

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

Piera L. Ghia (CNRS, IJCLab, Orsay)

HAWC, Mexico



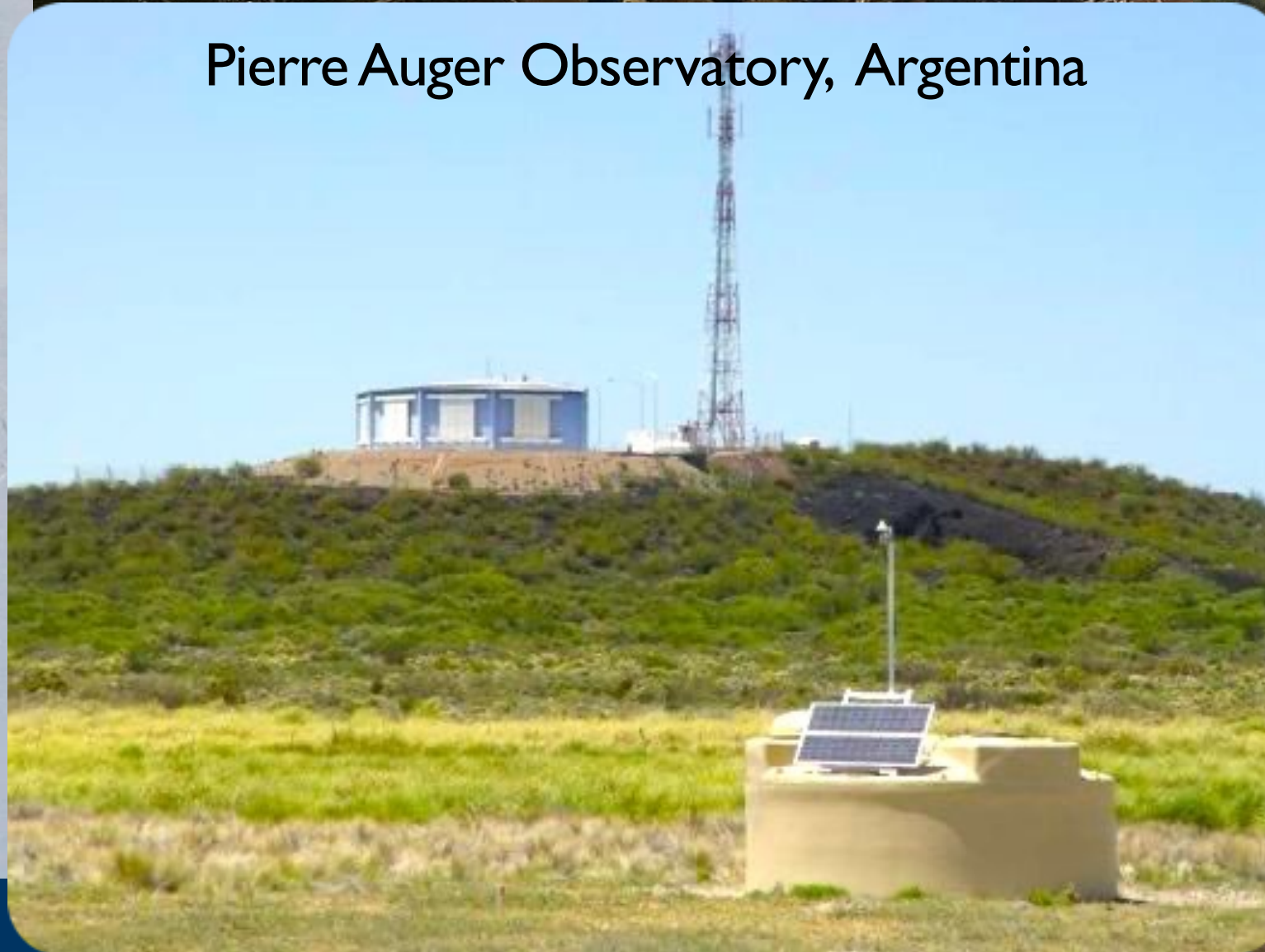
LHAASO, China



TUNKA, Siberia



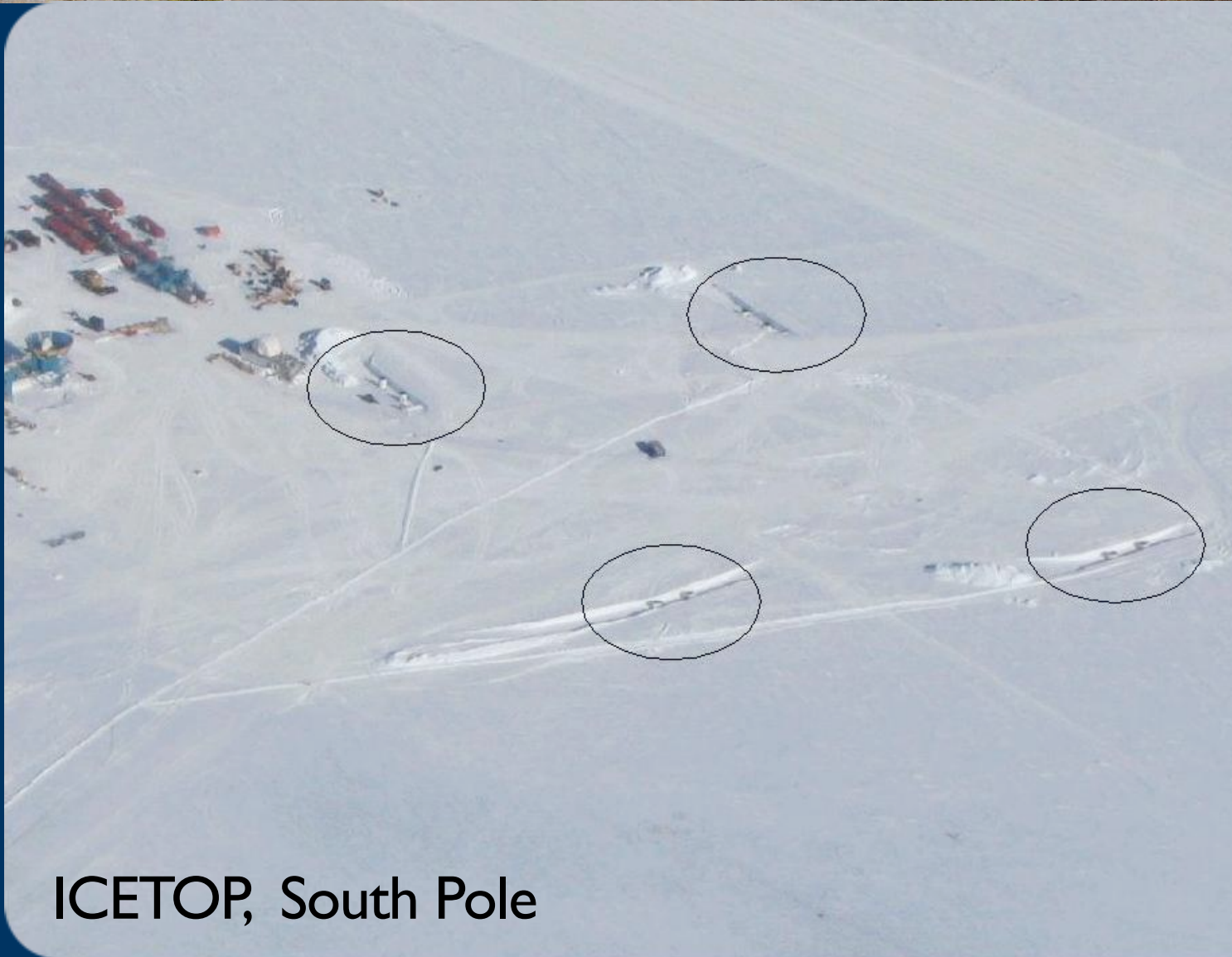
Pierre Auger Observatory, Argentina



Telescope Array, Utah



ICETOP, South Pole



Tibet AS-gamma, Tibet



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

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

(from Bruno Rossi, “Cosmic Rays”, foreword, 1964)

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

Outline

PROLOGUE: why detecting Extensive Air Showers?

Extensive Air Shower detection: an historical perspective

(The minuteness of the phenomena -

The adventurous excursions of the observers)

Modern Extensive Air Shower detectors

(The minuteness of the phenomena -

The adventurous excursions of the observers)

EAS observables: two exemplary instruments

(The delicacy of the observations)

From EAS observables to cosmic rays properties

(The subtlety of the analysis)

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

Outline (Part I)

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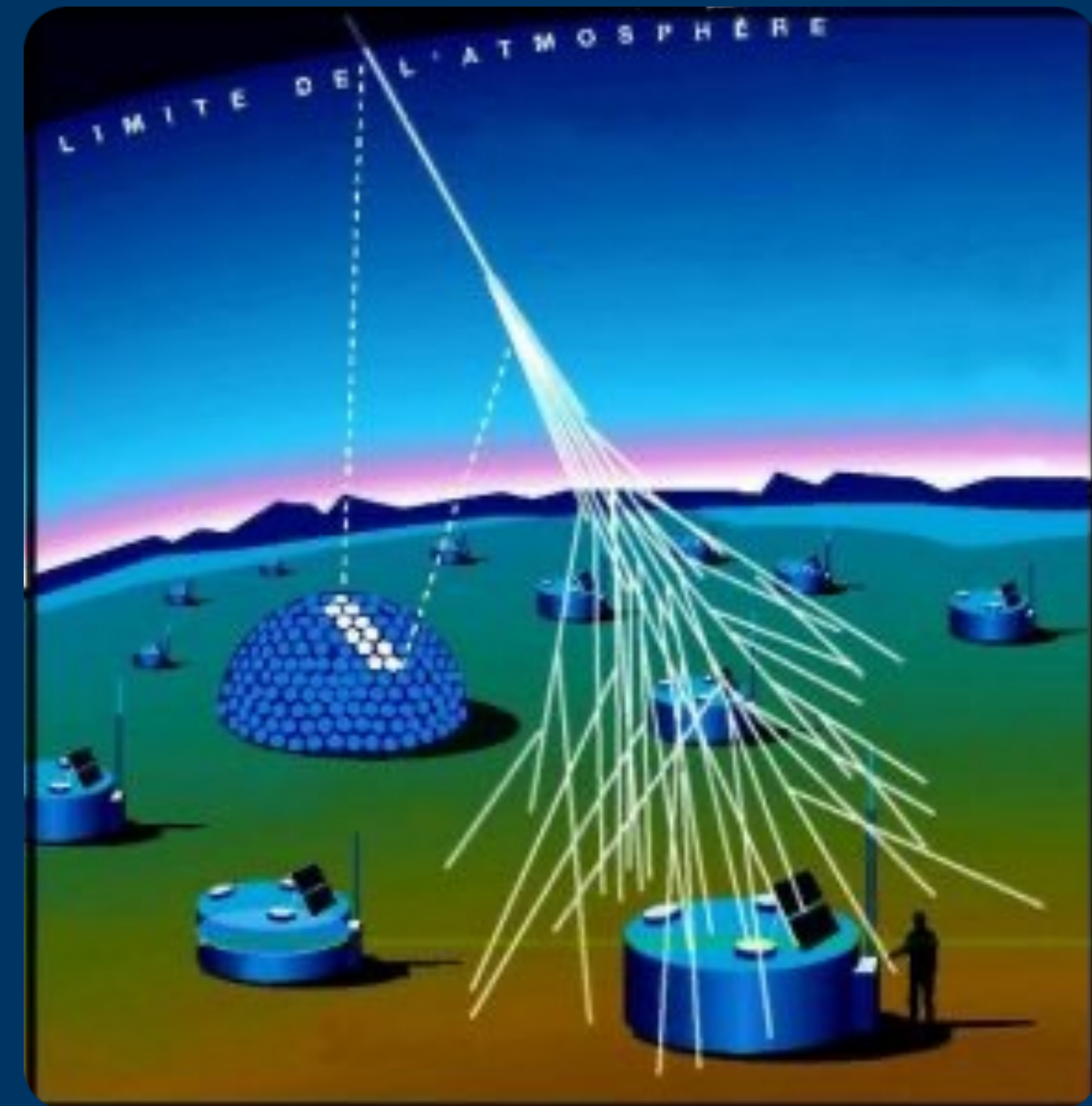
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From EAS observables to cosmic rays properties

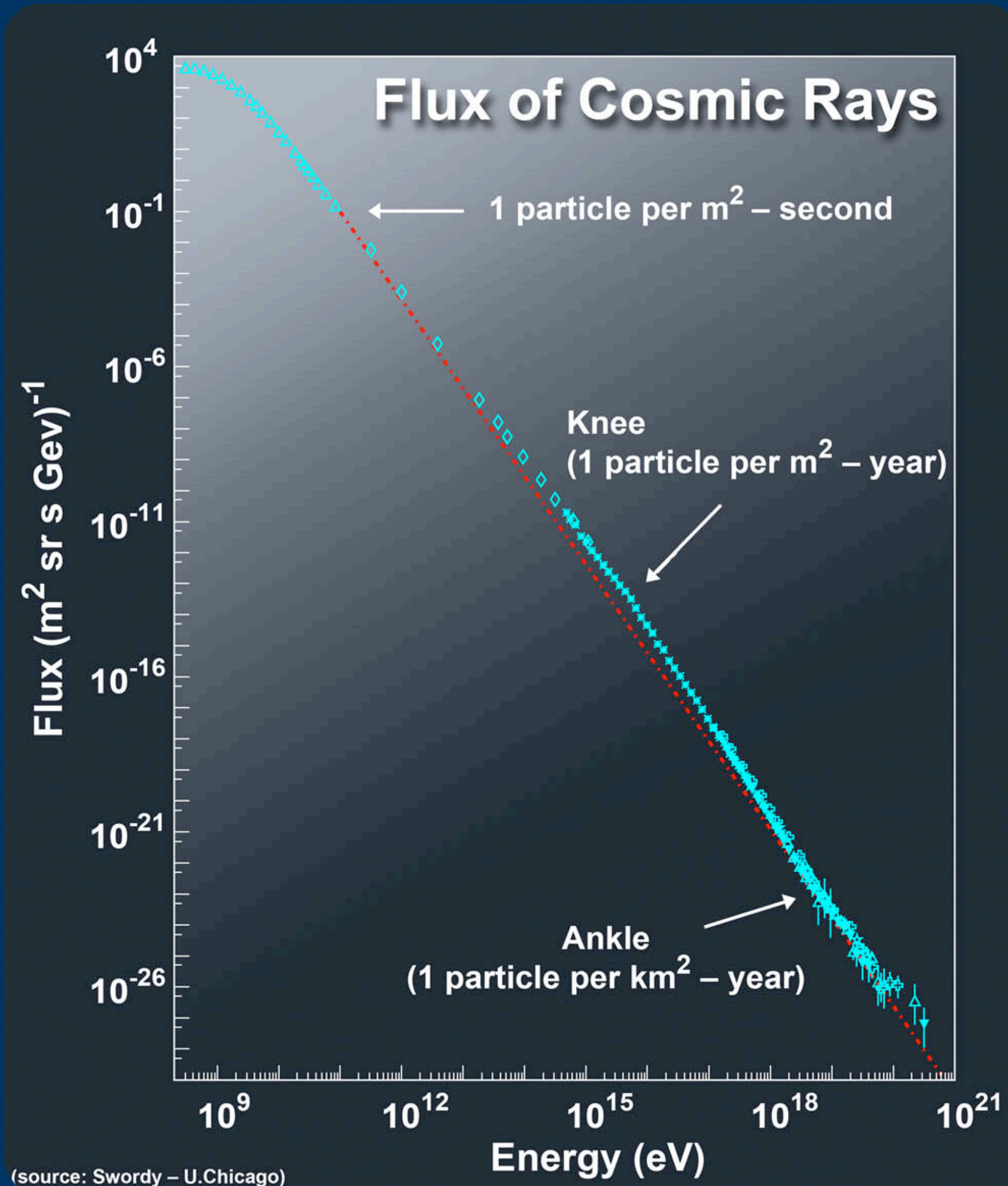
(The subtlety of the analysis)

Prologue:
Why detecting
extensive air
showers?



What we know about cosmic rays (flux and energy)

“Coming out of space and incident on the high atmosphere, there is a thin rain of charged particles known as the primary cosmic ray radiation” (Cecil Powell, Nobel Prize Lecture, 1950)

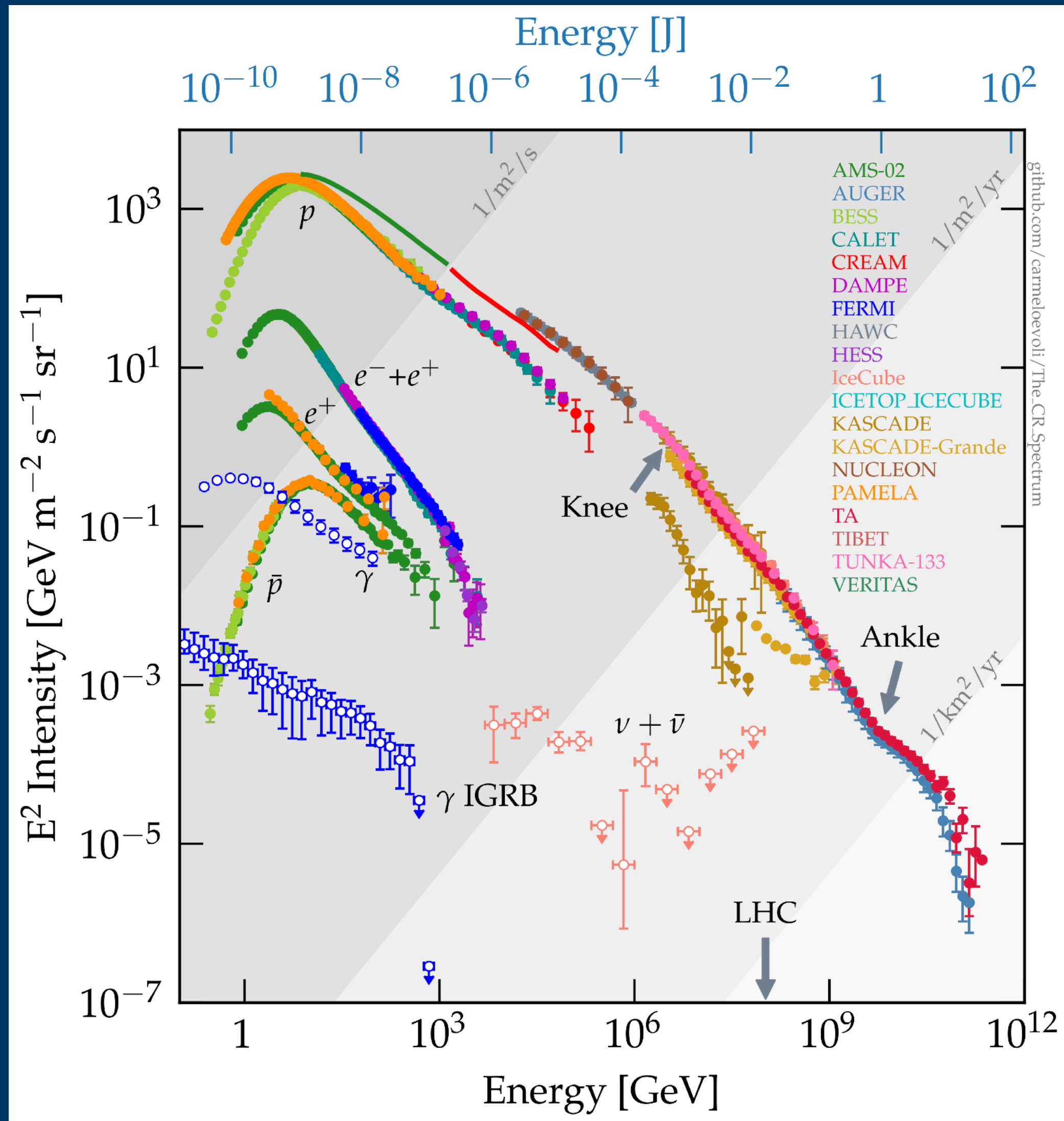


Most striking features of cosmic rays : their energies span a very wide range (≈ 13 decades), as well as their flux does (> 30 decades!)

Yet, the flux as a function of energy (i.e., energy spectrum) look overall quite regular, **approximately representable by a power-law functional form : $(E^{-\gamma}, \gamma \approx 3)$**

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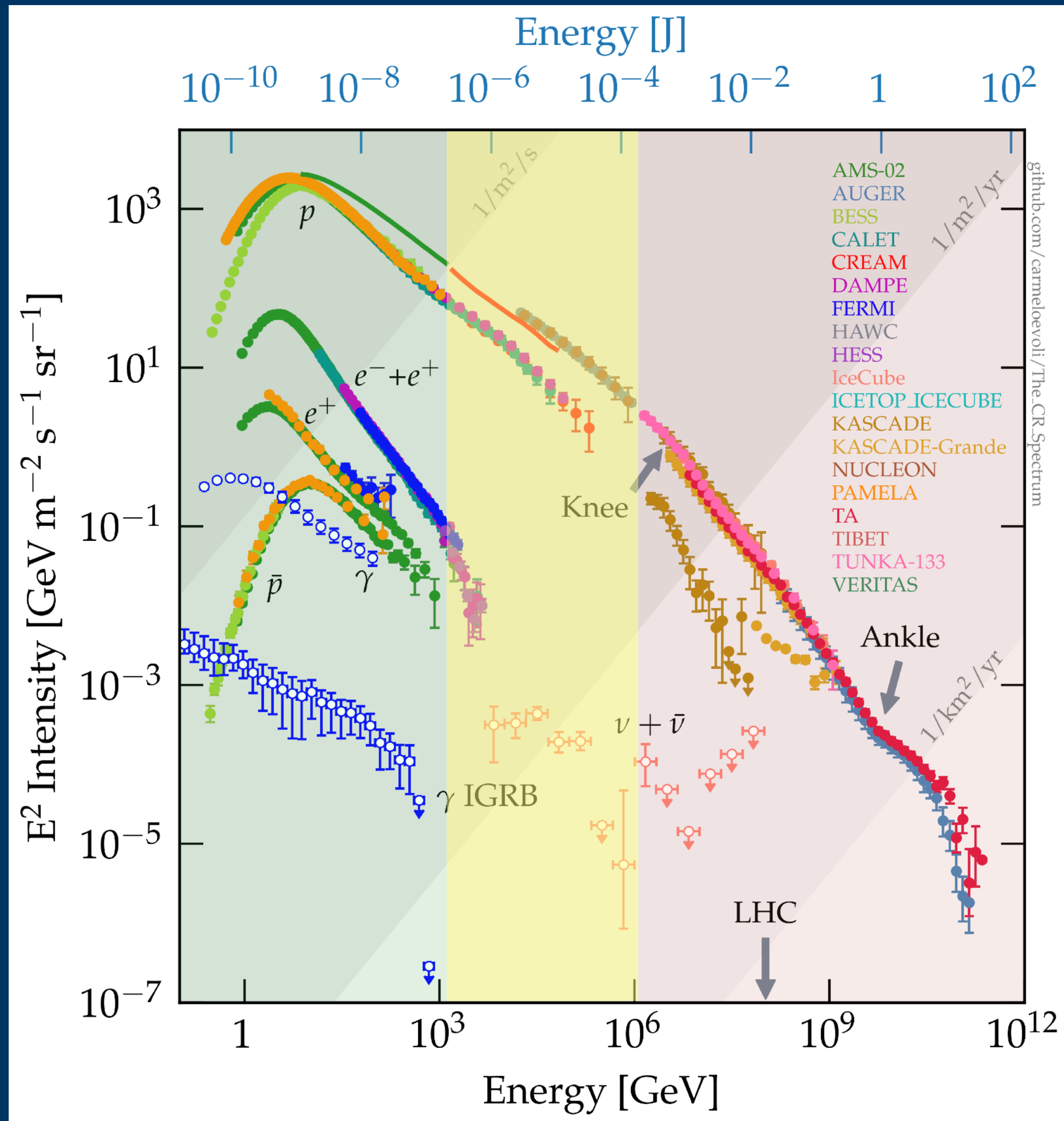


