Can high energy neutrino annihilation on relic neutrinos generate the observed highest energy cosmic-rays?

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Abstract

Annihilation of high energy, $\sim 10^{21}$ eV, neutrinos on big bang relic neutrinos of $\sim 1$ eV mass, clustered in the Galactic halo or in a nearby galaxy cluster halo, has been suggested to generate, through hadronic $Z$ decay, high energy nucleons and photons which may account for the detected flux of $> 10^{20}$ eV cosmic-rays. We show that the flux of high energy nucleons and photons produced by this process is dominated by annihilation on the uniform, non-clustered, neutrino background, and that the energy generation rate of $\sim 10^{21}$ eV neutrinos required to account for the detected flux of $> 10^{20}$ eV particles is $> 10^{48}$ erg/Mpc$^3$ yr. This energy generation rate, comparable to the total luminosity of the universe, is $\sim 4$ orders of magnitude larger than the rate of production of high energy nucleons required to account for the flux of $> 10^{19}$ eV cosmic-rays. Thus, in order for neutrino annihilation to contribute significantly to the detected flux of $> 10^{20}$ eV cosmic-rays, the existence of a new class of high-energy neutrino sources, likely unrelated to the sources of $> 10^{19}$ eV cosmic-rays, must be invoked.

Key words: High energy cosmic-rays; High energy neutrinos; Neutrino mass
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1 Introduction

The Fly’s Eye [1] and AGASA [2] experiments confirmed the existence of a break in the energy spectrum of high energy cosmic rays at $\sim 5 \times 10^{18}$ eV, for which evidence existed with weaker statistics in the data of previous experiments (Haverah Park, Yakutsk, Sugar, see e.g. [3] for a review). Fly’s Eye data also strengthen the evidence for a change in primary composition from predominantly heavy nuclei below the break to predominantly light nuclei above the break. These features strongly suggest, when coupled with the lack
of anisotropy that would be expected for cosmic-rays (CRs) of Galactic origin, that below $\sim 10^{19}$eV the CRs are mostly heavy ions of Galactic origin, and that an extra-Galactic component of protons dominates above $\sim 10^{19}$eV. This conclusion is further supported by the fact that the CR energy spectrum is consistent with a cosmological distribution of sources of protons, with injection spectrum $dN/dE \propto E^{-2.2}$ typically expected for Fermi acceleration [4]. In particular, there is evidence for the existence of a Greisen-Zatsepin-Kuzmin (GZK) “cutoff”, i.e. for the suppression of CR flux above $\sim 5 \times 10^{19}$eV expected due to interaction of protons with the microwave background radiation [5].

The evidence for GZK suppression is strengthened by recent AGASA data [6]. In Fig. 1, the CR spectrum reported by the Fly’s Eye and the AGASA experiments [1,6] is compared with the flux expected for a homogeneous cosmological distribution of sources, each generating a power law differential spectrum of high energy protons $dN/dE \propto E^{-2.2}$ (For the model calculation we have used a flat universe with zero cosmological constant, $H_0 = 75$km s$^{-1}$, and time independent energy generation rate per comoving unit volume $5 \times 10^{44}$erg/Mpc$^3$yr; The spectrum is insensitive to the cosmological parameters and to source evolution, since most of the cosmic rays arrive from distances $< 1$Gpc [4]). The deficit in the number of events detected above $5 \times 10^{19}$eV, compared to a power-law extrapolation of the flux at lower energy, is consistent with that expected due to a cosmological GZK suppression. However, with current data the “cutoff” is detected with only $2\sigma$ significance [7].

The number of events detected above $10^{20}$eV is consistent with that expected based on the cosmological model presented in Fig. 1 (There is an apparent “gap” between the highest and second highest energy events detected by the Fly’s Eye [8]. However, assuming that the cosmological model is valid, the probability that such an apparent “gap” would be observed is $\sim 15\%$ [4,8]). Nevertheless, the detection of $> 10^{20}$eV events does pose challenges to most models of CR production. The high energies rule out most of the acceleration mechanisms so far discussed [9], and since the distance traveled by such particles must be smaller than 100Mpc [10] due to their interaction with the micro-wave background, their arrival directions are inconsistent with the position of astrophysical objects, e.g. jets of powerful radio galaxies [11], that are likely to produce high energy particles [12].

