Neutrino Astronomy with the IceCube Observatory

Implications for Astroparticle Physics

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University of Wisconsin - Madison

Vulcano Workshop May 30, 2008
Outline

neutrinos

cosmic rays

gamma rays

neutrino astronomy

particle physics

toward a km³ Observatory

AMANDA & IceCube
galactic cosmic rays
galactic cosmic rays

observed energy density
\[ \rho \sim 10^{-12} \text{ erg/cm}^3 \]

\[ \equiv \]

supernova remnants
\[ \sim 10^{50} \text{ erg / 50 years} \]
\[ \rho \sim 10^{-12} \text{ erg/cm}^3 \]

\[ \downarrow \]

\[ \Rightarrow \] SNR as sources of galactic cosmic rays

\[ \Rightarrow \] shock front from Supernovæ ... PeVatrons

T.K. Gaisser, T. Stanev - PDG
solar shock acceleration
well known

observed shocks in SNR

p + (p or \(\gamma\)) \rightarrow \pi^{\pm} + X \rightarrow \nu_{e}, \nu_{\mu} + X \quad \text{neutrinos ...}
\rightarrow \pi^{0} + X \rightarrow \gamma \gamma + X \quad \text{gamma rays ...}

Flux \sim E_{p}^{-2} \quad \text{(Fermi acceleration)}

protons @ knee produce \sim 300\text{ TeV} \gamma \text{ rays}

neutrino and gamma
connection

Chandra
SN 1006
$\gamma$ ray observations

**HESS/Magic observations $\approx 10$'s TeV**

PeV particles escape within $\sim 1,000$ yr

low energy particles mostly confined and released in later times

only young SNR ($\approx 1,000$ yr) emit $>10$ TeV $\gamma$ rays and $\nu$

PeV particles hitting molecular clouds can produce *delayed* multi-TeV $\gamma$ rays and $\nu$

hard spectra because not yet steepened by diffusion

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[Graphical representation of SNR and CLOUD at 1 Kpc showing energy vs. time distribution, with indications for Cherenkov telescopes (e.g. HESS, Magic) and Air shower arrays (Milagro).]
γ ray observations

TeV γ rays in correlation with molecular clouds
hadronic acceleration?

Aharonian et al., Nature 439 (2006), 695
HESS: RX J1713 TeV γ rays in correlation with molecular clouds hadronic acceleration?

- Diffuse Model
- Sgr B Region
- HESS J1745-290

Hard spectral index $2.29 \pm 0.07 \pm 0.20$

CR propagation model in 10,000 years from GC

Aharonian et al., Nature 439 (2006), 695
γ rays and ν’s

Milagro measurement at ~100 TeV

strong indication of proton acceleration

ν’s as uncontroversial sign of hadronic acceleration

⇒ Neutrino Telescopes
extra-galactic cosmic rays

observed energy density
\( \rho \sim 3 \times 10^{-19} \text{ erg/cm}^3 \times 10^{10} \text{y} \)
\( \rho \sim 10^{44} \text{ erg/yr/Mpc}^3 \)
\( \cong \)
GRB
\( \sim 10^{51} \text{ erg} \times 300/\text{y/Gpc}^3 \)
\( \rho \sim 10^{44} \text{ erg/yr/Mpc}^3 \)
\( \Downarrow \)
GRB/AGN as source candidates of extra-galactic cosmic rays

\( \Rightarrow \)
large sizes and intense magnetic fields
Protons with $E > 10^{19}$ eV almost undeflected

