Inspecting the supernova-gamma-ray-burst connection with high-energy neutrinos

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Long-duration gamma-ray bursts (GRBs) have been often considered as the natural evolution of some core-collapse supernovae (SNe). While GRBs with relativistic jets emit an electromagnetic signal, GRBs with mildly relativistic jets are opaque to photons and therefore could be detectable through neutrinos only. We discuss the possibility that successful GRBs and mildly relativistic jets belong to the same class of astrophysical transients with different Lorentz factor $\Gamma_b$ and study the production of high-energy neutrinos as a function of $\Gamma_b$, by including both proton-photon and proton-proton interactions. By assuming a SN-GRB connection, we find that the diffuse neutrino emission from optically thick jets with Lorentz factors lower than the ones of successful GRBs can be one of the main components of the observed IceCube high-energy neutrino flux. Moreover, under the assumption that all these jets belong to the same class of astrophysical transients, we show that the IceCube high-energy neutrino data provide indirect constraints on the rate of nonsuccessful jets, favoring a local rate lower than tens of percent of the local SN rate. These limits are currently comparable to dedicated searches on choked sources and are expected to become tighter with the accumulation of more high-energy neutrino data.

I. INTRODUCTION

Gamma-ray bursts (GRBs) are among the most energetic astrophysical transients [1–3] and possibly sources of ultra-high-energy cosmic rays [4,5]. Several observations point toward a connection between long-duration GRBs and core-collapse supernovae (SNe) [6]. The most likely scenario is that an accretion disk surrounding a black hole forms soon after the core collapse, and a jet originates [7]. Such a hypothesis is supported by the fact that SNe and GRBs are expected to release a comparable amount of kinetic energy.

Once the jet is formed, two extreme scenarios may beforeseen: the jet is either highly or mildly relativistic. The former corresponds to an ordinary long-duration GRB with Lorentz factor $\Gamma_b$ of $\mathcal{O}(10^2 - 10^3)$, where the emission of high-energy neutrinos is accompanied by an electromagnetic counterpart. The latter stands for a baryon-rich jet with a Lorentz factor of a few, where no electromagnetic counterpart is expected, the jet is optically thick, and only neutrinos are able to escape; in the following, these jets will be dubbed as “baryon-rich or low-$\Gamma_b$ jets.”

The IceCube telescope at the South Pole should be sensitive to any of the above classes of GRBs, given their sizeable neutrino production. However, all the GRB dedicated searches performed from IceCube over the past years reported negative results [8–13], constraining the theoretical models employed to explain the GRB neutrino emission [14–16].

The IceCube experiment recently detected astrophysical neutrinos with the highest energies ever observed [17–22]. The current data set is compatible with an equal distribution of such neutrinos in flavor and an isotropic allocation in the sky. Various astrophysical sources such as starburst galaxies, low-luminosity gamma-ray bursts, and active galactic nuclei have been considered as they might produce a neutrino flux comparable to the detected one [1,23–26]. However, more recent analyses point toward a lower neutrino flux from star-forming galaxies and blazars than previously expected; see, e.g., Refs. [27–29]. Such recent developments leave open the quest on the origin of the IceCube high-energy events and suggest faint or low-luminosity sources as plausible components of the measured flux (see also the discussion in Refs. [30,31]), besides yet unknown astrophysical sources. The diffuse neutrino emission from low-luminosity GRBs [32–35] could indeed partly explain the IceCube PeV events [36–39].

In this paper, we assume that high- and low-$\Gamma_b$ jets belong to the same GRB family [6,7,40–44] and that the low rate of such jets progressively increases as $\Gamma_b$ decreases, reflecting the fact that the baryon-rich sources could be more abundant than the ordinary GRBs [45,46]. We expect that PeV neutrinos are mostly produced through proton-photon ($p\gamma$) interactions in jets with high $\Gamma_b$, while TeV neutrinos are emitted from baryon-rich sources mostly by means of proton-proton ($pp$) interactions [45–49]. To estimate the high-energy neutrino emission from astrophysical jets as a function of $\Gamma_b$, we model the neutrino emission as generally as possible and by including both $pp$ and $p\gamma$ interactions. We tune the local rate of high-$\Gamma_b$ bursts
to the observed one of high-luminosity GRBs and assume that the one of the low-$\Gamma_b$ jets is a fraction of the local core-collapse SN rate.

The purpose of our work is to investigate whether IceCube high-energy neutrino data can constrain the SN-GRB connection and possibly allow us to extrapolate upper bounds on the abundance of baryon-rich jets. We also discuss the range where $pp$ and $p\gamma$ interactions dominate the neutrino production as a function of the Lorentz factor $\Gamma_b$ and find that optically thick jets with $\Gamma_b$ lower than the one of successful GRBs, e.g., $\Gamma_b \sim \mathcal{O}(10 - 100)$, could provide a substantial contribution to the observed IceCube flux of high-energy neutrinos.

