High Energy (Multimessenger) Astroparticle Physics 2017/18

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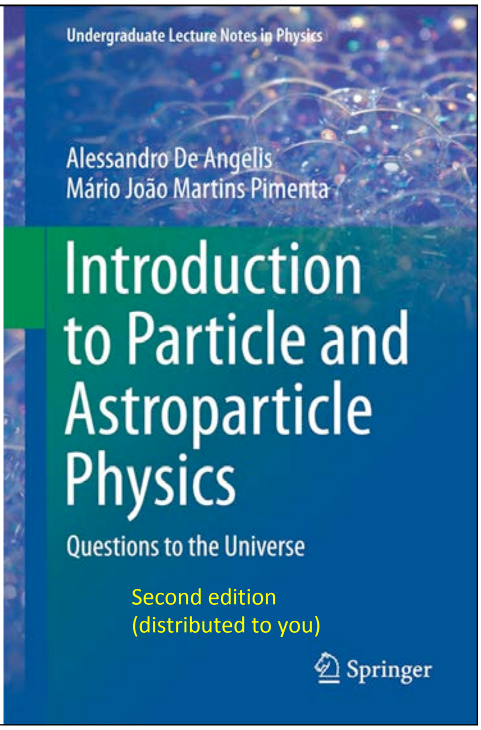
1. Introduction

About this course

- 8 lectures from Feb 20 to Mar 6
- 2 sessions "hands on" on analysis of experimental data. Mar 7 & Mar 8
  - Monday, 14:30
  - Wednesday, 16:30
- What you will learn:
  - Cosmic rays and detectors
  - Fermi acceleration mechanism
  - The sources of cosmic rays
  - TeV-PeV gamma-ray astrophysics
  - Neutrino astrophysics
  - The Dark Matter problem
  - Gravitational waves & multiwavelength astrophysics
  - Open problems; the future
  - Analyze data from Fermi
- How you will be evaluated:
  - Seminar on a topic of your choice



Syllabus

Date	Subject	Reference	Notes/Exercises
Feb 20, 15h (Room 315 Paolotti)	Introduction; high-energy physics phenomena in the Universe; history of cosmic ray research	1; 3 (excluding 3.2.1)	
Feb 21, 15h (Room 315, 3h)	EM & hadronic showers in the atmosphere; HE cosmic ray detectors: hadrons, electrons, neutrinos, gamma rays, GW	4.1; 4.2.1-.5; 4.3.2; 4.5.1-2; 4.5.4; 4.5.3; 4.6	
Feb 22, 9h30 (Room 315)	Fermi acceleration mechanism; Production of γ-rays and νs; top-down mechanisms	10.1	
Feb 26, 15h (Room 315)	Dark Matter; WIMPs and their signatures	8.1; 8.4; 8.5; 10.1.4; 10.4.2.4; 10.4.1.3-.4	
Feb 27, 15h (Room 315, 3h)	Propagation of GW and of charged cosmic rays. Propagation of gamma rays and neutrinos; axions	10.3; 10.4.2.5-.6	
Feb 28, 15h (Room 315)	Possible acceleration sites: implications	10.2	
Mar 5, 15h (Room 313)	Results on charged cosmic rays and on gamma rays	10.4.1-2	
Mar 6, 15h (Room 313)	Neutrinos and gravitational waves. The future	10.4.3, 10.4.4; 10.5	
Mar 7, 15h (Room to be confirmed, 3h)	Laboratory on Fermi-LAT data analysis I	Lab	
Mar 8, 9h30 (Room to be confirmed, 3h)	Laboratory on Fermi-LAT data analysis II	Lab	
TBD	Presentations by the students		

Note: Reference to chapters & sections is done to the textbook by De Angelis and Pimenta, "Introduction to particle and astroparticle physics", Springer 2015, 2nd edition in preparation, 2018.

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Introducing myself…

- Professor of physics at the Universities of Udine, Padova and Lisbon, I work in high-energy astrophysics (I am the PI of the e-ASTROGAM satellite, look the internet)
- Main interests: HE particle astrophysics (in particular with gamma rays) and fundamental physics with accelerators
- Graduated in Padova (bubble chamber physics), post-doc (calibration and commissioning of a calorimeter) and then research associate and staff member at CERN (1993-1999)
  - Convenor of the QCD group and responsible of the software for physics analysis of the DELPHI experiment at LEP. Wrote the first HEP paper using artificial Neural Networks
- Comeback to Italy in 1999, moving to gamma-ray astroparticle physics (simulation, software, physics analysis)
  - GLAST satellite (aka *Fermi*), from NASA
  - MAGIC telescope, in Canary Islands. Scientific coordinator from 2005 to 2007
  - Cherenkov Telescope Array
  - e-ASTROGAM satellite since 2016
- Author or co-author of more than 600 scientific publications, and 2 books (one of popularization: L'enigma dei raggi cosmici, Springer).
- Courses lectured during the recent years: Electricity and Magnetism, Quantum Physics, Quantum ChromoDynamics, Astroparticle Physics, Particle Physics

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e-ASTROGAM
at the heart of the extreme Universe
http://eastrogam.iaps.inaf.it
https://arxiv.org/abs/1611.02232
(Exp. Astronomy 17)
An observatory for gamma rays
In the MeV/GeV domain
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The last 10 years have been the golden years of experimental very high energy astrophysics

- 2003-2010: Hypernovae produce long gamma-ray bursts (GRBs)
- 2007-2017: Cosmic rays beyond 8 EeV come from AGN (the region of accretion of SMBH in galaxies)
- 2007-2017: Cosmic rays from 100 TeV to 1 PeV come from supernova remnants
- 2013: Astrophysical neutrinos above 100 TeV come from extragalactic sources, probably AGN. Less than 5% come from GRBs
- 2015: Gravitational wave (GW) emission accompanies BH-BH mergings, and there are quite a lot of them
- 2017: NS-NS mergers produce GW and short GRBs (up to ~MeV)
- 2018: Flaring blazar produce simultaneous neutrino and gamma-ray emissions)

Five Nobel Prizes (2002, 2006, 2011, 2015 and 2017) to astroparticle physics in the new millennium

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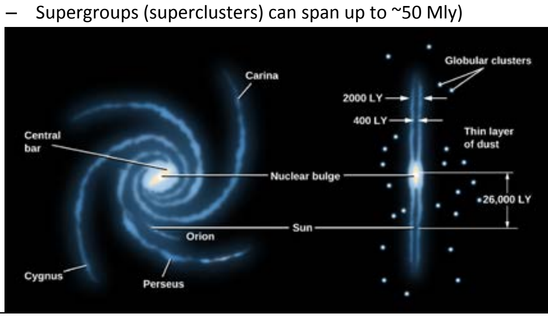
A look at the Universe around us (homogeneity?)

- The Milky Way is a spiral galaxy some 100 000 light-years (ly) across, 1000 ly to 2000 ly thick, with the Solar System located within the disk, about 30 000 ly away from the Galactic Center, in the Orion arm.
  - The stars in the inner 10 000 ly form a bulge. The GC hosts the supermassive BH SgrA* of some 4 million solar masses, as determined by studying the orbits of nearby stars.
  - The interstellar medium (ISM) is filled by partly ionized gas, dust and cosmic rays and it accounts for some 15% of the total mass of the disk.
  - A magnetic field of a few G interacts with the ISM.
- With its 10^{11} stars, the Milky Way is relatively large. Teaming up with the similar-sized Andromeda galaxy, it has gravitationally trapped many smaller galaxies: together, they all constitute the so-called Local Group
  - more than 50 galaxies, including numerous dwarf galaxies-some are just spherical collections of hundreds of stars that are called globular clusters
  - The Local Group covers a diameter of 10 Mly (i.e., 3.1 Mpc); it has a total mass of about 10^{12} solar masses.
  - Supergroups (superclusters) can span up to ~50 Mly)



Cosmological principle?

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The Universe is expanding

- In 1929 Hubble, studying the emission of radiation from galaxies, compared their speed (calculated from the Doppler shift of their emission lines) with distance, and discovered that

$$v = H_0 d$$

H_0 ~ 68 km/s/Mpc ~ 1/14 Gyr

- Galaxies are observed to move away at speeds proportionally higher for larger distances. The Hubble constant describes the rate of increase of recession velocities for increasing distance. The Doppler redshift

$$z = \Delta\lambda/\lambda$$

can thus also be used as a metric of the distance of objects

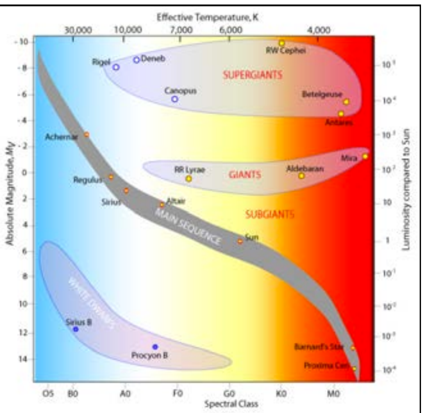
- A simple interpretation of the Hubble law is that, if the Universe had always been expanding at a constant rate, about 14 billion years ago its volume was zero-naively, we can think that it exploded through a quantum singularity, such an explosion being usually called the “Big Bang.” This age is consistent with present estimates of the age of the Universe within gravitational theories and slightly larger than the age of the oldest stars, which can be measured from the presence of heavy nuclei. The picture looks consistent.
- The adiabatic expansion of the Universe entails a freezing with expansion, which in the nowadays quiet Universe can be summarized as a law for the evolution of the temperature T on the size

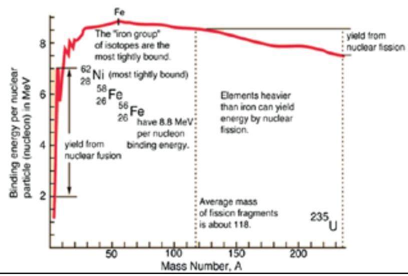
$$T = b/R$$

The present temperature is ~2.7 K, and can be measured from the spectrum of the blackbody radiation (the so-called cosmic microwave background, or CMB, permeating the Universe).

Stars

- Stars also formed by gravitational instabilities. Clouds of gas formed after primordial nucleosynthesis (mostly H and He) collapse and, if their mass is suitable, eventually form stars.
- Stellar masses are limited by the conditions that (i) nuclear reactions can switch on in the stellar core (> 0.1 solar masses), and (ii) the radiation drag of the produced luminosity on the plasma does not disrupt the star’s structure (< 100 solar masses).
- For a star like the Sun, formation takes ~ 50 Myr; the total lifetime is ~11 Gyr before collapsing to a white dwarf, and in the case of our Sun some 4.5 billion years are already gone.
- The fate of a star depends on its mass. The heavier the star, the larger its gravitational energy, and the more eective are the nuclear processes powering it. The outer layers are supported against gravity until the stellar core stops producing fusion energy; then the star
- Main-sequence stars over 8 solar masses can die in a very energetic explosion called a (core-collapse, or Type II) supernova. The star's core, made of iron (mass defect per nucleon is maximum) collapses and the released gravitational energy (~10^{46} J) goes as heating the overlying mass
- Elements: (H, He), CNO, Si, Fe
- The heavier the star, the more effective the fusion process, and the shorter the lifetime.