Cosmic rays above $6 \times 10^{19}$ eV

Consistent with GZK cutoff

Protons from nearby AGN sources with $p$-value $= 1.7 \times 10^{-3}$

To be confirmed with more experimental data
neutrinos and cosmic rays

nearby AGN (as Cen A) possible hadronic acceleration sites and sources of TeV \( \gamma \) rays

if \( \gamma \) rays flux from Cen A is from \( \pi \) and normalizing to Auger observation

\[
\frac{dN_\nu}{dE} \leq 5 \times 10^{-13} \left( \frac{E}{\text{TeV}} \right)^{-2} \text{TeV}^{-1} \text{cm}^{-2} \text{s}^{-1}
\]

\[\downarrow\]

\[
\frac{dN_\nu}{dE_{\text{diff}}} = 2 \times 10^{-9} \left( \frac{E}{\text{GeV}} \right)^{-2} \text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}
\]
neutrinos and GZK cutoff

Auger suggests a CR composition heavier than pure $H \approx 10^{19} \text{ eV}$
even if dip at $\sim 10^{19} \text{ eV}$ is signature of $p\gamma_{\text{CMB}} \rightarrow e^+e^-$

if heavy CR then cosmogenic $\nu$'s are suppressed

Auger spectrum & composition consistent with $\sim$CNO masses or $p+Fe$ mixture. But NOT consistent with injected $p/He$ only.

L.A. Anchordoqui, et al., arXiv:0709.0734v1
neutrinos and GZK cutoff

Auger suggests a CR composition heavier than pure H $\approx 10^{19}$ eV

even if dip at $\sim 10^{19}$ eV is signature of $p\gamma_{\text{CMB}} \rightarrow e^+e^-$

if heavy CR then cosmogenic $\nu$'s are suppressed

<table>
<thead>
<tr>
<th>Auger sp mix</th>
<th>50% Fe, 50% p</th>
<th>1.6-2.1</th>
<th>$10^{22}$ eV</th>
<th>0.15-0.043</th>
<th>0.11-0.034</th>
</tr>
</thead>
<tbody>
<tr>
<td>10% Fe, 90% p</td>
<td>1.4-1.9</td>
<td>$10^{21}$ eV</td>
<td>0.14-0.10</td>
<td>0.11-0.080</td>
<td></td>
</tr>
<tr>
<td>3% Fe, 97% p</td>
<td>2.1</td>
<td>$10^{22}$ eV</td>
<td>0.68</td>
<td>0.51</td>
<td></td>
</tr>
<tr>
<td>1% Fe, 99% p</td>
<td>1.4-1.9</td>
<td>$10^{21}$ eV</td>
<td>0.74-0.53</td>
<td>0.59-0.43</td>
<td></td>
</tr>
<tr>
<td>p+Fe mix</td>
<td>100% p (for comparison)</td>
<td>2.2</td>
<td>$10^{22}$ eV</td>
<td>0.76</td>
<td>0.60</td>
</tr>
</tbody>
</table>

L.A. Anchordoqui, et al., arXiv:0709.0734v1

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Who is in IceCube?

University of Canterbury, Christchurch, New Zealand
Chiba University, Japan
Clark-Atlanta University, USA
Univ. of Maryland, USA
University of Kansas, USA
Southern Univ. and A&M College, Baton Rouge, LA, USA
University of Alaska – Anchorage, USA
Institute for Advanced Study, Princeton, NJ, USA
Bartol Research Inst, Univ of Delaware, USA
Pennsylvania State University, USA
University of Wisconsin-Madison, USA
University of Wisconsin-River Falls, USA
LBNL, Berkeley, USA
UC Berkeley, USA
UC Irvine, USA

Univ. of Wisconsin-Madison, USA

Univ. of Wisconsin-River Falls, USA

University of Alaska – Anchorage, USA

Institute for Advanced Study, Princeton, NJ, USA

LBNL, Berkeley, USA

UC Berkeley, USA

UC Irvine, USA

Univ. of Wisconsin-Madison, USA

University of Alaska – Anchorage, USA

Institute for Advanced Study, Princeton, NJ, USA

LBNL, Berkeley, USA

UC Berkeley, USA

UC Irvine, USA

Université Libre de Bruxelles, Belgium
Vrije Universiteit Brussel, Belgium
Université de Mons-Hainaut, Belgium
Universiteit Gent, Belgium
Universität Mainz, Germany
RWTH Aachen Universität, Germany

