Results from IceCube

Dawn Williams, University of Alabama
36th International Cosmic Ray Conference
July 29, 2019
Madison, WI
THE ICECUBE COLLABORATION

FUNDING AGENCIES

- Fonds de la Recherche Scientifique (FRS-FNRS)
- Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
- Federal Ministry of Education and Research (BMBF)
- German Research Foundation (DFG)
- Deutsches Elektronen-Synchrotron (DESY)
- Japan Society for the Promotion of Science (JSPS)
- Krist and Alice Wallenberg Foundation
- Swedish Polar Research Secretariat
- The Swedish Research Council
- University of Wisconsin Alumni Research Foundation (UWARF)
- US National Science Foundation (NSF)
IceCube Science

2 Highlight Talks (D. Soldin and D. Williams)
36 parallel talks
43 posters

Bartos and Kowalski 2017
The IceCube Neutrino Observatory

IceCube Lab

IceTop
- 61 stations, each with
  2 IceTop Cherenkov detector tanks
  2 optical sensors per tank
  324 optical sensors

IceCube Array
- 86 strings including 8 DeepCore strings
- 60 optical sensors on each string
- 5160 optical sensors
- December, 2010: Project completed, 86 strings

DeepCore
- 8 strings-spacing optimized for lower energies
- 480 optical sensors

Effiel Tower
- 324 m

Bedrock

Penetrator
HV Divider
DOM Mainboard
Delay Board
LED Flasher Board
Muon metal grid

PMT
RTV gel
Glass Pressure Housing
Neutrino Signatures in IceCube

Cascade

- $\nu_e$ CC
- Most $\nu_\tau$ CC
- All flavor NC

Double cascade from high energy $\nu_\tau$

10° angular resolution (> 100 TeV)
15% deposited energy resolution

Track

- $\nu_\mu$ CC

0.3° angular resolution (> 100 TeV)
Factor of 2 energy resolution
Atmospheric Muons and Neutrinos

Muons (downgoing): 3 kHz at trigger level
Atmospheric Neutrinos: few hundred per day
Astrophysical Neutrinos: 10-100 per year above background

Model: Enberg, Reno, Sarcevic
Astrophysical Neutrinos

High energy starting events (HESE) tracks and cascades

Through-going tracks
Astrophysical Neutrinos

Through-going 9.5 years

HESE 7.5 years

Updated calibration, updated background modeling and systematics

Updated calibration, updated background modeling and systematics, new double cascade identifier

J. Stettner NU4a

A. Schneider NU4b
Single power law astrophysical neutrino spectrum

IceCube Preliminary

- HESS (7.5y Full-sky)
  - PoS(ICRC2019)1004
- Cascades (4y Full-sky)
  - PoS(ICRC2017)968
- Through-going Muon-Neutrinos
  - (9.5y Northern-hemisphere)
  - PoS(ICRC2019)1017

J. Stettner NU4a
A. Schneider NU4b
A tau neutrino candidate in the 7.5 year HESE sample: “Double Double”

![Diagram of IceCube Preliminary](image)

J. Stachurska NU8f

**Negative energy asymmetry**

HESE with ternary topology ID
- Best fit: 0.29 : 0.50 : 0.21
- Sensitivity, E^{-2.9} spectrum
- 1 : 1 : 1 flavor composition

**Work in Progress**
Double pulse waveform search

“Double Double” is the only event that passes both the double cascade search and double pulse waveform criteria from two independent searches.

J. Soedingrekso PS1-117
L. Wille NU11c
Search for partially contained cascades

Glashow resonance candidate

L. Lu PS1-115
High energy neutrino physics

Nature 551 (2017) 596-600

Neutrino DIS Cross Section measurement with the 7.5 year HESE sample

Neutrino DIS Cross Section measurement with the 7.5 year HESE sample

Neutrino DIS Cross Section measurement with the 7.5 year HESE sample

Neutrino DIS Cross Section measurement with the 7.5 year HESE sample

Inelasticity

DIS Cross Section

T. Yuan NU2h
Also see S. Robertson PS2-65
All sky combined 10 year search

Using high energy through-going tracks and tracks optimized for point source searches

New source list of 110 Galactic and Extragalactic objects

Hottest spot in Northern Hemisphere coincides with 2.9σ excess at the position of NGC 1068

T. Carver NU5c

NASA, ESA & A. van der Hoeven
All sky combined 10 year search

1. NGC 1068
2. TXS 0506 + 056
3. PKS 1424 + 240
4. GB6 J1542+6129

Source list search is incompatible with background at 3.3σ (2.25σ without TXS 0506)

Preliminary
Joint Southern Sky Search with ANTARES

Up to a factor of 2 improvement in point source sensitivity compared to individual analyses

G. Illuminati (NU5b)
Joint search for Galactic diffuse neutrino emission with IceCube tracks and ANTARES cascades + tracks

