Broadband transmission of Ernie and Bert: The TANAMI view of the IceCube PeV neutrino events

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on behalf of the TANAMI and the Fermi-LAT collaborations

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Abstract

The IceCube Collaboration has reported the discovery of a neutrino flux in excess of the atmospheric background. Due to low atmospheric background at PeV energies, the highest energy events are the most likely ones to be of extraterrestrial origin. We study the multiwavelength properties of AGN from the TANAMI sample that are positionally coincident with the PeV neutrino events. We combine multiwavelength data, including *Fermi*-LAT, X-ray data and radio VLBI images to construct broadband spectra and present parametrizations of the broadband spectral energy distributions. Assuming the X-ray to γ-ray emission originates in the photoproduction of pions by accelerated protons, the integrated predicted neutrino luminosity of these sources is high enough to explain the detected PeV events.

Introduction: IceCube neutrinos at PeV energies

The IceCube Collaboration's announcement of the discovery of a neutrino flux in excess of the atmospheric background is a watershed in multimessenger astronomy. Due to the steeply falling atmospheric background spectrum, events at PeV energies most likely have an extraterrestrial origin (Aartsen et al. 2014, see Fig. 1), and the search for the sources in which these neutrinos originated is ongoing (Anchordoqui et al. 2014; Dermer et al. 2014; Padovani et al. 2014). We show why AGN are the most likely candidates for these sources and examine whether they are able to explain the observed flux (Krauß et al. 2014).

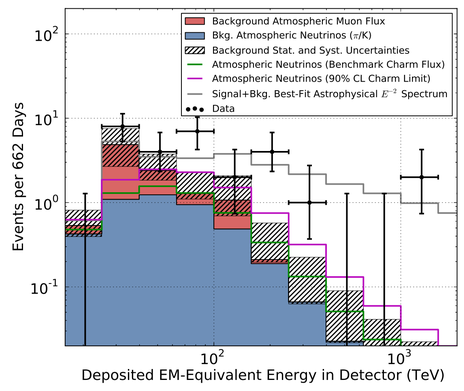

Fig. 1. Energy of IceCube detected neutrino event vs. number of detected neutrino events in the first two years. An excess is seen at PeV energies (IceCube Collaboration, 2013).

Possible astrophysical sources

- Isotropic distribution of all IceCube events → **extragalactic origin** likely
- Single source in the **Galactic center** excluded by ANTARES (Adrián-Martínez et al. 2014).
- **Gamma-ray Burst (GRB)** origin unlikely, no GRBs found at position and time consistent with PeV events.

→ AGN/Blazars are the most likely extragalactic candidate sources (Mannheim, 1993; Halzen, 2005).

AGN/Blazars: Particle acceleration in jets

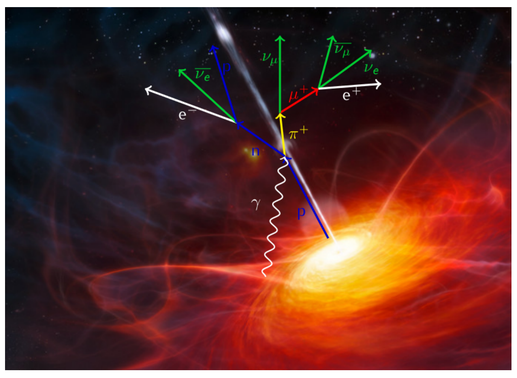

Fig. 2. Low energy photons (e.g., from the accretion disk) interact with high-energy protons. Subsequent pions decay into neutrinos/high-energy photons, amongst others (adapted from ESO/M.Kornmesser).

Assuming that protons are accelerated in the jet, pions are created by interactions with UV photons (e.g., from the accretion disk and the jet). Subsequent decays produce high-energy photons and neutrinos, besides other particles (Mannheim, 1993). We can estimate the maximum neutrino fluence by using the integrated flux of the high energy hump $F_\gamma = F_\nu$, where the symbols have their usual meanings. In other words:

The neutrino fluence can be calculated directly from the integrated flux of the high-energy hump.

