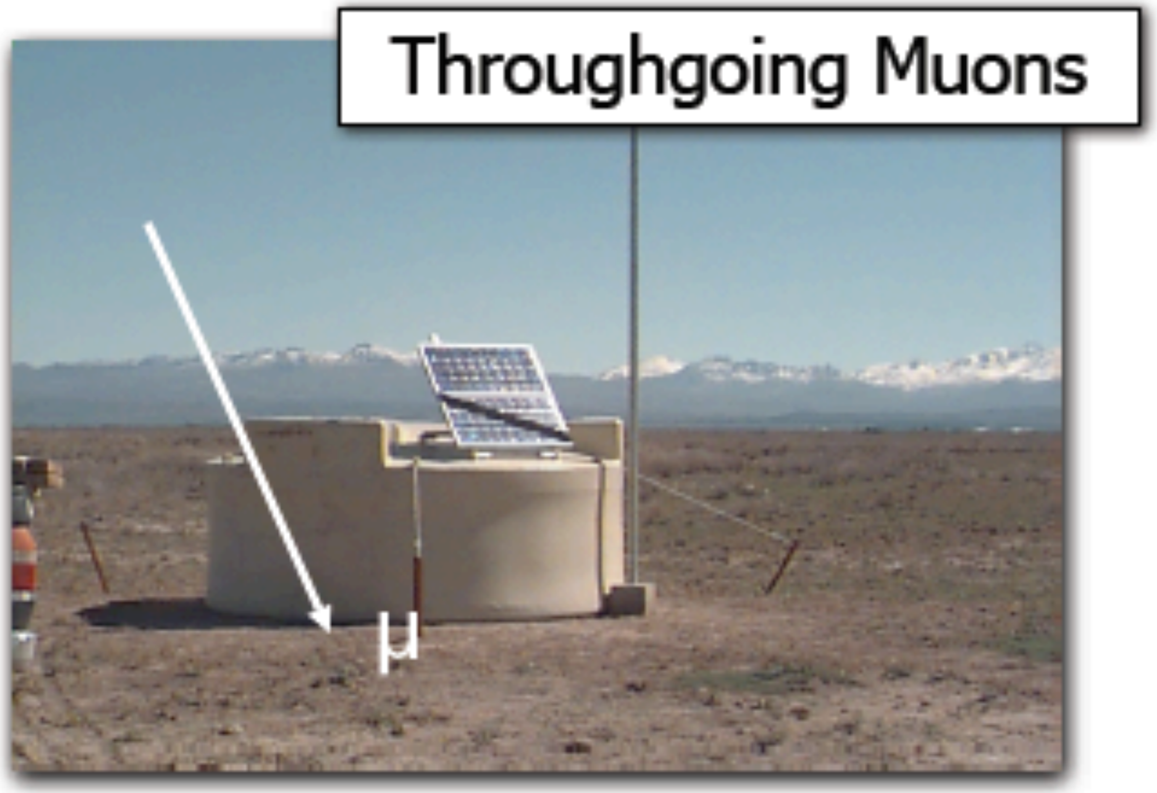


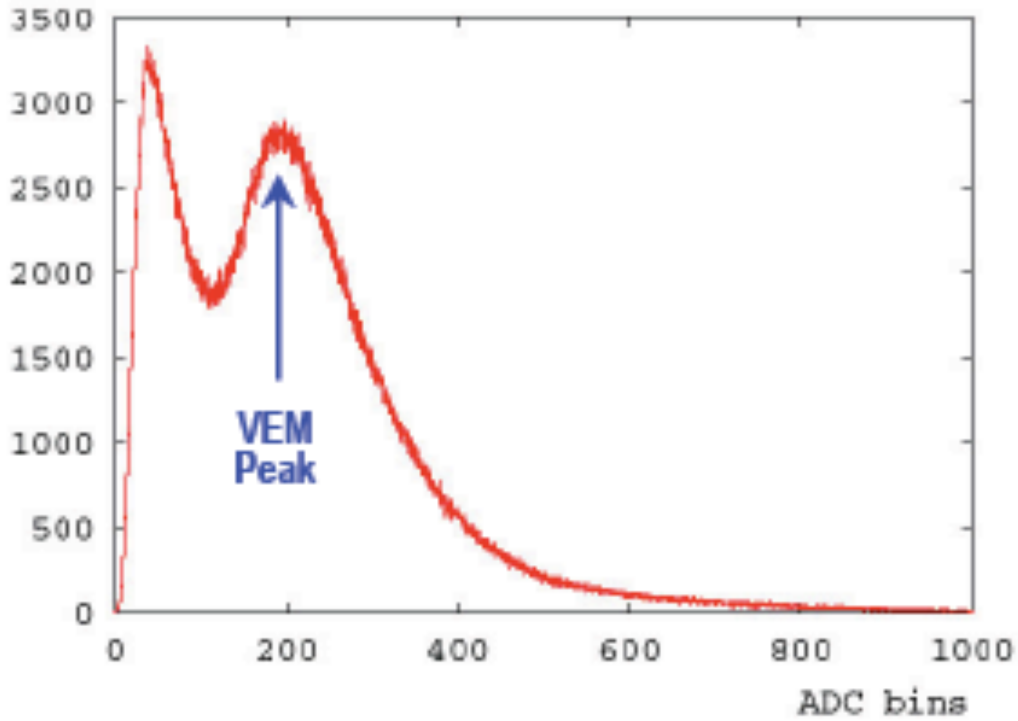
Schmidt telescope
13 m² mirror

440 PMTs camera

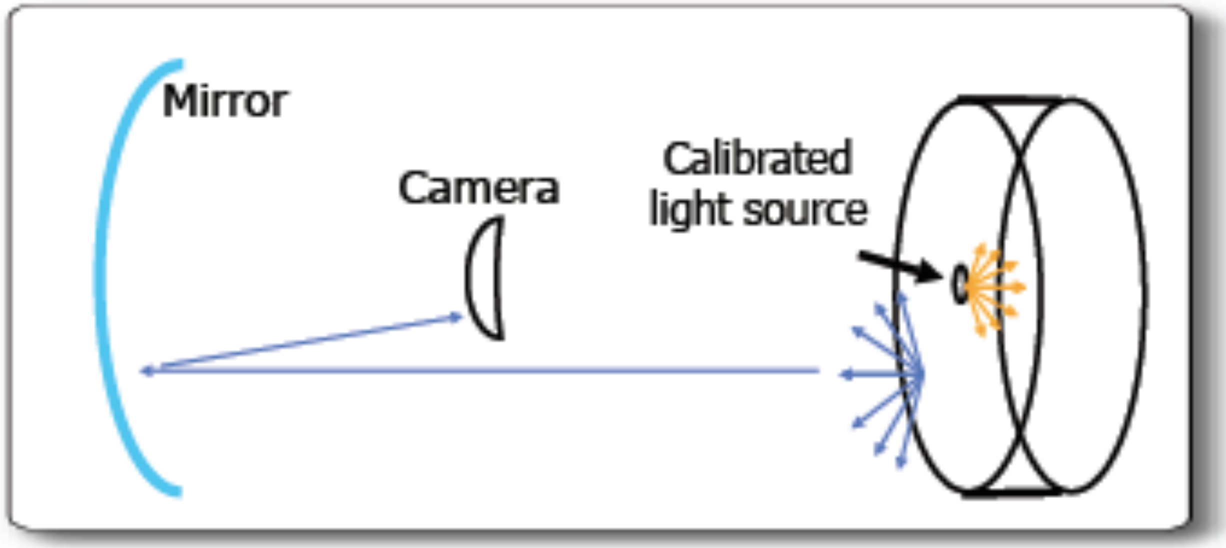
THE CALIBRATION

Surface detector



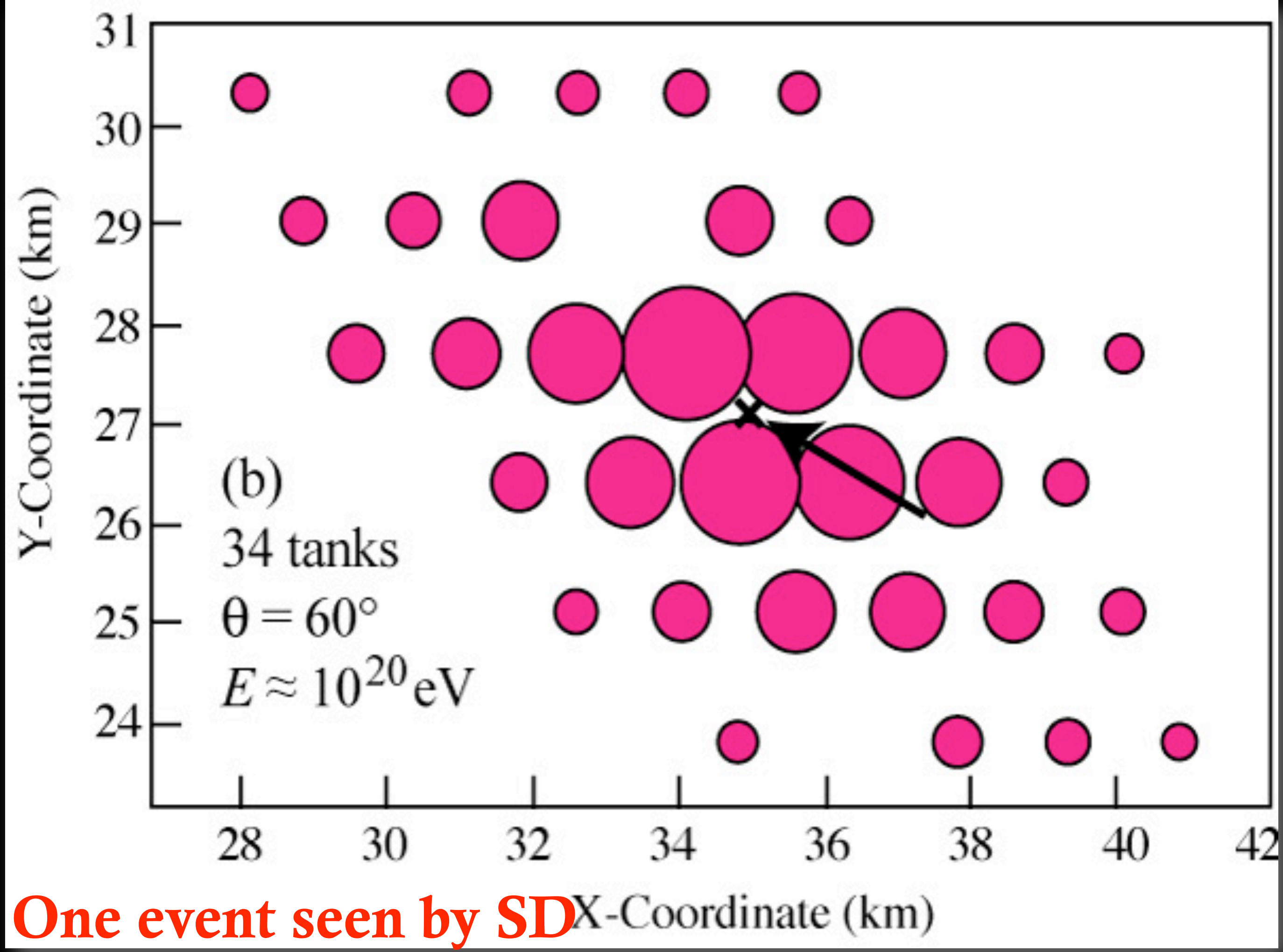


Fluorescence detector

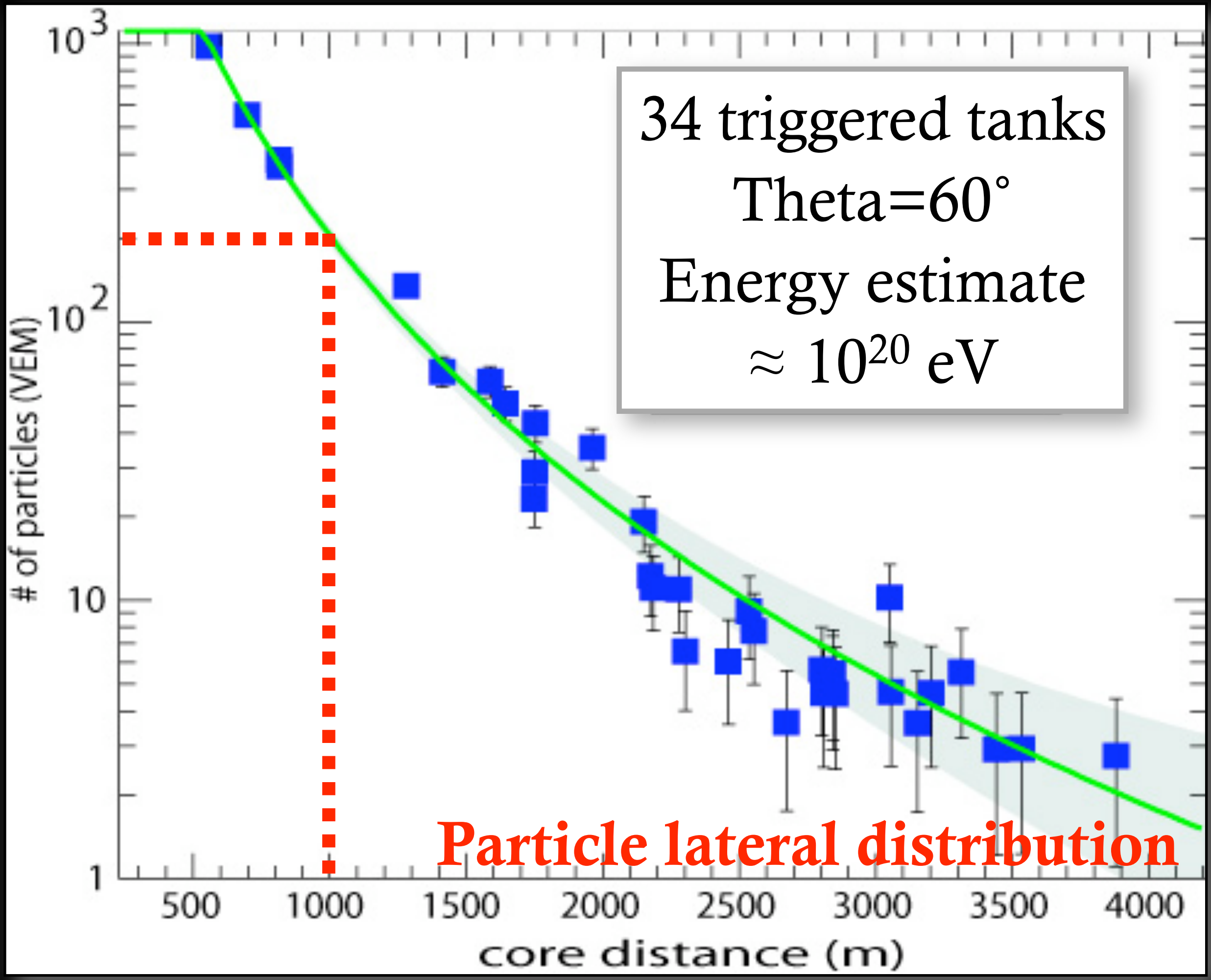


HOW DOES AN EVENT LOOK LIKE IN THE SURFACE DETECTOR ?

SD measures the lateral structure of the shower at ground



One event seen by SD



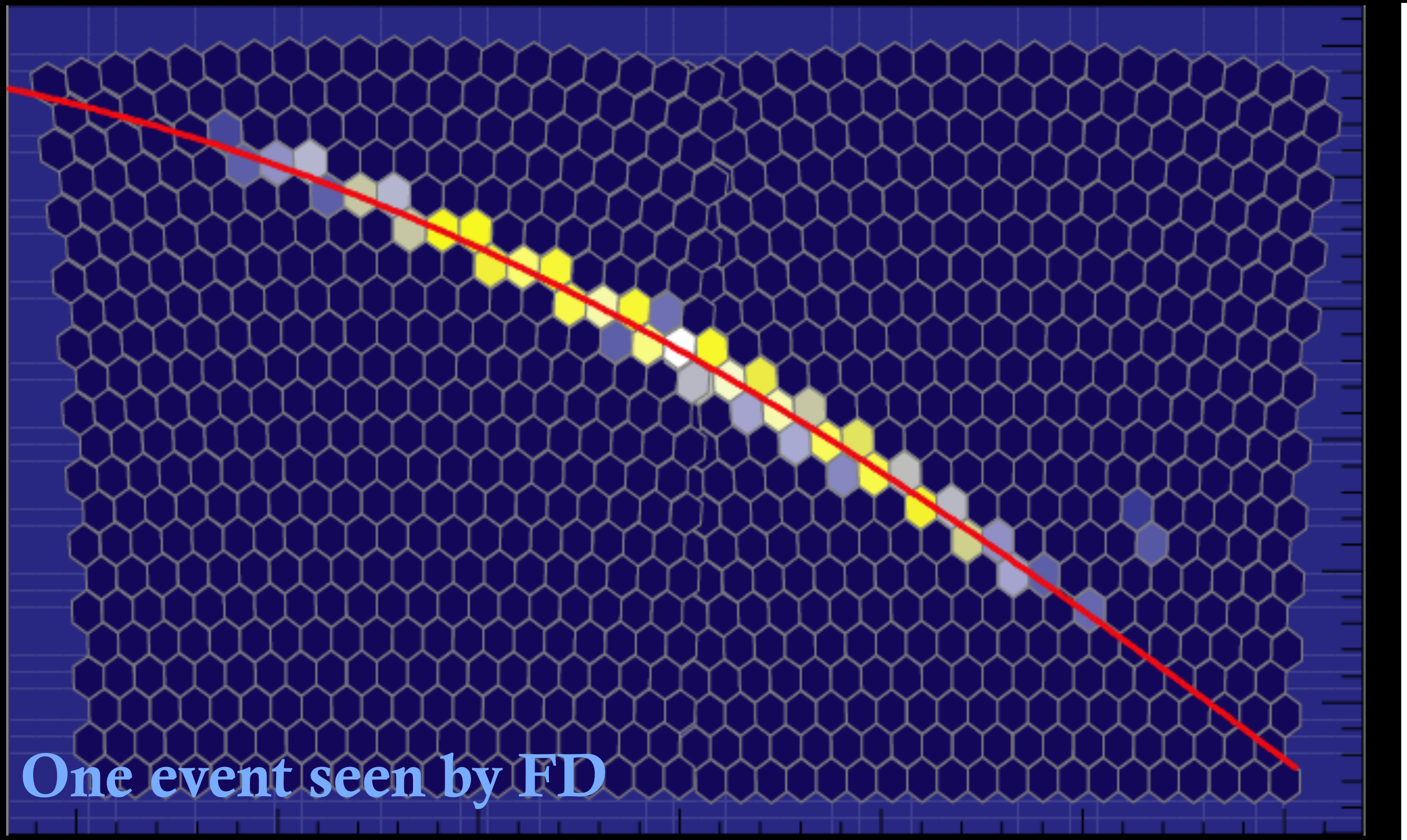
34 triggered tanks
Theta=60°
Energy estimate
≈ 10^{20} eV

