High-energy astrophysical neutrinos are produced in central parsec-scale regions of radio-bright active galaxies

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ABSTRACT

Observational information on high-energy astrophysical neutrinos is being continuously collected by the IceCube observatory. However, sources of the neutrinos are still unknown. In this paper we use radio very-long-baseline interferometry (VLBI) data for a complete VLBI-flux-density limited sample in a statistical manner in order to address the problem of the origin of astrophysical neutrinos with energies above 200 TeV. We find that active galactic nuclei (AGN) positionally associated with IceCube events have typically stronger parsec-scale cores than the rest of the sample, with the post-trial p-value of chance coincidence of $p = 0.2\%$. We select four strongest ones as highly probable associations: 3C 279, NRAO 530, PKS 1741−038, and 4C +06.69. Moreover, we find that the epochs of increase in radio emission at frequencies above 10 GHz coincide with neutrino arrival times for VLBI-selected AGN in IceCube error regions, the most pronounced example being PKS 1502+106. We conclude that AGN with bright Doppler-boosted jets constitute an important population of neutrino sources. High-energy neutrinos are produced in their central parsec-scale regions, probably in proton-photon interactions at or around the accretion disk. Radio-bright AGN likely associated with neutrinos have very diverse $\gamma$-ray properties suggesting that $\gamma$ rays and neutrinos are produced in different regions of the AGN and are not directly related. A small viewing angle of the jet-disk axis is however required to detect either of them.

Keywords: neutrinos – galaxies: active – galaxies: jets – quasars: general – radio continuum: galaxies

1. INTRODUCTION

Extraterrestrial neutrinos with energies $E \gtrsim 50$ TeV have been convincingly observed by the IceCube experiment since 2012 (Aartsen et al. 2013a,b; for the most recent updates see Aartsen et al. 2019). In 2019, the Baikal–GVD (Gigaton Volume Detector) experiment has reported on the first few $E > 100$ TeV neutrino candidates (Avrorin et al. 2019), confirming the IceCube observation from the Northern hemisphere. Indications to the astrophysical high-energy neutrino flux have also been found by the ANTARES experiment (Fusco & Versari 2019). Despite these various observations, the origin of the energetic astrophysical neutrinos remains unknown (for a review, see e.g. Ahlers & Halzen 2018). Since the arrival directions of the neutrinos do not demonstrate any significant Galactic anisotropy (see, e.g. Troitsky 2015; Albert et al. 2018), their origin in extragalactic sources is often assumed. Active galactic nuclei (AGN) have been discussed as potential neutrino emitters long before the neutrino detection (Berezinsky 1977; see also, e.g., Eichler 1979; Berezinskii & Ginzburg 1981 for subsequent early studies). Further interest in this class of sources have been heated by the observation of a $\gamma$-ray flare of a blazar in directional and, to a certain precision, temporal co-
incidence with a neutrino event detected by IceCube (Aartsen et al. 2018a), supplemented by an excess of lower-energy events from the same direction found in the archival data (Aartsen et al. 2018b). Nevertheless, the origin of the entire population of observed neutrinos in blazars is strongly constrained by the lack of clusters (multiplets) in the arrival directions, by stacking analyses and by diffuse γ-ray observations (see, e.g., Murase & Waxman 2016; Murase et al. 2018; Yuan et al. 2019).

However, joint analyses of IceCube data sets obtained with various experimental techniques reveal a possibility that the observed astrophysical neutrino flux is formed by two distinct components, a softer one dominating the flux at \( E \sim 50 – 100 \) TeV and a harder one, which is important above \( E \sim 200 \) TeV (Palladino & Vissani 2016; Ahlers & Halzen 2018). While the origin of the entire population of neutrinos in active galaxies is strongly constrained (see, e.g., Yuan et al. 2019, and section 4 below), these constraints are relaxed for the hard component considered alone. So the origin of the dominant part of observed neutrinos above \( \sim 200 \) TeV in powerful AGN remains probably the best option. In the present study, we concentrate on this higher-energy component of the neutrino flux.

It is usually assumed that high-energy neutrinos are produced in decays of charged \( \pi \) mesons, which are in turn born as secondary particles in interactions of energetic protons with ambient matter or radiation. Acceleration of the protons and presence of sufficiently abundant targets are therefore the key conditions for the neutrino production. In principle, they may be realized in various parts of AGN, and two general classes of models are considered with the neutrino production zone located either in central (accretion disk, jet launching and acceleration region, broad-line region) or in extended (kiloparsec-scale jets, blobs, lobes, hot spots) parts of a galaxy; see, e.g., reviews by Murase (2017); Mészáros (2017); Böttcher (2019); Cerruti (2019) and references therein. It is a nontrivial task to distinguish between these two scenarios observationally because poor angular resolution of astronomical instruments, especially of those working at high energies, prevents one from direct localization of the regions where the radiation co-produced with neutrinos comes from. In addition, low directional resolution of neutrino experiments and high rate of atmospheric background events make the association of detected neutrinos with particular candidate sources challenging.

The aim of the present work is to alleviate these difficulties and to obtain direct observational evidence in favour of one of the scenarios. To distinguish between central and outer parts of active galaxies, we use very-long-baseline interferometric (VLBI) radio observations capable to resolve central parsecs of AGN even at cosmological distances, while the problem of source associations is addressed by a statistical approach. Note that the accretion disk is not visible in radio and the jet acceleration and collimation zone is resolved only for nearby AGN (Kovalev et al. 2019). However, activity observed in the apparent jet base by VLBI with a typical resolution in the plane of the sky of about 1 pc is shown to be a good tracer of what is happening in and around the nucleus (e.g., Marscher et al. 2002; Pushkarev et al. 2010).

The rest of the paper is organized as follows. In section 2, we introduce data sets used in our analysis: IceCube neutrino events (subsection 2.1), VLBI observations (subsection 2.2) and the radio monitoring archive (subsection 2.3). Section 3 presents the description and results of performed statistical analyses. In section 4, we compare our results with previous studies and briefly discuss their implications for models of high-energy astrophysical neutrino production. We summarize our conclusions in section 5.

2. DATA

2.1. IceCube events

IceCube detects high-energy neutrino events of two types, cascades and tracks. The former are seen as showers which develop within the detector volume; the energy of the primary neutrino is determined relatively good but the arrival direction is uncertain. For the latter, the situation is opposite: relatively narrow tracks pass through the detector, the angular resolution is normally of the order of 1° but a part of the energy of secondary particles is left outside the instrumental volume, hence the energy of the primary particle is determined with large uncertainties. On average, track events which passed selection criteria correspond to higher energies in comparison with cascade events. In the present study, we concentrate on the track events only because of their better angular resolution and higher neutrino energies. We are interested in neutrinos with estimated energies \( E \gtrsim 200 \) TeV because it is the value above which, assuming two flux components, the hard-spectrum component starts to dominate. This can be seen, for instance, by comparison of the best-fit spectra obtained by IceCube from the analysis of starting events (more sensitive at lower energies) and of Northern-hemisphere muon tracks (more sensitive at higher energies), as reported by Aartsen et al. (2019). Remarkably, this value \( E = 200 \) TeV is also the threshold value for some published IceCube Northern-hemisphere muon track data sets (Aartsen et al. 2016, 2017a, p. 30), which gives ad-
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Figure 1. IceCube event locations on the sky, represented by blue error ellipses. Dark blue ellipses are original reported positional errors, light blue ones — enlarged to account for systematics according to our analysis, see subsection 3.1 for details and subsection 2.1 for event sample selection. Stars represent all AGN within neutrino error regions from our complete VLBI sample of AGN. Color represents the 8 GHz flux density integrated over VLBI images of these AGN. Members of the complete 8-GHz VLBI sample located outside the ellipses are shown by grey dots. The shown object names denote four AGN with strongest parsec-scales jets which are the most probable neutrino associations according to our analysis: 1253−055 (3C 279), 1730−130 (NRAO 530), PKS 1741−038, and 2145+067 (OR 103). We also show the location of the first neutrino association TXS 0506+056.

