

Chapter 2

The GZK Neutrino Flux

The main research topic of this thesis are the so-called GZK neutrinos. Shortly after the discovery of the **Cosmic Microwave Background (CMB)** an interaction between this omnipresent photon radiation and **Ultra-High Energy Cosmic Rays (UHECRs)** was predicted in the mid sixties by Greisen [1], Zatsepin and Kuzmin [2], named the GZK mechanism. In this interaction, pions are generated with a resonance in the cross section for cosmic ray energies slightly above the production threshold. Due to the resonance, the mean free path of cosmic rays with sufficient energy is reduced to some tens of Mpc. Since no source candidates of such high energy cosmic rays have been observed within this distance, a cutoff in the cosmic rays spectrum is expected. Furthermore, a guaranteed flux of neutrinos was predicted by Berezhinsky and Zatsepin in 1969 [3] to result from the GZK mechanism. This flux is a decay product from the generated pions and is estimated to be very small. Interactions of neutrinos from this flux are expected to happen at a rate of less than once per year in one gigaton of target material. Therefore, extremely large detector volumes are needed to investigate the GZK neutrino flux.

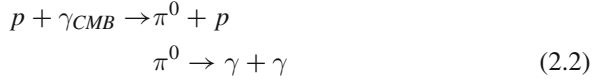
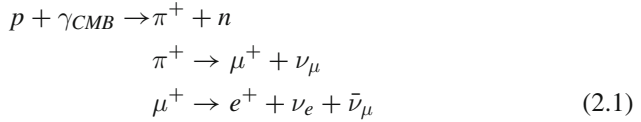
The GZK interaction depends on different factors. Most prominent among these factors are the mass composition of UHECRs, the distribution of sources throughout the Universe and their acceleration properties. Information about all three astrophysical features can be obtained by investigating the neutrino flux. Moreover, due to the predicted cutoff in the cosmic-ray spectrum, only a very small number of cosmic rays with energies above the cutoff are expected to reach the Earth. Thus, they can only be studied via GZK neutrinos.

The present chapter is a summary of various theoretical discussions. Neutrino production via the GZK mechanism is explained and the dependencies of the flux on different prerequisites are discussed. In addition, the informative potential of a neutrino flux measurement about cosmic rays in this energy region is shortly presented.

2.1 Neutrino Production in the GZK Mechanism

In 1965 the Cosmic Microwave Background radiation was observed by Penzias and Wilson [4] as an unknown black body radiation of 3.5 K. This result was first interpreted by Dicke et al. as a hint for the Big Bang to be the origin of our Universe [5]. Nowadays, very precise measurements of the CMB exist which confirm its general isotropy in intensity and Kelvin scale temperature as well as its black-body radiation spectrum [6].

It was realized as a necessary consequence of this omnipresent, isotropic radiation that cosmic ray particles (in the following represented by protons) would interact with it and produce pions through the so-called GZK mechanism [1, 2]. Such pions decay rapidly on their way through the Universe into final states that include neutrinos. The dominant reactions in the GZK mechanism are sketched in Eqs. 2.1 and 2.2.



This generation of pions is also denoted as photopion production.

Both, charged and neutral pions are produced in the interactions in Eqs. 2.1 and 2.2, but neutrinos are only produced in the decay of charged pions. Neutral pions instead decay mostly into gamma rays. Neglecting subsequent decays and interactions of produced neutrons, roughly 1/3 of the proton energy is transferred to neutrinos in photopion production. This ratio increases with rising proton energies due to an increasing cross section for π^\pm compared to π^0 [7], which is illustrated in Fig. 2.1. The lower energy threshold E_{th} for the GZK mechanism can be calculated via the center of mass energy to

$$E_{th} \approx \frac{6.8 \cdot 10^{16} \text{ eV}^2}{E_\gamma}. \tag{2.3}$$

In this equation, E_γ is the energy of the interacting photon from the CMB. The threshold energy is inversely proportional to the CMB energy spectrum, which shifts upwards with a growing redshift of the interaction [7]. For example, assuming a CMB peak energy of 1 meV, the threshold cosmic ray energy is 6.8×10^{19} eV. Slightly above this threshold, the cross section for pion production rises to a peak value of roughly 500 μb at the $\Delta^+(1232)$ resonance (Fig. 2.1). From the energy dependence of the shown cross section the shape of the resulting neutrino flux spectrum can be deduced (Fig. 2.2). A two peak spectrum is expected. The muon neutrino flux will peak at a neutrino energy corresponding to the resonance energy of the

