21st ISCRA
August 2018

High Energy Cosmic Rays I

Some background on Extensive Air Showers

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Overview

Lecture 1:

Some more history and more physics of showers

Pioneering Projects – driven by technical innovations

History of Fluorescence Radiation

Towards the Auger Observatory

- **The story of Cygnus X-3 – from confusion to triumph!**
- **The Auger Observatory**

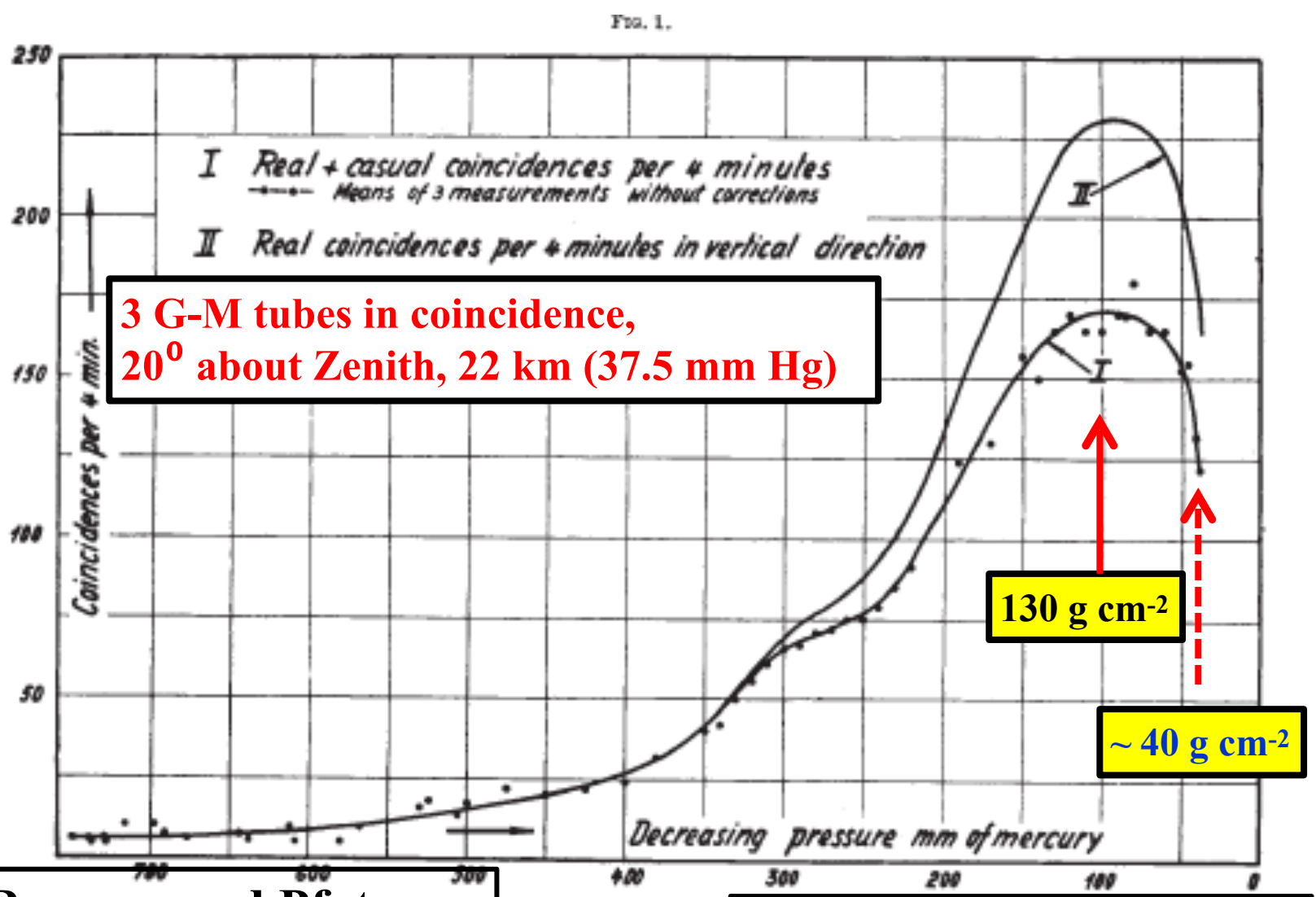
Lecture 2: Results at the Highest Energies

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'

Nominated for Nobel Prize by Schrodinger in 1938
Obituary by P M S Blackett 1973

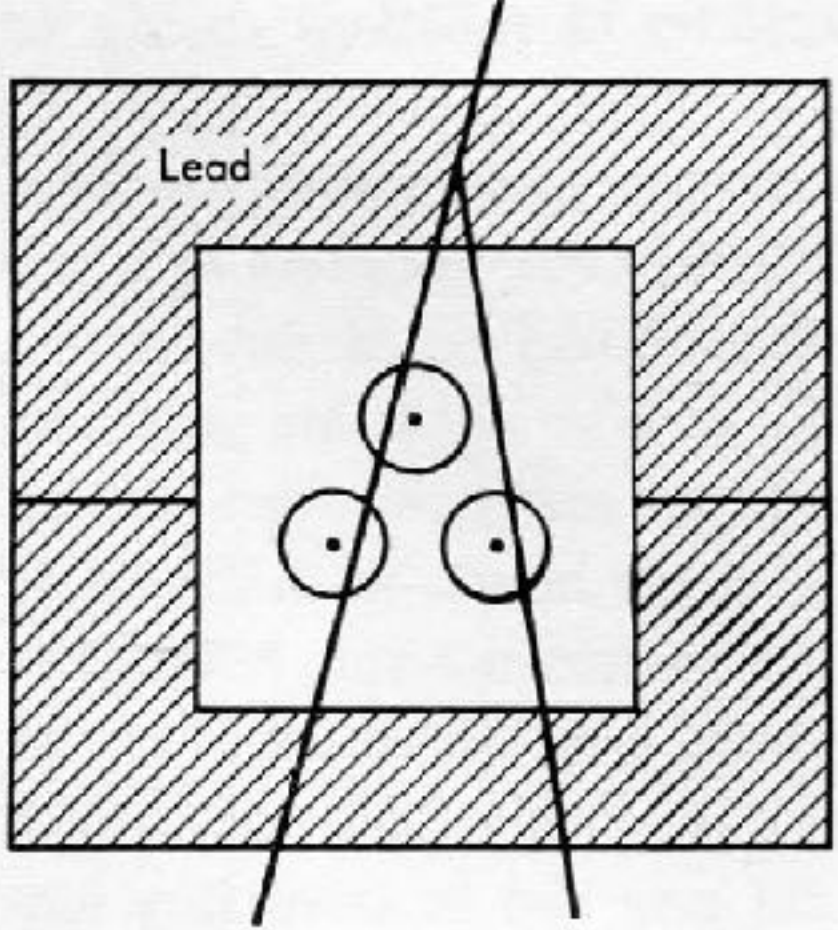


Regener and Pfotzer:
Nature 136 718 1935

Carlson and Watson 2015
History of Geophysics
and Space Science

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

Rossi Transition Curves



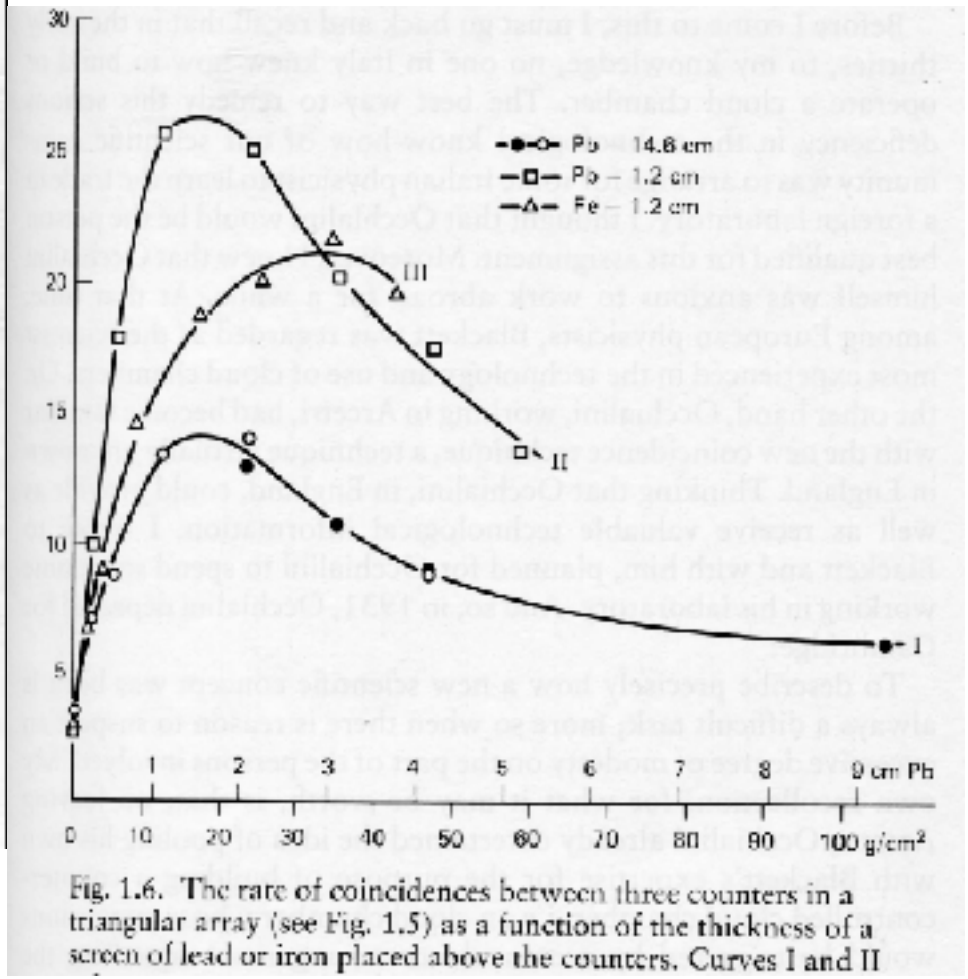


Fig. 1.6. The rate of coincidences between three counters in a triangular array (see Fig. 1.5) as a function of the thickness of a screen of lead or iron placed above the counters. Curves I and II

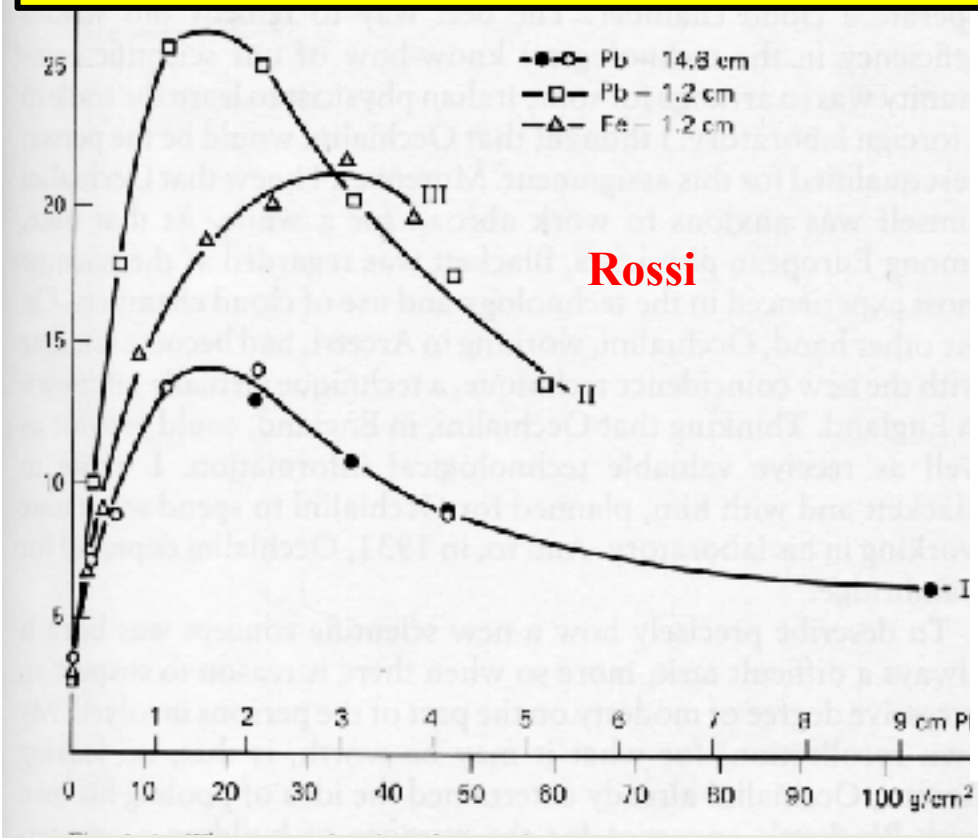
Rossi 1933: Coincidence rate much higher with top lead blocks (~ 10 cm thick) in place

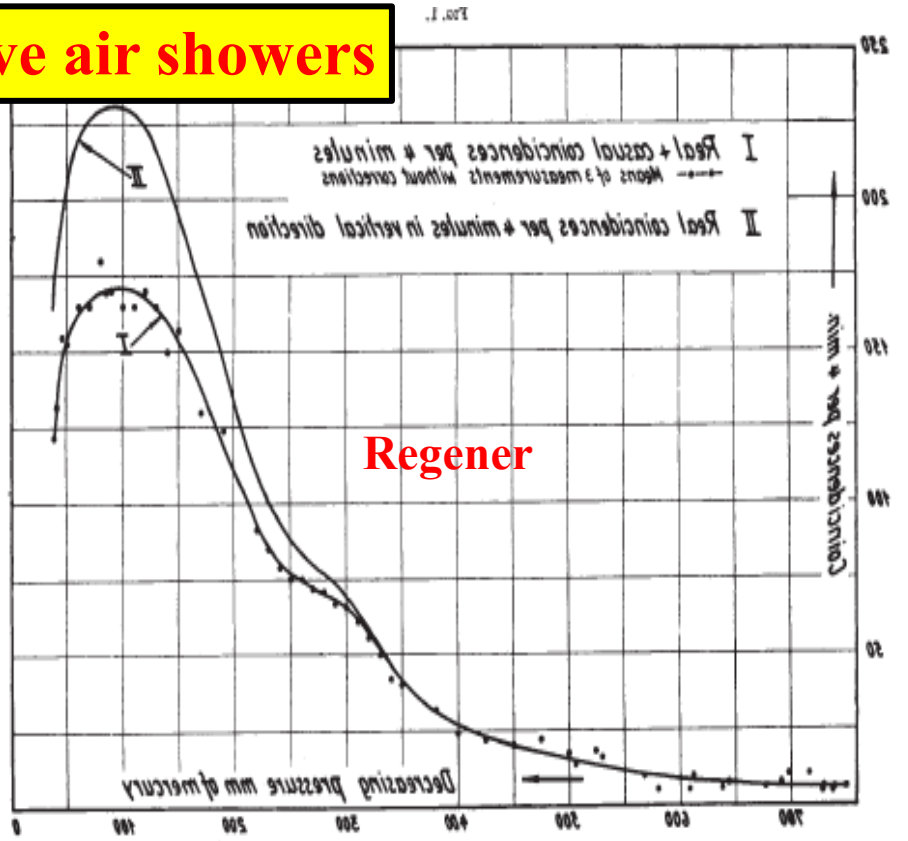
Rejected by Naturwissenschaften

Rossi 1933: Zeitschrift für Physik

But with support of Heisenberg, published in Physikalische Zeitschrift

Prediction and discovery of extensive air showers



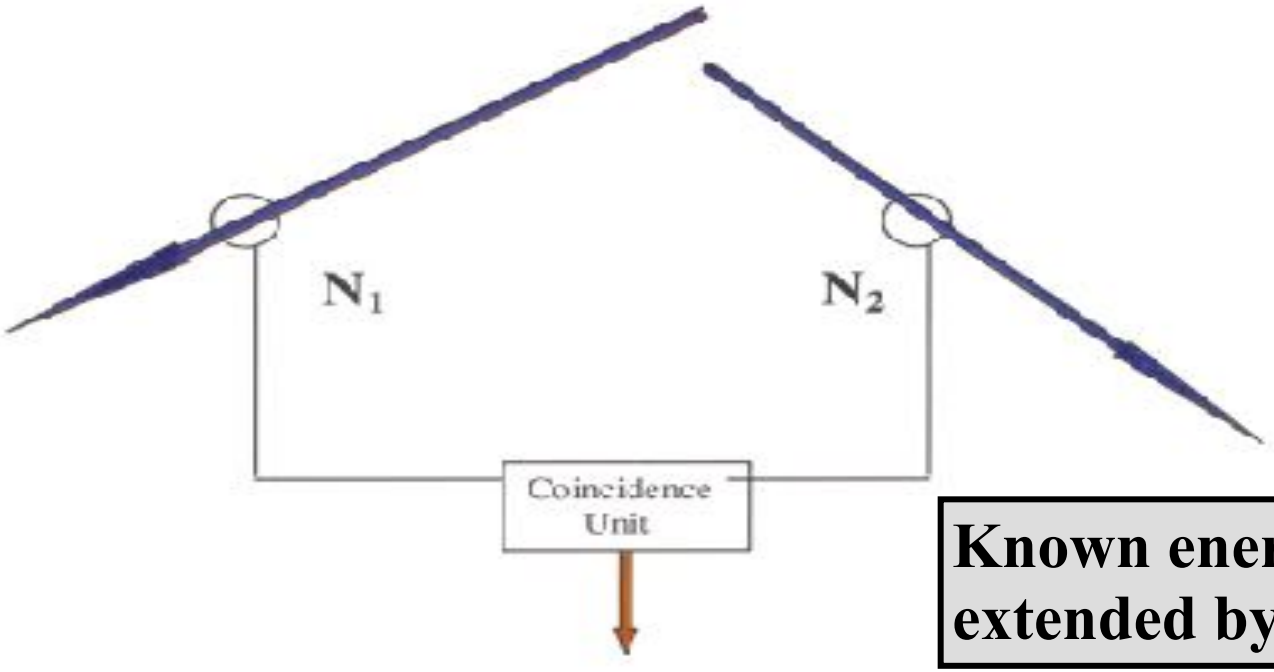


The idea of an air-shower was discussed in the mid-1930s by Bothe and Schmeiser and they, Kolhöster et al., and Auger reported relevant observations in 1938.

'Luftschauer'

Also, in interpreting the work of Regener, Bethe and Heitler (1937) reached similar conclusions from a theoretical position.

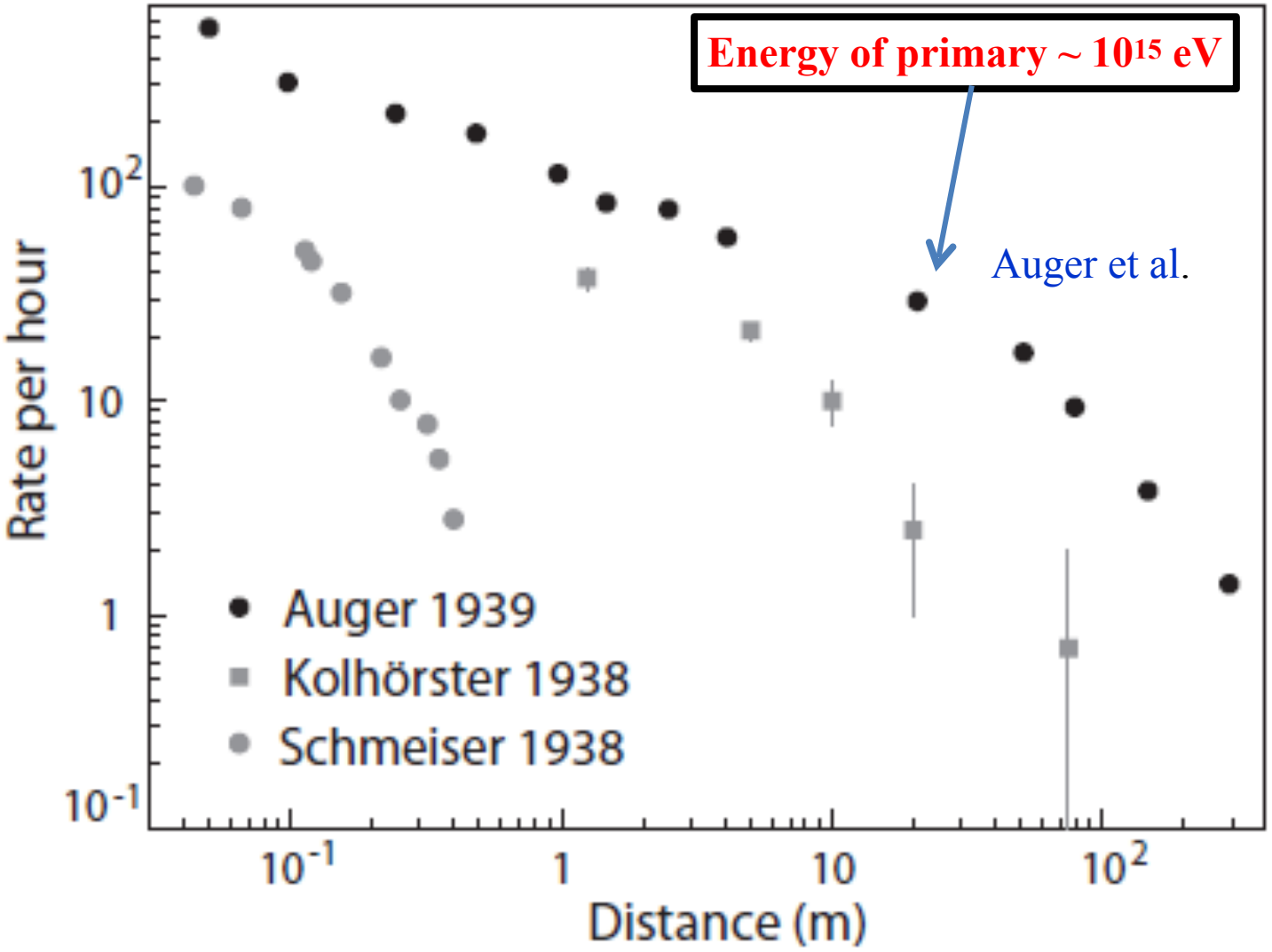
Discovery of Extensive Air Showers: Pierre Auger (1938)



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

Needed photons of ~10^{15} eV!



