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Cosmic Rays

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In this talk I present resent results on high energy cosmic rays, including energy spectra, composition and the study of arrival directions of cosmic ray primaries. Some related results in gamma-ray astronomy and selected recent advances in theory are also covered.

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1. Introduction

The question of origin of high energy cosmic rays belongs to the list of one of the most interesting and important problems in particle astrophysics. Without exaggeration one can characterize resent years of research in this field as a quest for cosmic ray sources. In this talk I'll concentrate on this particular topic as well as on related problems of the cosmic ray spectrum and the mass composition, covering both the area of the Ultra-High Energy Cosmic Rays (UHECR) and recent related results in the gamma-ray astronomy.

All related studies in this area of research are centered, one way or another, around Greisen, Zatsepin and Kuzmin (GZK) effect. And here is how and why.

2. Ultra-high energy cosmic rays

2.1 Propagation of the ultra-high energy cosmic rays

1. Greisen-Zatsepin-Kuzmin cutoff. Immediately after the discovery of the relict Cosmic Microwave Background Radiation (CMBR), Greisen, Zatsepin and Kuzmin [1] have realized that the highest energy protons should catastrophically loose energy in photo-production of pions on this universal background. This process limits the distance to farthest sources of observed rays to be roughly 100 Mpc and should lead to the cut-off in the energy spectrum.

The findings of Greisen, Zatsepin and Kuzmin are based on solid fundamental physics which involves precisely measured cross-sections in a GeV energy range (in the center of mass reference frame) and on validity of Lorentz transformations. The question of whether the GZK-cut-off is present or not in the cosmic ray data is of fundamental importance since the absence of the GZK cut-off would be inevitable signal of the new physics.

On the other hand, observational confirmation of the cut-off in the highest-energy part of the cosmic ray spectrum would signify that the UHECR propagation length at high energies becomes substantially shorter than the characteristic length at which the Universe becomes homogeneous. Since the matter distribution is non-uniform being averaged over the scales of a few hundred Mpc, one generally expects the UHECR flux to be anisotropic, showing both point sources and flux variations at large angular scales.

That is why a lot of efforts had being devoted to the careful measurements of the ultra-high energy cosmic ray spectrum, while the GZK effect is behind the growing interest in the ultra-high energy cosmic ray research.

2. Magnetic fields. Beyond that, the prospects of charged particles astronomy strongly depend on the anticipated deflections of primaries in Galactic and extragalactic magnetic fields. Galactic magnetic fields are well under control, for the recent study see [2]. In the regular Galactic magnetic field, for particles coming across the Galactic disc, deflections for protons are expected to be on the level of 2°. For the discussion of weaker deflections in the turbulent component of the Galactic magnetic field see e.g. Ref. [3].

Extra-galactic magnetic fields have not been measured yet[1] (except for central regions of galaxy clusters). Known observational bounds on the strength and correlation length of EGMF

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[1] The evidence for gamma-ray halos around active galactic nuclei resulting from intergalactic magnetic fields is, in fact, absent [4].

are summarized in the Ref. [5]. The deflection angle of UHECR with energy E in a homogeneous random extra-galactic magnetic field B with coherence length λ can be estimated as

$$\frac{\Delta\theta}{Z} < 0.4^\circ \ \frac{10^{20}\ \mathrm{eV}}{E} \ \frac{B}{10^{-10}\ \mathrm{G}} \ \sqrt{\frac{L}{100\ \mathrm{Mpc}}}\sqrt{\frac{\lambda}{1\ \mathrm{Mpc}}}\,, \tag{2.1}$$

where Z is the atomic charge of a cosmic ray primary, and L is the distance to the source. However, the estimate based on the assumption of a Gaussian homogeneous field is not really applicable to the local highly structured Universe. E.g., deflections are strong after passing clusters and substantial after passing filaments. But those structures occupy small volume and deflections may be small for many viewing directions. Numerical modeling of magnetic field formation in the local Universe show that the deflections at highest energies around GZK cut-off are indeed negligible for protons for 99% of viewing directions [6, 7].

