IceCube-DeepCore-PINGU

IPP AGM/Town Hall Meeting
June 2014

Darren R. Grant
The IceCube Neutrino Observatory

Completed
December 18, 2010

DeepCore Array
8 strings with dense spacing optimized for lower energies
480 total optical sensors

IceCube Array
86 total strings, including 8 DeepCore strings
60 optical sensors on each string
5160 optical sensors

IceCube Lab

IceTop
81 Stations, each with 2 Cherenkov detector tanks and 2 optical sensors per tank
324 total optical sensors.

AMANDA-II Array
IceCube pre-cursor

Digital Optical Module
IceCube

- 78 Strings
- 125m string spacing
- 17m DOM spacing

IceCube (top centre view)

digital optical module - DOM
IceCube

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IceCube (top centre view)

- Add 8 strings
- 75m string spacing
- 7m DOM spacing
- Add 40 strings (baseline target)
- ~20m string spacing
- 3-5m DOM spacing
- ~15x higher photocathode density

analysis completed on WestGrid's Jasper Cluster

digital optical module - DOM
IceCube-DeepCore

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IceCube-DeepCore

DeepCore low-en working group convened @ U. Alberta; Simulations completed on Compute Canada
IceCube-DeepCore-PINGU

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IceCube-DeepCore-PINGU top view
The physics with future atmospheric neutrino detectors

Covered in today’s talk

• Gain sensitivity to atmospheric neutrinos in the region below 10 GeV with very high statistics
  • Provide a definitive measurement of the neutrino mass hierarchy (NMH)
  • Will help pin down \((\Delta m_{23})^2\) and test maximal mixing, \(\nu_\tau\) appearance

• Probe lower mass WIMPs

• Gain increased sensitivity to supernovae neutrino bursts, Earth tomography

• Initiate an extensive calibration program to improve systematics knowledge

• Pathfinder technological R&D for the Megaton Ice Cherenkov Array (MICA)
Using atmospheric neutrinos to measure the NMH

Up to 20% differences in $\nu_\mu$ survival probabilities for various energies and baselines, depending on the neutrino mass hierarchy.
Neutrinos

\[ \Delta m^2_{32} = 2.32 \times 10^{-3} \text{ eV}^2 \]
\[ \sin^2(2\theta_{23}) = \frac{\pi}{4} \]

\[ P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta) \sin^2 \left( \frac{\Delta m^2 L}{4E} \right) \]

Antineutrinos

Lines of constant L/E

Earth’s outer core

Increasing density

Normal hierarchy

Inverted hierarchy
• Distinctive (and quite different) hierarchy-dependent signatures are visible in both the track and cascade channels
  
  • Full MC for detector efficiency, reconstruction, and particle ID included
PINGU and the NMH - predicted sensitivity

• With baseline geometry, a determination of the mass hierarchy with $3\sigma$ significance appears possible with 3.5 years of data

• Primary estimate uses parametric detector response model based on simulations

• Vetted against full Monte Carlo studies with more limited statistics and range of systematics

• Optimization of detector geometry & analysis techniques and more detailed treatment of systematics underway
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PINGU and the NMH - predicted sensitivity

![Graph showing NMH significance vs. PINGU livetime](arXiv:1401.2046)
Several current or planned experiments will have sensitivity to the neutrino mass hierarchy in the next 10-15 years

- NB: median outcomes shown – large fluctuations possible

Widths indicate main uncertainty

- LBNF/NOvA: $\delta_{CP}$
- JUNO: $\sigma_E$ (3.0-3.5%)
- PINGU/INO: $\theta_{23}$
  (38.7°–51.3°, 40°–50°)
- Other projections presented here assume worst-case parameters (1st octant)

PINGU timeline based on aggressive but feasible schedule

- LBNE from LBNE-doc-8087-v10, Hyper-K from arXiv:1109.3262 (2011), all others from Blennow
Path to PINGU

- Jan 2014 - PINGU Letter of Intent
- May 2014 - P5 decision: “Further development for PINGU is recommended”; Application as IPP project submitted
- Jun 2014 - Submission of CFI IF for PINGU project
- Fall 2014 - US NSF white paper/Early Concept Proposal submitted for review
- Jun 2015 - MREFC (major research equipment and facilities construction) Conceptual Design submission; CFI IF award decision
- Sep 2015 - CDR passed/begin R&RA funding
- Jun 2016 - Preliminary design review
- Jan 2017 - Final design review; start construction; remainder CFI IF released
- Dec 2018 - first 8 PINGU strings
- Dec 2019 - next 18 PINGU strings
- Dec 2020 - PINGU complete
IceCube-DeepCore-PINGU and Canada

