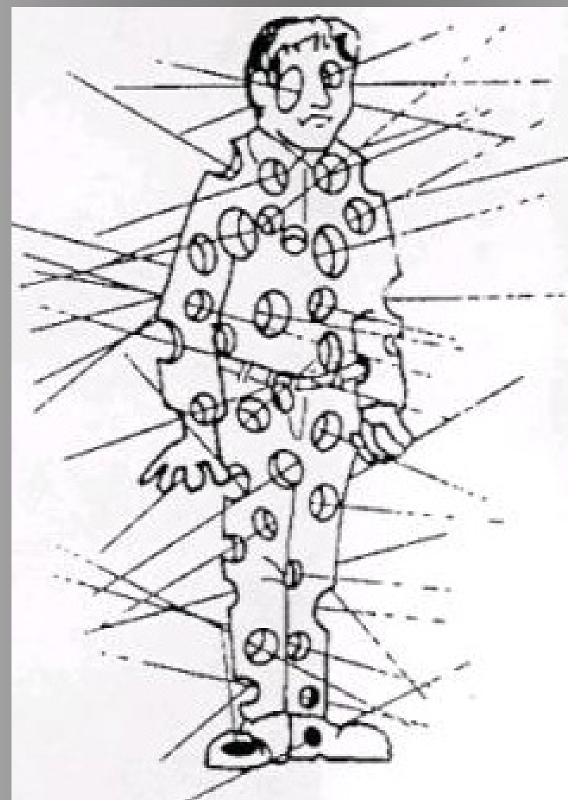
Introduction to COSMIC RAYS

Sesto Fiorentino, Spring-2005

WARNING



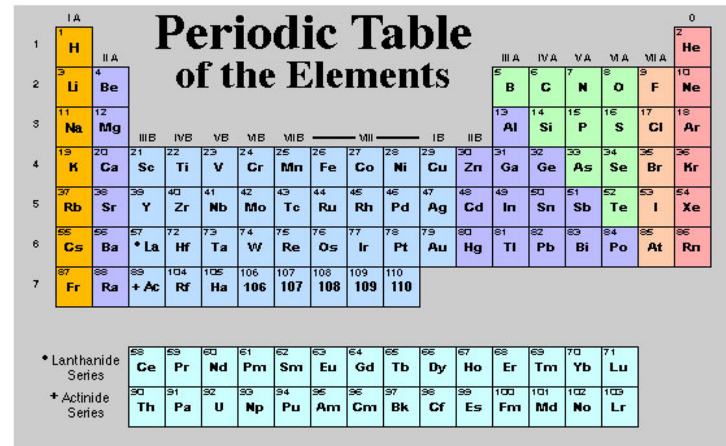
More than 100,000 cosmic rays will hit each of you during this lecture

What are Cosmic Rays?

Cosmic Rays (CR) are high-energy particles of extraterrestrial origin

The astrophysical field of activity for particle and nuclear physics

"Classical" **CR** are nuclei or ionized atoms ranging from a single proton up to an iron nucleus and beyond, but being mostly **protons** (~90%) and α **particles** (~9%).



However the above definition is much wider and includes in fact all stable and quasistable particles:

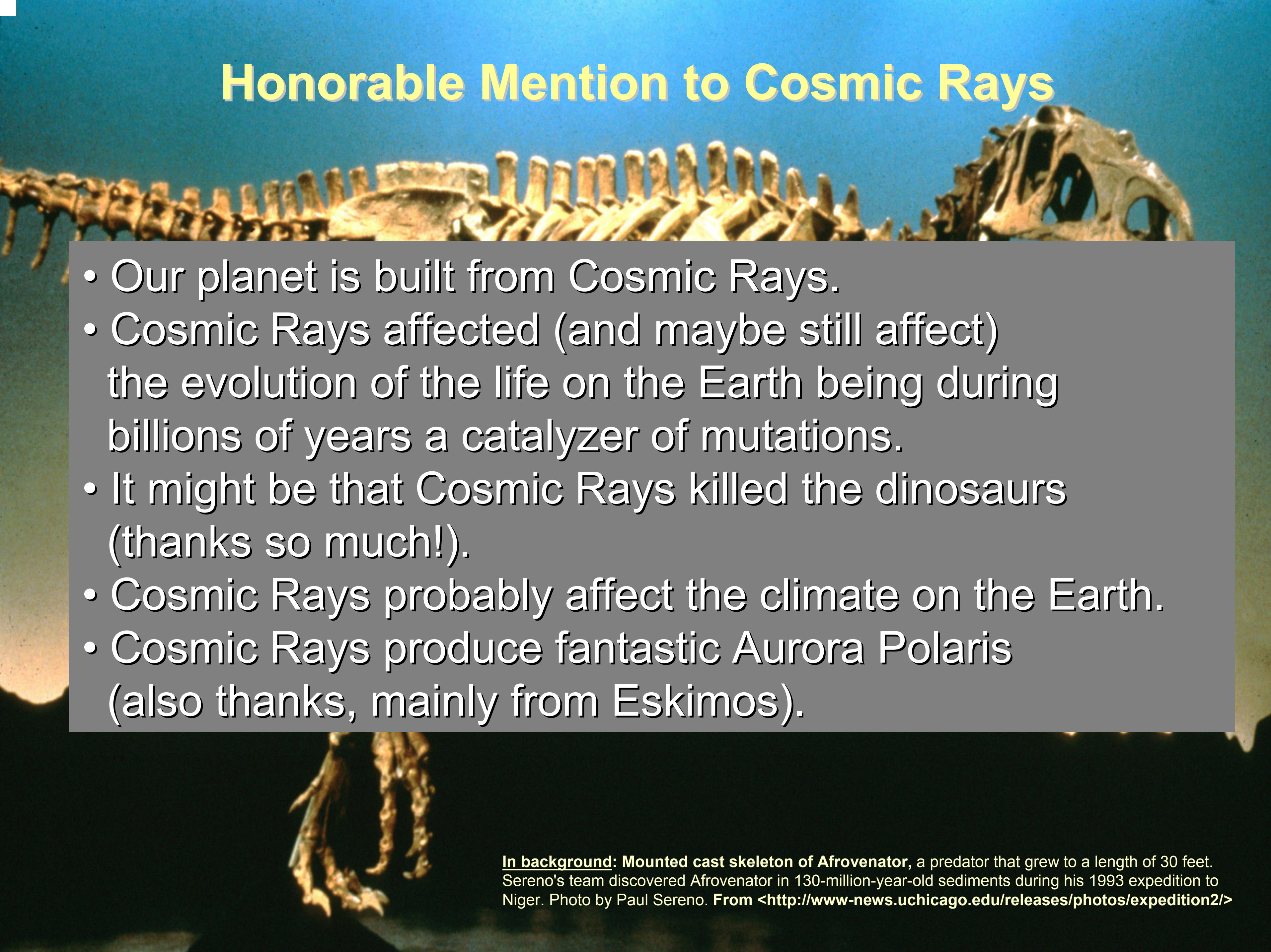
- neutrons,
- antiprotons & (maybe) antinuclei,
- hard gamma rays ($\lambda < 10^{-12}$ cm),
- electrons & positrons,
- neutrinos & antineutrinos,
- esoteric particles (WIMPs, magnetic monopoles, mini black holes,...).

Secondary CR (produced by the primaries in the Earth's atmosphere) consist of essentially all elementary particles and nuclei (both stable and unstable). The most important are

- nucleons, nuclei & nucleides,
- (hard) gammas,
- mesons ($\pi^{\pm}, \pi^{0}, K^{\pm}, \ldots, D^{\pm}, \ldots$),
- charged leptons ($e^{\pm}$, $\mu^{\pm}$, $\tau^{\pm}$),
- neutrinos & antineutrinos (ν_e, ν_μ, ν_τ).

Honorable Mention to Cosmic Rays

- Our planet is built from Cosmic Rays.
- Cosmic Rays affected (and maybe still affect) the evolution of the life on the Earth being during billions of years a catalyzer of mutations.
- It might be that Cosmic Rays killed the dinosaurs (thanks so much!).
- Cosmic Rays probably affect the climate on the Earth.
- Cosmic Rays produce fantastic Aurora Polaris (also thanks, mainly from Eskimos).



__In background__**: Mounted cast skeleton of Afrovenator,** a predator that grew to a length of 30 feet. Sereno's team discovered Afrovenator in 130-million-year-old sediments during his 1993 expedition to Niger. Photo by Paul Sereno. **From <http://www-news.uchicago.edu/releases/photos/expedition2/>**

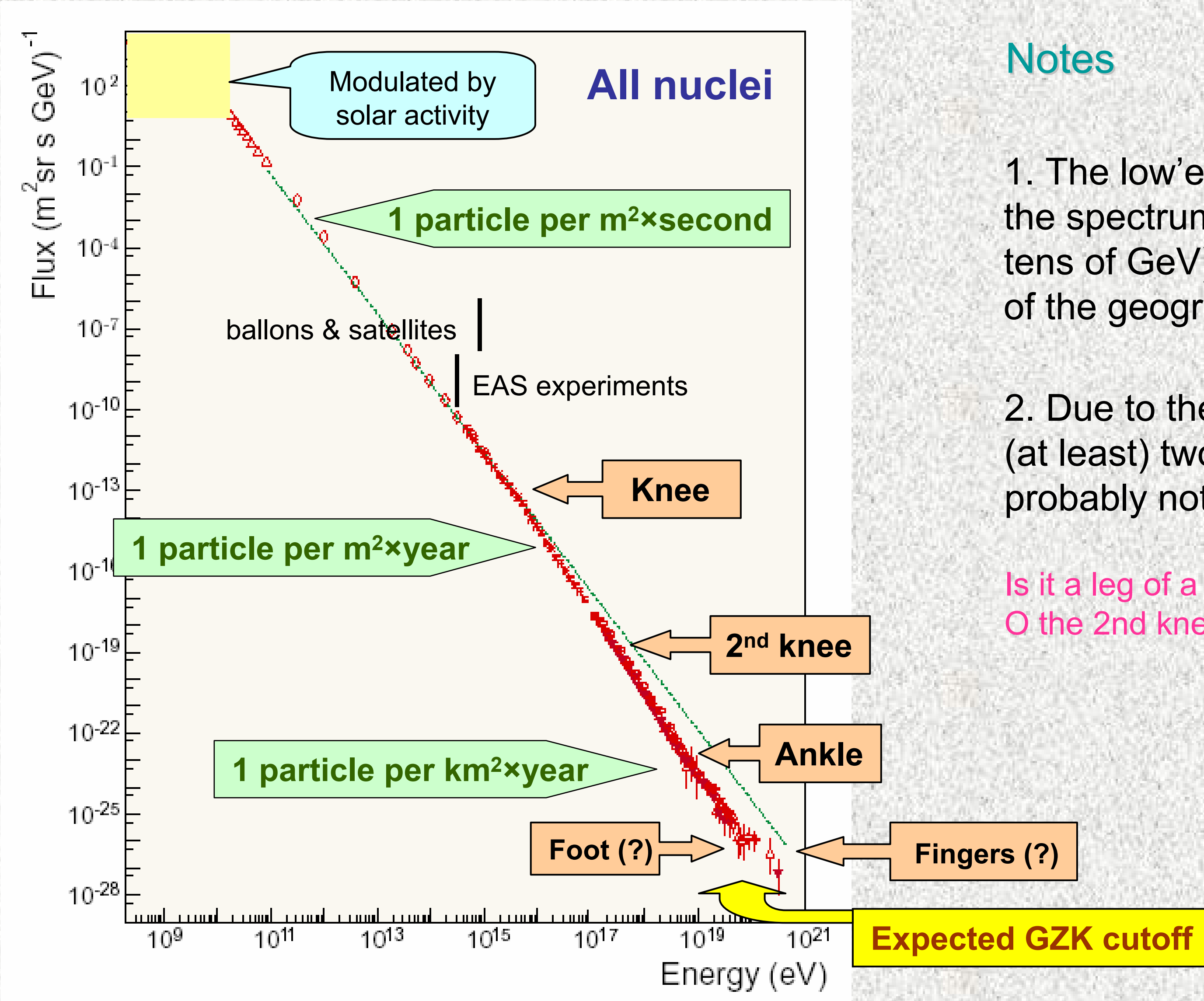
The energy range of our interest is ~100 MeV to (at least) 1 ZeV

International System of Units (SI)

value	SI prefix	symbol
10	deca	da
10^{2}	hecto	h
10^{3}	kilo	k
10^{6}	mega	M
10^{9}	giga	G
10^{12}	tera	T
10^{15}	peta	P
10^{18}	exa	E
10^{21}	zetta	Z
10^{24}	yotta	Y

~13 orders!

