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THE ROYAL SWEDISH ACADEMY OF SCIENCES

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Scientific Background to the Nobel Prize in Physics 2026

# "FOR DECISIVE CONTRIBUTIONS TO THE ICECUBE NEUTRINO OBSERVATORY AND THE DISCOVERY OF HIGH-ENERGY NEUTRINOS OF ASTROPHYSICAL ORIGIN"

The Nobel Committee for Physics

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BOX 50005 (LILLA FRESCATIVÄGEN 4 A), SE-104 05 STOCKHOLM, SWEDEN
TEL +46 8 673 95 00 ⋆ WWW.KVA.SE

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The Royal Swedish Academy of Sciences has decided to award
the Nobel Prize in Physics 2026 to

**Francis Halzen**

*"for decisive contributions to the IceCube Neutrino Observatory and the discovery of high-energy neutrinos of astrophysical origin"*

## Introduction

The neutrino was proposed by W. Pauli (awarded the Nobel Prize in Physics, 1945, "*for the discovery of the Exclusion Principle, also called the Pauli Principle*") in 1930 to explain the continuous beta-decay spectrum observed for radioactive elements. Experimental confirmation was provided in 1956 by C. Cowan and F. Reines using a nuclear reactor as a potent source of antielectron neutrinos. In 1995, Reines was awarded the Nobel Prize in Physics "*for the detection of the neutrino*" (Cowan had passed away in 1974).

In 1988, L.M. Lederman, M. Schwartz and J. Steinberger were awarded the Nobel Prize in Physics "*for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino*". It is now known that there are three neutrino flavour eigenstates: $\nu_e$, $\nu_\mu$ and $\nu_\tau$. These are superpositions of three mass eigenstates, where the sub-eV masses and mass ordering are unknown. In 2015, the Nobel Prize in Physics was awarded to T. Kajita and A.B. McDonald "*for the discovery of neutrino oscillations, which shows that neutrinos have mass*".

Once discovered by Cowan and Reines, the neutrino was immediately understood to be an ideal astronomical messenger, since it is electrically neutral and only subject to weak or gravitational interactions. This means that the neutrino can provide an unobstructed view of dense celestial sources without being absorbed or magnetically deflected within the source or en route to the Earth. In 2002, R. Davis Jr. and M. Koshiba were awarded the Nobel Prize in Physics "*for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos*" after the detection of megaelectronvolt (MeV, $10^6$ eV) neutrinos from the Sun and the 160,000-light-year distant supernova 1987A.

This year, the Nobel Prize in Physics recognises the discovery of a diffuse flux of astrophysical neutrinos, which extends to petaelectronvolt (PeV, $10^{15}$ eV) energies. Such neutrinos probe

cosmic-ray acceleration sites, where it is thought that highly relativistic protons or nuclei collide with ambient matter or radiation to produce charged pions, which subsequently decay, producing neutrinos. This milestone discovery in astroparticle physics has been made possible using data recorded by the IceCube Neutrino Observatory – a cubic-kilometre–sized detector located at a depth of ~2 km in the polar ice, close to the Amundsen-Scott South Pole Station. IceCube is a National Science Foundation (NSF)–managed research facility, operated as an international collaboration involving ~450 people from 58 institutions in 14 countries.

Francis Halzen has long been the driving force behind the IceCube Neutrino Observatory. As Principal Investigator from its beginnings, he has spearheaded the collective work by scientists and engineers that resulted in a volume of instrumented Antarctic ice sufficiently large to detect high-energy neutrinos of astrophysical origin. His scientific vision thus provides the basis for new research in the future of this field.

**Neutrino production in cosmic accelerators**

Cosmic rays were discovered in 1912 by V.F. Hess (Nobel Prize in Physics 1936). Since then, the cosmic radiation has been extensively studied and is now known to comprise primarily protons and helium nuclei, which continuously impinge on the Earth's atmosphere [1].

The cosmic-ray energy spectrum is measured up to ~$10^{20}$ eV – an energy which greatly exceeds that in terrestrial accelerator beams [e.g., 7 TeV ($7\times10^{12}$ eV) at the CERN Large Hadron Collider]. The energy spectrum can be described by a broken power law, where a spectral break at a few petaelectronvolts is referred to as the "knee". Up to this energy, cosmic rays are believed to originate within the Milky Way with centurial supernova explosions responsible for the acceleration.

Around a few exaelectronvolts (EeV, $10^{18}$ eV), a second feature called the "ankle" marks where the gyroradius of a proton exceeds the galactic scale, and an extragalactic component becomes dominant. The exaelectronvolt flux is small – roughly one cosmic-ray particle per year reaches a square kilometre on the Earth's surface. Above ~50 EeV, the cosmic-ray flux rapidly diminishes as cosmic rays interact with cosmic microwave background photons – the GZK (Greisen-Zatsepin-Kuzmin) cut-off.

As outlined in the Appendix, extragalactic cosmic rays may be accelerated within an active galactic nucleus (AGN). In an AGN, matter is accreted onto a supermassive black hole lying at the centre of a galaxy, which releases gravitational energy. A fraction of this energy powers two collimated jets of relativistic plasma, which are launched in opposite directions along the rotation axis, perpendicular to the plane of the accretion disk. The jets propagate outwards for up to several hundred thousand light years, until they terminate against the intergalactic medium.

At these termination shock fronts, as well as those within the jet, the kinetic energy of the outflow is converted into particle acceleration. Particles are repeatedly scattered back and forth across shock fronts, successively gaining energy (so-called first-order Fermi acceleration).