The measurements of Schmeiser and Bothe, Kolhöster et al., and Auger et al. **(Kampert and Watson 2012)**

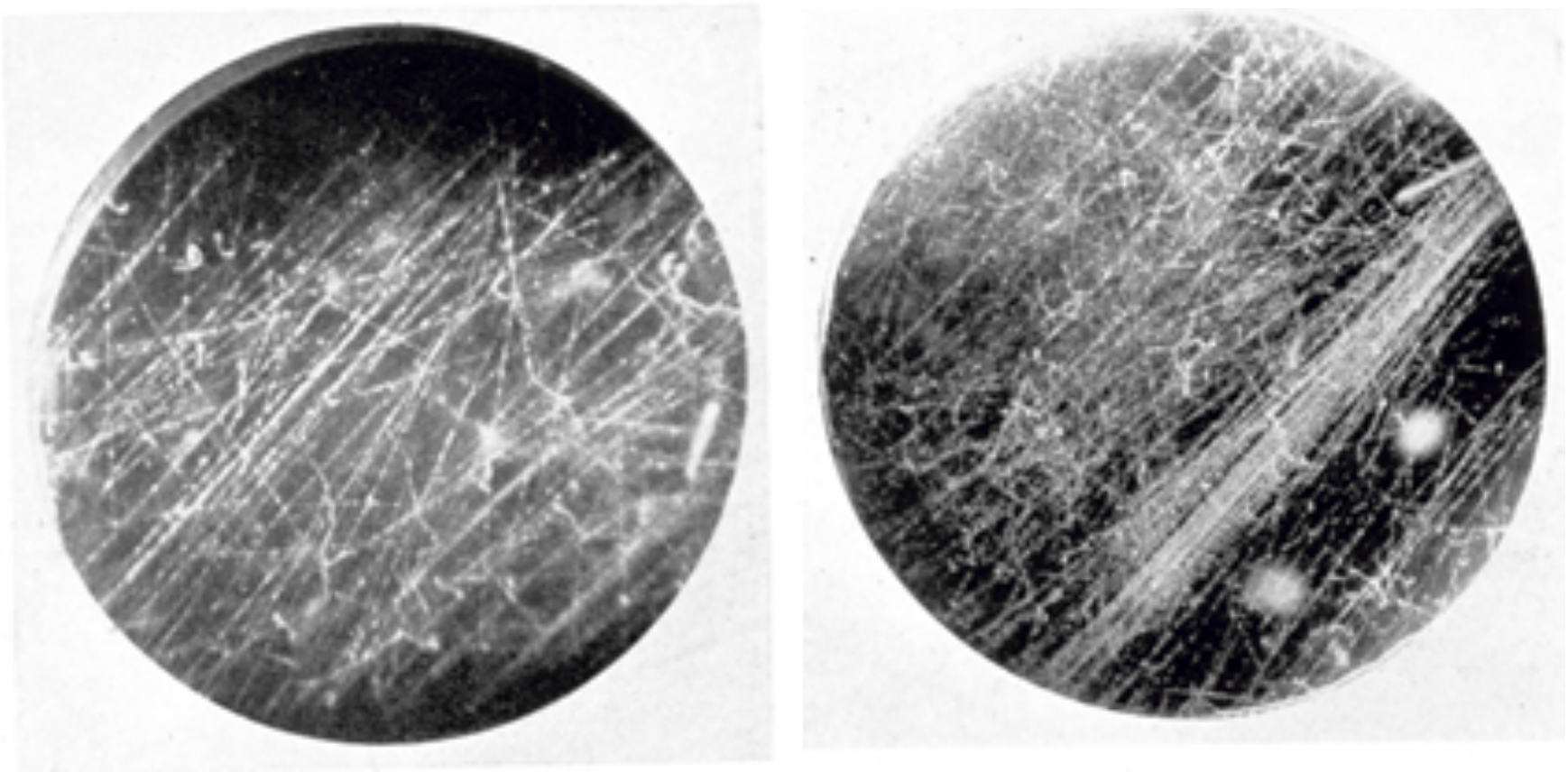
- but Rossi had beaten everyone by about 4 years

Rossi: La Ricerca Scientifica 1934

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

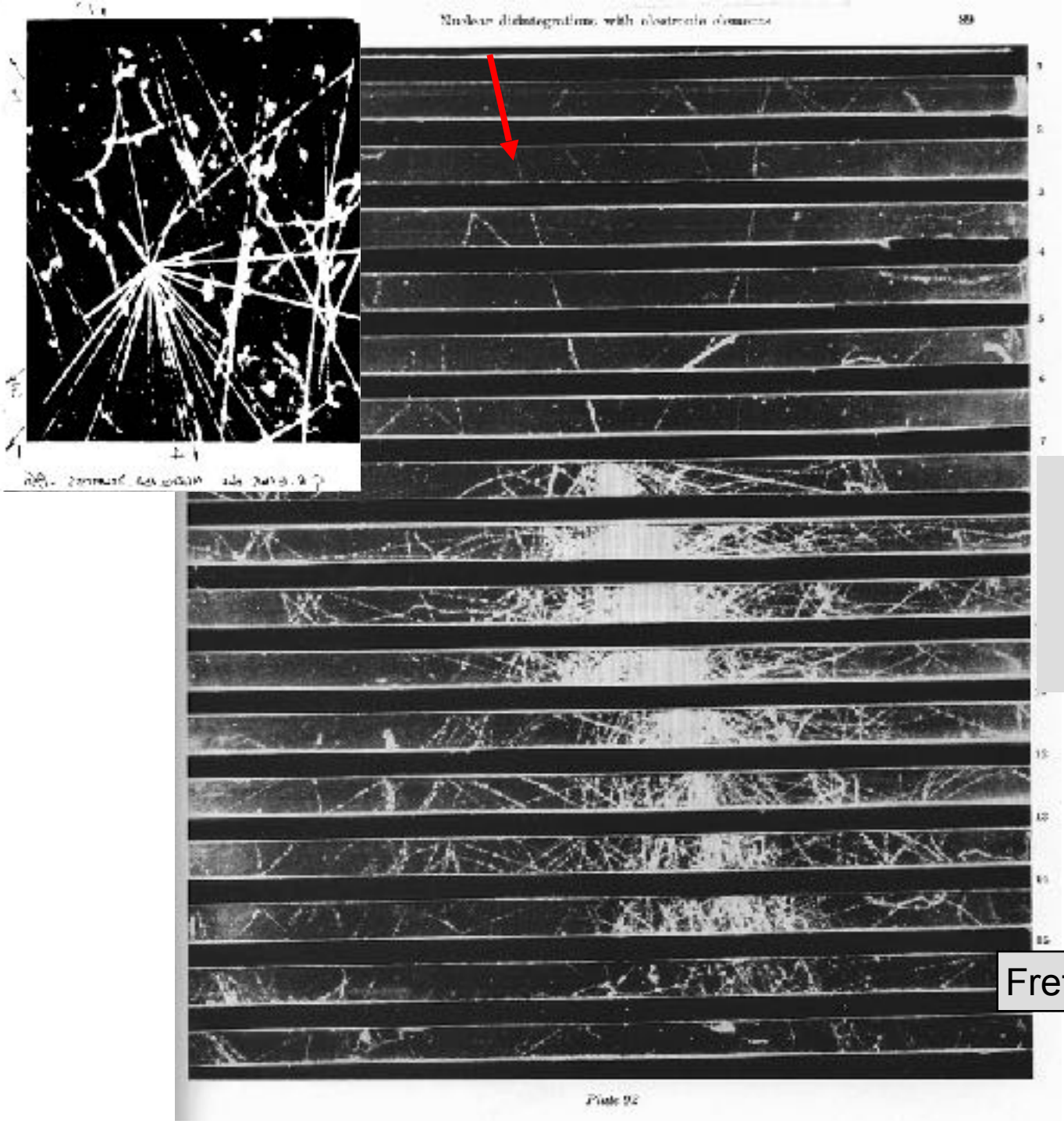
"The frequency of coincidences .....appears to be greater than would have been predicted from the resolving power of the coincidence circuit.....
..... it seem that once in a while the recording equipment is struck by *very extensive showers of particles*.....
(he used 'sciami molto estesi di corpuscoli')
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." (1990)



5.5 m

J G Wilson and C B A Lovell, Nature 1938



1.3 cm Pb

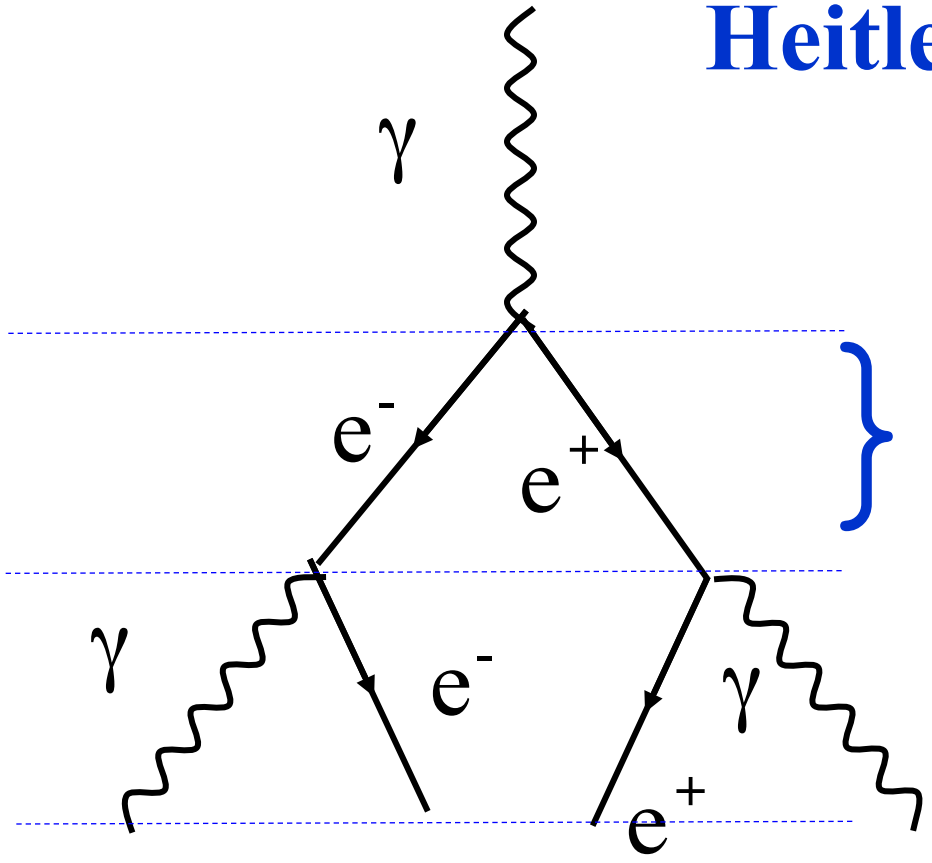
10 GeV proton

Shower initiated by proton in lead plates of cloud chamber

Detectors can find particle number and arrival times

Fretter: Echo Lake, 1949

Heitler Model



d = mean distance

d

$$d = \lambda_r \ln 2$$

λ_r = 37 g cm^{-2} in air

(radiation length)

Things the Heitler Model does well:

$N_{max} \sim E_o$ - but not constant of proportionality

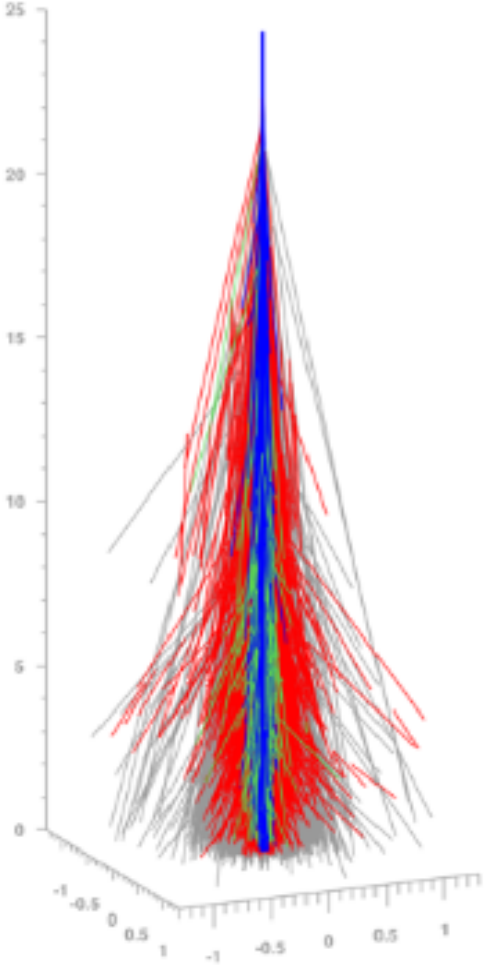
$X_{max} \sim \log E_o$

$$\Lambda \equiv \frac{\mathrm{d}\, X_{max}}{\mathrm{d} \log_{10} E_o} = 2.3\, \lambda_r = (85 \text{ g cm}^{-2})/\text{decade}$$

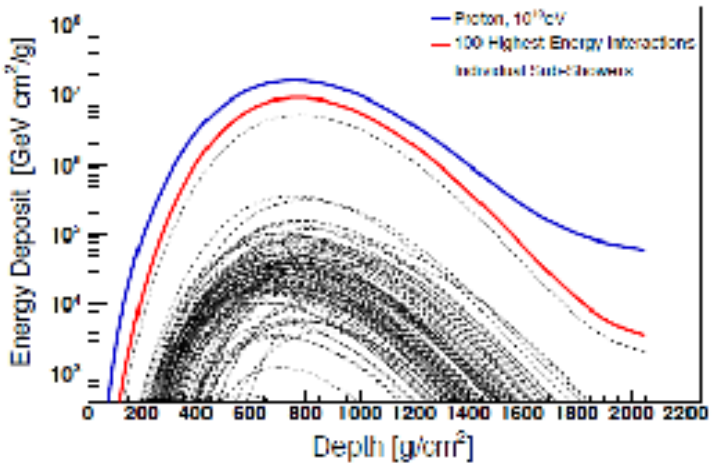
Now known as the ELONGATION RATE

Introduced by Linsley (1977)

Importance of different interaction energies



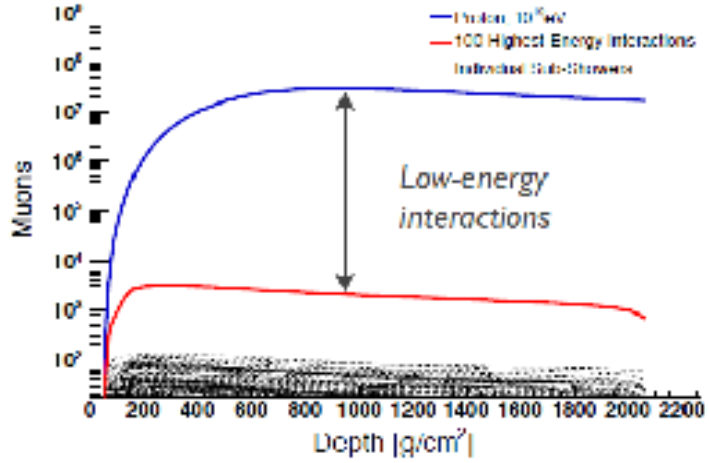
Electrons



Shower particles produced in 100 interactions of highest energy

Electrons/photons: high-energy interactions

Muons

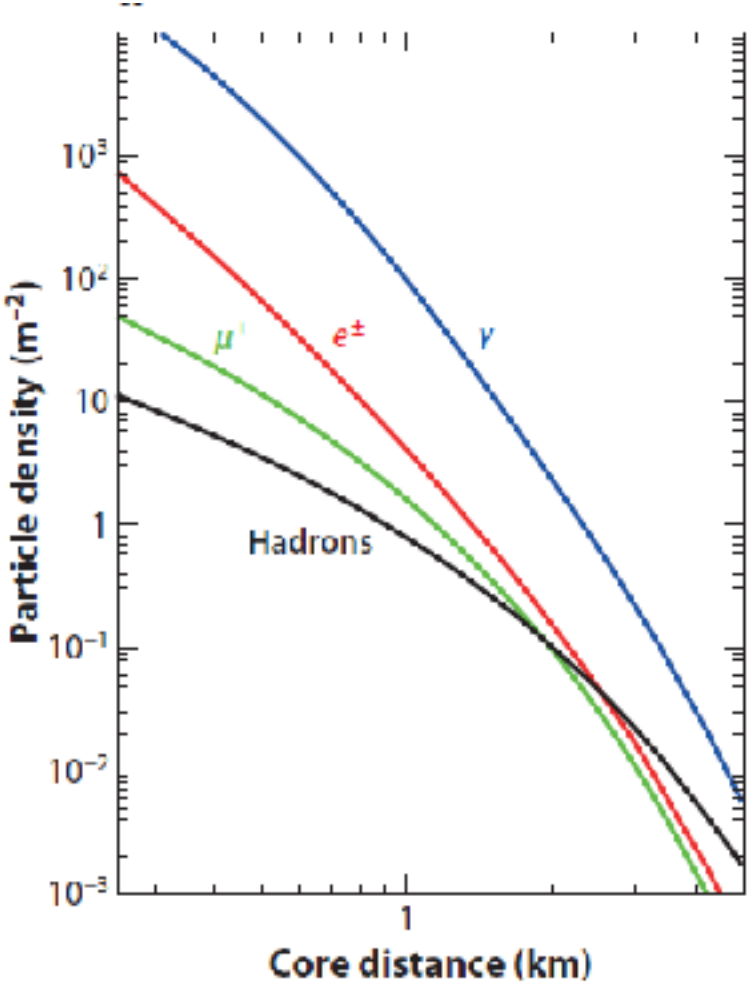


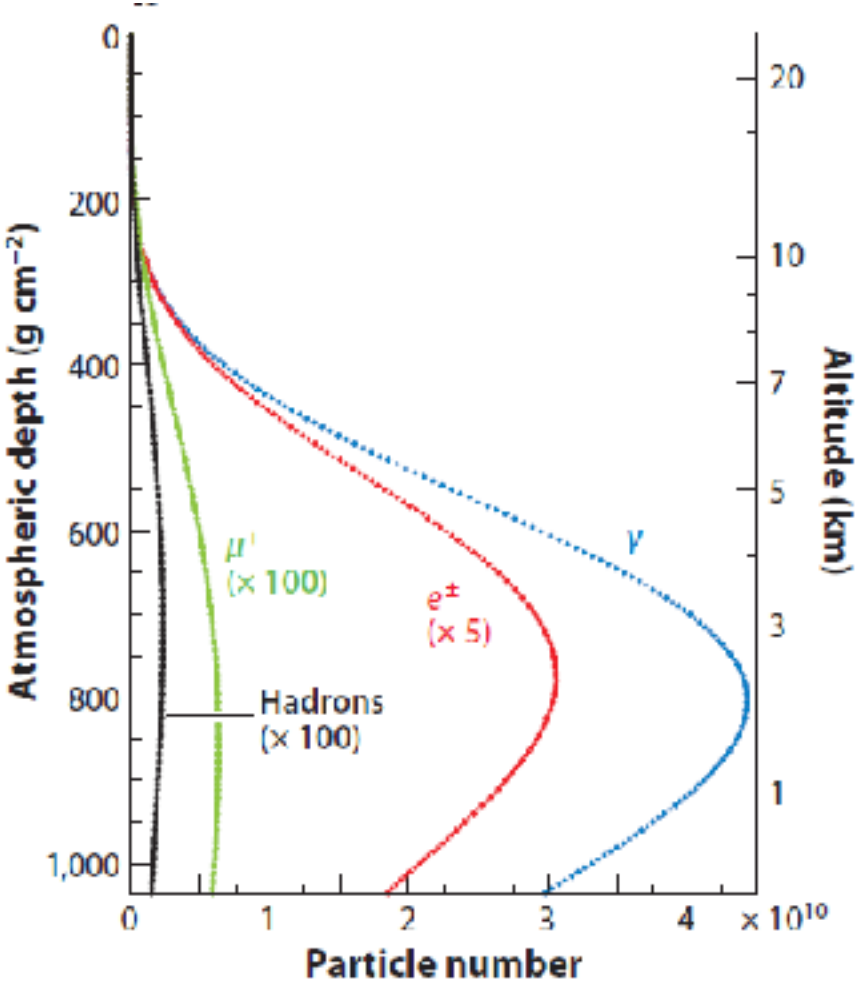
(Ulrich, APS 2012)

Muons/hadrons: low-energy interactions

Muons: majority produced in low energy interactions (30-200 GeV lab.)

