

# Ultra high energy cosmic rays

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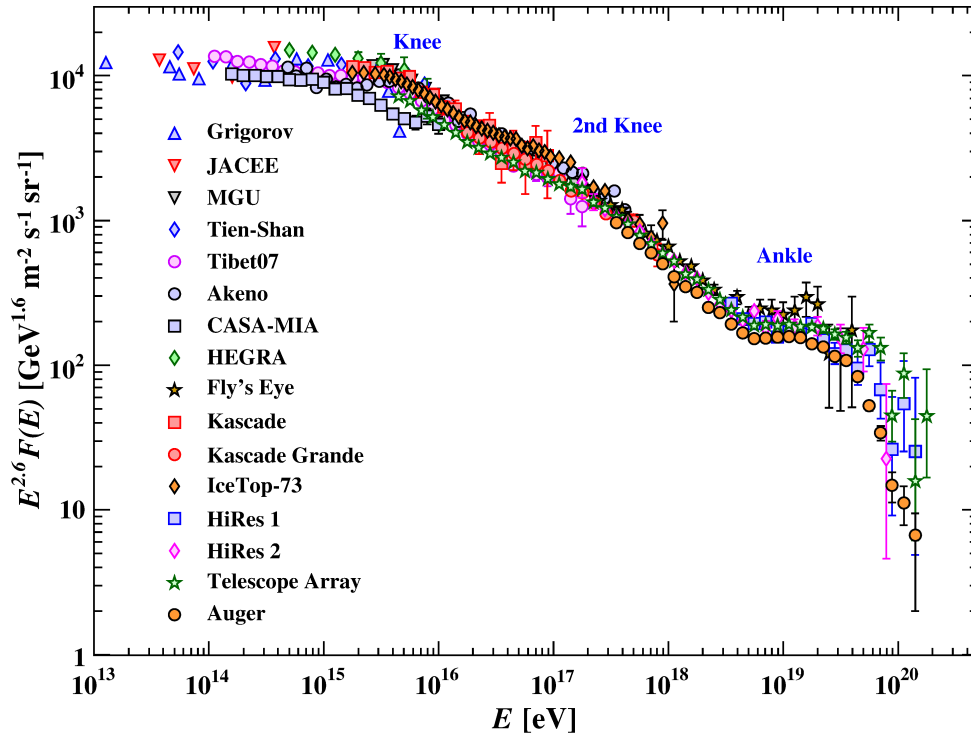
**Abstract.** Ultra high energy cosmic rays are the highest-energy particles ever observed in nature. Although known for more than half a century, their origin is still baffling scientists. They are most likely linked to some of the most violent phenomena in the universe but the nature of their sources remains a mystery, and so does the physical mechanism to accelerate particles to extreme energies. Here we review the different aspects of ultrahigh energy cosmic rays, emphasizing the key achievements over the past decade in our understanding of their origin. We also give a brief account of upcoming experiments and the prospects of progress in this field of research.

## 1. Introduction

Cosmic rays are high-energy particles coming from outside the solar system that strike the Earth from all directions [1]. They consist of atomic nuclei, mainly protons, but also include  $\alpha$ -particles and heavier nuclei. The origin of these particles is still mysterious. We do not know where they come from, and this is the longstanding question in this field of research. As they are electrically charged, they interact with the cosmic magnetic fields during propagation and undergo deflections. When cosmic rays reach the Earth, any information about their origin, as might be expected, is lost.