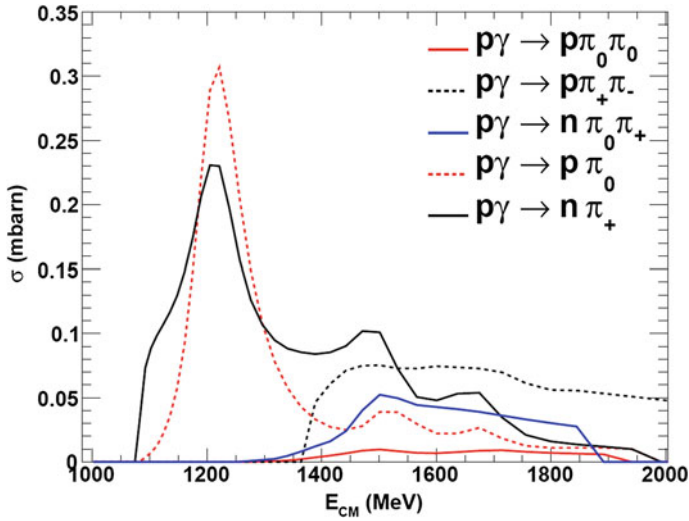


Fig. 2.1 The cross section for pion production in the interaction of protons and gamma rays. Interesting for the GZK mechanism is the Δ^+ resonance, where the cross section peaks to around $500 \mu\text{b}$ in total [8]

interaction. The electron neutrino spectrum will have two peaks, one corresponding to the resonance and one additional low energy component from the decaying neutron in Eq. 2.1. In general, the neutrino flux $F(E_\nu)$ can be calculated by integrating a source function L and the neutrino yield Y over the proton energy E_p and the redshift z [7]:

$$F(E_\nu) = \frac{c}{4\pi E_\nu} \cdot \int \int L(z, E_p^s) Y(E_p^s, E_\nu, z) \frac{dE_p^s}{E_p^s} dz. \quad (2.4)$$

The source function $L(z, E_p^s)$ describes the density and energy spectrum of the UHECRs. It depends on the production energy at the sources, their redshift distribution throughout the Universe and the energy loss of the cosmic ray particle during propagation. Furthermore, it scales inversely with the adiabatic expansion of the Universe. The neutrino yield function $Y(E_p^s, E_\nu, z)$ can be derived from Monte Carlo simulations with the given prerequisites of pion production cross section and the energy spectrum of the CMB. Apart from its influence on the CMB spectrum, the redshift of the interaction becomes important in the yield function if it is very small, comparable to the interaction length of the UHECRs. In this case, not all energy is transferred in photopion production and a lower number of neutrinos than expected is produced. This effect vanishes at distances above roughly 200 Mpc, where the number of produced neutrinos saturates [7].

An example for a flux calculated from Eq. 2.4 under certain assumptions for L and Y is displayed in Fig. 2.2. Models used, especially the model for the source function,

