PROCEEDINGS OF SCIENCE

Neutrino Energy Distributions of astrophysical sources: the GRB example.

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Neutrino astronomy is an emerging field allowing us to study the most energetic phenomena in the Universe. While some first neutrino sources have been recently identified, the origin of the full high-energy diffuse neutrino flux is still unknown. Gamma-ray bursts (GRBs) were believed to be a promising candidate to contribute to the diffuse flux. However, no significant counterpart neutrinos were observed in association with GRBs, despite numerous searches. To assess if GRBs are capable of emitting high-energy neutrinos, more refined analyses are now required. This project proposes an original approach based on the construction of "Neutrino Energy Distributions" (NEDs), which can be considered as the neutrino analog of spectral energy distributions in electromagnetic astronomy. By combining theoretical predictions from various models, NEDs provide a powerful tool to perform detailed, multi-energy studies. This contribution will first motivate the necessity of NEDs in neutrino astronomy, then review the theoretical neutrino emission processes in Gamma-ray Bursts and finally present two practical analyses examples.

39th International Cosmic Ray Conference (ICRC2025)
15–24 July 2025
Geneva, Switzerland

ICRC 2025
The Astroparticle Physics Conference
Geneva July 15-24, 2025

*Speaker

1. Introduction

Neutrino astronomy is a rapidly evolving field, where several important breakthroughs have been made, starting with the discovery of an astrophysical neutrino flux [1] and the identification of individual neutrino sources [2–4]. Despite the observation of these sources, the origin of the full diffuse flux is still unknown and requires further investigation.

Gamma-ray bursts (GRBs) have been believed to be the potential source of ultra-high-energy cosmic rays for a long time [5]. If they are indeed able to accelerate cosmic rays to relativistic speeds within the jet, interactions with high-energy (HE) photons produced in the radiation region(s) seem unavoidable, leading to HE neutrino production through photomeson interactions. This argument placed GRBs as natural candidates to account for part of the remaining neutrino flux.

Unfortunately, none of the analyses so far could claim a significant observation of neutrinos in association with GRBs [6, 7]. The most sensitive detector at the moment is the IceCube Neutrino Observatory [8]. Their most recent search was a set of stacking analyses on different GRB catalogs, looking for correlated neutrino observations with GRBs not only during the prompt phase, but also during the precursor and afterglow emission. The searches were made with a single event sample named the IceCube gamma-ray follow-up (GFU) data consisting of well-reconstructed, high-energetic muon tracks. They reported no coincident observations and constrained the prompt emission of all GRBs in the universe to represent <1% of the diffuse astrophysical neutrino flux, and <24% for emission on timescales up to 10^4s [6].

Other analyses have been conducted in search of counterpart neutrinos from particularly bright events, such as GRB221009A, called "the brightest of all time" or the BOAT [9, 10]. In this particular case, the follow-up has been made with multiple event selection samples of IceCube, and thus covering a larger range of energies. No significant observations of neutrinos from this particular event were made either, but upper limits on the flux were given for each sample, assuming it follows a power law.

Despite the non-detection of neutrinos, astrophysicists have started to constrain the different GRB models existing in the literature [9, 11]. Several event selections are used to cover different energy ranges, from MeV to PeV, but the model constraints are computed independently for each range. Doing so, the studies are blind to the fact that they are sensitive to common parameters, as described in Section 2.

The procedures described above could not find any significant signal and revealed that it is time to move on to more detailed analyses. We highlight two potential shortcomings. First, the data in different energy ranges are often treated separately in distinct statistical analyses, missing the enhancement a combination would bring. There has been many efforts in the IceCube collaboration to extend the sensitivity in the low energy range <TeV, providing the opportunity to do multi-energy studies. This point is even more important since multiple neutrinos detectors are under construction and it will soon become crucial to develop a framework where it is possible to combine different data sets. Second, in many studies, the neutrino flux is often assumed to be a single power-law $\Phi(E) \sim E^{-\gamma}$ over an energy range of interest. It is a simple approximation that cannot hold when considering a neutrino emission over several decades in energy, and there exist multiple theoretical models in the literature that are more realistic and ready to be used.

In these proceedings, we introduce Neutrino Energy Distributions (NEDs), which are the neutrino equivalent of Spectral Energy Distributions in electromagnetic astronomy. NEDs will address the aforementioned shortcomings of current analyses as they provide a detailed description of the neutrino flux from a particular source over a wide energy range, from ∼ GeV to EeV, enabling precise multi-energy studies. We implemented a code that groups multiple theoretical models: it takes some source parameters as inputs, such as the initial bulk Lorentz factor Γ, the total isotropic gamma ray energy E^{γ}_{iso}, and returns the neutrino flux calculated for the chosen models. We focus on the case of GRBs in this work but all the previous considerations apply to any neutrino-emitting source and we plan to develop NEDs for other promising sources.

