Fundamental Neutrino Physics with IceCube and PINGU

Doug Cowen
University of Manchester and Penn State
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Introduction

• Neutrino Oscillations
• The Detectors:
  • IceCube & DeepCore (taking data)
  • PINGU (proposed as part of IceCube Gen2)
• The Source:
  • Atmospheric neutrinos
• The Signature:
  • Interactions in ice
  • Oscillations
Reasons to Care About Neutrinos

• “Brian Cox” reasons:
  • Ubiquity:
    • $10^{11} \text{v/s/cm}^2 \ & \sim 300 \text{ in every cm}^3 \text{ of space}$
  • Critical for life
    • Fusion in stars requires emission of v’s
  • “Tiniest” or most “anti-social” of all fundamental particle(s)
    • Solar neutrinos can pass unscathed through light-year-long column of lead
    • $\sim 10^{24} \text{ neutrinos will pass through your body in your lifetime; only } \sim 1 \text{ will deign to touch you}$

• Other good reasons:
  • Least understood fundamental particles in the Standard Model
  • Studying neutrino properties could yield hints for new physics
  • Their detection poses an irresistible experimental challenge
Neutrino Oscillations

• General 3-flavor mixing described by Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix
  
  • analogous to CKM matrix for quarks, but with larger off-diagonal elements

• Different L/E regimes require different sources and detectors

\[
U_{PMNS} = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

\[
\begin{bmatrix}
s_{ij} \equiv \sin \theta_{ij} \\
c_{ij} \equiv \cos \theta_{ij}
\end{bmatrix}
\]

\[
\text{atmospheric, beam} 
\quad \text{reactor, beam} 
\quad \text{solar}
\]
Neutrino Oscillations

• General 3-flavor mixing described by Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix
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0 & -s_{23} & c_{23}
\end{pmatrix} \begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix} \begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}$$

\[ s_{ij} \equiv \sin \theta_{ij} \]
\[ c_{ij} \equiv \cos \theta_{ij} \]
• Detectors have a wide range of sizes

• For higher $E(\nu)$, events are rarer but brighter

• Leads to construction of bigger but more sparsely instrumented detectors

![Graph showing the relationship between energy threshold and photon energy area/detector volume.]

Define: $\text{Photon effective area} = \text{equivalent area of 100\% photon (collection) efficiency}$ not included here.

Except for absorption, detectors require about the same number of photoelectrons per event.

*)

A. Karle
The Detectors  The Source  The Signature

IceCube & DeepCore

Digital Optical Module (DOM)

PINGU (Top View)
The Detectors

- IceCube
- DeepCore
- PINGU

- Top view of the PINGU new candidate detector

- 86 strings, 60 DOMs/string
- 40 strings, 96 DOMs/string
The Detectors  The Source  The Signature
The Detectors  The Source  The Signature
- IceCube DeepCore
  - More densely instrumented region at bottom centre of IceCube
  - Below 2100m, clearest ice
    - $\lambda_{\text{att}} \sim 50$ m
    - radiopure
  - IceCube provides active downward-going muon veto
From the Cherenkov light pattern we can reconstruct each event's:

- direction,
- energy, and
- ~flavor
Atmospheric Neutrinos

• Production mechanism
• Wide variety of energies and baselines
• Lots of possible oscillation signatures

\[ p + N \rightarrow X + \pi^\pm, K^\pm \]

\[ \mu^\pm + \bar{\nu}_\mu \]

\[ e^\pm + \nu_e + \bar{\nu}_\mu . \]
Atmospheric Neutrinos

- Production mechanism
- Wide variety of energies and baselines
- Lots of possible oscillation signatures
Atmospheric Neutrino Flux

Atmospheric $\nu$ Energy Spectrum

IceCube and PINGU will each see tens of thousands of $\nu$/yr
Atmospheric Neutrinos

• Production mechanism
• Wide variety of energies and baselines
• Lots of possible oscillation signatures

Mena, Mocioiu & Razzaque, Phys. Rev. D 78, 093003

\[ L = d_L \]
The Detectors  The Source  The Signature

- Simulated $\nu_\mu$ CC event, $E_\nu = 9.3$ GeV
  - 4.4 GeV initial cascade, 4.9 GeV muon
- Physics hits only (no noise)
• Simulated $\nu_\mu$ CC event, $E_\nu = 9.3$ GeV
  • 4.4 GeV initial cascade, 4.9 GeV muon
• Physics hits only (no noise)
The Detectors  The Source  The Signature

1.7 GeV $\nu_\mu$

4.4 GeV $\nu_\mu$

4.7 GeV $\nu_e$

11.8 GeV $\nu_\mu$

Size of circles: $N_\gamma$.
Color: $t_\gamma$. 

