Neutrino Astronomy with the IceCube Observatory

Implications for Astroparticle Physics

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Vulcano Workshop May 30, 2008
outline

neutrinos

cosmic rays

gamma rays

neutrino astronomy

particle physics

toward a km$^3$ Observatory

AMANDA & IceCube
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
solar shock acceleration
well known

observed shocks in SNR

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

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

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

neutrino and gamma connection
γ 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

Gabici, Aharonian: arXiv:0705.3011

HESS/Magic observations

- $\ll 10’s$ TeV
- Cherenkov telescopes (e.g., HESS, Magic)
- Air shower arrays (Milagro)

Gabici, Aharonian, arXiv:0705.3011
γ ray observations

TeV γ rays in correlation with molecular clouds hadronic acceleration?

Aharonian et al., Nature 439 (2006), 695
HESS: RX J1713

Aharonian et al., Nature 439 (2006), 695

teV γ rays in correlation with molecular clouds hadronic acceleration?

density of molecular clouds CR propagation model in 10,000 years from GC

γ ray observations

hard spectral index 2.29 ± 0.07 ± 0.20

HESS J1745-290

Galactic Longitude (degrees)

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:
  \[ \rho \sim 3 \times 10^{-19} \text{ erg/cm}^3 (\times 10^{10} \text{y}) \]
  \[ \rho \sim 10^{44} \text{ erg/yr/Mpc}^3 \]

- GRB:
  \[ \sim 10^{51} \text{ erg} \times 300/\text{y/Gpc}^3 \]

\[ \Rightarrow \]

GRB/AGN as source candidates of extra-galactic cosmic rays

\[ \Rightarrow \]

large sizes and intense magnetic fields
cosmic ray astronomy?

protons with $E \geq 10^{19}$ 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 $\approx 10^{19}$ 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

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

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if heavy CR then cosmogenic \( \nu \)'s are suppressed

Auger spectrum & composition consistent with \( \sim \)CNO masses or \( p+\text{Fe} \) mixture. But NOT consistent with injected \( p/\text{He} \) only.

| Auger sp consister p+Fe mix with injected p/He only. | Fe+p | 10^{-19} | 10^{-18} | 10^{-17} | 10^{-16} |
|--------------------------------------------------|------|---------|---------|---------|---------|
| 50% Fe, 50% p | 1.6-2.1 | 10^{22} eV | 0.15-0.043 | 0.11-0.034 |
| 10% Fe, 90% p | 1.4-1.9 | 10^{21} eV | 0.14-0.10 | 0.11-0.080 |
| 3% Fe, 97% p | 2.1 | 10^{22} eV | 0.68 | 0.51 |
| 1% Fe, 99% p | 1.4-1.9 | 10^{21} eV | 0.74-0.53 | 0.59-0.43 |
| 100% p (for comparison) | 2.2 | 10^{22} eV | 0.76 | 0.60 |

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

Astronomical Messengers

Neutrinos
Protons
Photons

Log(E) (eV)
10 11 12 13 14 15 16 17 18 19 20 21 22
Who is in IceCube?

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
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

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, Netherlands

Amundsen-Scott Station, Antarctica
IceCube Observatory

km$^3$ neutrino telescope

IceTop
Air shower detector threshold ~ 300 TeV

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

AMANDA/IceCube muon accumulated exposure

Antares deployment
Apr. 2008 KM3NeT CDR

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 July 2005

AMANDA
19 Strings
677 Modules
detecting neutrinos

preliminary unfolded atmospheric neutrino spectrum

limits on charm production in AMANDA-II 2000-2003

$\Theta_{\mu\nu} \approx 0.65 \cdot (E_\nu/\text{TeV})^{-0.48}$

(3 TeV $< E_\nu < 100$ TeV)

Phys.Rev.D76:042008,2007, Erratum-ibid.D77:089904,2008
detecting neutrinos

IceCube-9
Phys.Rev.D76:027101, 2007

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

IceCube-9
Phys.Rev.D76:027101, 2007

atmospheric $\nu_\mu$

experimental data

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

J. Pretz

D. Chirkin
detecting neutrinos

IceCube-22

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

svm: 1.5
preliminary on going analysis

28 events / day
25% efficiency @ 95% purity

IceCube-9

atmospheric νμ experimental data

16 events / day
25% efficiency @ 95% purity

J. Pretz

Phys.Rev.D76:027101, 2007

D. Chirkin
understanding the background
understanding the background

AMANDA-II

J. Hodges, G. Hill

Phys.Rev.D76:042008,2007, Erratum-ibid.D77:089904,2008

C. Waltham - ICRC2001

Through-Going Muon Zenith Angle Distribution (PRELIMINARY)

SNO

Through-Going Muon Zenith Angle Distribution (PRELIMINARY)

