ITP-Budapest 581 DESY 02-014

Relic neutrino masses and the highest energy cosmic rays

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We consider the possibility that a large fraction of the ultrahigh energy cosmic rays are decay products of Z bosons which were produced in the scattering of ultrahigh energy cosmic neutrinos on cosmological relic neutrinos. We compare the observed ultrahigh energy cosmic ray spectrum with the one predicted in the above Z-burst scenario and determine the required mass of the heaviest relic neutrino as well as the necessary ultrahigh energy cosmic neutrino flux via a maximum likelihood analysis. We show that the value of the neutrino mass obtained in this way is fairly robust against variations in presently unknown quantities, like the amount of neutrino clustering, the universal radio background, and the extragalactic magnetic field, within their anticipated uncertainties. Much stronger systematics arises from different possible assumptions about the diffuse background of ordinary cosmic rays from unresolved astrophysical sources. In the most plausible case that these ordinary cosmic rays are protons of extragalactic origin, one is lead to a required neutrino mass in the range 0.08 eV $\leq m_\nu \leq$ 1.3 eV at the 68 % confidence level. This range narrows down considerably if a particular universal radio background is assumed, e.g. to 0.08 eV $\leq m_\nu \leq$ 0.40 eV for a large one. The required flux of ultrahigh energy cosmic neutrinos near the resonant energy should be detected in the near future by AMANDA, RICE, and the Pierre Auger Observatory, otherwise the Z-burst scenario will be ruled out.

PACS numbers: 14.60.Pq, 98.70.Sa, 95.85.Ry, 95.35.+d

I. INTRODUCTION

Big bang cosmology predicts the existence of a background gas of free photons and neutrinos. The measured cosmic microwave background (CMB) radiation supports the applicability of standard cosmology back to photon decoupling which occured approximately one hundred thousand years after the big bang. The relic neutrinos, on the other hand, have decoupled when the universe had a temperature of one MeV and an age of just one second. Thus, a measurement of the relic neutrinos, with a predicted average number density of

$$\langle n_{\nu_i}\rangle_0 = \langle n_{\bar\nu_i}\rangle_0 = \frac{3}{22}\underbrace{\langle n_\gamma\rangle_0}_{\rm CMB} \simeq 56\ {\rm cm}^{-3}\,, \qquad (1)$$

per light ($m_{\nu_i} \ll 1$ MeV) neutrino species i, would provide a new window to the early universe. Their predicted number density is comparable to the one of the microwave photons. However, since neutrinos interact only weakly, the relic neutrinos have not yet been detected directly in laboratory experiments [1, 2, 3, 4, 5, 6, 7].

Recently, an indirect detection possibility for relic neutrinos has been discussed [8, 9]. It is based on so-called Z-bursts resulting from the resonant annihilation of ultrahigh energy cosmic neutrinos (UHECνs) with relic neutrinos into Z bosons [10, 11, 12] (cf. Fig. 1). On resonance, the corresponding cross section is enhanced by several orders of magnitudes. If neutrinos have non-vanishing masses m_{ν_i} – for which there is rather convincing evidence in view of the apparent observation of neutrino oscillations [13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36] – the respective resonance energies, in the rest system of the relic neutrinos, correspond to

$$E_{\nu_i}^{\rm res} = \frac{M_Z^2}{2\,m_{\nu_i}} = 4.2\cdot 10^{21}\ {\rm eV}\left(\frac{1\ {\rm eV}}{m_{\nu_i}}\right)\,, \qquad (2)$$

with M_Z denoting the mass of the Z boson. These

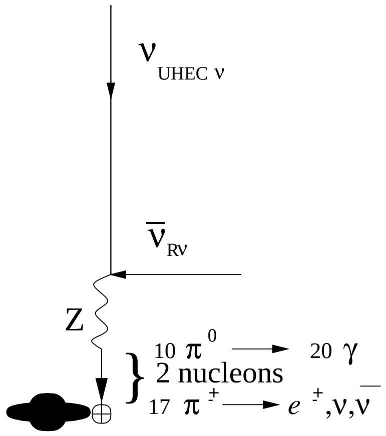

FIG. 1: Illustration of a Z-burst resulting from the resonant annihilation of an ultrahigh energy cosmic neutrino on a relic (anti-)neutrino.

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resonance energies are, for neutrino masses of $\mathcal{O}(1)$ eV, remarkably close to the energies of the highest energy cosmic rays observed at Earth by collaborations such as AGASA [37], Fly's Eye [38, 39, 40], Haverah Park [41, 42], HiReS [43], and Yakutsk [44] (for a review, see Ref. [45]). Indeed, it was argued [8, 9] that the ultrahigh energy cosmic rays (UHECRs) above the predicted Greisen-Zatsepin-Kuzmin (GZK) cutoff [46, 47] around $4 \cdot 10^{19}$ eV are mainly protons (and, maybe, photons) from Z decay. In this way, one possibly also solves one of the outstanding problems of ultrahigh energy cosmic ray physics [48], namely the apparent observation of cosmic rays with energies above the GZK cutoff, in an elegant and economical way without invoking new physics beyond the Standard Model, except for neutrino masses. The GZK puzzle hinges on the fact that nucleons with super-GZK energies have a short attenuation length of about 50 Mpc, due to inelastic interactions with the cosmic microwave background, while plausible astrophysical sources for those energetic particles are much farther away [49, 50]. Ultrahigh energy neutrinos produced at cosmological distances, on the other hand, can reach the GZK zone unattenuated and their resonant annihilation on the relic neutrinos could just result in the observed cosmic rays of the highest energies. Moreover, at present this annihilation process may be the only way to detect the relic neutrino background, a basic ingredient of our cosmological picture.

The Z-burst hypothesis for the ultrahigh energy cosmic rays was discussed in many papers [51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66]. The required UHECν fluxes were estimated in Ref. [51] for different spectral indices. In Ref. [52], particle spectra were determined numerically for case studies which supported the Z-burst scenario. The effect of possible lepton asymmetries was studied in Ref. [54]. In Ref. [59], the analysis of the Z-burst mechanism was advocated as one of the few possibilities for an absolute neutrino mass determination.

In the present paper, we present the details of (and extend) our recent quantitative investigation of the Z-burst scenario [61] (see also Refs. [62, 64]), where we have determined the required mass of the heaviest relic neutrino as well as the necessary ultrahigh energy cosmic neutrino flux via a maximum likelihood analysis. But before we start this enterprise, we shall briefly review the current knowledge of the absolute scale of neutrino masses.

Neutrinos almost certainly have non-vanishing masses and mix. This follows from the apparent observation of neutrino oscillations whose evidence is compelling for atmospheric neutrinos [13, 14, 15, 16, 17], strong for solar neutrinos [18, 19, 20, 21, 22, 23, 24], and so-far unconfirmed for neutrinos produced in the laboratory and studied by the LSND collaboration and others [25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36]. However, neutrino oscillations are sensitive only to the mass (squared) splittings $\triangle m_{ij}^2 = m_{\nu_i}^2 - m_{\nu_j}^2$, not to the individual masses, $(m_{\nu_4} >)\ m_{\nu_3} > m_{\nu_2} > m_{\nu_1}$, themselves. Only a lower bound on the mass of the heaviest neutrino can be derived from these observations, e.g.

$$m_{\nu_3} \geq \sqrt{\triangle m_{\rm atm}^2} \gtrsim 0.04 \text{ eV} \tag{3}$$

from the atmospheric mass splitting in a three neutrino flavour scenario and

$$m_{\nu_4} \geq \sqrt{\triangle m_{\rm LSND}^2} \gtrsim 0.4 \text{ eV} \tag{4}$$

from the still allowed value of the LSND mass splitting in a four flavour scenario, respectively (for a recent compilation of global analyses on mass splitting and mixing parameters, see for example Refs. [67, 68, 69] and references therein).

For an investigation of the absolute scale of neutrino masses one has to exploit different types of experiments, such as the search for mass imprints in the endpoint spectrum of tritium beta (β) decay or the search for neutrinoless double beta ($0\nu 2\beta$) decay. At present, these direct kinematical measurements of neutrino masses provide only upper limits, e.g.

$$m_\beta \equiv \sqrt{\sum_i |U_{ei}|^2\, m_{\nu_i}^2} < 2.2 \div 2.5 \text{ eV} \quad (95\,\%\text{ C.L.})\,, \tag{5}$$

with U being the leptonic mixing matrix, for the effective mass measured in tritium β decay [70, 71, 72, 73], and

$$\langle m_\nu \rangle \equiv \left| \sum_i U_{ei}^2\, m_{\nu_i} \right| < 0.33 \div 1.35 \text{ eV} \quad (90\,\%\text{ C.L.}) \tag{6}$$

for the Majorana neutrino mass parameter [74, 75, 76, 77, 78] appearing in $0\nu 2\beta$ decay. The recently reported evidence for neutrinoless double beta decay and correspondingly deduced parameter range [79]

$$\langle m_\nu \rangle = (0.11 \div 0.56) \text{ eV} \quad (95\,\%\text{ C.L.}) \tag{7}$$

has been seriously challenged by Refs. [80, 81]. Combining the experimental constraints from oscillations and from tritium β decay, one infers upper bounds on the mass of the heaviest neutrino [82],

$$m_{\nu_3} < \sqrt{m_\beta^2 + \triangle m_{\rm atm}^2} \lesssim 2.5 \text{ eV}\,, \tag{8}$$

in a three flavour, and

$$m_{\nu_4} < \sqrt{m_\beta^2 + \triangle m_{\rm LSND}^2} \lesssim 3.8 \text{ eV}\,, \tag{9}$$

in a four flavour scenario, respectively. For further recent investigations of the relationship between oscillation phenomena, β decay and $0\nu 2\beta$ decay, in particular with respect to the neutrino mass spectrum, one may also consult Refs. [83, 84, 85, 86, 87, 88, 89, 90] and references cited therein.

Further information on the absolute scale of neutrino masses can be obtained through cosmological and astrophysical considerations. Neutrinos in the $0.1 \div 1$ eV mass range have cosmological implications since they represent a non-negligible part of dark matter. This gives the opportunity to put upper limits on neutrino masses from cosmology [91, 92]. Analyses of galaxy clustering, including recent CMB measurements and other cosmological constraints, give an upper bound

$$\sum_i m_{\nu_i} < 1.8 \div 4.4 \text{ eV} \tag{10}$$

on the sum of the neutrino masses [93, 94, 95, 96]. From the spread of arrival times of neutrinos from supernova SN 1987A, coupled with the measured neutrino energies, a time-of-flight limit of $m_\beta < 23$ eV can be derived [97, 98], which, however, is not competitive with the direct limit (5).

It is extremely welcome that the Z-burst scenario opens a further and timely window to the absolute neutrino mass scale, since the opportunities to determine this crucial quantity are rare at present. In addition, its verification would give us an indirect detection of the so elusive relic neutrinos and, finally, offer an explanation of the origin of the highest energy cosmic rays.

The organization of the present paper is as follows. In Section II we describe our determination of the proton and photon spectra at Earth, which originate from Z-bursts taking place mainly at extragalactic distances. We discuss in detail the main ingredients in the predictions of the spectra, such as the details of Z production and hadronic decay, the propagation of nucleons and photons through the diffuse extragalactic photon background, the diffuse flux of ultrahigh energy cosmic neutrinos, and the relic neutrino number density, as well as their anticipated uncertainties. The comparison of the Z-burst spectra with the observed ultrahigh energy cosmic ray spectrum is presented in Section III. The required absolute neutrino mass, as well as the necessary ultrahigh energy cosmic neutrino flux, are determined via a maximum likelihood analysis for various assumptions about the nature of the background of ordinary cosmic rays from unresolved astrophysical sources and variations of the diffuse extragalactic photon background notably in the radio band. On the basis of these studies we find that the Z-burst determinations of the mass of the heaviest neutrino as well as of the neutrino flux are fairly robust. We find a required neutrino mass range of $0.08 \text{ eV} \leq m_\nu \leq 1.3$ eV at the 68 % confidence level, if the background of ordinary cosmic rays is of extragalactic origin. This range narrows down considerably if a particular universal radio background is assumed, e.g. to $0.08 \text{ eV} \leq m_\nu \leq 0.40$ eV for a large one. In Section IV we discuss the implications of our findings for future laboratory studies such as the tritium beta decay and neutrinoless double beta decay, as well as for astrophysical and cosmological neutrino investigations. This section contains also our conclusions.