D. Cowen/Manchester and Penn State
• Using just $\nu$–induced Cherenkov light, IceCube and PINGU can separate tracks from showers
  • tracks: $\nu_\mu$ CC interactions with sufficiently energetic muon
  • showers: all other $\nu$ interactions
• Provides sensitivity to
  • $\nu_\mu$ disappearance
  • $\nu_\tau$ appearance
  • the neutrino mass hierarchy

Mena, Mocioiu & Razzaque, Phys. Rev. D78, 093003
Atmospheric Neutrino Oscillations

- Atmospheric neutrinos are observed over wide range of energies & pathlengths
  - oscillations produce distinctive pattern in \((E_\nu, \cos \theta)\) space
  - can combat systematics using events in “side band” regions where oscillations do not occur
- For reference:
  - at \(L = d_E\), \(P(\nu_\mu \rightarrow \nu_\mu) = 0\) at \(E_\nu \sim 25\) GeV
  - see MSW and parametric oscillations below \(E_\nu \sim 20\) GeV
IceCube/DeepCore $\nu_\mu$ Disappearance

- IceCube has done three analyses so far (two published, third on the way)
  - PRL 111, 081801 (2013)
  - PRD 91, 072004 (2015)
- Differences mainly in sophistication of event reconstruction
- Focus here on the second published analysis and the third analysis in progress
IceCube/DeepCore $\nu_\mu$ Disappearance

• Analysis steps
  • Reject downward going cosmic ray muon background
    • initially, $\downarrow\mu$ outnumber $\nu_\mu$(CC) by $10^5$:1
    • use IceCube and outer layers of DeepCore to veto $\downarrow\mu$
      • Achieve 1:1 with 40% signal retention
  • Require minimum number of “direct” (~unscattered) photons in each event to ensure good reconstruction
Analysis steps (continued)

- Fit each event assuming a point-like or track-like hypothesis

- Keep only track-like events
  - selection criteria keep only those $\nu_\mu$ CC events with $L_\mu > \sim 20$ m

- Estimate event energy from shower at vertex and $L_\mu$
  - Energy of remaining neutrinos from simulation:

### Data
- Neutrino simulation
- Atm. muons (from data)
- Neutrinos + Atm. muons
IceCube/DeepCore $\nu_\mu$ Disappearance

- Fit for $\theta_{23}$ and $\Delta(m_{32})^2$ parameters
- Systematics
  - $\Phi_{atm}$ normalization, spectral index, $v_e/v_\mu$ ratio
  - cross section uncertainties (very modest effect)
  - detector uncertainties: DOM efficiency (impacts mass splitting) and ice properties (impact mixing angle)
    - These are the biggest systematic uncertainties
  - $\theta_{13}$ treated as nuisance parameter, other oscillation parameters fixed to world averages
- Results
  - Using 953 days of detector livetime, observed 5174 events
    - no oscillation expectation: 6830
    - overall signal efficiency, relative to initial sample of contained events, is $\sim 3\%$
  - $\sigma_{stat}$, $\sigma_{syst}$ comparable in magnitude; $\sim 80\%$ DIS; $\sim 5\%$ $\mu$
IceCube/DeepCore $\nu_\mu$ Disappearance

Final Result

Precision comparable to world’s best measurements!
Uses highest energy $\nu_{\text{atm}}$ sample ever.
Underway: Third $\nu_\mu$ Disappearance Analysis

- Employs improved reconstruction
  - better resolutions on angle, energy
  - $\sim 7x$ better signal efficiency ($\sim 20\%$)
Near Future: $\nu_\tau$ Appearance

Example: for a $\nu_\tau$ flux that is 1.0x that which is expected from standard oscillations, DeepCore can exclude the no-$\nu_\tau$ hypothesis (norm = 0.0) at the level of 4-6.5$\sigma$ in 90% of the cases.

In the standard oscillation scenario, $\nu_\tau$ norm = 1
The Precision IceCube Next Generation Upgrade can do everything DeepCore can do, only better.

And it can do things IceCube/DeepCore cannot.