DESY Zeuthen, Germany
Universität Wuppertal, Germany
Universität Dortmund, Germany
Humboldt Universität, Germany
MPIfK Heidelberg, Germany

Uppsala Universitet, Sweden
Stockholms Universitet, Sweden
University of Oxford, UK
Universiteit Utrecht, Netherland

Amundsen-Scott Station, Antarctica
IceCube Observatory

$14\text{ km}^3$

neutrino telescope

IceTop
Air shower detector threshold $\sim 300\text{ TeV}$

IceCube

2007-2008:
18 Strings

2006-2007:
13 Strings
total of 40 Strings

2005-2006:
8 Strings

2004-2005:
1 String
first data 2005
upgoing muon 18.
Juli 2005

AMANDA
19 Strings
677 Modules

InIce
70-80 Strings,
60 Optical Modules
17 m between Modules
125 m between Strings

Accumulated Exposure at 100 TeV

AMANDA/IceCube muon
accumulated exposure

Antares deployment
Apr. 2008 KM3NeT CDR
detecting neutrinos

preliminary unfolded atmospheric neutrino spectrum

\[ \Theta_{\mu\nu} \approx 0.65^\circ (E_\nu / \text{TeV})^{-0.48} \]

(3 TeV < \( E_\nu < 100 \text{ TeV} \))

limits on charm production in AMANDA-II 2000-2003

\[ \Phi(E^2, E_{\nu}^2) \, \text{d}E \, \text{d}E' \]

Barr et al. atm. \( \nu \)

Honda et al. atm. \( \nu \)

Max uncertainty in atm. \( \nu \)

Martin GBW model

Martin GBW 2000-3 AMANDA-II limit

Naumov ROPM model

Naumov ROPM 2000-3 AMANDA-II limit

CharmC model

CharmC 2000-3 AMANDA-II limit

CharmD model

CharmD 2000-3 AMANDA-II limit
detecting neutrinos

IceCube-9

atmospheric $\nu_\mu$

experimental data

1.7 events / day
3% efficiency @ 90% purity

exp : 234 events         ($\theta > 100^\circ$)
sim : $211 \pm 76.1$ (syst) $\pm 14.5$ (stat)

detecting neutrinos

IceCube-9

atmospheric $\nu^\mu$

experimental data

J. Pretz

1.7 events / day
3% efficiency @ 90% purity

exp : 234 events (\(\theta>100^\circ\))

sim : 211\(\pm76.1\) (syst)\(\pm14.5\) (stat)

IceCube-22

preliminary on going analysis

D. Chirkin
detecting neutrinos

IceCube-9

1.7 events / day
3% efficiency @ 90% purity
exp : 234 events         (θ>100°)
sim : 211±76.1(syst)±14.5(stat)

IceCube-22
preliminary on going analysis

28 events / day
25% efficiency @ 95% purity
understanding the background
understanding the background

Through-Going Muon Zenith Angle Distribution (PRELIMINARY)

- Data 2000 - 2003
- Uncertainty in atmospheric \( \nu \) flux
- Bartol atms. \( \nu \) model
- Honda atms. \( \nu \) model
- Bartol & Honda av. atms. \( \nu \) model
- dCorsika atms. \( \mu \)
- Signal \( \nu \)

Cosine of Reconstructed Zenith Angle

Intensity (\( \mu/cm^2/sr \))

- Atmospheric Muons
- \( \nu_\mu \) Induced Flux (No oscillations)
- \( \nu_\mu \) Induced Flux (SK\( \nu_\mu \rightarrow \nu_\mu \))
- All Sky Data, 149 days

J. Hodges, G. Hill

understanding the background
understanding the background

- Trigger Level
- Final Cut Level

IceCube-22 2007
preliminary

- Single Atm. Muons
- Coincident Atm. Muons
- Atm. Neutrinos (Bartol et al.)
- Data

