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Z-bursts from the Virgo cluster

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Resonant annihilation of ultra-high energy cosmic neutrinos (UHECν) on the cosmic neutrino background (CνB) into Z bosons—the Z-burst mechanism—and its associated absorption and emission phenomenology provide a unique, albeit indirect, probe of the CνB in its present state. In this paper, we examine the implications of gravitational clustering of the CνB in nearby galaxy clusters for the Z-burst phenomenology. In particular, we study the emission features of the Z-decay products originating from the Virgo cluster, and the potential of future cosmic ray experiments to observe clustering-enhanced Z-burst rates. We find that a detector with an exposure equivalent to three years of observations at the Extreme Universe Space Observatory (EUSO) will very likely measure these enhanced rates together with the associated UHECν flux, provided that the latter saturates current observational limits and the neutrino masses are quasi-degenerate, $m_{\nu_i} \gtrsim 0.1$ eV. In the case of UHECν fluxes below the electromagnetic cascade limit, or a hierarchical neutrino mass spectrum, an experimental sensitivity exceeding that of EUSO by at least two orders of magnitude is required to detect the clustering enhancements with any certainty.

I. INTRODUCTION

The existence today of a 1.95 K cosmic neutrino background (CνB)—an exact analogue of the 2.73 K cosmic microwave background (CMB)—is a fundamental prediction of the standard big bang theory. Permeating the universe at an average number density of $\bar{n}_{\nu_i} = \bar{n}_{\bar{\nu}_i} \simeq 56$ cm^{-3} per flavour, these relics of the big bang trace their origin to the freeze-out of the weak interaction when the universe was a mere one second old ($T \sim 1$ MeV), predating even the CMB photons by thirteen orders of magnitude in time. Yet, for the same reason that they decoupled so early, the CνB neutrinos have so far escaped direct detection in a controlled laboratory setting. To date, cosmological measurements such as the CMB anisotropies and the large-scale matter power spectrum, and, independently, the observed light elemental abundances, provide the best probe of the CνB's presence in the *early stages* of cosmological evolution (e.g., [1]). It is therefore our view that alternative avenues, however indirect, that could potentially afford us a glimpse of the CνB *as it is today* should be thoroughly explored.

One such avenue is the Z-dip/burst mechanism and its associated phenomenology [2], which proposes to exploit the resonant annihilation of hypothetical ultra-high energy cosmic neutrino (UHECν) beams on the CνB as a target. Supposing such beams exist, the annihilation process $\nu_{\rm UHEC\nu} + \bar{\nu}_{\rm C\nu B} \to Z \to$ hadrons proceeds at the resonance energy $E^{\rm res}_{\nu_i}$ with a cross section enhanced by several orders of magnitude compared to non-resonant scattering, and

$$E^{\rm res}_{\nu_i} = \frac{m_Z^2}{2 m_{\nu_i}} = 4.2 \times 10^{21} \left(\frac{\rm eV}{m_{\nu_i}}\right) \ {\rm eV} \qquad (1)$$

is a function of the neutrino and the Z masses, m_{ν_i} and m_Z, alone. The annihilation can be detected as absorption dips in the incident UHECν flux at $E \sim E^{\rm res}_{\nu_i}$ ("Z-dips") [2, 3] and/or as emission features in the Z-decay products (nucleons and photons) [4]. Indeed, in the latter case, the happy coincidence between $E^{\rm res}_{\nu_i} \sim 10^{21}$ eV (for $m_{\nu_i} \sim 1$ eV) and the energies of the most energetic cosmic rays observed by AGASA [5], Fly's Eye [6], HiRes [7], Yakutsk [8], and Haverah Park [9] has long led to a possible identification of ultra-high energy cosmic rays (UHECR) above the Greisen–Zatsepin–Kuzmin (GZK) cut-off energy $E_{\rm GZK} \sim 4 \times 10^{19}$ eV [10] with Z-burst nucleons and photons [4, 11].

Clearly, the success of the Z-burst mechanism as a means to detect the CνB and/or as an explanation of UHECR depends first and foremost on the UHECν fluxes (the beam); Figures 1 and 2 summarise the current status of the search for such fluxes, the projected sensitivities of ongoing and planned experiments, and predictions from various theoretical models. A second factor is the nature of the CνB density distribution (the target). To this end, it is important to note that an oscillation interpretation of the atmospheric and solar neutrino data (e.g., [28]) implies that at least two of the mass eigenstates in the CνB are nonrelativistic today, i.e., $m_{\nu_i} \gg T_\nu \sim (4/11)^{1/3}\, T_\gamma \sim 2$ K $\sim 10^{-4}$ eV, and at least one mass must exceed $\sqrt{\Delta m^2_{\rm atm}} \sim 0.05$ eV. These nonrelativistic neutrinos are subject to gravitational clustering on existing cold dark matter (CDM) and baryonic structures, possibly causing the local CνB density to depart from the cosmological average.

Standard large-scale structure theories tell us that, in the currently favoured ΛCDM cosmology, $\{\Omega_m, \Omega_\Lambda, h\} =$

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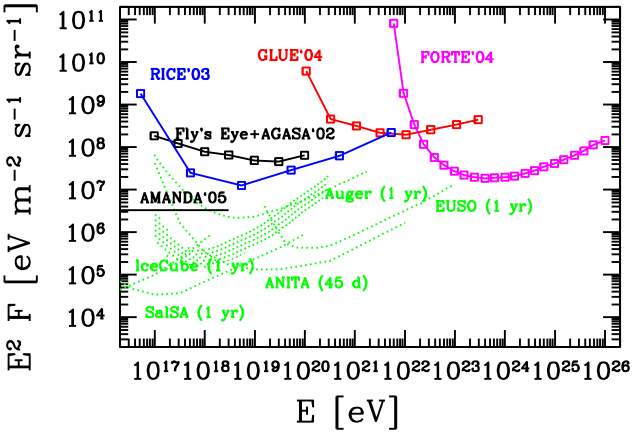

FIG. 1: Upper limits on the diffuse neutrino flux per flavour $F_{\nu_\alpha} + F_{\bar{\nu}_\alpha}$, $\alpha = e, \mu, \tau$, from RICE [12], GLUE [13], Fly's Eye+AGASA [14], FORTE [15] and AMANDA (assuming an E^{-2} differential spectrum) [16], assuming full flavour mixing en route to Earth. Also shown are the projected sensitivities of Auger in ν_e, ν_μ modes and in ν_τ mode (bottom swath) [17], ANITA [18], EUSO [19], IceCube [20], and SalSA [21], i.e., one event per energy decade for the indicated duration. A prototype of the full ANITA experiment, ANITA-lite [22], should constrain the $10^{19} \div 10^{22}$ eV region in the very near future.

$\{0.3, 0.7, 0.7\}$, fluctuations in the CνB ought to track their CDM counterparts at scales above the neutrino free-streaming length (e.g., [1]). The inferred local large-scale matter distribution from peculiar velocity measurements [29] therefore precludes any increase in the relic neutrino content of the local GZK zone (~ 50 Mpc) by more than a factor of two due to gravitational clustering alone [30]. However, clustering in local gravitational potential wells such as galaxies and galaxy clusters may still be sizeable on the sub-Mpc to Mpc scale. Indeed, for neutrino masses satisfying experimental and cosmological bounds,[1] detailed calculations show that the CνB overdensities in the largest galaxy clusters ($\sim 10^{15}$ $M_\odot$) can be as much as a thousand within the central ~ 100 kpc region [30, 37]. An immediate consequence for the Z-burst scenario is a possible directional dependence in its emission features, even if the UHECν sources are isotropically distributed; the highest number of Z-burst events should originate from the directions of nearby galaxy clusters.

The implications of gravitational neutrino clustering for the Z-burst emission spectra were first investigated quantitatively in reference [37]. In the present paper, we extend the said analysis in several ways:

1. We present a more accurate determination of the CνB overdensities in and around galaxies and galaxy clusters based on the calculations of reference [30], which take into account nonlinear effects in the clustering process. The linearised method adopted in [37] systematically underestimates the overdensities by a factor of several particularly in the virialised region of large galaxy clusters.

2. We compute both the primary nucleon and photon spectra. A generic feature of the Z-burst scenario is a photon to nucleon ratio of almost 20:1 at the Z production site. This ratio is greatly reduced upon arrival at Earth because of the much shorter attenuation length for photons than for nucleons. Still, unless the photons are heavily attenuated by a strong universal radio background (URB) and/or by strong extragalactic magnetic fields ($\gtrsim 10^{-10}$ G), we expect a predominance of photons in the observed primaries.