Terminology: PINGU is part of IceCube-Gen2, a proposed IceCube upgrade including an enlarged high energy in-ice array and more expansive surface veto, and possibly a radio array.
PINGU Physics Goals

- Neutrino oscillations
  - Neutrino mass hierarchy
  - Muon neutrino disappearance
  - Tau neutrino appearance
- WIMP dark matter
- Earth tomography
- Supernovae
- Low $E_\nu$ point sources,...
PINGU Physics Goals

- Neutrino oscillations
  - Neutrino mass hierarchy
  - Muon neutrino disappearance
  - Tau neutrino appearance
- WIMP dark matter: Reaches very low $m(\chi)$.
- Earth tomography: Unique measurement.
- Supernovae: New sensitivity to $E(\nu)$.
- Low $E_{\nu}$ point sources,...
The Neutrino Mass Hierarchy

One of the few remaining unmeasured fundamental parameters in particle physics

"Normal"

\[ \Delta m^2(\text{atm}) \]

\[ \Delta m^2(\text{sun}) \]

"Inverted"

\[ \Delta m^2(\text{atm}) \]

\[ \Delta m^2(\text{sun}) \]

...PINGU can exploit matter effects at \( E_\nu \sim 5-15 \text{ GeV} \) to distinguish

Semi-Useful Factoid: The total mass in neutrinos in the universe differs in these two cases by about the mass of our galaxy: \( M_{\nu,\text{tot}}(\text{IH}) - M_{\nu,\text{tot}}(\text{NH}) \sim M(\text{MilkyWay}) \)
The NMH Signature in PINGU

\[ \nu_\mu + \text{anti-}\nu_\mu = [\text{pattern A}] \]

Measurement looks for difference between patterns A & B

\[ \cos(\theta) \]

Without ability to distinguish \(\nu_\mu\) from anti-\(\nu_\mu\), \(A = B\).
The NMH Signature in PINGU

Normal Hierarchy

\[ \nu_\mu + \text{anti-}\nu_\mu = \text{[pattern A]} \]

But:

\[ \sigma(\nu) \sim 2\sigma(\text{anti-}\nu) \]

\[ \phi(\nu_{\text{atm}}) > \phi(\text{anti-}\nu_{\text{atm}}) \]

Now A≠B!

Inverted Hierarchy

\[ \cos(\theta) \]
The NMH Signature in PINGU

- Our MC-based analysis is mature. Many challenges have been overcome:
  - Fully simulated event selection & reconstruction
    - Reconstruction required new IceCube approach for contained events
    - Reconstruction also required new optimizer and lots of CPU
  - Particle ID (PID)
    - Required new IceCube approach for low $E_\nu$ events
  - Long list of systematic errors (more details later)
    - Required new interfaces with code e.g. GENIE, exhaustive exploration of flux and cross section parameters, non-trivial adaptation of systematics space optimizer, large simulated datasets,...
  - Multiple statistical approaches in good agreement
    - Development of several new IceCube techniques and codes, adaptation of external (SK) code to run on GPUs,...
Visualizing the NMH Signature

- Expect $\sim 50k \nu_\mu + \nu_{\mu}$, $\sim 40k \nu_e + \nu_e/yr$: Largest ever sample in this $E$ range
- $\sim 25\%$ energy resolution, $\sim 15^\circ$ directional resolution
- PID with 90\% purity for tracks above $\sim 10GeV$
- Plots of (NH–IH) show distinctive patterns in $(E, \cos \theta)$ space:

\begin{align*}
E \text{ (GeV)} & \\
\cos(\theta_{\text{zen}}) & \\
10^{-1} & 10^{1}
\end{align*}
Predicted NMH Sensitivity

• Results from log-likelihood ratio (LLR) and faster $\chi^2$–pull approaches agree well

• Large list of systematics incorporated from
  • Oscillation parameter uncertainties
  • Flux and interaction uncertainties
  • Detector uncertainties
Systematic Parameters

• Oscillation parameters (from nu-fit.org [1]):
  ✦ $\Delta m^2_{31}$ (NH/IH) = 0.00246 / -0.00237 eV [2] (no prior)
  ✦ $\theta_{23}$ (NH/IH) = 42.3° / 49.5° (no prior)
  ✦ $\theta_{13}$ = 8.5° ± 0.2°

• Detector/flux/cross sections:
  ✦ event rate (effective area, flux normalization) = nominal (no prior)
  ✦ energy scale = nominal ± 0.10 (from current calibration data)
  ✦ $\nu_e/\nu_\mu$ ratio = nominal ± 0.03 (ref [2])
  ✦ $\nu/\text{anti-}\nu$ ratio = nominal ± 0.10 (ref [2] and [3])
  ✦ atmospheric spectral index: nominal ± 0.05 (ref [2])
  ✦ Also studied separately:
    - detailed cross section systematics based on GENIE [3] parameters
    - detailed atmospheric flux uncertainties from [2]

