Recent results from the IceCube Neutrino Observatory and the prospects for IceCube-Gen2

Erik Blaufuss
Brookhaven National Lab
Colloquium
March 12, 2024

Photo credit: J. Werthebach IceCube/NSF
Over a decade ago, IceCube announced the discovery of astrophysical high-energy neutrinos.

Many questions still remain!

Today I’ll cover:

What is IceCube and how does it work?

IceCube’s measurement of astrophysical neutrinos

Recent source search results

Realtime alerts, TOO neutrino searches

Future prospects
Neutrinos can be created by hadronic interactions with protons or photons within or near cosmic accelerators.

At the highest energies, neutrinos are an astronomical messenger with several advantages:

- Neutral
- Freely propagate from source regions
• Similar energy densities observed for extra-galactic components
  • Diffuse gamma-rays
  • Extra-galactic cosmic rays
  • Astrophysical neutrinos
  • All potentially arising from a common source class
Clear ice serves as both a target medium and a Cherenkov radiator.

Digital optical modules (phototubes and data acquisition).

Cable for power, communication and support.
1 km$^3$ of natural clear ice

→ The South Pole glacial icecap

NSF South Pole Station

NSF McMurdo Station
The IceCube Digital Optical Module (DOM)

~98% of DOMs still returning high quality data in 2022
~98% of DOMs still returning high quality data in 2022.
IceCube sensitive to all $\nu$ flavors

**CC Muon Neutrino**

$\nu_\mu + N \rightarrow \mu + X$

factor of $\approx 2$ energy resolution
$< 1^\circ$ angular resolution

**Neutral Current / CC Electron Neutrino**

$\nu_e + N \rightarrow e + X$

$\nu_x + N \rightarrow \nu_x + X$

$\approx \pm 15\%$ deposited energy resolution
$\approx 10^\circ$ angular resolution
(at energies $\approx 100$ TeV)

**CC Tau Neutrino**

$\nu_\tau + N \rightarrow \tau + X$

“double-bang” and other signatures (simulation)
(not observed yet)
Observing charged particles in Ice.

0.01% of all Cherenkov photons generated by a 100 TeV muon in ice.
Observing charged particles in Ice.

0.01% of all Cherenkov photons generated by a 100 TeV muon in ice.
Identifying Astrophysical Neutrinos

- At lower energies, backgrounds dominate detection
  - Atmospheric muons (Southern hemisphere)
  - Atmospheric neutrinos (Northern hemisphere)
- Prefer high energy events
  - Through-going tracks
  - High-Energy Starting Events
  - Cascade/Shower Events
An established diffuse astrophysical neutrino flux

9.5 yr Up-going tracks

Spectral index: -2.37
Atm-only hypothesis rejected at 5.6σ

IceCube, Astrophys. J. 928 (2022) 50

7.5 yr Starting tracks

Spectral index:
-2.87
Atm-only hypothesis rejected at >5σ

Identified 7 ντ candidates in 10yr
Reject no-Tau hypothesis at 5σ

arXiv:2403.02516
Identifying sources of astrophysical neutrinos

- Several strategies used to find evidence for sources
  - Search for excess of events from a single point or source region in the sky
    - Including coincidences with a catalog of known high-energy sources
  - Look in realtime for transient photon signals in correlation with detection of a likely astrophysical neutrino
    - Realtime neutrino alert program
  - Search in realtime for neutrinos from identified transient phenomena
    - TOO searches: GRBs, Gravitational wave events, etc…
Neutrino events - Tracks

- Through-going muon tracks give preferred for astronomy
  - Best angular resolution and largest effective volumes
- All-sky sensitivity.
  - Different backgrounds in Northern/Southern skies.
  - Sensitivity to different energies
- South Pole location:
  - Stable operations - 99% uptime
  - Uniform sensitivity at a given declination
  - Efficient: ~100,000 track candidates per year. (~4 mHz)
- Available in **realtime** for alerts and target-of-opportunity searches
Searching for neutrino sources

Majority of the events are background in searches for neutrino sources
Searching for neutrino sources

Combine knowledge of background and source properties to better identify sources

Unbinned maximum likelihood search technique on a fine grid over the entire sky

Credit: H. Niederhausen
Searching for neutrino sources

• Blind analysis
• Backgrounds are modeled in data-driven approach
• Randomization in time removes accumulation along source region due to Earth’s rotation
  • Example: Source is Galactic plane
• Chance probability of final analysis calculated from distribution of randomized pseudo-experiments
Searching for neutrino sources

• Blind analysis
• Backgrounds are modeled in **data-driven** approach
• Randomization in time removes accumulation along source region due to Earth’s rotation
  • Example: Source is Galactic plane
• Chance probability of final analysis calculated from distribution of randomized pseudo-experiments
Previous Point Source Results