Cosmological $\gamma$-ray bursts (GRBs) are likely sources of high-energy CRs, which may account for the CR flux above $10^{19}$eV as well as for the $> 10^{20}$eV events [13]. This model recently gained support form GRB afterglow observations [14]. Other models for the production of ultra-high energy CRs were suggested, where the highest energy events are produced by the decay of super-massive elementary particles related to grand unified theories (see, e.g., [15] for recent review). Sources of such particles may be topological defects, left over from a
phase transition associated with the symmetry breaking of the grand unified theory [16]. While no firm prediction exists of the CR flux in these theories, a generic feature of the super-massive particle decay scenarios is that the injection spectrum is much harder than expected for Fermi acceleration. Therefore, this scenario can account only for the flux of $> 10^{20}$eV particles, and can not simultaneously explain the origin of $10^{19} - 10^{20}$eV CRs.

It has recently been suggested that annihilation of high energy, $\sim 10^{21}$eV, neutrinos on big bang relic neutrinos of $\sim 1$eV mass, clustered in the Galactic halo or in a nearby galaxy cluster halo, may generate high energy nucleons and photons which may account for the detected flux of $> 10^{20}$eV cosmic-rays [17]. The existence of $> 10^{21}$eV neutrino flux was argued plausible based on the argument that the mechanism producing the observed high energy, $> 10^{19}$eV, particles, most likely protons, also produces charged pions of comparable energy, which subsequently decay to produce neutrinos. It was suggested that the generation spectrum extends well beyond $10^{20}$eV, and that while nucleons produced by a distant source, e.g. a powerful radio galaxy, lose their energy interacting with the micro-wave background, high-energy neutrinos propagate without energy losses and may annihilate on relic neutrinos, producing $> 10^{20}$eV nucleons and photons at small distances that would allow them to propagate to Earth. In Sec. 2 we derive the energy density of high energy neutrinos required to account for the observed rate of $> 10^{20}$eV air showers. The implications of our results are discussed in Sec. 3.

2 The high energy neutrino density

Hot Big Bang cosmology predicts the existence of a neutrino background, similar to the photon micro-wave background. The energy distribution of neutrinos (of mass $m_\nu$, below 1MeV, the decoupling temperature) is predicted to be a Fermi-Dirac distribution with temperature smaller than that of the photon background, $T_\gamma = 2.73$K, by a factor $(11/4)^{1/3}$. The corresponding number density of neutrinos is $n_B = 54$ cm$^{-3}$, with a similar density of anti-neutrinos (we assumed a single helicity state; the presence of two helicity states would increase the density by at most a factor 2, and will not change the conclusions derived below). Neutrino mass smaller than $\sim 5$eV is consistent with Big Bang cosmology [18]. Furthermore, there are several indications that neutrinos are indeed massive. The simplest explanation for the discrepancy between observed and predicted solar neutrino fluxes (see [19] for a review) involves $\nu_e - \nu_\mu$ oscillations driven by neutrino mass difference, and the common explanation to the atmospheric neutrino anomaly involves $\nu_\mu - \nu_\tau$ oscillations. While the mass difference implied for $\nu_e - \nu_\mu$ oscillations is much smaller than 1eV$^2$, the common explanation to the atmospheric anomaly is oscillation to $\nu_\tau$ with mass $\sim 0.03$eV [20].
High energy neutrinos may interact with the background neutrinos and annihilate, producing $Z$-bosons which immediately decay, with 70% probability for hadronic decay. With standard weak interaction, the annihilation cross section is strongly peaked at the resonant neutrino energy $\epsilon^R = M_Z^2/2m_\nu = 4 \times 10^{21} (m_\nu/1\text{eV})^{-1}\text{eV}$, and the energy-averaged cross section, defined as $\bar{\sigma} \equiv \int ds \sigma_{\nu\nu}(s)/M_Z^2$ where $s$ is the square of the center of momentum energy, is $\bar{\sigma} = 4\pi G_F/\sqrt{2} = 4 \times 10^{-32}\text{cm}$ [21]. The relative energy width of the resonance peak (FWHM) is $\sim 3\%$. $Z$ decay produces on average 2.7 nucleons and anti-nucleons, and 30 high energy photons through $\pi^0$ decay. A single nucleon carries, on average, a fraction $\sim 0.025$ of the $Z$ energy [22], and a single photon carries, on average, energy lower by a factor of $\sim 10$ compared to the nucleon energy [17,22]. For a neutrino mass $m_\nu < 10\text{eV}$ for the background neutrinos, the highest energy nucleons produced by the decay of $Z$-bosons created from annihilation of resonant ($\epsilon^R$) high energy neutrinos and background neutrinos have energy $\geq 2 \times 10^{20}\text{eV}$, and could in principle account for the observed highest energy CR events.