The paper is organized as follows. In Sec. II, we define the jet emission model and estimate the expected high-energy neutrino production from these sources. In Sec. III, we study the diffuse emission of high-energy neutrinos and provide a substantial contribution to the observed IceCube flux of high-energy neutrinos. The paper is organized as follows. In Sec. II, we define the jet emission model and estimate the expected high-energy neutrino production from these sources. In Sec. III, we study the diffuse emission of high-energy neutrinos and provide a substantial contribution to the observed IceCube flux of high-energy neutrinos.

II. HIGH-ENERGY NEUTRINO PRODUCTION IN RELATIVISTIC JETS

In this section, we define a generic model for the high-energy neutrino emission from astrophysical relativistic jets by including $pp$ and $p\gamma$ interactions. Besides studying the cooling of protons as a function of $\Gamma_b$, we discuss cooling processes of pions, kaons, and muons as well as the expected neutrino fluence.

A. Jet emission properties

Independently from the bulk Lorentz factor $\Gamma_b$, we consider a typical jet with total energy $E_j \sim 3 \times 10^{51}$ erg, jet opening angle $\theta_j \sim 5$ deg, total duration $t_j \sim 10$ s, and total jet luminosity $L_j \sim E_j / t_j \sim 10^51$ erg s$^{-1}$ [3]. Internal shocks between the jet plasma ejecta occur at $r_j \sim 2\Gamma_b^2ct_e/(1 + z)$ with $t_e \sim 0.1$ s the jet variability time, $c$ the speed of light, and $z$ the redshift.

The isotropic luminosity carried by photons in successful bursts is $L_{iso} = 2(1 + z)^2L_j\epsilon_e/(0.3\theta_j^2)$, with $\epsilon_e = 0.1$ the energy fraction carried by electrons [3,38,50]. In general, one could expect the jet properties to vary as a function of $\Gamma_b$. However, we do not have data on baryon-rich jets and assume that their properties are on average comparable to the ones of successful bursts for the sake of simplicity. The similarity between kinetic energies of relativistic GRB jets and nonrelativistic SN explosions may support such an assumption. Nevertheless, we refer the interested reader to Sec. IV for a discussion on the dependence of our results on the adopted model parameters.

To characterize the typical photon energy, we introduce the Thomson optical depth [48],

$$\tau_T = \frac{\sigma_T n_e \bar{r}_j}{\Gamma_b},$$

with the comoving electron density similar to the one of baryons,

$$n_e = n'_p = \frac{L_j(1 + z)^4}{m_p c^2 \Gamma_b^5 \pi \theta_j^2 \bar{r}_j^2},$$

where $n'_p = |E_j(1 + z)/m_p c^2 \Gamma_b V'|$, $m_p$ is the proton mass, and $V' = 2\pi \theta_j^2 \Gamma_b r_j c t_j/(1 + z)$ is the comoving volume.

The energy associated to the jet magnetic field $B$ is

$$B^2 = \frac{8\pi}{3}\frac{e_B E_j(1 + z)}{\pi \theta_j^2 \bar{r}_j^2 ct_j \Gamma_b},$$

$e_B = 0.1$ being the fraction of the total energy converted into magnetic energy. Note that we adopt $B^2/(8\pi) = 4e_B E_j/V'$ [3,38]. Previous work on the topic does not always include the constant numerical factor in the definition of the magnetic energy density (see, e.g., Ref. [14]); therefore, care should be taken when comparing our results with the ones reported in part of the existing literature.

In the case of optically thin sources ($\tau_T < 1$), the photon energy distribution is nonthermal with a typical energy $E'\gamma = (h \epsilon_e^2 m_p^2 c B^2)/(m_e^3 c)$ [51], i.e.,

$$E'_{\gamma,\text{non-th}} = \frac{(1 + z)\epsilon_e \epsilon_{\gamma,\text{non-th}}}{\Gamma_b \epsilon_{e,2}^{3/2}} \text{MeV},$$

with $\epsilon_e \approx 0.1$ the energy fraction carried by the electrons. The subscripts in the above equation stand for the typical order of magnitude of the quantities defining $E'_{\gamma,\text{non-th}}$, i.e., $\epsilon_{\gamma,1} = \epsilon_e/0.1L_{iso,52} = \bar{L}_{iso}/(10^{52}$ erg), and similarly for the other variables.

On the other hand, when $\tau_T \geq 1$, photons thermalize and have an average blackbody temperature [48]:

$$E'_{\gamma,\text{th}} = \frac{(15h^3 \epsilon_e^2 \epsilon_{\gamma,\text{th}} E_j)}{2\pi \theta_j^2 \bar{r}_j^2} \text{MeV},$$

Therefore, the most general expression for the characteristic photon energy is...
\[ E'_p = \begin{cases} E'_{p,\text{th}} & \text{for } \tau'_T > 1 \\ E'_{p,\text{non-th}} & \text{for } \tau'_T \leq 1. \end{cases} \] (6)

Note that, although Eq. (6) defines characteristic photon energies, we include specific spectral shapes of the non-thermal and thermal photon energy spectra in the numerical computations as well as in the following discussion (including Fig. 2).

