RESEARCH ARTICLE SUMMARY

NEUTRINO ASTROPHYSICS

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

INTRODUCTION: Neutrinos are tracers of cosmic-ray acceleration: electrically neutral and traveling at nearly the speed of light, they can escape the densest environments and may be traced back to their source of origin. High-energy neutrinos are expected to be produced in blazars: intense extragalactic radio, optical, x-ray, and, in some cases, γ-ray sources characterized by relativistic jets of plasma pointing close to our line of sight. Blazars are among the most powerful objects in the Universe and are widely speculated to be sources of high-energy cosmic rays. These cosmic rays generate high-energy neutrinos and γ-rays, which are produced when the cosmic rays accelerated in the jet interact with nearby gas or photons. On 22 September 2017, the cubic-kilometer IceCube Neutrino Observatory detected a ~290-TeV neutrino from a direction consistent with the flaring γ-ray blazar TXS 0506+056. We report the details of this observation and the results of a multiwavelength follow-up campaign.

RATIONALE: Multimessenger astronomy aims for globally coordinated observations of cosmic rays, neutrinos, gravitational waves, and electromagnetic radiation across a broad range of wavelengths. The combination is expected to yield crucial information on the mechanisms energizing the most powerful astrophysical sources. That the production of neutrinos is accompanied by electromagnetic radiation from the source favors the chances of a multiwavelength identification. In particular, a measured association of high-energy neutrinos with a flaring source of γ-rays would elucidate the mechanisms and conditions for acceleration of the highest-energy cosmic rays. The discovery of an extraterrestrial diffuse flux of high-energy neutrinos, announced by IceCube in 2013, has characteristic properties that hint at contributions from extragalactic sources, although the individual sources remain as yet unidentified. Continuously monitoring the entire sky for astrophysical neutrinos, IceCube provides real-time triggers for observatories around the world measuring γ-rays, x-rays, optical, radio, and gravitational waves, allowing for the potential identification of even rapidly fading sources.

RESULTS: A high-energy neutrino-induced muon track was detected on 22 September 2017, automatically generating an alert that was distributed worldwide within 1 min of detection and prompted follow-up searches by telescopes over a broad range of wavelengths. On 28 September 2017, the *Fermi* Large Area Telescope Collaboration reported that the direction of the neutrino was coincident with a cataloged γ-ray source, 0.1° from the neutrino direction. The source, a blazar known as TXS 0506+056 at a measured redshift of 0.34, was in a flaring state at the time with enhanced γ-ray activity in the GeV range. Follow-up observations by imaging atmospheric Cherenkov telescopes, notably the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescopes, revealed periods where the detected γ-ray flux from the blazar reached energies up to 400 GeV. Measurements of the source have also been completed at x-ray, optical, and radio wavelengths. We have investigated models associating neutrino and γ-ray production and find that correlation of the neutrino with the flare of TXS 0506+056 is statistically significant at the level of 3 standard deviations (sigma). On the basis of the redshift of TXS 0506+056, we derive constraints for the muon-neutrino luminosity for this source and find them to be similar to the luminosity observed in γ-rays.

CONCLUSION: The energies of the γ-rays and the neutrino indicate that blazar jets may accelerate cosmic rays to at least several PeV. The observed association of a high-energy neutrino with a blazar during a period of enhanced γ-ray emission suggests that blazars may indeed be one of the long-sought sources of very-high-energy cosmic rays, and hence responsible for a sizable fraction of the cosmic neutrino flux observed by IceCube. ■

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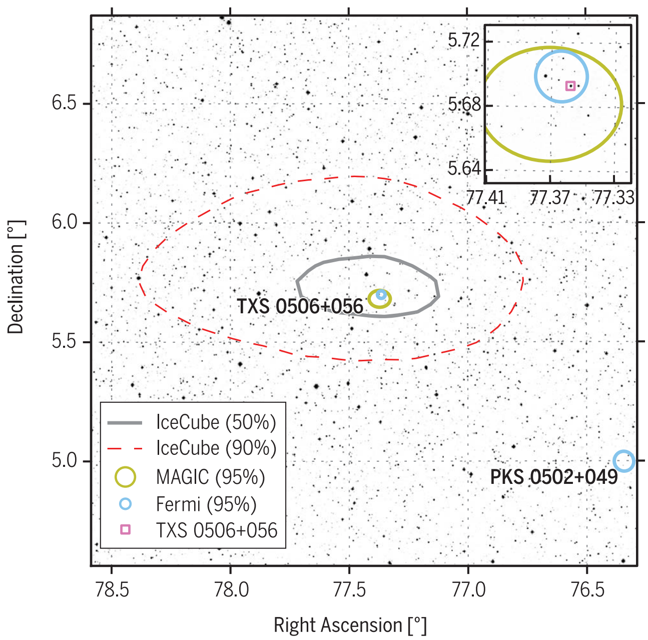

Multimessenger observations of blazar TXS 0506+056. The 50% and 90% containment regions for the neutrino IceCube-170922A (dashed red and solid gray contours, respectively), overlain on a V-band optical image of the sky. Gamma-ray sources in this region previously detected with the *Fermi* spacecraft are shown as blue circles, with sizes representing their 95% positional uncertainty and labeled with the source names. The IceCube neutrino is coincident with the blazar TXS 0506+056, whose optical position is shown by the pink square. The yellow circle shows the 95% positional uncertainty of very-high-energy γ-rays detected by the MAGIC telescopes during the follow-up campaign. The inset shows a magnified view of the region around TXS 0506+056 on an R-band optical image of the sky.

The list of author affiliations is available in the full article online.
*The full lists of participating members for each team and their affiliations are provided in the supplementary materials.
†Email: analysis@icecube.wisc.edu
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RESEARCH ARTICLE

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Previous detections of individual astrophysical sources of neutrinos are limited to the Sun and the supernova 1987A, whereas the origins of the diffuse flux of high-energy cosmic neutrinos remain unidentified. On 22 September 2017, we detected a high-energy neutrino, IceCube-170922A, with an energy of ~290 tera–electron volts. Its arrival direction was consistent with the location of a known γ-ray blazar, TXS 0506+056, observed to be in a flaring state. An extensive multiwavelength campaign followed, ranging from radio frequencies to γ-rays. These observations characterize the variability and energetics of the blazar and include the detection of TXS 0506+056 in very-high-energy γ-rays. This observation of a neutrino in spatial coincidence with a γ-ray–emitting blazar during an active phase suggests that blazars may be a source of high-energy neutrinos.

