Special Topics in Particle Physics

Introduction and the Standard Model

Historical perspective and astrophysical context

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Why Astroparticle physics?

How can we study particle physic from an experimental point of view?

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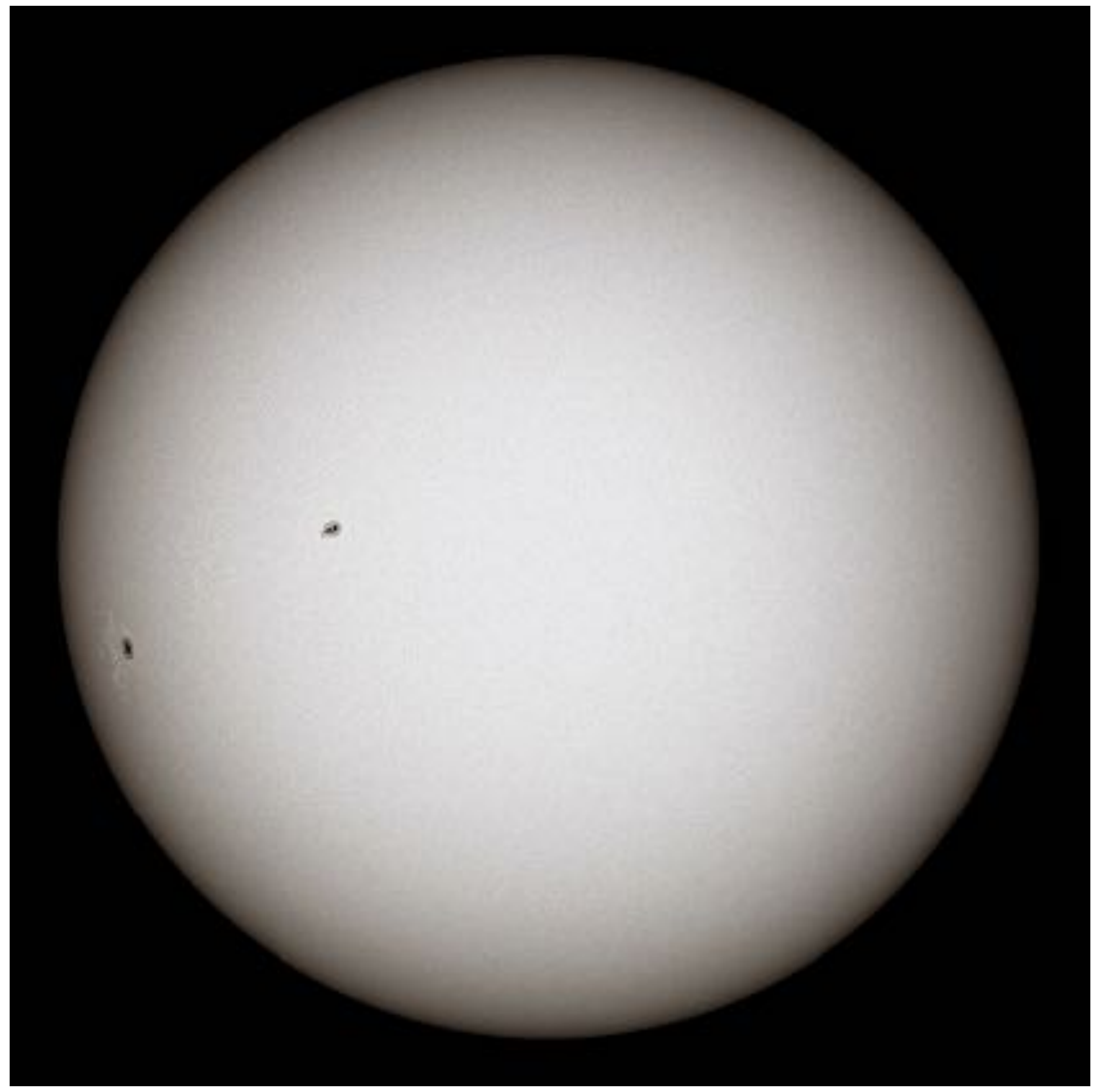
Astrophysics

Astrophysical objects produce and accelerate elementary particles



The Sun photographed on the 8th of May, 2019 in white light (true color).

Particle physics labs

Experiments on Earth, like particle accelerators

The Tevatron (background circle), a synchrotron collider type particle accelerator at Fermi National Accelerator Laboratory (Fermilab), Batavia, Illinois, USA.

Why Astroparticle physics?

What astrophysical phenomena do you know that is relevant for particle physics?

- Solar neutrinos
- The Solar wind -> produces the aurora on Earth and other planets
- Supernova explosions: neutrinos + cosmic rays
- Cosmic rays -> particle showers, Van Allen radiation belts
- Big-bang nucleosynthesis
- High energy particle production in AGN, GRBs etc…
- Missing matter in the Universe (dark matter, dark energy)

Why does the Sun produce neutrinos?

What is the Solar wind?

What are cosmic rays?

What are the radiation belts?

How did the first atoms get produced in the Universe?

How did the rest of the atoms get produced?

What is an AGN?

Historical perspective - Neutrinos

Precise knowledge of **particle physics is necessary to understand many astrophysical contexts**, particularly **since comparable experimental conditions cannot be prepared in the laboratory.** The astrophysical environment therefore constitutes an important laboratory for high energy physicists.

The observations of our **Sun in the light of neutrinos,** in the Homestake Mine (Davis experiment) in 1967, constitutes the **birth of astroparticle physics,** even though the first measurements of solar neutrinos by this radiochemical experiment were performed without directional correlation.

It is only since the Kamiokande (Kamioka Nucleon Decay Experiment) experiment of 1987, and later the Super-Kamiokande experiment, that one has been able to ‘see’ the Sun in real time by measuring the **direction of the emitted neutrinos.**

Another neutrino detection was from the **supernova** in the Large Magellanic Cloud in 1987 (**SN 1987A**), whose neutrino burst could be recorded in the large water Cherenkov detectors of Kamiokande and IMB (Irvine–Michigan–Brookhaven collaboration) and in the scintillator experiment at Baksan.

Historical perspective - cosmic rays

Presently, the fields of **gamma and neutrino astronomy are expanding rapidly**. The discovery of gravitational waves in 2015 has added a new domain to astronomy.

Why are the gravitational waves relevant to particle physics?

Astronomy with charged particles, however, is a different matter. **Irregular interstellar and intergalactic magnetic fields randomize the directions of charged cosmic rays. Only particles at very high energies travel along approximately straight lines through magnetic fields.** This makes astronomy with charged particles possible, if the intensity of energetic primaries is sufficiently high.

Actually, there are tentative hints that the **highest-energy cosmic rays** ($>10^{19}$eV) **have a non-uniform distribution** and possibly originate from the supergalactic plane. This plane is an accumulation of galaxies in a disk-like fashion, in a similar way that stars form the Milky Way. Other possible sources, however, are individual galactic nuclei (like M87) at cosmological distances.

The milestones, which have contributed to the new discipline of astroparticle physics, are presented in chronological order.

Early Indications of Celestial Phenomena in the Sky

It is interesting to point out the observations of the **Vela supernova** by the Sumerians **6000 years ago**.

This supernova exploded in the constellation Vela at a distance of 1500 light-years. **Today the remnant of this explosion is visible, e.g., in the X-ray and gamma range. -> clearly also produces high energy particles.**

Vela X1 is a binary, one component of which is the **Vela Pulsar**. The naming scheme of X-ray sources is such that Vela X1 denotes the strongest (‘the first’) X-ray source in the constellation Vela.

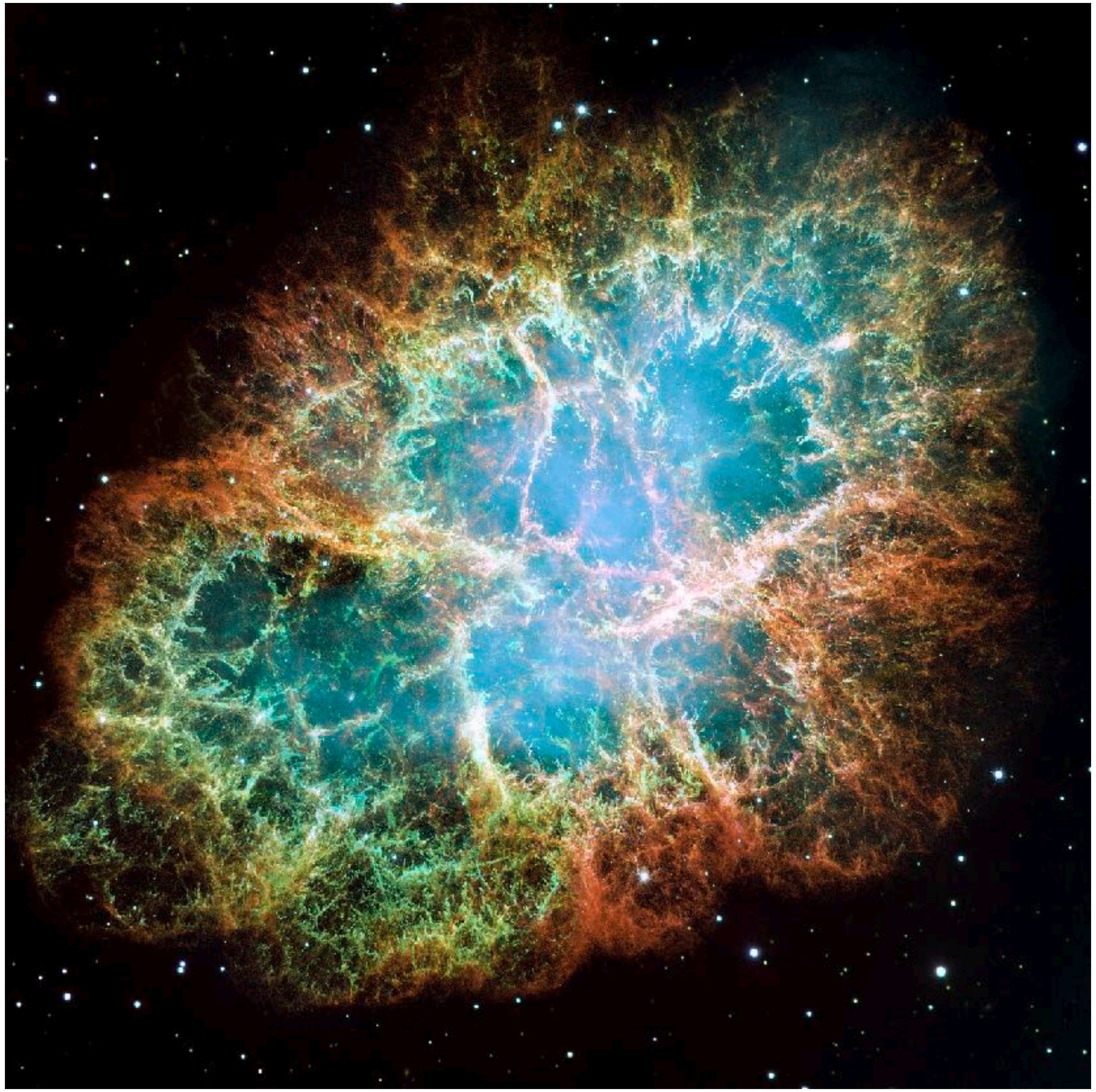
X-ray image (ROSAT telescope): the Vela supernova remnant

What is a pulsar?

Early Indications of Celestial Phenomena in the Sky

The second spectacular **supernova** explosion was observed in **China in 1054.** The relic of this outburst is the **Crab Nebula**, whose remnant **also emits X rays and gamma rays** like Vela X1.

Because of its time-independent brightness the Crab is often used as a ‘standard candle’ in gamma-ray astronomy. -> It can be used for calibrating gamma-ray observations.

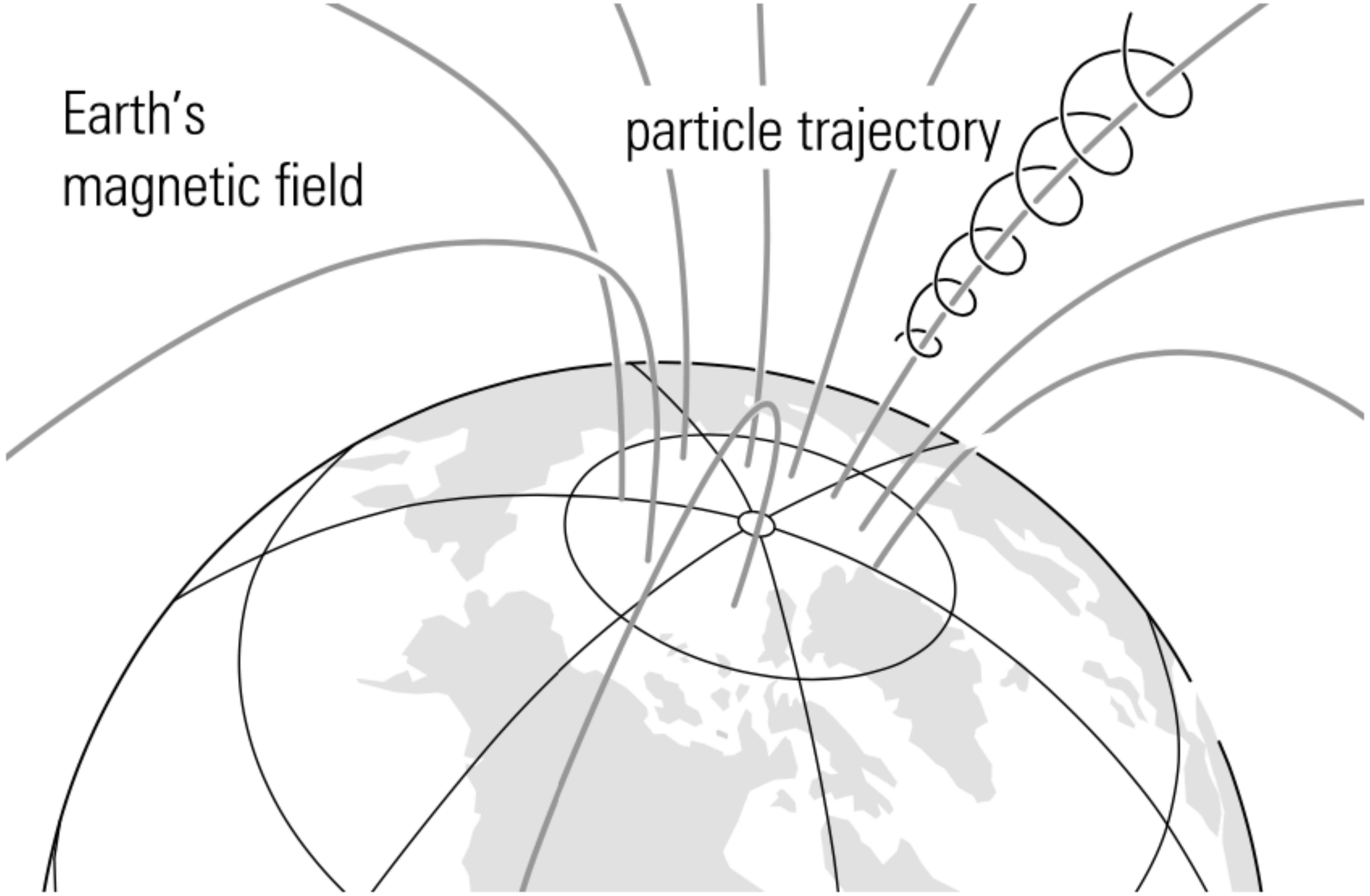


The Crab supernova remnant (Hubble Space Telescope)

Early Indications of Celestial Phenomena in the Sky

The observation of the **northern lights** (Gassendi 1621 and Halley 1716) lead Mairan, in 1733, to the idea that this phenomenon might be of **solar origin**.

Northern and southern lights are caused by **solar electrons and protons** incident in the polar regions **traveling on helical trajectories along the Earth's magnetic field lines**. At high latitudes, the charged particles essentially **follow the magnetic field lines. This allows them to penetrate much deeper into the atmosphere, compared to equatorial latitudes,** where they have to cross the field lines perpendicularly.



Helical track of an electron in the Earth's magnetic field

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Eielson Air Force Base, Alaska — The Aurora Borealis, or Northern Lights, shines above Bear Lake

Discoveries in the 20th Century

The discovery of X rays, radioactivity, and the electron already indicated a particle physics aspect of astronomy.

At the turn of the century Wilson (1900) and Elster and Geitel (1900) were concerned with measuring the **remnant conductivity of air**. Rutherford realized in 1903 that shielding an electroscope reduced the remnant conductivity. It was only natural to assume that the **radioactivity of certain ores present in the Earth's crust, was responsible for this effect.**

In 1910, Wulf measured a **reduced intensity in an electrometer at the top of the Eiffel tower,** apparently confirming the **terrestrial origin of the ionizing radiation.**

Measurements by Hess (1911/1912) **with balloons at altitudes of up to 5 km showed that**, in addition to the terrestrial component, **there must also be a source of ionizing radiation, which becomes stronger with increasing altitude** (Figs. 1.4 and 1.5). **-> extraterrestrial origin**

Fig. 1.4 Victor Hess at a balloon ascent for measuring cosmic radiation [4]

How can a cloud chamber measure the mass and charge of particles?

Discoveries in the 20th Century

This extraterrestrial component was confirmed by Kohlhörster two years later (1914).

By developing the **cloud chamber** in 1912, made it possible to detect and **follow the tracks left by ionizing particles. -> measure the mass and charge of the particles.**

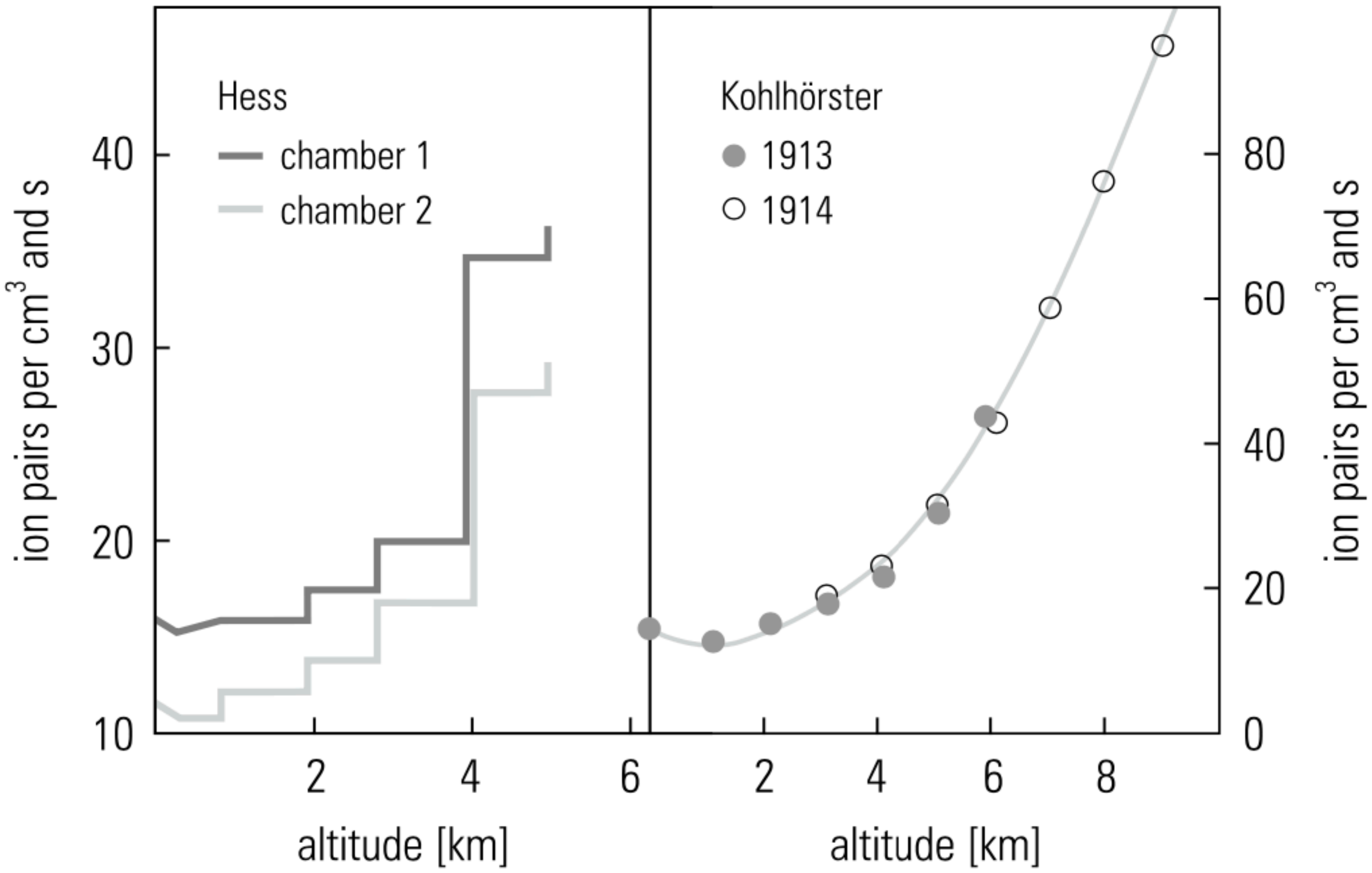


Fig. 1.5 Measurements of Hess (*left*) and Kohlhörster (*right*) showing the dependence of ionization on the altitude in the atmosphere [5, 6]

Discoveries in the 20th Century

In parallel to these experimental observations, Einstein developed his theories of special and general relativity (1905 and 1916). The theory of ***special relativity*** is of paramount importance for particle physics, while the prevailing domain of general relativity is cosmology.