**B. Proton acceleration and cooling processes**

The acceleration time (acc) of a proton with comoving energy \( E'_p \) is

\[ t'_\text{acc} = \frac{E'_p}{B' e c} = 3.7 \times 10^{-9} \frac{E'_{p,\text{GeV}} \theta_{j,1}^3 t_{\nu,-2} \Gamma_{b,2,5}^3}{\varepsilon_{B,-1}^1 E'_{j,51}^1 (1 + z)^2}, \] (7)

under the assumption of perfectly efficient acceleration.

In the presence of a magnetic field, protons are subject to synchrotron cooling (sync) besides being accelerated:

\[ t'_\text{sync} = \frac{3 m_p^3 c^3 8 \pi}{4 \sigma_{\gamma} m_c^2 E'_p B'^2} \approx 5 \times 10^9 \frac{\theta_{\gamma}^2 \theta_{j,1}^3 \Gamma_{b,2,5}^6 t_{\nu,-2} E'_p^{-1}}{E'_{p,\text{GeV}} \varepsilon_{B,-1}^1 (1 + z)^3}, \] (8)

The inverse Compton process (IC) is another cooling channel. We express it as a function of \( E'_p \) for the Thomson and Klein-Nishina regimes [48],

\[ t'_\text{IC} = \begin{cases} \frac{3 m_p^3 c^3}{4 \sigma_{\gamma} m_c^2 E'_p E'_c} \approx 5 \times 10^9 \frac{\theta_{\gamma}^2 \theta_{j,1}^3 \Gamma_{b,2,5}^6 t_{\nu,-2} E'_p^{-1}}{E'_{p,\text{GeV}} \varepsilon_{B,-1}^1 (1 + z)^3}, \\ \frac{3 E'_p}{4 m_p c^2 \varepsilon_{B,-1}^1 E'_p} \approx 6 \times 10^5 \frac{E_{b,2,5} \theta_{j,1}^3 \Gamma_{b,2,5}^6 t_{\nu,-2} E'_p^{-1}}{E'_{p,\text{GeV}} \varepsilon_{B,-1}^1 (1 + z)^3}, \end{cases} \] (9)

respectively, for \( E'_p \ll (\gg) m_c^2 c^4 / E'_c \), and with the comoving photon density

\[ n'_\gamma = \frac{2 E'_{\gamma} \varepsilon_{\gamma}}{\pi \theta_{\gamma}^2 \theta_{j,1}^1 \Gamma_{b,2,5}^3 E'_{\gamma}}. \] (10)

Because of the high density of photons, \( e^+ e^- \) pairs may be produced through the Bethe-Heitler (BH) process: \( p \gamma \to p e^+ e^- \). The BH cross section is defined as in, e.g., Ref. [52],

\[ \sigma_{\text{BH}} = \alpha r_e^2 \left( \frac{28}{9} \ln \left[ \frac{2 E'_{p} E'_{\gamma}}{m_p m_e c^2} \right] - \frac{106}{9} \right), \] (11)

with \( \alpha \) the fine-structure constant and \( r_e \) the classical electron radius; the corresponding comoving cooling time is [48]

\[ t'_\text{BH} = \frac{E'_p (m_c^2 c^4 + 2 E'_p E'_{\gamma})^{1/2}}{2 n'_\gamma \sigma_{\text{BH}} m_c c^3 (E'_p + E'_{\gamma})}. \] (12)

The characteristic times of \( p \gamma \) and \( pp \) interactions can be of relevance for the proton cooling, besides producing high-energy neutrinos as we will see in the next section. These are

\[ t'_p = \frac{E'_p}{c \sigma_{p\gamma} n'_\gamma \Delta E_p} \approx 1.5 \times 10^4 \frac{\Gamma_{b,2,5}^6 \theta_{j,1}^3 t_{\nu,-2} E'_p}{E_{j,51}^1 (1 + z)^{3/2}}, \] (13)

\[ t'_p = \frac{E'_p}{c \sigma_{pp} n'_\gamma \Delta E_p} \approx 1.4 \times 10^4 \frac{\Gamma_{b,2,5}^6 \theta_{j,1}^3 t_{\nu,-2} E'_p}{E_{j,51}^1 (1 + z)^{3/2}}, \] (14)

with cross sections \( \sigma_{p\gamma} \approx 5 \times 10^{-28} \text{ cm}^{-2} \) and \( \sigma_{pp} \approx 5 \times 10^{-26} \text{ cm}^{-2}, \) respectively, and \( \Delta E_p / E'_p = 0.2(0.8) \) for \( p \gamma \) (\( pp \)) interactions [48]. In the above equations, we neglect the integral over the energy range of the cross sections as well as the multipion production for sake of simplicity. Such approximations are not crucial given the purpose of our study, but we refer the interested reader to Refs. [14,53,54] for a discussion on the role of these factors on the total expected neutrino flux. Note that the expression for \( t'_p \) is valid for \( E'_p \) above the threshold energy of the \( \Delta \) resonance due to \( p \gamma \) interactions \( (E'_{p,\text{th}} = (m_\Delta c^2)^2 - (m_p c^2)^2)/4E'_p \) [38,55].

