School for Astroparticle Physics 2015
Obertrubach-Bärnfels, Germany

(Some) history of Cosmic Ray Research

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Definition of ‘History’

Oxford University:-

History began yesterday

Outline:-

- **The Early Days: discovery and demonstration that cosmic rays were charged particles**

- **The Discovery of Extensive Air-Showers**

- **Methods of Detection**
  The discovery and importance of Cherenkov Radiation
  The Fluorescence Technique

- **The Pierre Auger Observatory: history and recent results**

A unifying thread will be extensive air showers

No time to discuss role of cosmic rays in the development of particle physics

"Those who became interested in cosmic rays tended to be rugged individualists, to be iconoclasts, and to march to the drummer in their own heads rather than some distant one"

Val Fitch: Rev Mod Phys 71 S25 1999

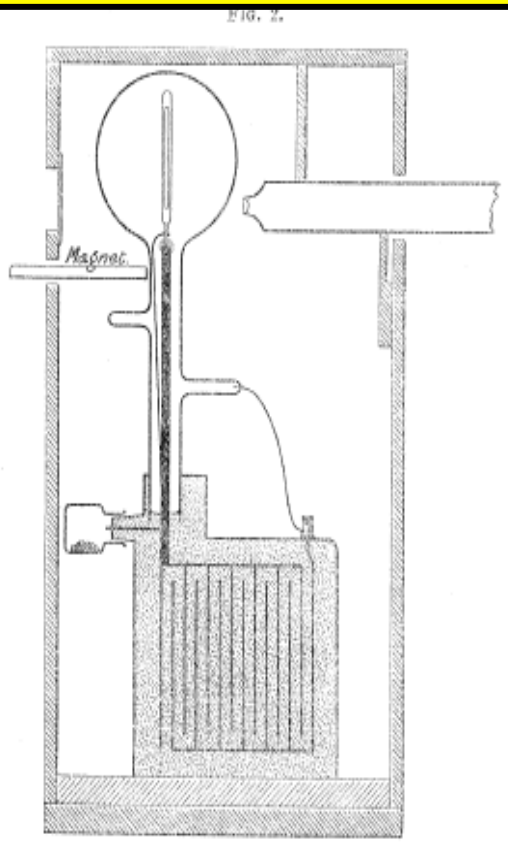
This article, and the one by Cronin (below), give good accounts of the role played by cosmic rays in the development of particle physics

J W Cronin, European Phys J H 36 183 2011; arXiv 1111.5328

See also
K-H Kampert and A A Watson, European Phys J H 37 359 2012; arXiv 1207.4823

Charles Augustin de Coulomb: 1785

Detector used in the first search for cosmic rays



C T R Wilson, Proc Roy Soc A 68 151 1901

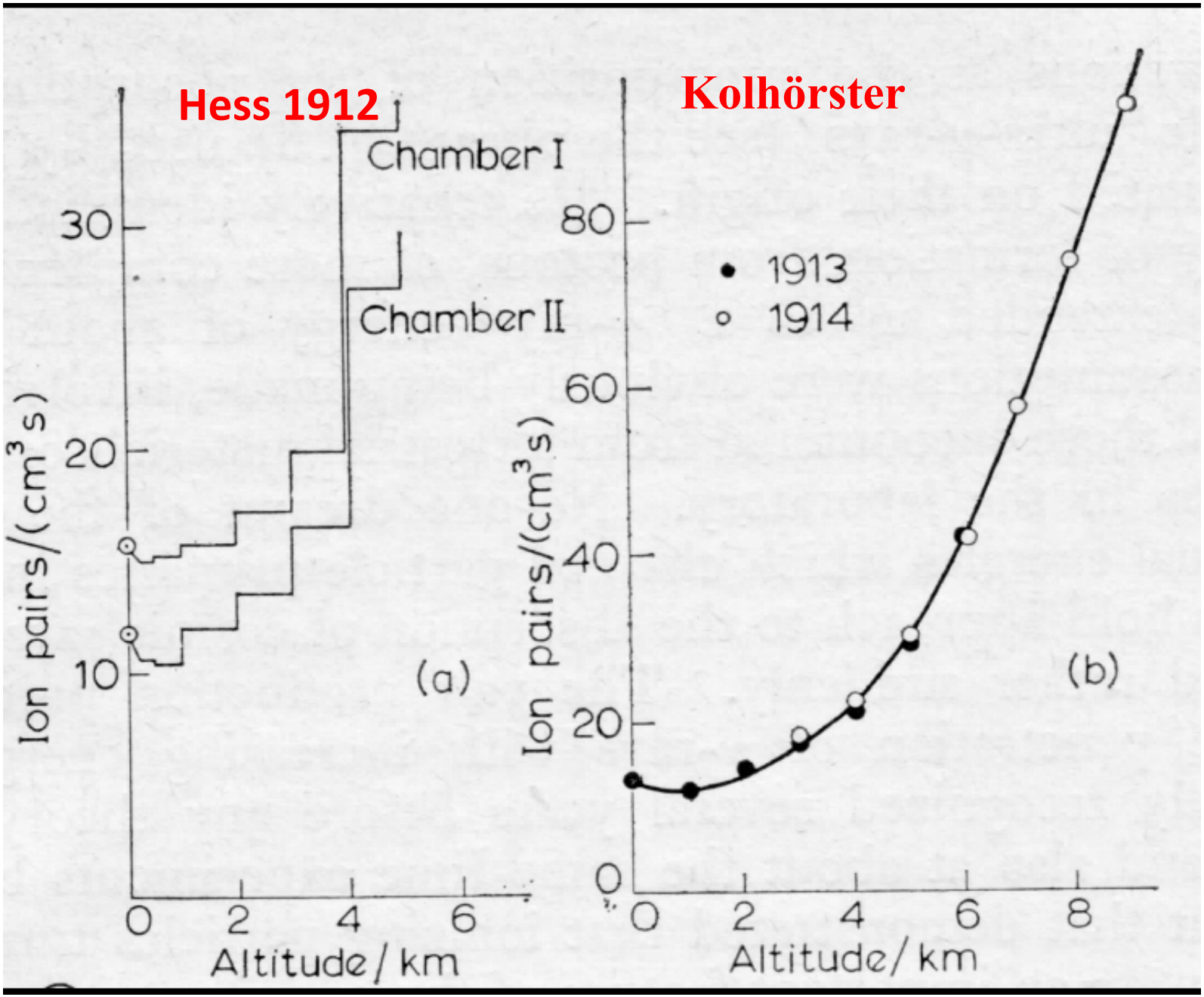
"the continuous production of ions in dust-free air could be explained as being due to radiation from sources outside our atmosphere, possibly radiation like Röntgen rays or cathode rays, but of enormously greater penetrating power"

Diplomarbeit Georg Federmann
Institut für Radiumforschung und Kernphysik
Wien, 2003

???????

Victor Hess at the balloon-landing (1912)

Aeronautisches Gelände im Wiener Prater, von dem aus V. F. Hess in den Jahren 1911/12 seine ersten Freiballon-Forschungsfahrten unternommen hatte. (Courtesy of Heeresgeschichtliche Museum, Vienna)



From J G Wilson 'Cosmic Rays', 1975

After WWI, research in cosmic rays was dominated by US physicists – particularly R A Millikan – for many years

Hess Phys Zeit 27 159 (1926)

Not pleased with Millikan

Zu der eingangs zitierten Veröffentlichung von A. Millikan möchte ich vorerst bemerken, daß er die Geschichte der Entdeckung der Höhenstrahlung in einer Weise darstellt, die Mißverständnisse hervorrufen könnte[3]).

1) Physik. Zeitschr. 13, 1084, 1912; Wien. Ber. IIa, 121, 2001, 1912.

2) Physik. Zeitschr. 14, 610, 1913; Wien. Ber. IIa, 132, 1053, 1913.

3) Die neuerliche Feststellung der Existenz und der hohen Durchdringungskraft der Höhenstrahlung durch Millikan und seine Mitarbeiter wurde von amerikanischen naturwissenschaftlichen Zeitschriften wie „Science", „Scientific Monthly" zum Anlaß genommen, um für die Höhenstrahlung die Bezeichnung „Millikan-Strahlen" vorzuschlagen. Da es sich hier nur um die Bestätigung und Erweiterung der Ergebnisse der von Gockel, von mir und von Kolhörster 1910 bis 1913 ausgeführten Strahlungsmessungen im Ballon handelt, ist diese Benennung als irreführend und unberechtigt abzulehnen.

Hess: Physik. Zeitschr. 27, 159, (1926)

As concerns the publication of Millikan, cited above, I would like to remark that he tells a story of the discovery of "hohenstrahlung" that could be easily misunderstood.

3) The recent determination by Millikan and his colleagues of the high penetrating power of "hohenstrahlung" has been an occasion for American scientific journals such as "Science" and "Scientific Monthly" to introduce the term "Millikan Rays". Millikan's work is only a confirmation and extension of the results obtained by Gockel, by myself, and by Kolhörster from 1910 to 1913 using balloon borne measurements of the rays. To refuse to acknowledge our work is an error and unjustified.

Slide from Jim Cronin

Erich Regener – a forgotten cosmic-ray pioneer

Per Carlson and Alan A.Watson

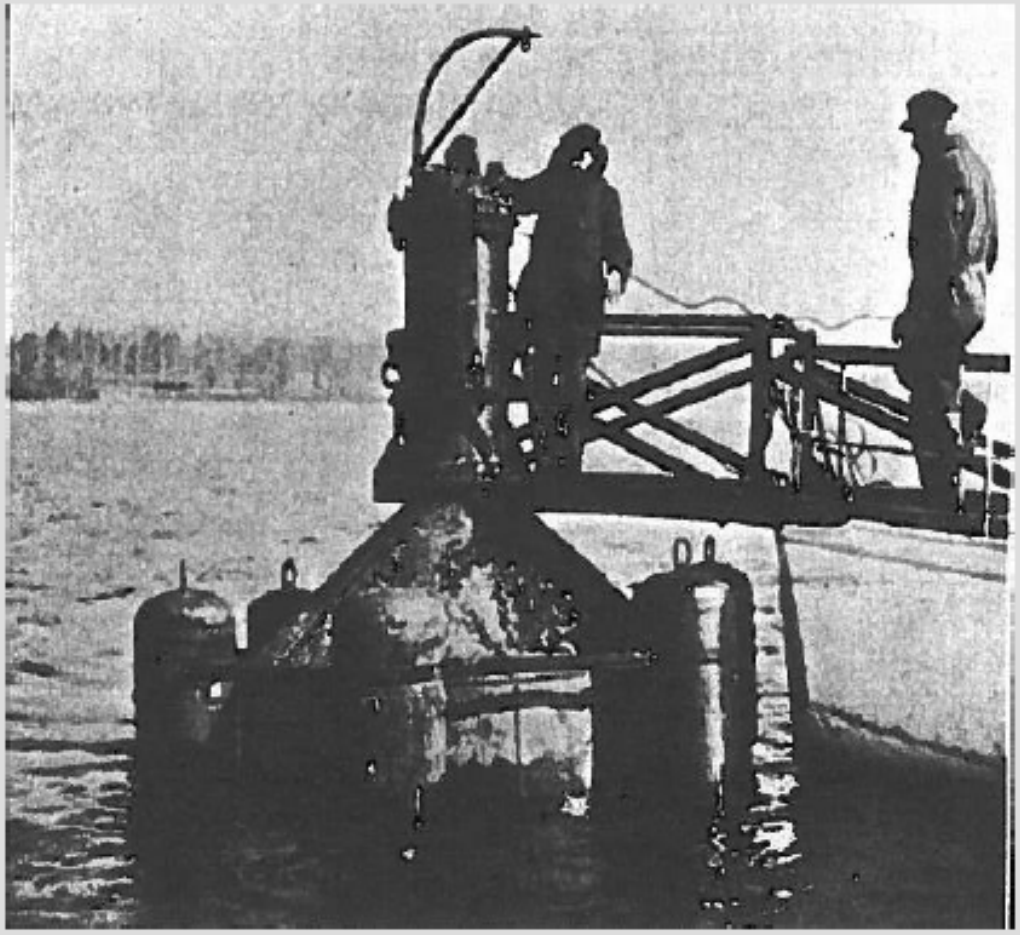
see also Hist. Geo. Space Sci 5 pp 1-8 2014

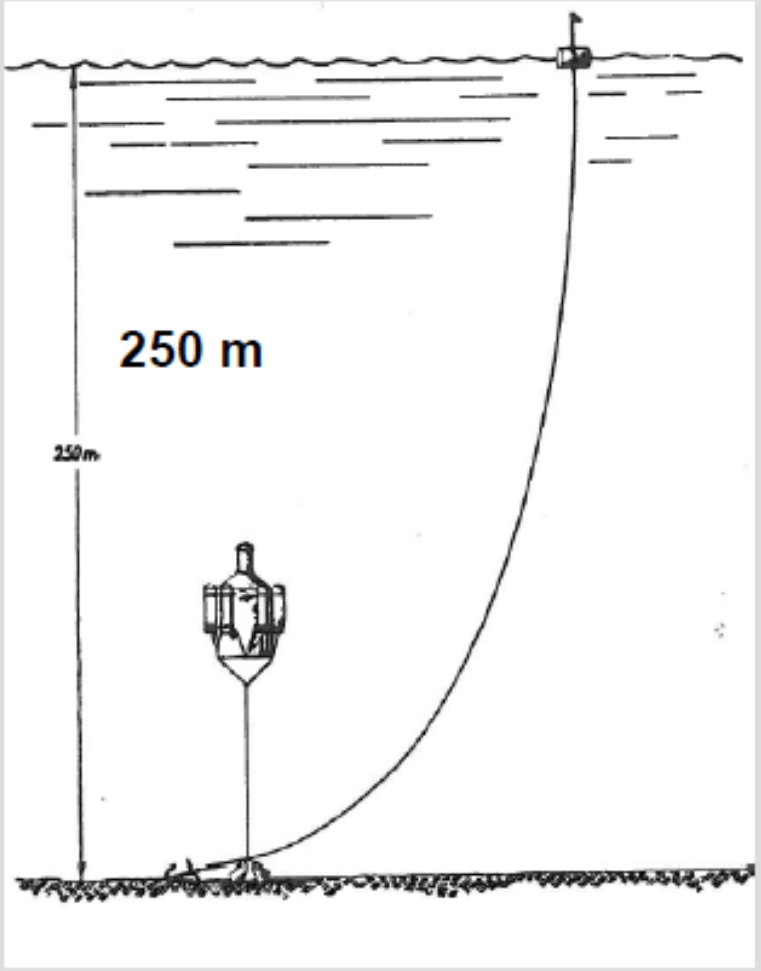
Born West Prussia 1881
Full prof. Technical univ. Stuttgart 1920
"Provisional retirement" 1937
Return to Stuttgart 1946
Vice president, Max Planck Society 1948
Retired 1951
Died 1955, 73 years old

Excellent contributions to cosmic-ray physics, in particular atmospheric ionisation

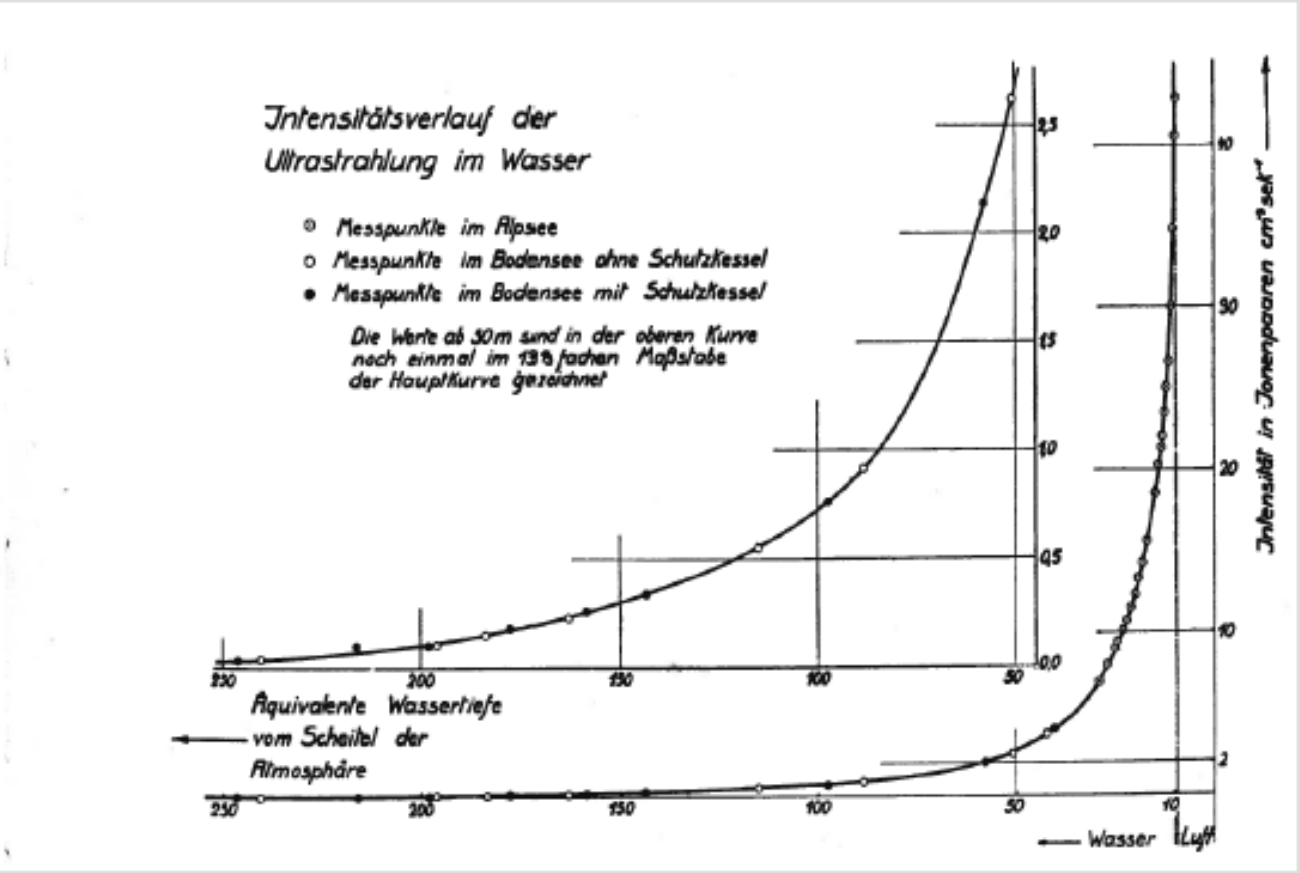
APS April meeting 2013, Denver

Lake Constance (Bodensee) in early 1930s





Regener reached a depth of over 230 m and observed a continous decrease of the radiation. Millikan had stated that between 57 and 67 m depth there was no further decrease.



Ion pairs $cm^{-3}s^{-1}$

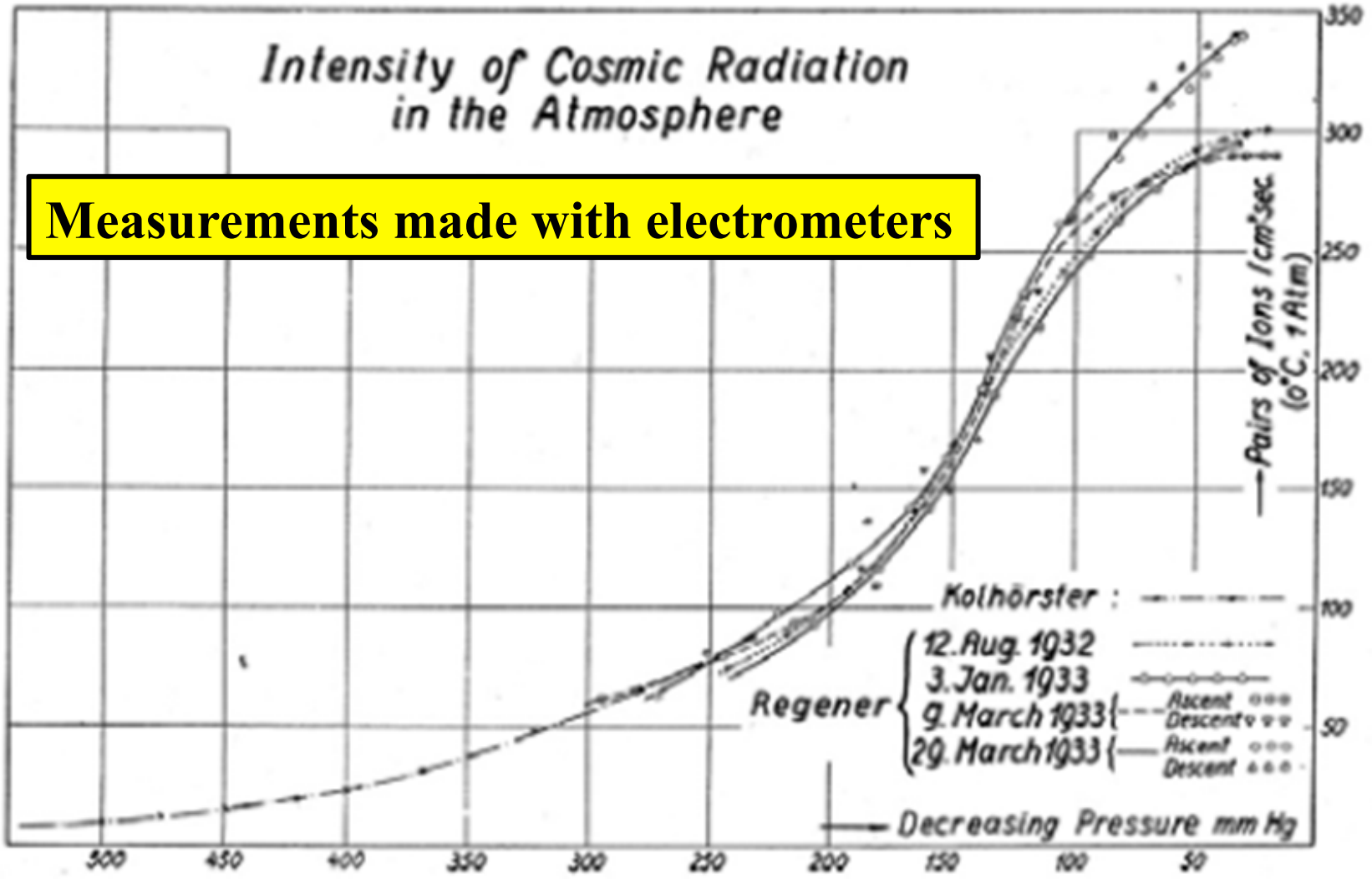
Depth (m)

During the 1930s, Regener greatly extended the observations of Hess, Kolhörster, Millikan and others

– his work indirectly led to searches for air-showers

Rutherford (1931):
'Thanks to the fine experiments of Millikan and the even more far-reaching experiments of Regener we now have a curve of the absorption of these radiations in water and in air that we may safely rely upon'

Photo from article by Rossi 1985



Ion pairs cm^{-3} s^{-1}

Decreasing Pressure of mercury

Regener's data from flights in 1932 and 1933

Regener: Nature 131 130 1933 – based on similar, earlier, work

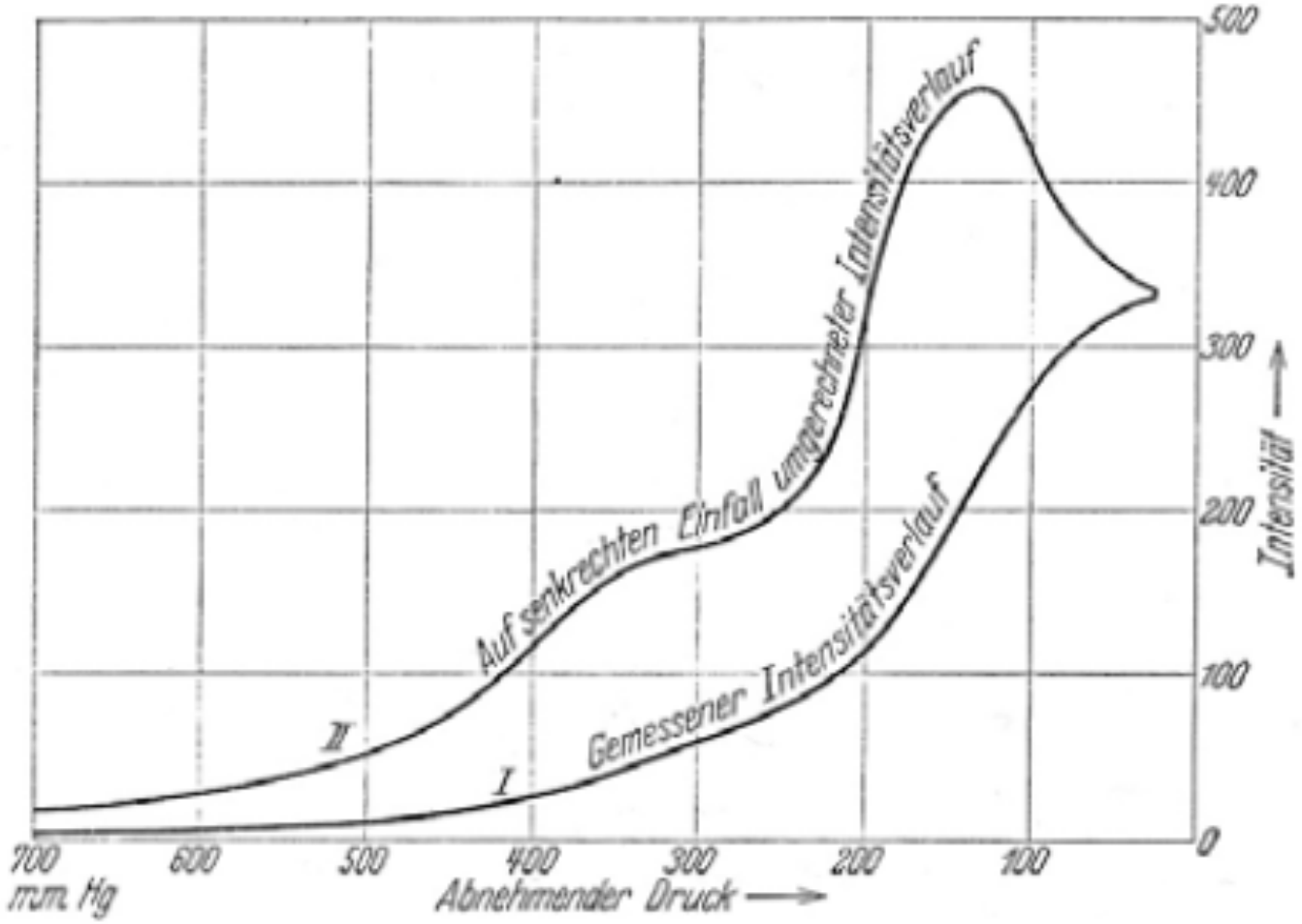
The graphical integration of the curve, giving the ionisation as a function of the height, makes it possible to calculate the total number of ions, produced by total absorption of cosmic rays by a column of air of 1 sq. cm. section. The [illegible] $1{\cdot}02 \times 10^8$ pairs of ions is found. Millikan and Cameron [illegible] which gave a [illegible] due to [illegible] in the [illegible] required to produce [illegible] electron-volts the fluctuation [illegible] the earth from the cosmic rays [illegible] $5{\cdot}2 \times 10^{-3}$ erg. cm.$^{-2}$ sec.$^{-1}$.

From the astrophysical point of view, the great energy of cosmic rays is remarkable. A body which

Used by Baade and Zwicky in famous paper suggesting that cosmic rays were produced by supernovae

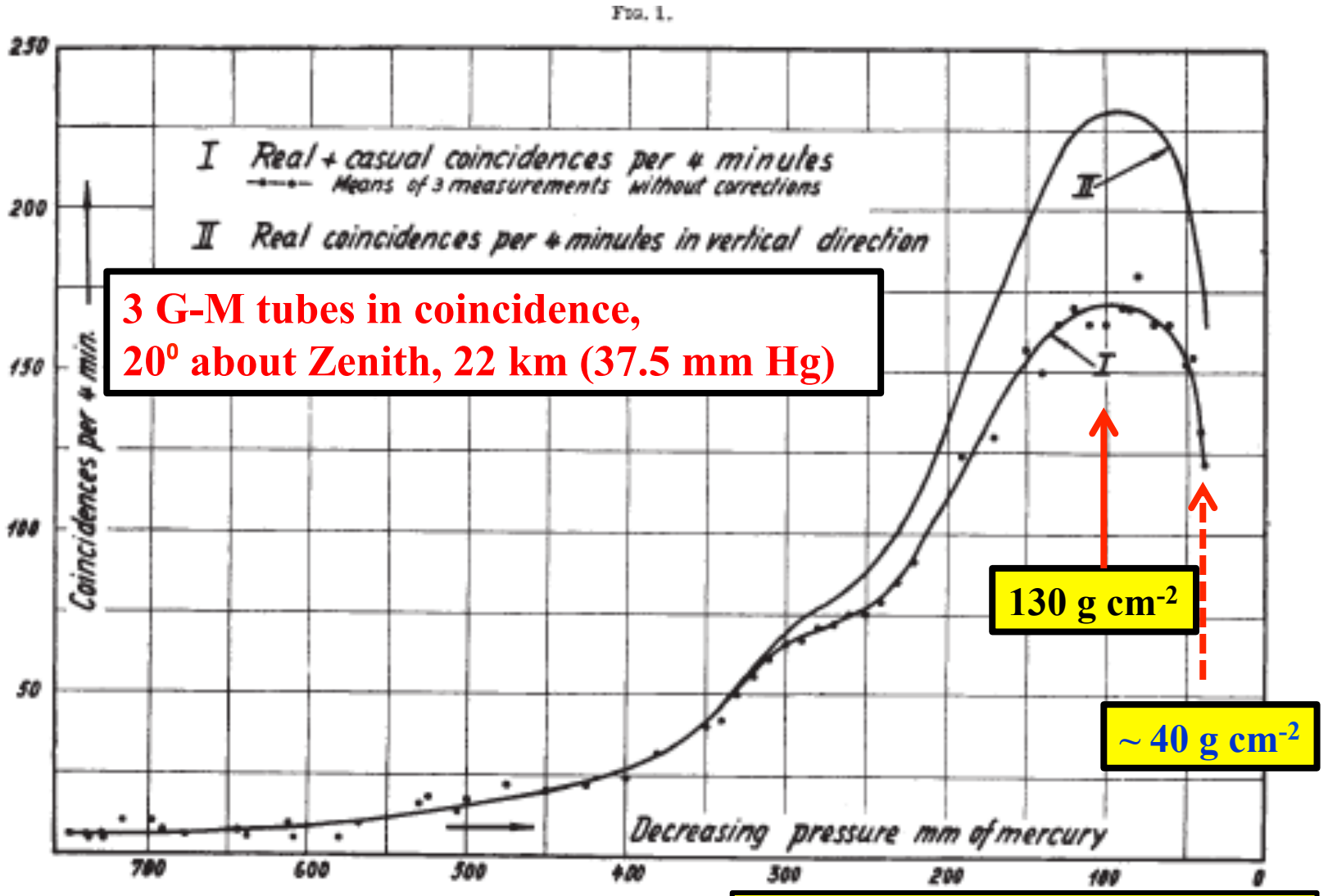
Proc Nat Acad Sci 20 259 1934

Energy Density in Cosmic Rays = 0.11 eV cm^{-3}



Gross (1933) analysed data to show that there was a maximum of ionisation production at about 130 mm Hg (170 g cm^{-2})

I – Measured; II – Converted to Vertical ionisation distribution



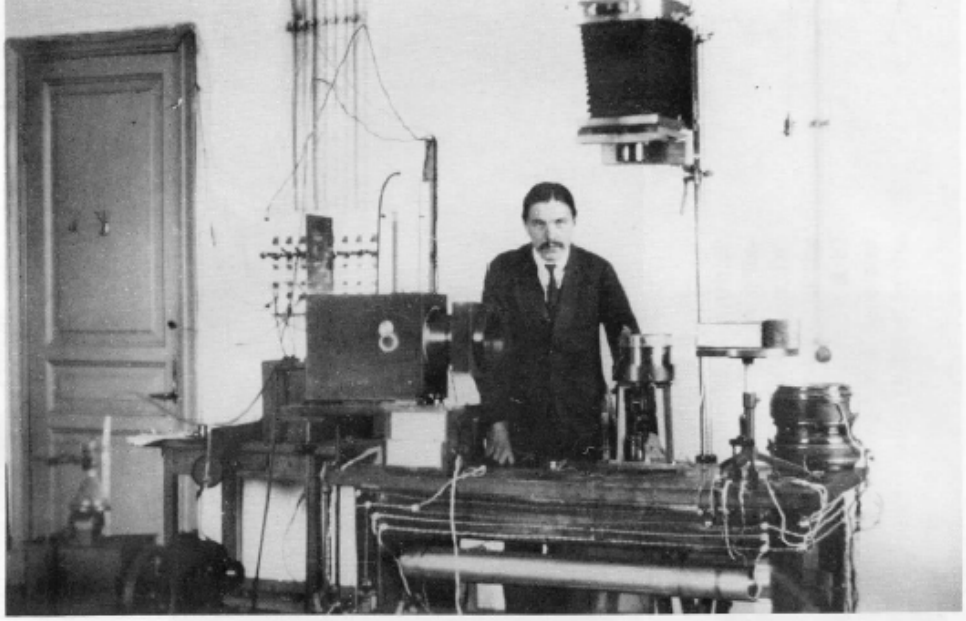
Regener and Pfotzer:
Nature 136 718 1935

'Pfotzer Maximum' ???
Papers in 1936
At least, the 'Regener-Pfotzer Maximum'

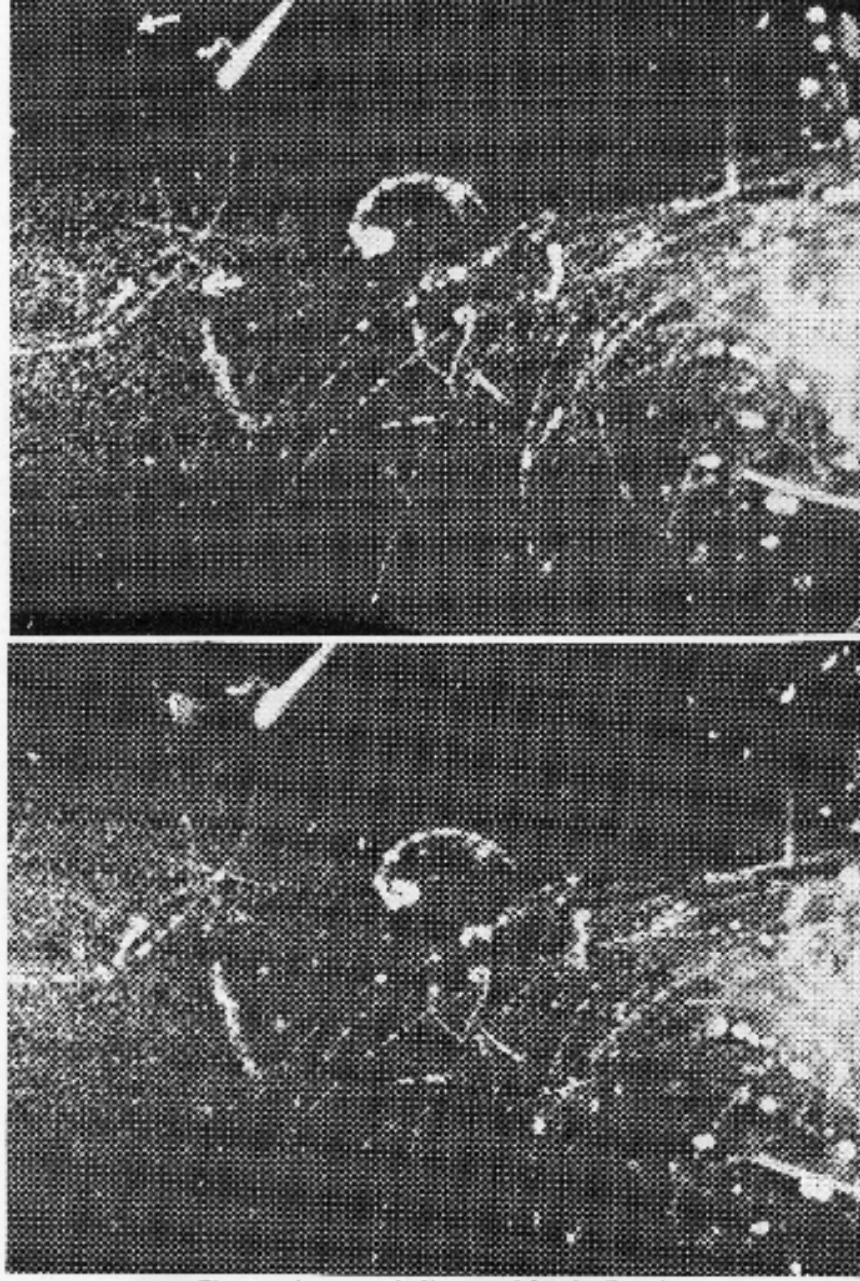
Up until the early 1930s there was debate – often heated – as to whether cosmic rays were 'waves' or 'corpuscles': Regener favoured the wave hypothesis

Fig. 20. With Eric Regener and Lise Meither on the Bodensee, in a motorboat equipped for under water experiments. Regener had baptized the boat "Undula "to reaffirm his faith in the wave nature of cosmic rays. Here, following a discussion on this subject, he was telling me: "If it turned out that you are right, I would have to rename my boat "Korpuskel," which does not sound as nice as "Undula"!"