Shower components as a function of distance and depth





Engel et al. Ann Rev NPS 2011

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

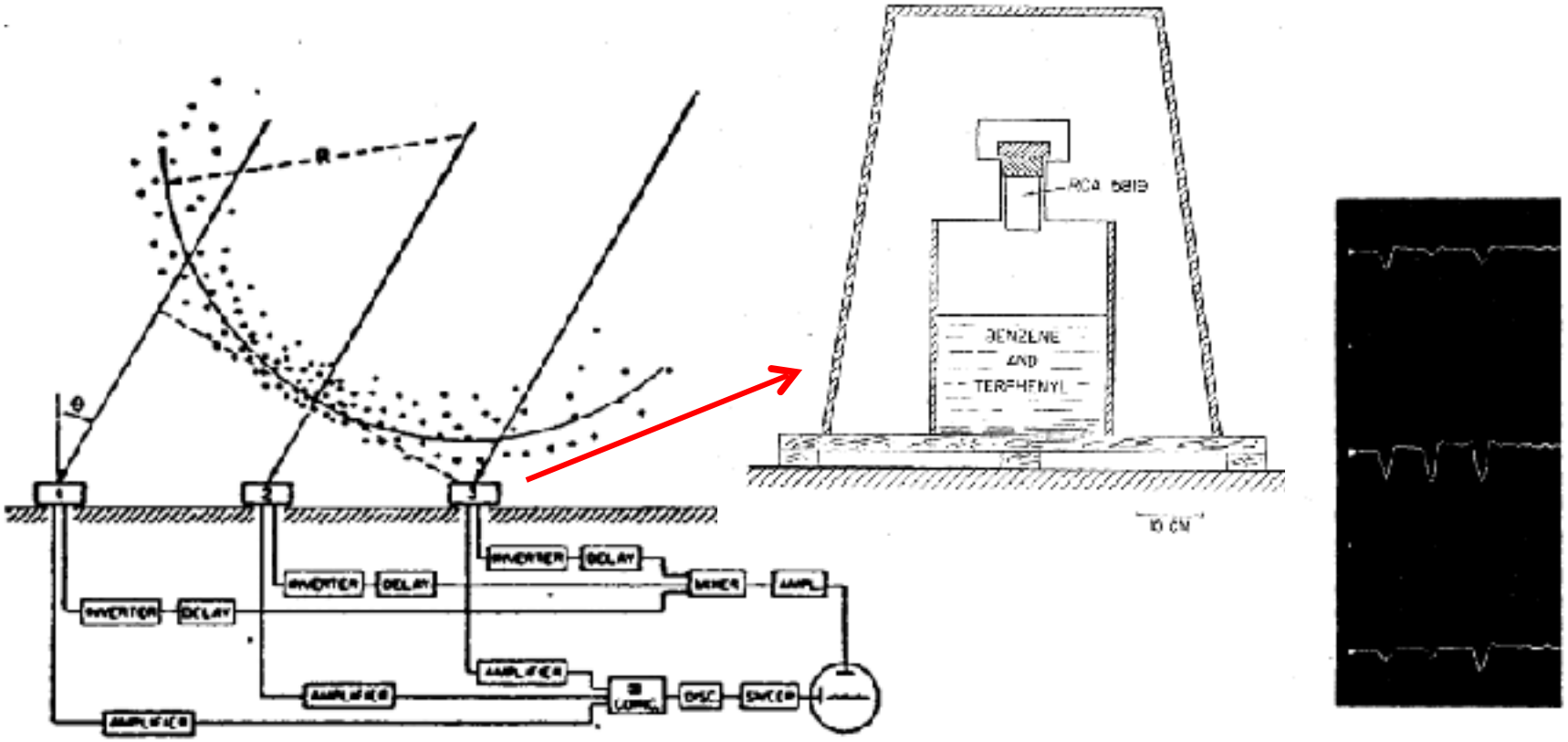
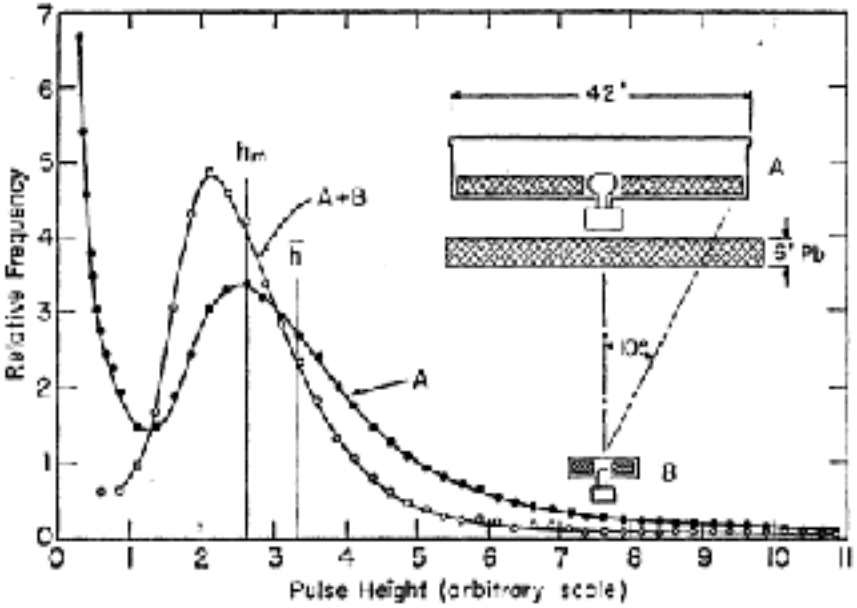


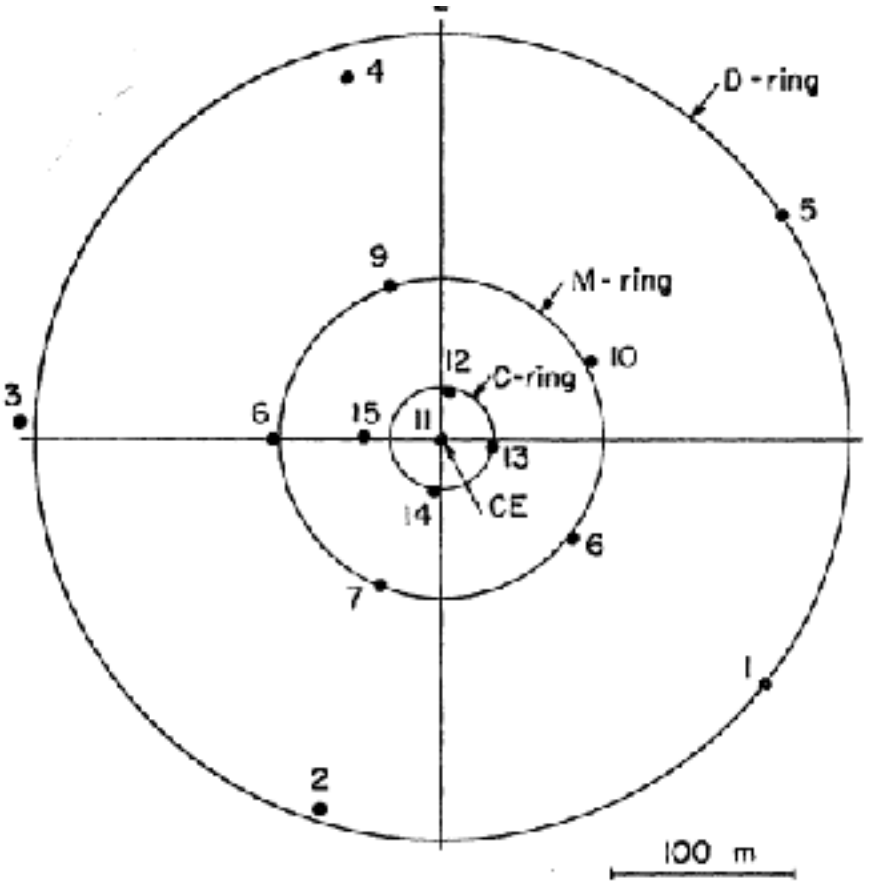
FIG. 2. Block diagram of the apparatus with a schematic representation of an air shower about to strike the counters. The counters are in arrangement II.

Directional uncertainty ~ 7°

Thickness of electron disc and fact that electrons lead muons close to the axis (a detector covered with lead)

MIT Agassiz Experiment and first spectrum results



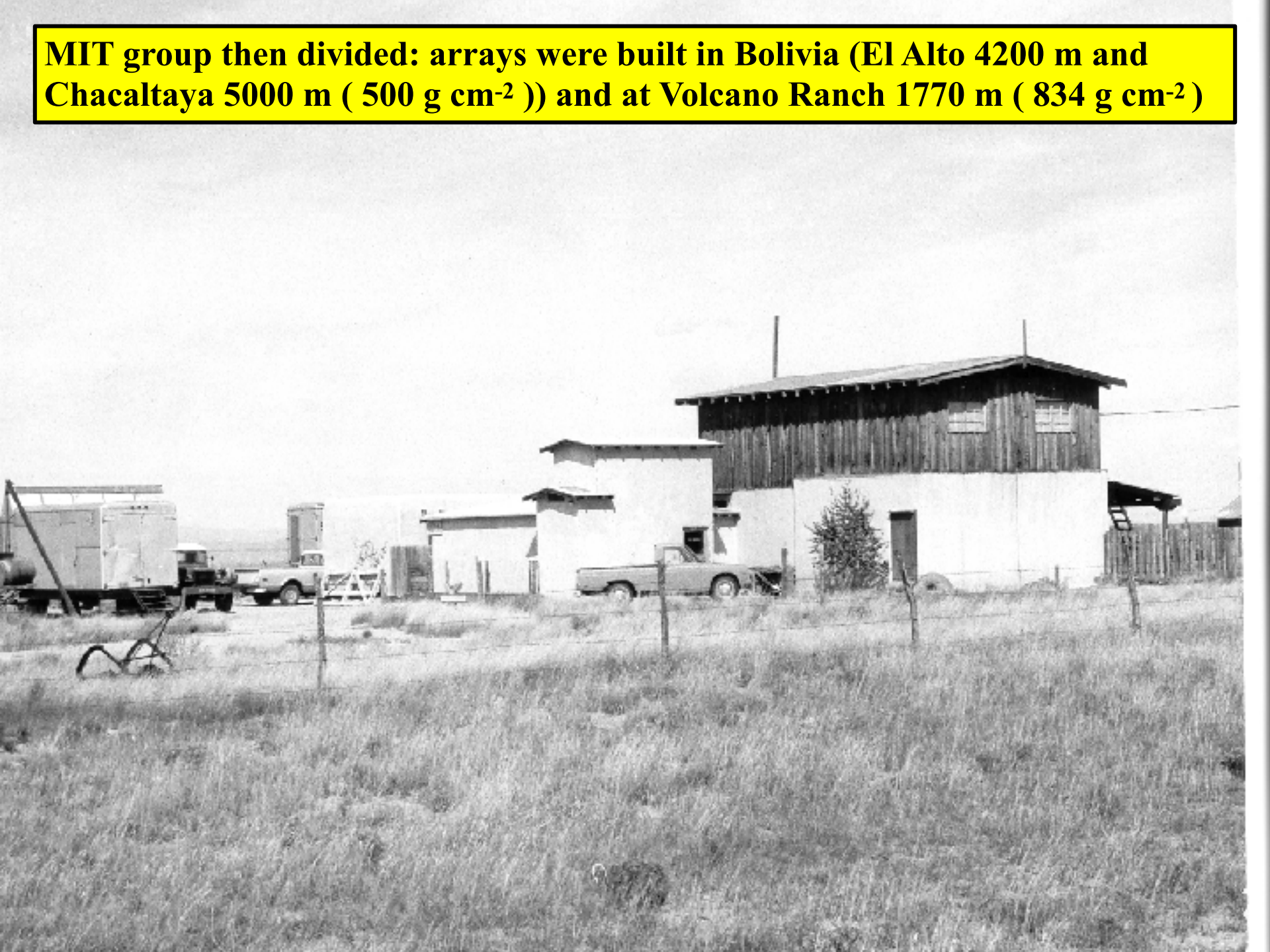


Largest event, N = 2.6 x 10^9

(late 1950s)

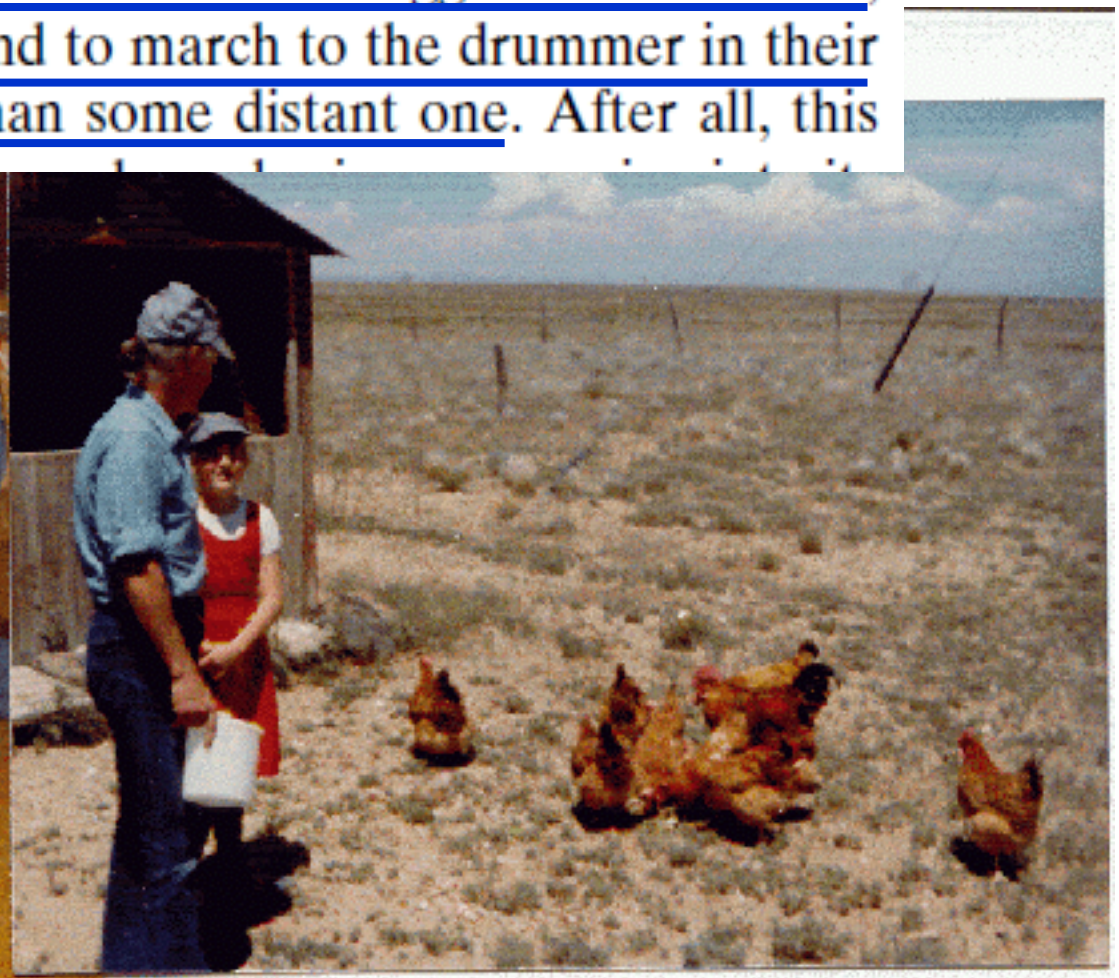
E ~ 3 x 10^{18} eV

MIT group then divided: arrays were built in Bolivia (El Alto 4200 m and Chacaltaya 5000 m (500 g cm^{-2})) and at Volcano Ranch 1770 m (834 g cm^{-2})

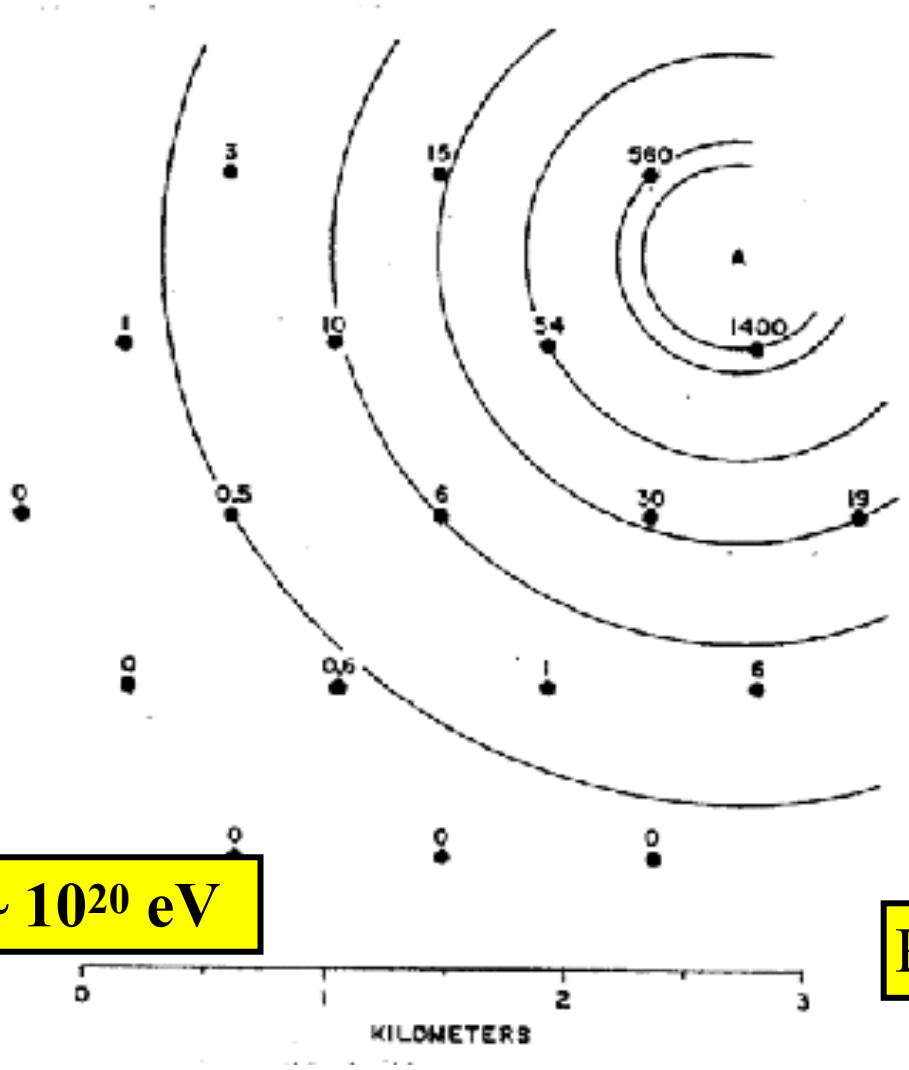


John Linsley was one of the last cosmic ray physicists who fitted the description of Val Fitch:

ing with Anderson's positron. Those who became interested in cosmic rays tended to be rugged individualists, to be iconoclastic, and to march to the drummer in their own heads rather than some distant one. After all, this