C. Finley
**astrophysical neutrinos: point sources**

**AMANDA-II 2000-2006**

- Maximum significance = \(3.38\sigma\) near \((11.4h, +54^\circ)\)
- 95% chance to obtain maximum significance \(\geq 3.38\sigma\) in random skymaps

- Preliminary

- 6595 events in 3.8 yr
- 4.8 events / day
- 23% efficiency @ 95% purity

- Sensitivity and flux limit

- Median angular resolution: \(1.5^\circ \downarrow - 2.5^\circ \rightarrow\)
astrophysical neutrinos: point sources

AMANDA-II 2000-2006

Abdo thesis defense, March 2007

6595 events in 3.8 yr
4.8 events / day
23% efficiency @ 95% purity

median angular resolution
1.5° ↓ - 2.5° →
The probability of obtaining a p-value = 0.0086 for at least one of the 26 sources is 20%.

The 90% confidence level limit on the per-source flux for the six sources, excluding systematics, is $9.6 \times 10^{-12}$ TeV cm$^{-2}$ s$^{-1}$ over the energy region 1.8 TeV - 2.1 PeV.
IceCube-9 2006

234 events in 137.4 days
1.7 events / day
median angular resolution $\sim 2^\circ$

maximum significance = $3.35\sigma$ near (18.4h, +20.4°)

60% chance to obtain maximum significance $\approx 3.35\sigma$ in random skymaps

highest fluctuation on the list of 26 sources is $\sigma = 1.77$ (p-value = 0.04) in the direction of Crab Nebula

the probability for a p-value = 0.04 for at least one of the 26 sources is 65%.
astrophysical neutrinos: point sources

IceCube-22 2007

simulated skymap

285 days livetime
20-30 events / day
median angular resolution $\sim 1.5^\circ$

IC-22 expected to be x5 more efficient & x7 more sensitive than IC-9

preliminary on going analysis

C. Finley, J. Dumm
astrophysical neutrinos: diffuse sources

AMANDA-II 2000-2003 \(\rightarrow\) IceCube

\(E^2 \Phi < 7.4 \times 10^{-8}\) GeV cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\)

\(dN_\nu / dE_{\text{diff}} = 2 \times 10^{-9} \left(\frac{E}{\text{GeV}}\right)^{-2}\) GeV\(^{-1}\) cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) → Auger - diffuse as reference

astrophysical neutrinos: UHE diffuse sources

AMANDA -II 2000-2002

$E^2 \Phi_{\nu_{\text{diff}}}(E) [\text{GeV} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}]$

$10^{-7}$

$10^{-7}$

$4$ $5$ $6$ $7$ $8$ $9$ $10$ $11$

$log_{10}(E_\nu [\text{GeV}])$

Pred. Lim. Model

- ▲ P96
- ■ M95 RL B
- ○ H&Z97
- * St05
- ● MPR00

$E^2 \Phi_{\nu_{\text{diff}}}(E) [\text{GeV} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}]$

$10^{-6}$

$10^{-7}$

$4$ $5$ $6$ $7$ $8$ $9$ $10$ $11$ $12$ $13$

$log_{10}(E_\nu [\text{GeV}])$

AMANDA-B10

Z-Burst (Yosh98)

ATm (Lip93)

ANITA-lite

RICE

AMANDA-II cascade

Baikal

TD (Si98)

AMANDA-II diffuse x3

AGN (P96) x 3/2

AGN (St05) x3

GZK (Eng01)

WB x 3/2 max evol

L. Gerhardt

astrophysical neutrinos: UHE diffuse sources

AMANDA-II 2003-2004 ⟹ IceCube

5σ detection

preliminary

J. Lundberg

astrophysical neutrinos: UHE diffuse sources

AMANDA-II 2003-2004 ⟹ IceCube

analyzing IceCube data to detect diffuse HE/UHE/EHE neutrinos

IceCube-80 predicted to improve sensitivity by at least \( x10 \)
astrophysical neutrinos: UHE diffuse sources

AMANDA -II 2003-2004 ⟹ IceCube

Analyzing IceCube data to detect diffuse HE/UHE/EHE neutrinos.

