Professor V. A. Dogel

Story about Cosmic Ray

(historical review + a toy model of cosmic ray origin)

April, 28, 1911

Heike **Kamerlingh-Onnes,**

the discovery of superconductivity at temperatures of liquid Helium,

Centenary of Superconductivity

August, 7, 1912

Centenary of Cosmic Ray Discovery

INTRODUCTION

Units in Astrophysics

$$1\ eV = 1.6 \times 10^{-12}\, erg$$

$$1\ eV = 2.418 \times 10^{14}\, Hz$$

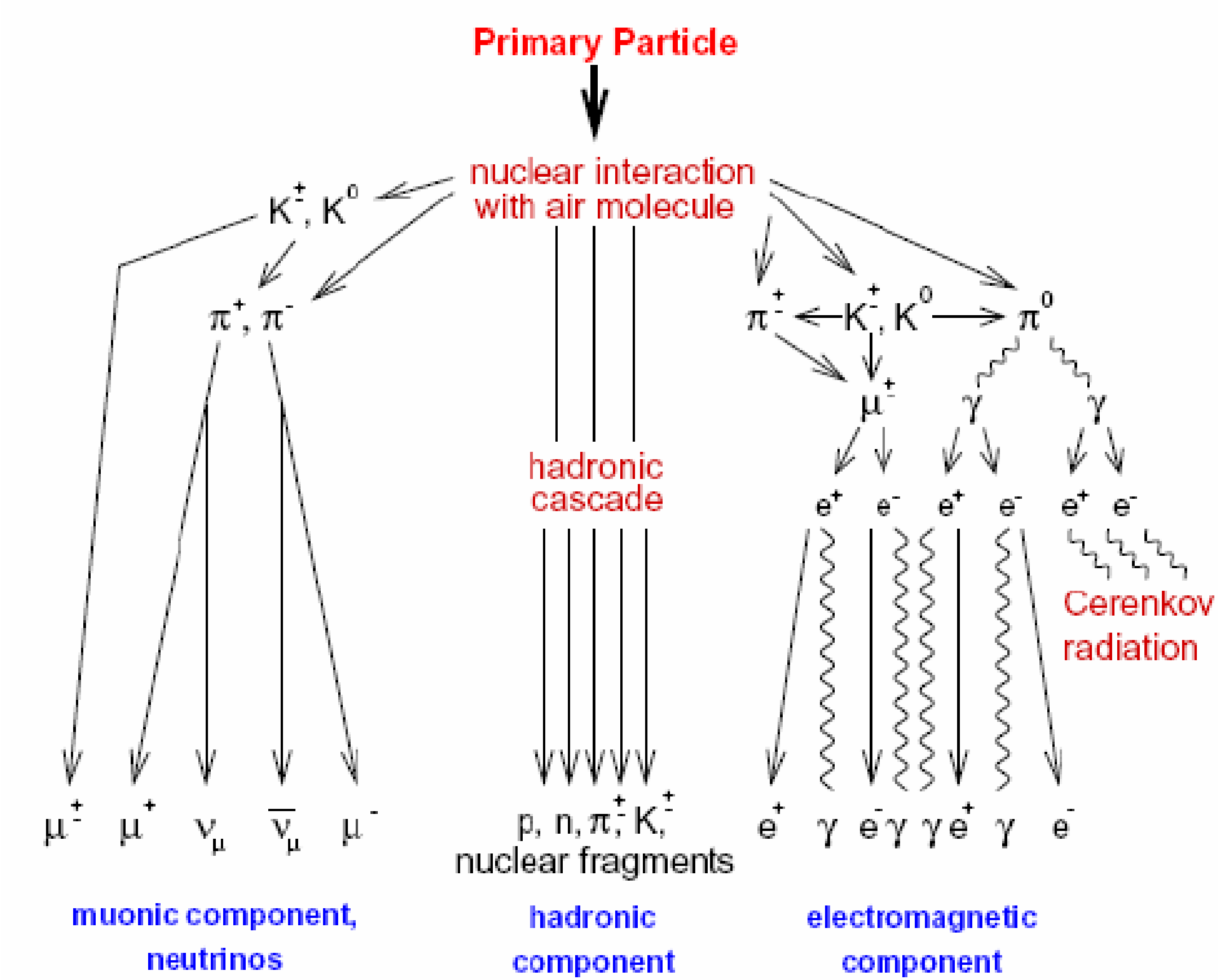
$$\varepsilon \sim \left(1.24 \times 10^{-6} \big/ \lambda(m) \right) eV$$

$$1\ K \simeq 10^{-4}\, eV$$

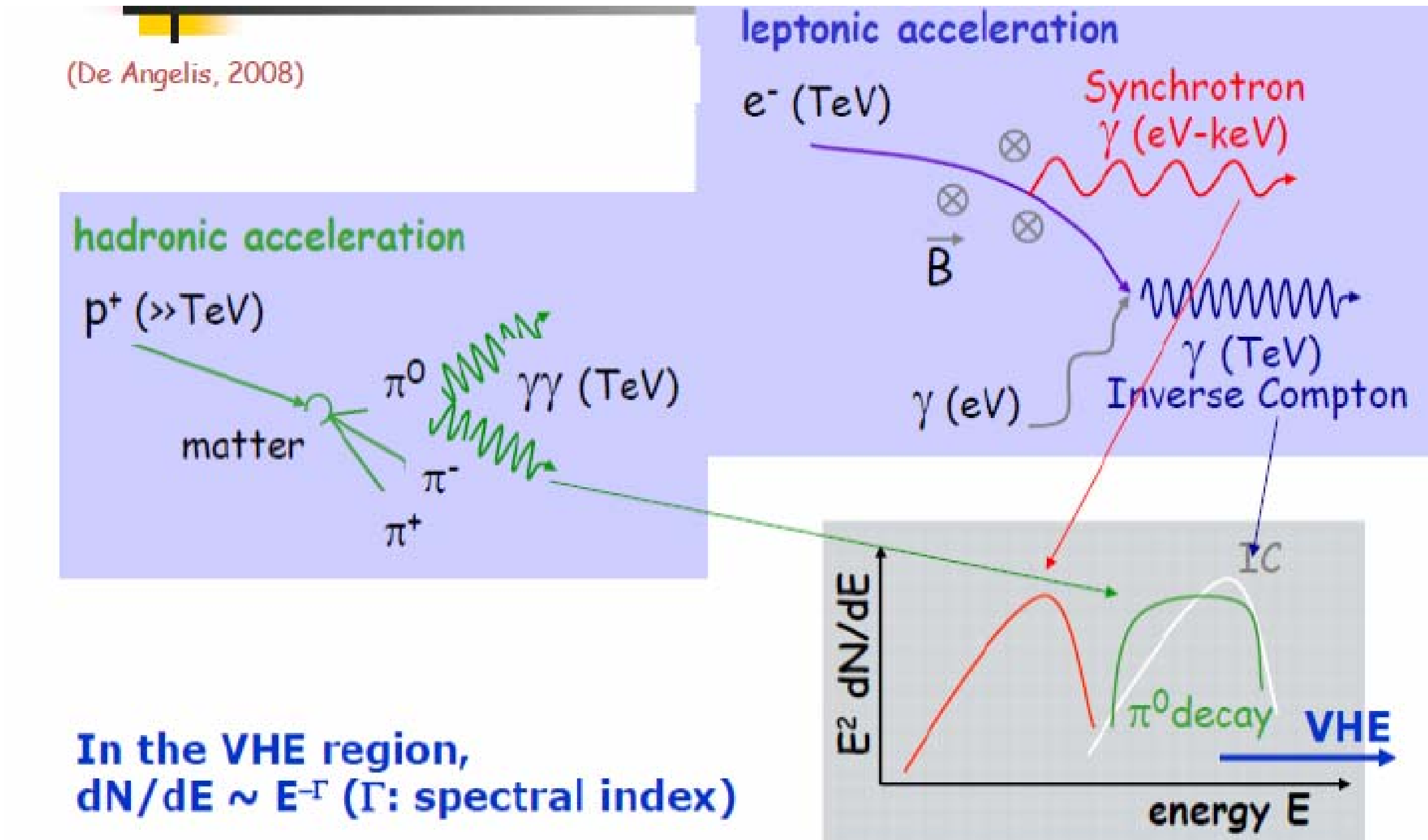
$$1\ pc \simeq 3\ 10^{18}\, cm$$

$$1\ M_{\odot} = 2\ 10^{33}\, gr$$

Interactions of CRs in the Atmosphere

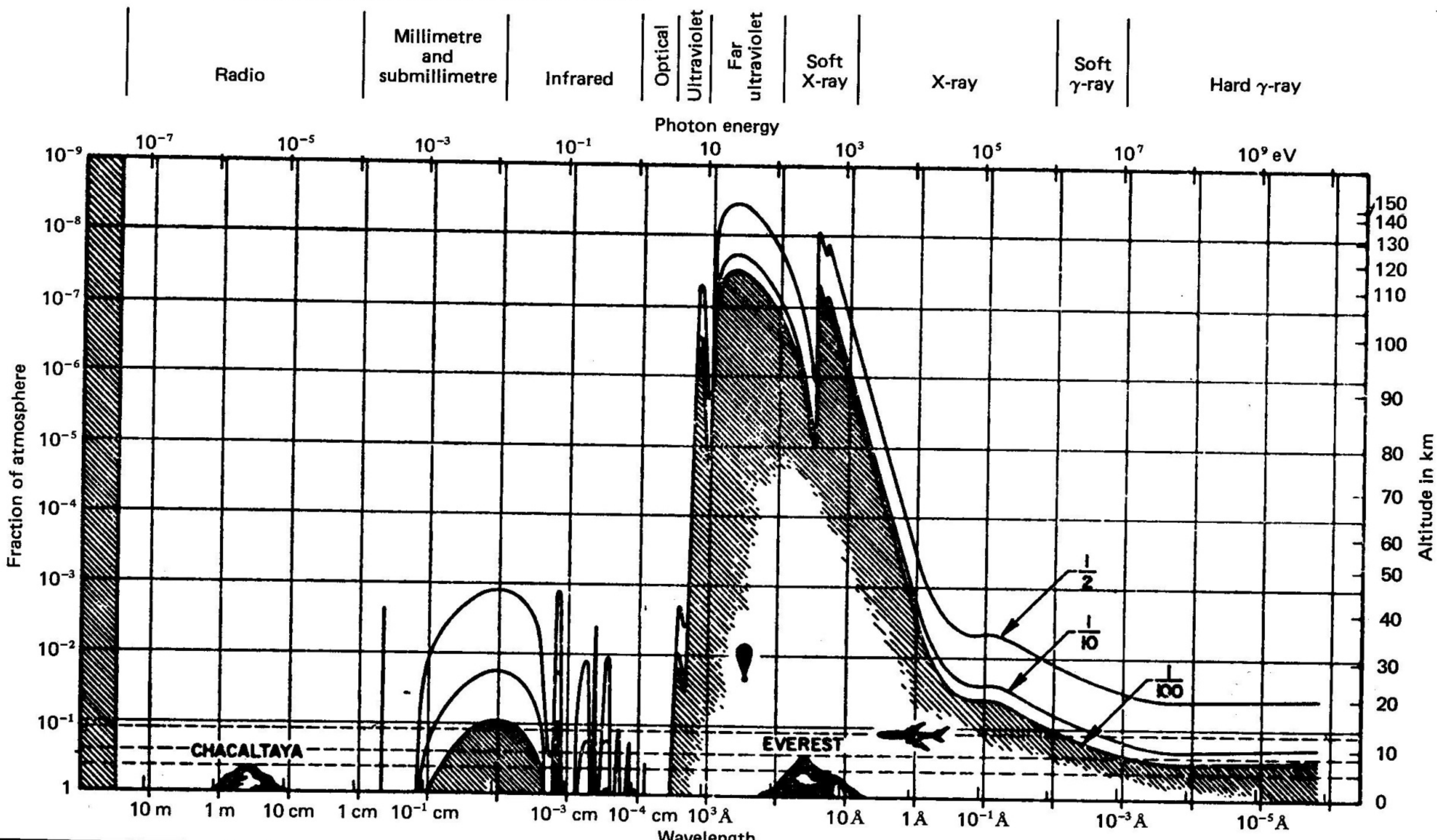


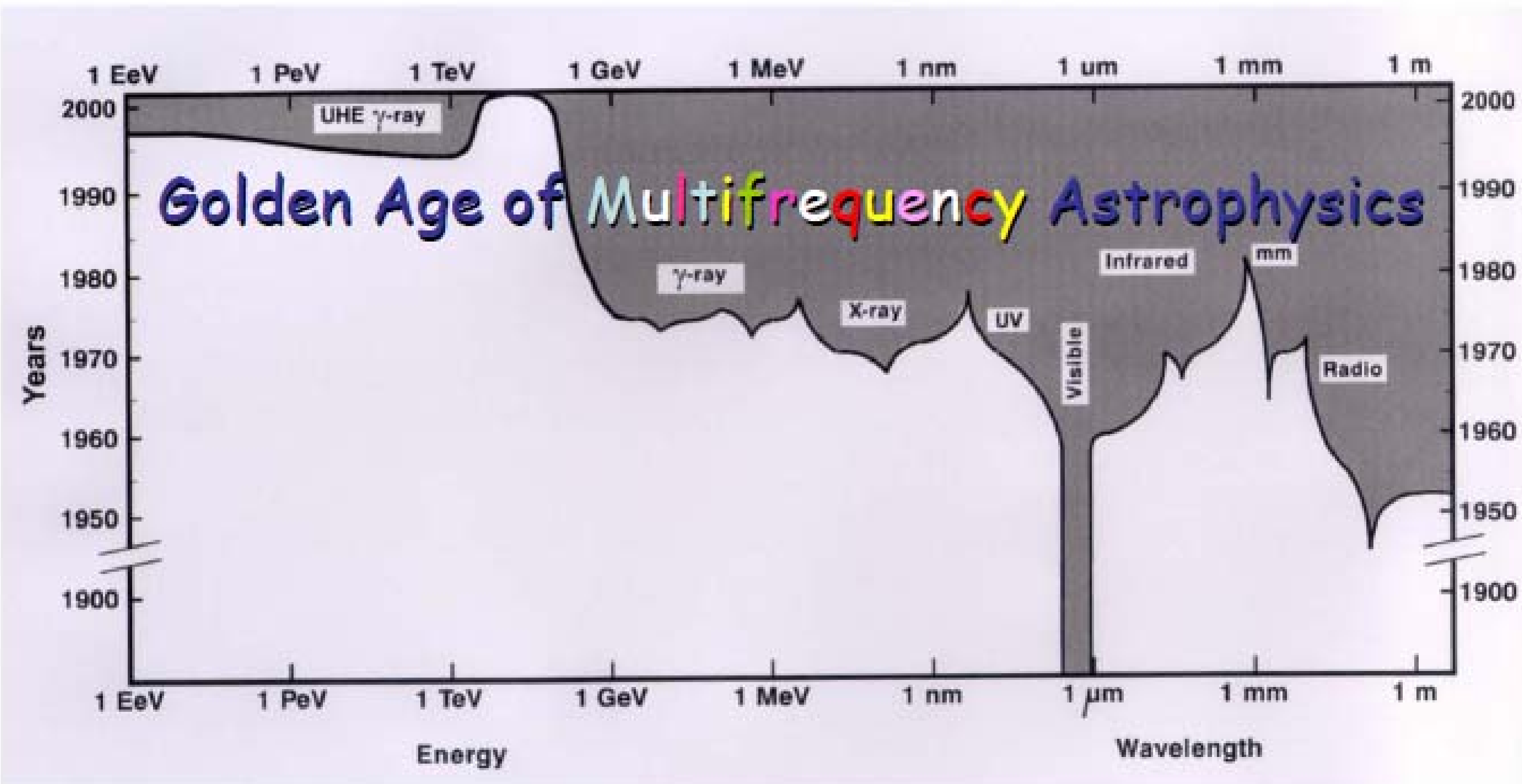
Mechanisms of CR Radiation



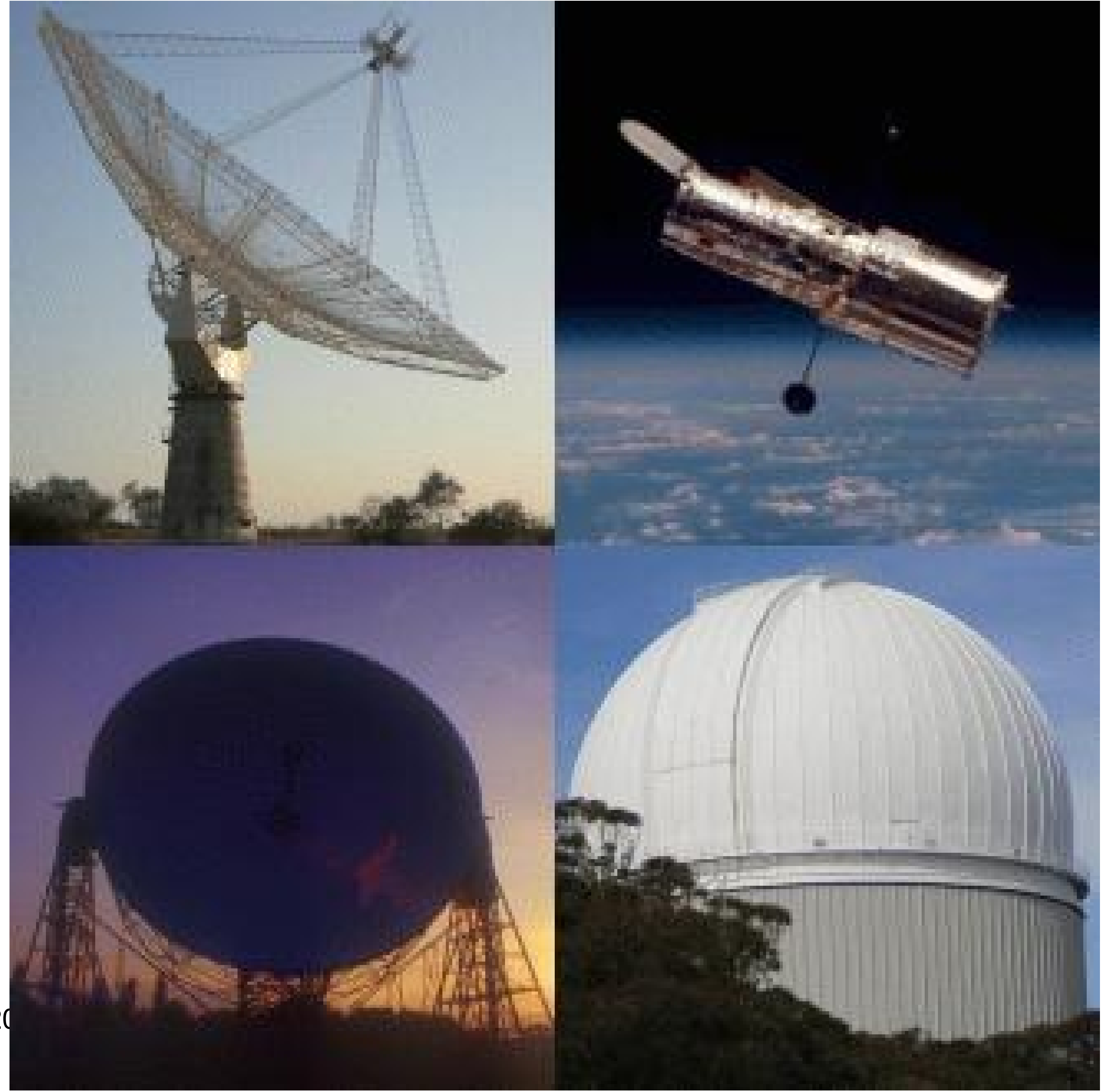
Atmosphere Transparency

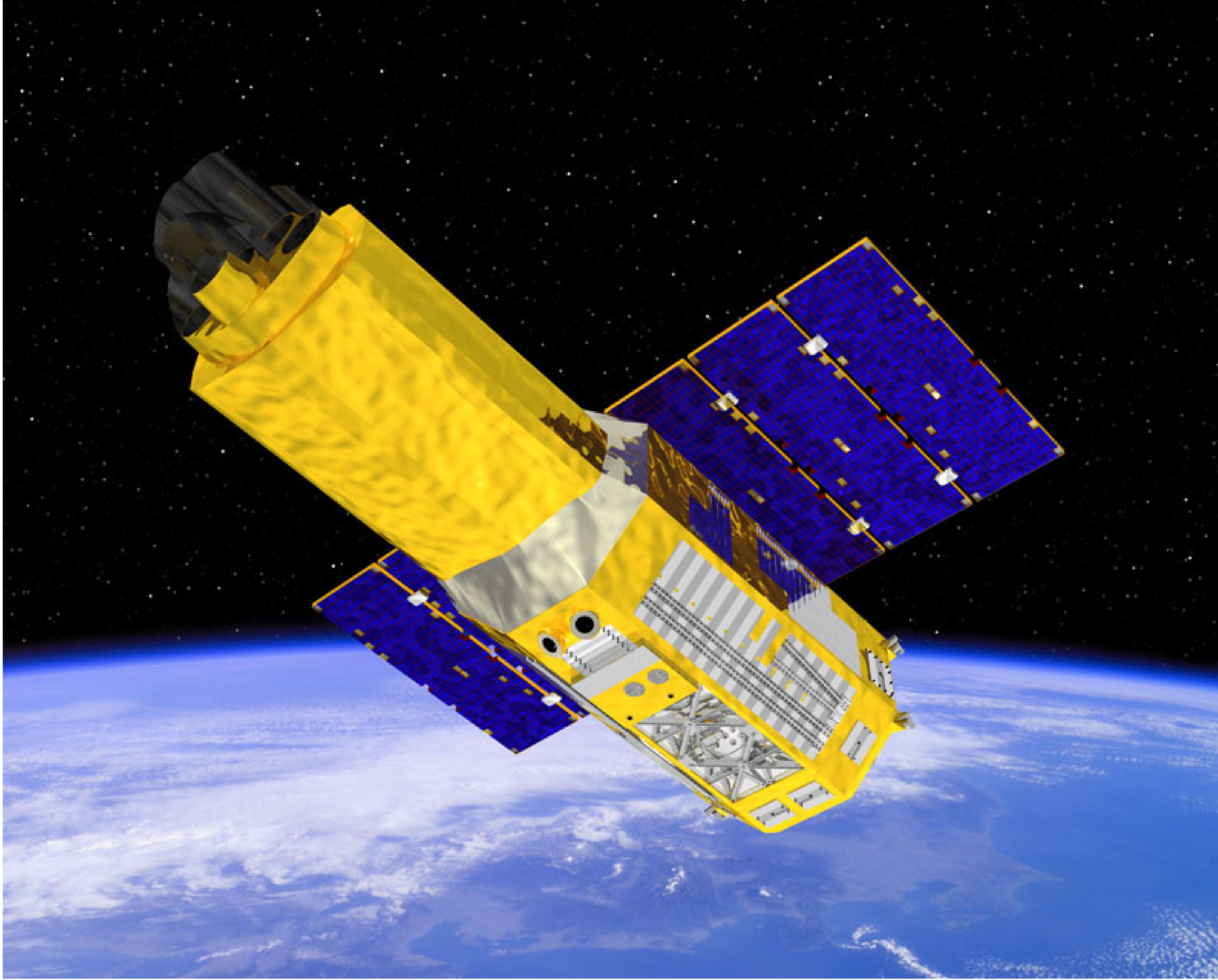
Fig. 1.1 Attenuation of electromagnetic radiation in the atmosphere. Solid curves indicate the altitude (and corresponding pressure as a fraction of 1 atmosphere) at which the indicated fractional attenuation occurs for radiation of a given wavelength. Along the top of the diagram are the conventional designations of the different wavebands. (Adapted from Giacconi, Gursky & Van Speybroeck, 1968.)