Since the sources of highest energy cosmic rays should be within GZK sphere, the trajectories of protons with $E > 10^{20}$ eV, are not strongly bent by either Galactic or extra-galactic magnetic fields and resulting deflections are comparable to the angular resolution of modern UHECR detectors. One may anticipate bright future for the emerging charged particles astronomy, if substantial fraction of cosmic ray primaries consists of protons. This highlights also the importance of the studies of UHECR mass composition.

2.2 Energy Spectrum

In the past four decades which had followed the GZK findings, the number of events with energies beyond the expected cut-off, as measured by different installations, had being growing with time, without cut-off indication, while no nearby sources where identified. In particular, the spectrum measured by the AGASA ground array of particle detectors [8] is shown in Fig. 1. The GZK-suppression was first observed by HiRes [9] using different technique which makes use of fluorescence light telescopes, see Fig. 1. It became clear that the hybrid approach, with simultaneous use of the ground array and the fluorescent light measurements, is necessary. Such hybrid approach should reduce systematic errors, and should allow more precise determination of physical characteristics of primary particles, just because more parameters of air shower are measured, and this became the design of the latest generation of cosmic ray observatories, the Pierre Auger project in the South hemisphere of Earth [11] and the Telescope Array in the North [12].

Pierre Auger Observatory (PAO) consists of array of 1600 water Cherenkov detectors covering an area of about 3000 km^2 and of four stations of Fluorescence Detectors (FDs) located on the periphery of the ground array. PAO is the largest CR observatory in the world both in its physical extent and in the number of participating institutions and scientists. It is collecting data since January 2004. The Telescope Array project is a collaboration between universities and institutes in Japan, U.S.A., Korea, Russia, and Belgium. The Telescope Array (TA) experiment is located in the high desert in Millard County, Utah, USA. It currently consists of three stations of FDs and of array of 507 Surface Detectors (SDs) which together amount to the largest hybrid installation in the northern hemisphere to observe UHECRs. The SDs are deployed on a grid of 1.2 km spacing and cover a ground area of approximately 700 km^2. TA observations started in November 2007 for FD and in March 2008 for SD.

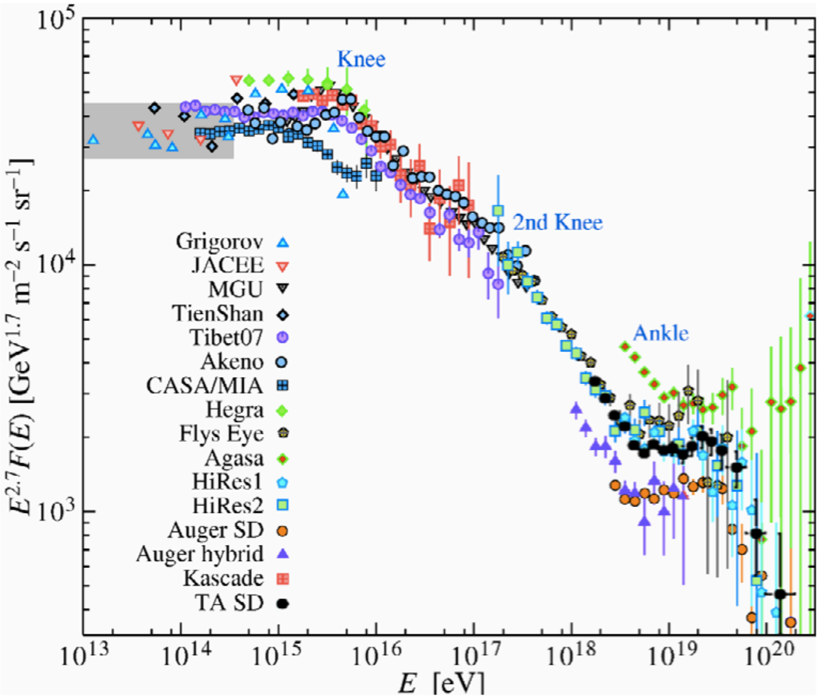

Figure 1: Overall cosmic ray spectrum. Adapted from Ref. [10] with the Telescope Array data being added.

