IceCube Results & PINGU Perspectives

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September 2014
Neutrino Oscillation Workshop
Otranto, Lecce, Italy
IceCube Detector

• ~1km$^3$ of instrumented ice
• Uses ~5k optical sensors across 86 vertical strings to detect Cherenkov radiation
• Deployed 1.5 - 2.5km below the surface
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NuMu
6.08e+04
44.43 deg
357.53 deg
100/446 shown, max E(GeV) = 56675.77
100/444 shown, max E(GeV) = 1.58
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6.08e+04
44.43 deg
357.53 deg
100/446 shown, max $E(\text{GeV}) = 56675.77$
100/444 shown, max $E(\text{GeV}) = 1.58$
Track topology
(e.g. induced by muon neutrino)

Good pointing,
$0.2^\circ - 1^\circ$

Lower bound on energy for through-going events
Track topology
(e.g. induced by muon neutrino)

Good pointing,
0.2° - 1°
Lower bound on energy for through-going events

Cascade topology
(e.g. induced by electron neutrino)

Good energy resolution,
15%
Some pointing,
10° - 15°
IceCube Classic
High Energy Starting Events (HESE)
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• Follow-up to observation of two events > 1 PeV in IceCube search for Ultra-High Energy (GZK) neutrinos
High Energy Starting Events (HESE)

• Follow-up to observation of two events > 1 PeV in IceCube search for Ultra-High Energy (GZK) neutrinos

• Use outermost layer of IceCube as a veto region
  • Identifies possible muon background
  • Enforces neutrino interaction containment
High Energy Starting Events (HESE)

- Follow-up to observation of two events > 1 PeV in IceCube search for Ultra-High Energy (GZK) neutrinos

- Use outermost layer of IceCube as a veto region
  - Identifies possible muon background
  - Enforces neutrino interaction containment

- Focused on brightest events with > 6000 photoelectrons
High Energy Neutrinos

- Ultra-high energy IceCube (GZK) astrophysical search found 2 anomalous background events in 2 years of data

1.04±0.16 PeV

1.14±0.17 PeV
High Energy Neutrinos

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1.04±0.16 PeV

1.14±0.17 PeV
3-year HESE Result

- 36(+1) events total
  - 8.4 ± 4.2 atm. muons
  - 6.6^{+5.9}_{-1.6} atm. neutrinos

- 5.7σ rejection of only atmospheric neutrino flux

- Consistent with 1:1:1 flavor ratio
HESE-III Sky Map

- No significant evidence for clustering

arXiv:1405.5303
Natural Neutrino Flux (>1 GeV)
Natural Neutrino Flux (>1 GeV)

- Combination of conventional neutrino, high energy astrophysical, and possible prompt neutrinos from charm hadron decay
Combination of conventional neutrino, high energy astrophysical, and possible prompt neutrinos from charm hadron decay
Natural Neutrino Flux (>1 GeV)

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Natural Neutrino Flux (>1 GeV)

- Combination of conventional neutrino, high energy astrophysical, and possible prompt neutrinos from charm hadron decay
Prompt Neutrino Flux

![Graph showing the Prompt Neutrino Flux](Image)
Prompt flux more closely follows the incident CR energy spectrum ($E^{-2}$) than the conventional neutrino spectrum ($E^{-2.7}$ to -3.7).
Prompt Neutrino Flux

- Prompt flux more closely follows the incident CR energy spectrum ($E^{-2}$) than the conventional neutrino spectrum ($E^{-2.7}$ to $-3.7$).
- Prompt $\nu_e$ versus $\nu_\mu$ channel is advantageous due to conventional $\nu_\mu$ bkg.
Prompt Component

Southern sky
0.2 \leq \cos \theta_{\text{rec}} < 1.0

Northern sky
-1.0 \leq \cos \theta_{\text{rec}} < 0.2
Prompt Component

- Prompt can be constrained by flux in the 10-50 TeV range
  - Higher energy is dominated by astrophysical flux
  - Lower energy is dominated by conventional flux (pion/kaon decay)
Prompt Component

- Prompt can be constrained by flux in the 10-50 TeV range
  - Higher energy is dominated by astrophysical flux
  - Lower energy is dominated by conventional flux (pion/kaon decay)
- Northern vs. Southern sky comparison weakly breaks the degeneracy between the astrophysical and prompt flux
A Prompt Result

- Places upper limits on some prompt models (<1.4 ERS model)
Fundamental Physics with DeepCore
DeepCore
DeepCore

- Low-energy extension
  - Closer instrumentation
  - Clearer Ice
  - Higher efficiency PMTs
DeepCore