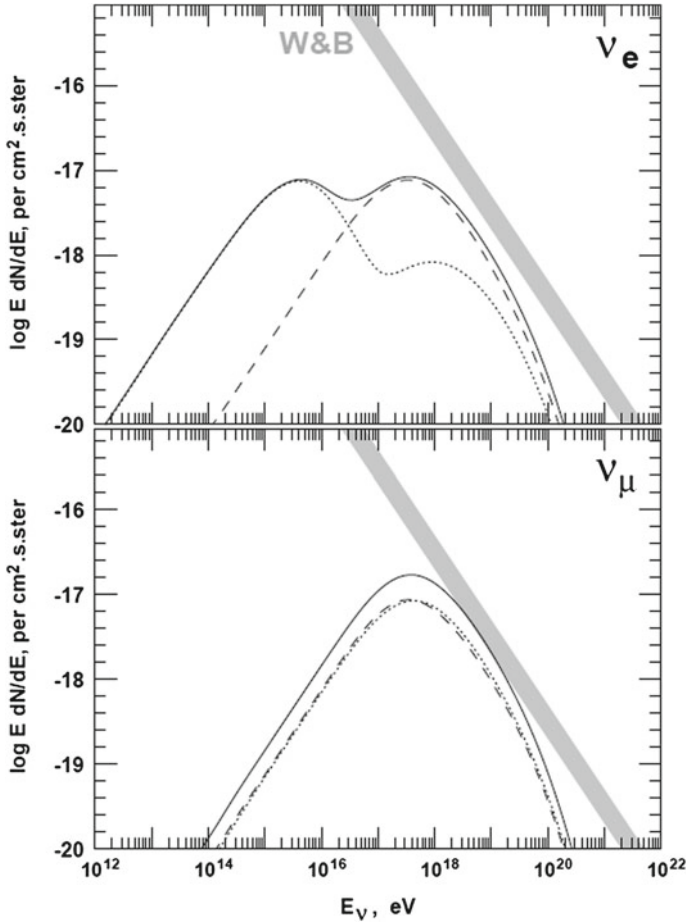


Fig. 2.2 An example of a neutrino flux generated by ultra-high energy protons, plotted versus energy. The *upper panel* shows the flux for ν_e , the *lower panel* for ν_μ . Neutrinos and antineutrinos are denoted by the *dashed* and *dotted* lines respectively. The *solid line* indicates the total flux from neutrinos of one flavor [7]

have big uncertainties, which make absolute flux predictions with the current knowledge impossible. Still it can be noted that the flux expectation is very low. Given the low cross section for neutrino interactions, different flux models result in less than one interaction per year per cubic kilometer of dense matter. It can be easily deduced that a detector exposure of several hundred km^3 years is needed to investigate the flux properties.

As explained, the cross section for photopion production has a resonance at $\Delta^+(1232)$. The resulting mean free path of cosmic rays with energies above approximately 10^{19} eV drops drastically to less than 10 Mpc. Until now, very few source candidates with high enough acceleration power to produce such energetic cosmic

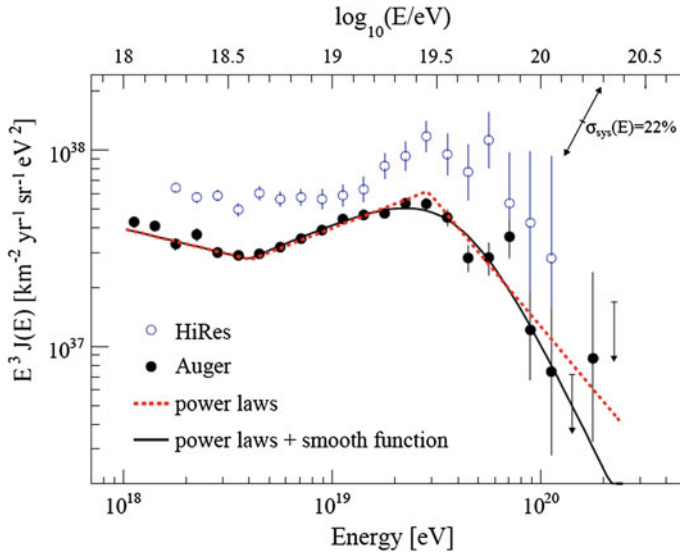


Fig. 2.3 The GZK cutoff as measured by the Pierre Auger Observatory and the HiRes Observatory [10]

rays have been observed within this range. Thus, nearly no cosmic rays with energies above the resonance are expected to arrive at Earth. This expected cutoff has indeed been measured by the High Resolution Fly's Eye Observatory (HiRes [9], now included in the Telescope Array Observatory) and confirmed by the Pierre Auger Observatory [10], as shown in Fig. 2.3. Still, these measurements do not provide evidence for a strong appearance of the GZK process and there can be other reasons for the cutoff, i.e. source exhaustion and the cosmic ray composition. These conditions and their influence on the GZK mechanism will be explained in the following section.

2.2 Dependencies and Implications

The dependencies of the GZK neutrino flux which have been explained so far are the cross section of the interaction and the CMB spectrum, which are measured very precisely. In Eq. 2.4, these dependencies determine the neutrino yield function Y , which is thus very well understood. The main uncertainties for the neutrino production are instead part of the source function L , determining the energy and density of UHECR at a certain point in the Universe. The most important parts of the source model are:

- the cosmic ray composition,
- the emission spectrum of cosmic ray sources,
- the source evolution throughout the Universe.