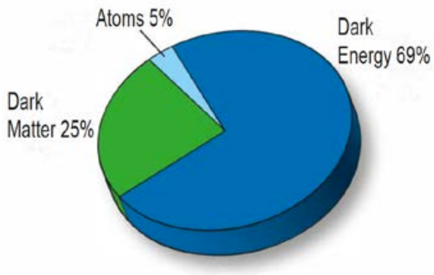
Expansion, composition, fate of the Universe

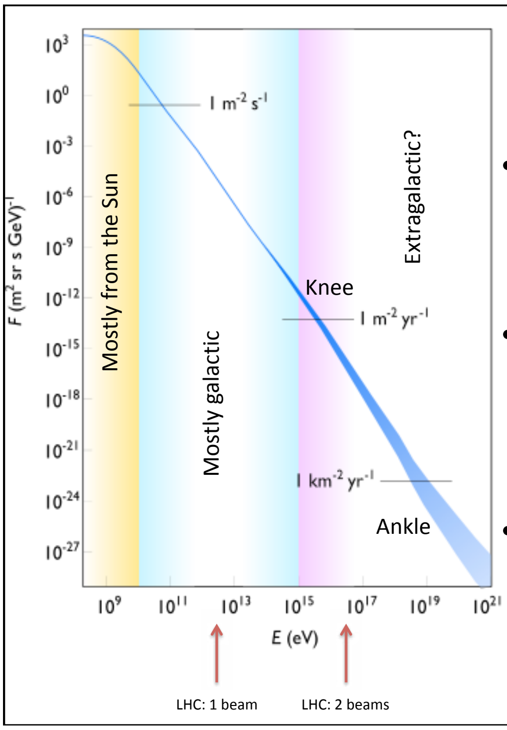
For a flat Universe $\frac{mv_{esc}^2}{2} - GM\frac{m}{r} = \frac{mv_{esc}^2}{2} - G\left[\left(\frac{4}{3}\pi r^3\right)\rho\right]\frac{m}{r} = 0 \Longrightarrow v_{esc} = \sqrt{\frac{8}{3}\pi G r^2 \frac{\rho}{c^2}}$

$$v = H_0 r < v_{esc} = \sqrt{\frac{8}{3}\pi G r^2 \frac{\rho}{c^2}} \Longrightarrow \rho > \rho_{crit} = \frac{3H_0^2 c^2}{8\pi G}$$

~ 5 GeV/m^3

- The study of stellar motions in galaxies indicates the presence of a large amount of unseen mass in the Universe. This mass seems to be of a kind presently unknown to us; it neither emits nor absorbs electromagnetic radiation (including visible light) at any signicant level. We call it dark matter: its abundance amounts to an order of magnitude more than the conventional matter we are made of.
- Dark matter represents one of the greatest current mysteries of astroparticle physics. Indications exist also of a further form of energy, which we call dark energy.
- We live in a world mostly unknown. The evolution of the Universe and our everyday life depend on this unknown external world.
  - The ultimate destiny of the Universe, a perpetual expansion or a recollapse, depends on its energy density
  - Moreover, every second, high-energy particles (above 1 GeV) of extraterrestrial origin pass through each square centimeter on the Earth, and they are messengers from regions where highly energetic phenomena take place. These are the cosmic rays
  - It is natural to try to use these messengers in order to obtain information on the highest energy events occurring in the Universe, and on its composition.





Short phenomenology of Cosmic Rays

- Cosmic rays (CR) are subatomic particles reaching the Earth from outside
- They are mostly protons
  - But the minority (heavy nuclei, neutrinos, gammas, antimatter… is very important)
- The flux depends strongly on energy
  - They reach the highest energies, up to 10^{21} eV

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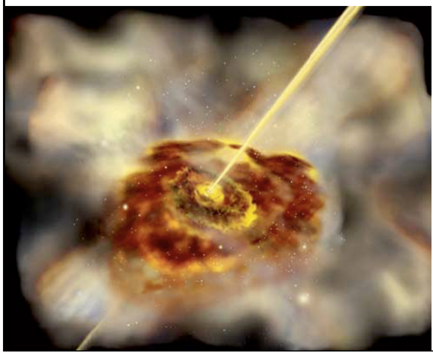
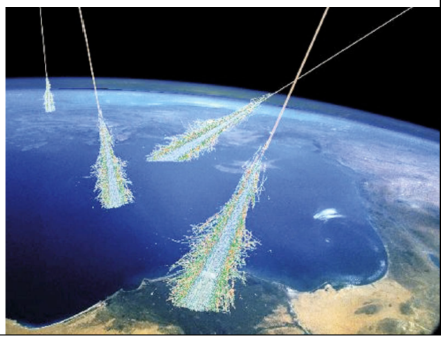
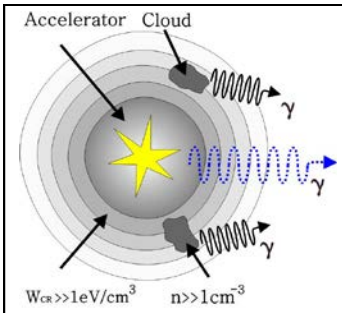
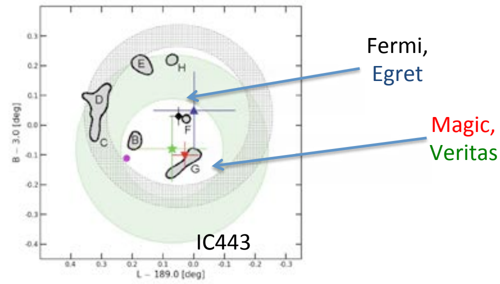
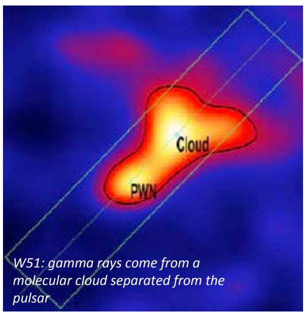
- Kinetic energy is likely to come from potential gravitational energy (collapses of astrophysical objects)
  - Below ~10^7 GeV: likely to be Galactic (supernova remnants)
  - Above: likely to be extragalactic (accreting supermassive black holes: Active Galactic Nuclei)
- Once CR hit the atmosphere, they are absorbed generating showers of particles



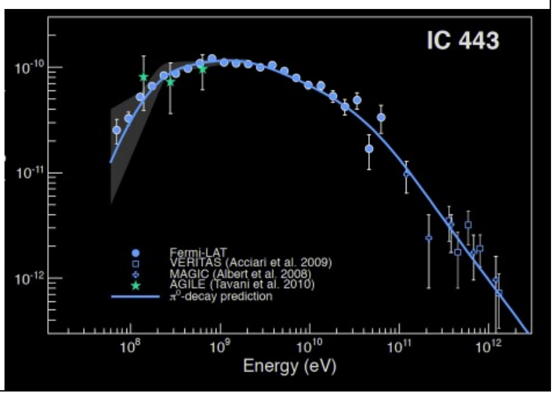




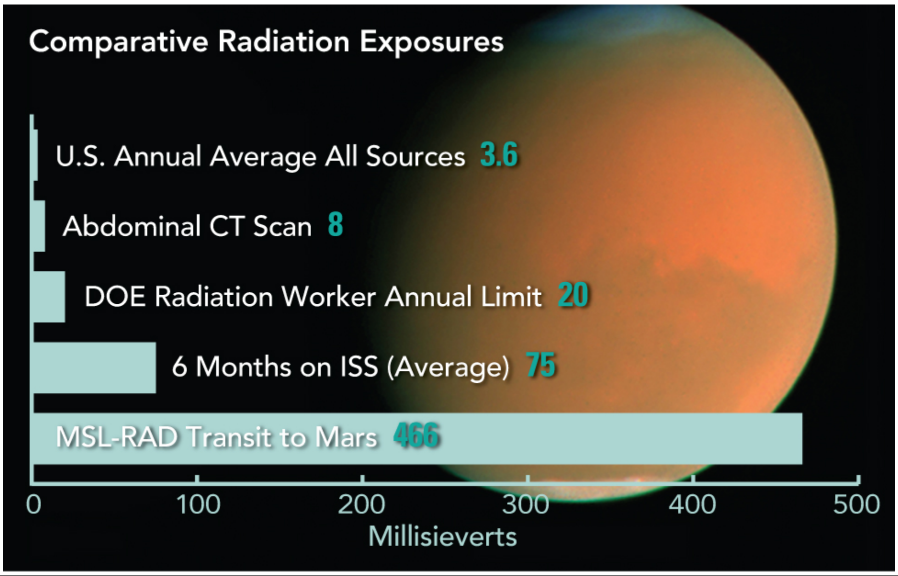




W51: gamma rays come from a molecular cloud separated from the pulsar



Cosmic Rays on Mars

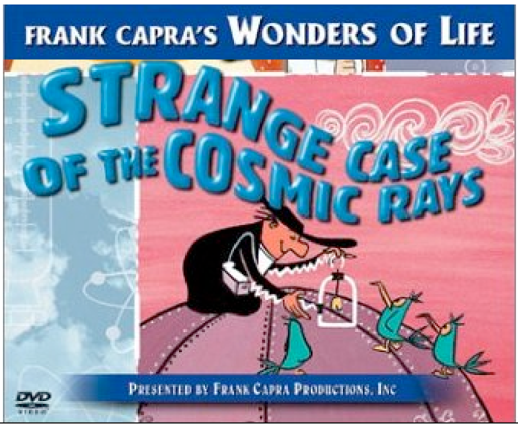


But they are also at the origin of life:

Carbon has extraterrestrial origin

The CH3 sequence is activated by cosmic rays

How did we learn all this?
(history of a 100-years investigation)



(F. Capra/W. Disney production, a 1957 movie written by Anderson & Rossi)

Electroscopes discharge spontaneously. Why?