Let us first consider the rate of high energy showers due to annihilation of high energy neutrinos with a homogeneous neutrino background. The rate per unit volume of $Z$ production is

$$\dot{n}_Z = \int d\epsilon \frac{dn}{d\epsilon} \sigma_{\nu\nu}(\epsilon) cn_B, \quad (1)$$

where $n_B$ is the number density of background neutrinos (or anti-neutrinos) and $dn/d\epsilon$ is the number density per unit energy of high energy neutrinos. We note here that, as suggested by oscillation evidence, neutrino flavor eigenstates may be different than their mass eigenstates, and since neutrinos produced by astrophysical sources are expected to be electron and muon neutrinos from pion decay, the $Z$ production rate is smaller than given by (1) by a factor $|<\nu_\alpha|\nu_m>|^2$, where $|\nu_\alpha>$ is the flavor eigenstate and $|\nu_m>$ is the massive neutrino eigenstate. If, as suggested by present data, the massive, $\sim 1\text{eV}$, neutrino is mainly mixed with $\nu_\tau$, then the annihilation rate of $\nu_e, \mu$ expected to be produced by astrophysical sources will be smaller than given in (1). However, since we are interested in obtaining a lower limit to the density of high energy neutrinos required to produce $\dot{n}_Z$ high enough to account for the observed flux of CRs above $10^{20}$, we conservatively assume that $|<\nu_\alpha|\nu_m>|^2$ is of order unity for the high energy neutrinos.

The integral in (1) is dominated by the contribution from $\epsilon \sim \epsilon^R$. We may therefore replace the derivative $dn/d\epsilon$ in the integrand with its value at $\epsilon = \epsilon^R$. For $m_\nu \sim 1\text{eV}$ the background neutrinos are nonrelativistic, and the square of the center of momentum energy is $s = 2\epsilon m_\nu c^2$. Changing the integration
variable $\epsilon$ to $s$, we find
\begin{equation}
\dot{n}_{Z} = cn_{B}\bar{\sigma} \left[ \frac{dn}{d\epsilon} \right]_{\epsilon=\epsilon_{R}}.
\end{equation}

The high-energy protons and photons produced by $Z$ decay lose energy as they propagate through the microwave background. This limits the distance out to which $Z$ decays contribute to the observed rate of air showers above $10^{20}$ eV to $r_{CR} < 100$ Mpc. The flux per solid angle of high energy cosmic-rays producing showers above $10^{20}$ eV, and originating in $Z$ decays, is therefore
\begin{equation}
\dot{j}_{CR} = \frac{1}{4\pi} \dot{n}_{Z} N_{CR}(m_{\nu}) r_{CR},
\end{equation}

where $N_{CR}(m_{\nu})$ is the average number of protons and photons above $10^{20}$ eV produced by the decay of a $Z$-boson of energy $\epsilon_{R}$.

Using eqs. (2,3) we may derive the number density $[dn/d\epsilon]_{\epsilon=\epsilon_{R}}$ of high energy neutrinos in the energy range $\Delta\epsilon \approx \epsilon_{R}$ around $\epsilon = \epsilon_{R}$, required to produce a given CR flux $\dot{j}_{CR}$,
\begin{equation}
n^{R} \equiv \left[ \frac{dn}{d\epsilon} \right]_{\epsilon=\epsilon_{R}} = \frac{4\pi \dot{j}_{CR}}{cn_{B}\bar{\sigma} r_{CR} N_{CR}(m_{\nu})}.
\end{equation}