Systematics Impacts (4yr significances)

<table>
<thead>
<tr>
<th>Syst.</th>
<th>NH</th>
<th>IH</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>5.4σ</td>
<td>5.5σ</td>
</tr>
<tr>
<td>Osc. only</td>
<td>3.4σ</td>
<td>2.9σ</td>
</tr>
<tr>
<td>Flux only</td>
<td>4.3σ</td>
<td>4.6σ</td>
</tr>
<tr>
<td>Det. only</td>
<td>4.4σ</td>
<td>4.6σ</td>
</tr>
<tr>
<td>All</td>
<td>3.1σ</td>
<td>2.9σ</td>
</tr>
</tbody>
</table>

Predicted NMH Sensitivity

Predict $3\sigma$ significance in 3.5-4yrs of live time (@NuFit 2014 values).

(Shorter if include data from ~10 yrs DeepCore + partially deployed PINGU.)
Predict 3\(\sigma\) significance in 3.5-4yrs of live time (@NuFit 2014 values).

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NuFit 2014 values: ~most conservative!
Predicted NMH Sensitivity

Predict 3σ significance in 3.5-4yrs of live time (@NuFit 2014 values).

(Shorter if include data from ~10 yrs DeepCore + partially deployed PINGU.)

We are currently doing a “dry run” NMH analysis with DeepCore. Expect ~1σ significance.

NuFit 2014 values: ~most conservative!
Sensitivity to the Neutrino Mass Hierarchy

- **Running:** NOvA, T2K
  - $\delta_{CP} = 90^\circ$, $\theta_{23} = 40^\circ$, NH
  - $\delta_{CP} = -90^\circ$, $\theta_{23} = 40^\circ$, NH

- **Atmospheric:** MTon Ice/Water Cherenkov
  - $\theta_{23} = 49^\circ$, NH
  - $\theta_{23} = 51^\circ$, NH

- **Atmospheric:** Calorimeter
  - $\delta_{CP} = -90^\circ$, $\theta_{23} = 40^\circ$, NH
  - $\delta_{CP} = 90^\circ$, $\theta_{23} = 51^\circ$, IH

- **Reactor**
  - $\sigma(E) = 3\%$
  - $\sigma(E) = 3.5\%$

- **Future Longbaseline**
  - $\delta_{CP} = 90^\circ$, 34 kT
  - $\delta_{CP} = -90^\circ$, 10 kT

- **DeepCore analyses:** underway


- **PINGU (and ORCA)** are low cost.
- **PINGU construction** is low risk and fast. NMH measurement very competitive.
PINGU $\nu_{\text{atm}}$ Oscillation Physics

World-class measurements of atmospheric $\nu$ mixing parameters via $\nu_\mu$ disappearance and $\nu_{\tau}$ appearance

- T2K 2014
- T2K 2014 - projected 2020
- NOvA- projected 2020 (95% CL)
- PINGU 3 year, maximal mixing

| $|\Delta m^2_{31}|$ | 10^{-3} eV^2 |
|-------------------|-------------|
| Normal mass ordering assumed, 90% CL contours |

$\sin^2(\theta_{23})$

Preliminary studies observation possible with around 1 month of

Livetime (months)

$\tau_{\nu}$

Precision on

$\sigma$

Expected

68% CL

90% CL

SK (90% CL)

OPERA (90% CL)
DM, Tomo., SNe

- Solar WIMP dark matter searches would be competitive with Super-K down to 5GeV
- Earth tomography
  - Requires many MT·yrs of data, but unique capability
- Supernova detection would benefit from closer DOM spacing
  - gain measurement of energy spectrum

<table>
<thead>
<tr>
<th>$M_\chi$ (GeV)</th>
<th>$\sigma_p,SD$ (cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PINGU 5 yr</td>
<td></td>
</tr>
<tr>
<td>Super-K 2015</td>
<td></td>
</tr>
<tr>
<td>IceCube 15 yr</td>
<td></td>
</tr>
</tbody>
</table>

Rej. of Outer Core Comp in (CL,%) vs. Z/A ratio

- Figure 3: (a) Expected confidence level for rejecting a specific outer core composition with respect to iron plotted as a function of the corresponding Z/A ratio. A generic detector case with an energy resolution of 20% and an angular resolution of $0.25\times(E/GeV)$ is shown as an example. The colour indicates the exposure time given in megaton-years. We indicate the Z/A ratios for some selected outer core composition models (see Table 1 for details) as black dotted vertical lines. (b) The same plot as (a) for a larger Z/A range. Sensitivity dependences on (c) energy resolution and (d) angular resolution for a generic detector with an exposure time of 30 megaton-years for an angular resolution of $0.25\times(E/GeV)$ and an energy resolution of 20%, respectively.
UK Involvement in Gen2