- 1785: Coulomb found that electroscopes can spontaneously discharge by the action of the air and not by defective insulation
- 1835: Faraday confirms the observation by Coulomb, with better insulation technology
- 1879: Crookes measures that the speed of discharge of an electroscope decreased when pressure was reduced (conclusion: direct agent is the ionized air)

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100 years later: cause might be radioactivity

- 1896: spontaneous radioactivity discovered by Becquerel
- 1898: Marie (31) & Pierre Curie discover that the Polonium and Radium undergo transmutations generating radioactivity (radioactive decays)
  - Nobel prize for the discovery of the radioactive elements Radium and Polonium: the 2nd Nobel prize to M. Curie, in 1911
  - In the presence of a radioactive material, a charged electroscope promptly discharges
  - Some elements are able to emit charged particles, that in turn can cause the discharge of the electroscopes.
  - The discharge rate of an electroscope was then used to gauge the level of radioactivity

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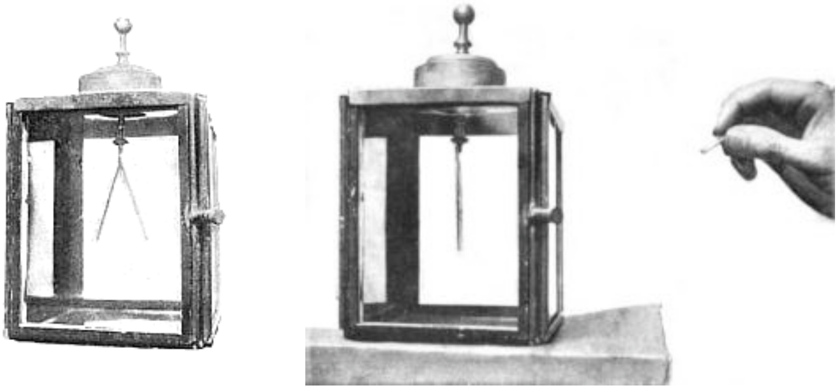

Discharge of an electroscope by a radioactive material (Duncan 1902)

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Where does natural radioactivity come from?

- For sure in part from the soil
- For sure in part from the Sun
- From the atmosphere?
- Is this the full story?

- In the beginning, the dominant opinion was that (almost) all the high energy radiation was coming from the soil

The experiments at the beginning of the XX century

- 1900: Wilson and Elster & Geitel improve the technique for a careful insulation of electroscopes in a closed vessel, improving the sensitivity
- 1901: Wilson makes the proposal of an extraterrestrial origin. His measurements in tunnels however show no reduction in ionization

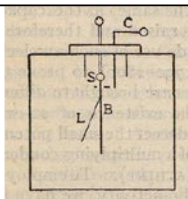


FIG. 6.—Elster and Geitel Electroscope.


(C.T.R. Wilson)

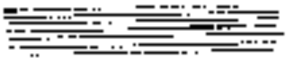
1903-06: Rutherford & Cooke and McLennan & Burton show that ionization is marginally reduced when an electroscope is surrounded by metal shields. McL&B put also the electroscope in a box, and they fill it with water. Mache compares the variations of the radioactivity when the electroscope is surrounded by shields of metal with the diurnal variations; no significant reduction

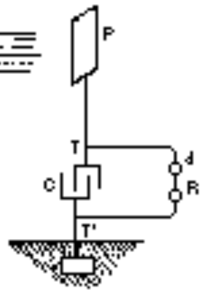

(Elster, Geitel)

- In 1901 Nikola Tesla patented (US patent #685,957/8) an "Apparatus for the Utilization of Radiant Energy

  These radiations are generally considered to be ether vibrations of extremely small wave lengths […]

  This phenomenon, I believe, is best explained as follows: the sun as well as other sources of radiant energy throw off minute particles of matter positively electrified, which […] communicate an electrical charge





1 particle/cm^2/s

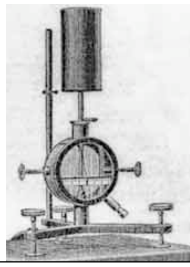
<E> ~ 3 GeV

- Could it work?
  Yes
- How much power can it generate
  $P < 3$ GeV x 10000 CR/sm^2
  $\Rightarrow P < 5\ \mu W/m^2$
  (Solar energy: ~ 200 W/m^2)

The experiments in the beginning of the XX century

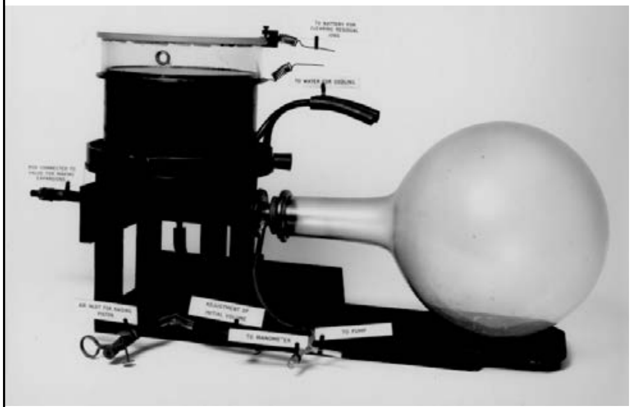
- 1907: Strong studies radioactivity in a variety of places including (1) his lab (2) the center of a cistern filled with rain water and (3) the open air; results dominated by statistical & systematic errors
- 1907-08: Eve makes measurements over the Atlantic Ocean, which indicate as much radioactivity over the centre of the ocean as he had observed in England and in Montreal. He makes also systematic measurements, later used by Wulf, Pacini, Hess
- 1908: Elster & Geitel observe a fall of 28% when the apparatus is taken from the surface down to the bottom of a salt mine. They conclude that, in agreement with the literature, the Earth is the source of the penetrating radiation and that certain waters, soils and salt deposits, are comparatively free from radioactive substances, and can therefore act as efficient screens

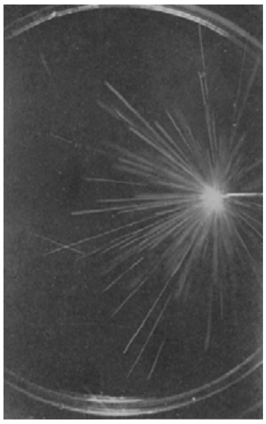
(Eve, Rutherford)



In parallel, the cloud chamber…

'the most original and wonderful instrument in scientific history' (Rutherford)

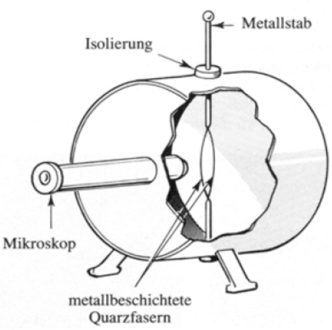




Wilson obtained the first images of the tracks of α and β particles. As Blackett remarked, '[The many exquisite photographs …] still remain among the technically best photographs ever made.'

Father Wulf: a true experimentalist

- Theodor Wulf, German Jesuit, professor in Holland and in Rome, perfected the electroscope in 1908-09, up to a sensitivity of 1 volt (and making it transportable)



The Wulf experiments (1909-1910)

- Wulf had the idea if measuring radioactivity on top of the Eiffel tower (~300 m) and compare to ground, at day and night
  - The decisive measurement: Wulf was on a Easter holiday trip to Paris and brought a few electroscopes with him
- If most of the radioactivity was coming from the soil, an exponential decrease $e^{-h/\lambda}$ was expected
- Results were not conclusive
  - Note: at that time people were convinced that natural radioactivity was mostly due to gamma rays
- Taken as a confirmation of the dominant opinion: radioactivity came from the soil

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Domenico Pacini's break-through

- Domenico Pacini (1878-1934), meteorologist in Roma and then professor in Bari, makes measurements in 1907-1911, first comparing the rate of ionization on mountains at different altitudes, over a lake, and over the sea
  - Comparing measurements on the ground and on a sea a few km off the coast in Livorno, a 30% reduction of radioactivity
  - A hint that the soil is not (the only) responsible of radiation: *in the hypothesis that the origin of penetrating radiations is only in the soil … it is not possible to explain the results obtained* (Pacini 1910; quoted by Hess)

- In June 1911, the winning idea: immersing an electroscope 3m deep in the sea (at Livorno and later in Bracciano) Pacini, 33-y-old, finds a significant (20% at 4.3σ) reduction of the radioactivity

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Coll' apparecchio alla superficie del mare si ebbe una perdita oraria di Volta:

13,2 — 12,2 — 12,1 — 12,6 — 12,5 — 13,5 — 12,1 — 12,7

media 12,6 equivalente a ioni 11 per cm³ al 1".
Coll' apparecchio immerso:

10,2 — 10,3 — 10,3 — 10,1 — 10,0 — 10,6 — 10,6.

media 10,3 equivalente a ioni 8,9 per cm³ al 1".
La differenza fra questi due valori è di ioni 2,1.

"The explanation appears to be, due to the absorbing power of water and the minimum amount of radioactive substances in the sea, that radiation coming from the outside is absorbed when the apparatus is immersed. (Nuovo Cim., February 1912)"

Pacini concludes that *"a sizable cause of ionization exists in the atmosphere, originating from penetrating radiation, independent of the direct action of radioactive substances in the ground."*

Pacini's experiment marked the beginning of the underwater technique for CR studies

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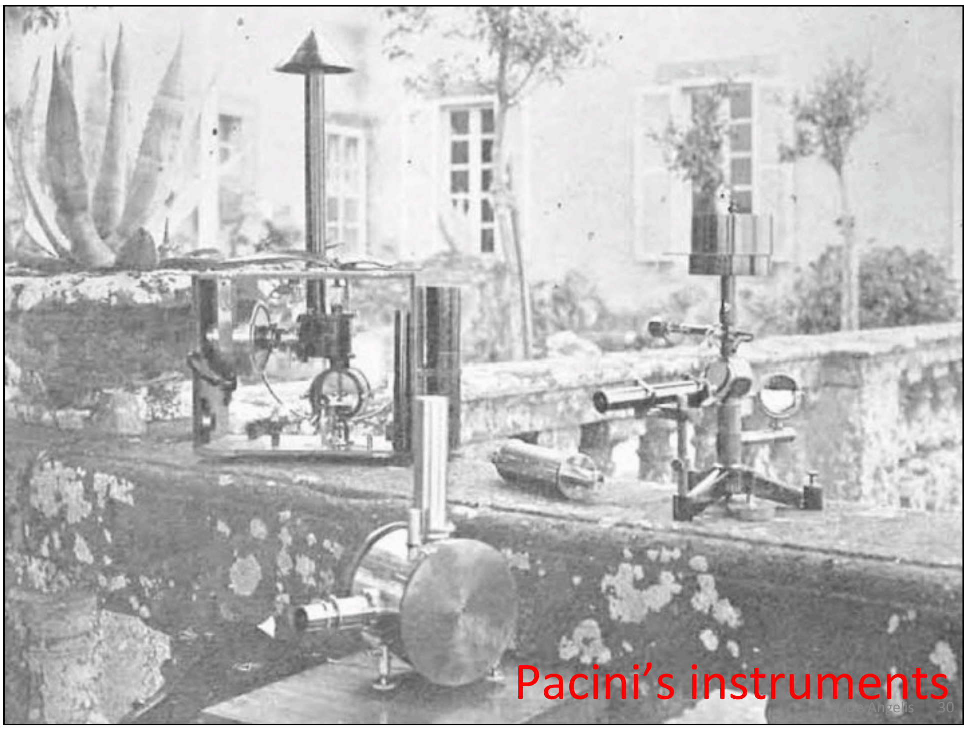
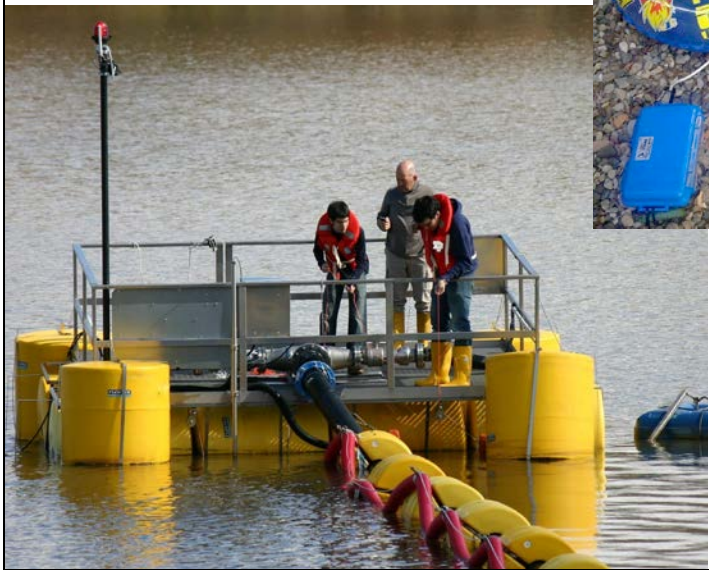


