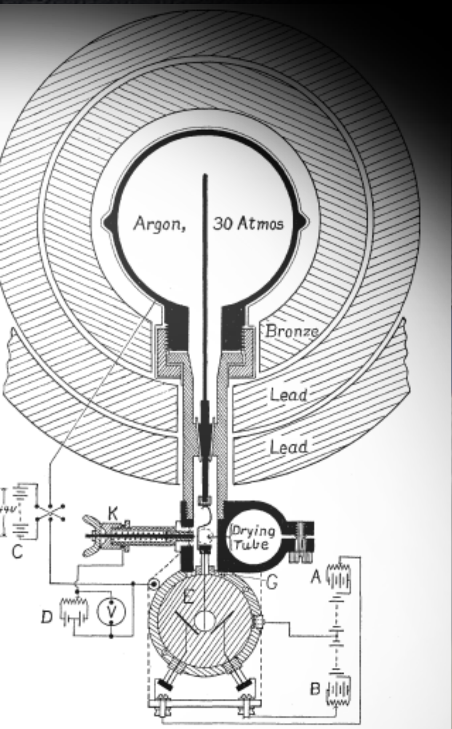
COSMIC RAY DETECTION

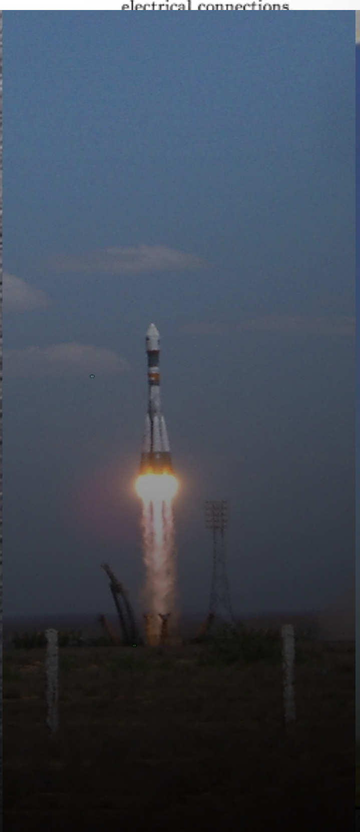
Piera L. Ghia (LPNHE-CNRS, Paris)

``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



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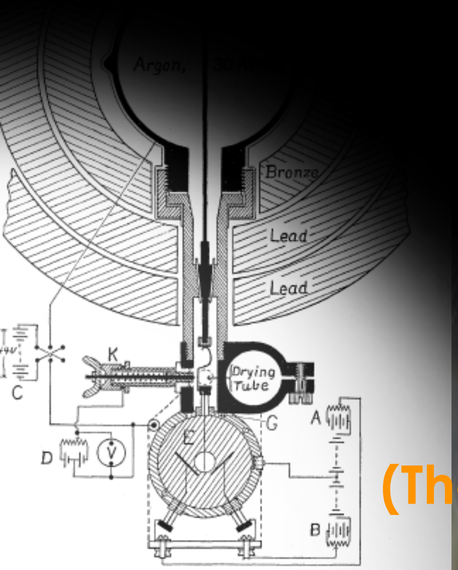
Outline

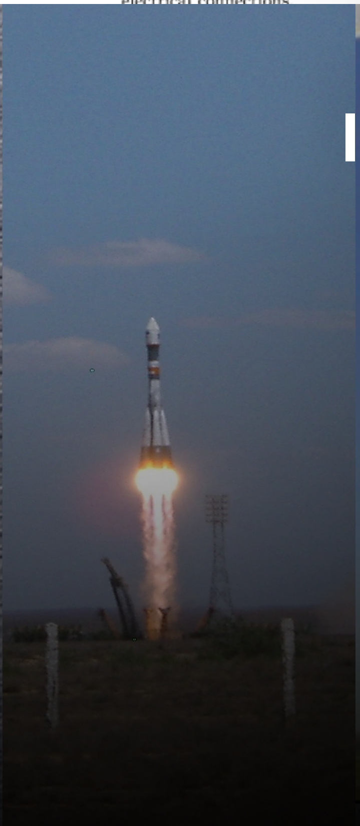


2. Cosmic-ray ionization chamber, electrometer, and electrical connections

(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)

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

V. From EAS observables to CR parameters

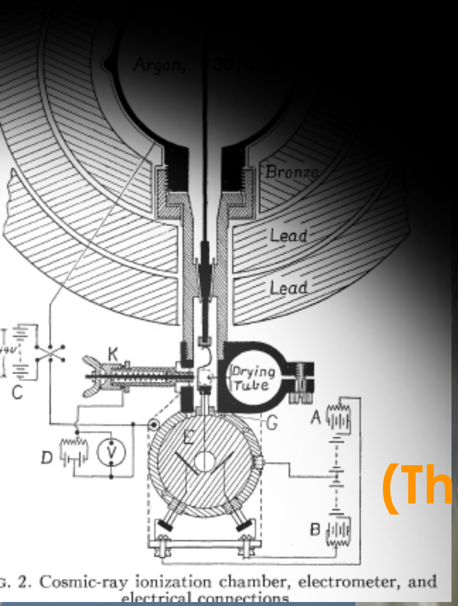
VI. An exemplary case: The Pierre Auger Observatory

Today

(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?



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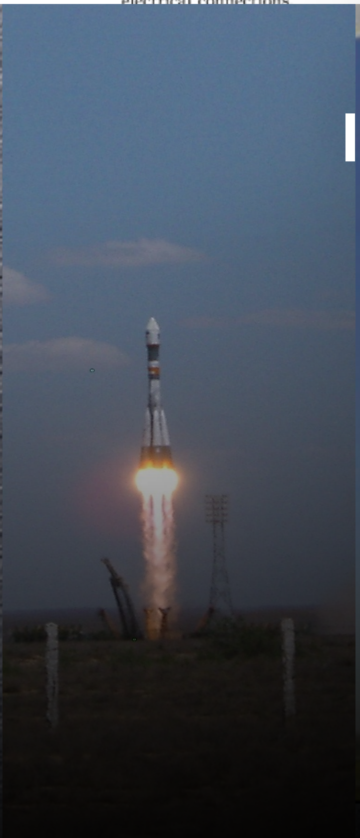

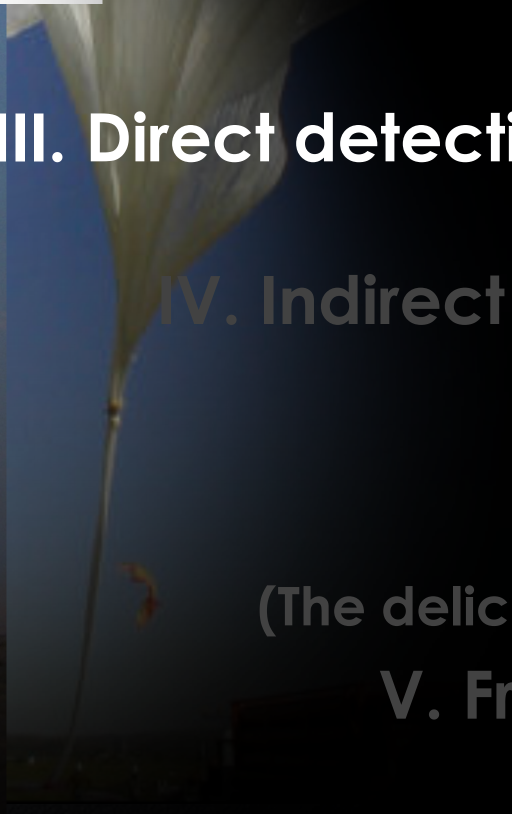

III. Direct detection of CRs: balloon- and space-borne experiments

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

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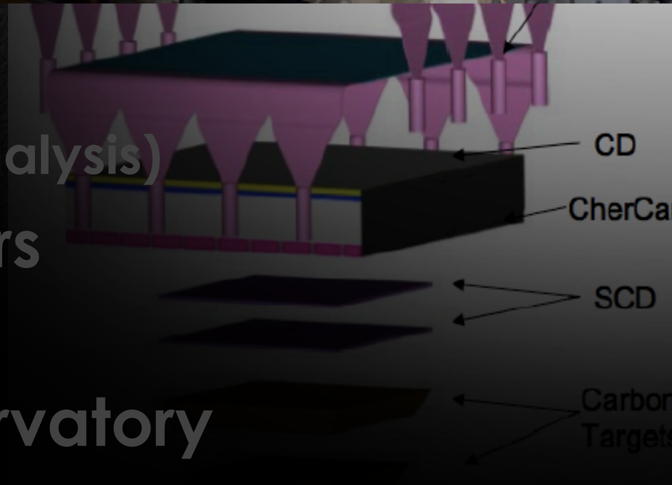


VI. An exemplary case: The Pierre Auger Observatory

The minuteness of the phenomena
The grandeur of the inferences

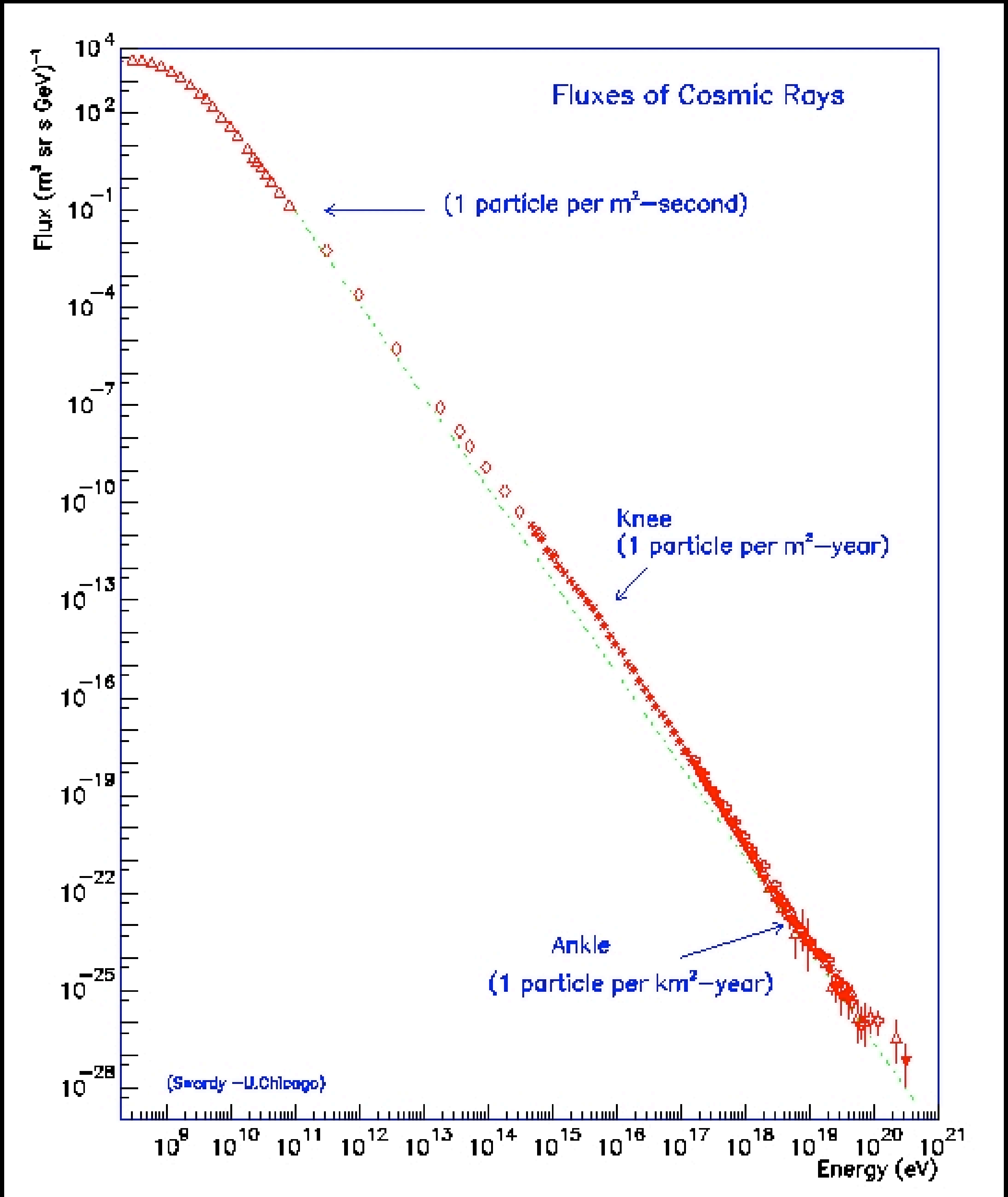
Ia. Cosmic rays: what do we know?

(Cosmic rays in a nutshell)

WHAT DO WE KNOW ON COSMIC RAYS?

The energy spectrum

"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)



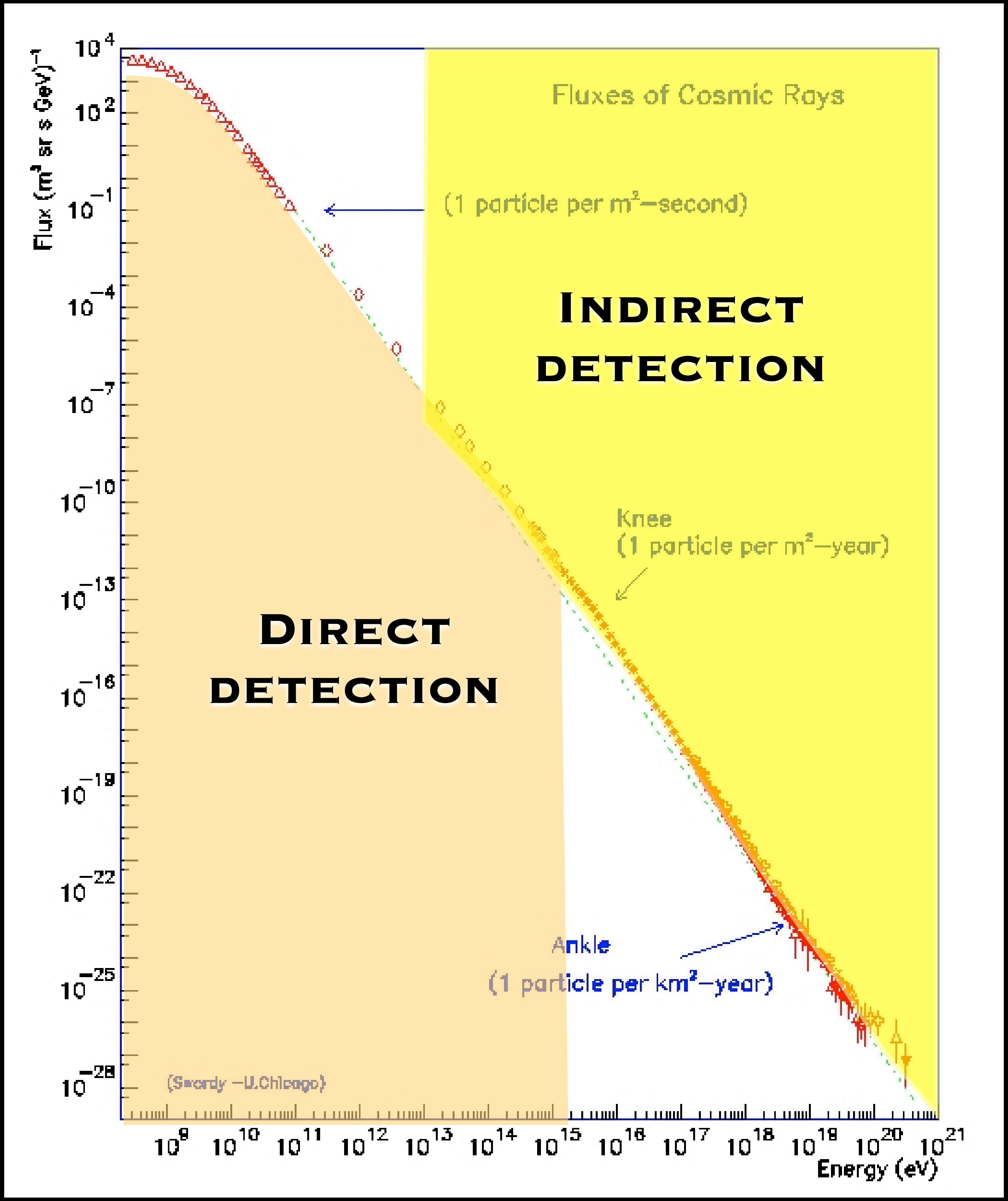
The most striking feature of the cosmic rays is the fact that they span a very wide range of energies.

The energy spectrum is of power-law form ($E^{-\gamma}$, $\gamma \approx 3$): it is extremely regular over ≈ 13 decades (spanning 32 decades in flux!)

WHAT DO WE KNOW ON COSMIC RAYS?

The flux (vs detection)

"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)



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

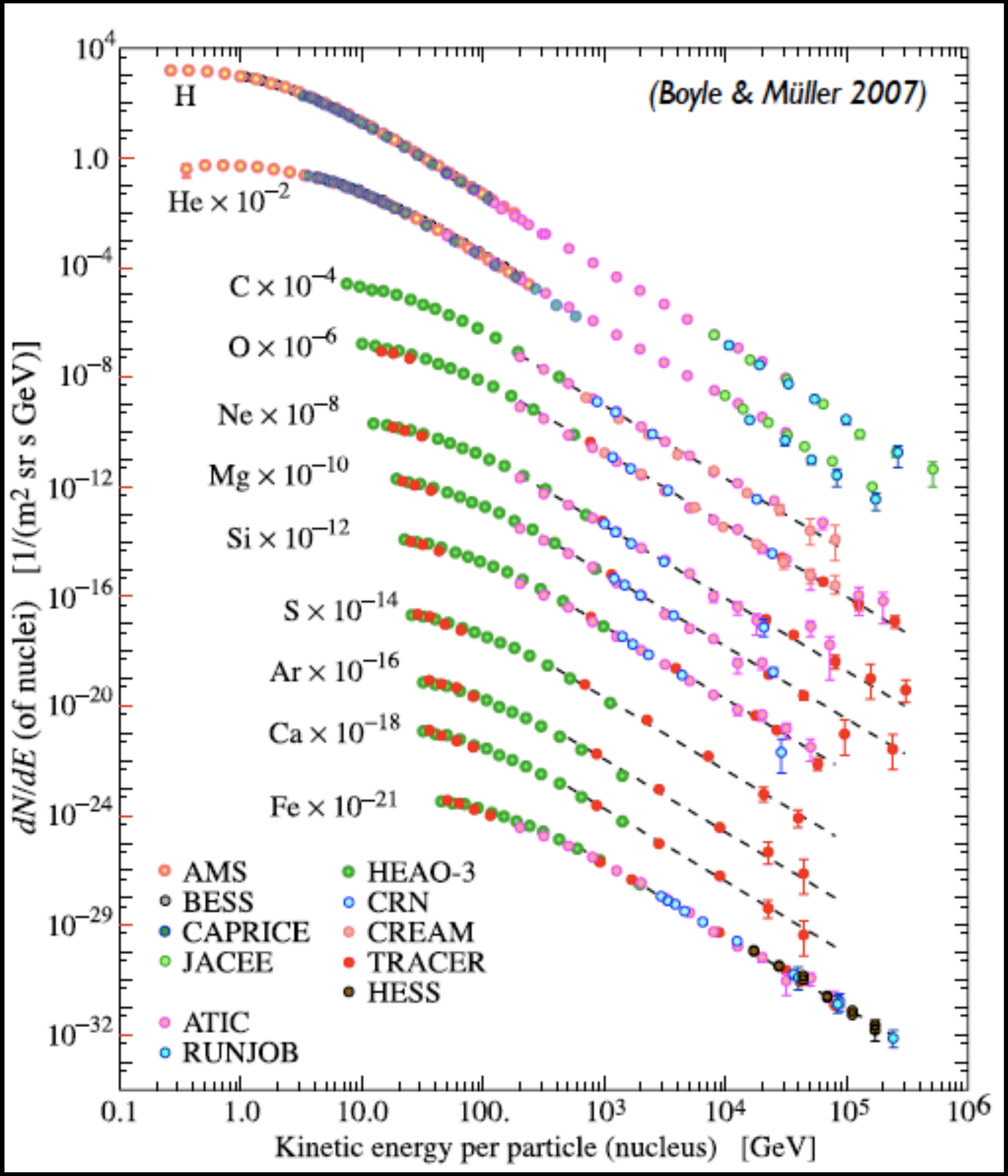
High energy cosmic rays: very rare (1/km^2 y), but "penetrating" up to ground (atmospheric air-showers).
Indirect detection: long-lived large arrays (ground level)

Large telescopes
Extensive Air showers arrays

WHAT DO WE KNOW ON COSMIC RAYS?

The spectrum and chemical composition at low energies

At energies up to ≈ 10^{14} eV, cosmic rays are directly measured, through detectors on balloons or satellites (see later ;-)



In the direct-measurement energy region, about 98% of the particles are protons and nuclei; ≈ 2% are electrons. Of the protons and nuclei, ≈ 87% are protons, ≈ 12% are helium nuclei and the remaining ≈ 1% heavier nuclei

Power laws holds also for individual elements

Index almost identical for all of them. Sligthly harder for heavier elements

WHAT DO WE KNOW ON COSMIC RAYS?

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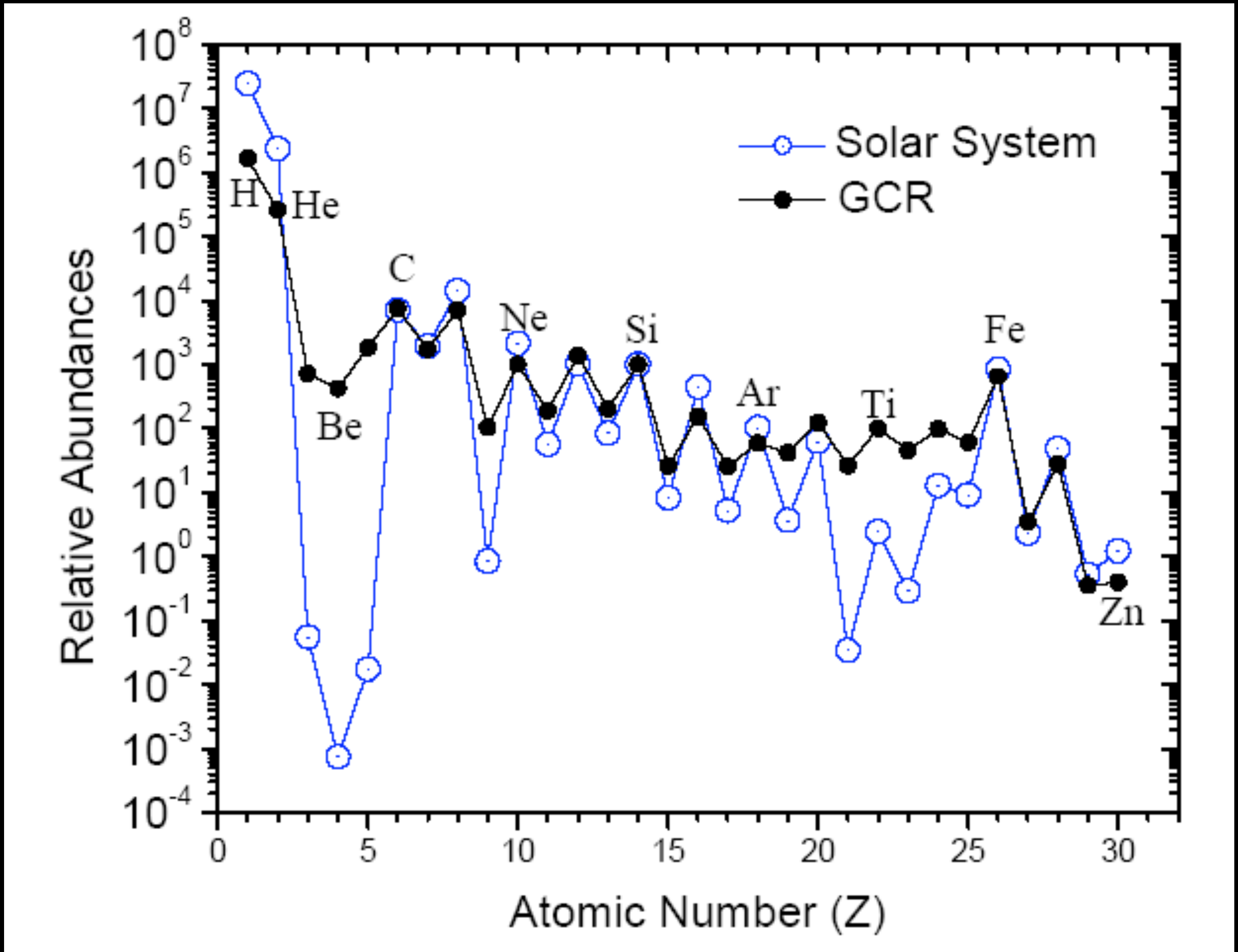


ABUNDANCES OF ELEMENTS IN CR AT ≈ 1 GEV COMPARED TO THOSE OF THE SOLAR SYSTEM

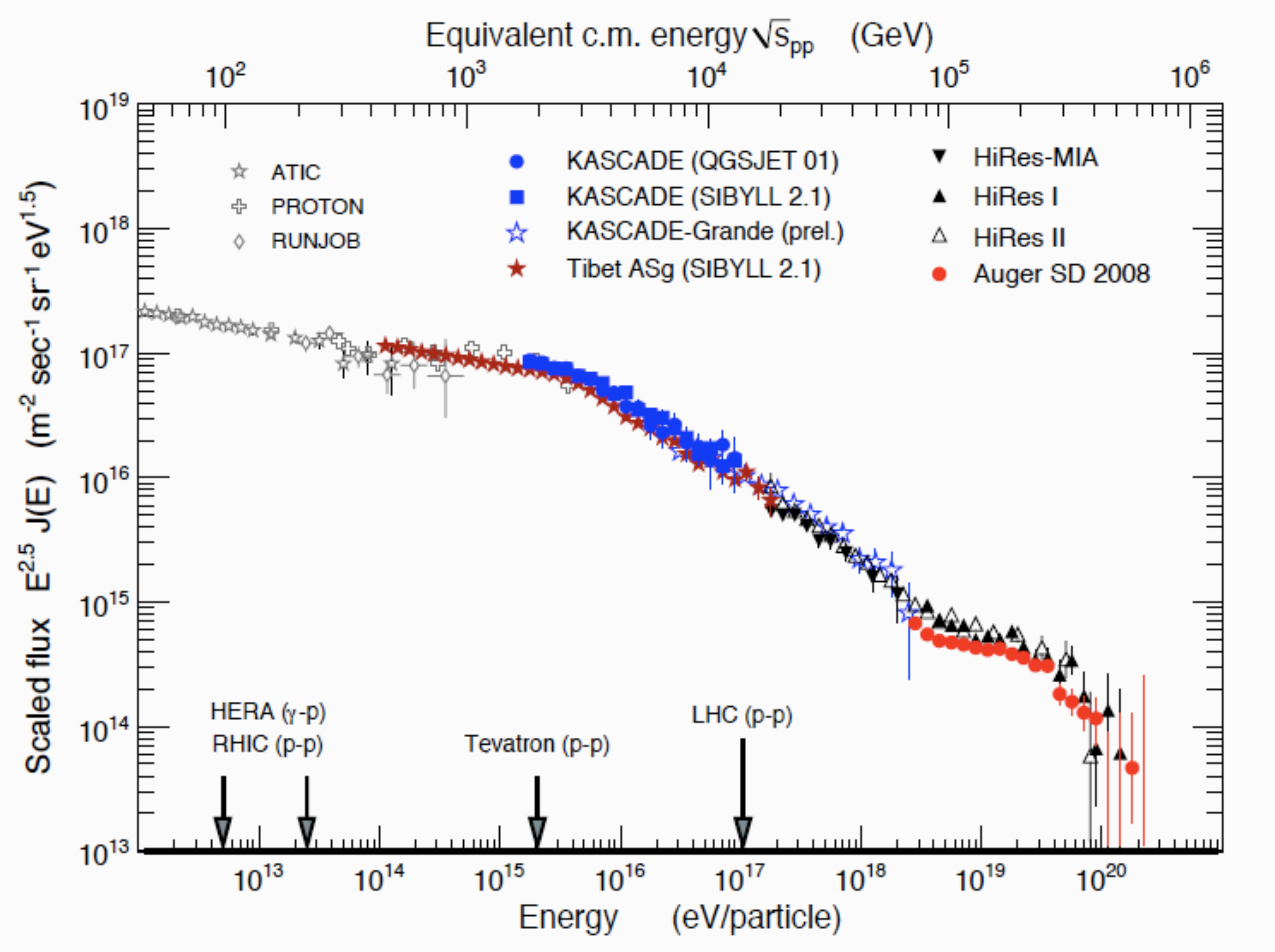
The distribution of elemental abundances in the CR is not so different from those of typical Solar System abundances.

