Latest results from the IceCube Neutrino Observatory

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XLIVth Rencontres de Moriond
ELECTROWEAK INTERACTIONS AND UNIFIED THEORIES....
March 7 – 14, 2009
Outline

• Motivation
• The IceCube Neutrino Observatory
• Pole/Detector Status
• Summary of Recent Results
• Conclusions
Neutrinos
• Unobscured view into depth of space
• Point back to their sources
• Cover entire energy spectrum

Protons
• bent below about 10 EeV
• above ~55EeV attenuated (GZK cut-off)

Photons
• scattered/absorbed above 50 TeV
Protons interact in “target area” to produce pions:
\[ p + (p \text{ or } \gamma) \rightarrow \pi^0 \rightarrow \gamma \gamma \]
\[ \rightarrow \pi^\pm \rightarrow \nu_e \nu_\mu \rightarrow \nu_e \nu_\mu \nu_\tau \]
(1:2:0) (1:1:1)
Neutral pions → Photons
Charged pions → Neutrinos
Oscillations result in equal flavor ratio at detector

Source Candidates:
- Supernova Remnants
- Gamma Ray Bursts
- Active Galactic Nuclei
- ...

P. Mészáros, Science 2001

Carsten Rott
Moriond EW, March 2009
Neutrinos interact in or near the detector. Depending on the interaction, a lepton (CC) or a shower (NC) is produced. 

- $\mathcal{O}(\text{km})$ muons from $\nu_\mu$
- $\mathcal{O}(10\text{m})$ cascades from $\nu_e$, $\nu_\tau$, NC

Array of optical sensors capture the light.

Cherenkov Radiation

Muon Neutrino
• **IceTop**
  - 80 Stations (2 tanks each)
  - Surface air shower array
  - 300TeV threshold

• **IceCube InIce**
  - 80 Strings with 60 DOMs each
  - Hexagonal pattern with an interstring distance of 125 m
  - Vertical DOM spacing of 17 m
  - Optimized for TeV range

• **AMANDA**
  - 19 strings with 677 modules total
  - 10-20 m vertical spacing
  - 40-50 m horizontal spacing

• **Deep Core**
  - 6 Strings with 60 High Quantum Efficiency DOMs (vert. spacing 7 m)
  - Low Energy extension (20-100GeV)

IceCube will instrument a volume of one cubic kilometer of Antarctic ice by 2011
Measure individual photon arrival time:
- 2 ping-ponged four-channel Analog Transient Waveform Digitizers:
  - 128 samples (400 ns max range)
  - ~3.3 ns bin
  - 400 pe / 15 ns
- fast Analog-to-Digital Converter:
  - 40 MHz
  - 6.4 μs range

Example:
Digitized Waveform

Hardware extremely reliable

Diehard Hamamatsu PMT (R-7081-02)

- Dark Noise rate ~ 700 Hz
- Local Coincidence rate ~ 15 Hz
- Deadtime < 1%
- Signal digitized in the ice

*arXiv:0810.4930 (accepted NIM)*
Season Deployed

<table>
<thead>
<tr>
<th>Season</th>
<th>Deployed</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004-2005</td>
<td>1 string</td>
</tr>
<tr>
<td>2005-2006</td>
<td>8 strings</td>
</tr>
<tr>
<td>2006-2007</td>
<td>13 strings</td>
</tr>
<tr>
<td>2007-2008</td>
<td>18 strings</td>
</tr>
<tr>
<td>2008-2009</td>
<td>18+1 strings</td>
</tr>
</tbody>
</table>
Atmospheric Neutrinos

### Strings

<table>
<thead>
<tr>
<th>Strings</th>
<th>μ rate</th>
<th>ν 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>~1000 Hz</td>
<td>~110 / day</td>
</tr>
<tr>
<td>IC80*</td>
<td>~1650 Hz</td>
<td>~220 / day</td>
</tr>
</tbody>
</table>