II. Z-BURST SPECTRA

Our comparison of the Z-burst scenario with the observed UHECR spectrum proceeds as follows. First, we determine the probability of Z production as a function of the distance from Earth. Secondly, we exploit collider experiments to derive the energy distribution of the produced protons and photons in the laboratory (lab) system. Thirdly, we consider the propagation of the protons and photons, i.e. we determine their energy losses due to pion and/or e^+e^- production through scattering on the diffuse extragalactic background photons and due to their redshift. The last step is the comparison of the predicted and the observed spectra and the extraction of the required mass of the heaviest relic neutrino and of the necessary UHECν flux.

Our prediction of the differential proton flux, i.e. the number of protons arriving at Earth with energy E per units of energy (E), of area (A), of time (t) and of solid angle (Ω),

$$F_{p|Z}(E) = \frac{\mathrm{d}N_{p|Z}}{\mathrm{d}E\,\mathrm{d}A\,\mathrm{d}t\,\mathrm{d}\Omega}\,, \tag{11}$$

from Z-bursts can be summarized as

$$\begin{aligned} F_{p|Z}(E) = \sum_i \int_0^\infty \mathrm{d}E_p \int_0^{R_{\max}} \mathrm{d}r \\ \times \Bigg[\int_0^\infty \mathrm{d}E_{\nu_i}\, F_{\nu_i}(E_{\nu_i}, r)\, n_{\bar\nu_i}(r) \\ + \int_0^\infty \mathrm{d}E_{\bar\nu_i}\, F_{\bar\nu_i}(E_{\bar\nu_i}, r)\, n_{\nu_i}(r) \Bigg] \\ \times \sigma_{\nu_i\bar\nu_i}(s)\, \mathrm{Br}(Z \to \text{hadrons})\, \frac{\mathrm{d}N_{p+n}}{\mathrm{d}E_p} \\ \times (-)\frac{\partial}{\partial E} P_p(r, E_p; E)\,, \end{aligned} \tag{12}$$

with the following important building blocks: the UHECν fluxes $F_{\nu_i}(E_{\nu_i}, r)$ at the energies E_{ν_i} ($\approx E^{\rm res}_{\nu_i}$) and at the distance r of Z production to Earth, the number density $n_{\nu_i}(r)$ of the relic neutrinos, the Z production cross section $\sigma_{\nu_i\bar\nu_i}(s)$ at centre-of-mass (cm) energy squared $s = 2\, m_{\nu_i}\, E_{\nu_i}$, the branching ratio $\mathrm{Br}(Z \to$ hadrons), the energy distribution $\mathrm{d}N_{p+n}/\mathrm{d}E_p$ of the produced protons (and neutrons) with energy E_p, and the probability $P_p(r, E_p; E)$ that a proton created at a distance r with energy E_p arrives at Earth above the threshold energy E.

A similar expression as Eq. (12) holds for the differential photon flux from Z-bursts,

$$F_{\gamma|Z}(E) = \sum_i \int_0^\infty \mathrm{d}E_\gamma \int_0^{R_{\max}} \mathrm{d}r \tag{13}$$

$$\times \left[\int_0^\infty \mathrm{d}E_{\nu_i}\, F_{\nu_i}(E_{\nu_i}, r)\, n_{\bar\nu_i}(r) + \int_0^\infty \mathrm{d}E_{\bar\nu_i}\, F_{\bar\nu_i}(E_{\bar\nu_i}, r)\, n_{\nu_i}(r) \right]$$
$$\times \sigma_{\nu_i\bar\nu_i}(s)\, \mathrm{Br}(Z \to \mathrm{hadrons})\, \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}$$
$$\times (-) \frac{\partial}{\partial E} P_\gamma(r, E_\gamma; E)\,.$$

Here, the photon propagation function $P_\gamma(r, E_\gamma; E)$ gives the expected number of detected photons above the threshold energy E if one photon started from a distance of r with energy E_γ. Note, that the P_γ function has a different interpretation than the P-function of protons. This arises from the fact that the number of photons – in distinction to the number of protons – is not conserved during their propagation.

The building blocks related to Z-production and decay – $\sigma_{\nu_i\bar\nu_i}$, the hadronic branching ratio, and the momentum distributions $\mathrm{d}N_i/\mathrm{d}E_i$ – are very well, and the propagation functions P_i are fairly well determined, whereas the first two ingredients, the flux of UHECνs, $F_{\nu_i}(E_{\nu_i}, r)$, and the radial distribution of the relic neutrino number density $n_{\nu_i}(r)$, are much less accurately known. In the following we shall discuss all these ingredients in detail.

A. Z production and decay

At LEP and SLC millions of Z bosons were produced and their decays analyzed with extreme high accuracy. Due to the large statistics, the uncertainties of our analysis related to Z decay turned out to be negligible.

Let us start with a review of the Standard Model neutrino annihilation cross section. The s-channel Z-exchange annihilation cross section into any fermion anti-fermion $(f\bar f)$ pair is given by (see e. g. Refs. [11, 99])

$$\sigma^Z_{\nu_i\bar\nu_i}(s) = \frac{G_F^2\, s}{4\,\pi}\, \frac{M_Z^4}{(s - M_Z^2)^2 + M_Z^2\,\Gamma_Z^2}\; N_{\mathrm{eff}}(s)\,, \qquad (14)$$

where s is the cm energy squared, Γ_Z is the total width of the Z boson, and N_{eff} is the effective number of annihilation channels,

$$N_{\mathrm{eff}}(s) = \sum_f \theta(s - 4\, m_f^2) \times \frac{2}{3}\, n_f \left(1 - 8\, T_{3\,f}\; q_f\, \sin^2\theta_W + 8\, q_f^2 \sin^4\theta_W\right)\,. \qquad (15)$$

Here the sum is over all fermions with $m_f < \sqrt{s}/2$, with charge q_f (in units of the proton charge), isospin $T_{3\,f}$ ($1/2$ for u, c and neutrinos; $-1/2$ for d, s, b and negatively charged leptons), and $n_f = 1(3)$ for leptons (quarks (q)). With $\sin^2\theta_W = 0.23147(16)$ for the $\sin^2$ of the effective Weinberg angle and $G_F = 1.16639(1)\times 10^{-5}$ GeV^{-2} for the Fermi coupling constant [100], formula (14) gives, at the Z-mass,

$$\sigma(\nu_i\bar\nu_i \to Z^* \to \text{all } q\bar q)\,|_{s=M_Z^2} \;=\; 314.9 \text{ nb}\,, \qquad (16)$$
$$\sigma(\nu_i\bar\nu_i \to Z^* \to \text{all } f\bar f)\,|_{s=M_Z^2} \;=\; 455.6 \text{ nb}\,, \qquad (17)$$

with a branching ratio $\sigma(\nu_i\bar\nu_i \to Z^* \to \text{all } q\bar q)/\sigma(\nu_i\bar\nu_i \to Z^* \to \text{all } f\bar f)\,|_{s=M_Z^2} = 0.6912$, in good agreement with the experimental result [100],

$$\mathrm{Br}(Z \to \mathrm{hadrons}) = (69.89 \pm 0.07)\,\%\,. \qquad (18)$$

Later we shall exploit the following simplification which arises due to the fact that the cross section (14) is sharply peaked at the resonance cm energy squared $s = M_Z^2$. Correspondingly, it acts essentially like a δ-function in the integration over the energies E_{ν_i} of the incident neutrinos in Eqs. (12) and (13), and we can assume that the UHECν fluxes are constant in the relevant energy region. Thus, introducing the energy-averaged annihilation cross section [9, 10],

$$\langle\sigma_{\mathrm{ann}}\rangle \equiv \int \frac{\mathrm{d}s}{M_Z^2}\, \sigma_{\mathrm{ann}}(s) = 2\,\pi\,\sqrt{2}\, G_F = 40.4 \text{ nb}\,, \qquad (19)$$

which is the effective cross section for all neutrinos within $1/2\,\delta E^{\mathrm{res}}_{\nu_i}/E^{\mathrm{res}}_{\nu_i} = \Gamma_Z/M_Z = 2.7\,\%$ of their peak annihilation energy, we can write

$$\int_0^\infty \mathrm{d}E_{\nu_i}\, F_{\nu_i}(E_{\nu_i})\, \sigma_{\nu_i\bar\nu_i}(s = 2\, m_{\nu_i}\, E_{\nu_i}) \qquad (20)$$
$$\simeq E^{\mathrm{res}}_{\nu_i}\, F_{\nu_i}(E^{\mathrm{res}}_{\nu_i})\, \langle\sigma_{\mathrm{ann}}\rangle\,.$$

In view of the expected rapid decrease of the UHECν flux at increasing energies (cf. Section II C), we neglect t-channel W- and Z-exchange annihilation processes. On resonance, the s-channel Z-exchange processes completely overwhelm them. Fairly above the resonant energies, on the other hand, they eventually dominate but are probably unobservable due to the lack of an appreciable UHECν flux.

Next, we turn to the energy distribution of the protons and photons in Z decay. We combined existing published and some improved unpublished data on the momentum distribution,

$$\mathcal{P}_p\,(x) \equiv \frac{\mathrm{d}N_p}{\mathrm{d}x}\,, \qquad x \equiv \frac{p_p}{p_{\mathrm{beam}}}\,, \qquad (21)$$

of protons (p) (plus antiprotons $(\bar p)$) in Z decays [101, 102, 103, 104, 105], see Fig. 2 (top). The experimental data, ranging down to $x \approx 8 \cdot 10^{-3}$, were combined with the predictions from the modified leading logarithmic approximation (MLLA) [106, 107, 108] at low x. The $p + \bar p$ multiplicity is $\langle N_p\rangle = \int_0^1 \mathrm{d}x\, \mathcal{P}_p(x) = 1.04 \pm 0.04$ in the hadronic channel [100].

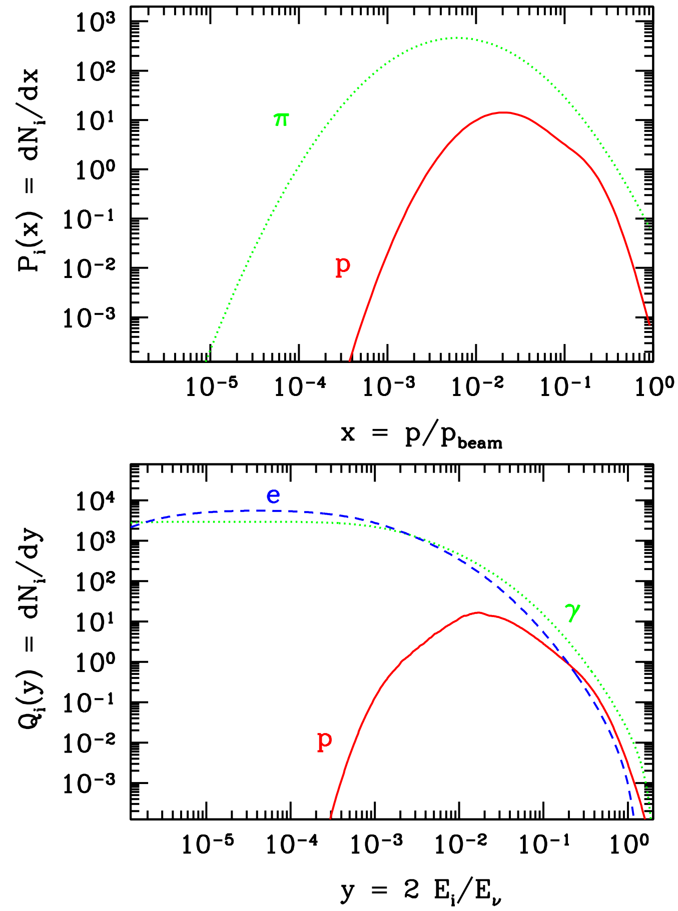

FIG. 2: Momentum distributions in hadronic Z decays. *Top:* Combined data from Refs. [101, 102, 103, 104, 105] on proton (plus antiproton) momentum distribution (solid), normalized to $\langle N_p\rangle = 1.04$, and charged pion momentum distributions (dotted), normalized to $\langle N_{\pi^\pm}\rangle = 16.99$. *Bottom:* Distribution of protons ("p"; solid), photons ("γ"; dotted) and electrons ("e"; dashed) in the lab system, in which the target relic neutrino is at rest.

