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nature physics

ARTICLES

PUBLISHED ONLINE: 18 APRIL 2016 | DOI: 10.1038/NPHYS3715

Coincidence of a high-fluence blazar outburst with a PeV-energy neutrino event

M. Kadler[1]*, F. Krauß[1,2], K. Mannheim[1], R. Ojha[3,4,5], C. Müller[1,6], R. Schulz[1,2], G. Anton[7], W. Baumgartner[3], T. Beuchert[1,2], S. Buson[8,9], B. Carpenter[5], T. Eberl[7], P. G. Edwards[10], D. Eisenacher Glawion[1], D. Elsässer[1], N. Gehrels[3], C. Gräfe[1,2], S. Gulyaev[11], H. Hase[12], S. Horiuchi[13], C. W. James[7], A. Kappes[1], A. Kappes[7], U. Katz[7], A. Kreikenbohm[1,2], M. Kreter[1,7], I. Kreykenbohm[2], M. Langejahn[1,2], K. Leiter[1,2], E. Litzinger[1,2], F. Longo[14,15], J. E. J. Lovell[16], J. McEnery[3], T. Natusch[11], C. Phillips[10], C. Plötz[12], J. Quick[17], E. Ros[18,19,20], F. W. Stecker[3,21], T. Steinbring[1,2], J. Stevens[10], D. J. Thompson[3], J. Trüstedt[1,2], A. K. Tzioumis[10], S. Weston[11], J. Wilms[2] and J. A. Zensus[18]

The astrophysical sources of the extraterrestrial, very high-energy neutrinos detected by the IceCube collaboration remain to be identified. Gamma-ray (γ-ray) blazars have been predicted to yield a cumulative neutrino signal exceeding the atmospheric background above energies of 100 TeV, assuming that both the neutrinos and the γ-ray photons are produced by accelerated protons in relativistic jets. As the background spectrum falls steeply with increasing energy, the individual events with the clearest signature of being of extraterrestrial origin are those at petaelectronvolt energies. Inside the large positional-uncertainty fields of the first two petaelectronvolt neutrinos detected by IceCube, the integrated emission of the blazar population has a sufficiently high electromagnetic flux to explain the detected IceCube events, but fluences of individual objects are too low to make an unambiguous source association. Here, we report that a major outburst of the blazar PKS B1424–418 occurred in temporal and positional coincidence with a third petaelectronvolt-energy neutrino event (HESE-35) detected by IceCube. On the basis of an analysis of the full sample of γ-ray blazars in the HESE-35 field, we show that the long-term average γ-ray emission of blazars as a class is in agreement with both the measured all-sky flux of petaelectronvolt neutrinos and the spectral slope of the IceCube signal. The outburst of PKS B1424–418 provides an energy output high enough to explain the observed petaelectronvolt event, suggestive of a direct physical association.

The neutrino excess detected by IceCube comprises 37 events (from May 2010 to May 2013) with energies between 30 TeV and 2 PeV, rejecting a purely atmospheric origin at a significance of 5.7 standard deviations[1–3]. These events show a broad distribution across both hemispheres of the sky consistent with an extragalactic source population. Owing to the very steep background of atmospheric neutrinos, events at petaelectronvolt energies are best suited for attempting to establish associations with individual blazars. In the first two years of observations, IceCube detected two events with about 1 PeV of deposited energy[1,2] (HESE-14 and HESE-20; dubbed 'Bert' and 'Ernie'). A third event at 2 PeV (HESE-35; dubbed 'BigBird') was recorded in the third year of IceCube data[3] on 4 December 2012. The IceCube analysis concentrated on very high-energy events with interaction signatures that were fully contained within the detector (high-energy starting events; HESEs). In combination with an equal-neutrino-flavour flux at Earth[4], this resulted in most of the detected events being cascade-like, with relatively large median positional uncertainties (R_{50}) of typically 10° to 20° so that the field of interest ($\Omega_{\nu}^{R_{50}}$) of a given HESE event typically covers more than 300 square degrees. Although a number of different source classes have been discussed as a possible origin of a diffuse neutrino flux[5–15], no individual astrophysical object has been identified so far from which a neutrino flux with a substantial Poisson probability for a detection by IceCube is expected.

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[1]Institut für Theoretische Physik und Astrophysik, Universität Würzburg, Emil-Fischer-Str. 31, 97074 Würzburg, Germany. [2]Dr. Remeis Sternwarte & ECAP, Universität Erlangen-Nürnberg, Sternwartstrasse 7, 96049 Bamberg, Germany. [3]NASA, Goddard Space Flight Center, Greenbelt, Maryland 20771, USA. [4]University of Maryland, Baltimore County, Baltimore, Maryland 21250, USA. [5]Catholic University of America, Washington DC 20064, USA. [6]Department of Astrophysics/IMAPP, Radboud University Nijmegen, PO Box 9010, 6500 GL Nijmegen, The Netherlands. [7]ECAP, Universität Erlangen-Nürnberg, Erwin-Rommel-Str. 1, 91058 Erlangen, Germany. [8]Istituto Nazionale di Fisica Nucleare, Sezione di Padova, 35131 Padova, Italy. [9]Dipartimento di Fisica e Astronomia G. Galilei, Universita di Padova, 35131 Padova, Italy. [10]CSIRO Astronomy and Space Science, ATNF, PO Box 76, Epping, New South Wales 1710, Australia. [11]Institute for Radio Astronomy and Space Research, Auckland University of Technology, Auckland 1010, New Zealand. [12]Bundesamt fur Kartographie und Geodäsie, 93444 Bad Kötzting, Germany. [13]CSIRO Astronomy and Space Science, Canberra Deep Space Communications Complex, PO Box 1035, Tuggeranong, Australian Capital Territory 2901, Australia. [14]Dip. di Fisica, Universita di Trieste, 34128 Trieste, Italy. [15]Instituto Nazionale di Fisica Nucleare, Sezione di Trieste, via Valerio 2, I-34127 Trieste, Italy. [16]School of Mathematics & Physics, University of Tasmania, Private Bag 37, Hobart, 7001 Tasmania, Australia. [17]Hartebeesthoek Radio Astronomy Observatory, PO Box 443, Krugersdorp 1740, South Africa. [18]Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany. [19]Observatori Astronòmic, Universitat de València, C/ Catedrático José Beltrán no. 2, 46980 Paterna, València, Spain. [20]Departament d'Astronomia i Astrofísica, Universitat de València, C/Dr. Moliner 50, 46100 Burjassot, València, Spain. [21]Department of Physics and Astronomy, University of California at Los Angeles, Los Angeles, California 90095, USA.
*e-mail: matthias.kadler@astro.uni-wuerzburg.de

