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 ≤ m_ν ≤ 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 ≤ m_ν ≤ 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.

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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 occurred 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

$$\langle n_{\nu_i}\rangle_0 = \langle n_{\bar{\nu}_i}\rangle_0 = \frac{3}{22} \langle n_\gamma\rangle_0 \simeq 56 \text{ cm}^{-3},$$

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.

Recently, an indirect detection possibility for relic neutrinos has been discussed. 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 (cf. Fig. 1). On resonance, the corresponding cross section is enhanced by several orders of magnitudes. If neutrinos have non-vanishing masses $m_{\nu_i}$ – for which there is rather convincing evidence in view of the apparent observation of neutrino oscillations – the respective resonance energies, in the rest system of the relic neutrinos, correspond to

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

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.
resonance energies are, for neutrino masses of $O(1)$ eV, remarkably close to the energies of the highest energy cosmic rays observed at Earth by collaborations such as AGASA [35], Fly’s Eye [38], [39], Haverah Park [12, 13], HiRes [13], and Yakutsk [11] (for a review, see Ref. [13]). Indeed, it was argued [11] that the ultrahigh energy cosmic rays (UHECRs) above the predicted Greisen-Zatsepin-Kuzmin (GZK) cutoff [40, 41] 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 [14], 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 [19, 20]. 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 [15, 16, 17, 18, 19, 20]. UHECν fluxes were estimated in Ref. [21] for different spectral indices. In Ref. [22], particle spectra were determined numerically for case studies which supported the Z-burst scenario. The effect of possible lepton asymmetries was studied in Ref. [23]. In Ref. [24], 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 [25] (see also Refs. [26, 27]), 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, 37, 38]. However, neutrino oscillations are sensitive only to the mass (squared) splittings $\Delta m^2_{ij} = m^2_i - m^2_j$, not to the individual masses, $(m_{\nu_3} > m_{\nu_2} > m_{\nu_1})$, themselves.

Only a lower bound on the mass of the heaviest neutrino can be derived from these observations, e.g.

$$m_{\nu_3} \geq \sqrt{\Delta m^2_{atm}} \gtrsim 0.04 \text{ eV} \quad (3)$$

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

$$m_{\nu_4} \geq \sqrt{\Delta m^2_{LSND}} \gtrsim 0.4 \text{ eV} \quad (4)$$

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. [28, 29] 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 ($\beta$) 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.

$$m_\beta \equiv \sqrt{\sum_i |U_{e i}|^2 m^2_{\nu_i}} < 2.2 \pm 2.5 \text{ eV} \quad (95 \text{ \% C.L.}) \quad (5)$$

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

$$\langle m_\nu \rangle = \sum_i U^2_{ei} m_{\nu_i} < 0.33 \pm 1.35 \text{ eV} \quad (90 \text{ \% C.L.}) \quad (6)$$

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

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

has been seriously challenged by Refs. [78, 79]. Combining the experimental constraints from oscillations and from tritium $\beta$ decay, one infers upper bounds on the mass of the heaviest neutrino [26],

$$m_{\nu_3} < \sqrt{m^2_\beta + \Delta m^2_{atm}} \lesssim 2.5 \text{ eV}, \quad (8)$$

in a three flavour, and

$$m_{\nu_4} < \sqrt{m^2_\beta + \Delta m^2_{LSND}} \lesssim 3.8 \text{ eV}, \quad (9)$$

in a four flavour scenario, respectively. For further recent investigations of the relationship between oscillation phenomena, $\beta$ decay and 0$\nu$2$\beta$ decay, in particular with respect to the neutrino mass spectrum, one may also consult Refs. [30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40] and references cited therein.

Further information on the absolute scale of neutrino masses can be obtained through cosmological and astrophysical considerations. Neutrinos in the $0.1 \pm 1$ 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 \cite{11, 12}. Analyses of galaxy clustering, including recent CMB measurements and other cosmological constraints, give an upper bound

\[
\sum m_{\nu_i} < 1.8 \div 4.4 \text{ eV} \quad (10)
\]

on the sum of the neutrino masses \cite{23, 24, 25, 26}. From the spread of arrival times of neutrinos from supernova SN 1987A, coupled with the measured neutrino energies, a time-of-flight limit of \( m_\beta < 23 \text{ eV} \) can be derived \cite{27, 28}, which, however, is not competitive with the direct limit \cite{29}.

