SuperGZK neutrinos: testing physics beyond the Standard Model

Veniamin Berezinsky

INFN, Laboratori Nazionali del Gran Sasso, I-67010 Assergi (AQ), Italy
and Institute for Nuclear Research of the RAS, Moscow, Russia

The sources and fluxes of superGZK neutrinos, $E > 10^{20} \text{ eV}$, are discussed. The most promising sources are reionization bright phase, topological defects, superheavy dark matter and mirror matter. The energy of neutrinos can be above the GUT scale ($\sim 10^{16} \text{ GeV}$). The predicted fluxes are observable by future space detectors EUSO and OWL.

I. INTRODUCTION

The abbreviation ‘SuperGZK neutrinos’ implies neutrinos with energies above the Greisen-Zatsepin-Kuzmin \cite{1} cutoff $E_{\text{GZK}} \sim 5 \times 10^{19} \text{ eV}$. Soon after theoretical discovery of the GZK cutoff it was noticed that this phenomenon is accompanied by a flux of UHE neutrinos, that in some models can be very large \cite{2}. In 80s it was realized that topological defects can produce unstable superheavy particles with masses up to the GUT scale \cite{3} and neutrinos with tremendous energies can emerge in this process \cite{4}.

It has been proposed that SuperGZK neutrinos can be detected with help of horizontal Extensive Air Showers (EAS) \cite{5}. The exciting prospects for detection of SuperGZK neutrinos have appeared with the ideas of space detection, e.g. in the projects EUSO\cite{6} and OWL\cite{7}. The basic idea of detection can be explained by example of EUSO.

A superGZK neutrino entering the Earth atmosphere in near-horizontal direction produces an EAS. The known fraction of its energy, which reaches 90\%, is radiated in form of isotropic fluorescent light. An optical telescope from a space observatory detects this light. Since the observatory is located at very large height ($\sim 400 \text{ km}$) in comparison with thickness of the atmosphere, the fraction of detected flux is known, and thus this is the calorimetric experiment (absorption of light in the upward direction is small). A telescope with diameter $2.5 \text{ m}$ controls the area $\sim 10^5 \text{ km}^2$ and has a threshold for EAS detection $E_{\text{th}} \sim 1 \times 10^{20} \text{ eV}$.

II. SOURCES OF SUPERGZK NEUTRINOS

The sources can be of the accelerator and non-accelerator origin.

Accelerator sources

A source comprises an accelerator and target. Low energy photons inside the source or outside it (e.g. CMB photons) are usually more efficient for neutrino production than gas. The problem is acceleration to $E \gg 1.1 \times 10^{20} \text{ eV}$. For shock acceleration the maximum energy can reach optimistically $E_{\text{max}} \sim 10^{21} \text{ eV}$ for protons. There are some other, less developed accelerator mechanisms (e.g. unipolar induction, acceleration in strong e-m waves), which hopefully can provide larger $E_{\text{max}}$. An interesting mechanism with very large $E_{\text{max}}$ has been recently proposed in Ref.\cite{8}.

The large neutrino fluxes at the superGZK energies is also a problem for accelerator sources.

Non-accelerator (top-down) sources

Topological Defects (TD) and Superheavy Dark Matter (SHDM) can easily produce required superGZK energies. In both cases the superGZK neutrinos are produced in the decays of very heavy particles, unstable gauge and Higgs particles in case of TDs, and quasistable particles in case of SHDM. Neutrinos are born mostly in pion decays and have $E_{\text{max}} \sim 0.1m_X$. A natural upper limit for mass is $m_X \leq m_{\text{GUT}} \sim 10^{16} \text{ GeV}$.

TDs differ substantially by mechanisms of SH particle production.

They include emission of X-particles through cusps in superconducting cosmic strings. In this case the energy of X-particle is boosted by the Lorentz-factor of the cusp which can reach $\Gamma \sim 10^4 - 10^6$.