$\phi \sim E^{-3.7}$

**IceCube-22 Data vs. Monte Carlo Simulation Data**

- Cosmic Ray Induced Muons
- Coincident Cosmic Ray Induced Muons
- Neutrinos
- All Simulated Muons & Neutrinos
- IceCube-22 Data

**Neutrinos**

**Muons**
IceCube is a multipurpose detector sensitive to **neutrinos of all flavors** at energies from $\sim10^{11}$ to $10^{20}$ eV + (MeV bursts)

<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 $\nu$,</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>
<tr>
<td>Coverage/Directionality</td>
<td>All sky, but no directionality</td>
<td>Up-going</td>
<td>Up-going</td>
<td>Horizontal, down-going IceTop/InIce</td>
<td>Down-going</td>
</tr>
</tbody>
</table>
• Maximum significance is $3.38\sigma$ at $\delta=54^\circ$, $\alpha=11.4$ hr
• 95% of randomized sets have same or greater significance

1387 days of livetime
6595 Neutrino candidates

SuperK data, González-García, Maltoni, & Rojo, JHEP 0610 (2006) 075

Preliminary

arXiv 0902.0675 (submitted to PRD)

arXiv 0809.1646

http://www.icecube.wisc.edu/science/data
5114 neutrino candidates in 276 days livetime

Hottest spot found at r.a. 153°, dec. 11°
est. pre-trial p-value: \(-\log_{10}(p): 6.14\)
(4.8 sigma)

**Post-trials p-value of analysis is \(~ 1.34\% (~ 2.2 \text{ sigma})\)** ...
search in 2.5 degree bins

background calculation from same declination band

large irreducible background just below the horizon

Coordinates:
Dec. 1.00°, RA 103.5° (6.9 h)
P-value:
2.9x10^{-5} (pre-trial prob.)
Bin content:
8 events with 1.2 expected (109 in dec. band)

The trial-corrected probability for a random excess of the same or larger value in 37.4% of scrambled maps, i.e. not significant.
Atmospheric neutrinos behave like $E^{-3.7}$

Typical extraterrestrial fluxes are expected to behave like $E^{-2}$

Do we see any extraterrestrial flux component?

Look for excess of events at high energy, or high number of channels.

IC9: $N_{ch} \geq 60$

IC9 sensitivity:

$E^2 \Phi < 1.4 \times 10^{-7}$ GeV/cm$^2$ s sr (for $E \lesssim 10$ PeV)

AMANDA II Limit: $E^{-2} < 7.4 \times 10^{-8}$ GeV cm$^2$ s$^{-1}$ sr$^{-1}$

Figure 1. $N_{ch}$ for the AMANDA-II 2000–2003 diffuse muon neutrino analysis compared to atmospheric neutrino expectations [6, 8].

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arXiv:0712.3524
• Look for an excess of neutrinos in the direction of the sun
• No evidence for a signal observed
• Upper limits on muon flux from neutralino annihilations in the Sun

Under the assumption of equilibrium condition in the Sun, a limit on the WIMP-Nucleon cross-section can be obtained

For spin-dependent couplings, IceCube’s sensitivity is about 2-orders of magnitude better than direct searches

arXiv: 0902.2460 (submitted to PRL)
Moon shadow observed in first 3 months of IC40 data
• Validates pointing capabilities:
  Angular resolution:
  – IceCube 22 < 1.5°
  – IceCube 80 < 1°
• Used to determine detector angular resolution

Cosmic rays blocked by the moon lead to a point-like deficit in the distribution of down-going muons in the detector

Preliminary

obs, from Moon

93000
92000
91000
90000
89000
88000

exp=(ave of dummy moons)

93000
92000
91000
90000
89000

obs-exp

Preliminary

0 1 2 3 4 5 Δθ(^°)

