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Cosmic rays above the ankle from Z-bursts

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Abstract

Neutrinos from far away sources annihilating at the Z resonance on relic neutrinos may give origin to the ultrahigh-energy cosmic rays. Here we present predictions of this mechanism with relic neutrinos lighter than 1 eV, which do not gravitationally cluster. We show that not only the super GZK events, but the “ankle” and all events above it can be accounted for. Most primaries above the ankle are predicted to be nucleons up to $10^{20.0}$ eV and photons at higher energies. We also find an accumulation at the GZK cutoff energy, a hint of which can be seen in the data.

1 Introduction

The existence of ultrahigh-energy cosmic rays (UHECR) with energies above the Greisen-Zatsepin-Kuzmin (GZK) cutoff [1] of about 5×10^{19} eV, presents an outstanding problem [2]. Nucleons and photons with those energies have short attenuation lengths and could only come from distances of 100 Mpc or less [3,4], while plausible astrophysical sources for those energetic particles are much farther away.

An elegant and economical solution to this problem, proposed by T. Weiler [5], consists of the production of the necessary photons and nucleons close to Earth, in the annihilation at the Z-resonance of ultrahigh-energy neutrinos coming from remote sources, ν_{UHE} , and relic background neutrinos. These events were named “Z-bursts” by T. Weiler. One of the most appealing features of the “Z-bursts” scenarios is that the energy scale of 10^{20-21} eV, at

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which the unexpected events have been detected, is generated naturally given the possible mass range of relic neutrinos. The Z -resonance occurs when the energy of the incoming ν_{UHE} is $E_{\nu_{\text{UHE}}} = E_{Res}$,

$$E_{Res} = \frac{M_Z^2}{2 m_\nu}, \quad (1)$$

where m_ν is the mass of the relic neutrinos. This is the new cutoff of the UHECR energy in these models. It depends inversely on the mass of the relic neutrinos. Since arguments of structure formation in the Universe show $m_\nu <$ few eV, then $E_{\nu_{\text{UHE}}} > 10^{21}$ eV, precisely above the GZK cutoff, as needed.

In this paper we concentrate on a particular “Z-bursts” scenario [6,7], in which the relic neutrinos are lighter than 1 eV. These lighter neutrinos, contrary to those in the original scenario, cannot be gravitationally bound, they have a constant density over the whole Universe. In particular, we concentrate on relic neutrinos with mass compatible with Super-Kamiokande results, if neutrino masses are hierarchical (however the results we obtain apply to heavier relic neutrinos, while light enough to not cluster). Super-Kamiokande has provided a strong evidence for the oscillation in atmospheric showers of two neutrino species with masses m_1, m_2 and $\delta m^2 = m_1^2 - m_2^2 = (1-8) \times 10^{-3}$ eV, consisting mostly of about equal amounts of ν_μ and another flavor eigenstate neutrino, ν_τ or a sterile neutrino [8]. If neutrino masses are hierarchical, as those of the other leptons and quarks, then the heavier of the two oscillating neutrinos, call it ν_{SK} , has a mass $m_{\text{SK}} = \sqrt{\delta m^2} \simeq 0.07$ eV. With $m_\nu = m_{\text{SK}}$, the new UHECR cutoff becomes

$$E_{Res} \simeq 0.6 \times 10^{23} \text{ eV}. \quad (2)$$

Due to the large multiplicity of the Z -decays, after energy losses in the propagation (as shown in detail here) this value of E_{Res} predicts many super GZK UHECR events (many more than with eV relic neutrino masses).

We agree with Farrar and Piran [9], who have argued that any mechanism accounting for the events beyond the GZK cutoff should also account for the events down to the ankle, including their isotropy and spectral smoothness. We show here that the model we consider can account for the ankle and all the events above it if the position of the ankle is close to that measured by AGASA, $E_{ankle} = 10^{19.0}$ eV (see [10], in particular Table V, and references therein). Moreover, a reliable prediction of the model is that most primaries above the ankle should be nucleons up to about $10^{20.0}$ eV and photons at higher energies. We also find that nucleons do accumulate at the GZK cutoff energy, which could account for the hint of a slight accumulation seen in the data. Photons become dominant at energies higher than 10^{20} eV in our model. So

these photons are all above the threshold energy (which is about 5×10^{19} eV) to pair produce in the Earth’s magnetic field (which should generate a certain amount of north-south asymmetry in the arrival direction distribution).

