59th Krakow School of Theoretical Physics
Zakopane June 2019

Probing the Violent Universe with multi-messenger eyes: gravitational waves, high-energy neutrinos, gamma rays, and cosmic rays

Ultra High-Energy Cosmic Rays
Lecture 1

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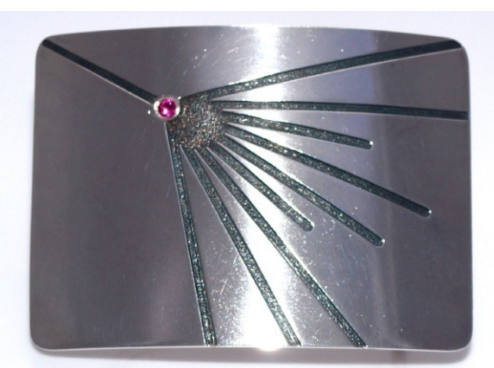

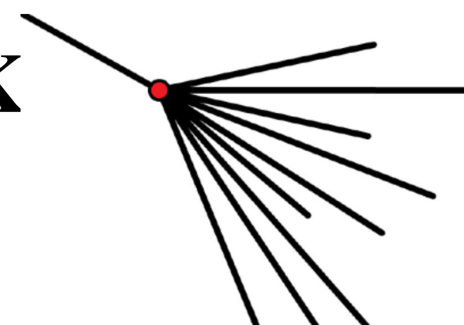

Union Internationale de Physique Pure et Appliquée.	International Union of Pure and Applied Physics.
====	====
COLLOQUE SUR LES RAYONS COSMIQUES	SYMPOSIUM ON COSMIC-RAYS
Cracovie - Octobre 1947.	Krakow - October 1947.

Sommaire

—— TABLE DES COMMUNICATIONS ——

LISTE DES PARTICIPANTS POLONAIS.

Over 60 from Poland

Prof. J.ADAMCZEWSKI (Gdańsk); Prof. J.BLATON (Kraków) ; O.BLATON (Kraków) ; Dr. I.BÓBR (Warszawa) ; B. BURAS (Warszawa) ; Inz. BURZYNSKI (Gdansk) ; E.DMOCHOWSKI (Lodz) ; Inz. S.FABIANI (Kraków); A. GARNYSZ (Kraków) ; J.GIERULA (Kraków) ; J.GORSKI (Kraków) ; J. GRYCZA (Poznan) ; GUNTHER (Warszawa) ; A.HRYNKIEWICZ (Kraków) ; INGARDEN (Wrocław) ; Prof. A.JABŁONSKI (Torun) ; Dr.A.JAGIELSKI (Kraków) ; J.JANIK (Kraków) ; L.JURKIEWICZ (Kraków) ; E.JUSKIEWICZ (Gdańsk) ; Dr. E. KALINOWSKA (Swider) ; J.KALISZ (Kraków) ; M.KOGUT (Kraków) ; Dr. T.KOPCEWICZ (Warszawa) ; M.KUNISZ (Kraków) ; Prof. S.LORIA (Wrocław) ; Prof. S.MAJEWSKI (Warszawa) ; Dr. MAJEWSKA (Warszawa) ; B.MAKIEJ (Kraków) ; Prof. T.MALARSKI (Gliwice) ; M. MASSALSKI (Kraków) ; M. MASSALSKA (Kraków) ; Prof. M.MIESOWICZ (Kraków) ; ST. MORKOWSKI (Dzierzoniów) ; K. MORKOWSKA (Dzierzoniów) T. MORSTIN (Kraków) ; M.MOSCICKI (Poznan) ; Dr. L. NATANSON (Warszava) Prof. NIEWODNICZANSKI (Kraków) ; Prof. W.NIKLIBORC (Wrocław); Prof. C.PAWLOWSKI (Warszawa) ; Dr. T.PIECH (Kraków) ; Prof. A. PIEKARA (Gdańsk) ; J. PNIEWSKI (Warszawa) ; Prof. M.PUCHALIK (Gliwice) ; Dr. J.RAYSKI (Warszawa) ; Dr. J.ROLINSKI (Warszawa) ; Prof. W.RUBINOWICZ (Warszawa) ; RZEWUSKI (Warszawa) ; T.STALINSKI (Warszawa) ; Prof. E.SKORKO (Lódz) ; M. SKORKO (Lódz) ; Prof. A. SOLTAN (Warszawa) ; Prof.L. SOSNOWSKI (Warszawa); Dr.STACHURSKA (Lublin) ; SZPILECKI (Gliwice) ; Dr. W.ŚCISŁOWSKI (Warszawa) ; Dr. B.ŚREDNIAWA (Kraków) ; B. TWAROWSKA (Warszawa) ; Dr. W. TURCZYNSKI (Torun) ; Prof. W. URBANSKI (Lublin) ; M. WERTENSTEIN (Warszawa) ; Dr. J.WESOŁOWSKI (Kraków) ; C. WESOŁOWSKA (Kraków) ; Prof. WEYSSENHOFF (Kraków) ; Prof. K. ZAKRZEWSKI (Kraków).

IV.- RESOLUTION ON NAMES FOR THE ELEMENTARY PARTICLES

Résolution sur les noms des particules élémentaires

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The Cosmic Ray Commission of the International Union of Physics, in its meeting at Cracow (9 October 1947).

1) recognizes the convenience of uniform names for the elementary particles.

2) recognizes that it may be undesirable to make an official recommendation on name in any particular case until widespread usage justifies such a recommendation.

3) notes that the term nucleon has found quite general recognition as a common term to denote both neutrons and protons.

4) recommands therefore that the term nucleon receives officise recognition for this purpose.

5) reports that charged particles of mass intermediate between the mass of an electron and the mass of a proton.

a) are generally called mesons in Argentina, Brazil, Denmark, Mexico, Eire, England, Holland, Italy, Norway, Sweden, Switzerland and the U.S.S.R.

b) are called mesotons and mesons by comparable numbers of investigators in the United States.

c) and are in France sometimes called mesotons, but more often mesons.

6) recommends no official action on name for the particle of intermediate mass until there is greater unanimity of usage, but

7) proposes in accordance with the unanimous desire of its members to employ the term meson in the report of the proceedings of the Cracow conference.

8) recognizes the general use of the term electron to denote both positive and negative particles of electronic mass.

9) looks with favor upon the terms positon and negaton as means to distinguish between the two signs of charge.

10) asks the Secretary of this Conference to communicate this resolution to the editors of *Nature*, *The Physical Review*, *Le Journal de Physique* and to the Secretary of the Academy of Sciences of the U.S.S.R.

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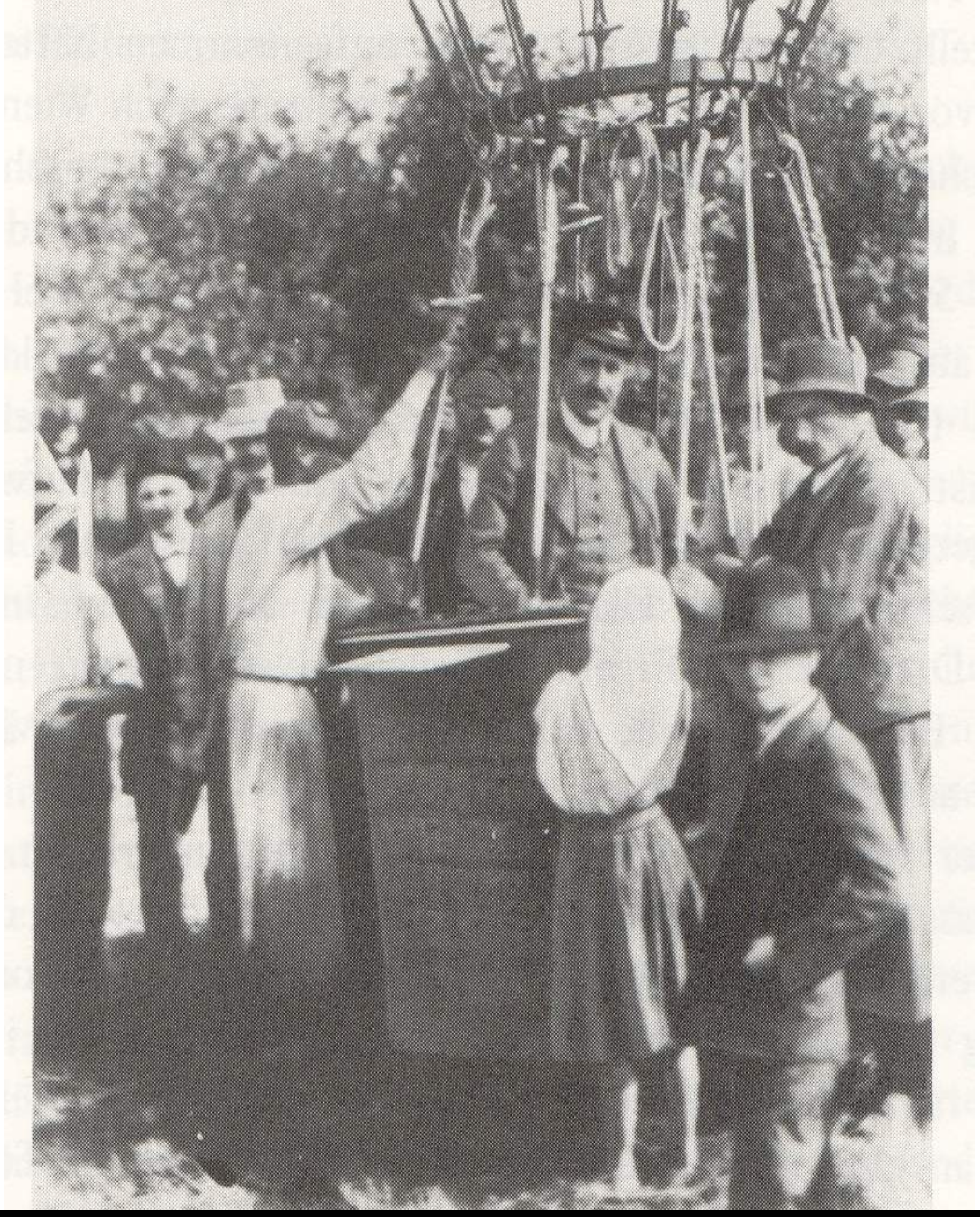
Lecture 1: Something about air showers; history and the phenomenon

Lecture 2: Energy Spectrum, Arrival Directions and Mass Compostion

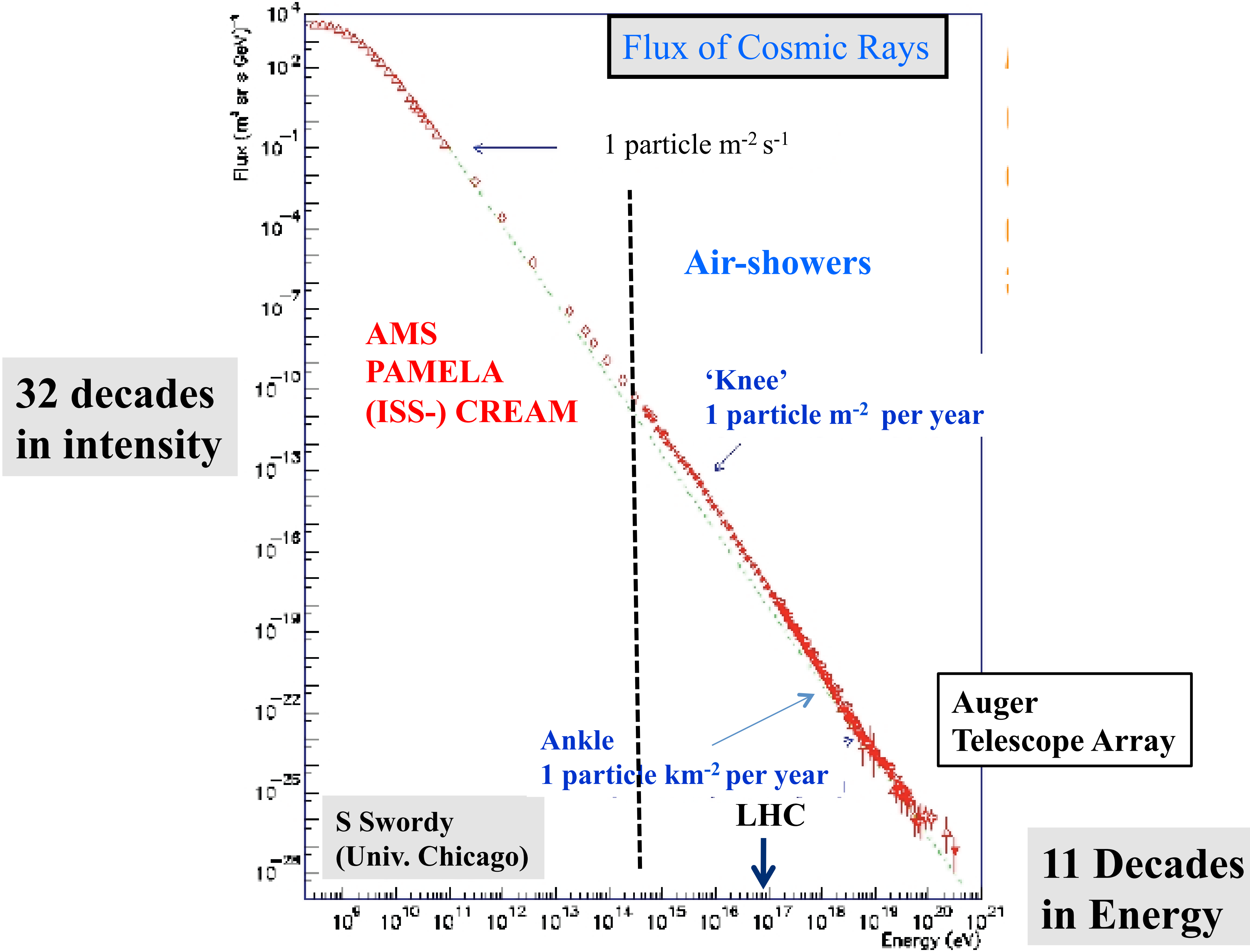
Lecture 3: Hadronic interactions
Search for non-hadronic primaries (neutrinos, photons, monopoles
The Future



To 5 km
without oxygen!

Victor Hess at the balloon-landing (1912)

????



Flux of Cosmic Rays
1 particle m-2 s-1
Air-showers
AMS
PAMELA
(ISS-) CREAM
'Knee'
1 particle m-2 per year
Ankle
1 particle km-2 per year
Auger
Telescope Array
LHC
S Swordy
(Univ. Chicago)
32 decades
in intensity
11 Decades
in Energy
Flux (m2 sr s GeV)-1
Energy (eV)

Some key points about UHECR

LOCAL: If particles are > 5 x 10^{19} eV, then they must be local (**GZK effect**)

Local depends on energy:

>4 x 10^{19} eV   50% from within 130 Mpc

>10^{20} eV   50% from within 20 Mpc

So **ANISOTROPIES** might be expected from **nearby sources**

Difficult to accelerate:

(i) Diffusive Shock Acceleration may not work

(ii) Greisen's argument (1965)

(i) accelerator > Larmor radius

(ii) synchrotron losses< energy gain

$W_{magnetic} > 300\Gamma^5$ ergs,

so for 10^{20} eV, $\mathbf{W_{magnetic} > 10^{57}}$ **erg**

Overview:

Why study High Energy Cosmic Rays

How we study them: some historical background
Pierre Auger Observatory as an example

Results on energy spectrum
Results on arrival directions

Results on mass composition
- **deficiencies in understanding of hadronic physics**
- **hadronic physics trans-LHC**

Searches for non-nuclear particles
Monopoles, photons and neutrinos

What does all of this tell us about UHECR origins?