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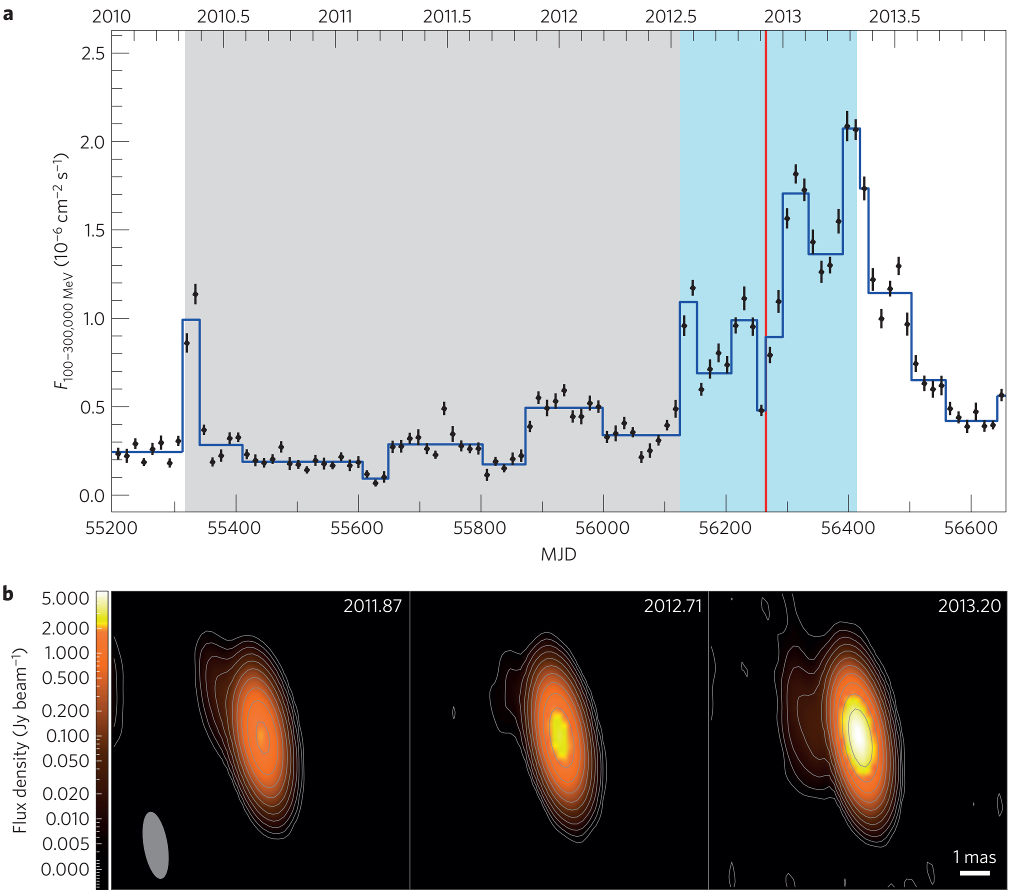

Figure 1 | TANAMI γ-ray and radio monitoring of PKS B1424-418. a,The Fermi/LAT γ-ray light curve is shown as two-week binned photon fluxes between 100 MeV and 300 GeV (black), the Bayesian blocks light curve (blue), and the HESE-35 time stamp (red line). The HESE period (May 2010 to May 2013) and the included outburst time range are highlighted in colour. Only statistical uncertainties are considered and shown at a 1 sigma confidence level. **b**, VLBI images show the core region at 8.4 GHz from 13 November 2011 (2011.87), 16 September 2012 (2012.71) and 14 March 2013 (2013.20) in uniform colour scale. 1 mas corresponds to about 8.3 pc. All contours start at 3.3 mJy beam^{-1} and increase logarithmically by factors of 2. The images were convolved with the enclosing beam from all three observations of 2.26 mas × 0.79 mas at a position angle of 9.5°, which is shown in the bottom left. The peak flux density increases from 1.95 Jy beam^{-1} (April 2011) to 5.62 Jy beam^{-1} (March 2013).

Owing to the Earth's opacity, the IceCube HESE analysis detects events at petaelectronvolt energies mainly from the southern sky[3]. Thus, contemporaneous astronomical data to probe the various source hypotheses can best be obtained via Southern Hemisphere monitoring programmes. TANAMI is a multiwavelength programme[16,17] that monitors the brightest γ-ray-loud active galactic nuclei (AGN) located at declinations below −30°. It comprises the ideal database to estimate the diffuse neutrino flux owing to the integrated emission of AGN in a given large field at a given time, as well as the maximal-possible neutrino flux associated with an individual object of the sample.

Blazars are radio-loud AGN with jets oriented close to the line of sight. This substantially increases the apparent brightness of these objects owing to the Doppler boosting of the emission from the relativistically moving emission zones. A direct association of a petaelectronvolt neutrino with an individual γ-ray blazar would have the important implication that a sizeable fraction of their observed γ-ray emission must be due to hadronic decays, and suggests that some blazar jets are also sources of ultrahigh-energy cosmic rays[18]. The X-ray and γ-ray emission of blazars may originate from the photoproduction of pions by accelerated protons[19]. Protons that are accelerated in the jet (for example, through shock acceleration) could interact with 'seed' photons (for example, ultraviolet photons from the accretion disk surrounding the central supermassive black hole). The resulting cascades produce charged and neutral pions, which decay and produce neutrinos and high-energy photons. Simple estimates and detailed Monte Carlo simulations show[5,20] that in this scenario $F_\gamma \lesssim F_\nu$, where the X-ray to γ-ray energy flux F_γ (formatted as in Table 1 with a subscript γ) is integrated over the high-energy spectral energy distribution (SED). If the seed photons are provided by a blue/ultraviolet bump component, as is typical in the blazar subclass of flat-spectrum radio quasars (FSRQs), and if the proton spectra steepen owing to energy losses, the neutrino spectrum is expected to peak at petaelectronvolt energies[5]. Attributing the high-energy electromagnetic emission to these photohadronic processes, the maximal-possible neutrino petaelectronvolt emission can be estimated from the measured integrated flux of high-energy photons.

