IceCube: Status and Results

- Introduction
- Detector Description and Status
- Physics with IceCube, Some Recent Results
- Conclusions
- Acknowledgement

Ali R. Fazely, Southern University for the IceCube Collaboration
icecube.wisc.edu

Miami Conference, 12/14-19/2010
Latest News!

Completion of the IceCube Detector

- The IceCube Detector will be fully installed by Sunday 12/19/2010 and the press release from NSF will follow on Monday.

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What is IceCube?

- A gigaton neutrino detector funded through the National Science Foundation and EU funding agencies
- We are in our 7th project year and will complete construction in 2011
- We are building the largest Neutrino Telescope at the geographic South Pole
- The project is on schedule and it has just begun to produce exciting physics.
- http://icecube.wisc.edu/

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IceCube Collaboration

36 collaborating institutions

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Cosmic Rays: A century old puzzle

Victor Hess
Nobel Prize 1936

Balloon flights
1911-1913

- Power law over many decades
- Origin Uncertain

Extra Galactic?
Galactic?

Cosmic ray spectrum

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IceTop
Air shower detector
threshold ~ 300 TeV

InIce
80-86 Strings,
60 Optical
Modules per
String

Deep Core

✓ Completion: January 2011
✓ 2008: 40 Strings (This Analysis)
✓ 2009: 59 Strings
✓ 2010: 79 Strings

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Nuclei are easy to detect with balloon and satellites. Lack directional information and limited to sub-PeV energies.
Observing the Universe

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

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Neutrinos as Cosmic Messengers

- Protons: deflected by magnetic fields.
- Photons: easily absorbed by CMB backgrounds.
- Neutrinos: not deflected by magnetic fields. Low interaction cross-section.

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Cerenkov Radiation - the electromagnetic "sonic boom"
Neutrino interactions

\[
\begin{align*}
\nu_e(\bar{\nu}_e) + ^{16}\text{O} & \rightarrow \nu_e(\bar{\nu}_e) + X \\
\nu_\mu(\bar{\nu}_\mu) + ^{16}\text{O} & \rightarrow \nu_\mu(\bar{\nu}_\mu) + X \\
\nu_\tau(\bar{\nu}_\tau) + ^{16}\text{O} & \rightarrow \nu_\tau(\bar{\nu}_\tau) + X
\end{align*}
\]
Digital Optical Module

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Sensing Neutrino Light

IceCube “Digital Optical Module” (DOM)

Power consumption: 3W

- 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 $O(2 \text{ nsec})$

Hamamatsu R7081, 10 inch PMT
33 cm Benthosphere

Main board
Flasher Board

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IceCube Construction
Event Topologies

- $\nu_\mu$ produce $\mu$ tracks
  - Angular Res $\sim 0.7^0$
  - $E_{\text{res}} \log(E) \sim 0.3$

- $\nu_e$ CC, $\nu_x$ NC create showers
  - $\sim$ point sources, ‘cascades’
  - $E_{\text{res}} \log(E)=0.1-0.2$

- $\nu_\tau$ double bang events, others

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Real and Possible ET Neutrino Sources

The sun

Supernova 1987A

Active Galactic Nuclei

Gamma Ray Bursts

Dark Matter?

GZK ν

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Plethora of Physics

- Neutrinos from the sun and SN1987A have been observed
- IceCube can search for SN event with high sensitivity.
- We want to search for higher energy neutrinos and open up a new window to the universe.
- Searches also can be done for neutrino oscillations, wimps, magnetic monopoles....

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The majority of triggers in IceCube are from atmospheric muons.

We record over $6 \times 10^9$ muons and 74,000 atmospheric muon neutrinos.
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 $\sim E^{-3.7}$ Spectrum
• Prompt $\sim E^{-2.7}$ Spectrum

\[ p + ^{16}O \rightarrow \pi^+ , K^+, D^+, \text{etc.} \]
\[ \pi^+ \rightarrow \nu_\mu + \mu^+ \]
\[ \bar{\nu}_\mu + e^+ + \nu_e \]

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Flux Models and Limits

Upper Limit on Astrophysical $E^{-2} \nu_\mu$

$E^2 < 8.9 \times 10^{-9} \text{ GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$

$4.54 < \log_{10}(E / \text{GeV}) < 6.84$

This Result
This Result

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Results

- Diffuse Astrophysical Muon Neutrino Upper Limit is $E^2 < 8.9 \times 10^{-9} \text{ GeV cm}^{-2} \text{s}^{-1} \text{ sr}^{-1}$
  - Optimistic Astrophysical models ruled out: No surprises and IceCube is in it for the long haul
  - Atmospheric neutrino spectrum measured at high energies from 332.4 GeV to 83.7 TeV
  - No Evidence for Prompt Atmospheric Flux
  - Prompt Atmospheric Models constrained

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Point Source Search (IC40)

- 40-string (6 months) All sky search
- Livetime: 175.5 days
- 17777 events (6796 up, 10981 down)
- Hot spot at $\alpha = 7h 40m$, $\delta = 15.4^\circ$
- Pre-trial significance of $10^{-4.4}$
- Post-trials p-value after R.A. scrambling = 61% (all sky)
- Improved signal efficiency, acceptance and background rejection.

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Gamma Ray Bursts (22 strings)
A. Kappes et al., ICRC 2009 (Lodz)

- Source stacking: 41 GRBs observed by SWIFT, etc., summed to estimate a total neutrino flux
- Upper limits set for precursor, prompt neutrino flux
- Full detector: $5\sigma$ GRB neutrino observation within 2 years (assuming Waxman-Bahcall flux)

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Gamma Ray Bursts, IC-40 and IC-59
(Preliminary)

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• *Relative intensity* of the cosmic ray event rate: for each declination belt of width $3^\circ$, the plot shows the number of events relative to the average number of events in the belt.

