ICECUBE

ICECUBE UPGRADE

ICECUBE GEN2

The IceCube Upgrade Design and Science Goals

Aya Ishihara for the IceCube collaboration

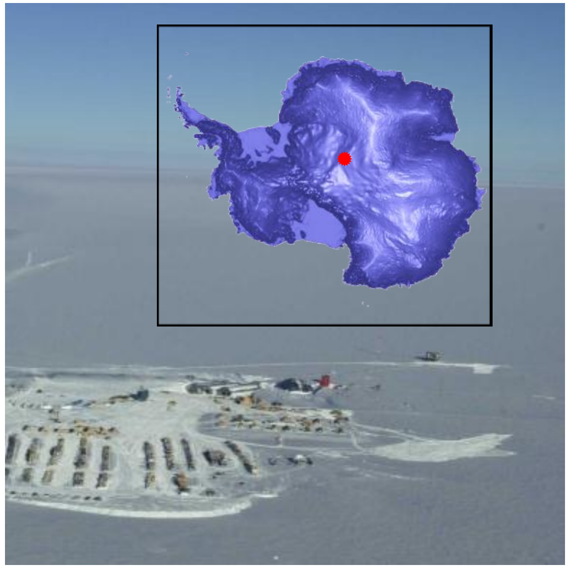
千葉大学 CHIBA UNIVERSITY

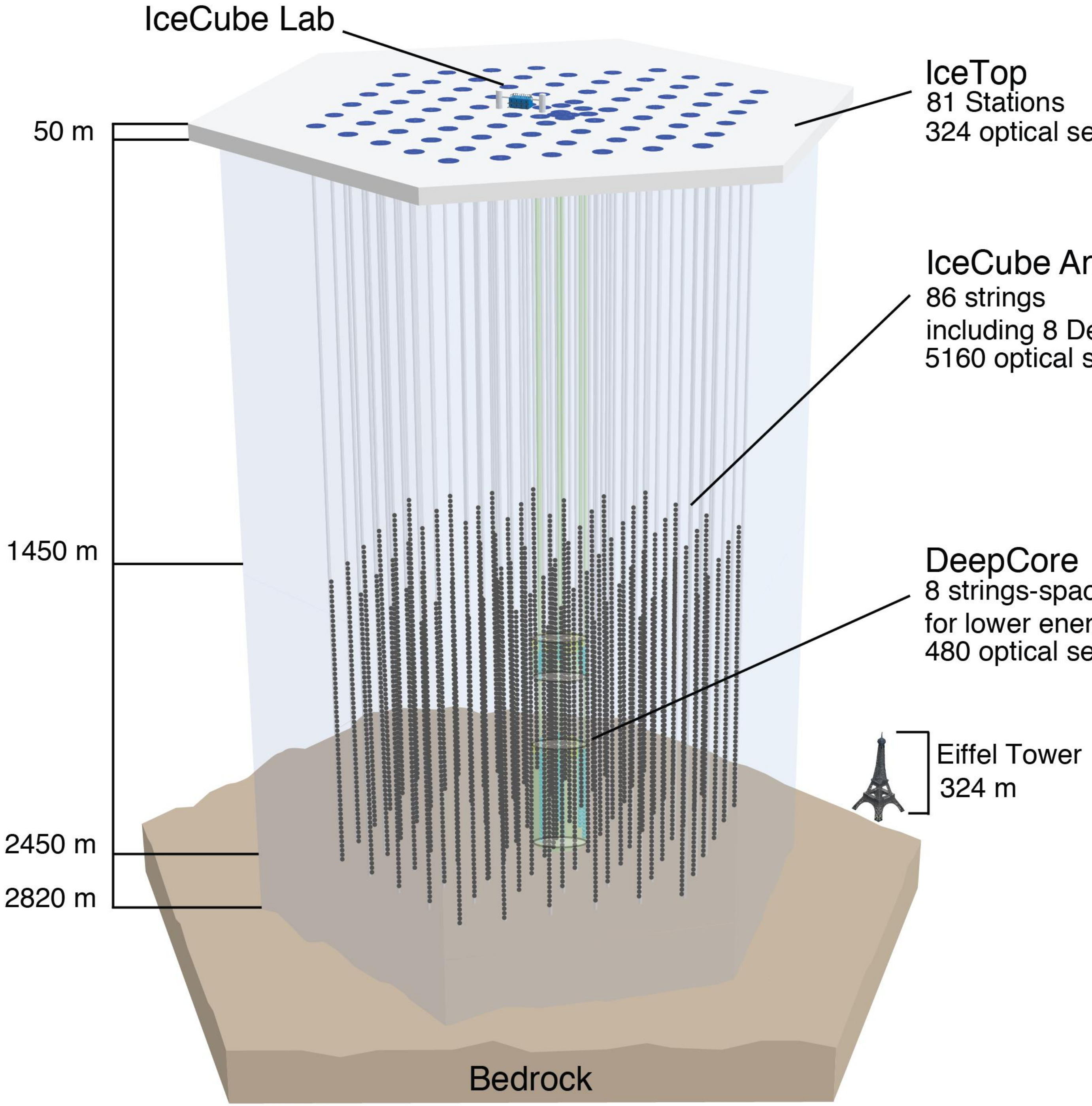
ICEHAP

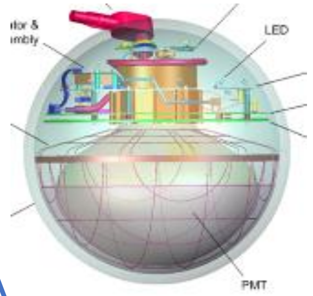
ICRC2019
36th International Cosmic Ray Conference - Madison, WI, USA
THE ASTROPARTICLE PHYSICS CONFERENCE