By now, the GZK-suppression is confirmed both by the Auger observatory [13] and by TA collaboration [14] (with the significance of more than 20σ in just PAO data.), see Fig. 1. An absence of the suppression would have signify a new physics, as we have stressed already, and a new physics can reveal itself in a different way in detectors which operate using different principles [15]. In this respect it is important that SD detectors of the Telescope Array are identical to those which were used by the AGASA.

Though all recent spectra show the suppression at high energies, at the face value spectra are different, moreover leading to different conclusions after theoretical modeling of propagated spectra. Namely, assume simple power laws for the cosmic evolution of CR spectral emission rate per comoving volume

$$J_{source} \propto E^{-\beta}\,(1+z)^m, \tag{2.2}$$

where z is cosmological redshift. Then the measured spectra after propagation of primaries in cosmological backgrounds are fitted by Fe primaries in the case of PAO [16]. On the other hand the spectra of HiRes and TA are fitted by protons [17], see Fig. 2. Moreover, in this latter case the modeling extends to a lower energies while the position and a shape of the spectral feature called "ankle" do agree naturally with a theoretical prediction for the change of the initial power low spectrum after accounting for the energy losses due to e^+e^- pair creation in interactions of primary protons with CMBR [17].

While this conclusion and differences may look dramatic, note, that PAO and HiRes/TA spectra match after 20% shift in energy scale.

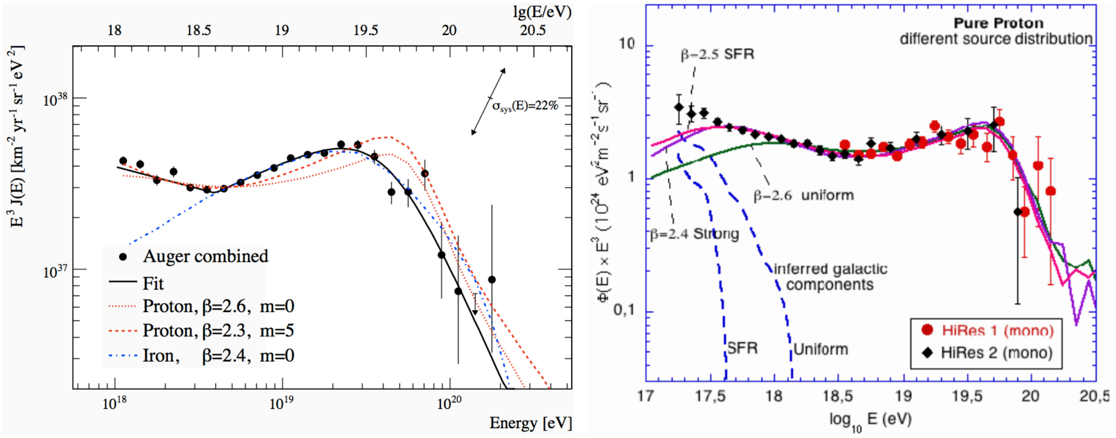

Figure 2: Theoretical modeling of energy spectra. Left panel: PAO data can be described by Fe primaries. Right panel: HiRes/TA data can be described by proton primaries. In both cases simple power laws for the injection spectra are assumed and primaries are propagated over cosmological backgrounds, β and m are defined in Eq. (2.2).

2.3 Mass Composition.

Longitudinal development of cosmic-ray air showers strongly depends on the primary energy and their particle type. FDs directly observe longitudinal shower development. Because of that, the fluorescence technique is particularly suited for the determination of the mass (chemical) composition of UHECR, though the information about longitudinal shower development can be extracted indirectly from SDs as well.