The TANAMI project

Tracking Active Galactic Nuclei with Austral Milliarcsecond Interferometry (TANAMI) regularly monitors 84 extragalactic jets south of −30° declination with VLBI techniques at two frequencies (8.4 and 22.3 GHz). TANAMI is using the Australian/South-African Long Baseline Array (LBA+) as well as the IVS antennas TIGO, O'Higgins, and Warkworth (see Fig. 1). Besides providing VLBI images and kinematic studies, TANAMI aims to study the multiwavelength properties of blazars and other extragalactic jets (Ojha et al. 2010, `http://pulsar.sternwarte.uni-erlangen.de/tanami`). We use archival quasi-simultaneous multiwavelength data in order to create broadband spectra.

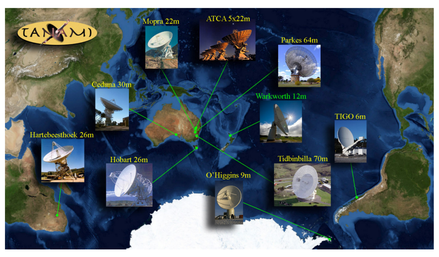

Fig. 3. The TANAMI Array

Results I: VLBI images

Six TANAMI sources are located in the 1σ median positional uncertainty region for the two PeV events, three in each of the fields (see Table 1). Of the twelve brightest γ-ray sources (in the two fields) from the 2FGL catalog (Nolan et al. 2012), only these six sources have correlated VLBI flux densities at 8.4 GHz above 400 mJy.

Table 1. TANAMI sources compatible with the two IceCube PeV events.

Source	R.A.[°]	Dec[°]	z	Class.	Θ [°]
0235−618	39.2218△	−61.6043△	0.47♦	FSRQ♦	5.61
0302−623	45.9610†	−62.1904†	1.35♦	FSRQ♦	5.98
0308−611	47.4838†	−60.9775†	1.48♦	FSRQ♦	7.39
1653−329	254.0699△	−33.0369△	2.40◇	FSRQ◇	11.18
1714−336	259.4001⋆	−33.7024⋆	?	BL Lac▲	7.87
1759−396	270.6778•	−39.6689•	1.32■	FSRQ■	12.50

Columns: (1) IAU B1950 name, (2) right ascension, (3) declination, (4) redshift, (5) optical classification, (6) angular distance to IceCube event coordinates ♦Healey et al. (2008), △Cutri et al. (2003), †Lambert & Gontier (2009), ⋆Immer et al. (2011), •Fomalont et al. (2003), ▲Véron-Cetty & Véron (2006), ■Massaro et al. (2009), ◇Masetti et al. (2008)

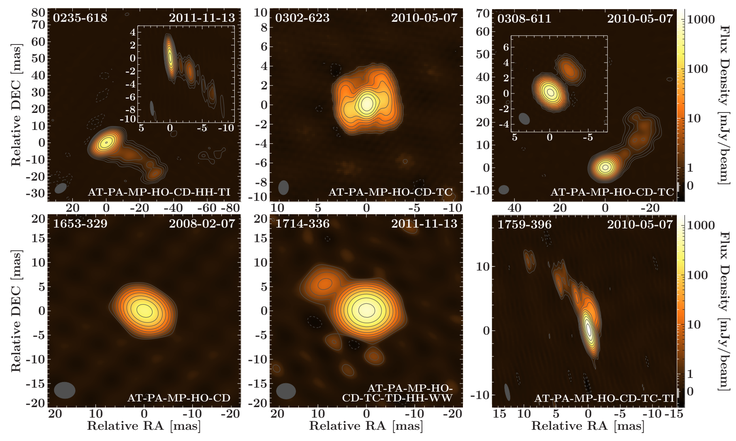

Fig. 4. TANAMI VLBI images at 8.4 GHz, restoring beams are shown in the bottom left corners. Contour lines start at $3\sigma_{\rm rms}$ and increase logarithmically by factors of 2. The array is given in the bottom right corner: PA: Parkes, AT: ATCA, MP: Mopra, HO: Hobart, CD: Ceduna, HH: Hartebeesthoek, TC: Tigo, TI: Tidbinbilla (70 m), TD: Tidbinbilla (34 m), WW:Warkworth (Krauß et al. 2014).