Golden Age of Multifrequency Astrophysics
1 EeV
1 PeV
1 TeV
1 GeV
1 MeV
1 nm
1 um
1 mm
1 m
2000
1990
1980
1970
1960
1950
1900
UHE γ-ray
γ-ray
X-ray
UV
Visible
Infrared
mm
Radio
Years
1 μm
Energy
Wavelength





Radio to Gamma Images of the Galaxy

Radio 400 MHz

Radio 2.7 GHz

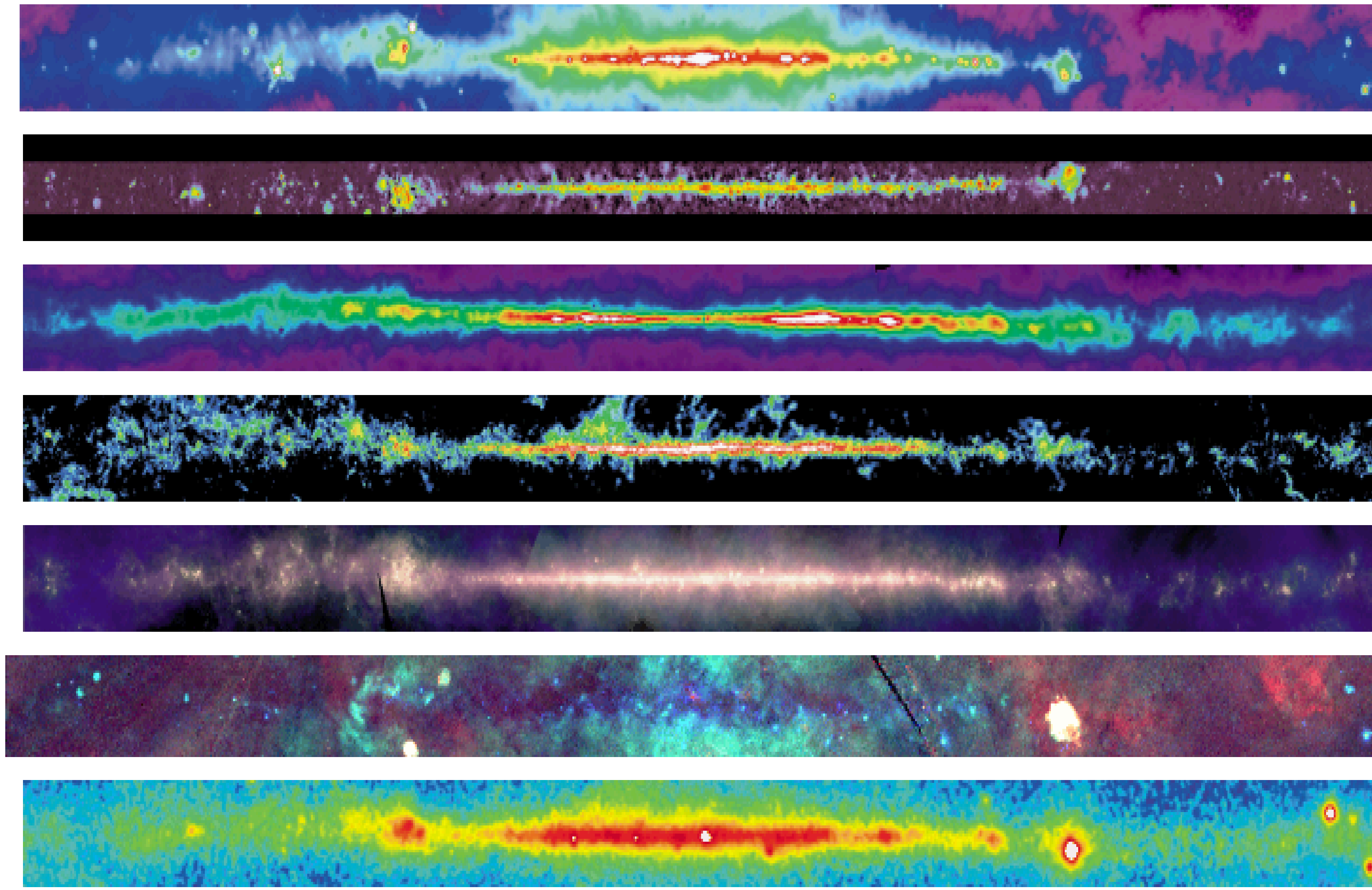
Atomic hydrogen

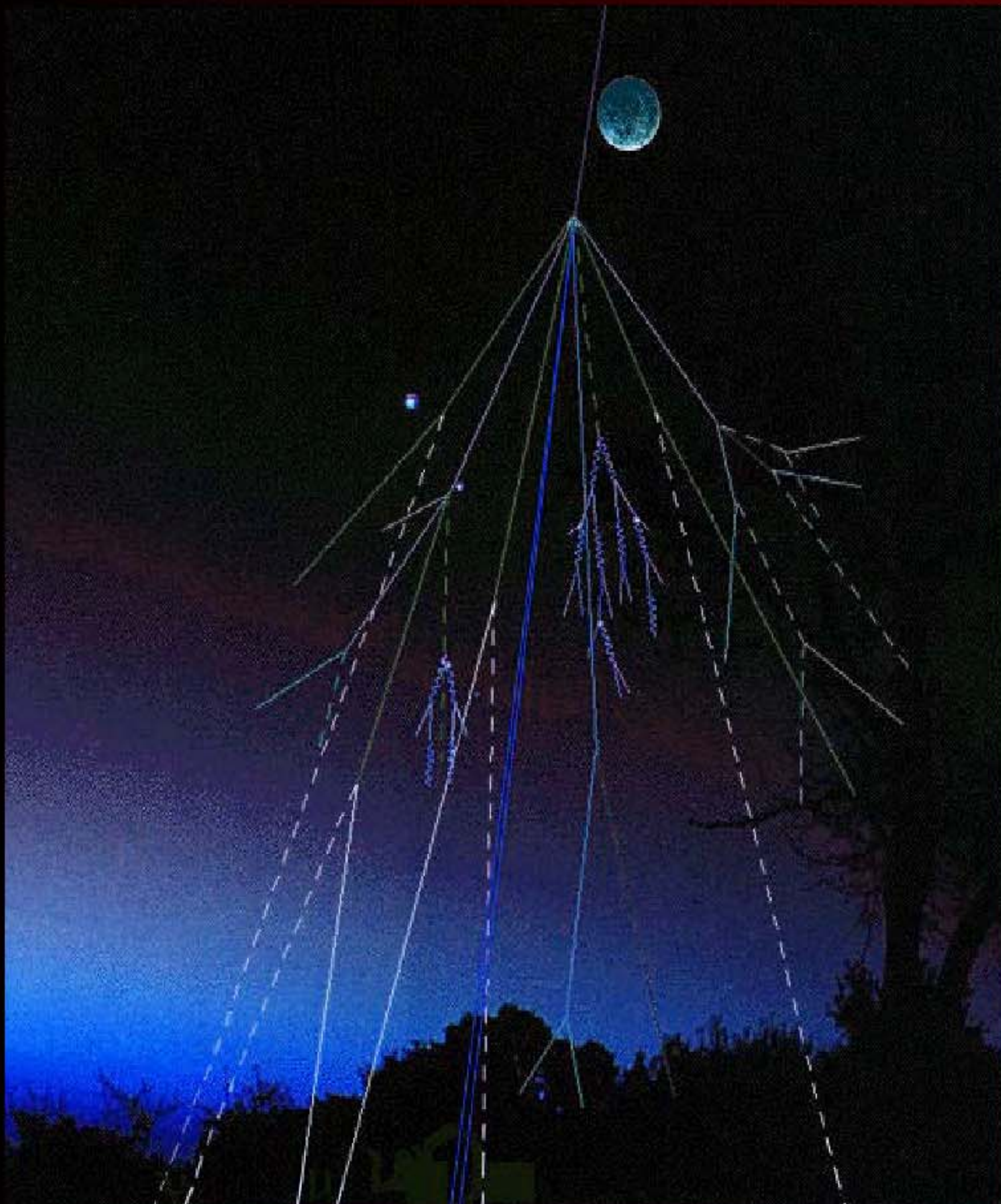
Molecular hydrogen

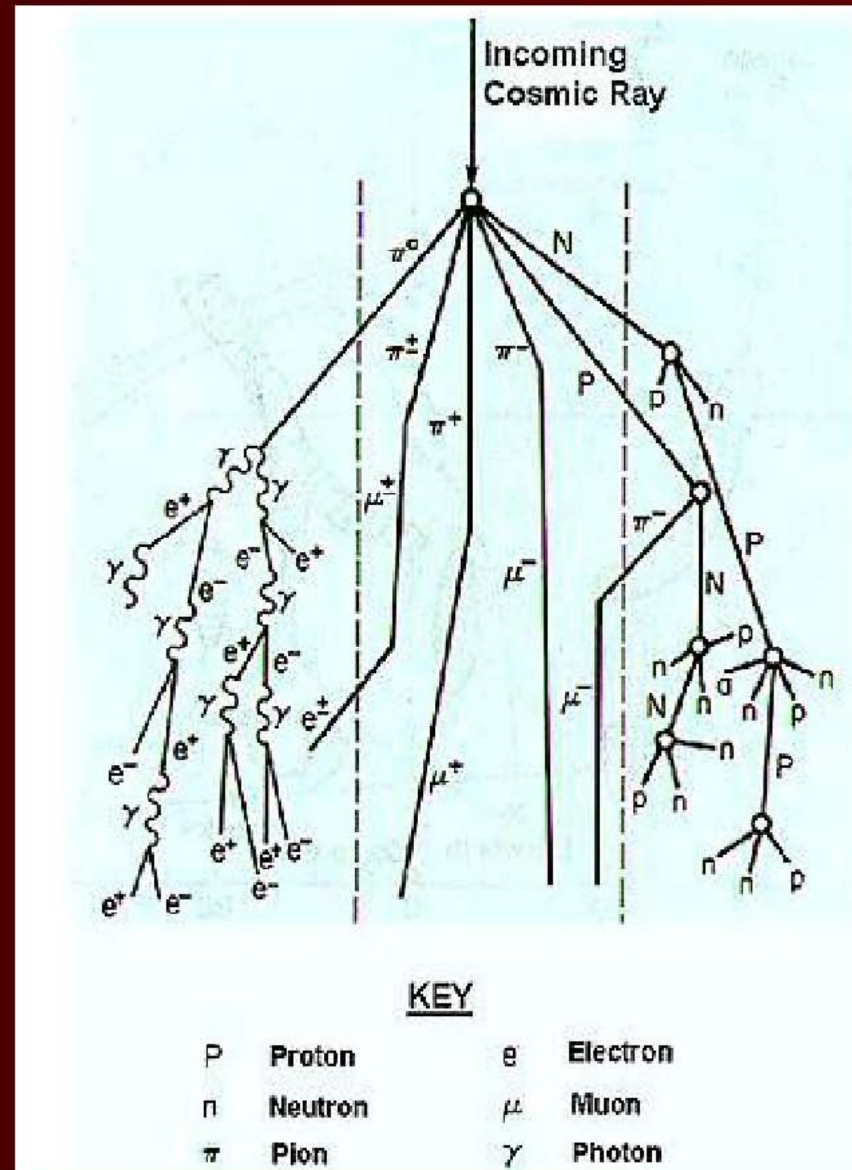
IR

X-rays

Gamma >100 MeV







Incoming
Cosmic Ray
KEY
P Proton
n Neutron
π Pion
e Electron
μ Muon
γ Photon

382 mirror tiles. Automatic remote alignment

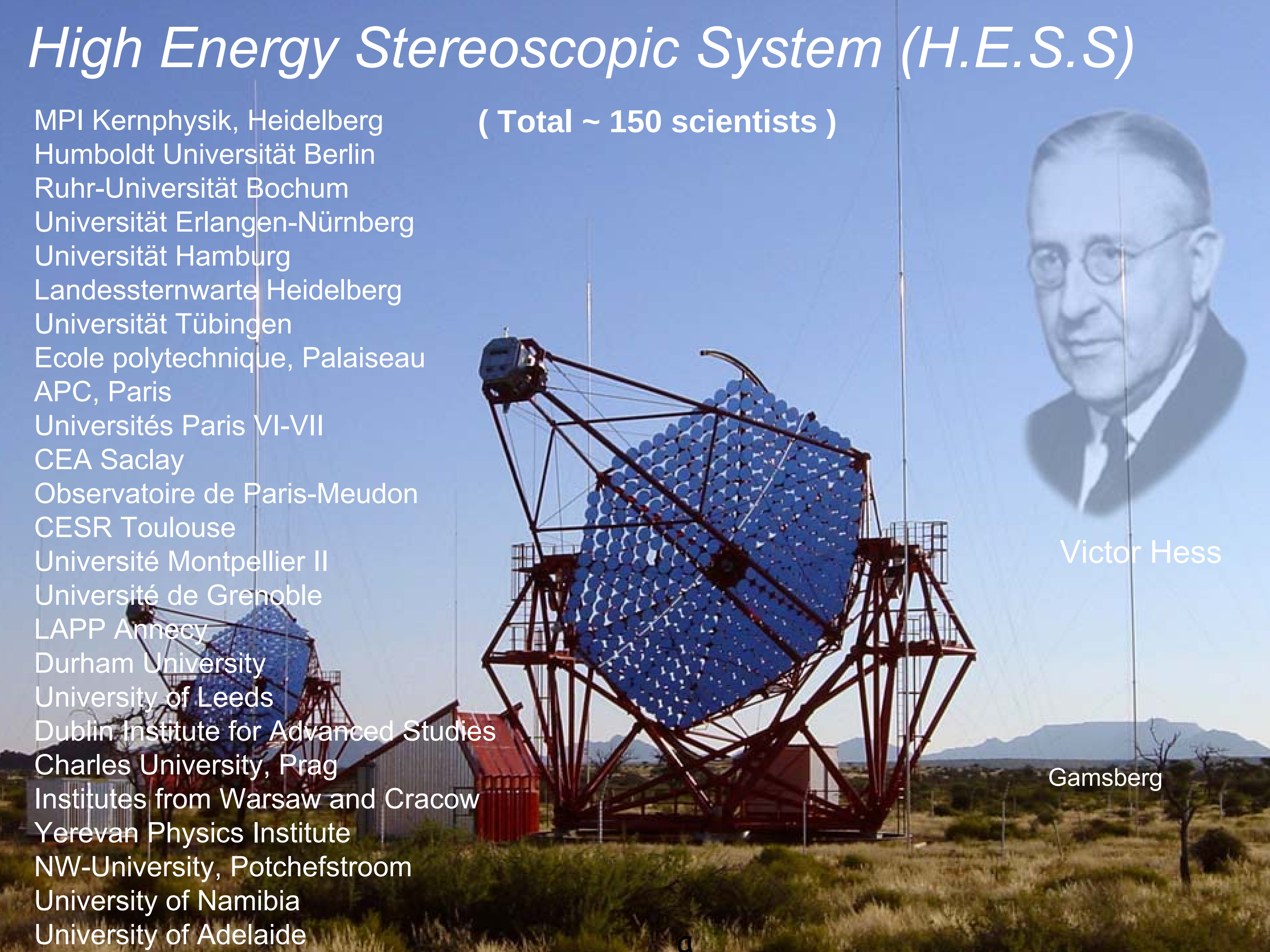
H.E.S.S. Camera

H.E.S.S. telescope
array in Namibia

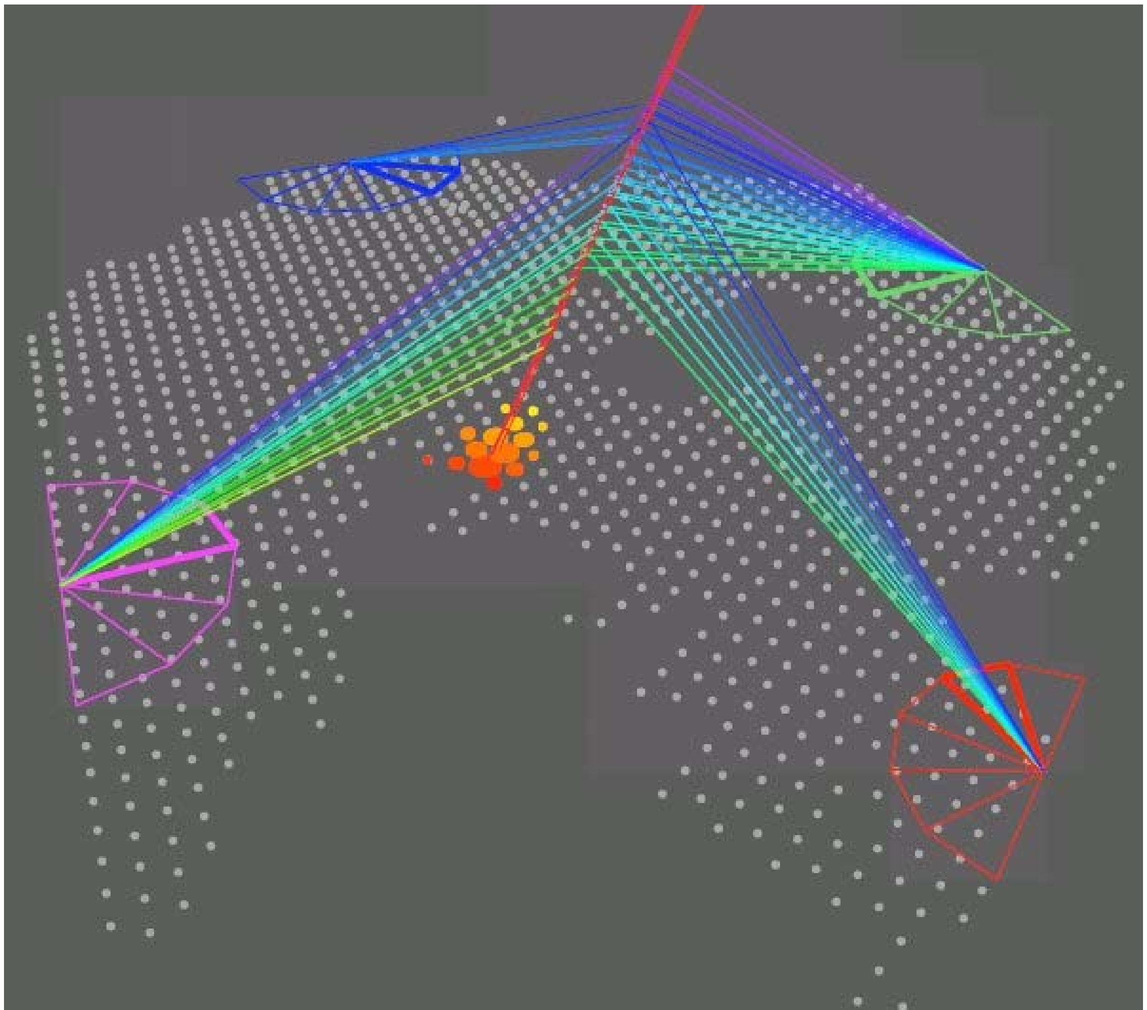
High Energy Stereoscopic System (H.E.S.S)

(Total ~ 150 scientists)

MPI Kernphysik, Heidelberg
Humboldt Universität Berlin
Ruhr-Universität Bochum
Universität Erlangen-Nürnberg
Universität Hamburg
Landessternwarte Heidelberg
Universität Tübingen
Ecole polytechnique, Palaiseau
APC, Paris
Universités Paris VI-VII
CEA Saclay
Observatoire de Paris-Meudon
CESR Toulouse
Université Montpellier II
Université de Grenoble
LAPP Annecy
Durham University
University of Leeds
Dublin Institute for Advanced Studies
Charles University, Prag
Institutes from Warsaw and Cracow
Yerevan Physics Institute
NW-University, Potchefstroom
University of Namibia
University of Adelaide



Auger Observatory



STORY of the DISCOVERY

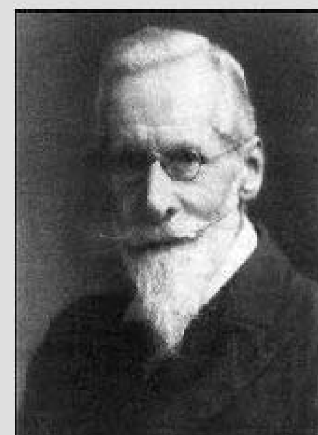
The story begins in the eighteenth century when a spontaneous discharge of an electroscope was found

18th and 19th centuries

1785 Coulomb: ***Spontaneous discharge***

1835 Faraday: ***Confirmes discharge***

1879 Crookes: ***Discharge rate is reduced with reduced pressure***



- By 1785 de Coulomb found that electroscopes can spontaneously discharge due to the action of the air.
- The explanation of this phenomenon came in the beginning of the 20th century and paved the way to one of mankind's revolutionary scientic discoveries: cosmic rays.

- In 1861-1862 the Maxwell's theory appeared and then was experimentally confirmed.

$$qurl\ H = \frac{1}{c}\frac{\partial E}{dt} + \frac{4\pi}{c}\left(j + j^{i}\right) \qquad qurl\ E = -\frac{1}{c}\frac{\partial H}{dt}$$

$$div\ H = 0 \qquad div\ E = 4\pi\left(\rho + \rho^{i}\right)$$

- Among the most interesting experiments were those concerning the conduction of electricity through gases.

In 1896 Becquerel discovered the natural radioactivity of several elements which was observed in the form of α-, β-, and γ-particles which caused ionization of air. A few years later, Marie and Pierre Curie discovered “radioactive decays".

In the presence of a radioactive material, a charged electroscope promptly discharges.

The cosmic ray story itself begins in about 1900 when it was found that electroscopes discharged even in the dark, far away from sources of natural radioactivity. The electroscope was a key instrument at that time to measure the amount of radiation. **The origin of this ionization was a major puzzle.**

Wilson 1901

After experimenting with a gold leaf electroscope, Wilson concludes

"It is unlikely, therefore, that the ionization is due to radiation which has traversed our atmosphere; it seems, as Geitel concludes, a property of air itself"

Rutherford showed that the most of the ionization was due to radioactive elements in rocks.

In the 1909 review by Kurz three possible sources for the penetrating radiation were discussed: an extra-terrestrial radiation possibly from the Sun, radioactivity from the crust of the Earth, and radioactivity in the atmosphere.

General view of 1908:

Radioactivity in the soil is the source of this enigmatic radiation.

Theodore Wulf (1868-1946), German scientist and a Jesuit priest, visits friends in Paris easter 1910. He brings his electroscope and climbs the Eiffel tower.....

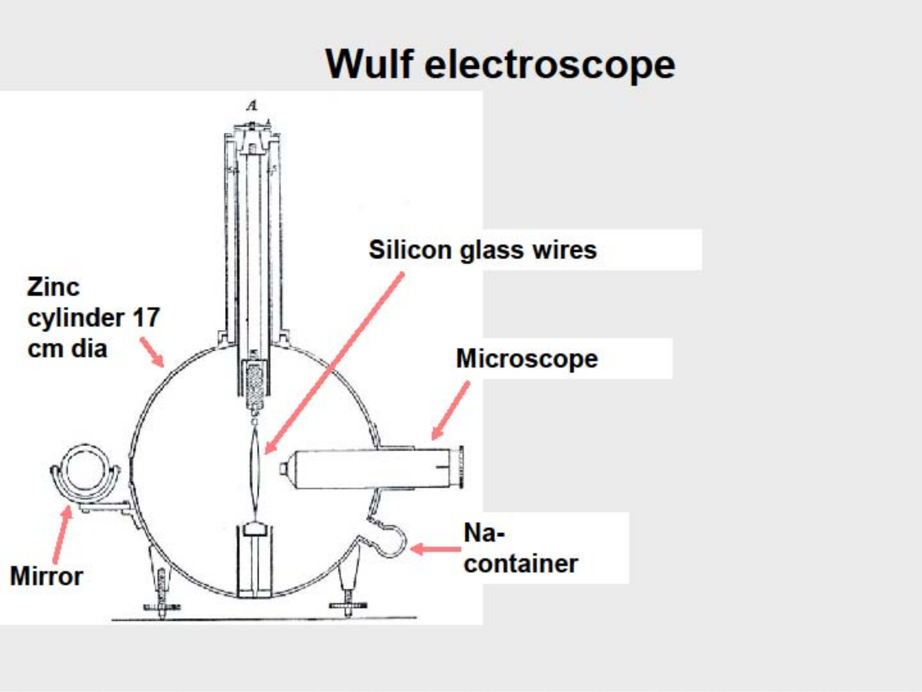
Th. Wulf Phys. Zeitschr. 11, 811 (1910)
(Phys. Inst. Des Ignat.-Koll., Valkenburg, Holland)

Datum	Ort	Ionen / ccm sec
28. März	Valkenburg	22,5
29. „	Paris, Boden	17,5
30. „	„ Eiffelturm	16,2
31. „	„ „	14,4
1. April	„ „	15,0
2. „	„ „	17,2
3. „	„ Boden	18,3
4. „	Valkenburg	22,0

Expected with an 80 m absorption length was a few percent of the radiation at ground. Results requires another source for the gamma-radiation or a significantly weaker absortion of gamma..OR?

Is the radiation coming from the tower structure?

- To protect from the natural ionization from the Earth surface Wulf suggested to put an electroscope on the top of Eiffel Tower, whose height was 330 m.



- In 1910 Wulf found that ionization fell indeed, from 6×10^6 ions/m^3 to 3.5×10^6 ions/m^3 .
- However, absorption in air of the most penetrating γ-rays was known. The intensity of ionization should have halved in only 80 m height and would have negligible at the top of the Tower.

Hess's predecessors.

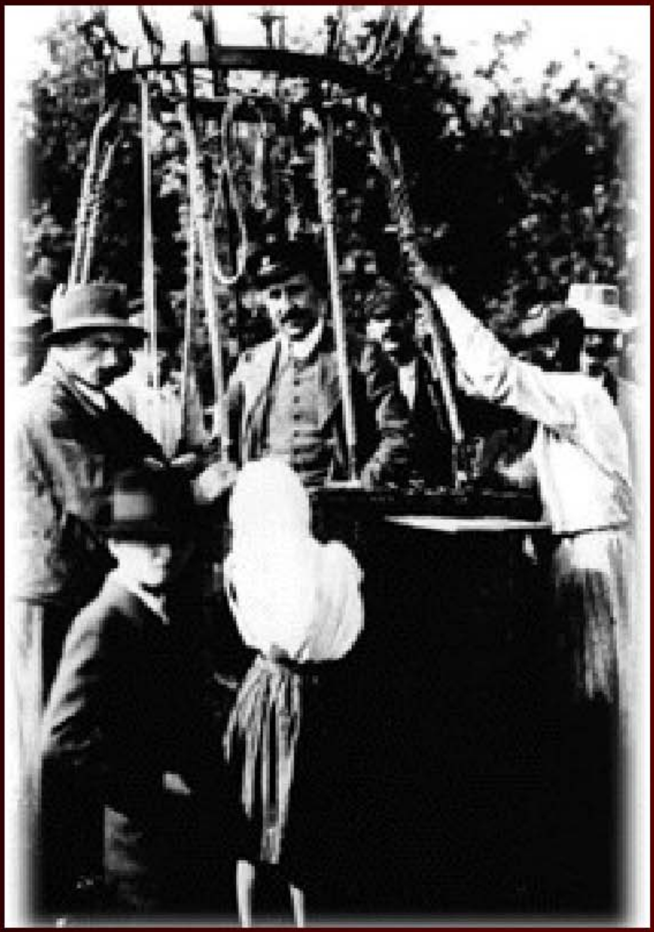
- In 1906 **O.W Richardson** assumed that a significant part of ionizing radiation might be extraterrestrial.
- In 1910 **Gockel** from Switzerland performed balloon experiments with electroscope (the first flight.was in December 1909). He reached the altitude 4500 m and found that contrary to expectations the ionizing radiation there was significantly higher than observed at the sea level. However, this conclusion contradicted the results of **Karl Bergwitz** (1911) who had found on a balloon ride that at the altitutde 1300 m the ionization rate was reduced to 24%of its value on the ground.
- The person who cleared up the situation was **Victor Hess**. He concluded that a significant part of this radiation contained in the uppermost layers of the Earth.

