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TANAMI counterparts to IceCube high-energy neutrino events

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on behalf of the TANAMI and the *Fermi*-LAT Collaborations

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Since the discovery of a neutrino flux in excess of the atmospheric background by the IceCube Collaboration, searches for the astrophysical sources have been ongoing. Due to the steeply falling background towards higher energies, the PeV events detected in three years of IceCube data are the most likely ones to be of extraterrestrial origin. Even excluding the PeV events detected so far, the neutrino flux is well above the atmospheric background, so it is likely that a number of sub-PeV events originate from the same astrophysical sources that produce the PeV events. We study the high-energy properties of AGN that are positionally coincident with the neutrino events from three years of IceCube data and show the results for event number 4. IC 4 is a event with a low angular error ($7^\circ.1$) and a large deposited energy of 165 TeV. We use multiwavelength data, including *Fermi*-LAT and X-ray data, to construct broadband spectra and present parametrizations of the broadband spectral energy distributions with logarithmic parabolas. Assuming the X-ray to γ -ray emission in blazars originates in the photoproduction of pions by accelerated protons, their predicted neutrino luminosity can be estimated. The measurements of the diffuse extragalactic background by *Fermi*-LAT gives us an estimate of the flux contributions from faint unresolved blazars. Their contribution increases the number of expected events by a factor of ~ 2 . We conclude that the detection of the IceCube neutrinos IC4, IC14, and IC20 can be explained by the integral emission of blazars, even though no individual source yields a sufficient energy output.

I. INTRODUCTION

The IceCube Collaboration's announcement of the discovery of a neutrino flux in excess of the atmospheric background is an inflection point in multimessenger astronomy [11]. Due to the steeply falling atmospheric background spectrum, events at the highest energies most likely have an extraterrestrial origin [1].

Neutrino emission from the jets of active galactic nuclei (AGN) [17] and cores [23] has been predicted, but alternative possibilities are gamma-ray bursts [25] and pevatrons in the Galactic center region [5]. All IceCube events are consistent with an isotropic distribution, and therefore extragalactic sources are the prime candidates. Only the predicted flux of $\sim 10^{-8}$ GeV/cm²/s/sr at energies from 100 TeV to a few PeV from AGN jets matches the observed excess flux well [15].

AGN with jets that are observed at small angles to the line of sight are called 'blazars'. Their non-thermal emission becomes relativistically boosted. The low energy emission is generally attributed to synchrotron emission. Emission at higher energies can be explained by hadronic and leptonic models. In hadronic models, protons (as well as electrons) are accelerated in the jet. The protons interact with seed photons

at lower energies (e.g., from the accretion disk or external radiation fields) and produce pions [pion photoproduction; 16]. Subsequent pion decays produce neutrinos and γ -rays. Currently, the observed spectral energy distributions (SEDs) of AGN can be described equally well with hadronic and leptonic emission processes due to a large number of free parameters [e.g., 7]. Unambiguous evidence of hadronic processes could be provided by an association of neutrino events with an individual blazar. In pion photoproduction, the neutrino flux can be directly calculated from the observed flux of the high-energy bump in the SED $F_\nu = F_\gamma$. This estimate has been confirmed by Monte-Carlo simulations [19]. The neutrino fluence can therefore be estimated directly from the integrated X-ray to γ -ray flux of the broadband SED.

Due to the large angular uncertainties, several possible candidate blazars can be identified for each of the IceCube shower events. We have previously shown [14] that the 2 events at PeV energies from the first two years of IceCube (IC20, dubbed 'Ernie' and IC 14, 'Bert') can be explained calorimetrically by the six candidate blazars from the TANAMI sample. Here, we study the multiwavelength properties of AGN from the TANAMI sample, as well as *Fermi* blazars that are positionally coincident with the neutrino events