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How we detect (and study) cosmic rays

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

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

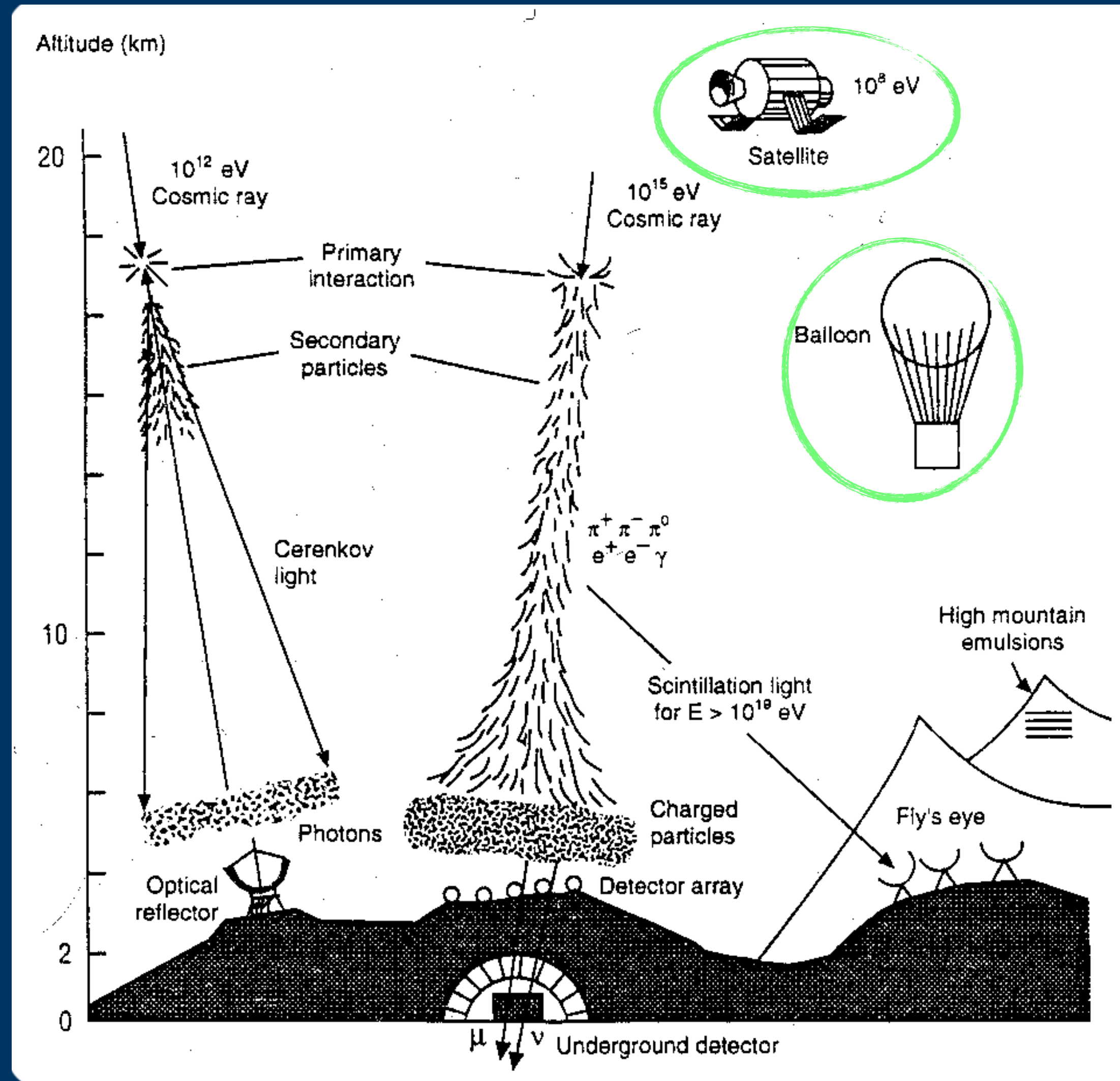
High energy CRs: rarer ($< 1/\text{m}^2/\text{y}$), but “penetrating” in atmosphere via the creation of extensive air showers

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

NB. The distinction between low- and high-energy physics has evolved over time. Currently, long-duration experiments in space can reach up to 10^6 GeV, whilst telescopes or particle detector arrays can go as low as 10^3 GeV

How we detect (and study) cosmic rays

Different detection approaches depending on CR flux and energy



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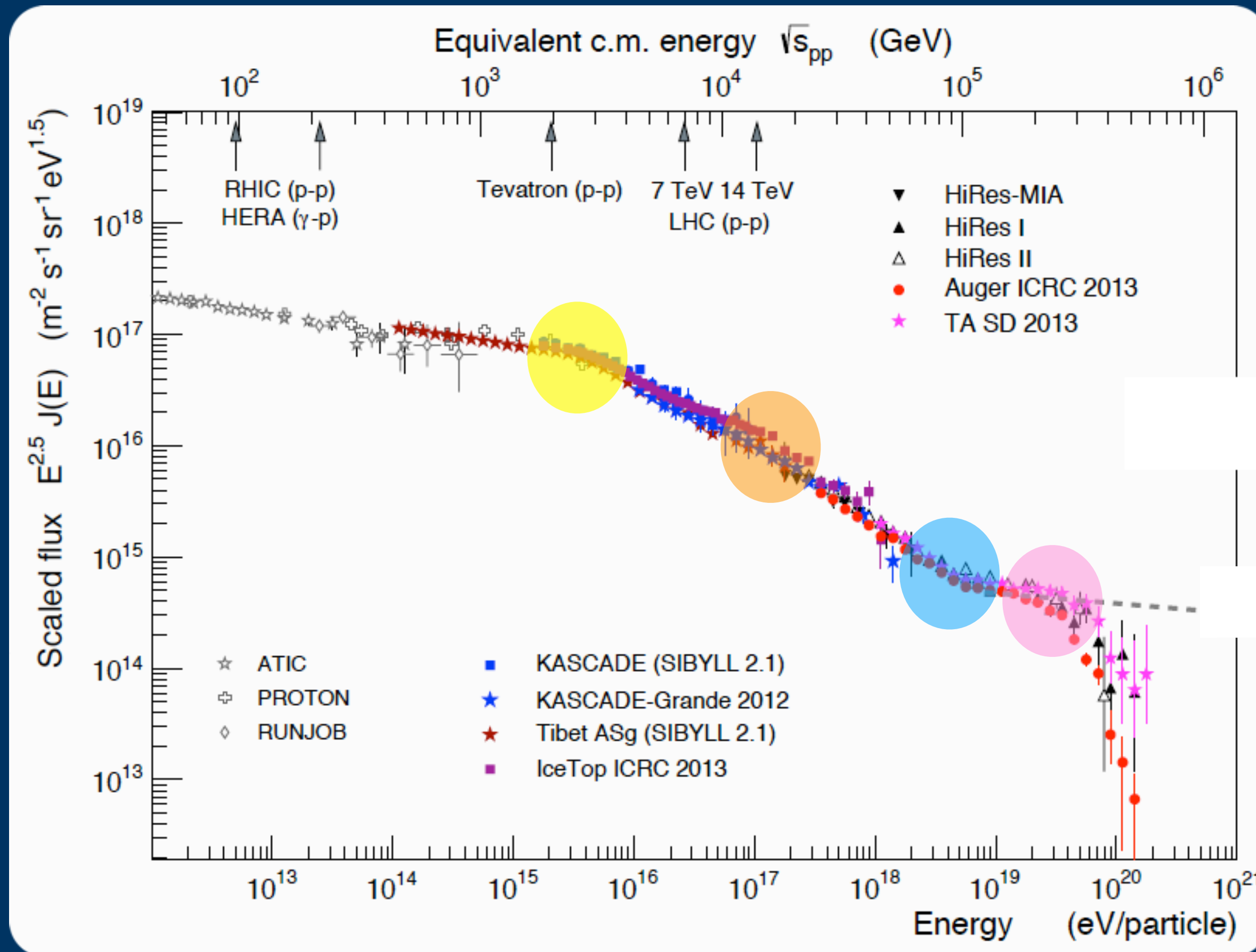
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Why it is worth to study high-energy cosmic rays

The energy spectrum of high-energy cosmic rays shows, in fact, a few “irregularities”



ALL-PARTICLE ENERGY SPECTRUM MEASURED BY
DIFFERENT EAS ARRAYS. SPECTRUM SCALED BY $E^{2.5}$ TO
BETTER EVIDENCE THE “IRREGULARITIES”

A softening (“knee”) at $\approx 3 \cdot 10^{15}$ eV

A softening (“II knee”) at $\approx 10^{17}$ eV

A hardening (“ankle”) at $\approx 5 \cdot 10^{18}$ eV

A “2-step suppression” at $\approx 1-5 \cdot 10^{19}$ eV

These irregularities must 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

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” (Isaac Newton, 1675)



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)

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 (this lecture) and of the physical processes involved (see Tanguy Pierog's lectures)



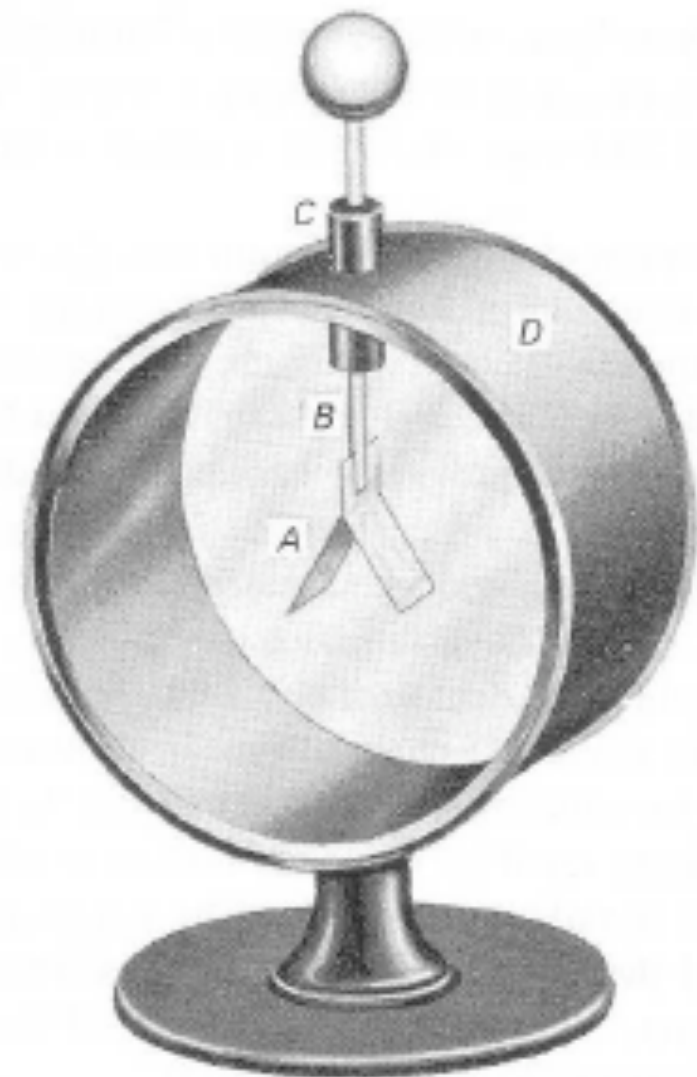
Chartres Cathedral
South Rose
St Luke above Jeremiah

The very first steps towards the discovery of EAS

The discovery of cosmic rays: the “electroscope” era

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.

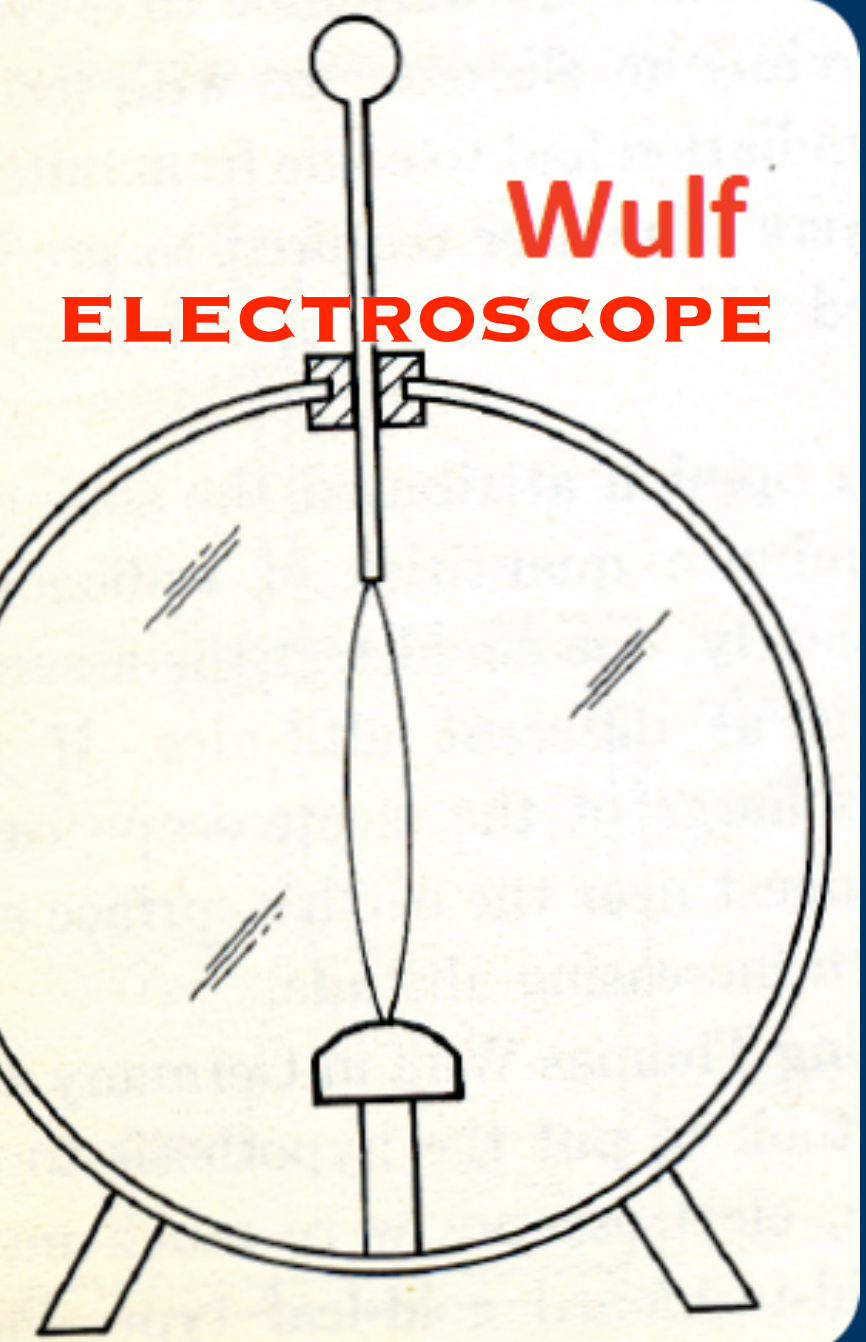
Electroscopes were widely used to explore radioactive materials.



**GOLD-LEAVES
ELECTROSCOPE**

First electroscopes developed at the end of the XVIII century.

When it is given an electric charge, the metal 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.



**Wulf
ELECTROSCOPE**

Puzzle: 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!

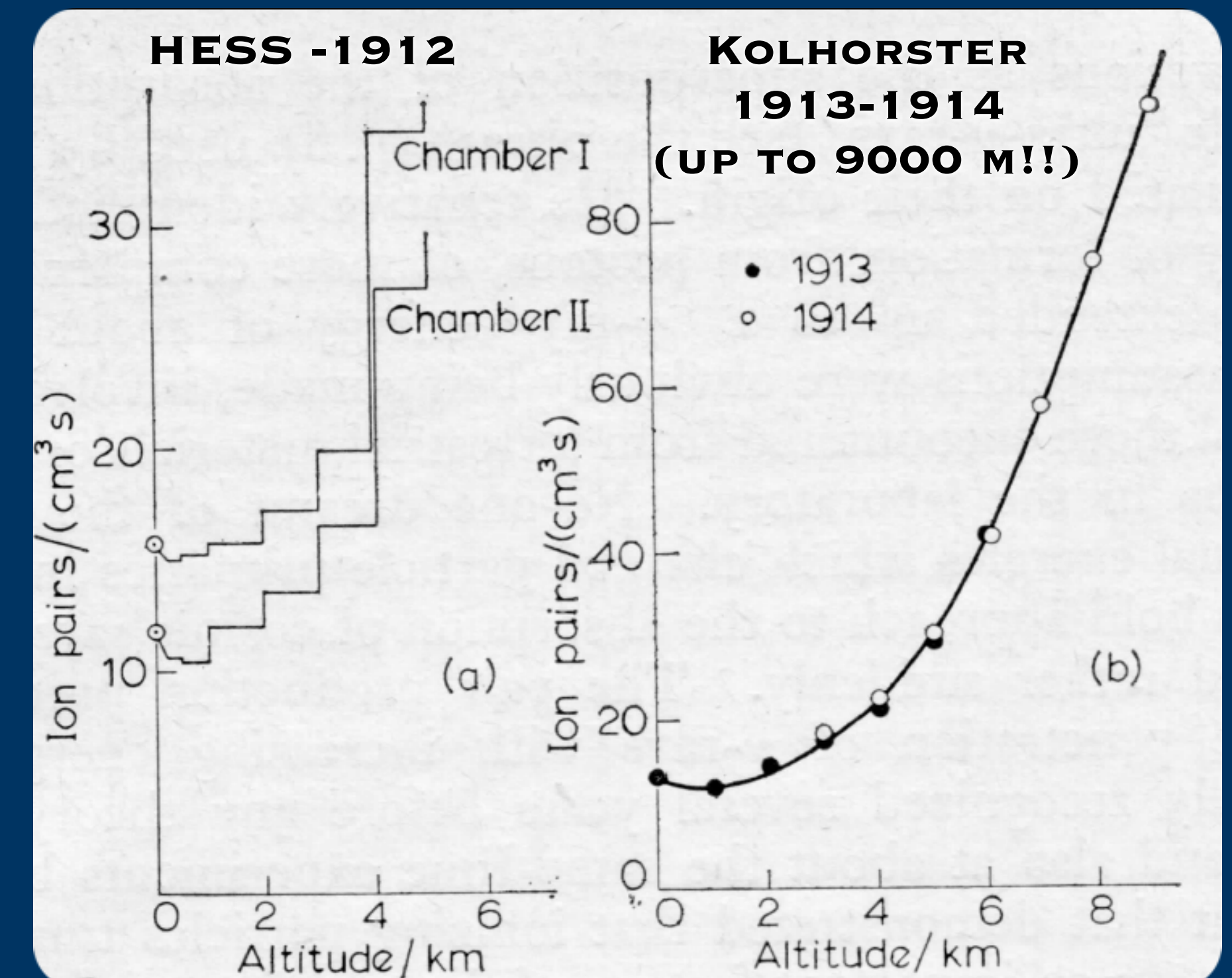
The very first steps towards the discovery of EAS

The discovery of cosmic rays: the “electroscope” era

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 and great courage**



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

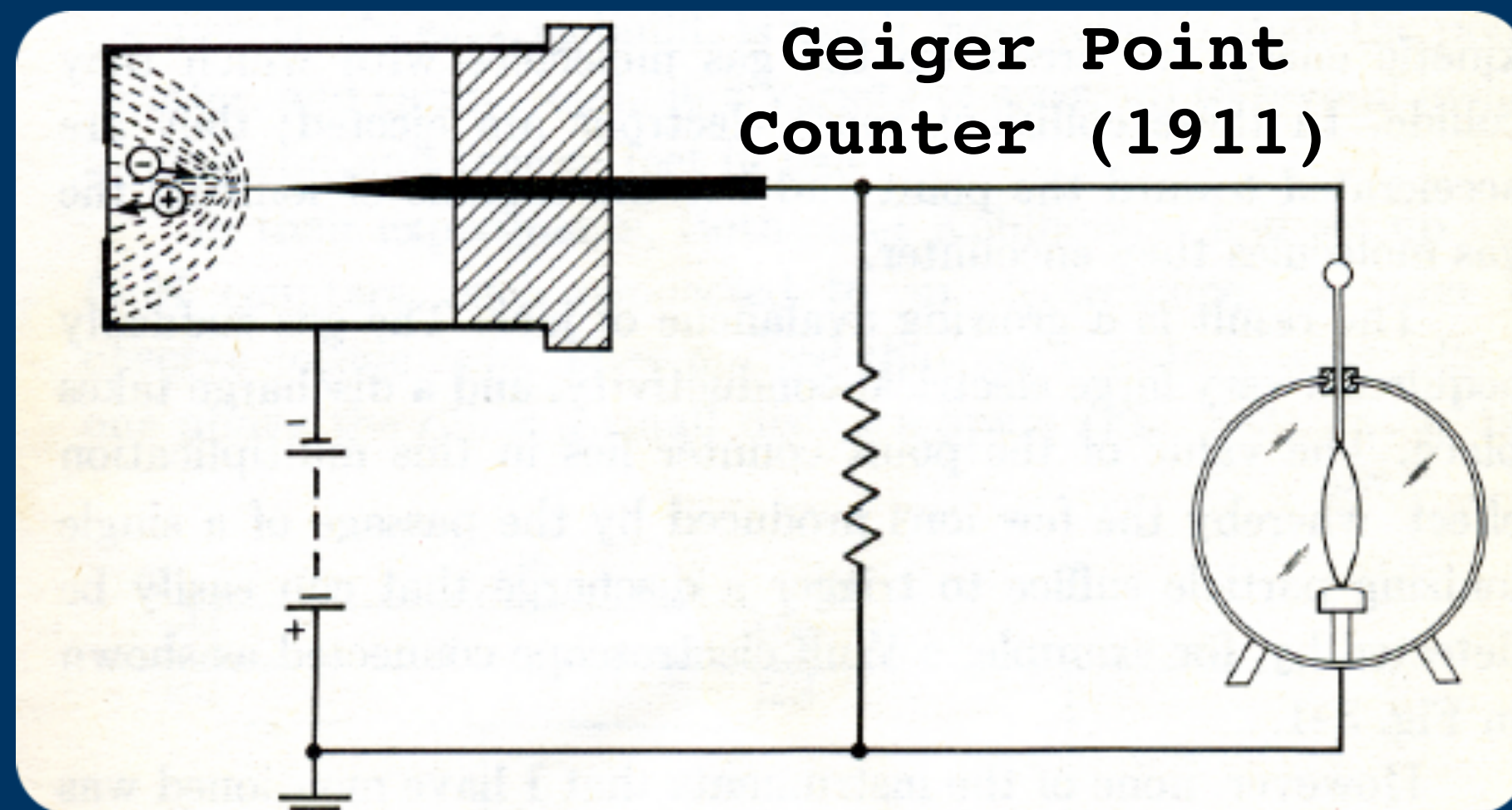


“The only possible way of interpret my findings was to conclude to the existence of a hitherto unknown and very penetrating radiation, coming from above and probably of extra-terrestrial origin” (V. Hess 1912)

