The next generation of Neutrino telescopes - ICECUBE
Design and Performance, Science Potential

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Munich
The IceCube Collaboration

Institutions: 11 US, 9 European institutions and 1 Japanese institution; ≈110 people

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19. Vrije Universiteit Brussel, Brussel, Belgium
20. Chiba University, Japan
Outline of Talk

1. Overview
2. Muon neutrinos from:
   •   a) diffuse sources
   •   b) point sources
   •   c) Gamma ray bursts
3. Electron Neutrinos: Cascades
4. Tau Neutrinos
5. The surface component: IceTop
6. Detector: Optical sensor
7. Summary
IceCube has been designed as a discovery instrument with improved:

- telescope area
- detection volume
- energy measurement of secondary muons and electromagnetic showers
- identification of neutrino flavor
- angular resolution
IceCube

• 80 Strings
• 4800 PMT
• Instrumented volume: 1 km$^3$
  (1 Gt)
Project status

- Approved by the National Science Board
- Startup funding is allocated.
- Construction is in preparation (Drill, OM design, OM production, DAQ and test facilities).
- Construction start in 04/05; possibly a few initial strings in 03/04.
- Flavours and energy ranges

- Filled area: particle id, direction, energy
- Shaded area: energy only
- Detect neutrinos of all flavours at energies from $10^7$ eV (SN) to $10^{20}$ eV
Neutrino sky as seen by AMANDA

Monte Carlo methods are verified on data.

Methods are not yet optimized and fully developed for high energies.
### Signals and Background rejection

**Backgrounds:**
- Atmospheric neutrinos
- Cosmic ray muons (misreconstructed downgoing)

<table>
<thead>
<tr>
<th>Type of Neutrino source</th>
<th>Rejection method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Diffuse source (AGN, GRB, ..)</td>
<td>Up/Down: &lt;1E-8 and energy*</td>
</tr>
<tr>
<td>2. Point Sources (AGN, WIMP)</td>
<td>&amp;&amp; Direction</td>
</tr>
<tr>
<td>3. Burstlike Point Sources (GRB or AGN with time structure)</td>
<td>&amp;&amp; Time Stamp (GRB: secs, AGN: h,d)</td>
</tr>
</tbody>
</table>

*At very high energies (>≈PeV), the downgoing signals can be accepted*
Track reconstruction in low noise environment

- Typical event: 30 - 100 PMT fired
- Track length: 0.5 - 1.5 km
- Flight time: ≈4 µsecs
- Accidental noise pulses: 10 p.e. / 5000 PMT/4µsec

AMANDA-II

10 TeV

1 km
Angular resolution < 1° (med)

- Resolution ≈ 0.8 deg (median)
- Improves slightly with energy
- Better near horizon: ≈0.7° (Sample more strings)

Search bin ≈ 1.0°
Solid angle: \(2\pi/6500\)
Effective area for muons

Geometric detector area = 1km²
Eff. area = $A_{\text{gen}} \times \left(\frac{N_{\text{det.}}}{N_{\text{gen}}}\right)$
Efficiency $\approx$ effective area/km²

Muon energy is the energy at closest approach to the detector

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

- Trigger: allows non contained events
- Quality cuts: for background rejection
- Point source selection: soft energy cut for atmos. neutrino rejection (Assumed spectrum: $E^{-2}$, time of exposure 1 year)
Effective areas are given after quality cuts (including up/down separation where needed).

Note that the detector is sensitive to downward going muons at energies above 1 PeV.
### Point sources: event rates

Flux equal to current AMANDA limit
\[ \frac{dN}{dE} = 10^{-6}E^{-2}/(\text{cm}^2 \text{ sec GeV}) \]

<table>
<thead>
<tr>
<th></th>
<th>Atmospheric Neutrinos</th>
<th>AGN* (E^{-2})</th>
<th>Sensitivity (E^{-2}/(cm^2 sec GeV))</th>
</tr>
</thead>
<tbody>
<tr>
<td>All sky/year (after quality cuts)</td>
<td>100,000</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Search bin/year</td>
<td>20</td>
<td>2300</td>
<td>-</td>
</tr>
<tr>
<td>1 year: Nch &gt; 32</td>
<td>0.91</td>
<td>610</td>
<td>5.3 x 10^{-9}</td>
</tr>
<tr>
<td>3 year: Nch &gt; 43 (7 TeV)</td>
<td>0.82</td>
<td>1370</td>
<td>2.3 x 10^{-9}</td>
</tr>
</tbody>
</table>
Compare to Mrk 501 gamma ray flux