The most significant observable in cosmic-ray physics is definitely the all-particle energy spectrum, that is differential flux versus energy as shown in Figure 1. The most striking aspects of this spectrum is that it covers a very wide range of energy, extending beyond  $10^{20}$  eV, which is much higher than anything achieved in human-made particle accelerators including the Large Hadron Collider (LHC). In addition, the flux is very steep and decreases dramatically with increasing energy (Please note that the scales are logarithmic). To outline the special features of the spectrum, the differential flux is multiplied here by  $E^{2.6}$  (where  $E$  is the energy). Indeed, the energy spectrum of cosmic rays is observed with two steepenings at about  $3 \times 10^{15}$  and  $8 \times 10^{16}$  eV, commonly called the "knee" and the "second knee" of the spectrum, respectively, and then a flattening around  $4 \times 10^{18}$  eV denoted as the "ankle" of the spectrum. All these spectral peculiarities are not yet fully understood. Nevertheless, it is generally assumed that cosmic rays below  $10^{18}$  eV originate in our Galaxy, and then the knee could indicate that the Galactic sources have reached their limits for the acceleration of cosmic-ray protons [3]. The second knee may have a similar origin but is rather related to heavier cosmic rays, especially iron [4]. As for the ankle, the most popular explanation is that it reflects the transition from the Galactic flux to an extragalactic flux beginning to predominate around  $10^{18}$  eV [5].