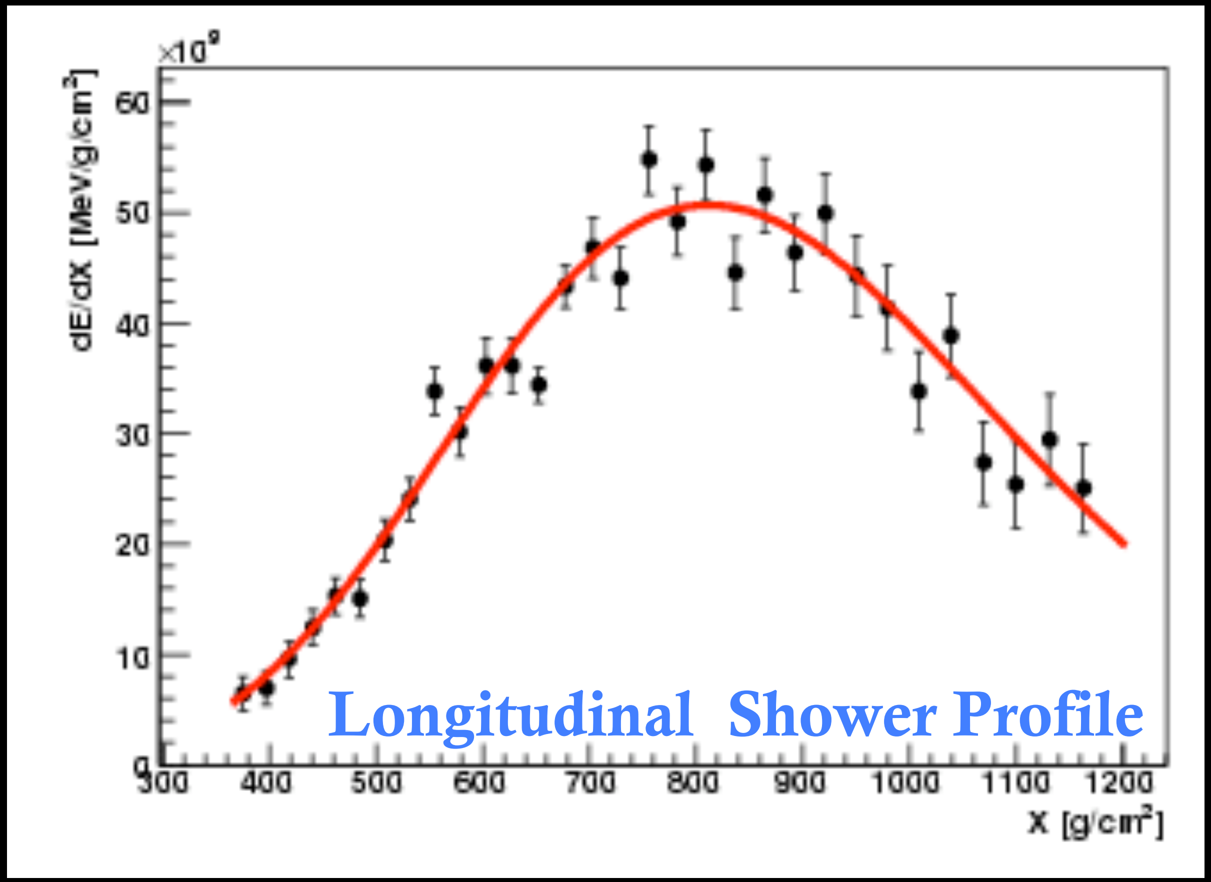
Particle lateral distribution

- Reconstruct geometry (arrival direction & impact point)
- Fit particle lateral distribution (LDF)
- S(1000) [signal at 1000 m] is the Auger energy estimator (“ideal” distance depends on detectors spacing)

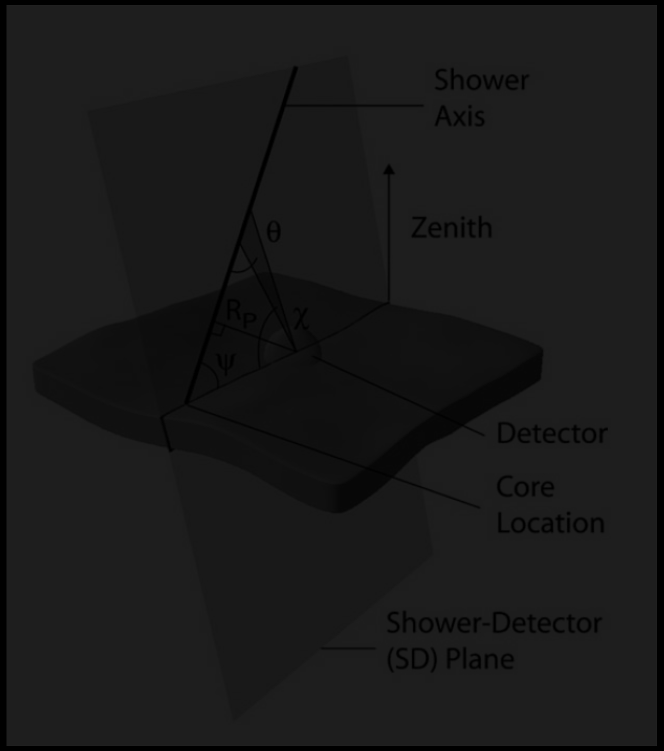
HOW DOES AN EVENT LOOK LIKE IN THE FLUORESCENCE DETECTOR ?

FD records the longitudinal profile of the shower during its development in atmosphere


One event seen by FD



Longitudinal Shower Profile



- *Reconstruct geometry (shower detector plane, SDP, and shower axis in SDP)*
- *Fit longitudinal shower profile*
- *E ∝ area under the curve*
- *Calorimetric measurement*

WHAT DO WE AIM AT MEASURING?

The same as in direct measurements:

AIMS:

Particle identification

Energy

Arrival direction

N.B.

DIRECT MEASUREMENT: To identify the primary particle we need in general two different measurements that depend in different ways on mass, charge, velocity

INDIRECT MEASUREMENT: To infer more precise information on the primary particle we need in general measurements of as many as possible components of the produced shower (HYBRID DETECTOR :-)

ARRIVAL DIRECTION

Most straightforward measurements by EAS arrays

The shower axis preserves the direction of the incoming particle

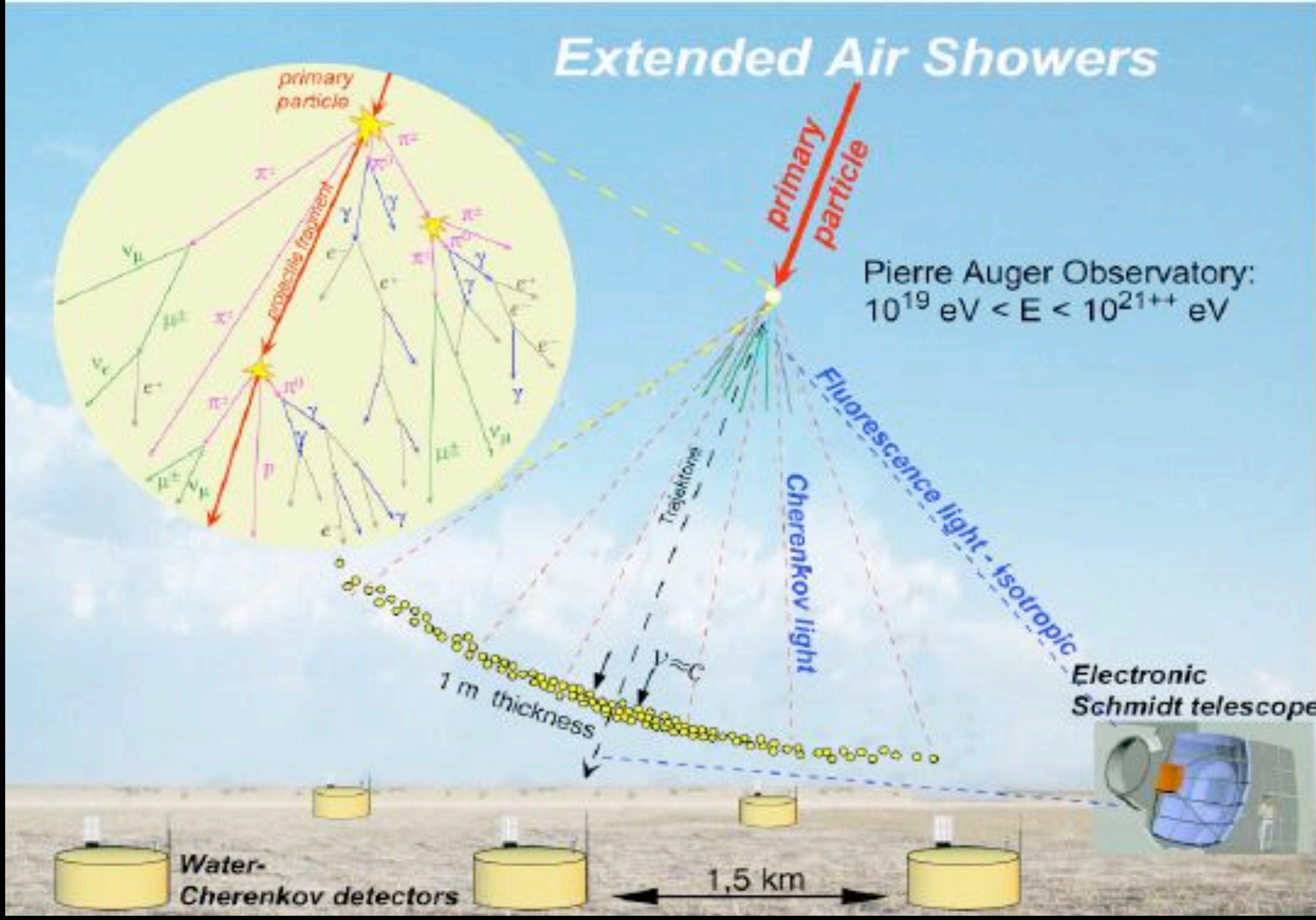
Time of flight technique:

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

Angular accuracy

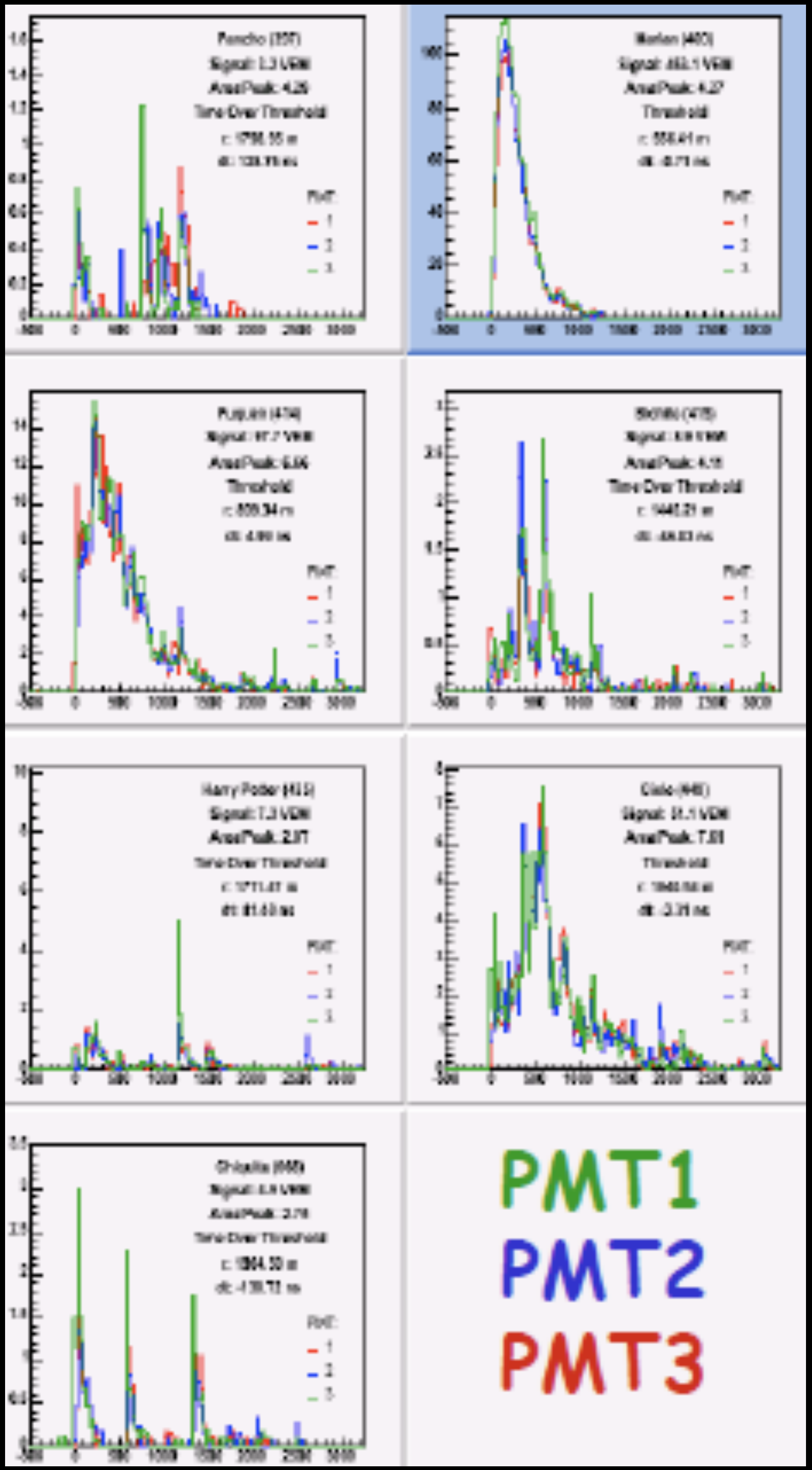
Less than degree for particle arrays

Fraction of degree for “light” arrays



ARRIVAL DIRECTION FROM THE SURFACE DETECTOR

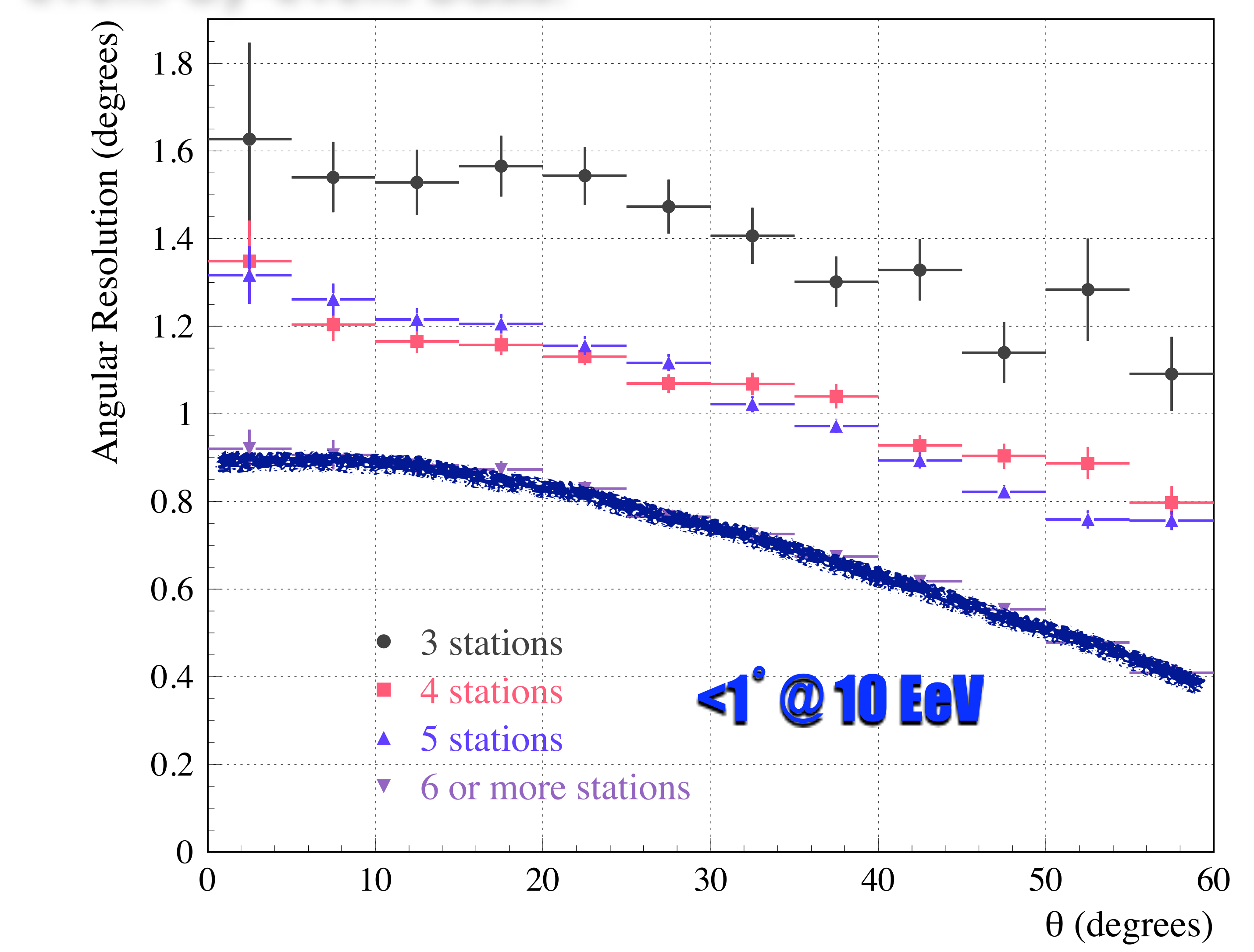
CR arrival direction: from relative arrival times of signals at ground detectors



FADC traces in an event

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

Angular resolution: estimated from the fit on an event-by-event basis.



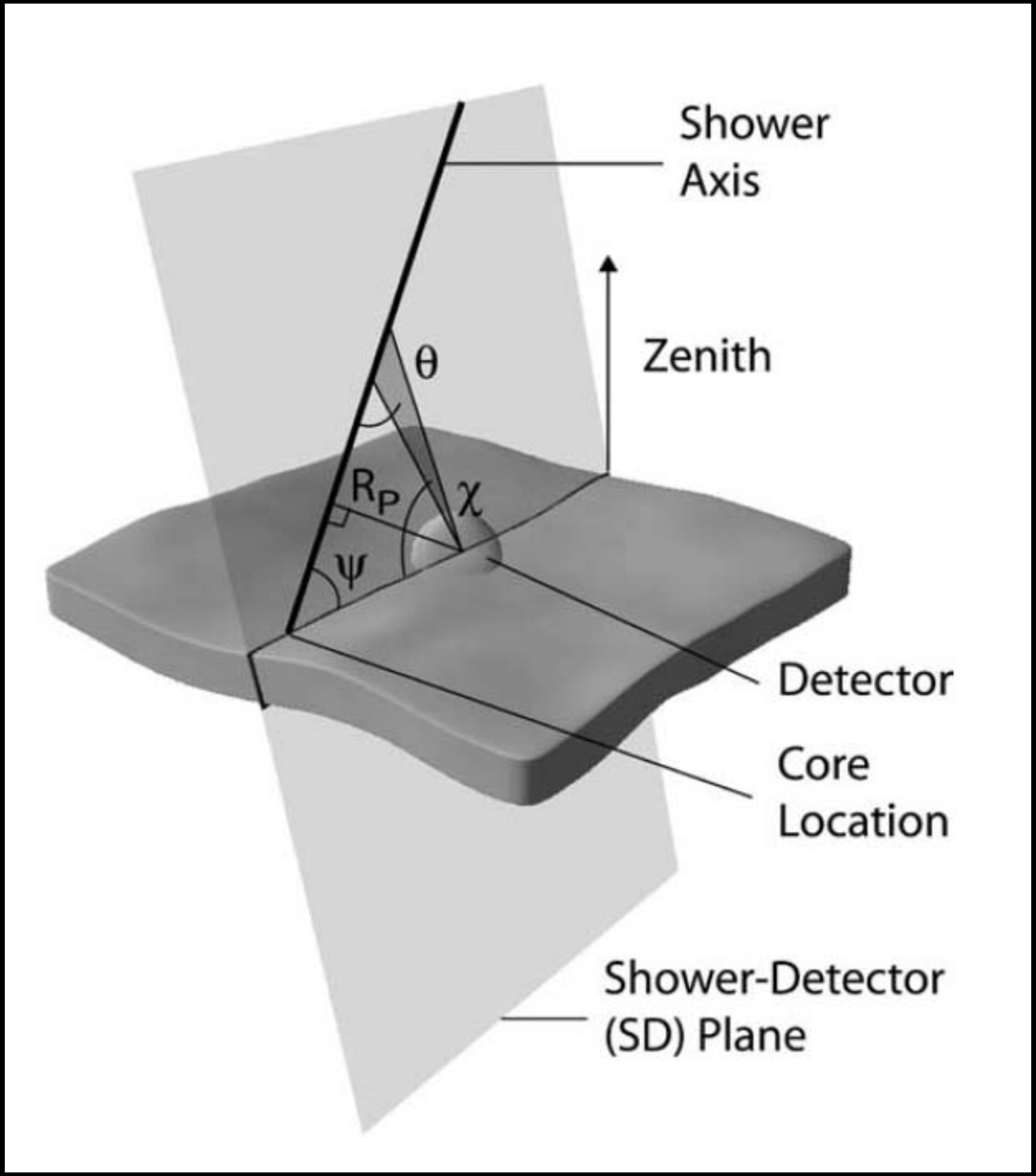
$E > 10^{18}$ eV ($> 10^{19}$ eV): ≥ 3 (6) tanks: $< 2^\circ$ (1°)