The proceeding is structured as follows: Section 2 will review the principal neutrino production mechanism occurring in GRBs and how we build NEDs, we present some practical examples of analyses using NEDs in Section 3, and we conclude in Section 4.

2. GRB NEDs

GRBs are the brightest electromagnetic bursts in the universe. They are often classified in two categories called long and short GRBs, produced when rapidly rotating massive stars collapse or during binary neutron star mergers, respectively. These events leave a newborn central compact object, either a black hole or neutron star, which launches relativistic jets that emit the luminous gamma-ray signals. These jets can accelerate non-thermal protons in different sites, and are expected to produce neutrinos with different energies, as illustrated in Figure 1. In this section, we briefly review some popular models that predict neutrino emissions at different stages of the jet evolution in the fireball picture, and show how their combination results in a NED.

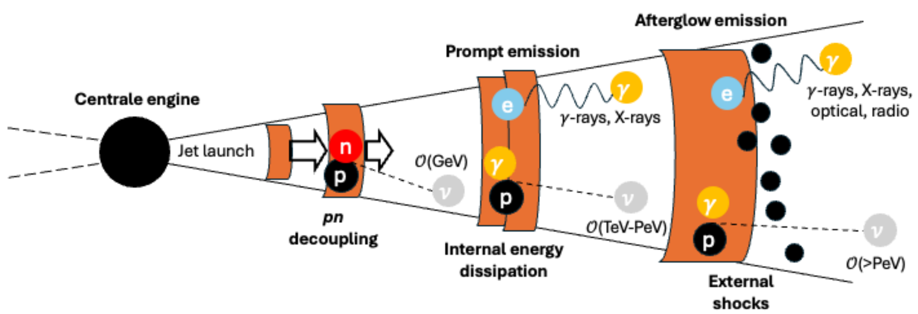

Figure 1: Schematic picture of neutrino emission in distinct radiation regions.

2.1 GeV neutrinos from pp and pn interactions

At the beginning of jet expansion, the thermal energy (or magnetic energy for Poynting flux dominated GRBs) provided by the central engine is partially converted to kinetic energy of the ejecta. The outflow keeps accelerating until it reaches a limit Lorentz factor Γ, then evolves with a constant speed in a period called coasting. The density in the first moments is so high that protons, neutrons and photons are strongly coupled. However, as the material expands, the density drops and the protons decouple from the neutrons. Murase et al describe two mechanisms that can generate a relative velocity between the two components above pion threshold [11]. If the decoupling occurs before coasting, only protons continue to accelerate and inelastic pn collisions occur, producing $\sim$ 1–10 GeV neutrinos. Otherwise, internal collisions of neutron-loaded outflows with different velocities can also lead to pn interactions, producing $\sim$ 30–300 GeV neutrinos. These models are particularly sensitive to the baryonic loading and the number ratio of neutrons to protons. All parameter dependencies are indicated in Table 1.

2.2 Neutrinos from prompt emission

To produce the powerful non-thermal radiation observed during the prompt phase of gamma ray bursts, the kinetic energy of the outflow must be dissipated, via mechanisms like shocks, turbulence, or magnetic reconnection, to non-thermal particle energy. The accelerated protons interact with gamma rays emitted by the co-accelerated electrons and produce high-energy neutrinos via photomeson processes. Three prominent scenarios are often discussed in the literature: the dissipative photosphere [12], the internal shocks (IS) [13], and the Internal-Collision-induced Magnetic Reconnection And Turbulence (ICMART) [14] models.

In the dissipative photosphere model, dissipation processes are believed to occur below the photosphere so particles can be accelerated and interact with gamma-rays released at the photosphere, around $r_{\mathrm{ph}} \sim 10^{12}$ cm. In the IS model, particles are accelerated at shocks created when outflows of the jet with different velocities collide. The typical collision radius can be estimated as $r_{\mathrm{IS}} = 2\Gamma^2 c\delta t \simeq 10^{13} - 10^{14}$ cm for typical GRB parameters. Finally, the ICMART model predicts a Poynting flux dominated jet, where the magnetic field lines remain well ordered up to a high dissipation radius $r_{\mathrm{ICMART}} \sim 10^{15}$ cm, where a strong run-away magnetic dissipation process occurs.

Although these models differ by the dissipative process that is taking place, their neutrino emission is computed with a single framework described in [15], but with a different radius for the dissipation region. This last characteristic is crucial as the particle number densities depend on the emission region radius, and it directly impacts the interaction rate, and thus the predicted neutrino flux (the larger the dissipation radius, the smaller the neutrino flux).

In addition to the dissipation radius, the models depend on many different parameters, as shown in Table 1. Most of these parameters are related to the gamma-ray spectrum and can be obtained from electromagnetic observations.

