Neutrino Astrophysics with IceCube

Jim Braun for the IceCube Collaboration
INFO Workshop, Santa Fe, 2009
The IceCube Collaboration

USA:
Bartol Research Institute, Delaware
University of California, Berkeley
University of California, Irvine
Pennsylvania State University
Clark-Atlanta University
Ohio State University
Georgia Tech
University of Maryland
University of Alabama, Tuscaloosa
University of Wisconsin-Madison
University of Wisconsin-River Falls
Lawrence Berkeley National Lab.
University of Kansas
Southern University and A&M College, Baton Rouge
University of Alaska, Anchorage

UK:
Oxford University

Switzerland:
EPFL

Sweden:
Uppsala Universitet
Stockholm Universitet

Germany:
DESY-Zeuthen
Universität Mainz
Universität Dortmund
Universität Wuppertal
Humboldt Universität
MPI Heidelberg
RWTH Aachen

Japan:
Chiba University

New Zealand:
University of Canterbury

33 institutions, ~250 members
http://icecube.wisc.edu
IceCube: Design and Construction Status

Neutrino Astrophysics with IceCube:

- Astrophysical Neutrino Searches
- Supernovae
- Atmospheric Neutrinos
- IceCube DeepCore Extension
- Indirect Dark Matter Searches
Optical Cherenkov Detection

Cherenkov light mapped by optical sensors
Drilling and Deployment

String 49 Drill/Ream/Deployment Profile

- Depth of drill head (m)
- Depth of Bottom DOM (m)
- DOM installation: ~6min/DOM
- String drop: 18 m/min
- Final depth (prel): 2451.0 m

Graph showing time (in hrs) from Jan 27, 7:05 am to Jan 28, 11:23 am.
Digital Optical Module (DOM)

- HV
- Flasher Board with 12 LEDs
- DOM Main Board
  - Power consumption: 3 W
  - Digitize at 300 MHz for 400 ns
  - Dynamic range 200pe/15 nsec
  - Excalibur FPGA/ARM CPU
  - Digital data transmission over copper

- 10 inch Hamamatsu R7081 PMT
- Pressure Sphere

Clock stability: $10^{-10} \approx 0.1$ nsec / sec
Synchronized to GPS every $\approx 10$ sec

Optical noise rate $\sim 300$ Hz in ice


Digitized Waveform
Time Calibration

Synchronize DOM clock with GPS master clock

Custom PCI card (DOR) connects surface PC to DOMs and GPS clock

Symmetric DOR-DOM pulses are timestamped at TX and RX

Average of DOM and DOR TX and RX times provides a calibration point

Time calibration is automatic and accurate to \(~2\) ns
Event Topologies

Type: NuMu
E (GeV): 1.75e+05
Zen: 67.64 deg
Azi: 277.32 deg

\( \nu_\mu \)

\( \nu_e \)

16 PeV \( \nu_\tau \) simulation
Neutrino Astrophysics with IceCube

<table>
<thead>
<tr>
<th>Energy range</th>
<th>~MeV</th>
<th>GeV-TeV</th>
<th>TeV-PeV</th>
<th>PeV-EeV</th>
<th>&gt;EeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics</td>
<td>Supernovae</td>
<td>Dark Matter, Oscillations, Atmospheric ν,</td>
<td>Point sources, GRB, Diffuse</td>
<td>GZK Neutrinos, Cosmic Rays</td>
<td>?</td>
</tr>
<tr>
<td>Signature</td>
<td>Average increase in the PMT counting rate</td>
<td>Tracks, Contained Events</td>
<td>Tracks, Cascades</td>
<td>Tracks, Cascades, Double Bang, Lollipops</td>
<td>Christmas Tree</td>
</tr>
</tbody>
</table>
Cosmic Ray Accelerators

Fermi shock acceleration with spectral index $\Gamma \sim -2$

SN Remnants

AGN

GRB 080319b

PDG
Astronomical Messengers

P. Gorham

Astrophysical beam dump

[Diagram showing various astronomical messengers and their interactions, including protons (p), muons (ν_μ), and neutrinos (ν_e, ν_μ, ν_τ), with a galaxy and observable distance on the x-axis and log of particle or photon energy on the y-axis.]
Milagro Sources

MGRO J1906+08 \( \Gamma \sim -2 \)

MGRO J2019+37 \( \Gamma > -2.2 \)

MGRO J2031+41 \( \Gamma \sim -2 \)

VERITAS (Proc. 30th ICRC) Sky Direction E-W (°)

PRELIMINARY

\( \phi_0 = 3.23 \pm 0.45 \times 10^{-12} \text{ cm}^2 \text{ s}^{-1} \text{ TeV}^{-1} \)

