High Energy (Multimessenger) Astroparticle Physics 2020/21

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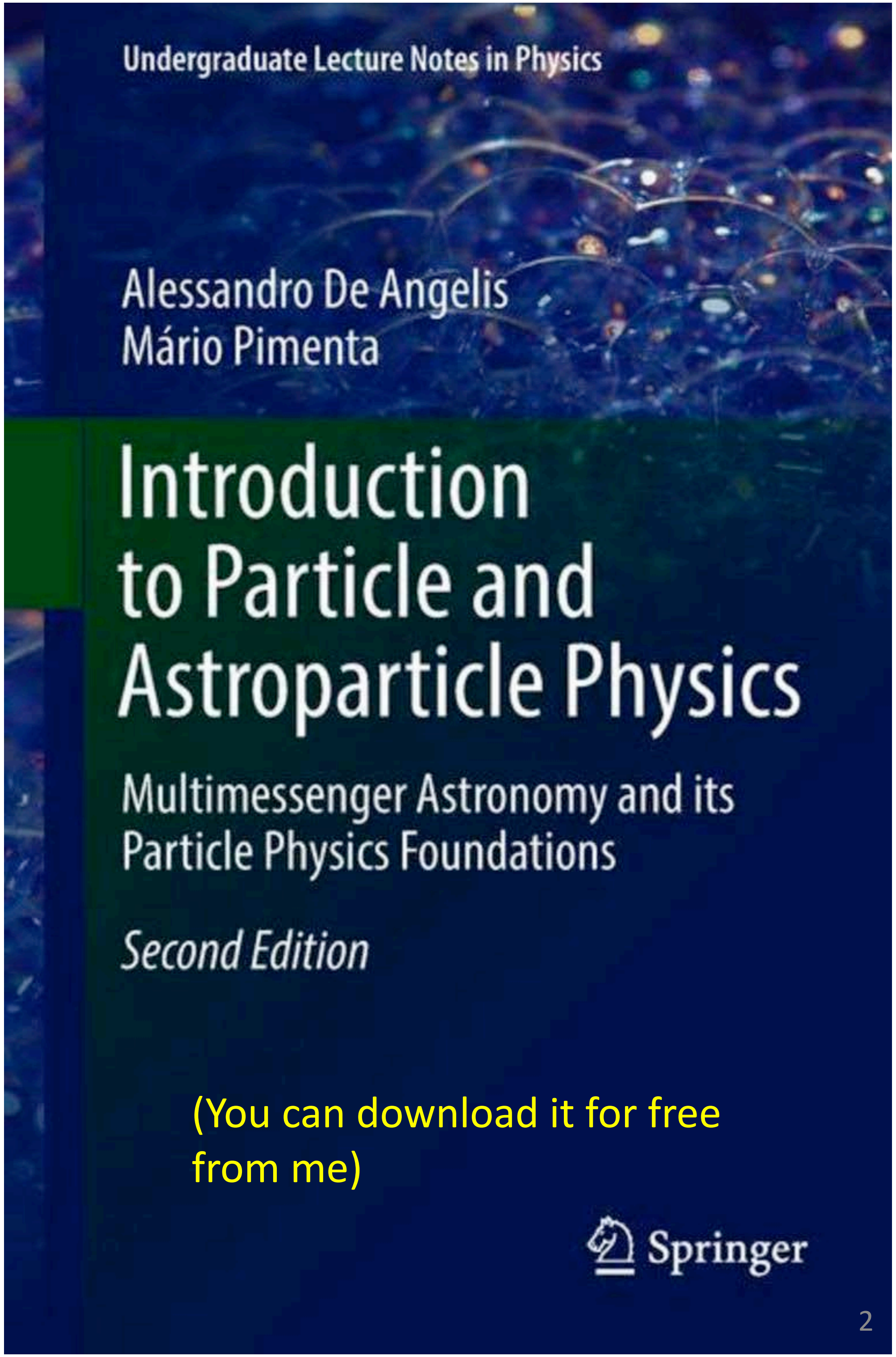
About this course

- 8 lectures in 2-3 weeks, end of January/beginning of February
- 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, neutrinos & multiwavelength astrophysics
  - Open problems; the future
- How you will be evaluated:
  - A seminar on a topic of your choice



(You can download it for free from me)

Syllabus

1. Introduction; high-energy physics phenomena in the Universe; history of cosmic ray research (Chap. 1 and Chap. 3 excluding 3.2.1 in the textbook)
2. How to detect high-energy cosmic rays (2.5-.6; 4.1; 4.2; 4.3.2; 4.4 excluding 4.4.1-2; 4.5; 4.6) FRI 16:30
3. Astrophysical mechanisms of particle acceleration (10.1) MON 18/1 1630
4. The budget of energy and matter in the Universe; Dark Matter and its signatures (8.1; 8.4; 8.5; 10.1.4; 10.4.1.3-.4; 10.4.2.4) TUE 1630
5. Acceleration sites and sources (10.2) WED 1630
6. Propagation of GW and of charged cosmic rays. Propagation of gamma rays and neutrinos; axions, ALPs and mirror photons (10.3) THU 1630
7. More experimental results on cosmic rays; multimessenger astrophysics (10.4). The final exam. FRI 1630
8. A look to the future (10.5) MON 25/1 1630
9. (IF POSSIBLE) Laboratory: Analysis of Fermi-LAT data, with prof. F. Longo (optional for Astronomy students)
10. (IF POSSIBLE) Laboratory: Analysis of Fermi-LAT data, with prof. F. Longo (optional for Astronomy students)

(Note: apart from Wed 20/1, we can move all lectures to 9:00, morning)

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 ASTROGAM concept satellite: ASTROGAM, e-ASTROGAM, AS-ASTROGAM…, look in the web)

- 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. Project scientist from 2005 to 2007 and in 2010.
  - Cherenkov Telescope Array
  - ASTROGAM satellite since 2016
  - SWGO Observatory in South America since 2019

- Author or co-author of >700 scientific publications, and three 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

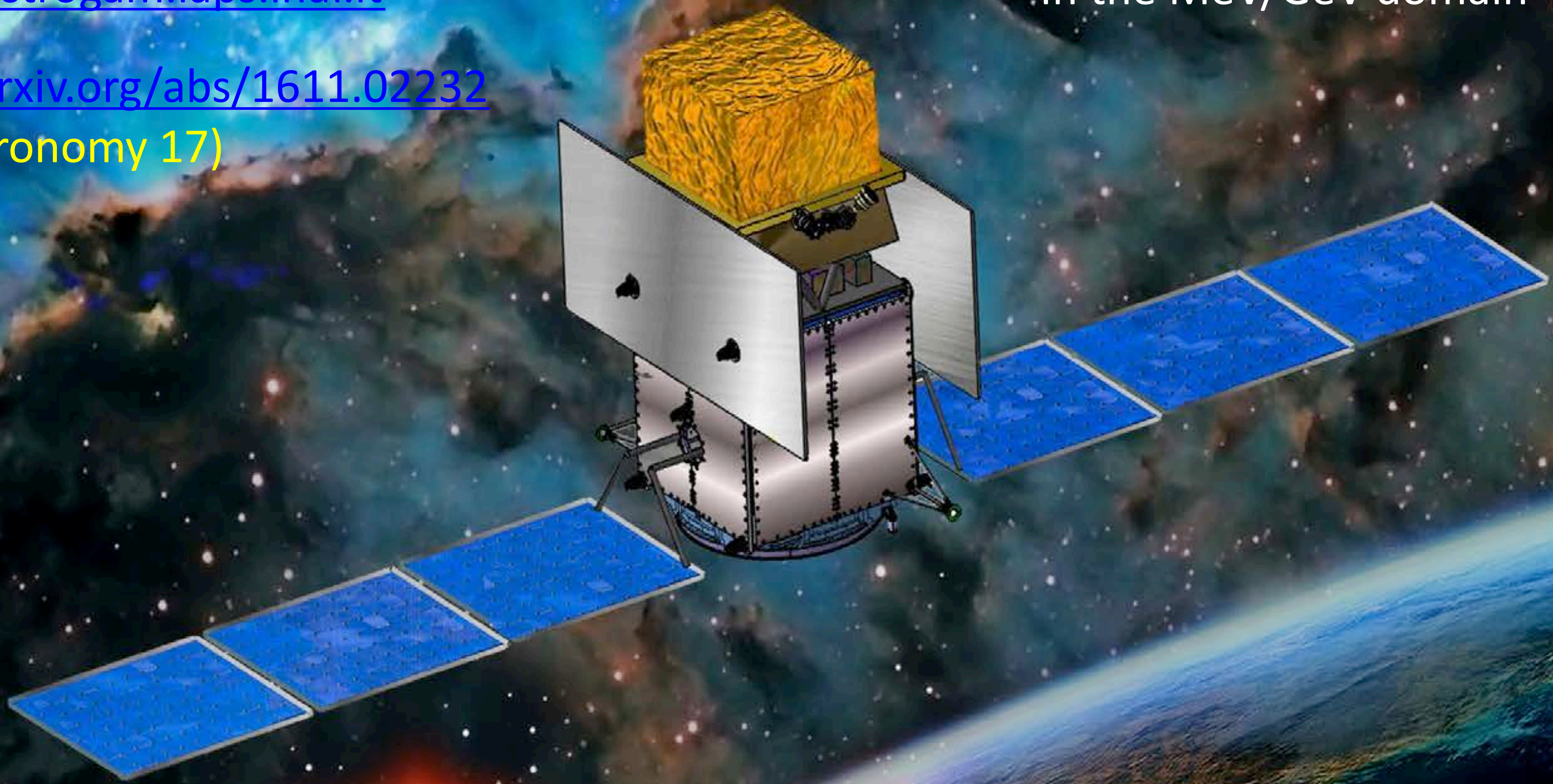
e-ASTROGAM

at the heart of the extreme Universe

An observatory for gamma rays
In the MeV/GeV domain

http://eastrogam.iaps.inaf.it

https://arxiv.org/abs/1611.02232
(Exp. Astronomy 17)



The last 10 years have been the golden years of experimental very high energy astrophysics, that became multimessenger (Photons, GW, neutrinos)

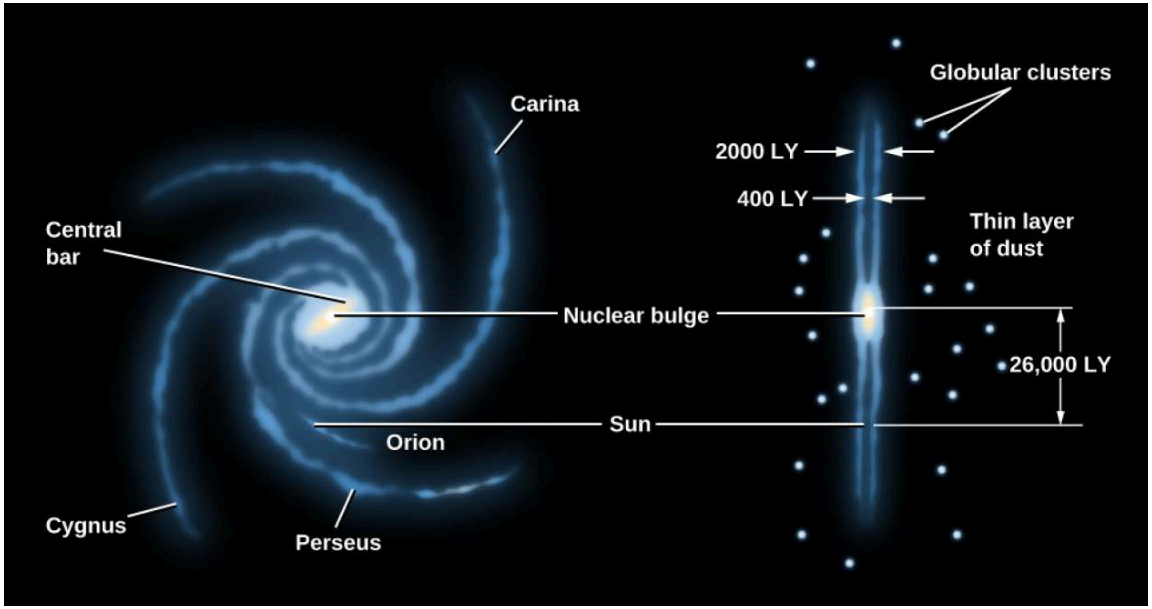
- 2003-2010: Hypernovae produce long gamma-ray bursts (GRBs)
- 2007-2017: Cosmic rays beyond 8 EeV come from AGN (the region of accretion of SMBH in galaxies)
- 2007-2017: Cosmic rays from 100 TeV to 1 PeV come from supernova remnants
- 2013: Astrophysical neutrinos above 100 TeV come from extragalactic 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

Seven Nobel Prizes (2002, 2006, 2011, 2015, 2017, 2019, 2020) to astroparticle physics/cosmology in the new millennium

Impressive fallout on fundamental physics

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 μG 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?

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

$$v = H_0 d$$

$H_0 \sim 70$ 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 simplified 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.

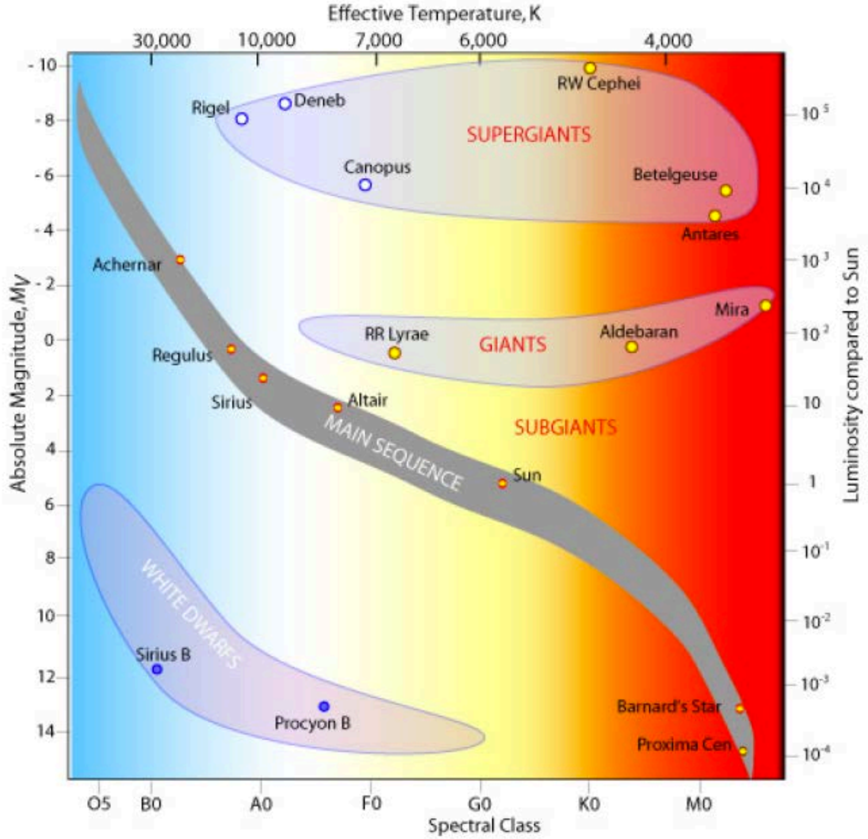
- The adiabatic expansion of the Universe entails a freezing with expansion, which in the nowadays quiet Universe can be summarized as a law for the evolution of the temperature T on the size

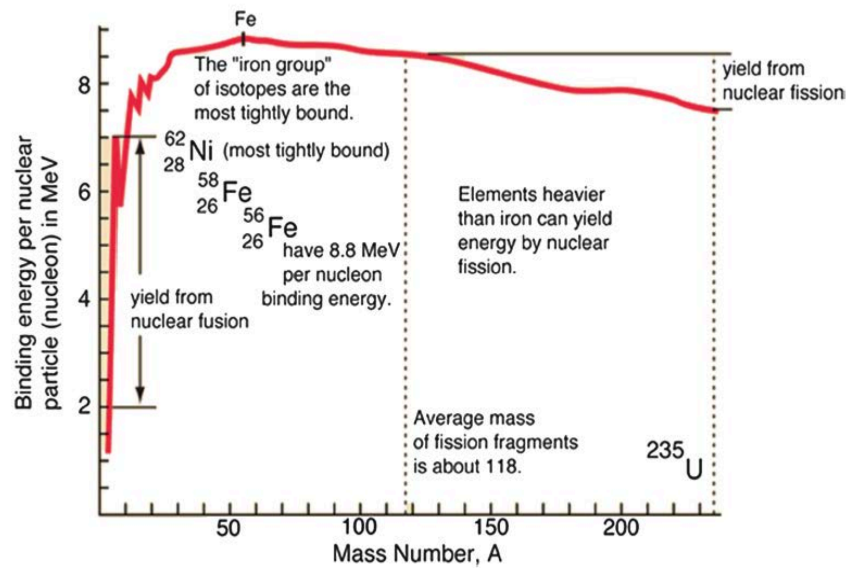
$$T = b/R$$

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 effective 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.