Rossi 1985



1924 – "Stone age" of the nuclear physics. The first observations of the Compton-effect of γ-rays with a cloud-chamber in a magnetic field (about 1000 gauss).



The cosmic-ray track discovered for the first time.

<Ed> Contributed by D. V. Skobeltzyn. See p. 47. This stereoscopic pair of photos published in *Zs. f. Physik*, 43, 363, Fig. 12 in 1927. The track is indicated by a black (two white arrows. H = 1030.

In the 1920s, the cloud chamber had not been used in the study of cosmic rays

The sensitive time was ~ 1/100 s

But a remarkable picture was taken by Skobeltzyn in 1927 during a study of the Compton Effect

By chance he observed a high-energy cosmic ray adding weight to corpuscular ideas

Bothe and Kolhörster then carried out a series of beautiful experiments that aimed to distinguish between the two hypotheses

They used the Geiger counters and a photographic method of recording coincidences

Key work by Bothe and Kolhöster (1929):
- established corpuscular nature of radiation

"Unfortunately, the collaboration with Geiger came to an end in 1925, when Geiger was called to Kiel University. When dividing up the field on which we had hitherto worked together, the coincidence method was, at Geiger's generous suggestion, allocated to me."

Bothe, Nobel Prize Address (1954)

Dr. Werner Kolhörster im Jahre 1912.

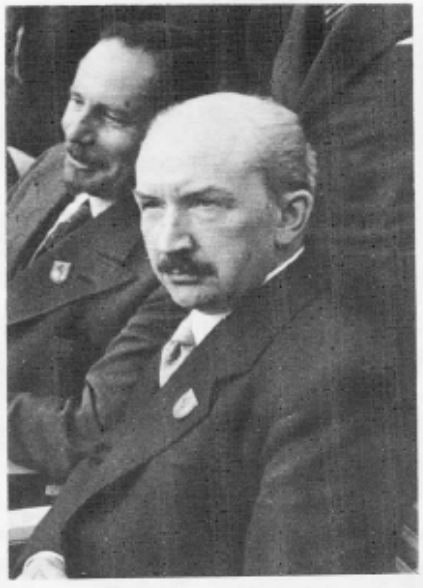
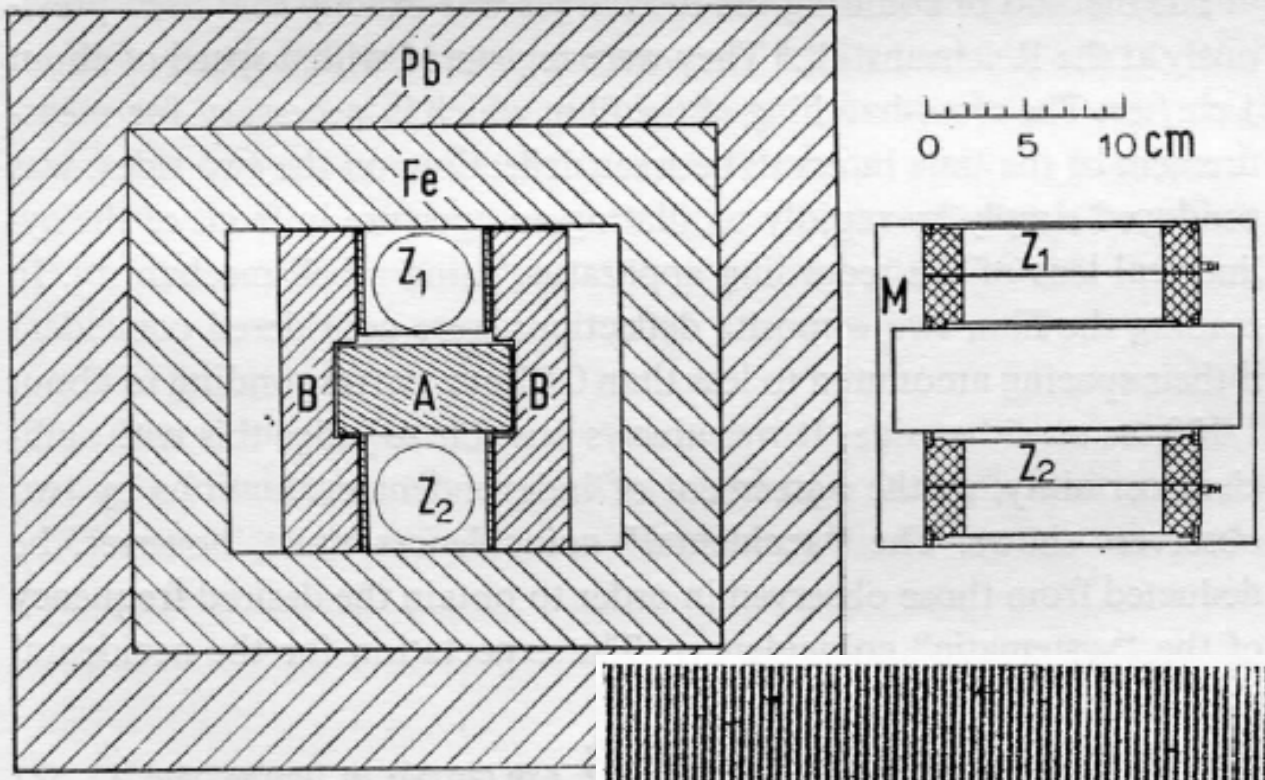


Fig. 2. Professor Walter Bothe (1891–1957) (right), Nobel prize winner 1954, (coincidence method and discovery of artificial nuclear gamma radiation) and Professor Erich Regener (1881–1955) at a meeting in 1937. (Courtesy of Max-Planck-Institut für Kernphysik, Heidelberg).



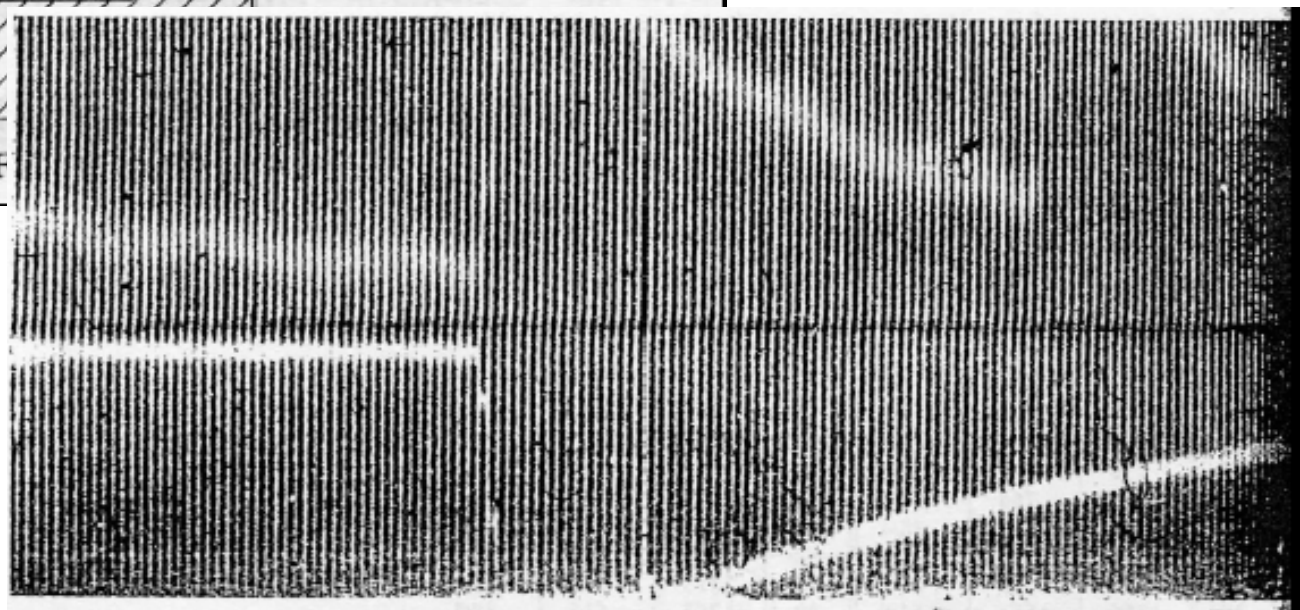


Fig. 7. Beispiel einer Koinzidenz. Streifenabstand $^1/_{1000}$ Sekunde. Oben e-Ausschläge, unten $h\nu$-Ausschlag.

A second way of establishing 'corpuscular' or particle nature:-

Study cosmic-ray intensity as function of latitude

1927: Observations by Clay between Netherlands and Dutch East Indies
Showed decrease of several percent near Suez Canal

1928: Millikan et al had not discovered any significant change between Bolivia (19^0 S) and Pasadena (34^0 N) nor between Pasadena and Churchill, Canada (59^0 N)

1928: Bothe and Kolhörster found no variation with latitude in North Sea - but this did not deter them from acknowledging Clay's work

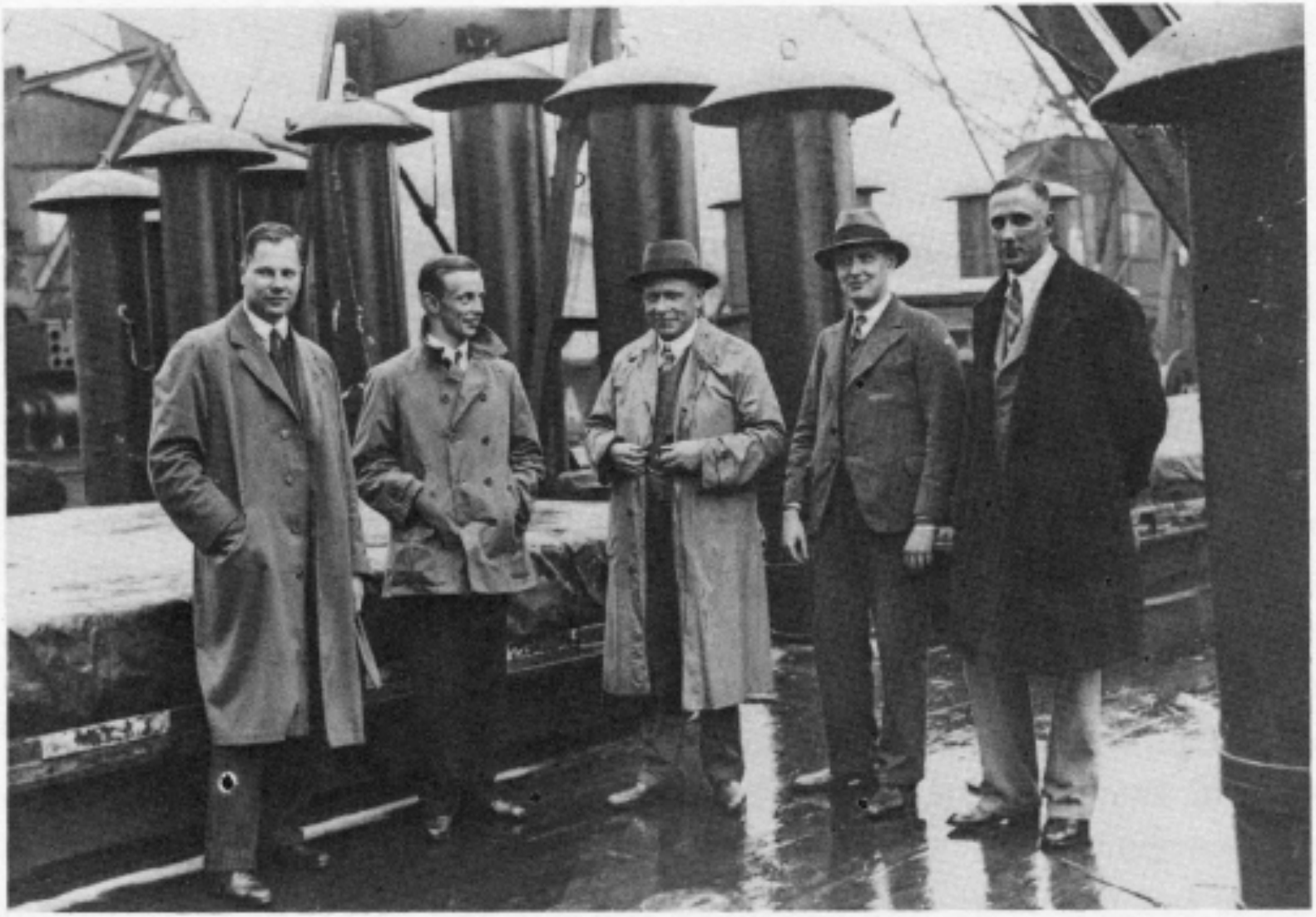
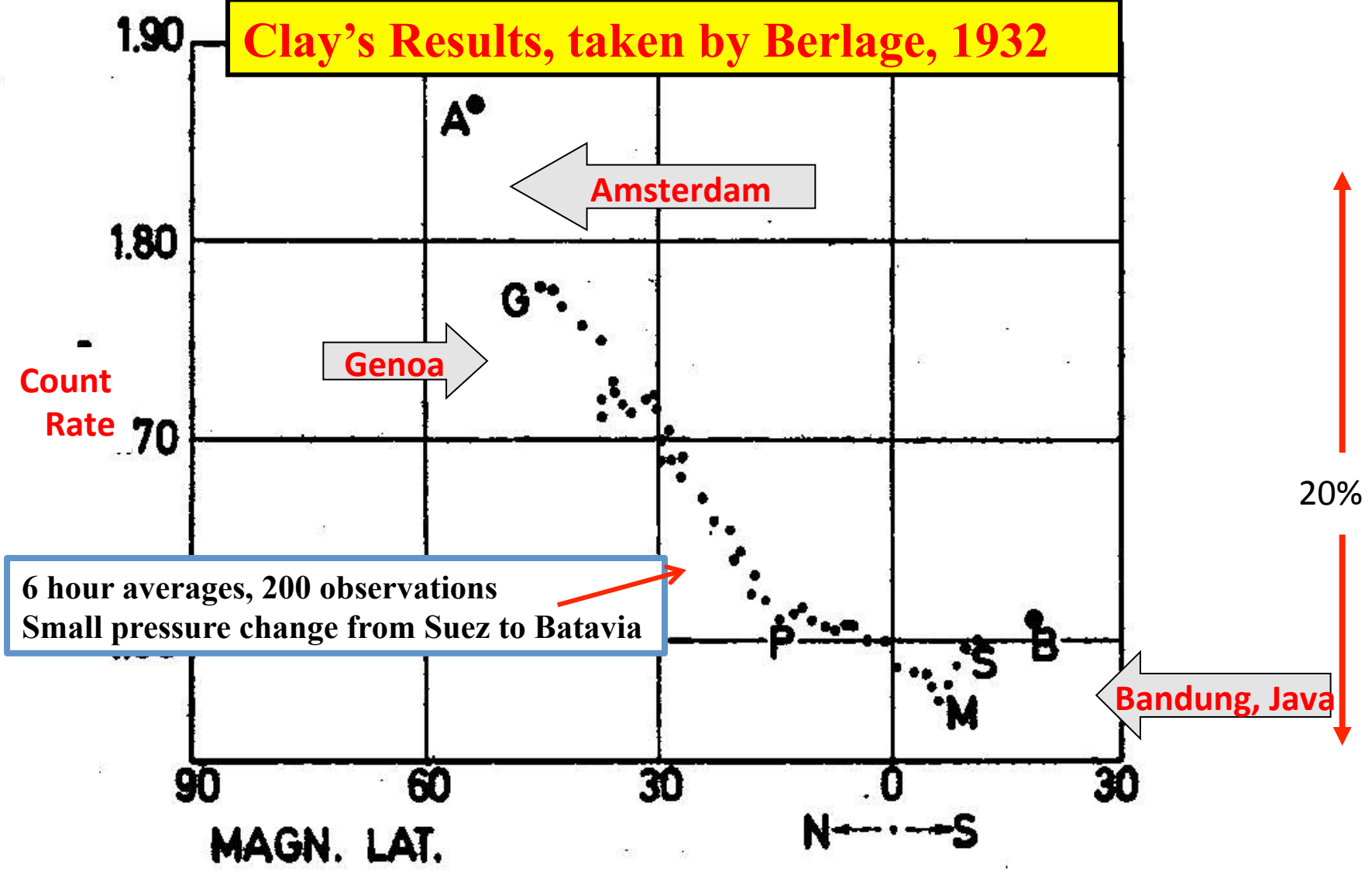


Fig. 12. Jacob Clay (middle) and his collaborators before their departure on a cosmic ray research trip by boat to the East Indies.

Source: Physics in Amsterdam: A Brief History, A J Knox 1990



Counting Rate at sea-level as a function of the position of the ship with respect to the earth's magnetic field which is nearly horizontal at the earth's equator

Ionisation Chambers provided by Steinke: hourly observations

Millikan did not believe the results of Clay and there was in general doubt about them as others had not replicated his data - though on shorter voyages and over more limited latitude ranges

Early 1932: Arthur Compton: mounted major expeditions to study this problem

***Betty Compton*: Chicago 1931**

"I remember going without a winter coat so that we could do some of the preliminary research at Chicago because at the moment they didn't think cosmic rays were anything that was very vital".

FIG. 1. Map showing location of our major stations for observing cosmic rays.

Compton Phys Rev 43 387 1933: World-wide survey involving > 60 scientists

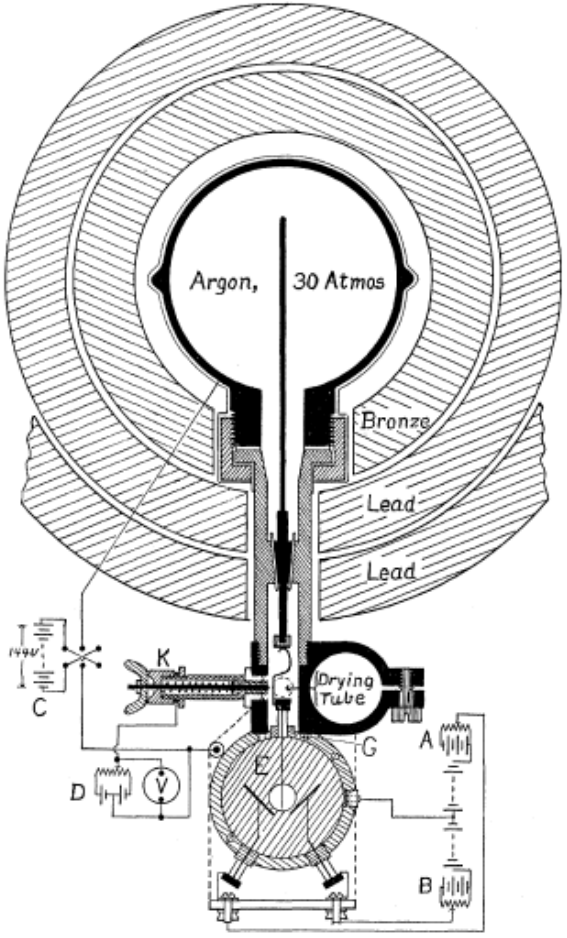
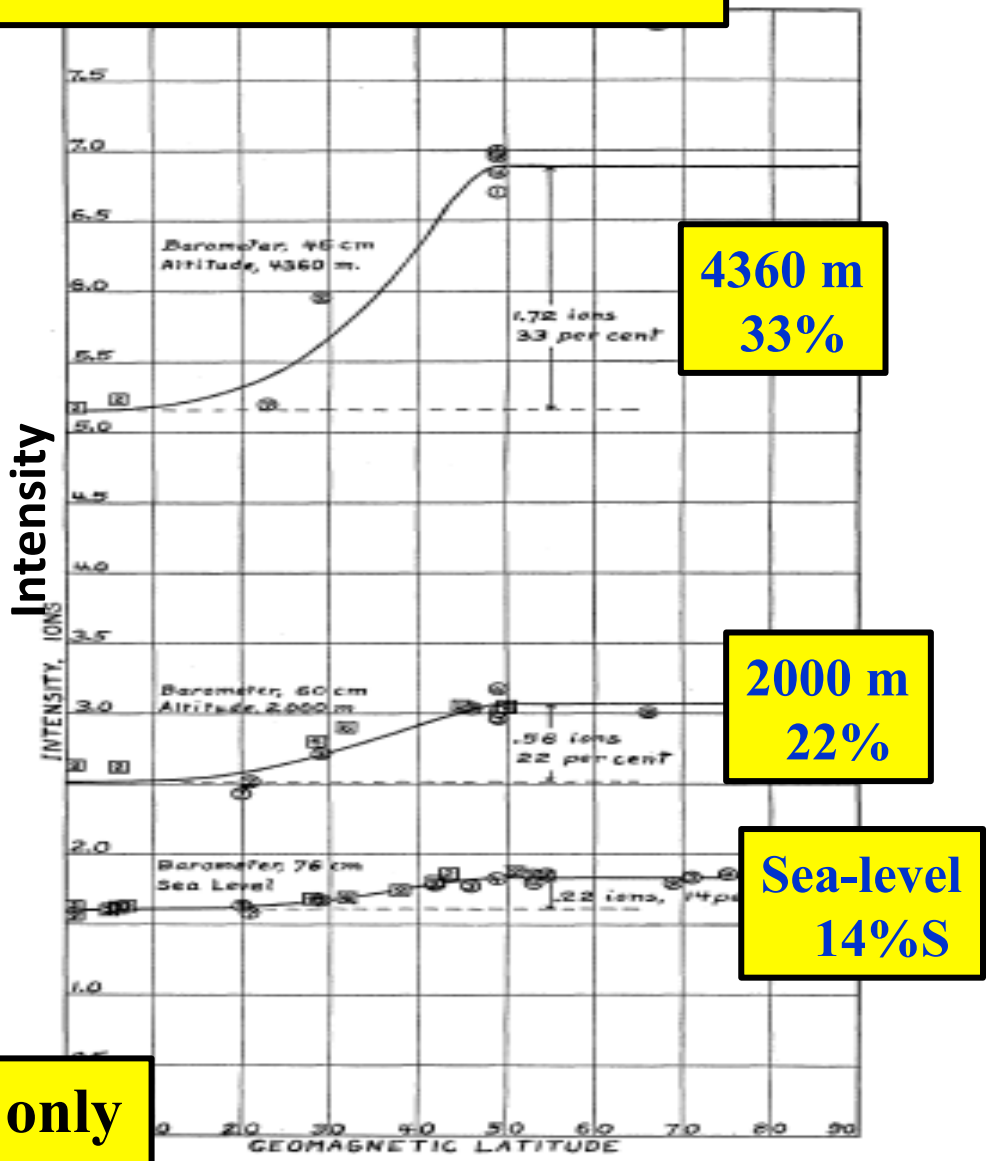


FIG. 2. Cosmic-ray ionization chamber, electrometer, and electrical connections



Geomagnetic Latitude

Two people lost their lives – but only Compton signed the paper!

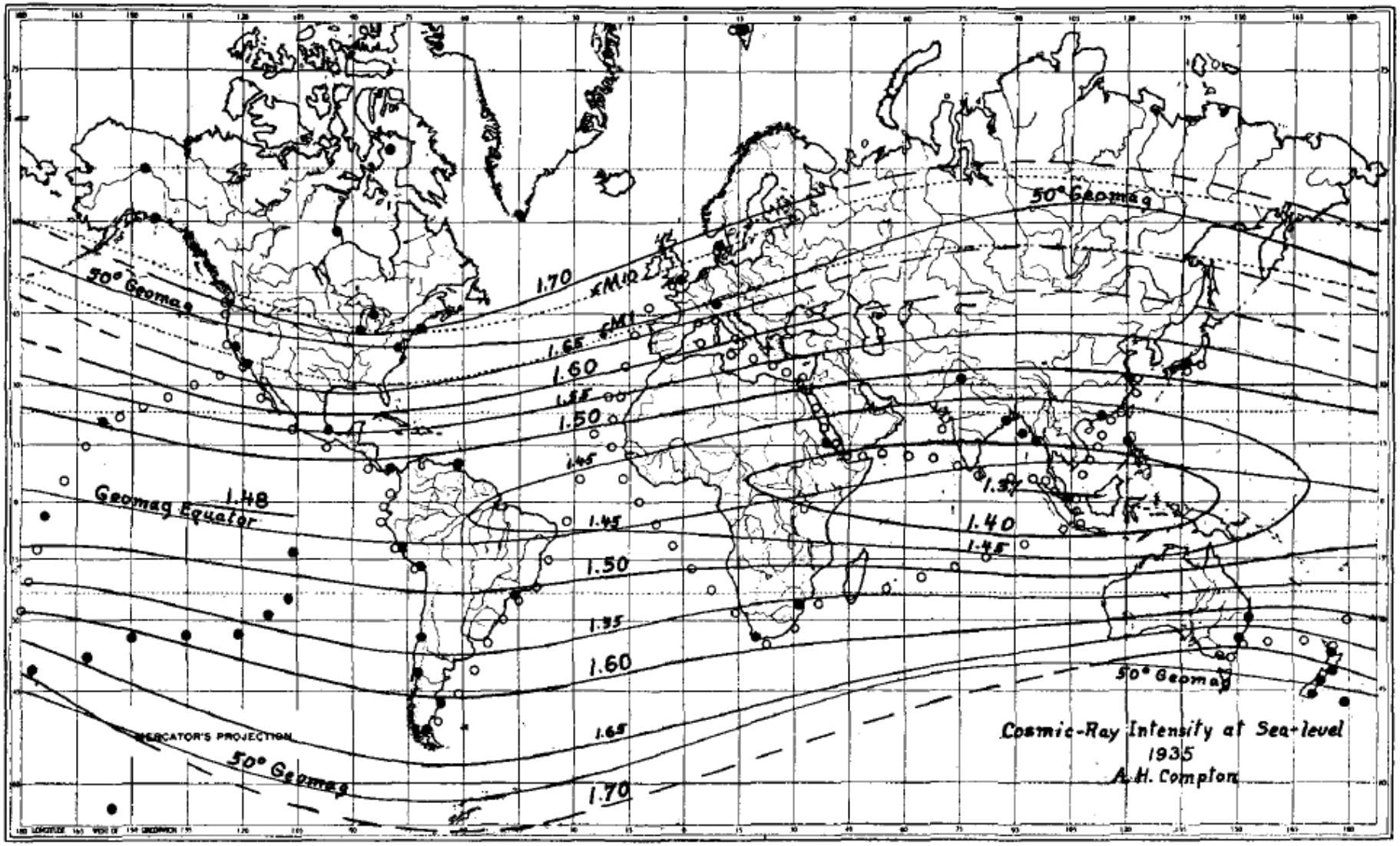


FIG. 1. Curves of equal cosmic-ray intensity (isocosms), showing approximate parallelism with parallels of geomagnetic latitude and with curves of equal auroral frequency (M1 and M10).

'Isocoms' as reported by A H Compton, Rev Sci Inst 7 70 1936

Report by William Lawrence: NYT 1932

The New York Times

VOL. LXXXII...No. 27,370. December 31,1932

MILLIKAN RETORTS HOTLY TO COMPTON IN COSMIC RAY CLASH

Debate of Rival Theorists Brings Drama to Session of Nation's Scientists.

THEIR DATA AT VARIANCE

New Findings of His Ex-Pupil Lead to Thrust by Millikan at 'Less Cautious' Work.

In an atmosphere surcharged with drama, in which the human element was by no means lacking, the two protagonists presented their views with the vehemence and fervor of those theoretical debates of bigone days when learned men clashed over the number of angels that could dance on the point of a needle. Dr. Millikan particularly sprinkled his talk with remarks directly aimed at his antagonist's scientific acumen. There was obvious coolness between the two men when they met after the debate was over.

H. Hoerlin, Nature 132 61 1933 - a PhD student of Regener

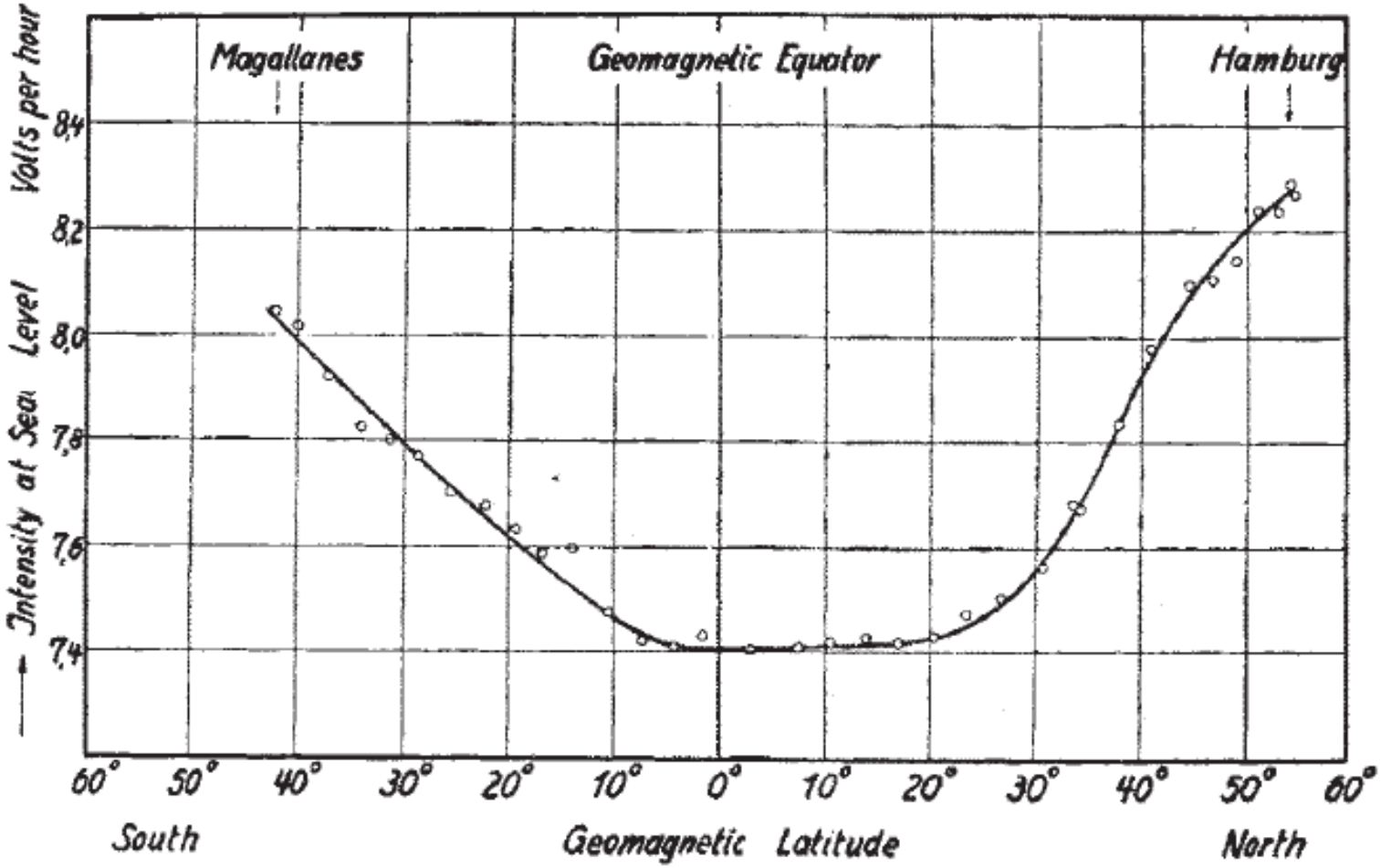
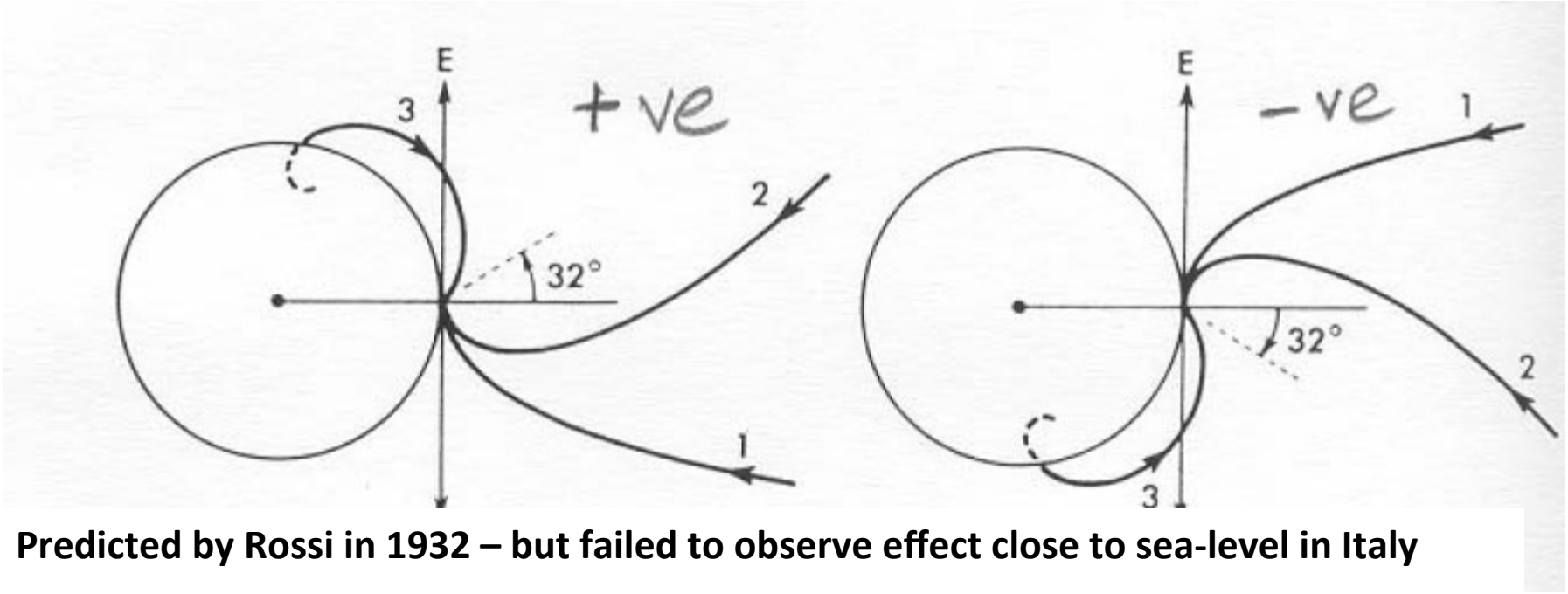


FIG. 1.