Schwarzschild had already drawn correct conclusions for the **existence of black holes** as early as 1916, and Eddington had verified the predicted **gravitational bending of light passing near the Sun** during the solar eclipse in 1919.

The experimental observation of the deflection of light in gravitational fields also constituted the discovery of ***gravitational lensing***. This is when the image of a star appears to be displaced due to the gravitational lensing of light that passes near a massive object. This effect can also lead to double, multiple, or ring-shaped images of a distant star or galaxy if there is a massive object in the line of sight between the observer on Earth and the star.

It was only in **1979 that multiple images of a quasar (double quasar) could be observed**.

This was followed in 1988 by an **Einstein ring in a radio galaxy**.

Other configurations caused by gravitational lensing, like the Einstein cross were also seen (Figs. 1.7 and 1.8).

Why is special relativity important for particle physics?

Discoveries in the 20th Century

Depending on the geometry of the lensing, we can get different lensed images.

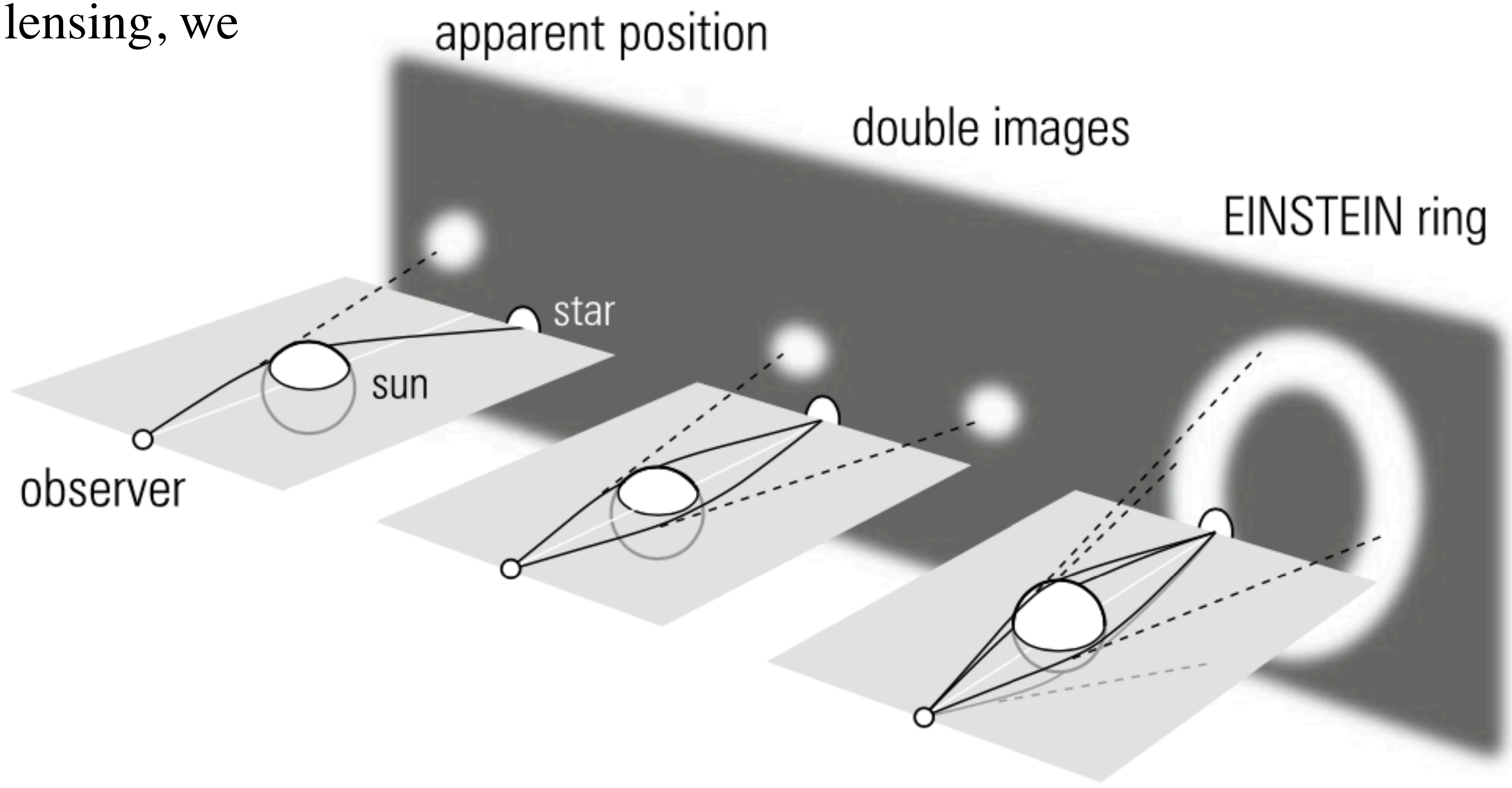
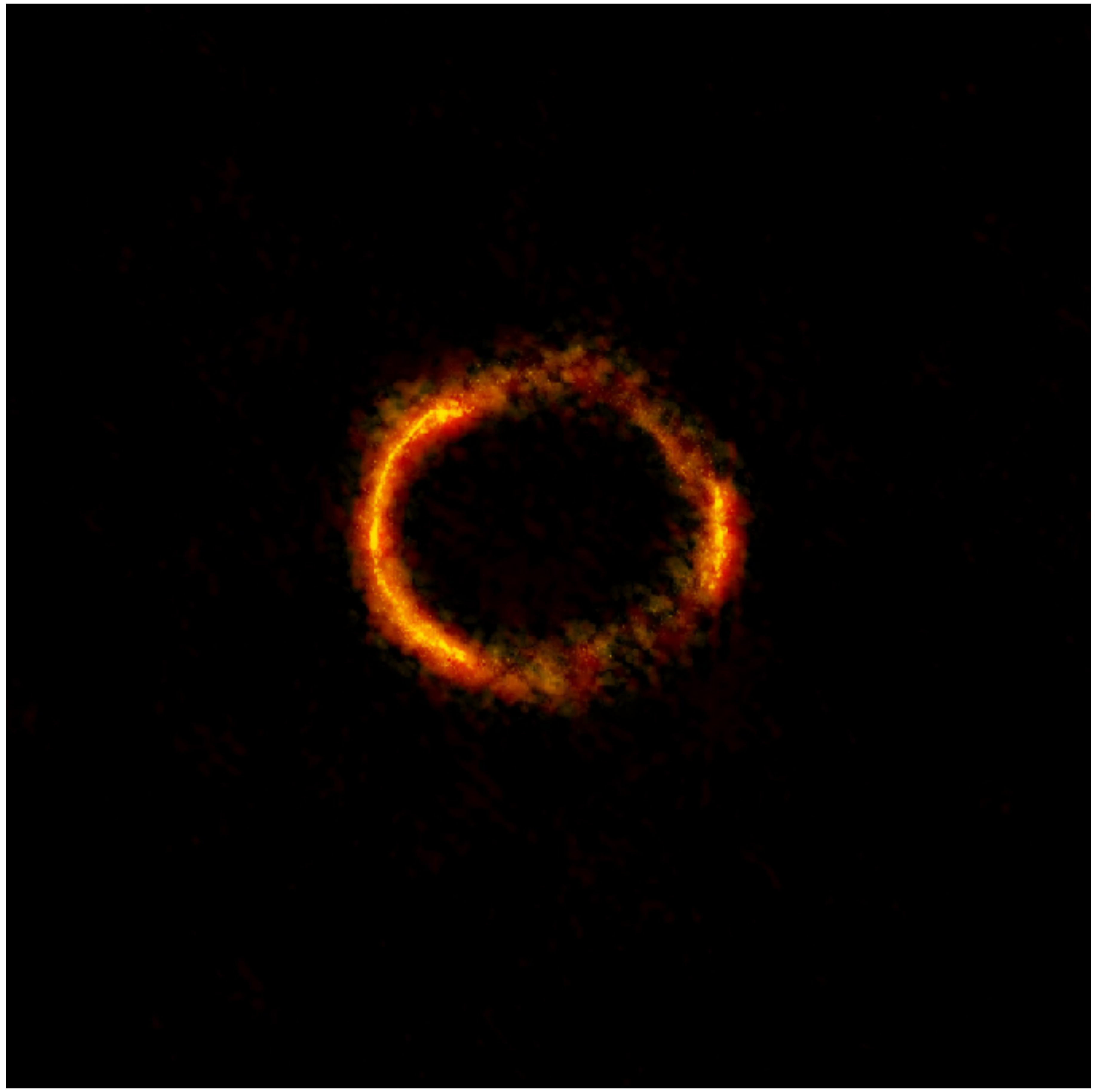
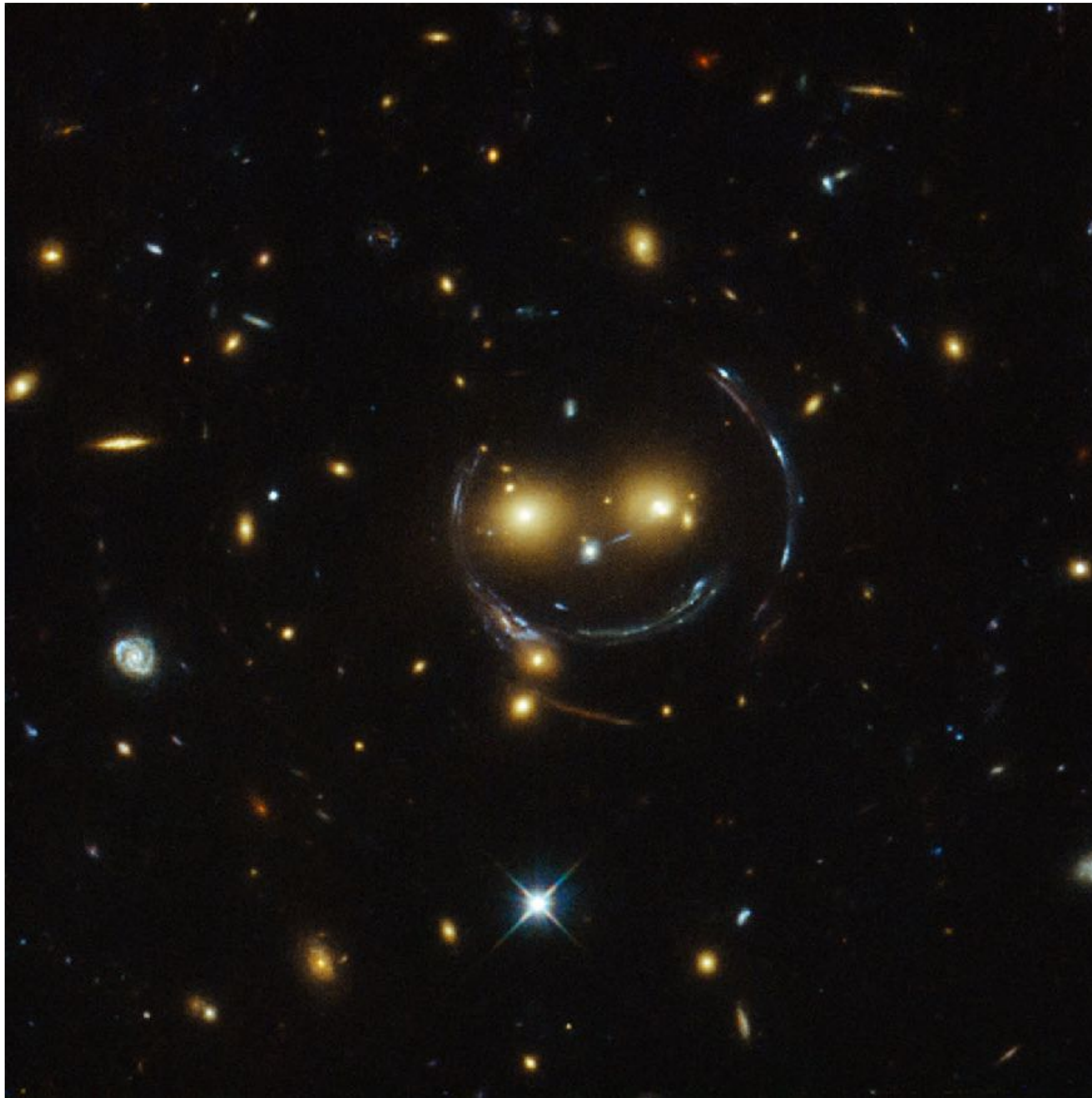


Fig. 1.7 Gravitational lensing. **a** light deflection, **b** double images, **c** Einstein ring

Einstein rings and crosses

If a quasar or other bright source lies exactly along the line of sight to the lensing mass, then it will be imaged as an **Einstein ring** encircling the lens





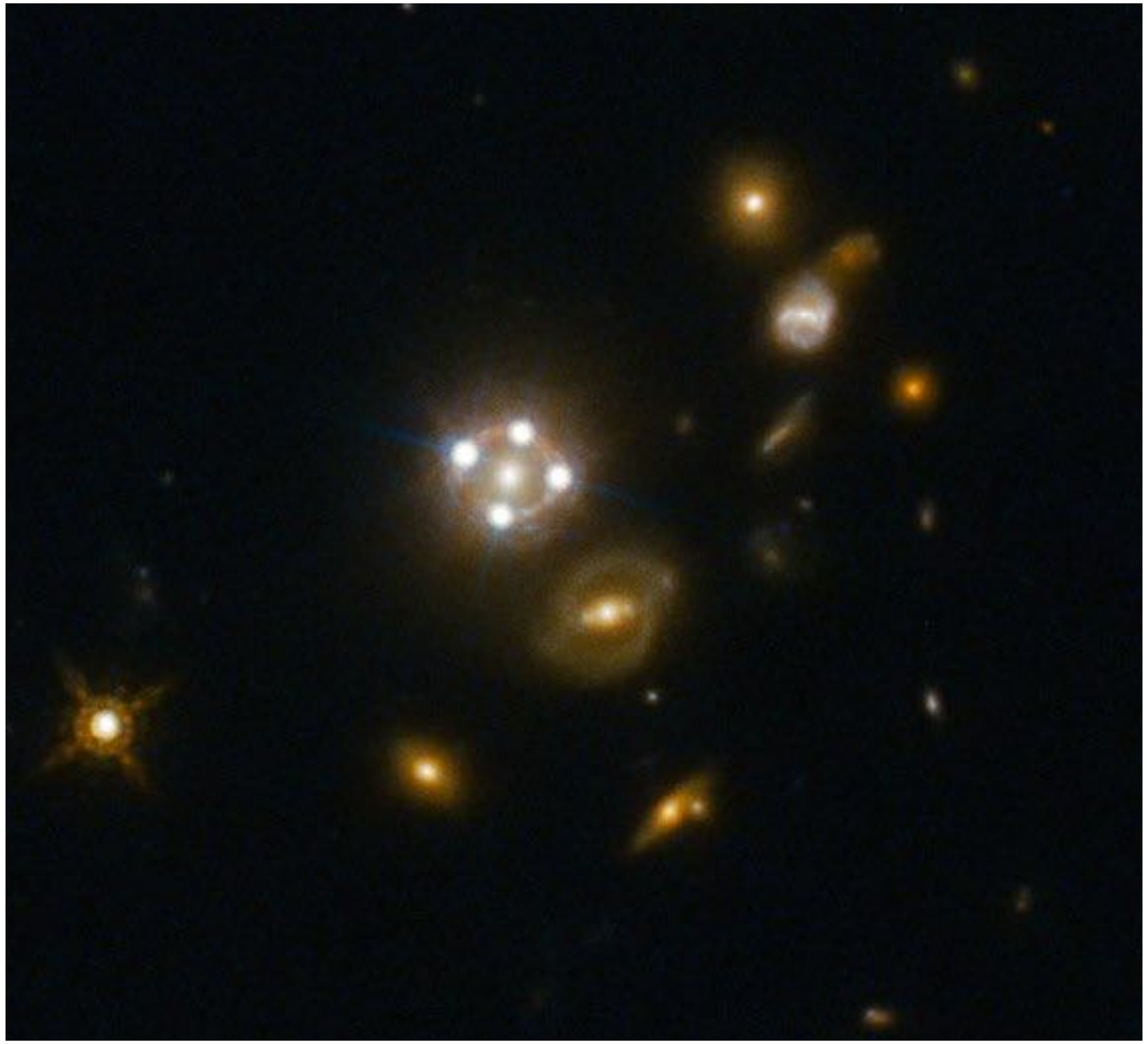
Einstein rings and crosses

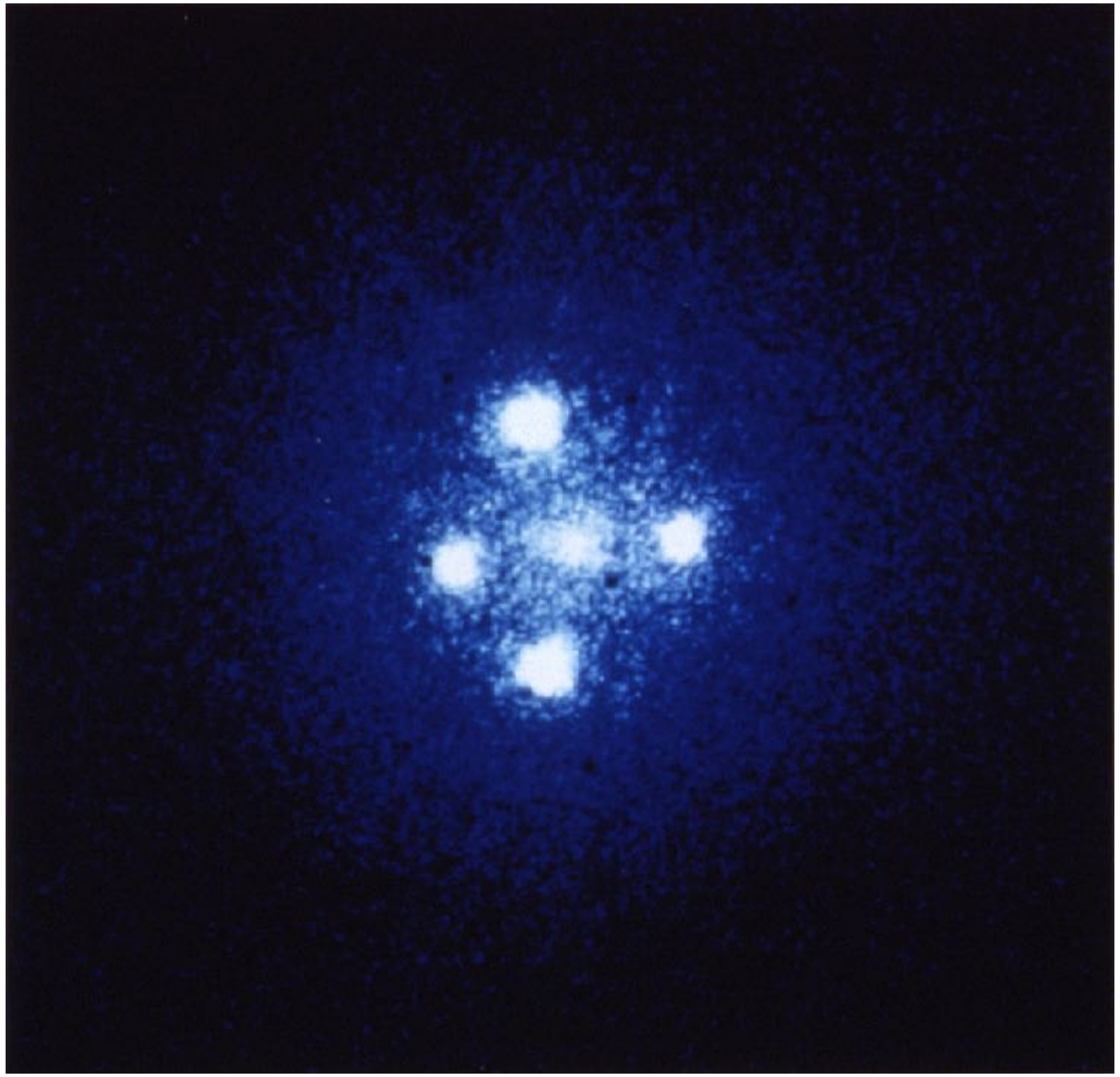
More modern observations of the bending of light:
gravitational lensing

https://www.eso.org/public/videos/eso1522b/

Einstein rings and crosses

If the lensing mass is represented with and **isothermal ellipsoid**, then it can **produce either three or five images** (an extended distribution of mass will produce an odd number of images). If we get 4 or 5 images, then we get an Einstein cross.