Since the discovery of a diffuse flux of high-energy astrophysical neutrinos (*1*, *2*), IceCube has searched for its sources. The only nonterrestrial neutrino sources identified previously are the Sun and the supernova 1987A, producing neutrinos with energies millions of times lower than the high-energy diffuse flux, such that the mechanisms and the environments responsible for the high-energy cosmic neutrinos are still to be ascertained (*3*, *4*). Many candidate source types exist, with active galactic nuclei (AGN) among the most prominent (*5*), in particular the small fraction of them designated as radio-loud (*6*). In these AGNs, the central supermassive black hole converts gravitational energy of accreting matter and/or the rotational energy of the black hole into powerful relativistic jets, within which particles can be accelerated to high energies. If a number of these particles are protons or nuclei, their interactions with the radiation fields and matter close to the source would give rise to a flux of high-energy pions that eventually decay into photons and neutrinos (*7*). In blazars (*8*)—AGNs that have one of the jets pointing close to our line of sight—the observable flux of neutrinos and radiation is expected to be greatly enhanced owing to relativistic Doppler boosting. Blazar electromagnetic (EM) emission is known to be highly variable on time scales from minutes to years (*9*).

Neutrinos travel largely unhindered by matter and radiation. Even if high-energy photons (TeV and above) are unable to escape the source owing to intrinsic absorption, or are absorbed by interactions with the extragalactic background light (EBL) (*10*, *11*), high-energy neutrinos may escape and travel unimpeded to Earth. An association of observed astrophysical neutrinos with blazars would therefore imply that high-energy protons or nuclei up to energies of at least tens of PeV are produced in blazar jets, suggesting that they may be the birthplaces of the most energetic particles observed in the Universe, the ultrahigh-energy cosmic rays (*12*). If neutrinos are produced in correlation with photons, the coincident observation of neutrinos with electromagnetic flares would greatly increase the chances of identifying the source(s). Neutrino detections must therefore be combined with the information from broadband observations across the electromagnetic spectrum (multimessenger observations).

To take advantage of multimessenger opportunities, the IceCube neutrino observatory (*13*) has established a system of real-time alerts that rapidly notify the astronomical community of the direction of astrophysical neutrino candidates (*14*). From the start of the program in April 2016 through October 2017, 10 public alerts have been issued for high-energy neutrino candidate events with well-reconstructed directions (*15*).

We report the detection of a high-energy neutrino by IceCube and the multiwavelength/multi-instrument observations of a flaring γ-ray blazar, TXS 0506+056, which was found to be positionally coincident with the neutrino direction (*16*). Chance coincidence of the IceCube-170922A event with the flare of TXS 0506+056 is statistically disfavored at the level of 3σ in models evaluated below, associating neutrino and γ-ray production.

The neutrino alert

IceCube is a neutrino observatory with more than 5000 optical sensors embedded in 1 km^3 of the Antarctic ice-sheet close to the Amundsen-Scott South Pole Station. The detector consists of 86 vertical strings frozen into the ice 125 m apart, each equipped with 60 digital optical modules (DOMs) at depths between 1450 and 2450 m. When a high-energy muon-neutrino interacts with an atomic nucleus in or close to the detector array, a muon is produced moving through the ice at superluminal speed and creating Cherenkov radiation detected by the DOMs. On 22 September 2017 at 20:54:30.43 Coordinated Universal Time (UTC), a high-energy neutrino-induced muon track event was detected in an automated analysis that is part of IceCube's real-time alert system. An automated alert was distributed (*17*) to observers 43 s later, providing an initial estimate of the direction and energy of the event. A sequence of refined reconstruction algorithms was automatically started at the same time, using the full event information. A representation of this neutrino event with the best-fitting reconstructed direction is shown in Fig. 1. Monitoring data from IceCube indicate that the observatory was functioning normally at the time of the event.

A Gamma-ray Coordinates Network (GCN) Circular (*18*) was issued ~4 hours after the initial notice, including the refined directional information (offset 0.14° from the initial direction; see Fig. 2). Subsequently, further studies were performed to determine the uncertainty of the directional reconstruction arising from statistical and systematic effects, leading to a best-fitting right ascension (RA) $77.43^{+0.95}_{-0.65}$ and declination (Dec) $+5.72^{+0.50}_{-0.30}$ (degrees, J2000 equinox, 90% containment region). The alert was later reported to be in positional coincidence with the known γ-ray blazar TXS 0506+056 (*16*), which is located at RA 77.36° and Dec +5.69° (J2000) (*19*), 0.1° from the arrival direction of the high-energy neutrino.

The IceCube alert prompted a follow-up search by the Mediterranean neutrino telescope ANTARES (Astronomy with a Neutrino Telescope and Abyss environmental RESearch) (*20*). The sensitivity of ANTARES at the declination of IceCube-170922A is about one-tenth that of IceCube's (*21*), and no neutrino candidates were found in a ±1 day period around the event time (*22*).

An energy of 23.7 ± 2.8 TeV was deposited in IceCube by the traversing muon. To estimate the parent neutrino energy, we performed simulations of the response of the detector array, considering that the muon-neutrino might have interacted outside the detector at an unknown distance. We assumed the best-fitting power-law energy spectrum for astrophysical high-energy muon neutrinos, $dN/dE \propto E^{-2.13}$ (*2*), where N is the number of neutrinos as a function of energy E. The simulations yielded a most probable neutrino energy of 290 TeV, with a 90% confidence level (CL)

*The full lists of participating members for each team and their affiliations are provided in the supplementary materials.
†Email: analysis@icecube.wisc.edu

lower limit of 183 TeV, depending only weakly on the assumed astrophysical energy spectrum (25).

The vast majority of neutrinos detected by IceCube arise from cosmic-ray interactions within Earth's atmosphere. Although atmospheric neutrinos are dominant at energies below 100 TeV, their spectrum falls steeply with energy, allowing astrophysical neutrinos to be more easily identified at higher energies. The muon-neutrino astrophysical spectrum, together with simulated data, was used to calculate the probability that a neutrino at the observed track energy and zenith angle in IceCube is of astrophysical origin. This probability, the so-called signalness of the event (14), was reported to be 56.5% (17). Although IceCube can robustly identify astrophysical neutrinos at PeV energies, for individual neutrinos at several hundred TeV, an atmospheric origin cannot be excluded. Electromagnetic observations are valuable to assess the possible association of a single neutrino to an astrophysical source.