• Low-energy extension
  • Closer instrumentation
  • Clearer Ice
  • Higher efficiency PMTs

• Use surrounding IceCube as a veto volume
DeepCore

- Low-energy extension
  - Closer instrumentation
  - Clearer Ice
  - Higher efficiency PMTs

- Use surrounding IceCube as a veto volume

- Oscillation Physics
  - $\nu_\mu$ disappearance
  - $\nu_\tau$ appearance*

*Covered later for PINGU
Neutrino Oscillation

$\nu_\mu$ disappearance

$\nu_\tau$ appearance

$\nu_\mu$ disappearence


$\sim 12,700 \text{km}$

IceCube
DeepCore
Neutrino Oscillation

- Northern Hemisphere $\nu_\mu$ oscillating over one earth radii produces $\nu_\mu$ ($\nu_\tau$) oscillation minimum (maximum) at $\sim 25$ GeV

$\nu_\mu$ (appearance)

$\nu_\tau$ (appearance)

$\nu_\mu$ (disappearance)

Neutrino Oscillation

- Northern Hemisphere $\nu_\mu$ oscillating over one earth radii produces $\nu_\mu (\nu_\tau)$ oscillation minimum (maximum) at $\sim 25$ GeV
- Beam never turns off

IceCube
DeepCore


$\nu_\mu$ disappearance
$\nu_\tau$ appearance

Oscillation Probabilities

$\nu_\mu \rightarrow \nu_\mu$
$\nu_\mu \rightarrow \nu_\tau$

$\sim 12,700 \text{ km}$
Neutrino Oscillation

- Northern Hemisphere $\nu_\mu$ oscillating over one earth radii produces $\nu_\mu$ ($\nu_\tau$) oscillation minimum (maximum) at $\sim$25 GeV
  - Beam never turns off
  - Samples all terrestrial baselines

$\nu_\mu$ Disappearance in DeepCore

- High-purity analysis selected 5293 events over 2011-2014

<table>
<thead>
<tr>
<th>Type</th>
<th>Osc.</th>
<th>No Osc.</th>
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<td>$\nu_\mu$</td>
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<td>5900</td>
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<td>$\nu_e$</td>
<td>678</td>
<td>650</td>
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<td>$\nu_{NC}$</td>
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<tr>
<td>Atm. $\mu$</td>
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<tr>
<td><strong>Total</strong></td>
<td>5178</td>
<td>7022</td>
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</table>
Oscillation Contours

90% CL contours  

IceCube Preliminary
Next?
Two Directions
Two Directions

• Higher energy
  • Point sources
  • Neutrino flavor ratios
  • HEX - High Energy Extension
Two Directions

• Higher energy
  • Point sources
  • Neutrino flavor ratios
  • HEX - High Energy Extension

• Lower Energy - just past DeepCore at the $O(1)$ GeV sensitivity:
  • Resolve the ordering of the Neutrino Mass Hierarchy
  • Improve neutrino oscillation
    • $\nu_\tau$ appearance
    • non-maximal $\theta_{23}$
  • GeV mass Dark Matter
  • PINGU
Two Directions

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Precision IceCube Next Generation Upgrade

Letter of Intent - arXiv:1401.2046
Precision IceCube Next Generation Upgrade

- Use existing and familiar technology to infill DeepCore

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- Improve rejection of cosmic ray muon background

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Precision IceCube Next Generation Upgrade

- Use existing and familiar technology to infill DeepCore
- Improve rejection of cosmic ray muon background
- Primary physics goal is resolving neutrino mass hierarchy

Letter of Intent - arXiv:1401.2046
PINGU Simulation
Event

• 9.28 GeV Neutrino, 4.9 GeV muon, 4.5 GeV cascade

DeepCore

DeepCore+PINGU
PINGU Simulation

Event

- 9.28 GeV Neutrino, 4.9 GeV muon, 4.5 GeV cascade
PINGU Simulation
Event

- 9.28 GeV Neutrino, 4.9 GeV muon, 4.5 GeV cascade
- ~20 vs. ~50 Hit Modules
PINGU Neutrino Mass Hierarchy
PINGU Neutrino Mass Hierarchy

$P(\nu_e \rightarrow \nu_x)$ with Travel Through the Earth - 10 GeV, $179^\circ$

- Normal Hierarchy
- Inverted Hierarchy
PINGU Neutrino Mass Hierarchy

$P(\nu_e \to \nu_\mu)$ with Travel Through the Earth - 10 GeV, 179°

$P(\nu_e \to \nu_\mu)$ with Travel Through the Earth - 6 GeV, 126°

D. Jason Koskinen - NOW 2014
Inverted/Normal hierarchy has up to a 20% difference in oscillation probability for specific energies and zenith angles (baselines)
Neutrino Mass Hierarchy by Eye