In case of network of monopoles connected by strings, monopoles move with large acceleration $a$ and can thus radiate the gauge bosons such as gluons, $W^\pm, Z^0$. Neutrinos appear in their decays, in case...
of gluons through production and decays of pions. The typical energy of radiated quanta is $E \sim a\Gamma_M$, where $\Gamma_M$ is the Lorentz-factor of the monopole.

In *necklaces*, where each monopole (antimonopole) is attached to two strings, all monopoles and antimonopoles inevitably annihilate in the end of evolution, producing neutrinos in this process (see Subsection IV C).

*Vortons* can decay due to quantum tunnelling, producing neutrinos.

In some of the cases listed above the neutrino energies can be larger (due to Lorentz factor) than the GUT scale.

*SHDM* is very efficiently produced at inflation due to gravitational radiation and is accumulated in galactic halos with overdensity $\sim 10^5$. Neutrinos are produced at the decay of these particles mostly in extragalactic space. (see Subsection IV D).

For more details of the top-down particle production see reviews [9].

III. UPPER LIMITS ON DIFFUSE NEUTRINO FLUXES

*Cascade upper limit* [5, 12]

Production of HE neutrinos is accompanied by photons and electrons which start e-m cascade colliding with target photons $(\gamma + \gamma_{\text{tar}} \rightarrow e^+ + e^-, \quad e + \gamma_{\text{tar}} \rightarrow e^+ + \gamma')$. The cascade photons get into range observed by EGRET, and the energy density of these photons, $\omega_{\text{cas}}$, put the upper limit on diffuse HE neutrino flux $J_{\nu}(E)$ as it follows from the obvious chain of inequalities [5, 12]:

$$\omega_{\text{cas}} > \omega_{\nu}(E) \equiv \frac{4\pi}{c} \int_{E}^{\infty} E J_{\nu}(E) dE > \frac{4\pi}{c} E \int_{E}^{\infty} J_{\nu}(E) dE = \frac{4\pi}{c} E J_{\nu}(>E),$$

from which the bound for differential neutrino flux follows

$$E^2 I_{\nu}(E) \leq (c/4\pi)\omega_{\text{cas}}.$$  \hspace{1cm} (1)

The upper bound Eq. (1) is obtained under assumptions that neutrinos are produced in the chain of decays of particles (e.g. pions, $W$ and $Z^0$), where electrons or photons appear too, and that the sources are not opaque for the cascade photons. In fact cascade can develop inside a source, provided that produced cascade photons are not absorbed by gas in the source. Only fully opaque (‘hidden’) sources escape the bound Eq. (1), e.g. see Subsection IV E.

This bound has a great generality. It is valid for photon and proton target and for any spectrum index (in this case the bound becomes up to factor 2 stronger [12], p.359).

*Waxman-Bahcall (WB) upper limit* [13]

If UHE protons escape freely from a source, their flux should be less than the observed one. It gives the WB bound on neutrino flux produced by escaping protons. It is obtained for a specific shape $(1/E^2)$ of the production spectrum. This bound is much stronger than the cascade limit, but it is not valid for many sources and models (e.g. for TDs and SHDM, where production of protons is negligible, for acceleration sources at high redshift, from which UHE protons do not reach us, for clusters of galaxies, since time of CR exit from there is larger than age of universe, for some specific AGN models, e.g. the Stecker model etc). However, it is valid for diffuse flux from some interesting sources like GRBs and some models of AGN.

*Mannheim-Protheroe-Rachen (MPR) upper bound* [14]

As compared to the WB bound, the MPR limit is valid for sources with various optical depths and for different maximal acceleration energies. It is weaker than WB bound, and for high and low energies differ not too much from the cascade limit.

