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CAN WE OBSERVE NEUTRINO FLARES IN COINCIDENCE WITH EXPLOSIVE TRANSIENTS?

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Abstract. The new generation of powerful instruments is reaching sensitivities and temporal resolutions that will allow multi-messenger astronomy of explosive transient phenomena, with high-energy neutrinos as a central figure. We derive general criteria for the detectability of neutrinos from powerful transient sources for given instrument sensitivities. In practice, we provide the minimum photon flux necessary for neutrino detection based on two main observables: the bolometric luminosity and the time variability of the emission. This limit can be compared to the observations in specified wavelengths in order to target the most promising sources for follow-ups. Our criteria can also help distinguishing false associations of neutrino events with a flaring source. We find that relativistic transient sources such as high- and low-luminosity gamma-ray bursts (GRBs), blazar flares, tidal disruption events, and magnetar flares could be observed with IceCube, as they have a good chance to occur within a detectable distance. Of the nonrelativistic transient sources, only luminous supernovae appear as promising candidates. We caution that our criterion should not be directly applied to low-luminosity GRBs and type Ibc supernovae, as these objects could have hosted a choked GRB, leading to neutrino emission without a relevant counterpart radiation. We treat the concrete example of PKS 1424-418 major outburst and the possible association with an IceCube event IC 35.

Keywords: Neutrinos, transients

1 Introduction

With their improved sensitivity and time resolution together with the possibility of fast follow-up, current instruments allow the observation of Galactic and extragalactic transient phenomena over a wide energy range. The recent advances in neutrino and gravitational-wave detection open promising perspectives for transient multi-messenger studies. High-energy neutrinos are expected to play a key role in this picture as undeflected signatures of hadronic acceleration.

Recently, IceCube has opened exciting perspectives in neutrino astronomy by detecting very high energy astrophysical neutrinos Aartsen et al. (2013) and has developed and enhanced methods for time-variable searches Abbasi et al. (2012). So far, no neutrino detection has been confirmed in association with a transient source. In this context, it appears timely to derive general criteria for the detectability of neutrinos from powerful transient sources.

We focus in this work on sources that are characterized by short, violent, and irregular emissions, sometimes in addition to a quiescent emission, and that are usually associated with the acceleration of leptonic and hadronic particles. Photo-hadronic and hadronic interactions can lead to a neutrino production. Here we focus on the production of neutrino flares: we aim at constraining the parameter space of bursts and flares detectable in neutrinos by providing necessary conditions on the background fields of the source. Predicting neutrino flux levels is not the scope of this study; we focus here on estimating lower limits on the photon flux of the flare, which is required for the efficient production of a neutrino flare.

We demonstrate that we can describe the large variety of existing sources with a handful of variables: the distance from the source $D_{\rm s}$, the isotropic bolometric luminosity of the flare $L_{\rm bol}$ and its peak energy $\epsilon_{\rm peak}$, the variability timescale of the emission $t_{\rm var}$, and the bulk Lorentz factor of the outflow Γ. We calculate in the

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$L_{\rm bol} - t_{\rm var}$ parameter-space the maximum accessible neutrino energy in these sources and the minimum flux of photons in a flare required at a specific given wavelength, in order to allow detectability of a neutrino flare with IceCube.

2 Maximum accessible proton energy and indicative maximum neutrino energy

We consider a proton[*] of energy $E_p = \gamma_p m_p c^2$, accelerated in a one-zone region of size $R = \beta c \Gamma^2 t_{\rm var}(1+z)^{-1}$, bulk Lorentz factor $\Gamma = (1-\beta^2)^{-1/2}$, and of magnetic field strength B, in a source located at redshift z. We derive the mean magnetic field strength by setting $L_B = \eta_B L_{\rm bol}$, where $L_{\rm B}$ is the magnetic luminosity, defined as $L_B \sim (1/2)\beta c \Gamma^2 R^2 B'^2$.[†]

