Neutrino oscillation measurements with IceCube DeepCore.
The IceCube Neutrino Observatory
The IceCube Neutrino Observatory
The IceCube Neutrino Observatory

Frank-Tamm formula

\[
\frac{d^2 N_\gamma}{d\Omega d\lambda} = 2\pi \alpha z^2 \frac{1}{\lambda^2} \left( 1 - \frac{1}{\beta^2 n^2} \right)
\]
The IceCube Neutrino Observatory

Frank-Tamm formula

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\frac{d^2 N_{\gamma}}{d \Omega d\lambda} = 2\pi \alpha z^2 \frac{1}{\lambda^2} \left(1 - \frac{1}{\beta^2 n^2}\right)
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\]
The IceCube Neutrino Observatory

Ice

Cherenkov radiation

1.5 km

42° in ice

Frank-Tamm formula

\[
\frac{d^2 N_\gamma}{dld\lambda} = 2\pi\alpha z^2 \frac{1}{\lambda^2} \left(1 - \frac{1}{\beta^2 n^2}\right)
\]

DOMS

1.0 km

2.5 km

300 MSPS

400 ns

40 MSPS

6.4 µs
The IceCube Neutrino Observatory

10 Year anniversary for full array!

<table>
<thead>
<tr>
<th></th>
<th>Spacing [m]</th>
<th>Energy threshold [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Horiz.</td>
<td>Vertical</td>
</tr>
<tr>
<td>IceCube</td>
<td>125</td>
<td>17</td>
</tr>
<tr>
<td>DeepCore</td>
<td>~50</td>
<td>7</td>
</tr>
</tbody>
</table>

Can access atmospheric neutrino oscillations

+DeepCore PMTs with higher quantum efficiency
Neutrino oscillations
The Standard Paradigm

\[ |\nu_a\rangle = \sum U_{\alpha k}^* |\nu_k\rangle \]

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

Atmospheric
Accelerator

Accelerator
Reactor

Reactor
Solar

Two-neutrino vacuum approximation:

Amplitude

Frequency

To first order, DeepCore is sensitive to $\Delta m_{32}^2$ and $\theta_{23}$
Atmospheric neutrinos
Probe of oscillations at high energies and long baselines

Free neutrino beam from cosmic ray interactions
• Mixed composition of (anti-)$\nu_\mu$ and (anti-)$\nu_e$
• Observable over a wide range, from few GeV — 100’s TeV
• Arrival direction used as proxy for distance travelled: $\cos(\theta_{\text{zenith}}) \propto L$

At 5 GeV, operating well above tau-production threshold
Filtering and reconstruction

See posters #157, #164 for more on DeepCore reconstruction
Filtering and reconstruction

See posters #157, #164 for more on DeepCore reconstruction

Background rejection

2 data samples, 3 years of data

- Noise: 0.1%, <0.1%
- Atmospheric muons: 8.1%, 4.6%
- Tau neutrinos: 3.8%, 3.4%
- Muon neutrinos: 64.6%, 66.5%
- Electron neutrinos: 23.4%, 25.6%
Filtering and reconstruction

See posters #157, #164 for more on DeepCore reconstruction

Background rejection

2 data samples, 3 years of data

- Noise: 0.1% (<0.1%)
- Atmospheric muons: 8.1%, 4.6%
- Neutrino tau (ντ): 3.8%, 3.4%
- Neutrino muon (νμ): 64.6%, 66.5%
- Neutrino electron (νe): 23.4%, 25.6%

"Cascade-like": NC interactions, ν_e CC and 83% ν_τ CC

"Track-like": ν_μ CC and some ν_τ CC (17%)
Filtering and reconstruction

See posters #157, #164 for more on DeepCore reconstruction

Background rejection

2 data samples, 3 years of data

Using track length as Flavour ID

“Cascade-like”: NC interactions, $\nu_e$ CC and 83% $\nu_\tau$ CC

“Track-like”: $\nu_\mu$ CC and some $\nu_\tau$ CC (17%)

Resolutions
@20 GeV:

<table>
<thead>
<tr>
<th></th>
<th>Tracks</th>
<th>Cascades</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>24 %</td>
<td>29 %</td>
</tr>
<tr>
<td>Zenith</td>
<td>10°</td>
<td>16°</td>
</tr>
</tbody>
</table>

by DESY.
Analysis strategy
Shape-only comparison between data and weighted MC

\[ \chi^2 = \sum_{i \in \text{bins}} \frac{(n_i^{\nu+\mu} - n_i^{\text{data}})^2}{(\sigma_i^{\nu+\mu})^2 + (\sigma_i^{\text{data}})^2} \]

- **Cascade-like**
  - Vary $\Delta m^2$
  - $(2.526 - 2.778) \times 10^{-3} \text{eV}^2$

- **Track-like**
  - Vary $\theta_{23}$
  - 40 to 45°
Analysis strategy

Shape-only comparison between data and weighted MC

\[ \chi^2 = \sum_{i \in \text{bins}} \frac{(n_i^{\nu+\mu} - n_i^{\text{data}})^2}{(\sigma_i^{\nu+\mu})^2 + (\sigma_i^{\text{data}})^2} \]

- Vary $\nu_e/\nu_{\mu}$ by 5%
- Vary local ice properties
- Vary $\Delta m^2 (2.526 - 2.778) \times 10^{-3} \text{eV}^2$
- Vary $\theta_{23}$ 40 to 45°

Nuisance parameters for syst. uncertainties:
- Initial Flux
- Detector
- Cross-section
- Background
- and subdominant oscillation params

- Vary atm. $\mu$ fraction by 0.9%
Analysis strategy
Shape-only comparison between data and weighted MC

\[ \chi^2 = \sum_{i \in \text{bins}} \frac{(n_i^{\nu+\mu} - n_i^{\text{data}})^2}{(\sigma_i^{\nu+\mu})^2 + (\sigma_i^{\text{data}})^2} + \sum_{j \in \{\text{syst}\}} \frac{(s_j - \hat{s}_j)^2}{\sigma_j^2} \]

Nuisance parameters for syst. uncertainties:
- Initial Flux
- Detector
- Cross-section
- Background
- and subdominant oscillation params

Vary $\Delta m^2$
- $(2.526 - 2.778) \times 10^{-3}$ eV$^2$

Vary $\theta_{23}$
- 40 to 45°

Vary $\nu_e/\nu_\mu$
- by 5%

Vary local ice properties

Vary atm. $\mu$
- fraction by 0.9%
Standard oscillation results


\[ \Delta m^2_{32} = 2.55^{+0.12}_{-0.11} \times 10^{-3} \text{eV}^2 \]
\[ \sin^2 \theta_{23} = 0.58^{+0.04}_{-0.13} \]

\[ N_{\text{obs}} = 62112 \]
\[ \chi^2 = 127.6 \]
\[ p = 55\% \]

Norm \( \nu_\tau^{(CC+NC)} = 0.73^{+0.34}_{-0.24} \) Reject no-\( \nu_\tau \) with 3.2\( \sigma \) (CC+NC)
Standard oscillation results

$\Delta m_{32}^2 = 2.55^{+0.12}_{-0.11} \times 10^{-3} \text{eV}^2$

$\sin^2 \theta_{23} = 0.58^{+0.04}_{-0.13}$

$N_{\text{obs}} = 62112$

$\chi^2 = 127.6$

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Norm $\nu_\tau^{(CC+NC)} = 0.73^{+0.34}_{-0.24}$

Reject no-$\nu_\tau$ with 3.2$\sigma$ (CC+NC)
On the horizon…

8 y oscillation sample with > 300k neutrinos

Honda et al.
PRD 92, 023004 (2015)

Barr et al.
PRD 74 094009 (2006)

GENIE 2.8.6
(GRV98)
On the horizon…
8 y oscillation sample with > 300k neutrinos


Link to MCEq on github
On the horizon…

8 y oscillation sample with > 300k neutrinos

Fedynitch et al.,

Honda et al.
PRD 92, 023004 (2015)

Barr et al.
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Flux

Link to MCEq on github

Genie2.8.6 (GRV98)
On the horizon…

8 y oscillation sample with > 300k neutrinos

Honda et al.
PRD 92, 023004 (2015)

Barr et al.
PRD 74 094009 (2006)

Fedynitch et al.,

Alternative xsec models (CSMS), see A. Cooper-Sarkar, et al. JHEP 08 (2011) 042

Standard oscillation 8 y projections

Unprecedented with atmospheric neutrinos

See posters #547 and #167 for more details

Improved detector calibration, event selection, reconstruction, PID and systematic treatment
Searching beyond the $\nu$SM

Non-standard oscillation patterns

Favourable phase space
- High energies: access new physics coupling to $\tau$-sector
- Long trajectories: exposure to new fields/interactions

Model dependent searches for new physics, e.g.:
- eV-scale sterile neutrinos
- Non-standard interactions
- ….+ much more!