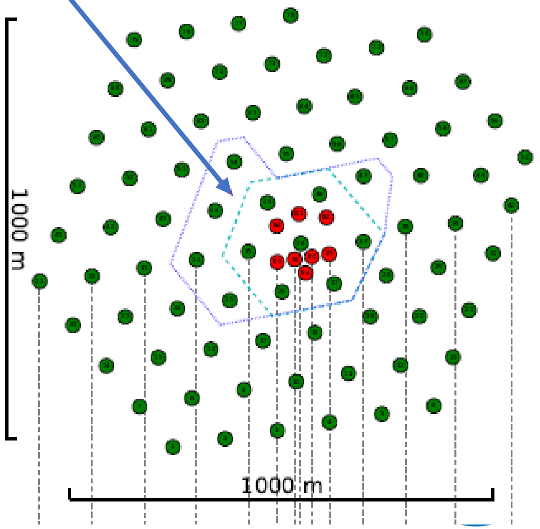
IceCube

@ Amundsen-Scott South Pole station





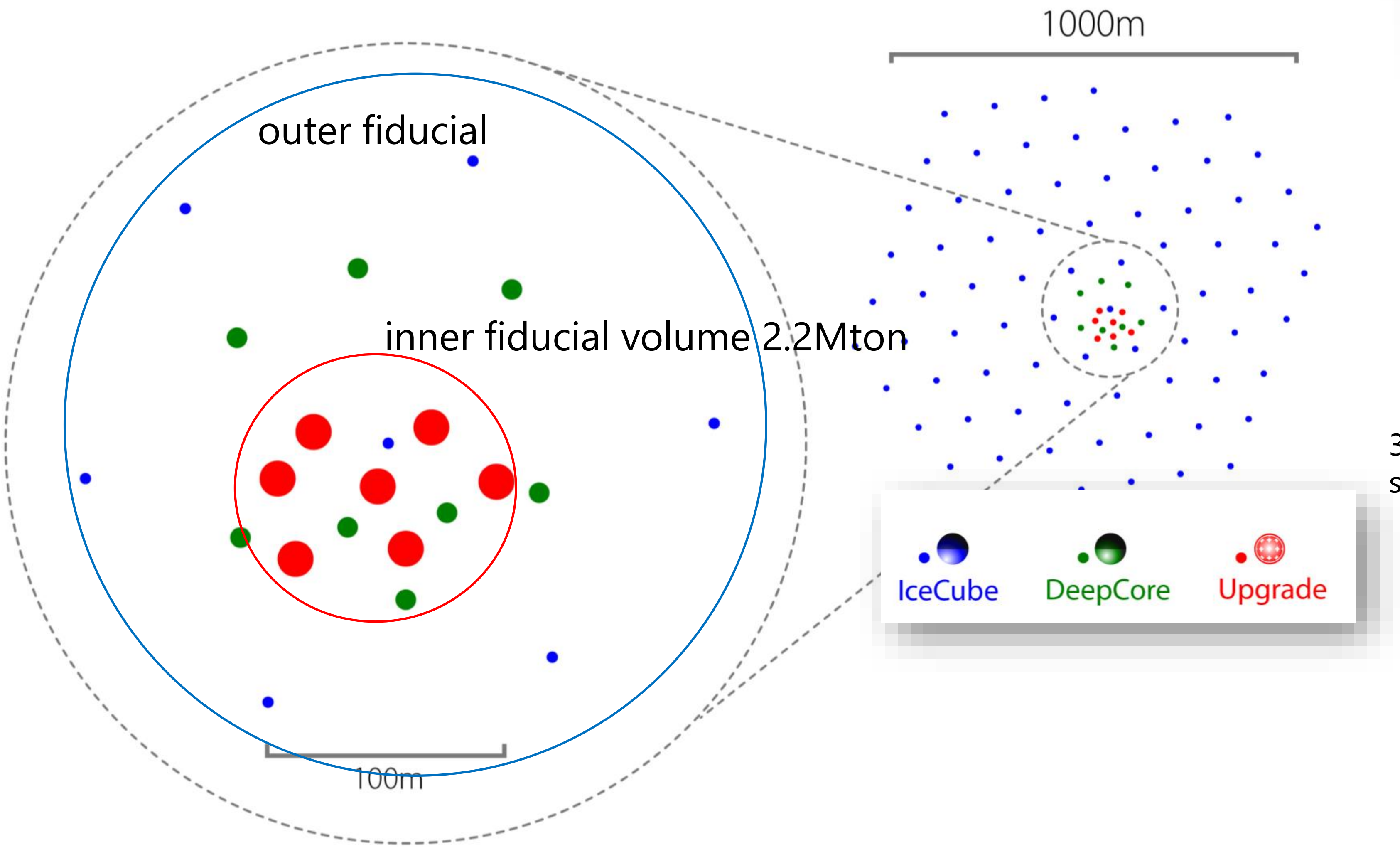


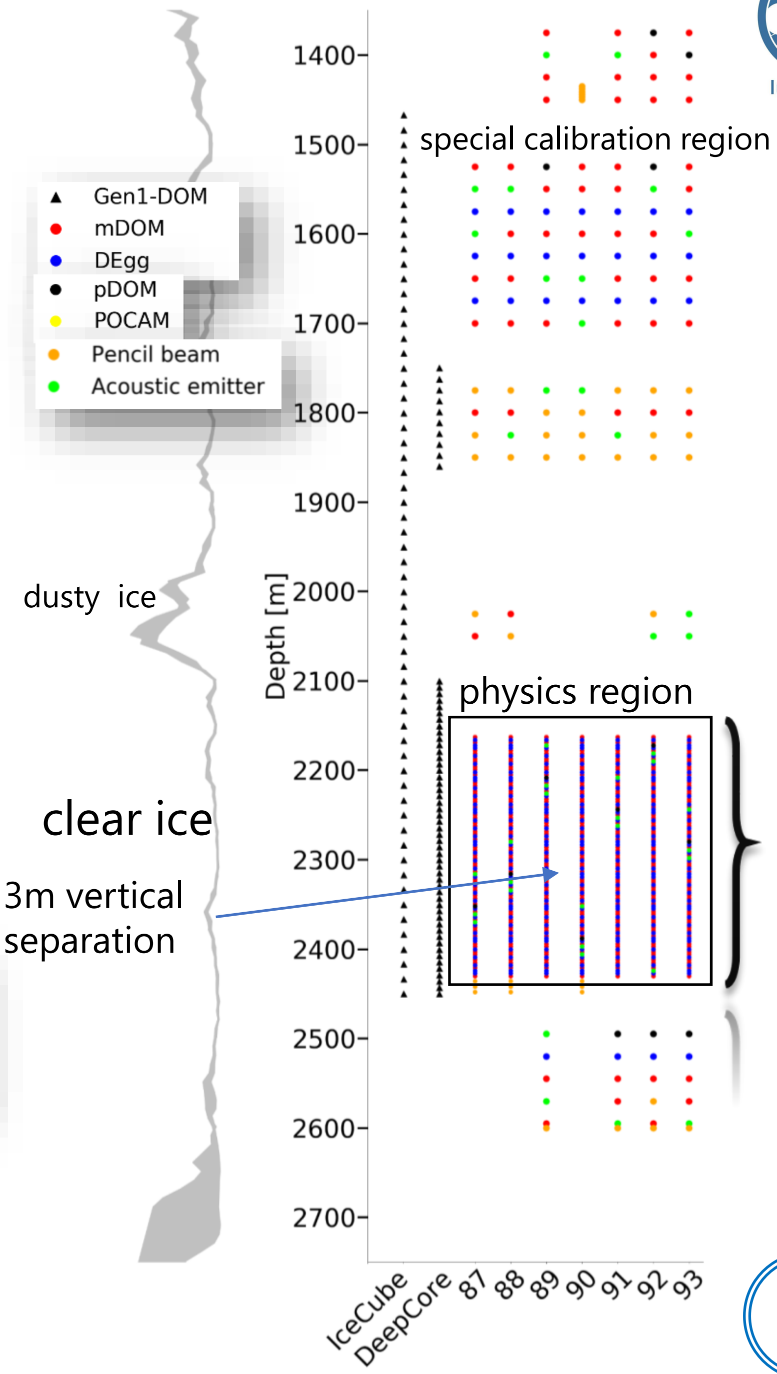


IceCube Upgrade

Geometry optimized for

- GeV neutrinos
- Calibration of the IceCube detector





Why GeV Neutrinos so Interesting?

Neutrino Oscillations!