Track-Like Events (mainly CC $\nu_\mu + \bar{\nu}_\mu$)

Preliminary 1-year exposure

Energy [GeV] vs. $\cos(\nu)$

$\sqrt{N_{IH} - N_{NH}} \over \sqrt{N_{NH}}$
Systematics

• Several of the main systematics have been examined
Mass Hierarchy Bottom Line

First octant only

- Tracks
- Cascades
- Multichannel

NMH significance vs. PINGU livetime [yrs]

Preliminary

$\sqrt{t}$
$\nu_\tau$ Appearance in PINGU
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- Direct measure of $|U_{\tau 3}|^2$
$\nu_\tau$ Appearance in PINGU

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- Energy and zenith angle excess in cascade channel
- PINGU plots currently use same initial Boosted Decision Tree as NMH, but secondary selection for `cascades’
$\nu_\tau$ Appearance in PINGU

- Direct measure of $|U_{\tau 3}|^2$

- Energy and zenith angle excess in cascade channel

- PINGU plots currently use same initial Boosted Decision Tree as NMH, but secondary selection for `cascades'
Measuring $\nu_\tau$ Appearance
Measuring $\nu_\tau$ Appearance

PINGU $E_\nu \in [1,80]$ GeV preliminary
Measuring $\nu_\tau$ Appearance

**Left Panel:**
- **PINGU**
- $E_\nu \in [1,80]$ GeV
- Events/year
- $\cos(\text{Zen})$ vs. Events/year
- $\nu_e$, $\nu_\mu$, $\nu_\tau$

**Right Panel:**
- True $\nu_\tau$ normalization
- Expected vs. measured $\nu_\tau$ norm=1
- Livetime (months)
- $\pm 1\sigma$, $\pm 2\sigma$
Conclusions

• IceCube is opening a new window on neutrino astronomy with $5.7\sigma$ observation of astrophysical neutrinos and probing atmospheric charm meson production.

• Potential with PINGU to quickly resolve the ordering of the neutrino mass hierarchy in addition to enhancing other physics ($\nu_\tau$ appearance, non-maximal $\theta_{23}$, O(1) GeV dark matter,...)
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• IceCube is opening a new window on neutrino astronomy with 5.7σ observation of astrophysical neutrinos and probing atmospheric charm hadron production
• Potential with PINGU to quickly resolve the ordering of the neutrino mass hierarchy in addition to enhancing other physics (ντ appearance, non-maximal θ23, O(1) GeV dark matter,...)
Backup
Science Portfolio (Partial)

• Measurements
  • Cosmic Ray Anisotropy - arXiv:1105.2326
  • Diffuse Neutrino Flux - arXiv:1104.5187
  • Atmospheric Neutrino Spectrum - arXiv:1010.3980
  • Neutrino Oscillation - arXiv:1305.3909
  • Atmospheric Electron Neutrino Flux - arXiv:1212.4760

• Searches
  • Supernova 2008D - arXiv:1101.3942
  • Neutrino Induced Cascades - arXiv:1101.1692
  • Neutrino Emission Constraints on 2010 Crab Flare - arXiv:1106.3484
  • Point Sources - arXiv:1406.6757, 1307.6669
  • Gamma Ray Burst Neutrino Emission - arXiv:1204.4219
  • Slow Magnetic Monopole - arXiv:1402.3460
  • Dark Matter - arXiv:1406.6868, 1303.3473, 1212.4097
HESE-III Event Breakdown