3. As in [37], we assess the experimental prospects for observing enhanced Z-burst rates from nearby galaxy clusters, focussing on our nearest neighbour: Virgo. At an average distance of ~ 15 Mpc from the Milky Way and with a mass close to $10^{15} M_\odot$ [38], the Virgo cluster is able to accumulate a sizeable excess of relic neutrinos while sitting close enough such that the Z-burst primaries suffer minimal energy loss during their propagation to Earth. If clustering-enhanced Z-bursts were to be seen at all, the Virgo cluster would be the prime site.

For rate estimates, we shall take the Extreme Universe Space Observatory (EUSO) experiment [39] as our fiducial detector. The sensitivity of EUSO to UHECR and UHECν above 10^{20} eV is about three orders of magnitude beyond what is available to date from AGASA and HiRes. As presently designed, EUSO will consist of a two-metre Fresnel lens positioned on the International Space Station at a height of 400 km. The lens will focus near-UV fluorescence emitted by radial de-excitation of N_2 in the air shower. EUSO operates as a space-based eye looking for tracks in one gigantic cloud chamber: the Earth's atmosphere. The lens' opening angle will be 60°, giving the instrument an enormous field of view (FOV), $\pi \times (\tan 30^\circ \times 400 \text{ km})^2 = 1.7 \times 10^5 \text{ km}^2$. Since the atmospheric density decreases exponentially with altitude with an 8 km scale-height, the EUSO FOV encompasses

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[1] Limits on the neutrino mass derived from cosmological measurements, especially the matter power spectrum $P(k)$, depend on the data sets used and the priors assumed. For example, analyses including also the Lyman α data and information on the dark matter–galaxy bias tend to produce bounds that are much tighter than those derived from the shape of $P(k)$ alone. Furthermore, the neutrino mass appears in combination with several other uncertain cosmological parameters in the determination of $P(k)$, such as a running scalar spectral index $n_s(k)$ and the effective number of thermalised fermionic degrees of freedom N_ν. These degeneracies can lead to considerable relaxation in the bound on m_{ν_i}. In the present work, we take a conservative upper limit of $\sum_i m_{\nu_i} < 1.8$ eV (2σ) [31] for three degenerate neutrinos, derived from the SDSS galaxy power spectrum [32] and the WMAP data [33] assuming a constant n_s and $N_\nu = 3$. Laboratory bounds from tritium β-decay experiments, $m_\nu \lesssim 2.2$ eV [34], and from neutrinoless double beta decay, $m_\nu \lesssim (0.66 \div 2.70)$ eV [35], are not yet competitive. See the reviews [1, 36].

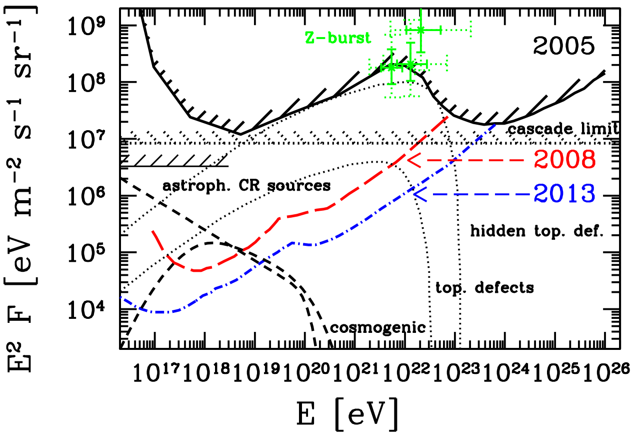

FIG. 2: Prospects for ultra-high energy neutrino detection in the next decade (fluxes required to produce one event per energy decade). For the year 2008 (long dashed/red line), we assume three years of Auger data and one 15-day ANITA flight. For 2013 (dash-dot/blue line), we assume 8/3/3/4 yr Auger/EUSO/IceCube/SalSA, and three ANITA flights. These curves are indicative only. The sensitivity will improve if we consider also the Westerbork radio observatory [23], if further projects such as Auger North and OWL [24] are realised, or if the EUSO or ANITA flight times are extended. Also shown are a wide sample of UHECν flux predictions, the current observational upper bound (solid shade) from Figure 1, and the electromagnetic cascade limit from EGRET [25, 26]. The points labelled "Z-burst" (green) denote the UHECν fluxes required to explain the post-GZK events observed by AGASA in terms of Z-burst secondaries [27].

an equivalent of 1.4×10^6 km^3 of air at surface density, corresponding to more than a Teraton of mass.

Due to the thin height of the Earth's atmosphere, the distance d between the EUSO lens and the observable air shower is highly constrained. For a shower directly below the lens, $d = 400$ km to within a few percent; for an event on the periphery of the FOV, d increases by only $1/\cos 30^\circ = 1.15$. Thus, the energy threshold for EUSO, determined by the $1/d^2$ fall-off of signal, is quite sharp. In its presently planned configuration, the threshold of EUSO is a few times 10^{19} eV, fortuitously positioned to observe the region at and above the GZK cut-off.

The duration of the EUSO experiment is nominally three years, but extensions beyond that seem likely. On the other hand, the smaller Auger Project [40] will likely collect data for a decade, so that its exposure (product of acceptance and time) may come to rival that of EUSO. Unfortunately, the present configuration for Auger is limited to the Southern Hemisphere, casting a blind eye in the direction of Virgo. Other existing cosmic ray facilities are not competitive with the size of the EUSO FOV. The angular resolution expected for EUSO showers is about one degree, or 20 mrad. Other neutrino telescopes also offer similar resolutions. As we shall show later, the CνB "halo" expected for the Virgo cluster spans several to ten degrees, so a one-degree resolution is sufficiently fine for the task at hand.

The paper is structured as follows. In section II we describe the calculational procedure for the Z-burst fluxes. Section III discusses the modelling of the CνB density distribution. Our predictions for the Z-burst fluxes originating from the Virgo cluster and the corresponding event rates expected at EUSO are presented in sections IV and V respectively. We conclude in section VI.

II. PRELIMINARIES

The differential flux in particle species ψ ($\psi = \gamma, p{+}n$),

$$F_{\psi|Z}(E,\theta,\phi) \equiv \frac{dN_{\psi|Z}}{dE\;dA\;dt\;d\Omega}, \tag{2}$$

denotes the number of ψ particles arriving at Earth with energy E in the direction $\{\theta,\phi\}$, where $\{0,0\}$ labels the centre of the Virgo cluster (i.e., galaxy M87), per unit energy per unit area A per unit time t per unit solid angle Ω. In the Z-burst scenario, this is given by [27]

$$\begin{aligned} F_{\psi|Z}(E,\theta,\phi) \;=\; & \sum_i \int_0^\infty dE_\psi \int_0^{R_{\max}} dr \int_0^\infty dE_{\nu_i} \\ & \times\, F_{\nu_i}(E_{\nu_i},r)\; n_{\bar{\nu}_i}(r,\theta,\phi) \\ & \times\, \sigma_{\nu_i\bar{\nu}_i}(s)\;\mathrm{Br}(Z\to\text{hadrons})\;\frac{dN_\psi}{dE_\psi} \\ & \times\, \left|\frac{\partial P_\psi(r,E_\psi;E)}{\partial E}\right| + (\nu_i \leftrightarrow \bar{\nu}_i), \end{aligned} \tag{3}$$

where $F_{\nu_i}(E_{\nu_i},r)$ is the ith mass UHECν flux[2] at energy E_{ν_i} at the Z production point at a "look-back" time $t = r/c$, $n_{\nu_i}(r,\theta,\phi)$ the CνB number density, $\sigma_{\nu_i\bar{\nu}_i}(s)$ the Z production cross section at centre-of-mass energy $\sqrt{s} = \sqrt{2m_{\nu_i}E_{\nu_i}}$, $\mathrm{Br}(Z\to\text{hadrons}) = (69.89 \pm 0.07)$ % the branching ratio, dN_ψ/dE_ψ the energy distribution of the produced ψ particles with energy E_ψ, and the propagation function $P_\psi(r,E_\psi;E)$ gives the expected number of ψ arriving at Earth with energies above the threshold E per particle created at r with energy E_ψ.[3]

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[2] Technically, one should write F_{ν_i} as $\sum_\beta |U_{\beta i}|^2 F_{\nu_\beta}$, where $|U_{\beta i}|^2 = |<\nu_\beta|\nu_i>|^2$ is the projection probability for flavour eigenstate β onto mass eigenstate i, and F_{ν_β} is the initial flux of flavour β. However, this exactness introduces an unnecessary layer of detail for the investigation performed here.