Finally, protons are subject to the adiabatic cooling (ac), the time scale in the comoving frame of which is given by

\[ t'_\text{ac} = \frac{\bar{r}_j}{\Gamma_{b,c}} \approx 6.3 \, s \Gamma_{b,2,5} t_{\nu,-2} (1 + z)^{-1}. \] (15)

The total cooling time of protons in the comoving frame is given by the superposition of the cooling processes mentioned above:

\[ t'_c = t'_\text{syn} + t'_\text{IC} + t'_\text{BH} + t'_p + t'_p + t'_\text{ac}. \] (16)

The maximum proton energy \( (E'_{p,\max}) \) is determined by

\[ t'_c = t'_\text{acc}, \] (17)

while the minimum proton energy \( (E'_{p,\min}) \) is given by the proton rest mass.

To provide an idea of the relevant cooling processes for protons for both high and low \( \Gamma_b \)'s, Fig. 1 shows the (inverse of) the proton cooling time scales as functions of the comoving proton energy for \( \Gamma_b = 300 \) (top panel) and \( \Gamma_b = 3 \) (bottom) jets at \( z = 1 \). In the high-\( \Gamma_b \) case, the maximum proton energy is \( E'_{p,\max} = 1.5 \times 10^6 \text{ GeV} \), and it is determined by the competition of the shock acceleration with synchrotron cooling characterized by \( t'_\text{sync} \). The
adiabatic cooling becomes instead the dominant cooling process for $\Gamma_b$ higher than the one shown here. The low-$\Gamma_b$ case has a maximum proton energy $E_{p,\text{max}} = 9.5 \times 10^8$ GeV fixed by the photomeson cooling ($t'_{\text{pp}}$). Note that $pp$ interactions occur for the whole proton energy range independently from $\Gamma_b$, while $p\gamma$ interactions are relevant for $E'_p$ larger than the threshold energy of the $\Delta$ resonance. However, as discussed in the next section, the energy range where $p\gamma$ interactions are relevant becomes smaller as $\Gamma_b$ decreases, until $p\gamma$ interactions are negligible for low $\Gamma_b$ and only $pp$ interactions affect the neutrino spectrum (see the case shown in the bottom panel of Fig. 1).

C. Meson cooling processes and neutrino production

High-energy neutrinos are produced by the protons interacting with the synchrotron photons ($p\gamma$ interactions) and with the protons present in the shock region ($pp$ interactions) [56,57]. Both interactions produce $\pi^\pm$ and $K^\mp$ that then decay to muons and neutrinos.

Pions and kaons are affected by hadronic cooling,

$$t'_h = \frac{E'_p}{\Delta E'_x |\sigma_h| n'_p} = t'_{\text{pp}},$$

with $\Delta E'_x = 0.8 E'_x$ the energy lost by the incident meson in each collision (Figs. 18 and 19 in Ref. [58]) and $\sigma_h = 5 \times 10^{-26}$ cm$^{-2}$ the cross section for meson-proton collisions [59]. Similarly to protons, pions, kaons, and muons are also subject to synchrotron and IC cooling [defined as in Eqs. (8) and (9) with $E'_p \to E'_x$ and $m_p \to m_a$, where $a = \pi$, $K$, and $\mu$] as well as to adiabatic cooling [Eq. (15)].

The total cooling time of pions, kaons, and muons is

$$t'_c = t'_{\text{syn}} + t'_{\text{hc}} + t'_{\text{IC}} + t'_{\text{ac}}.$$

(Note that muons are not subject to hadronic cooling.) As explained in the next section, by comparing the above cooling times with the lifetime of mesons and muons, one can predict the expected neutrino spectrum.

D. Neutrino energy spectrum

We assume an initial proton spectrum that scales as $E_p^{-2}$. As for $p\gamma$ interactions, the comoving proton energy to produce a $\Delta$ resonance (and therefore to generate neutrinos) is $E'_p \gtrsim [(m_\Delta c^2)^2 - (m_p c^2)^2]/(4E_r')$. This energy will affect the correspondent neutrino spectrum at

$$E'_{\nu,b} = a_l \left( \frac{\Gamma}{1+z} \right)^2 \frac{(m_\Delta c^2)^2 - (m_p c^2)^2}{4E_r'}$$

$$\simeq 7.5 \times 10^5 \text{ GeV} \left( \frac{a_l}{0.05} \right) \frac{\Gamma_{b,2.5}^2}{(1+z)^2 E_{r,\text{MeV}}},$$