Energy Spectrum

If the acceleration mechanism is electromagnetic, then the maximum energy possible should be $E_{max} \sim Z$

Sources

The trajectories of charged CR are curved in Galactic and extra-Galactic magnetic fields: Larmor Radius ~ E/Z

Gamma-Rays and Neutrinos

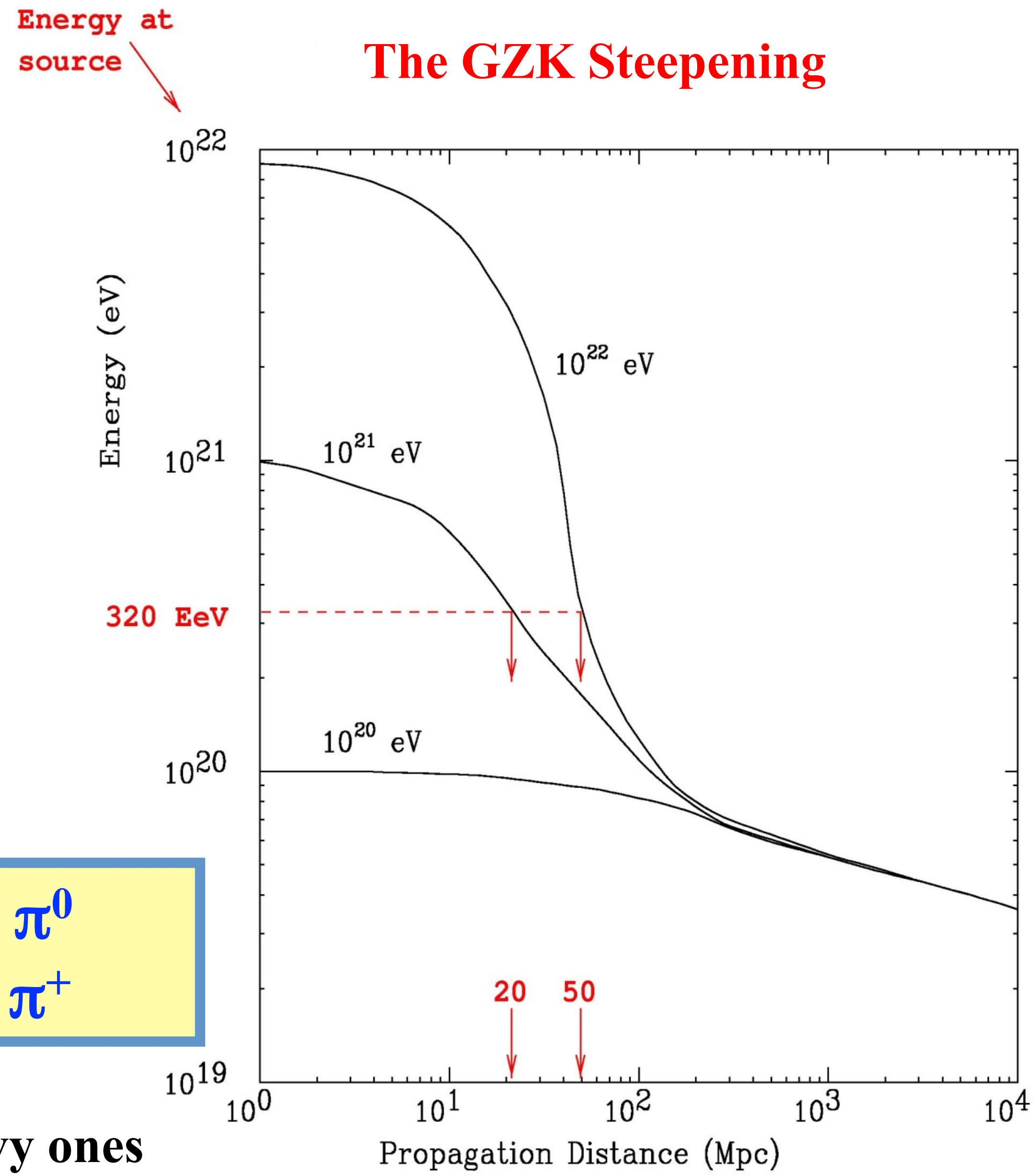
Direct tracers of acceleration sites *(and* $Z = 0$*)*

Direct contributors to multi-messenger astronomy

Only prediction in UHECR

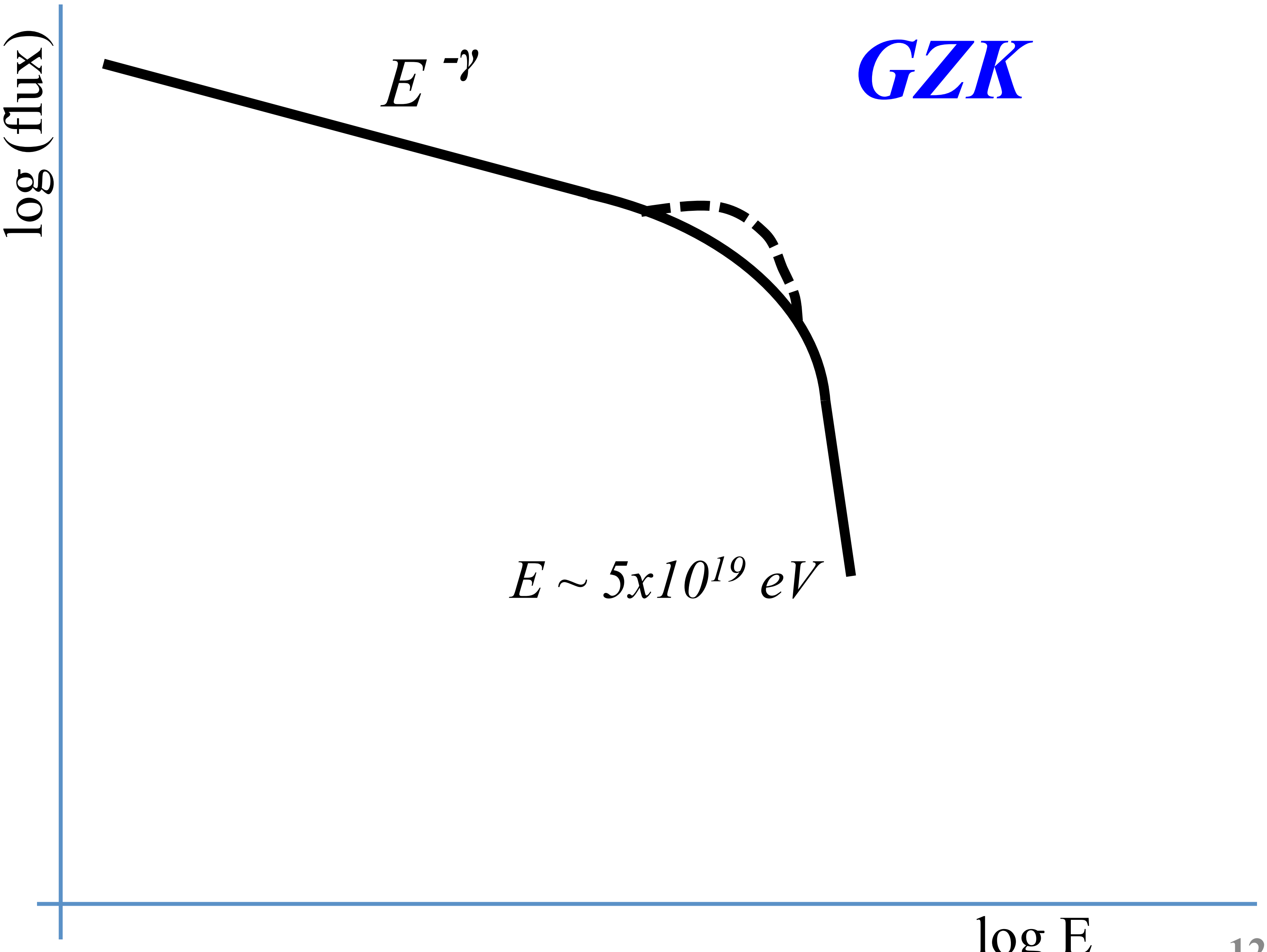
"GZK" effect

First pointed out in 1966 in two papers, one by Greisen and one by Zatsepin & Kuz'min



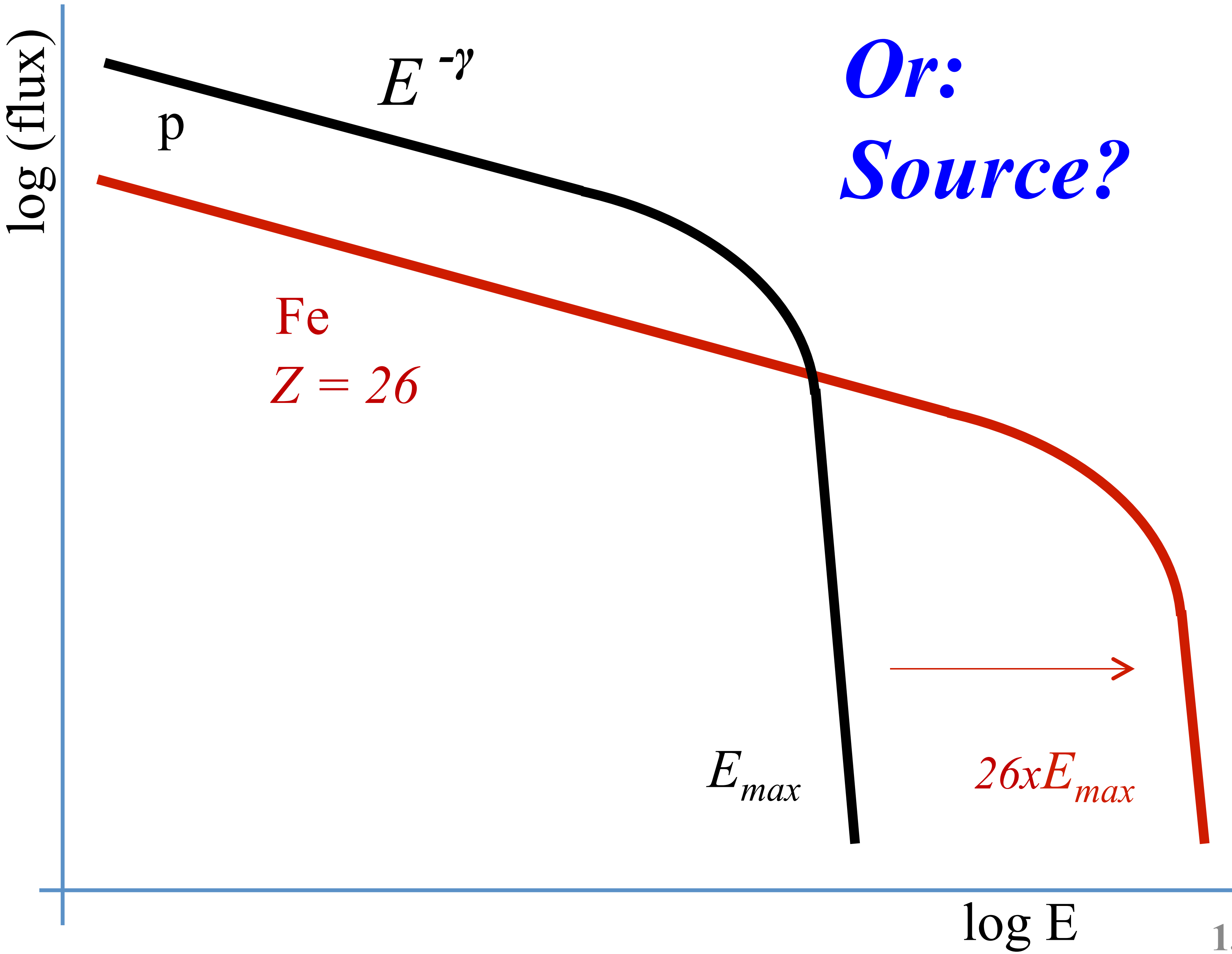
$$p + \gamma\,(2.7^{o}K) \rightarrow \Delta \rightarrow p\ \pi^{0}$$
$$\rightarrow n\ \pi^{+}$$

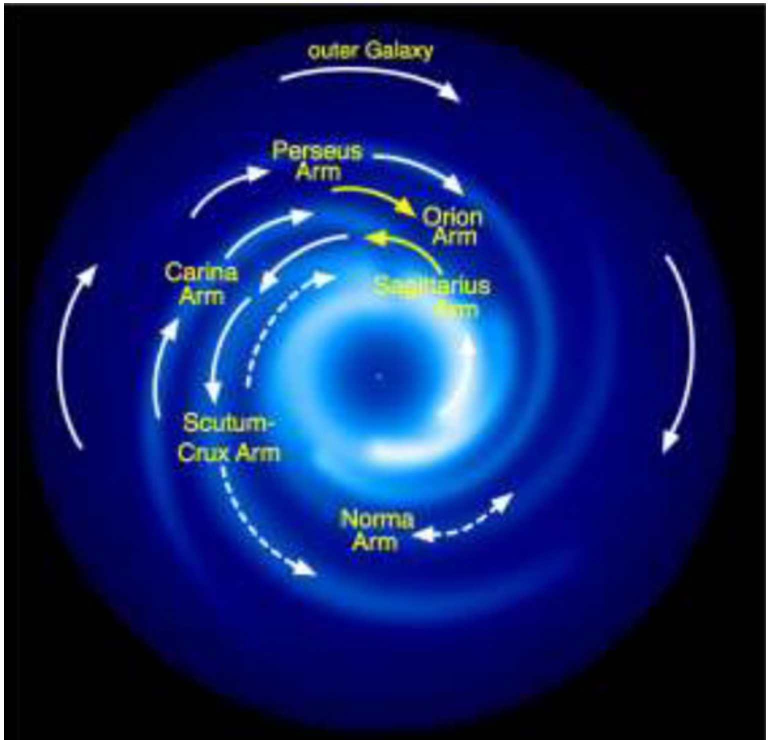
Nuclei **photo-disintegrate, heavy ones at similar thresholds, distances**

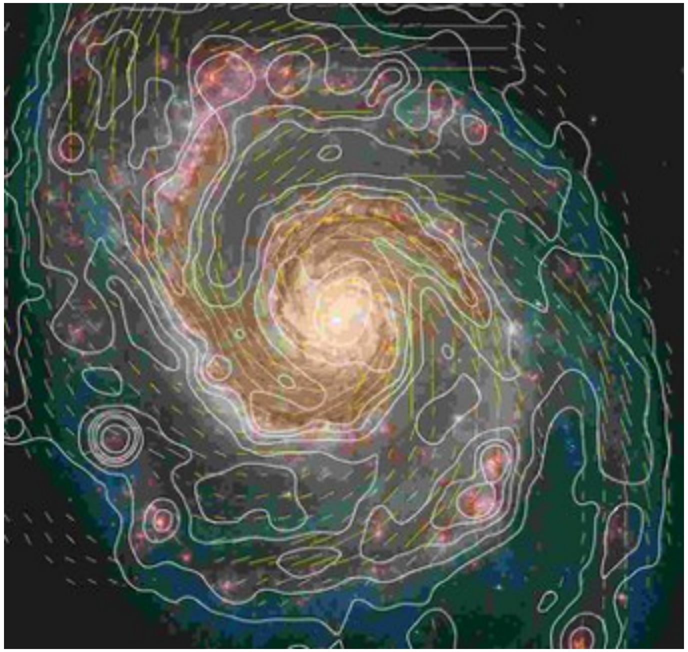


log (flux)
$E^{-\gamma}$
GZK
$E \sim 5x10^{19}$ eV
log E

Or: Source?





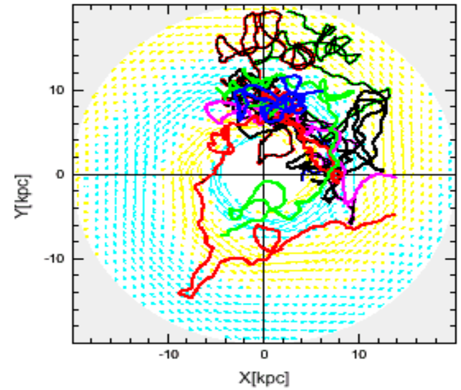


Our Galactic magnetic field

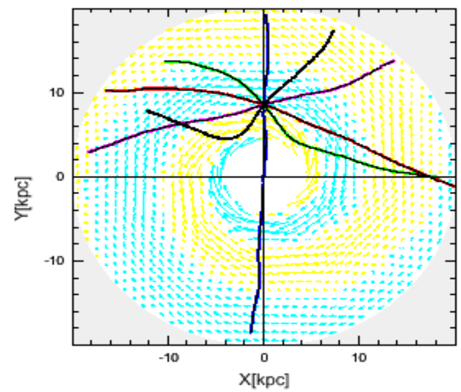
- **a few μGauss**
- **geometry known poorly**

Trajectories of Cosmic Ray Protons in the Galaxy

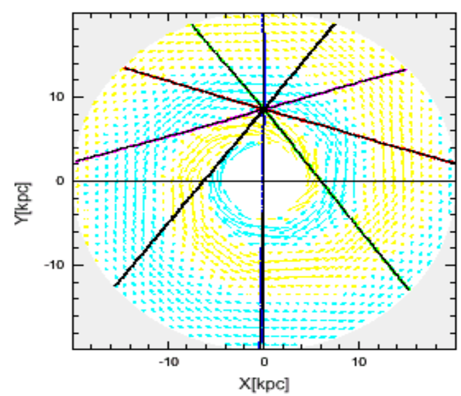
- **protons are trapped in our Galaxy up to ~10^{18}eV**
- **protons can travel straight lines above ~10^{20}eV**
- **charged-particle astronomy?**



E=10^{18}eV



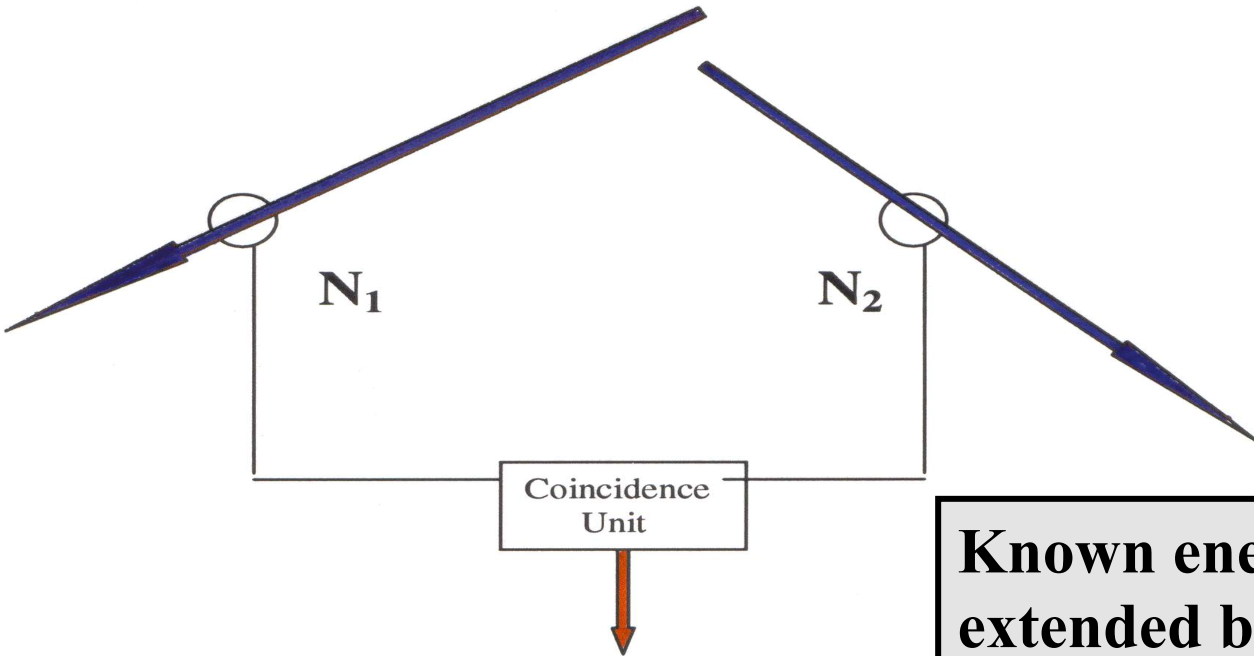
E=10^{19}eV



E=10^{20}eV

High-energy cosmic rays are studied using the phenomenon of Extensive Air Showers