Also measurements between Europe and Buenos Aires by Leprince-Ringuet and Auger

East-West Effect: **Positive and negative particles in plane of geomagnetic equator. B-field is out of paper.**
Rossi extracted essence from Störmer's papers

From Rossi 'Cosmic Rays' (1964): see also Rossi Phys Rev 1932 BUT his predictions ignored



Predicted by Rossi in 1932 – but failed to observe effect close to sea-level in Italy

1933: Johnson, and Compton and Alvarez found effect in Mexico City, 2250 m
de Benedetti and Rossi in Eritrea, 2370 m above sea-level

10% effect
– the particles are dominantly positively charge: protons or e+?

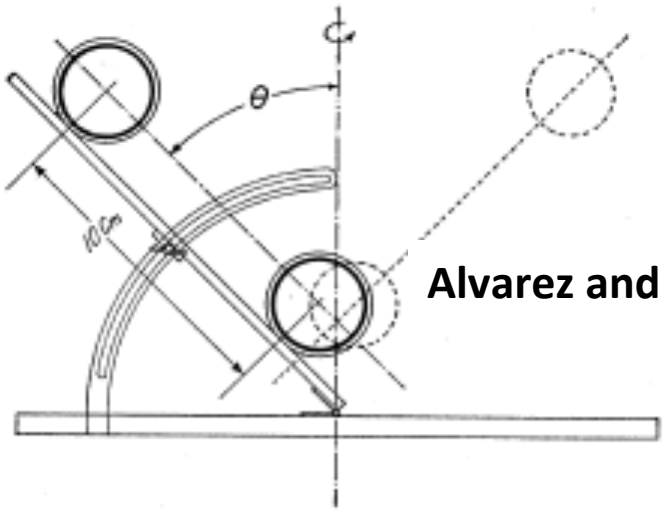


FIG. 1. Arrangement of coincidence counting tubes for studying East-West asymmetry of cosmic rays.

Alvarez and Compton

TABLE I. *East-west measurements at Mexico City, April, 1933.*

Geomagnetic latitude 29°N, elevation 2310 m, barometer, 56.5 cm.

Zenith angle		West	East	West/East
15°	Counts	5370	4856	
	Rate	6.83±0.07	6.64±0.07	1.03±0.02
0°	Counts	4897	4869	
	Rate	5.79±0.06	5.49±0.06	1.055±0.015
45°	Counts	2691	2693	
	Rate	3.70±0.05	3.30±0.05	1.12±0.02

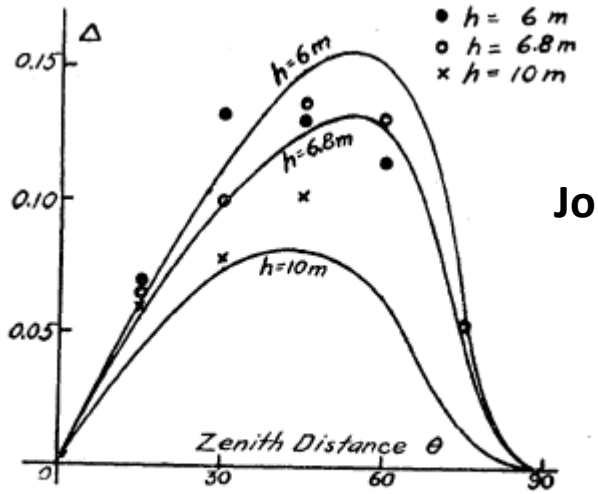


FIG. 1. Calculated and observed asymmetries for three elevations on the magnetic equator.

Johnson

TABLE I. *Measurement of the azimuthal effect at different zenith angles.*

Rossi

z	Direction	Total counts	Rate (min.$^{-1}$)	W/E ratio
(a) counters unshielded. $d = 6.5$ cm^9				
45°	W	4734	5.01±0.052	
45°	E	4078	4.32±0.049	1.161±0.017
(b) counters shielded, 16 mm lead+2 mm brass. $d = 12$ cm				
45°	N	2516	1.39±0.02	
45°	W	2669	1.47±0.02	
45°	S	2446	1.35±0.02	
45°	E	2246	1.24±0.02	1.188±0.022
30°	W	4290	2.08±0.022	
30°	E	3710	1.80±0.021	1.157±0.018
15°	W	3962	2.48±0.028	
15°	E	3570	2.23±0.026	1.11±0.018

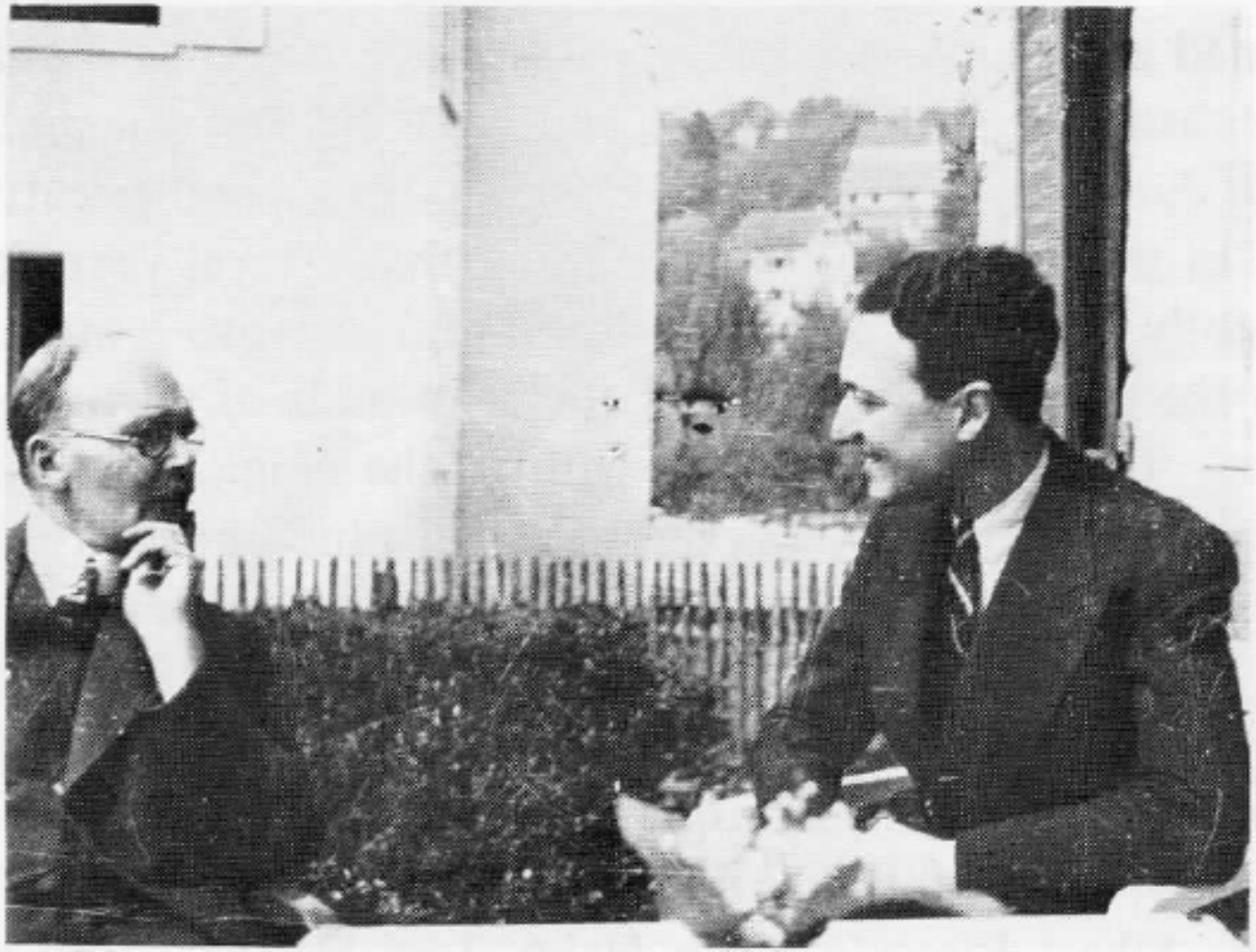


Fig. 12. With Professor Hans Geiger in Tübingen.

Rossi's work: Coincidence Circuit, Nature 125 636 1930

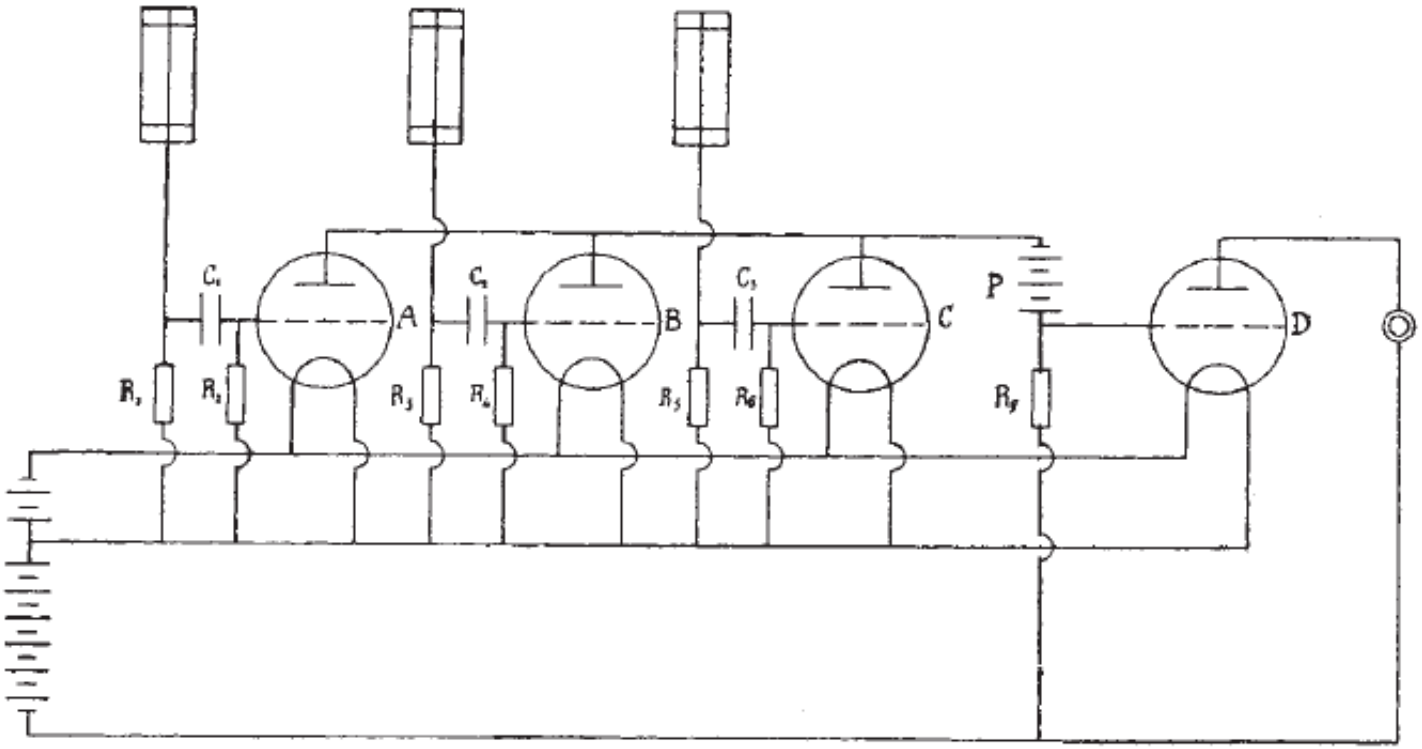
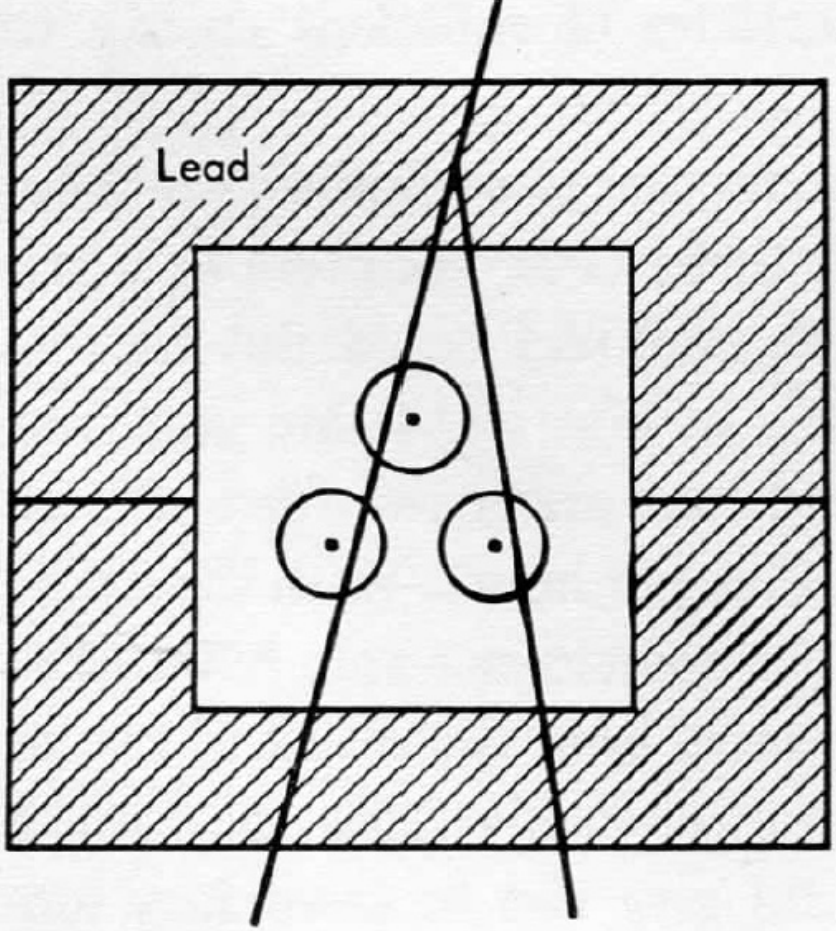


FIG. 1.

It appears that the triple coincidences method is the only one available for studying the form of the paths of cosmic rays, and I mean to employ it in experiments on the magnetic deviation of these radiations.

BRUNO ROSSI.

Physical Institute of
the University of Florence,
Arcetri, Italy, Feb. 7.



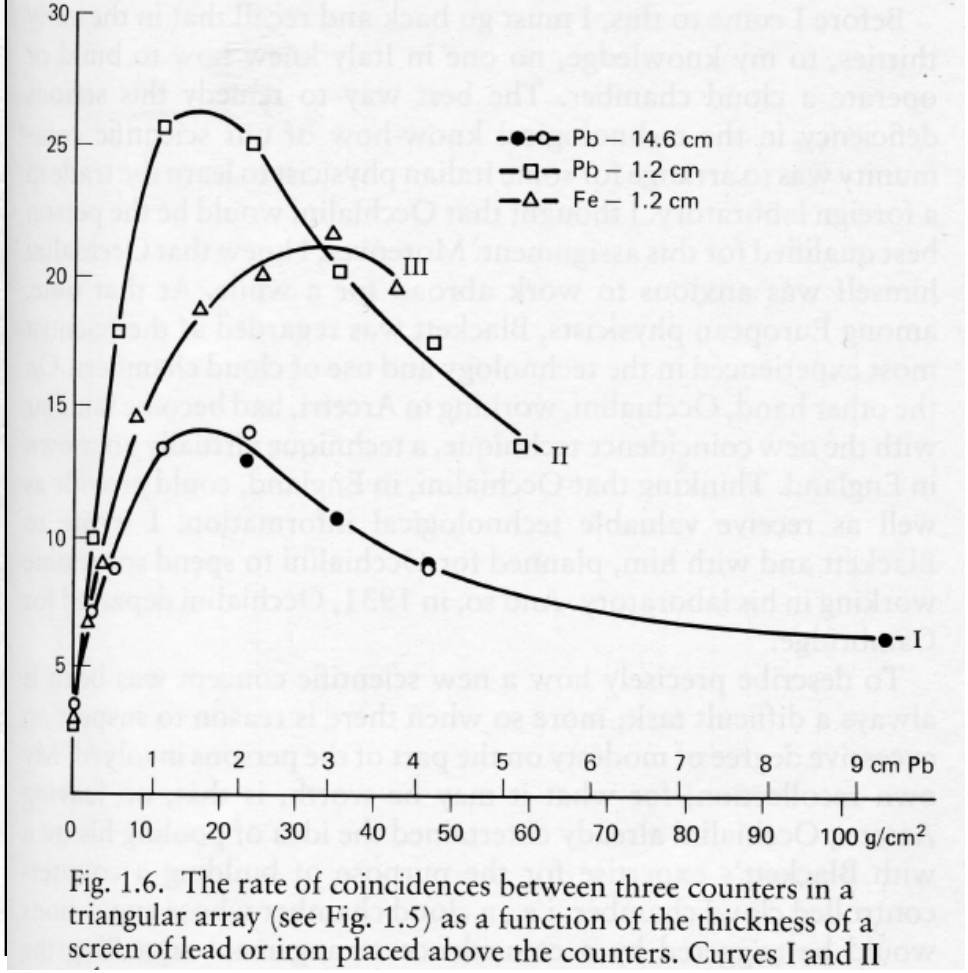


Fig. 1.6. The rate of coincidences between three counters in a triangular array (see Fig. 1.5) as a function of the thickness of a screen of lead or iron placed above the counters. Curves I and II

Rossi 1932: Coincidence rate much higher with top lead blocks (~ 10 cm thick) in place

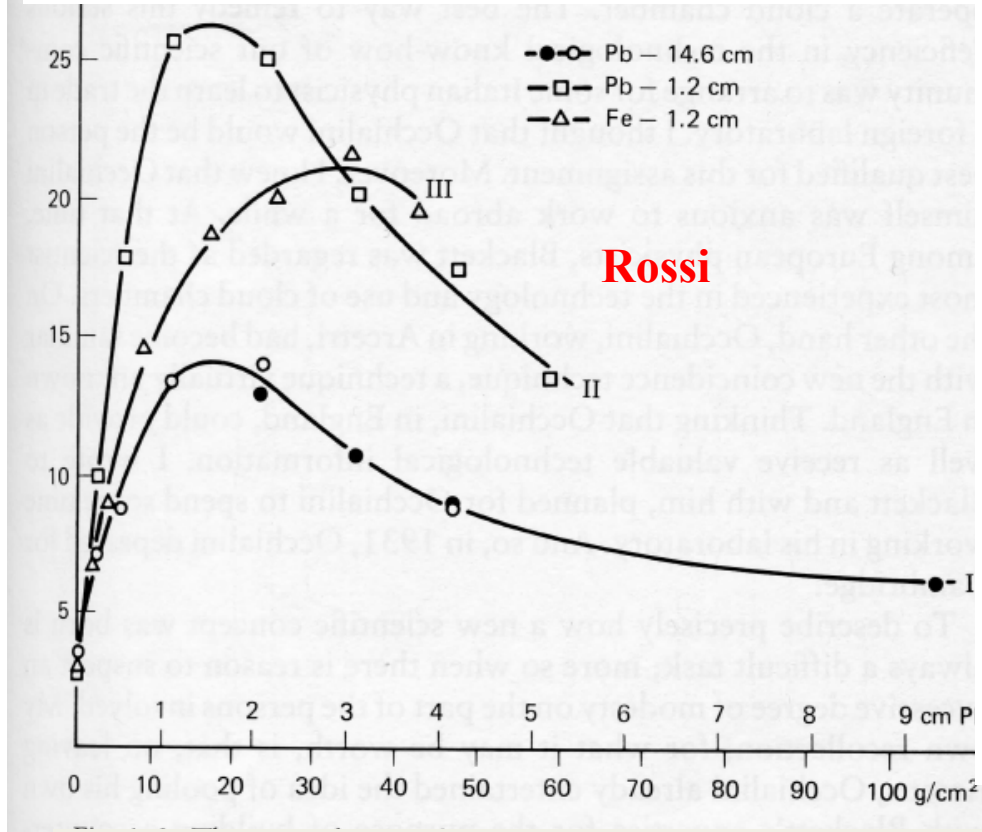
Rossi 1933: Zeitschrift für Physik

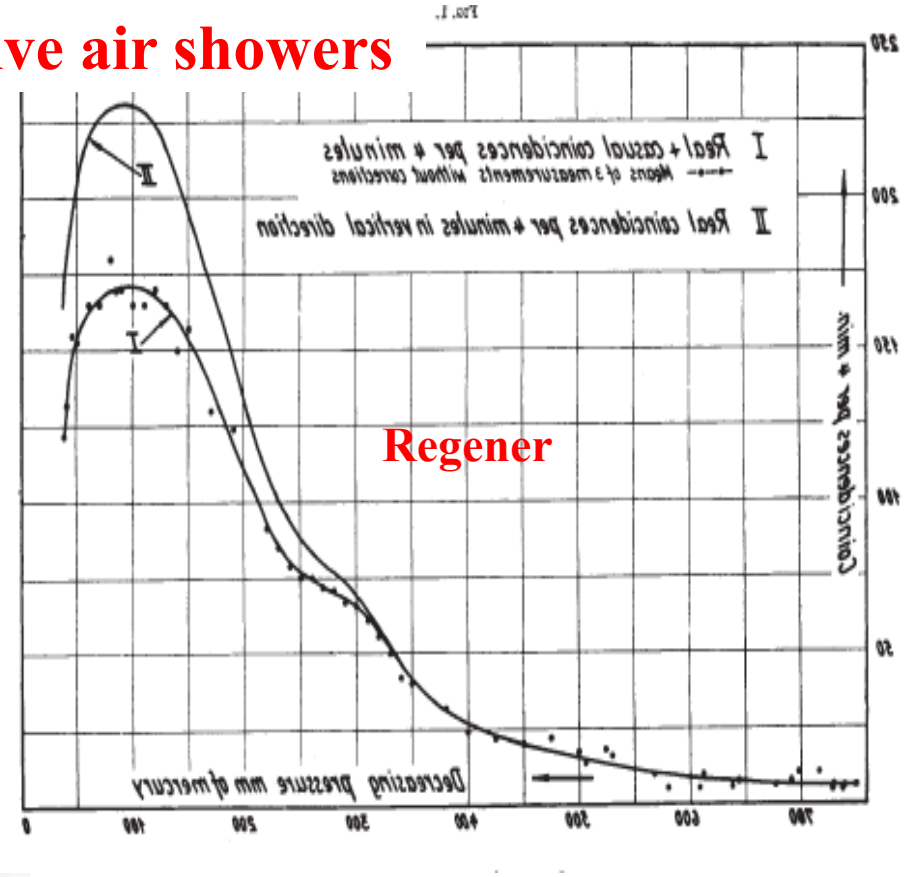
Rejected by Naturwissenschaften

Rossi Transition Curves

With support of Heisenberg, published in Physikalische Zeitschrift

Prediction and discovery of extensive air showers





The idea of an air-shower was discussed in the mid-1930s by Bothe and Schmeiser and they, Kolhöster et al., and Auger reported relevant observations in 1938. **'Luftschauer'**
Also, in interpreting the work of Regener, Bethe and Heitler (1937) reached similar conclusions from a theoretical position.

- but Rossi had beaten everyone by about 4 years

Rossi's translation of part of his 1934 paper (1990):

(Rossi: La Ricerca Scientifica 1934)

"The frequency of coincidences .....appears to be greater than would have been predicted from the resolving power of the coincidence circuit.....

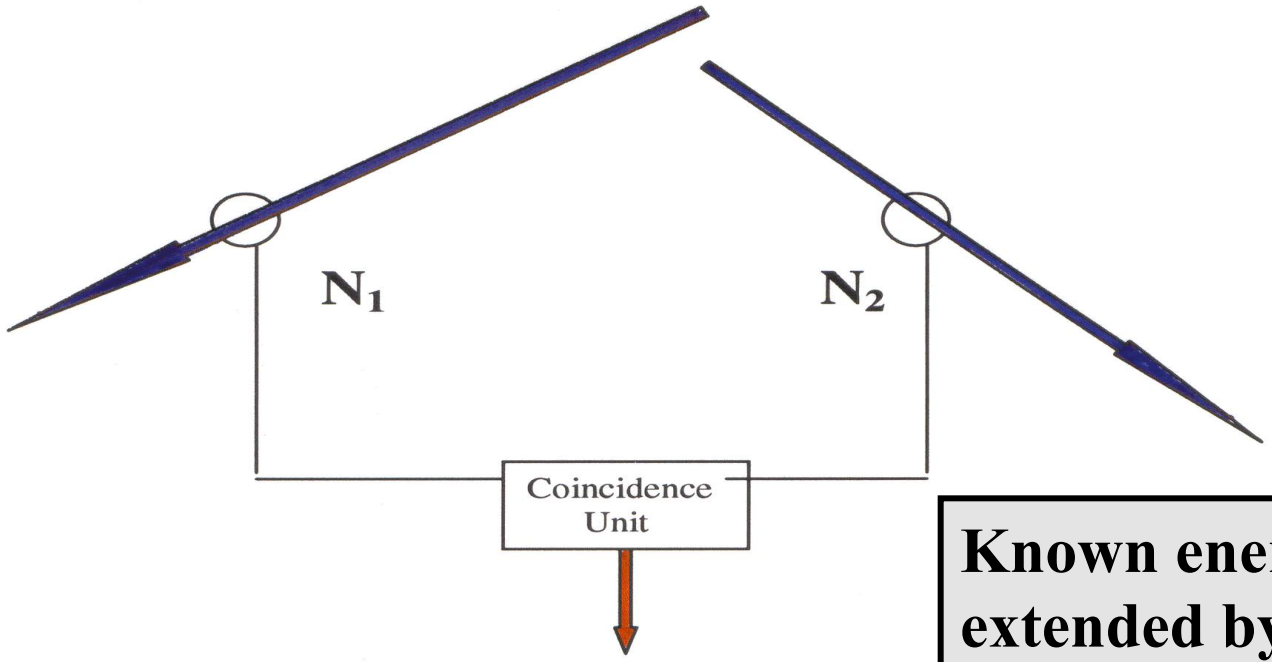
..... it seem that once in a while the recording equipment is struck by *very extensive showers of particles*.....

(he used 'sciami molto estesi di corpuscoli')

Unfortunately I did not have the time to study this phenomenon more closely."

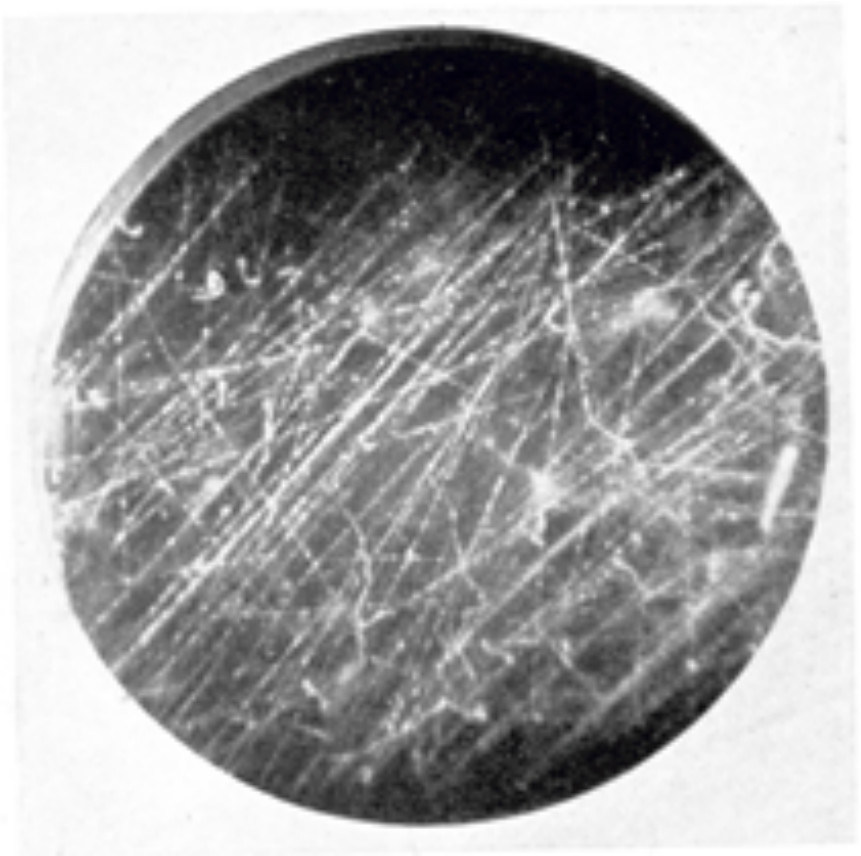
"This, I believe, was the first observation of those extensive air showers which were studied in some detail by Pierre Auger ..... which more recently became the object of a major research project by the MIT cosmic-ray group."

