IceCube-DeepCore-PINGU: Atmospheric Neutrino Physics at the South Pole

D. Jason Koskinen
Why Neutrinos?
Standard Model

Quarks

- u
- c
- t
- d
- s
- b

Bosons

- Y
- Z^0
- W
- g
- H^0

Leptons

- e
- \(\nu_e\)
- \(\mu\)
- \(\nu_\mu\)
- \(\tau\)
- \(\nu_\tau\)
Neutrino Mixing Diagram

\[
\begin{pmatrix}
|\nu_e\rangle \\
|\nu_\mu\rangle \\
|\nu_\tau\rangle \\
\end{pmatrix}
= \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3} \\
\end{pmatrix}
\begin{pmatrix}
|\nu_1\rangle \\
|\nu_2\rangle \\
|\nu_3\rangle \\
\end{pmatrix}
\]
Neutrino Mixing Diagram

Experiment type: Solar & Reactor

Channel: \((\nu_e \rightarrow \nu_\mu)\)

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]
Neutrino Mixing Diagram

Experiment type  
Solar & Reactor

Short Baseline (SBL) & Off-Axis

Oscillation

Channel

Solar & Reactor

Short Baseline (SBL) & Off-Axis

\[ \nu_e \rightarrow \nu_\mu \]

\[ \nu_\mu \rightarrow \nu_e \]
Neutrino Mixing Diagram

Experiment type
- Solar & Reactor
- Short Baseline (SBL) & Off-Axis
- Atmospheric & Long Baseline

Oscillation Channel
- Solar & Reactor: \( \nu_e \rightarrow \nu_\mu \)
- Short Baseline (SBL) & Off-Axis:
  - \( \nu_e \rightarrow \nu_e \)
  - \( \nu_\mu \rightarrow \nu_e \)
- Atmospheric & Long Baseline:
  - \( \nu_\mu \rightarrow \nu_\mu \)
  - \( \nu_\mu \rightarrow \nu_\tau \)

\[
\left( \begin{array}{c}
|\nu_e\rangle \\
|\nu_\mu\rangle \\
|\nu_\tau\rangle \\
\end{array} \right) = \left( \begin{array}{ccc}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3} \\
\end{array} \right) \left( \begin{array}{c}
|\nu_1\rangle \\
|\nu_2\rangle \\
|\nu_3\rangle \\
\end{array} \right)
\]

\[\Delta m_{12}^2, \Delta m_{23}^2\]
Large Weak Mixing

PMNS - $\nu$ Mixing

\[
\left( \begin{array}{c}
|\nu_e\rangle \\
|\nu_\mu\rangle \\
|\nu_\tau\rangle \\
\end{array} \right) = \left( \begin{array}{ccc}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3} \\
\end{array} \right) \left( \begin{array}{c}
|\nu_1\rangle \\
|\nu_2\rangle \\
|\nu_3\rangle \\
\end{array} \right)
\]
Large Weak Mixing

PMNS - \( \nu \) Mixing

\[
\begin{pmatrix}
|\nu_e\rangle \\
|\nu_\mu\rangle \\
|\nu_\tau\rangle
\end{pmatrix}
= 
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{pmatrix}
|\nu_1\rangle \\
|\nu_2\rangle \\
|\nu_3\rangle
\end{pmatrix}
\]

\[
\begin{pmatrix}
\sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\
\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \\
-\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}}
\end{pmatrix}
\]
Large Weak Mixing

PMNS - ν Mixing

\[
\begin{pmatrix}
|\nu_e\rangle \\
|\nu_\mu\rangle \\
|\nu_\tau\rangle
\end{pmatrix}
= 
\begin{pmatrix}
\sqrt{2} & \sqrt{1} & 0 \\
\sqrt{3} & \sqrt{3} & \sqrt{1} \\
-\sqrt{1} & \sqrt{1} & \sqrt{2} \\
\sqrt{6} & \sqrt{6} & \sqrt{2} \\
\sqrt{1} & -\sqrt{1} & \sqrt{1} \\
\sqrt{3} & \sqrt{3} & \sqrt{2}
\end{pmatrix}
\begin{pmatrix}
|\nu_1\rangle \\
|\nu_2\rangle \\
|\nu_3\rangle
\end{pmatrix}
\]
Large Weak Mixing