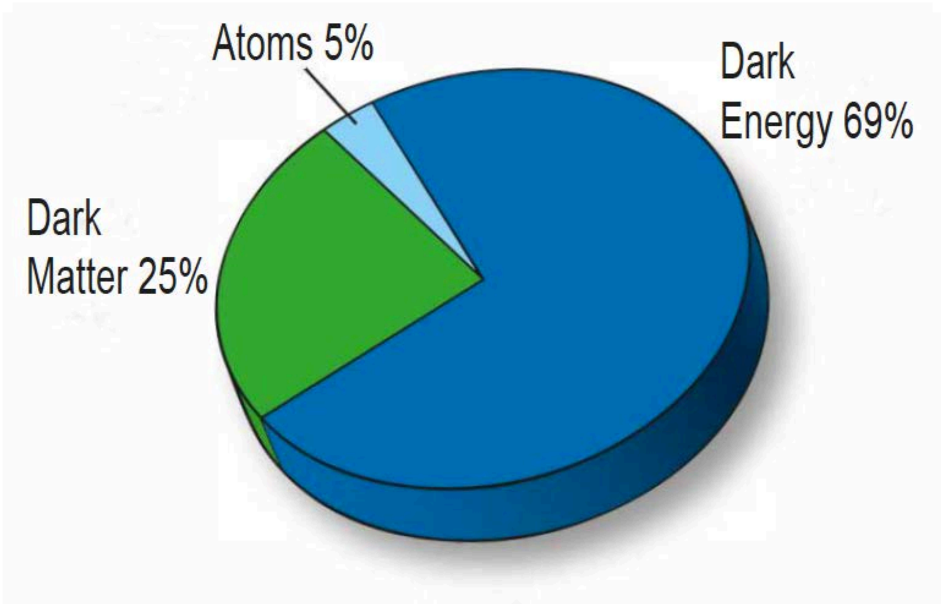
Expansion, composition, fate of the Universe

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

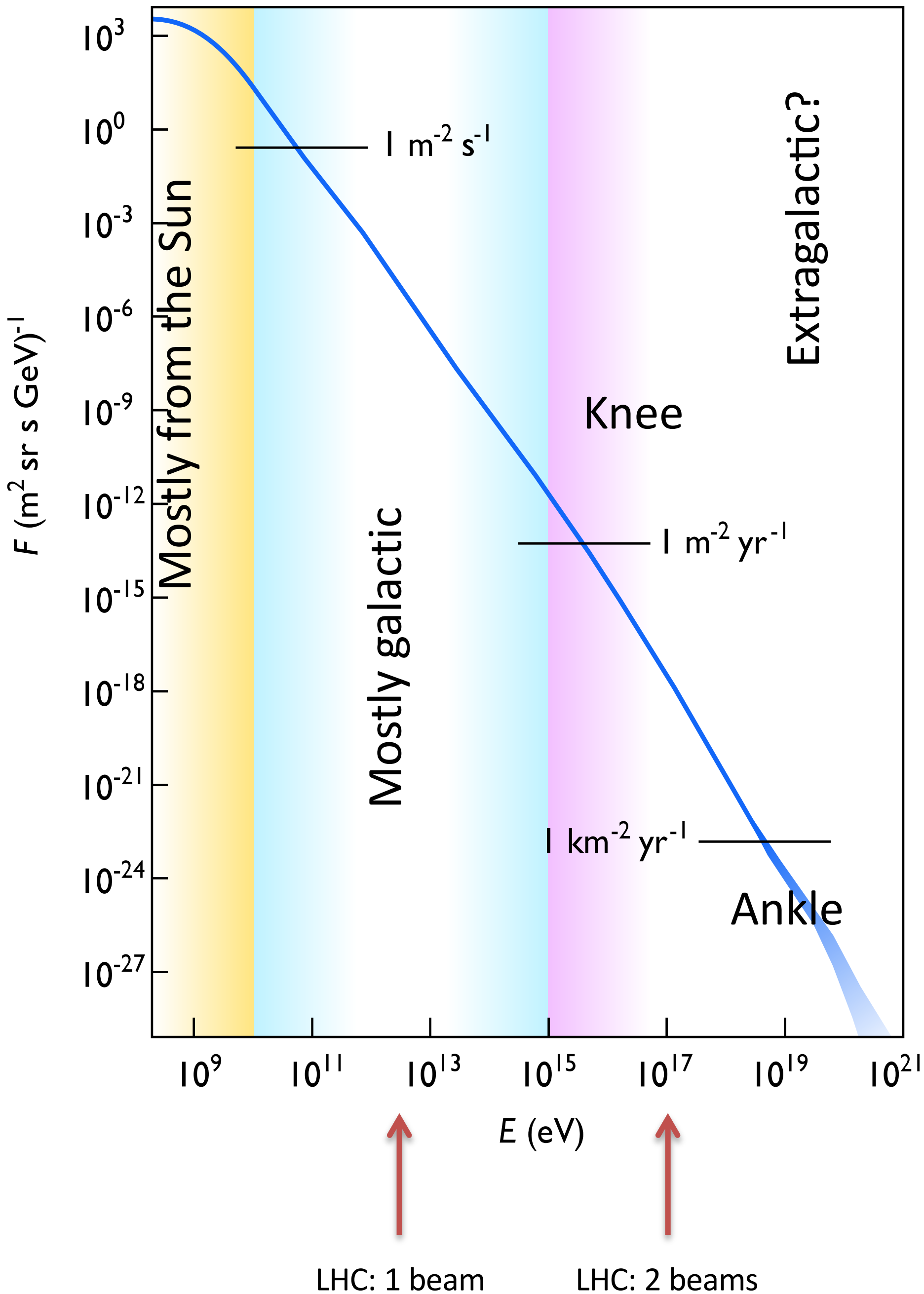
$$v = H_0 r < v_{esc} = \sqrt{\frac{8}{3}\pi G r^2 \frac{\rho}{c^2}} \Longrightarrow \rho > \boxed{\rho_{crit} = \frac{3H_0^2 c^2}{8\pi G}}$$

~ 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.

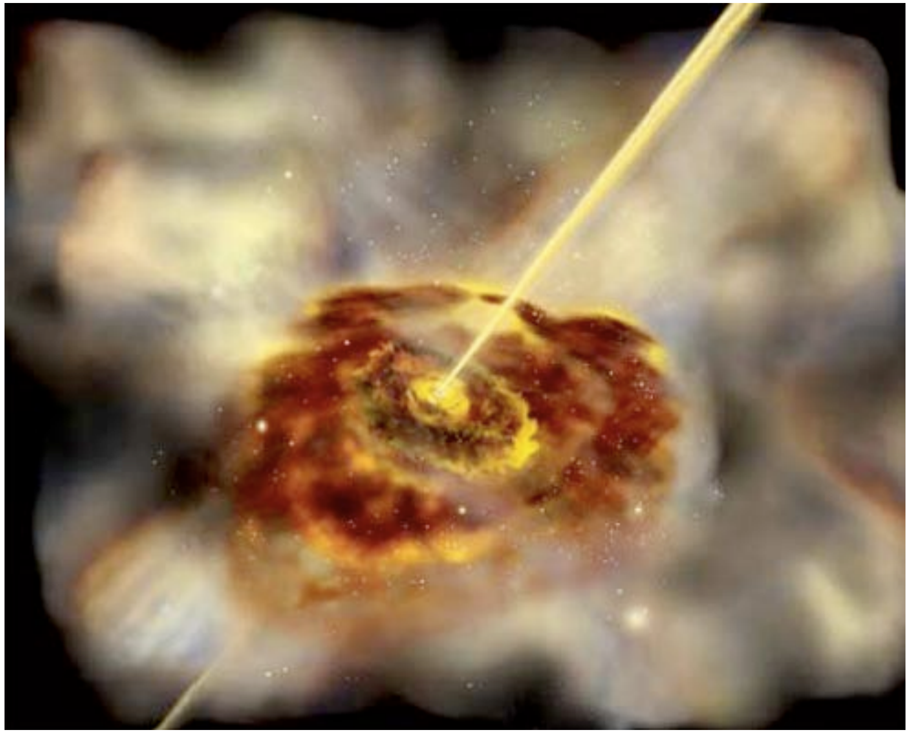


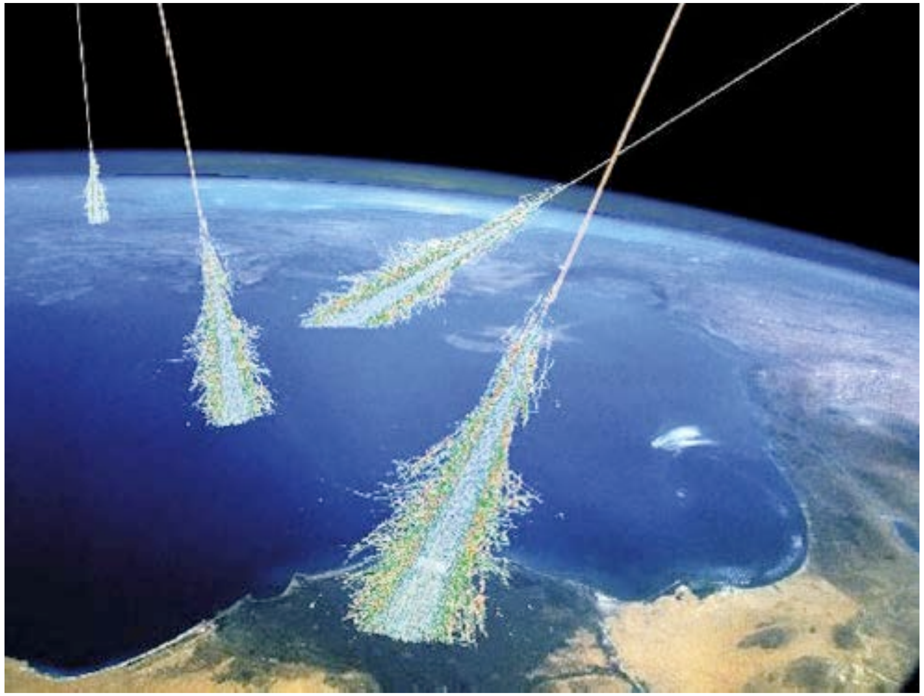
Short phenomenology of Cosmic Rays

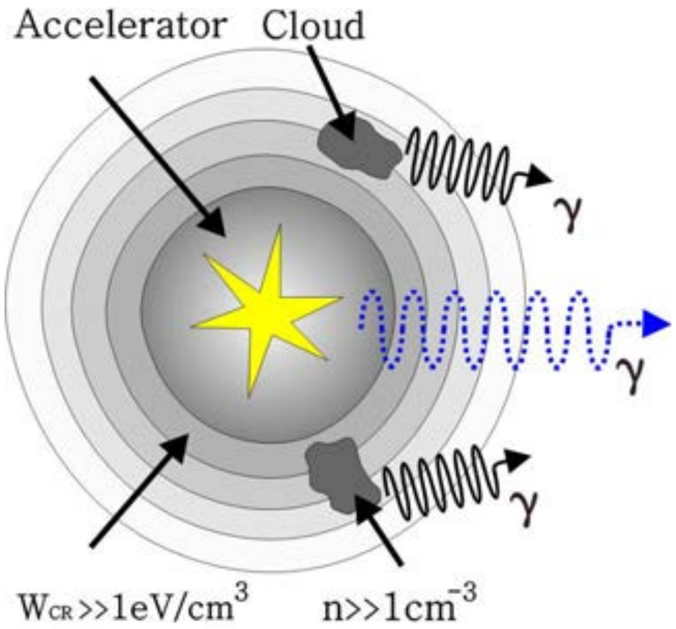


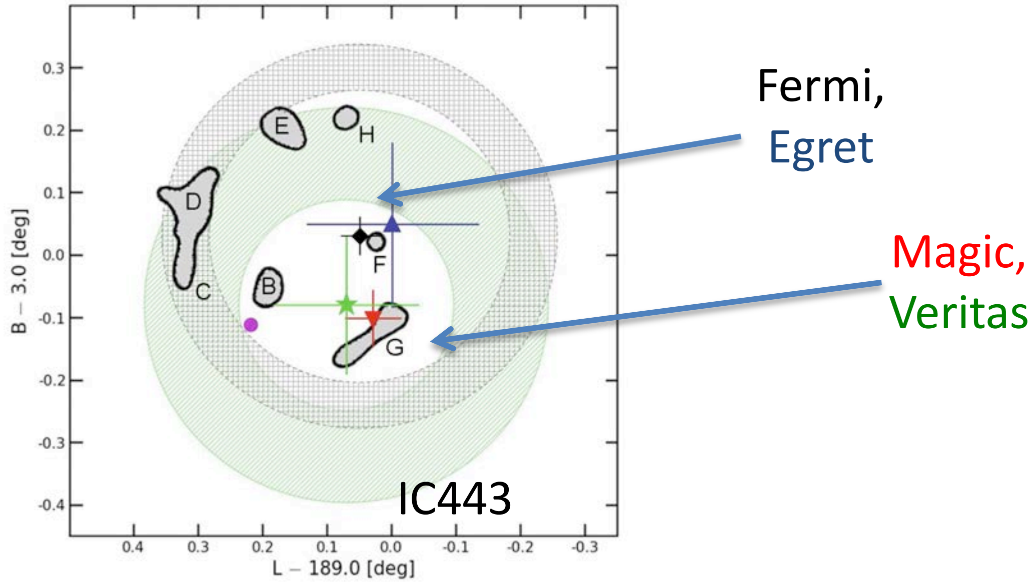
- Cosmic rays (CR) are subatomic particles reaching the Earth from outside
- They are mostly protons
  - But the minority (heavy nuclei, neutrinos, gammas, antimatter... is very important)
- The flux depends strongly on energy
  - They reach the highest energies, up to 10^{21} eV

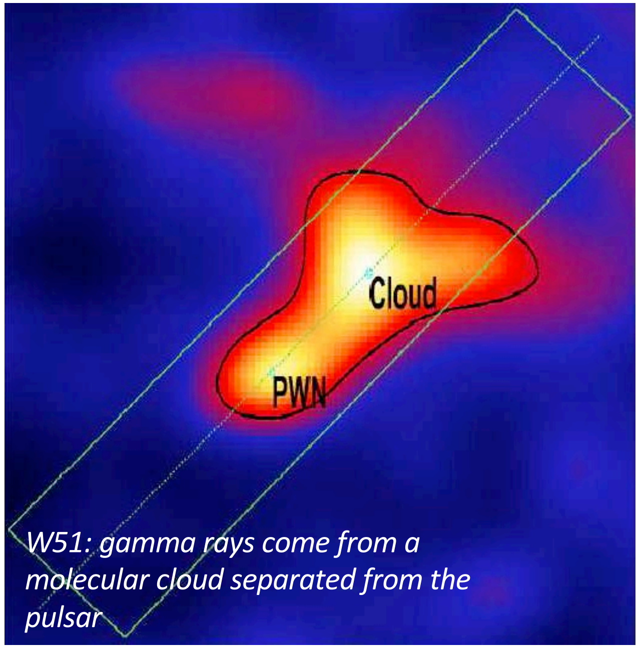
- Kinetic energy is likely to come from potential gravitational energy (collapses of astrophysical objects)
  - Below ~10^7 GeV: likely to be Galactic (supernova remnants)
  - Above: likely to be extragalactic (accreting supermassive black holes: Active Galactic Nuclei)
- Once CR hit the atmosphere,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