Discoveries in the 20th Century

A clearer picture about the nature of cosmic rays had emerged. Using new detector techniques in 1926, Hoffmann observed **particle multiplication under absorbing layers** ('Hoffmann's collisions'). **-> particle showers**

In 1927, Clay demonstrated the **dependence of the cosmic-ray intensity on the geomagnetic latitude.** This was a clear indication of the **charged-particle nature of cosmic rays,** since photons would not have been influenced by the Earth's magnetic field.

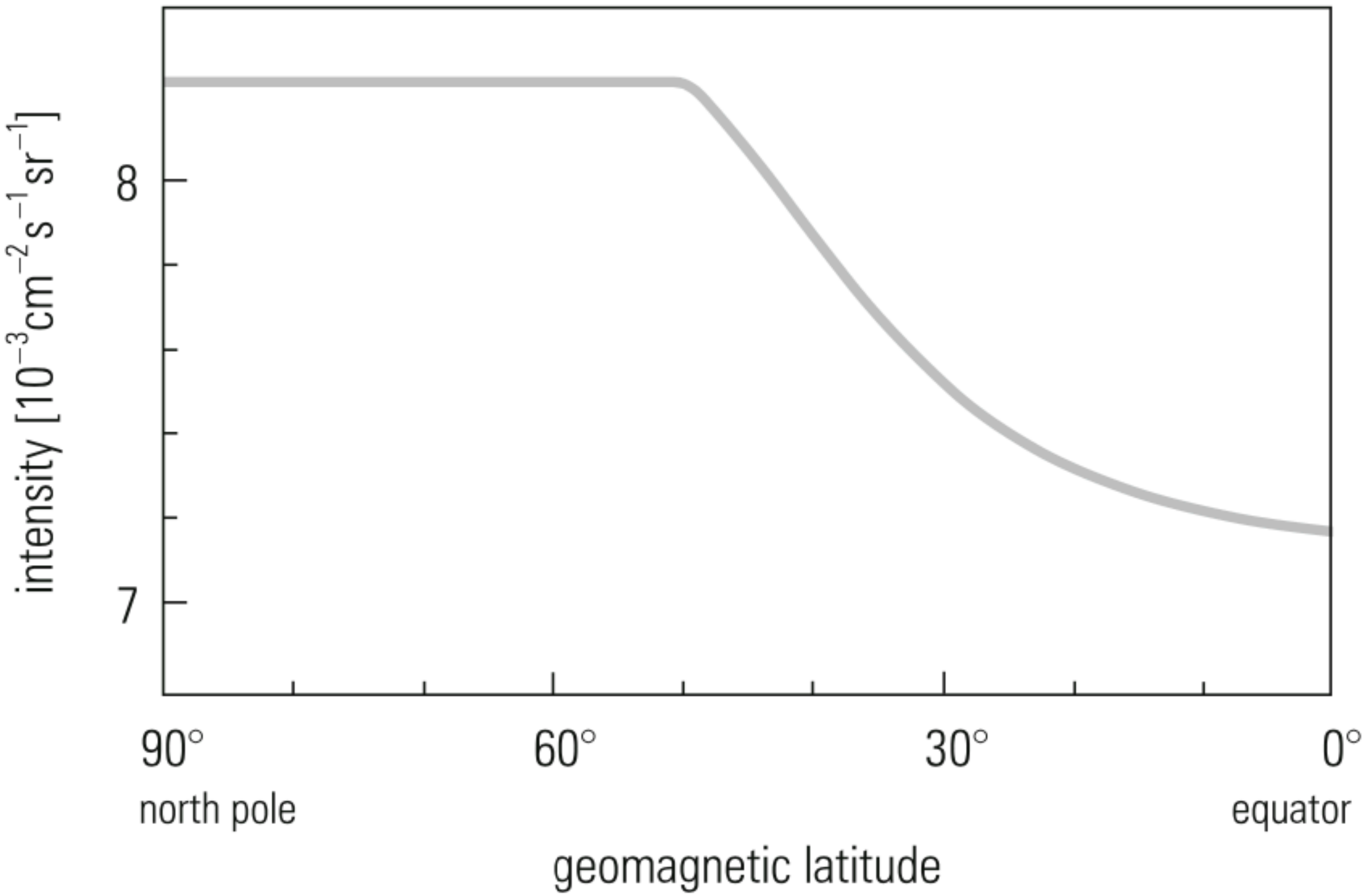
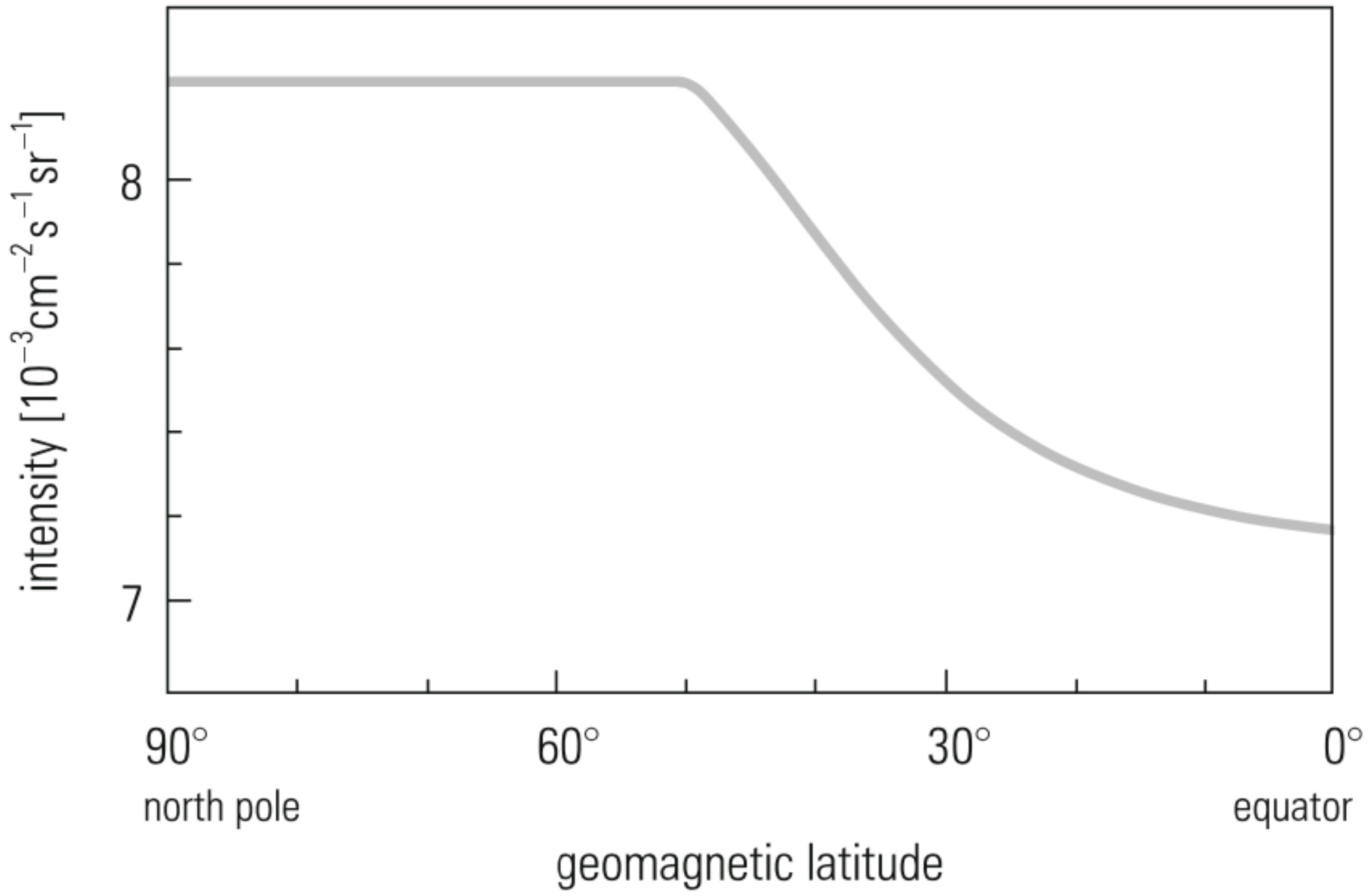


Fig. 1.9 Latitude effect: geomagnetic and atmospheric cutoff

Discoveries in the 20th Century



Primary cosmic rays can penetrate deep into the atmosphere at the Earth's poles, by traveling parallel to the magnetic field lines. At the **Equator** they would feel the **full component of the Lorentz force** ($\boldsymbol{F} = e(\mathrm{v} \times \boldsymbol{B})$;

$\boldsymbol{F}$—Lorentz force, v—velocity of the cosmic-ray particle, $\boldsymbol{B}$—Earth's magnetic field, e—elementary charge:

at the poles $\mathrm{v} \parallel \boldsymbol{B}$ holds with the consequence of $\boldsymbol{F} = \mathbf{0}$**,** while at the Equator one has $\mathrm{v} \perp \boldsymbol{B}$, which leads to $|\boldsymbol{F}| = e\,\mathrm{v}\,B$).

This *latitude effect* was controversial at the time, because expeditions starting from medium latitudes (≈50○ north) to the Equator definitely showed this effect, whereas expeditions to the North Pole observed no further increase in cosmic-ray intensity. This result could be explained by the fact that **charged cosmic-ray particles not only have to overcome the magnetic cutoff, but also suffer a certain ionization energy loss in the atmosphere. (-> they loose energy trough ionising the atoms in the atmosphere)** This **atmospheric cutoff of about 2GeV prevents a further increase in the cosmic-ray intensity towards the poles** (Fig. 1.9).

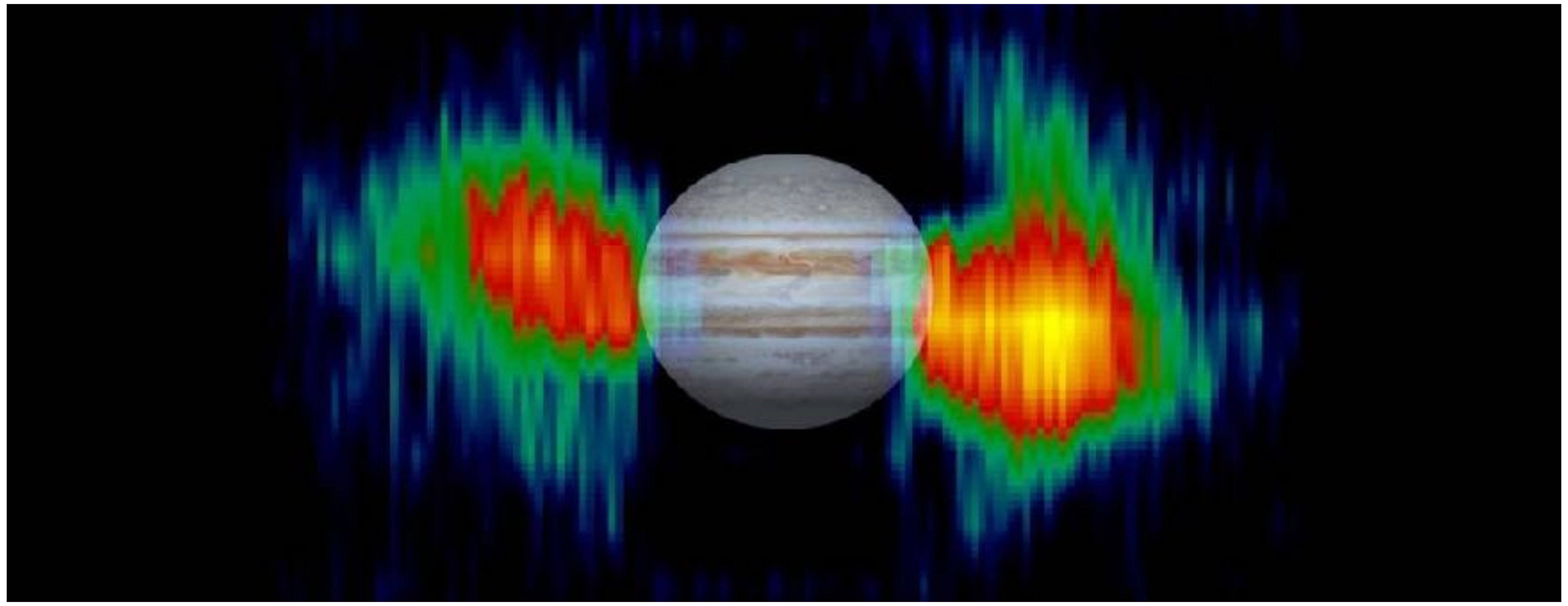
Discoveries in the 20th Century

As early as 1930, Störmer **calculated trajectories of charged particles through the Earth's magnetic field** to better understand the geomagnetic effects. He realized, that **most particles failed to reach sea level due to the action of the magnetic field.**

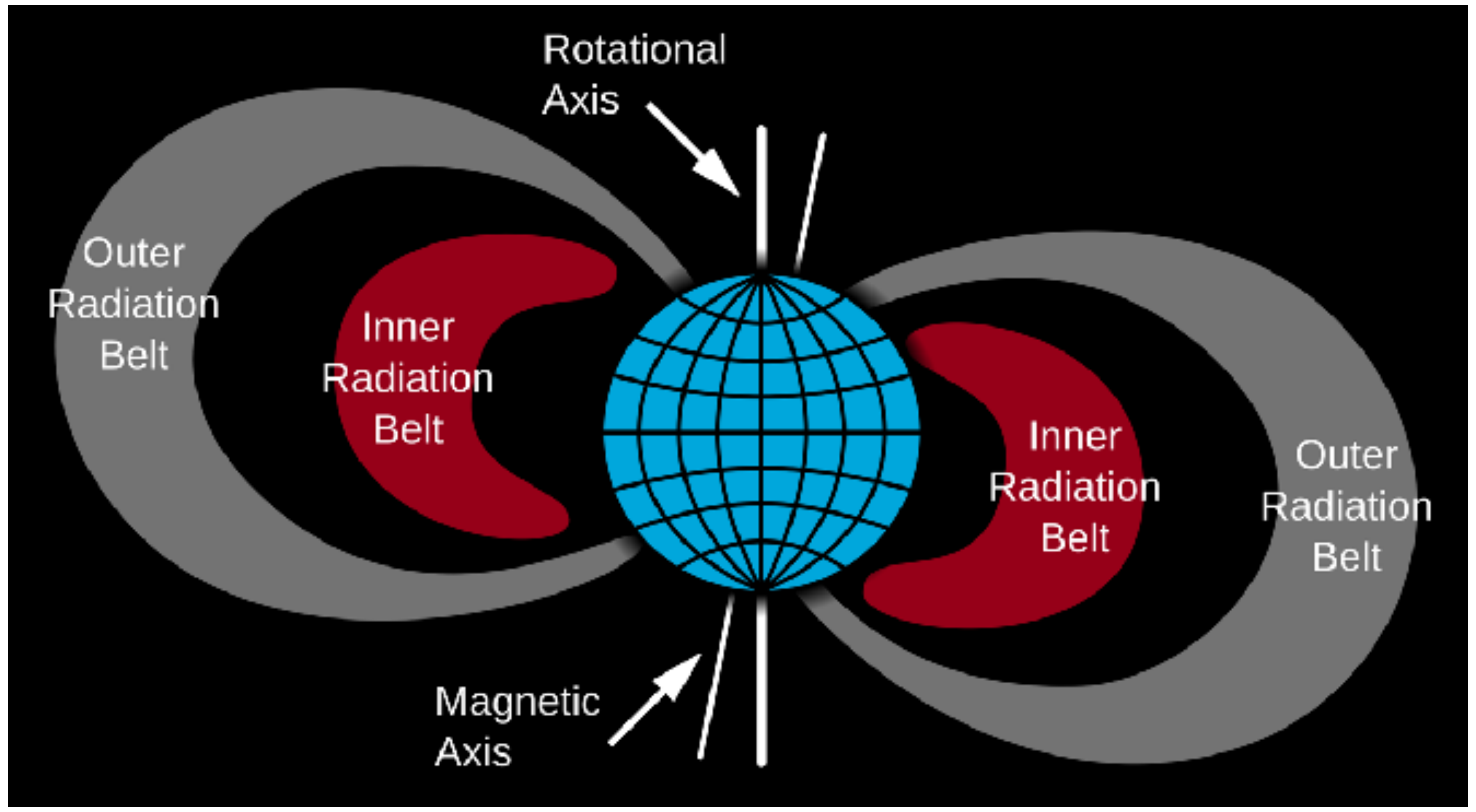
After further investigation he found that **particles with certain momenta could be trapped by the magnetic field, which caused them to propagate back and forth from one magnetic pole to the other in a process called 'magnetic mirroring'.**

The accumulated particles form radiation belts, which were discovered in 1958 by Van Allen with experiments on board the Explorer I satellite (Fig. 1.10).

Jupiter's radiation belts



Earth's radiation belts



Discoveries in the 20th Century

The inner and outer Van Allen belts result from different processes.

The **inner belt is mainly composed of energetic protons** produced from the **decay of neutrons**, which are themselves the result of **cosmic ray collisions in the upper atmosphere**.

The **outer Van Allen belt consists mainly of electrons**. They are **injected from the geomagnetic tail following geomagnetic storms,** and are subsequently energized through wave-particle interactions.

