Limits to the UHE neutrino flux from Gamma-Ray Bursts with the Pierre Auger Observatory

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Abstract

The Surface Detector of the Pierre Auger Observatory is sensitive to UHE neutrinos through the observation of deeply initiated inclined down-going showers produced by neutrino interactions in the atmosphere. A method to search for neutrino candidates in the background of nucleonic showers based on the Fisher discriminant already exists and a blind scan of the data collected between 1 Nov 07 and 31 May 10 revealed no neutrino candidates, so that a limit to the diffuse flux of UHE neutrinos has been placed. Using the same set of data and identification criteria, in this note we constrain the UHE neutrino flux from Gamma-Ray Bursts.

1. Introduction

Ultra-High Energy neutrinos (UHEν) with energies above EeV are unique messengers of the most energetic processes occurring in the Universe [1], since they propagate through space practically without deflection or absorption.

Although the primary goal of the surface detector (SD) of the Pierre Auger Observatory [3, 4] is to detect Ultra-High Energy Cosmic Rays (UHECRs), UHEνs can also be identified. In principle the concept for identification of ν-induced showers in the much larger background of nucleonic-induced showers is rather simple: while protons, heavier nuclei and even photons interact shortly after entering the atmosphere, neutrinos can generate showers initiated deeply into the atmosphere. These deep and young showers can be distinguished because they generate broad signals in the water Cherenkov stations of the SD, that spread in time over hundreds of nano-seconds, while the signals induced by nucleonic showers typically have tens of nano-seconds in duration.

In previous works [5, 6] methods to select deep inclined showers induced by down-going neutrinos at the SD of the Pierre Auger Observatory were established. In particular, using data taken at the SD in the period from 1 January 2004 until 31 October 2007, a search was performed for neutrinos interacting in the atmosphere and inducing downward-going inclined showers with $75° < \theta < 90°$ (where θ is the zenith angle). For that purpose a blind scan was performed over the data collected in the period from 1

November 2007 until 31 May 2010. No events passed the cuts on a Fisher discriminant variable - which was constructed from the observables related to the spread in time of the signals in the earliest stations of the event, and optimized to separate neutrino candidates from background nucleonic showers. The probabilities of identifying neutrino-induced showers were obtained in Monte Carlo simulations as a function of time, neutrino flavour, neutrino energy E_ν, zenith angle θ, and neutrino interaction depth D. As a result a limit to the diffuse flux of UHEν (i.e. from an ensemble of unresolved sources) was produced [5, 6].

In this note we use the same identification probabilities and data period to place limits on the flux of UHEν from Gamma-Ray Bursts (GRBs) [2].

2. The GRB sample

We firstly obtained a list of the GRBs detected by gamma-ray satellite experiments occurring during the blind search period (1 Nov 07 - 31 May 10). This information was collected using the Gamma-Ray Burst On-line Index (GRBOX [7]), a compilation of different GRB catalogs including those from the SWIFT and Fermi satellites.

We then selected those GRBs with known arrival direction and time duration (T90), as this information is needed to compute the exposure of the SD during the occurrence of the GRB. Using the equatorial coordinates and times of the GRBs, we computed the GRB zenith angle θ as seen from the location of the SD. Since all GRBs in our sample last from T90 $\sim$0.1 s to $\sim$100 s, θ changes by much less than 1° during T90 and we assumed it to be constant. We then apply the following cuts to the GRBs in our sample:

- We select those GRBs with $\theta \in [75°, 90°]$, since down-going neutrino identification criteria were optimized for that angular range. The list of GRBs selected up to this point is shown in Table 1.
  Supongo que hoy en día habría que mirar en las tres ventanas DGL, DGH y ES
- We reject from the list in Table 1 those GRBs occuring during dead-time periods of the SD. These are indicated with shaded rows in Table 1, with the darker-shaded rows corresponding to GRBs occuring during the so-called "Comms. Crisis" period.
- A sub-class of GRBs known as X-Ray Flashes (XRF) have low-luminosities (typically smaller than the other GRBs), and it is unlikely that they can accelerate CRs up to $\sim 10^{18}$ eV and produce neutrinos above $\sim 10^{17}$ eV [14]. There are 2 XRF in the list of GRBs which are not used in this analysis marked with "XRF" in Table 1.
- In this work we only consider neutrinos produced in the prompt phase of the GRB, i.e. in internal shocks. The spectrum is composed of a series of power-law functions [8] with slopes and energy breaks determined by the shape of the $\gamma-$ray flux emitted by the GRB. An accurate calculation of the shape of the neutrino spectra for each of the selected GRBs would require a knowledge of the following parameters:

- the γ-ray luminosity which has been measured for all GRBs in our sample
- the redshift which has only been measured for a few GRBs in our sample
- the Lorentz factor of the boosted GRB jet, or the fraction of jet energy in electrons and magnetic field which have not been measured for any GRB in our sample.