Remake of the Pacini experiment in 2011

(G. Batignani et al., Giornale di Fisica, Sept. 2011)



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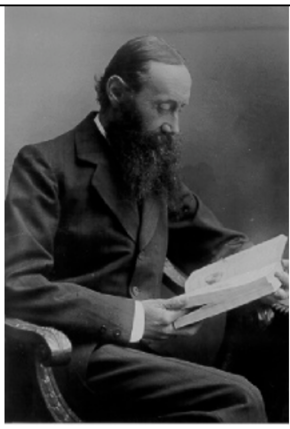
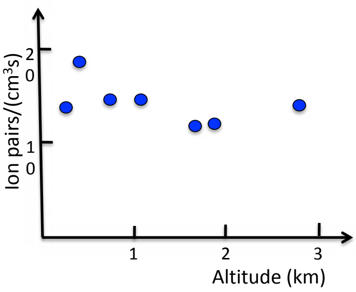
Balloon experiments: Gockel

Note: Gay Lussac and Biot flew to 6400 m in 1804 to study properties of air at different p, T. Robertson and Lhoest had reached nearly 7000 m in a 5 h flight from Hamburg to Hannover in 1803, to measure B





- How to increase the sensitivity of Wulf's measurements on the Eiffel tower? Flying on balloons!
- The first balloon flights with the purpose of studying the properties of penetrating radiation were arranged in 1909, in Germany by Bergwitz, and in Switzerland by A. Gockel, professor at the University of Fribourg
- Ascending up to 4000 m, Gockel found that the ionization did not decrease with height as expected on the hypothesis of a terrestrial origin
  - Copyright of the term "kosmische Strahlung"

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A new boost: Hess

- The Austrian Victor Hess (1883-1964), at that time working in Wien and in Graz, started studying Wulf's electroscope, and measuring carefully the absorption coefficients of radioactivity in air
  - Thorough check & improvement of Eve's work; separation between alpha, beta, gamma
- In 1911, he continued his studies with balloon observations: he made 2 ascensions at ~1300 m, measuring possible variations of radioactivity, and found no effect. He had 3 Wulf electroscopes in Zn boxes of different thicknesses

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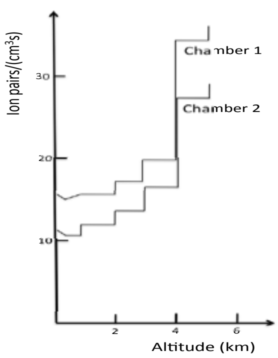
Hess' final balloon flights



- From April 1912 to August 1912 Hess had the opportunity to fly 7 times. In the final flight, on August 7, Hess, 29-y-old, reached 5200 m
  - His results showed that the ionization, after passing a minimum, increased considerably with height
  - He concluded that the increase of the ionization with height is due to a radiation coming from above, and thought that this radiation had extra-terrestrial origin

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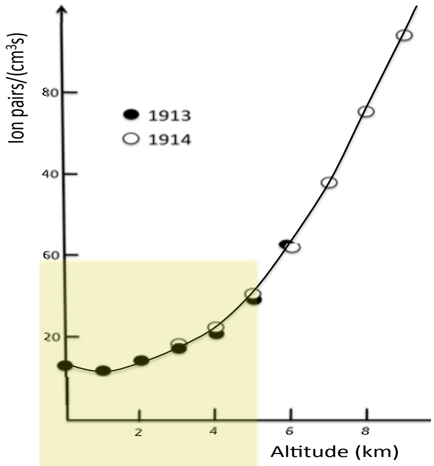
Kolhörster and the final confirmation



The final flight by Kolhörster would be performed on 28 June 1914, the same day of the assassination of Archduke Franz Ferdinand of Austria on the roman bridge of Sarajevo: WWI starts

- The results by Hess were later confirmed by the 26-y-old Kolhörster in a number of flights up to 9200 m
  - An increase of the ionization up to 10x at sea level found
- The absorption coefficient of the radiation from top was also estimated, and turned out to be 8 times smaller than the absorption coefficient of air for gamma rays as known at the time
  - This result was neglected by the writer and by the readers!

35

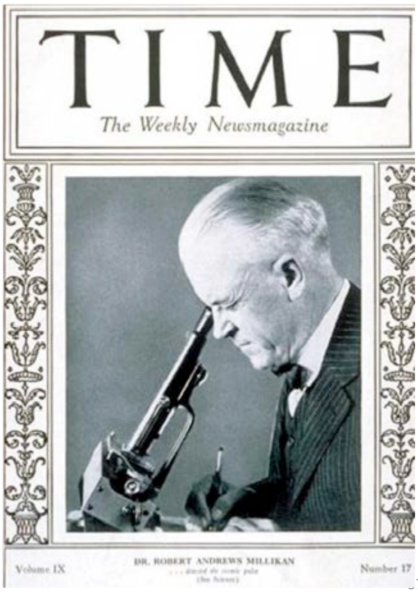
Word War I washes everything out… and science restarts in the new world

- During WWI and immediately after, few investigations were performed. Kolhörster improved his apparatus and made measurements in 1923 in agreement with earlier balloon flights
- There were, however, also negative attitudes against extraterrestrial radiation. Hoffmann (1924), and Behounek (1925), using newly developed electrometers, concluded that ionization was due to radioactive elements in the atmosphere
- After the war, the focus of the research moved to the US; Millikan & Bowen developed a low mass (200 g) electrometer and ion chamber for unmanned balloon flights using data transmission technology developed during the war
  - In flights up to 15000 m in Texas they found a radiation intensity ¼ the intensity reported by Hess and Kolhörster. They attributed this difference to a turnover in the intensity at higher altitude, being unaware that a (latitude) geomagnetic effect existed
  - Millikan concluded that there was no extraterrestrial radiation: his statement at the American Physical Society in 1925 was “The whole of the penetrating radiation is of local origin". Millikan was strongly attacked, e.g., by Compton.

36

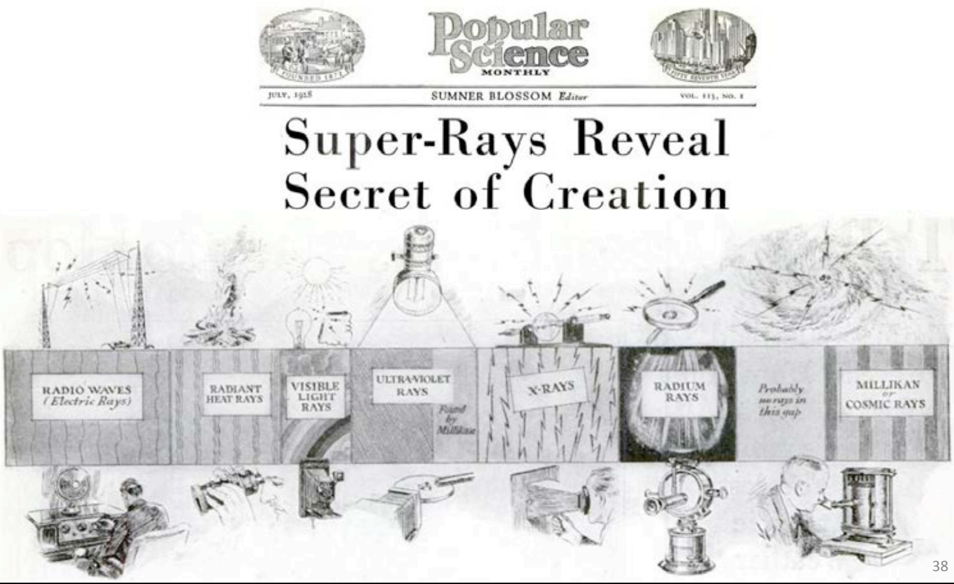
Truth reestablished (but merit stolen)

- In 1926, however, Millikan and Cameron carried out absorption measurements of the radiation at various depths in lakes at high altitudes
  - They reproduced Pacini's depth effect, and they concluded that these particles shoot through space equally in all directions, calling them "cosmic rays"
  - In the conclusive Phys. Rev. article, they ignored Wulf, Gockel, Pacini, Hess
- Millikan was handling with energy and skill the communication with media, and in the US the discovery of cosmic rays became, according to the public opinion, a success of American science
  - Millikan argued that the cosmic rays were the "birth cries of atoms" in our galaxy



37

Marketing cosmic rays



38

[...]

From the lips of Dr. Millikan in Washington, I heard the thrilling story of his discovery. I found him a vital, dynamic man of sixty, whose handshake crushed my fingers and whose simple word: carried the assurance of authority. That story was one of years of fruitless experiment, bitter disappointment, physical hardship, and final triumph. He told of struggles up rugged mountains on two continents to find and measure the elusive rays—then of a flash of inspiration only a few weeks ago that proved the rays the actual messengers of creation.

If the rays came from outside, Millikan reasoned, they should be hundreds of times stronger at the top of the earth's

Dr. Millikan (left) and Dr. G. Harvey Cameron with electroscopes they sank in California and Bolivia mountain lakes to detect cosmic rays. The instruments were raised and examined through the eyepiece

air than at the bottom. He resolved to send a sounding balloon with instruments to record them clear to the top of the atmosphere.

work apparently wasted.

"Then," said Millikan, "we saw what fools we had been to carry building materials up that mountain. Why build a wall, when you can bury an electroscope at the bottom of a mountain lake just as easily as you can hide it behind a lead screen, and the water of the lake will serve as the equivalent of many feet of lead. The next thing to do was to go at it sensibly. We would climb to the top of 15,000-foot Mount Whitney, in southern California—the highest mountain in the United States—and there, under its brow, would sink our electroscopes in the pure, snow-fed waters of Muir Lake."

With Dr. Cameron and a couple of students, Millikan toiled up Mount Whitney in August, 1925, and found the secret of the stars.

Two thousand feet from the top, they had to shoulder the boats, lumber to build rafts, and instruments their mules had carried.

Anxiously they sank their electroscopes. A cry of triumph echoed through the frosty air. There were cosmic rays—rays that pierced the water for fifty feet, downward, and then stopped!