IceCube-80 predicted to improve sensitivity by at least x10 as reference.

5σ detection preliminary.

J. Lundberg

conclusions

• AMANDA has had an excellent role in developing neutrino telescopes

• a km$^3$ neutrino observatory is under construction at the South Pole

• will collect unprecedented statistics of neutrinos

• sensitivities closer to neutrino predictions
  • origin of cosmic ray and gamma ray connection
  • smoking gun for hadronic processes in CR sources
  • probe GZK neutrinos

• planning multi-messenger campaigns

• IceCube data filtered online and processed North for short-term analysis

• will be complete in 2011: 4,800 DOMs InIce and 320 DOMs @ IceTop
spare slides
neutrino statistics

<table>
<thead>
<tr>
<th>geometry</th>
<th>year</th>
<th>livetime</th>
<th>up muons</th>
<th>efficiency</th>
<th>purity</th>
<th>status</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC-9</td>
<td>2006</td>
<td>137.4 d</td>
<td>233 (1.7/d)</td>
<td>3%</td>
<td>~90%</td>
<td>final</td>
</tr>
<tr>
<td>IC-22</td>
<td>2007</td>
<td>285 d</td>
<td>~7,980 (~28/d)</td>
<td>25%</td>
<td>95%</td>
<td>preliminary</td>
</tr>
<tr>
<td>IC-40</td>
<td>2008</td>
<td>~365 d</td>
<td>~40,000 (110/d)</td>
<td></td>
<td></td>
<td>predicted</td>
</tr>
<tr>
<td>IC-80</td>
<td>2011</td>
<td>~365 d</td>
<td>~80,000 (220/d)</td>
<td></td>
<td></td>
<td>predicted</td>
</tr>
</tbody>
</table>

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Graph showing energy distribution with different geometric configurations.
alternative oscillations
Violation of Lorentz Invariance

AMANDA -II 2000-2006

neutrinos have distinct maximum velocity eigenstates $\neq c$, and difference $\delta c/c$ results in oscillations

\[
P_{\nu\mu\rightarrow\nu\mu} = 1 - \sin^2 2\Theta \sin^2 \left( \frac{\Delta m^2 L}{4E} \mathcal{R} \right)
\]

\[
\sin^2 2\Theta = \frac{1}{\mathcal{R}^2} \left( \sin^2 2\theta_{23} + R^2 \sin^2 2\xi + 2R \sin 2\theta_{23} \sin 2\xi \cos \eta \right)
\]

\[
\mathcal{R} = \sqrt{1 + R^2 + 2R(\cos 2\theta_{23} \cos 2\xi + \sin 2\theta_{23} \sin 2\xi \cos \eta)}
\]

\[
R = \frac{\delta c \ E}{c \ 2 \ \Delta m^2_{23}}
\]

maximal mixing, $\delta c/c = 10^{-27}$
Violation of Lorentz Invariance

AMANDA -II 2000-2006 : sensitivity

\[ P_{\nu_\mu \rightarrow \nu_\mu} = 1 - \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E} \right) \]
\[ \sin^2 2\theta = \frac{1}{\mathcal{R}^2} \left( \sin^2 2\theta_{23} + R^2 \sin^2 2\xi + 2R \sin 2\theta_{23} \sin 2\xi \cos \eta \right) , \]
\[ \mathcal{R} = \sqrt{1 + R^2 + 2R (\cos 2\theta_{23} \cos 2\xi + \sin 2\theta_{23} \sin 2\xi \cos \eta)} , \]
\[ R = \frac{\delta c}{c} \frac{E}{2 \Delta m^2_{23}} \]

