One Century of Cosmic Rays

A particle physicist's view

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CERN

One Century of Cosmic Rays

A particle physicist's view

Pre-history: Common roots in the 19th century

Discovery: Adventures in the early 20th century

What are they? Discoveries up to ~1950

Neutrino astronomy: A new view of the cosmos

Gamma-ray astronomy: A new way to view of the cosmos

…with interludes from particle physics

There are more things in heaven and earth than are dreamt of in your philosophy …

William Shakespeare (Hamlet)

Some pre-history

1785 Charles de Coulomb discovers the spontaneous discharge of isolated electrified bodies

1834 Michael Faraday makes further investigations; he introduces the term ‘ion’

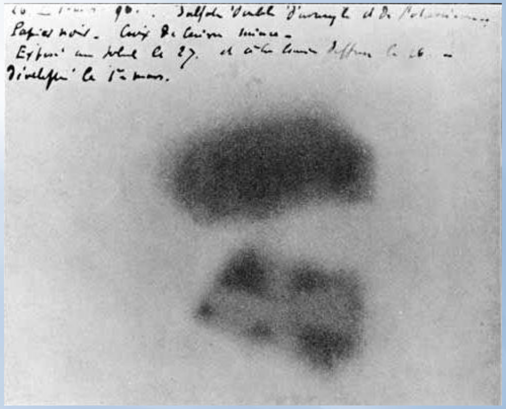
1879 William Crookes discovers the speed of discharge decreases when the pressure is reduced

→ ionization of air

Some pre-history

1895 Charles Wilson invents the cloud chamber

1895 Wilhem Röntgen discovers x-rays while investigating cathode rays in a 'Crookes' tube



1896 Henri Becquerel discovers radioactivity while investigating the production of x-rays

1897 J J Thomson discovers that cathode rays consist of particles much smaller than the atom → the electron

Some pre-history

1899 Ernest Rutherford discovers two forms of radioactivity: α and β

1900 Philippe Villard discovers a third, penetrating type of radioactivity, named γ rays by Rutherford

~1900 Wilson in Scotland, and Julius Elster and Hans Geitelin in Germany improve the insulation of electroscopes and hence the sensitivity

1900 Wilson suggests ionization of air could be due to extremely penetrating extraterrestrial radiation

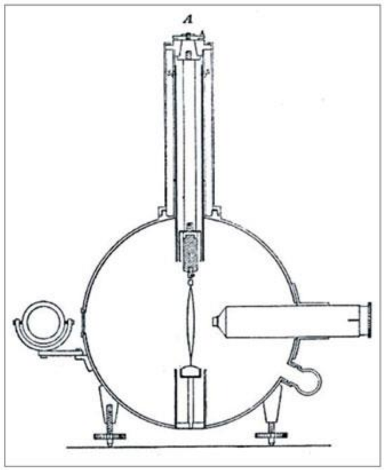
Discovery

1900-1903 Franz Linke makes 12 balloon flights during PhD studies at Berlin University

He finds ionization ‘*between 1 and 3 km the same amount; above it is larger … up to a factor of 4 (at 5500 m), The uncertainties in the observations […] only allow the conclusion that the reason for the ionization has to be found first in the Earth*’

He made the right measurement, but reached the wrong conclusions

Discovery



1909 Theodor Wulf perfects the portable electroscope and finds the amount of radiation at the top of the Eiffel Tower (300 m) is '*not even half of its ground value*'

1909 Karl Bergwitz in a balloon finds ionization at 1300 m is about 24% of the value on the ground

Alfred Gockel flies up to 3000 m; he introduces the term 'kosmische Strahlung', or 'cosmic radiation'

