Flavor And Energy Inference For The High-Energy IceCube Neutrinos And Applications In Quantum Spacetime Models

Giacomo D'Amico*

Dipartimento di Fisica, Università di Roma "La Sapienza",
P.le A. Moro 2, 00185 Roma, Italy INFN, Sez. Roma1, P.le A. Moro 2, 00185 Roma, Italy
**E-mail: ab_giacomo.damico@uniroma1.it*

A flavor and energy inference analysis is presented for each high-energy neutrino event observed by the IceCube observatory during six years of data taking. For each event the main observables in the IceCube detector are the deposited energy and the event topology (showers or tracks) produced by the Cherenkov light by the transit through a medium of charged particles created in neutrino interactions. Using Bayesian inference and Markov chain Monte Carlo it is possible to reconstruct from these observables the properties of the astrophysical neutrino which generated such event. In the end, in the contest of a multi-messenger astrophysics, it is speculated that some aspects of IceCube data may be manifestations of quantum-gravity-modified laws of propagation for neutrinos. A speculation which, as testified by some recent publications, has attracted an increasing interest.

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1. Introduction

The largest neutrino telescope to date is the IceCube Neutrino Observatory at the geographic South Pole. After six years of data taking [1], from early 2010 to early 2016 for a total of 2078 days, 74 cointened "high-energy starting event" (HESE) with deposited energies above 30 TeV have provided the evidence for the existence of an extraterrestrial neutrino flux. The discovery of this flux has motivated a vigorous program of studies to unravel their origin [2] and their properties [3–5].

In previou works IceCube data have been analyzed and discussed in detail (see Ref. [2,3,6] and references therein) using a maximum-likelihood approach over the whole collection of events. Although useful informations about the energy behavior and the flavor composition has already been explored, it has never been performed an inference analysis of the properties of each single astrophysical neutrino.

This inference analysis for the energy of the astrophysical neutrinos will be then used in order to suggest that some aspects of IceCube data might be manifestations of quantum-gravity-modified laws of propagation for neutrinos. The prediction of a neutrino emission associated with gamma ray bursts (GRBs) is generic within the most widely accepted astrophysical models [7]. After a few years of operation IceCube still reports [8] no conclusive detection of GRB neutrinos, contradicting some influential predictions [9–12] of the GRB-neutrino observation rate by IceCube. From the viewpoint of quantum-gravity/quantum-spacetime research it is interesting to speculate that the IceCube results for GRB neutrinos might be misleading because of the assumption that GRB neutrinos should be detected in very close temporal coincidence with the associated -rays: a sizeable mismatch between GRB-neutrino detection time and trigger time for the GRB is expected in several much-studied models of neutrino propagation in a quantum spacetime (see Refs.[13–15] and references therein).

2. Neutrino inference analysis and assumptions on the astrophysical flux

IceCube detects neutrinos by observing Cherenkov light produced by charged particles created in neutrino interactions as they transit the ice within the detector. At this range of energies, the way neutrinos interact is deep-inelastic scattering with nuclei in the detector material. There are two possible interactions: charged-current (CC) or neutral-current (NC) interactions. In both a cascades of hadrons is created at the neutrino interaction vertex and for CC interaction this shower is accompanied by an outgoing charged lepton which may itself trigger another overlaid cascades. IceCube events have two basic topologies: tracks and showers. Considering the energy involved for this analysis we assume tracks are made only by ν_μ CC interactions and by ν_τ CC interactions in which the tau lepton decays in $\nu_\tau \mu \nu_\mu$. Showers instead are those events without visible muon tracks and are formed by particle showers near the neutrino vertex. While the particle content of showers created by final-state hadrons, electrons, and taus is different, the IceCube detector is currently insensitive to the difference. This means that a shower is produced in ν_e CC interaction, ν_τ CC interactions (where the produced τ does not decay in the muonic channel), and in all-flavor NC interactions. In Table 1 we summarize all parameters and the sequence of events that, given a neutrino with energy E_ν, cause an observed-deposited energy $E_{dep.}^{obs.}$ in the detector. In a certain sense, we need to go backwards through the whole chain of events in order to infer the neutrino energy E_ν from the observed-deposited energy $E_{dep.}^{obs.}$ and its topology.