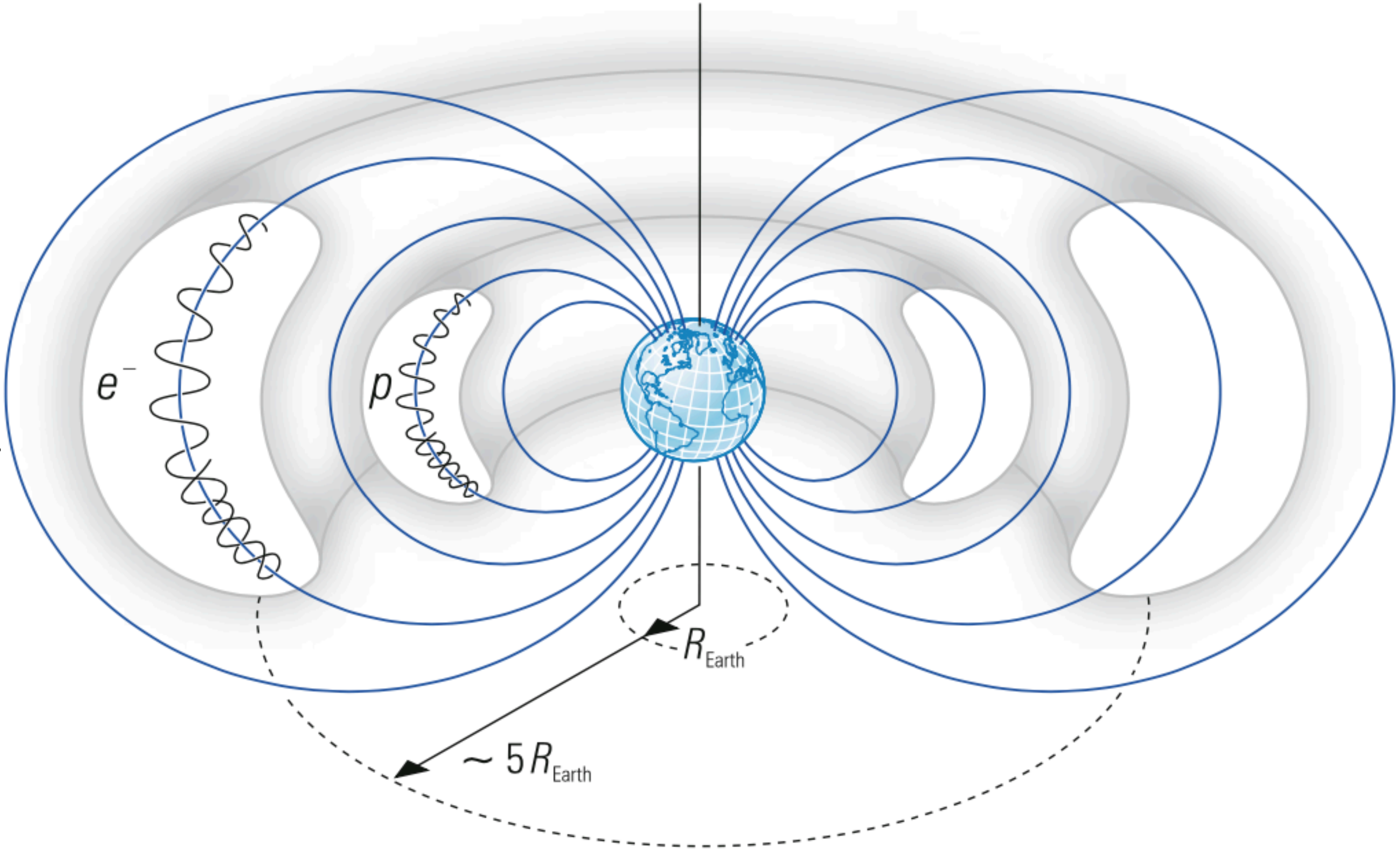
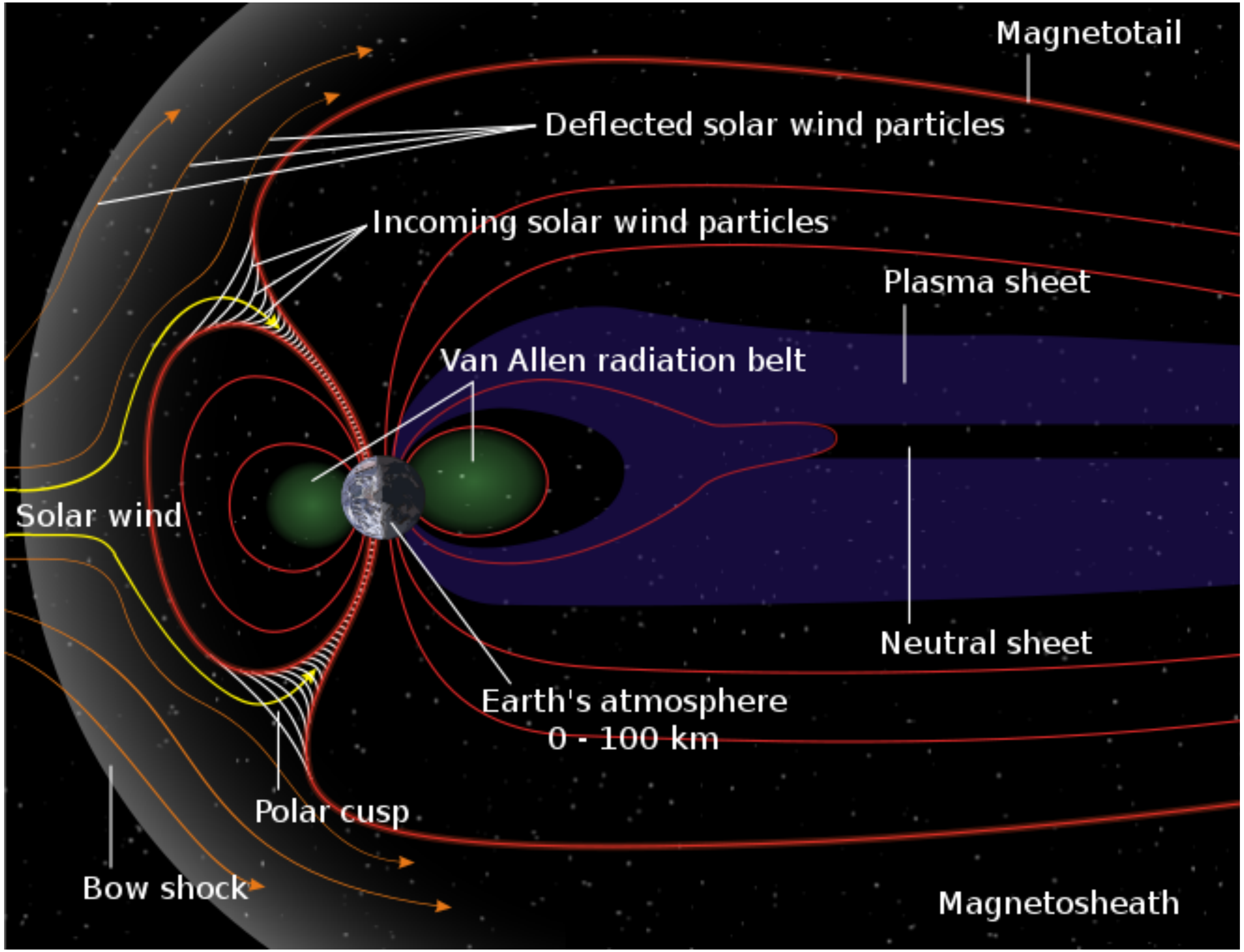


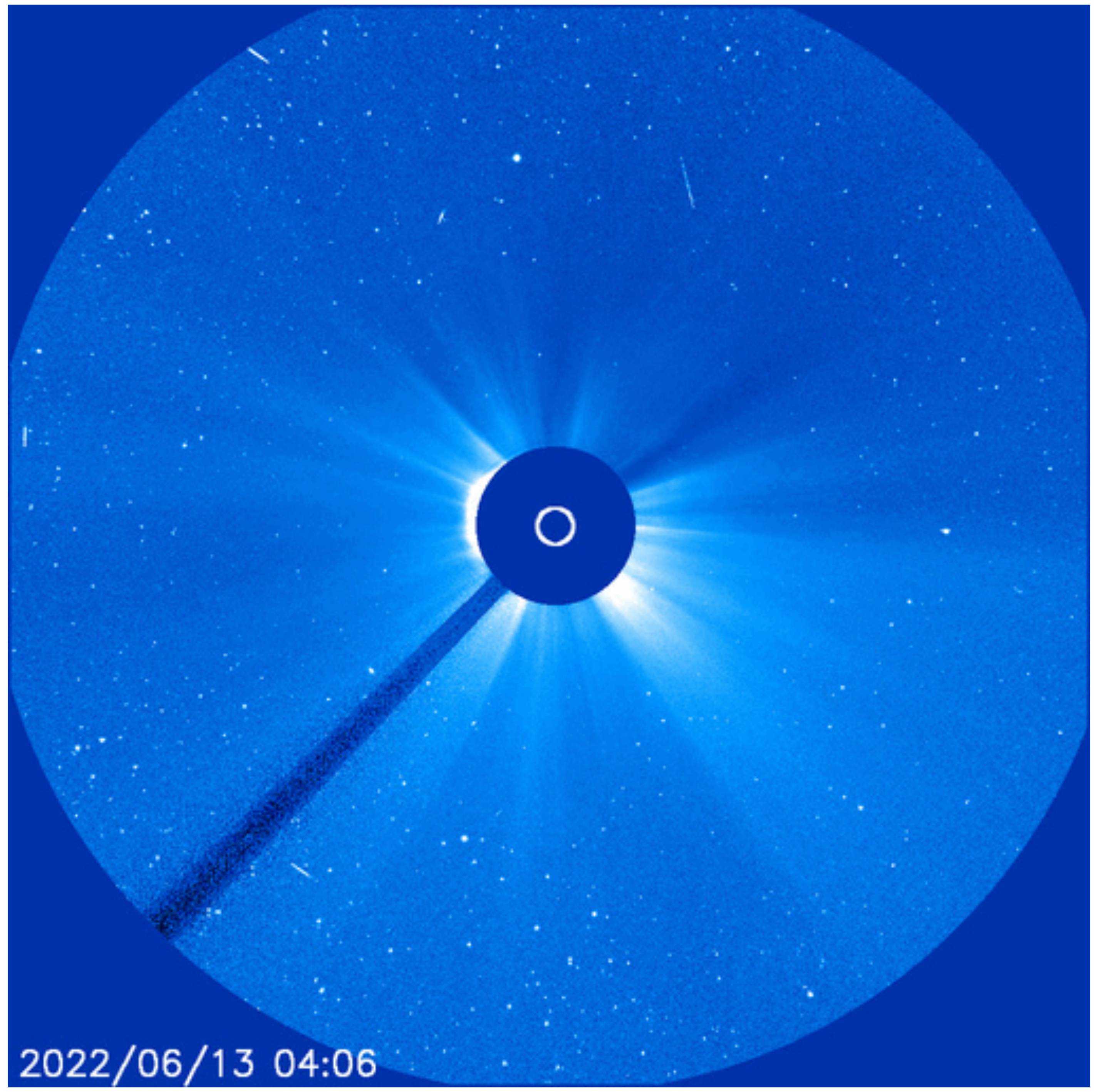
Fig. 1.10 Van Allen radiation belts

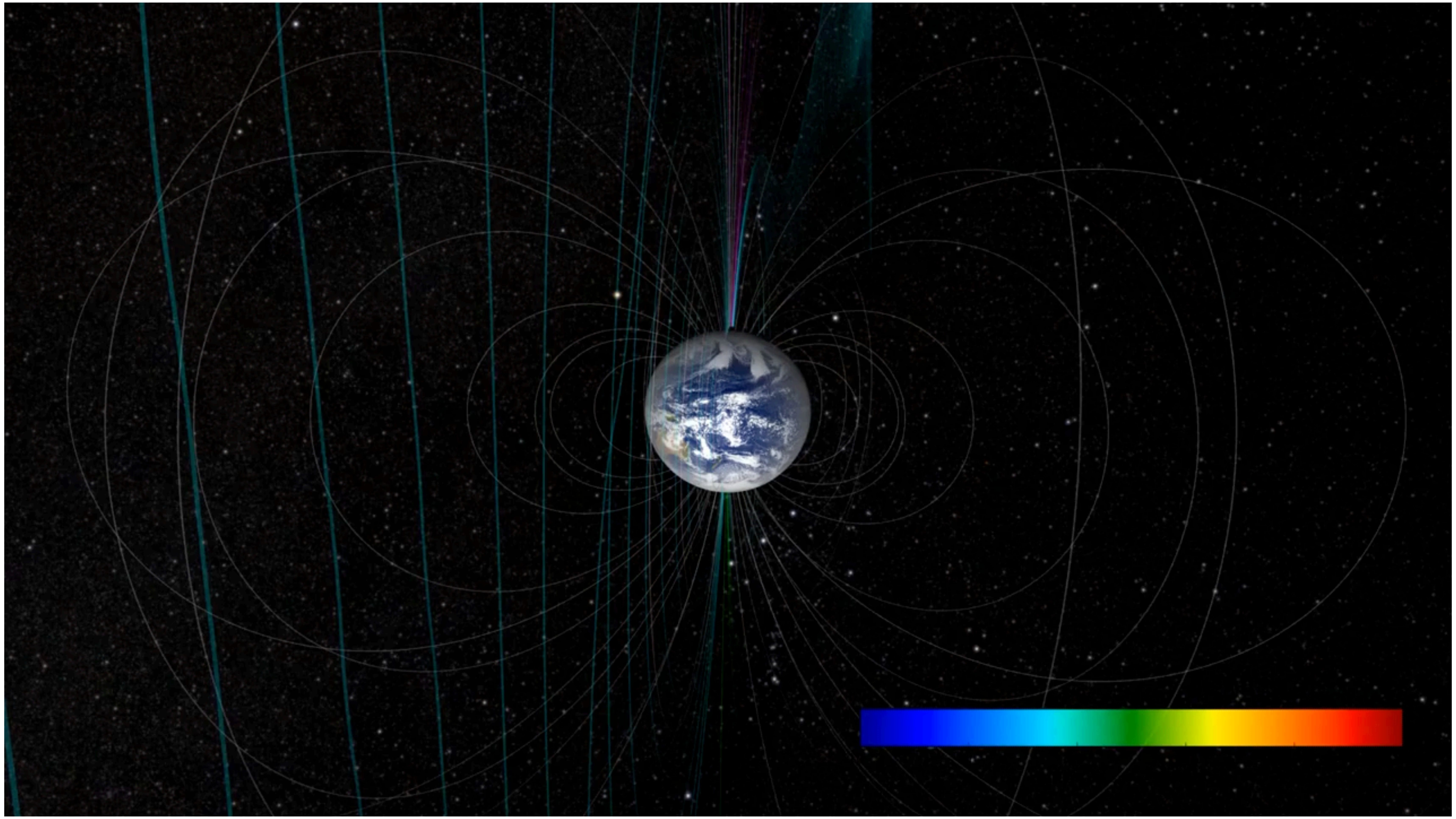
Discoveries in the 20th Century



Earth’s magnetosphere

Discoveries in the 20th Century





Earth’s magnetosphere during a CME

https://www.youtube.com/watch?v=DyuTyEw3etk

Discoveries in the 20th Century

The final **proof that primary cosmic rays consist predominantly of positively charged particles** was established by the observation of the ***east–west effect***.

In the direction of incidence of cosmic-ray particles at the North Pole, one finds a higher intensity from the west compared to the east.

The origin of this asymmetry relates to the possible trajectories of positively charged particles from easterly directions do not reach out into space (dashed tracks in Fig. 1.11) which reduces the intensity from these directions.

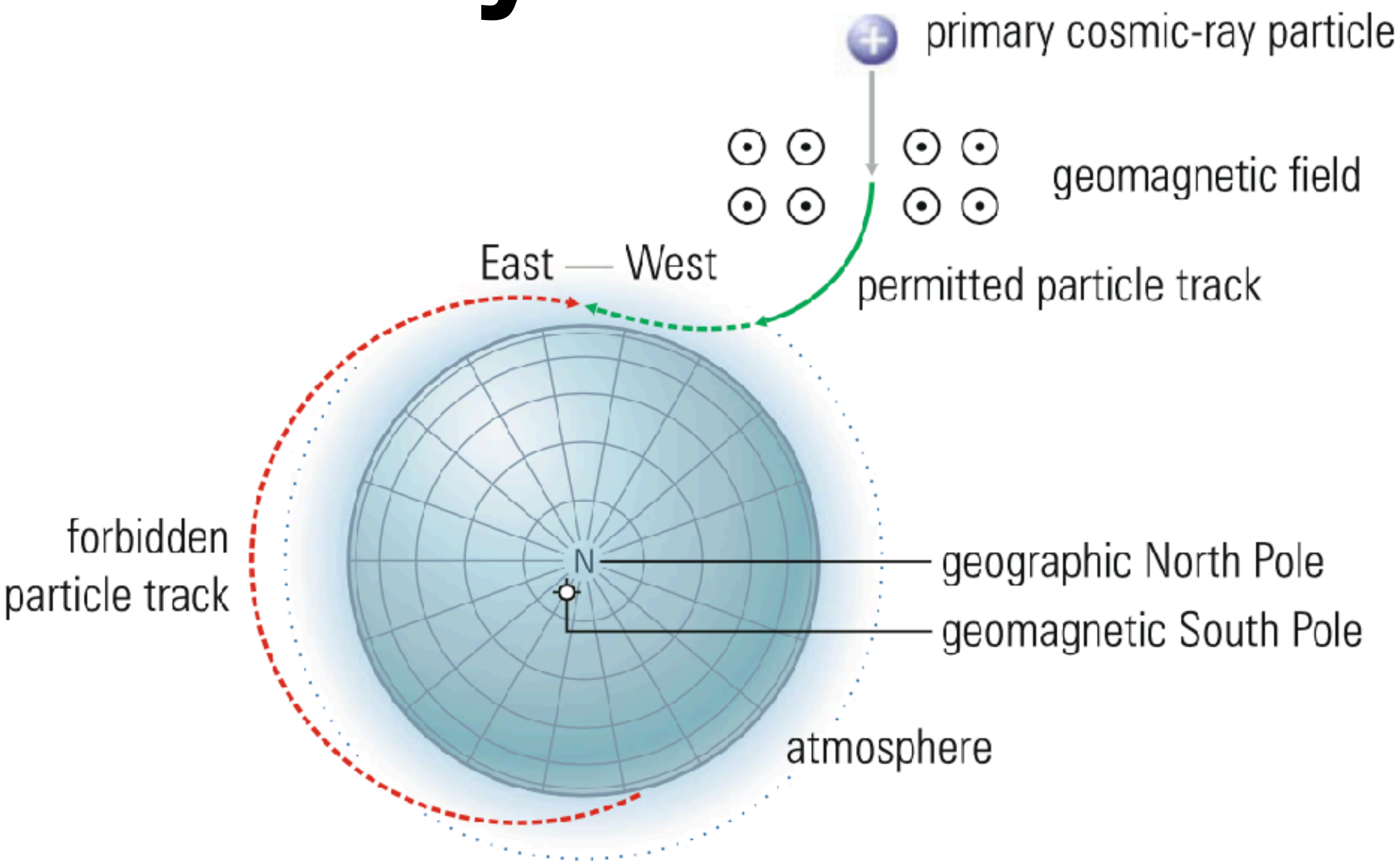


Fig. 1.11 East–west effect [8]

In 1933, Rossi showed in a coincidence experiment (a detector that can detect simultaneously arriving cosmic rays -> particle showers with many secondary particles) that **secondary cosmic rays at sea level initiate cascades**.

Discoveries of New Elementary Particles in Cosmic Rays

- Up to the thirties, only electrons, protons (as part of the nucleus), and photons were known as elementary particles.
- The **positron** was discovered in a cloud chamber by Anderson in 1932. This was the antiparticle of the electron, which was predicted by Dirac in 1928.
- This, and the discovery of the **neutron** by Chadwick in 1932, started a new chapter in elementary particle and astroparticle physics.
- Additionally in 1930, Pauli postulated the existence of a neutral, massless spin-$1/2$ particle to restore the validity of the energy, momentum, and angular-momentum conservation laws that appeared to be violated in nuclear beta decay.
- This hypothetical enigmatic particle, the **neutrino**, could only be shown to exist in a reactor experiment in 1956. It eventually lead to a completely new branch of astronomy; *neutrino astronomy* is a classic example of a perfect interplay between elementary particle physics and astronomy.

Discoveries of New Elementary Particles in Cosmic Rays

After discovering the neutron, the second building block of the nucleus, the question arose of **how atomic nuclei could stick together**. Although neutrons are electrically neutral, the protons would electrostatically repel each other.

Based on the range of the nuclear force and Heisenberg's uncertainty principle, **Yukawa** predicted in 1935 that unstable **mesons of 200-fold electron mass could possibly mediate nuclear forces.**

Initially it appeared that the muon, discovered in 1937 from cosmic ray detections (see Fig. 1.12), had the required properties of the hypothetical Yukawa particle. The **muon,** however, had **no strong interactions with matter,** and it soon became clear that the muon was a heavy counterpart of the electron.

The situation became even more critical when Perl discovered another, even heavier lepton, the **tau**, in 1975.