Median cascade resolution $< 10^\circ$ above 40 TeV with deep learning

P-value for KRA$\gamma$ with 5 PeV cutoff is $2\sigma$

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<table>
<thead>
<tr>
<th>Template</th>
<th>7yr Cascades</th>
<th>Previous Work</th>
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<tbody>
<tr>
<td></td>
<td>p-value</td>
<td>Sensitivity</td>
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<tr>
<td>KRA$\gamma$5</td>
<td>0.021</td>
<td>0.58</td>
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<tr>
<td>KRA$\gamma$50</td>
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<tr>
<td>Fermi-LAT $\pi^0$</td>
<td>0.030</td>
<td>2.3</td>
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</table>
Stacked search for neutrino emission from HAWC 2HWC catalog
Template analysis for neutrino emission from Galactic plane and certain source regions
Most significant result is for J1857+027 (p value 0.02 before trials correction)
Coincident search with UHECR and neutrinos

A. Barbano NU6c

Combined ANTARES, IceCube, PAO and TA search for common origin of high energy neutrinos and cosmic rays

Neutrino cascades and UHECR arrival directions

Three searches:
1. Neutrino/UHECR cross-correlation
2. Search for neutrino clusters in direction of UHECR
3. Search for UHECR clusters in direction of neutrinos

No significant correlations seen
IceCube Realtime Alerts

IceCube sending alerts since April 2016
Updated alerts as of June 2019

Initial GCN Notice followed by GCN Circular with updated reconstruction

C. Tung NU9b

<table>
<thead>
<tr>
<th>Updated alerts</th>
<th>Gold</th>
<th>Bronze</th>
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<tbody>
<tr>
<td>Signalness</td>
<td>&gt; 50%</td>
<td>&gt; 30%</td>
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<tr>
<td>Expected signal/yr</td>
<td>6.6</td>
<td>2.8</td>
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<tr>
<td>Expected bkgd/yr</td>
<td>6.1</td>
<td>14.7</td>
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Gold
IC190619A

Bronze
IC190712A

Online Event Filtering System → IceCube Live South → Gold Alert

South Pole, Antarctica

IceCube Data Center, Madison WI

Followup Reconstructions

AMON & GCN

Median alert latency: 33 seconds
A high energy neutrino in coincidence with a flaring blazar

Correlation of IC170922A with TXS 0506+056 preferred to chance at 3σ level

Excess of neutrinos observed between September 2014 and March 2015

Background only hypothesis rejected at 3.5σ

Blazar redshift 0.3365 +/- 0.0010 (Paiano et al.)
AMON: IceCube+HAWC Sub-threshold Coincident Analysis

Goal: enhance sensitivity to transient events with search for coincidences between sub-threshold events in AMON and HAWC

1 event with FAR < 1/year found in 1.85 years

Eventually run this search in real time
IceCube Follow-up of External Triggers

IceCube observes the whole sky with > 99% uptime

Follow up on internal and external triggers

67 analyses performed as of July 10, 2019

No statistically significant results
IceCube Follow-up of Gravitational Wave Events

Two analyses in LVC O3 run:
1. A search for point-like neutrino sources coincident with the reported LVC alert skymap.
2. A Bayesian search considering the combined GW + neutrino joint significance with astrophysical priors such as distance.

A. Keivani NU6a
R. Hussain NU9d
Also see G. de Wasseige (NU6e) for low energy neutrino search from compact binary mergers
Search for Neutrinos from S190728q

See A. Keivani, NU6a (Saturday) for Bayesian search, R. Hussain, NU9d (Tuesday) for generic transient search

<table>
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<tr>
<th>dt (ns)</th>
<th>RA (deg)</th>
<th>Dec (deg)</th>
<th>Ang. Uncert. (deg)</th>
<th>P-value (Bayesian)</th>
<th>P-value (generic transient)</th>
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<tr>
<td>-360</td>
<td>312.87</td>
<td>5.85</td>
<td>4.81</td>
<td>0.010 (2.33 σ)</td>
<td>0.016 (2.21 σ)</td>
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Searches for Dark Matter

Combined limits from ANTARES and IceCube
N. Iovine DM2f

Limits from HESE 7.5
Also set limits on DM decay and DM-neutrino scattering
C. Arguelles PS1-95
Planning the Future of IceCube

- The origin of astrophysical neutrinos is largely unresolved.
- IceCube-Gen2 is a proposed multi-cubic-kilometer neutrino detector designed to be sensitive to 5x fainter sources.
- Wide-band neutrino observatory with optical and radio detectors, surface array.
The IceCube Upgrade

Approved by NSF, planned to deploy in 2022-23
7 new strings near the center of IceCube

A. Ishihara NU7a

New multi-PMT sensors

New calibration devices

L. Classen PS3-98
A. Ishihara PS3-123
D. Van Eijk PS3-130
The IceCube Upgrade will have world-leading sensitivity to atmospheric tau neutrino appearance.
Calibration in the IceCube Upgrade

C. Fruck PS3-114
A. Ishihara PS3-117
C. Tonnis PS3-118
J. Auffenberg PS3-131

Camera system

Precision Optical Calibration Module (POCAM)

Median angular error vs Deposited energy [TeV]

- Expected (stat. only)
- Observed (sys. + stat.)
Summary

• IceCube has observed astrophysical neutrinos in multiple channels
• The first tau neutrino candidate has been detected
• IceCube plays a major role in multi-messenger astronomy and has seen the first indications of astrophysical neutrino sources
• The IceCube Upgrade has been approved, inaugurating the next phase of discovery in IceCube
Layer of dust in IceCube