Following the alert, IceCube performed a complete analysis of relevant data prior to 31 October 2017. Although no additional excess of neutrinos was found from the direction of TXS 0506+056 near the time of the alert, there are indications at the 3σ level of high-energy neutrino

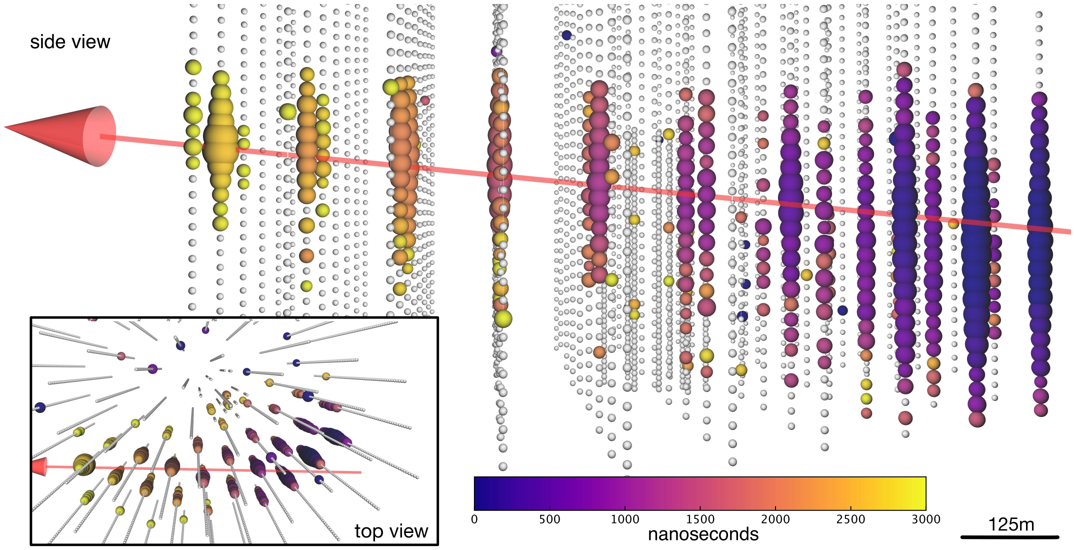

Fig. 1. Event display for neutrino event IceCube-170922A. The time at which a DOM observed a signal is reflected in the color of the hit, with dark blues for earliest hits and yellow for latest. Times shown are relative to the first DOM hit according to the track reconstruction, and earlier and later times are shown with the same colors as the first and last times, respectively. The total time the event took to cross the detector is ~3000 ns. The size of a colored sphere is proportional to the logarithm of the amount of light observed at the DOM, with larger spheres corresponding to larger signals. The total charge recorded is ~5800 photoelectrons. Inset is an overhead perspective view of the event. The best-fitting track direction is shown as an arrow, consistent with a zenith angle $5.7^{+0.50}_{-0.30}$ degrees below the horizon.

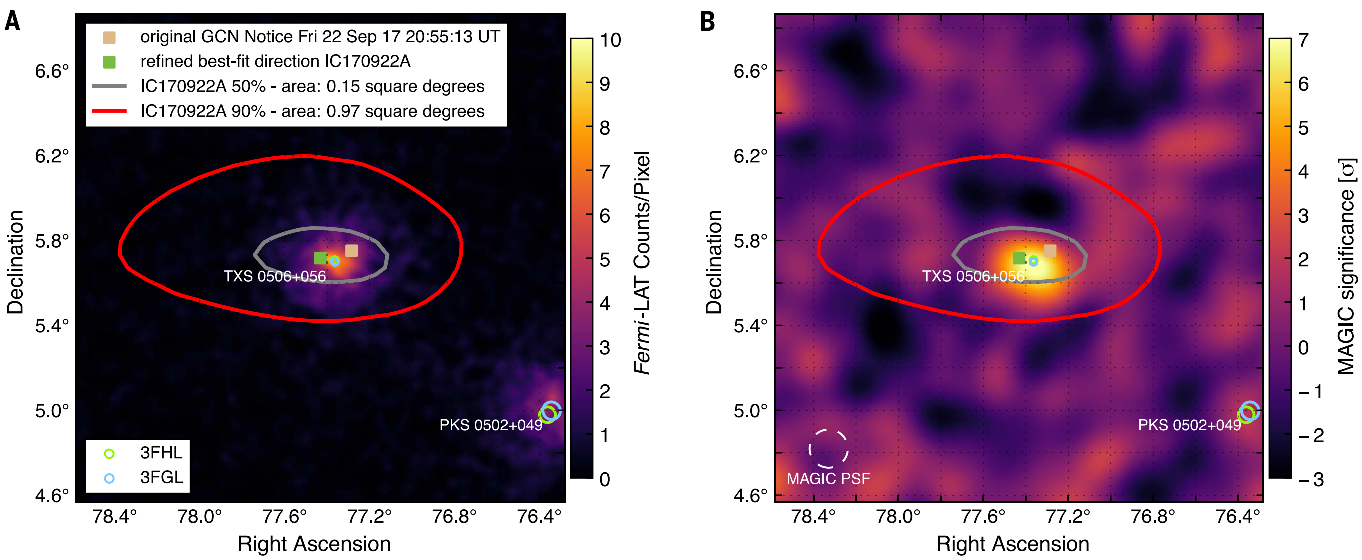

Fig. 2. *Fermi*-LAT and MAGIC observations of IceCube-170922A's location. Sky position of IceCube-170922A in J2000 equatorial coordinates overlaying the γ-ray counts from *Fermi*-LAT above 1 GeV (**A**) and the signal significance as observed by MAGIC (**B**) in this region. The tan square indicates the position reported in the initial alert, and the green square indicates the final best-fitting position from follow-up reconstructions (18). Gray and red curves show the 50% and 90% neutrino containment regions, respectively, including statistical and systematic errors. *Fermi*-LAT data are shown as a photon counts map in 9.5 years of data in units of counts per pixel, using detected photons with energy of 1 to 300 GeV in a 2° by 2° region around TXS0506+056. The map has a pixel size of 0.02° and was smoothed with a 0.02°-wide Gaussian kernel. MAGIC data are shown as signal significance for γ-rays above 90 GeV. Also shown are the locations of a γ-ray source observed by *Fermi*-LAT as given in the *Fermi*-LAT Third Source Catalog (3FGL) (23) and the Third Catalog of Hard *Fermi*-LAT Sources (3FHL) (24) source catalogs, including the identified positionally coincident 3FGL object TXS 0506+056. For *Fermi*-LAT catalog objects, marker sizes indicate the 95% CL positional uncertainty of the source.

emission from that direction in data prior to 2017, as discussed in a companion paper (26).