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

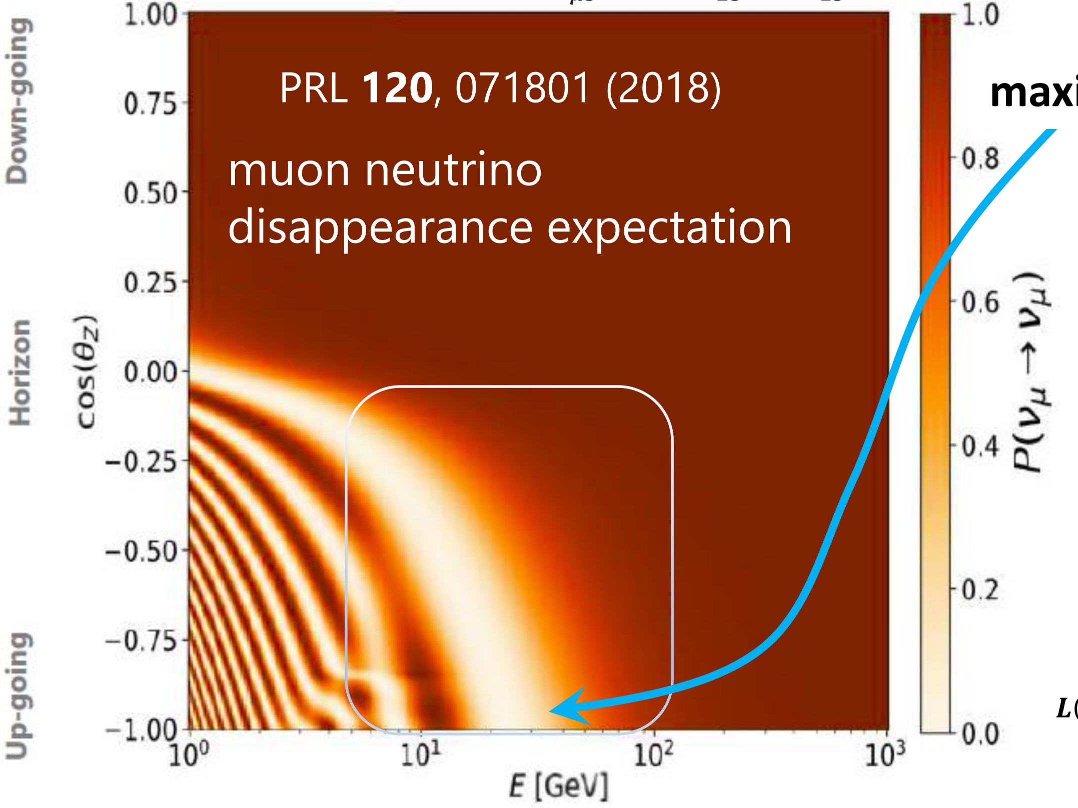
$$U_{\mu 3} = \sin\theta_{23}\cos\theta_{13}$$

$$P_{\nu_\mu \to \nu_\tau} = \sum_{j,k} U_{\mu j} U^*_{\tau j} U^*_{\mu k} U_{\tau k} \exp\left(i \frac{\Delta m^2_{jk} L}{2E_\nu}\right)$$

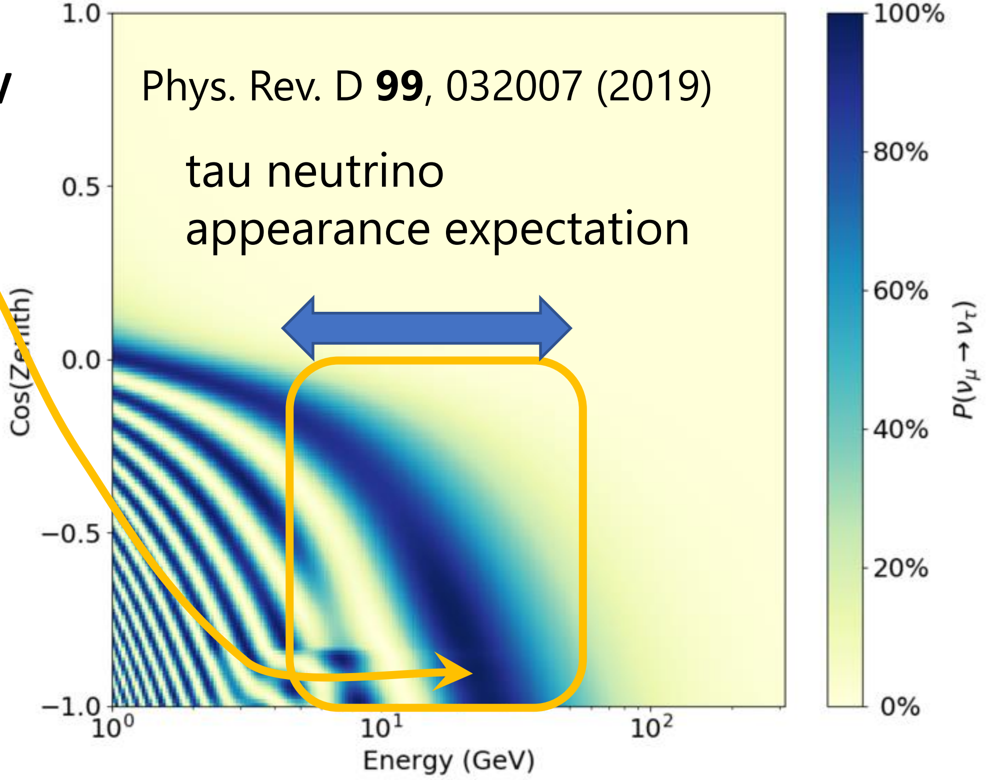
$$\approx \cos^4\theta_{13}\sin^2 2\theta_{23}\sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right)$$

$$L = L(\theta)$$

maximal at 25 GeV



$L(\theta = 0) = 12700$ km



Neutrino Oscillations

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} \longrightarrow U^{3\times 3}_{PMNS} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

assuming unitarity!