A BIRD'S EYE VIEW OF THE ALL-PARTICLE CR SPECTRUM

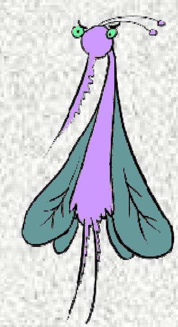


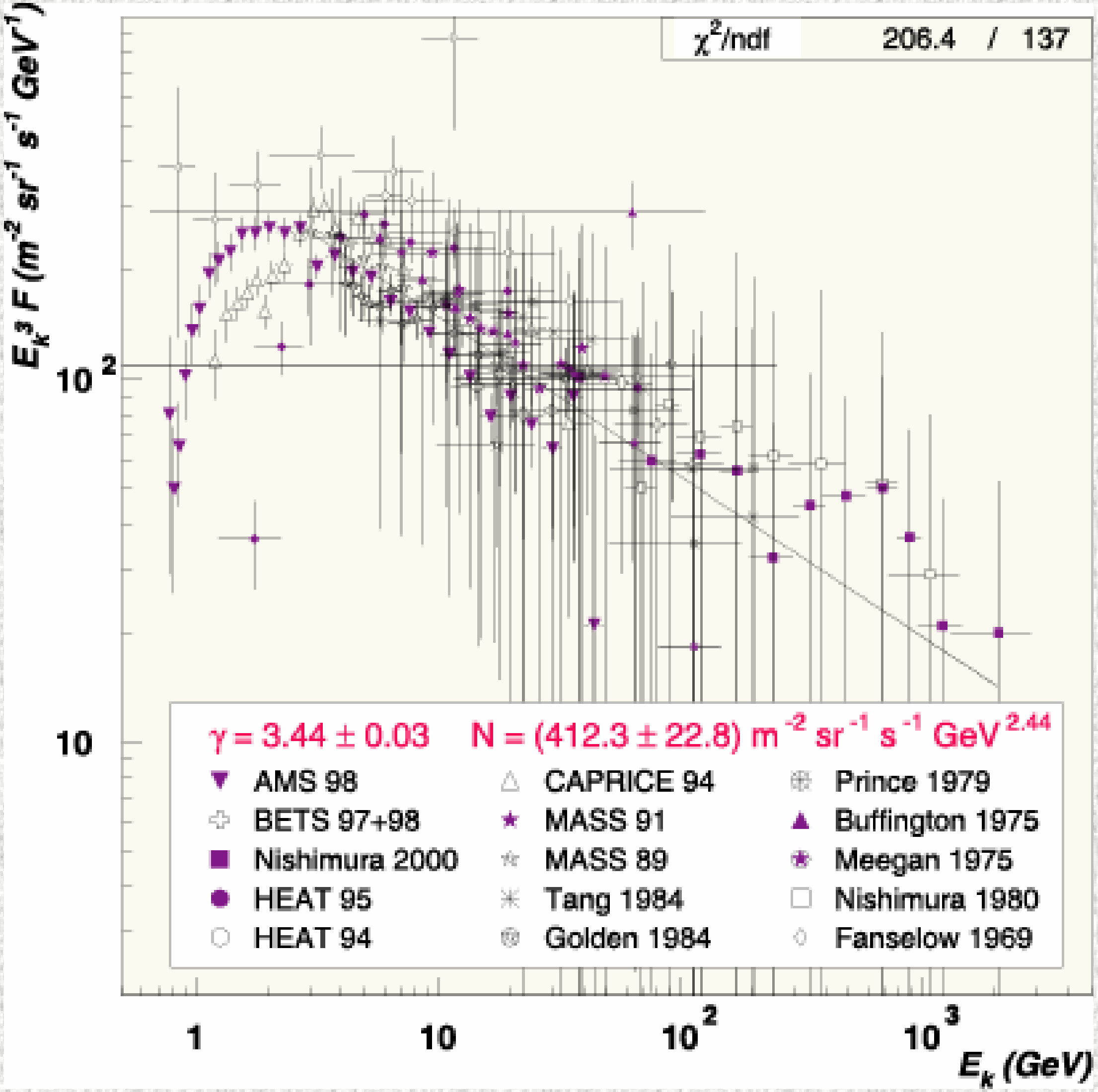
Notes

1. The low'energy part of the spectrum (below some tens of GeV) is dependent of the geographycal position.

2. Due to the presence of (at least) two knees this is probably not a human leg.

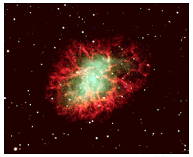
Is it a leg of a bug?
O the 2nd knee is a bug?

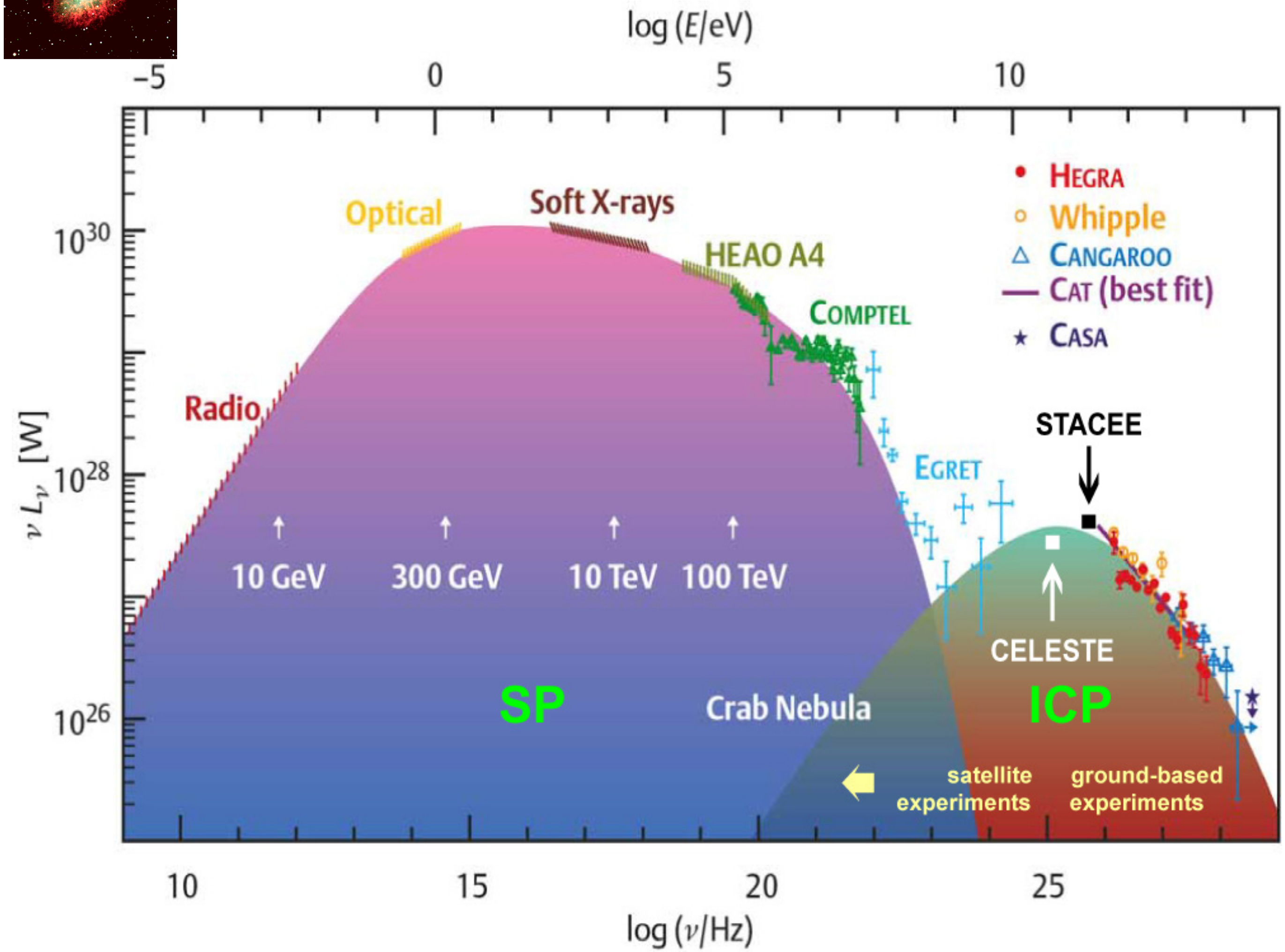




Single power law fit of the electron Local Interstellar Spectrum (multiplied by E_k^3), after a rescaling. The obtained spectral index is 3.44 +/- 0.03 between ~3 GeV and ~2 TeV.

From D. Casadei & V. Bindi, "The origin of cosmic ray electrons and positrons," ApJ **612** (2004) 262-267.





Spectral energy distribution of the unpulsed electromagnetic emission from the Crab Nebula.
(Two recent data points from CELESTE and STACEE measurements are added to the original figure.)

[From von H. Völk, "Gamma-Astronomie mit abbildenden Cherenkov-Teleskopen," Sterne und Weltraum **38** (1999) 1064-1070; see also F.A. Aharonian and A.M. Atoyan, "Nonthermal Radiation of the Crab Nebula," astro-ph/9803091.]

Wide-range spectrum from the Crab nebula shows two peaks, **SP** and **ICP**, which are interpreted as **synchrotron emission** from high energy electrons and **inverse Compton scattering** of synchrotron photon by the same electrons.

The electron energies producing the dominant SP at lower energies are indicated by the arrows. The Compton Gamma Ray Observatory (CGRO) telescopes COMPTEL and EGRET determine the synchrotron fall-off and the transition to the ICP expected at some tens of GeV and indicated by the Cherenkov telescope measurements.

The gap between the satellite and ground-based experiments are now being filled by Cherenkov telescopes using large-area solar power collectors.

One surprise from ultra-high energy

All particles, including meson and baryon resonances, become (quasi)stable. Does our extrapolation of known physics of particle interactions remain correct in the UHE region?

Particle	Mass, m (MeV/c^2)	Mean life, τ (s)	$c\tau$ (cm)	Decay length at E = 100 EeV
n (neutron)	939.6	8.857×10^{2}	2.655×10^{13} (1.775 au)	2.826×10^{24} cm (0.916 Mpc)
μ (muon)	105.7	2.197×10^{-6}	6.586×10^{4}	6.234×10^{16} cm (4167 au)
τ (tauon)	1777	2.906×10^{-13}	8.711×10^{-3}	4.902×10^{8} cm (4902 km)
D^+	1869	1.051×10^{-12}	3.150×10^{-2}	1.685×10^{9} cm (16,851 km)
$\rho(770)$	771	9.82×10^{-20} (Γ = 149.2 MeV)	2.944×10^{-9}	382 cm
$\Delta(1232)$	1232	7.9×10^{-20} (Γ = 120 MeV)	2.368×10^{-9}	192 cm

1 au = 149 597 870 660 m, 1 pc = 1 au/(1 arc sec) = 3.085 677 580 7 × 10 16 m = 3.262 ly

Plan of the Course

«Я планов наших люблю громадье…»

В. Маяковский

''I like the whacker of our plans…''

V. Mayakovsky

INTRODUCTION TO COSMIC RAYS
(preliminary plan of lectures)

V. A. Naumov

May 10, 2004

Preliminaries

1. Foreword (what are Cosmic Rays?)
2. Historical Background (from Victor Hess to AMS)
3. Overview of the primary spectrum and composition
   - Some definitions
   - CR composition at low energies
   - A bird's eye view of the all-particle CR spectrum
   - The Sun in short (photospheric features, sunspot cycle, etc.)
   - CR neutron monitoring (in short)
   - Low- and intermediate energy part of the spectrum for the main nuclear groups
   - Around the knee (poly-gonato model)
   - Local intersellar spectar of electrons and positrons
   - Antiprotons and antinuclei in CR
   - Gammas and neutrinos (in short)

Part I: interactions of Particle with matter

1. Propagation of high-energy particles through matter (an insight into the classical transport theory)
   - Transport equation for nucleons and nuclei
   - Light meson production
   - Charm hadroproduction
   - Muon and τ lepton production
   - Neutrino production
   - Muon propagation through dense media
     - *Muon-matter interactions (ionization and δ electron production, multiply Coulomb scattering, direct l^+l^- and $\bar{q}q$ pair production, bremsstrahlung, photonuclear interaction)*
     - *LPM effect and longitudinal density effect (dielectric suppression)*
     - *Some methods for solving the transport equation*
     - *Deep underground and underwater data*
   - Neutrino propagation through dense media
     - *CC and NC neutrino interactions with electrons*
     - *CC and NC neutrino interactions with nucleons*
     - *Z factor method for solving the transport equations*
   - Neutrino-induced electrons, muons and τ leptons
2. High-energy neutrino oscillations in vacuum and matter (an insight into the quantum transport approach)

Part II: Acceleration and propagation in cosmos

1. Some mechanisms for acceleration of charged particles in cosmos
    - Fermi acceleration
        - Kinematics
        - Regular acceleration
        - Stochastic acceleration
    - Alfv́en acceleration (magnetic pumping)
2. Possible sources of cosmic rays

Part III: Ultra-high energy cosmic rays

1. Astrophysical Background
    - Acceleration
    - Energy loss for protons and nuclei
        - Adiabatic fractional energy loss due to the expansion of universe
        - $e^{+}e^{-}$ pair production
        - Photopion production and photodesintegration
    - Propagation in the Galaxy
    - Propagation in intergalactic space
        - Greisen-Zatsepin-Kuzmin cutoff
        - Arrival directions and distances

2. Design of Extensive Air-Shower (EAS) detectors and data analysis principles

   - Detection and analysis methods
     - Detection and analysis with ground arrays
     - Detection and reconstruction with fluorescence detectors
     - Other proposals (satellite-borne and balloon-borne detection of UHECR by the radio method)
   - Past and present experiments
     - Volcano Ranch array
     - Haverah Park array
     - Sydney University array (SUGAR)
     - Yakutsk array
     - Fly's Eye detector
     - HiRes Fly's Eye detector
     - Akeno Giant Air-Shower Array (AGASA)
   - Starting and (far)future experiments
     - Pierre Auger observatory
     - Telescope Array project
     - Space program KOSMOTEPETL (TUS, KLYPVE)
     - "Airwatch from Space" (EUSO, OWL, ...)