The Volcano Ranch Array: Linsley (1963)



Energy ~ 10^{20} eV

Pre-GZK prediction

J. Linsley, L. Scarsi and B. Rossi 1961

Time resolution ~300 ns

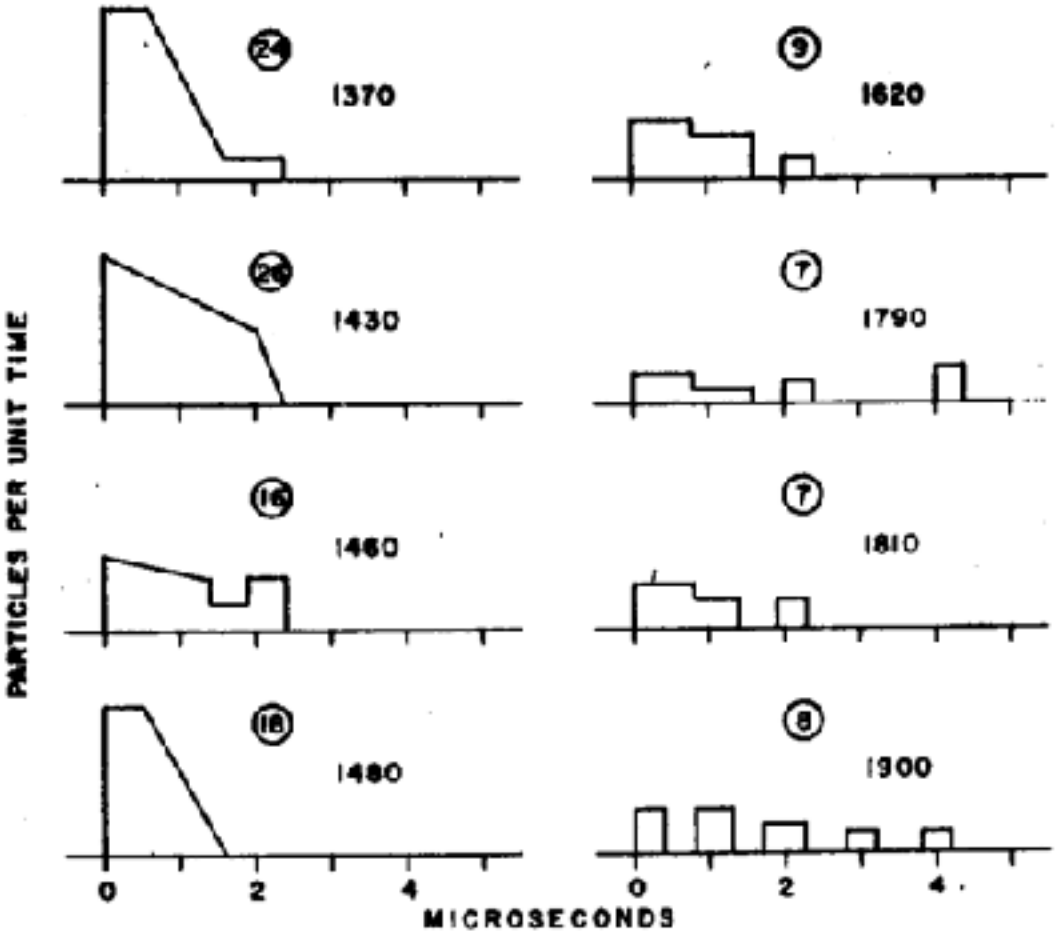


FIG. 3. Distributions in arrival time of shower particles at the eight detectors furthest from the shower axis. The number of particles included in each distribution (to which the areas have been normalized) is shown circled. Distances from the shower axis are also given.

Phys Rev 1962

Muons lead electrons

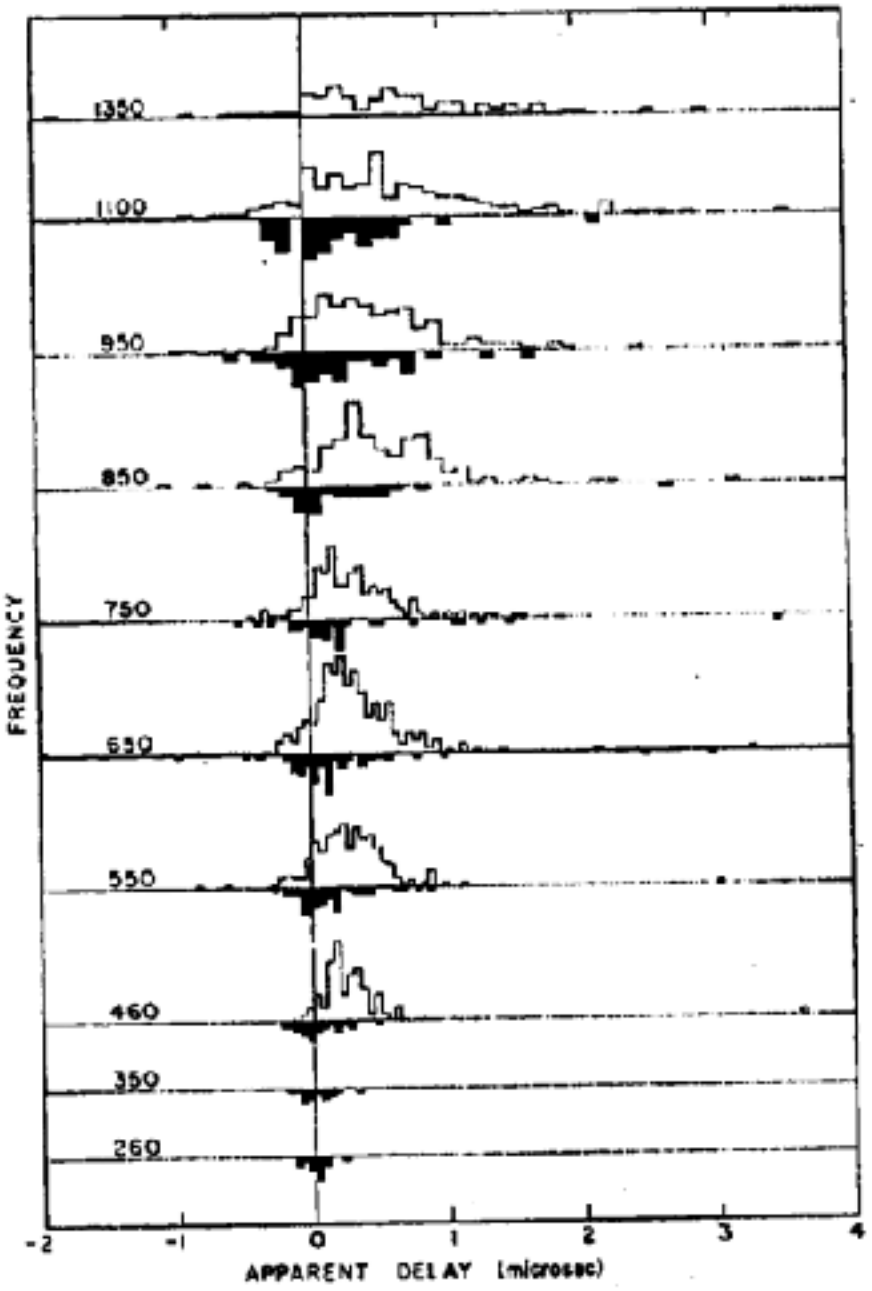


TABLE I. Single-particle
tangent plane, for vari

Distance (m)	Shielded detecto Mean	Medi
260	0.03 ±0.02	0.04 ±
350	0.04 ±0.03	0.03 ±
460	0.05 ±0.04	0.02 ±
550	0.14 ±0.05	0.07 ±
650	0.14 ±0.03	0.13 ±
750	0.26 ±0.10	0.14 ±
850	0.20 ±0.04	0.10 ±
950	0.30 ±0.06	0.18 ±
1100	0.38 ±0.07	0.20 ±
1350	...	..

the result for several c
est to the largest that

I

The large pulses w
plane, so as to minim
investigate the fluctu
the smallest pulses,
Measurements of t_{obs}
distance from the s
interval we plotted t
apparent delays. We
median of each distri
for pulses from the
the shielded detecto
the data were also se
to the zenith angle of
of frequency distribu

Homework for tomorrow:

- **Bassi, Clark and Rossi found that the electrons arrived EARLIER than the muons**

- **Linsley and Scarsi found that electrons arrived LATER than the muons**

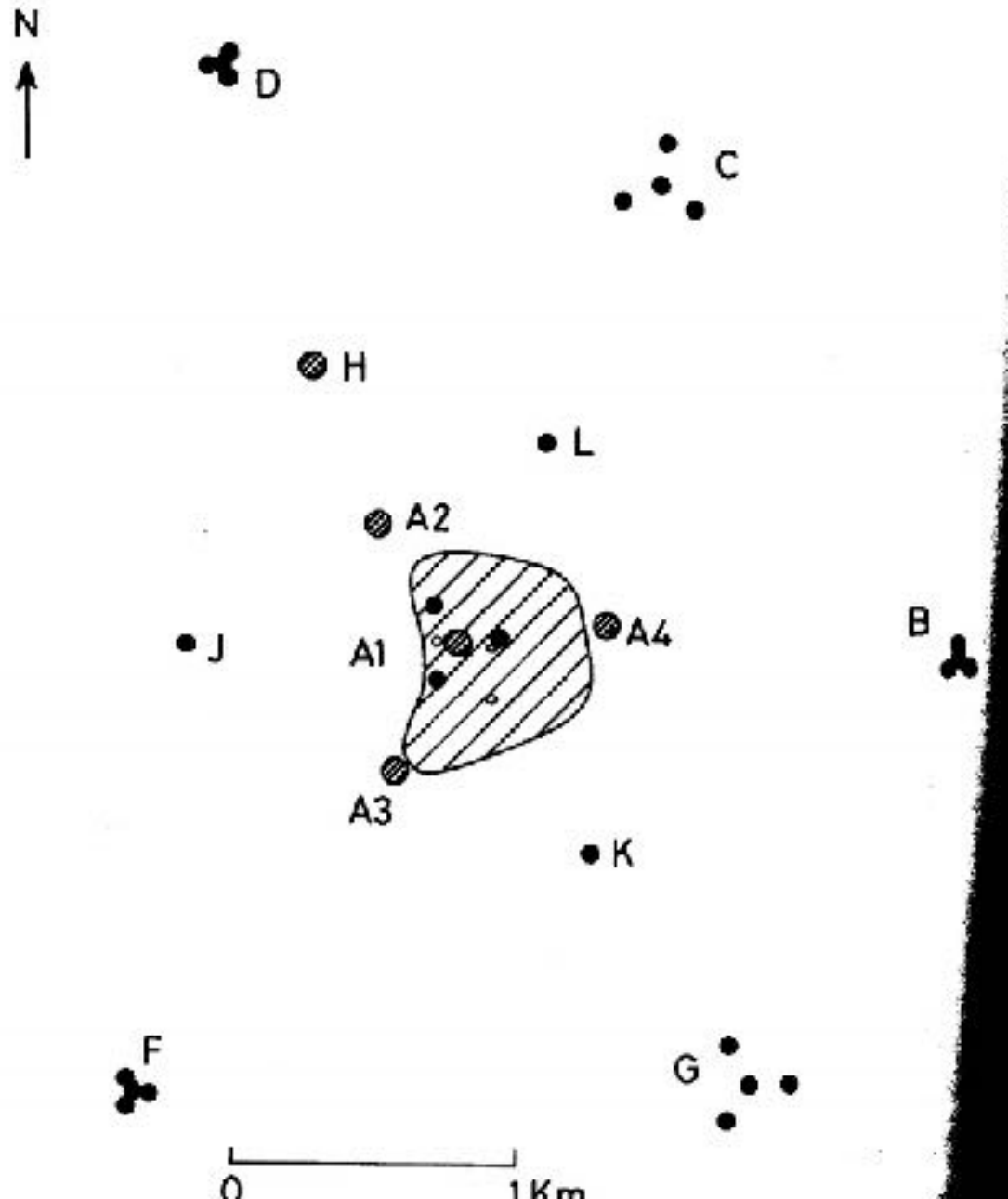
Why?

What about the photons?

The shower array at Haverah Park. The area enclosed was ~12 km²

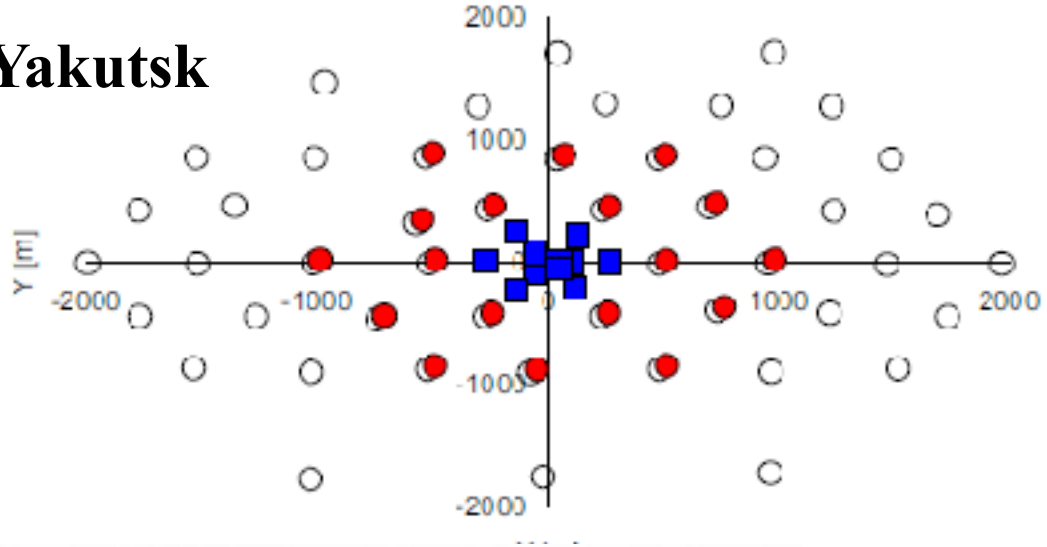
Each point in the diagram represents one or more tanks of water

Haverah Park 1967 - 1987




End of project party:
water still drinkable after 25 years

Yakutsk



25 km² for many years

Now 8 km²

Fluorescence Radiation:

Idea occurred to three or four people simultaneously
First discussed by Suga at meeting in Chacaltaya in 1962

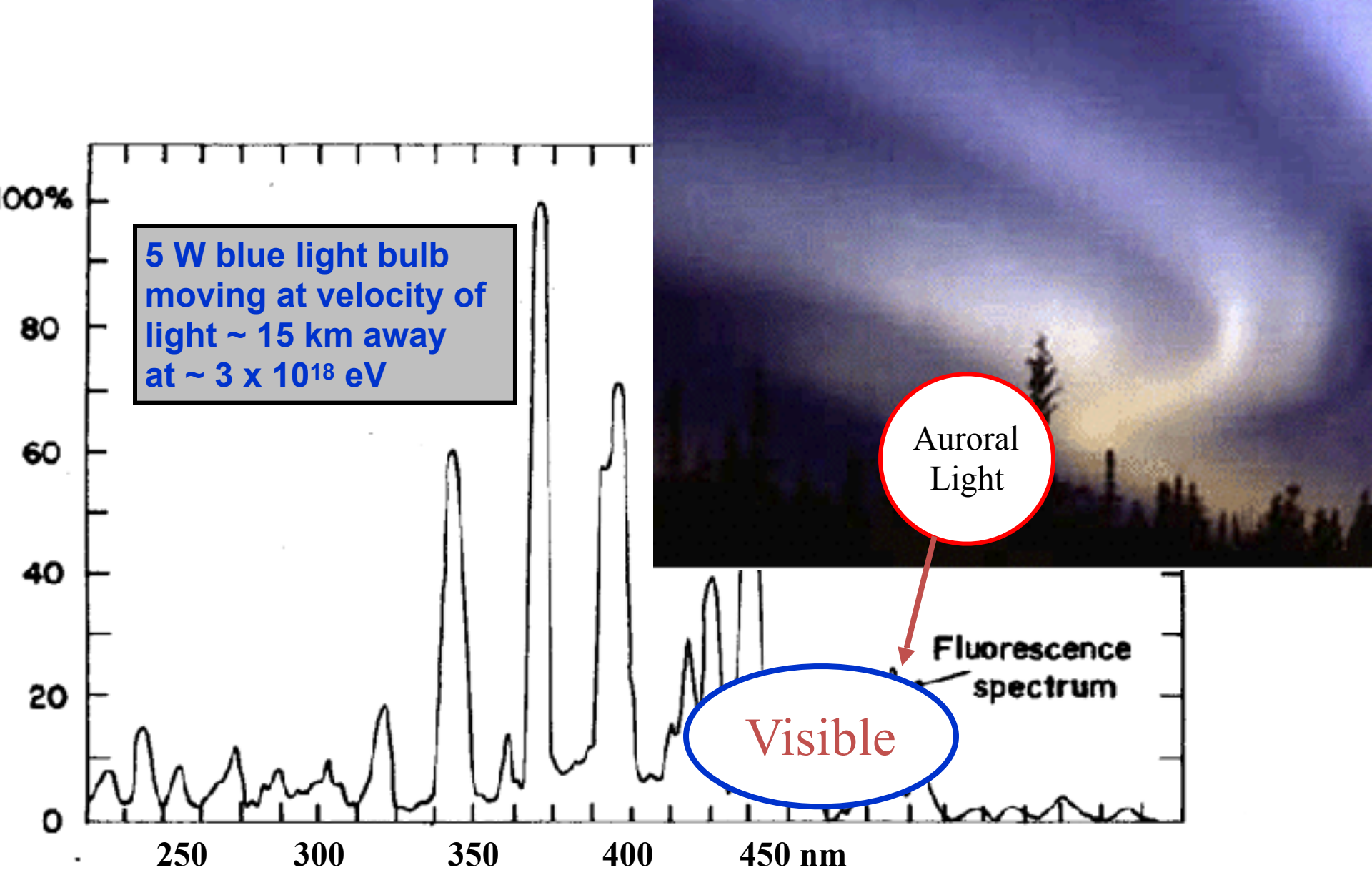
- **Chudakov knew of this in 1950s and explored properties in case it was a background for Cherenkov radiation when**

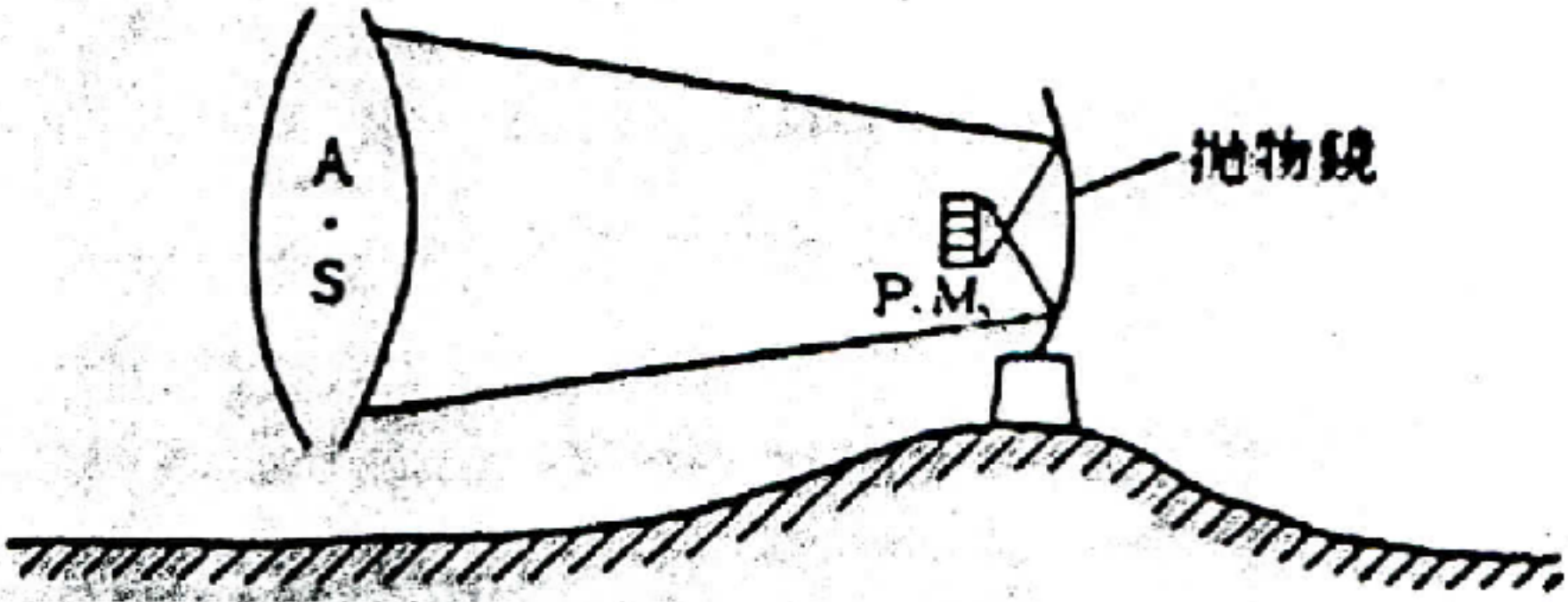
- **Oda and/or Suga developed ideas in Japan**

- **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**

(Similar work was done at Harwell using infra-red radiation)

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


5 W blue light bulb moving at velocity of light ~ 15 km away at ~ 3 x 10^18 eV
Auroral Light
Fluorescence spectrum
Visible
100%
80
60
40
20
0
250
300
350
400
450 nm



第3図　1958年集録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)**

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

VOLUME 16, NUMBER 17 PHYSICAL REVIEW LETTERS 25 APRIL 1966

Preprint: "END TO THE COSMIC-RAY SPECTRUM"

END TO THE COSMIC-RAY SPECTRUM?