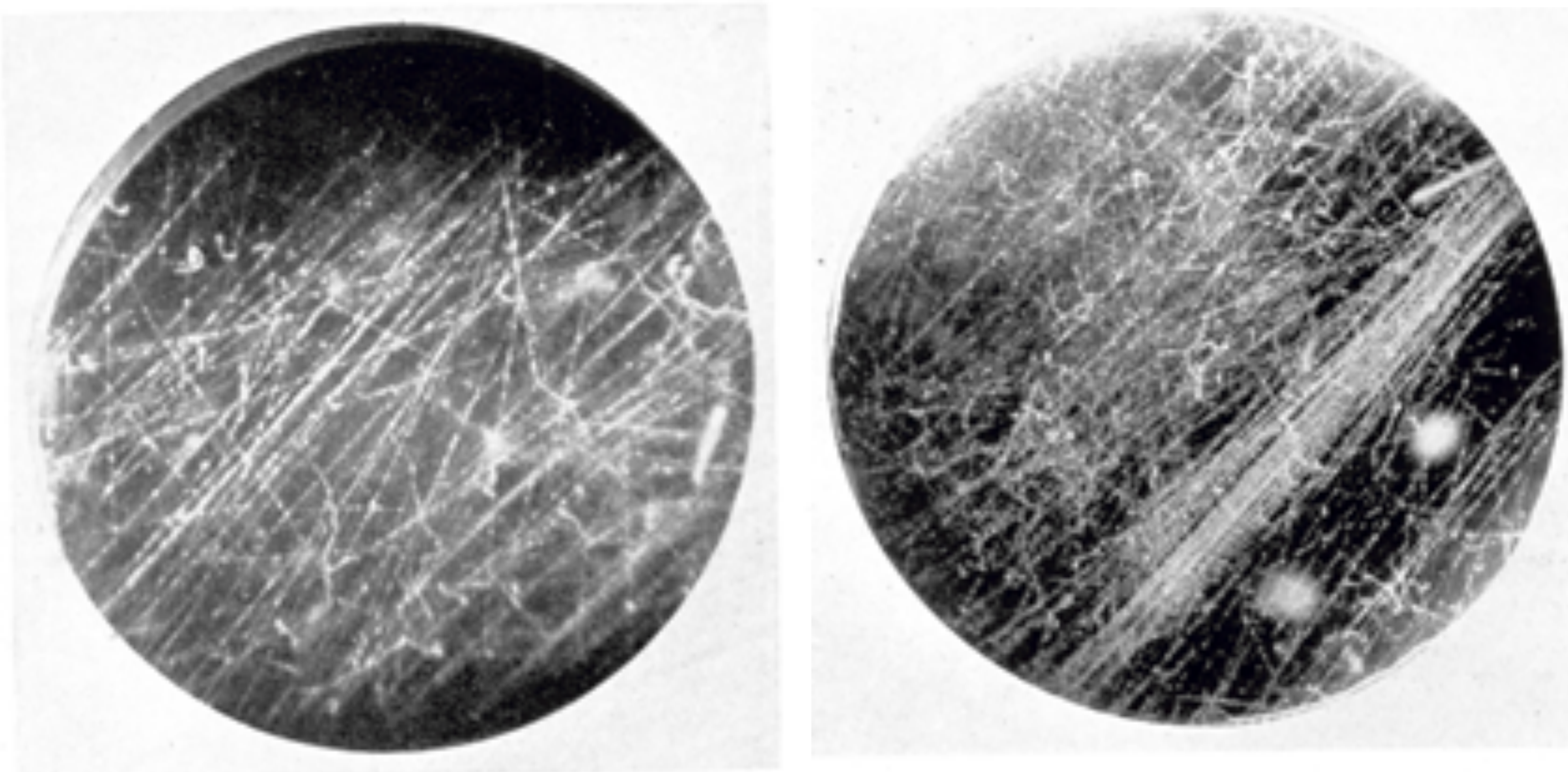
Discovery of Extensive Air Showers: Pierre Auger (1938)



Known energy scale extended by ~10^6

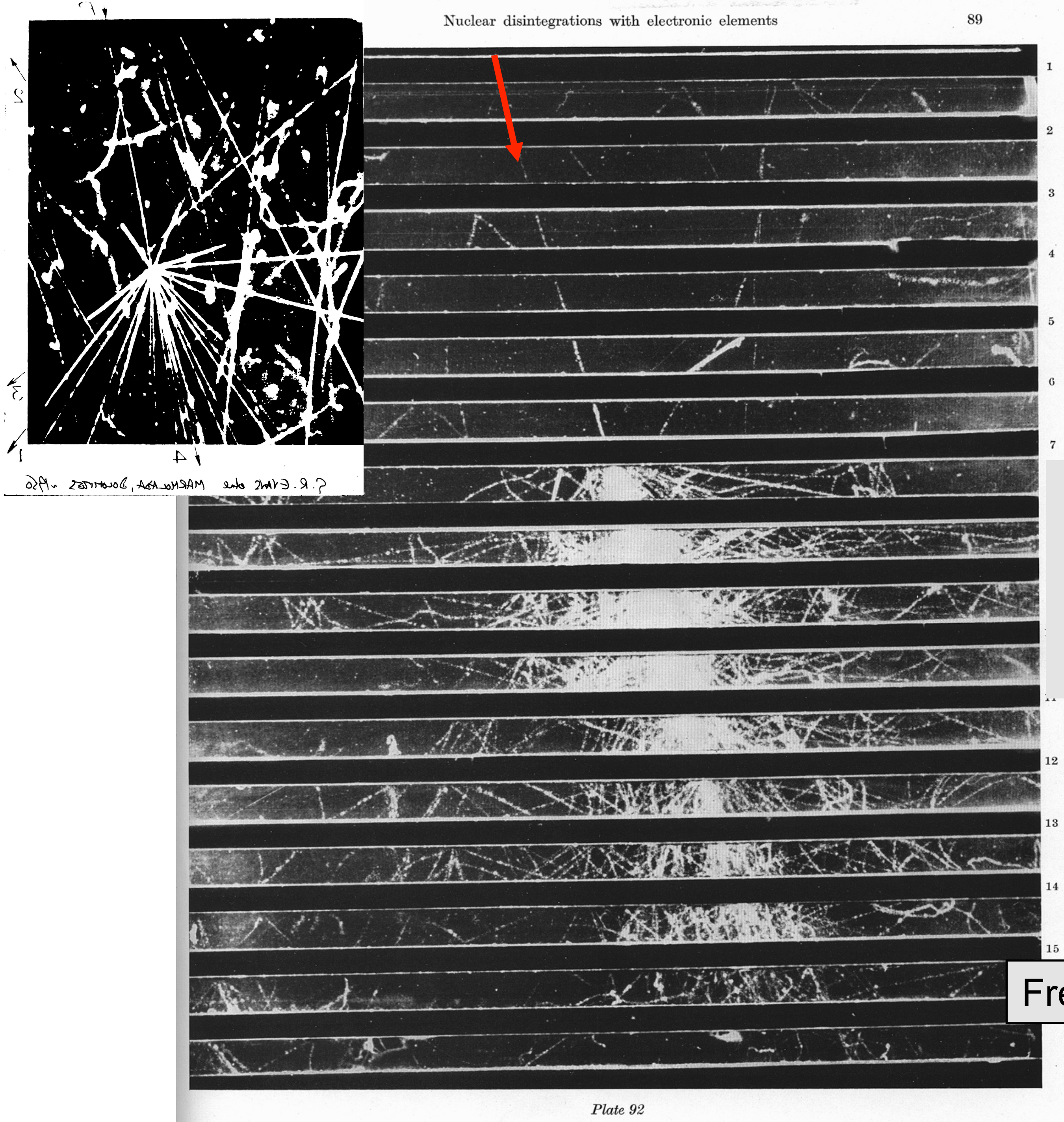
Observed Rate was found to be much higher than the Calculated Chance Rate ($2N_1N_2\tau$) – even when the counters were as far as 300 m apart

Needed photons of ~10^{15} eV!



5.5 m

J G Wilson and C B A Lovell, Nature 1938



1.3 cm Pb

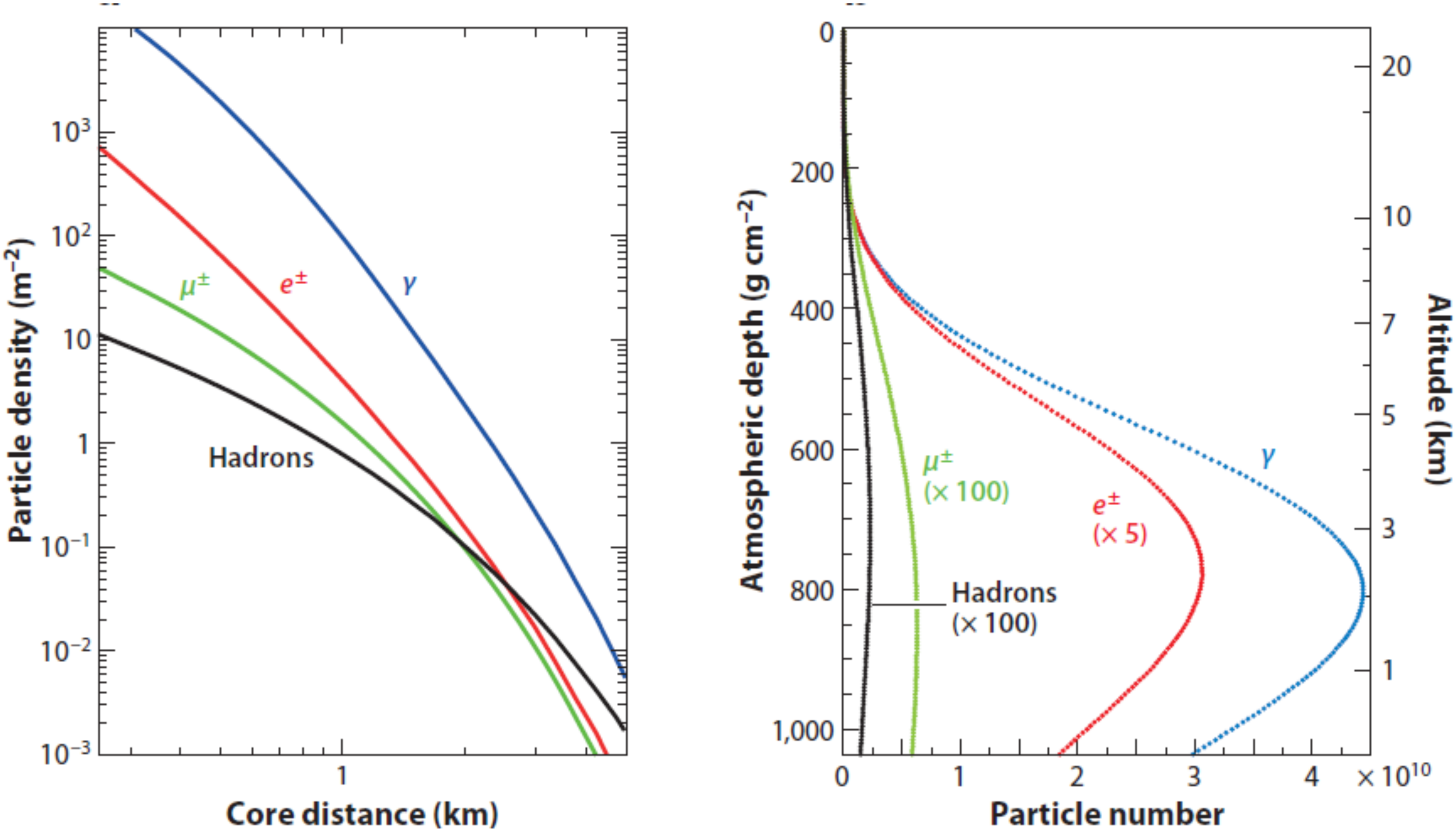
10 GeV proton

Shower initiated by proton in lead plates of cloud chamber

Detectors can find particle number and arrival times

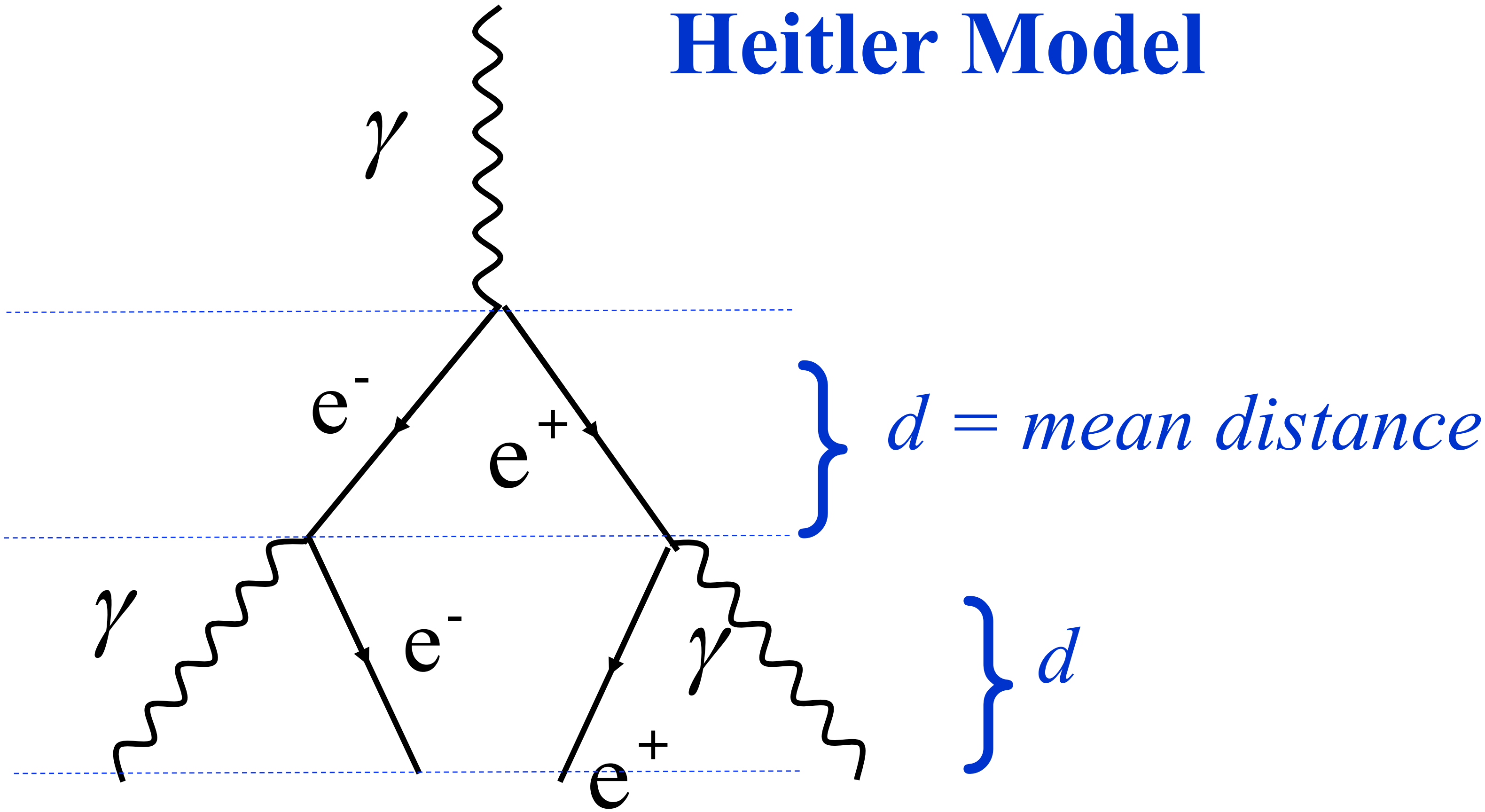
Fretter: Echo Lake, 1949

Shower components as a function of distance and depth



Engel et al. Ann Rev NPS 2011

Heitler Model



$$d = \lambda_r \ln 2$$

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

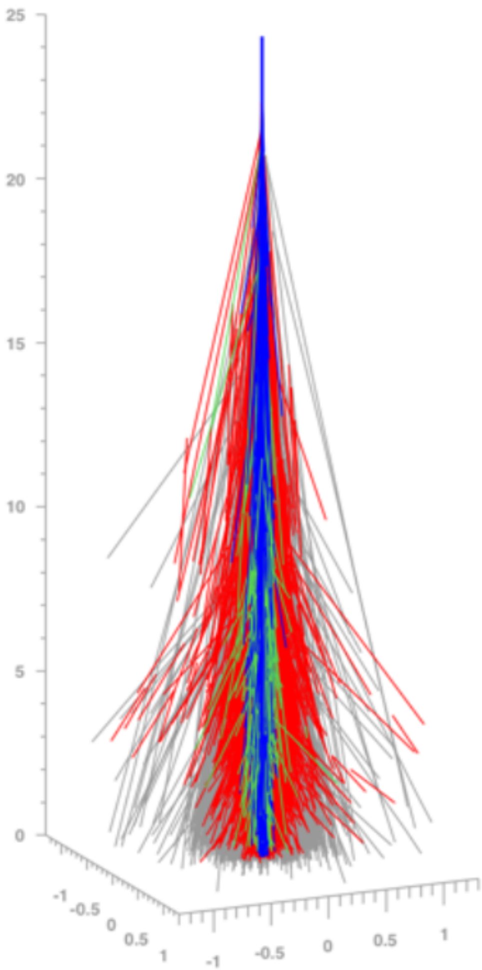
$X_{max} \sim \log E_o$

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

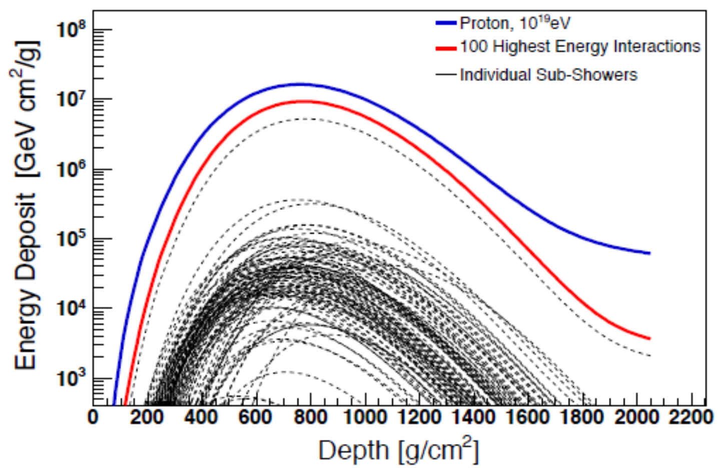
Now known as the ELONGATION RATE

Introduced by Linsley (1977)