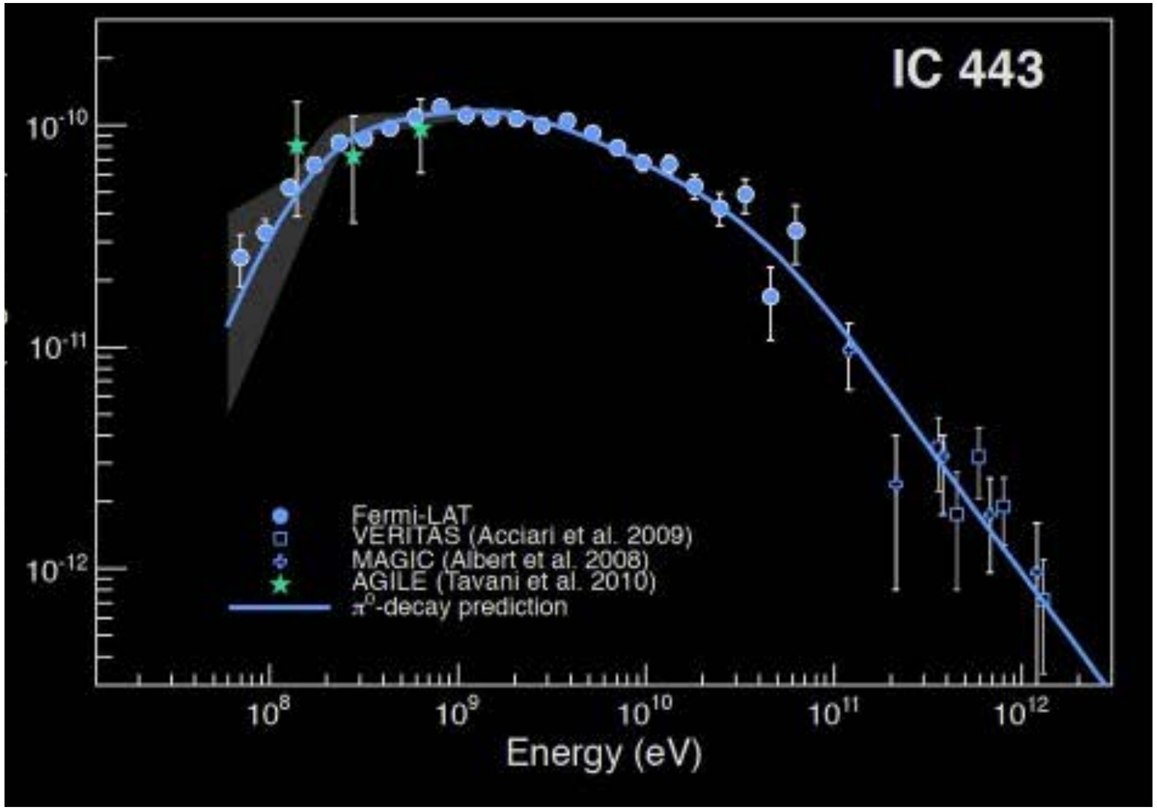




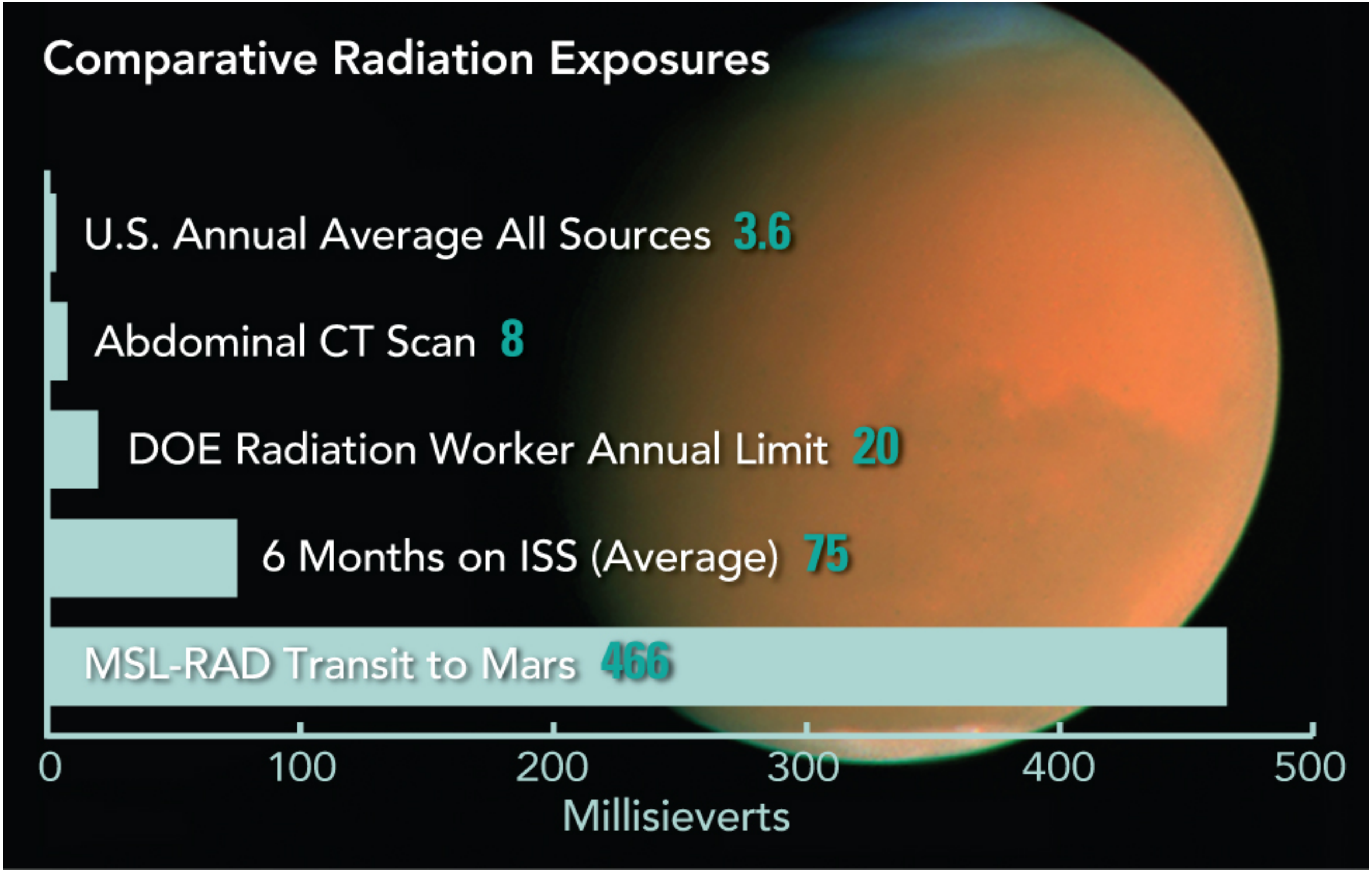

Accelerator
Cloud
γ
γ
γ
W_{CR}>>1eV/cm3
n>>1cm-3


Fermi,
Egret
Magic,
Veritas
IC443
B – 3.0 [deg]
L – 189.0 [deg]
E
H
D
C
F
B
G


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


IC 443
Energy (eV)
Fermi-LAT
VERITAS (Acciari et al. 2009)
MAGIC (Albert et al. 2008)
AGILE (Tavani et al. 2010)
π^0-decay prediction

Cosmic Rays on Mars

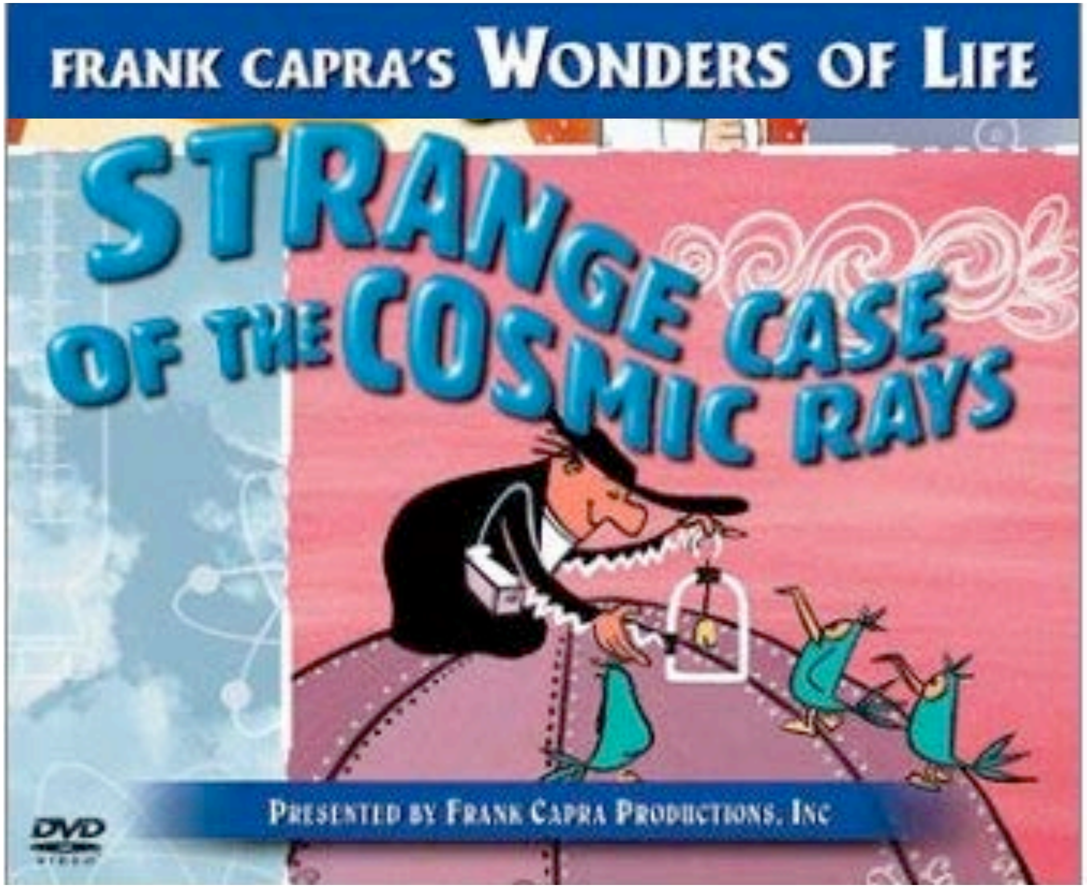


But they are also at the origin of life:

Carbon has extraterrestrial origin

The CH3 sequence is activated by cosmic rays

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



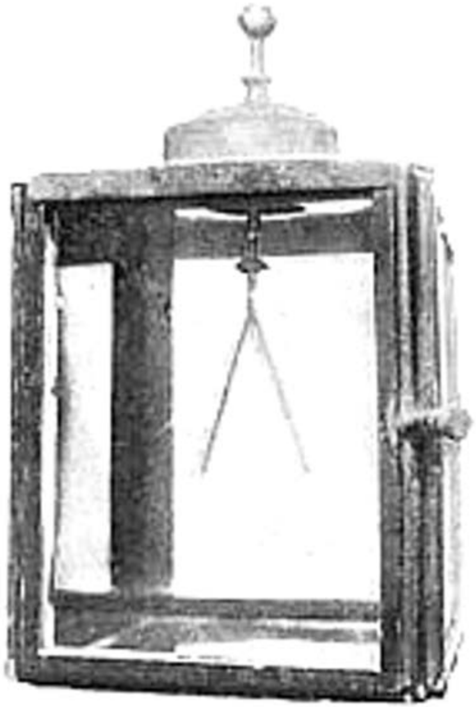
(F. Capra/W. Disney production, a 1957 movie written by Anderson & Rossi)

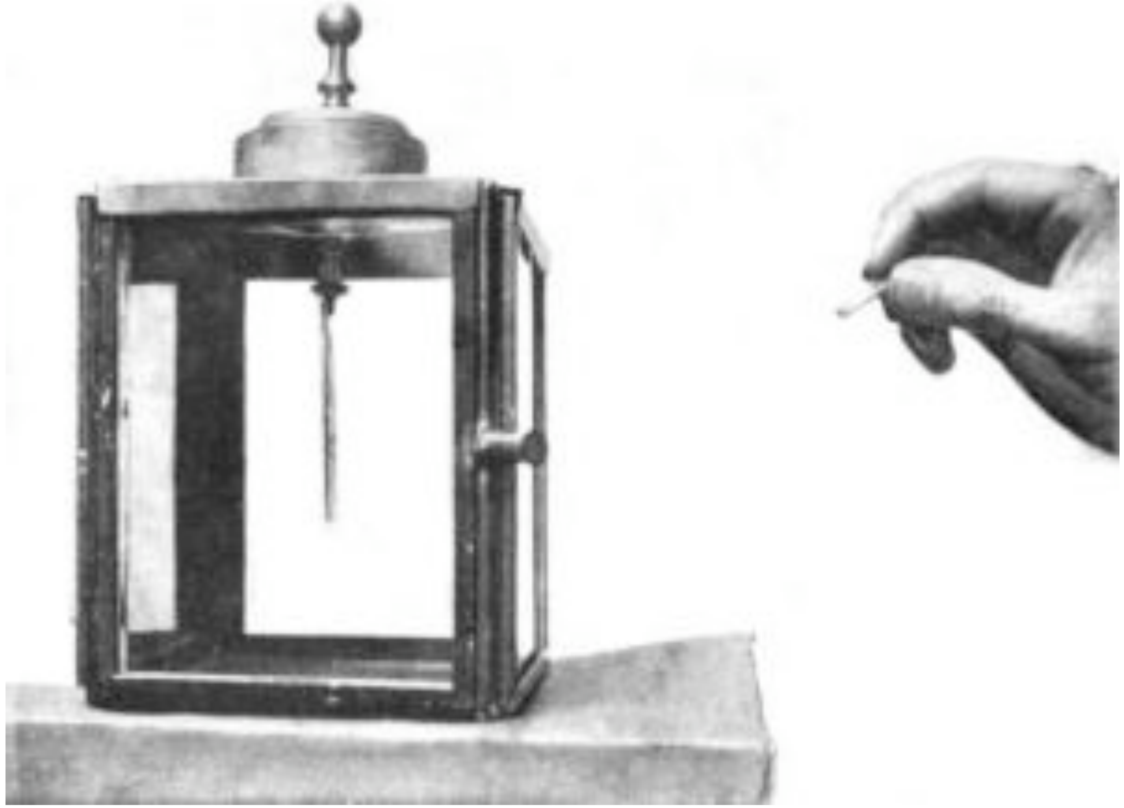
Electroscopes discharge spontaneously. Why?

- 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)

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





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

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

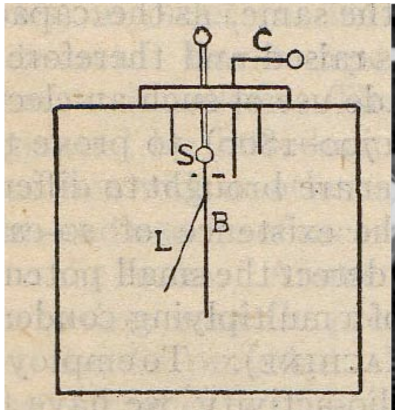


FIG. 6.—Elster and Geitel Electroscope.


(C.T.R. Wilson)

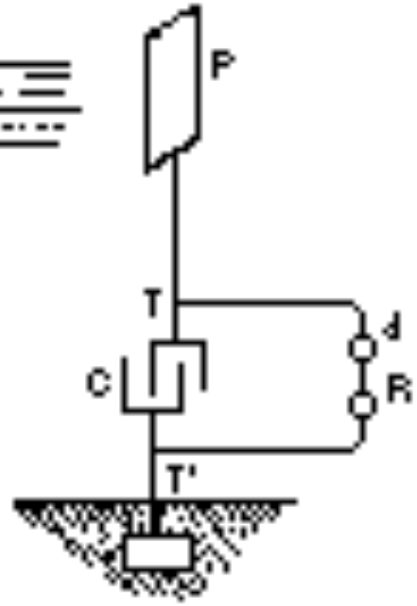
1903-06: Rutherford & Cooke and McLennan & Burton show that ionization is marginally reduced when an electroscope is surrounded by metal shields. McL&B put also the electroscope in a box, and they fill it with water. Mache compares the variations of the radioactivity when the electroscope is surrounded 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 wel as other sources of radiant energy throw off minute particles of matter positively electrified, which […] communicate an electrical charge



- Could it work?

  Yes

- How much power can it generate

  $P < 3\ GeV \times 10000\ CR/sm^2$

  $\Rightarrow P < 5\ \mu W/m^2$

  (Solar energy: ~ 1000 W/m²)

1 particle/cm^2/s

<E> ~ 3 GeV

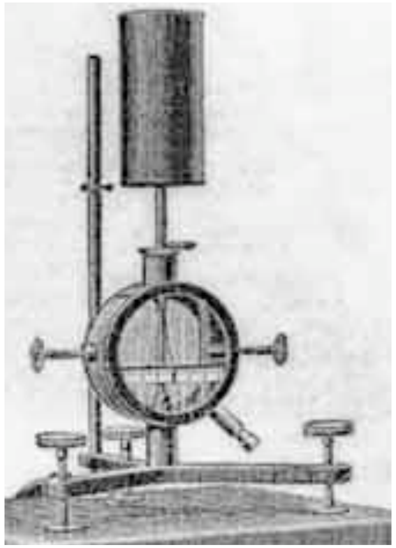
The experiments in the beginning of the XX century

- 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

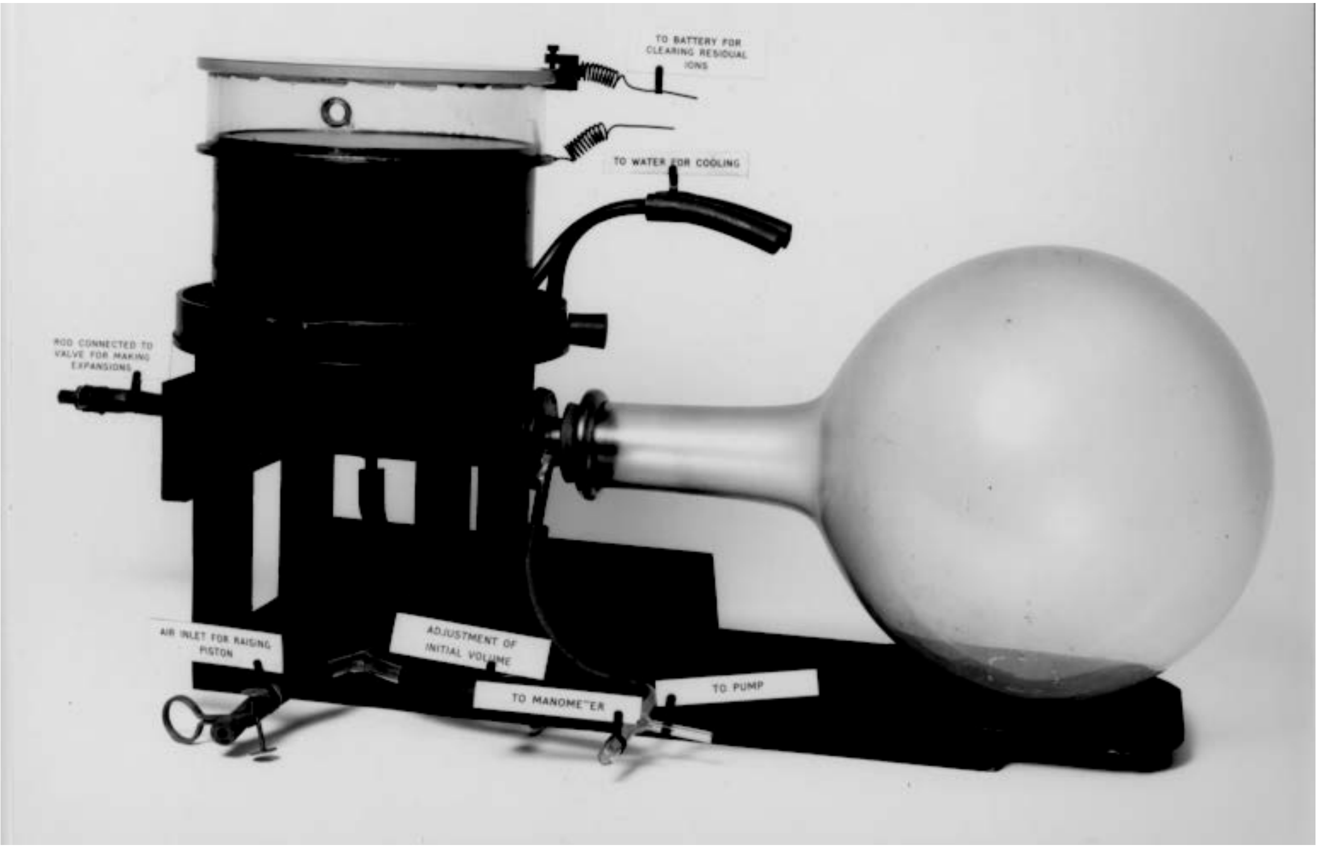
- 1908: Elster & Geitel observe a fall of 28% when the apparatus is taken from the surface down to the bottom of a salt mine. They conclude that, in agreement with the literature, the Earth is the source of the penetrating radiation and that certain waters, soils and salt deposits, are comparatively free from radioactive substances, and can therefore act as efficient screens

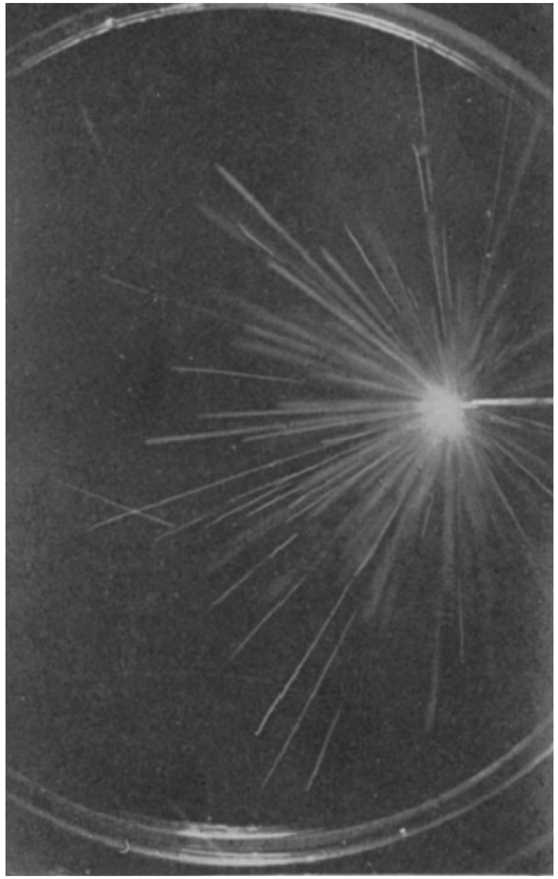
(Eve, Rutherford)



In parallel, the cloud chamber…

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

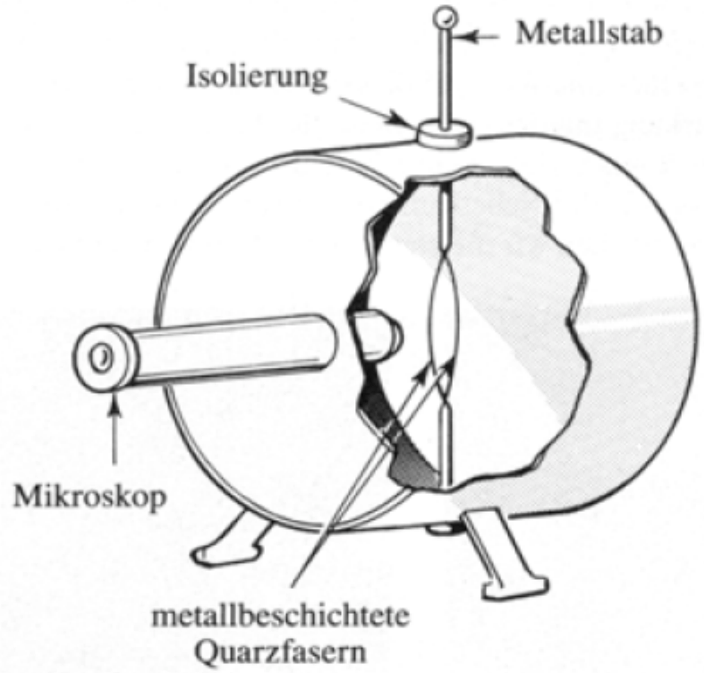




Wilson obtained the first images of the tracks of α and β particles. As Blackett remarked, ‘[The many exquisite photographs …] still remain among the technically best photographs ever made.’