High-energy γ-ray observations of TXS 0506+056

On 28 September 2017, the *Fermi* Large Area Telescope (LAT) Collaboration reported that the direction of origin of IceCube-170922A was consistent with a known γ-ray source in a state of enhanced emission (16). *Fermi*-LAT is a pair-conversion telescope aboard the *Fermi Gamma-ray Space Telescope* sensitive to γ-rays with energies from 20 MeV to greater than 300 GeV (27). Since August 2008, it has operated continuously, primarily in an all-sky survey mode. Its wide field of view of ~2.4 steradian provides coverage of the entire γ-ray sky every 3 hours. The search for possible counterparts to IceCube-170922A was part of the *Fermi*-LAT collaboration's routine multiwavelength, multimessenger program.

Inside the error region of the neutrino event, a positional coincidence was found with a previously cataloged γ-ray source, 0.1° from the best-fitting neutrino direction. TXS 0506+056 is a blazar of BL Lacertae (BL Lac) type. Its redshift of $z = 0.3365 \pm 0.0010$ was measured only recently based on the optical emission spectrum in a study triggered by the observation of IceCube-170922A (28).

TXS 0506+056 is a known *Fermi*-LAT γ-ray source, appearing in three catalogs of *Fermi* sources (23, 24, 29) at energies above 0.1, 50, and 10 GeV, respectively. An examination of the *Fermi* All-Sky Variability Analysis (FAVA) (30) photometric light curve for this object showed that TXS 0506+056 had brightened considerably in the GeV band starting in April 2017 (16). Independently, a γ-ray flare was also found by *Fermi*'s Automated Science Processing [ASP (25)]. Such flaring is not unusual for a BL Lac object and would not have been followed up as extensively if the neutrino were not detected.

Figure 3 shows the *Fermi*-LAT light curve and the detection time of the neutrino alert. The light curve of TXS 0506+056 from August 2008 to October 2017 was calculated in bins of 28 days for the energy range above 0.1 GeV. An additional light curve with 7-day bins was calculated for the period around the time of the neutrino alert. The γ-ray flux of TXS 0506+056 in each time bin was determined through a simultaneous fit of this source and the other *Fermi*-LAT sources in a 10° by 10° region of interest along with the Galactic and isotropic diffuse backgrounds, using a maximum-likelihood technique (25). The integrated γ-ray flux of TXS 0506+056 for $E > 0.1$ GeV, averaged over all *Fermi*-LAT observations spanning 9.5 years, is $(7.6 \pm 0.2) \times 10^{-8}$ cm^{-2} s^{-1}. The highest flux observed in a single 7-day light curve bin was $(5.3 \pm 0.6) \times 10^{-7}$ cm^{-2} s^{-1}, measured in the week 4 to 11 July 2017. Strong flux variations were observed during the γ-ray flare, the most prominent being a flux increase from $(7.9 \pm 2.9) \times 10^{-8}$ cm^{-2} s^{-1} in the week 8 to 15 August 2017 to $(4.0 \pm 0.5) \times 10^{-7}$ cm^{-2} s^{-1} in the week 15 to 22 August 2017.

The Astro-Rivelatore Gamma a Immagini Leggero (*AGILE*) γ-ray telescope (31) confirmed the elevated level of γ-ray emission at energies above 0.1 GeV from TXS 0506+056 in a 13-day window (10 to 23 September 2017). The *AGILE* measured flux of $(5.3 \pm 2.1) \times 10^{-7}$ cm^{-2} s^{-1} is consistent with the *Fermi*-LAT observations in this time period.

High-energy γ-ray observations are shown in Figs. 3 and 4. Details on the *Fermi*-LAT and *AGILE* analyses can be found in (25).

Very-high-energy γ-ray observations of TXS 0506+056

Following the announcement of IceCube-170922A, TXS 0506+056 was observed by several ground-based Imaging Atmospheric Cherenkov Telescopes (IACTs). A total of 1.3 hours of observations in the direction of the blazar TXS 0506+056 were taken using the High-Energy Stereoscopic System (H.E.S.S.) (32), located in Namibia, on 23 September 2017 [Modified Julian Date (MJD)