\( \gamma = 2.08 \pm 0.10 \)

arXiv:0801.2391v2
IceCube Muon Events

<table>
<thead>
<tr>
<th>Strings</th>
<th>$\mu$ rate</th>
<th>$\nu$ rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMANDA</td>
<td>80 Hz</td>
<td>4.8 / day</td>
</tr>
<tr>
<td>IC22</td>
<td>550 Hz</td>
<td>28 / day</td>
</tr>
<tr>
<td>IC40</td>
<td>1200 Hz</td>
<td>110 / day*</td>
</tr>
<tr>
<td>IC80</td>
<td>1650 Hz*</td>
<td>220 / day*</td>
</tr>
</tbody>
</table>
The Moon Shadow

5.34σ deficit found
6.1σ expected

Confirms muon pointing resolution in IC-40
Muon Energy Resolution

Pair-creation
Bremsstrahlung

\( e^+e^- \)
\( \pi \)
\( \gamma \)

Energy Resolution
\[ \sigma(\log_{10}E) \sim 0.3 \]

Source: D. Chirkin, UW
Astrophysical Neutrino Searches

Signal PDF:

\[ S_i(\vec{x}_i, \vec{x}_s, E_i, t_i) = P(E_i) \cdot P(|\vec{x}_i - \vec{x}_s|) \cdot P(t_i) \]

**Energy**
- Extraterrestrial neutrinos should be more energetic than atmospheric neutrinos

**Space Angle**
- Extraterrestrial neutrinos from a point source cluster around the source location

**Time**
- Neutrinos from GRBs and flaring AGN should be clustered in time

Each term provides additional power to reject background
Neutrino Point Source Search

Signal PDF: \[ S_i(\vec{x}_s, \gamma, \vec{x}_i, E_i, \sigma_i) = \frac{1}{2\pi\sigma_i^2} e^{-\frac{|\vec{x}_i - \vec{x}_s|^2}{2\sigma_i^2}} \cdot P(E_i|\gamma) \]

Space Angle Term:

Assume \( P(|x_i - x_s|) \) is a 2-D Gaussian

Space angle uncertainty \( \sigma_i \) can be measured for each event during reconstruction

Energy Term:

Assume emission follows a power law energy spectrum
Neutrino Point Source Search

Background: Events are uniform in RA

\[ \mathcal{B}_i = \frac{1}{\Omega} \cdot P_{bkgd}(E_i) \]

Assume a fraction of events are signal, remainder are background

Partial probability for each event:

\[ P(\vec{x}_s, n_s, \gamma, \vec{x}_i, E_i, \sigma_i) = \frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) \mathcal{B}_i \]

Likelihood function:

\[ \mathcal{L}(\vec{x}_s, n_s, \gamma) = \prod_{i=1}^{N} P(\vec{x}_s, n_s, \gamma, \vec{x}_i, E_i, \sigma_i) \]

Numerically minimize -Log L with respect to \( n_s \) and \( \gamma \), obtaining best fit values \( \hat{n}_s, \hat{\gamma} \)

Log likelihood:

\[ \lambda = -2 \cdot \log \left[ \frac{\mathcal{L}(\vec{x}_s, n_s = 0)}{\mathcal{L}(\vec{x}_s, \hat{n}_s, \hat{\gamma})} \right] \]

95 of 100 data sets randomized in RA have a significance $\geq 3.38\sigma$

**AMANDA Analyses:** Milagro stacking, AGN stacking, multipole search → Negative results

*Phys. Rev. D 79, 062001 (2009)*

*arXiv:0906.3942*
Hottest spot found at r.a. 153°, dec. 11°
pre-trial p-value: $7 \cdot 10^{-7}$ (4.8 sigma)
est. nSrcEvents = 7.7  est. gamma = 1.65

A search based on a list of sources yields no significant excess

Accounting for all trials, p-value for analysis is 1.34% (2.2 sigma).

At this significance level, consistent with fluctuation of background.
Number of hit modules: 148
Estimated angular error: 0.84°
IceCube 22 String

PeV – EeV neutrino-induced muons are more energetic than the vast majority of cosmic ray muons

Selecting such high energy muons provides sensitivity in the downgoing direction

No excesses observed in binned search (p=0.37)
Search of the Galactic Plane with IceCube-22 + AMANDA

Optimized for low energy; no significant excess observed
IC40 and IC22 $E^{-2}$ Sensitivity and Disc Potential

$\Phi^0$ [TeV$^{-1}$ cm$^{-2}$ s$^{-1}$]

- IC40: 175.5d Sensitivity
- IC40: 175.5d Disc Potential
- IC22: 275.7d Sensitivity
- IC22: 275.7d Disc Potential

sin($\delta$)

Preliminary

IC40 6-month Results to be presented at ICRC
40 String Detector and Beyond

E^{-2} Flux that 40 strings of IceCube can discover at 5sigma and 50% prob

E^{-2} Flux that 40 strings of IceCube can exclude at 90% cl

same for full IceCube (cuts based on 40 string analysis)
Multiwavelength Flare Search
IC22: No neutrino correlations to photon high states of several objects (e.g. 1ES 1959, Cygnus X-1)

