Recent Results & Status of IceCube

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(Stockholm Univ.)
for IceCube Collaboration
Outline

- Introduction
- The IceCube Detector
- Recent Results
- Current Status
- Future: Deep Core
- Conclusion

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Vol. 315, issue 5818
Nature-produced High E Particles

At earth we observe:
-- Cosmic rays (~80% protons)
-- Photons
-- Neutrinos

We would like to answer:
-- What are the sources?
-- What's the physics at/near the sources?
Detecting Astrophysical Particles

- Photons get absorbed (or pair-production) above 50 TeV.
- Protons get bent below 10 EeV and strongly attenuated above 50 EeV (GZK cut-off).
- Neutrinos cover all energy range, point back, but hard to detect.
Neutrino Telescope

Requirements:
-- Large detection volume to compensate for small cross section and small flux of neutrinos
-- Optically transparent medium: water, ice

Detectors:
-- Water: DUMAND, Baikal, ANTARES, NESTOR, NEMO, KM3Net
-- Ice: AMANDA, IceCube (successor of AMANDA)

<table>
<thead>
<tr>
<th>Medium</th>
<th>Water</th>
<th>Ice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Northern</td>
<td>Southern</td>
</tr>
<tr>
<td>Deployment</td>
<td>Mostly year-round</td>
<td>austral summer</td>
</tr>
<tr>
<td>PMT noise rate</td>
<td>~ 40 KHz</td>
<td>~0.5 KHz</td>
</tr>
<tr>
<td>Scattering length</td>
<td>&gt; 100 m @ 466 nm</td>
<td>~ 20 m @ 400 nm</td>
</tr>
<tr>
<td>Absorption length</td>
<td>~ 60 m @ 466 nm</td>
<td>~110 m @ 400 nm</td>
</tr>
<tr>
<td>Detector geometry</td>
<td>Unstable</td>
<td>Stable</td>
</tr>
</tbody>
</table>
The IceCube Collaboration

USA (15):
- Bartol Research Institute, Delaware
- Pennsylvania State University
- UC Berkeley
- UC Irvine
- Clark-Atlanta University
- University of Maryland
- 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
- University of Alabama
- Georgia Tech University
- Ohio State University

UK (1):
- Oxford University

Sweden (2):
- Stockholm University
- Uppsala University

Germany (7):
- Universität Mainz
- DESY-Zeuthen
- Universität Dortmund
- Universität Wuppertal
- Humboldt Universität
- MPI Heidelberg
- RWTH Aachen

Netherlands (1):
- Utrecht University

Belgium (4):
- Université Libre de Bruxelles
- Vrije Universiteit Brussel
- Universiteit Gent
- Université de Mons-Hainaut

Switzerland (1):
- EPFL, Lausanne

Japan (1):
- Chiba University

New Zealand (1):
- University of Canterbury

~250 members
33 institutions
9 countries
Amundsen-Scott South Pole Station

Antarctica

South Pole

New Station

Skyway

~1 Km

Summer: ~240 people
Winter: ~50 people

IceCube

AMANDA II
The IceCube Detector

IceTop (air shower array):
- 80 stations
- 2 frozen-water tanks / station
- 2 DOMs / tank

IceTop

AMANDA: 1996 - 2008
- 19 strings
- 677 OMs total
- 10-20 m vertical spacing
- ~40 m between strings

Deep Core

InIce:
- 80 strings
- 60 DOMs / string
- 17 m vertical spacing
- 125 m between strings

AMANDA

InIce:

I’ll get back to this later.

Dark09, Christchurch, New Zealand
String Deployment

- Hose reel
- Drill tower
- 5 MW Hot water generator
- Hot-water drilling

Drilling to 2500 m < 40h
String deployment ~ 12h

speed: ~90m/hr
Ice Properties

Average optical parameters:
\[ \lambda_{\text{abs}} \sim 110 \text{ m} @ 400 \text{ nm} \]
\[ \lambda_{\text{sca}} \sim 20 \text{ m} @ 400 \text{ nm} \]

At bottom half of detector (very clear ice):
\[ \lambda_{\text{abs}} \sim 220 \text{ m}, \lambda_{\text{sca}} \sim 40 \text{ m} @ 400 \text{ nm} \]
**Digital Optical Module (DOM)**

- **Hamamatsu R7081-02** (10”, 10-stage, $10^7$ gain)

- Time-stamp at the DOM
- Capture complex waveforms at PMT anode with Analog Transient Waveform Digitizer (ATWD) & fADC

**Digitized waveform**
Neutrino Detection

Method: detect Cherenkov light from secondary particles produced by neutrino interaction

Track

Cascade

Dark09, Christchurch, New Zealand

IceCube Talk
Seo, Stockholm Univ.