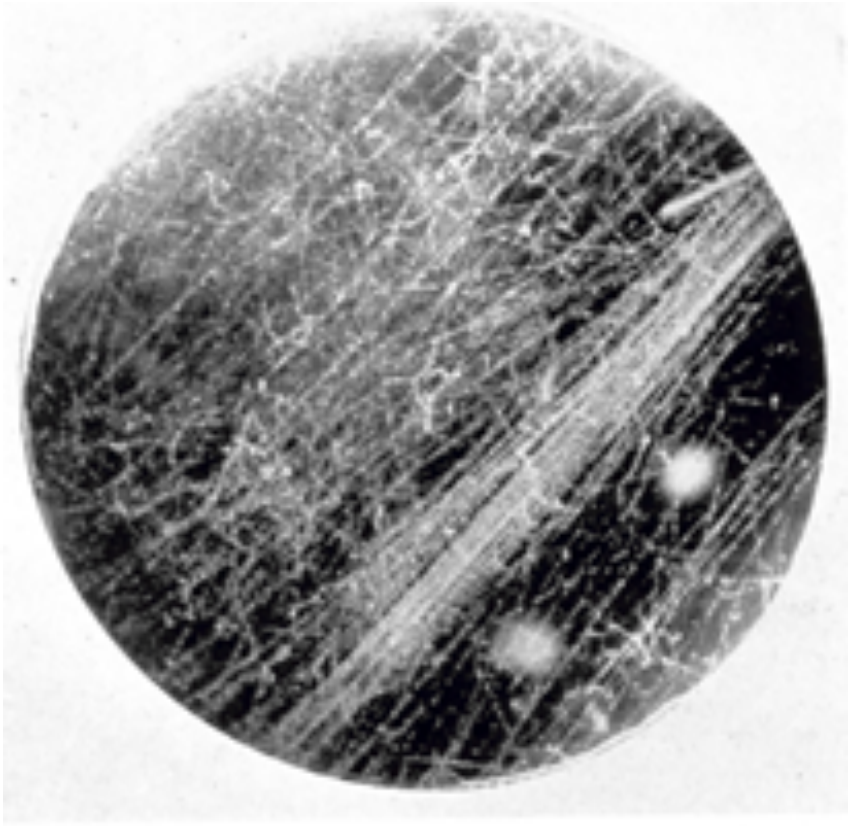
Discovery of Extensive Air Showers: Pierre Auger (1938)



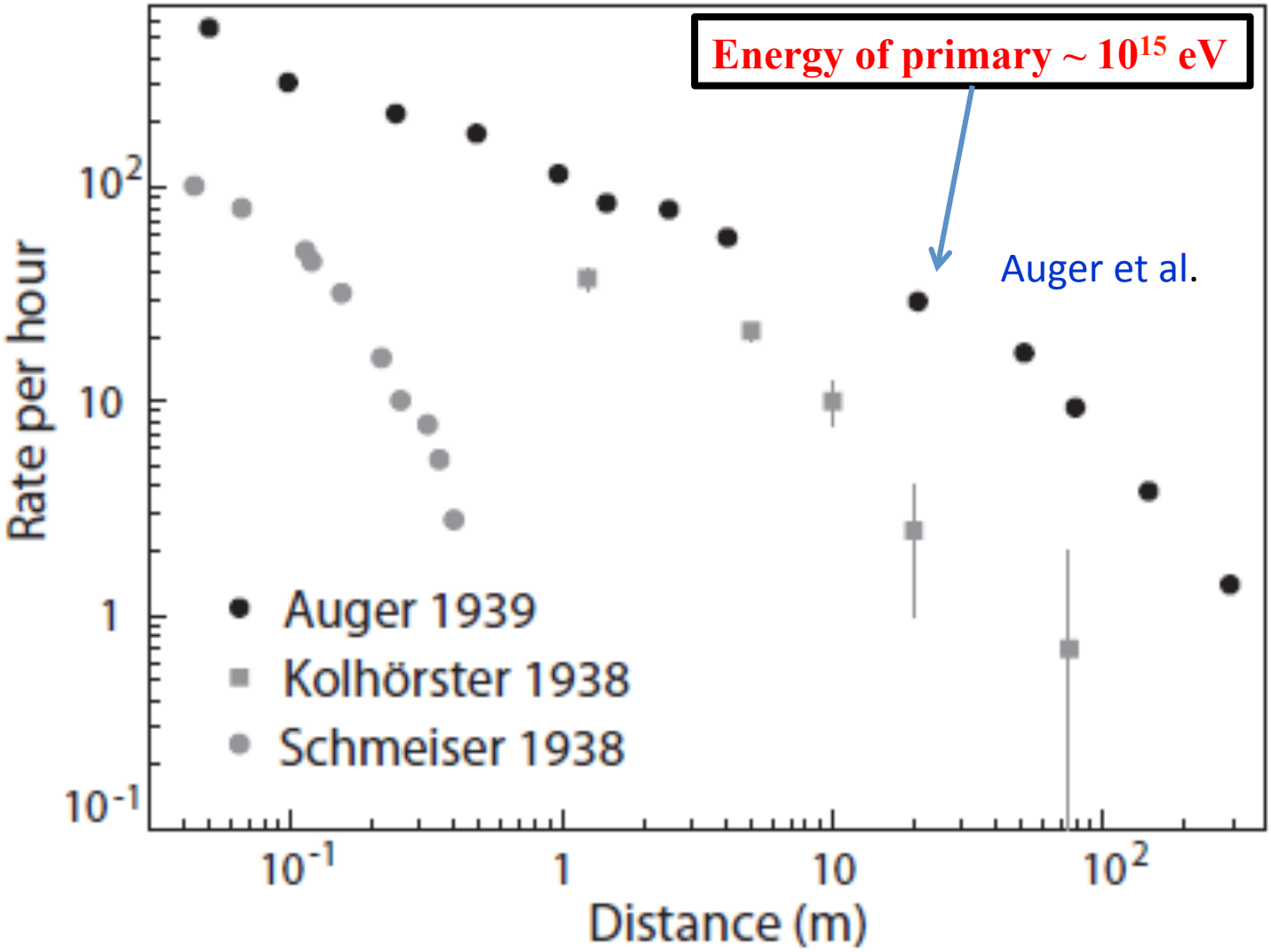
Known energy scale extended by ~10^6

Observed Rate was found to be much higher than the Calculated Chance Rate ($2N_1N_2\tau$) – even when the counters were as far as 300 m apart

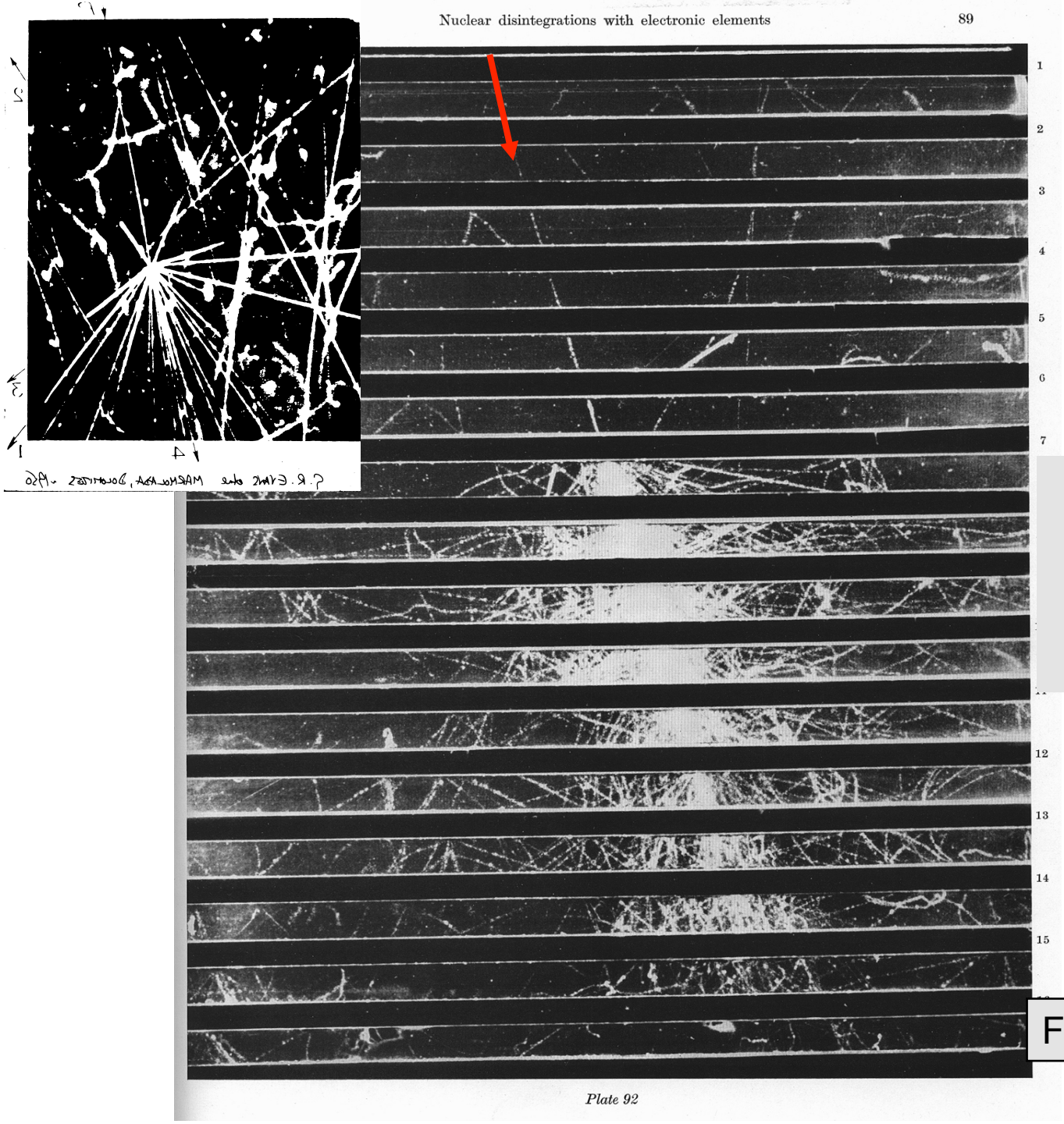




Wilson and Lovell, Nature 1938



The measurements of Schmeiser and Bothe, Kolhöster et al., and Auger et al.



1.3 cm Pb

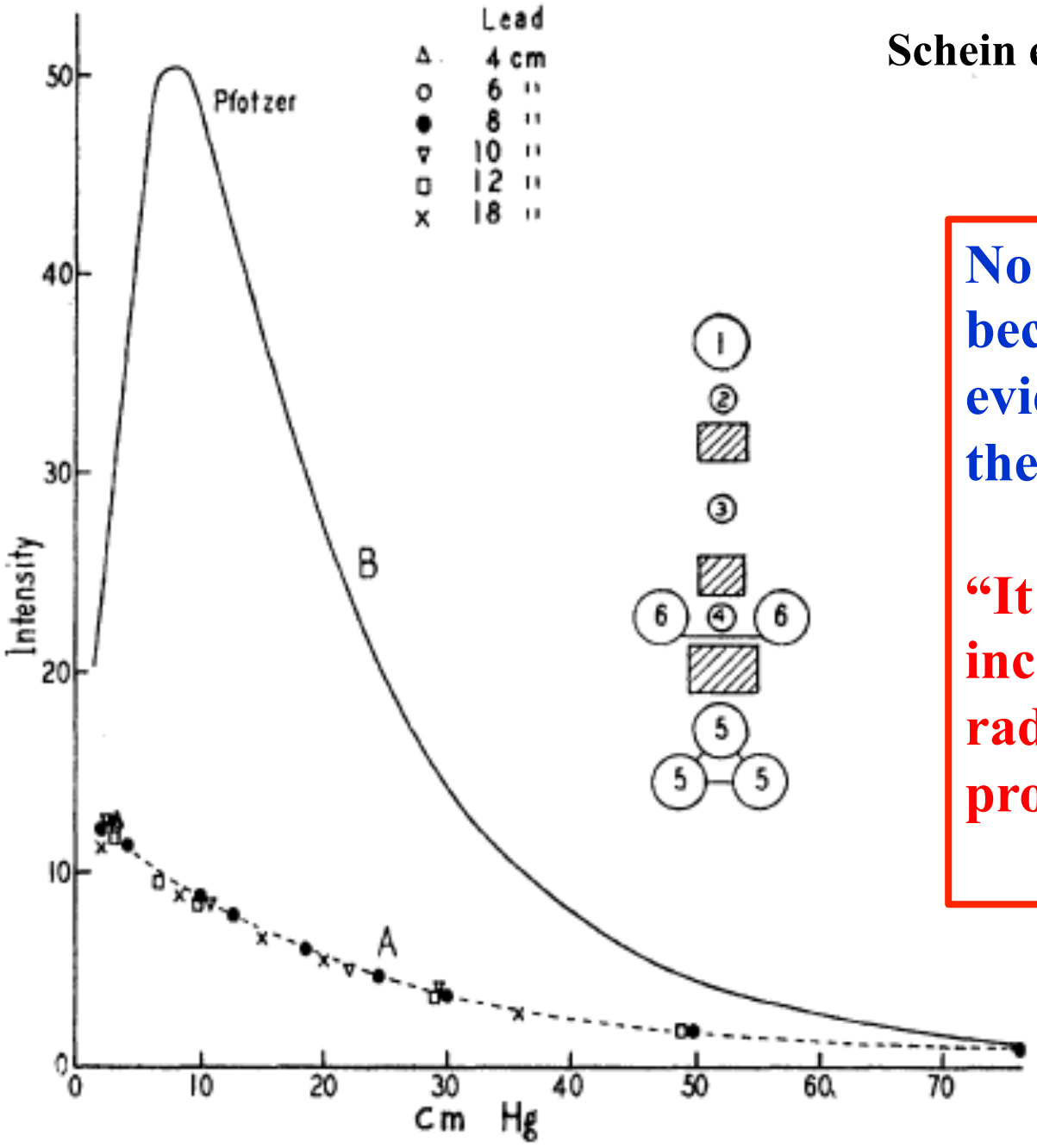
10 GeV proton

Shower initiated by proton in lead plates of cloud chamber

Detectors can find particle number and arrival times

Fretter: Echo Lake, 1949

Schein et al., Phys Rev 59 615 1941



No electrons < 10^{12} eV because there no evidence of showers in the outlying counters

"It is probable that the incoming cosmic radiation consists of protons"

OBITUARY

Prof. E. Regener

Erich Regener, who died on February 27, was born in Schleussenau near Bromberg on November 12, 1881. He studied physics under E. Warburg in Berlin, worked from 1909 onwards with H. Rubens at the Physics Department of the University of Berlin, and became, in 1911, professor of physics and meteorology in the Landwirtschaftliche Hochschule, Berlin. In 1920 he was appointed director of the Physics Department of the Technical High-school at Stuttgart, which, under him as experimental physicist, and with P. P. Ewald as theoretical physicist, soon became a lively centre of learning and research.

Regener is perhaps best known for his work on the intensity of cosmic rays under water and in the upper atmosphere. He was a pioneer in both fields, and at one time held both the depth and height records for cosmic-ray measurements: 230 m. below the surface of Lake Constance and 25 km. up in the atmosphere. These two achievements revealed his great experimental skill and ingenuity in the design of apparatus. Regener also made many important contributions to atmospheric physics, particularly in the study of ozone and of the physics of the crystallization of water.

During the Hitler regime, Regener had to resign his post at Stuttgart as his wife was a non-Aryan. However, he found support from the more liberal Kaiser-Wilhelm-Gesellschaft, as director of a laboratory at Friedrichshafen for the investigation of the stratosphere. When, during the War, his laboratory was destroyed during an air raid, he built a small research station at Weissenau on Lake Constance, which, after the War, became part of the Max-Planck-Gesellschaft. Both his children by his first wife (who died shortly after the War) had to emigrate as 'half-Aryan': his son Victor, also distinguished as a physicist, to the United States, and his daughter, married to the physicist Dr. Rathgeber, to Australia. After the War, Regener became a senator and vice-president of the Max-Planck-Gesellschaft.

Regener possessed exceptional personal charm and a wide liberal culture. He was both a good violinist and a keen yachtsman. His death means the loss to German science of a creative experimental physicist and one who, having weathered the devastation of the Hitler regime and of the War, afterwards did much to help to rebuild its great tradition.

P. M. S. Blackett

Obituary written by P M S Blackett Nature 1955

Erich Regener's son went to the US and established an important cosmic ray group at the University of New Mexico

Key paper on the statistics of small numbers

He banished use of +/-1!

His son is now a mathematician in Canada

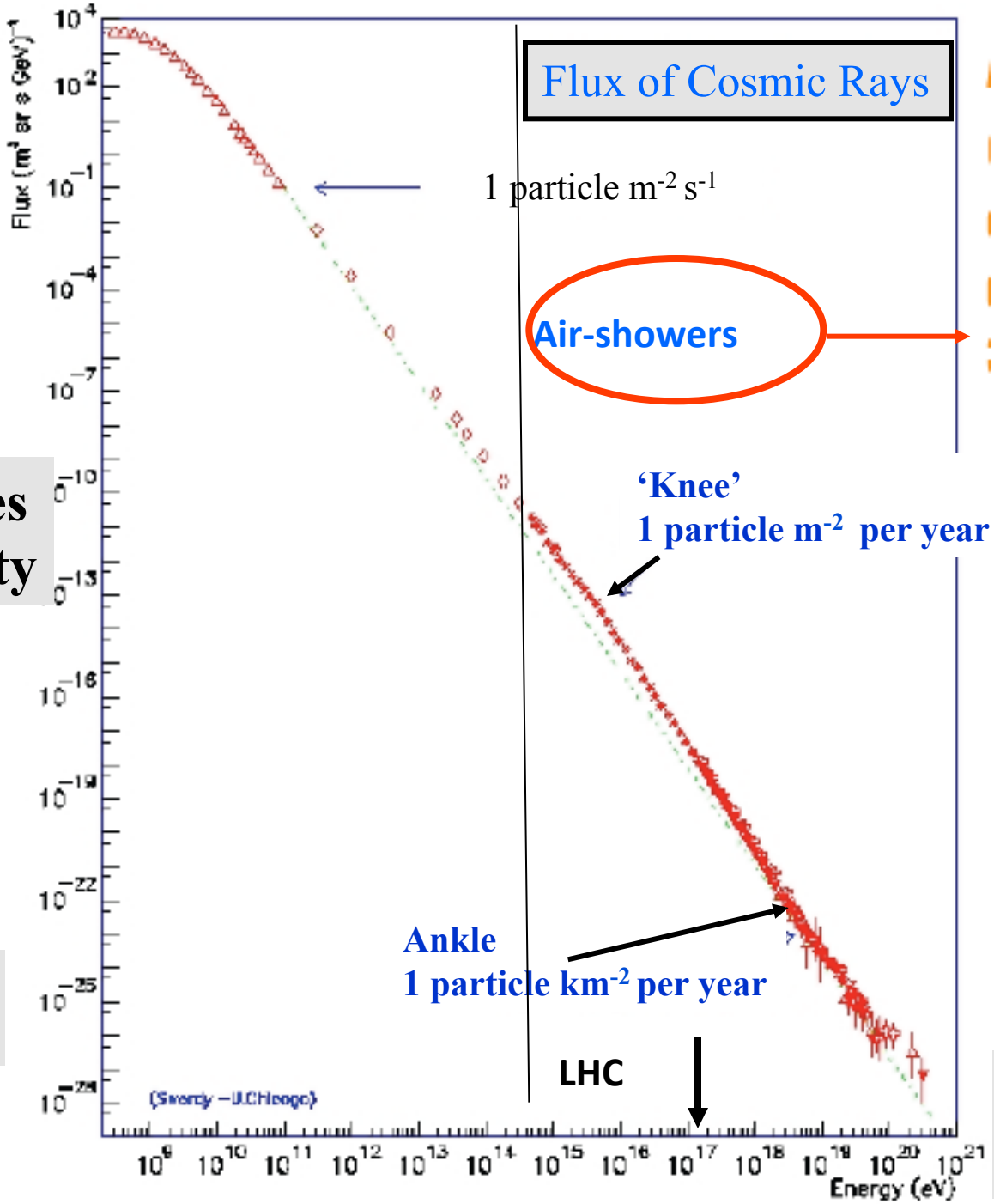
Regener's daughter married Henri Rathgeber: they emigrated to Australia

He worked first in Melbourne and then in the cosmic ray group in Sydney

Their son, Michael, was brilliant at electronics and worked in Sydney cosmic ray group

Erich Regener was nominated for the Nobel Prize by Schrödinger in 1939

What an amazing legacy!



25 decades in intensity

S Swordy (Univ. Chicago)

11 Decades in Energy

1948 – 1958: Decem Anni Mirabiles (i)

An extraordinary decade for development of studies of air-showers

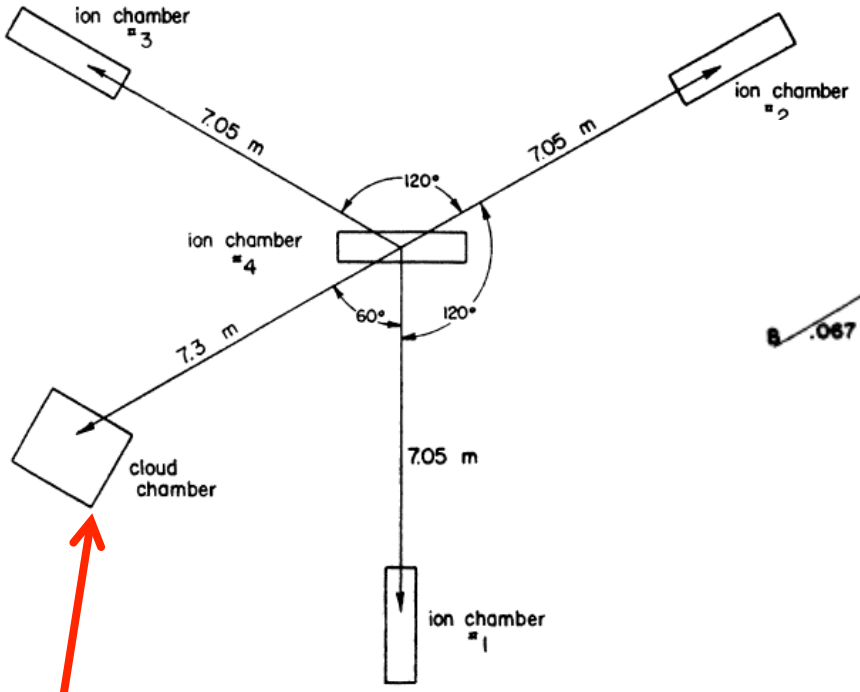
1948: Rossi at MIT – study of individual events

1948: Core location by Williams

1953: Bassi, Clark and Rossi: scintillators and fast timing

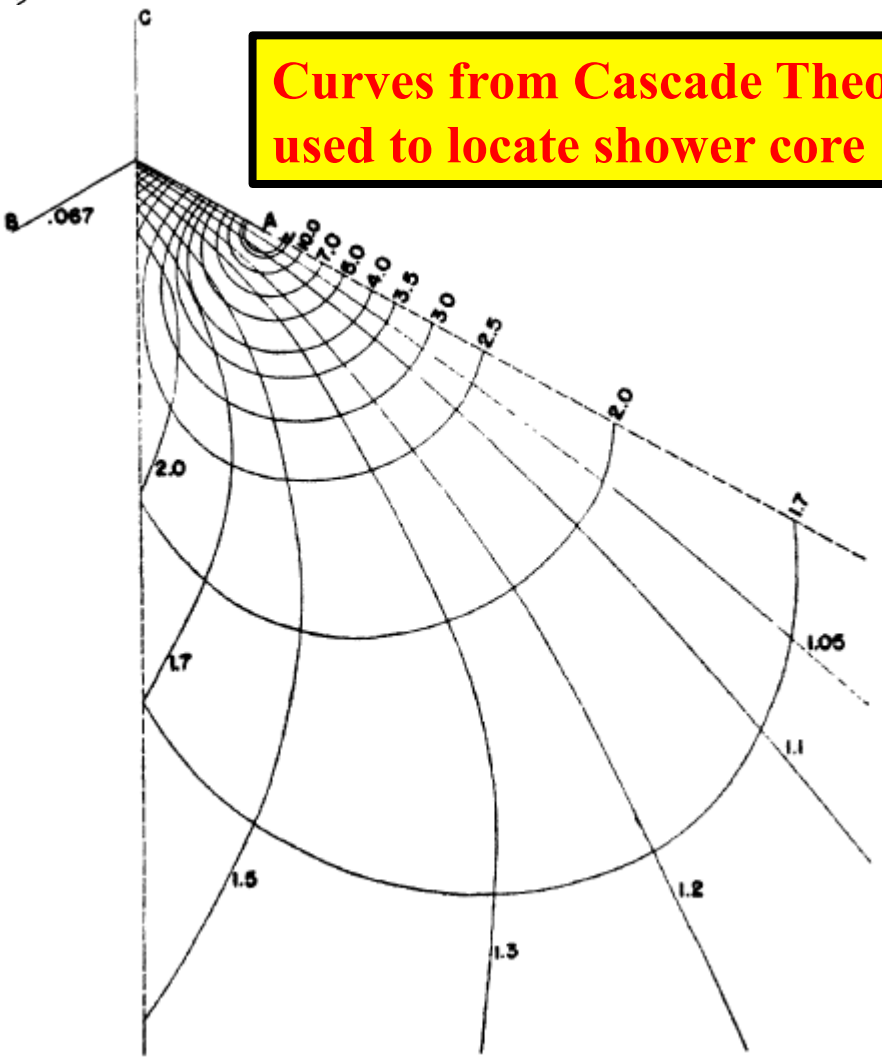
1953 – 1958: Agassiz Experiment
→ Chacaltaya (BASJE – Bolivia, Japan and USA)
and Volcano Ranch (MIT)

Core Location by Williams (1948)



Cloud Chamber (Hazen) used to show that most showers < 30 °

Curves from Cascade Theory – used to locate shower core



1953: Bassi, Clark and Rossi – scintillators and fast timing

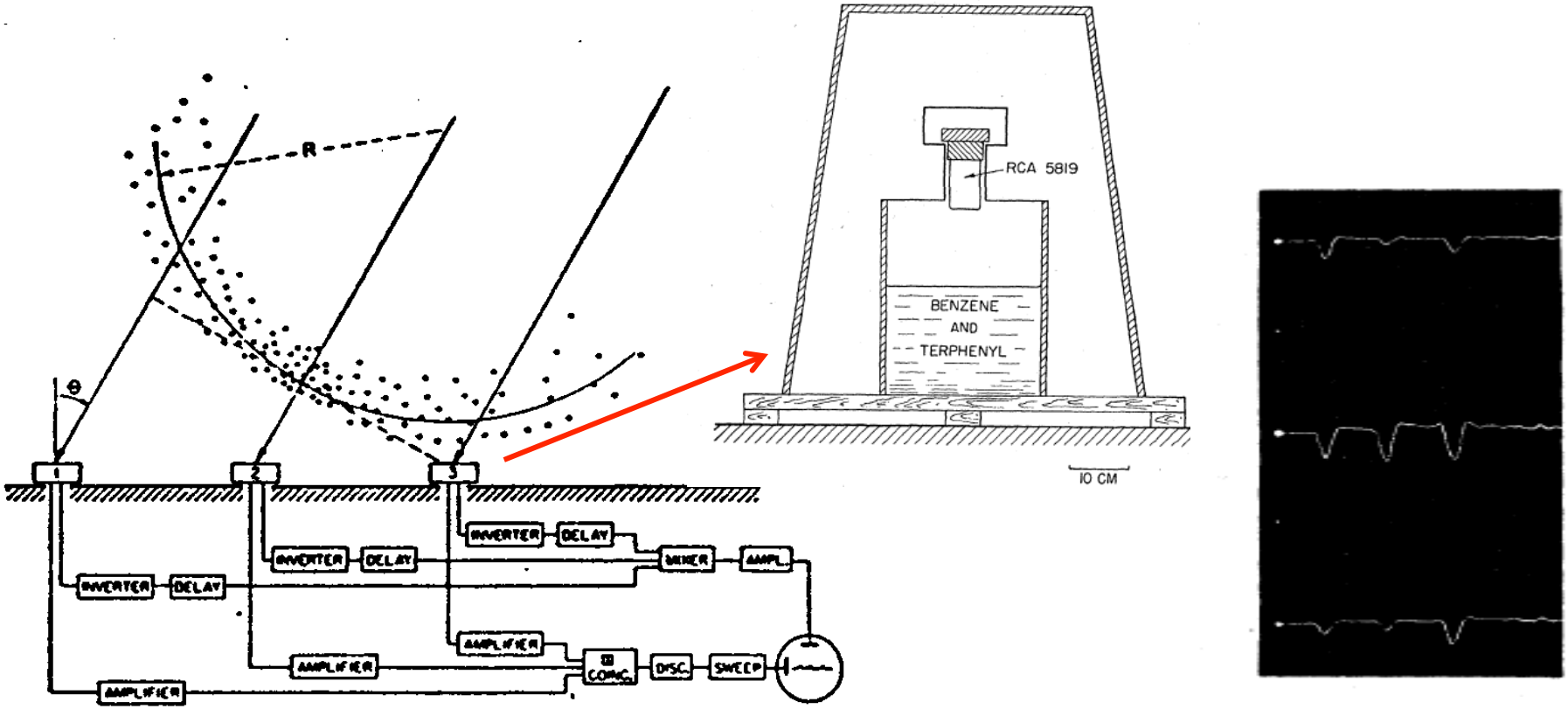
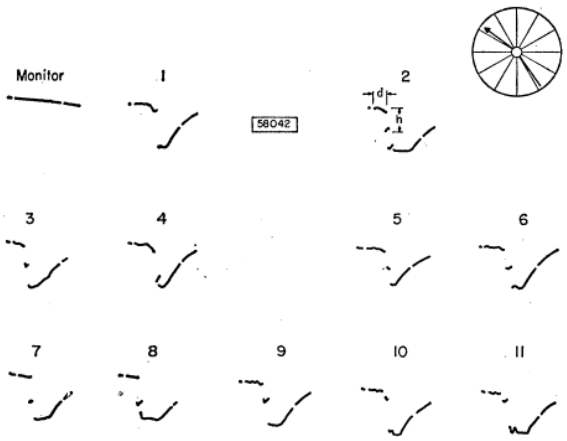


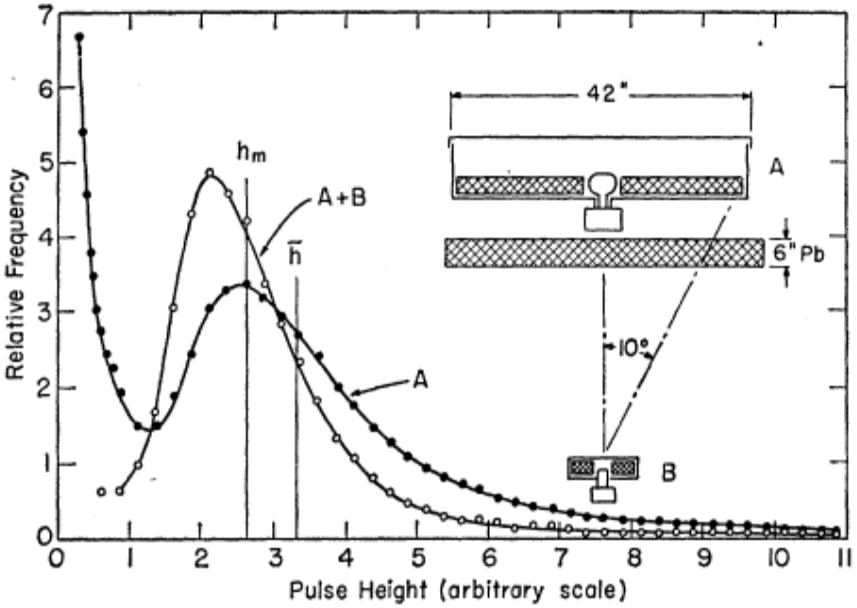
FIG. 2. Block diagram of the apparatus with a schematic representation of an air shower about to strike the counters. The counters are in arrangement II.

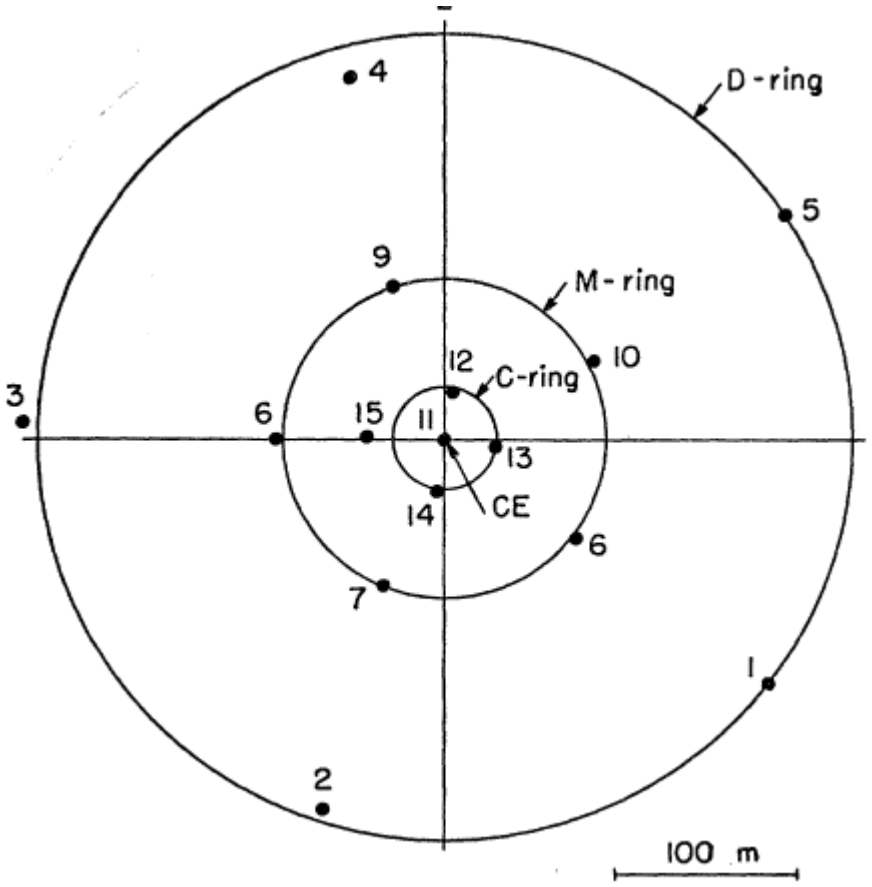
Directional uncertainty ~ 7°

Thickness of electron disc and fact that electrons lead muons close to the axis: inferences about energy of nucleons

MIT Agassiz Experiment - led to first UHECR detector





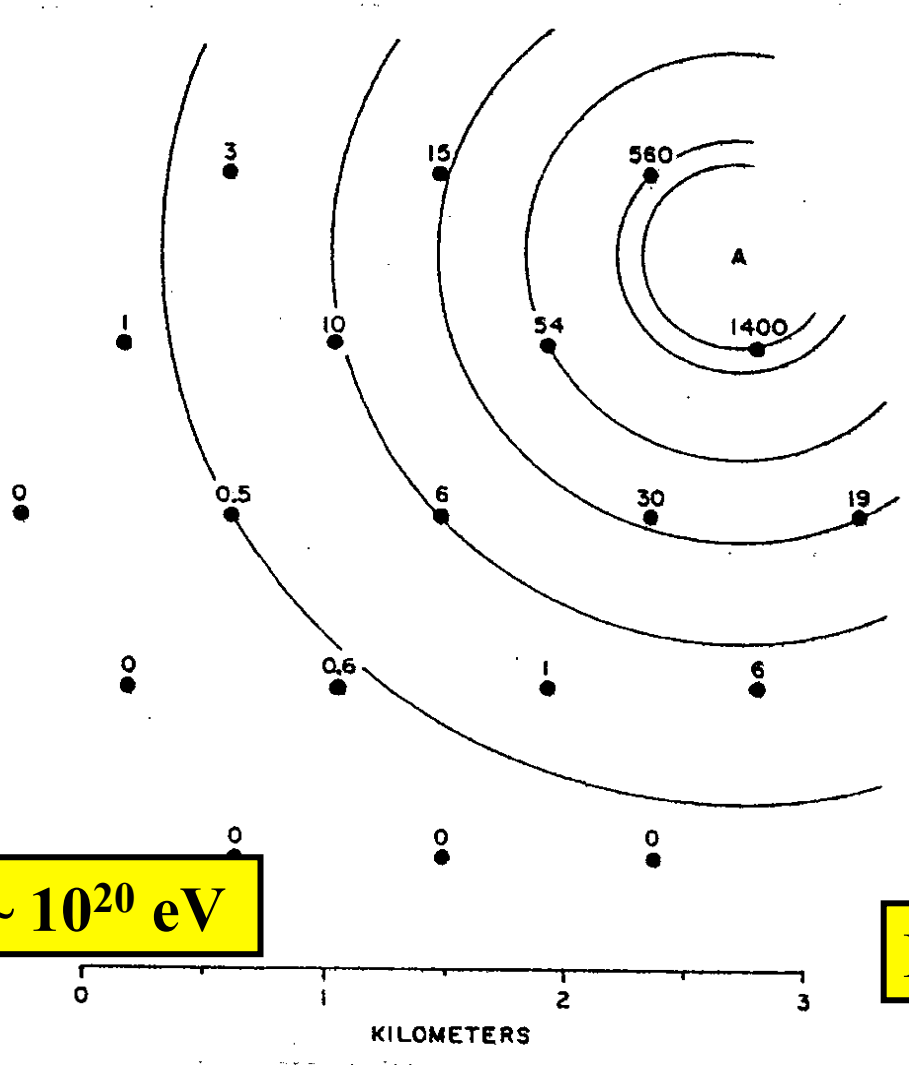


Largest event, N = 2.6 x 10^9

E ~ 3 x 10^{18} eV (1958)

John Linsley – the pioneer in the searches for the highest-energy cosmic-rays – checking for rattlesnakes at Volcano Ranch

The Volcano Ranch Array: Linsley (1963)



John Linsley was one of the last cosmic ray physicists who fitted the description of Val Fitch

Energy ~ 10^{20} eV

Pre-GZK prediction

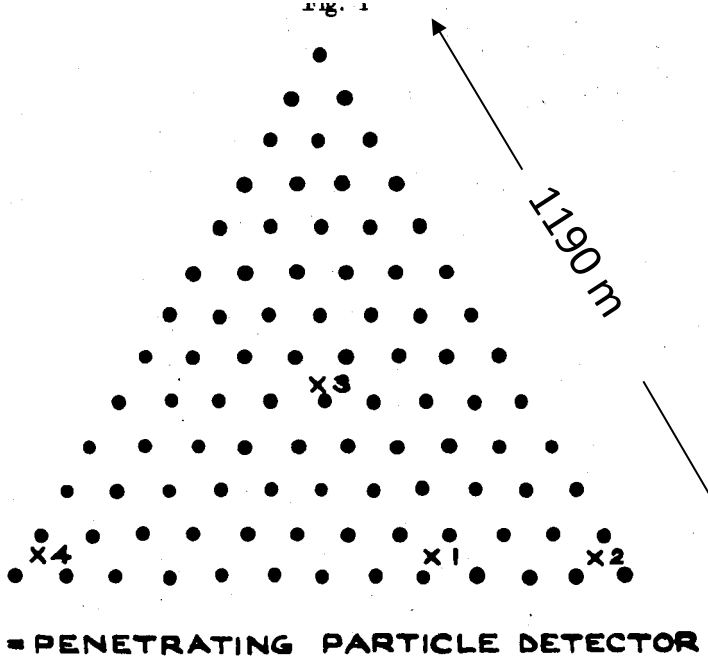
1948 – 1958: Decem Anni Mirabiles (ii)

Harwell Array:

(i) **Anisotropy < 10%, ruled out solar origin theory of Richtmeyer and Teller, and also Alfvèn**

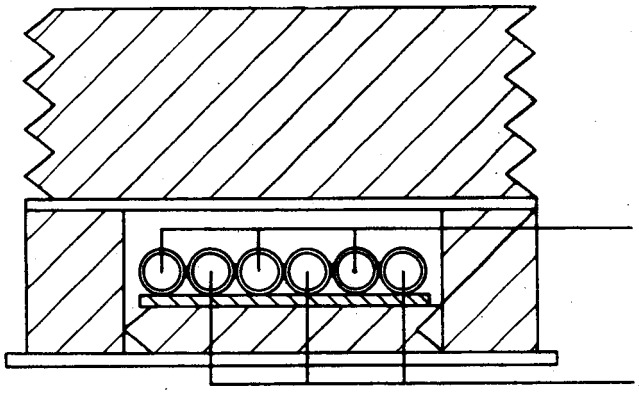
(ii) **Test of air-Cherenkov light ideas of Blackett**
→ gamma-ray astronomy at 1 TeV

(iii) **Water-Cherenkov detector (Neil Porter)**
-> Haverah Park, Auger …….