But, do we really know

$$U^{3\times 3}_{PMNS}{}^{\dagger} U^{3\times 3}_{PMNS} = 1$$

or possibly…

$$U^{\text{Extended}}_{\text{PMNS}} = \begin{pmatrix} \overbrace{\begin{matrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{matrix}}^{U^{3x3}_{\text{PMNS}}} & \begin{matrix} \cdots & U_{en} \\ \cdots & U_{\mu n} \\ \cdots & U_{\tau n} \end{matrix} \\ \begin{matrix} \vdots & \vdots & \vdots \end{matrix} & \begin{matrix} \ddots & \vdots \end{matrix} \\ \begin{matrix} U_{s_n 1} & U_{s_n 2} & U_{s_n 3} \end{matrix} & \begin{matrix} \cdots & U_{s_n n} \end{matrix} \end{pmatrix}$$

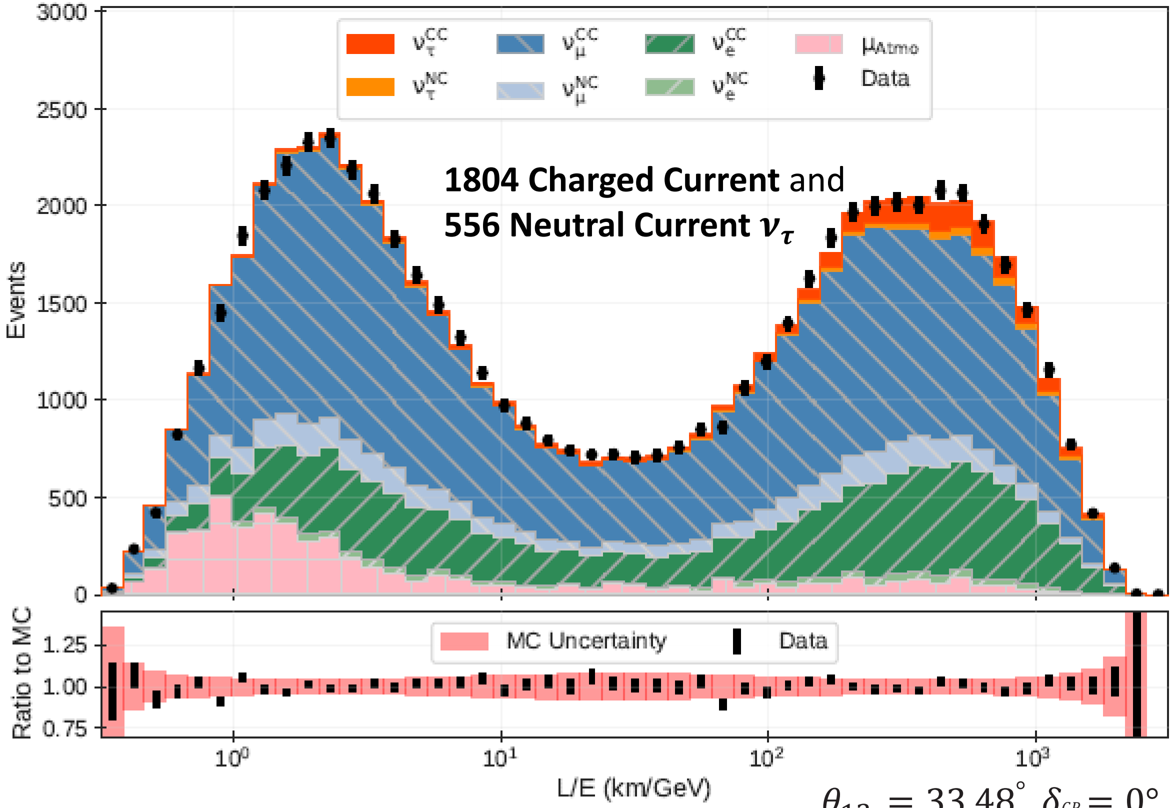
?!

Parke and Ross-Lonergan
Phys. Rev. D 93, 113009 (2016)

Tau-neutrino Appearance with DeepCore

from 3 years data analysis (7 year sample currently on-going)