Discoveries of New Elementary Particles in Cosmic Rays

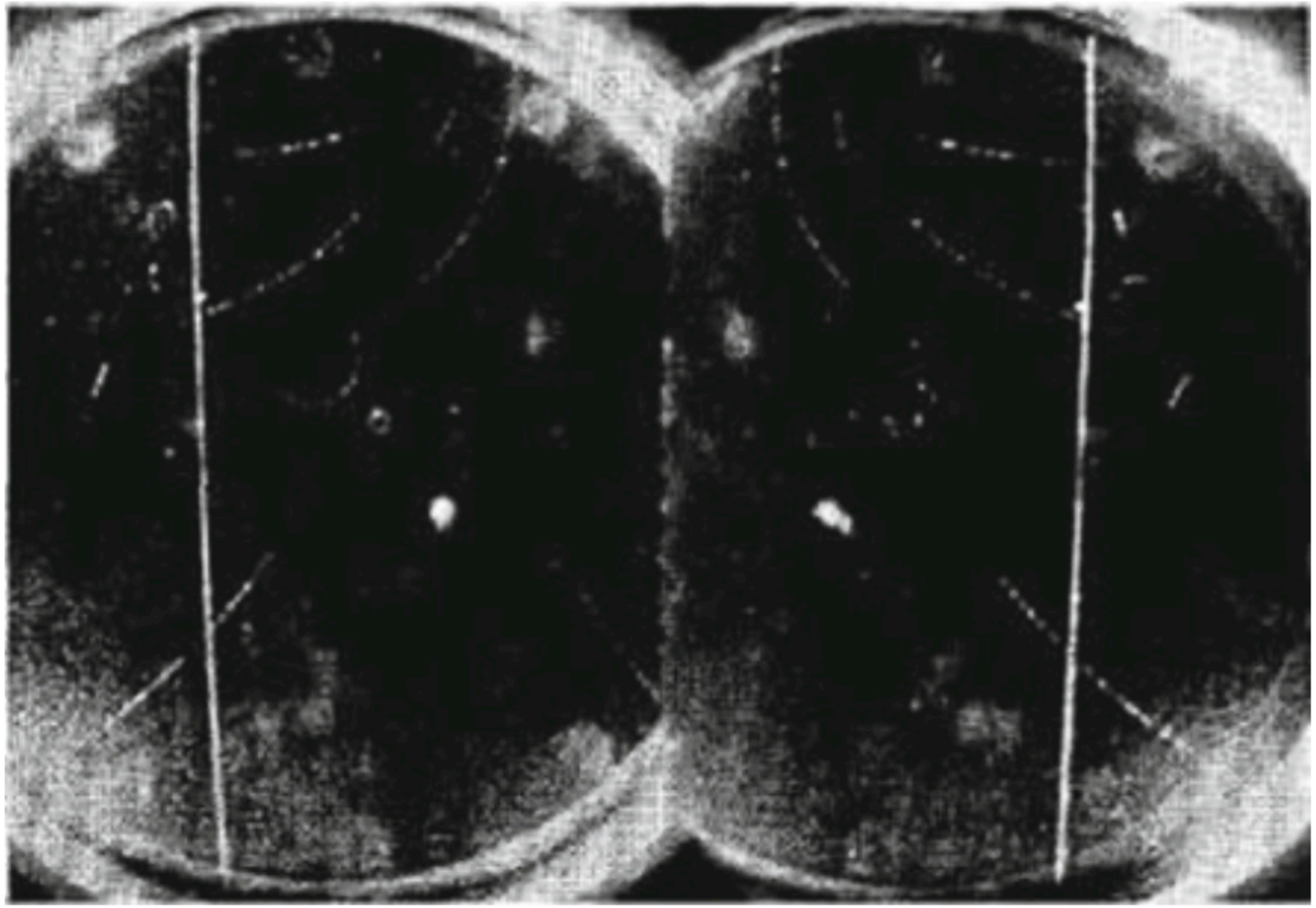


Fig. 1.12 Stereo view of a cosmic-ray muon in a cloud chamber (Anderson and Neddermeyer) [9]

Discoveries of New Elementary Particles in Cosmic Rays

The discovery of the **strongly interacting charged pions ($\pi^{\pm}$)** in 1947 by Lattes, Occhialini, Powell, and Muirhead, using nuclear emulsions **exposed to cosmic rays** at mountain altitudes, solved the puzzle about the Yukawa particles (see Fig. 1.13). The pion family was supplemented in 1950 by the discovery of the **neutral pion (π^0)**. Since 1949, pions can also be produced in particle accelerators.

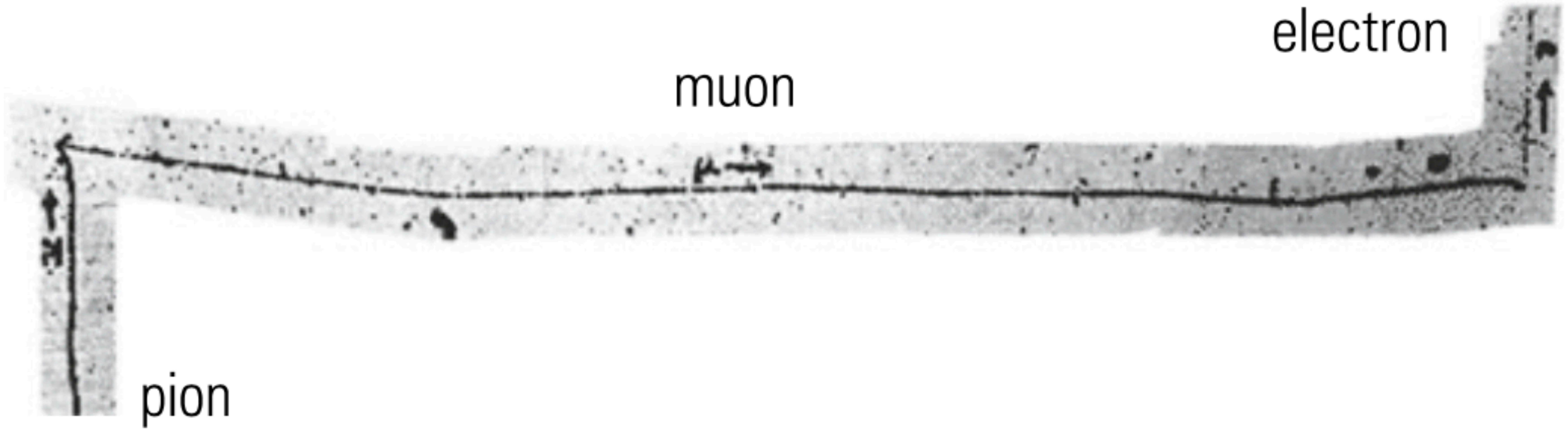


Fig. 1.13 Decay of a charged pion into a muon and subsequently into an electron in a nuclear emulsion [10]

Discoveries of New Elementary Particles in Cosmic Rays

Up to this time, **elementary particles were predominantly discovered in cosmic rays.**

In addition to the muon ($\mu^{\pm}$) and the pions (π^{+},π^{-},π^{0}), tracks of **charged and neutral kaons** were observed in cloud-chamber events. Neutral kaons revealed themselves through their decay into two charged particles. This made the K^0 appear as an upside-down ‘V’, because only the ionization tracks of the charged decay products of the K^0 were visible in the cloud chamber (Rochester and Butler 1947, Fig. 1.14).

In 1951, some of the upside-down ‘V’s, which were thought to be neutral kaons, were in fact recognized as **Lambda baryons**, which also decayed relatively quickly into two charged secondaries ($\Lambda^0 \rightarrow p + \pi^-$). In addition, the **$\Xi$ and Σ hyperons** were **discovered in cosmic rays**.

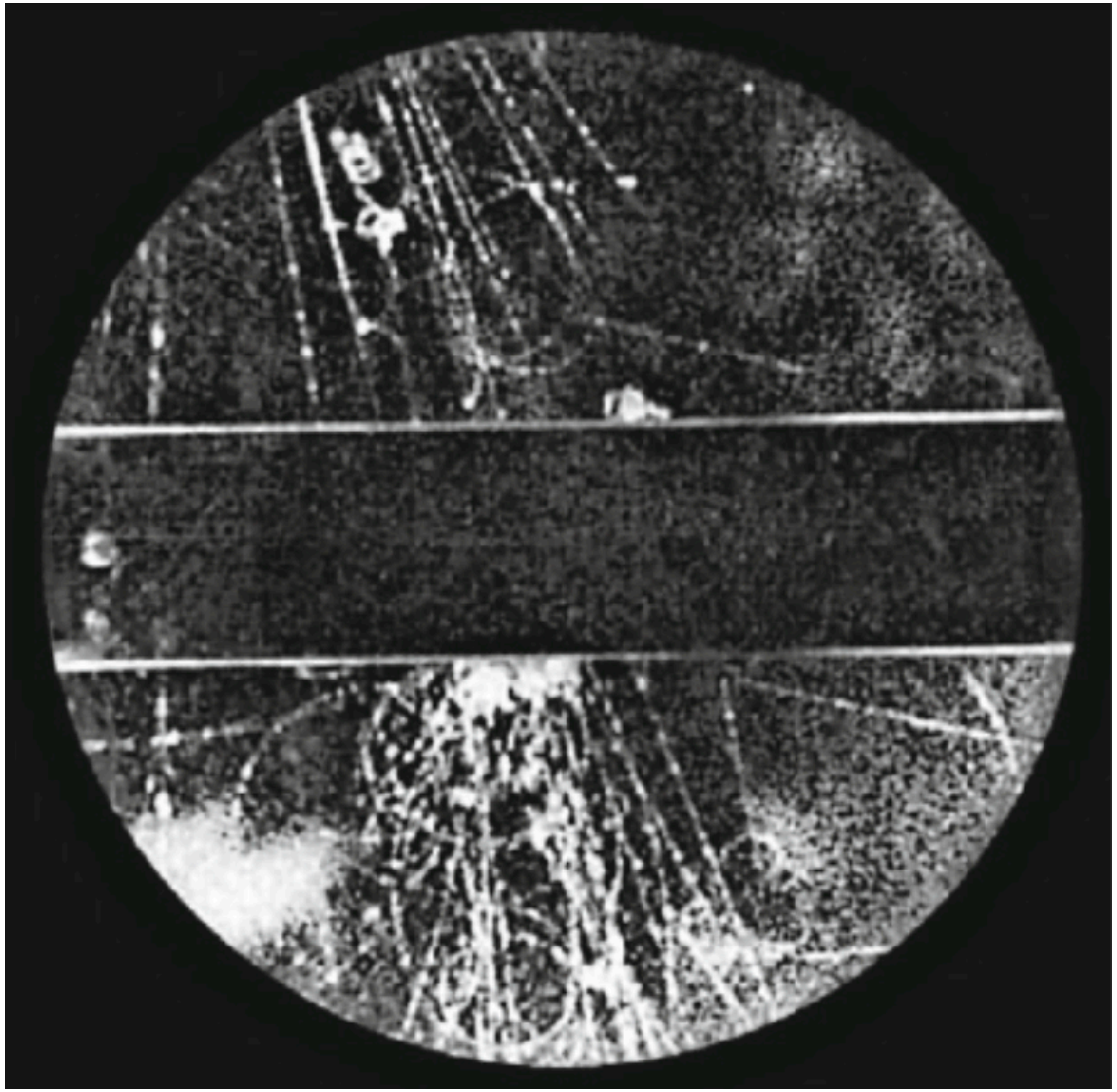


Fig. 1.14 Decay of a neutral kaon in a cloud chamber. The two tracks of the decay pions are visible at the *lower right*

Discoveries of New Elementary Particles in Cosmic Rays

In 1954 Yehuda Eisenberg exposed a stack of nuclear emulsions at an altitude of 30km to **cosmic rays**, and he found tracks that could have originated from the decay of an **Omega minus** (Ω^-).

Apart from studying local interactions of **cosmic-ray particles, their global properties were also investigated.** The showers observed under lead plates by Rossi were also found in the atmosphere (Pfotzer 1936). **The interactions of primary cosmic rays in the atmosphere initiate *extensive air showers*,** (Auger 1938). These showers lead to a maximum intensity of cosmic rays at altitudes of 15 km above sea level ('Pfotzer maximum', Fig. 1.15).

One year earlier (1937), Bethe and Heitler, and at the same time Carlson and Oppenheimer, developed the **theory of electromagnetic cascades,** which was successfully used to **describe the extensive air showers**.

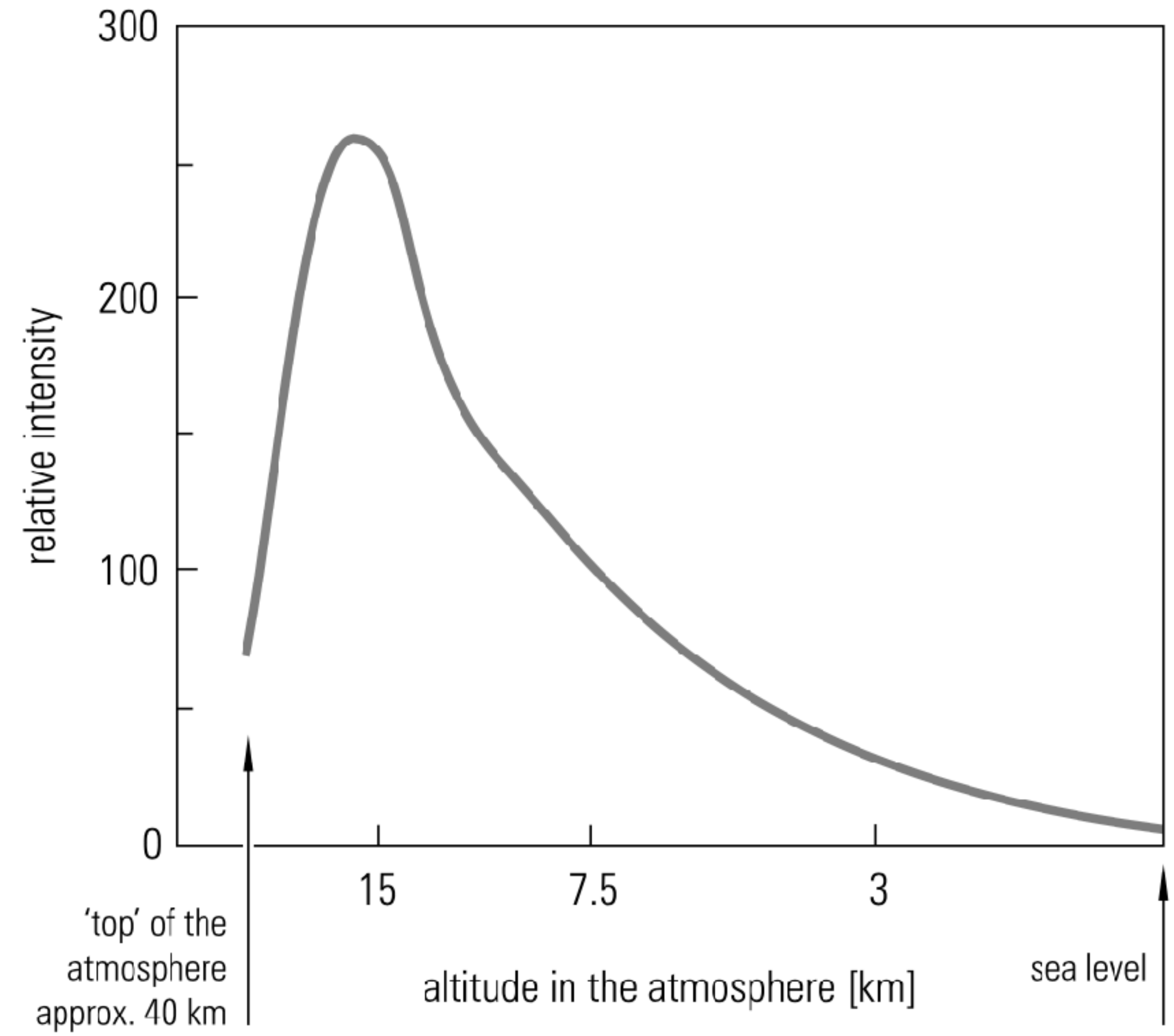


Fig. 1.15 Intensity profile of cosmic-ray particles in the atmosphere

Discoveries of New Elementary Particles in Cosmic Rays

In 1938, Bethe together with Weizsäcker, solved the long-standing mystery of the **energy generation in stars**. The **fusion of protons leads to the production of helium nuclei**, in which the binding energy of 6.6 MeV per nucleon is released, making the stars shine.

In 1937, Forbush realized that a **significant decrease of the cosmic-ray intensity correlated with an increased solar activity.** The active Sun appears to create some sort of ***solar wind* that consists of charged particles**, whose **flux generates a magnetic field in addition to the geomagnetic field**. The solar activity thereby **modulates the galactic component of cosmic rays** (Figs. 1.16, 1.17).

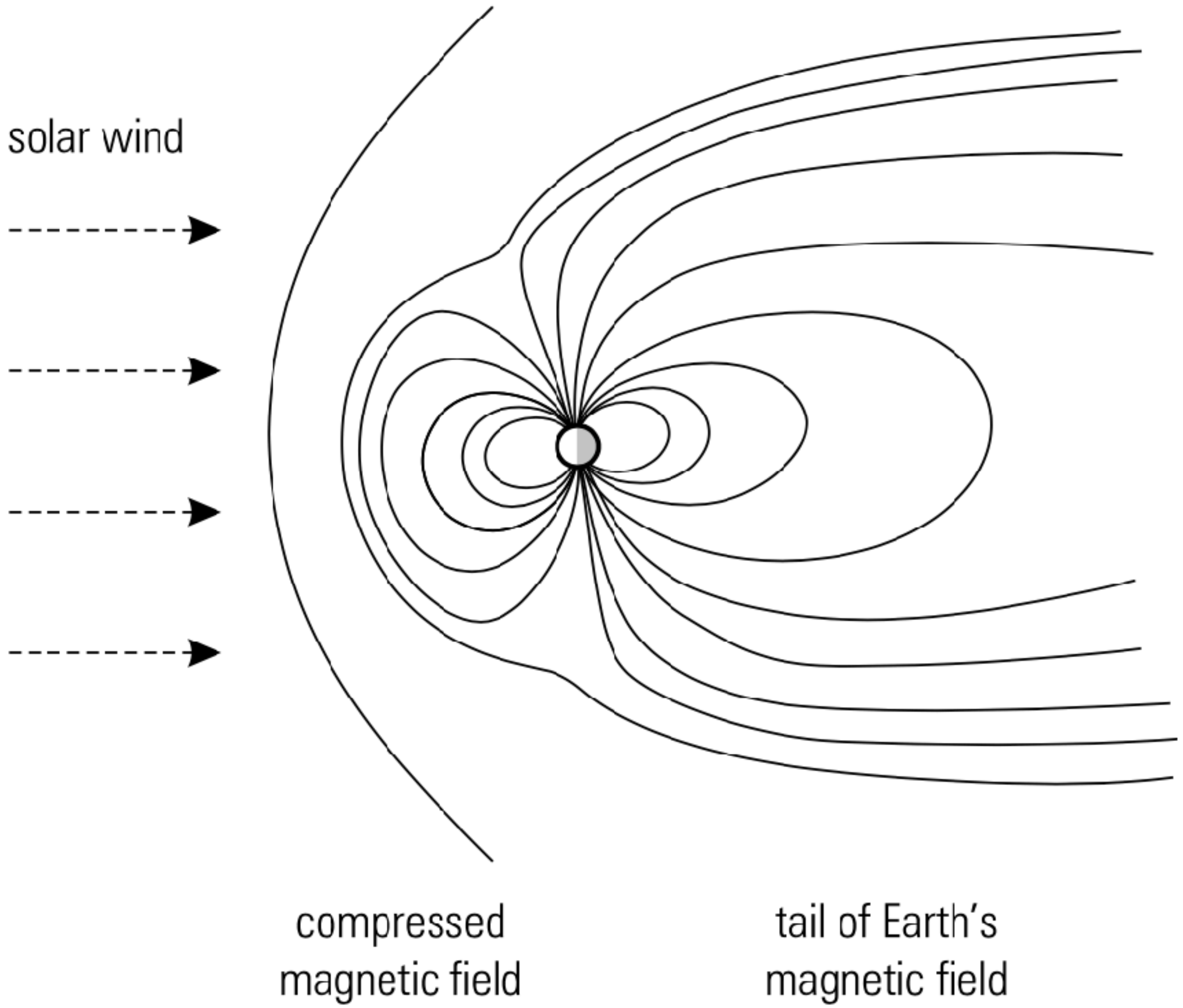


Fig. 1.16 Influence of the solar wind on the Earth's magnetic field

Discoveries of New Elementary Particles in Cosmic Rays

The observation that the **tails of comets always point away from the Sun** led Biermann to conclude in 1951, that some kind of **solar wind must exist**. This more or less continuous particle flux was first directly **observed by the Mariner 2 space probe** in 1962. The solar wind consists **predominantly of electrons and protons**, with a small admixture of **α particles**. The particle intensities at a distance of one astronomical unit (the distance from Sun to Earth) are 2×10^8 ions/(cm^2 s). **This propagating solar plasma carries part of the solar magnetic field with it, thereby preventing some primary cosmic-ray particles to reach the Earth.**

In 1949 it became clear that primary **cosmic rays consisted mainly of protons**.

