Special Topics in Particle Physics

Primary Cosmic Rays

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Primary Cosmic Rays

Cosmic rays provide important information about high-energy processes occurring in our galaxy and beyond. Cosmic radiation **produced in the sources is usually called *primordial cosmic rays*.**

This radiation is **modified during its propagation** in galactic and extragalactic space. Particles of galactic origin pass on average through a **column density of 6 g/cm^2 before reaching the top of the Earth**'s atmosphere.

Of course, the atmosphere does not really have a 'top' but it rather exhibits an exponential density distribution. It has become common practice to understand under the **top of the atmosphere an altitude of approximately 40 km**. This height corresponds to a residual column density of 5 g/cm^{2}corresponding to a pressure of 5 mbar due to the residual atmosphere above altitudes of 40km. **Cosmic rays arriving at the Earth's atmosphere are usually called *primary cosmic rays*.**

Sources of cosmic rays accelerate predominantly **charged particles such as protons and electrons**. Since all elements of the periodic table are produced during element formation, **nuclei as helium, lithium, and so on can be also accelerated.**

Cosmic rays represent an **extraterrestrial or even extragalactic matter sample** whose chemical composition exhibits certain **features similar to the elemental abundance in our solar system.**

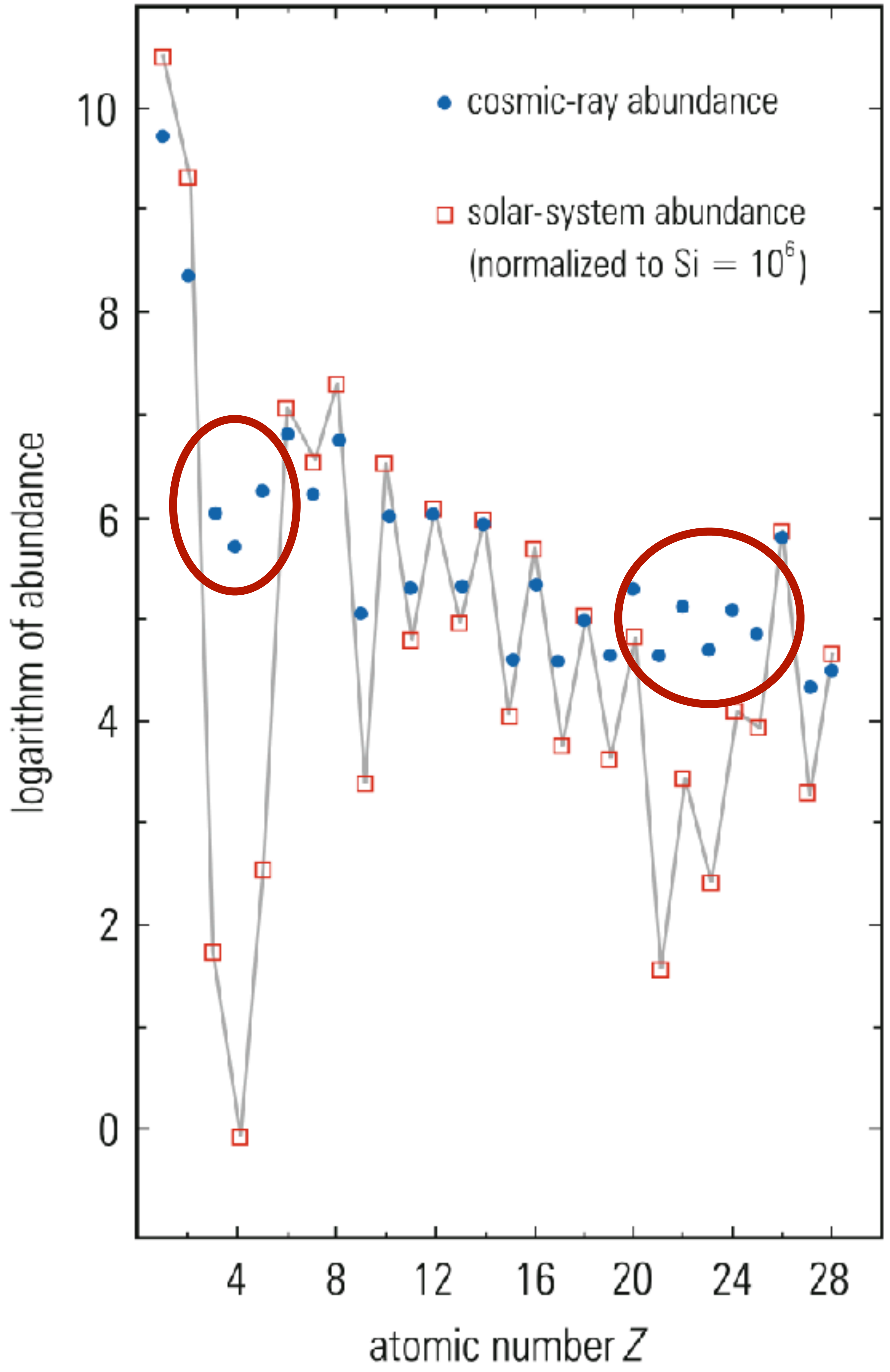
Primary Cosmic Rays

Charged cosmic rays accelerated in sources **can produce a number of secondary particles by interactions in the sources themselves.**

These mostly **unstable secondary particles**, i.e., **pions and kaons, produce stable particles in their decay,** i.e., photons from $\pi^0 \rightarrow \gamma + \gamma$ and neutrinos from $\pi^+ \rightarrow \mu^+ + \nu_\mu$ decays. Secondary particles also emerge from the sources and **can reach Earth**. Let us first discuss the originally accelerated charged component of primary cosmic rays.

Charged primary cosmic rays

Fig. 6.1 Elemental abundance of primary cosmic rays for $1 \leq Z \leq 28$



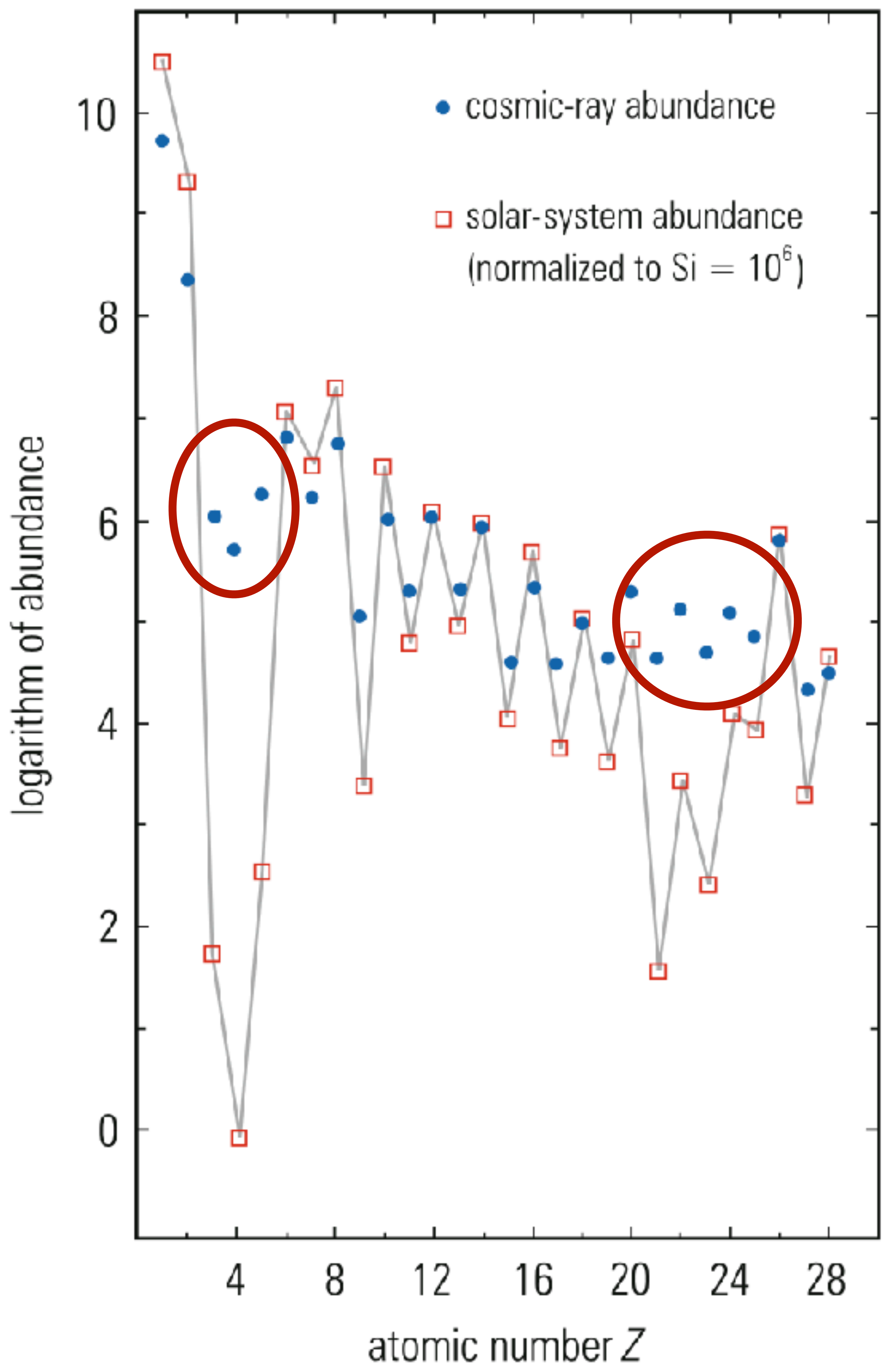
The elemental abundance of primary cosmic rays is shown in Figs. 6.1 and 6.2 in comparison to the chemical composition of the solar system. **Protons are the dominant particle** species (≈85%) **followed by α particles** (≈12%). Elements with a nuclear charge $Z \geq 3$ **represent only a 3% fraction** of charged primary cosmic rays.

The chemical composition of the solar system, shown in Figs. 6.1 and 6.2, has **many features in common** with that of cosmic rays.

What about the discrepancies?

Charged primary cosmic rays

Fig. 6.1 Elemental abundance of primary cosmic rays for $1 \leq Z \leq 28$



What about the discrepancies?

However, remarkable **differences are observed for lithium, beryllium, and boron** ($Z = 3$–5), **and for the elements below the iron group** ($Z < 26$).

The **larger abundance of Li, Be, and B** in cosmic rays can easily be understood by **fragmentation of the heavier nuclei** carbon ($Z = 6$) and, in particular, oxygen ($Z = 8$) in galactic matter on their way from the source to Earth.

Charged primary cosmic rays

In the **same way the fragmentation** or spallation **of the relatively abundant element iron** populates elements below the iron group.

The general trend of the dependence of the chemical composition of primary cosmic rays on the atomic number can be understood by **nuclear physics arguments.** In the framework of the **shell model** it is easily explained that **nuclear configurations with even proton and neutron numbers (even–even nuclei - ee) are more abundant compared to nuclei with odd proton and neutron numbers (odd–odd nuclei - oo).**

As far as stability is concerned, even–odd and odd–even nuclei are associated with abundances between ee and oo configurations.

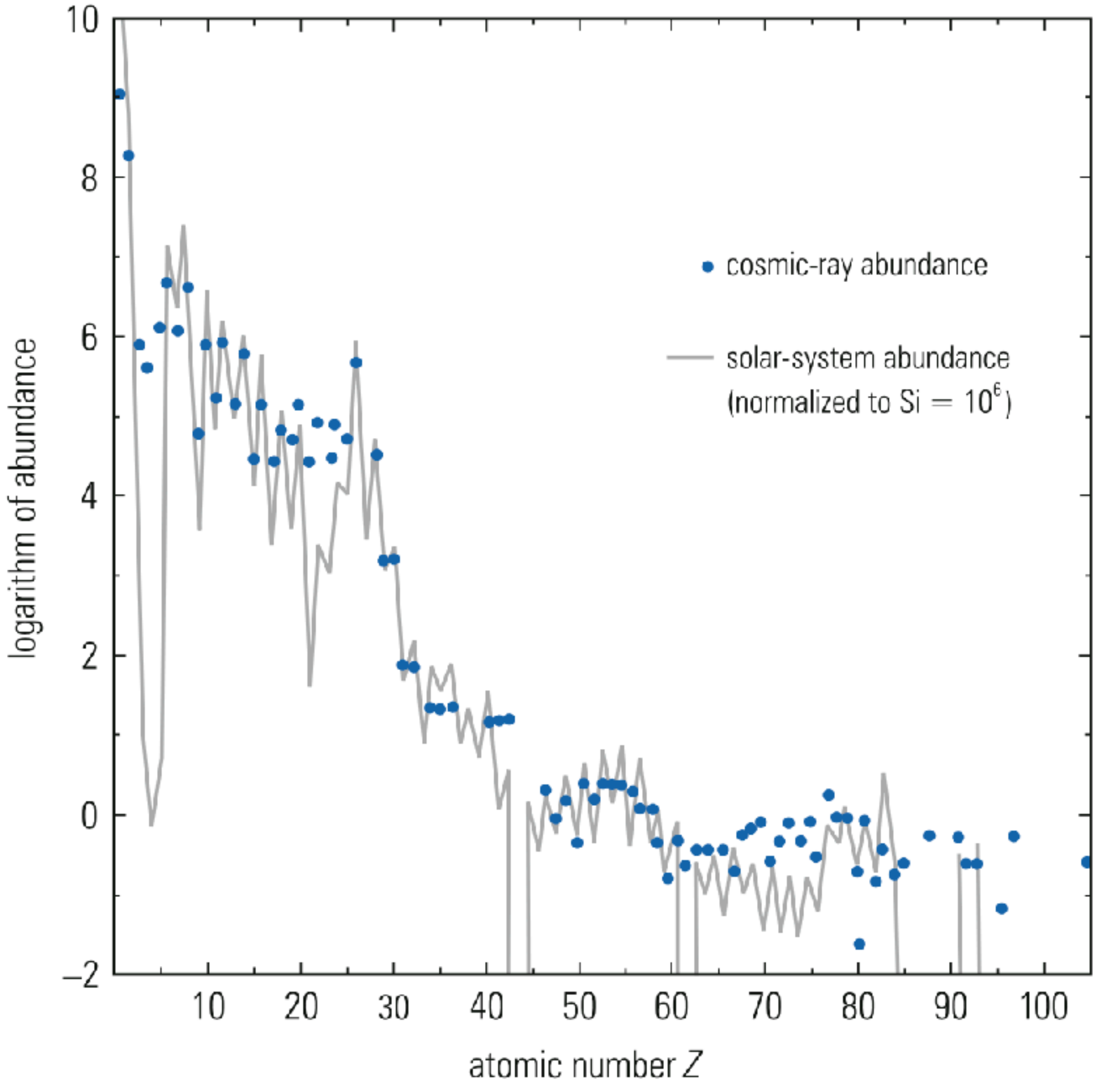


Fig. 6.2 Elemental abundance of primary cosmic rays for $1 \leq Z \leq 100$

Charged primary cosmic rays

Extremely stable nuclei occur for filled shells ('magic nuclei'), where the **magic numbers** (2, 8, 20, 50, 82, 126) refer separately to protons and neutrons.

As a consequence, **doubly magic nuclei (like helium and oxygen) are particularly stable and correspondingly abundant.**

But **nuclei with a large binding energy such as iron,** which can be produced in fusion processes, **are also relatively abundant in charged primary cosmic rays.**

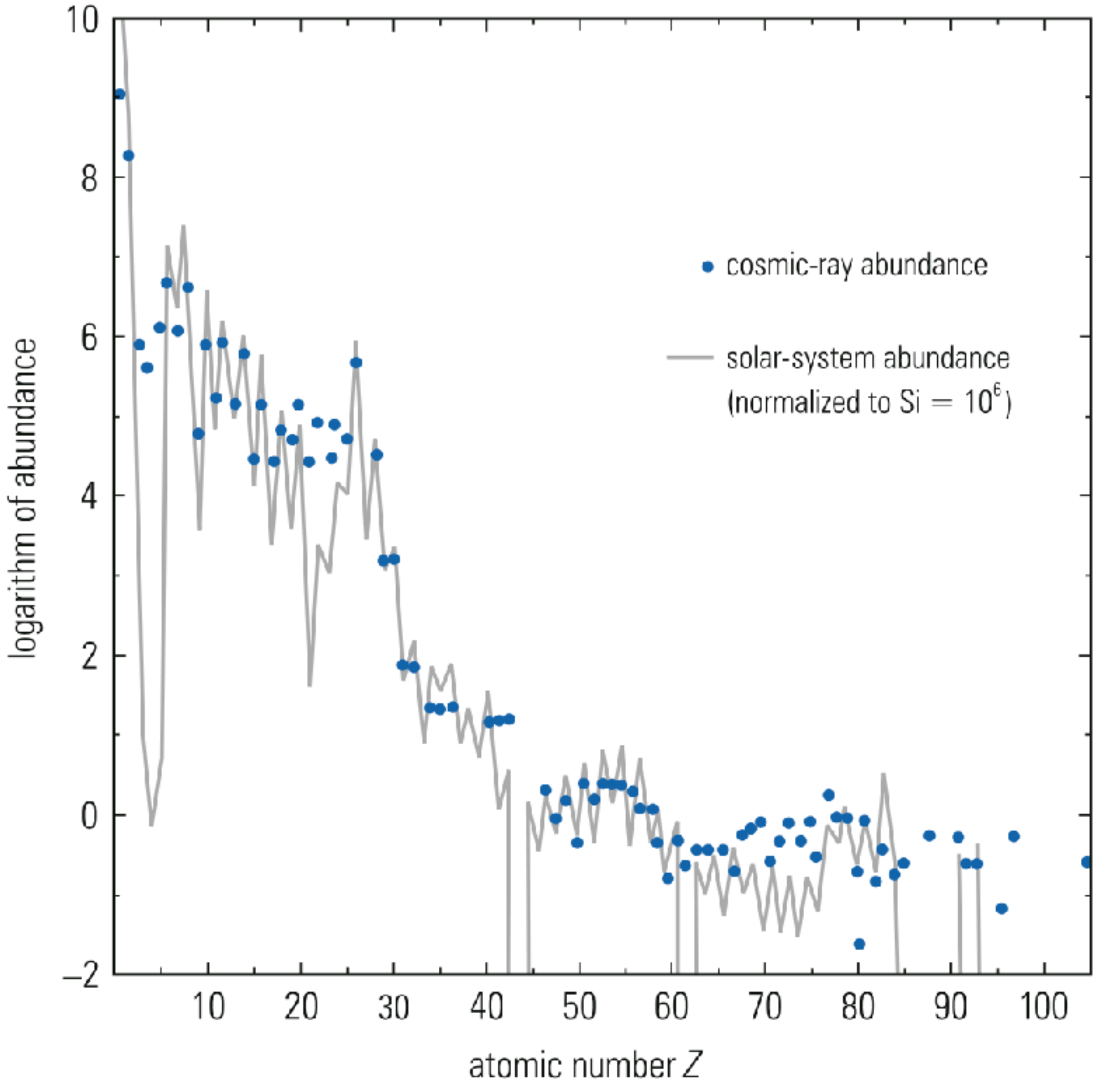


Fig. 6.2 Elemental abundance of primary cosmic rays for $1 \leq Z \leq 100$

Charged primary cosmic rays

The **energy spectra of primary nuclei** of hydrogen, helium, carbon, and iron are shown in Fig. 6.3 for a particular epoch of the solar cycle.

The low-energy part of the primary spectrum is modified by the Sun's and the Earth's magnetic field. The 11-year period of the sunspot cycle modulates the intensity of low-energy primary cosmic rays (<1 GeV/ nucleon).