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)

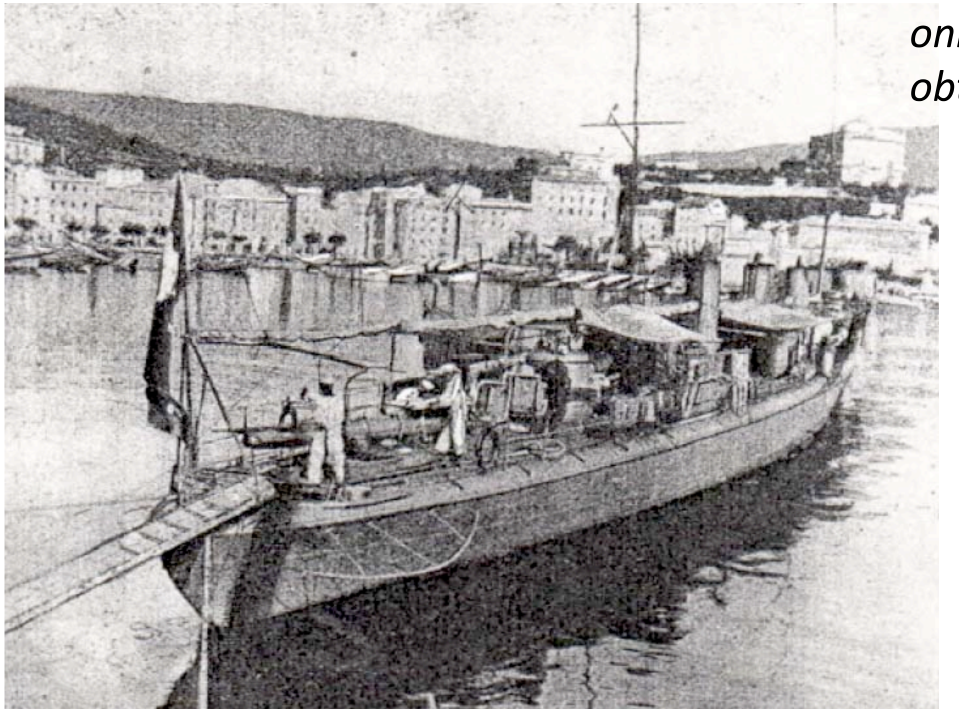


The Wulf experiments (1909-1910)

- 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

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

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 cm^3 al 1".

Coll' apparecchio immerso:

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

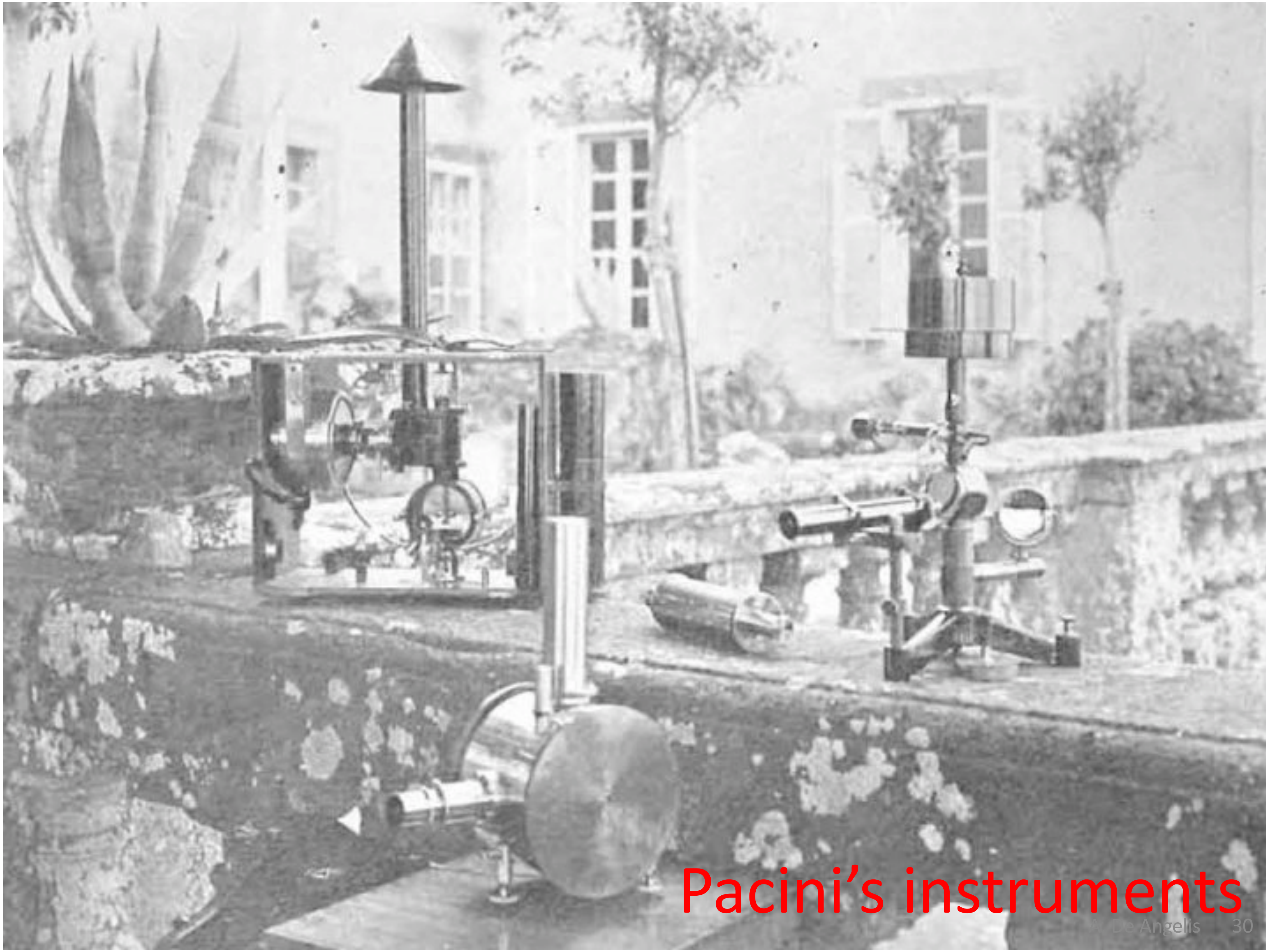
media 10,3 equivalente a ioni 8,9 per cm^3 al 1".

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."*

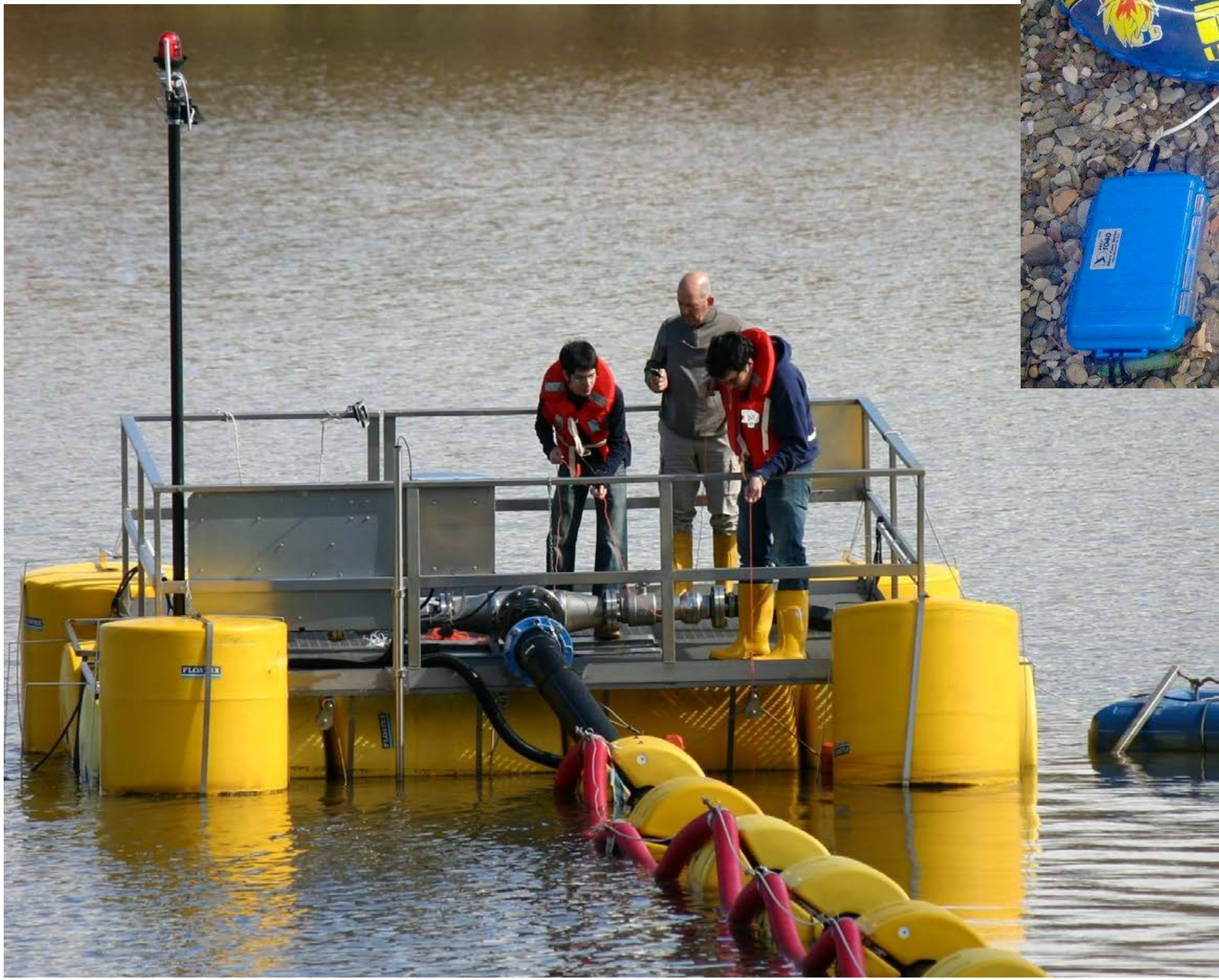
Pacini's experiment marked the beginning of the underwater technique for CR studies



Pacini’s instruments

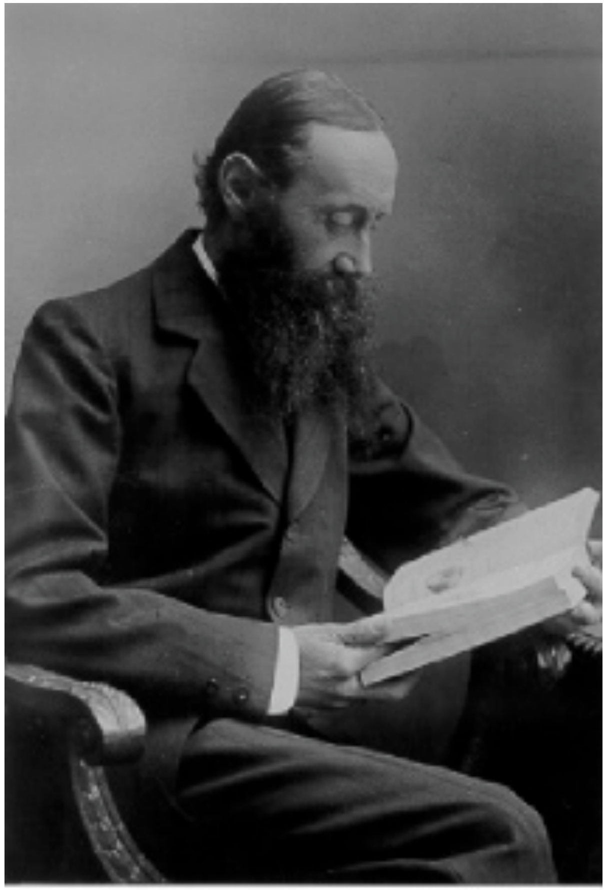
Remake of the Pacini experiment in 2011

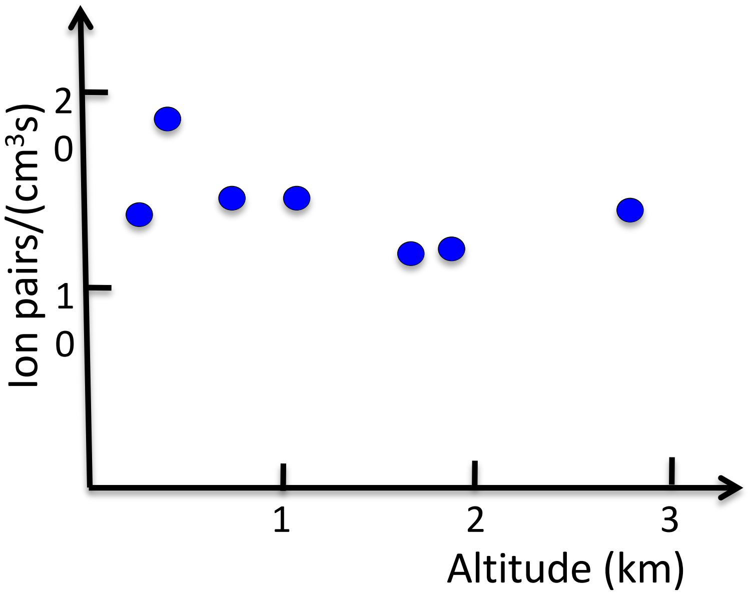
(G. Batignani et al., Giornale di Fisica, Sept. 2011)



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





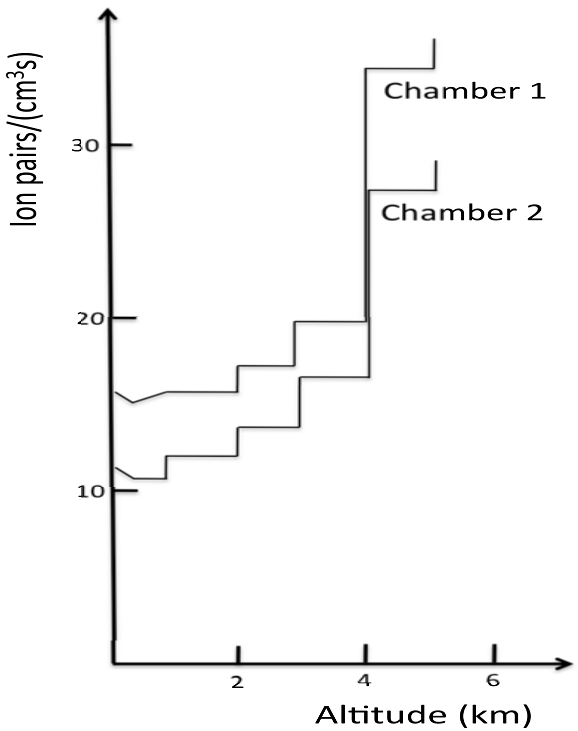
- How to increase the sensitivity of Wulf's measurements on the Eiffel tower? Flying on balloons!
- The first balloon flights with the purpose of studying the properties of penetrating radiation were arranged in 1909, in Germany by Bergwitz, and in Switzerland by A. Gockel, professor at the University 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"

A new boost: Hess


(Wien 1907)

- 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

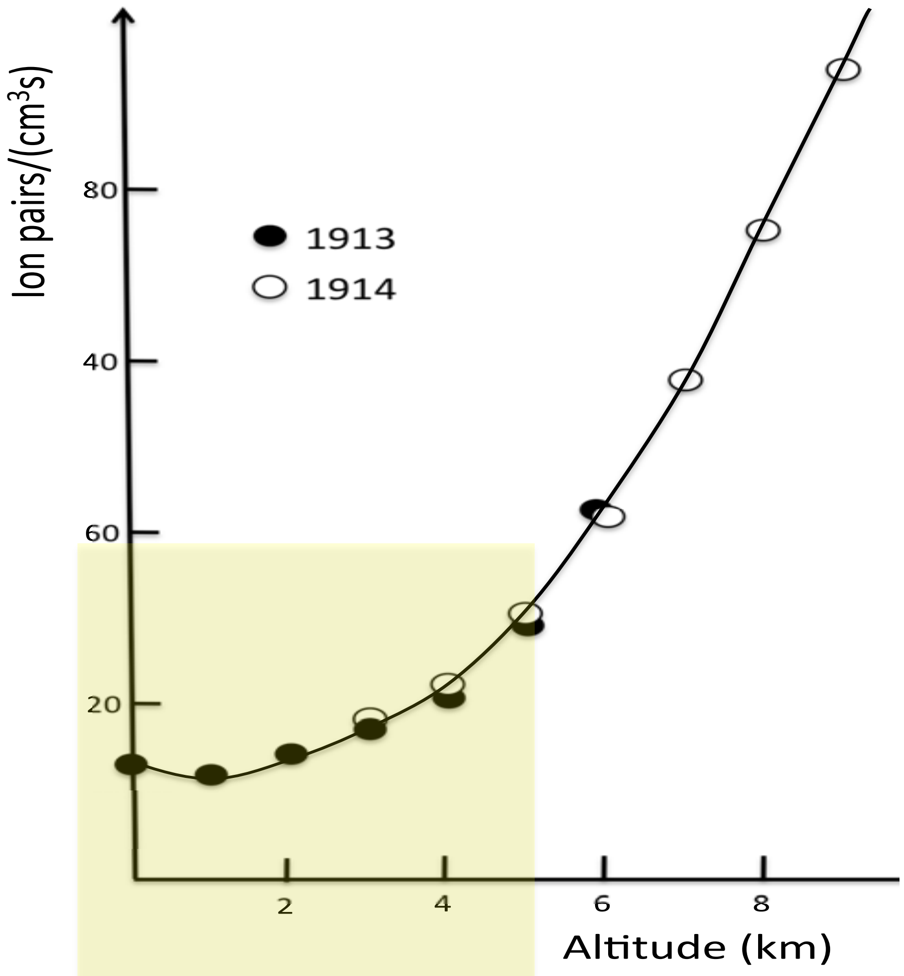
Hess' final balloon flights



- 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

Remake of Hess' experiment in 2012

Kolhörster and the final confirmation



- 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!