- Anyway, also Hess and Kolhörster were not referenced (Gockel, whose measurement had not succeeded, was). Bergwitz, Hess and Kolhörster wrote an article emphasizing their priority on the balloon results (Phys. Zeit. 1926).

39

Hess Phys Zeit 27 159 (1926)

Not pleased with Millikan

Zu der eingangs zitierten Veröffentlichung von A. Millikan möchte ich vorerst bemerken, daß er die Geschichte der Entdeckung der Höhenstrahlung in einer Weise darstellt, die Mißverständnisse hervorrufen könnte[3]).

1) Physik. Zeitschr. 13, 1084, 1912; Wien. Ber. IIa, 121, 2001, 1912.

2) Physik. Zeitschr. 14, 610, 1913; Wien. Ber. IIa, 132, 1053, 1913.

3) Die neuerliche Feststellung der Existenz und der hohen Durchdringungskraft der Höhenstrahlung durch Millikan und seine Mitarbeiter wurde von amerikanischen naturwissenschaftlichen Zeitschriften wie „Science", „Scientific Monthly" zum Anlaß genommen, um für die Höhenstrahlung die Bezeichnung „Millikan-Strahlen" vorzuschlagen. Da es sich hier nur um die Bestätigung und Erweiterung der Ergebnisse der von Gockel, von mir und von Kolhörster 1910 bis 1913 ausgeführten Strahlungsmessungen im Ballon handelt, ist diese Benennung als irreführend und unberechtigt abzulehnen.

Hess: Physik. Zeitschr. 27, 159, (1926)

As concerns the publication of Millikan, cited above, I would like to remark that he tells a story of the discovery of hohenstrahlung that could be easily misunderstood.

3) The recent determination by Millikan and his colleagues of the high penetrating power of hohenstrahlung has been an occasion for American scientific journals such as "Science" and "Scientific Monthly" to introduce the term "Millikan Rays". Millikan's work is only a confirmation and extension of the results obtained by Gockel, by myself , and by Kolhörster from 1910 to 1913 using balloon borne measurements of the rays. To refuse to acknowledge our work is an error and unjustified.

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Exchange of letters between Pacini and Hess

- Pacini to Hess, March 1920: … *[in your] paper entitled `The problem of penetrating radiation of extraterrestrial origin' … the Italian measurements …, which take priority [for] the conclusions that you … draw, are missing; and I am so sorry about this, because in my own publications I never forgot to mention and cite anyone...*

- Hess to Pacini, March 1920: … *My short paper … is a report of a public conference, and therefore has no claim of completeness…*

- Pacini to Hess, April 1920: *[…but] several authors are cited whereas I do not see any reference to my relevant measurements … performed underwater in the sea and in the Bracciano Lake, that led me to the same conclusions that the balloon flights have later confirmed. …*

- Hess to Pacini, May 1920: *… I am ready to acknowledge that certainly you had the priority in expressing … in `Nuovo Cimento', February 1912, the statement that a non terrestrial radiation of 2 ions/cm³/s at sea level is present. However, the demonstration of the existence of a new source of penetrating radiation from above came from my balloon ascent to a height of 5000 meters on August 7 1912, in which I have discovered a huge increase in radiation above 3000 meters. …*

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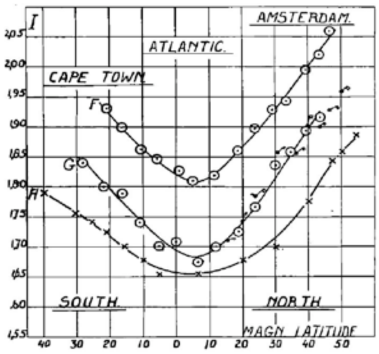
Charged or neutral?

- It was generally believed that the cosmic radiation was gamma because of its penetrating power (the penetrating power of relativistic charged particles was not known)
  - Millikan had put forward the hypothesis that the gamma rays were produced when protons and electrons form He nuclei in interstellar space
- The geomagnetic effect in CR (the CR flux depends on latitude) was discovered accidentally in 1927 by the Dutch researcher J. Clay
  - Clay was measuring radiation in Java; in 1927 he carried his detector in a trip from Java to Genova
- Confirmed by Clay himself in 1928 (Java to Amsterdam), by Kolhörster, by Rossi, by Compton+



42

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In the meantime (late '20s), Geiger counters enter the game

- Easier measurement
- Fast response (possibility of building coincidences)

(Hans Geiger in 1928)

Beppo Occhialini: "the Geiger-Muller counter was like the Colt in the Far West: a cheap instrument usable by everyone on one's way through a hard frontier."

44

Arthur Compton organized a world wide survey of the dependence of cosmic intensity on geomagnetic latitude.

Fig. 6. Compton with the special ionization chamber which he designed and used for his world-wide cosmic-ray survey during 1931–33, which proved that cosmic rays are charged particles.

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GEOGRAPHIC STUDY OF COSMIC RAYS 389

FIG. 1. Map showing location of our major stations for observing cosmic rays.

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Bruno Rossi memoir 1984

For me, the turning point in the search came in the fall of 1929, with the appearance, in Zeitschrift für Physik, of the historical paper "Das Wesen der Höhenstrahlung" by W. Bothe and W. Kolhörster (Bothe and Kolhörster, 1929)

Until then, I had not been particularly interested in the phenomenon of the "Höhenstrahlung" or "cosmic radiation," using the suggestive expression introduced by Robert Millikan. I had not thought that it would offer, to me at least, a profitable field of research.

I had not been seduced by Millikan's well publicized theory, maintaining that cosmic rays were the "birth cry of atoms" in cosmic space, being born, in the form of γ-rays, when hydrogen atoms "fused" to form the heavier elements. To my skeptical mind, this was a romantic idea, lacking sound experimental support.

On the other hand, I had accepted, uncritically, the prevailing view that primary cosmic rays were high-energy γ-rays. Therefore I read with particularly keen interest the paper by Bothe and Kolhörster relating the first attempt to submit this assumption to a direct test.

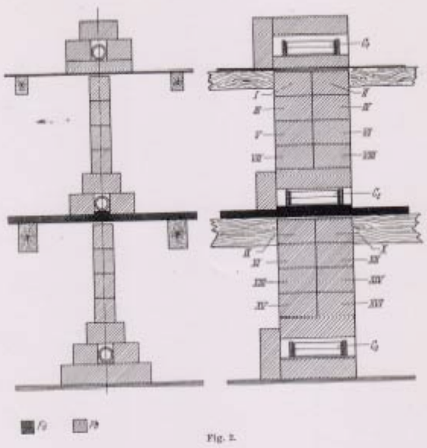
Y. Sekido and H. Elliot (eds.), Early History of Cosmic Ray Studies, 53–73.

47

A dramatic result
by Bruno Rossi

(with Heisenberg!)

B. Rossi
Zeit. f Physik 82 151 (1933)



~ 50% of radiation at sea level can penetrate 1 metre of lead.

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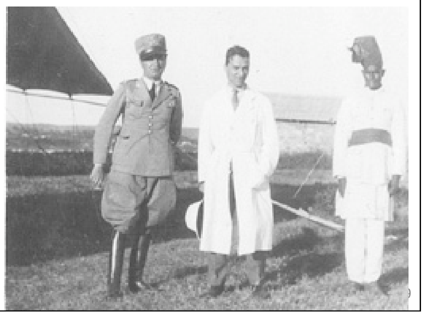
Positive or negative?
The East-West effect

- 1933-34: three independent experiments (Alvarez & Compton, Johnson, Rossi) find that the intensity of CR is greater from the West than from the East => most primary cosmic rays are positively charged particles
  - In the course of his East-West experiment, Rossi (28 yr old) in Eritrea discovers cosmic-ray air showers, but does not study them in detail
    - Publication in Italian, again…
    - Auger will re-discover and study in larger detail in 1936



Rossi, La Ric. Sc. Suppl. 1 (1934) 579

OSSERVAZIONE

La frequenza delle coincidenze registrate con i contatori lontani l'uno dall'altro e indicata nelle tabelle sotto il nome di « coincidenze casuali », appare più elevata di quella che sarebbe stata prevedibile in base al potere risolutivo delle registrazioni, misurato a Padova prima della partenza ($2 \cdot 10^{-4}$ sec. per la registr. II). Ciò fece nascere il dubbio che tali coincidenze non fossero, in realtà, tutte casuali. Questa ipotesi sembra essere avvalorata dalle due seguenti osservazioni:

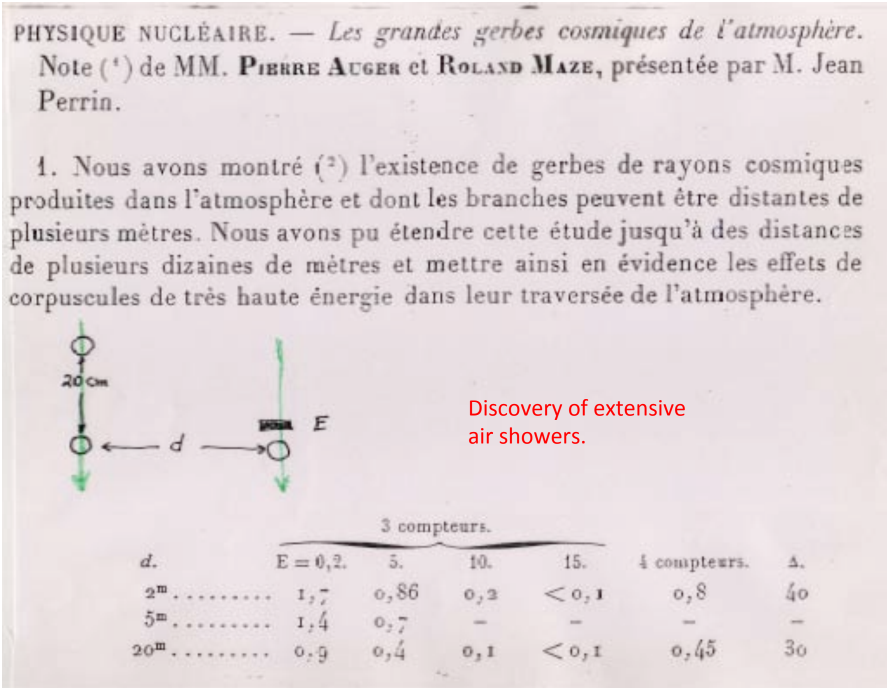
1º) In 21 ore e 37 minuti vennero registrate fra tre contatori allontanati e disposti in modo che uno stesso corpuscolo non potesse attraversarli, 14 coincidenze. Se queste fossero da considerarsi come casuali, alla registrazione dovrebbe venir attribuito un potere risolutivo di circa 0,02 sec.; ma in questo caso fra due contatori scoperti dovrebbero prodursi circa 200 coincidenze casuali all'ora, mentre in realtà se ne osservano solamente 6.

2º) Quando in una delle due registrazioni adoperate i contatori erano disposti in modo da registrare le coincidenze doppie « casuali », le rare coincidenze segnate da questa registrazione erano spesso accompagnate da una coincidenza simultanea della seconda registrazione.