2.3.1 Fe or protons at highest energies?

The atmospheric depth at which the number of shower particles reaches maximum, X_{max}, is especially good indicator for a primary particle type. The behavior of $\langle X_{max}\rangle$ with energy, as obtained by PAO [18], HiRes [19] and TA [20] experiments is shown in Fig. 3. Other observables sensitive to the mass composition are also presented for the case of PAO. Namely, from top to bottom in the left panel of Fig. 3 are shown respectively: the muon production depth, asymmetry of signal rise-time, $\langle X_{max}\rangle$ and RMS(X_{max}). (The first two observables are extracted from SDs.)

We see that HiRes and TA data show consistency with proton-dominated composition in all measured energy range. On the other hand, all indicators obtained by Pierre Auger Observatory are suggesting that the average mass of cosmic rays above 3 EeV gradually increases approaching iron.

Note that a 20% relative shift in energy should be applied when comparing these results, see previous section. This leads to somewhat reduced statistics for HiRes/TA for any fixed value of re-mapped energy bins. Also, the presented results for HiRes/TA were obtained in the stereo mode of FD observations, while PAO data on $\langle X_{max}\rangle$ and RMS(X_{max}) correspond to hybrid events. This translates to a different possible systematics. Note also that the mass composition is not observed directly, it is extracted after comparison with Monte-Carlo predictions. The later are suffering from unsertainties in unmeasured yet details of hadronic interactions at high energies. Current

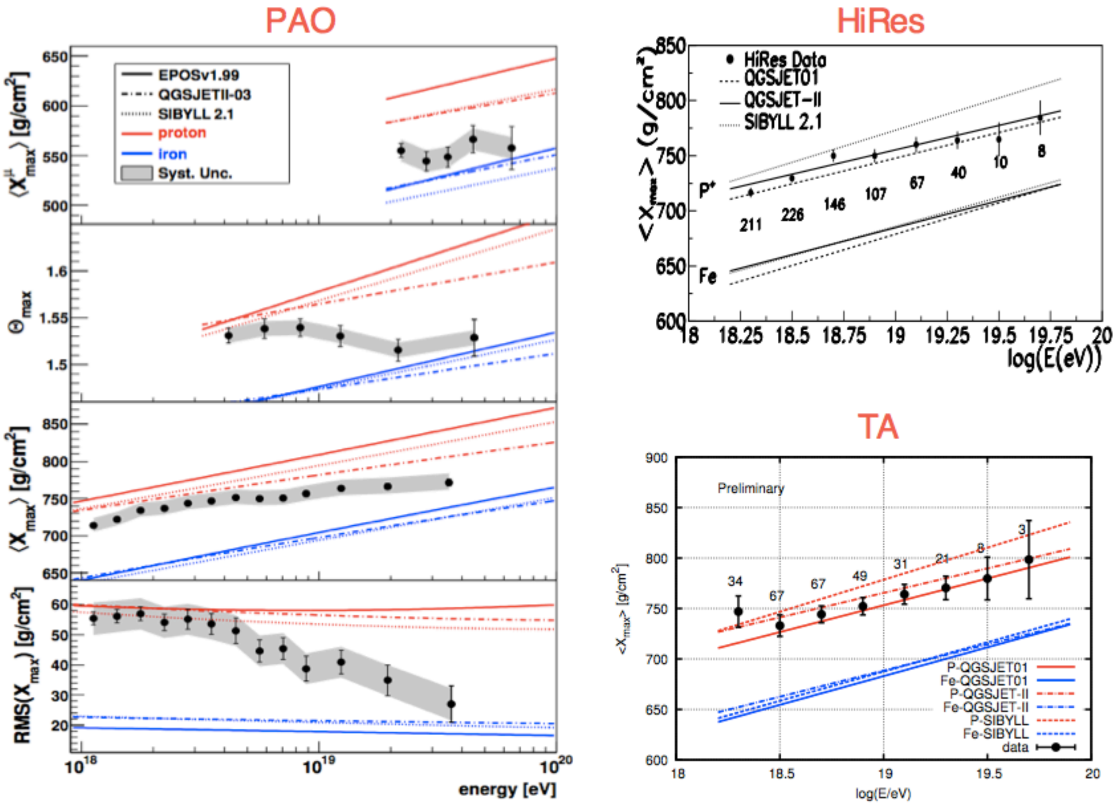

Figure 3: Various observables sensitive to mass composition compared to model predictions as functions of primary energy.