Let us return to the issue of the isotropy of the events above the ankle, i.e., the absence of a correlation with the galactic halo. Because the relic neutrinos we assume do not gravitationally cluster, the isotropy of the events reflects the isotropy of the ultrahigh-energy neutrino sources. In particular, relic neutrinos of mass m_{SK} require a large flux of neutrinos with energies of the order of 10^{23} eV. It is unlikely that active galactic nuclei [11], neutron stars [12], or other astrophysical sources could produce such a high energy flux of ultrahigh-energy neutrinos. Topological defects [13], or superheavy relic particles [7], could instead easily generate the requisite flux of primary neutrinos (but there are still problems with these sources). For example, with unstable superheavy relic particles, which form part of the cold dark matter, decaying mostly into neutrinos [7], the directions of UHECR could map the distribution of parent particles (which should coincide with the distribution of cold dark matter) at large redshifts. This is because the initial energy of the ν_{UHE} produced in the decay needs to be redshifted to the energy of the “ Z -burst” in its way to the Earth. Directional clustering, evident in the existing data [14], would then reflect the distribution of matter at a certain red shift determined by this process of “cosmological filtering”. Thus, absence of directional correlations with the galactic halo, as well as directional clustering, could be easily accommodated [7].

Besides, ν_{UHE} produced by unstable superheavy relic particles would have a spectrum opposite to an astrophysical spectrum, growing rapidly with energy, up to a sharp cutoff at an energy of the order of the parent particle mass. This spectrum has almost no neutrinos at low energy where bounds exist [7,15]. Most bounds on “ Z -bursts” models (see for example [11]) assume that the ν_{UHE} have a typical astrophysical spectrum, decreasing with energy as $E^{-\gamma}$, with γ a number of order one. These bounds do not hold if the ν_{UHE} spectrum has a very different energy dependence. However, a model for these parent particles is arguably difficult to obtain [16,17]. Moreover, the EGRET bound on the diffuse low-energy gamma ray flux resulting from the “ Z -bursts” imposes important constraints [18], which might rule out heavy particles decaying mostly into neutrinos as sources [19].

In the next section we present our simulations and the resulting spectrum of UHECR. We would like to point out that the main result of this paper, the fact that “ Z -bursts” can account for the ankle and all events above it, does also hold for larger relic neutrino masses, for which the problem of the sources becomes less severe. In fact even if we used m_{SK} here, our considerations apply with trivial changes to other masses for which relic neutrinos are too light to gravitationally cluster. As the relic neutrino mass increases, all the features in

the spectrum we find here should move progressively to lower energies.

2 Spectrum of UHECR from “Z-bursts”

We have performed simulations of the photon, nucleon and neutrino fluxes coming from a uniform distribution of “Z-bursts”, namely $\nu\bar{\nu}$ annihilations at the Z pole ($\nu\bar{\nu} \rightarrow Z \rightarrow p\gamma\dots$), with the energy of Eq. 2, corresponding to relic neutrinos of mass m_{SK} . The “Z-bursts” were simulated using PYTHIA 6.125 [20], and the absorption of photons and nucleons was modeled using energy attenuation lengths provided by Bhattacharjee and Sigl [21], supplemented by radio-background models by Protheroe and Biermann [22].

We simulated a uniform distribution of about 10^7 Z particles up to a maximum $z_{\text{max}} = 2$. Even if the shape of the spectrum of nucleons and photons changes somewhat with other Z particle distributions, the main features of the spectrum stated here remain the same.

The decay of the Z bosons through all possible channels was done automatically by the PYTHIA routines [20], using the default options of this program. For comparison with the other figures we show in Fig. 1 the spectra given by PYTHIA, normalized per Z boson (not including redshifts and energy absorption). The multiplicities that PYTHIA gives per Z-decay are (in each case counting particles and antiparticles) 1.6 nucleons, 17 photons, 15 ν_e , 30 ν_μ and 0.23 ν_τ .