The **active Sun reduces the cosmic-ray intensity** because **a stronger magnetic field** created by the Sun prevents galactic charged particles from reaching Earth.

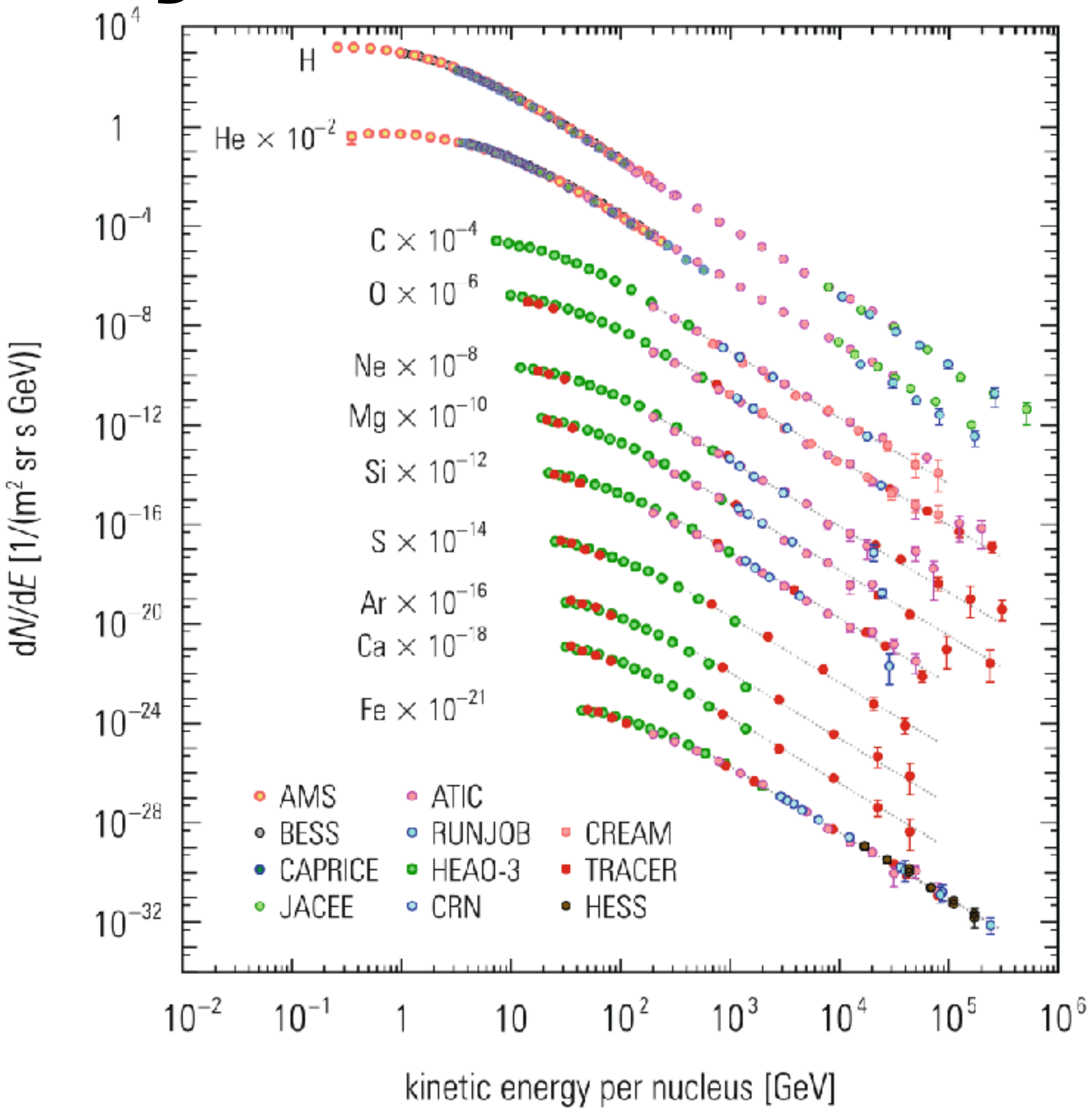
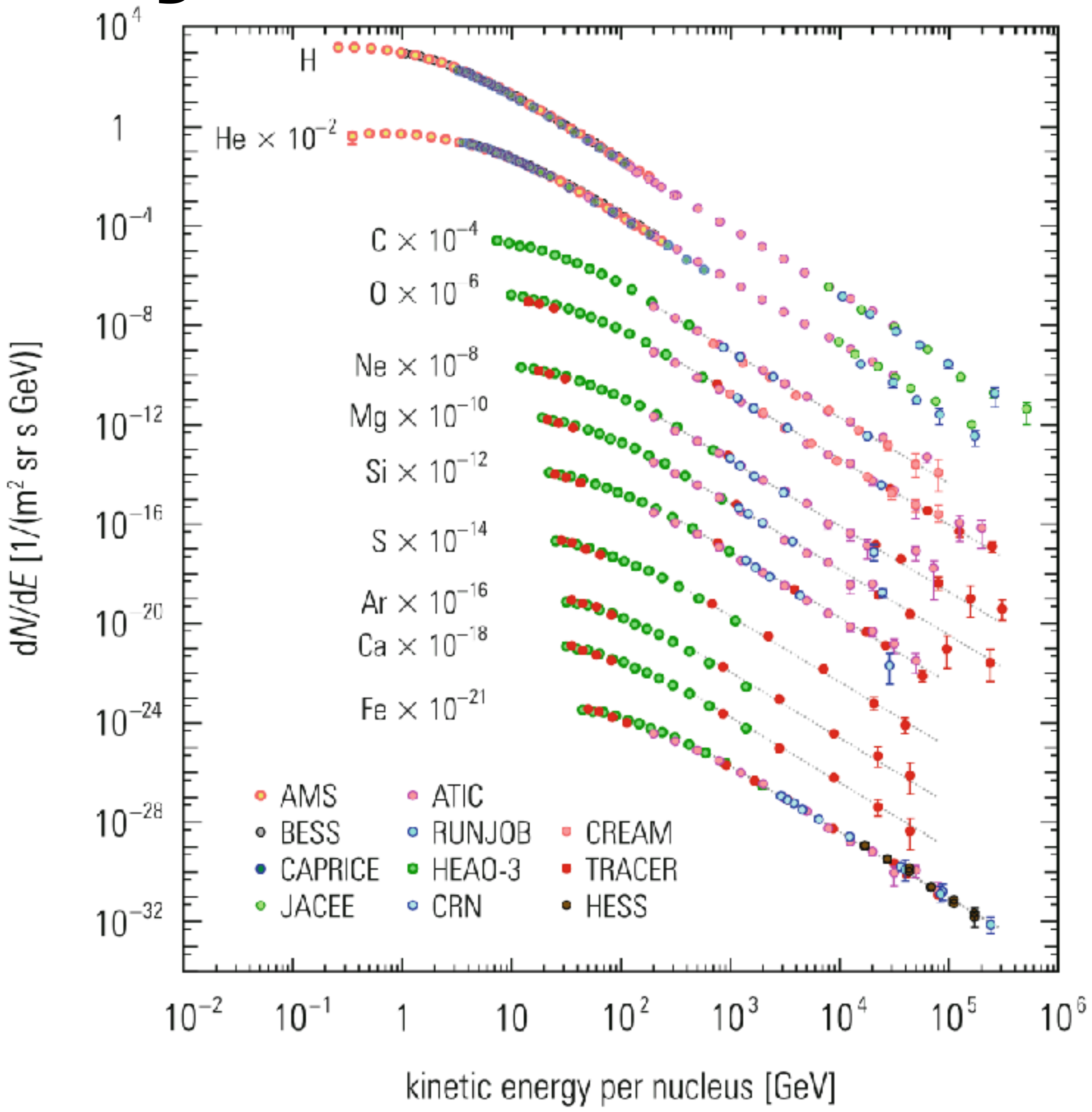


Fig. 6.3 Energy spectra of the main components of primary cosmic rays from direct measurements. The various data have been obtained from balloon measurements, from satellites, and an experiment at the International Space Station ISS [52]

Charged primary cosmic rays

In general, the **intensity decreases with increasing energy** so that a direct observation of the high-energy component of cosmic rays at the top of the atmosphere with balloons or satellites eventually runs out of statistics.

Measurements of the charged component of primary cosmic rays at energies in excess of **several hundred GeV must therefore resort to indirect methods.** The **atmospheric air Cherenkov technique** or the measurement of **extensive air showers via air fluorescence** or particle sampling **can in principle cover this part of the energy spectrum**, however, a **determination of the chemical composition** of primary cosmic rays by this indirect technique is **particularly difficult**.



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Charged primary cosmic rays

Furthermore, the particle intensities at these high energies are extremely low. For particles with energies in excess of about 10^{19}eV the rate is only 1 particle per km^2 and year.

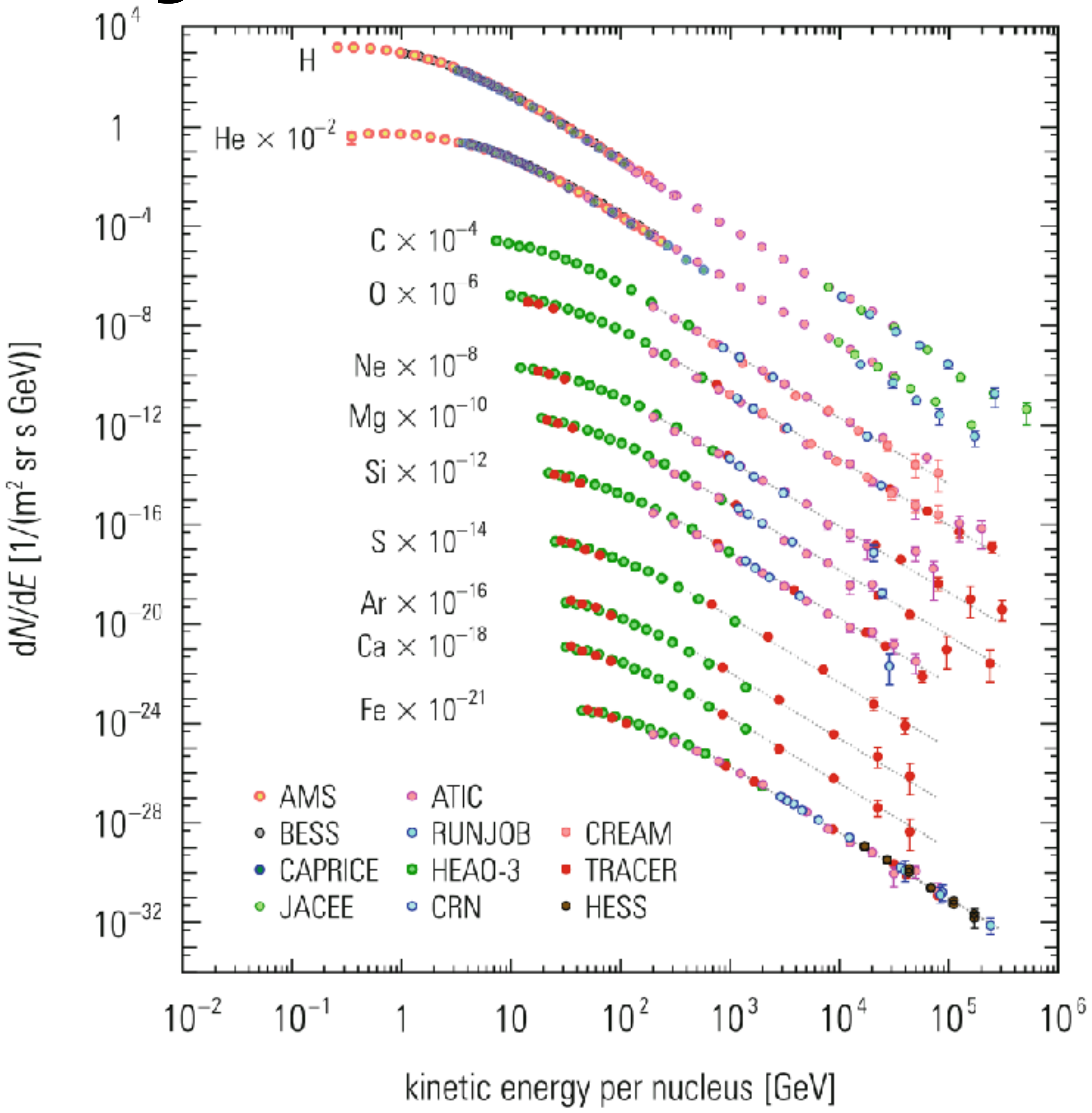

Fig. 6.3 Energy spectra of the main components of primary cosmic rays from direct measurements. The various data have been obtained from balloon measurements, from satellites, and an experiment at the International Space Station ISS [52]

Charged primary cosmic rays

The **all-particle spectrum of charged primary cosmic rays is relatively steep** so that practically no details are observable.

Only after multiplication of the intensity with a power of the primary energy, **structures in the primary spectrum** become visible (Figs. 6.4 and 6.5).

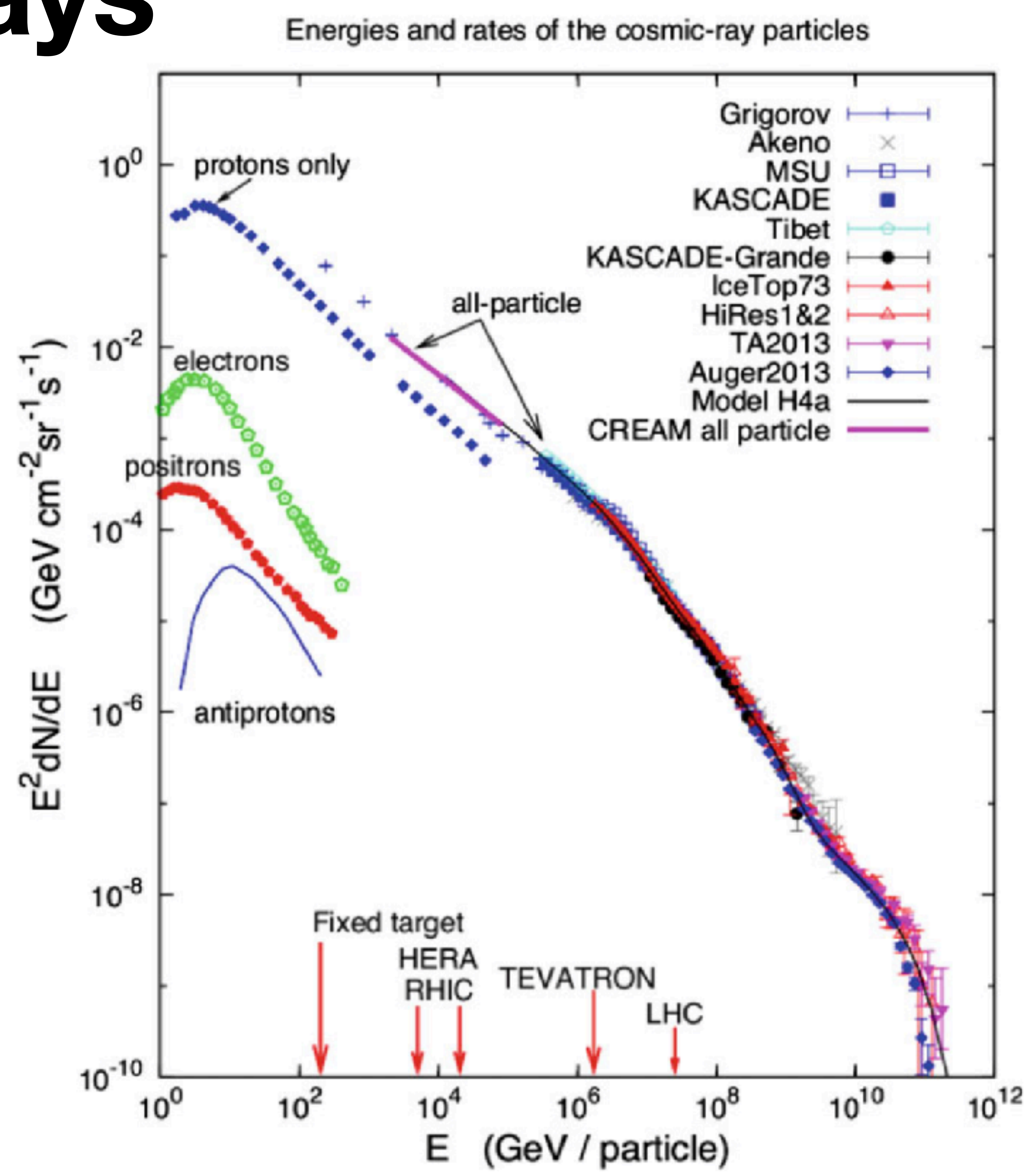

Fig. 6.4 The primary all-particle spectrum measured by different experiments scaled with the square of the primary energy. The contributions from electrons, positrons, and antiprotons as measured by the PAMELA experiment are shown [53]

Charged primary cosmic rays

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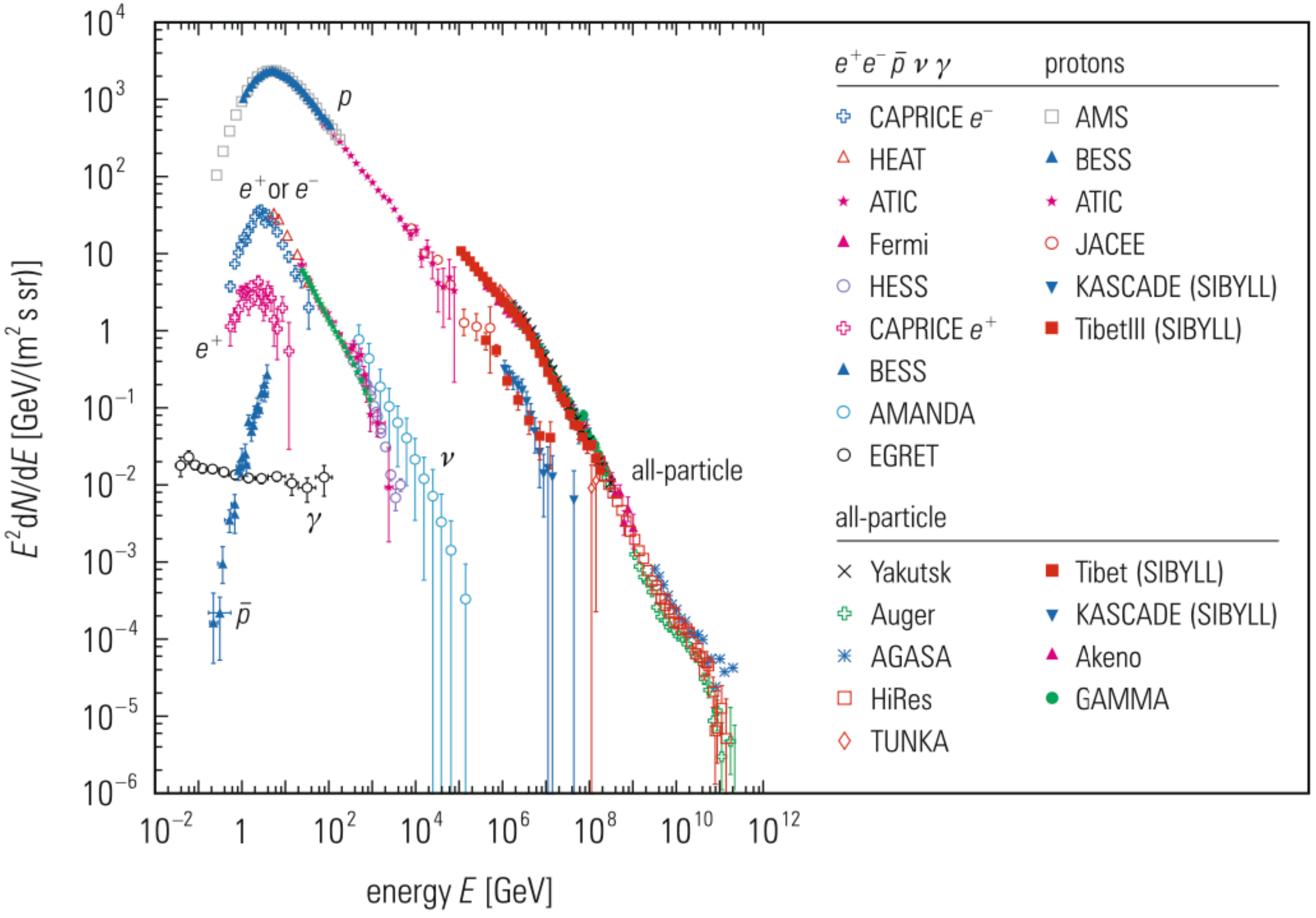


Fig. 6.5 Compilation of primary cosmic-ray spectra, including neutrinos and photons [54]

Charged primary cosmic rays

The results on the electron spectrum have been extended to very high energies (up to 20 TeV) by the H.E.S.S. experiment (Fig. 6.6).