and forthcoming LHC results [21] should greatly improve our understanding here. However, it is unlikely that these yet unknown details are responsible for the difference between PAO and HiRes/TA.

2.3.2 Constraint on the photonic fraction.

A spectrum suppression at highest energies does not necessarily mean the GZK-effect. It may as well signify that the acceleration limit was reached by cosmic sources. Detection of photon or neutrino primaries would certainly help to disentangle these two alternatives. Photons and neutrino appear in a true GZK-effect as a by-product of photo-nuclear reactions. Expected fractions of these neutral primaries are small, see Section 3, and by now they were not detected. Current observational limit on the flux of photons and neutrino can be found in Refs. [22, 23].

2.4 Arrival Directions.

Anisotropy of arrival directions of primaries is a key to identifying the UHECR sources. Establishing the level of anisotropy is also an important step in ironing out the chemical composition of UHECR and measuring parameters of the intergalactic medium such as strength of magnetic fields and intensity of photon background radiation.

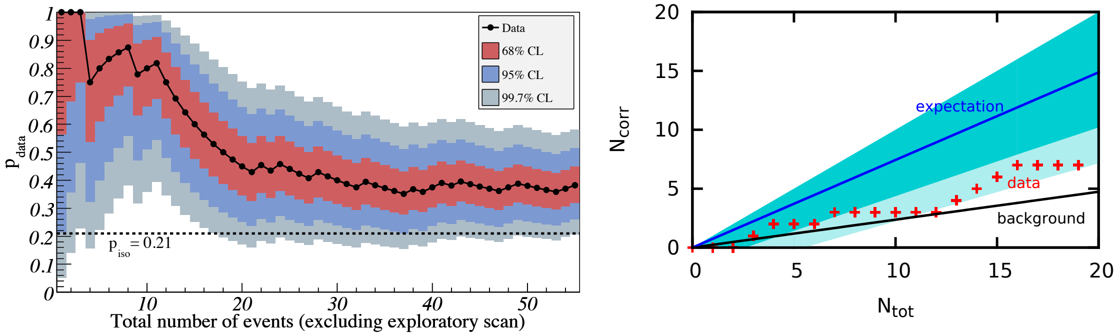

Figure 4: Amount of correlating events as functions of exposure. Left panel PAO, right panel TA.

Observation of the GZK-cutoff in the highest-energy part of the cosmic ray spectrum strongly suggest that the UHECR propagation length at high energies becomes substantially shorter than the size of the Universe, as were predicted by Greisen, Zatsepin and Kuzmin, and therefore their sources must be within at most a few hundred Mpc from Earth. Since the matter is distributed non-uniformly at these scales, one generally expects the UHECR flux to be anisotropic, possibly showing both point sources and variations at large angular scales.

i) *Auto-correlations.*

Clustering of CR arrival directions has been reported in the AGASA data at the angular scale of 2.5° and at highest energies. However, no significant clustering is observed currently, neither in PAO, nor in the HiRes/TA data.

ii) *Correlations with AGN.*

Pierre Auger Observatory has reported correlation [24] between highest energy cosmic rays and population of all known nearby (closer than 75 Mpc) AGNs. The correlation was observed at an angle of 3.1°. In the control data set, the number of correlating events was 9 out of 13, which corresponds to about 69% of events.