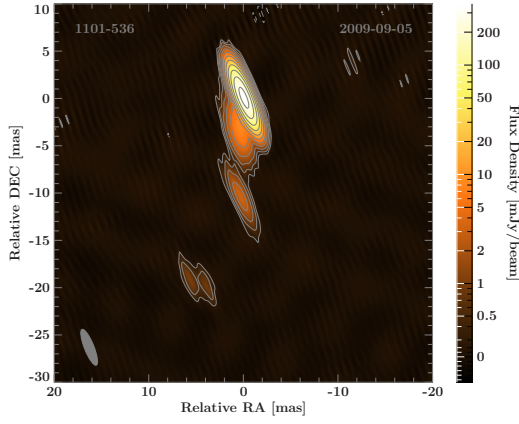


FIG. 1: First-epoch TANAMI VLBI image of 2FGL J1103.9–5356 at 8.4 GHz. The color scale indicates the flux density distribution, the white contours are scaled logarithmically and increase by factors of 2, with the lowest contour set to the 3σ -noise-level. The gray ellipse in the lower left corner shows the beam with (4.1×1) mas at 22° . This blazar shows a bright radio core with a brightness temperature of $T_B = 5.43 \times 10^{10}$ K (for $S_{\text{core}} \sim 0.39$ Jy) and a single-sided jet in southern direction.

from three years IceCube data. We address the question whether the sub-PeV neutrino events can be explained by blazars in the error field. In particular, we calculate the expected neutrino fluence of the four blazars in the field of IceCube event 4 (IC4). IceCube event number 4 has a lower median angular error of 7.1° compared to the PeV events with error radii of up to 13° and a higher energy than most of the other IC events (165 TeV), i.e., has a low probability of being of atmospheric origin. Inside the IC4 error field, there are four γ -ray bright AGN listed in the 2LAC catalog [2]. We report on the multiwavelength properties of these four sources below.

II. MULTIWAVELENGTH DATA

Tracking Active Galactic Nuclei with Austral Milliarcsecond Interferometry (TANAMI)[27] [21] is a multiwavelength program that monitors extragalactic jets of the Southern Sky.

Figure 1 shows the first-epoch high-resolution image of 2FGL J1103.9–5356 (PKS 1101–536) obtained with Very Long Baseline Interferometry (VLBI) at 8.4 GHz. An 8.4 GHz VLBI image of PKS 1104–445 has been shown by [21]. Both sources show core-dominated radio structures typical for blazars with a single-sided jet, indicating relativistically beamed emission. The two other IC 4 candidate sources have not been observed in the TANAMI VLBI program as of 2015.

X-ray data taken during the IceCube period are

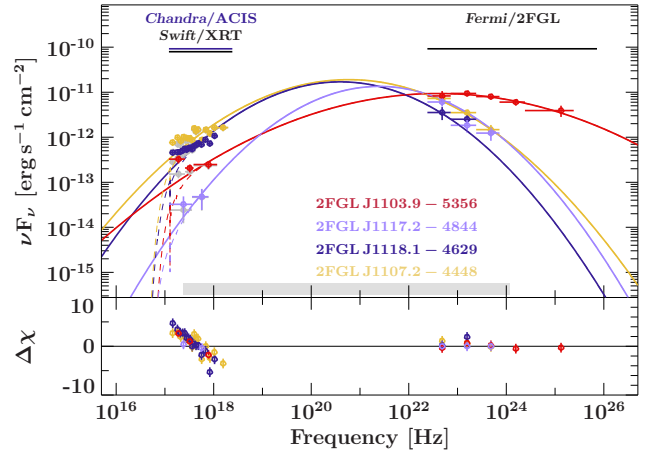


FIG. 2: X-ray to γ -ray SED of all four 2LAC sources including a log parabola fit to the data. The gray area shows the energy range used for the calculation of the neutrino events

from the TANAMI program and the public archives of Swift [8] and Chandra. Swift/XRT and Chandra/ACIS data were reduced with standard methods, using the most recent software packages (HEASOFT 6.15.1, CIAO 4.6) and calibration databases. Spectra were grouped to a minimum signal-to-noise ratio of 5 to ensure the validity of χ^2 statistics. For a low SNR, the spectra were grouped to a minimum signal-to-noise ratio of 2 and the use of Cash statistics [9]. Spectral fitting was performed with ISIS 1.6.2 [10]. The X-ray data were deabsorbed using the Galactic N_H value [13], abundances from [26], and cross sections from [24]. We have used the γ -ray spectra from the 2FGL catalog [20].