The total energy density associated with high energy neutrinos is expected to be larger by a factor $\Delta\epsilon > 1$ than the energy $\epsilon^{R} n^{R}$ associated with neutrinos in the energy range $\Delta\epsilon \sim \epsilon^{R}$, since one does not expect the neutrino energy distribution to be strongly peaked at $\epsilon^{R}$. If the high energy neutrino flux is indeed produced by the sources of $> 10^{19}$ eV CRs, then one expects the neutrino distribution to be approximately given by $dn/d\epsilon \propto \epsilon^{-2}$ [23], for which the energy density in neutrinos of energy $10^{19}$ eV to $10^{20}$ eV is $E_{\nu}(>10^{19}$ eV) $= \epsilon^{R} n^{R} \log(\epsilon^{R}/10^{19}$ eV) $\approx 5 \epsilon^{R} n^{R}$. Thus, the energy density of $> 10^{19}$ eV neutrinos required to produce the observed rate of showers above $10^{20}$ eV, $\dot{j}_{CR} \approx 10^{-16}$ m$^{-2}$s$^{-1}$sr$^{-1}$ (see Fig. 1), is
\begin{equation}
E_{\nu}(>10^{19}$ eV) $= \frac{4\pi cM_{Z}^{2}\dot{j}_{CR}}{n_{B}\bar{\sigma} r_{CR} m_{\nu} N_{CR}(m_{\nu})}$
\approx 10^{-16} (f_{\Delta\epsilon}/5) \left[ \frac{N_{CR}(m_{\nu}) m_{\nu}}{3 \text{eV} \frac{r_{CR}}{100 \text{Mpc}}} \right]^{-1} \text{erg/cm}^{3}.
\end{equation}

$E_{\nu}$ depends only weakly on $m_{\nu}$, since $N_{CR}(m_{\nu}) m_{\nu} \approx 3$ eV independent of the value of $m_{\nu}$. For $m_{\nu} \sim 1$ eV, the resonant energy is $\epsilon^{R} \sim 4 \times 10^{21}$ eV, and the average energy of the nucleons produced in the $Z$ decay is $\sim \epsilon^{R}/40 \sim$
Since the average number of nucleons produce in the decay is 2.7, we have \( N_{CR}(m_\nu) m_\nu \simeq 3 \text{eV} \) for \( m_\nu \sim 1 \text{eV} \). For higher \( m_\nu \) the resonant energy decreases, and only a small fraction of the resulting nucleons have energy above \( 10^{20} \text{eV} \). For \( m_\nu \sim 10 \text{eV} \), \( \epsilon^R \sim 4 \times 10^{20} \text{eV} \) and since (on average) only \( \sim 10\% \) of the nucleons carry \( \sim 1/4 \) the \( Z \) energy [22], we have \( N_{CR}(m_\nu) m_\nu \simeq 3 \text{eV} \) for \( m_\nu \sim 10 \text{eV} \). For \( m_\nu \sim 0.1 \text{eV} \), the resonant energy is \( \epsilon^R \sim 4 \times 10^{22} \text{eV} \), so that the average energy of the photons produced in the decay is \( \sim \epsilon^R/400 \sim 10^{20} \text{eV} \), and the photons also contribute to \( j_{CR} \). Since the average number of photons produced in the decay is 30, we have \( N_{CR}(m_\nu) m_\nu \simeq 3 \text{eV} \) for \( m_\nu \sim 0.1 \text{eV} \).

The energy density \( E_\nu \), required for \( Z \) decays to contribute significantly to the observed rate of \( \geq 10^{20} \text{eV} \) air-showers, may be reduced if the local density of background neutrinos is higher than the average density \( n_B \), due to clustering. For \( m_\nu \sim 1 \text{eV} \), the background neutrinos are non-relativistic at present, and are expected to cluster in the gravitational potential wells of galaxies and clusters. Let us first consider clustering in the halo of the Galaxy. The density of neutrinos in the Galactic halo depends on the details of the halo formation. However, Pauli’s exclusion principle allows to put an upper limit to the number density \( n_C \) of neutrinos clustered in the Galactic halo. This limit is approximately given by \( n_C \leq (4\pi/3)(p_{\text{max}}/h)^3 \), where \( p_{\text{max}} \approx 21/2 m_\nu v_r \) is the maximum momentum of bound neutrinos and \( v_r = 220 \text{km/s} \) is the Galactic rotation speed. A limit lower by a factor of 2 is obtained by requiring the neutrino phase space density, approximately given by \( n_C/(4\pi p_{\text{max}}^3/3) \), to be smaller than the maximum phase space density of the uniform background, \( 1/2h^3 \). This requirement follows from the assumption that neutrino clustering results from gravitational collapse of the uniform neutrino background. In this process, the phase space density is conserved along particle trajectories, and therefore the maximum phase space density can not increase [24]. The neutrino density in the halo is therefore constrained by

\[
n_C < 1.5 \times 10^3 \left( \frac{m_\nu}{1 \text{eV}} \right)^3 \left( \frac{v_r}{220 \text{km/s}} \right)^3 \text{cm}^{-3}. \tag{6}
\]

