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Neutrino astronomy: The story so far

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Summary. — The IceCube project transformed a cubic kilometer of transparent natural Antarctic ice into a Cherenkov detector. It discovered PeV-energy neutrinos originating beyond our Galaxy with an energy flux that is comparable to that of GeV-energy gamma rays and EeV-energy cosmic rays. We review the results from IceCube's first decade of operations: the measurement of the diffuse flux, which has been characterized with multiple techniques, and the search for its sources. We subsequently review the multimessenger data that identified the supermassive black hole TXS 0506+056 as a source of cosmic neutrinos and draw attention to the accumulating indications that cosmic neutrinos are associated with gamma-ray–obscured active galaxies.

1. – Neutrino astronomy: A brief introduction

The shortest wavelength radiation reaching us from the universe is not radiation at all; it consists of cosmic rays—high-energy nuclei, mostly protons. Some reach us with extreme energies exceeding 10^8 TeV from a universe beyond our Galaxy that is obscured to gamma rays and from which only neutrinos reach us as astronomical messengers [1]. Their origin is still unknown, but the identification of a supermassive black hole powering a cosmic-ray accelerator [2, 3] represents a breakthrough towards a promising path for resolving the century-old puzzle of the origin of cosmic rays: multimessenger astronomy.

The rationale for searching for cosmic-ray sources by observing neutrinos is straightforward: in relativistic particle flows near neutron stars or black holes, some of the gravitational energy released in the accretion of matter is transformed into the acceleration of protons or heavier nuclei, which subsequently interact with ambient radiation or dust, hydrogen, and dense molecular clouds to produce pions and other secondary particles that decay into neutrinos. Isospin dictates that both neutral and charged secondary pions are produced; while charged pions decay into neutrinos, neutral pions decay into gamma rays. The fact that cosmic neutrinos are inevitably accompanied by high-energy photons transforms neutrino astronomy into multimessenger astronomy.

A main challenge of multimessenger astronomy is to separate these photons, which we will refer to as *pionic* photons, from photons radiated by electrons that may be accelerated along with the cosmic ray protons. Another challenge is to identify the electromagnetic energy associated with the pionic photons because they do not reach our telescopes with their initial energy but do so after losses suffered in the extragalactic background light (EBL). PeV photons interact, mostly with microwave photons, to produce an e^+e^- pair that initiates an electromagnetic shower that consists of GeV photons when reaching the Earth. As is the case for constructing a neutrino beam in a particle physics laboratory, neutrinos are produced in a so-called beam dump with a target transforming the energy of the proton beam into neutrinos. Powerful neutrino sources within reach of IceCube's sensitivity require a dense target that is likely to be obscured to pionic gamma rays; they are likely to be gamma-ray-obscured sources. Their energy may be spread over the electromagnetic spectrum and emerge at MeV, X-ray, and lower energies. Evidence emerges that this is indeed the case.

With 10 years of data, the emergence of active galaxies as sources of cosmic rays was not unexpected [4, 5]. The detailed blueprint for a cosmic-ray accelerator must meet two challenges: the highest energy particles in the beam must reach energies beyond 10^8 TeV for extragalactic sources, and their luminosity must accommodate the observed flux. Both requirements represent severe constraints that have guided theoretical speculations towards active galaxies; for a recent review see Ref. [6]. In contrast with our own Galaxy hosting a black hole at its center that is mostly dormant, in an active galaxy the rotating supermassive black hole absorbs the matter in the host galaxy at a very high rate. Fast spinning matter falling onto the active galactic nucleus (AGN) swirls around the black hole in an accretion disk, like the water approaching the drain of your bath tub. When the accretion disk comes in contact with the rotating black hole, its space-time drags on the magnetic field, winding it into a tight cone around the rotation axis into a jet of particles; see fig. 1. Not just particles but huge "blobs" of plasma from the accretion disk are flung out along these field lines. When the jet runs into a target material, for instance, the ubiquitous 10 eV ultraviolet photons in some galaxies, neutrinos can be produced. Production of high-energy neutrinos in the cores of the AGN may also result from the acceleration of cosmic rays in the high field regions associated with the accretion disk or the corona surrounding it [7].

Two general scenarios can accommodate the diffuse cosmic neutrino flux observed by IceCube: protons accelerated at the black hole interact with nearby high-density targets [8,9], or, alternatively, diffuse through the galaxy to produce neutrinos in collisions with interstellar matter [10].

2. – The discovery of high-energy cosmic neutrinos

Close to the National Science Foundation's research station located at the geographical South Pole, the IceCube project [11] transformed one cubic kilometer of natural Antarctic ice into a Cherenkov detector. The deep ice of the Antarctic glacier constitutes the detector, forming both support structure and Cherenkov medium. Below a depth of 1,450 meters, a cubic kilometer of glacial ice is instrumented with 86 cables called "strings," each of which is equipped with 60 optical sensors; see fig. 2. Each digital optical module (DOM) consists of a glass sphere containing the photomultiplier and the electronics board that captures and digitizes the signals locally using an onboard computer; see fig. 3. The digitized signals are given a global time stamp with residuals accurate to 2 ns and are subsequently transmitted to the surface. Processors at the