Additional technical motivation for this cut. Therefore, we fix the condition $E \geq 200$ TeV for all tests discussed below. A study of validity of our conclusions for less energetic neutrinos is beyond the scope of the present paper.

The largest published IceCube data set of high-energy track events is given by Extremely High Energy (EHE) alerts and alert-like (EHEA) events. It includes events which passed selection criteria (Aartsen et al. 2017b) for the EHE type alerts issued by IceCube between July 2016 and May 2019. The list of events before September 2017, including early events which arrived before the launch of the alert system but satisfied the same criteria, is published online (IceCube Collaboration 2018). Details of similar events observed after September 2017 are available through the Gamma-ray Coordinates Network (GCN) and Astroparticle Messenger Observatory Network (AMON) notices, see also IceCube Catalogue of Astrophysical Neutrino Candidates. For one event, we use detailed information from Aartsen et al. (2018a). By construction, EHEA events have good angular resolution (we found that the 90% containment area on the celestial sphere $\Omega_{90} < 10$ sq. deg) and high estimated energies (certainly above 200 TeV). There are 33 events in this EHEA sample.

In order to use the largest available sample of highest-energy neutrino events of similar quality, we supplement the EHEA sample with 23 more events satisfying the following criteria: (i) track morphology, (ii) $E > 200$ TeV, (iii) $\Omega_{90} < 10$ sq. deg. These events were selected from all other publicly available IceCube event lists. They include High Energy Starting Event (HESE)

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1 https://icecube.wisc.edu/science/data/TXS0506_alerts
2 https://gcn.gsfc.nasa.gov/gcn_main.html
3 https://www.amon.psu.edu
4 https://gcn.gsfc.nasa.gov/amon.html
5 https://neutrino-catalog.icecube.aq
alerts and alert-like events (HESEA), “GOLD” and “BRONZE” alerts from IceCube Collaboration (2018) and GCN/AMON; HESE lists from Aartsen et al. (2014, 2015, 2017a, p. 54) and Northern-hemisphere muon track (MUONT) event lists from Aartsen et al. (2016, 2017a, p. 30). For a few HESE alerts, the estimated energy of the neutrino was not published; we then used the deposited charge (number of photoelectrons) divided by 100 as a proxy for the energy in TeV, cf. Aartsen et al. (2014).

For the IceCube events, coordinate-wise intervals with 90% statistical coverage are reported in the published data we use. In addition, systematic errors are not always published, but are present in the determination of the arrival directions. These errors are related in particular, but not exclusively, to the lack of knowledge of ice properties and depend not only on the arrival direction but also on the part of the installation where the event was observed and are therefore hard to model; they are taken into account in our analysis as discussed in section 3.

Therefore, our sample of IceCube high-energy neutrinos includes 36 events with $E > 200$ TeV; known arrival directions, 90% confidence level (CL) statistical uncertainty ellipses on the celestial sphere and arrival times. Note that a significant part of these events is not astrophysical: even at high energies, the atmospheric background is essential. For instance, the expected fraction of non-astrophysical events in the EHEA sample, assuming $E^{-2}$ astrophysical spectrum, is 32% (Aartsen et al. 2017b); for a softer assumed spectrum or for other event classes the background contribution is even larger. We also note that, at present, neither Baikal-GVD nor ANTARES published detailed information on track events above 200 TeV.

### 2.2. VLBI observations of AGN

For our analysis we used 8 GHz VLBI observations compiled in the Astrogeo\(^6\) database, comprising the visibility and imaging data acquired from geodetic VLBI observations (Petrov et al. 2009; Pushkarev & Kovalev 2012; Piner et al. 2012), the Very Long Baseline Array (VLBA) calibrator surveys (VCS; Beasley et al. 2002; Fomalont et al. 2003; Petrov et al. 2005, 2006; Kovalev et al. 2007; Petrov et al. 2008; Petrov 2016; Gordon et al. 2016) and other 8 GHz global VLBI, VLBA, EVN (the European VLBI Network), and LBA (the Australian Long Baseline Array) observations (Petrov et al. 2011a; Petrov 2011; Petrov et al. 2011b; Petrov 2012, 2013; Schinzel et al. 2015; Shu et al. 2017; Petrov et al. 2019). Their positions are determined and presented within the VLBI-based Radio Fundamental Catalogue\(^7\) (RFC). We note that a special effort was made by the VCS program observations to compile a complete sample of AGN limited on the flux density integrated over VLBI images $S_{\nu=15\text{GHz}} > 150$ mJy at 8 GHz and a similar effort was made with LBA observations. The resulting sky coverage can be seen in Figure 1. The sample consists of 3388 objects.

We use in our analysis the flux density integrated over VLBI images of AGN and call it throughout the paper the “VLBI flux density.” For majority of Doppler-boosted AGN which comprise our sample it is dominated by emission of the apparent parsec-scale jet base, see detailed discussion in subsection 4.1. If an object was imaged by VLBI at more than one epoch at a given frequency band of 8 GHz, an average of the VLBI flux density is used in the analysis of this subsection.

Note that the image database as well as the catalog contain data for other wavelengths (2.3, 5, 15, 22 GHz) as well as down to much lower flux density level. However, the deep statistically complete sample was constructed at 8 GHz only. Most of the other wavelengths lack data below $−30^\circ$ declination. The 15 GHz band is complete down to $S_{\nu=15\text{GHz}} = 1.5$ Jy thanks to the MOJAVE project (Lister et al. 2019). All together, the VLBI catalog contains measurements for more than 16 thousand AGN. At the same time full samples at different bands might be biased, e.g., towards $\gamma$-ray selected AGN (e.g., Schinzel et al. 2015; Lister et al. 2018), AGN seen through the galactic plane (Petrov et al. 2011a; Petrov 2012), optically bright AGN (Petrov 2011, 2013), etc. The 22 GHz sample might be biased towards the most compact AGN selected to serve for the high frequency realization of the celestial reference frame (Charlot et al. 2010). That is why, to achieve the most robust results, we use only the 8 GHz sample in our statistical studies.

### 2.3. RATAN-600 AGN monitoring

The Russian RATAN-600 radio telescope (Korolkov & Pariiskii 1979) of the Special Astrophysical Observatory is monitoring at 1-22 GHz a sample of AGN selected on their VLBI flux density since late 1980s. Details of observations, data analysis, observing sample, and results can be found in Kovalev (1997); Kovalev et al. (1999, 2000, 2002). The measurements of a target at a given observing epoch occur simultaneously at 1, 2, 5, 8, 11,
and 22 GHz. For the analysis in this paper we drop the lowest two frequencies since they are often affected by Radio Frequency Interference (RFI) which became stronger during the years used in this paper: 2009 – 2019, inclusive.

Originally, RATAN observing sample was selected on the basis of correlated VLBI flux density measurements by Preston et al. (1985). It was later supplemented by new objects found by the VCS survey. It has good completeness characteristics down to $S_{8\text{GHz}} \approx 0.4 \text{ Jy}$ and contains AGN with parsec-scale radio jets. Due to the ring-shape and transit observing mode of the telescope, the best monitored part of the sample with 3-4 epochs per year is restricted to the declination range $-30^\circ < \delta < 43^\circ$ which is similar to the main sky coverage by the IceCube high-energy track events in our sample. The full RATAN-600 dataset which was used by us in the analysis has 1099 sources with $\geq 5$ epochs, 758 of which were observed 10 times or more.

There is a rich multi-frequency dataset produced by the F-GAMMA AGN broad-band spectrum monitoring program (Fuhrmann et al. 2016). Unfortunately, the published data cover the period until 2015 only (Angelakis et al. 2019). This is not long enough for our analysis since many neutrino events were collected after 2015. We have not used these data in the paper.