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 neutron 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 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 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 UHEC\( \nu \) 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 \( (\Omega) \),

\[
F_{p|Z}(E) = \frac{dN_{p|Z}}{dE dA dt d\Omega},
\]

from Z-bursts can be summarized as

\[
F_{p|Z}(E) = \sum \int_0^\infty dE_{\nu_i} \int_0^{R_{\text{max}}} dr \times \int_0^\infty dE_{\bar{\nu}_i} F_{\nu_i}(E_{\nu_i}, r) n_{\nu_i}(r)
\]

\[
+ \int_0^\infty dE_{\bar{\nu}_i} F_{\bar{\nu}_i}(E_{\bar{\nu}_i}, r) n_{\bar{\nu}_i}(r)
\]

\[
\times \sigma_{\nu_i\bar{\nu}_i}(s) Br(Z \rightarrow \text{hadrons}) \frac{dN_{p+n}}{dE_p} \times (-) \frac{\partial}{\partial E_p} P_p(r, E_p; E),
\]

with the following important building blocks: the UHEC\( \nu \) fluxes \( F_{\nu_i}(E_{\nu_i}, r) \) at the energies \( E_{\nu_i} \approx E_{\nu_i}^{\text{res}} \) 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 \( s = 2 E_{\nu_i} E_{\bar{\nu}_i} \), the branching ratio \( Br(Z \rightarrow \text{hadrons}) \), the energy distribution \( dN_{p+n}/dE_p \) 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,

\[
F_{\gamma|Z}(E) = \sum \int_0^\infty dE_{\gamma} \int_0^{R_{\text{max}}} dr
\]
Here, the photon propagation function $P_s(r, E_\gamma; E)$ gives the expected number of detected photons above the threshold energy $E$ if one photon started from a distance of $r$ with energy $E_\gamma$. Note that the $P_s$ function has a different interpretation than the $P$-function of protons. This arises from the fact that the number of photons is distinct to the number of protons — it 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 $dN_i/dE_i$ — are very well determined. The propagation functions $P_s$ are fairly well determined, whereas the first two ingredients, the flux of UHEC$\nu$s, $F_{\nu_i}(E_{\nu_i}, r)$, 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 antifermion $(f\bar{f})$ pair is given by (see e.g. Refs. [11, 99])

$$\sigma_{\nu_i\nu_i}(s) = \frac{G_F^2 s}{4\pi} \frac{M_Z^4}{(s - M_Z^2)^2 + M_Z^4} N_{\text{eff}}(s),$$

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

$$N_{\text{eff}}(s) = \sum_f \theta(s - 4m_f^2) \times$$

$$\times \left[ \frac{2}{3} n_f \left( 1 - 8 T_3 f q_f \sin^2 \theta_W + 8 q_f^2 \sin^4 \theta_W \right) \right].$$

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,

$$\sigma(\nu_i\bar{\nu}_i \to Z^* \to all \bar{q}q) \big|_{s=M_Z^2} = 314.9 \, \text{nb},$$

$$\sigma(\nu_i\bar{\nu}_i \to Z^* \to all \bar{f}f) \big|_{s=M_Z^2} = 455.6 \, \text{nb},$$

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

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

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 $\delta$-function in the integration over the energies $E_{\nu_i}$ of the incident neutrinos in Eqs. (12) and (13), and we can assume that the UHEC$\nu$ fluxes are constant in the relevant energy region. Thus, introducing the energy-averaged annihilation cross section [9, 10]

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

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

$$\int_0^\infty dE_{\nu_i} F_{\nu_i}(E_{\nu_i}) \sigma_{\nu_i\nu_i}(s = 2m_{\nu_i} E_{\nu_i})$$

$$\approx E_{\nu_i}^{\text{res}} F_{\nu_i}(E_{\nu_i}^{\text{res}}) \langle \sigma_{\text{ann}} \rangle.$$  

In view of the expected rapid decrease of the UHEC$\nu$ flux at increasing energies (cf. Section 14), 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 UHEC$\nu$ 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,

$$P_p(x) = \frac{dN_p}{dx}, \quad x = \frac{p_p}{p_{\text{beam}}},$$

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 $x \approx 8 \times 10^{-3}$, were combined with the predictions from the modified leading logarithmic approximation (MLLA) [106, 107, 108] at low $x$. The $p + \bar{p}$ multiplicity is $\langle N_p \rangle = \int_0^1 dx P_p(x) = 1.04 \pm 0.04$ in the hadronic channel [100].
energy distribution of the produced protons with energy neutrinos and the outgoing hadrons (cf. [109])). The γ of protons ("p"; solid), photons ("e"; dashed) in the lab system, in which the target relic ν is at rest.