[3] In the process of becoming nonrelativistic, the CνB neutrinos lose their handedness and depolarise to populate all of their spin states. If neutrinos are Majorana particles, as is predicted by the most neutrino mass models, then all CνB spin states will participate in annihilation, and equation (3) is correct as written. However, if neutrinos are Dirac particles, then half of the nonrelativistic spin states are "sterile" states, and the rate presented in (3) should be reduced by a half.

Since the cross section $\sigma_{\nu_i\bar{\nu}_i}(s)$ is sharply peaked at the resonance energy $s = m_Z^2$, we may approximate

$$\int_0^\infty dE_{\nu_i} F_{\nu_i}(E_{\nu_i}) \sigma_{\nu_i\bar{\nu}_i}(s) \simeq E^{\rm res}_{\nu_i} F_{\nu_i}(E^{\rm res}_{\nu_i}) \langle \sigma_{\rm ann} \rangle, \tag{4}$$

where the superscript "res" denotes resonance, and $\langle \sigma_{\rm ann} \rangle = \int ds\ \sigma_{\rm ann}/m_Z^2 = 40.4$ nb is the energy-averaged s-channel Z-exchange annihilation cross section. The UHECν fluxes are modelled as

$$F_{\nu_i}(E_{\nu_i}, r) = F_{\nu_i}(E_{\nu_i}, 0)[1 + z(r)]^\alpha, \tag{5}$$

given our insufficient knowledge about their sources. Here, $F_{\nu_i}(E_{\nu_i}, 0)$ is the neutrino flux incident on Earth, the index α characterises the sources' cosmological evolution, and the redshift $z(r)$ is related to the look-back time via $dz = -(1+z)H(z)\ dr/c$, with $H(z) = H_0\ [\Omega_m(1+z)^3 + \Omega_\Lambda]^{1/2}$ linking the Hubble parameter at z to its present value, $H_0 = h\ 100\ {\rm km\ s^{-1}\ Mpc^{-1}}$. Furthermore, we take $n_{\nu_i}(r,\theta,\phi) \simeq n_{\bar{\nu}_i}(r,\theta,\phi)$,[4] since significant relic neutrino–antineutrino asymmetries ($\gtrsim 1$) are incompatible with big bang nucleosynthesis in the presence of bi-large mixing inferred from the solar and atmospheric neutrino experiments [41].[5] Thus, together with the definition $F^{\rm res}_{\nu_i} \equiv F_{\nu_i}(E^{\rm res}_{\nu_i}, 0) + F_{\bar{\nu}_i}(E^{\rm res}_{\bar{\nu}_i}, 0)$, equation (3) now becomes

$$\begin{aligned} F_{\psi|Z}(E,\theta,\phi) \ = & \sum_i 2\ {\rm Br}(Z \to {\rm hadrons})\ \langle \sigma_{\rm ann} \rangle\ F^{\rm res}_{\nu_i} \\ & \times \int_0^\infty dE \int_0^{R_{\rm max}} dr\ (1+z)^\alpha\ n_{\nu_i}(r,\theta,\phi) \\ & \times\ \mathcal{Q}_\psi(y)\ \left| \frac{\partial P_\psi(r, E_\psi; E)}{\partial E} \right| . \end{aligned} \tag{6}$$

The functions $\mathcal{Q}_\psi(y) = E_\nu/2 \cdot dN_\psi/dE_\psi$, with $y = 4 m_\nu E_\psi/m_Z^2$, are the boosted momentum distributions from hadronic Z-decay, normalised to $\langle N_{p+n} \rangle = 2.04$ for $\psi = p+n$, and to $\langle N_\gamma \rangle = 2\langle N_{\pi^0} \rangle + \langle N_{\pi^\pm} \rangle = 37$ for $\psi = \gamma$.[6] Detailed forms for $\mathcal{Q}_\psi(y)$ can be found in reference [27].

The propagation functions $P_\psi(r, E_\psi; E)$ account for the interactions encountered by ψ between its production point and Earth. For $\psi = p+n$, energy loss arises primarily from pion and e^+e^- production through nucleon scattering on the CMB. The corresponding $P_{p+n}(r, E_{p+n}; E)$ has been calculated in detail in [43], and is publicly available at [44]. For the computation of $P_\gamma(r, E_\gamma; E)$, we adopt the continuous energy loss approximation, which asserts that the photon energy degradation proceeds as

$$dE = -E \left[\frac{dr}{\ell_z(E)} - \frac{dz}{1+z} \right], \tag{7}$$

in which $\ell_z(E) = (1+z)^{-3} \ell_0(E(1+z))$, and $\ell_0(E)$ is the photon energy attenuation length due to pair and double-pair production on the diffuse extragalactic photon background, and inverse Compton scattering of the produced pairs. Values for $\ell_0(E)$ incorporating various assumptions about the poorly known URB can be found in [45] and are summarised in [27]. Furthermore, we assume the number of photons N_γ to be constant at energies $\gtrsim 10^{18}$ eV due to the small inelasticities in this energy range. Below $\sim 10^{18}$ eV, N_γ increases as $dN_\gamma = N_\gamma dr/\ell_z(E)$, so as to maintain energy conservation (excluding losses due to the universal expansion).

III. NEUTRINO DENSITY DISTRIBUTION

The CνB density distribution in the universe is taken to be uniform and at the cosmological average $\bar{n}_{\nu_i} = \bar{n}_{\bar{\nu}_i}$ ($\simeq 56\ {\rm cm}^{-3}$ at $z = 0$), except in the vicinity of a galaxy cluster, in which case we use the neutrino number densities provided in reference [30] (reproduced here in Figure 3). These densities are obtained by solving, with a particle realisation, the Vlasov and Poisson equations,

$$\frac{\partial f}{\partial \tau} + \frac{\boldsymbol{p}}{a m_{\nu_i}} \cdot \frac{\partial f}{\partial \boldsymbol{x}} - a m_{\nu_i} \nabla \phi \cdot \frac{\partial f}{\partial \boldsymbol{p}} = 0, \tag{8}$$

$$\nabla^2 \phi = 4\pi G a^2 [\rho_m(\boldsymbol{x}, \tau) - \bar{\rho}_m(\tau)] . \tag{9}$$

Here, $f(\boldsymbol{x}, \boldsymbol{p}, \tau)$ is the neutrino phase space distribution, where $\boldsymbol{x}$, $\boldsymbol{p}$, and τ are the usual comoving coordinates, conjugate momentum, and conformal time, respectively; a is the scale factor, $\bar{\rho}_m$ the mean universal matter density, and we assume a ΛCDM cosmology with $\{\Omega_m, \Omega_\Lambda, h\} = \{0.3, 0.7, 0.7\}$. The halo density profile is taken to be of the Navarro–Frenk–White form [46],

$$\rho_m(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2} , \tag{10}$$

where r is the radial distance from the halo centre, and the parameters r_s and ρ_s are determined by the halo's virial mass $M_{\rm vir}$ and concentration c via

$$\rho_s \ = \ \frac{200}{3} \frac{c^3}{\ln(1+c) - c/(1+c)}, \tag{11}$$

$$r_s \ = \ \frac{1}{c} \left(\frac{3}{800\pi} \frac{M_{\rm vir}}{\bar{\rho}_m} \right)^{1/3} . \tag{12}$$

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[4] It is interesting that the presence of a neutrino–antineutrino asymmetry increases both $n_{\nu_i} + n_{\bar{\nu}_i}$ and $|n_{\nu_i} - n_{\bar{\nu}_i}|$, while at the same time driving one of n_{ν_i} or $n_{\bar{\nu}_i}$ to zero exponentially. This has the curious consequence of increasing the Z-burst rate, but not necessarily the Z-dip depth. For the latter, the severe suppression of n_{ν_i} or $n_{\bar{\nu}_i}$ in the CνB gives an asymptotic depth of one half for the Z-dip. Of course, the increased number of events concomitant with a neutrino–antineutrino asymmetry improves the statistics of the dip.

[5] Constraints on the cosmological ν_μ and ν_τ neutrino–antineutrino asymmetries are applicable insofar as large-angle $\nu_e \leftrightarrow \nu_{\mu,\tau}$ oscillations are operational prior to neutrino decoupling. An obvious way to evade these bounds is to suppress these oscillations by way of new, non-standard matter effects. One such scenario is presented in [42], in which the suppression arises from a hypothetical flavour-dependent neutrino–majoron coupling.