As usually done in literature, let D denote the observed data, in our case the observed-deposited energy $E_{dep.}^{obs.}$ and the event topology (track or shower), and θ denote the model parameters, which are summarized in the first column of Table 1. Formal inference then requires setting up a joint probability distribution $f(D, \theta)$ (here and in the rest of this paper we will refer simply as f to all distributions). This joint distribution comprises two parts: a prior distribution $f(\theta)$ (see the second column of Table 1) and a likelihood $f(D|\theta)$. Defining $f(\theta)$ and $f(D|\theta)$ gives the full probability distribution

$$f(D, \theta) = f(D|\theta) \cdot f(\theta). \tag{1}$$

Having observed D, one can then obtain the distribution of θ conditional on D by applying the Bayes theorem

$$f(\theta|D) = \frac{f(D|\theta) \cdot f(\theta)}{\int f(D|\theta) \cdot f(\theta)\, d\theta}. \tag{2}$$

This is called the posterior distribution of θ and is the object of our Bayesian-inference analysis. From the posterior distribution of θ one can then obtain the

Table 1. Table of all parameters used in this analysis along with their associated prior probability distribution. The last column shows the references where these parameters are discussed in detail.

Parameters		Prior probability distribution	Ref.
		Flux parameters	
r	(anti-neutrino/neutrino ratio)	$\delta(r-1)$	16
ℓ	(neutrino flavor)	$1/3, \quad \ell = e$ $1/3, \quad \ell = \mu$ $1/3, \quad \ell = \tau$	17
γ	(spectral index)	$\delta(\gamma-2)$	1,18
E_ν	(neutrino energy)	$E_\nu^{-2} / \left((60\,\text{TeV})^{-1} - (3\,\text{PeV})^{-1}\right)$	1,18
		Deep-inelastic scattering parameters	
k	(neutrino-nucleon interaction)	$A_1 + A_2 \cdot \ln(\epsilon - A_3), \quad k = \text{NC}$ $1 - A_1 - A_2 \cdot \ln(\epsilon - A_3), \quad k = \text{CC}$	19,20
y	(inelasticity parameter)	$d\sigma_k(E_\nu)/dy$	19,21
		τ-decay parameters	
j	(τ-decay channel)	$0.18, \quad j = \tau \to \nu_\tau e \nu_e$ $0.18, \quad j = \tau \to \nu_\tau \mu \nu_\mu$ $0.12, \quad j = \tau \to \nu_\tau \pi$ $0.26, \quad j = \tau \to \nu_\tau \rho$ $0.13, \quad j = \tau \to \nu_\tau a_1$ $0.13, \quad j = \tau \to \nu_\tau X \quad (X \neq \pi, \rho, a_1)$	22
z	(energy fraction E_{ν_τ}/E_τ)	$4/3\left(1 - z^3\right), \quad \text{if } j = \tau \to \nu_\tau e \nu_e \text{ or } \nu_\tau \mu \nu_\mu$ $(a_\pi + b_\pi \cdot z)\,\theta(1 - r_\pi - z), \quad \text{if } j = \tau \to \nu_\tau \pi$ $(a_\rho + b_\rho \cdot z)\,\theta(1 - r_\rho - z), \quad \text{if } j = \tau \to \nu_\tau \rho$ $(a_{a_1} + b_{a_1} \cdot z)\,\theta(1 - r_{a_1} - z), \quad \text{if } j = \tau \to \nu_\tau a_1$ $1/0.3\,\theta(0.3 - z), \quad \text{if } j = \tau \to \nu_\tau X \quad (X \neq \pi, \rho, a_1)$	22–24
z'	(energy fraction E_ℓ/E_τ)	$4 - 12z' + 12z'^2 - 4z'^3, \quad \text{if } j = \tau \to \nu_\tau e \nu_e \text{ or } \nu_\tau \mu \nu_\mu$	22,23
		Deposited Energy	
$E^{obs.}_{dep.}$	(observed deposited energy)	$\mathcal{N}(E^{obs.}_{dep.} \,\vert\, E_{dep.}, \sigma_{E_{dep.}})$	3,5

expected value of a given parameter by integrating over the remaining parameters or study the dependence between parameters x and y by applying the product rule $f(x|y, D) = f(x, y|D)/f(y|D)$.

From Eq. 2, one recovers the maximum likelihood approach as a special case that holds under particular conditions, such as many data points and vague priors, which clearly are not satisfied in this analysis.

