UHECR2022: L'Aquila: 3 – 7 October 2022

Historical Remarks on UHECR Measurements with EAS Surface Detector Arrays

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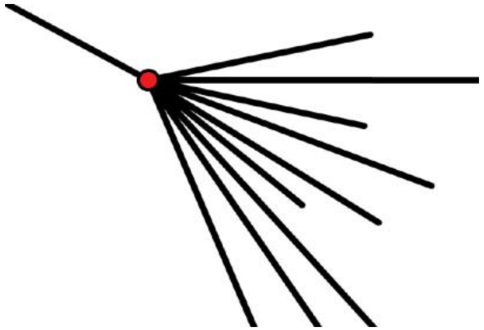


Cosmic-ray physicists, since the time of Victor Hess, have always being studying Ultra High-Energy Cosmic Rays – the highest energy particles in the Universe – but they didn't always know this

As time has passed, the energy of UHECRs studied has increased

– from ~10 GeV in the early 1930s to over 100 EeV since 1963

Outline:

Evolution of the field, trying to show the importance of new techniques and ideas

- **with attention to arrays of surface detectors – air-shower arrays**

Won't discuss the Telescope Array or the Auger Observatory – not yet history!

Will concentrate on the 'LEGACIES' from different projects

The Geiger Counter was the tool that led to discovery of extensive air showers

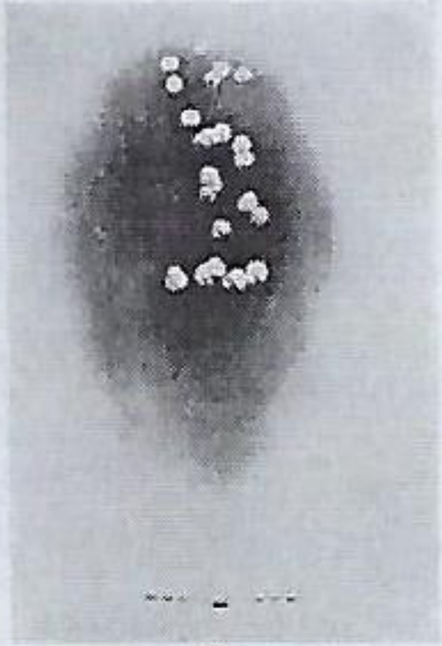
- Rossi – serendipitously (1934) *‘sciami’*
- Schmeiser and Bothe (1938) - looking for air showers *“Luftschauer”*
- Kolhörster, Matthes and Weber (1938) – looking for air showers
- Pierre Auger (1938) – serendipitously - using improvements to resolving time of coincidence circuits by Roland Maze

Apparently unaware of the German work

– uniquely, Auger was in a position to explore the phenomenon further

Auger et al. extended the energy scale to ~1 PeV: reported in Chicago in 1939

B



C

P. Auger

BALLOON FLIGHT OF JANUARY, 1943, CONDUCTED BY THE AUTHOR, SCHEIN, AND ROGOZINSKI FOR THE MEASUREMENT OF EXTENSIVE (OR AUGER-) SHOWERS IN THE STRATOSPHERE

A. The balloons are assembled on Stagg Field at the University of Chicago, Chicago, … for the w…

B. …

C. … the balloons is the frame supporting the counters and recording apparatus.

Auger et al. made an important balloon flight rising to 15 km (~120 g cm^{-2})

INVESTIGATION OF EXTENSIVE ATMOSPHERIC SHOWERS IN THE STRATOSPHERE

By: AUGER, P; ROGOZINSKI, A; SCHEIN, M
PHYSICAL REVIEW Volume: 67 Issue: 1-2 Pages: 62-62 Published: 1945

F8. Investigation of Extensive Atmospheric Showers in the Stratosphere. P. AUGER, A. ROGOZINSKI, AND MARCEL SCHEIN, *University of Chicago.*—To measure the frequency of extensive atmospheric showers at high altitudes a counter apparatus of large linear dimensions (10 meter) was constructed and sent to the stratosphere. The essential part of the apparatus consisted of six large Geiger-Mueller counters (area 125 cm^2) arranged in a horizontal plane. The maximum separation between counters was 7 meters. Another set of 4 small counters (area 15 cm^2), separated by 50-cm distance, was placed in the middle between the large counters. Six different combinations of threefold coincidences were registered simultaneously. The coincidence circuits had a resolving time of 2×10^{-6} second and therefore chance coincidences could be neglected. The results show that from sea level to an altitude of 15 km the shower rate increases by a factor of 4 for showers of 2-m average spread and by a factor of 30 for showers of 50-cm average spread. It was also found that in the high altitude no coincidences occurred between the set of small counters and any of the large ones which was frequently the case at sea level. This demonstrates that at 15-km altitude the air showers consist of a very narrow and dense bundle of particles. According to the cascade theory these showers must be in the initial stages of their development.

O O O oooo O O O
50 cm
←---------------- 10 m ---------------→ 4

Work largely paused during WWII:

- Blackett and Lovell (1941) – idea of detection through radar – called ‘radio echoes’. First noticed by A C B Lovell and J G Wilson at radar site in Yorkshire (on 4 September 1939) – meteors and Jodrell Bank

- D V Skobletzyn (PhD adviser of G T Zatsepin) initiated shower studies in USSR –soon after Battle of Stalingrad (ended February 1943).

  Observations began in the Pamirs in autumn of 1944

  Extended separation of Geiger counters achieved by Pierre Auger et al.

- **Post WWII, Geiger counters were only the only technique available for nearly another 10 years**
  - **cloud chambers too small and difficult to operate for long periods**
- **Important work in USSR – knee of spectrum – a recurring theme**
- **Key legacy work**

Discovery of the knee

ON THE SIZE SPECTRUM OF EXTENSIVE AIR SHOWERS

G. V. KULIKOV and G. B. KHRISTIANSEN

Moscow State University

Submitted to JETP editor April 22, 1958

J. Exptl. Theoret. Phys. (U.S.S.R.) 35, 635-640 (September, 1958)

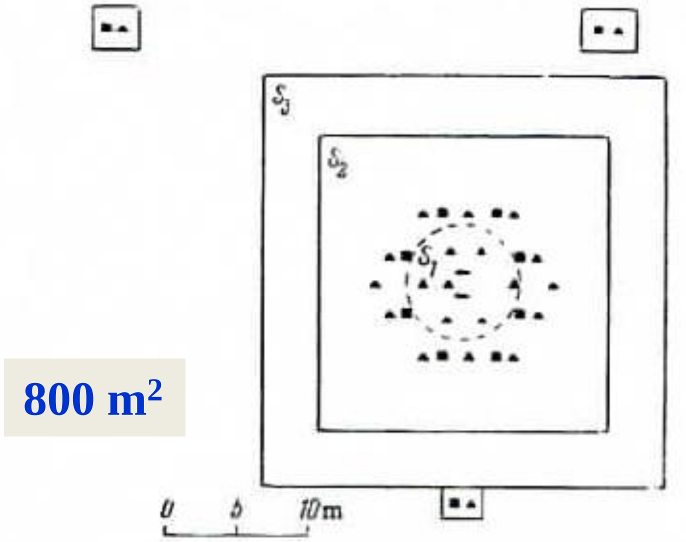


FIG. 1. Diagram of the hodoscope array used for the study f the size spectrum of EAS. ■ – group of 24 hodoscope coun-

Finally, we should like to mention that the conclusions of the present work with respect to the irregularity in the size spectrum of EAS cannot be regarded as final, since the experimental data on which they are based do not possess a sufficient statistical accuracy. The results, however, stress the great urgency of further experiments on the size spectrum of EAS.

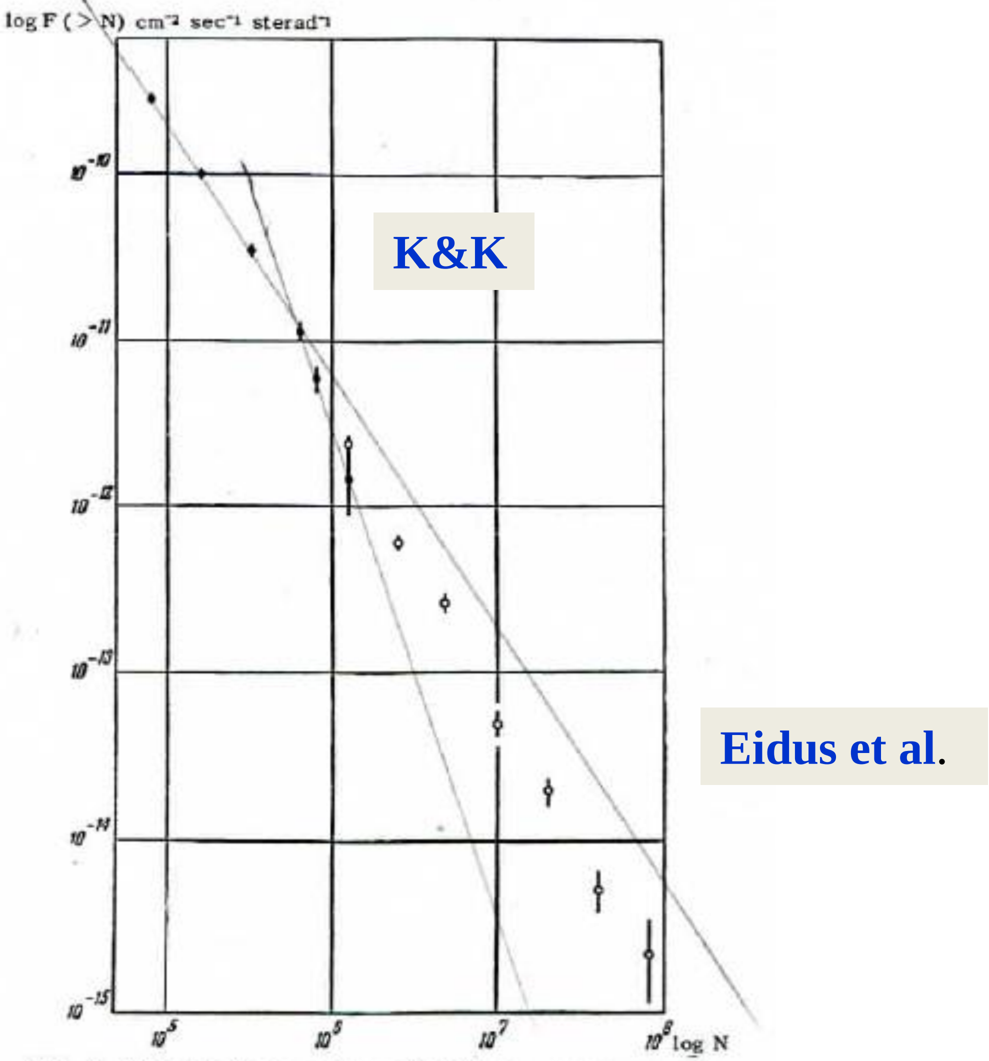
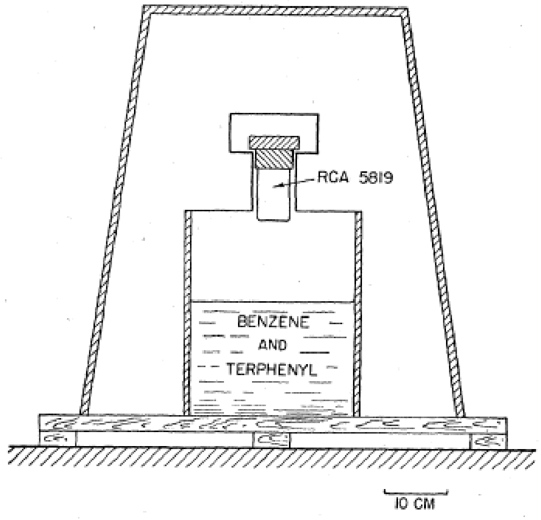


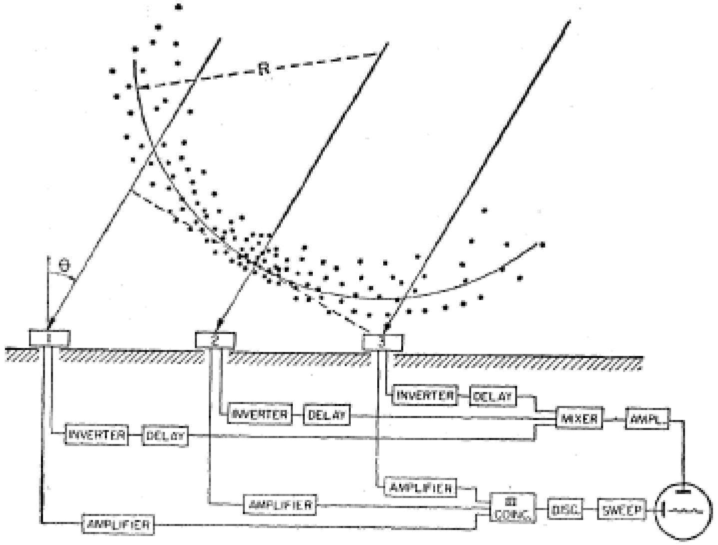
FIG. 2. Integral size spectrum of EAS. ● – measurements of the present experiment, o – measurements of reference 7.