Light elements (Li, Be, B) in CRs are overabundant relative to Solar System ones. Excess also of elements with atomic number and mass just less than those of Fe (i.e., elements between Ca and Fe). This is due to CR propagation in the inter-stellar medium: spallation collisions.

WHAT DO WE KNOW ON COSMIC RAYS?

The spectrum and chemical composition at high energies

At energies above ≈ 10^{14} eV, cosmic rays are indirectly measured, through detectors at ground level through extensive air showers (see on thursday ;-).



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

The CR spectrum shows three "irregularities":

a "knee" at 5 10^{15} eV: due to the "bending" of lighter elements, it could be due to source (maximum energy) or propagation effects (escape from the Galaxy)

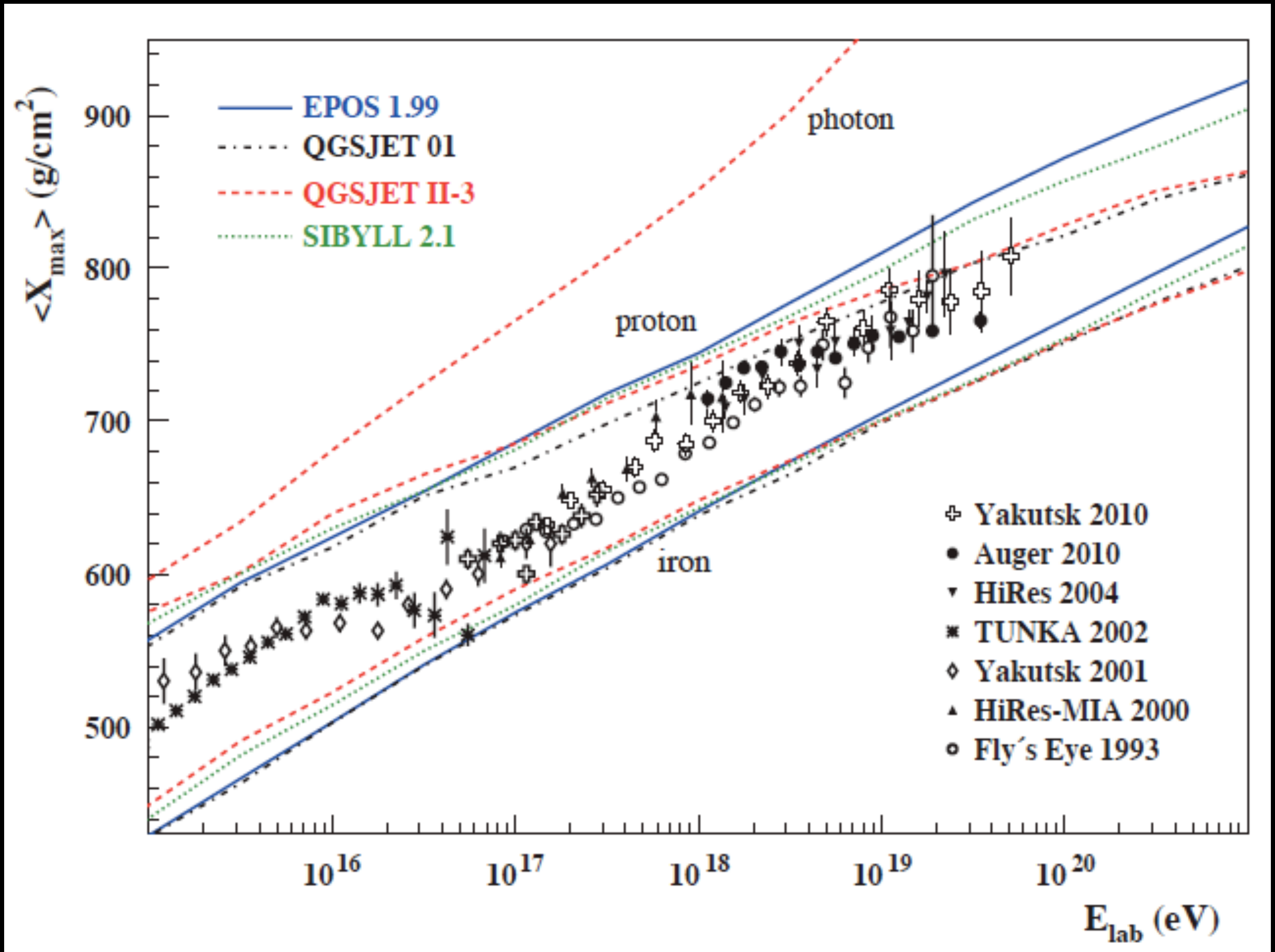
an "ankle" at 3 10^{18} eV: it could either mark the transition between a galactic and an extra-galactic CR origin, or be the signature of interactions of EG protons on background photons

a "suppression" at 5 10^{19} eV: it could be due either to propagation (GZK effect) or source effects (maximum energy)

WHAT DO WE KNOW ON COSMIC RAYS?

The spectrum and chemical composition at high energies

At energies above ≈ 10^{14} eV, cosmic rays are indirectly measured, through detectors at ground level through extensive air showers (see later ;-). Single elements cannot be distinguished but only "inferred"



Xmax vs energy, as measured by different EAS arrays. Expectatations for simulated EAS are also shown

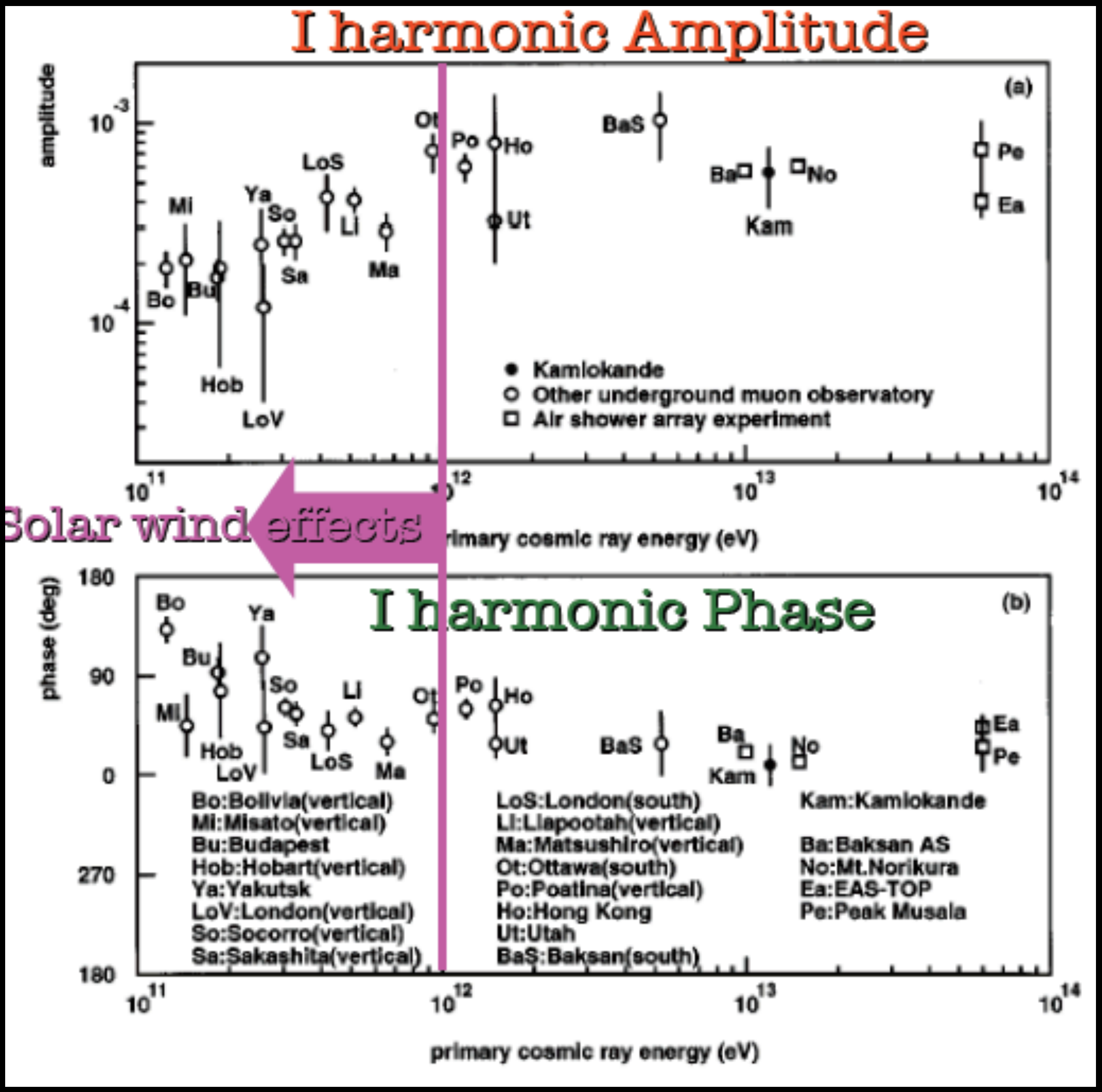
The most common way of inferring the primary composition by indirect measurements is by the determination of the depth of shower maximum in atmosphere, Xmax (see on thursday ;-)

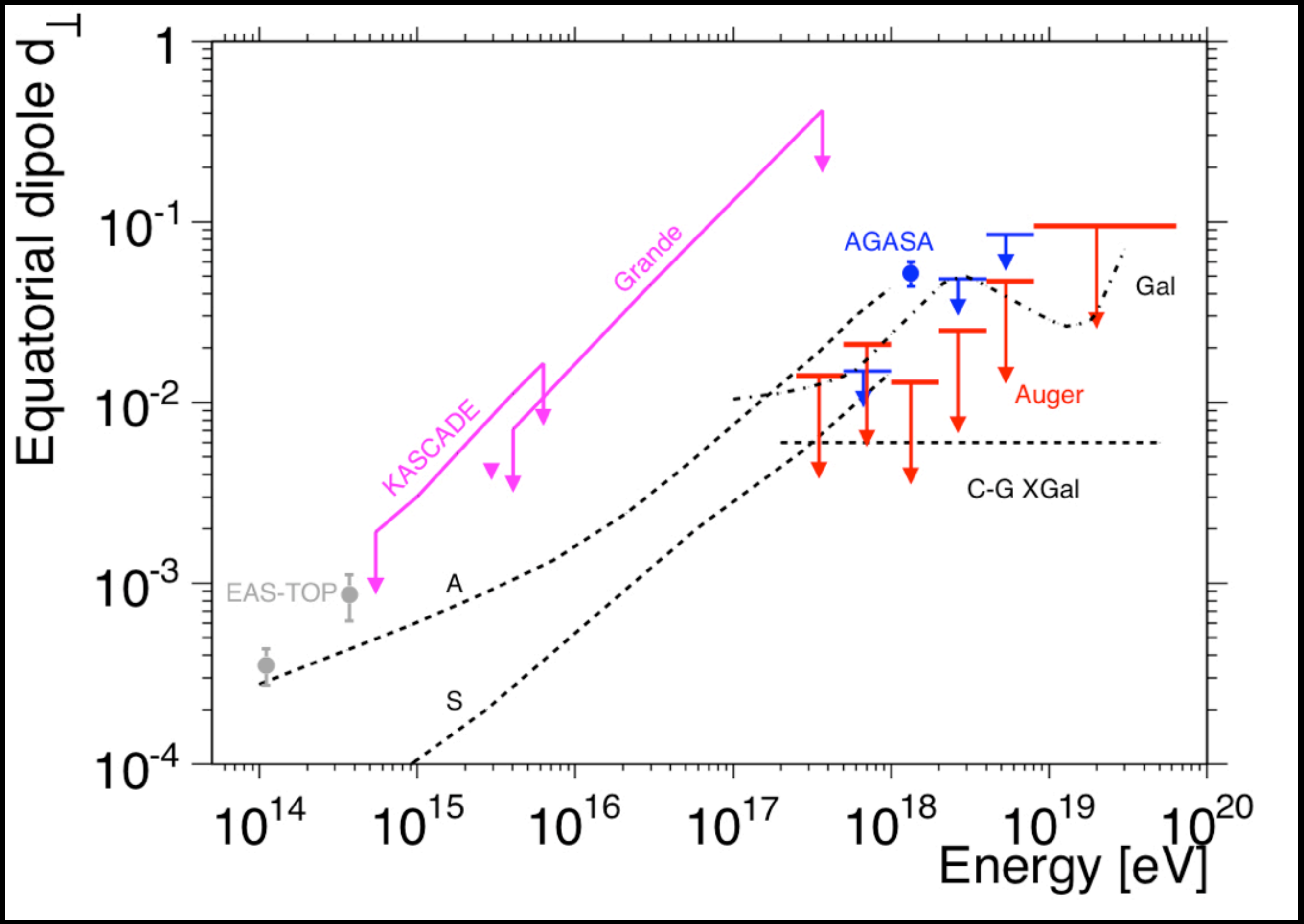
Xmax depends on primary mass. From comparisons with what expected from shower simulations, one can infer the trend of average mass vs energy

WHAT DO WE KNOW ON COSMIC RAYS?

Arrival directions (sources)

CRs below 10 GeV are influenced by solar modulation. Information about their arrival directions at the Solar System is lost when they reach Earth. CR above 10^{12} eV are likely to preserve information about their arrival direction at the Solar System when they arrive at Earth.





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%.

WHAT DO WE KNOW ON COSMIC RAYS?

Arrival directions (sources)

Although CR above 10^{12} eV are likely to preserve information about their arrival direction at the Solar System when they arrive at Earth, due to deflections in the galactic magnetic field, they do not preserve information about their original travel direction and hence, about their sources.

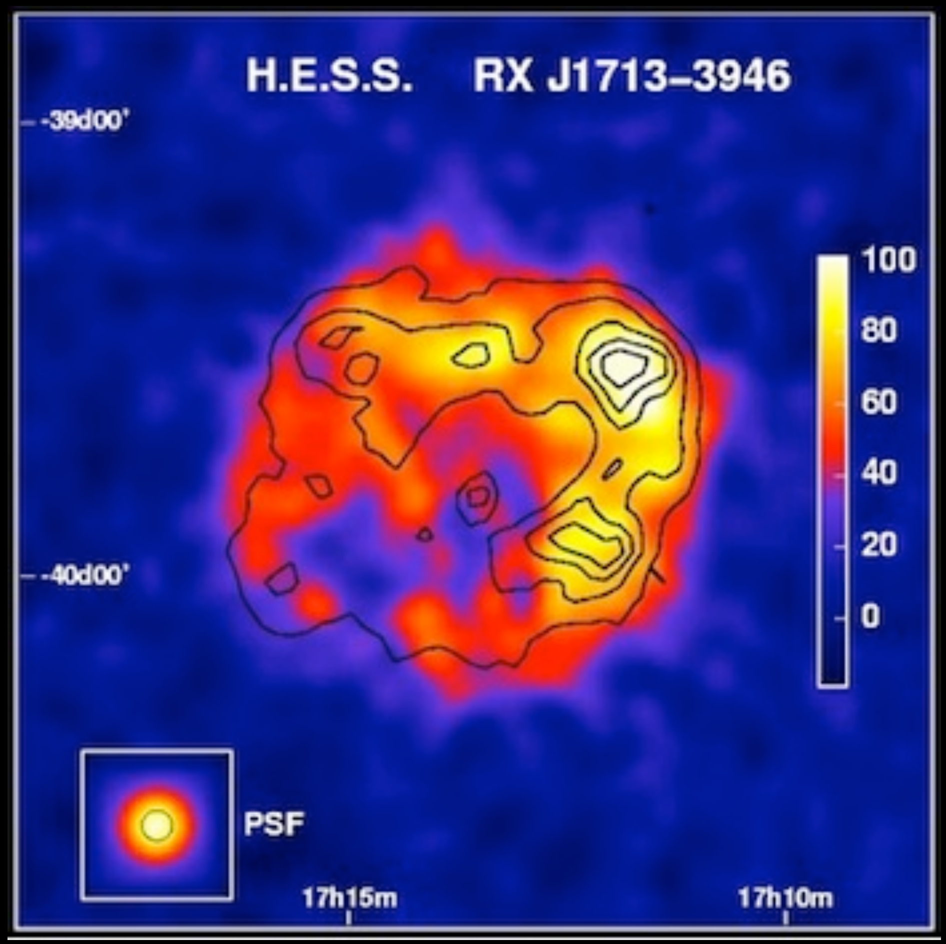
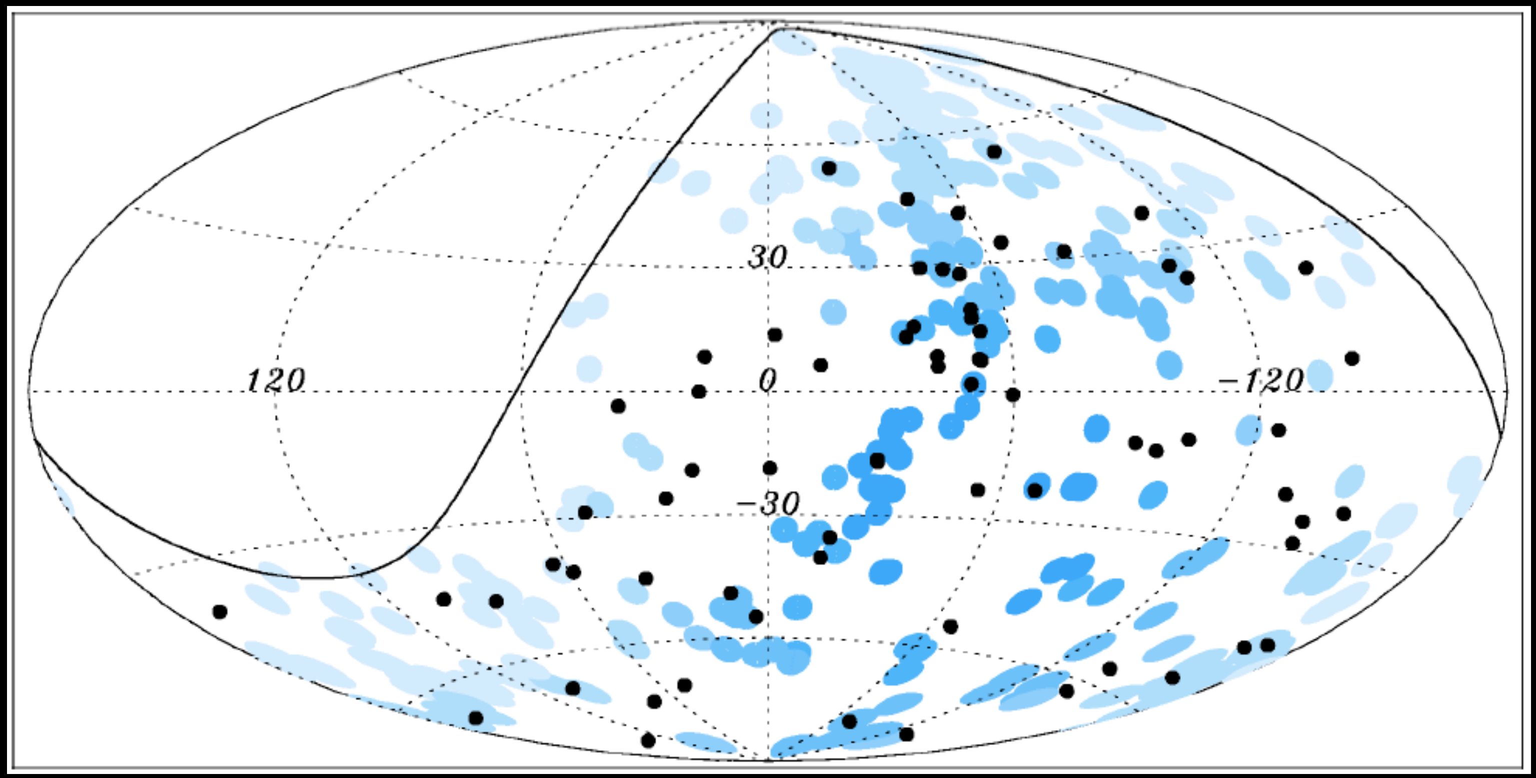


IMAGE OF A SNR IN GAMMA (HESS EXPERIMENT)



DISTRIBUTION OF AUGER EVENTS (E>50 EEV) IN THE SKY VS AGNS POSITIONS

Supernovae are prime candidates for the acceleration of galactic cosmic rays. Only possible observation through neutral gammas, produced by CR interactions in the source. No smoking gun found yet.

At energies > ≈ 10^{19} eV, low-Z CR are slightly deflected by magnetic fields. In principle, charged-particle astronomy may be possible. Possible source candidates: AGNs, gamma-ray bursts, radio-galaxies...

The minuteness of the phenomena
The grandeur of the inferences

Ia. Cosmic rays: how do we detect them?

(Principles of detection in a nutshell)

HOW DO WE DETECT COSMIC RAYS?

Cosmic rays are particles

Cosmic ray detectors are particle detectors

All particle detectors are based on the same fundamental principle: the transfer of part or all of the energy to the detector mass where it is converted into some other form more accessible to human "perception". The form in which the converted energy appears depend on the detector and its design.

i.e., The detection of a particle happens via their energy loss in the material it traverses ...

HOW DO WE DETECT COSMIC RAYS?

Cosmic rays are particles

Cosmic ray detectors are particle detectors

AMS scintillators (time of flight)

PAMELA Calorimeter

Wide choice of detectors:

dE/dX

Secondary/cascades measurements

Magnetic deflections

Transition radiation

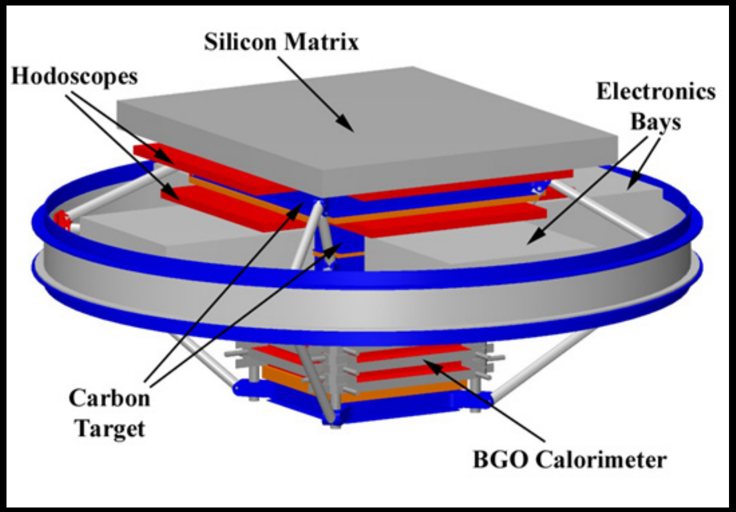
Cherenkov

Radio

HOW DO WE DETECT COSMIC RAYS?

Cosmic rays are particles

Cosmic ray detectors are particle detectors



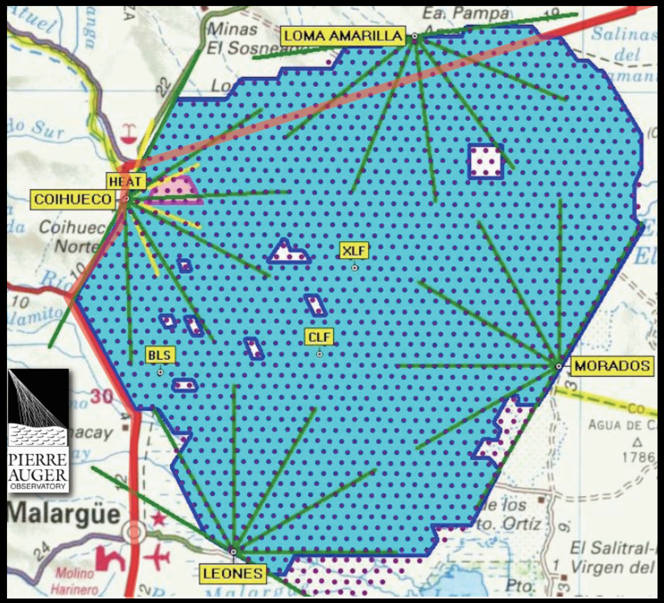
ATIC detector (60x60 cm)

Wide energy range: 10^6 - 10^{21} eV

Wide range of dimensions:

On balloon/space: O(m)

At ground: O(0.01-1000 km^2)



Auger detector (60x60 km)

Wide choice of detectors:

dE/dX

Secondary/cascades measurements

Magnetic deflections

Transition radiation

Cherenkov

Radio

HOW DO WE DETECT COSMIC RAYS?

Cosmic rays are particles

Cosmic ray detectors are particle detectors

AIMS:

Particle identification (mass, charge)

Energy (momentum)

Arrival direction

N.B. To identify a particle we need in general two different measurements that depend in different ways on mass, charge, velocity

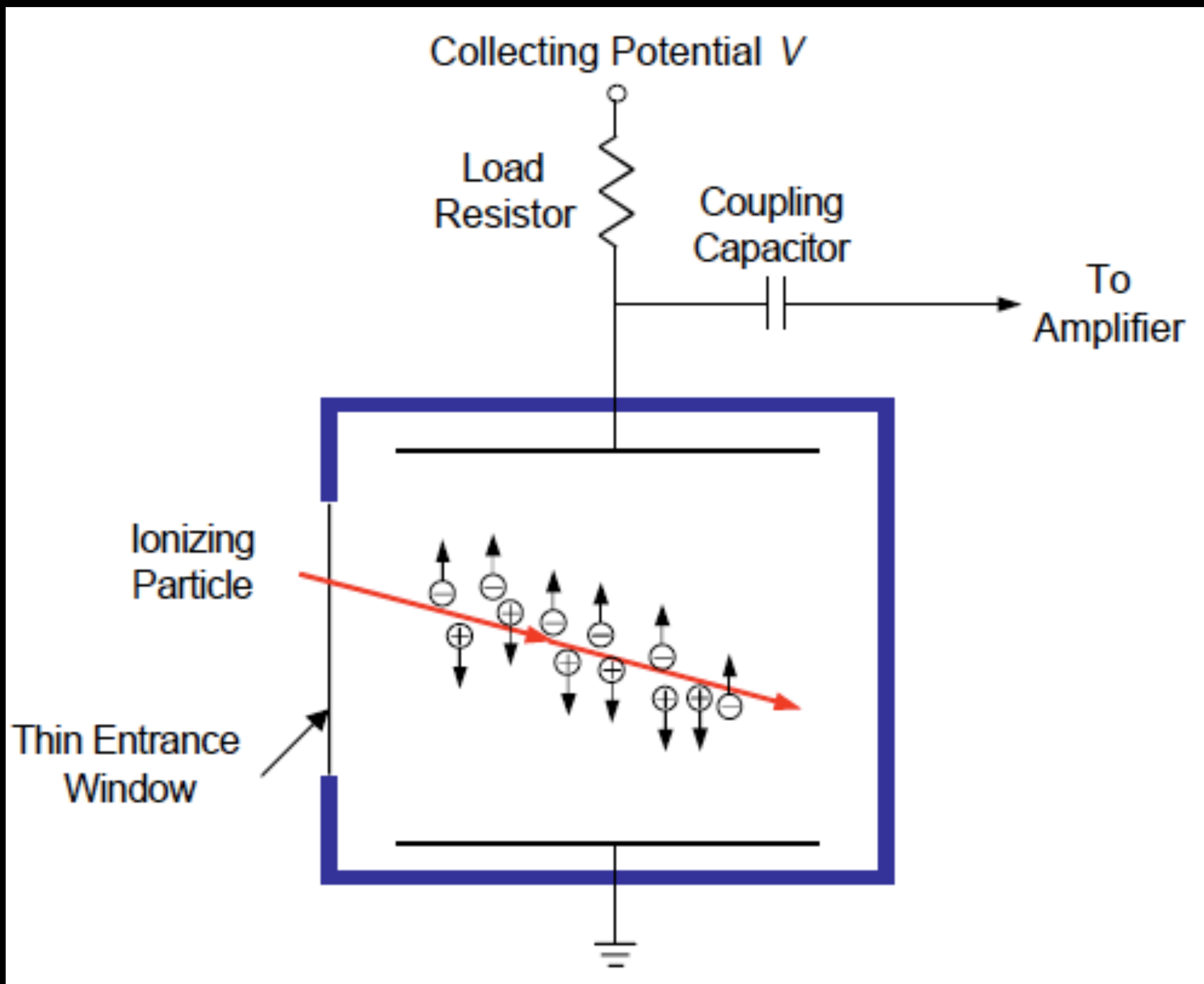
HOW DO WE DETECT COSMIC RAYS?