Kenneth Greisen

Cornell University, Ithaca, New York

(Received 1 April 1966)

The primary cosmic-ray spectrum has been measured up to an energy of 10^{20} eV,[1] and several groups have described projects under development or in mind[2] to investigate the spectrum further, into the energy range 10^{21}-10^{23} eV. This note predicts that above 10^{20} eV the primary spectrum will steepen abruptly, and the experiments in preparation will at last observe it to have a cosmologically meaningful termination.

The cause of the catastrophic cutoff is the intense isotropic radiation first detected by Penzias and Wilson[3] at 4080 Mc/sec (7.35 cm) and now confirmed as thermal in character by measurements of Roll and Wilkinson[4] at 3.2 cm wavelength. It is not essential to the present argument that the origin of this radiation conform exactly to the primeval-fireball model outlined by Dicke, Peebles, Roll, and Wilkinson[5]; what matters is only that the radiation exists and pervades the observable universe. The transparency of space at the pertinent wavelengths, and the consistency of intensity observations in numerous directions,

….in preparation are doomed to failure.

Sydney and Fly's Eye

Does the Cosmic Ray Energy Spectrum terminate?

Greisen-Zatsepin-Kuz'min – GZK effect (1966)

$$\gamma_{2.7\,K} + p \rightarrow \quad \Delta^{+} \quad \rightarrow \quad n + \pi^{+} \text{ or } p + \pi^{o}$$

and

$$\gamma_{IR/2.7\,K} + A \rightarrow \quad (A - 1) + n$$

- **Sources must lie within ~ 100 Mpc at 100 EeV**
  - **Note that neutrinos - of different energies – come from the decay of π^{+} and n**
  - **Photons from decay of π^{o}**

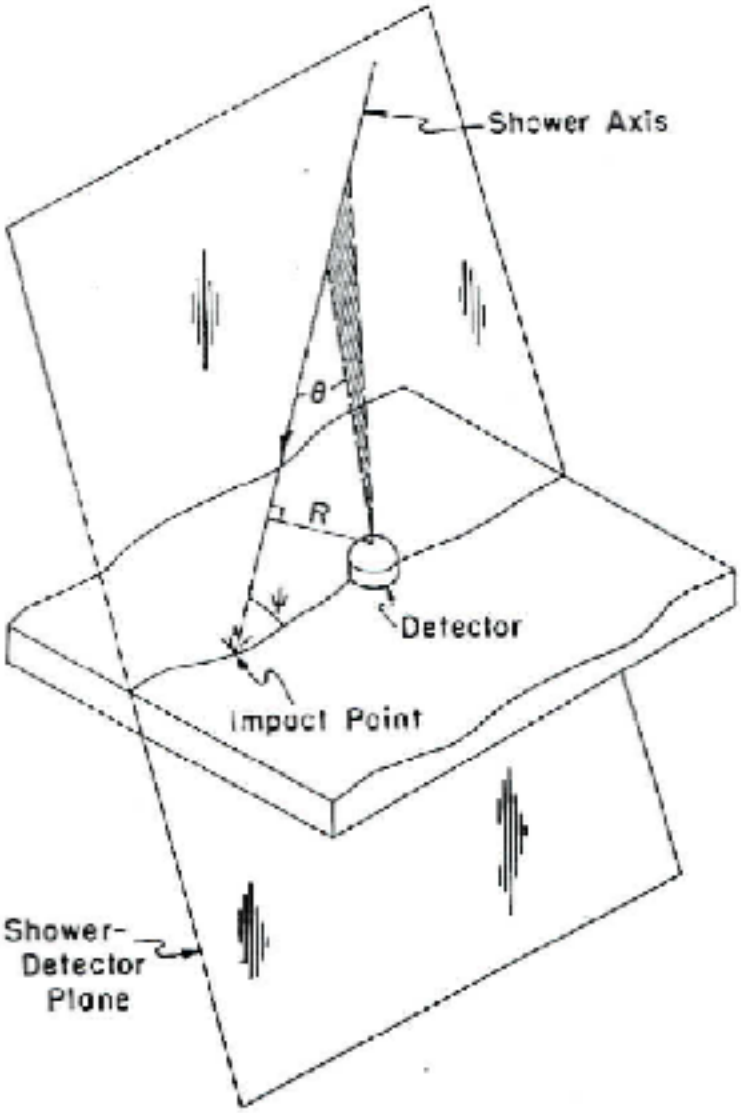
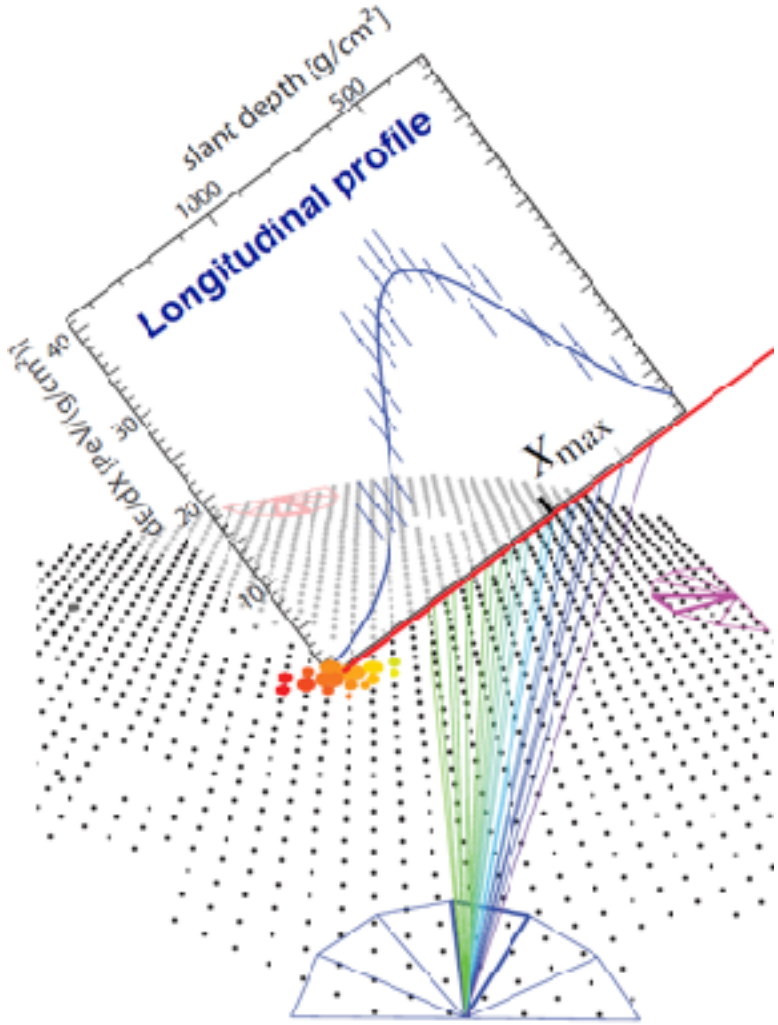


FIG. 1. Perspective view of shower geometry.

Alan Bunner: Masters Thesis, Cornell 1960 – pre-dates Chacaltaya (1962 meeting) but not INS picture at 1957 meeting

Energy from fluorescence measurements

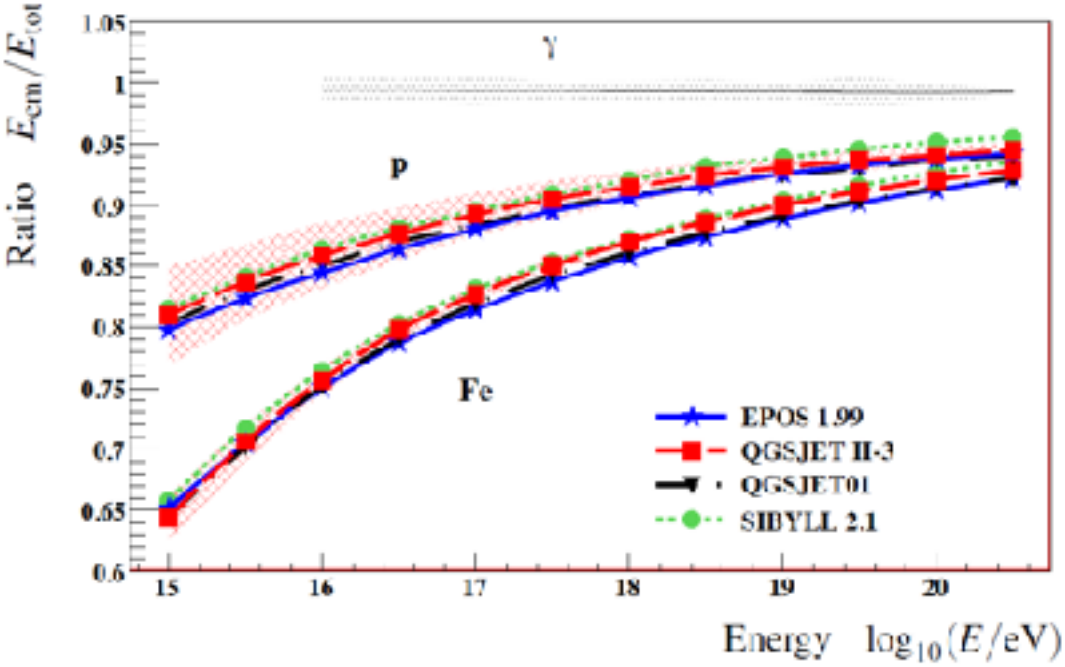


Example: event observed with Auger Observatory

Electrons:

$$E_{em} = \int \left. \frac{dE_{ion}}{dX} \right|_{meas.\ |\ extrap.} dX$$

$$E_{tot} = (1 + f_{cor})\, E_{em}$$



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

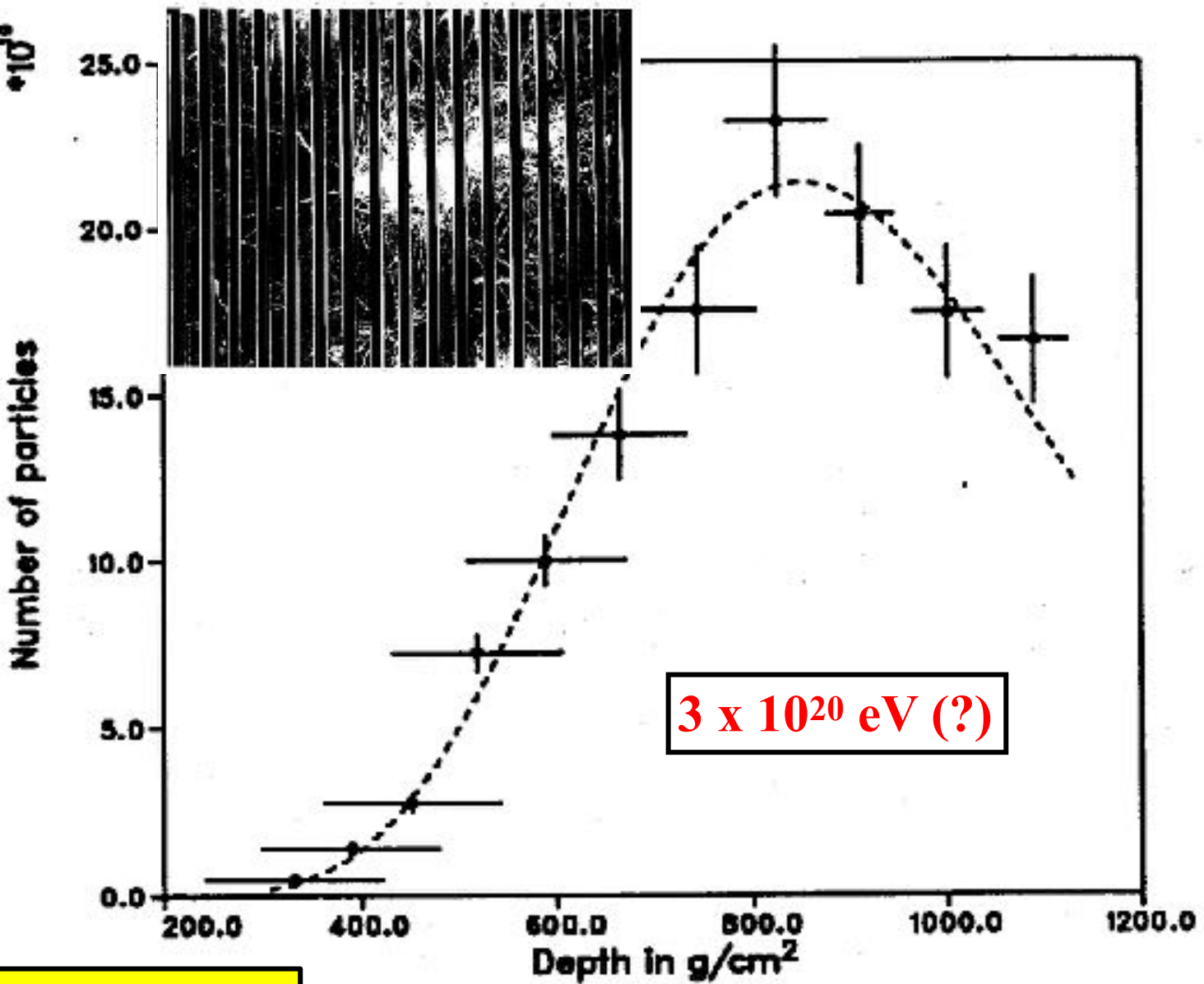
and

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

x 10^{10}



Reported in 1993 – detected some years before

TWO LARGE AIR SHOWER EXPERIMENTS

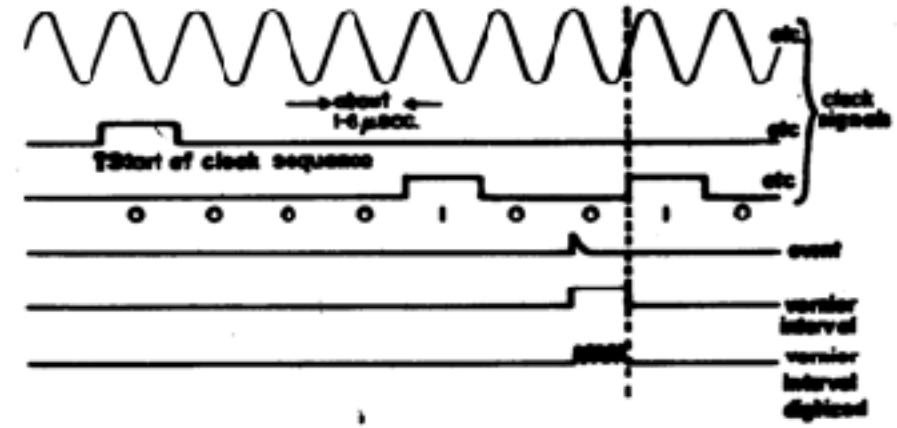
by

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

The University of Sydney

Jaipur Conference 1963

First discussion of stand-alone operation of detectors



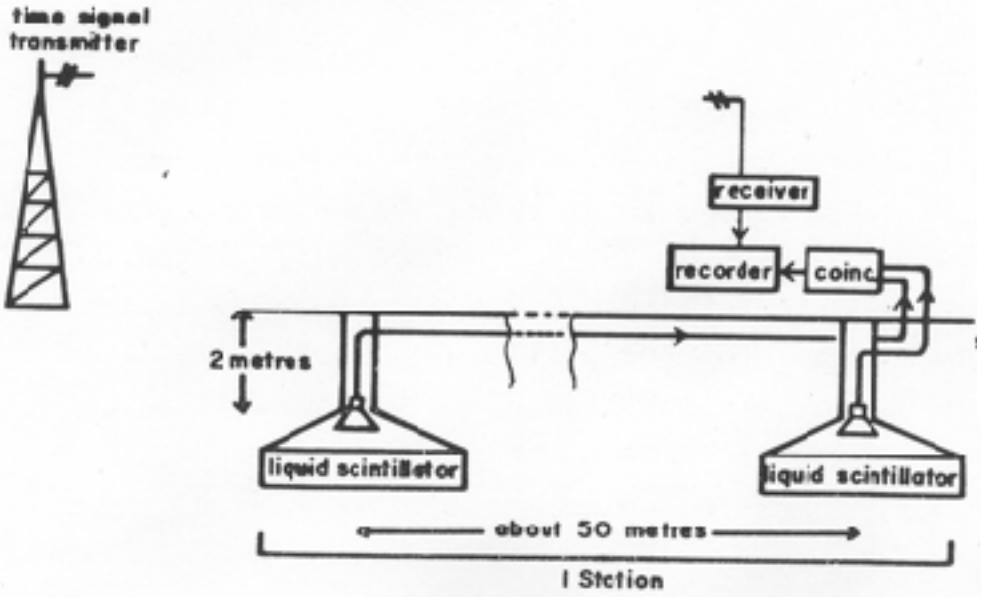
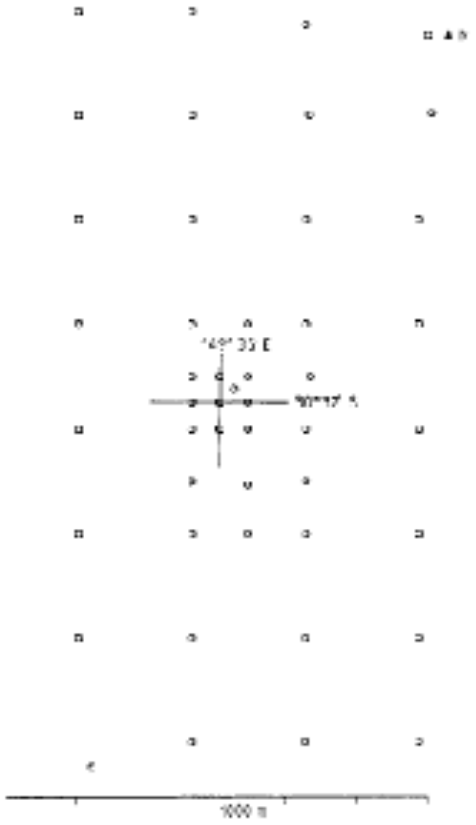


FIGURE 2

Sydney array was ~100 km² with 54 pairs of buried scintillators

Not very successful: really the technology was not quite there – but concept of 'stand alone detectors established