PMNS - $\nu$ Mixing

\[
\begin{pmatrix}
|\nu_e\rangle \\
|\nu_\mu\rangle \\
|\nu_\tau\rangle
\end{pmatrix}
= \begin{pmatrix}
\sqrt{2} & \frac{1}{\sqrt{3}} & 0 \\
\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\
\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\
\end{pmatrix}
\begin{pmatrix}
|\nu_1\rangle \\
|\nu_2\rangle \\
|\nu_3\rangle
\end{pmatrix}
\]
Large Weak Mixing

PMNS - $\nu$ Mixing

\[
\begin{pmatrix}
|\nu_e\rangle \\
|\nu_\mu\rangle \\
|\nu_\tau\rangle \\
\end{pmatrix}
= 
\begin{pmatrix}
\sqrt{\frac{2}{3}} \\
\frac{1}{\sqrt{6}} \\
\frac{-1}{\sqrt{6}} \\
\frac{1}{\sqrt{6}} \\
\frac{1}{\sqrt{6}} \\
\frac{\sqrt{3}}{2}
\end{pmatrix}
\begin{pmatrix}
|\nu_1\rangle \\
|\nu_2\rangle \\
|\nu_3\rangle
\end{pmatrix}
\]

Is Tribimaximal a real Symmetry?
Large Weak Mixing

PMNS - $\nu$ Mixing

$$\begin{pmatrix}
|\nu_e\rangle \\
|\nu_\mu\rangle \\
|\nu_\tau\rangle
\end{pmatrix} = \begin{pmatrix}
\sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \\
\frac{1}{\sqrt{6}} & \sqrt{\frac{1}{3}} & -\frac{1}{\sqrt{2}} \\
\frac{1}{\sqrt{6}} & \sqrt{\frac{1}{3}} & \frac{1}{\sqrt{2}}
\end{pmatrix} \begin{pmatrix}
|\nu_1\rangle \\
|\nu_2\rangle \\
|\nu_3\rangle
\end{pmatrix}$$

Is Tribimaximal a real Symmetry? Probably not
Large Weak Mixing

PMNS - $\nu$ Mixing

\[
\begin{pmatrix}
|\nu_e\rangle \\
|\nu_\mu\rangle \\
|\nu_\tau\rangle
\end{pmatrix}
= \begin{pmatrix}
\sqrt{\frac{2}{3}} \\
1 \\
\sqrt{\frac{1}{6}} \\
\end{pmatrix} \begin{pmatrix}
\sqrt{\frac{1}{3}} \\
\sqrt{\frac{1}{2}} \\
\sqrt{\frac{1}{3}} \\
\end{pmatrix} \begin{pmatrix}
\phi \\
\nu_1 \\
\nu_2
\end{pmatrix}
\]

Is Tribimaximal a real Symmetry?

CKM - Quark Mixing

\[
\begin{bmatrix}
|V_{ud}| & |V_{us}| & |V_{ub}| \\
|V_{cd}| & |V_{cs}| & |V_{cb}| \\
|V_{td}| & |V_{ts}| & |V_{tb}|
\end{bmatrix}
= \begin{bmatrix}
0.97428 \pm 0.00015 & 0.2253 \pm 0.0007 & 0.00347^{+0.00016}_{-0.00012} \\
0.2252 \pm 0.0007 & 0.97345^{+0.00015}_{-0.00016} & 0.0410^{+0.0011}_{-0.0007} \\
0.00862^{+0.00026}_{-0.00020} & 0.0403^{+0.0011}_{-0.0007} & 0.999152^{+0.000030}_{-0.000045}
\end{bmatrix}.
\]

Okay, but why so big versus CKM?
Importance of $|U_{\tau 3}|^2$

\[
\begin{bmatrix}
|U_{e3}|^2 \\
|U_{\mu 3}|^2 \sim \frac{1}{2} \\
|U_{\tau 3}|^2
\end{bmatrix}
\]

\[
\Delta m^2_{23} \quad \Delta m^2_{12}
\]

\[
\begin{bmatrix}
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|\nu_\mu\rangle \\
|\nu_\tau\rangle
\end{bmatrix}
= 
\begin{bmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\tau 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{bmatrix}
\begin{bmatrix}
|\nu_1\rangle \\
|\nu_2\rangle \\
|\nu_3\rangle
\end{bmatrix}
\]
• $|U_{\tau 3}|^2$ is the last unmeasured PMNS matrix element
Importance of $|U_{\tau 3}|^2$

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- Non-unitarity in the third mass eigenstate would be “New” physics
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- $|U_{\tau 3}|^2$ is the last unmeasured PMNS matrix element
- Non-unitarity in the third mass eigenstate would be “New” physics
  - Non-Standard Interactions?