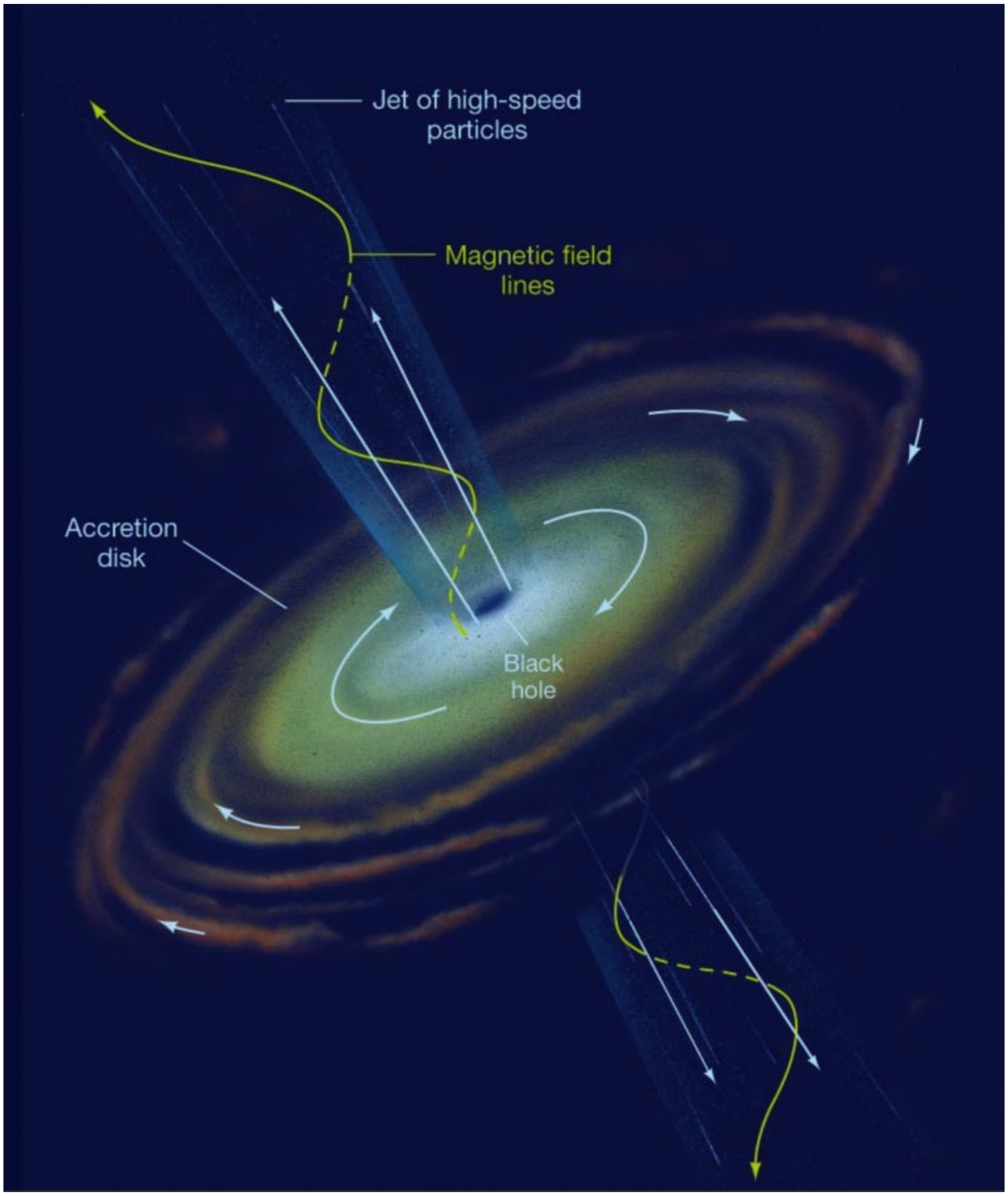

Fig. 1. – The accretion disk meets the spinning black hole that winds up the disk's magnetic field lines. Credit: Pearson Education, Inc., Upper Saddle River, New Jersey.

surface continuously collect the time-stamped signals from the optical modules, each of which functions independently. The digital messages are sent to a string processor and a global event trigger. They are subsequently sorted into the Cherenkov patterns emitted by secondary muon tracks produced by muon neutrinos, or particle showers for the case of electron and tau neutrinos, that reveal the flavor, energy, and direction of the incident neutrino [12]. Constructed between 2004 and 2010, IceCube has now taken 10 years of data with the completed detector.

