Latest Neutrino Oscillation Results from the Icecube Neutrino Observatory

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Why Study Neutrinos with IceCube?

- Many properties of the neutrino **have yet to be measured** (eg. mass ordering)

- **Neutrino oscillation** the only experimental evidence of non-conformity to the Standard Model (potential evidence for **new physics**)

- PMNS **unitarity constraints** are **weakest for the third generation** of neutrinos, **an area where IceCube is highly sensitive**

- IceCube offers **high statistics + large range of baselines and energies**
The IceCube Neutrino Telescope

- Deployed to detect neutrinos of astrophysical origin
- Optical Module (DOM): 30cm photomultiplier tube in pressured vessel
- Detect Cherenkov radiation from neutrino interactions in the ice
The IceCube Neutrino Telescope

• Sensitive to different types of interactions:

**Tracks**
\[ \nu^c_\mu, \nu^c_\tau \text{(some of the time)} \]

**Worse Energy Resolution**
**Better Pointing accuracy**

**Cascades**
\[ \nu^N_\mu, \nu^N_\tau, \nu^c_\tau \text{(most of the time), } \nu^c_e \]

**Better Energy Resolution**
**Worse Pointing accuracy**
High Energy vs. Low Energy

- Oscillation measurements are made at GeV energies
- Significantly lower energy range than the astrophysical regime
- Dim events pose a challenge for reconstructions

**PeV cascade of astrophysical origin**

**30 GeV atmospheric neutrino**
IceCube-DeepCore

- Inset of the IceCube detector
- 8 strings of high quantum efficiency DOMs
- 10 Mton fiducial volume (incl. neighbor IceCube strings)
- ~500 sensors in closer spacing
- Rest of IceCube is used as a veto region
Analysis technique

- **Wide range of L/E ratios covered** with DeepCore: $O(1\text{km}, 10\ 000\text{km})$ and $O(\text{GeV}, \text{TeV})$
Analysis technique

- Sample divided into zenith + energy bins
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\[ P(\nu_\mu \rightarrow \nu_\tau) \]
Analysis technique

- Sample divided into **zenith + energy bins**

- **Particle ID** (PID) to separate track-like from cascade-like (sensitive to different channels)

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Analysis technique

• Sample divided into **zenith + energy bins**

• **Particle ID** (PID) to separate track-like from cascade-like (sensitive to different channels)

• Look for **changes in the shape of these distributions**, induced by oscillation

• Large parameter space to **probe for new physics**
Data Samples

- **Two analyses samples** were produced on ~3 years of data
  - **Analysis sample A**: Simulated muon background, large statistical sample, additional systematics treatments
  - **Analysis sample B**: Data-driven background estimation, medium-sized statistical sample

- **Extensive cross-checks** performed between the two

![Data reduction chart](chart.png)

Data reduction chart (Analysis sample A):
\( \nu_\mu \) Disappearance

1707.07081

- **Strongest oscillation channel** in IceCube
- Compare data with expectation of standard neutrino oscillation
- Fit histograms to oscillation frequency \((\Delta m^2_{32})\) and strength \((\sin^2(\theta_{23}))\)
- Both analyses show large agreement with each other, and other experiments
$\nu_\tau$ Appearance

1901.05366

- Separate fit on the predicted number of tau neutrinos in the data (called the tau normalization $N_\tau$)

- $N_\tau \neq 1$ can indicate departure from unitarity (*provided the cross-section is known)

- **2000+ tau neutrinos** in sample $\mathcal{A}$

- Complementary to muon disappearance channel

\[
N_i^{\text{sim}} = N_\tau \cdot A_i \left( F_i^{\nu_e} P_{\nu_e \rightarrow \nu_\tau} + F_i^{\nu_\mu} P_{\nu_\mu \rightarrow \nu_\tau} \right)
\]

Nutau normalization ($N_\tau = 1 \rightarrow$ 3-flavour osc.)

Detector response

Oscillated atmospheric flux
Mass Ordering

1902.07771

- Vacuum oscillations perturbed by the presence of matter in the Earth
- Various matter effects induce distortions in the oscillogram
- Mass Ordering affects the type of particle experiencing the distortion (neutrinos vs. antineutrinos)
Mass Ordering
1902.07771

- **Weak signature** in IceCube, driven by difference in neutrino / antineutrino flux + cross-section

- Shown: Test statistic quantifying likelihood of favouring normal ordering

- **Proof-of-concept** for the IceCube Upgrade
Non-Standard Interactions
Publication in preparation

- Search for **additional physics scales** / light mediators acting on neutrino **while they propagate**

- Effect can be parametrized by an **effective Hamiltonian**:

\[
H_{\text{mat}} = \sqrt{2} G_F N_e(r) \left( 1 + \epsilon_\odot \right) \begin{pmatrix}
\epsilon_{ee}^\odot & \epsilon_{e\mu}^\odot & \epsilon_{e\tau}^\odot \\
\epsilon_{e\mu}^{\odot*} & \epsilon_{\mu\mu}^{\odot*} & \epsilon_{\mu\tau}^{\odot*} \\
\epsilon_{e\tau}^{\odot*} & \epsilon_{\mu\tau}^{\odot*} & \epsilon_{\tau\tau}^{\odot*}
\end{pmatrix}
\]