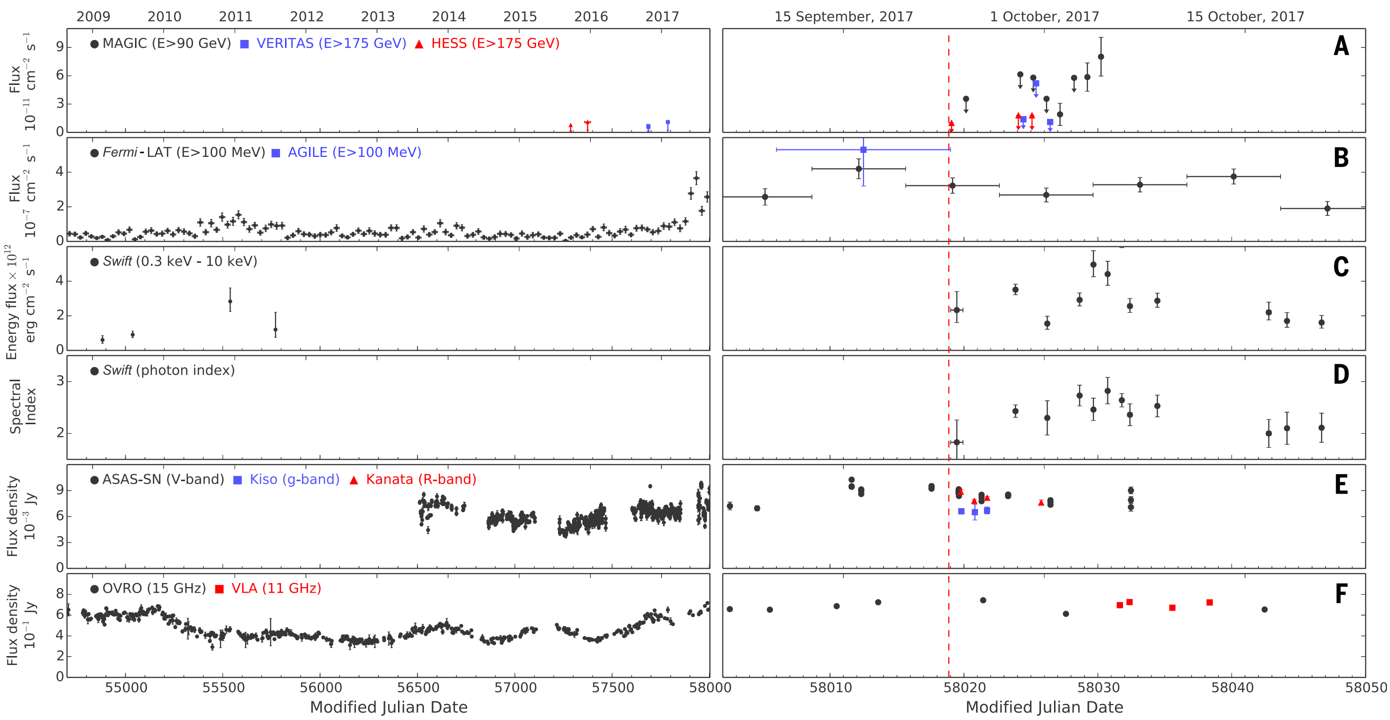

Fig. 3. Time-dependent multiwavelength observations of TXS 0506+056 before and after IceCube-170922A. Significant variability of the electromagnetic emission can be observed in all displayed energy bands, with the source being in a high-emission state around the time of the neutrino alert. From top to bottom: (**A**) VHE γ-ray observations by MAGIC, H.E.S.S., and VERITAS; (**B**) high-energy γ-ray observations by *Fermi*-LAT and *AGILE*; (**C** and **D**) x-ray observations by *Swift* XRT; (**E**) optical light curves from ASAS-SN, Kiso/KWFC, and Kanata/HONIR; and (**F**) radio observations by OVRO and VLA. The red dashed line marks the detection time of the neutrino IceCube-170922A. The left set of panels shows measurements between MJD 54700 (22 August 2008) and MJD 58002 (6 September 2017). The set of panels on the right shows an expanded scale for time range MJD 58002 to MJD 58050 (24 October 2017). The *Fermi*-LAT light curve is binned in 28-day bins on the left panel, while finer 7-day bins are used on the expanded panel. A VERITAS limit from MJD 58019.40 (23 September 2017) of 2.1×10^{-10} cm^{-2} s^{-1} is off the scale of the plot and not shown.

58019], ~4 hours after the circulation of the neutrino alert. A 1-hour follow-up observation of the neutrino alert under partial cloud coverage was performed using the Very Energetic Radiation Imaging Telescope Array System (VERITAS) γ-ray telescope array (*33*), located in Arizona, USA, later on the same day, ~12 hours after the IceCube detection. Both telescopes made additional observations on subsequent nights, but neither detected γ-ray emission from the source [see Fig. 3 and (*25*)]. Upper limits at 95% CL on the γ-ray flux were derived accordingly (assuming the measured spectrum, see below): 7.5×10^{-12} cm^{-2} s^{-1} during the H.E.S.S. observation period and 1.2×10^{-11} cm^{-2} s^{-1} during the VERITAS observations, both for energies E >175 GeV.

The Major Atmospheric Gamma Imaging Cherenkov (MAGIC) Telescopes (*34*) observed TXS 0506+056 for 2 hours on 24 September 2017 (MJD 58020) under nonoptimal weather conditions and then for a period of 13 hours from 28 September to 4 October 2017 (MJD 58024–58030) under good conditions. MAGIC consists of two 17-m telescopes, located at the Roque de los Muchachos Observatory on the Canary Island of La Palma (Spain).

No γ-ray emission from TXS 0506+056 was detected in the initial MAGIC observations on 24 September 2017, and an upper limit was derived on the flux above 90 GeV of 3.6×10^{-11} cm^{-2} s^{-1} at 95% CL (assuming a spectrum $dN/dE \propto E^{-3.9}$). However, prompted by the *Fermi*-LAT detection of enhanced γ-ray emission, MAGIC performed another 13 hours of observations of the region starting 28 September 2017. Integrating the data, MAGIC detected a significant very-high-energy (VHE) γ-ray signal (*35*) corresponding to 374 ± 62 excess photons, with observed energies up to about 400 GeV. This represents a 6.2σ excess over expected background levels (*25*). The day-by-day light curve of TXS 0506+056 for energies above 90 GeV is shown in Fig. 3. The probability that a constant flux is consistent with the data is less than 1.35%. The measured differential photon spectrum (Fig. 4) can be described over the energy range of 80 to 400 GeV by a simple power law, $dN/dE \propto E^{\gamma}$, with a spectral index $\gamma = -3.9 \pm 0.4$ and a flux normalization of $(2.0 \pm 0.4) \times 10^{-10}$ TeV^{-1} cm^{-2} s^{-1} at E = 130 GeV. Uncertainties are statistical only. The estimated systematic uncertainties are <15% in the energy scale, 11 to 18% in the flux normalization, and ±0.15 for the power-law slope of the energy spectrum (*34*). Further observations after 4 October 2017 were prevented by the full Moon.

An upper limit to the redshift of TXS 0506+056 can be inferred from VHE γ-ray observations using limits on the attenuation of the VHE flux due to interaction with the EBL. Details on the method are available in (*25*). The obtained upper limit ranges from 0.61 to 0.98 at a 95% CL, depending on the EBL model used. These upper limits are consistent with the measured redshift of $z = 0.3365$ (*28*).

No γ-ray source above 1 TeV at the location of TXS 0506+056 was found in survey data of the High Altitude Water Cherenkov (HAWC) γ-ray observatory (*36*), either close to the time of the neutrino alert or in archival data taken since November 2014 (*25*).

VHE γ-ray observations are shown in Figs. 3 and 4. All measurements are consistent with the observed flux from MAGIC, considering the differences in exposure, energy range, and observation periods.

Radio, optical, and x-ray observations

The Karl G. Jansky Very Large Array (VLA) (*37*) observed TXS 0506+056 starting 2 weeks after the alert in several radio bands from 2 to 12 GHz (*38*), detecting significant radio flux variability and some spectral variability of this source. The source is also in the long-term blazar monitoring program of the Owens Valley Radio Observatory (OVRO) 40-m telescope at 15 GHz (*39*). The light curve shows a gradual increase in radio emission during the 18 months preceding the neutrino alert.