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

J. Hodges, G. Hill

Phys.Rev.D76:042008,2007, Erratum-ibid.D77:089904,2008

C. Waltham - ICRC2001
understanding the background

AMANDA-II

Cosine of Reconstructed Zenith Angle

Events

SNO

Through-Going Muon Zenith Angle Distribution (PRELIMINARY)

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

J. Hodges, G. Hill

C. Waltham - ICRC2001

Phys.Rev.D76:042008,2007, Erratum-ibid.D77:089904,2008
understanding the background

![Graphs showing data analysis results](image)
astrophysical neutrinos: point sources

AMANDA-II 2000-2006

Maximum significance = 3.38σ near (11.4h, +54°)
95% chance to obtain maximum significance ≧ 3.38σ in random skymaps

median angular resolution
1.5° ↓ - 2.5° →

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

sensitivity and flux limit

E^2 dσ/dE (TeV cm^2 s)
Declination

J. Braun
astrophysical neutrinos: point sources

AMANDA-II 2000-2006

Preliminary

MGRO J2019+37
MGRO J2032+37
MGRO J2043+36

Abdo thesis defense, March 2007

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

J. Braun
## Astrophysical Neutrinos: Point Sources

### AMANDA-II 2000-2006

| Object                     | Dec° | RA° | \( \mu_0 \) | P-value |
|----------------------------|------|-----|-------------|---------|
| MGRO J2019+37              | 36.83| 304.83| 4.75        | 0.077   |
| Cyg OB2                    | 41.32| 308.29| 3.16        | 0.30    |
| Mrk 421                    | 38.21| 166.11| 1.26        | 0.82    |
| Mrk 501                    | 39.76| 253.47| 3.56        | 0.22    |
| 1ES 1959+650               | 65.15| 300   | 3.38        | 0.44    |
| 1ES 2344+514               | 51.71| 356.77| 2.84        | 0.44    |
| H 1426+428                 | 42.68| 217.14| 2.82        | 0.36    |
| BL Lac (QSO B2200+420)     | 42.28| 330.68| 2.54        | 0.38    |
| 3C66A                      | 43.04| 35.67 | 3.93        | 0.18    |
| 3C 454.3                   | 16.15| 343.49| 1.27        | 0.73    |
| 4C 38.41                   | 38.14| 248.82| 1.10        | 0.85    |
| PKS 0528+134               | 13.53| 82.74 | 1.60        | 0.64    |
| 3C 273                     | 2.05 | 187.28| 4.17        | 0.086   |
| M87                        | 12.39| 187.71| 2.18        | 0.43    |
| NGC 1275 (Perseus A)       | 41.51| 49.95 | 2.24        | 0.47    |
| Cyg A                      | 40.73| 299.87| 4.50        | 0.095   |
| SS 433                     | 4.98 | 287.96| 1.57        | 0.64    |
| Cyg X-3                    | 40.96| 308.11| 3.28        | 0.29    |
| Cyg X-1                    | 35.2 | 299.59| 2.00        | 0.57    |
| LS I 461 303               | 61.23| 40.13 | 7.21        | 0.033   |
| GRS 1915+105               | 10.95| 288.8 | 3.73        | 0.11    |
| XTE J1118+480              | 48.04| 169.55| 2.61        | 0.50    |
| GRO J0422+32               | 32.91| 65.43 | 1.40        | 0.76    |
| Geminga                    | 17.77| 98.48 | 6.07        | 0.0086  |
| Crab Nebula                | 22.01| 83.63 | 4.47        | 0.10    |
| Cas A                      | 58.82| 350.85| 1.93        | 0.67    |

The median angular resolution is 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} \text{ TeV cm}^{-2} \text{ s}^{-1} over the energy region 1.8 \text{ TeV} - 2.1 \text{ PeV}.

Stack Milagro sources: upward fluctuation with p-value = 0.19.

The 90% confidence level limit on the per-source flux for the six sources, excluding systematics, is 9.6 \times 10^{-12} \text{ TeV cm}^{-2} \text{ s}^{-1} over the energy region 1.8 \text{ TeV} - 2.1 \text{ PeV}.
maximum significance = \(3.35\sigma\) near \((18.4h, +20.4^\circ)\)

60% chance to obtain maximum significance \(\geq 3.35\sigma\) 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

IC-22 skymap

Fraction

\( \log_{10} \text{Energy/GeV} \)

\( \psi \) [°]
astrophysical neutrinos: diffuse sources

AMANDA-II 2000-2003 $\Rightarrow$ IceCube

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

$\frac{dN_\nu}{dE}$ diff $= 2 \times 10^{-9} \left( \frac{E}{\text{GeV}} \right)^{-2}$ GeV$^{-1}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$

Phys.Rev.D76:042008,2007, Erratum-ibid.D77:089904,2008
astrophysical neutrinos: UHE diffuse sources

AMANDA-II 2003-2004 ⟹ IceCube

5\sigma detection
astrophysical neutrinos: UHE diffuse sources

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

5σ detection

preliminary

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

IceCube predicted to improve sensitivity by at least x10 as reference

J. Lundberg

Astrophysical Journal 675 (2008) 1014-1024
AMANDA has had an excellent role in developing neutrino telescopes.