Absence of tau neutrino oscillation excluded at 3.2σ

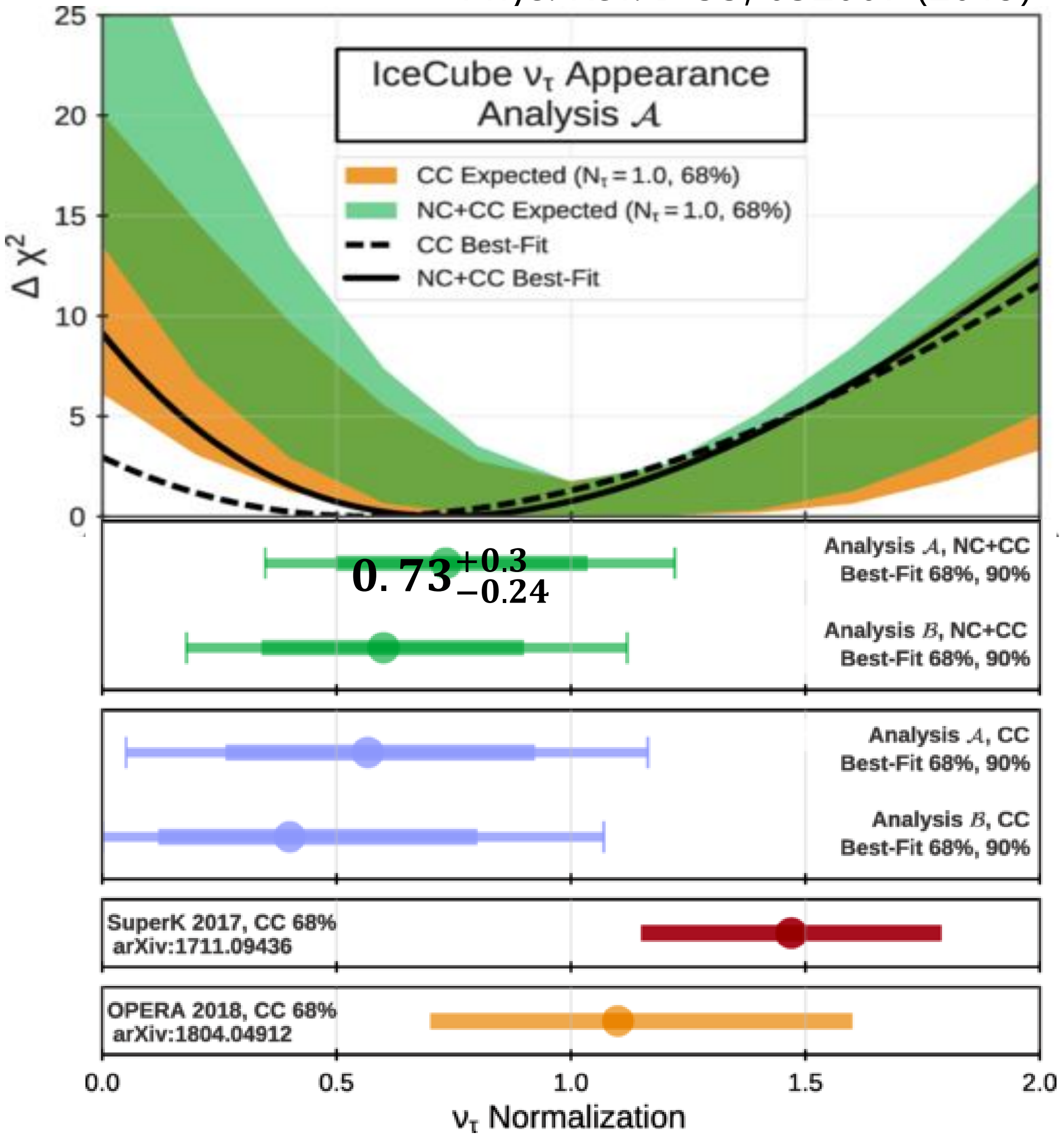


$\theta_{12} = 33.48^\circ, \delta_{CP} = 0^\circ$

$\Delta m^2_{21} = 7.5 \times 10^{-5}\,\mathrm{eV}^2$

no assumption on $\Delta m^2_{32}, \theta_{23}$, mass ordering

Phys. Rev. D **99**, 032007 (2019)



Densely Instrumented and Improved Optical Sensors

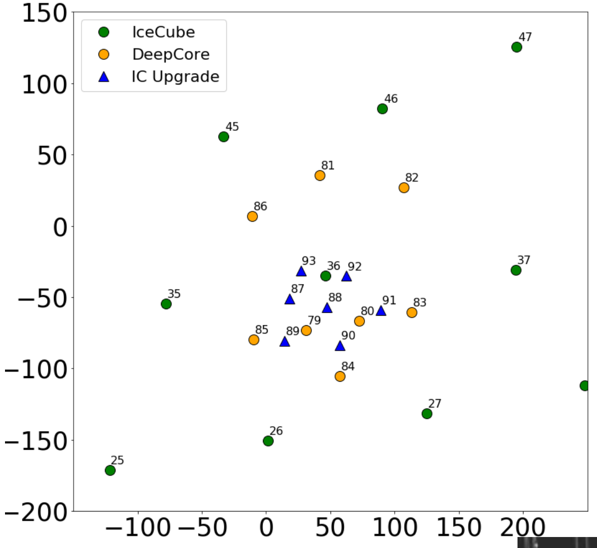
mDOM $24ch \times 3''PMT$

Poster3-98
(L.Classen)