Using eqs. (2) and (3), replacing \( n_B \) with \( n_C \) and \( r_{CR} \) with the halo radius \( r_H \), we find that the ratio of the flux of \( > 10^{20} \) nucleons and photons due to \( Z \) production by annihilation with neutrinos clustered in the Galactic halo to the flux due to annihilation on the uniform background is

\[
f_G/f_B < 0.01 \left( \frac{m_\nu}{1 \text{eV}} \right)^3 \frac{r_H}{50 \text{kpc}}. \tag{7}
\]

Thus, for \( m_\nu \sim 1 \text{eV} \), the rate of \( > 10^{20} \text{eV} \) showers due to annihilation on neutrinos clustered in the Galactic halo is two orders of magnitude smaller than that due to annihilation on the uniform neutrino background. The con-
tribution of Galactic halo neutrino annihilation increases with $m_\nu$, and for $m_\nu = 10$eV may be larger than the contribution due to annihilation on the uniform background by a factor $\sim 10$.

Finally, let us consider the contribution to $j_{CR}$ due to annihilation on background neutrinos clustered in a nearby galaxy cluster. The rate of $Z$ production in the cluster is

$$\dot{N}_Z = f_\nu \frac{M_c}{m_\nu} \sigma_c \left[ \frac{dn}{d\epsilon} \right]_{\epsilon = \epsilon_R},$$

(8)

where $M_c$ is the cluster mass, and $f_\nu$ is the fraction of cluster mass contributed by (background) neutrinos. The cluster mass is given by its velocity dispersion $\sigma_v$ and radius $R$, $M_c = 2R\sigma_v^2/G$. The ratio of high energy shower rate due to annihilation in the cluster, $\dot{N}_Z N_{CR}/4\pi d^2$ where $d$ is the cluster distance, to that due to annihilation on the uniform background, $\dot{n}_Z N_{CR}/d_{CR}$, is

$$f_C/f_B \simeq 0.03 \left( \frac{m_\nu}{1\text{eV}} \right)^{-1} \left( \frac{d}{20\text{Mpc}} \right)^{-2} \left( \frac{f_\nu}{0.1} \right) \left( \frac{R}{1\text{Mpc}} \right) \left( \frac{\sigma_v}{600\text{km/s}} \right)^2.$$  

(9)

Clearly, the contribution to high energy showers from neutrino annihilation in a nearby galaxy cluster is much smaller than the contribution from annihilation on the uniform background. We note here that in deriving eq. (8) we have assumed that the neutrinos are non-degenerate, so that the fraction $f_\nu$ is not limited by Pauli’s principle. This is not valid for small $m_\nu$. The cluster density at radius $R$ is $\sigma_v^2/2\pi GR^2$, implying a neutrino (anti-neutrino) density

$$n_C = 2.5 \times 10^4 (f_\nu/0.1) \left( \frac{m_\nu}{1\text{eV}} \right)^{-1} \left( \frac{R}{1\text{Mpc}} \right)^{-2} \left( \frac{\sigma_v}{600\text{km/s}} \right)^2 \text{cm}^{-3}.$$  

(10)

This density is lower than the upper limit imposed by eq. (6) for

$$m_\nu > 0.7 \left( \frac{f_\nu}{0.1} \right)^{1/4} \left( \frac{R}{1\text{Mpc}} \right)^{-1/2} \left( \frac{\sigma_v}{600\text{km/s}} \right)^{-1/4} \text{eV},$$  

(11)

where we have used $v_r = 2^{1/2}\sigma_v$. For $m_\nu < 0.7$eV the neutrino density is limited by the exclusion principle, and the neutrino fraction of cluster mass is proportional to $m_\nu^4$. Thus, although for low $m_\nu$, $m_\nu \sim 0.1$eV, photons produced in the $Z$ decay may contribute to the particle flux above $10^{20}$eV, the decrease in $f_\nu$ implies that the ratio $f_C/f_B$ is increasing with $m_\nu$ for $m_\nu < 0.7$eV.
3 Implications