In our simulation, each Z boson generated by PYTHIA was placed on the “event list” of the cascade generator at a randomly selected distance. The cascade of decay products was then boosted. The γ factor corresponding to an energy $E_\nu = E_{\text{res}}$ is

$$\gamma = \frac{E_\nu + m_\nu}{M_z} = 6.25 \times 10^{11}. \quad (3)$$

The gamma factor of each boost was actually corrected to include the redshift of the decaying Z particle. We then followed the propagation of the nucleons, photons and neutrinos resulting from the boosted Z decays. Neutrinos do not interact in their propagation. Thus, the energy spectra of the three kinds of neutrinos were simply generated by counting the number of particles per energy bin and normalizing this number to the total number of Z particles used.

We included energy absorption for nucleons and photons. Each nucleon or photon was created by PYTHIA in the initial cascade at a fixed position,

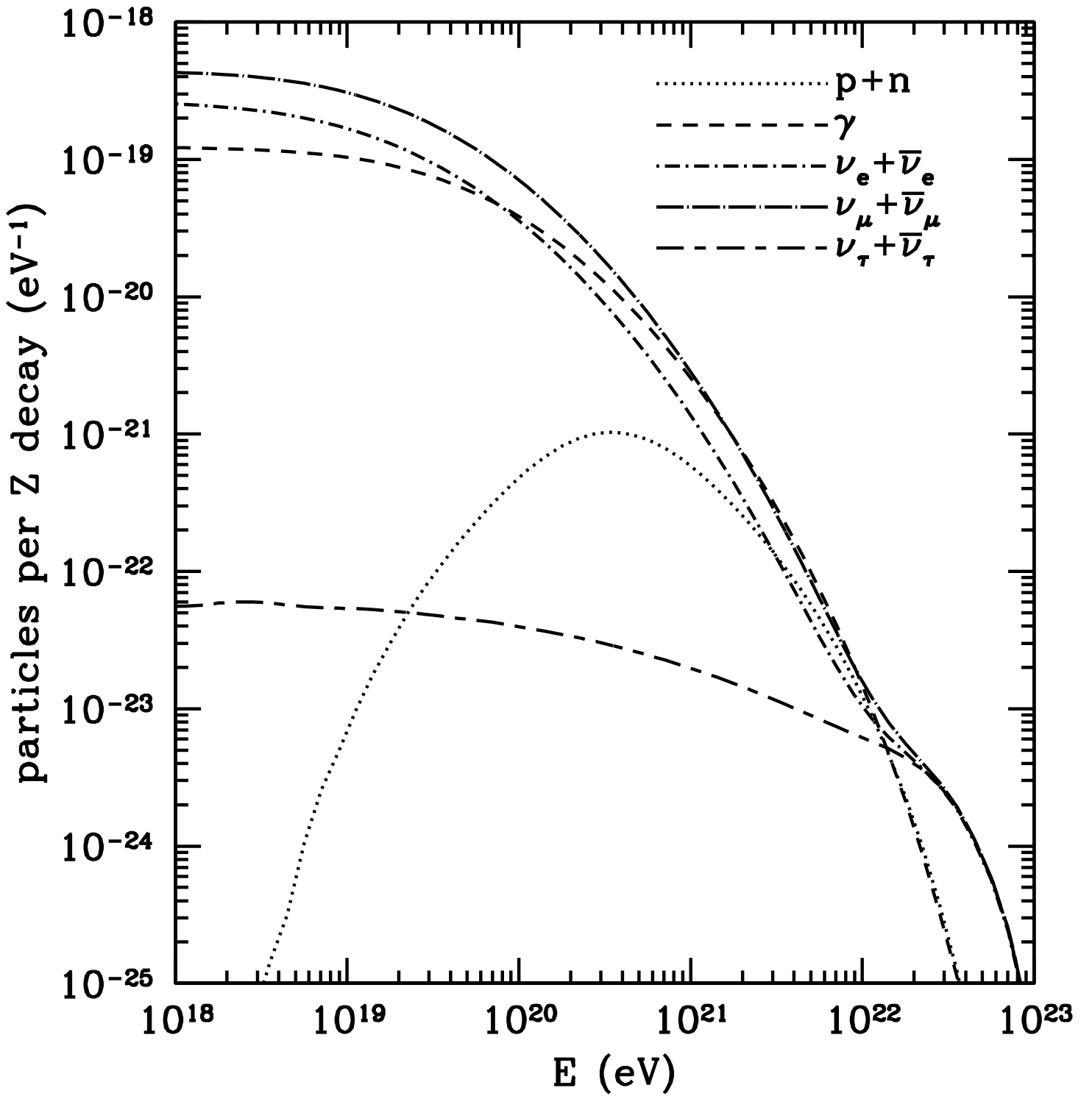


Fig. 1. Spectra of stable particles produced per Z decay by PYTHIA (no absorption or redshift included).