Planning of this array was well-before GZK prediction

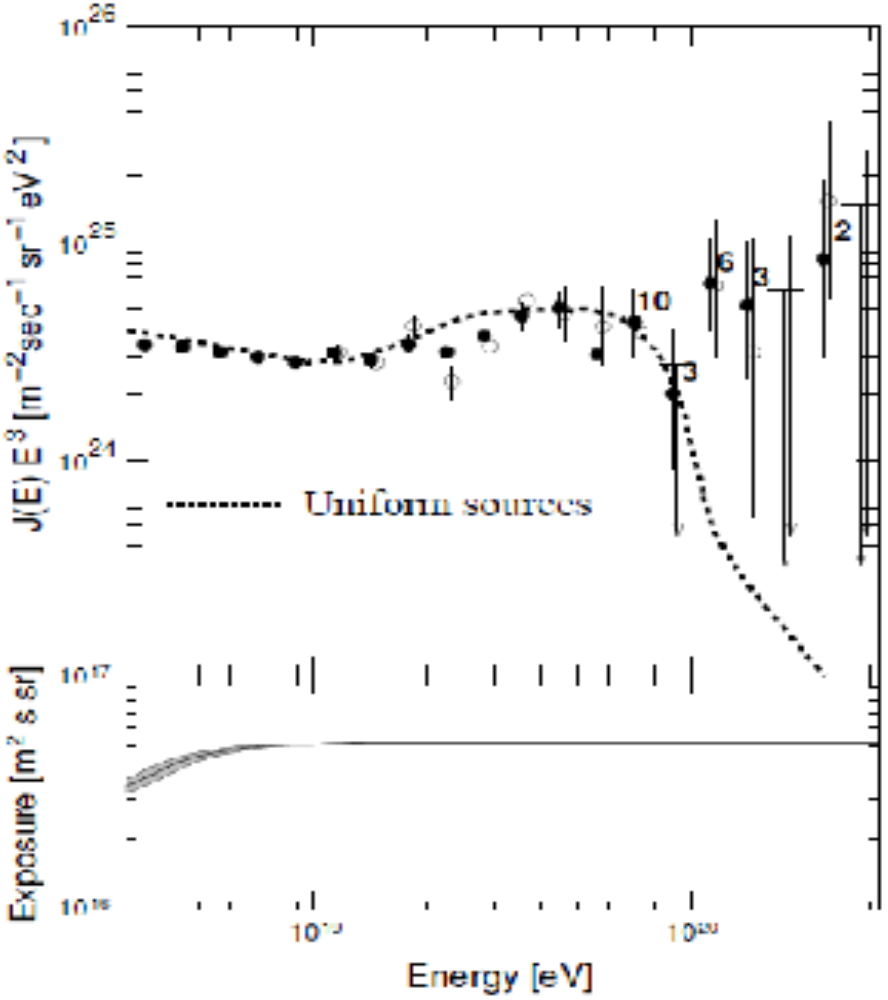
Next 100 km² array was AGASA in Japan

111 scintillators on 1 km² grid

Operated for 12 years

Very remarkable result

Huge number of explanations



The belief that the highest-energy cosmic rays cannot be explained within the current canon of astrophysical knowledge has led to a plethora of alternative suggestions. We discuss several of these in Secs. VII.H, VII.I, and VII.J. Here we give only an impression of the range of suggestions that have been made. One approach has been to invent mechanisms to avoid energy losses in the 2.7-K radiation field. For example, Farrar and Biermann (1998) have suggested that a stable supersymmetric hadron may be responsible for creating the largest showers. Alternatively Gonzales-Mestres (1997, 1998) and Coleman and Glashow (1998, 1999) have speculated that Lorentz invariance might break down at the Lorentz factors of interest so that the GZK cutoff is heavily suppressed. Exotic entities from the early universe have been invoked with the decay of topological defects, such as monopoles or strings, or the possibility of superheavy relic particles from the post-inflation era, all having their advocates. Some of these processes predict distinctive signatures in the form of copious fluxes of neutrinos and gamma rays, in addition to a hadronic channel.

Nagano and Watson: RMP 2000

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" ***Julian Barnes***

- **September 1982**

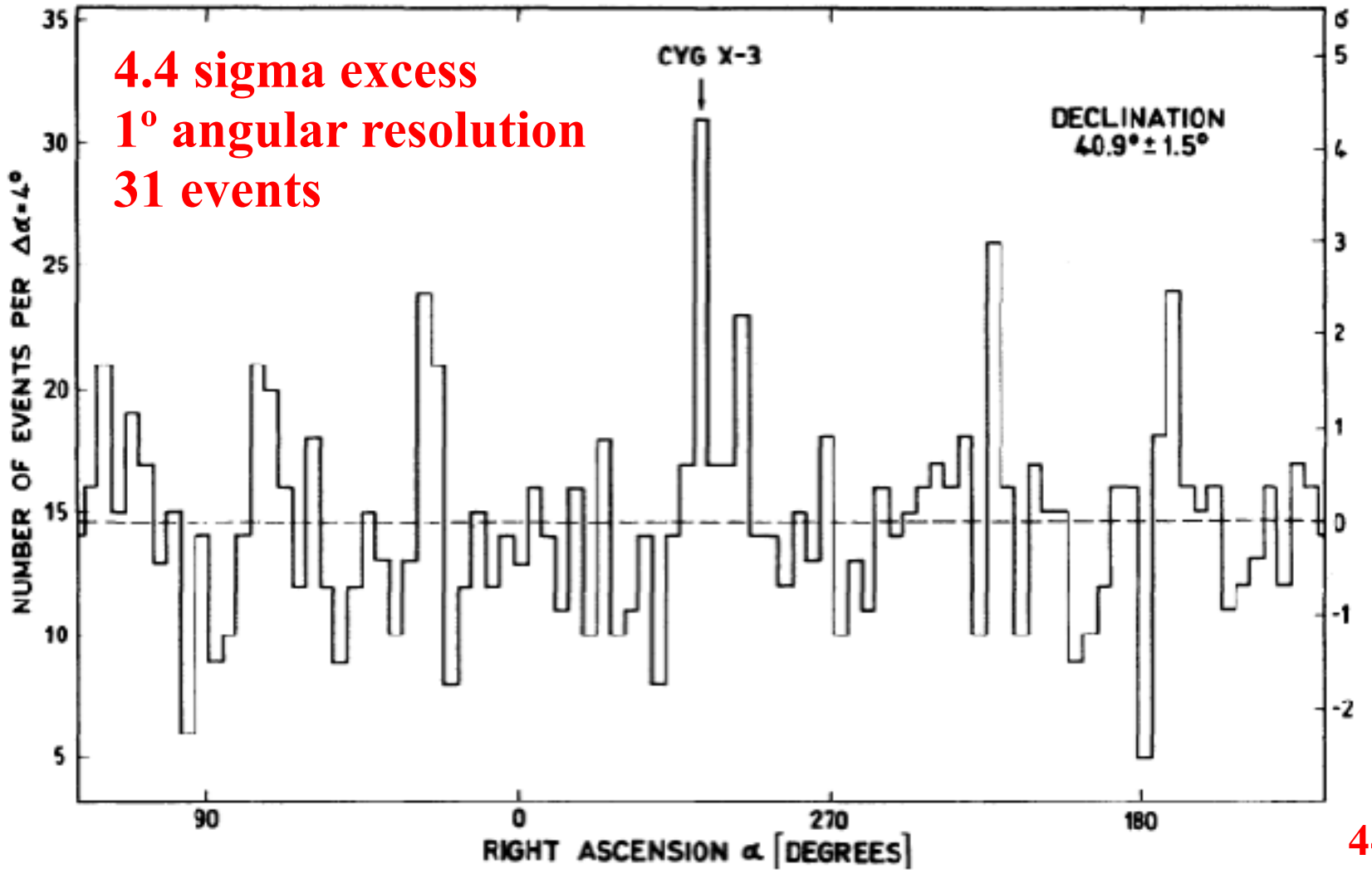
Bar in Rome with Jay Perrett and Wolf-Dieter Dau

during 8th European Cosmic Ray Symposium

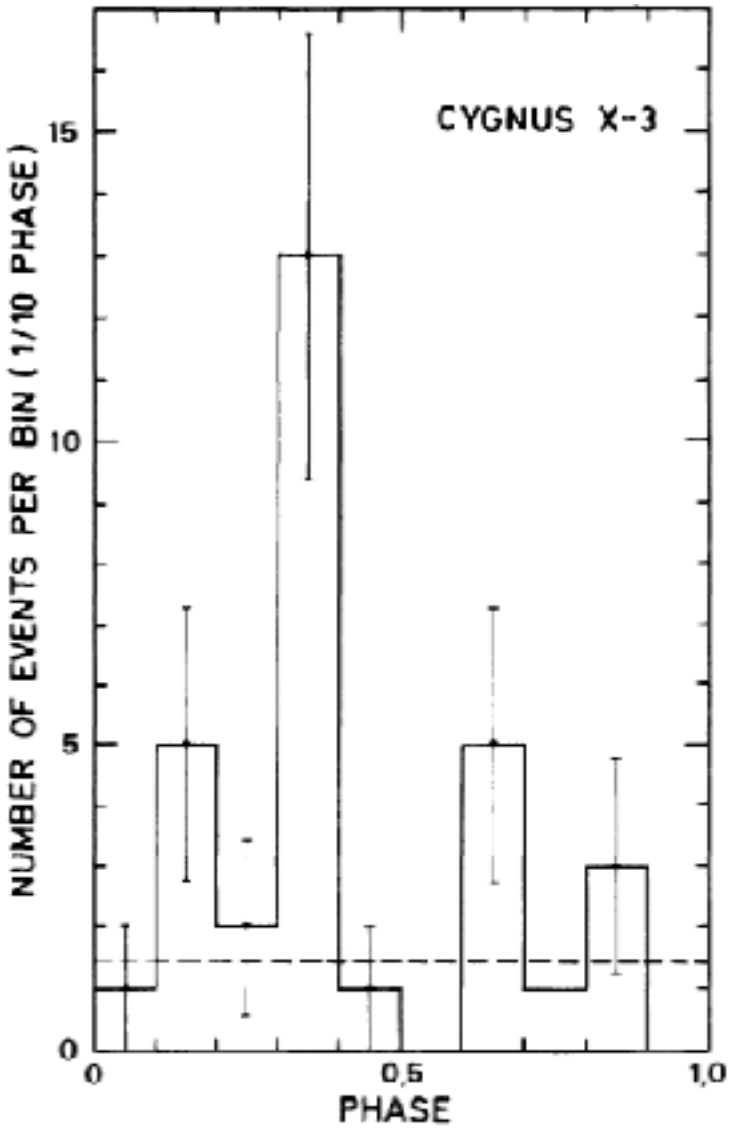
Wolf-Dieter
"I'm surprised that Samorski and Stamm are not here"

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



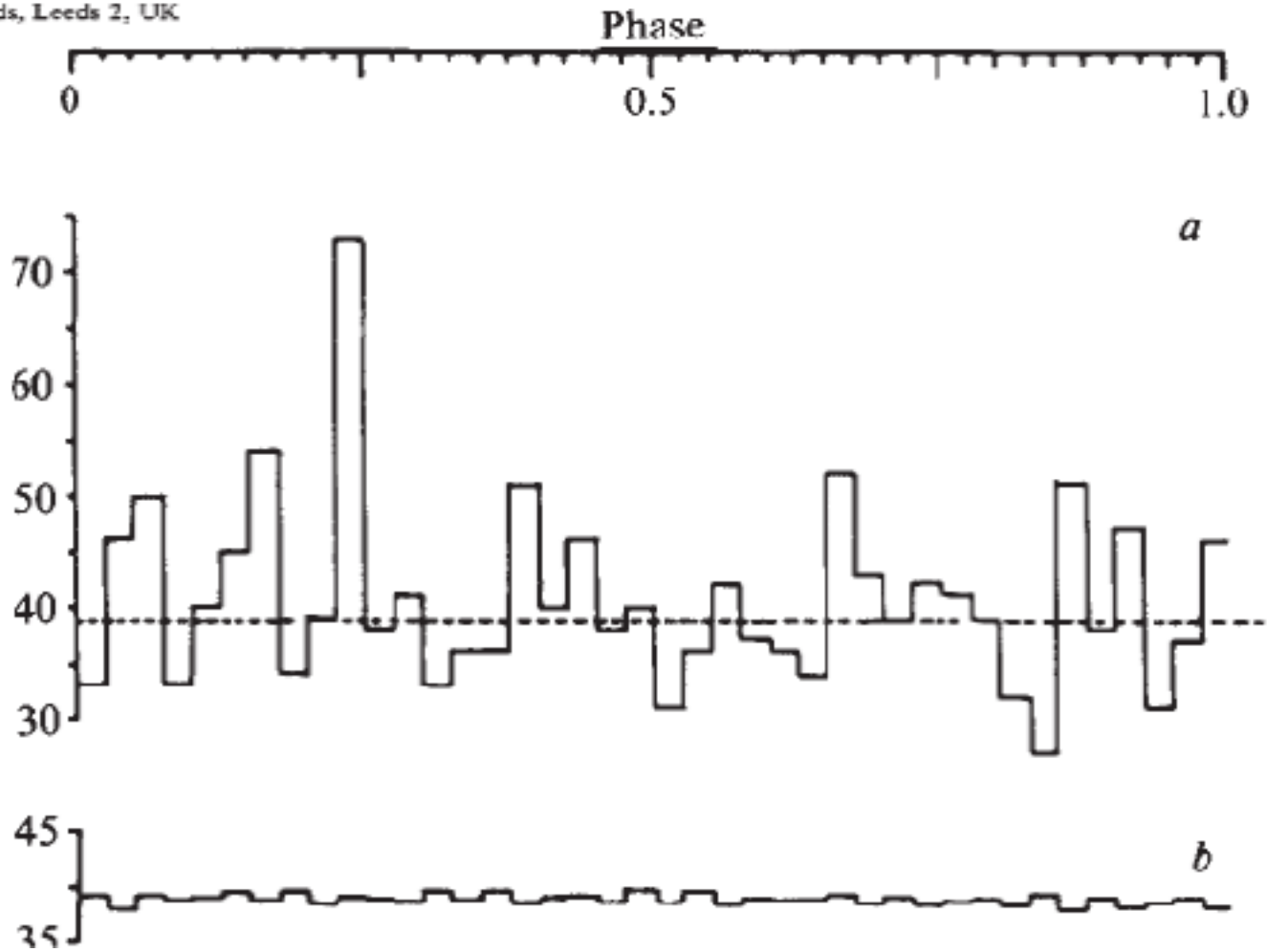
4.8 hours

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

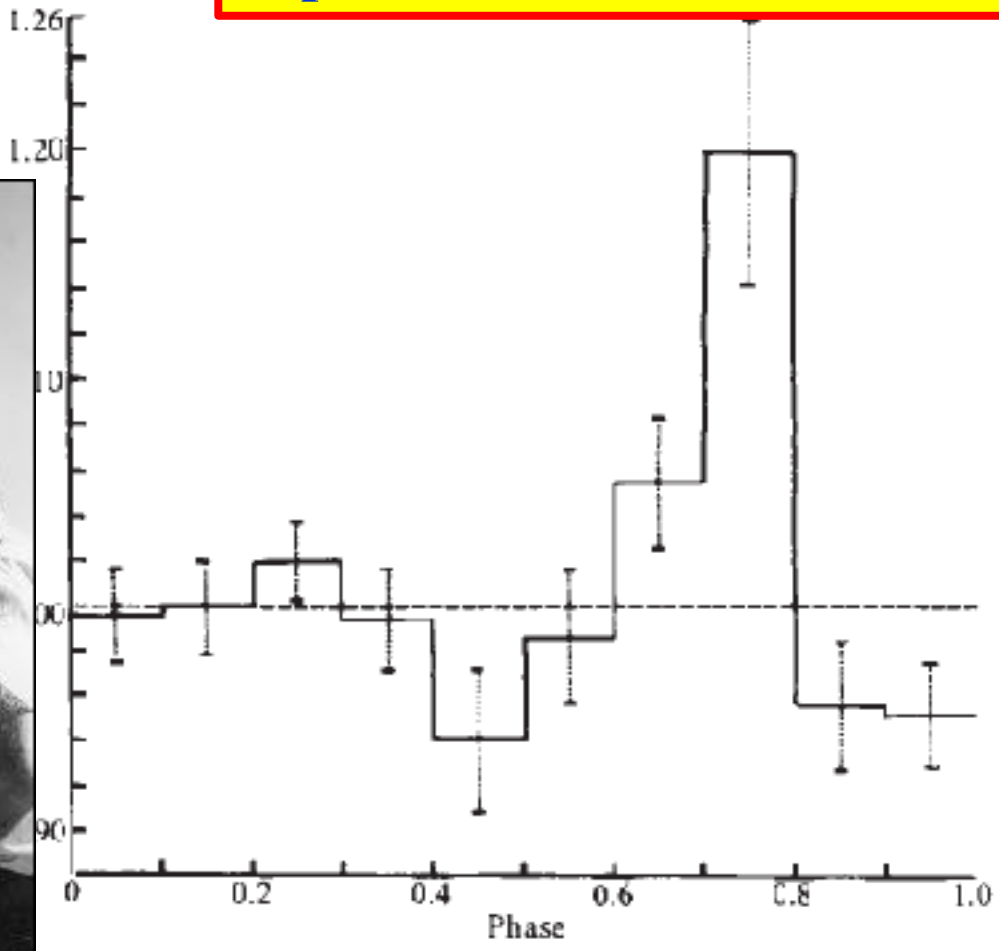
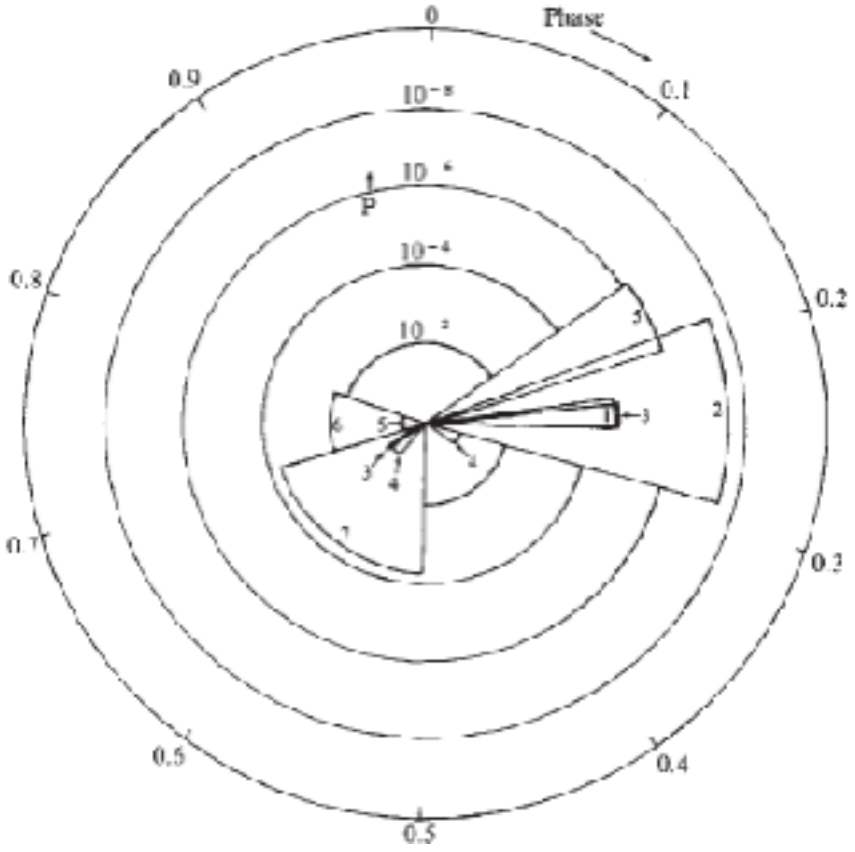
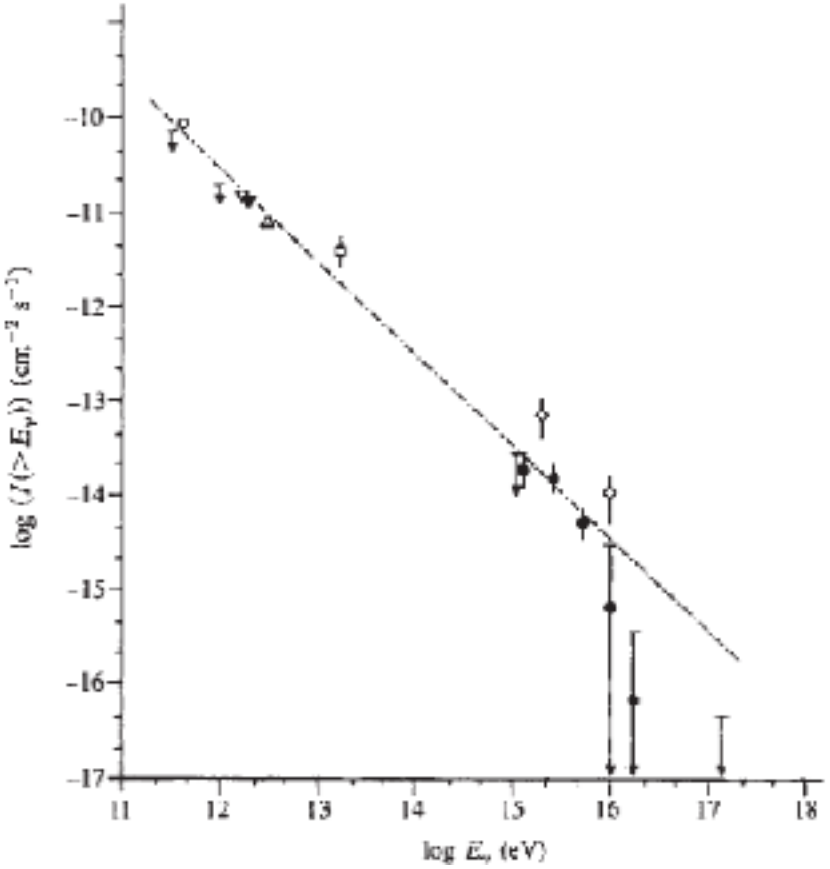


Fig. 1 Phase histogram of γ-ray emission from Cyg X-3.