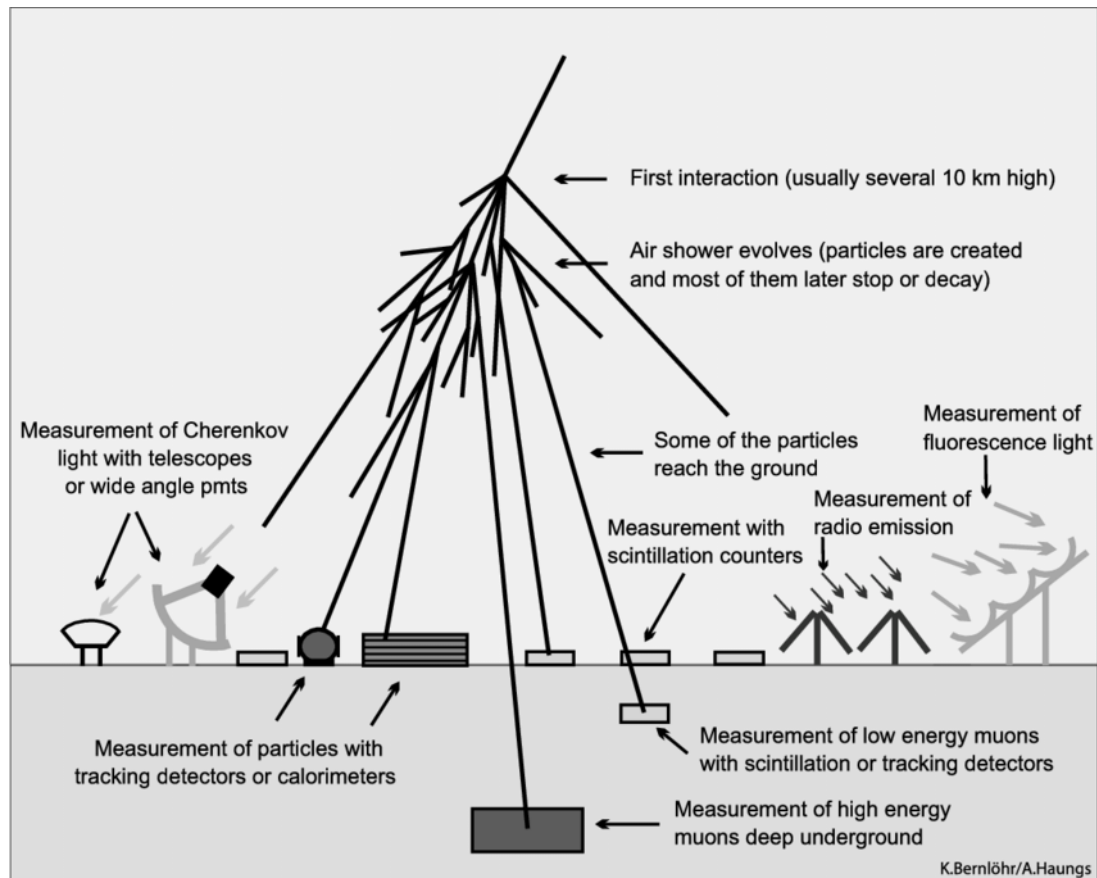


**Figure 1.** The all-particle energy spectrum of cosmic rays. Figure extracted from reference [2].

Ultra high energy (UHE) cosmic rays naturally lie at the most extreme right-hand side of the energy spectrum (Figure 1). Specifically, they denote cosmic particles with energies greater than  $10^{18}$  eV. Not only the origin of these particles is still unknown, but also the physical mechanism to accelerate particles to such huge energies [6, 7, 8, 9, 10]. The first observation of a cosmic particle in this energy range was achieved at the Volcano Ranch experiment in New Mexico in 1962 [11]. The energy was estimated at about  $10^{20}$  eV. The record holder so far is a cosmic particle with an energy of  $3 \times 10^{20}$  eV observed in 1991 by the Fly's Eye detector [5]. UHE cosmic rays are characterized by an extremely low flux, about 1 particle/year/km<sup>2</sup>. The question here is how it is possible to detect particles with such a low flux. In fact, it's rather impossible to detect these particles directly but it's quite possible to detect them indirectly through the phenomenon of extensive air showers (EAS). An EAS, as sketched in Figure 2, is caused by a single cosmic-ray particle of high energy when it enters the atmosphere and strikes an air nucleus, which results in a cascade of secondary particles to be detectable at the ground (and even underground). At very high energy EASs are accompanied by several radiations: Cerenkov light, radio emission and fluorescence light. Moreover, they spread over a large area on the ground, and then arrays of detectors operated for long times are necessary to study high-energy cosmic rays. There are two common types of detection technique used for studying UHE cosmic rays: arrays of surface detectors that measure the lateral distribution of the EAS on the ground, and fluorescence telescopes that observe the longitudinal development of the EAS in the atmosphere.

Another important issue about UHE cosmic rays is the so-called GZK effect, named after the physicists who discovered this phenomenon in 1966 [13, 14]. As UHE cosmic rays propagate from their sources to Earth, they interact with the low-energy photons of the cosmic microwave background (CMB) and produce pions through delta resonances:

$$p + \gamma_{\text{CMB}} \longrightarrow \Delta^+ \longrightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$$