Using TANAMI multiwavelength data, we previously compiled and discussed the multiwavelength properties of the six radio- and γ-ray-brightest blazars located inside the $\Omega_\nu^{R_{50}}$ fields of the two ~1 PeV events HESE-14 and HESE-20 from the first two years of IceCube data[5]. We found relatively low maximal neutrino fluxes of these six individual blazars owing to their low fluence over two years, but the diffuse flux due to the integrated emission of all blazars in the fields was found to be sufficiently high to expect up to two events. When the contribution of the large number of fainter sources from the blazar population is taken into account[21], the maximal-possible neutrino flux inside a given field is increased further. A high-angular-resolution point-source search with the

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Table 1 | Maximum-possible number of petaelectronvolt-neutrino events in 36 months (988 days live-time) of IceCube data for the 17 2LAC γ-ray blazars in the field of the 2 PeV IceCube event based on 2LAC catalogue γ-ray spectra and contemporaneous X-ray data.

2FGL name	Common name	F_γ (erg cm^{-2} s^{-1})	$N_{\nu,\mathrm{PeV}}^{\mathrm{max}}$
2FGL J1230.2-5258	PMN J1229-5303	$(2.4^{+1.5}_{-1.5}) \times 10^{-11}$	0.14
2FGL J1234.0-5733	PMN J1234-5736	$(1.1^{+0.4}_{-0.4}) \times 10^{-11}$	0.06
2FGL J1303.5-4622	PMN J1303-4621	$(1.9^{+0.6}_{-0.6}) \times 10^{-11}$	0.11
2FGL J1303.8-5537	PMN J1303-5540	$(1.04^{+0.11}_{-0.11}) \times 10^{-10}$	0.38
2FGL J1304.3-4353	1RXS 130421.2-435308	$(2.11^{+0.25}_{-0.25}) \times 10^{-11}$	0.12
2FGL J1307.5-4300	1RXS 130737.8-425940	$(8.4^{+1.7}_{-1.7}) \times 10^{-12}$	0.05
2FGL J1307.6-6704	PKS B 1304-668	$(1.54^{+0.15}_{-0.15}) \times 10^{-10}$	0.89
2FGL J1314.5-5330	PMN J1315-5334	$(8.1^{+0.9}_{-0.9}) \times 10^{-11}$	0.47
2FGL J1326.7-5254	PMN J1326-5256	$(1.04^{+0.21}_{-0.18}) \times 10^{-10}$	0.59
2FGL J1329.2-5608	PMN J1329-5608	$(1.38^{+0.36}_{-0.29}) \times 10^{-10}$	0.93
2FGL J1330.1-7002	PKS B 1326-697	$(1.53^{+0.11}_{-0.11}) \times 10^{-10}$	0.89
2FGL J1352.6-4413	PKS B 1349-439	$(5.4^{+1.0}_{-1.0}) \times 10^{-11}$	0.32
2FGL J1400.6-5601	PMN J1400-5605	$(6.9^{+0.8}_{-0.8}) \times 10^{-11}$	0.40
2FGL J1407.5-4257	CGRaBS J1407-4302	$(1.6^{+0.5}_{-0.5}) \times 10^{-11}$	0.09
2FGL J1428.0-4206*	PKS B1424-418*	$(2.04^{+0.17}_{-0.16}) \times 10^{-10*}$	1.57*
2FGL J1508.5-4957	PMN J1508-4953	$(7.6^{+3.0}_{-2.3}) \times 10^{-11}$	0.55
2FGL J1514.6-4751	PMN J1514-4748	$(5.6^{+0.6}_{-0.6}) \times 10^{-11}$	0.32
Sum (2LAC)			7.9

*The pre-outburst SED of PKS B1424-418 has been used for this calculation. See Table 2 for a comparison with maximal-possible and predicted neutrino output during outburst.

ANTARES neutrino telescope found a signal flux fitted by the likelihood analysis corresponding to approximately one event for each of the two blazars with the highest predicted neutrino fluxes, Swift J1656.3–3302 and TXS 1714–336. This result is consistent with the blazar-origin hypothesis of HESE-14 but it is also consistent with the hypothesis of a background signal[22]. No events were found for the HESE-20 candidate blazars, constraining the range of possible neutrino spectra to spectral indices flatter than −2.4 for the blazar-origin scenario. Although no conclusive association could be found, this result demonstrates the potential of identifying individual neutrino blazar sources, if suitable high-fluence candidates can be found.