The very first steps towards the discovery of EAS

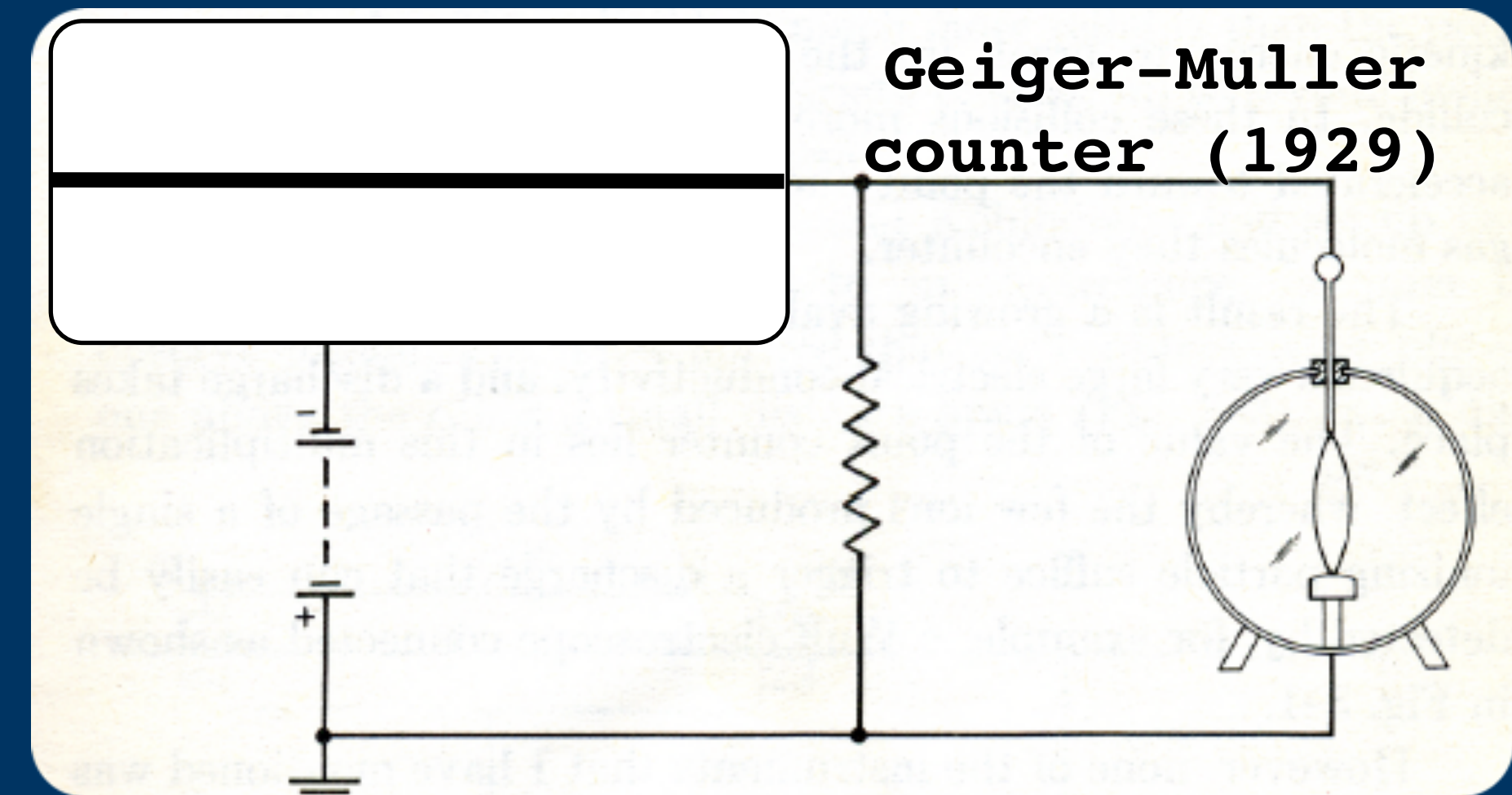
Towards the detection of single particles: Geiger counters

Electroscopes can only detect the combined ionising effect of many particles.
They cannot access 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 enough to counterpart the small intensity of CRs



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

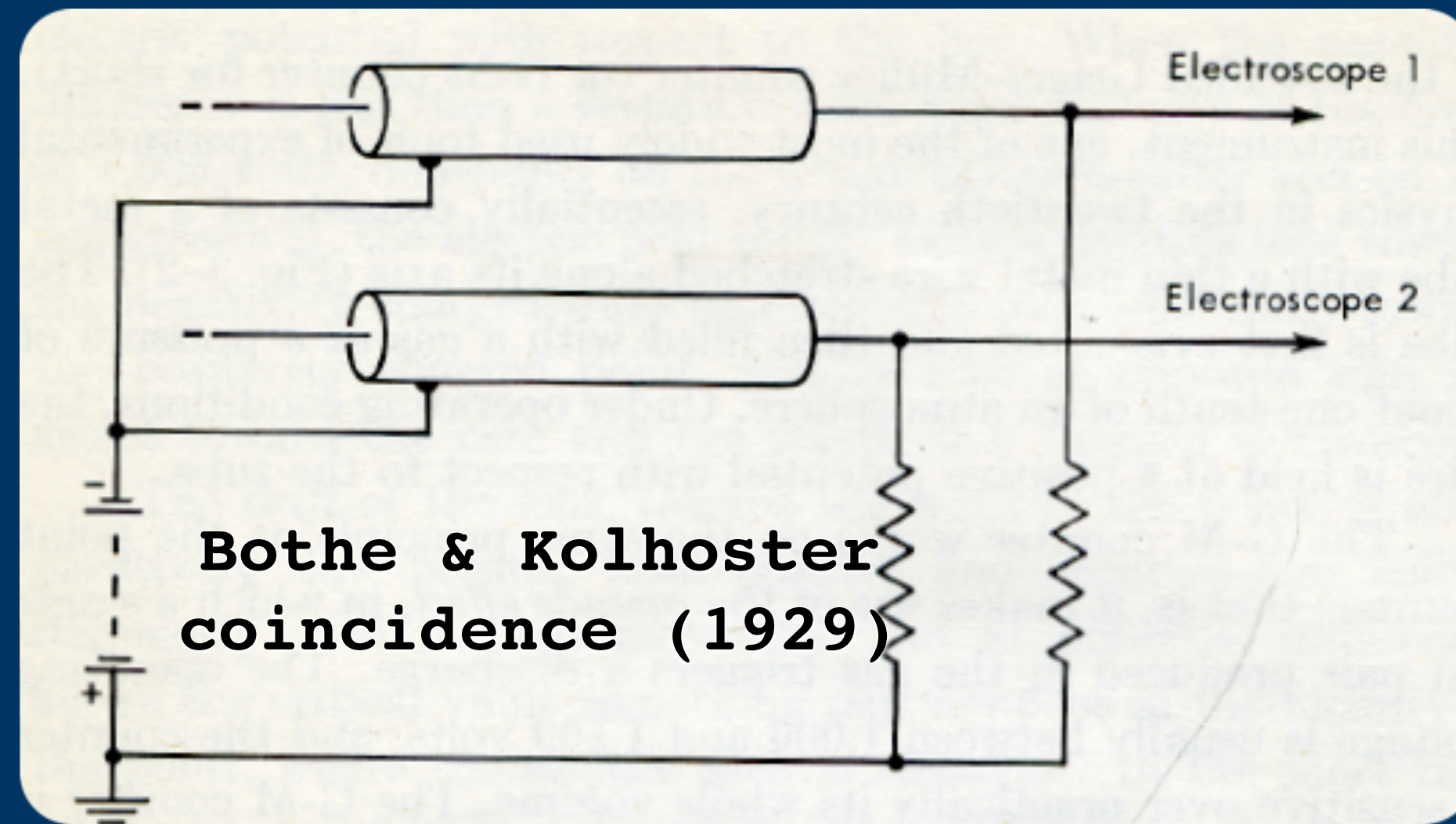
A metal tube filled with a gas with a thin metal wire stretched along its axis. Same principle as the point counter

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

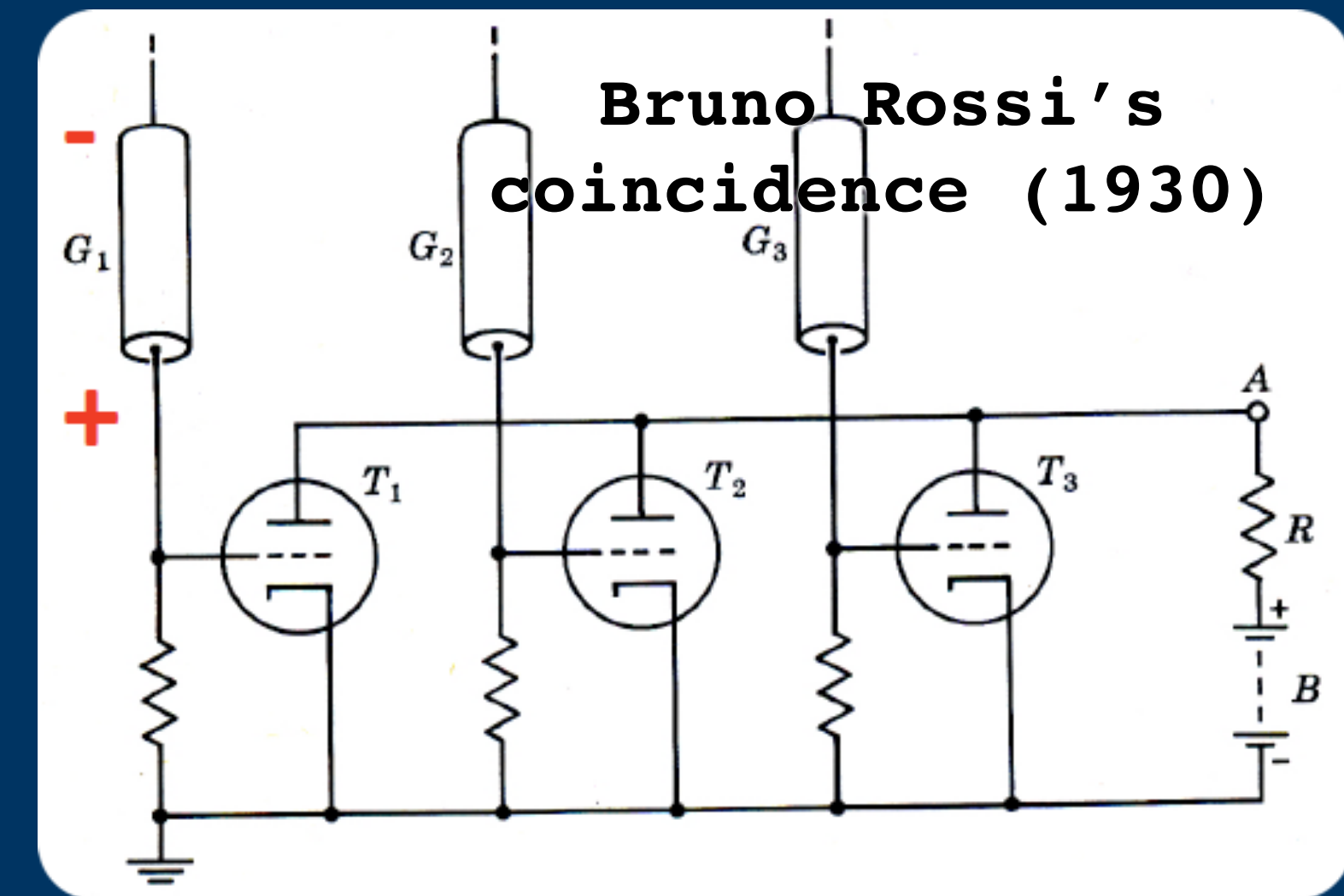
The invention of counting in coincidence (Bothe & Kolhoster; Rossi)



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: still finding coincidences

B&K concluded that “a corpuscular radiation was detected...unlikely to be a gamma-radiation...”



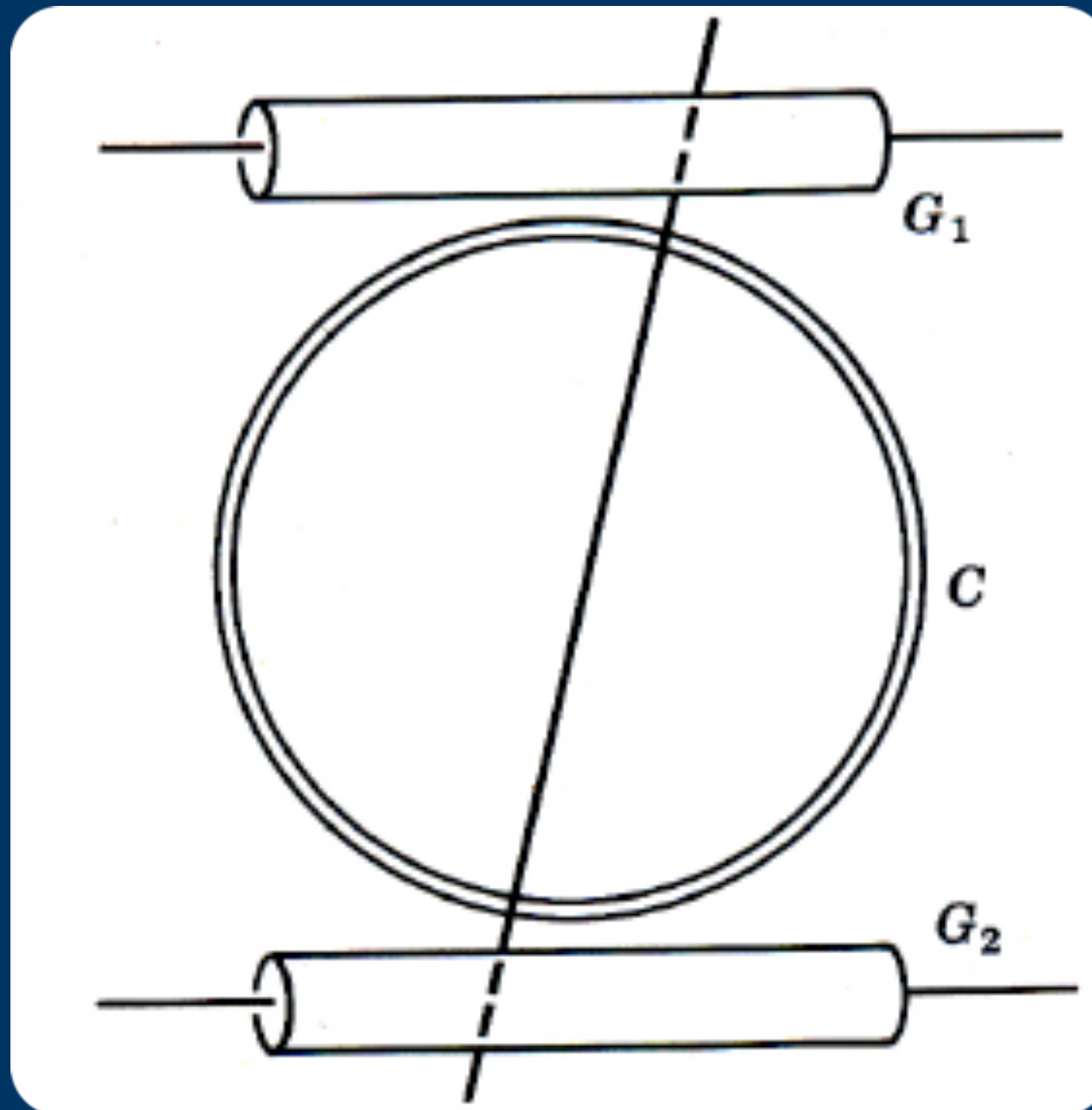
2 or more triodes coupled to G-M counters. When the grids were simultaneously driven to a negative potential by the coincident discharges of the 3 counters, a pulse appear at the plates.

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 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.



With their new cloud chamber, in 1933 Blackett and Occhialini observed tracks of many particles.

They clearly resulted from the interaction of a single high-energy cosmic ray near the chamber.

The invention of the counter-controlled cloud chamber and the discovery of these “showers” marked another milestone in cosmic-ray detection and study

The serendipitous observation of “sciami estesi”

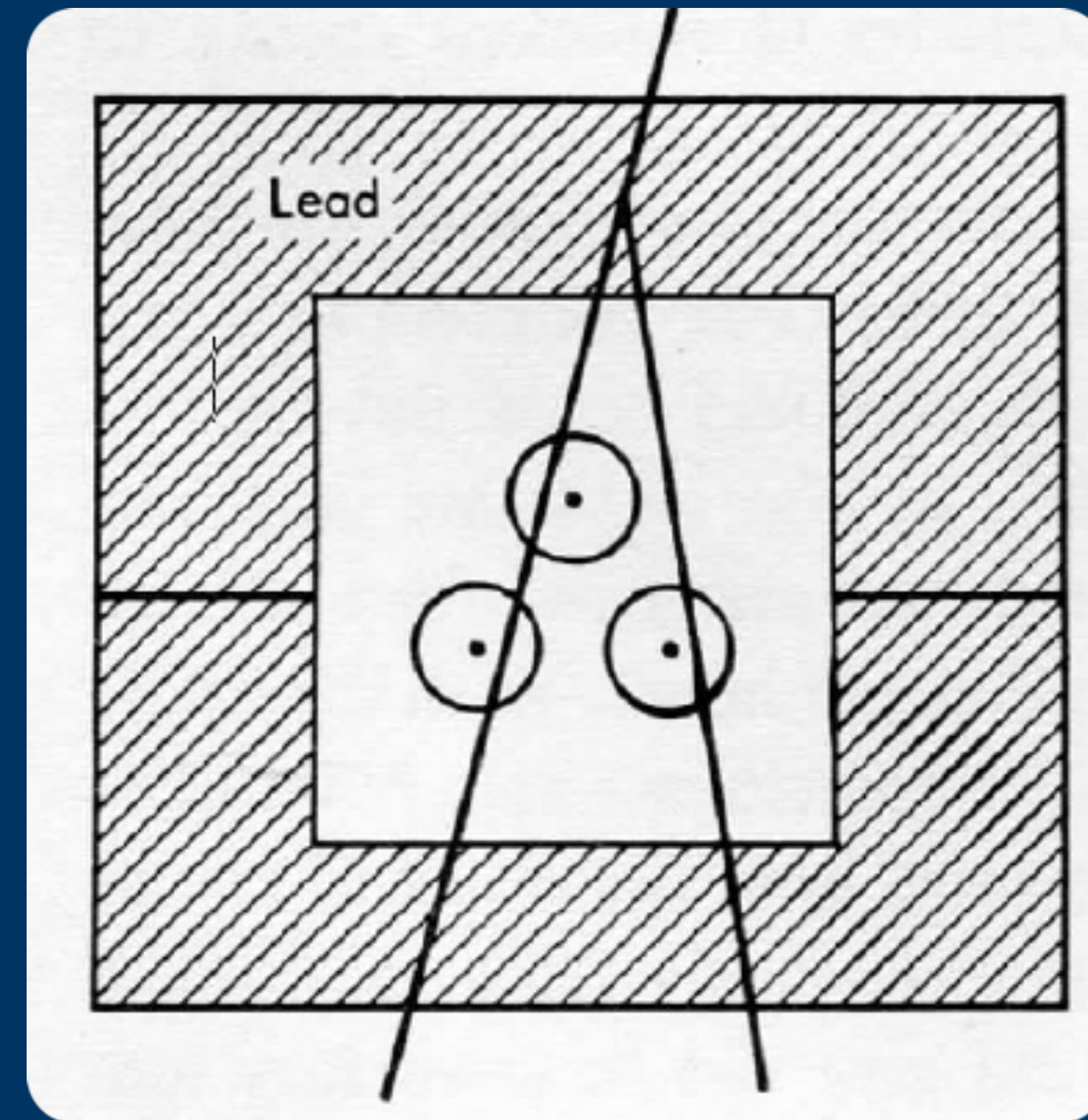
The first observation of “sciami estesi”

‘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 more lead was added. Coincidences were present also WITHOUT lead.

The coincidences could only have been the result of two or more ionising particles emerging simultaneously from the lead.



Rossi suspected that soft secondary particles were produced by cosmic particles either in the material or not

The discovery of Extensive Air Showers

Schmeiser & Bothe, Kolhörster, and Pierre Auger

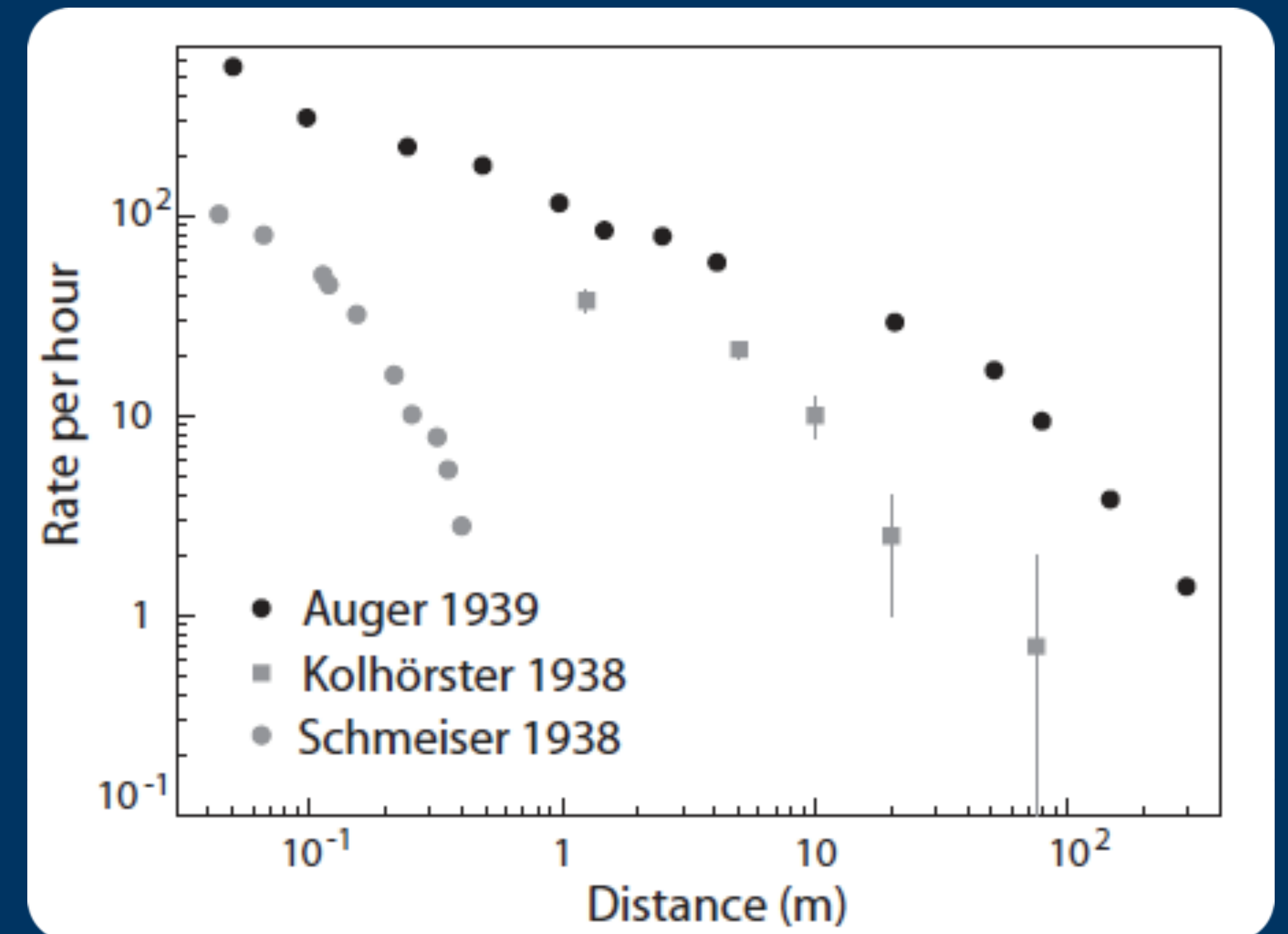
Schmeiser and **Bothe** pointed out that Rossi's observations implied the occurrence of showers in air and showed that particles in air showers had separations up to 40 cm. Independently, **Kolhörster** et al. reported data on the rate at which coincidences between a pair of Geiger counters fell as a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