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

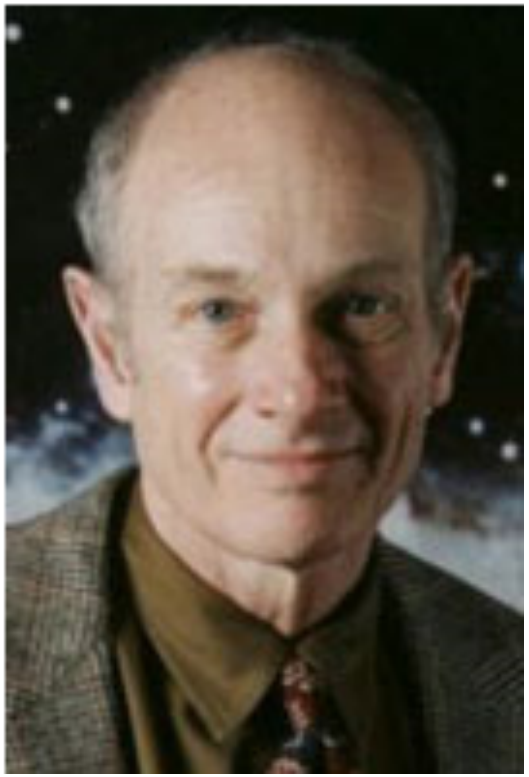
In Europe: Various groups at La Palma from Germany
Heinrich Meyer
Eckart Lorentz
Werner Hofmann and others

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

Important entrant

Jim Cronin (Nobel Prize 1980) for discovery of CP violation in 1964



Jim decided to build a detector in USA to check these findings

He visited a number of places, including Leeds, to check out his ideas

Our first meeting: November 1986

Different techniques gave different results

- but all agreed that rate of energetic cosmic rays is low:-

< 1 per km^2 per century at 10^{20} eV

(~ 10/min on earth's atmosphere)

1990: Needed larger areas > 1000 km^2

1991: Started working with Jim Cronin (Chicago) to form a collaboration to design and build such an instrument (3000 km^2) - and to raise the money

These efforts helped create the Pierre Auger Observatory

Haverah Park project was extremely successful and some important discoveries were made

The main conclusion, in some ways, was that the device was not big enough!

Rate at highest energies: only ~1 per sqkm per century

Clearly needed to build ~1000 km^2

Not too difficult to imagine how to do this - but the technology at the time was the limitation

1990: Retirement meeting in Nottingham

My conclusion: "We must build 1000 km^2"

1991: Dublin: International Cosmic Ray Conference

'You're not ambitious enough: we must build 5000 km^2'

- Jim Cronin's view

September – Christmas 1991:

Cronin in Leeds for 4 months: intensive planning

Excellent partnership

aaw: extensive air-showers

jwc: obsessed by project - plus huge range of contacts

I've said many times that Jim could get through doors that I could not even have knocked on:

e.g. UNESCO - $100,000

Strong mutual interest in malt whisky

Visited Islay – as noted in London Times Obituary!

1995: Design study at FNAL for 6 months

'Let a thousand flowers bloom'

Scintillators, Water-Cherenkov, Radio, RPCs for surface detectors – fluorescence only choice.

Water-Cherenkov detectors selected!

Site studies made simultaneously

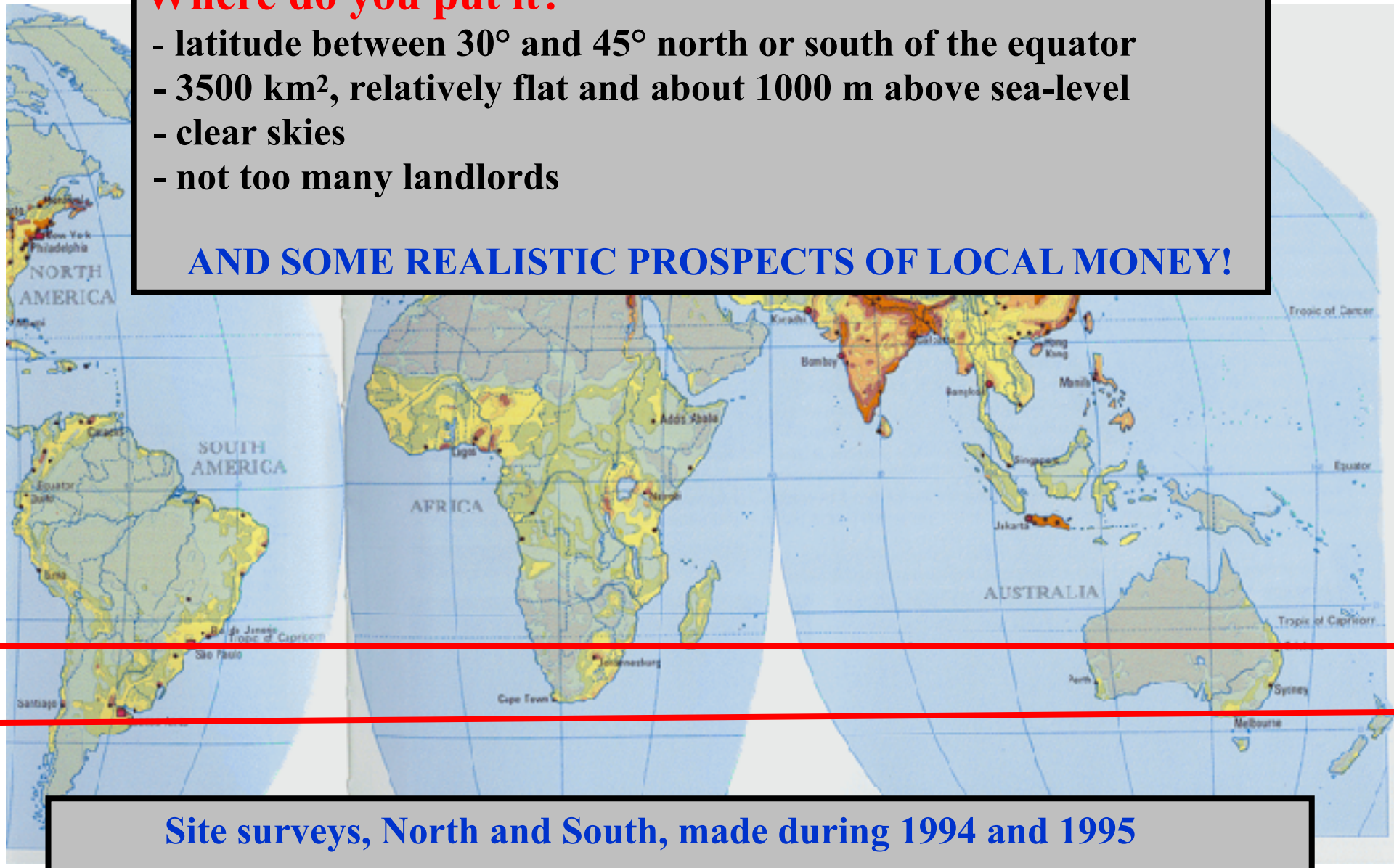
- **Chose Argentina for southern site**

  Not South Africa (letter from Mandela) or Australia

Where do you put it?

- latitude between 30° and 45° north or south of the equator
- 3500 km², relatively flat and about 1000 m above sea-level
- clear skies
- not too many landlords

AND SOME REALISTIC PROSPECTS OF LOCAL MONEY!



Site surveys, North and South, made during 1994 and 1995

The Auger Schematic Design

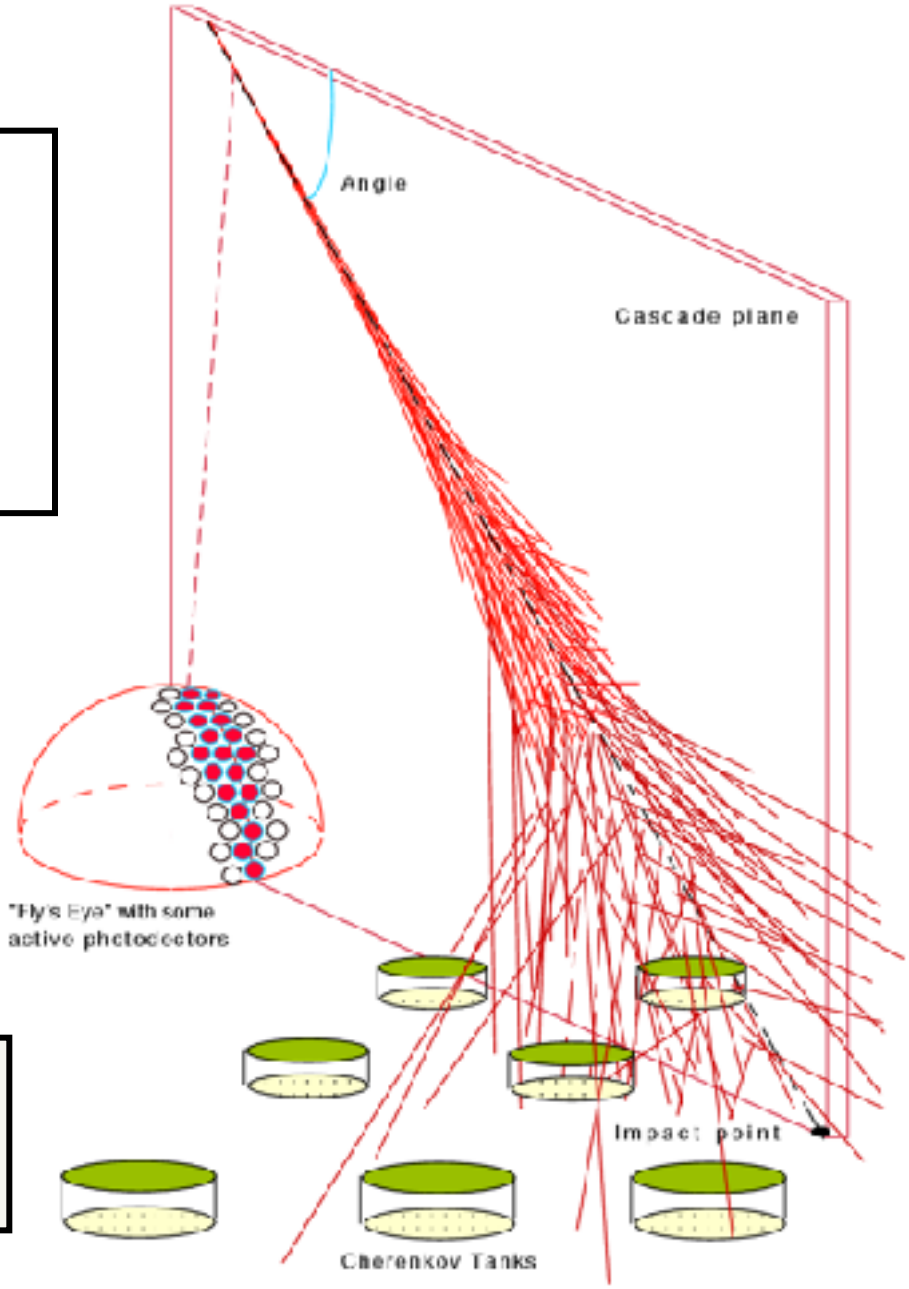
The design of the Pierre Auger Observatory marries two well-established techniques

→ the 'HYBRID' technique

Fluorescence →

AND

Arrays of water-Cherenkov detectors →

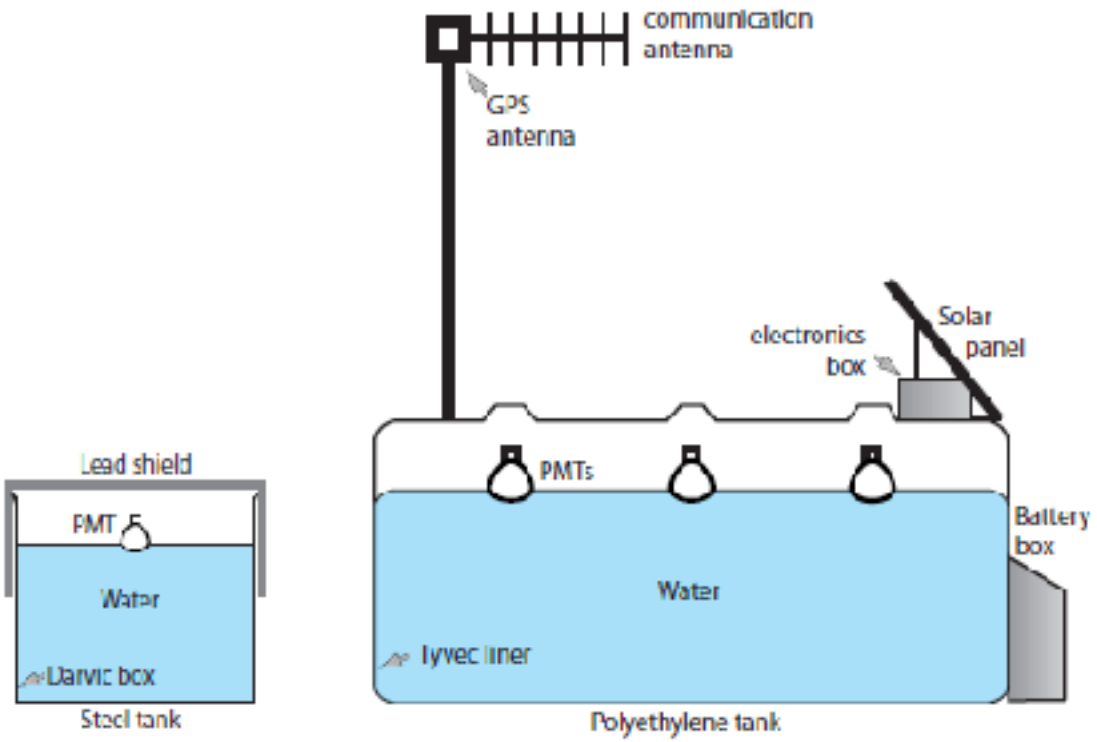


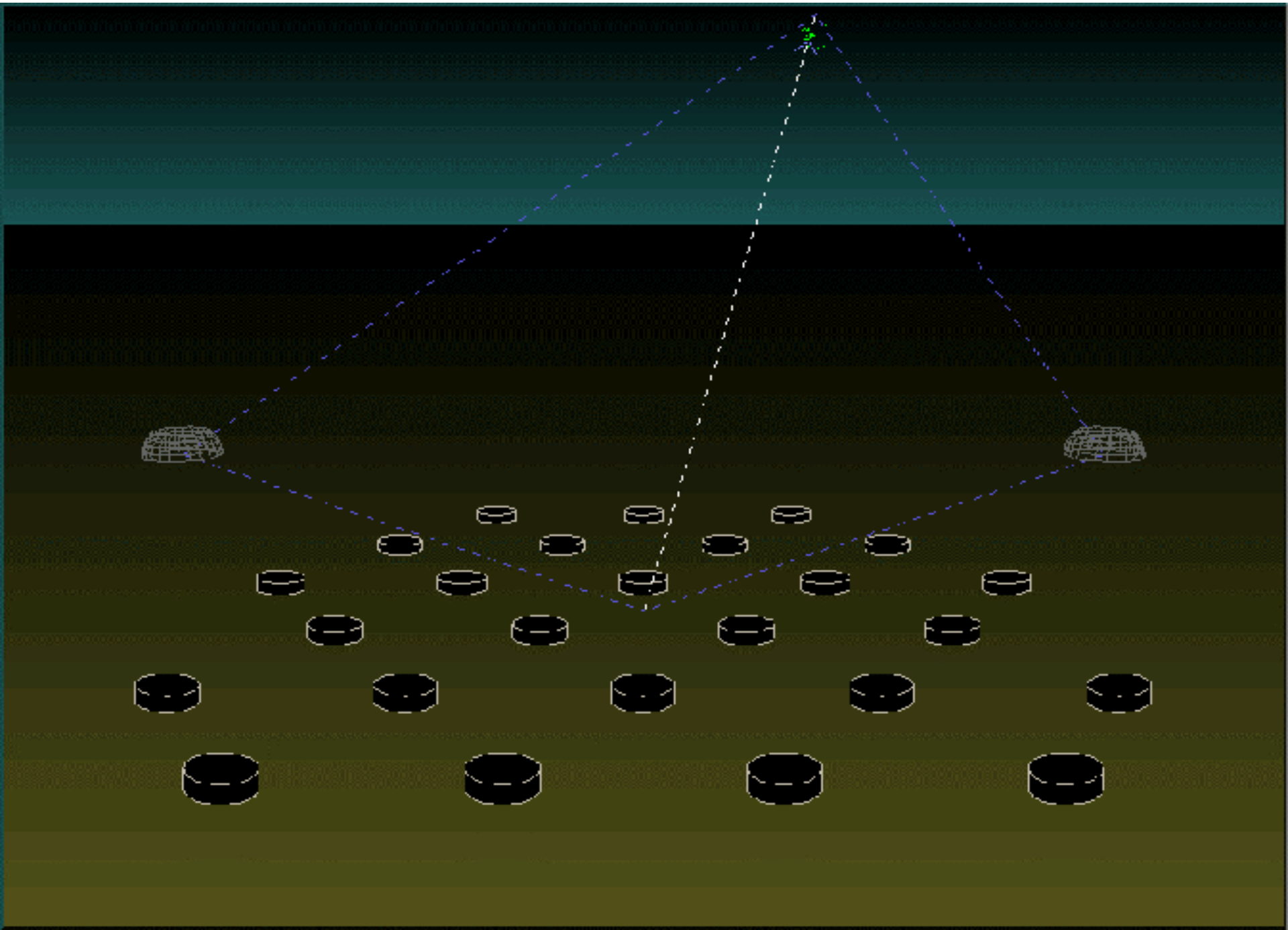
W-Ch introduced to Harwell Geiger Counter Array by Neil Porter

Silwood Park (Harold Allan), late 1950s:

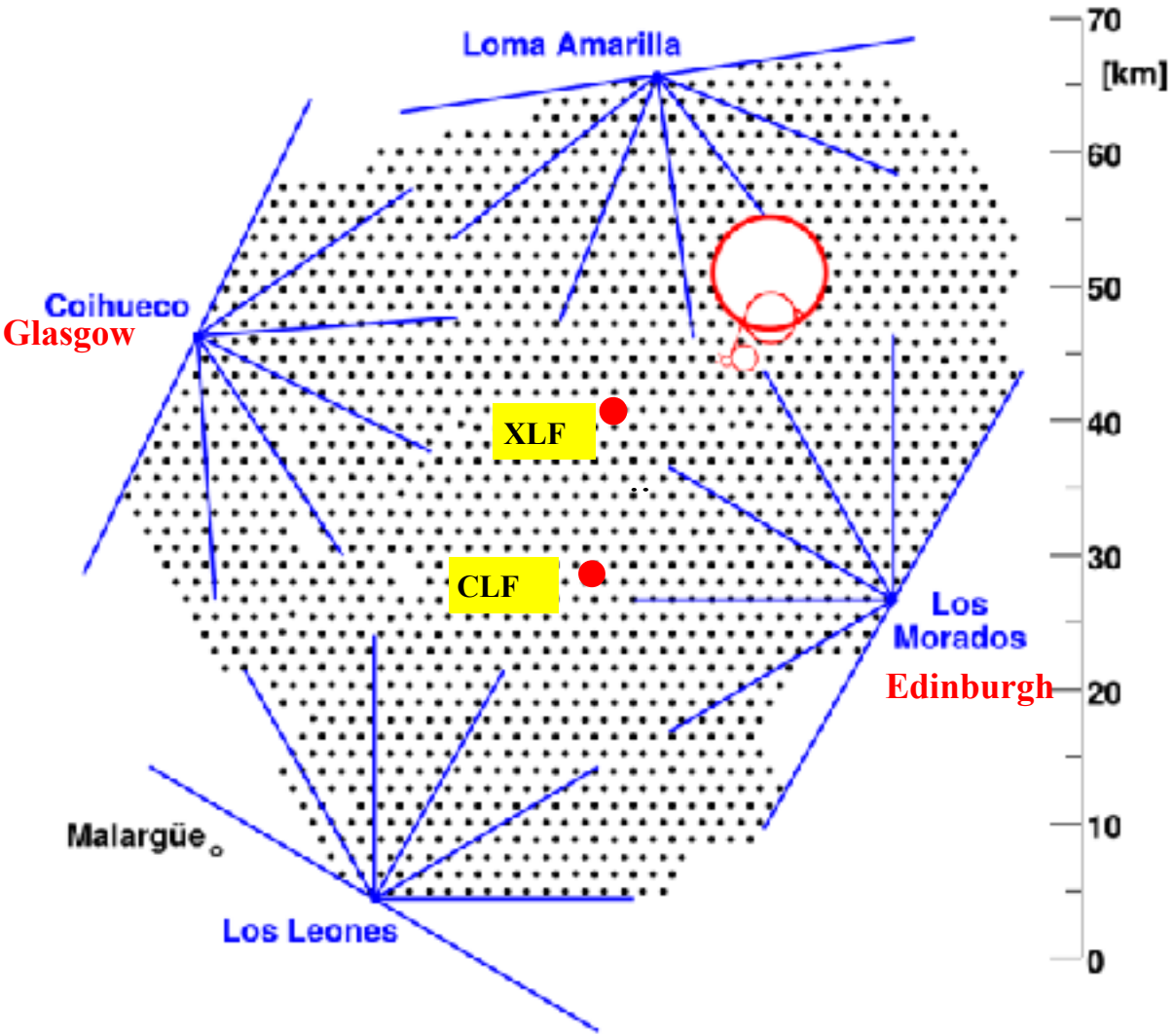
Haverah Park (J G Wilson et al)

and at Pierre Auger Observatory





The Pierre Auger Observatory: Malargüe, Argentina

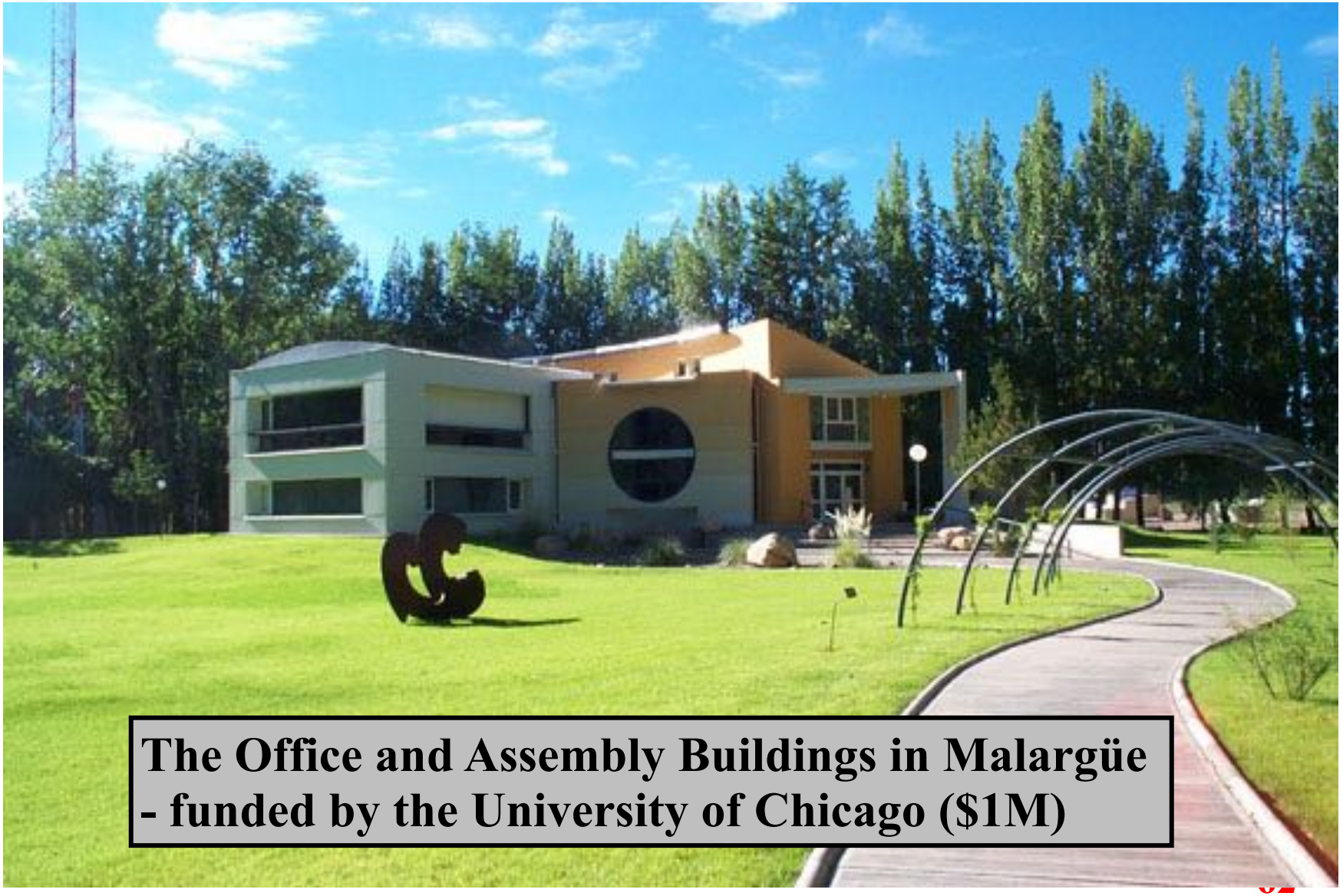


- 1600 water-Cherenkov detectors: 10 m² x 1.2 m
- 3000 km²
- Fluorescence detectors at 4 locations
- Two laser facilities for monitoring atmosphere and checking reconstruction
- Lidars at each FD site
- Capital cost ~$50M
- About 1/8th of area of Sicily

The Pierre Auger Collaboration

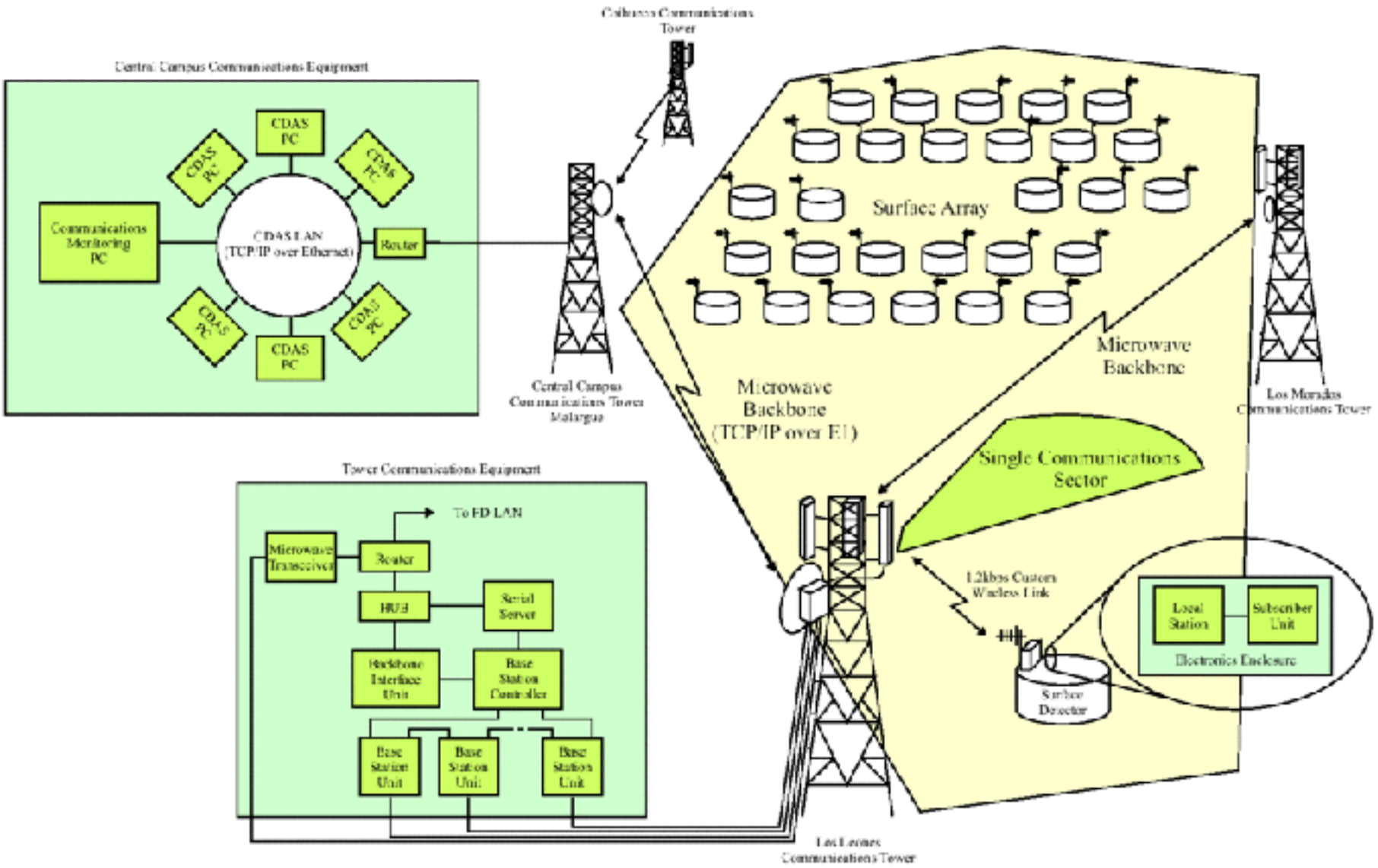
Croatia*	**Argentina**
Czech Republic	**Australia**
France	**Brasil**
Germany	**Bolivia***
Italy	**Mexico**
Netherlands	**USA**
Poland	**Vietnam***
Portugal	***Associate Countries**
Rumania	
Slovenia	**~ 400 PhD scientists from**
Spain	**~ 100 Institutions in 17 countries**
United Kingdom	

Campus of Auger Observatory in Malargüe



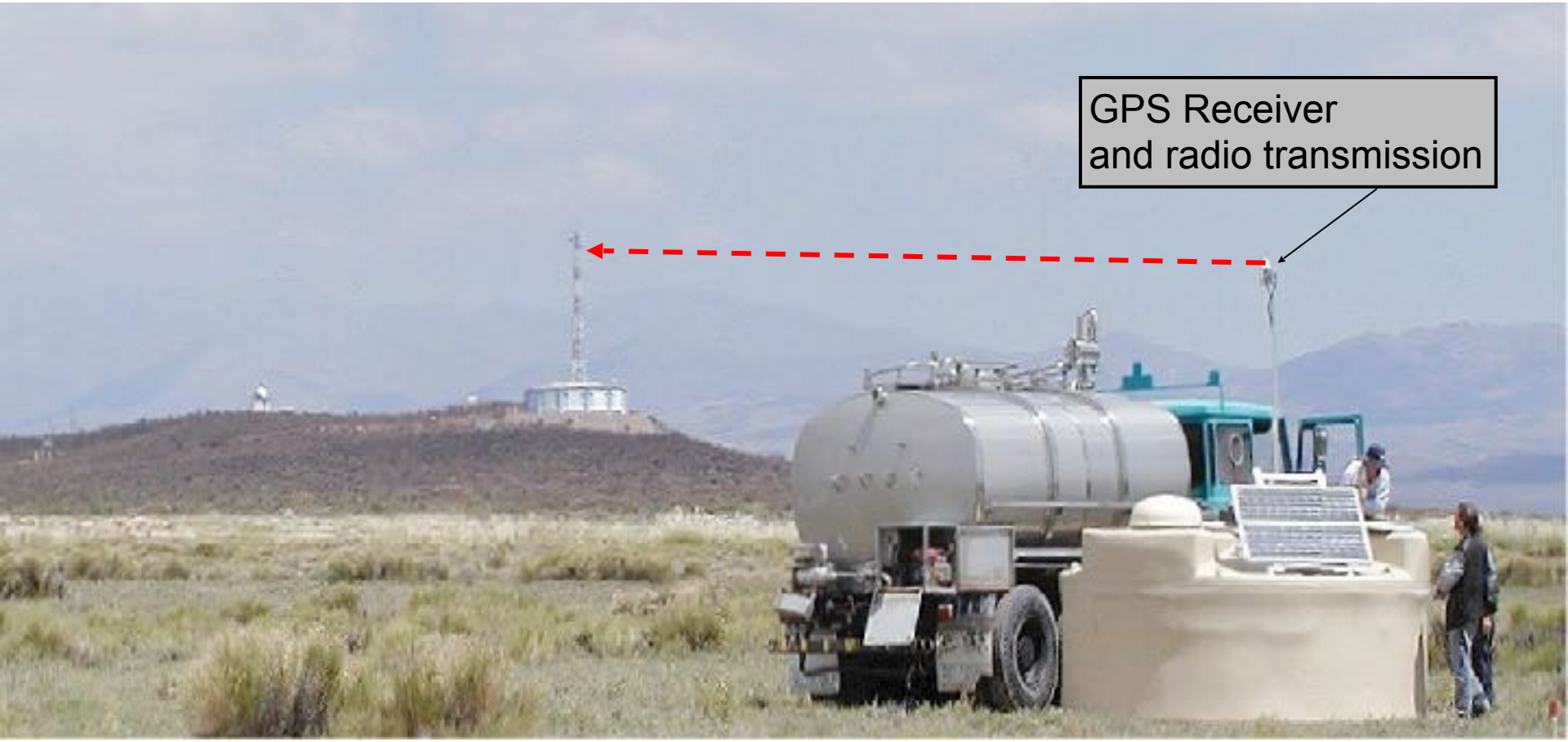
The Office and Assembly Buildings in Malargüe - funded by the University of Chicago ($1M)

Telecommunication system

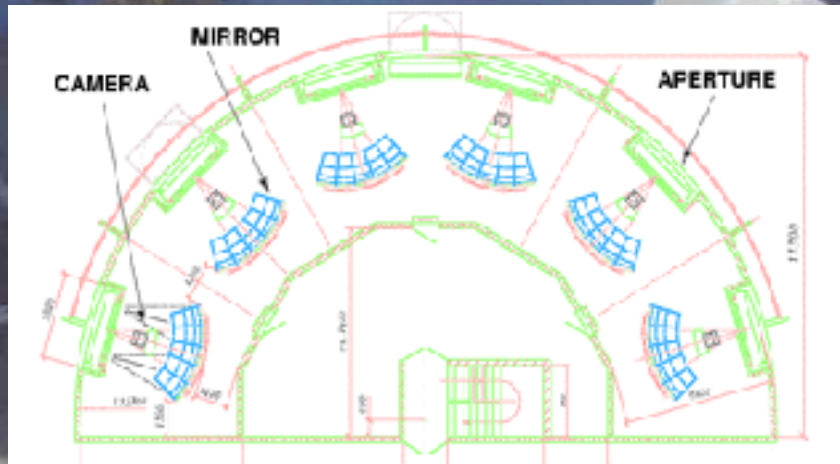


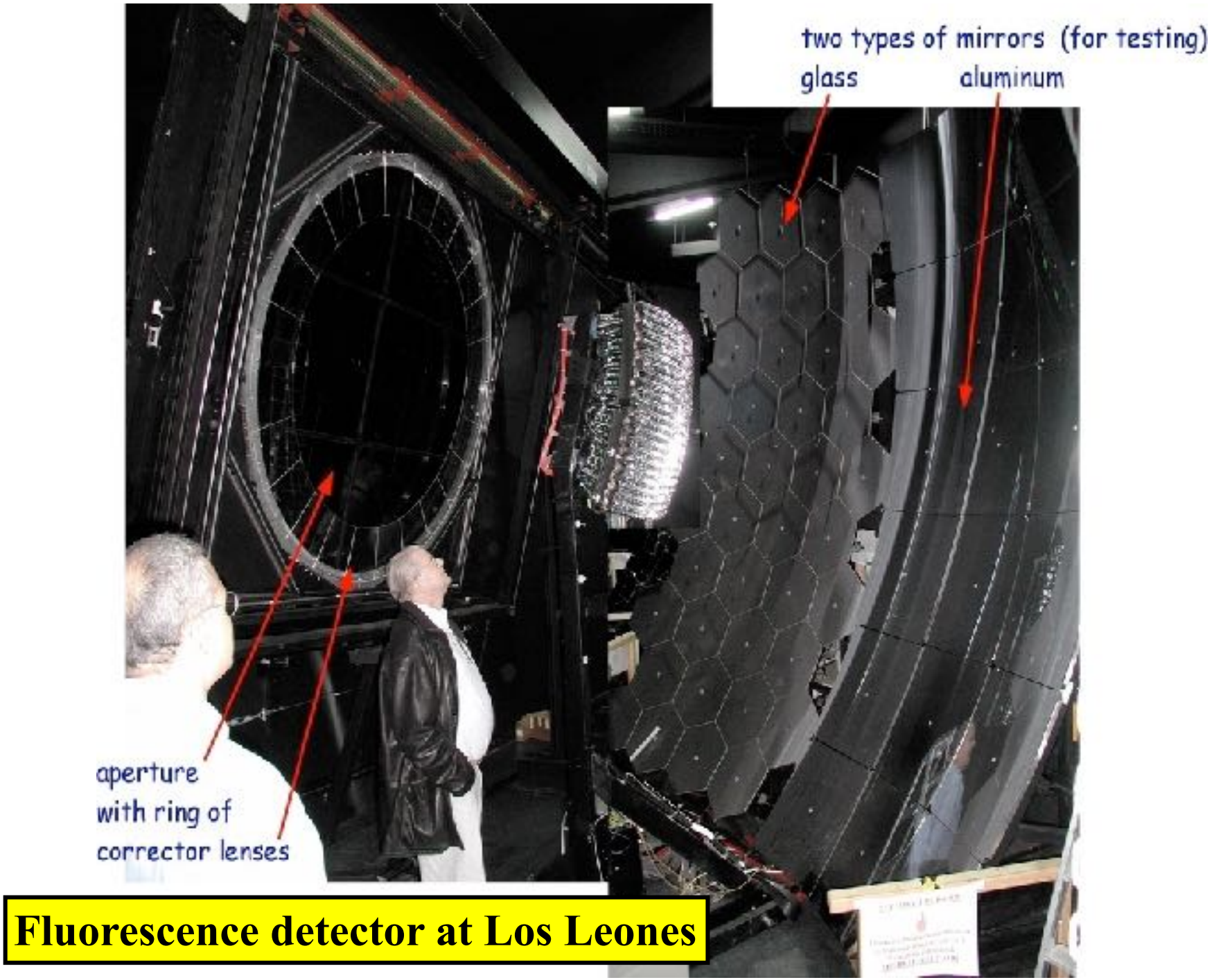

Paul Clark: Electrical Engineer
- now Director of Comms Design


29. 6. 1999


GPS Receiver
and radio transmission

Six Telescopes viewing 30° x 30° each





Fluorescence detector at Los Leones

Last tank deployed: 13 June 2008

Homework for tomorrow:

- **Bassi, Clark and Rossi found that the electrons arrived EARLIER than the muons**

- **Linsley and Scarsi found that electrons arrived LATER than the electrons**

Why?

What about the photon time delay?

Why is invisible energy correction smaller at higher energies and smaller for protons than for Fe nuclei?