IceCube: Revealing a Neutrino Picture of the Cosmos

- Introduction
- Detector Description
- Neutrino Window to the Cosmos
- Future Plans
- Conclusions

icecube.wisc.edu
Miami Conference, December 14-20, 2016
What is IceCube?

- A gigaton neutrino detector funded through the National Science Foundation and EU funding agencies.
- We are in our 13th project year and data taking with the full detector (86 strings) began in May 2011.
- IceCube is the largest Neutrino Telescope in operation.
- IceCube has opened up a neutrino window to the cosmos and has ushered in the dawn of Neutrino Astronomy. Science Cover Article November 22nd 2013, and PRL Cover, July 12, 2013.
- [http://icecube.wisc.edu/](http://icecube.wisc.edu/)

Cosmic Rays: A century old puzzle

Victor Hess
Nobel Prize 1936

Balloon flights 1911-1913

- Power law over many decades
- Origin Unknown

South Pole

Amundsen-Scott South Pole Station

Ali R. Fazeli, Miami Conference, December 14-19, 2018
The IceCube Detector

**IceTop**
Air shower detector
threshold ~ 300 TeV

**InIce**
86 Strings,
60 Optical Modules per String

**DeepCore**

- **Completion:** December 2010
- **86 strings**
- **2010:** 79 Strings
- **2009:** 59 Strings
- **2008:** 40 Strings
Observing the Universe

http://mwmw.gsfc.nasa.gov/mmw_allsky.html

Observing the Universe

Nuclei are easy to detect with balloon and satellites. Lack directional information and limited to sub-GeV energies.

A.R. Fazely, et al.,

Neutrinos as Cosmic Messengers

\[ p + \gamma (CMB) \rightarrow \Delta^+ \rightarrow n + \pi^+ \rightarrow v_\mu + \mu^+ \]
\[ \Downarrow p + e^- + v_e \downarrow v_\mu + v_e + e^+ \]

- **Protons:** deflected by magnetic fields.
- **Photons:** easily absorbed by CMB backgrounds.
- **Neutrinos:** not deflected by magnetic fields. Low interaction cross-section.
Slow History of Neutrinos!

1930 Pauli proposes Neutrinos

1956, Reines and Cowan discovery of neutrinos

1967, Davis Solar Neutrinos and their deficits

1987 Supernova IMB, Kamioka

1998 Neutrino Oscillations, Super-K

2013 Dawn of Neutrino Astronomy

Neutrino interactions

\[
\begin{align*}
\nu_e(\bar{\nu}_e) + ^{16}\text{O} &\to e (e^+) + X \quad (\text{CC}) \\
\nu_\mu(\bar{\nu}_\mu) + ^{16}\text{O} &\to \mu (\mu^+) + X \quad (\text{CC}) \\
\nu_\tau(\bar{\nu}_\tau) + ^{16}\text{O} &\to \tau (\tau^+) + X \quad (\text{CC}) \\
\nu_e(\bar{\nu}_e) + ^{16}\text{O} &\to \nu_e(\bar{\nu}_e) + X \quad (\text{NC}) \\
\nu_\mu(\bar{\nu}_\mu) + ^{16}\text{O} &\to \nu_\mu(\bar{\nu}_\mu) + X \quad (\text{NC}) \\
\nu_\tau(\bar{\nu}_\tau) + ^{16}\text{O} &\to \nu_\tau(\bar{\nu}_\tau) + X \quad (\text{NC}) \\
\nu(\bar{\nu})e &\to \nu(\bar{\nu})e (CC, NC) \\
\bar{\nu}_e + p &\to e^+ + n, \text{ Supernova}(CC)
\end{align*}
\]
Digital Optical Module

Sensing Neutrino Light

IceCube “Digital Optical Module” (DOM)

- Measure arrival time of every photon
- 2x 300MHz waveform digitizers
- 1x 40 MHz FADC digitizer
- Can trigger in coincidence w/ neighbor DOM
- Transmits data to surface on request
- Data sent over 3.3 km twisted pair copper cable
- Knows the time to within 3 nanoseconds to all other DOMs in the ice

Clock stability: $10^{-10} \approx 0.1 \text{ nsec / sec}$
Synchronized periodically to precision of $O(2 \text{ nsec})$

IceCube Construction

Event Topologies

\( \nu_e \) data (Big Bird, 2.2 PeV)
Energy resolution \( \approx 15\% \) E(vis)
Angular resolution \( \approx 10^\circ \)

\( \nu_\mu \) data (466 TeV)
Energy resolution \( \approx 2 \times E(\text{vis}) \)
Angular resolution \( < 1^\circ \)

\( \nu_\tau \) simulation (16 PeV)

How does IceCube work?

When a neutrino interacts with the Antarctic ice, it creates other particles. In this event graphic, a muon was created that traveled through the detector almost at the speed of light. The pattern and the amount of light recorded by the IceCube sensors indicate the particle’s direction and energy.