[6] The photon count includes also electrons and positrons from charged pion decay. These are relevant for the development of electromagnetic cascades.

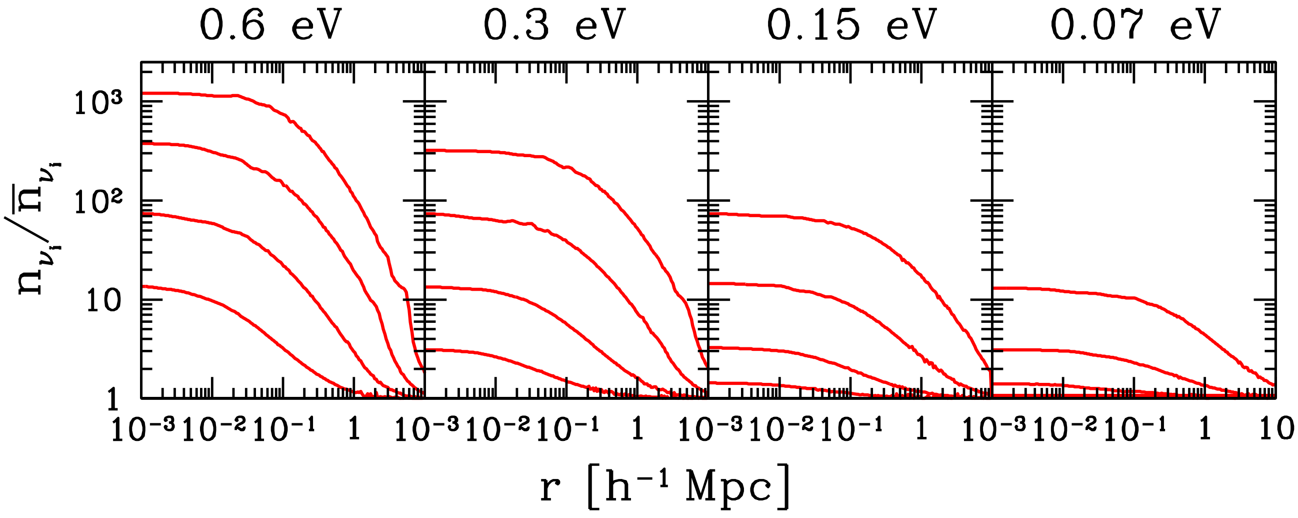

FIG. 3: Relic neutrino number density per mass eigenstate, $n_{\nu_i} = n_{\bar{\nu}_i}$, as a function of the radial distance from the halo centre, for halo virial masses (top to bottom) 10^{15}, 10^{14}, 10^{13}, 10^{12}, in units of $(0.7/h)\,M_\odot$, and neutrino masses indicated in the figure. All curves are normalised to the expected mean density $\bar{n}_{\nu_i} = \bar{n}_{\bar{\nu}_i} \simeq 56$ cm^{-3}.

In addition, high resolution simulations of reference [47] provide a tight correlation between c and $M_{\rm vir}$,

$$c(z) \simeq \frac{9}{1+z}\left(\frac{M_{\rm vir}}{1.5\times 10^{13} h^{-1} M_\odot}\right)^{-0.13}. \qquad (13)$$

The net result is a dependence of the halo density profile on the halo's virial mass alone.

IV. *Z*-BURST FLUXES FROM VIRGO

To estimate the Z-burst fluxes from the Virgo cluster, we assume the cluster's virial mass to be $10^{15} M_\odot$, centred on galaxy M87 at a distance $D \sim 15$ Mpc from Earth. We integrate equation (6) along the line of sight in the direction $\{\theta,\phi\}$. The upper integration limit is taken to be $R_{\rm max} = 3000$ Mpc, although the choice of $R_{\rm max}$ has little impact on the results, provided $R_{\rm max}$ exceeds the GZK distance ~ 50 Mpc. We note that contributions from gravitational clustering in the Milky Way halo ($\sim 10^{12} M_\odot$) are generally negligible despite its proximity. This is because enhancements in the CνB density therein are no more than a factor of twenty even for the most massive neutrino considered here, and regions of substantial overdensity ($n_{\nu_i}/\bar{n}_{\nu_i} \gtrsim 2$) are limited in extent ($\lesssim 100$ kpc).

Since the CνB distribution is not uniform inside the Virgo cluster but decreases with the halo radius, we expect the Z-burst fluxes to vary with angular distance θ (recall that $\{\theta = 0, \phi = 0\}$ labels the centre of the cluster) in the same manner. Figure 4 shows the predicted nucleon and photon fluxes as functions of E and θ for a range of neutrino masses and three different URB scenarios documented in the literature. The choice of α (i.e., the source evolution parameter) is irrelevant for Virgo Z-bursts, since the Virgo–Earth distance corresponds to a mere $z \sim 0.003$; we take $\alpha = 0$.

For definiteness, we have opted to evaluate the UHECν fluxes $F^{\rm res}_{\nu_i}$ at the electromagnetic (EM) cascade limit, although fluxes larger by a factor of five to twenty-five, depending on the neutrino mass, are permitted by observations. The EM cascade limit applies generally to transparent sources wherein neutrinos are produced in a chain of particle decays (e.g., pions, W, and Z). The decay process inevitably generates also photons and/or electrons with an energy fluence comparable to that of the neutrinos. Subsequent EM cascades via collisions with the diffuse extragalactic photon background, notably the CMB, bring the cascade photons into the energy range 30 MeV $\div$ 100 GeV probed by EGRET [25]. Observation of the diffuse extragalactic γ-ray background at these energies therefore places a convenient upper bound on the diffuse UHECν fluxes [48]. This is known as the EM cascade limit (or cascade limit, for short).[7]

For comparison purposes, we include in Figure 4 also the spectrum of cosmic ray protons produced at diffuse

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[7] The EM cascade limit presented in [26] (displayed here in Figure 2) derives from the estimate of the diffuse γ-ray background published in [25]. Recent works [49] suggest that the latter analysis may have overestimated the extragalactic contribution to the γ-ray background by roughly a factor of two. The EM cascade limit may therefore be stronger correspondingly.