Discovery

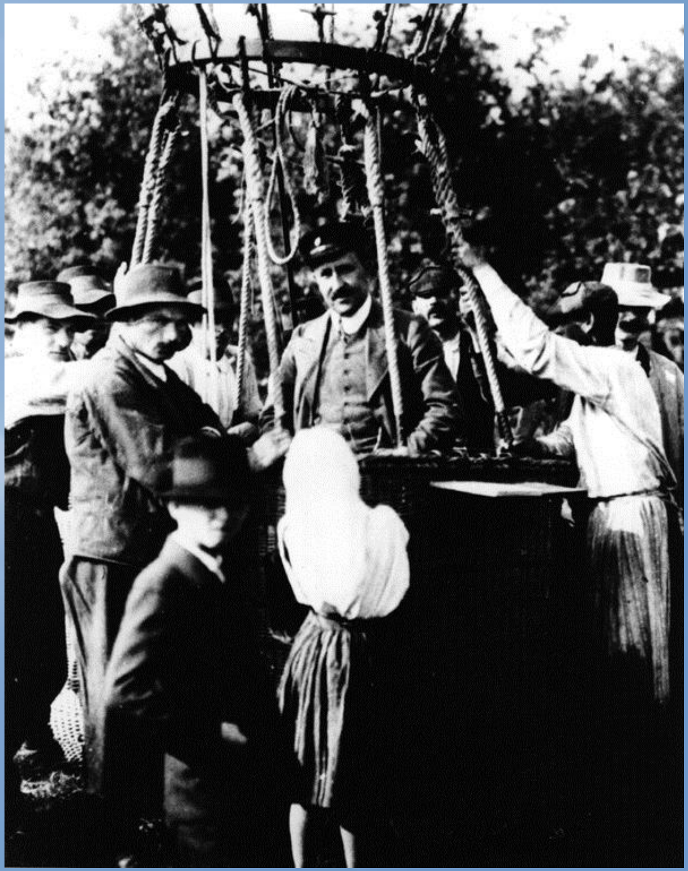
1911-1912 Domenico Pacini finds the rate of ionization at 3 m below water is 20% lower than at the surface: ‘*[It] appears … that a sizable cause of ionization exists in the atmosphere originating from penetrating radiation*’

1911 Ernest Rutherford analyses wide-angle α-particle scattering from gold leaf → the nucleus

1911 Roald Amundsen’s party reaches the South Pole

Discovery

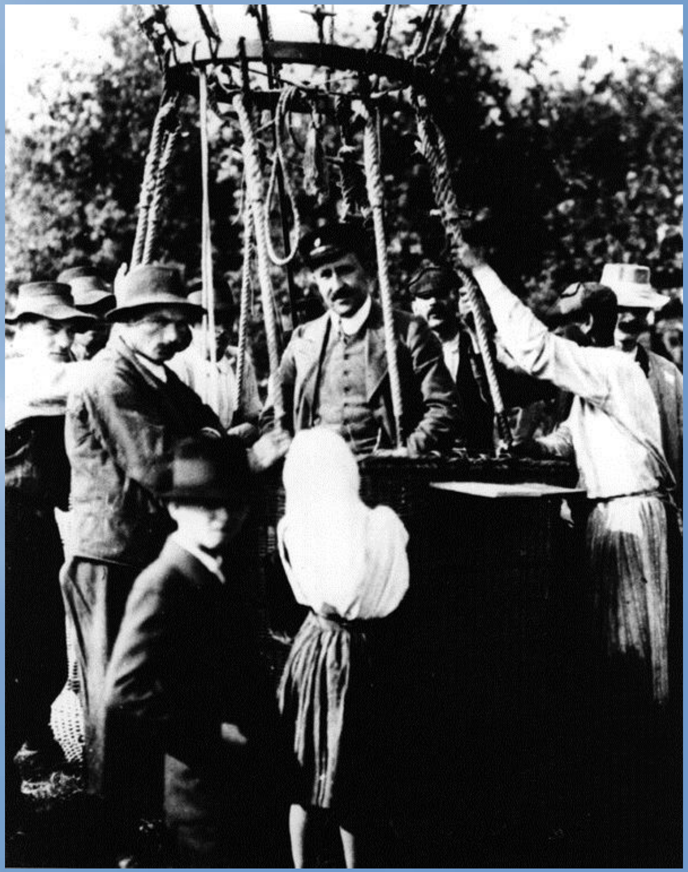
1911 Victor Hess finds on two balloon flights 'no essential change' in the amount of radiation compared with near the ground, indicating the existence of a radiation source in addition to γ-rays from radioactive decays in the Earth's crust



Discovery

7 August 1912 On the last of a series of balloon flights using two Wulf electroscopes:

'We took off at 6.12 a.m. from Aussig on the Elbe. We flew over the Saxony border by Peterswalde, Struppen near Pirna, Birchofswerda and Kottbus. The height of 5350 m was reached in the region of Schwielochsee. At 12.15 p.m. we landed near Pieskow, 50 km east of Berlin.'