Auger's 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 $\approx 10^{15}$ 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 late 1940s and early 1950s after the discovery of two charged and one neutral pion 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 $\approx 10^{10}$ EV)

The very first particle-detector arrays

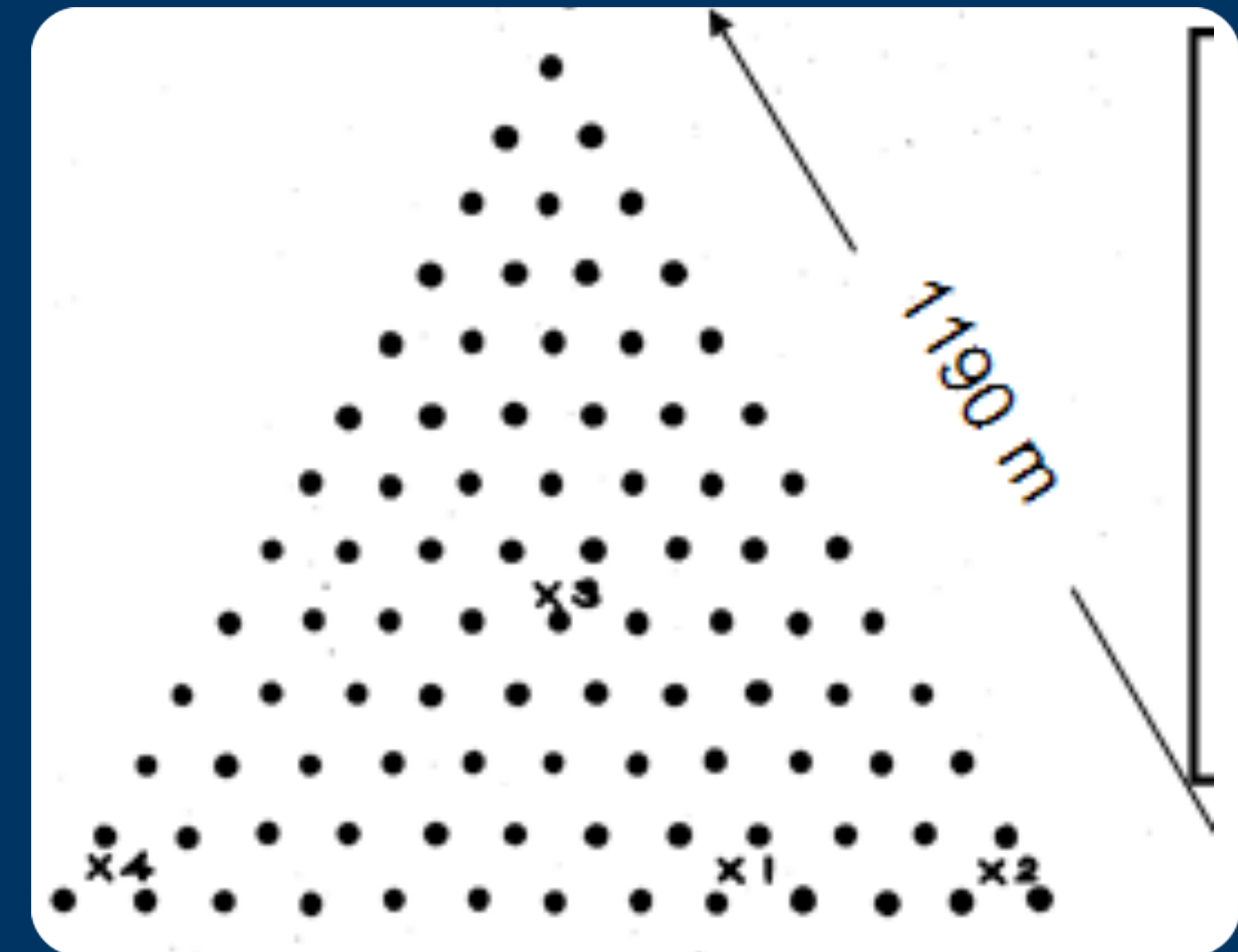
Skobeltsyn, Zatsepin, Miller (1947), Cranshaw & Galbraith (1954)

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)*

Image of a modern air shower (simulation!)

We now know much more on the EAS features (Tanguy Pierog's lecture)

**10^{14} EV SIMULATED
PROTON SHOWER**

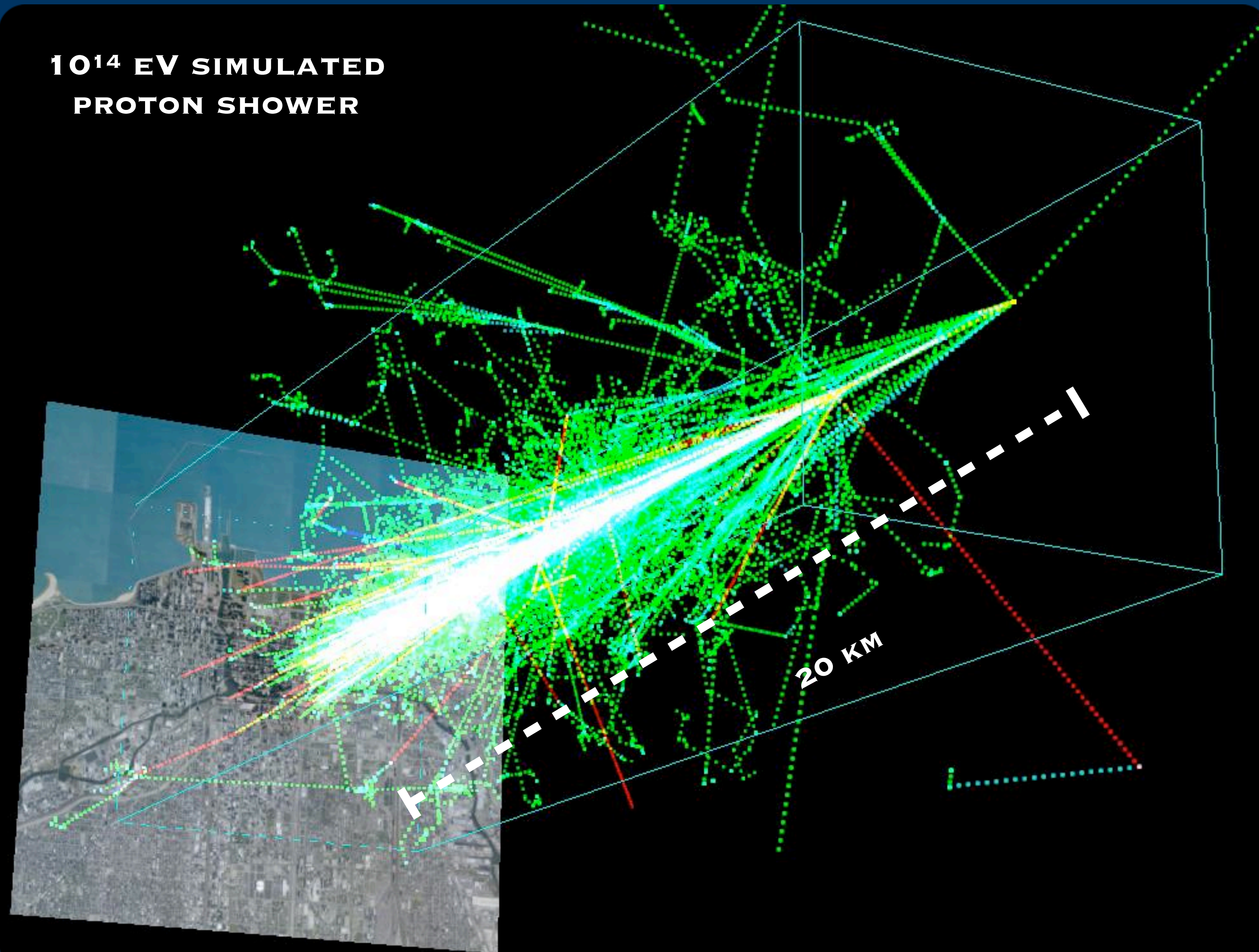
GREEN:

**ELECTRONS AND
POSITRONS**

CYAN: GAMMAS

RED: MUONS

WHITE: HADRONS



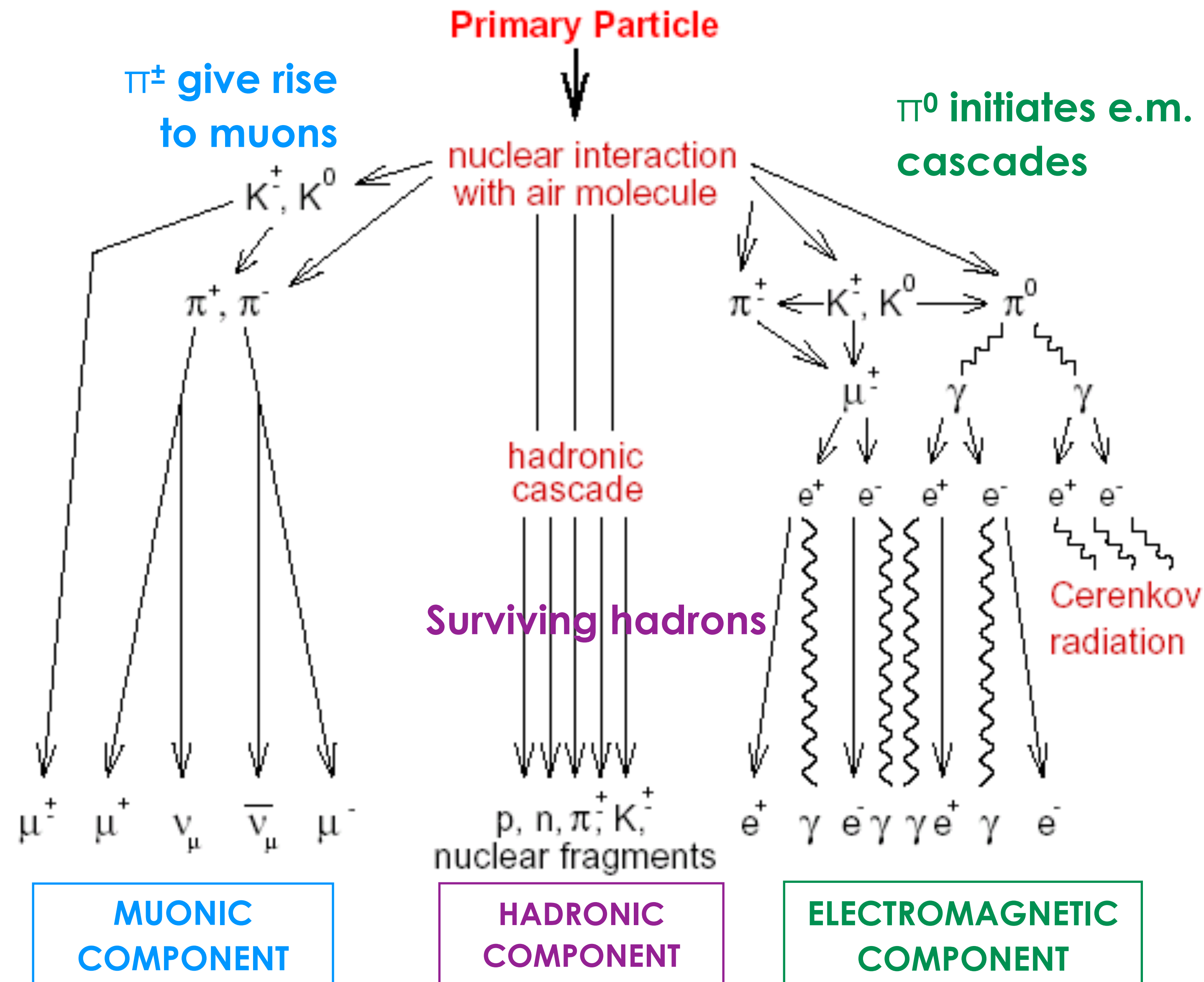
The atmosphere is used as an inhomogeneous calorimeter.

EAS can be detected over an extended area.

Large effective area of detection compensates the smallness of flux

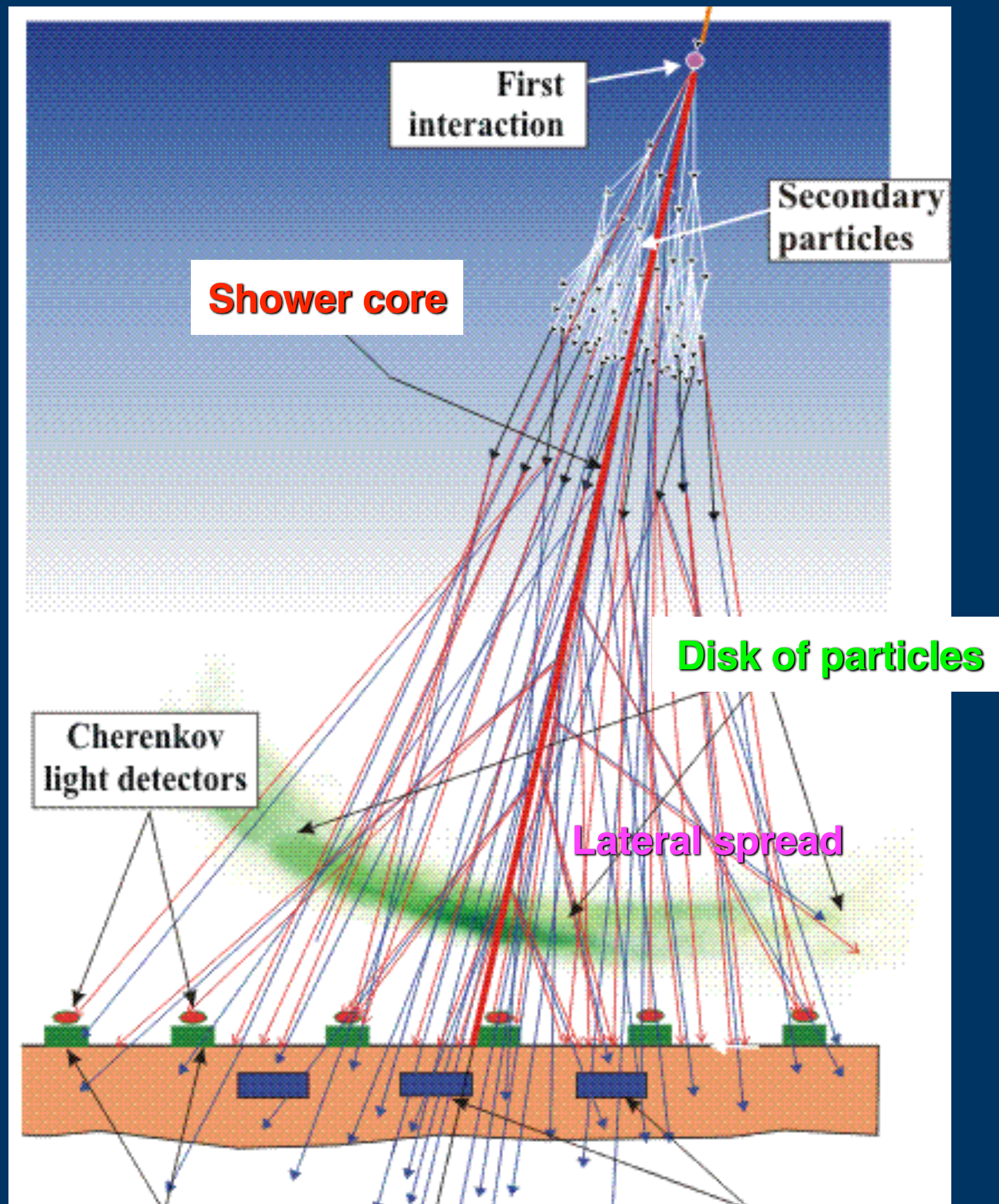
Extensive air showers: particles

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



Extensive air showers: particles

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

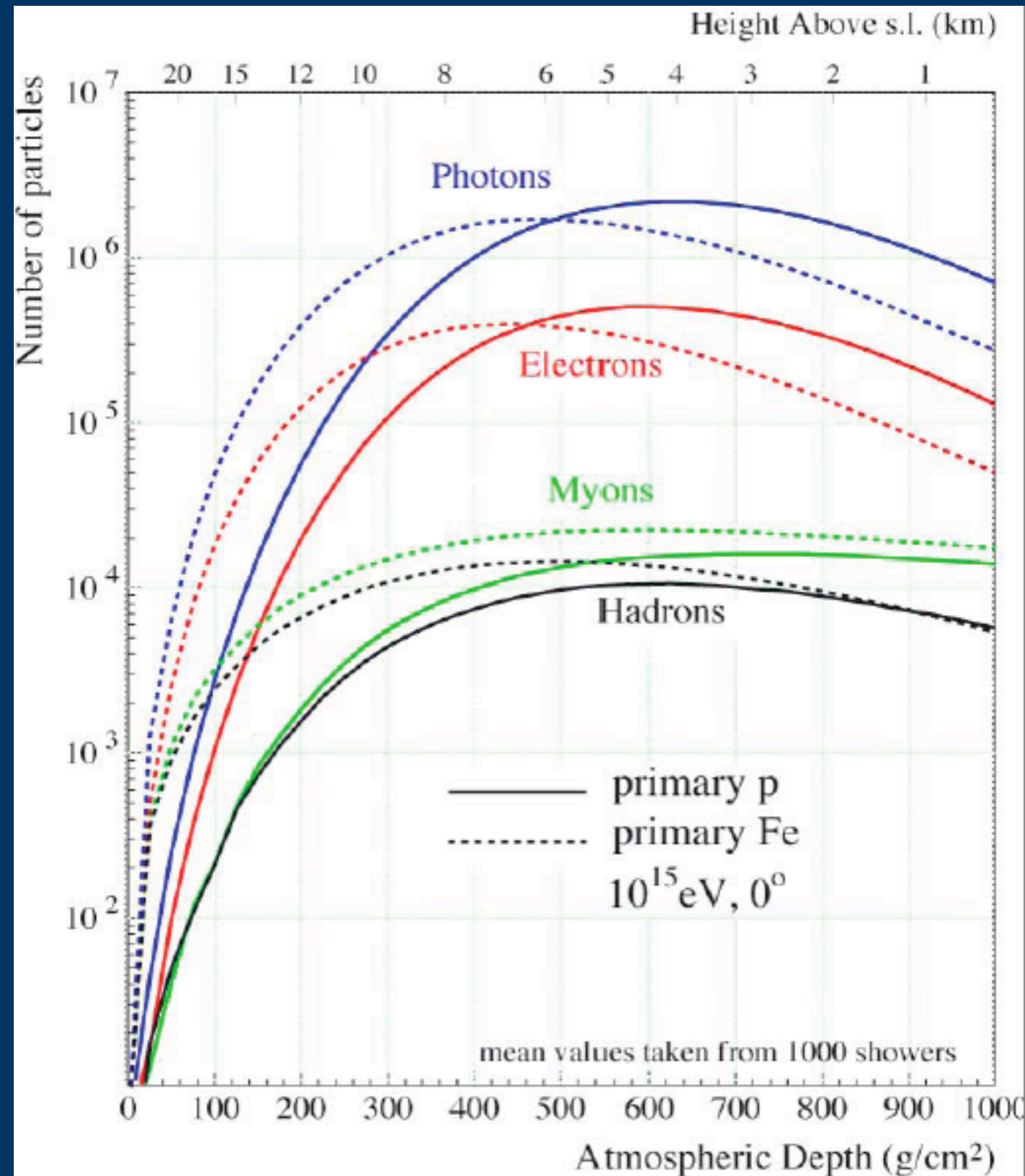
Due to different path lengths and velocities across the atmosphere shower particles are distributed over a wide area and within a **curved thick disk**

For example, a **shower from a CR of 10^{19} eV**:

- The **lateral spread** extends **up to over 15 km**
- Has a **thickness** that might be of **a few hundreds meters** (depending on the distance from the core)

Extensive air showers: particles

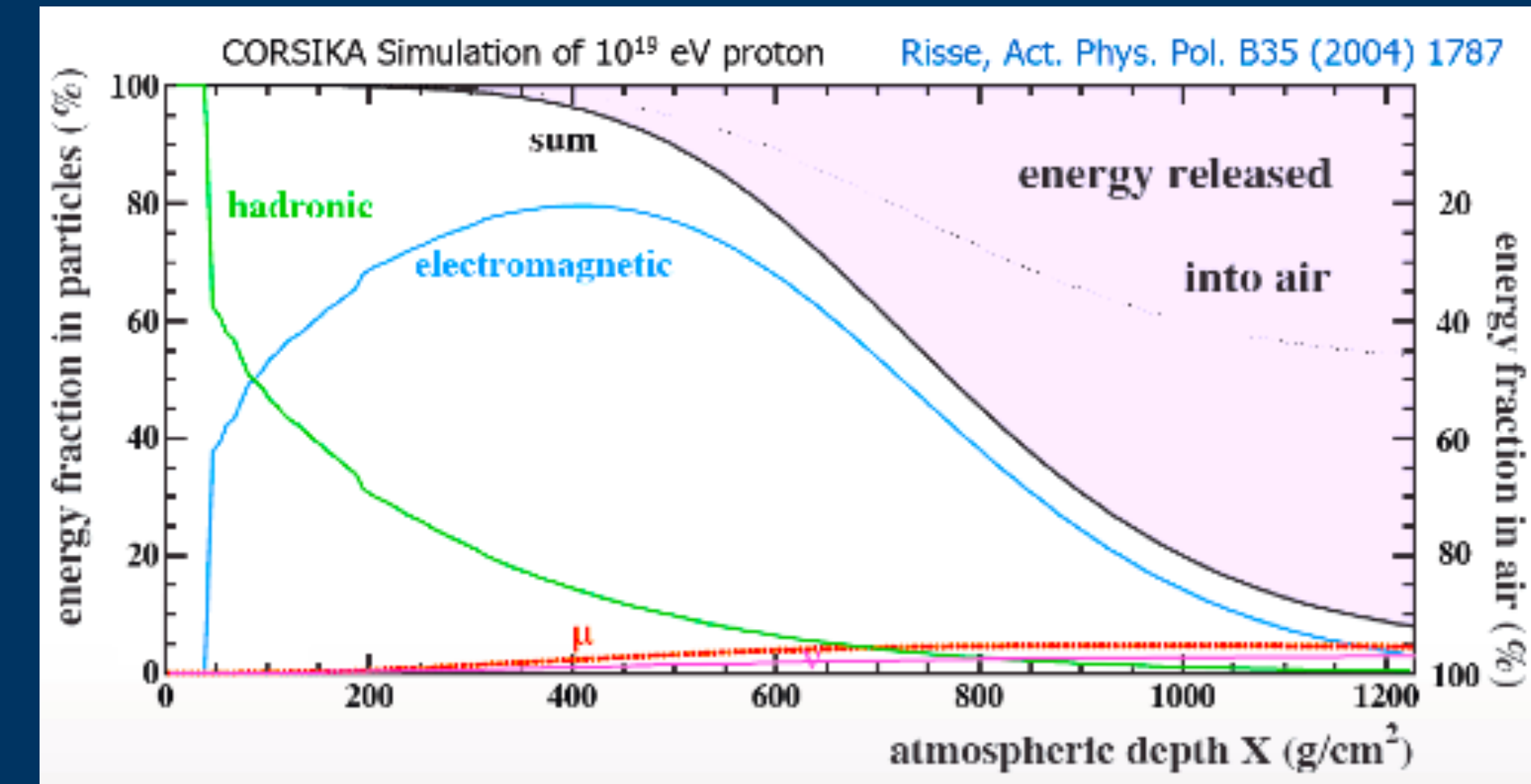
Longitudinal development



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

Showers started by heavier primaries (e.g., Fe) develop faster, i.e., reach the maximum higher in atmosphere

