# Neutrinos of Energy $\sim 10^{16}$ eV from Gamma-Ray Bursts in Pulsar Wind Bubbles

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The supranova model for $\gamma$-ray bursts (GRBs) is becoming increasingly more popular. In this scenario the GRB occurs weeks to years after a supernova explosion, and is located inside a pulsar wind bubble (PWB). Protons accelerated in the internal shocks that emit the GRB may interact with the external PWB photons producing pions which decay into $\sim 10^{16}$ eV neutrinos. A km$^2$ neutrino detector would observe several events per year correlated with the GRBs.

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The leading models for gamma-ray bursts (GRBs) involve a relativistic outflow emanating from a compact central source. The ultimate energy source is rapid accretion onto a newly formed stellar mass black hole. Long duration ($\gtrsim 2$ s) GRBs, which include all GRBs with observed afterglow emission and $\sim 2/3$ of all GRBs, are widely assumed to originate from a massive star progenitor. This is supported by growing evidence for GRBs occurring in star forming regions within their host galaxies [1]. The leading model for long duration GRBs is the collapsar model [2], where a massive star promptly collapses into a black hole and forms a relativistic jet that penetrates through the stellar envelope and produces the GRB. An interesting alternative (though somewhat more debated) model is the supranova model [3], where a supernova explosion leaves behind a supramassive neutron star (SMNS), of mass $\sim 2.5$–$3M_\odot$, which loses its rotational energy on a time scale, $t_{\rm sd} \sim$ weeks to years, and collapses to a black hole, triggering the GRB. The most natural mechanism by which the SMNS can lose its rotational energy is through a strong pulsar-type wind, which is expected to create a pulsar wind bubble (PWB) [4,5].

The prompt $\gamma$-ray emission in GRBs is believed to arise from internal shocks within the relativistic outflow, of average isotropic luminosity $L \sim 10^{52}$ erg/s, that form due to variability in its Lorentz factor, $\Gamma$, on a time scale $t_v$. These shocks accelerate electrons to relativistic random velocities, which then emit synchrotron (and perhaps also synchrotron self-Compton) radiation, that constitute the observed $\gamma$-ray emission. In the region where electrons are accelerated, protons are also expected to be shock accelerated: the conditions in the dissipation region allow proton acceleration up to $\varepsilon_{p,\max} \sim 10^{20}$ eV [6].

In this Letter we consider the neutrino production in GRBs that occurs inside PWBs, as is expected in the supranova model for GRBs. The neutrino production via photomeson interactions between the relativistic protons accelerated in the internal shocks and the synchrotron photons that are emitted in these shocks has already been calculated [7], while $p$-$p$ collisions were shown to be relatively unimportant. Therefore, we focus on neutrino production through photomeson interactions with the external photons from the rich radiation field inside the PWB. This process turns out to be dominant for a wide range of parameters: $t_{\rm sd} \lesssim 0.2$ yr for a typical GRB, and $t_{\rm sd} \lesssim 2$ yr for x-ray flashes. The neutrinos produced via this mechanism have energies $\varepsilon_\nu \sim 10^{15}$–$10^{17}$ ($10^{19}$) eV for typical GRBs (x-ray flashes) and are emitted simultaneously with the prompt $\gamma$-ray (x-ray) emission. Their energy spectrum consists of several power law segments, and its overall shape depends on the model parameters. For $t_{\rm sd} \lesssim 0.1$ yr, the $\nu$'s would not be accompanied by a detectable GRB. We find that the $\sim 10^{16}$ eV neutrino fluence from a GRB at $z \sim 0.1$–$1$ implies $\sim 0.01$–$1$ upward moving muons in a km$^2$ detector simultaneous with the $\gamma$ rays. The neutrino signal from an individual GRB that is pointed towards us, and is therefore detectable in $\gamma$ rays, is above the atmospheric neutrino background.

Recently, [8] calculated the neutrino emission in the supranova model from protons that escape the internal shocks region and produce pions inside the supernova remnant (SNR).