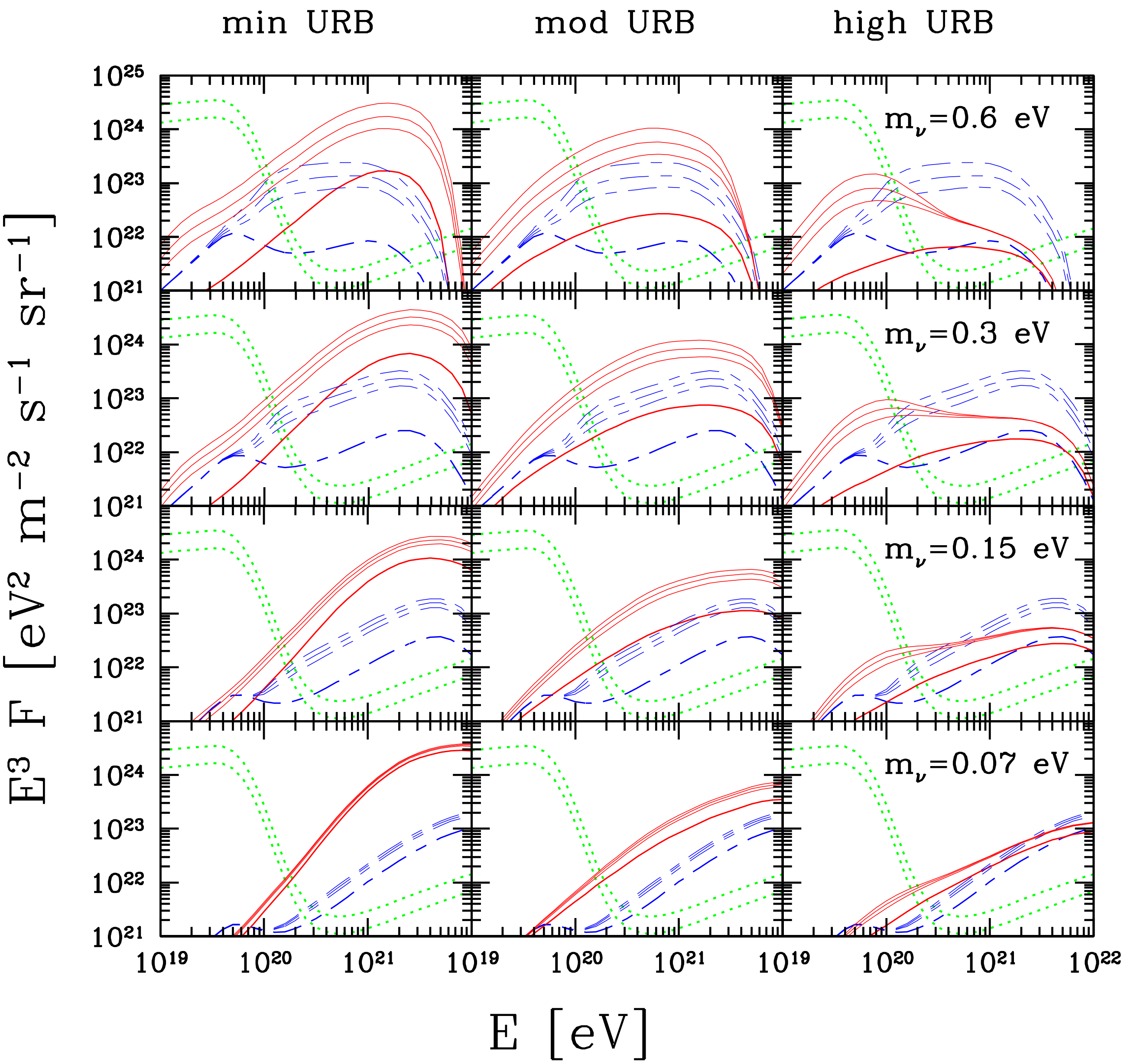

FIG. 4: Z-burst nucleon and photon fluxes from the Virgo cluster ($M_{\rm vir} = 10^{15} M_\odot$, $D = 15$ Mpc) per neutrino species for three URB scenarios (minimal, moderate, and high), assuming the EM cascade limited UHECν fluxes. Red (solid) lines represent photon fluxes originating from points located at angular distances (top to bottom) $\theta = 0°, 4°, 10°$, and $180°$ (i.e., an unclustered CνB) from galaxy M87. Blue (dashed) lines denote the corresponding nucleon fluxes. The Akeno+AGASA (upper) and Fly's Eye+HiRes (lower) normalised extragalactic proton fluxes are shown in green (dotted lines).

extragalactic sources,

$$F_{p|\rm bkd}(E; A, \beta) = \int_0^\infty dE_p \int_{R_{\rm min}}^{R_{\rm max}} dr (1+z)^n \; A \left(\frac{E_p}{\rm eV}\right)^{-\gamma} \times \left|\frac{\partial P_p(r, E_p; E)}{\partial E}\right| , \tag{14}$$

where $\{A, n, \gamma\} = \{2.37 \times 10^{-10}\ {\rm eV}^{-1}{\rm m}^{-3}{\rm s}^{-1}, 3.65, 2.54\}$ and $\{1.25 \times 10^{-10}\ {\rm eV}^{-1}{\rm m}^{-3}{\rm s}^{-1}, 3.45, 2.54\}$ are the best fit parameters for the existing Akeno+AGASA and Fly's Eye+HiRes data, respectively, in the energy range $10^{17.6} \div 10^{20}$ eV [50]. A lower integration limit of $R_{\rm min} = 50$ Mpc has been imposed in the evaluation of $F_{p|\rm bkd}$, since no known sources reside within this distance. The resulting spectrum exhibits an accumulation at the GZK scale 4×10^{19} eV, and a sharp drop beyond.

The GZK suppression of nucleons from distant sources provides a clean environment for the study of Z-burst events originated by cosmic neutrino messengers. For the cascade limited UHECν fluxes assumed here, it is clear from Figure 4 that Z-burst events dominate above 10^{20} eV, especially in the direction of Virgo. Note that substantial enhancements in the Z-burst fluxes due to CνB clustering on Virgo can still be seen at $\theta \sim 10°$, well beyond the cluster's visible region $\theta \lesssim 5°$. This follows from the assumption of an extended CDM halo, which accumulates neutrinos in the outer region gravitationally despite its seeming invisibility.

In Figure 5 we present the "sky map" of the energy-integrated Z-burst fluxes for nucleons plus photons above $E_{\rm th} = 2 \times 10^{20}$ eV, centred on the Virgo cluster:

$$J(E_{\rm th}, \theta) = \sum_{\psi=p+n,\gamma} \int_{E_{\rm th}}^{\infty} dE \; F_{\psi|Z}(E, \theta). \qquad (15)$$

The shape of this curve is not very sensitive to the choice of the URB, but is highly dependent on the neutrino mass, since the latter determines the amount of gravitational clustering available to the CνB. In principle, the angular distribution and the energy dependence of the Z-burst events provide independent confirmation of the neutrino mass (and a consistency check of the Z-burst mechanism). The angular resolution of EUSO and other UHECR detectors is typically one degree, sufficient to map out the shape of the extended Virgo halo.

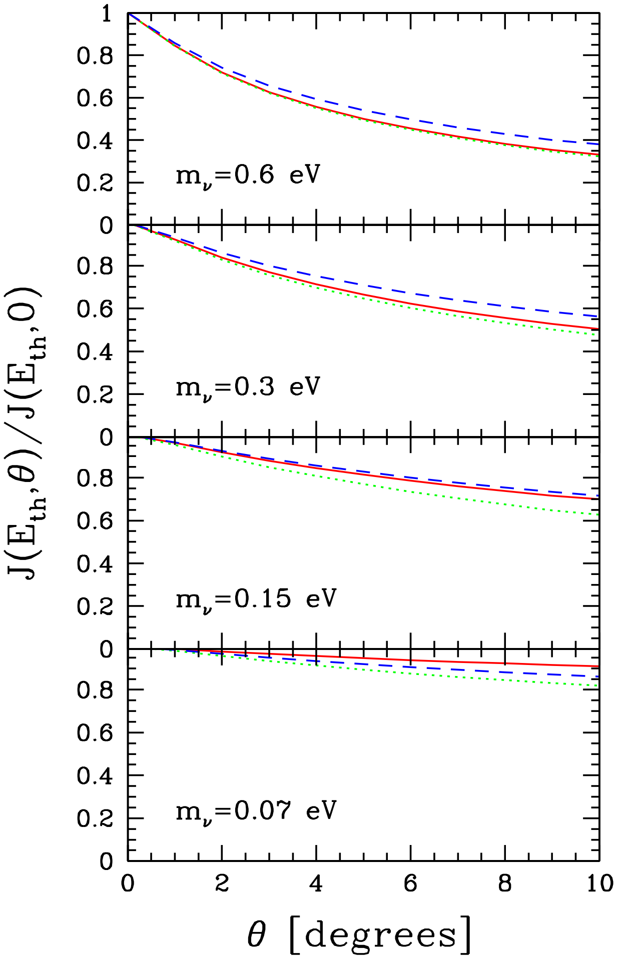

FIG. 5: Energy-integrated Z-burst fluxes (nucleons plus photons) above $E_{\rm th} = 2\times10^{20}$ eV as functions of angular distance from the centre of Virgo, normalised to their corresponding values at $\theta = 0°$. Red (solid), blue (dashed) and green (dotted) lines denote, respectively, the minimal, the moderate and the high URB scenarios.

V. EXPECTED EVENTS AT EUSO

The EUSO experiment detects UHECR by observing near-UV fluorescence emitted by nitrogen molecules in the extensive air showers generated by the primary cosmic ray particles' interactions with the Earth's atmosphere. For primary nucleons and photons, the cross section for interaction is sufficiently large that the interaction takes place high in the atmosphere with near unit probability. Thus, the acceptance of EUSO for nucleons and photons, $\mathcal{A}$, is just the projected FOV normal to the direction of the source, i.e., $\frac{1}{2}\times$ FOV $\sim 0.85 \times 10^5$ km^2, times the solid angle on the sky of the emitting region, times another factor $\frac{1}{2}$ accounting for the blockage of the upcoming beam by the opaque Earth, times the duty cycle of the instrument, i.e., the fraction of time "on". The EUSO instrument can record fluorescence signals only on moonless nights devoid of high cirrus clouds. The duty cycle for such clarity is estimated to be 20 %. This amounts to an all-sky acceptance of $\mathcal{A}_{4\pi} = 1.1 \times 10^5$ km^2 sr, including the duty cycle factor. The nominal duration of the EUSO experiment $\mathcal{T}$ is three years ($\sim 10^8$ s), so that an all-sky exposure of $\mathcal{E}_{4\pi} = \mathcal{A}_{4\pi}\mathcal{T} \simeq 1.1 \times 10^{13}$ km^2 s sr is anticipated. If the lifetime of EUSO is extended, the exposure will be proportionately larger.