Expected signatures are assessed by modifying neutrino mixing matrix and potential

\[ \hat{H} = \frac{1}{2E} \sqrt{\hat{M}^2 U^\dagger + \hat{V}_{\text{int}}} \]
Searching beyond the $\nu$SM
Non-standard oscillation patterns

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Expected signatures are assessed by modifying neutrino mixing matrix and potential

$$\hat{H} = \frac{1}{2E} \mathbf{U} \hat{M}^2 \mathbf{U}^\dagger + \hat{V}_{\text{int}}$$

For particular realisations of non-standard physics
Non-standard interactions

New constraints from 3-year DeepCore sample

New mediators, e.g. $Z'$
- Creates non-standard flavour changes
- Modifies effective matter potential experienced by neutrinos in transit through the Earth

$$H_{\text{mat}}(x) = \sqrt{2} G_F N_e(x) \left( \begin{array}{ccc}
1 & (\epsilon_{e\mu}^\oplus - \epsilon_{\mu\mu}^\oplus)(x) & \epsilon_{e\mu}^\oplus(x) & \epsilon_{e\tau}^\oplus(x) \\
\epsilon_{\mu\mu}^\oplus(x) & 0 & \epsilon_{\mu\tau}^\oplus(x) \\
\epsilon_{e\tau}^\oplus(x) & \epsilon_{\mu\tau}^\oplus(x) & (\epsilon_{\tau\tau}^\oplus - \epsilon_{\mu\mu}^\oplus)(x)
\end{array} \right)$$

for Earth: $\epsilon_{\alpha\beta}^\oplus(x) \approx \epsilon_{\alpha\beta} = \epsilon_{e\alpha\beta}^e + \epsilon_{e\alpha\beta}^\nu + 1.051 \epsilon_{e\alpha\beta}^\nu$

Results are consistent with the null hypothesis
- Constrain real couplings with phases fixed to 0
- *New* - full parameter fit includes complex phases

See poster #364 for more details.
Sterile Neutrinos

Resonant disappearance of anti-$\nu_\mu$

3+1 model: probes $\Delta m^2_{41}$, $\theta_{24}$, $\theta_{34}$
- Using 8 years of high-energy, through-going tracks ($\cos \theta_z < 0$)
- 305,735 events with >99% purity $\nu_\mu$
- High statistical precision required significant investment in modelling of systematic uncertainties

Two searches, both results consistent with null hypothesis

**Analysis I**: $\Delta m = 4.47$ eV$^2$, $\sin^2(2\theta_{24}) = 0.10$ ($\theta_{34} = 0$), $p = 8\%$

**Analysis II**: $\sin^2(2\theta_{24}) = 0.006$, $\sin^2(2\theta_{34}) = 0.40$, ($\Delta m = 50$ eV$^2$), $p = 19\%$

Results are robust against the removal of any single year of data or systematic uncertainty

*See poster #177 for more details*

The IceCube Upgrade
A multipurpose detector

IceCube Upgrade goals:
• Precision oscillation measurements
• Improved detector calibrations
• R&D for IceCube-Gen2

Key features
• > 800 new devices
• Reduced spacing between devices
• Explore the deep ice down to 2600 m

Fall  Now  Deploy  Gen2…
2018  2020  2022/23
New sensor designs

Increased effective area

DEgg
2x8” PMT
Produced at Chiba
Deploy ~300

mDOM
24x3” PMT
Produced at DESY&MSU
Deploy ~400

More total photocathode area, increased wavelength and angular acceptance
New sensor designs
Increased effective area

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*More total photocathode area, increased wavelength and angular acceptance*
IceCube Upgrade Events

