

# Are There EHE Signals?

**Shigeru Yoshida**

Department of Physics, Faculty of Science, Chiba University, Chiba 263-8522, Japan

E-mail: syoshida@hepburn.s.chiba-u.ac.jp

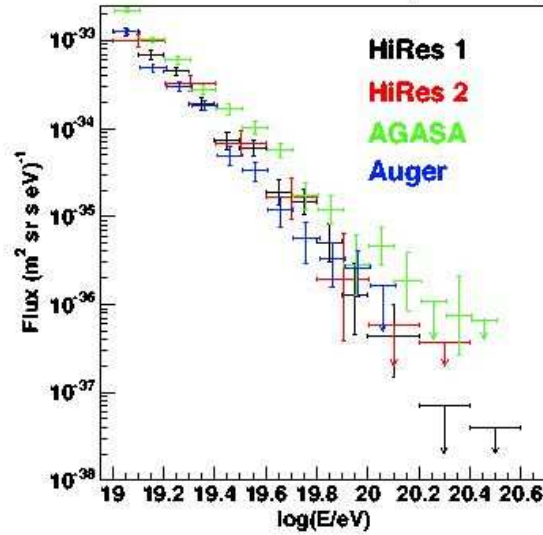
**Abstract.** The controversial results of the cosmic ray energy spectrum at extremely-high energies (EHE) can be interpreted from the same source model(s) by taking into account rather large statistical and systematic errors of the present measurements. In addition we might have considered too simple pictures on possible EHE cosmic ray sources. Taking into account possible range of the extragalactic magnetic field configuration in clusters of galaxies, the source distribution in space, and primary particle emission intensities at each source leads to non-unique solutions of energy spectrum at earth, which makes it more difficult to resolve the long-standing mysteries on generation mechanism and sites that can produce a particle of such high energies. An alternative and complementary approach to study their origin is to explore EHE universe by penetrating neutral charge particles - *neutrinos*. What we can learn from measurements of EHE cosmic neutrinos are discussed. We finally present a detection possibility by the IceCube neutrino observatory.

## 1. The measured EHE cosmic ray spectrum data - Are they really inconsistent?

It has now been well known that EHE cosmic ray spectrum measured by AGASA [1] without any indication of the predicted Greisen-Zatsepin-Kuzmin (GZK) suppression [2] beyond  $\sim 5 \times 10^{10}$  GeV appears inconsistent with the measurements by High Resolution Fly's Eye detectors [3] supporting the existence of the GZK feature. We should remark, however, that the present world data statistics is so small and the systematic uncertainty on the energy determination claimed in the measurements are large. Figure 1 shows that the spectral data measured by AGASA, HiRes and Auger [4] without using the usual trick that the flux is multiplied by  $E^3$  to enhance any tiny spectral structure. One can find that each data seems rather well agreed each other. In fact the recent paper [5] reported that the both AGASA and HiRes spectra are *consistent* with a single distribution. It essentially implies that the statistical and energy scale uncertainties are so large that there is room for a theoretical model that agrees with each pair of spectra. It is definitely too early to draw any conclusive remarks on the EHE cosmic ray spectrum before the next generation experiments such as the Auger observatory publish their data with one order of magnitude higher statistics and less energy scale uncertainties.

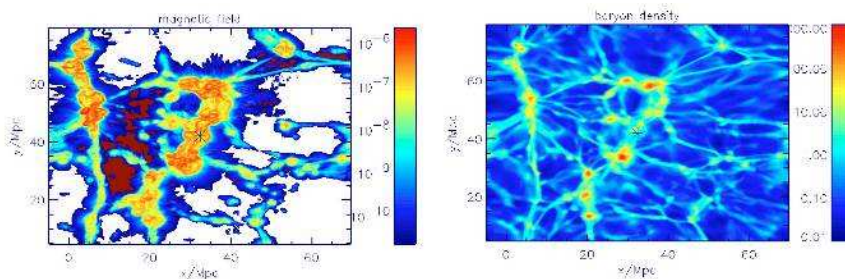
## 2. A cosmic variance to smear out EHE signal signatures