3. Summary of experimental results

   - Energy spectrum
   - Arrival direction distributions and clustering
   - Mass composition
     - *X_{max} vs energy from fluorescence and Cherenkov data*
     - *X_{max} estimates from water Cherenkov data*
     - *Mass composition from muon data*

- Neutron primaries
- Gamma primaries
- Neutrino primaries
- Unusual deeply penetrating particles (WIMPs, metastable quark matter, etc.)

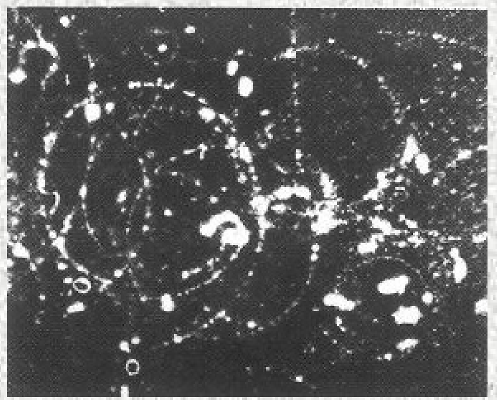
4. Models of origin of UHECR: Conventional acceleration ("bottom-up" scenarios) vs exotic sources ("top-down" scenarios)

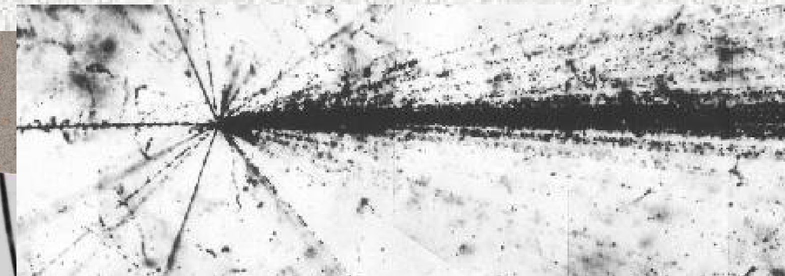
    - The Hillas diagram
    - Galactic origin of heavy primaries
    - Pulsars
    - Origin in nearby galaxies
    - Origin in distant radio galaxy jets and hot spots
    - Origin in colliding galaxy systems
    - Origin in large-scale structures (pancakes, filaments, flow shocks to clusters of galaxies)
    - Possible links with (cosmological) gamma-ray bursts
    - Microquasars
    - Photons, electrons and protons initiated by ultra-high energy cosmic neutrinos on relic neutrino background
    - Decay of metastable superheavy relic particles trapped in the Galactic halo
    - Evaporation of black holes
    - Topological defects created in the early universe (monopoles, vortons, cosmic strings, necklases, etc.)
    - Topological defects themselves as UHECR particles

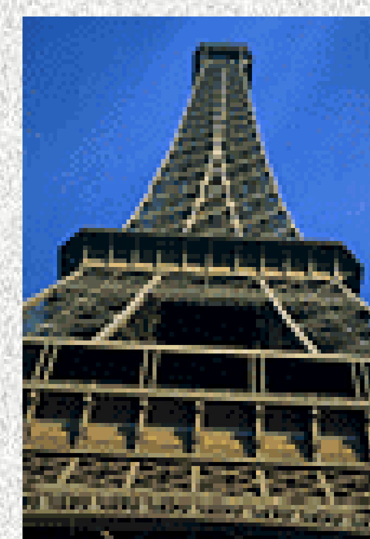
- Other exotics
  - *SUSY candidates (gluinos, neutralinos, etc.)*
  - *New hadrons (S^0, uchecron, glubolino, ...)*
  - *Stranglets*
  - *WIMPZILLAs*
- Lorentz symmetry violations with anomalous kinematics
- Modified dispersion relation from q-deformed noncommutative theory
- Space-time's unseen dimensiones, KK-modes, branes and all that
  - *Introduction to extra dimensions*
  - *Black hole and brane production in particle collisions*
  - *Probes of TeV scale gravity in cosmic-ray experiments*
  - *Distinguishing the black hole (0-brane) and p-brane production in neutrino-induced showers*
  - *Gravi-bursts: UHECR from localized gravity*

5. Concluding remarks

Historical Background



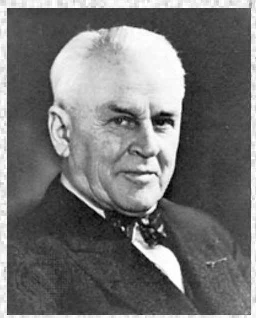




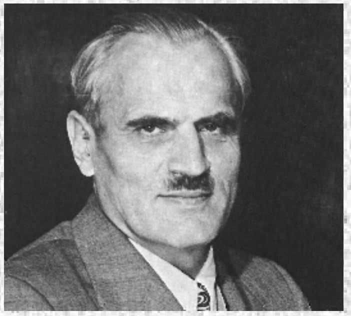
Charles Thomson Rees Wilson
(1869-1959)

Victor Franz Hess
(1883-1964)

Walther Bothe
(1891-1957)



Robert Andrews Millikan
(1868-1953)

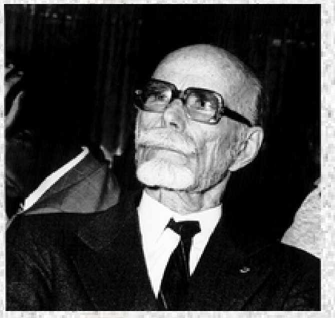


Arthur Holly Compton
(1892-1962)

Dmitry Vladimirovich
Skobeltzyn (1892-1982)

Hannes Olof Gösta Alfvén
(1908-1995)

Carl David Anderson
(1905-1991)



Pierre Victor Auger
(1899-1993)

Bruno Benedetto Rossi
(1905-1993)

Enrico Fermi
(1901-1954)

Georgy Timofeevich
Zatsepin (1917)

Before 1900 ("Prehistory")

At the close of the XIX century, scientists using gold-leaf electroscopes to study the conductivity of gases discovered that no matter how carefully they Isolated the instruments from possible sources of radiation they still discharged at a slow rate.

A gold-leaf Bennet-type electroscope (ca. 1880s) manufactured by Ducretet.

1900-1901 ("Birthday")

Two groups investigated this phenomenon, Julius Elster and Hans Friedrich Geitel in Germany, and Charles Thomson Rees Wilson in GB. Both groups concluded that some unknown source of continuous ionizing radiation existed. It was believed to be due to the natural radioactivity of the Earth. However Wilson surmised that the ionization might be

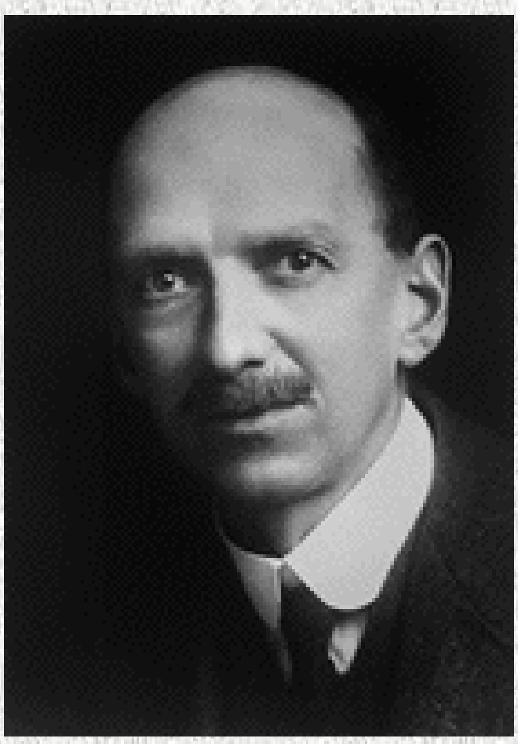
> ***"…due to radiation from sources outside our atmosphere, possibly radiation like Röntgen rays or like cathode rays, but of enormously greater penetrating power."***

Probably this hardy (but not mere) assertion by Wilson may be considered as the discovery of cosmic rays.*)

*) The grounds are essentially the same as for the atomic theory, created by Leucippus and Democritus…

Bearing in mind that just in **1900** Max Planck announced his revolutionary formula, one can conclude that

Cosmic Ray Physics was born (or at least conceived) at one time with Quantum Physics.

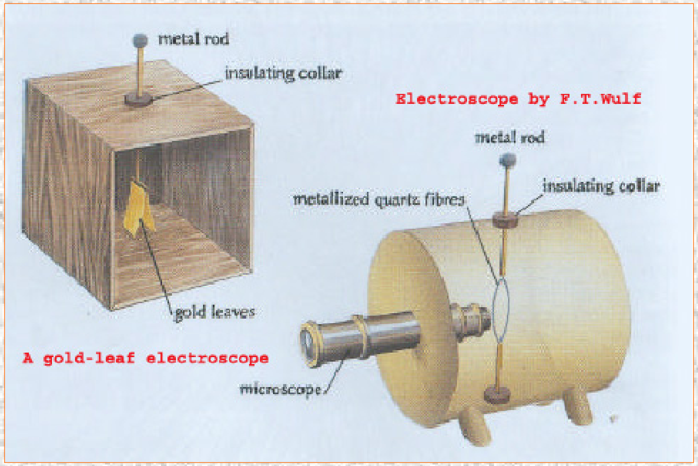


C.T.R. Wilson, alleged further of Cosmic Ray Physics.

Soon after, two Canadian groups, J. C. McLennan and E. F. Burton (**1902**) at the University of Toronto and Ernst Rutherford and H. Lester Cooke (**1903**) at McGill University, showed that **5 cm** of lead reduced this mysterious radiation by **30%**. An additional **5 t** of pig lead failed to reduce the radiation further.

1907-1910

Nothing significant happened until **1907** when Father Theodore Wulf of the Inst. of Physics of Ignatus College in Valkenburg, Holland, invented a new highly stable electroscope and ionization chamber that he used for studying the radiation emanating from the Earth. However he doubted the reliability of the instruments since the measurements atop the Eiffel Tower (at a height of about **330** meters) shown that the ionization was much higher than he had calculated.



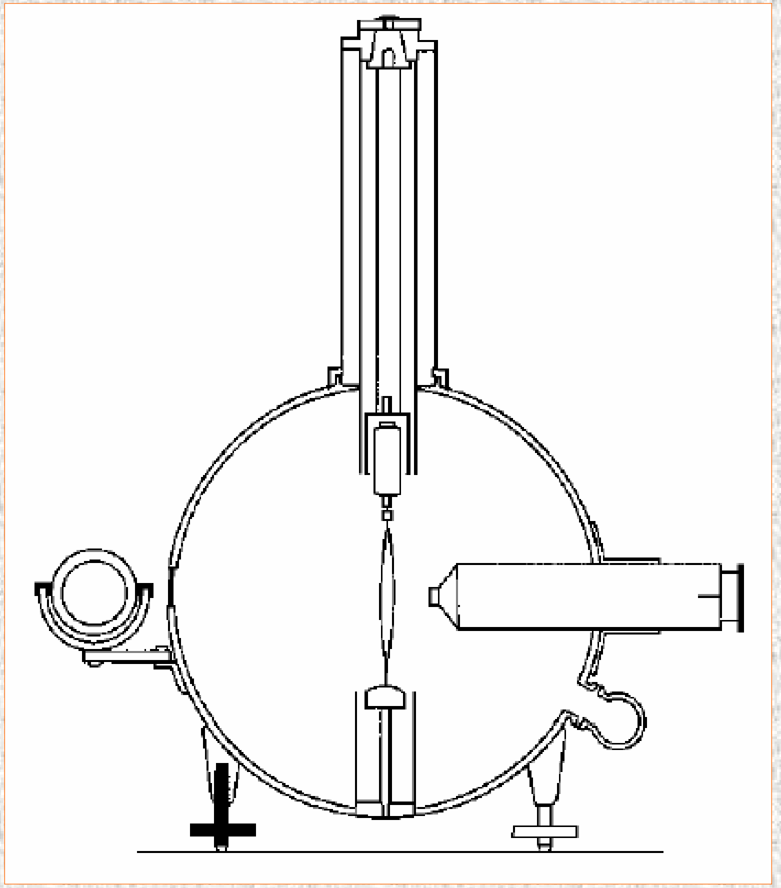
Wulf knew that radioactivity in the rocks give a natural radiation which must exponentially diminish with distance from the earth source. [At a height of **80 m** the ionization was expected to be **2** times smaller than at ground level.] But he found a radiation level of only **64%** below the value on the Earth's surface for the leakage rate. He surmised, therefore, that there was either an additional source of radiation from the upper atmosphere, or that the absorption of gamma rays in air was much smaller than had been assumed.