- The program is (quickly) developing
  - Currently 5 faculty (Alberta, Toronto) @ 2.0 FTE, 1 PDF, 2 PhD students, 4 summer students (~3.5% direct project impact within IceCube)
    - See talks by Ken Clark, Tania Wood, Sarah Nowicki this week
    - increasing to 6 faculty @ 3.7 FTE by 2017 (~8% direct impact IceCube; 30% of PINGU)
- Compute Canada resources have permitted key contributions:
  - nearly 1/2 the collaboration’s GPU computing
  - ~20% of the collaboration’s CPUs
  - generated the full simulation sets for PINGU design studies and DeepCore analyses
  - completed the high energy neutrino search analysis
- Building on established collaboration leadership:
  - Canadian researchers hold positions on the Collaboration, Publications, and Trigger-Filter-Transmission Boards; appointed as convener for the low-energy analysis group; D. Grant appointed co-convener for the PINGU upgrade
IceCube-DeepCore-PINGU and Canada

- Activities primarily supported via NSERC SAP Discovery Grants (renewal NOI to be submitted August 2014)

- CFI IF (in preparation). Full in-kind support secured for calibration and electronics R&D activities (in part at TRIUMF)
  - funding for ~30% of the PINGU optical modules (pending NSF MREFC).

<table>
<thead>
<tr>
<th>Start date</th>
<th>End date</th>
<th>Source</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Apr 2010</td>
<td>Mar 2013</td>
<td>NSERC (SAP Discovery, Individual)</td>
<td>$190,000</td>
</tr>
<tr>
<td>Apr 2013</td>
<td>Mar 2014</td>
<td>NSERC (SAP Discovery, Project)</td>
<td>$109,000</td>
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<tr>
<td>Jan 2014</td>
<td>Dec 2014</td>
<td>Compute Canada (RAC)</td>
<td>$975,936</td>
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<tr>
<td>Apr 2014</td>
<td>Mar 2015</td>
<td>NSERC (SAP Discovery, Project)</td>
<td>$180,000</td>
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<td>Sep 2015</td>
<td>Dec 2018</td>
<td>CFI IF (in preparation)</td>
<td>$12,200,000</td>
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</table>
Summary and Outlook

• IceCube and DeepCore paved the way: demonstration of a prolific low-energy neutrino physics in the Antarctic ice with leading sensitivity in the indirect dark matter search and a robust atmospheric neutrino oscillation programs of IceCube. A rich on-going analysis program.

• PINGU is being optimized

  • String and optical module placement has a fairly broad minimum for the NMH sensitivity.

  • Additional detectors (increasing from 60 to 96 modules per string) improves the resolution at low energies, significantly moving the 3 year significance from 2.8σ to nearly 3.3σ for a 10% increase in project cost.

• Beyond the atmospheric neutrino measurements, PINGU will increase the sensitivity to the low-mass indirect WIMP searches, supernova neutrinos, Earth tomography…
Summary and Outlook

PINGU advantages include:

- Use of the similar hardware and deployment techniques as IceCube would significantly reduce project risk

- Could be quick, dependent on funding (2 years of procurement and fabrication; 2-3 years of deployment)

- Is a natural part of a Next Generation IceCube Observatory (high energy extension, surface veto array). P5 final draft report “...and we encourage continued work to understand systematics. PINGU could play a very important role as part of a larger upgrade of IceCube, or as a separate upgrade, but more work is required.”

- NSF MREFC, and international partner proposals are now in preparation (still very early days of detector development; interested? come visit us)

- PINGU as a potential stepping stone: acting as a testbed for new photodetectors could lead to a multi-megaton fiducial detector (MICA) reaching a O(10 - 100 MeV) in the ice (supernova neutrinos, very low-mass WIMP searches, (potentially) proton decay).
The IceCube–PINGU Collaboration

International Funding Agencies

Fonds de la Recherche Scientifique (FRS–FNRS)
Fonds Wetenschappelijk Onderzoek–Vlaanderen (FWO–Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)

Deutsches Elektronen-Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
NSF–Office of Polar Programs
NSF–Physics Division

Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)
Backup slides
IceCube-DeepCore-PINGU

