Neutrinos from GRBs in the Fermi Era

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Abstract. We investigate the consequences of the redshift distribution of gamma-ray bursts on diffuse gamma-ray burst neutrino fluxes using a Monte Carlo simulation. We determine the systematic error introduced by the extrapolation from small samples to the quasi-diffuse flux. In addition, we reanalyze the computation of neutrino spectra from photon spectra measured for example by the Fermi Gamma-Ray Burst Monitor.

1. Introduction
Gamma-ray bursts (GRBs) are one of the most violent events in the universe. If a substantial amount of the energy of the GRB is stored in accelerated protons, a neutrino flux from photohadronic pion production is expected. Typically this interaction is described in the Δ-resonance approximation

\[ p + \gamma \rightarrow p + \pi^0 \quad \text{or} \quad n + \pi^+. \]  

The produced charged pions decay into muons and muon neutrinos. The muons subsequently decay into electron, electron neutrino and muon neutrino. Note that we do not distinguish between particles and antiparticles since for the neutrino flux, antineutrinos and neutrinos are summed over. The typical photon spectrum of a GRB can be fitted by a Band function [1] and approximated by a broken power law with index \( \alpha \) below the break and \( \beta \) above. For the proton spectrum usually an \( E^{-2} \) spectrum is assumed. The subsequent muon neutrino spectrum is then of the form

\[ \phi_{\mu}(E_\nu) \propto \begin{cases} \left( \frac{E_\nu}{E_{\nu,\text{break}}} \right)^{-\alpha_\nu} & \text{for } E_\nu < E_{\nu,\text{break}} \\ \left( \frac{E_\nu}{E_{\nu,\text{break}}} \right)^{-\beta_\nu} & \text{for } E_{\nu,\text{break}} \leq E_\nu < E_{\nu,\text{cool}} \\ \left( \frac{E_\nu}{E_{\nu,\text{break}}} \right)^{-\beta_\nu} \left( \frac{E_\nu}{E_{\nu,\text{cool}}} \right)^{-2} & \text{for } E_\nu \geq E_{\nu,\text{cool}} \end{cases} \]  

with \( E_{\nu,\text{break}} \) determined from the photon break energy and \( E_{\nu,\text{cool}} \) from the cooling of the secondaries by synchrotron radiation. In some works the cooling break of the pions is considered whereas in others the one of muons, see for example [2] for pions and [3] for muons. The indices of the neutrino spectrum are given by \( \alpha_\nu = 3 - \beta \) and \( \beta_\nu = 3 - \alpha \) for an \( E^{-2} \) proton spectrum.

2. Neutrino Production with NeuCosmA
For this work we use our code NeuCosmA which simulates neutrino fluxes from cosmic accelerators in a steady state approach. The included photohadronic interactions are taken from
[4] including resonant production, direct channels, multi pion production, and kaon and neutron production, based on SOPHIA [5]. Since statistics in neutrino observations are expected to be low, it is not required to consider a time-dependent approach. Therefore we use the steady state approach in which energy losses of the secondaries due to synchrotron radiation are included. The decays are taken from [6] and account for the helicity dependence of muon decays. Finally we account for flavor mixing and obtain the contribution of the different flavors to the spectrum at Earth. As shown in [7] the additional processes in the photohadronic interactions, direct and multi pion as well as Kaon production, the synchrotron cooling, and the flavor mixing lead to an enhancement of the neutrino spectrum and a typical multi-peak structure.

3. Aggregated Neutrino Fluxes from GRBs

Since one expects only low statistics for a single burst typically aggregated neutrino fluxes are considered. In this section we discuss the effect of parameter distributions on the aggregation of bursts. For this we use a Monte Carlo method to compute the neutrino flux on a burst-by-burst basis and sample over an input parameter distribution. We only consider the relative normalizations and normalize the aggregated flux to the Waxman-Bahcall (WB) limit [8, 9]. We sample over 10000 bursts representing 10 years of IceCube measurement with 1000 bursts per year. We use different distributions for several parameter as the magnetic field, the Lorentz factor and the parameter defining the photon spectrum, see [10], but here we only discuss the effect of the redshift distribution.

Since long GRBs are associated to core collapse supernovae, it is a good approximation to assume that the redshift distribution follows the star formation rate. We use the rate given by Hopkins and Beacom in [11] with a correction factor by Kistler et al. [12] to account for the fraction of stars resulting in a GRB. We then pick 10000 $z$ with the probability determined by the redshift distribution and compute the corresponding neutrino spectra, sum them up, and normalize them to the WB limit. Since all other parameter are fixed to the same value for all bursts the flux $E^2\phi_\nu$ of a single burst scales with $d_L^{-2}(z)$, where $d_L(z)$ is the luminosity distance. In figure 1 we show the analytic redshift distribution as a dashed curve and the redshift distribution of the used sample of 10000 bursts as histogram. In addition we show the shape of the relative contribution of individual bursts to the total flux as a function of the redshift which is the redshift distribution multiplied by $d_L^{-2}(z)$ as the solid curve (without scale). We see that although most GRBs are expected at redshifts of $z \approx 2 - 3$, the main contribution to the aggregated flux is from bursts with $z \approx 1$. This means that few bursts with smaller redshift typically dominate the neutrino flux. Therefore the common assumption $z \approx 2$ as for example used in [3, 13] easily leads to an overestimation of the neutrino flux when calculating back from the observed photon spectrum. Another implication are fluctuations in the quasi-diffuse flux for