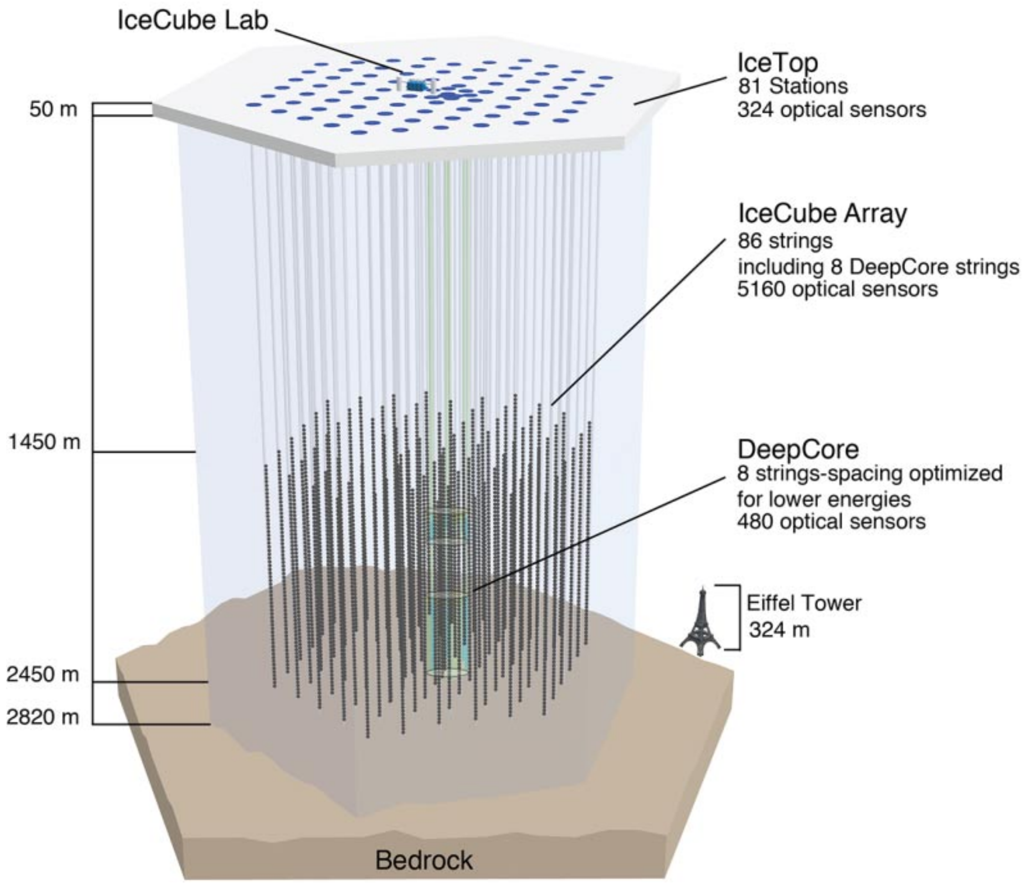

Fig. 2. – Architecture of the IceCube observatory.

For neutrino astronomy, the first challenge is to select a pure sample of neutrinos, more than 100,000 per year above a threshold of 0.1 TeV, from a background of ten billion atmospheric cosmic-ray muons, while the second is to identify the small fraction of these neutrinos that is astrophysical in origin. Atmospheric neutrinos are a background for cosmic neutrinos, at least at neutrino energies below ~ 100 TeV. Above this energy, the atmospheric neutrino flux reduces to a few events per year, even in a kilometer-scale detector, and thus neutrinos well above that energy are cosmic in origin.

The arrival direction of a secondary muon track and of an electromagnetic shower initiated by an electron or tau neutrino is determined by the arrival times of the Cherenkov photons at the optical sensors, while the number of photons is a proxy for the energy deposited by secondary particles in the detector and for the energy of the neutrino.

Muon tracks resulting from muon neutrino interactions can be pointed back to their sources with a $\leq 0.4°$ angular resolution for the highest energy events. In contrast, the reconstruction of cascade directions, in principle possible to within a few degrees, is still in the development stage in IceCube [13, 14], but determining their energy from the observed light pool is straightforward, and an energy resolution of better than 15% can be achieved. For illustration, we contrast in fig. 4 the Cherenkov patterns initiated by

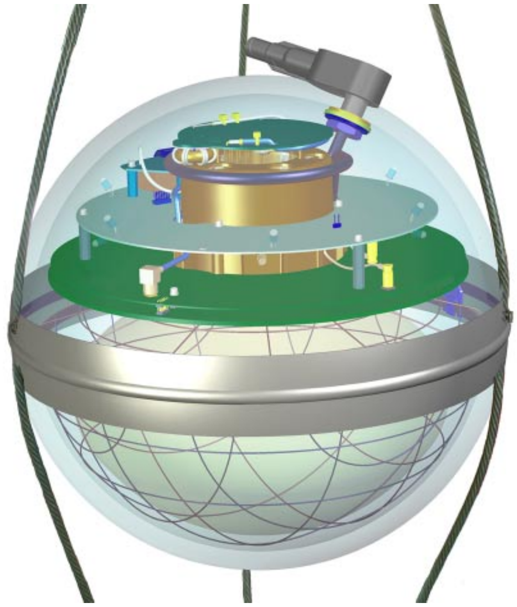

Fig. 3. – Digital optical module showing the down-facing 10-inch photomulitplier and the associated electronics that digitize the light signals.

an electron (or tau) neutrino of 1 PeV energy (top) and a neutrino-induced muon losing 2.6 PeV energy while traversing the detector (bottom).

The figure also captures the two leading methods used to isolate cosmic neutrinos from the background of muons and neutrinos originating in the atmosphere. The first is to specialize to *isolated* neutrino events that originate inside or, at higher energies, close to the instrumented detector volume and show no evidence of accompanying muons that would reveal their atmospheric origin. The second method is to use the Earth as a filter for the large flux of atmospheric muon neutrinos and select muon tracks initiated near or inside the detector by neutrinos that reach IceCube from the Northern Hemisphere after traversing the Earth. For each method, the key is the energy measurement because the atmospheric background is suppressed relative to the cosmic neutrino flux with increasing energy of the neutrino.

The diffuse flux of cosmic neutrinos has by now been characterized using a range of methods shown in fig. 5. The results of a search exclusively identifying showers that have been isolated from the atmospheric background down to energies below 10 TeV [15] and an energy spectrum of $E^{-2.5}$ agrees with the measurement for upgoing muons with a spectral index of $E^{-2.4}$ above an energy of ~ 100 TeV [16]. In general, analyses reaching lower energies exhibit larger spectral indices with the updated 7.5 years starting-event sample [17], yielding a spectral index value of -2.87 ± 0.2 for the 68.3% confidence interval.