III. RESULTS

Electromagnetic cascades in pion photoproduction emit at X-ray and γ -ray energies, and we approximate the non-thermal photon flux F_γ by the integrated flux between 1 keV and 5 GeV [14]. The broadband spectra were fit with a logarithmic parabola [18] including X-ray absorption.

The X-ray to γ -ray SEDs of all four sources are shown in Fig. 2. As shown by [14], this allows us to model the high-energy hump with logarithmic parabolas in order to estimate the integrated flux and the fluence in the IceCube integration period. This fluence can be used to directly estimate the number of neutrinos. Using the IceCube integration period of $\Delta t = 998$ days, and an effective area of $A_{\text{eff}} = 10^5 \text{ cm}^2$ for contained events, we obtain the values listed in Table I. The numbers would be lower for a realistic spectrum of the emitted neutrinos or if some fraction of the emission is produced in a leptonic, proton-synchrotron, or Bethe-Heitler process. The steepness of the blazar γ -

TABLE I: Integrated electromagnetic energy flux from 1 keV to 5 GeV and expected electron neutrino events in 998 days of IceCube data for the 4 candidate blazars of IceCube event 4. Uncertainties are statistical only.

Source	Assoc. source	$F_\gamma [10^{-11}]$	events
2FGL		[erg/s/cm ²]	
J1103.9–5356	PKS 1101–536	$7.6^{+1.7}_{-1.4}$	0.22 ± 0.05
J1107.2–4448	PKS 1104–445	$14.0^{+1.7}_{-1.8}$	$0.40^{+0.05}_{-0.06}$
J1117.2–4844	PMN J1117–4838	8^{+6}_{-5}	$0.23^{+0.18}_{-0.15}$
J1118.1–4629	PKS 1116–46	11.3 ± 0.6	0.33 ± 0.02
Sum			1.18 ± 0.18

ray luminosity function [22] further implies that in a large field, the neutrino fluence will have significant contributions from the brightest sources in the field, as well as from fainter, unresolved sources.

A. Contributions from unresolved blazars

At the sensitivity of current catalogs, a large number of faint blazars are not resolved into individual point sources by *Fermi*-LAT, but do contribute to the diffuse extragalactic gamma-ray background (EGB). In order to calculate the number of expected neutrinos, one should also consider the substantial contribution of this most numerous part of the blazar population. The fraction of blazars in the EGB has been estimate to lie between 50% and 80% [12]. At 100 GeV, half of the EGB has been resolved into individual blazars (mainly BL Lac type objects) by *Fermi*-LAT [4].

We compare the values of the EGB flux to the total flux of resolved blazars, in order to estimate the contributions from unresolved blazars, assuming pion photoproduction. We find a total integrated flux for all four 2LAC sources of $F_{100 \text{ MeV} - 820 \text{ GeV}} = 1.71 \times 10^{-7} \text{ ph/s/cm}^2$, which corresponds to $3.54 \times 10^{-6} \text{ ph/s/cm}^2/\text{sr}$ for a 7.1° error field. The extragalactic background is $F_{100 \text{ MeV} - 820 \text{ GeV}} = 7.2 \pm 0.6 \times 10^{-6} \text{ ph/cm}^2/\text{s/sr}$ [4], a factor of ~ 2 higher than the value for the resolved blazars. This suggest that a substantial fraction of the extragalactic neutrino flux in this field originates from faint, unresolved blazars, instead of the bright, low-redshift sources.

IV. CONCLUSION

Assuming that the high-energy emission originates in pion photoproduction, the maximum expected

number of electron neutrino events from all four 2LAC sources for IC4 is 1.18 ± 0.18 for 998 days. This is close to the number of detected events, but given the different factors that might reduce the neutrino output below the rate predicted by our basic model (leptonic contributions, neutrino spectra, etc.; see [14]) it seems unlikely that any of the individual brightest blazars in the field of IC4 can explain the observed neutrino flux. This situation is similar to the fields of the two PeV neutrinos IC14 and IC21 [14], where the predicted neutrino flux of the six brightest blazars matched the IceCube observed flux, but the individual sources fell short of yielding sufficient fluence. The integral flux of bright individual blazars and faint remote sources, however, rises a factor of 2 above the observed flux in this field, consistent with the hypothesis that the population of blazars as a whole can explain the IceCube results.

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