Showers started by the same kind of primary reach their maximum deeper in atmosphere if their energy is larger

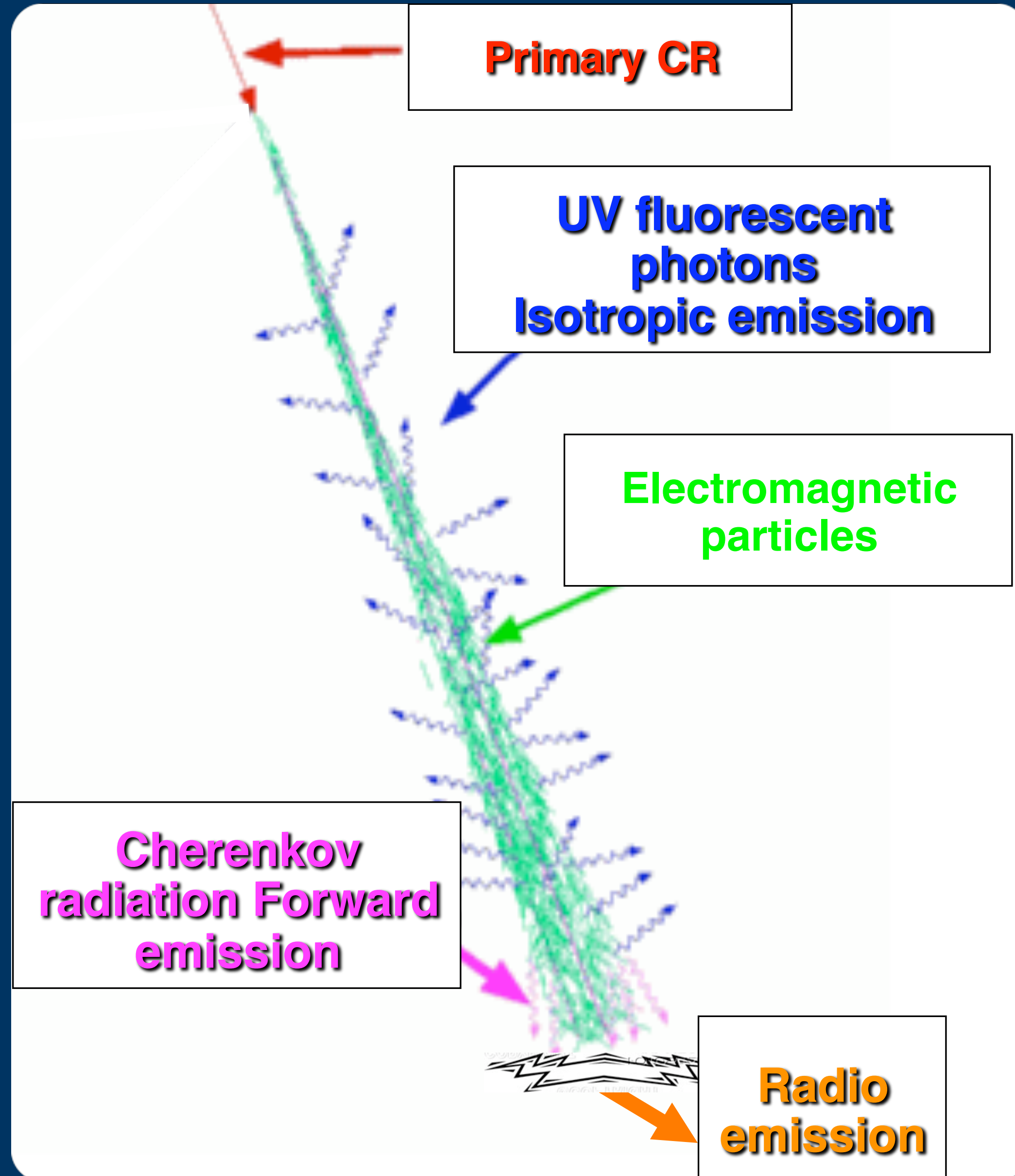


90% OF THE PRIMARY ENERGY OF THE COSMIC RAY IS DISSIPATED IN THE ATMOSPHERE DURING SHOWER DEVELOPMENT

e.g., a shower from a CR of 10^{19} eV:

- Contains about 10^{10} particles (mostly em, with about 10% of muons) at the maximum
- Reaches the maximum at about 3 km a.s.l.

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.

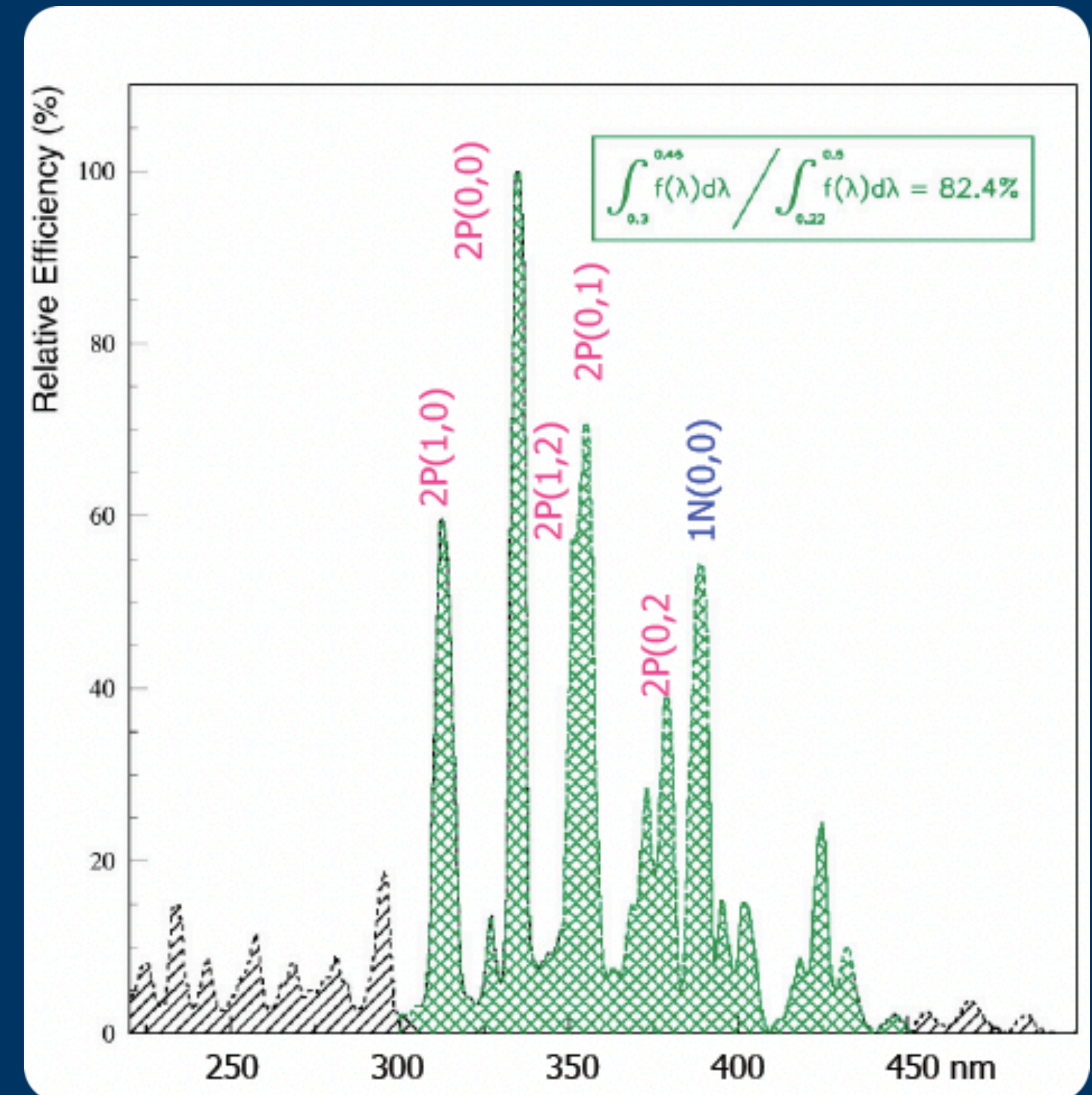
Fluorescence radiation

Charged particles from EAS interact with Nitrogen molecules in air. They get excited and 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** corresponds to approx. 4 photons per shower particle per metre of track in the atmosphere.

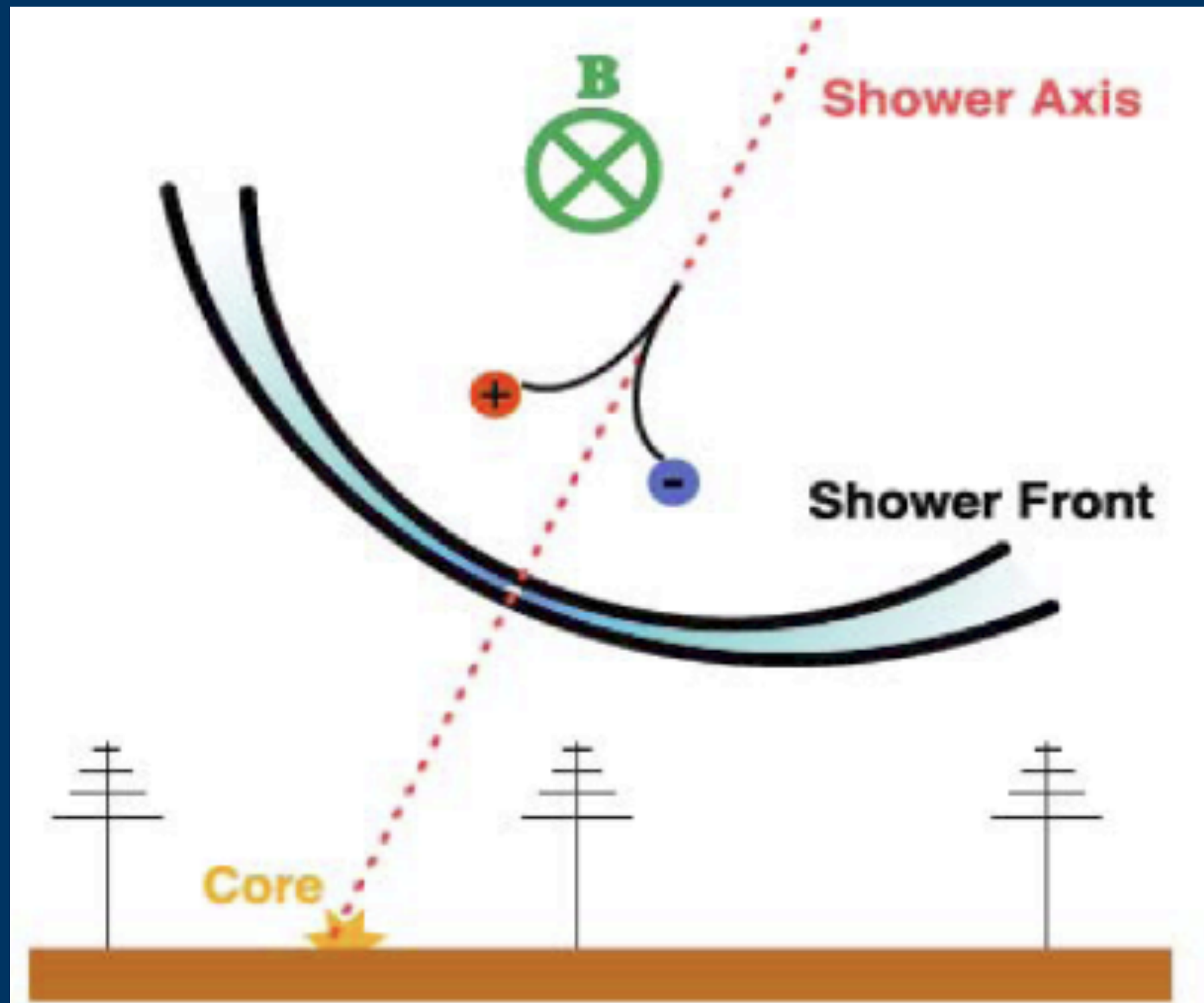
This radiation (commonly called **fluorescence light**) is **emitted isotropically**. It can travel several kilometres through the atmosphere and detected by an optical telescope, i.e., mirrors and PMTs, typically, equipped with fast response electronics (fluorescence detectors).

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)

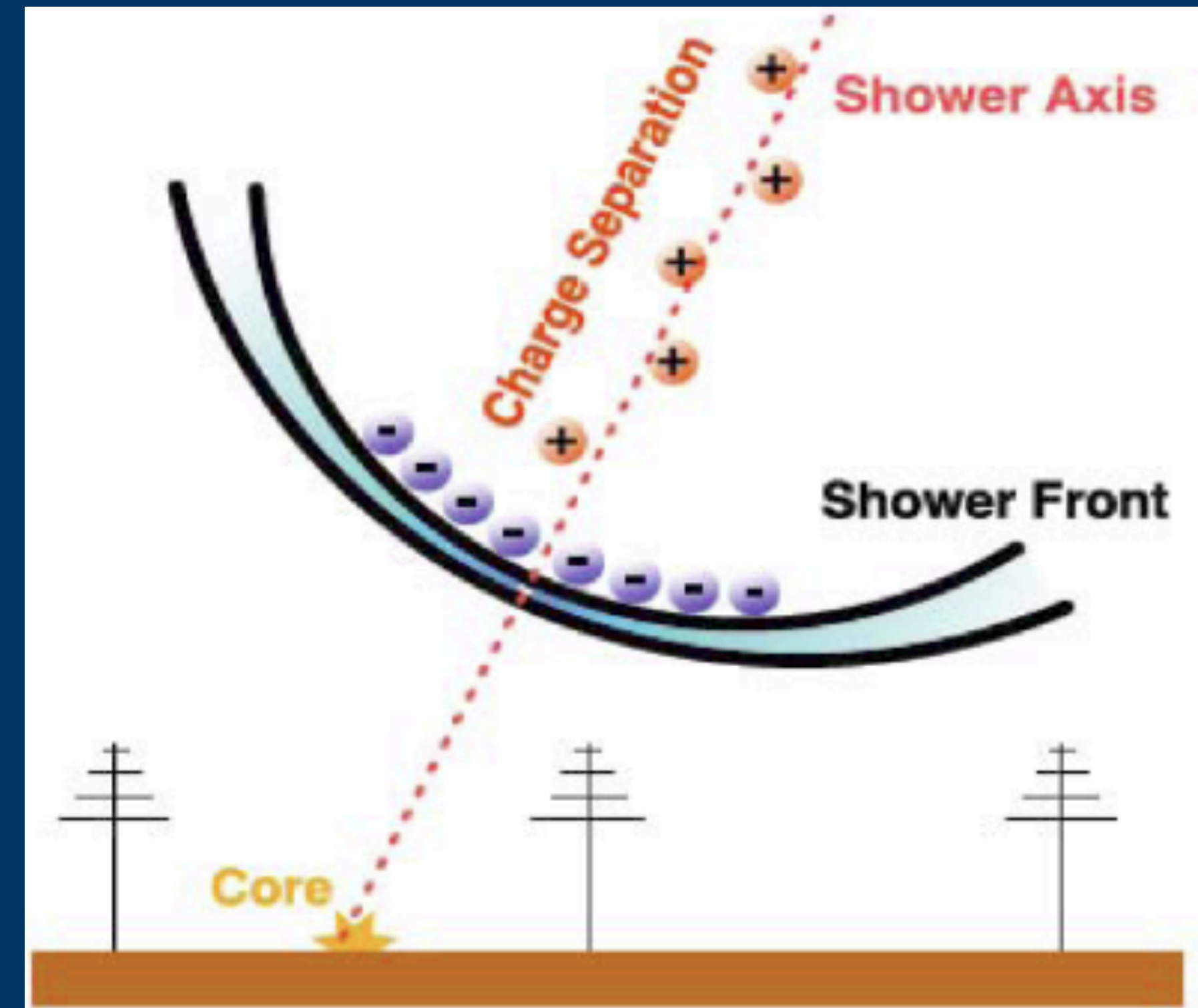


Fluorescence spectrum

Radio emission

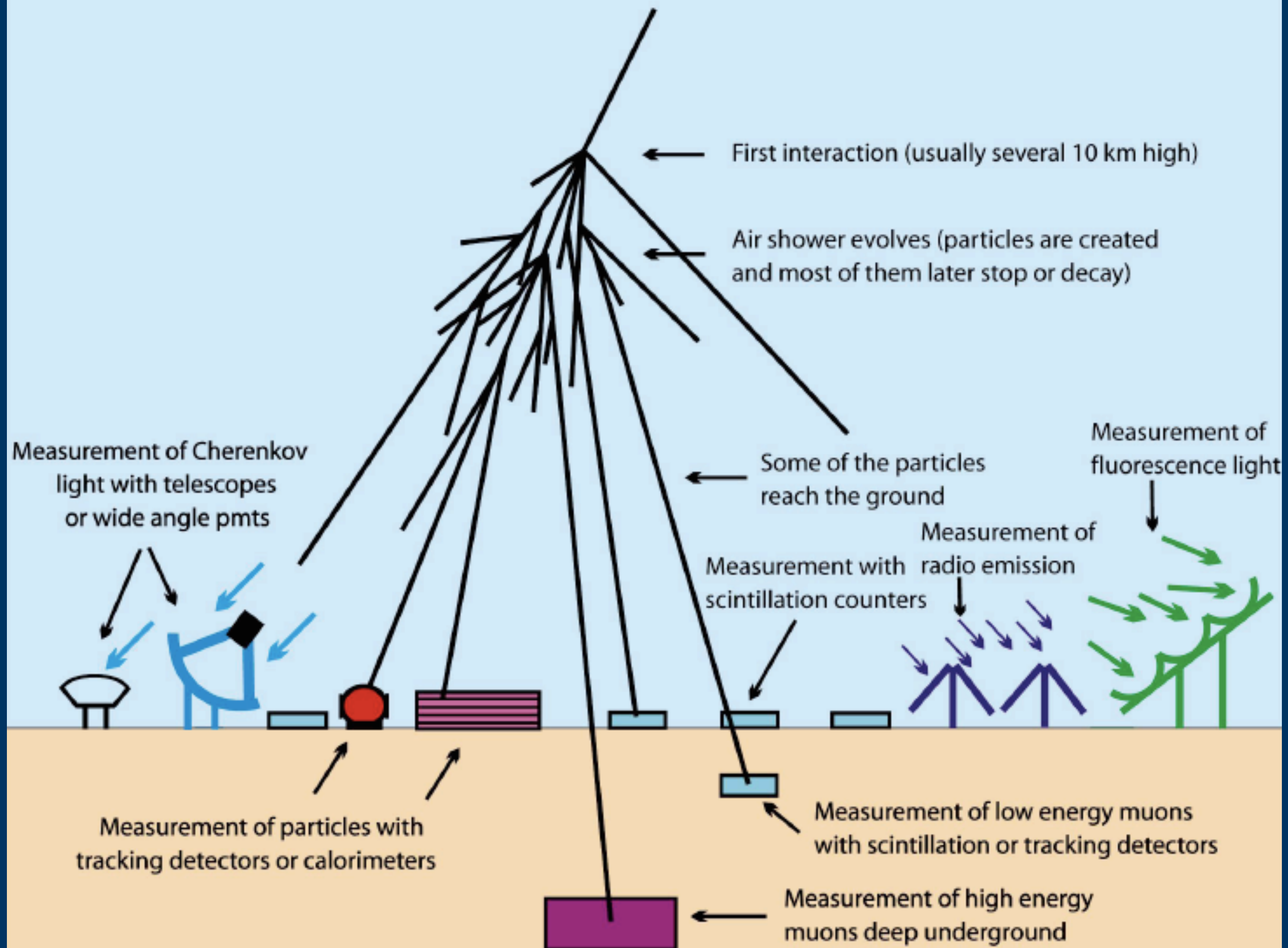


Geomagnetic effect: deflection of charged particles in Earth's magnetic field (B). Electric current develops when the plasma moves through B . Radiation emitted by time varying electric current