Discovery

7 August 1912

'In both γ-ray detectors the values at the greatest altitude are about 22–24 ions higher than at the ground. … By 3000 to 4000 m the increase amounts to 4 ions, and at 4000 to 5200 m fully to 16 to 18 ions, in both detectors. …The results of the present observations seem to be most readily explained by the assumption that a radiation of very high penetrating power enters our atmosphere from above … Since I found a reduction … neither by night nor at a solar eclipse, one can hardly consider the Sun as the origin.'

Interlude

1911 Wilson makes the first observation of particle tracks in a cloud chamber

1919 Rutherford announces the discovery of the proton

1927 Paul Dirac (right) predicts the existence of the 'anti-electron' – later named the positron

1930 Wolfgang Pauli: '*I have done a terrible thing. I have postulated a particle that cannot be detected*' – later named the neutrino

What are they?

1920s Robert Millikan is convinced the primaries are 'ultra' γ-rays – '*the birth-cry of atoms*'. He promotes the name 'cosmic rays'

1926-7 Jacob Clay measures ionization at varying latitudes travelling by sea between Amsterdam and the Dutch East Indies, and finds a fall of about 15%

This suggests that cosmic rays are charged particles

What are they?

1929 Walter Bothe and Werner Kohlhörster use the coincidence technique with Geiger-Müller tubes to detect single charged particles in cosmic rays. The G-M tubes are connected to fibre electrometers and photographed

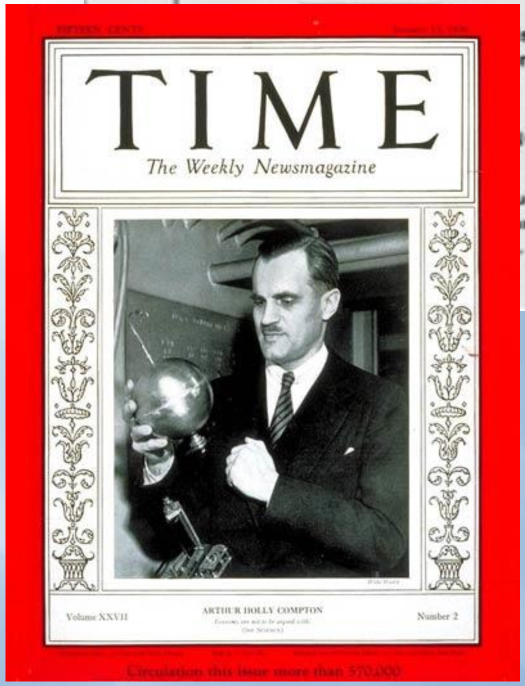
1930 Bruno Rossi develops the technique, inventing a coincidence circuit using vacuum triode valves – the first practical AND circuit – and confirms the results on cosmic rays

What are they?

1931 Rossi, left, Millikan, centre, and Arthur Compton at a conference in Rome. Rossi gave the introductory talk:

‘*Millikan clearly resented having his beloved theory torn to pieces by a mere youth, so much so that from that moment on he refused to recognise my existence*’

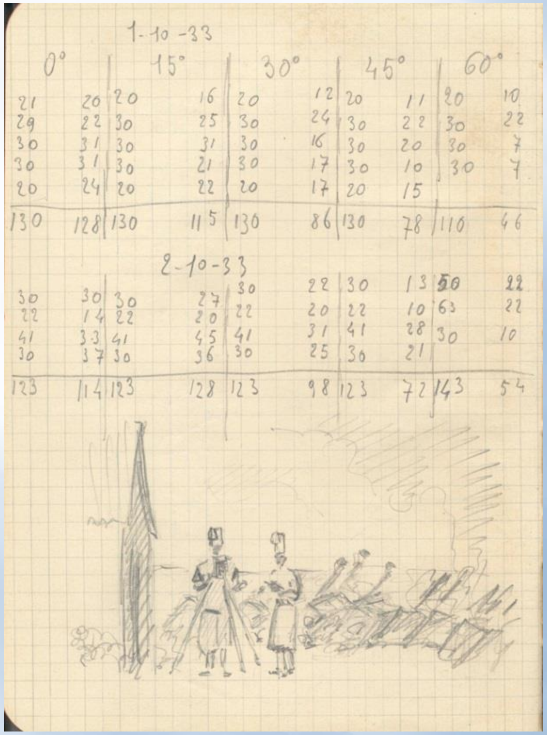
What are they?



1930s Compton leads a worldwide survey of geographic variations, comprehensively confirming the latitude effect

→ cosmic rays are charged particles

What are they?