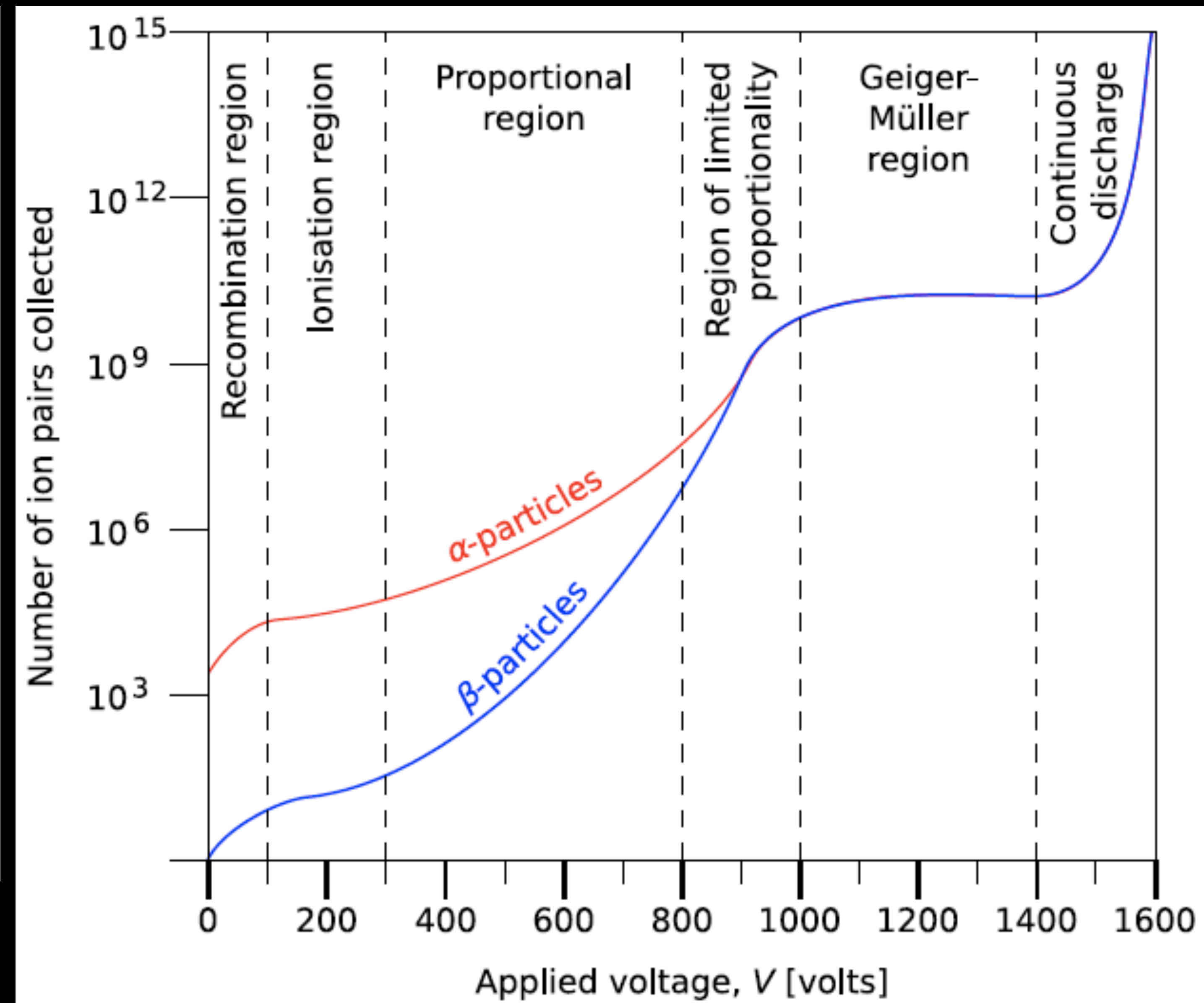
Detectors (vs observables)

Velocity:	Time-of flight	$\tau \propto 1/\beta$	γ,β
	Cherenkov angle	$\cos\theta = 1/\beta n$	
	Transition radiation	$\gamma \geq 1000$	
Energy loss:	Bethe-Bloch	$\frac{dE}{dx} \propto \frac{z^2}{\beta^2} \ln(a\beta\gamma)$	
Total energy:	Calorimeter	$E = \gamma m_0 c^2$	

HOW DO WE DETECT COSMIC RAYS?

Ionization detectors





A particle passing through a gas-filled counter will ionize the gas along its path

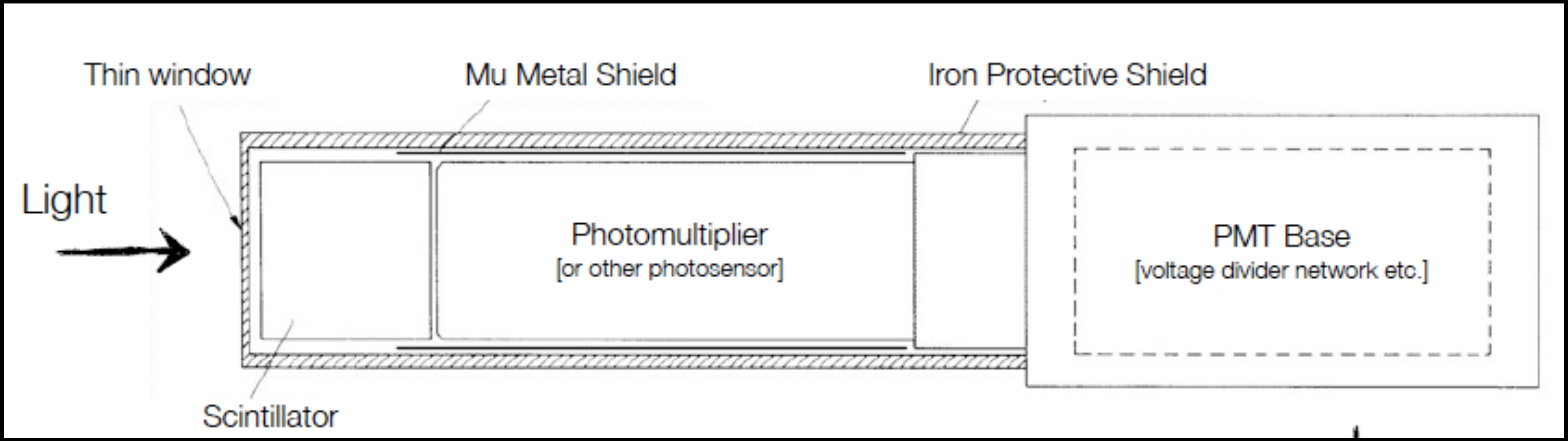
The applied voltage V between the electrodes will sweep the positive and negative charges toward the respective electrodes causing a charge Q to appear on the capacitor.

The charge Q collected (amplitude of pulse) depends on voltage V.

Higher mass particles produce more initial ions pairs

HOW DO WE DETECT COSMIC RAYS?

Scintillation detectors



SCHEME OF A SCINTILLATION + PMT DETECTOR

In scintillators, the energy loss dE/dX is converted into visible light (by human light or photomultiplier ;-)

Scintillators can be inorganic (i.e., iodide, fluoride: NaI CsI BaF2...; liquid noble gases, Ar, Xe...), or organic (hydrocarbon compounds), liquid, or plastic

A PLASTIC SCINTILLATOR IN THE UTAH DESERT (TELESCOPE ARRAY EXPERIMENT)

HOW DO WE DETECT COSMIC RAYS?

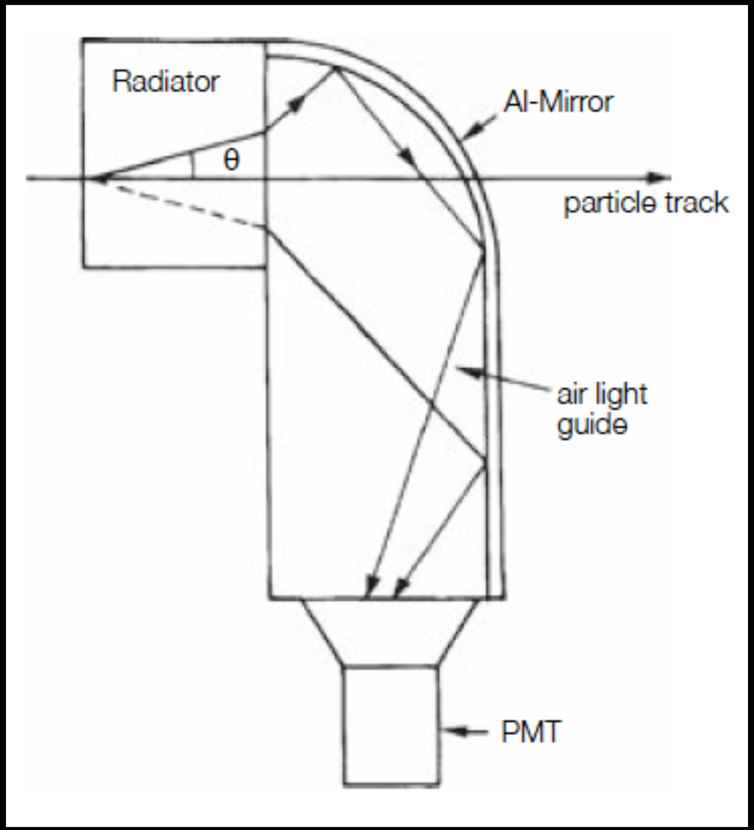
Cherenkov detectors

When a particle moves through a medium at a velocity greater than that of the light in that medium, Cherenkov radiation is emitted.

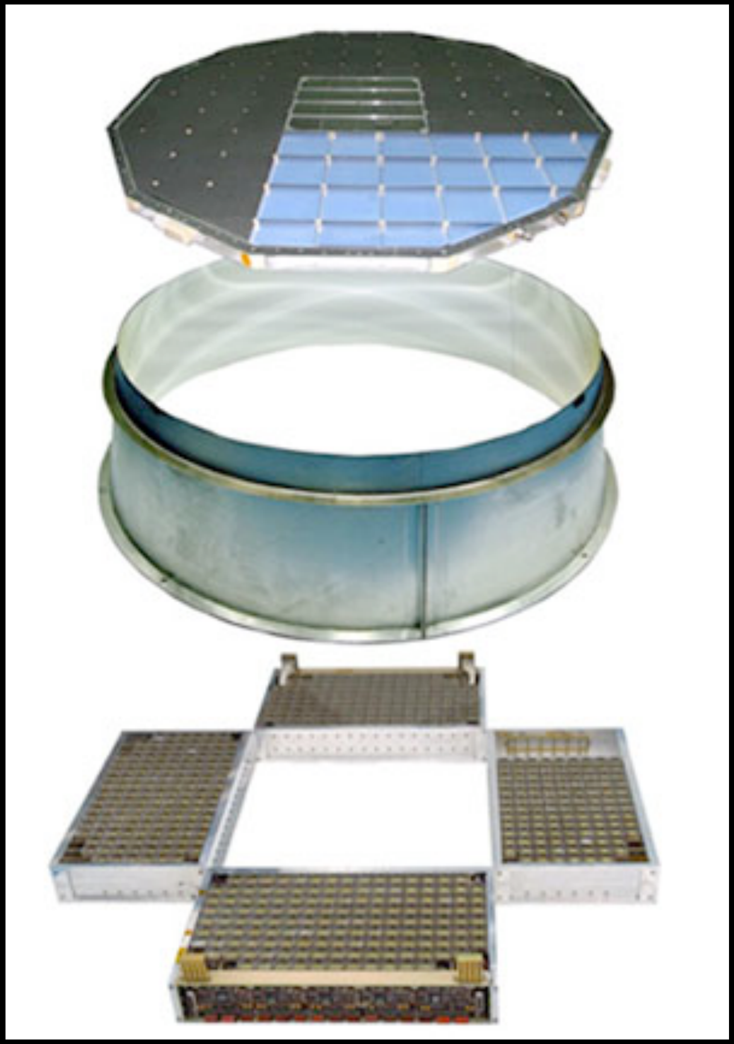
This phenomenon can be used to construct "threshold" detector, i.e., only if the velocity is large enough, it will emit radiation (and hence a signal)

The total emitted light is measured, this providing information on velocity of the particle

The light yield is very small. The light is focalized through mirrors towards PMTs used to produce a detectable signal



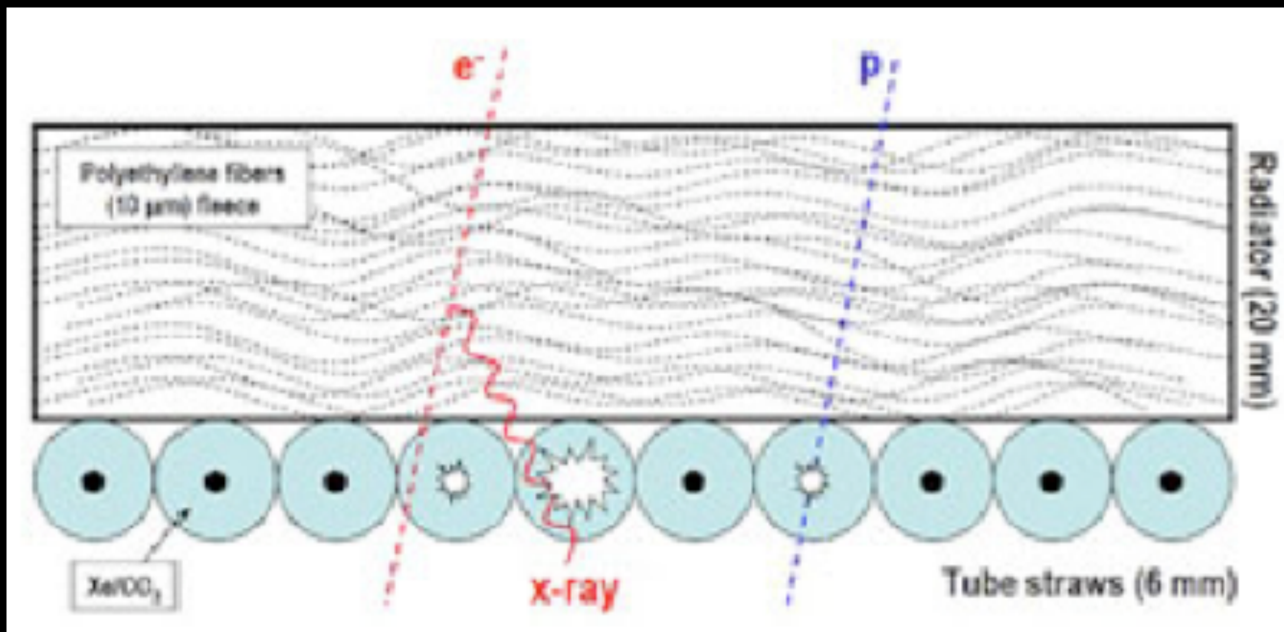
Working principle of a Cherenkov detector



AMS Cherenkov detector: radiator, mirror, PMTs

HOW DO WE DETECT COSMIC RAYS?

Transition radiation detectors



PRINCIPLE OF DETECTION OF TRANSITION RADIATION DETECTORS

THE TRANSITION RADIATION DETECTOR OF PAMELA

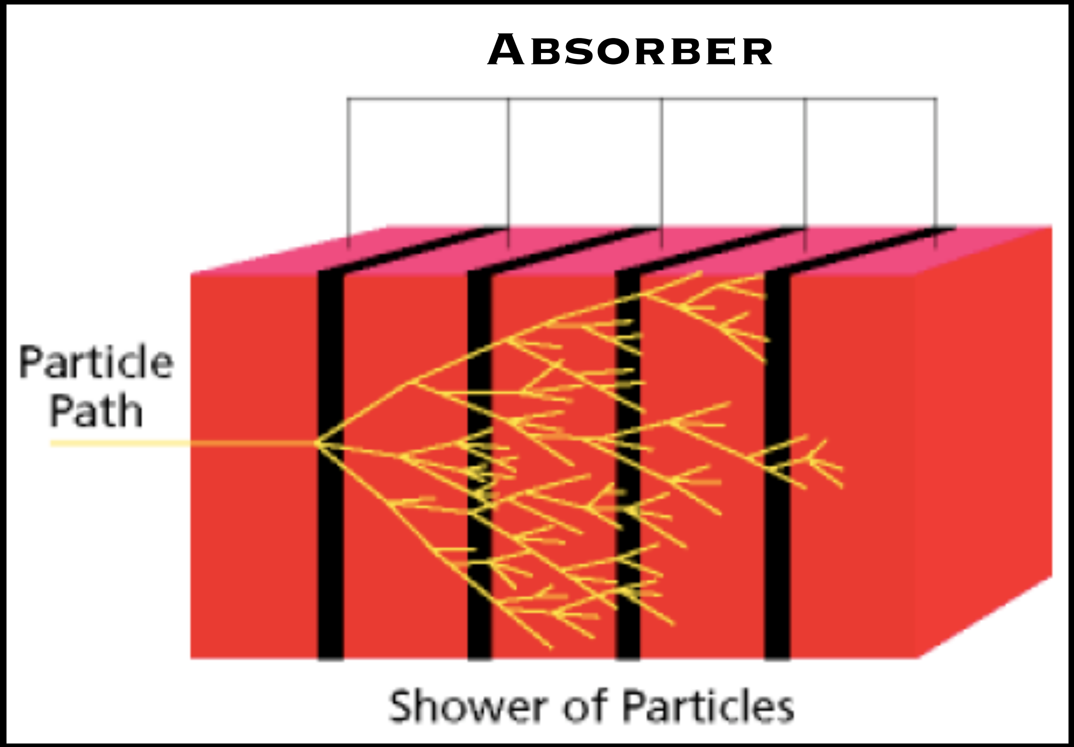
The transition radiation (in the X-ray region) is produced by a fast charged particle as it crosses the boundary between two media with different refraction indices.

The phenomenon is related to the energy of a particle and distinguishes different particle types. The probabily of radiation lineraly depends on γ. Lighter particles have higher probabilities than heavier ones.

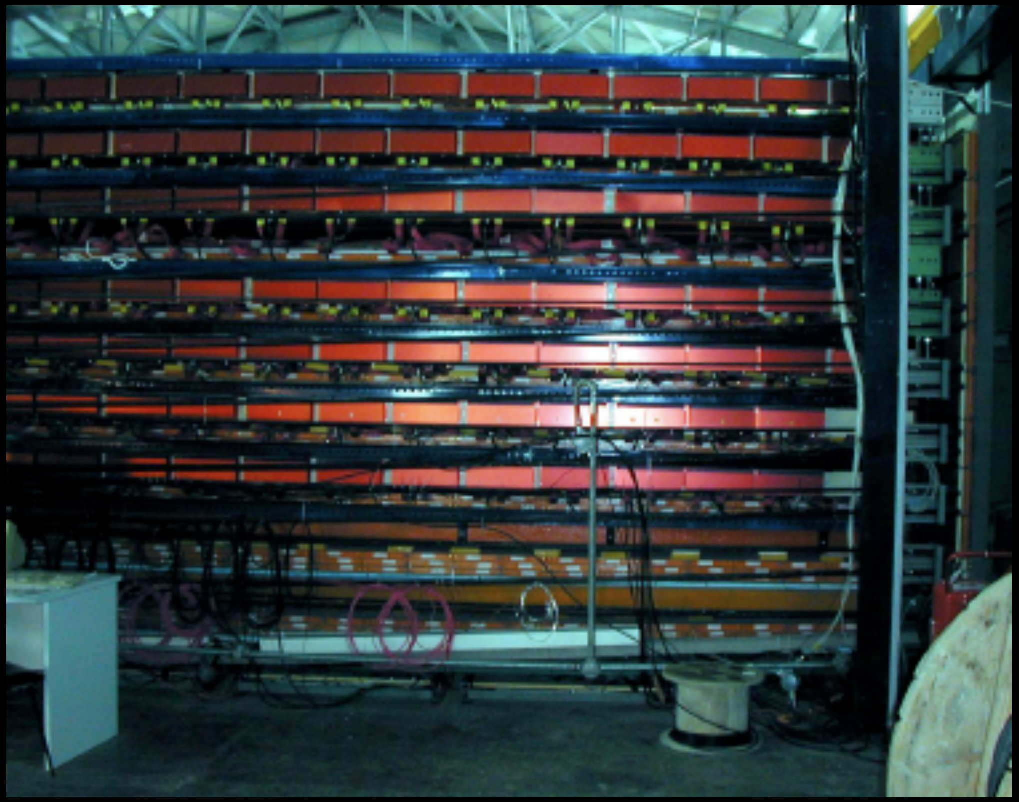
Emitted X-rays are then detected for example through ionizing detectors.

HOW DO WE DETECT COSMIC RAYS?

Calorimeter



Scheme of a calorimeter



The calorimeter of the EAS-TOP experiment

A calorimeter measures the energy lost by a particle that goes through it. It is usually designed to entirely stop or 'absorb' most of the particles coming from a collision, forcing them to deposit all of their energy within the detector.

Calorimeters typically consist of layers of 'passive' or 'absorbing' high–density material (lead for instance) interleaved with layers of 'active' medium such as scintillator or gaseous detectors (sampling calorimeters)

Electromagnetic calorimeters measure the energy of light particles – electrons and photons – as they interact with the electrically charged particles inside matter.

Hadronic calorimeters sample the energy of hadrons as they interact with atomic nuclei.

The delicacy of the observations
The adventurous excursions of the observers

Cosmic Rays detection and detectors: the early days

COSMIC RAY DETECTION: WHY STARTING WITH AN HISTORICAL PERSPECTIVE?

Nani gigantum humeris insidentes

It is (quite) easy today to talk about our knowledge of cosmic rays, and about the techniques used to detect them.

But many of the early results were confusing and clarity came slowly. The exploratory phase lasted almost 50 years.

During that time experimental tools slowly improved. As a result, the complexity of the processes was gradually recognized. In turn, experimental tools became more and more complex, thanks to the birth of particle-physics too (a daughter of cosmic-ray physics)

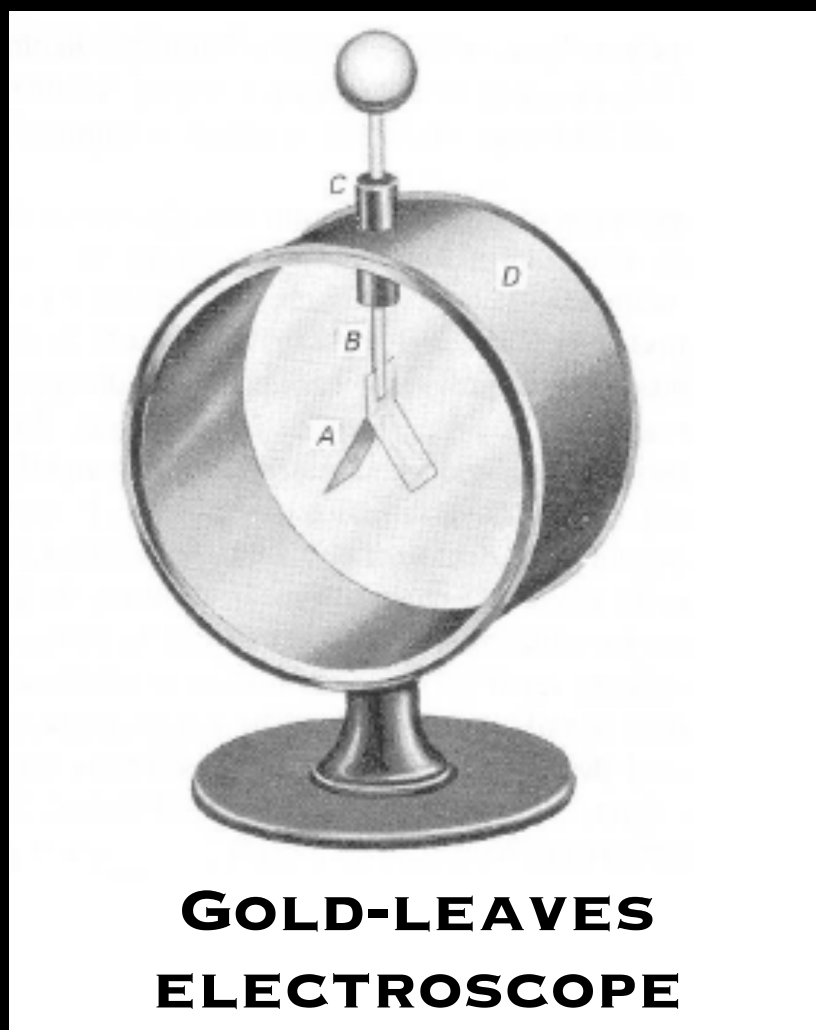
I make no apology for beginning with a few historical notes about the history of cosmic ray detection. This is much more than simply the recounting of some key events. Many of the present key ideas and experimental procedures have a long and distinguished history which reflects the insight and ingenuity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

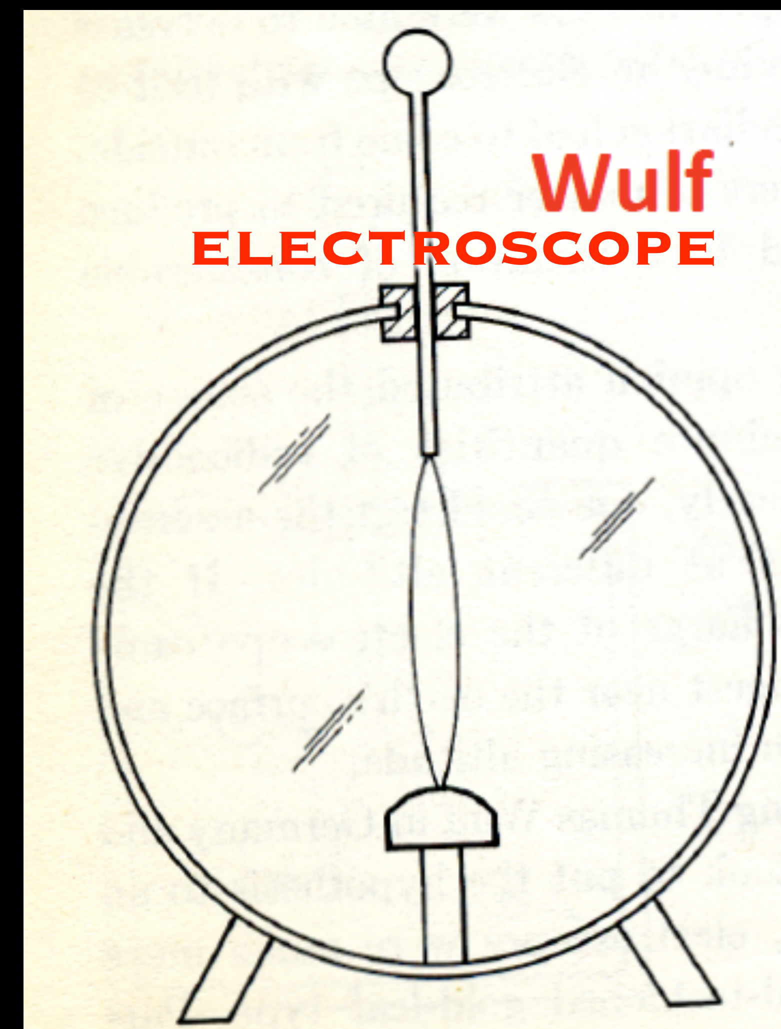
(inspired by Malcolm Longair)

HOW DID DETECTION OF COSMIC RAYS START?

Electroscopes

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 ionize gases, enabling the gas to conduct electricity. Electroscopes were widely used to explore radioactive materials.