Coincidence of HESE-35 with a major blazar outburst

The third petaelectronvolt neutrino (HESE-35) detected by the IceCube collaboration[3] had an energy of $2{,}004^{+236}_{-262}$ TeV and a median positional uncertainty of $R_{50} = 15.9°$ centred around the J2000 coordinates (208.4°, −55.8°) in right ascension (RA) and declination (Dec). Following our earlier strategy[5], we searched the $\Omega^{R_{50}}_{\mathrm{HESE\text{-}35}}$ field for positional coincidences with γ-ray-emitting AGN. In the second catalogue of AGN detected by the Fermi Large Area Telescope (2LAC)[23,24], which was based on Fermi/LAT all-sky observations between August 2008 and September 2010, a total of 20 γ-ray-bright AGN were found inside $\Omega^{R_{50}}_{\mathrm{HESE\text{-}35}}$. Seventeen of these AGN are blazars (2 FSRQs, 2 BL Lac objects, and 13 AGN of uncertain type), two are radio galaxies (Centaurus A and Centaurus B), and one is a starburst galaxy (NGC 4945). The radio galaxy Cen A is the closest AGN and the brightest radio source in $\Omega^{R_{50}}_{\mathrm{HESE\text{-}35}}$. However, the bulk of the radio emission is emitted from the kiloparsec-scale lobes of this FR I-type radio galaxy, and Padovani and Resconi[11] discard Cen A as a possible source of the IceCube event because the extrapolated SED at petaelectronvolt energies is too low in flux. The dominant blazar in $\Omega^{R_{50}}_{\mathrm{HESE\text{-}35}}$ is PKS B1424–418 at redshift $z = 1.522$ (ref. 25) and classified as an FSRQ. Owing to its relatively low γ-ray flux in the first three months of the Fermi mission in 2008, it was not included in the Fermi/LAT Bright Source List[26]. The source showed two γ-ray flares in 2009–2011[27] and is listed as a bright γ-ray source in all subsequent Fermi/LAT catalogues. Still, Padovani and Resconi[11] discarded it from their list of most-probable counterparts for the 2 PeV IceCube neutrino because of its relatively low γ-ray emission in the 2008–2011 period. In summer 2012, PKS B1424–418 commenced a pronounced rise in γ-ray brightness[28]. In contrast to previous flares, this increase marked the beginning of a long-lasting high-fluence outburst over more than a year with γ-ray fluxes exceeding 15 to 30 times the flux reported in the Fermi 2LAC (see Fig. 1) and which coincides with the petaelectronvolt-neutrino event HESE-35 both in position and in time. With a γ-ray photon fluence of (30.5 ± 0.3) cm^{-2}, PKS B1424–418 showed the absolute highest 100 MeV to 300 GeV γ-ray fluence of all extragalactic sources in the ∼9-month period between 16 July 2012 and 30 April 2013, which spans the arrival time of the petaelectronvolt neutrino inside the HESE time window.

Along with the very bright γ-ray emission, an increase in X-ray, optical and radio emission from PKS B1424–418 has also been reported[29–31]. Figure 1 shows a series of TANAMI very long-baseline interferometry (VLBI) images of PKS B1424–418 at 8.4 GHz observed between November 2011 and March 2013 (see Supplementary Methods). They show that the sharp increase in radio flux density from ∼1.5 Jy to ∼6 Jy took place inside the VLBI core, that is, on projected scales smaller than ∼3 pc (see Supplementary Table 1). The September 2012 image is the first VLBI epoch within the gigaelectronvolt high-fluence phase and also the first to show a substantial increase in the core flux density. This high-amplitude radio outburst is unparalleled in the TANAMI sample since the beginning of the programme in 2007. A physical association of the outburst of PKS B1424–418 and the petaelectronvolt-neutrino event is suggested given the unprecedented nature of these two events and the small a

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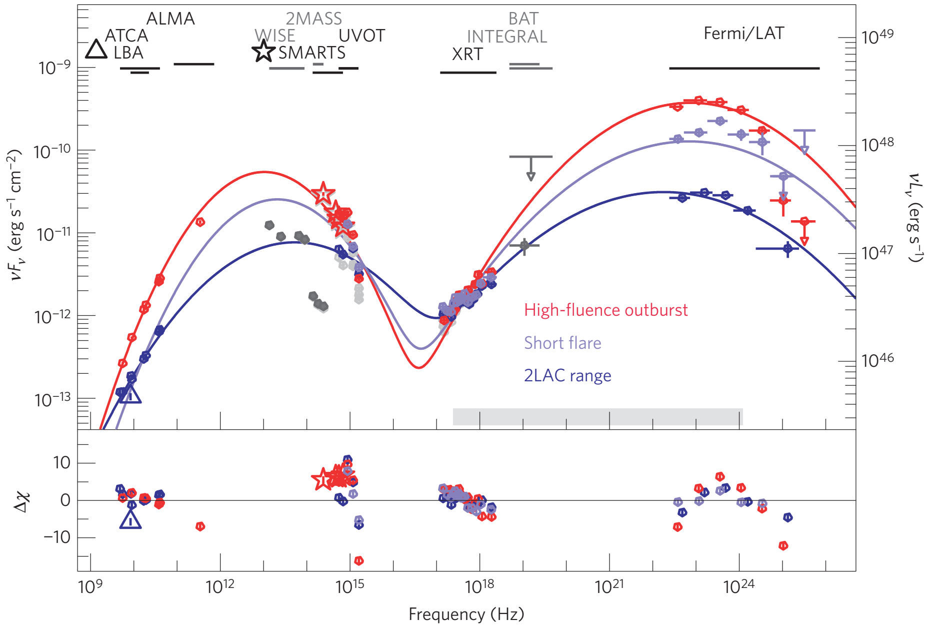

Figure 2 | Dynamic SED of PKS B1424–418. The multi-epoch SEDs are fitted with two log parabolas for the 2LAC period (purple), the short 2010 flare around MJD 55327 (blue), and the major outburst between MJD 56125 and MJD 56413 (red). The grey shaded area shows the kiloelectronvolt-to-gigaelectronvolt integration range for the neutrino fluence calculation. Statistical uncertainties are given at a 1 sigma confidence level, with the exception of the VLBI data, where a conservative 20% uncertainty was assumed to represent the dominant systematic uncertainties. Where not visible, the error bars are smaller than the symbol size. Upper limits (downward arrows) correspond to 2.5 sigma confidence levels and are neglected in the fits.

posteriori probability for a chance coincidence of about 5% (see Supplementary Methods).