+

D-Egg $2ch \times 8''PMT$

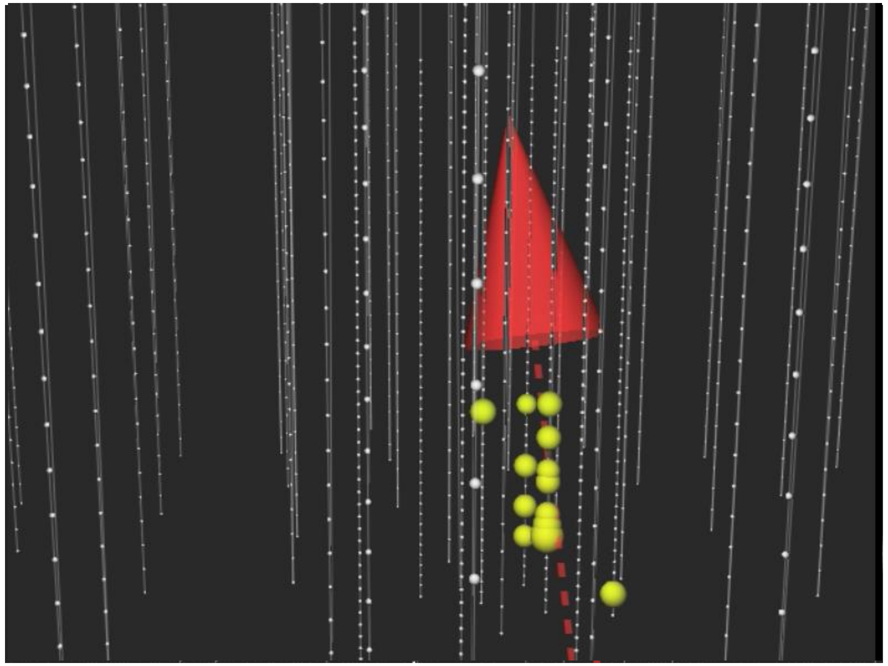
$\otimes$



=

>10 times more effective photocathode area per volume compared to DeepCore

Upward-going 20 GeV tau neutrino



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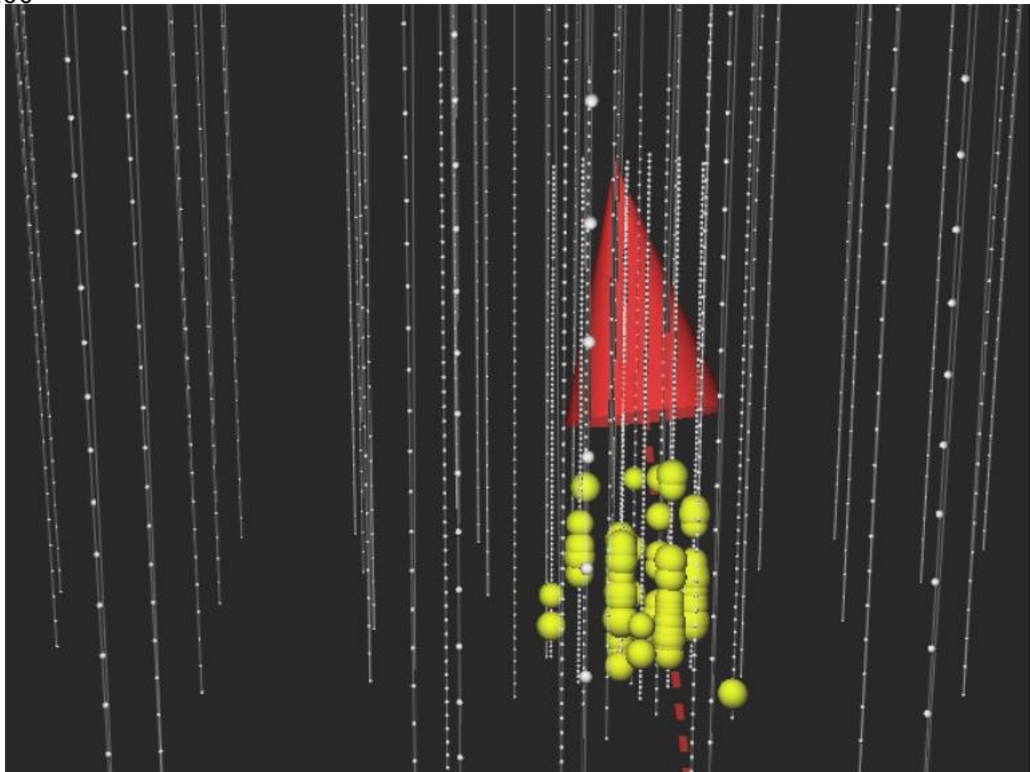
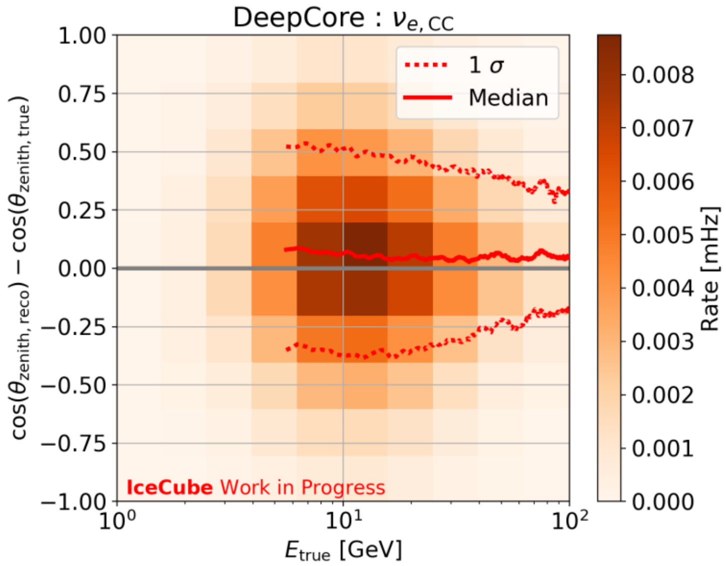
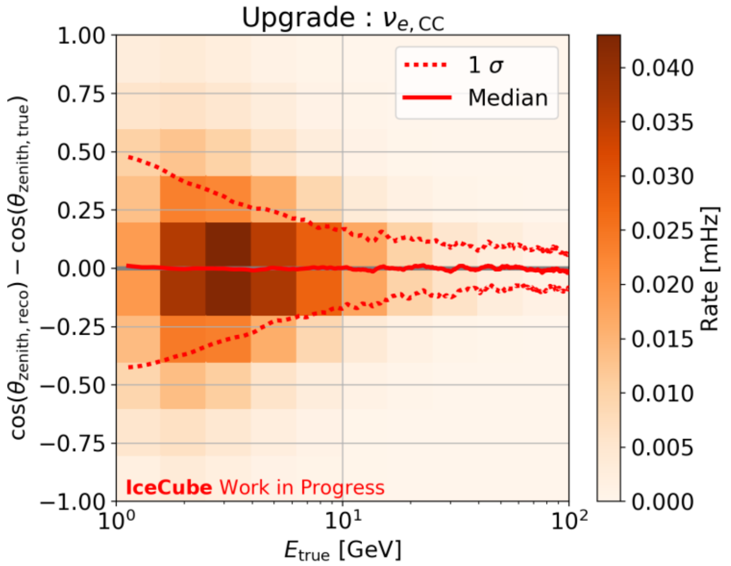


