Snowmass2021 - Letter of Interest

Detecting Cosmic Neutrino Counterparts with Next-Generation Gamma-Ray Telescopes

Thematic Areas:

☐ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
☐ (Other) *[Please specify frontier/topical group]*

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Abstract: The detection of the neutrino event IceCube-170922A conincident in direction and time with the flaring blazar TXS 0506+056 detected by *Fermi*-LAT lends support to the possibility that flaring blazars may be the source of the high-energy astrophysical neutrinos detected by IceCube. If confirmed, this may also have significant implications for the origin of high-energy cosmic ray acceleration. However, the optimal conditions for neutrino production in many physical scenarios are expected to be mostly opaque to high-energy γ-rays, as the GeV emission is reprocessed down to the MeV band. Currently, the MeV band is the least explored region of the electromagnetic spectrum. Using a toy model of neutrino production through $p\gamma$ interactions in blazar jets we used MEGAlib to simulate the observed emission by the next-generation MeV telescope AMEGO-X. We find that AMEGO-X would be sensitive to the reprocessed electromagnetic counterpart of the neutrino production, indicating that a next generation MeV telescope may provide the key data necessary to finally understand the nature of the high-energy astrophysical neutrinos and cosmic rays.

Introduction

High-energy cosmic rays (CRs) and neutrinos can reach energies far exceeding those obtained by even the Large Hadron Collider, and thus they serve as probes of fundamental physics at energies unattainable in terrestrial experiments. The origin of CRs and neutrinos, however, still remains an open question. Many astrophysical sources suspected of having the conditions necessary for CR acceleration also contain intense matter and radiation fields with which CRs interact, ultimately producing both neutrinos and γ-rays[1]. Thus the best approach for answering these fundamental questions is through multi-messenger campaigns, which leverage both neutrinos and photons.

Neutrinos have long garnered interest as the unfailing messengers of hadronic interactions in the Universe. With a low interaction cross section and being electrically neutral, they travel virtually unhindered through their sources and over cosmological distances, carrying information about regions from which neither high-energy γ-rays nor CRs can escape. The ratios of their three flavors (ν_e, ν_μ, ν_τ) measured at Earth may encode information about their production within their sources[2]. High-energy cosmic neutrinos also present the opportunity to test symmetries in the Standard Model, search for dark matter, and study neutrino oscillations and cross-sections[3].

γ-rays provide complementary information to the neutrinos. The strikingly similar intensities of the extragalactic γ-ray background and the CR and diffuse neutrino spectra may be a hint of a common origin (at least in part) for all of these phenomena[4]. Among the different possibilities, blazars (a subclass of AGN whose jets are directed very close to our line of sight with strong γ-ray variability) have long been of interest as possible sources of CRs and high-energy neutrinos.

The IceCube Neutrino Flux and Blazar Neutrino Flares: The Case of TXS 0506+056

The IceCube Neutrino Observatory has reported the detection of an isotropic flux of high-energy astrophysical neutrinos[5,6], the origin of which remains unknown, as well-established point sources have yet to be identified[7,8]. Recently, the track-like ν_μ event IceCube-170922A was found to be coincident in direction and time with a γ-ray flare from the blazar TXS 0506+056[9], which lends support to the possibility that relativistic blazar jets may be the first confirmed source of cosmic neutrinos. A later analysis showed that roughly three years earlier $\sim$13 neutrinos were detected by IceCube from the same direction in the sky[10]. This earlier 'neutrino flare' had no associated γ-ray flare detected by *Fermi*-LAT. Indeed, in many physical scenarios it is expected that the conditions in blazar jets that are instrumental for efficient neutrino production via photo-hadronic (pγ) interactions do not allow GeV γ-rays to escape, due to enhanced $\gamma\gamma$ optical depths[11], resulting in GeV γ-rays being reprocessed to the MeV band.

Observationally, MeV γ-rays are thus far one of the least explored bands in the electromagnetic (EM) spectrum, whereas theoretical models suggest that this band is the key to identity neutrino production and CR acceleration in blazar jets[12–14]. To fully understand the corresponding EM and neutrino signatures, support for both observational and theoretical multi-messenger studies will be essential. Leading the efforts in this pursuit is the All-Sky Medium Energy Gamma-ray Observatory (AMEGO)[15,16], a probe-class mission concept that combines high sensitivity in the 200 keV to 10 GeV energy range with a wide field of view, good spectral resolution, and polarization sensitivity. In particular, AMEGO's MeV sensitivity will improve upon previous MeV missions by an order-of-magnitude. A smaller-scale and lower cost pathfinder mission, called AMEGO-X, is also under development.