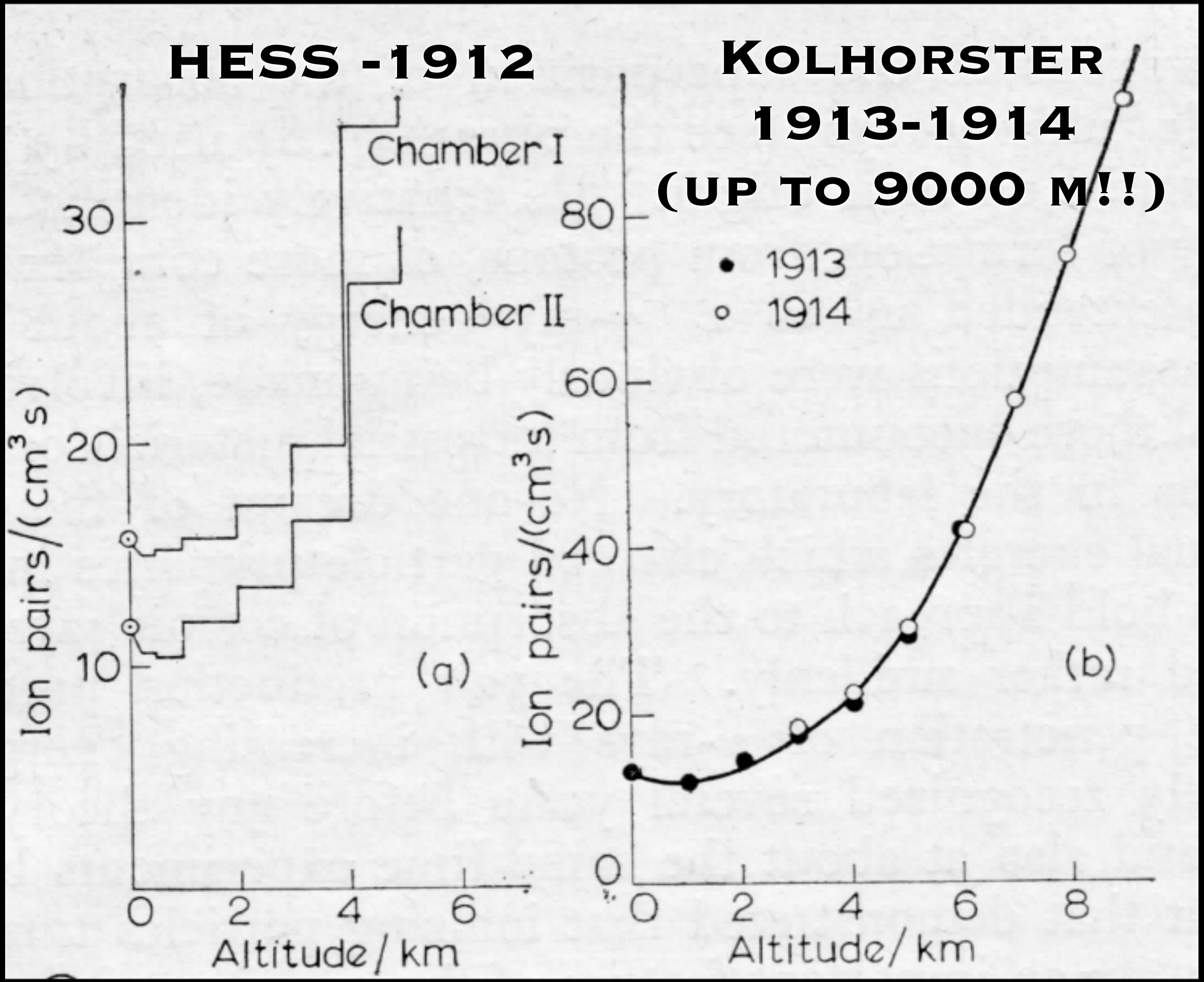
When an electroscope is given an electric charge, the leaves (or wires) repel each other and stand apart. Radiation can ionize the air in the electroscope and allow the charge to leak away: leaves or wires slowly come back together.

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!

HOW DID DETECTION OF COSMIC RAYS START?

Electroscopes on balloons

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)



Intensity of the ionizing radiation first decreased as the balloon went up and then was becoming more intense than at sea level. Experiments of great danger, great courage and great success

"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]

HOW DID DETECTION OF COSMIC RAYS EVOLVE?

Ionization chambers

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

Pioneering experiments (Millikan, Compton) used also ionization chambers

Electroscopes can only detect the combined ionizing effect of many particles. Similarly for Ionization chambers: the total ionisation is monitored in a closed cointainer.

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)

Ideal to survey variations of CR intensity vs altitude (e.g., Millikan, before 1920s) or vs latitude (e.g., Compton, during 1930s)

COMPTON IONIZATION CHAMBER

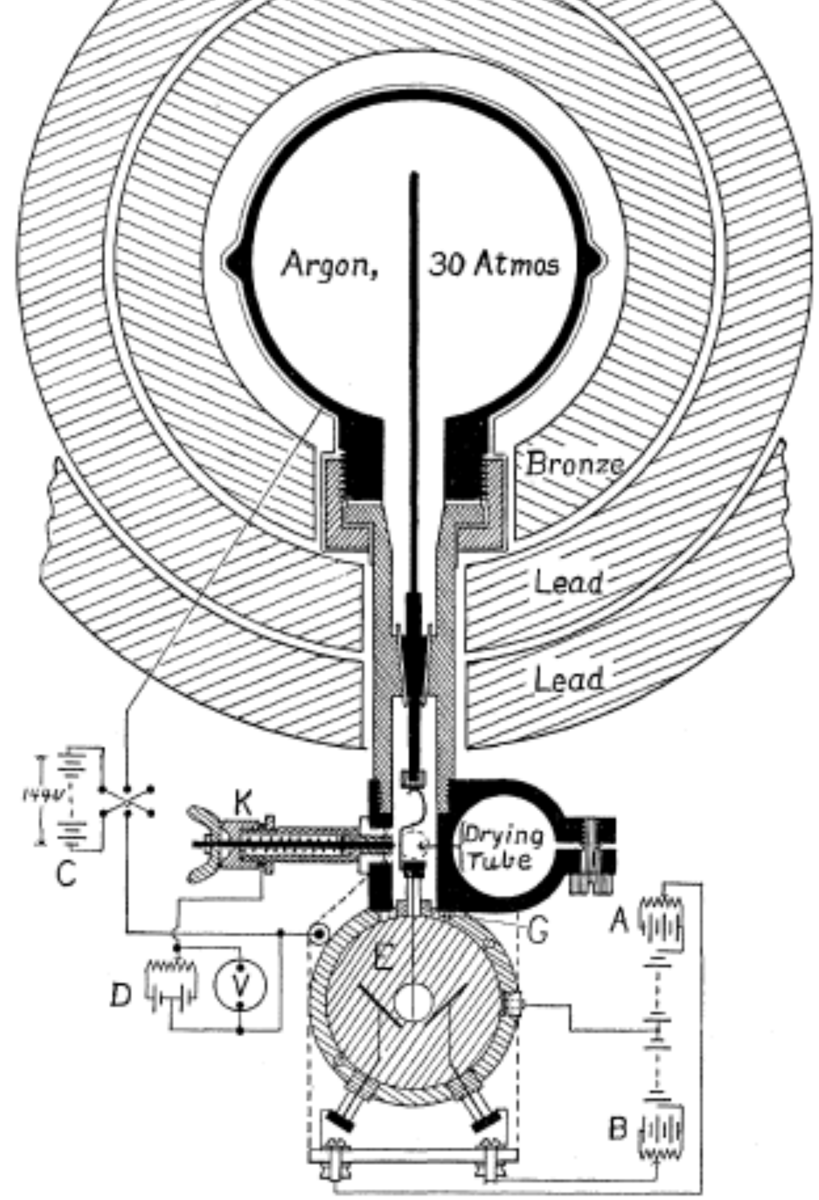


FIG. 2. Cosmic-ray ionization chamber, electrometer, and electrical connections.

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INFERENCES. Observations of variations of CR intensity vs altitude (e.g., Millikan, before 1920s) or vs latitude (e.g., Compton, during the 1930s)

Compton (1933): 8 expeditions to 69 stations, > 60 scientists – Two of whom died

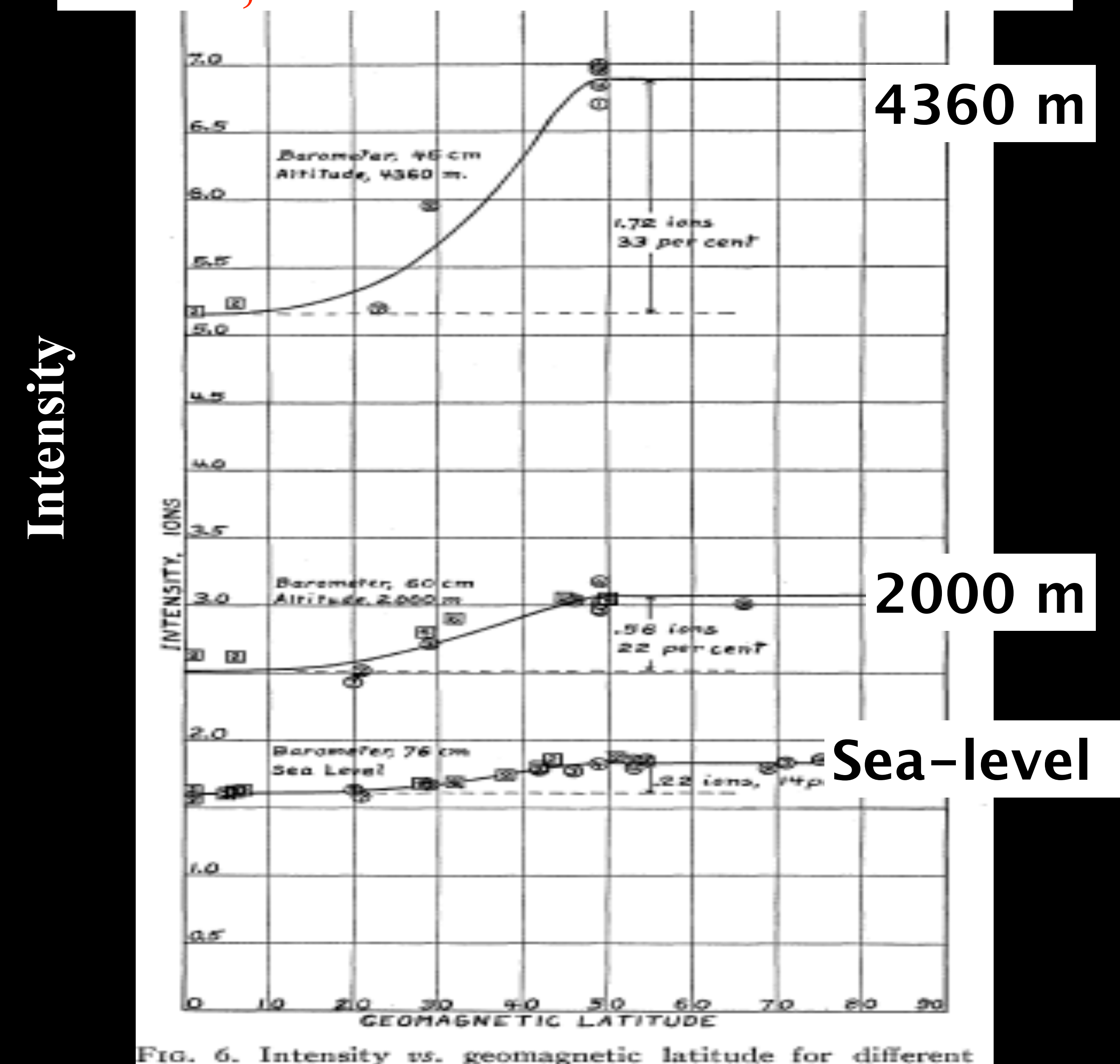


FIG. 6. Intensity *vs.* geomagnetic latitude for different elevations

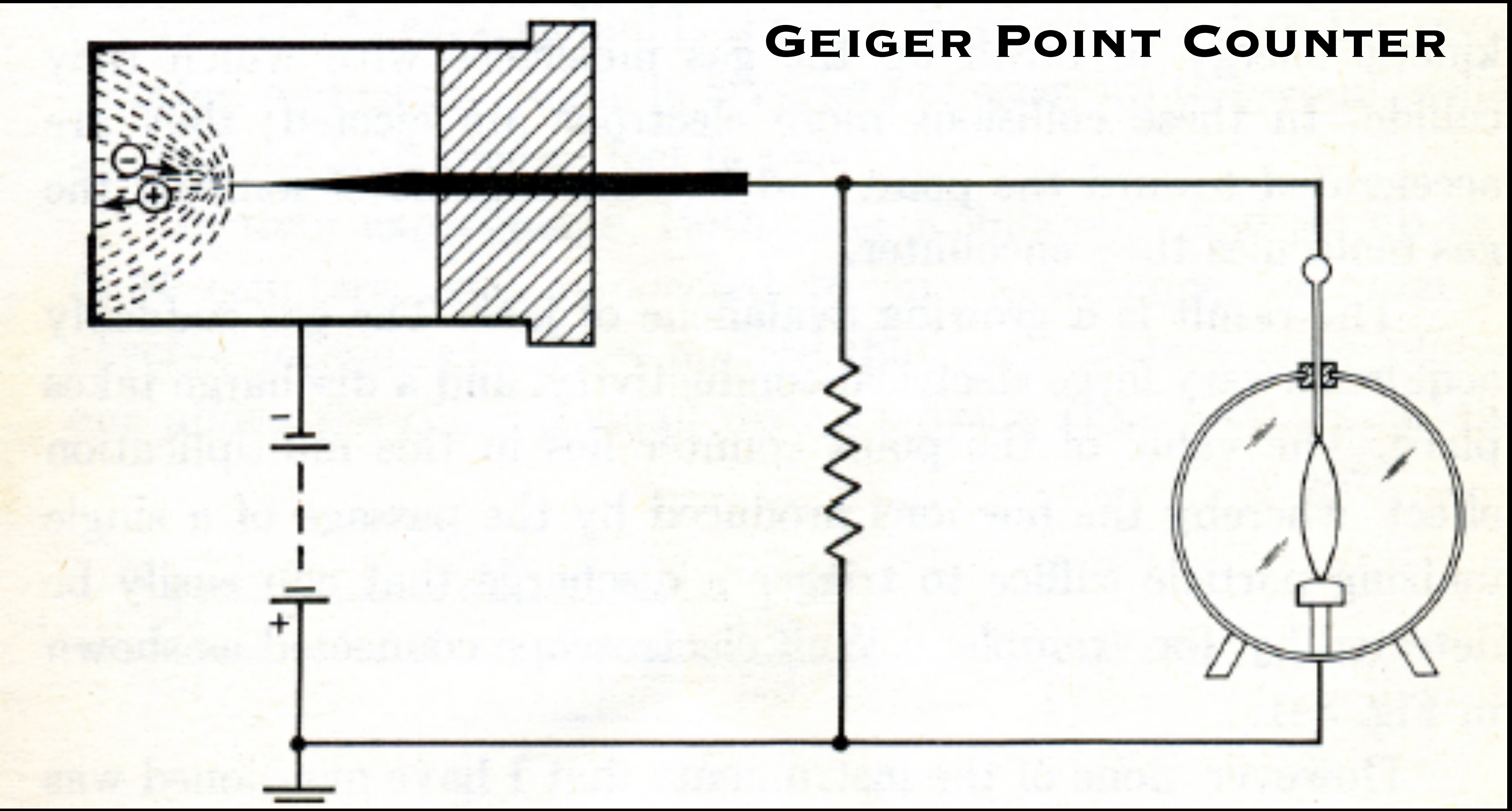
Geomagnetic Latitude

HOW DID DETECTION OF COSMIC RAYS EVOLVE?

Geiger point counter

The earliest detector for single particles was devised around 1911 by Hans Geiger: the point counter.

It is a thin point rod into a metal box filled with gas. A battery maintains the rod at positive potential (1000-1500 V) with respect to the box. Penetration of charged particles in the box through a window in front of the rod, produces ionization. Ions and electrons are accelerated: an avalanche of them constitutes a brief electrical current: the electroscope wires undergo a sudden deflection



The point counter was not very stable and could not be made sufficiently large to be of much use in the study of CRs whose intensity was quite small

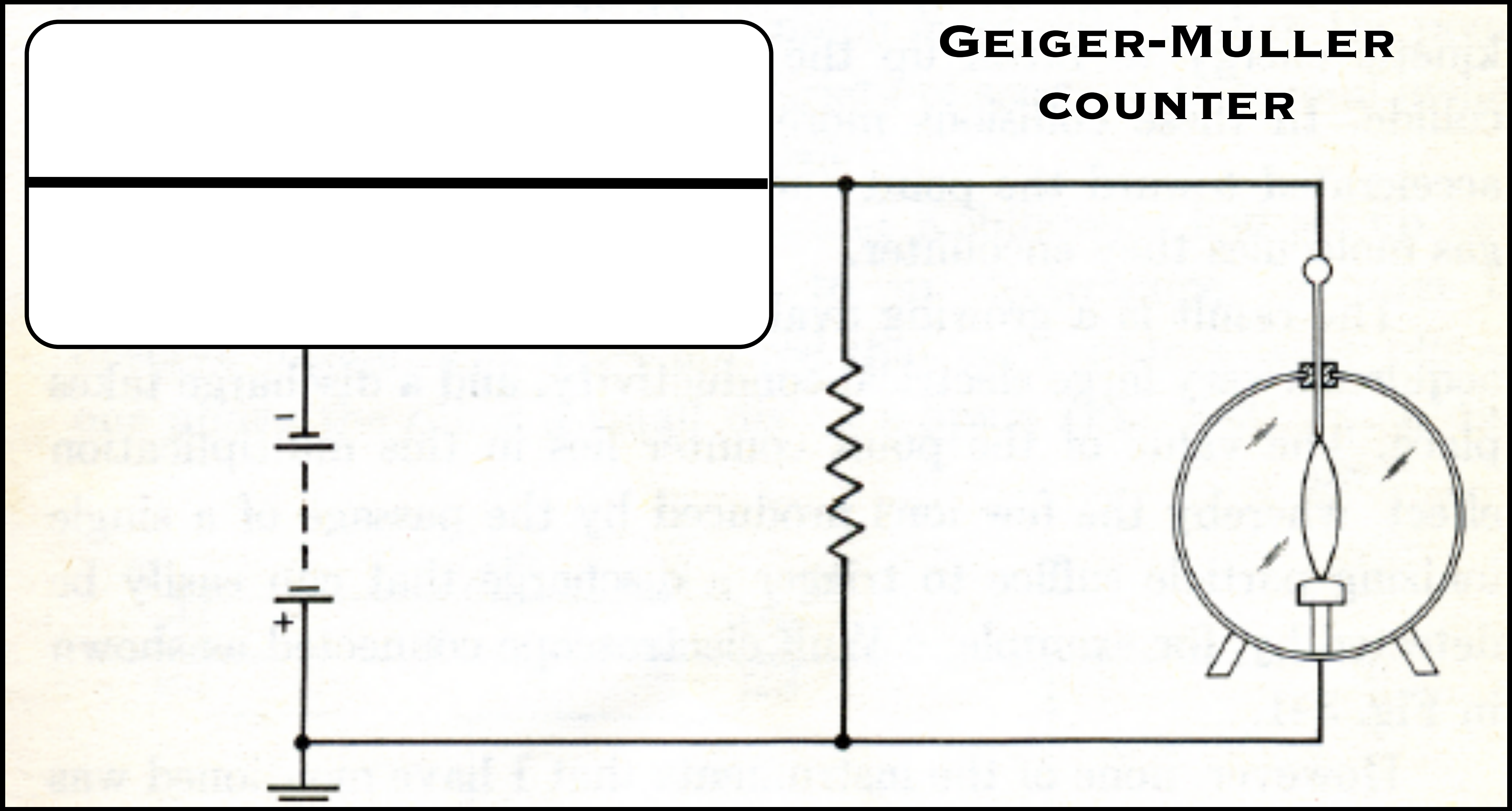
HOW DID DETECTION OF COSMIC RAYS EVOLVE?

Geiger-Muller counter

The answer to the need of CR physicists came in 1929 with the invention by Geiger and his student Muller of the so-called Geiger-Muller counter.

It consists of a metal tube (evacuated and filled with a gas) with a thin metal wire stretched along its axis. Same principle as the point counter (it makes use of the cascade effect).

It has fast response time: not only individual events can be identified but also their arrival times



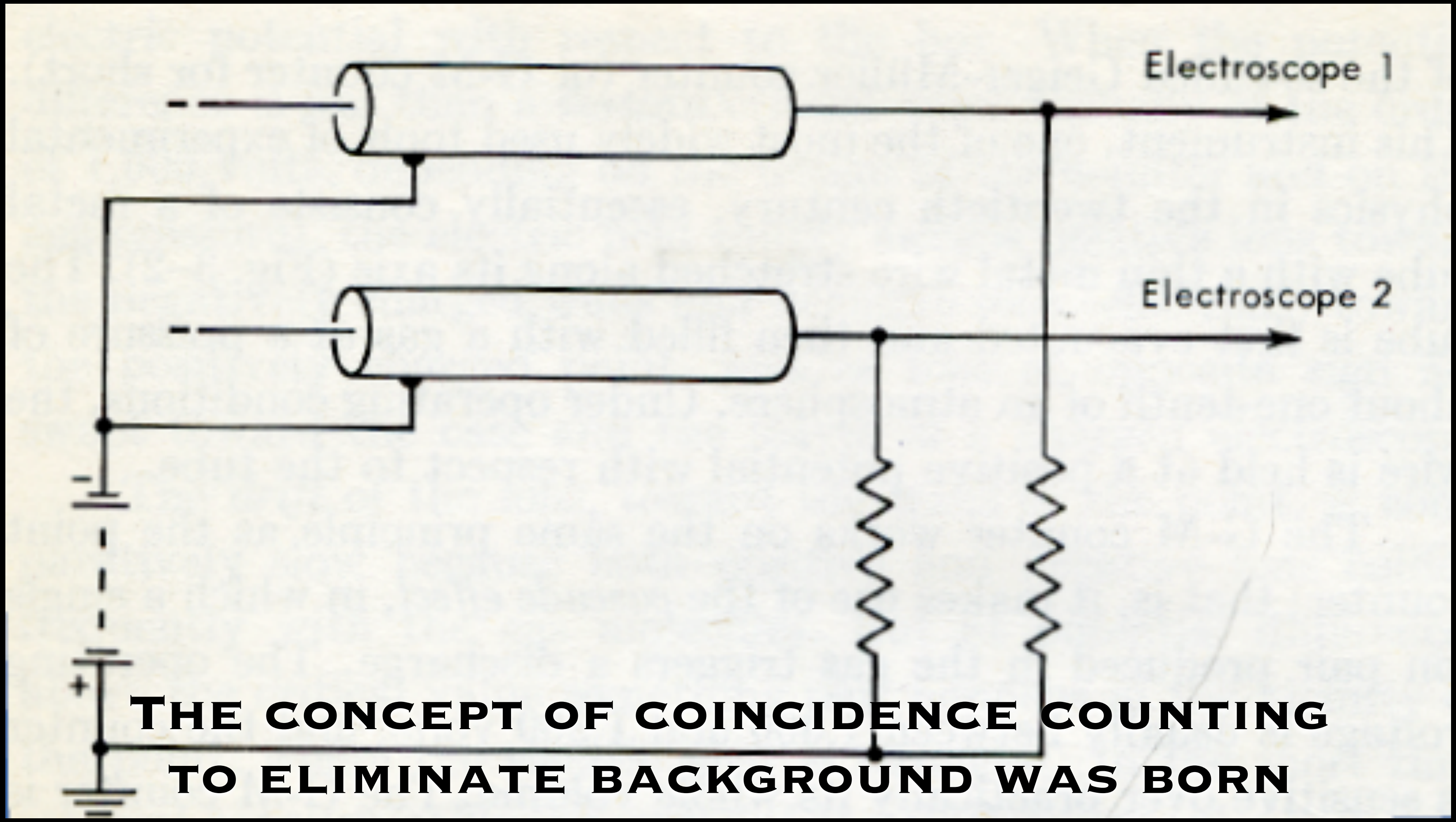
The G-M counter is easy to build, it is more stable than the point counter, and can be made in a variety of sizes. It became a crucial instrument to detect cosmic rays

HOW DID DETECTION OF COSMIC RAYS EVOLVE?

Bothe - Kohloster coincidence

Bothe and Kohlhoster (1929) pioneered the use of two G-M counters to study CR

They connected each G-M counter to an electroscope. They noticed that they, when placed one above the other a small distance apart, often discharged simultaneously. These coincidences were not by chance as they became less frequent when the distance increased.



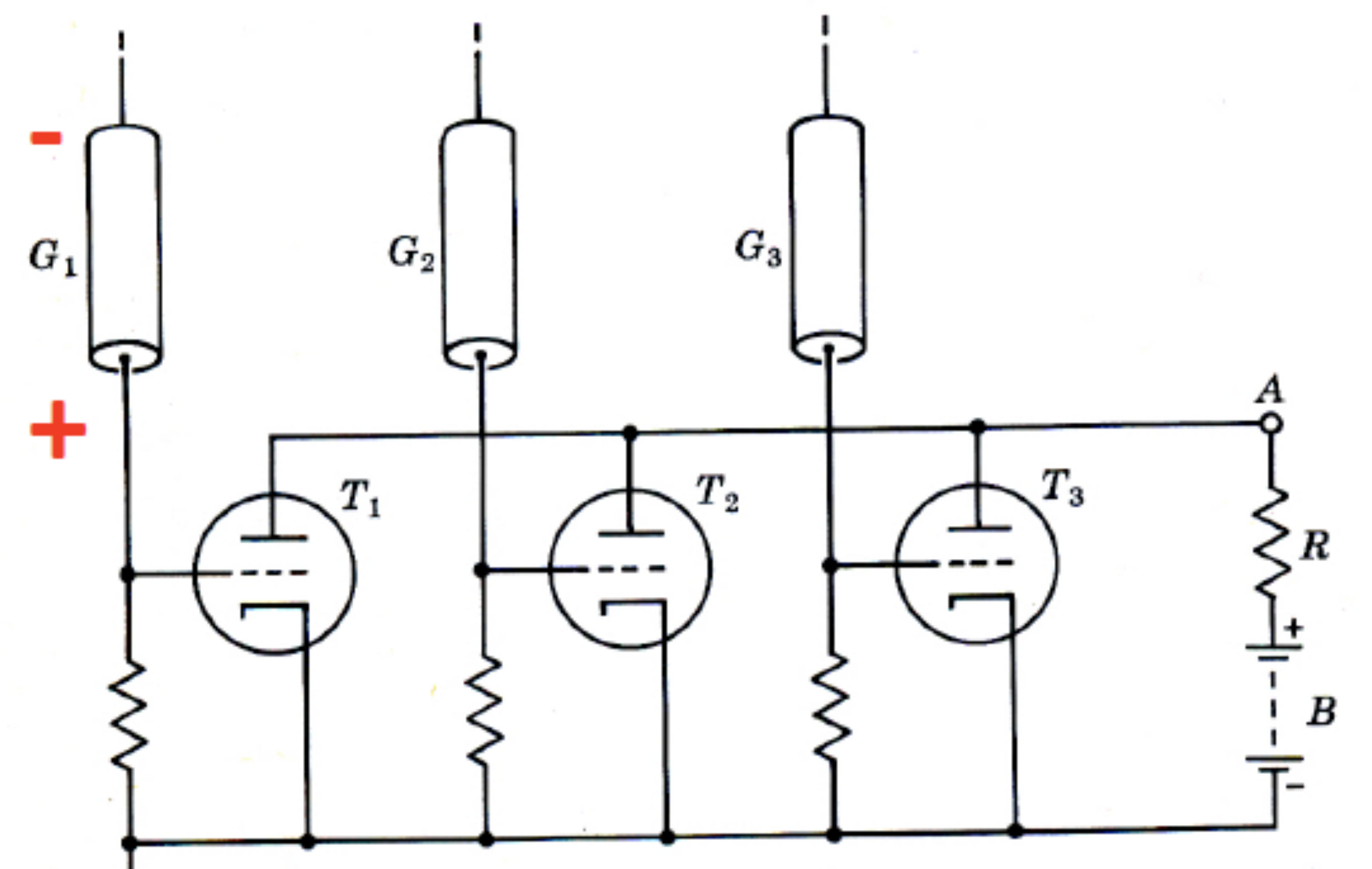
A milestone in the history of cosmic rays and their detection. For the first time, physicists had tried to determine the nature of CRs experimentally. By inserting absorbers (lead, gold) between the counters (and still finding coincidences) they concluded that "a corpuscolar radiation was detected...unlikely to be a gamma-radiation..."

HOW DID DETECTION OF COSMIC RAYS EVOLVE?

Rossi coincidence

Bruno Rossi (1930) greatly increased the sensitivity of the method by Bothe and Kohloster by developing a new electrical circuit to analyze signals from a CR telescope.

He obtained a better time resolution, and extended the coincidence to more than 2 counters



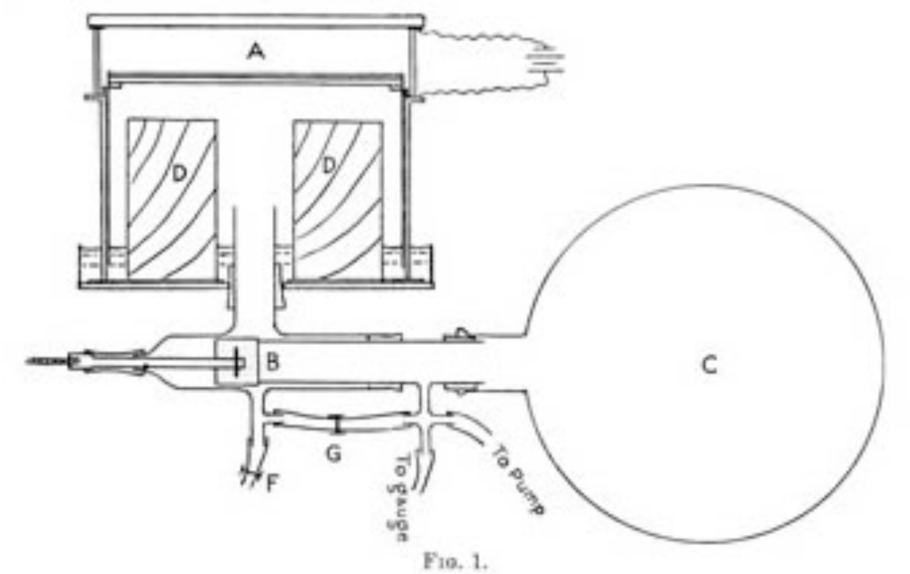
BRUNO ROSSI'S COINCIDENCE CIRCUIT

It consisted of of two or more triodes with the plates connected in parallel. The grids were coupled to the G-M counters. When the grids of the triodes were simultaneously driven to a negative potential by the coincident discharges of the 3 counters, the current would stop and a pulse appear at the plates.