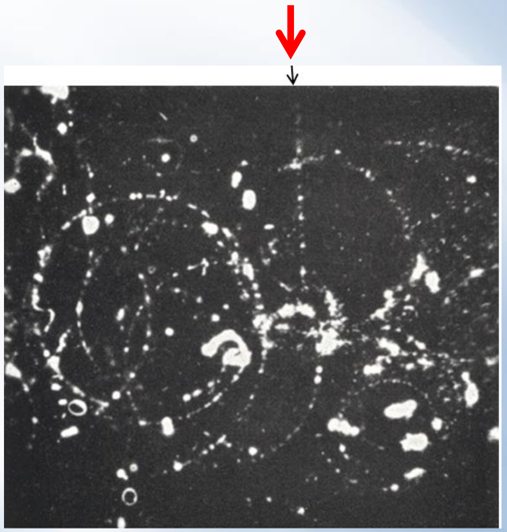


~1930 Rossi predicts asymmetry related to charge of cosmic rays: east-west effect, greatest near geo-magnetic equator

1933 Rossi confirms the effect in Eritrea, as do measurements by Johnson and by Alvarez and Compton in Mexico

→ cosmic rays are positive particles

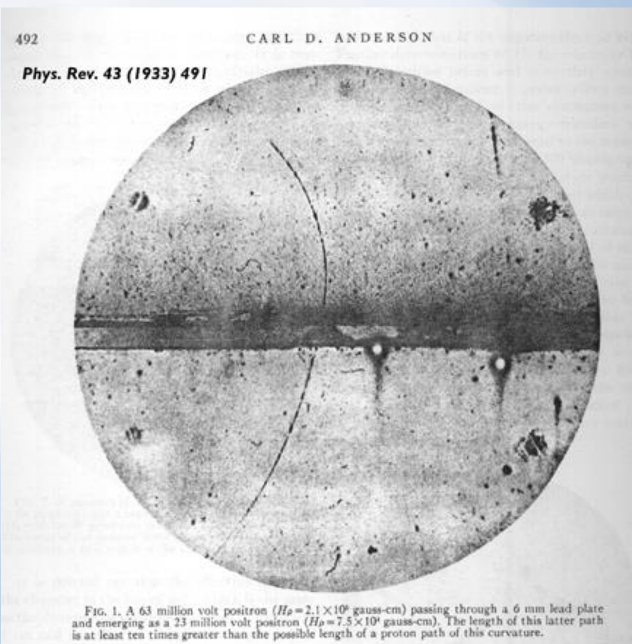
What are they?



1927 Dmitry Skobeltzyn places a cloud chamber in a strong magnetic field (1.5 kG) and observes some tracks that are almost straight, implying energetic particles – probably cosmic rays

1930 Robert Millikan suggests to Carl Anderson that he should study the energy of cosmic-ray particles in a cloud chamber

What are they?



1932 Anderson finds evidence in cosmic rays for positively charged lightly-ionizing particles – ‘positive electrons’ – marking the discovery of the ‘anti-electron’ or positron

1932 James Chadwick discovers the neutron

Interlude

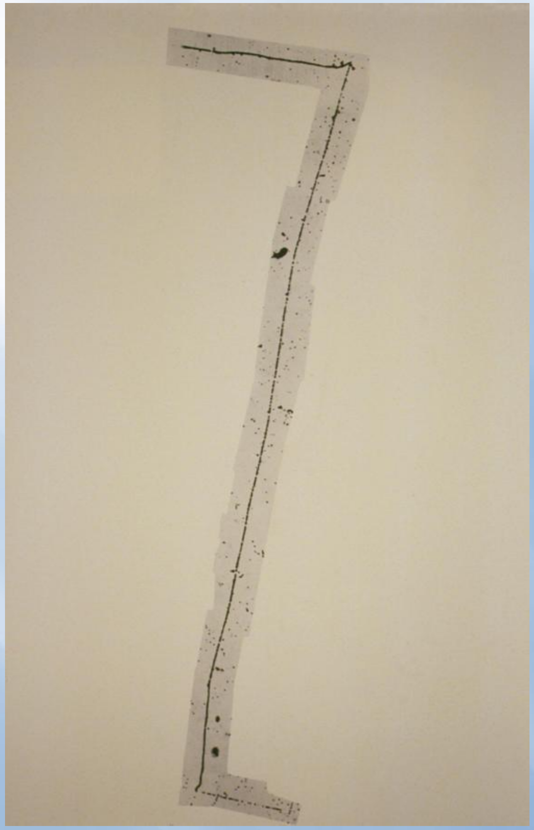
1934 Following Enrico Fermi's incorporation of the neutrino in his theory of β decay

proton	electron
neutron	*neutrino*
antiproton	positron
antineutron	*antineutrino*

1934 Pavel Cherenkov working under Sergei Vavilov discovers a new phenomenon: 'Cherenkov' radiation

What are they?