- 2000-03 analysis (Ahrens):
  \[ \delta c/c < 5.3 \times 10^{-27} \text{ (90\%CL)} \]
- Median sensitivity (\(\chi^2\) approx.):
  \[ \delta c/c < 4.3 \times 10^{-27} \text{ (90\%CL)} \]
- Sample sensitivity (1 MC experiment, full construction):
  \[ \delta c/c < 4.5 \times 10^{-27} \text{ (90\%CL)} \]
  (maximal mixing, \(\cos \eta = 0\))
Violation of Lorentz Invariance

AMANDA -II 2000-2006 : sensitivity

\[ P_{\nu_\mu \rightarrow \nu_\mu} = 1 - \sin^2 2\Theta \sin^2 \left( \frac{\Delta m^2 L}{4E} \right) \]

\[ \sin^2 2\Theta = \frac{1}{\mathcal{R}^2} \left( \sin^2 2\theta_{23} + R^2 \sin^2 2\xi + 2R \sin 2\theta_{23} \sin 2\xi \cos \eta \right) , \]

\[ \mathcal{R} = \sqrt{1 + R^2 + 2R(\cos 2\theta_{23} \cos 2\xi + \sin 2\theta_{23} \sin 2\xi \cos \eta) ,} \]

\[ R = \frac{\delta c}{c} \frac{E}{2 \Delta m^2_{23}} \]

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  (maximal mixing, \(\cos \eta = 0\))

Gonzalez-Garcia, astro-ph/0701333
Quantum Decoherence

interaction with foamy space-time structure may modify neutrino flavor

\[ P[\nu_\mu \rightarrow \nu_\mu] = \frac{1}{3} + \frac{1}{2} \left( e^{-\gamma L \cos^4 \theta_{23}} + \frac{1}{12} e^{-\gamma L (1 - 3 \cos 2 \theta_{23})^2} + 4e^{-\frac{\gamma L}{2} \cos^2 \theta_{23} \sin^2 \theta_{23}} \left( \cos \frac{L}{2} \sqrt{\left( \gamma_6 - \gamma_7 \right)^2 - \left( \frac{\Delta m^2_{43}}{E} \right)^2} \right) + \sin \frac{L}{2} \sqrt{\left( \gamma_6 - \gamma_7 \right)^2 - \left( \frac{\Delta m^2_{43}}{E} \right)^2} \right) \]

1:1:1 ratio after decoherence

characteristic exponential behavior

derived from Barenboim, Mavromatos et al. (hep-ph/0603028)

Energy dependence depends on phenomenology: \( \gamma_n = \gamma^n E^n, \ n \in \{-1, 0, 2, 3\} \)

- \( n = -1 \): preserves Lorentz invariance
- \( n = 0 \): simplest
- \( n = 2 \): recoiling D-branes
- \( n = 3 \): Planck-suppressed operators

*Ellis et al., hep-th/9704169
† Anchordoqui et al., hep-ph/0506168
Quantum Decoherence

AMANDA -II 2000-2006 : sensitivity

- ANTARES sensitivity (3 years)*:
  \[ \gamma^* < 2 \times 10^{-30} \text{ GeV}^{-1} \text{ (2-flavor)} \]

- This analysis (1 MC experiment, full construction):
  \[ \gamma^* < 2.0 \times 10^{-31} \text{ GeV}^{-1} \]
  
  (E^2 model, \( \gamma_3 = \gamma_8 = \gamma_6 = \gamma_7 \))

* Morgan et al., astro-ph/0412618
atmospheric neutrino deconvolution

AMANDA - II 2000-2006

2 parameter spectrum deconvolution


\[ \Phi_V = K \cdot \Phi_{\text{Bartol}} \cdot E^{-\delta \gamma} \]

99% CL excluded

J. Kelley

benchmark DPMJET-II with recent accelerator data

use charm production in CORSIKA

propagate charmed particles in CORSIKA
charm in the atmosphere

LEBC-EHS (all D)