When the value for a parameter was not available, an average value is used to estimate the shape of the spectrum as explained in the Appendix of [9]. When doing that we found that all GRBs follow a power-law shape that falls with energy as E^{-4} at energies above 10^{17} eV corresponding to the threshold for neutrino detection of the Pierre Auger Observatory. Hence, we assume an E^{-4} differential spectral shape for all GRBs in our sample in the whole energy range where the Auger Observatory is expected to be sensitive to neutrinos.

- An important step is to calculate the effective area of the SD to UHE neutrinos during the time-interval that neutrinos are expected to be produced according to GRB models. For this purpose, we used the available effective areas ($A_{\rm eff}$) that were produced for the down-going neutrino analysis [6]. To simplify the computationally intensive calculation, these $A_{\rm eff}$ were computed for a set of reference array configurations, assumed to be constant during periods of 3 days, and which correspond to a conservative estimate of the effective area of the array during that period. To avoid repeating this computationally intensive procedure for this analysis, for each GRB we used the effective area corresponding to the reference configuration of the 3-day period in which the GRB occurred. Using the T2-files we then computed the minimum number of active stations during the time-interval T90 at which the GRB occurs, and we checked whether the actual configuration of the array while the GRB was happening was the same or better (i.e. the same number of more active stations) than the reference configuration used. If this is the case, we select the GRB. Notice that, although we are being conservative, this requirement only rejects 4 GRB (see rows marked with asterisks in Table 1), while most of them are accepted (rows marked with an arrow). It is also important to note that 3 GRBs out of this 4 were already rejected by one of the other cuts above.

After this set of cuts we end up with a list of 43 GRBs that will be used in this analysis.

3. Models of UHE neutrino production in GRB

A few models of GRB origin and of UHE neutrino production in GRB exist. The most accepted one is the so-called fireball model, the prompt γ-rays are produced by synchrotron radiation and/or inverse Compton scattering of shocked-accelerated electrons in the internal collisions of a relativistic plasma along a jet (internal shocks). Later collisions of jetted material with the external medium (external shocks) produce lower energy X-rays, the so-called GRB afterglow [2]. Protons are also expected to be accelerated along with