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Figure courtesy A. Karle

Digital optical module - DOM
Oscillations with Atmospheric Neutrinos

- Neutrinos oscillating over one Earth diameter have a $\nu_\mu$ survival minimum at ~25 GeV
  - Hierarchy-dependent matter effects below ~12 GeV
- Neutrinos are available over a wide range of energies and baselines
  - Comparison of observations from different baselines and energies is crucial for controlling systematics
  - Essentially, a generalization of the up-down ratio approach
PINGU’s Atmospheric $\nu$ Signal

N(Events) Expected in PINGU per Year

<table>
<thead>
<tr>
<th>$\nu$ Type</th>
<th>Trigger Detector</th>
<th>Pass Baseline Analysis</th>
</tr>
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<tbody>
<tr>
<td>$\nu_e$ CC</td>
<td>52k</td>
<td>26k</td>
</tr>
<tr>
<td>$\nu_\mu$ CC</td>
<td>86k</td>
<td>35k</td>
</tr>
<tr>
<td>$\nu_\tau$ CC</td>
<td>6.4k</td>
<td>2.7k</td>
</tr>
<tr>
<td>$\nu_x$ NC</td>
<td>17k</td>
<td>7.9k</td>
</tr>
</tbody>
</table>

1 GeV < E < 80 GeV

IceCube $\nu$-induced cascades

IceCube

Super-K $\nu_\mu$

Fréjus $\nu_\mu$

Fréjus $\nu_e$

AMANDA $\nu_\mu$

Baseline Analysis

Pass

Trigger Detector

conventional $\nu_e$

conventional $\nu_\mu$

prompt $\nu_\mu$, $\nu_e$

Honda $\nu_\mu$

Bartol $\nu_e$

Honda $\nu_e$
PINGU and the NMH

- Cannot distinguish $\nu$ from $\overline{\nu}$ directly – rely instead on differences in fluxes, cross sections (and kinematics)

- Differences clearly visible in expected atm. muon ($\nu + \overline{\nu}$) rate even with 1 year’s data

- Note: detector resolutions not yet included here
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• Note: detector resolutions not yet included here
Once detector resolutions are included the signature of the hierarchy is apparent by looking at the pattern of expected excesses and deficits in the $E$ vs. $\cos(\theta_z)$ plane.

- Structure of the pattern gives some protection against systematics.

- Note: reconstructions included in these plots, but not yet particle ID.

Following JHEP, 2013(02), pp. 1-39
PINGU Particle ID

- $\nu_\mu$ CC events distinguishable by the presence of a muon track
- Distinct signatures observable in both track ($\nu_\mu$ CC) and cascade ($\nu_e$ and $\nu_\tau$ CC, $\nu_x$ NC) channels
Estimations from the full simulation operating on event histograms in Energy and cos(zenith)

- Fast evaluation using the Fisher Information Matrix (FIM) where the gradients at each point fully describe the parabolic minimum (invert and obtain the full covariance matrix for the experiment)

- Full analysis from pseudo data sets applied as templates; LLR provides degree of agreement between pseudo set and one hierarchy vs. the other.

- The Likelihood distributions are fit well by Gaussians; the two methods agree
PINGU and the NMH - applying the systematics

- Strongest impact from the Energy Scale and cross-section normalization, $\delta_{CP}$ has a minimal effect.

- Additional systematics currently being incorporated:
  - Particle ID performance
  - Cross-section details
  - Ice Model

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<tr>
<th>Parameter</th>
<th>Description</th>
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<tbody>
<tr>
<td>$\Delta m^2_{31}, \theta_{23}, \theta_{13}$</td>
<td>Oscillation parameters</td>
</tr>
<tr>
<td>$\nu / \bar{\nu}$ cross-section</td>
<td>Cross-section/flux normalization (fully degenerate)</td>
</tr>
<tr>
<td>$A_{\text{eff}}$ energy dependence</td>
<td>Degenerate with spectral index of atmospheric flux</td>
</tr>
<tr>
<td>Energy scale</td>
<td>$E_{\text{reco}}/E_{\text{true}}$</td>
</tr>
</tbody>
</table>
PINGU Digital Optical Module (PDOM)

DOM

Penetrator
PMT Base
HV Supply
Flasher Board
Main Board
Delay Board
Waist Band
Pressure Sphere
Mu-metal cage
Silicone Gel
PMT Photocathode

PDOM