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

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

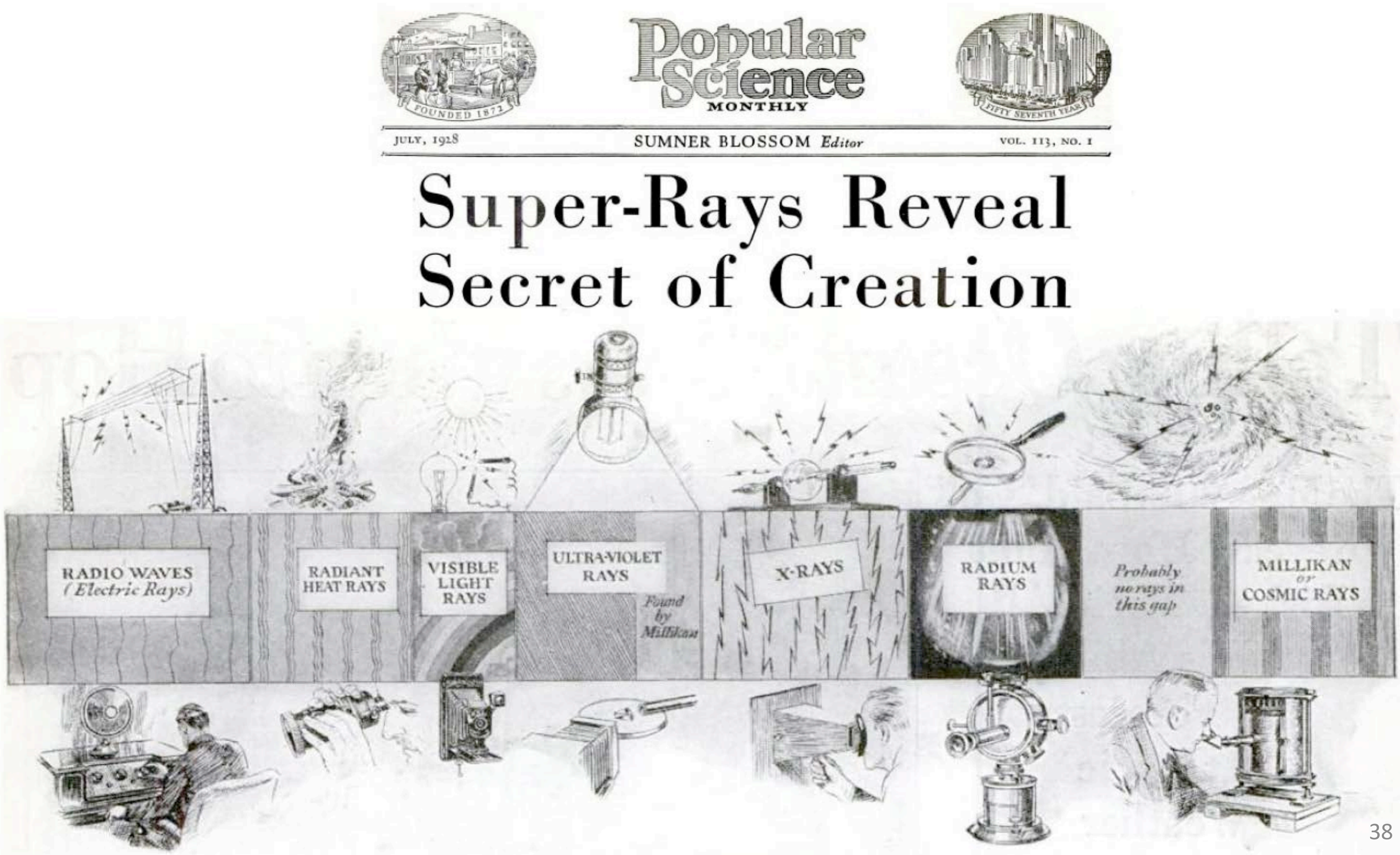
- There were, however, also negative attitudes against extraterrestrial radiation. Hoffmann (1924), and Behounek (1925), using newly developed electrometers, concluded that ionization was due to radioactive elements in the atmosphere

- 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.

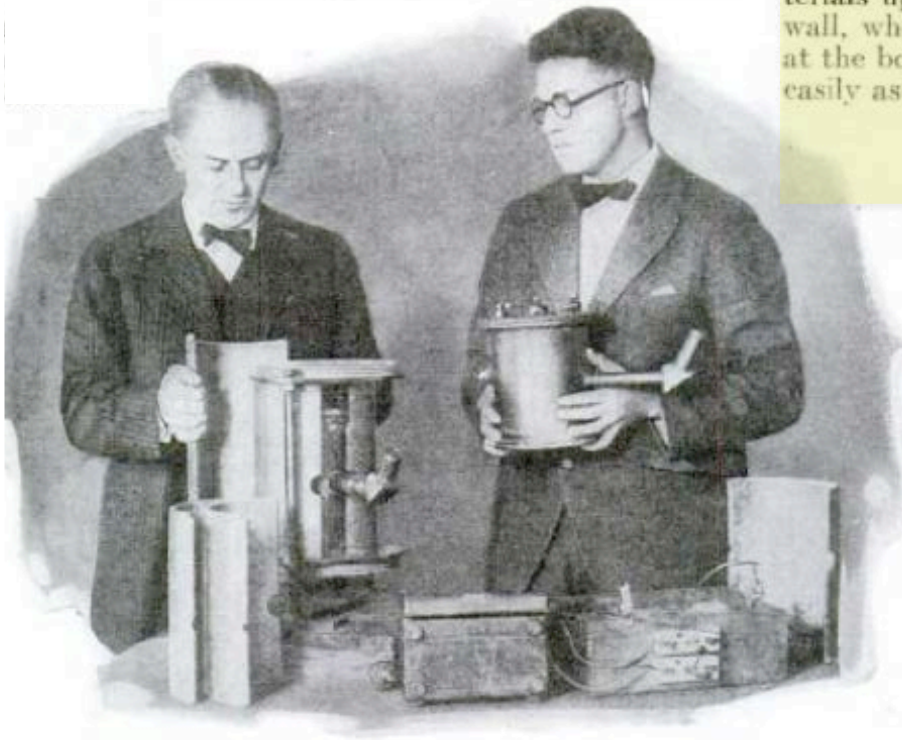
Marketing cosmic rays



[...]

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 words 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.

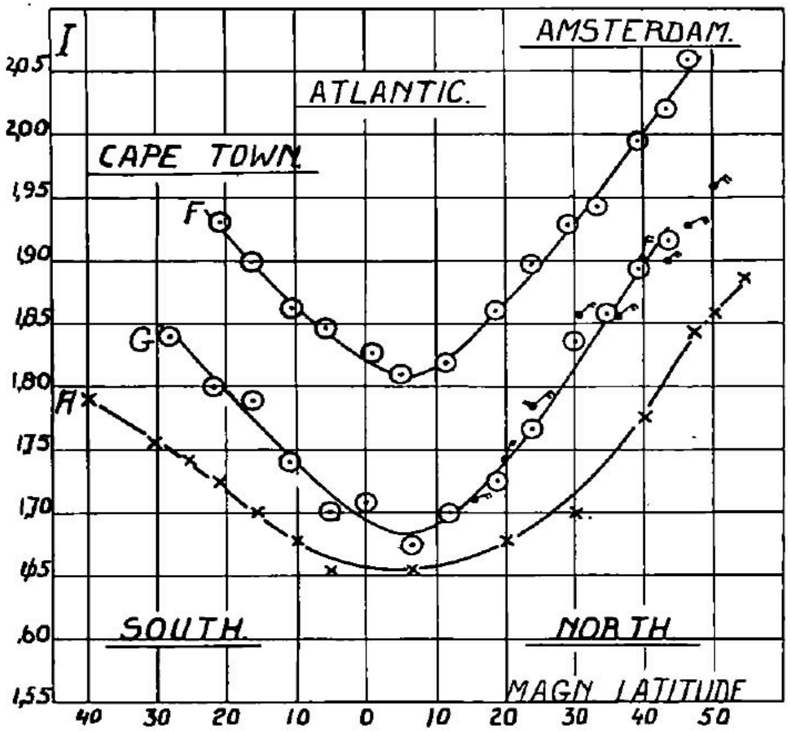
Two thousand feet from the top, they had to shoulder the boats, lumber to build rafts, and instruments their mules had carried.

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).

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+




RAK TAC TAC TAC TAC
HEAR THAT?? IT'S THE COSMIC RAYS!! I--I WARNED YOU ABOUT 'EM!!
THEY'RE PENETRATING THE SHIP!! OUR SHIELDING ISN'T STRONG ENOUGH!
BUT I DON'T FEEL ANYTHING!
NATURALLY! THEY'RE ONLY RAYS OF LIGHT! YOU CAN'T FEEL 'EM-- BUT THEY'LL AFFECT YOU JUST THE SAME!

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."

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.

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

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.

A dramatic result
by Bruno Rossi

(with Heisenberg!)

B. Rossi

Zeit. f Physik 82 151 (1933)

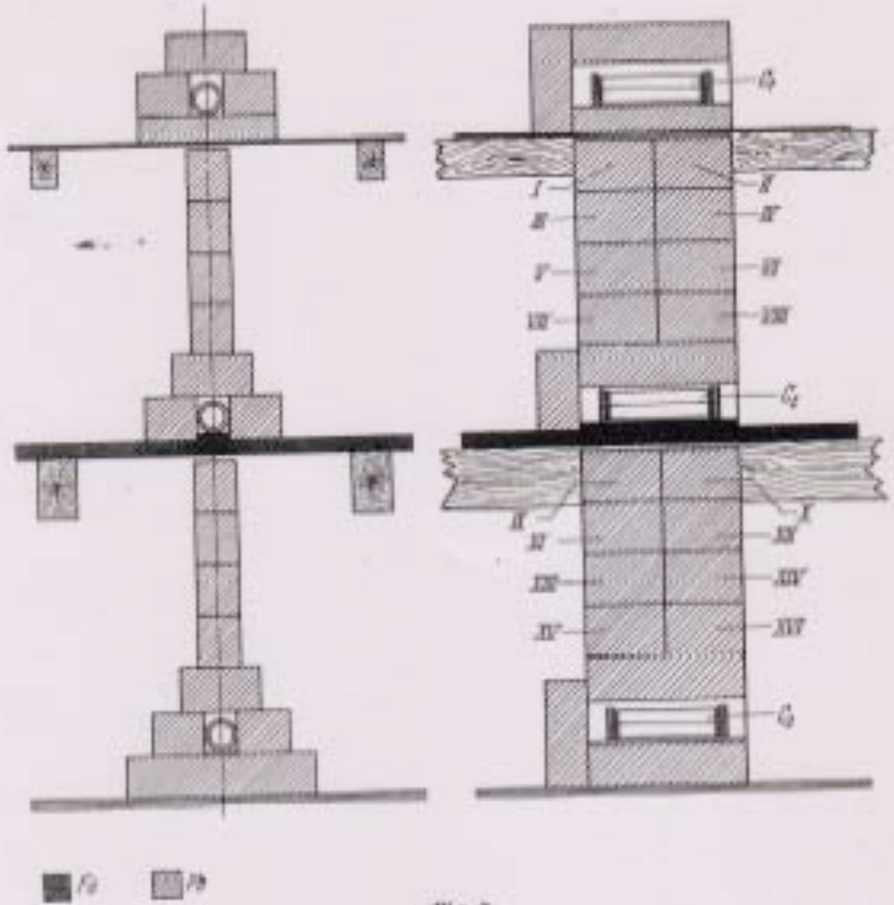
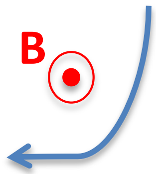


Fig. 2.

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

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:

1⁰) 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.

2⁰) 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.

A conjecture on the origin of CR

(Zwicky in 1930)

- In
  in
  d
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  vi ... ace
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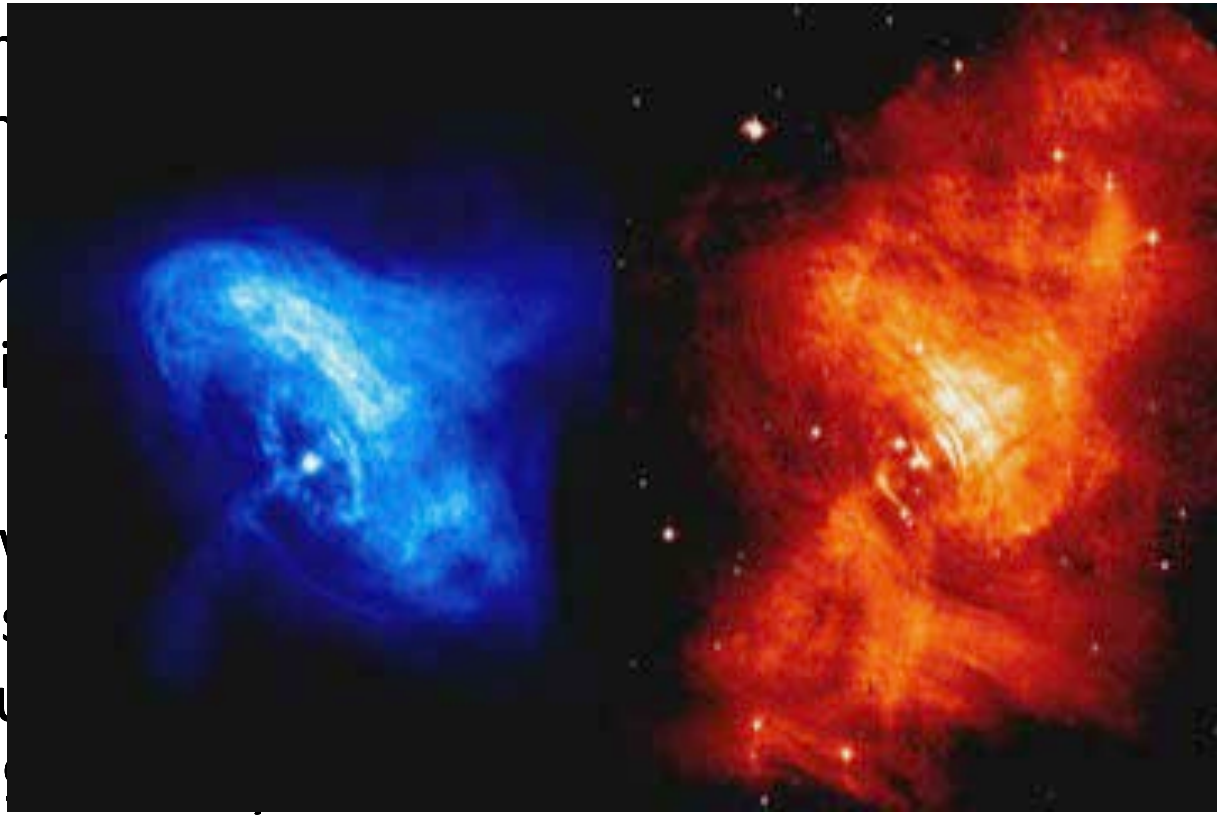
- Z ... can
  as
  su ... n
  1 ... :



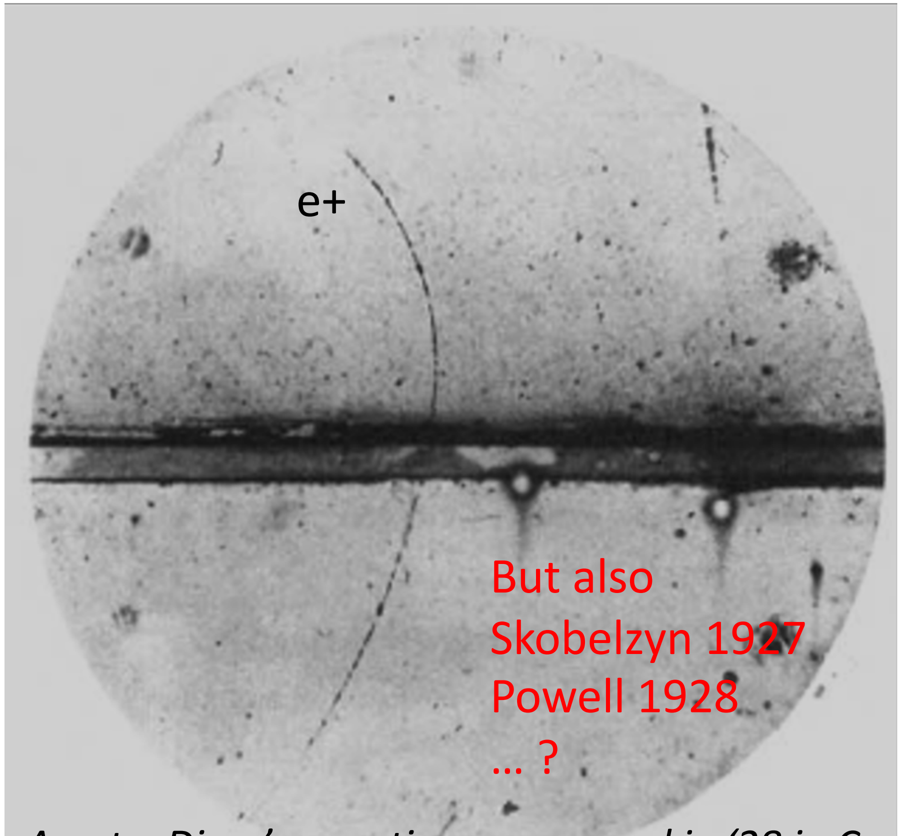
1. massive stars end their lives in explosions which blow them apart
2. such explosions produce cosmic rays
3. they leave behind a collapsed star made of densely-packed neutrons

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…

Antimatter
(the antielectron, or positron: Anderson 1933)

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



- 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.