GRB ID	DATE	TIME (UTC)	RA (deg)	DEC (deg)	T90 (s)	θ (deg)	MIN.N_{GRB}	N_{EXPO}	
100526B	2010/05/26	19:00:38	0.74	-37.91	64.00	75.60	1477	1441	←
100510A	2010/05/10	19:27:07	355.00	-18.87	31.00	84.06	1540	1505	←
100331A	2010/03/31	00:30:30	261.08	-58.95	15.00	78.20	1192	1071	←
100316D	2010/03/16	12:44:50	107.63	-56.25	240.00	87.98	1306	1348	* XRF
100225A	2010/02/25	02:45:31	310.30	-59.40	13.00	85.09	1567	1518	←
100116A	2010/01/16	21:31:00	305.02	14.45	110.00	79.09	1573	1543	←
091109B	2009/11/09	21:49:03	112.74	-54.09	0.19	89.54	1562	1478	←
091109A	2009/11/09	04:57:43	309.26	-44.16	48.00	75.15	1530	1478	←
090915	2009/09/15	15:35:36	238.02	15.49	8.00	89.83	1504	1468	←
090815C	2009/08/15	23:21:39	64.49	-65.94	0.60	78.58	1303	1234	
090727B	2009/07/27	23:32:29	343.36	-46.70	25.00	78.46	1406	1336	←
090717A	2009/07/17	00:49:32	86.75	-64.20	70.00	77.84	1454	1391	←
090706	2009/07/06	06:47:40	205.00	-47.10	100.00	77.60	1486	1385	←
090626	2009/06/26	04:32:09	169.25	-36.10	70.00	79.62	1459	1388	←
090625	2009/06/25	05:37:00	20.25	-6.40	51.00	87.51	1468	1404	←
090621C	2009/06/21	10:00:52	257.50	-28.47	59.90	76.50	1400	1400	←
090608	2009/06/08	01:15:27	100.25	-37.42	61.00	80.07	1474	1388	
090530	2009/05/30	03:18:18	179.42	26.59	48.00	77.37	1246	0	
090528B	2009/05/28	12:22:31	312.25	32.70	102.00	83.00	548	0	
090528A	2009/05/28	04:09:01	135.00	-35.80	68.00	79.71	1306	0	
090518	2009/05/18	01:54:44	119.95	0.76	6.90	78.78	700	0	
090515	2009/05/15	04:45:09	164.15	14.44	0.04	83.71	1380	0	
090429A	2009/04/29	04:53:39	90.56	-52.39	188.00	82.37	1349	0	
090427A	2009/04/27	23:26:27	235.93	-13.50	15.00	87.95	1509	0	
090418A	2009/04/18	11:07:40	269.31	33.41	56.00	76.39	1320	0	
090327	2009/03/27	09:41:42	29.50	-41.60	24.00	89.46	1568	1566	←
090324	2009/03/24	02:48:09	42.04	-48.15	30.00	77.15	1580	1550	←
090320A	2009/03/20	10:01:46	242.50	51.90	10.00	88.64	1422	1560	*
090307A	2009/03/07	03:46:37	244.99	-28.63	22.00	75.58	1577	1570	←
090222	2009/02/22	04:17:10	120.25	43.40	18.00	82.69	1573	1561	←
090202	2009/02/02	08:19:30	269.00	-2.50	66.00	80.78	1388	1386	←
090201	2009/02/01	17:47:02	92.05	-46.59	83.00	82.93	1392	1390	←
090129	2009/01/29	21:07:15	269.10	-32.79	17.50	84.07	1579	1548	←
090117B	2009/01/17	08:02:02	233.00	27.60	27.00	87.67	1570	1560	←
081223	2008/12/23	10:03:57	116.75	33.50	0.89	87.48	1578	1574	←
081221	2008/12/21	16:21:11	15.79	-24.55	34.00	89.92	1584	1578	←
081203B	2008/12/03	13:51:32	228.80	44.43	23.40	81.40	1588	1580	←
081126	2008/11/26	21:34:10	323.51	48.71	54.00	84.22	1596	1551	←
081121	2008/11/21	20:35:32	89.28	-60.60	14.00	80.45	1589	1589	←
081118A	2008/11/18	14:56:36	82.59	-43.30	67.00	89.29	0	1427	
081109B	2008/11/09	13:47:16	350.13	-55.91	100.00	87.50	1235	1603	*
081105B	2008/11/05	14:43:51	215.75	42.80	0.18	80.09	1594	1586	←
081016B	2008/10/16	19:47:14	14.56	-43.53	2.60	84.54	1592	1536	←
080927	2008/09/27	11:30:32	57.75	30.00	25.00	82.01	1592	1589	←
080916C	2008/09/16	00:12:45	119.85	-56.64	66.00	87.47	1578	1576	←
080822A	2008/08/22	12:41:59	75.28	45.28	0.10	82.27	1581	1570	←
080727B	2008/07/27	08:13:24	276.86	1.16	8.60	84.88	1561	1525	←
080725	2008/07/25	10:26:14	121.72	-13.99	120.00	82.45	1560	1525	←
080707	2008/07/07	08:27:53	32.62	33.11	27.10	82.48	1555	1554	←
080605	2008/06/05	23:47:57	262.13	4.02	20.00	83.73	1504	1449	←
080604	2008/06/04	07:27:01	236.97	20.56	82.00	79.05	1497	1449	←
080520	2008/05/20	22:20:24	280.19	-54.99	2.80	81.71	1506	1505	* XRF
080517	2008/05/17	21:22:51	102.24	50.74	64.60	89.07	1514	1508	←
080413A	2008/04/13	02:54:19	287.30	-27.68	46.00	89.39	1487	1483	←
080319A	2008/03/19	05:45:42	206.33	44.08	64.00	80.27	1451	1449	←
080315	2008/03/15	02:25:01	155.12	41.70	64.00	78.36	1328	1273	←
080212	2008/02/12	17:34:33	231.15	-22.74	123.00	88.75	1424	1416	←
080210	2008/02/10	07:50:05	251.27	13.83	45.00	77.25	0	751	
080120	2008/01/20	17:28:30	225.26	-10.87	20.00	81.57	1436	1428	←