with fixed energy and direction of motion with respect to the Earth frame of reference. The distance each particle had to travel before reaching Earth was compared with the appropriate attenuation length in space for the particle energy. If the distance was smaller than the attenuation length, the particle was assumed to reach Earth unchanged. In the opposite case, the energy and momentum of the particle were degraded by a factor $1/e$ after traveling a distance equal to the attenuation length (and the particle was placed again in the list constituting the cascade at the new position, with the degraded energy and momentum).

This process was continued until all nucleons and photons reached Earth and were counted in the final spectra, or until their energies became too small to be significant, in which case they were simply discarded from the cascade. At this point, the final nucleon and photon spectra were normalized to the total number of Z particles used (the same done with the neutrino spectra). The results are given in Fig. 2, with an approximate fit to the AGASA cosmic ray data [23]. We used the nucleon energy attenuation length given by Bhattacharjee and Sigl in the Fig. 9 of Ref. [21], based on results from Ref. [24] and [25].

The energy attenuation length of photons is poorly known, due to the uncertainty in the radio background. Using the attenuation length shown in Fig. 11 of Ref. [21], based on observations of Clark et al. [26], the resulting photon flux is shown in Figs. 2 and 3 as curve (1). Protheroe and Biermann [22] produced two models for the radio background which lead to shorter interaction lengths than those based on Clark et al. From the provided interaction lengths we constructed approximate attenuation lengths for the models of Protheroe and Biermann by reducing the attenuation length based on Clark et al. by the difference between the interaction lengths. With the attenuation lengths so constructed we obtained the curves (2) and (3) in Figs. 2 and 3. This is obviously only an approximation, since the mean interaction and energy attenuation lengths do not have exactly the same energy dependence. However, we believe the three curves we obtained give a good representation of the possible range of predicted photon fluxes, in view of the uncertainties related to the energy attenuation of photons in space.

We have arbitrarily used the middle photon flux, curve number (2), when computing the total flux. We added the proton and photon fluxes obtained in this paper to a power law spectrum with slope -3.23 found by AGASA to fit the data below the ankle (from $10^{17.6}$ to $10^{19.0}$ eV; see Table V of [10]). Our results depend very little on which of the three photon fluxes we use.

The fit of the AGASA data with our total flux provides the normalization of the photon and nucleon differential fluxes F , denoted as $d\phi/dE$ in the figures (in this case $F_{AGASA} = 10^{-14.2} (\text{m}^2 \text{ sr s})^{-1}$ $F_{P\bar{P}T\bar{H}IA} = 6 \times 10^{-15} (\text{m}^2 \text{ sr s})^{-1}$