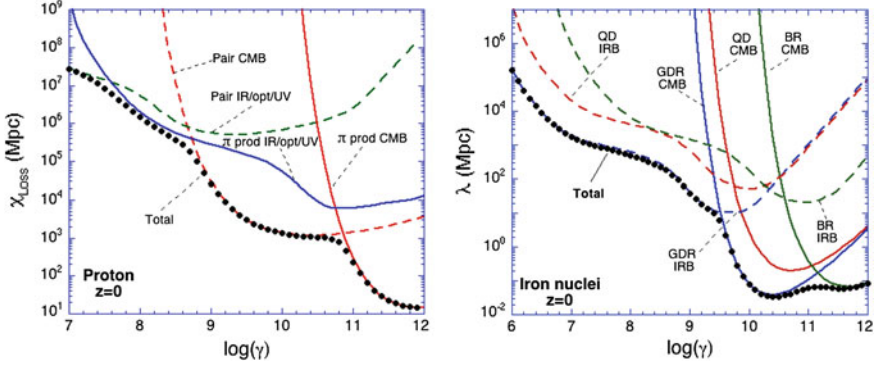


Fig. 2.4 The attenuation length for different energy loss mechanisms for protons (*left*) and iron nuclei (*right*). For the proton, e^+e^- pair production on the CMB is dominant up to the threshold energy for the GZK mechanism. For iron, the photo disintegration processes are dominantly the Giant Dipole Resonance (GDR) and the Quasi-Deuteron process. Photopion production is denoted as Baryonic Resonance (BR) [11]

These conditions and their influence on the GZK mechanism are strongly connected. Therefore, in the following only a qualitative explanation is attempted.

2.2.1 The Composition of Ultra-high Energy Cosmic Rays

The mass composition of the cosmic rays with energies above the photopion production threshold has a strong influence on the resulting neutrino flux due to the varying energy loss mechanisms and the limited production energy. If we assume cosmic rays at these energies to be dominated by protons, non-continuous energy losses other than the GZK mechanism can be neglected as shown in Fig. 2.4. The energy loss mechanisms for heavy nuclei instead differ strongly from those for protons. The dominant interactions with radiation are here photo disintegration processes, reducing the particle energy by emission of nucleons and alpha particles. In these processes neutrinos are only rarely produced through subsequent decays. The amount of energy per nucleon can be assumed constant in photo disintegration. Therefore, efficient photopion production can only happen at energies higher than $A \times E_{th}$, with A being the atomic number of the cosmic ray. Assuming a certain energy spectrum of UHECR, it becomes apparent that pure protons are highly favorable over heavier nuclei for the production of GZK neutrinos, since the threshold energy for photopion production is much lower.

The mass composition of UHECR is currently measured by two experiments, the Pierre Auger Observatory and Telescope Array, which disagree in their results [12, 13]. These two experiments measure the mass composition in multiple ways, for example via the average atmospheric depth of the maximum of cosmic-ray air showers in our atmosphere. From simulations, showers from heavy primary nuclei

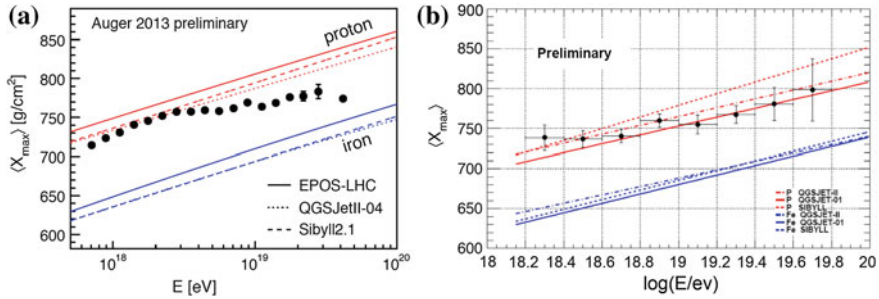


Fig. 2.5 The atmospheric depth of the shower maximum of air showers produced by cosmic rays with energies above 10^{18} eV measured by **a** the Pierre Auger Observatory [12] and **b** the Telescope Array Experiment [13]. The expectation for the depth of iron primary particles and protons is indicated in each plot by the red (proton) and blue (iron) lines. Differently dashed lines are produced with different shower simulations (different hadronic models) as indicated in the legends

are expected to develop less deeply in the atmosphere than proton showers. The shower depth measurements of the two experiments are displayed in Fig. 2.5. While the Auger data tends to a heavy composition, Telescope Array measurements predict a proton dominance in UHECRs. This disagreement illustrates the difficulties of measuring such a composition and consequently making predictions for the GZK neutrino flux. On the other hand a well understood neutrino flux measurement could put strong constraints on the mass composition.