PHYSICAL REVIEW VOLUME 92, NUMBER 2 OCTO 1953 1953

Distribution of Arrival Times of Air Shower Particles*

P. BASSI,† G. CLARK, AND B. ROSSI
Department of Physics and Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received July 13, 1953)





Introduction of Scintillators

– needed the invention of pmts and scintillation counters (made during WWII – by Curran)

Impact of MIT group under Rossi

‘Because of the originality of its conception and the significance of its results, it ranks among the foremost achievements of the MIT group”

Powerful conclusions from observations with just three detectors

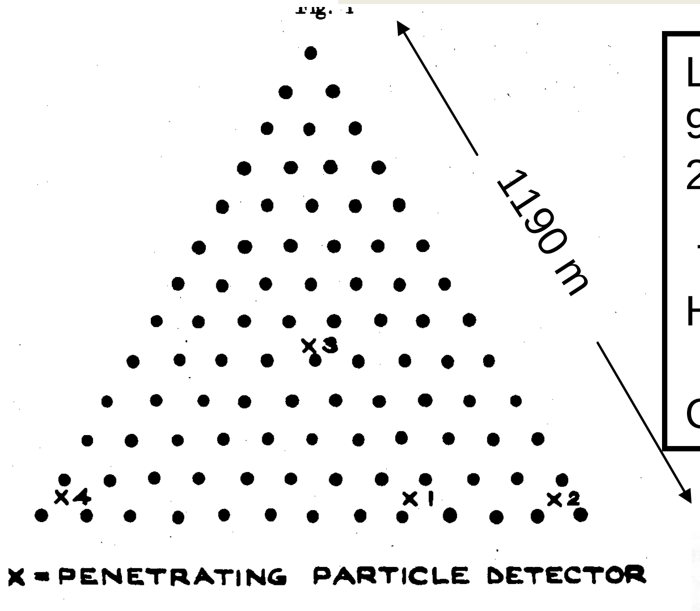
Including

1. **Disc is only ~ 2 m thick , and flat – so measuring shower directions is possible**

2. **Muons arrive a few metres after electrons**

3. **Electrons arise from nucleons of > 20 GeV, or front would be thicker**

Harwell Shower Array of GM-tubes: built on airfield ‘Outside the Wire’



Large GM array at Harwell, UK in mid-1950s
91 stations
2 x 200 cm^2 and 1 x 15 cm^2

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

Cherenkov light detection in 1953

- **Arrival Direction limits – ruled out Sun as source as advocated by Richtmyer, Teller and Alfvèn**
- **First air-Cherenkov light studies**
- **First Water-Cherenkov detector**

- **Bruno Pontecorvo was associated with this activity and was aware of the MIT work and of its importance**
- **para-terphenyl (3 g per litre) only available in US - very expensive for (1 m^2 x 20 cm) ~ $6000 (now $10/g x 3 printer ink)**
  John Jelley asked to investigate effect of reducing the concentration in benzene
- **Jelley found signal with a muon telescope without any para-terphenyl (1951)**
- **Water-Cherenkov detector then developed at Harwell by Neil Porter**

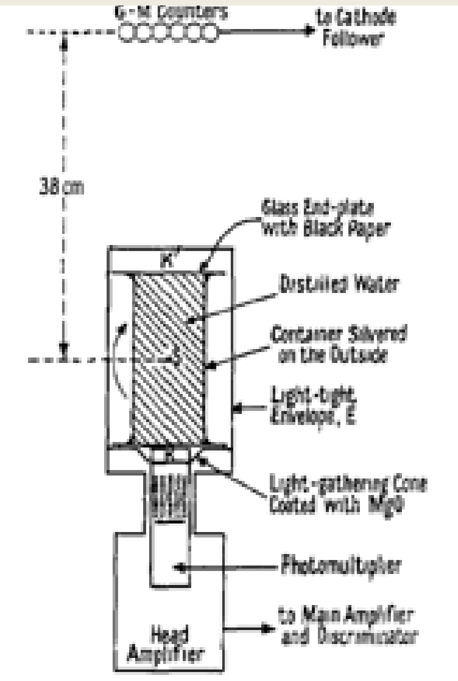
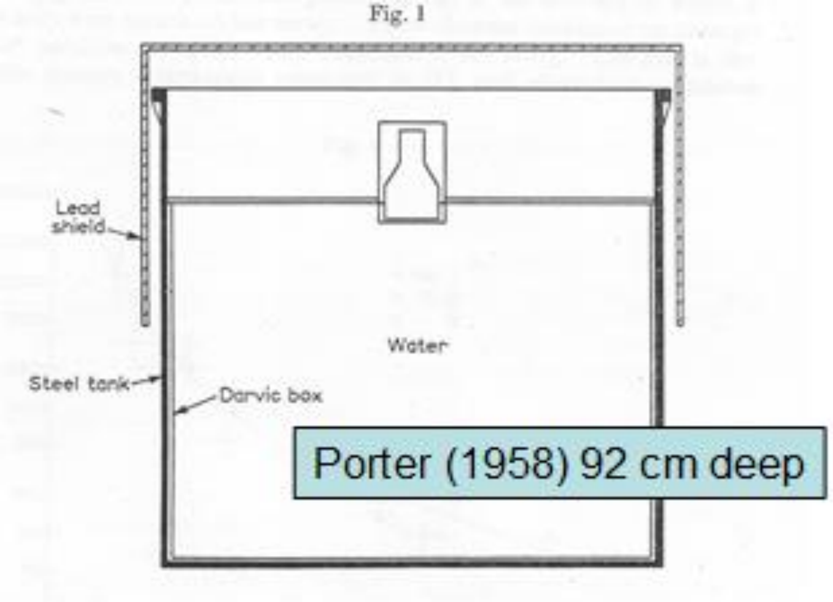
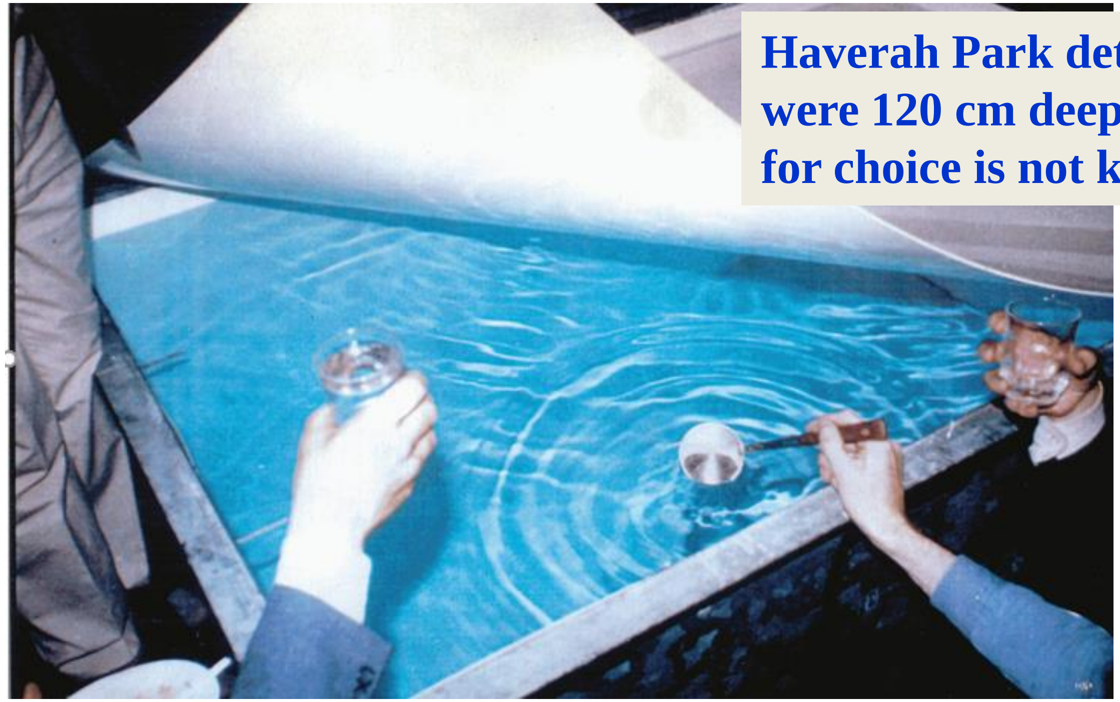


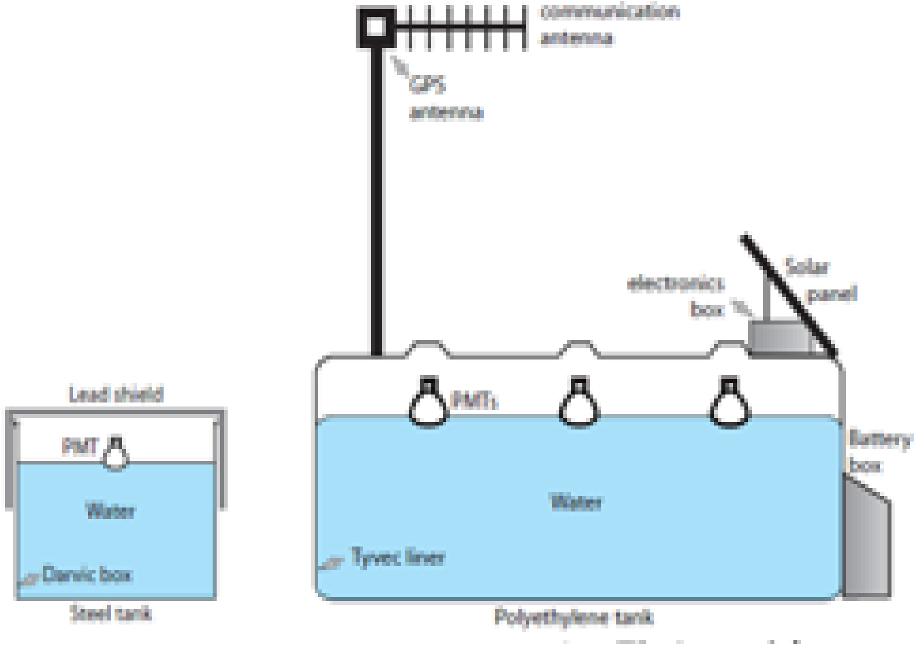
Figure 1 Essential features of apparatus