IceCube, PRL 124, 051103 (2020)

Per year:
90 billion atmospheric muons
80 thousand atmospheric neutrinos

2.9σ excess over background
An improved track dataset

- Improved calibrations and uniform processing
- 2 additional years of data from complete detector
- Improved energy and angular uncertainty estimates
- Focus on events from more sensitive northern sky

Data: May 2011 to May 2020
~99% detector uptime
~670,000 neutrinos selected (99.7% purity) out of ~1 trillion events recorded

IceCube Pass 2 data
Improved detector calibration, data filtering and processing applied to ALL years
An improved track dataset
Angular uncertainty

KDE methods used to better quantify expected angular spread of signal events
New machine learning techniques provide more accurate energy estimates, especially at TeV-energies.
Updated IceCube neutrino sky

Hottest spot all sky
Local p-value: $5 \times 10^{-8}$
After accounting for trials searching entire sky: $2.0\sigma$
Catalog of known high-energy sources

110 candidate sources defined a-priori
Hottest spot coincides with NGC 1068

At the NGC 1068 location:
Astrophysical neutrino events = 79 $^{+22}_{-20}$
Spectral index = -3.2 ± 0.2
Using 500 x 10⁶ simulated experiments generated from simulated exp and accounting for catalog size (110 candidate sources) yields:

\[ p\text{-value}: 1.1 \times 10^{-5} \ (4.2\sigma) \]
NGC 1068 - Multimessenger observations

NGC 1068 - long-studied, nearby AGN
Intense photon fields near AGN core modeled to prevent a strong gamma-ray signal and provide targets for p-\(\gamma\) neutrino production

(1) Y. Inoue et al., ApJL’20
(2) K. Murase et al., PRL’20
IceCube Astrophysical neutrino alerts

- Identify well reconstructed, high-energy neutrino candidates in real-time
- Transmit them to the North and advertise
  - Latency from detection to alert typically less than 1 minute
- Community observations to search for multi-messenger signals
- In operation since April 2016
IceCube Realtime Track Alerts

- Expanded and improved alert selection compared to first alert selection since 2019
- Targeting starting and through-going tracks
  - Neutrinos with smallest angular uncertainty
- Two selection levels
  - Gold alerts: average 50% likely astrophysical origin
  - Bronze alerts: average 30% likely astrophysical origin
- More alerts per year
  - Gold: 12/yr expected
  - Bronze 18/yr additional expected

Figure 2: IceCube realtime astrophysical neutrino alert angular resolution as a function of neutrino energy. The left panel presents the angular resolution for through-going neutrino selections (GFU and EHE) and the right panel presents the angular resolution for the HESE starting track selection. Alerts at the Gold and Bronze levels are issued based on these selections, with a minimum reported angular resolution for automated alerts of 0.2 degrees reported. In these figures, the Bronze alerts shown also include events selected by the Gold alerts.

Figure 3: IceCube realtime astrophysical neutrino alert declination distribution for Gold (left) and Bronze (right) alert levels. For each figure, the expected astrophysical neutrinos ($E_{\nu}^{2.19}$ spectrum assumed) and atmospheric neutrino components are shown in a stacked histogram. In these figures, the Bronze selections shown also include events selected by the Gold selection.
Multi-messenger alerts: TXS 0506+056

On September 22, 2017, IceCube issued a neutrino alert:

- ~290 TeV track alert neutrino (IceCube-170922A)
- Spatially coincident with a known blazar (TXS 0506+056) that was in a flaring state (~3σ significance)
- Blazar was also detected by the MAGIC air-Cherenkov telescope with γ-rays up to 400 GeV.
- Very active multi-messenger follow-up campaign that included observations from radio to γ-rays.
IceCube point source search: TXS 0506+056

Based on the neutrino alert - performed a search of historical neutrino track events

Evidence of time-dependent emissions is observed:
- September 2014 - March 2015
  - Independent of, and prior to neutrino alert
- 3.5σ excess over expected background
  - 13 ± 5 events over background

![Image of event weight and muon energy proxy](image.png)

Published in Science: IceCube Coll. Science 361 (2018) 147
GRB221009A - A nearby, bright GRB

@AstroColibri

Swift XRT GRB observations

Right Ascension 288.263
Declination +19.803
z 0.151 (GCN 32648)
T0 09 October 2022 13:16:59.99 UTC
T90 (Fermi-GBM Burst Cat.) 325.8 +/- 6.8 s
GRB221009A - A nearby, bright GRB