Field of view:
Continuous
24 h x 2 π sr
(northern sky)

Sensitivity of 3 years of IceCube
Point source sensitivity

\[ E^2(dN/dE) \text{ [GeV cm}^{-2}\text{s}^{-1}] \]

\[ E_{\nu} \text{ (GeV)} \]

- AMANDA-II (3 yr)
- AMANDA-B10 ('97)
- 3C273
- Crab
- AGN Core
- IceCube
- Atm. \( \nu \)}
Search for diffuse $\nu$-fluxes

Method:

1. Assume a diffuse neutrino flux (Hypothesis), e.g. the current AMANDA limit:
   \( \frac{dN}{dE} = 10^{-6}E^{-2}/(\text{cm}^2 \text{ sec GeV sr}) \)
   -> 11,500 events/year

2. The background is the atmospheric neutrino flux (after quality cuts): = 100,000 events/year

3. Apply energy cut.
Energy reconstruction

Small detectors: Muon energy is difficult to measure because of fluctuations in dE/dx.

IceCube: Integration over large sampling + scattering of light reduces the fluctuations in energy loss.

\[ E_\mu = 10 \text{ TeV} \approx 90 \text{ hits} \]

\[ E_\mu = 6 \text{ PeV} \approx 1000 \text{ hits} \]
Event rates before and after energy cut

Note:
- Neutrinos from Charm production included according to: Thunman, Ingelmann, Gondolo, Astropart. Phys. 5:309-332, 1996
• Optimize energy cut.
• Sensitivity of IceCube after 3 years of operation (90% c.l.):

$$\frac{dN}{dE} \leq 4.8 \times 10^{-9} \times E^{-2} \text{/(cm}^2 \text{ sec GeV)}$$
Example: Diffuse Fluxes - Predictions and Limits

from Mannheim & Learned, 2000

1. pp core AGN (Nellen)
2. pγ core AGN (Stecker & Salomon)
3. pγ „maximum model“ (Mannheim et al.)
4. pγ blazar jets (Mannheim)
5. pγ AGN (Rachen & Biermann)
6. pp AGN (Mannheim)
7. GRB (Waxman & Bahcall)
8. TD (Sigl)

IceCube
Macro
Baikal
Amanda
Sensitivity after 3 years
Look for excess of muons from the direction of the sun or the center of the earth.
WIMPs from the Sun with IceCube

- IceCube will significantly improve the sensitivity.
- Similar sensitivity to GENIUS, ...
Neutrinos from Gamma Ray Bursts

Reject background by:

- Energy (number of fired PMT)
- Angle (circular bin of 1° radius)
- Time ($\approx 10$ sec/GRB, coincident to known GRB, gamma ray signal, e.g. from satellite detector)
Neutrinos from Gamma Ray Bursts

For 1000 GRB observed:

- Expected signal: 11 upgoing muon events
- Expected background: 0.05 events

Essentially background free detector:
Only 200 GRB needed to detect standard fireball prediction (Waxman/Bahcall 99)
The length of the actual cascade, $\approx 10$ m, is small compared to the spacing of sensors

$\Rightarrow \approx$ roughly spherical density distribution of light

$1 \text{ PeV} \approx 500$ m diameter

Local energy deposition = good energy resolution of neutrino energy

Cascade event

$\nu_e + N \rightarrow e^- + X$

Energy = 375 TeV
Event rates of cascades ($\nu_e$)

Assumed flux: $\frac{dN}{dE} = 10^{-7}E^{-2}/(\text{cm}^2 \text{ sec GeV sr})$

Rates at trigger level
Effective volume after background rejection: 1 km$^3$ for $E>30\text{TeV}$
Double Bang

$\nu_\tau + N \rightarrow \tau^- + X$

$\nu_\tau + X (82\%)$

Regeneration makes Earth quasi transparent for high energy $\nu_\tau$; (Halzen, Salzberg 1998, …) Also enhanced muon flux due to Secondary $\mu$, and $\nu_\mu$ (Beacom et al., astro/ph 0111482)

$E \ll 1\text{PeV}$: Single cascade (2 cascades coincide)