• First Observation of the Anisotropy for the southern sky.


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### Relative Intensity of Cosmic Rays (IC22, IC40 & IC59)


<table>
<thead>
<tr>
<th>Year</th>
<th>Rate (Hz)</th>
<th>LiveTime (Days)</th>
<th>CR Median Energy (TeV)</th>
<th>Median Angular Resolution (degrees)</th>
<th>Number of Events (billion)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007-IC22</td>
<td>240</td>
<td>~226</td>
<td>~19</td>
<td>3</td>
<td>~4</td>
</tr>
<tr>
<td>2008-IC40</td>
<td>780</td>
<td>~324</td>
<td>~19</td>
<td>3</td>
<td>~15</td>
</tr>
<tr>
<td>2009-IC59</td>
<td>1300</td>
<td>~324</td>
<td>~19</td>
<td>3</td>
<td>~35</td>
</tr>
</tbody>
</table>

IC40 & IC59 results are preliminary

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Systematic checks (IC59):

- **A1 (10^{-4})** (sidereal) \( \pm 0.1 \)
- **A1 (10^{-4})** (solar) \( \pm 0.1 \)
- **A1 (10^{-4})** (anti-sidereal) \( \pm 0.11 \)
- **\Phi1 (deg)** (sidereal) \( 55.1 \pm 0.89 \)
- **\Phi1 (deg)** (solar) \( 90.9 \pm 3.6 \)
- **\Phi1 (deg)** (anti-sidereal) \( 36.7 \pm 14.1 \)

Observation of the solar dipole effect and the absence of the anti-sidereal signal insures the reliability of the observation.

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Sidereal anisotropy by Tibet Array and IceCube

- Tibet Array
  - 5 TeV
- IceCube-59
  - 20 TeV

- Data from May 2009-2010
- Median angular resolution 3°
- Median Energy resolution 20 TeV
- Anisotropy is a continuation of previously measured large scale anisotropy observed in northern locations.

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Results Summary

- First skymap reporting a significant large scale anisotropy in the southern hemisphere sky.
- At 20 TeV the anisotropy is in remarkable agreement with previous northern sky measurements.
- The result is supported by the observation of solar dipole effect together with the absence of the anti-sidereal signal.
- At higher energies around (400 TeV) the anisotropy disappears.
- Source for large scale anisotropy is unknown
- Galactic Environment?
- SNR inducing a large scale anisotropy?
Supernova Detection with IceCube

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Supernova 1987A

Sanduleak -69 202

Supernova 1987A
23 February 1987

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Type II Supernova

On average, every 30 years or so in our galaxy a massive star with $M > 8M_\odot$ explodes.

*Gravitational instability due to* C, O, and Si fusion into a Fe – Ni core

Gravity overcomes the electron pressure and collapse begins; nuclear densities are reached with a core radius of $R \sim 10$ km, with $E = GM^2/R \sim 10^{59}$ MeV

Neutrinos are trapped in the neutrinosphere and materials bounce, cooling of the neutron star by neutrino emission, shock wave and explosion $E_{\text{kin}} \sim 0.01 E$.

99% of the energy is carried off by neutrinos!

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Neutrino Spectra from SN

Totani et al., (1998)

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SN87A Events
IMB & Kamioka
Electron anti-neutrino spectrum


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SN $\bar{\nu}_e + p \rightarrow e^+ + n$ Scattering

Energy Distribution of Electron Neutrinos (MeV)

Energy Distribution of Positrons (MeV)

Counts

Counts

Cosine of the angle of the positrons

Mean 16.07
ALLCHAN 1.0000

Mean 22.05
ALLCHAN 20.00

SN87A from IMB and Kamioka

MC

Mean 0.3892E-01
ALLCHAN 0.2458E-01

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Mean
ALLCHAN 32.74

— ICECUBEMC Simulation
(average DOM settings)
SN $\nu_e p \rightarrow e^+ n$, AHA Model

Mean
ALLCHAN 0.2096E+05

— ICECUBEMC Simulation
(average DOM settings)
SN $\nu_e p \rightarrow e^+ n$, AHA Model

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XY Hit distribution for SN positrons, i3geant, average DOM QE, 27% higher for DeepCore (AHA Ice Model)
ZX Hit distribution for SN positrons, i3geant, average DOM QE, 27% higher for DeepCore (AHA Ice Model)
For a SN with $10\ M_\odot$ at a distance of $10\ kpc$, the dominant neutrino reaction is $\bar{\nu}_e p \rightarrow n e^+$ with a flux-integrated CC cross section of:

$$\sigma = 0.24 \times 10^{-40}\ cm^2\ (Vogel\ and\ Beacom,\ Struma\ and\ Vissani,\ Llewellyn\ and\ Smith)\ at\ T = 5\ MeV$$

The SN detection method in IceCube is based on an overall count-rate increase in the DOM's.

We expect a sensitive range of $\sim 60\ kpc\ (LMC)$.
IceCube SN Sensitivity

Recently, our Geant MC indicates that a trigger based on two-DOM coincidence may be possible.

This method will substantially reduce the background and will dramatically increase the sensitivity of the IceCube detector to well beyond the LMC.

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Conclusions

- IceCube is almost complete and will be fully operational soon (78 + 8 DeepCore).
- Data has been analyzed for diffuse neutrinos, anisotropy, GRB’s, point sources ...
- No surprises yet, but with the full detector operating, we are eager to analyze future data and ever hopeful!
- SN detection capability of IceCube looks ever more promising.
- Stay tuned!

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Acknowledgement

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