More detail in every event

- **DeepCore**
  - 21 GeV $\nu_\tau$ interaction

- **Upgrade**
  - + factor 2-4 increase in rates over DeepCore (depending on energy/interaction type)
IceCube Upgrade Events

More detail in every event

DeepCore

21 GeV $\nu_\tau$ interaction

Upgrade

+ factor 2-4 increase in rates over DeepCore (depending on energy/interaction type)
IceCube Upgrade Potential

Precision measurements of standard oscillations

Similar improvements expected in Beyond νSM searches
IceCube Upgrade

Opportunities for improved detector calibrations

New calibration devices at shorter distances
- Multi-wavelength
- Both isotropic and (rotating) beamed emission profiles
- Self-monitoring light sources
- Large dynamic range

Impact on science
- Reduced detector-related uncertainties for *entire* detector, including archival data
- New opportunities for ice studies/glaciology

IceCube Upgrade

Opportunities for improved detector calibrations

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**IceCube Upgrade**

**Opportunities for improved detector calibrations**

- New calibration devices at shorter distances
  - Multi-wavelength
  - Both isotropic and (rotating) beamed emission profiles
  - Self-monitoring light sources
  - Large dynamic range

**Impact on science**

- Reduced detector-related uncertainties for *entire* detector, including archival data
- New opportunities for ice studies/glaciology

Summary

IceCube DeepCore provides complementary measurements of standard atmospheric mixing parameters.

Higher energies and longer baselines provide unique sensitivity to New Physics and world-leading constraints.

New oscillation measurements from IceCube DeepCore with 8 y live time are coming soon.

IceCube Upgrade will enable more precise measurements of low energy neutrino properties, and better calibrations will benefit entire IceCube science program.
Thank you!

**Novel reconstruction tools**
- 164. Application of Convolutional Neural Networks to Reconstruct GeV-Scale IceCube Neutrino Events
  Jessica Micallef (Michigan State University)
  Poster session 4
- 157. Deep Learning Classifier for Low-Energy Events in IceCube
  Maria Prado Rodriguez (University of Wisconsin-Madison)
  Poster Session 1

**Interactions/cross section**
- 203. Measuring neutrino cross-section with IceCube at intermediate energies (~100 GeV to a few TeV)
  Sarah Nowicki (Michigan State University)
  Poster session 4
- 171. Measurement of the Earth Density Profile with Atmospheric Muon Neutrinos Collected by IceCube
  Kotoyo Hoshina (University of Wisconsin Madison)
  Poster Session 1

**Standard Oscillations**
- 547. Atmospheric Neutrino Oscillations in IceCube DeepCore
  Kayla Leonard (University of Wisconsin - Madison)
  Poster session 4
- 167. Tau Neutrino Appearance with 8 years of IceCube Neutrino Data
  Mr Étienne Bourbeau (NBI)
  Poster session 3

**Beyond Standard Oscillations**
- 320. Searching for neutrino decoherence from quantum gravitational space-time fluctuations with IceCube
  Dr Tom Stuttard (Niels Bohr Institute, IceCube)
  Poster session 3
- 364. Non-standard neutrino interaction search with IceCube DeepCore
  Mrs Elisa Lohfink (Johannes Gutenberg-Universität, Mainz)
  Poster Session 2
- 177. Search for Light Sterile Neutrinos With Eight Years of IceCube Data
  Dr Carlos Arguelles (MIT)
  Poster Session 2
- 529. Light Unstable Sterile Neutrino Search in IceCube
  Marjon Moulai (Massachusetts Institute of Technology)
  Poster Session 2

Want more? Checkout these posters!
Backup
Neutrino oscillations
The experimental landscape

DeepCore measures oscillations at higher energies and over longer baselines (with differing matter profile) than accelerator experiments

Well above the tau production threshold

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

\[ U_{\text{PMNS}} \text{ unitarity implies, e.g.}: \quad |U_{e3}|^2 + |U_{\mu3}|^2 + |U_{\tau3}|^2 = 1 \]
DeepCore 3 year sample

Event rates vs. Selection
DeepCore 8 year sample
Revised event selection for better background rejection + higher signal efficiency
DeepCore 8 year sample

Data/MC Agreement
Analysis strategy
Pipeline overview

CR, hadron production/interaction, atmosphere

Hadronization with KNO and PYTHIA, GRV98 PDFs

Interaction

GENIE 2.8.6

Photon propagation

DOM response

Trigger

Remove atm. muons and pure noise triggers

Energy, zenith, PID

Filter/Reco

Honda, et al.