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|\nu_\tau\rangle \\
\end{pmatrix}
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U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \\
\end{pmatrix}
\begin{pmatrix}
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|\nu_2\rangle \\
|\nu_3\rangle \\
\end{pmatrix}
\]
Importance of $|U_{\tau 3}|^2$

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- Non-unitarity in the third mass eigenstate would be “New” physics
  - Non-Standard Interactions?
  - $\nu_1$ and $\nu_2$ non-unitary?
Importance of $|U_{\tau 3}|^2$

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- Non-unitarity in the third mass eigenstate would be “New” physics
  - Non-Standard Interactions?
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  - If unitary, not much room left for sterile neutrinos that couple to active states?

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\begin{pmatrix}
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|\nu_3\rangle
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\]
Importance of $|U_{\tau 3}|^2$

- $|U_{\tau 3}|^2$ is the last unmeasured PMNS matrix element
- Non-unitarity in the third mass eigenstate would be “New” physics
  - Non-Standard Interactions?
  - $\nu_1$ and $\nu_2$ non-unitary?
  - If unitary, not much room left for sterile neutrinos that couple to active states?

- Directly measured via observation of nutau appearance

$$
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\end{pmatrix}
= 
\begin{pmatrix}
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U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix}
\begin{pmatrix}
|\nu_1\rangle \\
|\nu_2\rangle \\
|\nu_3\rangle
\end{pmatrix}
$$
Neutrino Experimental Landscape
• Reactor neutrino experiments dominate the < 1 GeV non-accelerator region

*Boxes provide sense of scale for physics sensitive regions
*concept from D. Grant
Experimental Landscape

- Reactor neutrino experiments dominate the < 1 GeV non-accelerator region
- Accelerator - Beam and Detector are optimized

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Accelerator based

Non-accelerator based

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Neutrino Telescopes (IceCube, ANTARES, etc...)

Gamma Ray Bursts

νμ - Disappearance
Dark Matter
ντ - Appearance

*Boxes provide sense of scale for physics sensitive regions
*concept from D. Grant
- ~1km$^3$ of instrumented ice
- Uses 5160 Digital Optical Modules (DOMs) across 86 strings within the ice to detect Cherenkov radiation
- 160 Cherenkov tank surface array (IceTop)
- Deployed 1.5-2.5km below the surface
- ~1km$^3$ of instrumented ice
- Uses 5160 Digital Optical Modules (DOMs) across 86 strings within the ice to detect Cherenkov radiation
- 160 Cherenkov tank surface array (IceTop)
- Deployed 1.5-2.5km below the surface
Detection Principles

**$\nu_\mu$**
Tracks:
- through-going muons
- km long at high energy

**$\nu_\tau, \nu_e$**
Cascades:
- Neutral current for all flavors
- few m at low energy
- Charged current for $\nu_e$ and low-E $\nu_\tau$

**$\nu_\tau$**
Composites:
- Starting tracks
- high-E (PeV) $\nu_\tau$ (Double Bangs)
- Good directional and energy resolution
The IceCube Collaboration

36 institutions - 4 continents - ~250 Collaborators
• DeepCore
  • Increased sensitivity at energies < 100-200 GeV
  • 8 special Strings plus 12 closest IceCube-standard Strings
  • Denser DOM and String spacing
  • Deepest and clearest Ice
  • Higher efficiency photon sensors
  • Lower trigger threshold
Neutrino Physics is a Numbers Game
Size Matters

- IceCube gains a dramatic improvement in sensitivity to neutrinos < 100 GeV with DeepCore

![Physical Deep Core Volume ~28 MT](image)

Effective volume for muons from $\nu_\mu$ interacting in Deep Core

![Graph](image)
Size Matters

- IceCube gains a dramatic improvement in sensitivity to neutrinos < 100 GeV with DeepCore
• IceCube gains a dramatic improvement in sensitivity to neutrinos < 100 GeV with DeepCore

Effective volume for muons from $\nu_\mu$ interacting in Deep Core

![Physical Deep Core Volume ~28 MT](image)

![Graph showing effective volume vs. energy](image)
Cosmic Ray

\( \mu \)

Trigger Level

\( 10^6 : 1 \)

\( \nu_\mu \)
• Trigger level background to signal ratio is $10^6$ : 1

• DeepCore uses IceCube as an active veto to reject down-going atmospheric muons and neutrinos
  