with $E_r$ the characteristic energy of the photon spectrum [Eq. (6)]. The numerical factor $a_l$ is $a_l = 0.05$ (20% being the fraction of $E_p$ that goes into pions and 1/4 being the fraction of the $E_\nu$ carried by neutrinos), $a_{\pi_K} = 0.05$ (as 3/4 is the energy fraction transferred from pions to muons and 1/3 takes into account the three-body decay of the muon), $a_\mu = 0.1$ (20% is the fraction of $E_p$ that goes into $E_\mu$, and 1/2 is the fraction of $E_K$ carried by neutrinos), and $a_{\mu_K} = 0.033$ for muons originating from the kaon decay. Note that Eq. (20) defines a spectral break in the neutrino energy spectrum for $\tau_f \ll 1$, where the photon spectrum is a broken power law; it represents the threshold energy of the neutrino spectrum for the case with $\tau_f \gg 1$ (see Fig. 2).
The initial neutrino energy spectrum before being affected by meson cooling processes is sketched in Fig. 2 for $\tau_T \gg 1$ (top) and $\tau_T \ll 1$ (bottom). For $\tau_T \gg 1$, given the sharp drop of the blackbody energy spectrum (see Sec. II A), the neutrino spectrum can be approximated by a rectangular function different from zero for $E_{\nu,b} < E_{\nu} < E_{\nu,max}$. For $\tau_T \ll 1$, the neutrino spectrum will be the same as the proton spectrum above $E_{\nu,b}$, while it will be harder at lower energies (see also the discussion in Refs. [38,55]).

Because of the cooling processes of pions, kaons, and muons described in Sec. II C, the neutrino spectrum is given by

$$
\left( \frac{dN_{\nu}}{dE_{\nu}} \right)_{\text{inj}} = \left( \frac{dN_{\nu}}{dE_{\nu}} \right)_{0} \left[ 1 - \exp \left( - \frac{t_{c,a} m_{u}}{E_{\nu} \tau_{a}} \right) \right],
$$

with $E_{\nu}^{2} (dN_{\nu}/dE_{\nu})_{0}$ defined as in Fig. 2 according to the value of $\tau_T$ and $\tau_{a}$ as the lifetime of mesons or muons. The minimum and maximum energies of the neutrino spectrum are defined by the minimum and maximum proton energies introduced in Sec. II B.

The $\nu_e$ and $\nu_\mu$ neutrino energy spectra produced from pion decay are

$$
\left( \frac{dN_{\nu_e}}{dE_{\nu}} \right)_{\text{inj},\pi} = \left( \frac{dN_{\nu_e}}{dE_{\nu}} \right)_{\mu},
$$

$$
\left( \frac{dN_{\nu_\mu}}{dE_{\nu}} \right)_{\text{inj},\pi} = \left( \frac{dN_{\nu_\mu}}{dE_{\nu}} \right)_{\pi} + \left( \frac{dN_{\nu_e}}{dE_{\nu}} \right)_{\pi}.
$$

Similar relations hold for neutrinos produced by kaon decay. No $\nu_\tau$'s are produced at the source. However, neglecting nonstandard scenarios, the three neutrino flavors become similarly abundant after flavor oscillations on their way to Earth [25]. Flavor conversions in matter might also occur while neutrinos are propagating within the jet in optically thick sources (see, e.g, Refs. [60–64]). However, in the following, we will neglect flavor oscillations in matter as they would not affect our conclusions. Nonetheless, future constraints on the neutrino flavor ratio observed on Earth might provide us with indirect information on the progenitor structure of optically thick sources in the case of the successful observation of baryon-rich bursts.

By adapting the normalization proposed in Ref. [65], the observed neutrino spectrum for a single source at redshift $z$ and for each neutrino production channel $a$ is

$$
F_{\nu}(E_{\nu}, z) = \frac{1}{2 \pi \theta_{b}^{2} \Gamma_{b}} E_{\nu} N_{a} f_{p} [1 - (1 - \chi_{p}) r_{p}^{2}] \left( \frac{dN_{\nu}}{dE_{\nu}} \right)_{\text{inj}}
$$

with $N_{a} = N_{\mu_{a}} = 0.12, N_{K} = 0.01, N_{\mu_{K}} = 0.003$ [38], and $t_{p}' = \tau_{pp}'(z, E_{\nu}) + \tau_{pp}'(z, E'_{\nu}) = \tau_{f}/\Gamma_{b}(\sigma_{pp} n_{p}^{+} + \sigma_{pp} n_{p}^{-})$ [48], and $(dN_{\nu}/dE_{\nu})_{\text{inj}}$ is the normalized spectrum that satisfies $\int dE_{\nu} E_{\nu}^{2} (dN_{\nu}/dE_{\nu})_{\text{inj}} = 1$. The factor $f_{p}$ takes into account the effect of spectral breaks,

$$
f_{p} = \frac{\int_{0}^{\infty} dE_{\nu} E_{\nu}^{2} (\frac{dN_{\nu}}{dE_{\nu}})_{\text{inj, no-break}}}{\int_{0}^{\infty} dE_{\nu} E_{\nu}^{2} (\frac{dN_{\nu}}{dE_{\nu}})_{\text{inj, no-break}}},
$$

where $(dN_{\nu}/dE_{\nu})_{\text{inj, no-break}} \propto E_{\nu}^{-2}$ is the neutrino spectrum without any cooling breaks [Eq. (21)] as well as the break due to the threshold of $p_{T}$ interaction [Eq. (20)]; the denominator is therefore proportional to $\ln(E_{\nu,max}/E_{\nu,min})$. Finally, the neutrino energy in the jet frame is related to that in the observer frame through $E'_{\nu} = E_{\nu}(1 + z)/\Gamma_{b}$, and $d_{L}(z)$ is the luminosity distance defined in a flat $\Lambda$CDM cosmology with $\Omega_{m} = 0.32, \Omega_{\Lambda} = 0.68$, and $H_{0} = 67$ km s$^{-1}$ Mpc$^{-1}$ for the Hubble constant [66].