\[ \gamma_{p} \] the spin

\[ \gamma_{p} \] to

\[ \gamma_{p} \] is the angle between the incom-

\[ \gamma_{p} \] is also displayed in Fig. 2 (bottom).

\[ \gamma_{p} \] is the momentum distribution of the electrons

\[ \gamma_{p} \] 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 \( Q_{p} \), 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

\[ Q_{p} = \left( 1 + \frac{\langle N_{n} \rangle}{\langle N_{p} \rangle} \right) Q_{p}(y), \quad (24) \]

where the neutron (\( n \)) (plus antineutron (\( \bar{n} \)) multiplicity, \( \langle N_{n} \rangle = \int_{0}^{\infty} dy Q_{n}(y) \), is ≈ 4% smaller than the proton’s \( \bar{n} \).

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

\[ Q_{\gamma}(y) = \int_{-1}^{1} dw \frac{2 - q}{1 + w} Q_{\pi}(\frac{2 - y}{1 + w}), \quad (25) \]

where the scaled energy distribution \( Q_{\pi}(y) \), with \( y = 2E_{\pi}/E_{\nu} \), is given by Eq. (23), with \( m_{\pi} \rightarrow m_{\pi} \) and \( P_{p} \rightarrow P_{\pi} \), the momentum distribution of pions in hadronic Z decay. For the latter distribution, we take the measured one of charged pions \( P_{\pi} \) from hadronic Z decay \( \frac{1}{101} \) (top), \( \frac{102}{104} \) (bottom), compare favorably with the ones presented in Ref. [60] 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, \( Z \rightarrow \pi^{\pm} + X \rightarrow e^{\pm} + X \) (cf. Fig. 1), and their scaled energy distribution in terms of \( y = 2E_{e}/E_{\nu} \) reads

\[ Q_{e}(y) = \int_{-1}^{1} dw \int_{0}^{2} dx \frac{1}{xw + \sqrt{x^{2} + (2m_{e}/m_{\pi})^{2}}} \]

\[ \times Q_{\pi}(\frac{2y}{xw + \sqrt{x^{2} + (2m_{e}/m_{\pi})^{2}}}) P_{e}(x), \quad (26) \]

where \( P_{e} \) is the momentum distribution of the electrons in the rest system of the charged pion. The energy distribution \( Q_{e} \) is also displayed in Fig. 2 (bottom).

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 \( \theta \) is the angle between the incoming neutrinos and the outgoing hadrons (cf. [100])). The energy distribution of the produced protons with energy \( E_{p} \) entering the Z-burst spectrum \( [22] \),

\[ \frac{dN_{p}}{dE_{p}} = \frac{2}{E_{\nu}} \frac{dN_{p}}{dy} = \frac{2}{E_{\nu}} Q_{p}(y), \quad (22) \]

with \( y = 2E_{p}/E_{\nu} \), is finally obtained after a Lorentz transformation from the cm system to the lab system,

\[ Q_{p}(y) = \sum_{-1,1} \frac{3}{8} \int_{-1}^{+1} dw (1 + w^{2}) \]

\[ \times \frac{1}{1 - w^{2}} \left| \frac{\pm y - w}{\pm y^{2} - w^{2} - (1 - w^{2})(2m_{p}/M_{Z})^{2}} \right| \]

\[ P_{p} \left( \frac{-wy \pm \sqrt{y^{2} - (1 - w^{2})(2m_{p}/M_{Z})^{2}}}{1 - w^{2}} \right), \]

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 ("\( \gamma \"; dotted) and electrons ("e"; dashed) in the lab system, in which the target relic neutrino is at rest.
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 $\approx 4 \cdot 10^{19} \text{ eV}$ lose a large fraction of their energy due to pion and $e^+e^-$ production through scattering on the CMB and due to their redshift [16] [17]. 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

$$dz = -(1+z)H(z) \, dr/c, \quad (27)$$

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

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

for the relation of the Hubble expansion rate at redshift $z$ to the present one. Uncertainties of the latter, $H_0 = h \times 100 \text{ km/s/Mpc}$, with $h = (0.71 \pm 0.07) \times 0.95 = 0.68$, are included. In Eq. (28), $\Omega_M$ and $\Omega_\Lambda$, 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 more than 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 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 [107]

$$\text{http://www.desy.de/~uhecr}.$$

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.