- 1912. The big breakthrough came in 1912 and 1913 when Hess and then Kohlhoerster made balloon flights in order to elucidate the role of the Earth in which they measured the ionization of atmosphere.
- In 1912 Hess had flown to 5 km, and Kohlhoerster in 1914 had made ascent to 9 km.
- Especially successful was the flight of August, 7, 1912 - the birthday of cosmic rays discovered by V.Hess when he reached an altitude 5 km.
- At high latitude the ionization rate was several times higher than observed at the sea level. Radioactive elements in the upper atmosphere?

Discovery of Cosmic Rays - August, 7, 1912

Next year - Centenary of the Discovery

Extraterrestrial Origin



- Increase of ionizing radiation with altitude
- 1912 Victor Hess‘ balloon flight up to 17500 ft. (without oxygen mask!)
- Used gold leaf electroscope

Sir Arnold Wolfendale

Hess 7th flight

7 August 1912

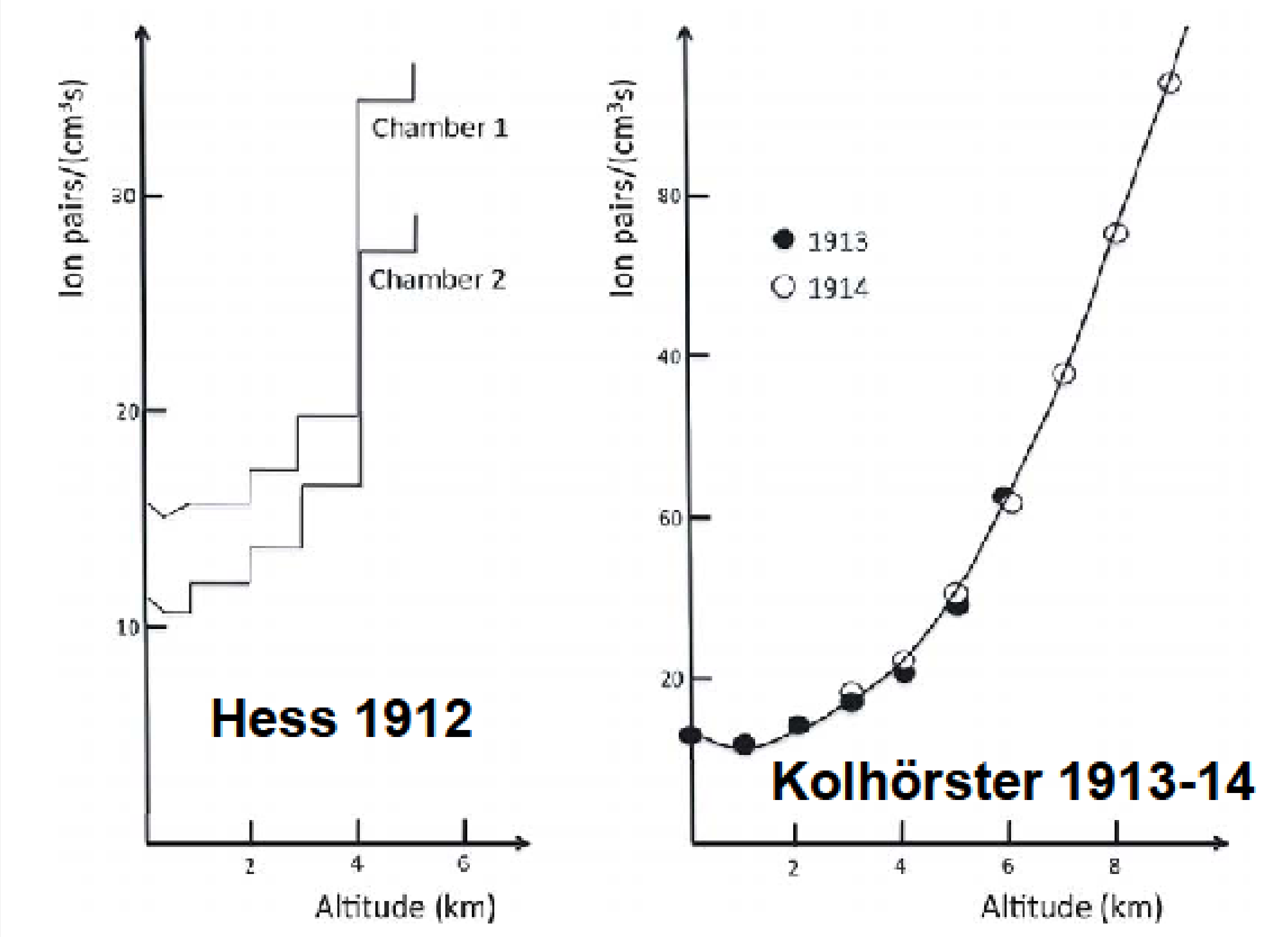
Following Elbe in the Bohemian (Böhmen) countryside.

Diplomarbeit Georg Federmann
Institut für Radiumforschung und Kernphysik
Wien, 2003

- Hess concluded that the increase of the ionisation with height must be due to radiation coming from above, and he thought that this radiation was of extra-terrestrial origin. He also excluded the Sun as the direct source of this hypothetical penetrating radiation due to there being no day-night variation.
- The results by Hess were later conrfimed by Kolhoerster in a number of flights up to 9200 m. The absorption coefficient of the radiation was estimated to be 10^{-5} per cm of air that was eight times smaller than the absorption coeffcient of air for gamma rays as known at the time.

Dr. Werner Kolhörster im Jahre 1912.

Ionization as function of altitude



V.F. Hess

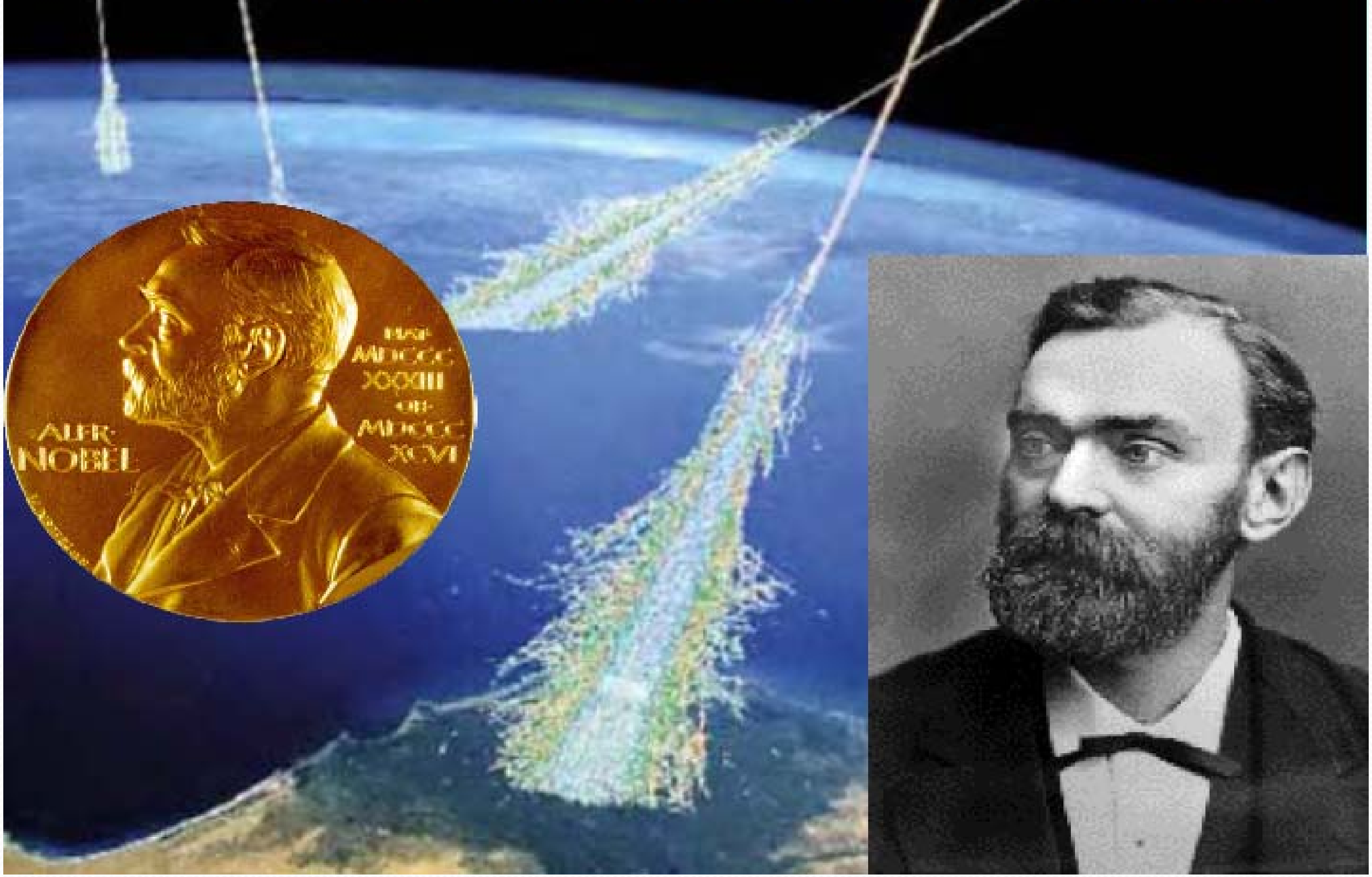
Phys. Zeit. 13(1912)1804

Reported at a meeting in Munster, September 1912

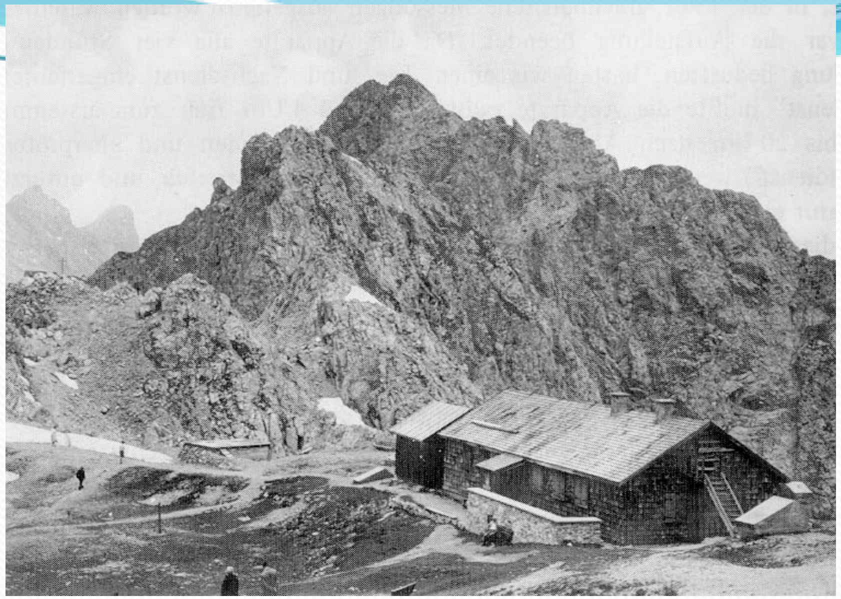
The results of the present observations seem to be most readily explained by the assumption that a radiation of very high penetrating power enters our atmosphere from above, and still produces in the lowest layers a part of the ionization observed in closed vessels.

(Transl. A.M Hillas, Cosmic Rays, Pergamon 1972)

1936: The Nobel Prize to Hess



10 December 1936, Stockholm

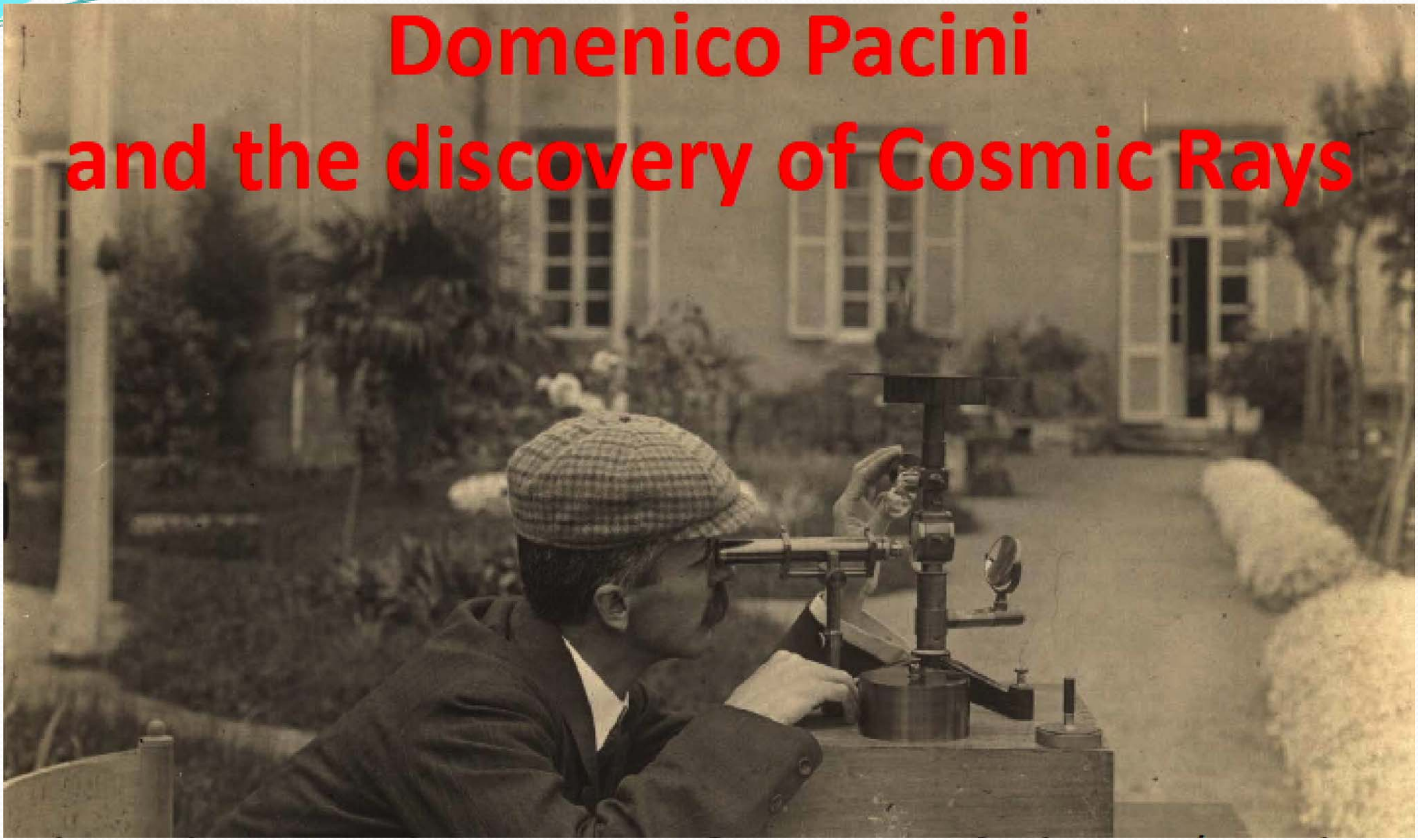


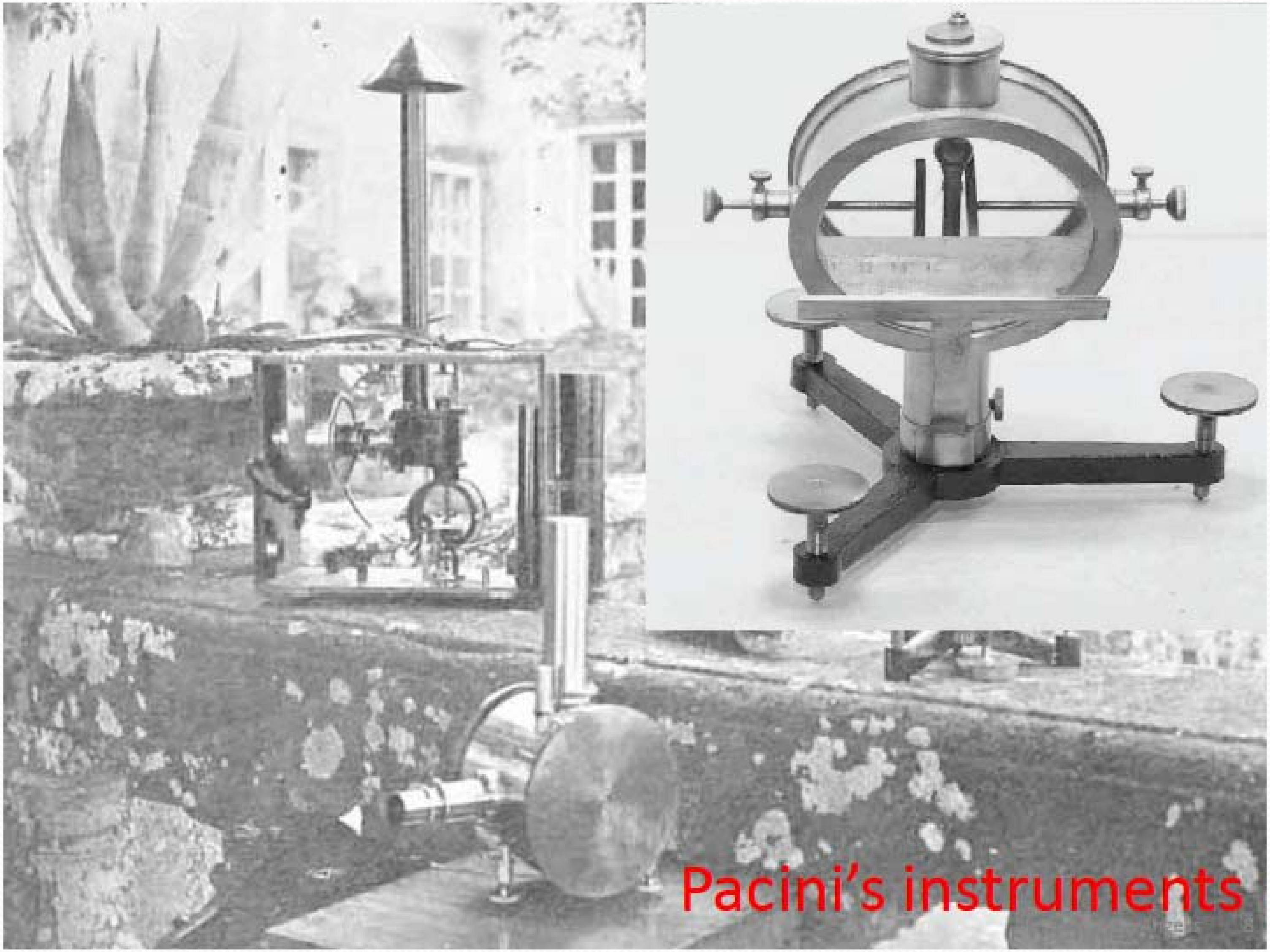
Austrian alps cosmic ray station

Particles or e-m rays??

Victor Hess Nobel Prize 1936

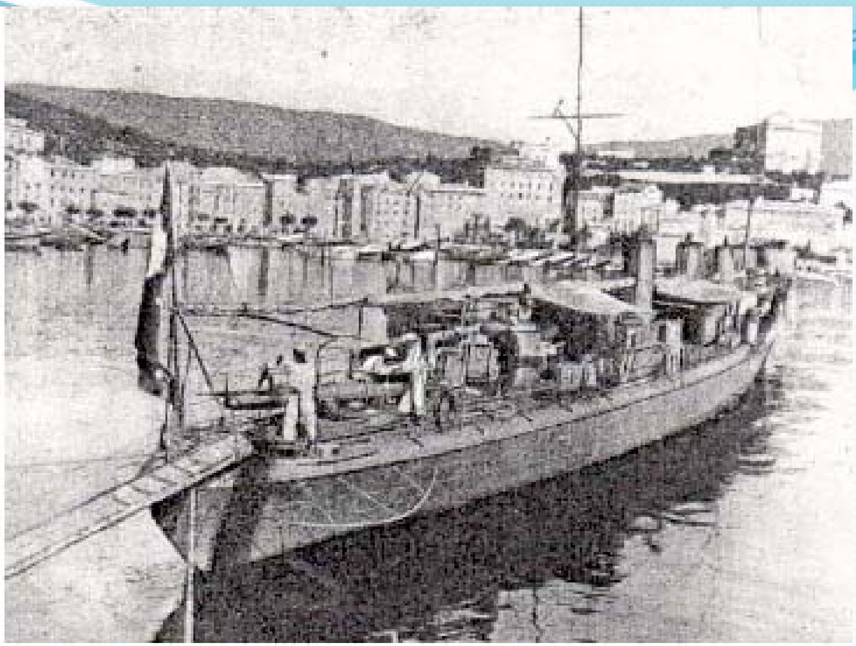
Domenico Pacini and the discovery of Cosmic Rays




Pacini's instruments

Researches in 1908-1910

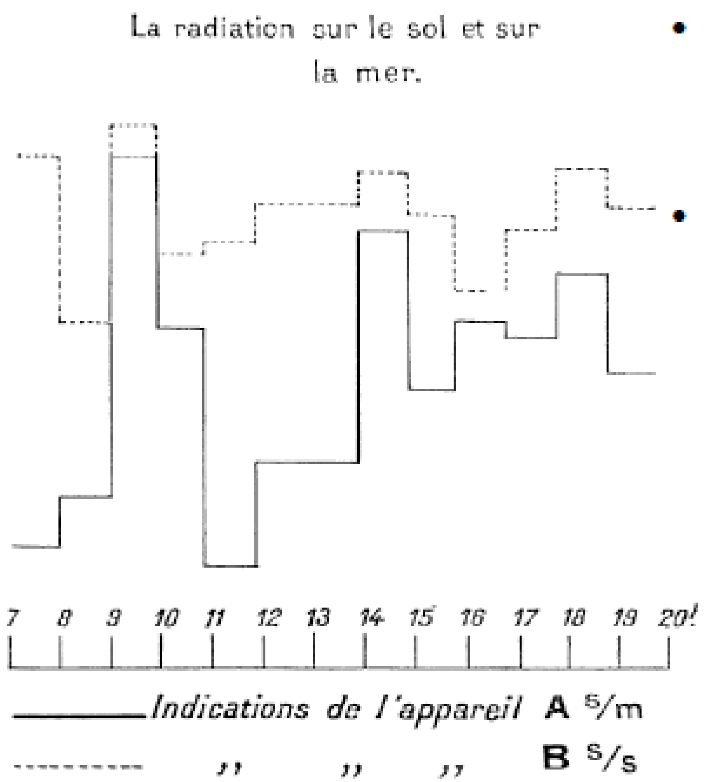
- Since end 1908, Pacini can use the destroyer "Fulmine" from the Navy
- 1908/1910: compares measurements on the shore with values on the sea, and with previous measurements on the mountains and in Forme
- Fluctuations appear similar, which raises in Pacini doubts about the Terrestrial origin



- In 1909 he presents his results to the "Accademia dei Lincei" (the national Academy of Sciences)
  - *"in the hypothesis that the origin of all penetrating radiations is in the soil [...] it seems not possible to explain the results obtained."*

The measurement in 1910

(quoted by Hess)



- First, two electroscopes (A and B) with walls of different thickness are cross-calibrated
- Simultaneous measurements are performed at ground and on the sea's surface, and then the instruments are exchanged
- "The number of ions due to penetrating radiation on the sea is estimated to be 2/3 of that on the ground"
- ``the evolution of the phenomenon on the sea surface and on the land reveals for both the same trend of the penetrating radiation during the ten days of observation [...] But it is clear that in order to show the existence of a possible correlation [...] a period of time longer than that I dedicated to the experiment would be needed.''

"such results seem to indicate that *a substantial part of the penetrating radiation in the air [...] has an origin independent of the direct action of active substances in the [...] Earth's crust.*"

"Observations that were made on the sea during the year 1910 led me to conclude that a significant proportion of the pervasive radiation that is found in air had an origin that was independent of direct action of the active substances in the upper layers of the Earth's surface. The results indicated that a source of ionization existed on the sea surface, where possible effects from the soil are small, that had such an intensity that could not be explained on the basis of the known distribution of radioactive substances in water and in air."