Figure 3 shows the fluence of a burst at $z = 1$ as a function of $\Gamma_{b}$ as from Eq. (24) and after flavor oscillations. For $\Gamma_{b} = 3$ and 30, the spectrum is clearly dominated by
FIG. 3. Expected fluence for a single flavor of an astrophysical burst at $z = 1$ with $\Gamma_b = 3$ (black), 30 (red), 80 (blue), 300 (green), and 500 (violet). While $pp$ interactions dominate for $\Gamma_b = 3$ and 30, $py$ interactions are responsible for shaping the neutrino spectrum in the case of $\Gamma_b = 300$ and 500. The case with $\Gamma_b = 80$ is an intermediate case where both $pp$ and $py$ interactions are effective, although only the latter component is visible here.

$pp$ interactions, while for $\Gamma_b = 300$ and 500, it is dominated by $py$ interactions. The spectrum at $\Gamma_b = 80$ is mainly determined by $pp$ interactions at low energies (not visible in the plot because the flux is lower than the bottom value of the $y$ axis of the plot) and by $py$ interactions in the region around $10^7$ GeV. The sharp rise of the neutrino spectrum at about $10^7$ GeV is due to the fact that this object is optically thick ($\tau_\nu > 1$) and the corresponding initial neutrino spectrum has a sharp rise due to the blackbody photon spectrum distribution (see Fig. 2).

III. DIFFUSE HIGH-ENERGY NEUTRINO EMISSION FROM ASTROPHYSICAL BURSTS

We assume that the redshift evolution of baryon-rich and ordinary high-luminosity GRBs is a function of the redshift and of the Lorentz boost factor; $R_j(z, \Gamma_b) d\Gamma_b = R(z) \xi(\Gamma_b) d\Gamma_b$ is the formation rate density of the bursts with the Lorentz factor between $\Gamma_b$ and $\Gamma_b + d\Gamma_b$. The redshift-dependent part of $R_j(z, \Gamma_b)$ follows the star formation rate [67]

$$R(z) \propto \left[ (1 + z)^{p_1 k} + \left( \frac{1 + z}{5000} \right)^{p_2 k} + \left( \frac{1 + z}{9} \right)^{p_3 k} \right]^{1/k},$$

with $k = -10$, $p_1 = 3.4$, $p_2 = -0.3$, and $p_3 = -3.5$, and is normalized such that $R(0) = 1$. As for the $\Gamma_b$ dependence on the rate, we assume $\xi(\Gamma_b) = \Gamma_b^\alpha \beta_\Gamma$ and fix the parameters $\alpha$ and $\beta_\Gamma$ in such a way that

$$\int_1^{10^3} d\Gamma_b \Gamma_b^\alpha \beta_\Gamma = R_{SN}(0) \zeta_{SN} \frac{\theta_{SN}^2}{2},$$

$$\int_{200}^{10^{10}} d\Gamma_b \Gamma_b^\alpha \beta_\Gamma = \rho_{0,HL-GRB},$$

where $\zeta_{SN}$ is the fraction of core-collapse SNe that develop jets, $\theta_{SN}^2/2$ is the fraction of the jet pointing toward us, $R_{SN}(0) = 2 \times 10^5$ Gpc$^{-3}$ yr$^{-1}$ [68,69] is the local SN rate, and $\rho_{0,HL-GRB} = 0.8$ Gpc$^{-3}$ yr$^{-1}$ is an optimistic estimation of the observed local high-luminosity GRB rate [70]. To give an idea of the dependence of $R_j(z, \Gamma_b)$ on $\Gamma_b$, Fig. 4 shows $R_j(z = 0, \Gamma_b)$ as a function of $\Gamma_b$ for fixed $\rho_{0,HL-GRB}$ and $\zeta_{SN} = 1$, 100%, respectively.