The Hillas criterion [2] must be met; i.e., the magnetic field strength and physical size of the accelerating region must together be sufficient to confine and accelerate a particle to the required energy before its gyroradius becomes too large and the particle escapes. Identification of acceleration sites using terrestrial observations of high-energy cosmic rays is complicated by the significant angular smearing caused by intervening magnetic fields [3].

During acceleration, cosmic-ray protons ($p_{CR}$) are thought to pass through dense clouds of dust and gas ($p_{target}$) or intense radiation fields ($\gamma_{target}$) and interact; i.e.,

$$p_{CR} + p_{target} \rightarrow n\pi\ (\pi^{0/+/-}) + X$$

or

$$p_{CR} + \gamma_{target} \rightarrow \Delta^{+} \rightarrow \begin{cases} p + \pi^{0} \\ n + \pi^{+} \end{cases}.$$

The $\Delta^{+}$ is a short-lived excited state of the proton with mass ~1232 MeV and spin 3/2. The neutral pion ($\pi^{0}$) decays into a final state comprising two gamma-rays ($\pi^{0} \rightarrow \gamma + \gamma$), while the charged pion decay produces neutrinos; e.g.,

$$\pi^{+} \rightarrow \nu_{\mu} + \mu^{+},$$

followed by:

$$\mu^{+} \rightarrow e^{+} + \nu_{e} + \overline{\nu_{\mu}}\,.$$

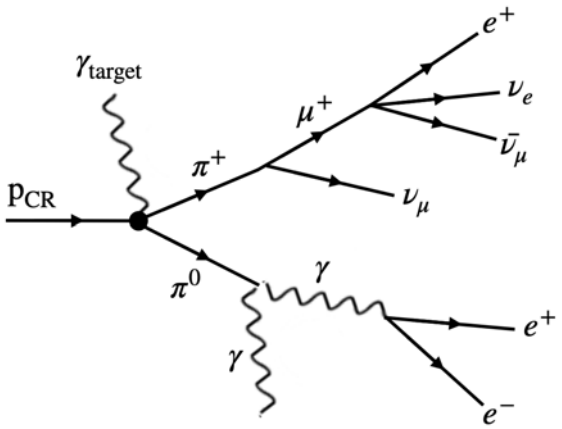


***Figure 1.*** *A schematic illustration of the production of charged ($\pi^+$) and neutral pions ($\pi^0$) in a p+$\gamma$ interaction. The decay of charged pions yields neutrinos, whereas neutral pion decay yields gamma-rays.*

Neutrino production in the case of a p+$\gamma$ interaction is illustrated in Figure 1. The energy flux ($E^2 \frac{dN}{dE}$) of gamma-rays is related to that of neutrinos (all flavours) as follows:

$$E_\gamma^2 \frac{dN_\gamma}{dE_\gamma} \approx \frac{4}{K_\pi} \frac{1}{3} E_\nu^2 \frac{dN}{dE_\nu}\Big|_{E_\nu = E_\gamma/2},$$

with $K_\pi$ denoting the production ratio of charged to neutral pions. For p+p interactions, $K_\pi \approx 2$, while for p+$\gamma$ interactions, $K_\pi \approx 1$. In the photoproduction process, the pion receives ~20% of the proton energy, and consequently the gamma-ray receives a tenth of the proton energy and the neutrino a further factor of two less than the gamma-ray [4]. Protons accelerated up to petaelectronvolt – exaelectronvolt ($10^{15}$ – $10^{18}$ eV) energies can thus be studied using neutrinos in the energy range of tens of teraelectronvolts to tens of petaelectronvolts.

Unlike charged cosmic rays, neutrinos are not deflected by galactic and intergalactic magnetic fields, and unlike gamma-rays, they can escape optically thick sources without subsequent attenuation caused by interactions with the extragalactic background light or cosmic microwave background. Moreover, gamma-rays can also be generated by electrons in synchrotron or inverse Compton processes, which complicates source diagnosis. In the burgeoning field of multi-messenger astronomy, information gleaned from high-energy neutrinos, ultra-high–energy cosmic rays, gamma-rays and, potentially, gravitational waves are combined with the aim of providing a complete picture of cosmic accelerators.

**Detecting high-energy neutrinos on Earth**

At teraelectronvolt energies and above, neutrino interactions are dominated by deep inelastic scattering. As shown in Figure 2, a neutrino weakly interacts with quarks in the nucleons ($N$) of the detection medium. A charged-current interaction,

$$\nu_l + N \rightarrow l^- + \mathrm{X},$$

results in a charged lepton ($l^-$), and a cascade of particles (X) from the disintegrated nucleus. A neutral-current interaction,

$$\nu_l + N \rightarrow \nu_l + \mathrm{X},$$

results in a cascade alone.

Cherenkov light is created when the charged lepton or cascade particles traverse a dielectric medium with refractive index, n, at a speed, v, which exceeds the phase velocity of light in the medium; i.e., v>c/n, where c is the speed of light in a vacuum. In water (n=1.33 at 20°C), the Cherenkov emission threshold is 0.75c, which corresponds to an energy threshold of 160 MeV for a muon. Neutrino telescopes identify interacting neutrinos by detecting this UV-dominated Cherenkov light.