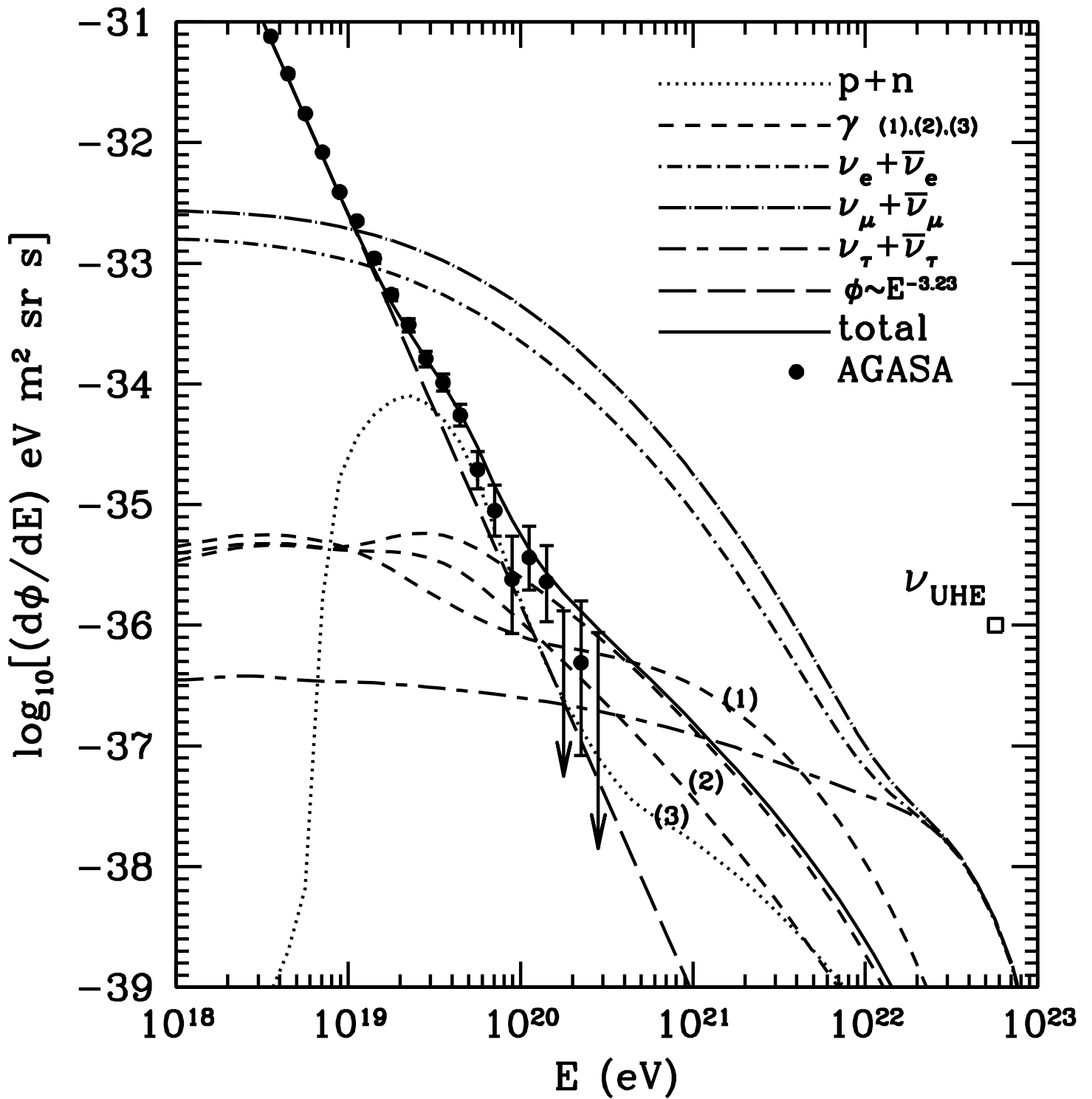


Fig. 2. Predicted spectra from “Z-bursts” with a uniform distribution up to $z = 2$, added to a power law spectrum which fits the data below the ankle. Primaries above the ankle are nucleons up to $10^{20.0}$ eV and photons at higher energies.

F_{PYTHIA}), that allows us to determine the (assumed homogeneous and isotropic) flux of ultrahigh-energy neutrinos close to the Z -resonance energy of Eq. 2 (at some energy between $E_{Res}/(1 + z_{max}) = E_{Res}/3$ and E_{Res}) to be

$$F_{\nu_{UHE}} \simeq 1 \times 10^{-36} \frac{1}{\text{eV m}^2 \text{ sr s}} , \quad (4)$$

if no lepton asymmetry is assumed in the neutrino background. This flux is shown in Figs. 2 and 3, with the label “ ν_{UHE} ”. With the level of accuracy of our simulation we can only determine the order of magnitude of this flux. Moreover, for the light neutrinos we are considering, present experimental bounds allow for a lepton asymmetry which could increase the number of relic neutrinos by a factor smaller than 10, reducing the necessary $F_{\nu_{UHE}}$ by the same factor.

We have continued the power law spectrum accounting for the events below the ankle, presumably due to galactic sources, way beyond the ankle, while this contribution may die out at or soon above the ankle. In any event, without adding up the power law, i.e., taking into account only the photon and nucleon fluxes from “ Z -bursts” computed here, we had made a very similar fit [27], with which we had obtained the same $F_{\nu_{UHE}}$.

As we just mentioned, without making an assumption on the spectrum of ν_{UHE} , the “ Z -bursts” mechanism provides an estimate of the ν_{UHE} flux only close to the Z -resonance energy E_{Res} (at some energy between $E_{Res}/(1 + z_{max}) = E_{Res}/3$ and E_{Res}). It is interesting to point out that, on the basis of that one estimate, the “Goldstone Experiment” (GLUE) [28] could start testing our model after about 300 hours of observation. This can be seen in Fig. 3, where we show the present limits of this experiment, based on about 30 hours of observation. In Fig. 3 the fluxes of Fig. 2 have been multiplied by E^2 . GLUE searches for lunar radio emissions from interactions of neutrinos above 10^{19} eV of energy and is expected to accumulate 120 hours of observation later this year.