In the cm system of the Z production the angular distribution of the hadrons is determined by the spin 1/2 of the primary quarks and thus proportional to $1+w^2 = 1+\cos^2\theta$ (here θ is the angle between the incoming neutrinos and the outgoing hadrons (cf. [109])). The energy distribution of the produced protons with energy E_p entering the Z-burst spectrum (12),

$$\frac{{\rm d}N_p}{{\rm d}E_p} = \frac{2}{E_\nu}\,\frac{{\rm d}N_p}{{\rm d}y} \equiv \frac{2}{E_\nu}\,\mathcal{Q}_p(y)\,, \tag{22}$$

with $y = 2E_p/E_\nu$, is finally obtained after a Lorentz transformation from the cm system to the lab system,

$$\mathcal{Q}_p(y) = \sum_{+,-}\frac{3}{8}\int_{-1}^{+1}{\rm d}w\,(1+w^2) \tag{23}$$

$$\times\,\frac{1}{1-w^2}\left|\frac{\pm y - w\sqrt{y^2-(1-w^2)(2m_p/M_Z)^2}}{\sqrt{y^2-(1-w^2)(2m_p/M_Z)^2}}\right|$$

$$\mathcal{P}_p\left(\frac{-wy\pm\sqrt{y^2-(1-w^2)(2m_p/M_Z)^2}}{1-w^2}\right),$$

where m_p is the proton mass. The first line comes from the angular distribution, the second line is the Jacobian and the third one is the momentum distribution at the inverted momentum. The scaled energy distribution $\mathcal{Q}_p$, as defined in Eq. (22) and given by Eq. (23), is displayed in Fig. 2 (bottom).

Neutrons produced in Z decays will decay and end up as UHECR protons. They are taken into account according to

$$\mathcal{Q}_{p+n}(y) = \left(1+\frac{\langle N_n\rangle}{\langle N_p\rangle}\right)\,\mathcal{Q}_p(y)\,, \tag{24}$$

where the neutron (n) (plus antineutron ($\bar n$)) multiplicity, $\langle N_n\rangle = \int_0^2{\rm d}y\,\mathcal{Q}_n(y)$, is $\approx 4\%$ smaller than the proton's [110].

Photons are produced in hadronic Z decays via fragmentation into neutral pions, $Z\to\pi^0+X\to 2\,\gamma+X$ (cf. Fig. 1). The corresponding scaled energy distribution in the lab system, defined analogously to Eq. (22), reads

$$\mathcal{Q}_\gamma(y) = \int_{-1}^{1}{\rm d}w\,\frac{2}{1+w}\,\mathcal{Q}_{\pi^0}\left(\frac{2\,y}{1+w}\right)\,, \tag{25}$$

where the scaled energy distribution $\mathcal{Q}_{\pi^0}(y)$, with $y = 2\,E_{\pi^0}/E_\nu$, is given by Eq. (23), with $m_p\to m_{\pi^0}$ and $\mathcal{P}_p\to\mathcal{P}_{\pi^0}$, the momentum distribution of pions in hadronic Z decay. For the latter distribution, we take the measured one of charged pions $\mathcal{P}_{\pi^\pm}$ from hadronic Z decay [101, 102, 103, 104, 105] (cf. Fig. 2 (top)), normalized such that $\langle N_\gamma\rangle = \int_0^2{\rm d}y\,\mathcal{Q}_\gamma(y) = 20.97$ [100]. Note, that the distributions $\mathcal{Q}_i$, $i = p,\gamma$, presented in Fig. 2 (bottom), compare favorably with the ones presented in Ref. [66] based on the event generator PYTHIA [111].

Electrons (and positrons) from hadronic Z decay are also relevant for the development of electromagnetic cascades. They stem from decays of secondary charged pions, $Z\to\pi^\pm+X\to e^\pm+X$ (cf. Fig. 1), and their scaled energy distribution in terms of $y = 2\,E_e/E_\nu$ reads

$$\mathcal{Q}_{e^\pm}(y) \;=\; \int_{-1}^{1}dw\int_0^2 dx\,\frac{1}{xw+\sqrt{x^2+(2\,m_e/m_\pi)^2}} \tag{26}$$

$$\times\,\mathcal{Q}_{\pi^\pm}\left(\frac{2\,y}{xw+\sqrt{x^2+(2\,m_e/m_\pi)^2}}\right)\mathcal{P}_e(x)\,,$$

where $\mathcal{P}_e$ is the momentum distribution of the electrons in the rest system of the charged pion. The energy distribution $\mathcal{Q}_{e^\pm}$ is also displayed in Fig. 2 (bottom).

B. Propagation of nucleons and photons through the diffuse extragalactic photon background

The cosmic microwave background is known to a high accuracy. It plays the key role in the determination of the probability $P_p(r, E_p; E)$ that a proton created at a distance r with energy E_p arrives at Earth above the threshold energy E, suggested in Ref. [112] and determined for a wide range of parameters in Ref. [113]. The propagation function P_p takes into account the fact that protons of extragalactic (EG) origin and energies above $\approx 4 \cdot 10^{19}$ eV lose a large fraction of their energy due to pion and e^+e^- production through scattering on the CMB and due to their redshift [46, 47]. In the present analysis we have included new results for $P_p(r, E_p; E)$ which include now variations in the cosmological parameters, in extension to the already published form [113] exploited in Ref. [61]. In our analysis we go, according to

$$\mathrm{d}z = -(1+z)\, H(z)\, \mathrm{d}r/c\,, \tag{27}$$

out to distances $R_{\rm max}$ (cf. (12)) corresponding to redshift $z_{\rm max} = 2$ (cf. Ref. [114]). We use the expression

$$H^2(z) = H_0^2\, \left[\Omega_M\, (1+z)^3 + \Omega_\Lambda\right] \tag{28}$$

for the relation of the Hubble expansion rate at redshift z to the present one. Uncertainties of the latter, $H_0 = h$ 100 km/s/Mpc, with $h = (0.71 \pm 0.07) \times^{1.15}_{0.95}$ [100], are included. In Eq. (28), Ω_M and Ω_Λ, with $\Omega_M + \Omega_\Lambda = 1$, are the present matter and vacuum energy densities in terms of the critical density. As default values we choose $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$, as favored today. Our results turn out to be pretty insensitive to the precise values of the cosmological parameters.

The simulations needed for the computation of $P_p(r, E_p; E)$ require large computer power. We have used a farm of personal computers (PCs) consisting of 128 parallel 1.7 GHz Pentium 4 processors – normally devoted to QCD lattice calculations [115] – and have exploited about 3 hours CPU time to determine $P_p(r, E_p; E)$ in a range of $r \lesssim 4000$ Mpc, 10^{18} eV $\lesssim E_p \lesssim 10^{26}$ eV, and 10^{18} eV $\lesssim E \lesssim 10^{26}$ eV, for each fixed value of the cosmological parameters. The simulation was carried out in small (10 kpc) steps in r. For each step, the statistical energy losses due to pion/e^+e^- production and redshift are taken into account [113]. In this connection, the advantage of our formulation of the Z-burst spectrum (cf. (12)) in terms of the probability $P_p(r, E_p; E)$ becomes evident. We have to determine the latter only once and for all. Without the use of $P_p(r, E_p; E)$, we would have to perform a simulation for any variation of the input spectrum, notably for any change in the neutrino mass. Our maximum likelihood analysis, involving the neutrino mass as a free parameter, would thus require excessive computer power – on the order of 300 hours on the above PC farm for fixed cosmological parameters. Since $P_p(r, E_p; E)$ is of universal usage, we have decided

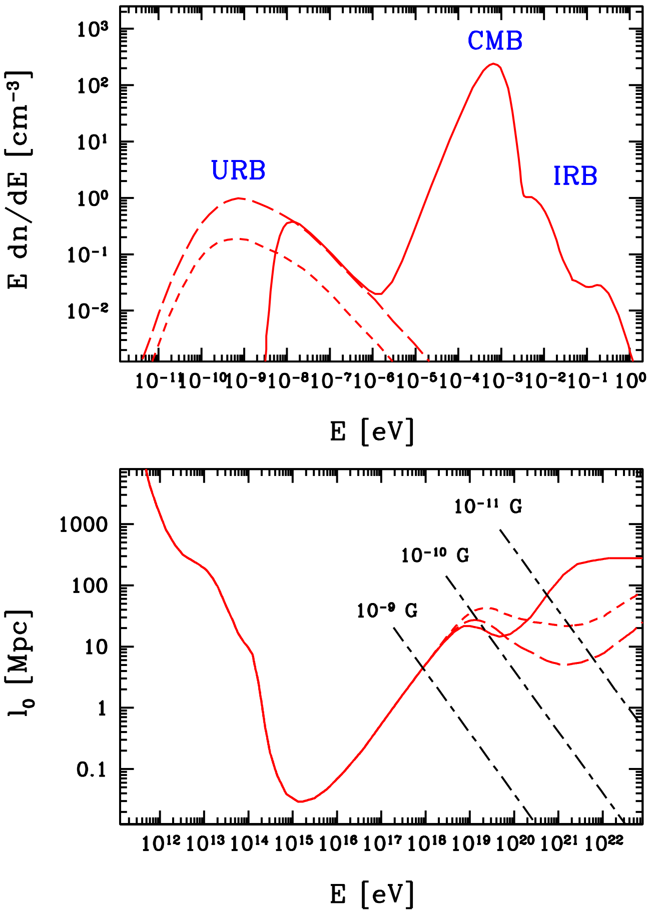

FIG. 3: *Top:* The intensity spectrum of the diffuse extragalactic photon background at redshift $z = 0$ from Ref. [116] (solid). Different estimates from Ref. [118] of the universal radio background (URB) are also indicated: high URB (long-dashed) and moderate URB (short-dashed). *Bottom:* Photon energy attenuation length l_0 at $z = 0$ corresponding to the photon background shown above [116] (solid). Variations of l_0 arising from different assumptions about the URB (cf. Ref. [118] and top) are also indicated: high URB (long-dashed) and moderate URB (short-dashed). Shown is furthermore the energy attenuation length for electrons due to synchrotron radiation (long-dashed-short-dashed), for different magnitudes of the extragalactic magnetic fields.

to make the corresponding numerical data for the probability distribution $(-)\partial P_p(r, E_p; E)/\partial E$ available for the public via the World-Wide-Web URL

http://www.desy.de/˜uhecr .

The determination of the photon propagation function $P_\gamma(r, E_\gamma; E)$, entering the photon flux prediction (13), was done as follows. In distinction to the case of the proton propagation function, we used here the continuous energy loss (CEL) approximation which largely simplifies the work and reduces the required computer resources – we have estimated the necessary CPU time for a full simulation on the PC farm mentioned above to 1000 hours per fixed set of the cosmological parameters. In the CEL approximation, the energy (and number) of the detected photons is a unique function of the initial energy and distance, and statistical fluctuations are neglected. A full simulation of the photon propagation function will be the subject of a later work.

The processes that are taken into account are pair production on the diffuse extragalactic photon background (cf. Fig. 3 (top)), double pair production and inverse Compton scattering of the produced pairs. We comment also on synchrotron radiation in a possible extragalactic magnetic field (EGMF). For the energy attenuation length of the photons due to these processes, we exploited the values quoted in Ref. [116] (see also Ref. [117]) and the further ones presented in Fig. 3 (bottom) which incorporate various assumptions about the poorly known universal radio (URB) (from Ref. [118]) and infrared (IRB) backgrounds. We shall analyse later the dependence of the neutrino mass and other fit parameters on these variations. Note, that, in view of the recent URB estimates in Ref. [118], the ones presented in Fig. 3 (top)), which are based on Ref. [119], can be referred to as "minimal" URB.

The computation of the photon propagation function $P_\gamma(r,E_\gamma;E)$ was carried out in the following way. The energy attenuation of photons in the CEL approximation was calculated according to

$$dE = -E\left(\frac{\mathrm{d}r}{l_z(E)} - \frac{\mathrm{d}z}{1+z}\right)\,, \tag{29}$$

where $l_z(E) = (1+z)^{-3}\, l_0(E(1+z))$ is the energy attenuation length at redshift z. The number of photons was assumed to be constant at ultrahigh energies $\gtrsim 10^{18}$ eV, due to the small inelasticities in this energy range. Below, it was increased in a way to maintain energy conservation (except for the redshift contribution):

$$\mathrm{d}N_\gamma = -N_\gamma\,\frac{\mathrm{d}r}{l_z(E)}\,. \tag{30}$$

The $P_\gamma(r,E_\gamma;E)$ function was then obtained by integration of these equations. In the ultrahigh energy region – which is most relevant for us since we perform our fit to the cosmic ray data there – the approximation described above gives the photon flux quite reliable, while at lower energies it yields an upper bound.

C. UHECν fluxes

Presently unknown ingredients in the evaluation of the Z-burst spectra (12) and (13) are the differential fluxes F_{ν_i} of ultrahigh energy cosmic neutrinos (see e. g. Refs. [120, 121, 122] for recent reviews). Present experimental upper limits on these fluxes are rather poor (cf. Fig. 4 and Refs. [128, 129]).