3. STATISTICAL ANALYSIS
3.1. Flux density of AGN radio emission from parsec scales

We use VLBI flux density of AGN to determine whether neutrino-emitting ones tend to be stronger in terms of their radio emission from compact parsec-scale central regions. Taking the complete sample (subsection 2.2) we compute the average VLBI flux density, $v$, of sources inside error regions of IceCube events, and test if it is significantly higher than could arise by chance. We average flux densities using geometric mean (or, equivalently, arithmetic mean of logarithms) here and throughout this paper because their range covers several orders of magnitude. A Monte-Carlo method is employed for significance testing in the following way:

- Compute the statistic of interest using real positions of IceCube events IceCube. Denote its value as $v_{\text{real}}$.
- Repeat $N = 10000$ times the following:
  - Shift IceCube events to random right ascension coordinates, keeping declinations and error regions unchanged\(^8\);
  - Compute the same statistic for these randomly shifted events in place of real ones. Denote this value $v_i$, $1 \leq i \leq N$.
  - The empirical distribution of $v_i$ represents the test statistic distribution under the null hypothesis that the statistic is not related to detected neutrinos. We use this to show corresponding intervals in our plots.
  - Count random realizations with values not lower than the real one: $M = \sum_i (v_i \geq v_{\text{real}})$ (swap the sign if testing for difference in the opposite direction). Calculate the p-value estimate as $p = \frac{M + 1}{N + 1}$ following Davison & Hinkley (2013).

Because of the complications discussed in subsection 2.1, we choose to introduce the systematic error as a free parameter common to all events and determine its optimal value from observations; this freedom is taken into account as multiple trials in the Monte-Carlo simulations estimating the significance of the observed correlations (see, e.g., Tinyakov & Tkachev 2004). Technically, we initially obtain 90% coverage regions by multiplying the reported statistical errors by the ratio of corresponding quantiles of two- and one-dimensional Gaussian distributions $\frac{\sqrt{\log 10}}{\text{erf}^{-1}(0.9)} \approx 1.30$. Then we linearly add an unknown value to errors in all directions, corresponding to the unaccounted systematic error. Each of the resulting regions is bounded by 4 quarters of ellipses, as IceCube reports two-sided uncertainties in both Right Ascension and Declination directions. The modified test statistic is computed as follows:

- For each assumed value of the systematic error $0 \leq x \leq 1^\circ$ (we take 50 uniformly-spaced points) compute the raw p-value as described above, using the average flux density $v$ of AGN as the test statistic, and increasing the error regions of all

\(^8\) For the South Pole location of IceCube, this is equivalent to randomizing sidereal arrival time of the event. To a good approximation, the sensitivity of the experiment depends on the zenith angle only (Aartsen et al. 2017), and constant zenith angles correspond to constant declinations. Note certain drawbacks of this method for cases when reshuffled error ellipses overlap with original ones, especially close to Celestial poles; however, for our purposes this would result in a conservative estimate of the chance of random coincidence because any possible true correlation would only increase the background estimated in this way.
events by $x$ is all directions. Denote this $p$-value as $p_i$.

• Take the minimum of those raw $p_i$ values. This minimum is called the pre-trial $p$-value.

The final post-trial $p$-value is calculated by plugging this test statistic (pre-trial $p$-value) into the Monte-Carlo testing method outlined above. This makes our estimate unaffected by the multiple comparisons issue.

This approach results in the chance probability $p = 0.2\%$ of average AGN flux density around IceCube detections being as high as observed, thus we conclude that the effect is significant. The minimum pre-trial $p$-value is $0.09\%$ obtained for additional error of $\approx 0.5^\circ$. This can be interpreted as a rough estimate of IceCube systematic errors, though more knowledge about the distribution of statistical errors than available in the event catalogues is required to study it in more detail. Further in this subsection we use error regions enlarged by this value, $0.5^\circ$.

Figure 2 visually compares the average of actual VLBI flux density values for AGN within neutrino error regions for randomly-shifted positions of neutrino events. It is clear that the actual AGN being selected as possible neutrino counterparts are, on average, stronger on parsec scales. Note that the same analysis performed by us for 2, 5, 15, and 22 GHz data results in a similar outcome. However, we do not use these results here because only 8 GHz VLBI sample has the desired completeness as discussed in subsection 2.2.

We stress that VLBI observations are crucial for this result. This is illustrated by performing the same analysis for the NVSS (NRAO VLA Sky Survey, Condon et al. 1998) catalogue containing a complete sample of 2 million radio sources without selection by the compact VLBI component. It does not show any significant difference in flux density between sources inside IceCube error regions and randomly selected ones. However, limiting this analysis to the intersection of NVSS and our 8 GHz VLBI complete sample (2919 sources) leads to a slightly significant difference in NVSS flux density: minimum pre-trial $p$-value is $2\%$. This effect does not appear when analysing the same number of sources selected as strongest by NVSS flux density itself. It would be interesting to analyse VLASS (VLA Sky Survey, Myers & VLASS Survey Team 2018) in this way when the data become available, as it has higher sensitivity and resolution compared to NVSS, and probes scales closer to those of VLBI.

Now after we established that neutrino-emitting AGN have stronger compact radio emission than others, the next logical step is to estimate how many sources drive this effect. We repeat our analysis dropping the strongest sources in terms of their flux density one by one until significance disappears, as illustrated in Figure 3. P-value rises above $5\%$ level when 4 objects are removed, and we interpret this as the number of AGN likely emitting IceCube-detected neutrinos. These four strongest objects are 1253−055 (3C 279), 2145+067 (OR 103), PKS 1741−038, and 1730−130 (NRAO 530). See Table 1 for their properties. To our knowledge, none of these AGN were singled out as sources of observed IceCube neutrinos before.

Note that the TXS 0506+056 blazar possibly associated with neutrino detection 170922A (Aartsen et al. 2018a) is not among these. Its average VLBI flux density from 13 observing epochs in 1995-2018 is only 0.4 Jy. However, its single-dish and VLBI flux density has risen up to more than 1.5 Jy by 2019 (e.g., Ros et al. 2019; Kovalev et al. 2019, see also public MOJAVE 15 GHz
VLBA data\(^9\)). Another notable AGN not included in these four strongest AGN is the quasar PKS 1502+106 (e.g., Abdo et al. 2010) corresponding to a recent event 190730A (Taboada & Stein 2019). Its average VLBI flux density from 17 epochs in 2001-2018 is 1.5 Jy while its flux density is rising in 2019 according to the Owens Valley Radio Observatory (OVRO, Kiehlmann et al. 2019). MOJAVE observations\(^{10}\) and RATAN-600 (Table 2) to the level of 3-4 Jy. This suggests that the four chosen above brightest AGN in our sample as the most probably neutrino associations are not the only associations in the VLBI-selected AGN sample. This is partly due to the historic average VLBI flux density values being used. An apparent next step would be a temporal correlation analysis.

### 3.2. Temporal variability

Using the average VLBI flux density of AGN we managed to find out that neutrino-emitting ones have stronger parsec-scale radio emission, and even made a list of four AGN with bright Doppler-boosted parsec-scale jets which likely caused corresponding IceCube events. However, the question remains if other, fainter, VLBI-selected AGN emit IceCube-detected neutrinos, or it is just those extremely strong ones. It is expected (see, e.g., Murase 2017) that neutrinos can be associated with flares in central regions, be it the immediate vicinity of the black hole or parts of the jet close to its origin. Studies of TXS 0506+056 (Aartsen et al. 2018a; Kovalev et al. 2019, and many others) support this prediction, however to our knowledge this has not yet been confirmed for larger samples of AGN.

We study the correlation of radio variability with neutrino detections by making use of RATAN-600 AGN monitoring data covering the time range 2009-2019, inclusive (subsection 2.3). We have chosen to use the measurements at the highest RATAN frequency of 22 GHz for statistical analysis, as flares are typically more pronounced at shorter wavelengths due to synchrotron opacity effects, see for details subsection 4.1. For each source within IceCube error regions we compute the radio activity index \( R_{22\text{GHz}} \) defined as the ratio of average RATAN flux density at 22 GHz within \( \Delta T \) (i.e., \( \pm \Delta T/2 \)) around neutrino detection epoch to the average values outside of this time range. Then the ratios \( R_{22\text{GHz}} \) corresponding to all sources within the error regions are averaged to form a single number — the test statistic. This value being higher than expected by chance would mean that neutrinos do correlate with flares seen in radio observations. We test this hypothesis in the very same way as described in subsection 3.1.