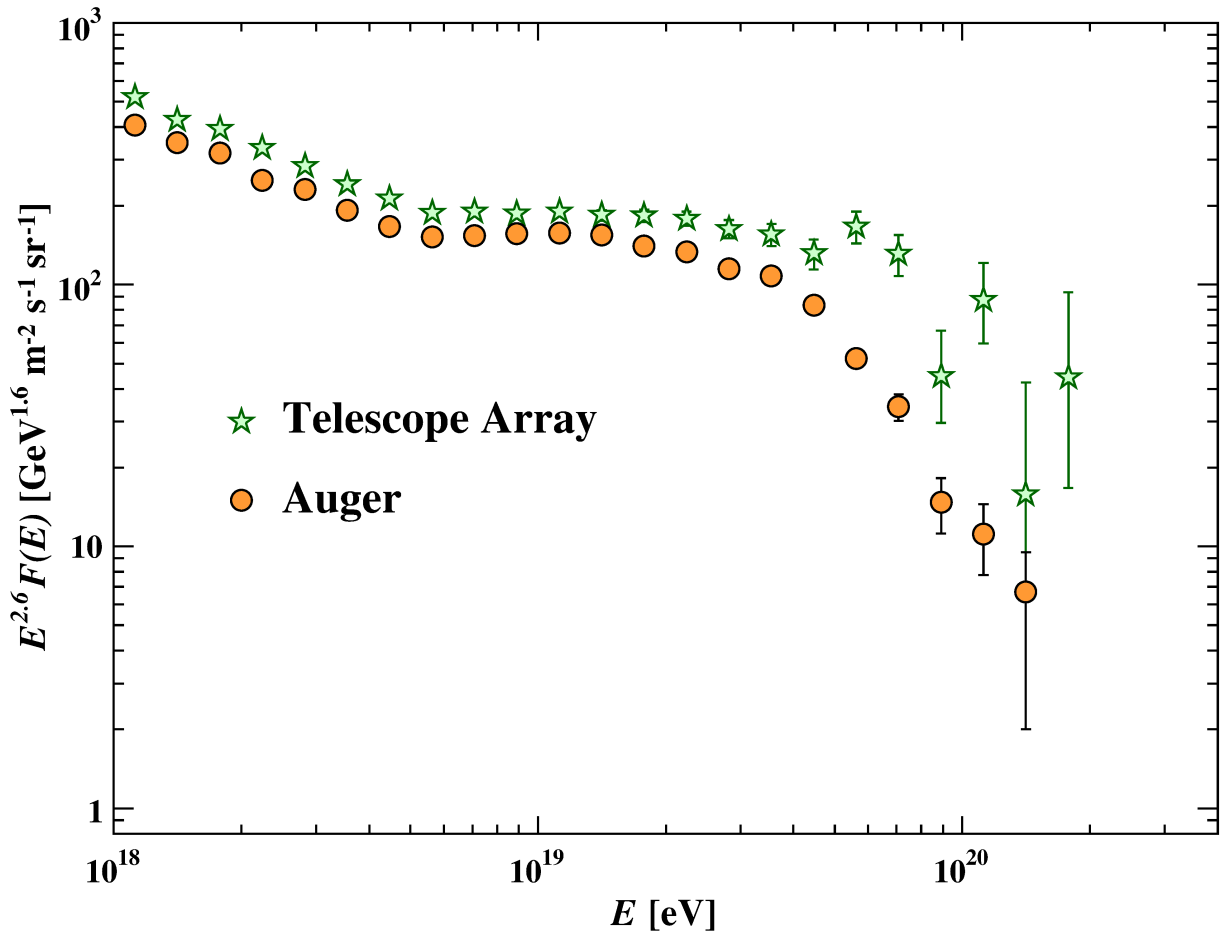
**Figure 2.** Sketch of the different ways to study experimentally an extensive air shower. Figure extracted from reference [12].

For protons, this energy loss process occurs above a threshold energy of about  $5 \times 10^{19}$  eV. This also means that the energies of cosmic-ray protons should then not exceed this limit if they are cosmological in origin. The photo-dissociation of heavy cosmic-ray nuclei seems to have a similar effect [15]. However, several hundreds of cosmic rays above the GZK limit have been observed so far, which makes clear that the sources of these particles are nearby, certainly somewhere in the local universe within a few tens of Mpc.

## 2. Current status of observations

Much progress in this field has been made in recent years with the advent of a new generation of large-scale experiments, namely the Pierre Auger Observatory in Argentina [16] and the Telescope Array (TA) experiment in the USA [17]. Both are hybrid detectors, employing two complementary observation techniques in order to improve data as to quality and quantity. They combine a huge array of surface detectors with a collection of large air fluorescence telescopes. The main experimental observables are:

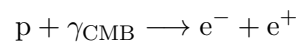
- (i) the energy of the primary particle, from which the energy spectrum of cosmic rays is built;
- (ii) the shower maximum depth (the atmospheric depth at which an EAS reaches its maximum in terms of total number of secondary particles), which is very sensitive to the mass of the primary particle and thus to the elemental composition;
- (iii) the arrival direction of the primary particle which is necessary for studying anisotropy.