Importance of different interaction energies



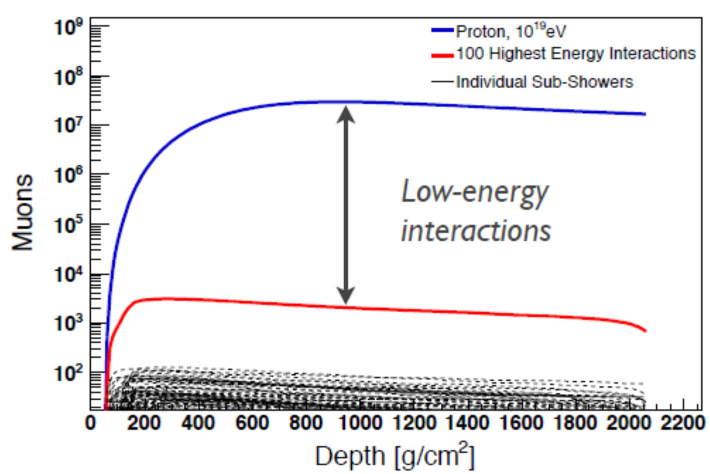
Electrons



Shower particles produced in 100 interactions of highest energy

Electrons/photons: high-energy interactions

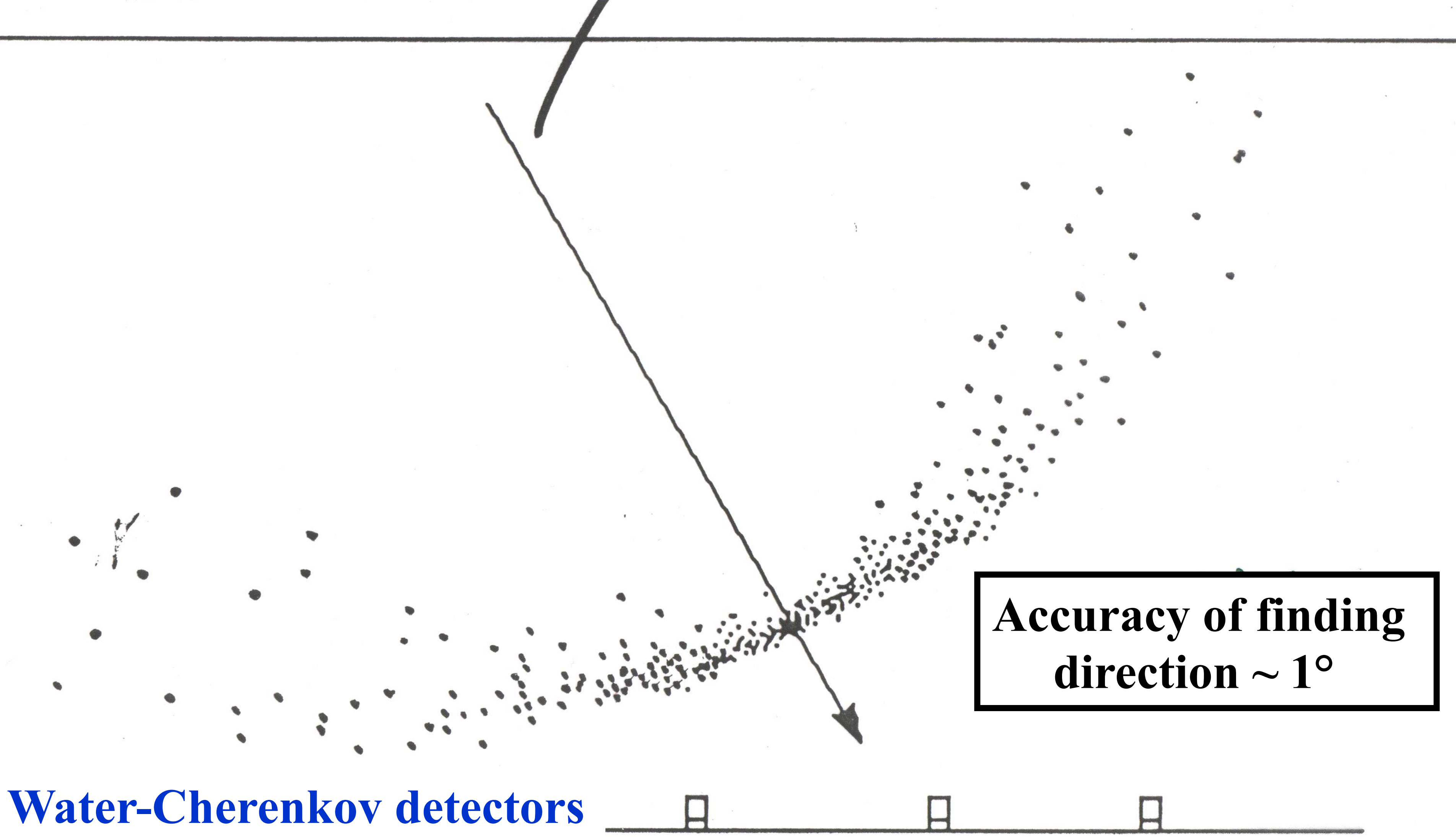
Muons



(Ulrich, APS 2012)

Muons/hadrons: low-energy interactions

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

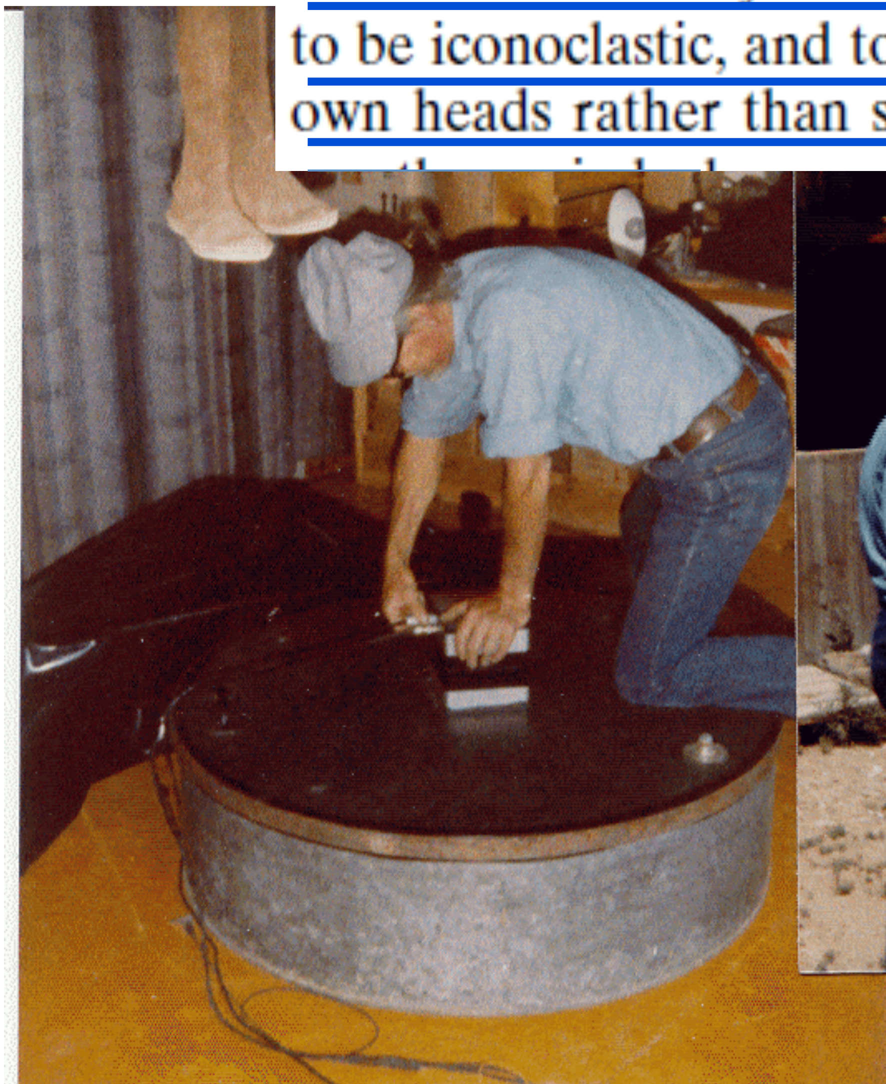


‘Fast timing’ gives the direction:

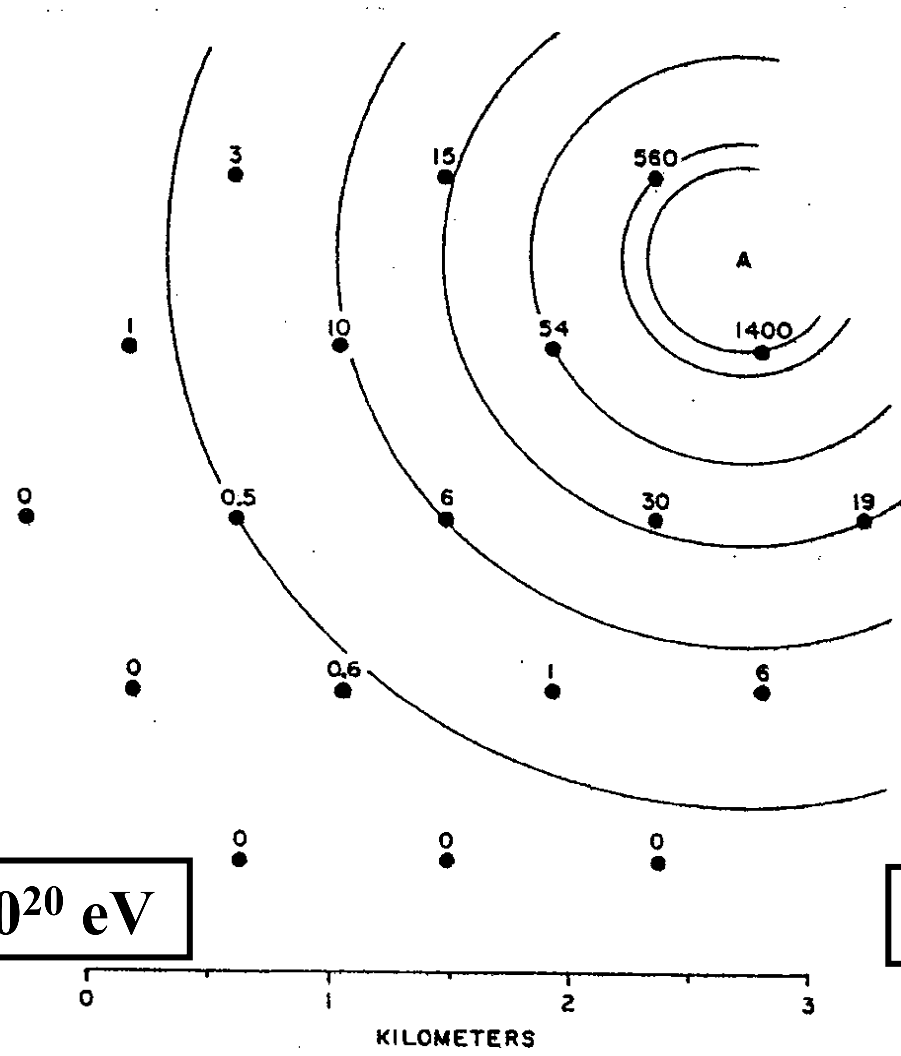
This is crucial when trying to establish the origin of the particles which travel across magnetic fields

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



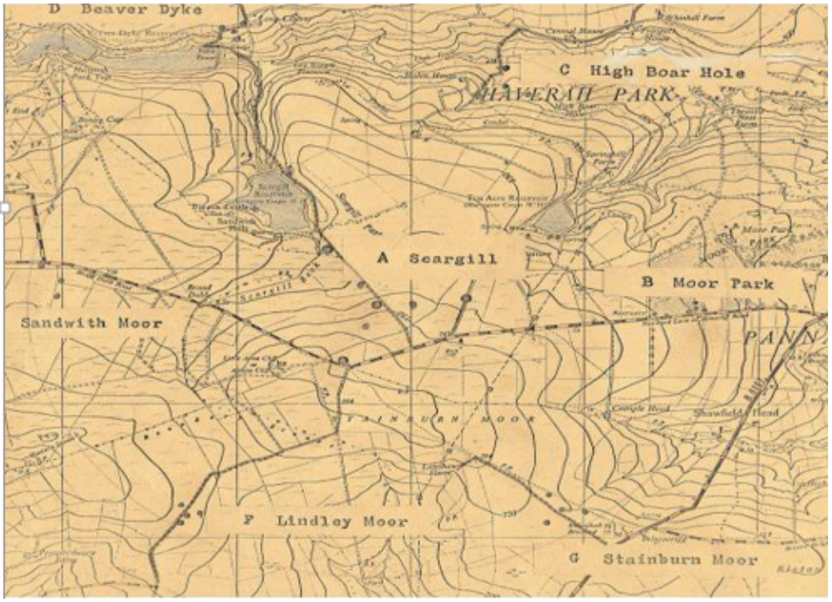
The Volcano Ranch Array: Linsley (1963)

