Neutrino oscillations and PMNS unitarity with IceCube/DeepCore and the IceCube Upgrade

Tom Stuttard for the IceCube collaboration

Niels Bohr Institute
NuFACT 2019
Huge 1 km$^3$ detector

\textbf{GeV – PeV $\nu$}

Atmospheric & astrophysical

IceCube Lab

50 m

1450 m

2450 m

2820 m

Bedrock

IceCube Array

1 Gton

DeepCore

10 Mton

Eiffel Tower

324 m

Dense DeepCore sub-array

Sensitivity to $O(10 \text{ GeV}) \, \nu$

5160 PMTs detect Cherenkov photons
Detecting neutrinos

- Primarily detect $\nu$-ice Deep Inelastic Scattering (DIS) interactions
- Charged- and Neutral-Current (CC/NC)

Two event topologies @ oscillation energies:

- Hadronic shower
  - NC/CC
  - Nucleon
  - Cascade
  - Track

Approx spherical $\nu_e$ CC
$\nu_\tau$ CC
$\nu$ NC

| Detected light |
| 35 GeV |

$\nu/l(= e, \mu, \tau)$
Atmospheric neutrino oscillations in DeepCore

- mHz atmospheric neutrino detection rate @ O(10 GeV)
- Maximal $\nu_\mu$ disappearance for Earth-crossing (up-going) neutrinos
PMNS unitarity

- **PMNS** mixing matrix is **unitary** in standard oscillation picture
  - e.g. mixing between the 3 known neutrino flavours

- Additional (sterile?) states → 3x3 matrix is subset of full unitary matrix

- Test unitarity by measuring 3x3 matrix elements
  - $\nu_\tau$ elements least well measured

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

- Measure \( \nu_\tau \) sector via \( \nu_\mu \rightarrow \nu_\tau \) measurements (\( \nu_\tau \) appearance)

**Challenging** measurement:
- CC cross section suppressed by \( \tau \) mass \( \rightarrow \) low stats
- Produced \( \tau \) decays \( \sim \) instantly \( \rightarrow \) PID difficult

- 3 measurements to date
  - Beam: OPERA
  - Atmospheric: SuperK, DeepCore

- Can interpret results as:
  - PMNS elements measurement
  - \( \nu_\tau \) cross section measurement
$\nu_\tau$ appearance @ DeepCore

Strong $\nu_\mu \rightarrow \nu_\tau$ oscillations for Earth-crossing neutrinos
$$\nu_\tau$$ appearance @ DeepCore

Appearance probability

Detected $$\nu_\tau$$ (truth)

IceCube Simulation
flux + oscillations
cross section + detector efficiency + cuts

Event rate [arb. units]
**ντ appearance @ DeepCore**

**Appearance probability**

**ντ signal (reconstructed)**

**Cannot ID individual ντ**
- Mostly appear as cascades

**Detected ντ (truth)**

**Statistically fit overall ντ contribution**
- Perform νμ disappearance fit
- Allow ντ normalisation to vary w.r.t. unitarity
DeepCore $\nu_\tau$ appearance results

- 2 measurements performed with 3 years of DeepCore data [PRD 2019]

Data vs MC (best fit)

Data fit in [energy, cos(zenith), PID] space
Searching for 3D distortions (shape-only)
DeepCore $\nu_\tau$ appearance results

• 2 measurements performed with 3 years of DeepCore data [PRD 2019]

Results

Nominal expectation
Unitary 3v PMNS

3x3 PMNS is subset of NxN?

Fewer $\nu_\tau$

More $\nu_\tau$

$\nu_\tau$ cross section

$\nu_\tau$ template scale relative to unitary expectation
DeepCore $\nu_\tau$ appearance results

- 2 measurements performed with 3 years of DeepCore data [PRD 2019]
DeepCore $\nu_\tau$ appearance results

- 2 measurements performed with 3 years of DeepCore data [PRD 2019]

**Results**

- Consistent with unitarity
- 35% precision (1$\sigma$)
- Modest increase in precision w.r.t SuperK

DeepCore results
(Consistent)
DeepCore $\nu_\tau$ appearance results

- 2 measurements performed with 3 years of DeepCore data \[\text{PRD 2019}\]
- Consistent results

**Take away message**

- World-leading $\nu_\tau$ appearance measurement precision @ DeepCore
- Results consistent with standard oscillation picture