Maximal-possible petaelectronvolt-neutrino output

Can the calorimetric output of this single blazar outburst account for the necessary petaelectronvolt-neutrino flux corresponding to the HESE-35 event? And is a possible association in agreement with the observed all-sky rate of petaelectronvolt events and with the lack of obvious additional associations of petaelectronvolt events with other bright blazars? In the following, we use the HESE-35 field before the onset of the PKS B1424–418 outburst as representative of the full sky to predict the number of petaelectronvolt-neutrino events in IceCube from blazars, first as a population and second as individual sources. We then compare the predicted numbers to the observed IceCube results. We start by considering only electron neutrinos, which are prone to produce cascade events in the IceCube detector. Later on, we show how the influence of other flavours is implicitly accounted for. The maximal-possible number of neutrinos detected in a solid angle Ω is (neglecting neutrino oscillations)

$$N^{\max}_{\nu,\mathrm{PeV}}(\Omega) = A_{\mathrm{eff},\nu_e} \cdot \left(\frac{F_\gamma}{E_\nu}\right) \cdot \Delta t \qquad (1)$$

where F_γ is the γ-ray energy flux of all blazars located inside Ω integrated between 5 keV and 10 GeV, $\Delta t = 988$days is the live-time of the three-year HESE period, and A_{eff,ν_e} is the effective area of the IceCube HESE analysis[2] at petaelectronvolt energies for charged-current interactions of electron neutrinos. So far, three petaelectronvolt neutrinos have been detected by IceCube, of which two had an energy of ~1 PeV and one had an energy of ~2 PeV. The IceCube effective area evaluated at the geometric mean of the three events' effective areas is $\sim 2.2\times10^5\ \mathrm{cm}^2$. The integrated emission from the 17 2LAC blazars in the $\Omega^{R_{50}}_{\text{HESE-35}}$ field predicts a maximum of ~7.9 neutrino petaelectronvolt events (see Table 1) but we also need to consider the contribution of fainter blazars, which are not listed as resolved sources in the 2LAC catalogue. In total, blazars make up ~50% of the extragalactic γ-ray background (EGB)[32,33] but the integrated flux for all 2LAC blazars inside $\Omega^{R_{50}}_{\text{HESE-35}}$ is only $F_{100\,\mathrm{MeV}-820\,\mathrm{GeV}} = 8.5\times10^{-7}\ \mathrm{ph\,cm^{-2}\,s^{-1}}$. Distributed over $\Omega^{R_{50}}_{\text{HESE-35}}$, this corresponds to $3.5\times10^{-6}\ \mathrm{ph\,cm^{-2}\,s^{-1}\,sr^{-1}}$, which accounts for only about 30% of the EGB. Thus, we may expect about $(0.2/0.3)\times7.9 \sim 5.3$ additional neutrinos at petaelectronvolt energies from faint unresolved blazars within $\Omega^{R_{50}}_{\text{HESE-35}}$ (taking their EGB contribution as a proxy for their integrated kiloelectronvolt-to-gigaelectronvolt output). Thus, the maximal-possible number of neutrinos predicted by this model from blazars in the $\Omega^{R_{50}}_{\text{HESE-35}}$ field is

$$N^{\max}_{\nu,\mathrm{PeV}}(\Omega^{R_{50}}_{\text{HESE-35}}) \sim 13 \qquad (2)$$

which includes maximal-possible petaelectronvolt-neutrino counts from all γ-ray blazars from the 2LAC catalogue plus a maximal-possible contribution of the large population of faint unresolved blazars.

Predicted petaelectronvolt-neutrino output

By extrapolating from the fairly representative $\Omega^{R_{50}}_{\text{HESE-35}}$ field (before the onset of the outburst of PKS B1424–418), we estimate the maximal number of petaelectronvolt-neutrino events from all blazars (both resolved and unresolved) over three years from the full southern sky to be

$$N^{\max}_{\nu,\mathrm{PeV}}(2\pi) = 13\cdot\frac{2\pi}{\Omega^{R_{50}}_{\text{HESE-35}}} \sim 336 \qquad (3)$$

This number of events would be expected if only electron neutrinos would be produced, if all blazars harboured dense ultraviolet photon fields due to the emission of optically thick accretion disks as is typical for FSRQs, and if the neutrino spectrum peaked sharply at petaelectronvolt energies. All three conditions are clearly not fulfilled as only three events have been detected, leading to an empirical scaling factor of

$$f_{\mathrm{emp}} = \frac{N^{\mathrm{obs}}_{\nu,\mathrm{PeV}}(2\pi)}{N^{\max}_{\nu,\mathrm{PeV}}(2\pi)} \sim \frac{3}{336} \sim 0.009 \qquad (4)$$

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Table 2 | Contributions of PKS B1424–418, other 2LAC blazars and faint blazars to the predicted neutrino output for the pre-outburst 27-month period, for the 9-month outburst and for the full 36-month HESE period.

		27 months (pre-outburst)			9 months (outburst)			Full HESE period		
Source(s)	$f_{\rm II}$	$N^{\rm max}_{\nu,\rm PeV}$	$N^{\rm pred}_{\nu,\rm PeV}$	Contribution (%)	$N^{\rm max}_{\nu,\rm PeV}$	$N^{\rm pred}_{\nu,\rm PeV}$	Contribution (%)	$N^{\rm max}_{\nu,\rm PeV}$	$N^{\rm pred}_{\nu,\rm PeV}$	Contribution (%)
PKS B1424–418	1	1.2	0.03	10	4.5	0.11	39	5.7	0.14	49
2LAC blazars	0.5	4.7	0.06	20	1.6	0.02	7	6.3	0.08	27
Faint blazars	0.5	4.0	0.05	17	1.3	0.02	6	5.3	0.07	23
Sum		9.9	0.14	47	7.4	0.15	52	17.3	0.29	100

This can be compared to a theoretical value $f_{\rm th}$, which accounts for physically motivated realistic deviations from the three ideal conditions. The theoretical scaling factor allows us to predict the number of detectable petaelectronvolt events $N_\nu^{\rm pred}$ as

$$N^{\rm pred}_{\nu,\rm PeV}(\Omega^{R_{50}}_{\rm HESE\text{-}35}) = f_{\rm th} \times N^{\rm max}_{\nu,\rm PeV}(\Omega^{R_{50}}_{\rm HESE\text{-}35}) \tag{5}$$