HOW DID DETECTION OF COSMIC RAYS EVOLVE?

Cloud chamber

Developed at the same time as the Geiger point-counter (around 1911), the Wilson cloud chamber was the mostly widely used tracking detector in CR and nuclear physics.

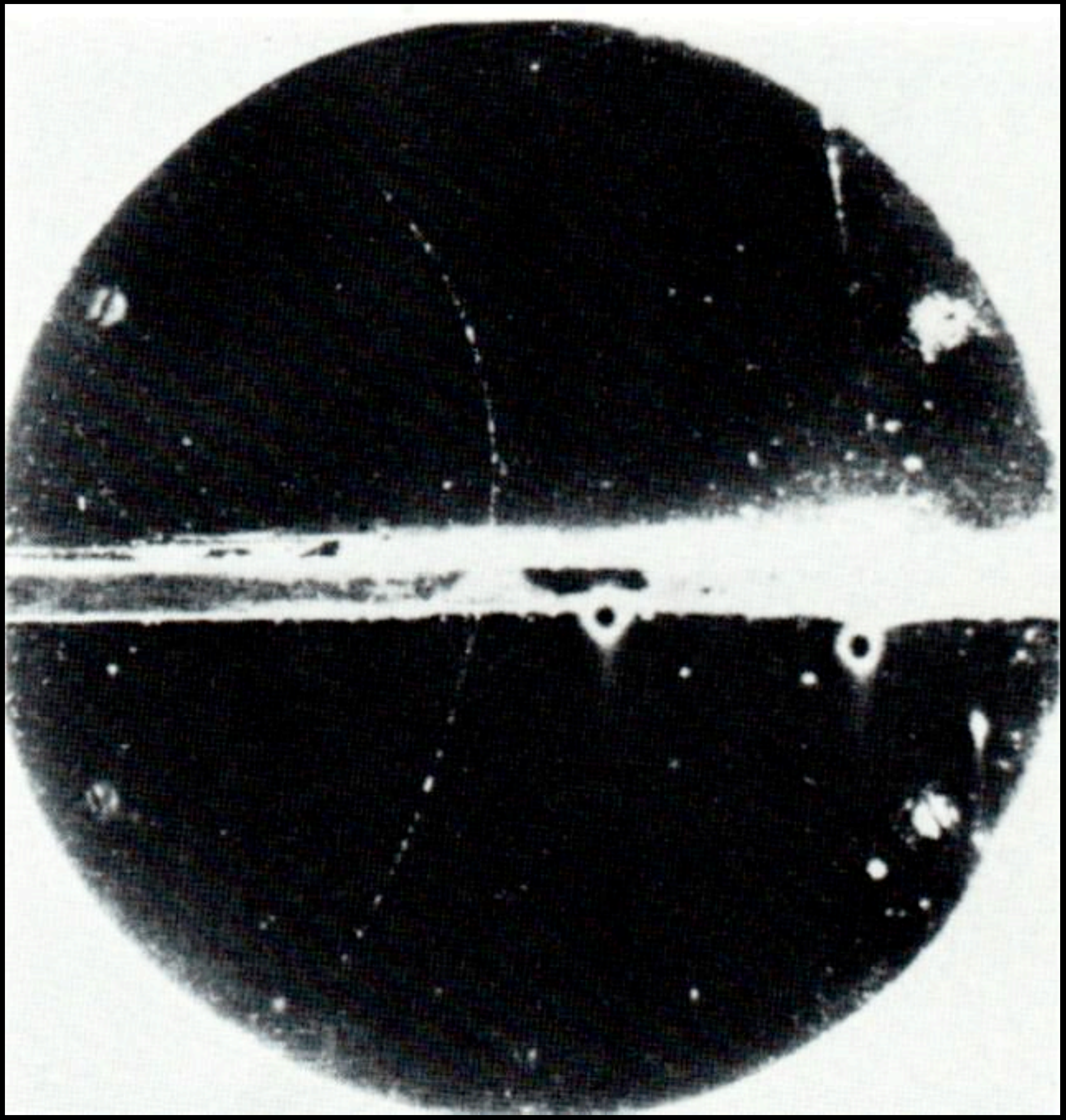


A diagram of Wilson's apparatus. The cylindrical cloud chamber ('A') is 16.5cm across by 3.4cm deep.

Expansion cloud chamber.

When the piston is pulled back rapidly, the gas and vapor in the chamber expand. The resulting drop in temperature is sufficient for condensation of the vapor that takes place around any ions present in the gas.

Cloud chambers were combined with magnetic fields to deflect particles (charge studies): Skobeltzyn 1927



Cloud chamber track of the positron, discovered by Carl Anderson in 1932 (Nobel prize 1936, with V. Hess)

HOW DID DETECTION OF COSMIC RAYS EVOLVE?

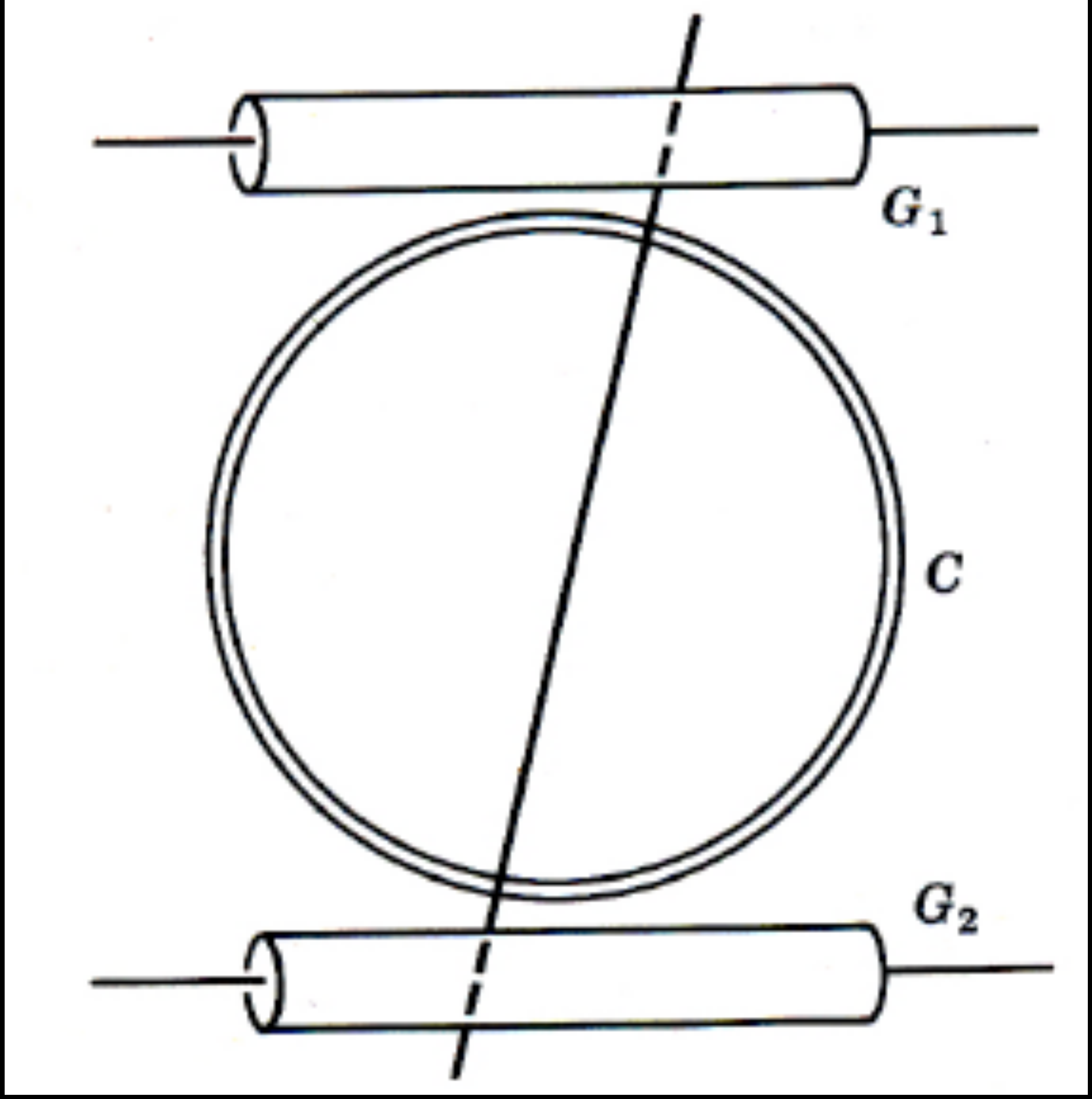
Counter-controlled cloud chamber

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.

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), another milestone in the history of CR detection.

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.



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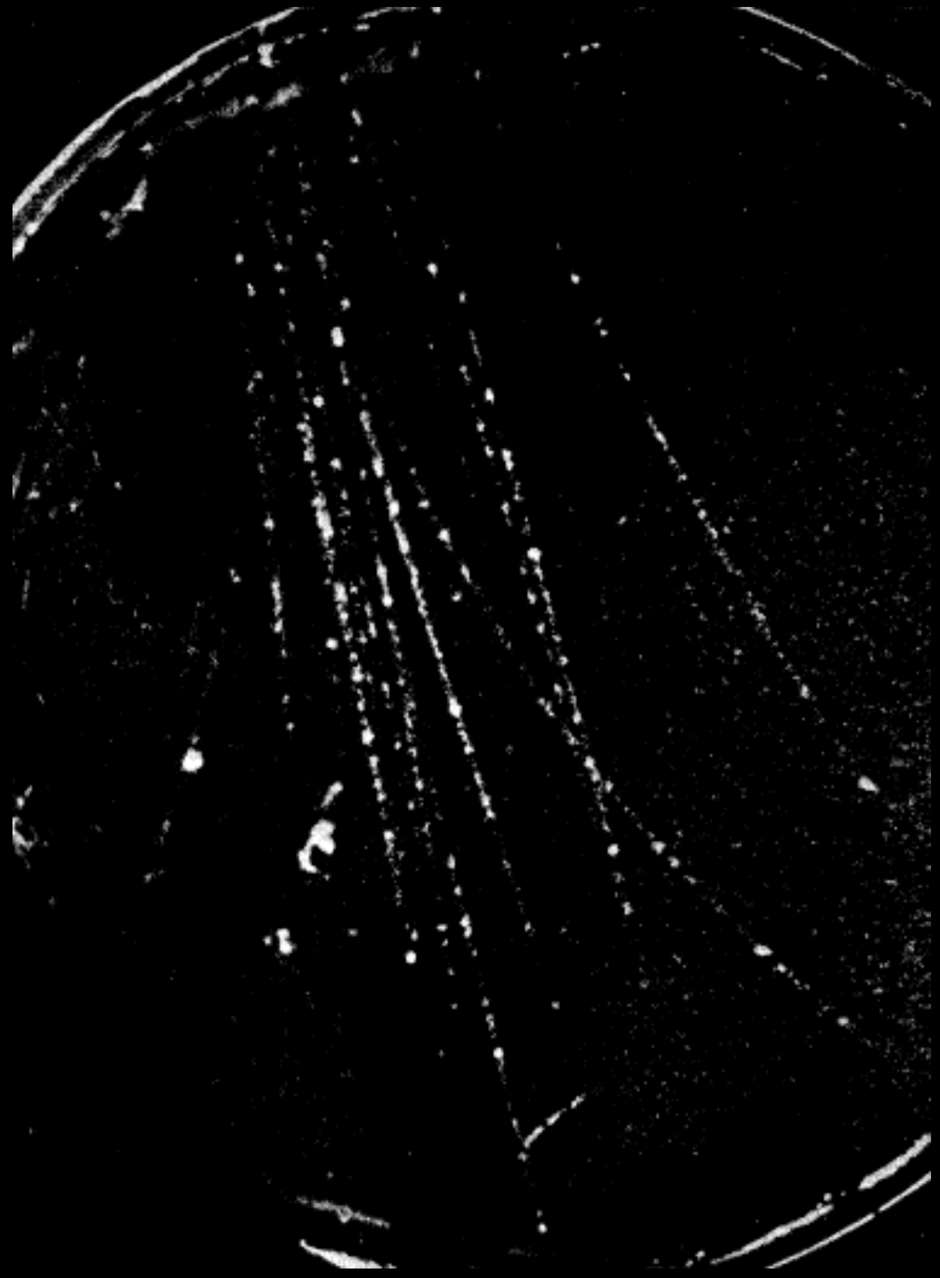
With their new cloud chamber, in 1933 Blackett and Occhialini observed tracks of many particles that clearly resulted from the interaction of a single high-energy cosmic ray somewhere near the chamber. The discovery of these “showers” marked another milestone in CR research.



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 DID DETECTION OF COSMIC RAYS EVOLVE?

Photographic emulsions

Cloud chambers are truly wonderful tools. Physicist can "see" elementary particles, and their collisions. But because of the low density of gases, very few particles entering a cloud chamber collide with nuclei or stop.

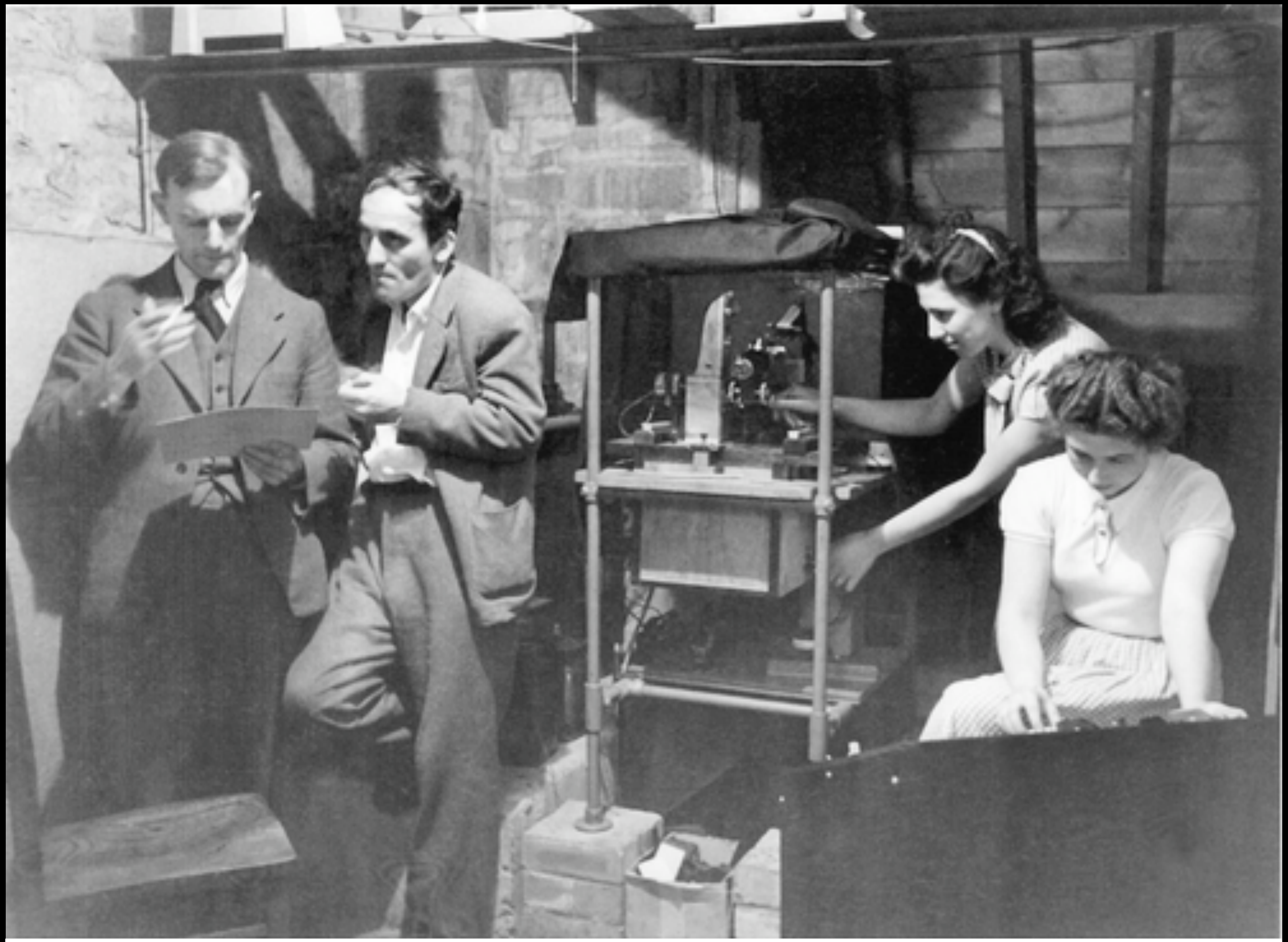
The observation of interactions and decays requires a dense substance (e.g., photographic/nuclear emulsions) in which particles can collide with high chance, or rest, leaving visible tracks.

When light falls on a photographic emulsion, it produces submicroscopic changes that show up after chemical treatment (development).

When fast particles pass through a photographic emulsion, they produce similar changes.

Photographic emulsions were used in 1930s and 1940s, at mountain altitudes or in the stratosphere on balloons.

After their development, photographic plates must be looked at through microscopes. Scanning was a labrious procedure (similar to reading "Le Monde" with a lens that shows only 3-4 letters at a time ;-)



Cecil Powell (left) and Giuseppe ("Beppo") Occhialini. The two women are operating a projection microscope used at that time for photomicrography and to study events at high magnification

HOW DID DETECTION OF COSMIC RAYS EVOLVE?

Nuclear emulsions

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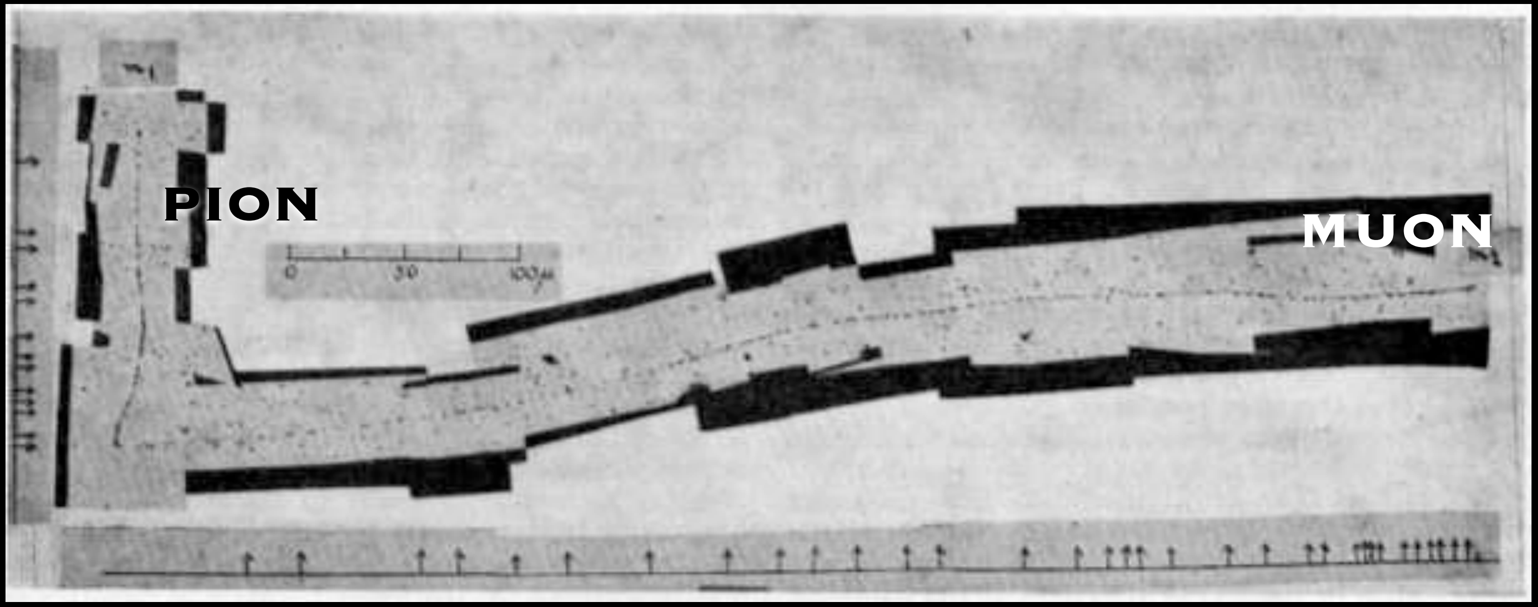
But ordinary emulsions are sensitive only to "slow" particles, that leave a very dense track of ions. Moreover, until mid-40s emulsions were very thin: particles should travel almost perfectly parallel to the plane to leave a decent track.

Powell and Occhialini (1945) invented the technique of producing thick emulsions by "stacking" layers and layers of the, to be separately developed. The result was a 3D picture of the interaction taking place in the emulsion.



A pion coming to rest in a nuclear emulsion, and a muon rising from the end of the pion track (Lattes, Muirhead, Occhialini, Powell, 1947)

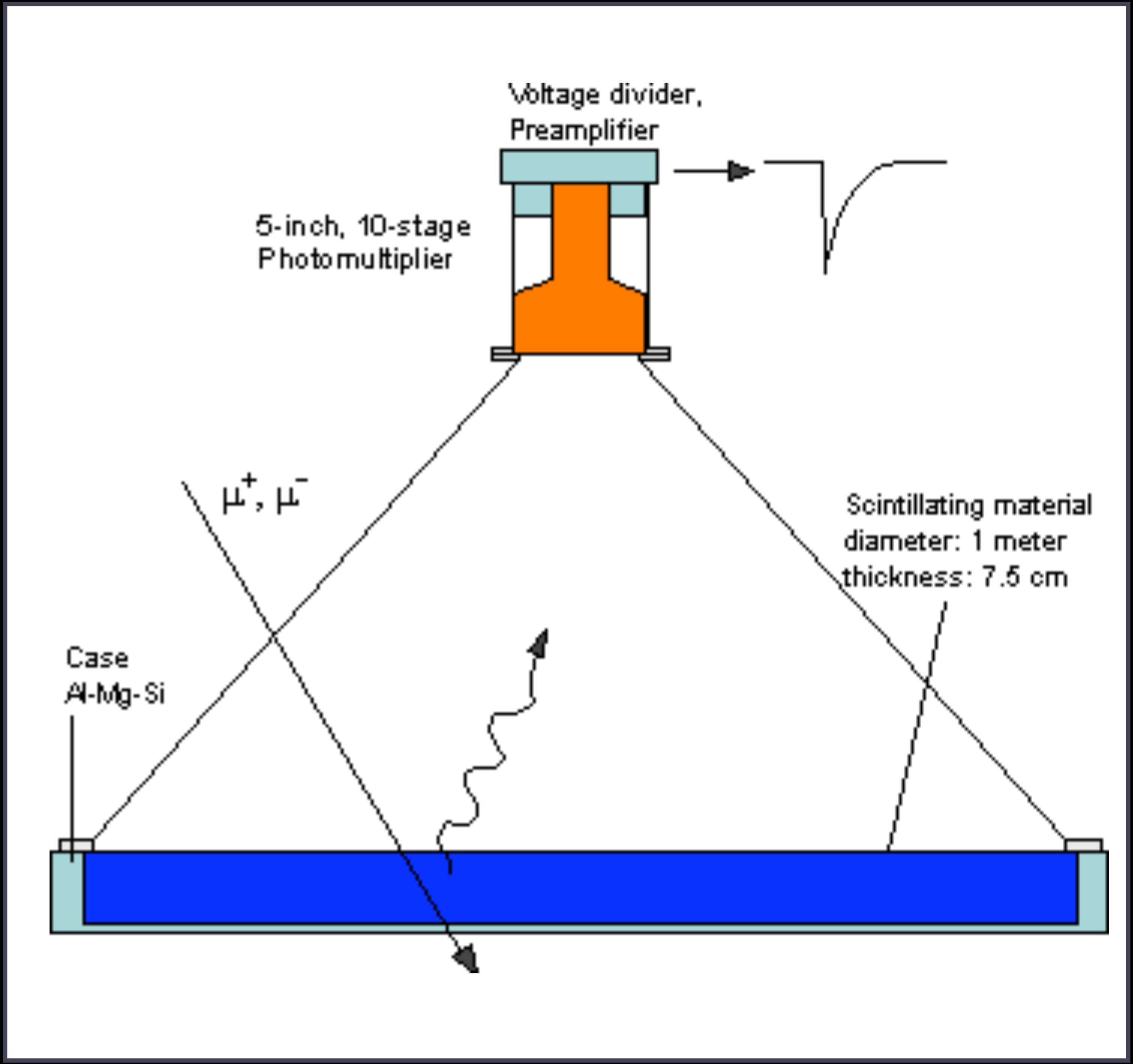
HOW DID DETECTION OF COSMIC RAYS EVOLVE?

Scintillators and photomultipliers

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). Nowadays, eyes have been substituted by photomultiplier arrangements

A scintillation detector works on the principle that an ionizinig particle produces a brief flash of light (scintillation) when it goes through a clear material.

The light is measured by a photomultiplier tube (PMT) that produces a voltage pulse when the light falls on the tube's sensitive face.



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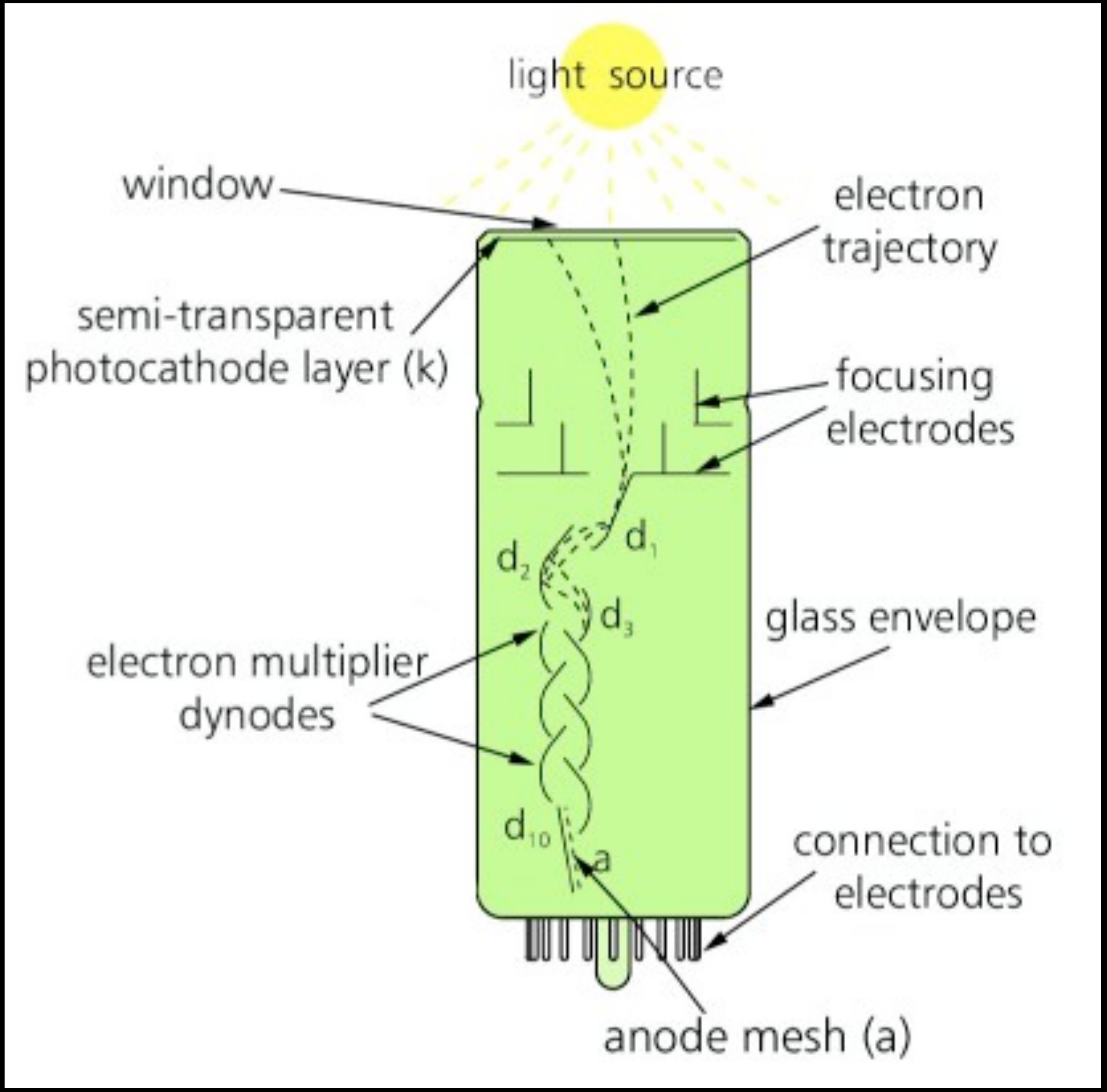
Photomultipliers tubes were developed in mid 40s (after World War II)

They are electron tube devices that convert light into a measurable electric current.