We plug this test statistic and additional trial range of \( 1 \, \text{yr} \leq \Delta T \leq 3 \, \text{yr} \) for 50 uniformly spaced values, limited on the lower end by the observational cadence. The post-trial p-value is 5% which is not strongly significant, but, in the context of results of subsection 3.1, can definitely be considered suggestive. For comparison, the minimum raw pre-trial p-value is 1% obtained at \( \Delta T = 1 \, \text{yr} \) and additional positional error of 0.7\(^\circ\).

It is worth noting that the optimal value for the systematic error in subsection 3.1 was slightly different, 0.5\(^\circ\). This is a perfect illustration of the statistical nature of our approach. Indeed, the analyses in subsection 3.1 and subsection 3.2 are based on completely different sets of radio data and, because of the smaller number of monitored sources, only a subset of our neutrino sample contributed to the second analysis. As we have already pointed out, see subsection 2.1, systematic errors vary from event to event, but we do not take this variation into account. Consequently, one expects a certain difference between average systematic errors for different sets of events. This is precisely what we see: the values of additional errors determined in two analyses are different but are of the same order. This represents an additional consistency check for our analysis. Because of slightly larger error regions for the variability study, one neutrino event and three sources not present in Table 1 contribute to the results of this subsection, see Table 2.

In addition we can compute the same activity index for different time lags. RATAN-600 measurements for all sources are effectively shifted in time while neutrino detection dates stay fixed. We show the ratio \( R \) averaged across all AGN versus time lag for the four frequency bands of 5, 8, 11, and 22 GHz in Figure 4. Values of \( \Delta T \) and additional positional errors are those giving the lowest p-value for zero-lag comparison, as explained above. This plot indicates that at two highest frequencies, 22 and 11 GHz, there is a pronounced significant peak around zero lag, while no structure is visible at 8 and 5 GHz. This is in a qualitative agreement with the nature of VLBI parsec-scale jet radio emission, see section 4 for a detailed discussion.

As illustrated by Figure 4, the correlation we detect happens on timescales of months. These are the smallest scales we probe here due to cadence of RATAN monitoring, so the question whether there is an even stronger correlation at the days or weeks timescale remains open. We note that the monitoring sample was originally se-

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9 [http://www.physics.purdue.edu/astro/MOJAVE/sourcepages/0506+056.shtml](http://www.physics.purdue.edu/astro/MOJAVE/sourcepages/0506+056.shtml)

10 [http://www.physics.purdue.edu/astro/MOJAVE/sourcepages/1502+106.shtml](http://www.physics.purdue.edu/astro/MOJAVE/sourcepages/1502+106.shtml)
Table 1. IceCube high energy neutrino events positionally associated with VLBI-compact AGN.

| Date       | Category | IceCube event | E  | Name                  | z  | $S_{8\text{GHz}}^{\text{VLBI}}$ (Jy) | $d_{\text{err}}$ (s) | $\gamma$-ray flux ($10^{-9}\text{cm}^{-2}\text{s}^{-1}$) |
|------------|----------|---------------|----|-----------------------|----|-------------------------------------|-------------------|-------------------------------------------------|
| 2010-10-09 | EHEA     | 660           |    | 2201+098              | 1.00| 0.20                                | 0.99              | 1.70                                             |
|            |          |               |    | 2157+102              | 0.19| 1.20                                | 0.79              | 0.24                                             |
| 2010-11-13 | MUONT    | 520           |    | 1855+031              | 0.68| 1.44                                | 0.97              | 0.97                                             |
|            |          |               |    | 1853+027              | 0.16| 2.07                                | 1.45              | ...                                              |
| 2011-07-14 | HESEA    | 253           |    | 0429+415              | 1.02| 1.39                                | 1.34              | 1.90                                             |
| 2011-09-30 | EHEA     |               |    | 1855+031              | 0.68| 1.44                                | 0.97              | 0.97                                             |
|            |          |               |    | 1853+027              | 0.16| 2.07                                | 1.45              | ...                                              |
| 2012-05-23 | EHEA     |               |    | 1123+264              | 2.35| 0.88                                | 0.44              | 0.83                                             |
| 2012-09-22 | EHEA     |               |    | 0435+217              | 1.30| 0.20                                | 2.30              | 1.65                                             |
| 2012-10-11 | EHEA     | 210           |    | 1337-013              | 1.62| 0.21                                | 0.79              | 1.52                                             |
| 2013-06-27 | HESEA    | 200           |    | 0611+131              | 0.74| 0.33                                | 0.91              | 1.21                                             |
| 2013-10-14 | MUONT    | 390           |    | 0208+106              | 0.20| 0.66                                | 0.67              | 1.95                                             |
| 2013-10-23 | EHEA     |               |    | 2007+131              | 1.89| 1.60                                | 1.60              | ...                                              |
| 2013-12-04 | EHEA     |               |    | 1909-151              | 0.31| 1.36                                | 1.57              | ...                                              |
| 2014-01-08 | EHEA     |               |    | 2256+017              | 2.66| 0.18                                | 0.53              | 1.44                                             |
| 2014-02-03 | EHEA     |               |    | 2326-150              | 2.46| 0.53                                | 2.58              | 1.35                                             |
| 2015-01-27 | MUONT    | 210           |    | 0643+057              | 0.16| 1.48                                | 1.95              | ...                                              |
| 2015-08-12 | EHEA     | 380           |    | 2145+067              | 0.99| 6.60                                | 1.38              | 2.05                                             |
|            |          |               |    | 2149+069              | 1.36| 0.89                                | 1.00              | 2.17                                             |
|            |          |               |    | 2149+056              | 0.74| 0.50                                | 0.44              | 0.75                                             |
| 2015-08-31 | EHEA     |               |    | 0333+321              | 1.26| 1.62                                | 1.76              | 1.57                                             |
| 2015-09-04 | MUONT    | 220           |    | 0849+287              | 1.28| 0.33                                | 1.03              | 2.07                                             |
| 2015-09-26 | EHEA     |               |    | 1253-055              | 0.54| 15.38                               | 1.52              | 1.57                                             |
| 2015-11-14 | MUONT    | 740           |    | 0459+135              | 0.45| 0.64                                | 1.22              | 1.92                                             |
| 2016-01-28 | EHEA     |               |    | 1730-130              | 0.90| 3.98                                | 1.71              | 1.73                                             |
|            |          |               |    | 1735-150              | 0.18| 1.14                                | 0.89              | ...                                              |
| 2016-03-01 | MUONT    | 380           |    | 0103+156              | 0.20| 0.88                                | 2.00              | ...                                              |
| 2016-06-10 | EHEA     |               |    | 0629-141              | 1.02| 0.55                                | 0.96              | 0.80                                             |
|            |          |               |    | 0628-133              | 1.02| 0.34                                | 1.72              | 1.44                                             |
| 2017-09-22 | EHEA     | 290           |    | 0506+056              | 0.34| 0.42                                | 0.08              | 0.14                                             |
| 2017-11-06 | EHEA     |               |    | 2255+071              | 2.37| 0.26                                | 1.87              | 1.23                                             |
| 2018-09-08 | EHEA     |               |    | 1502+106              | 1.84| 1.46                                | 0.31              | 0.25                                             |
|            |          |               |    | 1451+106              | 0.19| 2.32                                | 1.65              | ...                                              |
| 2019-07-30 | GOLD     | 299           |    | 1500+094              | 0.18| 1.17                                | 1.32              | ...                                              |