Focussing on flares has some important theoretical consequences. $t_{\rm var}$ is related to the size of the emitting region R by a condition of causality: $R \sim \beta\Gamma^2(1+z)^{-1} c t_{\rm var}$, where βc is the velocity of the outflow, and z the redshift of the source. The particle escape time is limited by the dynamical time $t_{\rm dyn} = \Gamma^2 t_{\rm var}(1+z)^{-1}$, which corresponds to the adiabatic energy loss time. In the same way, we consider only photo-hadronic interactions of accelerated hadrons on the *flaring* radiation, as interactions with steady baryon and photon fields would produce a neutrino emission diluted over time.

The acceleration timescale can be related to the particle Larmor time $t_{\rm acc} = \eta t_{\rm L}$, regardless of the acceleration mechanism (unless one invokes peculiar non-conducting plasmas) and in most cases $\eta \gg 1$ Lemoine & Waxman (2009). Given the complexity of particle acceleration models, we consider in the following the maximally efficient acceleration timescale, with $\eta \sim 1$; therefore $t'_{\rm acc} = E'_p / c\, e\, B'$. This timescale is usually overly optimistic in terms of efficiency; it is thus conservative to derive the necessary condition for detectability.

The maximum energy of accelerated particles is set by the competition between energy gains and energy losses: $t_{\rm acc} < \min(t_{\rm dyn}, t_{\rm syn})$ where $t_{\rm syn}$ is the synchrotron energy-loss timescale. In presence of strong magnetic fields, synchrotron cooling can be stronger than adiabatic energy losses. We assume that the magnetic luminosity of the considered region is fully radiated during the flare and set $\eta_B = 1$, which is valid if the dominant emission process is synchrotron radiation. Other energy-loss processes can influence the maximum energy of particles. We choose to neglect them here, as it preserves the *maximum achievable* nature of $E_{p,\rm max}$.

Photohadronic interactions can generate neutrinos through the production of charged pions and their subsequent decay.[‡] Neutrinos produced by photohadronic interactions typically carry 5% of the initial energy of hadrons. However, pions and muons can experience energy losses by adiabatic or synchrotron cooling before they decay. The muon decay time is usually the main limiting factor for neutrino production.

We find that for nonrelativistic outflows ($\Gamma \sim 1$), mild luminosities $L_{\rm bol} > 10^{36}$ erg s^{-1} and variability timescales longer than $t_{\rm var} \sim 10\,$s are required to reach $E_\nu > 100\,$TeV, which is the lower limit of the IceCube detection range. Sensitivities of future experiments such as GRAND Martineau-Huynh et al. (2016), aiming at energies $E_\nu > 1$ EeV, would be reached for higher luminosities $L_{\rm bol} > 10^{42}$ erg s^{-1} and longer variability timescales $t_{\rm var} > 10^6\,$s. We find that high-luminosity (HL) GRBs can accelerate protons up to $10^{20}\,$eV, which corresponds to classical estimates Waxman & Bahcall (2000). They could in principle produce very high energy neutrinos, with $E_\nu \lesssim 10^{18}$ eV. In this case, muon decay constitutes a very strong limiting factor and hence the maximum energy strongly depends on the variability timescale. Blazars, low-luminosity (LL) GRBs, and tidal disruption events (TDE) are also powerful accelerators with $E_\nu \lesssim 10^{18}$ eV.

3 Neutrino flux and detectability limit

We consider that the photon spectrum of the flare follows a broken power-law over $[\epsilon_{\rm min}, \epsilon_{\rm max}]$, with a break energy $\epsilon_{\rm b}$ and spectral indices $a < b$, with $b > 2$. This type of spectrum is adequate to model nonthermal processes such as synchrotron emission. However, the spectral energy distribution (SED) of explosive transients shows great diversity, and our approach could be refined by using more realistic SED. The maximum achievable neutrino flux can be estimated from the proton energy spectrum Waxman & Bahcall (1999): $E_\nu^2 F_\nu = 3/8 f_{p\gamma} E_p^2 F_p$, where $f_{p\gamma} \equiv t'_{\rm dyn}/t'_{p\gamma}$ is the photo-pion production efficiency. The photo-pion production timescale $t'_{p\gamma}$ depends

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[*] For maximization reasons, we concentrate on the proton case, which should lead to the highest rates of neutrino production compared to heavier nuclei.