*Neutrino production in the GRB.*—The internal shocks in GRBs are believed to be mildly relativistic. Therefore, the proton energy distribution should be close to that for Fermi acceleration in a Newtonian shock, $dn_p/d\varepsilon_p \propto \varepsilon_p^{-2}$. Moreover, the power law index of the electron and proton energy spectra should be the same, and the values inferred for the electrons (from the GRB spectrum) are $dn_e/d\varepsilon_e \propto \varepsilon_e^{-p}$ with $p \sim 2$–$2.5$. We therefore adopt $dn_p/d\varepsilon_p \propto \varepsilon_p^{-2}$. Primed (unprimed) quantities are measured in the comoving (laboratory) frame. Protons of energy $\varepsilon_p$ interact mostly with photons that satisfy the $\Delta$ resonance condition, $\varepsilon_{p,\Delta} = 0.3\,{\rm GeV}^2/\varepsilon_\gamma$. The minimal photon energy relevant for $p\gamma$ interactions is $\varepsilon_{\gamma,\min} = 0.3\,{\rm GeV}^2/\varepsilon_{p,\max} \sim 3 \times 10^{-3}$ eV. For reasonable parameters [$t_{{\rm sd},-1} = t_{\rm sd}/(0.1\,{\rm yr}) \gtrsim 0.26$] this falls above the self-absorption frequency [5], and the relevant part of the PWB spectrum consists of two power laws: $dn_\gamma/d\varepsilon_\gamma \propto \varepsilon_\gamma^{-3/2}$ for $\varepsilon_\gamma < \varepsilon_{\gamma b} = h\nu_{bm}$ and $\propto \varepsilon_\gamma^{-s/2-1}$ for $\varepsilon_\gamma > \varepsilon_{\gamma b}$, where $\nu_{bm} \approx 1.6 \times 10^{15} t_{sd,-1}^{-3/2}$ Hz is the peak frequency of the PWB $\nu F_\nu$ spectrum, $n_\gamma$ is the photon number density, and $s \approx 2.2$ is the power law index of the PWB electrons. Photons of energy $\varepsilon_{\gamma b}$ satisfy the $\Delta$ resonance condition with protons of energy

$$\varepsilon_{pb} = 4.4 \times 10^{16} \frac{\xi_{e/3}^2 \beta_{b,-1}^{3/2} t_{\mathrm{sd},-1}^{3/2}}{\eta_{2/3}^{5/2} \epsilon_{be/3}^2 \epsilon_{bB,-3}^{1/2} E_{53}^{1/2} \gamma_{4.5}^2} \ \mathrm{eV}, \quad (1)$$

where $\beta_b c = 0.1\beta_{b,-1} c$ is the velocity of the SNR shell, $\gamma_w = 10^{4.5}\gamma_{4.5}$ and $E_{\mathrm{rot}} = 10^{53} E_{53}$ erg are the Lorentz factor and total energy of the pulsar wind, respectively, $\xi_e = \xi_{e/3}/3$ ($\eta = \eta_{2/3} 2/3$) is the fraction of the wind energy in $e^\pm$ pairs (protons), and $\epsilon_{be} = \epsilon_{be/3}/3$ ($\epsilon_{bB} = 10^{-3}\epsilon_{bB,-3}$) is the fraction of PWB energy in electrons (magnetic field). The corresponding neutrino energy is $\varepsilon_{\nu b} \approx \varepsilon_{pb}/20 \sim 2 \times 10^{15} t_{\mathrm{sd},-1}^{3/2}$ eV, similar to that expected from the $p\gamma$ interactions with GRB photons [7], for $t_{\mathrm{sd}} \sim 0.1$ yr. The GRB emission can be detected simultaneously with these $\nu$'s only if the Thompson optical depth is $\lesssim 1$, which can be obtained for $t_{\mathrm{sd}} \sim 0.1$ yr only if the SNR shell is clumpy [5]. For a uniform shell we need $t_{\mathrm{sd}} \gtrsim 0.4$ yr, and in turn $\varepsilon_{\nu b} \gtrsim 2 \times 10^{16}$ eV.