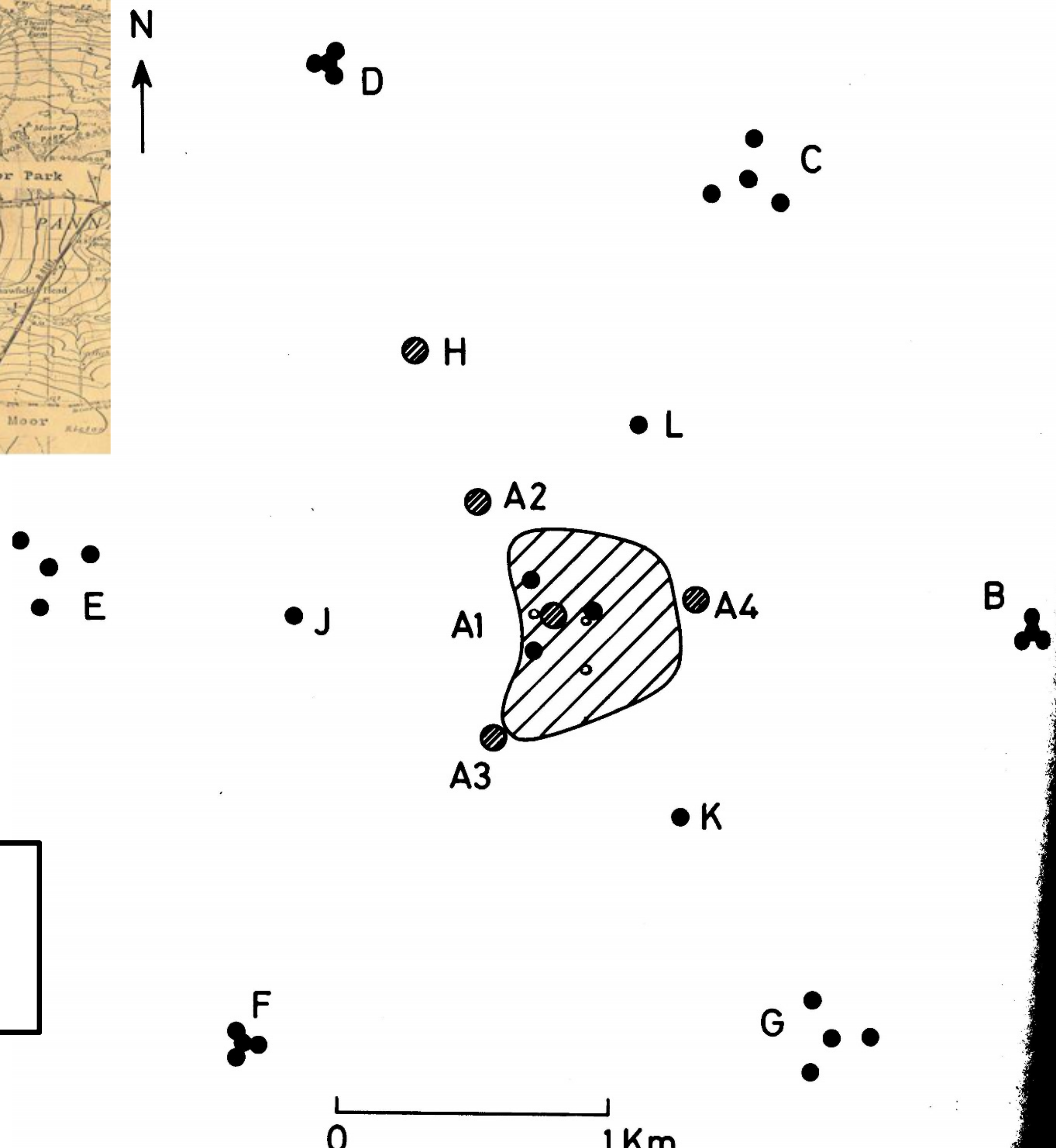


Energy ~ 10^{20} eV

Pre-GZK prediction

Haverah Park 1967 - 1987



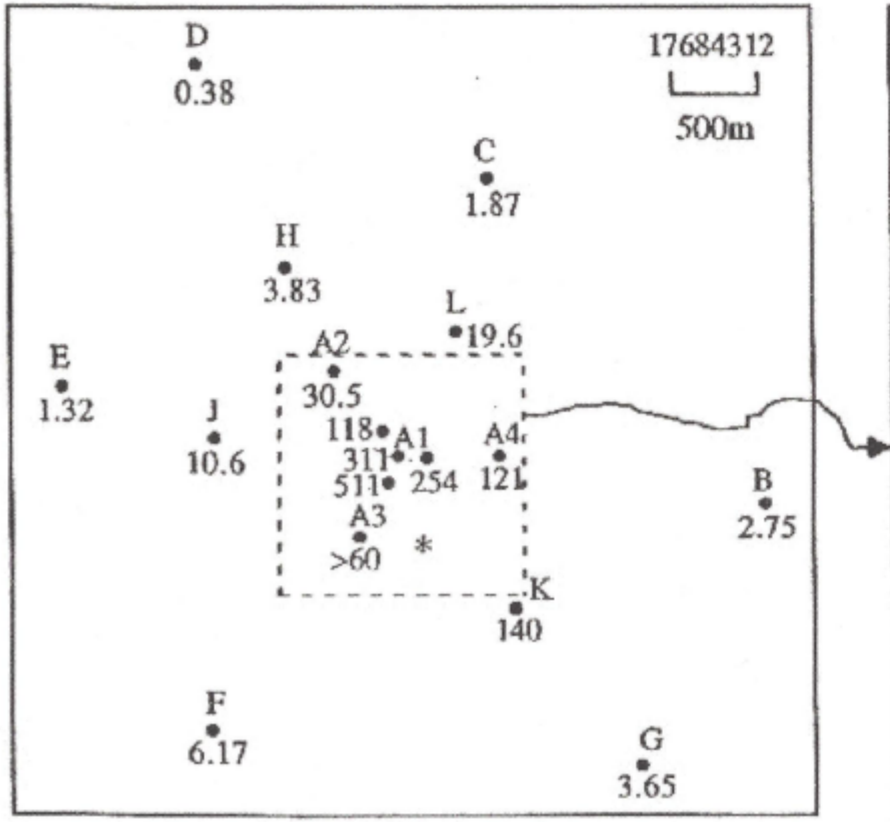


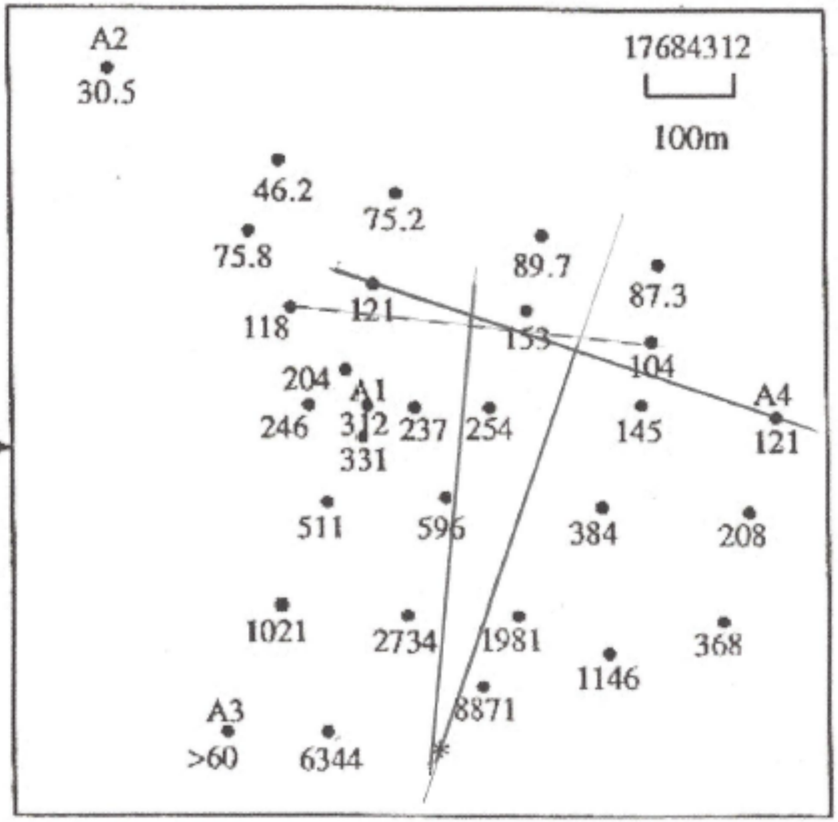
The shower array at Haverah Park. The area enclosed was ~12 km^2

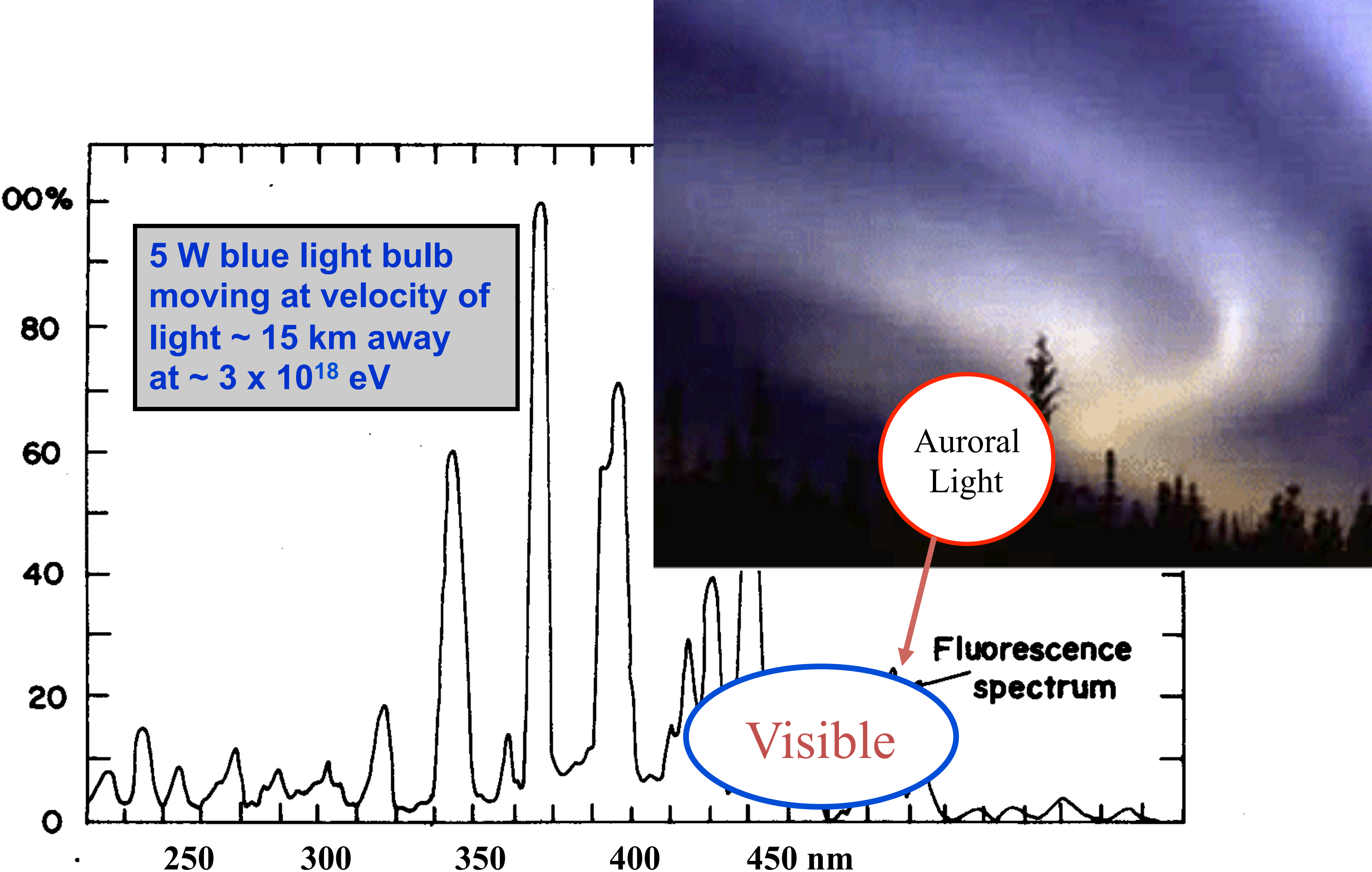
Each point in the diagram represents one or more tanks of water

End of project party:
water still drinkable after 25 years

Event with energy of ~ 8 x 10^{19} eV recorded at UK Array, Haverah Park






5 W blue light bulb
moving at velocity of
light ~ 15 km away
at ~ 3 x 10^18 eV
00%
80
60
40
20
0
250
300
350
400
450 nm
Auroral
Light
Fluorescence
spectrum
Visible

Fluorescence Radiation:

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

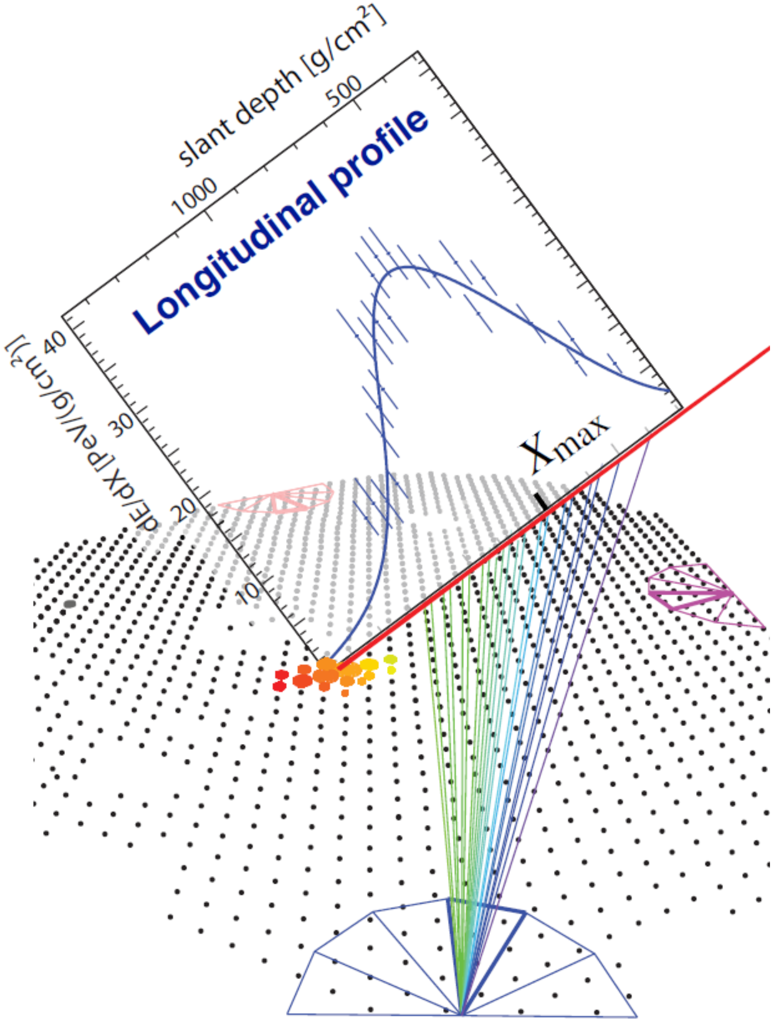
- **Chudakov knew of this in 1950s and explored properties in case it was a background for Cherenkov radiation when**

- **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

Energy from fluorescence measurements

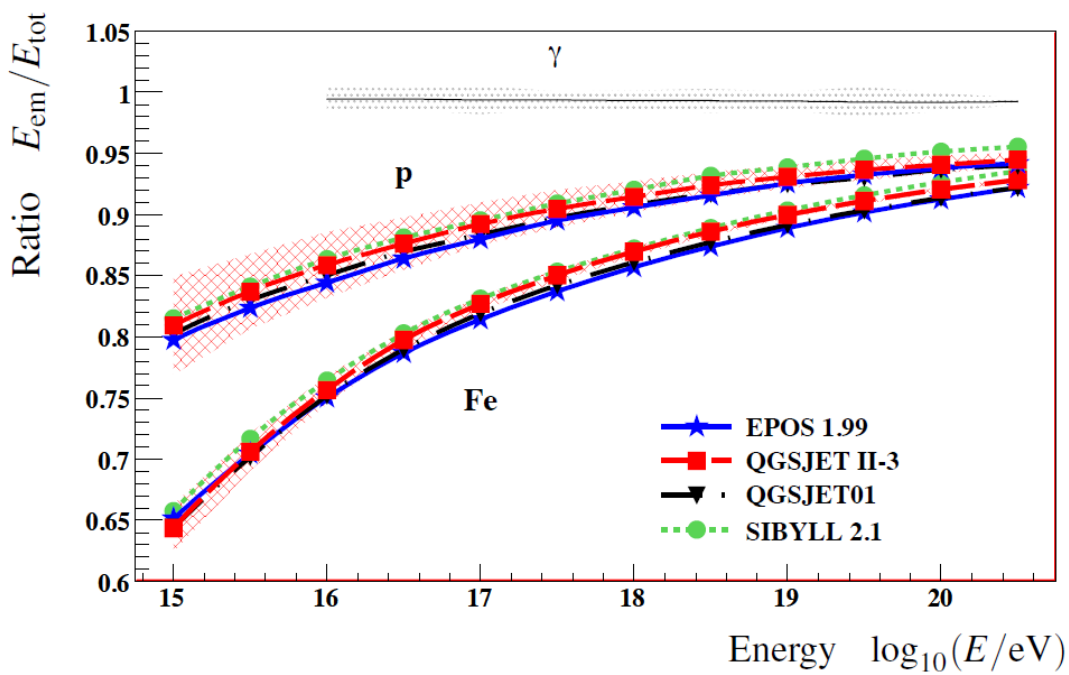


Example: event observed with Auger Observatory

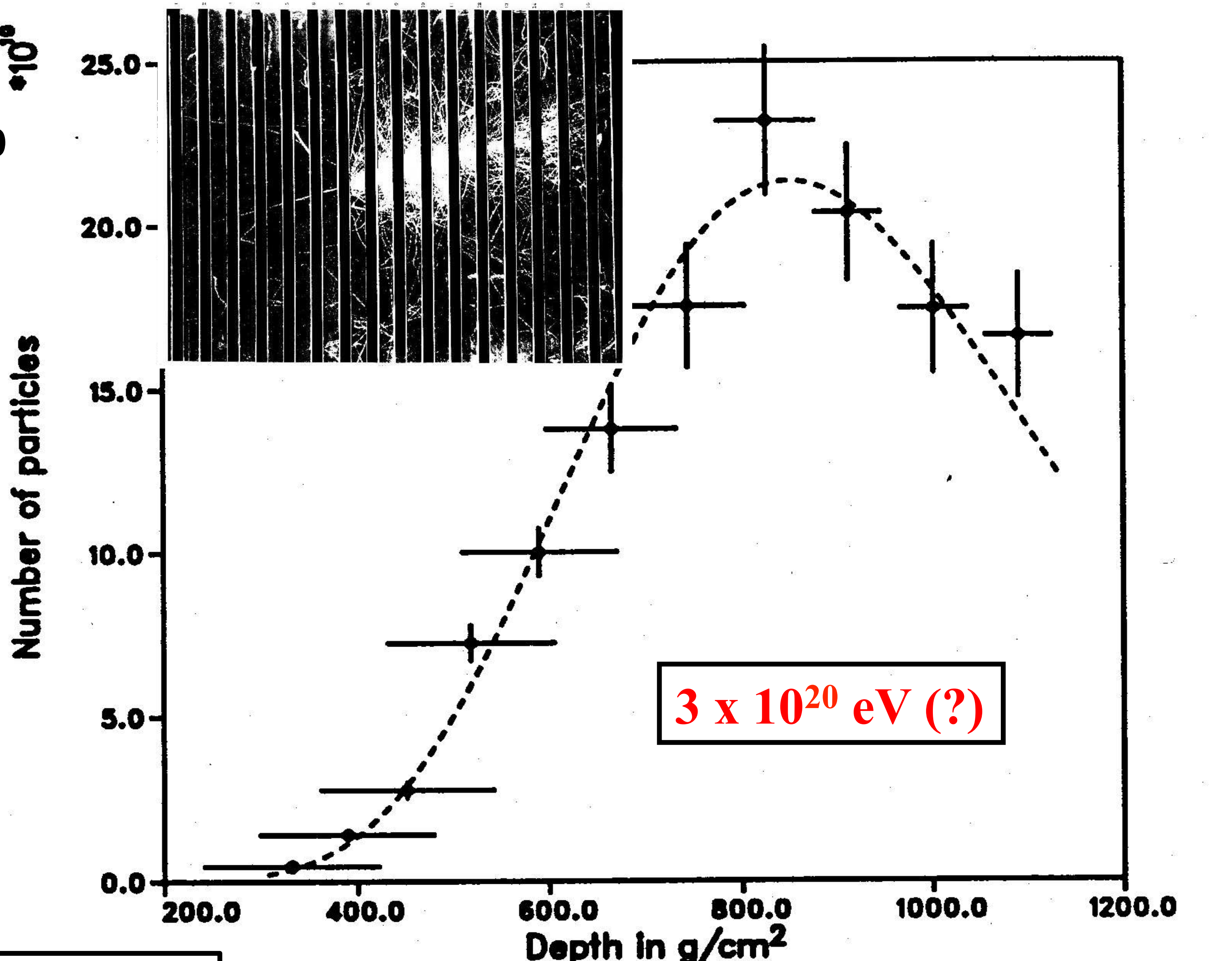
Electrons:

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

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



$\times 10^{10}$



Reported in 1993 – detected some years before

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

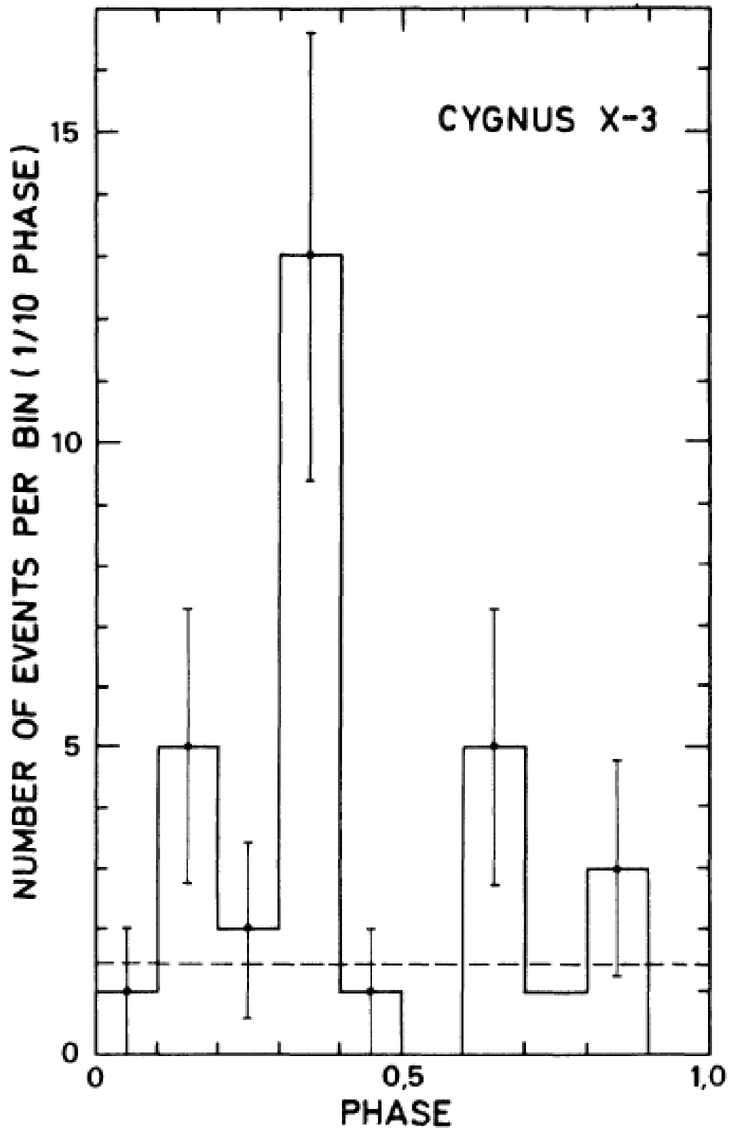
The main conclusion, in some ways, was that the device was not big enough

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

31 events



Samorski and Stamm 1983

Photons of 1 PeV from Cygnus X-3

4.8 hours

Many people from particle physics entered field

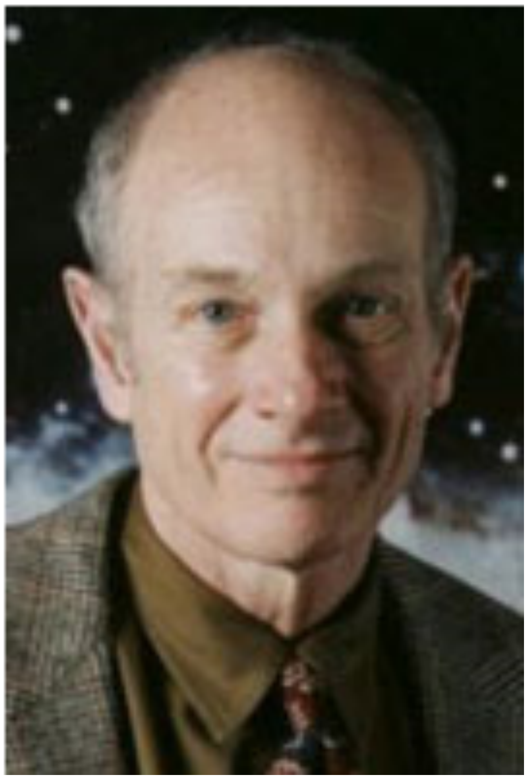
In USA: Wisconsin, Hawaii, Minnesota groups
at Haleakala and South Pole at TeV energies

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

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

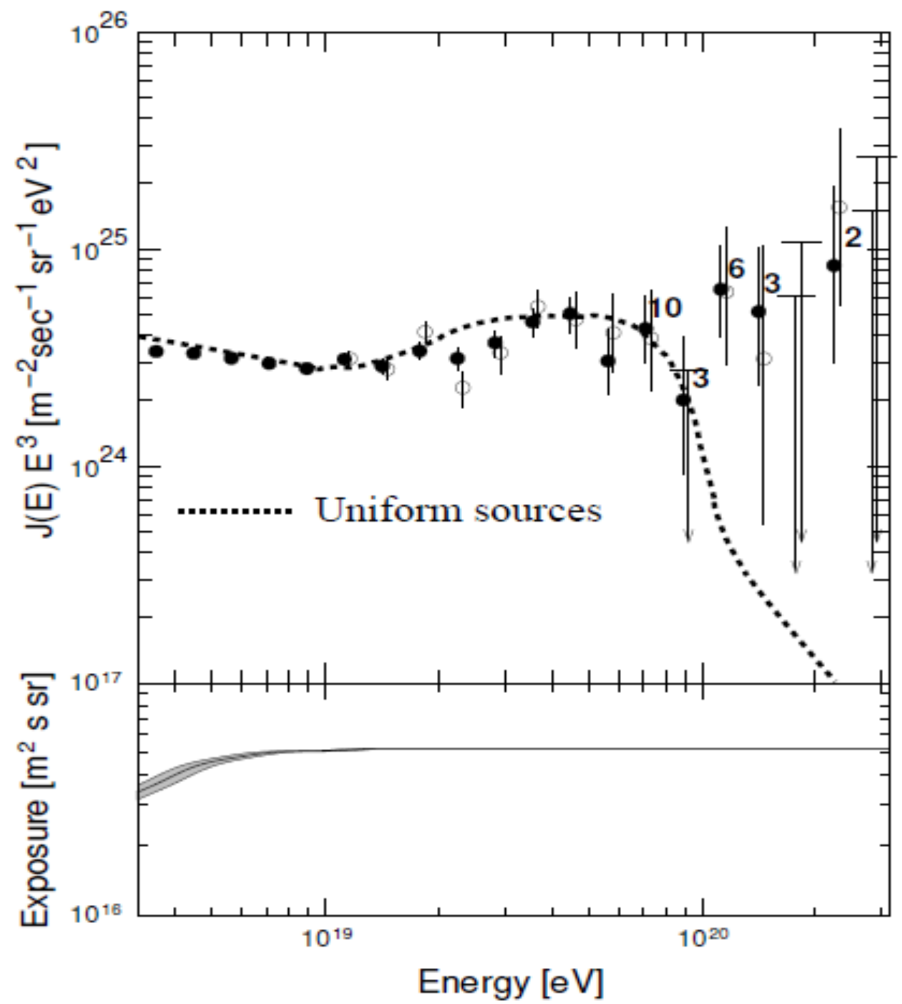
100 km² array (AGASA) in Japan

111 scintillators on 1 km² grid

Operated for 12 years

Very remarkable result (1993)

Huge number of explanations



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

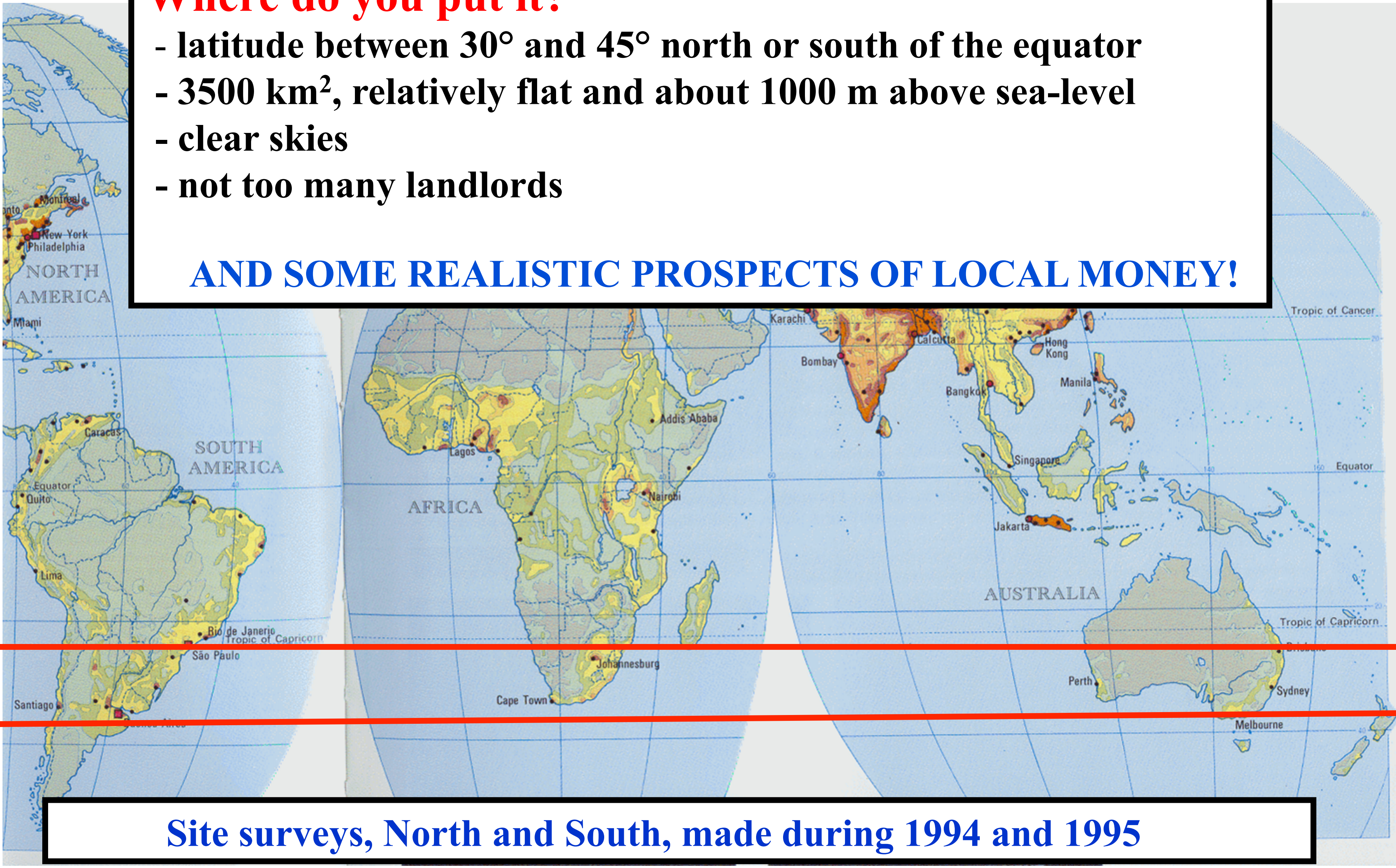
- **Chose Argentina for southern site**

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 km^2, 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

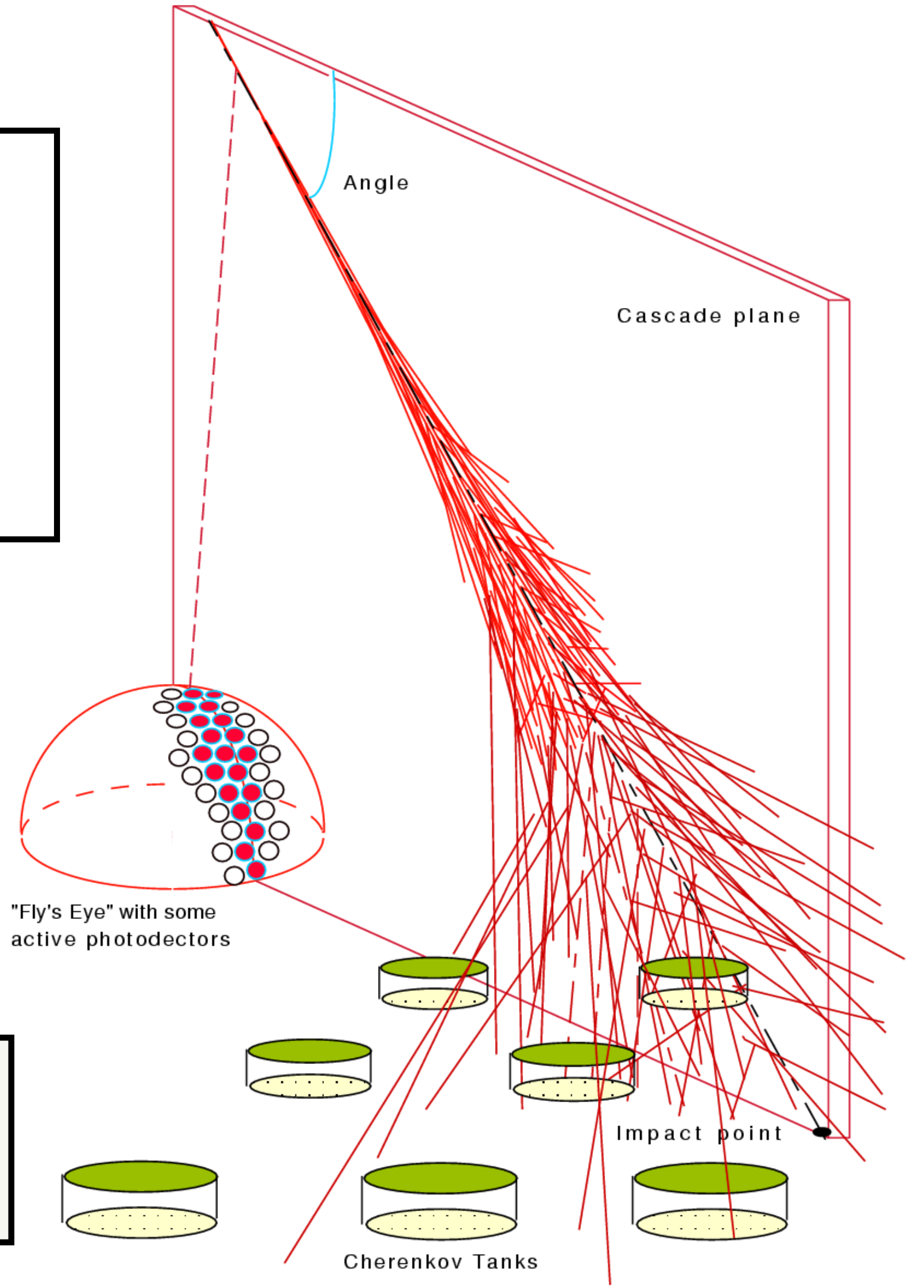
The design of the Pierre Auger Observatory marries two well-established techniques