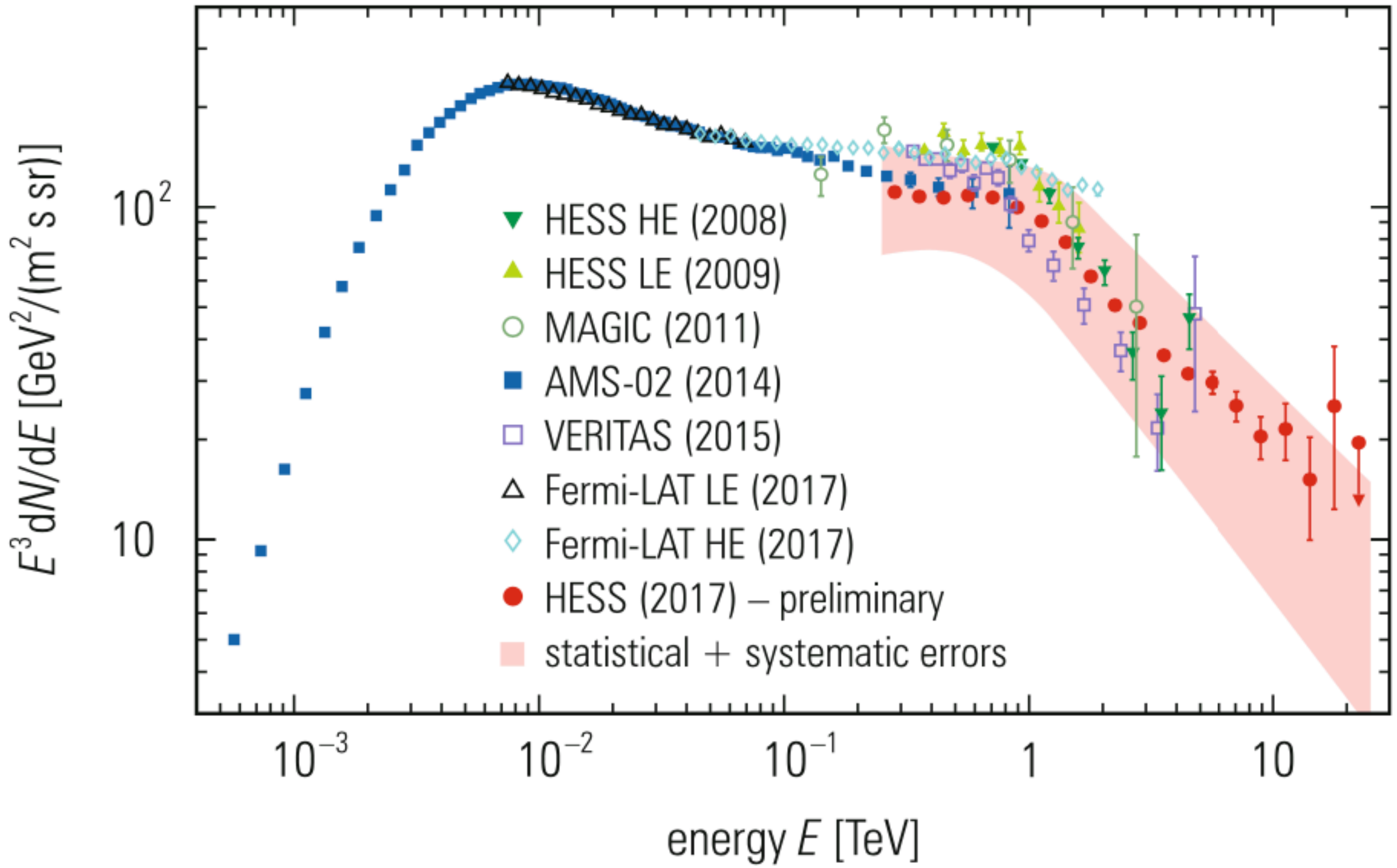
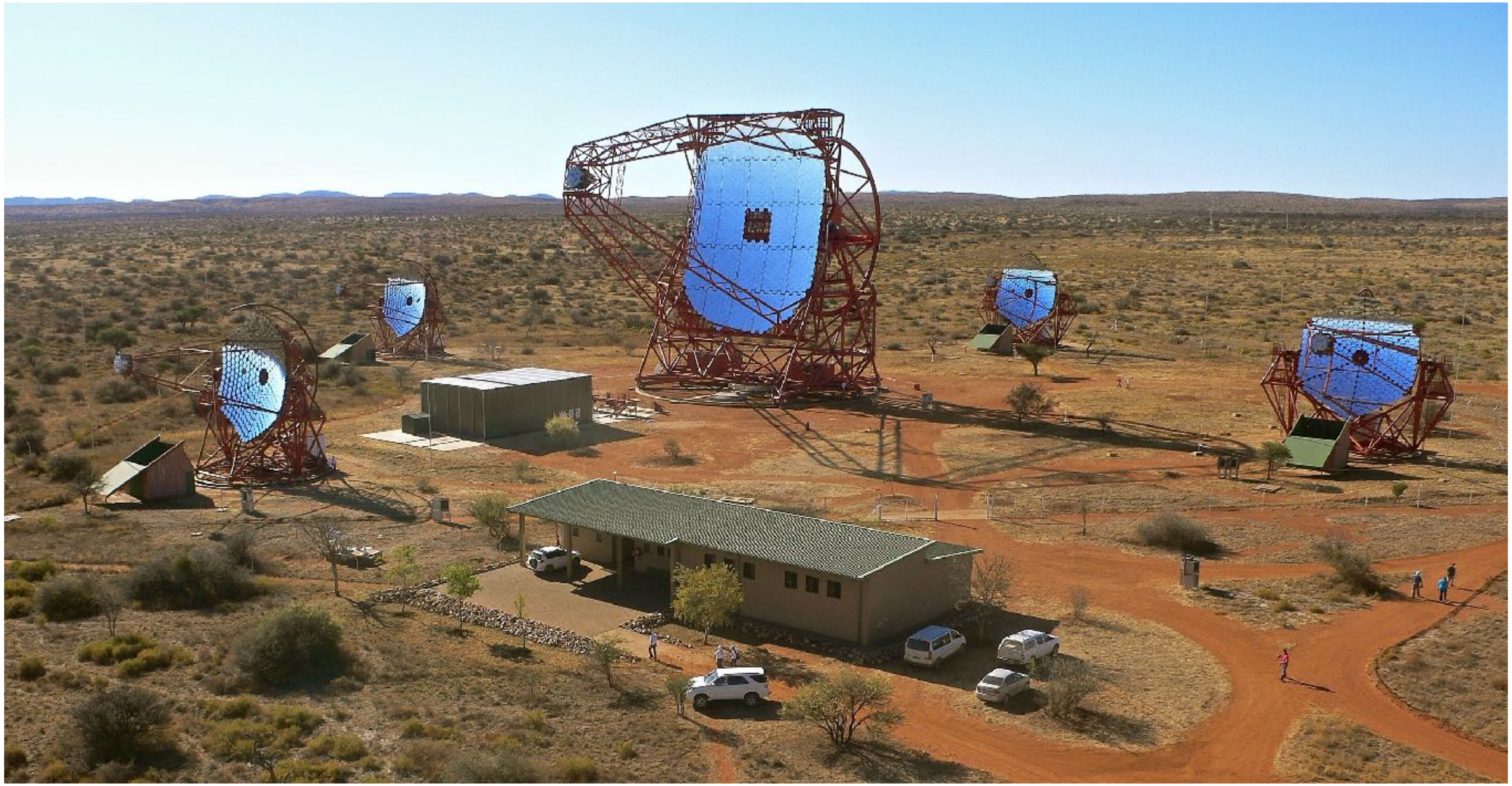


Fig. 6.6 Cosmic-ray-electron energy spectrum measured with H.E.S.S. (*red dots*) compared to previous measurements from various experiments. The shape of the electron spectrum and its steepening at energies around 1 TeV could give answers to various production and propagation models [56]

Charged primary cosmic rays



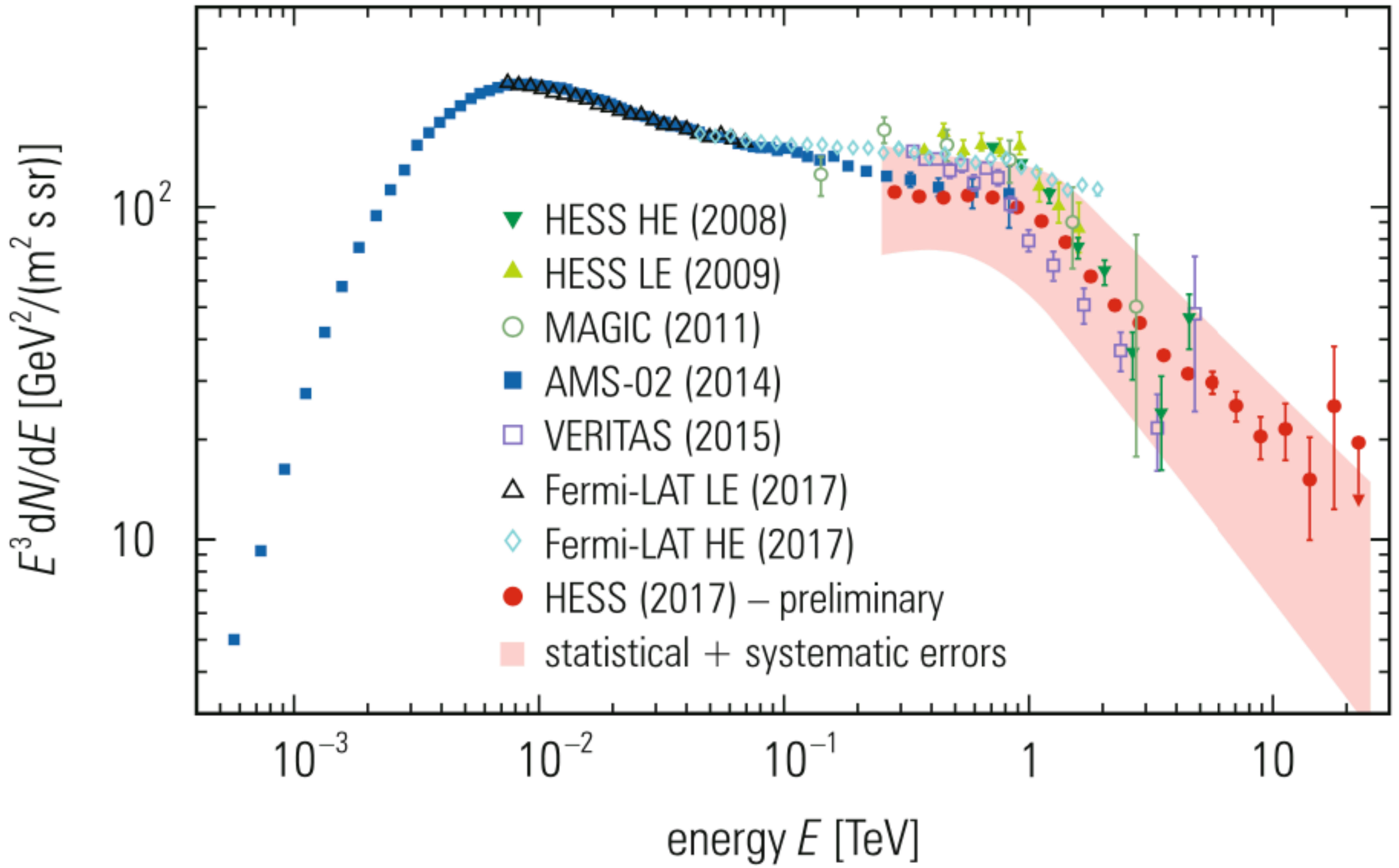
The H.E.S.S. II five-telescope gamma-ray experiment in Namibia.

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

Charged primary cosmic rays

When **cosmic-ray experiments without magnetic spectrometers measure electrons they cannot distinguish electrons form positrons.** So, the electron spectrum is the **combined spectrum** of electromagnetically interacting charged particles, but, since **positrons are suppressed** compared to electrons, such spectra are **called electron spectra.**

Around 1 TeV there is a structure, which is also observed by the new CALET experiment on the ISS. Insofar this structure should not be over-interpreted. Better statistics is required. This feature certainly requires further investigations.



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Charged primary cosmic rays

The **bulk of cosmic rays up to** at least an energy of **10^{15} eV** is believed to **originate from within our galaxy**. Above that energy, which is associated with the so-called ***'knee'*, the spectrum steepens. Above the so-called *'ankle'*** at energies around **10^{19} eV** the **spectrum slightly flattens** again for a short energy span and for energies in excess of **6×10^{19} eV the spectrum shows a strong cutoff** (see also Figs. 6.7, 6.8, and 6.9).

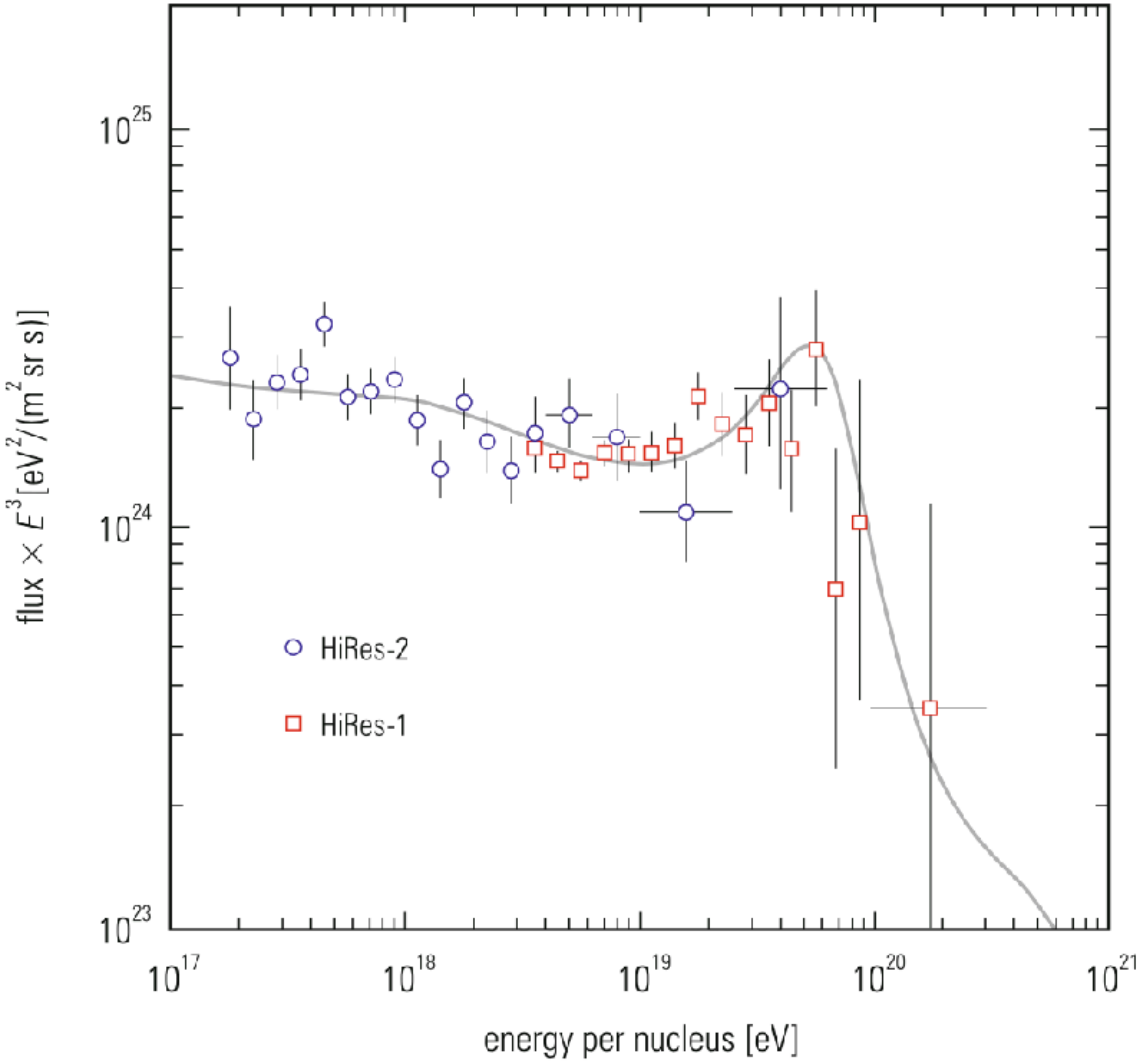

Fig. 6.7 Energy spectrum of primary cosmic rays scaled by a factor of E^3. The data are from the Utah high resolution experiment [57]