The internal shocks occur over a distance $\Delta R \sim R = 2\Gamma^2 c t_v$. Thus, the optical depth to photopion production at the $\Delta$ resonance, for protons of energy $\varepsilon_p$, is

$$\tau_{p\gamma} = \sigma_{p\gamma} \varepsilon_\gamma \frac{dn_\gamma}{d\varepsilon_\gamma} R = \frac{\xi_{e/3}^3 E_{53}^{1/2} \Gamma_{2.5}^2 t_{v,-2} (\varepsilon_p/\varepsilon_{pb})^\beta}{f_{1/3}^2 \eta_{2/3}^{5/2} \epsilon_{be/3}^{5/2} \gamma_{4.5}^2 \beta_{b,-1}^{1/2} t_{\mathrm{sd},-1}^{3/2}}, \quad (2)$$

where $\Gamma_{2.5} = \Gamma/10^{2.5}$, $t_v = 10^{-2} t_{v,-2}$ s, $\sigma_{p\gamma} \approx 0.5$ mb, $\varepsilon_\gamma = 0.3\,\mathrm{Gev}^2/\varepsilon_p$, $f = f_{1/3}/3$ is the fractional PWB radius up to which most of its radiation is emitted, and $\beta = s/2$ ($1/2$) for $\varepsilon_p < \varepsilon_{pb}$ ($\varepsilon_p > \varepsilon_{pb}$) is the spectral slope of the seed PWB synchrotron photons. The fraction of the proton energy that is lost to pion production is [9]

$$f_{p\pi}(\varepsilon_p) \approx 1 - e^{-\tau_{p\gamma}(\varepsilon_p)/5} \approx \min[1, \tau_{p\gamma}(\varepsilon_p)/5]. \quad (3)$$

The factor 5 is since the proton loses $\sim$0.2 of its energy in a single interaction. We denote $\varepsilon_p$ for which $f_{p\pi}(\varepsilon_p) \approx 1$ by $\varepsilon_{p\tau} = 10^{18} \varepsilon_{p\tau 18}$ eV [i.e., $\tau_{p\gamma}(\varepsilon_{p\tau}) \equiv 5$], and obtain

$$\varepsilon_{p\tau 18} = \begin{cases} \dfrac{0.20 f_{1/3}^{20/11} \eta_{2/3}^{25/11} \epsilon_{be/3}^{3/11} \beta_{b,-1}^{43/22} t_{\mathrm{sd},-1}^{63/22}}{\xi_{e/3}^{8/11} \epsilon_{bB,-3}^{1/2} E_{53}^{21/22} \gamma_{4.5}^{2/11} \Gamma_{2.5}^{20/11} t_{v,-2}^{10/11}}, & \dfrac{\varepsilon_{p\tau}}{\varepsilon_{pb}} < 1, \\ \dfrac{1.2 f_{1/3}^4 \eta_{2/3}^{5/2} \epsilon_{be/3}^3 \gamma_{4.5}^2 \beta_{b,-1}^{5/2} t_{\mathrm{sd},-1}^{9/2}}{\xi_{e/3}^4 \epsilon_{bB,-3}^{1/2} E_{53}^{3/2} \Gamma_{2.5}^4 t_{v,-2}^2}, & \dfrac{\varepsilon_{p\tau}}{\varepsilon_{pb}} > 1, \end{cases} \quad (4)$$

The decay of charged pions created in interactions between PWB photons and GRB protons produces high energy $\nu$'s, $\pi^+ \to \mu^+ + \nu_\mu \to e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$, where each neutrino receives $\sim$5% of the proton energy.

The energy of the protons accelerated in the internal shocks of GRBs is expected to be similar to the $\gamma$-ray energy output in the GRB [6]. This implies a $\nu_\mu$ fluence,

$$f_{\nu_\mu} = f_0 f_{p\nu}, \qquad f_0 = \frac{E_{\gamma,\mathrm{iso}}}{32\pi d_L^2} = 10^{-5} \frac{E_{\gamma,53}}{d_{L28}^2} \frac{\mathrm{erg}}{\mathrm{cm}^2},$$
$$f_{p\nu} = \frac{\int d\varepsilon_p (dN_p/d\varepsilon_p) \varepsilon_p f_{p\nu}(\varepsilon_p)}{\int d\varepsilon_p (dN_p/d\varepsilon_p) \varepsilon_p}, \quad (5)$$