- Oxford University
  - Subir Sarkar
  - Full membership
    - Theoretical aspects of high energy neutrino interactions
- University of Manchester
  - Justin Evans, Stefan Soldner-Rembold, Steven Wren (grad. student)
  - Associate membership
    - Analyze DeepCore data for NMH
    - Contribute to aspects of Gen2 DAQ firmware development
    - Co-chair PINGU analysis working group
- Queen Mary University London
  - Teppei Katori, Shivesh Mandalia (grad. student)
  - Associate membership
    - Differential cross section analysis
    - PINGU software, Gen2 PMT and DOM noise studies and modeling
The IceCube–PINGU Collaboration

University of Alberta–Edmonton (Canada)
University of Toronto (Canada)
Clark Atlanta University (USA)
Drexel University (USA)
Georgia Institute of Technology (USA)
Lawrence Berkeley National Laboratory (USA)
Massachusetts Institute of Technology (USA)
Michigan State University (USA)
Ohio State University (USA)
Pennsylvania State University (USA)
South Dakota School of Mines & Technology (USA)
Southern University and A&M College (USA)
Stony Brook University (USA)
University of Alabama (USA)
University of Alaska Anchorage (USA)
University of California, Berkeley (USA)
University of California, Irvine (USA)
University of Delaware (USA)
University of Kansas (USA)
University of Maryland (USA)
University of Wisconsin–Madison (USA)
University of Wisconsin–River Falls (USA)
Yale University (USA)

Stockholms universitet (Sweden)
Uppsala universitet (Sweden)
Niels Bohr Institutet (Denmark)
Queen Mary University of London (UK)
University of Oxford (UK)
University of Manchester (UK)
Université libre de Bruxelles (Belgium)
Université de Mons (Belgium)
Universiteit Gent (Belgium)
Vrije Universiteit Brussel (Belgium)

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

12 Countries
45 Institutions
260 Scientists

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–Synchrontron (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)
Conclusions

• DeepCore has produced neutrino oscillation results that are highly competitive on the world stage
  • Even better results are in the pipeline
• The PINGU physics case is compelling
  • The neutrino mass hierarchy is a fundamental parameter
    • The PINGU NMH significance has been very robust
  • Capable of numerous other high-profile, very competitive measurements
• Community interest in PINGU is strong and growing
  • Endorsed by high-profile “P5” panel in the US
  • PINGU LoI(v1) has 65 total citations (19 in refereed journals)
    • LoI(v2) in the works
  • So far this year there have been PINGU talks at ~10 conferences
• If you’re interested in joining Gen2, let me know!
DeepCore $\nu_\mu$ Disappearance Systematics

Reduction in uncertainty with parameter fixed:

<table>
<thead>
<tr>
<th></th>
<th>$\sin^2(\theta_{23})$</th>
<th>$(\Delta m^2_{31})(10^3 \text{ eV}^2)$</th>
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</thead>
<tbody>
<tr>
<td>PRD Errors</td>
<td>0.10</td>
<td>0.20</td>
</tr>
<tr>
<td>Hole Ice</td>
<td>29.9%</td>
<td>2.3%</td>
</tr>
<tr>
<td>DOM Efficiency</td>
<td>0.73%</td>
<td>19.1%</td>
</tr>
<tr>
<td>Spectral index $\gamma$</td>
<td>0.13%</td>
<td>8.7%</td>
</tr>
<tr>
<td>$[\Phi(\nu_e)/\Phi(\nu_\mu)]_{\text{atm}}$</td>
<td>0.05%</td>
<td>0.94%</td>
</tr>
<tr>
<td>Atm. $\mu$ bkgd.</td>
<td>0.00%</td>
<td>0.72%</td>
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</tbody>
</table>
Calibration of DeepCore

• Ice properties are calibrated with a variety of light sources
  • “dust logger” run down through select holes
  • *in situ* LED light sources on each DOM
    • 12 independent LEDs (6 horizontal, 6 at 45°)
  • *in situ* lasers

• Downward-going muons calibrate directionality and DOM efficiency

• Moon shadow calibrates directionality
Calibration: Ice Properties

- Depth dependence of $\lambda_{\text{eff}}$ and $\lambda_{\text{abs}}$ from in situ LEDs
- Ice below $\sim 2100$ m in DeepCore and PINGU fiducial regions is very clear ($\lambda_{\text{eff}} \sim 50$ m and $\lambda_{\text{abs}} \sim 150$ m)
- Constant temperature $\sim 30^\circ\text{C}$
### Table 14: Summary of proposed PINGU calibration devices and their purposes.