Charged primary cosmic rays

UTAH'S FLY'S EYE TELESCOPE ARRAY

https://science.utah.edu/faculty/utahs-flys-eye-telescope-array/

Charged primary cosmic rays

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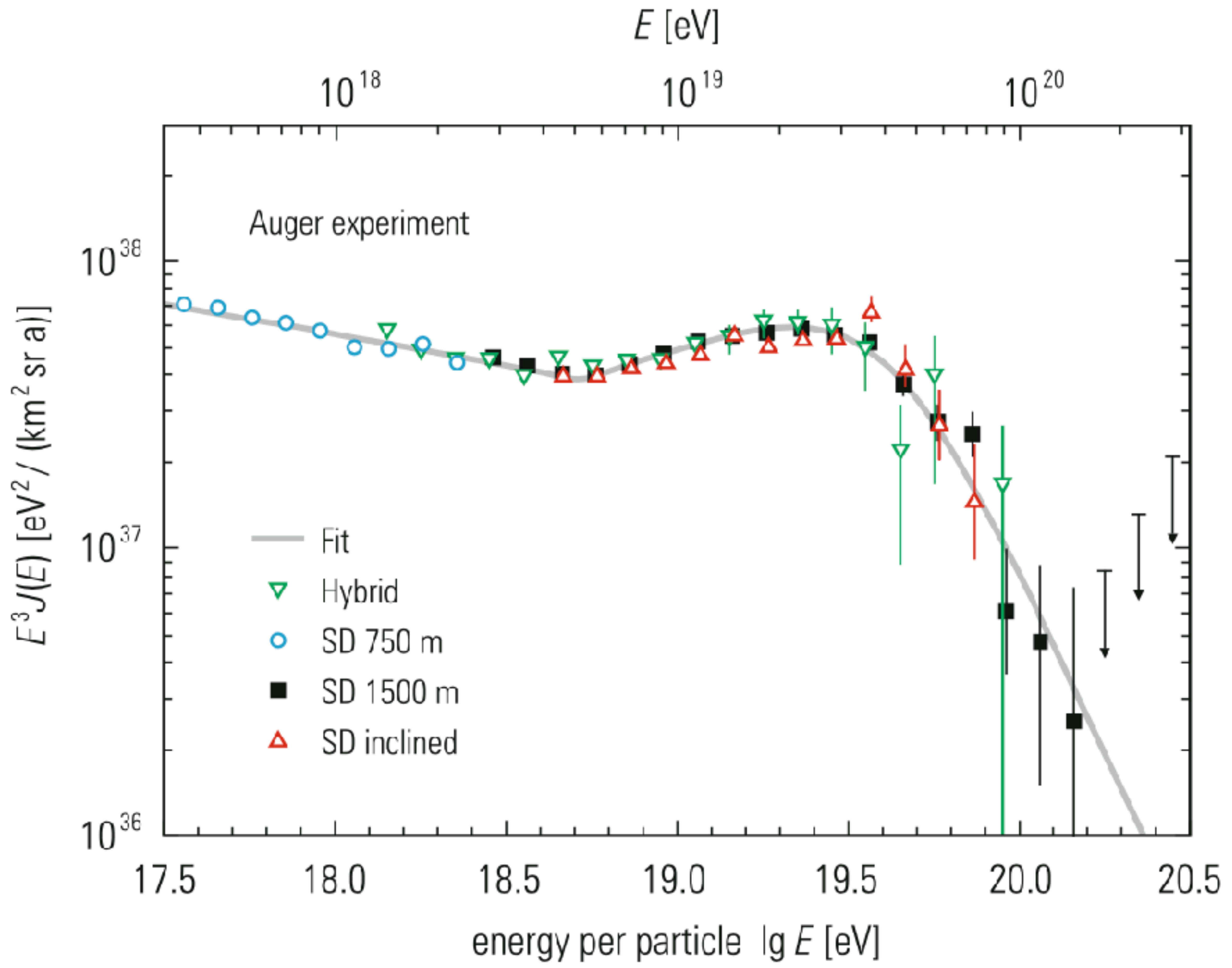


Fig. 6.8 Energy spectrum of primary cosmic rays scaled by E^3. The results from the Auger experiment clearly show the cutoff of the energy spectrum above 6×10^{19} eV (*SD* stands for the surface Cherenkov detectors, and *Hybrid* includes the surface detectors and results from the fluorescence telescopes) [58]

Charged primary cosmic rays

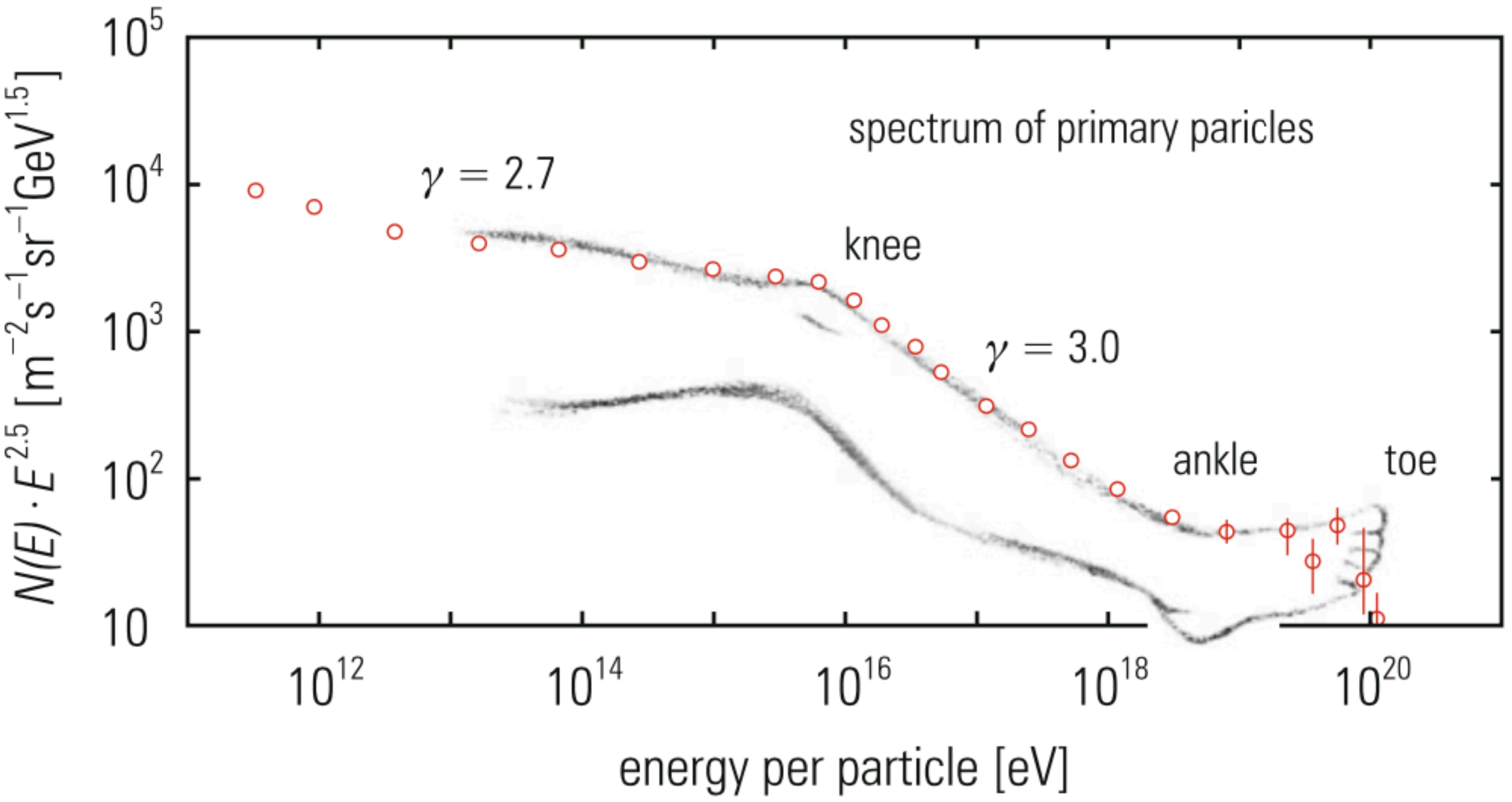


Fig. 6.9 Artist's view of the different structures of the spectrum of primary cosmic rays

Charged primary cosmic rays

For higher energies primary protons rapidly loose energy by interactions with the primordial background radiation.

Around these energies also a crossover from the galactic component to a **component of extragalactic origin might be conceivable.**

To compare the primary energies **with energies from accelerators, one has to convert the center-of-mass energy,** e.g., in storage rings to a laboratory energy. For the Large Hadron Collider **(LHC)** at CERN with a **center-of-mass energy of 14 TeV** the comparable energy **in a laboratory system** for the collision of a high-energy proton with a proton at rest using the relation $s = 2mE_{\mathrm{lab}}$ (m is the proton mass) is obtained to be about **10^{17} eV.**

Cosmic rays originate predominantly from within our Galaxy. Galactic objects do not in general have such a combination of size and magnetic field strength to contain particles at very high energies.

Charged primary cosmic rays

Because of the equilibrium between the centrifugal and Lorentz force (v $\perp$ ***B*** assumed) one has

$$mv^2/\varrho = Z\, e\, v\, B\,,$$

which yields for the momentum of singly charged particles

$$p = e\, \varrho\, B$$

(*p* is the particle momentum, *B* the magnetic field, v the particle velocity, *m* the particle mass, **ϱ the bending radius or gyroradius).**

For a large-area galactic magnetic field of $B = 10^{-10}$ T in the galaxy (about 10^5 times weaker compared to the magnetic field on the surface of the Earth) and a gyroradius of 5pc, from which **particles start to leak from the galaxy, particles with momenta up to**

$$p[\mathrm{GeV}/c] = 0.3\, B[\mathrm{T}]\, \varrho[\mathrm{m}]\,,$$

$$p_{\max} = 4.6 \times 10^6\,\mathrm{GeV}/c = 4.6 \times 10^{15}\,\mathrm{eV}/c$$ **can be contained.**

Charged primary cosmic rays

$$mv^2/\varrho = Z\, e\, v\, B\,,$$

1 parsec (pc) is a unit of distance in astronomy (1 pc = 3.26 light-years = 3.0857×10^{16} m).

Particles with energies **exceeding 10^{15} eV start to leak from the galaxy.** This causes the **spectrum to get steeper to higher energies**.

Since the **containment radius depends on the atomic number,** the position of the **knee should depend on the charge of primary cosmic rays in this scenario,** i.e., the knee for iron would be expected at higher energies compared to the proton knee.

And this was actually seen in the data of the KASCADE-Grande experiment at **around 80 PeV** (see Fig. 6.10).

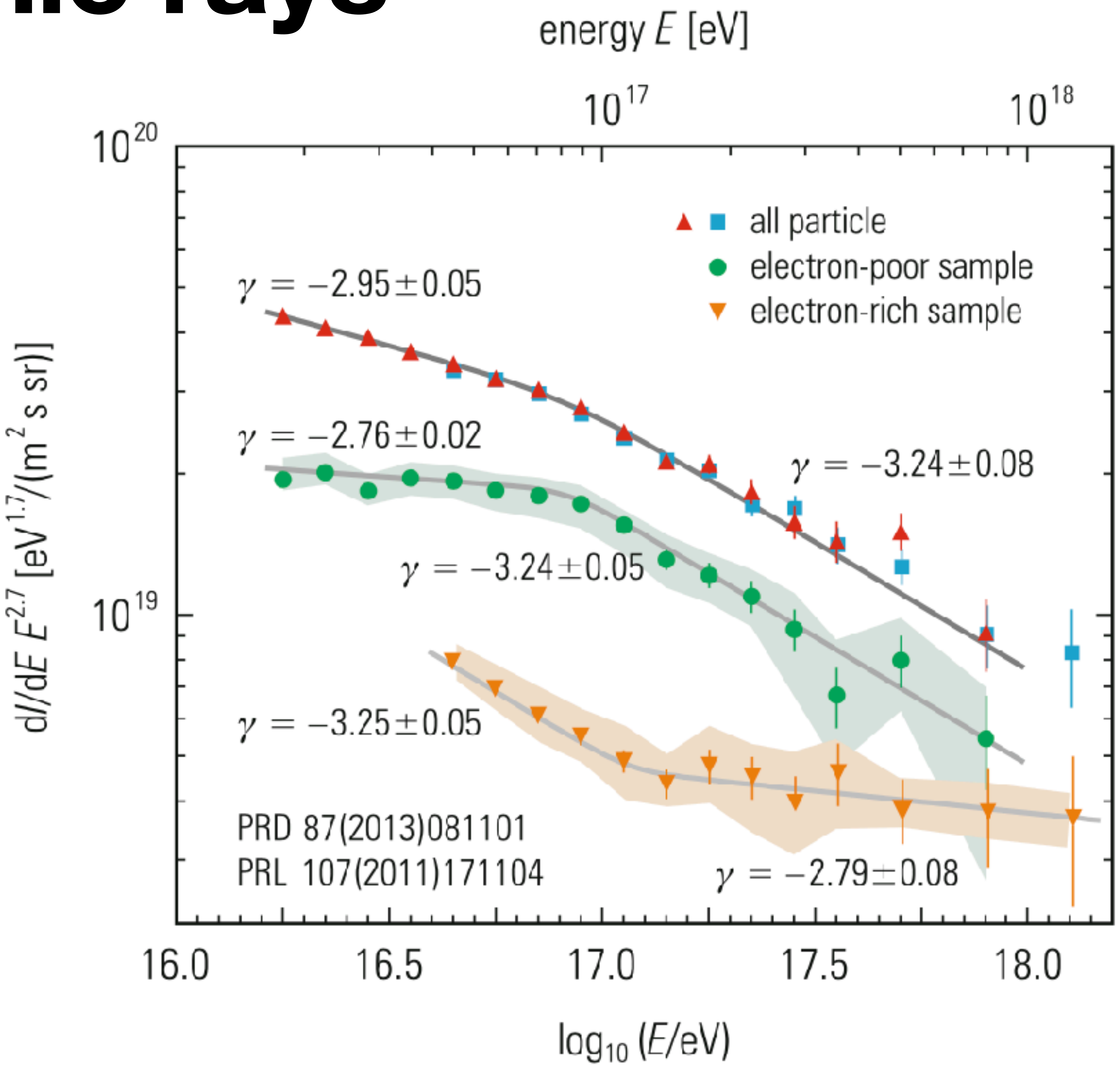


Fig. 6.10 Energy spectrum of primary particles in the energy range from 10 PeV to 1 EeV with data from KASCADE-Grande. The all-particle spectrum is separated into heavy primaries (electron-poor sample) and light primaries (electron-rich sample) [59]

Charged primary cosmic rays

KASCADE – Grande was an extensive air shower experiment array to study the cosmic ray primary composition and the hadronic interactions in the energy range $E_0=10^{16}-10^{18}$eV. The experiment was situated on site of the former Forschungszentrum Karlsruhe at 110m a.s.l, corresponding to an average athmospheric depth of 1022g/cm^2. It measured simultaneously the electromagnetic, muonic and hadronic componenets of extensive air showers of cosmic rays.

One of the main results obtained by these two experiments is a picture of increasingly heavier composition above the 'knee' caused by a break in the spectrum of the light components. Conventional acceleration models predict a change of the composition towards heavier components. The discovery of the knee in the heavy components, represented by iron, by KASCADE-Grande around 80 PeV was a convincing verification of these theories.

More on the instrument: https://cr.iap.kit.edu/kascade/

https://www.iap.kit.edu/kascade/english/

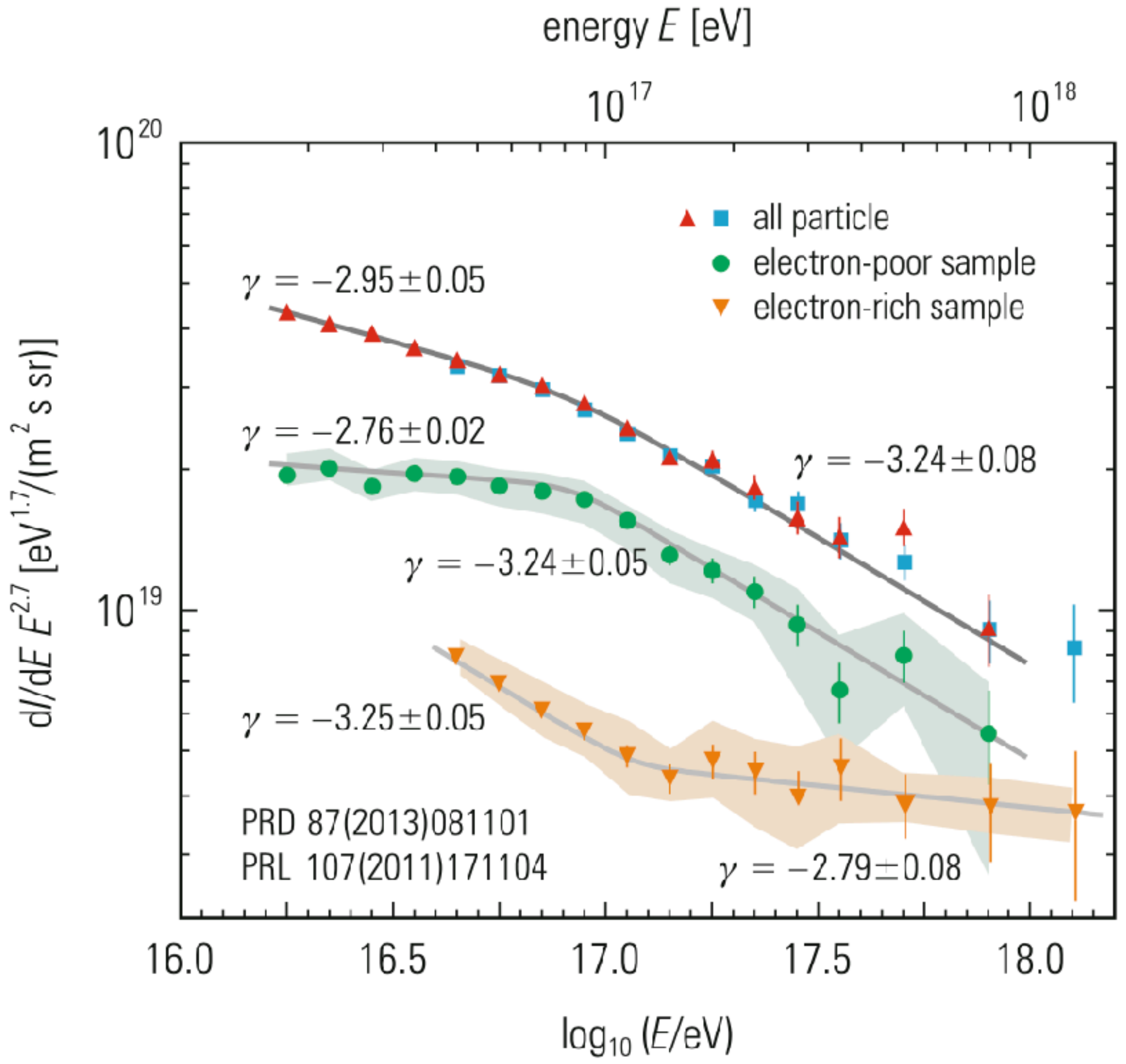
Charged primary cosmic rays

Figure 6.10 shows some details on the measurement of the primary spectrum in the energy range from 100TeV to 1EeV.

The air-shower data from KASCADE-Grande were separated into **two mass groups**, i.e., into groups of **heavy and light primary masses** according to the **observed electron–muon ratio in the air showers**.

In this energy range, e.g., **iron-induced showers tend to have more muons compared to proton-induced showers.**

Therefore, the sample of **electron-poor showers is enriched in heavy primaries** compared to the electron-rich sample, which is mainly caused by light primaries.