0 1 2 3 4 5 Δθ(^°)

obs: 88202 events
expected: 89522 events
deficit: -1320 events
error: 315 events
significance: -4.2 σ
• IceCube’s lowest energy threshold is realized in vertical events (due to its geometry)
• Can we see atmospheric neutrino oscillations?
• Expected results of $\chi^2$ test using the track length as energy estimator (under the assumption that remaining background can be rejected)

Unblinded a small subset of the IC22 data for validation purposes:
• Expected:
  • Signal (Muon Neutrinos): 1.81 (no-osc) / 1.42 (osc)
  • Background: 0.0 +/- 20.3
• Observed three events
Larger MC background dataset is currently studied

• Oscillation effects might be observable in IceCube 40 data
Deep Core Strings

- 6 strings with high quantum efficiency PMTs, densely spaced
- 7 “standard” IceCube strings
- Located in best ice (below 2100 m exceptionally clear)
- Interstring spacing 72m
- Uses high Quantum Efficiency PMTs, that have about 40% higher efficiency
- Located in the deep ice
- Lower atmospheric muon background
- Larger scattering length ~40m
Phenomenal austral summer season 08/09:
• 19 new strings deployed (incl. first Deep Core String)
• IceCube deployment is more than two thirds complete!
• IceCube is actively taking data and shows a good long-term hardware reliability
• New most stringent limit on spin-dependent WIMP-nucleon cross-section
• Many analyses with the 40-string detector underway ... stay tuned
The IceCube Collaboration

University of Alaska, Anchorage
University of California, Berkeley
University of California, Irvine
Clark-Atlanta University
University of Delaware / Bartol Research Institute
University of Kansas
Lawrence Berkeley Natl. Laboratory
University of Maryland
Pennsylvania State University
Southern University and A&M College
University of Wisconsin, Madison
University of Wisconsin, River Falls
Ohio State University
University of Alabama
Georgia Tech
Universität Dortmund
MPIfK Heidelberg
Humboldt Universität, Berlin
Universität Mainz
DESY, Zeuten
BUGH Wuppertal
RWTH Aachen

Stockholms Universitet
Uppsala Universitet
Vrije Universiteit Brussel
Université Libre de Bruxelles
Universiteit Gent
Université de Mons-Hainaut
Chiba University

University of Canterbury, Christchurch

Universiteit Utrecht

Oxford University
EPF Lausanne

Carsten Rott
Moriond EW, March 2009
Neutrinos from GRBs

- Search for events correlated in time and direction with observed GRBs
- Small time and space window reduces background rate
- 93 SWIFT bursts during IC22 runs
- IceCube will be able to detect Waxman-Bahcall or similar GRB fluxes within the next few years

arXiv:0902.0131 (GRB080319B)
Detector was running in test mode
• (9 out of 22 strings taking data)
• Expect 0.1 events
• No neutrino candidate near GRB coordinates
  → 90% upper flux limit

• Would expect ~1 event from similar burst in IceCube 80-strings

March 19, 06:12:49 UT (duration ~70 s)
• Position: RA = 217.9°, Dec = +36.3°
• Brightest (optical) GRB ever observed
• z = 0.94 (DA = 1.6 Gpc)
**Neutrino Event Identification**

**Tracks**

<table>
<thead>
<tr>
<th>IceCube</th>
<th>AMANDA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time Resolution</td>
<td>2 ns</td>
</tr>
<tr>
<td>Energy Resolution</td>
<td>0.3 – 0.4</td>
</tr>
<tr>
<td>Field of View</td>
<td>2π</td>
</tr>
<tr>
<td>Noise Rate</td>
<td>low</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>&lt;1°</td>
</tr>
</tbody>
</table>

**Cascades**

<table>
<thead>
<tr>
<th>IceCube</th>
<th>AMANDA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time Resolution</td>
<td>2 ns</td>
</tr>
<tr>
<td>Energy Resolution</td>
<td>0.18</td>
</tr>
<tr>
<td>Field of View</td>
<td>4π</td>
</tr>
<tr>
<td>Noise Rate</td>
<td>low</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>30°</td>
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</tbody>
</table>