Date: November 12, 2010  Duration: 3,800 nanoseconds  Energy: 71.4 TeV
Declination: -0.4°  Right Ascension: 110°  Nickname: Dr. Strangepork

Possible ET Neutrino Sources

- Solar Neutrinos
- Supernova 1987A
- Active Galactic Nuclei
- Gamma Ray Bursts
- Dark Matter?
- Cosmogenic Neutrinos

The majority of triggers in IceCube are from atmospheric muons.

We record over $6 \times 10^9$ muons and 74,000 atmospheric muon neutrinos per year.
<table>
<thead>
<tr>
<th>Configuration</th>
<th>Date</th>
<th>Livetime</th>
<th>$\mu$-rate (Hz)</th>
<th>$\nu$-rate/day</th>
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</thead>
<tbody>
<tr>
<td>AMANDA(19)</td>
<td>2000-06</td>
<td>3.8 years</td>
<td>100</td>
<td>5</td>
</tr>
<tr>
<td>IC9</td>
<td>2006</td>
<td>137 days</td>
<td>80</td>
<td>1.7</td>
</tr>
<tr>
<td>IC22</td>
<td>2007</td>
<td>275 days</td>
<td>600</td>
<td>28</td>
</tr>
<tr>
<td>IC40</td>
<td>2008-09</td>
<td>376 days</td>
<td>1100</td>
<td>38</td>
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<tr>
<td>IC59</td>
<td>2009-10</td>
<td>348 days</td>
<td>1900</td>
<td>125</td>
</tr>
<tr>
<td>IC79-DC6</td>
<td>2010-11</td>
<td>1.0 year</td>
<td>2250</td>
<td>170</td>
</tr>
<tr>
<td>IC86-DC8</td>
<td>5/2011-present</td>
<td></td>
<td>2700</td>
<td>190</td>
</tr>
</tbody>
</table>
Atmospheric Neutrinos

• Main Background to Astrophysical Search
• Created by high energy cosmic rays colliding with O and N in the Earth’s atmosphere
• Conventional (Pions & Kaons) vs. Prompt (Charmed Mesons)
• Conventional ~ E^{-3.7} Spectrum
• Prompt ~ E^{-2.7} Spectrum

\[ p + O N \rightarrow \pi^+, K^+, D^+, \text{etc.} \]
\[ \pi^+ \rightarrow \nu_\mu + \mu^+ \]
\[ \bar{\nu}_\mu + e^+ + \nu_e \]
Observation of Highest Energy Neutrinos Dubbed “Bert, Ernie & Big Bird”.
(PRL 111 021103 2013)

\[ \nu_\text{eCC on nuclei or electrons or } \nu_\text{x NC on nuclei and electrons} \]
Angular resolution on cascade events at these energies \( \sim 10^\circ \)

Aug., 9\textsuperscript{th}, 2011
Run 118545
-Event 63733662
NPE: \( 7.0 \times 10^4 \)
NDOM: 354
1.04 ± 0.16 PeV

Jan, 3\textsuperscript{rd}, 2012
Run 119316
-Event 36556705
NPE: \( 9.6 \times 10^4 \)
NDOM: 312
1.14 ± 0.17 PeV

Dec, 4\textsuperscript{th}, 2012
2.2 ± PeV

Observation of Highest Energy Neutrinos
2.6 ± 0.3 PeV, observed June 11, 2014
(ICRC 2015, July 30 to August 6, 2015, The Hague, The Netherlands.)

### Backgrounds for “Bert & Ernie”

<table>
<thead>
<tr>
<th>Background Source</th>
<th>Contribution Level (~616 days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric Muons</td>
<td>$0.038 \pm 0.004$</td>
</tr>
<tr>
<td>Neutrinos from pion and Kaon Decay</td>
<td>$0.012 \pm 0.001$</td>
</tr>
<tr>
<td>Prompt Neutrinos from Charm Production *</td>
<td>$0.033 \pm 0.001$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$0.082 \pm 0.001$</strong></td>
</tr>
</tbody>
</table>


**Significance = 2.8σ**

NPE Distributions

(PRL 111 021103 2013)

Results


Physics Cuts

1) PMT charge, \( Q > 6000 \) p.e., contained events within detector fiducial volume
2) Accept both tracks and cascades
3) Veto background atmospheric \( \mu \) and neutrinos
4) \( 60 \) TeV \(<\) \( E_{\text{dep}} \)< 3 PeV

54 events, (15 tracked, 39 cascades) observed.

Backgrounds are disfavored at a Significance of $7\sigma$

ICRC 2015, 4 years of data
arxiv.org/pdf/1510.05223v2

$$E^2 \Phi(E) = 0.84 \pm 0.3 \times 10^{-8} \text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$$

Results, Declination

ICRC 2015, 4 years of data

arxiv.org/pdf/1510.05223v2

Results, PMT Charge

ICRC 2015, 4 years of data

arxiv.org/pdf/1510.05223v2

Declination vs. deposited energy

ICRC 2015, 4 years of data
arxiv.org/pdf/1510.05223v2

A few observations.

