The IceCube Upgrade
Design and Science Goals

Aya Ishihara for the IceCube collaboration
IceCube

@ Amundsen-Scott South Pole station

IceCube Lab

IceTop
81 Stations
324 optical sensors

IceCube Array
86 strings
including 8 DeepCore strings
5160 optical sensors

DeepCore
8 strings-spacing optimized
for lower energies
480 optical sensors

Eiffel Tower
324 m
IceCube Upgrade

Geometry optimized for
- GeV neutrinos
- Calibration of the IceCube detector

inner fiducial volume 2.2Mton

outer fiducial

clear ice

dusty ice

3m vertical separation

special calibration region

275m
Why GeV Neutrinos so Interesting?

Neutrino Oscillations!

\[ P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - 4|U_{\mu 3}|^2(1 - |U_{\mu 3}|^2) \sin^2 \left( \frac{\Delta m^2_{32} L}{4E} \right) \]

\[ L = L(\theta) \]

\[ L(\theta = 0) = 12700 \text{ km} \]

\[ U_{\mu 3} = \sin \theta_{23} \cos \theta_{13} \]

maximal at 25 GeV

\[ P(\nu_\mu \rightarrow \nu_\tau) = \sum_{j,k} U_{\mu j} U_{\tau j}^* U_{\mu k} U_{\tau k} \exp \left( i \frac{\Delta m^2_{jk} L}{2E} \right) \approx \cos^4 \theta_{13} \sin^2 \theta_{23} \sin^2 \left( \frac{2 \Delta m^2_{31} L}{4E} \right) \]
Neutrino Oscillations

\[
\begin{bmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{bmatrix} =
\begin{bmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{bmatrix}
\begin{bmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{bmatrix}
\]

\[
U_{PMNS}^{3\times 3} =
\begin{bmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{bmatrix}
\begin{bmatrix}
c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta_{CP}} & 0 & c_{13}
\end{bmatrix}
\begin{bmatrix}
c_{12} & s_{12} & 0 \\
s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

assuming unitarity!

But, do we really know

\[
U_{PMNS}^{3\times 3} \dagger U_{PMNS}^{3\times 3} = 1
\]

or possibly...

\[
U_{PMNS}^{\text{Extended}} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} & \cdots & U_{e n} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \cdots & U_{\mu n} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \cdots & U_{\tau n} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
U_{s_{11}} & U_{s_{12}} & U_{s_{13}} & \cdots & U_{s_{1n}}
\end{pmatrix}
\]

?!
Absence of tau neutrino oscillation excluded at 3.2σ

\[ \Delta m^2_{21} = 7.5 \times 10^{-5} \text{eV}^2 \]

\[ \theta_{12} = 33.48^\circ, \delta_{CP} = 0^\circ \]

no assumption on \( \Delta m^2_{32}, \theta_{23}, \) mass ordering
Densely Instrumented and Improved Optical Sensors

mDOM 24ch × 3′′ PMT

D-Egg 2ch × 8′′ PMT

36cm

30cm

Poster3-98
(L. Classen)

Upward-going
20 GeV tau neutrino

>10 times more effective

photocathode area per volume
compared to DeepCore
Improved Reconstruction Capabilities

zenith angle reconstruction

energy reconstruction
More Events

Graphs showing data for different particle interactions and energy distributions.

- $\nu_\mu, cc$
- $\nu_\tau, cc$

- Inner fiducial (DeepCore)
- Outer fiducial (DeepCore)
- Inner fiducial (Upgrade)
- Outer fiducial (Upgrade)
Tau-neutrino Appearance Sensitivity

Consistency/inconsistency of Unitarity in 3x3 PMNS mixing matrix with 1 year of data

- Conservative assumption of inner fiducial volume event only analysis

Consistent with Unitary PMNS Mixing

less tau neutrinos

more tau neutrinos

IceCube Work in Progress

DeepCore 3 yr (1σ)

IceCube Upgrade

1 yr sensitivity (1σ)

DeepCore 3 yr (1σ)

IceCube Upgrade

1 yr sensitivity (1σ)

0.73^{+0.3}_{-0.24}

OPERA (1σ)

SuperK (1σ)

$N_{\nu_{\tau}}$

0.0 0.5 1.0 1.5
Muon-neutrino Disappearance Sensitivity

- Comparable precision to accelerator-based experiments in 3 yr
- Different L/E and systematics
Systematics Uncertainty

41% systematic uncertainty from detector calibration (detector errors are correlated)

- ice absorption sets viewing distance
- ice scattering differs arrival direction of photons

Calibration of **refrozen-ice**
- A bubble column is formed in the central region of deployment holes

Calibration of **bulk ice**
- Anisotropy of photon propagation in ice along glacial flow
  - **Wednesday NU-11d Talk by D. Chirkin**

*In the recently tau neutrino appearance analysis with DeepCore (Phys. Rev. D 99, 032007, 2019)*
Upgrade Calibration

Pencil beam (beaming light source)  
POCAM Poster3-114 (isotropic light source)

IceCube DOMs with new electronics (pDOM)  
LEDs in modules Poster3-117  
Cameras in modules Poster3-118

Improved calibration constants will be applied over 10 years of IceCube’s archived sample
Calibration of IceCube Main Array

- Calibration allows to make improved samples to access to CR/neutrino sources
  - angular reconstruction
  - flavor ID

**WORK IN PROGRESS**

Tuesday NU-8f
Talk by J. Stachurska
IceCube-Gen2 Facility

Surface array
- muon veto
- CR physics

Radio array
- cosmogenic neutrino
- neutrino >10 PeV

Dense array
- 26 strings
- 125-192 sensors/string
- ≈25m distance

Main array
- ≈100 strings
- ≈100 sensors/string
- 6 times more IceCube surface area
- 30% more extended above/below IceCube depth
Special R&D Sensors

New R&D sensors are also to be studied in the Upgrade array

Why we want sensors fit into narrow holes?

- Significant cost/time saving in Gen2 drilling!
  - If hole diameter becomes 1/3
    → drilling time/cost becomes 1/10
Summary and Outlook: Toward Gen2

- IceCube has established the way to observe neutrinos in GeV to PeV using naturally existing medium at South Pole.
- The Upgrade array with 7 strings of densely instrumented optical sensors to be deployed in 2022-2023 season.
- It will enhance the capability of GeV neutrino detections and leads to world-leading sensitivity to neutrino oscillations.
- Improved calibration of optical ice properties will reduce systematic uncertainties in reconstruction and astrophysical neutrino analysis.
- R&D opportunities as the first stage of IceCube-Gen2.