Optical observations were performed by the All-Sky Automated Survey for Supernovae (ASAS-SN) (*40*), the Liverpool Telescope (*41*), the

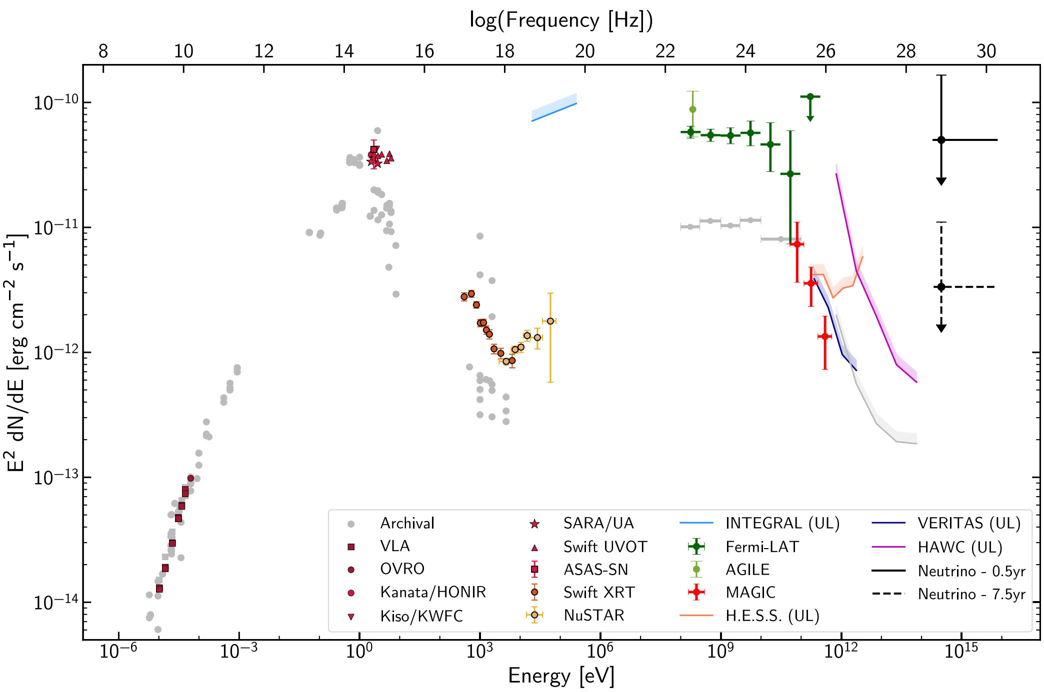

Fig. 4. Broadband spectral energy distribution for the blazar TXS 0506+056. The SED is based on observations obtained within 14 days of the detection of the IceCube-170922A event. The $E^2 dN/dE$ vertical axis is equivalent to a νF_ν scale. Contributions are provided by the following instruments: VLA (*38*), OVRO (*39*), Kanata Hiroshima Optical and Near-InfraRed camera (HONIR) (*52*), Kiso, and the Kiso Wide Field Camera (KWFC) (*43*), Southeastern Association for Research in Astronomy Observatory (SARA/UA) (*53*), ASAS-SN (*54*), *Swift* Ultraviolet and Optical Telescope (UVOT) and XRT (*55*), *NuSTAR* (*56*), *INTEGRAL* (*57*), *AGILE* (*58*), *Fermi*-LAT (*16*), MAGIC (*35*), VERITAS (*59*), H.E.S.S. (*60*), and HAWC (*61*). Specific observation dates and times are provided in (*25*). Differential flux upper limits (shown as colored bands and indicated as "UL" in the legend) are quoted at the 95% CL, while markers indicate significant detections. Archival observations are shown in gray to illustrate the historical flux level of the blazar in the radio-to-keV range as retrieved from the ASDC SED Builder (*62*), and in the γ-ray band as listed in the *Fermi*-LAT 3FGL catalog (*23*) and from an analysis of 2.5 years of HAWC data. The γ-ray observations have not been corrected for absorption owing to the EBL. SARA/UA, ASAS-SN, and Kiso/KWFC observations have not been corrected for Galactic attenuation. The electromagnetic SED displays a double-bump structure, one peaking in the optical-ultraviolet range and the second one in the GeV range, which is characteristic of the nonthermal emission from blazars. Even within this 14-day period, there is variability observed in several of the energy bands shown (see Fig. 3), and the data are not all obtained simultaneously. Representative $\nu_\mu + \bar{\nu}_\mu$ neutrino flux upper limits that produce on average one detection like IceCube-170922A over a period of 0.5 (solid black line) and 7.5 years (dashed black line) are shown, assuming a spectrum of $dN/dE \propto E^{-2}$ at the most probable neutrino energy (311 TeV).

Kanata Telescope (42), the Kiso Schmidt Telescope (43), the high-resolution spectrograph (HRS) on the Southern African Large Telescope (SALT) (44), the Subaru telescope Faint Object Camera and Spectrograph (FOCAS) (45), and the X-SHOOTER instrument on the Very Large Telescope (VLT) (46). The *V* band flux of the source is the highest observed in recent years, and the spectral energy distribution has shifted toward blue wavelengths. Polarization was detected by Kanata in the *R* band at the level of 7%. Redshift determination for BL Lac objects is difficult owing to the nonthermal continuum from the nucleus outshining the spectral lines from the host galaxies. Attempts were made using optical spectra from the Liverpool, Subaru, and VLT telescopes to measure the redshift of TXS 0506+056, but only limits could be derived [see, e.g., (47)]. The redshift of TXS 0506+056 was later determined to be $z = 0.3365 \pm 0.0010$ using the Gran Telescopio Canarias (28).

X-ray observations were made by the X-Ray Telescope (XRT) on the *Neil Gehrels Swift Observatory* (0.3 to 10 keV) (48), *MAXI* Gas Slit Camera (GSC) (2 to 10 keV) (49), Nuclear Spectroscopic Telescope Array (*NuSTAR*) (3 to 79 keV) (50), and the INTernational Gamma-Ray Astrophysics Laboratory (*INTEGRAL*) (20 to 250 keV) (51), with detections by *Swift* and *NuSTAR* . In a 2.1 square degree region around the neutrino alert, *Swift* identified nine x-ray sources, including TXS 0506+056.

