Searching for Diffuse Astrophysical Muon Neutrinos with IceCube

Sean Grullon
University of Wisconsin - Madison

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Overview
Overview

- High Energy Neutrino Astronomy

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- High Energy Neutrino Astronomy
- The IceCube Detector
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- Diffuse Search Strategy
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- The IceCube Detector
- Diffuse Search Strategy
- Analysis Results from 2008
Particle Physics Today:
Three Frontiers of Science
Cosmic Rays: A 100 year old mystery

Victor Hess
Nobel Prize
1936

Balloon flights
1911-1913

- Power law over many decades
- Origin Uncertain

Cosmic ray spectrum

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Energies and rates of the cosmic-ray particles

- Protons only
- All-particle
- Electrons
- Positrons
- Antiprotons

E kin (GeV / particle)
Neutrinos as Cosmic Messengers

Protons: deflected by magnetic fields.

Photons: easily absorbed by CMB and IR backgrounds. EM/Hadronic discrimination difficult.

Neutrinos: not deflected by magnetic fields. Low interaction cross-section.
Sources of High Energy Astrophysical Neutrinos
Sources of High Energy Astrophysical Neutrinos
Sources of High Energy Astrophysical Neutrinos

Supernova Remnants
Sources of High Energy Astrophysical Neutrinos

Supernova Remnants
Sources of High Energy Astrophysical Neutrinos

Supernova Remnants

Active Galactic Nuclei
Sources of High Energy Astrophysical Neutrinos

Supernova Remnants

Active Galactic Nuclei
Sources of High Energy Astrophysical Neutrinos

Supernova Remnants

Active Galactic Nuclei

Gamma Ray Bursts
ν beams: heaven and earth

- Accelerator
- Target
- Proton
- Directional beam
- Magnetic fields
- p, e±
- νμ, νe, νµ, e, μ, π±, γ
- Shock wave
- B field

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Atmospheric Neutrinos
• Main Background to Astrophysical Search
• Created by high energy cosmic rays impeding on Earth’s atmosphere
• Conventional (Pions & Kaons) vs. Prompt (Charmed Mesons)
Atmospheric Neutrinos

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- Created by high energy cosmic rays impeding on Earth’s atmosphere
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\[ p + ^{16}N \rightarrow \pi^+, K^+, D^+, \text{etc.} \]

\[ \pi^+ \rightarrow V_\mu + \mu^+ \]

\[ \bar{V}_\mu + e^+ + \nu_e \]
Atmospheric Neutrinos

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- Created by high energy cosmic rays impeding on Earth’s atmosphere
- Conventional (Pions & Kaons) vs. Prompt (Charmed Mesons)

\[ p + ^{16}N \rightarrow \pi^+, K^+, D^+, \text{etc.} \]
\[ \pi^+ \rightarrow \nu_\mu + \mu^+ \]
\[ \overline{\nu}_\mu + e^+ + \nu_e \]
Flux Model Predictions

- Atmospheric Neutrinos
- Gamma Ray Bursts
- Active Galactic Nuclei
- Waxman Bahcall Bound 1998 x 3/2
- Cosmogenic Neutrinos

\[ E^2 \frac{dN_\nu}{dE_\nu} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \]

\[ \log_{10} E_\nu [\text{GeV}] \]

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Flux Model Predictions

Diffuse Search Strategy:
What if there are no individually resolvable point sources of $\nu$s? Look for superposition of faint $\nu$ sources
IceCube Collaboration

35 collaborating institutions
The IceCube Detector

**IceTop**
Air shower detector
threshold ~ 300 TeV

**InIce**
80-86 Strings,
60 Optical Modules per String

- Completion: January 2011
- **2008:** 40 Strings (This Analysis)
- **2009:** 59 Strings