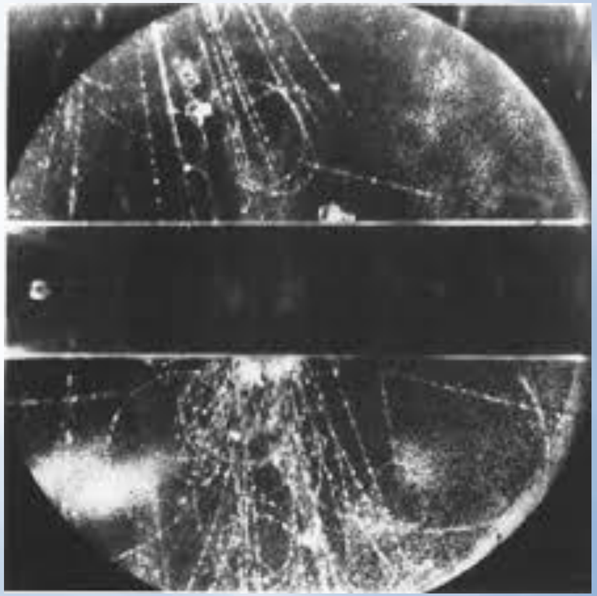
1937 Anderson and Seth Neddermeyer discover a particle of mass between the proton and electron: the mesotron



1947 Cecil Powell and colleagues using nuclear emulsions at the Pic du Midi discover a different, more strongly interacting particle of similar mass, and the decay chain

$$\pi \rightarrow \mu \rightarrow e$$

What are they?



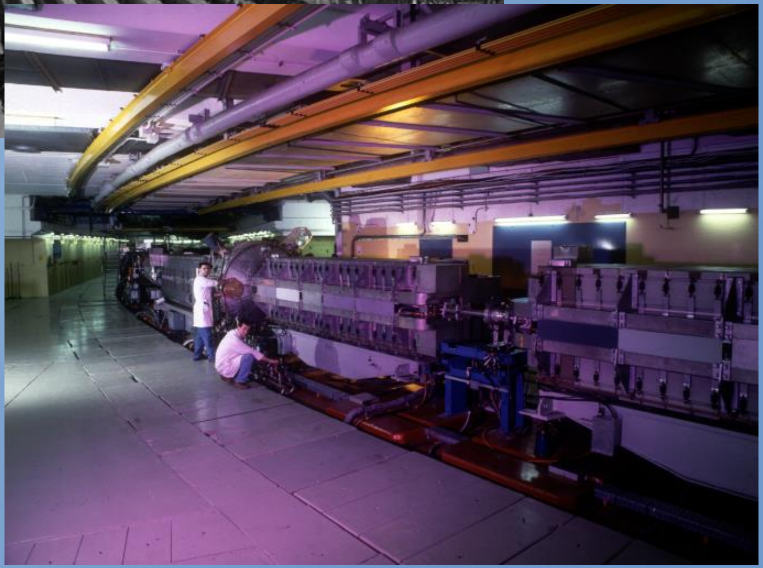
1937 George Rochester and Clifford Butler discover ‘V’ particles with about half the proton mass