What are the theoretical expectations for diffuse UHECν fluxes? More or less guaranteed are the so-called cosmogenic neutrinos which are produced when

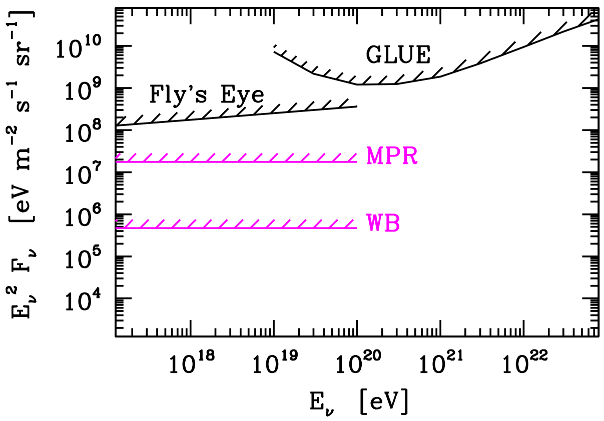

FIG. 4: Upper limits on differential neutrino fluxes in the ultrahigh energy regime. Shown are experimental upper limits on $F_{\nu_e}+F_{\bar\nu_e}$ from Fly's Eye [123] and on $\sum_{\alpha=e,\mu}(F_{\nu_\alpha}+F_{\bar\nu_\alpha})$ from the Goldstone lunar ultrahigh energy neutrino experiment GLUE [124], as well as theoretical upper limits on $F_{\nu_\mu}+F_{\bar\nu_\mu}$ from "visible" ("WB" [125, 126]) and "hidden" ("MPR" [127]) hadronic astrophysical sources.

ultrahigh energy cosmic protons scatter inelastically off the cosmic microwave background radiation [46, 47] in processes such as $p\gamma\to\Delta\to n\pi^+$, where the produced pions subsequently decay [130, 131]. These fluxes (for recent estimates, see Refs. [12, 117, 132, 133]) represent reasonable lower limits, but turn out to be insufficient for the Z-burst scenario. Recently, theoretical upper limits on the ultrahigh energy cosmic neutrino flux have been given in Refs. [125, 126, 127]. Per construction, the upper limit from "visible" hadronic astrophysical sources, i.e. from those sources which are transparent to ultrahigh energy cosmic protons and neutrons, is of the order of the cosmogenic neutrino flux and shown in Fig. 4 ("WB"; cf. Refs. [125, 126]). Also shown in this figure ("MPR") is the much larger upper limit from "hidden" hadronic astrophysical sources, i.e. from those sources from which only photons and neutrinos can escape [127, 134]. Even larger fluxes at ultrahigh energies may arise if the hadronic astrophysical sources emit photons only in the sub-MeV region – thus evading the "MPR" bound in Fig. 4 – or if the neutrinos are produced via the decay of superheavy relic particles [55, 57, 99, 135, 136, 137, 138, 139, 140], for which also the fragmentation function of the decay is of major interest [141, 142, 143, 144, 145, 146], or topological defects [48, 147].

In this situation of insufficient knowledge, we take the following approach concerning the flux of ultrahigh energy cosmic neutrinos, $F_{\nu_i}(E_{\nu_i},r)$. It is assumed to have the form

$$F_{\nu_i}(E_{\nu_i},r) = F_{\nu_i}(E_{\nu_i},0)\,(1+z)^\alpha\,, \tag{31}$$

where z is the redshift and where α characterizes the cosmological source evolution (see also Refs. [12, 52, 65]).

The flux at zero redshift, $F_{\nu_i}(E_{\nu_i},0) \equiv F_{\nu_i}(E_{\nu_i})$, is left open. For hadronic astrophysical sources it is expected to fall off power-like, $F_{\nu_i}(E_{\nu_i}) \propto E_{\nu_i}^{-\gamma}$, $\gamma \gtrsim 1$, at high energies. Due to this fact and because of the strong resonance peaks in the $\nu_i\bar{\nu}_i$ annihilation cross section (14) at the resonance energies (2), the Z-burst rate will be only sensitive to the flux at the resonant energy of the heaviest neutrino. Of course, the latter may be nearly degenerate with the other neutrino mass eigenstates, $m_{\nu_i} \approx m_\nu$, as it is the case for $m_{\nu_3} \gtrsim 0.1$ eV in a three flavour scenario. Correspondingly, our later fit to the UHECR data will be sensitive only to

$$F_\nu^{\rm res} = \sum_i \left[F_{\nu_i}(E_{\nu_i}^{\rm res}) + F_{\bar{\nu}_i}(E_{\nu_i}^{\rm res}) \right] , \qquad (32)$$

where the sum extends over the number of mass eigenstates which are quasi-degenerate with the heaviest neutrino. Note, finally, that, independently of the production mechanism, neutrino oscillations result in a uniform F_{ν_i} mixture for the different mass eigenstates i.

D. Neutrino number density

The dependence of the relic neutrino number density n_{ν_i} on the distance r is treated in the following way.

The question is whether there is remarkable clustering of the relic neutrinos within the local GZK zone of about 50 Mpc. It is known that the density distribution of relic neutrinos as hot dark matter follows the total mass distribution; however, with less clustering [148, 149]. In fact, for $m_\nu \lesssim 1$ eV, one expects pretty much that the neutrino number density equals the big bang prediction (1) [150]. To take above facts into account, the shape of the $n_{\nu_i}(r)$ distribution is varied, for distances below 100 Mpc, between the standard cosmological homogeneous case (1) and that of the total mass distribution obtained from peculiar velocity measurements [151, 152] (cf. Fig. 5 (top)). These peculiar measurements suggest relative overdensities of at most a factor $f_\nu = 2 \div 3$, depending on the grid spacing (cf. Fig. 5 (bottom)). A relative overdensity $f_\nu = 10^2 \div 10^4$ in our neighbourhood, as it was assumed in earlier investigations of the Z-burst hypothesis [8, 9, 51, 52, 53, 63], seems unlikely in view of these data. Our quantitative results turned out to be rather insensitive to the variations of the overdensities within the considered range.

For scales larger than 100 Mpc the relic neutrino density is taken according to the big bang cosmology prediction, $n_{\nu_i} = 56 \cdot (1+z)^3$ cm^{-3}. Possible uniform neutrino density enhancements due to eventual lepton asymmetries, as advocated in Ref. [54], are negligible in view of the recent, very stringent bounds on the neutrino degeneracies [153, 154]. In any case, such uniform enhancements change only the normalization of the Z-burst spectra and have no effect on their shape. Therefore, they could possibly milder the required UHECν flux, but the value of the neutrino mass inferred from the Z-burst scenario is not affected by them.

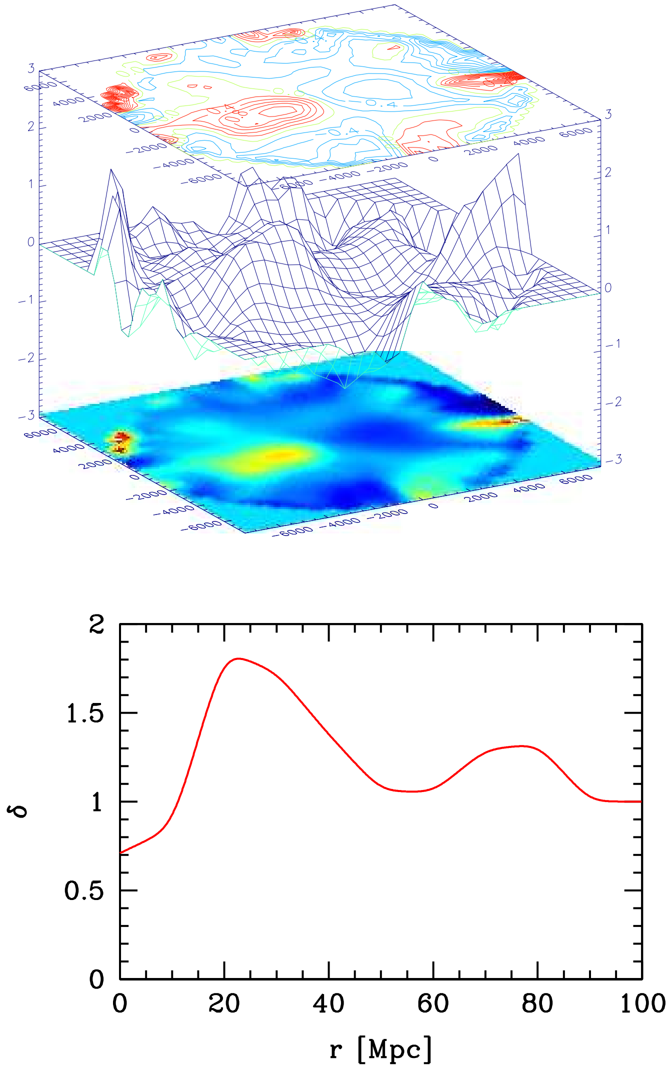

FIG. 5: *Top:* Mass density fluctuation field δ along the supergalactic plane as obtained from peculiar velocity measurements [151]. Shown are contours in intervals of $\delta = 0.2$, surface maps on a grid of spacing 500 km s^{-1}, corresponding to $5\,h^{-1}$ Mpc, with the height proportional to δ, and contrast maps. One recognizes some well-known structures in the nearby volume such as the Great Attractor at supergalactic coordinates (SGX ~ -2000 km s^{-1}, SGY ~ -500 km s^{-1}), the Perseus-Pisces complex (SGX ~ 6000 km s^{-1}, SGY ~ -1000 km s^{-1}), and the large void (SGX ~ 2500 km s^{-1}, SGY ~ 0 km s^{-1}) in between. *Bottom:* Mass density fluctuation field obtained from above data, averaged over all directions, for $h = 0.71$. The overdensities at around 20 and 80 Mpc reflect the Great Attractor and the Perseus-Pisces complex, respectively.

III. DETERMINATION OF THE REQUIRED NEUTRINO MASS AND THE NECESSARY UHECν FLUX

A. Generalities

The predicted spectra of protons and photons from Z-bursts, (12) and (13), can now be compared with the observed UHECR spectrum (cf. Fig. 6). Our analysis includes published UHECR data of AGASA [37], Fly's Eye [38, 39, 40], Haverah Park [41, 42], and HiReS [43], as well as unpublished one from the World Wide Web pages of the experiments on 17/03/01 (for a review, see Ref. [45]). Due to normalization difficulties we did not use the Yakutsk [44] results. We shall take into account the fact that above $4 \cdot 10^{19}$ eV less than 50 % of the cosmic rays can be photons at the 95 % confidence level (C.L.) [155] (see also Refs. [42, 156]).

As usual, each logarithmic unit between $\log(E/\mathrm{eV}) = 18$ and $\log(E/\mathrm{eV}) = 26$ is divided into ten bins. The predicted number of UHECR events in a bin is taken as

$$N(i) = \mathcal{E} \int_{E_i}^{E_{i+1}} \mathrm{d}E \left[F_{p|\mathrm{bkd}}(E) + F_{p(+\gamma)|Z}(E) \right] , \quad (33)$$

where $\mathcal{E} \approx 8 \cdot 10^{16}$ m$^2 \cdot$s$\cdot$sr is the total exposure (estimated from the highest energy events and the corresponding fluxes) and where $E_i = 10^{(18+i/10)}$ eV is the lower bound of the i^{th} energy bin. The first term in Eq. (33), $F_{p|\mathrm{bkd}}$, corresponds to the diffuse background of ordinary cosmic rays from unresolved astrophysical sources. Below the GZK cutoff, it should have the usual and experimentally observed power-law form [45]. The second term represents the sum of the proton and photon spectra, $F_{p|Z} + F_{\gamma|Z}$, Eqs. (12) and (13), from Z-bursts.

The separation of the flux into two terms (one from the power-law background and one from the Z-burst) is physically well motivated. The power-law part below the GZK cutoff is confirmed experimentally and, for extragalactic sources, it should suffer from the GZK effect. In the Z-burst scenario, cosmic rays are coming from another independent source (Z-bursts), too. What we observe is the sum of the two. As the detailed fits in the next section will show, the flux from Z-bursts is much smaller in the low energy region than the flux of the power-law background. Correspondingly, the low energy part of the spectrum (between $10^{18.5}$ and $10^{19.3}$ eV) has very little influence on the Z-burst fit parameters, notably on the neutrino mass.