Deep Core
• Cherenkov cone provides direction
Event Topologies

- $\nu_\mu$ produce $\mu$ tracks
  - Angular Res $\sim 0.7^0$ $\text{Eres} \log(E) \sim 0.3$
- $\nu_e$ CC, $\nu_\tau$ NC create showers
  - $\sim$ point sources, 'cascades'
  - $\text{Eres} \log(E) = 0.1-0.2$
- $\nu_\tau$ double bang events, others

350 TeV $\nu_e$ simulation

16 PeV $\nu_\tau$ simulation

Muon – IC 40 data

Run 110261 Event 350001
Tue Jan 29 09:44:39 2008
IceCube performance

Low noise rates: \( \sim 300\text{Hz} \) (SPE/sec)

Rate with correlated pulses
\( \sim 500\text{Hz} \)

Supernova detection

High duty cycle: >96%

Event rates (59 strings)

Muons: \( \sim 1.5 \text{ kHz} \)

Neutrinos: \( \sim 160/\text{day} \)

<table>
<thead>
<tr>
<th>Strings</th>
<th>Year</th>
<th>Livetime</th>
<th>( \mu ) rate</th>
<th>( \nu ) rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC9</td>
<td>2006</td>
<td>137 days</td>
<td>80 Hz</td>
<td>1.7 / day</td>
</tr>
<tr>
<td>IC22</td>
<td>2007</td>
<td>275 days</td>
<td>550 Hz</td>
<td>28 / day</td>
</tr>
<tr>
<td>IC40</td>
<td>2008</td>
<td>~365 days</td>
<td>1000 Hz</td>
<td>110 / day</td>
</tr>
<tr>
<td>IC59</td>
<td>2009</td>
<td>~365 days</td>
<td>1500 Hz</td>
<td>160 / day</td>
</tr>
<tr>
<td>IC86*</td>
<td>2011</td>
<td>~365 days</td>
<td>1650 Hz</td>
<td>220 / day</td>
</tr>
</tbody>
</table>
Astrophysical (signal) $\nu$

$\theta = 0^\circ$
$\cos \theta = 1$

$\theta = 180^\circ$
$\cos \theta = -1$

Atmospheric $\mu$

Cosmic ray
Step 1: Downgoing Muon Rejection

Apply quality cuts on Data, Corsika MC, and Atmospheric Neutrino MC.
Quality Parameters - Direct Hits
Quality Parameters - Direct Hits

Number of Direct Hits

$N_{\text{Dir}}$

Number of hits arriving within -15 ns to 75 ns of the expected arrival time of the Cherenkov cone at the OM
Quality Parameters - Direct Hits

**Number of Direct Hits**

$N_{\text{Dir}}$

Number of hits arriving within -15 ns to 75 ns of the expected arrival time of the Cherenkov cone at the OM

**Smoothness**

$S_{\text{Dir}}$

- $S_{\text{Dir}} = +1$ if direct hits are near the beginning of track
- $S_{\text{Dir}} = -1$ if direct hits are near the end of track
- $S_{\text{Dir}} = 0$ if evenly distributed along track
**Quality Parameters - Direct Hits**

**Number of Direct Hits**

- **NDir**: Number of hits arriving within -15 ns to 75 ns of the expected arrival time of the Cherenkov cone at the OM.

**Smoothness**

- **SDir**:
  - **SDir = +1** if direct hits are near the beginning of track
  - **SDir = -1** if direct hits are near the end of track
  - **SDir = 0** if evenly distributed along track

**Direct Length**

- **LDir**: Direct Hits projected onto reconstructed track. Direct Length is length between the furthest projected hits.
Split Reconstruction

Split hits in space/time to reconstruct two muons

\[ L_{\text{free} \mu} = L(E \mid \mu(\theta, \phi, x, y, z)) \]
Quality Parameters: Bayesian Ratio

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Quality Parameters: Bayesian Ratio

\[ \Phi_{\text{down} \mu}(\theta) \]

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Quality Parameters: Bayesian Ratio

\[ \Phi_{\text{down}_{\mu}}(\theta) \]

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

\[ \begin{align*}
\text{atmospheric muons} \\
\text{muons induced by atmospheric neutrinos}
\end{align*} \]