A km$^3$ neutrino observatory is under construction at the South Pole.

It 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

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

![Graph showing energy distribution](image)

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APOD 27

27
alternative oscillations
neutrinos have distinct maximum velocity eigenstates $\neq c$, and difference $\delta c / c$ results in oscillations

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

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

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

\[
R = \frac{\delta c E}{c} \frac{4E}{\Delta m^2_{23}}
\]

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

AMANDA-II 2000-2006: sensitivity

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

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

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

\[ R = \frac{\delta c E}{c} \frac{4E}{\Delta m^2_{23}} \]

- 2000-03 analysis (Ahrens):
  \[ \frac{\delta c}{c} < 5.3 \times 10^{-27} \text{ (90\%CL)} \]

- Median sensitivity (\(\chi^2\) approx.):
  \[ \frac{\delta c}{c} < 4.3 \times 10^{-27} \text{ (90\%CL)} \]

- Sample sensitivity (1 MC experiment, full construction):
  \[ \frac{\delta c}{c} < 4.5 \times 10^{-27} \text{ (90\%CL)} \]

99\% CL excluded

J. Kelley
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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- **Sample sensitivity (1 MC experiment, full construction):**
  \[ \delta c/c < 4.5 \times 10^{-27} \text{ (90\% CL)} \]

(maximal mixing, cos \eta = 0)

J. Kelley

Gonzalez-Garcia, astro-ph/0701333
Quantum Decoherence

interaction with foamy space-time structure may modify neutrino flavor

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

\[ + \sin \left[ \frac{L}{2} \sqrt{(\gamma_6 - \gamma)^2 - \left( \frac{\Delta m_{23}^2}{E} \right)^2} \right] \left( \frac{(\gamma_6 - \gamma)^2 - \left( \frac{\Delta m_{23}^2}{E} \right)^2}{(\gamma_6 - \gamma)^2 - \left( \frac{\Delta m_{23}^2}{E} \right)^2} \right) \]

characteristic exponential behavior

1:1:1 ratio after decoherence

Energy dependence depends on phenomenology: \( \gamma_6 = \gamma_7^* E^n \), \( n \in \{-1, 0, 2, 3\} \)

- \( n = -1 \) 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)*:
  \[ \gamma^* < 2 \times 10^{-30} \text{ GeV}^{-1} \] (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

likelihood fit bases on simulated neutrino with Bartol spectrum (Barr et al., Phys.Rev.D70:023006,2004)

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

99% CL excluded

J. Kelley

3 parameter spectrum deconvolution

likelihood fit bases on simulated neutrino with Bartol spectrum (Barr et al., Phys.Rev.D70:023006,2004)
benchmark DPMJET-II with recent accelerator data

use charm production in CORSIKA

propagate charmed particles in CORSIKA
charm in the atmosphere
charm in the atmosphere

**SELEX (Λ⁺)**

**SELEX (Λ_c)**

**SELEX (540GeVp)**

---

P. Berghaus, T. Montaruli, J. Ranft arXiv:0712.3089v2
charm in the atmosphere

preliminary

DPMJET $\nu_\mu$ Prompt Spectrum

- $E^2\frac{dN}{dE}(GeV/km^2)$ vs $log_{10}E[GeV]$ for different models.
- Models include: DPMJET CORSIKA prompt, Bertot cK, Neumov QGSM, Martin GBW.

DPMJET $\nu_\mu$ Ratio Model/MC

- Ratio of model predictions to data.
- Comparison of Naumov QGSM and Martin GBW predictions.

P.Berghaus, T.Montaruli, J.Ranft arXiv:0712.3089v2
indirect WIMP searches
low energy extension

IceCube+AMANDA

IceCube+DeepCore

- $E_\theta \gtrsim 30$ GeV
- atmospheric neutrinos
- oscillations
- galactic sources of $\lesssim 10$ TeV
- WIMP dark matter

use high QE PMT (+38%)
deploy first string in 08/09
other 5 strings in 09/10
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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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.
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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:
- $\lambda_{abs} \approx 110 \text{ m@400 nm}$
- $\lambda_{sca} \approx 20 \text{ m@400 nm}$
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

936 m

Flow direction

Hole 21
Hole 66
Hole 50
Hole 52