The total diffuse neutrino intensity from all bursts is therefore defined in the following way:

$$I(E_\nu) = \frac{1}{\sqrt{\Omega_M(1 + z)^3 + \Omega_\Lambda}} R_j(z, \Gamma_b) E_\nu f_{p} N_a$$

$$\times \left[ 1 - (1 - \chi_p)^{\tau_\nu} \right] \left( \frac{dN_{p\nu}}{dE_\nu} \right)_{osc}. \quad (29)$$

The top panel of Fig. 5 shows the total diffuse emission from astrophysical bursts as a function of the neutrino energy for one neutrino flavor obtained by assuming $[\zeta_{min}, \zeta_{max}] = [0, 7]$ and $[\Gamma_{b,min}, \Gamma_{b,max}] = [1, 10^7]$. The continuous line stands for $\zeta_{SN} = 10\%$, while the dashed (dot-dashed) line is obtained by adopting $\zeta_{SN} = 100\%$ (1%). For comparison, the IceCube data as well as a band corresponding to the single power-law fit [21] are shown. The figure shows that these jets could represent a major component of the flux of the IceCube neutrinos for $\zeta_{SN} < 10\%$, especially in the PeV energy range.
INSPECTING THE SUPERNOVA–GAMMA-RAY-BURST CONNECTION USING ICECUBE: NEW LIMITS AND THEORETICAL IMPLICATIONS

Figure 5. Top panel: Diffuse intensity for one neutrino flavor after flavor oscillations as a function of the energy and for $\zeta_{SN} = 1, 10$, and 100%, plotted with a dashed, solid, and dot-dashed lines, respectively. The blue band and the black data points correspond to the best-fit power-law model and the IceCube data from Ref. [21]. $\zeta_{SN} = 100\%$ is incompatible with the current IceCube data, while $\zeta_{SN} = 10\%$ is marginally allowed. Bottom panel: Partial contributions to the diffuse neutrino intensity for one neutrino flavor from different regimes of $\Gamma_b$, for $\zeta_{SN} = 10\%$. As $\Gamma_b$ increases, the neutrino spectrum peaks at larger neutrino energies.

Assuming that baryon-rich jets and ordinary GRBs all belong to the same family and evolve by following $R_j(z, \Gamma_b)$, one can also indirectly constrain the local rate of baryon-rich bursts by adopting the IceCube high-energy neutrino data. In fact, Fig. 5 suggests that a local rate of baryon-rich bursts by adopting the IceCube high-energy neutrino data set for particular values of $\zeta_{SN}$. Such jets belong to an intermediate class between choked and high-luminosity GRBs, which is optically thick and in which $p\gamma$ interactions are both relevant, as discussed in Sec. II D.

IV. UNCERTAINTIES OF THE JET MODEL PARAMETER

The results presented in Sec. III have been obtained by assuming a simple model with common properties for all GRBs, except for the Lorentz factor $\Gamma_b$. Our conclusions are, however, limited by the astrophysical uncertainties. For example, we assumed that the local rate of successful GRBs is given by $\rho_{0,HL-GRB} = 0.8 \text{ Gpc}^{-3} \text{ yr}^{-1}$ [70]; this is an optimistic assumption as the local rate could be as low as $0.5 \text{ Gpc}^{-3} \text{ yr}^{-1}$ [70]. We also consider the simplest possible scaling law of the local cosmic rate of astrophysical jets as a function of $\Gamma_b$ [Eq. (28)], given the lack of data; other possible scaling relations might describe better the real GRB family.

Although the high-energy neutrino flux detected by the IceCube telescope is in the same energy range where the

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3We define the “allowed region” (“not-allowed region”) as the region of the parameter space where $[E_j^2 I_j(E_j)]_{\text{IC,band}} \leq [E_j^2 I_j(E_j)]_{\text{IC,band}} \leq [E_j^2 I_j(E_j)]_{\text{IC,band}}$ for all energy points $E_j$ of the IceCube data; the “marginally allowed region” is the transition region of the parameter space where roughly half of all energy points fall within one of the two previous categories.
neutrino emission from intermediate-$\Gamma_b$ jets peaks, we are able to provide bounds on the local rate of baryon-rich GRBs as a function of the jet energy by assuming a SN-GRB connection. Such constraints are roughly compatible with the ones presented in Ref. [12], obtained for choked sources. Note, however, that the bounds on $(\bar{E}_j, \Gamma_b)$ in Ref. [12] were extrapolated on the basis of an analysis on point sources, and $\Gamma_b$ was considered a fixed parameter typical of choked GRBs. Under the assumption of the SN-GRB connection, we expect that upper limits on the abundance of choked sources are going to become more stringent in the near future in light of the increasing statistics of the IceCube data sets.

We have assumed in this work that the parameters of each GRB are fixed during its duration. However, by including multiple internal shocks and assuming a non-narrow distribution in $\Gamma_b$ in each GRB as, e.g., in the simulations presented in Ref. [73], a qualitatively similar phenomenology to the one described above might be of relevance also in the transition from optically thick to optically thin emission regions.

Thus far, we assumed that the burst duration is independent of $\Gamma_b$. If high-energy particles are emitted mainly through internal shocks, the internal collisions occurring between the plasma shells inside the jet could, however, spread out in time and yield burst durations longer than the assumed $\bar{t}_j = 10$ s for bursts with low $\Gamma_b$. Although the dependence of $t_j$ on $\Gamma_b$ is relevant to describe the physics of astrophysical bursts, our assumption [$t_j(\Gamma_b) = \text{const.}$] does not affect our conclusions; see the discussion about results presented in Fig. 7.