![Diffuse extragalactic photon background](image)
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

\[
dE = -E \left( \frac{dr}{l_\gamma(E)} - \frac{d\bar{z}}{1 + \bar{z}} \right),
\]

where \( l_\gamma(E) = (1 + \bar{z})^{-3} l_\gamma(E(1 + \bar{z})) \) is the energy attenuation length at redshift \( \bar{z} \). The number of photons was assumed to be constant at ultrahigh energies \( \gtrsim 10^{18} \text{ eV} \), 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):

\[
dN_\gamma = -N_\gamma \frac{dr}{l_\gamma(E)}. \tag{30}
\]

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 \( F_{\nu\gamma} \) of ultrahigh energy cosmic neutrinos (see e.g. Refs. [24], [22], [22] for recent reviews). Present experimental upper limits on these fluxes are rather poor (cf. Fig. 4 and Refs. [22], [29]).

What are the theoretical expectations for diffuse UHECν fluxes? More or less guaranteed are the so-called cosmogenic neutrinos which are produced when ultrahigh energy cosmic protons scatter inelastically off the cosmic microwave background radiation [4, 47] in processes such as \( \gamma \gamma \rightarrow \Delta \rightarrow n\pi^+ \), where the produced pions subsequently decay [130, 131]. These fluxes (for recent estimates, see Refs. [12], [17], [12], [13].) 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. [12], [12], [27]. 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. [12], [26], [26]). 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]. 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 [34], [57], [23], [133], [134], [137], [138], [139], [140], for which also the fragmentation function of the decay is of major interest [141].

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

\[
F_{\nu\gamma} (E_{\nu\gamma}, r) = F_{\nu\gamma} (E_{\nu\gamma}, 0) (1 + z)^{\alpha}, \tag{31}
\]

where \( z \) is the redshift and where \( \alpha \) characterizes the cosmological source evolution (see also Refs. [14], [52], [15]).
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 heaviest neutrino as hot dark matter follows the total mass distribution; however, with less clustering [148, 149]. In fact, one expects pretty much that the neutrino number density equals the big bang prediction (1) [150].

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

(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 mixture for the different mass eigenstates \( i \).

D. Neutrino number density

The dependence of the relic neutrino number density \( n_{\nu_i} \) 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 \( m_{\nu_i} \lesssim 1 \text{ eV} \), 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. 3 (top)). These peculiar measurements suggest relative overdensities of at most a factor \( f_\nu = 2 \div 3 \), depending on the grid spacing (cf. Fig. 3 (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, 11, 22, 23, 24], 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, \( n_{\nu_i} = 56 \cdot (1 + z)^3 \text{ cm}^{-3} \). Possible uniform neutrino density enhancements due to eventual lepton asymmetries, as advocated in Ref. [24], 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 UHEC\( \nu \) flux, but the value of the neutrino mass inferred from the Z-burst scenario is not affected by them.

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**FIG. 5:** Top: Mass density fluctuation field \( \delta \) 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 \( \delta \), and contrast maps. One recognizes some well-known structures in the nearby volume such as the Great Attractor at supergalactic coordinates (SGX \( \sim -2000 \text{ km s}^{-1} \), SGY \( \sim -500 \text{ km s}^{-1} \)), the Perseus-Pisces complex (SGX \( \sim 6000 \text{ km s}^{-1} \), SGY \( \sim -1000 \text{ km s}^{-1} \)), and the large void (SGX \( \sim 2500 \text{ km s}^{-1} \), SGY \( \sim 0 \text{ km s}^{-1} \)) 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 UHECR 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. 4). 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 [14] 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 $\log(E/eV) = 18$ and $\log(E/eV) = 26$ is divided into ten bins. The predicted number of UHECR events in a bin is taken as

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

where $\mathcal{E} \approx 8 \cdot 10^{16}$ m$^2$·s·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), $F_{p|\text{bk'd}}$, 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 $\mathcal{E} E^{\beta}$. The second term represents the sum of the proton and photon spectra, $F_{p|Z} + F_{p(+\gamma)|Z}$, 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 $F_{p|\text{bk'd}}$.

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 [43, 50] – a fact which is difficult to reconcile with the halo background model.

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. 4 (top)),

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

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. [4]), has been exploited in a recent Z-burst simulation [46].

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.