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### ν Detection Quality

#### Track

<table>
<thead>
<tr>
<th></th>
<th>IceCube-80</th>
<th>AMANDA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular resolution</td>
<td>&lt; 1°</td>
<td>2° ~ 3°</td>
</tr>
<tr>
<td>E resolution (\log_{10}(E/\text{GeV}))</td>
<td>~ 50%</td>
<td>~ 50%</td>
</tr>
<tr>
<td>Time resolution</td>
<td>~ 3 nsec</td>
<td>5 ~ 7 nsec</td>
</tr>
</tbody>
</table>

#### Cascade

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Angular resolution</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>E resolution (\log_{10}(E/\text{GeV}))</td>
<td>~ 20%</td>
<td>~ 20%</td>
</tr>
<tr>
<td>Time resolution</td>
<td>~ 3 nsec</td>
<td>5 ~ 7 nsec</td>
</tr>
</tbody>
</table>
### Event Rates

<table>
<thead>
<tr>
<th>Year</th>
<th>#Strings</th>
<th>Run Length</th>
<th>Trigger Rate</th>
<th>ν rate</th>
<th>CR μ Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>IC1</td>
<td>-</td>
<td>-</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>2006</td>
<td>IC9</td>
<td>137 days</td>
<td>150 Hz</td>
<td>~ 1.5/day</td>
<td>80 Hz</td>
</tr>
<tr>
<td>2007</td>
<td>IC22</td>
<td>319 days</td>
<td>670 Hz</td>
<td>~ 20/day</td>
<td>550 Hz</td>
</tr>
<tr>
<td>2008</td>
<td>IC40</td>
<td>~ 1 year</td>
<td>1400 Hz</td>
<td></td>
<td>1000 Hz</td>
</tr>
<tr>
<td>2011</td>
<td>IC80</td>
<td>10 years</td>
<td>TBD</td>
<td>~ 200/day</td>
<td>1650 Hz</td>
</tr>
</tbody>
</table>

### Data Transfer

-- Satellite: ~32.5 GB/day (Y2008), (pre-scaled) filtered events

-- Ship: once a year for all filtered events in tapes
Backgrounds

- **Backgrounds**
  - **atmospheric muons**
  - **muons induced by atmospheric neutrinos**
  - **Coincident muons**

\[ \frac{d\Omega}{d\Omega} \text{ (cm}^{-2} \text{s}^{-1} \text{sr}^{-1}) \]

- **Up (N)**
- **cos(zenith)**
- **Down (S)**

- Simulation

- IceCube Talk
  - Seo, Stockholm Univ.

Dark09, Christchurch, New Zealand
IceCube Physics Reach

Astronomy/Astrophysics:
-- point source search: GRB, AGN, etc...
-- diffuse search

Cosmic ray physics:
-- compositions, energy spectrum

HEP:
-- neutrino oscillations over cosmologically long baseline
-- atmospheric neutrino oscillations
-- charm production from high energy atmospheric neutrinos
-- etc…

New physics:
-- WIMPs, (GUT) monopoles, nuclearites, Q-balls, stau pairs
-- violation of Lorentz invariance, etc…
-- 3.8 years livetime data of AMANDA
-- Max. significance is $3.38\sigma$
-- However, 95% of randomized data sets showed significance of $3.38\sigma$ or greater.
IceCube 22 string Sky Map