In summary, IceCube has observed cosmic neutrinos using several methods for reconstruction and energy measurement and for rejecting background. Their results agree, pointing at extragalactic sources whose flux has equilibrated in the three flavors after propagation over cosmic distances [18], with $\nu_e : \nu_\mu : \nu_\tau \sim 1 : 1 : 1$. The diffuse energy flux of neutrinos originating beyond our Galaxy shown in fig. 5 is comparable to that of GeV-energy gamma rays observed by the NASA Fermi satellite.

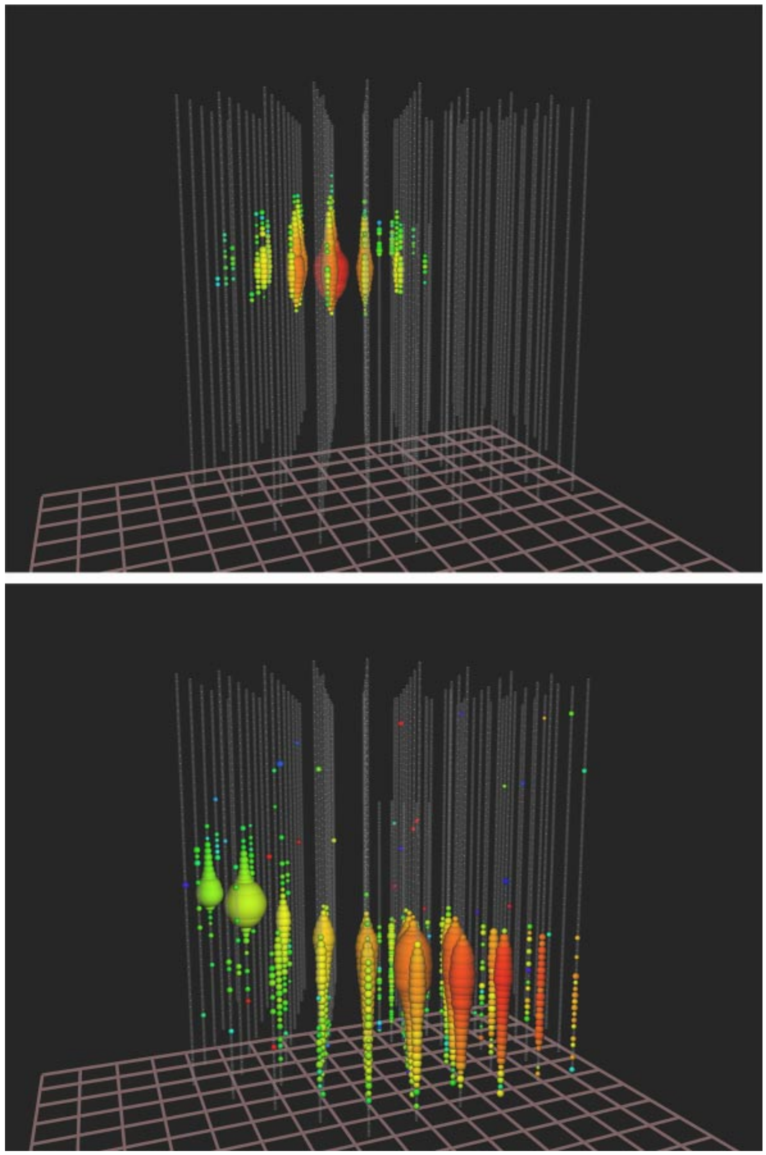

Fig. 4. – Top Panel: Light pool produced in IceCube by a shower initiated by an electron or tau neutrino of 1.14 PeV, which represents a lower limit on the energy of the neutrino that initiated the shower. White dots represent sensors with no signal. For the colored dots, the color indicates arrival time, from red (early) to purple (late) following the rainbow, and size reflects the number of photons detected. Bottom Panel: A muon track coming up through the Earth, traverses the detector at an angle of 11° below the horizon. The deposited energy, *i.e.*, the energy equivalent of the total Cherenkov light of all charged secondary particles inside the detector, is 2.6 PeV.