Φ unosc.
Primary cosmic ray model

Spectrum and composition

Dembinski, et al., https://pos.sissa.it/301/533/pdf
Flux uncertainties

Production uncertainty:
\( \pi^\pm \sim 10-30\% \)
\( K^\pm \sim 10-40\% \)

Experimental coverage of single \( \pi \) production yield

Flux uncertainties

Photon propagation
Complex, natural detector medium
Photon propagation
Complex, natural detector medium

Ice | Water | Ice

SPICE 3.2.1 ice model

IceCube
DeepCore
Dust layer
Per DOM

12 LEDs

Effective scattering coefficient [1/m]
Absorption coefficient [1/m]

Depth [m]

1000 1200 1400 1600 1800 2000 2200 2400 2600 2800
Local ice/DOM features

Still frame from camera

Model with no hole ice
Angular acceptance model
One direct simulation scenario
Detector recalibration

“With great statistics comes great responsibility”

Event readout

Waveform sampling & trigger

“Hard local coincidence” HLC

Trigger decision based on number of HLCs (+ optionally volume)
Neutrino interactions in IceCube

Event signatures

\[ \nu_e, \nu_\mu, \nu_\tau \]
Neutrino interactions in IceCube

Event signatures

\[ \nu_e \nu_\mu \nu_\tau \]

\[ \nu_e \nu_\mu \nu_\tau \]

\[ \nu_e \rightarrow e^- \]

\[ e^- \rightarrow \]
Neutrino interactions in IceCube

Event signatures

\[ \nu_e, \nu_\mu, \nu_\tau \]
Neutrino interactions in IceCube

Event signatures

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

$\nu_e$ -> $e$

$\nu_\mu$ -> $\mu$
Neutrino interactions in IceCube

Event signatures

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

$\nu_e$

$\nu_\mu$

$e$

$\mu$
Neutrino interactions in IceCube

Event signatures

\[ \nu_e, \nu_\mu, \nu_\tau \]

\[ \nu_e, \nu_\mu, \nu_\tau \]

\[ \nu_e \]

\[ \nu_\tau \]

\[ \nu_\mu \] (17%)

\[ \nu_\tau \] (83%)

\[ \mu \] (17%)

\[ \mu \]
Neutrino interactions in IceCube

Event signatures

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

$\nu_e$

$\nu_\tau$

$\nu_\mu$

$83\%$

$17\%$

“Cascades”
Neutrino interactions in IceCube

Event signatures

$\nu_e, \nu_\mu, \nu_\tau$

$\nu_e$

$\nu_\tau$

$\nu_\mu$

$\mu (17\%)$

$\nu_\tau (83\%)$

"Cascades"

"Tracks"
Neutrino interactions in IceCube

Event signatures

\[ \nu_e, \nu_\mu, \nu_\tau \]

\[ \nu_e, \nu_\mu, \nu_\tau \]

\[ \nu_e \]

\[ \nu_\tau \]

\[ \nu_\tau \]

\[ \nu_\mu \]

\[ \mu \]

\[ \mu \]

\[ \mu \]

\[ \tau \]

\[ \tau \]

(83%)

(17%)
Neutrino interactions in IceCube

Event signatures

\( \nu_e \nu_\mu \nu_\tau \)

\( \nu_e \)  

\( \nu_\tau \)  

(83\%)  

\( \nu_\mu \)  

\( \nu_\mu \) (17\%)
Event reconstruction

Performance

Resolution @ 20 GeV for tracks (cascades):
• 24% (29%) in energy
• 10° (16°) zenith

Classification @ 20 GeV:
• 50% of $\nu\mu$ CC events correctly classified as tracks
Detector systematics
Discrete MC sets mapped to continuous reweighing scheme
Neutrino oscillations