<table>
<thead>
<tr>
<th></th>
<th>LED flashers</th>
<th>POCAM</th>
<th>Cameras</th>
<th>MTOMs</th>
<th>Compass</th>
<th>Inclinometer</th>
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<td></td>
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<td></td>
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<td>Bulk ice</td>
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<td>✔</td>
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<tr>
<td>Hole ice</td>
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<td>✔</td>
<td>✔</td>
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<td>DOM sensitivity</td>
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<td>✔</td>
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<tr>
<td>Cable shadow</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>✔</td>
</tr>
</tbody>
</table>

**LED Flashers**

- LED light output: Photodiode monitoring of the LEDs on the control board will increase confidence in the laboratory characterization and will allow for better control of the brightness settings, especially at low light levels, which will be necessary in order to measure the ice properties across the short distances between PINGU DOMs.

- LED pulse timing profile: In IceCube, the minimum LED pulse width is 7 ns. In order to measure the scattering function more precisely over short distances, the LED pulse width should be reduced below 2 ns so that the time behavior of the received light is almost entirely due to scattering rather than the source pulse shape. R&D efforts are underway to determine the feasibility of producing a 1 ns pulse in ice. Pulse widths of 3 ns have been produced in the lab using IceCube LEDs, and it is expected that widths of 1-2 ns can be achieved with an updated driver circuit.

**Pingu’s close module spacing will enable us to better constrain ice properties, benefiting ν event reconstruction at all energies.**
Calibration

Making connections to physics measurements:

\[ \Delta m^2(31) \text{ 90\% CL} \]

Prior on Energy Scale (%)

N.B.: Blue line is just spline fit, has no physical significance.

3 yr PINGU

NuFit 2014

E_{\text{reco}} - E_{\text{true}} (GeV)

Evaluating detector systematics:
With DOM efficiency uncertainty conservatively set to IceCube value (10%), shift in its mean value has biggest impact on PINGU energy scale.
Most Recently Studied Systematic: $\delta_{CP}$

- $\delta_{CP}$ included as a nuisance parameter
- via $\chi^2$–Pull
- Initial LLR study used 4 fixed values; in agreement
- Not yet included in final significance plots
Neutrino Cross Sections

- At the $E_\nu$ relevant for DeepCore and PINGU, cross section dominated by DIS
- Would still be useful to measure $\sigma(\nu-\text{H}_2\text{O})$ in the 5–15 GeV energy range
- Minerva has a water target and can be used for this purpose
Neutrino Cross Section Systematics

- Performed full treatment of systematics through GENIE, varying over 10 separate parameters
- Impact on final significance much smaller than that of oscillation parameter uncertainties
- Largest impacts seen from $m_A$ in CCQE and resonance interactions, and higher twist parameters in Bodek-Yang DIS model
Atmospheric Flux Systematics
Using Downgoing $\nu$

NH true, $\theta_{23}^{NH} = 38^\circ$
NMH Synergy: $\nu_{\text{atm}}$ and $\nu_{\text{reactor}}$

- Assume we have two experiments, one using atmospheric $\nu$ and the other reactor $\nu$, each have sensitivity to the NMH.
- PINGU or ORCA, and JUNO or RENO-50
- When data are analyzed under the wrong hierarchy hypothesis, the best fit occurs at different values of $|\Delta m^2(31)|$
- Reason: $\nu_e$ and $\nu_\mu$ disappearance experiments measure different $\Delta m^2$’s
  - depends on $(m_3)^2$ and the flavor-averaged mass squared of states $m_1$ and $m_2$ (see eqns.)
- Implication: Global significance for rejecting the wrong hierarchy can improve faster than a simple quadratic sum

\[
\delta m^2_{\text{eff}} \bigg|_\alpha = m_3^2 - \left< m_\alpha^2 \right>_{12}
\]
\[
\left< m_\alpha^2 \right>_{12} = \frac{\left| U_{\alpha 2} \right|^2 m_2^2 + \left| U_{\alpha 1} \right|^2 m_1^2}{\left| U_{\alpha 1} \right|^2 + \left| U_{\alpha 2} \right|^2}
\]