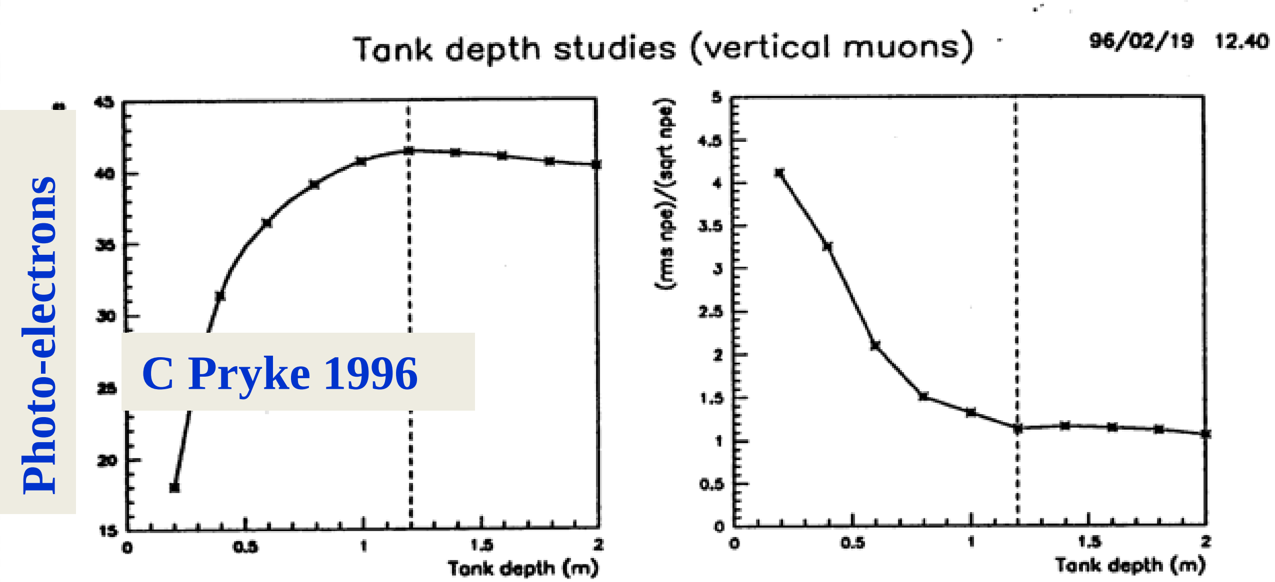


Porter (1958) 92 cm deep



Haverah Park detectors were 120 cm deep – reason for choice is not known





C Pryke 1996

Studies using scintillators and water-Cherenkov detectors confirmed observations of 'knee'

Fukui et al. 1960

Confirmation using scintillators

Integral spectrum

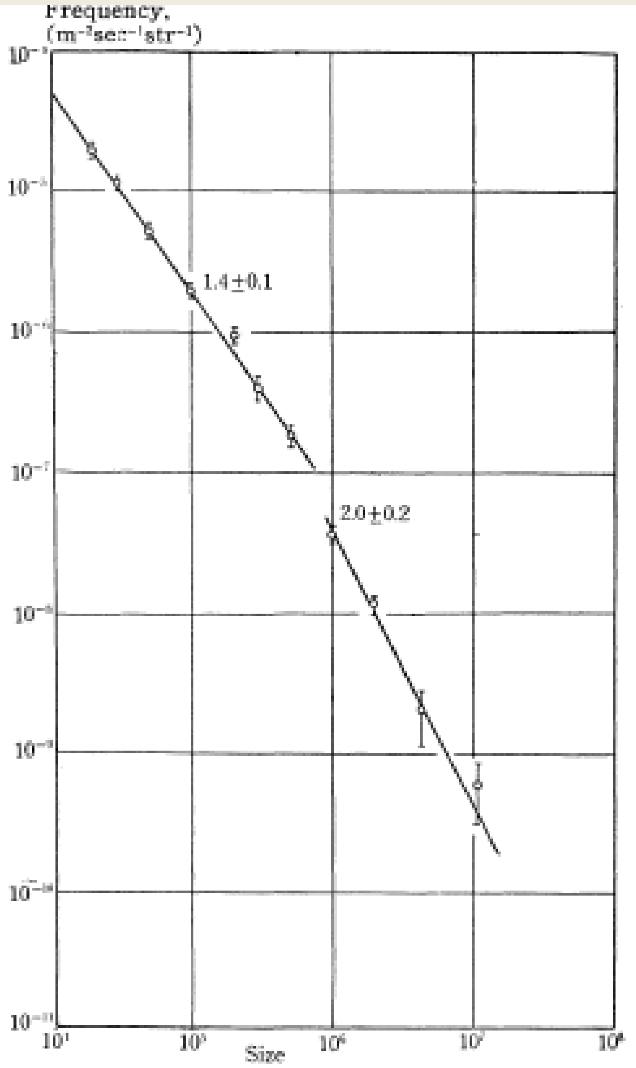


Fig. 11. The size spectrum or the frequency distribution of the total number of particles.

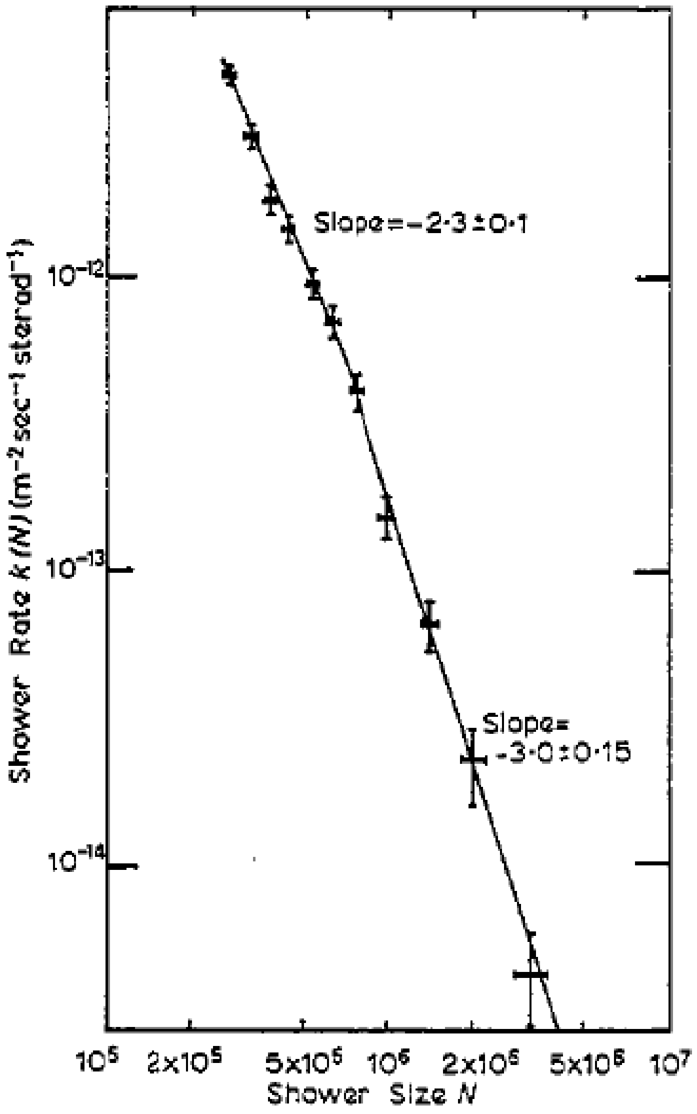
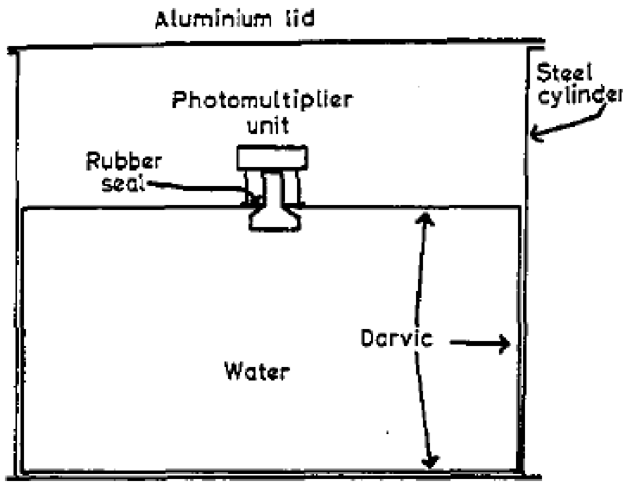


Figure 8. Differential spectrum of observed shower sizes.

Allan et al. 1960

Confirmation using water-Cherenkov detectors - 76 cm deep

Differential spectrum



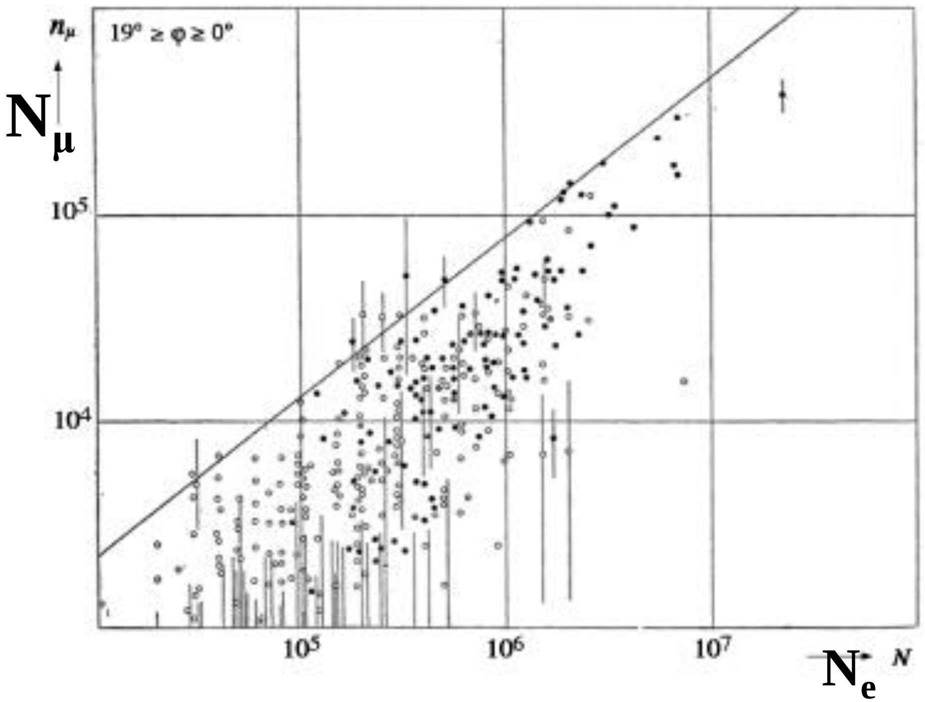
Japanese activities discussed in detail in Fukui et al. 1960:

Post WWII, destruction of cyclotrons at RIKEN, Kyoto and Osaka

Tomanaga established shower work at Mt Norikura (2770 m) and helped establish Institute for Nuclear Studies in Tokyo

Oda returned from Rossi's group in 1956

Built series of ever more complex shower arrays with Suga heavily involved



Also involvement of

Nishimura, Kamata, Nagano…

Major involvement in Chacaltaya of Suga, Kamata…

Led to Akeno and AGASA and involvement in Telescope Array

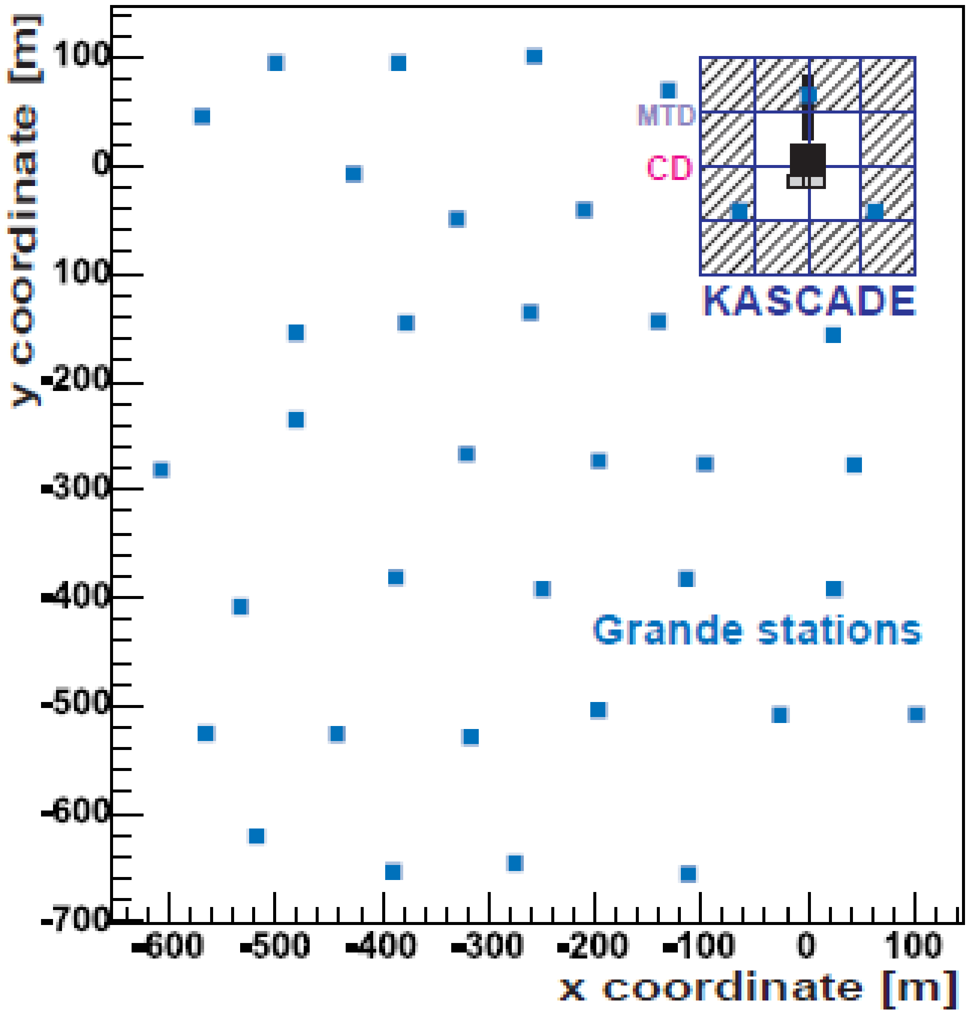
First detection of Fluorescence Radiation was made in Japan by Oda's group