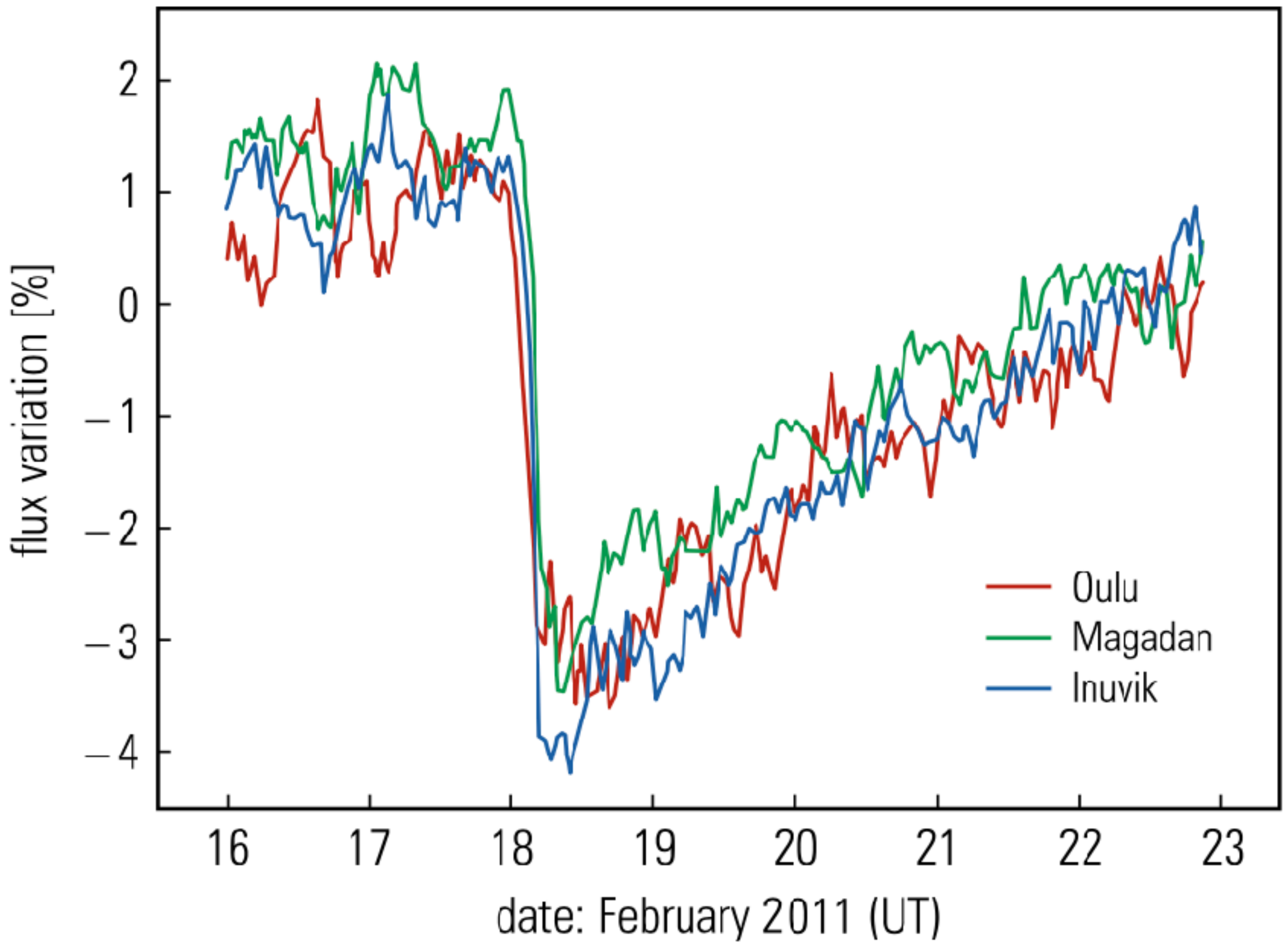


Fig. 1.17 Variation of the cosmic-ray intensity during a solar particle eruption (Forbush decrease). Such a solar wind of charged particles can present a serious radiation hazard for astronauts

Discoveries of New Elementary Particles in Cosmic Rays

Meanwhile, it had been **discovered that in addition to electrons, protons, and α particles, the whole spectrum of heavy nuclei existed in cosmic radiation.**

In 1950, ter Haar discussed **supernova explosions as the possible origin of cosmic rays**, an idea that was later confirmed by simulations and measurements.

The antiproton, the second known antiparticle, was found in an accelerator experiment by Chamberlain and Segrè in 1955.

Positrons and antiprotons were **later observed in primary cosmic rays**. It is, however, assumed that these cosmic-ray antiparticles do not originate from sources consisting of antimatter, but **are produced in secondary interactions between primary cosmic rays and the interstellar gas or in the upper layers of the atmosphere.**

Start of the Satellite Era

The launch of the first artificial satellite (Sputnik, October 4th, 1957) paved the way for developments that provided completely new opportunities in astroparticle physics.

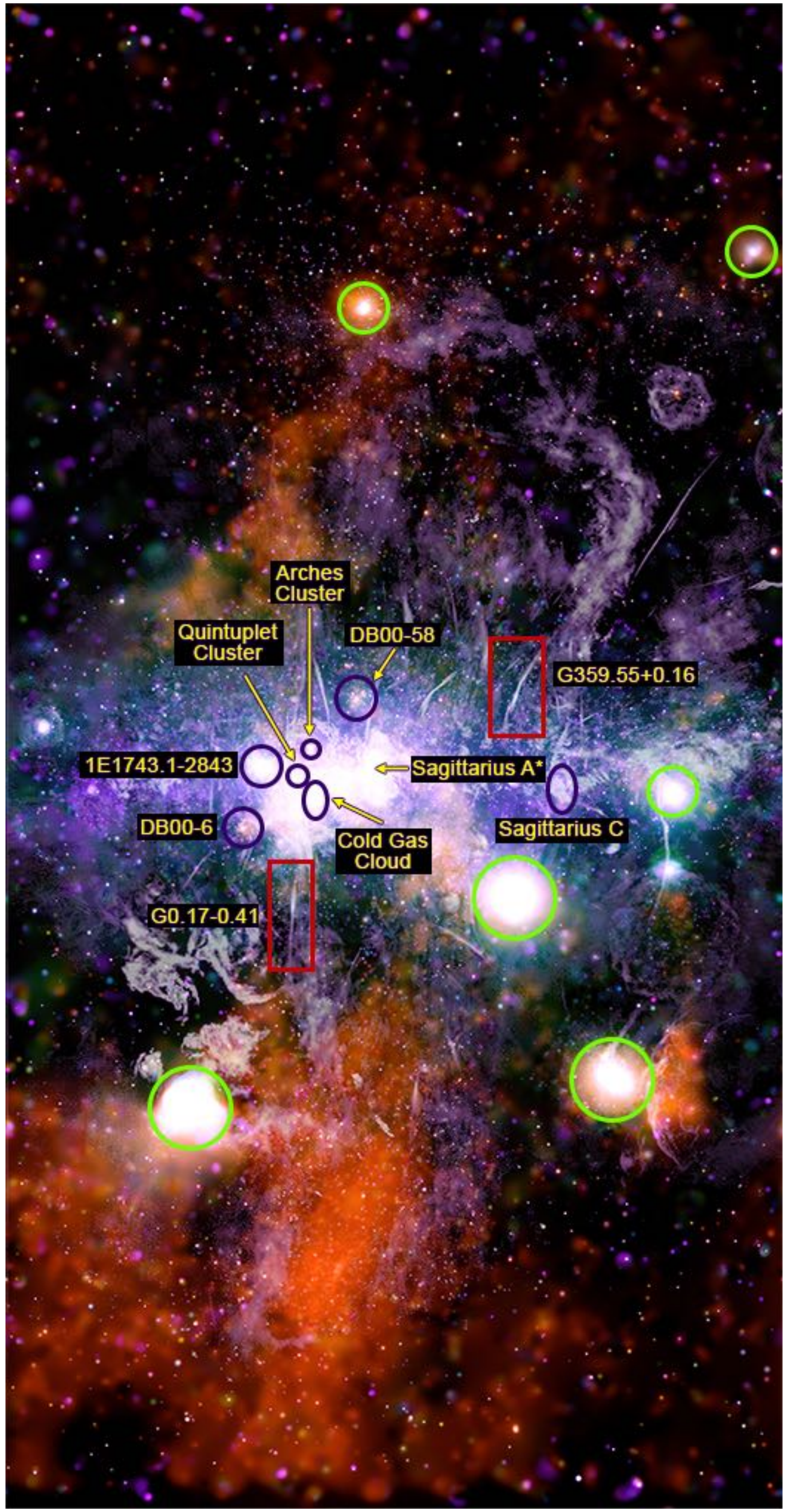
Why is it useful to have satellites?

Start of the Satellite Era

The launch of the first artificial satellite (Sputnik, October 4th, 1957) paved the way for developments that provided completely new opportunities in astroparticle physics.

The atmosphere represents an absorber with a thickness of ≈25 radiation lengths. The **observation of primary X rays and gamma radiation was previously impossible** due to their absorption in the upper layers of the atmosphere. This electromagnetic radiation can only be investigated—undisturbed by atmospheric absorption—at very high altitudes near the ‘top’ of the atmosphere. It still took some time until the first X-ray satellites and gamma satellites were launched.

The **galactic center was found to be bright in X rays and gamma rays,** and the first **point sources of high-energy astroparticles** could also be detected (Crab Nebula, Vela X1, Cygnus X3, . . .).



The Galactic Centre in a combination of X-ray and radio images

https://chandra.harvard.edu/photo/2021/gcenter/

Start of the Satellite Era

With the discovery of quasistellar radio sources (**quasars,** 1960), mankind advanced as far as to the edge of the universe. Quasars appear to outshine whole galaxies. Their distance is determined from the redshift of their spectral lines. A very distant quasar was discovered in 1999 with a redshift of $z = \dfrac{\lambda - \lambda_0}{\lambda_0} = 7.085$. An object even farther away is the galaxy Abell 1835 IR 1916 with a redshift of $z = 10$.

Its discovery was made possible through **light amplification by** a factor of about 50 resulting from strong **gravitational lensing** by a very massive galactic cluster in the line of sight to the distant galaxy.

This implies that the quasar is seen in a state when the universe was less than 5% of its present age. Consequently, this quasar resides at a distance of 13 billion light-years.

The Hubble telescope even found very distant galaxies with redshifts of up to $z = 11.9$.

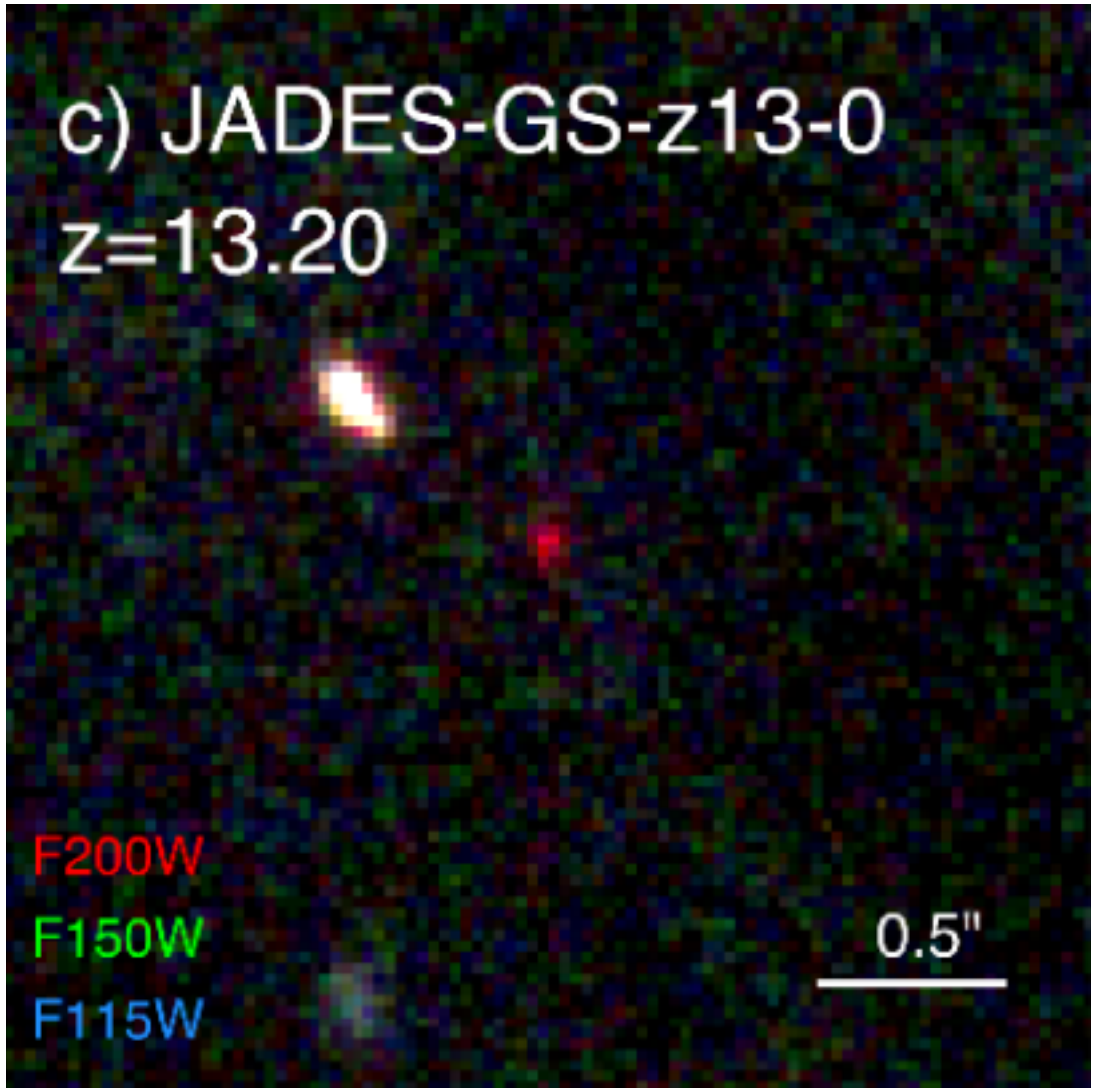
Is this still the most distant object known?

The largest redshift ever measured is actually that of the cosmic microwave background ($z \approx 1100$).

Start of the Satellite Era

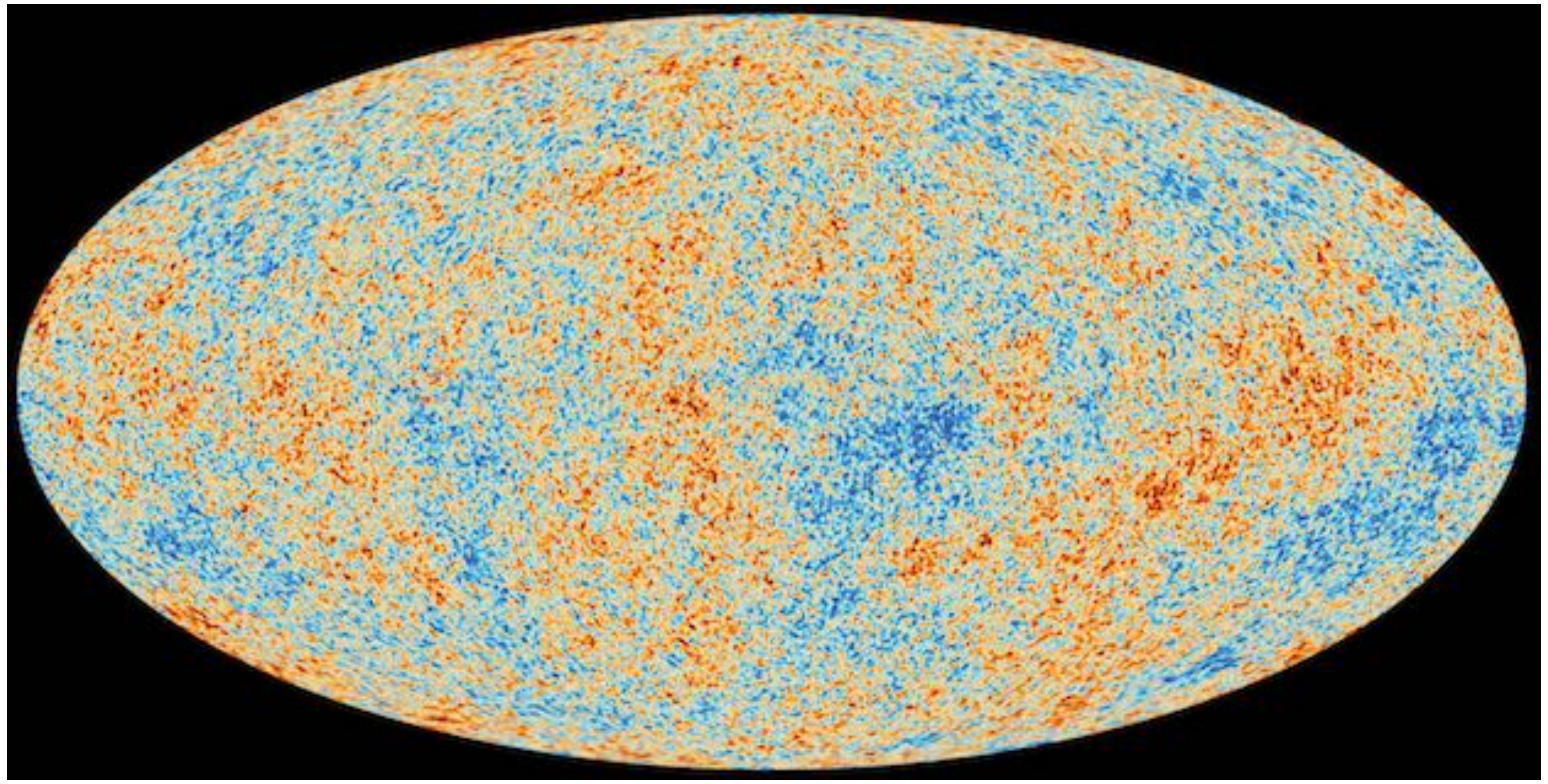
The most distant object in the Universe? In 2023.

This object was detected with the James Webb telescope and has an approximate redshift of z = 13.20 (redshift is determined with spectroscopy). The **age of the Universe is estimated to be z =13.787**



https://en.wikipedia.org/wiki/List_of_the_most_distant_astronomical_objects

Start of the Satellite Era



Planck image of the CMB

The expansion of the universe implies that it began in a giant explosion, some time in the past. Based on this **Big Bang hypothesis,** one arrives at the conclusion that this must have occurred **about 14 billion years ago.**

Gamow had been theoretising since the forties that there should be a residual radiation from the Big Bang. According to his estimate, the temperature of this radiation should be in the range of a few kelvin.

Penzias and Wilson detected this echo of the Big Bang, the **cosmic microwave background (CMB)** by chance in 1965, while they were trying to develop low-noise radio antennae.

The exact temperature of this blackbody radiation was measured to the blackbody temperature of 2.725 ± 0.001 K by the satellites WMAP (Wilkinson Microwave Anisotropy Probe) and Planck.

Spatial asymmetries of the 2.7-kelvin blackbody radiation at a level of $\Delta T/T \approx 10^{-5}$. This implies that **the early universe had a lumpy structure,** which can be considered as a seed for galaxy formation.

Start of the Satellite Era

After the electron antineutrino had been directly measured by Cowan and Reines in a reactor experiment, the famous two-neutrino experiment of Lederman, Schwartz, and Steinberger in 1962 represented an important step for the advancement of astroparticle physics.

This experiment demonstrated that **the neutrino emitted in nuclear beta decay is not identical with the neutrino occurring in pion decay ($\nu_\mu \neq \nu_e$).**

Why do we have this difference?

What is the reaction of these two decays?

At present, **three generations of neutrinos are known (ν_e, ν_μ, and ν_τ).**

Experiments at the Large Electron–Positron Collider (LEP) at CERN have demonstrated in 1989 that there are only three neutrino generations with masses below half of the Z mass. The direct observation of the tau neutrino was established only relatively recently (July 2000) by the DONUT experiment.

What are particle generations?

Start of the Satellite Era

The observation of solar neutrinos by the Davis experiment in 1967 marked the beginning of the discipline of neutrino astronomy.

Davis **measured a deficit in the flux of solar neutrinos**, which was confirmed by subsequent experiments.

In 1958 Pontecorvo highlighted the possibility of ***neutrino oscillations*.** Such oscillations ($\nu_e \rightarrow \nu_\mu$) are presently generally accepted as explanation of the solar neutrino deficit.

This would imply that neutrinos have a **very small non-vanishing mass.**

In the framework of the **electroweak theory** (Glashow, Salam, Weinberg 1967) that unifies electromagnetic and weak interactions, a non-zero neutrino mass was not foreseen.

The **introduction of quarks as fundamental constituents of matter**, and their description by the theory of **quantum chromodynamics**, extended the electroweak theory to the ***Standard Model of elementary particles***.

In this model, the masses of elementary particles cannot be calculated a priori. Therefore, small non-zero neutrino masses should not represent a real problem for the standard model, especially since it contains 25 free parameters that have to be determined by experimental information. However, three neutrino generations with non-zero mass would add another 7 parameters (three for the masses and four mixing parameters). It is generally believed that the standard model is not complete.

Start of the Satellite Era

In 1998 the Super-Kamiokande **experiment found evidence for a non-zero neutrino mass by studying the relative abundances of atmospheric electron and muon neutrinos.** The observed deficit of atmospheric muon neutrinos is explained by the assumption that neutrinos oscillate from one lepton flavour to another ($\nu_\mu \rightarrow \nu_\tau$). This is only possible if neutrinos have mass.

The **oscillation scenario for solar neutrinos was confirmed in 2001** by the SNO (Sudbury Neutrino Observatory) experiment by showing that the total flavour-independent neutrino flux from the Sun arriving at Earth (νe , $\nu\mu$, $\nu\tau$) was consistent with solar-model expectations. This observation finally solved the solar neutrino problem.