Figs. 3 and 4 include Akeno data taken from Fig. 23 of Ref. [10], originally from Ref. [29] (besides the AGASA data). In Fig. 4 we show our nucleon flux, only our middle photon flux (curve (2) in previous figures), the power law providing a good fit to data below the ankle, and the total flux (the sum of these three components).

We believe that Fig. 4, in which the plotted spectra have been multiplied by E^3 , shows best the change of slope close to the position of the ankle as measured by AGASA, $E_{ankle} = 10^{19.0}$ eV. Obtaining a value of E_{ankle} a factor of 3 smaller, close to $10^{18.5}$ eV as measured by Fly’s Eye (see Table V of [10]) may require to increase the z_{max} of the source distribution considerably

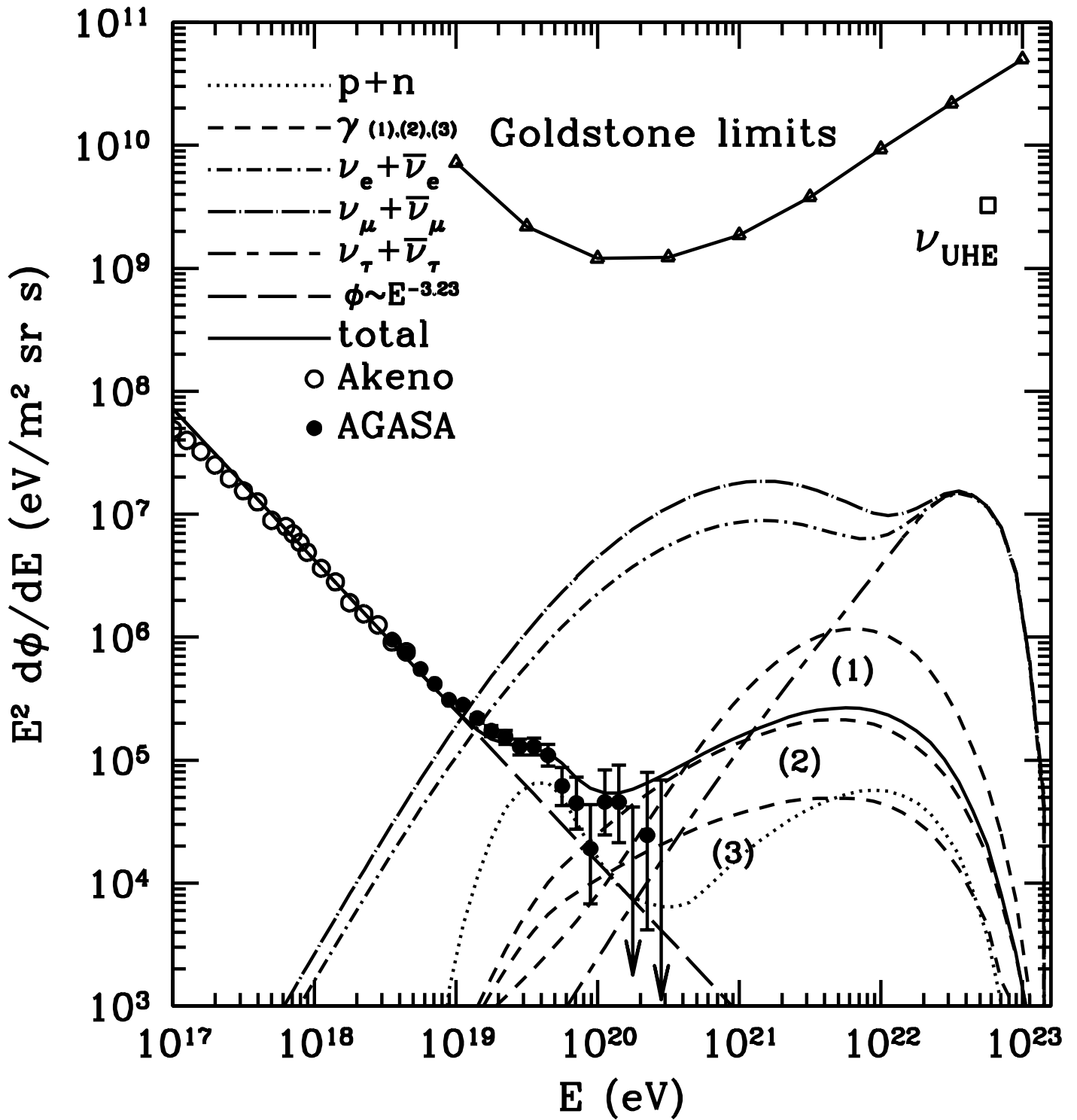


Fig. 3. The fluxes of Fig. 2 have been multiplied by E^2 . Data from Akeno are shown besides the AGASA data. “ ν_{UHE} ” labels the flux of UHE neutrinos predicted close to the Z-resonance energy.

(which would point to particles as sources), since this would move the lower energy edge of the nucleon flux to lower energies. Alternatively, larger values of the relic neutrino mass may also work to lower E_{ankle} , since all the features in the spectrum should move to lower energies (even if we used m_{SK} here, our considerations apply with trivial changes to other masses for which relic neutrinos are too light to gravitationally cluster).

In Fig. 4 one can clearly see the enhancement of the predicted flux at the GZK cutoff energy, at about 5×10^{19} eV, due to the accumulation of nucleons, which can also be seen in the AGASA data.

3 Conclusions