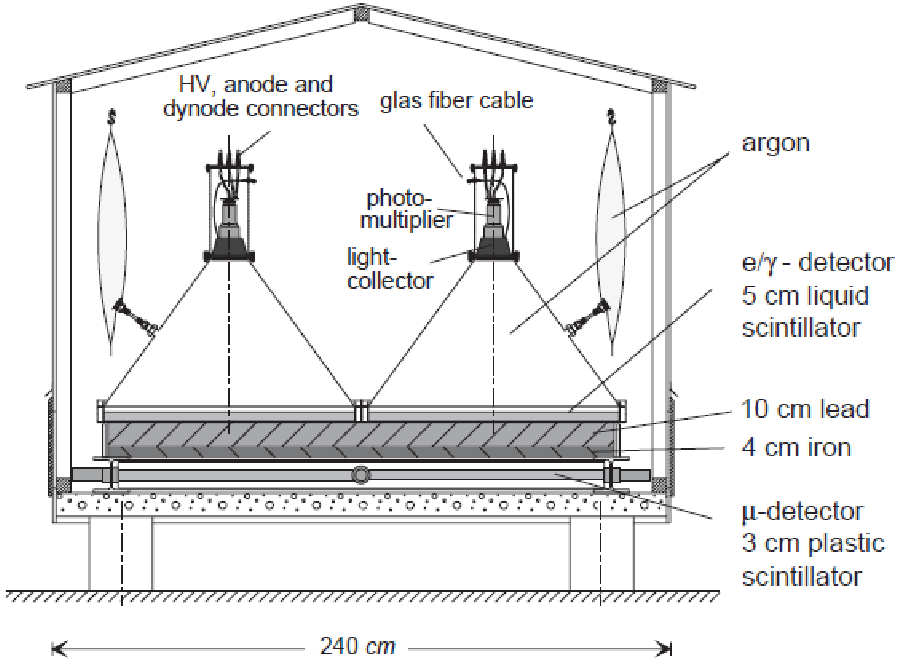
- Detections reported at Budapest ICRC (1969: Hara et al))

- Bruce Dawson convinced that fluorescence light was seen (arXiv:1112.56860)

- Fluorescence story from Pierre

Definitive answers on ‘knee’ region came from KASCADE project (Gerd Schatz)





KASCADE and KASCADE-Grande

Data on first and second knees

Measuring the energy spectrum

- At energies below around 30 PeV, the energy spectrum is model dependent

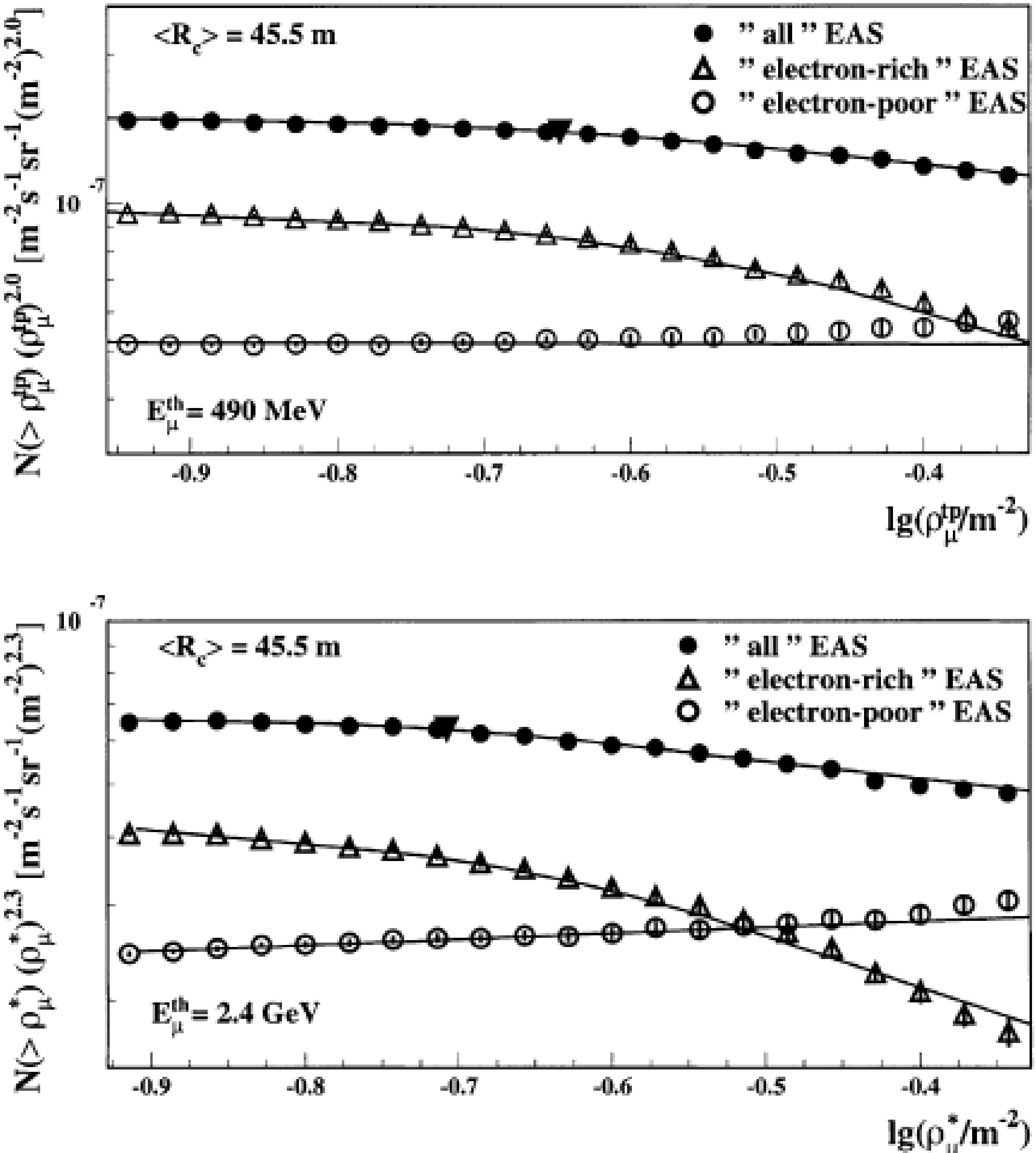
However, features of spectrum can be identified with skilful use of the basic data – and common sense - (KASCADE and KASCADE-Grande)

- The dependence on models becomes SMALLER as one moves to higher energies

Above ~ 0.3 EeV fluorescence radiation provides a calibration tool

Spectrum from Pierre Auger Observatory is constructed without resorting to models

‘Model-free’ analysis of KASCADE data showed that knee was a ‘light’ nucleus feature



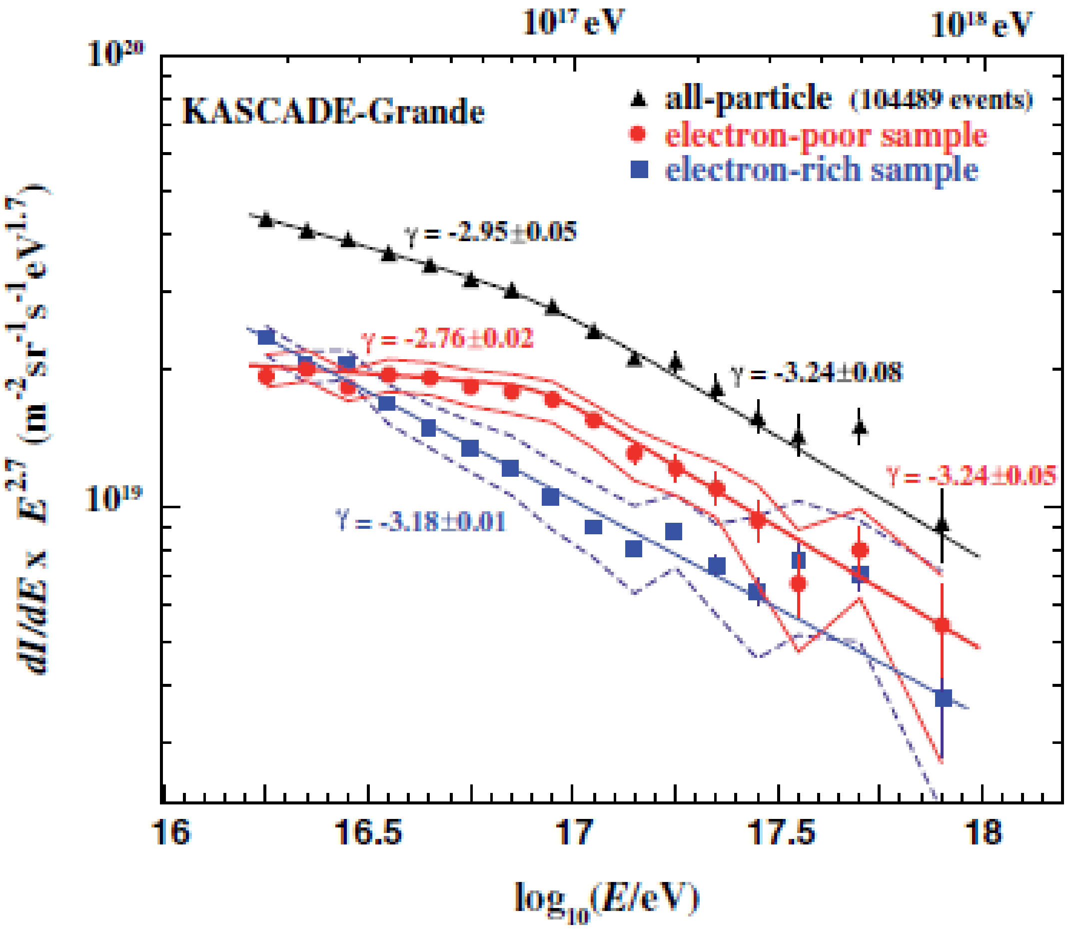


FIG. 4 (color online). Reconstructed energy spectrum of the electron-poor and electron-rich components together with the all-particle spectrum for the angular range 0°–40°. The error bars show the statistical uncertainties; the bands assign systematic uncertainties due to the selection of the subsamples. Fits on the spectra and resulting slopes are also indicated.