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*

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…)

Particles found in cosmic rays

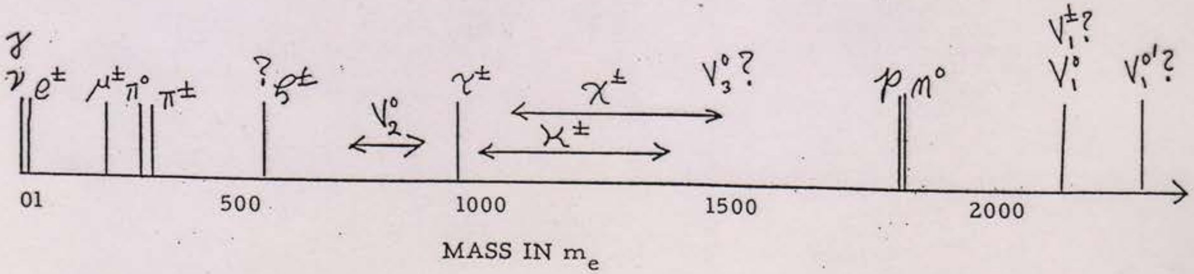
Positron
Muons
Charged Pions
K mesons
Lambda
Sigma
Xi

3rd Rochester Conference 1952 32

December

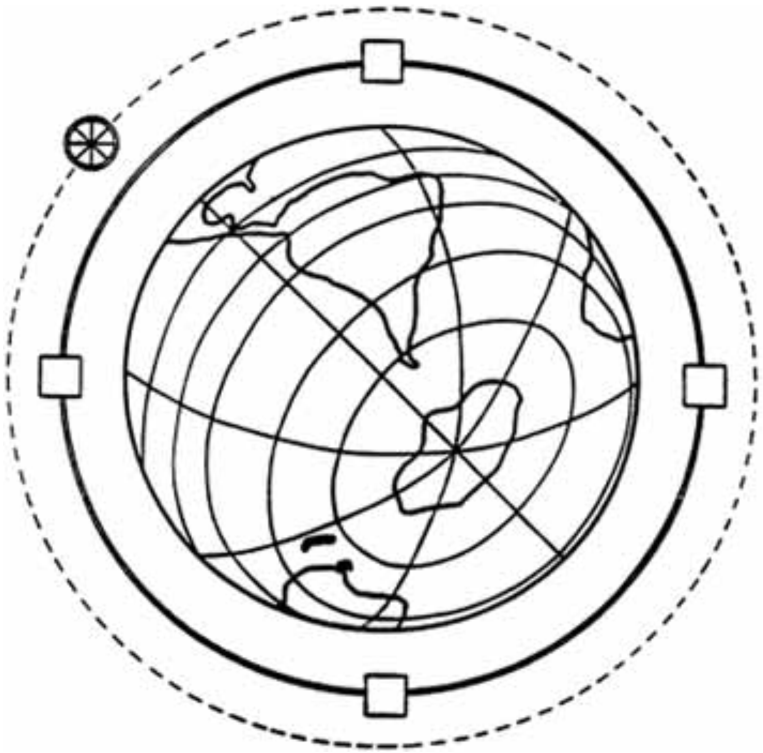
Appendix VI: THE UNSTABLE "ELEMENTARY" PARTICLES OR MEGALOMORPHS

Particle	Products	Observed by	Lifetime (sec.)	Q	Mass	Statistics	Spin	Parity
? $V_1^{0\prime}$	$\rightarrow p + \pi^-$	c. c.	$> V_1^0$	~75 Mev	$2270m_e$?	F. D.	n/2?	-
V_1^0	$\rightarrow p + \pi^-$	c. c.	3.5×10^{-10}	37 Mev	$2190m_e$	F. D.	n/2?	-
? $V_1^{\pm}$	$\rightarrow p + (?)^0$	c. c.	?	?	?	?	?	?
n^0	$\rightarrow p + e^- + \nu$	Spectro-graph & counters	740	783 Kev	$1837m_e$	F. D.	1/2	-
V_3^0	$\rightarrow K^- + \pi^+$	c. c.	?	?	$M_p > m_{V_3^0} > m_n$	?	?	?
K $\{S^{\pm}, \chi^{\pm}, V^{\pm}\}$	$\rightarrow \pi^{\pm} + (?)^0$; $m_0 \sim 800 m_e$	c. c.; c. c. & emul.	2×10^{-8} - 2×10^{-9}	115 Mev	$1400m_e$	B. E.	0?	S?
K $\{\kappa^{\pm}, V^{\pm}\}$	$\rightarrow \mu^{\pm} + ?2\nu$	emul. c. c.	?	?	$1100m_e$	F. D.?	1/2?	-
$\tau^{\pm}$	$\rightarrow \pi^{\pm} + \pi^+ + \pi^-$	emul. & c. c.	10^{-8} - 10^{-9}	75 Mev	$975m_e$	B. E.	0?	PS?
V_2^0	$\rightarrow \pi^+ + \pi^-$	c. c.	$\sim10^{-10}$	210 Mev	$850m_e$	B. E.	0?	S?
? $\zeta^{\pm}$	$\rightarrow \pi^{\pm} + (?\pi^0)$	emul.	$?10^{-11}$	40 Kev < Q < 6 Mev	$552m_e$	B. E.	0?	S?
$\pi^{\pm}$	$\rightarrow \mu^{\pm} + \nu$	counters	2.3×10^{-8}	5.9 Mev	$276m_e$	B. E.	0	PS
π^0	$\rightarrow 2\gamma$; $\rightarrow e^+ + e^- + \gamma$	counters; emul. & counters	$\leq 5\times10^{-15}$	135 Mev	$266m_e$	B. E.	0	PS
$\mu^{\pm}$	$\rightarrow e^{\pm} + 2\nu$	counters	2.15×10^{-6}	105 Mev	$212m_e$	F. D.	1/2	-



…and new hints for understanding (Fermi 1949)

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



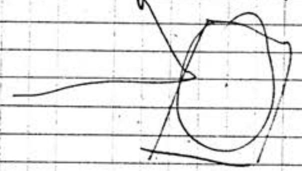
And also: the maximum possible energy for a terrestrial accelerator is ~ 5000 TeV (1954)

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

Dec 4 1948

Theory of cosmic rays

a) Energy acquired in collisions against cosmic magnetic fields



Non relativistic case

$$MV^2$$

(M = mass of particle V = velocity of moving field

(Proof: Head on collision gives energy gain

$$\frac{M}{2}(v+2V)^2 - \frac{Mv^2}{2} = \frac{M}{2}(4vV+4V^2) =$$

$$= M(2vV+2V^2) \qquad \text{Prob} = \frac{v+V}{2v}$$

Running after collision ($\text{prob} = \frac{v-V}{2v}$) gives energy gain

$$M(-2vV+2V^2)$$

Average gain order

$$MV^2$$

Relativistic: order

$$w\beta^2$$

CONGRÈS INTERNATIONAL SUR LE RAYONNEMENT COSMIQUE
BAGNÈRES-DE-BIGORRE, 6-12 Juillet 1953 Photo ALIX

Organized by Louis Leprince-Ringuet and Patrick Blackett

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…

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:

(...)

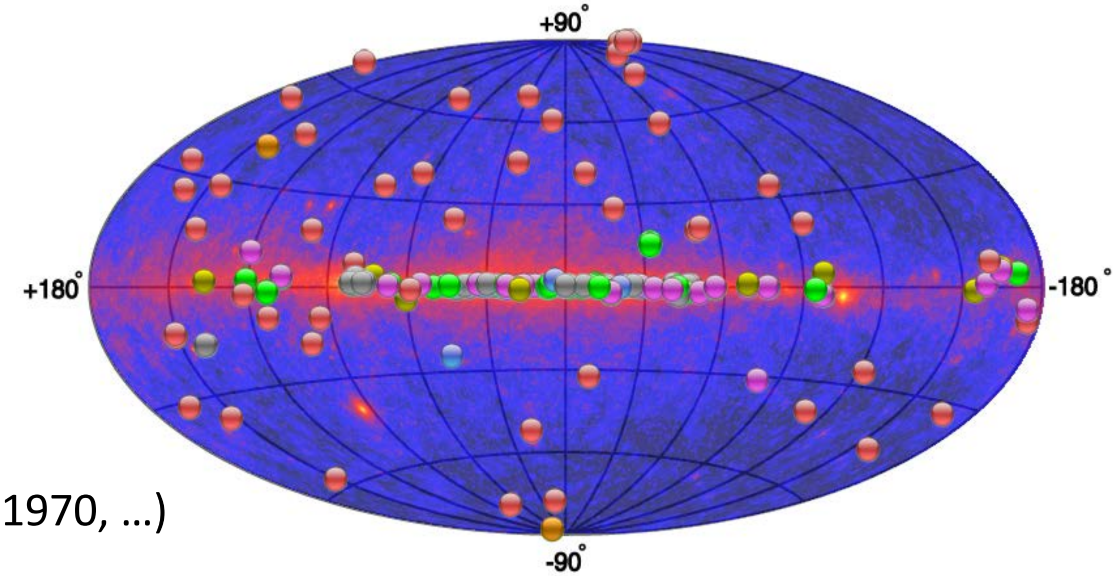
(c) The organization and sponsoring of international co-operation in nuclear research, including co-operation outside the Laboratory. This co-operation may include in particular:

- *(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

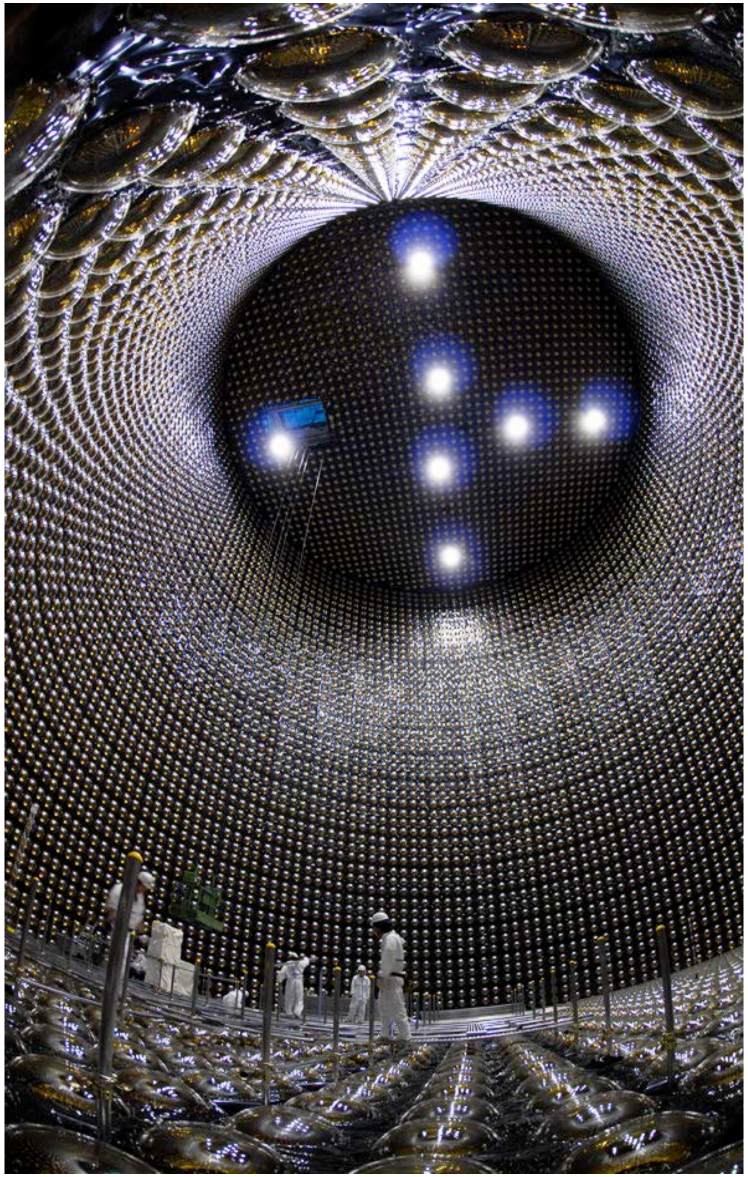
The flame still burns in the following years



- 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
- GW detectors
- …

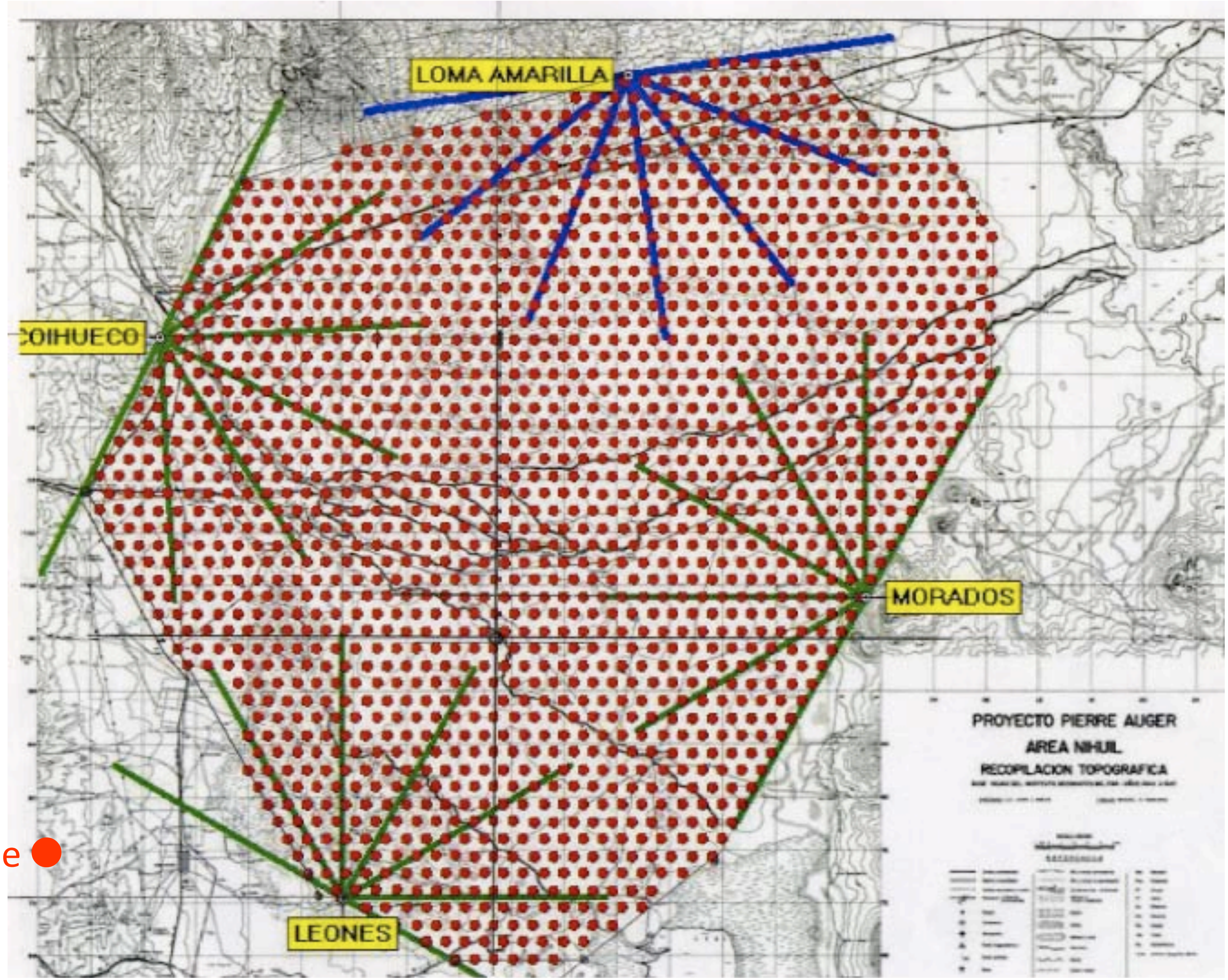
and CR continue to contribute to fundamental physics