Since UHE protons is subdominant component for most sources of superGZK neutrinos (see next Section), the WB and MPR bounds are not valid for them, and the cascade bound becomes most appropriate.
IV. DIFFUSE FLUXES OF SUPERGZK NEUTRINOS

A. AGN and other accelerator sources

The fluxes of UHE neutrinos produced in $p\gamma$ collisions with CMB photons by UHE protons from AGN (quasars and Seyfert galaxies) were calculated in Ref. [5] up to $E_{\text{max}} \sim 10^{21}$ eV. The assumed cosmological evolution of the sources up to redshift $z = 14$ with the evolutionary index $m = 4$ increases strongly the flux. The cascade upper bound has been taken into account.

Recently the detailed calculations of diffuse neutrino fluxes from evolutionary and non-evolutionary sources have been performed in Ref. [10] (see also [11]). The acceleration mechanisms are not specified, but it is assumed that generation spectra are flat and $E_{\text{max}}$ can reach $3 \times 10^{22}$ eV. Neutrinos are produced in collisions with CMB photons. The calculated fluxes agree by order of magnitude with those from Ref. [5].

![Diffuse neutrino flux from the reionization bright phase](image)

FIG. 1: Diffuse $\nu_\mu$ neutrino flux from the reionization bright phase at redshift $z_0 = 20$ and $z_0 = 5$ [15]. The cascade upper bound for $\nu_\mu$ neutrinos is shown by curve ‘cascade limit’.

B. Reionization bright phase

The WMAP detection of reionization [15] implies an early formation of stars at large redshifts up to $z \sim 20$, able to reionize the universe.

A plausible process is formation of very massive, $M > 100 M_\odot$, Population III stars with subsequent fragmentation to SN. Two-burst scenario of reionization is plausible: at $z \approx 15$ and $z \approx 6$ [16]. The fraction of baryonic matter in the form of compact objects is $\sim 0.01$ at $z \sim 10$ [15]. Fragmentation of massive Pop III stars into presupernovae and black holes results in CR acceleration by various mechanisms (shocks, jets in miniquasars and hypernovae etc). Not specifying them we shall assume that the energy release in the form of CR is $W_{\text{cr}} \sim 5 \times 10^{50}$ erg/$1 M_\odot$, generation spectrum is $\sim E^{-2.1}$ and $E_{\text{max}} = 1 \times 10^{13}$ GeV. Neutrinos are produced in collisions with CMB photons. In Fig[11] we present the calculated
neutrino spectrum for two values of $z$ (20 and 5) [17], together with cascade upper limit for one neutrino flavour. This model is very similar to the galactic bright phase (for a review see [12], p.352).

**FIG. 2**: Diffuse neutrino flux (curve $\nu$) from necklaces [18]. The curve $p$ shows the UHE proton flux, compared with the AGASA data, and two curves $\gamma$ show UHE photon flux for two cases of absorption.

### C. Necklaces

Necklaces are hybrid TDs (monopoles connected by strings) formed in a sequence of symmetry breaking phase transition $G \to H \times U(1) \to H \times Z_2$. In the first phase transition the monopoles are produced, and at the second each monopole gets attached to two strings.

The symmetry breaking scales of these two phase transitions, $\eta_m$ and $\eta_s$, are the main parameters of the necklaces. They give the monopole mass, $m \sim 4\pi\eta_m/e$, and tension of the string, $\mu \sim 2\pi\eta_s^2$. The evolution of necklaces is governed by ratio $r = m/\mu d$, where $d$ is a length of a string between two monopoles. During the evolution this length diminishes due to gravitational radiation, and in the end all monopoles and antimonopoles annihilate, producing high energy neutrinos as the dominant radiation. The diffuse neutrino flux from necklaces is given [18] in Fig. 2. Note, that the rate of UHE particle production in this model is $\dot{n}_X \sim r^2 \mu / t^3 m_X$, where $r$ tends in evolution of a necklace to $r_{\text{max}} \sim \eta_m/\eta_s \sim 10^{13}$ contrary to expectation in Ref.[10] that this parameter is typically $\sim 1$ for all TDs.