Second knee at around 0.1 EeV

Again inferred without resorting to assumptions about hadronic interactions

PRL 107 171104 2011

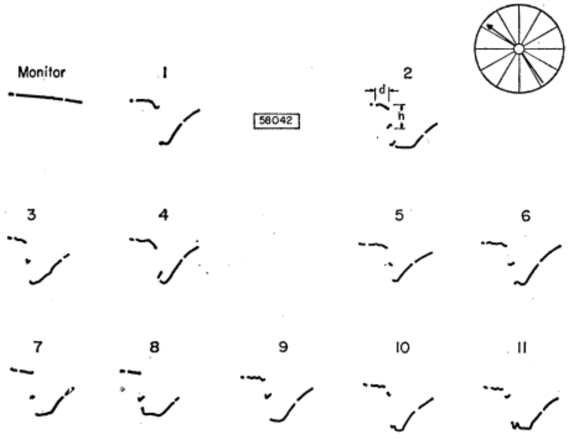
Comparison of features at the knee
ALL PARTICLE SPECTRUM

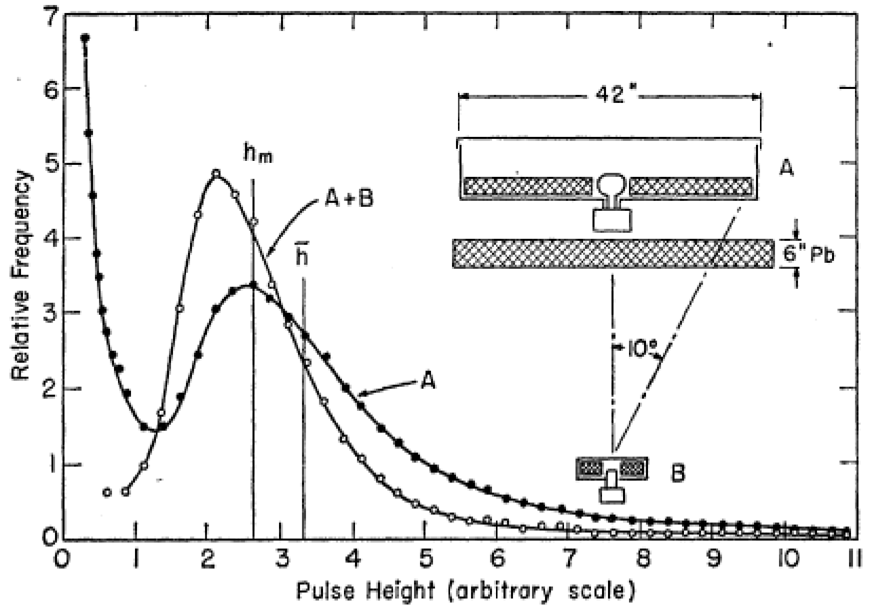
	Knee	γ_1	γ_2
QGSJET01	**4.0 +/-0.8 PeV**	**-2.70 +/- 0.01**	**-3.10 +/- 0.07**
Sibyll 2.1	**5.7 +/- 1.6 PeV**	**-2.70 +/- 0.06**	**-3.14 +/- 0.06**

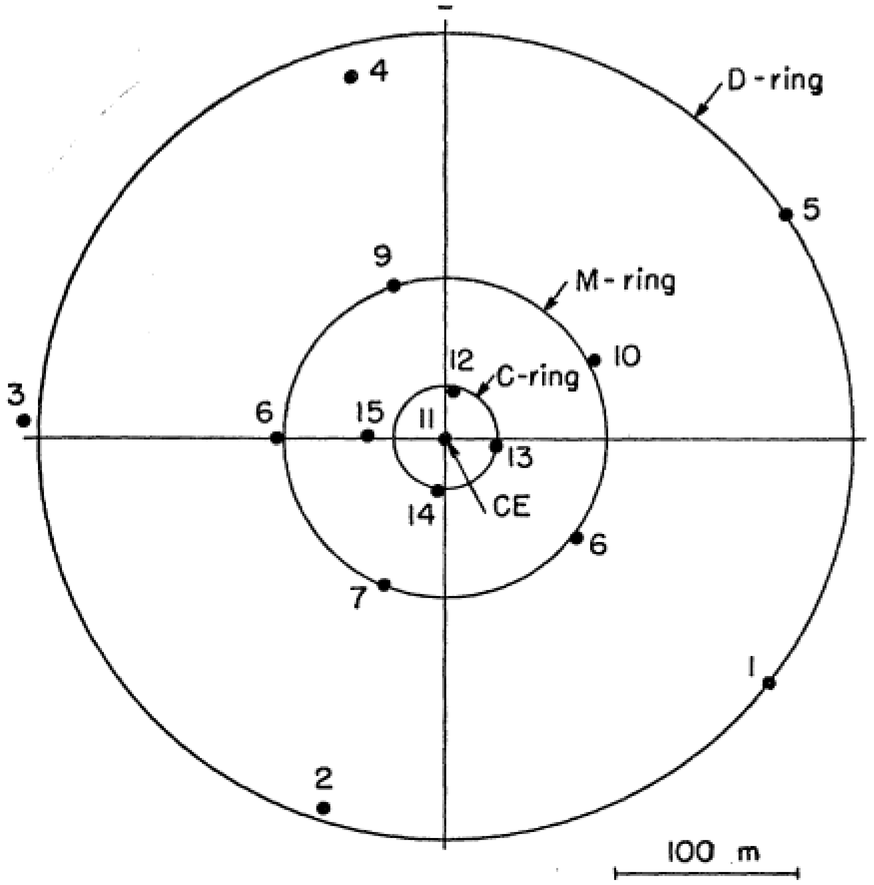
This gives a warning about the sensitivity of spectral details to mass and models – and this is at LOW energies

Life is easier at higher energies because of availability of fluorescence technique

MIT Agassiz Experiment – introduction of plastic scintillators







Pre-cursor for work at Chacaltaya and Volcano Ranch

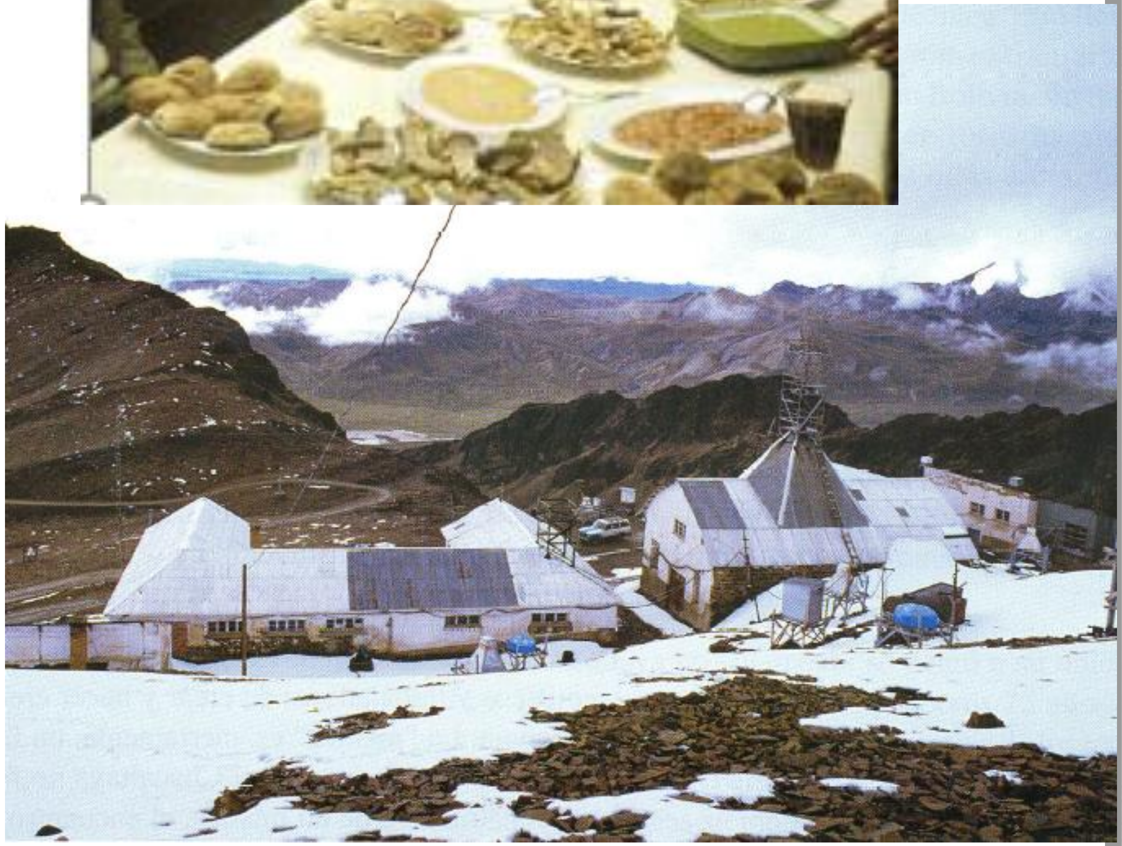
Largest event, N = 2.6 x 10^9

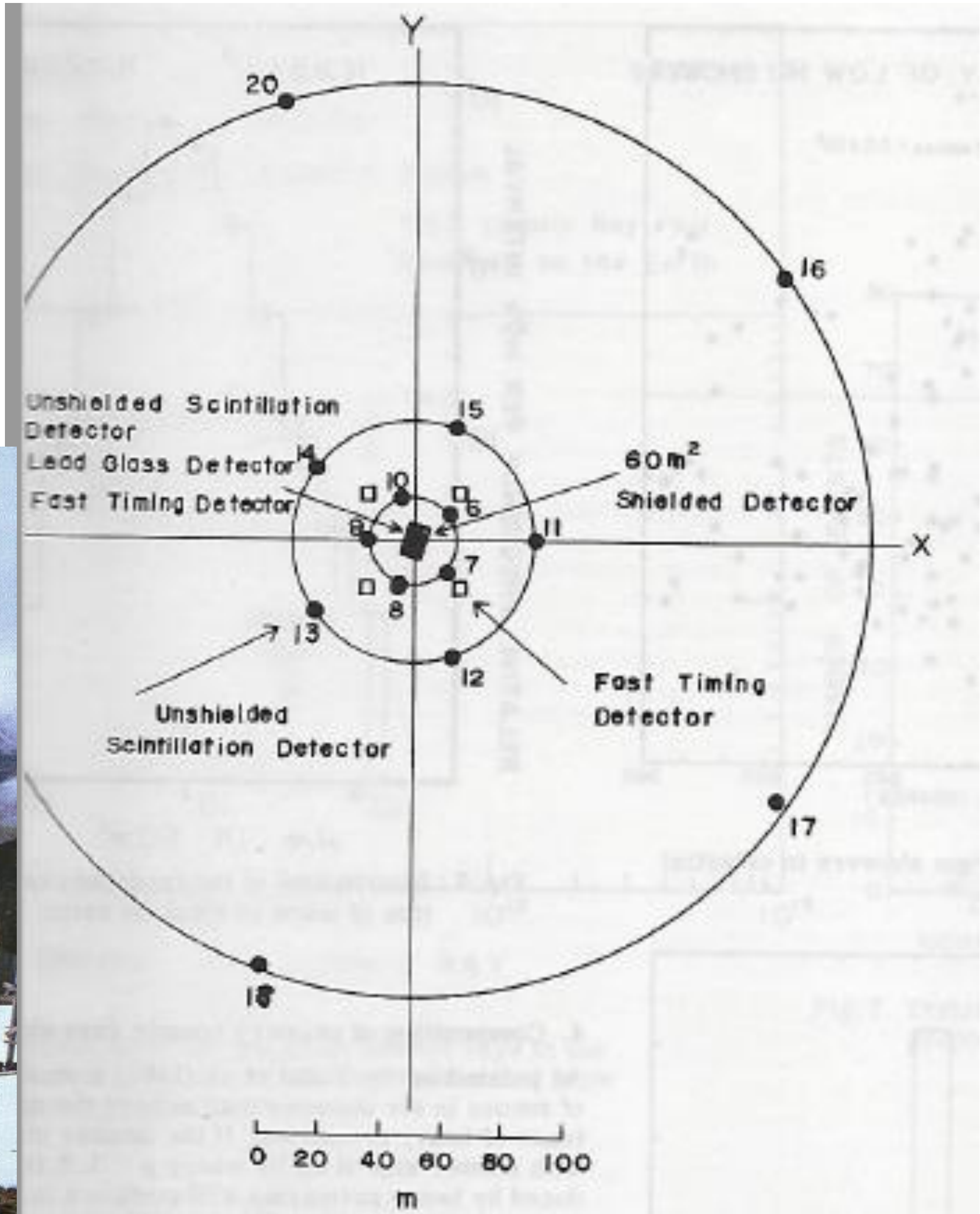
E ~ 3 x 10^{18} eV (1958)

Chacaltaya array:

BASJE

Bolivian-American Japanese experiment





SJE array (from October 1964) at Mount Chacaltaya 5200 m above
a level.