Note—AGN from the complete VLBI sample which fall into error regions of IceCube high-energy neutrino detections assuming the systematic error of 0.5°. See subsection 2.2 for characteristics of the VLBI sample, subsection 2.1 for IceCube events selection criteria and category notations, and subsection 3.1 for details on how we estimate the systematic uncertainty. If several AGN from our sample are found within an error region of a given event, we list them all ordered by decreasing VLBI flux density. The four most probable neutrino associations from the analysis of historic average VLBI flux densities are shown by the boldface font, see subsection 3.1 for details. Columns are as follows: (1), (2), (3) IceCube event parameters; (4), (5) AGN name in B1950 and J2000 formats; (6) Redshift taken from NASA/IPAC Extragalactic Database; (7) Average VLBI flux density at 8 GHz; (8) Angular separation on the sky between the AGN and corresponding IceCube event; (9) Angular separation divided by the original IceCube statistical uncertainty in the corresponding direction; (10) Gamma ray (1-100 GeV) flux of the AGN as measured by Fermi-LAT (The Fermi-LAT collaboration 2019).
Table 2. AGN within IceCube events error regions monitored by RATAN-600.

| IceCube event Date | Category | $E$ (TeV) | Name         | $z$ | # of epochs | $S_{\text{RATAN}}^{22\text{GHz}}$ (Jy) | $R_{22\text{GHz}}$ ($^\circ$) | $d/d_{\text{err\,event}}$ | $\gamma$-ray flux ($10^{-9}\text{cm}^{-2}\text{s}^{-1}$) |
|-------------------|----------|-----------|---------------|-----|-------------|--------------------------------------|----------------------------|--------------------------|--------------------------------|
| 2011-07-14        | HESEA    | 253       | 0429+415 J0432+4138 | 1.02 | 38          | 1.11                                 | 1.06 1.34                  | 1.90                     |                           |
| 2011-09-30        | EHEA     | · ·       | 1741-038 J1743-0350 | 1.05 | 38          | 3.40                                 | 1.37 0.75                  | 1.02                     | 0.36                     |
| 2012-05-23        | EHEA     | · ·       | 1123+284 J1125+2810 | 2.35 | 32          | 0.58                                 | 1.26 0.44                  | 0.83                     |                           |
| 2013-06-27        | HESEA    | 200       | 0611+131 J0613+1306 | 0.74 | 17          | 0.31                                 | 1.42 0.91                  | 1.21                     |                           |
| 2014-01-08        | EHEA     | · ·       | 2256+017 J2258+0203 | 2.66 | 24          | 0.25                                 | 2.01 0.53                  | 1.44                     |                           |
| 2015-08-12        | EHEA     | 380       | 2325-150 J2327-1447 | 2.46 | 25          | 0.40                                 | 1.92 2.58                  | 1.35                     |                           |
| 2015-08-31        | EHEA     | · ·       | 2145+067 J2148+0657 | 0.99 | 41          | 2.52                                 | 1.18 1.38                  | 2.05                     | 0.22                     |
| 2015-09-26        | EHEA     | · ·       | 2149+069 J2151+0709 | 1.36 | 27          | 0.55                                 | 0.93 1.00                  | 2.17                     |                           |
| 2015-11-14        | MUONT    | 740       | 0459+135 J0502+1338 | 0.45 | 32          | 0.41                                 | 1.32 1.22                  | 1.92                     | 0.31                     |
| 2016-01-28        | EHEA     | · ·       | 1730-130 J1733-1304 | 0.90 | 41          | 3.68                                 | 0.84 1.71                  | 1.73                     | 6.66                     |
| 2017-09-22        | EHEA     | 290       | 0502+049 J0505+0459 | 0.95 | 26          | 0.65                                 | 1.34 1.30                  | 2.94                     | 6.56                     |
| 2018-10-23        | EHEA     | · ·       | 1749-101 J1752-1011 | 0.29 | 29          | 0.29                                 | 1.68 2.58                  | 1.73                     | 0.49                     |
| 2019-07-30        | GOLD     | 299       | 1502+106 J1504+1029 | 1.84 | 35          | 1.45                                 | 3.14 0.31                  | 0.25                     | 19.01                    |

Note.— AGN from the RATAN-600 monitoring program which fall into error regions of IceCube high-energy neutrino detections assuming the systematic error of 0.7°. See subsection 2.3 for the monitoring program characteristics, subsection 2.1 for IceCube events selection criteria and category notations, and subsection 3.2 for details on how we estimate the systematic uncertainty. If several AGN from the monitoring program are found within an error region of a given event, we list them all ordered by decreasing average flux density.

Columns are as follows: (1) — (6) and (10) — (12) Same as corresponding columns in Table 1; (7) Number of observations by RATAN-600 from 2009 to 2019; (8) Average flux density at 22 GHz; (9) Ratio of average flux density within 1 yr (i.e., ±0.5 yr) around IceCube event to the average outside of this period.

Sources absent in Table 1 due to slightly different assumed systematic errors.
Figure 4. Ratio of RATAN-600 flux densities within 1 yr period around the corresponding IceCube event to the average outside this time range. Each point here represents the average of this ratio for a specific time delay for all AGN inside error regions. Filled areas indicate 68% intervals of Monte-Carlo realizations for randomly shifted event positions.

(4.1) Central parsec-scale regions of radio-bright AGN are probable production sites of high energy neutrinos

Our analysis demonstrates that neutrinos are commonly produced in AGN with strong radio emission coming from the compact central parsec-scale region. This is implied by both results presented in the previous section. First, the flux density integrated over a VLBI image of an AGN (subsection 3.1) is dominated by the compact emission of its core — the apparent base of the parsec-scale jet (e.g., Kovalev et al. 2005; Pushkarev & Kovalev 2012). The deprojected distance from the apparent VLBI core to the nucleus is estimated to be of the order of 10 pc (Pushkarev et al. 2012; Plavin et al. 2019).

Second, variability of radio flux density on the time scale of months can only be related to VLBI-compact regions due to the causality arguments. And in case of major flares they can only be related to the dominant parsec-scale feature, the core. Significant correlation between the arrival dates of neutrino events and the increase of the total radio flux density is only seen at the two highest frequencies above 10 GHz in Figure 4. This is easy to understand from the physics of AGN jet synchrotron radiation. The analysis was dealing with the flux density values around the neutrino event normalized by an average flux density outside this time range of those with high values of $R_{22\,\text{GHz}}$ in Table 2 are of interest for further more detailed studies.

4. INTERPRETATION AND DISCUSSION

4.1. Central parsec-scale regions of radio-bright AGN are probable production sites of high energy neutrinos

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(Table 2). The fraction of core radiation and the relative strength of the flares $R$ are decreasing with decreasing frequency (Aller et al. 1992; Kovalev et al. 2002; Fuhrmann et al. 2016) due to the steep synchrotron spectrum of extended optically thin jet away from the core (e.g., Hovatta et al. 2014). At lower frequencies the optically thin jet becomes stronger. Additionally, while the radio frequency decreases the core flares both peak with an increasing delay and have longer characteristic time scale due to the synchrotron opacity effect. These will decrease the relative flare strength with decreasing radio frequency. Note that the peak at 11 GHz is weaker and slightly (about 1/4 yr) delayed relative to 22 GHz as expected, although we do not assess statistical significance of this difference.

VLBI turns out to be the key to the high-energy neutrino associations. VLBI-selected samples of extragalactic radio sources should contain AGN which generate neutrino. We predict that analyzing such samples will allow researchers to find AGN with their activity associated with neutrino outside of major flares. In the latter case, additional neutrino events from the directions of these strongest AGN being capable to produce observable neutrino outside of major flares. In the latter case, additional neutrino events from the directions of these sources, as well as from other sources with high VLBI flux densities might be expected.

Once we have established that central parsec-scale regions of radio-bright AGN are probable production sites of at least a large part of the higher-energy ($E > 200$ TeV) neutrinos detected by IceCube, we now discuss implications of this observation for particular models of the neutrino origin.