There is a bit different version of that story according to which Wulf speculated that the radiation might have an extraterrestrial origin and suggested doing similar measurements at higher altitudes.

1910-1911

At about the same time A. Gockel in Switzerland carried a Wulf's instrument in a balloon flight to **4.5 km**. He also questioned from his (still qualitative) measurements whether there might exist a new radiation superposed on the radiation from Earth.

"The point of real significance... is that the readings did not fall at all to zero at altitudes above 1,000 m as they were obliged to do, as shown repeatedly before 1910, if the earth were the source of the observed effects." (R. A. Millikan)



A chart of the electroscope and ionization chamber by F.Th. Wulf (1909).

1911–1913

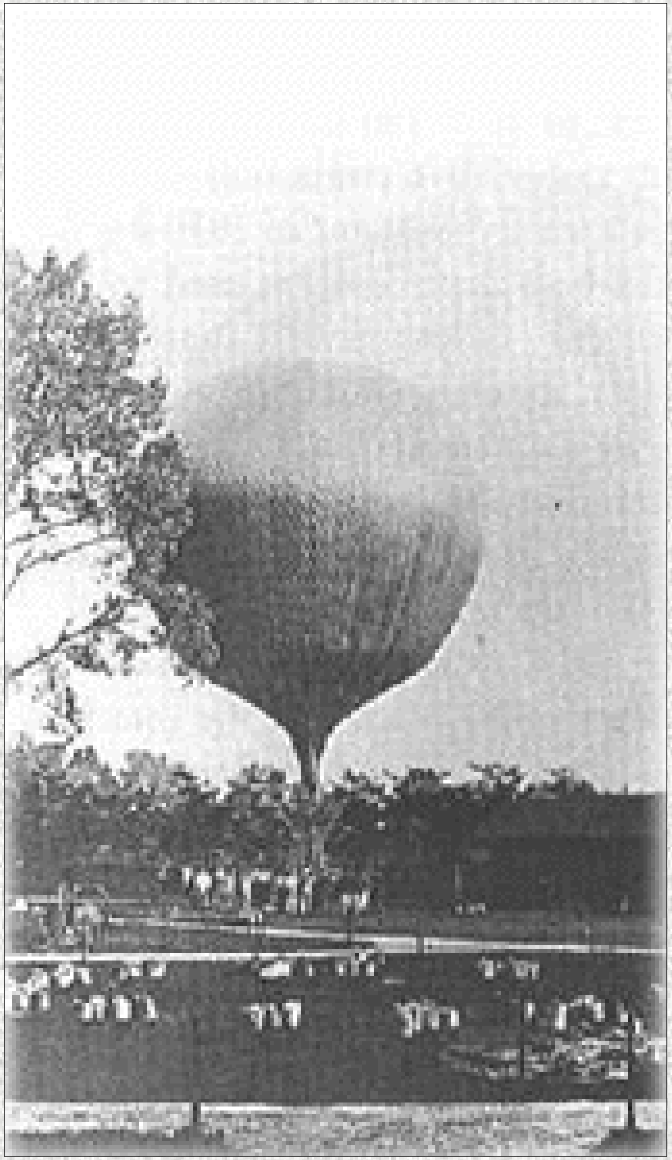
Von Victor Franz Hess, studying at the Radium Inst., Vienna, decided to take the experiment a step further and a few thousand meters higher. In 10 balloon ascents (with open gondola) reaching altitudes of **17,500 ft** (about **5.3 km**), he found that radiation slowly decreased with height (up to about **700 m**) but then at about **1.5 km** it began to rise, until at **5 km** it was over twice the surface rate. Hess concluded:

"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, and still produces in the lowest layers a part of the ionization observed in closed vessel."

Hess also cognized that the ionization was similar for day and night time and did not decrease on his flight during a solar eclipse on April 12, 1912; he concluded the sun could not be the main source of the radiation.

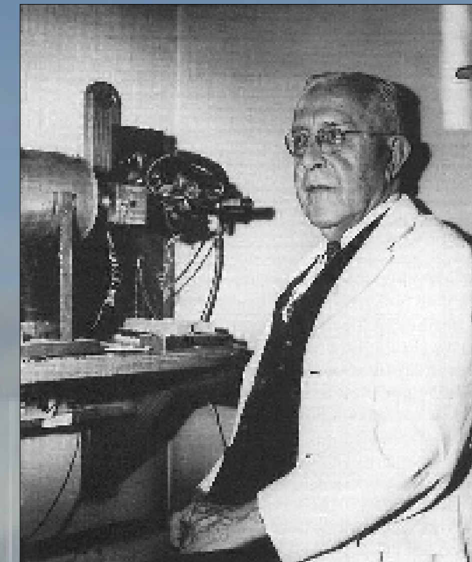
Victor Hess (*the official father of Cosmic Ray Physics*) with his crew and some gapers after the landing around Pieskow town.

The flight of Hess & crew on August 7, 1912, started in Aussig at 06:12 and reached the maximum height of 5350 m at 10:45. The landing took place near Pieskow in Brandenburg at 12:15.



Launching the hydrogen-filled Böhmen (1912).

Victor Hess won
The Nobel Prize in Physics 1936
"for his discovery of cosmic radiation" .



Background of the slide:

H.E.S.S. (**H**igh **E**nergy **S**tereoscopic **S**ystem) a next-generation system of **I**maging Atmospheric Cherenkov Telescopes for the investigation of cosmic gamma rays in the 100 GeV energy range.

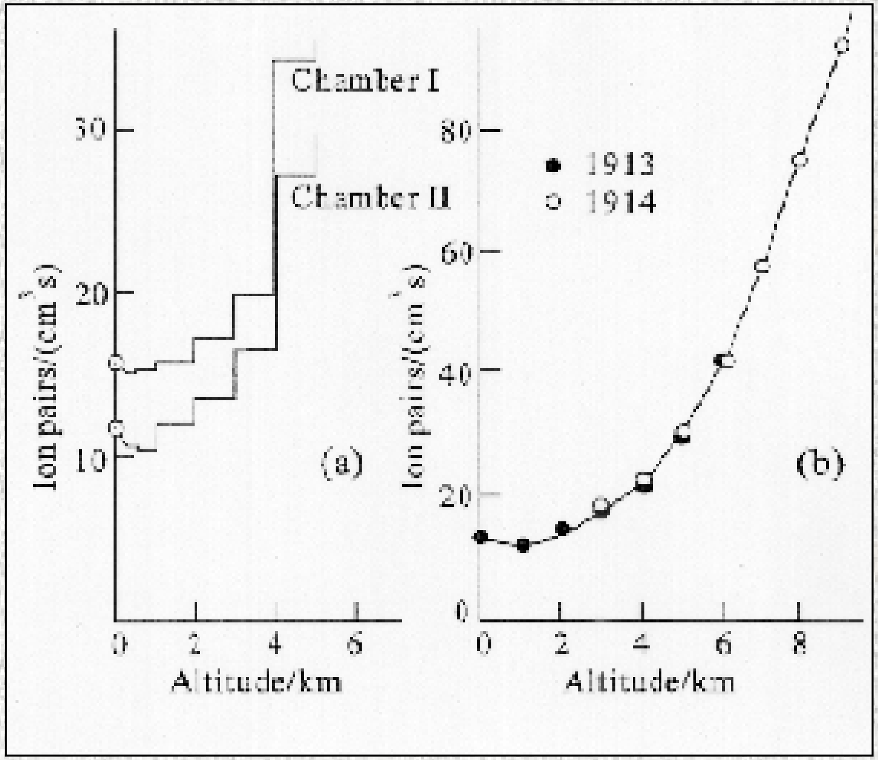
Classic references:

- V.F. Hess, Physik. Zeitschr. **12** (1911) 998.
- V.F. Hess, Physik. Zeitschr. **13** (1912) 1084.
- V.F. Hess, Physik. Zeitschr. **14** (1913) 610.

1913-1914

Werner Kolhörster confirmed that the ionization increases up to **9 km** (the increase there was a factor of about **7**) and found that the absorption coefficient for the radiation is much lower than one for gamma rays.

Hess, Kolhörster, Bothe, Regener and some other workers proceeded their studies even during the World War I.



Variation of ionization with altitude according to (**a**) Hess (1912) and (**b**) Kolhörster (1913,1914).

1923-1926

R.A. Millikan and I.S. Bowen developed (**1923**) a low mass (190 g) electrometer and ion chamber for unmanned balloon flights using radiosonar technology developed during World War I. In balloon flights to **15 km** in Texas they were surprised to find a radiation intensity not more than **one-fourth** the intensity reported by Hess and Kolhörster.

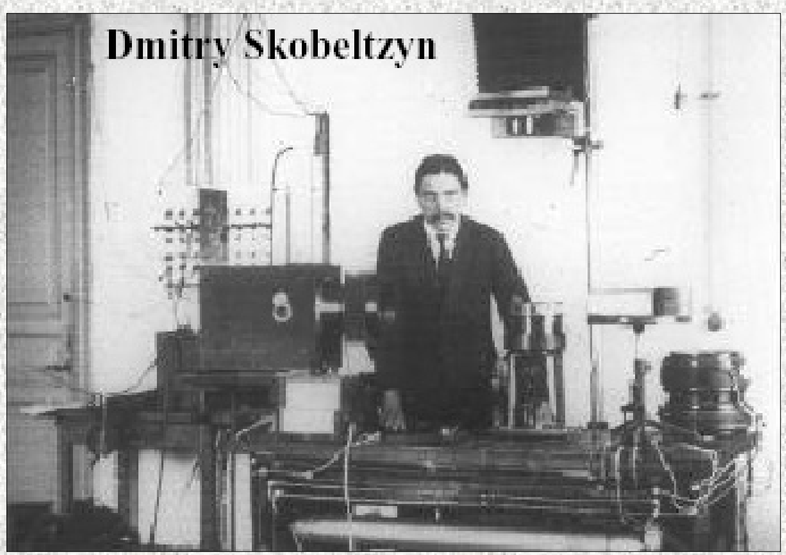
Millikan and Bowen attributed this difference to a turnover in the intensity at higher altitude, being unaware that a geomagnetic latitude cutoff existed between the measurement in Europe and Texas.

Thus, Millikan believed that there was no extraterrestrial radiation until he and Cameron (**1926**) carried out absorption measurements of the radiation at various depths in snow-fed lakes at high altitudes. Based upon the absorption coefficients and altitude dependence of the radiation, Millikan and Cameron concluded that the radiations were high energy gamma rays with enormous penetrability and that "these rays shoot through space equally in all directions". They argued that the radiations are "… generated by nuclear changes having energy values not far from [those that they recorded] in nebulous matter in space."

To describe the incoming entities Millikan and Cameron coined the term "***Cosmic Rays***". It was a bit unfortunate title because the vast majority of the incoming "radiation" turns out to be (sub)nuclear particles (including electrons and neutrinos) rather than gamma rays.

Millikan than proclaimed that this cosmic radiation was the "birth cries of atoms" in our galaxy. Now this idea also seems to be too poetic.

1927-1928



Dmitry V. Skobeltzyn, a young researcher from Leningrad Physicotechnical Institute used a newly invented cloud chamber in combination with magnetic field (H=1500 to 2000 Gauss). He observed the tracks with no deflection left by highly relativistic charged particles arriving in the chamber from the atmosphere.

The momentum of these particles (in fact electrons) was estimated to be larger than **20 MeV/c**, and hence they could not have been the decay products of radioactive elements. Skobeltzyn demonstrated that these particles often appear as groups of a few particles.

This was the first observation of a ***cosmic-ray shower phenomenon***.

In **1928** at a London conference, Skobeltzyn reported discovering that the relativistic particles are a manifestation of cosmic rays in the atmosphere. He showed that the estimate of the ionization produced by these particles agreed with the then available experimental data on geophysical ionization. Thus, proceeding from his experiments, Skobeltzyn really introduced into physics the modern notion of “cosmic rays”.