It should be noted that more realistic model calculations involving many unknown parameters complicate data interpretation to identify EHE particle emitters even if Auger provides statistically rich data. Our usual hypothesis that the sources are distributed homogeneously and isotropically and that magnetic field in their propagation space is negligible may be unlikely to represent the reality. Once one considers other scenarios where EHE particles radiated from

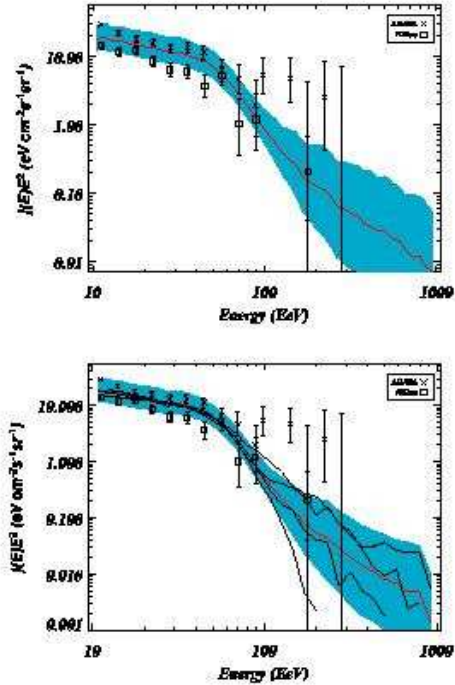


**Figure 1.** The AGASA [1], HiRes [3], and the preliminary Auger [4] spectra taken from Ref [5].

anisotropic structured spatial distribution of sources are propagating in magnetized space, there are so many various models to predict similar energy spectrum and cosmic ray anisotropy because it is not straightforward to decouple poorly known magnetic field effects from source distribution structures in the observational data. We do not know what class of astronomical sources is radiating EHE particles. We do not know if our local universe is magnetized or not. We do not know how much there is a cosmic variance such as luminosity of EHE particles in each source. All these unknown factors are combined together in probing EHE cosmic ray origin from the observations. A good example is found in the recent extensive study [6, 7]. They calculated energy spectra and anisotropy of cosmic rays for various scenarios where the sources are distributed isotropically or according to the baryon density distribution obtained from a cosmological large scale structure simulation. Figure 2 shows the magnetic field configuration and source spatial distribution obtained in their simulation. One of the major problems is where the cosmic ray observer (*i.e.*, *us*) is located in this space. Our neighborhood is magnetized? If so, then how much? And how many sources exist in this large structure? The present observations rule out a few of rather exotic possibilities like the highly magnetized observers, but many other



**Figure 2.** A realization of possible extragalactic magnetic field configuration in log-scale of Gauss (left panel) and baryon density in units of average baryon density (right panel) [6].

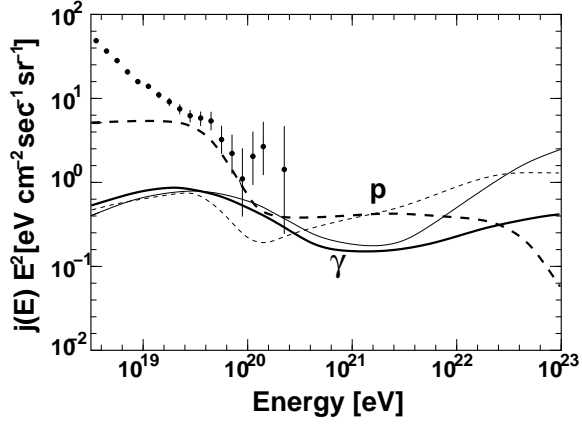


**Figure 3.** Energy spectra predicted in the case of proton injection at the sources, without (top panel) and with (bottom panel) extragalactic magnetic field [7]. The average (solid line) and cosmic variance (shaded band) result from various realization of source properties and locations. The data points are taken from AGASA and HiRes.