LEBC-MPS (all D)

charm in the atmosphere

**SELEX (Λ⁺)**

- Red: DPMJET (old)
- Blue: DPMJET (new)
- Green: DPMJET (bugfix)
- Black: Experimental

**SELEX (Λ₋)**

- Red: DPMJET (old)
- Blue: DPMJET (new)
- Black: Experimental

**SELEX (Λ_c)**

- Red: DPMJET (old)
- Blue: DPMJET (new)
- Green: DPMJET (bugfix)
- Black: Experimental

**SELEX (540 GeVp)**

- Red: DPMJET (old)
- Blue: DPMJET (new)
- Black: Experimental
charm in the atmosphere
indirect WIMP searches

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

Neutralino Mass (GeV)

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

PRELIMINARY

PRELIMINARY

O$_{\chi^2} >$ O$_{\chi^2}^{\text{thr}}$
(CDMS+XENON10)

E$^{\text{thr}}_{\mu} = 1$ GeV

$0.05 < \Omega \chi^2 < 0.2$

AMANDA-II 2003

IceCube-22 2007

SUPER-K 1996-2001

BAKSAN 1978-95

MACRO 1989-98

IceCube

Sensitivity
(5 yr)


AMANDA-II 2003 (hard)

AMANDA-II 2003 (soft)

SUPER-K 1996-2001 (soft)

Muon flux from Sun [km$^2$ yr$^{-1}$]

Super-K

CDMS

XENON10

IceCube-22

AMANDA-II

SUPER-K


AMANDA-II 2003 (hard)

AMANDA-II 2003 (soft)

SUPER-K 1996-2001 (soft)

Neutrino mass [GeV/c$^2$]

Preliminary
low energy extension

IceCube+AMANDA

IceCube+DeepCore

- $E_{\text{th}} \gtrsim 30 \text{ GeV}$
- atmospheric neutrinos
- oscillations
- galactic sources of $\lesssim 10 \text{ TeV}$
- WIMP dark matter

use high QE PMT (+38%)

deploy first string in 08/09

other 5 strings in 09/10
hardware
the DOM

DOM Requirements

• Fast timing: resolution < 5 ns
  DOM-to-DOM on LE time.

• Pulse resolution < 10 ns

• Optical sens. 330 nm to 500 nm

• Dynamic range
  - 1000 pe / 10 ns
  - 10,000 pe / 1 us.

• Low noise: < 500 Hz background

• High gain: $O(10^7)$ PMT

• Charge resolution: $P/V > 2$

• Low power: 3.75 W

• Ability to self-calibrate

• Field-programmable HV generated internal to unit.

• Flasher board – capable of emitting optical pulses $O(20)$ ns wide > $10^9 \gamma$/pulse

• 10000 psi external
the DOM

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• Fast timing: resolution < 5 ns
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• Flasher board – capable of emitting optical pulses O(20) ns wide > 10^9 γ/pulse

• 10000 psi external
This is the core of the DAQ. It contains an Altera Excalibur ARM CPU / 400 k-gate FPGA which controls most aspects of the acquisition and communications with the surface. All aspects except bootloader program remotely reloadable.

Fast waveform capture via 1 of 2 ATWD ASICs which capture 4 ch at 200 MSPS – 800 MSPS, 128 samples deep and 10-bits wide. ATWDs operate in “ping-pong” mode – true deadtimeless operation possible. 3 ch are high, medium, low gain (14-bit effective dynamic range).

Slow waveform capture from 40 MHz 10-bit FADC which captures long slow pulses for 6.4 usec.

Digital communication to surface using electrical pairs – two DOMs per pair. Electrical penetrators more robust. Communication bandwidth 1 Mbit.
This is the core of the DAQ. It contains an Altera Excalibur ARM CPU / 400 k-gate FPGA which controls most aspects of the acquisition and communications with the surface. All aspects except bootloader program remotely reloadable.