Parrebbe dunque (poichè il dubbio di possibili disturbi venne escluso con opportune esperienze di controllo), che di tanto in tanto giungessero sugli apparecchi degli sciami molto estesi di corpuscoli, i quali determinassero coincidenze fra contatori anche piuttosto lontani l'uno dall'altro.

Mi è mancato purtroppo il tempo di studiare più da vicino questo fenomeno per stabilire con sicurezza l'esistenza dei supposti sciami di corpuscoli ed investigarne l'origine.

50



PHYSIQUE NUCLÉAIRE. — *Les grandes gerbes cosmiques de l'atmosphère.* Note (¹) de MM. PIERRE AUGER et ROLAND MAZE, présentée par M. Jean Perrin.

1. Nous avons montré (²) l'existence de gerbes de rayons cosmiques produites dans l'atmosphère et dont les branches peuvent être distantes de plusieurs mètres. Nous avons pu étendre cette étude jusqu'à des distances de plusieurs dizaines de mètres et mettre ainsi en évidence les effets de corpuscules de très haute énergie dans leur traversée de l'atmosphère.

d.	3 compteurs. E = 0,2.	5.	10.	15.	4 compteurs.	Δ.
2^m	1,7	0,86	0,2	< 0,1	0,8	40
5^m	1,4	0,7	–	–	–	–
20^m	0,9	0,4	0,1	< 0,1	0,45	30

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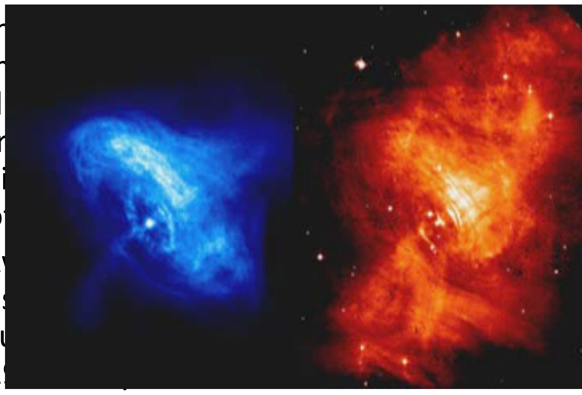
A conjecture on the origin of CR

(Zwicky in 1930)



- In … in … d … fr … ed … vi … face … o
- Z … can … a … s … in … 1 … :
  1. massive stars end their lives in explosions which blow them apart
  2. such explosions produce cosmic rays
  3. they leave behind a collapsed star made of densely-packed neutrons

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Most discoveries in elementary particle physics in the early years due to cosmic rays

- Thanks to the development of cosmic ray physics, scientists knew then that astrophysical sources were providing very-high energy bullets entering the atmosphere
- It was then obvious to investigate the nature of such bullets, and to use them as probes to investigate matter in detail, along the lines of the experiment made by Rutherford in 1900
  - Important contributions by W. Heisenberg in this phase
- Particle physics, the science of the fundamental constituents of matter, started with cosmic rays. Many fundamental discoveries were made…

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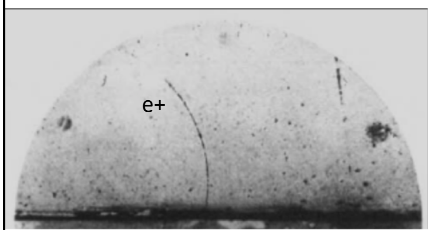
Antimatter (the antielectron, or positron: Anderson 1933)

- *Consistent with Weil's interpretation of Dirac's equation (1927-28) …*



But also
Skobelzyn 1927
Powell 1928
… ?

- Picture taken by Anderson in 1932 of a cloud chamber (Nobel to Wilson in 1927) in the presence of a magnetic field
- The band across the middle is a Pb plate, which slows down the particles. The momentum of the track after crossing the plate is smaller than before
- From the direction in which the path curves one can deduce that the particle is positively charged
- Mass can be deduced from the long range of the track - a proton would have come to rest in a shorter distance

=> It is a positive electron!

At the same time, gamma -> e+e- (Occhialini & Blackett)

A note: Dirac's equation announced in '28 in Cambridge; at the same conference Skobelzyn spoke about some unexplainable "wrong charge" events.

54

1936: The Nobel prize to Hess (& Anderson)

Hess was awarded the 1936 Nobel Prize in physics, shared with Anderson. Hess was nominated by Clay, Compton:

- *The time has now arrived, it seems to me, when we can say that the so-called cosmic rays have their origin at remote distances from the Earth […] and that the use of the rays has by now led to results of such importance that they may be considered a discovery of the first magnitude. [...] It is, I believe, correct to say that Hess was the first to establish the increase of the ionization observed in electroscopes with increasing altitude; and he was certainly the first to ascribe with confidence this increased ionization to radiation coming from outside the Earth*

Ahead of time

- Franz Linke, meteorologist; PhD: "Messungen elektrischer Potentialdifferenzen vermittels Kollektoren im Ballon und auf der Erde"
- 12 balloon flights: Sept. 1900 – Aug. 1903, with an Elster-Geitel 2-leaf electrometer
- Summary of his thesis: "Luftelektrische Messungen bei 12 Ballonflügen", Berlin 1904
- "Would one compare the presented values with those on ground, at 1000 m altitude where the measurements in general began the leakage [ionisation] is smaller than on ground, between 1 and 3 km of the same amount, and above larger than on Earth, with values increasing up to a factor of 4 at 5500 m altitude[…]. The uncertainties of the observations […] only allow the conclusion that the reason of the ionisation has to be found first in the Earth"

→ no reference in later papers, not known why

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Nominations for Nobel Prize 1936

Hess

Prof Clay (Netherlands)
Prof Compton (Chicago) with Anderson

Anderson

Prof Millikan (Pasadena)
Prof Nagoya (Tokyo)
Prof Dressmann (Berlin)
Prof von Laue (Berlin)
Prof Planck (Berlin)
Prof Perrin (Paris) with Blackett
Prof M. de Broglie (Paris) with Blackett
Prof L. de Broglie (Paris) with Blackett and Occhialini

57

Later, many new discoveries in fundamental physics from cosmic rays

- 1937: The muon, or mu lepton, discovered by Neddermeyer+(mistaken for the pion until 1947: Conversi, Pancini, Piccioni)
- 1947: Pion (or π meson), the first meson, discovered by Lattes, Occhialini & Powell (predicted by Yukawa in 1935)
- 1947: Kaon (or K meson), the first strange particle, discovered by Rochester & Butler
- 1951: Λ, the first strange baryon, discovered by Armenteros+
- 1951-54: Parity violation (G-stack, the first European collaboration – mother of the modern HEP collaborations)

- CR physics is relatively cheap, which is important in the post-war conditions of European science (mountain-top labs, balloons…)

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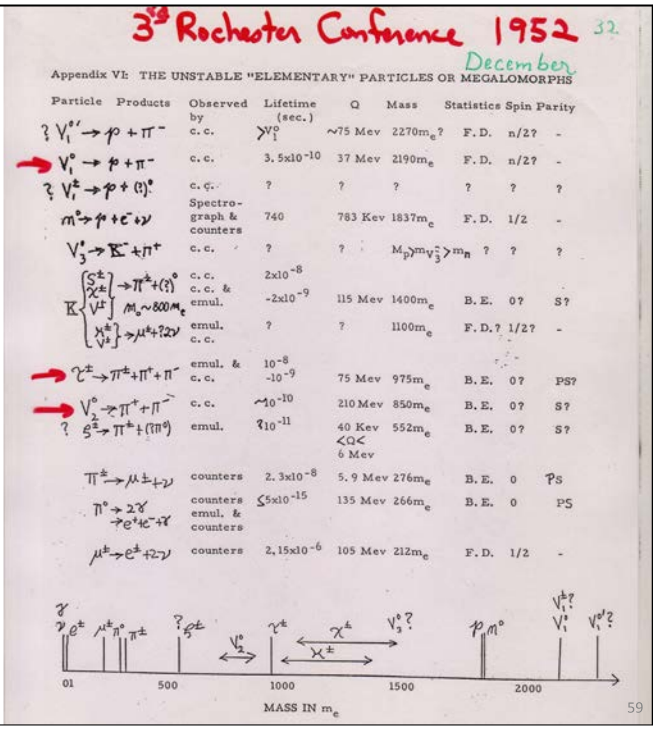
Particles found in cosmic rays

- Positron
- Muons
- Charged Pions
- K mesons
- Lambda
- Sigma
- Xi



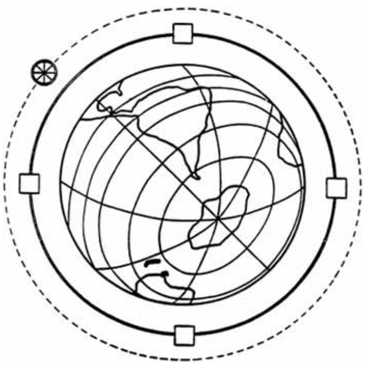
3rd Rochester Conference 1952 — December

Appendix VI: THE UNSTABLE "ELEMENTARY" PARTICLES OR MEGALOMORPHS

Particle Products	Observed by	Lifetime (sec.)	Q	Mass	Statistics	Spin	Parity
? $V_1^{0\prime} \to p + \pi^-$	c. c.	$> V_1^0$	~75 Mev	$2270 m_e$?	F. D.	n/2?	-
$V_1^0 \to p + \pi^-$	c. c.	3.5×10^{-10}	37 Mev	$2190 m_e$	F. D.	n/2?	-
? $V_1^{\pm} \to p + (?)^0$	c. c.	?	?	?	?	?	?
$n^0 \to p + e^- + \nu$	Spectrograph & counters	740	783 Kev	$1837 m_e$	F. D.	1/2	-
$V_3^0 \to K^- + \pi^+$	c. c.	?	?	$M_p > m_{V_3^-} > m_n$	?	?	?
K { $S^{\pm}, \chi^{\pm}, V^{\pm}$ } $\to \pi^{\pm} + (?)^0$, $M_0 \sim 800 m_e$	c. c. / c. c. & emul.	2×10^{-8} - 2×10^{-9}	115 Mev	$1400 m_e$	B. E.	0?	S?
K { $\kappa^{\pm}, V^{\pm}$ } $\to \mu^{\pm} + ?2\nu$	emul. c. c.	?	?	$1100 m_e$	F. D.?	1/2?	-
$\tau^{\pm} \to \pi^{\pm} + \pi^+ + \pi^-$	emul. & c. c.	10^{-8} - 10^{-9}	75 Mev	$975 m_e$	B. E.	0?	PS?
$V_2^0 \to \pi^+ + \pi^-$	c. c.	$\sim 10^{-10}$	210 Mev	$850 m_e$	B. E.	0?	S?
? $\varsigma^{\pm} \to \pi^{\pm} + (?\pi^0)$	emul.	$?10^{-11}$	40 Kev < Q < 6 Mev	$552 m_e$	B. E.	0?	S?
$\pi^{\pm} \to \mu^{\pm} + \nu$	counters	2.3×10^{-8}	5.9 Mev	$276 m_e$	B. E.	0	PS
$\pi^0 \to 2\gamma$, $\to e^+ + e^- + \gamma$	counters, emul. & counters	$\lesssim 5 \times 10^{-15}$	135 Mev	$266 m_e$	B. E.	0	PS
$\mu^{\pm} \to e^{\pm} + 2\nu$	counters	2.15×10^{-6}	105 Mev	$212 m_e$	F. D.	1/2	-