ARRIVAL DIRECTION FROM THE FLUORESCENCE DETECTOR

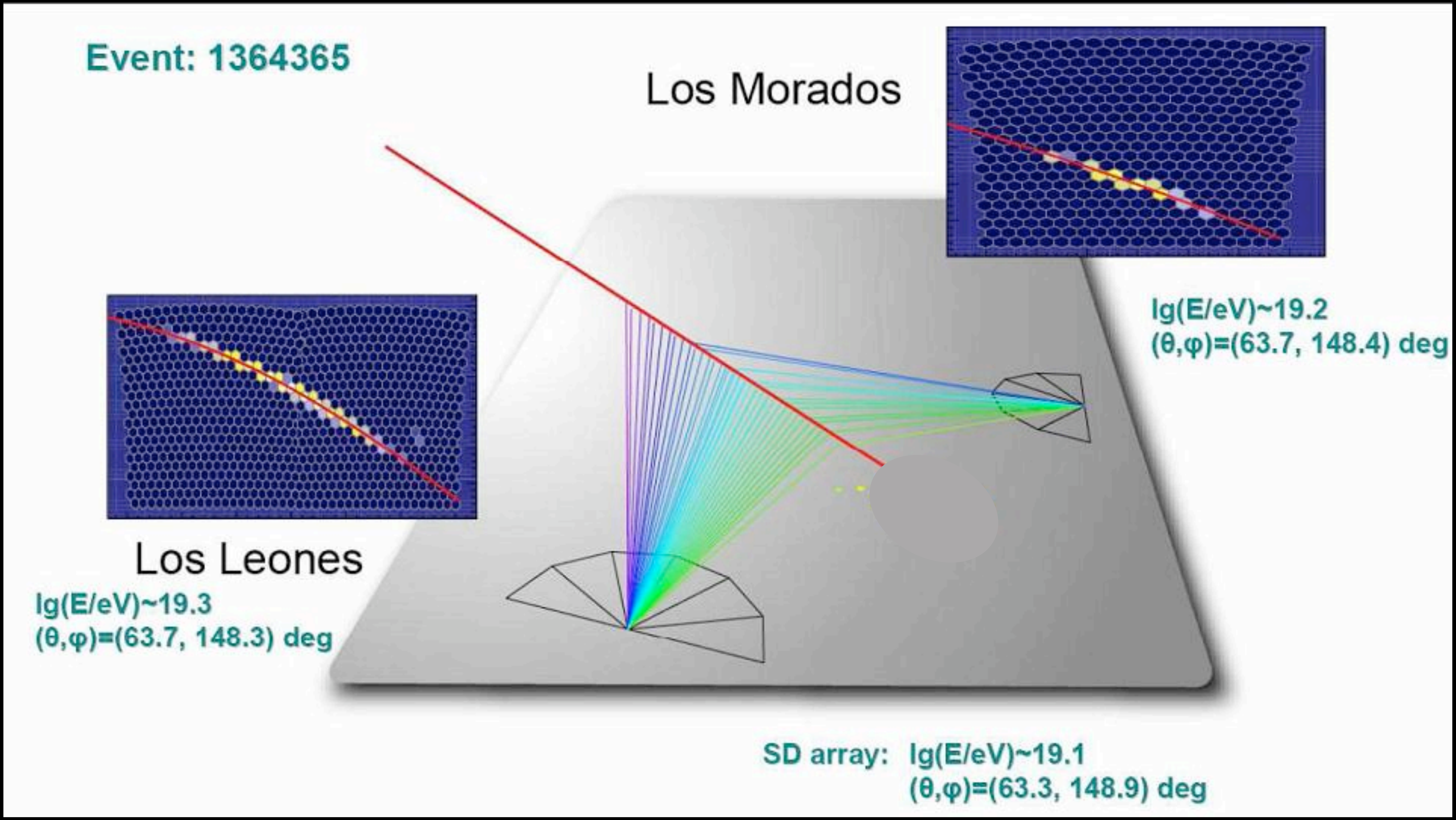
The arrival direction is obtained in two steps:

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 EAS axis. The orientation of the shower axis within the SDP is obtained using the trigger times from the PMTs.

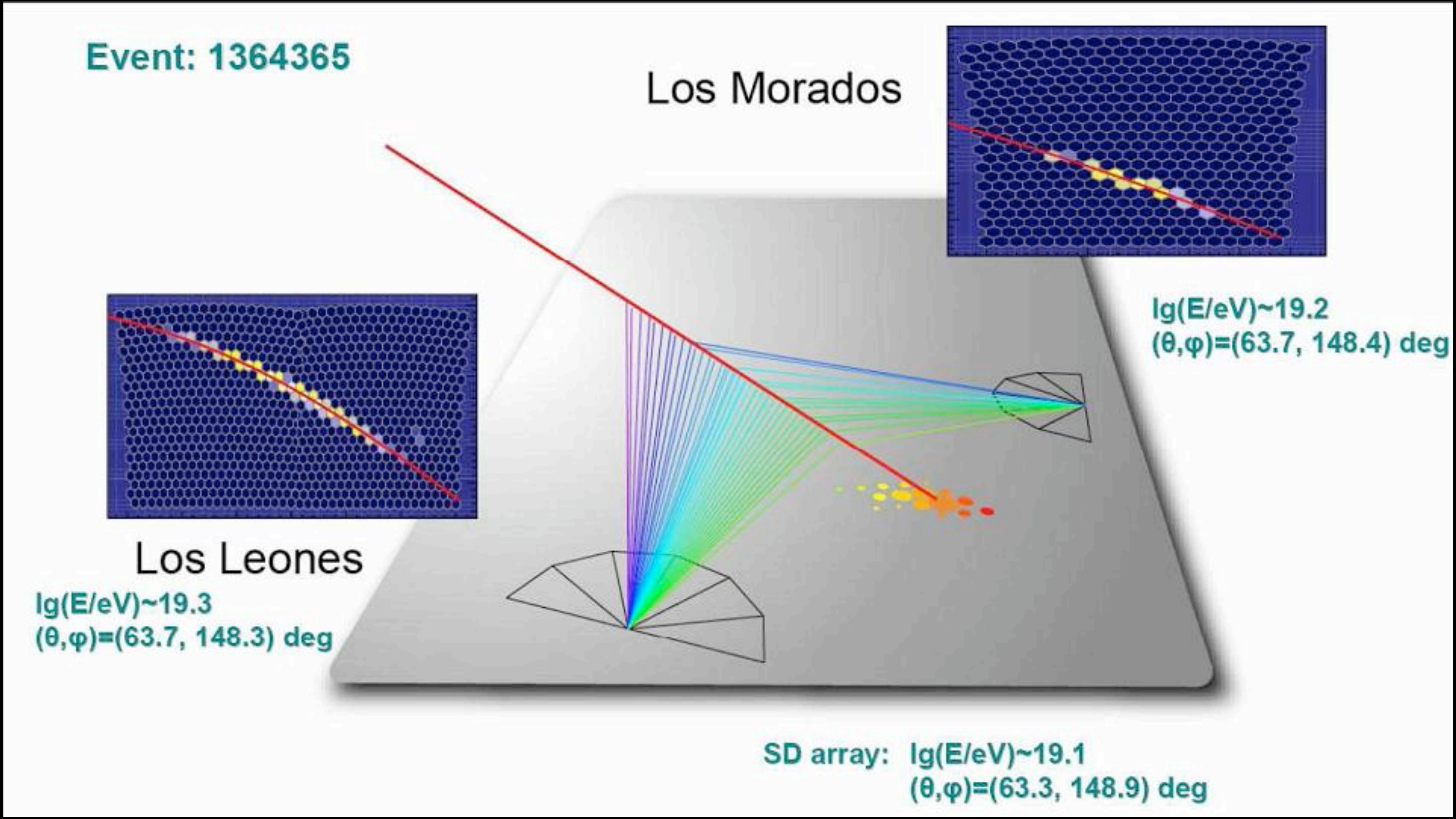


ARRIVAL DIRECTION FROM THE FLUORESCENCE DETECTOR



When an EAS is observed by two or more FDs, the arrival direction is defined by the intersection of the SDPs. Higher precision, check of the geometry

ARRIVAL DIRECTION FROM THE **HYBRID DETECTOR**



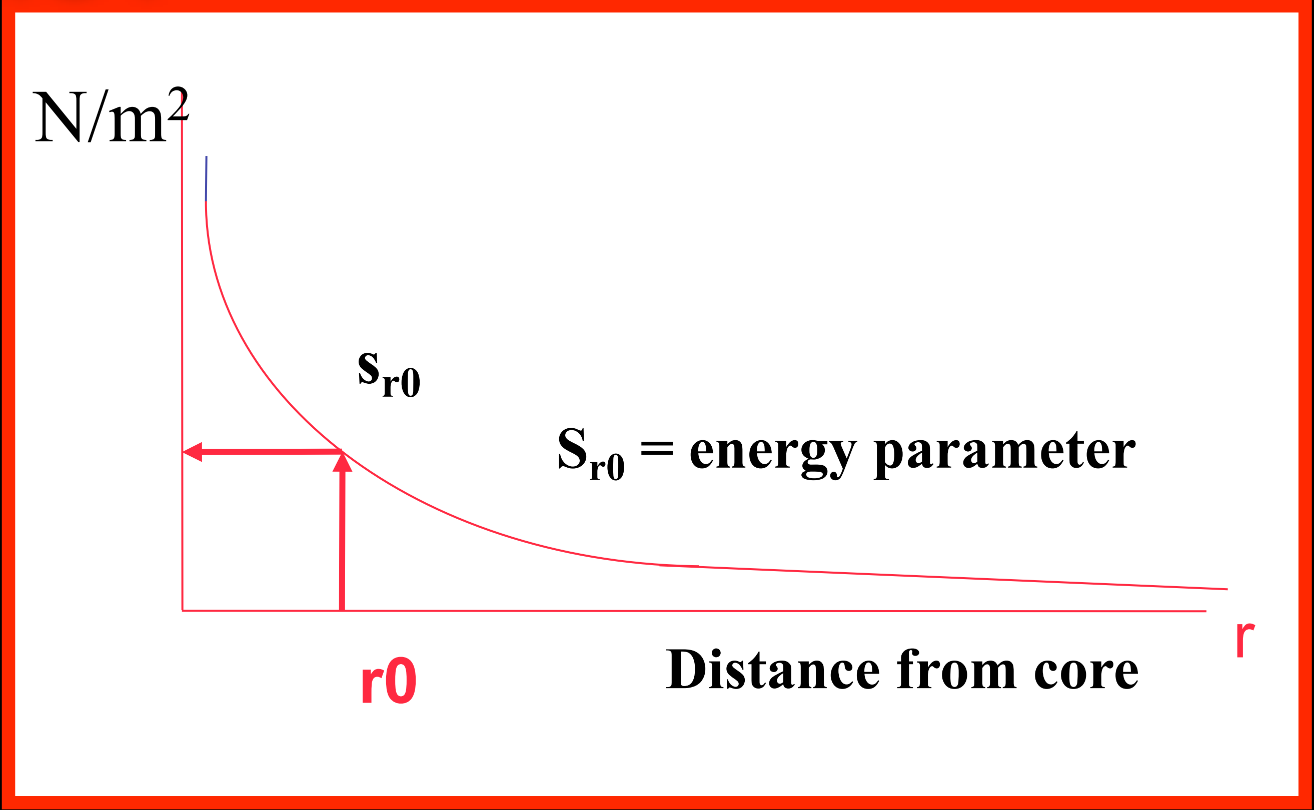
When an EAS is observed by SD and FD simultaneously (hybrid event), the geometry of the shower is fixed by SD (core position).

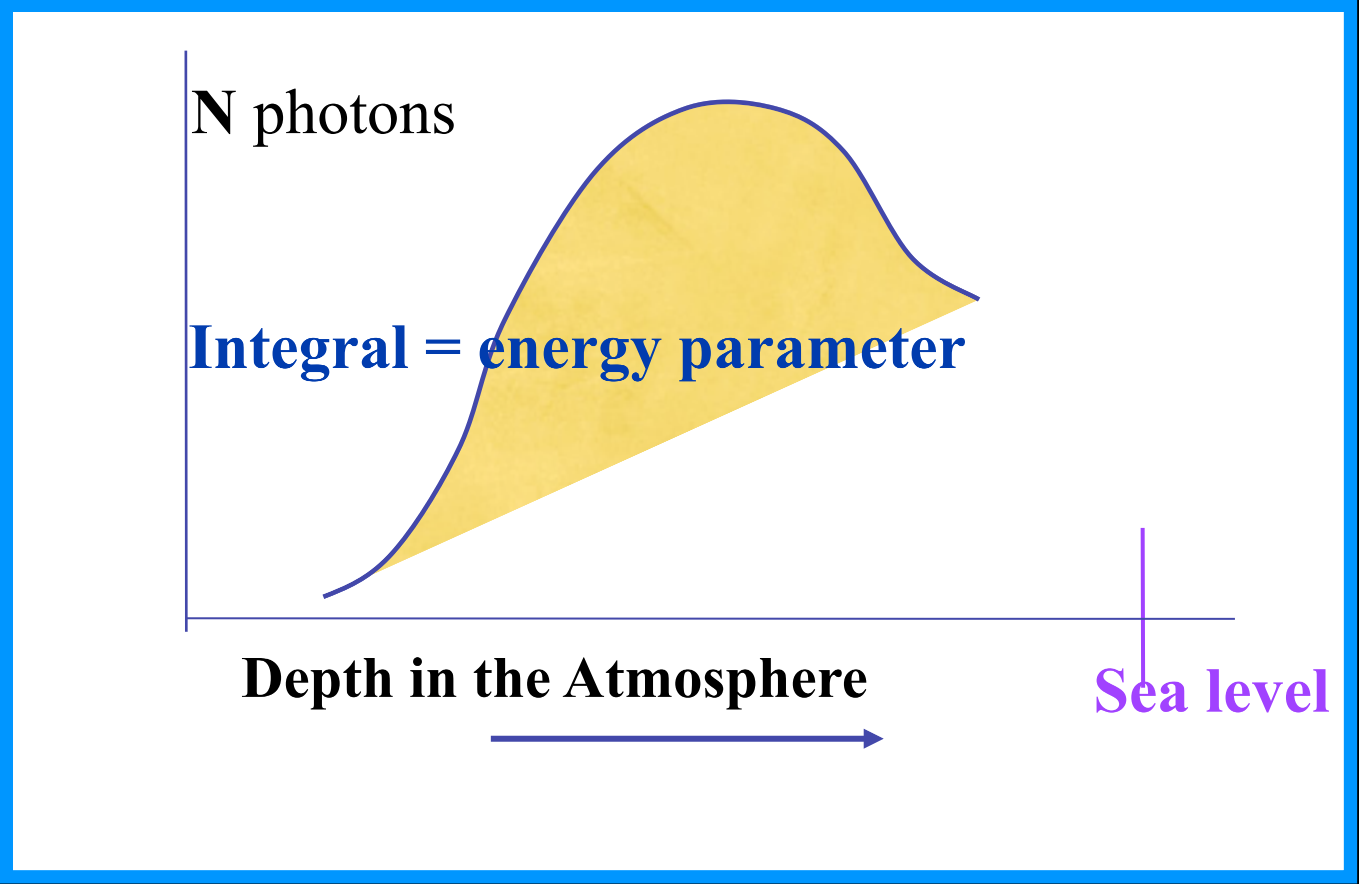
The angular resolution becomes ≈ 0.5 deg

ENERGY

Different energy estimators:

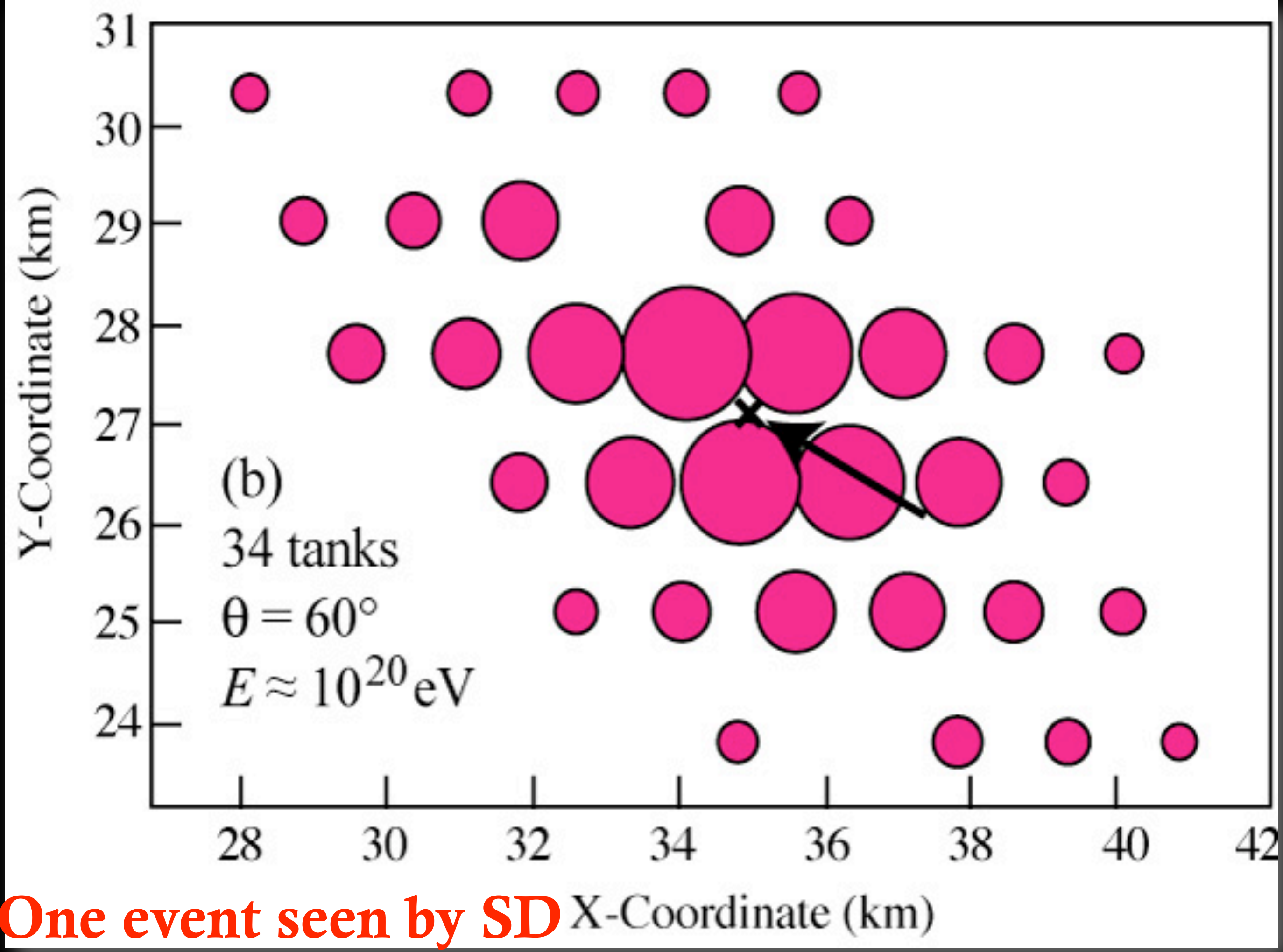
- **Number of electrons Ne**: at shower maximum Ne is proportional to primary energy (need of MC)
- **Lateral distribution of particles**: there is a distance, r_0, at which density fluctuations are minimal with respect to primary energy/mass: S (r_0) is the energy estimator (need of MC)
- **Number of muons Nμ** : less absorbed, "flatter" longitudinal development, less fluctuations. Less numerous than electrons, but ≈ independent of mass (need MC)
- **Cherenkov and fluorescence photons**: direct measurement of shower energy deposited in atmosphere (total number of Cherenkov photons; longitudinal shower profile). Model independent