The extragalactic background suffers of course from GZK attenuation. Correspondingly, we take the above power-law, \( A \cdot E_p^{-\beta} \), 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 \( P_p(r, E_p; E) \),

\[
\mathcal{E} F_p|_{\text{bkd}}(E; A, \beta) = \int_0^\infty dE_p \int_0^{R_{\text{max}}} dr \left( 1 + z(r) \right)^3 \times \frac{A}{1\,\text{eV}} \left( \frac{E_p}{1\,\text{eV}} \right)^{-\beta} \times (-) \frac{\partial P_p(r, E_p; E)}{\partial E},
\]

(EG bk’d).

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

As far as the Z-burst spectra entering our prediction are concerned, we proceed as follows. We shall mainly concentrate on the case where there is only one relevant neutrino mass scale \( m_\nu \), either because there are three neutrino types with nearly degenerate neutrino masses, \( m_\nu \approx m_\nu \), 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 UHECR fluxes are expected to fall with increasing energy. Therefore, we fit only one neutrino mass parameter \( m_\nu \). In this case, the spectra (12) and (13) for protons and photons from Z-bursts can be written as

\[
\mathcal{E} F_{i|Z}(E; B, m_\nu) = B \int_0^\infty dE_i \int_0^{R_{\text{max}}} dr \left( 1 + z(r) \right)^{3/2} \delta_\nu(r)
\]

\[
\times \frac{4 m_\nu}{M_Z^2} Q_i \left( y = \frac{4 m_\nu E_p}{M_Z^2} \right) \times (-) \frac{\partial P_p(r, E_p; E)}{\partial E}, \quad i = p, \gamma,
\]

where \( \alpha \) is the cosmological evolution parameter, \( \delta_\nu(r) \) is the mass density fluctuation field (cf. Fig. 2 (bottom)); normalized to one, and \( Q_i \) are the boosted momentum distributions from hadronic Z decay, normalized to \( \langle N_{p+\gamma} \rangle = 2.04 \), for \( i = p \), and to \( \langle N_{\gamma} \rangle = 2 \langle N_{p+\gamma} \rangle + \langle N_{\gamma} \rangle = 37 \), for \( i = \gamma \). We are left here with two fit parameters, the mass \( m_\nu \) 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

\[
\frac{B}{E} = Br(Z \rightarrow \text{hadrons}) R_{\text{max}} \langle n_\nu(0) \rangle \langle \sigma_{\text{ann}} \rangle E_{\nu}^{\text{res}} F_{\nu}^{\text{res}}.
\]

Note, that the neglect of finite width effects, \( 1/2 \delta E_{\nu}^{\text{res}}/E_{\nu}^{\text{res}} = \Gamma_Z/M_Z = 2.7 \% \), in our implementation 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 \( m_\nu \), we use the maximum likelihood method and minimize the \( \chi^2 \) of the above function.

\[
\chi^2 = 2 \log\left( \frac{E_{\text{min}}}{E_{\text{max}}/eV} \right) - 2 \log\left( \frac{E_{\text{min}}}{E_{\text{max}}/eV} \right) + 2 \log\left( \frac{E_{\text{min}}}{E_{\text{max}}/eV} \right) - 2 \log\left( \frac{E_{\text{min}}}{E_{\text{max}}/eV} \right),
\]

where \( \sigma_{\text{ann}} = 37 \), for \( i = \gamma \) which is a bin.

For comparison with recent work on the Z-burst scenario, we have done also fits with no background component, \( F_p|_{\text{bkd}} = 0 \) in Eq. (33), and a larger lower end, \( \log(E_{\text{min}}/eV) = 19.4 \pm 2.0 \). Such a scenario, with \( E_{\text{min}} \lesssim E_{\text{GZK}} \approx 4 \times 10^{19} \,\text{eV} \), 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 \( E_{\nu}^{\text{res}} \) in order to produce a Z. Large \( E_{\nu}^{\text{res}} \) results in a large Lorentz boost, thus large \( E_\nu \), resp. \( E_\gamma \). In this way the shape of the detected energy \( E \) spectrum determines the mass of the relic neutrino. The sum of the necessary UHECR fluxes \( F_{\nu}^{\text{res}} \), on the other hand, is determined by the over-all normalization \( B \).
TABLE I: Results of fits, for a strong UHE\γ attenuation 
\((h = 0.71, \Omega_M = 0.3, \Omega_{\Lambda} = 0.7, z_{\text{max}} = 2)\). 
\textit{Top:} Assuming a halo UHECR background according to Eq. (35). \textit{Middle:} Assuming an extragalactic UHECR background according to Eq. (34). \textit{Bottom:} Assuming no UHECR background above \(E_{\text{min}}\), for different values of the lower end \(E_{\text{min}}\) of the fit 
\((\alpha = 0)\).