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: … *anyway several authors are cited but 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. …*

Hess' book on cosmic radiation

- Hess published in 1940 the book *Weltraumstrahlung und ihre biologische Wirkung*, with Eugster. A translated/updated edition (Cosmic radiation and its biological effects) was published by Fordham University Press in 1949
- Chapter 1 (written by Hess) was dedicated to the history of CR. Hess made the clear statement that Pacini was the first to oppose the idea that radioactivity on the soil is the only source of the radiation:
  - *"The first who expressed some doubts as to the correctness of this view was D. Pacini, who, in 1910, from measurements over sea and on shores at Livorno concluded that part of the observed ionization might be due to sources other than the known radioactive substances."*

1909-1914

In action on penetrating radiation:

Pacini, Wulf, Hess, Kohlhörster

Improvements and experiments:

Electroscope improvements
On sea, in sea, on Eiffel tower, with balloons

Common view 1912-14:

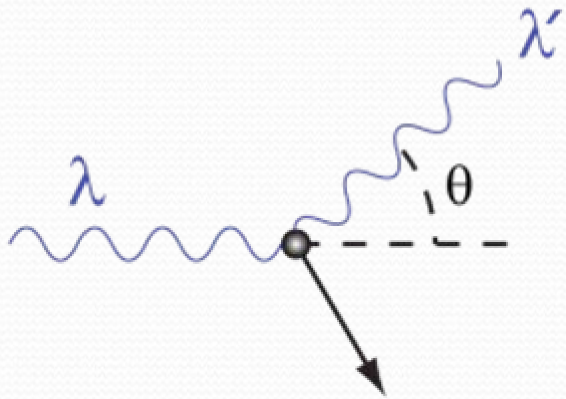
There is a radiation coming from outside the earth

But:

Not everybody believed an external source for the radiation

- It was not too much extrapolation to assume that the *cosmic radiation* or *cosmic rays*, as they were named by Milliken in 1925, were γ-rays with greater penetrating power than those observed in natural radioactivity.
- But the really essential question of the nature of the high-altitude radiation found no experimental answer

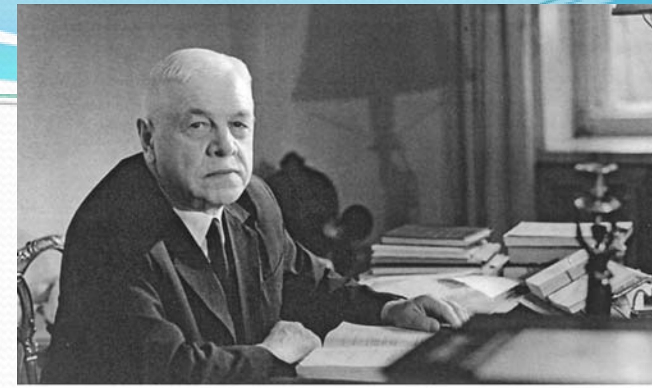
- “Mile stone” of 1920s – Compton effect. At that time and the Compton effect and



- the rate of ionisation losses of charged particles were known. Bethe-Bloch formula for ionization losses

$$\frac{dE}{dx} = -\frac{2\pi Z^2 e^4 n}{mv^2} \ln \Lambda$$

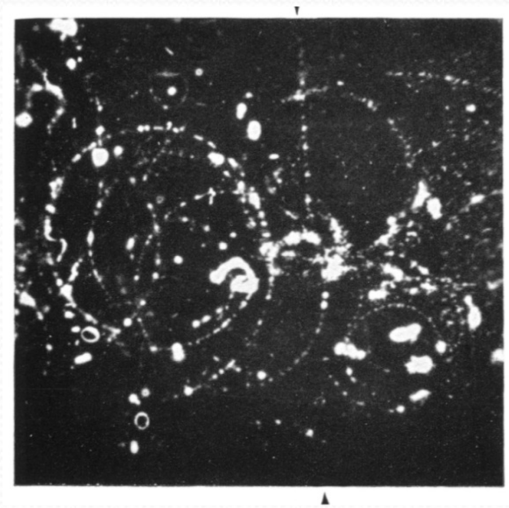
During a study of the Compton Effect Skobelzyn (1926) found electron tracks which were not of radioactive origin, whose great magnetic rigidity indicated an energy of at least 1.5×10^7 eV which he identified as secondary electrons produced by the “Hess ultra gamma-radiation”. By chance he observed high energy cosmic rays.



Академик Д.В. Скобельцын в рабочем кабинете (1966 г.).

He found also tracks of positrons but did not identified them as they are electrons coming from below.

Latter, in 1930, Millikan and Anderson analysing the tracks of cosmic rays in the cloud chamber found tracks identical to electrons but with a positive electric charge.



The first cosmic ray particle to be recognised in a cloud chamber by Skobelzyn. The particle is not deflected significantly in the magnetic field.

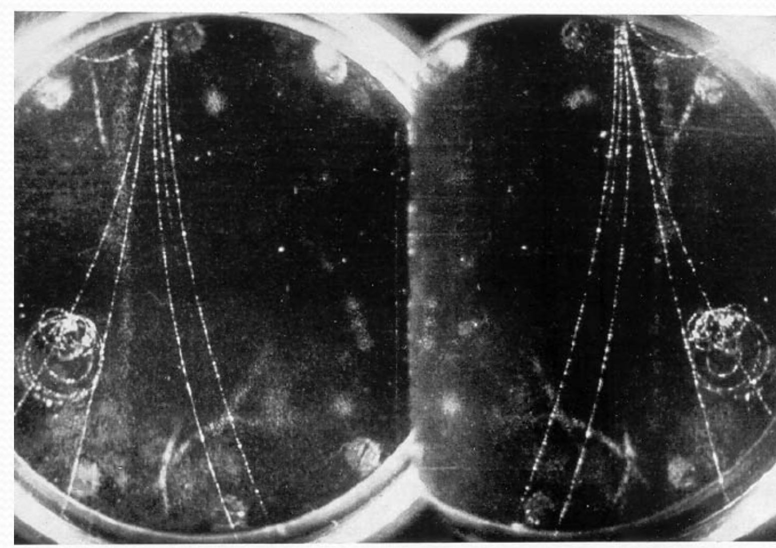


Plate 32. C. D. Anderson and S. H. Neddermeyer, Pasadena, Phys. Rev. **50**, 263 (1936).

Bothe and Kolhöster perfomed a series of beautiful experiments that aimed to distinguish between the two hypotheses of cosmic rays: corpuscular and electromagnetic.

Dr. Werner Kolhörster im Jahre 1912.

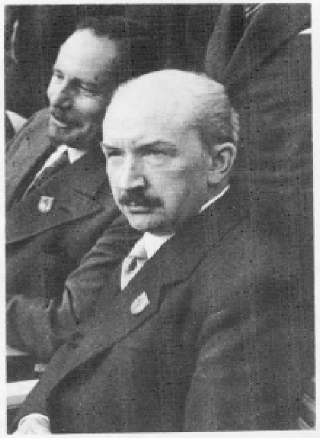
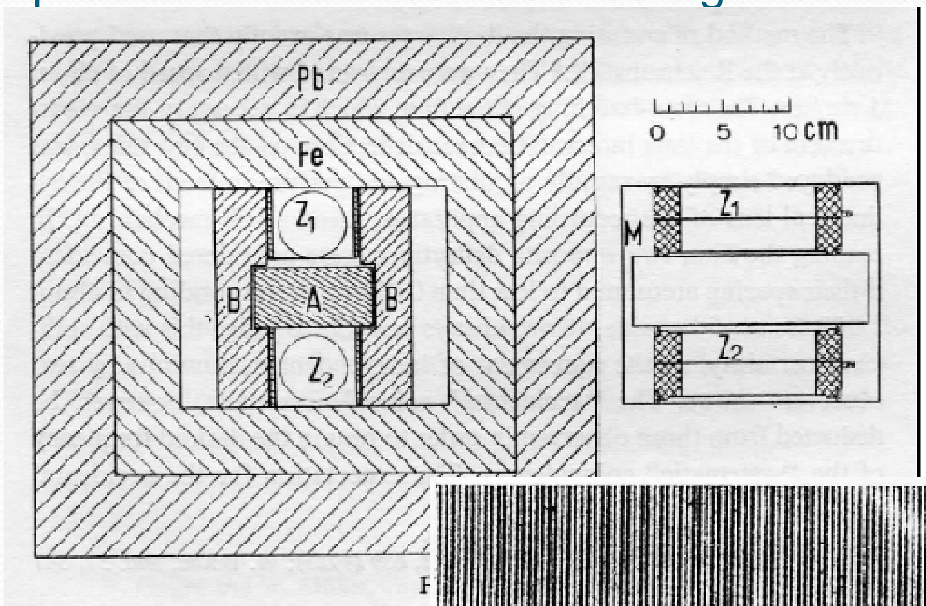


Fig. 2. Professor Walter Bothe (1891–1957) (right), Nobel prize winner 1954, (coincidence method and discovery of artificial nuclear gamma radiation) and Professor Erich Regener (1881–1955) at a meeting in 1937. (Courtesy of Max-Planck-Institut für Kernphysik, Heidelberg).

They used the newly developed Geiger-Müller Counters, but with the coincidences recorded by a photographic method. Lead was 150 years old and free from γ-radiation. Each coincidence signifies the passage of one and the same co



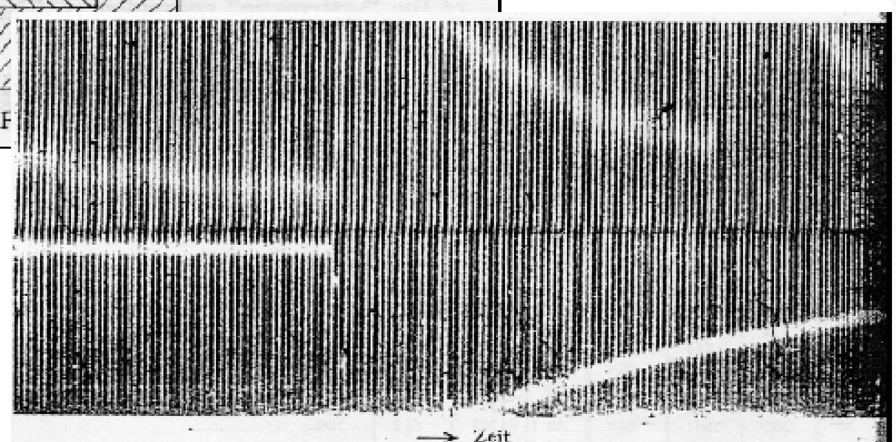
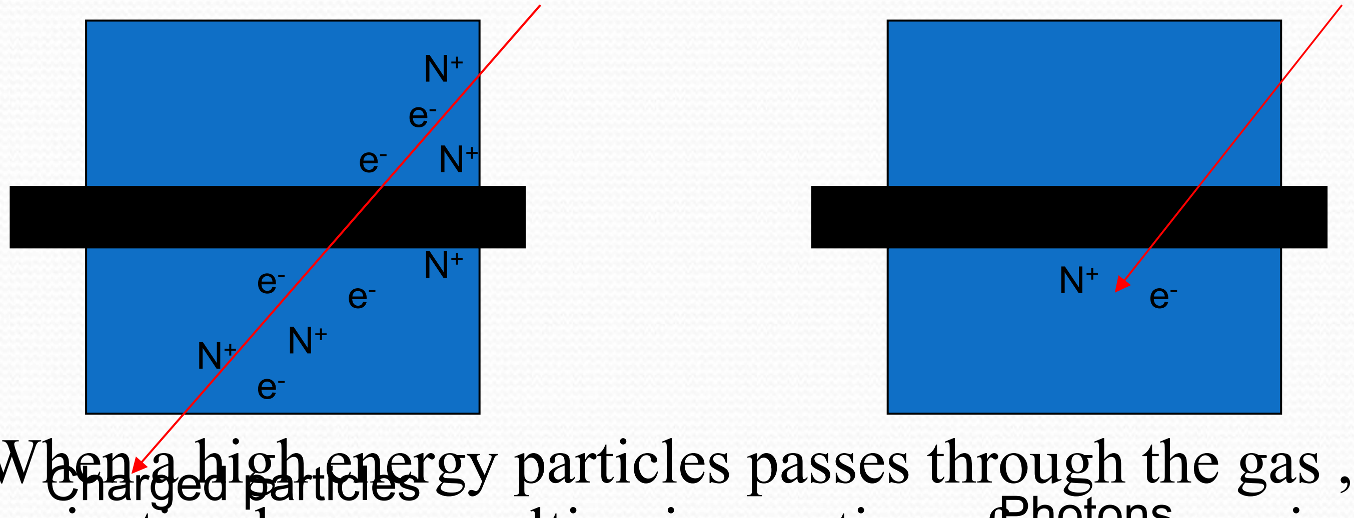
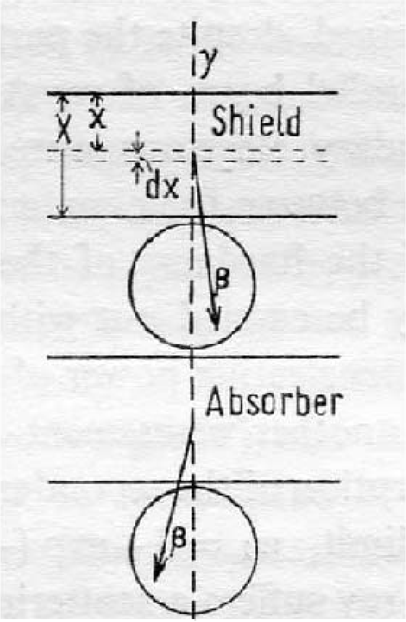


Fig. 7. Beispiel einer Koinzidenz. Streifenabstand 1/1000 Sekunde. Oben ε-Ausschläge, unten Δε-Ausschlag.

- 1929. Experiments of Bothe and Kolhoester with the Geiger-Mueller detector which enabled to detect individual cosmic rays.
- They used two counters, one placed above other, and placed slabs of lead and gold between them.



- When a high energy particles passes through the gas , it suffers ionization losses resulting in creation of numerous ion-electron pairs whereas, when X or γ-ray enters the gas an ion-electron pair is created at a single point of photoinization.



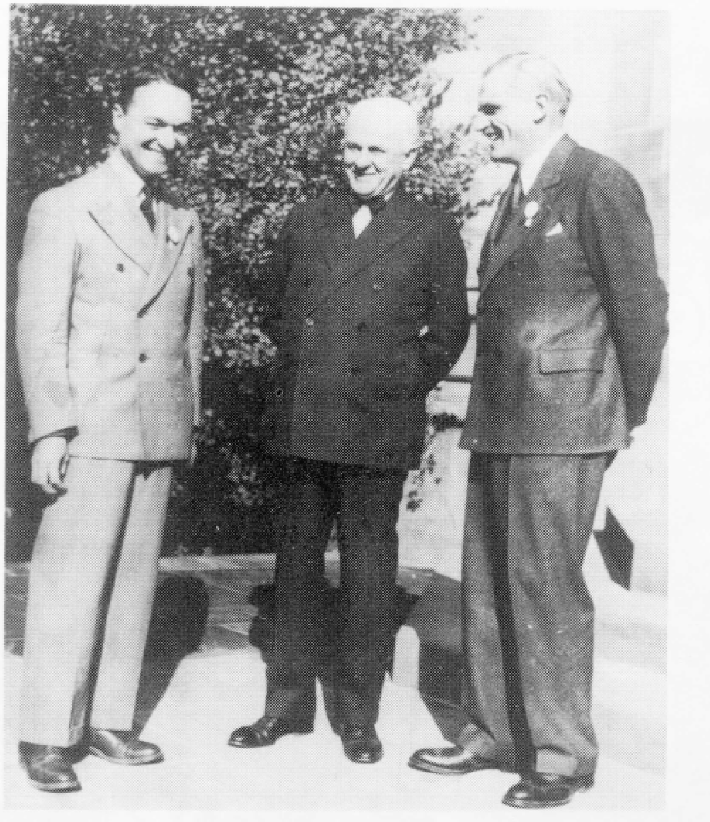
Chance of a coincidence being produced by two Compton electrons was very small.

Concluded that there were particles in the cosmic ray beam.

Regarding these experiments alone, one cannot help being prompted to say that ultra-radiation is not of a wave nature, but consists rather of high velocity electrons. This, indeed, was the general conclusion arrived at by Bothe and Kolhörster.

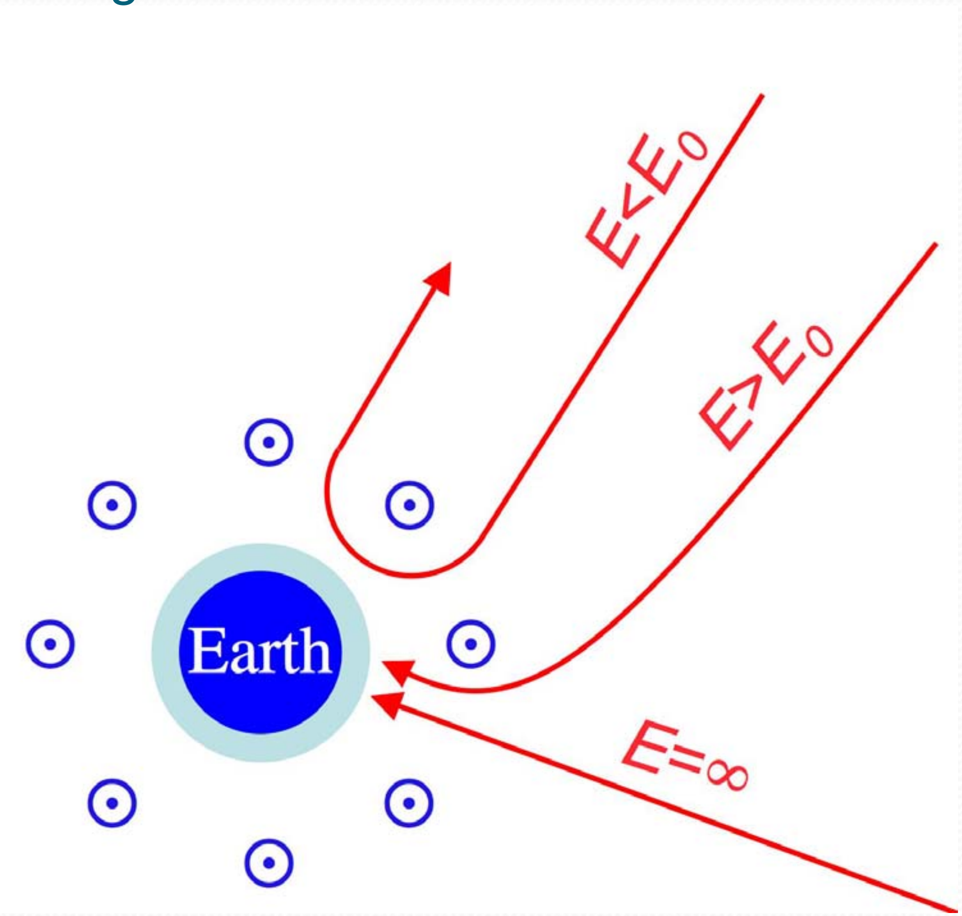
They estimated the energy of these particles to be 10^9 -10^{10}эВ.

- β-rays from radioactive sources could penetrate only less than 1 mm of lead
- In triple-coincidence experiments, Rossi found that cosmic rays could traverse 1 m of lead, so energy of particles triggering counters had to be GeV



:. 16. With Millikan and Compton at the Rome conference.

It was concluded by Clay that if such radiation of charged particles came from the external universe, its intensity at the earth's surface would depend on the magnetic latitude.



Cosmic ray intensity as function of latitude

1927: Start of observations by Clay between Netherlands and Dutch East Indies
Showed decrease of several percent near Suez Canal

1928: Millikan et al had not discovered any significant change between Bolivia (19° S) and Pasadena (34° N) and between Pasadena and Churchill, Canada (59° N)

1928: Bothe and Kolhöster found no variation with latitude in North Sea
- but this did not deter them from acknowledging Clay's work

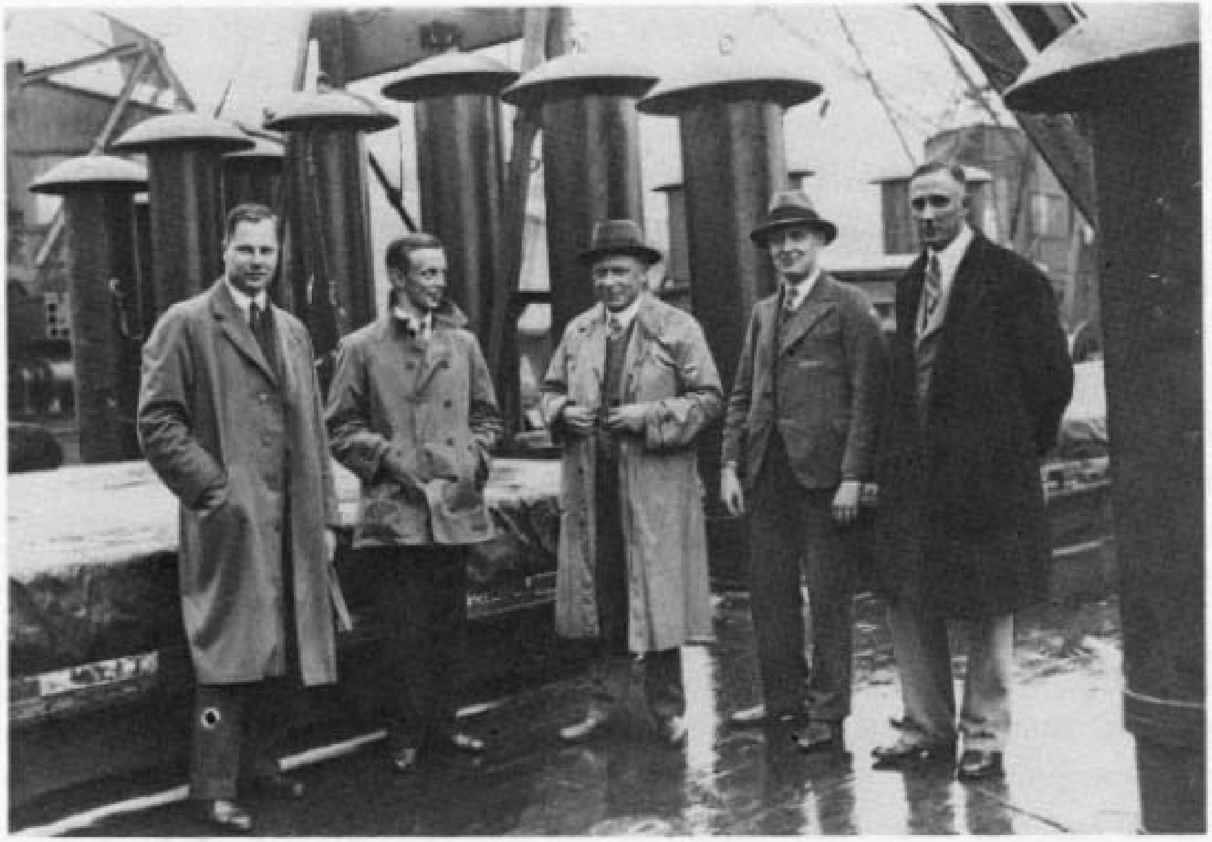
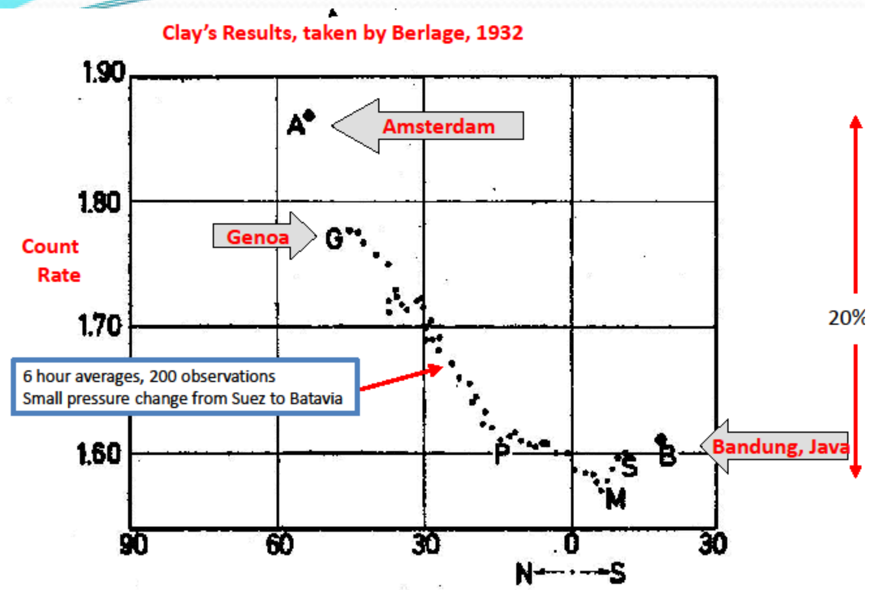


Fig. 12. Jacob Clay (middle) and his collaborators before their departure on a cosmic ray research trip by boat to the East Indies.