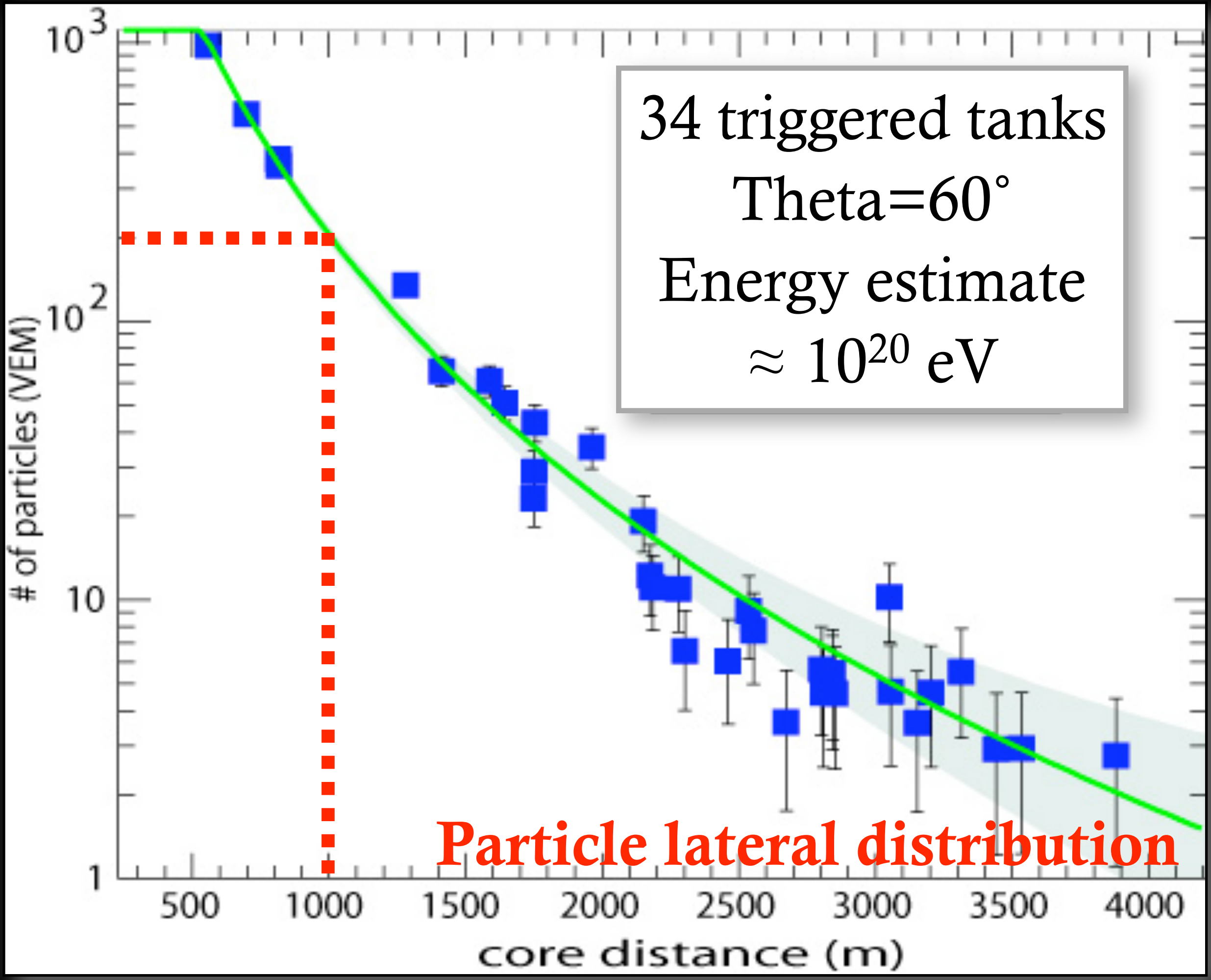


ENERGY DETERMINATION AT AUGER: I

Surface detector



One event seen by SD



34 triggered tanks
Theta=60°
Energy estimate
$\approx 10^{20}$ eV

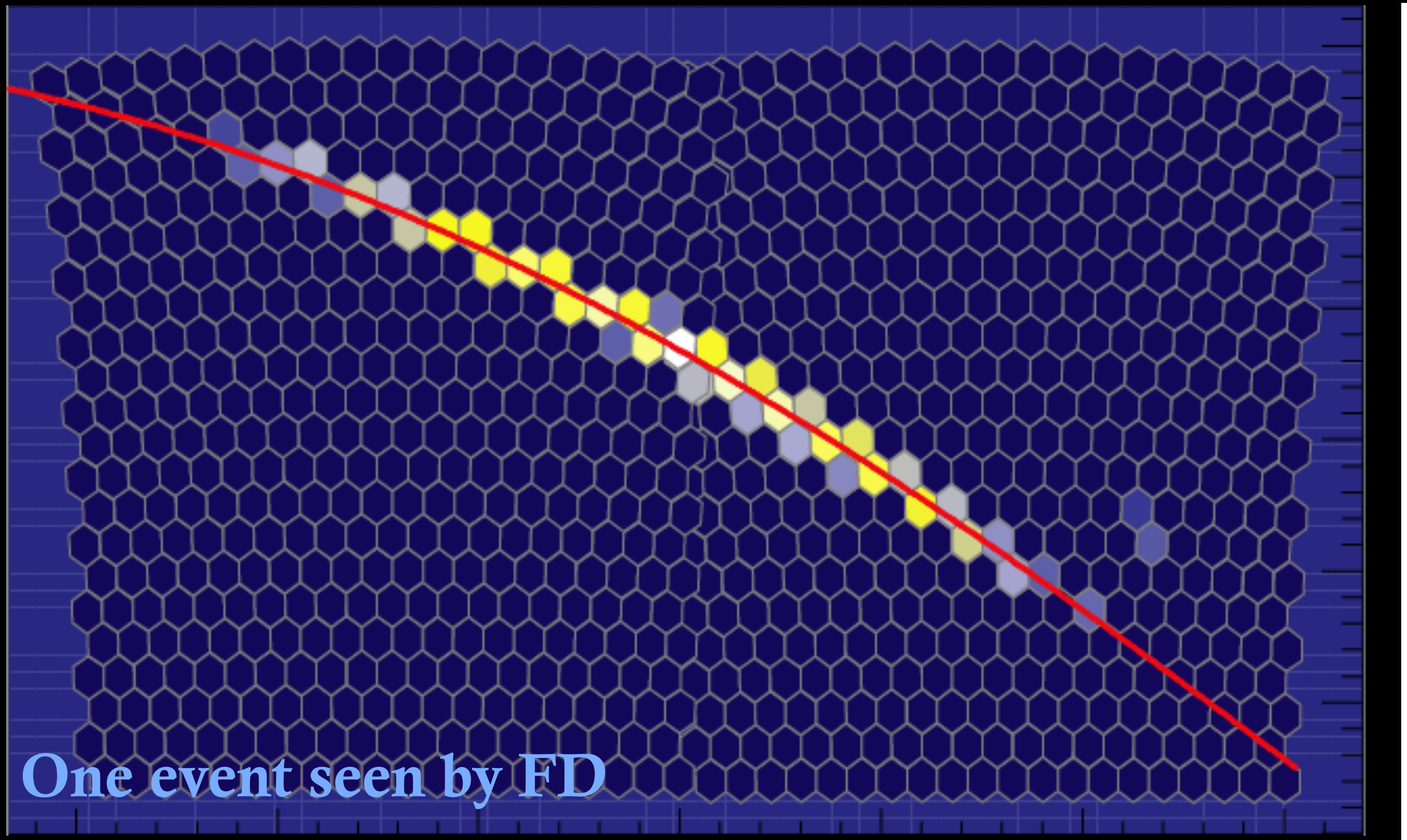
Particle lateral distribution

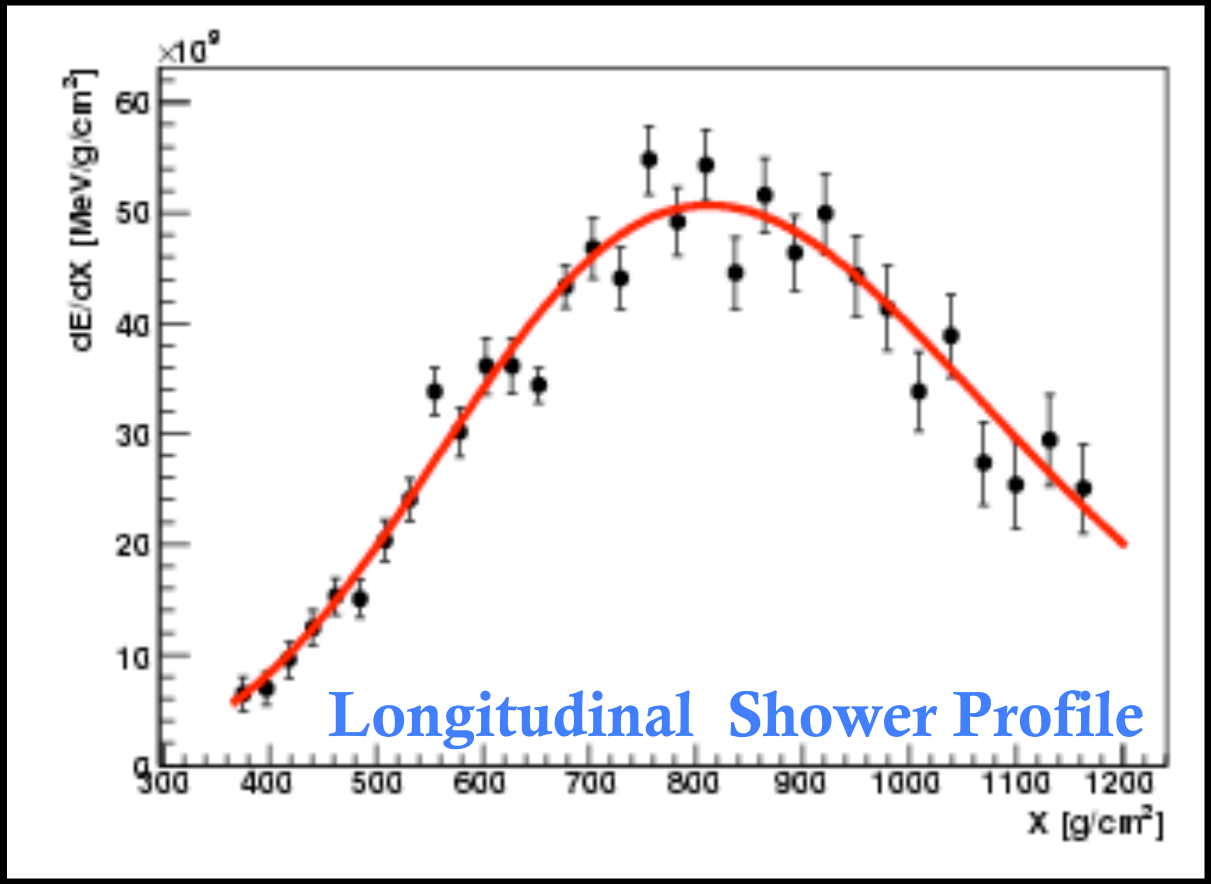
- Reconstruct geometry (arrival direction & impact point)
- Fit particle lateral distribution (LDF)
- S(1000) [signal at 1000 m] is the Auger energy estimator

  ("ideal" distance depends on detectors spacing)

ENERGY DETERMINATION AT AUGER: II

Fluorescence detector

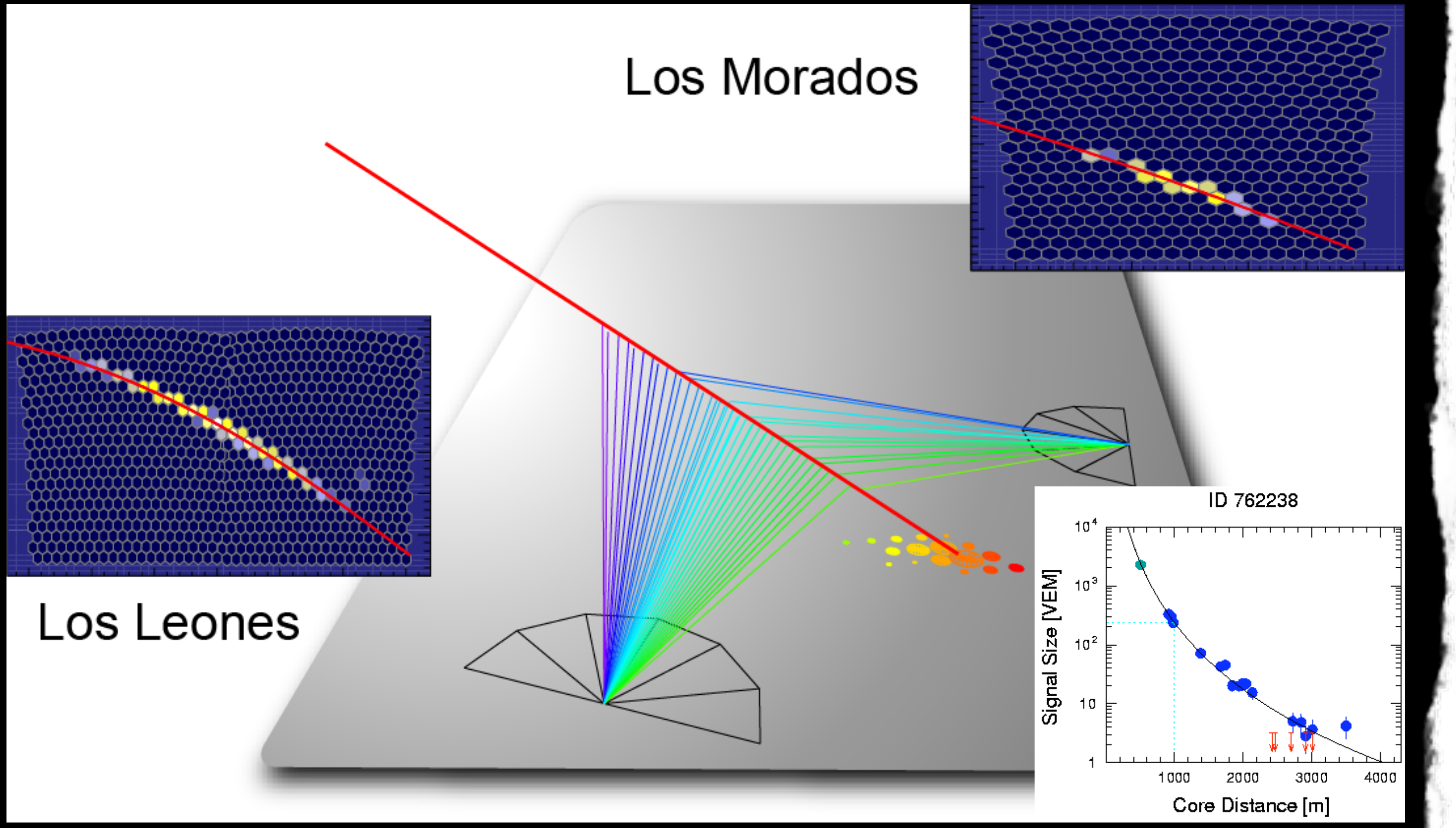


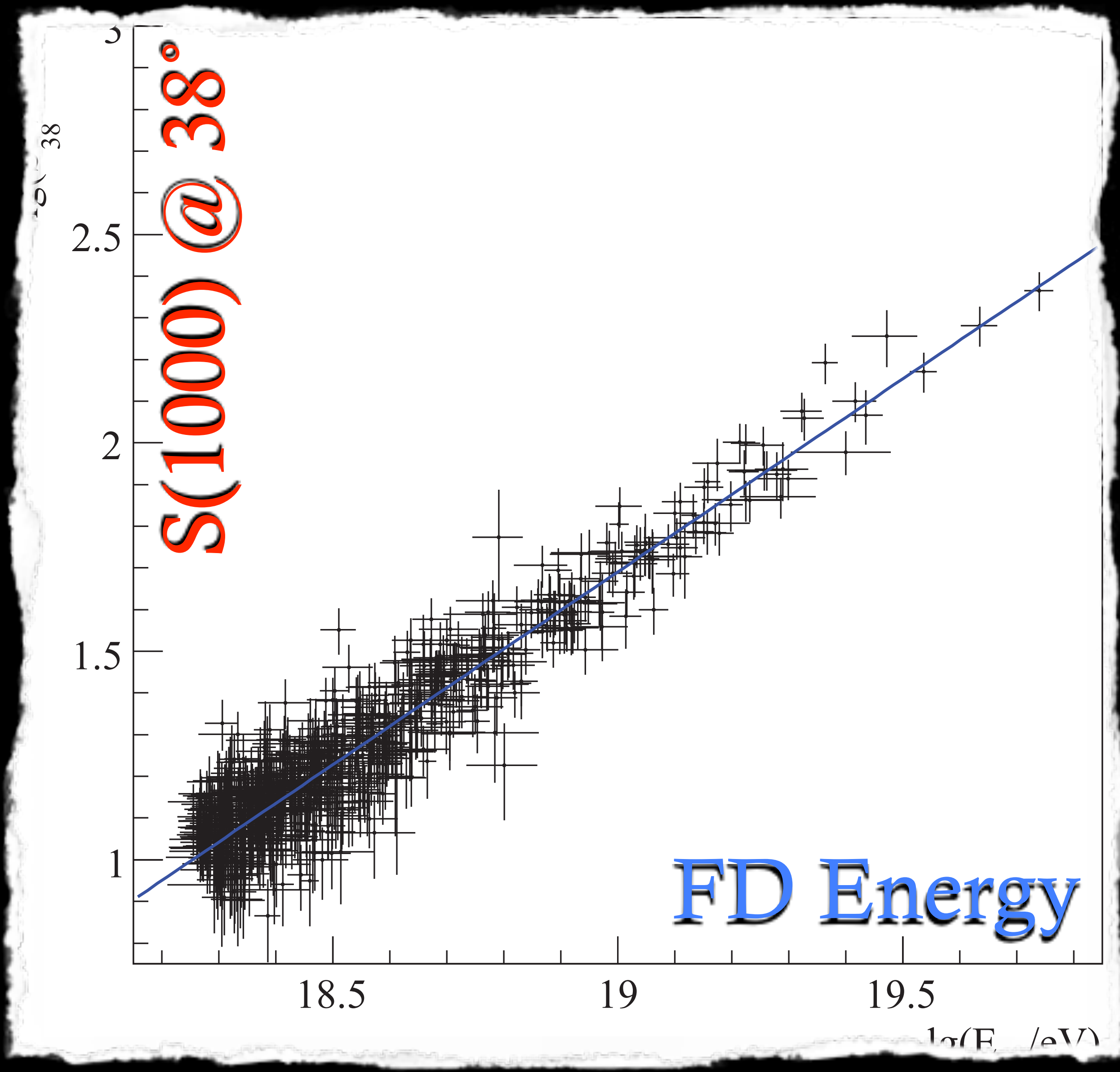


- Reconstruct geometry (shower detector plane, SDP, and shower axis in SDP)
- Fit longitudinal shower profile
- E ∝ area under the curve
- Calorimetric measurement