Geomagnetic effects and CR charge

1927: During his trip from Amsterdam to Java, J. Clay – by carrying ionization detectors onboard ships – discovered that the ionization rate increased with latitude. It was the first observation of a ***geomagnetic latitude effect*** and very important evidence that the sources of ionization were, at least in part, ***charged particles*** deflected by an external field. In the period from 1928 to 1932 Clay investigated the latitude effect further by taking the ionization camber on 3 sea voyages between Europe and Java via the Suez Canal. He again found a consistently lower intensity near the equator.

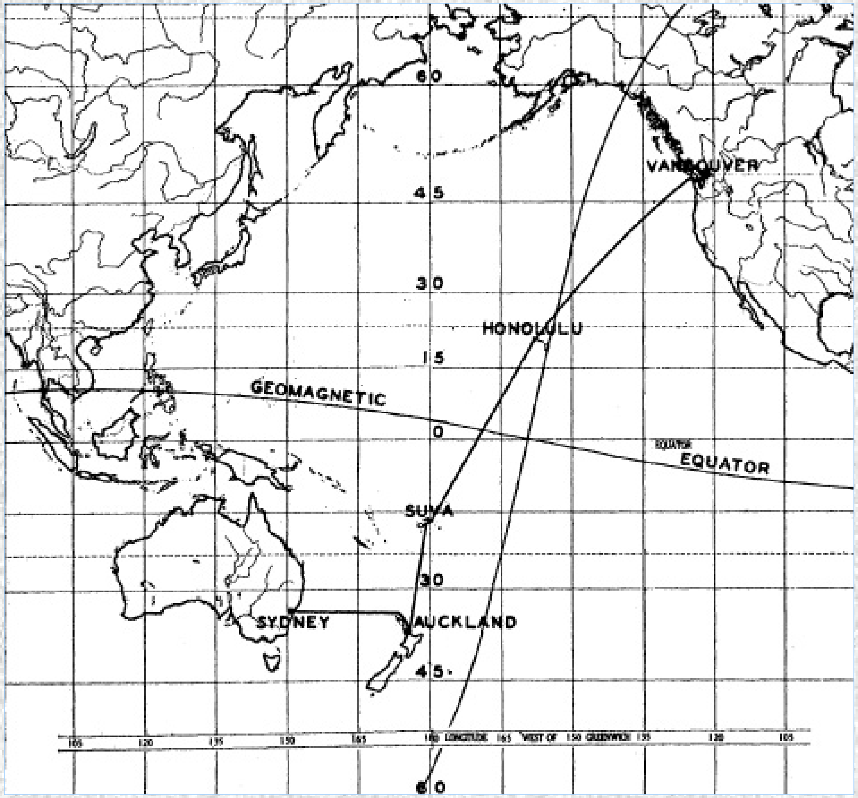
1930: Bruno Rossi, using Störmer's theory, showed that if the cosmic rays were predominantly of one charge or the other there should be an ***east–west effect***.

1933: Two American groups, Thomas H. Johnson of the Bartol Research Foundation and Luis Alvarez and Arthur H. Compton of the University of Chicago, simultaneously and independently measured the east–west effect predicted by Rossi. It showed the cosmic radiation to be predominantly ***positively charged***.

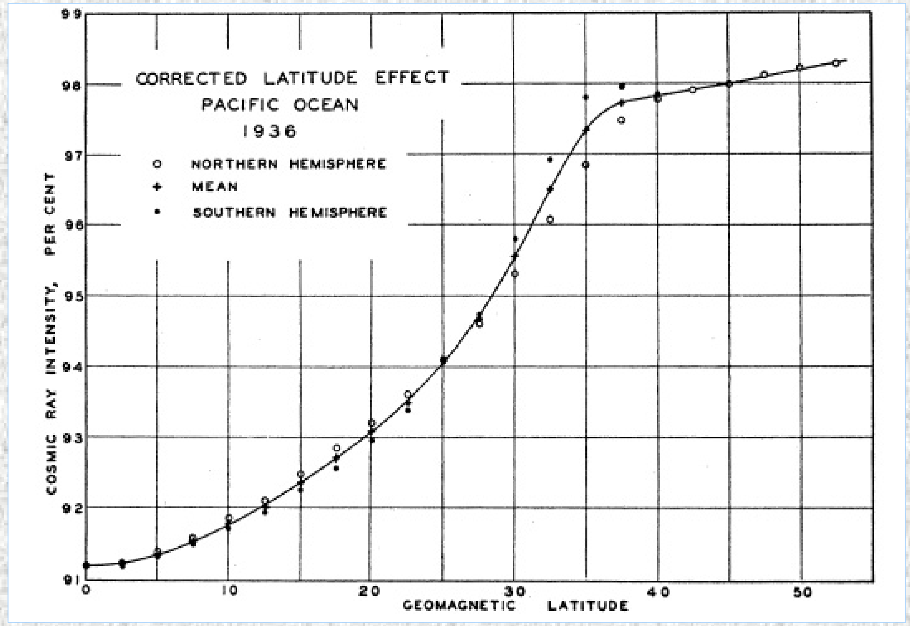
1933-1937: After some doubts concerning the Clay's results were expressed by several other researchers (in particular, by Millikan), the finding was confirmed by Compton. He arranged for measurements to be made at about **70** locations world-wide with improved ionization chambers and calibrated at each site with a standard radium source. [The Earth was divided into nine zones and teams, with all investigators using identical Ion chambers.] Compton obtained the difference of about **10%** between ionization rate at equator and at a latitude of **50^{o}**. It was also obtained that this difference increased with altitude.

1938: T.H. Johnson and collaborators confirmed that the ionization rate increased from east to west viewing angle, indicating that the ionization was due to positively charged particles correctly assumed to be ***protons***.

Late 1930s: In a series of balloon flights, M. Schein and his coworkers used Geiger counter telescopes interspersed with lead absorbers to determine that most of the primary particles were not electrons and hence ***protons*** were most plausibly the dominant constituent.



The route of motor ship ***Aorangi*** (of Canadian Australasian Steamship Company) through Pacific Ocean between Vancouver, British Columbia and Sydney, New South Wales.



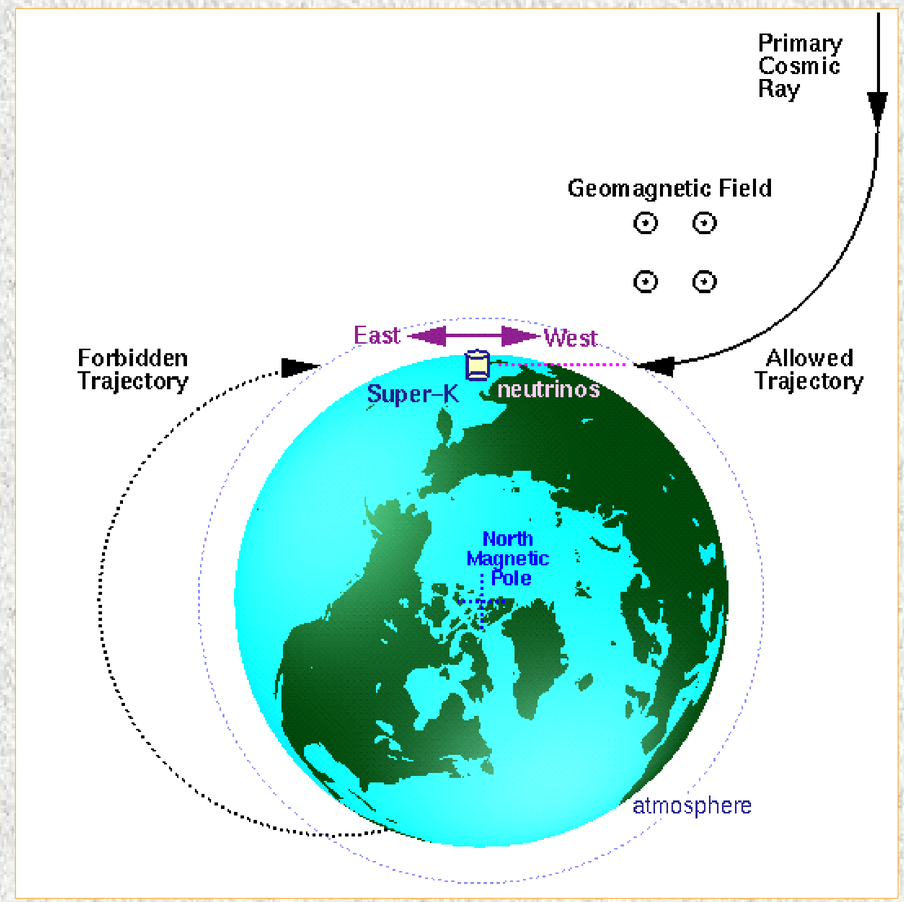
Geomagnetic latitude effect averaged for complete year's data for both hemispheres. The curve has been corrected for the external atmospheric temperature coefficient. The records were made during 12 voyages between Vancouver and Sydney, from March 17, 1936 to January 18, 1937, using a Carnegie model-C cosmic-ray meter (Compton-Bennett ionization chamber).

Reference:

A.H. Compton and R.N Turner, Phys. Rev. **52** (1937) 799.

The above listed results finally proved

- ✓ *that there were the latitude and east-west effects,*
- ✓ *that cosmic rays were (predominantly) charged particles,*
- ✓ *that these particles were (predominantly) positively charged,*
- ✓ *that Millikan was wrong.*

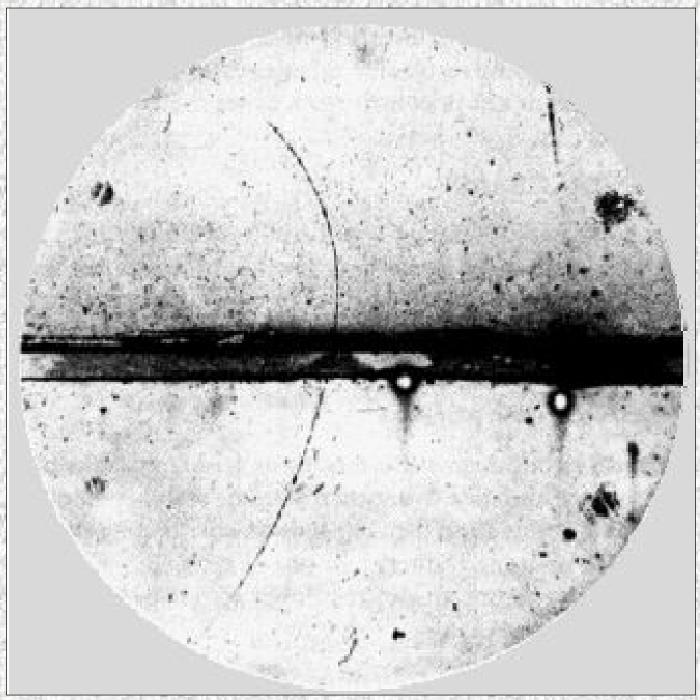


Later, the geomagnetic effects were studied extensively by many researchers, in particular, by Marcello Conversi, University of Rome.

CR and discovering new particles

1932: Carl David Anderson from Caltech discovered ***positron*** (e^+) [predicted by P.A.M. Dirac in 1928] in cosmic-ray initiated events in cloud chamber. The signature of the e^+ was a curvature of its track opposite to one of e^-. The track direction was determined by energy lost as a lead plate traversed.

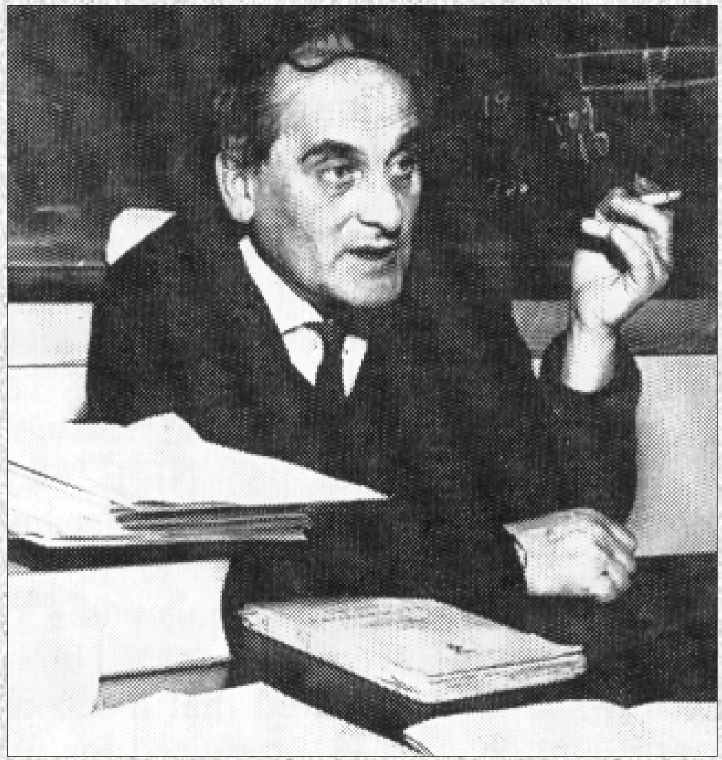
Carl David Anderson won
The Nobel Prize in Physics 1936
"for his discovery of the positron"



The project was initiated by Millican's group at California Institute of Technology for purpose of studying ground level CR. It involved photographing, at random expansion, a large Wilson's chamber in a very strong magnetic field.