There are internal tensions withing AGN interpretation though [25]. Strictly speaking, the fact of correlations (say with the AGN population) tells us only that the distribution of arrival directions is non-isotropic (with the AGNs being possible candidates). Indeed, it is not possible to prove statistical hypothesis, it can be disfavored only. To test a hypothesis, the expected specific signal should be confronted with the data. And the data are disfavoring AGN hypothesis, e.g. there are such peculiarities as the lack of events from the Virgo region [25]. Also, correlations with AGNs are absent in the HiRes data [26]. These peculiarities are suggesting an alternative explanation for the Auger correlation signal. For example, Cen A is the closest radiogalaxy by chance projected on the local Large Scale Structure (LSS). It is outside of HiRes and TA field of view. If it is the source, it will contribute to the fake correlation with LSS and to this extent such source(s) may create fake correlations with the AGN population [25, 27, 28].

In the data-set collected by Pierre Auger after the initial publication, the correlation signal with AGN became significantly weaker, see Fig. 4 and Ref. [29]. Auger original AGN hypothesis is not supported by TA data as well [30], see Fig. 4.

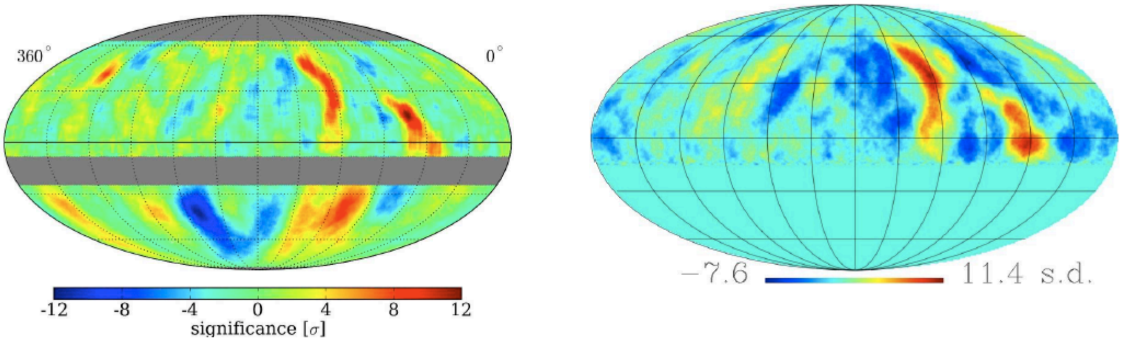

Figure 5: Small-scale anisotropy of TeV CR in Milagro and IceCube data (left panel) and in ARGO/YBJ data (right panel).

iii) *Correlations with LSS.*

Instead of testing correlations with a particular class of sources, more general procedure would be to test whether CR events are produced by sources that follow the matter distribution in the Universe [25, 31]. Such correlation should be inevitably present at high energies if UHECR primaries are protons, extra-galactic fields are reasonably small, and the number of sources is not small. In this approach it was found that the HiRes data are incompatible with the matter tracer model at a 95% confidence level [32].

iv) *Puzzling anisotropy at low energies.*

Recently a puzzling small-scale structures in the distribution of arrival directions of TeV hadronic primaries has been reported by several experiments. Using seven years of data, the Milagro collaboration published the detection of two regions of enhanced flux in the Northern sky with amplitude 10^4 and a median energy of 1 TeV with significance $> 10\sigma$ [33]. The same excess regions also appear on sky-maps obtained by ARGO-YBJ [34]. Similar structures are observed by IceCube in the Southern sky [35], see Fig. 5.

Small-scale anisotropies may indicate nearby sources of cosmic rays. However, such an interpretation is facing problems at low energies. E.g. the Larmor radius of a 10 TeV proton in a 2μG magnetic field is 0.005 pc. This makes it impossible for charged particles to point back to their sources if conventional propagation mechanisms are assumed. Further, the decay length of 10 TeV neutron is 0.1 pc, which is orders of magnitude smaller than the distance to any potential astrophysical high energy particle accelerator. No compelling explanation has been found for this anisotropy yet.