Nunokawa et al., PRD 72, 013009 (2005)
NMH, CMB, and 0νββ

![Diagram showing the exclusion of mass values for neutrinos in the context of normal and inverted hierarchies. The image includes the current cosmology limits and future cosmology projections.](Guzowski et al., http://arxiv.org/abs/1504.03600 arXiv:1309.5383v3)
Neutrino Oscillations at the TeV-PeV Scale

- After (standard) oscillations, all sources should end up in the triangle
  - pure neutron-escape scenario is disfavored
PINGU Meff

![Graph showing the relationship between effective mass and neutrino energy. The graph includes two lines: one for $\nu_\mu$ CC and another for $\nu_\mu$ NC. The effective mass is plotted on the y-axis, and neutrino energy is plotted on the x-axis. There is a note that the graph is preliminary.]
Estimated Cost & Timeline

- **Cost:** Many items are common between various Gen2 subdetectors
  - Drill, module and cable engineering, calibration
  - Devices, software, project management,...
  - Anticipate significant contributions for hardware from partner countries

- **Timeline:** short, but start time is not yet known.

### Cost for PINGU Component

<table>
<thead>
<tr>
<th></th>
<th>Cost for PINGU Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardware</td>
<td>$48M</td>
</tr>
<tr>
<td>Logistics</td>
<td>$23M</td>
</tr>
<tr>
<td>Contingency</td>
<td>$16M</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>$88M</strong></td>
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<tr>
<td>Partner Contributions</td>
<td>–$25M</td>
</tr>
<tr>
<td><strong>Total US Cost</strong></td>
<td><strong>$63M</strong></td>
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</tbody>
</table>
Tau Neutrino Appearance: PINGU

![Graph showing significance to exclude no \( \nu_\tau \) appearance (\( \sigma \)) vs. livetime (months). The graph includes expected values and \( \pm 1\sigma \) and \( \pm 2\sigma \) shaded regions. The PINGU logo is also displayed.]
World-class measurements of atmospheric neutrino parameters via $\nu_\mu$ disappearance and $\nu_\tau$ appearance.
Inelasticity

- Inelasticity distribution is different for neutrinos and anti-neutrinos.
- Inclusion of inelasticity in the NMH analysis could improve significance by 20-50% (Ribordy and Smirnov, 1303.0758).
Log-Likelihood Ratio

- Generate templates for all oscillation/systematic parameters and hierarchies
- Create pseudo-dataset by pulling from the template and adding Poissonian fluctuations
- Calculate the likelihood of the pseudo-dataset using ALL templates
- Use the best likelihood to determine the LLR, and repeat many times
- Determine the proportion of the distribution which lies beyond the median point in the opposite distribution, giving the p-value for this test

\[
LLR = \frac{\sum_{N=0}^{N_{\text{bins}}} L(\text{Data}_{\text{NH}}|\text{Template}_{\text{IH}})}{\sum_{N=0}^{N_{\text{bins}}} L(\text{Data}_{\text{NH}}|\text{Template}_{\text{NH}})}
\]

\[
LLR = \frac{\sum_{N=0}^{N_{\text{bins}}} L(\text{Data}_{\text{IH}}|\text{Template}_{\text{IH}})}{\sum_{N=0}^{N_{\text{bins}}} L(\text{Data}_{\text{IH}}|\text{Template}_{\text{NH}})}
\]
NOvA, PINGU and $\delta_{CP}$

- Explore impact of knowing NMH at several selected points

If PINGU says NH, good $\delta_{CP}$ and octant resolution for NOvA

<table>
<thead>
<tr>
<th>$\theta_{23}$</th>
<th>fraction of $\delta_{CP}$ within 2$\sigma$</th>
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<tbody>
<tr>
<td>Unknown NMH</td>
<td>0.68</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NH</td>
<td>0.14</td>
<td>0.57</td>
<td>0.00</td>
<td></td>
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If PINGU says NH, improves NOvA's $\delta_{CP}$ measurement

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<th>fraction of $\delta_{CP}$ within 2$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unknown NMH</td>
<td>0.00</td>
<td>0.89</td>
<td>0.90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NH</td>
<td>0.00</td>
<td>0.36</td>
<td>0.46</td>
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If PINGU says NH, good $\delta_{CP}$ and octant resolution for NOvA

NOvA error ellipses: M. Messier, R. Patterson; theoretical curves based on Nunokawa et al. 0710.0554
NOvA, PINGU and $\theta_{23}$