The scaling factor is factorized into a flavour factor $f_{\rm I}$, a factor accounting for the different classes of blazars $f_{\rm II}$, and a spectrum factor $f_{\rm III}$:

$$f_{\rm th} = f_{\rm I} \times f_{\rm II} \times f_{\rm III} \tag{6}$$

The IceCube data indicate an equal flavour ratio[4] so that the flavour factor would be 1/3 if only electron neutrinos are accounted for when computing the maximal event numbers. When adding the two other flavours, it has to be considered that the number of detected cascade events due to muon and tau neutrinos is lower than for electron neutrinos because of the energy-dependent cross-sections and inelasticities for neutral-current and charged-current interactions. Assuming an underlying neutrino power law with slope -2.3, as observed by IceCube[2], we estimate a fraction of $f_{\rm I} \sim 0.5$ for cascade events at $(1-2)$ PeV in IceCube. The deepest available Fermi/LAT point-source catalogues contain a fraction of FSRQs of about $f_{\rm II} \sim 0.5$ (and about the same numbers of BL Lac objects)[23]. For our basic model of a sharply peaked neutrino spectrum due to photopion production from monoenergetic ultraviolet photons, $f_{\rm III}$ would be equal to unity. In a realistic scenario, a range of Doppler shifts (depending on the location of the seed-photon sources with respect to the relativistic jet base as discussed in our earlier work[5]) causes broader spectra extending to lower neutrino energies. Considering also broadening due to the different redshifts of sources, an output range of $\sim$30 TeV to $\sim$10 PeV can be expected. We note that this naturally avoids a hard spectrum above petaelectronvolt energies[34] consistent with the absence of observed Glashow-resonance events at 6.7 PeV. In addition, models that consider proton–proton collisions or assume accretion tori with virial temperatures of $\sim 10^9$ K rather than optically thick accretion disks[7,35,36] also predict softer spectra. Using a spectral index of -2.3 as measured by IceCube[3] and the (30 TeV to 10 PeV) bandwidth of the spectrum reduces the number of petaelectronvolt output neutrinos by $f_{\rm III} = 0.05$, so that we estimate

$$f_{\rm th} = 0.5 \times 0.5 \times 0.05 \sim 0.0125 \tag{7}$$

(see equation (4)). Our model thus predicts $0.0125 \times 336 \sim 4$ events at petaelectronvolt energies from the full southern sky, which is remarkably close to the observed three petaelectronvolt events. We conclude that the measured γ-ray emission of the blazars in the $\Omega^{R_{50}}_{\rm HESE\text{-}35}$ field allows us to reproduce both the measured all-sky flux of petaelectronvolt neutrinos and the measured spectral slope of the IceCube signal assuming a simple photohadronic emission model of FSRQs.

Predicted petaelectronvolt-neutrino output

If Ω becomes small, containing only one individual FSRQ, we can set $f_{\rm II} = 1$. The predicted number of petaelectronvolt neutrinos for an individual FSRQ is then

$$N^{\rm pred}_{\nu,\rm PeV}({\rm FSRQ}) = 0.025 \times N^{\rm max}_{\nu,\rm PeV}({\rm FSRQ}) \tag{8}$$

from which Poisson probabilities for detections of neutrinos from individual sources can be calculated. For the 2LAC sources in the $\Omega^{R_{50}}_{\rm HESE\text{-}35}$ field, we find relatively low maximal-possible neutrino values ($N^{\rm max}_{\nu,\rm PeV} \sim 0.04 - 0.9$) in 16 of the 17 cases, from which small predicted neutrino counts are predicted ($N^{\rm pred}_{\nu,\rm PeV} \sim 0.001 - 0.023$), corresponding to small individual Poisson probabilities for any neutrino detections during the three-year IceCube integration of ($P \lesssim 0.1\% - 2.2\%$). PKS B1424–418 in its pre-outburst state reached a maximal-possible neutrino event number of $N^{\rm max}_{\nu,\rm PeV} \sim 1.6$ and a predicted neutrino event number of $N^{\rm pred}_{\nu,\rm PeV} \sim 0.04$ ($P \lesssim 3.9\%$).

Petaelectronvolt-neutrino output of PKS B1424-418

In Fig. 2, we show the average broadband SED of PKS B1424–418 for the 2LAC period, the 2010 short flare around MJD 55327 (see Fig. 1), and the major outburst phase between 16 July 2012 and the end of the IceCube period in April 2013 (see Supplementary Methods for details of the SED production). In spite of the relatively high fluxes during the 2010 flare, the short duration yields only a small fluence, resulting in a low maximal-possible neutrino value of $N^{\rm max}_{\nu,\rm PeV} \sim 0.2$. As discussed above, the two-year 2LAC period yields a substantially higher fluence. Scaling down from 3 years to 27 months, we derive $N^{\rm max}_{\nu,\rm PeV} \sim 1.2$ ($N^{\rm pred}_{\nu,\rm PeV} \sim 0.03$) for the first 27 months of the HESE time range. During the major outburst, the source increased its predicted neutrino-production rate by more than an order of magnitude, yielding a maximal-possible neutrino event number of 4.5 ($N^{\rm pred}_{\nu,\rm PeV} \sim 0.11$). Table 2 summarizes the various contributions of PKS B1424–418, the remaining 2LAC blazars and fainter blazars below the 2LAC threshold. The largest contribution to the overall signal is derived for PKS B1424–418 (49%), with 39% being attributed to the nine-month outburst period and 10% to the pre-outburst phase. The Poisson probability to detect a neutrino associated with the nine-month high-fluence outburst of PKS B1424–418 is at a considerable level (about 11%). Our model thus allows us to plausibly associate an individual blazar during a rare major outburst with the highest-energy extraterrestrial neutrino detected by IceCube so far.

Petaelectronvolt neutrinos from other bright blazars

If our model is correct, it also has to explain the non-detection of petaelectronvolt neutrinos in positional agreement with other high-fluence blazars and with the detection statistics of sub-petaelectronvolt-neutrino events. We note that the positional uncertainties R_{50} given by the IceCube team are median values, which means that only half of all events originate inside their measured $\Omega^{R_{50}}_{\nu}$ fields whereas the other half are coming from larger offset angles. Above, we have calculated the maximal number of neutrino events that can be explained by individual astrophysical

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Table 3 | Ranked list of the 10 highest-fluence blazars during the three-year HESE period.