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\[
L_{\text{free}\mu} = L(E \mid \mu(\theta, \phi, x, y, z))
\]

\[
L_{\text{down}\mu} = L(E \mid \mu(\theta, \phi, x, y, z)) \Phi_{\text{down}\mu}(\theta)
\]
Quality Parameters: Bayesian Ratio

\[ \Phi_{\text{down}_\mu}(\theta) \]

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Quality Parameters: Bayesian Ratio

\[ \Phi_{down\mu}(\theta) \]

Test Statistic:

\[ \log \frac{L_{free\mu}}{L_{down\mu}} \]

\[ L_{free\mu} = L(E \mid \mu(\theta, \phi, x, y, z)) \]

\[ L_{down\mu} = L(E \mid \mu(\theta, \phi, x, y, z)) \Phi_{down\mu}(\theta) \]
Quality Parameters: Bayesian Ratio

\[ \Phi_{down\mu}(\theta) \]

Test Statistic:

\[ \log \frac{L_{free\mu}}{L_{down\mu}} \]

Can do the same w/ Coincident Muons!

\[
L_{free\mu} = L(E \mid \mu(\theta, \phi, x, y, z)) \\
L_{down\mu} = L(E \mid \mu(\theta, \phi, x, y, z)) \Phi_{down\mu}(\theta)
\]
Quality Parameters - Paraboloid Sigma
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Local Minima

-LL

1 σ uncertainty
Quality Parameters - Paraboloid Sigma

1 sigma uncertainty in direction reconstruction
Final Neutrino Sample

- **Strict Blindness** policy in IceCube.
- 6 months of data below region of interest $\log_{10}(dE/dX) < 0.8$ GeV/m.
- Data sample **7164 events** given an expectation of **7133 atmospheric neutrinos** with **99.5% purity**.
- **Astrophysical $E^{-2}$ efficiency**: 36.2%.
- **Straight cuts** used:

<p>| | | |</p>
<table>
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<th></th>
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<tbody>
<tr>
<td>LDirC &gt; 240</td>
<td>BayesRatio &gt; 25</td>
<td>MPE Zenith &gt; 90</td>
</tr>
<tr>
<td>$</td>
<td>SDirC</td>
<td>&lt; 0.54</td>
</tr>
<tr>
<td>NDirC &gt; 5</td>
<td>Paraboloid Sigma &lt; 3</td>
<td>$mrlogl &lt; 8$</td>
</tr>
</tbody>
</table>
Energy Distribution - 6 Months
IC40 Data

Neutrino Level - 6 months blinded

- data: 7164 Events
- corsika total: 70 Events
- coinc corsika: 0 Events
- atm nu: 7133 Events
- E^-2: 36.2
Step 2: Diffuse Analysis Strategy

Find an excess of astrophysical neutrinos \((E^{-2})\) over atmospheric neutrinos \((E^{-3.7})\) at the high-energy tail of an energy distribution.
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Find an excess of astrophysical neutrinos \((E^{-2})\) over atmospheric neutrinos \((E^{-3.7})\) at the high-energy tail of an energy distribution
Energy Estimation

• Convert what is measured, Cherenkov light, to an estimate of the Muon energy.
• Simplest estimation: **Number of Triggered Optical Modules (NCh)**
• More Sophisticated: **Muon Energy Loss (dE/dX)**
Reconstructing The Muon Energy Loss
Reconstructing The Muon Energy Loss

Approximate as:
Reconstructing The Muon Energy Loss

Approximate as:

Incorporate Ice Properties:

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Reconstructing The Muon Energy Loss

Approximate as:

Incorporate Ice Properties:

Formulate LLH:

Incorporate Ice Properties:

shallow  deep
Reconstructing The Muon Energy Loss

Approximate as:

Incorporate Ice Properties:

Formulate LLH:

\[-\log P(n_i | \{\mu_i\}) = -\sum_{i=1}^{k} n_i \log(\mu_i/\mu) - N \log \mu + \mu\]
Muon Energy Correlation – 40 Strings