where $E_{\gamma,\mathrm{iso}} = 10^{53} E_{\gamma,53}$ erg is the isotropic equivalent energy in $\gamma$ rays, $f_{p\nu}(\varepsilon_p) = f_{p\pi}(\varepsilon_p) f_{\pi\nu}(\varepsilon_p)$, while $f_{p\pi}(\varepsilon_p)$ is given in Eq. (3), and $f_{\pi\nu}(\varepsilon_p)$ is the fraction of the original pion energy, $\varepsilon_\pi \approx 0.2\varepsilon_p$, that remains when it decays. We have taken into account that, although the initial neutrino flavor ratio $\Phi_{\nu_e}:\Phi_{\nu_\mu}:\Phi_{\nu_\tau}$ is 1:2:0, neutrino oscillations cause it to be 1:1:1 at the earth.

The pions may lose some energy via synchrotron or inverse-Compton (IC) emission. If these energy losses are important, then the final energy left in the $\pi^+$ when it decays, out of which 3/4 goes to neutrinos, can be much smaller than its original energy. We find that $f_{\pi\nu}(\varepsilon_p) \approx 1 - \exp(-t'_{\mathrm{rad}}/\tau'_\pi) \approx \min(1, t'_{\mathrm{rad}}/\tau'_\pi)$, where $\tau'_\pi \approx 2.6 \times 10^{-8} \varepsilon'_\pi/(m_\pi c^2)$ s is the lifetime of the pion, and $t'_{\mathrm{rad}} = (t'^{-1}_{\mathrm{syn}} + t'^{-1}_{\mathrm{IC}})^{-1} \approx \min(t'_{\mathrm{syn}}, t'_{\mathrm{IC}})$ is the time for radiative losses due to both synchrotron and IC losses, the times for which are $t'_{\mathrm{syn}}$ and $t'_{\mathrm{IC}}$, respectively. We have

$$t'_{\mathrm{syn}} = \frac{3 m_\pi^4 c^3}{4\sigma_T m_e^2 \varepsilon'_\pi U'_B}, \qquad t'_{\mathrm{IC}} = \frac{3 m_\pi^4 c^3}{4\sigma_T m_e^2 \varepsilon'_\pi U'_\gamma(\varepsilon'_\pi)}, \quad (6)$$

where $U'_B = B'^2/8\pi$ is the energy density in the magnetic field, within the shocked fluid behind the internal shocks, and $U'_\gamma(\varepsilon'_\pi)$ is the energy density of photons below the Klein-Nishina limit, $\varepsilon'_{\gamma,KN} = (m_\pi c^2)^2/\varepsilon'_\pi$. IC losses due to scattering of the GRB photons were shown to be unimportant [7]. We consider the IC losses due to the up-scattering of the external PWB photons, and find

$$t'_{\mathrm{syn}}/\tau'_\pi = 0.21\, \epsilon_e \epsilon_B^{-1} L_{52}^{-1} \Gamma_{2.5}^8 t_{v,-2}^2 \varepsilon_{\pi 18}^{-2}, \quad (7)$$
$$t'_{\mathrm{IC}}/\tau'_\pi = 0.67 f_{1/3}^2 \xi_{e/3}^{-1} \epsilon_{be/3}^{1/2} \epsilon_{bB,-3}^{-1/2} E_{53}^{-1} \beta_{b,-1}^2 t_{\mathrm{sd},-1}^3 \varepsilon_{\pi 18}^{-2},$$

where $\epsilon_e$ and $\epsilon_B$ are the equipartition parameters of the GRB, and $\varepsilon_{\pi 18} = \varepsilon_\pi/10^{18}$ eV. The radiative losses become important for $t'_{\mathrm{rad}} < \tau'_\pi$, which corresponds to $\varepsilon_p > \varepsilon_{ps} = \min(\varepsilon_{ps}^{\mathrm{syn}}, \varepsilon_{ps}^{\mathrm{IC}}) \approx 5\varepsilon_{\pi s} \approx 20\varepsilon_{\nu s}$, where