For the Virgo cluster, the expected number of Z-burst primaries in the energy interval (E_j, E_{j+1}) originating within an angular distance θ from the cluster centre is given by

$$N_{\psi,j}(\theta) = \frac{\mathcal{E}_{4\pi}}{4\pi} \int_{E_j}^{E_{j+1}} dE \int_0^{2\pi} d\phi' \int_0^{\theta} d\theta' \sin\theta' F_{\psi|Z}(E, \theta', \phi'). \qquad (16)$$

Figures 6 and 7 show the integral (16) evaluated for $\theta = 10°$, assuming, respectively, UHECν fluxes at the current observational and the EM cascade limits, with $j = 1, \ldots, 4$ designating the four logarithmic bins between $10^{20} \div 10^{22}$ eV. Also displayed in the figures are the numbers of extragalactic background protons anticipated in the same solid angle $\Delta\Omega = 2\pi(1 - \cos\theta) \simeq 0.1$ ster, and of Z-burst events in the same $\Delta\Omega$ for an unclustered CνB.

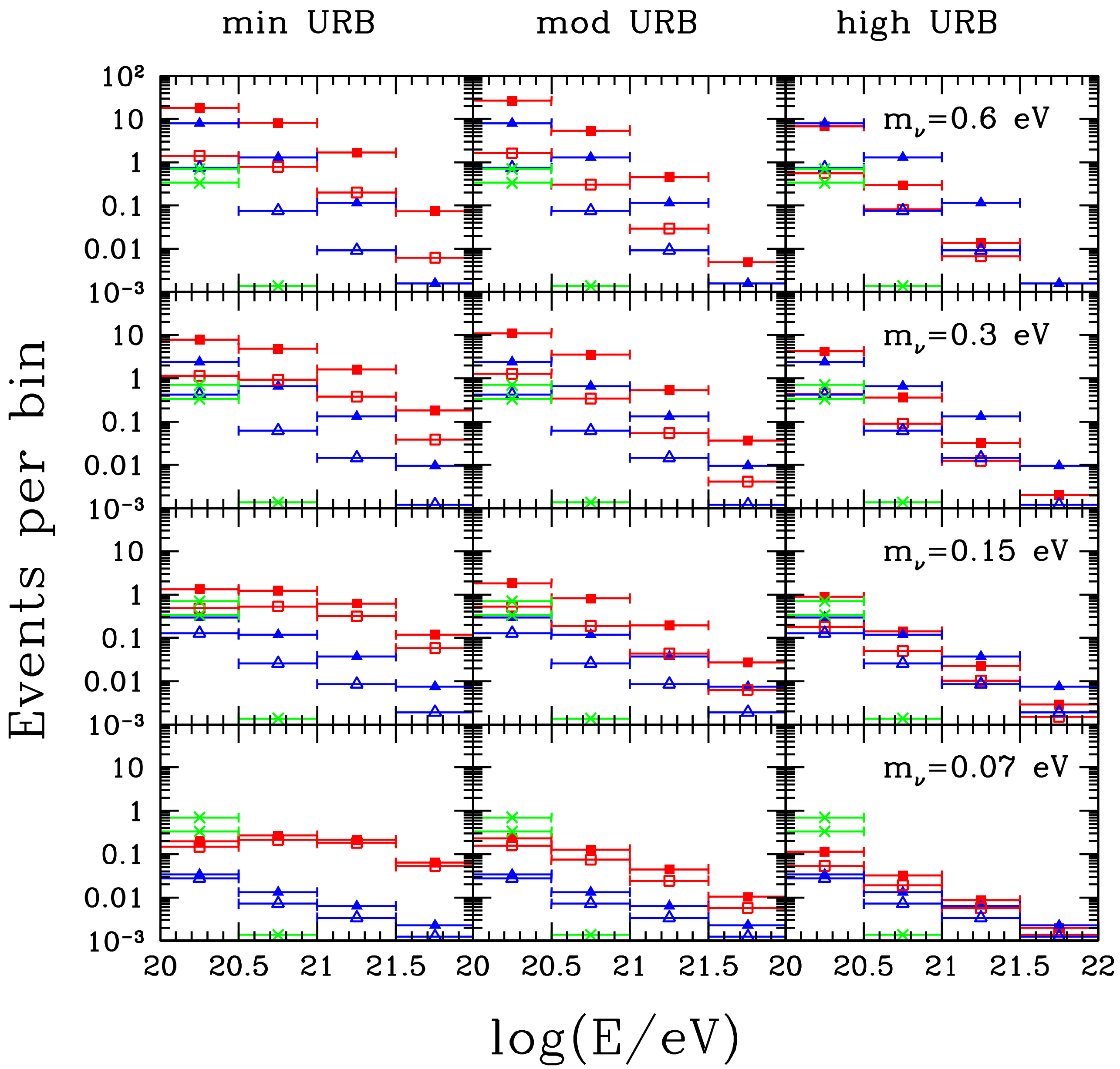

FIG. 6: Number of Z-burst events per neutrino species originating within $\theta = 10^\circ$ from M87 expected at EUSO in three years, assuming UHECν fluxes at the current observational limits. Solid red squares denote the photon events, while solid blue triangles refer to the nucleons. The corresponding predictions for an unclustered CνB in the same solid angle $\Delta\Omega \simeq 0.1$ ster are indicated by the open red squares and open blue triangles. The number of extragalactic background protons anticipated in $\Delta\Omega$, assuming the Akeno+AGASA (upper) and the Fly's Eye+HiRes (lower) normalisations, are represented by the green crosses.

A. Most optimistic scenario: hidden sources

As is evident in Figure 6, the most favourable circumstances under which clustering-enhanced Z-burst emissions from the Virgo cluster may be observed occur when (i) the UHECν fluxes saturate the current observational bounds, and (ii) the neutrino masses are "large" and quasi-degenerate, $m_{\nu_i} \gtrsim 0.1$ eV.[8] The resulting number of events at EUSO in the ~ 0.1 ster solid angle can be

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[8] The mass splittings inferred from the atmospheric and solar neutrino oscillation experiments [28], $\Delta m^2_{\rm atm} \sim 2 \times 10^{-3}$ eV and $\Delta m^2_{\rm sun} \sim 7 \times 10^{-5}$ eV^2, respectively, imply that the three mass eigenstates are quasi-degenerate when $m_\nu \gg \sqrt{\Delta m^2_{\rm atm}}$.

quite large, totalling ~ 100 events in the energy decade $10^{20} \div 10^{21}$ eV for $m_{\nu_i} = 0.6$ eV, ~ 40 for $m_{\nu_i} = 0.3$ eV, and ~ 10 for $m_{\nu_i} = 0.15$ eV, for three degenerate species. The corresponding numbers for an unclustered CνB are ~ 6, ~ 4, and ~ 2.

Theoretical models capable of generating neutrino fluxes at these formidable energies and magnitudes—either by way of "bottom-up" astrophysical accelerators, or through "top-down" decays of super heavy particles from beyond the standard model—are not lacking (e.g., [51]). The significant hurdle facing these UHECν sources is that they must be opaque to nucleons and high energy ($\gtrsim 100$ MeV) photons, in order not to exceed the diffuse γ-ray background observed by the EGRET experiment (cf. the EM cascade limit described in section IV). A proof-of-principle candidate is a mirror (hidden) topological defect coupled to the standard model (SM) through mirror–SM neutrino oscillations; by construction, the resulting SM neutrino fluxes is free to saturate the upper observational limits [52]. Furthermore, because photons are regenerated by Z-decays, their subsequent EM cascade down to the energy range probed by EGRET can lead to additional constraints on the UHECν sources, particularly on the sources' cosmological evolution parameter α. For UHECν fluxes saturating current observational limits, sources with $\alpha < 0$ are consistent with the EGRET bound [53].[9] The next generation of UHECν observatories will put these neutrino source scenarios to a definitive test (cf. Figure 2).

If neutrino masses are not quasi-degenerate, but rather hierarchical with $m_{\nu_i} \lesssim 0.1$ eV, then their clustering in Virgo is small or negligible. For $m_{\nu_i} = 0.07$ eV, the clustered and the unclustered rates differ generally by no more than a factor of two (cf. Figures 5 and 6). Judging from our numbers in Figure 6 (bottom row), even for an optimised UHECν flux and the best URB scenario, an experiment with at least ten times the exposure of EUSO (three years) is required to record one clustering-enhanced Z-burst event from Virgo, another two times to record an event within $\Delta\Omega$ with no CνB clustering, and another five times to resolve the difference between the two at 1σ.