  • Atmospheric muon rejection of $\sim 8 \times 10^3$ with neutrino retention of $\sim 99\%$

• Further rejection employed offline
Neutrino Oscillation Source

- Northern Hemisphere $\nu_\mu$ oscillating over one earth radii produces $\nu_\mu (\nu_\tau)$ oscillation minimum(maximum) at ~25 GeV
- Covers all possible terrestrial baselines
- "Beam" is free and never turns off

\[ \nu_\mu \rightarrow \nu_\mu \]
\[ \nu_\tau \rightarrow \nu_\mu \]

• IceCube + DeepCore will collect ~200k isotropic neutrinos at trigger level, tens of thousands have undergone oscillation
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• 8 hours of real data

• Preliminary event selection

• Up-Going muon neutrino “candidate”
  • ~15 GeV from track length
• 8 hours of real data
• Preliminary event selection
• Up-Going muon neutrino "candidate"
  • ~15 GeV from track length
Muon Neutrino Disappearance

- 1 year data with 79 total strings (Includes DeepCore)
- Tests oscillation hypothesis using high energy IceCube techniques
- Additional analyses using dedicated DeepCore methods are on-going
  - Higher event rate
  - Better reconstructions
• Instead of fitting $\sin^2 2\theta_{23}$ fit $\sin \theta_{23}$

• The large and already well measured value of $\theta_{13}$ increases the chance

• Requires lots of events
  • 10 years DeepCore exposure
Generic Oscillation

Fixed Baseline $L$

$$P(\nu_\mu \rightarrow \nu_\mu)$$

$\Delta m_{23}^2$

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

$\nu_\mu$ Energy

Energy (GeV)

$\mu \nu \rightarrow \mu \nu$
Tau Neutrino Appearance

- Neutral Current, Charged Current $\nu_e$, and CC $\nu_\tau$ events produce cascade-like signatures
- Look for statistical excess in cascade events
- DeepCore has been infilled with 2 additional strings
  - Increases $\nu_\tau$ event rate by $> 15\%$
Atmospheric flux

- Previous IceCube + AMANDA searches have been insensitive to neutrino induced cascades.
- DeepCore cascade candidate event
• DeepCore cascade candidate event
Neutrino Induced Cascades

- First observation of neutrino induced cascades in IceCube
- Higher average energy (~180 GeV) than oscillation region
Challenges
• After online DeepCore filter there is bkg:signal of 1,000+:1
• Background rejection methods work at higher energies (>~100 GeV), away from low NChannel region
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After online DeepCore filter there is bkg:signal of 1,000+:1

Background rejection methods work at higher energies (> ~100 GeV), away from low NChannel region
Noise Effect

• After online DeepCore filter there is bkg:signal of 1,000+:1
• Background rejection methods work at higher energies (> ~100 GeV), away from low NChannel region
Noise Removal

Before

- Algorithm based on IceCube “TrackEngine” hit clustering trigger
- Hough Transform of angles ($\theta, \phi$) between hits
  - Noise should be relatively unclustered
  - Physics (neutrinos, muons, etc...) should create clustered hits
Noise Removal

- Algorithm based on IceCube “TrackEngine” hit clustering trigger
- Hough Transform of angles ($\theta, \phi$) between hits
  - Noise should be relatively unclustered
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• IceCube-DeepCore is statistical powerhouse
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• Muon disappearance
  • Low energy angular/energy reconstruction(s) are key for a precision measurement
IceCube-DeepCore Wrapup

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- Muon disappearance
  - Low energy angular/energy reconstruction(s) are key for a precision measurement
- Tau appearance
  - Deployment of DeepCore has resulted first observation of neutrino induced cascades in IceCube
• IceCube-DeepCore is statistical powerhouse

• Muon disappearance
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• Chance to do simultaneous fit to both numu disappearance and nutau appearance
IceCube-DeepCore Wrapup

- IceCube-DeepCore is statistical powerhouse
- Muon disappearance
  - Low energy angular/energy reconstruction(s) are key for a precision measurement
- Tau appearance
  - Deployment of DeepCore has resulted first observation of neutrino induced cascades in IceCube
- Chance to do simultaneous fit to both numu disappearance and nutau appearance
- Moving down in energy from traditional IceCube physics presents new challenges
Where are we going?
• DeepCore has access to the first oscillation minima/maxima

![Oscillation Probabilities](image)