The **idea of mixing was already known from the quark sector,** where the d, s, and b couple as mixed states in **weak interactions**.

How is this relevant for the weak interaction?

What is the Kobayashi-Maskawa matrix?

The **discovery of charmed mesons in cosmic rays** (Niu et al. 1971) and the confirmation, by accelerator experiments, for the existence of a fourth quark extended the standard model of Gell-Mann and Zweig to four quarks (up, down, strange, and charm).

Start of the Satellite Era

The theory of general relativity and Schwarzschild's ideas on the **formation of gravitational singularities** were supported in 1970 by precise investigations of the strong **X-ray source Cygnus X1**. Optical observations of Cygnus X1 indicated that this compact X-ray source is **ten times more massive than our Sun**. The **rapid variation in the intensity of X rays from this object leads to the conclusion that this source only has a diameter of about 10 km**. A typical neutron star has a similar diameter to this, but is only three times as heavy as the Sun. An object that was as massive as Cygnus X1 would experience such a large gravitational contraction, which would overcome the Fermi pressure of degenerate neutrons. This leads to the conclusion that **a black hole must reside at the center of Cygnus X1.**

By 1974, Hawking had already managed to unify some aspects of the theory of general relativity and quantum physics. He was able to show that **black holes could evaporate** by producing fermion pairs from the gravitational energy outside the event horizon. If one of the fermions escaped from the black hole, its total energy and thereby its mass would be decreased (***Hawking radiation***). The time constants for the evaporation process of massive black holes, however, exceed the age of the universe by many orders of magnitude.

There were some hopes that gravitational waves, which would be measured on Earth, could resolve questions on the formation of black holes.

Start of the Satellite Era

Taylor and Hulse succeeded in providing **indirect evidence for the emission of gravitational waves** in 1974, by observing a **binary system that consisted of a pulsar and a neutron star**. They were able to precisely test the predictions of general relativity. The decreasing orbital period of the binary is directly related to the energy loss by the emission of gravitational radiation.

A breakthrough was achieved by the **direct discovery of gravitational waves by the LIGO** (Advanced Laser Interferometer Gravitational Wave Observatory) telescope in 2015. LIGO had observed three events of **mergers of heavy black holes** in two independent Michelson interferometers about 3000 km apart.

The discovery of g***amma-ray bursters*** **(GRB)** in 1967. It came as a surprise when gamma-ray detectors on board military reconnaissance satellites, observed γ bursts from space. Gamma-ray bursters light up only once and are mostly short-lived, with **burst durations lasting from 10 ms to a few seconds.** There is also a component of bursts with relatively long duration. It is conceivable that γ bursts are caused by **supernova explosions or by collisions between neutron stars.**

Contributions of Accelerators to Cosmic Rays

It might appear that the elementary-particle aspect of astroparticle physics has been completed by the discovery of the *b* quark (Lederman 1977) and *t* quark (CDF collaboration 1995). There are now six known leptons (ν_e, e^-; ν_μ, μ^-; ν_τ, τ^-) along with their antiparticles ($\bar{\nu}_e$, e^+; $\bar{\nu}_\mu$, μ^+; $\bar{\nu}_\tau$, τ^+). These are accompanied by six quarks (up, down; charm, strange; top, bottom) and their corresponding six antiquarks.

These matter particles can be arranged in three families or '**generations**'. **Measurements of the primordial deuterium, helium, and lithium abundance in astrophysics** had already given some indication that there may be **only three families** with light neutrinos. This astrophysical result was later confirmed beyond any doubt by experiments at the electron–positron collider LEP in 1989.

The standard model of elementary particles, with its three fermion generations, was also verified by the **discovery of gluons**, the carriers of the strong force (DESY, 1979, and the **bosons** of the weak interaction ($W+$,$W-$,Z) at CERN in 1983).

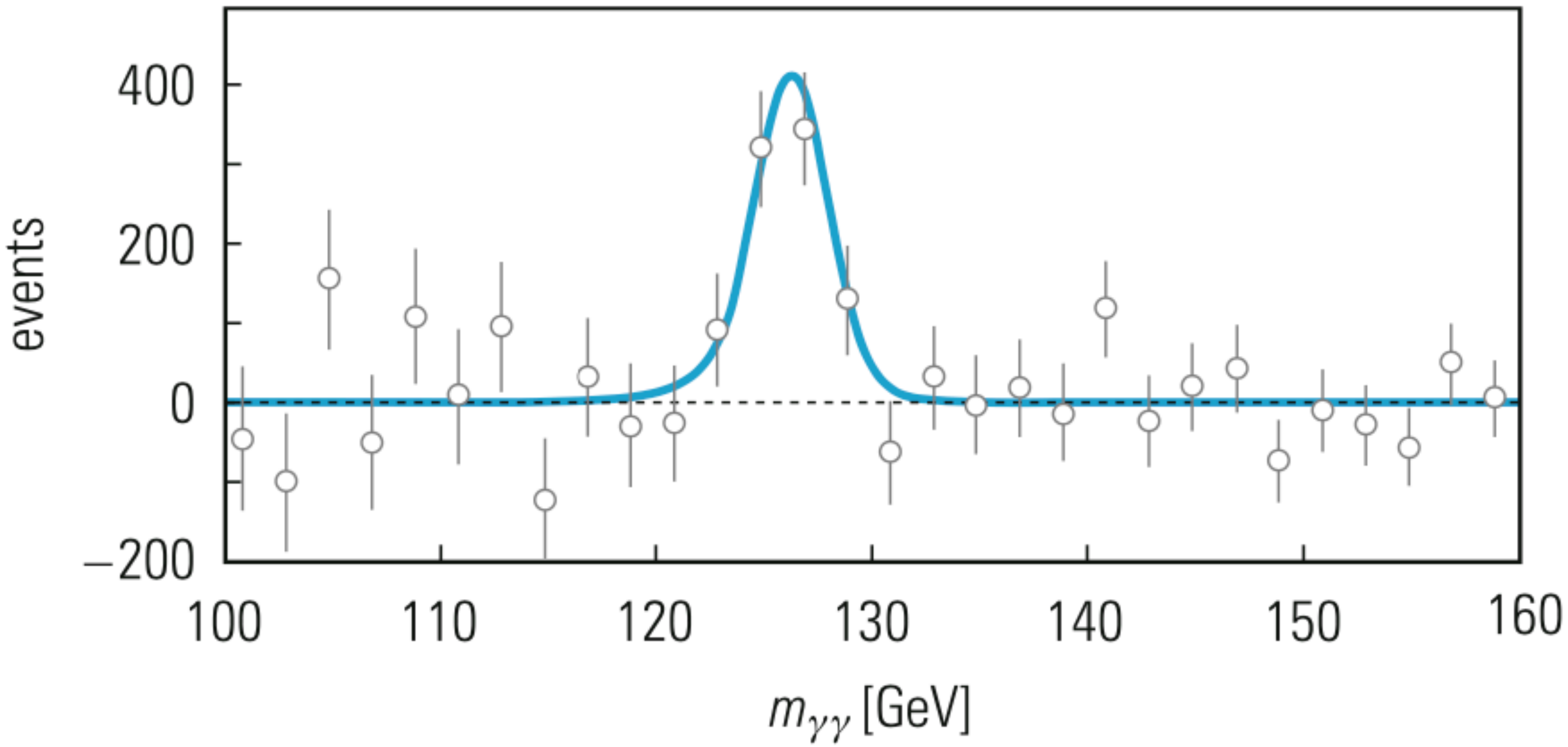
The discovery of **asymptotic freedom of quarks** in the theory of the strong interaction by Gross, Politzer, and Wilczek.

What is the asymptotic freedom?

Contributions of Accelerators to Cosmic Rays

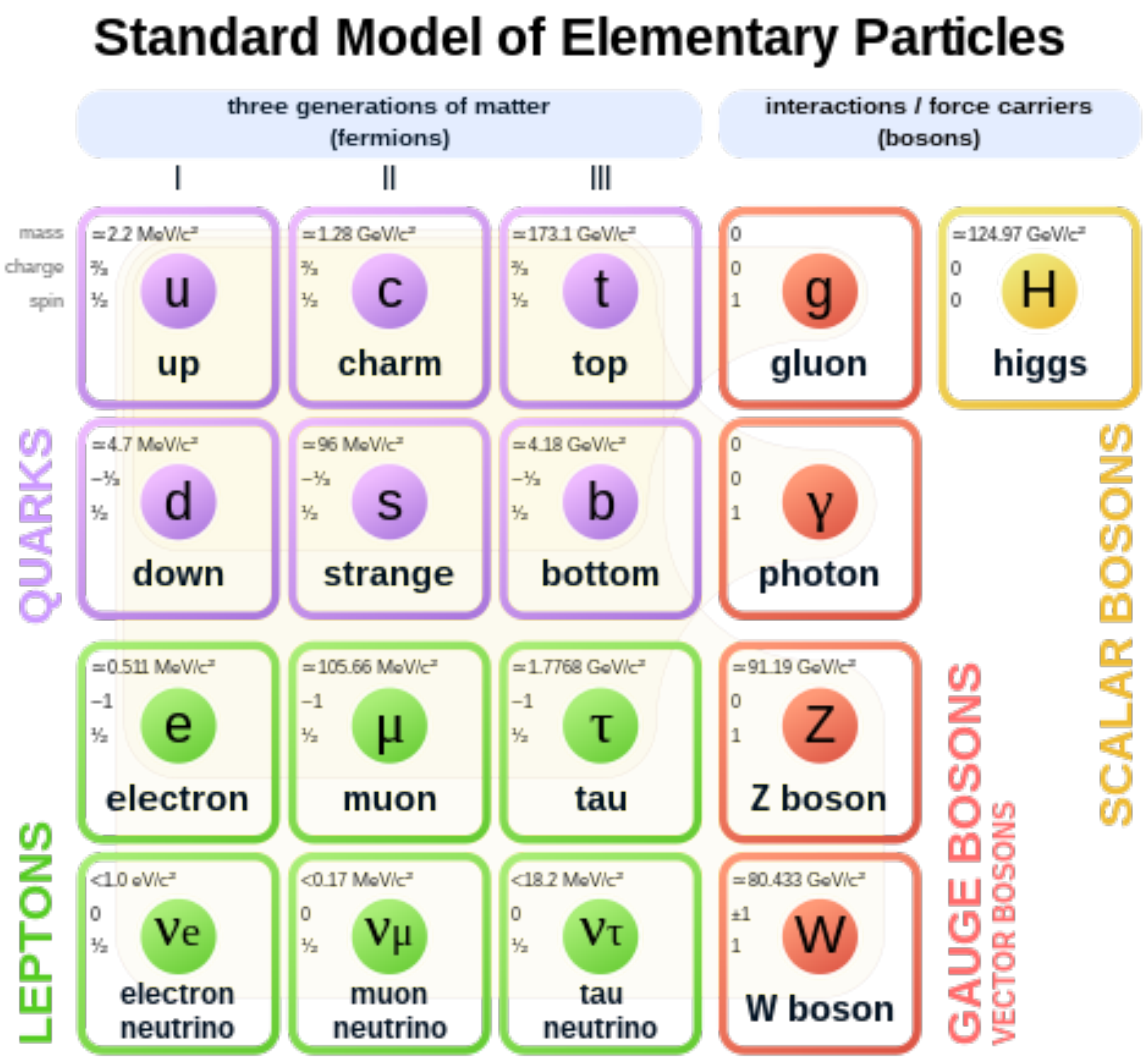
In the standard model of electroweak and strong interactions, the mass generation is believed to come about by a *spontaneous symmetry breaking*, the so-called Higgs mechanism. This process favours the existence of at least one additional massive neutral boson. The Higgs particle providing masses for the fundamental fermions was found at the Large Hadron Collider (LHC) at CERN in 2012.

Fig. 1.23 Invariant $\gamma\gamma$ mass distribution showing the production of the Higgs boson in the mass range around 125 GeV/c^2. The background-subtracted results are from the ATLAS experiment at the LHC [22]



Contributions of Accelerators to Cosmic Rays

- Particles interact via four forces of nature:
  - **strong interaction**, which binds the quarks together into hadrons;
  - **the electromagnetic interaction** between the charged leptons and quarks;
  - **the weak interaction** responsible for β decay; and
  - **gravity**.

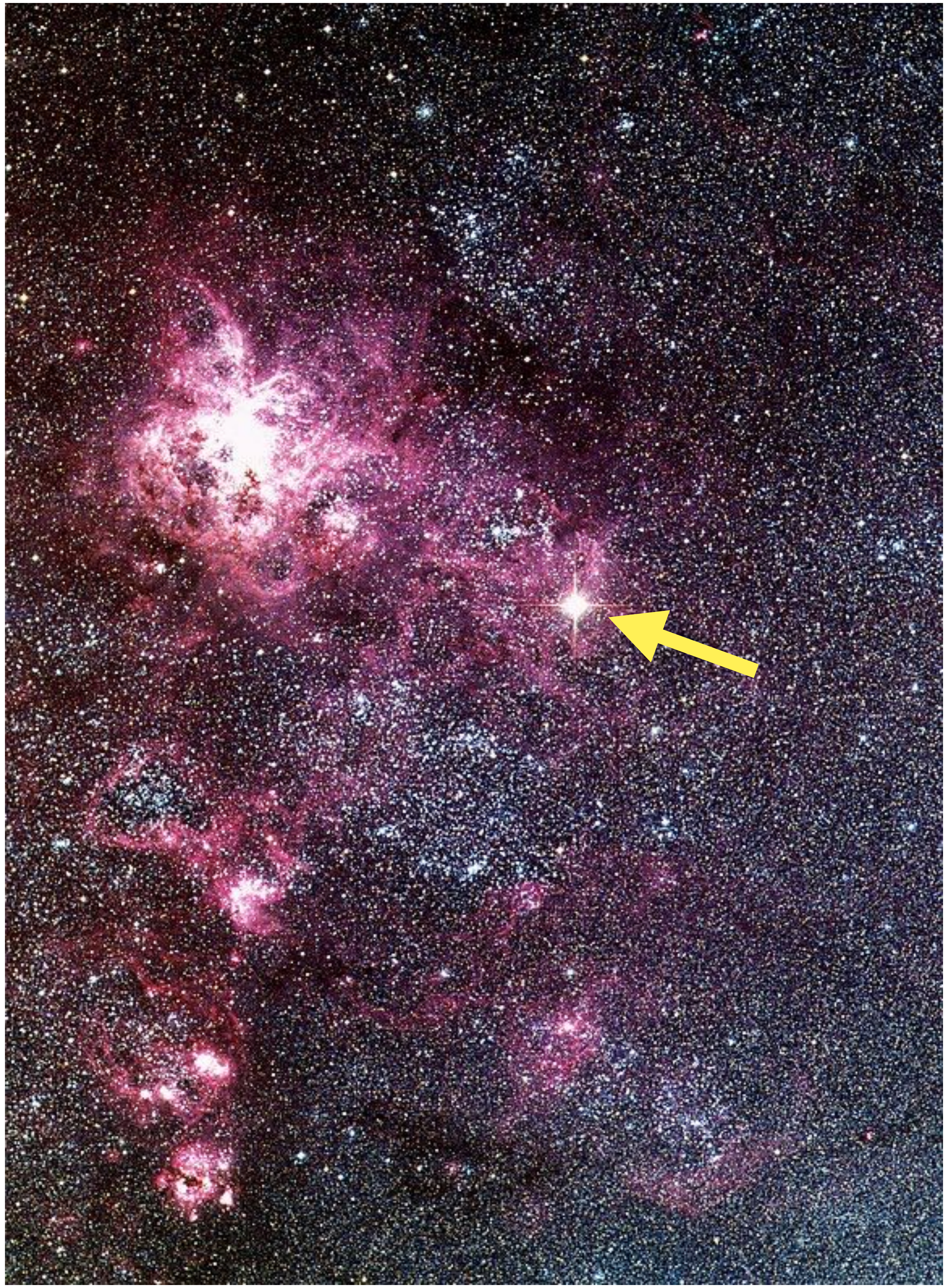


More Cosmic Rays

The observation of the **supernova explosion 1987A**, with the burst of **extragalactic neutrinos**, mad it possible to measure 25 neutrinos out of a possible 10^{58} emitted. This allowed elementary particle physics investigations what was inaccessible in laboratory experiments.

The **dispersion of arrival times** enabled physicists to **derive an upper limit of the neutrino mass** ($m\nu_e < 10$ eV). The mere fact that the neutrino source was 170 000 light-years away in the Large Magellanic Cloud, allowed a **lower limit on the neutrino lifetime to be estimated**.

The **gamma-ray emission** from SN 1987A gave confirmation that **heavy elements up to iron, cobalt, and nickel were synthesized in the explosion**, in agreement with predictions of supernova models. As the first optically visible supernova since the discovery of the telescope, SN 1987A marked an ideal symbiosis of astronomy, astrophysics, and elementary particle physics (Figure).



More Cosmic Rays

The successful launch of the high-resolution **X-ray satellite ROSAT** in 1990 paved the way for the discovery of numerous X-ray sources. The **Hubble telescope**, which was started in the same year, provided optical images of stars and galaxies in hitherto unprecedented quality. The successful mission of ROSAT was followed by the X-ray satellites **Chandra** and XMM-Newton, both launched in 1999. Presently, the launch of the INTEGRAL satellite in 2002 and the start of the **FERMI telescope** (FGST—Fermi Gamma Ray Space Telescope) in 2008 provide also important contributions to the field of **X-ray and gamma astronomy**. **NuSTAR** (Nuclear Spectroscopic Telescope Array), launched in 2012, is a space-based X-ray telescope that uses Wolter telescopes to focus high-energy X rays from astrophysical sources. It covers the energy range from 3 to 79 keV, thereby extending the energy range of earlier space instruments.

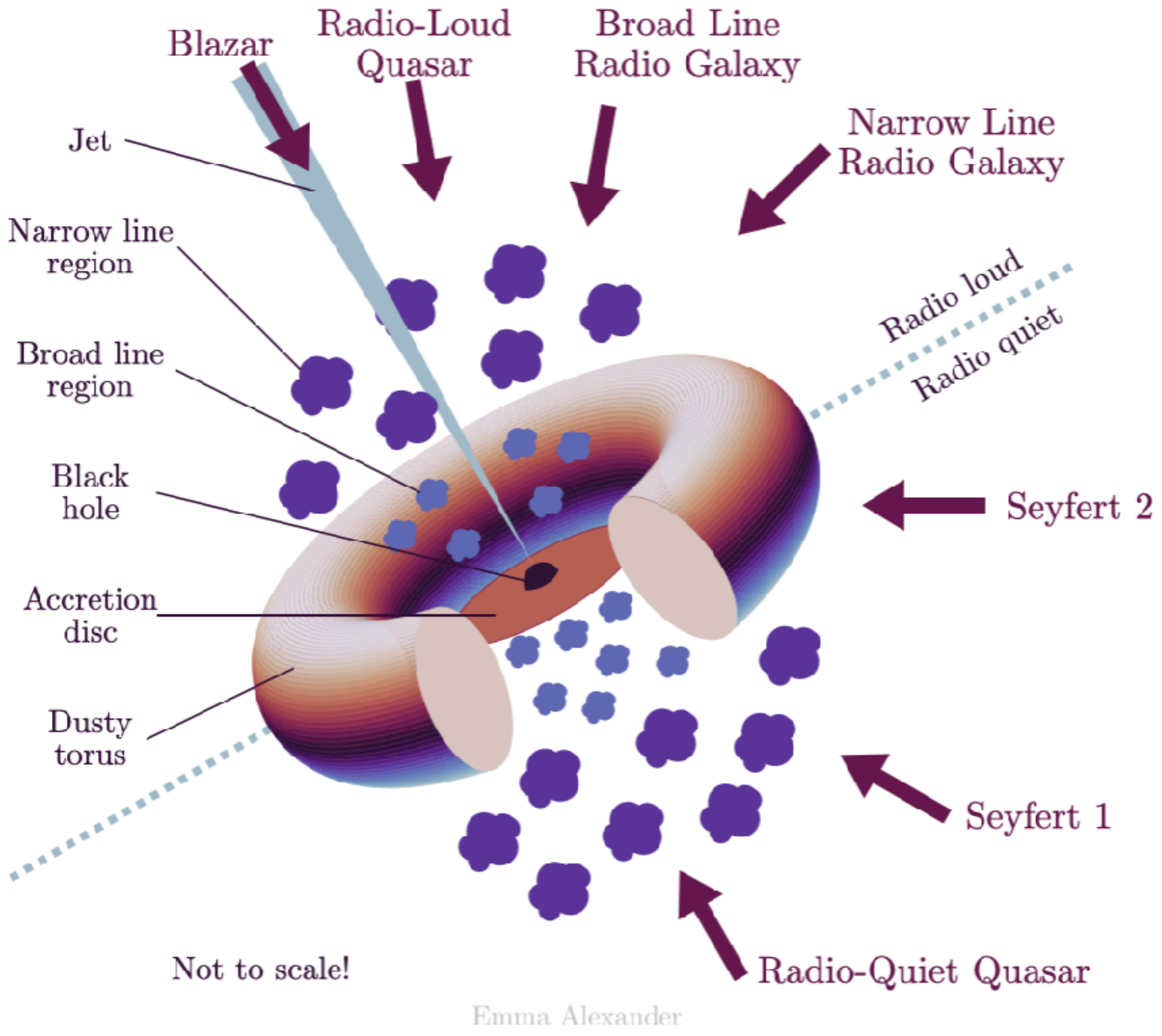
The **Compton Gamma-Ray Observatory** (CGRO, launched in 1991) opened the door for **GeV gamma astronomy**. The earthbound **atmospheric air Cherenkov telescopes (H.E.S.S.**, see also Fig. 1.25) and **MAGIC** (Major Atmospheric Gamma Imaging Cherenkov Telescopes) and other **air-shower experiments** were able to search for and identify **TeV point sources in our Milky Way** (e.g., Crab Nebula) and in **extragalactic distances** (1992, Markarian 501, Markarian 421). The active galactic nuclei of the Markarian galaxies are also considered excellent candidate sources of high-energy hadronic charged cosmic rays.