- Explore impact of knowing NMH at several selected points

If PINGU says NH, good $\delta_{CP}$ and octant resolution for NOvA

If PINGU says NH, improves NOvA's $\delta_{CP}$ measurement

If PINGU says NH, good $\delta_{CP}$ and octant resolution for NOvA

<table>
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<tr>
<th>$\theta_{23}$</th>
<th>MinDist[(PPbar)--($\delta_{CP}$ ellipse)]</th>
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<tbody>
<tr>
<td>Unknown NMH</td>
<td>$0.2\sigma$</td>
<td>$0.9\sigma$</td>
<td>$2.6\sigma$</td>
</tr>
<tr>
<td>NH</td>
<td>$1.7\sigma$</td>
<td>$0.9\sigma$</td>
<td>$2.6\sigma$</td>
</tr>
<tr>
<td>Unknown NMH</td>
<td>$2.6\sigma$</td>
<td>$0.6\sigma$</td>
<td>$1.0\sigma$</td>
</tr>
<tr>
<td>NH</td>
<td>$5.4\sigma$</td>
<td>$1.0\sigma$</td>
<td>$1.1\sigma$</td>
</tr>
</tbody>
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NOvA error ellipses: M. Messier, R. Patterson; theoretical curves based on Nunokawa et al. 0710.0554
The Digital Optical Module

- Cable Penetrator Assembly
- PMT High Voltage Base Board
- High Voltage Generator & Digital Control Assembly
- LED
- Flasher Board
- Main Board
- Delay Board
- Mu-Metal Magnetic Shield Cage
- Glass Pressure Sphere
- PMT
Another view, this time from the side and with PINGU included, too.
Additional Reasons

- **Theoretical milestones**
  - Pauli: $\nu$
  - Pontecorvo: $\nu_\alpha \rightarrow \nu_\beta$

- **Experimental milestones**
  - $\nu_e$
  - $\nu_\mu$
  - SN1987a
  - Kamioka et al.: $\nu$ Telescopes
  - MSW: $\nu_\alpha \rightarrow \nu_\beta$ in matter

- **Solar $\nu$ Problem**
- **Future HE $\nu$ Detectors**
- **Future Atm. $\nu$ Detectors**
Additional Reasons

- **Theoretical milestones**
- **Experimental milestones**

**Logarithmic Scale**

- $\log(V_{\text{det}})$ (m$^3$)

- **SN1987a**: $\nu_\alpha \rightarrow \nu_\beta$
- **Kamioka et al.**: $\nu_\tau$
- **MSW**: $\nu_\alpha \rightarrow \nu_\beta$ in matter
- **Solar $\nu$ Problem**
- **Pontecorvo**: $\nu_\alpha \rightarrow \nu_\beta$
- **Pauli**: $\nu$

**Time Periods**

- 1930
- 1940
- 1950
- 1960
- 1970
- 1980
- 1990
- 2000
- 2010
- 2020

**Future HE $\nu$ Detectors**

**Future Atm. $\nu$ Detectors**
Sample High E\(_{\nu}\) Events

Declination -13.2°
 deposited E: 82 TeV

Declination -0.4°
 deposited E: 71 TeV

Declination 40.3°
 deposited E: 253 TeV

D. Cowen/Manchester and Penn State
Size Scale
Size Scale
High Energy Atmospheric Neutrino Appearance and Disappearance with IceCube

The IceCube neutrino observatory, buried deep in the ice at the South Pole, has detected neutrinos that span over five orders of magnitude in energy. Fulfilling one of its original stated goals of discovering cosmological ultrahigh energy neutrinos, its large instrumented volume also provides us with a surprisingly powerful instrument for studying neutrino oscillations with an unprecedented statistical sample of energetic atmospheric neutrinos.

In this presentation we will describe the IceCube detector and focus on its current and future atmospheric neutrino oscillation measurements with DeepCore, IceCube’s low-energy in-fill array. We will also describe a new proposed low-energy extension, the Precision IceCube Next Generation Upgrade (PINGU), highlighting its ability to measure one of the remaining fundamental unknowns in particle physics, the neutrino mass hierarchy.
Reasons to Care About Neutrinos

• “Brian Cox” reasons:
  • Ubiquity:
    • $10^{11}$ $\nu$/s/cm$^2$ & $\sim$300 in every cm$^3$ of space
  • Critical for life
    • Fusion in stars requires emission of $\nu$’s
  • “Tiniest” or most “anti-social” of all fundamental particle(s)
    • Solar neutrinos can pass unscathed through light-year-long column of lead
    • $\sim10^{24}$ neutrinos will pass through your body in your lifetime; only $\sim1$ will deign to touch you

• Other good reasons:
  • Least understood fundamental particles in the Standard Model
  • Studying neutrino properties could yield hints for new physics
  • Their detection poses an irresistible experimental challenge