Position of shielded detectors on the array.

Fig. 2



§ 2. EXPERIMENTAL ARRANGEMENT

"Outside the wire"

Large GM array at Harwell, UK in mid-1950s: 0.6 km^2

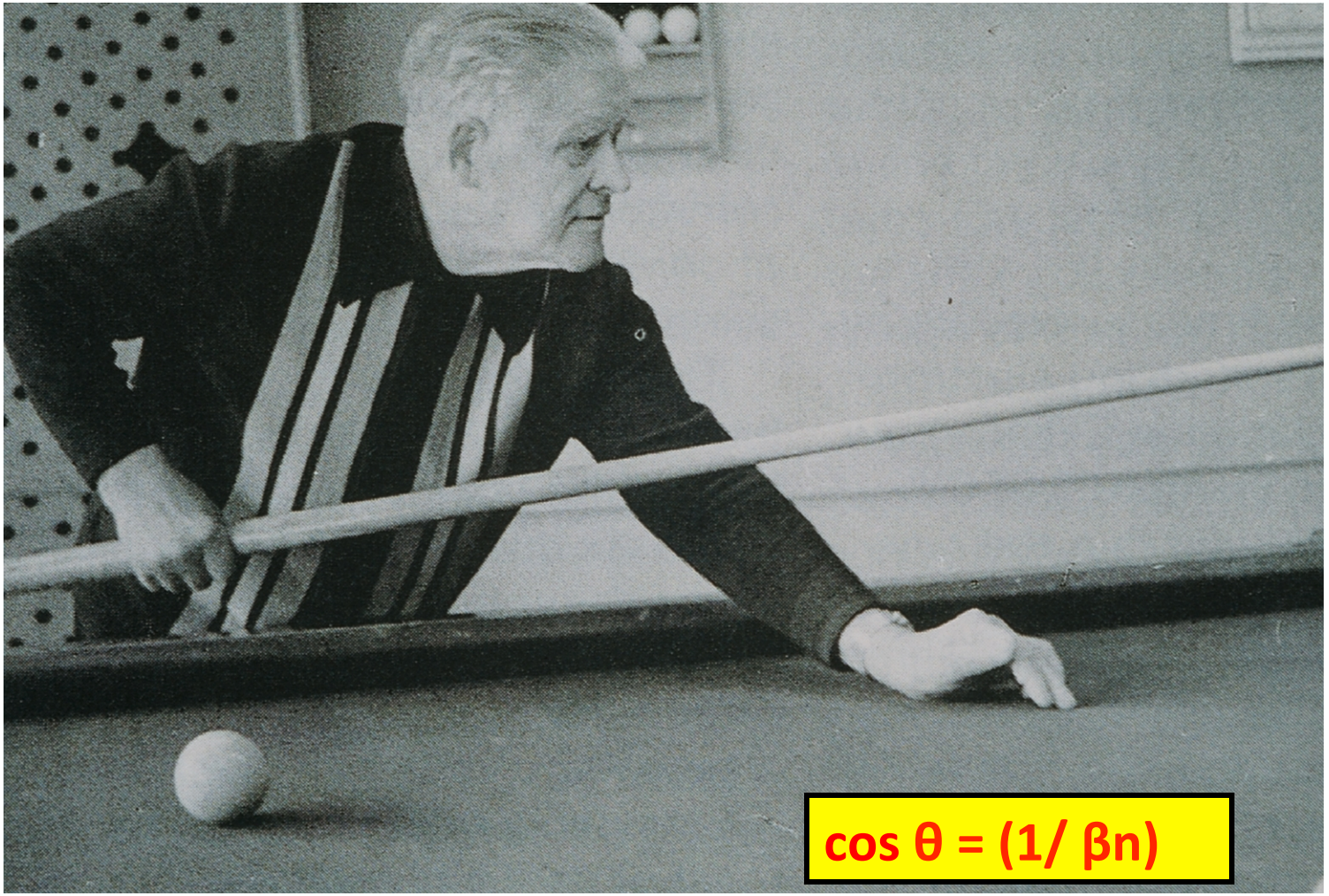
91 stations

GM 2 x 200 cm^2 and 1 x 15 cm^2

T E Cranshaw, W Galbraith, N A Porter, A M Hillas……..

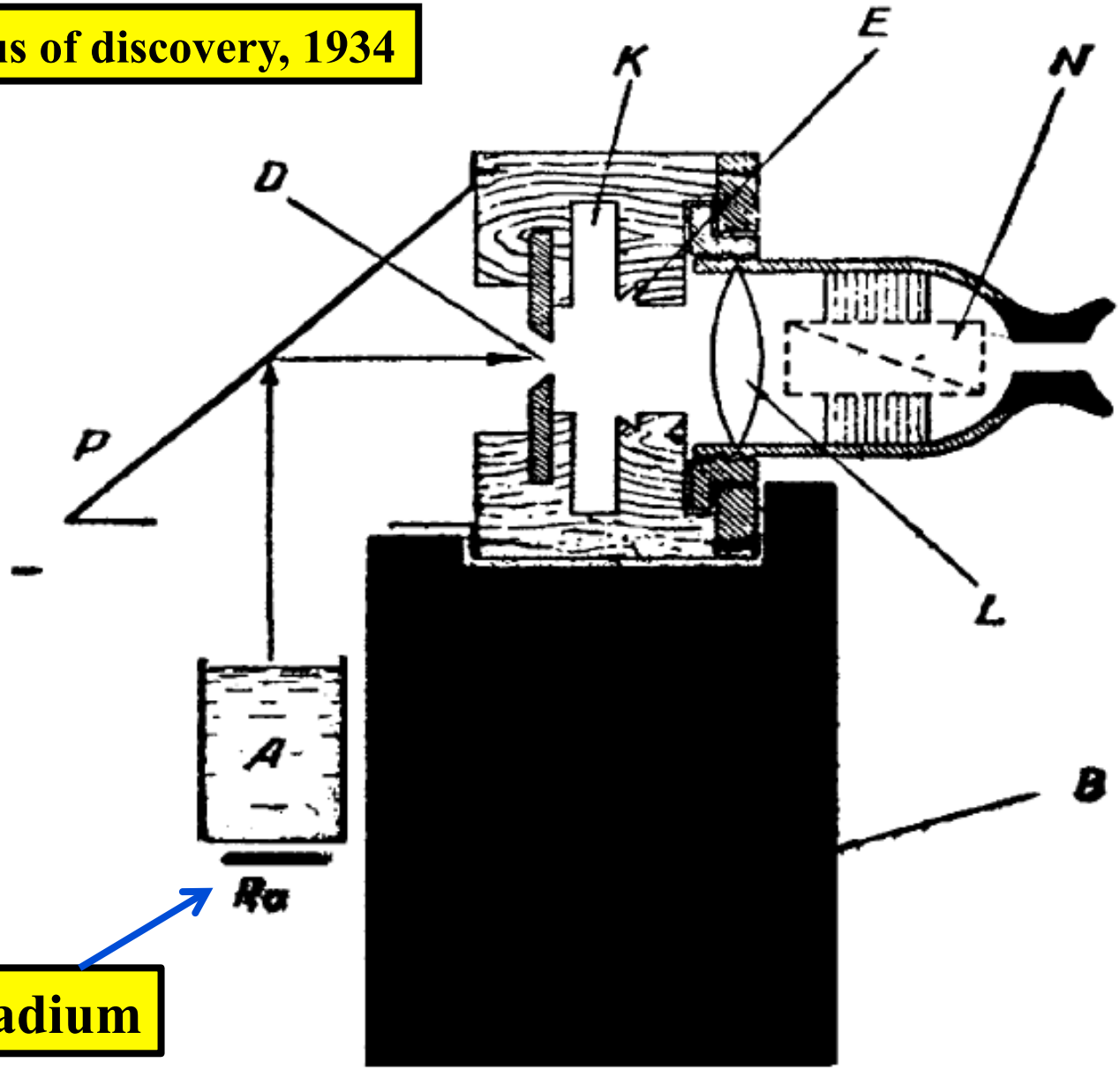
First Cherenkov light detection in air-showers (1953)

Pavel Alexeyevich Cherenkov: 1904 – 1990
born and educated in Voronezh, USSR ~ 600 km from Moscow



From CERN Courier 1990? Photo by Yu Tumanov

Apparatus of discovery, 1934



radium

Fig. 1.

Chudakov: Phys Rev 52 378 1937

(rejected by Nature)

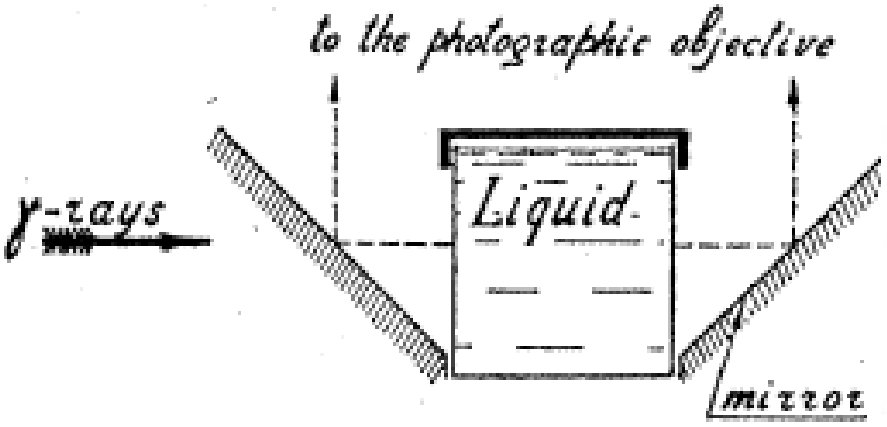


FIG. 1. Arrangement of apparatus.

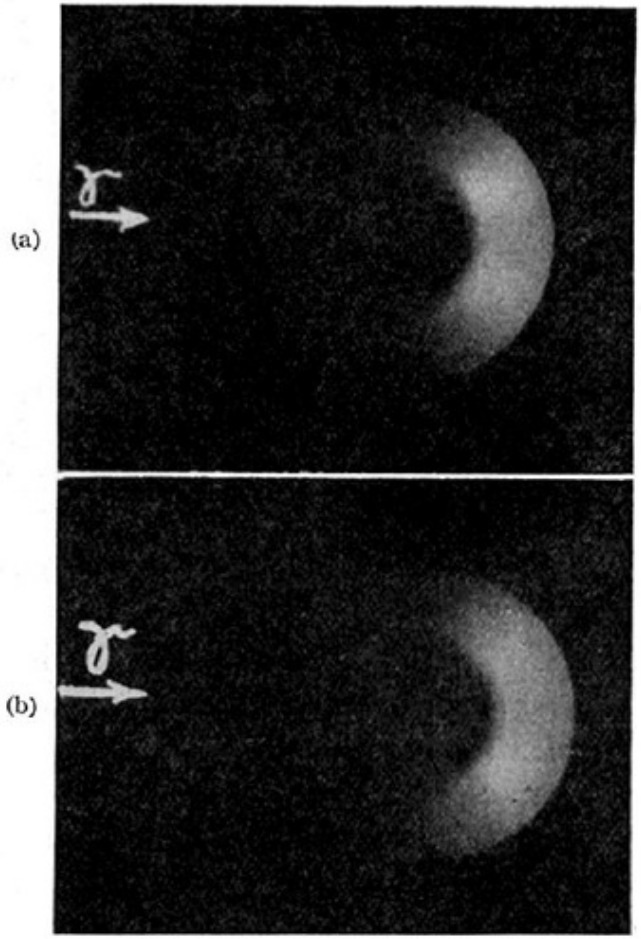


FIG. 2. Photographs showing asymmetry of luminescence. (a) water· $n = 1.337$; (b) benzene, $n = 1.513$.

Visible Radiation Produced by Electrons Moving in a Medium with Velocities Exceeding that of Light

In a note published in 1934[1] as well as in the subsequent publications[2–4] the present author reported his discovery of feeble visible radiation emitted by pure liquids under the action of fast electrons (β-particles of radioactive elements or Compton electrons liberated in liquids in the process of scattering of γ-rays). This radiation was a novel phenomenon, which could not be identified with any of the kinds of luminescence then known as the theory of luminescence failed to account for a number of unusual properties (insensitiveness to the action of quenching agents, anomalous polarization, marked spacial asymmetry, etc.) exhibited by the radiation in question. In 1934 the earliest results obtained in the experiments with γ-rays led S. I. Wawilow[5] to interpret the radiation observed as a result of the retardation of the Compton electrons liberated in liquids by γ-rays. A comprehensive quantitative theory subsequently advanced by I. M. Frank and I. E. Tamm[6] afforded an exhaustive interpretation of all the peculiarities of the new phenomenon, including its most remarkable characteristic —the asymmetry.

(Vavilov)

P A Cherenkov Phys Rev 52 378 1937

Vavilov asked Tamm and Frank to try to explain the observations

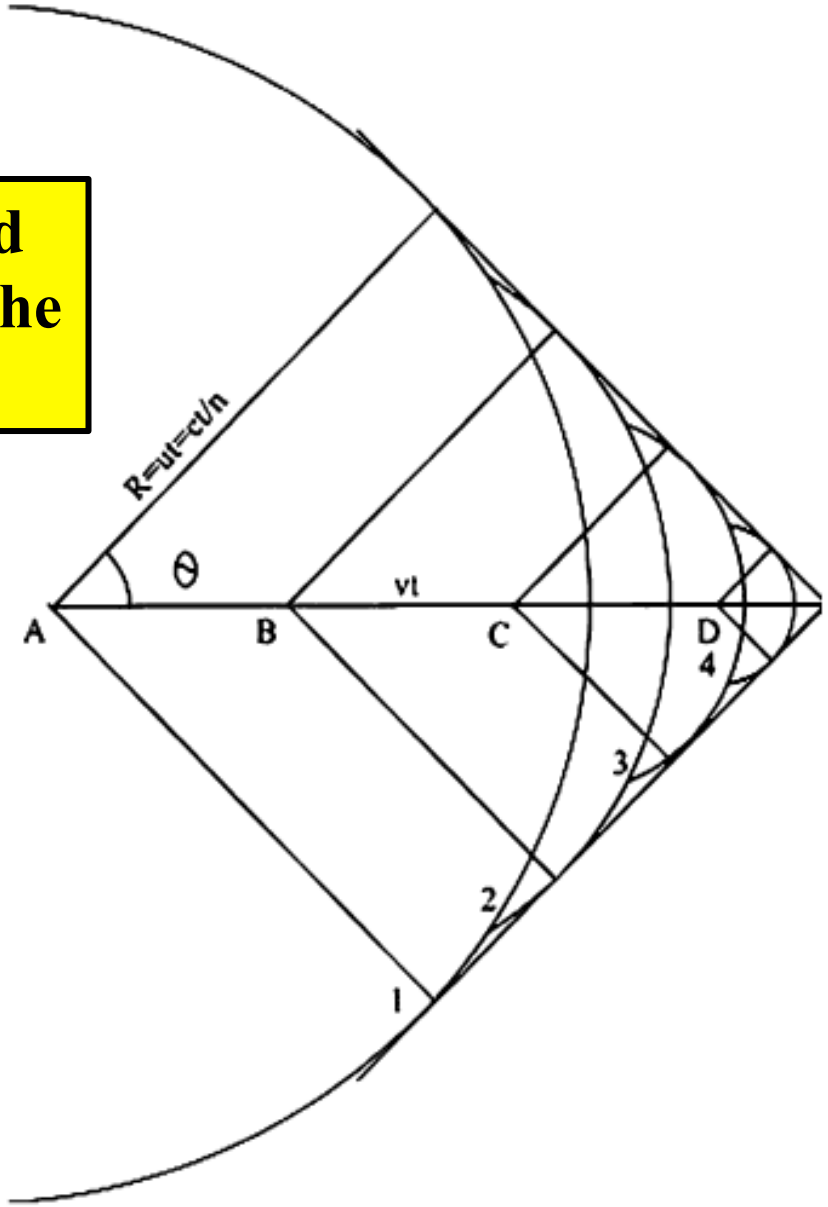


Fig. 4. Movement of a charge particle in a medium with a velocity $v > u$. v—particle velocity; u—the speed of light in the medium having the refraction factor n.

Cherenkov, Frank and Tamm were awarded the Nobel Prize in 1958
Vavilov had died 1951; all had been awarded the Stalin prize in 1947

I E Tamm, Nobel Prize Lecture, December 1958

We perceive the Mach waves radiated by a projectile as its familiar hissing or roaring. That is why, having understood the quite similar mechanism of the Vavilov-Čerenkov radiation of light by fast electrons, we have nicknamed it « the singing electrons ».

I should perhaps explain that we in the USSR use the name « Vavilov-Čerenkov radiation » instead of just « Čerenkov radiation » in order to emphasize the decisive role of the late Prof. S. Vavilov in the discovery of this radiation.

Vavilov had been elected an Academician in 1932 at the age of 41

It was Vavilov who got Frank and Tamm to take an interest in the observations of Cherenkov: he was an Academician.

Frank apparently helped with some of these observations.

Vavilov had a difficult time in the Stalin era: his brother was a geneticist who opposed Lysenko's ideas and accordingly was sentenced to death, commuted to 20 years
- but he died in prison.

Vavilov looked after his brother's family
– probably quite dangerous

Also kept much of Soviet Science alive:
stressful dealings with Stalin

Died of a heart attack before he could have shared Nobel Prize

Memories of his daughter, NIMA 533 1 2005 and CERN Article

But Stalin came close to Cherenkov too.

His father, a farmer, was exiled and his father-in-law sent to the 'Northern Regions' in 1930.

Cherenkov sent his coat to his father-in-law and the family dried bread from their rations to send too.

Memories of his daughter, NIMA 533 1 2005 and CERN Article

Cherenkov's full scientific career could be described in more detail, but I would like to concentrate here on one outstanding feature, one "hour of destiny"—the discovery of Cherenkov radiation. The phenomenon was not and probably could not have been discovered earlier by somebody more experienced in physics than Cherenkov was in the 1930s. To determine the nature of the faint blue light produced in different liquids by gamma rays from a radioactive source seemed to require a young fellow from a rural area, inexperienced but with immense patience and vigor.

A E Chudakov, Obituary of Cherenkov, Physics Today p 106 December 1992

Nevertheless, when considering the glorious development of the Cherenkov technique in experimental physics, I imagine a young and enthusiastic fellow who for several years started his working day by spending an hour in a totally dark room to prepare his eyes to observe faint light, and who scrupulously repeated the observations again and again, varying the liquids and the geometry of the experiment, trying to find the clue to the nature of the puzzling radiation that now bears his name.

Chudakov: ***loc cit***

***On Chudakov's Obituary of Cherenkov*…… "I remember how a whole delegation from Lebedev Institute visited Chudakov when he wrote the above-mentioned obituary. People from this institute always insisted on this Vavilov-Cherenkov nomenclature. You know, the natural feeling of hierarchy obliges some people to include big boss. At the moment of his discovery Cherenkov was a post-graduate and had a reputation of a simpleton, while Vavilov was academician (very important title), director of the institute, and even President of Academy of Sciences. It is true that Vavilov gave Cherenkov the topic of his study and was his supervisor, but Chudakov told me that from his point of view Vavilov never understood properly the essence of this effect. He was too much involved into his luminescence studies."**

A E Lidvansky (private communication)

Fig. 4. Pavel Alexeevich was the only soviet scientist who has received the Nobel Prize before electing him into Academy of Sciences USSR. The highest world-famed recognition has come to him abroad earlier than at home. Only in 1964 he was elected by the correspondent member, and in 1970 full member of the Academy of Sciences USSR.

Memoir by his daughter: NIMA 533 1 2005

- **L Mallet: Observed emission of light when 30 mg of radium, as a source of γ- rays**

"Luminescence de l'eau et des substances organique soumises au rayonnement γ"

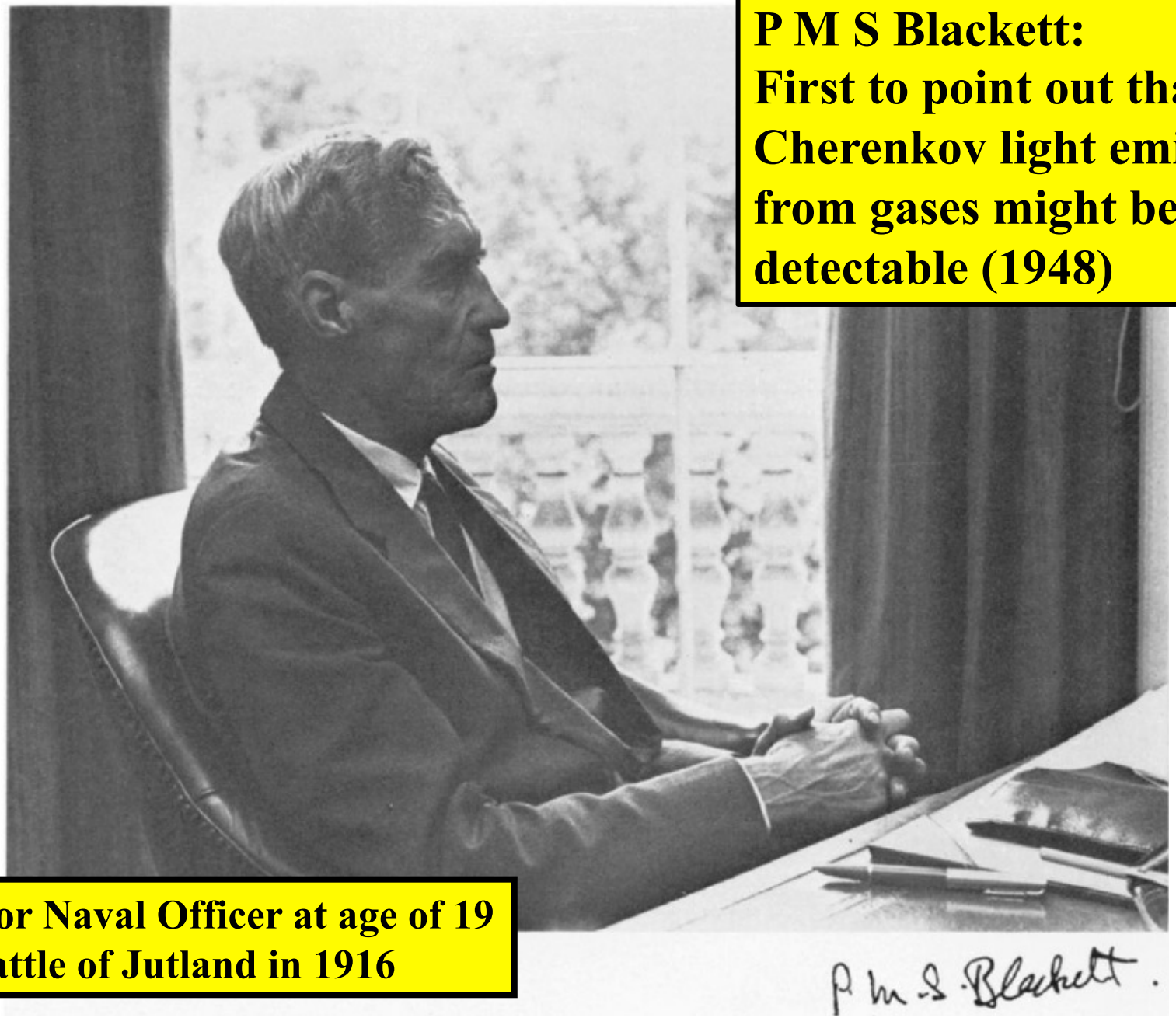
C. R. Acad. Sci (Paris) 1926, 1927 and 1928

- **Bluish-white light seen with source inside and outside water**
- **Most of radiation at short wavelengths**
- **Continuous spectrum** (spectrometer designed by Fabry)
- **BUT: Did not observe asymmetry of radiation and made no attempt to study polarisation**

(J V Jelley 'Cherenkov Radiation and its applications' Pergammon Press 1958)

Radiation also seen by Curies from solutions of radium salts

Jelley proposed 'Heaviside-Mallet' radiation


P M S Blackett:
First to point out that Cherenkov light emission from gases might be detectable (1948)
Junior Naval Officer at age of 19 at Battle of Jutland in 1916
P M S Blackett.

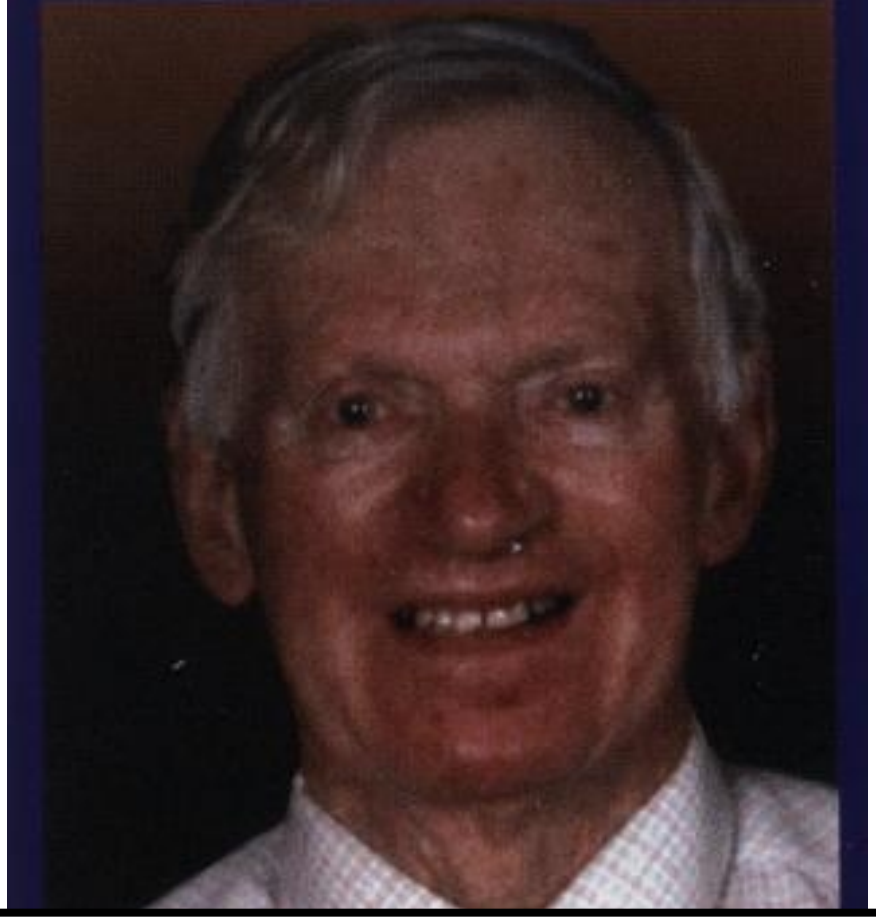
In air at n.t.p. Blackett derived values of $E_c = 20$ MeV for electrons and 4000 MeV for mesons, and taking a value of ω_0 equivalent to 2000 Å he found the energy loss to be 4 eV/cm, or 0.2% of the ionization loss. Taking account of the known cosmic ray energies, he estimated the Cherenkov flux for electrons at sea level to be 2.3×10^6 eV cm^{-2} s^{-1} or 1.5×10^{-6} erg cm^{-2} s^{-1}.

The conference was concerned with the light of the night sky and aurorae and Blackett deduced that this Cherenkov radiation from the cosmic ray electrons would be 10^{-4} of the night sky light. 'Presumably such a small intensity of light could not be detected by normal methods. It is however interesting to note that the light would still exist under an opaque layer of very high cloud. Thus the Cherenkov radiation of cosmic rays sets a limit, even if an unrealizable one to the darkness of the darkest night.' Although Blackett did not publish again on this topic he became interested in the contemporary work on the quantum efficiency of the eye, and concluded that the extensive air showers should produce a flash of light which he should be able to see by lying down and looking vertically upwards under suitable dark sky conditions. He proceeded to carry out this investigation himself. His

Bernard Lovell, Biographical Memoirs of Royal Society

John Jelley and Bill Galbraith were stimulated by Blackett's ideas to make observations

Nature 171 349 1953



The feasibility of detecting neutrinos of cosmic origin by radio frequency Cherenkov radiation in Antarctic ice

J.V. Jelley

29, Abbott Road, Abingdon, Oxon OX14 2DT, UK

Received 12 December 1995; revised 23 February 1996; accepted 11 March 1996

Observations made (i) with free-running time base on an oscilloscope and then (ii) with the scope triggered by small GM array. Data from only two dark periods in autumn 1952 used for first paper (Nature 1953)

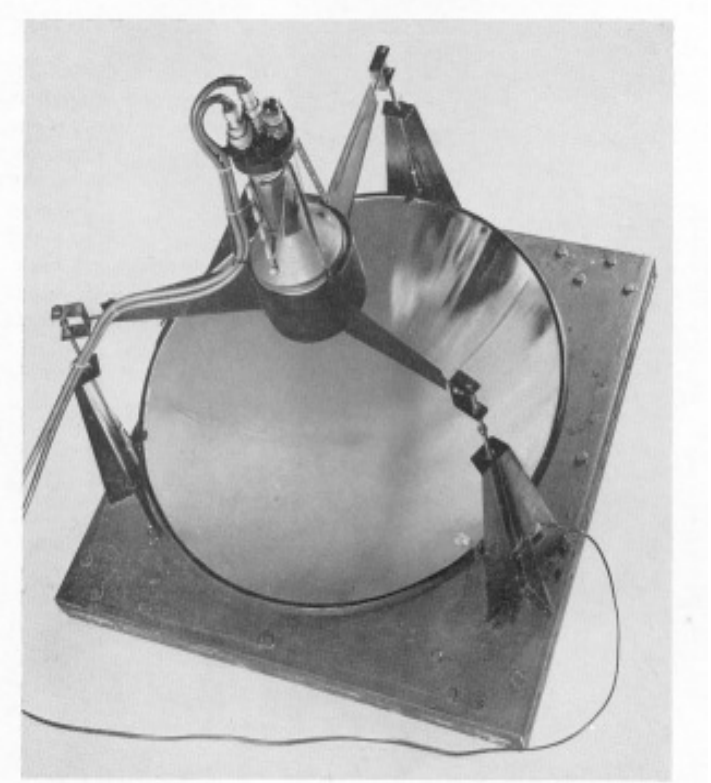


Plate II. Čerenkov light receiver (GALBRAITH and JELLEY[2])

Initial work at Harwell - need for a bed - and then at Pic du Midi where they measured properties of the radiation detected, including observing the polarisation. Experimental *tour de force*.