Source: Physics in Amsterdam: A Brief History, A J Knox 1990

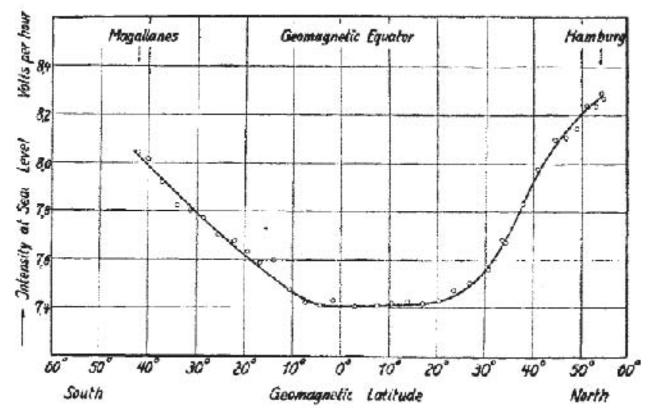
Clay's Results, taken by Berlage, 1932



Counting Rate at sea-level as a function of the position of the ship with respect to the earth's magnetic field which is nearly horizontal at the earth's equator

Ionisation Chambers provided by Steinke: hourly observations

Hoerlin, Nature 132 61 1933



Also measurements between Europe and Buenos Aires by Leprince-Ringuet and Auger

Compton's expeditions

- Compton had a Guggenheim Fellowship in Lahore, India, in 1927-28

"Upon his arrival in Calcutta, Arthur learned that he was expected immediately to lead a cosmic ray expedition to Darjeeling in the foothills of the Himalayas--and that he was supposed to supply the experimental apparatus.Seeking out physicist C. V. Raman, who would win the Nobel Prize in 1930, he got the help he needed to rig an electroscope out of the bowl of a hookah--and it worked".

Betty Compton: Interview AIP 1968

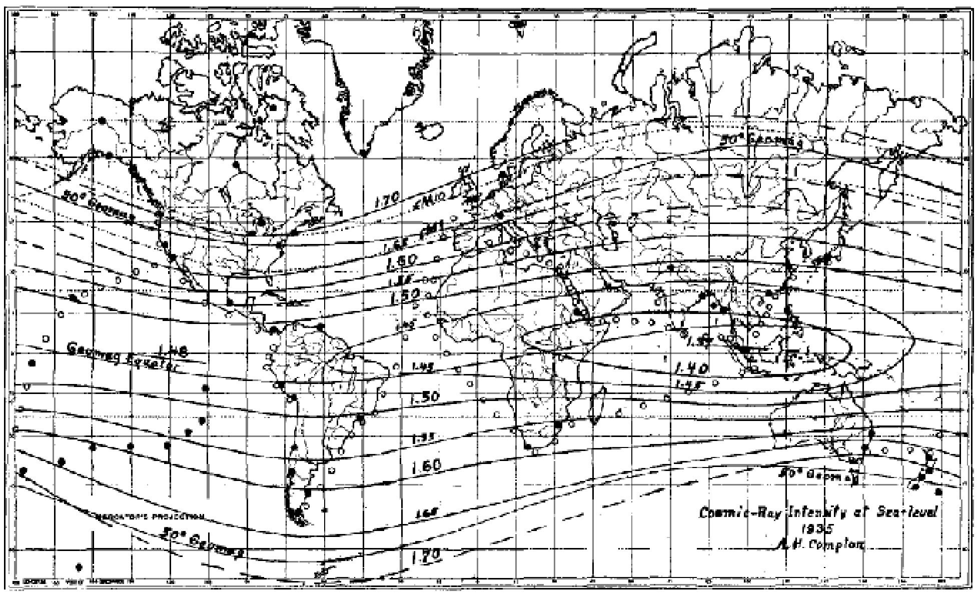


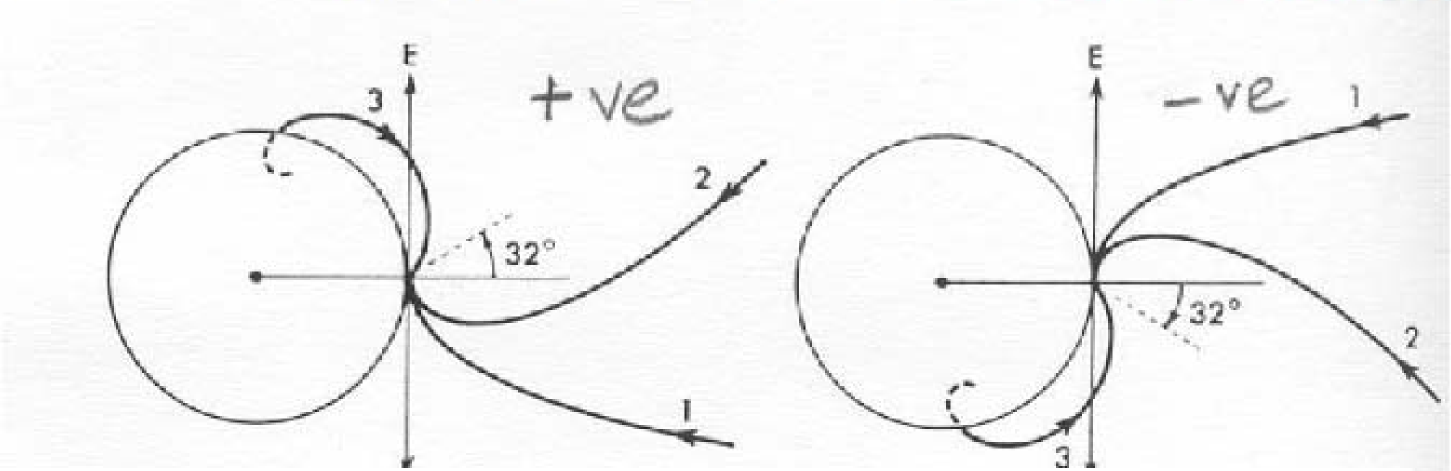
FIG. 1. Curves of equal cosmic-ray intensity (isocosms), showing approximate parallelism with parallels of geomagnetic latitude and with curves of equal auroral frequency (M1 and M10).

'Isocoms' as reported by A H Compton, Rev Sci Inst 7 70 1936 25

The results were interpreted as showing that at least some of the particles are charged and that at least some come from outside the atmosphere.

East-West Effect: Positive and negative particles in plane of geomagnetic equator. B-field is out of paper. Rossi extracted essence from Störmer's papers

From Rossi 'Cosmic Rays' (1964): see also Rossi Phys Rev 1932 **BUT his predictions ignored**



Predicted by Rossi in 1932 – but failed to observe effect close to sea-level in Italy

1933: Johnson, and Compton and Alvarez found effect in Mexico City, 2250 m
de Benedetti and Rossi in Eritrea, 2370 m above sea-level

10% effect
– the particles are dominantly positively charge: protons or e+?

So, are cosmic rays protons or positrons?

Very early studies of the dependence of cosmic ray intensity on altitude led to an examination of the effect of lead absorbers. It was found by many workers (e.g. Rossi, (1933) and Street et al. (1935)) that there were two components to the cosmic radiation in the

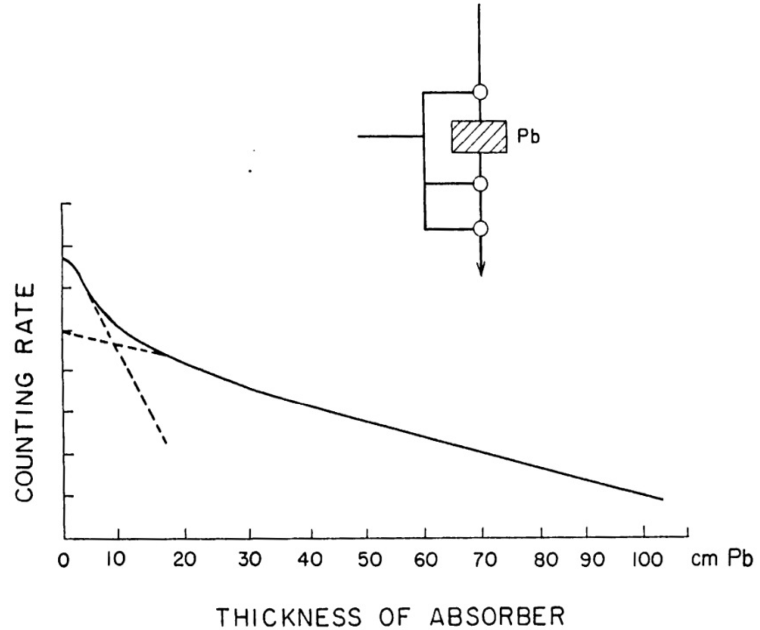


Fig. 1.1 Separation of the soft and the hard components by the triple coincidence method. The solid curve represents the counting rate in arbitrary units versus the thickness of a lead absorber inserted between two counters. The counting rate is decomposed into two parts as indicated by the dashed curves; the steeper one represents the counting rate due to the soft component, whereas the less steep one is due to the hard component.

The Nature of the Primary Cosmic Radiation and the Origin of the Mesotron

Marcel Schein, William P. Jesse and E. O. Wollan
Ryerson Physical Laboratory, University of Chicago, Chicago, Illinois
March 13, 1941

During the past year, our counter measurements of the vertical intensity and the production of mesotrons at high altitudes have been continued.[1] In these measurements various arrangements of counters in three-, four- or fivefold coincidences have been used. The vertical intensity has been obtained with lead thicknesses of 4, 6, 8, 10, 12 and 18 cm interposed between the counter tubes. The combined results of these experiments are plotted as Curve *A* of Fig. 1. It is seen from these measurements that the intensity of the hard component increases continuously to the highest altitudes reached. In our previous paper a single point of low statistical weight indicated a maximum in the mesotron curve which is not confirmed in our subsequent experiments. In the original experiments with 8 and 10 cm of lead we considered the possibility of a contribution at very high altitudes to the observed intensity from primary electrons with sufficient energy to penetrate the lead ($E>10^{10}$ ev). This consideration led us to carry out the experiments with greater and with smaller lead thicknesses. The close agreement between the points obtained with the various thicknesses to pressures of 2 cm Hg (less than 1 radiation unit from the top of the atmosphere) is evident from the figure. This shows that measurements of the hard component made at very high altitudes with lead thicknesses even as small as 4 cm are not appreciably affected by electrons.

Further evidence that the traversing particles are not electrons was obtained by an arrangement of side counters registering showers generated in the lead by the traversing particles. A typical arrangement is shown in the figure in which counters 1, 2, 3, 4 and 2, 3, 4, 5 register the vertical intensities for 4 and 6 cm of lead, respectively, and counters 1, 2, 6, 4 and 2, 6, 4, 5 register particles accompanied by showers. If the traversing particles are electrons, there is a high probability of generating in the first 2 cm of lead a shower of many particles. In no case were more than a few percent of the traversing particles accompanied by shower counts in the side counters.

Because of the constancy of the penetrating power of the particles which we measure, and because they are not shower producing, we conclude that there are no electrons of energies between 10^9 and 10^{12} ev present at the highest altitudes reached. Since the energy required for electrons to penetrate the earth's magnetic field of 51° geomagnetic latitude is about 3×10^9 ev, and since our measurements were carried out to within the first radiation unit from the top of the atmosphere, it seems difficult to assume the presence of electrons ($E<10^{12}$ ev) in the primary cosmic radiation and, hence, they must be replaced by some penetrating type of charged particles. The mesotrons themselves cannot be the primaries because of their spontaneous disintegration. Hence, it is probable that the incoming cosmic radiation consists of protons. The following facts support this assumption.

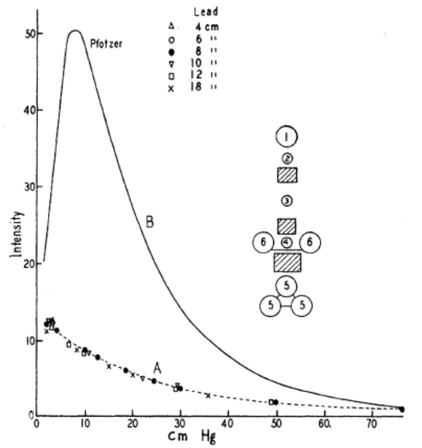


Fig. 1. Curve *A*: Intensity of the hard component for various lead thicknesses as a function of pressure in cm Hg. Curve *B*: Total vertical intensity of cosmic rays obtained by Pfotzer as a function of pressure.

1. Another experiment which we have performed at high altitudes shows that mesotrons which can penetrate 18 cm of lead are produced in multiples mainly by ionizing nonshower producing particles.[2]
2. The number of incident particles as determined by Bowen, Millikan and Neher[3] from their ionization chamber measurements at high altitudes is approximately the same as the number of penetrating particles which we observe close to the top of the atmosphere.
3. The measurements of the east-west asymmetry of cosmic rays have led Johnson[4] to suggest that the primaries of the hard component are probably protons. (In order to make it certain that all the incoming cosmic rays are positively charged, an east-west experiment for penetrating particles should be carried out at high altitudes.)

We hope to continue these observations with lower thicknesses of lead to compare with the measurements without absorption screen made by Pfotzer. Since we have assumed that the primary cosmic radiation consists of protons, the electrons known to exist in large numbers in air at high altitudes (curve *B*) must be of secondary origin. Furthermore, as seen from our experiments, the average energy of these electrons is low ($E<10^9$ ev). These facts suggest that the electrons in the atmosphere arise mainly from the decay of the mesotron and knock-on processes.

The writers wish to express to Professor A. H. Compton their appreciation for his support of these experiments and his continued interest in them.

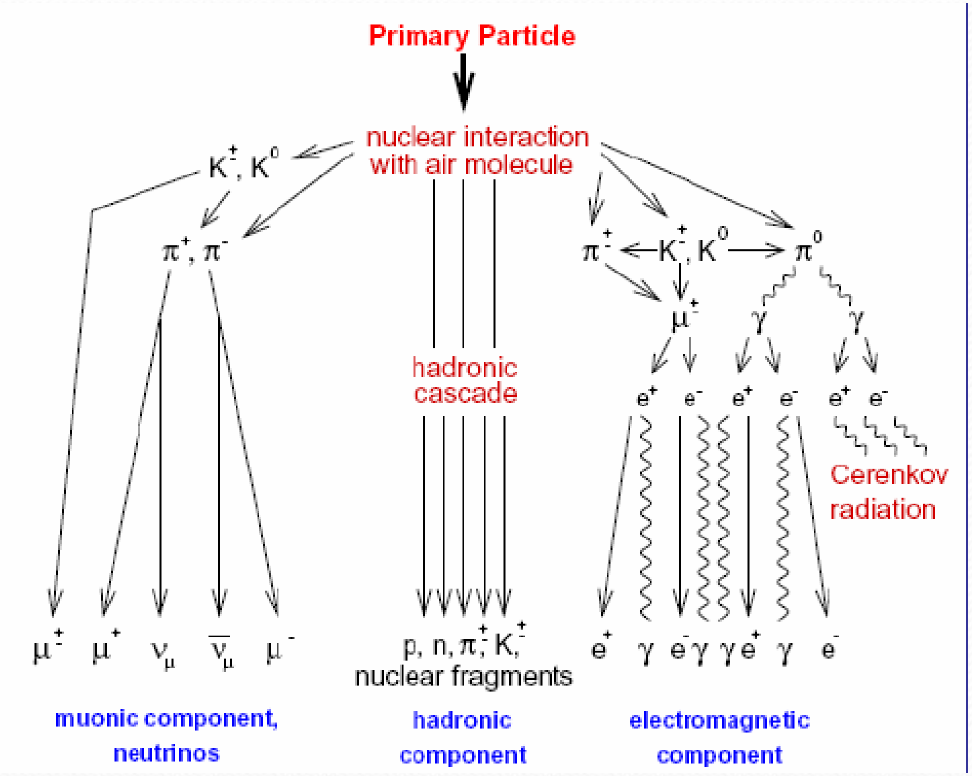
[1] M. Schein, W. P. Jesse and E. O. Wollan, Phys. Rev. **57**, 847 (1940).
[2] This process is in addition to the process already reported of the production of mesotrons by non-ionizing radiation.
[3] I. S. Bowen, R. A. Millikan and H. V. Neher, Phys. Rev. **53**, 217 (1938).
[4] T. H. Johnson, Rev. Mod. Phys. **11**, 208 (1939).

No electrons $<10^{12}$ eV

"It is probable that the incoming cosmic radiation consists of protons."

- Intensive absorption in first cms of lead is typical for high energy electrons. The absorption coefficient measured in the stratosphere (altitude 20 km) for the hard component corresponds to that of protons.
- It was concluded that the main part of the hard component are relativistic protons.
- The soft componet was interpreted by Bhabha (1938) in terms of electron secondaries (‘knock-on electrons’) and by Euler and Heisenberg (1938) as due to ‘meson-decay’.

Interactions of CRs in the Atmosphere



- Origin of the ionizing radiation:

  radioactivity in the soil - radiation coming from the top of the atmosphere – radiation coming from outside the atmosphere
- Composition of the ionizing radiation:

  gamma-rays of radioactive elements – gamma-rays with energies much higher than produced in decay processes – charged particles (electrons?) – particles with a positive charge (protons or positrons?) - protons

“Godfathers” of the Theory of Cosmic Rays

V.L.Ginzburg

1916-2009

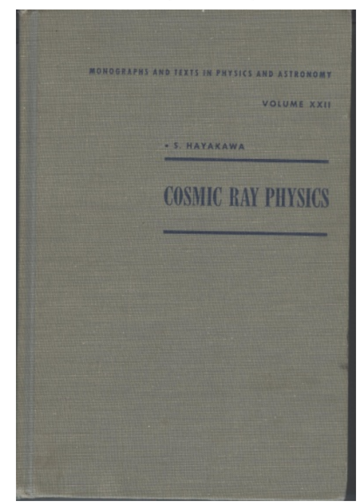
S.I.Syrovatskii

1925-1979

SATIO HAYAKAWA

(1923–1992)

1963, “Bible” of cosmic ray physics

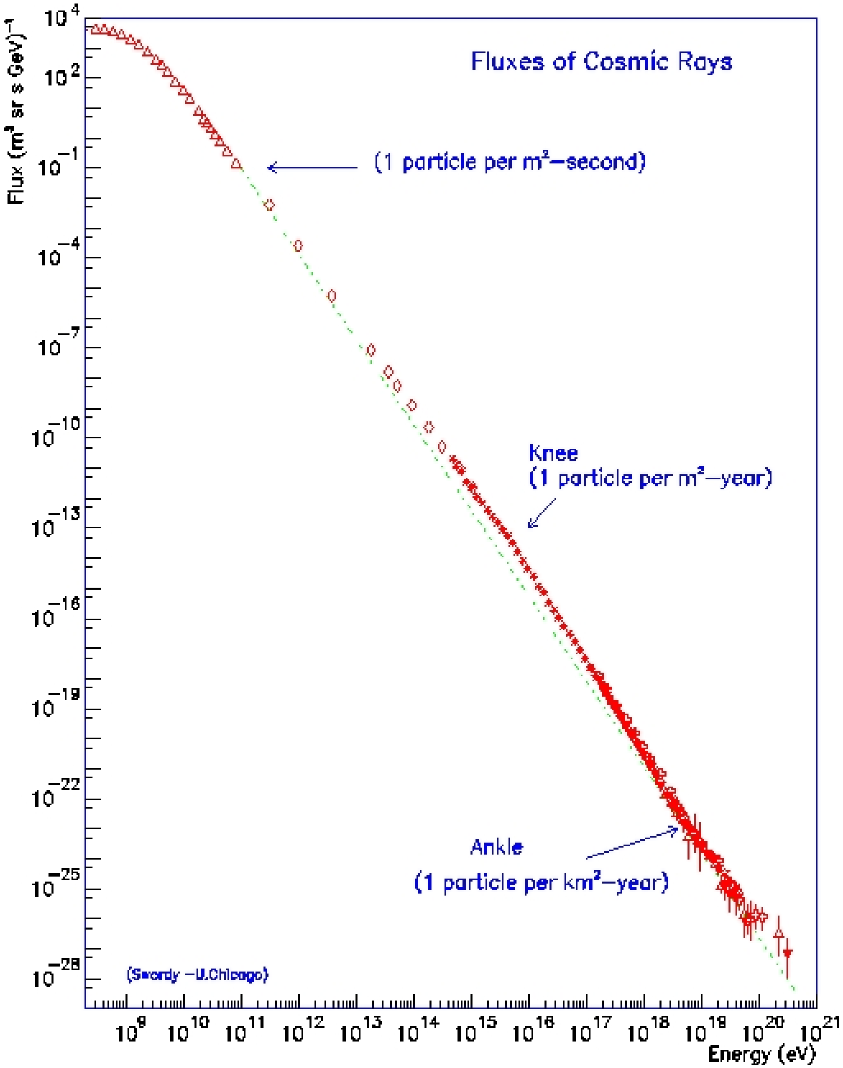


1969

THEORY of COSMIC RAY ORIGIN

Cosmic Rays (CRs) in the Galaxy

Cosmic Rays = energetic nuclear particle component, impinging on Earth's atmosphere from ~ uniform population in the Milky Way (Electrons ~ 1%)



- **Energy spectrum** over ~ 11 decades
  Single power law $\propto E^{-2.7}$ below ~ 3×10^{15} eV ("knee"). Energy density in Galaxy beyond knee negligible (~ 10^{-3} of total)

- **Source spectrum** below "knee" $\propto E^{-2.0}$ to $E^{-2.1}$, very hard ~ equal energy/decade

- **Total energy density** E_c ~ 1 eV/cm^3
  ~ $(B^{ISM})^2/8\pi$ ~ E_{turb}^{ISM} ~ E_{turb}^{ISM}

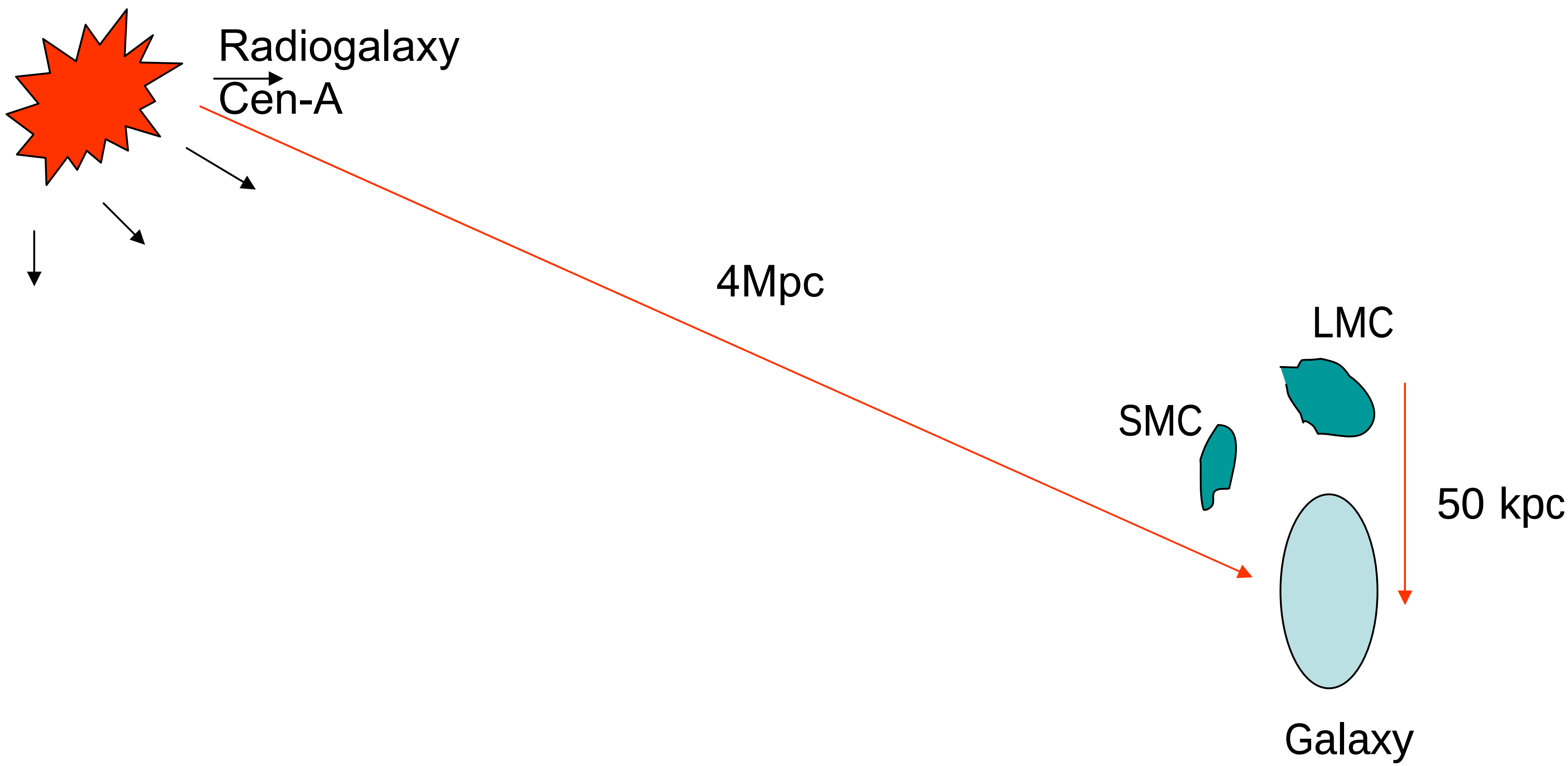
- **Energy input rate** into CRs ≈ 10^{41} erg/s

➡ **Cosmic Rays = nonthermal relativistic gas of high pressure in Galaxy**

Models of Cosmic Ray Origin

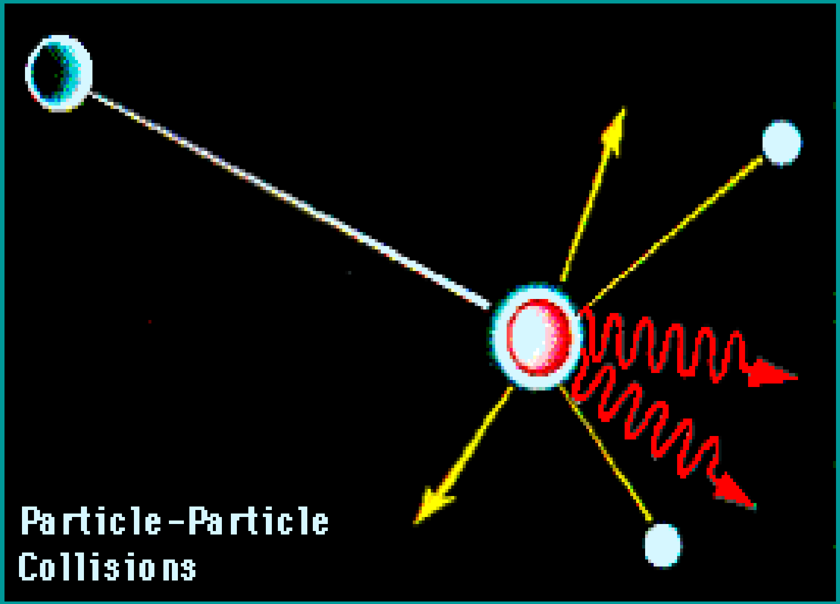
- Solar (Alfven)
- Extragalactic (Burbidge)
- Galactic (Ginzburg)

- Extragalactic Burbidge's model



Radiation Mechanisms of Protons

$$p + p \rightarrow p + p + a(\pi^+ + \pi^-) + b\pi^0,$$
$$p + p \rightarrow p + n + \pi^+ + c(\pi^+ + \pi^-) + d\pi^0,$$
$$p + p \rightarrow n + n + 2\pi^+ + f(\pi^+ + \pi^-) + g\pi^0,$$
$$p + p \rightarrow D + \pi^+ + l(\pi^+ + \pi^-) + t\pi^0,$$



$$\Phi_\gamma(E_\gamma) \sim \int_{E_p} d^3r\, n_g(r)\sigma(E_p, E_\gamma)N_p(E_p, r)$$

Ginzburg's Test (1972)

- Galactic origin: $N_{CR} \neq const$
- Extragalactic model: $N_{CR} = const$
- Gamma-rays in EG model (E>100 MeV):

$$F_{SMC} \approx (2.4 \pm 0.5) \times 10^{-7}\ ph/cm^2/s$$

- From the EGRET data1993 $F_{SMC} < 0.5 \times 10^{-7}\ ph/cm^2/s$

CRs are of the Galactic origin!!!