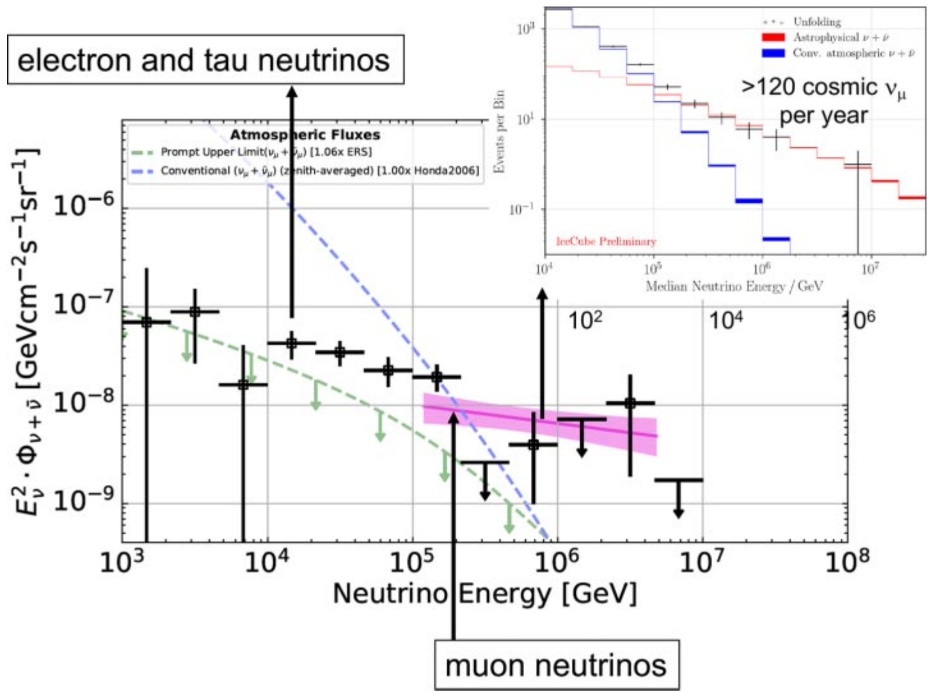

Fig. 5. – The flux of cosmic muon neutrinos [16] inferred from the eight-year upgoing-muon track analysis (red solid line) with 1σ uncertainty range (shaded range; from fit shown in upper-right inset) is compared with the flux of showers initiated by electron and tau neutrinos [15]. The measurements are consistent assuming that each flavor contributes an identical flux to the diffuse spectrum.

There is another method to conclusively identify neutrinos of cosmic origin: the observation of very high energy tau neutrinos. For neutrino energies well below 100 GeV, tau neutrinos are produced in the atmosphere by the oscillations of muon neutrinos into tau neutrinos. Above that energy they must be of cosmic origin, produced in cosmic accelerators whose neutrino flux has approximately equilibrated between the three flavors after propagating over cosmic distances. Two such candidate events have been identified [19].

Yet another independent confirmation of the observation of neutrinos of cosmic origin appeared in the form of the Glashow resonance event. The event was identified in a dedicated search for partially contained events: an antielectron neutrino interacting with an atomic electron produced an event compatible with an incident neutrino energy of 6.3 PeV, characteristic of the resonant production of a weak intermediate W^- [20].

The arrival directions of the astrophysical muon tracks are isotropically distributed over the sky. Surprisingly, there is no evidence for a correlation to nearby sources in the Galactic plane; IceCube is recording a diffuse flux of extragalactic sources. However, after analyzing 10 years of data [21], evidence emerged that the neutrino sky is not completely isotropic. The anisotropy results from four sources —TXS 0506+056 among them (more about that source next)— that emerge as point sources above the $\sim 4\sigma$ level (pretrial); see fig. 6. The strongest of these sources is the nearby active galaxy NGC 1068, also known as Messier 77.

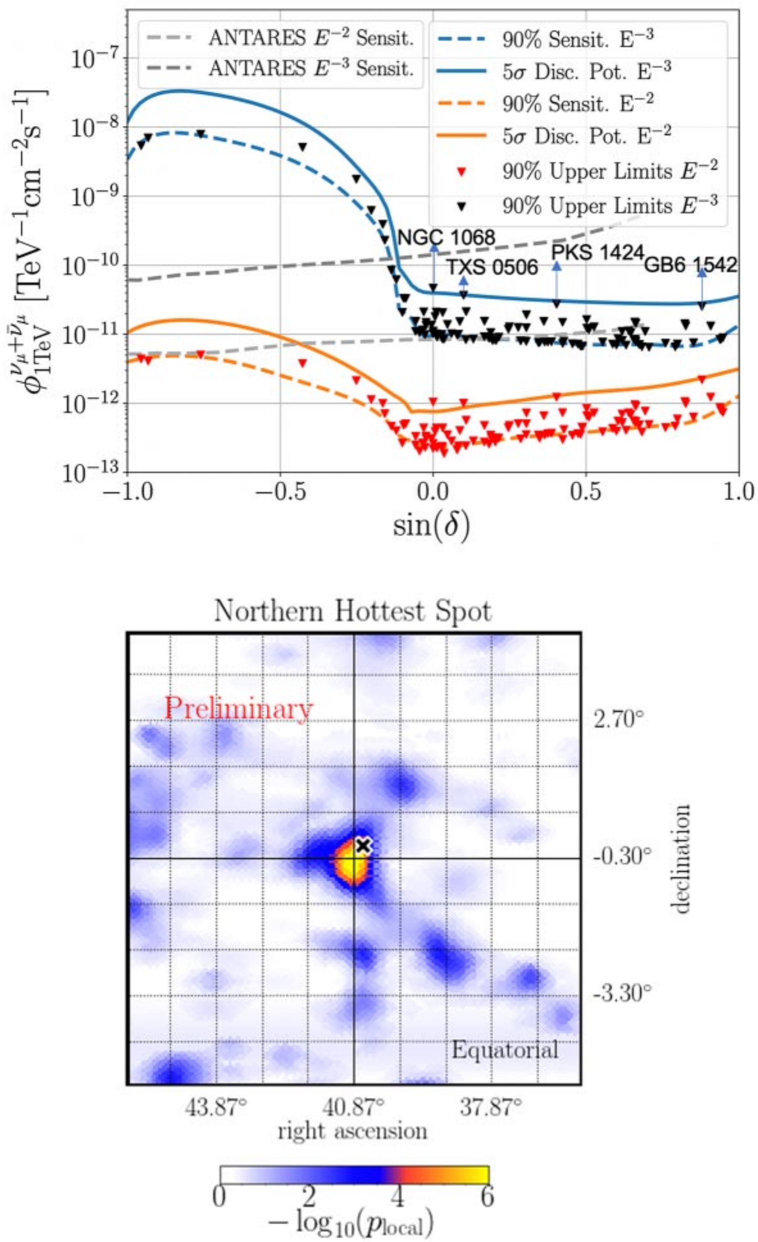

Fig. 6. – Top Panel: Upper limits on the flux from candidate point sources of neutrinos in 10 years of IceCube data assuming two spectral indices of the flux. Four sources exceed the 4σ level (pretrial) and collectively result in a 3σ anisotropy of the sky map. Bottom Panel: Association of the hottest source in the sky map as well as the strongest source in the list of candidate sources with the active galaxy NGC 1068.