$E \approx 1\text{PeV}$: Double bang

$E \gg 1\text{PeV}$: partially contained (reconstruct incoming tau track and cascade from decay)
$\nu_\tau$ at $E>\text{PeV}$: Partially contained

- The incoming tau radiates little light.
- The energy of the second cascade can be measured with high precision.
- Signature: Relatively low energy loss incoming track: would be much brighter than the tau (compare to the PeV muon event shown before)

Result: high eff. Volume; Only second bang needs to be seen in Ice3

10-20 OM early hits measuring the incoming $\tau$-track

**Photoelectron density**

**Timing, realistic spacing**
Shown is the expected photoelectron signal density of a tau event. The first $\nu_\tau$ interaction is at $z=0$, the second one at $\approx 225$ m. The diagram spans about 400 m x 800 m.
Capture Waveform information (MC)

- Complex waveforms provide additional information

Events / 10 nsec

0 - 4 μsec

E=10 PeV
Design parameters:

- Time resolution: $\leq 5 \text{ nsec}$ (system level)
- Dynamic range: 200 photoelectrons/15 nsec
- (Integrated dynamic range: $> 2000$ photoelectrons)
- Digitization depth: 4 $\mu$sec.
- Noise rate in situ: $\leq 500$ Hz

For more information on the Digital Optical Module: see poster by R. Stokstad et al.
Coincident events

• Two functions
  – veto and calibration
  – cosmic-ray physics

• Energy range:
  – \( \sim 3 \times 10^{14} \) -- \( 10^{18} \) eV
  – few to thousands of muons per event

• Measure:
  – Shower size at surface
  – High energy muon component in ice

• Large solid angle
  – One IceTop station per hole
  – \( \sim 0.5 \) sr for C-R physics with “contained” trajectories
  – Larger aperture as veto
Schematic of IceTop detector

- Two Ice Cherenkov tanks at top of each IceCube hole
  - Each 3.6 m²; local coincidence for muon vs. shower discrimination
  - Calibration with single muons @ ~1KHz per tank
- Integrated into IceCube
  - construction
  - trigger
  - data acquisition
- Heritage:
  - Haverah Park
  - Auger
Expectation for coincident events

• $\sim 10^9$ IceTop-IceCube coincidences/year
• Calibration beam for IceCube
• $\sim 100$/day with multi-TeV $\mu$ in IceCube
• Air shower physics to $10^{18}$ eV

Some numbers:
Shower energy
Number of muons / shower
Number of events / year

<table>
<thead>
<tr>
<th>$E_{\text{shower}}$ log(E/eV)</th>
<th>Log($N_\mu$) (1500m)</th>
<th>Events/ year</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>20</td>
<td>5e7</td>
</tr>
<tr>
<td>16</td>
<td>130</td>
<td>5*105</td>
</tr>
<tr>
<td>17</td>
<td>700</td>
<td>5000</td>
</tr>
<tr>
<td>18</td>
<td>4000</td>
<td>50</td>
</tr>
</tbody>
</table>
SPASE - AMANDA: Energy resolution of air shower primary

Energy resolution of air shower primary for $1 < E/\text{PeV} < 10$:

$$\sigma_E \approx 7\% \log(E)$$

(Mass independent; based on MC)
Measuring mass and energy of cosmic ray primary particle

Unfolding energy and mass using SPASE and AMANDA
Supernova detection in IceCube

- $\nu_e + p \rightarrow n + e^+ (10-40 \text{ MeV})$
- Low PMT noise (<500Hz) increase due to the positrons
- AMANDA/IceCube records noise on the PMTs over 0.5 sec and summing up total rate over 10 sec intervals.
- Detectors to be connected to Supernova Early Warning System

AMANDA

SPASE-2

100 m

Grid

North

IceCube

Skiway

South Pole

Dome
Project status

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• Startup funding is allocated.
• Construction is in preparation (Enhanced Hotwater Drill, OM design, OM production facilities, DAQ and test facilities).
• Construction start in 04/05; possibly a few initial strings in 03/04.
• Then 16 strings per season, increased rate may be possible.
Summary

- IceCube array allows
  - Very good event reconstruction (E, θ, ϕ).
  - High sensitivity to muon-, electron-, tau-neutrinos.
  - Particle identification over wide energy range.
- IceCube is a multipurpose detector covering a wide range of energies, signals, discovery potentials.
- Size and quality of information provides sensitivity in discovery range.
- Construction is in preparation.