ENERGY DETERMINATION AT AUGER: III

Hybrid detector





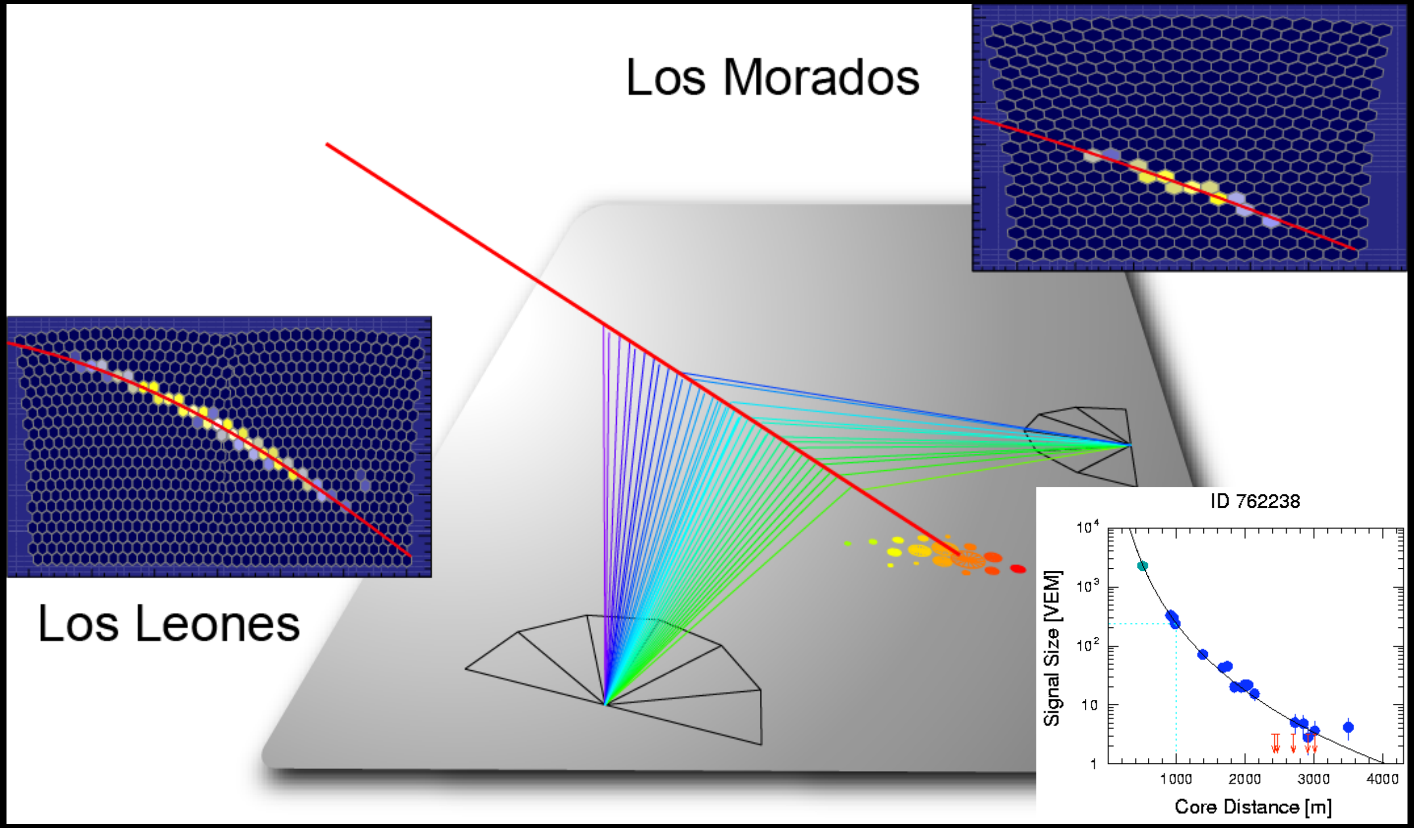
Hybrid Events are used to calibrate the SD energy estimator, S(1000)

[converted to the median zenith angle, S38]

with the FD calorimetric energy

ENERGY DETERMINATION AT AUGER: III

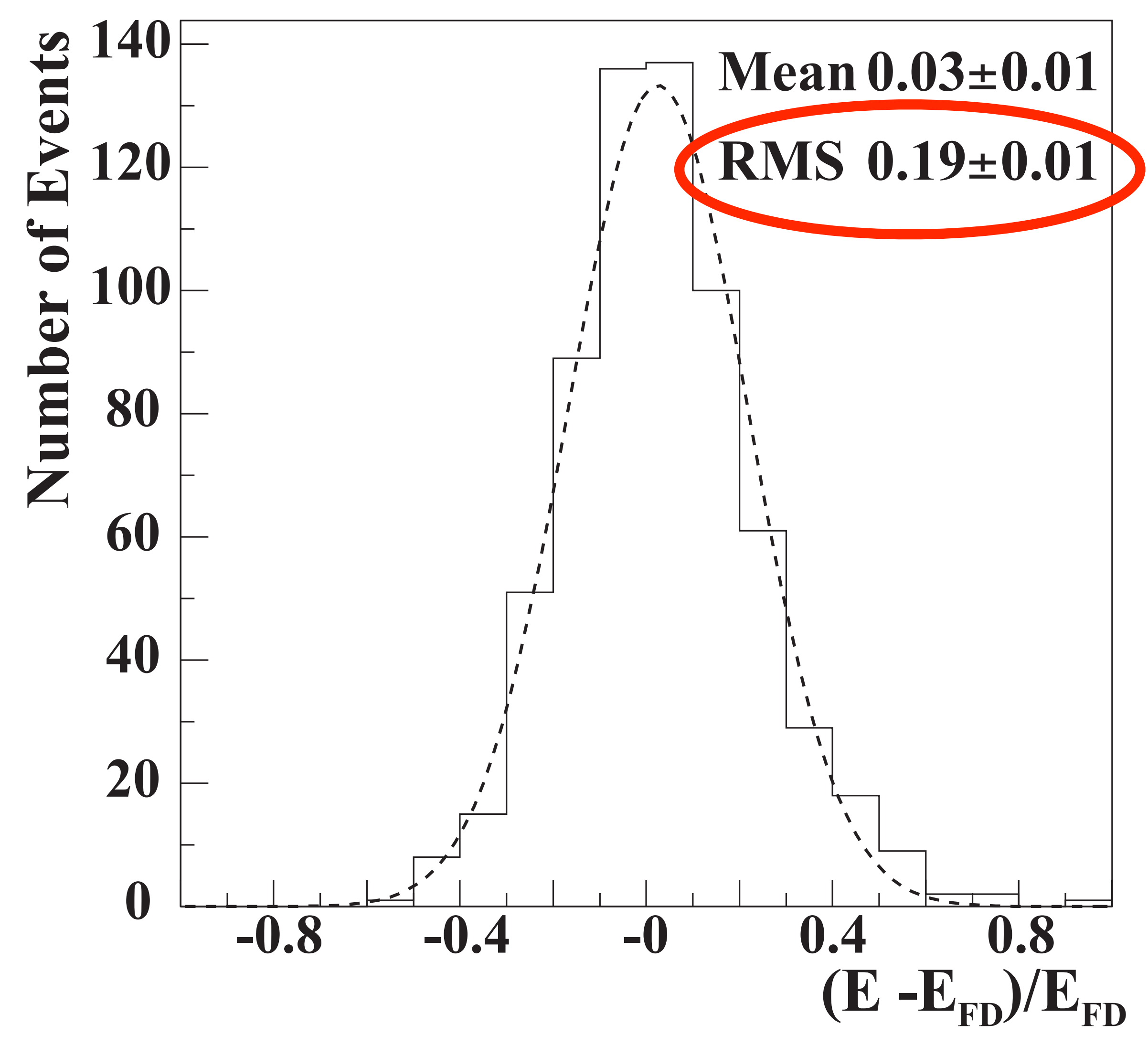
Hybrid detector



Absolute energy scale from FD

Source	Systematic uncertainty
Fluorescence yield	14%
P,T and humidity effects on yield	7%
Calibration	9.5%
Atmosphere	4%
Reconstruction	10%
Invisible energy	4%
TOTAL	22%

Largest systematics from fluorescence yield

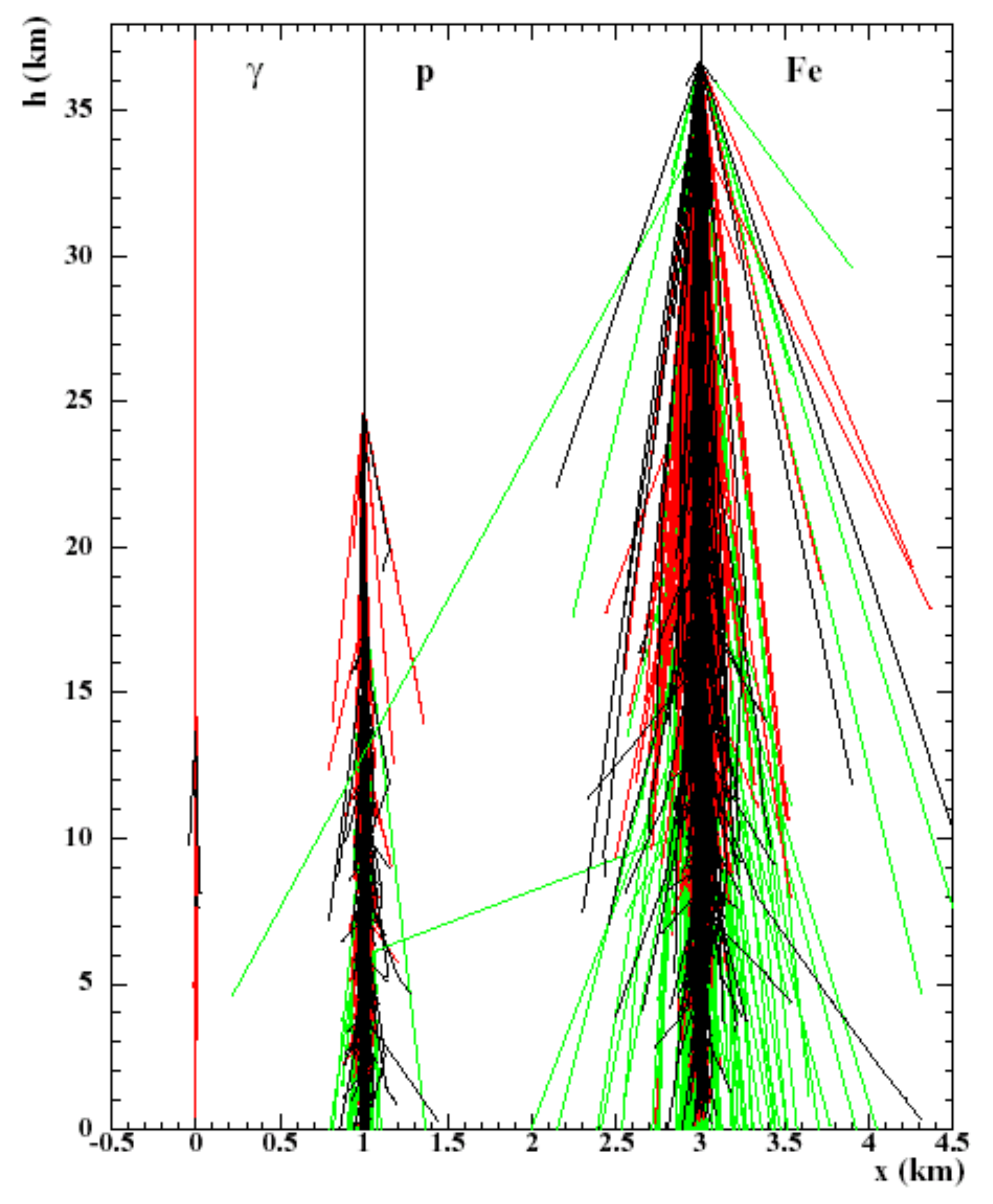


Energy resolution:

statistical ≈ 19%

systematical ≈ 22%

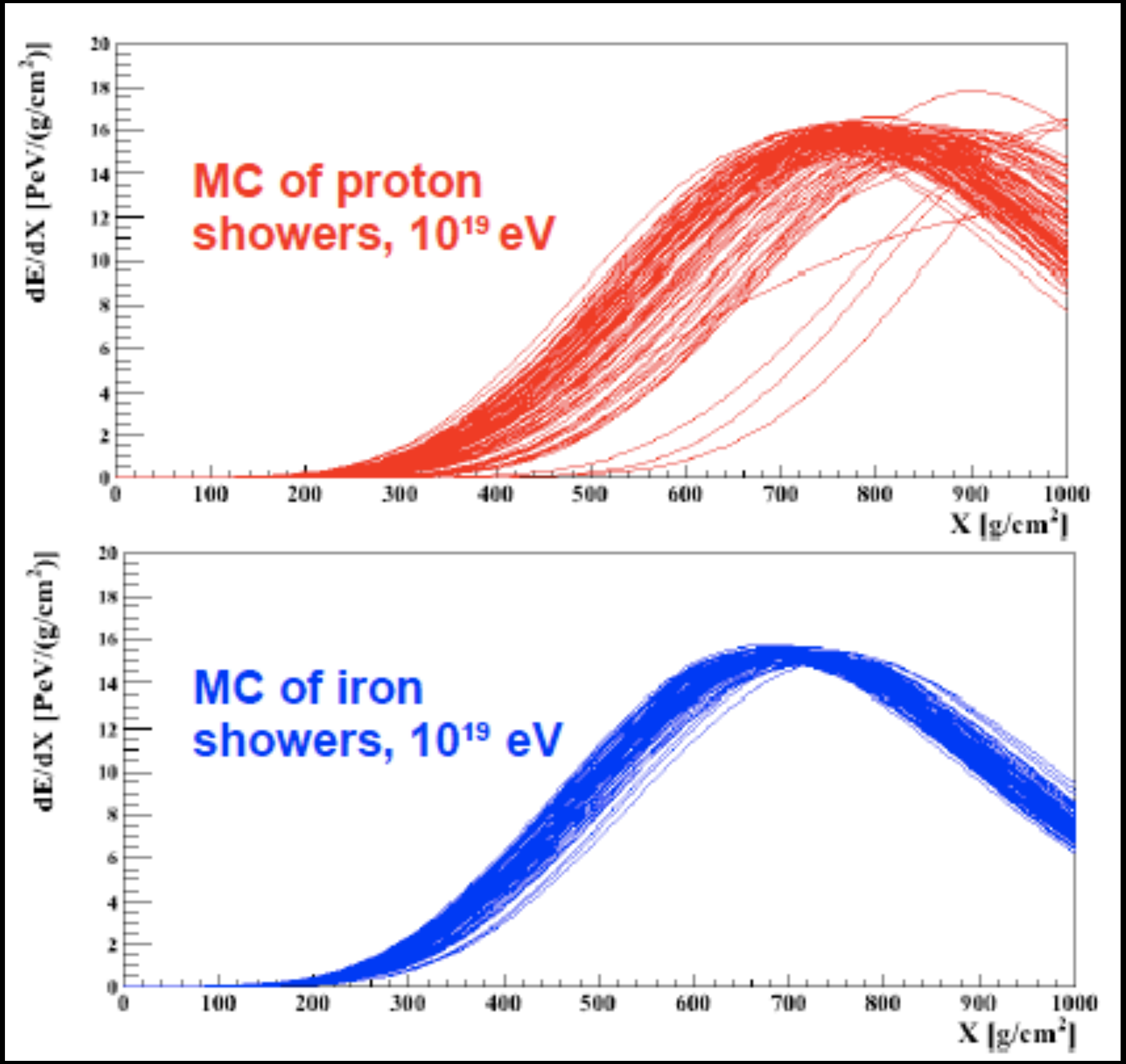
MASS COMPOSITION



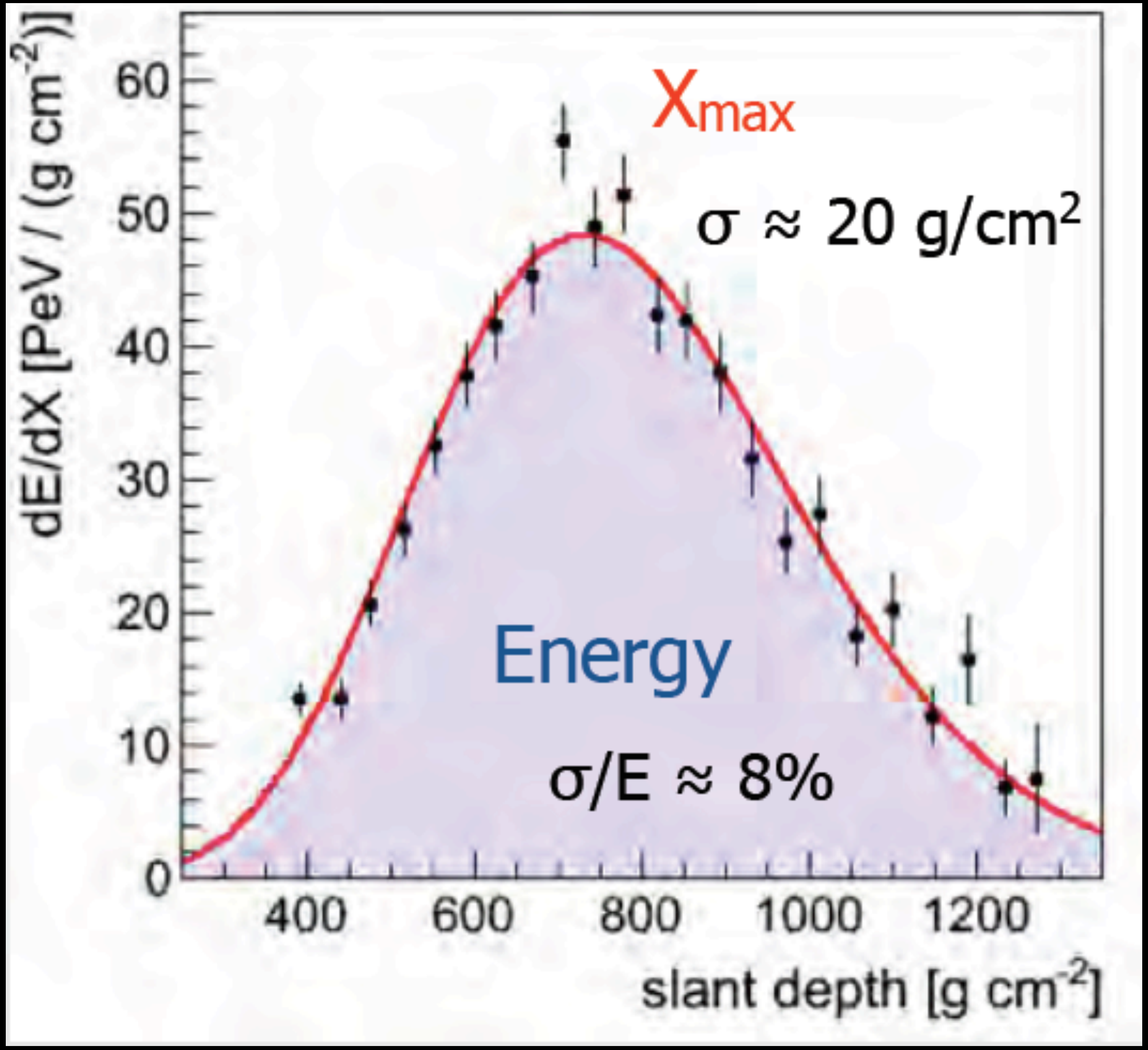
- Observables sensitive to composition:
  - Relative number of electrons and muons (primary nucleus produces more muons than a primary proton)
  - Depth of shower maximum (at fixed energy, a nucleus-shower develops faster than a proton-shower)
  - Shower front curvature (the higher the first interaction, the flatter the front)
- Subtlety of the analysis:
  - Great complexity: requires the use of shower simulations
  - Uncertainties in the simulations:
    - Sensitivity to nuclear models (interaction CR-air nucleus)
    - Energy domain not always covered by accelerators

MASS COMPOSITION WITH THE FLUORESCENCE DETECTOR

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



EAS development observed by FD: Xmax accuracy ≈ 20 g/cm2 (by "stereo" events)



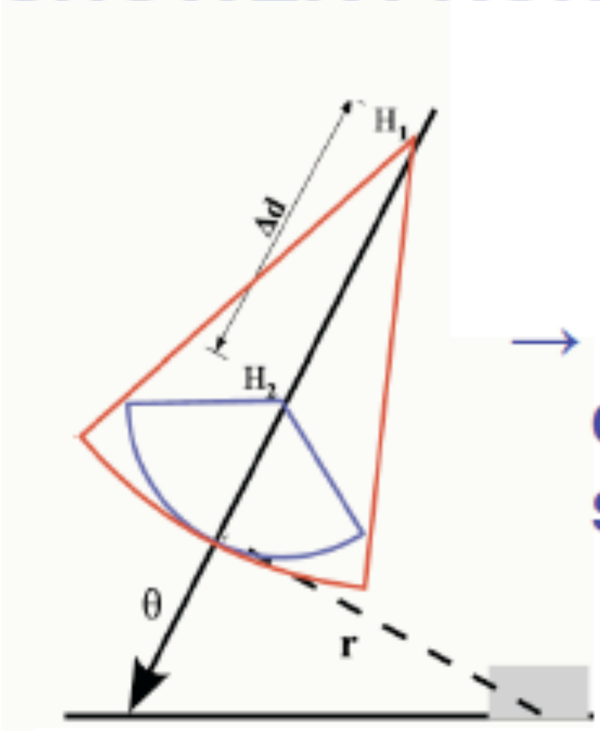
First interaction of heavy primaries is shallower and fluctuates less.
RMS(Xmax) mass sensitive too

N.B.: the "correspondence" XMAX-mass depends on extrapolations of hadronic models at UHE!