| Halo UHECR background + strong UHE\γ attenuation | \(m_\nu\) [eV] | \(\chi^2_{\text{min}}\) | \(A\) | \(B\) | \(\beta\) |
|---|---|---|---|---|---|
| \(\alpha\) \(-3\) | 4.46\(\pm2.22(4.80)\) | 15.90 | 1.46 \(\cdot 10^{23}\) | 1049 | 3.110 |
| \(\alpha\) | 3.46\(\pm1.73(4.03)\) | 15.64 | 1.62 \(\cdot 10^{23}\) | 770 | 3.111 |
| \(\alpha\) | 2.51\(\pm1.45(3.30)\) | 15.53 | 1.65 \(\cdot 10^{23}\) | 551 | 3.111 |

| EG UHECR background + strong UHE\γ attenuation | \(m_\nu\) [eV] | \(\chi^2_{\text{min}}\) | \(A\) | \(B\) | \(\beta\) |
|---|---|---|---|---|---|
| \(\alpha\) \(-3\) | 0.26\(\pm0.20(0.63)\) | 25.82 | 5.00 \(\cdot 10^{21}\) | 150 | 2.465 |
| \(\alpha\) | 0.26\(\pm0.19(0.63)\) | 26.41 | 5.98 \(\cdot 10^{21}\) | 144 | 2.466 |
| \(\alpha\) | 0.20\(\pm0.11(0.17)\) | 26.89 | 7.23 \(\cdot 10^{21}\) | 142 | 2.467 |

| No UHECR background + strong UHE\γ attenuation | \(\log(E_{\text{min}}/\text{eV})\) | \(m_\nu\) [eV] | \(\chi^2_{\text{min}}\) | \(A\) | \(B\) | \(\beta\) |
|---|---|---|---|---|---|---|
| \(19.4\) | 2.25\(\pm0.64(1.46)\) | 21.81 | – | 1251 | – |
| \(19.5\) | 1.31\(\pm0.63(1.44)\) | 16.01 | – | 846 | – |
| \(19.6\) | 0.85\(\pm0.67(1.62)\) | 14.80 | – | 670 | – |
| \(19.7\) | 0.46\(\pm0.32(0.87)\) | 8.03 | – | 445 | – |
| \(19.8\) | 0.42\(\pm0.11(1.25)\) | 7.99 | – | 460 | – |
| \(19.9\) | 0.76\(\pm0.10(2.50)\) | 5.52 | – | 733 | – |
| \(20.0\) | 1.71\(\pm1.49(4.47)\) | 2.68 | – | 2021 | – |

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

\[\chi^2(\beta^\prime, A^\prime, B^\prime, m_\nu) = \chi^2(m_\nu) + 1.\] 

(39)

Here \(\beta^\prime, A^\prime, B^\prime\) are defined in such a way that the \(\chi^2\) function is minimized in \(\beta, A\) and \(B\), at fixed \(m_\nu\).

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 \(O(10^{-9})\) G. We shall refer to this scenario in the following as “strong” UHE\γ attenuation. Our best fits to the observed data from this scenario (cf. Table I) can be seen in Fig. 3 for evolution parameter \(\alpha = 0\). We find a neutrino mass of \(m_\nu = 3.46\pm1.73(4.03)\) eV for the case that the UHECR background protons are of halo type [24], \(m_\nu = 0.20\pm0.19(0.61)\) 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 UHE\γ attenuation such that the Z-burst photons can be neglected \((\alpha = 0, h = 0.71, \Omega_M = 0.3, \Omega_{\Lambda} = 0.7, z_{\text{max}} = 2)\). \textit{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 photons (dash-dotted), whereas the almost horizontal contribution (long-dashed) is the first, power-law-like term of Eq. (33). \textit{Middle:} The case of an “extragalactic” UHECR background. \textit{Bottom:} The case of no UHECR background above \(E_{\text{min}}\).
extragalactic type \(^{(35)}\), and \(m_\nu = 0.40^{+0.32}_{-0.16}(0.87)\) 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 \(\chi^2\) analysis described in Section II 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 \(\chi^2_{\text{min}} = 15.64\) and \(\chi^2_{\text{min}} = 25.82\) in the halo and the extralactic background case, respectively, whereas in the no background case, for \(E_{\text{min}} = 10^{19.7}\) eV, we have 9 bins with 2 fitted parameters and \(\chi^2_{\text{min}} = 8.03\), see Table I. In the latter case, however, which was advocated strongly in Ref. \(^{(5)}\), a remarkable dependence of the fitted mass on the value of \(E_{\text{min}}\) 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 \(\chi^2\) fits without a Z-burst component (cf. Fig. 8) are far worse: we find \(\chi^2_{\text{min}} = 41.37\) in the former, and \(\chi^2_{\text{min}} = 38.25\) 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 UHE\(\gamma\) 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. \(^{(16)}\), a universal radio background on the level of the one from Ref. \(^{(19)}\) (cf. Section II B and Fig. 3 (top)). The corresponding fits, for our three background scenarios, can be seen in Fig. 8 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 \(^{(12, 154, 155)}\). 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 \(m_\nu = 0.77^{+0.48}_{-0.30}(1.36)\) eV, are compatible, at about the 2 \(\sigma\) level, with the corresponding values found in the case of strong UHE\(\gamma\) attenuation. As before, in the “no” background scenario, we find a strong dependence of the fitted mass on the value of \(E_{\text{min}}\).