Of course, if there is indeed a large UHECν flux, it can also be measured directly by EUSO. It is a simple matter to obtain a good estimate of the EUSO acceptance and exposure for neutrinos from those for cosmic ray nucleons and photons. To a very good approximation, the atmospheric density decreases exponentially vertically, with a scale-height of $x_h \sim 8$ km. Thus, the effective volume is $x_h \times$ FOV. The nucleon density in this volume is $\rho(x = 0) \times N_A$, where $\rho(x = 0)$ is the atmospheric density at sea level in g cm^{-3}, and N_A is Avogadro's number. Thus, relative to the aperture for cosmic rays, we have for neutrinos an extra factor of $2\, x_h\, \rho(0)\, N_A\, \sigma_{\nu N}$, where $\sigma_{\nu N} \approx 0.77 \times 10^{-31}\, (E_\nu/10^{20}\text{ eV})^{0.36}$ cm^2 [54] is the neutrino–nucleon cross section, and the factor of two arises because for each neutrino with an oblique trajectory, the extra path length compensates the reduced projection of the FOV. Putting in numbers (e.g., the vertical slant-depth, $x_h\, \rho(0) = 1030$ g cm^{-2}, is a well known number), one arrives at $\mathcal{A}^\nu_{4\pi} = 0.9 \times 10^{-4}\, (E_\nu/10^{20}\text{ eV})^{0.36}\, \mathcal{A}_{4\pi} \approx 10^{-4} \times \mathcal{A}_{4\pi}$ at $E_\nu = 10^{20}$ eV, with an increase in $\mathcal{A}^\nu_{4\pi}$ of 2.3 per decade of energy beyond 10^{20} eV. The estimate of this factor assumes that the experimental efficiencies for cosmic rays and for neutrinos are the same.[10] For EUSO, the efficiencies for cosmic rays and for neutrinos are each near unity at energies above 10^{20} eV. The discriminator between cosmic ray and neutrino initiated events is the depth of the origin of the shower in the atmosphere. For hadrons and photons, the shower begins high in the atmosphere, while for neutrinos it begins much lower, where the air is densest.

In its all-sky search, EUSO should record some $\sim \mathcal{E}^\nu_{4\pi}\, E_\nu\, F_\nu(E_\nu)$ UHECν events at energies above E_ν. In the energy interval $10^{21} \div 10^{22}$ eV, this is of order 200 events per neutrino flavour for F_ν at the observational limit, and ten times fewer for F_ν at the cascade limit. This measurement will establish the absolute normalisation of the UHECν flux, thereby removing the final uncertainty in the Z-burst calculation. It is therefore probable that clustering-enhanced Z-burst emissions and UHECν events will be simultaneously measured as soon as EUSO has completed its nominal three-year flight, if conditions (i) and (ii) are indeed satisfied. In such a case, the associated Z-dips [55] in the incident UHECν flux will also have been resolved by the next generation of dedicated UHECν detectors such as ANITA in the same time frame. Remarkably, viable UHECν fluxes and neutrino masses in the ~ 0.1 eV ballpark are also able to produce the correct amount of Z-burst nucleons and photons to explain the cosmic ray events observed by AGASA at energies above the GZK cut-off.

It is interesting to note that if EUSO, or any successor experiment, succeeds in measuring Z-bursts *and* the diffuse UHECν rate at $E^{\text{res}}_{\nu_i}$, then the neutrino–nucleon cross section $\sigma_{\nu N}$ can be inferred at $E^{\text{res}}_{\nu_i} \sim 10^{22}$ eV, far above energies available to terrestrial accelerators. The ratio of the Z-burst rate and the diffuse UHECν rate

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[9] The EGRET constraint on α in [53] applies only to a homogeneous CνB. However, we do not expect it to be too seriously affected by enhanced Z-burst emissions from gravitational clustering at Virgo. This is because the enhancements are no more than a factor of twenty, and are concentrated in a small solid angle, $\Delta\Omega \sim 0.1$ ster, less than one hundredth of the whole sky. Changes in the all-sky emission rate due to enhanced emissions from Virgo can only be at the $\lesssim 15$ % level. Other galaxy clusters of comparable sizes are likely too far (i.e., $\gtrsim 50$ Mpc, outside the GZK zone) to be of great concern.

[10] This same factor describes the relative acceptances and exposures of any experiment triggering on downcoming and horizontal atmospheric events. Besides EUSO, another large area example is the Pierre Auger Observatory.

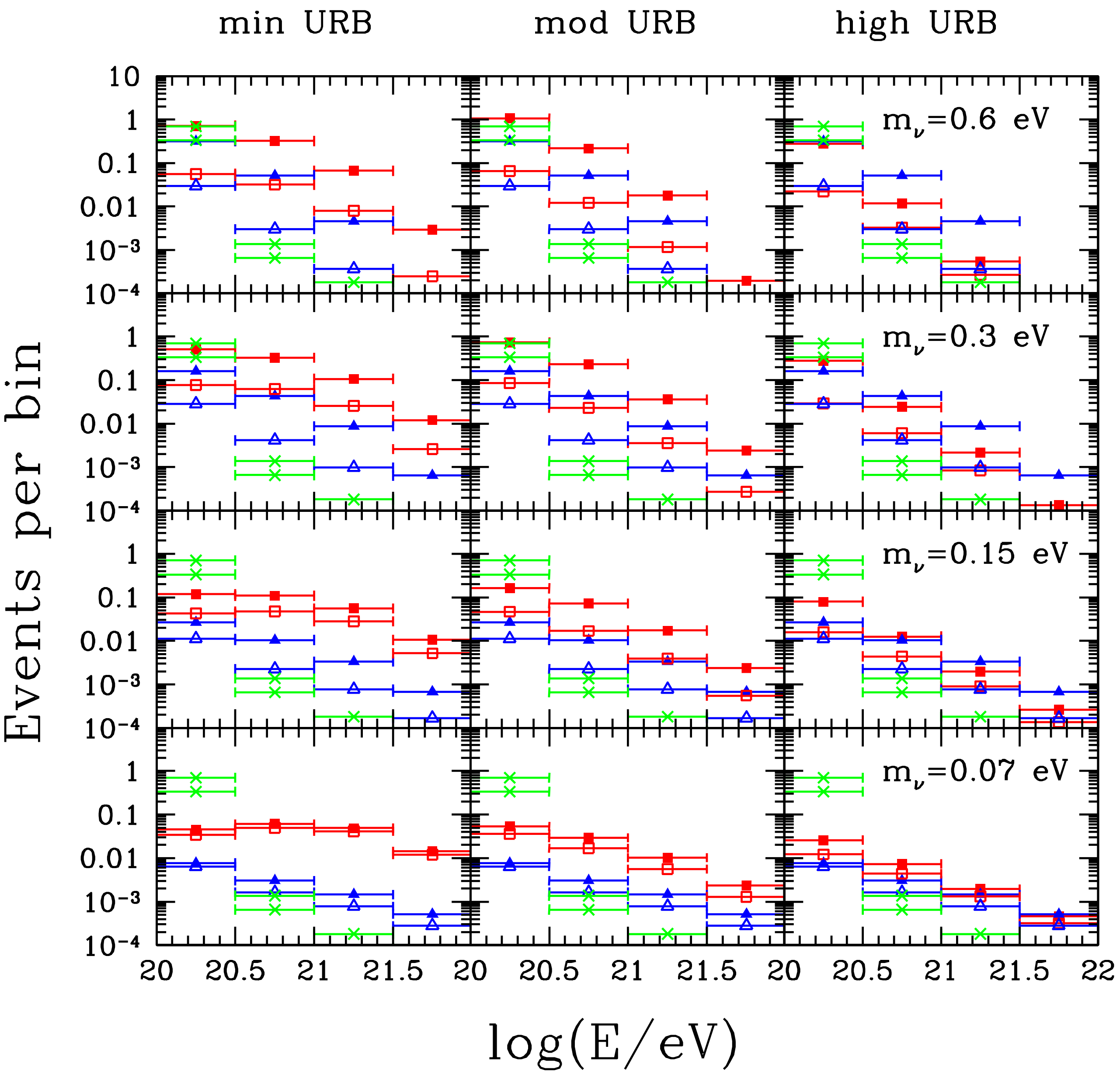

FIG. 7: Same as Figure 6, but for the EM cascade limited UHECν fluxes.

is independent of the flux, but dependent on the two cross sections, $\langle\sigma_{\rm ann}\rangle$ and $\sigma_{\nu N}$. The former is determined purely by weak interaction physics to be 40.4 nb, leaving only $\sigma_{\nu N}$, which depends on the QCD dynamics of the nucleon, as the unknown variable.