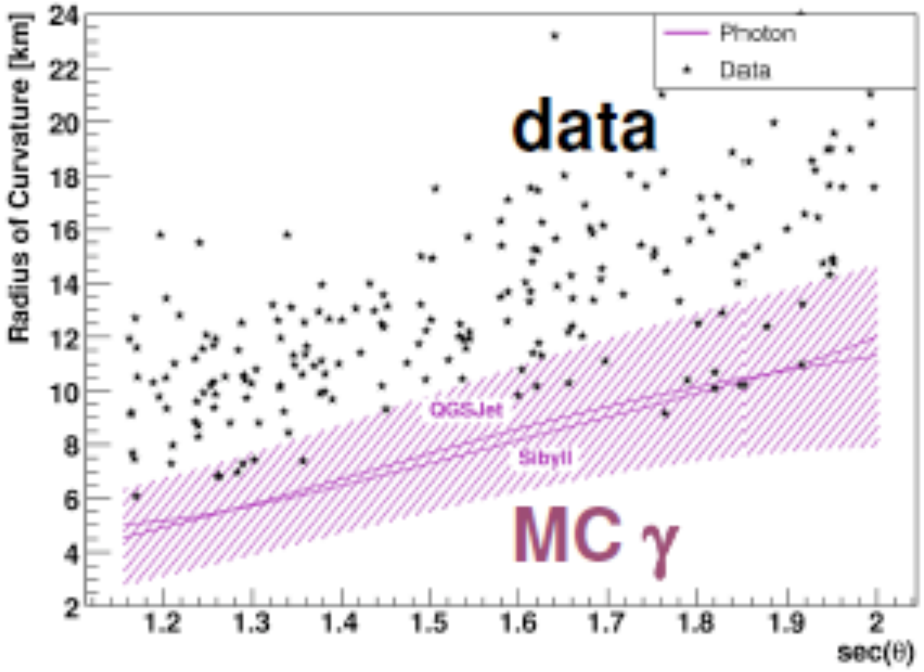
MASS COMPOSITION WITH THE SURFACE DETECTOR

PHOTONS: from EAS structure

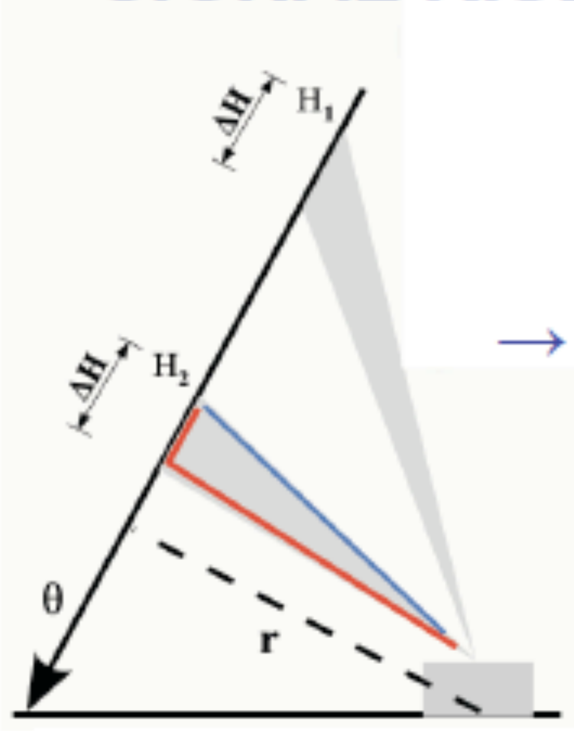
SHOWER FRONT CURVATURE



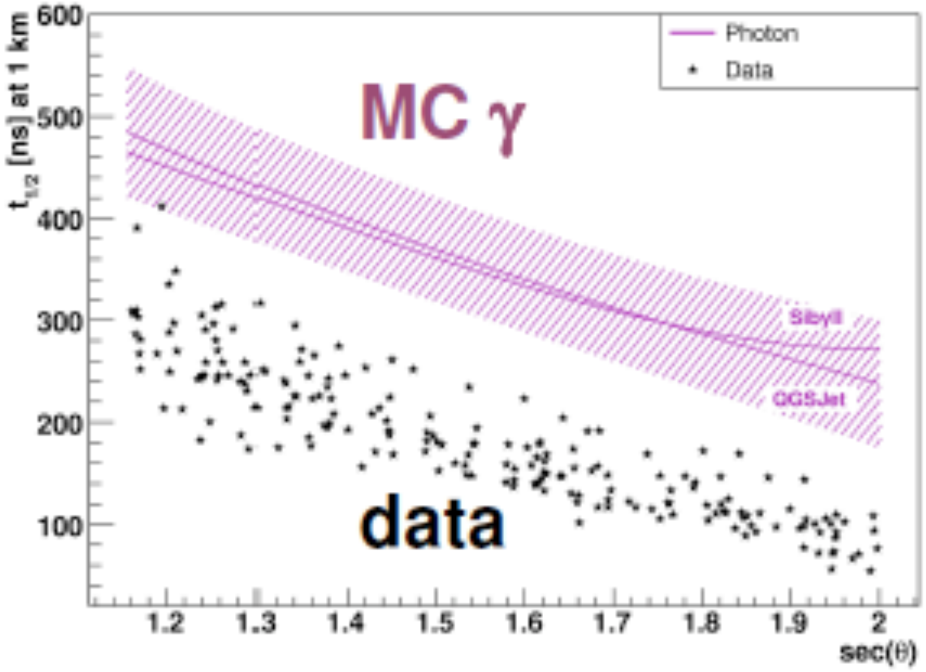
→ smaller radius of curvature of the shower front



SIGNAL RISE TIME

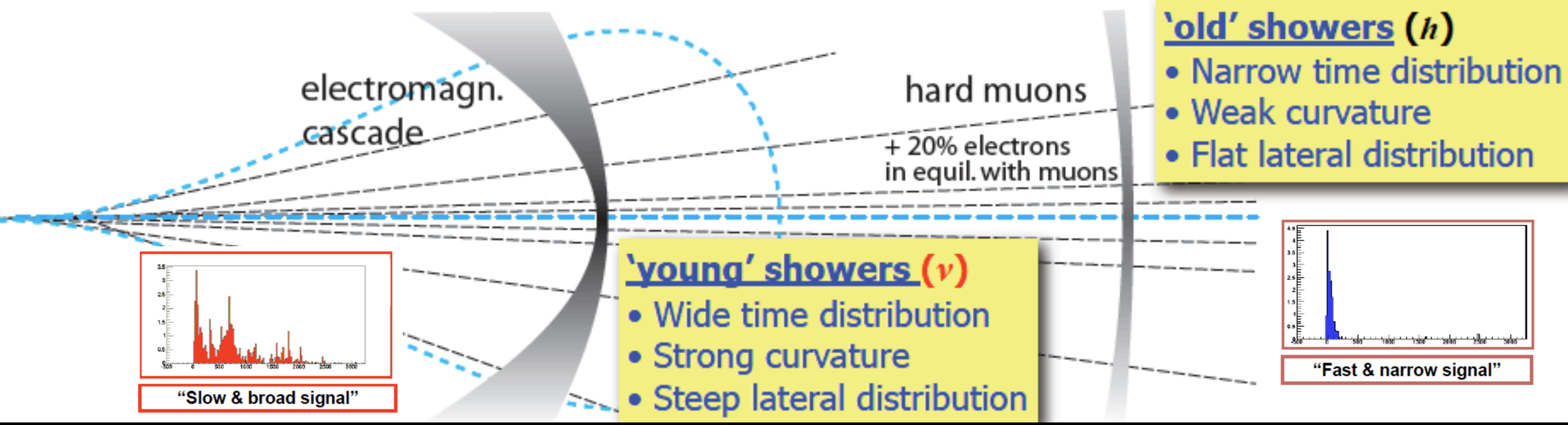


→ larger time spread and longer signal risetime



MASS COMPOSITION WITH THE SURFACE DETECTOR

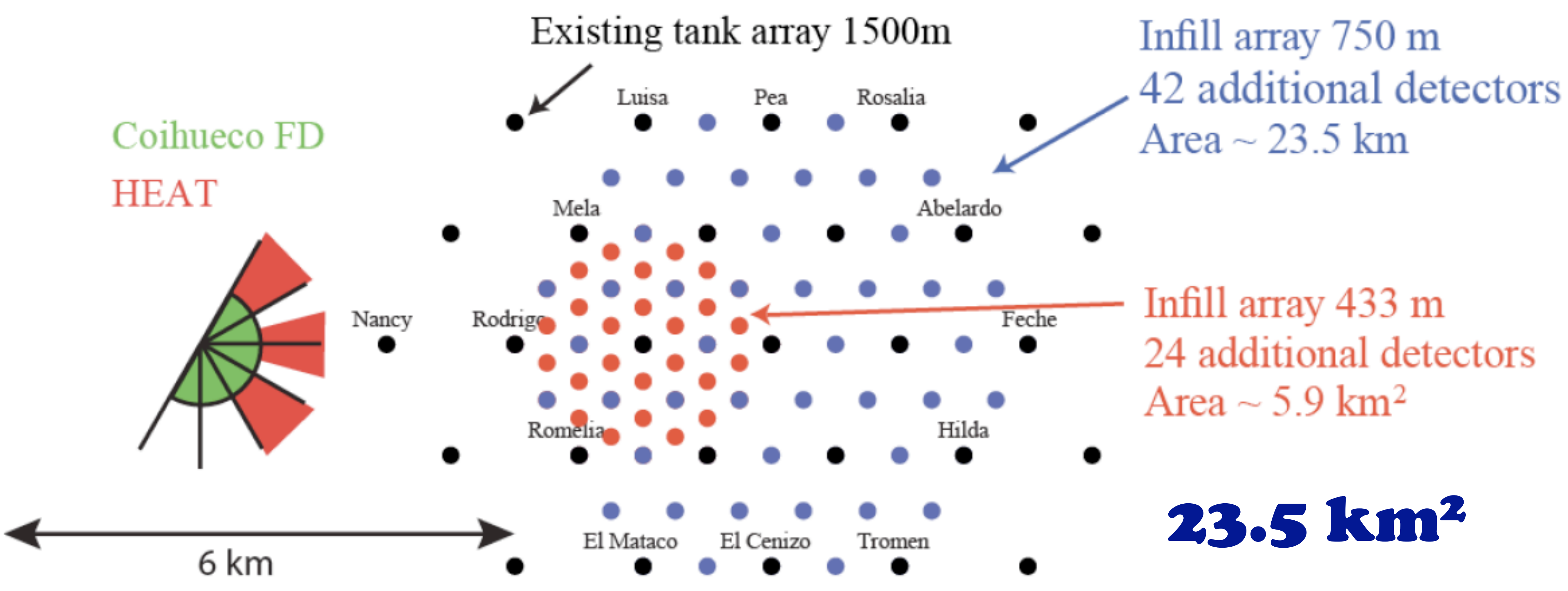
NEUTRINOS: from the "age" of horizontal showers



'young' showers (ν)
- Wide time distribution
- Strong curvature
- Steep lateral distribution

'old' showers (h)
- Narrow time distribution
- Weak curvature
- Flat lateral distribution

AUGER EXTENSION TO LOWER ENERGIES: AMIGA and HEAT



Existing tank array 1500m

Infill array 750 m
42 additional detectors
Area ~ 23.5 km

Infill array 433 m
24 additional detectors
Area ~ 5.9 km²

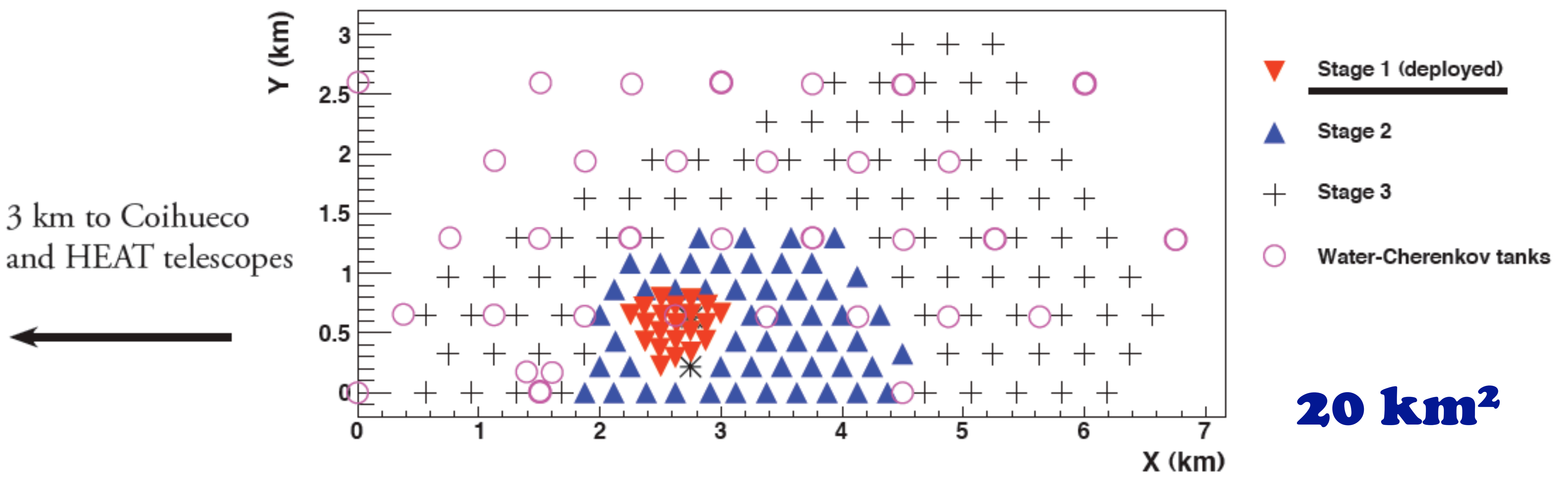
23.5 km²

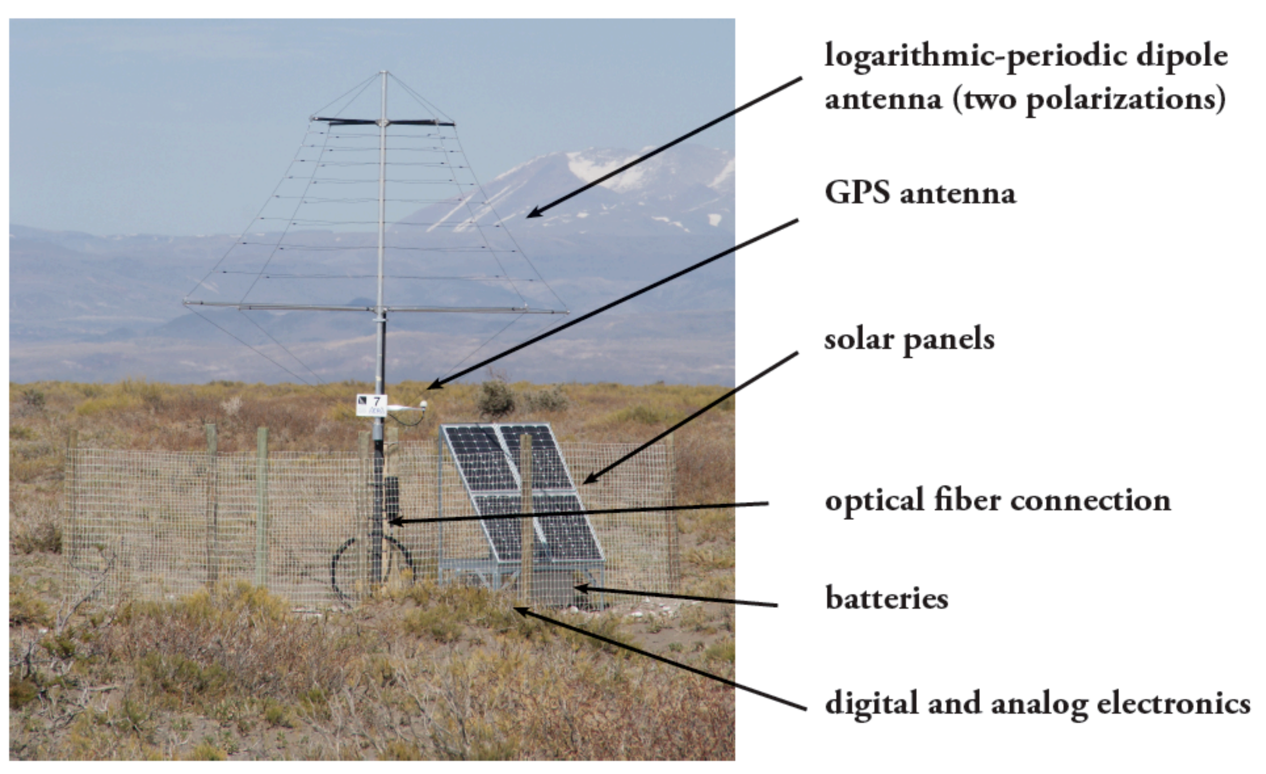
HEAT: 3 additional FD telescopes looking "higher" in the sky

AMIGA: denser EAS array: water Cherenkov + buried muon counters

- "Hybrid" detector: **61 (+24)** water Cherenkov (Infill) + **3** fluorescence detectors (Heat)
- Infill fully efficient above **0.3 EeV** (**100% d.c**), Heat&&Infill above **0.1 EeV** (but ≈ **13%** d.c.)
- Infill stations and HEAT in operation. Muon counters under construction.
- Nominal Infill: ≈ **700** (**20**) (**4**) events/month above **3x 10^{17}** (**10^{18}**) (**3x 10^{18}**) **eV**