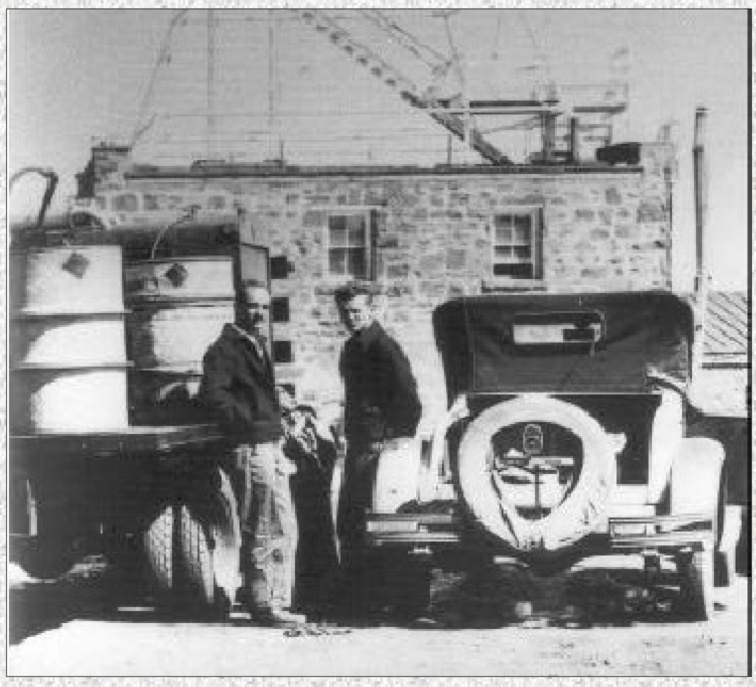
The discovery of e^+ was quickly confirmed by Patrick M.S. Blackett and Giuseppe Occhialini of the Cavendish Laboratory in Cambridge (**1933**), who had arranged GM counters to trigger their cloud chamber on select events (instead of random expansion) and clearly demonstrated e^+e^- pairs emerging from absorbers located in or above it.

Patrick M.S. Blackett



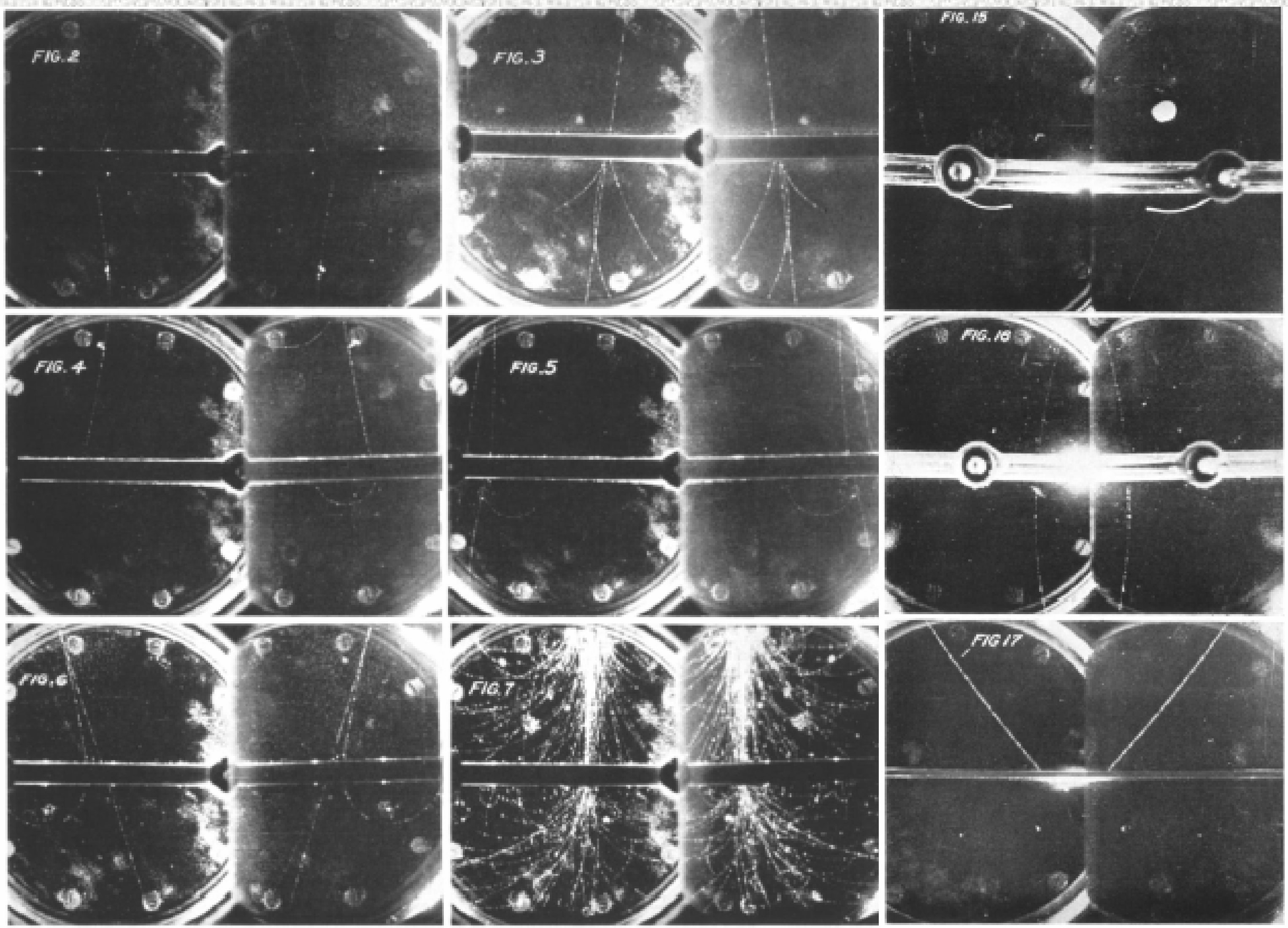
Giuseppe Occhialini (Beppo)

1937: Carl D. Anderson and his graduate student, Seth H. Neddermeyer, determined to follow Millikan's lead and take their cloud chamber (with a 1 cm platinum plate and magnetic field) to high altitudes and various latitudes. The cloud chamber was mounted on an old flatbed truck and, with great difficulty, driven to the summit of Pike's Peak. In fact, they were towed up most of the way. The two experimenters found evidence for a new short-lived particle intermediate in mass between the electron and the proton. This was originally called the ***mesotron***, but is now known as the μ ***meson*** or ***muon,*** a heavy sibling of the electron. Photographs taken in Pasadena and in Panama confirmed the existence of this new particle.



Carl D. Anderson and Seth H. Neddermeyer with their flatbed truck.

Anderson and Neddermeyer used a special selection of photographs of low momentum particles (100-500 MeV/c) and measured the momenta before and after the particles pass through the plate thus evaluating the fraction of energy they lose. Two kinds of events were observed: **“showering”** particles (either as they enter the chamber or after passing the platinum plate) and **“penetrating”** single-track particles.



Some examples of showering and penetrating single-track events in the experiments by Anderson and Neddermeyer.

[**Reference**: C.D. Anderson and S.H. Neddermeyer, Rev. Mod. Phys. **11** (1939) 191.]

Almost simultaneously (**1937**) and independently the muon was discovered in cosmic rays by J.C. Street and E.C. Stevenson at Harvard University.

1939: Franco Rassetti measured the muon lifetime. He found a value of about **1.5×10^{-5} s**. Improved results, near **2.2×10^{-6} s**, were obtained by Bruno Rossi and Norris Nereson, and independently by group of Roland Maze.

The term "mesotron"

"An editorial problem has arisen with regard to the designation of the particle of mass intermediate between the electron and the proton. In the original papers and discussion no less than six different names were used. A vote indicated about equal choice between meson and mesotron with no considerable support for mesoton, barytron, yukon or heavy electron. Except where the authors have indicated a distinct preference to the contrary, we have chosen to use the term mesotron."

Arthur H. Compton
*for the Editorial Board of **Reviews of Modern Physics,** 1939*

A confusion

As long as 10 years since the muon was discovered, the physics community believed that it is just the particle predicted by Hideki Yukawa (**1935**) to account for the short-range strong force between protons and neutrons in nuclei.

From **1941** and through the years of World War II, three young Italian physicists, Oreste Piccioni, Marcello Conversi and Ettore Pancini, carried on a series of observations of "mesotrons" stopped in matter (Tomonaga-Araki experiment), which seemed at the beginning to support Yukawa's predictions. They were able to achieve a high level of precision and stability by innovating upon instruments and techniques of the Italian cosmic ray tradition.

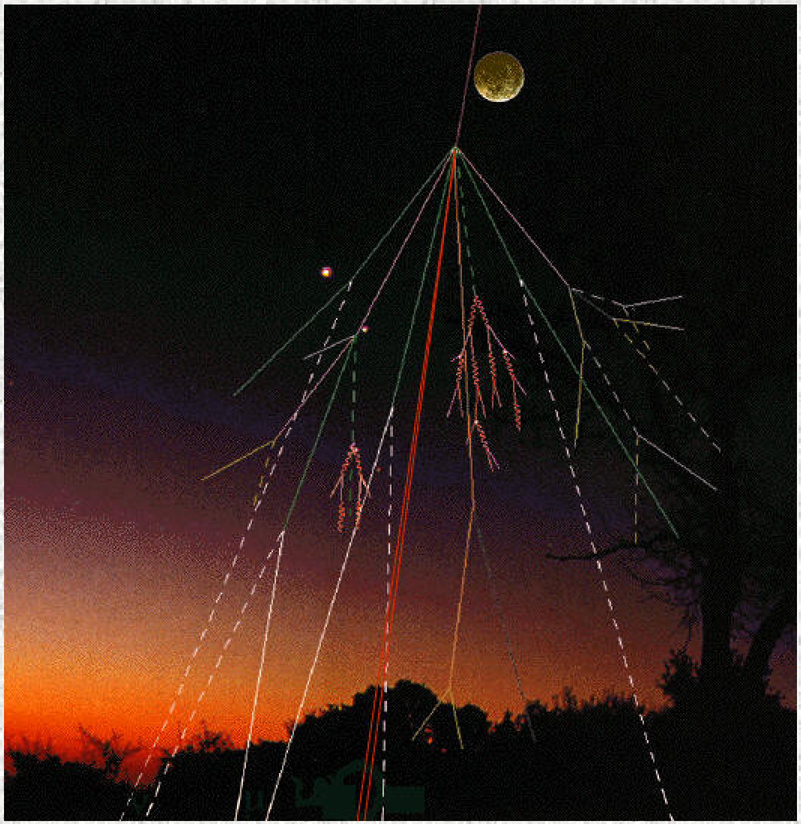
At the end of **1946**, they reported that the rates of absorption of mesotrons in light materials were in catastrophic disagreement with the theory.

> If the mesotrons were not the nuclear quanta, what were they?
> And what new kind of phenomenon was their β-like decay?

Famous exclamation by Isidor Isaac Rabi: ***"Who ordered that?"***

EAS

1938: Pierre Victor Auger, Raymond Maze, Roland Maze and Thérèse Grivet-Meyer positioned their particle detectors high in the Alps. They obtained that two detectors distanced many meters one from another detected the arrival of particles at exactly the same time.



Thus Pierre Auger and collaborators discovered the ***extensive air showers*** (***EAS***), the cascades of secondary particles and nuclei produced by the collision of primary high-energy particles with air molecules. In this way, changing the distance between detectors, Auger could observe particles with energies of about **1 PeV** (**10^{15} eV**) - ten million times higher than reached so far.*)

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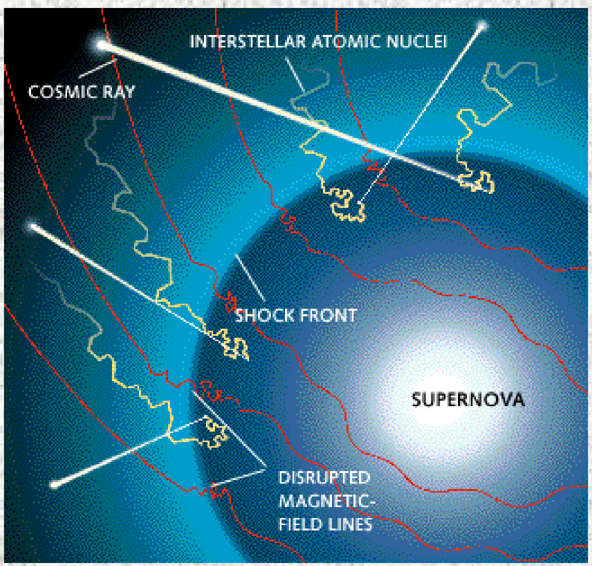
*) Of course, this is the today's estimaton. Auger was not able to say something about the primary energy.