3. – Identifying neutrino sources: The supermassive black hole TXS 0506+056

Since 2016, the IceCube multimessenger program has grown from Galactic supernova alerts and attempts to match neutrino observations with early LIGO/Virgo gravitational wave candidates to a steadily expanding set of automatic filters that selects in real time rare, very high energy neutrino events that are likely to be cosmic in origin [22]. Within less than a minute of their detection in the deep Antarctic ice, the arrival directions of the neutrinos are reconstructed and automatically sent to the Gamma-ray Coordinate Network for potential follow-up by astronomical telescopes.

On September 22, 2017, the tenth alert, IceCube-170922A [23], reported a well-reconstructed muon that deposited 180 TeV inside the detector, corresponding to an energy of the parent neutrino of 290 TeV. Its arrival direction was aligned with the coordinates of a known Fermi blazar, TXS 0506+056, to within 0.06°. The source was "flaring" with a gamma-ray flux that had increased by a factor of seven in recent months. A variety of estimates converged on a probability on the order of 10^{-3} that the coincidence was accidental. The identification of the neutrino with the source reached the level of evidence, but not more than that. What clinched the association was a series of subsequent observations, culminating with the optical observation of the source switching from an "off" to an "on" state two hours after the emission of IC-170922A, conclusively associating the neutrino with TXS 0506+056 [24]:

- The redshift of the host galaxy was measured to be $z \simeq 0.34$ [25]. It is important to realize that nearby blazars like the Markarian sources are at a distance that is ten times closer, and therefore TXS 0506+056, with a similar flux despite the greater distance, is one of the most luminous sources in the universe. This suggests that it belongs to a special class of sources that accelerate proton beams in dense environments, revealed by the neutrino. That the source is special eliminates any conflict between its observation and the lack of correlation between the arrival directions of IceCube neutrinos and the bulk of the blazars observed by Fermi [26]. Such limits implicitly assume that all sources in an astronomical category are identical, and this is a strong, unstated assumption as underscored by this observation.

- Originally detected by NASA's Fermi [27] and Swift [28] satellites, the alert was followed up by ground-based air Cherenkov telescopes [29]. MAGIC detected the emission of gamma rays with energies exceeding 100 GeV starting several days after the observation of the neutrino [30]. Given its distance, this establishes the source as a relatively rare TeV blazar.

- Given where to look, IceCube searched its archival neutrino data up to and including October 2017 for evidence of neutrino emission at the location of TXS 0506+056 [3]. When searching the sky for point sources of neutrinos, two analyses have been routinely performed: one that searches for steady emission of neutrinos and one that searches for flares over a variety of timescales. Evidence was found for 19 high-energy neutrino events on a background of fewer than 6 in a burst lasting 110 days. This burst dominates the integrated flux from the source over the last 9.5 years of archival IceCube data, leaving the 2017 flare as a second subdominant feature. We note that this analysis applied a published prescription to data; the chance that this observation was a fluctuation is small.

- Radio interferometric images [31, 32] of the source revealed a jet that loses its tight collimation beyond 5 milliarcseconds running into material that is likely the target for producing the neutrinos. The origin of this target material is still a matter of debate. Speculations include the merger with another galaxy that may supply plenty of material to interact with the jet of the dominant galaxy. Alternatively, the jet may interact with the dense molecular clouds of a star-forming region or simply with supermassive stars in the central region of the host galaxy [31, 32]. Also, in a so-called structured jet, the accelerated protons may collide with a slower moving and denser region of jetted photons. Additionally, the VLBA data reveal that the neutrino burst occurs at the peak of enhanced radio emission at 15 GHz, which started five years ago. The radio flare may be a signature of a galaxy merger; correlations of radio bursts with the process of merging supermassive black holes have been anticipated [33].
- The MASTER robotic optical telescope network has been monitoring the source since 2005 and found the strongest time variation of the source in the last 15 years to occur two hours after the emission of IC170922, with a second variation following the 2014-15 burst [24]. The blazar switches from the "off" to the "on" state two hours after the emission of the neutrino. They argue that the observation conclusively associates the source with the neutrino [24].

In summary, both the multiwavelength campaign [2] and the observation of the source in archival neutrino data [3] provide statistically independent evidence for TXS 0506+056 as a source of high-energy neutrinos. When combined, they reach a level of 4.4σ. This does not take into account the significance contributed by the optical and TeV associations on timescales of hours and days, discussed above. It is challenging to evaluate the final combined significance because of the a posteriori nature of these considerations but conclude that the association of neutrinos with the source summarized above is totally compelling.

We would also like to draw attention to a more recent alert, IC-190730A, sent by IceCube on July 30, 2019. A well-reconstructed 300-TeV muon neutrino was observed in spatial coincidence with the blazar PKS 1502+106 [34]. With a reconstructed energy just exceeding that of IC-170922A, it is the highest energy neutrino alert so far. OVRO radio observations [35] show that the neutrino is coincident with the peak flux density of a flare at 15 GHz that started five years prior [36], matching the similar long-term radio outburst observed from TXS 0506+056 at the time of IC-170922A. Even more intriguing is the fact that the gamma-ray flux observed by Fermi shows a clear minimum at the time that the neutrino is emitted; see fig. 7. We infer that at this time the jet meets the target that produces the neutrino. Inevitably, the accompanying high-energy gamma rays will be absorbed and their electromagnetic energy cascade down to energies below the Fermi threshold, *i.e.*, MeV or X-rays. For a discussion, see Ref. [37], where we argue that cosmic neutrinos are produced by temporarily gamma-suppressed blazars, or, more likely, any other category of AGN.