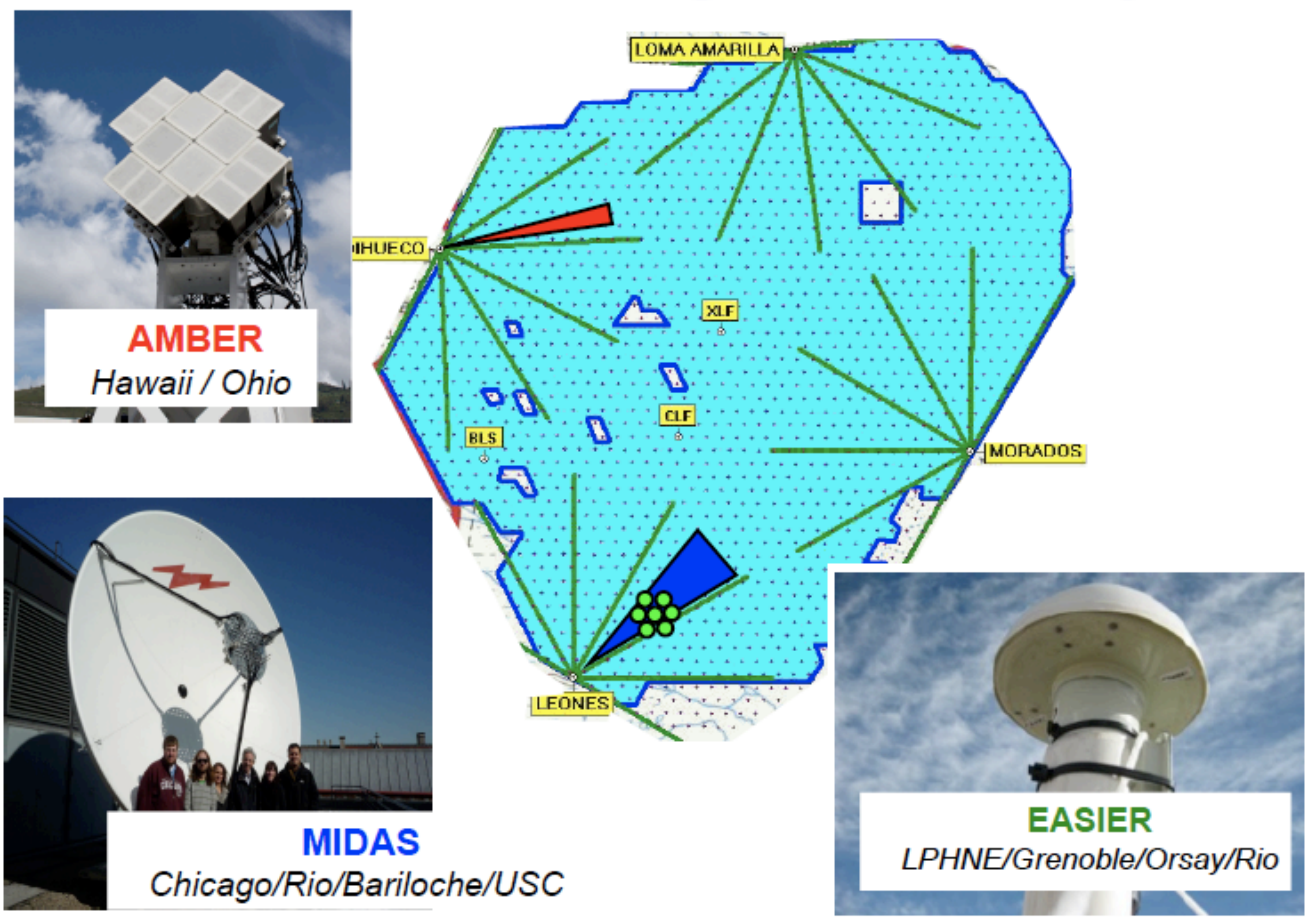
AUGER EXTENSION TO RADIO-TECHNIQUES: AERA





- Foreseen layout: 160 antennas over 20 km2 (spacing 250-350 m)
- Currently: 21 150 m spaced antennas (since Sept 2010)
- Aim: “FD-like” detector (EAS longitudinal development), but with > 90% d.c.
- Energy threshold: ≈ 10^{17} eV

GHz R&D AT THE PIERRE AUGER OBSERVATORY



AMBER
Hawaii / Ohio

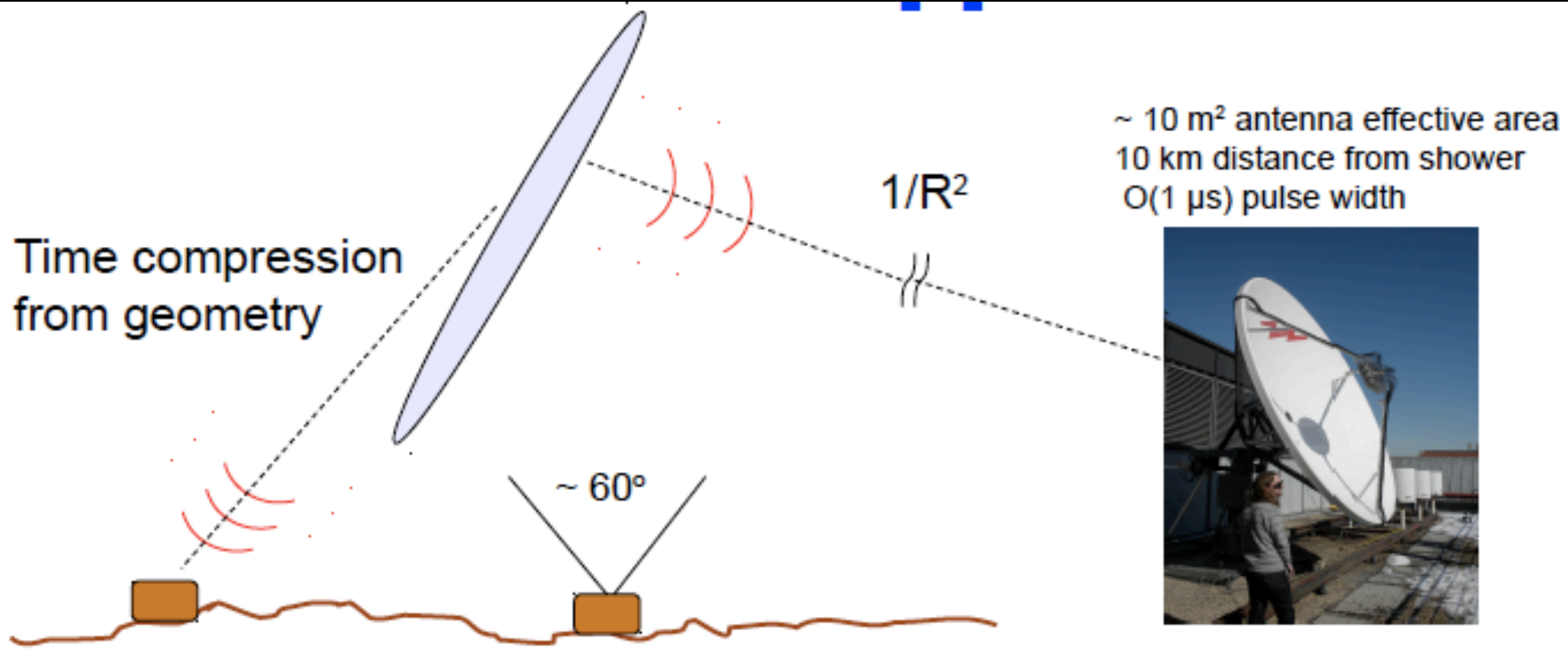
MIDAS
Chicago/Rio/Bariloche/USC

EASIER
LPHNE/Grenoble/Orsay/Rio

Credit Pedro Facal

GHz R&D AT THE PIERRE AUGER OBSERVATORY

Two different approaches



~ 10 m² antenna effective area
10 km distance from shower
O(1 μs) pulse width

0.003 m² antenna effective area
Large field-of-view
1 km distance from shower
O(100 ns) pulse width

EASIER: install a wide aperture antenna at the Surface Detector stations

MIDAS/AMBER: use a parabolic dish reflector instrumented with an array of feeds, 'Radio fluorescence'.

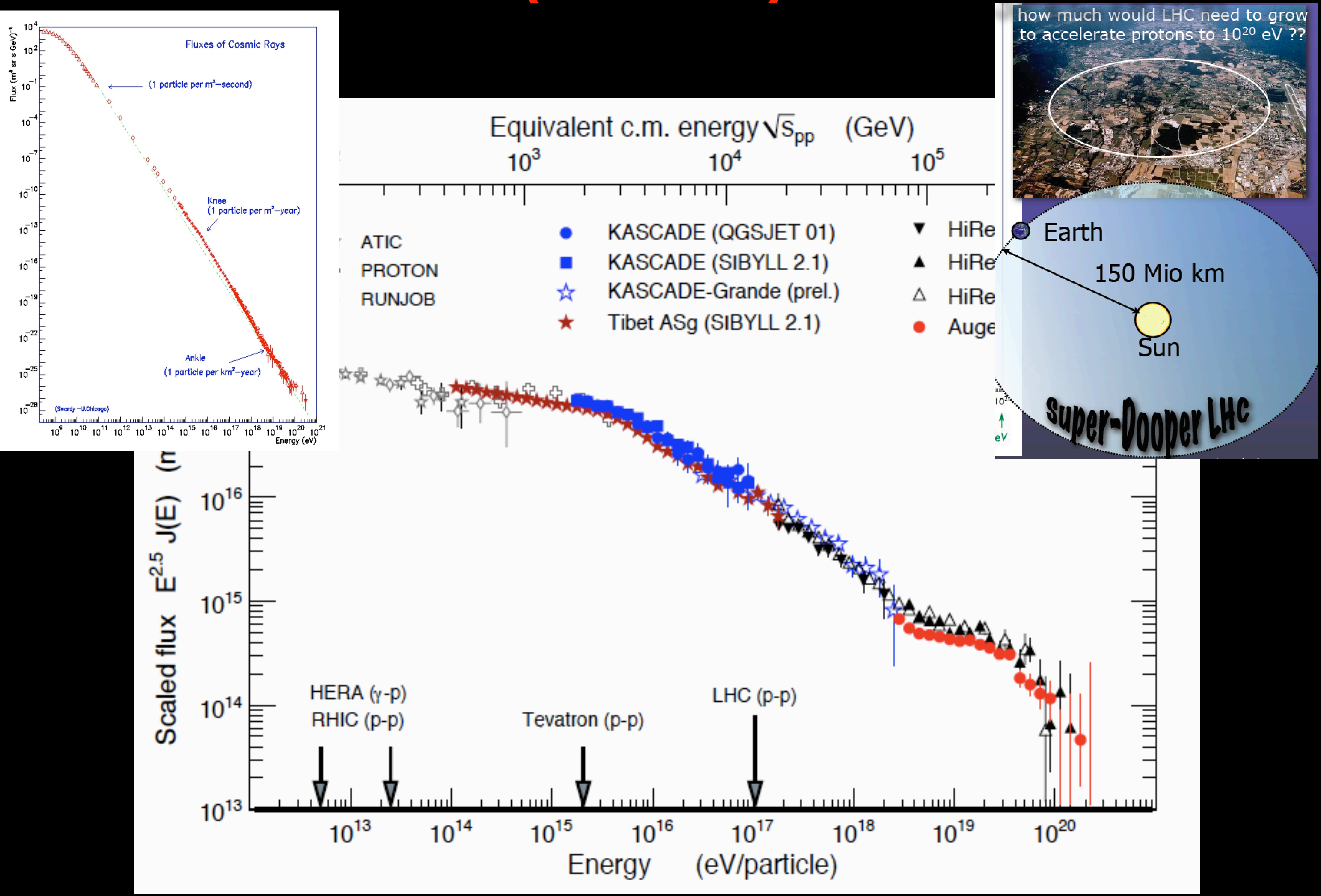
Credit Pedro Facal

Conclusions

Why do we study cosmic rays?

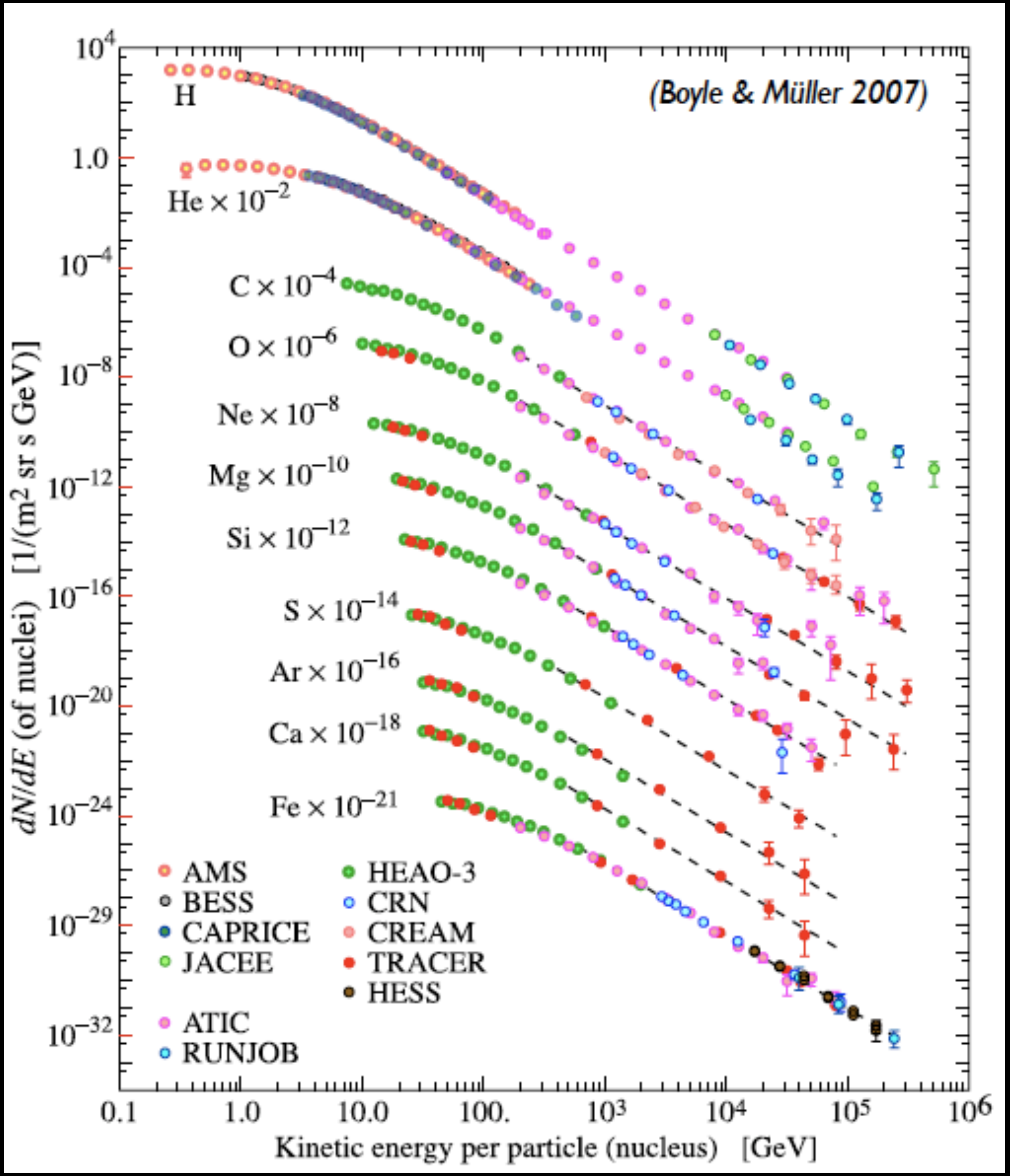
(not only because we are adventurous
or because measurements are challenging ;-)

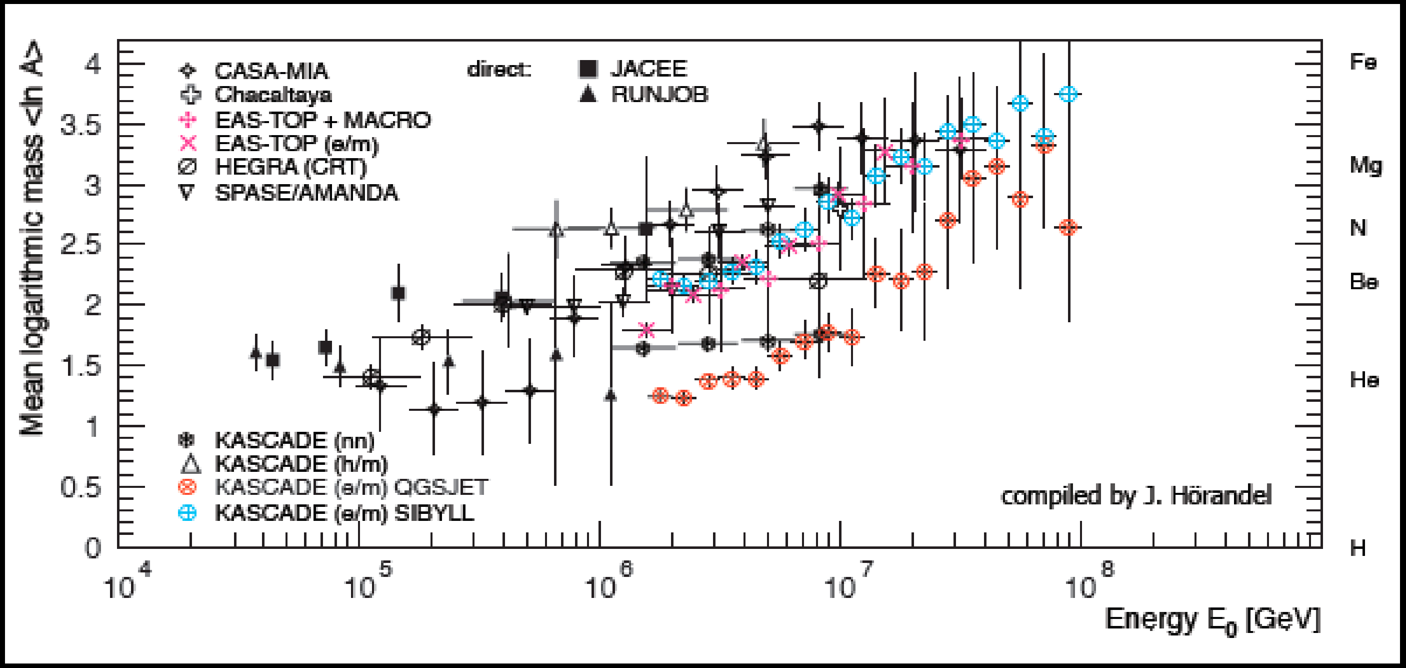
BECAUSE OF THEIR (AMAZING) ENERGY SPECTRUM

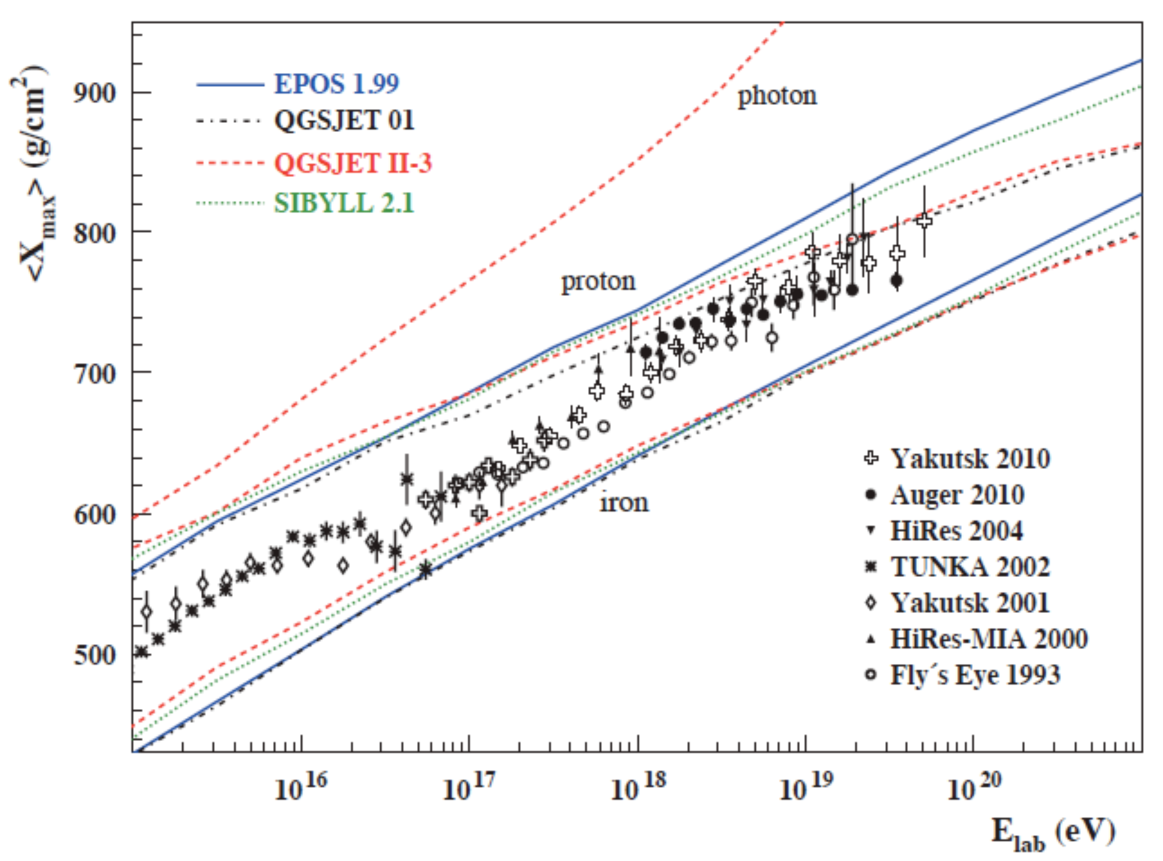


how much would LHC need to grow to accelerate protons to 10^{20} eV ??