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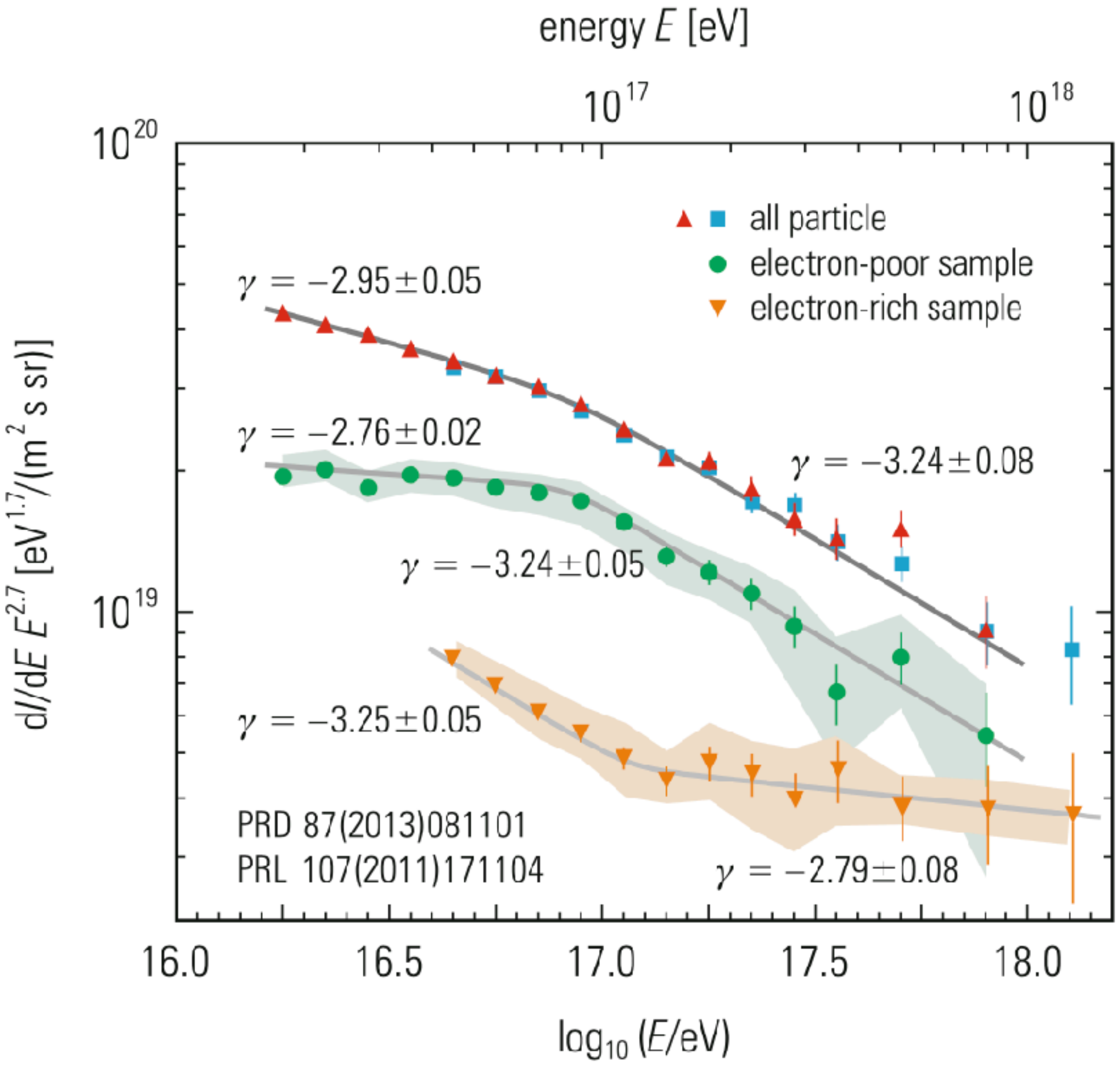
Charged primary cosmic rays

The spectrum of **heavy primaries** (electron-poor) shows a **clear knee-like feature** at an energy of about 80 PeV (8×10^{16} eV), which is interpreted as **'iron knee'.**

The selection of heavy primaries enhances the knee-like feature that is already present in the all-particle spectrum. **The first knee, the 'proton knee' is around 3PeV.**

With the nuclear charge of iron ($Z = 26$), the observed steepening at 8×10^{17} eV **fits well into the assumption that the containment of primaries in the Milky Way depends on the charge of the primaries.**

The light primaries (electron-rich) exhibit a **flattening** at somewhat higher energies, which could be understood as the **onset of extragalactic protons.**



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Charged primary cosmic rays

Another possible reason for the knee in cosmic radiation could be related to the fact that **10^{15} eV is about the maximum energy that can be supplied by supernova explosions**.

For higher energies a different acceleration mechanism is required, which might possibly lead to a steeper energy spectrum.

The knee could in principle also have its origin in a **possible change of interaction characteristics of high-energy particles.** It is in principle conceivable that the interaction cross section changes with energy giving rise to features at the knee of the primary cosmic-ray spectrum. **There is presently no evidence for this from accelerator data at quite high energies,** so this is considered rather unlikely.

The slight steepening of the spectrum beyond 80 PeV is related to the fact that heavy nuclei like iron start to leak from the galaxy. One could argue that magnetic confinement is the reason for this interpretation. The events beyond several 10^{19} eV could be of extragalactic origin.

Charged primary cosmic rays

The small dip at energies around 10^{19} eV (see Fig. 6.7) could be the consequence of ***e*+*e*− pair production of primary particles on photons of the blackbody radiation.** By this process primary protons would lose some energy. The exact shape of the spectrum in this energy range depends on the variation of the energy-dependent cross section for e^+e^- pair production.

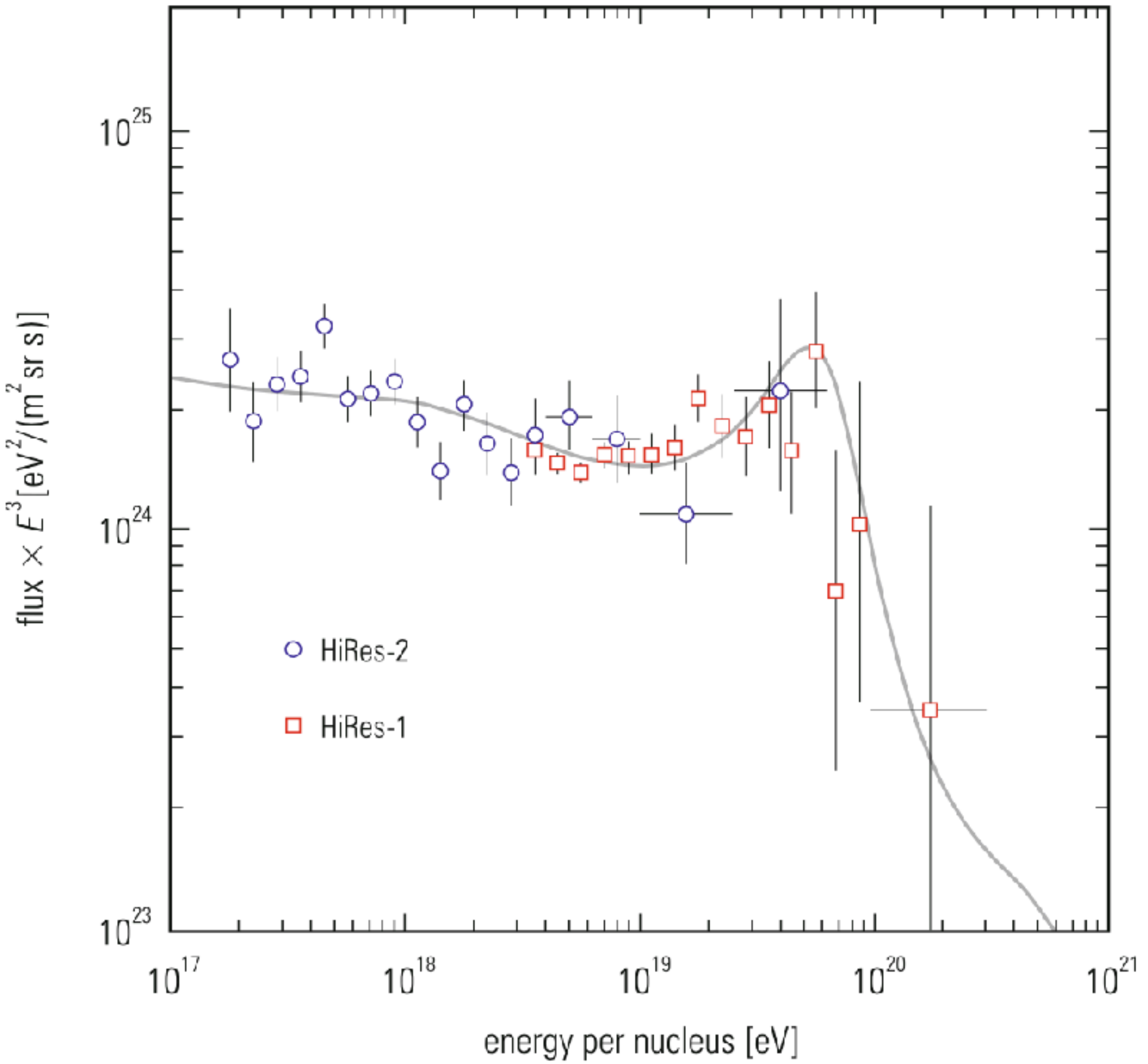


Fig. 6.7 Energy spectrum of primary cosmic rays scaled by a factor of E^3. The data are from the Utah high resolution experiment [57]

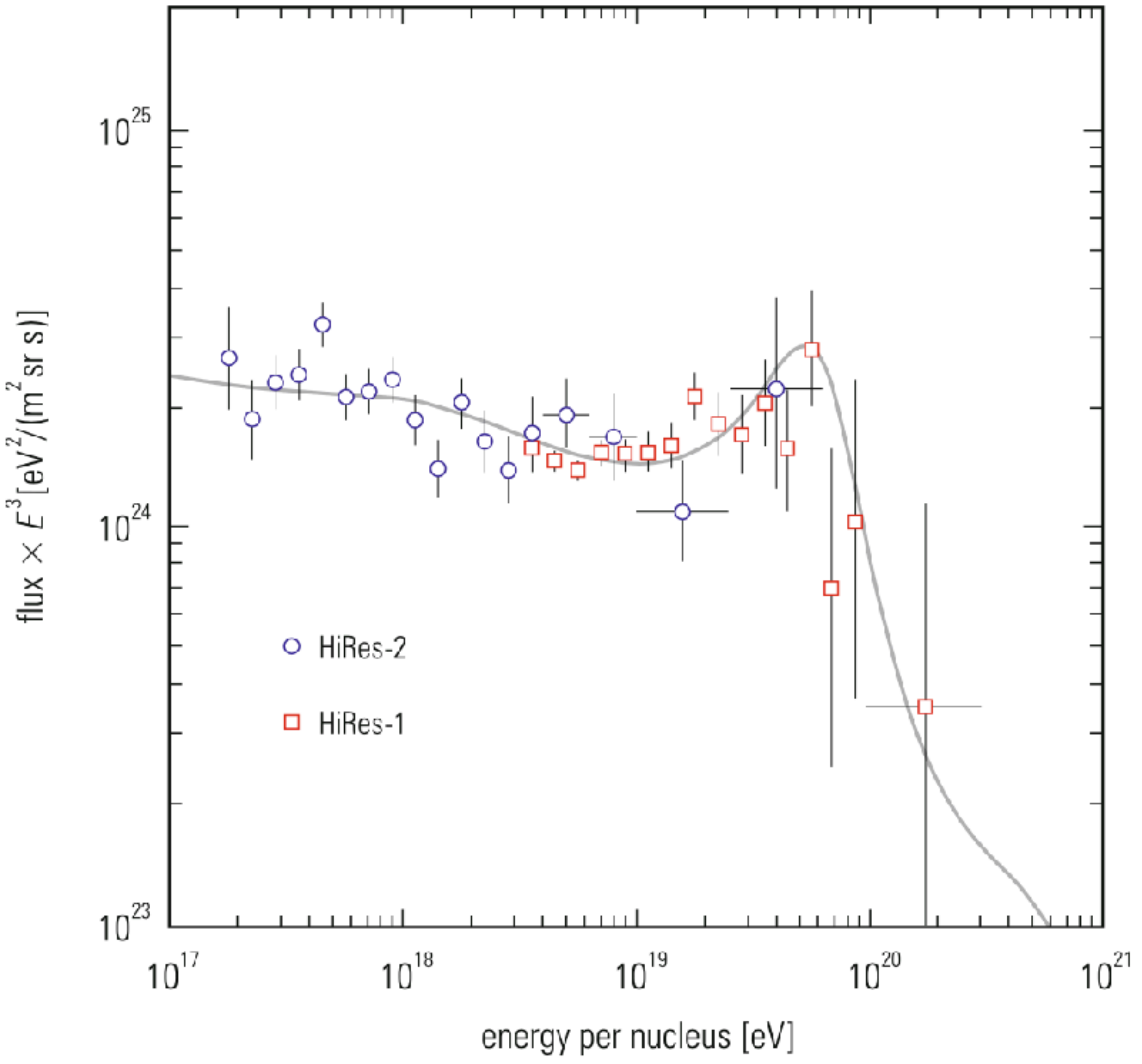
Charged primary cosmic rays

There are good reasons to expect a cutoff of the spectrum beyond 6×10^{19} eV.

In 1966 it was realized by **Greisen, Zatsepin, and Kuzmin (GZK)** that cosmic rays above the energy of approximately 6×10^{19} eV **would interact with the cosmic blackbody radiation.** Protons of higher energies would rapidly lose energy by this interaction process **causing the spectrum to be cut off at energies around 6×10^{19} eV.** Primary protons with these energies produce pions on blackbody photons via the Δ resonance according to

$$\gamma + p \rightarrow p + \pi^0, \;\; \gamma + p \rightarrow n + \pi^+ ,$$

thereby losing a large fraction of their energy.



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Charged primary cosmic rays

The threshold energy for the photo production of pions can be determined from four-momentum conservation

$$(q_\gamma + q_p)^2 = (m_p + m_\pi)^2$$

(q_γ , q_p are four-momenta of the photon or proton, respectively; m_p, m_π are proton and pion masses) yielding

$$E_p = (m_\pi^2 + 2m_p m_\pi)/4E_\gamma$$

for head-on collisions.

A typical value of the Planck distribution corresponding to the blackbody radiation of temperature 2.7 K is around 1.1 meV. With this photon energy the threshold energy for the photo production of pions is

$$E_p \approx 6 \times 10^{19}\,\mathrm{eV}$$

Charged primary cosmic rays

It is, however, not guaranteed that the cutoff is due to this process of photo production. It is also conceivable that the **possible sources of cosmic rays just run out of power to produce particles with energies beyond several 10^{19} eV.** This scenario is actually supported by the recent Auger data.

The observation of **several events in excess of 10^{20} eV**, therefore, represents a certain **mystery** (see also Fig. 6.9).

The **Greisen– Zatsepin–Kuzmin cutoff** limits the mean free path of high-energy protons to something like **50Mpc.**

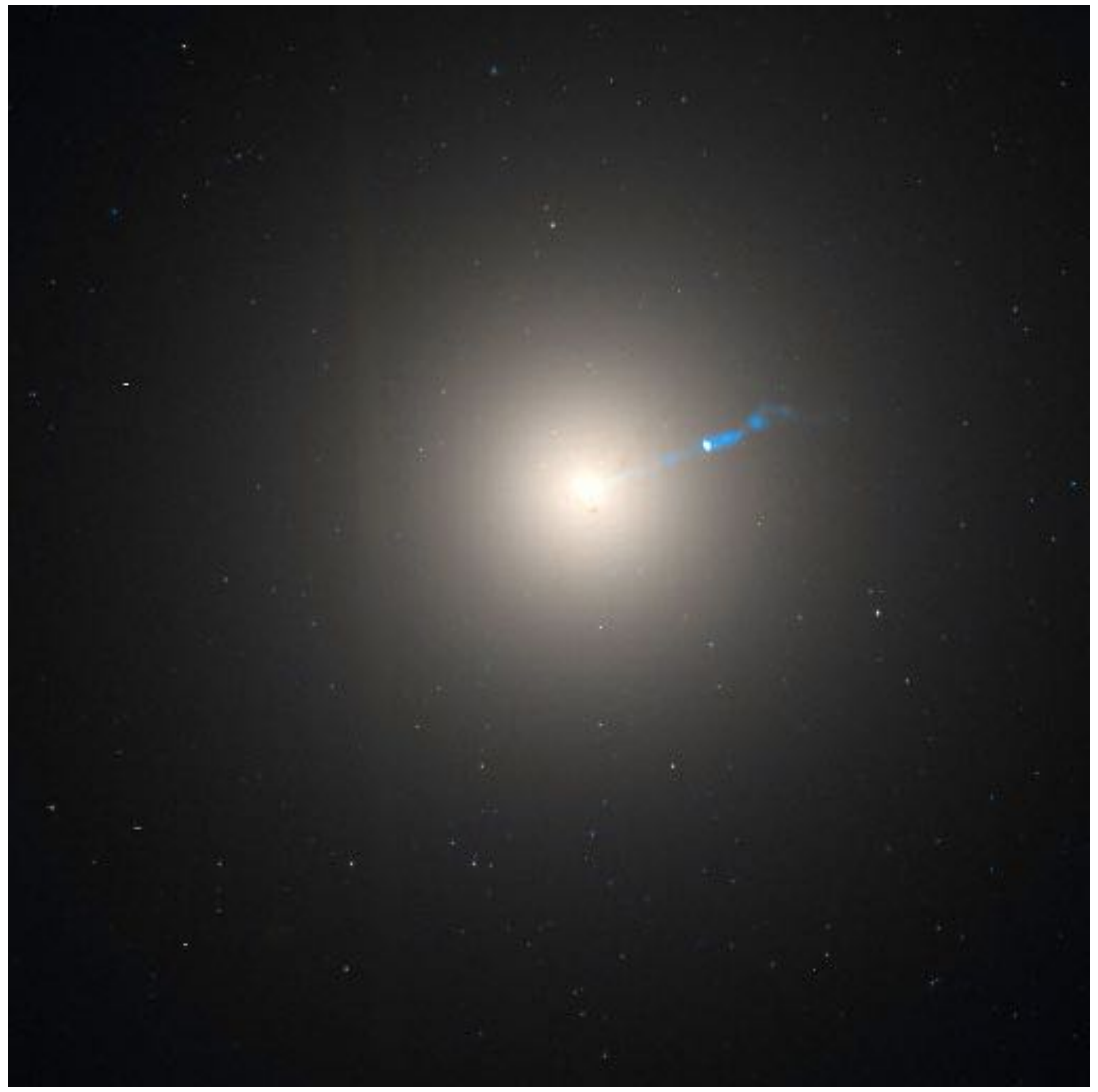
Photons as candidates for primary particles have even shorter **mean free paths (≈50 kpc)** because they produce electron pairs in gamma–gamma interactions with blackbody photons, infrared, starlight photons, or photons from the radio range ($\gamma + \gamma \rightarrow e^{+} + e^{-}$). This reasoning is supported by the **Auger experiment, which has no evidence for photons beyond 10^{18} eV.**

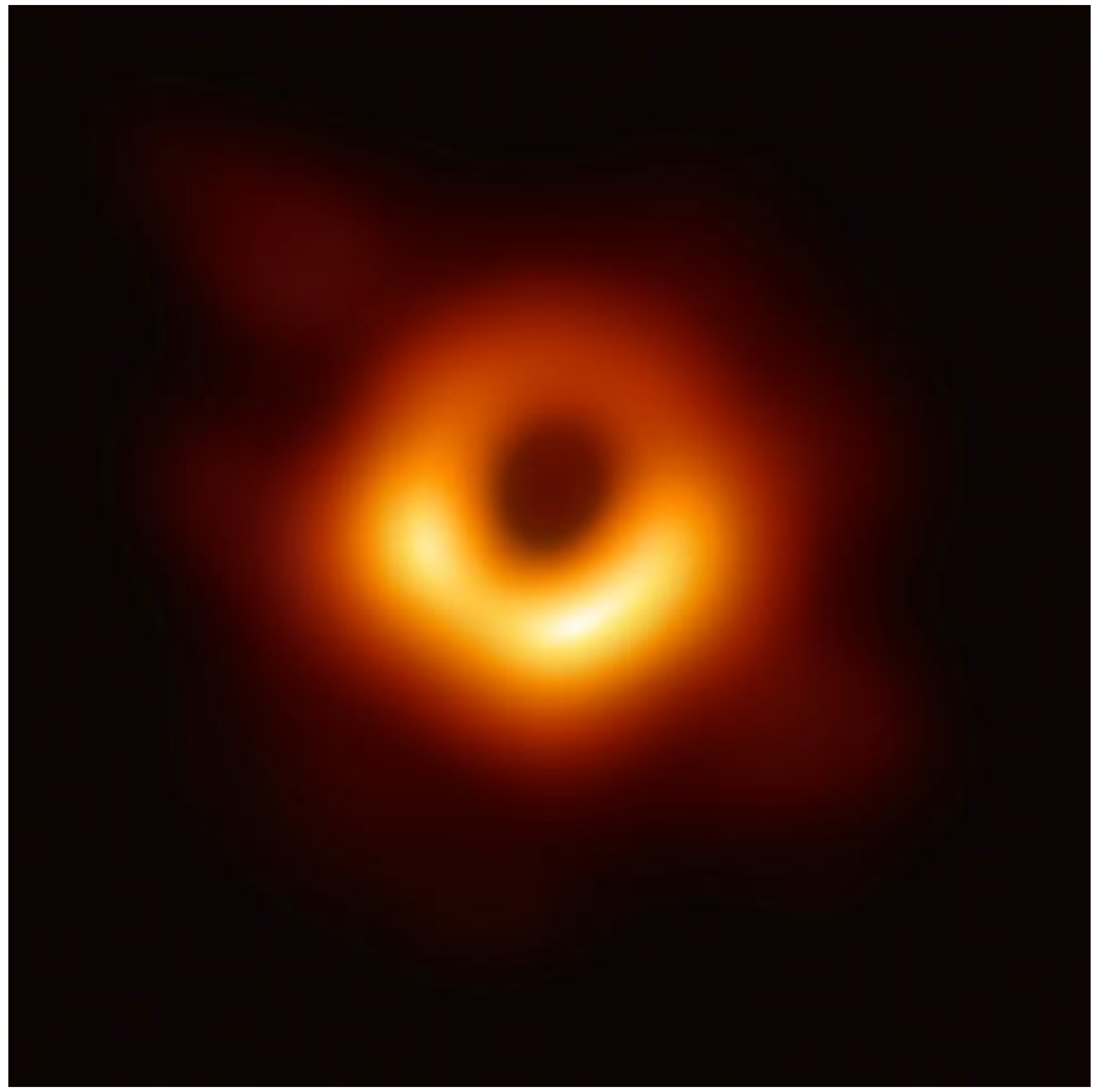
Charged primary cosmic rays

The hypothesis that **primary neutrinos** are responsible for the highest-energy events is rather **unlikely.** The **interaction probability for neutrinos in the atmosphere is extremely small** ($<10^{-4}$).