### 4.2. Implications for models and the lack of $\gamma$-ray associations

At high energies, all interactions of energetic protons with ambient radiation or matter are dominated by the production of lightest strongly interacting particles, $\pi$ mesons, which carry away most of the initial proton’s energy. The probabilities to create one of three species of the mesons, $\pi^0, \pi^+$ and $\pi^-$, are roughly equal. All the mesons are unstable particles and decay: the energy of charged $\pi^\pm$ is carried out mostly by neutrinos while that of every $\pi^0$ is split between two photons. These physical processes are behind any non-exotic scenario of production of energetic (above the proton rest energy of $\sim 1$ GeV) astrophysical neutrinos, in this way inevitably accompanied, at the production, by $\gamma$-rays of similar energies. Models of neutrino production in AGN therefore require either proton-proton ($pp$) or proton-photon ($p\gamma$) interactions (see Eichler & Schramm 1978; Cerruti 2019, for the earliest and the latest reviews and further references). In the central parts of radio loud AGN, $p\gamma$ interactions are always dominant because of strong radiation fields and relatively low target matter density. The situation may be different in low-luminosity AGN or in large-scale jets but both are disfavoured by our present results.

For the $p\gamma$ scenarios, two ways of reasoning constrain multiwavelength properties of the neutrino emitting regions (see, e.g., Böttcher 2019; Cerruti 2019, and references therein). Firstly, from the kinematics of $\pi$-meson, and subsequent neutrino, production, it is easy to see that in radio loud AGN, the use of synchrotron photons as the targets for $p\gamma$ collisions would result in too high neutrino energies: to have enough energy to produce a $\pi$ meson on a soft synchrotron photon, the initial proton should be too energetic itself. If this scenario explains the flux of neutrinos detected by IceCube at sub-PeV energies, then the flux at higher energies, above a few PeV, should be even higher. This would contradict to upper limits from IceCube non-detections. In addition, this mechanism would require a total power of accelerated proton beam orders of magnitude higher than the Eddington luminosity of a supermassive black hole in the nucleus of an active galaxy. These considerations disfavour synchrotron photons as the main target, so some other source of radiation is required. In the central parsec, the emission from the accretion disk is an obvious candidate.
Secondly, the photon-photon cross section is two orders of magnitude larger than the $p\gamma$ one for relevant energies. This means that if $p\gamma$ interactions are efficient in a neutrino-production zone, then secondary energetic $\gamma$-rays, accompanying the neutrino production, interact even faster. They initiate electromagnetic cascades of $e^+e^-$ pair production and inverse-Compton scattering which efficiently transfer the energy of the $\gamma$-ray photons down to the X-ray band: no high-energy photons escape from the neutrino production region. Therefore, if any $\gamma$-ray emission is observed from the same source, it should come from a different place than the neutrino emission and be produced by means of a different mechanism, so any connection between them is indirect (see, e.g., Reimer et al. 2019, and reviews cited above). This is precisely what we observe in this study: the neutrino emission is related to the parsec-scale radio flux density, while $\gamma$-ray fluxes of the radio-bright AGN from Table 1 differ by orders of magnitude even for the four strongest radio sources which dominate the correlation.

VLBI radio flux density comes from Doppler-boosted collimated parsec-scale jets with small viewing angles. Intrinsic opening angles of the jets are of the order of 1° (Pushkarev et al. 2017). Our results imply that neutrinos are emitted in narrow beams pointing to the observer which makes it possible to detect these neutrinos at the Earth. It is interesting to note that the same beaming stands behind the $\gamma$-ray activity of some of VLBI-selected AGN (Savolainen et al. 2010; Lister et al. 2015), despite the fact that the origins of $\gamma$-rays and neutrinos are not directly related.

4.3. Relation to previous statistical studies

These considerations, formulated on general grounds in various previous studies and detailed for a particular blazar example TXS 0506+056 (e.g., Gao et al. 2019; Petropoulou et al. 2019) help to understand the key difference between our study and a number of other correlation and stacking analyses aimed to figure out or to constrain plausible sources of IceCube neutrinos. Previous works mostly concentrated on $\gamma$-ray selected AGN as potential candidate neutrino sources (e.g., Padovani et al. 2016; Kadler et al. 2016; Aartsen et al. 2017; Neronov et al. 2017; Palladino & Vissani 2017; Righi et al. 2019; Krauß et al. 2018; Huber 2019). Constraints on the population of neutrino-emitting AGN (e.g., Yuan et al. 2019) also select them by their $\gamma$-ray luminosities. Contrary, our observations support the theoretical conclusion explained above: $\gamma$-ray emission is not necessarily a tracer of the neutrino emission.

Only in a few studies, arrival directions of high-energy astrophysical neutrinos were compared with positions of AGN selected by other criteria than the $\gamma$-ray loudness. Padovani et al. (2018) used various criteria related to the estimated power of large-scale jets, testing therefore non-central parts of active galaxies, complementarily to our approach. Kun et al. (2017) selected flat-spectrum radio quasars (FSRQ) by broadband radio-to-microwave spectral properties. Though the class of sources tested and the radio selection are common to their and our studies, our present work differs in the key point, the use of the VLBI flux density and a VLBI-selected sample. To our best knowledge, none of previous studies of IceCube neutrinos attempted to distinguish between central and extended parts of AGN, like we do here.

4.4. Relation to previous theoretical studies

The origin of high-energy astrophysical neutrinos in $p\gamma$ interactions in central parsecs of radio-bright active galaxies, supported by our study, has serious theoretical grounds (see, e.g., Stecker et al. 1991; Neronov & Semikoz 2002; Stecker 2013; Kalashev et al. 2015). The importance of the jet kinematics for the neutrino observations, as revealed by our study, had been predicted by Neronov & Semikoz (2002) long before the start of IceCube observations. Interestingly, they determined a short list of potential neutrino-loud blazars which includes one of the four brightest sources from Table 1. In addition, radio quasars exhibit strong evolution with redshift, $\sim (1 + z)^5$, which helps to relax (Neronov & Semikoz 2018) clustering constraints, especially for high neutrino energies $E > 200$ TeV we study here. Our results therefore agree well with theoretical expectations and other observational constraints.

In the scenario favoured by our observations, there remains one important unconstrained element, that is how the protons are accelerated in the direct vicinity of a black hole. Among possible mechanisms one may mention stochastic (Dermer et al. 1996) or electrostatic (Rieger & Mannheim 2000; Neronov et al. 2009; Istomin & Sol 2009; Ptitsyna & Neronov 2016) ones, but detailed quantitative modelling is necessary to understand whether required proton energies can be obtained in these ways in radio-bright AGN. In any case, the maximal proton energies achievable in their central parsecs are probably much lower than those required for ultra-high-energy cosmic rays (UHECR), which agrees well with the lack of observed correlations between UHECR and neutrino arrival directions (cf. Aublin et al. 2019; Palladino et al. 2019).

5. SUMMARY

The aim of the present study was to test whether high-energy neutrinos are produced in AGN and, if
so, to locate neutrino-emitting regions within the active galaxies. We used a set of 56 published IceCube events with relatively good angular resolution and estimated neutrino energies above 200 TeV. Arrival directions of these events were correlated with positions of radio sources from a complete flux-density-limited sample of 3388 VLBI-compact AGN. The test statistic used was based on the average historic VLBI flux density which is attributed to parsec-scale regions in centers of active galaxies. We obtained a positive correlation: sources directionally coincident with neutrino events within statistical and systematic errors have, on average, higher VLBI flux density with respect to random expectations. We estimate the significance of the correlations by Monte-Carlo simulations; the p-value to observe the excess as a random fluctuation in the data is \( p \approx 0.2\% \) after correction for multiple trials. We determine four particular brightest sources which dominate the observed correlation.

Further, we use a set of RATAN-600 data on monitoring the total radio flux density of VLBI-selected AGN and demonstrate that higher than average flux densities at frequencies above 10 GHz correspond to periods of neutrino detections. This effect remains significant even when the four sources singled out by the average-VLBI-flux-density analysis are removed from the sample. This means that other AGN from the VLBI-selected sample are also neutrino emitters. In particular, the strongest flux density enhancement at the time of a neutrino event is observed for PKS 1502+106 which is a probable source of the 2019-07-30 event but is not among the four objects discussed above.