- From recent Fermi data (2010)

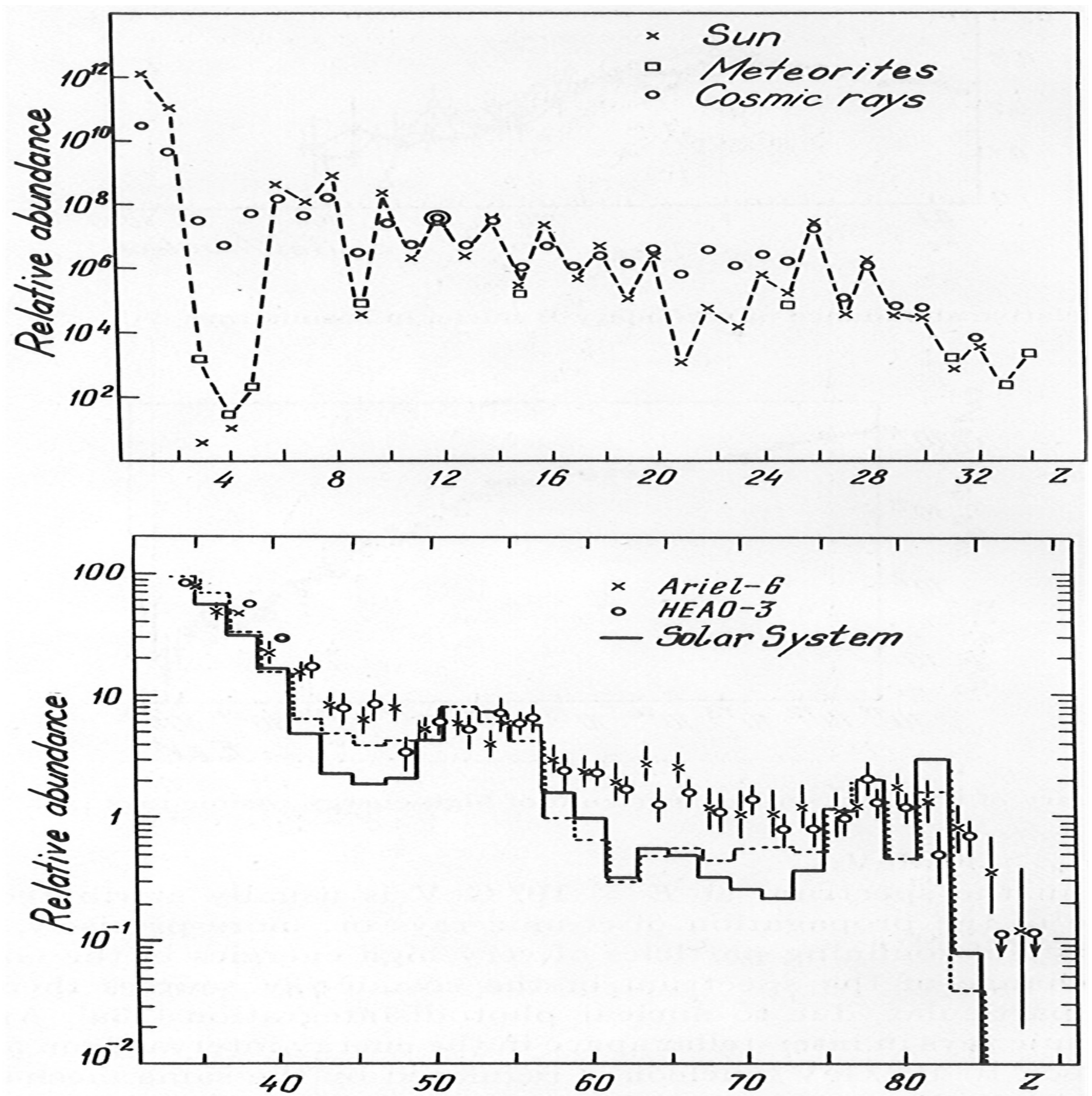
$$F_{SMC} \approx 3.7 \times 10^{-8}\ ph/cm^2/s$$

Chemical composition

Groups of nuclei	Z	CR	Universe
Protons (H)	1	700	3000
α (He)	2	50	300
Light (Li, Be, B)	3-5	1	0.00001*
Medium (C,N,O,F)	6-9	3	3
Heavy (Ne->Ca)	10-19	0.7	1
V. Heavy	>20	0.3	0.06

Note: Overabundance of light elements → spallation!

CR Chemical composition



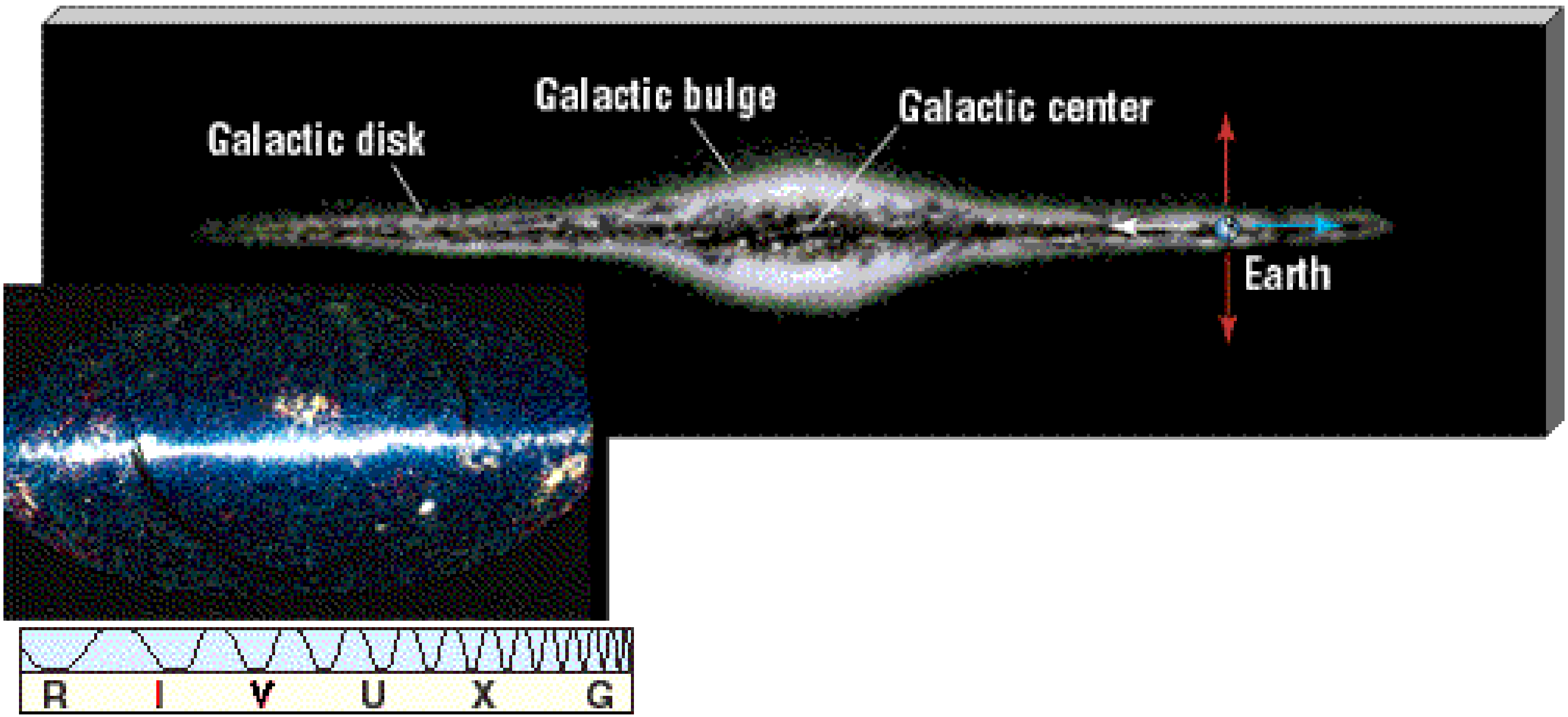
Origin of the light elements Li, Be, B??

Origin of light elements

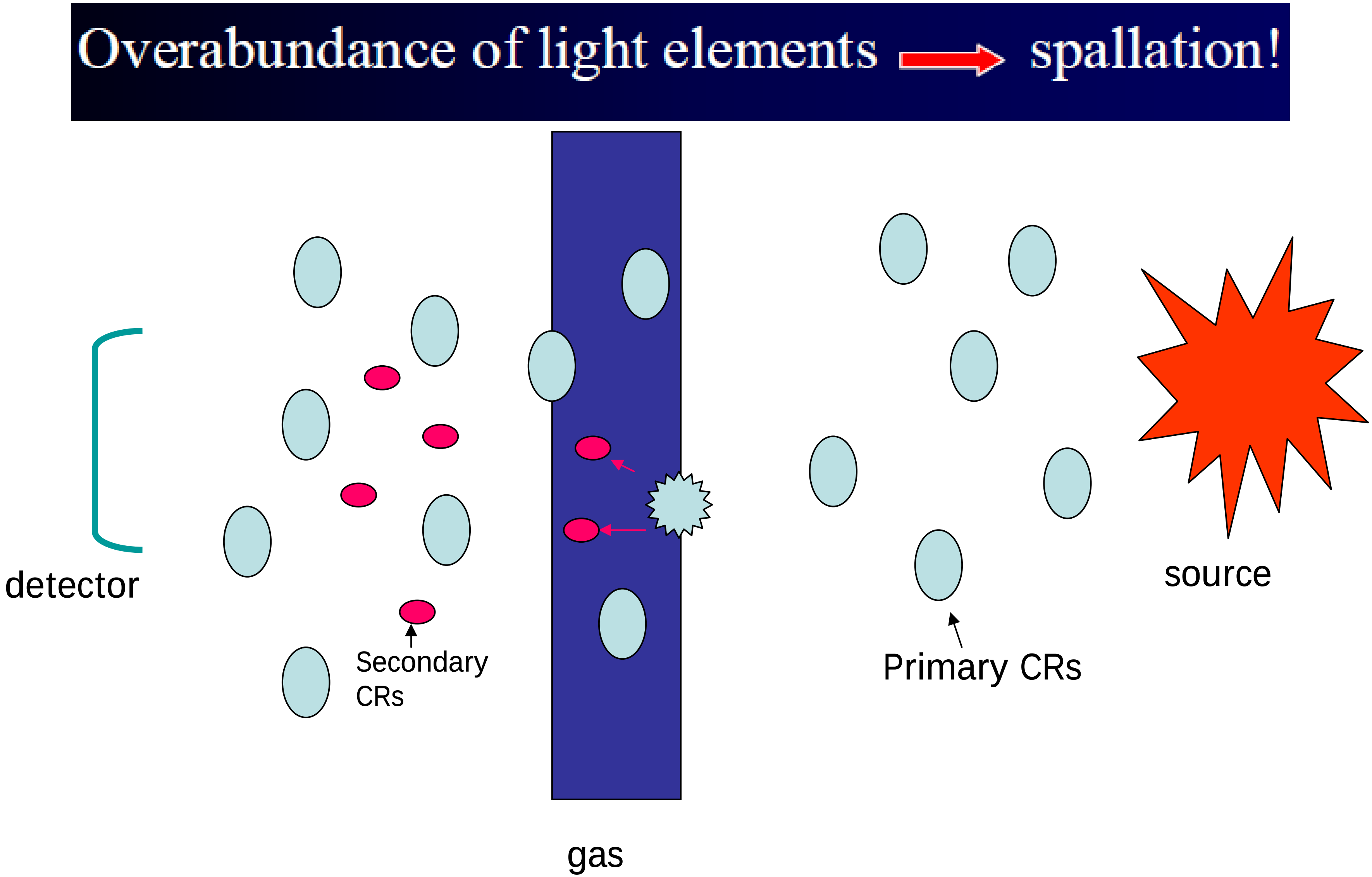
- Over-abundance of light elements caused by fragmentation of ISM particles in inelastic collision with CR primaries
- Use fragmentation probabilites and calculate transfer equations by taking into account all possible channels

Our Galaxy

$$R_G \approx 15\ kpc,\ \ d_G \approx 500\ \ pc,\ \ R_\odot \approx 8.5\ kpc$$



Secondary Cosmic Rays



$$\frac{N_s}{T} \approx \bar{n}\sigma c N_p$$

$$\frac{N_s}{N_p} = \bar{n}\sigma c T$$

$$x = \bar{\rho} c T, \quad \bar{\rho} = m_p \bar{n}$$

$$x_{CR} \approx 10 \;\; gr/cm^2$$

CR Luminosity

$$L_{cr} \approx \frac{W_{cr}}{T_{cr}} = \frac{w_{cr} V_G c \bar{\rho}}{T_{cr} c \bar{\rho}} = \frac{c w_{cr} M_H}{x}$$

$$\approx 3 \cdot 10^{40} \, erg/s$$

$$w_{cr}^{\odot} = 1.4 \times 10^{-12} \; erg/s$$

$$M_G = 10^{43} \, gr$$

$$x = 10 \;\; gr/cm^2$$

Energy Output of Galactic Sources

- Supernova explosions – 10^{42} erg/s;
- Neutron Stars – 10^{41} erg/s;
- Stellar winds from O/B stars – 10^{41} erg/s;
- Flare stars - 3 10^{40} erg/s.
- 1934. Baade and Zwicky related appearance of SN
. to the formation of neutron stars and generation of
. Cosmic rays

- 1-10% of the SN energy output is enough for CR
.production

Cosmic ray Clocks

- Some secondary nuclei are radioactive. They decay with a characteristic time τ_{sr}

$$Be^{10} \to^{\beta^-} B^{10}, \ \tau \approx 2.2\ 10^6 \frac{E}{mc^2} \ years$$

- Then for stable and radioactive nuclei we have the equations

$$\sum_j n_H \mathrm{v} \sigma^s_{ij} N^p_j = \frac{N^s_i}{T}$$

$$\sum_j n_H \mathrm{v} \sigma^{sr}_{lj} N^p_j = \frac{N^{sr}_l}{T} + \frac{N^{sr}_l}{\tau_{sr}}$$

$$\frac{N^{sr}_l}{N^s_i} = \frac{1/T}{\left(1/T + 1/\tau_{sr}\right)} \frac{\sum_j n_H \mathrm{v} \sigma^{sr}_{lj} N^p_j}{\sum_j n_H \mathrm{v} \sigma^s_{ij} N^p_j} \Rightarrow \ T!!!$$

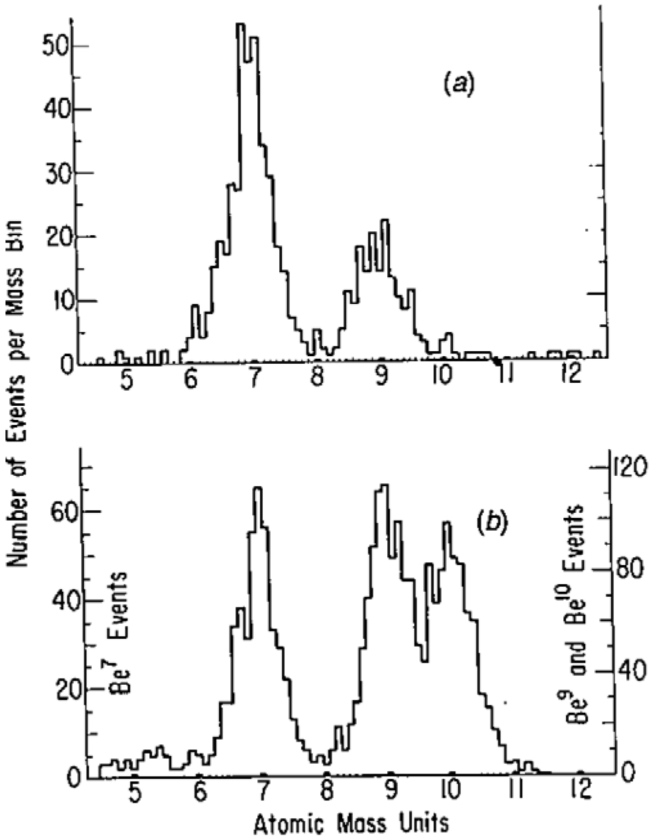
$$x(E) = \bar{\rho} c T(E) \propto E^{-(0.3 \div 0.6)} \to T(E) \propto E^{-(0.3 \div 0.6)}$$

Radioactive Be^{10} is produced in the spallation of C and O nuclei, as well as other isotopes Be^7 and Be^9.

In cosmic rays the ratio $$\frac{Be^{10}}{\left[Be^7 + Be^9 + Be^{10}\right]} = 0.028$$

Then !!!!

$$T \simeq 2\ 10^7\ years$$



Cosmic ray Propagation in the Galaxy

- The velocity of CRs is $c = 3 \cdot 10^{10}\ cm/s$
- Then for the time 10^7 years CRs pass through the distance 10^{25}cm, or 3 Mpc
- On the other hand, the thickness of the galactic disk is about 300-500 pc and its radius is about 10-15 kpc
- Important conclusion – CRs propagate chaotically in the Galaxy, like diffusion
- The diffusion coefficient of CRs in the Galaxy is

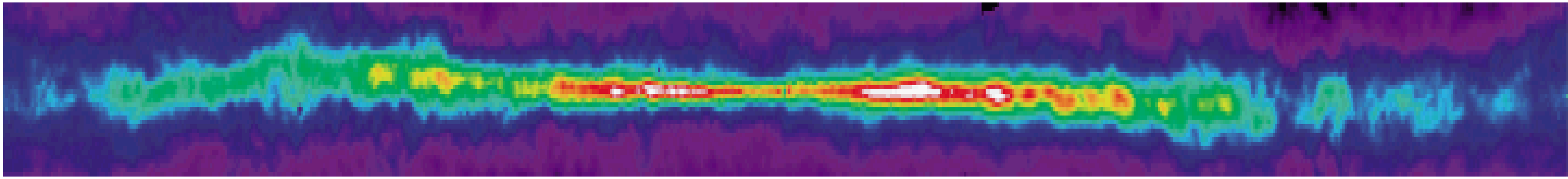
$$D_{CR} \approx 3 \cdot 10^{27}\, cm^2 / s$$

Evidence for CR halo from CR chemical composition

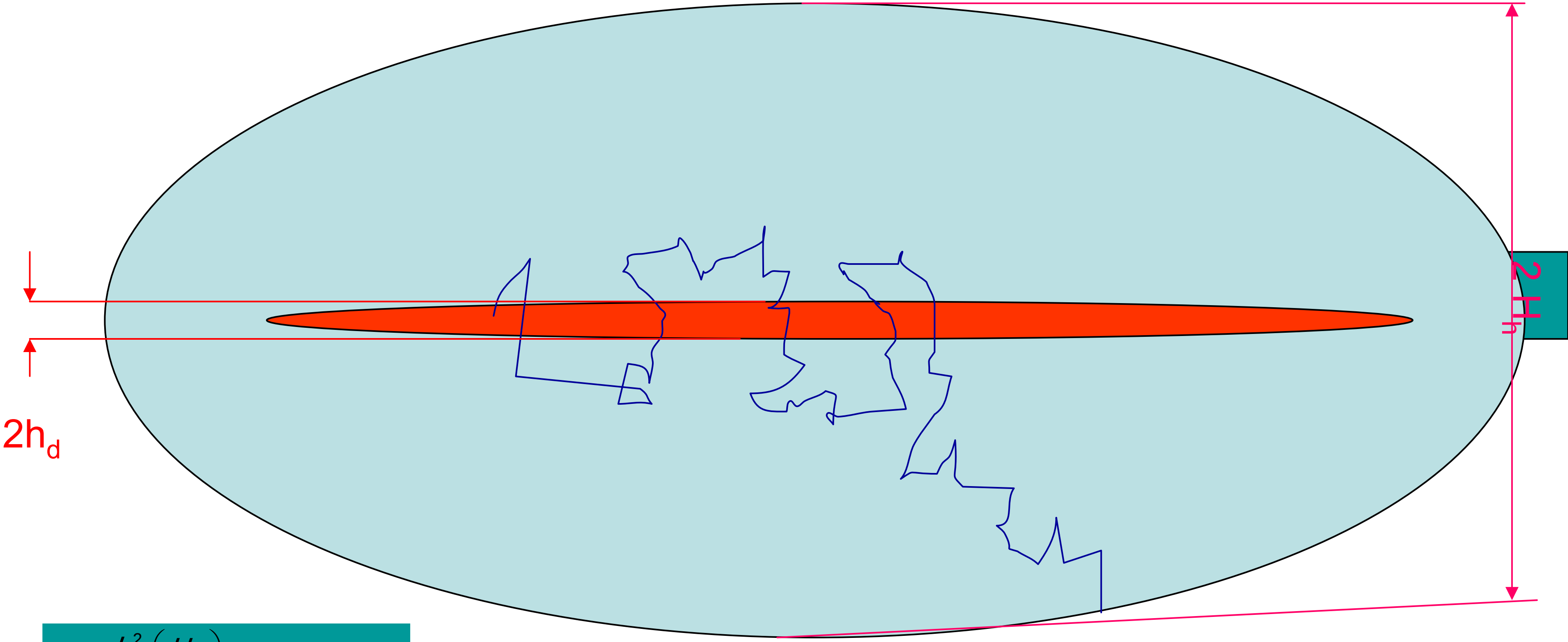
•Average density of the gas traversed by CR in the Galaxy

$$x = \bar{n} m_p c T_{cr} \approx 6-10 \;\; gr \;\; cm^{-2}, \quad T_{cr} \approx 2 \cdot 10^7 \, years \;\; \Rightarrow \;\; \bar{n} \approx 0.2 \;\; cm^{-3}$$

•Gas density derived from direct observations: n~1 cm^{-3}.