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 air

Different detectors for different observables

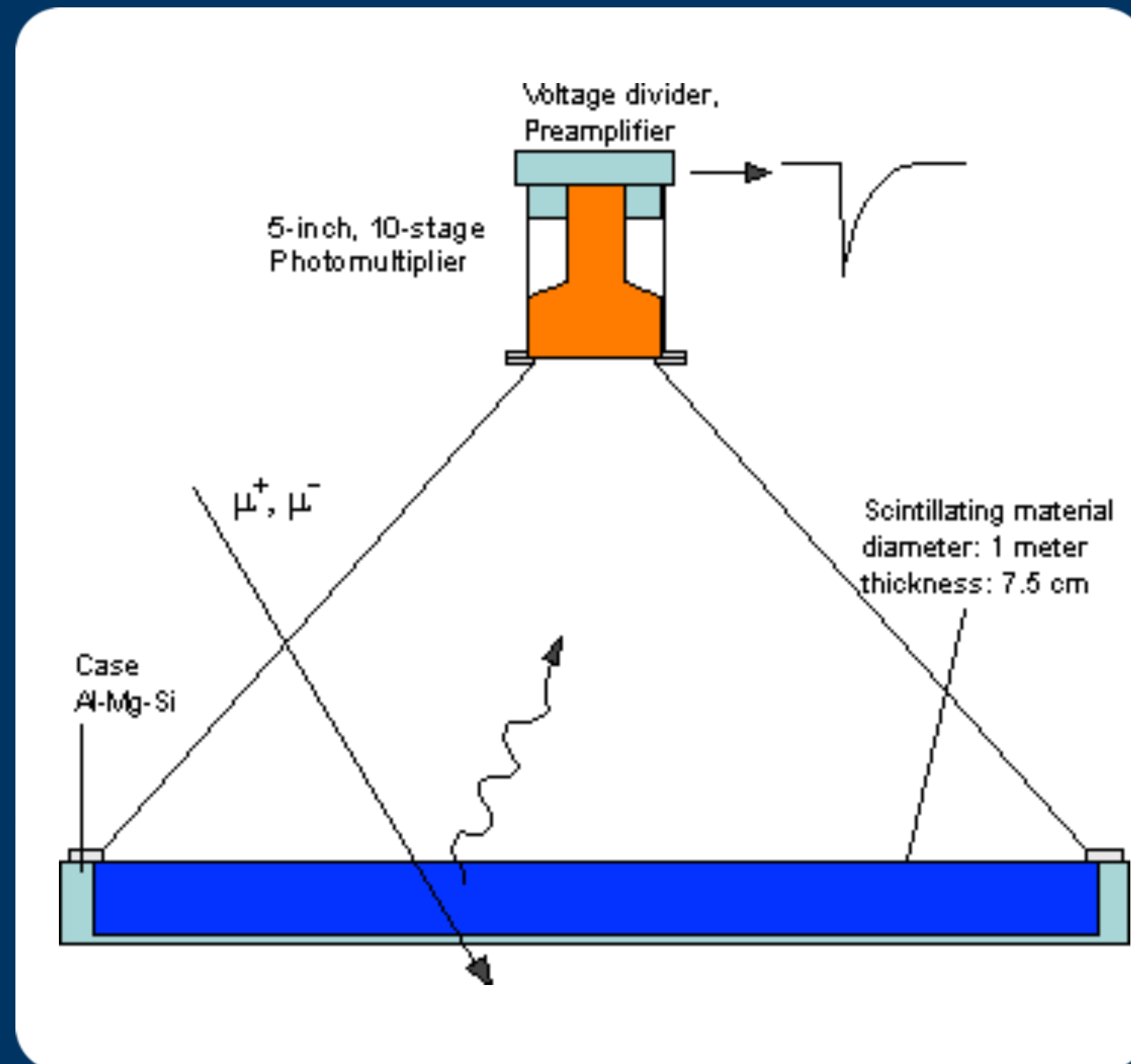


EAS particles: particle detectors

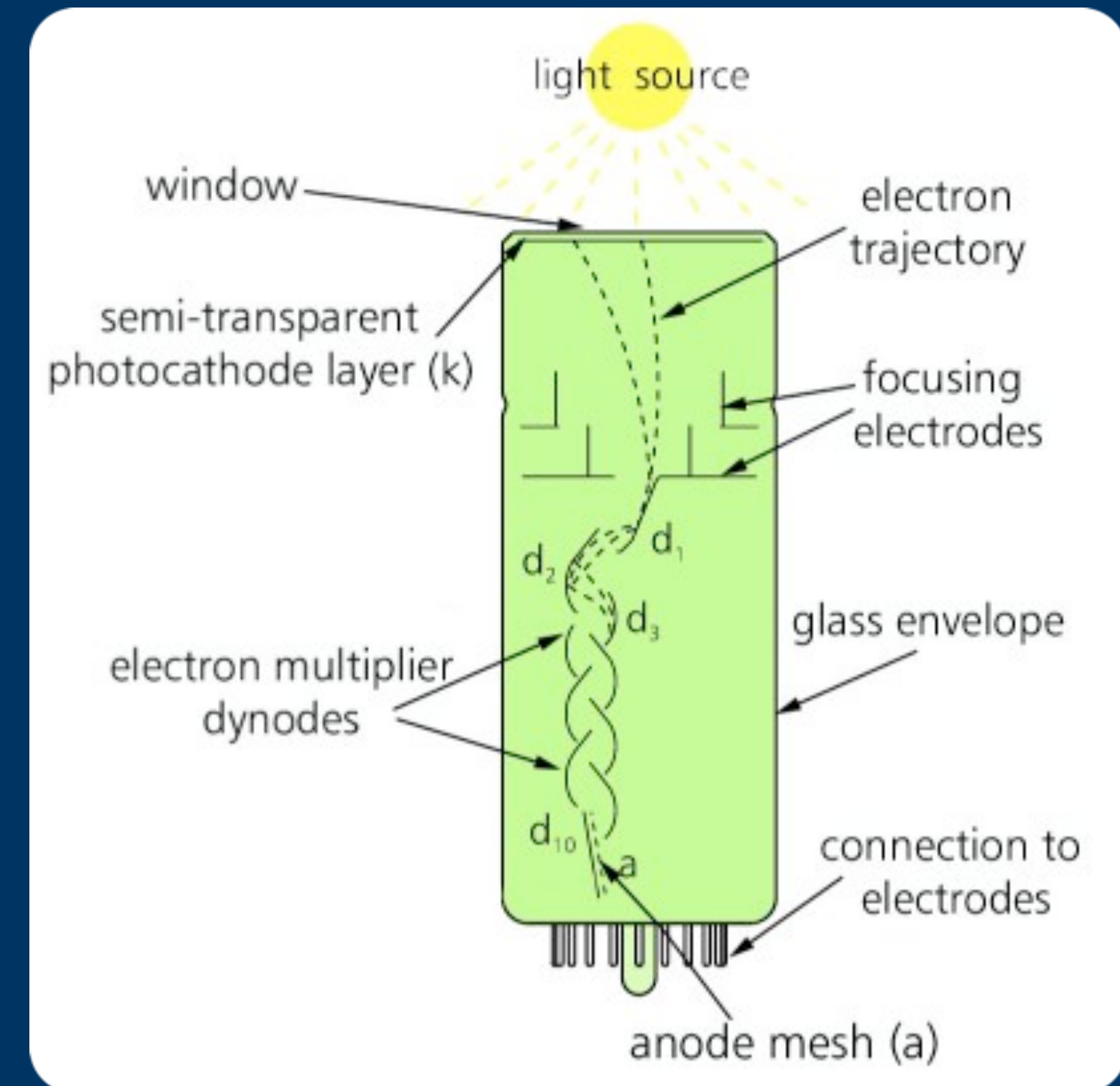
Nani gigantum humeris insidentes (1940s)

Scintillation detectors are historical devices. Rutherford used a scintillating zinc-sulphide screen to count alpha-particles (Crookes tubes). Photons were looked at by eye (by microscopes in dark rooms)!!!

Their use was boosted by the **invention of PMTs**.



**THE FIRST SCINTILLATOR COUNTER
WAS INVENTED IN 1944 WITHIN THE
MANHATTAN PROJECT**



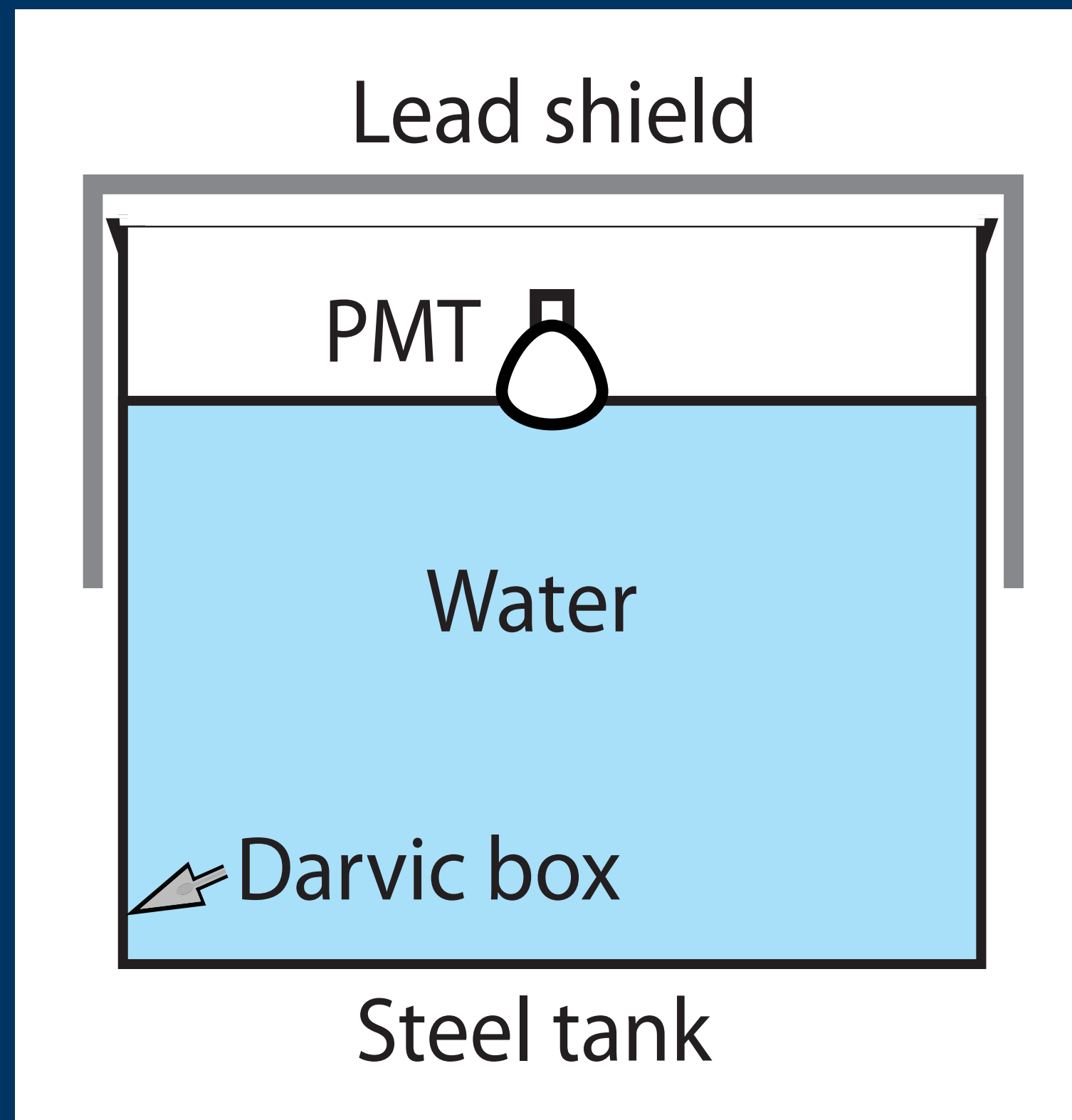
**PHOTOMULTIPLIERS TUBES WERE
DEVELOPED IN MID 40S (AFTER
WORLD WAR II)**

EAS particles: particle detectors

Nani gigantum humeris insidentes (1950s)

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

The idea of using the Cherenkov effect in water for particle detection dates back to the 1950s



Water-Cherenkov detectors were first developed at Culham UK (Porter, 1958).

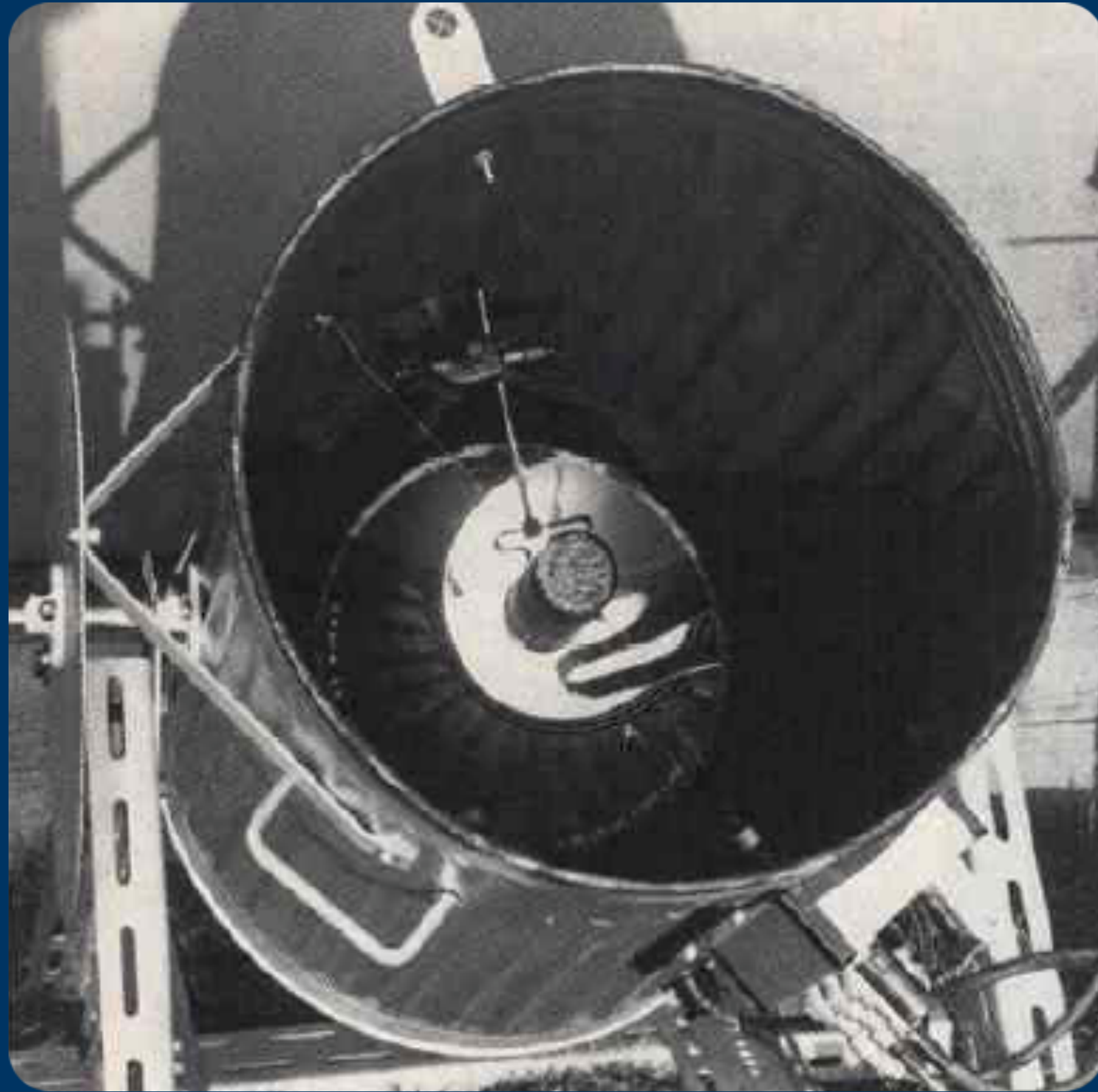
They used a box of Darvic, a material used for sandwich boxes containing an inhibitor of bacterial growth. This allowed to prevent bacterial growth in unfiltered water and realise a stable detector.

**SCHEME OF THE FIRST WCD.
DEPTH WATER = 92 CM, AREA = 1.44 M²**

EAS radiation: Cherenkov detectors

Nani gigantum humeris insidentes (Blackett, Galbraith, Jelley)

Cherenkov effect again, but, in this case, in air (1940s-1950s)



**GALBRAITH, KELLEY (1952):
CHERENKOV LIGHT EXPERIMENT IN A
GARBAGE CAN**

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.

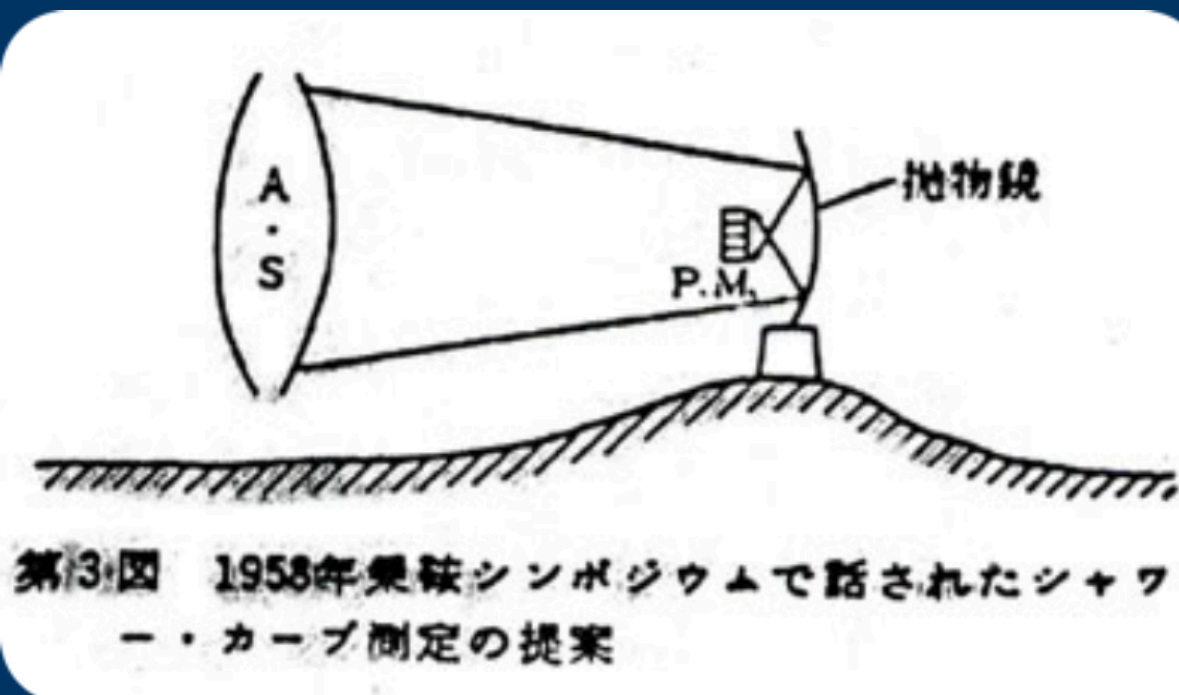
Soon after PMTs were invented, and used to detect Cherenkov light produced by showers (**Galbraith and Kelley, 1952**).

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

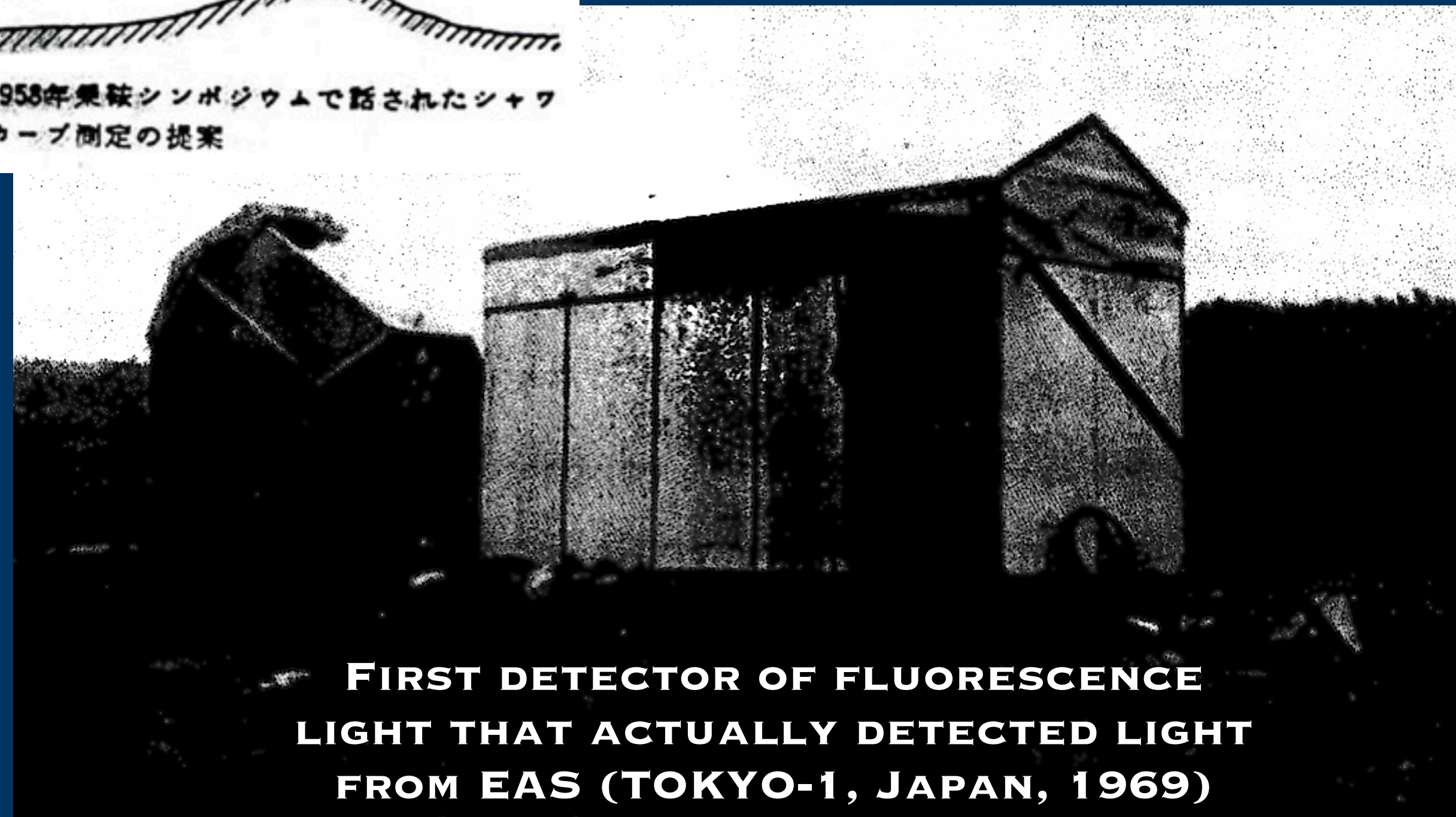
EAS radiation: Fluorescence detectors

Nani gigantum humeris insidentes: Chudakov, Greisen, Suga (late 1950s, 1960s, 1970s)

The idea of exploiting air-fluorescence occurred in the post-Manhattan project, to detect X-rays from nuclear explosions, i.e., as a monitoring tool



SKETCH OF THE VERY FIRST CONCEPT OF A PMT CAMERA VIEWING THE FLUORESCENCE LIGHT FROM AN AIR SHOWER COLLECTED WITH A MIRROR (1957)



The method was first discussed in the context of cosmic rays in a forum by **Suga** in 1962. During the discussion following his presentation, **Chudakov** (URSS) reported the measurements of air-fluorescence made in 1955–1957.

The use of fluorescence radiation to detect EAS was also studied by **Greisen** (USA, 1967-1968) who measured the spectrum of the light produced by particles in air

First detection of fluorescence light from EAS by Japan and US groups in 1970s: it marked a breakthrough for EAS detection as it allows huge volumes of atmosphere to be monitored by optical telescopes

Radio emission: radio detectors

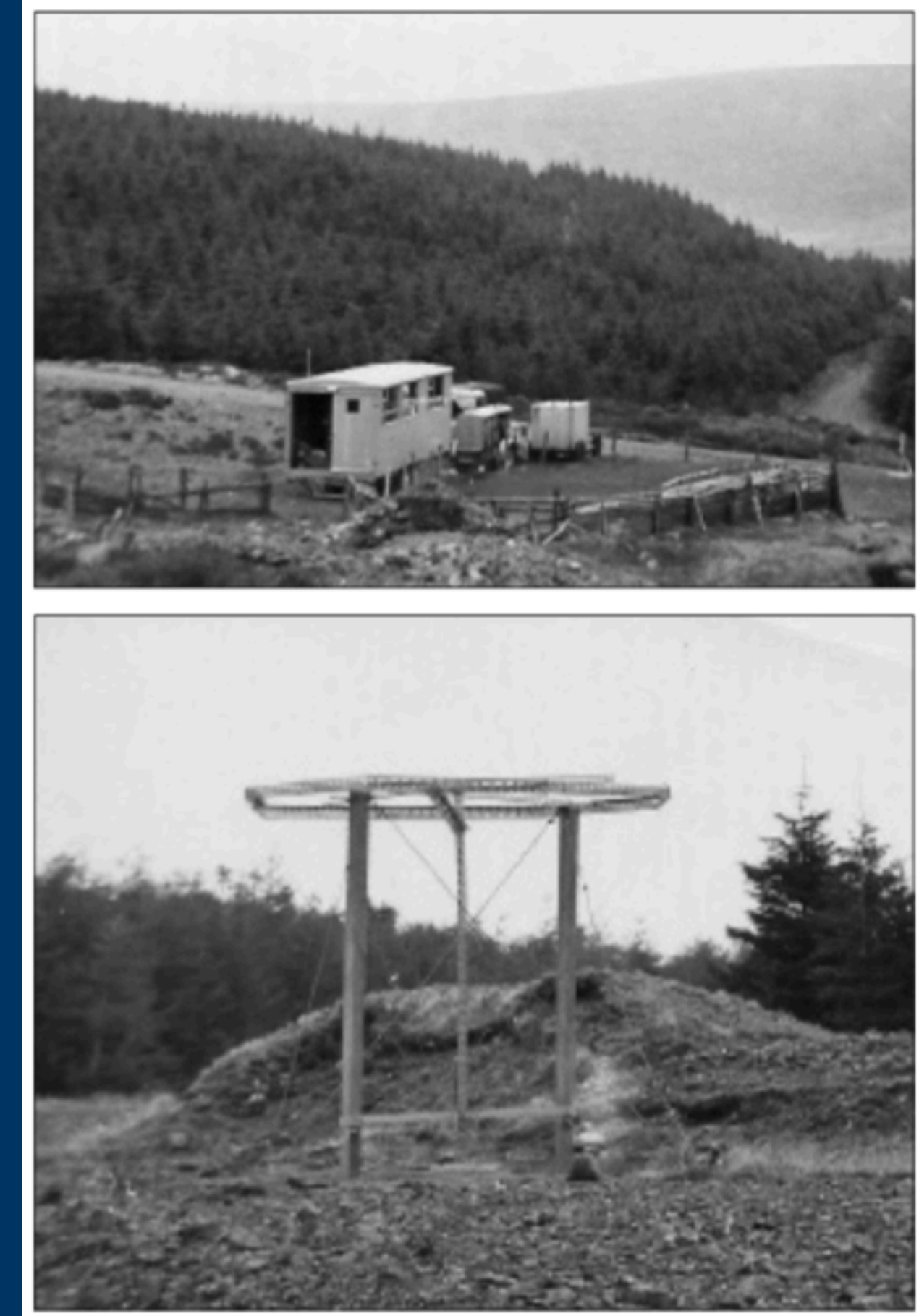
Nani gigantum humeris insidentes (Jelley, Askaryan, Kahn & Lerche, 1960s)

The possibility that the shower particles may emit at radio wavelengths was first suggested by **John Jelley** in his book on Cherenkov radiation (1958). Early measurements were unsuccessful.