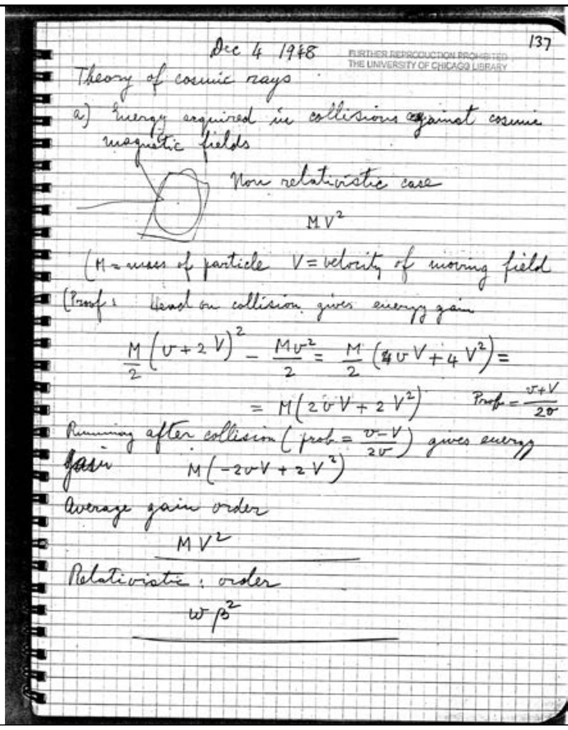
…and new hints for understanding (Fermi 1949)

- Proposal of 2nd order acceleration (Fermi, PR, 1949)



And also: the maximum possible energy for a terrestrial accelerator is ~ 5000 TeV (1954)

Fermi's 2nd order theory for acceleration of cosmic rays



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Organized by Louis Leprince-Ringuet and Patrick Blackett

62

L. Leprince-Ringuet

J. de Physique (Colloque #8) V 43 (1982)

38

Au Pic du Midi c'était Ch. Peyrou, B. Grégory, A. Lagarrigue, R. Armenteros, F. Müller puis A. Astier. Ont participé non seulement les français mais aussi des étrangers comme Ronald Rao de Princeotn, Tinlot de Rochester, Destaebler de Mit et aussi B. Le Fretter, en partie. Vous savez ce qui a été étudié au Pic. Le congrès de Bagnères de Bigorre en 1953, je dirais, a sonné le glas des rayons cosmiques et c'est Powell lui-même qui, dans son discours de clôture a dit : "Messieurs, maintenant nous sommes envahis, nous sommes sumbergés, ce sont les accélérateurs". Effectivement, la plupart des laboratoires de rayons cosmiques dont le nôtre, ici à l'Ecole Polytechnique, puis au Collège de France, se sont o-rientés vers les grands accélérateurs de particules et je voudrais vous dire aussi que le mot hypéron a été annoncé pour la première fois au congrès de Bagnères. Il y avait B. Rossi, E. Amaldi, C. Powell. Et on s'est demandé comment appeler ces nouvelles particules qui s'arrêtaient, qui étaient lourdes et qui donnaient un méson. Alors on a proposé divers noms. [Et je dois dire que c'est ma principale contribution à la physique, j'ai prononcé le mot hypéron] : le mot hypéron n'a pas été bien accueilli par Rossi. Rossi a dit "oh, hypéron, piperone, ça va pas". Et au contraire Powell était là et a dit "oh hypéron (prononcer haiperon) mervelous". Et on a dopté le mot hypéron. Et il a à Bagnères de Bigorre l'avenue de l'hypéron: c'est peut être le seul endroit au monde où une particule fondamentale a donné un nom à une avenue.

63

The 1953 CRC at Bagneres de Bigorre (Cronin 2011, arXiv:111.5338)

- From the concluding remarks by Leprince-Ringuet:

"If we want to draw certain lessons from this congress let's point out first that in the future we must use the particle accelerators. Let's point out for example the possibility that they will permit the measurement of certain fundamental curves (scattering, ionization, range) which will permit us to dierentiate effects such as the existence of pi mesons among the secondaries of K mesons.

I would like to finish with some words on a subject that is dear to my heart and is equally so to all the "cosmicians", in particular the "old timers". […] We have to face the grave question: what is the future of cosmic rays? Should we continue to struggle for a few new results or would it be better to turn to the machines?

One can no doubt say that that the future of cosmic radiation in the domain of nuclear physics depends on the machines […]. But probably this point of view should be tempered by the fact that we have the uniqueness of some phenomena, quite rare it is true, for which the energies are much larger […]"

- Then the accelerator era starts… And a particle zoo…

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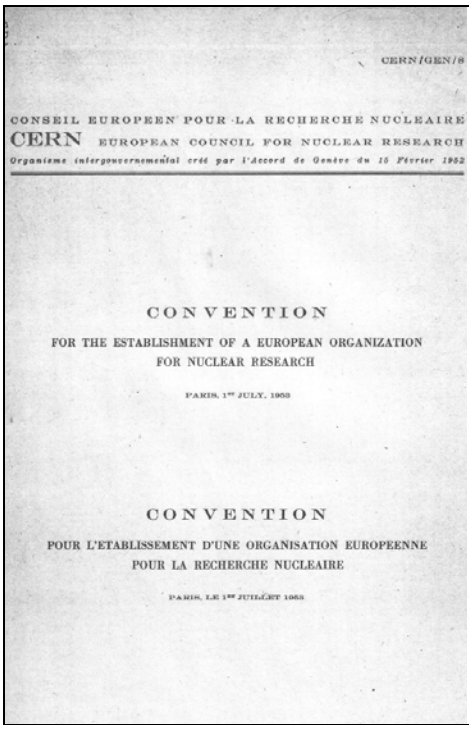
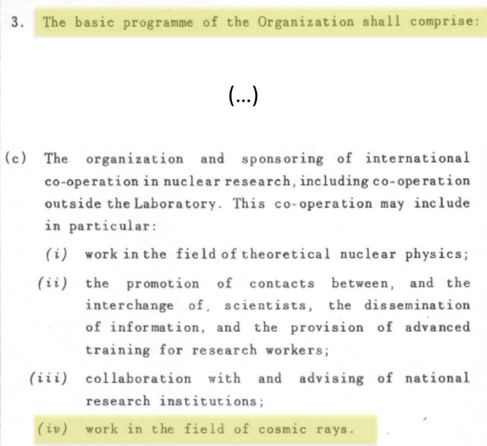

CERN/GEN/8

CONSEIL EUROPEEN POUR LA RECHERCHE NUCLEAIRE
CERN EUROPEAN COUNCIL FOR NUCLEAR RESEARCH
Organisme intergouvernemental créé par l'Accord de Genève du 15 Février 1952

CONVENTION
FOR THE ESTABLISHMENT OF A EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
PARIS, 1st JULY, 1953

CONVENTION
POUR L'ETABLISSEMENT D'UNE ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
PARIS, LE 1er JUILLET 1953

1953: research on cosmic rays is in CERN's constitution


3. The basic programme of the Organization shall comprise:

(…)

(c) The organization and sponsoring of international co-operation in nuclear research, including co-operation outside the Laboratory. This co-operation may include in particular:

(i) work in the field of theoretical nuclear physics;

(ii) the promotion of contacts between, and the interchange of, scientists, the dissemination of information, and the provision of advanced training for research workers;

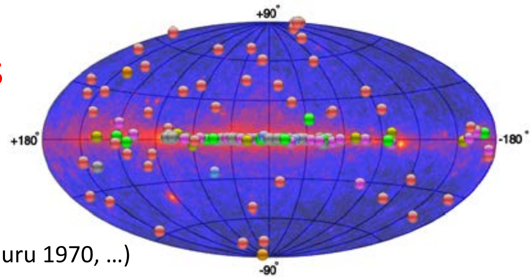
(iii) collaboration with and advising of national research institutions;

(iv) work in the field of cosmic rays.

Legacy from G-stack

The Organization shall (…) confine its activities to (…) the construction and operation of one or more international laboratories for research on high-energy particles, including work in the field of cosmic rays

The flame still burns in the following years



- CMB (1964)
- X-ray astrophysics
  - Rockets (1962) and satellites (Uhuru 1970, …)
- VHE gamma-ray astrophysics
  - Many attempts in '60-'70; observation of Crab above 100 GeV, Weekes et al. 1989
  - Present large-scale IACTs HESS, MAGIC, VERITAS → CTA; Agile, Fermi satellites
- EHE cosmic detectors
  - Observation of a particle ~ 10^{20} eV in 1962 at Volcano Ranch (Linsley, Scarsi et al. 1962)
  - 1966: the GZK limit
  - …
  - Present large-scale detectors: the Pierre Auger laboratory
- Neutrino detectors
- …

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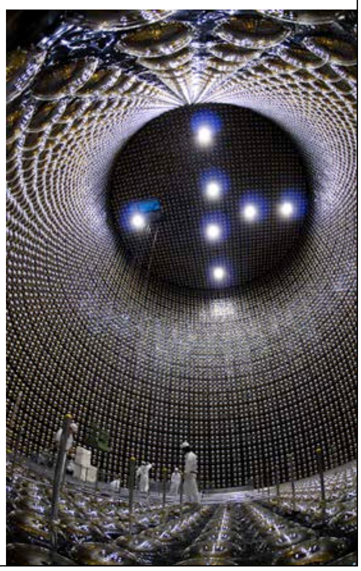
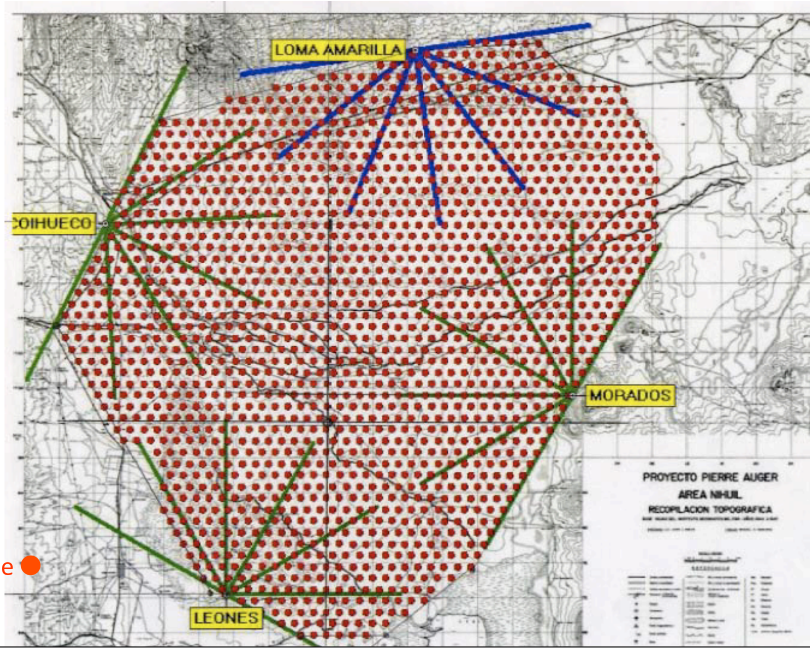
and CR continue to contribute to fundamental physics