Use of Cherenkov light in studying EAS: Zatsepin and Chudakov Developed very strongly in USSR from 1950s

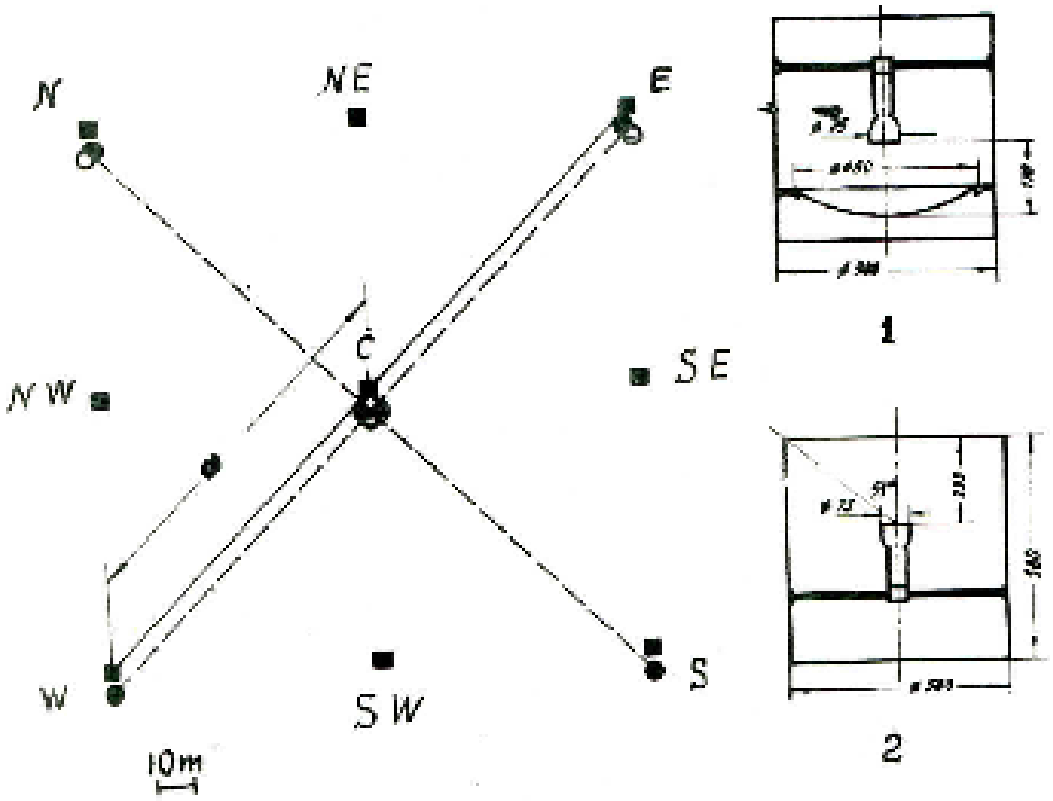
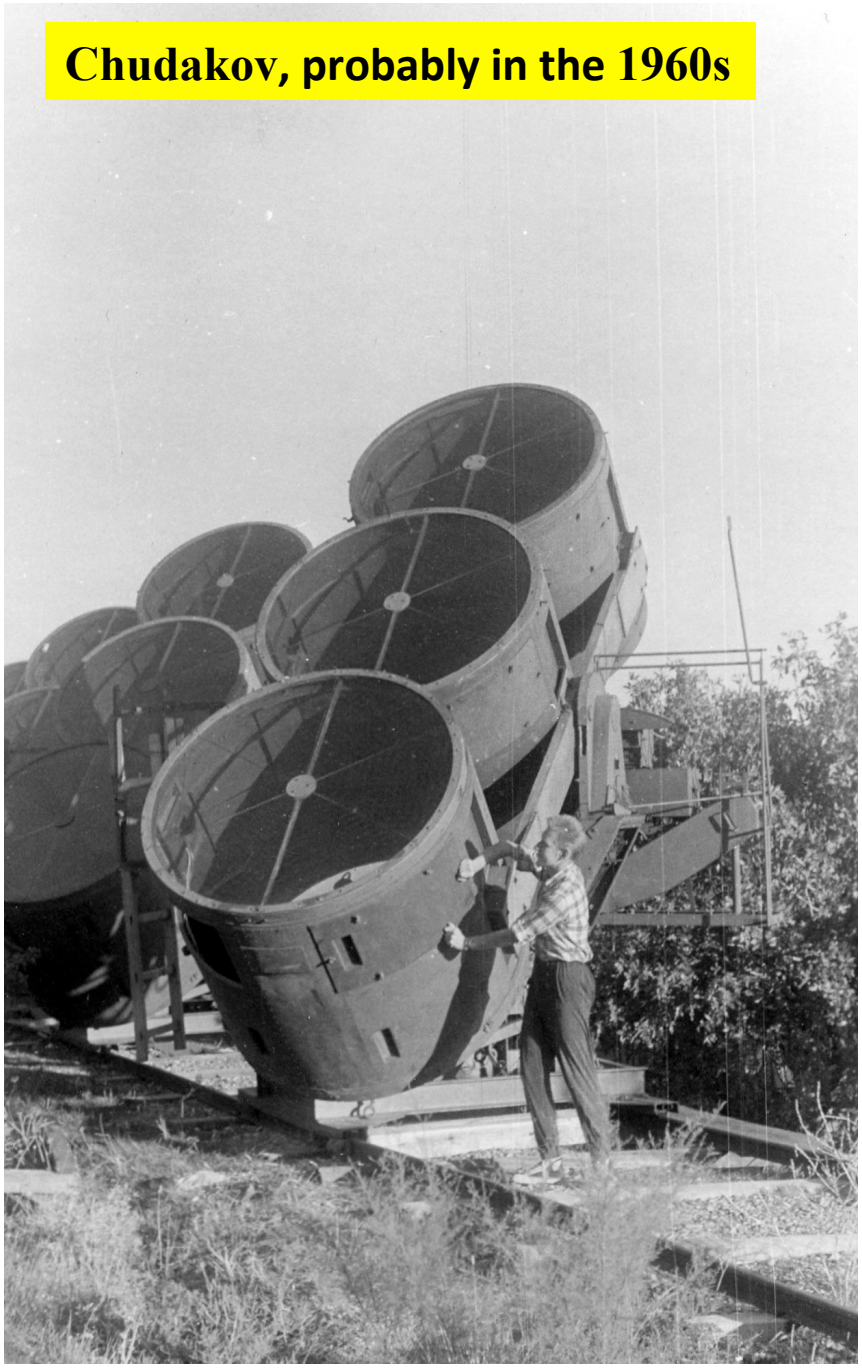


Fig.1. Station layout. 1.Detector with mirror.
● Optical detector without mirror.
○ Optical detector with mirror.
□ Hodoscope location.

ICRC Moscow 1959


Chudakov, probably in the 1960s


Zatsepin at Pylos, 2004

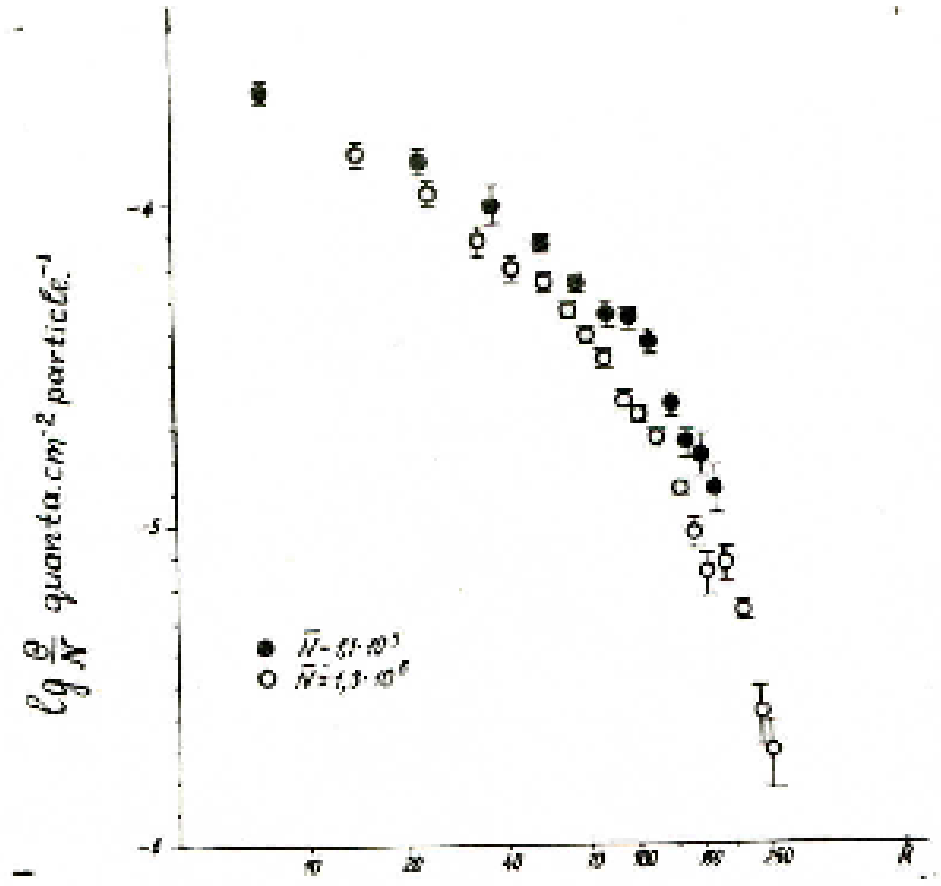


Fig. 3. Dependence of light intensity on the distance in metres to the shower axis for showers with various numbers of particles.

Chudakov et al., measurements during 1956 - 58

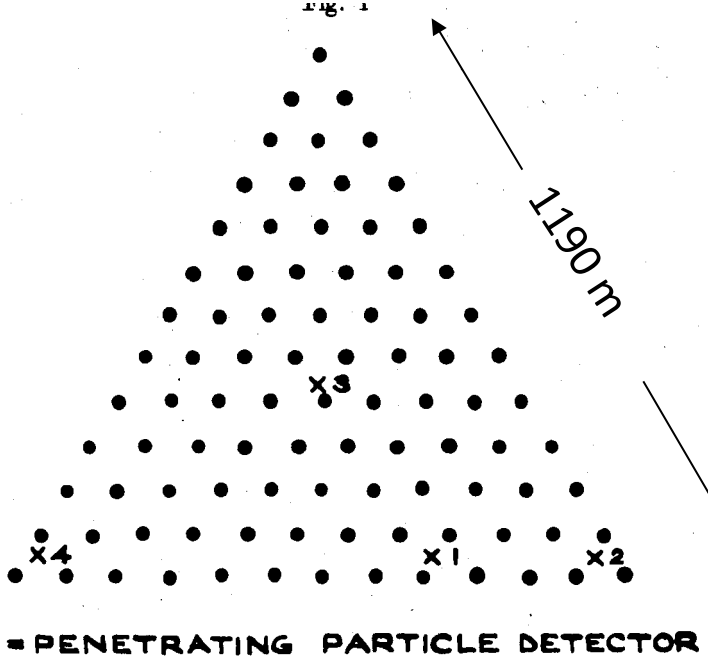
Cherenkov light and the track-length integral

$$(1 - F)E_0 \simeq \alpha \int_0^\infty N(t)dt,$$

F = fraction of energy carried by muons, neutrinos

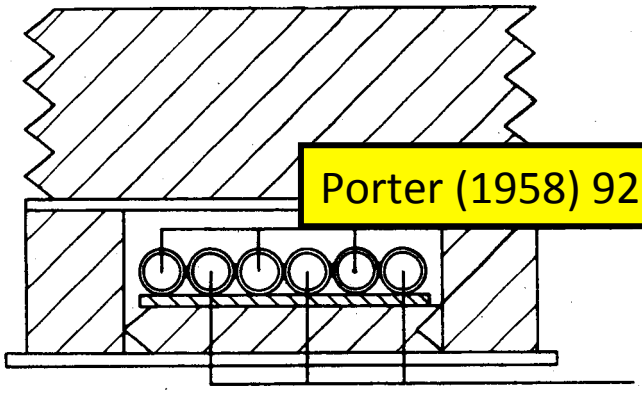
1.4 x 10^6 particles yielded 1.2 x 10^5 photons

Assume electrons > 50 MeV → 5.2 x 10^{15} eV



Position of shielded detectors on the array.

Fig. 2



§ 2. EXPERIMENTAL ARRANGEMENT

Large GM array at Harwell, UK in mid-1950s: 0.6 km^2

91 stations

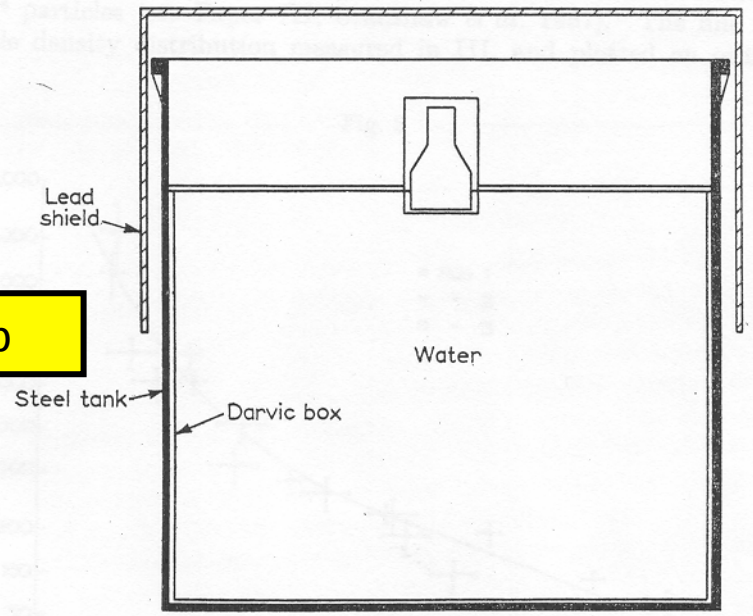
GM 2 x 200 cm^2 and 1 x 15 cm^2

T E Cranshaw, W Galbraith, N A Porter, A M Hillas……..

First water-Cherenkov detector

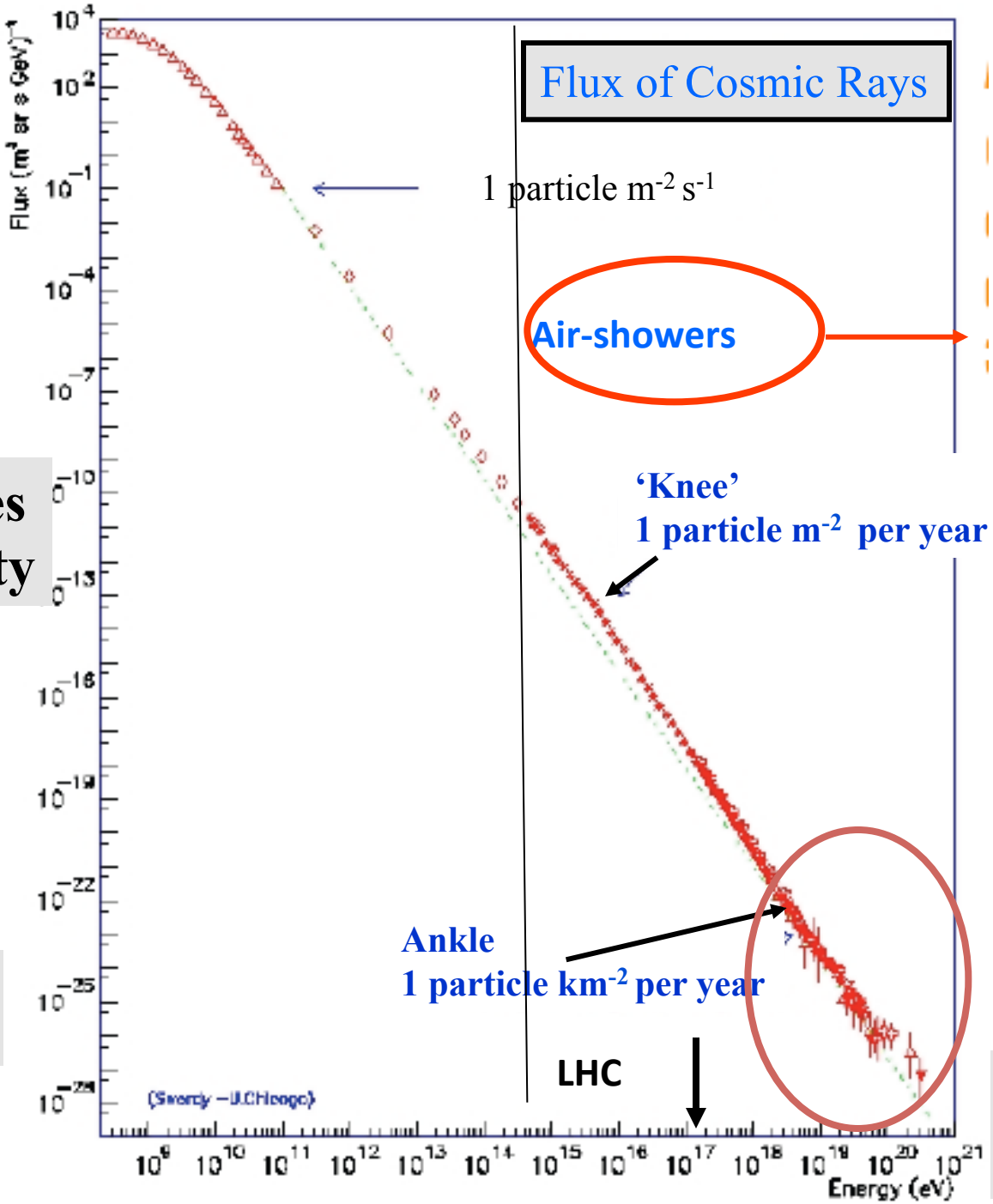
Porter (1958) 92 cm deep

Fig. 1



Neil Porter, at Harwell, was the first to design a water-Cherenkov detector for use in extensive air showers

Neil Porter also showed that human eye could detect light from muon: Nature 1962 – letter in the Psychology section!



25 decades in intensity

S Swordy (Univ. Chicago)

11 Decades in Energy

One of the early motivations for studying cosmic rays using extensive air showers was the expectation that anisotropies would be discovered

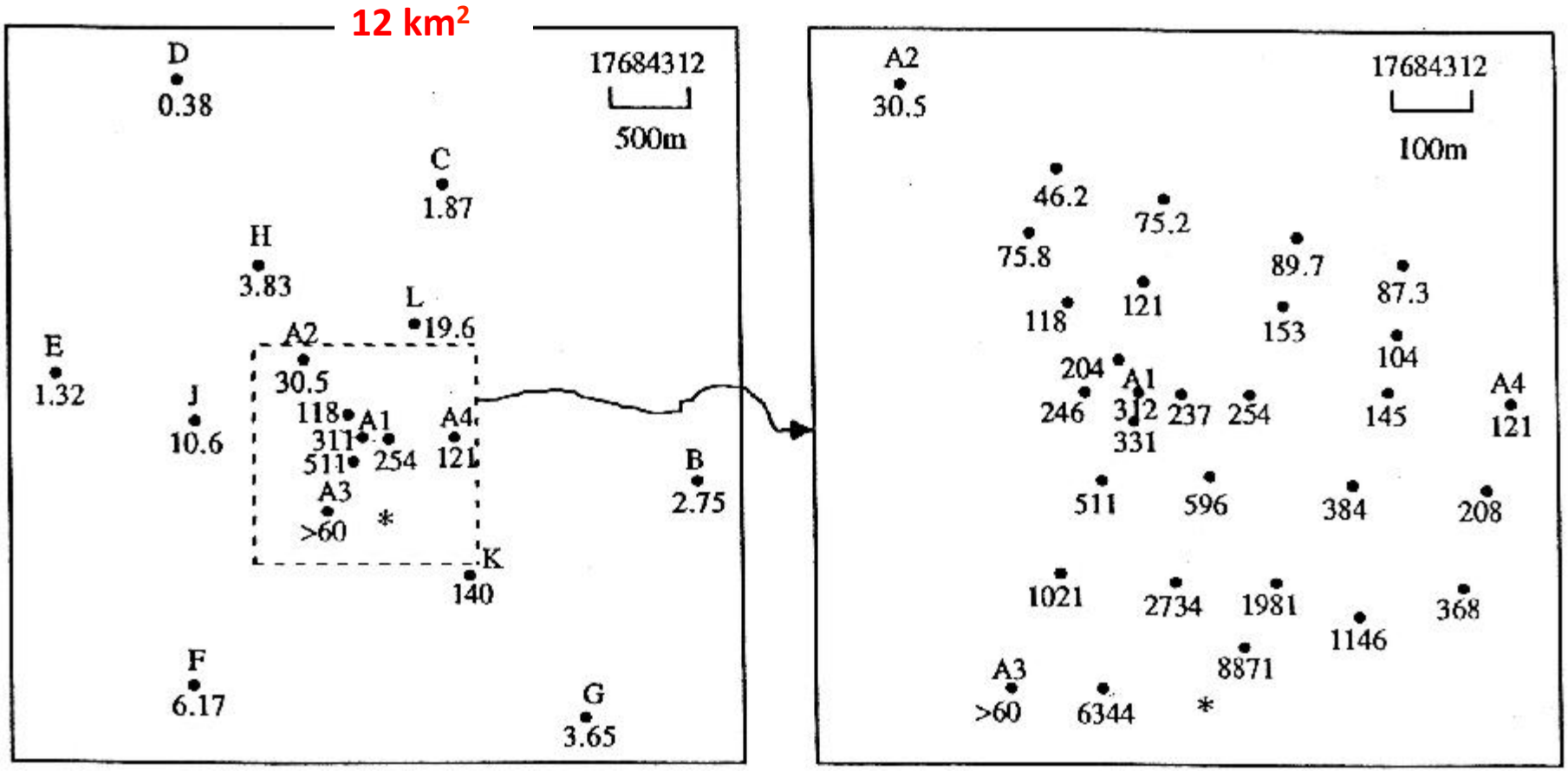
This led to the construction of larger and larger shower arrays
- 'large' meant a few square kilometres

Volcano Ranch (US), Haverah Park (UK), SUGAR (Australia), Yakutsk (Siberia)……

1965: Discovery of 2.7 K cosmic microwave radiation

1966: Prediction of interaction of cosmic rays and CMR

Event with energy of ~ 8 x 10^{19} eV, well above GZK limit



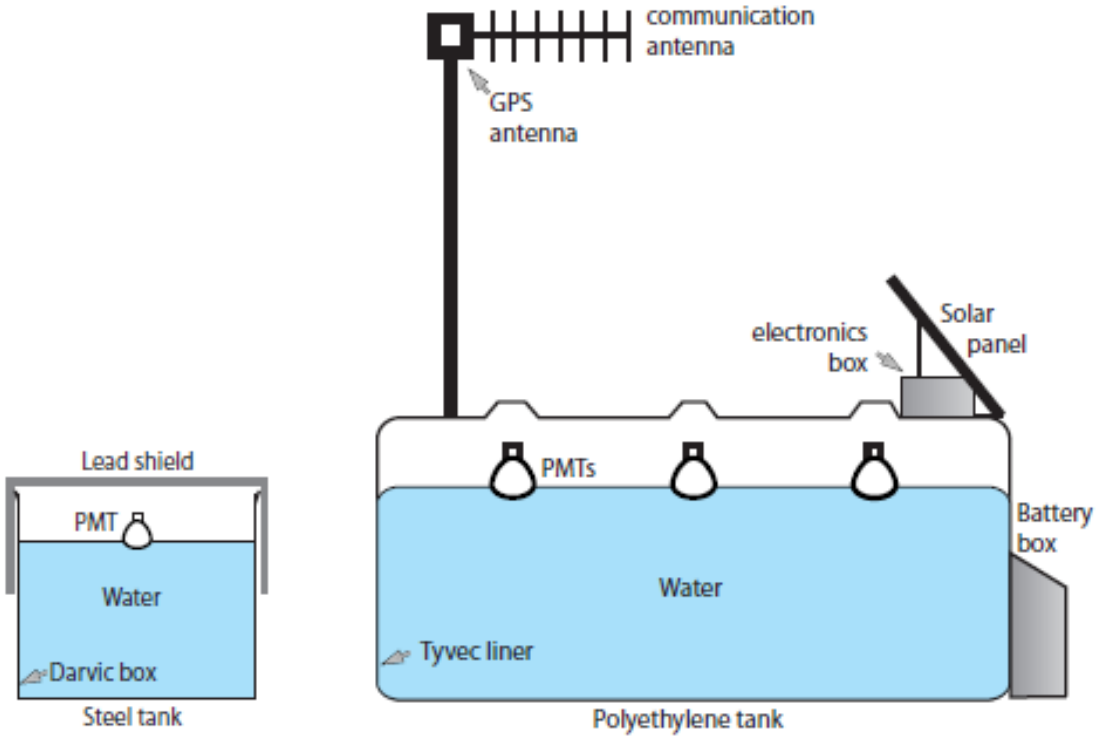
Haverah Park ~ 20 miles north of Leeds, to west of Harrogate, England: operated from 1967 - 1987


End of project party:
water still drinkable after 25
years

Silwood Park (Harold Allan), late 1950s:
this was prototype work for Haverah Park

Haverah Park (J G Wilson et al)

and at Pierre Auger Observatory



1948 – 1958: Decem Anni Mirabiles (iii)

Fluorescence Radiation:

Idea occurred to three or four people simultaneously

- **Chudakov knew of this in 1950s and explored properties in case it was a background for Cherenkov radiation when**

- **Oda and/or Suga developed ideas in Japan**

- **Greisen developed ideas in USA, *perhaps* building on work at Los Alamos - he was at the Trinity test - to detect fluorescence induced by X-rays from nuclear explosions**

Paper describing this work remains classified – Teller Light in title - cited by Utah in NSF application of 1973 for Fly's Eye


Another method

A. Chudakov **(After talk by Suga at La Paz Symposium 1962)**

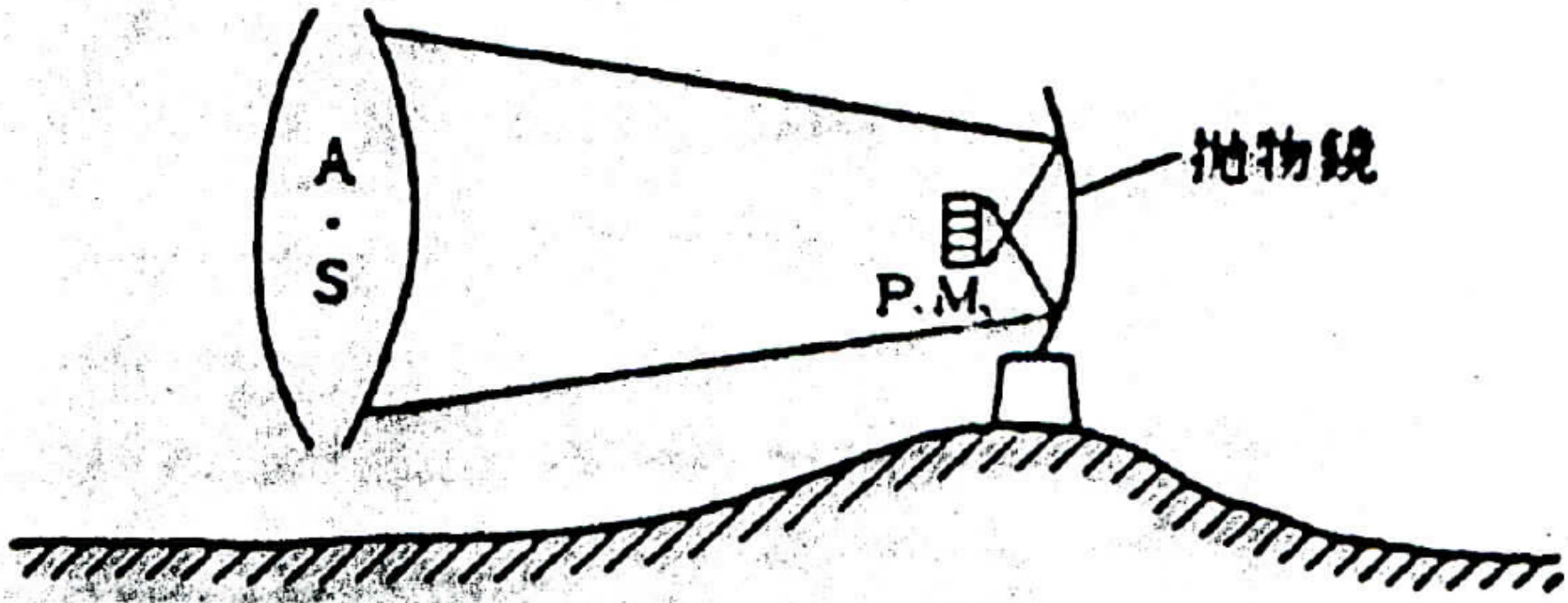
In 1955-1957 I have examined a possibility of using the scintillation of the air in order to record high energy air showers. Some experimental investigations were made to establish the energy threshold of this method.

1) The output of the ionisation light for 1 Mev electrons in air for different density was obtained in the form $y = \frac{1000 \text{ light quanta}}{1 + P/P_o}$ $(\text{Mev})^{-1}$ P-pressure of air, $P_o = 10\text{mm Hg}$, (in some disagreement with presented results).

2) The experimental attempts to improve the ratio $\frac{\text{signal}}{\text{noise}}$ by using filters which absorbed night-sky light, did not give practical results.

3) The proposed project of arrangement was not the same, as presented here and consisted of great number of photomultipliers, looking in zenith with the open angle $\sim 90°$ and separated one from another by a distance about 7 km. In this case the calculated sensitivity of the method occured to be about 10^{20} ev. primary energy. A very complete information about the individual shower (position of the axis, angles, number of particles on different levels of penetration) can be obtained for energy $\gtrsim 10^{21}$ ev.

(Also see Belyaev and Chudakov: Bull Acad Sci USSR 30 1700 1966)



第3図　1958年秉秋シンポジウムで話されたシャワー・カーブ測定の提案

Proceedings of Norikura meeting in Summer 1957, published in 1958 in INS Report

Goro Tanahashi (INS)worked as a post-doc in Greisen's group

On returning to Japan helped the INS group to set up a fluorescence system at Mt Dodaira in Japan.

Detections were reported at the Budapest ICRC (Hara et al 1970) in 1969.

I have a copy of a letter of congratulations that Greisen sent to Tanahashi.

Bruce Dawson (Adelaide) is rather convinced that the Japanese did make the first detections of showers (arXiv 1112.5686)

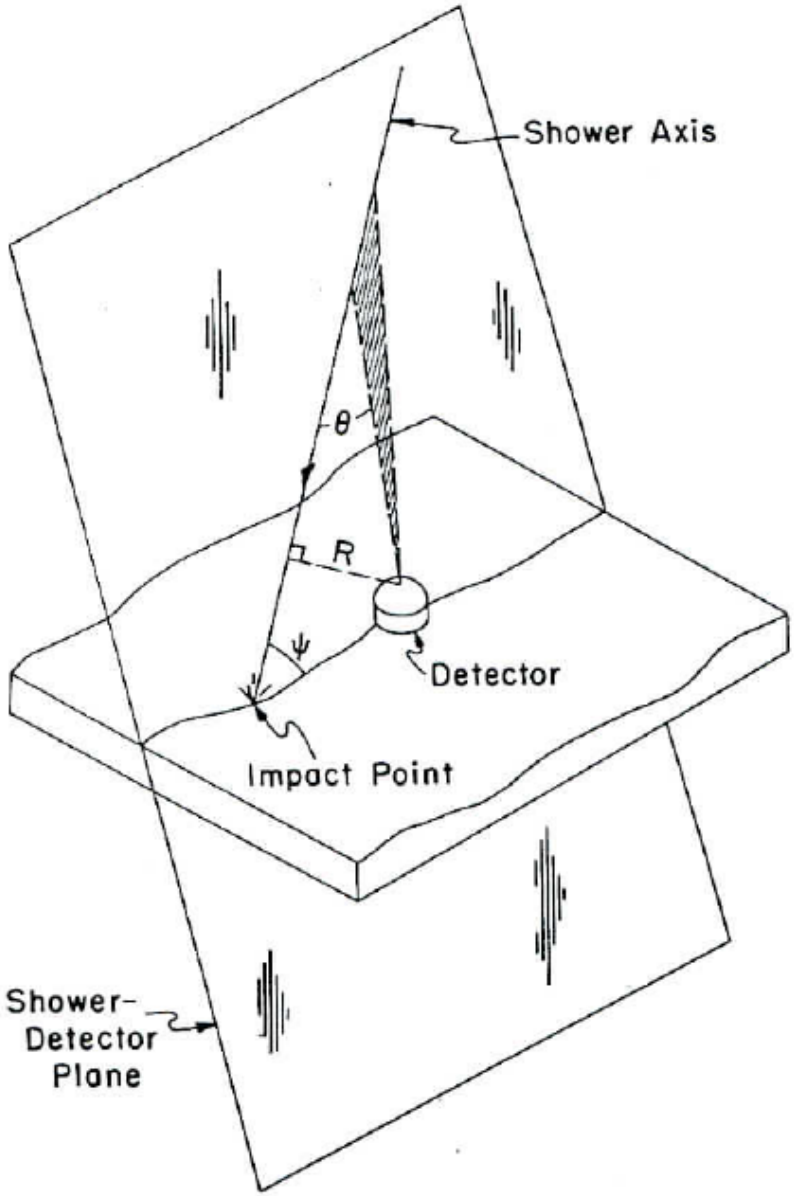


FIG. 1. Perspective view of shower geometry.

Alan Bunner: Masters Thesis, Cornell 1960

It became apparent that the detection of air showers by fluorescent light could only be made successful by (a) operating in a different part of the earth where the weather would permit observing during four times as many hours per year, and where the lower atmosphere is also free of the particles and aerosols *that cause Mie scattering; and* (b) taking full advantage of modern electronic technology in the information processing, so as to separate the air shower patterns from the background noise without loss or degradation of information in doing so. This would be an engineering task of considerable magnitude and cost.

With considerable relief at the termination of a long period of arduous and rather unrewarding effort, the recording stations were shut down in January, 1972, ten years after initiating the proposal that the work be begun.

From Greisen's final report to AEC, 1972

Measurement of Light Emission from Remote Cosmic-Ray Air Showers

H. E. Bergeson, G. L. Cassiday, T.-W. Chiu, D. A. Cooper, J. W. Elbert, E. C. Loh, D. Steck, and W. J. West
Department of Physics, University of Utah, Salt Lake City, Utah 84112

and

J. Linsley
Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico 87131

and

G. W. Mason
Department of Physics and Astronomy, Brigham Young University, Provo, Utah 84602
(Received 28 June 1977)

Extensive air-shower trajectories and sizes (numbers of charged particles) have been measured using an optical detection system at Volcano Ranch Station near Albuquerque, New Mexico. Light produced by atmospheric scintillation and Cherenkov emission by shower particles was measured at distances of 0.7 to ~10 km. The shower sizes determined by the optical measurements are in satisfactory agreement (an average of 10% higher) with measurements by the ground-level scintillation-counter array at Volcano Ranch.

PRL 1977

Linsley proposed that a fluorescence detector should be put into space in 1979.

Eventually led to EUSO (ESA phase A (with Livio Scarsi)
and then to JEM-EUSO

Where would we be without Cygnus X-3?