Table 1: list of GRBs (obtained from GRBOX [7] and sorted in time) with known arrival direction (RA, DEC) and time duration (T90) detected by satellites during the period in which we blindly searched for neutrinos in the SD data (1 Nov 07 - 31 May 10), and having zenith angle θ as seen from the SD of the Pierre auger Observatory $\theta \in [75°, 90°]$. The shaded rows correspond to GRBs occuring during bad periods and not used, with those rows in darker gray indicating the GRBs occuring during the so-called "Comms. Crisis" period. Two GRBs classified as X-Ray Flashes (XRF) are not used due to their low luminosities which make them unlikely candidates of UHE neutrino production. In the column labeled "MIN.N_{GRB}" we give the minimum number of active stations during the whole duration of the GRB. In the column "N_{EXPO}" we give the number of stations used for the exposure already calculated in previous analysis (see text for more details). The arrows indicate the selected GRBs after applying the cut MIN.$N_{GRB} \geq N_{EXPO}$. Those GRBs not passing this cut are labeled with asterisks. We use 43 GRBs in this analysis.

electrons in the shocks. High energy neutrinos would then be produced by photonuclear ($p\gamma$) interactions of protons with observed prompt γ-rays as well as with afterglow photons.

4. Method: Limits to the neutrino fluence

4.1. Limits to individual GRBs

In the same way as in [6] we compute the effective area defined as the integral of the efficiency ε over core position $\vec{r}$:

$$A_{\mathrm{i,eff}}(E_\nu, \theta(t), D, t) = \int \varepsilon_i(\vec{r}, E_\nu, \theta(t), D, t)\,\mathrm{d}A \tag{1}$$

where D is the neutrino injection depth (in g cm^{-2}) measured in slanted from ground, $\theta(t)$ is the zenith angle of the GRB as seen from the SD array, which in general depends on time t and the GRB position in the sky. Since GRBs typically last a time T90$<$ 200 s, we will assume that $\theta(t)$ does not change in T90, i.e. all the neutrino flux emitted during T90 would arrive at the SD with the same zenith angle equal to θ_{GRB}.

A combined exposure can be easily obtained by integrating in time over T90, and injection depth D.

$$\mathcal{E}_{\mathrm{GRB}}(E_\nu) = \frac{1}{m}\sum_i \left[\omega_i\,\sigma_i(E_\nu)\cos\theta_{\mathrm{GRB}} \iint A_{\mathrm{i,eff}}(E_\nu, \theta_{\mathrm{GRB}}, D, t)\,\mathrm{d}D\,\mathrm{d}t\right] \tag{2}$$

Note that the only GRBs contributing are those that are visible from the SD with $75^\circ < \theta_{\mathrm{GRB}} < 90^\circ$.

The sum in Eq.(2) runs over the 3 neutrino flavours (with relative wight ω_i) and the CC and NC interactions; m is the mass of a nucleon. Here we assume a full $\nu_\tau \leftrightarrow \nu_\mu$ mixing, leading to $\omega_i = 1$ for the three flavours. The possibility that the ν_τ interacts in the mountains surrounding the Pierre Auger Observatory is not accounted for in the calculation of the exposure.