In theory, Bayesian methods are straightforward: the posterior distribution contains everything you need to carry out inference. In practice, the posterior distribution can be difficult to estimate precisely. A useful tool to derive the posterior distribution of Eq. 2 is the Markov Chain Monte Carlo (MCMC) technique. In a MCMC instead of having each point being generated one independently from another (like in a Monte Carlo), the sequence of generated points takes a kind of random walk in parameter space. In particular, for this work we performed the MCMC using the Gibbs sampling algorithm[25], in order to explore the entire parameter space of the posterior distribution. This allows us to derive the unknown and potentially complex distribution $f(\theta|D)$ and estimate all neutrino properties we are interested in.

3. Astrophysical neutrinos affected by in-vacuo dispersion

Focusing only on shower events, for which the energy inference is less problematic, and focusing on the class of scenarios whose predictions for energy (E_ν) dependence of Δt (the mismatch between GRB-neutrino detection time and trigger time for the GRB) can all be described in terms of the formula [a] (working in units with the speed-of-light scale c set to 1)

$$\Delta t = \eta_X \frac{E_\nu}{M_P} D(z) \pm \delta_X \frac{E_\nu}{M_P} D(z)\,, \tag{3}$$

one finds that 9 IceCube neutrinos fit the requirements for candidate GRB neutrinos affected by in-vacuo dispersion. The properties of these 9 candidates are summarized in Fig. 1. The correlation between $|\Delta t|/(1+z)$ and $E^*/(1+z)$ [b] for

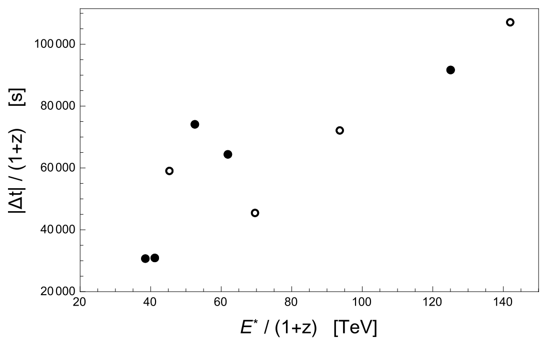

Fig. 1. Points here in figure correspond to the 9 GRB-neutrino candidates picked up by the selection criteria, characterized in terms of their values of $\Delta t/(1+z)$ and $E^*/(1+z)$. Filled points correspond to "late neutrinos" ($\Delta t > 0$), while unfilled points correspond to "early neutrinos" ($\Delta t < 0$).

[a]Here the redshift- (z-)dependent $D(z)$ carries the information on the distance between source and detector, and it factors in the interplay between quantum-spacetime effects and the curvature of spacetime. With M_P we denote the Planck scale ($\simeq 1.2 \cdot 10^{28} eV$) while the values of the parameters η_X and δ_X characterize the specific scenario one intends to study.

[b]E^* is a "distance-rescaled energ" defined as $E \cdot D(z)/D(1)$.

the 9 GRB-neutrino candidates highlighted in Fig.1 is of 0.866. We then ask[26,27] how often a time-randomization procedure produces 9 or more GRB-neutrino candidates with correlation ≥ 0.866, and remarkably we find that this happens only in 0.11% of cases.