Mena, Mocioiu & Razzaque, *Phys. Rev. D* 78, 093003
• DeepCore has access to the first oscillation minima/maxima
• Neutrino Hierarchy
• DeepCore has access to the first oscillation minima/maxima
• Neutrino Hierarchy
• GeV Dark Matter
Beyond DeepCore
Beyond DeepCore

IceCube
Beyond DeepCore

IceCube

DeepCore
Beyond DeepCore

IceCube

DeepCore
Beyond DeepCore

IceCube  DeepCore
Beyond DeepCore

IceCube

DeepCore

PINGU
Idea

• Using existing and familiar technology (hot water drill, HQE PMT DOMs) infill DeepCore with additional Strings

• Drive neutrino energy reach down to few GeV while maintaining multi-megaton scale size

• Precision IceCube Next Generation Upgrade (PINGU)
PINGU: Possible Geometry

- ~20 strings within DeepCore volume w/ short string-string spacing
  - IC-IC: 125m
  - DC-DC: ~80m
  - PINGU-PINGU: <= 26m
- Shorter DOM-DOM spacing
  - IC-IC: 17m
  - DC-DC: 7m
  - PINGU-PINGU: <= 5m
- R & D for future water/ice cerenkov
Increased effective volume for energies below ~10 GeV

Several megatons effective volume at a few GeV
DeepCore Only

- 9.28 GeV Neutrino, 4.9 GeV muon, 4.5 GeV cascade
DeepCore Only

- 9.28 GeV Neutrino, 4.9 GeV muon, 4.5 GeV cascade
- ~20 vs. ~50 Hit Modules
With an infill that achieves ~GeV resolution, the 2nd oscillation minimum becomes accessible.

Improve both track and cascade reconstruction.

Low energy oscillation features

- Matter effects (MSW) change oscillations at lower energy
- Earth density changes also alter the oscillations
- Normal/Inverted Hierarchy

![Graph showing NuMu survival probability with energy on the x-axis and probability on the y-axis. The graph compares normal and inverted hierarchies with sin^2(2\theta_{13}) = 0.1. DeepCore and PINGU are marked on the graph.]
\[(N^H - N^{NH})/(N^{NH})^{1/2} \text{ [PINGU 1 Year]}\]

*reproduction using of technique described in Akhmedov, Razzaque, Smirnov arXiv:1205.7071v3
 hierarchy

\[ \frac{N^H - N^{NH}}{(N^{NH})^{1/2}} \text{ [PINGU 1 Year]} \]

*reproduction using of technique described in Akhmedov, Razzaque, Smirnov [arXiv:1205.7071v3]*

smeared: 3 GeV in energy and 11.25° in angular resolution

\[ \frac{N^H - N^{NH}}{(N^{NH})^{1/2}} \text{ [PINGU 1 Year]} \]
Experimental Landscape

Oscillation
IceCube-DeepCore Physics
PINGU
Beyond

Accelerator based

Non-accelerator based

Super-K
KamLAND
Borexino
Double Chooz
Daya Bay
SNO

Neutrino Telescopes (IceCube, ANTARES, etc...)

DeepCore

10 TeV
10 PeV
1 TeV
10 GeV

Neutrino Hierarchy

High Precision $\nu_\mu$ - Disappearance

Manageable $\nu_\tau$ - Appearance

GeV Mass
Dark Matter

D. Jason Koskinen - Brookhaven - September, 2012
Thursday, September 6, 12
Experimental Landscape

- Oscillation
- IceCube-DeepCore Physics
- PINGU
- Beyond

Non-accelerator based

- Borexino
- KamLAND
- Double Chooz
- Daya Bay
- SNO

DeepCore

PINGU

Accelerator based

- Neutrino Telescopes (IceCube, ANTARES, etc...)

- GeV Mass Dark Matter
- Manageable $\nu_\tau$ - Appearance
- High Precision $\nu_\mu$ - Disappearance
- Neutrino Hierarchy

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Thursday, September 6, 12
PINGU Advantages

- Relatively quick, cost effective, huge and unique
  - 2 season deployment w/ additional ~1.5 year procurement/shipping
  - $O(25-30M)$
- Megaton size at GeV energies
- Samples many angle, many baselines and crosses the earth core

- Enhance on-going DeepCore physics
  - muon disappearance
    - $\theta_{23}$ maximal mixing
    - octant of $\theta_{23}$
  - tau appearance

- Gains sensitivity to the rich neutrino oscillation features
  - 2nd oscillation minima/maxima
  - Neutrino hierarchy
PINGU Advantages