$$\varepsilon_{ps18}^{\mathrm{syn}} = 2.3\, \epsilon_e^{1/2} \epsilon_B^{-1/2} L_{52}^{-1/2} \Gamma_{2.5}^4 t_{v,-2}, \quad (8)$$

$$\varepsilon_{ps18}^{\mathrm{IC}} = 4.1 f_{1/3} \xi_{e/3}^{-1/2} \epsilon_{be/3}^{1/4} \epsilon_{bB,-3}^{-1/4} E_{53}^{-1/2} \beta_{b,-1} t_{\mathrm{sd},-1}^{3/2}. \quad (9)$$

The protons may also lose energy via $p\gamma$ interactions with GRB photons [7], However, $\tau_{p\gamma}$ for this process is typically $\lesssim 1$, so that it does not have a large effect on $p\gamma$ interactions with PWB photons, on which we focus.

Since the lifetime of the muons is $\sim$100 times longer than that of the pions, they would have significant radiative losses at an energy of $\varepsilon_{\mu s} \sim \varepsilon_{\pi s}/10 \approx \varepsilon_{ps}/50$. This causes a reduction of up to a factor of 3 in the total neutrino flux in the range $\sim$(0.1–1)$\varepsilon_{\nu s}$, since only $\nu_\mu$ that are produced directly in $\pi^+$ decay contribute considerably to the neutrino flux. Note that since both ratios in Eqs. (7) scale as $\varepsilon_\pi^{-2}$, we always have $t'_{\mathrm{rad}}/\tau'_\pi \propto \varepsilon_\pi^{-2}$, and therefore the spectrum steepens by a factor of $(\varepsilon_\nu/\varepsilon_{\nu s})^{-2}$ for $\varepsilon_\nu > \varepsilon_{\nu s}$. This is also evident from the fact that $f_{\pi\nu}(\varepsilon_p \approx 5\varepsilon_\pi) \approx \min(1, t'_{\mathrm{syn}}/\tau'_\pi, t'_{\mathrm{IC}}/\tau'_\pi)$.

Figure 1 shows the proton energies corresponding to the neutrino break energies $\varepsilon_{\nu s}$, $\varepsilon_{\nu b}$ and $\varepsilon_{\nu\tau} \approx \varepsilon_{p\tau}/20$, as a function of $t_{\rm sd}$. From Eqs. (2), (8), and (9) we see that $\tau_{p\gamma} \propto \Gamma^2 t_{\rm sd}^{-3/2}$, $\varepsilon_{ps}^{\rm syn} \propto \Gamma^4$ and $\varepsilon_{ps}^{\rm IC} \propto t_{\rm sd}^{3/2}$. For a fixed value of $t_{{\rm sd},-1} = 1$, $\Gamma_{2.5} \gtrsim 1$ implies $\tau_{p\gamma} \gtrsim 1$ and $\varepsilon_{ps} = \varepsilon_{ps}^{\rm IC} =$ const $\sim 10^{18}$ eV, while $\Gamma_{2.5} \lesssim 1$ implies $\varepsilon_{ps} = \varepsilon_{ps}^{\rm syn} \propto \Gamma^4$. This implies a stronger neutrino emission which can reach higher energies for larger values of $\Gamma$. Since a larger $\Gamma$ implies a lower typical synchrotron frequency for the prompt GRB, this may apply to x-ray flashes, if they are indeed GRBs with relatively large Lorentz factors $\Gamma$ and/or a large $t_v$ [10].