- 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



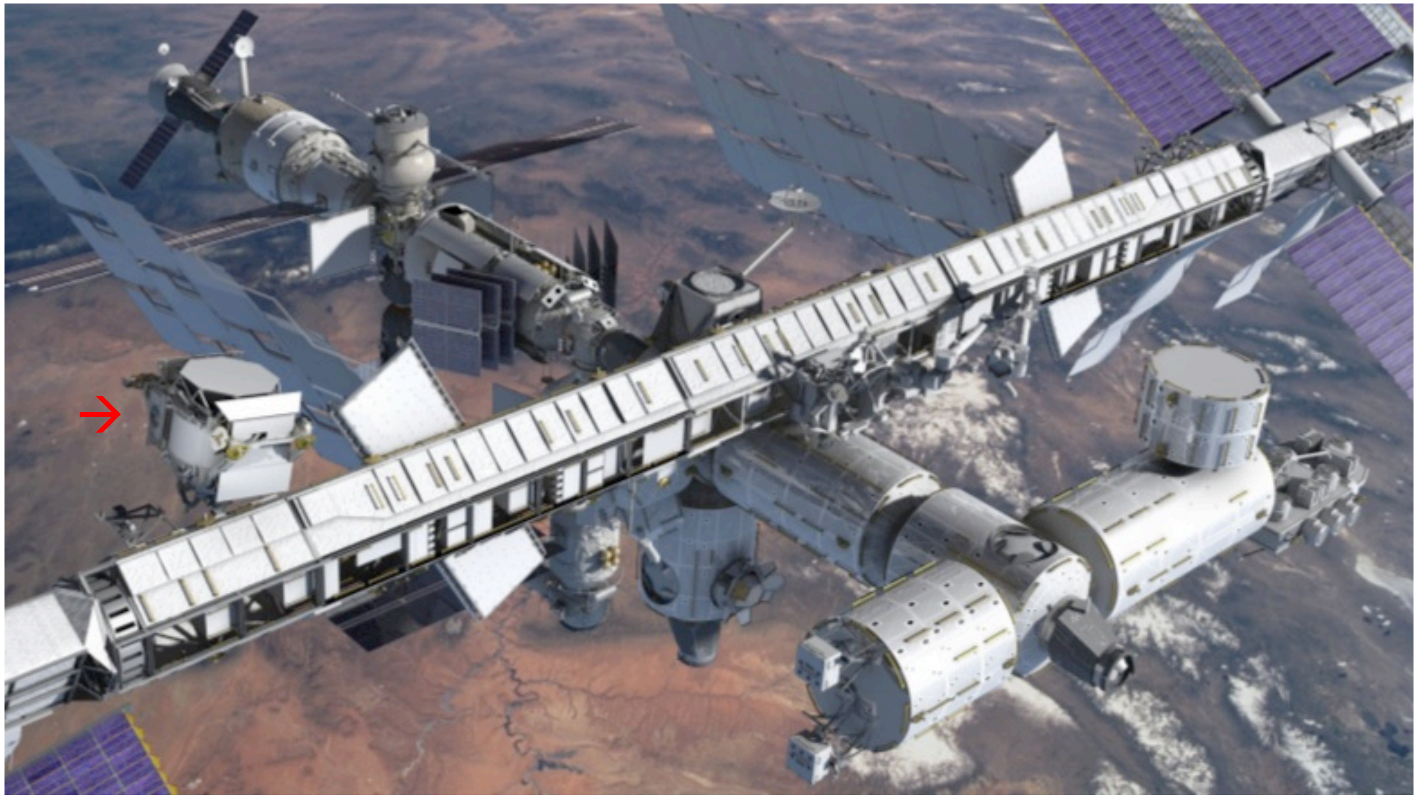
Malargue

12

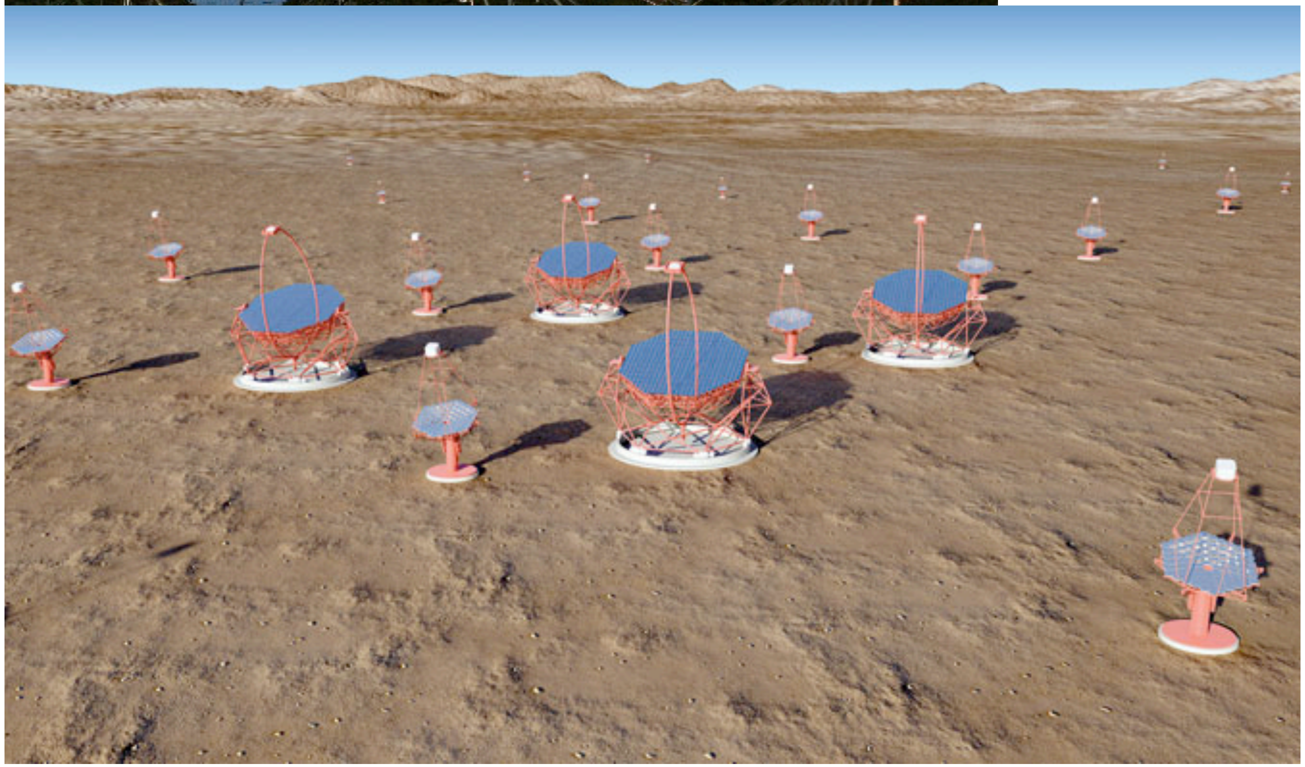
Alpha Magnetic Spectrometer

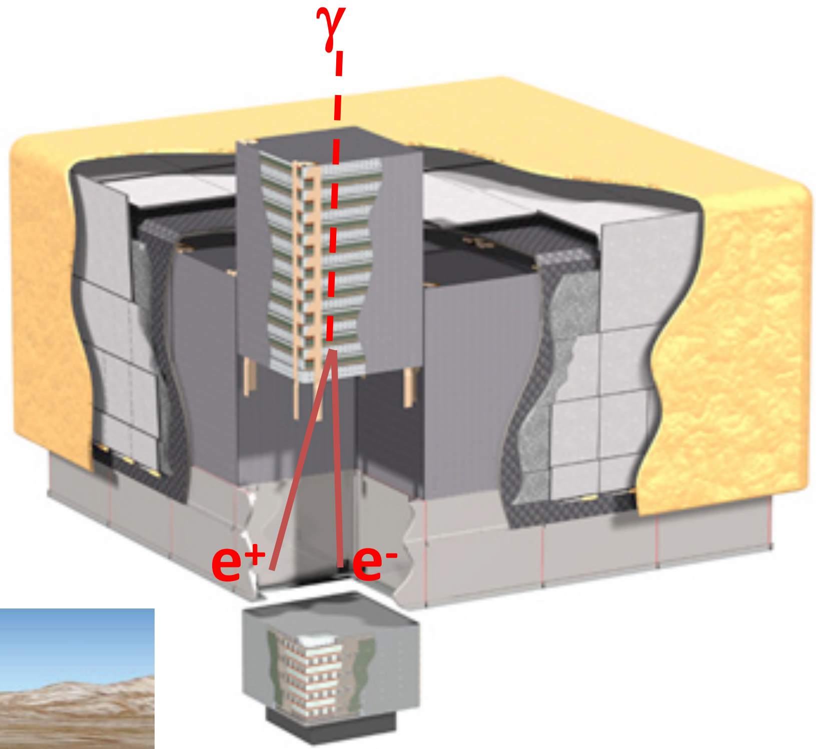
Measures in fine detail cosmic rays $< \text{some } 10^{11}$ eV : dark matter, antimatter, exotic particles

Launched May 16, 2011



The direct probes of cosmic particle accelerators

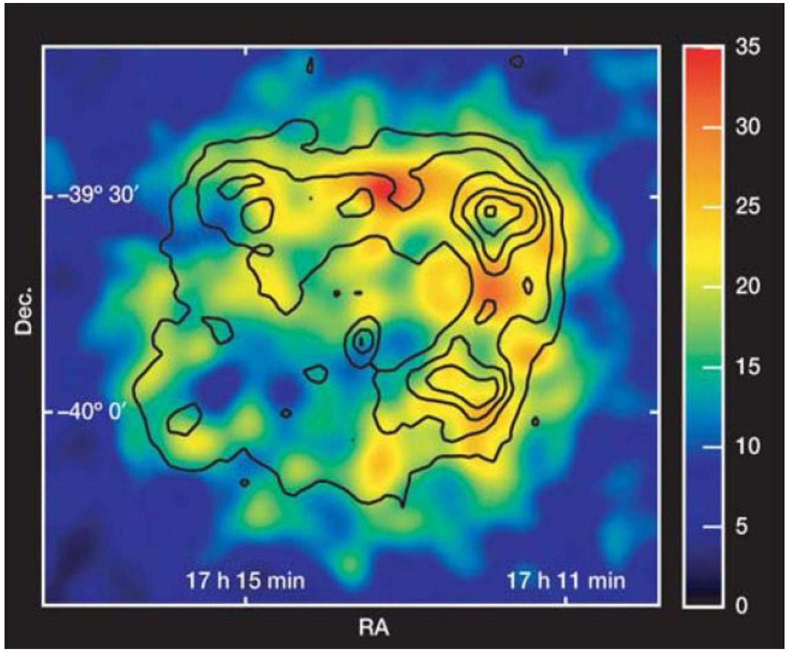


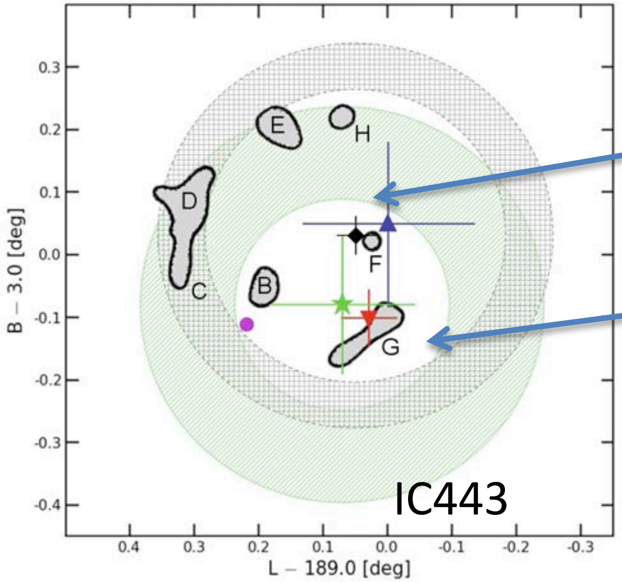


Sources of CR up to the knee

Cherenkov telescopes & X/gamma satellites

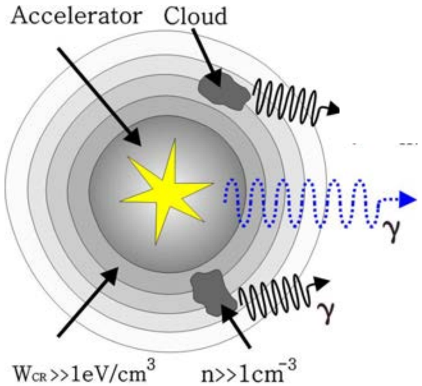
- Marginal evidence that SNR are sources of CR up to ~1000 TeV come from morphology studies of RX J1713-3946 (H.E.S.S. 2004)
- Striking evidence from the morphology of IC443 (MAGIC + Fermi/Agile 2010)
- Now ~ 10 SRNs accelerating hadrons are known (HESS, MAGIC, VERITAS, Fermi), plus a Pevatron in the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

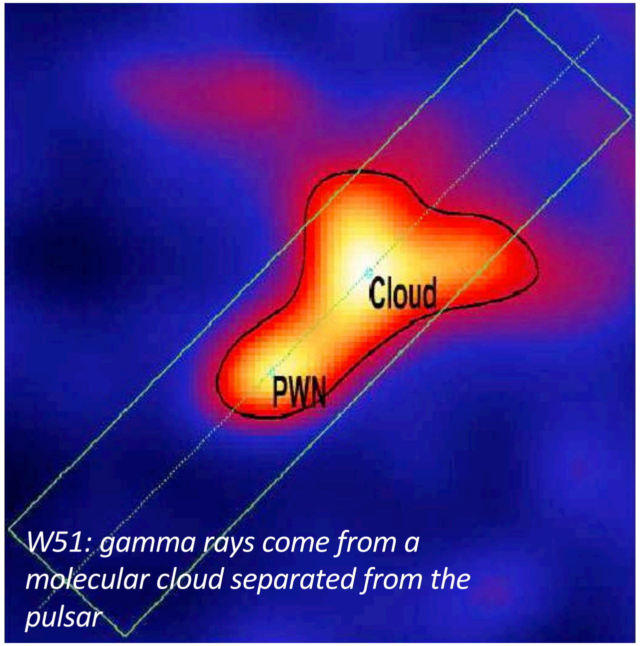




Fermi, Egret

Magic, Veritas

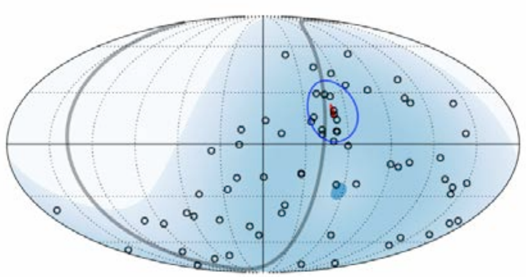




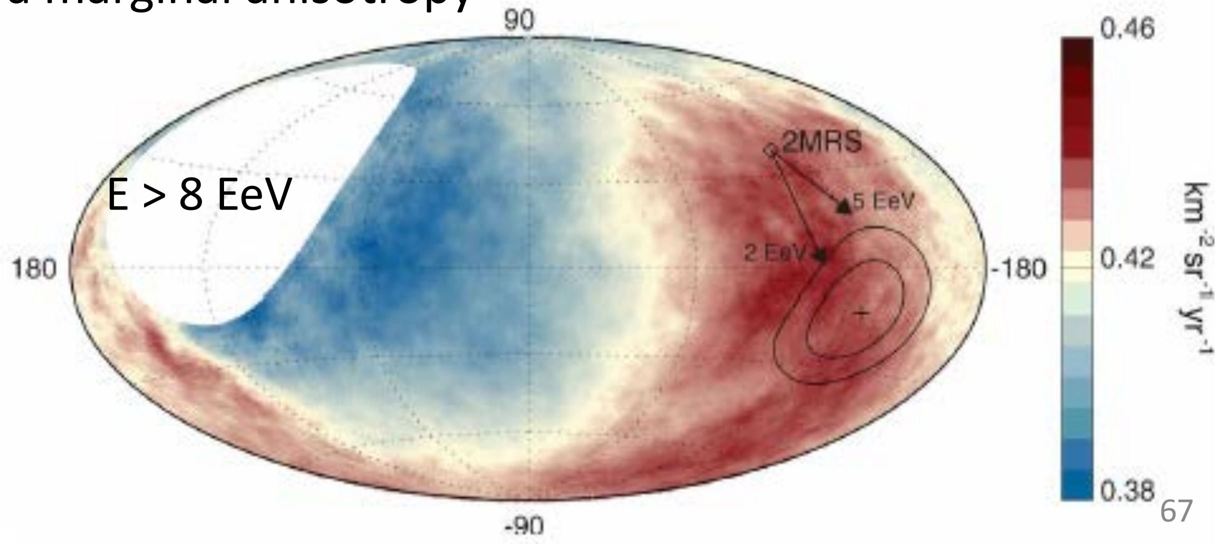
W51: gamma rays come from a molecular cloud separated from the pulsar

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

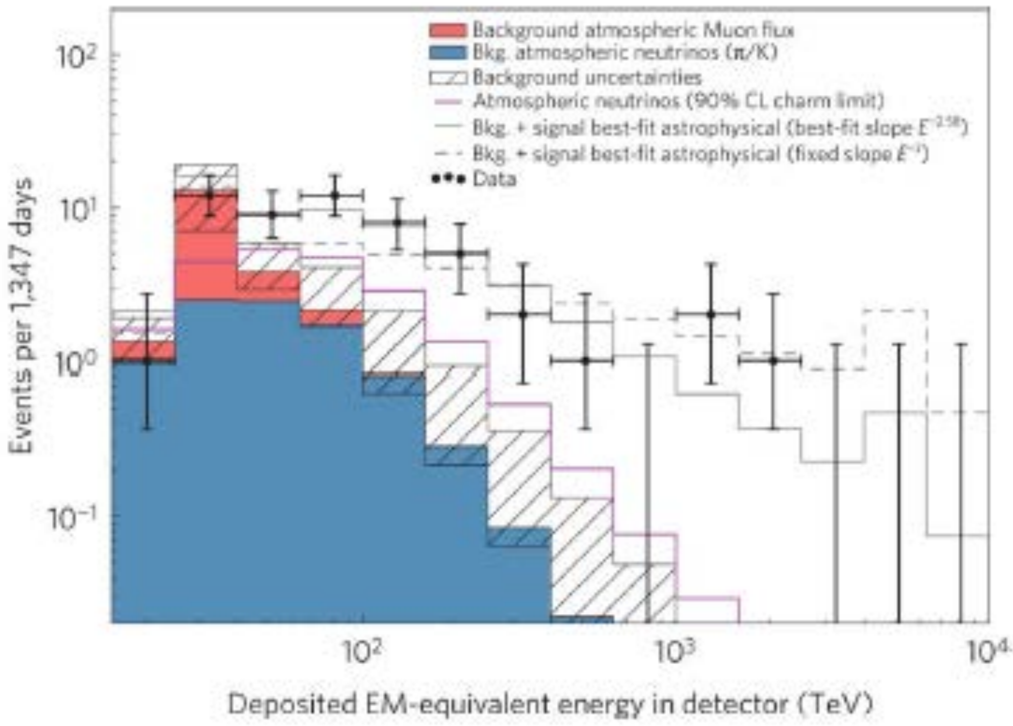
- In ~30 000 cosmic rays with energies above 8 EeV recorded over a period of 12 years, the Pierre Auger Observatory has evidenced at more than 5σ a dipole anisotropy
- If UHE cosmic rays originate from an inhomogeneous distribution of sources and then diffuse through intergalactic magnetic fields, one 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