It is worth mentioning that all of these models are one-zone models, meaning that photons, cosmic rays are assumed to be produced in the same emission region. More realistic multi-zone models exist where the dissipation occurs at multiple regions, and different messengers are also produced at different regions. Such an IS model predicts considerably lower neutrino fluxes, leaving a greater part of the parameter space unconstrained than in single-zone models [16]. These models are not yet incorporated in our GRB NEDs.

2.3 High-energy neutrinos from external shocks

Following the prompt emission phase, the jet interacts with the surrounding interstellar medium (ISM), and is decelerated as a relativistic forward shock develops into it. Simultaneously, a reverse shock travels back into the jet and quickly crosses it. The emission produced by synchrotron radiation in these external shocks is responsible for the long-lasting afterglow observed in gamma-ray bursts.

Since the emission region is much larger than for the prompt phase, particle densities and neutrino production efficiency are lower, making them harder to detect. As the afterglow photon spectrum is softer, afterglow neutrinos have higher energies, $E_\nu \sim 0.1 - 10$ EeV.

We only implemented the forward shock model, described in [17], where four evolution scenarios are considered, depending on the shock evolution that can be adiabatic or radiative, and the ISM which is homogeneous or follows a density profile $n(r) \propto r^{-2}$ due to enhanced stellar activity prior to the burst.

2.4 Neutrino Energy Distribution

Our code outputs the neutrino energy distribution for a user-specified GRB. The user simply provides the desired acceleration mechanisms and the corresponding parameter values listed in Table 1, and the code returns the resulting NED. Two examples are presented in Figure 2, where the parameters are chosen from typical long GRB values.

Specifically, for the left plot, we adopt a bulk Lorentz factor $\Gamma = 650$, a redshift $z = 1$, an isotropic-equivalent energy release $E_{\rm iso} = 1.2 \times 10^{55}$ erg, and a prompt gamma-ray luminosity $L_\gamma = 1.9 \times 10^{54}$ erg s^{-1}. The prompt photon spectrum is modeled with a break energy $E_{\rm break} = 300$ keV, low-energy photon index $\alpha = 0.97$, and high-energy index $\beta = 2.37$. For the hadronic component, we assume a power-law proton spectrum with spectral index $s = 2$, and set the ratio of neutron to proton number densities to unity, $n_n/n_p = 1$. The microphysical parameters are $\epsilon_p = 0.8$, $\epsilon_e = 0.1$, and $\epsilon_B = 0.1$, representing the fractions of dissipated energy carried by protons, electrons, and magnetic fields, respectively. We adopt the same parameters on the right plot except for $\Gamma = 300$, $E_{\rm iso} = 1.2 \times 10^{54}$ erg, $L_\gamma = 1.9 \times 10^{53}$ erg s^{-1}, and z = 0.1.

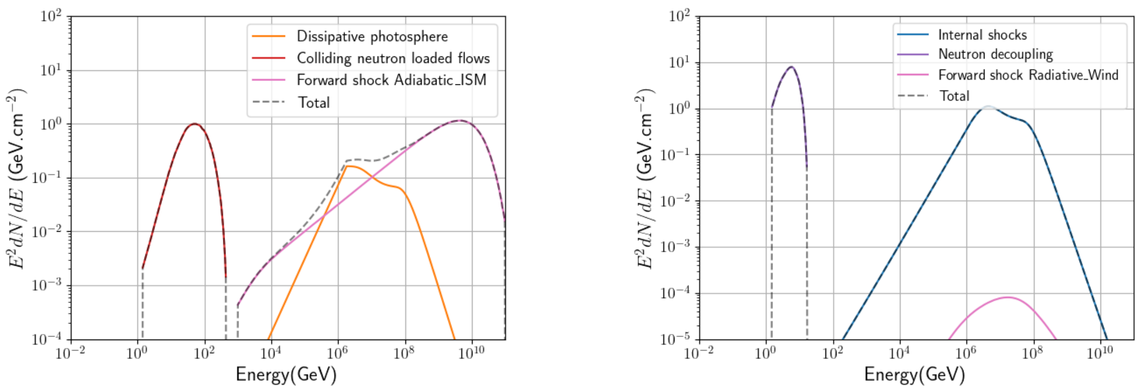

Figure 2: Two example of NED for different choices of inputs; colors indicate the emission models, $\Gamma = 650$ (300), $E_{\rm iso} = 1.2 \times 10^{55}$ (10^{54}) erg, $L_\gamma = 1.9 \times 10^{54}$ (10^{53}) erg s^{-1}, and z = 1 (0.1) in the left (right) plot and the other parameters are described in Section 2.4

3. Applications

In this section, we present two practical applications of NEDs: enhancing follow-up analyses and enabling the search for specific astrophysical sources (in this case GRBs) with neutrino observatories.