@AstroColibri

Swift XRT GRB observations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Ascension</td>
<td>288.263</td>
</tr>
<tr>
<td>Declination</td>
<td>+19.803</td>
</tr>
<tr>
<td>z</td>
<td>0.151 (GCN 32648)</td>
</tr>
<tr>
<td>T0</td>
<td>09 October 2022 13:16:59.99 UTC</td>
</tr>
<tr>
<td>T90 (Fermi-GBM Burst Cat.)</td>
<td>325.8 +/- 6.8 s</td>
</tr>
</tbody>
</table>

J. Thwaites - IceCube
TOO: Neutrinos from gravitational wave events with IceCube

- High-energy neutrinos can provide important information:
  - Coincident detection could reduce localization uncertainty and aid follow-up optical source searches
  - Provide understanding of particle acceleration and high-energy emission from compact objects
  - Realtime searches for neutrinos in Run O4 now ongoing

![Diagram of high-energy neutrino limits](image_url)

GW170817 Neutrino limits (fluence per flavor: $\nu_x + \bar{\nu}_x$)

- $\pm 500$ sec time-window
  - ANTARES
  - IceCube
  - Auger
  - $0^\circ$, $4^\circ$, $8^\circ$
    - Kimura et al.
    - EE moderate
    - EE optimistic

- $14$ day time-window
  - ANTARES
  - IceCube
  - Auger
  - Fang & Metzger
    - $30$ days
    - $3$ days

Galactic Neutrinos

- **Galactic neutrino sources**
  - Cosmic ray accelerators
  - Not yet identified
  - Use gamma ray emission as a proxy

- **Diffuse galactic neutrino emission**
  - Cosmic ray measurement
  - Gamma ray measurements
  - Cosmic ray diffusion
  - Gas density
Diffuse Galactic Neutrinos

• Expected signal, but strength is low
• *Fermi*-LAT \( \pi^0 \) spectrum \( (E^{-2.7}) \)
  • Neutrinos expected from \( \pi^+/\pi^- \)
• Concentrated in southern sky
• Challenging region to probe for IceCube
• How do we see the galaxy with any sensitivity?

1. NASA/DOE/Fermi LAT Collaboration: https://svs.gsfc.nasa.gov/11342
New Cascade Selection

• Goals of a new selection:
  • Increase efficiency to low energy events by using ML
  • Take more events at high energy that aren’t fully contained
  • Tailor background cuts at final level to galactic source sensitivity
Analysis Level Sample

- 10 years of cascade-like events
  - Machine learning selection and reconstruction
  - 60,000 events
  - 30x more events than previous cascade selection
- Improved angular resolution
- **3-4x Sensitivity**

IceCube Collaboration*†, Science 380, 1338-1343 (2023). DOI: 10.1126/science.adc9818
Models of Galactic Emission

• (3) diffuse models as spatial templates
  • Point Source → Template
    • (1) Fermi $\pi^0$
    • (2) KRA$\gamma$
    • Fixed spectrum
    • Fit for flux normalization
• (3) stacking source searches
  • Supernova Remnants
  • Pulsar Wind Nebulae
  • Unidentified Gamma-Ray Sources

Results

- Identified High-Energy neutrinos from the Milky Way galaxy for the first time
  - Global significance of 4.5σ
  - 3σ significance from stacking catalogs
Multi-Wavelength Milky Way

- Galactic Coordinates
- +/- 10 deg
Multi-Wavelength Milky Way Messenger

- Galactic Coordinates
- +/- 10 deg
The High Energy Neutrino Sky

The image shows a probability density map of neutrino fluxes with contours indicating the 68% and 95% confidence levels. The map includes points for TXS 0506+056 and NGC 1068, with a p-value of 0.2% (2.9 σ) for TXS 0506+056 and 0.001% (4.2 σ) for NGC 1068. The figure also includes a time-dependent analysis result for the IC86b data period (2012-2015), showing changes in the test statistic (TS) as a function of the spectral index parameter and the fluence at 100 TeV. The analysis is performed at the coordinates of TXS 0506+056, and the contours are shown to indicate statistical uncertainty. Systematic uncertainties are not included.

DOI: 10.1126/science.adc9818
DOI: 10.1126/science.aat2890
The High Energy Neutrino Sky

The plot shows the energy spectrum of neutrinos from various sources. The sources include:

- **isotropic γ-ray background** (Fermi)
- **high-energy neutrinos** (IceCube)
- **ultra-high energy cosmic rays** (Auger)

The P-value for the isotropic γ-ray background (Fermi) is 0.2%. The plot includes data from different experiments like IceCube and ESTES. The plot also shows the energy spectrum in logarithmic scale (\(E^2 \phi\) vs. energy \(E\)).