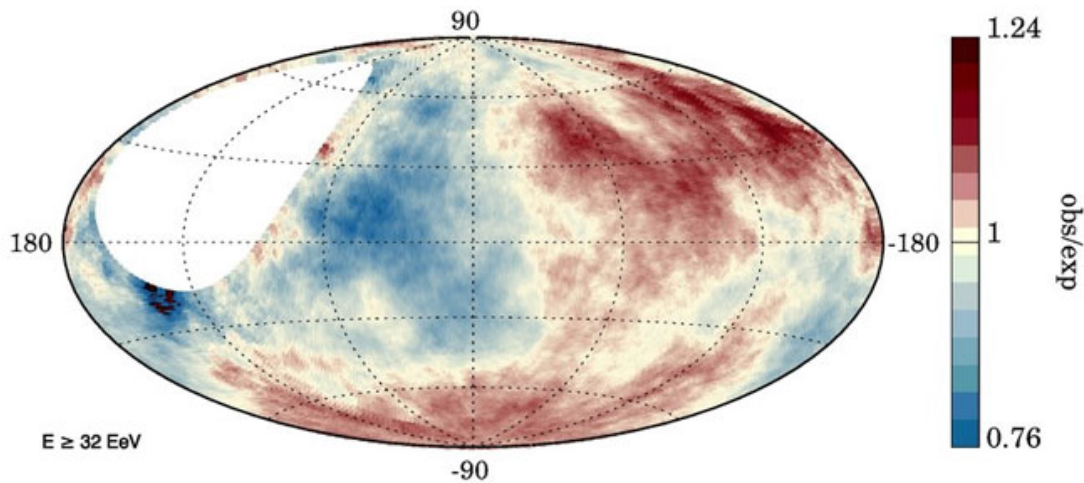
**Figure 3.** The all-particle energy spectrum of cosmic rays at the highest energies. Figure extracted from reference [2].

### 2.1. Energy spectrum

Measuring the energy spectrum of UHE cosmic rays is very important for understanding their origin. The observed spectrum, as can be seen in Figure 3, exhibits two major features not yet well understood. There is first a hardening at about  $4 \times 10^{18}$  eV known as the ankle of the spectrum as aforementioned, and then a softening above  $5 \times 10^{19}$  eV. Besides the possible interpretation of the ankle being the signature of the transition from Galactic to extragalactic cosmic rays, another proposed explanation is that the dip structure observed in the region of the ankle results from the interaction of extragalactic cosmic-ray protons with the photons of the CMB with production of electron-positron pairs [18]:



The second feature of the spectrum, that is the flux suppression above  $5 \times 10^{19}$  eV, occurs at almost the same energy as expected from the long-sought GZK effect [19, 20, 21, 22]. However, one cannot exclude the possibility of running out of energy at cosmic accelerators [23]. The spectra measured by TA and Auger Observatory agree within systematic errors below  $10^{19}$  eV. However, a large difference remains at and beyond the flux suppression and could hint at fundamental differences between the northern and southern skies.



**Figure 4.** Maps in Galactic coordinates of the ratio between the observed fluxes in different energy bins and the isotropic expectations. Figure extracted from reference [32].

### 2.2. Mass composition

The energy spectrum alone does not provide a reasonable basis to conclude about the origin of UHE cosmic rays. The mass composition of these particles offers additional key information and imposes constraints on acceleration and propagation models. Unfortunately, the determination of the primary mass in EAS measurements is not possible on an event-by-event basis. It is rather inferred on a statistical basis from the comparison of the measured shower maximum depth with predictions from theoretical models. Moreover, the hadronic interaction is poorly known at the highest energies, which entails a number of uncertainties in the assessment of the mass composition. The measurements of both TA and Auger indicate a proton composition around the ankle [24, 25]. Above  $10^{19}$  eV, the Auger data show a trend towards a heavier primary composition, while TA data suggest a light composition in the same energy range. So, at the highest energies the elemental composition of cosmic rays is still a matter of debate. It should be noted that a joint working group from both collaborations addressed this issue and concluded that the measurements by TA and Auger are consistent within systematic errors at all energies [26]. At this point, Auger results can neither be confirmed nor refuted by TA, due to statistical limitations.