The magnitude of the petaelectronvolt neutrino–nucleon interaction cross-section (~$10^{-33}$ $cm^2$), combined with the steeply falling neutrino energy spectrum expected from astrophysical sources (a typical power law index is −2.5), means that a cubic-kilometre–scale detector is required to achieve practical detection rates. The use of large volumes of liquid water as a Cherenkov medium was independently proposed in 1960 by M. Markov [5], F. Reines [6] and K. Greisen [7]. In 1975, Reines and J. Learned initiated influential workshops, which resulted in plans to establish a kilometre-scale detector by deploying “strings” of optical sensors (photomultiplier tubes, PMTs) anchored to the sea floor.

The approach was pioneered by the DUMAND project at a depth of 4800 m off the coast of Hawaii. One string was deployed in 1993, but suffered technical problems and failed after a short time. Moreover, measurement backgrounds from ocean bioluminescence and $^{40}K$ were identified, which affected measurement sensitivity. The project was cancelled in 1995, but its technological

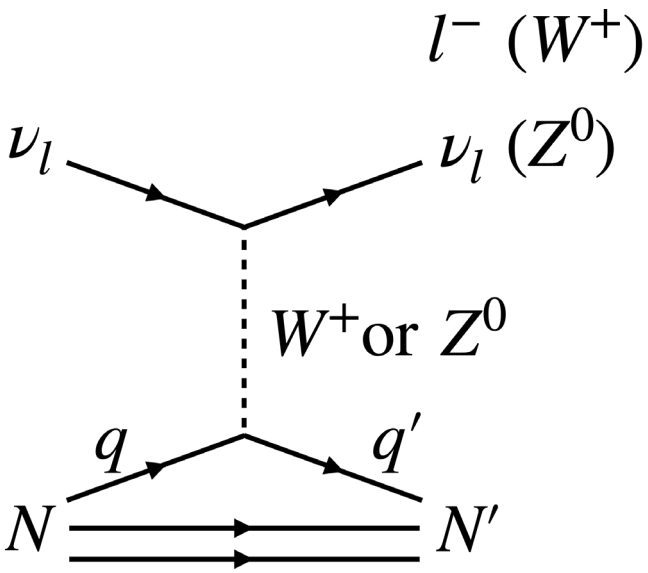


***Figure 2.*** *A neutrino of any flavour ($\nu_l$) interacts with a nucleon (N) in the detection medium (time flows from left to right). In such deep inelastic scattering events, the neutrino transfers momentum to the nucleon, causing it to dissociate (N´), yielding a hadronic cascade in the ice. The cascade particles give rise to Cherenkov light. In the case of a charged current interaction (mediated by a $W^+$ boson), the neutrino interaction yields a charged lepton ($l^-$) of the same flavour as the neutrino. This lepton also produces a Cherenkov light signal. If instead a neutral current interaction takes place (mediated by a $Z^0$ boson), there is no additional production of Cherenkov light, since the final-state neutrino is electrically neutral.*

legacy was crucial for the water-based neutrino telescope endeavours that followed. These include the Baikal neutrino telescope, deployed in a freshwater lake in Siberia [8, 9], and the ANTARES neutrino telescope, situated in the Mediterranean Sea off the coast of Toulon [10], which is also one of the locations of the related KM3NeT project [11].

## Neutrino detection in ice

During the autumn of 1987, Halzen gave a talk at the University of Kansas. A glaciologist in the audience, E. Zeller, informed Halzen about Russian plans to detect radio emission from charged particles produced in neutrino interactions in the Antarctic ice. Halzen, together with colleagues T. Stanev and E. Zas, deduced that the detection threshold would be too high for petaelectronvolt astrophysical neutrinos.

Halzen's thoughts turned to neutrino detection via Cherenkov light. The idea to establish a neutrino detector with ice as both the target and Cherenkov radiator medium was first reported [12] in June 1988 by Halzen and Learned. In a popular science article, Halzen reminisced [13]:

> "*I suspect that others must have contemplated the same idea and given up on it. Had I not been completely ignorant of what was then known about the optical properties of natural ice, I would probably have done the same. Instead, I sent a flurry of E-mail messages to my friend John G. Learned, then the spokesperson for the Deep Underwater Muon and Neutrino Detector (DUMAND).*
> …
> *Learned immediately appreciated the advantages of an Antarctic neutrino telescope.*"

Learned continued to focus on leading the development of the DUMAND project, while Halzen devoted his career to the development of ice-based neutrino detection – a journey which eventually led to the IceCube Neutrino Observatory [14].

A milestone on the way to a large-scale neutrino detector was reported in 1991. Photomultiplier tubes placed into existing boreholes on the Greenland icesheet [15] were used to detect the Cherenkov light produced within the ice by cosmic-ray muons created in the atmosphere. The measurements showed that the ice was sufficiently transparent to Cherenkov light, which informed discussions of a kilometre-scale detector [16].

The Antarctic Muon and Neutrino Detection Array (AMANDA) [17] subsequently demonstrated the instrumentation approach eventually used for IceCube, whereby strings of photomultiplier tubes are deployed into kilometre-deep holes in the ice. The holes were drilled using a high-pressure hot water system originally pioneered for glaciology. AMANDA was constructed in a number of phases between 1993 and 2000. Halzen was a driving force on AMANDA.

An important discovery was that 50-$\mu$m air bubbles trapped in the ice at the initial deployment depth (800 m to 1000 m) resulted in a scattering length for Cherenkov light of <50 cm. This hampered the reconstruction of neutrino trajectories, motivating subsequent string deployment between 1500 m and 2000 m. In March 2001, results on atmospheric neutrinos (50 GeV to a few TeV) were published [18], demonstrating the feasibility of large-scale ice-based neutrino detection. The AMANDA Collaboration went on to publish a broad range of results [19], including

limits on the magnitude of the astrophysical neutrino flux. AMANDA was decommissioned in 2009.