In this paper we considered a particular “Z-bursts” scenario [6,7], in which the relic neutrinos are lighter than 1 eV, and thus do not gravitationally cluster. Using in particular 0.07 eV relic neutrinos, we have shown that “Z-bursts” may account not only for the super GZK events, but for the “ankle” and all UHECR events above it, including their isotropy and spectral smoothness. In our simulation we found the “ankle” close to $E_{ankle} = 10^{19.0}$ eV as measured by AGASA. A reliable prediction of the model is that most primaries above the ankle should be nucleons up to about $10^{20.0}$ eV and photons at higher energies. Moreover, the nucleons do accumulate at the GZK cutoff energy, which could account for the hint of a slight accumulation seen in the data. The model predicts a new cutoff, which with 0.07 eV relic neutrinos is at $E_{Res} \simeq 0.6 \times 10^{23}$ eV.

We have not included the effect of extragalactic magnetic fields, thus for the predictions of this paper to be true these fields should be sufficiently small, probably smaller than 10^{-9} G.

Finally let us comment on recent related papers. Photon and nucleon spectra very similar to those presented here are shown in Fig. 2a of Ref. [30] corresponding to “Z-bursts” with 0.1 eV relic neutrinos and a different model for the distribution of “Z-bursts” with redshift up to $z_{max} = 3$. This model satisfies the EGRET bound on low energy photons (even if with astrophysical sources emitting only UHE neutrinos). This reassures us that the result we present here is robust. The EGRET bound has been computed for various “Z-bursts” scenarios [30,31], including the particular one we concentrated on here [18], which seems to work well with sources emitting only UHE neutrinos. The most serious problem with these sources may be the electroweak cascading of the UHE neutrinos produced in the decays, as recently claimed in [19].