Using the exposure $\mathcal{E}(E_\nu, \delta)$ in Eq. (2), the total expected number of events within an energy range can be obtained for a flux of UHEν from a GRB $\Phi_{\mathrm{GRB}}(E_\nu)$ (per unit energy, area and time) by integrating over energy:

$$\mathcal{N}_{\mathrm{GRB}} = \int_{E_{\mathrm{min}}}^{E_{\mathrm{max}}} \Phi(E_\nu)\,\mathcal{E}_{\mathrm{GRB}}(E_\nu)\,\mathrm{d}E_\nu \tag{3}$$

Before $\mathcal{N}_{\mathrm{GRB}}$ can be computed, a functional form for the ν flux $\Phi(E_\nu)$ has to be assumed. As explained above, assuming $\Phi_{\mathrm{GRB}}(E_\nu) = k_{\mathrm{GRB}} \cdot E_\nu^{-4}$ and a 1:1:1 flavour ratio, we can obtain an integrated limit at 90% CL on the value of k_{GRB} in a Feldman-Cousins [10] approach ($\mathcal{N} = 2.44$ for a background of 0 events) as:

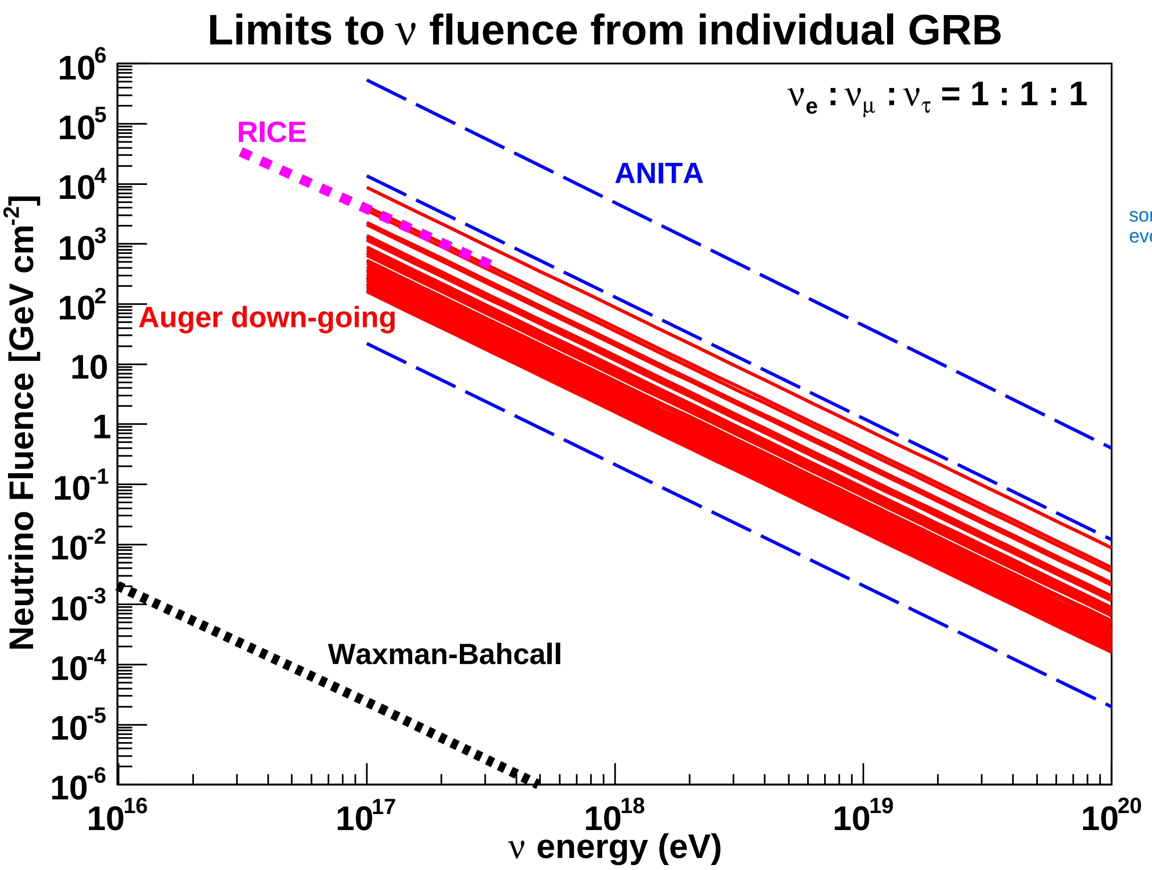
$$k_{\mathrm{GRB}} = \frac{2.44}{\int_{E_{\mathrm{min}}}^{E_{\mathrm{max}}} E_\nu^{-4}\,\mathcal{E}_{\mathrm{GRB}}(E_\nu)\,\mathrm{d}E_\nu} \tag{4}$$