Chronology (Experiment)

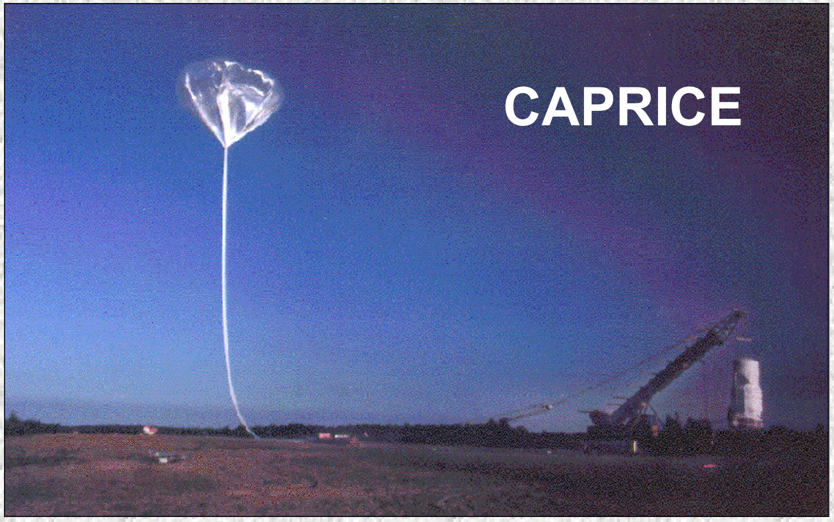
- **February 28, 1942:** First detection of solar cosmic rays.
- **1948:** Phyllis Frier et al. discovered He and heavier elements in CR.
- **May 11, 1950:** U.S. Naval Research Lab fired the Viking research rocket at the intersection of the geographic and geomagnetic equators, to collect cosmic ray and pressure and temperature data.
- **1959:** K.I. Gringauz (Moscow) flew "ion traps" on Soviet Luna 2 and 3 space missions. Explorer VII was launched into Earth orbit with a particle detector.
- **1977:** Voyager 1 and 2 spacecrafts were launched to an interstellar mission.
- **1977-1982:** E.A. Bogomolov et al. (Leningrad) in a series of balloon-born experiments discovered antiprotons in CR.
- **1990:** Ulysses mission was launched for the first time out of the ecliptic plane and passed through the solar poles to study the 3D picture of solar wind and cosmic rays.

Chronology (Theory)

- **1934:** W. Baade and F. Zwicky suggested that supernova explosions are the sources of cosmic rays. They therefore linked the neutron star formation and cosmic ray generation.
- **1949:** E. Fermi suggested (by applying some ideas of H.O.G. Alfvén) that CR could be accelerated through their interactions with interstellar magnetic field irregularities. The paper by Fermi laid the groundwork for the modern theory of cosmic ray acceleration and transport.
- **1964**: The basic model of the origin of galactic cosmic rays was developed by V.L. Ginzburg and S.I. Syrovatskii.
- **1966:** K. Greisen (Cornell University) and, independently, G.T. Zatsepin and V.A. Kuzmin (Moscow Lebedev Institute) predicted the upper limit of the cosmic ray spectrum.
- **1977:** Independently 4 theoretical groups, G.F. Krymsky, I. Axford et al., A.R. Bell, R.D. Blanford and J.P. Ostriker suggested that the cosmic rays are (1st order) Fermi accelerated by supernova shocks in a hot interstellar medium.

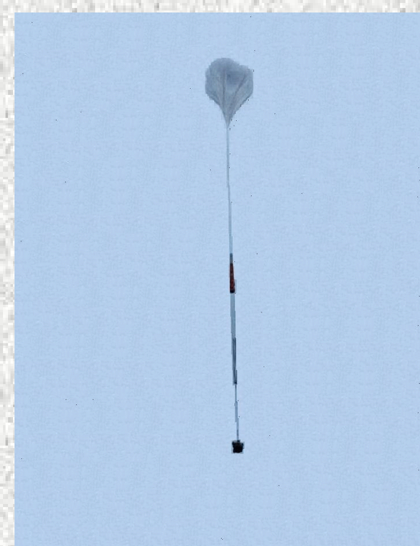


Current balloon experiments



←TS93

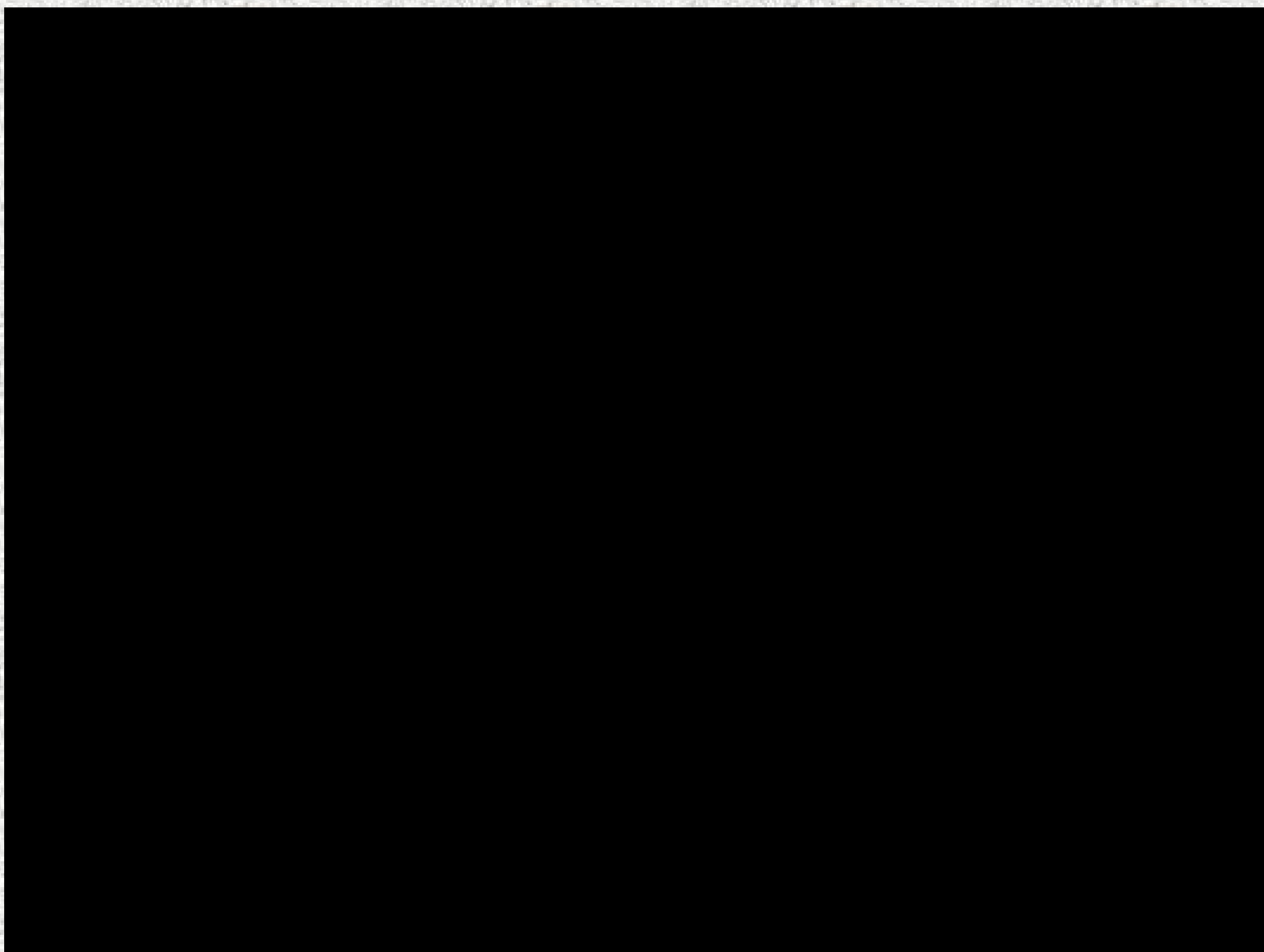
HEAT→



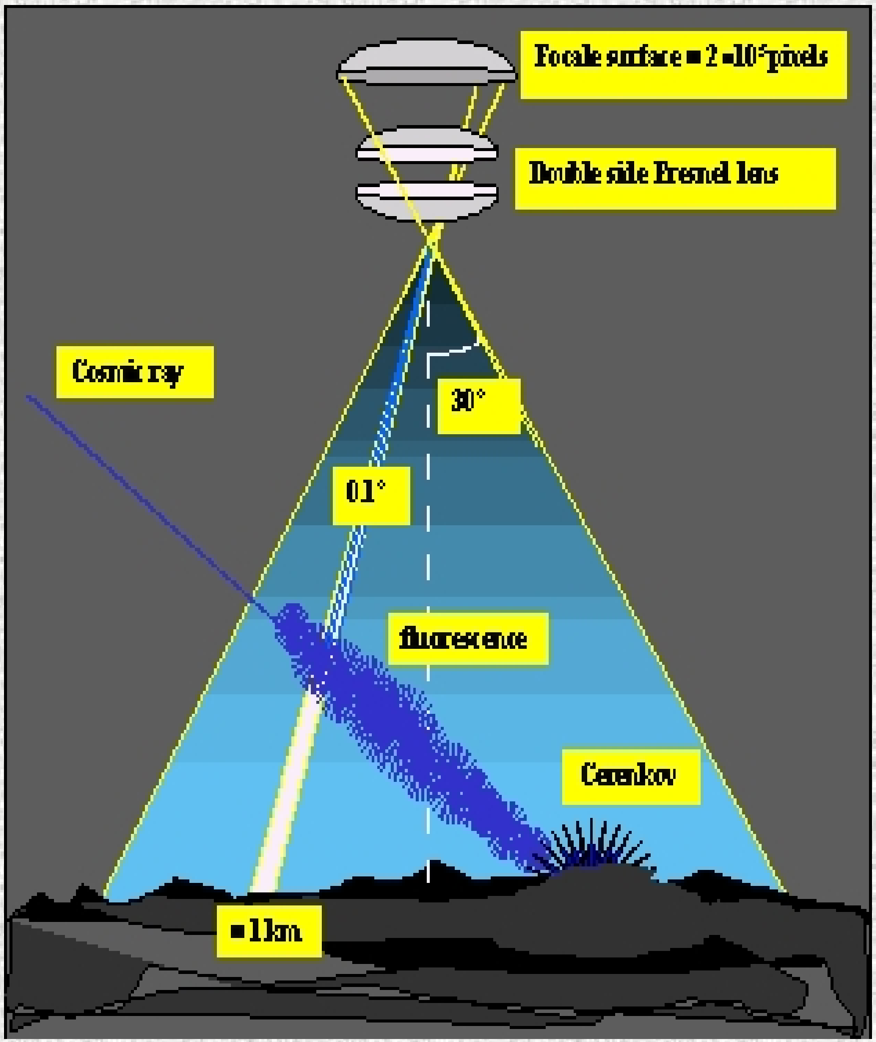
AMS
(Alpha Magnetic Spectrometer)