### All Events

<table>
<thead>
<tr>
<th></th>
<th>Muons</th>
<th>$\pi/K$ atm. $\nu$</th>
<th>Prompt atm. $\nu$</th>
<th>$E^{-2}$ (best-fit)</th>
<th>Sum (central)</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tot. Events</td>
<td>8.4 ± 4.2</td>
<td>6.6$^{+2.2}_{-1.6}$</td>
<td>&lt; 9.0 (90% CL)</td>
<td>23.8</td>
<td>38.8</td>
<td>37 (36)</td>
</tr>
<tr>
<td>Up</td>
<td>0</td>
<td>4.0</td>
<td>&lt; 5.8</td>
<td>8.2</td>
<td>12.2</td>
<td>9</td>
</tr>
<tr>
<td>Down</td>
<td>8.4</td>
<td>2.6</td>
<td>&lt; 3.2</td>
<td>15.6</td>
<td>26.6</td>
<td>27</td>
</tr>
<tr>
<td>Track</td>
<td>~ 7.6</td>
<td>4.5</td>
<td>&lt; 1.7</td>
<td>4.5</td>
<td>16.7</td>
<td>8</td>
</tr>
<tr>
<td>Shower</td>
<td>~ 0.8</td>
<td>2.1</td>
<td>&lt; 7.3</td>
<td>19.3</td>
<td>22.2</td>
<td>28</td>
</tr>
<tr>
<td>Fraction Up</td>
<td>0%</td>
<td>61%</td>
<td>65%</td>
<td>34%</td>
<td>31%</td>
<td>25%</td>
</tr>
<tr>
<td>Fraction Down</td>
<td>100%</td>
<td>39%</td>
<td>35%</td>
<td>66%</td>
<td>69%</td>
<td>75%</td>
</tr>
<tr>
<td>Fraction Tracks</td>
<td>&gt; 90%</td>
<td>69%</td>
<td>19%</td>
<td>19%</td>
<td>43%</td>
<td>24%</td>
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<tr>
<td>Fraction Showers</td>
<td>&lt; 10%</td>
<td>31%</td>
<td>81%</td>
<td>81%</td>
<td>57%</td>
<td>76%</td>
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### $E_{dep} < 60$ TeV

<table>
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<tr>
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<th>Prompt atm. $\nu$</th>
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<th>Sum (central)</th>
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<tr>
<td>Tot. Events</td>
<td>8.0</td>
<td>4.2</td>
<td>&lt; 3.7</td>
<td>2.2</td>
<td>14.4</td>
<td>16</td>
</tr>
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<td>4</td>
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<tr>
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<td>8.0</td>
<td>1.7</td>
<td>&lt; 1.4</td>
<td>1.1</td>
<td>10.7</td>
<td>12</td>
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<td>2.9</td>
<td>&lt; 0.7</td>
<td>0.4</td>
<td>10.5</td>
<td>4</td>
</tr>
<tr>
<td>Shower</td>
<td>~ 0.8</td>
<td>1.4</td>
<td>&lt; 3.0</td>
<td>1.8</td>
<td>4.0</td>
<td>12</td>
</tr>
<tr>
<td>Fraction Up</td>
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<td>60%</td>
<td>63%</td>
<td>51%</td>
<td>26%</td>
<td>25%</td>
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<tr>
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<td>40%</td>
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<td>49%</td>
<td>74%</td>
<td>75%</td>
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<tr>
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<td>19%</td>
<td>72%</td>
<td>25%</td>
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<tr>
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<td>&lt; 10%</td>
<td>32%</td>
<td>81%</td>
<td>81%</td>
<td>28%</td>
<td>75%</td>
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### $60$ TeV $< E_{dep} < 3$ PeV

<table>
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<th>$E^{-2}$ (best-fit)</th>
<th>Sum (central)</th>
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<td>2.4</td>
<td>&lt; 5.3</td>
<td>18.2</td>
<td>21.0</td>
<td>20</td>
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<tr>
<td>Up</td>
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<td>1.4</td>
<td>&lt; 3.5</td>
<td>6.5</td>
<td>8.0</td>
<td>5</td>
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<tr>
<td>Down</td>
<td>0.4</td>
<td>0.9</td>
<td>&lt; 1.8</td>
<td>11.7</td>
<td>13.0</td>
<td>15</td>
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<td>Track</td>
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<td>1.7</td>
<td>&lt; 1.0</td>
<td>3.8</td>
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<tr>
<td>Shower</td>
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<td>&lt; 4.2</td>
<td>14.4</td>
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<td>16</td>
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<tr>
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<td>61%</td>
<td>67%</td>
<td>36%</td>
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<td>25%</td>
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<tr>
<td>Fraction Down</td>
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<td>62%</td>
<td>75%</td>
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<td>71%</td>
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<td>80%</td>
<td>79%</td>
<td>72%</td>
<td>80%</td>
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Potential High Energy Extension (HEX)

Spacing 1 (120m): IceCube (1 km³) + 98 strings (1,3 km³) = 2,3 km³

Spacing 2 (240m):
  IceCube (1 km³) + 99 strings (5,3 km³) = 6,3 km³

Spacing 3 (360m):
  IceCube (1 km³) + 95 strings (11,6 km³) = 12,6 km³

Chosen geometry not optimum (i.e. for HESE)
... historically chosen to demonstrate that we do respect boundary conditions

*courtesy of C. Wiebusch (RTWH Aachen)
Dark Matter in PINGU

- Probes lower mass region
- Independent test of Spin-Independent results from direct detection experiments