Location: Ra: 153.375°, Dec: 11.375°

Estimated pre-trial significance (p-value): -log10(p): 6.13995

p-value of post-trials: ~1.34%

Dark09, Christchurch, New Zealand

IceCube Talk
Seo, Stockholm Univ.
Astrophysical $\nu$ Diffuse Flux Limit

AMANDA 3.8 yr limit: $10^{-11} \sim 10^{-10} E^2 d\Phi/dE \ (\text{TeVcm}^{-2}\text{s}^{-1})$

Expected IceCube80 (1 yr) sensitivity: $10^{-12} \sim 10^{-11} E^2 d\Phi/dE \ (\text{TeVcm}^{-2}\text{s}^{-1})$
-- atmospheric $\nu$ are irreducible BG.
-- AMANDA measurement is similar to the two popular atm. $\nu$ models.

SuperK data,
González-García, Maltoni, & Rojo,
JHEP 0610 (2006) 075
**Super Nova Monitoring**

*Bursts of low-energy (MeV) neutrinos from core collapse supernovae*

\[ \nu_e + p \rightarrow n + e^+ \]

The produced positron is emitted almost isotropically

- **20 MeV Positron showers**
- **O(10cm) long tracks**
- **IceCube Talk**
- **Seo, Stockholm Univ.**

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**SNEWS** (SuperNova Early Warning System) is a collaborative effort among Super-K, SNO, LVD, KamLAND, AMANDA, BooNE and gravitational wave experiments

- AMANDA sees 90% of the galaxy
- IceCube will see out to the LMC (Large Magellanic Cloud, ~50 kpc)

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Dark09, Christchurch, New Zealand
**Preliminary**

- **IceCube WIMP Search: Indirect**

  - Direct search: $0.05 < \Omega \chi^2 < 0.20$
  - Indirect search: $E_{\text{max}} = 1 \text{ GeV}$

  - **CDMS(2008)**$	imes$**XENON10(2007)**
  - **IceCube-22 2007** (hard)
  - **IceCube-22 2007** (soft)
  - **SUPER-K 1996-2001** (soft)

  - **Muon flux from Sun** [km$^2$ yr$^{-1}$]
  - **Neutralino mass** [GeV/c$^2$]

  Preliminary looking for excess $\nu_\mu$ in the Sun direction

  -- No excess was observed w/ 22 strings.

  -- We set 90% CL on the muon flux from Sun.

  -- We also set current best limit on SD x-section.

  See A. Rizzo’s talk!
Sub-relativistic Monopoles

\[ m_M \geq 10^{16} \text{ GeV (GUT)} \]

\[ M + p \rightarrow M + e^+ + \pi^0(2\gamma) \rightarrow \text{em shower} \]

-- catalysis of nucleon decay by GUT magnetic monopoles (\( \sigma \approx 10^{-56}\text{cm}^2 \))

-- baryon & lepton number violation

Rubakov-Callan mechanism:

\[ \sigma = \frac{\sigma_0}{\beta^n} \cdot F(\beta), \quad n = 1 \text{ or } 2 \]

\[ \sigma_0 = \text{typical strong int. x-section} \]

\[ F(\beta) = \text{suppression factor} \]

(smaller for higher Z atom & lower \( \beta \))

Hydrogen: \( \sigma = 0.18 \frac{\sigma_0}{\beta^2} \)

Oxygen: \( \sigma = \frac{\sigma_0}{\beta_{\text{nucl}}} \)

*** We also have preliminary flux limits on relativistic monopole search w/ AMANDA.

AMANDA 2001 (64 live days)

\[ \sigma_0 (\text{cm}^2): \bullet 1.7 \cdot 10^{-28} \quad \Delta 5.1 \cdot 10^{-28} \quad \Delta 1.6 \cdot 10^{-27} \quad \Delta 5.1 \cdot 10^{-27} \]

\[ \text{parker bound} \quad \text{im best} \quad \text{macro best} \quad \text{uniform dark matter} \]

\[ \beta = v/c \]

\[ \text{magnetic monopoles} \]

\[ \text{preliminary} \]
Violation of Lorentz Invariance

Violation of Lorentz Invariance (VLI):

-- one of the aspects in quantum gravity

-- natural in Planck scale (~$10^{19}$ GeV)