"History is that certainty produced at the point where the imperfections of memory meet the inadequacies of documentation"

- **September 1982**

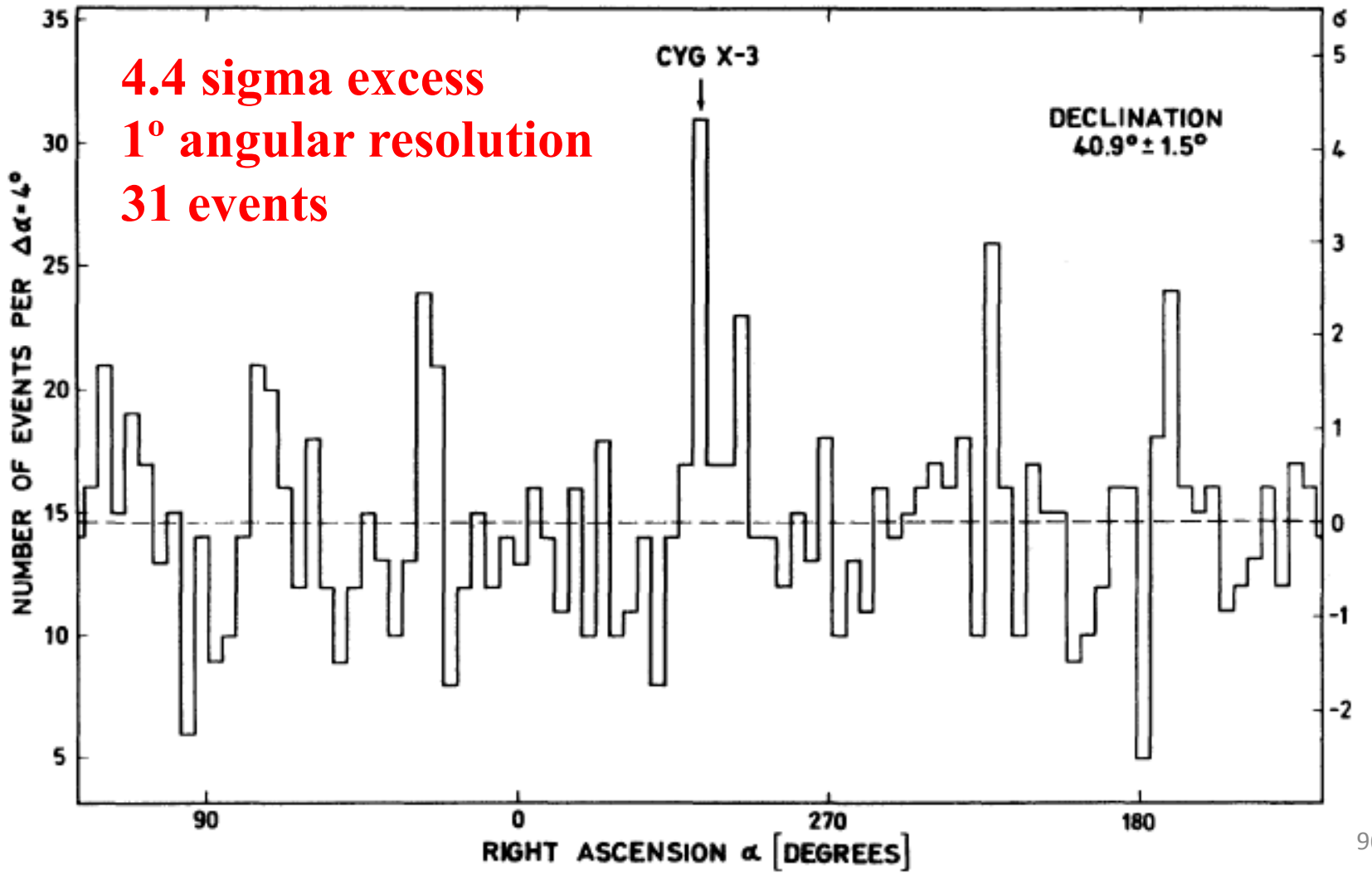
Bar in Rome with Jay Perrett and Wolf-Dieter Dau

during 8th European Cosmic Ray Symposium

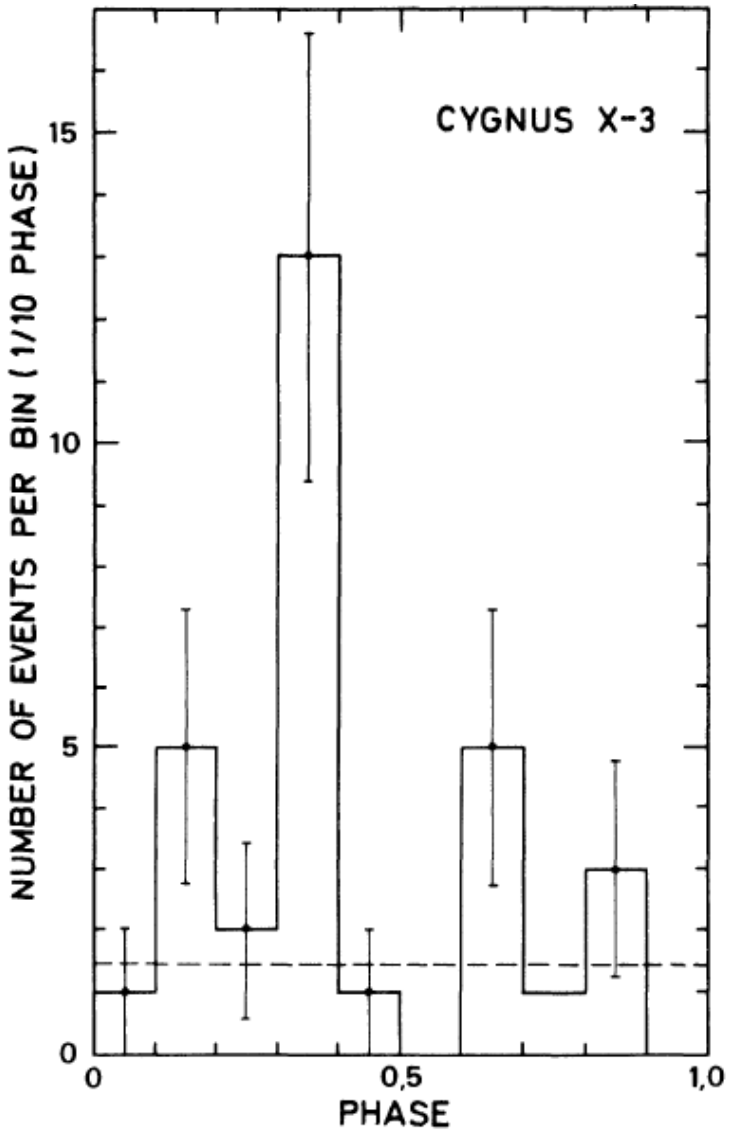
Wolf-Dieter
"I'm surprised that Samorski and Stamm are not here"

Samorski and Stamm: ApJ Letters 268 L17 May 1983

DETECTION OF 2×10^{15} TO 2×10^{16} eV GAMMA-RAYS FROM CYGNUS X-3



31 events



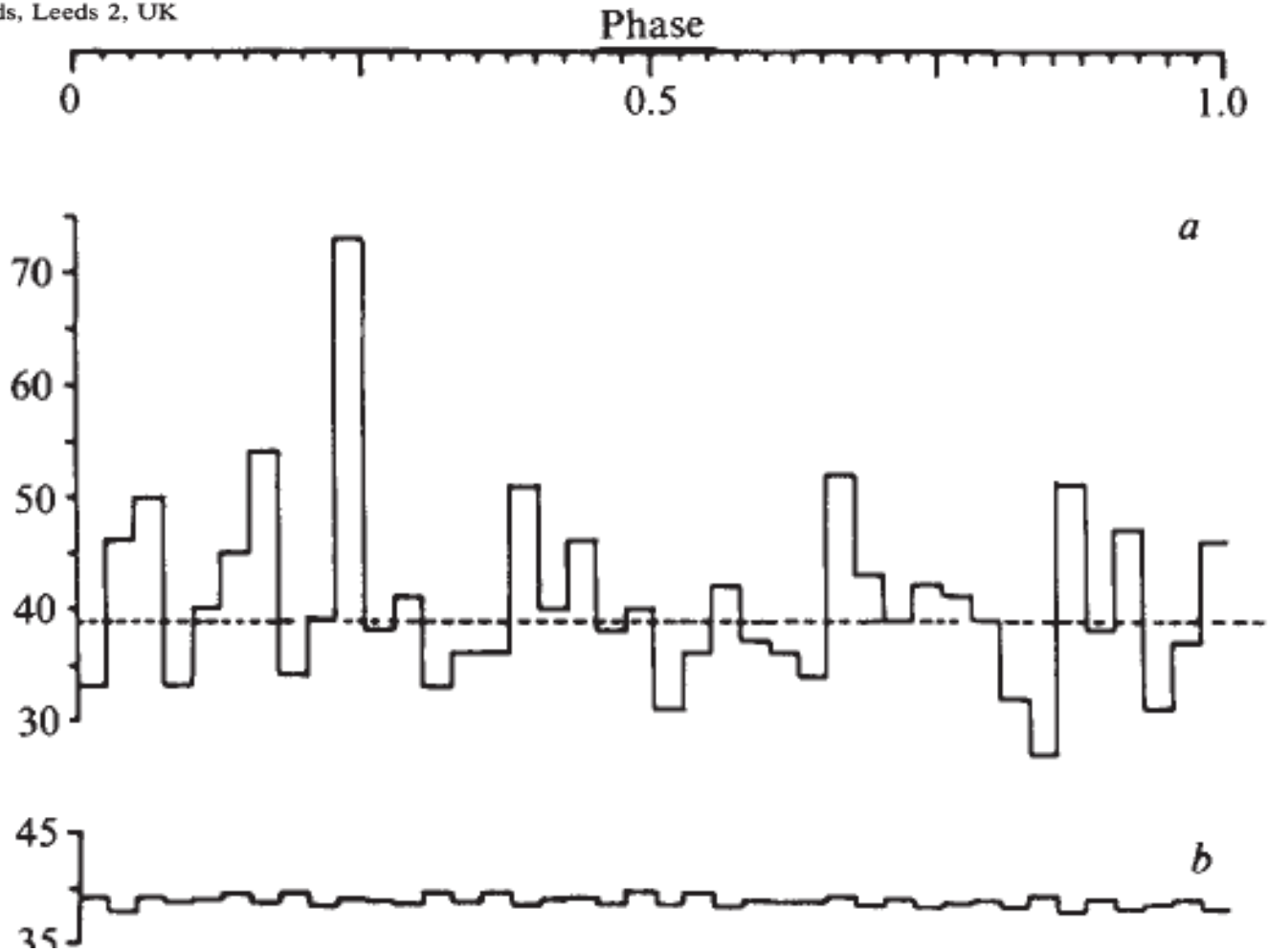
4.8 hours

Observation of γ rays $>10^{15}$ eV from Cygnus X-3

Nature 305 784 October 1983

J. Lloyd-Evans, R. N. Coy, A. Lambert, J. Lapikens, M. Patel, R. J. O. Reid & A. A. Watson

Department of Physics, University of Leeds, Leeds 2, UK



Observations by Haverah Park group appeared to confirm Kiel results

Poorer angular Resolution

1.7 sigma DC

Very small temporal overlap

γ-Ray observations of Cygnus X-3 at energies of 10^{12}eV

Nature Vol. 289 12 February 1981

S. Danaher, D. J. Fegan & N. A. Porter

Physics Department, University College, Dublin, Ireland

T. C. Weekes

Mount Hopkins Observatory, Harvard-Smi
Astrophysics, Amado, Arizona 85640

Apparently significant peak at phase of ~ 0.75

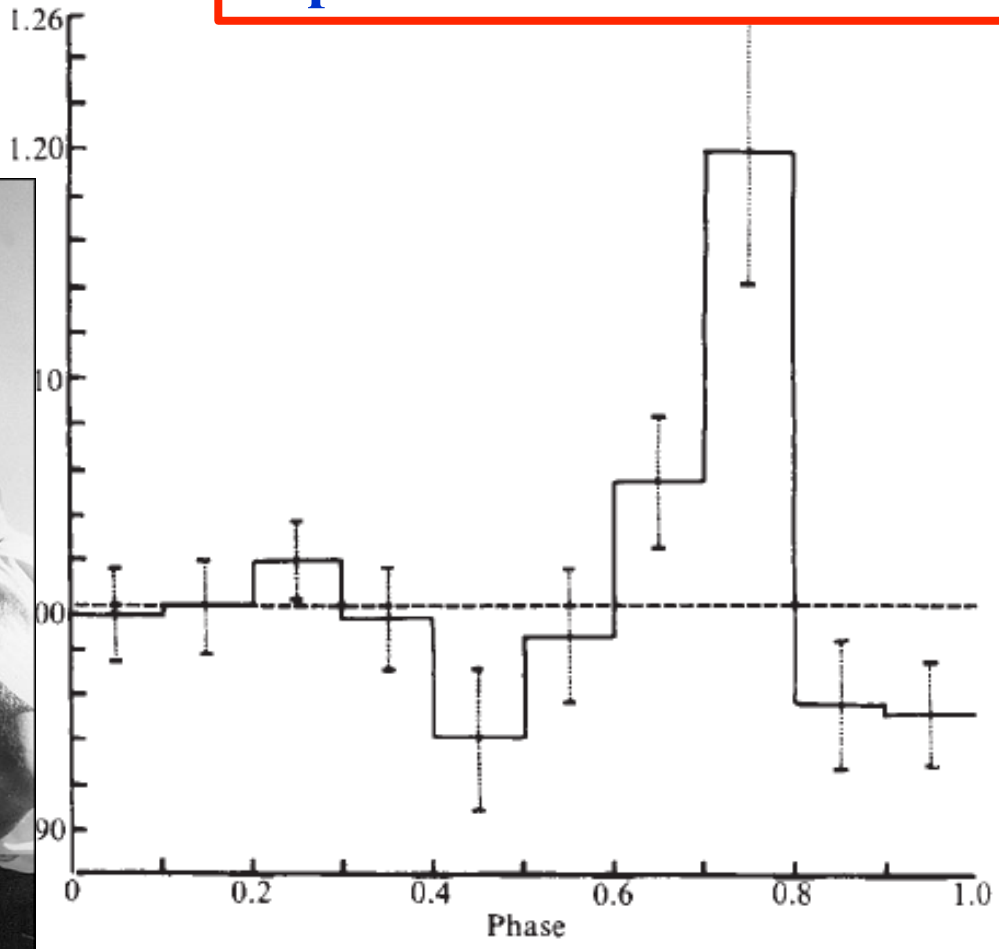
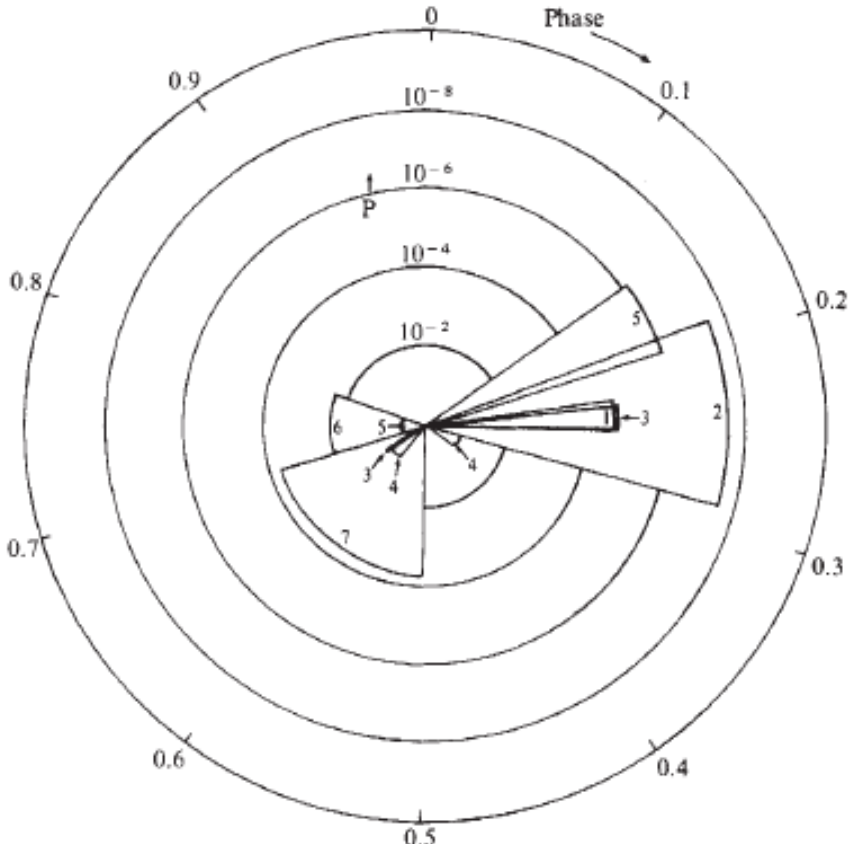
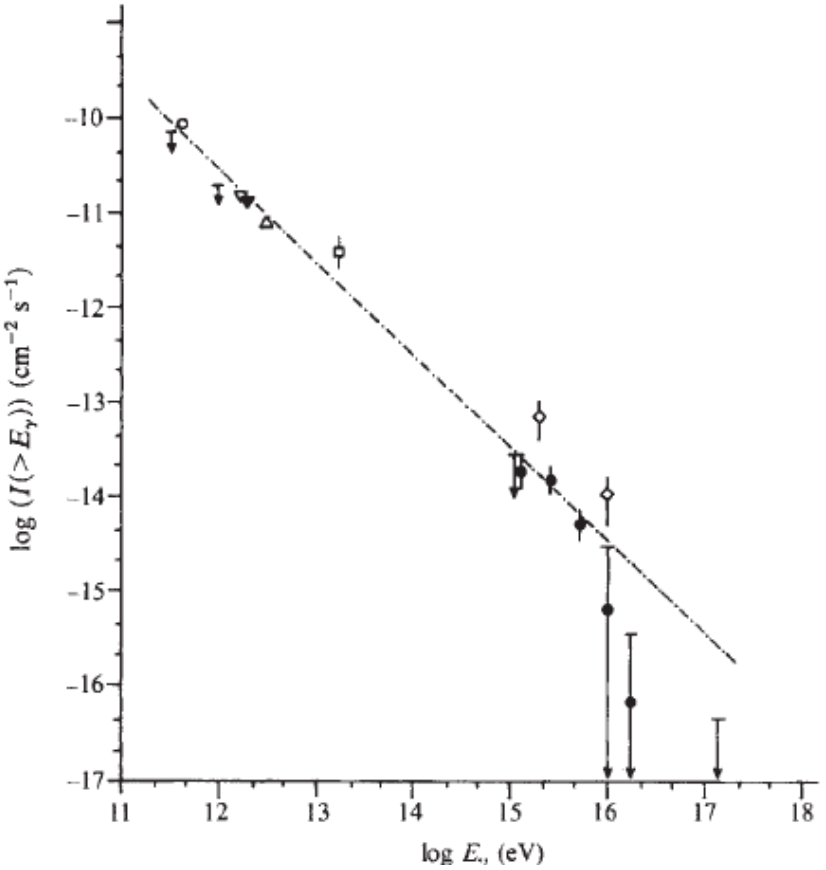


Fig. 1 Phase histogram of γ-ray emission from Cyg X-3.





Often forgotten – before Crab detection in 1989 at TeV energies by Whipple and others - that the air-shower results were consistent with prior claims at TeV energies

Also dramatic radio flares, sometimes on 26 September

Many people from particle physics entered field

In USA: **Wisconsin, Hawaii, Minnesota groups**
at Haleakala and South Pole at TeV energies

Cronin in Dugway with CASA at 100 TeV energies
Yodh at Los Alamos with CYGNUS

In Europe: **Various groups at La Palma from Germany**
Heinrich Meyer
Eckart Lorentz
Werner Hofmann and others

La Jolla Conference 1985: Rapporteur talk/aaw

Explorations with the existing air-shower arrays
- **and many 2 to 2.5 sigma results from objects that were in the beam of an array**

Problems and worries began to appear

- **Muons were found by Kiel group in some of the Cygnus showers**

- **Workers on proton decay experiment in Soudan Mine claimed signals from Cygnus X3**

- **The whole subject became a complete mess**

What happens on Cygnus X-3?

The notion that a periodic X-ray source may also be giving off streams of massive particles which are unknown from accelerator experiments is still, against the odds, alive.

John Maddox

Marshak et al PRL 54 2079 1985

Battistoni et al
Phys Lett 155B 465 1985

Ruddick PRL 57 531 1986
CYGNETS

In principle, the argument is simple enough. Here is a set of data that cannot easily be explained in terms of existing theories, so why not invent a novel particle to account for what may be happening? The innovation in Ruddick's argument is that the primary novel particles (called "cygnets", which is natural enough given where they come from) do not interact directly with terrestrial nucleons to give the muons observed, but instead do so through the intermediary of a second unknown particle, necessarily more massive than the first. Ruddick argues that neither particle need have been observed in accelerator experiments.

The temptation to mock at the invention of a new particle of matter to solve each new problem in astrophysics should be firmly suppressed. By any yardstick, Cygnus X-3 is a remarkable object. Most

Cronin pressed on with CASA

My group went to the South Pole

On La Palma people edged from cosmic rays into TeV astronomy

- **Cosmic rays of intermediate energies**

Jim Cronin: CASA detector:

1 km^2 specifically designed to look for Cygnus X-3

- had signal been there would have seen several events per transit

- supplemented by MIA detectors for muons

- results related to mass composition

- main science return was probably γ-ray limit from Galactic Plane

In 1995, at Rome ICRC, Jim Cronin gave a review talk on h
γ-ray astronomy had evolved in terms of detector develo

• Negative results from CASA which was hugely ensitive than previous shower arrays

• Studies of the Solar Magnetic field w as the Tibet array

• AIROBICC and TeV detecto Plama

• MILAGRO at Los Al

"Old problems and new mysteries have appeared and there are new res armed with enthusiasm and new technology to solve problems and unravel the new mysteries.

This is the legacy of Cygnus X-3."

Another legacy was the Pierre Auger Observatory

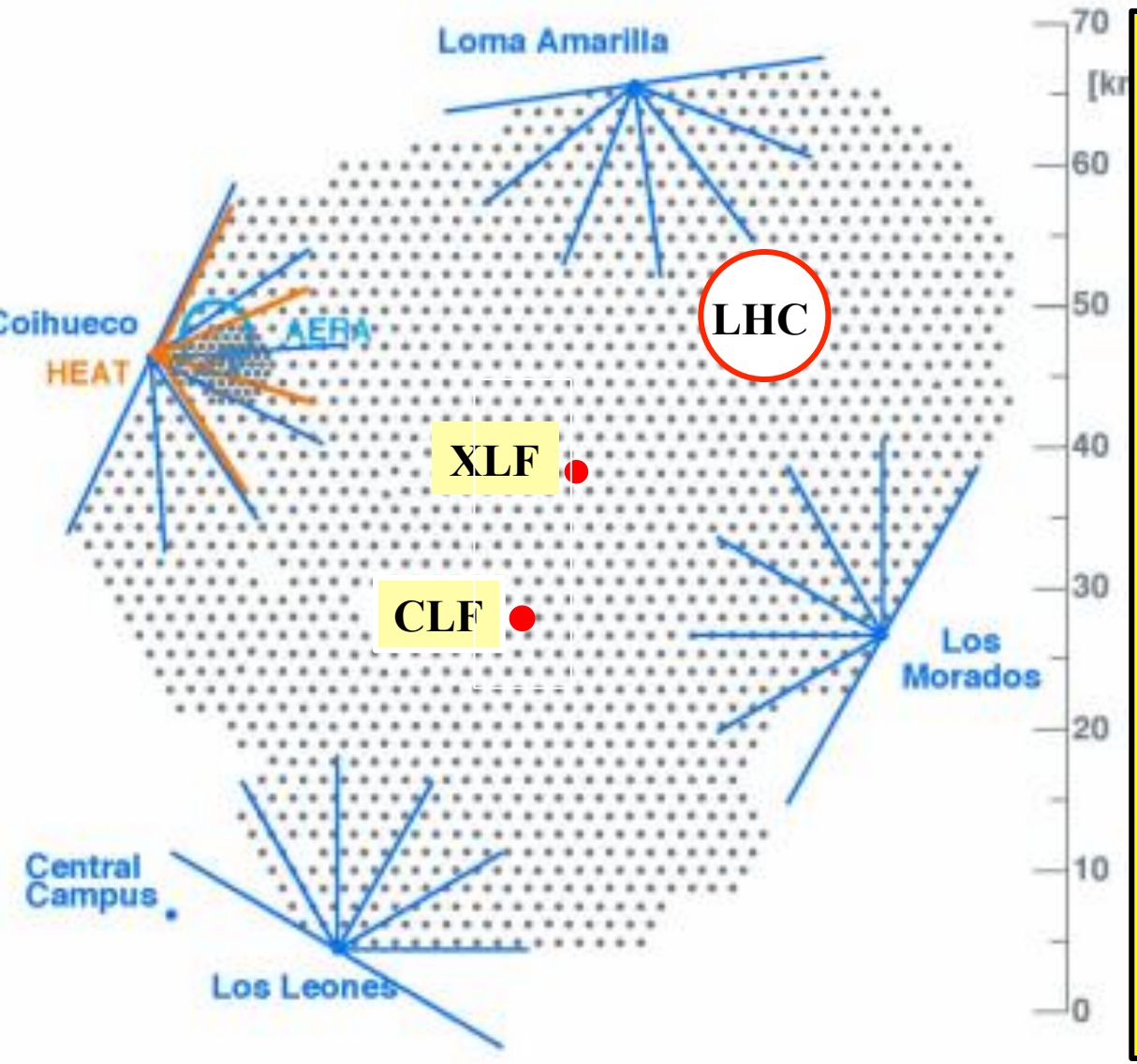
Development of the Auger Observatory (August1991 – yesterday)

The Pierre Auger Collaboration

Czech Republic	Argentina
France	Australia
Germany	Brasil
Italy	Bolivia*
Netherlands	Colombia*
Poland	Mexico
Portugal	USA
Rumania	
Slovenia	**Associate Countries*
Spain	
(United Kingdom)	~ 400 PhD scientists from
	~ 100 Institutions in 17

Aim: To measure properties of UHECR with unprecedented precision to discovery properties and origin of UHECR

The Pierre Auger Observatory



- 1600 water-Cherenkov detectors: 10 m^2 x 1.2 m
- 3000 km^2
- Fluorescence detectors at 4 locations
- Two laser facilities for monitoring atmosphere and checking reconstruction
- Lidars at each FD site
- Radio detection at AERA
- Muon detectors – buried

Getting to know Jim Cronin

Les Arcs: March 1981

Leeds: November 1986

European Cosmic Ray Symposium: Nottingham, UK, 1990

- **There are probably events beyond the GZK steepening at ~ 5 x 10^{19} eV**

- **Arrival Directions seemed to be very uniform**

"The problem is lack of exposure: while it has been clear for many years 1000 km^2 of instrumented area is needed, but progress towards getting this has been slow."

"The experimental problems are challenging and subtle but certainly soluble. All that is need is dedication, money and patience."

Jim Cronin: Dublin ICRC August 1991

"You're not nearly ambitious enough:

We should build 5000 km^2"

This was the starting point of the what has become the Pierre Auger Observatory

Early name – P5000 – or Giant Array Project

Jim had sabbatical leave in Leeds for 4 months in late 1991.

His idea had been to work on some CASA data that seemed to suggest it might be possible, perhaps making use of the Monte Carlo codes of Michael Hillas, to deduce the flux of protons at ~ 100 TeV.

In fact, most of the time was spent on early planning for what became the Auger Observatory.

Some test measurements were made at Haverah Park and contacts were developed with our Electronic Engineers (led to GPS studies, largely by Clem Pryke).

- **Discussions entirely about a surface array**

- **How to do the timing**

- **Lots of Monte Carlo calculations (lines of code)**

- **How to collect data from remote stations**

Nuclear Physics B (Proc. Suppl.) 28B (1992) NOVEMBER 1992

Major Meeting in Paris in April 1992 organised by Murat Boratav

COSMIC RAYS ABOVE 10^{19} eV - 1992

Proceedings of the International Workshop on Techniques to Study Cosmic Rays with Energies Greater than 10^{19} eV

Paris, France
22–24 April 1992

Edited by

Murat BORATAV
University of Paris 6
Paris, France

James W. CRONIN
University of Chicago
Chicago, IL, USA

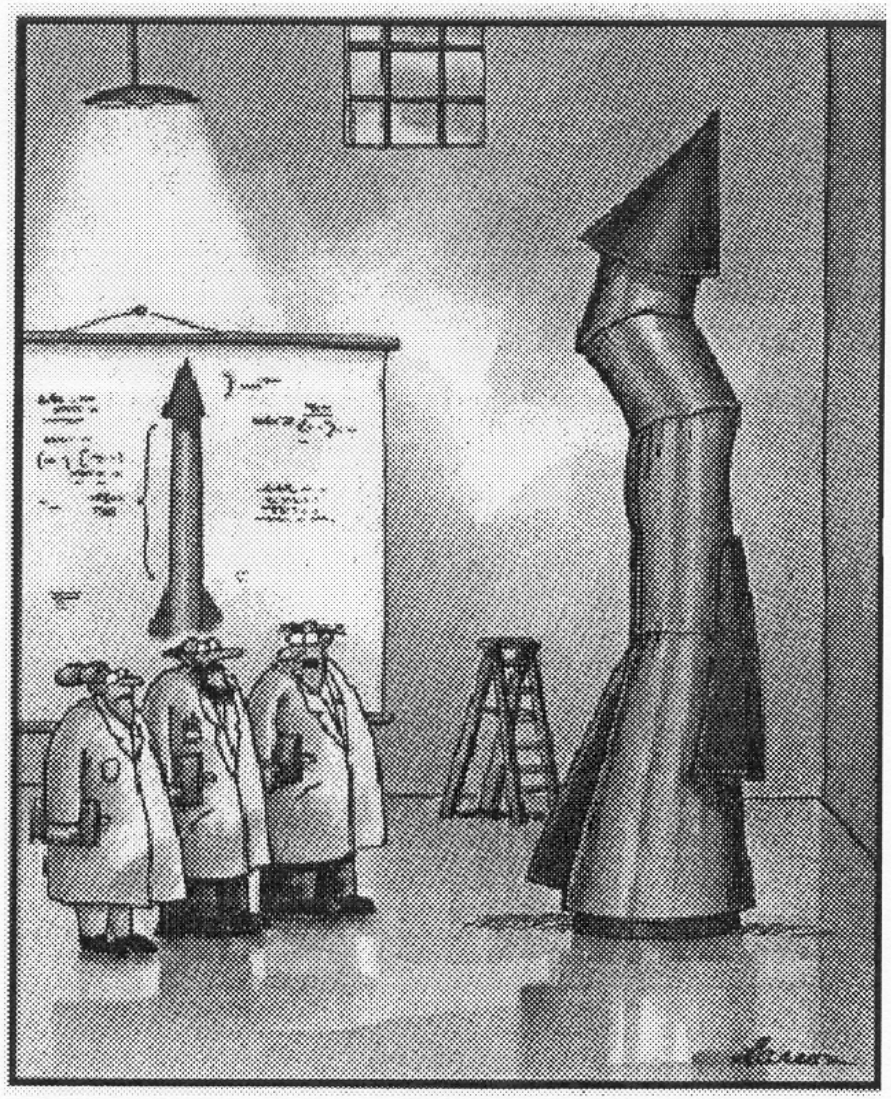
Alan A. WATSON
University of Leeds
Leeds, United Kingdom

Followed by workshops in Adelaide (January 1993) and Tokyo (September, 1993)

Some reflections post-Paris

- **Really the French were not very keen**
- **German situation was very complicated**
- **Italian groups (mainly Palermo and Naples) were rather reluctant to get involved under Jim's leadership as John Linsley had different ideas as to how things should be done**
- **From the UK, this was our only hope!**

How did it all start?



t's time we face reality my friends: we should keep to ground detectors."

For the first eighteen months or so, Jim and I were in favour of using only a ground array.

This was probably our worst piece of misjudgement throughout the whole enterprise.

Situation changed after Tokyo Workshop in Sept 1993 – convincing arguments particularly from Bruce Dawson and Paul Sommers

MAJOR PROBLEMS TO BE OVERCOME

- **LACK OF MONEY TO DO ANYTHING**
- **Fight for recognition that the project was worthy of attention**
- **Site surveys**
- **Develop a collaboration of critical mass and competence and with money to build a capital project of ~$100M**
- **How was the worth of the project to be assessed?**
- **A vulnerability, as with neutrino astronomy and, to a lesser extent, ground based gamma ray astronomy at that time, that there are no hard theoretical numbers demanding the construction of an instrum of a certain size**

- **Contrast search for the W and Z, or the Higgs particle**

Coping with the lack of Money

Small amounts of money for travel and limited R&D from budgets of interested Laboratories (e.g. Leeds: sale of lead previously used for muon shielding and Aluminium lids)

UNESCO: Jim, with Murat Boratav, persuaded Director General to give significant support for three years (travel, visits by scientists from developing countries to design studies)

Private donors whom Jim knew:

Robert Galvin, son of founder of Motorola
David Grainger, benefactor of University of Chicago

Jim could get through doors that I could never even have knocked on!

August – September 1994

Visit to Far East with Jim

Japan
South Korea
Hong Kong
China
Vietnam – **Vice-President of the Communist Party**
Australia

Naming of the project:

A Unique **G**iant **E**AS **R**ecorder → A.U.G.E.R

→ Auger

Pierre Auger, Paris 1981

Design Workshop in FNAL

Role of Fermilab Director, John Peoples

"I do not remember a time when there was any doubt that we would participate in this project. John said at the time that had recently read a book that was about or touched on the question of the source of cosmic rays.

He was convinced that this was important work.

He agreed to support the workshop, provided space and people to help me organize it. There was a cost to John in all of this as there was a lot of hostility at Fermilab toward resources diverted from anything other than maintaining the machine and the big collider detectors. This hostility was running particularly high because of the perceived number of people in the Computing Division working the Sloan Sky Survey".

Paul Mantsch, Auger Project Manager

The Design Study

Studies of various surface detector designs:

RPCs, water-Cherenkov, scintillators, radio….
"Let a thousand flowers bloom…."

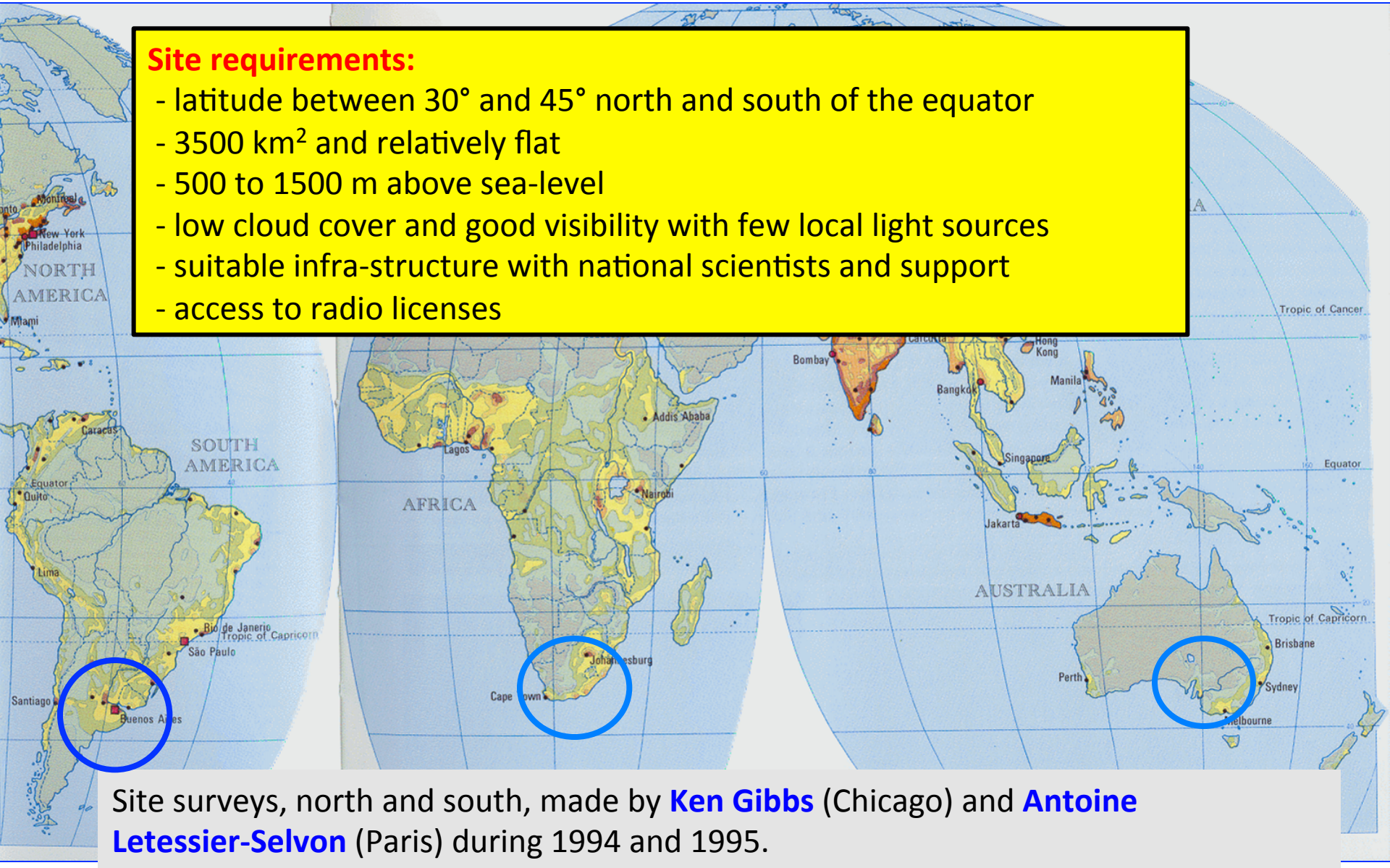
Hybrid approach: ground array and fluorescence detectors - chose water as surface detector

Very extensive Monte Carlo calculations

Two sites to give all sky coverage

Each site ~3000 km^2 : site survey was contemporaneous
Approximate cost ~$100M

Design Study document completed in October 1995



Site surveys, north and south, made by **Ken Gibbs** (Chicago) and **Antoine Letessier-Selvon** (Paris) during 1994 and 1995.