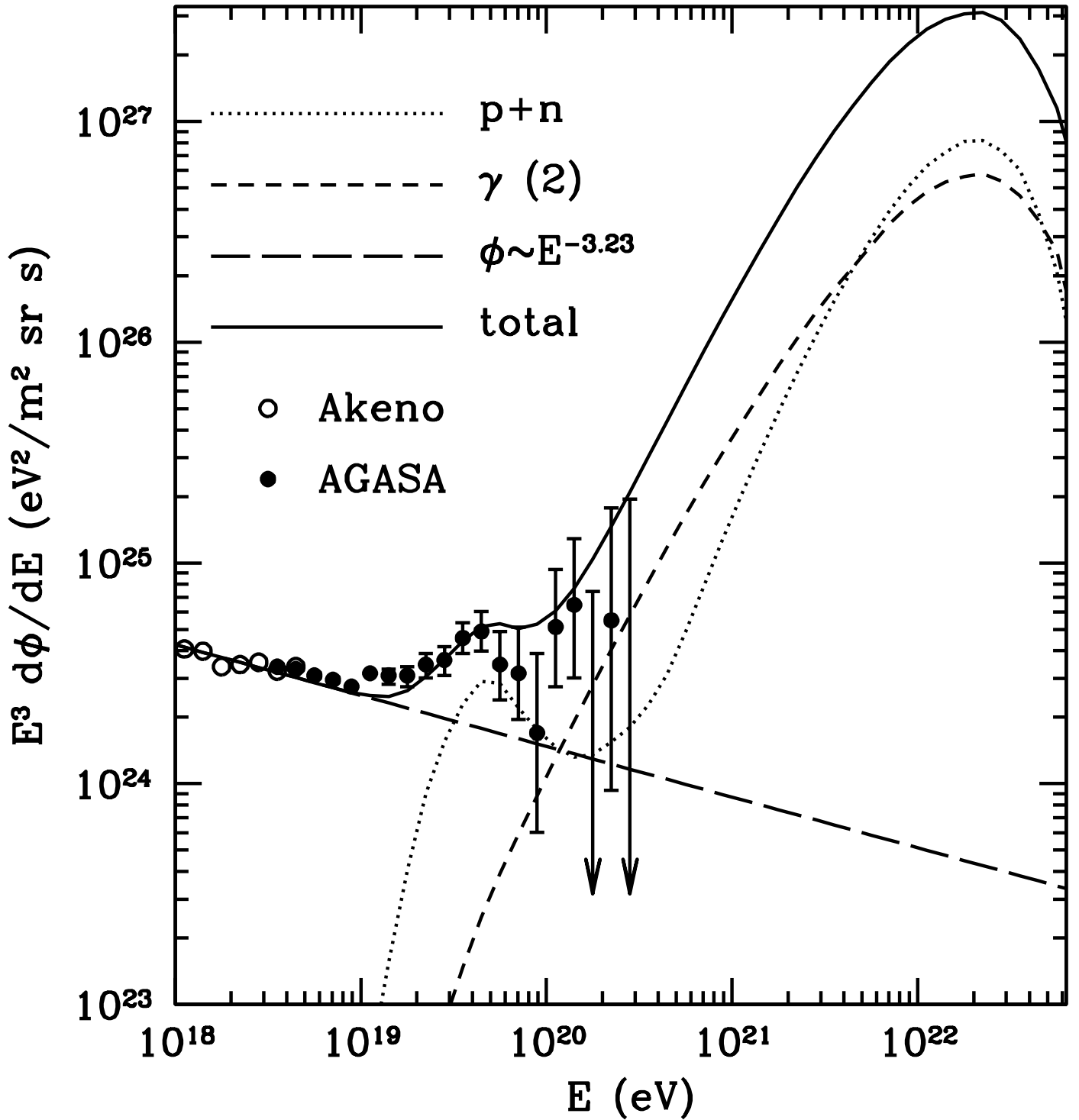


Fig. 4. The fluxes of Fig. 2 have been multiplied by E^3 . The position of the “ankle” is close to $10^{19.0}$ eV as measured by AGASA. The predicted accumulation at the GZK cutoff energy, about 5×10^{19} eV, can also be seen in the data.

Events above the ankle have been previously fitted with “ Z -bursts” products plus an additional hypothetical component of galactic or extragalactic protons in Ref. [32], varying the relic neutrino mass, in an attempt to provide a determination of this mass using UHECR data. However the normalization and slope of the extra proton flux and the normalization of the nucleon flux from “ Z -bursts” (photons from “ Z -bursts” were neglected) were taken as fitting parameters. This procedure does not make clear if it is actually the “ Z -bursts” which account for the change of slope at the “ankle” and for the events above the “ankle”. Moreover, with this procedure [32], there is no prediction of the position of the ankle, since this is one of the parameters to be fitted by the sum of the mentioned two fluxes. Here we took instead the measured flux below the ankle, with the measured slope and normalization. We considered it to be of galactic origin, as the correlation with the galactic center of the arrival directions measured by AGASA around 10^{18} eV [33] seems to indicate. Then we added to this fixed flux the new component due to “ Z -bursts”, which led us to find a prediction for the position of the ankle, and the normalization of the flux of primaries due to “ Z -bursts”.

We believe our flavor of “ Z -bursts” provides a plausible explanation to the puzzle of ultrahigh-energy cosmic rays, not only for the super GZK events, but for the “ankle” and all events above it.

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