[†] All primed quantities are in the comoving frame of the emitting region. Quantities are labeled $Q_x \equiv Q/10^x$ in cgs units or in eV for particle energies.

[‡] The resulting flavor composition is $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$, and the expected flavor composition at Earth is $1 : 1 : 1$ when long-baseline neutrino oscillations are accounted for. The fluxes we calculate account for all neutrino flavors.

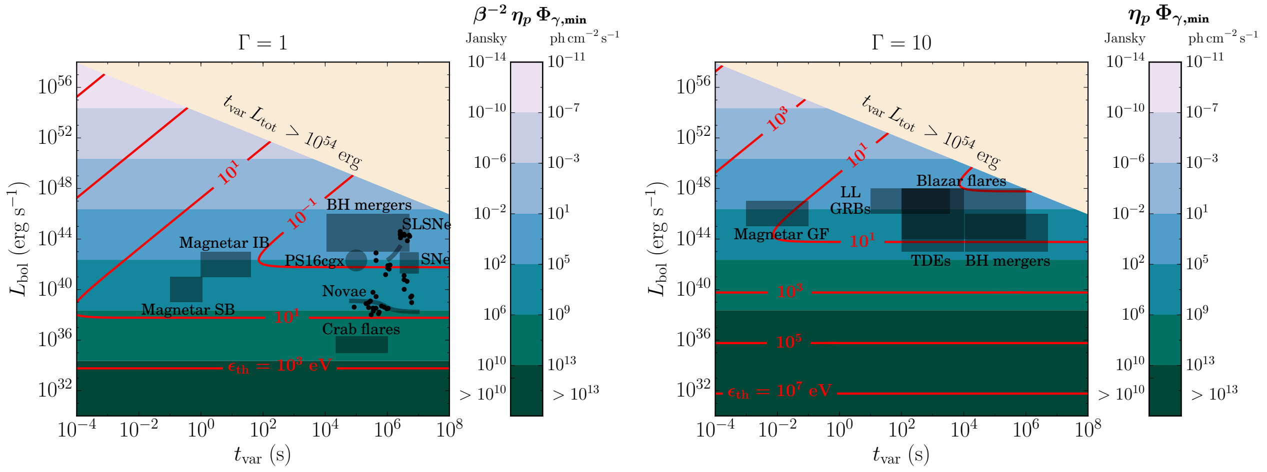

Fig. 1. Minimum photon flux $\Phi_{\gamma,\rm min}$ (color map, in Jy and $\rm ph\,cm^{-2}\,s^{-1}$) as a function of $L_{\rm bol}$ and $t_{\rm var}$ for $\Gamma = 1, 10$. A neutrino flare *can* be detectable if the observed photon flux $\Phi_{\gamma,\rm obs} \gtrsim \Phi_{\gamma,\rm min}$, above $\epsilon_{\rm th}$ (red lines) for soft photon spectra, and at $\epsilon_{\rm b}$ for hard spectra. Here $\eta_B = \eta_p = 1$. Overlaid are examples of explosive transients in the $L_{\rm bol} - t_{\rm var}$ parameter space.

on the interaction threshold energy $\epsilon'_{\rm th}$, the cross-section $\sigma_{p\gamma}$ and the inelasticity $\kappa_{p\gamma}$. We assume that a fraction η_p of the bolometric source luminosity is channelled into a population of accelerated protons, with a peak luminosity $\sim \eta_p L_{\rm bol}$.