Besides the no UHECR background scenario, the Z-
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 $h = 0.61 \div 0.9$, $\Omega_M$, $\Omega_\Lambda$, $z_{\text{max}} = 2 \div 5$, 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 UHE$\gamma$ attenuation case (cf. Fig. 10). Note, that a value of $m_\nu = 0.07$ eV, as studied recently in Ref. [16] 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

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
\text{Halo UHECR background + minimal URB} & $m_\nu$ [eV] & $\chi^2_{\text{min}}$ & $A$ & $B$ & $\beta$ \\
\hline
$-3$ & $3.69^{+3.81}_{-1.69}$ & 15.69 & 4.76 $\cdot 10^{42}$ & 1060 & 3.146 \\
$0$ & $3.71^{+3.04}_{-1.22}$ & 15.36 & 1.05 $\cdot 10^{44}$ & 827 & 3.166 \\
$3$ & $3.01^{+1.13}_{-0.92}$ & 15.20 & 1.55 $\cdot 10^{44}$ & 642 & 3.171 \\
\hline
\text{EG UHECR background + minimal URB} & $m_\nu$ [eV] & $\chi^2_{\text{min}}$ & $A$ & $B$ & $\beta$ \\
\hline
$-3$ & $0.79^{+0.49}_{-0.31}$ & 24.19 & 5.73 $\cdot 10^{31}$ & 125 & 2.466 \\
$0$ & $0.79^{+0.48}_{-0.30}$ & 24.52 & 6.44 $\cdot 10^{31}$ & 120 & 2.467 \\
$3$ & $0.79^{+0.45}_{-0.31}$ & 24.77 & 7.55 $\cdot 10^{31}$ & 122 & 2.468 \\
\hline
\text{No UHECR background + minimal URB} & $\log(E_{\text{min}}/\text{eV})$ & $\chi^2_{\text{min}}$ & $A$ & $B$ & $\beta$ \\
\hline
19.4 & $3.00^{+0.67}_{-0.31}$ & 14.43 & – & 1380 & – \\
19.5 & $2.50^{+0.76}_{-0.55}$ & 11.88 & – & 1111 & – \\
19.6 & $2.50^{+0.84}_{-0.60}$ & 11.86 & – & 1079 & – \\
19.7 & $1.80^{+0.75}_{-0.51}$ & 8.02 & – & 680 & – \\
19.8 & $2.00^{+0.95}_{-0.67}$ & 7.74 & – & 812 & – \\
19.9 & $3.00^{+1.34}_{-1.06}$ & 4.93 & – & 1699 & – \\
20.0 & $4.60^{+1.74}_{-1.22}$ & 2.33 & – & 4881 & – \\
\hline
\end{tabular}
\caption{Results of fits, for a photon attenuation as in Ref. [16] (“minimal" URB) and vanishing EGMF ($h = 0.71$, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, $z_{\text{max}} = 2$). \textit{Top:} Assuming a halo UHECR background according to Eq. (54). \textit{Middle:} Assuming an extragalactic UHECR background according to Eq. (53). \textit{Bottom:} Assuming no UHECR background above $E_{\text{min}}$, for different values of the lower end $E_{\text{min}}$ of the fit ($\alpha = 0$).}
\end{table}
TABLE III: Results of fits, for a photon attenuation as in Fig. 1 (bottom), short-dashed line ("moderate" URB) and vanishing EGMP ($h = 0.71, \Omega_M = 0.3, \Omega_\Lambda = 0.7, z_{\text{max}} = 2$). Top: Assuming a halo UHECR background according to Eq. (53). Middle: Assuming an extragalactic UHECR background according to Eq. (63). Bottom: Assuming no UHECR background above $E_{\text{min}}$, for different values of the lower end $E_{\text{min}}$ of the fit ($\alpha = 0$).