Altogether, these results suggest that a significant part of observed \( E > 200 \) TeV astrophysical neutrinos are produced in central parsec-scale regions of radio-bright active galaxies with narrow Doppler-boosted relativistic jets pointing to the observer. These neutrino associations are found to be not dependent on the \( \gamma \)-ray fluxes of potential sources. The results of our study support models in which protons are accelerated in collimated beams close to the central black hole of a powerful AGN and subsequently interact with ambient radiation from the accretion disk. Charged \( \pi^\pm \) mesons born in these interactions pass their energy to \( E > 200 \) TeV neutrinos eventually detected at the Earth, while accompanying neutral \( \pi^0 \) mesons decay to energetic photons which cascade down to X-ray energies in the same environment. The \( \gamma \) radiation, if any, is therefore not directly related to the neutrino emission.

For the first time, our study invokes the statistical power of VLBI observations to the problem of high-energy neutrino origin. It clearly reveals a significant population of potential neutrino sources, radio-bright AGN, and even singles out neutrino emitting regions within them. These results may be used in future quantitative models of the neutrino production. One should note however that, given (i) the statistical nature of our results, (ii) a large number of non-astrophysical background events in the data set, and (iii) the energy cut \( E > 200 \) TeV selecting only the highest-energy IceCube events, we might reveal only one of several populations of neutrino sources.

Further observations will test and detail our findings. For our selection cuts, we expect about five IceCube alerts per year assuming the currently operated public alert system; soon a similar number of track-like events will start coming from Baikal-GVD. In addition, liquid-water experiments, Baikal-GVD and KM3NeT, will also provide cascade events with good angular resolution. From the radio astronomy side, it is important to continue monitoring VLBI-selected AGN with single dish radio telescopes on a regular basis. Unfortunately, there is a worrisome trend in the world to finish such projects including the Michigan University program (Aller et al. 2017), the F-GAMMA program (Angelakis et al. 2019), the OVRO program (Richards et al. 2011). Dedicated VLBI monitoring observations of VLBI-compact AGN selected from within the neutrino positions immediately after alerts might help to directly relate neutrino production to parsec-scale properties of corresponding synchrotron flares.

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REFERENCES

Aartsen, M. G., et al. 2013a, Phys. Rev. Lett., 111, 021103, doi: 10.1103/PhysRevLett.111.021103
—. 2013b, Science, 342, 1242856, doi: 10.1126/science.1242856
—. 2014, Phys. Rev. Lett., 113, 101101, doi: 10.1103/PhysRevLett.113.101101
Aartsen, M. G., et al. 2015, in Proceedings, 34th International Cosmic Ray Conference (ICRC 2015): The Hague, The Netherlands, July 30-August 6, 2015. https://arxiv.org/abs/1510.05223
—. 2016, Astrophys. J., 833, 3, doi: 10.3847/0004-637X/833/1/3
—. 2017a. https://arxiv.org/abs/1710.01191
—. 2017b, Astropart. Phys., 92, 30, doi: 10.1016/j.astropartphys.2017.05.002
Aartsen, M. G., Abraham, K., Ackermann, M., et al. 2017, ApJ, 835, 151, doi: 10.3847/1538-4357/835/2/151
Aartsen, M. G., et al. 2017, Astrophys. J., 835, 45, doi: 10.3847/1538-4357/835/1/45
—. 2018a, Science, 361, eaat1378, doi: 10.1126/science.aat1378
—. 2018b, Science, 361, 147, doi: 10.1126/science.aat2890
Aartsen, M. G., et al. 2019, in 36th International Cosmic Ray Conference (ICRC 2019) Madison, Wisconsin, USA, July 24-August 1, 2019. https://arxiv.org/abs/1907.11699
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010, ApJ, 710, 810, doi: 10.1088/0004-637X/710/1/810
Ahlers, M., & Halzen, F. 2018, Progress in Particle and Nuclear Physics, 102, 73, doi: 10.1016/j.ppnp.2018.05.001
Albert, A., et al. 2018, Astrophys. J., 868, L20, doi: 10.3847/2041-8213/aaeecf
Aller, M., Aller, H., & Hughes, P. 2017, Galaxies, 5, 75, doi: 10.3390/galaxies5040075
Aller, M. F., Aller, H. D., & Hughes, P. A. 1992, ApJ, 399, 16, doi: 10.1086/171898
Angelakis, E., Fuhrmann, L., Myserlis, I., et al. 2019, A&A, 626, A60, doi: 10.1051/0004-6361/201834363
Aublin, J., et al. 2019, EPJ Web Conf., 210, 03003, doi: 10.1051/epjconf/201921003003
Avrorin, A. D., et al. 2019, in Proceedings of the 36th International Cosmic Ray Conference (ICRC2019). https://arxiv.org/abs/1908.05430
Beasley, A. J., Gordon, D., Peck, A. B., et al. 2002, ApJS, 141, 13, doi: 10.1086/339806
Berezinskii, V. S., & Ginzburg, V. L. 1981, MNRAS, 194, 3, doi: 10.1093/mnras/194.1.3
Berezinsky, V. 1977, in Proceedings of the Neutrino-77 Conference, Moscow, 177
Böttcher, M. 2019, Galaxies, 7, 20, doi: 10.3390/galaxies7010020
Cerruti, M. 2019, arXiv e-prints, arXiv:1912.03666. https://arxiv.org/abs/1912.03666
Charlot, P., Boboltz, D. A., Fey, A. L., et al. 2010, AJ, 139, 1713, doi: 10.1088/0004-6256/139/5/1713
Condon, J. J., Cotton, W. D., Greisen, E. W., et al. 1998, The Astronomical Journal, 115, 1693, doi: 10.1086/300337
Davison, A. C., & Hinkley, D. V. 2013, Bootstrap Methods and Their Application (New York, NY, USA: Cambridge University Press)
Dermer, C. D., Miller, J. A., & Li, H. 1996, Astrophys. J., 456, 106, doi: 10.1086/176631
Eichler, D. 1979, ApJ, 232, 106, doi: 10.1086/157269
Eichler, D., & Schramm, D. N. 1978, Nature, 275, 704, doi: 10.1038/275704a0
Fomalont, E. B., Petrov, L., MacMillan, D. S., Gordon, D., & Ma, C. 2003, AJ, 126, 2562, doi: 10.1086/378712
Fuhrmann, L., Angelakis, E., Zensus, J. A., et al. 2016, A&A, 596, A45, doi: 10.1051/0004-6361/201528034
Fusco, L. A., & Versari, F. 2019, in International Cosmic Ray Conference, Vol. 36, Proceedings of the 36th International Cosmic Ray Conference (ICRC2019), 891
Gao, S., Fedynitch, A., Winter, W., & Pohl, M. 2019, Nat. Astron., 3, 88, doi: 10.1038/s41550-018-0610-1
Gordon, D., Jacobs, C., Beasley, A., et al. 2016, AJ, 151, 154, doi: 10.3847/0004-6256/151/6/154
Hovatta, T., Aller, M. F., Aller, H. D., et al. 2014, AJ, 147, 143, doi: 10.1088/0004-6256/147/6/143
Huber, M. 2019, in 36th International Cosmic Ray Conference (ICRC2019). https://arxiv.org/abs/1908.08458
IceCube Collaboration. 2018, doi: 10.21234/B4KS6S
Istomin, Y. N., & Sol, H. 2009, Ap&SS, 321, 57, doi: 10.1007/s10509-009-0008-8
Kadler, M., et al. 2016, Nature Phys., 12, 807, doi: 10.1038/nphys3715.10.1038/NPHYS3715
Kalashev, O., Semikoz, D., & Tkachev, I. 2015, J. Exp. Theor. Phys., 120, 541, doi: 10.1134/S106377611503022X
Kiehlmann, S., Hovatta, T., Kadler, M., Max-Moerbeck, W., & Readhead, A. C. S. 2019, The Astronomer’s Telegram, 12996, 1
Korolkov, D. V., & Pariiskii, I. N. 1979, S&T, 57, 324
Kovalev, Y., Kardashev, N., Kovalev, Y., et al. 2019, Advances in Space Research, doi: 10.1016/j.asr.2019.04.034
Kovalev, Y. A. 1997, Bulletin of the Special Astrophysics Observatory, 44, 50
High-energy neutrinos are generated in radio-bright galaxies