Then, **Askaryan** (1962) suggested that the em shower could contain an excess of electrons, caused by the in-flight annihilation of positrons. Because the relativistic electrons move in a thin disk, they could emit coherent Cherenkov radiation at wavelengths of a few metres, i.e, in the MHz range. First observations at 44 MHz were reported by Jelley (1965) in coincidence with GM counters.

Kahn and Lerche (1966) were the first to show the importance of the Earth's magnetic field in determining the intensity of the radio pulse.

Self-triggering experiments failed and the technique was abandoned until the beginning of the XXI century.



FIRST RADIO-ONLY EXPERIMENT IN UK (1969) WITH FOUR CONICAL ANTENNAS OPERATING BETWEEN 30 AND 60 MHz, TRIGGERING AN OSCILLOSCOPE AND CAMERA RECORDING UPON COINCIDENCES BETWEEN PULSES FROM THE ANTENNAS.

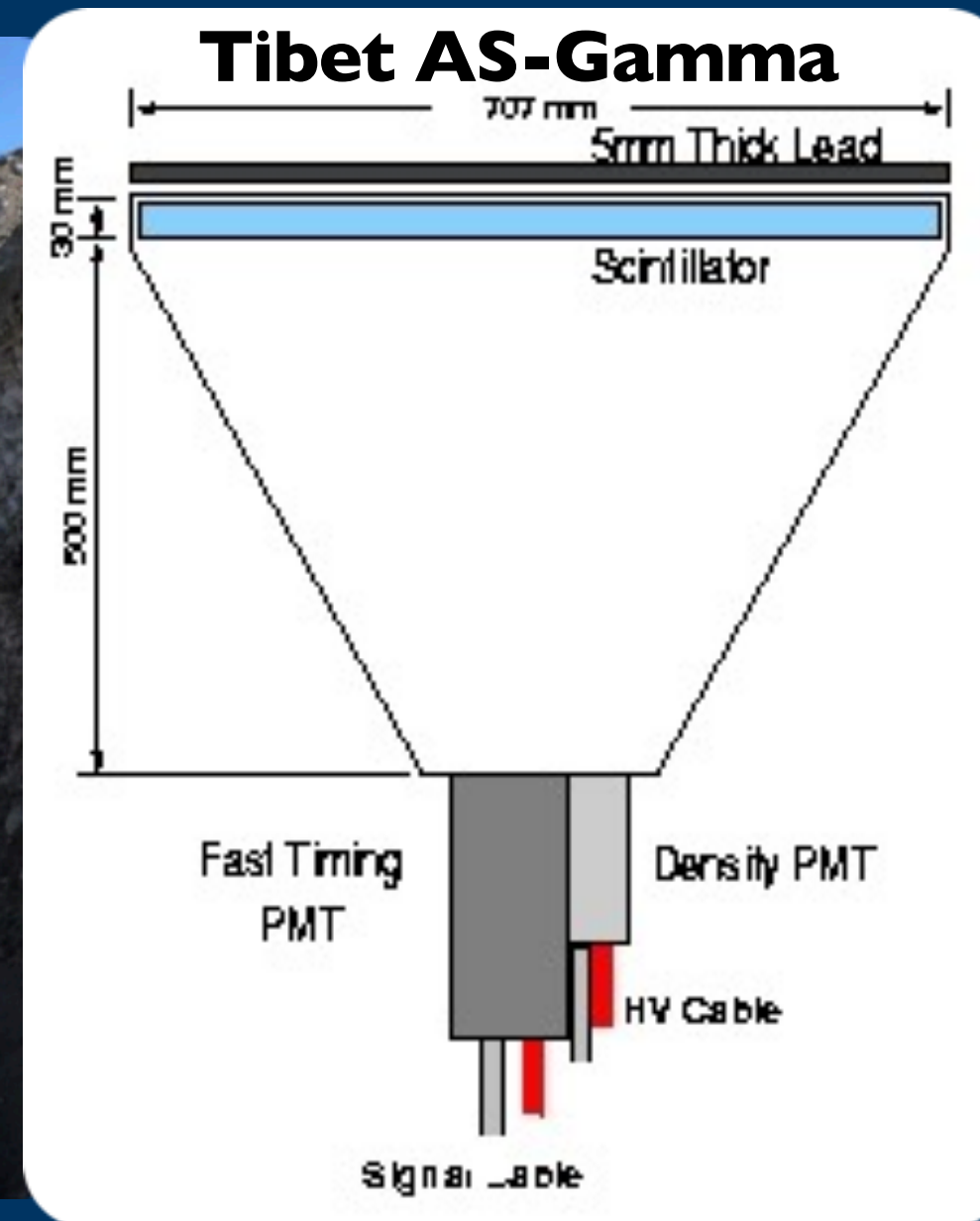
Old principles and ideas in modern EAS experiments

Examples of particles detectors

Telescope Array



AMIGA @ Auger



Pros:

≈ 100% duty cycle

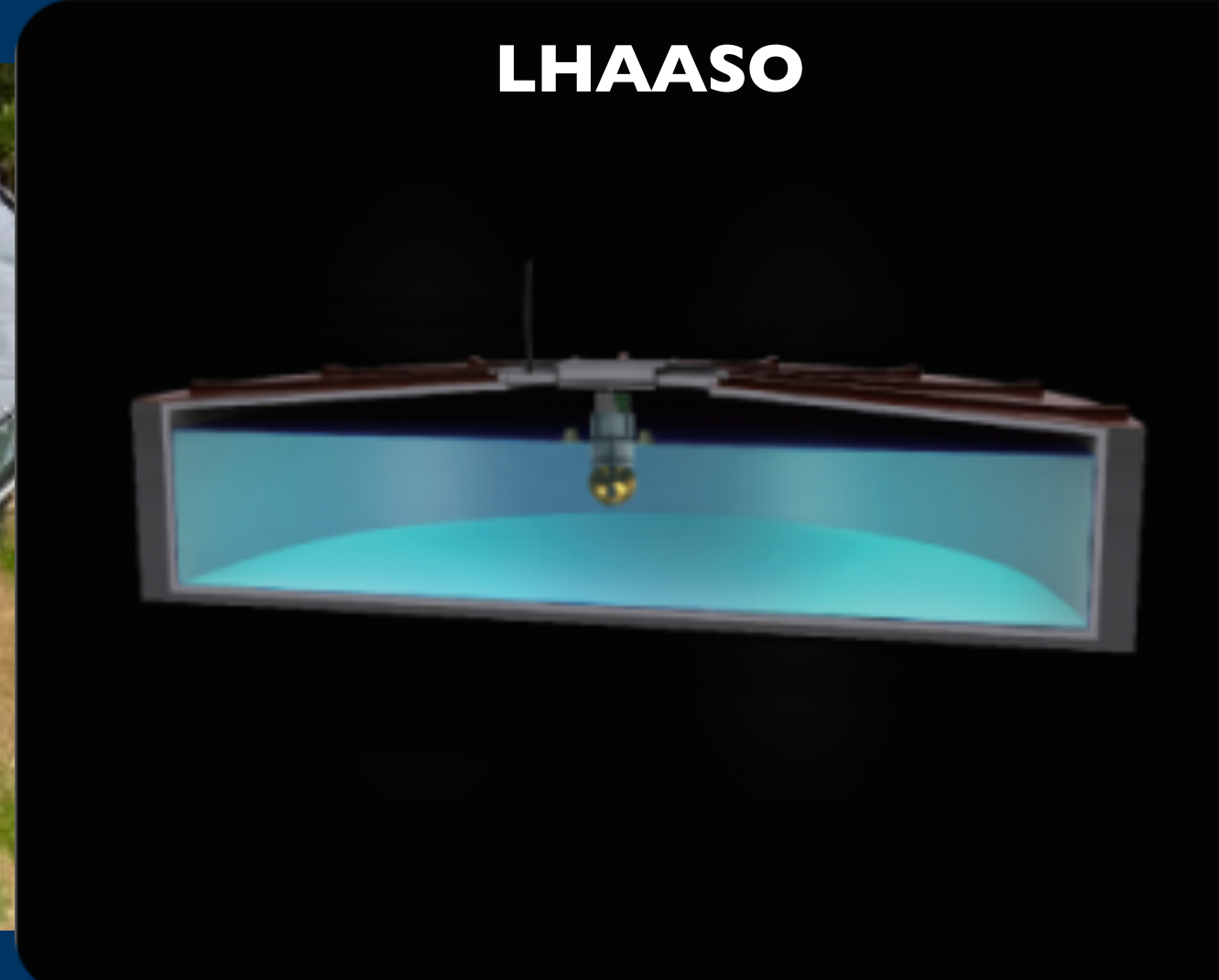
Cons: observation
at one depth only
(no longitudinal
development)

Pierre Auger Observatory,



HAWC

LHAASO



ICETOP



Old principles and ideas in modern EAS experiments

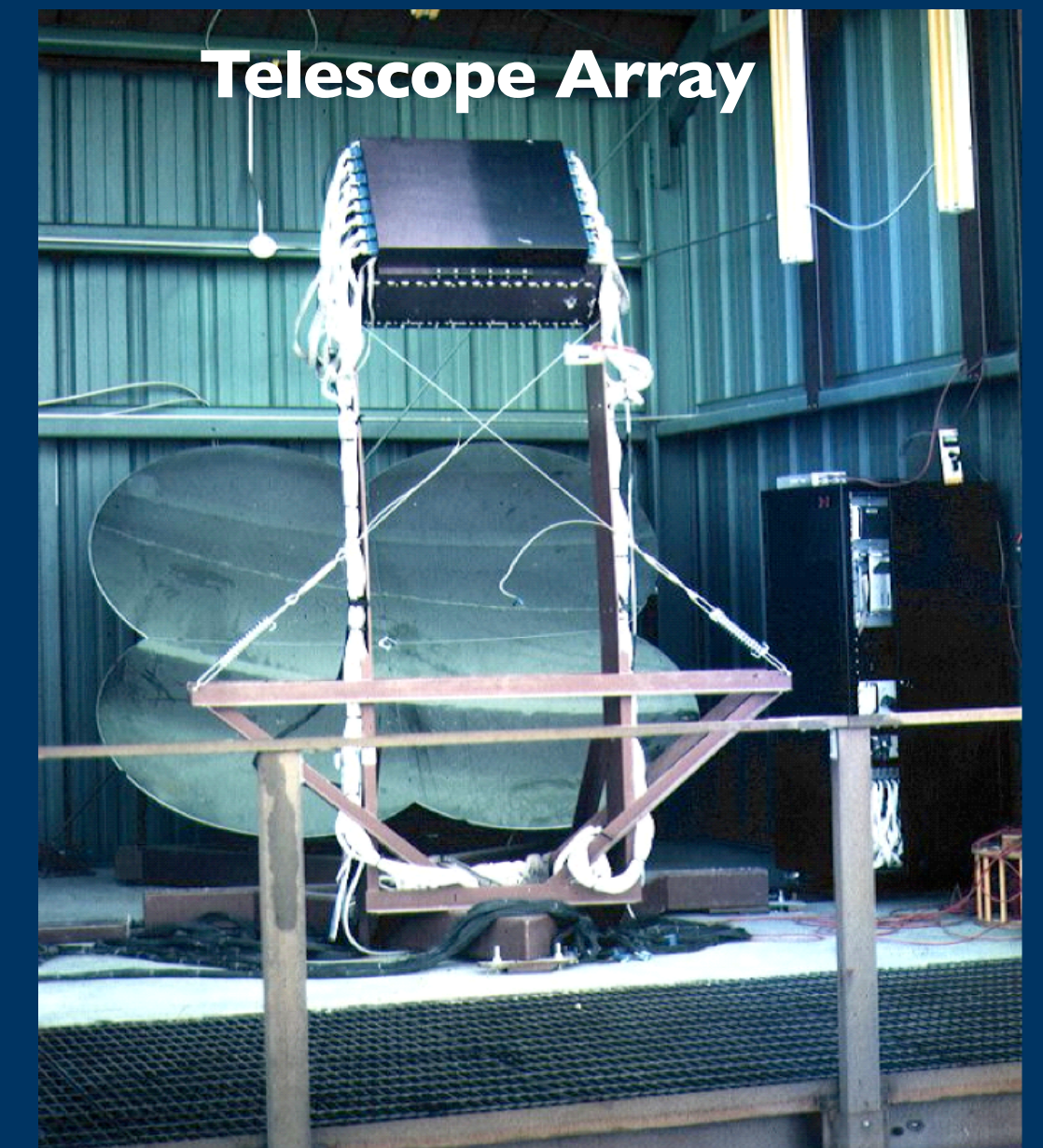
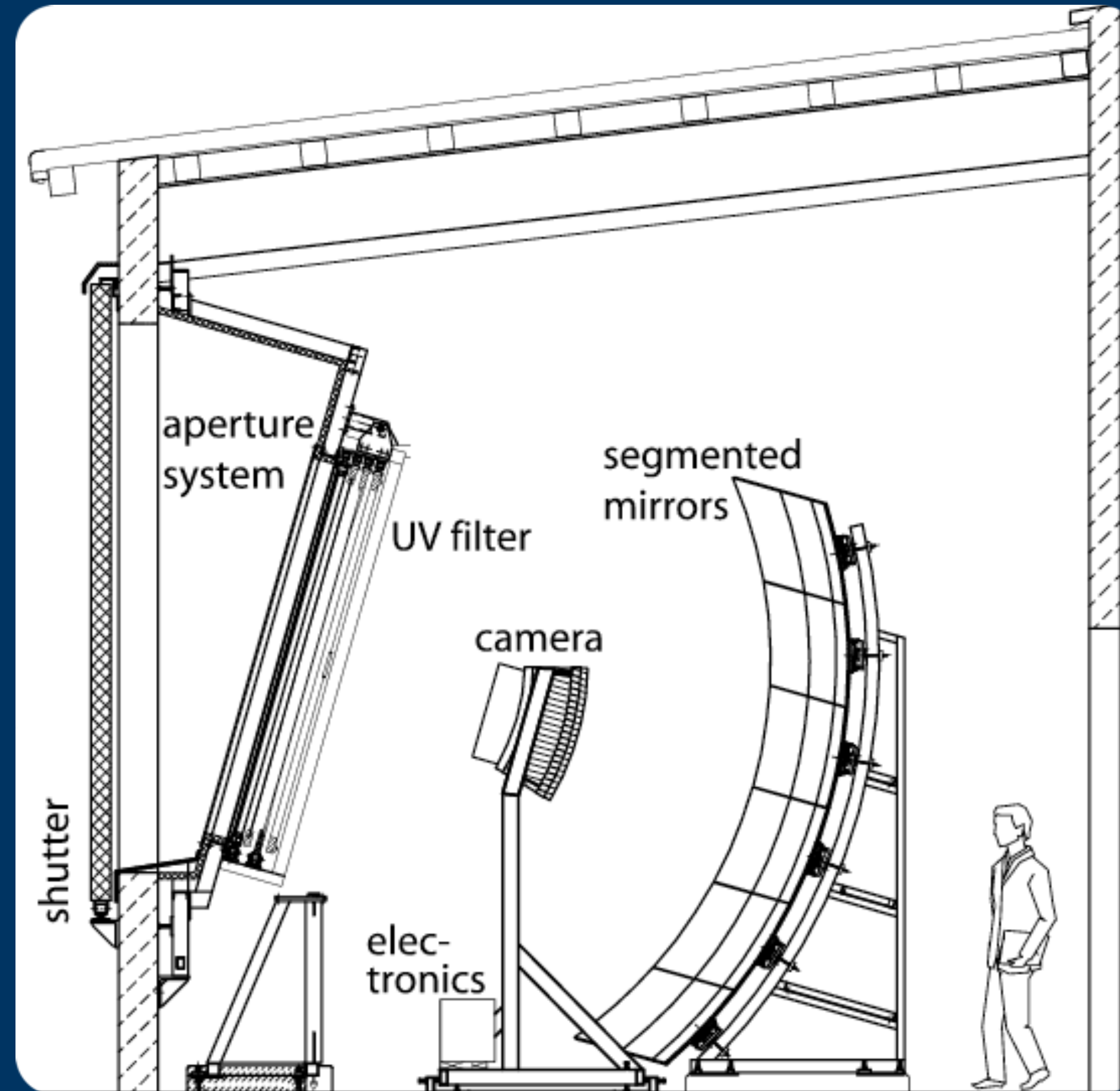
Examples of optical detectors

EAS Cherenkov or fluorescence light is collected by a **mirror** and **imaged onto a camera made by PMTs** or **directly by the PMT looking upside 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: $\approx 10\%$ duty cycle



TUNKA



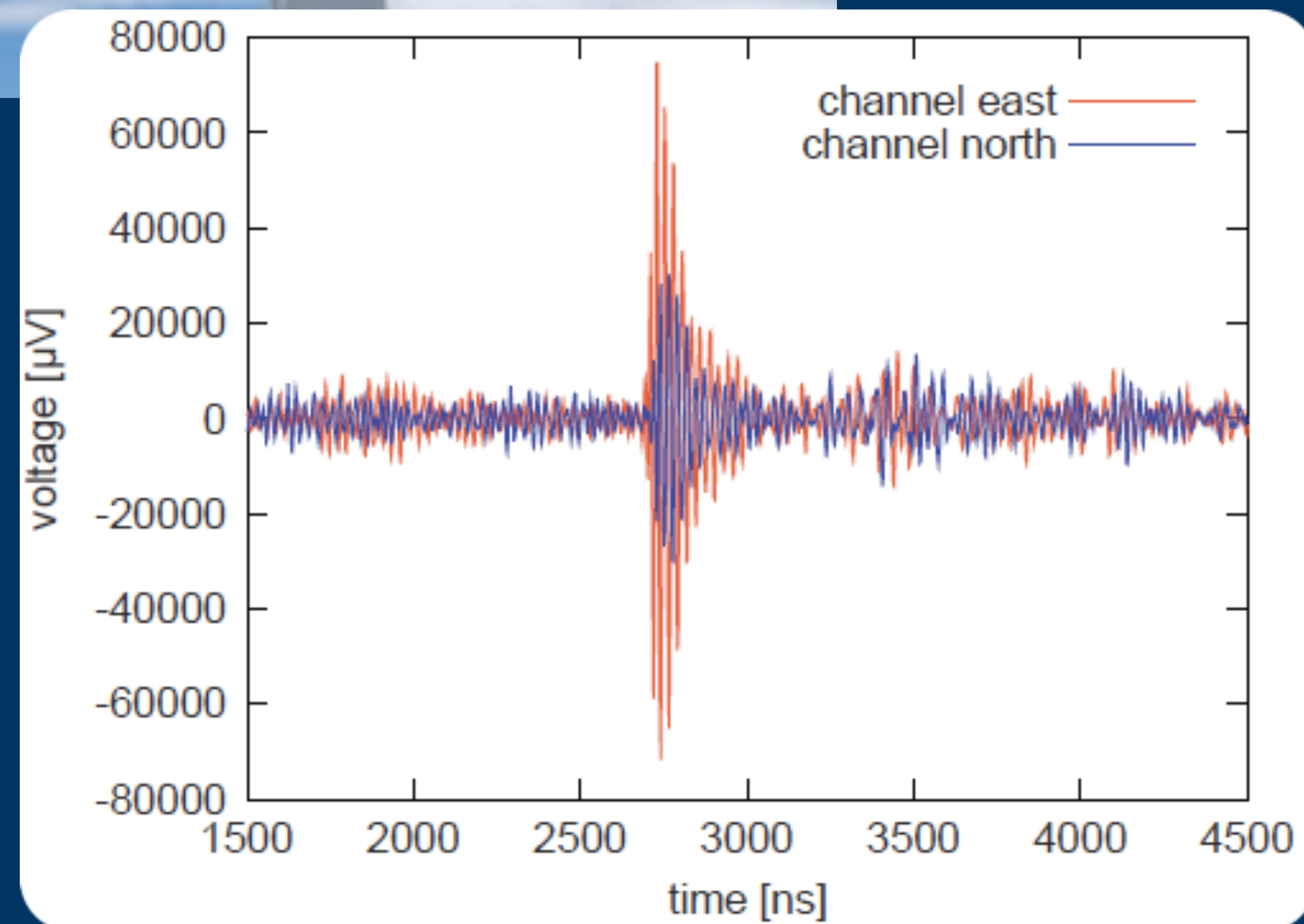
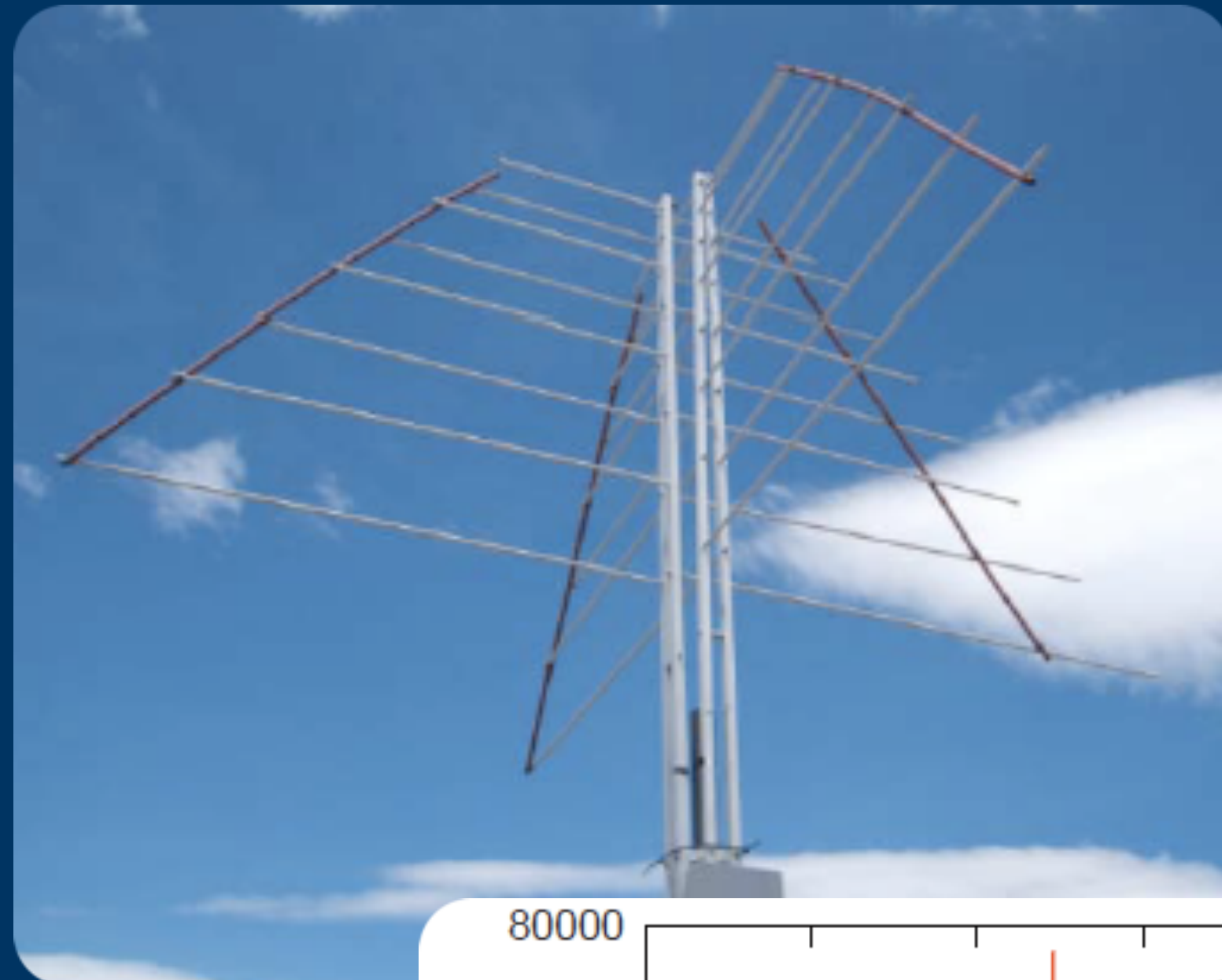
Old principles and ideas in modern EAS experiments

Examples of radio detectors

The measurement of the radio signal requires a **radio antenna**.