We shall study several possibilities for the background term $F_{p|\mathrm{bkd}}$.

The first one is based on the assumption that the diffuse background of ordinary cosmic rays even above the GZK cutoff at $4 \cdot 10^{19}$ eV consists of protons which are produced in our neighborhood – within our galactic halo or at least within the GZK zone of about 50 Mpc. We shall refer to this possible cosmic ray background in the following as the "halo background". We should note, however, that there are no apparent suitable astrophysical sources within the GZK distance to which the highest energy events point [49, 50] – a fact which is difficult to reconcile with the halo background model.

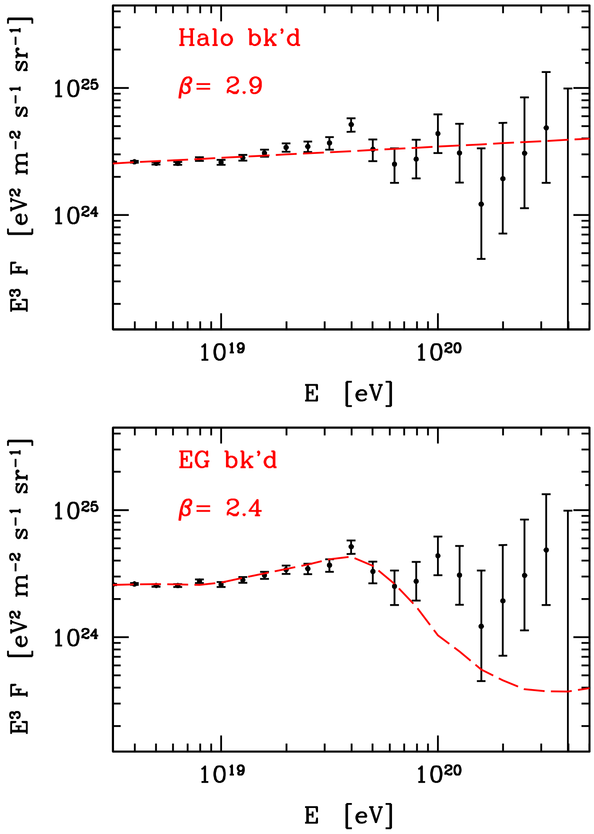

FIG. 6: The available UHECR data with their error bars and the best fits (long-dashed) from ordinary cosmic ray protons originating from our local neighbourhood ("halo background"; *top*) and originating from diffuse extragalactic sources ("EG background"; *bottom*), respectively. For the latter case, the bump at $4 \cdot 10^{19}$ eV represents protons injected at high energies and accumulated just above the GZK cutoff due to their energy losses. The predicted fall-off for energies above $4 \cdot 10^{19}$ eV can be observed.

For the halo background, no GZK attenuation is included. The spectrum is assumed to have the usual power-law behavior which describes the data well for smaller energies [37, 45] (cf. Fig. 6 (top)),

$$\mathcal{E}\, F_{p|\mathrm{bkd}}(E; A, \beta) = \quad (34)$$
$$\frac{A}{1\,\mathrm{eV}} \left(\frac{E}{1\,\mathrm{eV}} \right)^{-\beta} \qquad (\mathrm{Halo\ bk'd}) \, .$$

A similar background model, however with a fixed power-law index $\beta = 3.23$, as found by AGASA to fit the data from $10^{17.6} \div 10^{19}$ eV (cf. Table V in Ref. [45]), has been exploited in a recent Z-burst simulation [66].

In the second case, we assume that the diffuse background of ordinary cosmic rays comes from protons which originate from uniformly distributed, extragalactic sources – hence we name it "extragalactic background". In view of the observed distribution of arrival directions of UHECRs, this assumption seems to be phenomenologically more realistic than the halo background model. Though there are some peculiarly clustered events, the overall distribution at present statistics seems to be practically uniform [157, 158, 159].

The extragalactic background suffers of course from GZK attenuation. Correspondingly, we take the above power-law (34), $A \cdot E_p^{-\beta}$, as an injection spectrum and take its modification due to the interactions with the CMB photons into account with the help of the proton propagation function $P_p(r, E_p; E)$,

$$\begin{aligned} \mathcal{E}\, F_{p|\mathrm{bkd}}(E; A, \beta) &= \\ & \int_0^\infty \mathrm{d}E_p \int_0^{R_{\max}} \mathrm{d}r\ (1+z(r))^3 \\ & \times \frac{A}{1\,\mathrm{eV}} \left(\frac{E_p}{1\,\mathrm{eV}}\right)^{-\beta} \\ & \times (-)\frac{\partial P_p(r, E_p; E)}{\partial E} \qquad (\mathrm{EG\ bk'd})\,. \end{aligned} \tag{35}$$

The predicted spectrum of the extragactic background protons shows an accumulation at around the GZK scale $4 \cdot 10^{19}$ eV and a sharp drop beyond (see Fig. 6 (bottom)).

As far as the Z-burst spectra entering our prediction (33) are concerned, we proceed as follows. We shall mainly concentrate on the case where there is only one relevant neutrino mass scale m_ν, either because there are three neutrino types with nearly degenerate neutrino masses, $m_{\nu_i} \approx m_\nu$, or there is one neutrino which is much heavier than the other ones such that the contribution of the latter to the cosmic ray spectrum can be neglected since the corresponding resonance energies are much larger and the UHECν fluxes are expected to fall with increasing energy. Therefore, we fit only one neutrino mass parameter m_ν. In this case, the spectra (12) and (13) for protons and photons from Z-bursts can be written as

$$\begin{aligned} \mathcal{E}\, F_{i|Z}(E; B, m_\nu) &= \\ & B \int_0^\infty \mathrm{d}E_i \int_0^{R_{\max}} \mathrm{d}r\ (1+z(r))^{3+\alpha}\ \delta_n(r) \\ & \frac{4\, m_\nu}{M_Z^2}\, \mathcal{Q}_i \left(y = \frac{4\, m_\nu\, E_i}{M_Z^2} \right) \\ & \times (-)\frac{\partial P_i(r, E_i; E)}{\partial E}, \qquad i = p, \gamma\,, \end{aligned} \tag{36}$$

where α is the cosmological evolution parameter, $\delta_n(r)$ is the mass density fluctuation field (cf. Fig. 5 (bottom)), normalized to one, and $\mathcal{Q}_i$ are the boosted momentum distributions from hadronic Z decay, normalized to $\langle N_{p+n} \rangle = 2.04$, for $i = p$, and to $\langle N_\gamma \rangle = 2\,\langle N_{\pi^0}\rangle + \langle N_{\pi^\pm}\rangle = 37$, for $i = \gamma$. We are left here with two fit parameters, the mass m_ν of the heaviest neutrino and the overall normalization B, which may be expressed, on account of Eqs. (20) and (32), in terms of the original quantities entering Eqs. (12) and (13), as

$$\frac{B}{\mathcal{E}} = \mathrm{Br}(Z \to \mathrm{hadrons})\, R_{\max}\, \langle n_{\nu_i} \rangle_0\, \langle \sigma_{\mathrm{ann}} \rangle\, E_\nu^{\mathrm{res}}\, F_\nu^{\mathrm{res}}\,. \tag{37}$$

Note, that the neglection of finite width effects, $1/2\,\delta E_{\nu_i}^{\mathrm{res}}/E_{\nu_i}^{\mathrm{res}} = \Gamma_Z/M_Z = 2.7\,\%$, in our implementation (36) of the Z-burst spectra is perfectly adequate in view of the relative errors $\gtrsim 50\,\%$ which we will find later from our fits.

The expectation value for the number of events in a bin is given by Eq. (33). To determine the most probable value for m_{ν_j} we use the maximum likelihood method and minimize [160] the $\chi^2(\beta, A, B, m_{\nu_j})$,

$$\chi^2 = \sum_{\log\left(\frac{E_i}{\mathrm{eV}}\right)=18.5}^{\log\left(\frac{E_i}{\mathrm{eV}}\right)=26.0} 2\left[N(i) - N_{\mathrm{o}}(i) + N_{\mathrm{o}}(i) \ln\left(N_{\mathrm{o}}(i)/N(i)\right)\right], \tag{38}$$

where $N_{\mathrm{o}}(i)$ is the total number of observed events in the i^{th} bin. Since the Z-burst scenario results in a quite small flux for lower energies, we take the lower bound just below the "ankle": $E_{\min} = 10^{18.5}$ eV. Our results are insensitive to the definition of the upper end (the flux is extremely small there) for which we choose $\log(E_{\max}/\mathrm{eV}) = 26$. The uncertainties of the measured energies are about 30% which is one bin. By means of a Monte Carlo analysis, we take these uncertainties into account and include the corresponding variations in our final error estimates.

For comparison with recent work on the Z-burst scenario [65], we have done also fits with no background component, $F_{p|\mathrm{bkd}} = 0$ in Eq. (33), and a larger lower end, $\log(E_{\min}/\mathrm{eV}) = 19.4 \div 20.0$. Such a scenario, with $E_{\min} \lesssim E_{\mathrm{GZK}} \approx 4 \cdot 10^{19}$ eV, was advocated in Ref. [65] as appropriate to explain all UHECR data above the GZK cutoff by the Z-burst model and to attribute all UHECR data below the cutoff to ordinary astrophysical extragalactic sources.

B. Fit results

Qualitatively, our analysis can be understood as follows. In the Z-burst scenario a small relic neutrino mass needs a large incident neutrino energy E_ν^{res} (2) in order to produce a Z. Large E_ν^{res} results in a large Lorentz boost, thus large E_p resp. E_γ. In this way the *shape* of the detected energy (E) spectrum determines the mass of the relic neutrino. The sum of the necessary UHECν fluxes F_ν^{res}, on the other hand, is determined by the over-all *normalization* B.

TABLE I: Results of fits, for a strong UHEγ attenuation ($h = 0.71, \Omega_M = 0.3, \Omega_\Lambda = 0.7, z_{\rm max} = 2$). *Top:* Assuming a halo UHECR background according to Eq. (34). *Middle:* Assuming an extragalactic UHECR background according to Eq. (35). *Bottom:* Assuming no UHECR background above $E_{\rm min}$, for different values of the lower end $E_{\rm min}$ of the fit ($\alpha = 0$).

Halo UHECR background + strong UHEγ attenuation					
α	m_ν [eV]	$\chi^2_{\rm min}$	A	B	β
-3	$4.46^{+2.22(4.80)}_{-1.64(2.88)}$	15.90	$1.46 \cdot 10^{43}$	1049	3.110
0	$3.46^{+1.73(4.03)}_{-1.34(2.32)}$	15.64	$1.62 \cdot 10^{43}$	770	3.111
3	$2.51^{+1.45(3.30)}_{-1.05(1.80)}$	15.53	$1.65 \cdot 10^{43}$	551	3.111
EG UHECR background + strong UHEγ attenuation					
α	m_ν [eV]	$\chi^2_{\rm min}$	A	B	β
-3	$0.20^{+0.20(0.63)}_{-0.11(0.18)}$	25.82	$5.00 \cdot 10^{31}$	150	2.465
0	$0.20^{+0.19(0.61)}_{-0.12(0.18)}$	26.41	$5.98 \cdot 10^{31}$	144	2.466
3	$0.20^{+0.19(0.59)}_{-0.11(0.17)}$	26.89	$7.23 \cdot 10^{31}$	142	2.467
No UHECR background + strong UHEγ attenuation					
$\log(E_{\rm min}/{\rm eV})$	m_ν [eV]	$\chi^2_{\rm min}$	A	B	β
19.4	$2.28^{+0.64(1.46)}_{-0.58(1.06)}$	21.81	–	1251	–
19.5	$1.31^{+0.63(1.44)}_{-0.53(0.80)}$	16.01	–	846	–
19.6	$0.85^{+0.67(1.62)}_{-0.31(0.55)}$	14.80	–	670	–
19.7	$0.40^{+0.32(0.87)}_{-0.16(0.27)}$	8.03	–	445	–
19.8	$0.42^{+0.41(1.25)}_{-0.18(0.29)}$	7.99	–	460	–
19.9	$0.76^{+1.06(2.50)}_{-0.39(0.58)}$	5.52	–	733	–
20.0	$1.77^{+1.49(3.47)}_{-1.01(1.47)}$	2.68	–	2021	–

Our fitting procedure involves four parameters: β, A, B and m_ν. The minimum of the $\chi^2(\beta, A, B, m_\nu)$ function is $\chi^2_{\rm min}$ at $m_{\nu\,{\rm min}}$ which is the most probable value for the mass, whereas the $1\,\sigma$ (68%) confidence interval for m_ν is determined by

$$\chi^2(\beta', A', B', m_\nu) \equiv \chi^2_o(m_\nu) = \chi^2_{\rm min} + 1\,. \qquad (39)$$

Here β', A', B' are defined in such a way that the χ^2 function is minimized in β, A and B, at fixed m_ν.