DOI: 10.1126/science.adc9818

DOI: 10.1126/science.aat2890
Upgrade plans

- Two-tier effort
  - IceCube Upgrade - funded
    - Focus on improved calibration and low energy neutrino physics
  - Test new technologies
  - Deployment now 2025/26
- IceCube Gen2
  - Focused on larger samples of astrophysical neutrinos over a wide energy range

Ice is stable: Able to reprocess decade+ of neutrinos with improved analyses and systematics
New instrumentation

- Several new optical sensors planned for IceCube Upgrade
  - pDOM - refurbished DOMs
  - mDOM - 24 x 3” PMTs
  - DEgg - 2 x 8” PMTs
- New electronic designs for future detectors
- New Calibration devices
  - Built-in Flashers
  - Dedicated light sources
IceCube Gen

- Looking forward, to get larger and better samples of astrophysical neutrinos, a larger detector is needed
- Envision a wide-band neutrino observatory
  - 8-10 x larger optical Cherenkov detector
  - Neutrino astronomy and multi-messenger astrophysics
- Askaryan radio detector array
- Probe neutrinos beyond EeV energies
- Surface particle detector
  - Detailed cosmic ray spectrum and composition measurements and veto capabilities

Figure 17: Left: Discovery potential of IceCube and IceCube-Gen2 for neutrino flares similar to the one observed for TXS0506+056 in 2014/15 which lasted 158 days. Shown is the projected significance of the observation as a function of the flare duration. The flux and spectral index of the assumed flare are the ones observed for TXS0506+056 (see Figure 16) and assumed constant within the flare duration, i.e., the neutrino fluence increases with flare duration. Green dotted lines mark the $5 \sigma$ discovery threshold, as well as the lower threshold for sending alerts to partner telescopes for follow-up observations.

Right: Significance of the observations of NGC 1068 as a function of observation time for IceCube and IceCube-Gen2, assuming the best-fit neutrino flux derived in [27]. IceCube-Gen2 will allow to firmly discover the brightest AGNs on the neutrino sky. Figure 17 (right side) shows the expected significance as a function of observation time for NGC 1068. A detection at $10 \sigma$ significance is expected after 10 years, allowing a precise measurement of the spectral shape of the neutrino emission that is key to understanding the acceleration processes in the source. Figure 18 shows the differential sensitivity of IceCube-Gen2 in relation to the spectrum of NGC 1068 inferred from the IceCube data, a model of the neutrino emission, and observations of the source in gamma rays, underlining the strong gain in sensitivity with IceCube-Gen2 even for soft spectrum sources. In addition to the direct observations, precise spectrum and flavor ratio measurements (see Section 2.2.6) of the diffuse flux will support the study of the acceleration processes and environmental conditions in AGN cores and/or jets.

2.2.2 Cosmic-ray production in tidal disruption events

Another proposed transient source of high-energy CR and neutrinos is the tidal disruption of stars by supermassive black holes [171–174]. Such TDEs occur when a star is disintegrated by strong gravitational forces as it spirals towards the black hole. TDEs have been detected across a range of wavelengths, and, in some cases, have been observed to launch relativistic particle jets.

Observations of the first coincidences between TDE and high-energy neutrinos open a great perspective for IceCube-Gen2. Figure 19 shows the expected rate of associations between neutrinos and TDEs for IceCube-Gen2, based on current IceCube observations. In combination with the much deeper survey depth that next-generation optical survey telescopes will provide one can expect $O(10)$ coincidences per year. The
Future of IceCube

- Gen2-Radio
- Gen2-Optical
- IceCube
- IceCube Upgrade

Energy bins:
- EeV
- PeV
- TeV
- GeV
Summary

• Over more than 10 years of operation, IceCube has developed strong evidence for an astrophysical flux of neutrinos
  
  • First evidence for point sources (TXS 0506+056, NGC 1068,… ) are emerging, pointing to AGN as source class
  
  • Galactic plane revealed in neutrinos - more detailed studies underway
  
  • IceCube continues a strong multi-messenger effort
    
    • Realtime alerts: High energy tracks and cascade to community
      
      • Have delivered some interesting and tantalizing correlations.
    
    • TOO neutrino searches following interesting alerts in other messengers.

• Coming next: IceCube Upgrade and the path toward IceCube Gen2

The future looks bright for Neutrino Astronomy!
Thanks!
Weather for South Pole Station
Today is Saturday, July 4th 12:32am

Temperature
-78.3 °C -108.9 °F

Windchill
-108.8 °C -163.9 °F

Wind
16.6 kts Grid 143

Barometer
671.3 mb (3,340 m/10,958 ft)