Swift monitored the x-ray flux from TXS 0506+056 for 4 weeks after the alert, starting 23 September 2017 00:09:16 UT, finding clear evidence for spectral variability (see Fig. 3D). The strong increase in flux observed at VHE energies over several days up until MJD 58030 (4 October 2017) correlates well with an increase in the x-ray emission during this period of time. The spectrum of TXS 0506+056 observed in the week after the flare is compatible with the sum of two power-law spectra, a soft spectrum with index -2.8 ± 0.3 in the soft x-ray band covered by *Swift* XRT, and a hard spectrum with index -1.4 ± 0.3 in the hard x-ray band covered by *NuSTAR* (25). Extrapolated to 20 MeV, the *NuSTAR* hard-spectrum component connects smoothly to the plateau (index -2) component observed by the *Fermi*-LAT between 0.1 and 100 GeV and the soft VHE γ-ray component observed by MAGIC (compare Fig. 4). Taken together, these observations provide a mostly complete, contemporaneous picture of the source emissions from 0.3 keV to 400 GeV, more than nine orders of magnitude in photon energy.

Figures 3 and 4 summarize the multiwavelength light curves and the changes in the broadband spectral energy distribution (SED), compared to archival observations. Additional details about the radio, optical, and x-ray observations can be found in (25).

Chance coincidence probability

Data obtained from multiwavelength observations of TXS 0506+056 can be used to constrain the blazar-neutrino chance coincidence probability. This coincidence probability is a measure of the likelihood that a neutrino alert like IceCube-170922A is correlated by chance with a flaring blazar, considering the large number of known γ-ray sources and the modest number of neutrino alerts.

Given the large number of potential neutrino source classes available, no a priori blazar-neutrino coincidence model was selected ahead of the alert. After the observation, however, several correlation scenarios were considered and tested to quantify the a posteriori significance of the observed coincidence. Testing multiple models is important as the specific assumptions about the correlation between neutrinos and γ-rays have an impact on the chance coincidence probability. In each case, the probability to obtain, by chance, a degree of correlation at least as high as that observed for IceCube-170922A was calculated using simulated neutrino alerts and the light curves of *Fermi*-LAT γ-ray sources. Given the continuous all-sky monitoring of the *Fermi*-LAT since 2008, all tests utilized 28-day binned γ-ray light curves above 1 GeV from 2257 extragalactic *Fermi*-LAT sources, derived in the same manner as used for the analysis of TXS 0506+056 γ-ray data.

To calculate the chance probabilities, a likelihood ratio test is used that allows different models of blazar-neutrino flux correlation to be evaluated in a consistent manner. All models assume that at least some of the observed γ-ray flux is produced in the same hadronic interactions that would produce high-energy neutrinos within the source. Our first model assumes that the neutrino flux is linearly correlated with the high-energy γ-ray energy flux (4). In this scenario, neutrinos are more likely to be produced during periods of bright, hard γ-ray emission. In the second model, the neutrino flux is modeled as strongly tied to variations in the observed γ-ray flux, regardless of the average flux of γ-rays. Here, a weak or a strong γ-ray source is equally likely to be a neutrino source if the neutrino is temporally correlated with variability in the γ-ray light curve. Third, we consider a correlation of the neutrino flux with the VHE γ-ray flux. Because hadronic acceleration up to a few PeV is required to explain the detected neutrino energy, VHE γ-ray sources are potential progenitors. Full details and results from these analyses are presented in (25).

The neutrino IceCube-170922A was found to arrive in a period of flaring activity in high-energy γ-rays. Prior to IceCube-170922A, nine public alerts had been issued by the IceCube real-time system. Additionally, 41 archival events have been identified among the IceCube data recorded since 2010, before the start of the real-time program in April 2016, which would have caused alerts if the real-time alert system had been in place. These events were also tested for coincidence with the γ-ray data.

Chance coincidence of the neutrino with the flare of TXS 0506+056 is disfavored at the 3σ level in any scenario where neutrino production is linearly correlated with γ-ray production or with γ-ray flux variations. This includes look-elsewhere corrections for all 10 alerts issued previously by IceCube and the 41 archival events. One of the neutrino events that would have been sent as an alert and had a good angular resolution (<5°) is in a spatial correlation with the γ-ray blazar 3FGL J1040.4+0615. However, this source was not in a particularly bright emission state at the detection time of the corresponding neutrino. Therefore, a substantially lower test statistic would be obtained in the chance correlation tests defined in this paper (25).

We have investigated how typical the blazar TXS 0506+056 is among those blazars that might have given rise to a coincident observation similar to the one reported here. A simulation that assumes that the neutrino flux is linearly correlated with the blazar γ-ray energy flux shows that in 14% of the signal realizations, we would find a neutrino coincident with a similarly bright γ-ray state as that observed for TXS 0506+056 (25). The detection of a single neutrino does not allow us to probe the details of neutrino production models or measure the neutrino–to–γ-ray production ratio. Further observations will be needed to unambiguously establish a correlation between high-energy neutrinos and blazars, as well as to understand the emission and acceleration mechanism in the event of a correlation.

Discussion

Blazars have often been suggested as potential sources of high-energy neutrinos. The calorimetric high-energy output of certain candidate blazars is high enough to explain individual observed IceCube events at 100-TeV to 1-PeV energies (63). Spatial coincidences between catalogs of blazars and neutrinos have been examined in (64), while (65) investigated one shower-like event with several thousand square degrees angular uncertainty observed in time coincidence with a blazar outburst. A track-like event, IceCube-160731, has been previously connected to a flaring γ-ray source (66). However, the limited evidence for a flaring source in the multiwavelength coverage did not permit an identification of the source type of the potential counterpart (66).

Owing to the precise direction of IceCube-170922A, combined with extensive multiwavelength observations, a chance correlation between a high-energy neutrino and the potential counterpart can be rejected at the 3σ level. Considering the association between IceCube-170922A and TXS 0506+056, γ-ray blazars are strong candidate sources for at least a fraction of the observed astrophysical neutrinos. Earlier studies of the cross-correlation between IceCube events and the γ-ray blazar population observed by *Fermi*-LAT demonstrated that these blazars can only produce a fraction of the observed astrophysical neutrino flux above 10 TeV (4). Although these limits constrain the contribution from blazars to the diffuse neutrino background, the potential association of one or two high-energy neutrinos to blazars over the total observing time of IceCube is fully compatible with the constraint.

Adopting standard cosmological parameters (67) $H_0 = 67.8, \Omega_m = 0.308, \Omega_\lambda = 0.692$, where H_0 is the Hubble constant, Ω_m is the matter density, and Ω_λ is the dark energy density, the observed redshift of $z = 0.3365$ implies an isotropic γ-ray luminosity between 0.1 and 100 GeV of 1.3×10^{47} erg s^{-1} in the ±2 weeks around the arrival time of the IceCube neutrino, and a luminosity of 2.8×10^{46} erg s^{-1}, averaged over all *Fermi*-LAT observations. Observations in the optical, x-ray, and VHE γ-ray bands show typical characteristics of blazar flares: strong variability on time scales of a few days and an indication of a shift of the synchrotron emission peak toward higher frequencies. VHE γ-ray emission is found to change by a factor of ~4 within just 3 days. Similarly, the high-energy γ-ray energy band shows flux variations up to a factor of ~5 from one week to the next.