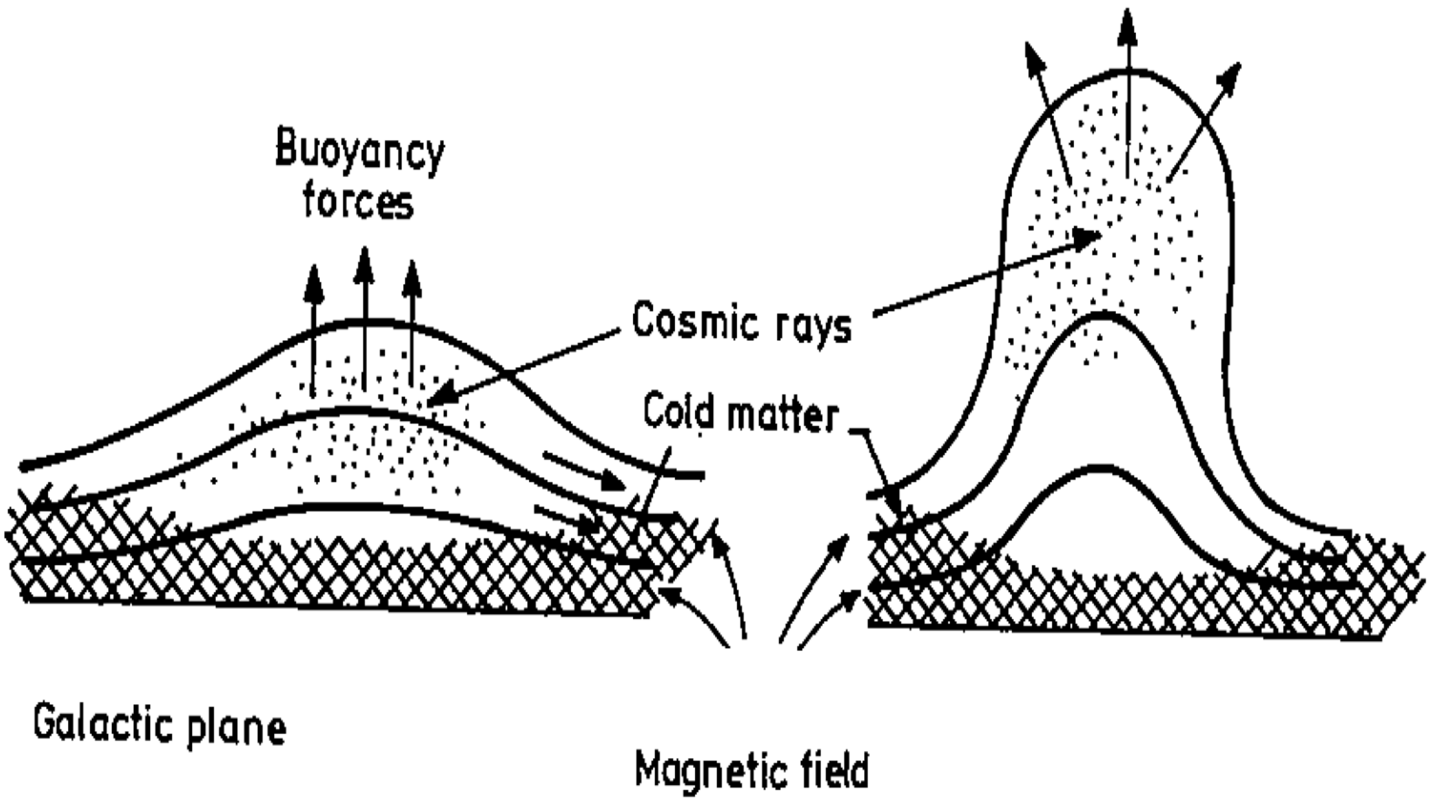
•Conclusion: most of their lifetime CRs spend outside the Galactic disk



$$T_r \sim \frac{h_d^2}{D}\left(\frac{H_h}{h_d}\right) \sim 2\;10^7\ years$$

$$x_{CR} \approx 10\ \ gr/cm^2 \Rightarrow T_{CR} \sim \frac{H_h^2}{D} > 2\;10^7 years = T_r \sim \sqrt{\tau T_{CR}}$$

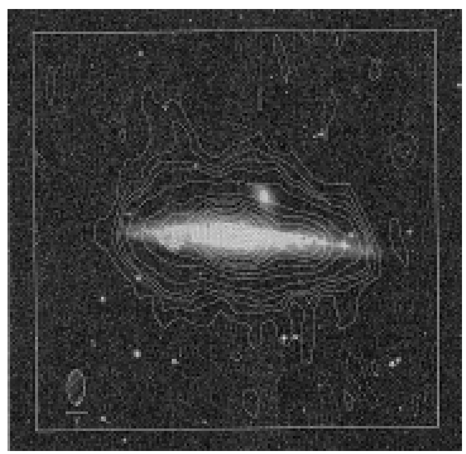
- It is well-known from laboratory thermal fusion experiments how it is difficult to confine a plasma even in special configurations of magnetic field because of different plasma instabilities.
- Therefore, it is difficult to imagine that a mixture of magnetic fields, hot plasma and cosmic rays can be confined in the thin galactic disk.
- Parker Instability



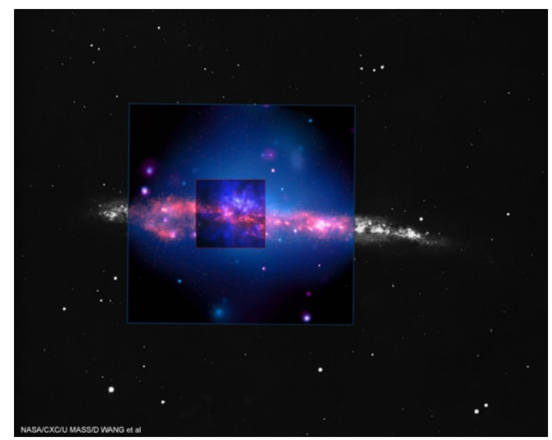
- It is natural to assume that CRs fill an extended region around the disk – so-called the Galactic halo (Pikelner 1953, Ginzburg 1954).

NGC 4631

Optic range



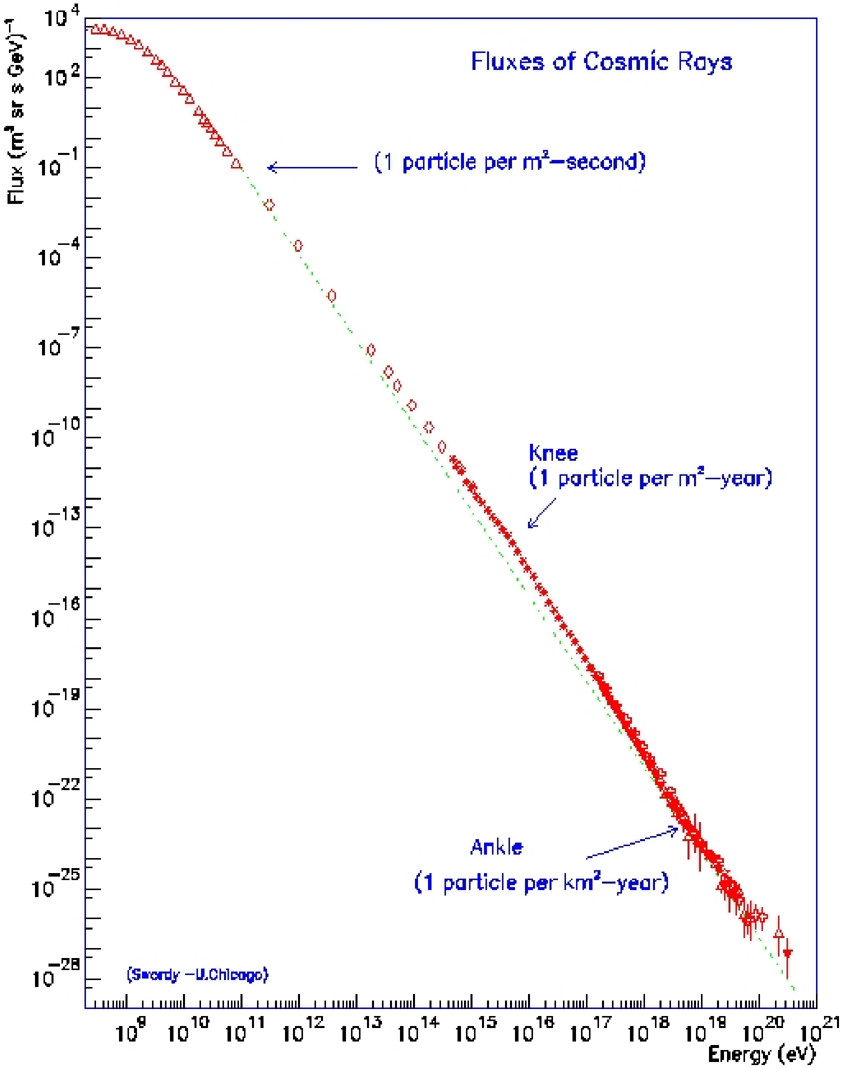
radio



Thermal X-rays

Cosmic Rays (CRs) in the Galaxy

Cosmic Rays = energetic nuclear particle component, impinging on Earth's atmosphere from ~ uniform population in the Milky Way (Electrons ~ 1%)



- **Energy spectrum** over ~ 11 decades
  Single power law $\propto E^{-2.7}$ below ~ 3 x 10^{15} eV ("knee"). Energy density in Galaxy beyond knee negligible (~ 10^{-3} of total)

- **Source spectrum** below "knee" $\propto E^{-2.0}$ to $E^{-2.1}$, very hard ~ equal energy/decade

- **Total energy density** $E_C \sim 1$ eV/cm^3
  $\sim (B^{ISM})^2/8\pi \sim E_{turb}^{ISM} \sim E_{turb}^{ISM}$

- **Energy input rate** into CRs $\approx 10^{41}$ erg/s

➡ **Cosmic Rays = nonthermal relativistic gas of high pressure in Galaxy**

General remarks

- Requirements for mechanisms of CR acceleration
  1. A power law spectrum for particles of all types;
  2. The spectral index is about 2.5-2.7 which is constant over the energy range of almost six orders of a magnitude;
  3. The acceleration should generate particles with energies from $\sim 10^9$ eV to $10^{17} \sim 10^{19}$ eV;
  4. The acceleration mechanism should reproduce the CR chemical abundance

General principles of acceleration

- The general expression for the acceleration of charged particles

$$\frac{d}{dt}\left(\gamma m\vec{v}\right) = e\left(\vec{E} + \frac{1}{c}\vec{v} \times \vec{B}\right)$$

- In most astrophysical conditions static electrical fields cannot be maintained because of very high electrical conductivity
- Therefore acceleration can be associated either with non-stationary electrical fields or with time varying magnetic field
- In a static magnetic fields, no work is done on the particle
- If the magnetic field is time-varying work can be done by the induced electric field

$$curl\ \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t}$$

CR acceleration
Second order Fermi acceleration (1949)

- Alfven, Richtmyer and Teller – cosmic rays are of the solar origin and are kept near the Sun by magnetic fields;
- The argument was that the size of solar system is about $\sim 10^{14}$ cm while for the Galaxy we have $\sim 10^{21}$ - 10^{22} cm cm and it is very hard to find source which can fill this huge volume by CRs;
- Fermi supposed that CR acceleration occurs in the whole volume of the Galaxy due to the interaction of CRs with wandering magnetic fields which occupy the interstellar space;
- Due to high conductivity these waves propagate through the medium without damping with the Alfven velocities

$$V_A = \frac{H}{\sqrt{4\pi\rho}}$$

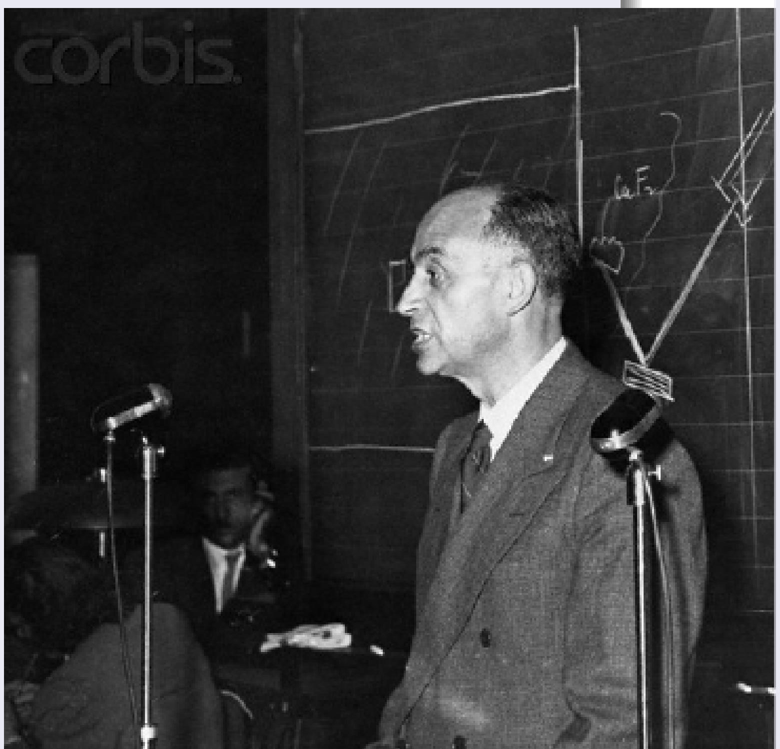
- The rate of energy gain is very slow but this mechanism is capable of building up necessary energies

In the Beginning: What did astrophysicists know and when did they know it?

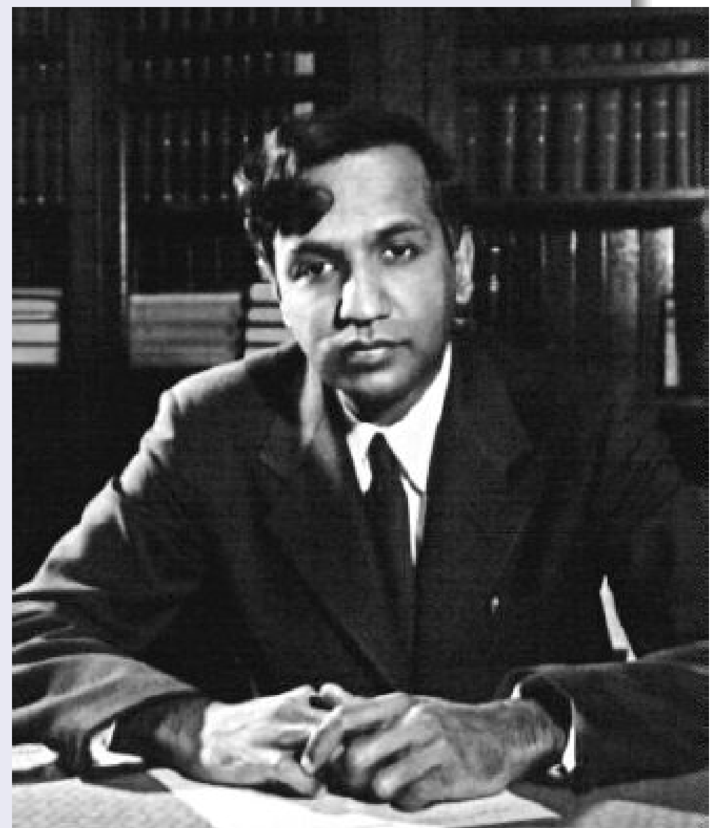
- Gas component:: discovered before <1900, neutral and ionized phase
- Dust component: reddening/extinction (1930s), DIBs ('30s), reflection nebulae, light echos (earlier)
- H II regions: Strömgren (1933), also related to the diffuse radiation field of the Galaxy (this can be considered the precursor to the studies in H I, both at 21 cm and Ly α)
- Molecular component: CH, CN, CH^+
- Large scale motions of the gas phase: identification of clouds from aomic absorption
- Filamentary structures: < 1900
- Differential Galactic rotation: stellar ('20s), gas (H I 21 cm) ('50s);
- Spiral streucture: first reported results in 1954 from 21 cm surveys but indications already from H II regions and associations
- Large scale radio emission: continuum emission at MHz frequencies, discrete sources

The protagonists

Enrico Fermi, 1949



Chandrasekhar, ca. 1947

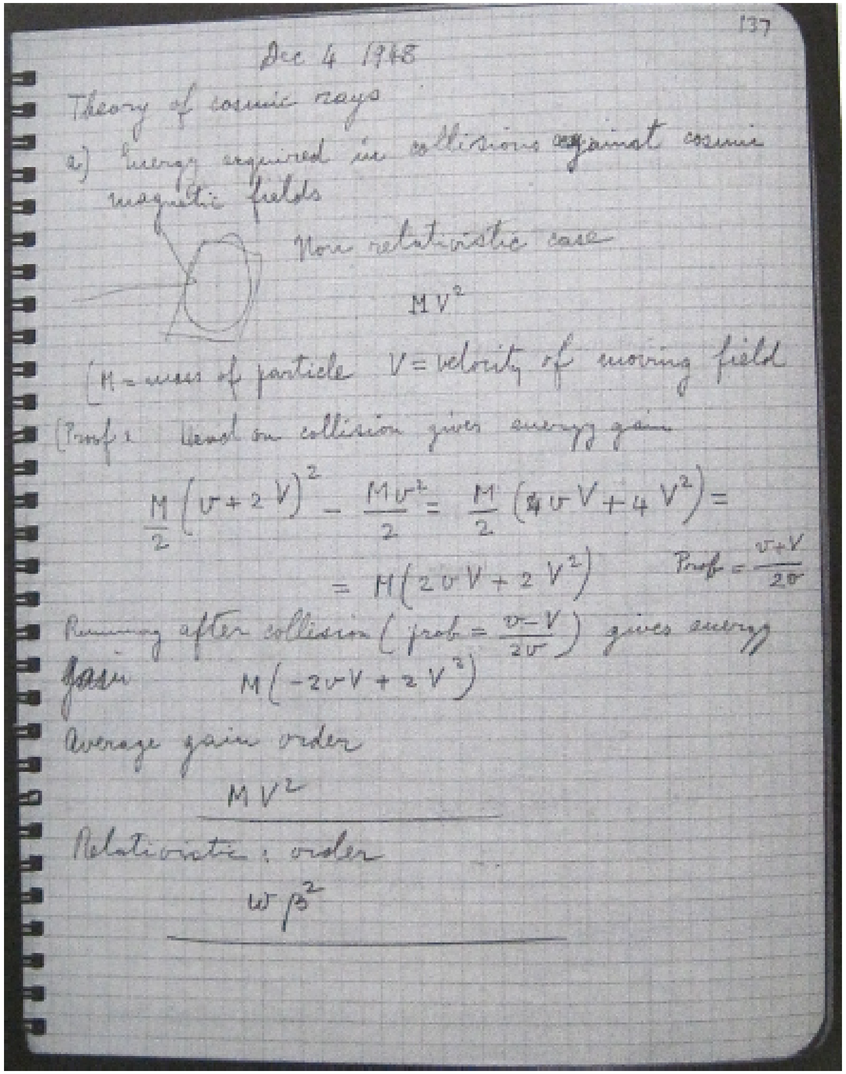


The other side of the argument: local origin and solar system trapping

Hannes Alfvén, 1942

Edward Teller, 1945

The start: notebook entry:The result of corridor conversations with Teller and Alfvén on the problem.



137

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

[Prob: 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

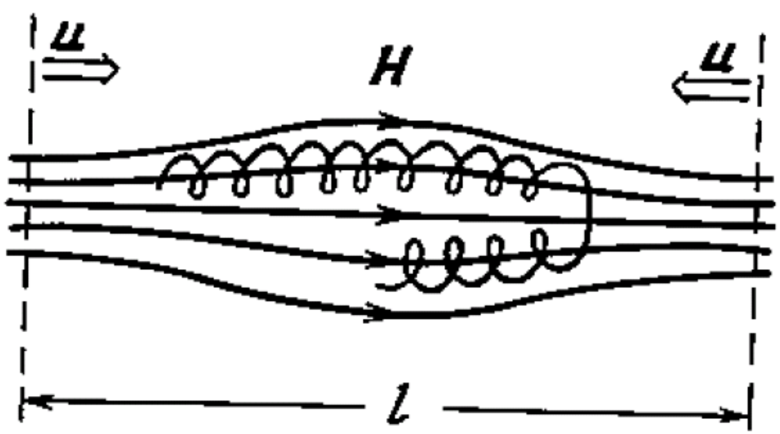
Relativistic: order

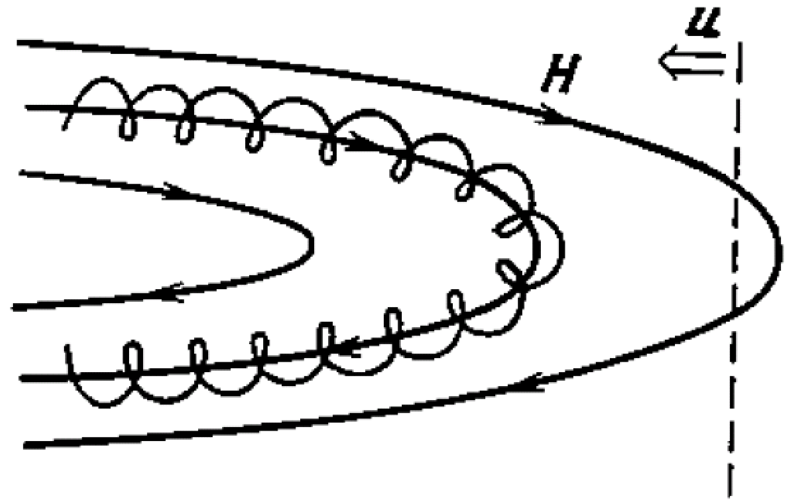
$w\beta^2$

- Kinks generated incoherently by turbulent motions in the interstellar clouds (state unspecified but already known to be ionized) produce pitch angle scattering of orbiting ions (and electrons).
- The ionic motions are lossless, hence their motions are adiabatic relative to field fluctuations (and structural changes).
- Head on, oppositely directed collisions between clouds and ions more likely than overtaking.
- Kinematics (as also done in Compton & Getting).
- An invariant, the projected magnetic dipole for orbiting particles, is conserved through gradient accelerations, magnetic mirrors. Fermi labeled this "type A" acceleration.
- Configurational changes that reflect the ions without mirroring, curvature. Fermi labeled this "type B", it's the one illustrated in the paper.
- Ions are injected at higher than thermal energies, there must be sources but they are distributed throughout the Galaxy.
- The injection must account for the heavy nuclear component of the CRs but that wasn't possible in this picture.

- In Fermi's original version, charged particles are reflected from "magnetic mirrors" associated with irregularities of the Galactic magnetic field
- The mirrors are moving with velocities V and the particles gain energy from these reflections;

$$\frac{(p \cos \vartheta)^2}{H} = const$$

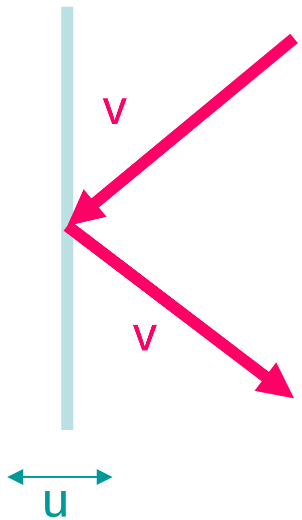


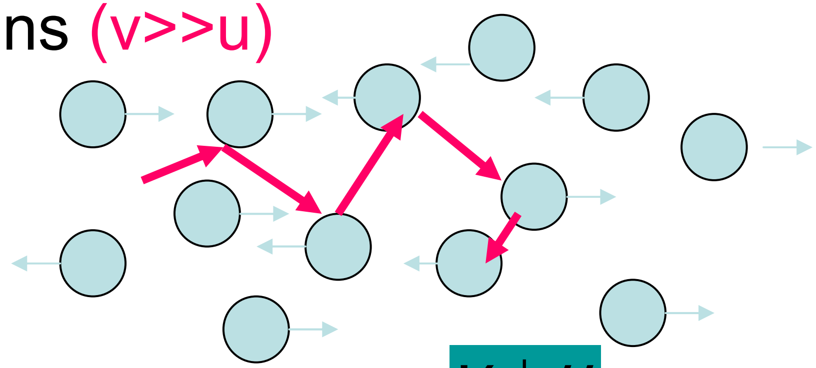


Type A reflection

Type B reflection

Main idea (!!!!!) - different frequency of collisions with head-on and following collisions (v>>u)





Relative velocity $v \pm u$

$$\Delta E = \pm 2uv\cos\vartheta$$

Frequency of collisions with head-on and following clouds

$$\nu \approx n_{cl}\sigma(v \pm u)$$

$$\Delta\nu \approx 2n_{cl}\sigma u$$

The rate of energy increase

$$\frac{dE}{dt} \approx \Delta E\,\Delta\nu = \sigma n_{cl}\frac{2u^2}{v}E = \alpha E$$

Fermi, E. 1949, Phys. Rev., 72, 1169: "On the origin of cosmic radiation"

- In the general discussion (Part I) Fermi returns to his chain reaction calculation and compares the loss of cosmic rays with the *replication factor* for neutrons.
- The field is frozen into the gas motions by the partial ionization of the ISM.
- Assuming that encounters with magnetic inhomogeneities change the energy by reflecting the particle, the energy increases as $\Delta E/E \sim (V/c)^2$ per reflection, hence $E = E_0 \exp t/\tau_a$. If the particles are lost on a timescale τ_L, the probability of loss being $dP(t) \sim [\exp -t/\tau_L] dt/\tau_L$, then the spectrum of particles becomes $dN(E) \sim E^{-(1+\tau_a/\tau_L)} dE$.
- In F49, this loss was assumed to be collisional (hence the cross section for nuclear collisions is larger than that of the protons and their spectra should be different), in F54 it had changed to any form of loss (residence time in the Galaxy). The order of the exponent indicated that $\tau_a \approx \tau_L$.

$$\frac{d}{dE}\left(\alpha EN\right)+\frac{N}{T}=0 \qquad \Rightarrow$$

$$N = AE^{-(1+\alpha T)}$$

Fermi to Alfven, preprint of the Phys. Rev. paper

December 24 1948

Dr. H. Alfven
Royal Institute of Technology
Stockholm, Sweden

Dear Dr. Alfven:

I am enclosing the rough draft of a paper on the origin of the cosmic radiation that I propose to send shortly to the Physical Review. You will notice that the ideas that I am presenting are almost directly opposite to those that have recently been discussed by yourself and by Teller.

Of course I am not sure that they are correct but it seems to me that the various orders of magnitude adopted are not unduly stretched and that one can make an apparently good case for my view that the cosmic rays originate and are accelerated primarily in the interstellar space of the galaxy.

I would be very anxious to have your opinion and criticism of this theory. I still remember with great pleasure the most informative discussion that I had with you on your theory of the magneto-elastic phaenomana. As you see I have immediately put to work what I had learned.