**Track-Like IceCube AMANDA**

Muon from IC40 Data

**Cascade-Like IceCube AMANDA**

16 PeV ντ simulation
<table>
<thead>
<tr>
<th>Obj. Name</th>
<th>ra(deg)</th>
<th>dec(deg)</th>
<th>p-value (pre-trial)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MGRO_J2019+37</td>
<td>(304.830, 36.830)</td>
<td>0.251</td>
<td></td>
</tr>
<tr>
<td>MGRO_J1908+06</td>
<td>(287.270, 6.280)</td>
<td>----</td>
<td></td>
</tr>
<tr>
<td>Cyg_OB2</td>
<td>(308.083, 41.510)</td>
<td>----</td>
<td></td>
</tr>
<tr>
<td>SS_433</td>
<td>(287.957, 4.983)</td>
<td>0.317</td>
<td></td>
</tr>
<tr>
<td>Cyg_X-1</td>
<td>(299.591, 35.202)</td>
<td>----</td>
<td></td>
</tr>
<tr>
<td>LS I +61_303</td>
<td>(40.132, 61.229)</td>
<td>----</td>
<td></td>
</tr>
<tr>
<td>GRS_1915+105</td>
<td>(288.798, 10.946)</td>
<td>----</td>
<td></td>
</tr>
<tr>
<td>XTE_J1118+480</td>
<td>(169.545, 48.037)</td>
<td>0.082</td>
<td></td>
</tr>
<tr>
<td>GRO_J0422+32</td>
<td>(65.428, 32.907)</td>
<td>----</td>
<td></td>
</tr>
<tr>
<td>Geminga</td>
<td>(98.476, 17.770)</td>
<td>----</td>
<td></td>
</tr>
<tr>
<td>Crab_Nebula</td>
<td>(83.633, 22.014)</td>
<td>----</td>
<td></td>
</tr>
<tr>
<td>Cas A</td>
<td>(350.850, 58.815)</td>
<td>----</td>
<td></td>
</tr>
<tr>
<td>Mrk_421</td>
<td>(166.114, 38.209)</td>
<td>----</td>
<td></td>
</tr>
<tr>
<td>Mrk_501</td>
<td>(253.468, 39.760)</td>
<td>----</td>
<td></td>
</tr>
<tr>
<td>1ES 1959+650</td>
<td>(299.999, 65.149)</td>
<td>0.071</td>
<td></td>
</tr>
<tr>
<td>1ES 2344+514</td>
<td>(356.770, 51.705)</td>
<td>----</td>
<td></td>
</tr>
<tr>
<td>H_1426+428</td>
<td>(217.136, 42.672)</td>
<td>----</td>
<td></td>
</tr>
<tr>
<td>1ES 0229+200</td>
<td>(38.202, 20.287)</td>
<td>----</td>
<td></td>
</tr>
<tr>
<td>BL Lac</td>
<td>(330.680, 42.278)</td>
<td>0.368</td>
<td></td>
</tr>
<tr>
<td>S5_0716+71</td>
<td>(110.473, 71.343)</td>
<td>0.309</td>
<td></td>
</tr>
<tr>
<td>3C66A</td>
<td>(35.665, 43.035)</td>
<td>0.313</td>
<td></td>
</tr>
<tr>
<td>3C 454.3</td>
<td>(343.491, 16.148)</td>
<td>----</td>
<td></td>
</tr>
<tr>
<td>4C_36.41</td>
<td>(248.815, 38.135)</td>
<td>----</td>
<td></td>
</tr>
<tr>
<td>PKS_0528+134</td>
<td>(82.735, 13.532)</td>
<td>----</td>
<td></td>
</tr>
<tr>
<td>3C_273</td>
<td>(187.278, 2.052)</td>
<td>0.369</td>
<td></td>
</tr>
<tr>
<td>M87</td>
<td>(187.706, 12.391)</td>
<td>----</td>
<td></td>
</tr>
<tr>
<td>NGC_1275</td>
<td>(49.951, 41.512)</td>
<td>0.213</td>
<td></td>
</tr>
<tr>
<td>Cyg_A</td>
<td>(299.868, 40.734)</td>
<td>----</td>
<td></td>
</tr>
</tbody>
</table>