**The IceCube Neutrino Observatory**

Building on the success of AMANDA, a proposal to establish the IceCube Neutrino Observatory was submitted to the NSF in 1999, with Halzen as Principal Investigator. The NSF approved funding in March 2002, and construction started in 2004. IceCube [20] was established in the Antarctic ice close to the Amundsen-Scott South Pole Station.

The Cherenkov light signal is detected using strings of 60 optical sensors, each comprising a 25.4-cm-diameter downward-facing hemispherical photomultiplier tube with integrated digitizing electronics, deployed over a kilometre deep every 17 m. Photomultiplier data are sent to the surface through electrical cables. Using the hot water drilling technique, a total of 86 strings were deployed from 2005 to 2010, at depths between 1450 m and 2450 m, in a hexagonal array with a triangular grid spacing of 125 m. The resulting cubic kilometre of ice (a target mass of ~1 Gt) instrumented with over 5000 optical sensors is shown schematically in Figure 3.

Below a depth of ~2100 m, where the ice is clearest, the absorption (scattering) length for Cherenkov light is ~200 m (~50 m). The refractive index of the ice is ~1.31, with birefringent properties that were recently revealed [21].

An array of surface-ice Cherenkov detectors (“IceTop”) located above IceCube measures cosmic-ray air showers in the 300-TeV to 1-EeV energy range. IceTop provides a “veto” for in-ice events over a limited solid angle.

Since completion in 2011, IceCube has monitored the neutrino sky with an uptime exceeding 99%. Neutrino interactions recorded by IceCube have two primary topologies – tracks and cascades, as shown in Figure 4. The number of detected Cherenkov photons is used to determine the deposited energy, while the relative arrival times of photons determines the neutrino direction.

A muon neutrino that interacts through a charged-current process will produce a muon, which may traverse IceCube leaving a track-like signature. Muon neutrinos are detected even when they interact far outside of the IceCube volume, since a teraelectronvolt muon has a kilometre range

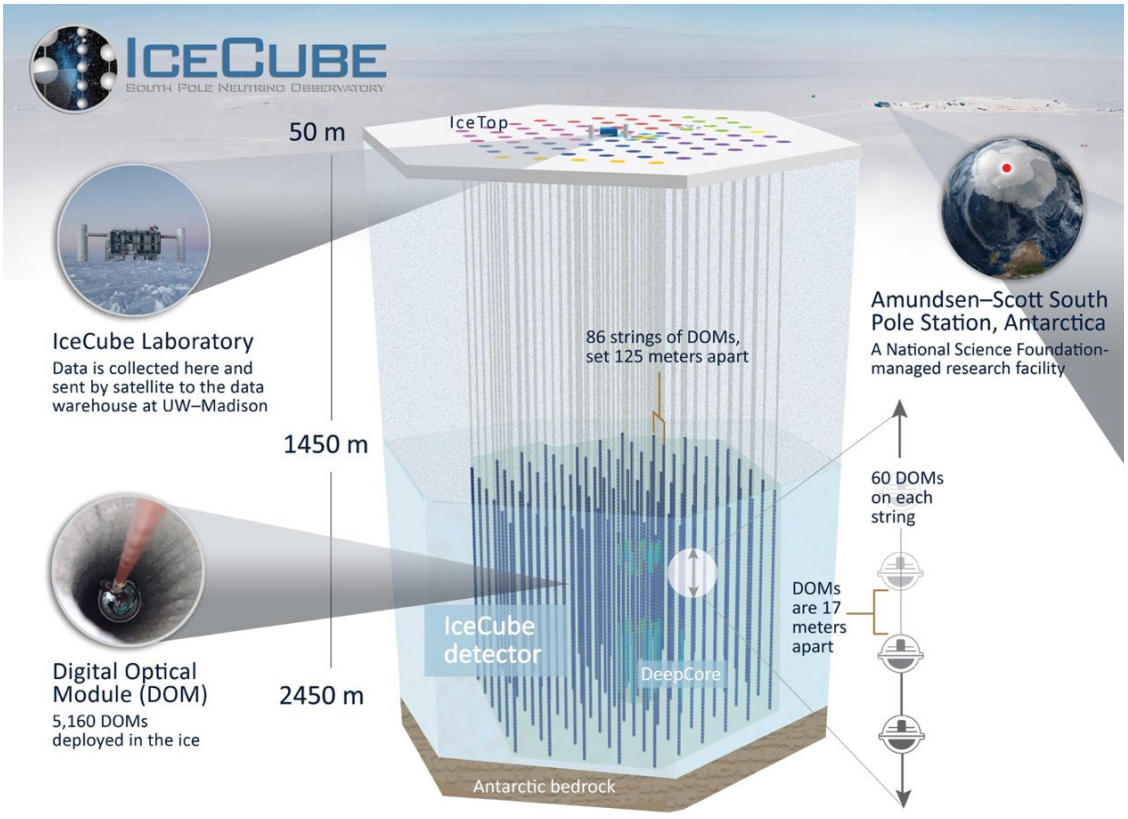


***Figure 3.*** *A schematic illustration of the IceCube Neutrino Observatory. Figure credit: IceCube Collaboration.*

(or tens of kilometres at exaelectronvolt energies). The effective detection volume therefore greatly exceeds the geometrical volume of instrumented ice.