We work under the assumption that internal collisionless shocks are able to accelerate protons efficiently for any Lorentz factor $\Gamma_b$. As discussed in Refs. [37,74–76], this might not be the case if radiation-mediated shocks occur in choked sources; as a consequence, proton acceleration could not be as efficient as considered here, and the correspondent neutrino energy fluxes from baryon-rich sources might be affected. However, as shown in Fig. 5, the upper bound on $\xi_{\text{SN}}$ should not be affected, since it is only indirectly constrained from the IceCube data from jets with intermediate $\Gamma_b$ that should, at least partially, evade the radiation-dominated regime. To prove that, we include the condition to avoid radiation-mediated shocks for our representative case with $\xi_{\text{SN}} = 0.1$, following the discussion in Ref. [37]. We vary the burst duration as a function of $\Gamma_b$ in such a way to recover the conservative bound: $\tau_{\text{F}} \leq 1$ [see Eq. (1)] for any redshift $z$. Specifically, we consider $t_j = 10$ s for $130 < \Gamma_b \leq 10^3$, $t_j = 500$ s for $50 < \Gamma_b \leq 130$, and $t_j = 10^6$ s for $\Gamma_b \leq 50$. Note that such a choice of $t_j$ is also responsible for lower jet luminosities as $\Gamma_b$ decreases in agreement with the upper bounds on the luminosity shown in Fig. 3 of Ref. [37] in order to evade the radiation-dominated regime. The total neutrino intensity computed within this setup is plotted in Fig. 7 (dashed violet curve), and it should be compared with the continuous green curve representing the total diffuse intensity for constant $t_j = 10$ s also shown in the top panel of Fig. 5. The condition $\tau_{\text{F}} \leq 1$ affects the leading cooling processes discussed in Sec. II B as a function of $\Gamma_b$ and the final shape of the expected neutrino intensity as shown in Fig. 7, but it does not drastically modify our conclusions.
Reference [77] pointed out that the collimation shock in the jet inside the star might be of relevance for the jet dynamics and, as discussed in Ref. [37], it might also affect the neutrino production. On the basis of the study presented here, we conclude that our main results are robust even with respect to the inclusion of such an effect now discarded. Nevertheless, further modeling of the jet properties by adding all the factors mentioned above is required, especially in light of the fact that jets with intermediate values of $\Gamma_b$ could produce a neutrino diffuse flux comparable to the one detected from IceCube.

V. CONCLUSIONS

The most likely scenario explaining the formation of the long-duration astrophysical bursts is the development of a jet out of a black hole or an accretion disk, soon after the core collapse of a supernova. However, observational evidence suggests that only a small fraction of supernovae evolves into high-luminosity gamma-ray bursts with highly relativistic jets. Probably, softer jets, invisible or scarcely visible electromagnetically, could originate from the remaining optically thick supernova heirs. These objects are possibly even more abundant that the ones leading to visible GRBs and have been dubbed baryon-rich jets in this work.

In this paper, we study the SN-GRB connection, by assuming that ordinary high-luminosity GRBs and baryon-rich jets originate from the same class of sources having core-collapse supernovae as common progenitors. We hypothesize that the local rate of such sources decreases as the Lorentz boost factor $\Gamma_b$ increases. To investigate the neutrino emission from this class of astrophysical jets, we define a general neutrino emission model, including hadronuclear and photomeson interactions as well as cooling processes for mesons and protons. For simplicity, we assume that ordinary GRBs and baryon-rich jets have identical jet properties except for the Lorentz factor $\Gamma_b$, although we prove that our conclusions should not drastically change with respect to variations of the other model parameters.

We find that the neutrino fluence peaks in different energy ranges according to the Lorenz boost factor, ranging from TeV energies for low-$\Gamma_b$ bursts to PeV energies for high-$\Gamma_b$ bursts. The neutrino production in low-$\Gamma_b$ jets is mainly due to hadronuclear interactions, while it is mainly determined by photon-meson interactions for bursts with high $\Gamma_b$.

The high-energy neutrino flux currently observed by the IceCube telescope could be generated, especially in the PeV region, from bursts with intermediate values of $\Gamma_b$ with respect to the typical ones of baryon-rich and bright GRBs: $\Gamma_b \in [10, 130]$. Such sources with intermediate values of $\Gamma_b$ are optically thick, therefore not or scarcely visible in photons, and $pp$ and $p\gamma$ interactions are both effective for what concerns the neutrino production.

Under the assumption that supernovae evolve in astrophysical bursts with variable $\Gamma_b$, we point out that by comparing the diffuse emission of high-energy neutrinos from jets with intermediate values of $\Gamma_b$ with the current best fit of the IceCube high-energy neutrino flux one could put indirect constraints on the local rate of choked GRBs. We find that the present IceCube data sets favor a local rate of choked sources lower than tens of percent of the local core-collapse supernova rate. Such constraints are roughly compatible with upper limits coming from dedicated searches on choked sources from the IceCube Collaboration. However, we expect them to become tighter in the near future in light of the increasing IceCube statistics and future generation neutrino telescopes [78].

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