3. Gamma astronomy

While we have slow but steady progress in UHECR physics (recall that the flux of cosmic rays at highest energies is only a particle per square km per century) the situation is rapidly changing in the gamma ray astronomy - a huge number of new sources was detected in recent years by H.E.S.S., MAGIC, VERITAS and Fermi/LAT. This opens up a wide arena of studies in astroparticle physics. A current list of VHE γ-ray sources discovered by Imaging Atmospheric Cherenkov Telescopes can be found e.g. in [36]. A variety of recent results obtained using the first year data of Fermi/LAT

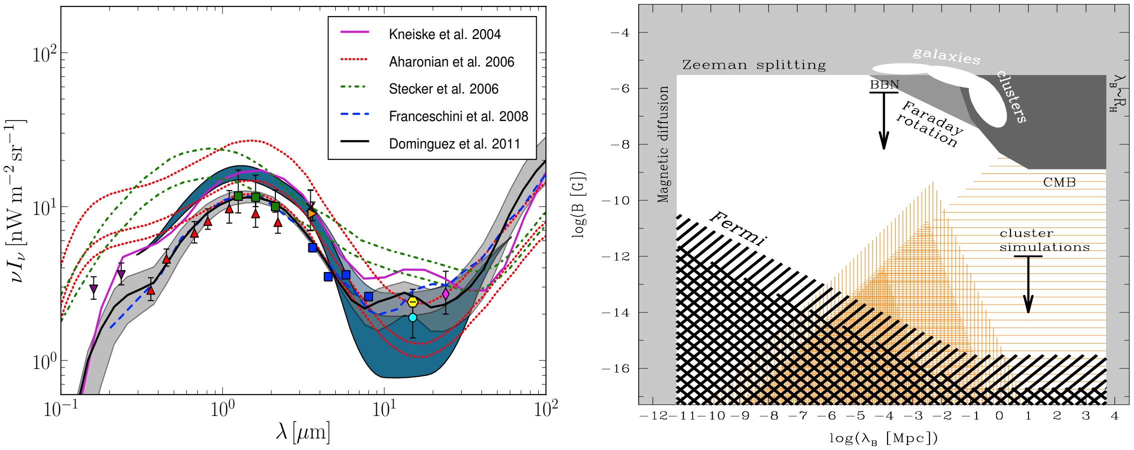

Figure 6: Constraints from Fermi/LAT data. Left panel: constraints on EBL which are derived from transparency of the Universe to TeV radiation $\gamma\gamma \to e^+e$, from Ref. [40]. Right panel: constraints on EGMF which were derived from Fermi/LAT limits on cascade emission of HESS TeV blazars, from Ref. [41].

are described in Ref [37]. In this talk I'll concentrate on those resent results which are of relevance for UHECR physics.

Alongside with many other sources, the Fermi/LAT collaboration have made detailed observations of the radiogalaxy Cen A [38], which is potential source of UHECR, as was discussed in previous section. The conclusion is that it's unlikely for protons to be accelerated in Cen A to energies above 4×10^{19} eV, although this is possible for heavier ions, see also [39].

Recent Femi/Lat data allow also to put important constraints on various cosmological backgrounds which are influencing propagation of UHECR as well as on the properties of their sources. When TeV photons are propagating over cosmological distances, they are loosing energy in electromagnetic cascade triggered by interactions with Extragalactic Background Light (EBL), i.e. with infrared and optical photons. This limits the distance to the sources of TeV photons, similarly to the GZK cut-off in UHECR physics. With growing capabilities of TeV telescopes, more distance sources were discovered putting ever stronger limits from above on the intensity of EBL. With the Fermi data it became possible to constrain EBL to the narrow bands, see Fig.6.