For a neutrino detector of flux sensitivity $s_{\rm exp}$ and fluence sensitivity $\mathcal{S}_{\rm exp} \sim t_{\rm var} s_{\rm exp}$, we calculate the minimum photon flux required to reach the experimental detection limit, defining $\Phi_\gamma \equiv L/(4\pi D_{\rm L}^2 \epsilon)$[§]

$$\Phi_{\gamma,\rm min} = \frac{8}{3}\frac{4\pi\beta^2 c^2 \Gamma^4 \mathcal{S}_{\rm exp}}{\langle\sigma_{p\gamma}\kappa_{p\gamma}\rangle}\eta_p^{-1} L_{\rm bol}^{-1}(1+z)^{-1} \simeq 2\,{\rm Jy}\ \eta_p^{-1}\Gamma_2^4\, L_{\rm bol,52}^{-1}\,(1+z)^{-1}\ . \qquad (3.1)$$

The flux should be estimated at the minimum threshold energy $\epsilon_{\rm th} = \Gamma\,\epsilon''_{\rm th}\, m_p c^2/(1+z)E'_{p,\rm max}$ for soft photon spectra ($a > 1$), and at the observed spectral break energy $\epsilon_{\rm b}$ for hard photon spectra ($a < 1$). For IceCube, the sensitivity is characterized by a minimum fluence $\mathcal{S}_{\rm IC} = 5 \times 10^{-4}$ TeV cm^{-2} for $E_\nu = 10\,\rm TeV{-}10\,PeV$, which corresponds to a detection limit $s_{\rm IC} \sim 10^{-11}$ TeV cm^{-2} s^{-1} for a one-year data collection. The planned sensitivities for ARA, ARIANNA, CHANT, or GRAND are 1, 1.5, or 2 orders of magnitude better, respectively, than IceCube, at $E_\nu \sim 1$ EeV. In the following, we set the cosmic-ray loading factor $\eta_p = 1$ as a standard estimate, but most conservative limits should be obtained for $\eta_p = 100$.

We show in Figure 1 the minimum photon flux required to reach IceCube detection limit in the $L_{\rm bol} - t_{\rm var}$ parameter space for $\Gamma = 1, 10$. We set $\eta_p = \eta_B = 1$. We locate also concrete examples of explosive transients in the parameter space. The blazar case is discussed in Section 4.

In practice, here we describe how these figures can be used to determine whether an explosive transient could have a chance to be detected in neutrinos with IceCube. 1) Choose a bulk Lorentz factor Γ for the outflow.[¶] 2) Identify a broken power-law shape in the source emission, roughly measure the break energy $\epsilon_{\rm b}$ and whether the spectrum is soft ($a > 1$) or hard ($a < 1$) below the break. 3) Locate the source in the $L_{\rm bol} - t_{\rm var}$ parameter space and read the required flux $\Phi_{\gamma,\rm min}$ (colored contours). 4) Compare $\Phi_{\gamma,\rm min}$ with the observed flux of the source $\Phi_{\gamma,\rm obs}$, around the threshold energy $\epsilon_{\rm th}$ for soft spectra ($a < 1$), or at the break energy $\epsilon_{\rm b}$ for hard spectra ($a < 1$). A neutrino flare associated with the photon flare *can* be detectable if $\Phi_{\gamma,\rm obs} \gtrsim \Phi_{\gamma,\rm min}$.

We note that for many sources, $\Phi_{\gamma,\rm obs} \ll \Phi_{\gamma,\rm min}$ over the whole radiation spectrum, thus the knowledge of $\epsilon_{\rm th}$ or $\epsilon_{\rm b}$ is not necessary to conclude on the non-detectability. For more refined cases, however, we caution that $\epsilon_{\rm th}$ is a minimum value because it was derived from $E_{p,\rm max}$ (a maximum value). When checking detectability, one might wish to extend the comparison between $\Phi_{\gamma,\rm obs}$ and $\Phi_{\gamma,\rm min}$ for $\epsilon_{\rm th} > \epsilon_{\rm th,min}$, in case the actual maximum

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[§] We note that Φ_γ is a directly measurable quantity

[¶] In general, for a given luminosity, a higher Γ implies a higher $\Phi_{\gamma,\rm min}$ (Eq. 3.1), and is thus worse in terms of constraints. This can be kept in mind for sources with large uncertainties on Γ.

proton energy is lower than $E_{p,\max}$. Extrapolation of spectra should be conducted with care, always trying to maximize the photon flux, in order to avoid missing a detectable case.