Microquasars

IC22: No periodic emission for 7 microquasars in the Northern Sky

Unbiased Flare Search
To be presented at ICRC
GRB 080319b

March 19, 06:12 UT (duration ~70s)
Brightest (optical) GRB (mag. ~5.3)
z = 0.94 (DA = 1.6 Gpc)

Data consistent with 0.0
events within window

Konus X-ray

IceCube Data

preliminary

Calculated GRB080319B fluence
90% C.L. upper flux limit
Systematic error

\[ E^2 \times \frac{dN}{dE} (\text{GeV cm}^{-2}) \]

\[ E_v (\text{GeV}) \]

arXiv:0902.0131
Northern Hemisphere GRBs

41 satellite triggered bursts during IC22

Expect:
~0.03 prompt events
~0.3 precursor events

Data consistent with zero signal
Northern Hemisphere GRBs

Most sensitive limits still from AMANDA 1997 – 2003 (419 bursts)


Binned Searches

Full IceCube detector would detect this flux at 5σ in less than one year (100 Swift + Fermi bursts)
Supernovae

~MeV SN neutrinos produce an increase in photon rates

No pointing resolution

5σ detection to ~50 kpc in full IceCube

Measurement of neutrino light curves:
~10^6 neutrinos at 7.5 kpc

Presented at ICRC 2009
Diffuse Neutrino Fluxes

Preliminary IC40 diffuse sensitivity >5x better than AMANDA

New AMANDA UHE diffuse limit near W&B Bound (ICRC 2009)
No evidence of QD or VLI effects
($\delta c/c < 2.8 \times 10^{-27}$ 90% CL)

New measurement of the atmospheric neutrino flux with AMANDA

IceCube DeepCore

6 strings with dense DOM spacing and high QE PMTs

Located in deep, clear ice

Will improve IceCube physics reach at 10 – 100 GeV
Neutrino Physics with Deep Core

Selection of starting muons allows $4\pi$ acceptance

Upper half of IceCube is an active muon veto

Good sensitivity to atmospheric oscillations with DeepCore

$\Delta m^2 = 0.0024$, $\sin^2(2\theta) = 1$
WIMP Capture and Annihilation

WIMPs accumulate at center of massive objects and annihilate

- Capture rate dependent on WIMP-nucleon cross section
- Annihilation rate should approach equilibrium with capture rate

Annihilation produces a neutrino flux at Earth

- Neutrino spectra dependent on annihilation mode

\[ \Gamma_A \sim \frac{1}{2} \Gamma_C \]

\[ \chi\chi \rightarrow \begin{array}{c} WW \\rightarrow \nu, e^- \end{array} \text{etc.} \]
WIMP Capture

Always fully visible (vertical upgoing events)

Small mass

Sun below horizon half of the year

Large mass

GC always above the horizon, with large CR background

Extreme mass
AMANDA 2000-2006

AMANDA 2001-2003

IC22

PRL 102, 201302 (2009)

arXiv:0906.1615
$0.05 < \Omega_{\chi} h^2 < 0.20$

Indirect searches - $E_{\mu}^{\text{thr}} = 1$ GeV

- BAKSAN 1978-1995
- MACRO 1989-1998
- SUPER-K 1996-2001
- IceCube-22 2007 (soft)
- IceCube-22 2007 (hard)
- AMANDA 2001-2003 (soft)
- AMANDA 2001-2003 (hard)
- AMANDA 2000-2006 (soft)
- AMANDA 2000-2006 (hard)

- $\sigma_{SI} < \sigma_{SI}^{\text{lim}}$ CDMS(2008)+XENON10(2007)
- $\sigma_{SI} < 0.001\sigma_{SI}^{\text{lim}}$ CDMS(2008)+XENON10(2007)

Muon flux from the Sun (km$^2$ y$^{-1}$)

Neutralino mass $m_\chi$ (GeV)

Preliminary

arXiv:0906.1615
$0.05 < \Omega_\chi h^2 < 0.20$

- CDMS (2008)
- COUPP (2008)
- KIMS (2007)
- SUPER-K 1996-2001
- IceCube-22 2007 (soft)
- IceCube-22 2007 (hard)
- IceCube-80+DeepCore 1800d sens. (hard)
- AMANDA 2001-2003 (soft)
- AMANDA 2001-2003 (hard)
- AMANDA 2000-2006 (soft)
- AMANDA 2000-2006 (hard)

Neutralino-proton SD cross-section $\sigma_{SD}$ (cm$^2$)

Neutralino mass $m_\chi$ (GeV)

Preliminary

arXiv:0906.1615
Summary

IceCube is now ~70% complete with 19 new strings installed this past season.

We observe no evidence of an astrophysical neutrino flux.

IceCube sensitivity is rapidly improving and 40-string analyses are underway.

New WIMP-proton spin-dependent cross section limits complement those from direct detection experiments.

The DeepCore extension will improve physics reach at low energies.