The neutrino trajectory can be reconstructed with an angular resolution of 0.3° at 100 TeV. The energy of individual muons can be determined within a factor of ~2 due to the stochastic nature of the muon energy loss (e.g., ionisation, bremsstrahlung, photo-ionisation). The neutrino energy spectrum is unfolded from the deposited energy distribution.

Cascades arise from charged-current electron and tau neutrino interactions, as well as neutral-current interactions of all neutrino flavours. The resulting electromagnetic or hadronic shower is typically less than ~10 m in length, which is smaller than the distance between strings, resulting in a spherical pattern of reconstructed Cherenkov light. This means that the angular resolution is

worse than for tracks, at around 5° for energies above 50 TeV. Since the interaction event is well-contained, the energy resolution is ~8% at 100 TeV, i.e., far superior to that for tracks.

Tau neutrinos that undergo a charged-current interaction in the ice produce a so-called "double-bang" signature [22], with two spatially separated cascades – one from the tau neutrino interaction and the other from decay of the resulting tau lepton. With a tau decay length of ~50 m/PeV, detecting such events requires a favourable event geometry. IceCube instead detects tau neutrinos by identifying characteristic light patterns across multiple optical modules and strings as each cascade passes by.

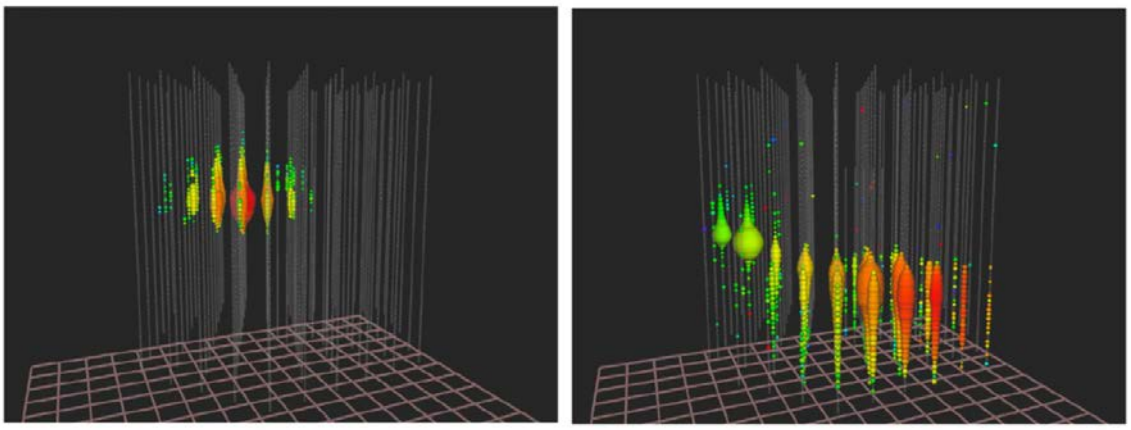

***Figure 4:*** *Left panel: The Cherenkov light signal produced by a cascade resulting from a neutral-current interaction of a neutrino of any flavour or a charged-current interaction of an electron or tau neutrino. The deposited energy is 1.14 PeV. Strings of optical sensors are marked as vertical lines of white dots. The colour codes the arrival time from red (early) through the rainbow to purple (late), while the size of the "blob" represents the number of Cherenkov photons detected. Right panel: a muon track that traverses IceCube from 11° below the horizon. The deposited energy is 2.6 PeV. Figure credit: IceCube Collaboration.*

To identify high-energy astrophysical neutrino interactions, two measurement backgrounds need to be suppressed during data analysis. With regard to the first background suppression, cosmic-ray muons are produced in the decay of pions and kaons in the atmosphere above IceCube. The muon flux peaks in the zenith direction and decreases as the incidence angle approaches the horizon. This background is effectively suppressed by selecting tracks that arrive from directions below the horizon. In a typical analysis (such as that described below), the initial 3-kHz atmospheric muon background can be reduced to $\mu$Hz-level in this manner.

The second suppression concerns the approximately 100,000 neutrinos that are registered annually above ~0.1 TeV. The majority are created in the Earth's atmosphere by pion and muon decay. The atmospheric neutrino flux may also contain so-called prompt neutrinos from the decay of charm mesons. These neutrinos are expected to have a flatter energy spectrum than those from lighter mesons. Above a few tens of teraelectronvolts, the astrophysical neutrino flux ($\sim E^{-2.5}$) emerges above the steeply falling atmospheric background flux ($\sim E^{-3.7}$). Per year, ~100 neutrinos are expected to be of astrophysical origin.

**IceCube results on high-energy astrophysical neutrinos**

In 2013, after two years of data collection, two petaelectronvolt neutrino events (1.04 PeV and 1.14 PeV) were discovered in the data, providing the first evidence for high-energy astrophysical neutrinos [23]. The two events were found serendipitously [24], while searching for GZK neutrinos at the exaelectronvolt energy scale using "starting event" data collected between May 2010 and May 2012. The instrumented volume of ice is divided into an outer veto shield and a ~500 megaton inner detection volume. Neutrinos from any direction, which first interact within the detection volume of IceCube, are referred to as "starting events". This event selection provides additional discrimination against atmospheric muon events impinging the detection volume from the outside.

The first two PeV events informed subsequent data analysis strategy and paved the way for the discovery of 28 high-energy (30 TeV–1.14 PeV) astrophysical neutrinos in the same dataset [25]. A total of 21 events were cascades, and the remaining 7 were muon tracks. In 2014, published results [26] rejected a purely atmospheric explanation for data collected 2010–2013 at 5.7σ level.