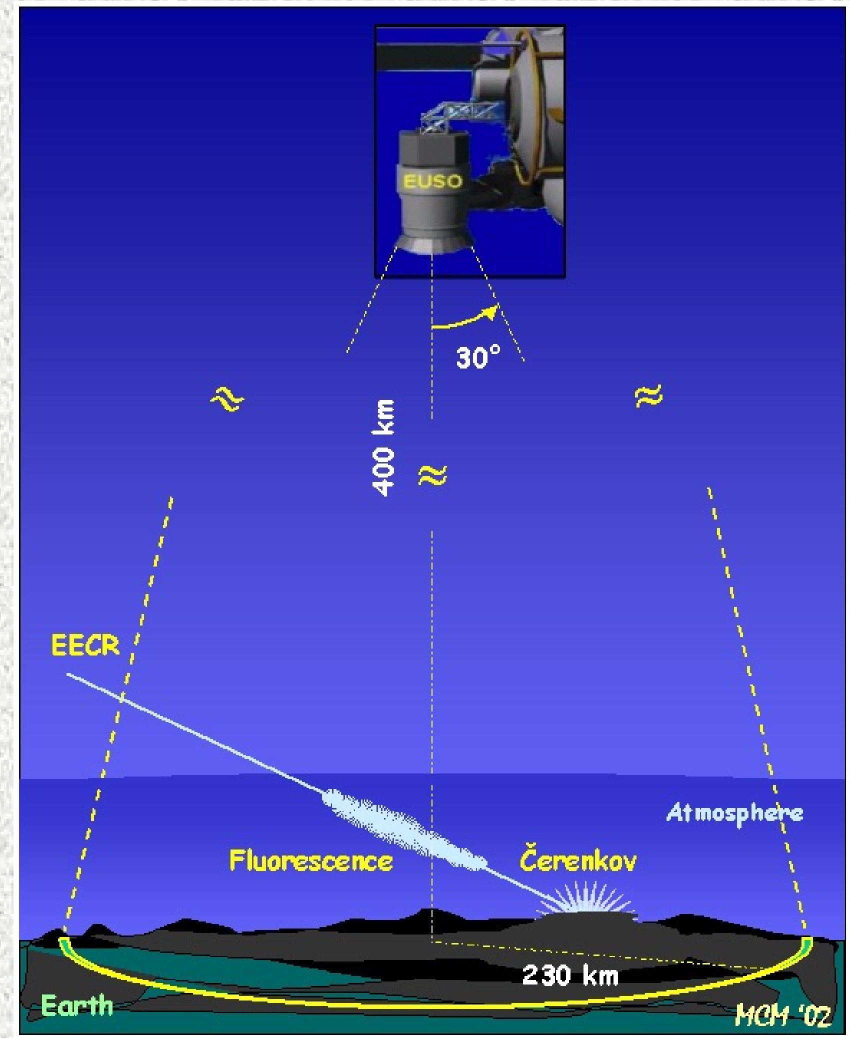

AMS
NASDA

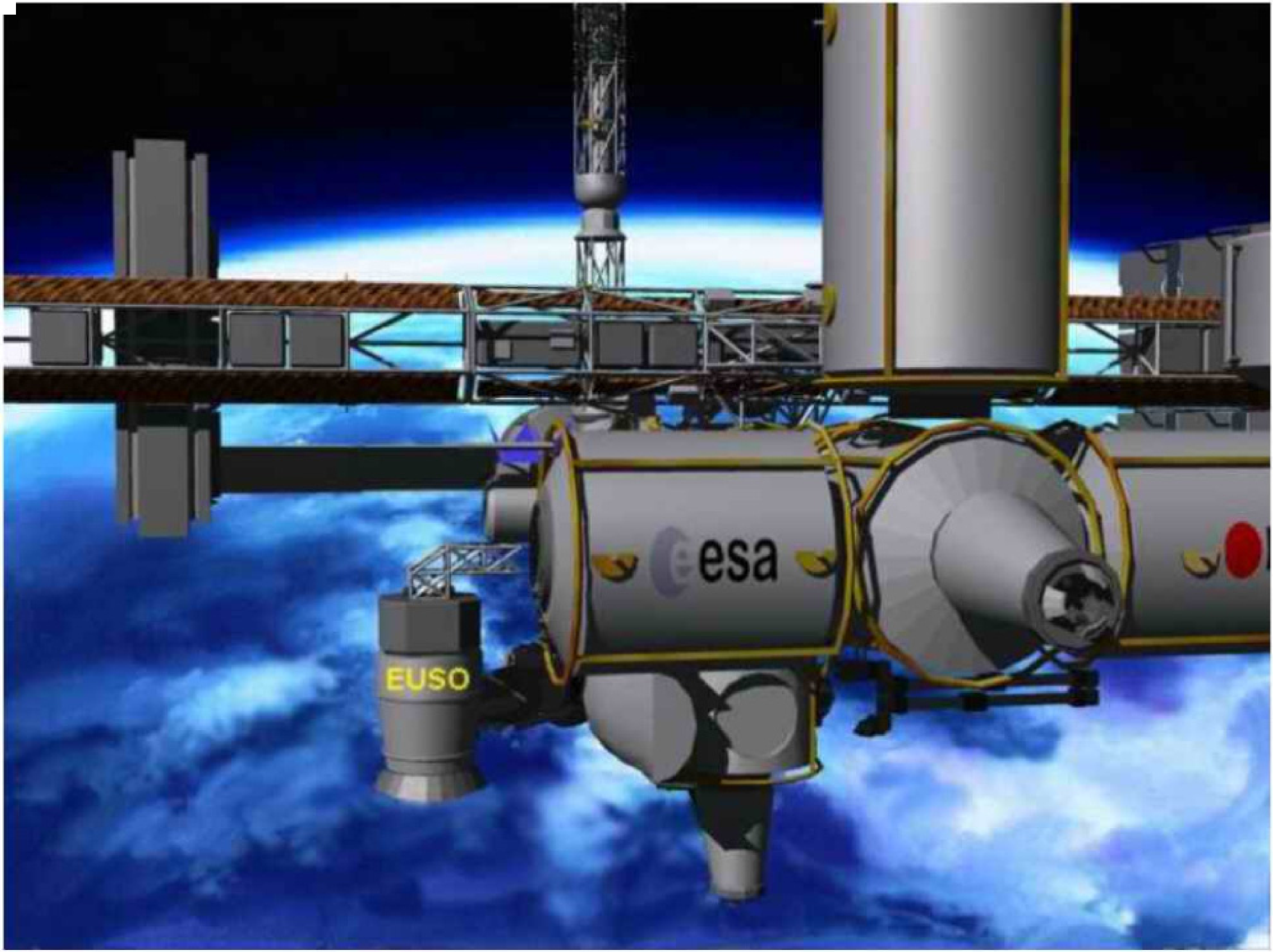
Z burst



Project EUSO
(Extreme Universe Space Observatory)

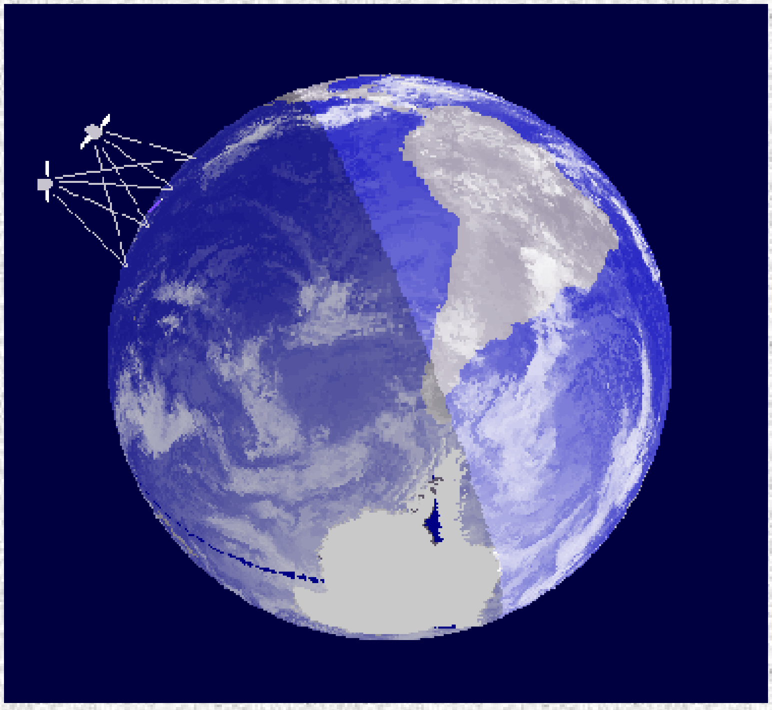


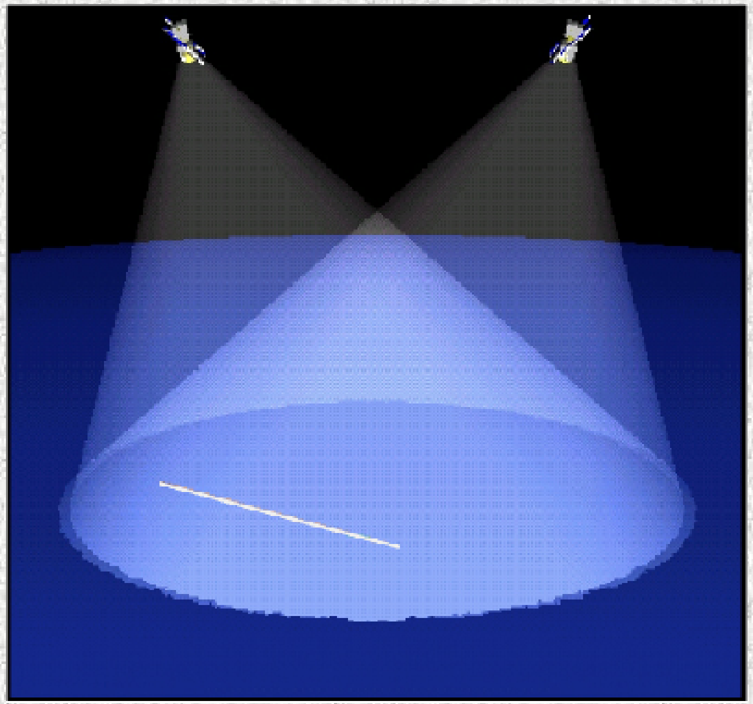



esa
EUSO

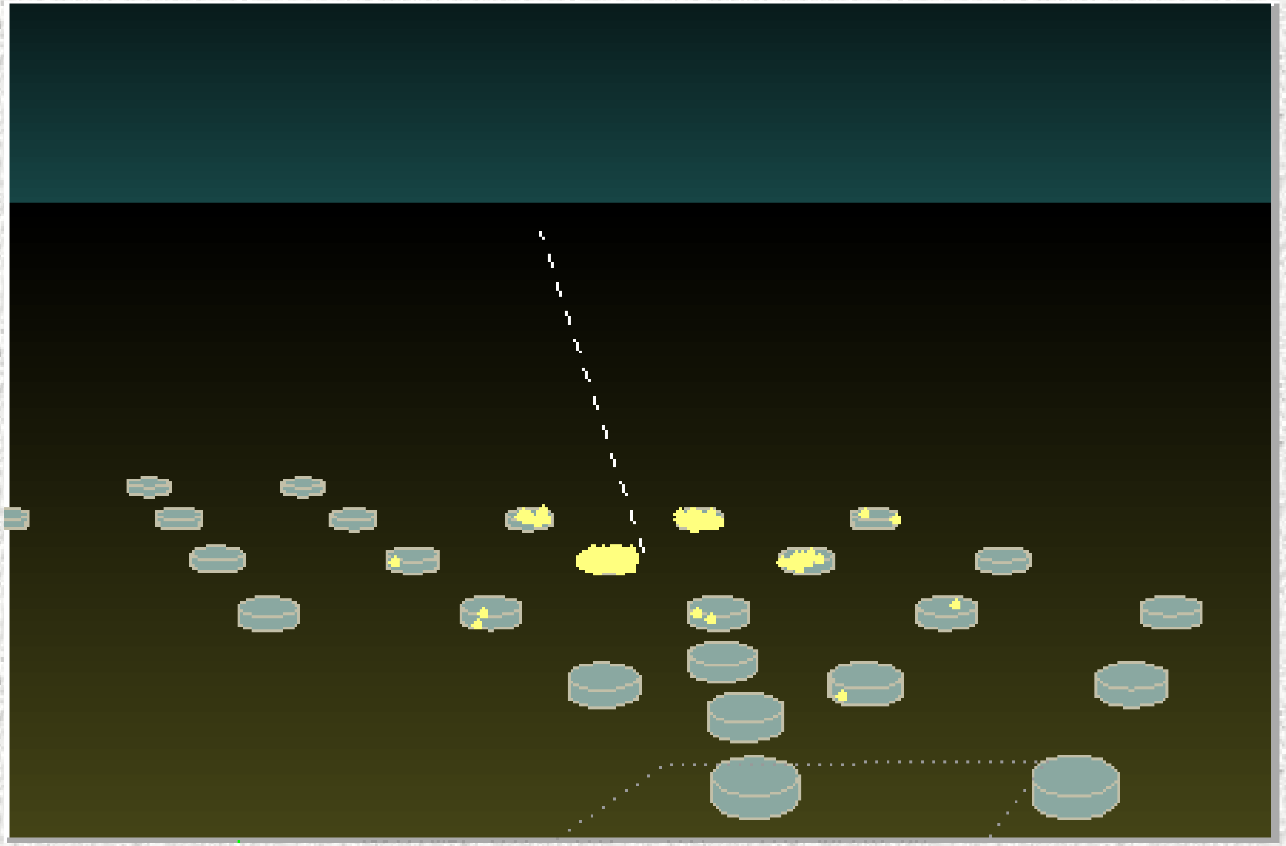
Deployment of EUSO telescope in the ISS

Project OWL
(Orbiting Wide angle Light concentrators)





Pierre Auger Cosmic Ray Observatory



Development and detection of an EAS in the Pierre Auger Cosmic Ray Observatory Engineering Array
Shower particles travel at essentially the speed of light. They spread out from the shower axis in a thin "shower front." You can see curvature in the shape of this front. The moving rectangle is the "shower plane" that is tangent to the shower front at the shower axis. Green dots represent electrons and positrons. Red dots represent muons. Notice that the light detected in a water tank station depends on its distance from the shower axis. The tank closest to the core gets a much stronger signal than those that are far from the axis. The arrival direction is calculated from the shower front arrival times at the different water tank detectors.