Chacaltaya (5200 m) in Bolivia:

Major motivation was to search for photons using 60 m^2 muon detector as a veto

Also developed the 'Constant Intensity Cut' method

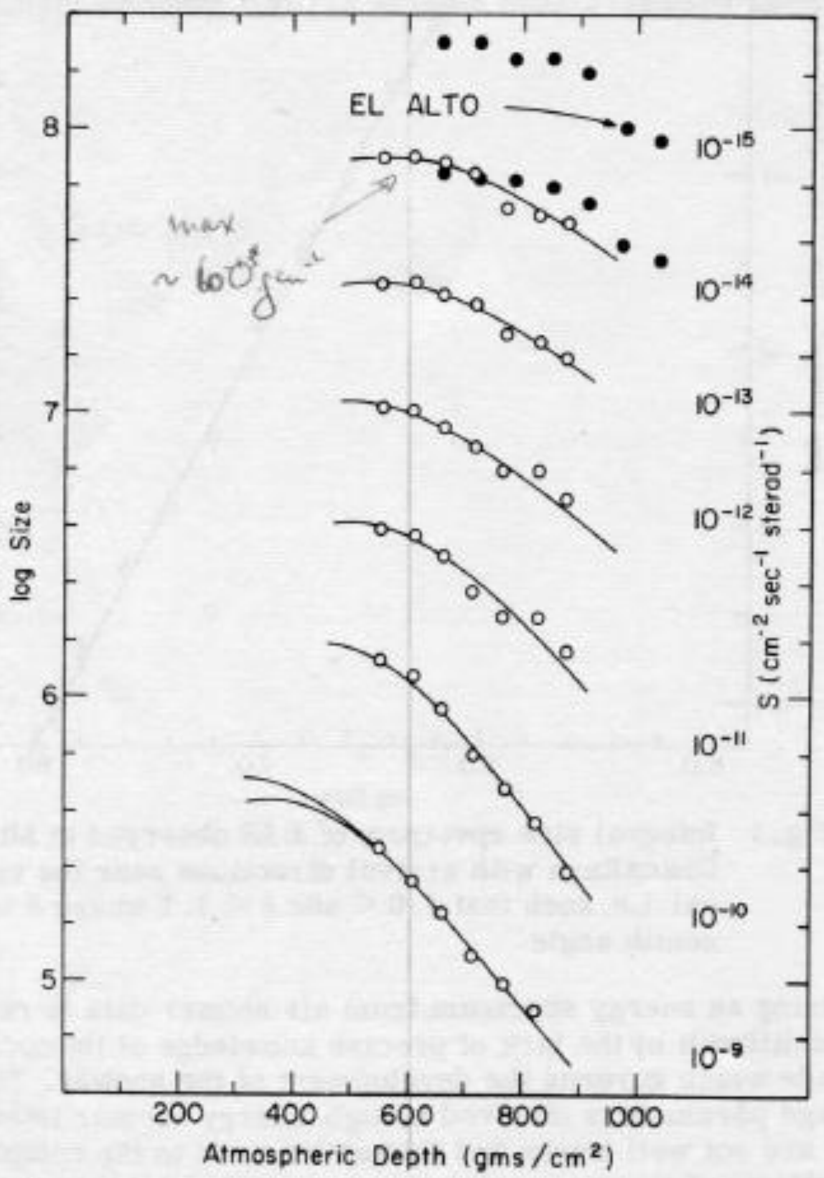


Fig. 3 Longitudinal development curves obtained from constant intensity cuts on the plots of the size spectra obtained for various zenith angles, or effective atmospheric depths. The smooth curves are drawn to fit the data points.

X_{max} ~ 600 g cm^{-2} at ~ 0.1 EeV is not out of line with modern measurements made using fluorescence detectors (and radio)

The first Giant Arrays

Volcano Ranch – established in late 1950s – 8 km^2 scintillators with one muon detector
operation between 1959 and 1963 (not continuously)
44 events above 10 EeV

Haverah Park – array of 12 km^2 data taking from 1967 - 1987
~150 water-Cherenkov detectors, muon detectors, muon spectrograph, scintillators, air-Cherenkov light detection, radio studies
~100 events above 10 EeV

SUGAR (Sydney) ~ 100 km^2 : 54 buried liquid scintillators as muon detectors
11 years from ~1968
~400 events above 10 EeV

Yakutsk – 18 km^2 : scintillators, muon detectors extensive array of air-Cherenkov receivers.
Operational since 1974 ---- with various configurations and changes in number of detectors
~300 events above 10 EeV

John Linsley - Two Nobel Prize nominations (by Pierre Auger)

Volcano Ranch 1770 m (834 g cm^{-2})

The Volcano Ranch Array: Linsley (1963)

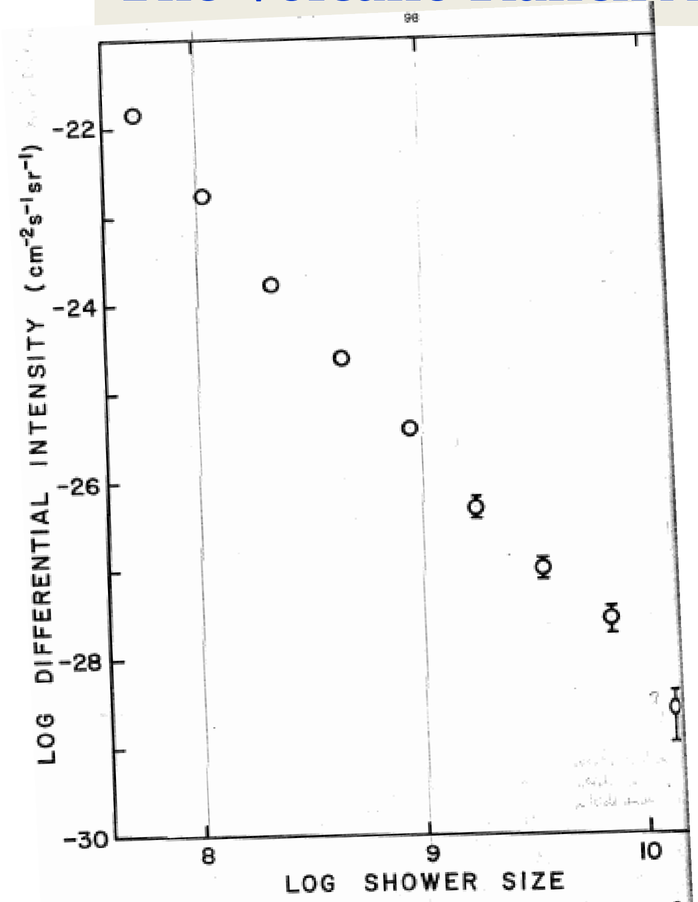
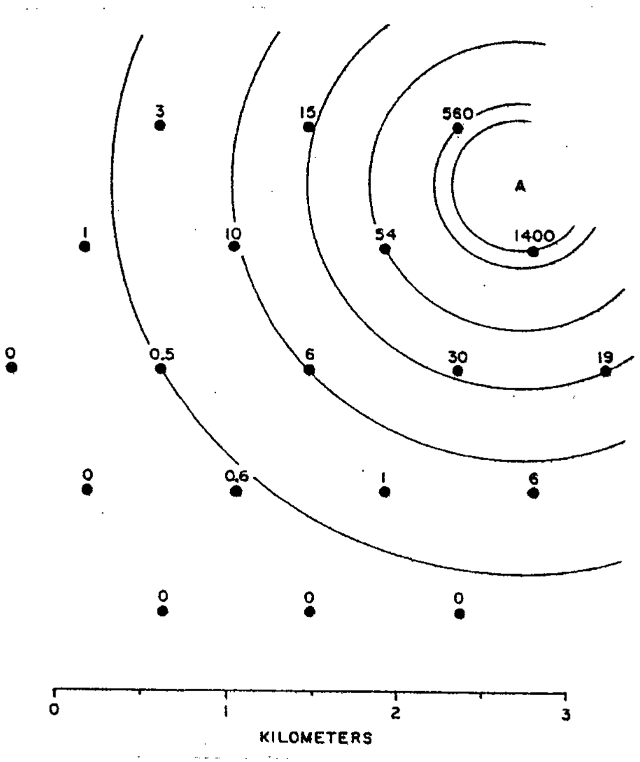


FIGURE 4. The differential shower size spectrum at 820 g cm^{-2}



- Built and operated virtually single-handedly
- Early help from Scarsi
- 500 electronic valves!

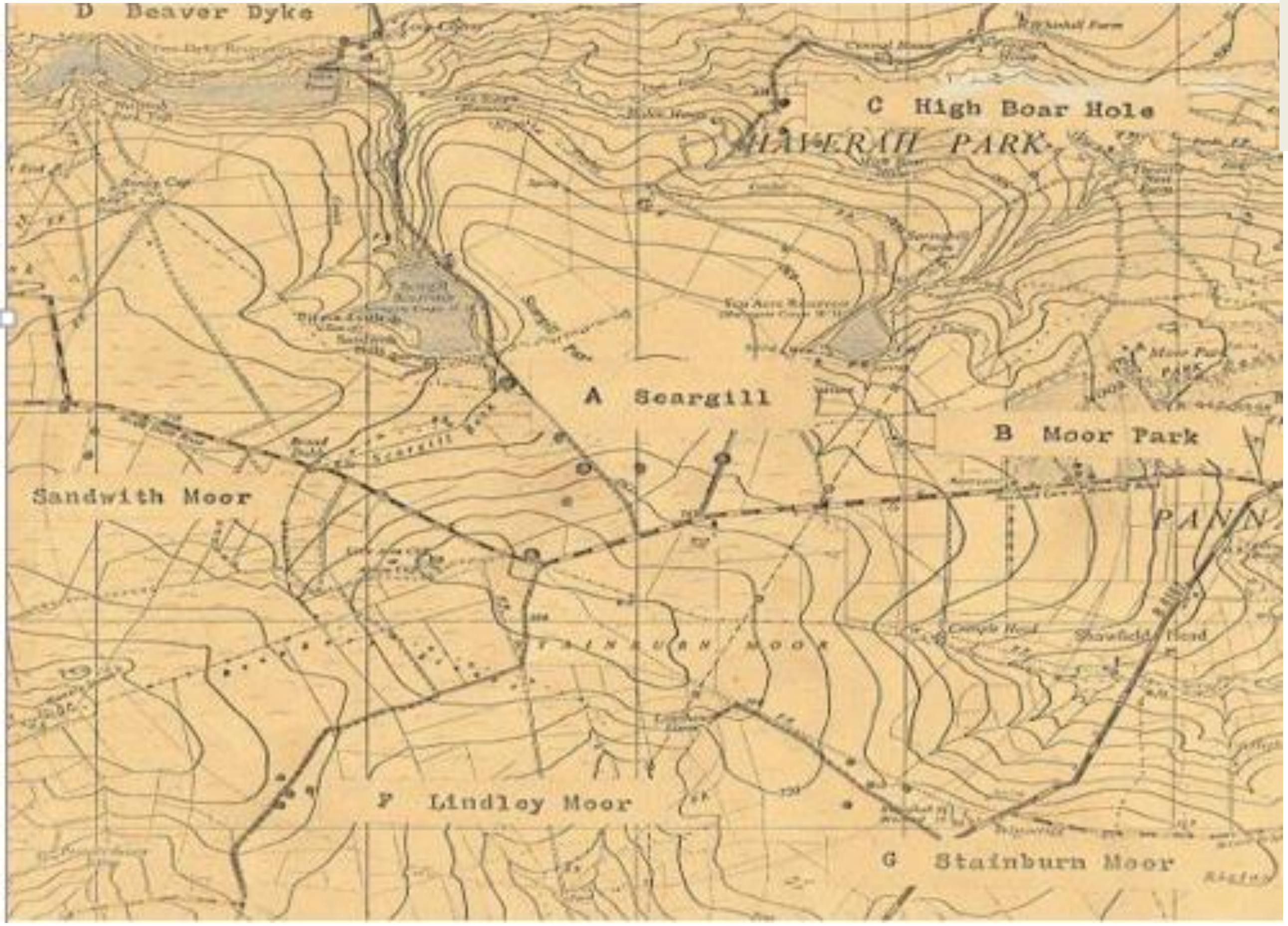
First evidence of Ankle:

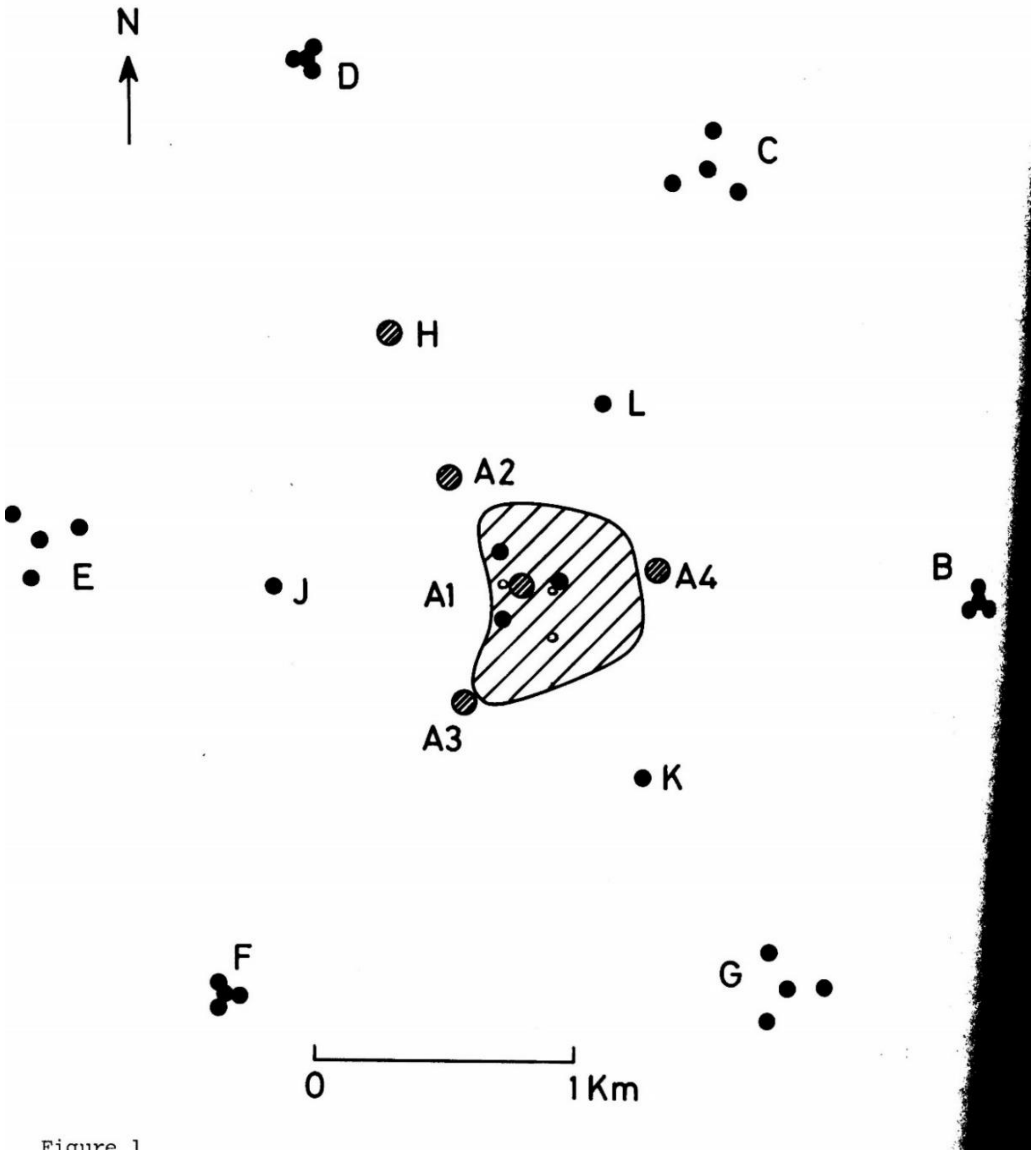
ICRC Jaipur 1963

Energy ~ 10^{20} eV
- pre-GZK prediction

Strong push by Blackett after closure of Harwell:

UK National Effort under J G Wilson (Leeds)

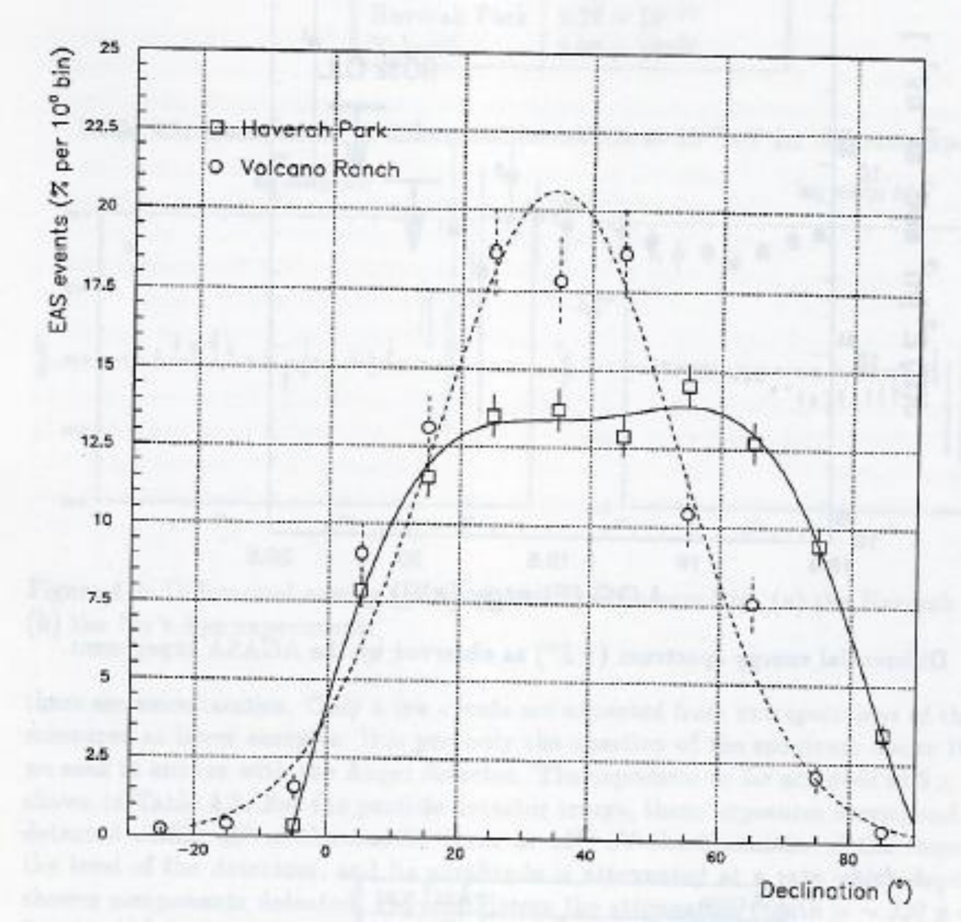




Groups from Imperial College, Durham, Nottingham and Leeds involved

Comprehensive examination of shower properties

- Muon-scintillator-water-Cherenkov comparison
- Muon spectrograph
- Extensive muon studies above ~250 MeV
- Radio studies
- Air-Cherenkov studies
- Analysis techniques – similar to MIT, but r_opt (Hillas)
- Energy spectrum – ankle confirmed
- Arrival directions – broad declination distribution
- Mass estimates from risetime studies – elongation rate measured independent of models



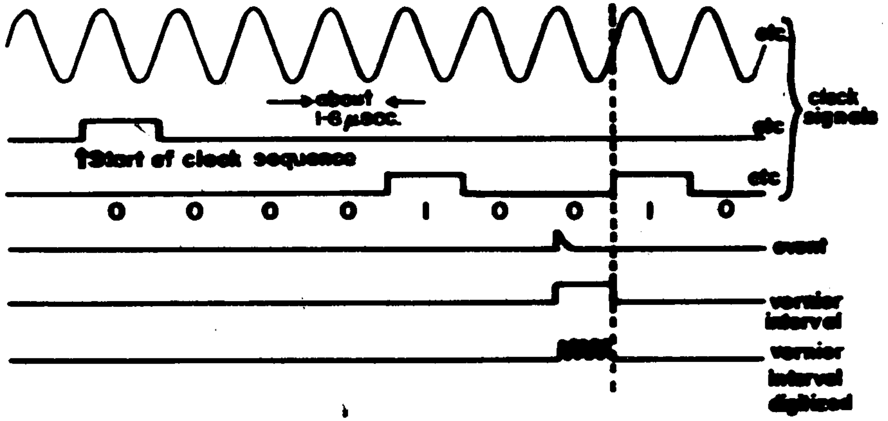
HP only to 60º, but still x2 solid angle coverage
Powerful argument for W-C for Auger Observatory

TWO LARGE AIR SHOWER EXPERIMENTS

by

C.B.A. McCusker, H.D. Rathgeber & M.M. Winn

The University of Sydney



SUGAR Array: Jaipur ICRC 1963:

- First discussion of ‘stand-alone’ operation of detectors
- Murray Winn invented the method
- Key idea for Auger Observatory and TA efforts

- but after-pulsing issues, and reliance on muons, made accurate energy measurements difficult

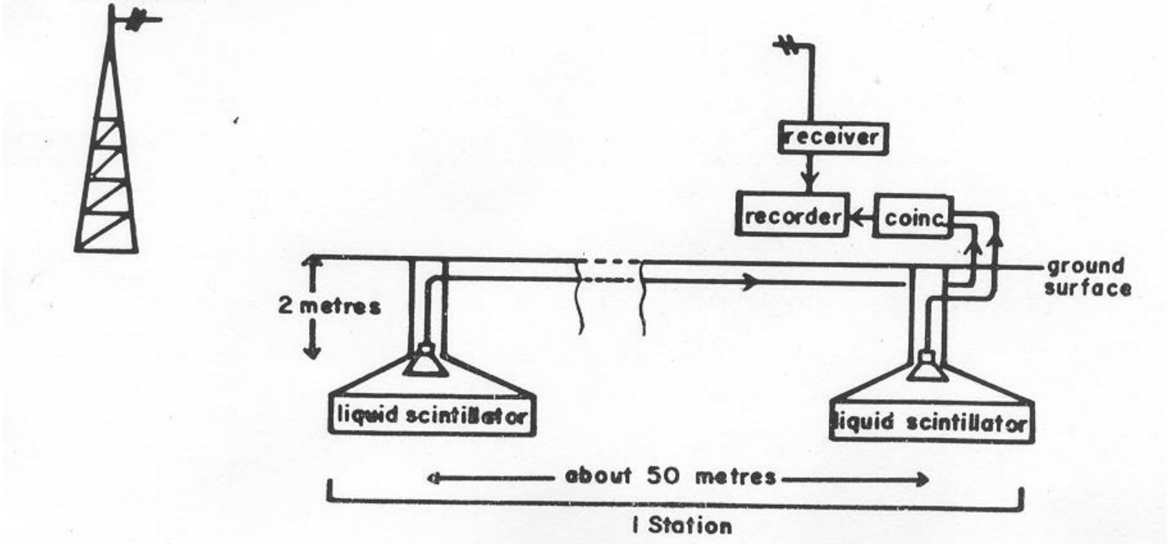
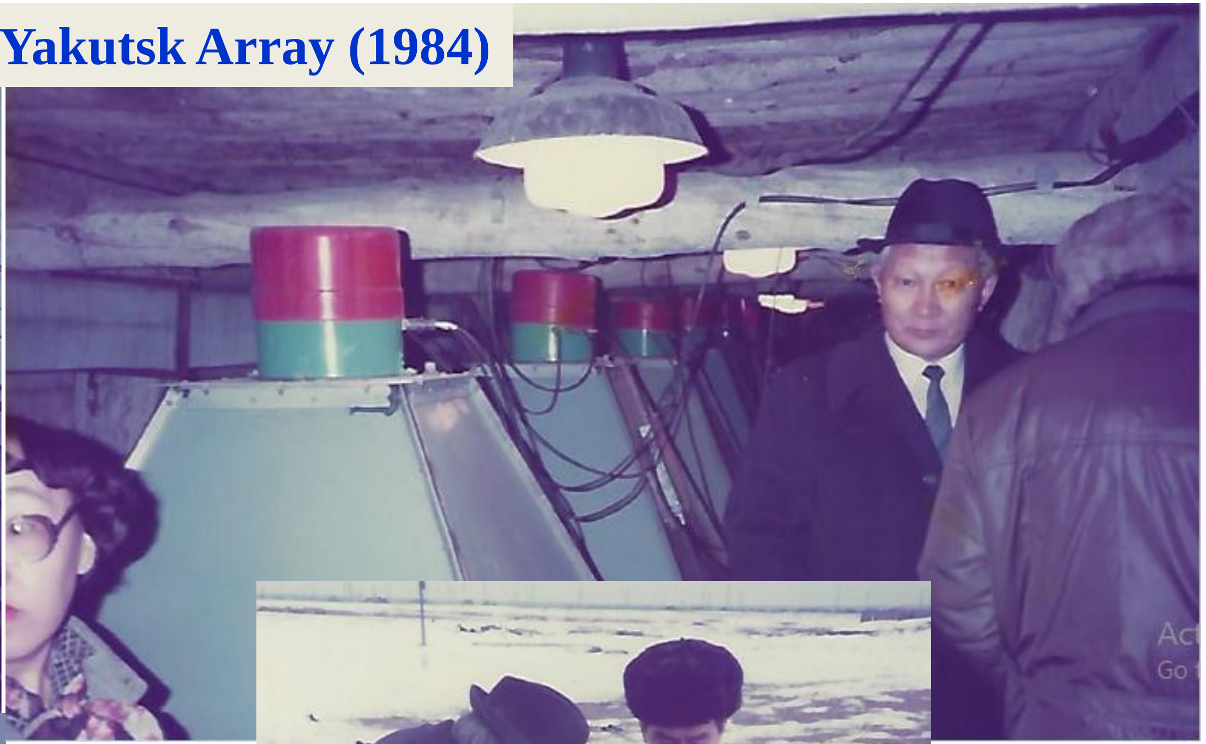