-- but also feasible in much lower energy

-- can be tested in, for example,

(A) neutrino oscillation (different from mass osc.):
   different osc. prob. (velocity eigen state),
   no $\nu$ mass dependence but $L/E$

(B) observing higher UHE $\nu$ flux than that of WB bound:
   $E_{\text{thresh}}$ for $\nu$ interactions can be modified by VLI
VLI Preliminary Result

--- AMANDA data (3.8 live years) showed **no evidence** for $\nu$ osc. Induced by VLI

--- $\delta c/c < 2.8 \times 10^{-27}$ (90%CL) with $P_{\nu_\mu \rightarrow \nu_\mu}$ (maximal mixing)

cf. SuperK + K2K limit: $\delta c/c < 1.9 \times 10^{-27}$ (90%CL)

$\xi$: VLI mixing angle in 2 flavor system

$\Delta \delta = \delta c/c$
IceCube Deployment Status

In 2008, 40 strings (50%) taking physics data

(98% DOMs are fully functional.)

In 2008, 40 strings (50%) taking physics data

Deployed 15+1 strings in 2008/09
Future: Deep Core

• To improve low E event efficiency
  -- indirect DM search, atm. ν osc, etc..

• total 6 strings (75 m apart)
  cf. nominal strings: 125 m apart

• 60 DOMs/string
  -- high QE DOMs
    (~ 35% more light yield)
  -- DOMs are densely spaced

• 4 π detector:
  -- veto surrounding bottom inner core (6 DC + 7 IC)
  -- explore southern sky as well as Galactic Center
\( \nu \) Effective Area Comparison

\( \nu \) effective area increased by deep core in low E region

Preliminary
Conclusion

- IceCube has been taking data smoothly with > 50% detector: 100% detector is expected in 2011.

- We have very interesting results with IceCube 22 strings and complete AMANDA 7 years data, which will be published soon.

- However we have no evidence for a source of extra-terrestrial neutrinos yet.

- IceCube deep core will play a critical role in low E physics including indirect Dark Matter search.

- Future extensions optimized for EHE neutrinos are being considered.
Swedish ice breaker

LC-130 Hercules landing at SPole

Thank you!

IceCube Counting House

Myself 01.31.2006
Backup slides
Search for $\nu$ from GRB

Time window search:
--- search around GRB duration ($T_{90}$):
  this reduces BG significantly.
--- use GRB trigger info from other exp. (BATSE, Swift, Fermi, etc…)

Rolling search:
--- scan through all the data in a given year and search for a statistically significant signal within a fixed time duration.
ν Flux Limits from GRB

All flavor limits by AMANDA

ν_e + ν_e + ν_μ + ν_μ + ν_τ + ν_τ

Cascade (Rolling)

Cascade (Trig & Roll)

ν_μ search:
Over 400 Northern Hemisphere GRBs

Cascade search
Trigger search with 73 GRBs
Rolling search for 2001-2003

--R03b:
Supranova model

--WB03:
Waxman-Bahcall model

--R03a:
Choked Burst model

--MN06:
Murase Nagataki model

ν_μ search:
Over 400 Northern Hemisphere GRBs

Cascade search
Trigger search with 73 GRBs
Rolling search for 2001-2003
-- Relativistic monopoles will leave very bright track in ice medium:
\[ \sim 8300 \times \text{muon} \]
\[
(g^2 = \left[ \frac{n^*e}{(2\alpha)} \right]^2 = \sim 8300 \ e^2 \text{ for } n = 1.33)
\]

-- Slowly moving (down to $\beta \sim 0.5$) monopoles can be detected via $\delta$ electrons generated along the monopole path.

-- IceCube will be large improvement
  - Bigger effective area

-- IceCube will push limit towards
\[ \sim 10^{-19} \ \text{cm}^{-2} \ \text{s}^{-1} \ \text{sr}^{-1} \]
GUT Magnetic Monopole

- grand unification core
  - virtual X-bosons ($10^{-29}$ cm)
- electroweak unification
  - virtual $W, Z, \gamma, g$ ($10^{-16}$ cm)
- confinement region
  - $g, \gamma$ ($10^{-13}$ cm)
- condensate
  - fermion-antifermion pairs ($r \sim m_f^{-1}$)