Other IceCube alerts have triggered intriguing observations. Following up on a July 31, 2016, neutrino alert, the AGILE collaboration, which operates an orbiting X-ray and gamma-ray telescope, reported a day-long blazar flare in the direction of the neutrino one day before the neutrino detection [38]. A tentative but very intriguing association of an IceCube alert [39] has been made with a tidal disruption event, an anticipated source of high-energy neutrino emission. Even before IceCube issued automatic alerts, in April 2016, the TANAMI collaboration argued for the association of the highest energy

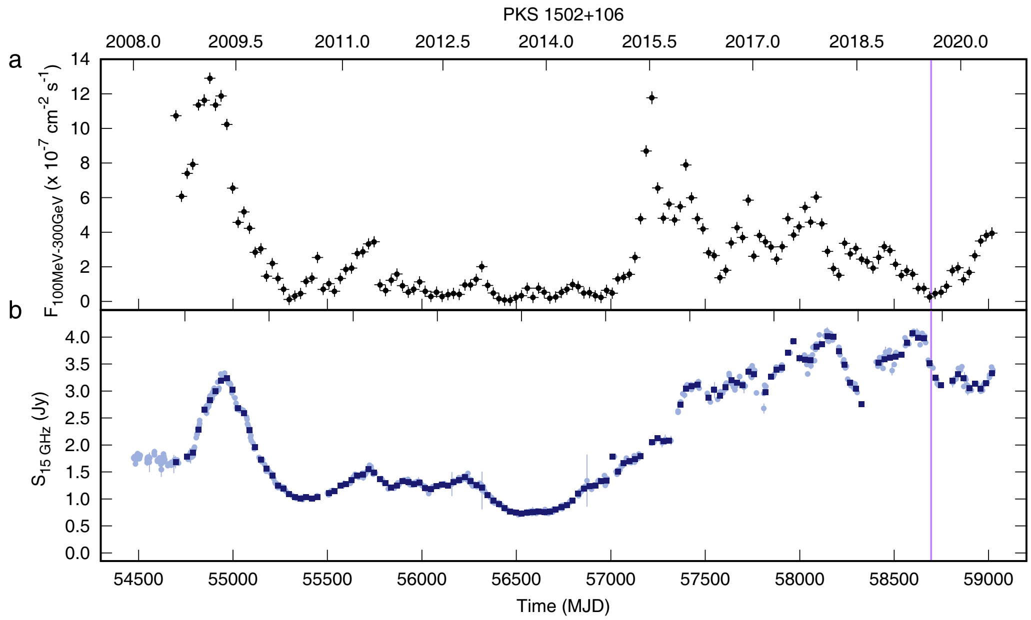

Fig. 7. – Temporal variation of the γ-ray and radio brightness of PKS 1502+106. Top Panel: Fermi-LAT likelihood light curve integrated between 100 MeV and 300 GeV (marked by black dots with error bars). Bottom Panel: OVRO flux density curve of PKS 1502+106 plotted with light blue dots, which is superimposed by the radio flux density curve binned to the Fermi-LAT light curve (marked with dark blue squares). The detection time of the neutrino IC-190730A is labeled by a vertical purple line.

IceCube event at the time, dubbed "Big Bird," with the flaring blazar PKS B1424-418 [40]. Interestingly, the event was produced at a minimum of the Fermi flux [37], as expected for a neutrino source and as is also the case for PKS 1502+106. AMANDA, IceCube's predecessor, observed three neutrinos in coincidence with a rare flare of the blazar 1ES 1959+650, detected by the Whipple telescope in 2002 [41]. However, none of these identifications reach the significance of the observations triggered by IC-170922A.

In summary, there are indications that cosmic neutrinos originate in a relatively small fraction of AGN that are gamma-ray-obscured. Also, in the case of NGC 1068, the neutrino flux is not accompanied by pionic gamma rays that have lost energy in the source to be shifted below the energy threshold of the Fermi satellite [21]. Finally, an investigation of the diffuse cosmic neutrino energy flux below 100 TeV suggests that the accompanying gamma-ray flux exceeds the Fermi observations unless the gamma rays lose energy in the sources before losing additional energy in the extragalactic background light; for a discussion, see, for instance, references [42-44].