Since then, IceCube has periodically published updated results on high-energy astrophysical neutrinos [27]. The most recent results were published in March 2026 [28], including a down-going muon neutrino with a reconstructed energy of $11.4^{+2.46}_{-2.53}$ PeV. The neutrino was recorded on 31 March 2019, and the observation is the highest energy neutrino published by IceCube to date.

The all-flavour astrophysical neutrino energy spectrum was measured by analysing the complementary track and cascade samples of neutrino interactions. A total of 231,486 tracks (8.5 years live time) and 10,569 cascades (10.5 years live time) were recorded between May 2010 and May 2021. The muon track sample [29] predominantly covers the Northern sky, while the all-flavour cascade sample [30] covers the entire sky.

The energy distribution of track and cascade events is shown in Figure 5. The distributions are characterised using a maximum-likelihood fit, which includes the astrophysical neutrino flux, the conventional ("long-lived" pion/kaon decay) and prompt ("short-lived" charm hadron decay) atmospheric neutrino background, and the atmospheric muon background. Background fluxes are modelled using Monte Carlo simulations. Systematic uncertainties, e.g., arising from the optical properties of the ice (absorption and scattering), are included as nuisance parameters. A high-energy astrophysical neutrino flux is required to fully describe the energy distribution of track and cascade events recorded by IceCube.

A variety of hypotheses on the spectral shape of the high-energy astrophysical neutrino flux have been examined. There is evidence for a flatter neutrino spectrum below ~30 TeV, while at higher energies the spectrum is well-described by a power law, as shown in Figure 6. In the range 5 TeV–10 PeV, a single power law is rejected with a significance exceeding 4σ. Information on the spectral shape is a powerful input when modelling sources of astrophysical neutrinos, e.g., indicating transition between contributing source populations or production regions. As expected for a collection of predominantly extragalactic neutrino sources, no significant anisotropy in the neutrino arrival direction on the sky is observed.

Figure 6 shows the flux contribution from high-energy neutrinos produced in the Milky Way. Results on galactic neutrinos were first published in 2023 [31], with a statistical significance of 4.5σ reported. No point sources were identified. The neutrinos are produced when cosmic-ray protons and nuclei are accelerated within the Milky Way and interact with the interstellar gas. The signal is consistent with expectations from measurements of diffuse ($\pi^0$ decay) gamma-rays by the Fermi Gamma-ray Space Telescope.

Earlier this year, IceCube released updated results [32], describing an observation of high-energy galactic neutrinos with a statistical significance of 5.7σ. Based on 12 years of data, this establishes the Milky Way as the first source of high-energy neutrinos where the 5σ discovery threshold is exceeded. Once again, no point sources were identified. The flux contribution from a possible point source of neutrinos, NGC 1068 – an active galactic nucleus, which is discussed in the Appendix – is also shown. Both the galactic and point source neutrino fluxes are small compared to the diffuse astrophysical neutrino flux.

As discussed above, tau neutrino interactions can be identified in IceCube due to structure in the cascade topology. High-energy tau neutrinos can be produced in the atmosphere due to the oscillation of muon neutrinos, but only for energies <100 GeV. Above this energy, a tau neutrino must be of astrophysical origin. Results for seven high-energy tau neutrinos (20 TeV–1 PeV) were published in 2024 [33]. The absence of an astrophysical tau neutrino flux is ruled out at 5σ level.