1951 Butler and colleagues discover a neutral ‘V’ slightly heavier than the proton

1950s These are recognised as new, ‘strange’, particles: K and Λ

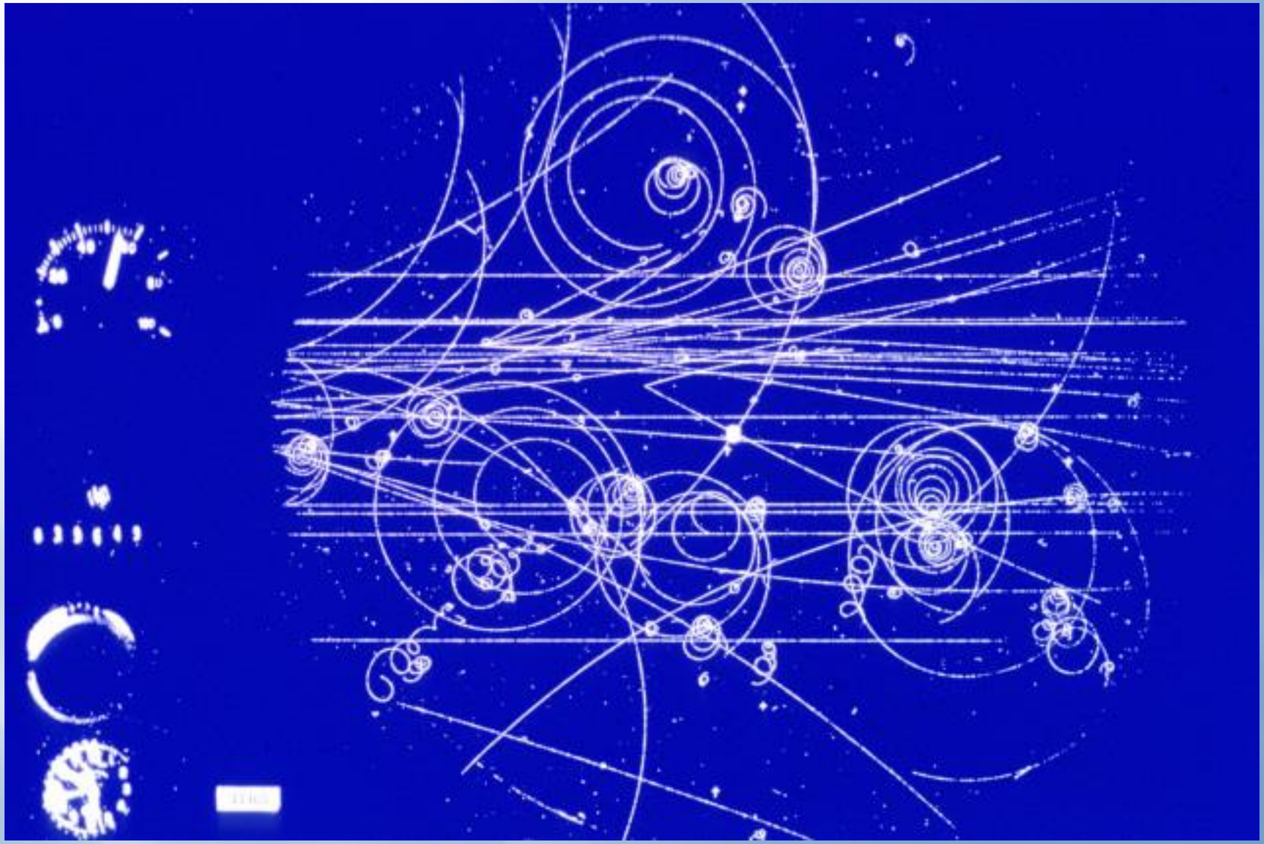
Interlude

1950-60s Particle accelerators begin to provide 'man-made' cosmic rays, revealing many more short-lived particles



1954 CERN is founded

Interlude



1960 The decay of a Λ particle in CERN's 32 cm liquid hydrogen bubble chamber

Interlude

1955 Owen Chamberlain and colleagues discover the antiproton

1956 Fred Reines and Clyde Cowan detect neutrinos for the first time, emitted from a nuclear reactor

1962 Leon Lederman, Melvin Schwartz and Jack Steinberger discover there are two neutrinos – one associated with the electron, the other with the muon

1964 Murray Gell-Mann and George Zweig propose particle substructure: quarks

Interlude

1964 The particles of matter

up quark	electron
down quark	neutrino
strange quark	muon
	muon-neutrino

… and their antiparticles

Neutrino astronomy

1960 Moisey Markov suggests using Cherenkov light in a deep lake or ocean to detect atmospheric neutrinos; Kenneth Greisen proposes using a water Cherenkov detector in a deep mine for neutrino astronomy

1961 Raymond Davis begins construction of his first solar neutrino detector

1964 Davies and John Bahcall argue the case for detecting solar neutrinos through capture on chlorine nuclei in ~ 400 000 litres of perchloroethylene