Kovalev, Y. A., Kovalev, Y. Y., & Nizhelsky, N. A. 2000, PASJ, 52, 1027, doi: 10.1093/pasj/52.6.1027
Kovalev, Y. Y. 2009, ApJL, 707, L56, doi: 10.1088/0004-637X/707/1/L56
Kovalev, Y. Y., Kovalev, Y. A., Nizhelsky, N. A., & Bogdantsov, A. B. 2002, PASA, 19, 83, doi: 10.1071/AS01109
Kovalev, Y. Y., Nizhelsky, N. A., Kovalev, Y. A., et al. 1999, A&AS, 139, 545, doi: 10.1051/aas:1999406
Kovalev, Y. Y., Petrov, L., Fomalont, E. B., & Gordon, D. 2002, AJ, 133, 1236, doi: 10.1086/511157
Kovalev, Y. Y., Pushkarev, A. B., Nokhrina, E. E., et al. 2019, arXiv e-prints, arXiv:1907.01485. https://arxiv.org/abs/1907.01485
Krauß, F., Deoskar, K., Baxter, C., et al. 2018, Astron. Astrophys., 620, A174, doi: 10.1051/0004-6361/201834183
Kun, E., Biermann, P. L., & Gergely, L. Á. 2017, MNRAS, 466, L34, doi: 10.1093/mnrasl/slw228
Lister, M. L., Aller, M. F., Aller, H. D., et al. 2018, ApJS, 234, 12, doi: 10.3847/1538-4365/aa9e44
Lister, M. L., Homan, D. C., Hovatta, T., et al. 2019, ApJ, 874, 43, doi: 10.3847/1538-4357/ab08ee
Marscher, A. P., Jorstad, S. G., Gómez, J.-L., et al. 2002, Nature, 417, 625, doi: 10.1038/nature00772
Mészáros, P. 2017, Annual Review of Nuclear and Particle Science, 67, 45, doi: 10.1146/annurev-nucl-101916-123304
Murase, K. 2017, Active Galactic Nuclei as High-Energy Neutrino Sources, ed. T. Gaisser & A. Karle, 15–31, doi: 10.1142/9789814759410_0002
Murase, K., Oikonomou, F., & Petropoulou, M. 2018, ApJ, 865, 124, doi: 10.3847/1538-4357/aada00
Murase, K., & Waxman, E. 2016, PhysRevD.94.103006, doi: 10.1103/PhysRevD.94.103006
Myers, S. T., & VLASS Survey Team, S. S. G. S. 2018, in American Astronomical Society Meeting Abstracts, Vol. 231, American Astronomical Society Meeting Abstracts #231, 231.08
Neronov, A., & Semikoz, D. V. 2018. https://arxiv.org/abs/1811.06356
Neronov, A., Semikoz, D. V., & Ptitsyna, K. 2017, Astron. Astrophys., 603, A135, doi: 10.1051/0004-6361/201630098
Neronov, A. Yu., Semikoz, D. V., & Tkachev, I. I. 2009, New Journal of Physics, 11, 065015, doi: 10.1088/1367-2630/11/6/065015
Neronov, A. Yu., & Semikoz, D. V. 2002, Phys. Rev., D66, 123003, doi: 10.1103/PhysRevD.66.123003
Padovani, P., Resconi, E., Giommi, P., Arsioli, B., & Chang, Y. L. 2016, Mon. Not. Roy. Astron. Soc., 457, 3582, doi: 10.1093/mnras/stw228
Padovani, P., Turcati, A., & Resconi, E. 2018, MNRAS, 477, 3469, doi: 10.1093/mnras/sty877
Palladin, A., van Vliet, A., Winter, W., & Franckowiak, A. 2019. https://arxiv.org/abs/1911.05756
Petropoulou, M., et al. 2019. https://arxiv.org/abs/1911.04010
Petrov, L. 2011, AJ, 142, 105, doi: 10.1088/0004-6265/142/4/105
—. 2012, MNRAS, 419, 1097, doi: 10.1111/j.1365-2966.2011.19765.x
—. 2013, AJ, 146, 5, doi: 10.1088/0004-6256/146/1/5
—. 2016, ArXiv e-prints. https://arxiv.org/abs/1610.04951
Petrov, L., de Witt, A., Sadler, E. M., Phillips, C., & Horiiuchi, S. 2019, MNRAS, 485, 88, doi: 10.1093/mnras/stz242
Petrov, L., Gordon, D., Gipson, J., et al. 2009, Journal of Geodesy, 83, 859, doi: 10.1007/s00190-009-0304-7
Petrov, L., Kovalev, Y. Y., Fomalont, E., & Gordon, D. 2005, AJ, 130, 2473, doi: 10.1086/469930
Petrov, L., Kovalev, Y. Y., Fomalont, E. B., & Gordon, D. 2006, AJ, 131, 1097, doi: 10.1086/499947
—. 2008, AJ, 136, 580, doi: 10.1088/0004-6256/136/2/580
—. 2011a, AJ, 142, 35, doi: 10.1088/0004-6256/142/2/35
—. 2011b, MNRAS, 414, 2528, doi: 10.1111/j.1365-2966.2011.18570.x
Piner, B. G., Pushkarev, A. B., Kovalev, Y. Y., et al. 2012, ApJ, 758, 84, doi: 10.1088/0004-637X/758/2/84
Plavin, A. V., Kovalev, Y. Y., Pushkarev, A. B., & Lobanov, A. P. 2019, MNRAS, 485, 1822, doi: 10.1093/mnras/stz504
Preston, R. A., Morabito, D. D., Williams, J. G., et al. 1985, AJ, 90, 1599, doi: 10.1086/113869
Ptitsyna, K., & Neronov, A. 2016, A&A, 593, A8, doi: 10.1051/0004-6361/201527549
Pushkarev, A. B., Hovatta, T., Kovalev, Y. Y., et al. 2012, A&A, 545, A113, doi: 10.1051/0004-6361/201219173
Pushkarev, A. B., & Kovalev, Y. Y. 2012, A&A, 544, A34, doi: 10.1051/0004-6361/201219352
Pushkarev, A. B., Kovalev, Y. Y., & Lister, M. L. 2010, ApJL, 722, L7, doi: 10.1088/2041-8205/722/1/L7
Shu, F., Petrov, L., Jiang, W., et al. 2017, ApJS, 230, 13, doi: 10.3847/1538-4365/aa71a3
Stecker, F. W. 2013, Phys. Rev., D88, 047301, doi: 10.1103/PhysRevD.88.047301
Stecker, F. W., Done, C., Salamon, M. H., & Sommers, P. 1991, Phys. Rev. Lett., 66, 2697, doi: 10.1103/PhysRevLett.66.2697,10.1103/PhysRevLett.69.2738
Taboada, I., & Stein, R. 2019, The Astronomer's Telegram, 12967, 1
Teräsranta, H., Achren, J., Hanski, M., et al. 2004, A&A, 427, 769, doi: 10.1051/0004-6361:20041289
The Fermi-LAT collaboration. 2019, arXiv e-prints, arXiv:1902.10045. https://arxiv.org/abs/1902.10045
Tinyakov, P., & Tkachev, I. 2004, Phys. Rev., D69, 128301, doi: 10.1103/PhysRevD.69.128301
Troitsky, S. 2015, JETP Lett., 102, 785, doi: 10.1134/S0021364015240133
Yuan, C., Murase, K., & Mészáros, P. 2019, arXiv e-prints, arXiv:1904.06371. https://arxiv.org/abs/1904.06371