Fast waveform capture via 1 of 2 ATWD ASICs which capture 4 ch at 200 MSPS – 800 MSPS, 128 samples deep and 10-bits wide. ATWDs operate in “ping-pong” mode – true deadtimeless operation possible. 3 ch are high, medium, low gain (14-bit effective dynamic range).

Slow waveform capture from 40 MHz 10-bit FADC which captures long slow pulses for 6.4 usec.

Digital communication to surface using electrical pairs – two DOMs per pair. Electrical penetrators more robust. Communication bandwidth 1 Mbit.
- DOMs independently collect and buffer up to 8k waveforms.

- DOM communication handled at surface by DOR card – hosted by standard industrial PCs called ‘DOMHub.’

- Beyond Linux driver DAQ software is a distributed set of Java applications.

- Data is time coordinated and sorted by processing nodes which may in future perform data reduction.

- Triggers take sorted streams; request to event builder to grab data from string processors and IceTop data handlers to make events.

- Note: data from deep-ice and surface arrays participate in triggers and are bundled together at event level.

- Online filter at pole selects ‘interesting’ events for transmission north over satellite (limited bandwidth).

- All data taped – raw data rate currently 70 GB / day.
DOMs contain 2 wire pair (UP, DN) for exchanging LC signals between adjacent DOMs on string†. DOM FPGA trigger logic can abort waveform capture on absence of one or both signals. LC signals are binary-coded digital – DOMs can “relay” LC info thru; in this manner LC can span up to 4 DOMs distant in either direction.

IceCube currently running in NN mode – that is DOM trigger requires adjacent hit (red circles) – as shown in case A to right. In this mode B and D would not trigger, C would trigger only 1 and 2 and reject 4.

This has advantage of (a) **dramatically** reducing amount of data sent over 1 Mbit link to surface (see figure) and (b) makes array virtually “noiseless.” Disadvantage is that real photon hits are lost in ice.

IceCube baseline – operate in “soft” LC mode: waveforms suppressed /wo/ LC requirement, all hit timestamps (12 bytes) sent to surface.
waveform digitization

ATWD digitization

- 300 MHz sampling + 128 bins = 425 ns
- 3 different amplitude gains: x1, x8, x64

fADC digitization

- 40 MHz + 255 bins = 6.4 μs
calibration in short

- time calibrations
  sync DOM (20 MHz) oscillator to surface clock (every 3 sec) - RAPCal : $\sigma \sim 2$ ns
  PMT transit time correction (with flashers) : $\sigma \sim 2$ ns
  waveform sampling time calibration (every month) - DOMCal

- amplitude calibrations
  waveform and amplitude (every month) - DOMCal : detected p.e. with $\approx 10\%$

- geometry calibrations
  laser ranger : DOM-to-DOM on the string $17 \pm 0.04$ m
  relative DOM depth precision $\sim 1$ m (wrt to surface coordinates and cable length)

- energy calibrations
  calibration flashers (fully characterized blue LED)
  “standard candle” with Cherenkov-like emission of known photons
  atmospheric muon and muon-neutrino spectrum (MC-dependent)

- pointing calibration
  AMANDA-II / SPASE : $< 0.5^\circ$
  shadow of the moon : $3\sigma$ in 1 yr in AMANDA (on-going), in 1 month in IceCube

- IceTop calibrations (VEM – Vertical Muon Equivalent)
Polar ice optical properties

Measurements:
- in-situ light sources
- atmospheric muons

Average optical ice parameters:
- $\lambda_{\text{abs}} \sim 110 \text{ m @ } 400 \text{ nm}$
- $\lambda_{\text{sca}} \sim 20 \text{ m @ } 400 \text{ nm}$

Ice Properties

- Analyses are sensitive to the optical properties of the ice.
- Below 1400 m, dominated by impurities in the ice
- Measure with ‘dust logger’
  - Ice layers are not completely planar
  - Up to 70 m/km tilt

Flow direction

936 m

Hole 21
Hole 66
Hole 50
Hole 52