### 2.3. Anisotropy

As cosmic rays are charged particles, their propagation is normally affected by extragalactic and Galactic magnetic fields, but the higher the energy the smaller the deflection. Auger and TA experiments have both found indications of intermediate-scale anisotropy in the arrival directions of observed cosmic rays with energies above the GZK limit [27, 28]. The TA data collected over an 11-year period show a concentration of events (hotspot) above  $5.7 \times 10^{19}$  eV around the Ursa Major with a Li-Ma statistical significance of  $5.1 \sigma$  [29]. The Auger data of nearly 15 years of operation indicate as well the existence of an excess above  $3.8 \times 10^{19}$  eV around Cen A with a local Li-Ma significance of  $5.6 \sigma$  [30]. Furthermore, Auger reported the detection of a large-scale anisotropy in the arrival direction distribution of cosmic rays above  $8 \times 10^{18}$  eV at more than a  $5.2 \sigma$  level of significance (Figure 4), described by a dipole with an amplitude of about 6.6% [31]. All these observations may very well constitute the first experimental pieces of evidence for an extragalactic origin of cosmic rays at the highest energies.

### 3. Potential sources

#### 3.1. Minimum requirements

To accelerate cosmic rays to ultra high energies, potential sources must first meet some minimum requirements. First, accelerators must provide the required energy budget to produce the observed flux of UHE cosmic rays. The energy production rate estimated by the Auger collaboration is given by [33]:

$$\mathcal{L}_0 \approx 5 \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1} \quad (1)$$

Actually, the true value of  $\mathcal{L}_0$  depends on the nature of the sources, the profile of the injected spectrum, the primary composition, the source luminosity evolution, etc.

In addition, a particle can stay in the acceleration region as long as its Larmor radius does not exceed the size of the accelerator. This confinement condition is commonly known as the "Hillas condition" [6]. The maximum energy achievable by a source is then given by:

$$E_{\max} \approx q \beta R B \quad (2)$$

where  $q$  is the electric charge of the particle,  $R$  the characteristic size of the accelerator and  $B$  its magnetic field ( $\beta$  can be considered here as the efficiency of the accelerator). The confinement condition is well illustrated in the so-called Hillas plot (Figure 5). It gives candidate acceleration sites as a function of their characteristic size and magnetic field strength. To accelerate a given particle species above  $10^{20}$  eV objects must lie above the corresponding lines. One can see that only a few astrophysical sources satisfy this necessary, but not sufficient, condition. It should be stressed here that acceleration also relies on other key factors, such the physical mechanism of acceleration, and the process of energy loss in the environment of the source.