B. Less optimistic scenario: transparent sources

For transparent sources, the EM cascade limit on the UHECν fluxes applies, thereby excluding Z-burst emissions as an explanation of the AGASA post-GZK excess (cf. Figure 2). Nevertheless, EUSO has a projected exposure three orders of magnitude larger than the exposures of existing experiments; one may therefore hope for the eventual discovery of Z-burst events in the future, even if Z-bursts are not the source of the AGASA events. However, with a cascade limited UHECν flux, the observation of Z-burst rates in the direction of Virgo seems difficult to realise even with three years of EUSO. This remains true even with the substantial clustering enhancement available to quasi-degenerate neutrinos (Figure 7). Better statistics may be achievable by widening the solid angle about Virgo, but inevitably at the expense of narrowing the tell-tale gap between the clustered and unclustered rates. Furthermore, to pursue this low signal-to-noise scenario, one would likely require a more accurate modelling of gravitational neutrino clustering in the local universe—something beyond our simple halo description. All in all, a larger experiment is required. The OWL and multi-OWL proposals [24] would put (multi) satellites into orbit, to provide a FOV that dwarfs even EUSO. Experiments using LOw-Frequency radio antenna ARrays (LOFARs) have also been proposed. The prototype for this kind of detector has just reported positive identification of UHECR [56]. The Westerbork [23] LOFAR facility in the Netherlands may offer the potential to improve the event rates of UHECR and UHECν by two or more orders of magnitude beyond EUSO.

Suppose the UHECν flux comes from transparent sources, in which case it is cascade limited and cannot explain the post-GZK events in AGASA. Further suppose that the post-GZK AGASA spectrum and rate are correct. Then, is the “background-free” window for neutrino physics above $E_{\rm GZK}$ closed? The answer is, not necessarily, if the CνB does cluster sufficiently. In Figure 8, we show events in the energy interval $10^{20} \div 10^{21}$ eV and in a ~ 0.1 ster solid angle, projected for three years of EUSO observations, assuming the apparent post-GZK AGASA flux (assumed to be isotropic). This is to be compared with the clustering-enhanced Z-burst emissions from the Virgo cluster, also shown. The latter constitute up to 3 % and 20 % of the projected primary events for $m_{\nu_i} = 1.5$ eV and 0.6 eV, respectively, and dominate, albeit at a lower rate, beyond $10^{20.5}$ eV. Thus, detecting Z-burst emissions with an observatory larger than EUSO, even in the face of less than optimal UHECν fluxes and a possible post-GZK cosmic ray background, may not be entirely hopeless if the CνB clusters appreciably.

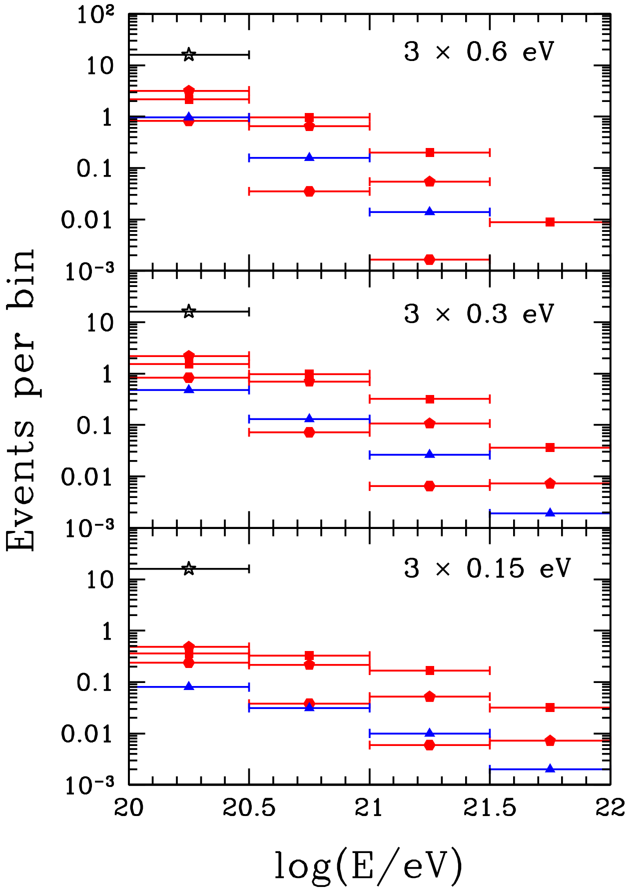

FIG. 8: Number of Z-burst events, for three quasi-degenerate neutrinos, originating within $\theta = 10^\circ$ from M87 expected at EUSO in three years, assuming the cascade limited UHECν fluxes. Triangles denote the nucleon events, while the squares, pentagons and hexagons refer respectively to the photon events for the minimal, moderate and high URB scenarios. The stars indicate the number of events observed by AGASA in the same energy range ($10^{20} \div 10^{20.5}$ eV) projected for three years of EUSO observations in the same solid angle.

VI. CONCLUSION

Resonant annihilation of ultra-high energy cosmic neutrinos (UHECν) on the cosmic neutrino background (CνB) into Z bosons—the Z-burst mechanism—is a unique, albeit indirect, process capable of revealing the CνB in its present state. The annihilation can be detected as absorption dips in the incident UHECν flux and/or as emission features in the Z-decay products (nucleons and photons) at energies above the Greisen–Zatsepin–Kuzmin (GZK) cut-off. General Z-burst absorption and emission phenomenology, including the possibility that Z-decay products may constitute the post-GZK ultra-high energy cosmic ray (UHECR) events observed by AGASA, has been investigated in a number of recent publications. In the present work, we have considered exclusively the implications of a non-uniform CνB for the Z-burst emission rates and sky map. In particular, we have focussed on the effects of augmentations to the CνB number density in and around large galaxy clusters due to gravitational clustering, and the potential of future cosmic ray experiments, especially the Extreme Universe Space Observatory (EUSO), to observe clustering-enhanced Z-burst emission rates originating from the nearby Virgo cluster.

The GZK suppression of nucleons from extragalactic sources provides a clean environment for the study of Z-burst initiated events at energies above $\sim 10^{20}$ eV. Indeed, for UHECν fluxes saturating the electromagnetic cascade limit, Z-burst nucleon and photon fluxes originating from a uniform CνB already dominate at these energies. Gravitational CνB clustering at the Virgo cluster further enhances the fluxes by up to a factor of several to more than forty, depending on the neutrino mass, at the centre of the cluster (Figure 4). The enhancement decreases with angular distance from the centre in a manner highly sensitive to the neutrino mass (Figure 5). This angular dependence of the emission events can in principle serve as an independent probe of the neutrino mass, the shape of the Virgo halo, as well as the Z-burst mechanism as a whole.

However, the statistics of Z-burst observation is necessarily limited by the magnitude of the available UHECν flux. For three years of EUSO observations, we find that a detection of clustering-enhanced Z-burst rates from the Virgo cluster is probable, provided that the UHECν fluxes are close to current observational limits (Figure 6). Sources capable of generating such large fluxes will most likely involve physics beyond the standard model. A quasi-degenerate neutrino mass spectrum is also desirable, since gravitational clustering is considerably more efficient for "large" neutrino masses, $m_{\nu_i} \gtrsim 0.1$ eV (Figure 3). Under these favourable conditions, one would also expect the associated absorption dips in the incident UHECν flux to be resolved by EUSO and/or other forthcoming dedicated UHECν detectors.

In the case of less than optimal UHECν fluxes, e.g., fluxes below the electromagnetic cascade limit, or a hierarchical neutrino mass spectrum, the observation of enhanced Z-burst rates in the direction of Virgo seems to require an experimental sensitivity exceeding that of EUSO by at least two orders of magnitude (Figure 7). The Westerbork radio observatory in the Netherlands offers a tremendous new reach in UHECν and UHECR detection by looking for signals of their interactions with the lunar regolith. If it establishes a UHECν flux at energies above 10^{21} eV, then the final uncertainty in the Z-burst mechanism is removed. This allows definite predictions to be made for associated Z-burst emissions from the Virgo cluster. Such measurements would finally establish the existence (or not) of the cosmic neutrino background.

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