→ **the 'HYBRID' technique**

Fluorescence →

AND

Arrays of water-Cherenkov detectors →

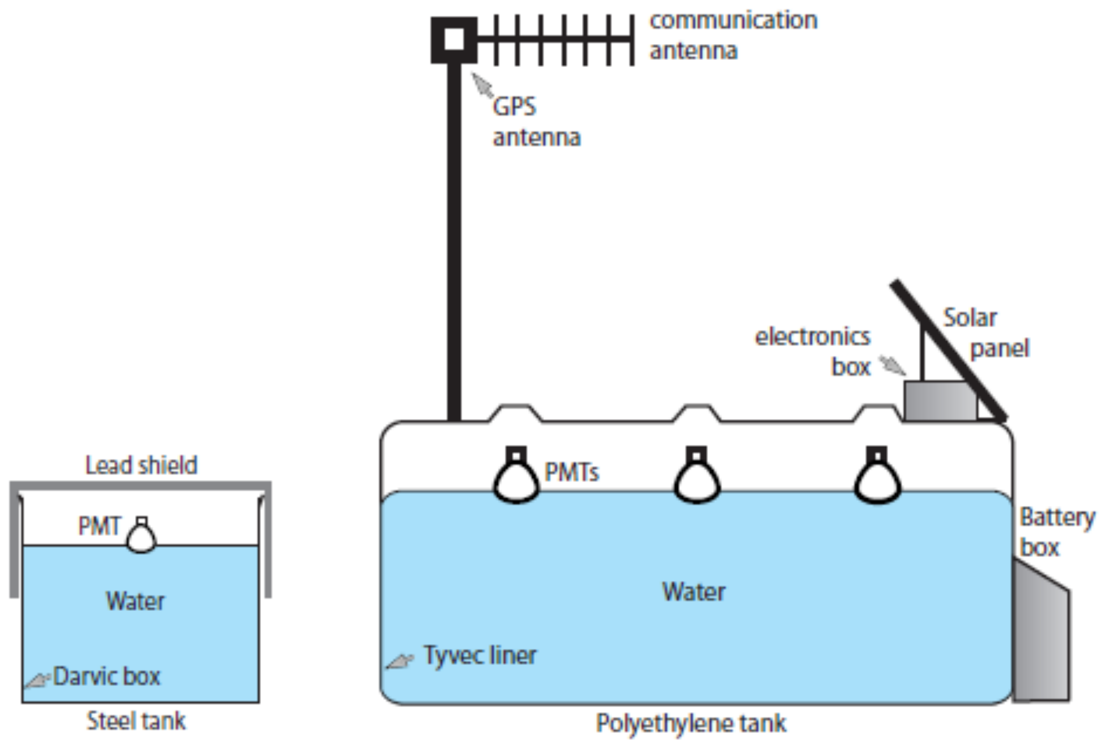


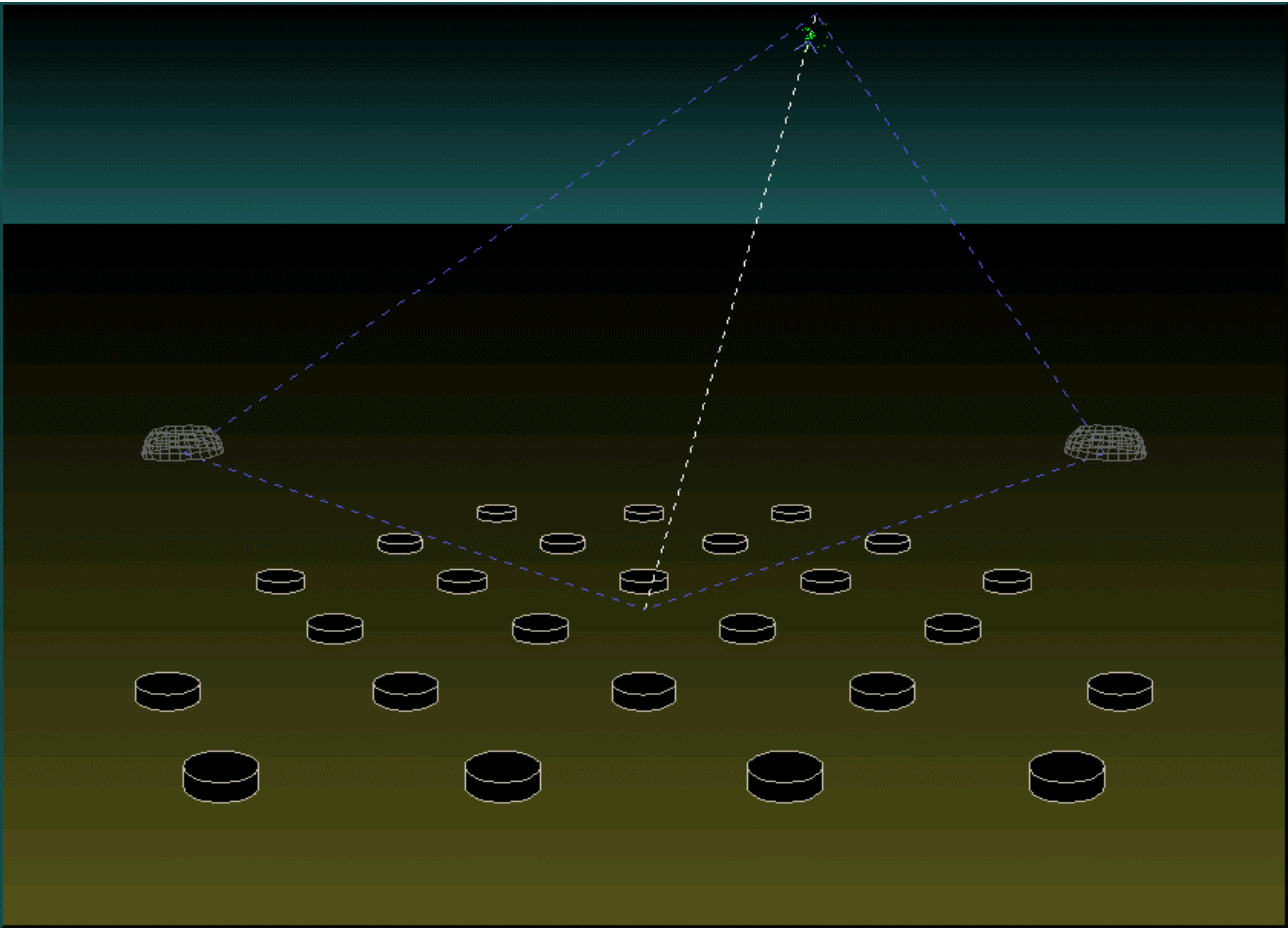
Water-Cherenkov detectors introduced to Harwell Geiger Counter Array by Neil Porter (indirect contribution from Bruno Pontecorvo)

Silwood Park (Harold Allan) late 1950s:

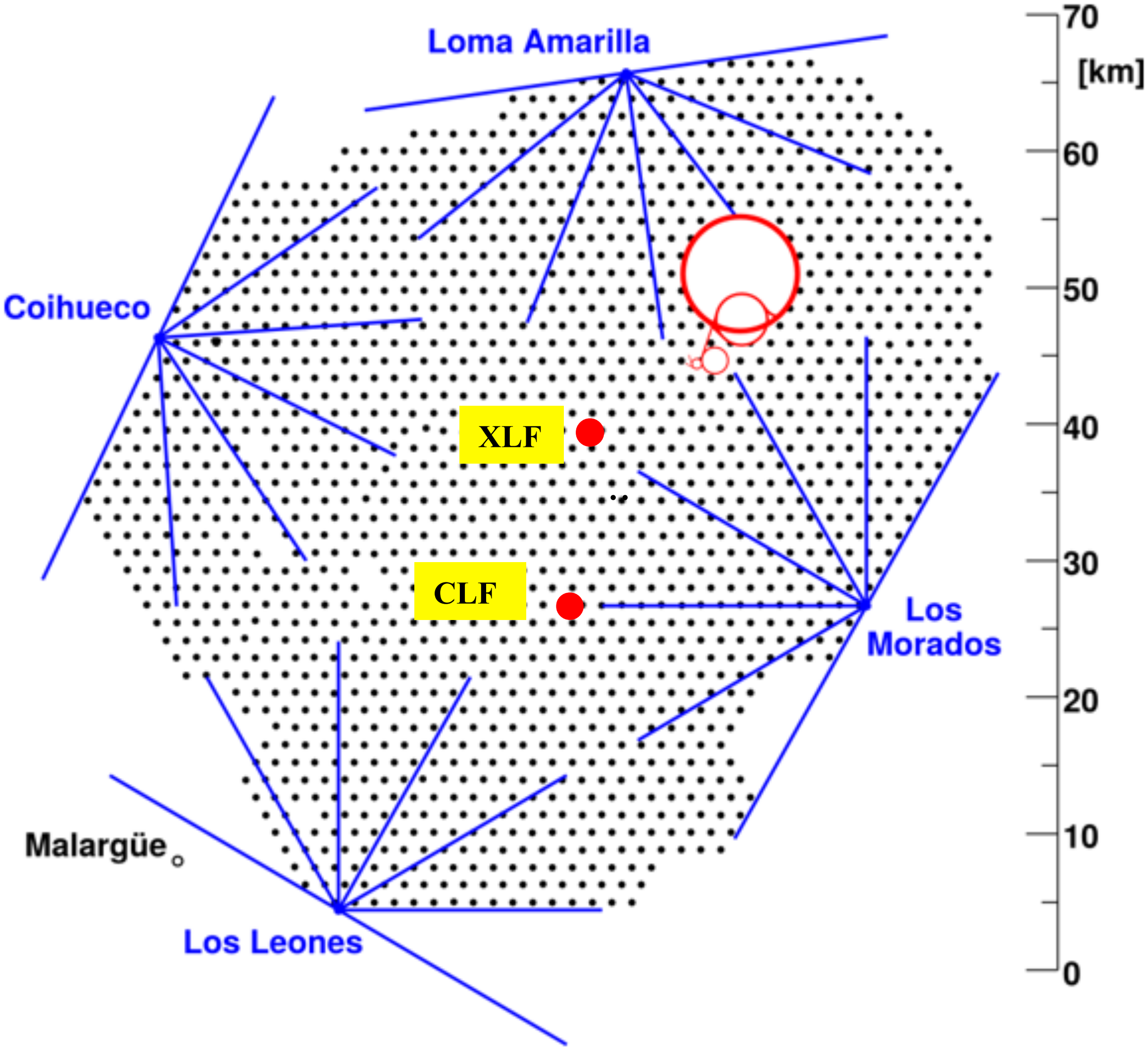
Haverah Park (J G Wilson et al)

Auger Observatory





The Pierre Auger Observatory: Malargüe, Argentina



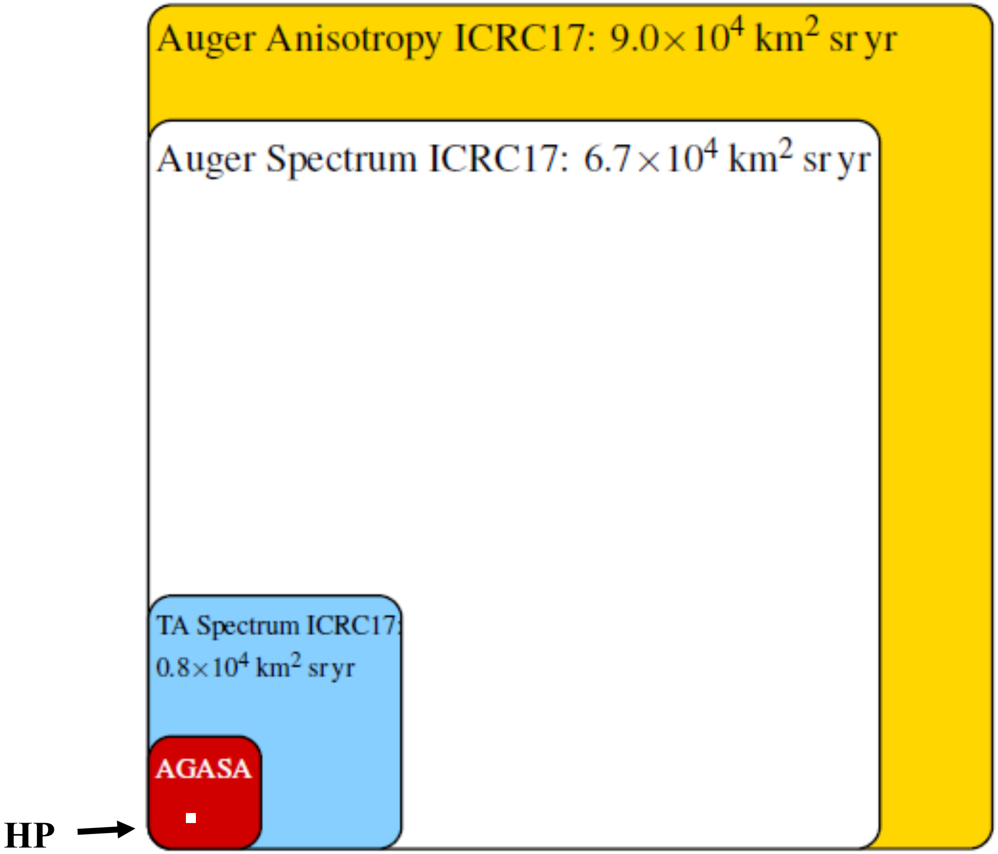
- 1600 water-Cherenkov detectors: 10 m^2 x 1.2 m
- 3000 km^2
- Fluorescence detectors at 4 locations
- Two laser facilities for monitoring atmosphere and checking reconstruction
- Lidars at each FD site
- Capital cost ~$50M
- Area of Krakow: 327 km^2

The Pierre Auger Collaboration

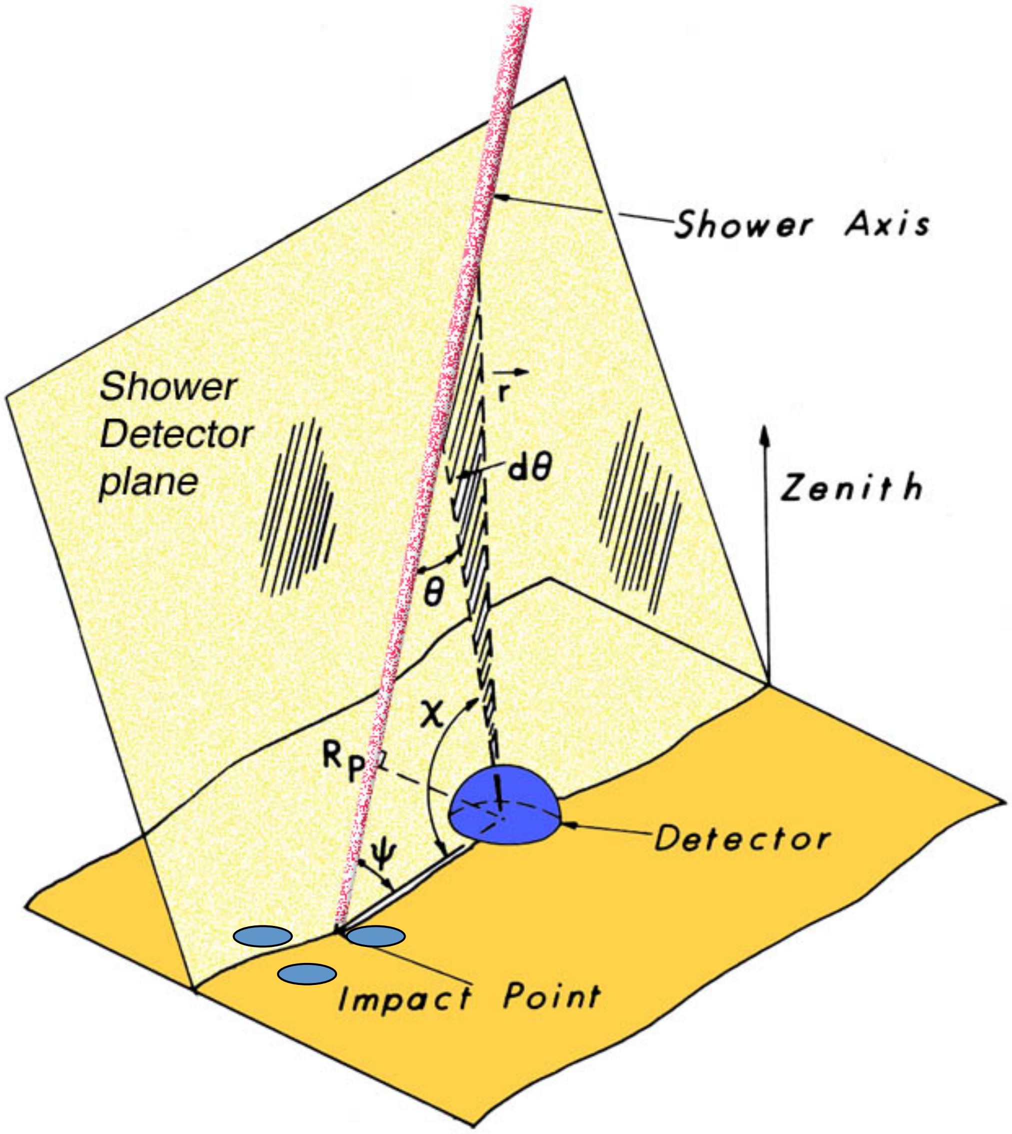
Czech Republic	Argentina
France	Australia
Germany	Brasil
Italy	Colombia
Netherlands	Mexico
Poland (Łódź, Kraków)	USA
Portugal	
Rumania	
Slovenia	~ 400 PhD scientists from
Spain	~ 100 Institutions in 17 countries
United Kingdom	

2004: Data taking started with about 200 water-Cherenkov detectors and two fluorescence telescopes - 13 years after first discussions

Soon surpassed the exposure at Haverah Park accrued in 20 years – now over 67,000 km^2 sr years



After Michael Unger 2017



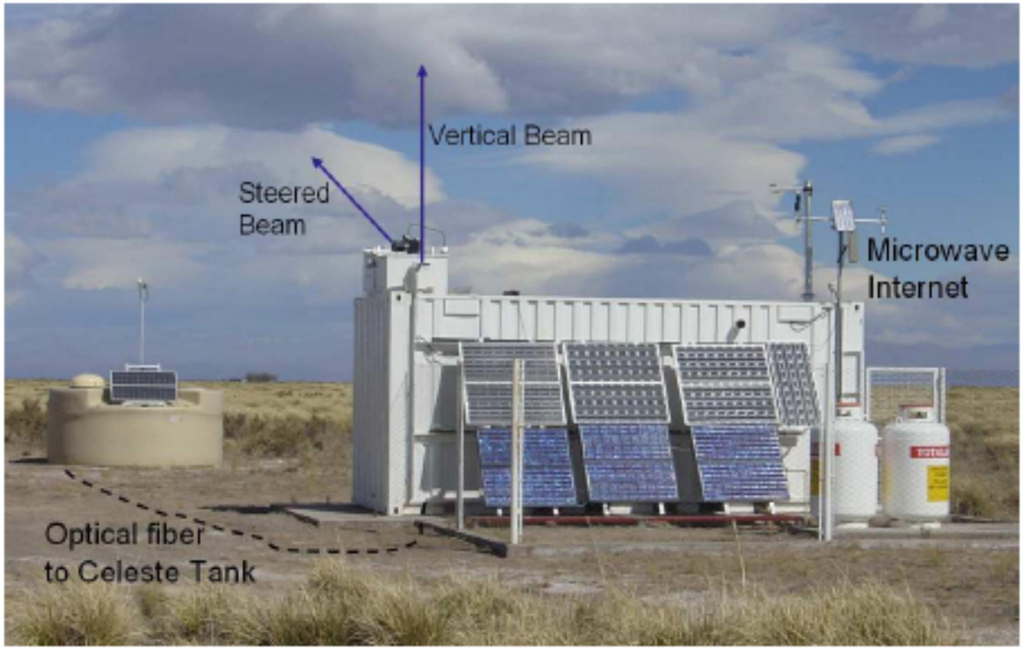
Important feature of the hybrid approach