2.2.2 The Cosmic Ray Emission Spectrum

The acceleration and emission of UHECRs is one more important parameter in the GZK neutrino production. So far, no acceleration mechanism has been proven to produce cosmic ray energies significantly above 10^{16} eV [14]. Under the assumption of dominantly heavy UHECRs, this can be extended to around 10^{18} eV [15], which is still below the threshold for photopion production. The most prominent model for high energy acceleration is the acceleration through shocks, also referred to as first order Fermi acceleration, in objects like Supernova Remnants, Active Galactic Nuclei and Gamma-ray Bursts. In this model, particles are accelerated during statistical crossings of electromagnetic shock fronts, gaining a small amount of energy with each crossing. The resulting spectrum from this shock acceleration follows a power law as $dN/dE = E^{-2}$ [14]. Particles can only be accelerated in this way, as long as they are contained in the object. Once they reach a critical energy, they escape and are not further accelerated. This critical energy is limited by the Hillas condition [16]

$$B \times L > \frac{2E}{Z\beta}. \quad (2.5)$$

In this equation B denotes the magnetic field in the object and L its size. The parameter E stands for the energy of the particle, Z for its charge and $\beta = v/c$ denotes its speed relative to the speed of light. In current observations no objects have been found which allow acceleration to sufficient energies for the GZK mechanism.

Other, more exotic Top-Down models consider decays of super-massive particles into Standard-Model particles, which in principle could provide enough energy. In such decays ultra-high energy photons would be produced which have not been observed so far. Experiments like Auger strongly constrain their flux in the latest measurements and rule out most of the Top-Down models [17].

The existence of UHECRs on the other hand has been proven, as visible in Fig. 2.3. Cosmic rays are at least accelerated to energies of 10^{20} eV but their abundance at these energies throughout the Universe is mostly unknown. It is possible to extrapolate the primary cosmic ray spectrum from the one observed on Earth when accounting for all known energy loss mechanisms. Due to large uncertainties on these losses, for example due to the unknown mass composition, the extrapolation will not be able to provide a very precise result. If cosmic rays are not accelerated to energies sufficiently high above the threshold energy for photopion production, this interaction does not occur very often and the neutrino flux measured at Earth will be relatively low. An indication for no acceleration beyond the Δ resonance would be the absence of the pronounced peak in the GZK neutrino spectrum. Consequently, measurements of the neutrino flux in the GZK energy range will provide information about the existence of cosmic rays with energies above 10^{20} eV and about their energy spectrum.

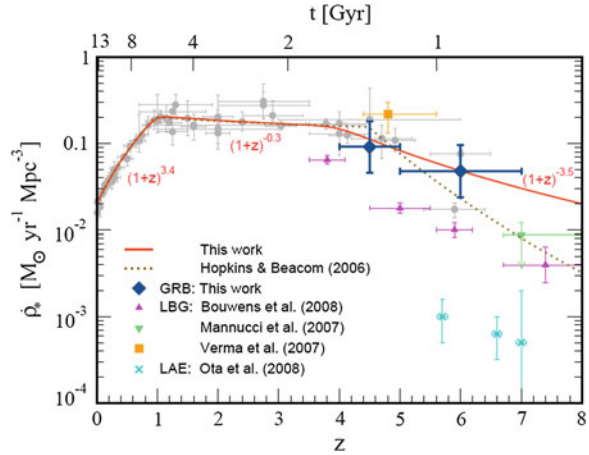
2.2.3 The Evolution of Cosmic Ray Sources

The distribution or evolution of cosmic ray sources in the Universe is important due to continuous energy loss of cosmic ray particles during propagation. It has been shown in [7] that neutrino production from protons rises up to a propagation distance of about 200 Mpc. Thus, if produced closer than this distance, less neutrinos are produced by emitted protons. In addition, the redshift of the interaction is important due to a changing CMB spectrum. At higher redshifts, the mean photon energy is higher and the threshold energy for photopion production consequently lower. The redshift also influences the neutrino flux shape through adiabatic energy loss of neutrinos propagating in an expanding Universe, which does however not affect their abundance.

In summary more distant sources appear to be favorable for GZK neutrino production. For the distribution of sources normally two possibilities are considered: isotropic distribution or a distribution coupled to the star formation rate.

A possible star formation rate, shown in Fig. 2.6, is discussed in [18], deduced from measurements of ultraviolet and far infrared radiation. Compared to an isotropic

Fig. 2.6 The star formation rate from measurements of UV radiation (*light grey dots*) including Gamma-ray Burst measurements with fit models shown as *solid* and *dashed lines* [18]



assumption, the star formation rate is higher at large redshifts. Hence, an assumption of isotropically distributed sources would result in a conservative limit for the neutrino flux. The coupling to the measured star formation rate though seems to be a more realistic model to follow.