As can be seen from Fig. 1, for relevant parameters, there are four different orderings of these break energies: (i) $\varepsilon_{\nu\tau} < \varepsilon_{\nu b} < \varepsilon_{\nu s}$, (ii) $\varepsilon_{\nu b} < \varepsilon_{\nu\tau} < \varepsilon_{\nu s}$, (iii) $\varepsilon_{\nu b} < \varepsilon_{\nu s} < \varepsilon_{\nu\tau}$, (iv) $\varepsilon_{\nu s} < \varepsilon_{\nu b} < \varepsilon_{\nu\tau}$. Each ordering results in a different shape for the spectrum, that consists of three or four power laws, as can be seen in Fig. 2 (solid line). The peak of the $\varepsilon_\nu^2(dN_\nu/d\varepsilon_\nu)$ spectrum, in units of $f_0$, is

$$\begin{aligned}
&\frac{(4+s)/4s + \ln(\varepsilon_{\nu s}/\varepsilon_{\nu\tau})}{[(4+s)/2s + \ln(\varepsilon_{\nu s}/\varepsilon_{\nu\tau})]^2}, && \varepsilon_{\nu\tau} < \varepsilon_{\nu b} < \varepsilon_{\nu s},\\
&\frac{5/4 + \ln(\varepsilon_{\nu s}/\varepsilon_{\nu\tau})}{[5/2 + \ln(\varepsilon_{\nu s}/\varepsilon_{\nu\tau})]^2}, && \varepsilon_{\nu b} < \varepsilon_{\nu\tau} < \varepsilon_{\nu s},\\
&(3/16)\sqrt{\varepsilon_{\nu s}/\varepsilon_{\nu\tau}}, && \varepsilon_{\nu b} < \varepsilon_{\nu s} < \varepsilon_{\nu\tau},\\
&\frac{s(4-s)}{16}(\varepsilon_{\nu s}/\varepsilon_{\nu b})^{s/2}\sqrt{\varepsilon_{\nu b}/\varepsilon_{\nu\tau}}, && \varepsilon_{\nu s} < \varepsilon_{\nu b} < \varepsilon_{\nu\tau}.
\end{aligned} \tag{10}$$

For example, spectrum (iii) applies for $t_{\rm sd} = 0.4$ yr, where the GRB is detectable, and is given by

$$\frac{\varepsilon_\nu^2 \frac{dN_\nu}{d\varepsilon_\nu}/f_0}{\frac{3}{16}\sqrt{\varepsilon_{\nu s}/\varepsilon_{\nu\tau}}} = \begin{cases} (\frac{\varepsilon_{\nu b}}{\varepsilon_{\nu s}})^{1/2}(\frac{\varepsilon_\nu}{\varepsilon_{\nu b}})^{s/2}, & \varepsilon_\nu < \varepsilon_{\nu b},\\ (\varepsilon_\nu/\varepsilon_{\nu s})^{1/2}, & \varepsilon_{\nu b} < \varepsilon_\nu < \varepsilon_{\nu s},\\ (\varepsilon_\nu/\varepsilon_{\nu s})^{-3/2}, & \varepsilon_{\nu s} < \varepsilon_\nu < \varepsilon_{\nu\tau},\\ (\frac{\varepsilon_{\nu s}}{\varepsilon_{\nu\tau}})^{3/2}(\frac{\varepsilon_\nu}{\varepsilon_{\nu\tau}})^{-2}, & \varepsilon_\nu > \varepsilon_{\nu\tau}. \end{cases} \tag{11}$$

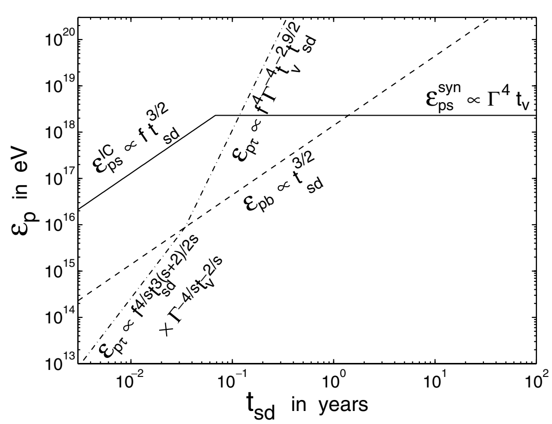


FIG. 1. The proton energies that correspond to break energies in the neutrino spectrum, $\varepsilon_\nu \approx \varepsilon_p/20$, as a function of $t_{\rm sd}$.