BECAUSE WE DO NOT KNOW WHAT EXACTLY THEY ARE





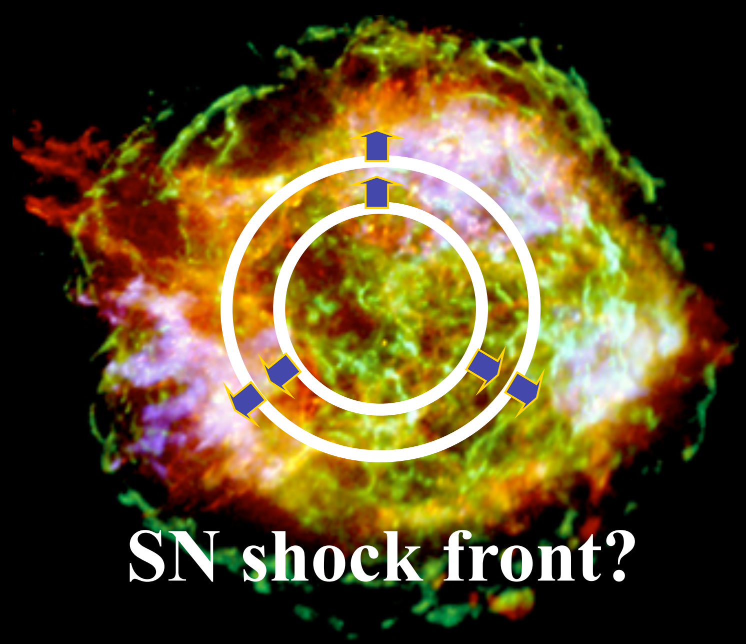


Well...we know quite well their composition at lower energies

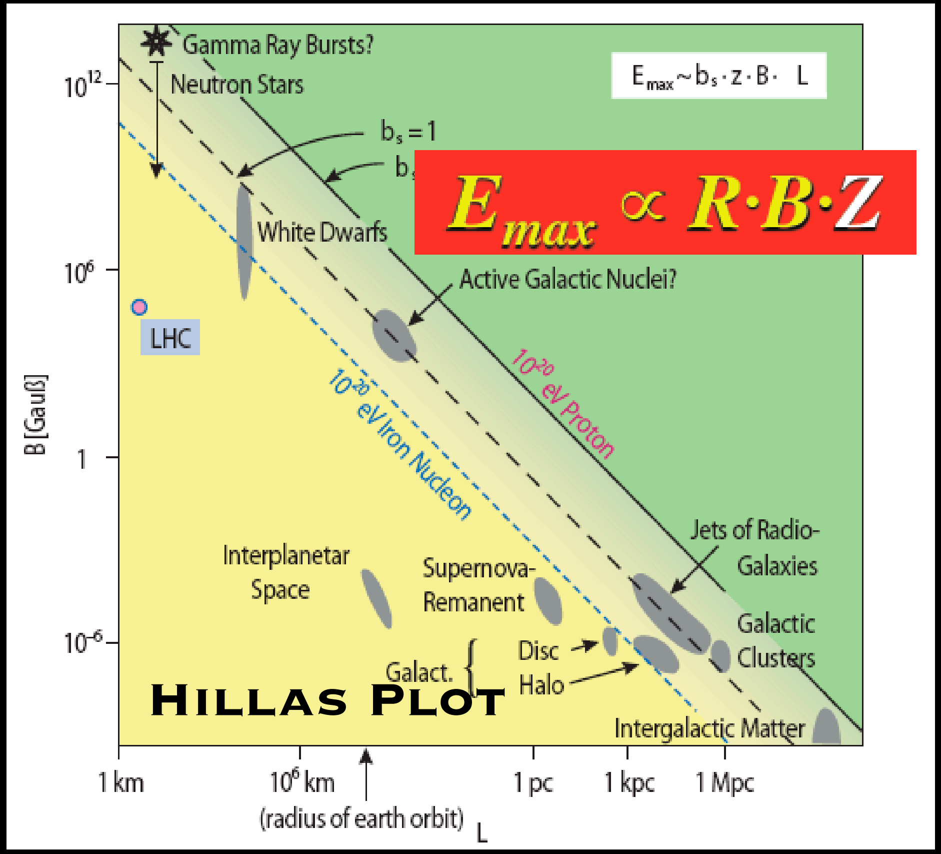
...But at higher ones the situation is still quite confused...

BECAUSE WE WOULD LIKE TO IDENTIFY THEIR SOURCES...

	PRODUCTION	PROPAGATION
GALACTIC CRS	Fermi mechanism: diffusive shock acceleration. Natural power law. Cutoff energy of different elements ≈ Z Best candidates: SNR	Galactic CRs completely diffused and isotropized by GMF. CR-astronomy not possible. γ-rays and neutrinos smoking-gun
EXTRA-GALGALACTIC CRS	Source size & magnetic field constraint to accelerate CRs to the highest energies: AGNs, GRBs,Radiogalaxies lobes …	Highest energy (low-Z) CRs marginally deflected by GMF. CR-astronomy possible



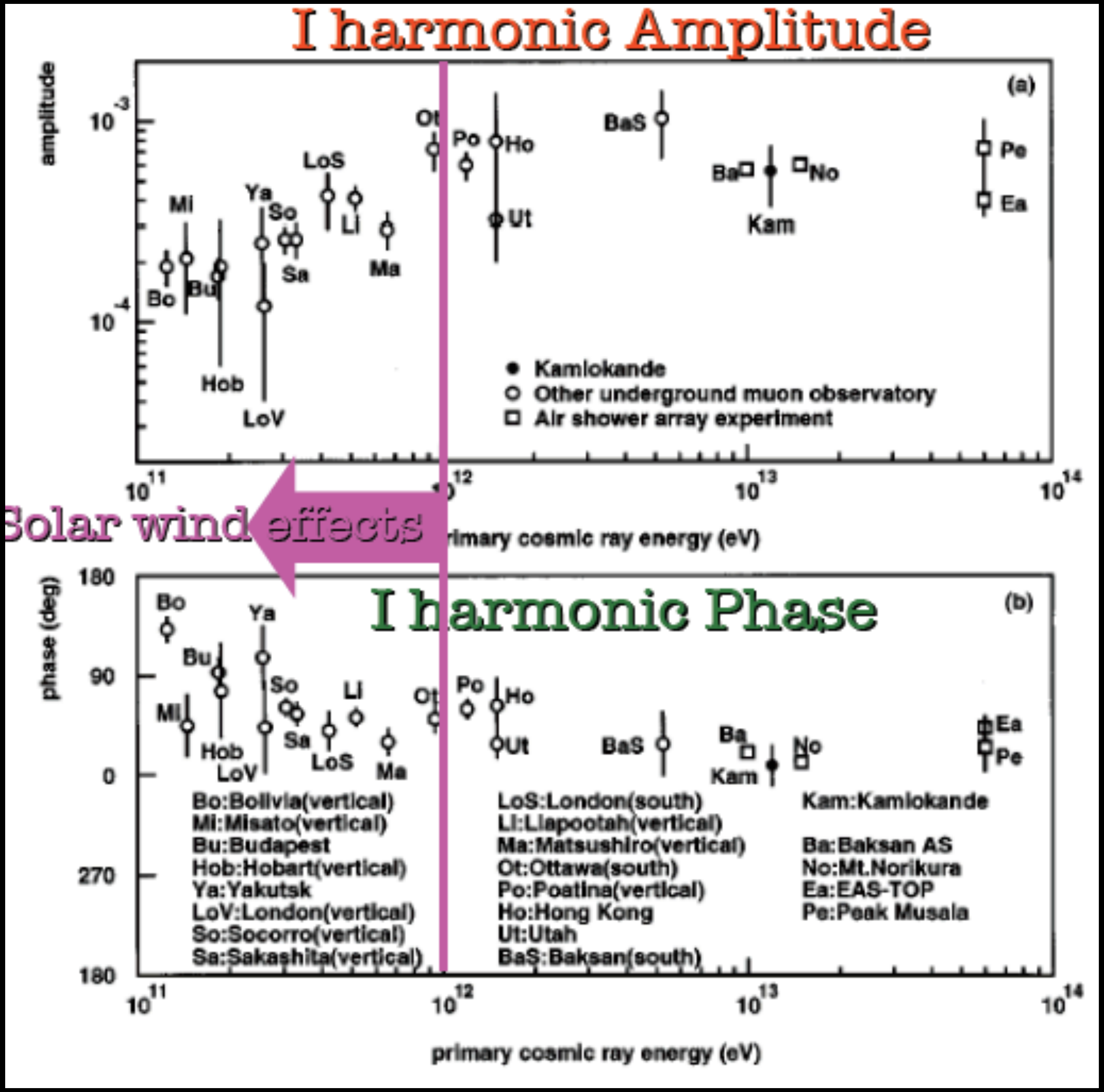
SN shock front?

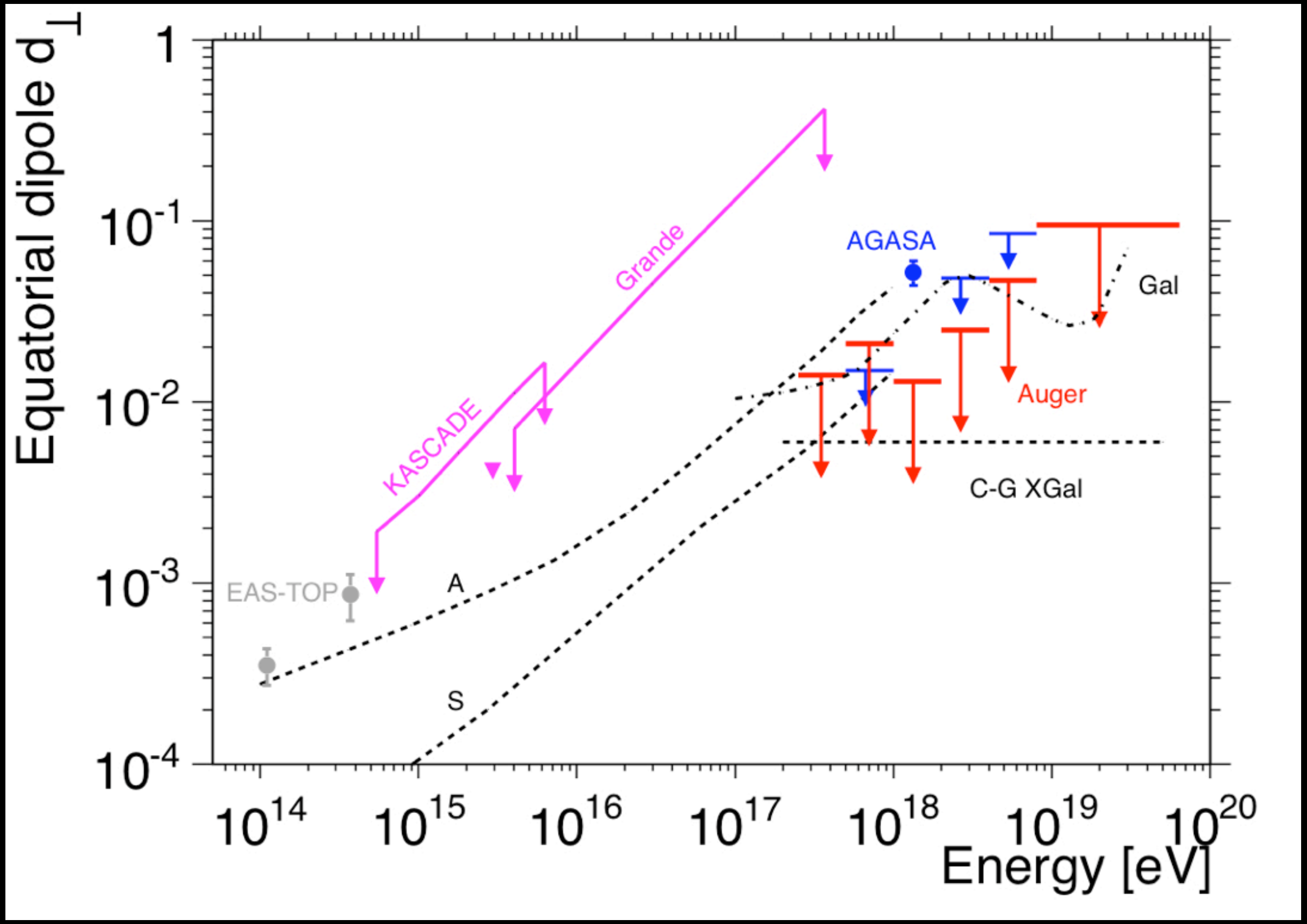


$E_{max} \propto R \cdot B \cdot Z$

HILLAS PLOT

ALTHOUGH WE KNOW THEY ARE QUITE ISOTROPIC...





The distribution of arrival directions of high-energy cosmic rays is remarkably uniform, anisotropy only being detected at the level of less that 0.1%.

...WE MAY HAVE SOME HINTS...

Gammas from SNR: are they from electrons or hadrons?

Will the correlation between Auger events and extra-galactic nearby matter be confirmed by other experiments and/or an increased dataset? Do we need a proton/heavy discriminator (gamma-astronomy-like?)

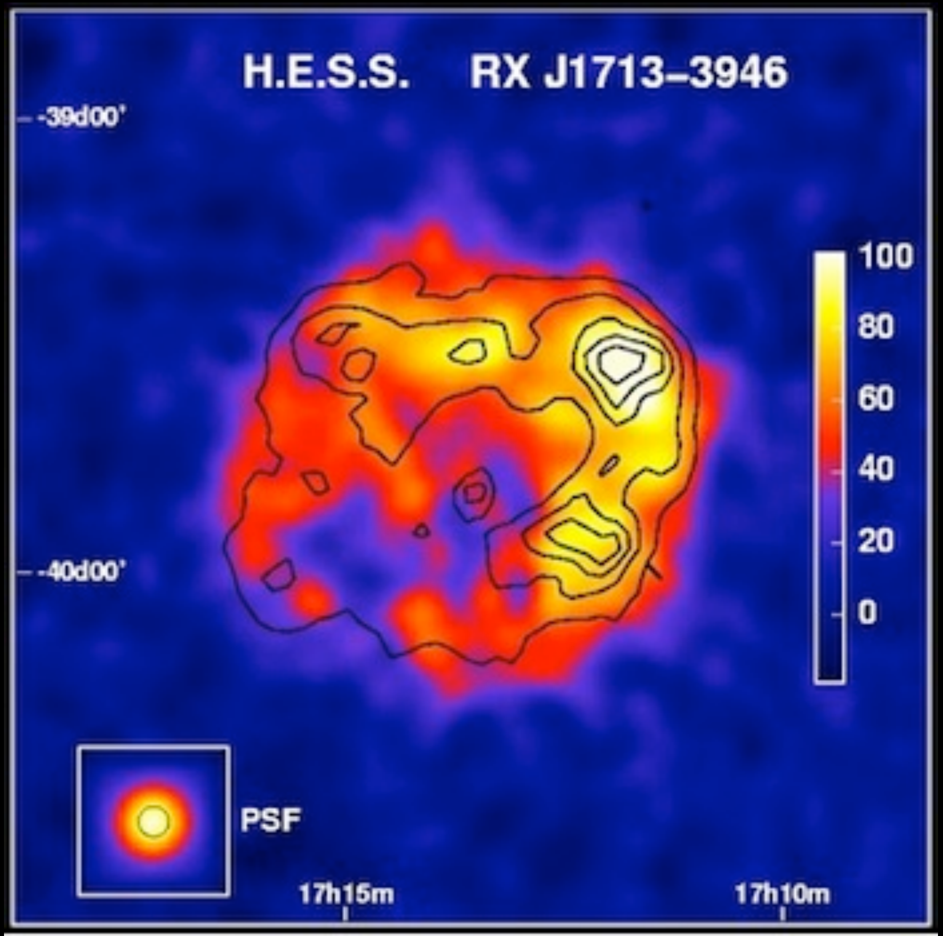
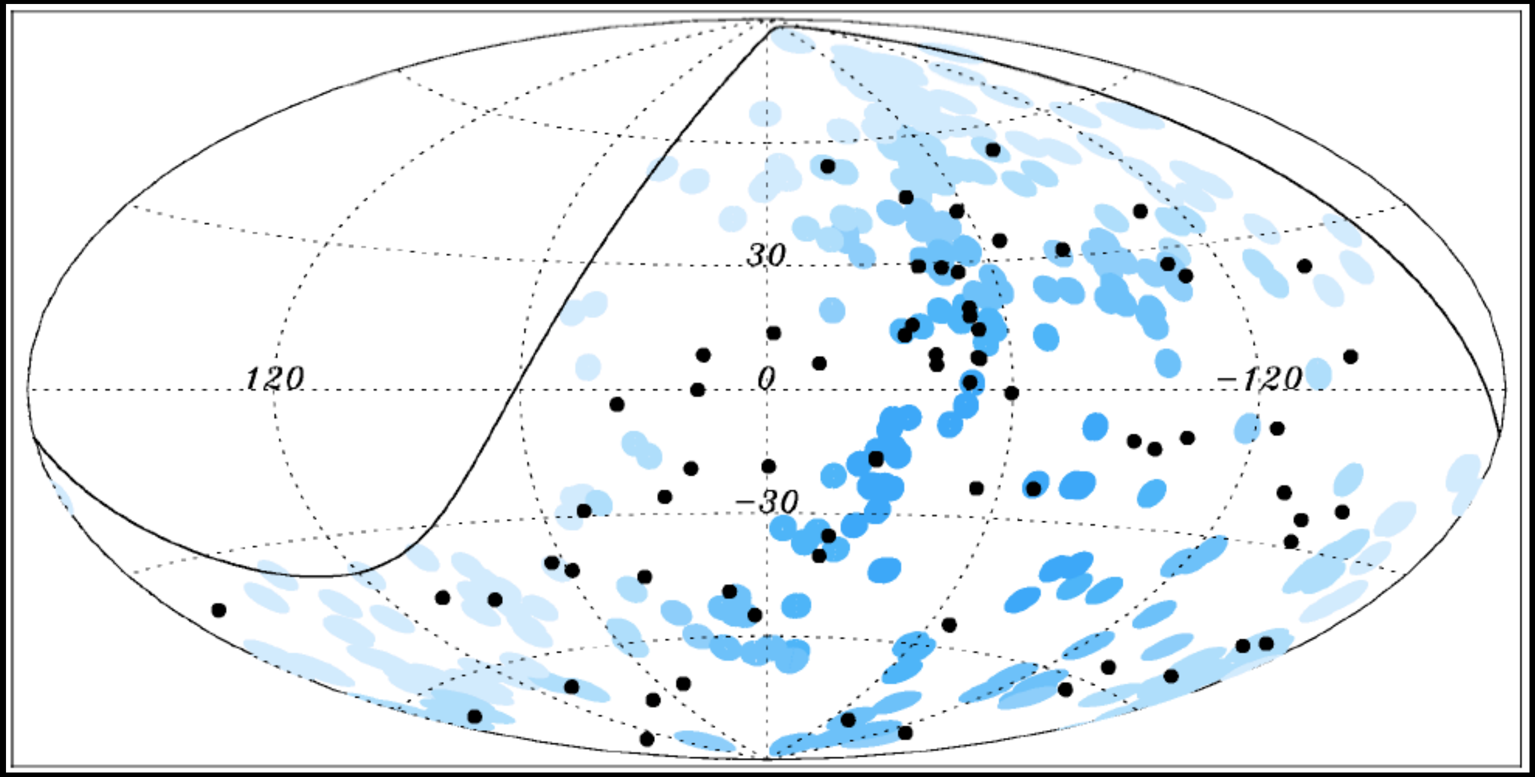


Image of a SNR in gamma (HESS experiment)



Distribution of Auger events (E>50 EeV) in the sky vs AGNs positions

THANKS FOR LISTENING

AND THANKS TO THE ORGANZIERS....