Because of their low interaction probability **one would expect that the primary vertices for neutrinos would be distributed uniformly in the atmosphere.** In contrast, one observes that the **first interaction takes place predominantly in the 100 mbar layer, which is characteristic of hadron or photon interactions.**

One way out would be to assume that after all **protons are responsible for the events with energies exceeding 6×10^{19} eV.** This would support the idea that the sources of the highest-energy cosmic-ray events are **relatively close.** A candidate source is **M87**, an elliptic giant galaxy in the Virgo Cluster at a distance of **15 Mpc**. From the center of M87 a jet of 1500 pc length is ejected that could be the source of energetic particles. M87, also known as Virgo A (3C274), is one of the brightest radio sources in the sky





Charged primary cosmic rays

An extreme alternative is the assumption that new, so far **unknown** elementary particles or unexpected phenomena or interaction processes are responsible for the extreme high-energy events.

Considering the **enormous rigidity of these high-energy particles** and the weakness of the intergalactic magnetic field, one would **not expect substantial deflections** of these particles over distances of 50 Mpc. This would imply that one can consider to do astronomy with these extremely high-energy cosmic rays. There is, however, **no clear correlation of the arrival directions** of these high-energy cosmic-ray events with known astronomical sources in the immediate neighbourhood of our galaxy or in the close local cluster of galaxies.

Antiparticles are extremely rare in primary cosmic rays. The measured primary antiprotons are presumably generated in interactions of primary charged cosmic rays with the interstellar gas. **Antiprotons can be readily produced according to**

$$p + p \rightarrow p + p + p + \bar{p}$$

while positrons are most easily formed in pair production by energetic photons.

Charged primary cosmic rays

The **flux of primary antiprotons** for energies >10 GeV has been measured to be

$$\left.\frac{N(\bar{p})}{N(p)}\right|_{>10\,\mathrm{GeV}} \approx 10^{-4} .$$

The **fraction of primary electrons in relation to primary protons is only 1%**.

Primary positrons constitute only 10% of the electrons at energies around 10 GeV. They are presumably also consistent with secondary origin. There is, however, an **increase over the expected positron flux at energies around 100GeV**, as measured by the PAMELA and AMS experiment.

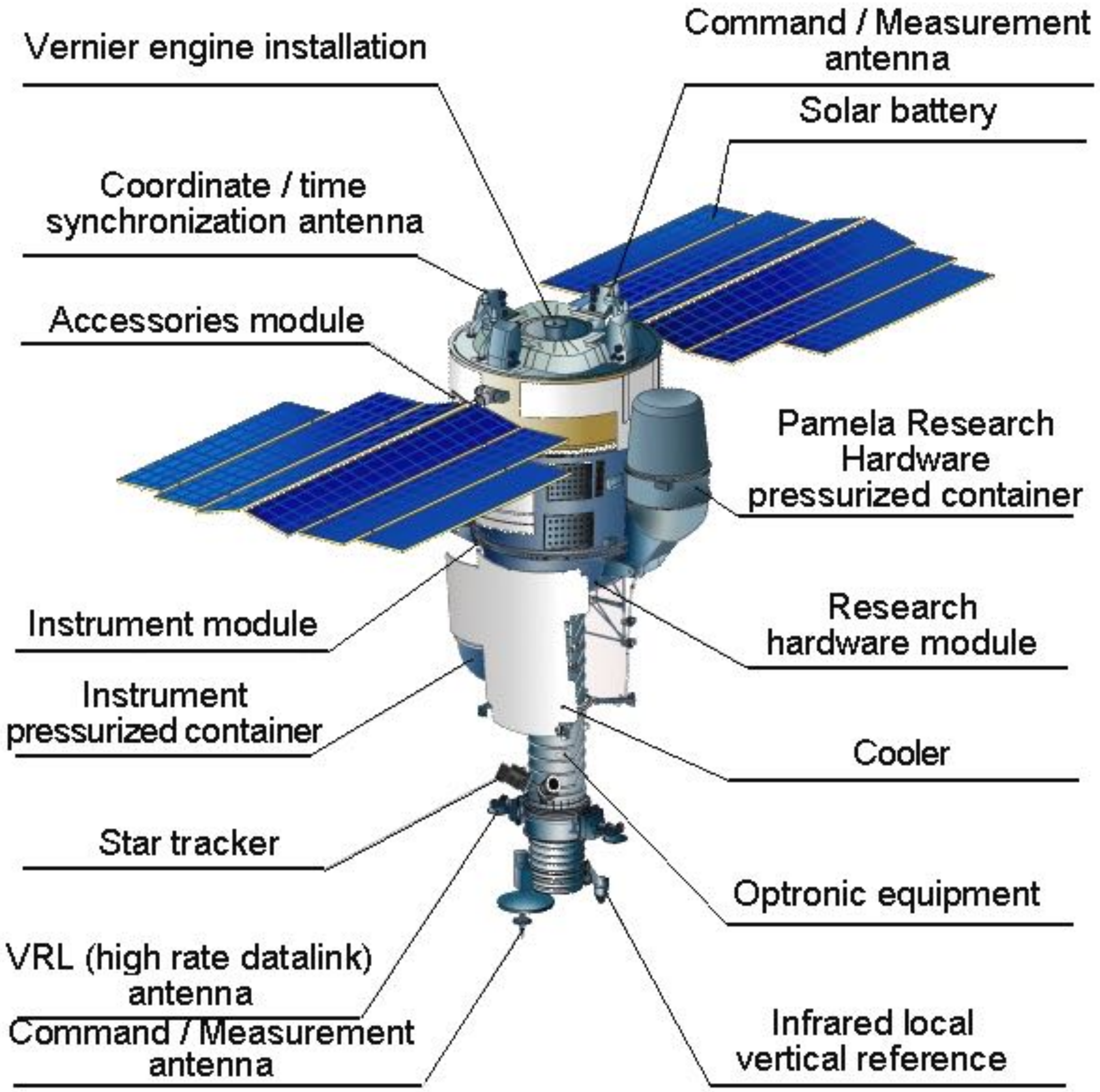
The **reason for this excess is so far unknown,** but nearby supernova explosions or pulsars might have injected positrons into our galaxy.

Charged primary cosmic rays

PAMELA (Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics) was a cosmic ray research module attached to an **Earth orbiting satellite**.

PAMELA was launched on 15 June 2006 and was the first **satellite-based experiment dedicated to the detection of cosmic rays, with a particular focus on their antimatter component, in the form of positrons and antiprotons.** Other objectives included long-term monitoring of the s**olar modulation of cosmic rays, measurements of energetic particles from the Sun, high-energy particles in Earth's magnetosphere and Jovian electrons.** It was also hoped that it may detect evidence of dark matter annihilation.

PAMELA operations were terminated in 2016, as were the operations of the host-satellite Resurs-DK1.



Charged primary cosmic rays

The Alpha Magnetic Spectrometer (AMS-02) is a particle physics experiment module that is mounted on the International Space Station (ISS). The module is a detector that measures antimatter in cosmic rays

Charged primary cosmic rays

Are there Stars and galaxies made of antimatter?

To find out **whether there are stars of antimatter in the universe**, the **existence of primary antinuclei** (antihelium, anticarbon) must be established because **secondary production of antinuclei with $Z \geq 2$ by cosmic rays is practically excluded.** The **non-observation of primary antimatter with $Z \geq 2$** is a strong hint that our universe is matter dominated. There are, however, some **antihelium candidates** found by the AMS experiment.

One might wonder whether the **continuous bombardment of the Earth with predominantly positively charged particles (only 1% are negatively charged) would lead to a positive charge-up of our planet.** This, however, is not true. When the rates of primary protons and electrons are compared, one normally considers only energetic particles. The spectra of protons and electrons are very different with electrons populating mainly low-energy regions. **If *all* energies are considered, there are equal numbers of protons and electrons so that there is no charge-up of our planet.**

Charged primary cosmic rays

The **chemical composition of high-energy primary cosmic rays (>10^{15} eV) is to large extent an unknown** territory.

If the current models of **nucleon–nucleon interactions are extrapolated** into the range beyond 10^{17} eV (corresponding to a center-of-mass energy of $\gtrsim$14 TeV in proton–proton collisions) **and if the muon content and lateral distribution** of muons in extensive air showers **are taken as a criterion for the identity** of the primary particle, then one would arrive at the conclusion that the chemical composition of primary cosmic rays beyond the knee (>10^{15} eV) **changes towards to a higher fraction of heavy nuclei**.

The KASCADE-Grande experiment has clear indications of a steepening of the primary spectrum beyond 80 PeV, which is interpreted as *iron knee*. When in the sample of air showers the **fraction of heavy primaries is enhanced by selecting muon-rich showers**, there is a very **pronounced steepening at 80PeV** in the position, where one would expect the iron knee (see Fig. 6.10). **This means that heavy nuclei with energies beyond 80 PeV are leaking from our galaxy**, in agreement with expectations from galactic containment.

Charged primary cosmic rays

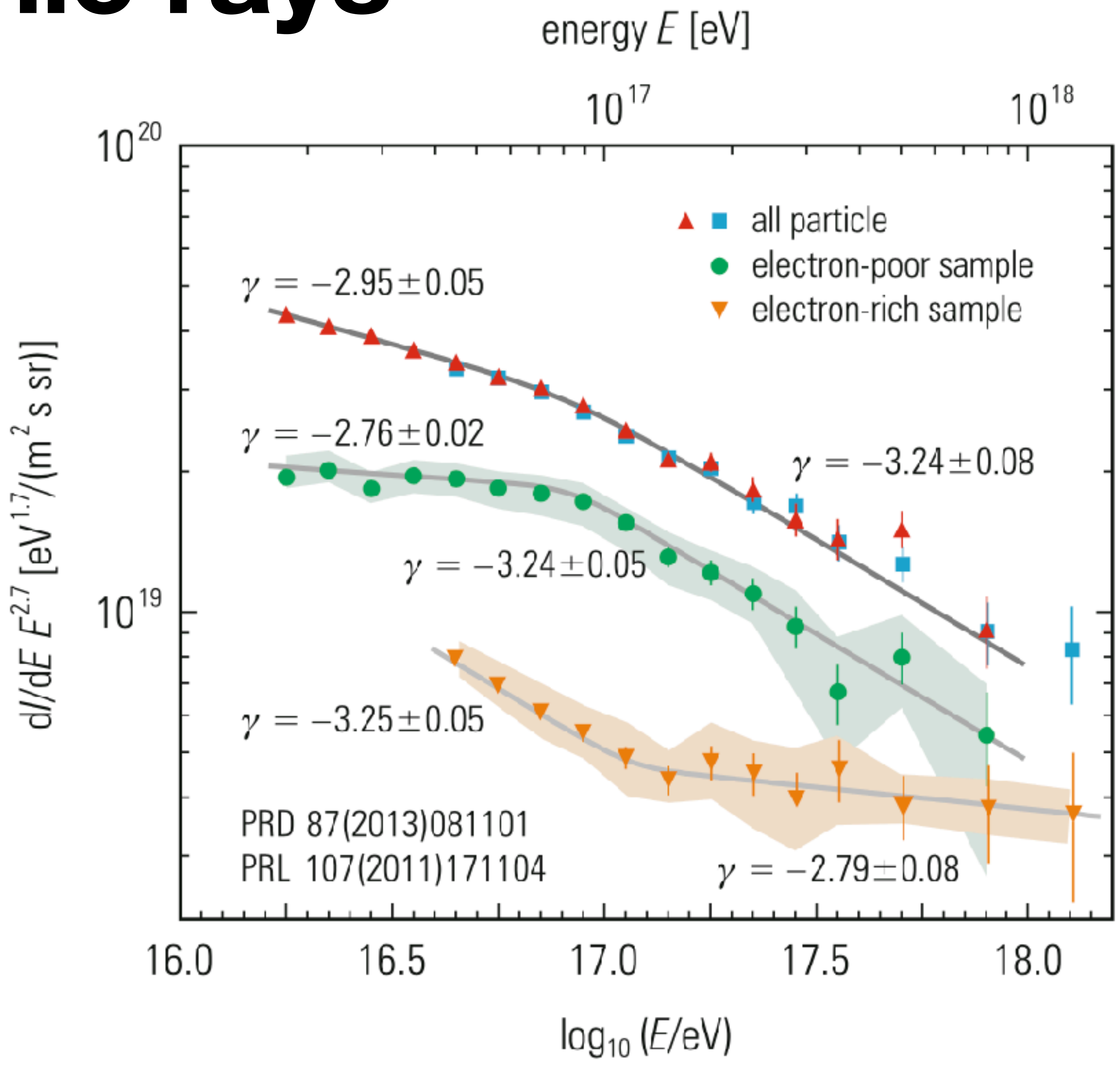


Fig. 6.10 Energy spectrum of primary particles in the energy range from 10 PeV to 1 EeV with data from KASCADE-Grande. The all-particle spectrum is separated into heavy primaries (electron-poor sample) and light primaries (electron-rich sample) [59]

Charged primary cosmic rays

Even though cosmic rays have been discovered more than 100 years ago, their origin is still an open question.

It is **generally assumed that active galactic nuclei, quasars, or supernova explosions are excellent source candidates for high-energy cosmic rays,** but **there is no direct evidence** for this assumption.

In the energy range **up to 100TeV individual sources have been identified by primary gamma rays.** It is conceivable that gamma rays of these energies are **decay products of elementary particles** (π^0 decay, Centaurus A?), which have been **produced by those particles that have been originally accelerated in the sources.** Therefore, it would be interesting to see the sources of cosmic rays in the light of these originally accelerated particles.

This, however, presents a serious problem: **photons and neutrinos travel on straight lines in galactic and intergalactic space, therefore pointing directly back to the sources**.

Charged particles, on the other hand, are **subject to the influence of homogeneous or irregular magnetic fields.** This causes the accelerated particles to travel along **chaotic trajectories** thereby losing all directional information before finally reaching Earth. Therefore, it is of very little surprise that **the sky for charged particles with energies below 10^{14} eV appears completely isotropic**. The level of observed anisotropies lies below 0.5%.

Charged primary cosmic rays

There is some hope that for energies **exceeding 10^{18} eV a certain directionality could be found**. It is true that also in this energy domain the galactic magnetic fields must be taken into account, however, the deflection radii are already rather large.

The situation is even more complicated because of the **uncertain topology of galactic magnetic fields.** In addition, one must in principle know the **time evolution of magnetic fields over the last ≈200 million years** because the sources can easily reside at distances of >50 Mpc (~163 million light-years).

For **simultaneous observation of cosmic-ray sources in the light of charged particles and photons**, one must take into account that **charged particles are delayed with respect to photons** because they travel on longer trajectories due to the bending by magnetic fields and have different propagation speeds.

Since the **magnetic deflection is proportional to the charge of a particle,** proton astronomy is more promising than astronomy with heavy nuclei.

Charged primary cosmic rays

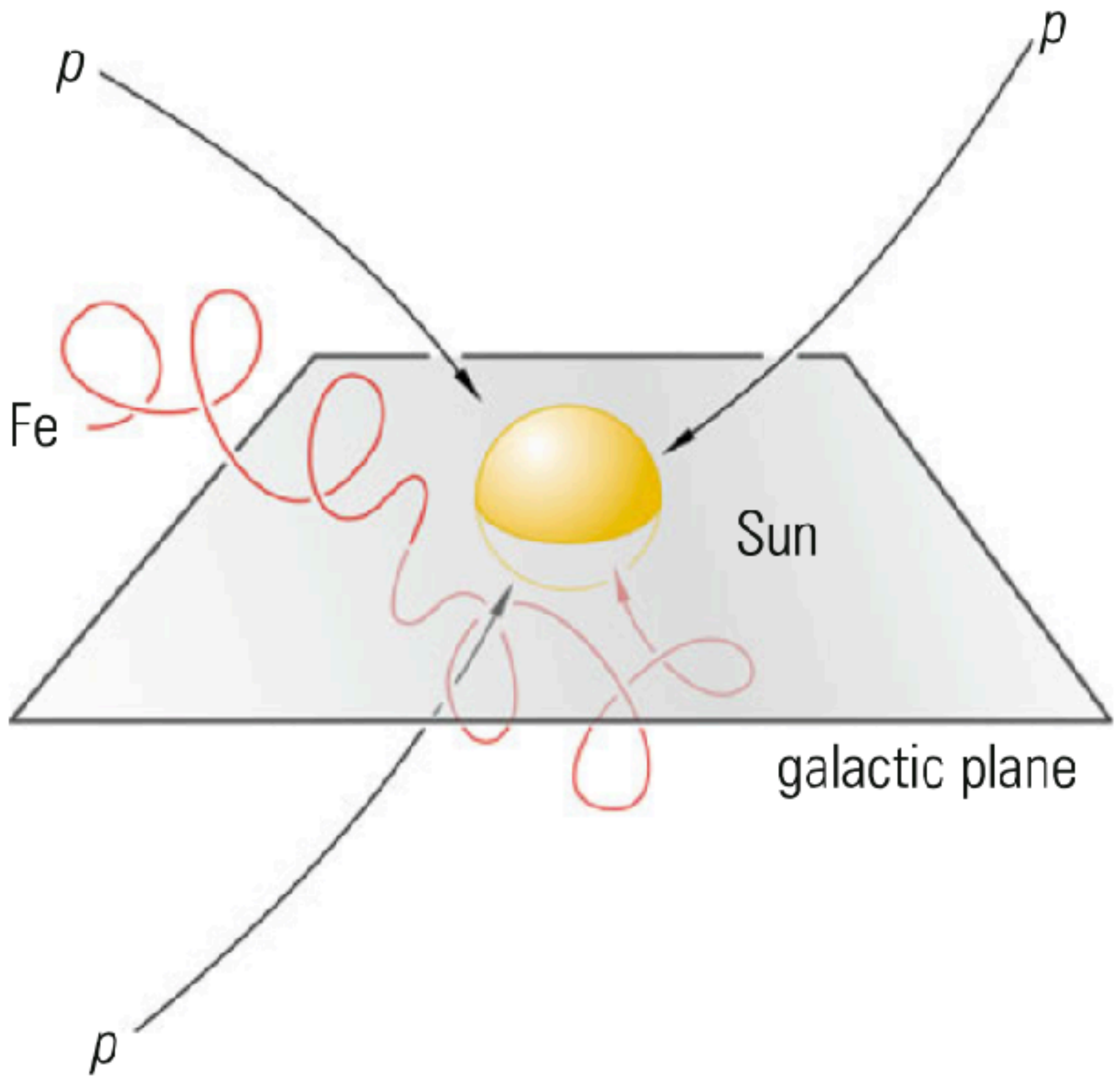


Fig. 6.11 Sketch of proton and iron trajectories in our Milky Way at energies of around 10^{18} eV