What are active galactic nuclei (AGN)?

The unified model of AGN

Active Galactic Nuclei (AGN) are supermassive black holes in the centres of galaxies that are actively accreting material and produce high energy phenomena.

Unified model of AGN adapted from Urry & Padovani (1995). The thick arrows represent different viewing angles, and the observed object which results from them. Note the asymmetry of the diagram; this is to demonstrate the two different possibilities of radio loud/quiet and is not representative of a single object.

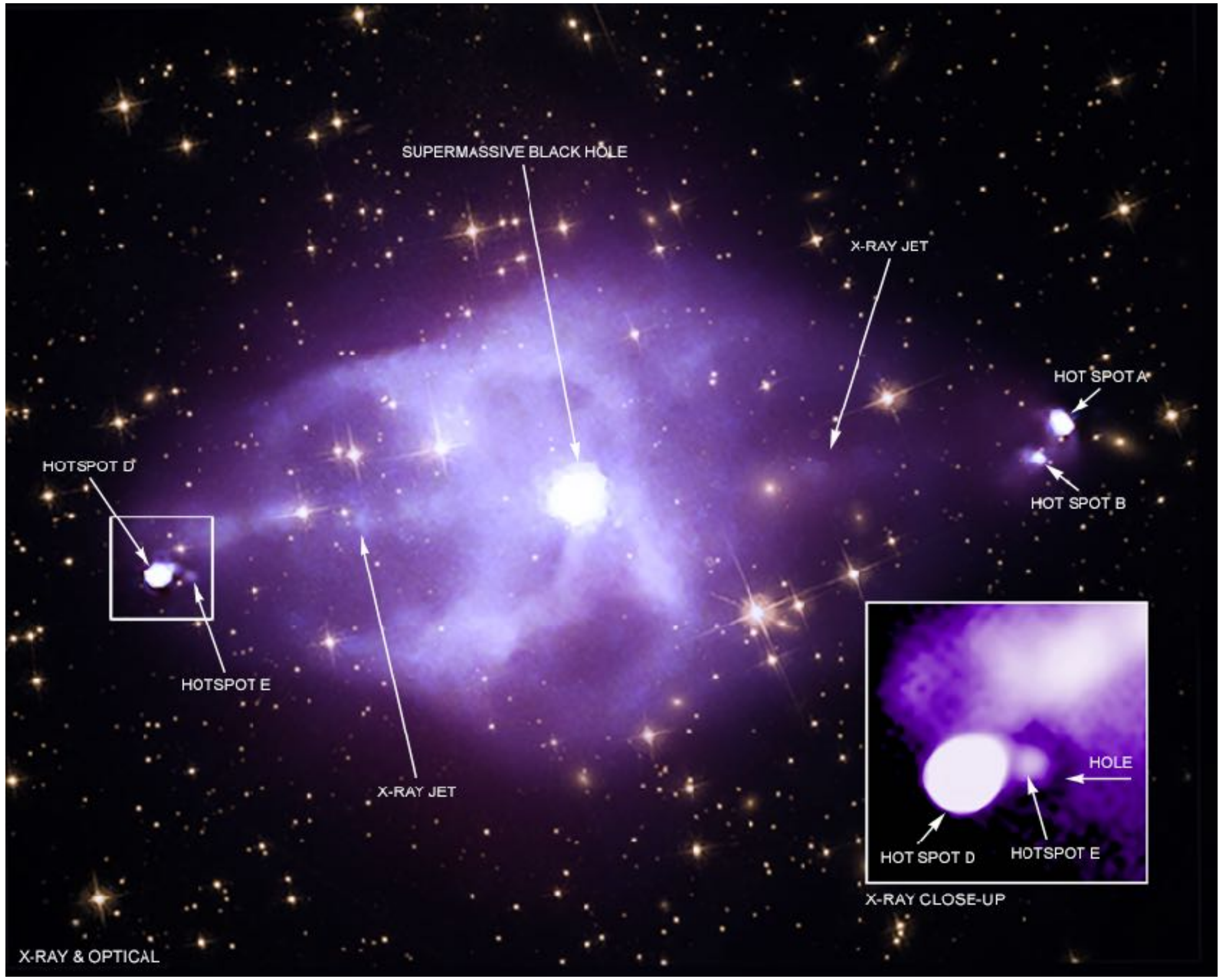


AGN

Examples:

Cyg A in radio + optical

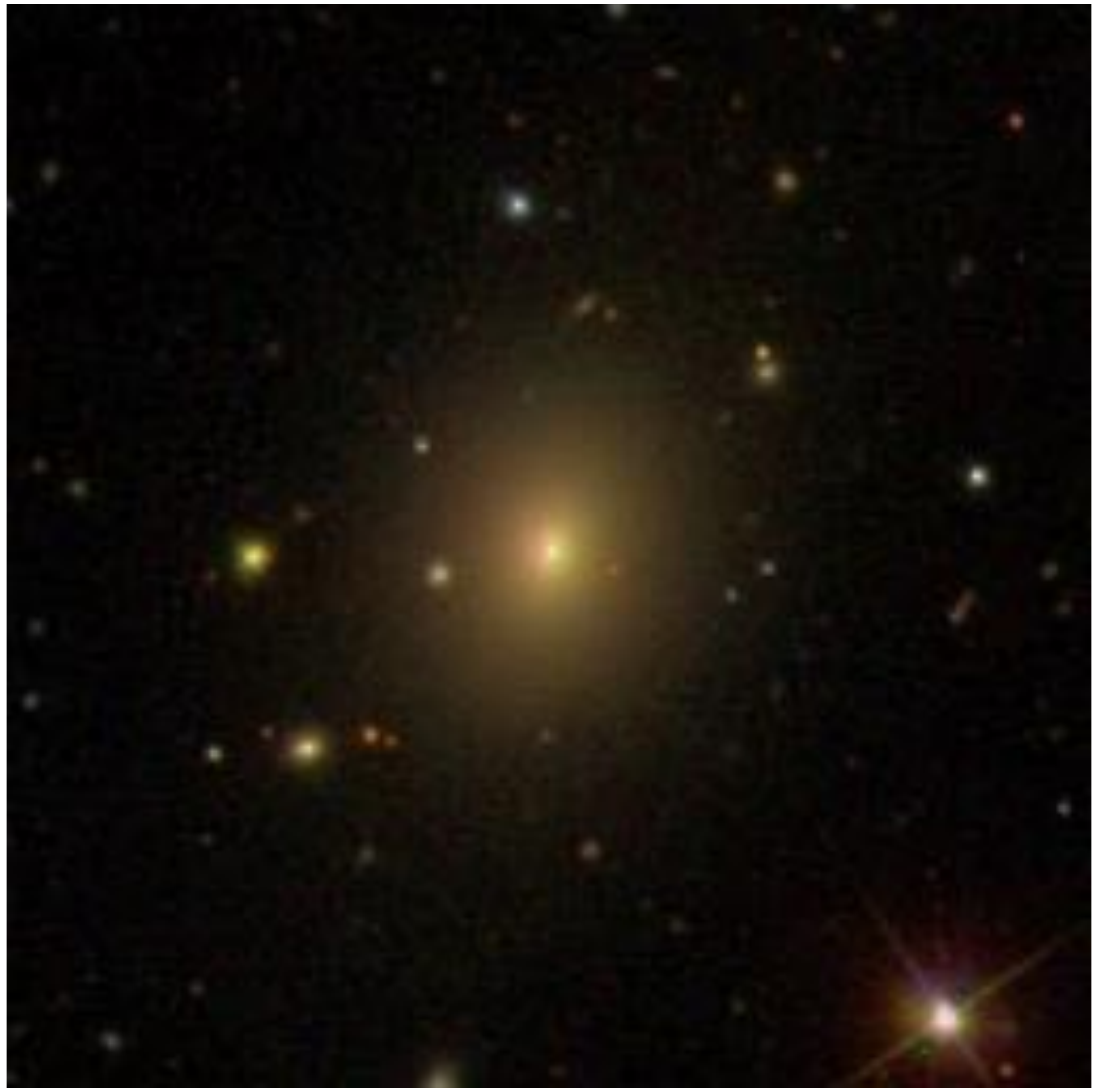
Cyg A in X-rays



AGN

Examples:

Markarian 501



Markarian 421

The unified model of AGN

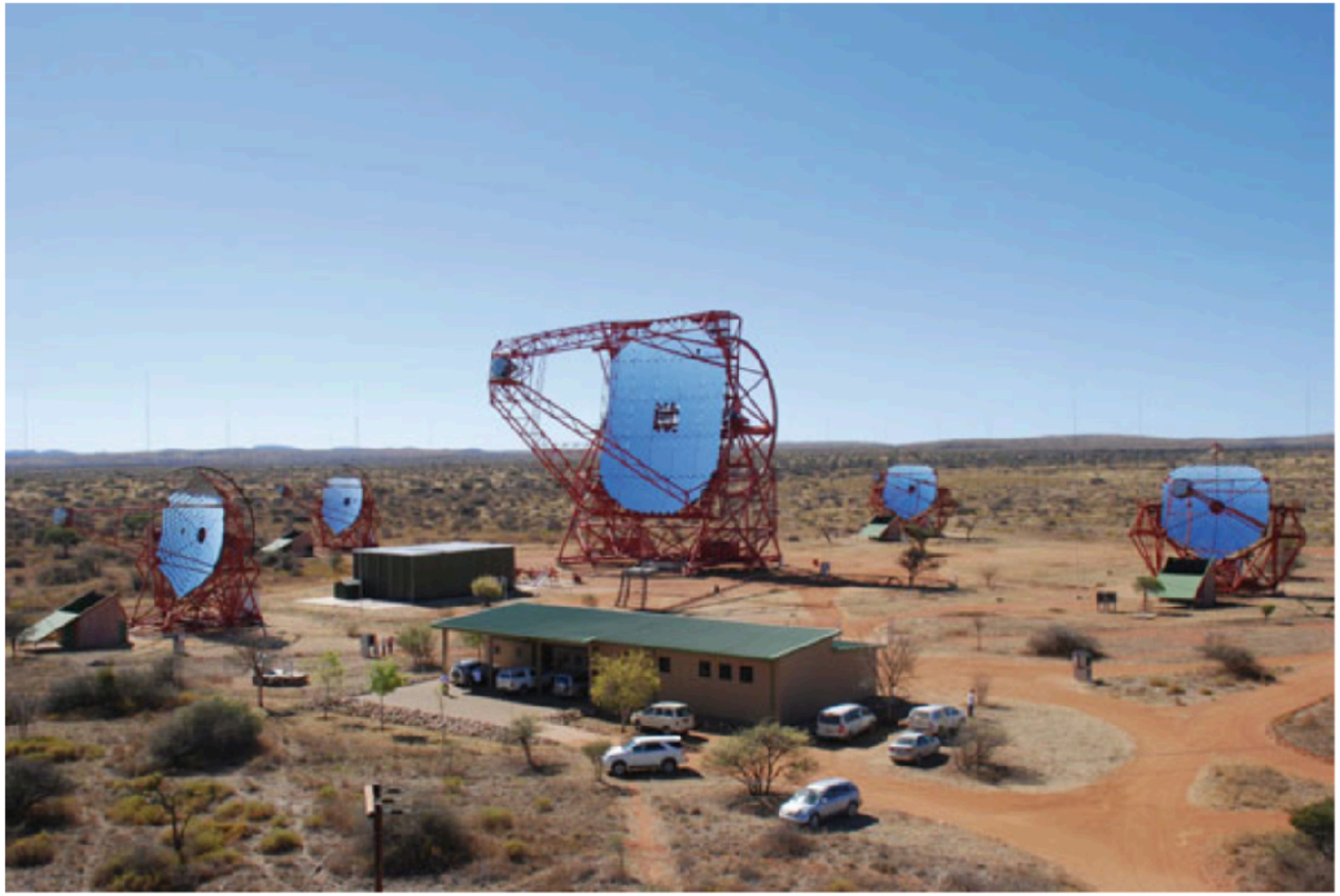


Fig. 1.25 The H.E.S.S. Cherenkov telescope array in Namibia for the measurement of high-energy gamma rays (H.E.S.S. = High Energy Stereoscopic System) [24]

Open Questions

A still unsolved question of astroparticle physics is the problem of ***dark matter* and *dark energy*.** From the observation of orbital velocities of stars in our Milky Way and the velocities of galaxies in galactic clusters, it is clear that **the energy density of the visible matter in the universe is insufficient to correctly describe its dynamics** (Fig. 1.26).

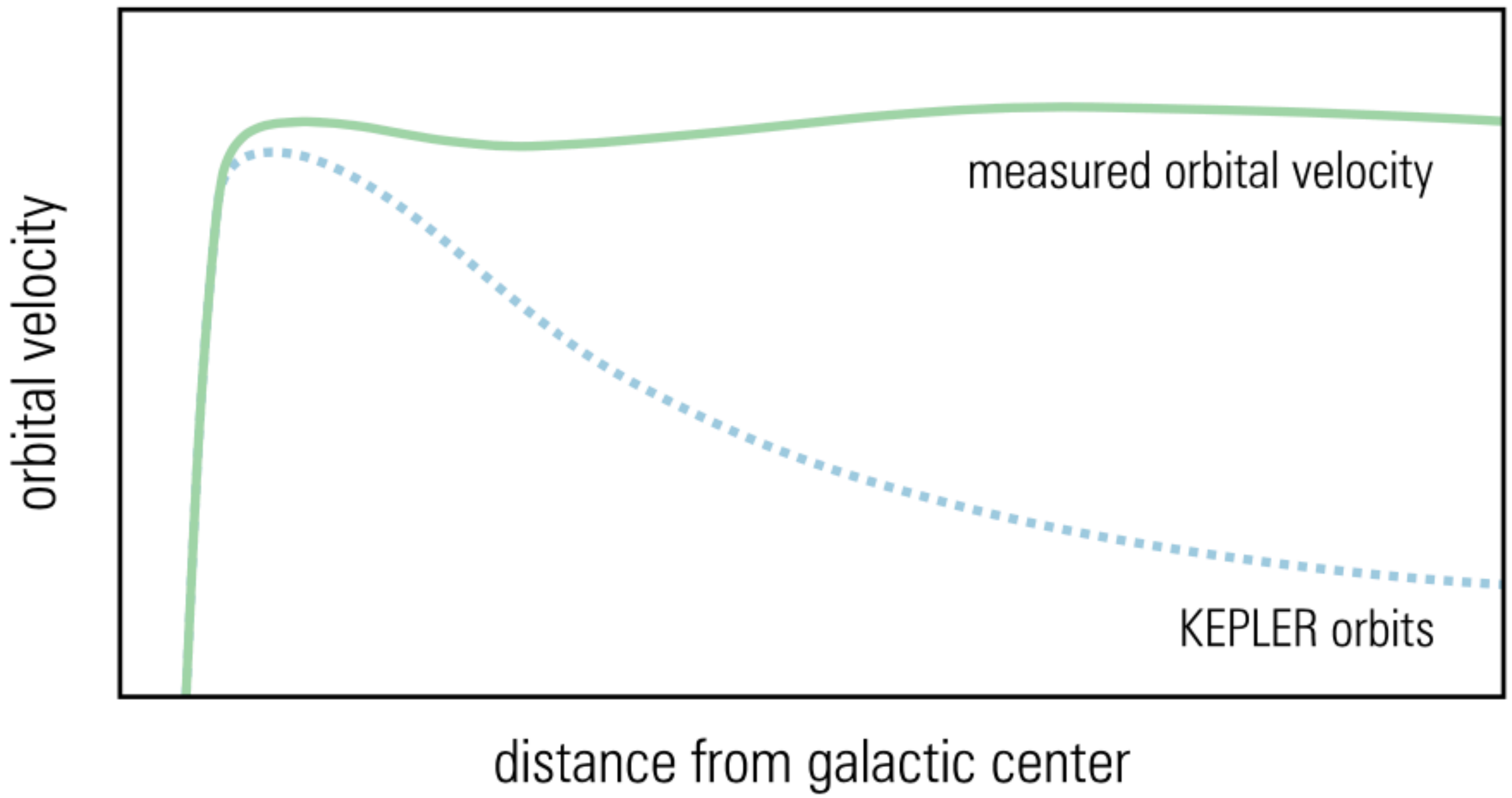


Fig. 1.26 Sketch of typically measured rotational star velocities in galaxies in comparison to expectations based on Keplerian orbits

Open Questions

Since the early nineties, the MACHO (search for MAssive Compact Halo Objects) and EROS (Expérience pour la Recherche d'Objets Sombres) experiments have searched for **compact, non-luminous, Jupiter-like objects in the halo of our Milky Way**, using the technique of microlensing. Some candidates have been found, but their number is nowhere near sufficient to explain the missing dark matter in the universe. One can conjecture that **exotic, currently unknown particles** (supersymmetric particles, WIMPs (Weakly Interacting Massive Particles), ...), **or massive neutrinos may contribute** to solve the problem of the missing dark matter.

A non-vanishing **vacuum energy density** of the universe is also known to play a decisive role in the dynamics and evolution of the universe. The idea of a vacuum energy had already been introduced in 1915 by Einstein in the form of a cosmological constant Λ.

The neutrinos clearly have some mass. The presently favoured mass of 0.05 eV for ν_τ , however, is **insufficient to explain the dynamics of the universe alone**.

Open Questions

A very important **unsolved problem in cosmology is the dominance of matter**.

It is true that *CP*-violating effects are known from particle physics. However, the size of the effect is **insufficient to explain the disappearance of antimatter.** Results from the satellite PAMELA and the AMS experiment on board the space station ISS do find an increase in the positron production at high energies, but these positrons could have also been produced in supernova explosions, neutron stars, quasars, or active galactic nuclei. It has been argued that the dominance of matter over antimatter **may originate from the fact that neutrinos and antineutrinos behave possibly in a different way in neutrino oscillations.** The search for antiparticles in primary cosmic rays and the theoretical understanding of a possible strong matter–antimatter-asymmetric effect is still an important aspect in particle physics and astronomy.

An equally exciting discovery is the **measurement of the acceleration parameter of the universe**. Based on the ideas of the classical Big Bang, **one would assume that** the initial expansion would be **slowed down by gravitation**. Observations on distant supernova explosions, however, indicate that in early cosmological epochs the rate of expansion was smaller than today. The finding of an ***accelerating universe***—which is now generally accepted—has important implications for cosmology. It **suggests that the largest part of the missing substance of the universe is stored as dark energy in a dynamical vacuum**.

Open Questions

Finally, it should be highlighted that the discovery of ***extrasolar planets*** (Mayor and Queloz 1995) has led to the resumption of discussions on the **existence of extraterrestrial intelligence**. Until now about 4000 extrasolar planets have been discovered. Among those there are more than 500 systems with two up to seven planets (status 2018). It is estimated that there might be millions of planets with **habitable zones** in the Milky Way.

The object Kepler-452b found in 2015 is an Earth-like planet in the habitable zone of its parent star. It looks as if it is a rocky planet like our Earth. The associated star is in the constellation Cygnus at a distance of 1400 light-years.

One of the planets closest to Earth is orbiting the star Epsilon Eridani. It is also in the habitable zone of its star. Its distance from Earth is only 10 light-years.

Even closer is **Proxima Centauri b** orbiting the 4.2-light-years-distant dwarf star Proxima Centauri in 11.2 days in a **habitable zone**.