- \( \epsilon_{a\beta}^\odot \) : relative strength of coupling w.r.t strength of the weak interaction

- Explores a **richer variety of coupling strength parametrizations** than previous results:
  - 2 searches for **non-universal** interactions \( \Rightarrow \) **Single, real parameter fits**
  - 3 searches for **flavour-changing** interactions \( \Rightarrow \) **Single, complex parameter fits**
  - 1 search exploring an **effective vacuum parametrization** \( \Rightarrow \) **3 parameter fits (less model-dependent)**

1805.04530
Non-Standard Interactions
Publication in preparation

Results are for Normal Ordering

- No NSI discovered
- Results are independent of the scale of new physics
- Improves / set new limits on multiple parameters
- Complements searches using non-oscillation-based experiments
Next Generation of analyses

- 4 additional years of data available (total of 7.5 years)
- Improved characterization of ice properties + PMT charge response
- New machine learning tools for refined classification
- Better treatment of atmospheric flux systematics
- Improved event reconstructions
- Expanded searches for new physics
IceCube Upgrade (deployment in 2022-2023)

- Will be able to reconstruct 1 GeV events

21 GeV Tau Neutrino

In DeepCore

In the Upgrade
Conclusion

• New set of results on three years of data now complete

• All results agree with the standard 3-flavour oscillation paradigm

• Not covered here: Sterile Neutrino Search (see J. Hignight’s talk on Friday)

• 7 years results coming soon

• The Upgrade will be awesome
Backup - Analysis technique - Backgrounds

Atmospheric Muons

- Cascade-like
- Track-like

- Main Background component
- Affect mostly downgoing region

Detector Noise

- Light from scintillation in the DOM glass
- Complex time structure
- Minimal effect at final level
Backup – IceCube sensitivity to anti-neutrinos

Neutrino Flux directionality:

(1502.03916)

Cross-Section:

(PDG Review)

Matter effect in the Earth:

(1902.07771)
Backup - Analysis technique (Systematics)

- Low energy means low light yield, and therefore higher sensitivity to systematics

- **Ice properties**

- **Instrumental response** of the DOM

- Additional uncertainties from theoretical modeling of:
  - Atmospheric air showers
  - Nuclear cross-sections
Backup – Additional NSI Results

Effective Vacuum Parametrization results:

[Graphs showing results for effective vacuum parametrization with various plots and data points.]
Backup – Additional NSI Results

Single-parameter searches (assuming complex phases):

![Graph showing single-parameter searches](image)

- $\epsilon_{ee}^+ - \epsilon_{\mu\mu}^+$
- $\epsilon_{\tau\tau}^+ - \epsilon_{\mu\mu}^+$
Measuring Neutrino Oscillations

- Neutrino wavefunction after travelling a distance L: \( |\nu_i(L)\rangle = e^{-i\frac{m_i^2 L}{2E}} |\nu_i(0)\rangle \)

- The probability of measuring flavour state \( \alpha \) as state \( \beta \) at that distance is given by:

\[
P_{\alpha \rightarrow \beta} = |\langle \nu_\beta(L) | \nu_\alpha \rangle|^2 = \delta_{\alpha\beta} - 4 \sum_{i>j} \text{Re}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2 \left( \frac{\Delta m_{ij}^2 L}{4E} \right) + 2 \sum_{i>j} \text{Im}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin \left( \frac{\Delta m_{ij}^2 L}{2E} \right)
\]

Oscillation experiments measurements therefore depend on:

- **Mixing elements** \( U_{\alpha i} \)
- **Squared mass differences** \( \Delta m_{ij}^2 \)
- **Baseline-to-energy ratio** \( \frac{L}{E} \)
Constraints on mixing matrix elements

For $\nu_e$'s:

- $\sim 10^{10}$ neutrinos / s / cm$^2$ (solar neutrinos)
- $\sim 10^8$ anti-neutrinos / s / cm$^2$ (2 km away from nuclear reactor)
- First direct detection (Cowan + Reines): 3 neutrinos / hour

Large wealth of data can constrain $\nu_e$ mixing to $\sim 1\%$ level

(From 1508.05095)
Constraints on mixing matrix elements

For $\nu_\tau$'s:

- $\sim 10^{-10}$ Prompt neutrinos / cm$^2$ / s (undiscovered)

- Since their discovery (2000): <10 direct detections (using accelerators)

Mixing parameters for $\nu_\tau$ weakly constrained, especially if one removes unitarity requirements

(From 1508.05095)
What do we mean by unitarity?

- Probabilities must be conserved
- This implies that $U^\dagger U = I$
- Departure from unitarity could imply additional dimensions (sterile neutrinos) or non-standard interactions

Normalisation of $\nu_e$

$$
\begin{pmatrix}
U_{e1}^2 + U_{e2}^2 + U_{e3}^2 \\
U_{\mu1}^2 \\
U_{\tau1}^2
\end{pmatrix}
= 1
$$

Unitarity triangles

$$
\begin{bmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{bmatrix}
\begin{bmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{bmatrix}
= \begin{bmatrix} 1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1 \end{bmatrix}
$$