- Relatively quick, cost effective, huge and unique
  - 2 season deployment w/ additional ~1.5 year procurement/shipping
  - $O(25-30M)$
  - Megaton size at GeV
  - Samples whole earth core
  - Enhance on-going DeepCore physics
    - muon disappearance
      - $\theta_{23}$ maximal mixing
      - octant of $\theta_{23}$
      - tau appearance
    - Gains sensitivity to the rich neutrino oscillation features
      - 2nd oscillation minima/maxima
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"Anything worth doing is worth overdoing"
Really Beyond DeepCore

IceCube  
DeepCore  
PINGU
Really Beyond DeepCore

IceCube
DeepCore
PINGU
Really Beyond DeepCore

IceCube  DeepCore  PINGU
Low Energy Large Volume

- South Pole Infrastructure
  - No excavation
  - Deployment is a now a refined process
- Unchanging, low-background ice
- Move from GeV to tens of MeV
  - Cherenkov ring imaging
  - IceCube/DeepCore style single-PMT module is no longer attractive
- Multi-megaton Ice Cherenkov Array (MICA)
Cerenkov Ring Imager

- 120 strings of 125 composite DOMs each
  - Instrumented volume of 250 m height, ~40 m radius
- 1 MegaTon fiducial volume, at depths of 2200-2450 m

Courtesy P. Kooijman
• Extend core-collapse SN search beyond Milky Way

• 5 megaton detector with sensitivity down to 15 MeV

Kistler et. al. arXiv:0810.1959
Proton Decay Rings

\[ p \rightarrow \pi^0 + e^+ \]

(run 1 event 2) perfect photon counting (all photons \( \lambda \in [265 \text{ nm}; 675 \text{ nm}] \))

IceCube coordinates, ref. depth \( (z = 0) \) is 1948.07 m; \( N_{\text{string}} = 40 \); \( d_{\text{DOM},z} = 1 \text{ m} \); \( N_{\text{DOM}} = 7040 \)

S. Bohaichuk & D. Grant, U. of Alberta
Upgrade path towards $\delta_{CP}$?

- Measurement of $\delta_{CP}$ in principle possible, but challenging
  - Requires:
    - Electromagnetic shower ID (here: 1% mis-ID)
    - Energy resolution (here: 20% x E)
    - Maybe: volume upgrade (here: ~ factor two)
    - Project X
  - Performance and optimization of PINGU, and possible upgrades (MICA, ...) require further study

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“Superbeam FNAL-PINGU?”, W. Winter
MICA Physics

- Extra galactic supernova
- Proton Decay
- Detector for Neutrino Factory, Beta beam or Super Beam
  - Mass Hierarchy, Lepton CP Violation
  - Option for PINGU as well depending on beam characteristics
  - Using PMTs, ~90% of detector cost is electronics
• Atmospheric neutrinos (still) offer rich physics
  • IceCube + DeepCore is a statistical juggernaut, $O(100,000)$ triggered events/year
  • DeepCore + IceCube has observed neutrino induced cascades and numu disappearance

• Proposed extensions
  • PINGU - Down to $O(1)$ GeV improves oscillation searches, lower mass Dark Matter, and neutrino hierarchy resolution
  • MICA - Down to $O(10)$ MeV opens up new physics
Thanks
Neutrino Oscillation

Flavor Eigenstate

\[
\begin{pmatrix}
|\nu_e\rangle \\
|\nu_\mu\rangle \\
|\nu_\tau\rangle
\end{pmatrix}
\]

Mass Eigenstate

\[
U_{\text{PMNS}} = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\]

\[
\begin{pmatrix}
|\nu_1\rangle \\
|\nu_2\rangle \\
|\nu_3\rangle
\end{pmatrix}
\]

- Neutrino flavor eigenstates are related to mass eigenstates via the PMNS Unitary mixing matrix.
Reactor/Solar

- Optimized for MeV anti-neutrinos undergoing inverse beta decay
- High precision
- Isotropic sources

Borexino | SNO | Daya Bay
Measuring Oscillation Parameters

\[
\left( \begin{array}{c} \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} \right) = \left( \begin{array}{ccc} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{array} \right) \left( \begin{array}{c} \nu_1 \\ \nu_2 \\ \nu_3 \end{array} \right)
\]

underlying nature of weak mixing
\[ \begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix} \]