"Figure 1. Distribution of 10000 bursts $d\bar{N}/dz$ as a function of redshift (histogram), the exact distribution function based on the star formation rate from Hopkins and Beacom [11] with the correction from Kistler et al. [12] (dashed curve) and the shape of the relative contribution of the individual GRBs $d_L^{-2} d\bar{N}/dz$ (solid curve, without scale)."
Table 1. Probability to be within 20% of diffuse limit and level of systematic error at 90% CL for three sample sizes. This table is adapted from [10].

| Sample size | 100 | 300 | 1000 |
|-------------|-----|-----|------|
| Probability to be within 20% of diffuse limit | 37% | 50% | 69% |
| Level of systematic error at 90% CL | ±50% | ±35% | ±25% |

small samples. To quantify these fluctuations we compute the energy flux density in the quasi-diffuse flux of the small sample and compare it to the energy flux density in the high statistics or diffuse limit. From the computation of 100,000 samples of one sample size we can determine the probability to obtain an energy flux density of a diffuse flux from a specific sample size which is within 20% of the diffuse limit. For 10 years of IceCube (≈ 10,000 bursts) the probability is 97%. This means that 10,000 bursts is a good approximation for the diffuse limit. The probabilities for the sample sizes: 100, 300 and 1000 bursts are shown in the upper row of table 1. In the lower row the systematic error at 90% CL is shown. This error characterizes the range in the energy flux density of the quasi-diffuse flux in which 90% of all 100,000 cases of a specific sample size are found. We see that for a sample size of 100 bursts, as for example used in recent IceCube analysis [13], the systematic error is of the order of ±50%.

4. Comparison of Calculation Methods
In this last section we discuss the expected neutrino spectrum for GRB091024 computed from the photon spectrum measured by the Fermi Gamma-Ray Burst Monitor (GBM). We compare the results of four models, all based on the fireball phenomenology. We call the first model the conventional fireball model (CFB). It is the model used in the IceCube analyses described in appendix A of [3], based on [2, 14]. An $E^{-2}$ proton spectrum interacts with a power law photon spectrum to produce pions via the $\Delta$-resonance. The exact photon spectrum is determined by the measured photon spectrum of the burst. The neutrino spectrum, coming from the decay of the pions and subsequently muons is assumed to have two breaks. The first coming from the break in the photon spectrum and the second from the break in the muon spectrum due to synchrotron losses. The normalization of the neutrino spectrum is determined by assuming that a constant fraction of the energy in the proton spectrum goes into neutrinos. The second and third model is model FB-D of [10]. The photon and the proton spectrum in the source are computed in the fireball framework from the measured photon spectrum. The photohadronic interactions, the decays and the flavor mixing is calculated with NeuCosmA. The difference between the second and the third model is the usage of full photohadronics (second), meaning additional pion and kaon modes to the $\Delta$ resonance, or the WB $\Delta$-resonance (third). The fourth model (RFB) is an analytical version of the third model, to determine the origin of the huge differences between the CFB and the numerical results. In figure 2 we show the predicted neutrino spectrum for GRB091024 calculated with the four different models. We see that in contrary to the CFB the RFB has three breaks. One from the break in the photon spectrum, one from the cooling break of the muons, and the third from the cooling break of the pions which is neglected in the CFB. The first break is at slightly higher energies in the RFB because the pion production efficiency peaks at higher center-of-mass energies than the threshold for heads-on collisions, see figure 4 in [4]. The cooling break is a function of the variability time in the fireball model, see Eq. (A5) in [3]. In this reference the cosmic time dilation of the variability time is neglected such that the cooling break is at larger energies in the CFB than in the RFB. The normalization of the CFB is more than one order of magnitude higher than in the RFB.
This is coming from several approximations made in [14, 3] as for example neglecting the energy dependence of the mean free path of the protons, the energy dependence of the photons, and the width of the \( \Delta \)-resonance, for details see [15, 16]. The numerical results based on the WB \( \Delta \)-approximation nicely match the results of the RFB. The results of the numerical model with full photohadronics is larger due to the additional production modes, see [7] for comparison, but still one order of magnitude below the CFB.

5. Summary

We have shown the effect of the parameter distribution on the quasi-diffuse neutrino flux for 10,000 bursts at the example of the redshift distribution. We have seen that not the most frequent bursts with \( z \approx 2 \)–3 contribute most but bursts with \( z \approx 1 \). In addition we have shown that low statistics as for example for a sample of 100 bursts lead to large uncertainties in the extrapolated quasi-diffuse flux. Additional uncertainties of other astrophysical parameters lead to even larger uncertainties in the quasi-diffuse flux. Finally we have seen that the normalization of the neutrino spectrum computed from the measured fluence of a burst based on [3] overestimates the neutrino flux by up to one order of magnitude.

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