As already mentioned, presently there is no evidence that the observed highest energy cosmic rays are photons. Let us start therefore with the assumption (cf. Ref. [61]) that the ultrahigh energy photons from Z-bursts can be neglected in the fit in comparison to the protons. This is certainly true for a sufficiently large universal radio background, e. g. on the level of the maximal one estimated in Ref. [118] and/or for a sufficiently strong extragalactic magnetic field $\mathcal{O}(10^{-9})$ G. We shall refer to this scenario in the following as "strong" UHEγ attenuation. Our best fits to the observed data from this scenario (cf. Table I) can be seen in Fig. 7, for evolution parameter $\alpha = 0$. We find a neutrino mass of $m_\nu = 3.46^{+1.73(4.03)}_{-1.34(2.32)}$ eV for the case that the UHECR background protons are of halo type (34), $m_\nu = 0.20^{+0.19(0.61)}_{-0.12(0.18)}$ eV, if they are of

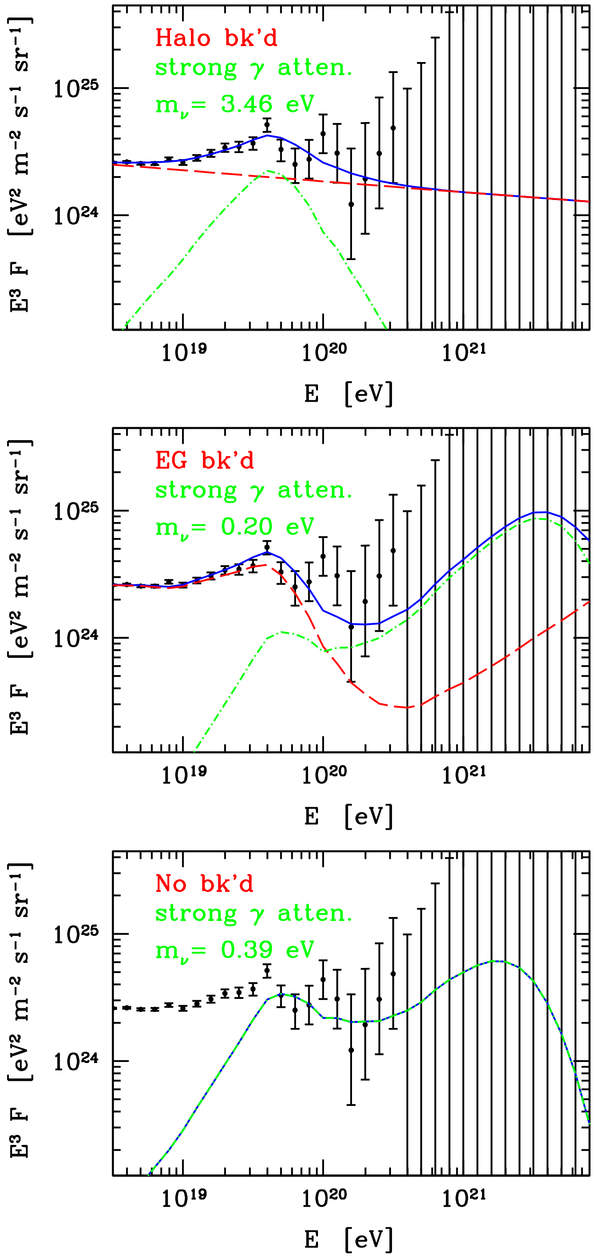

FIG. 7: The available UHECR data with their error bars and the best fits from Z-bursts, for a strong UHEγ attenuation such that the Z-burst photons can be neglected ($\alpha = 0, h = 0.71, \Omega_M = 0.3, \Omega_\Lambda = 0.7, z_{\rm max} = 2$). *Top:* Best fit for the case of a halo background (solid line). The bump around $4 \cdot 10^{19}$ eV is mainly due to the Z-burst protons (dash-dotted), whereas the almost horizontal contribution (long-dashed) is the first, power-law-like term of Eq. (33). *Middle:* The case of an "extragalactic" UHECR background. The first bump at $4 \cdot 10^{19}$ eV represents protons produced at high energies and accumulated just above the GZK cutoff due to their energy losses. The bump at $2 \cdot 10^{21}$ eV is a remnant of the Z-burst energy. The long-dashed line shows the contribution of the power-law-like spectrum with the GZK effect included. *Bottom:* The case of no UHECR background above $\log(E_{\rm min}/{\rm eV}) = 19.7$.

extragalactic type (35), and $m_\nu = 0.40^{+0.32(0.87)}_{-0.16(0.27)}$ eV, if there are are no background protons above $10^{19.7}$ eV, respectively. The first numbers are the $1\,\sigma$, the numbers in the brackets are the $2\,\sigma$ errors. This gives an absolute lower bound on the mass of the heaviest neutrino of $m_\nu > 0.02$ eV at the 95% C.L., which is comparable to the one obtained from the atmospheric mass splitting in a three flavour scenario, Eq. (3).

The surprisingly small uncertainties are based on the χ^2 analysis described in Section III A. The inclusion of the already mentioned 30 % uncertainties in the observed energies by a Monte Carlo analysis increases the error bars by about 10 %. Note, that the relative errors in the extragalactic and in the no background cases are of the same order. This shows that the smallness of these errors does not originate from the low energy part of the background component.

The fits are rather good: for 21 non-vanishing bins and 4 fitted parameters they can be as low as $\chi^2_{\rm min} = 15.64$ and $\chi^2_{\rm min} = 25.82$ in the halo and the extralactic background case, respectively, whereas in the no background case, for $E_{\rm min} = 10^{19.7}$ eV, we have 9 bins with 2 fitted parameters and a $\chi^2_{\rm min} = 8.03$, see Table I. In the latter case, however, which was advocated strongly in Ref. [65], a remarkable dependence of the fitted mass on the value of $E_{\rm min}$ is observed. The $\pm\,2\,\sigma$ fits are shown in Fig. 8. As it should be, the spread is small in the region where there are data, whereas it can be quite large in the presently unexplored ultrahigh energy regime. Finally, let us mention that, both in the "halo" as well as in the extragalactic background cases, the χ^2 fits *without* a Z-burst component (cf. Fig. 6) are far worse: we find $\chi^2_{\rm min} = 41.37$ in the former, and $\chi^2_{\rm min} = 38.25$ in the latter, for 21 non-vanishing bins and 2 fitted parameters. This finding suggests that the power-law background terms alone cannot describe the data.

In addition to the case of strong UHEγ attenuation, corresponding to a large universal radio background or a large extragalactic magnetic field, let us consider now the case of a "minimal" URB. Here, we assume a vanishing EGMF and exploit, as in Ref. [116], a universal radio background on the level of the one from Ref. [119] (cf. Section II B and Fig. 3 (top)). The corresponding fits, for our three background scenarios, can be seen in Fig. 9 and Table II. Note, that our best fits are still compatible with the already mentioned upper limits on the photon fraction of the observed ultrahigh energy cosmic rays [42, 155, 156]. We observe that the value of the neutrino mass found in both the halo background scenario, with $m_\nu = 3.71^{+1.40(3.27)}_{-1.12(1.96)}$ eV, as well as in the extragalactic background scenario, with $m_\nu = 0.77^{+0.48(1.36)}_{-0.30(0.51)}$ eV, are compatible, at about the 2 σ level, with the corresponding values found in the case of strong UHEγ attenuation. As before, in the "no" background scenario, we find a strong dependence of the fitted mass on the value of $E_{\rm min}$.

Besides the no UHECR background scenario, the Z-

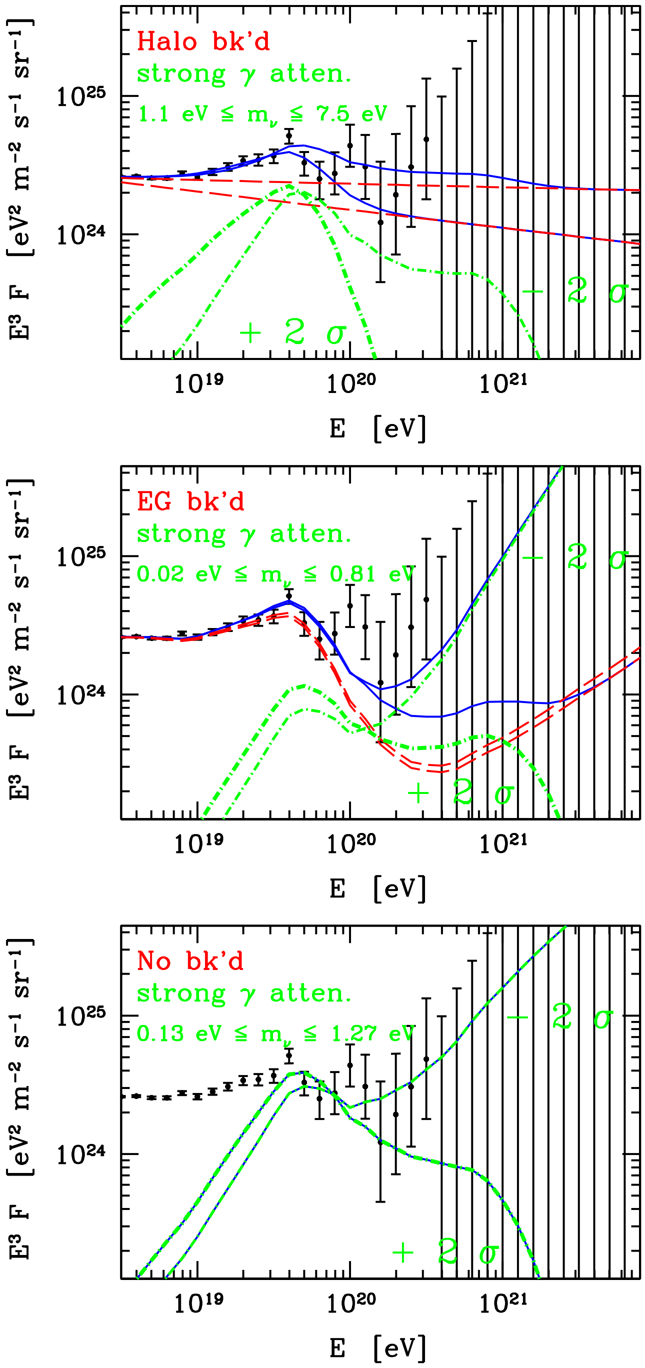

FIG. 8: The available UHECR data with their error bars and the $\chi^2_{\rm min} \pm 4$ fits (solid lines) from Z-bursts, for a halo (*top*), an extragalactic (*middle*), and no (*bottom*) UHECR background (long-dashed lines), and a strong UHEγ attenuation such that the Z-burst photons can be neglected and only the Z-burst protons (dash-dotted lines) have to be taken into account in the fit ($\alpha = 0, h = 0.71, \Omega_M = 0.3, \Omega_\Lambda = 0.7, z_{\rm max} = 2$).