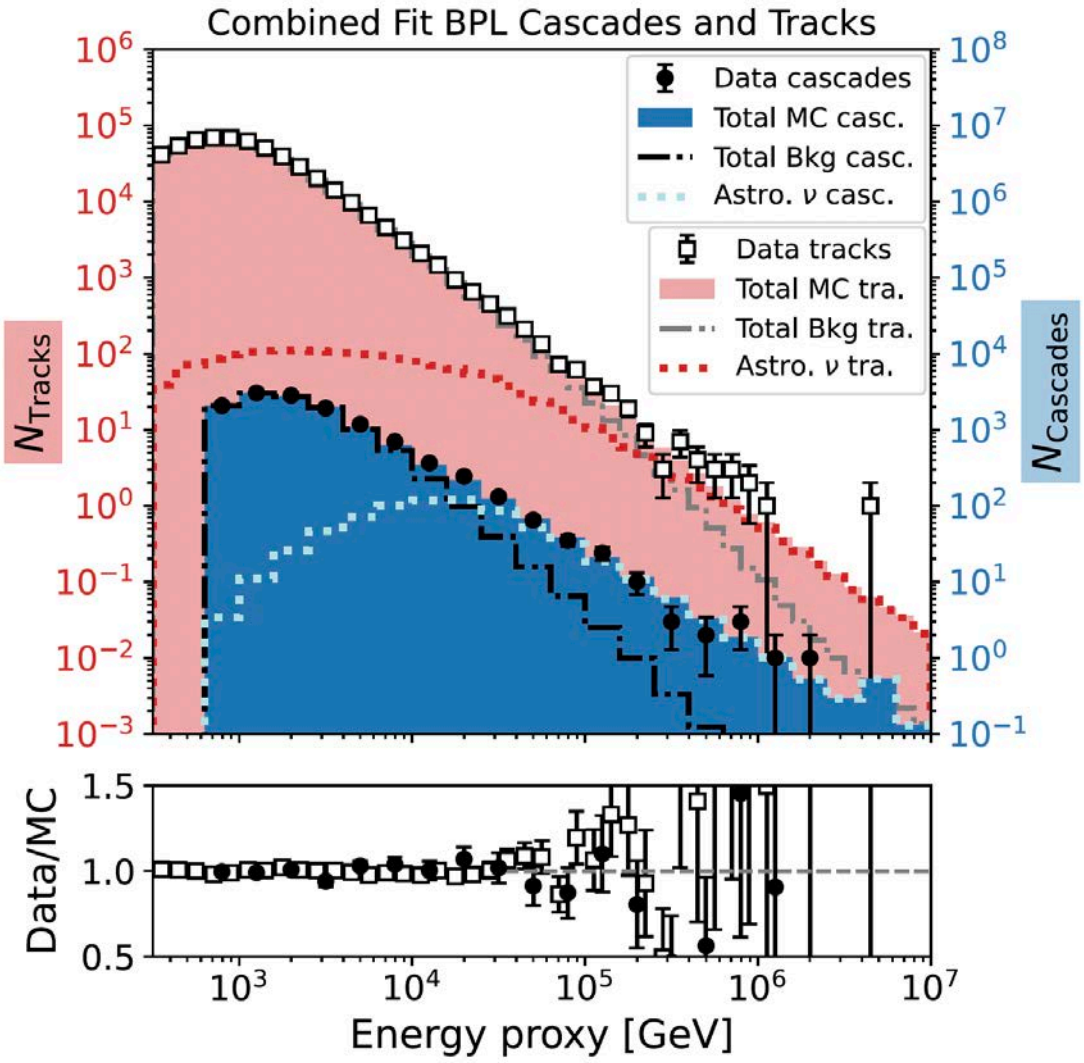


***Figure 5.*** *The energy distribution of cascade and track events, with contributions from astrophysical (Astro.) neutrinos [assuming the best-fit broken power-law (BPL) spectrum], total Monte Carlo (MC) background (Bkg) (atmospheric neutrinos and muons), and the total contribution from data. Note the different scales for tracks (left axis) and cascades (right axis). The energy proxy represents the energy reconstructed for the given event type. Figure credit: IceCube Collaboration, Physical Review Letters 136 (2026) 121002.*

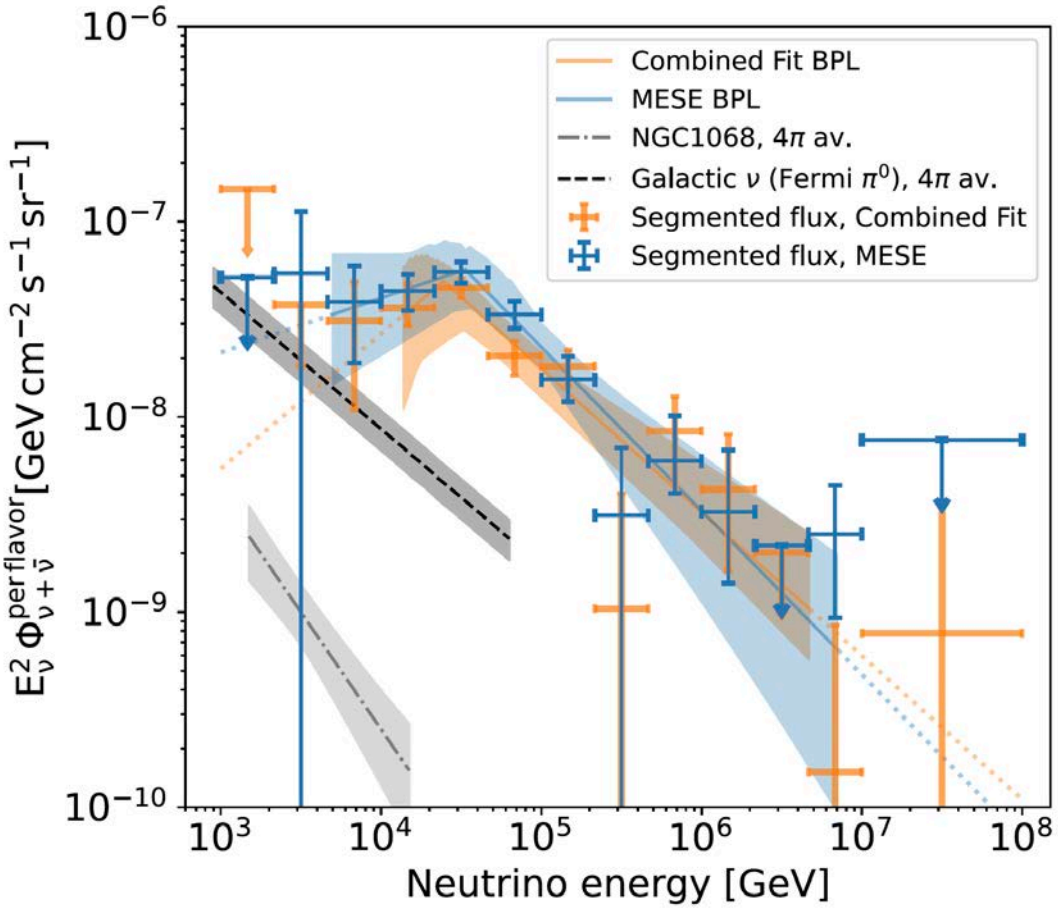


***Figure 6.*** *The fit to the astrophysical neutrino flux, Φ(E), multiplied by E², where E is the neutrino energy. Orange markers and shaded regions are for the combined fit of cascade and track events. A broken power-law (BPL) neutrino spectrum is assumed. The blue markers and shaded region are for a complementary analysis of so-called Medium Energy Starting Events (MESE), which is not described in this report. The combined fit analysis allows stronger constraints on the higher-energy spectral index, while MESE gives stronger constrains on the lower-energy spectral index, due to their respective sensitive energy ranges. The shaded regions show 68% confidence level uncertainties. The flux from the candidate neutrino source, active galaxy NGC 1068, and Milky Way (Galactic ν) are small compared to the astrophysical neutrino flux. Figure credit: IceCube Collaboration, Physical Review Letters 136 (2026) 121002.*