Experimentally measured values
• Experimentally $|U_{\tau 3}|^2$ is measured via an energy dependent excess of tau neutrinos over a long baseline using the weak mixing angles

$$P_{\nu_\mu \rightarrow \nu_\tau} = \sin^2(2\theta_{23}) \sin^2 \left( \frac{\Delta m_{32}^2 L}{4E} \right)$$

$L =$ Length
$E =$ Neutrino Energy
Measuring Oscillation Parameters

\[
\begin{pmatrix}
|v_e\rangle \\
|v_\mu\rangle \\
|v_\tau\rangle
\end{pmatrix}
= \begin{pmatrix}
c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\
-s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\
s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}
\end{pmatrix}
\begin{pmatrix}
v_1 \\
v_2 \\
v_3
\end{pmatrix}
\]

- Experimentally $|U_{\tau 3}|^2$ is measured via an energy dependent \textbf{excess} of tau neutrinos over a long baseline using the weak mixing angles
  \[
P_{\nu_\mu \rightarrow \nu_\tau} = \sin^2(2\theta_{23}) \sin^2 \left( \frac{\Delta m_{32}^2 L}{4E} \right)
\]
  \(L = \text{Length}\)
  \(E = \text{Neutrino Energy}\)

- $|U_{\mu 3}|^2$ is measured via an energy dependent \textbf{deficit} of muon neutrino events over a long baseline
  \[
P_{\nu_\mu \rightarrow \nu_\mu} = 1 - \sin^2(2\theta_{23}) \sin^2 \left( \frac{\Delta m_{32}^2 L}{4E} \right)
\]
Generic Oscillation

Fixed Baseline $L$

\[ P(\nu_\mu \rightarrow \nu_\mu) \]

\[ \nu_\mu \text{ Energy} \]
Generic Oscillation

P(ν_μ → ν_μ)

ν_μ Energy

sin^2(2θ_{23})

Fixed Baseline L
Fixed Baseline L

\[ P(\nu_\mu \rightarrow \nu_\mu) \]

\[ \sin^2(2\theta_{23}) \]

\[ \Delta m_{23}^2 \]

\[ \nu_\mu \text{ Energy} \]

\[ \nu_\text{Energy} \]
• Accelerators use variable energy neutrino beam to select region of interest
• Place Far Detector km away from beam
• Event timing and direction provide excellent background rejection
Neutrino Mixing Diagram

\[
\begin{pmatrix}
|\nu_e\rangle \\
|\nu_\mu\rangle \\
|\nu_\tau\rangle \\
\end{pmatrix}
= 
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3} \\
\end{pmatrix}
\begin{pmatrix}
|\nu_1\rangle \\
|\nu_2\rangle \\
|\nu_3\rangle \\
\end{pmatrix}
\]

\[\Delta m^2 \]

\[\Delta m^2_{23} \quad \Delta m^2_{12} \]
Neutrino Mixing Diagram

Experiment type | Oscillation |
--- | --- |
Solar & Reactor | Channel |

\( \nu_e \rightarrow \nu_\mu \)
Neutrino Mixing Diagram

Experiment type
- Solar & Reactor
- Off-Axis & SBL

Oscillation Channel
- \( \nu_e \rightarrow \nu_\mu \)
- \( \nu_\mu \rightarrow \nu_e \)

\[
\begin{pmatrix}
|\nu_e\rangle \\
|\nu_\mu\rangle \\
|\nu_\tau\rangle \\
\end{pmatrix}
= 
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3} \\
\end{pmatrix}
\begin{pmatrix}
|\nu_1\rangle \\
|\nu_2\rangle \\
|\nu_3\rangle \\
\end{pmatrix}
\]

Off-Axis Accelerator & Short Baseline
- Daya Bay

\[ |U_{e3}|^2 \quad |U_{\tau3}|^2 \quad |U_{\mu3}|^2 \]

\[ \Delta m_{23}^2 \quad \Delta m_{12}^2 \]
Neutrino Mixing Diagram

Experiment type

<table>
<thead>
<tr>
<th>Solar &amp; Reactor</th>
<th>Off-Axis &amp; SBL</th>
<th>Atmospheric &amp; LBL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oscillation Channel</td>
<td>$(\nu_e \rightarrow \nu_\mu)$</td>
<td>$(\nu_e \rightarrow \nu_\mu)$, $(\nu_\mu \rightarrow \nu_e)$</td>
</tr>
</tbody>
</table>