They consist of a "cathode" made of photosensitive material, followed by an electron collection system, an electron multiplier section ("dynode string") and finally an anode from which the final signal can be taken. All parts are usually housed in an evacuated glass tube.

A high voltage is applied to cathode, dynodes and anode: potential "ladder" alone the length of the tube



HOW DID DETECTION OF COSMIC RAYS EVOLVE?

Cherenkov detectors

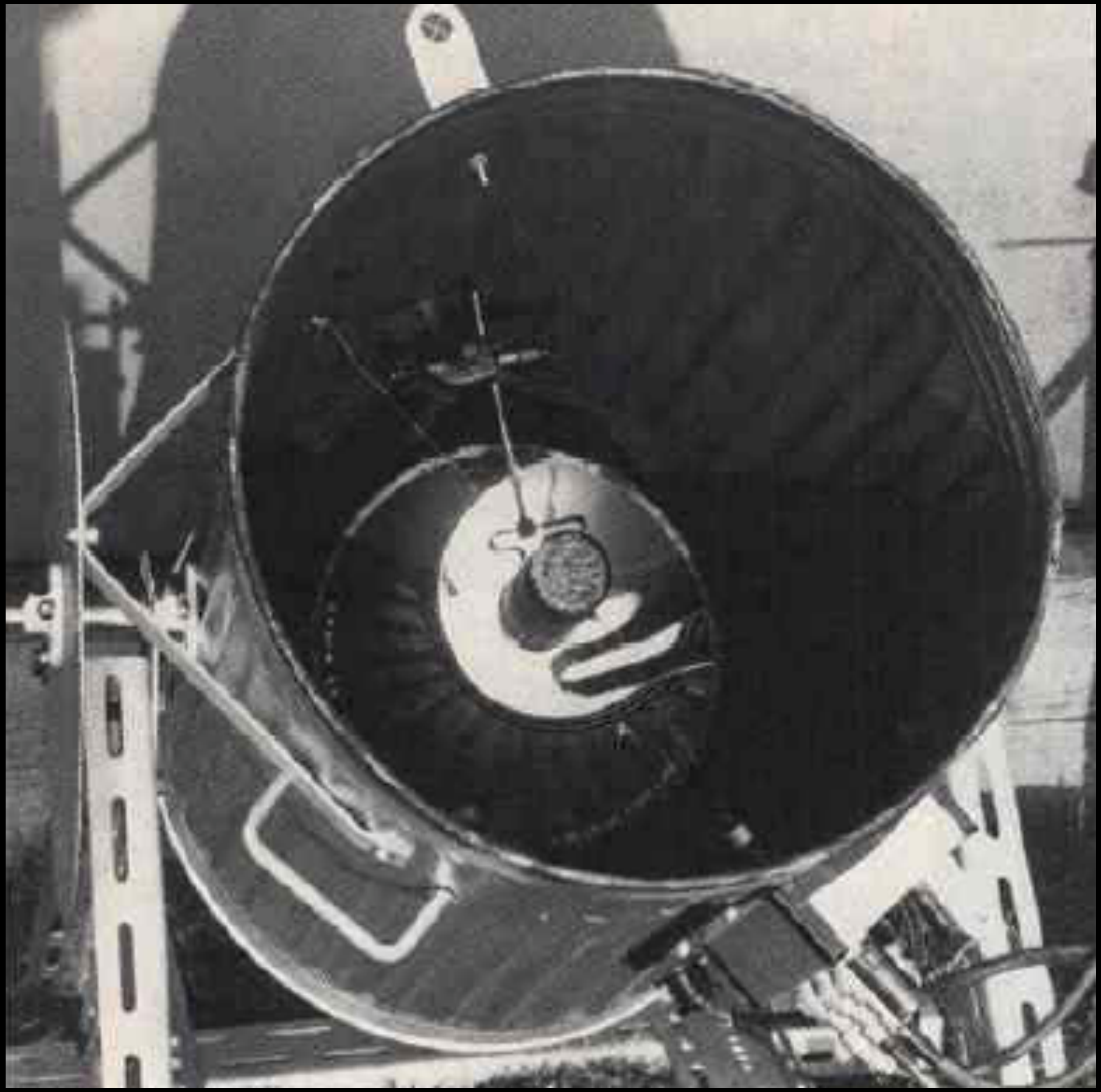
When a particle moves through a medium at a velocity greater than c, it emits Cherenkov radiation (Cherenkov, Frank, Tamm, 1933). In Russia, the radiation is called Vavilov-Cherenkov radiation (Vavilov was Cherenkov's director)

In 1948, Blackett was the first to discuss Cherenkov radiation in air.

concluding that CR showers should produce a flash of light

that he 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)



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

The delicacy of the observations
The adventurous excursions of the observers

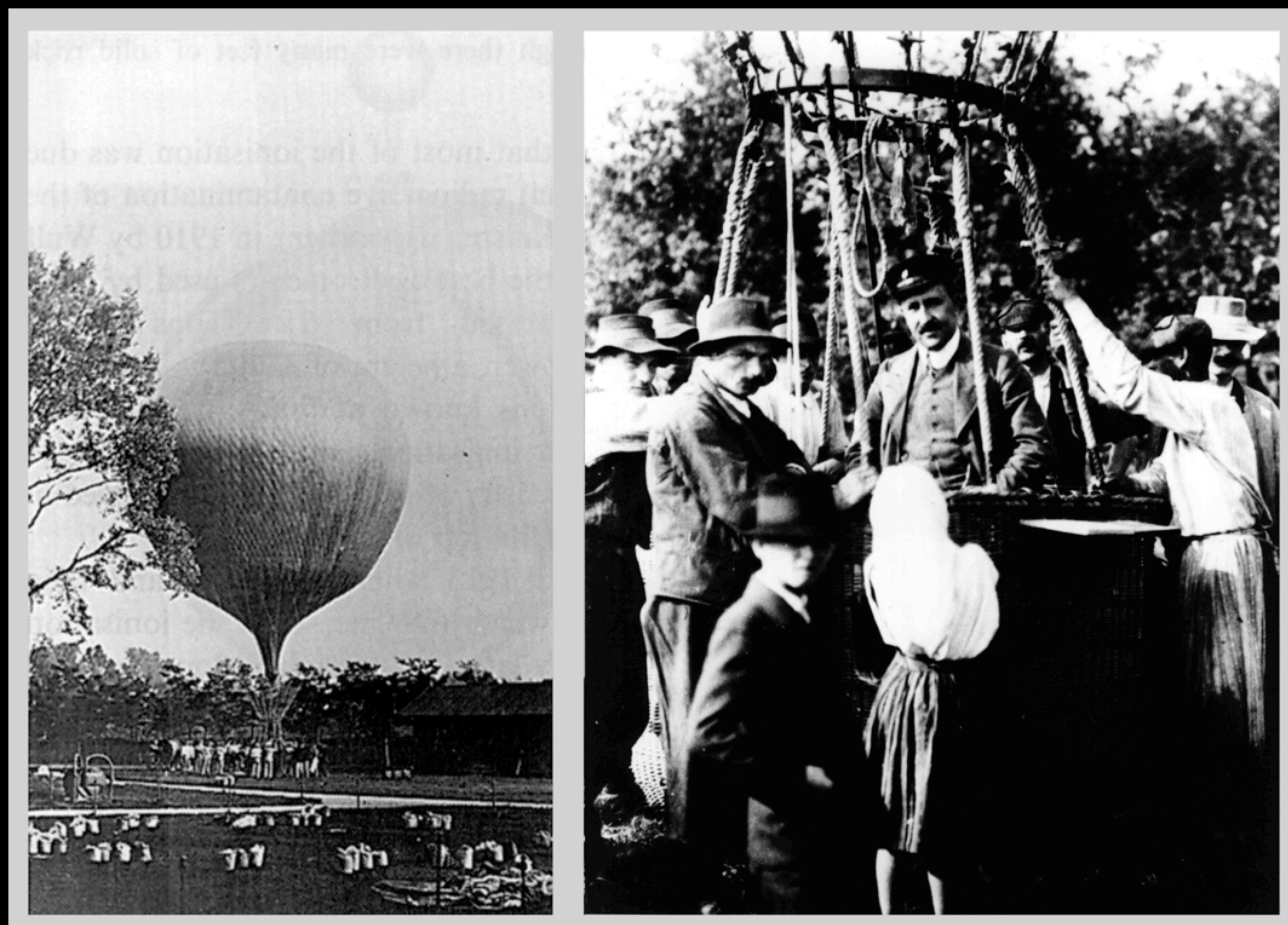
Direct detection of CRs: balloon- and space-borne experiments

Ballooning: 1912-1932

Cosmic rays studies were attacked at first only through manned balloons

Measurements were done by electroscopes or ionization chambers

Unsophisticated instruments: observers needed to be on-board



All started with the balloon flight by Viktor Hess, 1912

Ballooning: 1932-1947

A step forward was taken when balloons could reach the stratosphere

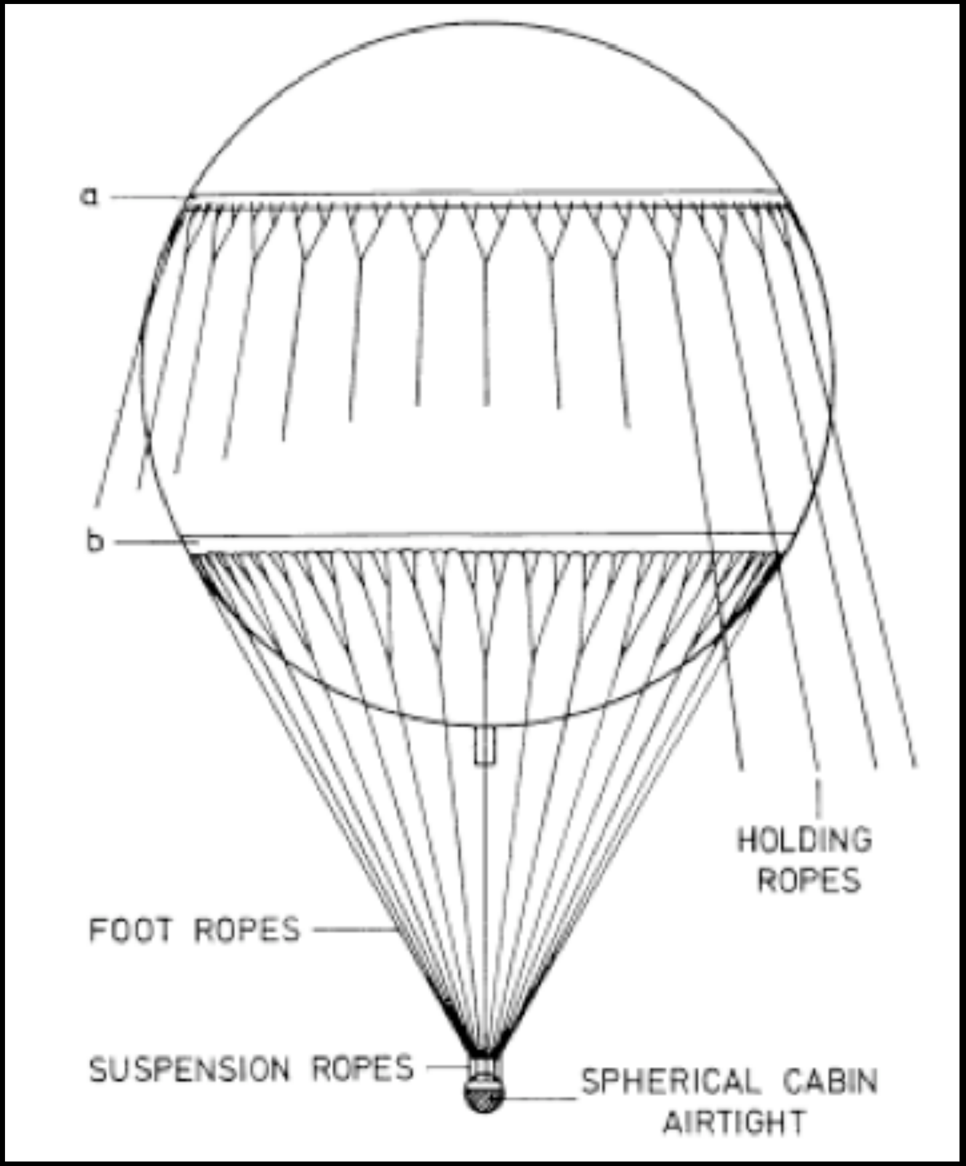
Manned flights up to 23000 m (pressurized cabins).

Sounding balloons up to 30000 m (radio-transmitting devices).

More and more complex payloads were carried by balloons (e.g., Piccard, Regener, Pfotzer, Vernov, Schein)

G-M counters were used (also in coincidence, and/or with lead absorber) for ionization detection, and photographic emulsions for tracking.

The first space-based "laboratories" were born



Stratospheric balloon (at ≈ 16 km)
Auguste Piccard, 1931

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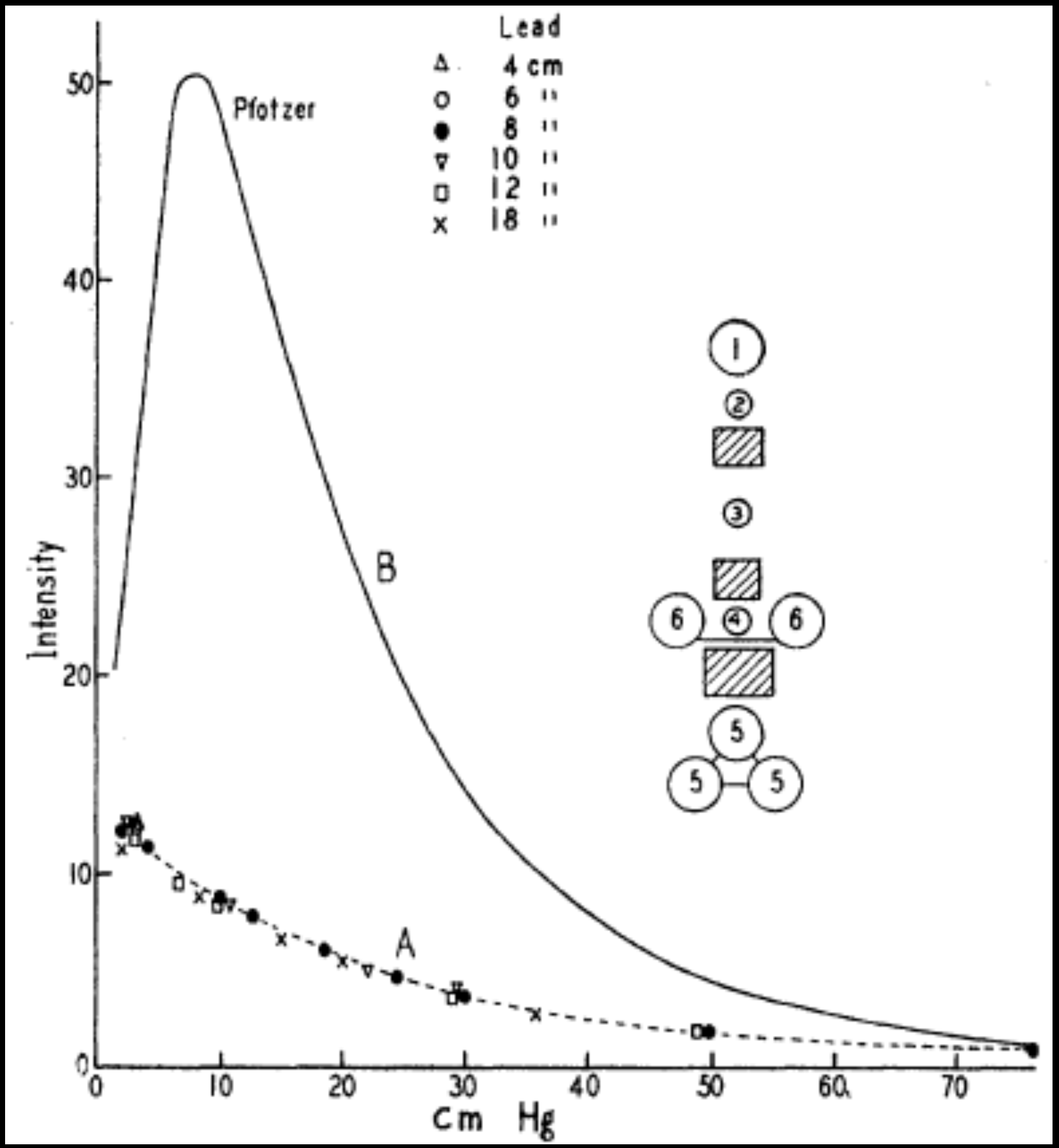
GRANDEUR of INFERENCE:

The positively-charged primaries were mainly protons (Schein, 1941)



Intensity vs height, with G-M counters and different thicknesses of lead absorbers (Schein, 1941)

Ballooning: 1947 - (start of modern era)

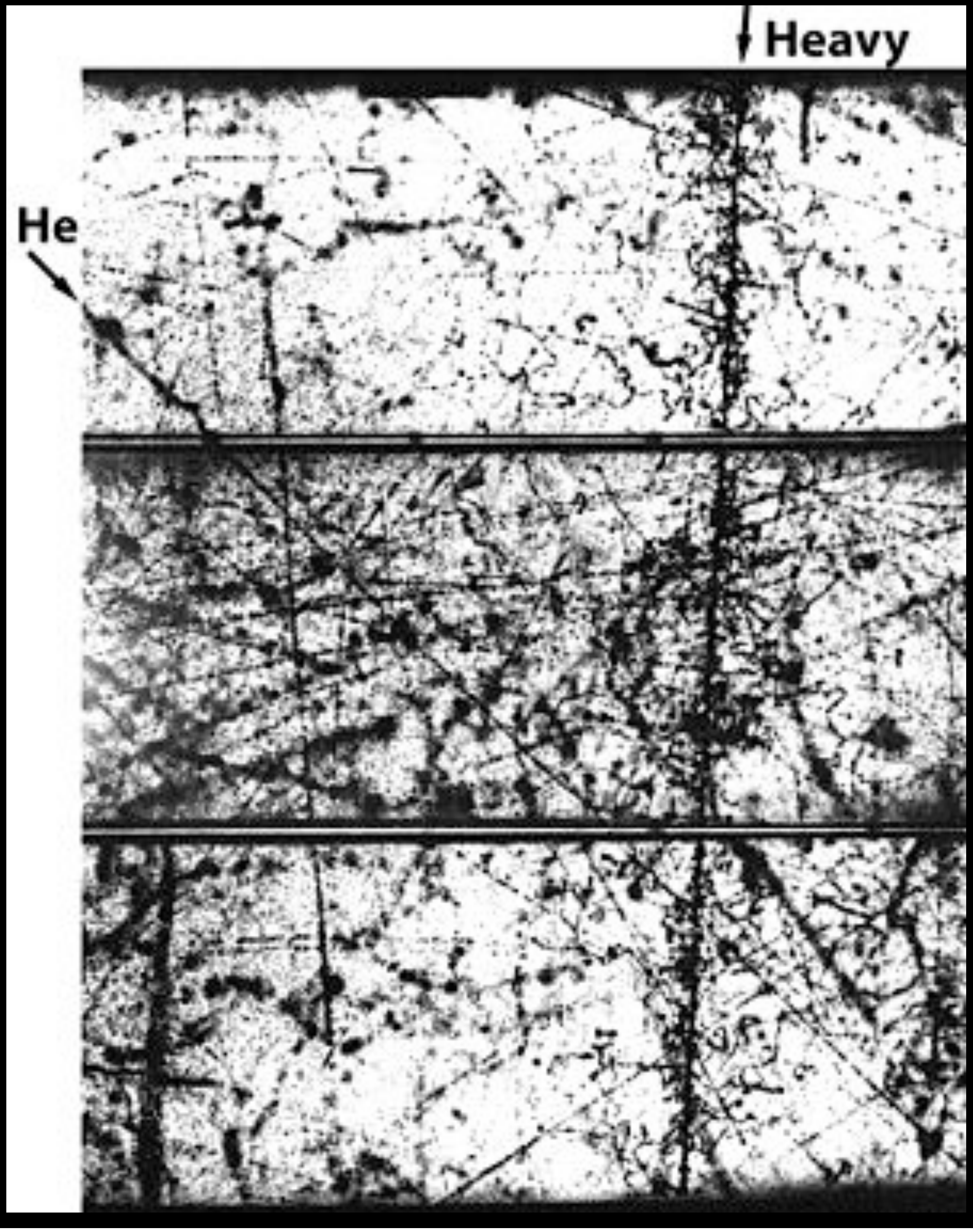
A new final era began in 1947 when plastics, suitable for the construction of very big balloons with light-weight skin and able to withstand heavy payloads, became available

Heavier complex payloads could be carried by balloons, including cloud chambers (and emulsions)

These were the prelude to experiments on spacecrafts

GRANDEUR of INFERENCE:

e.g., Freier, Ney, Oppenheimer, Peters, Lofgren, Bradt (1948) found for the first time evidence of heavy nuclei among primary CR. They did so by sending a sounding balloon up to 29000 m carrying nuclear-emulsion plates, and a small cloud chamber



First evidence of a heavy primary nucleus (Nuclear emulsion from balloon flight by Bradt and Peters, 1948)

From balloons to satellites

Due to the development of the space technique (starting from end of the 50s) the possibility arose to launch heavy satellites with scientific equipment weighing several tons

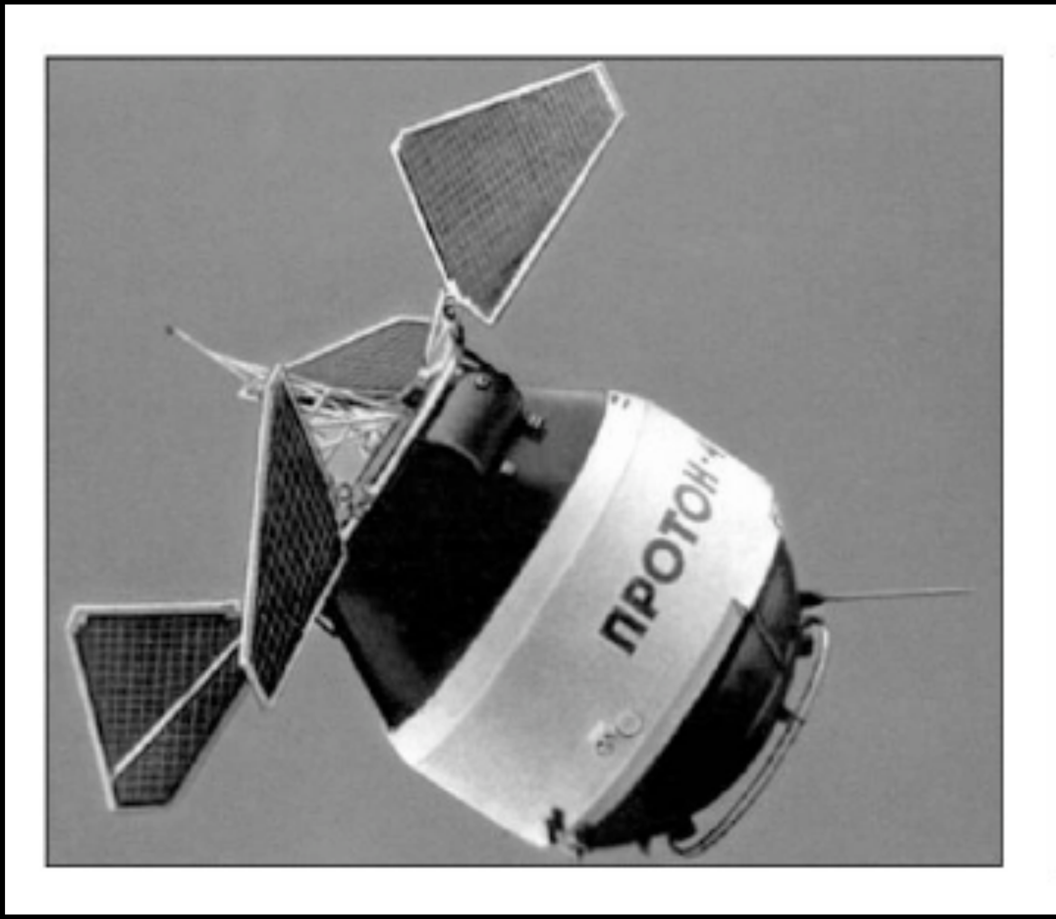
Vernon et al (URSS) arranged the first CR space experiment on the Second Soviet Satellite (1957). In the same year, US scientists (Van Allen et al) launched the Explorer I satellite.

First used instruments were simple G-M counters.

Earth's radiation belts were discovered.

A serie of satellites carrying cosmic ray laboratories were called Proton (1965-1968)

The main instrument was a ionization calorimeter.



Proton-4 satellite (1969-1970)
Grigorov and Vernov

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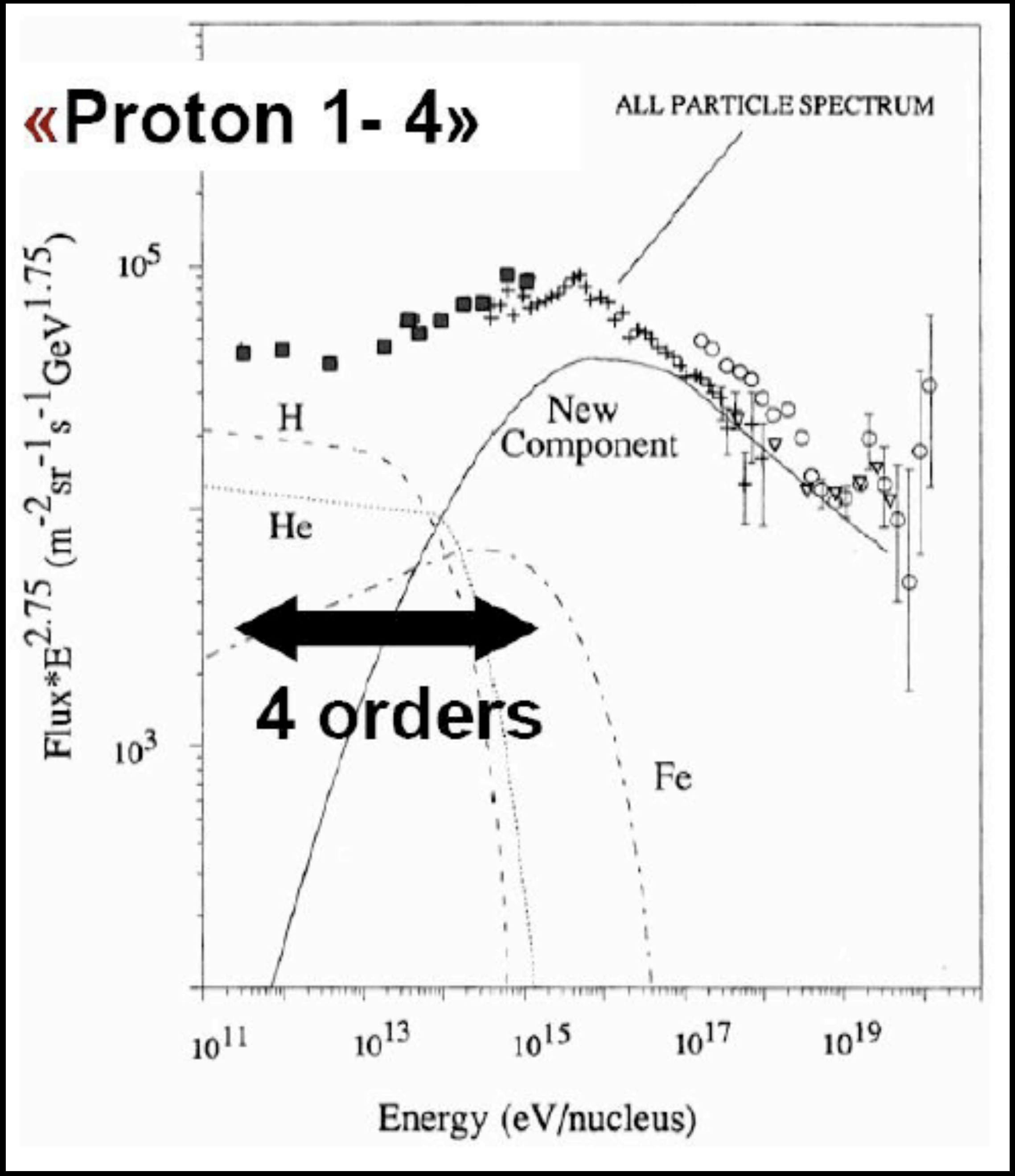
GRANDEUR OF THE INFERENCES:

Measurement of the all-particle spectrum up to 10^{15} eV



Measurement of the CR flux by Proton

PRINCIPLES OF A BALLOON/SPACE CR TELESCOPE

For the study of cosmic rays, particle detectors are built into "telescopes".