— ***Toy Model and MEGAlib Simulations*** — We can make inferences about the kinds of MeV observations that would have been possible with AMEGO-X during the first neutrino flare of TXS 0506+056 by using a toy model. We modeled the flare as a sudden injection of γ-rays arising from inelastic collisions between accelerated CRs and photons in the jet. For $p\gamma$ interactions, the in-source γ-ray fluence is closely related[17] to the neutrino fluence measured by IceCube[10] (corrected for redshift[18] and relativistic beaming). For the jet radiation field, we used a spectral energy distribution motivated by the blazar sequence[19–22]. The γ-rays propagate down the jet, producing $e^\pm$ pairs in their collisions with jet photons. As the pairs propagate down

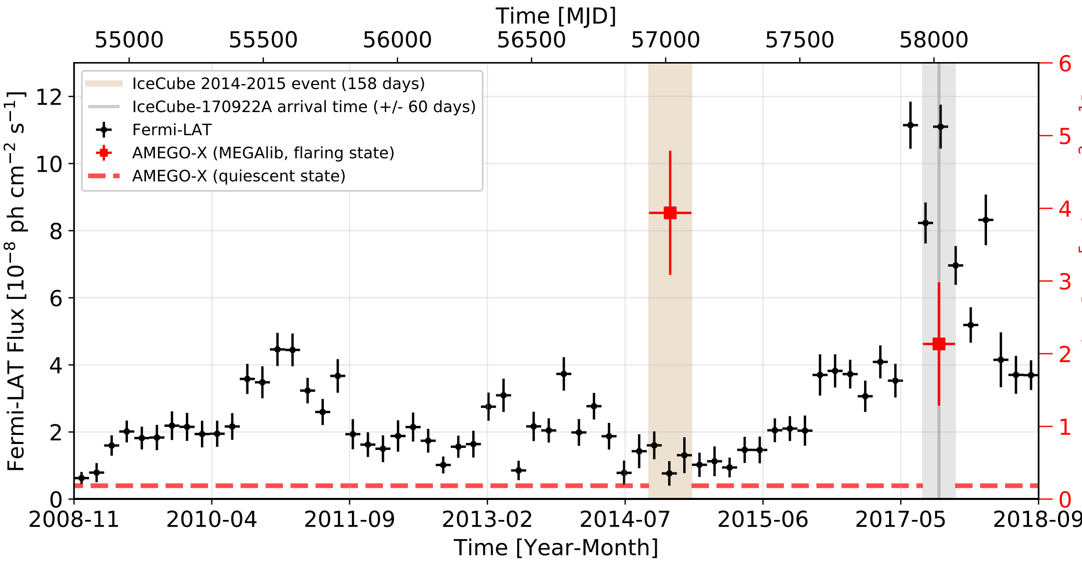

Figure 1: **Observations in the MeV energy range will be essential for issuing high-energy transient alerts and providing robust identification of high-energy neutrino sources.** *The detection of the cosmic neutrino IceCube-170922A coincident in direction and time with a γ-ray flare from the blazar TXS 0506+056 detected by* Fermi-*LAT shows the necessity of EM observations. We have modeled the expected MeV emission based on the neutrino fluence and found that the next generation telescope AMEGO-X would have detected a bright flare from the down-processed high-energy emission.*

the jet, they lose energy through inverse Compton (IC) scattering of jet photons and synchrotron radiation. We allow the spectrum of the pairs to evolve in time, accounting for energy losses, and calculate the light curve and the average spectrum of IC-scattered MeV γ-rays.

With the derived γ-ray spectrum and light curve for the first neutrino flare, we simulated the expected observations from AMEGO-X using the Medium-Energy Gamma-ray Astronomy library (MEGAlib). We also simulated the second neutrino event based on the SED modeling from Keivani+20[23] and assuming the light curve that was observed by *Fermi*-LAT[24]. Results for the simulations are shown in Fig. 1. The black data points show LAT data from over $\sim$ 10 years of observations. The tan band marks the first neutrino event (158 days[10]) and the grey band marks the second neutrino event (120 days[9]). During the second flare, the rise in the LAT flux is coincident with the arrival time of the ν_μ event. In contrast, there was no coincident GeV flare seen during the first event. However, our toy model shows that this event would have been significantly detected by AMEGO-X in the MeV band. Thus, an MeV telescope such as AMEGO-X may be capable of providing the key data needed to robustly determine the origins of high-energy cosmic neutrinos and to garner vital insights into the hadronic physics in their sources.

Summary and Conclusion

The origin of high-energy astrophysical neutrinos detected by IceCube remains unknown, and the sources of high-energy CRs have been a mystery for over a century. Obtaining a better understanding of these fundamental questions will require a multi-messenger approach, for which observations of EM counterparts, particularly in the MeV band, are crucial. The detection of IceCube-170922A coincident in direction and time with a *Fermi*-LAT–detected flare in blazar TXS 0506+056 supports the notion that blazars may be sources of astrophysical neutrinos and CR accelerators. However, an earlier event of $\sim$13 neutrinos from the same source did not coincide with an enhanced flux of GeV γ-rays. This can be understood in the context of $p\gamma$ interactions occurring in intense radiation fields, which leads to down-processing GeV γ-rays to the MeV band. Using a toy model of this process we ran simulations with MEGAlib and found that a future MeV telescope such as AMEGO-X would be sensitive to this emission.

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