Off-Axis Accelerator & Short Baseline

Atmospheric & Long Baseline

Solar/Reactor

Oscillation

Channel

Experiment type

Solar & Reactor

Off-Axis & SBL

Atmospheric & LBL

$\nu_1$ | $\nu_2$ | $\nu_3$

$\nu_e$ | $\nu_\mu$ | $\nu_\tau$

$U_{e1}$ | $U_{e2}$ | $U_{e3}$

$U_{\mu1}$ | $U_{\mu2}$ | $U_{\mu3}$

$U_{\tau1}$ | $U_{\tau2}$ | $U_{\tau3}$

$\Delta m^2_{23}$

$\Delta m^2_{12}$

$\nu^e_3$

$\nu^\tau_3$

$\nu^\mu_3$

$\nu^\tau_3$
New World - New Physics

- Oscillation
- IceCube-DeepCore Physics
- PINGU
- Beyond

$\sigma/E (cm^2/GeV)$

- GENIE $\nu_\mu$ CC
- ANIS $\nu_\mu$ CC (CTEQ5)
- CSS $\nu_\mu$ CC

$1 \times 10^{-39}$

- O16/16
- H1

$log_{10}(E_\nu GeV)$

- Thursday, September 6, 12
Why Water?

* R. Svoboda, Fundamental Physics at the Intensity Frontier

IMB  22 ktons
Super-Kamiokande

LBNE  200 ktons

Hyper-K, MEMPHYS  440-540 ktons
**Why Not Ice?**

Many, Many, 10,000s of ktons

Why Water?

- IMB
- Super-Kamiokande
- LBNE
- Hyper-K, MEMPHYS

DeepCore

*R. Svoboda, Fundamental Physics at the Intensity Frontier*
• 1 year data with 79 total strings (Includes DeepCore)
• Monte Carlo signal only

Preliminary

- Unoscillated
- Oscillated

No Reconstruction

\[ \theta_{23} = \pi/4 \]
\[ \Delta m_{23}^2 = 2.4 \times 10^{-3} \text{ eV} \]
\[ \cos(\text{zenith}) < -0.6 \]
Vetoes

- Online DeepCore veto gets rid of ~100x background CR muons. Still 1,000:1 - Bkg:Signal
- TimeVeto - 70% BKG rejection at ~5% signal loss
- ConeCut - 80% BKG rejection at ~5% signal loss
Vetoes

- Online DeepCore veto gets rid of $\sim 100x$ background CR muons
- TimeVeto - 70% BKG rejection at $\sim 5\%$ signal loss
- ConeCut - 80% BKG rejection at $\sim 5\%$ signal loss

![Graph showing efficiency vs. DCog_t - ICog_t](image-url)
• With an infill that achieves ~GeV resolution, the 2nd oscillation minimum becomes accessible

• Improve Cascade reconstruction

• Tau appearance

Figure 12: The precision measurements of CP phase $\delta_{CP}$ and $\sin^2 2\theta_{13}$ for three single-baseline neutrino experiments: Beta Beam (BB), Neutrino Factory (NF), and SuperBeam (SB). The contours represent the $1\sigma$, $2\sigma$ and $3\sigma$ confidence levels (2 d.o.f.). Filled contours represent the PINGU benchmark setups, unfilled contours the reference setups. The crosses mark the best fit value of $\sin^2 2\theta_{13}$ and $\delta_{CP}$. Here we assume the normal (true) hierarchy, the inverted (fit) hierarchy solution can be ruled out by the experiments.
• 3.94 GeV Neutrino, 3.88 GeV muon, 0.29 GeV cascade
Possible Module

- Based on a KM3NeT proposed design

- One meter glass cylinder containing 30 3” PMTs and associated electronics
  - Comparable width to IceCube DOM
  - Effective photocathode area of 265 sq. in. – 3.4x that of standard 10” IceCube PMT, but granular

- Could allow spatial imaging of Cherenkov ring

Courtesy P. Kooijman
Cherenkov ring
from 50 cm μ track

Strings, roughly to
scale for 10 m spacing
Challenges
NoiseEngine

- Noise removal algorithm based on IceCube “TrackEngine” hit clustering trigger

- Hough Transform of angles ($\theta, \phi$) between hits
  - Noise should be relatively unclustered
  - Physics (neutrinos, muons, etc...) should create clustered hits
• Solar Neutrinos - Look hard enough and you’ll find something Bahcall

• Some of the best neutrino detectors in history did wonderful physics beyond their original design (MACRO, IMB, Super-K, Soudan-2, etc...) why not IceCube?

• OPERA can’t measure tau oscillation parameters. How much wiggle room for unitarity in utau3?