References

1. M. G. Aartsen *et al.*, The IceCube Neutrino Observatory - Contributions to ICRC 2017 Part II: Properties of the Atmospheric and Astrophysical Neutrino Flux (2017).
2. M. G. Aartsen *et al.*, Search for astrophysical sources of neutrinos using cascade events in IceCube, *Astrophys. J.* **846**, p. 136 (2017).
3. S. Palomares-Ruiz, A. C. Vincent and O. Mena, Spectral analysis of the high-energy IceCube neutrinos, *Phys. Rev.* **D91**, p. 103008 (2015).
4. M. G. Aartsen *et al.*, Observation and Characterization of a Cosmic Muon Neutrino Flux from the Northern Hemisphere using six years of IceCube data, *Astrophys. J.* **833**, p. 3 (2016).
5. M. G. Aartsen *et al.*, Energy Reconstruction Methods in the IceCube Neutrino Telescope, *JINST* **9**, p. P03009 (2014).
6. M. Chianese, R. Mele, G. Miele, P. Migliozzi and S. Morisi, Use of ANTARES and IceCube data to constrain single power-law neutrino flux (2017).
7. T. Piran, Gamma-ray bursts: A puzzle being resolved, *Phys. Rept.* **333**, 529 (2000).
8. M. Aartsen, M. Ackermann, J. Adams, J. Aguilar, M. Ahlers, M. Ahrens, I. Al Samarai, D. Altmann, K. Andeen, T. Anderson *et al.*, Extending the search for muon neutrinos coincident with gamma-ray bursts in icecube data, *The Astrophysical Journal* **843**, p. 112 (2017).
9. E. Waxman and J. N. Bahcall, High-energy neutrinos from cosmological gamma-ray burst fireballs, *Phys. Rev. Lett.* **78**, 2292 (1997).
10. J. P. Rachen and P. Meszaros, Cosmic rays and neutrinos from gamma-ray bursts, *AIP Conf. Proc.* **428**, 776 (1998).
11. D. Guetta, D. Hooper, J. Alvarez-MuÃ±iz, F. Halzen and E. Reuveni, Neutrinos from individual gamma-ray bursts in the batse catalog, *Astroparticle Physics* **20**, 429 (2004).
12. M. Ahlers, M. C. Gonzalez-Garcia and F. Halzen, GRBs on probation: testing the UHE CR paradigm with IceCube, *Astropart. Phys.* **35**, 87 (2011).
13. G. Amelino-Camelia, Quantum-spacetime phenomenology, *Living Reviews in Relativity* **16**, p. 5 (2013).
14. U. Jacob and T. Piran, Neutrinos from gamma-ray bursts as a tool to explore quantum-gravity-induced lorentz violation, *Nature Physics* **3**, p. 87 (2007).
15. G. Amelino-Camelia and L. Smolin, Prospects for constraining quantum gravity dispersion with near term observations, *Physical Review D* **80**, p. 084017 (2009).
16. H. Nunokawa, B. Panes and R. Zukanovich Funchal, How Unequal Fluxes of

High Energy Astrophysical Neutrinos and Antineutrinos can Fake New Physics, *JCAP* **1610**, p. 036 (2016).
17. M. G. Aartsen *et al.*, Flavor Ratio of Astrophysical Neutrinos above 35 TeV in IceCube, *Phys. Rev. Lett.* **114**, p. 171102 (2015).
18. E. Waxman and J. N. Bahcall, High-energy neutrinos from astrophysical sources: An Upper bound, *Phys. Rev.* **D59**, p. 023002 (1999).
19. R. Gandhi, C. Quigg, M. H. Reno and I. Sarcevic, Ultrahigh-energy neutrino interactions, *Astropart. Phys.* **5**, 81 (1996).
20. A. Cooper-Sarkar, P. Mertsch and S. Sarkar, The high energy neutrino cross-section in the Standard Model and its uncertainty, *JHEP* **08**, p. 042 (2011).
21. A. Connolly, R. S. Thorne and D. Waters, Calculation of High Energy Neutrino-Nucleon Cross Sections and Uncertainties Using the MSTW Parton Distribution Functions and Implications for Future Experiments, *Phys. Rev.* **D83**, p. 113009 (2011).
22. S. I. Dutta, M. H. Reno and I. Sarcevic, Tau neutrinos underground: Signals of muon-neutrino —¿ tau neutrino oscillations with extragalactic neutrinos, *Phys. Rev.* **D62**, p. 123001 (2000).
23. P. Lipari, Lepton spectra in the earth's atmosphere, *Astroparticle Physics* **1**, 195 (1993).
24. K. Hagiwara, K. Mawatari and H. Yokoya, Tau polarization in tau neutrino nucleon scattering, *Nucl. Phys.* **B668**, 364 (2003), [Erratum: Nucl. Phys.B701,405(2004)].
25. A. E. Gelfand, Gibbs sampling, *Journal of the American Statistical Association* **95**, 1300 (2000).
26. G. Amelino-Camelia, L. Barcaroli, G. D'Amico, N. Loret and G. Rosati, IceCube and GRB neutrinos propagating in quantum spacetime, *Phys. Lett.* **B761**, 318 (2016).
27. G. Amelino-Camelia, G. D'Amico, G. Rosati and N. Loret, In-vacuo-dispersion features for GRB neutrinos and photons, *Nat. Astron.* **1**, p. 0139 (2017).