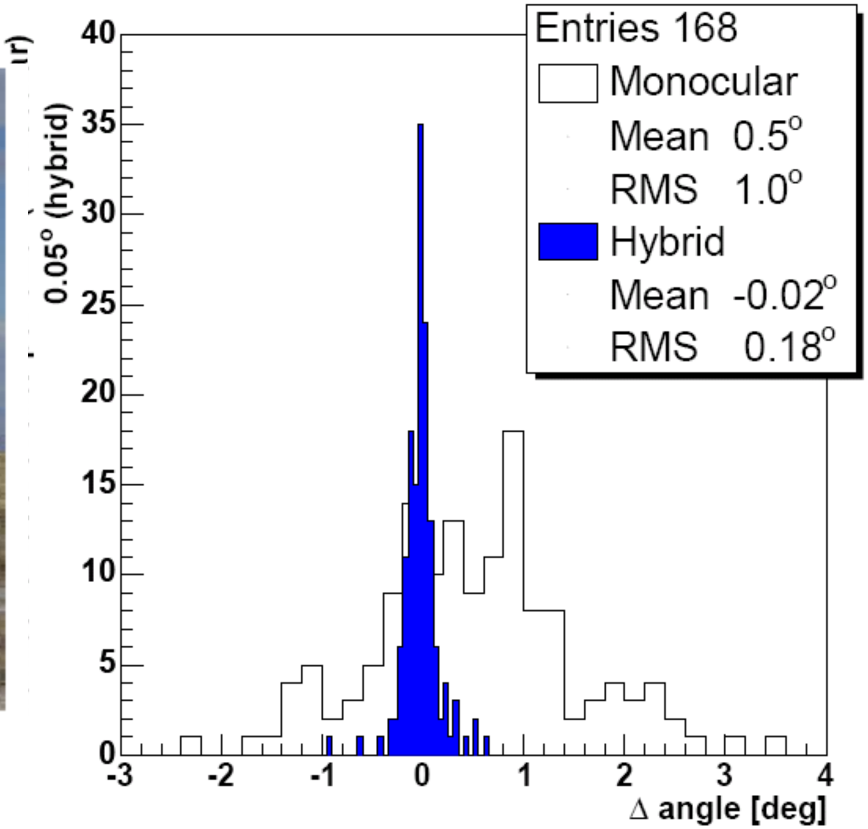
Precise shower geometry from degeneracy given by SD timing

Essential step towards high quality energy and X_{max} resolution

Times at angles, χ , are key to finding R_p

Angular Resolution from Central Laser Facility

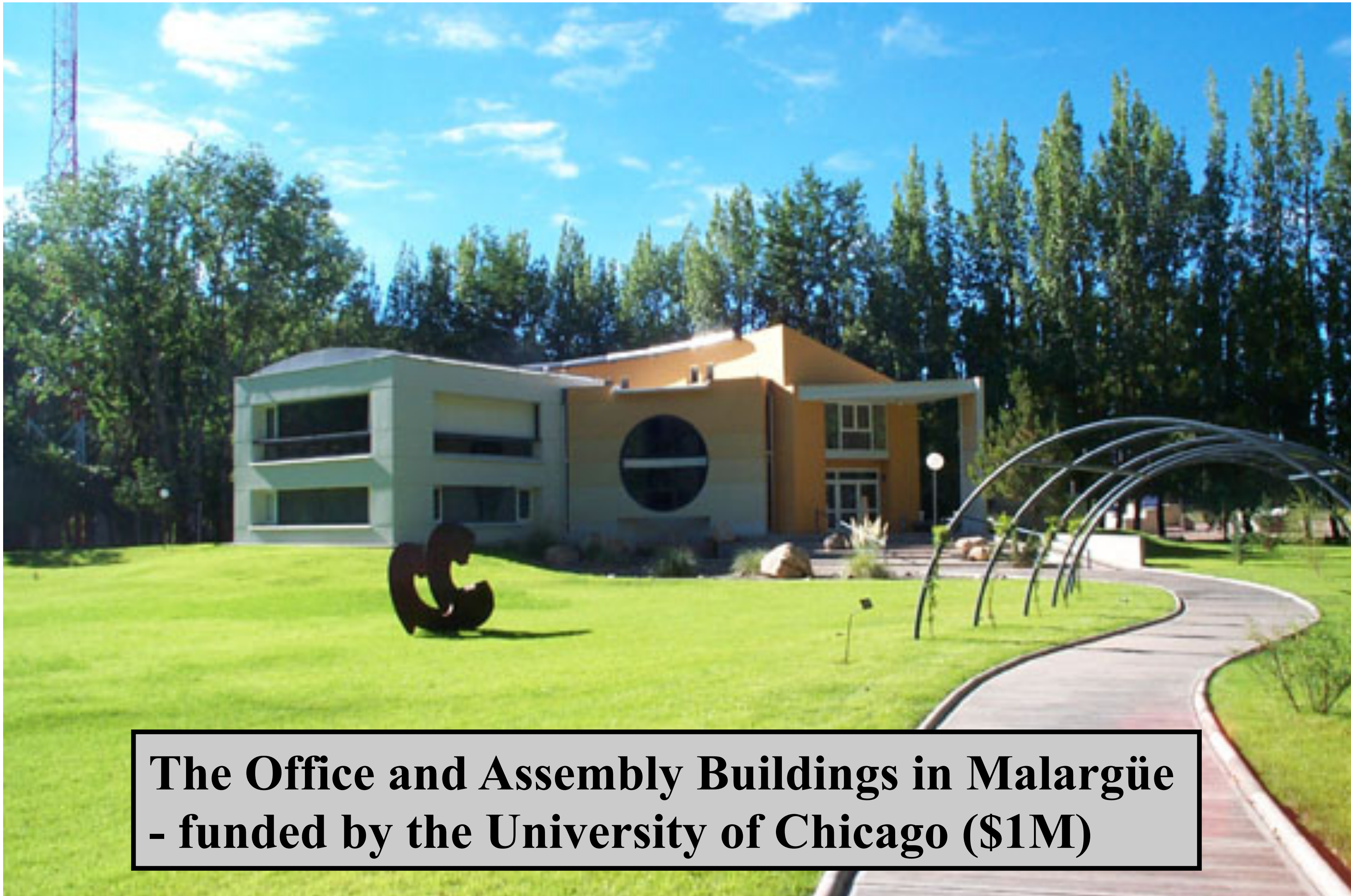




355 nm, frequency tripled, YAG laser, giving < 7 mJ per pulse: GZK energy

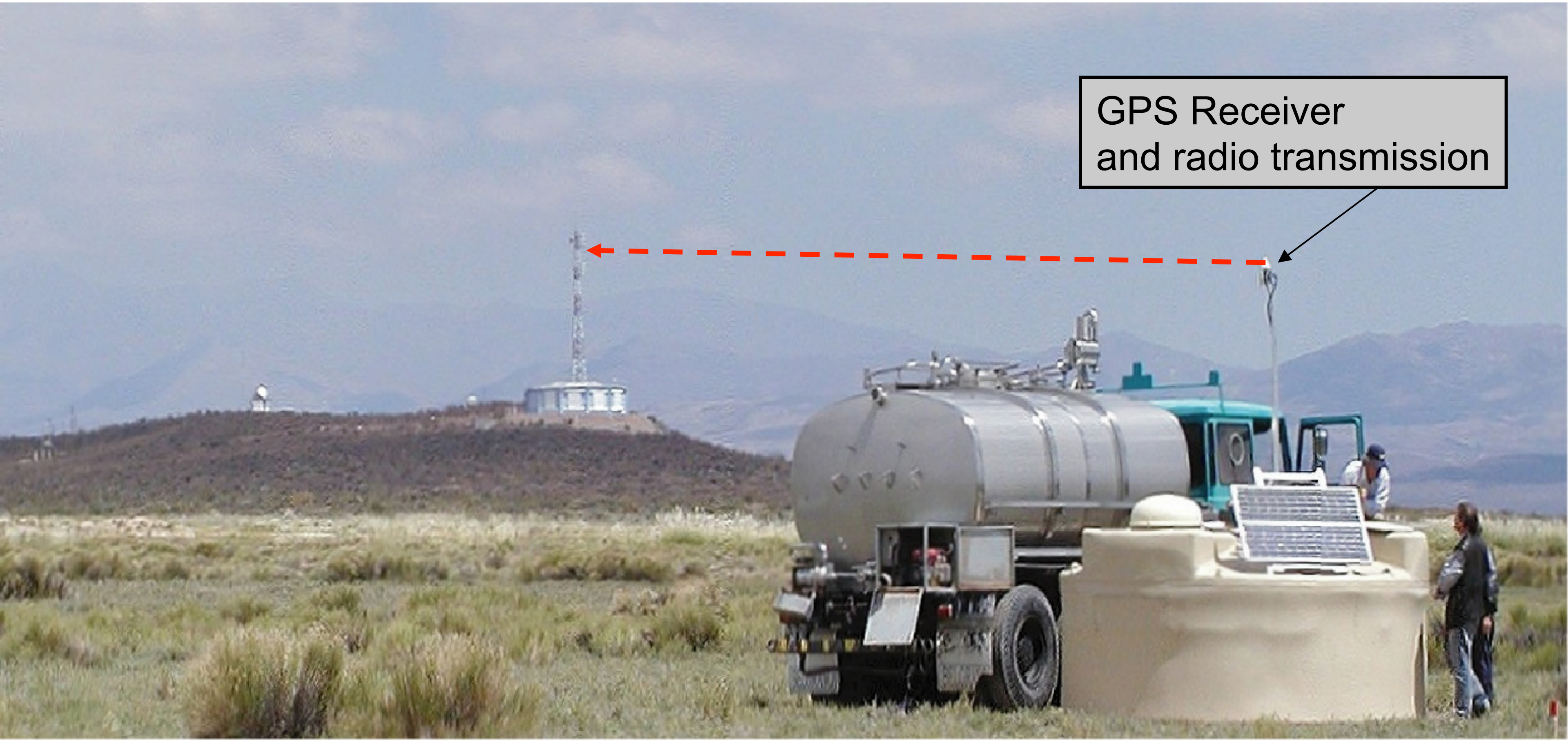
Mono/hybrid rms 1.0°/0.18°

Campus of Auger Observatory in Malargüe

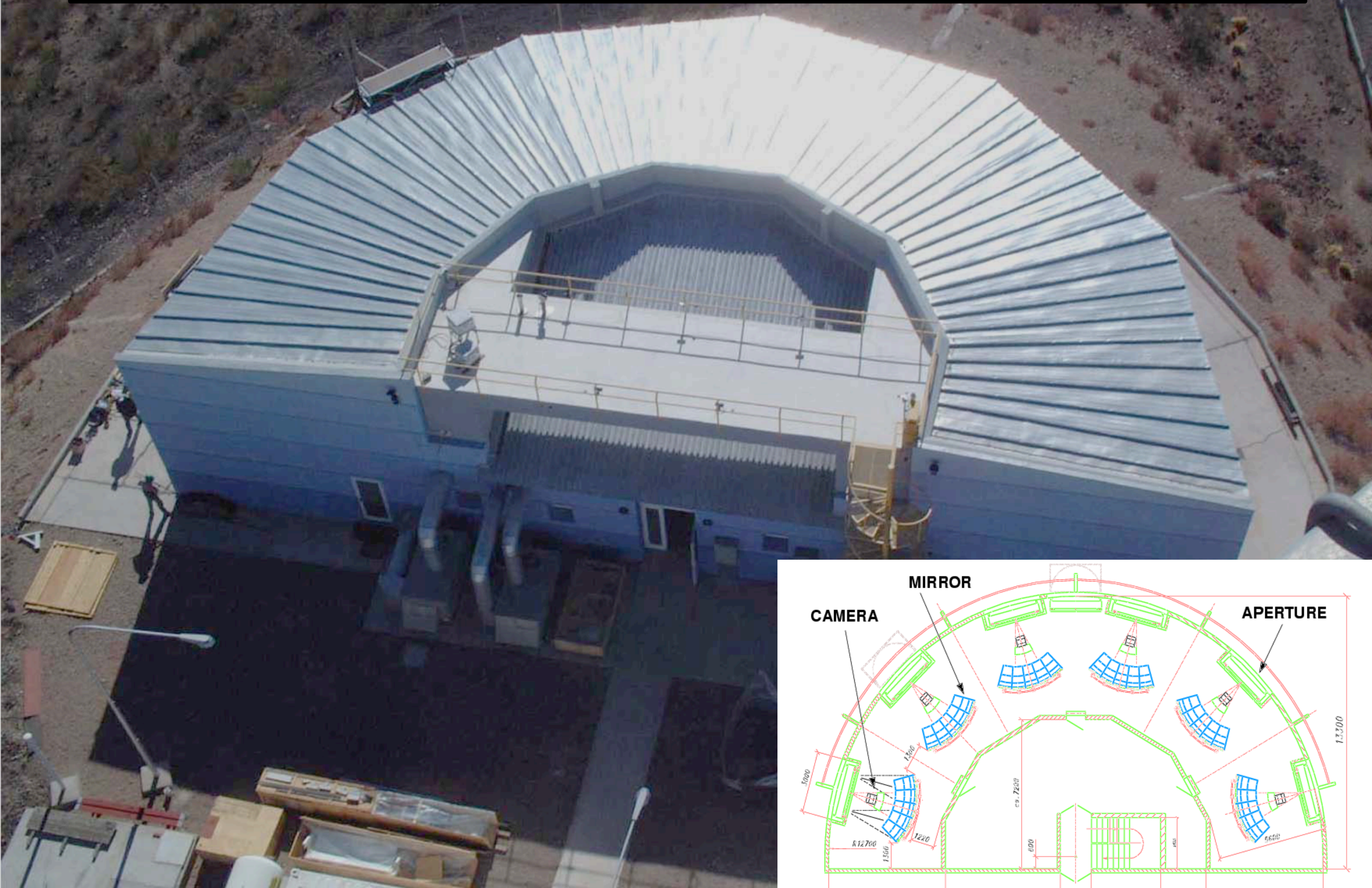


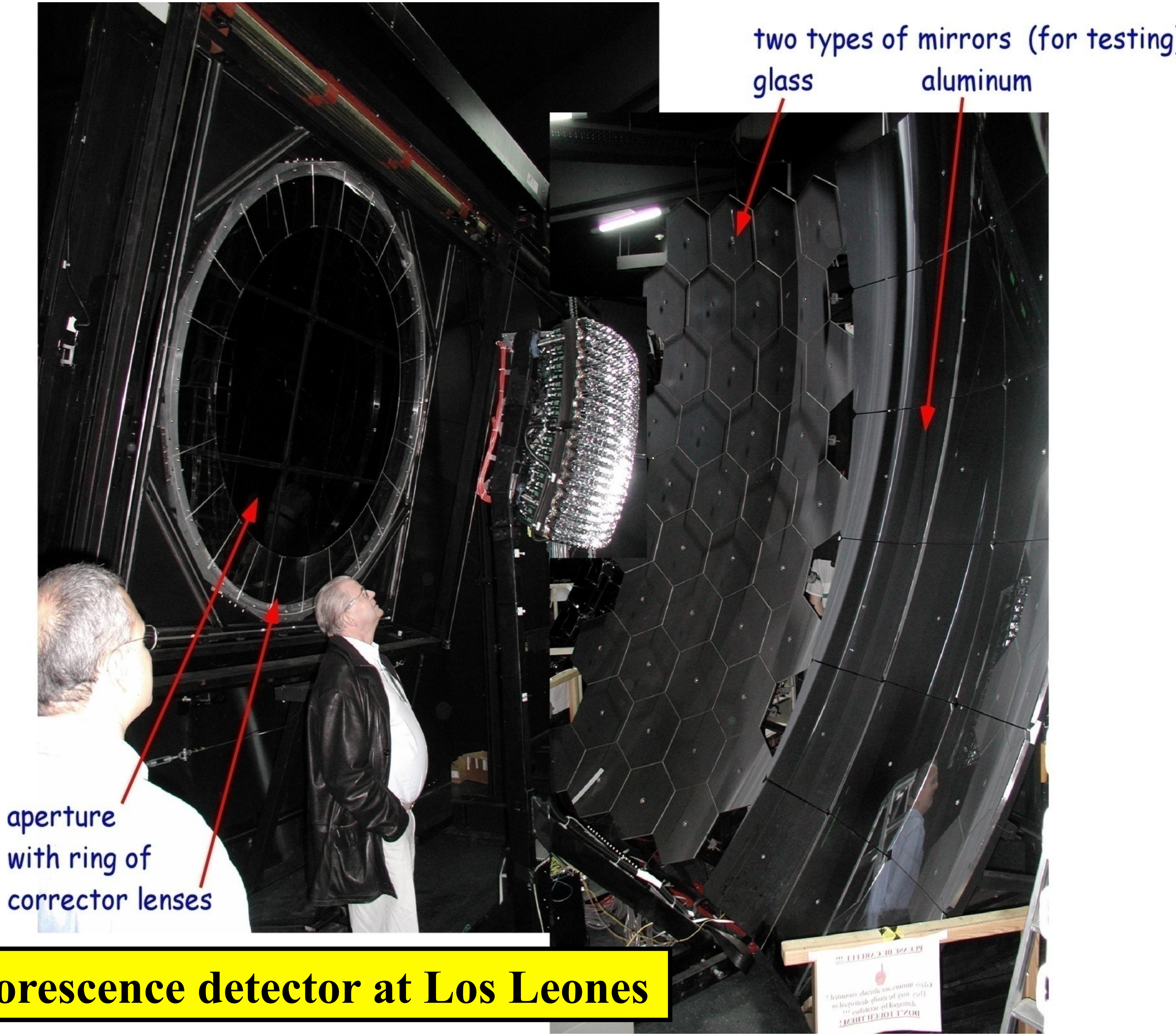
The Office and Assembly Buildings in Malargüe - funded by the University of Chicago ($1M)


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