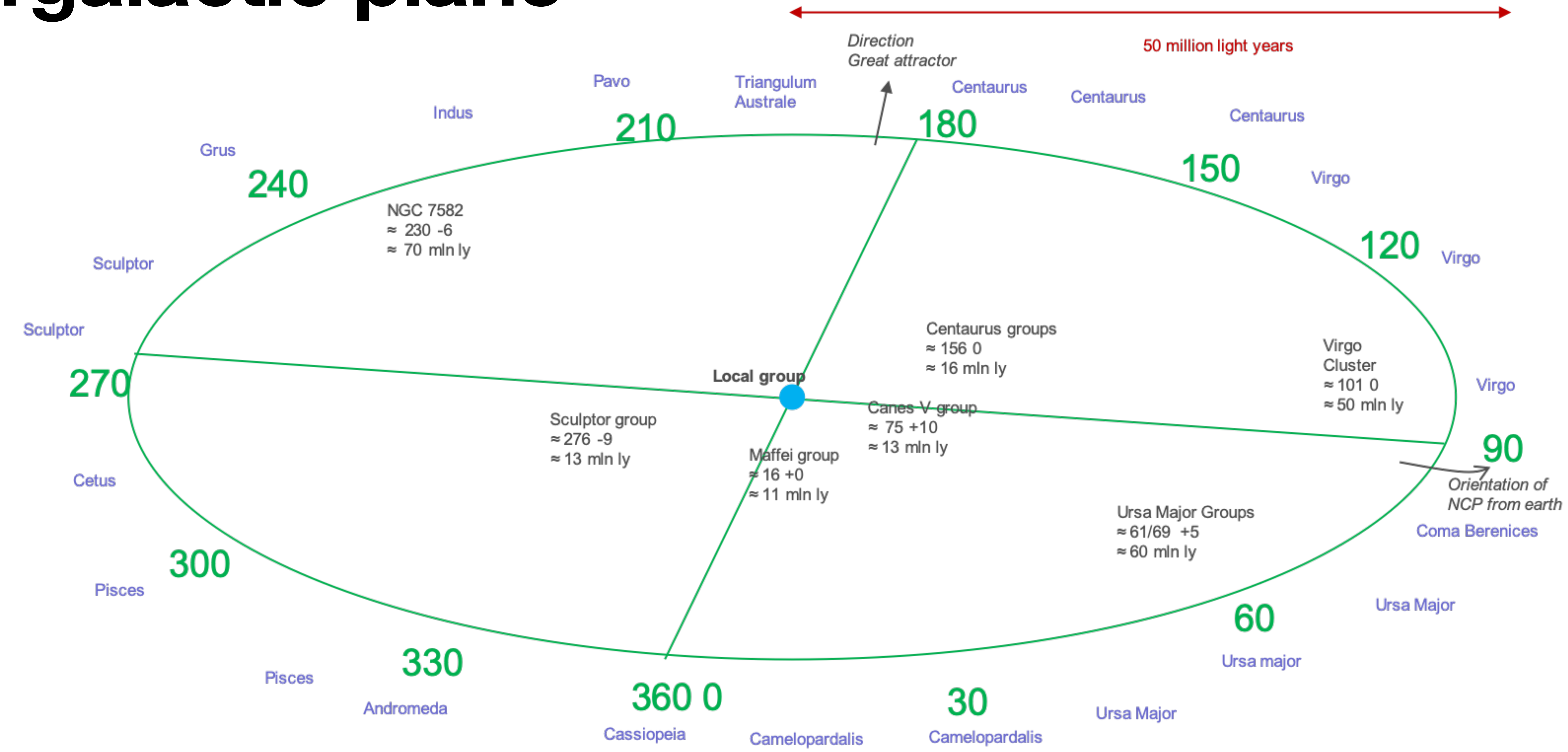
This idea is outlined in Fig. 6.11, where the **trajectories of protons and an iron nucleus ($Z = 26$) at an energy of 10^{18} eV are sketched for our galaxy.**

There are some hints that the **origins of some of the events** with energies $>10^{19}$ eV could lie in the **supergalactic plane**, a cluster of relatively close-by galaxies including our Milky Way.

It has also been discussed that the **galactic center** of our Milky Way and, in particular, the Cygnus region could be responsible for a certain anisotropy at 10^{18} eV.

It must, however, be mentioned that claims for such a possible correlation are **based on very low statistics.** They certainly need further experimental confirmation.

Supergalactic plane



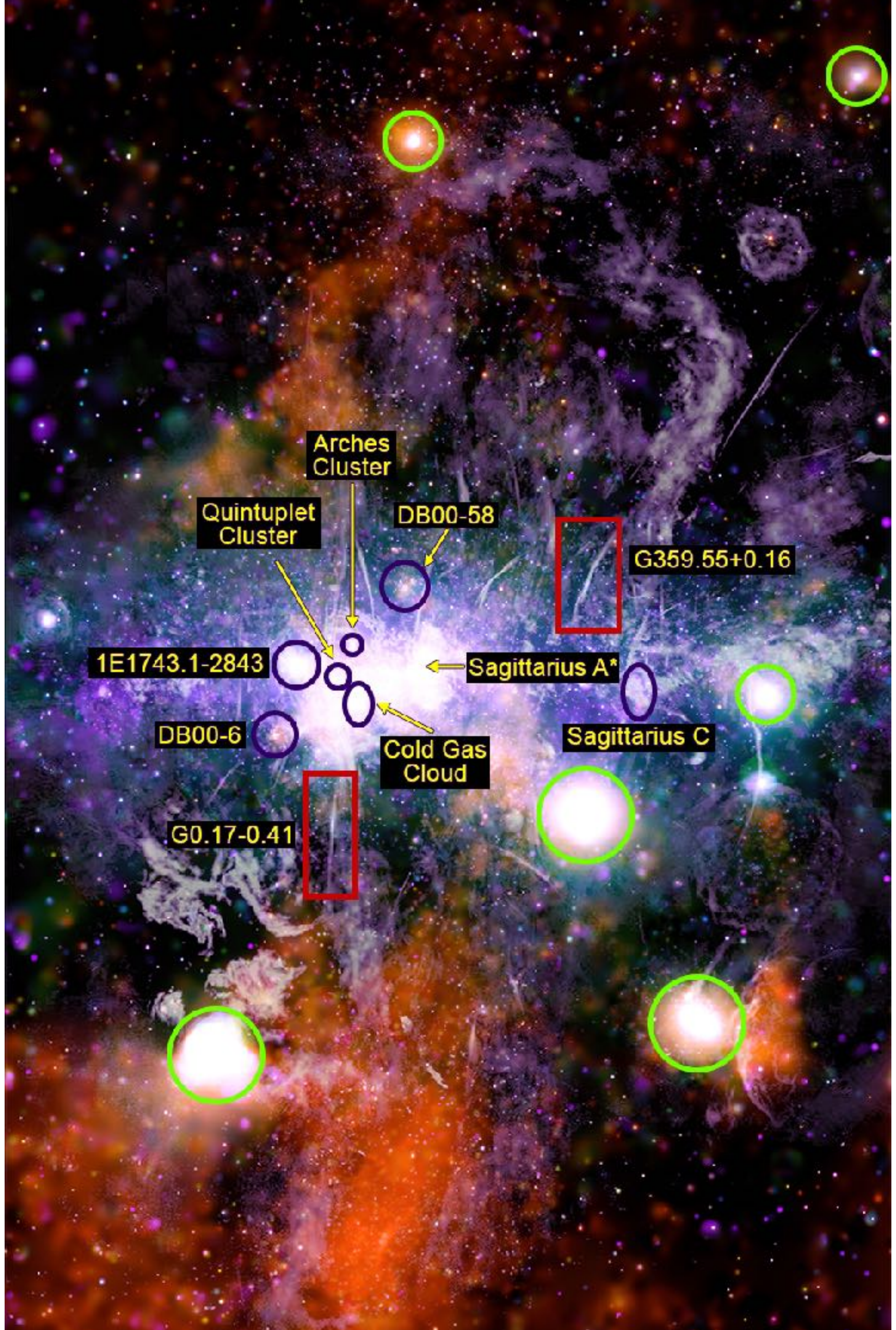
Nearby galaxies and galaxy clusters plotted in the supergalactic plane

Map constructed from Simbad data 2021

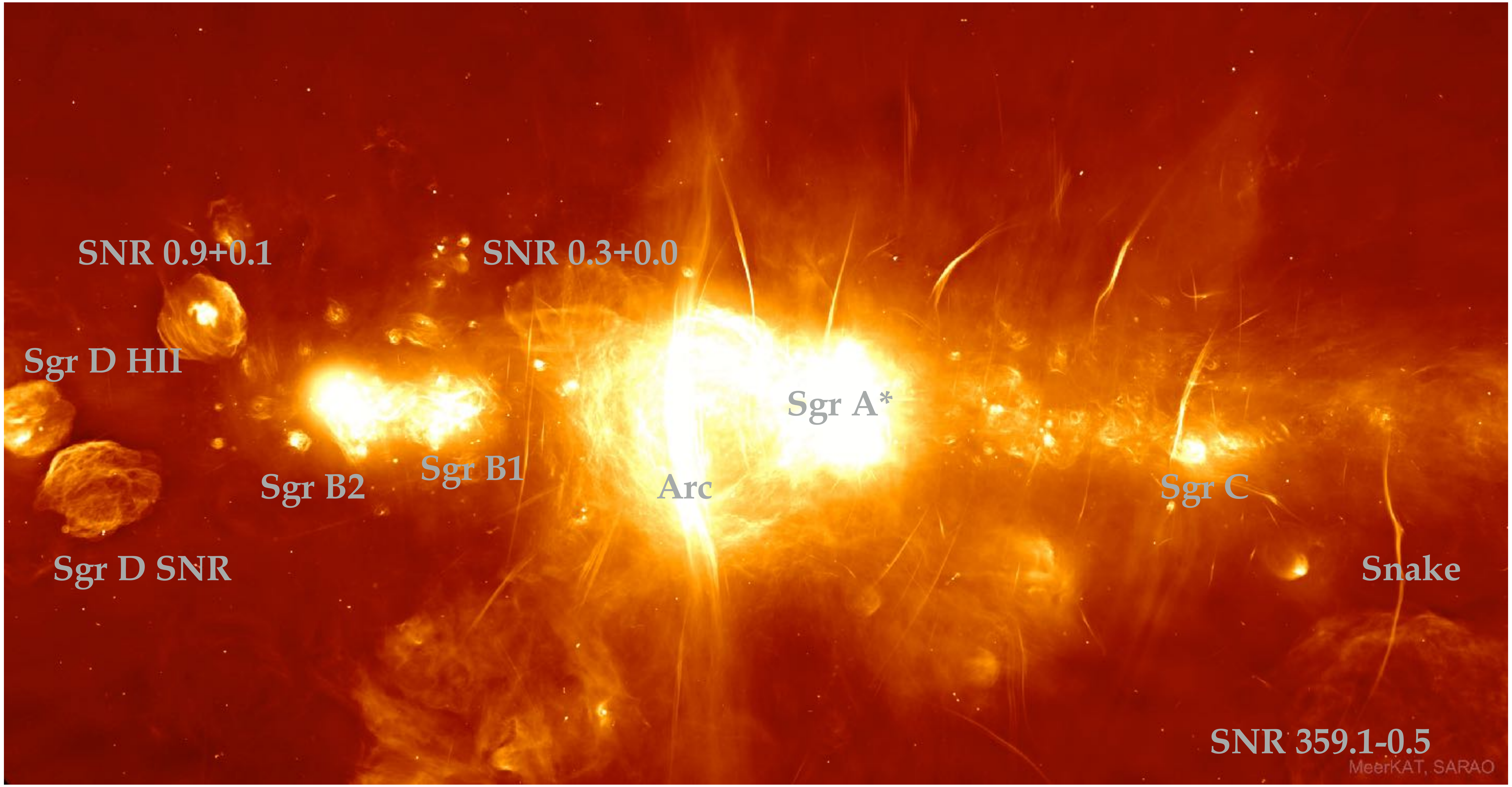
The Galactic centre

A panorama of the Galactic Center builds on previous surveys from Chandra and other telescopes.

This latest version expands Chandra's high-energy view farther above and below the plane of the galaxy than previous imaging campaigns. **X-rays from Chandra** are orange, green, and purple, showing different X-ray energies, and the **radio data from MeerKAT are grey.**



The Galactic centre



Nature of the highest energy cosmic rays

Some basic ideas on the highest energy cosmic rays.

The historic first event in the very-high-energy domain was the *Oh-My-God* event observed by John Linsley on the Dugway Proving Ground in Utah in October **1991**. The energy of this spectacular event was **3×10^{20} eV.**

We will discuss a few possibilities for sources for such rare events, **sometimes also called Zevatrons**, named in analogy to Lawrence Berkeley National Laboratory's Bevatron and Fermilab's Tevatron.

It has to be kept in mind that all such events are **measured using the air-shower technique**. The **experimental error of the energy assignment is typically ±30%.**

A possible systematic uncertainty could arise from the **Landau–Pomeranchuk–Migdal (LPM) effect,** which may not have been correctly considered in the shower simulation. The LPM effect states that **at high energies or high matter densities, the cross sections for bremsstrahlung and electron–positron pair production decrease**. If not properly considered this might lead to a **misassignment of the energy of a shower.**

Nature of the highest energy cosmic rays

Landau–Pomeranchuk–Migdal (LPM) effect: A high energy particle undergoing multiple soft scatterings from a medium will experience interference effects between adjacent scattering sites. From uncertainty as the longitudinal momentum transfer gets small the particles **wavelength will increase, if the wavelength becomes longer than the mean free path in the medium then the scatterings can no longer be treated as independent events, this is the LPM effect.** The Bethe–Heitler spectrum for multiple scattering induced radiation assumes that the scatterings are independent, the quantum interference between successive scatterings caused by the LPM effect leads to suppression of the radiation spectrum relative to that predicted by Bethe–Heitler.

The formulas for bremsstrahlung and pair creation in matter are **inapplicable at high energy or high matter density**. The effect of **multiple Coulomb scattering by neighboring atoms reduces the cross sections for pair production and bremsstrahlung.**
The effect is experimentally confirmed.

Nature of the highest energy cosmic rays

Using typical numbers of the magnetic field and the size of our Galaxy one arrives at a maximum energy, which can probably be produced and stored, of

$$E_{\text{max}} = 10^5\,\text{TeV}\;\frac{B}{3\times 10^{-6}\,\text{G}}\;\frac{R}{50\,\text{pc}}\,.$$

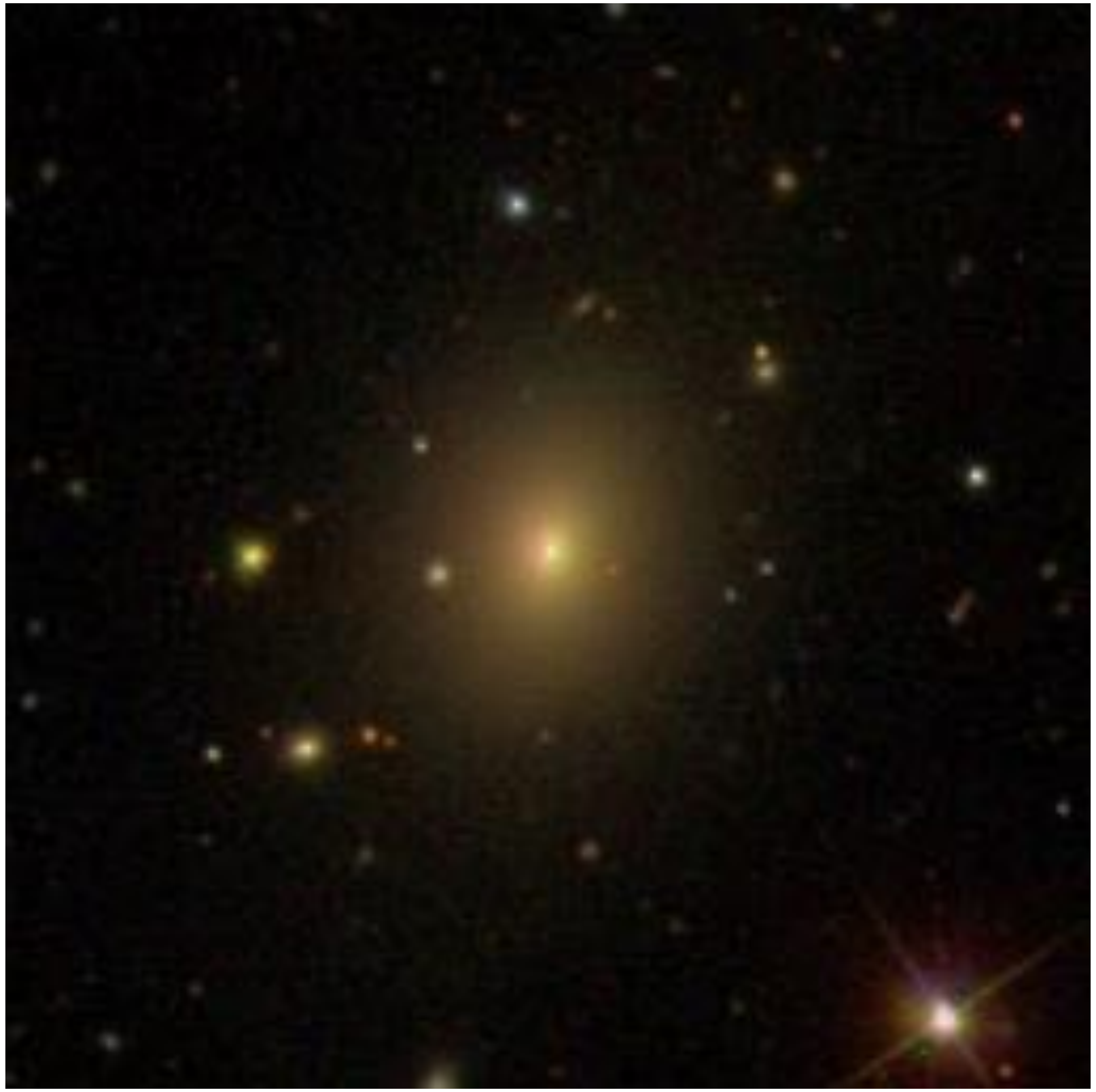
When $B = 3\ \mu\text{G}$ and $R = 5$ kpc are generously assumed, one gets