No other neutrino event that would have passed the selection criteria for a high-energy alert was observed from this source since the start of IceCube observations in May 2010. The muon neutrino fluence for which we would expect to detect one high-energy alert event with IceCube in this period of time is 2.8×10^{-3} erg cm^{-2}. A power-law neutrino spectrum is assumed in this calculation with an index of −2 between 200 TeV and 7.5 PeV, the range between the 90% CL lower and upper limits for the energy of the observed neutrino [see (*25*) for details].

The fluence can be expressed as an integrated energy flux if we assume a time period during which the source was emitting neutrinos. For a source that emits neutrinos only during the ~6-month period corresponding to the duration of the high-energy γ-ray flare, the corresponding average integrated muon neutrino energy flux would be 1.8×10^{-10} erg cm^{-2} s^{-1}. Alternatively, the average integrated energy flux of a source that emits neutrinos over the whole observation period of IceCube (i.e., 7.5 years) would be 1.2×10^{-11} erg cm^{-2} s^{-1}. These two benchmark cases are displayed in Fig. 4. In an ensemble of faint sources with a summed expectation of order 1, we would anticipate observing a neutrino even if the individual expectation value is ≪1. This is expressed by the downward arrows on the neutrino flux points in Fig. 4.

The two cases discussed above correspond to average isotropic muon neutrino luminosities of 7.2×10^{46} erg s^{-1} for a source that was emitting neutrinos in the ~6-month period of the high-energy γ-ray flare, and 4.8×10^{45} erg s^{-1} for a source that emitted neutrinos throughout the whole observation period. This is similar to the luminosity observed in γ-rays and thus broadly consistent with hadronic source scenarios (*68*).

A neutrino flux that produces a high-energy alert event can, over time, produce many lower-energy neutrino-induced muons in IceCube. A study of neutrino emission from TXS 0506+056 prior to the high-energy γ-ray flare, based on the investigation of these lower-energy events, is reported in a companion paper (*26*).

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images were mainly examined by H.M. and H.N. M.Y. reduced the polarimetric data. K.S.K. supervised all of the above. T.M. conducted the optical imaging observations of TXS 0506+056 with the KWFC instrument on the Kiso Schmidt telescope and reduced the data. Y.M. conducted optical spectroscopic observations of the TXS 0506 +056 with the FOCAS spectrograph on the 8.2 m Subaru telescope. The data are reduced and examined by M.Y. and T.M. **Kapteyn:** W.C.K. obtained and reduced the optical observations at the Kapteyn telescope. **Liverpool Telescope:** I.S. and C.C. obtained, reduced, and analyzed the Liverpool Telescope spectra. ***Swift*/*NuSTAR*:** A.K. led reduction of *Swift* XRT data, and J.J.D. led reduction of *NuSTAR* data. D.B.F. carried out the joint *Swift* XRT + *NuSTAR* analysis, and A.K. managed author contributions to this section. **VERITAS:** The construction, operation, and maintenance of the VERITAS telescopes, as well as the tools to analyze the VERITAS data, are the work of the the VERITAS Collaboration as a whole. The VERITAS Collaboration contacts for this paper are M.S. and D.A.W. **VLA/17B-403:** GRS wrote the Director's Discretionary Time proposal for the VLA observations. A.J.T. performed the VLA data reduction and analyses in consultation with the rest of the team. A.J.T. and G.R.S. wrote the VLA-related text in consultation with the rest of the team. G.R.S. contributed to writing the entire paper. **Competing interests:** All collaborations declare no competing interests. **Data and materials availability: IceCube:** All IceCube data related to the the results presented in this paper are provided in the supplementary materials (*25*). ***Fermi*-LAT:** The *Fermi*-LAT data are available from the *Fermi* Science Support Center http://fermi.gsfc.nasa.gov/ssc and https://www-glast.stanford.edu/pub_data/1483/. **MAGIC:** The MAGIC data and analysis results are accessible at https://magic.mpp.mpg.de/public/public-data/ ***AGILE*:** The *AGILE* data are available at www.ssdc.asi.it/mmia/index.php?mission=agilemmia. Data analysis software and calibrations are available at http://agile.ssdc.asi.it/publicsoftware.html. **ASAS-SN:** The ASAS-SN light curves are available at https://asas-sn.osu.edu **HAWC:** The HAWC data are available at https://data.hawc-observatory.org/datasets/ic170922/index.php. **H.E.S.S.:** The H.E.S.S. data are available at https://www.mpi-hd.mpg.de/hfm/HESS/pages/publications/auxiliary/auxinfo_TXS0506.html ***INTEGRAL*:** The *INTEGRAL* data and analysis software are available at www.isdc.unige.ch/. **Kanata, Kiso and Subaru observing teams:** Data taken with the Kiso, Kanata, and Subaru telescopes are available in the archive SMOKA https://smoka.nao.ac.jp/, operated by the Astronomy Data Center, National Astronomical Observatory of Japan. The Subaru data were taken in the open-use program S16B-071I. **Kapteyn:** The Kapteyn data were taken from (*53*) **Liverpool Telescope:** The Liverpool Telescope data are available in the telescope archive at http://telescope.livjm.ac.uk/cgi-bin/lt_search. ***Swift*/*NuSTAR*:** The *Swift* data are available at www.swift.ac.uk/archive/obs.php. The initial tiling observations, shortly after the IceCube trigger, are targetIDs 10308-10326. The monitoring ObsIDs observed from 23 September to 23 October are 00010308001, 00083368001-006, 00010308008-013. The *NuSTAR* data are available at https://heasarc.gsfc.nasa.gov/FTP/nustar/data/obs/03/9//90301618002/ under ObsID 90301618002. **VERITAS:** The VERITAS data are available at https://veritas.sao.arizona.edu/veritas-science/veritas-results-mainmenu-72/490-ic-result **VLA/17B-403 team:** The VLA data are available through the NRAO Science Data Archive https://archive.nrao.edu/archive/advquery.jsp under Project Code 17B-403.

SUPPLEMENTARY MATERIALS

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