It is conventional in the literature [11, 13, 14] to place limits on the fluence $\mathcal{F}_{GRB}$ defined as the energy emitted in neutrinos per unit area which can be easily obtained from the flux simply doing:

$$\mathcal{F}_{GRB} = E_\nu^2\ \mathrm{T90}\ k_{\mathrm{GRB}}\ E_\nu^{-4} \tag{5}$$

k*E^-4 tiene unidades de neutrinos/(tiempo * energia * m^2) , luego por E^2 pasa a tener energia/tiempo,de ahí que Fluence tiene unidades de energía / m^2

In Fig. 1 we plot the limits to neutrino fluence as obtained for the 43 GRBs used in this analysis (Auger down-going). We also show the 3 best limits obtained for the 12 GRBs in the field of view of ANITA-II [13], as well as the best limit to the 5 GRBs considered by the RICE experiment [14]. A theoretical model of neutrino production in GRBs [15] is also plotted.



son los límites para todos los eventos?

Figure 1: Auger limits to neutrino fluence from the 43 individual GRBs selected in this analysis. We have assumed a differential down-going neutrino flux decreasing with energy as E^{-4} for the 43 GRBs in the energy range $10^{17} - 10^{20}$ eV (see text for more details). The limits are based on no neutrino candidates found during the search period from 1 Nov 07 until 31 May 10. Also shown are the 3 best limits obtained for the GRBs in the ANITA-II field of view in 2009 [13], as well as the best limit to the GRBs in the field of view of the RICE experiment in 2005 [14]. The theoretical fluence expected from the Waxman-Bahcall [15] fireball model is also plotted. In all cases we plot the limits to single neutrino flavour fluences.

4.2. Stacking (aggregate) limits

We can also place stacking (aggregate) limits to the neutrino fluence by considering all the GRBs in our sample. The total expected event rate from the 43 GRBs with $75^\circ < \theta_{\rm GRB} < 90^\circ$ is given by

$$\mathcal{N}^{\rm tot}_{\rm GRB} = \sum_{\rm GRB} \mathcal{N}_{\rm GRB} = \sum_{\rm GRB} \int_{E_{\rm min}}^{E_{\rm max}} k_{\rm GRB} \cdot E_\nu^{-4}\, \mathcal{E}_{\rm GRB}(E_\nu)\, {\rm d}E_\nu \tag{6}$$

where we have assumed that all GRBs contributing to the total event rate have the same functional dependence for the neutrino flux. The stacked limit is then given by:

$$k_{\mathrm{GRB}}^{\mathrm{stack}} = \frac{2.44}{\sum_{\mathrm{GRB}} \int_{E_{\min}}^{E_{\max}} k_{\mathrm{GRB}} \cdot E_\nu^{-4}\, \mathcal{E}_{\mathrm{GRB}}(E_\nu)\, \mathrm{d}E_\nu} \tag{7}$$

A corresponding fluence $\mathcal{F}_{\mathrm{GRB}}^{\mathrm{stack}}$ can be obtained from $k_{\mathrm{GRB}}^{\mathrm{stack}}$ using Eq. (5). This is shown in Fig. 2 along with the stacking limit obtained with the 5 GRBs considered by the RICE experiment [14], as well as the corresponding limit obtained with the 215 GRBs in the field of view of IceCube [12]. A theoretical model of neutrino production in GRBs [15] scaled to 43 and 215 GRBs is also shown. A corresponding aggregate ANITA-II limit has not been published, but as explained in [13] it should be close to the best limit to individual GRBs shown in Fig. 1, and very close to our aggregate limit.