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REFERENCES

[1] Aartsen M. G. *et al.*, *Science*, **342** (2013) 1242856.
[2] Aartsen M. *et al.*, *Science*, **361** (2018) eaat1378.
[3] Aartsen M. *et al.*, *Science*, **361** (2018) 147.
[4] Gaisser T. K., Halzen F. and Stanev T., *Phys. Rep.*, **258** (1995) 173.
[5] Learned J. and Mannheim K., *Annu. Rev. Nucl. Part. Sci.*, **50** (2000) 679.
[6] Blandford R., Meier D. and Readhead A., *Annu. Rev. Astron. Astrophys.*, **57** (2019) 467.
[7] Murase K., Kimura S. S. and Meszaros P., *Phys. Rev. Lett.*, **125** (2020) 011101.
[8] Halzen F. and Zas E., *Astrophys. J.*, **488** (1997) 669.
[9] Becker Tjus J., Eichmann B., Halzen F., Kheirandish A. and Saba S., *Phys.Rev.D*, **89** (2014) 123005.
[10] Hooper D., *JCAP*, **09** (2016) 002.
[11] Aartsen M. G. *et al.*, *JINST*, **12** (2017) P03012.
[12] Halzen F., *Eur. Phys. J. C*, **46** (2006) 669.
[13] Aartsen M. *et al.*, *JINST*, **9** (2014) P03009.
[14] Yuan T., *TeV Particle Astrophysics 2017 (TeVPA2017), Columbus, Ohio, USA* (2017).
[15] Aartsen M. G. *et al.*, *Phys. Rev. Lett.*, **125** (2020) 121104.
[16] Aartsen M. G. *et al.*, *PoS*, **ICRC2017** (2017).
[17] Abbasi R. *et al.*, to be published in *Phys. Rev. D* (2020).
[18] Aartsen M. G. *et al.*, *Phys. Rev. Lett.*, **114** (2015) 171102.
[19] Abbasi R. *et al.*, to be published in *PLR* (2020).
[20] Aartsen M. G. *et al.*, *Nature*, **591** (2021) 220.
[21] Aartsen M. G. *et al.*, *Phys. Rev. Lett.*, **124** (2020) 051103.
[22] Abbasi R. *et al.*, *Astrophys. J.*, **910** (2021) 4.
[23] Kopper C. and Blaufuss E., GRB Coordinates Network, Circular Service, No. 21916, #1 (2017).
[24] Lipunov V. M., Kornilov V. G., Zhirkov K., Gorbovskoy E., Budnev N. M., Buckley D. A. H., Rebolo R., Serra-Ricart M., Podesta R., Tyurina N., Gress O., Sergienko Y., Yurkov V., Gabovich A., Balanutsa P., Gorbunov I., Vlasenko D., Balakin F., Topolev V., Pozdnyakov A., Kuznetsov A., Vladimirov V., Chasovnikov A., Kuvshinov D., Grinshpun V., Minkina E., Petkov V. B., Svertilov S. I., Lopez C., Podesta F., Levato H., Tlatov A., Van Soelen B., Razzaque S. and Böttcher M., *Astrophys. J. Lett.*, **896** (2020) L19.
[25] Paiano S., Falomo R., Treves A. and Scarpa R., *Astrophys. J.*, **854** (2018) L32.
[26] Aartsen M. G. *et al.*, *Astrophys. J.*, **835** (2017) 45.
[27] Tanaka Y. T., Buson S. and Kocevski D., *The Astronomer's Telegram* 10791 (2017).
[28] Keivani P. A. E. A., Kennea J. A., Fox D. B., Cowen D. F., Osborne J. P., Marshall F. E. and Swift-IceCube Collaboration, *The Astronomer's Telegram* 10792 (2017).
[29] Mirzoyan R., *The Astronomer's Telegram* 10817 (2017).
[30] Ansoldi S. *et al.*, *Astrophys. J. Lett.*, **863** (2018) L10.
[31] Britzen S., Fendt C., Böttcher M., Zajacek M., Jaron F., Pashchenko I., Araudo A., Karas V. and Kurtanidze O., to be published in *Astron. Astrophys.*
[32] Kun E., Biermann P. L. and Gergely L. A., *Mon. Not. R. Astron. Soc.*, **483** (2019) L42.
[33] Gergely L. Á. and Biermann P. L., *Astrophys. J.*, **697** (2009) 1621.
[34] Lipunov V., Gorbovskoy E., Kornilov V., Tyurina N., Balakin F., Vladimirov V., Balanutsa P., Kuznetsov A., Vlasenko D., Gorbunov I., Pozdnyakov A., Zimnukhov D., Senik V., Chasovnikov A., Grinshpun V., Pogrosheva T., Rebolo R., Serra M., Podesta R., Lopez C., Podesta F., Francile C., Levato H., Buckley D., Gress O., Budnev N. M., Ershova O., Tlatov A., Dormidontov D., Yurkov V., Gabovich A. and Sergienko Y., *The Astronomer's Telegram* 12971 (2019).

[35] Kiehlmann S., Hovatta T., Kadler M., Max-Moerbeck W. and Readhead A. C. S., *The Astronomer's Telegram* 12996 (2019).

[36] Karamanavis V., Fuhrmann L., Krichbaum T. P., Angelakis E., Hodgson J., Nestoras I., Myserlis I., Zensus J. A., Sievers A. and Ciprini S., *Astron. Astrophys.*, **586** (2016) A60.

[37] Kun E., Bartos I., Becker Tjus J., Biermann P. L., Halzen F. and Mező G., *Astrophys. J. Lett.*, **911** (2021) L18.

[38] Lucarelli F. *et al.*, *Astrophys. J.*, **846** (2017) 121.

[39] Stein R., Velzen S. v., Kowalski M., Franckowiak A., Gezari S., Miller-Jones J. C. A., Frederick S., Sfaradi I., Bietenholz M. F., Horesh A. *et al.*, *Nat. Astron.*, **5** (2021) 510.

[40] Kadler M. *et al.*, *Nat. Phys.*, **12** (2016) 807.

[41] Daniel M. K. *et al.*, *Astrophys. J.*, **621** (2005) 181.

[42] Ackermann M. *et al.*, *Phys. Rev. Lett.*, **116** (2016) 151105.

[43] Murase K., Guetta D. and Ahlers M., *Phys. Rev. Lett.*, **116** (2016) 071101.

[44] Halzen F., *PoS*, **ICRC2019** (2019) 021.