New results from the IceCube Neutrino Observatory

Thursday, November 3, 1:00 PM CDT

Master of Ceremony
Albrecht Karle, University of Wisconsin–Madison

Opening Remarks
Denise Caldwell, National Science Foundation
Steve Ackerman, University of Wisconsin–Madison

Presentations
Justin Vandenbroucke, University of Wisconsin–Madison
Elisa Resconi, Technical University of Munich
Hans Niederhausen, Michigan State University and Technical University of Munich
Ignacio Taboada, Georgia Institute of Technology

Question & Answer Session
Evidence for neutrino emission from the nearby active galaxy NGC 1068

IceCube Collaboration*†
Galaxies: much more than starlight

Emission powered by a central black hole (millions to billions of solar masses) can outshine all the stars

How is that possible?
What can neutrinos tell us?

New information, complementary to all forms of light

Point back to their source

Unveil hidden phenomena

Neutrino image of the Sun

Supernova

Credit: SuperK

Credit: NASA Hubble
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison

Digital Optical Module (DOM)
5,160 DOMs deployed in the ice

86 strings of DOMs, set 125 meters apart

60 DOMs on each string

DOMs are 17 meters apart

Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility

Antarctic bedrock

Credit: IceCube/NSF
IceCube Neutrino Observatory
at NSF’s Amundsen-Scott South Pole Station

Seven seasons of construction at South Pole (2003 to 2011)

Dedicated team and collaboration-wide effort critical to success
IceCube Collaboration:
more than 350 scientists from 58 institutions in 14 countries
What have we learned from IceCube?
The Universe glows brightly in high-energy neutrinos.

Neutrino energy density matches gamma rays and cosmic rays. Neutrinos in all directions (isotropic). What is producing them?
Prior IceCube results:  
**time-integrated neutrino source search**

Per year:
- 90 billion atmospheric muons
- 80 thousand atmospheric neutrinos

\[-\log_{10}(p_{\text{local}})\]
Prior IceCube results:
searching for statistical evidence of clustering

Per year:
90 billion atmospheric muons
80 thousand atmospheric neutrinos

$-\log_{10}(p_{\text{local}})$
Most significant position on sky: consistent with NGC 1068 (Messier 77), a Seyfert II galaxy (2.9 $\sigma$)

Per year:
- 90 billion atmospheric muons
- 80 thousand atmospheric neutrinos

NGC 1068 (Messier 77)
IceCube enhanced sensitivity to neutrino sources

Elisa Resconi, Technical University of Munich

Credit: Martin Wolf, IceCube/NSF
The new IceCube neutrino map

Equatorial Coordinate System

Grid 0.2° x 0.2°
Identified ‘hot’ spot

At the brightest location in full sky scan:
Mean astrophysical neutrino events = 81
Mean spectral index = 3.2
Is the ‘hot’ spot in coincidence with an object?

110 candidate sources
Hottest spot coincides with NGC 1068
Hottest spot coincides with NGC 1068

At the NGC 1068 location:
Astrophysical neutrino events = $79^{+22}_{-20}$
Spectral index = $3.2 \pm 0.2$
Evidence for neutrino emission from NGC 1068

At the NGC 1068 location:
Astrophysical neutrino events = $79^{+22}_{-20}$
Spectral index = $3.2 \pm 0.2$

Global significance $4.2\sigma$
NGC 1068: a non-jetted AGN with an obscured black hole

Credit: NASA/JPL-Caltech
NGC 1068 and the obscured core
NGC 1068 and the obscured core

Supermassive black hole

Ultrahot gas

Accretion disk

Credit: NASA/JPL-Caltech
We conclude that active galactic nuclei are powerful sources for accelerating particles to cosmic ray energies. The bulk of metagalactic cosmic rays is likely to originate in particular, in the Virgo supercluster. NGC 4151 and NGC 1068 are likely to be "local" metagalactic cosmic rays, including the ultra-high energy (E \geq 10^{19} \text{ eV}) aspect. The density of photons in the immediate vicinity may be too high (Blumenthal, 1970) to permit the acceleration of protons beyond \sim 10^{14} \text{ eV}, (except by beaming processes). The highest energy protons hence are accelerated somewhat farther out, or else by beaming (Lovelace, 1976). Gamma rays from the ergosphere of a black hole are degraded at energies above \sim 1 \text{ MeV}, and from a spiner, above \sim 1 \text{ GeV}. Neutrinos are not thus affected and would provide information on very high energy particles in active galactic nuclei.
NGC 1068: a cosmic obscured accelerator

(1) Y. Inoue et al., ApJL’20
(2) K. Murase et al., PRL’20
Improving searches for astrophysical neutrino sources

Hans Niederhausen, Michigan State University & Technical University of Munich

Credit: Martin Wolf, IceCube/NSF
neutrino events are characterized by reconstructed quantities **direction, energy, angular uncertainty**
An improved track dataset

data: May 2011 to May 2020

~99% detector uptime

~670,000 neutrinos selected (99.7% purity)
    out of ~1 trillion events recorded

multiple improvements
    detector calibration, data filtering and processing
    applied to entire dataset (all ~1 trillion events)

=> IceCube Pass 2 data
vast majority of the neutrinos are background in searches for extragalactic neutrino sources
need good reconstruction of directions and energies and model of how they differ between signal and background

We improved in both areas!
Analysis improvement - “Pointing with neutrinos”

directional distributions

better modeling of directional distributions of individual neutrinos (at TeV energies)
ionization dominates energy loss previously

machine learning provides more accurate and more precise energy estimates especially at TeV-energies

energy reconstruction

Analysis improvement - “Energy measurement”
on average:
new methods provide better source localization
new methods give higher significance
NGC 1068 is consistent with location of strongest clustering of neutrinos in the sky
using 500x10^6 computer experiments assuming no signal and accounting for catalog size (110 candidate sources) yields p~1.1x10^{-5}
Distribution of **neutrino events** around NGC 1068 matches our model predictions

Measured astrophysical neutrino events = 79
Improvements made new results possible

1) Improvements in data quality (updated calibrations, uniform processing)  “Pass2”
2) Improved statistical methods and reconstructions

![Diagram showing improvements in data quality and statistical methods](image)
What’s next after the neutrino observation of NGC 1068

Ignacio Taboada, Georgia Institute of Technology
Implications of the NGC 1068 neutrino observation

Active galaxies may contribute to a significant fraction of extragalactic neutrino flux.

NGC 1068 is opaque to high-energy gamma-rays.

NGC 1068 and TXS 0506+056 are different.

[17] IceCube. PRL. 125, 121104 (2020)
IceCube is getting better – and we are not finished

More to IceCube than “adding more years of data”

New instrumentation in 2025/2026 will improve angular resolution

The future IceCube-Gen2 will have even better sensitivity than IceCube

Credit: NASA, ESA & A. van der Hoeven

November 3, 2022

Ignacio Taboada | IceCube Collaboration
Many contributions by the entire collaboration

Last Digital Optical Module deployed December 2010
Credit: Gary Hill IceCube/NSF

Moreno Baricevic and Wenceslas Marie-Sainte
IceCube's 2022-23 winterovers
Credit: Ralf Auer Icecube/NSF

2019 Fall IceCube Collaboration Meeting
Chiba, Japan
Credit: IceCube Collaboration

... improved calibrations, data reprocessing, operations, and many critical activities
Evidence for neutrino emission from the nearby active galaxy NGC 1068