The measured neutrino energy flux is comparable to that observed for gamma-rays at lower energies, and cosmic rays at higher energies. This suggests that these particles are accelerated by the same class of sources, through related physical processes. Hadronic interactions are natural candidates: i.e., a source accelerates protons or nuclei (the ultra-high-energy cosmic rays measured by, e.g., the Pierre Auger Observatory); some of the protons or nuclei interact with matter or radiation in or near the source, to produce pions; the neutral pions decay into the gamma-rays seen by the Fermi Gamma-ray Space Telescope; and the charged pions decay into the neutrinos, which IceCube measures. In this way, all three messengers are tied together in terms of energy output, as discussed earlier.

## Summary and outlook

A diffuse flux of astrophysical neutrinos extending to petaelectronvolt energies ($10^{15}$ eV) has been discovered using data from the IceCube Neutrino Observatory. High-energy neutrinos are thought to be produced in the interactions of cosmic-ray protons and nuclei at celestial acceleration sites. The neutrinos deliver undistorted directional and spectral information, thereby opening a new observation window on the high-energy universe. IceCube results demonstrate that sources are predominately extragalactic.

Francis Halzen has made pivotal contributions to IceCube as Principal Investigator – from its invention and conceptual design, through the technically audacious construction, to routine science operations. Through his visionary leadership, Halzen created and nurtured an international collaboration, which was able to transform theoretical ideas on neutrino detection into precise observations and a vibrant experimental field.

The use of high-energy neutrinos in multi-messenger astronomy will be fully capitalised on during the next decade with a global network of next-generation neutrino telescopes with instrumented volumes exceeding a cubic-kilometre. These facilities include the IceCube-Gen2 Observatory (South Pole), KM3NeT (Toulon/Sicily, Mediterranean Sea), P-ONE (Vancouver Island, Pacific Ocean), TRIDENT (South China Sea), and Baikal-GVD (Lake Baikal, Siberia).

## Appendix: Sources of high-energy astrophysical neutrinos

IceCube has presented results showing that the reconstructed trajectories of high-energy astrophysical neutrinos can be traced back to an active galactic nucleus (AGN). An AGN is the

extremely bright central region of a galaxy. The emission arises from dust and gas, which falls into a rotating supermassive black hole, resulting in a collimated outflow of highly relativistic material, referred to as a "jet". The jet is thought to be formed when the accretion disk spacetime experiences the black hole, and the disk magnetic field is wound into a tight cone around the rotation axis, which acts to funnel a jet of highly relativistic particles. If the jet is directed to Earth, the AGN is referred to as a blazar. It remains unclear if the acceleration power stems from the rotational energy of the black hole or the magnetic energy in the rotating plasma. When the hadronic jet impacts target material, e.g., the coronal UV-photon field or the gas or dust, neutrinos are produced. The neutrino-AGN connection stems from the 1990s [34].

On 22 September 2017, IceCube detected a ~290-TeV muon neutrino (180 TeV deposited energy) from a direction within 0.06° of the sky position of the blazar TXS 0506+056 [35]. The source was "flaring", with a gamma-ray flux that had increased by a factor of 7 in recent months. Within a minute of the neutrino detection, an alert was distributed worldwide, prompting follow-up searches by telescopes over a broad range of wavelengths. Analysis of archived IceCube data [36] revealed a neutrino flare from September 2014 to March 2015, a 3.5σ detection.

High-energy neutrino emission from positions of known gamma-ray emitting sources has been found in archived IceCube data. After searching 110 such positions for a neutrino excess, IceCube announced in 2022 that 79 neutrinos in the energy range 1–10 TeV had been observed from the direction of the AGN NGC 1068 [37] [also known as Messier 77 (M77)], a detection over background of 4.2σ. NGC 1068 is among the brightest and closest AGN, lying in the constellation of Cetus, 46 million light-years from Earth. The AGN is radio-quiet with no discernible large-scale jet activity. Observations by the Atacama Large Millimeter/submillimeter Array (ALMA) and the X-ray space telescope NuSTAR [38] indicate that the 15-million-solar-mass super-massive black hole at the centre of the galaxy is blanketed by a thick layer of gas and dust. The gamma-ray energy flux measured by the Fermi Gamma-ray Space Telescope (0.1–30 GeV) is much less than the neutrino energy flux, and the MAGIC imaging atmospheric Cherenkov telescope did not detect any teraelectronvolt emission. The combination of these observations favours neutrino production through pion decay in the radiation-dense corona surrounding the central black hole. Time will tell if these observations confirm AGNs as sources of high-energy neutrinos.

Finally, gamma-ray bursts (GRBs) have also been proposed as a source of high-energy astrophysical neutrinos [39]. To complete the picture, it is worth noting that more than a thousand follow-up observations of GRBs (based on sky position and time) have been conducted, without any coincident detection of neutrinos.

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