We have shown that the energy density of high energy neutrinos required to generate the observed flux of $>10^{20}$ CRs by producing high energy nucleons and photons via the decay of $Z$-bosons resulting from the annihilation of the high energy neutrinos on a uniform neutrino background is $\sim 10^{-16}$ erg/cm$^3$, independent of neutrino mass $m_\nu$ for $0.1$eV $< m_\nu < 10$eV (cf. eq. 5; the required energy density is higher for $m_\nu < 0.1$eV, and for $m_\nu > 10$eV the $Z$ decay products are not energetic enough to account for the observed $> 2\times10^{20}$ eV CRs). The $>10^{20}$ CR flux produced by annihilation on background neutrinos clustered in a nearby galaxy cluster is 2 orders of magnitude smaller than that due to annihilation on the uniform background, independent of the value of $m_\nu$ (cf. eq. (9)). For $m_\nu \sim 1$eV, the CR flux resulting from annihilation on neutrinos clustered in the halo of our Galaxy is smaller by at least a factor $\sim 100$ than that due to annihilation on the uniform background (cf. eq. (7)).

The relative contribution of Galactic halo neutrino annihilation increases with increasing $m_\nu$, and may become comparable to the uniform neutrino background contribution for $m_\nu \sim 5$eV. For $m_\nu \sim 10$eV, annihilation on Galactic halo neutrinos may dominate, giving a CR flux higher by a factor $\sim 10$ compared to the flux due to annihilation on the uniform background. In this case, the lower limit to the energy density of high energy neutrinos required to produce the observed flux of $>10^{20}$ eV CRs is lowered by a factor of $\sim 10$ to $\sim 10^{-17}$ erg/cm$^3$.

For $m_\nu \sim 1$eV, the energy density in high energy neutrinos, $\sim 10^{-16}$ erg/cm$^3$, required to account for the observed flux of $>10^{20}$ eV CRs is $\sim 4$ orders of magnitude higher than the energy density in observed $>10^{19}$ eV cosmic-rays, $4\pi JE/c \simeq 10^{-20}$ erg/cm$^3$ (see Fig. 1). It is important to note here that although the life time of high energy neutrinos is longer than that of high energy protons, since $10^{19}$ eV protons suffer energy loss due to pair production on the microwave background while neutrinos lose energy only due to redshift, the life time of a $10^{19}$ eV proton, $\sim 3\times10^9$ yr, is comparable to the Hubble time, $\sim 10^{10}$ yr, and therefore to the neutrino life time. Therefore, the average (over time and volume) energy generation rate of high energy neutrinos required to produce the neutrino energy density necessary to account for the $>10^{20}$ eV events is at least $\sim 4$ orders of magnitude higher than the generation rate $\sim 5\times10^{44}$ erg/Mpc$^3$ yr of $>10^{19}$ eV protons required to account for the observed $>10^{19}$ eV CR flux [4]. This implies that in order for neutrino annihilation to contribute significantly to the detected flux of $>10^{20}$ eV cosmic-rays, the existence of a new class of high-energy neutrino sources, likely unrelated to the sources of $>10^{19}$ eV cosmic-rays, must be invoked. Furthermore, the energy generation rate of the high energy neutrino sources must be $\sim 10^{49}$ erg/Mpc$^3$ yr, comparable to the total photon luminosity of the universe.
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Fig. 1. The CR flux expected for a homogeneous cosmological distribution of sources, each generating a power law differential spectrum of high energy protons $dN/dE \propto E^{-2.2}$, compared to the Fly’s Eye and AGASA data (The AGASA flux at $3 \times 10^{18}$eV is $\sim 1.7$ times higher than that reported by the Fly’s Eye, corresponding to a systematic $\sim 20\%$ larger estimate of event energies in the AGASA experiment compared to the Fly’s Eye experiment [1,2]; We have therefore shifted upward (downward) the Fly’s Eye (AGASA) event energies by $10\%$). Integers indicate the number of events observed. 1σ energy error bars are shown for the highest energy events. The dashed line denotes the power law fit by Bird et al. [1] for the extra-galactic flux dominating above $\sim 5 \times 10^{18}$eV.