Best fit systematics

### Neutrino Flux & Cross Section:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Prior</th>
<th>Analysis A Calc</th>
<th>Analysis B Calc</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e/\nu_\mu$ Ratio</td>
<td>1.0 ± 0.05</td>
<td>1.03</td>
<td>1.03</td>
</tr>
<tr>
<td>$\nu_e$ Up/Hor. Flux Ratio ($\sigma$)</td>
<td>0.0 ± 1.0</td>
<td>-0.19</td>
<td>-0.18</td>
</tr>
<tr>
<td>$\nu/\bar{\nu}$ Ratio ($\sigma$)</td>
<td>0.0 ± 1.0</td>
<td>-0.42</td>
<td>-0.33</td>
</tr>
<tr>
<td>$\Delta\gamma_{\nu}$ (Spectral Index)</td>
<td>0.0 ± 0.1</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Effective Livetime (years)</td>
<td>-</td>
<td>2.21</td>
<td>2.24</td>
</tr>
<tr>
<td>$M_{A^{ee}}^{CCQE}$ (Quasi-Elastic) (GeV)</td>
<td>$0.99^{+0.248}_{-0.149}$</td>
<td>1.05</td>
<td>1.05</td>
</tr>
<tr>
<td>$M_{A^{re}}^{res}$ (Resonance) (GeV)</td>
<td>1.12 ± 0.22</td>
<td>1.00</td>
<td>0.99</td>
</tr>
<tr>
<td>NC Normalization</td>
<td>1.0 ± 0.2</td>
<td>1.05</td>
<td>1.06</td>
</tr>
</tbody>
</table>

### Oscillation:

- $\theta_{13}$ ($^\circ$): 8.5 ± 0.21
- $\theta_{23}$ ($^\circ$): 49.8 ± 50.2
- $\Delta m_{32}^2$ (10^{-3}eV²): 2.53 ± 2.56

### Detector:

- Optical Eff., Overall (%): 100 ± 10
- Optical Eff., Lateral ($\sigma$): 0.0 ± 1.0
- Optical Eff., Head-on (a.u.): -0.63 ± 0.64
- Local Ice Model: -
- Bulk Ice, Scattering (%): 100.0 ± 10
- Bulk Ice, Absorption (%): 100.0 ± 10

### Atmospheric Muons:

- Atm. $\mu$ Fraction (%): 8.1 ± 0.8
- $\Delta\gamma_{\mu}$ ($\mu$ Spectral Index, $\sigma$): 0.0 ± 1.0
- Coincident $\nu + \mu$ Fraction: 0.0 ± 0.1

### Measurement:

- $\nu_\tau$ Normalization: -0.73 ± 0.57

---

**IceCube Preliminary**

---

**Log$_{10}$ L/E (km/GeV)**

**MC Uncertainty**

**Data**

**Number of Events**

**Data/MC**
Non-standard disappearance at high energy due to $\varepsilon_{e\mu}$ & $\varepsilon_{\mu\tau}$

Less disappearance at high energy due to $\varepsilon_{e\tau}$ & $\varepsilon_{\tau\tau}$
eV Sterile Search

Impact of systematics
eV Sterile Search

Impact of systematics
eV Sterile Search
Impact of systematics
IceCube Upgrade Events

More detail in every event
The IceCube Upgrade
New technology
The IceCube Upgrade
New technology

IceCube Gen1 DOM

Upgrade module: DEgg

IceCube-Gen2
A vision for the future of neutrino astroparticle physics at the South Pole
Neutrino oscillations

Highest energy probe of atmospheric $\nu_\mu \rightarrow \nu_\tau$ mixing

Expected precision:

$\Delta m_{32}^2 \sim 1\% \ (1\sigma)$

$\theta_{23} \sim 4\% \ (1\sigma)$

depends on NMO and true $\theta_{23}$
Neutrino oscillations

Neutrino Mass Ordering

PINGU LOI Version 2 @ arXiv:1401.2046v2
NMO

Exploit synergy between JUNO and IceCube Upgrade

Ice anisotropy

South Pole ice anisotropy: Proceedings of ICRC2013 0580, 2014
SPICEcore

Many devices:
- Dust logger
- UV logger
- Luminescence logger
- Camera logger

Borehole drilled for glaciology purposes

Ice tilt

1.5km

350 m

1.7km

@12.7 cm