Parameters	**pn interactions**	**Prompt emission**	**External shocks**
Γ	×	×	×
Redshift (z)	×	×	×
E^{γ}_{iso}	×	×	×
L^{γ}_{iso}		×	
Microphysical params ($\epsilon_{e,p,B}$)	×	×	×
np ratio	×		
Dissipation radius		×	
Break energy E^{γ}_{b}		×	
Band indices (α, β)		×	
Accel. efficiency		×	
CR spectrum		×	×
ISM profile			×
ISM density			×

Table 1: Model dependency on physical parameters. A cross (×) indicates a dependency.

3.1 Upgraded GRB follow-ups

As described in the introduction, the IceCube Collaboration has performed a follow-up of the event GRB 221009A in multiple event selection samples independently. NEDs offer the opportunity to perform a single follow-up, combining all the information from the different datasets, with a detailed flux description. The MOMENTA software [18] provides the ideal framework for this task. It is capable of gathering the observations from independent datasets in a single Bayesian statistical analysis, and can handle any tabulated flux prior involving up to 2 free parameters. With this setup, one could try to perform a follow-up of the BOAT for a given choice of popular models while treating the Lorentz factor and the baryonic loading as free parameters to identify the allowed and excluded regions of the parameter space. Technically, it is also possible to compute Bayes factors for different choices of models in the NED, allowing one to determine which model configuration provides the best description of the data.

3.2 Search for astrophysical sources

So far, the neutrino detectors have relied on joint observations with electromagnetic telescopes to identify neutrino sources. However, NEDs make it possible to search for specific sources using neutrino observatories alone. Consider a search focused on a particular GRB, characterized by the parameters and acceleration mechanisms illustrated in Figure 2, left plot. It is possible to perform pseudo-experiments to simulate the footprints that such a source would leave in a given detector. As a concrete example, we used the instruments response functions (IRFs) of the IceCube PSTracks sample [19] to perform simulations of the signal produced in this GRB scenario, as shown in Figure 3.

It is possible to build a dataset of signal-like events by running many pseudo-experiments, and then train a machine learning algorithm to search for signal events in actual neutrino detector data. While this example focuses on a single event-selection sample, similar pseudo-experiments can be conducted for each of them. The machine learning model can then combine the information across

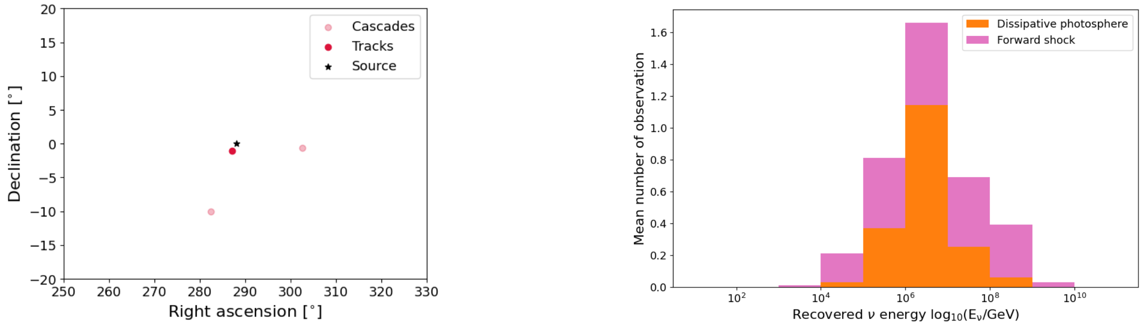

Figure 3: Signal observed by PSTracks in pseudo-experiments. (Left) Reconstructed direction of the neutrinos from a single experiment. (Right) Expected number of observations as a function of reconstructed energy, computed from 100 trials, the color indicate the mechanism responsible for the neutrino emission. The source is located at declination = 0° and right ascension = 288°, and its NED is the same as in Figure 2, left.

all datasets, improving sensitivity and classification performance. This procedure is realizable for any neutrino observatory as long as one disposes of the IRFs of the detector.

4. Summary and outlooks

We motivated how Neutrino Energy Distributions are needed to perform detailed neutrino astrophysics, as they allow to do multi-energy studies and provide more realistic flux description than simple power laws. We implemented NEDs for popular theoretical models of GRBs, allowing for great freedom in the choice of source parameters, and described two practical analysis ideas where they can be used.

In the future, the code will be made public after more models, and other IRFs, are implemented. We also plan to build NEDs for other promising neutrino-emitting astrophysical sources, such as supernova and active galactic nuclei. Finally, we encourage the reader to share with us any interesting neutrino emission model they would like to see implemented.

Acknowledgment

Moyaux Emile is a Research Fellow of the Fonds de la Recherche Scientifique – FNRS.

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