Argentina selected for South during meeting at UNESCO in November 1995

UNESCO
November 1995

President *Republic of South Africa*

Dear Sir

Scientific and engineering achievements are the cornerstones upon which the future generations in Southern Africa will attain their goals for the successful development and upliftment of our peoples. There is consequently an urgent need for South Africa to be at the leading edge of expertise in the world of technological endeavour.

Recently I have been informed of the Giant Air Shower Array project which is truly an international project destined to become one of the scientific highlights of this and the next decade and that South Africa has one of the favoured sites in the southern hemisphere.

I am placing my full weight behind the sitting of the project in South Africa as it is clear to me that it will provide an exciting new focus for our young potential scientists and enhance our Reconstruction and Development Program. Just as important however is that our own expertise could significantly contribute to the international community in the spheres of science, training and facilities.

As a developing country with a good foundation in the sciences and related technologies, South Africa will be in a favourable position to extend our knowledge base into the Southern African subcontinent to the mutual benefit for all should we be successful in being awarded the project.

I wish to reassure you of our total commitment should you consider South Africa as the site for this prestigious undertaking.

With best wishes to you and your colleagues.

Yours sincerely

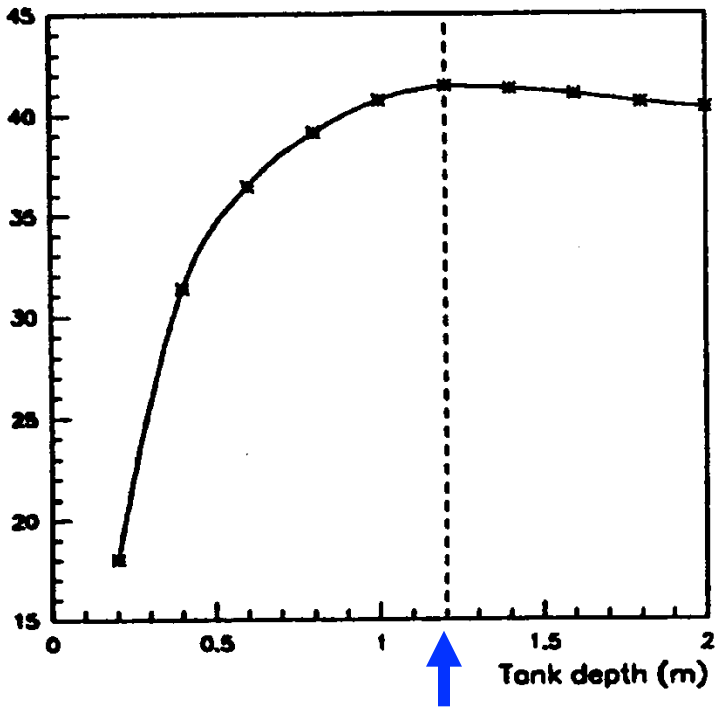
N R MANDELA

Dr M Boratav

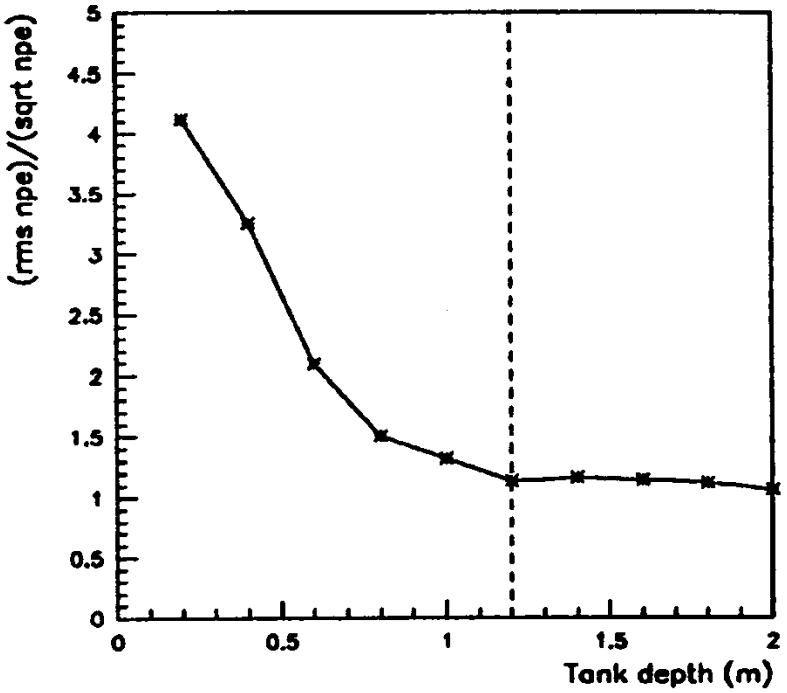
Alan/Terry - it seems 1.2m is close to optimum depth for a water C detector!

Glenn (& Pryke)

Tank depth studies (vertical muons) 96/02/19 12.40



N_{pe}



Haverah Park tank depth

Assessment of the Project (November 1995)

No host institution (unlike new projects at CERN, ESA, ESO, FNAL)

- better now in Europe with APPEC?

Formed own Review Committee

W I Axford (MPI: Director, Katlenburg-Lindau): Chair
R Cowsik (Indian Institute for Astrophysics, Bangalore, India)
M Demassieux, ENST (France)
R Eckers (Autralian National Telescope, Australia)
M-T Koshiba (Japan)
J Steinberger (CERN, Switzerland)

"But of course it is a favourable report: you chose the committee"

- an agency that will remain anonymous

The Search for Funding in the USA

All countries watched what the US was doing

Significant promises of funding from Argentina, Brasil and Mexico

US assessment by SAGENAP committee:

DIFFICULT! Third time lucky (April 1998)

BUT:

BUILD ONLY ONE ARRAY and GO SOUTH

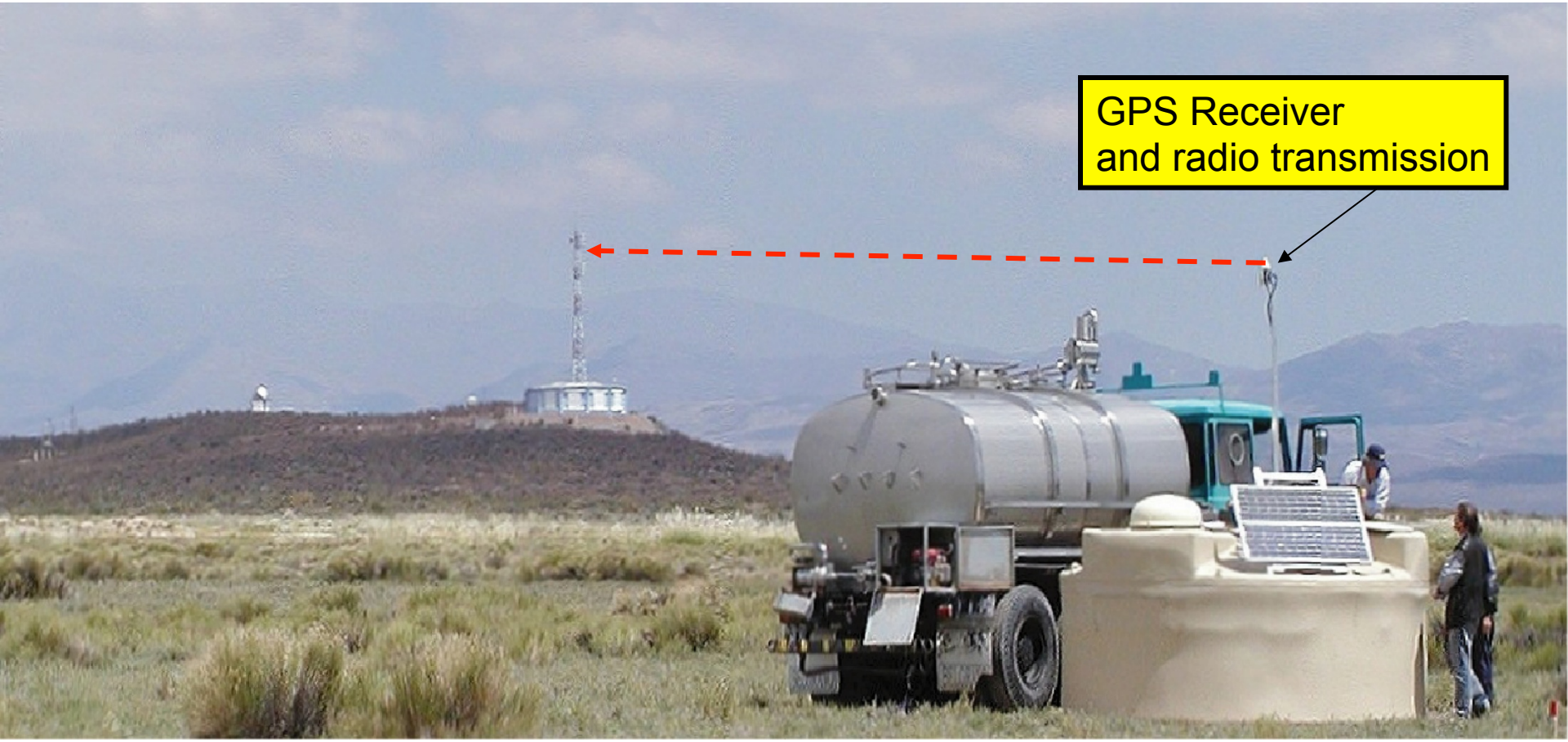
After US funding announced in 1998, funding from European Countries came relatively quickly.

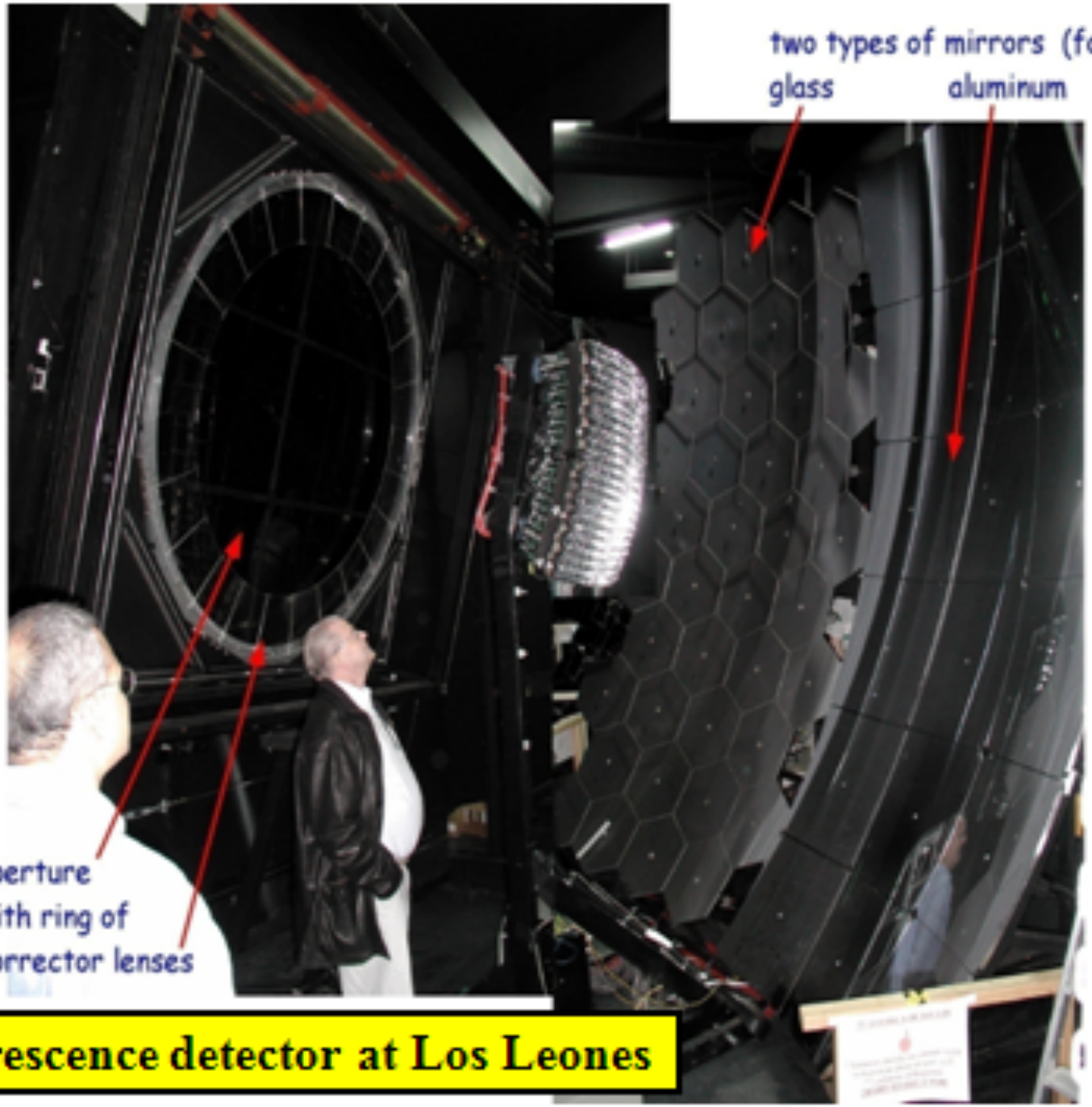
This allowed International Agreements to be signed

Ground breaking Ceremony in March 1999

17 March 1999: Ground Breaking Ceremony

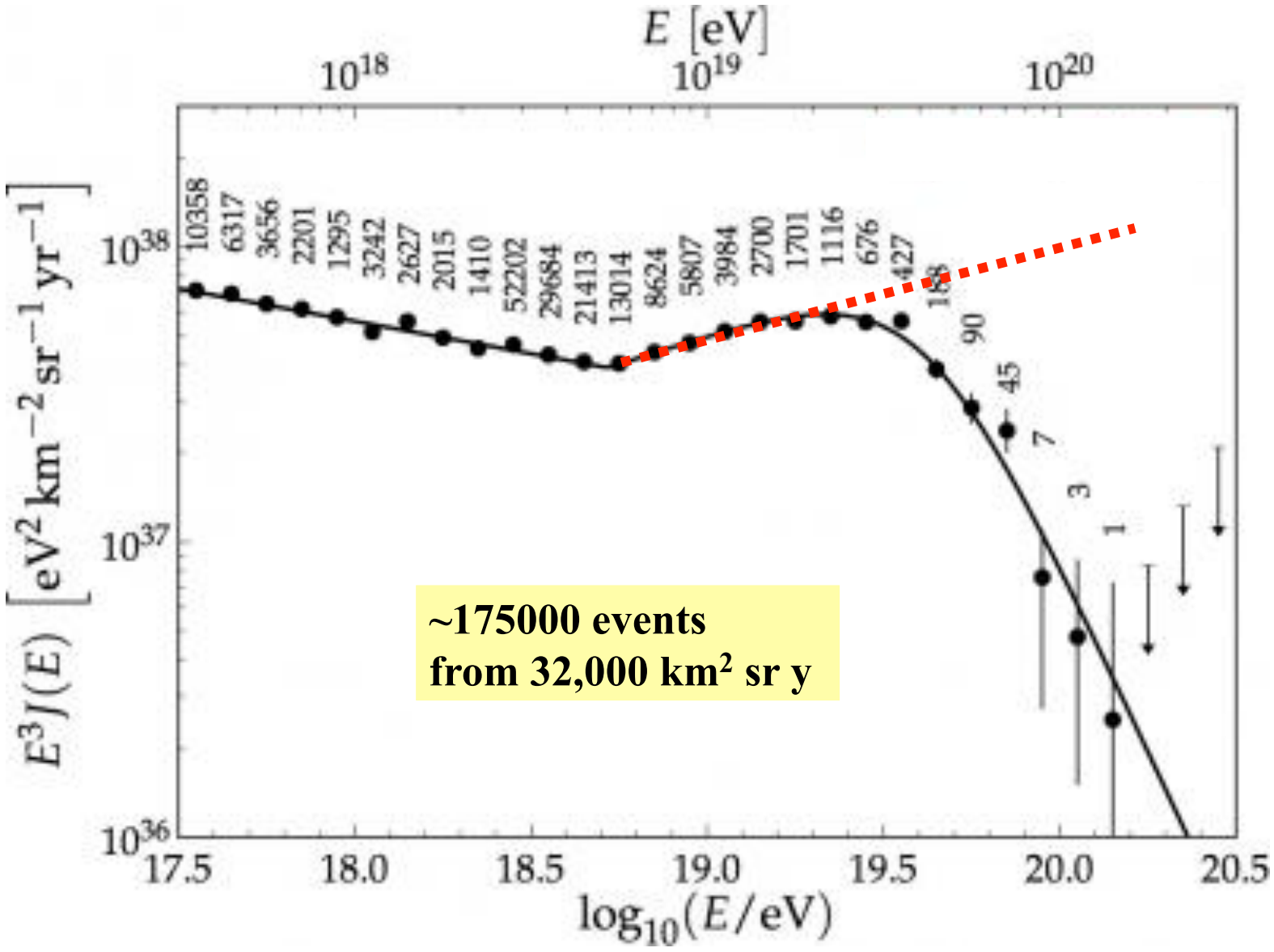
Ground Breaking Ceremony 17 March 1999

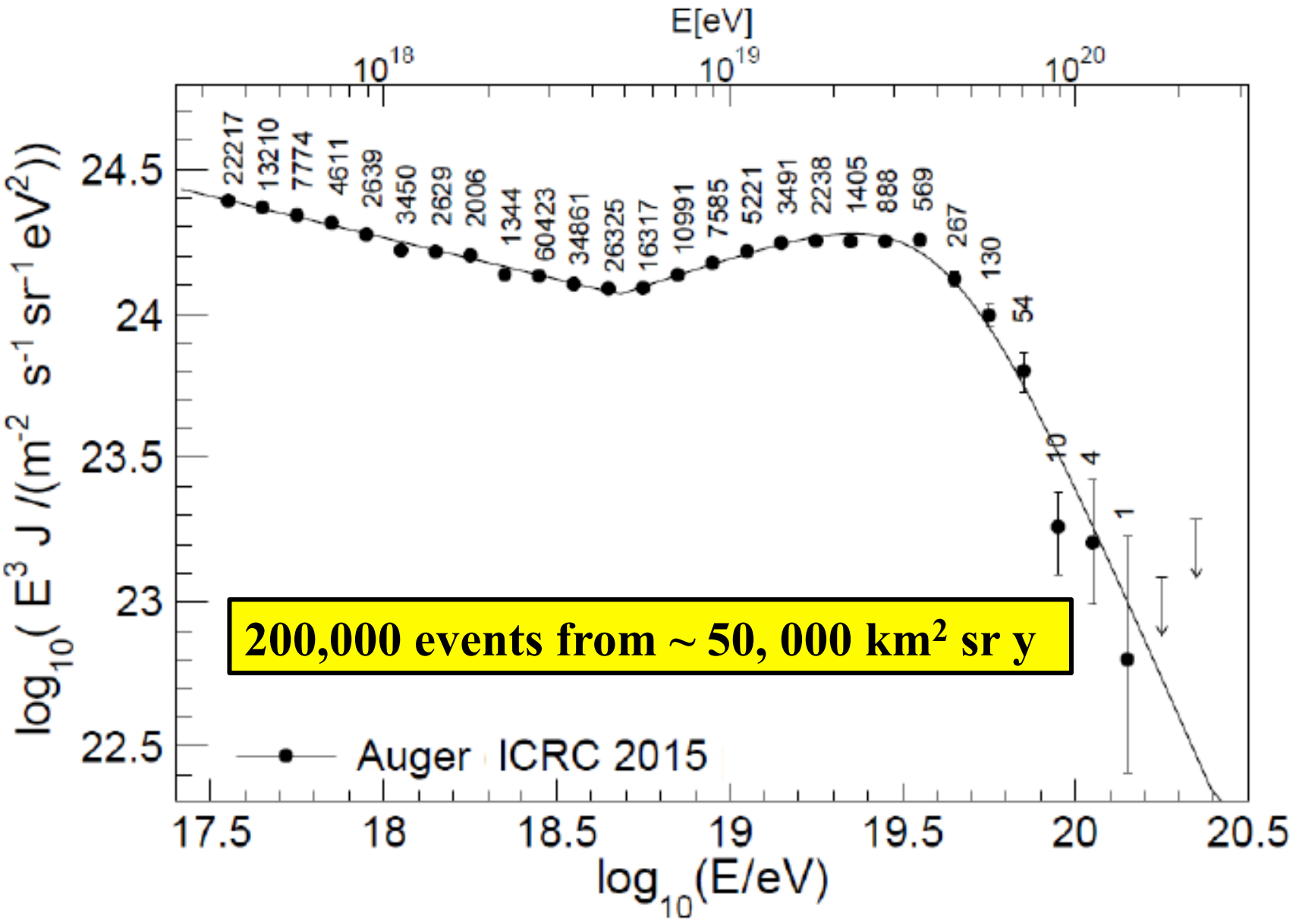

GPS Receiver
and radio transmission



Fluorescence detector at Los Leones

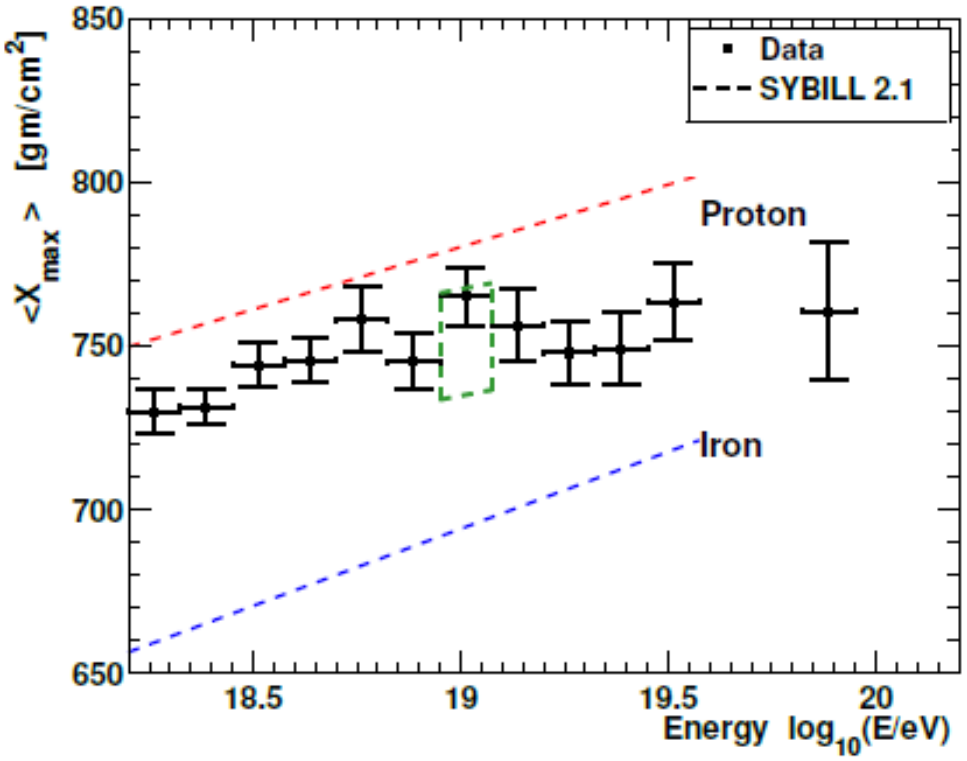
Auger Energy Spectrum from Vertical Events:2013




E[eV]
10^{18}
10^{19}
10^{20}
22217
13210
7774
4611
2639
3450
2629
2006
1344
60423
34861
26325
16317
10991
7585
5221
3491
2238
1405
888
569
267
130
54
10
4
1
24.5
24
23.5
23
22.5
$\log_{10}(E^3 J /(m^{-2} s^{-1} sr^{-1} eV^2))$
200,000 events from ~ 50, 000 km^2 sr y
Auger ICRC 2015
17.5
18
18.5
19
19.5
20
20.5
$\log_{10}(E/eV)$

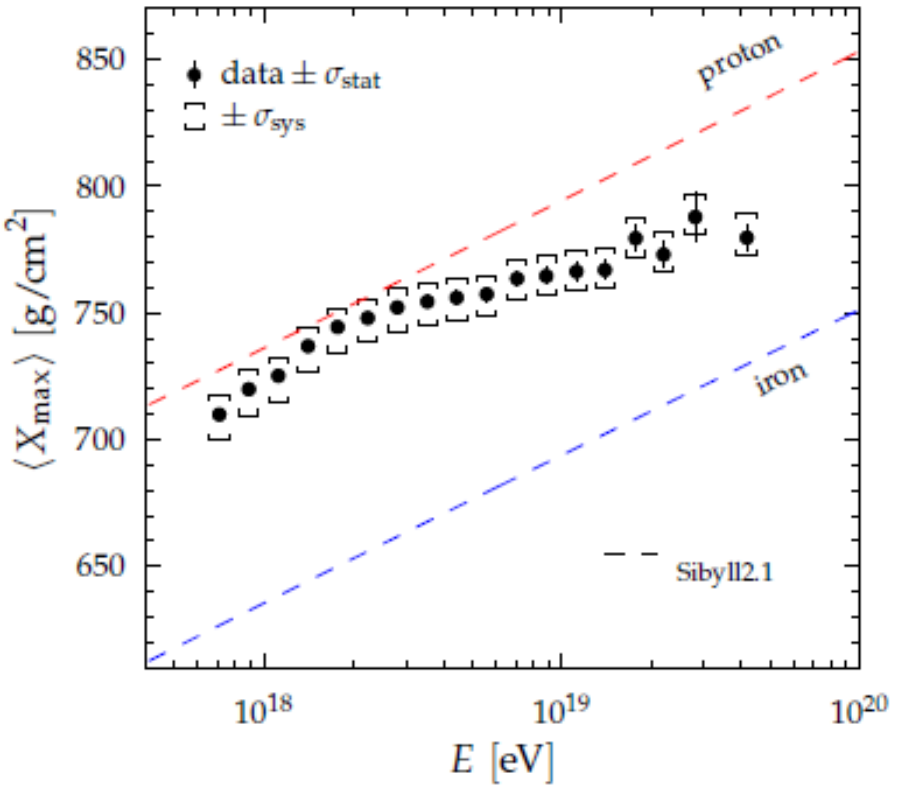
Average shower maximum

Telescope array



- EAS simulations are folded with detector response (det. resolution and bias introduced)
- Maximized statistics

Auger



- Unbiased estimate of X_{max} and higher moments
- Reduced statistics

4 m² Scintillators above Water-Cherenkov detectors

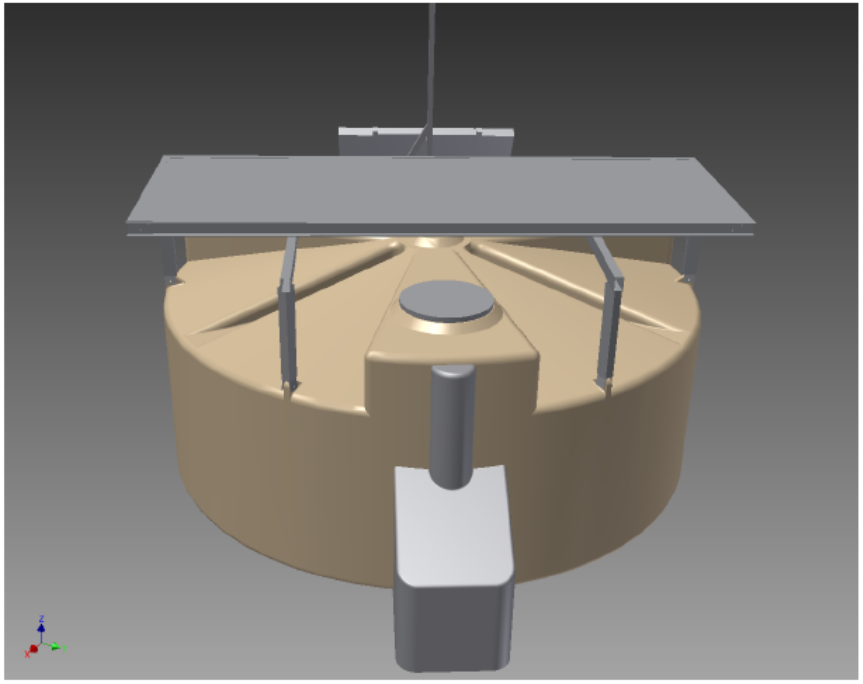
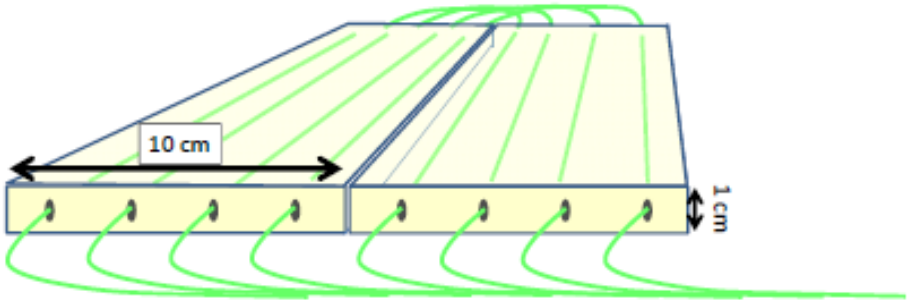


Figure 4.1: 3D view of a water-Cherenkov detector with a scintillator unit on top.

Scintillators respond to muons and electromagnetic component

Water-Cherenkov detectors absorb all of the em component and are fully sensitive to muons

It has been demonstrated with simulations that techniques exist to separate out the muon component



Buried Muon Detectors (1.3 m below surface)

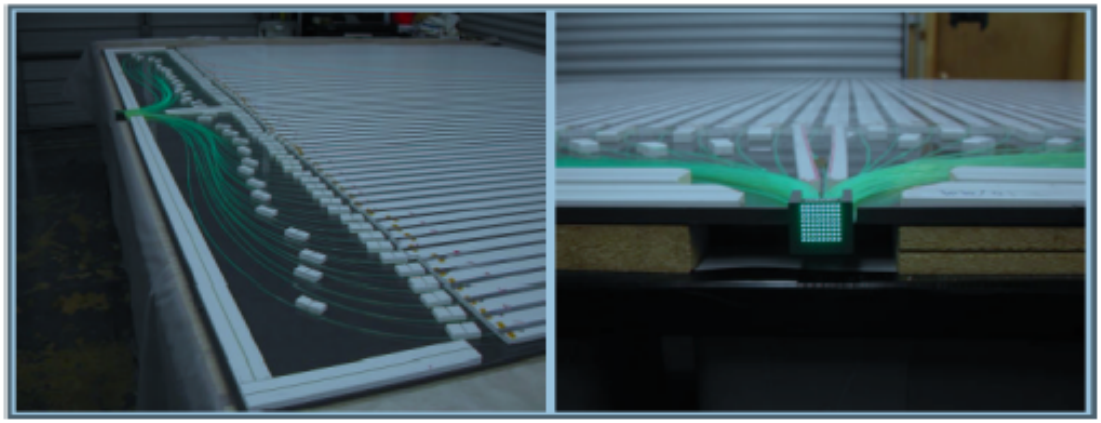
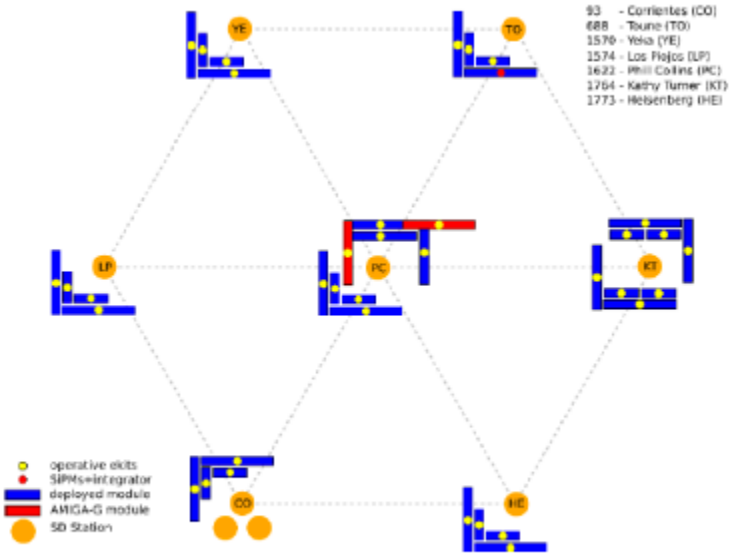


Figure 5.1: Scintillators strips: left: general mounting in the PVC housing, right: detail of the 64-pixel optical connectors.



60 x 20 m^2

Figure 5.2: AMIGA unitary cell.

Long-term Future

Auger Observatory is at least one-order of magnitude too small

Planned space projects are very important: is there something interesting to measure beyond the present questions?

Compare SPS and LEP

Young people working together and getting to know each other is necessary for any future World Observatory: Joint Working Groups – great success

How can a giant Observatory be created?

How can we take this concept forward?

Timescale is surely at least 10 years to begin