**Coming soon**

New measurement with $>5\times$ statistics
The IceCube Upgrade

• NSF have funded a $30M extension to IceCube
  • Deployment in 2022/3
• 700 multi-PMT sensors
• Improved ice calibration
A low energy neutrino detector

- **Dense instrumentation** in 2 Mton core
  - Large increase in photocathode density $\rightarrow$ sensitive to **1 GeV neutrinos**
Upgrade performance

- Major improvement in detection rate and energy/direction resolution
Upgrade performance

• Major improvement in detection rate and energy/direction resolution

Event rate

Cascade direction resolution

DeepCore

Upgrade

Huge increase in <10 GeV $\nu$ rate

Enhanced rate for all oscillation energies

3x improvement @ $\nu_\tau$ appearance energies
Oscillations @ the IceCube Upgrade

- $\nu_\tau$ appearance is Upgrade primary physics goal
- Broad oscillation program including mass ordering and BSM

\[ \nu_\tau \text{ appearance sensitivity (1 yr)} \]

- 10% precision after 1 year
  (6% after 3 years)
Oscillations @ the IceCube Upgrade

- $\nu_{\tau}$ appearance is Upgrade primary physics goal
- Broad oscillation program including mass ordering and BSM

$\nu_{\tau}$ appearance sensitivity (1 yr)

$\nu_{\mu}$ disappearance sensitivity (3 yr)

10% precision after 1 year (6% after 3 years)

Competitive with long baseline experiments in disappearance channel
Oscillations @ the IceCube Upgrade

- $\nu_\tau$ appearance is Upgrade primary physics goal
- Broad oscillation program including mass ordering and BSM

Take away message

- IceCube Upgrade will offer huge gains in neutrino rates and resolutions
- 10% $\nu_\tau$ appearance precision after only 1 year → major leap for PMNS unitarity studies
Other IceCube BSM oscillation searches

- IceCube/DeepCore is a versatile oscillations detector
  - Large range of energies, baselines, matter profiles
- Broad BSM oscillation program
Summary

• Testing **PMNS unitarity** offers a powerful, model-independent search for new neutrino states and other BSM physics

• Currently **limited by precision in** \( \nu_\tau \) **sector**, but improving with **world-leading** \( \nu_\tau \) **appearance** measurements by IceCube/DeepCore

• Recently funded **IceCube Upgrade can achieve 10% precision** in \( \nu_\tau \) sector after 1 year of operation

• Exciting IceCube/DeepCore/Upgrade oscillation physics program over the coming decade
Backup slides
## PMNS elements measured


<table>
<thead>
<tr>
<th>Experiment</th>
<th>Measured quantity with unitarity</th>
<th>Without unitarity</th>
<th>Normalisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor SBL ($\bar{\nu}_e \rightarrow \bar{\nu}_e$)</td>
<td>$4</td>
<td>U_{e3}</td>
<td>^2 \left(1 -</td>
</tr>
<tr>
<td>Reactor LBL ($\bar{\nu}_e \rightarrow \bar{\nu}_e$)</td>
<td>$4</td>
<td>U_{e1}</td>
<td>^2</td>
</tr>
<tr>
<td>SNO ($\phi_{CC}/\phi_{NC}$ Ratio)</td>
<td>$</td>
<td>U_{e2}</td>
<td>^2 = \cos^2 \theta_{13} \sin^2 \theta_{12}$</td>
</tr>
<tr>
<td>SK/T2K/MINOS ($\nu_\mu \rightarrow \nu_\mu$)</td>
<td>$4</td>
<td>U_{\mu3}</td>
<td>^2 \frac{(1 -</td>
</tr>
<tr>
<td>T2K/MINOS ($\nu_\mu \rightarrow \nu_e$)</td>
<td>$4</td>
<td>U_{e3}</td>
<td>^2</td>
</tr>
<tr>
<td>SK/OPEPA ($\nu_\mu \rightarrow \nu_\tau$)</td>
<td>$4</td>
<td>U_{\mu3}</td>
<td>^2</td>
</tr>
</tbody>
</table>
DeepCore $\nu_\mu$ disappearance

- 3 year result, 2018 PRL [1707.07081]
ντ appearance analysis templates

Truth parameters

Reconstructed parameters
$\nu_\tau$ appearance analysis systematics
Ice/detector uncertainties

$\kappa_1$

$\kappa_2 \neq \kappa_3$