- \( \text{dE/dX reco} \) more linearly correlated with Muon energy
Energy Resolution – 40 Strings

- $dE/dX_{\text{reco}}$ has narrower energy resolution

Width 0.27

Width 0.43
Energy Resolution Vs. Muon Energy – 40 Strings
Likelihood Methodology

- Likelihood - Product over binned Poisson Probabilities:

\[ L = P (\{n_i\} | \{\mu_i\}) = \prod_{i=1}^{k} \frac{\mu_i^{n_i}}{n_i!} e^{\mu_i} \]

\[ \mu_i = \epsilon (N_{c} p_{c,i} \Delta \gamma_{c} + N_{p} p_{p,i} \Delta \gamma_{p} + N_{a} p_{a,i} \Delta \gamma_{a}) \]

- Observable: **Muon Energy Loss dE/dX**
- **Physics Parameters:**
  - Astrophysical Normalization \((N_{a})\)
- **Nuisance Parameters:**
  - Conventional Normalization \((N_{c})\)
  - Prompt Normalization \((N_{p})\)
  - Detector Efficiency \((\epsilon)\)
  - Conventional Spectral Slope \((\Delta \gamma_{c})\)
  - Prompt Spectral Slope \((\Delta \gamma_{a})\)
Fit Example: IC40 Discovery Potential
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1 Year of Simulated IC40

- Atmos $\nu$: 11969 Events
- $E^{-2} \nu$: 278 Events
- Prompt $\nu$: 14 Events
- Data: 12156 Events

Events

$10^3$

$10^2$

$10$

$1$

$10^{-1}$

Log10($dE/dX$) GeV/m

-2

-1.5

-1

-0.5

0

0.5

1

1.5

2

2.5

3

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Allowed Regions - 300 Days IC40

Allowed Regions for Prompt & $E^{-2} \nu$

- 90% CL
- 3 \sigma CL
- 5 \sigma CL

Number of Prompt $\nu$

Number of $E^{-2} \nu$

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Allowed Regions - 300 Days IC40

5 Sigma: \( E^2 = 7.0 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \)
Allowed Regions - 300 Days IC40

Allowed Regions for Prompt & $E^{-2}$

5 Sigma:
$$E^2 = 7.0 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

5 Sigma (w/ charm assumption):
$$E^2 = 3.9 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$
LLH Fit Example: 300 days IC40, No Signal
Allowed Regions - 300 Days Atmospheric v only
Allowed Regions - 300 Days Atmospheric $\nu$ only

IC40 Diffuse Sensitivity:
$$E^2 < 1.17 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$
Flux Models, Sensitivities & Limits

IC40 Diffuse Sensitivity:
\[ E^2 < 1.17 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \]
\[ 3.57 < \log_{10}(E / \text{GeV}) < 6.57 \]
Systematic Uncertainties
Systematic Uncertainties

- Background Systematic Uncertainty
Systematic Uncertainties

- Background Systematic Uncertainty
  - Cosmic Ray Spectrum & Hadronic Interaction Model
Systematic Uncertainties

• Background Systematic Uncertainty
  ▶ Cosmic Ray Spectrum & Hadronic Interaction Model
  ▶ Conventional & Prompt Atmospheric Neutrino Flux
Systematic Uncertainties

- **Background Systematic Uncertainty**
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  - Conventional & Prompt Atmospheric Neutrino Flux

- **Optical Module Sensitivity**
Systematic Uncertainties

• Background Systematic Uncertainty
  ▶ Cosmic Ray Spectrum & Hadronic Interaction Model
  ▶ Conventional & Prompt Atmospheric Neutrino Flux

• Optical Module Sensitivity
  ▶ OM calibration error +/- 8%. Implemented in Nuisance Parameter $\epsilon$
Systematic Uncertainties

- **Background Systematic Uncertainty**
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  - Conventional & Prompt Atmospheric Neutrino Flux