In the case of direct measurements, the telescopes are flown over balloons, or rockets, or satellites.

Different detectors must be combined to achieve the indentification of the particle

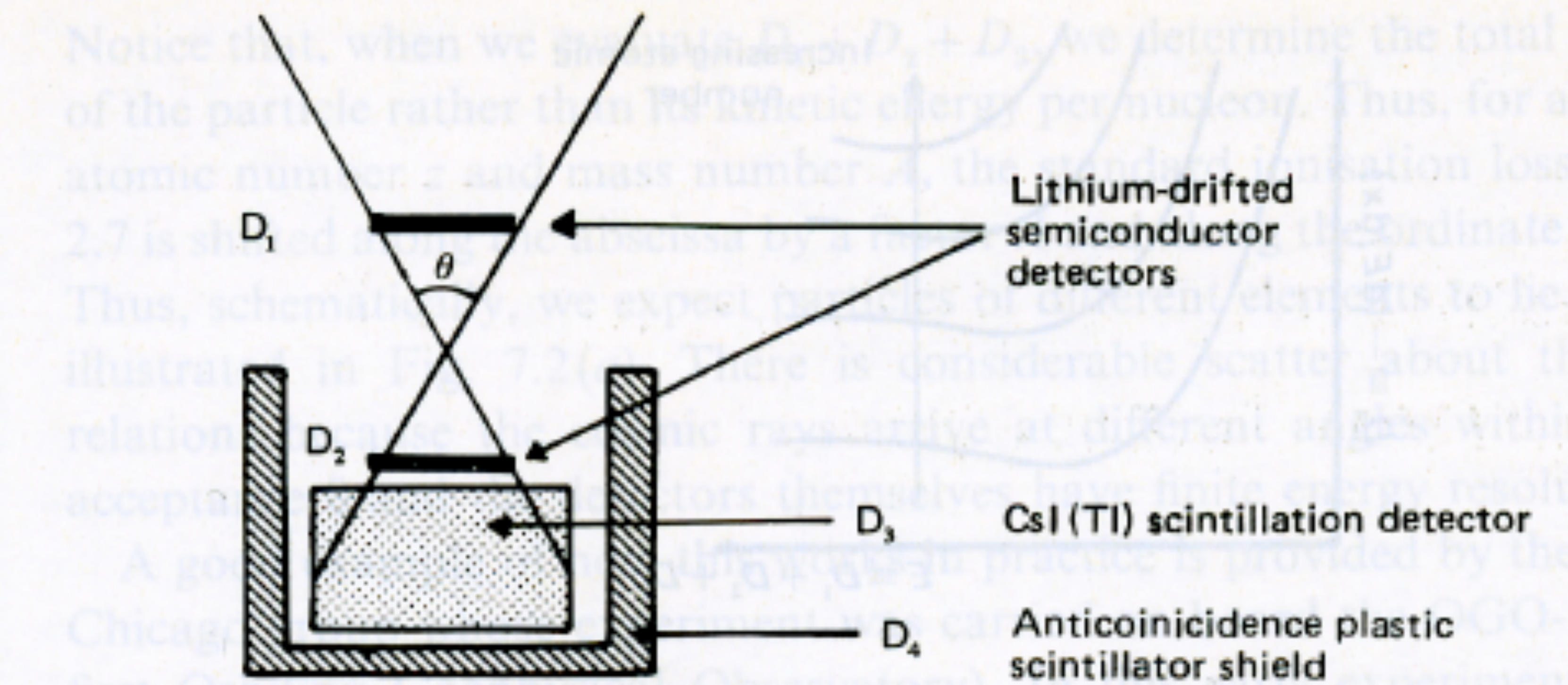


Figure 7.1. A simplified diagram showing the layout of the detectors of the cosmic ray telescope flown on board the IMP-III space probe. (From M. M. Shapiro and R. Silberberg (1970). *Ann. Rev. Nucl. Sci.*, **20**, 323.)

Ionization detectors (D1, D2) on top (to register the passage of the particle , to give the "geometry" of the detector, and to measure dE/dX)

A calorimeter (D3). The sum of signals registered in D1, D2, D3 give the total kinetic energy of the particle

Given dE/dX and E(kin), the charge can be determined.

Also the mass can be derived: dE/dX does not depend on the mass, but E(kin) does

PRINCIPLES APPLICATIONS ON BALLOONS

AESOP / LEE [Anti-Electron Sub Orbital Payload / Low Energy Electrons]
ANITA [Antarctic Impulse Transient Array] (radio frequency neutrino shower detection)
ATIC [Advanced Thin Ionization Calorimeter]
BESS [Balloon-borne Experiment with a superconducting Solenoid Spectrometer]
BETS [Balloon borne Electron Telescope with Scintillating fibers]
CAPRICE [Cosmic AntiParticle Ring Imaging Cherenkov Experiment]
CREAM [Cosmic Ray Energetics and Mass Balloon Experiment]
HEAT [High Energy Antimatter Telescope]
IMAX [Isotope Matter Antimatter Experiment] (see also here and here)
ISOMAX [Isotope Magnet Experiment]
JACEE [Japanese-American Collaborative Emulsion Experiment]
MASS.. [Matter Antimatter Superconducting Spectrometer]
RUNJOB [RUssian-Nippon JOint Balloon Experiment]
SMILI [Superconducting Magnet Instrument for Light Isotopes]
TIGER [Trans Iron Galactic Element Recorder]
TRACER [Transition Radiation Array for Cosmic Energetic Radiation]

PRINCIPLES APPLICATIONS ON BALLOONS

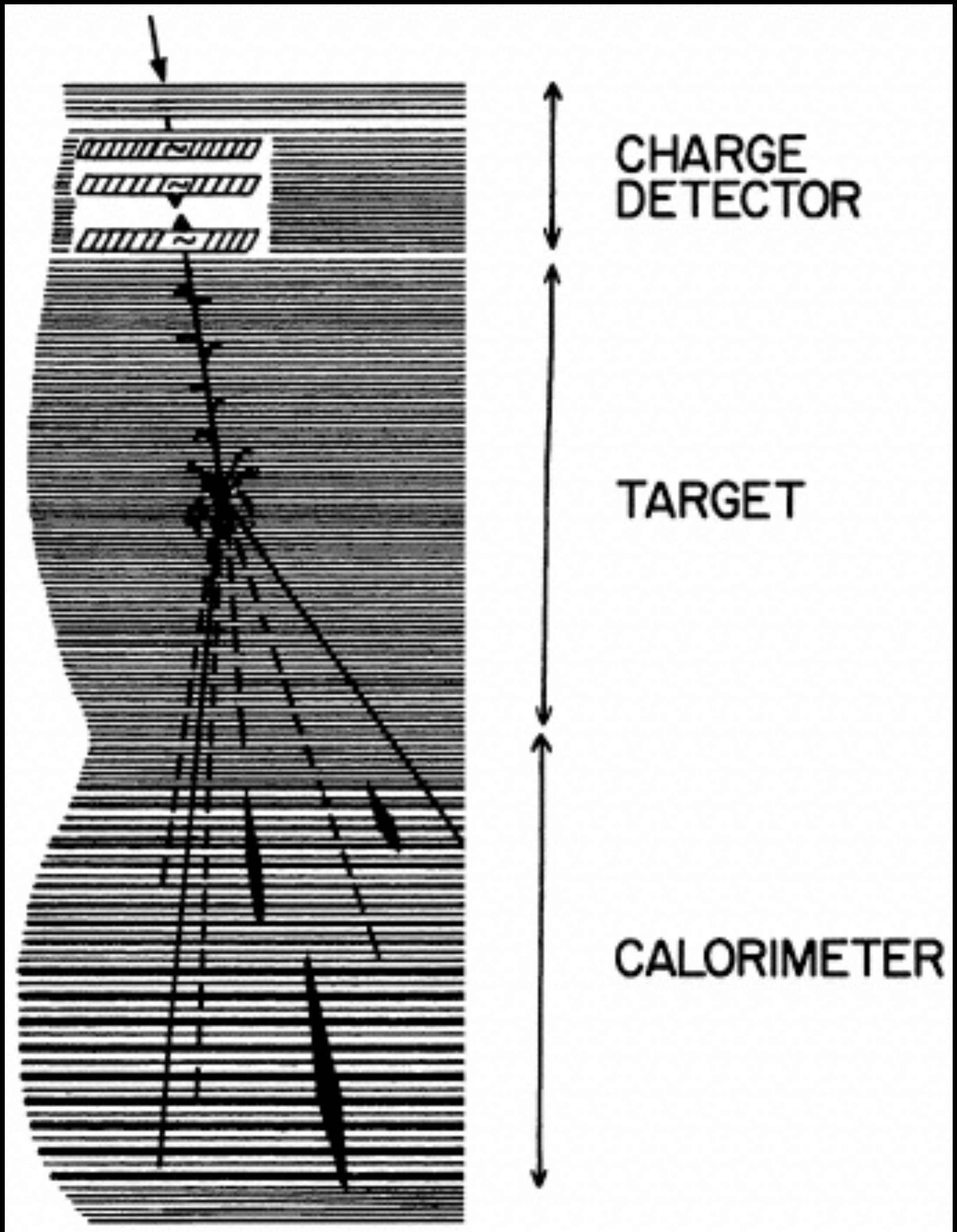
Nuclear emulsions, interleaved with converters, were used in JACEE and RUNJOB balloon flights to simultaneously measure the charge and energy of the primary particle. The payloads had to be recovered and the energy and charge information was extracted from the analysis of the emulsion data.

JACEE BALLOON
JAPANESE-AMERICAN
ANTARTIC BASE 1983-1996

RUNJOB BALLOON
RUSSIAN-NIPPONIC
KAMCHATKA BASE 1995-1999
(10 FLIGHTS)

Ballooning: JACEE

JACEE is an entirely passive calorimeter containing both thick (200–400 μm) and thin (50–100 μm) nuclear emulsions, as well as track detectors (CR-39 and lexan)



Charge measurement with thick emulsions: charge from the darkness of the track in the emulsion (ionization)

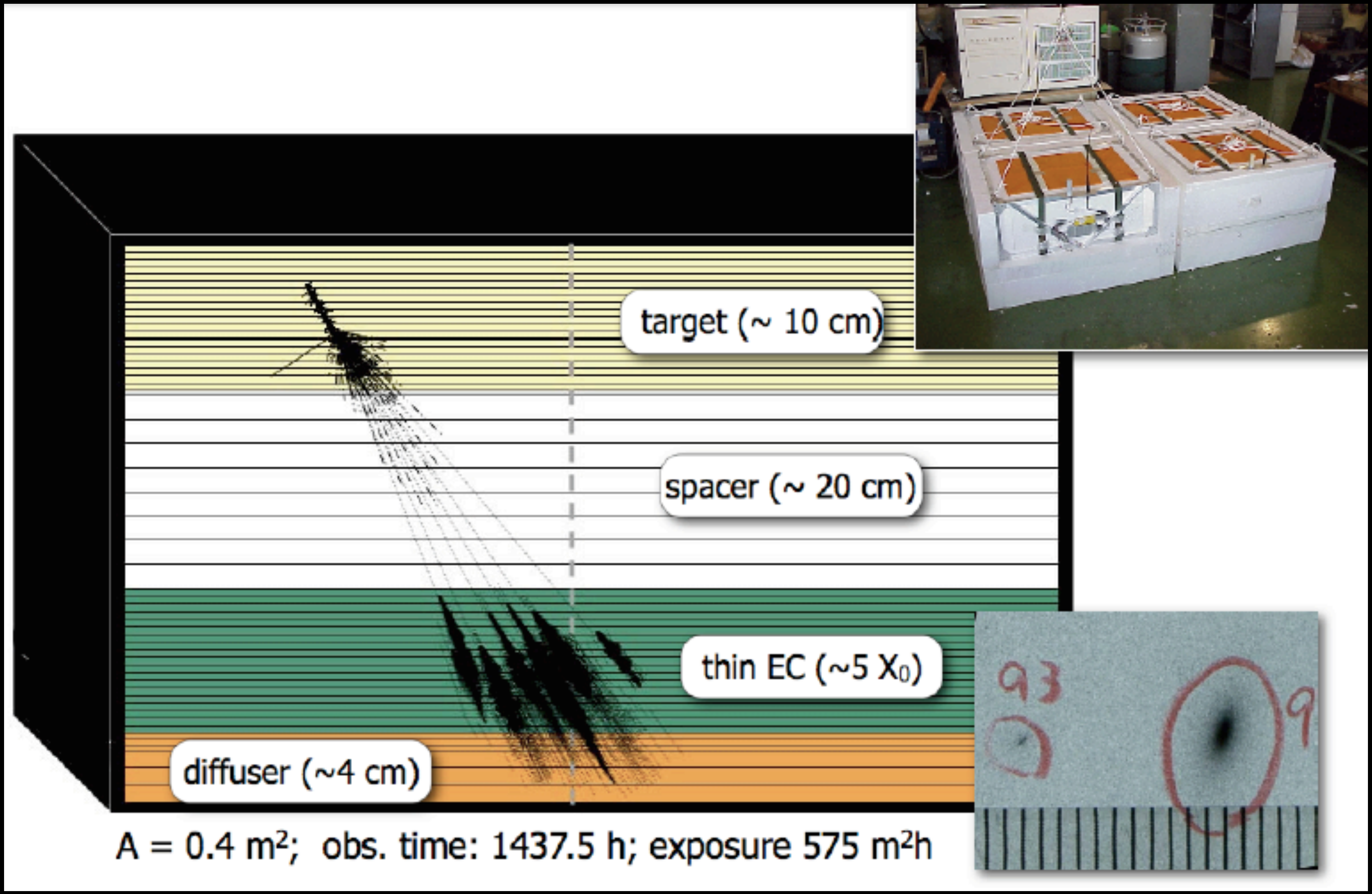
Target: the particle interacts. Nuclear interaction detected with thin emulsion

After a little space (to allow tracks to diverge sufficiently) there is the calorimeter: x-ray films and thin emulsions between lead plates

Scheme of JACEE

Ballooning: RUNJOB

RUNJOB has a similar conception.



Ballooning: RUNJOB

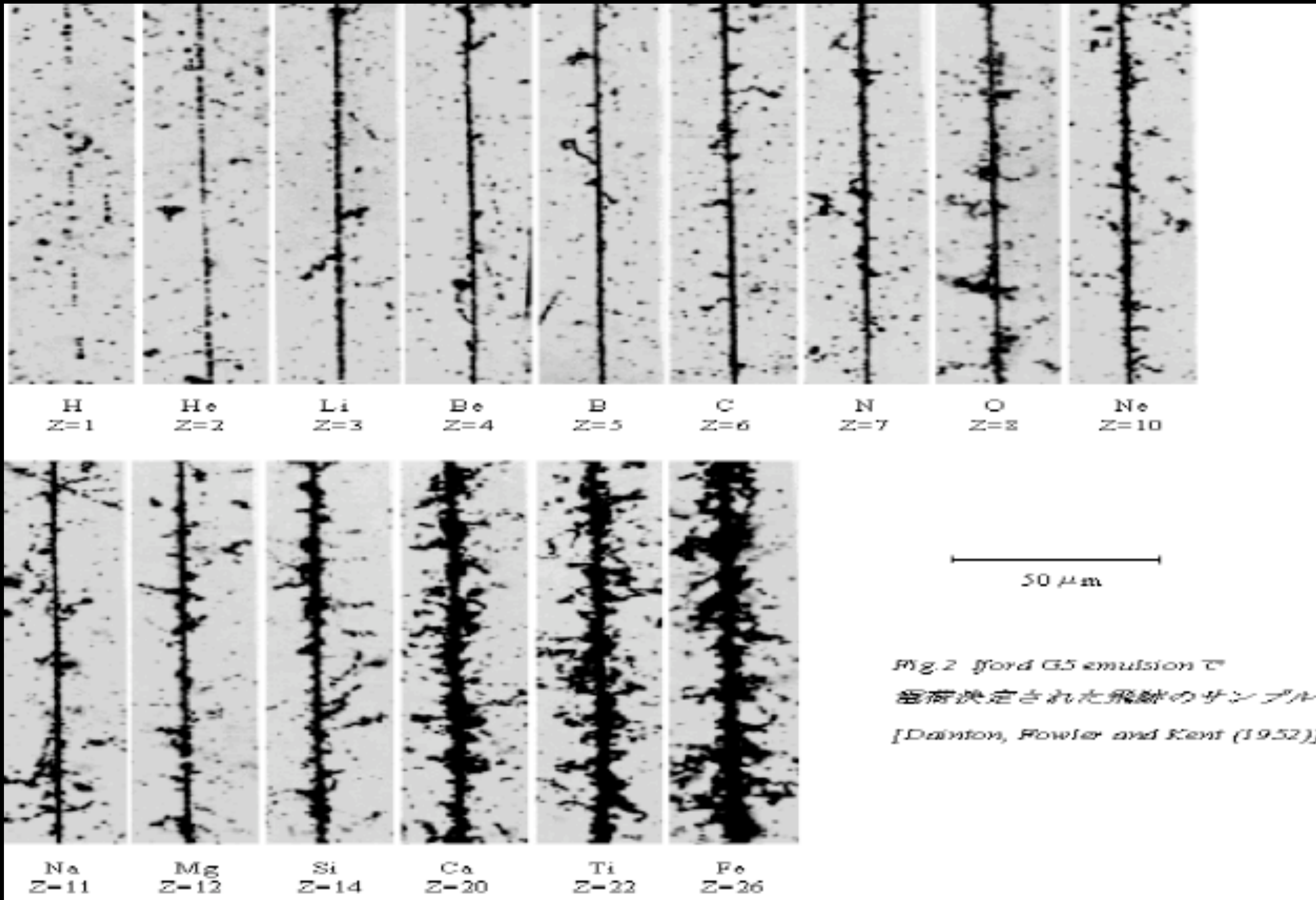
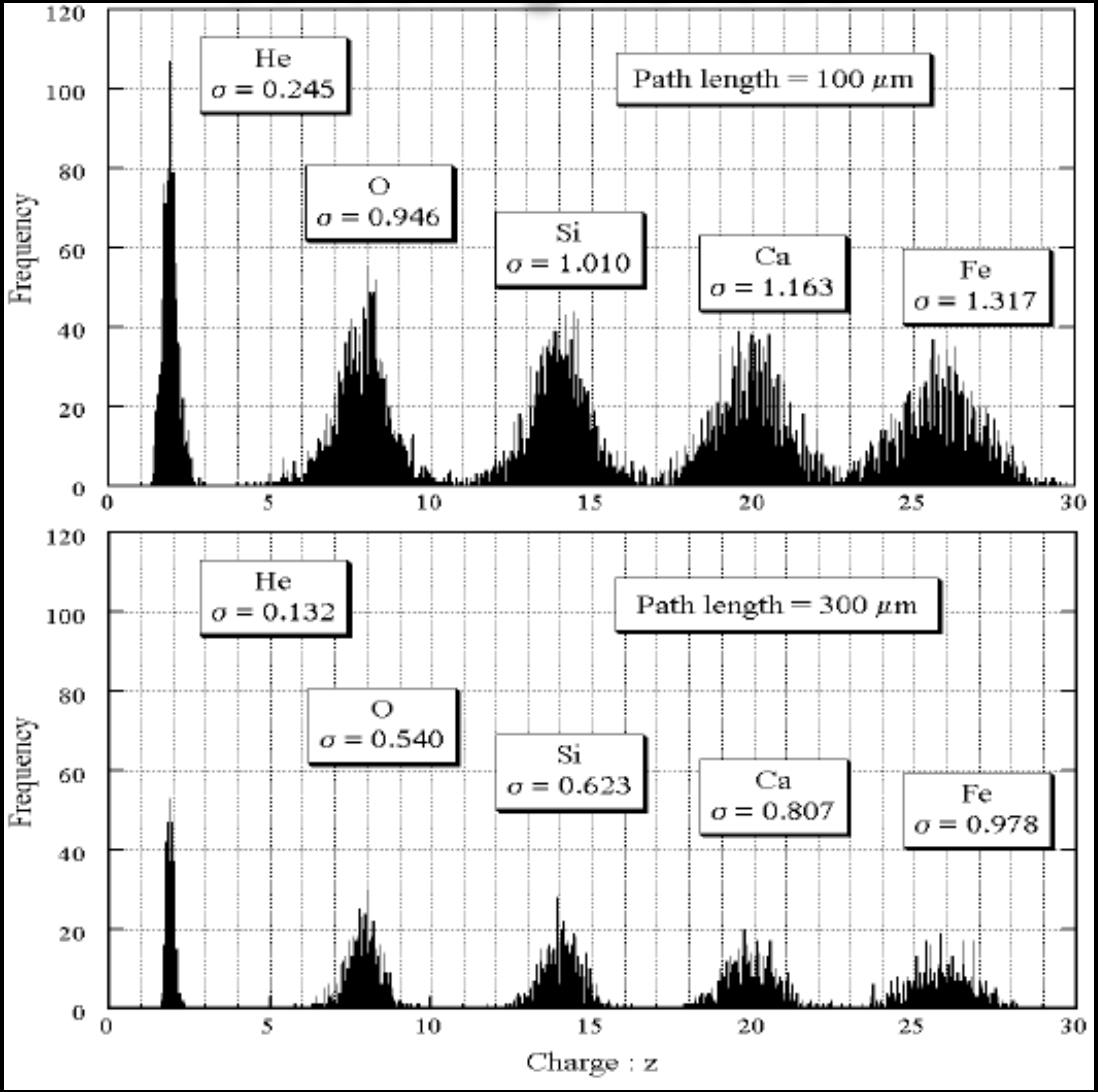


Fig.2 Ilford G5 emulsion で
電荷決定された飛跡のサンプル
[Dainton, Fowler and Kent (1952)]

Charge determination in RUNJOB

Ballooning: RUNJOB



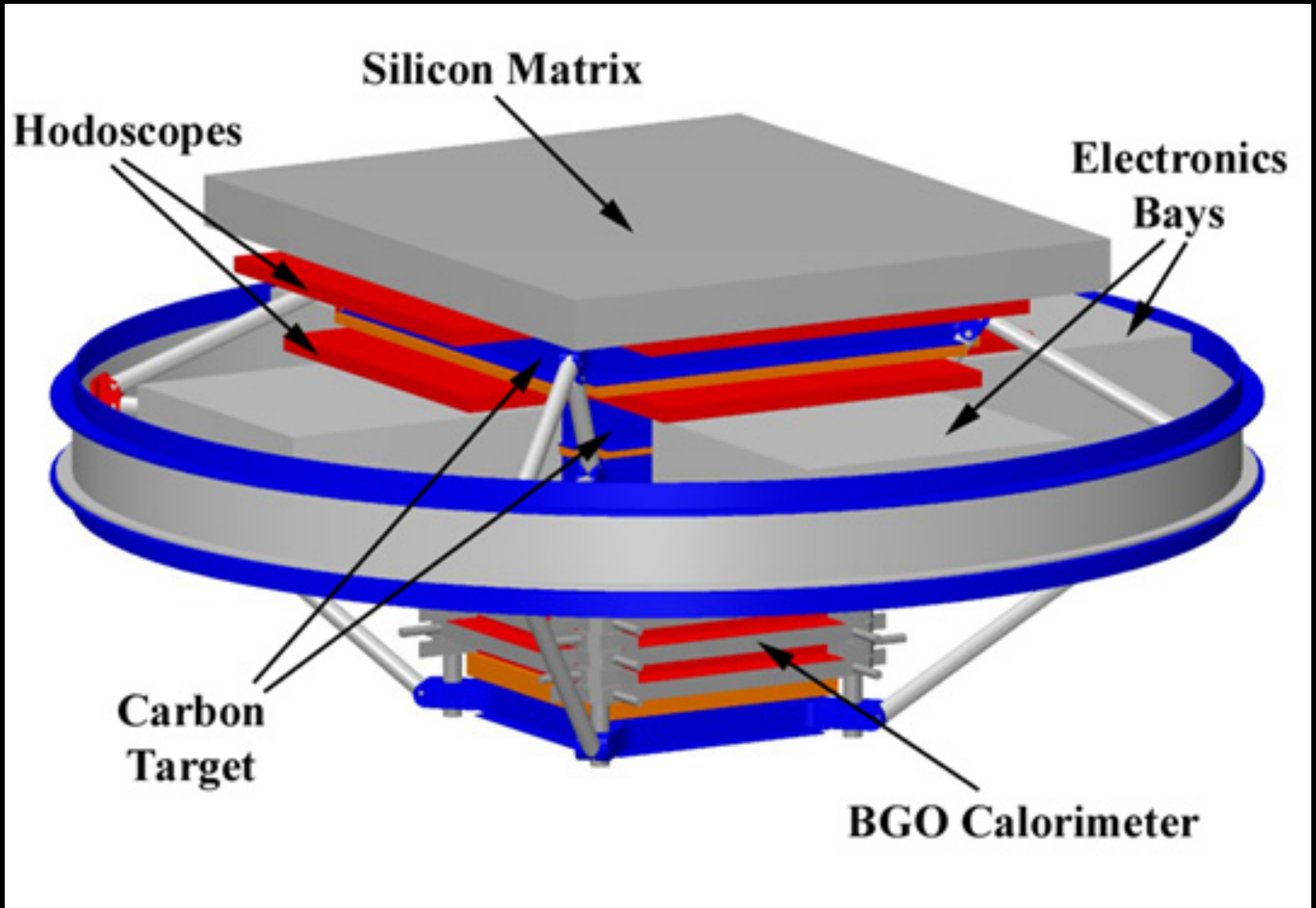
Charge resolution in RUNJOB

Ballooning: let's come to even more recent times...