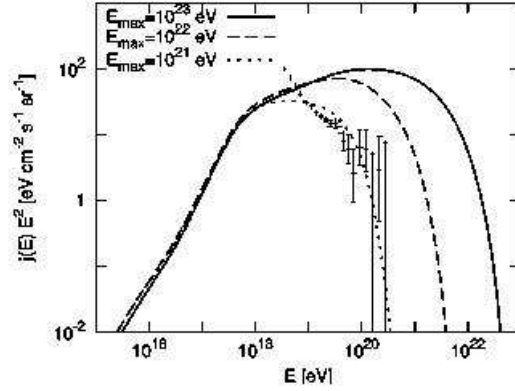
scenarios are still consistent with the data and will be difficult to distinguish between them even by the next generation experiments. One of the “allowed” scenario in their study is a case when sources are strongly magnetized and even an EHE particle of  $10^{20}$  eV is deflected by  $20^\circ$ ! The predicted energy spectrum in most of the scenarios has a large cosmic variance with less pronounced GZK feature. Figure 3 shows examples of the spectra [7]. One finds that a cosmic variance due to many possible realizations of source characteristics and locations leads to significant variations in the spectra, implying that it is not easy to withdraw source characteristics from the observational data. The future data will allow us to conclude EHE particles, if exist, are coming from extragalactic space, but may not be able to tell more details about their origin.

### 3. The Top Down scenario never dies

The top down scenario, where the EHE cosmic rays are created directly as decay or interaction products of particles with masses much higher than the observed energies rather than being accelerated from lower energies [8], has generally predicted predominant  $\gamma$ -rays and neutrinos initial production at EHE. A cosmic variance plays again to fit its prediction with the observational data. In this time, its origins are mainly the unknown universal radio background (URB) and the poorly-known extragalactic magnetic field. A “particle physics” variance like ratio of nucleons to  $\pi$  mesons in the hadronic jets from the heavy particle decay is also involved. An example among various realizations is shown in Figure 4 in form of the resultant energy spectra of nucleons and photons. It exhibits less pronounced GZK features with proton dominating the photon component because a stronger URB is assumed here. It is true that the cosmic ray and diffuse  $\gamma$ -ray data constrains the range of these unknown parameters, but there always seems a room for the model that shows acceptable agreements with the present and possibly future observational data.



**Figure 4.** Predicted energy spectrum of EHE particles in the Top down model with a specific set of unknown parameters such as the strength of URB [8]. Thick and thin line represents the SUSY and no-SUSY fragmentation functions, respectively.



**Figure 5.** Dependence of the average cosmogenic neutrino flux per flavor on the maximal injection energy  $E_{max}$  [10].

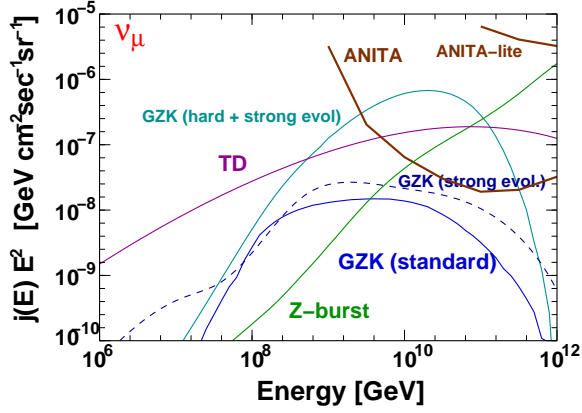
#### 4. Another approach : Looking for neutrinos

The EHE cosmic rays may produce neutrinos by various mechanisms, namely when they interact with surrounding matter or photon fields. Collisions of EHE cosmic ray nucleons and the cosmic microwave background photons produce cosmogenic neutrinos [9], occasionally called GZK neutrinos. The top down models and many other exotic models motivated by particle physics beyond the Standard Model predict predominant EHE neutrino fluxes. Because neutrinos have no charge and can propagate over cosmological distances, the local structures of the EHE cosmic-ray source spatial distribution, the extragalactic magnetic field, and the radio background are no longer involved with their flux predictions, which would provide unique probes for exploring the high energy universe without the complications you would have in interpreting the cosmic ray hadron data.