4 Implications for categories of transients and specific case studies

The general approach presented up to this point allows us to evaluate the detectability in neutrinos of a large variety of explosive transients. We study the implications for general source categories and examine several concrete examples. Here we discuss in detail Blazar flares, and illustrate with the case of PKS 1424-418 major outburst. We refer to our main study Guépin & Kotera (2017) for more detail about other categories of transients.

Blazars are a subset of AGN whose jet is pointed toward the observer. Unification models allow to set their mean bulk Lorentz factor to $\Gamma_{\rm j} \sim 10$. A blazar flare is a very fast and short increase in blazar luminosity, with $t_{\rm var} \sim 10^2 - 10^6\,$s. In realistic scenarii, the bulk Lorentz factor of the flare is $\Gamma \gtrsim 100$. Blazar SEDs exhibit two nonthermal peaks, at low and high energies. In some cases, Blazar flaring emissions can be described by a soft power-law from submillimeter to X-rays, with typically $L_{\rm b} \sim 10^{45}$ erg s^{-1} at $\epsilon_{\rm b} \sim 1$ keV.

The IceCube Collaboration has detected astrophysical neutrinos up to PeV energies. For the third PeV event (IC 35, $E_\nu \sim 2$ PeV), searches for coincidence with AGN flares revealed a possible association with the major outburst of the Blazar PKS 1424-418 Kadler et al. (2016). A bright γ-ray emission and an increase in X-ray, optical, and radio emissions were observed in 2012 - 2013. The flux necessary for detectability, $\Phi_{\gamma,\min} \sim 1.7 \times 10^3\,{\rm ph\,cm^{-2}s^{-1}}$, is very close to the observed flux. Therefore, neutrino flares associated with such outbursts could meet the IceCube detection requirement. However, the association between the neutrino event and the blazar outburst remains unclear. Moreover, the value of the bulk Lorentz factor can strongly influence the results: a larger value $\Gamma > 10$ would disfavor detection.

5 Conclusion

We have derived the minimum photon flux necessary for neutrino detection from explosive transients, based on two main observables: the bolometric luminosity $L_{\rm bol}$, and the time variability $t_{\rm var}$ of the flaring emission. Our minimum photon flux requirement can be compared at around the indicated energy to the observed photon flux from various transient sources, in order to assess their detectability in neutrinos.

We find that for nonrelativistic and mildly relativistic outflows, only the photon fields between IR to UV wavelengths are relevant for neutrino production. Sources flaring at very high energy with no optical counterparts will not be observed. Of the NR transient sources, SLSNe appear to be the most promising candidates. The production of very high energy neutrinos, up to $E_\nu = 1\,$EeV, requires relativistic outflows. Such neutrinos could be produced by HL GRBs, LL GRBs, blazars, or TDEs. As computed by several authors, very luminous short bursts (GRBs, magnetar flares) have a good chance of being observed. However, cooling processes could prevent detection by strongly reducing the flux at the highest energies. Pions or muons could also leave the flaring region before decaying, and thereby delay the neutrino flare.

Our criterion should not be directly applied to low-luminosity GRBs or type Ibc supernovae because these objects could be off-axis GRBs or have hosted a choked GRB, leading to neutrino emission without a relevant radiation counterpart. Nevertheless, this study can be applied to a wide range of well-known sources and sensitivities of projected instruments. Our results indicate that with an increase of one to two orders of magnitude in sensitivity, next-generation neutrino detectors could have the potential to discover neutrino flares in PeV or EeV energy ranges.

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