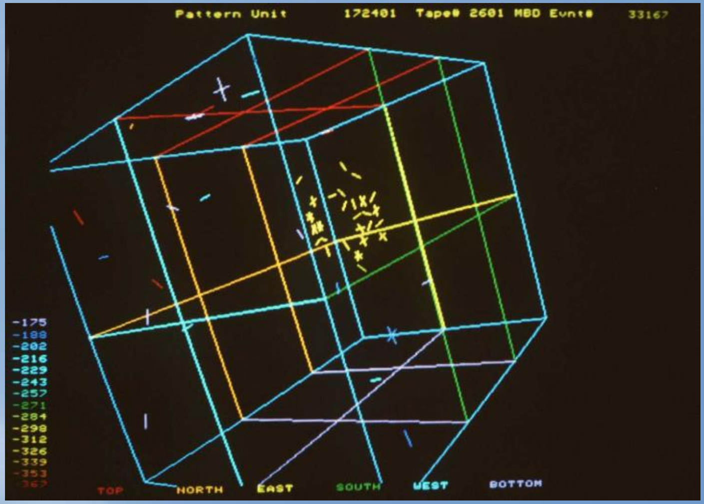
Neutrino astronomy

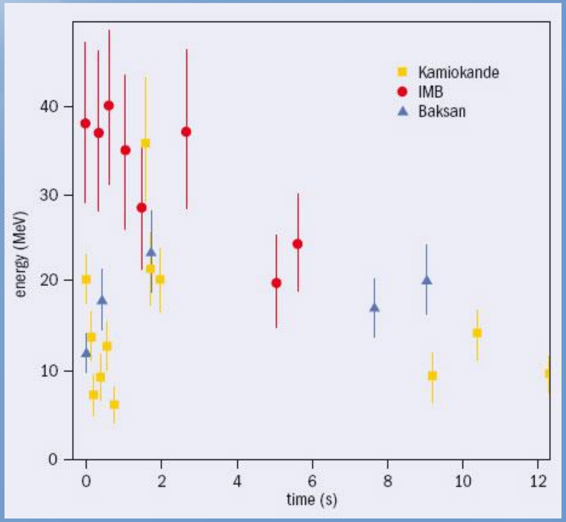
1965 Two groups detect cosmic-ray neutrinos: Reines using liquid scintillator in the East Rand gold mine in South Africa and a Bombay-Osaka-Durham collaboration operating in the Kolar Gold Field in India with an iron calorimeter

1968 Davis publishes results showing shortfall in the detected number of solar neutrinos – less than half

Neutrino astronomy

1987 Two water-Cherenkov experiments detect neutrinos from SN1987a in the Large Magellanic Cloud: the Irvine-Michigan-Brookhaven detector in Ohio and the Kamiokande detector in Japan. The Baksan scintillator telescope also detects the supernova



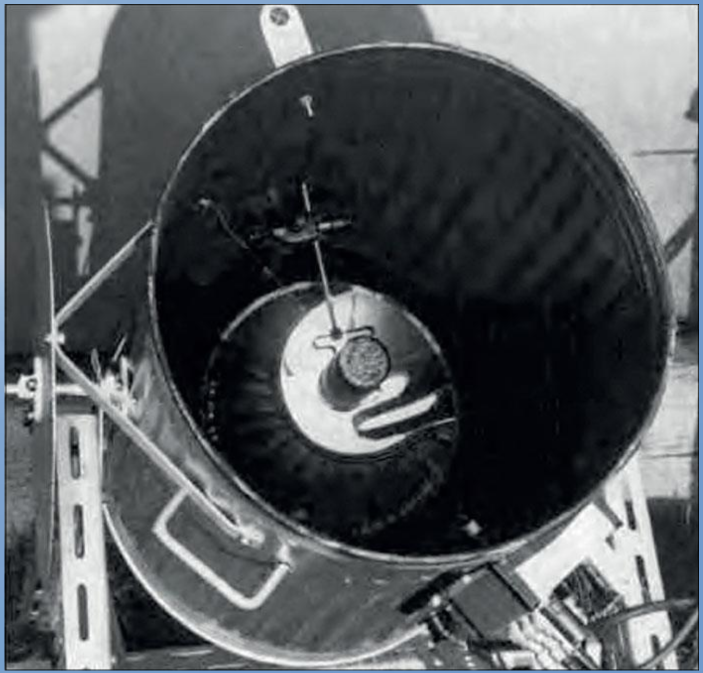


Neutrino astronomy is born

Gamma-ray astronomy

1947 Blackett estimates the contribution of cosmic-ray-induced Cherenkov light to be 0.01% of the total intensity of the night sky (general flux of cosmic rays)

1953 Bill Galbraith and John Jelley detect Cherenkov radiation from extended air showers with a dustbin, a 60 cm diameter mirror and a PMT at its focus in coincidence with a nearby Geiger-Müller array. They later confirm it is Cherenkov light in measurements at the Pic du Midi.