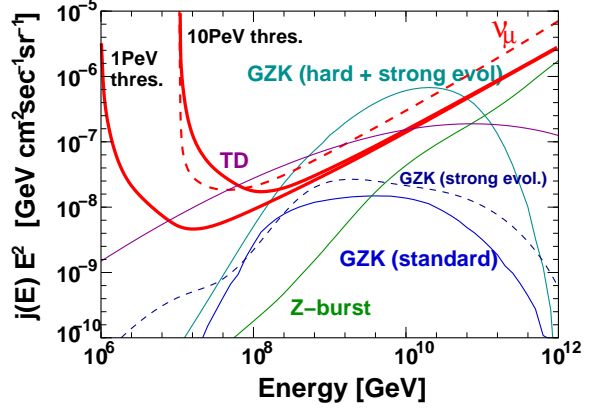
Measurements of the GZK neutrinos will also tell us the nature of the EHE particle origins. The neutrino fluxes below  $10^{10}$  GeV are sensitive to the source distributions and their luminosities at cosmological distances [11] while the fluxes in the higher energy region strongly depends on maximal energy of cosmic ray protons at injection from sources. Figure 5 illustrates this dependence.

The various model predictions of EHE neutrino fluxes are summarized in Figure 6. One finds that the measurement of EHE neutrino intensity and its energy distribution supplies us with probes of EHE particle origins with great deal.

Most of the predicted fluxes will be reachable by the future/on-going neutrino observatories. As shown in Figure 6, the balloon-based experiment to detect coherent radio Cherenkov emission from EHE neutrino-induced electromagnetic cascades, ANITA, will be sensitive to the most higher energy region in the spectra [13]. More traditional type of underground neutrino detectors such as the IceCube neutrino observatory [14] will be more sensitive to relatively lower energy regime at around  $10^8$  GeV as one finds in Figure 7. Note that the IceCube will look for downgoing events to enhance its detection sensitivity for detecting neutrinos with energies of  $\geq 10^6$  GeV.



**Figure 6.** Predicted energy spectra of EHE cosmic neutrinos in the various models - cosmogenic neutrinos (GZK standard) [11], cosmogenic neutrinos with stronger source evolution (GZK strong evol.) [10], the most optimistic case of the cosmogenic neutrino model with harder primary spectrum at sources (GZK hard + strong evol) [10], Top Down (TD) [8], and Z-burst [12] models. The upper limit on the diffuse neutrino fluxes by ANITA-lite and the projected sensitivity by Anita [13] are also shown as well.



**Figure 7.** The IceCube sensitivities on the EHE neutrino fluxes [15]. 90 % C.L. limits by a  $1\text{km}^2$  detection area with 10 years observation are drawn with the predicted cosmic fluxes. Line key is as in Figure 6. Note that the actual IceCube detection area for EHE neutrinos increases with energy and the resultant sensitivity is better than the one shown here. See section 5 and Ref. [16] for details.

## 5. The IceCube capability for the EHE neutrino search

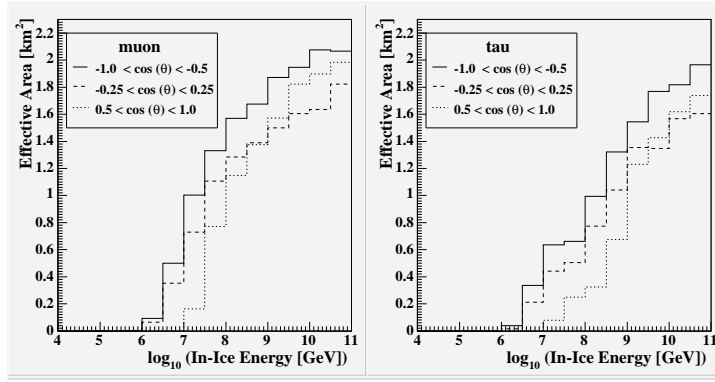
In the EHE region, because of the increase of the neutrino cross-section with energy, neutrinos are more likely to be involved in interactions with matter during their propagation than to penetrate through the Earth. Charged leptons and hadrons are generated in these interactions and the secondary produced  $\mu$ 's and  $\tau$ 's travel the Earth losing their energies by undergoing many radiative reactions, *i.e.* EM cascades generated by  $e^\pm$  pair creation, Bremsstrahlung, and hadronic cascades generated by the photonuclear interactions. The IceCube detector is to observe these secondary  $\mu$ 's and  $\tau$ 's as a main detectable channel of EHE signals [15].