Figure 2 shows the muon neutrino spectrum for our fiducial parameters (solid line). The spectrum of the other neutrino flavors is the same, while the spectrum of the $\gamma$ rays from the pion decay is almost the same, just substituting $\varepsilon_\gamma \approx 2\varepsilon_\nu$ and with a normalization larger by a factor of 4. In Fig. 2 we also compare our neutrino spectra with that of [7] for different internal shock parameters. We see that, for reasonably large values of $\Gamma$ and $t_v$, the PWB photons are the dominant target for photomeson interactions for $t_{\rm sd} \lesssim 4$ yr. The afterglow neutrino emission with $\varepsilon_\nu \gtrsim 10^{17}$ eV [11] should be distinguishable from the prompt emission (from $p\gamma$ interaction with either GRB or PWB photons) due to the very different spectrum, and may also be delayed in time.

*Implications.*—The high energy, $\sim 10^{16}$ eV, neutrinos produced by photomeson interactions between protons accelerated in the internal shocks of GRBs and the PWB photons may be detected by the future neutrino telescopes [12]. The probability, $P_{\nu\mu}$, that a neutrino would produce a high energy muon in the detector is approximately given by the ratio of the high energy muon range to the neutrino mean free path. For the neutrinos

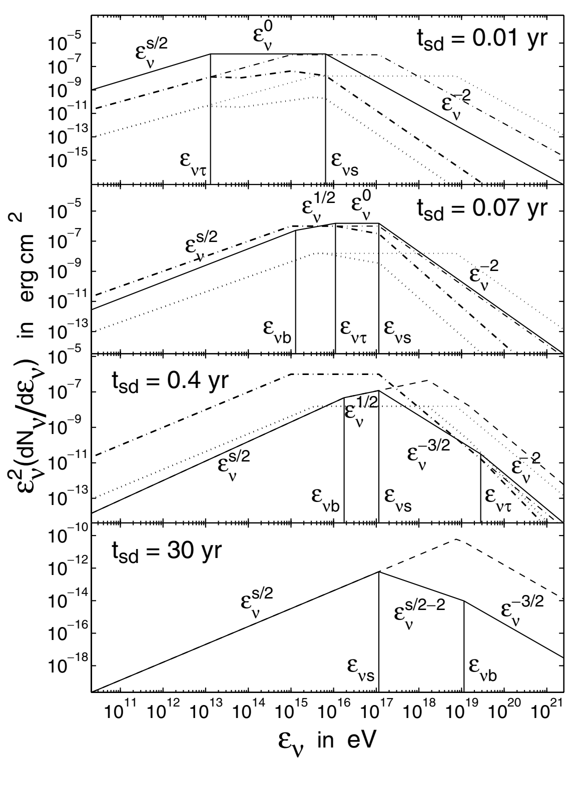


FIG. 2. The muon neutrino spectrum, for our fiducial parameters and $t_{\rm sd} = 0.01$, 0.07, 0.4, 30 yr, for $(\Gamma, t_{v,-2}) = (10^{2.5}, 1)$ (solid line), which correspond to the four different orderings of the break energies, and $(\Gamma, t_{v,-2}) = (600, 5)$ (dashed line). For comparison we show the spectrum of [7] for $(\Gamma, t_{v,-2}) = (10^{2.5}, 1)$ (dot-dashed line) and (600, 5) (dotted line), where the thick (thin) lines are with (without) the effects of the PWB radiation field (that inflict energy losses on the protons, pions, and muons).

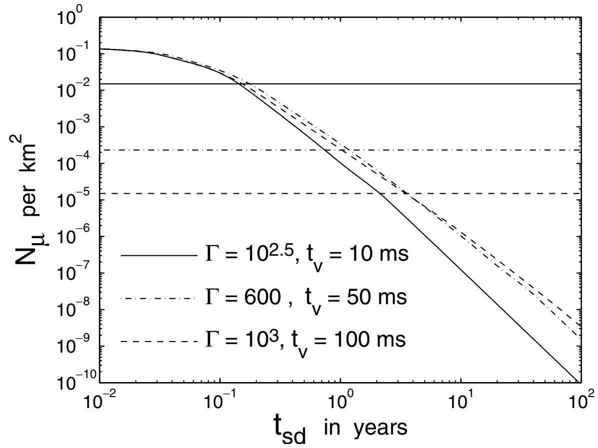


FIG. 3. The number of muon events per GRB in a km$^2$ detector, as a function of $t_{sd}$, for our fiducial parameters and three different values of $(\Gamma, t_v)$. The horizontal lines show the events expected due to $p\gamma$ interactions with GRB photons [7].