$$E_{\text{max}} = 10^7\,\text{TeV} = 10^{19}\,\text{eV}\,.$$

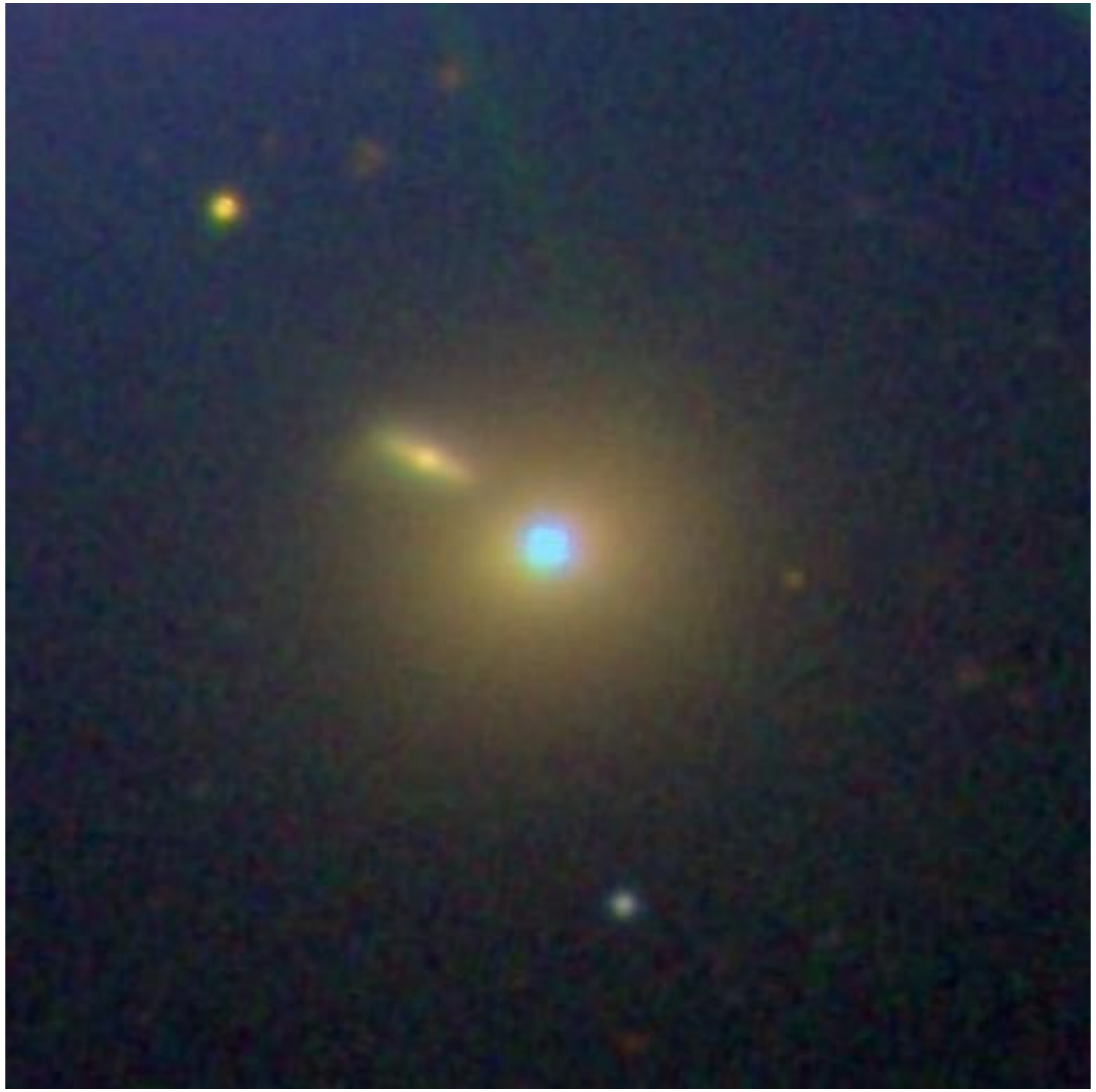
This equation tells us that our **Milky Way is unable to accelerate or store particles with higher energies,** so that one has to assume that such **particles must be extragalactic.**

The threshold energy for the **GZK cutoff** was **6×10^{19} eV**, leading to an attenuation length for protons of about 50Mpc. Therefore, **only nearby sources can be considered** as candidates for the high-energy particles. Possibly the Markarian galaxies **Mrk 421 and Mrk 501,** standing at distances of about 100 Mpc or **M87** (at 17 Mpc), are conceivable as candidates.

Nature of the highest energy cosmic rays



Mrk 501 - a blazar



Mrk 421 - a blazar: AGN with a jet pointing towards us

Nature of the highest er

It has to be mentioned that the GZK cutoff can possibly be **circumvented by assuming that the primaries are heavy nuclei.** For **iron primaries the GZK cutoff** would be in that case at $\mathbf{3.4 \times 10^{21}}$ **eV**.

The chemical composition at high energies is subject of current research, and there is no general agreement about the outcome (Fig 6.12).

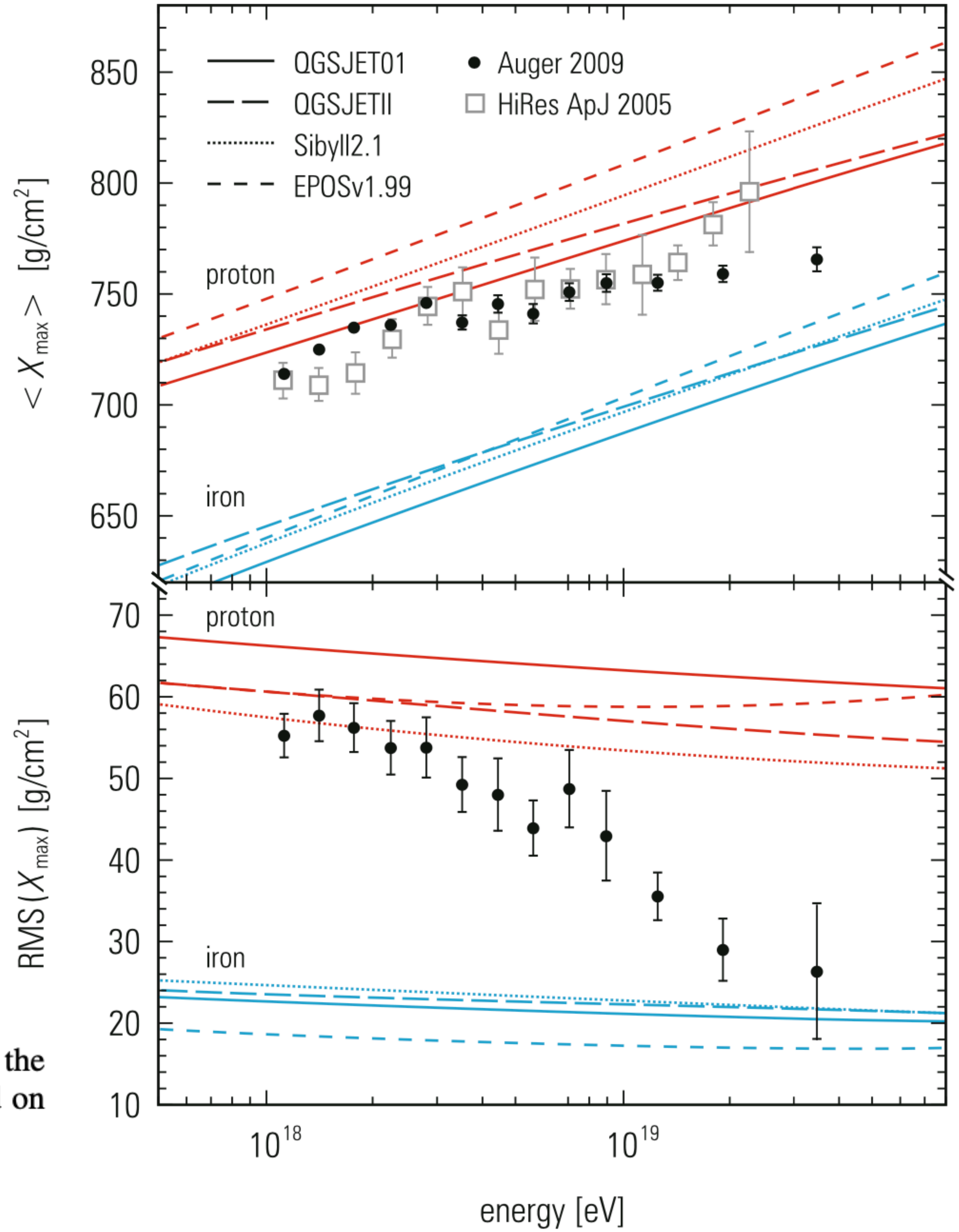


Fig. 6.12 Energy dependence of the position of the shower maximum $X_{\max}$ and its width for the Auger and HiRes experiments compared to various results of Monte Carlo simulations based on different hadronization models for protons and iron nuclei [61]

Nature of the highest energy cosmic rays

A somewhat **extreme and drastic assumption** would be to believe that the very energetic events were **due to a violation of Lorentz invariance**. If Lorentz transformations would depend not on the relative velocity differences rather on the absolute velocities, this would modify the threshold for the GZK cutoff.

A more mundane idea for the cutoff would be to assume that **cosmic accelerators just run out of power to produce higher-energy particles in sufficient numbers**.

Photons as origin of high-energy showers are even more problematic. **Photon– photon interactions** with cosmic microwave photons or photons in the infrared or radio domain would prevent them to arrive from larger distances.

Neutrinos as candidates also have problems to explain high-energy events. Their interaction cross section is so small that **one would need extreme neutrino fluxes to arrive at a significant rate of events.** Also the distribution of vertices of air-shower events in the atmosphere is in conflict with a neutrino hypothesis.

Also **WIMPs would only undergo rather weak or even superweak interactions,** which would make their origin for the energetic events very unlikely.

Nature of the highest energy cosmic rays

The fact that the arrival directions of the **high-energy events do not convincingly cluster** at some source candidate could be explained by the assumptions that the **galactic or extragalactic fields are stronger than anticipated**. There are in fact hints that the magnetic fields might lie in the μgauss rather than in the ngauss range.

Active **galactic nuclei** are frequently considered as potential **candidates for the highest-energy particles**. In particular, **blazars** with their powerful jets or even black holes are potential sources. The discovery of **black-hole mergers** in 2015 has shown that such cataclysmic events can convert masses effectively into radiation, or, why not also produce high-energy particles in these catastrophic events.

Blazars and black holes

Particle **jets from blazars or mergers of black holes** are a popular scenario of the possible production of particles of extreme energy (see Fig. 6.13). If such reasoning were correct, these candidate sources **should also be a rich source of high-energy neutrinos**, and ICECUBE would have a chance to detect them.

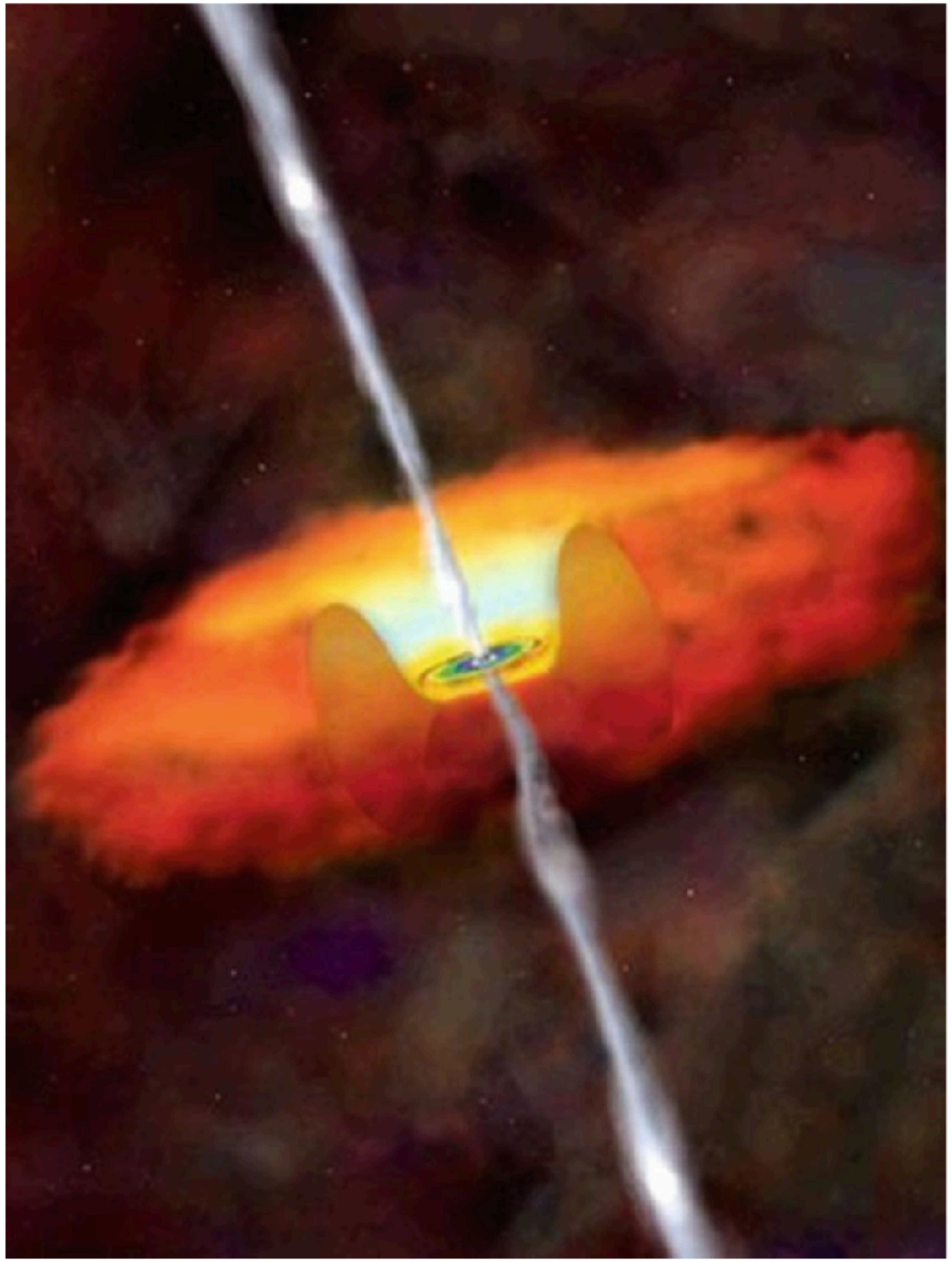


Fig. 6.13 Artist's view of a blazar ejecting jets, in which high-energy particles might be accelerated [62]

Blazars and black holes

Even though the origin of high-energy cosmic rays is an open question there are some tentative indications that at least some of them might come from the **super-galactic plane** (see also Fig. 7.36).

Obviously more events are required to establish such a correlation. Apart from Auger, also **ICECUBE** has a chance to find possible point sources, in particular, since they have seen **some extragalactic neutrinos in the PeV range.**

It is probably necessary—apart from collecting better statistics—to use larger detector systems or better detection techniques (e.g., JEM-EUSO - Joint Experiment Missions for Extreme Universe Space Observatory).

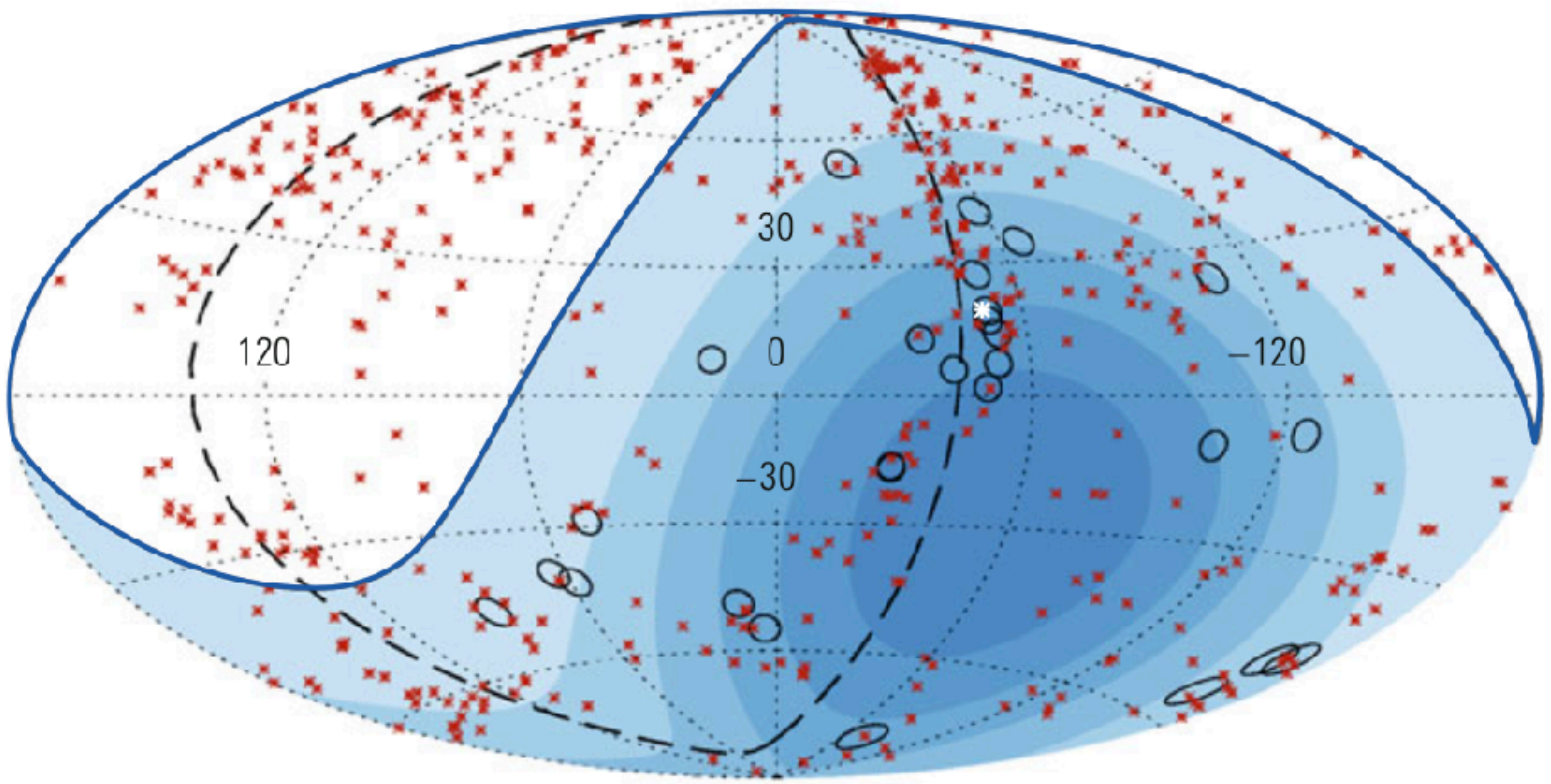


Fig. 7.36 Arrival directions of the 27 most energetic air showers measured from the Auger experiment in galactic coordinates. The energies of the air showers are larger than 57 EeV. They are shown as open circles. At the same time the positions of 471 active galactic nuclei (AGNs) within 75 Mpc are given as *red stars* ∗. The *blue region* defines—depending on the exposure time—the field of view of the Auger experiment. The *full line* shows the limit of the Auger acceptance. Centaurus A is marked as *white star* (∗). Two out of the 27 air-shower events arrive within the angular resolution of Auger from this direction. The *dashed line* indicates the position of the supergalactic plane [133]

Exotic events

Finally, it should be mentioned that some people try to explain an unknown by another unknown phenomenon. **High-energy particles may not be the product of an acceleration.** They could also be **decay products** of **unstable, primordial objects**. There are plenty of candidates for that:

- *heavy SUSY particles from supersymmetric theories*
- *topological defects*
- *domain walls*
- *magnetic monopoles (if they exist)*
- *cosmic strings*
- *cosmic loops of superconducting current*
- *necklaces*
- *massive metastable particles as remnants from the Big Bang or the inflation period*
- *particles from another universe?*

As one can see there are many ideas for powerful hotspots to produce exotic events in the universe or beyond.