Typically, one station consists of two antennas, aligned perpendicular to each other, allowing 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 ANTENNA



Detectors are combined 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:

- Air showers are re-absorbed high in the atmosphere: very high altitude needed
- Air shower are “small”: small spacing (order of few meters) needed or full ground coverage
- 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:

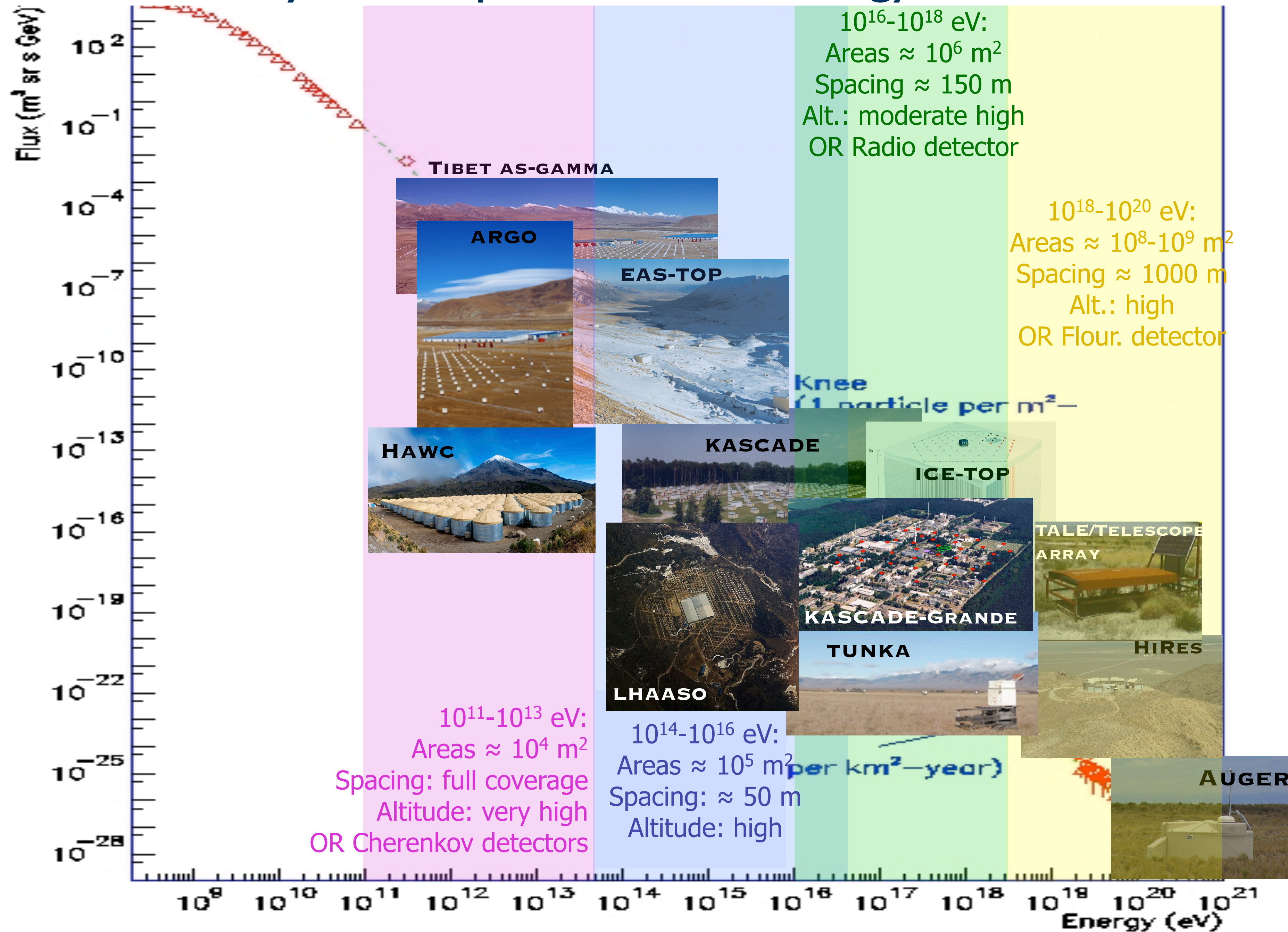
- Shower maximum deeper in atmosphere: sea level enough
- Low fluxes: areas $\approx 1 \text{ km}^2$ needed (detector spacing ≈ 150 m)

Above 10^{18} eV:

- Extremely low fluxes: huge area needed ($\approx 1000 \text{ km}^2$)
- Giant showers: adequate spacing ≈ 1000 m

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

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



e.g., to measure cosmic rays rays at $\approx 10^{11}$ - 10^{14} eV: HAWC

4100 m a.s.l (**Mexico**)

300 adjacent water-Cherenkov

+ 345 sparse small ones

Area $\approx 8 \times 10^4 \text{ m}^2$

In operation

Energy range: $5 \cdot 10^{11}$ -

$5 \cdot 10^{14}$ eV

Main physics aims: γ -ray astronomy, cosmic ray studies overlapping direct measurements



e.g., to measure cosmic rays rays at $\approx 10^{13}$ - 10^{15} eV: Tibet AS-gamma

4300 m a.s.l (**Tibet**)

697 scintillators @ 7.5 m

36 scintillators @ 15 m

Area $\approx 4 \times 10^4 \text{ m}^2$

In operation

Energy range: 10^{12} - 10^{15} eV

Main physics aims: γ -ray astronomy, cosmic ray studies overlapping direct measurements



Kazumasa Kawata/Tibet AS γ Collaboration

e.g., to measure cosmic rays rays at $\approx 10^{13}$ - 10^{17} eV: LHAASO

4410 m a.s.l (Sichuan, China)

78,000 m² water Cherenkov pond

+ 1.3 km² array of 5195 em detectors

+ 1188 muon-detectors

+ 18 Cherenkov telescopes

In operation

Energy range: 10^{11} - 10^{17} eV

Main physics aims: γ -ray astronomy, cosmic ray studies overlapping with direct measurements



e.g., to measure cosmic rays at $\approx 10^{14}$ - 10^{17} eV: ICETOP

South Pole (on top of IceCube)

80 stations: 160 ice Cherenkov detectors

In operation

125 m spacing, area $\approx 10^6 \text{ m}^2$

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

Main physics aims:
cosmic ray studies
between 1st and 2nd
knee



Credit Desy Zeuthen

e.g., to measure cosmic rays at $\approx 10^{15}$ - 10^{18} eV: TUNKA

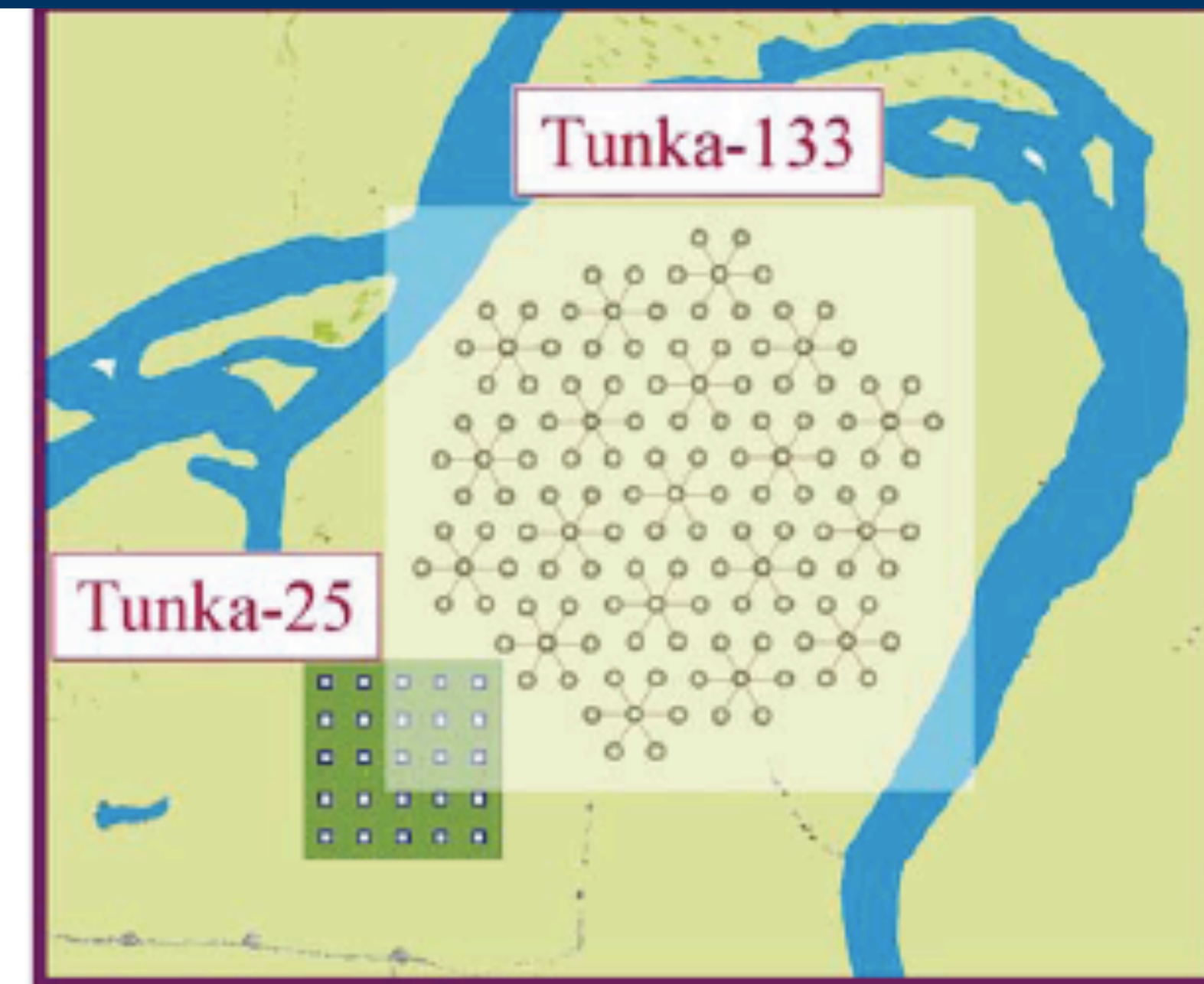
Tunka Valley
(Russia), 700 m
a.s.l.

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

Area 1 km²

Energy range:
 10^{15} - 5×10^{18} eV

Main physics
aims: cosmic
ray studies
between 1st
and 2nd knee



51° 48' 35" N
103° 04' 02" E
675 m a.s.l.



in operation

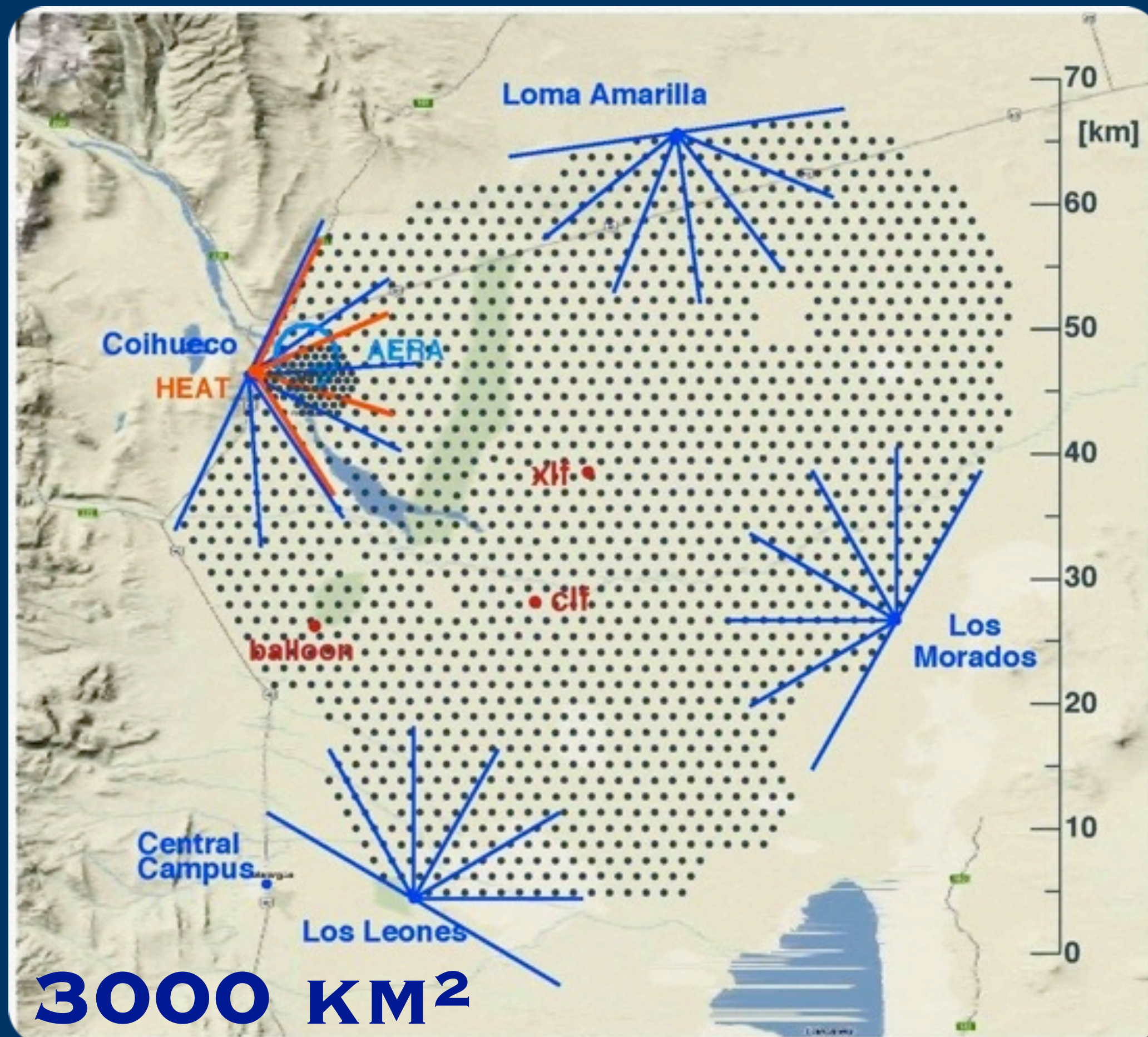
e.g., to measure cosmic rays rays above 10^{17} eV: the two giants

Pierre Auger Observatory, Malargüe, Argentina,
1400 m a.s.l.

1660 water-cherenkov detectors,

5 fluorescence detectors

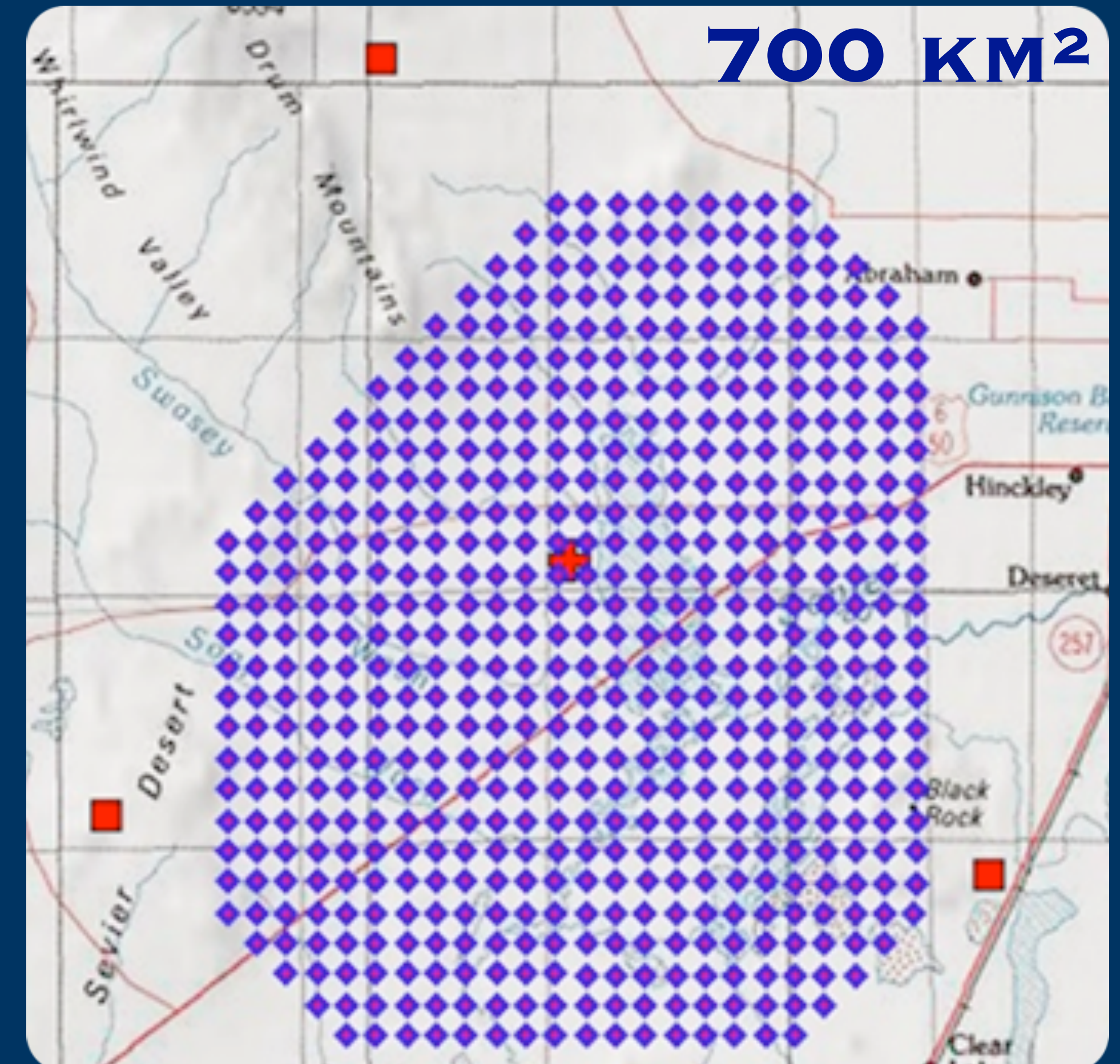
153 radio antennas



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

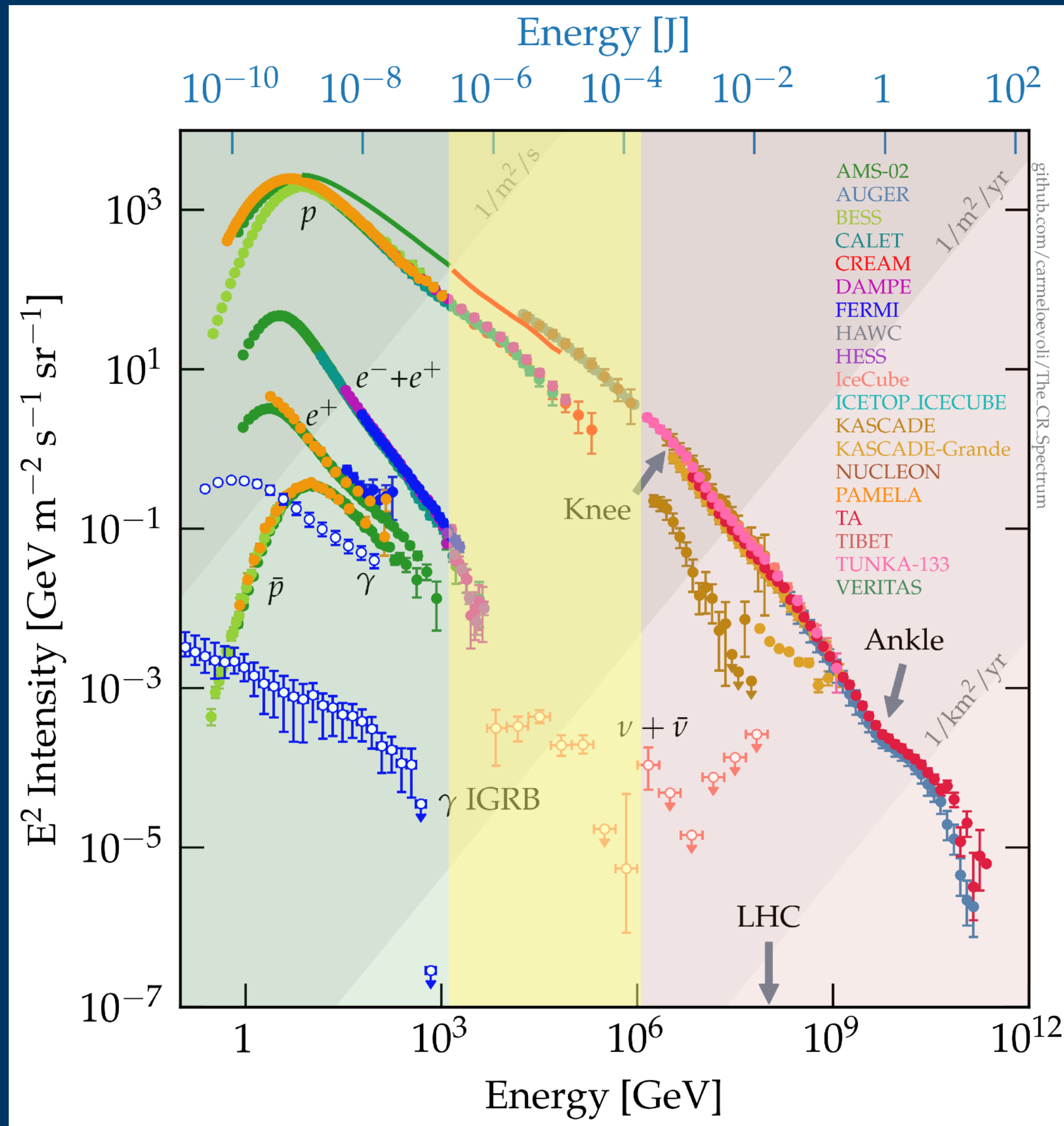
507 scintillator detectors

3 fluorescence detectors



And to finish: back to the beginning...

We talked at the beginning of cosmic ray energy, NOT of extensive air shower energy...



Direct detection: direct measurement of the cosmic ray energy (and mass/charge, and direction...)

Indirect detection: how do we estimate the energy (and mass/charge, and direction...) from extensive air showers, in which the primary cosmic ray has “diluted” its properties?

See you tomorrow for the answer :-)

Thanks for your attention and see you tomorrow!

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.

Enrico Fermi