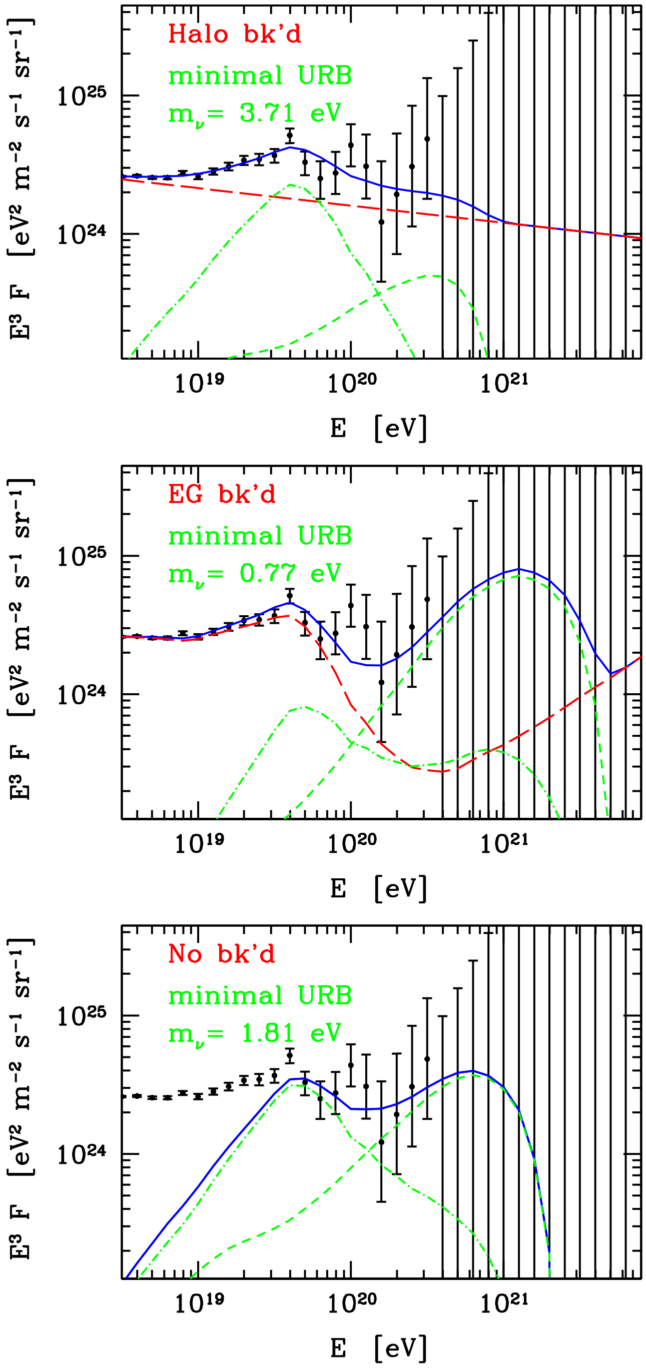

FIG. 9: The available UHECR data with their error bars and the best fits from Z-bursts, for an energy attenuation of photons as in Ref. [116] and a vanishing EGMF ($\alpha = 0, h = 0.71, \Omega_M = 0.3, \Omega_\Lambda = 0.7, z_{\rm max} = 2$). *Top:* Best fit for the case of a halo UHECR background (solid line), corresponding to the sum of the background protons (long-dashed), the Z-burst protons (dash-dotted) and the Z-burst photons (short-dashed). *Middle:* The case of an extragalactic UHECR background. *Bottom:* The case of no UHECR background above $\log(E_{\rm min}/{\rm eV}) = 19.7$.

TABLE II: Results of fits, for a photon attenuation as in Ref. [116] ("minimal" URB) and vanishing EGMF ($h = 0.71, \Omega_M = 0.3, \Omega_\Lambda = 0.7, z_{\rm max} = 2$). *Top:* Assuming a halo UHECR background according to Eq. (34). *Middle:* Assuming an extragalactic UHECR background according to Eq. (35). *Bottom:* Assuming no UHECR background above $E_{\rm min}$, for different values of the lower end $E_{\rm min}$ of the fit ($\alpha = 0$).

Halo UHECR background + minimal URB					
α	m_ν [eV]	$\chi^2_{\rm min}$	A	B	β
-3	$4.46^{+1.78(3.99)}_{-1.36(2.39)}$	15.69	$4.76\cdot 10^{43}$	1060	3.146
0	$3.71^{+1.40(3.27)}_{-1.12(1.96)}$	15.36	$1.05\cdot 10^{44}$	827	3.166
3	$3.01^{+1.13(2.62)}_{-0.92(1.56)}$	15.20	$1.55\cdot 10^{44}$	642	3.171
EG UHECR background + minimal URB					
α	m_ν [eV]	$\chi^2_{\rm min}$	A	B	β
-3	$0.79^{+0.49(1.40)}_{-0.31(0.53)}$	24.19	$5.73\cdot 10^{31}$	125	2.466
0	$0.77^{+0.48(1.36)}_{-0.30(0.51)}$	24.52	$6.44\cdot 10^{31}$	120	2.467
3	$0.79^{+0.45(1.32)}_{-0.31(0.53)}$	24.77	$7.55\cdot 10^{31}$	122	2.468
No UHECR background + minimal URB					
$\log(E_{\rm min}/{\rm eV})$	m_ν [eV]	$\chi^2_{\rm min}$	A	B	β
19.4	$3.08^{+0.78(1.68)}_{-0.58(1.05)}$	14.43	–	1380	–
19.5	$2.56^{+0.76(1.68)}_{-0.55(0.97)}$	11.88	–	1111	–
19.6	$2.51^{+0.84(1.87)}_{-0.60(1.05)}$	11.86	–	1079	–
19.7	$1.81^{+0.75(1.76)}_{-0.51(0.86)}$	8.02	–	680	–
19.8	$2.04^{+0.95(2.17)}_{-0.67(1.11)}$	7.74	–	812	–
19.9	$3.01^{+1.34(3.03)}_{-1.06(1.78)}$	4.93	–	1699	–
20.0	$4.67^{+2.12(4.60)}_{-1.74(2.95)}$	2.33	–	4881	–

burst determination of the neutrino mass seems reasonably robust. Its robustness with regard to changes of presently unknown quantities within their anticipated variations is further illustrated in Tables III and IV and in Fig. 10. For a wide range of cosmological source evolution ($\alpha = -3 \div 3$), Hubble parameters $h = 0.61 \div 0.9$, Ω_M, Ω_Λ, $z_{\rm max} = 2 \div 5$, for variations of the possible relic neutrino overdensity in our GZK zone within the limits discussed in Section II D, and for different assumptions about the diffuse extragalactic photon background, the results remain within the above error bars. The main uncertainties concerning the central values originate from the different assumptions about the background of ordinary cosmic rays. In the case that the ordinary cosmic rays above $10^{18.5}$ eV are protons and originate from a region within the GZK zone of about 50 Mpc ("halo"), the required mass of the heaviest neutrino seems to lie between 2.1 eV $\leq m_\nu \leq$ 6.7 eV at the 68 % C.L. ($\alpha \leq 0$, cf. below), if we take into account the variations between the minimal and moderate URB cases and the strong UHEγ attenuation case (cf. Fig. 10). Note, that a value of $m_\nu = 0.07$ eV, as studied recently in Ref. [66] in a simulation of the Z-burst scenario in the context of a halo background model, seems to lie more than $3\,\sigma$ away from

TABLE III: Results of fits, for a photon attenuation as in Fig. 3 (bottom), short-dashed line ("moderate" URB) and vanishing EGMF ($h = 0.71, \Omega_M = 0.3, \Omega_\Lambda = 0.7, z_{\max} = 2$). *Top:* Assuming a halo UHECR background according to Eq. (34). *Middle:* Assuming an extragalactic UHECR background according to Eq. (35). *Bottom:* Assuming no UHECR background above $E_{\min}$, for different values of the lower end $E_{\min}$ of the fit ($\alpha = 0$).

Halo UHECR background + moderate URB					
α	m_ν [eV]	$\chi^2_{\min}$	A	B	β
-3	$4.35^{+1.97(4.31)}_{-1.45(2.57)}$	15.69	$2.16 \cdot 10^{43}$	848	3.112
0	$3.62^{+1.61(3.66)}_{-1.20(2.13)}$	15.44	$2.38 \cdot 10^{43}$	662	3.113
3	$2.94^{+1.30(3.00)}_{-1.01(1.72)}$	15.26	$4.91 \cdot 10^{43}$	514	3.149
EG UHECR background + moderate URB					
α	m_ν [eV]	$\chi^2_{\min}$	A	B	β
-3	$0.32^{+0.29(0.84)}_{-0.17(0.27)}$	21.15	$4.95 \cdot 10^{31}$	60	2.465
0	$0.32^{+0.28(0.80)}_{-0.17(0.26)}$	21.29	$5.40 \cdot 10^{31}$	58	2.466
3	$0.31^{+0.28(0.78)}_{-0.17(0.26)}$	21.37	$5.94 \cdot 10^{31}$	56	2.466
No UHECR background + moderate URB					
$\log(E_{\min}/\mathrm{eV})$	m_ν [eV]	$\chi^2_{\min}$	A	B	β
19.4	$2.81^{+0.74(1.65)}_{-0.59(1.05)}$	15.01	–	1087	–
19.5	$2.18^{+0.73(1.65)}_{-0.52(0.92)}$	11.99	–	820	–
19.6	$2.04^{+0.81(1.84)}_{-0.56(0.97)}$	11.82	–	755	–
19.7	$1.12^{+0.59(1.50)}_{-0.40(0.64)}$	5.53	–	369	–
19.8	$1.04^{+0.75(1.92)}_{-0.44(0.69)}$	5.49	–	341	–
19.9	$1.66^{+1.31(3.03)}_{-0.81(1.23)}$	4.26	–	652	–
20.0	$2.81^{+2.15(5.03)}_{-1.44(2.24)}$	2.75	–	1728	–

our best fit values. The much more plausible assumption that the ordinary cosmic rays above $10^{18.5}$ are protons of extragalactic origin leads to a required neutrino mass of 0.08 eV $\leq m_\nu \leq 1.3$ eV at the 68 % C.L. ($\alpha \leq 0$) (cf. Fig. 10).

We performed a Monte Carlo analysis studying higher statistics. In the near future, the Pierre Auger Observatory [161, 162] will provide a ten times higher statistics, which reduces the error bars in the neutrino mass to about one third of their present values.

Let us consider next in more detail the γ ray spectra from Z-bursts, notably in the ~ 100 GeV region. As illustrated in Fig. 11, the EGRET measurements of the diffuse γ background in the energy range between 30 MeV and 100 GeV [163] put non-trivial constraints on the evolution parameter α. Whereas different values of α lead to very similar spectra in the ultrahigh energy region – which determines the neutrino mass – they are easily discriminated in $\lesssim$ TeV photons. Only evolution parameters $\alpha \lesssim 0$ seem to be compatible with the EGRET measurements (cf. Fig. 11), quite independently of different assumptions about the URB. These numerical findings are in fairly good agreement with other recent simulations [65].

TABLE IV: Results of fits, for strong and minimal photon attenuation (cf. Tables I and II, respectively), for extremal values of the (reduced) Hubble constant ($\alpha = 0, \Omega_M = 0.3, \Omega_\Lambda = 0.7, z_{\max} = 2$).

EG UHECR background + strong UHEγ attenuation					
h	m_ν [eV]	$\chi^2_{\min}$	A	B	β
0.61	$0.19^{+0.19(0.62)}_{-0.12(0.17)}$	28.27	$1.47 \cdot 10^{31}$	126	2.452
0.90	$0.21^{+0.20(0.64)}_{-0.11(0.18)}$	24.20	$8.93 \cdot 10^{32}$	168	2.529
EG UHECR background + minimal URB					
h	m_ν [eV]	$\chi^2_{\min}$	A	B	β
0.61	$0.64^{+0.42(1.23)}_{-0.25(0.44)}$	26.28	$1.46 \cdot 10^{31}$	97	2.452
0.90	$1.02^{+0.64(1.70)}_{-0.39(0.65)}$	22.39	$1.20 \cdot 10^{33}$	162	2.531
EG UHECR background + moderate URB					
h	m_ν [eV]	$\chi^2_{\min}$	A	B	β
0.61	$0.26^{+0.25(0.71)}_{-0.14(0.22)}$	22.91	$8.03 \cdot 10^{30}$	52	2.435
0.90	$0.40^{+0.37(1.03)}_{-0.20(0.32)}$	19.53	$8.41 \cdot 10^{32}$	64	2.529

The necessary UHECν flux at the resonant energy $E_\nu^{\rm res}$ is obtained via Eq. (37) from the fitted overall normalization B,

$$E_\nu^{\rm res}\, F_\nu^{\rm res} = 8.6 \cdot 10^{-16}\, \frac{1}{\mathrm{m^2\,s\,sr}}\, \frac{D_{H_0}}{R_{\max}}\, h\, B\,, \tag{40}$$

where $D_{H_0} = c/H_0 = 3 \cdot 10^3\, h^{-1}$ Mpc is the present size of the universe and where, on account of Eqs. (27) and (28), the ratio of the maximally considered distance of Z production, $R_{\max}$, and the size of the universe is given

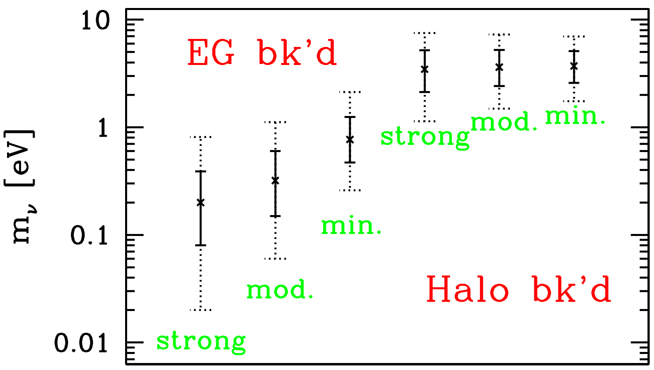

FIG. 10: Summary of the masses of the heaviest neutrino required in the Z-burst scenario, with their $1\,\sigma$ (solid) and $2\,\sigma$ (dotted) error bars, for the case of an extragalactic and a halo background of ordinary cosmic rays and for various assumptions about the diffuse extragalactic photon background in the radio band ($\alpha = 0, h = 0.71, \Omega_M = 0.3, \Omega_\Lambda = 0.7, z_{\max} = 2$). From left: strong γ attenuation, moderate and minimal URB.