Name	RA (°)	Dec (°)	F_γ (10^{-10} erg cm^{-2} s^{-1})	$N^{\mathrm{max}}_{\nu,\mathrm{PeV}}$	$N^{\mathrm{pred}}_{\nu,\mathrm{PeV}}$	$N^{\mathrm{pos}}_{\nu,\mathrm{PeV}}$
PKS B1830-211	+278.4	−21.1	(14.34 ± 0.27)	8.3	0.21	1
PKS B1510-089	+228.2	−9.1	(13.31 ± 0.13)	7.7	0.19	0
3C 454.3	+343.5	+16.2	(37.50 ± 01.3)	7.6	0.19	0
PKS B1424-418	+217.0	−42.1	(7.82 ± 0.16)	5.7	0.14	1
PKS B2326-502	+352.3	−49.9	(4.69 ± 0.10)	2.7	0.07	0
PKS B0537-441	+84.7	−44.1	(3.84 ± 0.08)	2.2	0.06	0
PKS B1222+216	+186.2	+21.4	(7.94 ± 0.12)	1.6	0.04	0
CTA 102	+338.2	+11.7	(6.42 ± 0.12)	1.3	0.03	0
B2 1633+38	+248.8	+38.1	(6.28 ± 0.09)	1.3	0.03	0
B2 1520+31	+230.5	+31.7	(4.75 ± 0.25)	1.3	0.02	0

Note that the IceCube effective area is substantially smaller for Northern Hemisphere petaelectronvolt sources than for the southern sky. Column 1, source name; columns 2 and 3, J2000 coordinates; column 4, integrated γ-ray flux between 5 keV and 10 GeV; columns 5 and 6, maximal-possible and predicted number of neutrino detections; column 7, number of petaelectronvolt events that might be associated with each source based on a positional coincidence.

sources within $\Omega_\nu^{R_{50}}$ for a high-confidence event. When asking for the maximal number of IceCube events that might be associated with a given astrophysical source, a larger radius has to be considered. For example, within $2 \times R_{50}$, PKS B1424–418 is in positional agreement with the sub-petaelectronvolt events HESE-16 ($30.6^{+3.6}_{-3.5}$ TeV at an offset of $1.5R_{50}$) and HESE-25 ($33.5^{+4.9}_{-5.0}$ TeV, $1.4R_{50}$) so that the data are not in disagreement with a rather broad and steep neutrino spectrum. A point-source search with ANTARES, following the strategy applied to the candidate blazars in the HESE-14 and HESE-20 fields[22], will be able to constrain the possible neutrino spectra. A preliminary analysis of the ANTARES collaboration[37] finds no excess signal at the position of PKS B1424–418, excluding the possibility of a very steep neutrino spectrum associated with the blazar outburst.

We have used the Fermi/LAT monitored source list light curves (http://fermi.gsfc.nasa.gov/ssc/data/access/lat/msl_lc) to identify candidate sources for high kiloelectronvolt-to-gigaelectronvolt fluence, compiled the average SEDs over the three-year HESE period for the top-ten candidate sources from the whole sky and derived their expected neutrino counts (see Table 3). For Northern and Southern Hemisphere events, we have used the effective areas for the appropriate minimum energy provided by the IceCube team[2]. We do not extend the list beyond rank 10, because for the tenth-ranked source, the maximal-possible neutrino output has already dropped by more than an order of magnitude to $\mathcal{O}(1)$. Only three other sources reach a predicted neutrino output comparable to PKS B1424–418. The two FSRQs PKS B1510–089 and 3C 454.3 both have a maximal petaelectronvolt-neutrino output of the order of 8 in 988 days but do not coincide with any of the three observed petaelectronvolt events. Applying the source scaling factor of 0.025 for the γ-ray FSRQs, the Poisson probability for detecting zero petaelectronvolt events from a source of this fluence is ~80%. On the other hand, the model predicts a ~50% probability to detect at least one neutrino from one of the four top-ranked high-fluence blazars and the detection of more than one petaelectronvolt event remains at a realistic probability of about 16%. The occurrence of multiple events is expected if a sparse population such as FSRQs produce a considerable fraction of the total IceCube intensity[15]. In this context, it is intriguing that also the gravitationally lensed blazar PKS B1830–211, which is the highest-ranked source in the top-10 blazar-fluence list, is located only marginally outside the $\Omega^{R_{50}}_{\text{HESE-14}}$ field of the petaelectronvolt event HESE-14, which was detected by IceCube on 9 August 2011, coinciding with a high-fluence outburst phase of this blazar. In addition, PKS B1830–211 is positionally coincident with the $\Omega_\nu^{R_{50}}$ fields of six additional sub-petaelectronvolt IceCube neutrino events and with the region of the highest, albeit not significant, point-source clustering test statistic of IceCube events[3]. The list of coincidences includes the high-energy events HESE-2 (117^{+15}_{-15} TeV, $0.3R_{50}$) and HESE-22 (220^{+21}_{-24} TeV, $1.2R_{50}$). However, ANTARES has measured an upper limit of 1.89×10^{-8} GeV cm^{-2} s^{-1} on the energy flux of neutrinos from PKS B1830–211 (ref. 38), assuming an E^{-2} neutrino spectrum. This value is very similar to the limit found for PMN J1802–3940, based on which an association with three or more IceCube neutrinos could be excluded at 90% confidence for neutrino spectral indices steeper than −1.8. The positional proximity of high-fluence blazars in our list to other IceCube sub-petaelectronvolt events or even the temporal proximity to high-fluence phases (see Supplementary Discussions) is likely to be coincidental in most cases because the atmospheric contribution increases and the IceCube effective area decreases rapidly below 100 TeV.