- **Optical Module Sensitivity**
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- **Systematic Errors in the Simulation**
Systematic Uncertainties

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  - Conventional & Prompt Atmospheric Neutrino Flux

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• **Systematic Errors in the Simulation**

• **Systematic Uncertainties of the Ice Properties**
Atmospheric $\nu$ systematic uncertainty

Spectrum of atmospheric $\nu_\mu + \text{anti-}\nu_\mu$

Honda 2006 Favored, used in analysis

$E^3 \frac{dN}{dE} \text{ [GeV}^2 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}]$

$10^{-1}$

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

- Bartol 2004 $\nu_\mu + \frac{1}{3} \text{ anti-}\nu_\mu$
- HKKM 2006 $\nu_\mu + \frac{1}{3} \text{ anti-}\nu_\mu$
Atmospheric $\nu$ systematic uncertainty

Honda 2006 Favored, used in analysis
Atmospheric $\nu$ systematic uncertainty

Spectrum of atmospheric $\nu_\mu +$ anti-$\nu_\mu$

$log_{10} [E (GeV)]$

$E^3 \frac{dN}{dE}$ [GeV$^2$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$]

- Bartol 2004 $\nu_\mu + 1/3$ anti-$\nu_\mu$
- HKKM 2006 $\nu_\mu + 1/3$ anti-$\nu_\mu$
Atmospheric $\nu$ systematic uncertainty

Prompt Atmospheric $\nu_\mu$ + anti-$\nu_\mu$ Spectra

$E^3 dN/dE$ [GeV$^2$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$]

- $\bullet$ Sarcevic et al max numu
- $\square$ Sarcevic et al std numu
- $\circ$ Sarcevic et al min numu
- $\ast$ Martin MRS numu
- $\downtriangledown$ Naumov RQPM numu

$log_{10} [E \text{ (GeV)}]$
Atmospheric $\nu$ systematic uncertainty

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$E^3 \frac{dN}{dE}$ [GeV$^2$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$]

$\log_{10} [E \text{ (GeV)}]$
Atmospheric $\nu$ systematic uncertainty

- Sarcevic Std pQCD used in analysis.
- Nuisance Parameters fit for deviations
Atmospheric $\nu$ systematic uncertainty

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Prompt Atmospheric $\nu_\mu + \text{anti-}\nu_\mu$ Spectra

- $E^3 \frac{dN}{dE}$ [GeV$^2$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$]
- $\log_{10} [E \text{ (GeV)}]$

Graph showing different spectra for various models and methods.
Atmospheric $\nu$ systematic uncertainty

Prompt Atmospheric $\nu_\mu + \text{anti-} \nu_\mu$ Spectra

- Sarcevic et al max numu
- Sarcevic et al std numu
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$E^3 dN/dE$ [GeV$^2$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$]

phenomenological
Naumov model disfavored

- Sarcevic Std pQCD used in analysis.
- Nuisance Parameters fit for deviations
Atmospheric $\nu$ systematic uncertainty

Prompt Atmospheric $\nu_\mu$ + anti-$\nu_\mu$ Spectra

- Sarcevic et al max numu
- Sarcevic et al std numu
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- Martin MRS numu
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Phenomenological Naumov model disfavored

$\Delta \gamma +/-. 0.03$

- Sarcevic Std pQCD used in analysis.
- Nuisance Parameters fit for deviations

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Systematic Uncertainties in the Simulation

- Uncertainties in neutrino cross-section (3%)
- Uncertainties in muon energy loss (1%)
- Reconstruction & Cut bias (2%)
- Background Contamination (0.5%)
Systematic Uncertainties of the Ice properties

- Uncertainty in scattering and absorption ± 10%
- Systematically vary ice properties in the simulation to get effect on sensitivity & final limit (underway)
Outlook & Conclusion

• IC40 Sensitivity is $E^2 < 1.17 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$

• Finish Systematic Ice Property Study

• Unblind full year of IC40 data

• Incorporate multi-channel information in future analyses.