### D. Superheavy dark matter (SHDM)

Production of SHDM particles naturally occurs in time varying gravitational field of the expanding universe at post-inflationary stage [19, 20]. This mechanism of production does not depend on the coupling of X-particles with other fields, and occurs even in case of sterile X-particles. The relic density of these particles is mainly determined (at fixed reheating temperature and inflaton mass) by mass $m_X$. SHDM can constitute all CDM observed in the universe, or be its subdominant component. The range of practical interest is given by masses $(3-10) \times 10^{13}$ GeV, at larger masses the SHDM is subdominant.

SHDM is accumulated in the Galactic halo with overdensity $\sim 10^5$. In many elementary-particle models SH particles can be quasi-stable with lifetime $\tau_X \gg 10^{10}$ yr. Such decaying particles produce UHECR with photons from the halo being the dominant component. The measured flux of these photons with corresponding signatures (anisotropy in the direction of Galactic Center and the muon-poor EAS) determines $\tau_X$ experimentally. Such precise determination of a parameter from experimental data has nothing to do with fine-tuning.
The energy spectrum of HE particles is now reliably calculated in the SUSY-QCD framework as $\sim \frac{dE}{E^2}$, there is an agreement between the calculations of different groups \cite{21, 22, 23}.

Neutrino flux from SHDM is given in Fig. 3 according to Refs. \cite{21, 24}. It is produced by decays of X-particles in extragalactic space, while UHECR signal is produced mainly by photons from X-particle decays in the Galactic halo.

E. Mirror matter

Mirror matter can be most powerful source of UHE neutrinos not limited by the usual cascade limit \cite{25}.

Existence of mirror matter is an interesting theoretical idea which was introduced by Lee and Yang (1956), Landau (1957) and most notably by Kobzarev, Okun and Pomeranchuk (1966) to have a space reflection operator $I_s$ commuting with Hamiltonian $[I_s, H] = 0$. The mirror particle space is generated by operator $I_s$, which transfers the left states of ordinary particles into right states of the mirror particles and vise versa. The mirror particles have interactions identical to the ordinary particles, but these two sectors interact with each other only gravitationally. Gravitational interaction mixes the visible and mirror neutrino states, and thus causes the oscillation between them.

A cosmological scenario must provide the suppression of the mirror matter and in particular the density of mirror neutrinos at the epoch of nucleosynthesis. It can be obtained in the two-inflaton model \cite{25}. The rolling of two inflaton to minimum of the potential is not synchronised, and when mirror inflaton reaches minimum, the ordinary inflaton continues its rolling, inflating thus the mirror matter produced by the mirror inflaton. While mirror matter is suppressed, the mirror topological defects can strongly dominate \cite{25}. Mirror TDs copiously produce mirror neutrinos with extremely high energies typical for TDs, and they are not accompanied by any visible particles. Therefore, the upper limits on HE mirror neutrinos in our world do not exist. All HE mirror particles produced by mirror TDs are sterile for us, interacting with ordinary matter only gravitationally, and only mirror neutrinos can be efficiently converted into ordinary ones due to oscillations. The only (weak) upper limit comes from the resonant interaction of converted neutrinos with DM neutrinos: $\nu + \bar{\nu}_{DM} \rightarrow Z^0$ \cite{25}.

In Fig. 4 UHE neutrino flux from mirror TDs is presented according to calculations \cite{18}. This model
provides the largest flux of superGZK neutrinos being not restricted by the standard cascade bound.

![FIG. 4: Diffuse neutrino flux from mirror necklaces](image)

V. CONCLUSIONS

The detectable fluxes of superGZK neutrinos ($E_\nu > 10^{20}$ eV) can be produced by accelerator and non-accelerator sources.

The accelerator sources need $E_{\text{max}} \gg 1 \times 10^{21}$ eV, which most probably implies the non-shock acceleration mechanisms.

The non-acceleration sources, topological defects and superheavy relic particles, involve physics beyond the Standard Model. Very high neutrino energies, in excess of the GUT scale, are possible for these sources. The fluxes are normally limited by the cascade bound. The largest flux (above the standard cascade bound) is predicted by the mirror matter model.

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