Constraining the neutrino velocity

Recently, a theoretical limit of $(v - c)/c \leq (0.5 - 1.0) \times 10^{-20}$ for superluminal neutrinos has been derived from constraints on vacuum pair emission and neutrino splitting[39]. Assuming a physical association between the outburst activity of PKS B1424–418 and the HESE-35 petaelectronvolt neutrino, an observational constraint on the neutrino velocity is implied: the maximal-possible time-travel delay between the beginning of the outburst and the arrival of the neutrino is ~160 days, constraining the relative velocity difference to $(v-c)/c \lesssim \mathcal{O}(10^{-11})$ (for a light travel time of 9.12 billion years). This is about two orders of magnitude more constraining than the neutrino-velocity limit derived from SN 1987A[40]. However, it cannot be formally excluded that the observed petaelectronvolt neutrino could be associated with the non-outburst phase or even a historical (or future) outburst of the source.

Summary and outlook

Tentative associations of high-energy neutrinos with flaring blazars have been suggested before[41,42] but it remained questionable whether a high-enough neutrino flux could be produced in the candidate flares[43]. Here, we have identified for the first time a single source that has emitted a sufficiently high fluence during a major outburst to explain an observed coinciding petaelectronvolt-neutrino event. There is a remarkable coincidence with the IceCube-detected petaelectronvolt-neutrino event HESE-35 with a probability of only ~5% for a chance coincidence. Our model reproduces the measured rate of petaelectronvolt events detected over the whole sky by IceCube and accounts for the distribution of neutrino events across the bandwidth expected for photohadronic neutrino production. A substantial increase of the significance of putative future coincidences between petaelectronvolt-neutrino events and high-fluence blazars could be achieved considering track events at smaller median angular errors or the observation of doublet events associated with the same blazar. However, it has to be kept in mind that only a small fraction of the total γ-ray emission of all blazars

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is associated with the brightest individual objects. In fact, only ∼70% of the blazar γ-ray emission has been resolved into point sources so far[32] by Fermi/LAT. For any individual petaelectronvolt-neutrino event, there will thus always remain a large probability of being associated with the population of faint remote sources, which are not contained in the bright-source γ-ray catalogues. We thus expect three out of ten future petaelectronvolt neutrinos to not be associated with any known γ-ray blazar. The recently reported multi-petaelectronvolt-neutrino-induced muon event detected by IceCube[44], which does not coincide with any known bright γ-ray source, might well be an event of this type. Within the next years of IceCube observations, the combination of improved number statistics and continuous multiwavelength monitoring of high-fluence blazars is the key to developing a consistent scenario of hadronic processes in AGN jets. This will also shed new light on the long-suspected role of AGN as sources of extragalactic cosmic rays[18].

Received 5 November 2015; accepted 3 March 2016;
published online 18 April 2016

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Acknowledgements

The authors thank B. Lott, L. Baldini, P. Bruel, S. Digel, J. Finke, D. Gasparini, N. Omodei, J. S. Perkins and A. Reimer for discussions that have significantly improved this publication. We acknowledge support and partial funding by the Deutsche Forschungsgemeinschaft grant WI 1860-10/1 (TANAMI) and GRK 1147, Deutsches Zentrum für Luft- und Raumfahrt grant 50 OR 1311/50 OR 1303/50 OR 1401, the German Ministry for Education and Research (BMBF) grants 05A11WEA and 05A14WE3, the Helmholtz Alliance for Astroparticle Physics (HAP), the Spanish MINECO project AYA2012-38491-C02-01, the Generalitat Valenciana project PROMETEOII/2014/057, the COST MP0905 action 'Black Holes in a Violent Universe' and NASA through Fermi Guest Investigator grants NNH09ZDA001N, NNH10ZDA001N, NNH12ZDA001N and NNH13ZDA001N. This study made use of data collected by the Australian Long Baseline Array (LBA) and the AuScope initiative. The LBA is part of the Australia Telescope National Facility, which is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO. AuScope Ltd is funded under the National Collaborative Research Infrastructure Strategy (NCRIS), an Australian Commonwealth Government Programme. This paper made use of data from the ALMA calibrator database: https://almascience.eso.org/alma-data/calibrator-catalogue. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada), NSC and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ. This paper also made use of up-to-date SMARTS optical/near-infrared light curves that are available at www.astro.yale.edu/smarts/glast/home.php. The Fermi–LAT Collaboration acknowledges support for LAT development, operation and data analysis from NASA and DOE (United States), CEA/Irfu and IN2P3/CNRS (France), ASI and INFN (Italy), MEXT, KEK, and JAXA (Japan), and the K. A. Wallenberg Foundation, the Swedish

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Research Council and the National Space Board (Sweden). Science analysis support in the operations phase from INAF (Italy) and CNES (France) is also gratefully acknowledged. We thank J. E. Davis and T. Johnson for the development of the slxfig module and the SED scripts that have been used to prepare the figures in this work.

Author contributions

The TANAMI programme is coordinated by R.O. and M.Kadler. F.K. led the multiwavelength data analysis and modelled the SED. K.M. led the theoretical interpretation of the SED data. C.M., R.S., J.T., B.C., A.Ka. (Univ. Würzburg), E.R., R.O. and M.Kadler analysed the LBA data. J.W. and N.G. were responsible for X-ray observations and data analysis. T.B., S.B., C.G., C.M., D.E.G., A.Kreikenbohm, K.L., E.L., F.L., T.S. and J.A.Z. contributed to the analysis and discussion of radio, optical/ultraviolet, X-ray and γ-ray data. LBA observations were conducted by P.G.E., S.G., H.H., S.H., J.E.J.L., T.N., C.Phillips, C.Plötz., J.Q., J.S., A.K.T. and S.W. Hard X-ray data were reduced and analysed by T.B., I.K., W.B. and M.L. G.A., T.E., D.E., C.W.J., A.Ka. (ECAP), U.K. and M.Kreter contributed to the discussion of neutrino astronomy aspects. M.Kadler, F.W.S. and J.S. led the neutrino-velocity discussion. D.J.T., R.O. and M.Kadler coordinated the TANAMI–LAT collaboration liaison. All authors discussed the results and commented on the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to M.Kadler.

Competing financial interests

The authors declare no competing financial interests.

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