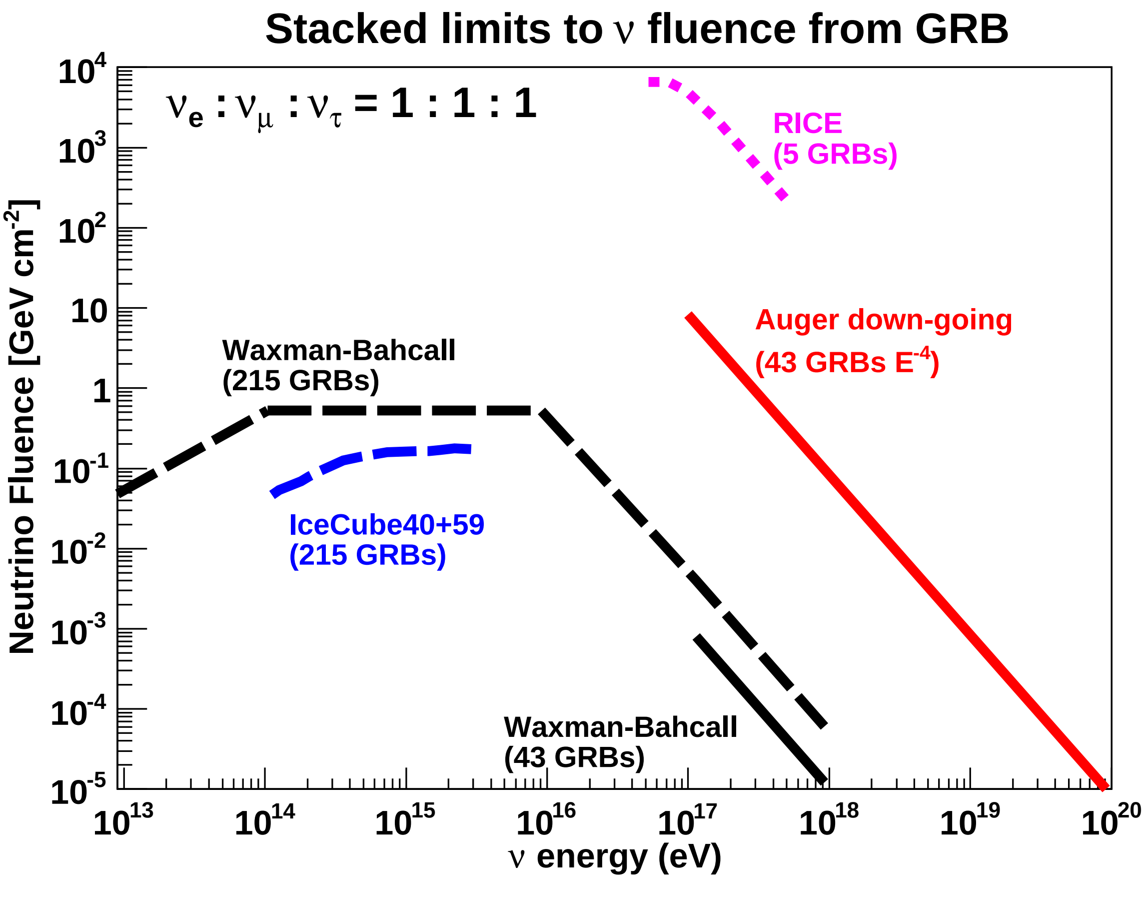


Figure 2: Auger stacked (aggregate) limits to neutrino fluence from the 43 GRBs in our sample, assuming an E^{-4} differential down-going neutrino flux for all the GRBs $10^{17} - 10^{20}$ eV. The limits are based on no neutrino candidates found during the search period, from 1 Nov 07 until 31 May 10. Also shown are the stacked limits obtained by IceCube [12] with 215 GRBs in its field of view, and RICE [14] with 5 GRBs. The theoretical neutrino fluence expected from 43 and 215 GRBs each of them described by the Waxman-Bahcall model [15] is also plotted. In all cases we have plotted the limits to single neutrino flavours.

5. Conclusions

In this note we have used the same identification criteria and blind period as in the search for downward-going neutrinos with the SD of the Pierre Auger Observatory [6] to place stringent limits on the fluence of UHEν from Gamma-Ray Bursts (GRBs) in the EeV energy range. We have identified 43 GRBs in the field of view of the Auger experiment during the blind search period 1 Nov 07 - 31 May 10, and we have placed limits to the neutrino fluence from each indvidual GRB as well as on the stacked (aggregate) fluence. Our individual limits are more stringent than those of RICE and those of ANITA-II except for 1 GRB in the ANITA sample. The stacked limits are more than 2 orders of magnitude better than that of RICE, and at the same level of the aggregate ANITA-II limit which should be dominated by their best individual limit. Also our limits are complementary to those placed with the IceCube experiment that typically apply at PeV energies. The expected fluence based on standard models of UHE neutrino production in GRBs is too low to expect a detection.

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