![Table III](image)

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 ($\alpha = 0, \Omega_M = 0.3, \Omega_\Lambda = 0.7, z_{\text{max}} = 2$).

![Table IV](image)

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

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

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 (29), the ratio of the maximally considered distance of Z production, $R_{\max}$, and the size of the universe is given.

![Figure 10](image)
by

\[
\frac{R_{\text{max}}}{D_{H_0}} = \int_0^{z_{\text{max}}} \frac{dz}{(1+z)^3} \sqrt{\Omega_M (1+z)^3 + \Omega_\Lambda}. \tag{41}
\]

This ratio is of order one; it equals 0.73 for \(\Omega_M = 0.3\), \(\Omega_\Lambda = 0.7\) and \(z_{\text{max}} = 2\). The required fluxes are summarized in Fig. 12 together with some existing upper limits and projected sensitivities of present, near 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 [124]. 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 \(f_\nu\) higher. They are consistent with the ones found in Refs. [55, 160]. 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. 1 [“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 \(\gamma\) 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 \(\gtrsim 10^{25}\) 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 [53, 57, 99, 133, 134, 135, 137, 138, 139, 140] or topological defect decays [147].

It should be stressed that, besides the neutrino mass, the UHE\(\nu\) 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 [152, 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 [1]. The mass of the heaviest relic neutrino turned out to have to lie in the range $2.1 \, \text{eV} \leq m_\nu \leq 6.7 \, \text{eV}$ on the 1σ level, if the background of ordinary cosmic rays above $10^{18.5} \, \text{eV}$ 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 $10^{18.5} \, \text{eV}$ are protons of extragalactic origin one is lead to a required neutrino mass in the range $0.08 \, \text{eV} \leq m_\nu \leq 1.3 \, \text{eV}$ at the 68% C.L. We have also analysed a case where there is no background of ordinary cosmic rays above, say, $10^{19.7} \, \text{eV}$. Here, we find $0.24 \, \text{eV} \leq m_\nu \leq 2.6 \, \text{eV}$. 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 $0.08 \, \text{eV} \leq m_\nu \leq 0.40 \, \text{eV}$, with a best fit value of $m_\nu = 0.20 \, \text{eV}$.

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), $0.04 \, \text{eV} \leq m_\nu \leq 2.5 \, \text{eV}$, in a three flavour or, from Eqs. (4) and (7), $0.4 \, \text{eV} \leq m_\nu \leq 3.8 \, \text{eV}$, 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, $m_\nu \approx \sqrt{\Delta m^2_{\text{atm}}} \approx 0.04 \div 0.08 \, \text{eV}$. However, our best fit values point more into the direction of a quasi-degenerate scenario, $m_\nu \approx m_\nu \gg \sqrt{\Delta m^2_{\text{atm}}}$. It is amusing to observe that the recently reported evidence for neutrinoless double beta decay, with $0.11 \, \text{eV} \leq \langle m_\nu \rangle \leq 0.56 \, \text{eV}$, if true, would point also into the same direction [4].

The above neutrino masses are in a range which can be explored by near-future laboratory experiments, like the KATRIN tritium β decay experiment [165], with a projected sensitivity of $m_\beta \gtrsim 0.3 \, \text{eV}$ within 6–7 years, or the 0νββ decay experiments NEMO-3 [170] and CUORE [171], which aim at $\langle m_\nu \rangle \geq 0.1 \, \text{eV}$, and their next-generation follow-up projects GENIUS [172] and EXO [173], with $\langle m_\nu \rangle \geq 0.01 \, \text{eV}$. Our mass range also compares favourably with the expected sensitivity $\sum_i (g_{\nu_i}/2) m_\nu \gtrsim 0.3 \, \text{eV}$ of near-future global cosmological analyses involving also new CMB measurements [13, 174], as well as $m_\beta \gtrsim 0.75 \div 1.8 \, \text{eV}$ 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 $10^{23} \, \text{eV}$, 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.

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