- Signal contains 41 cascades and 13 tracks
- Atmospheric neutrinos: track/cascade = 2
- Most events originate from southern sky because most HE neutrinos from northern sky are absorbed by the Earth
- Excess from the southern sky is not due to atmospheric $\nu_\mu$ because they are reduced in the south by $\mu$ rejection
The distribution of reconstructed muon energy proxy for events sample, compared to the expected distributions for an $E^{-2}$ flux. Significance $= 3.7\sigma$

$330 \text{ TeV} < E < 1.4 \text{ PeV}$

PRL 115, 081102 (2015)

$$\Phi(E_\nu) = 9.9^{+3.9}_{-3.4} \times 10^{-19} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1} \left(\frac{E_\nu}{100 \text{ TeV}}\right)^{-2}$$

Likelihood Search for a Point Source
- Test Statistic (TS) Calculation -

Maximize the likelihood $L$ at every point in the sky $x$

\[
L(x) = \prod_{i}^{n_{tot}} \left[ \frac{n_{s}}{n_{tot}} \times S_{i}(x) + \frac{n_{tot} - n_{s}}{n_{tot}} \times B_{i}(x) \right]
\]

Total # of events = 28
# of events from source varied to maximize $L$

Reconstruction map value at position $x$ from event $i$
Uniform value for each event at every position

* Events' energies not used in the likelihood

TS is calculated for every point in the sky $x$

\[
TS(x) = 2 \times \log \left( \frac{L(x)}{L_{0}(x)} \right)
\]

where $L_{0} = L(x, n_{s} = 0)$
Astrophysical Muon Neutrinos

Point Source Analysis

Test null hypothesis vs. most likely
L0: null hypothesis
L: maximized likelihood

x: tracked events
+: cascade events

No significant clustering
Cascade events p-value = 18%

Point Source Analysis

IC40 data 2008-2012 (508 GRBs in northern sky). No coincidence found. Note, analysis has very low background because both direction and timing coincidence are applied.

APJ, Letter 805 1, 2015
4 years of data, we found 1 neutrino event correlated with A GRB with $p = 0.46$

6 years of muon data. 
\[ p \text{ (North Sky)} = 0.29 \]
\[ P \text{ (Southern Sky)} = 0.17 \]

Overwhelmingly dominated by atmospheric neutrinos.
Search for neutrinos from Fermi-LAT blazars

FSRQ: flat-spectrum radio quasars; BL-LAC: BL-Lacertae

Search for neutrinos from Fermi-LAT blazars

IceCube Collaboration: arXiv:1611.03874

Search for neutrinos in coincidence with LIGO

GW150914

3 Muon neutrinos
($\Delta t = \pm 500 \text{ s}$)
With energies 175, 1.22, 0.33 TeV.
No coincidence was found. With LIGO.

$E_\nu \text{ (total)} = 5.4 \times 10^{51} - 1.3 \times 10^{54} \text{ erg}$

$E \text{ (gravity)} \approx 5.4 \times 10^{54} \text{ erg}$

Nine from ten integral tests show over-fluctuations, but none of them are significant. The largest over fluctuation, a 6% p-value, is observed for all 862 2LAC blazars combined using the model independent equal-weighting scheme. The differential test for all 2LAC blazars using equal source weighting (gamma and neutrino) reveals that the excess appears in the 5-10 TeV region with a local p-value of 2.6 σ. No correction for testing multiple hypotheses is applied, since even without a trial correction this excess cannot be considered significant.
Larger IceCubes, up to more than an order of magnitude in mass/volume. Much higher statistics in the PeV region, much higher energy neutrino acceptance, a deeper view of the cosmos and source ID of high energy neutrino production.

PINGU, acronym for Precision IceCube Next Generation Upgrade, is a proposed dense array and has physics goals such as precision measurements of neutrino oscillations (mass hierarchy, ...) and other physics such as test of low mass dark matter models. arXiv:1412.5106
Future Plans, IceCube-Gen2

A simulated 60-PeV horizontal muon

Completion date 2032!

Multi-component observatory:
- Surface air shower detector
- Gen2 High-Energy Array
- Sub-surface radio detector
- PINGU

Conclusions and Outlook

- IceCube has observed High Energy Astrophysical Neutrinos and has achieved its main goal of opening the era of neutrino astronomy.

- Further question: what is the origin of the high energy neutrinos?

- Real-time coincidence measurements are now possible with other detectors, such as optical, X-ray, gamma-ray and gravitational waves.

- Future plans: IceCube Extensions for Higher Energies and PINGU dense array for Neutrino Mass Hierarchy ... ...