studied here, $P_{\nu\mu} \approx 1.3 \times 10^{-3}(\varepsilon_\nu/10^3\ \mathrm{TeV})^\beta$, with $\beta = 1$ for $\varepsilon_\nu < 10^3$ TeV and $\beta = 1/2$ for $\varepsilon_\nu > 10^3$ TeV [12].

In Fig. 3 we report the expected number of events in a km$^2$ detector as a function of $t_{sd}$, for our fiducial parameters, for a GRB at $z \sim 1$ with $E_{\gamma,\mathrm{iso}} = 10^{53}$ erg. We consider three different sets of values for $\Gamma$ and $t_v$, and compare the resulting numbers with the expected number of events due to photomeson interactions with the GRB photons [7]. For a typical GRB with $\Gamma = 10^{2.5}$ and $t_v = 10$ ms, $\nu$'s from interactions with PWB photons dominate over $\nu$'s from GRB photons for $t_{sd} \lesssim 0.2$ yr.

GRBs that occur inside spherical PWBs with $t_{sd} \sim 0.1$–$0.2$ yr would have a peculiar and short lived afterglow emission [5]. Since they occur for a wide range of $t_{sd}$ values, we expect their rate to be similar to that of typical GRBs (i.e. $\sim 10^3\ \mathrm{yr}^{-1}$ beamed toward us). For these values of $t_{sd}$ we expect $\sim 0.01$–$0.1$ events per burst corresponding to the detection of several tens of neutrino induced muons per year. These neutrino bursts should be easily detected above the background, since the neutrinos would be correlated, both in time and direction, with the GRB $\gamma$ rays. Note that, at the high energy considered, knowledge of burst direction and time will allow us to discriminate the neutrino signal from the background by looking not only for upward moving neutrino induced muons, but also by looking for downgoing muons. For larger values of $0.2\ \mathrm{yr} \lesssim t_{sd} \lesssim 1$ yr, the neutrino flux due to $\rho\gamma$ interaction with the PWB photons will dominate over that due to $\rho\gamma$ interaction with the GRB photons [7], if the GRB has $\Gamma \gtrsim 600$ and $t_v \gtrsim 50$ ms. Since larger $\Gamma$ and $t_v$ imply a lower typical synchrotron frequency for the prompt GRB, this may apply to x-ray flashes, if they are indeed GRBs with relatively large Lorentz factors and/or a large variability time, $t_v$ [10]. For these events, no afterglow emission has been detected and this can be explained considering the fact that for $t_{sd} \lesssim 1$ yr the GRB would have a peculiar and short lived afterglow emission. The typical neutrino energy is expected to be in the range $\sim 10^{15}$–$10^{17}$ eV for typical GRBs, and $\sim 10^{15}$–$10^{19}$ eV for x-ray flashes.

We expect $10^{-5}$–$0.01$ events per x-ray flash for this range of $t_{sd}$ corresponding to a detection of 0.01–10 events per year. Again, these neutrino bursts should be easily detected above the background, since the neutrinos would be correlated, both in time and direction, with the x rays of the x-ray flashes. This neutrino emission would be simultaneous with the $\gamma$-ray/x-ray emission from the GRB and should be easily distinguishable from neutrinos emitted after the $\gamma$-ray phase of the GRB [11] or $\lesssim 100$ s before the GRB [13]. Detection of high energy neutrinos will test the shock acceleration mechanism and the suggestion that GRBs are the sources of ultrahigh energy protons, since $\gtrsim 10^{16}$ eV neutrino production requires protons of energy $\gtrsim 10^{18}$ eV, and will help to establish whether indeed most GRBs occur inside PWBs.

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