In the more recent generation of direct experiments, data is recorded electronically in-flight and transmitted to the ground. The design of the instrument usually includes a combination of charge detection and energy measurements, with detectors such as scintillator hodoscopes, Silicon detectors combined with a Calorimeter or a Transition Radiation Detector

Ballooning: ATIC

The Advanced Thin Ionization Calorimeter (ATIC) is designed to measure the energy spectrum of individual cosmic ray elements in the energy range 50 GeV-100 TeV (flown in 2007-2008)



Charge measurement with silicon detectors

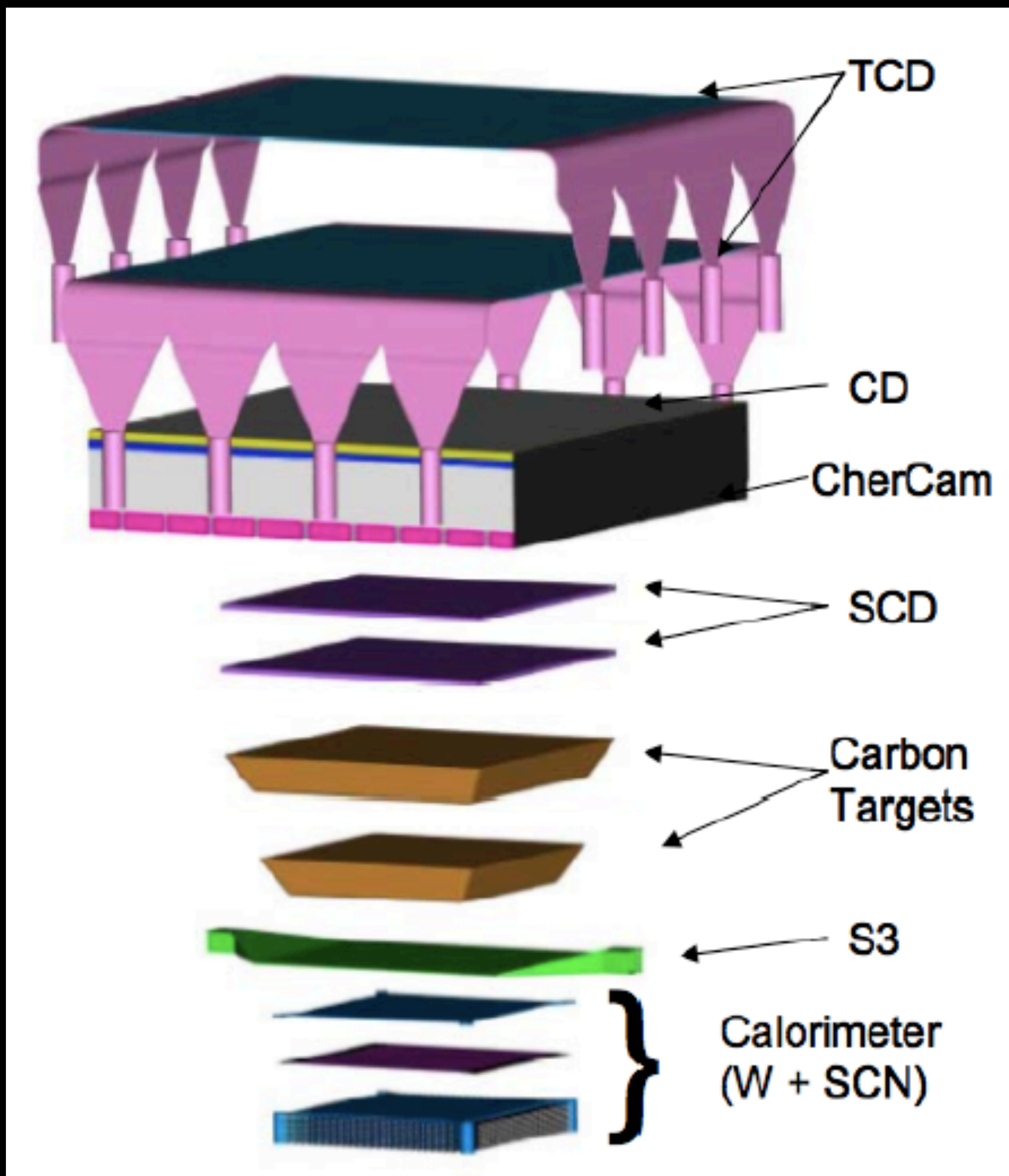
Target: hodoscopes (scintillators) and carbon. Charge and trajectory measurements

Energy measurement with ionization calorimeter. Layers of carbon and of Bismuth-Germanium-Oxide (BGO) scintillating crystals

Total weight: 1500 kg

Ballooning: CREAM

The Cosmic Ray Energetics And Mass (CREAM) is designed to measure CR elemental spectra using a series of ultra long duration balloon flights. The goal is to extend in energy direct measurement of CR composition providing calibration for indirect measurements (flown 2004-2010)



TOTAL WEIGHT: 1143 KG

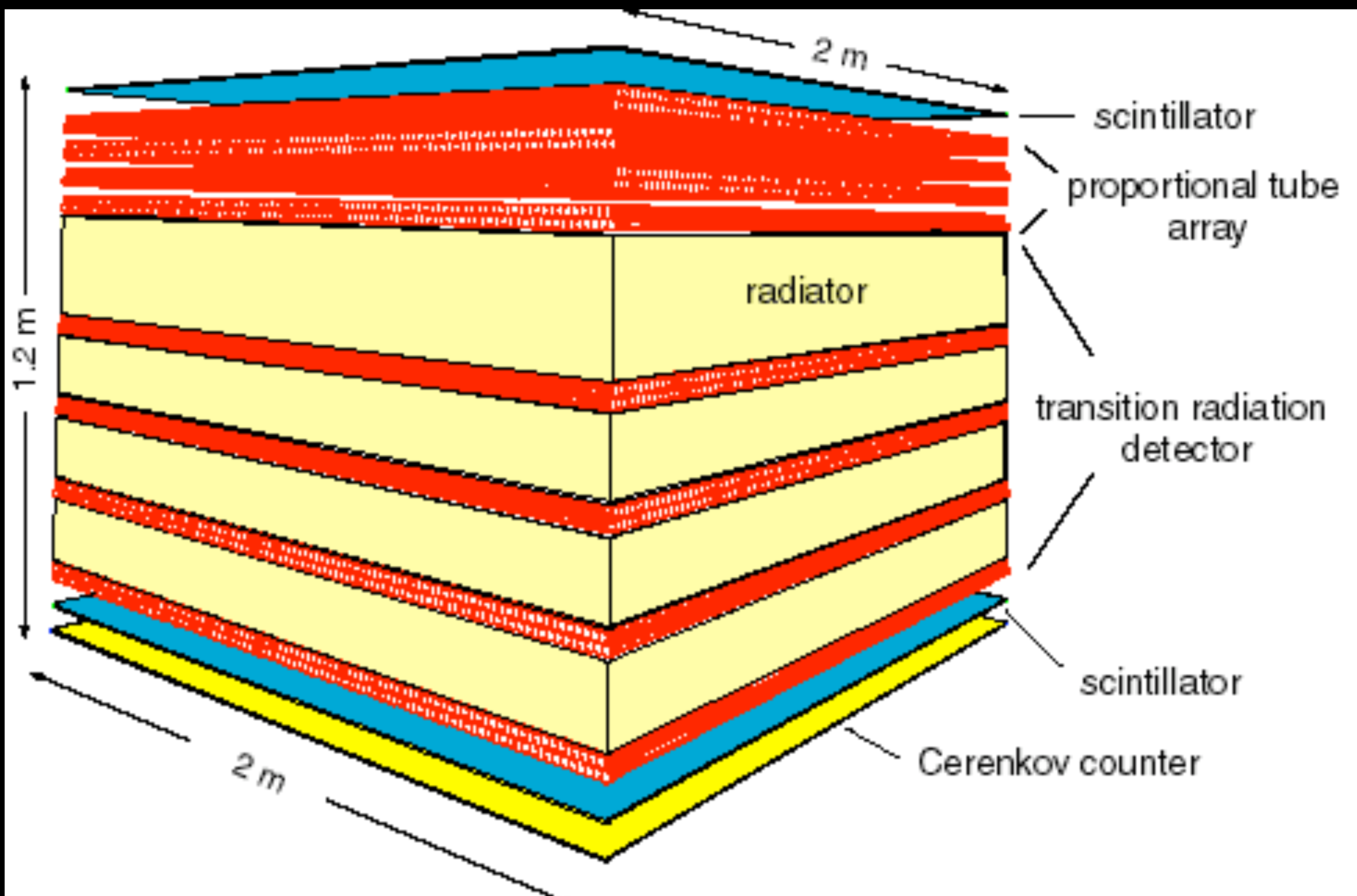
Charge and velocity measurement with Timing Charge Detector (TCD, scintillators), Supplemental measure of charge by Cherenkov Detector (CD), Cherenkov Camera (CherCam) and Silicon Charge detector (SCD)

Target: hodoscopes (scintillating fibers, S0-3) and carbon. Charge and trajectory measurements

Energy measurement with ionization calorimeter. Layers of Tungsten and scintillating fibers

Ballooning: TRACER

The Transition Radiation Array for Cosmic Energetic Radiation (TRACER) is an instrument for long-duration balloon borne measurements of heavy cosmic ray nuclei (boron to iron) from 10^{13} to ≈ 10^{15} eV/nucleon. It has flown in 2003-2006



Charge measurement: 2 layers of scintillators and 1 Cherenkov counter

Trajectory measurements by 8 double layers of proportional tubes

Energy measurement with transition radiation detector. Four radiators of plastic fiber material alternated with proportional tubes.

PRINCIPLES APPLICATION ON SATELLITES

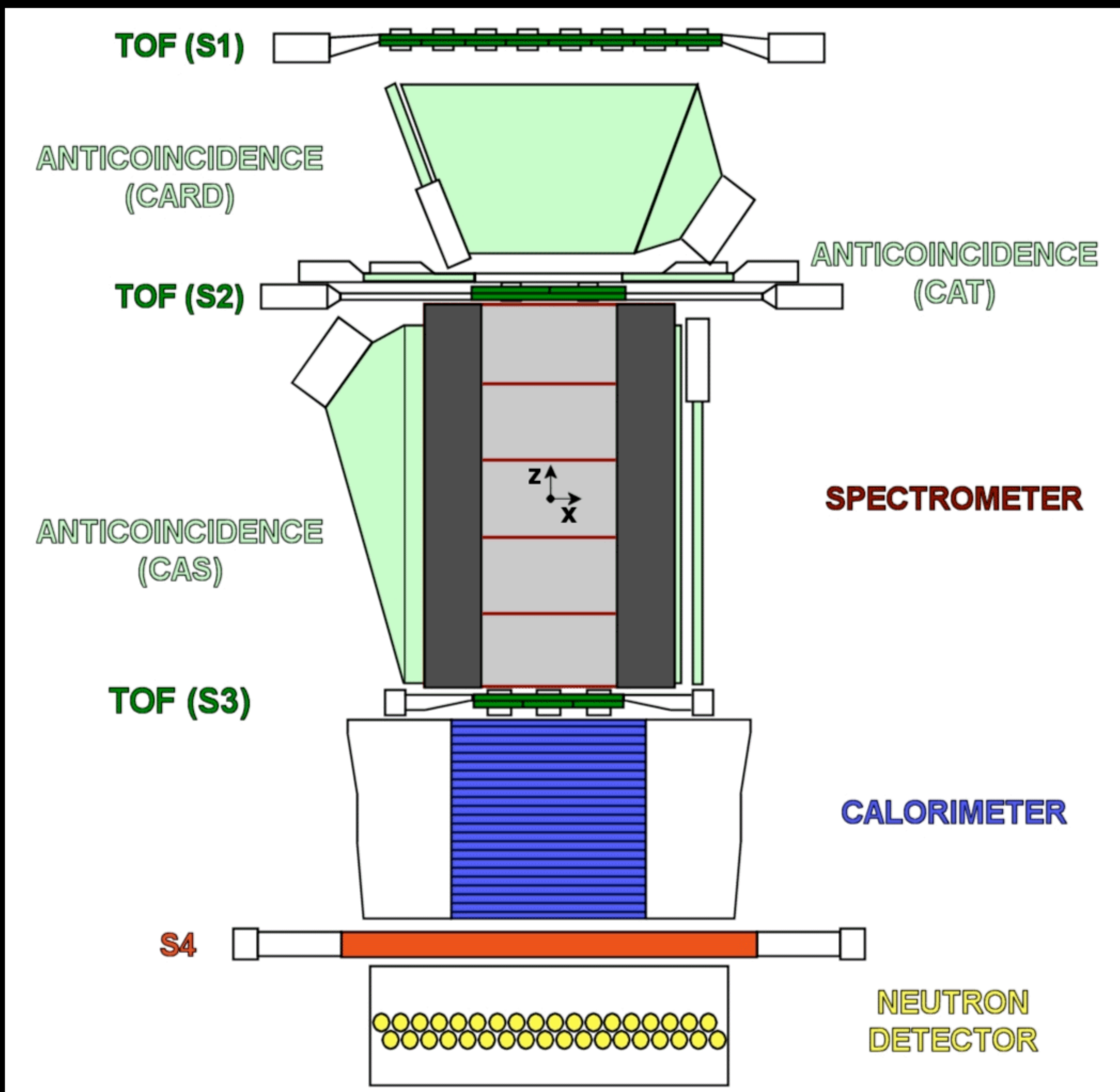
ACE [Advanced Composition Explorer] Mission mainly for solar particles
AMS [Alpha Magnetic Spectrometer]. International Space Station
ASCA [Advanced Satellite for Cosmology and Astrophysics]
Fermi Gamma-ray Space Telescope, (also cosmic rays)
NINA [New Instrument for Nuclear Analysis], low energy cosmic rays.
PAMELA (magnet spectrometer).

Pamela launch:
15 June 2006

AMS on the ISS
Launch: 19 May 2011

Space: PAMELA

PAMELA (Payload for Antimatter-Matter Exploration and Light Nuclei Astrophysics) is taking data on board the "Resurs-DK1" satellite. The instrument was designed to accurately measure the spectra of charged particles (including light nuclei) in the cosmic radiation, over an energy interval ranging from tens of MeV to several hundred GeV. In particular, it is optimized to identify the small component of CR antiparticles.



Mass and charge measurement: Time of Flight (scintillators)

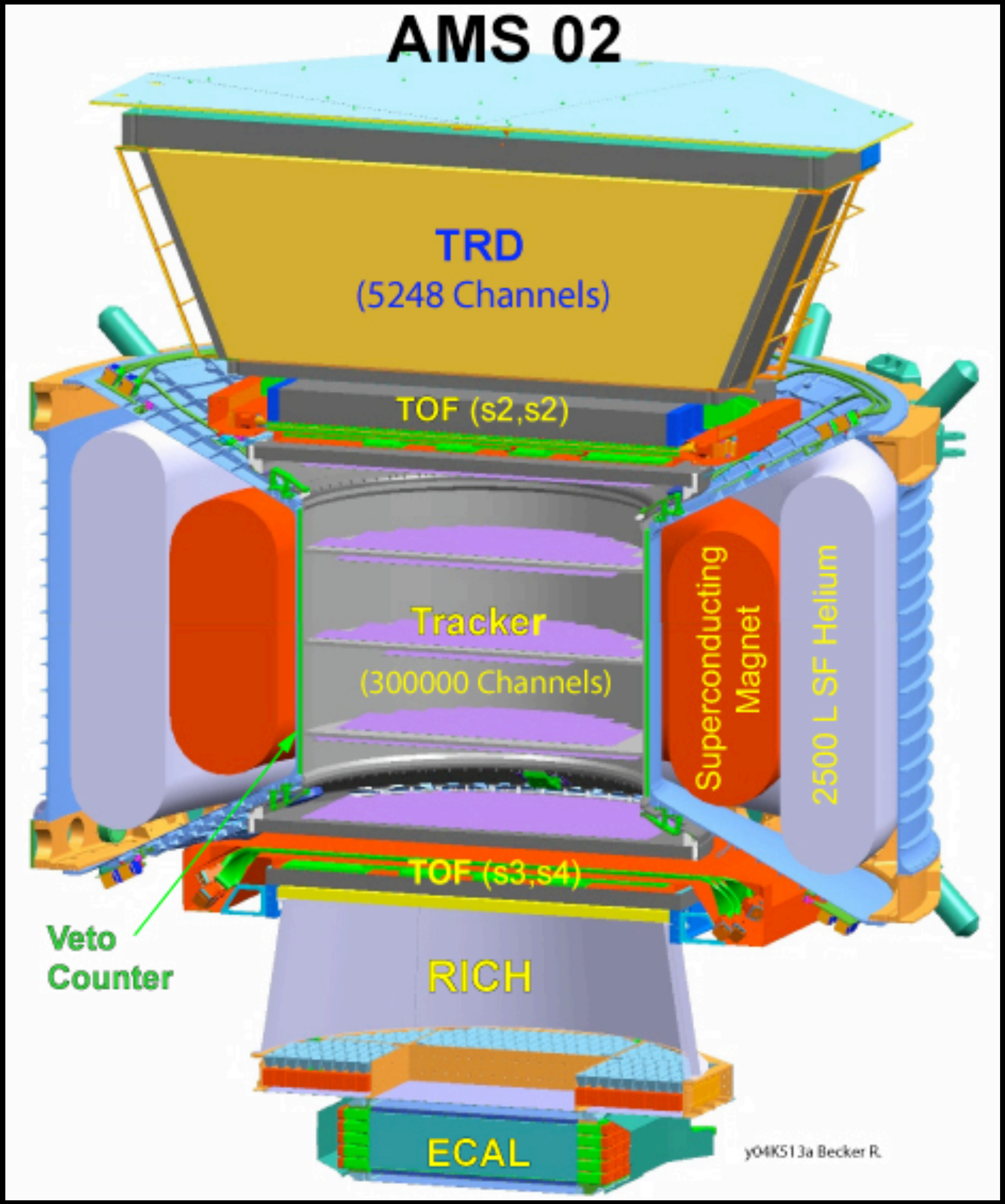
Charge sign (and value) measurement: Spectrometer (Si tracking system and permanent magnet)

Energy measurement: electromagnetic calorimeter . Silicium sensors alternated to Tungsten absorber

e.m./hadronic cascades discrimination: neutron detector

Space: AMS

The Alpha Magnetic Spectrometer (AMS-02) is designed to operate as an external module on the International Space Station. It mainly aims to search for antimatter, but it will perform too precision measurements of cosmic rays composition and flux.



Total weight: 8500 kg

Velocity and charge measurement: Time of Flight (scintillators)

Lorentz factor measurement: Transition Radiation Detector (tube straws and plastic radiator)

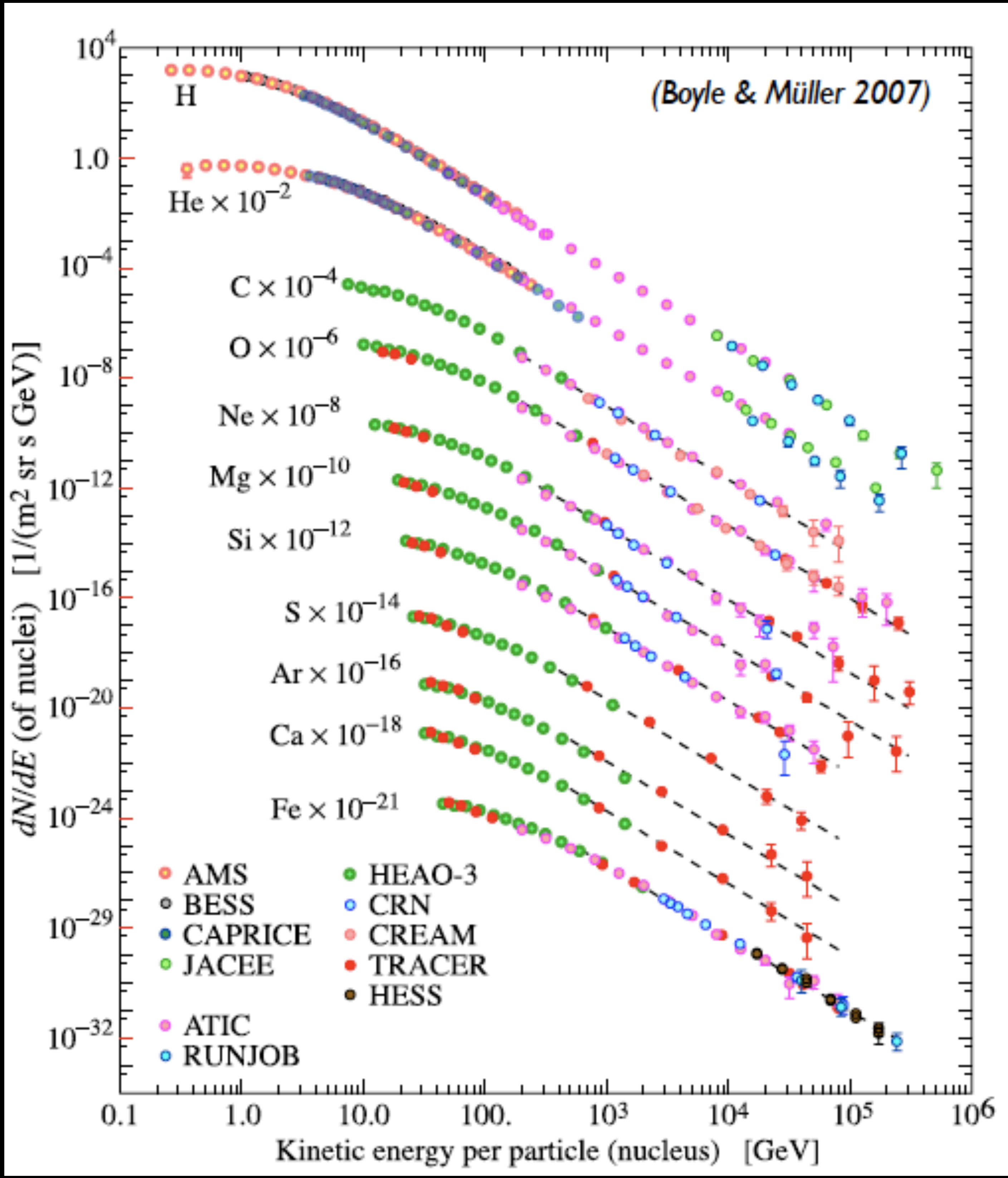
Charge sign (and value) measurement: Spectrometer (Si tracking system and magnet)

Velocity measurement: Ring Cherenkov detector (RICH)

Energy measurement: electromagnetic calorimeter . Scintillating fibers alternated to lead absorber

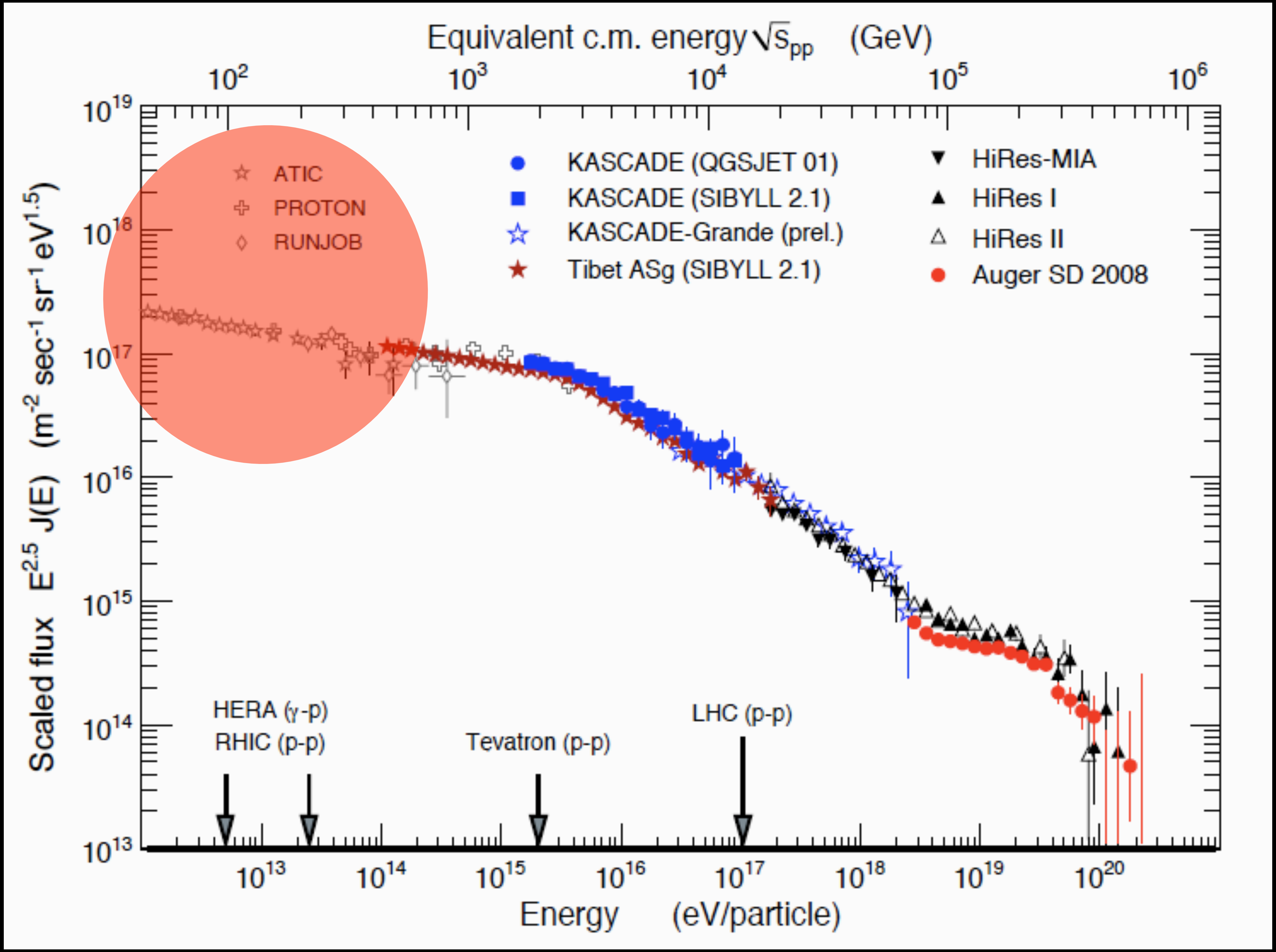
And to finish...

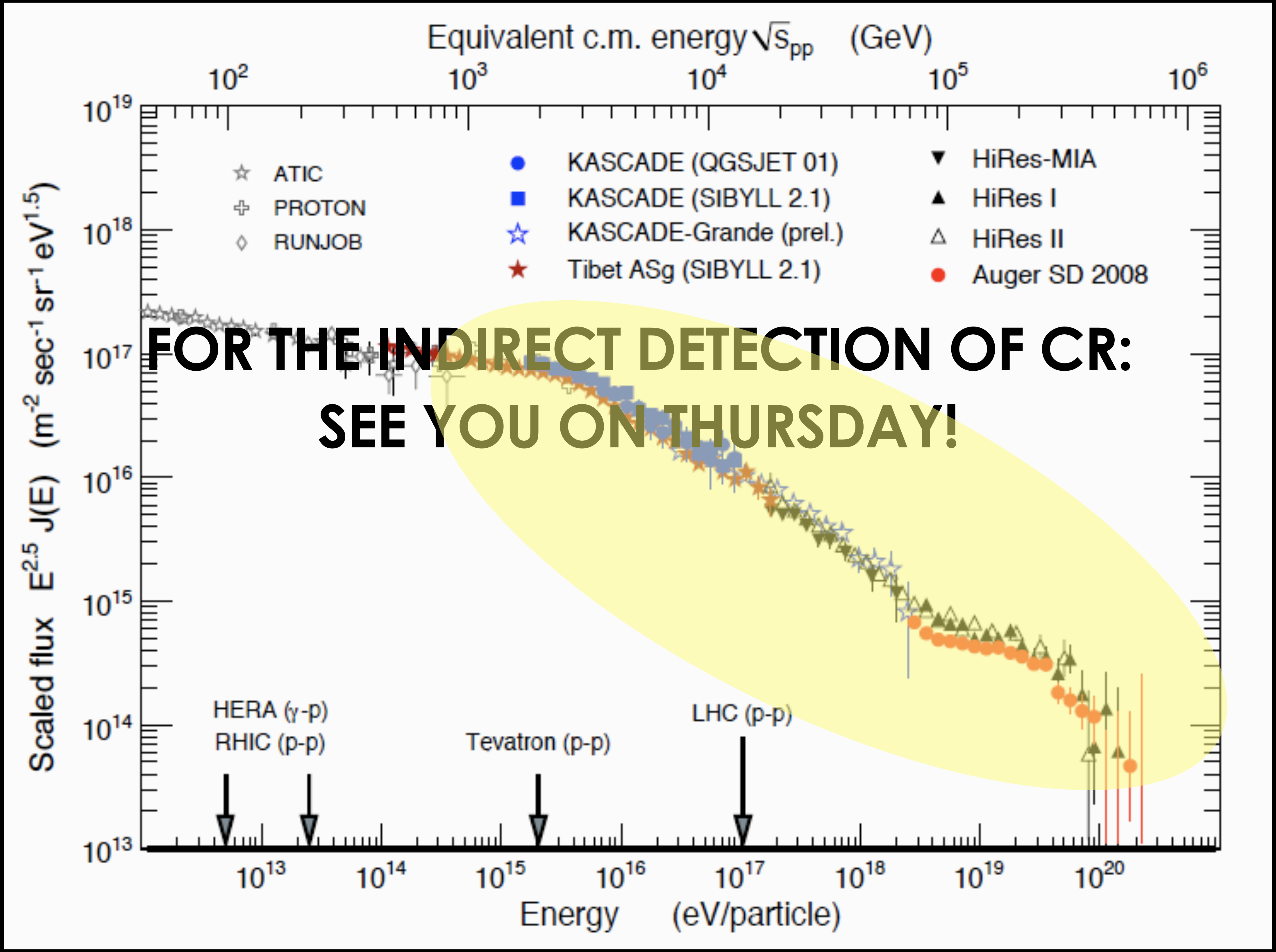
Grandeur of inferences: Fluxes of individual elements



And to finish...

Grandeur of inferences: All-particle spectrum





Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)
10^2
10^3
10^4
10^5
10^6
Scaled flux $E^{2.5}$ J(E) (m^{-2} sec^{-1} sr^{-1} $eV^{1.5}$)
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande (prel.)
Tibet ASg (SIBYLL 2.1)
HiRes-MIA
HiRes I
HiRes II
Auger SD 2008
HERA (γ-p)
RHIC (p-p)
Tevatron (p-p)
LHC (p-p)
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
Energy (eV/particle)
FOR THE INDIRECT DETECTION OF CR:
SEE YOU ON THURSDAY!

CREDITS AND REFERENCES

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 re-read five important books :

Bruno Rossi, Cosmic Rays, Mc Graw-Hill

Michael W. Friedlander, Cosmic Rays, Harvard University Press

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

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

William.R.Leo: Techniques for Nuclear and Particle Physics Experiments, Springer

And finally I am in debt with countless colleagues. I acknowledge in particular Jim Cronin and Alan Watson for illuminating discussions on the history of CR detection. The foundation of all what I know about CR and detectors have been taught to me by Carlo Castagnoli and Gianni Navarra, now gone, but still alive for me.