Gamma-ray astronomy

1959 Giuseppe Cocconi suggests the potential for observing cosmic γ-ray sources through the detection of air showers; he proposes that the Crab nebula should be a strong source of high-energy γ rays.

1960s Aleksandr Chudakov builds first air-Cherenkov telescope, with 12 searchlight mirrors, 1.5 m diameter, mounted on railway cars in the Crimea

Gamma-ray astronomy

1989 Trevor Weekes and colleagues observe TeV γ rays from the Crab with the Whipple Observatory imaging air Cherenkov telescope with a 10 m segmented mirror in data collected 12/1986 – 2/1988

OBSERVATION OF TeV GAMMA RAYS FROM THE CRAB NEBULA USING THE ATMOSPHERIC CERENKOV IMAGING TECHNIQUE

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ABSTRACT

The Whipple Observatory 10 m reflector, operating as a 37 pixel camera, has been used to observe the Crab Nebula in TeV gamma rays. By selecting gamma-ray images based on their predicted properties, more than 98% of the background is rejected; a detection is reported at the 9.0 σ level, corresponding to a flux of 1.8×10^{-11} photons cm^2 s^{-1} above 0.7 TeV (with a factor of 1.5 uncertainty in both flux and energy). Less than 25% of the observed flux is pulsed at the period of PSR 0531. There is no evidence for variability on time scales from months to years. Although continuum emission from the pulsar cannot be ruled out, it seems more likely that the observed flux comes from the hard Compton synchrotron spectrum of the nebula.

Gamma-ray astronomy

The observed flux [1.8 x 10^{-11} photons cm^{-2} s^{-1} above 0.7 TeV] is only 0.2% of the cosmic-ray background … The detection of such a weak flux from a steady source with a significance of 9 σ is a milestone in the development of ground-based γ-ray astronomy

Weekes et al. Astrophysical Journal **342** 379

γ-ray astronomy with imaging air Cherenkov telescopes is born

1989 Experiments at CERN's Large Electron-Positron collider show there are only 3 types of neutrino and hence only 3 generations of particles

Finale

- 1989 The particles of matter – almost complete

up	electron
down	electron-neutrino
charm	muon
strange	muon-neutrino
top	tau
bottom	*tau-neutrino*

And the era of astronomy with neutrinos and γ radiation in cosmic rays has begun, holding the promise of answering the question:

Where DO cosmic rays come from?

Acknowledgements

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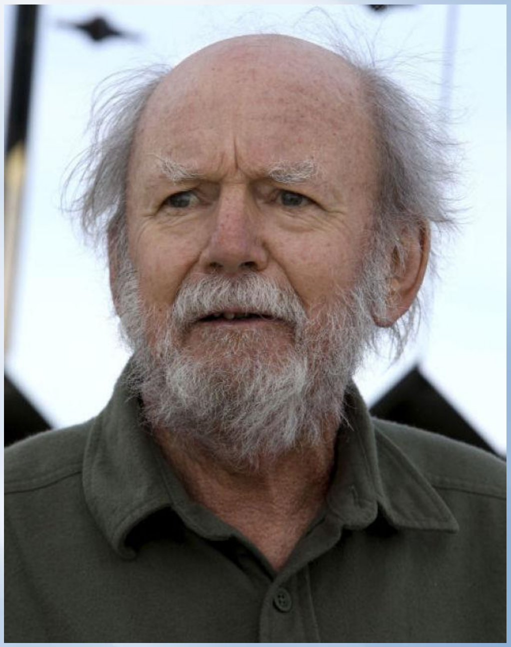
For the early studies of cosmic rays, I have been helped by Alessandro De Angelis and his papers: 2010 *Riv. Nuovo Cim.* 33 713; P Carlson and A De Angelis 2011 *Eur. Phys. J. H* 309
and
Cosmic Rays by A M Hillas, in the series "Selected readings in physics", Pergamon Press 1972

Thank you



Trevor Weekes
1940-2014

Ekart Lorenz
1938-2014