2.2.4 Neutrino Flux Expectations Under Varying Assumptions

In Fig. 2.7 neutrino flux expectations are shown which are calculated under various conditions as described in [19]. The mass composition is investigated, on the one hand for cosmic rays of a single type but with varying mass (Fig. 2.7a), on the other hand for differently weighted combinations of protons with other cosmic rays (Fig. 2.7b). In Fig. 2.7a two cases are plotted for the source evolution: the conservative isotropic assumption and the more realistic source evolution coupled to the star formation rate, shown in Fig. 2.6. The cosmic ray injection spectrum is extrapolated from latest flux measurements at Earth, accounting for redshift effects and other energy losses like photo disintegration and Bethe-Heitler pair production. For the observed cosmic ray spectrum the data from the Pierre Auger Observatory are chosen, which are systematically lower than other measurements, as can be seen from Fig. 2.3. In this way, the cosmic ray spectrum is assumed conservatively.

The two plots in Fig. 2.7 show clearly the strong influence of changing cosmic ray masses and source evolution on the neutrino flux. As expected the highest flux is produced from pure protons under the assumption of a non-isotropic source evolution. It should be noted that a mixed composition, including a small amount of protons, provides still a more efficient neutrino production than pure relatively light nuclei like helium. The shape of the spectrum and the peak position changes strongly for

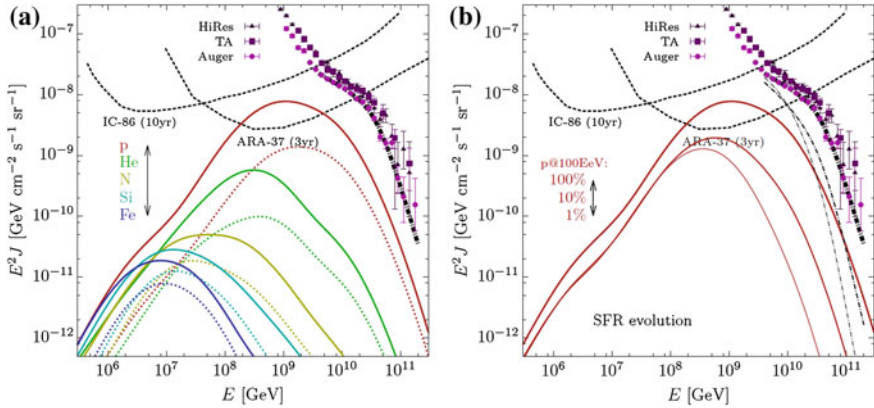


Fig. 2.7 The expectation of neutrino fluxes under various conditions. **a** The colored lines show neutrino fluxes under the assumption of different nuclei, dominant in UHECRs, for isotropic source distribution (dashed line) and source evolution following the star formation rate (solid line). The black dashed lines show the expected sensitivities of the IceCube detector and the full ARA detector. The data points display cosmic ray flux measurements from the Pierre Auger Observatory, Telescope Array and HiRes. This data is used to calculate the source spectrum for the cosmic rays. **b** The red lines indicate neutrino fluxes under the assumption of different amounts of proton contribution to UHECRs [19]

different cases, which supports the statement that a measurement of the GZK neutrino flux will provide valuable information about the discussed preconditions.

An interesting fact to mention in this GZK summary is the possibility to measure the GZK mechanism in photons instead of neutrinos. Gamma rays, produced during the GZK mechanism in the pion decay, accumulate in two energy regions after traveling through the universe. One region is above 10¹⁹ eV, close to the production energy. This is populated by photons which did not lose enough energy to enter the region of efficient production of e^+e^- pairs on the CMB or infrared background radiation. If the photon energy drops low enough to around 10¹⁸ eV, they will lose their energy rapidly in pair production and accumulate instead at energies right below the pair production threshold in the GeV range.

The Fermi-LAT experiment has set an upper limit on the GZK neutrino flux by measuring and limiting gamma ray fluxes between 100 MeV and 100 GeV [20]. The limit is calculated and shown in detail in [21]. In the highest energy region, around 10¹⁹ eV the Pierre Auger Observatory is currently conducting a gamma ray search and has provided limits for this region [17]. Since direct neutrino detection experiments currently put more stringent limits on the GZK flux than these two gamma ray measurements they will not be further discussed. Still they should be mentioned as an additional tool for the investigation of the GZK mechanism from a completely different detection method, which can become competitive in the coming years.

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