With the best wishes for a happy 1949,

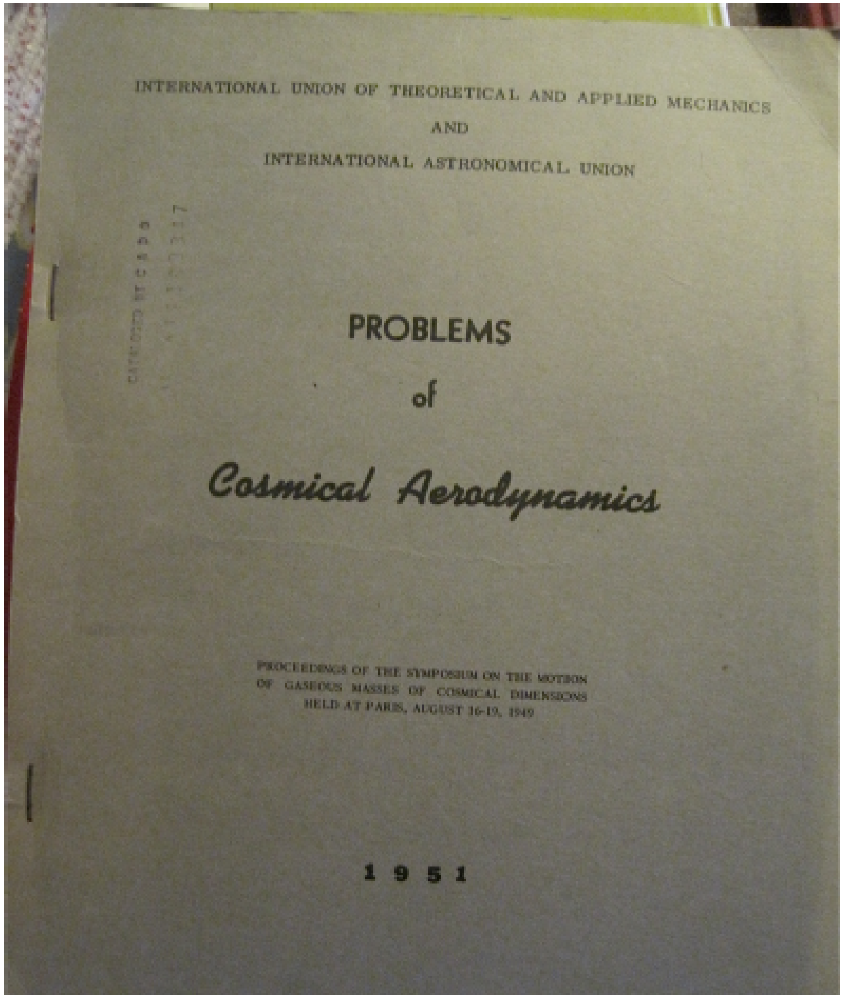
Sincerely yours

Enrico Fermi

Discovery of interstellar polarization: Hall and Hiltner (1949, Nature, 163, 283; also 1948, Science, 109, 165)

Looking for something else, the polarization of continuum emission from rotating stellar photospheres dominated by electron scattering, Hiltner (1947) finds a measurable effect but, on continued observation "... However, the observations made in connexion with this problem have led to the detection of a new phenomenon which appears to have a bearing on the constitution of interstellar matter." By May, this was shown to be correlated with reddening and therefore with the dust. This is explained by Davis & Greenstein (1949, Phys. Rev., 75, 1605) assuming spinning grains oriented with respect to a mean magnetic field and collisionally randomized in orientation while internally dissipatively relaxing. An alternative is proposed by Spitzer & Tukey (1951, ApJ, 114, 187). Davis estimated the strength of the field using the dispersion in the large scale orientation (Davis 1951, Phys. Rev. 81, 890).

The first meeting on astrophysical hydrodynamics Aug. 1949, joint IAU and IUTAP (sponsored by UNESCO, USAF)


INTERNATIONAL UNION OF THEORETICAL AND APPLIED MECHANICS
AND
INTERNATIONAL ASTRONOMICAL UNION

PROBLEMS
of
Cosmical Aerodynamics

PROCEEDINGS OF THE SYMPOSIUM ON THE MOTION
OF GASEOUS MASSES OF COSMICAL DIMENSIONS
HELD AT PARIS, AUGUST 16-19, 1949

1 9 5 1

The Paris meeting, first planned in late 1948 as a joint meeting between astrophysicists, physicists, applied mathematicians, and engineers, was the first time the astrophysics community heard about recent developments in turbulence theory (Kolmogorov theory in a summary by Batchelor and von Kárman, discussions with Heisenberg and von Weizsacker), MHD wave propagation in the ISM (Alfvén and van de Hulst), hydrodynamic shock phenomena (Burgers), and began debating the energetics of the interstellar gas and star formation. There were also discussions of the diffuse radio emission (including a very brief note on Sklovskii's (1952, Astr.Zh, 29, 418) work on synchrotron emission) and discussions of the 21 cm mapping of the Galaxy. Cosmic rays were (strangely) absent.

The other papers: collaboration with Chandrasekhar

- Chandrasekhar & Fermi 1953, ApJ, 118, 113: "Magnetic fields and spiral arms": the spatial scale on which the polarization seems to be co-aligned requires a stability of the field against random motions, this gives an estimate for the magnetic field mased on the Alfvénic Mach nmber of the clouds of order a few μG. Davis (1951) had published a brief note, with different assumed numbers, deriving a field strength about an order of magnitude higher.
- Chandrasekhar & Fermi 1953, ApJ, 118, 116: "Problems of gravitational stability in the presence of a magnetic field"
- Fermi 1954, ApJ, 119, 1: "Galactic magnetic fields and the origin of cosmic radiation": this was Fermi's final version of the turbulent mirror acceleration mechanism, and his last published discussion on the origin of cosmic rays (published almost coincident with his last hospitalization).
- Magnetic shocks: de Hoffmann & Teller (1950, Phys. Rev, 80, 692): this sudden change in the field is invoked to explain the reflection.

Fermi's Russell prize lecture (Boulder, Aug.1953)

- Hydromagnetic (a.k.a. Alfven) waves, generated incoherently by turbulent motions in the interstellar gas (state unspecified but already known to be ionized) produce pitch angle scattering of orbiting ions (and electrons).
- The ionic motions are lossless (no radiation), hence their motions are adiabatic relative to field fluctuations (and structural changes.
- Instead of collisional losses, introduced the "leaky box" assumption with a residence time of $\sim$15 MYr.
- An invariant, the projected magnetic dipole for orbiting particles, is conserved through gradient accelerations, magnetic mirrors. Fermi labeled this "type A" acceleration.
- Configurational changes that reflect the ions without mirroring, curvature. Fermi labeled this "type B" and argues that it was more likely than mirroring.
- Ions are injected at higher than thermal energies, there must be sources but they are distributed throughout the Galaxy.
- The injection must account for the heavy nuclear component of the CRs but that wasn't possible in this picture.

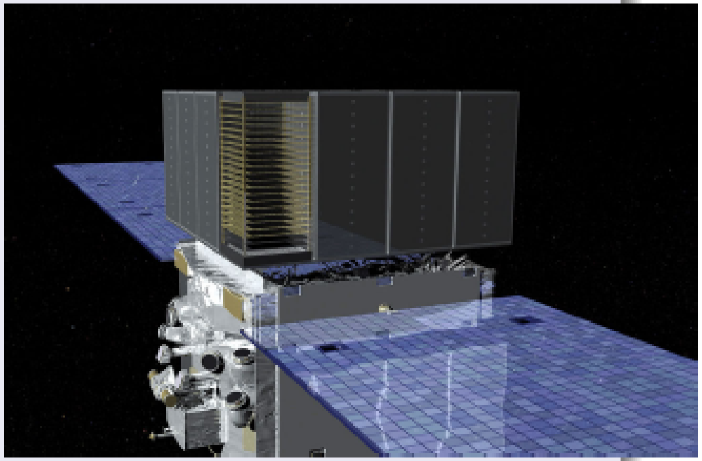
Fermi's continuing interest in the problem: interstellar magnetic fields and the "second hypothesis"

- Extension: trapping between moving magnetic mirrors until the pitch angle is sufficiently reduced to permit escape; if $C = \sin^2\theta/B$ is constant then if $B > C^{-1}$ the proton is excluded.
- Problem cited in F54, not apparent in F49: protons and nuclei have the same spectrum
- The second order gain in energy without trapping, no losses during the acceleration process, and random encounters with moving fields.
- Turbulent motions are superthermal but sub-Alfvenic, along field lines there are kinks (waves, shocks).
- The ISM is sufficiently ionized to permit the dragging of field lines

Fermi closed the Russell lecture with these thoughts: "A second question has to do with the energy balance of turbulence in the interstellar gas. If it is true that cosmic radiation leaks out of the galaxy in a time of the order of 10 million years, it is necessary that its energu is replenished a few hundred times during a time equal to the age of the universe. A simple estimate shows that the energy present in the galaxy in the form of cosmic rays is comparable to the kinetic energy due to the turbulence of the intergalactic [*sic*] gas. According to the present theory, the cosmic rays are accelerated at the expense of the turbulent energy. This last, therefore, must be continuously renewed by some very abundant source, psehaps like a small fraction of the radiation energy of the stars. In conclusion, I should like to stress the fact that, regardless of the details of the acceleration mechanism, cosmic radiation and magnetic fields in the galaxy must be counted as very important factors in the equilibrium of interstellar gas." In an "anticipation" of this last remark, see Chandrasekhar's Russell lecture (21 Jun 1949), published shortly after F49 (1949, ApJ, 110, 329: "Turbulence: A physical theory of astrophysical interest") without mentioning F49.

"Tell me, Chandra. When I die, will I come back as an elephant?"

Fermi/LAT



Chandra

Benefits of Fermi acceleration

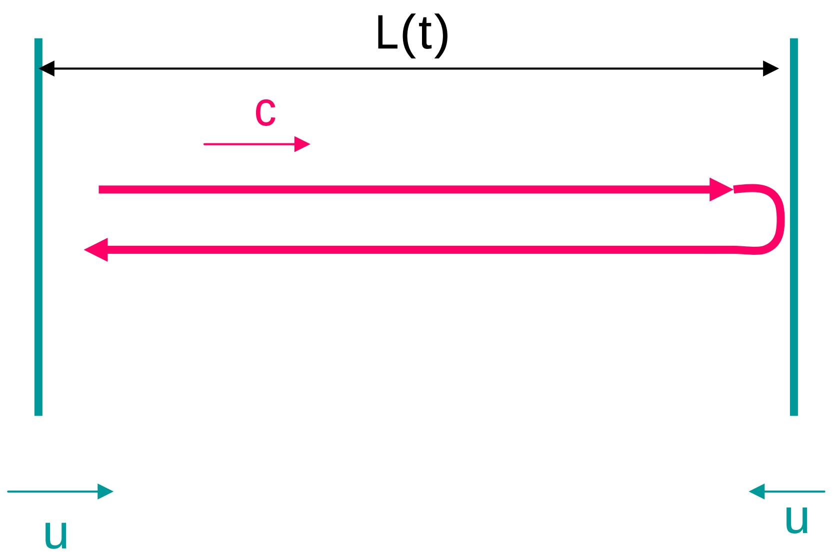
- Power-law spectra are generated (but !!! $N(E) \propto E^{-1}$)
- The maximum energy is in general limitless
- It can generate CRs everywhere in the Galactic volume

Problems of Fermi acceleration

- The ratio $V/c = 10^{-4}$ in the Galaxy. The mean free path between collisions is about 1 pc. So, the number of collisions would be one per 1 year. In order to increase the energy of a particle in three times we need about 10^8 collisions.

- We have nothing in this theory which tells us why the spectral index of CRs should be roughly 2.5.

First order stochastic acceleration



$$J_{\parallel} = \oint p_{\parallel} dl \simeq p\, L(t)$$

$$\frac{dp}{dt} = -\frac{J_{\parallel}}{L^2}\frac{dL}{dt} = -\frac{p}{L}\frac{dL}{dt} = -\frac{2u}{L}p$$

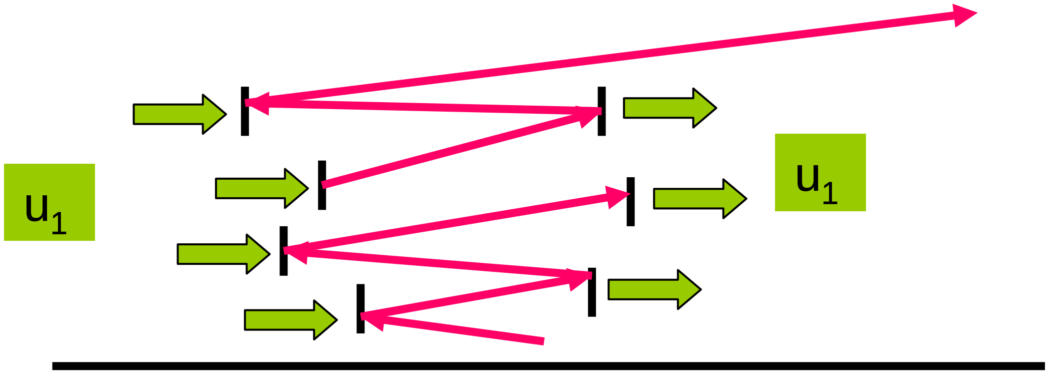
- The rate of FI acceleration

$$\frac{dL}{dt} = -2u, \quad then \left(\frac{dE}{dt}\right)_{FI} \approx 2u\frac{E}{L}$$

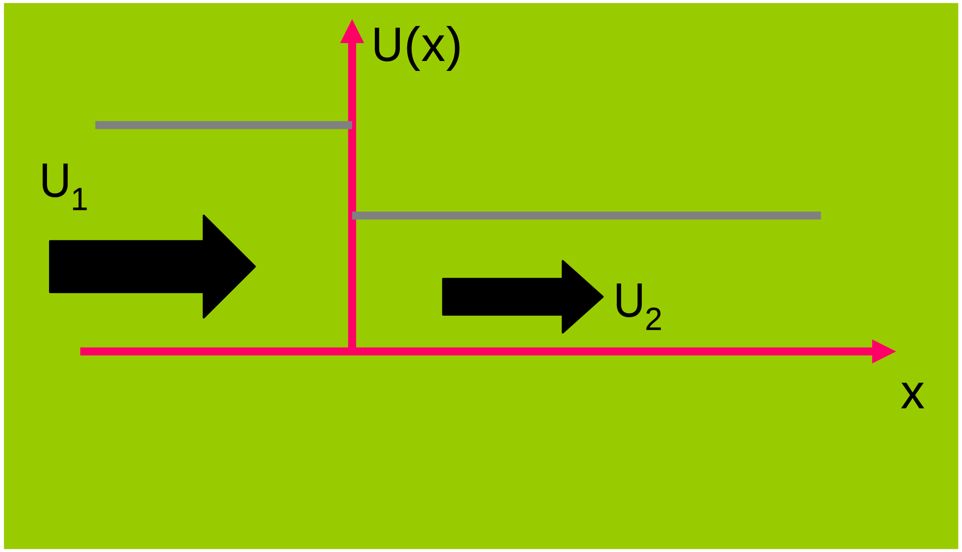
- The rate of FII acceleration

$$\left(\frac{dE}{dt}\right)_{FII} \approx 2\frac{u^2}{c}\frac{E}{L_{st}}$$

Convection with scattering

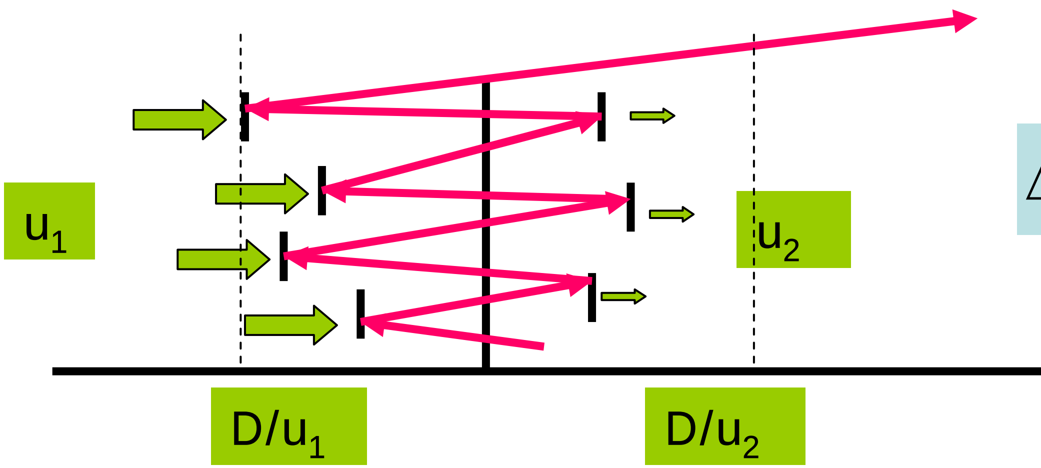


No acceleration



For strong shocks (M>>1) $u_1/u_2=4$

Jump of velocity + spatial diffusion



For each cycle of the front crossing

$$\Delta E \sim 2mv(u_1 - u_2) \quad \textit{Acceleration}!$$

Shock wave acceleration - formal solution
(Krymskii 1977, Axford et al. 1977, Blandford and Ostriker 1978, Bell 1978)

- One-dimensional equation

$$u(x) = \begin{cases} u_1, & x < 0 \\ u_2 = u_1 \frac{\kappa - 1}{\kappa + 1}, & x > 0 \end{cases}$$

For M>>1 and χ=5/3

$U_1 / U_2 = 4$

$$\frac{\partial}{\partial x}\left(D\frac{\partial f}{\partial x} - u(x) f\right) = -\frac{\nabla u(x)}{3}\frac{1}{p^2}\frac{\partial}{\partial p}\left(p^3 f\right)$$

$$\nabla u(x) = (u_2 - u_1)\delta(x)$$

$$\frac{\partial}{\partial x}\left(D\frac{\partial f}{\partial x} - u(x) f\right) = 0 \textit{ with boundary conditions}$$

$$f\Big|_{x=-\infty} = C_1(p) = C_0\delta(p - p_0), \quad f\Big|_{x=+\infty} < \infty, \textit{ at } x = 0 \textit{ we have}$$

$$\{f\}_0 = f_2 - f_1 = 0$$

$$\{u\}_0 f - \left\{D\frac{\partial f}{\partial x}\right\}_0 = \frac{u_2 - u_1}{3}\frac{1}{p^2}\frac{\partial}{\partial p}\left(p^3 f\right)$$

X<0

$$f(p, x) = C_1(p) + [C_2(p) - C_1(p)]\exp(u_1 x / D)$$

X>0

$$f(x > 0, p) = C_2(p)$$

- From the boundary condition at x=o we have the equation for $C_2(p)$

$$p\frac{dC_2}{dp} + \frac{3u_1}{u_2 - u_1}C_2 = \frac{3u_1}{u_2 - u_1}C_1$$

$$C_2(p) = \gamma \frac{C_0}{p_0}\Theta(p - p_0)\left(\frac{p}{p_0}\right)^{-\gamma}$$

$$C_2(p) = \gamma p^{-\gamma} \int C_1(p')p'^{\gamma-1}dp'$$

$$\gamma = \frac{3u_1}{u_1 - u_2}$$

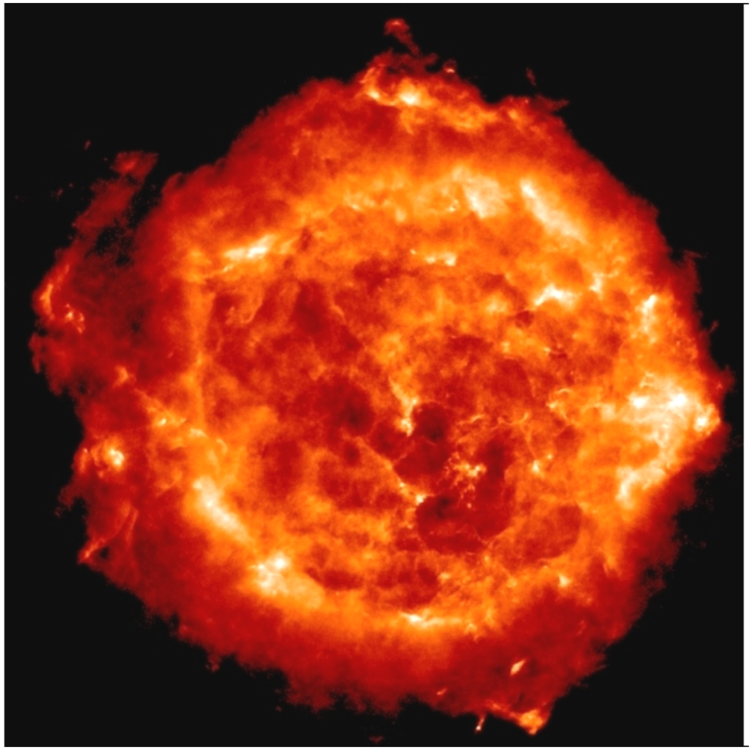
=4

and for the energy spectrum $N(E) = p^2 f(p)\dfrac{dp}{dE}$ *we have*

$N(E) \propto E^{-2}$ (!!!!!!)

Cosmic Ray Origin and Diffusive Shock Acceleration at Supernova Remnants

Cas A, nonthermal radio (6 cm, *VLA*)



1) Long-standing hypothesis since Baade & Zwicky (1934)

Apart from energetics, expected source spectrum very hard, $dN/dE \propto E^{-2}$, if result of diffusive shock acceleration

2) At the same time simplest realistic test case for the acceleration theory:

Point explosion (~ spherical symmetry)

Berezhko, Voelk etc

$$P_{cr} = \frac{4\pi}{3}\int_{p_0}^{\infty} p^3 cf \; dp$$

$$\rho u \frac{\partial u}{\partial x} = -\frac{\partial}{\partial x}\left(P_g + P_{cr}\right)$$

$$u\frac{\partial P_g}{\partial x} + \kappa \frac{\partial u}{\partial x} P_g = 0$$

$$u\frac{\partial P_{cr}}{\partial x} + \frac{4}{3}P_{cr}\frac{\partial u}{\partial x} = \frac{\partial}{\partial x} D \frac{\partial P_{cr}}{\partial x}$$

From 30% to 50% of the shock energy is transferred to the particles accelerated at the shock. In this sense the process of CR acceleration plays a role of an effective viscosity.

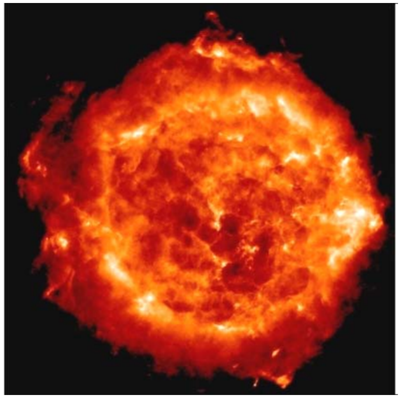
- **From known CR escape time (~ 3 x 10^7 yr):**

  > 10% of entire mechanical energy input into Interstellar Medium required to be converted into CRs (of relativistic energies > 1GeV)

- **Mechanical energy input mainly from Supernova explosions:**

  E_{sn} ~ 10^{51} erg with rate ~ 1 SN / 30 yr in our Galaxy

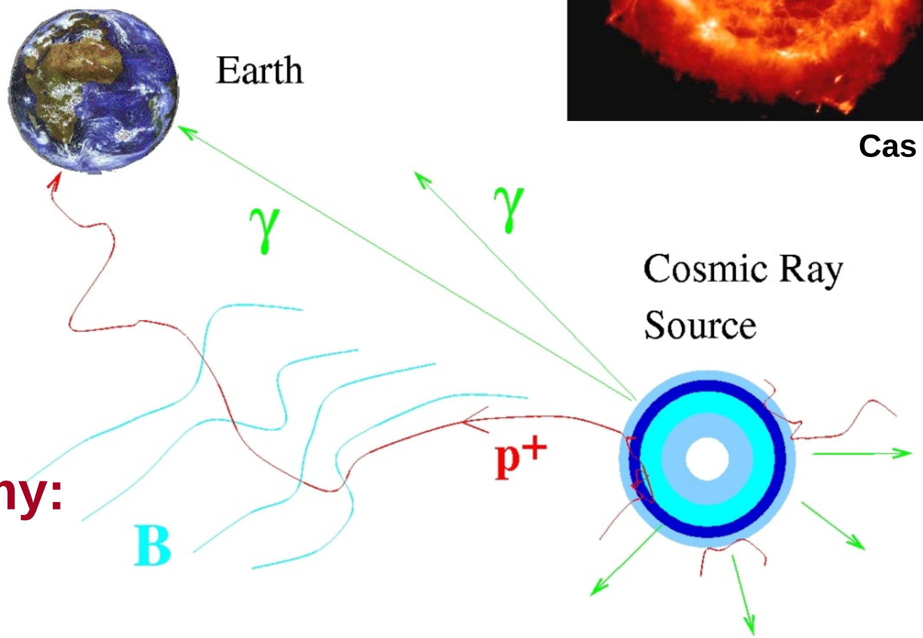
  Enormous overall efficiency requirement



Cas A

- **No direct detection of CRs:**

  Sources only identifiable through neutral secondary particles produced in inelastic collisions in their interior:
  Direct detection only with high-energy gamma rays or with high-energy neutrinos.
  Here only gamma-ray astronomy:
  From $\pi^o \Rightarrow 2\gamma$ (hadronic);
  IC, Bremsstrahlung (leptonic)



SNR RX J1713.7-3946 view in X-rays (SUZAKU contours) and UHE gamma-rays (HESS colour figure)

Nonthermal emission from the SNR RX J1713.7-3946 (Berezhko and Voelk, 2010)