**28 sources chosen in advance**

- Most significant excess is 1ES 1959+650 with a pre-trial p-value of 0.07
- Not significant after trial factor
Astrophysical $E^{-2}$ neutrino diffuse flux limits

- Amanda $\sim 2-3 \times 10^{-11}$ TeV/cm$^2$ s
- IC22 $\sim 8-30 \times 10^{-12}$ TeV/cm$^2$ s
- IC80 $\sim 2-20 \times 10^{-12}$ TeV/cm$^2$ s
- Data (275.7 days) 1885
  Background simulation:
  - CORSIKA muons 769 ± 25
  - Atm. neutrinos 853 ± 3
  Signal simulation:
  - $E^{-1.5}$ neutrino-signal
  - $E^{-2}$ neutrino-signal

Preliminary
- Atmospheric neutrinos behave like $E^{-3.7}$
- Typical extraterrestrial fluxes are expected to behave like $E^{-2}$
- Do we see any extraterrestrial flux component?

Look for excess of events at high energy, or high number of channels
IC9: $N_{ch} \geq 60$

Prompt Neutrino Flux
(charmed Mesons)

IC9 sensitivity:
$E^2 \Phi < 1.4 \times 10^{-7}$ GeV/cm$^2$ s sr (for $E \lesssim 10$ PeV)

AMANDA II Limit: $E^{-2} < 7.4 \times 10^{-8}$ GeV cm$^2$ s$^{-1}$ sr$^{-1}$
If the unbinned analysis is performed without the energy / NChan term, the original hottest spot is still an excess, but no longer significant at all.

(Note that the scale has changed and no spot is significant after trials).

=> The significance at this spot depends on contribution of high energy (high NChan) events.
Deep Core - Effective Area

Neutrino Effective Area for IceCube / IceCube+DeepCore

Average Effective Area $A_{\text{eff}}$ (m$^2$)

- $10^{-1}$
- $10^{-2}$
- $10^{-3}$
- $10^{-4}$
- $10^{-5}$

$log_{10}$ (Primary Neutrino Energy $E_\nu$ [GeV])

Upgoing Muon Neutrinos

- IceCube IC80 SMT8 + DeepCore SMT4
- IceCube IC80 SMT8

Preliminary Trigger Level
Product of two SVMs $Q_1 \times Q_2$ was used to remove background at final cut level. Data and simulation agree well.

At the final cut level, atm. neutrinos form biggest background.

Direction of the sun still remained scrambled to this point.
Relative efficiency to observe a photon from a down-going muon track

"Understanding of ice properties key to reliable event reconstruction"

Other exciting signatures ... Tau Search

Double Bang

$< \sim 20\text{PeV}$

[Learned & Pakvasa 1995]

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Branching fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \rightarrow \nu_\tau + e + \nu_e$</td>
<td>17.8%</td>
</tr>
<tr>
<td>$\tau \rightarrow \nu_\tau + X$ (hadronic)</td>
<td>$\sim 65%$</td>
</tr>
<tr>
<td>$\tau \rightarrow \nu_\tau + \mu + \nu_\mu$</td>
<td>17.4%</td>
</tr>
</tbody>
</table>

“Lollipop” – half double bang

[Beacom, Bell, Hooper, Pakvasa & Weiler 2005]

"Sugar daddy"

[DeYoung, Razzaque, & Cowen, 2007]

$\left\langle E_\mu \right\rangle = 0.35 \ E_\tau$

Searches for tau-neutrinos are underway ...

Carsten Rott

Moriond EW, March 2009