The estimated track energy tells if it is of cosmic origin. This is because the expected spectra of secondary  $\mu$ 's and  $\tau$ 's generated from the GZK neutrinos is much harder than that of atmospheric muons [15], and the measured energy (or its indicator) should be able to exclude the atmospheric muon events in a relatively straightforward manner. The extensive simulation study [16] demonstrated that defining the signal domain cut based upon the event geometry and its Cherenkov light luminosity indeed realize a EHE neutrino search by the IceCube detector. The effective area resulted from the EHE signal domain cut is plotted in Figure 8 as a function of incoming charged lepton energy for different zenith angles.

The resultant event rate of the cosmogenic neutrinos expected from the calculation by Ref. [11] is  $\sim 0.7\mu + \tau$ 's per year while the atmospheric  $\mu$  background rate is 0.03.

## 6. Summary

The apparent differences of the AGASA and HiRes measurements concerning existence of the GZK features are not significant because of their large statistical errors and energy scale uncertainties. Moreover, realistic physics models taking anisotropic structured spatial



**Figure 8.** Muon (left) and tau (tau) effective area as a function of incoming track energy with the 80 string configuration based on the EHE signal criteria with the IceCube detector [16]. Dashed line denotes horizontal events and dotted line represents down-going events. Solid line indicates up-going events, although the probability of having EHE neutrinos with up-going geometry is very low, because of the Earth’s sheltering effect.

distributions of sources, the cosmic variance, and the extragalactic magnetic field configurations complicates the data interpretation. This will be a potential problem in understanding of EHE cosmic ray origins even in the Auger era. A complementary measurements by searching for neutrinos is of great help because it would not involve many uncertain parameters such as the magnetic field effects and tell the nature of EHE particle emitters in more direct manner. Their detection difficulties will be overcome by the large neutrino detectors such as ANITA and IceCube and also by Auger and HiRes looking for neutrino-induced air showers.

### Acknowledgments

The author wishes to acknowledge the IceCube collaboration for the ongoing efforts to search for high energy neutrinos. He also thanks to the TeV 2006 conference organizers for their warm hospitality. This work was supported in part by the Grants-in-Aid (Grant # 15740135) in Scientific Research from the MEXT (Ministry of Education, Culture, Sports, Science, and Technology) in Japan.

### References

- [1] Takeda M *et al.*, 2003 *Astropart.Phys.* **19** 447
- [2] Greisen K, 1966 *Phys. Rev. Lett.* **16** 748; Zatsepin G T and Kuzmin V A, 1966 *Pisma Zh. Eksp. Teor. Fiz.* **4** 114 [*JETP. Lett.* **4**,78].
- [3] Abbasi R U *et al.*, 2005 *Astropart.Phys.* **23** 157; Abbasi R U *et al.*, 2004 *Phys. Rev. Lett.* **92** 151101
- [4] Auger Collaboration, 2005 *Proceedings 29th ICRC, Pune, India*, **10** p. 115
- [5] Connolly *et al.*, 2006 *Phys. Rev. D* **74** 043001
- [6] Sigl G, Francesco M, and Enßlin T A, 2004 *Phys. Rev. D* **70** 043007
- [7] Armengaud E, Sigl G, and Miniati F, 2005 *Phys. Rev. D* **72** 043009
- [8] Sigl G, Lee S, Bhattacharjee P, and Yoshida S, 1999 *Phys. Rev. D* **59** 043504
- [9] Berezhinsky V S and Zatsepin G T, 1969 *Phys. Lett.* **28B** 423.
- [10] Kalashev O E, Kuzmin V A, Semikoz D V, and Sigl G, 2002 *Phys. Rev. D* **66** 063004
- [11] Yoshida S and Teshima M, 1993 *Prog. Theor. Phys.* **89** 833
- [12] Yoshida S, Sigl G, and Lee S, 1998 *Phys. Rev. Lett.* **81** 5505
- [13] Barwick *et al.*, 2006 *Phys. Rev. Lett.* **96** 171101
- [14] Hanson K *et al.*, 2006 *this proceedings*
- [15] Yoshida S, Ishibashi R, and Miyamoto H, 2004 *Phys. Rev. D* **69** 103004
- [16] Ishihara A, 2006 astro-ph/0611794 (*Proceedings CRIS 2006* to appear in *Nucl. Phys. B. Suppl.*)