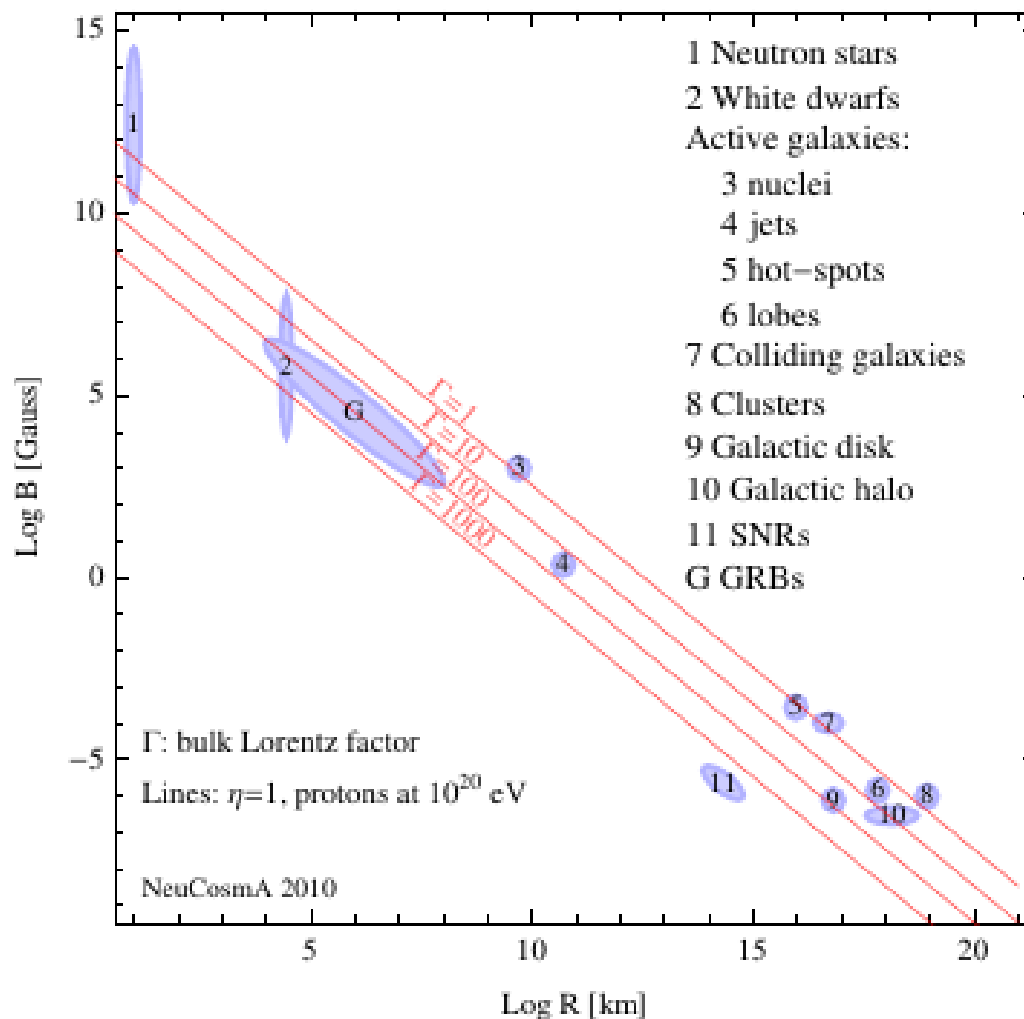
#### 3.2. Candidates

The most plausible sources of UHE cosmic rays that fulfill the minimum requirements, as discussed above, are the following.

- *Active galactic nuclei (AGN)* AGN are the most luminous persistent sources of electromagnetic radiation in the universe. They are the most promising candidate sources of UHE cosmic rays, especially AGN with powerful jets. Among these objects, blazars hold a key position as the jets are pointing to the Earth [35]. But the parent population of blazars, namely radio-galaxies with jets pointing away from the line of sight, are also potential sources. Cen A, which is the nearest of radio-galaxies, is a long-standing candidate [36].

- *Starburst galaxies* Starburst galaxies experience an exceptionally high star formation rate (SFR), typically 10 times higher than normal galaxies such as ours. The active regions of these objects often contain large amounts of very dense molecular gas and host intense magnetic and radiation fields [37]. These extreme conditions make them a preferred environment for the acceleration of cosmic rays up to the highest energies [38].

- *Gamma-ray bursts (GRBs)* GRBs are the brightest explosions in the observable universe, thought to be generated during the formation of black holes. Though they last only a very short time, they produce a huge amount of energy. They have long been discussed as potential sites for the acceleration of cosmic rays up to the highest energies [39, 40].



**Figure 5.** Hillas plot for potential sources of UHE cosmic rays, relating their size  $R$  and magnetic field strength  $B$ . To accelerate a given particle species above  $10^{20}$  eV objects must lie above the corresponding lines. Figure extracted from reference [34].

#### 4. Conclusion and perspectives

Despite the major advances made in the field of UHE cosmic rays, there are still some areas of concern. The ankle and the flux suppression of the energy spectrum are well established but not yet fully understood. For the primary chemical composition, a more complex picture is emerging. The anisotropy observed in the distribution of arrival directions above the ankle indicates an extragalactic origin, but the sources are still unknown. The next promising step is certainly the upcoming upgrade of the Pierre Auger Observatory and TA experiment, and the next generation of space-based detectors. The latter have the advantage of a much larger exposure and uniform coverage of the celestial sphere. The idea of the detection of UHE cosmic rays from space has already been developed in a number of projects: TUS [41], K-EUSO [42], JEM-EUSO [43], and POEMMA [44]. So, in the next decade there is great hope that some of the long-standing questions in this field of research will be fully answered.

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