Results II: Broadband spectra

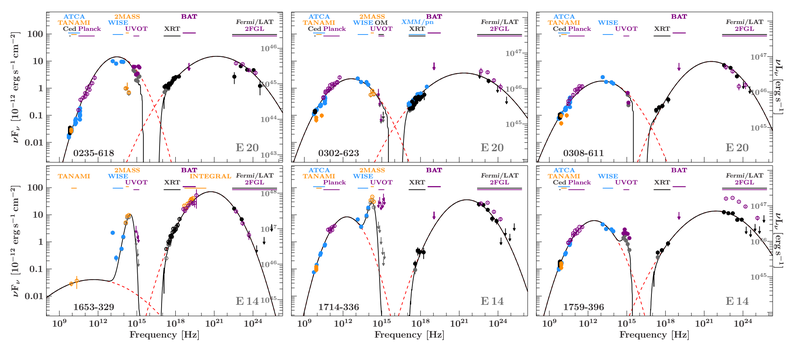

Fig. 5. Broadband SEDs for the six TANAMI blazars. Filled/open data points are from the IceCube integration period (2010 May–2012 May)/archival data outside the time period. Absorbed (X-ray) and reddened (optical/UV) data are shown in gray. The data have been parametrized with log parabolas (red dashed lines), as well as by an additional black-body component where necessary (Krauß et al. 2014).

We obtain values for the maximum expected neutrino fluence for each of the sources (see Table 2), by adopting $E_\nu = 1$ PeV as the neutrino-production peak energy, an exposure time of $\Delta t = 662$ days, an effective area of $A_{\rm eff} = 10^5\,{\rm cm}^2$ for contained PeV events, and the integrated 1 keV to 5 GeV flux. The sum of these values for the six blazars in 662 days is 1.9 ± 0.4. This is surprisingly close to the actual number of observed events. Assuming a more realistic neutrino spectrum lowers this number, but leaves room for the additional contributions from a large number of remote, faint blazars not included in the TANAMI sample.

Table 2. Integrated energy flux from 1 keV to 5 GeV and expected electron neutrino events at 1 PeV in 662 days of IceCube data for the six candidate blazars. Errors are statistical only.

Source	F_γ(erg cm^{-2} s^{-1})	events
0235−618	$(1.0^{+0.5}_{-0.5}) \times 10^{-10}$	$0.19^{+0.04}_{-0.04}$
0302−623	$(3.4^{+0.7}_{-0.7}) \times 10^{-11}$	$0.06^{+0.01}_{-0.01}$
0308−611	$(7.5^{+2.9}_{-2.9}) \times 10^{-11}$	$0.14^{+0.05}_{-0.05}$
1653−329	$(4.5^{+0.5}_{-0.5}) \times 10^{-10}$	$0.86^{+0.10}_{-0.10}$
1714−336	$(2.4^{+0.5}_{-0.6}) \times 10^{-10}$	$0.46^{+0.10}_{-0.12}$
1759−396	$(1.2^{+0.3}_{-0.2}) \times 10^{-10}$	$0.23^{+0.50}_{-0.40}$
Total		1.9 ± 0.4

Conclusion & Outlook

Bright AGN are able to calorimetrically explain the observed IceCube events at PeV energies.

- The assumptions leave room for contributions from unidentified, unresolved sources.
- The publication of the third IceCube event (Aartsen et al. 2014) includes six TANAMI sources in the field of view, including Centaurus A (Kadler et al., in prep).

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