If EGMF would be zero, all these electromagnetic cascade would end up in the Femi/Lat energy band, $E \lesssim 100$ GeV. On the other hand, with sufficiently strong extragalactic magnetic fields the cascading electrons are deflected away and this energy is diffused. Recently a lower bound $B \gtrsim 3 \times 10^{-16}$ G on the strength of EGMF had been derived [41], which stems from the non-observation of GeV gamma-ray emission from electromagnetic cascade initiated by TeV gamma-rays in intergalactic medium.

After subtracting out all γ-ray sources from the intensity maps, the important quantity is derived, which is proper diffuse γ-ray background. Due to Femi/Lat data the knowledge of this background has improved considerably. Current limits on this background became lower by an order of magnitude [42, 43] as compared to the EGRET era. The bulk of this improvement is actually not due to the better resolution of sources, but due to reduced confusion in particle type identification in on-board detectors of Femi.

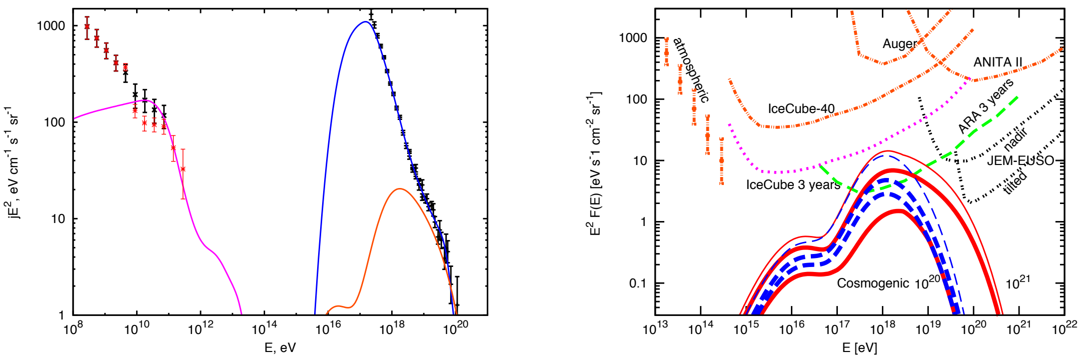

Figure 7: Left panel: Data points - Fermi diffuse background and UHECR flux. Solid lines - fit to the extragalactic proton primaries and resulting fluxes of GZK neutrino and diffuse γ-ray cascade. Right panel: Upper limits on the flux of GZK neutrino compared to sensitivities of various experiments. From Ref. [46].

Knowledge of the diffuse γ-ray background is very important for ultra-high energy cosmic ray physics. Energy which is lost in the GZK-processes (and in creation of e^+e^- pairs) ends up eventually, cascading, in the Fermi/LAT frequency band as well. Amount of transferred energy depends on the initial flux of UHECR. Therefore, upper limits on γ-ray background can be translated into limits on UHECR source properties. With new Fermi/LAT constraints on the diffuse γ-ray background an important constraints are already emerging [44, 45, 46]. E.g. for the injection spectrum and evolution parameter one finds $\beta > 2.4$ and $m < 4$, see Eq. (2.2). This also leads to the revised upper bounds for the expected flux of GZK neutrino and prospects of their detection.

4. Conclusions

There are many open and intriguing questions in the cosmic ray physics still. Though, by now, the spectrum supression at highest energies is firmly established, it's precise nature is under study. Further, the most pressing issues in the current CR research are related to the cosmic ray composition. Are primaries protons or heavy nuclei? We do not understand yet the origin of disagreement between PAO results favoring heavy composition, and HiRes/TA measurements pointing to protons. Last but not least, the most interesting unresolved questions are those related to the cosmic ray origin, their sources and anisotropy. In particular, is it true that the highest energy CR can be back-traced to the local population of AGNs, as initially was hinted by PAO? And, in this respect, is charged particle astronomy possible at all? In turn, this set of questions is tightly bound to the problem of CR composition. Increasing statistics of CR's and better understanding of shower development due to streaming LHC data should improve understanding of these issues, and, hopefully, lead to exciting discoveries.

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