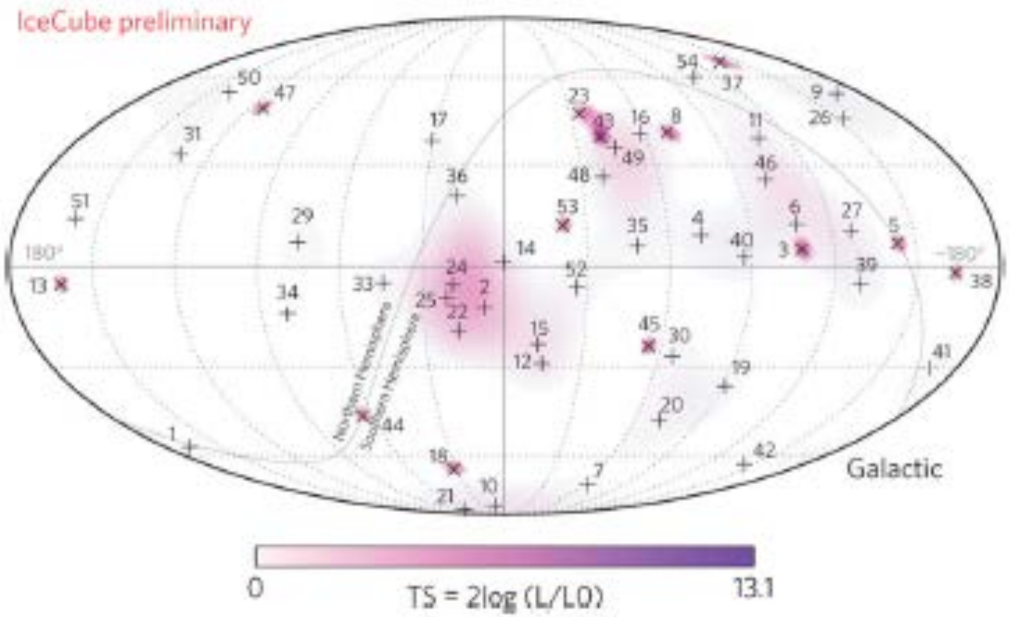
E > 55 EeV



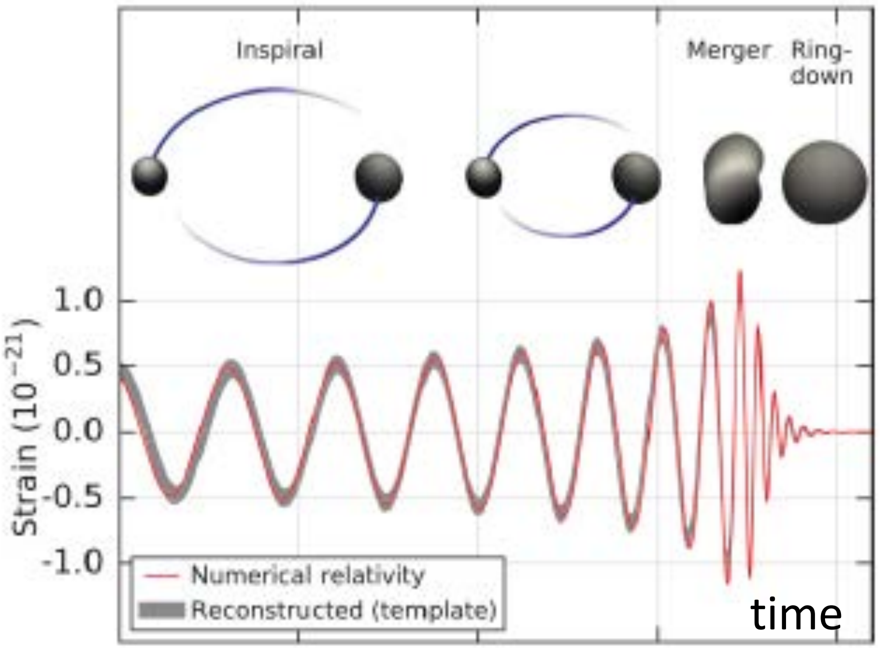
Astrophysical neutrinos (2013)

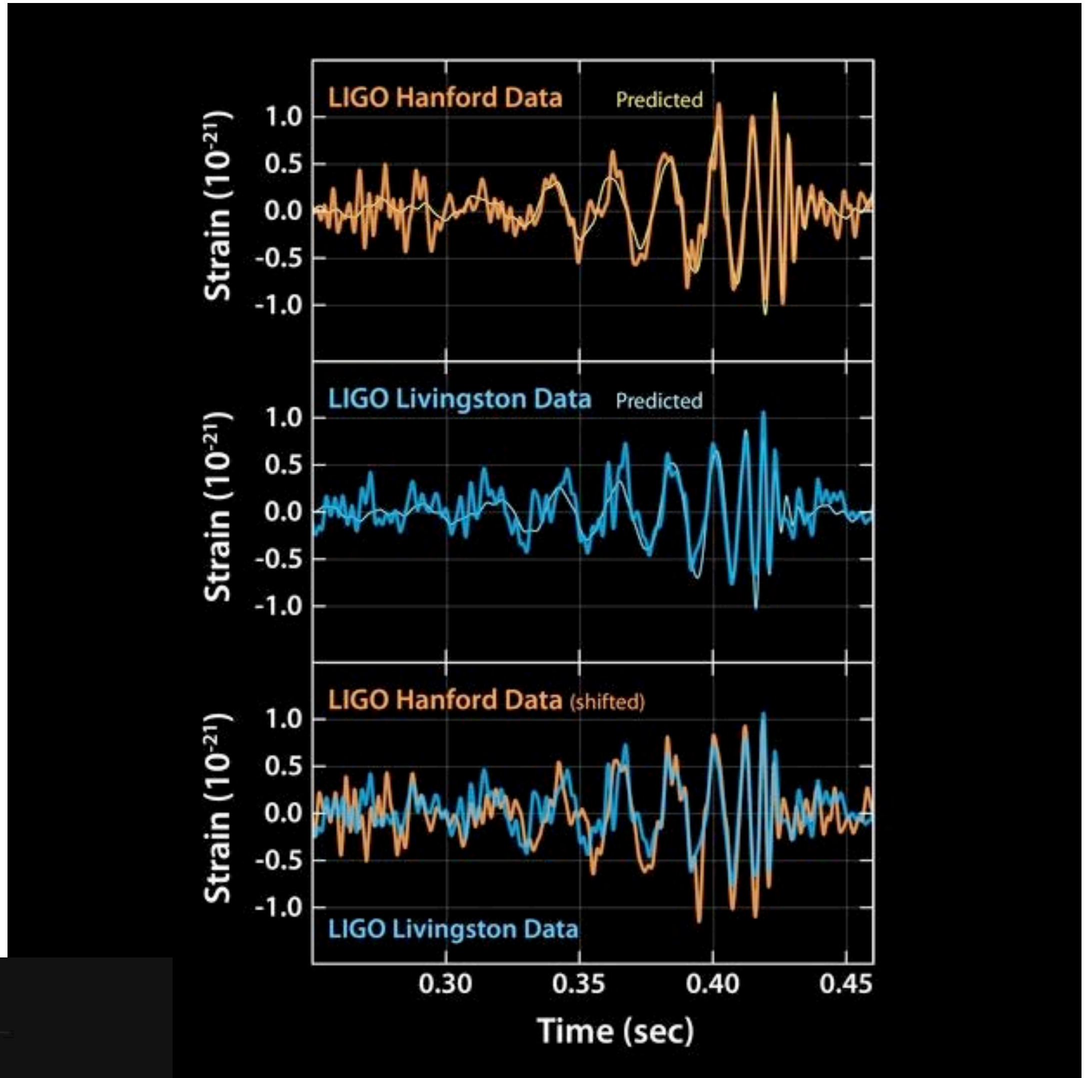


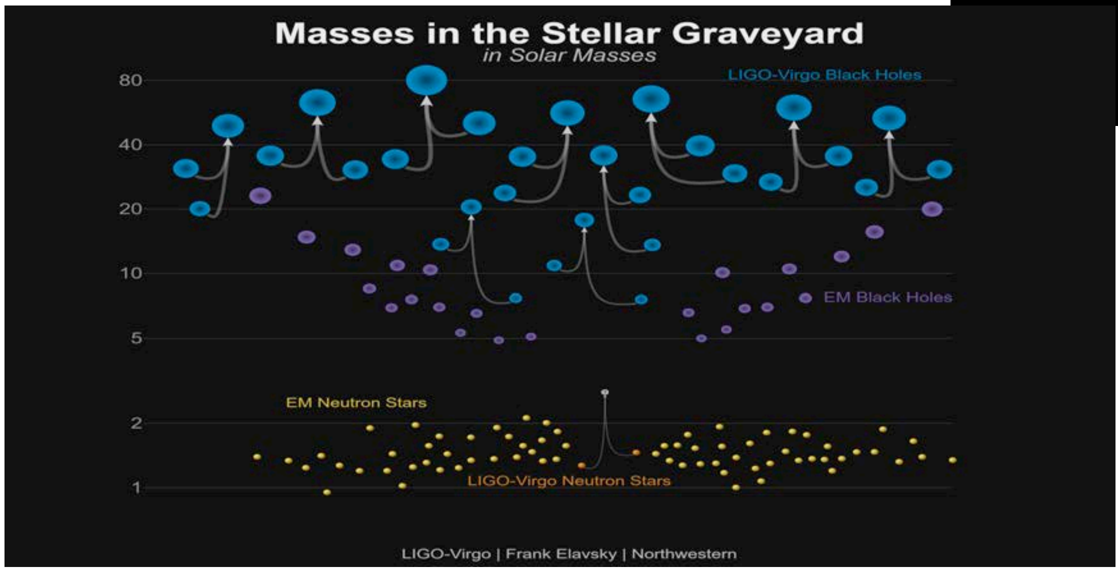
- Evidence that there are neutrinos above 20 TeV (and up to 10 PeV) coming from extragalactic sources, not GRB (probably AGN)



Gravitational Waves (2015-)

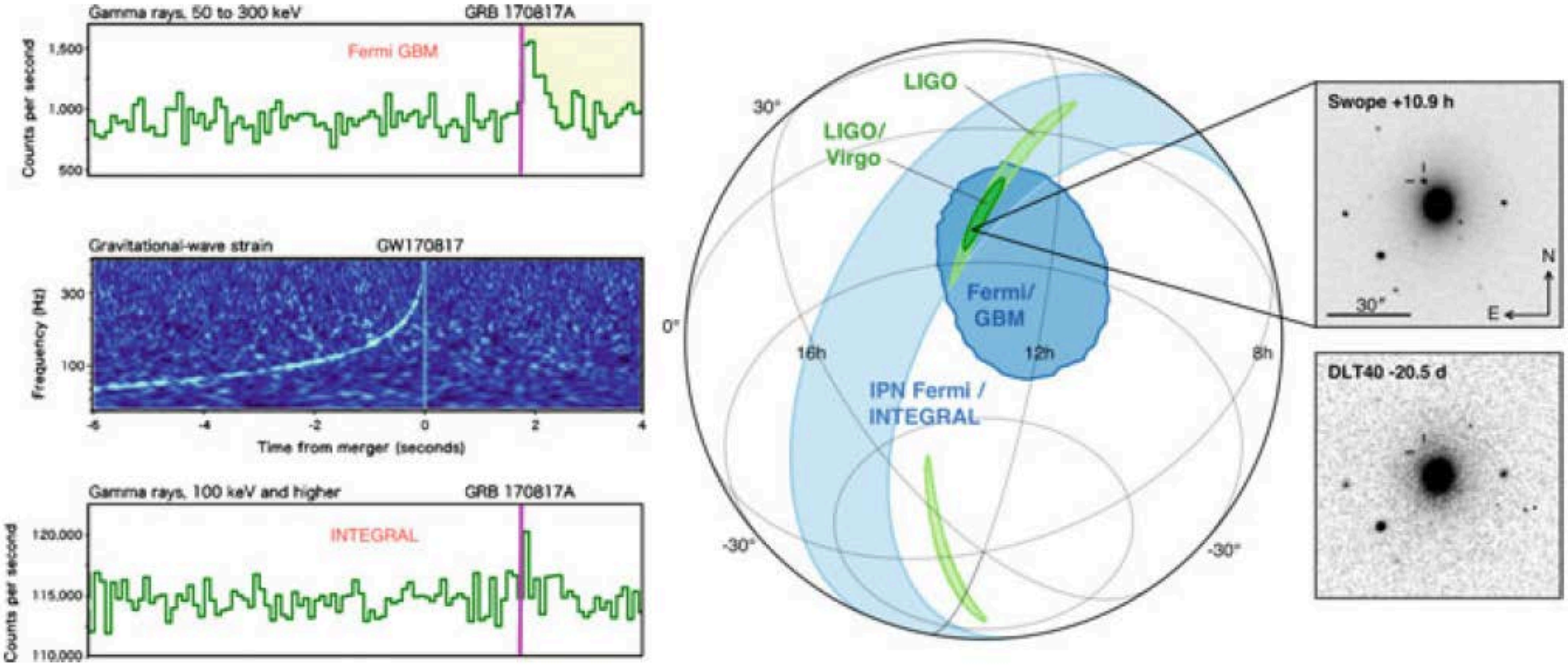




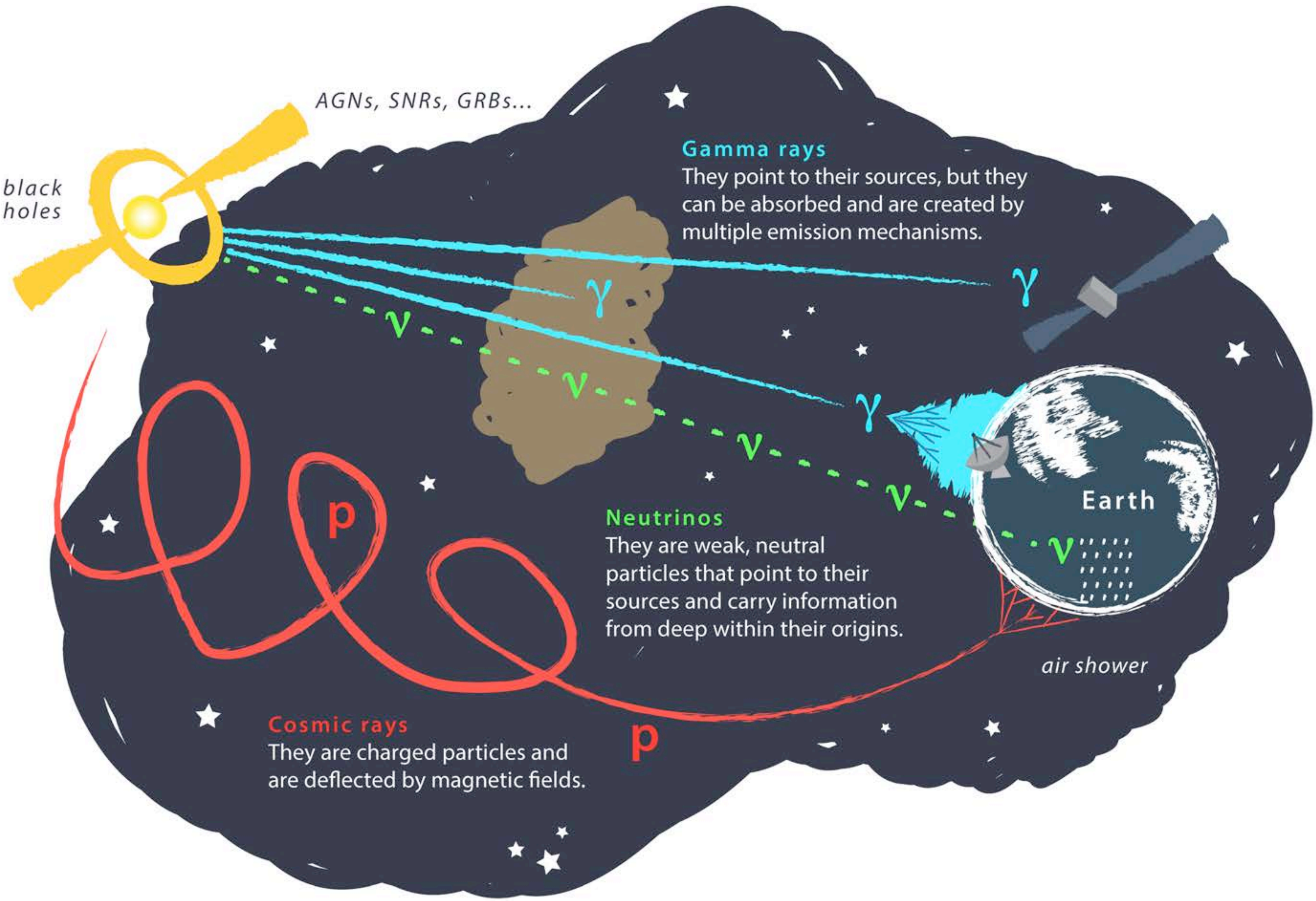


10 BH-BH fusions, 1 NS-NS
…and growing!

First simultaneous GW-gamma ray-optical observation (2017)



First simultaneous neutrino-gamma ray observation (2017/18)



Summary

- 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: Gamma-rays, Neutrinos, Gravitational Waves, Nuclei


EUROPA-CEPT 1983
VIKTOR FRANZ HESS 1883-1964
NOBELPREIS FÜR PHYSIK 1936
6 S
REPUBLIK ÖSTERREICH
350 FCFA
2009
Prémio Nobel da Física
Antoine Henri Becquerel (1852-1908)
Deteriorização Radioactiva
GUINÉ-BISSAU
REPUBLIQUE FRANÇAISE
0,60
POSTES
1867 MARIE CURIE 1934
ENRICO FERMI
1901-1954
800
ITALIA
€ 0,41
I.P.Z.S. - ROMA - 2001
C. BRUSCAGLIA
GUYANA $35⁰⁰
Arthur H. Compton (U.S.A.)
Physics 1927
100th Anniversary of the Nobel Prizes
"ВЕНЕРА-13" • "ВЕНЕРА-14"
к10
ПОЧТА СССР 1982
120
ՀԱՅԱՍՏԱՆ
75 c
REPÚBLICA ARGENTINA
CORREO OFICIAL
2007
OBSERVATORIO PIERRE AUGER
The Royal Society 350 Years
Atomic Structure Rutherford
1ST
Robert Millikan
37c
USA
80
NIPPON