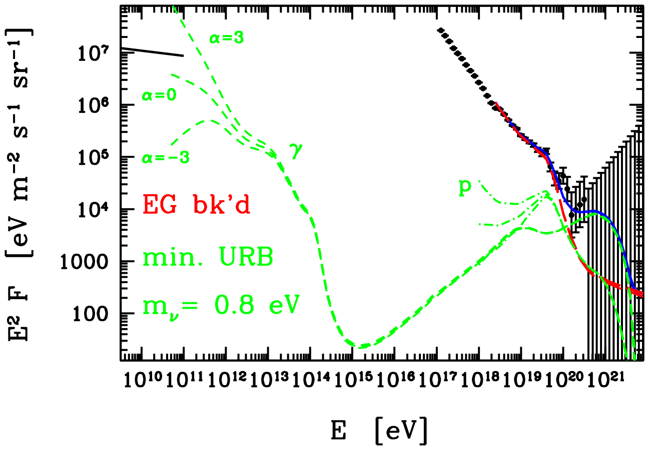

FIG. 11: The available UHECR data with their error bars and the best fit from Z-bursts, for various cosmological evolution parameters α and an energy attenuation of photons as in Fig. 3 (bottom) exploiting a "minimal" URB ($h = 0.71, \Omega_M = 0.3, \Omega_\Lambda = 0.7, z_{\rm max} = 2$). Also shown is the diffuse γ background in the energy range between 30 MeV and 100 GeV as measured by EGRET [163] (solid).

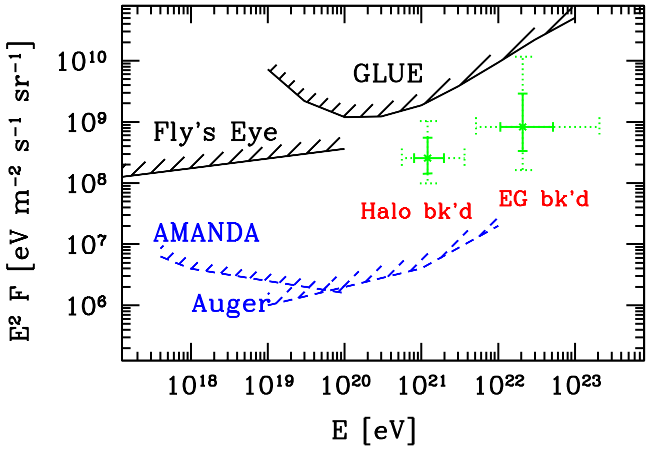

FIG. 12: Neutrino fluxes, $F = \frac{1}{3}\sum_{i=1}^{3}(F_{\nu_i} + F_{\bar\nu_i})$, required by the Z-burst hypothesis for the case of a halo and an extragalactic background of ordinary cosmic rays, respectively ($\alpha = 0, h = 0.71, \Omega_M = 0.3, \Omega_\Lambda = 0.7, z_{\rm max} = 2$). Shown are the necessary fluxes obtained from the fit results of Table I for the case of a strong UHEγ attenuation. The horizontal errors indicate the $1\,\sigma$ (solid) and $2\,\sigma$ (dotted) uncertainties of the mass determination and the vertical errors include also the uncertainty of the Hubble expansion rate. Also shown are upper limits from Fly's Eye [123] on $F_{\nu_e} + F_{\bar\nu_e}$ and the Goldstone lunar ultrahigh energy neutrino experiment GLUE [124] on $\sum_{\alpha=e,\mu}(F_{\nu_\alpha} + F_{\bar\nu_\alpha})$, as well as projected sensitivities of AMANDA [164, 165] on $F_{\nu_\mu} + F_{\bar\nu_\mu}$ and Auger [52, 166] on $F_{\nu_e} + F_{\bar\nu_e}$. The sensitiviy of RICE is comparable to the one of Auger [128].

by

$$\frac{R_{\rm max}}{D_{H_0}} = \int_0^{z_{\rm max}} {\rm d}z\, \frac{1}{(1+z)\sqrt{\Omega_M\,(1+z)^3 + \Omega_\Lambda}}\,. \qquad (41)$$

This ratio is of order one; it equals 0.73 for $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ and $z_{\rm max} = 2$. The required fluxes are summarized in Fig. 12, together with some existing upper limits and projected sensitivities of present, near future and future observational projects. They appear to be well below present upper limits and are within the expected sensitivity of AMANDA [164, 165], RICE [128], and Auger [166]. Clearly, these fluxes are higher than the ones advocated in Ref. [52] based on local neutrino overdensities $f_\nu = 10^2 \div 10^4$ on scales of about 5 Mpc. However, since we also took into account a background from ordinary cosmic rays, our normalization of the Z-burst component is different and correspondingly our fluxes are somewhat less than a factor of f_ν higher. They are consistent with the ones found in Refs. [65, 66]. As far as power-law extrapolations of the fluxes, $F_\nu \propto E^{-\gamma}$, below the resonance energy are concerned, we find, in agreement with Refs. [52, 53, 65], that indices $\gamma \gtrsim 1.5$ are excluded by the Fly's Eye limits [123] (cf. Fig. 12).

The required neutrino flux, for power-law extrapolations with index $\gamma \gtrsim 1$ to lower energies, is larger than the theoretical upper limit from "hidden" hadronic astrophysical sources, from which only photons and neutrinos can escape (cf. Fig. 4 ("MPR")). From an analysis of the assumptions behind this limit [127] one finds that one has to invoke hidden astrophysical sources whose photons somehow don't show up in the diffuse γ ray background measured by EGRET [64, 65]. In general, astrophysical sources for the required UHE neutrinos should be distributed with $\alpha < 0$, accelerate protons up to energies $\gtrsim 10^{23}$ eV, be opaque to primary nucleons and emit secondary photons only in the sub-MeV region. It is an interesting question whether such challenging conditions can be realized in BL Lac objects, a class of active galactic nuclei for which some evidence of zero or negative cosmological evolution has been found (see Ref. [167] and references therein) and which were recently discussed as possible sources of the highest energy cosmic rays [168]. Alternatively, one may invoke top-down scenarios [48] for the sources of the highest energy cosmic neutrinos such as unstable superheavy relic particle decays [55, 57, 99, 135, 136, 137, 138, 139, 140] or topological defect decays [147].

It should be stressed that, besides the neutrino mass, the UHECν flux at the resonance energy is one of the most robust predictions of the Z-burst scenario which can be verified or falsified in the near future. In this connection it is worthwhile to recall (cf. Section II D) that the current limits on neutrino degeneracies [153, 154] do not allow a remarkable uniform enhancement due to lepton asymmetries which otherwise would be welcome for a relaxation of the huge flux requirement [54].

IV. DISCUSSION AND CONCLUSIONS

We have presented a detailed comparison of the predicted spectra from Z-bursts – resulting from the resonant annihilation of ultrahigh energy cosmic neutrinos with relic neutrinos – with the observed ultrahigh energy cosmic ray spectrum, extending our earlier study [61]. The mass of the heaviest relic neutrino turned out to have to lie in the range 2.1 eV $\leq m_\nu \leq$ 6.7 eV on the 1 σ level, if the background of ordinary cosmic rays above $10^{18.5}$ eV consists of protons and originates from a region within a distance of about 50 Mpc. In the phenomenologically most plausible case that the ordinary cosmic rays above $10^{18.5}$ are protons of extragalactic origin one is lead to a required neutrino mass in the range 0.08 eV $\leq m_\nu \leq$ 1.3 eV at the 68 % C.L.. We have also analysed a case where there is no background of ordinary cosmic rays above, say, $10^{19.7}$ eV. Here, we find 0.24 eV $\leq m_\nu \leq$ 2.6 eV. The above neutrino mass ranges include variations in presently unknown quantities, like the amount of neutrino clustering, the universal radio background, and the extragalactic magnetic field, within their anticipated uncertainties. If it turns out that the highest energy cosmic rays are extragalactic protons rather than photons one has to invoke a large universal radio background and/or large extragalactic magnetic field to suppress the photons from Z-bursts. In this case and for our extragalactic background scenario, the neutrino mass range narrows down to 0.08 eV $\leq m_\nu \leq$ 0.40 eV, with a best fit value of $m_\nu = 0.20$ eV.

It is remarkable, that the mass ranges required in the Z-burst scenario coincide nearly perfectly with the present knowledge about the mass of the heaviest neutrino from oscillations and tritium β decay from Eqs. (3) and (8), 0.04 eV $\lesssim m_{\nu_3} \lesssim$ 2.5 eV, in a three flavour or, from Eqs. (4) and (9), 0.4 eV $\lesssim m_{\nu_4} \lesssim$ 3.8 eV, in a four flavour scenario. Our values, in the extragalactic background scenario, are still compatible with a hierarchical neutrino mass spectrum, with the largest mass suggested by the atmospheric neutrino oscillation, $m_{\nu_3} \approx \sqrt{\triangle m^2_{\rm atm}} \approx 0.04 \div 0.08$ eV. However, our best fit values point more into the direction of a quasi-degenerate scenario, $m_{\nu_i} \approx m_\nu \gg \sqrt{\triangle m^2_{\rm atm}}$. It is amusing to observe that the recently reported evidence for neutrinoless double beta decay, with 0.11 eV $\leq \langle m_\nu \rangle \leq$ 0.56 eV, if true, would point also into the same direction [79].

The above neutrino masses are in a range which can be explored by near-future laboratory experiments, like the KATRIN tritium β decay experiment [169], with a projected sensitivity of $m_\beta \gtrsim 0.3$ eV within $6 \div 7$ years, or the $0\nu 2\beta$ decay experiments NEMO-3 [170] and CUORE [171], which aim at $\langle m_\nu \rangle \gtrsim 0.1$ eV, and their next-generation follow-up projects GENIUS [172] and EXO [173], with $\langle m_\nu \rangle \gtrsim 0.01$ eV. Our mass range also compares favourably with the expected sensitivity $\sum_i (g_{\nu_i}/2)\, m_{\nu_i} \gtrsim 0.3$ eV of near-future global cosmological analyses involving also new CMB measurements [93, 174], as well as $m_\beta \gtrsim 0.75 \div 1.8$ eV expected from neutrino observations from supernovae explosions [175, 176].

From our fits, we could also determine the necessary ultrahigh energy neutrino flux at the resonance energy. Its prediction, in the context of the Z-burst scenario, turned out to be of similar robustness as the prediction of the mass of the heaviest neutrino. It was found to be consistent with present upper limits and detectable in the near future by the already operating neutrino telescopes AMANDA and RICE, and by the Pierre Auger Observatory, presently under construction. A search at these facilities is the most promising and timely step in testing the Z-burst hypothesis. One does not have to wait for future projects such as EUSO [177] for this critical investigation.

The required neutrino fluxes are enormous. If such tremendous fluxes of ultrahigh energy neutrinos are indeed found, one has to deal with the challenge to explain their origin. It is fair to say, that at the moment no convincing astrophysical sources are known which meet the requirements for the Z-burst hypothesis, i.e. which have no or a negative cosmological evolution, accelerate protons at least up to 10^{23} eV, are opaque to primary nucleons and emit secondary photons only in the sub-MeV region. Ideas to create the required neutrino fluxes from the decays of superheavy particles or topological defects do not seem to be too appealing since they invoke further new physics beyond neutrino masses.

Acknowledgments

We thank S. Barwick, O. Biebel, S. Bludman, W. Buchmüller, P. Di Bari, M. Kachelriess, K. Mannheim, H. Meyer, W. Ochs, K. Petrovay, S. Sarkar, F. Schrempp, D. Semikoz, G. Sigl, and E. Waxman for useful discussions. We thank the OPAL collaboration for their unpublished results on hadronic Z decays. This work was partially supported by Hungarian Science Foundation grants No. OTKA-T34980/T29803/-T22929/M28413/OMFB-1548/OM-MU-708.

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