FIGURE 2

The Yakutsk Array (1984)



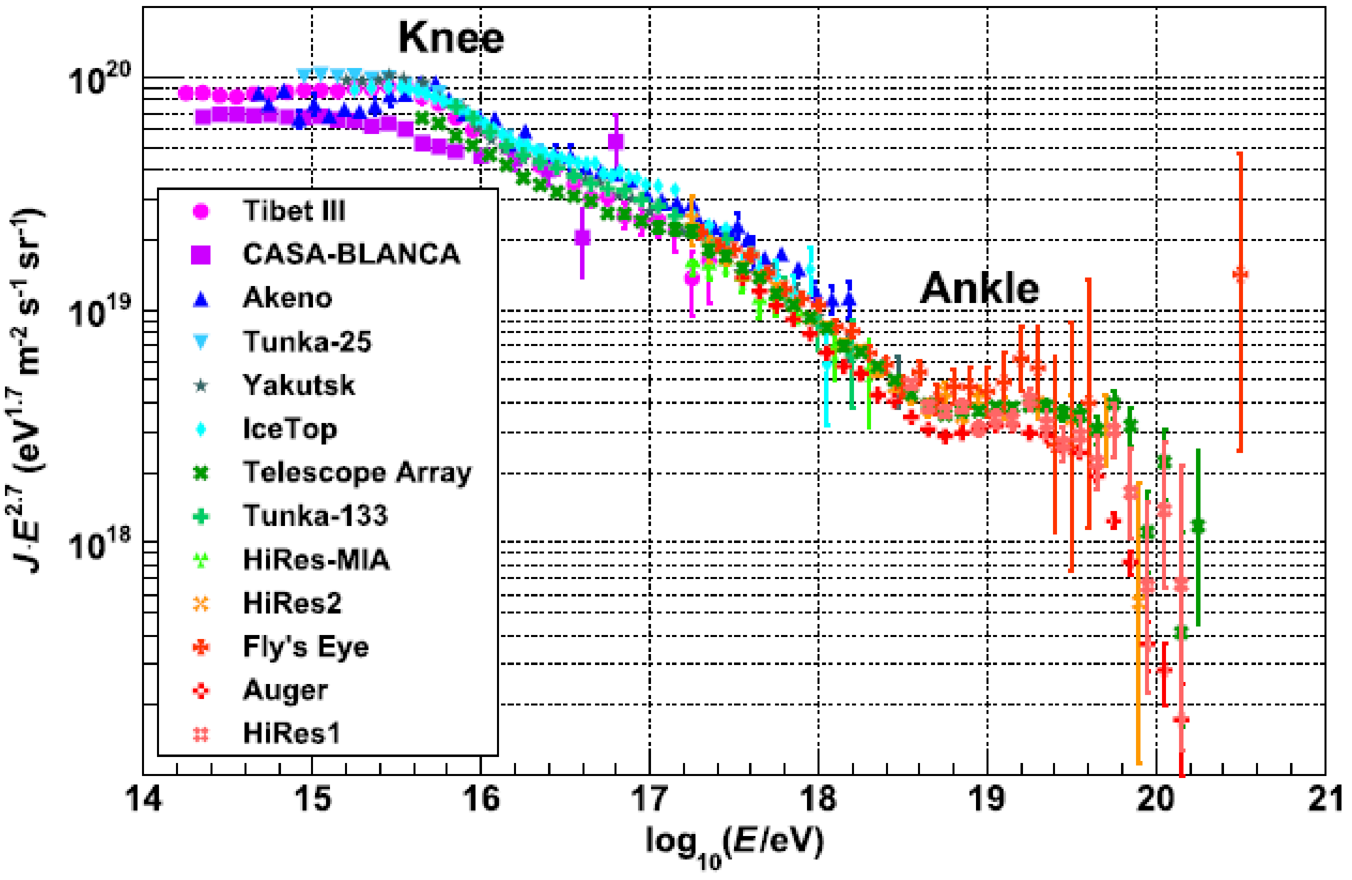
Very strong emphasis on muon detection and air-Cherenkov

- Effort to make calorimetric estimates of energies by summing energies in different components

- Elongation rate from air-Cherenkov studies

Building on long period of Air-Cherenkov work initiated by Chudakov and Zatsepin

Yakutsk results merit more detailed study



The Fly's Eye Proposal – 1 September 1974

RESEARCH PROPOSAL

to

THE NATIONAL SCIENCE FOUNDATION

by

Department of Physics
University of Utah
Salt Lake City, Utah 84112

COSMIC RAY STUDY OF ULTRA-HIGH ENERGY PROCESSES

Third Renewal Request of NSF GP 24452

Proposed Starting Date: September 1, 1974

Amount Requested: $604,300
Proposed Duration in Months: 24

Principal Investigator:
J. W. Keuffel
0671-16-6733
Phone: (801) 581-6628

Department Head:
Peter Gibbs
Professor of Physics, Chairman
(801) 581-6901

Co-Principal Investigators:
H. E. Bergeson
528-40-1948
Phone: (801) 581-7115

G. L. Cassiday

Authorized Signature

Planning blight finally broken
Japanese

Akeno and AGASA

AGASA results led directly to TA: to check AGASA spectrum and claims for clustering

27. Hoerlin, H., "Air Fluorescence Excited by High Altitude Nuclear Explosions," LA-3417-MS, Los Alamos Scientific Laboratory, Los Alamos, New Mexico (1965).

28. Mead, J.B., "Properties of Teller Light (Air Fluorescence) induced by 22-MeV Electrons," CRD Sigma 3, UCRL-7604, Lawrence Radiation Laboratory, Univ. of Calif., Livermore, California (1963).

In Section E is presented a Monte-Carlo simulation of the events to be expected. The effective area of the detector grows with the shower size, so that the rates fall off much slower than the cosmic ray spectrum. Assuming a constant spectral index, the rate of showers above 10^{16} eV would be 10^{6} yr^{-1}, about 10^{18} eV, 10^{4} yr^{-1}, and above 10^{20} eV, 20 yr^{-1}, where the rates quoted are the actual rates taking into account a duty cycle of 10% for clear, moonless nights. As an example, a shower of 10^{18} eV would produce ~ 500 photoelectrons in each of 15 phototubes against a background fluctuation of ~50 photoelectrons. Our simulation also indicates that only a very few showers would have been observable with the Cornell array and data handling system.

Nature 23 January 1965

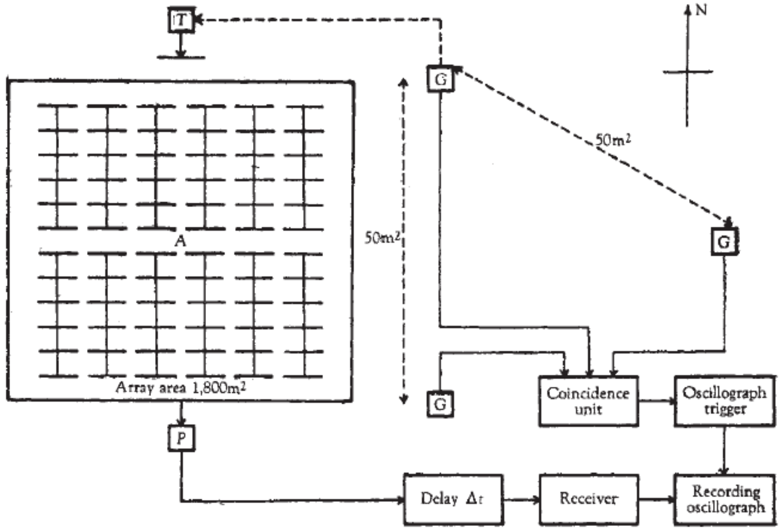
RADIO PULSES FROM EXTENSIVE COSMIC-RAY AIR SHOWERS

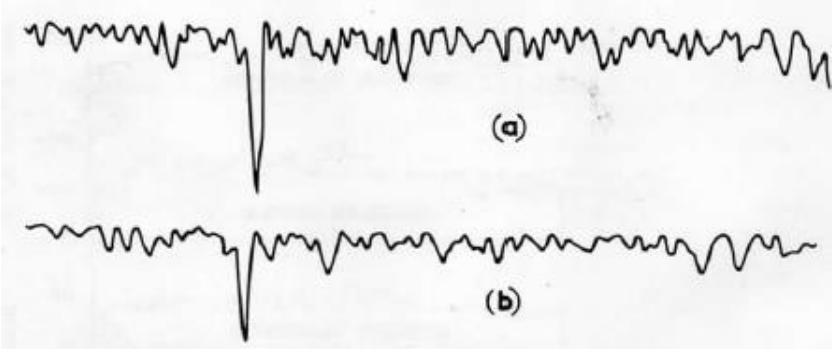
By DR. J. V. JELLEY and J. H. FRUIN
Atomic Energy Research Establishment, Harwell

PROF. N. A. PORTER and T. C. WEEKES
University College, Dublin

AND

PROF. F. G. SMITH and R. A. PORTER
University of Manchester, Nuffield Radio Astronomy Laboratories, Jodrell Bank





Greisen (ICRC London 1965)

"The technique is in its infancy, and too little is know to justify predictions. However we feel confident that this achievement is a significant breakthrough, and that further studies will reveal ways of obtaining types of information about showers that were not available by other means.

Method may offer new orders of angular resolution and may complement particle detectors by being to the condition of the showers far above ground level. Also it will be able to detect showers is steeply inclined directions, in which particles are absorbed before reaching the ground."

Some of the Legacies:

- Fast timing with scintillators (1953)
- Air-Cherenkov (1955)
- Water-Cherenkov detectors (1958)
- Muons for mass estimates (1962)
- Fluorescence discussions (1962 – but Chudakov had studied this earlier)
- Constant Intensity Cut method (1962)
- Autonomous stations (1963)
- Risetime studies (1963)
- Radio detection (1965)

We are the fortunate beneficiaries of many ideas and much work in the past!