- Cosmic rays and cosmological sources again move into the focus of VHE particle and gravitational physics
- One of the most important recent result on elementary particle physics came from cosmic rays: neutrino has a nonzero mass
  - Interplay between CR and accelerator physics, again
  - Solar neutrinos; KamLAND 2002 (reactor), Gran Sasso 2010 (accelerator), T2K 2011



The highest energy cosmic rays

3000 km^2



Malargue

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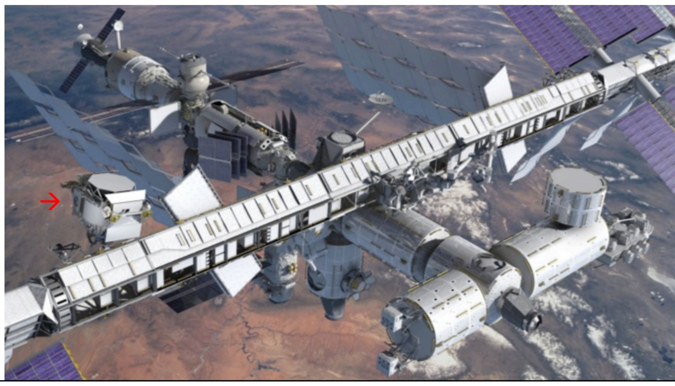
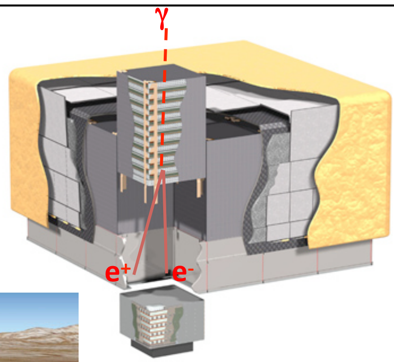
Alpha Magnetic Spectrometer

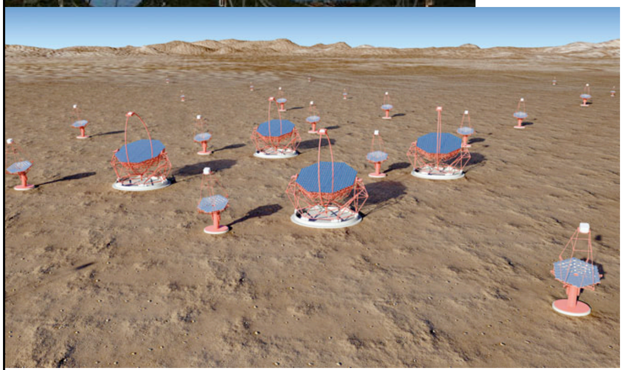
Measures in fine detail cosmic rays < some 10^{11} eV : dark matter, antimatter, exotic particles

Launched May 16, 2011



The direct probes of cosmic particle accelerators





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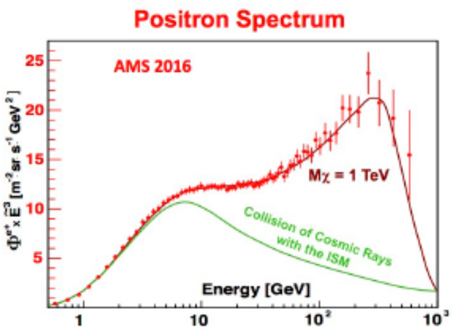
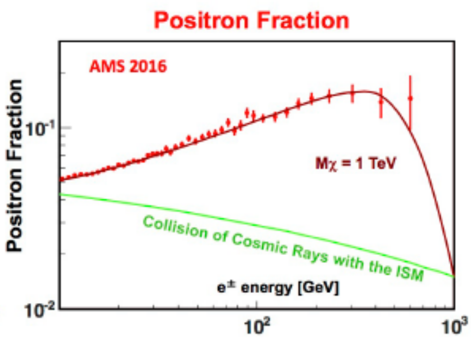
Excess of cosmic antimatter (PAMELA, AMS-02 2008-2016)





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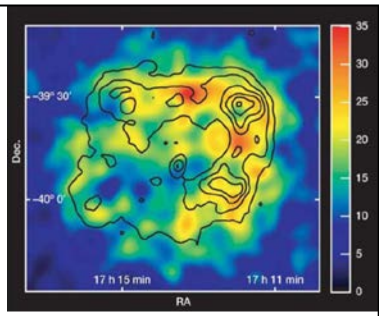
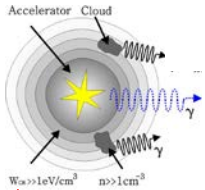
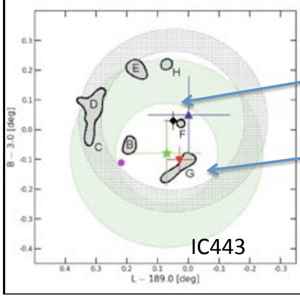
Sources of CR up to the knee

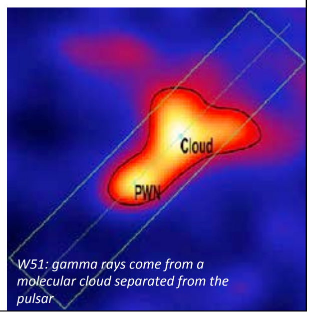
Cherenkov telescopes & X/gamma satellites

- Marginal evidence that SNR are sources of CR up to ~1000 TeV come from morphology studies of RX J1713-3946 (H.E.S.S. 2004)
- Striking evidence from the morphology of IC443 (MAGIC + Fermi/Agile 2010)
- Now ~ 10 SRNs accelerating hadrons are known (HESS, MAGIC, VERITAS, Fermi), plus a Pevatron in the GC region (H.E.S.S. 2016)



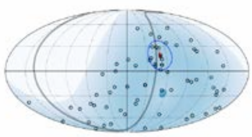


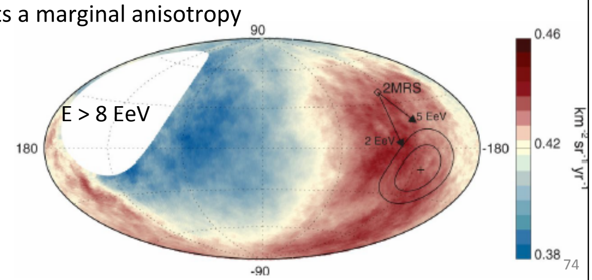




Evidence that (part of the) CR > 10^{19} eV come from AGN

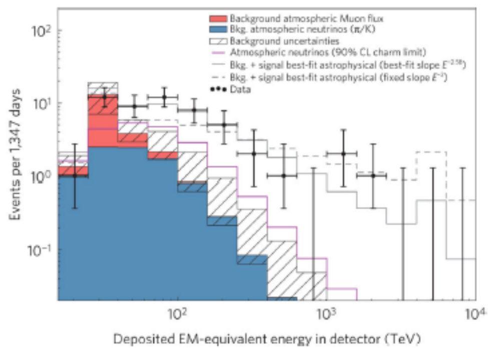
- In ~30 000 cosmic rays with energies above 8 EeV recorded over a period of 12 years, the Pierre Auger Observatory has evidenced at more than 5σ a dipole anisotropy
- If UHE cosmic rays originate from an inhomogeneous distribution of sources and then diffuse through intergalactic magnetic fields, one can expect dipole amplitudes growing with energy
- If the sources were distributed like galaxies, the distribution of which has a significant dipolar component, a dipolar cosmic-ray anisotropy would be expected
- Follows a claim (Auger 2007) of a correlation with Cen A
  - Also Telescope Array detects a marginal anisotropy

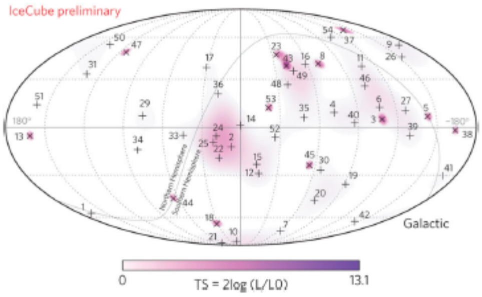

E > 55 EeV



Astrophysical neutrinos (2013)

- Evidence that there are neutrinos above 20 TeV (and up to 10 PeV) coming from extragalactic sources, not GRB (probably AGN)
- February 2018: a least one AGN located





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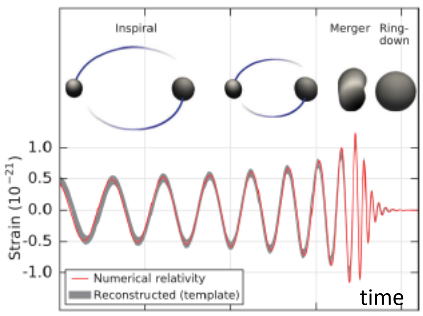
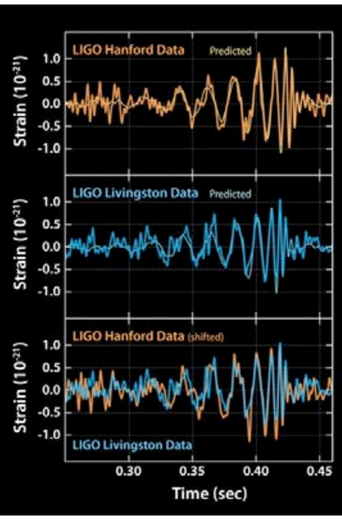
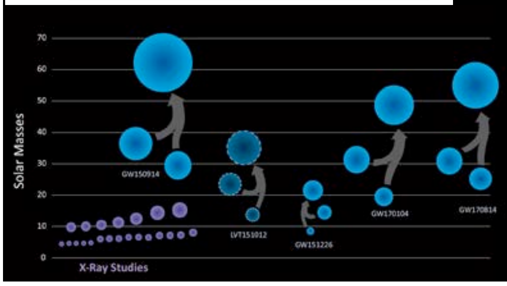
Gravitational Waves (2015-2017)







And on Oct. 16, 2017: simultaneous gw/ gamma ray event. NS-NS merger, with GRB

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Conclusion

- Cosmic Ray physics and particle physics at laboratories/accelerators are a successful example of an interplay between disciplines; after 100 years this cooperation is still at the cutting edge
  - A century of great discoveries, and more to come
- The work behind the discovery of CR involved scientists all around the world. It is a successful example of international cooperation
- There is an acceleration of the discovery in cosmic ray physics in the XXI century
- Multimessenger astrophysics!

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