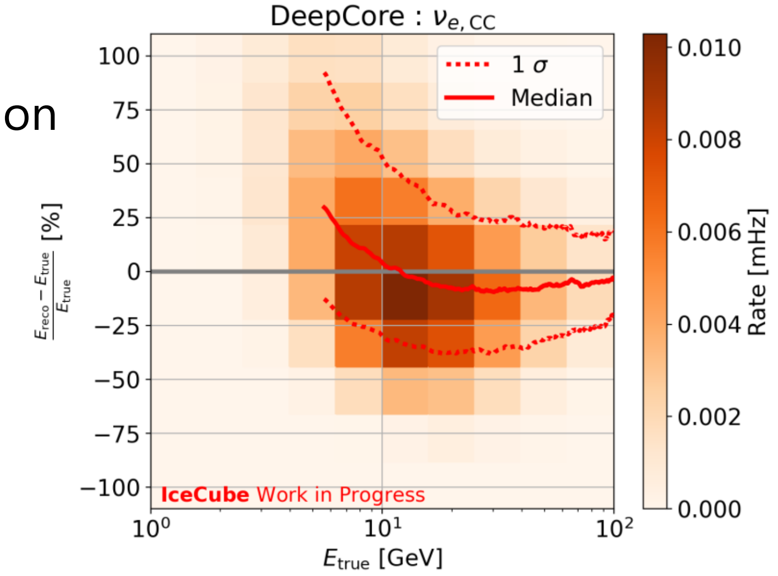
Improved Reconstruction Capabilities

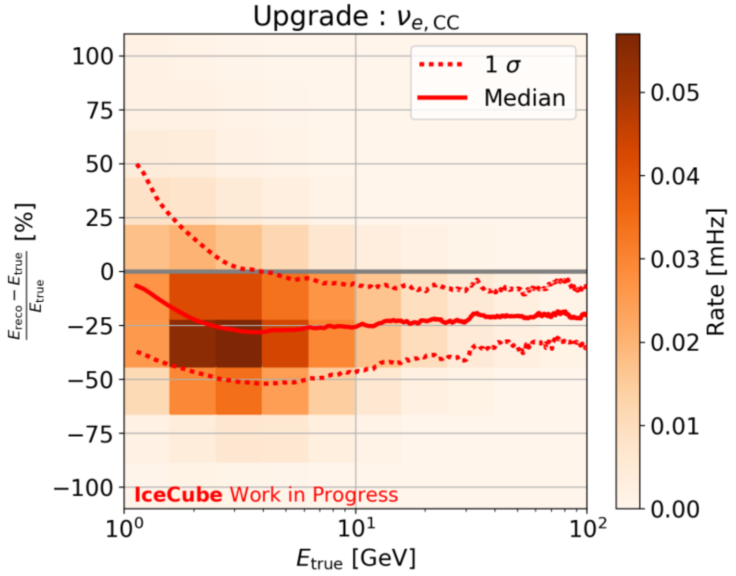




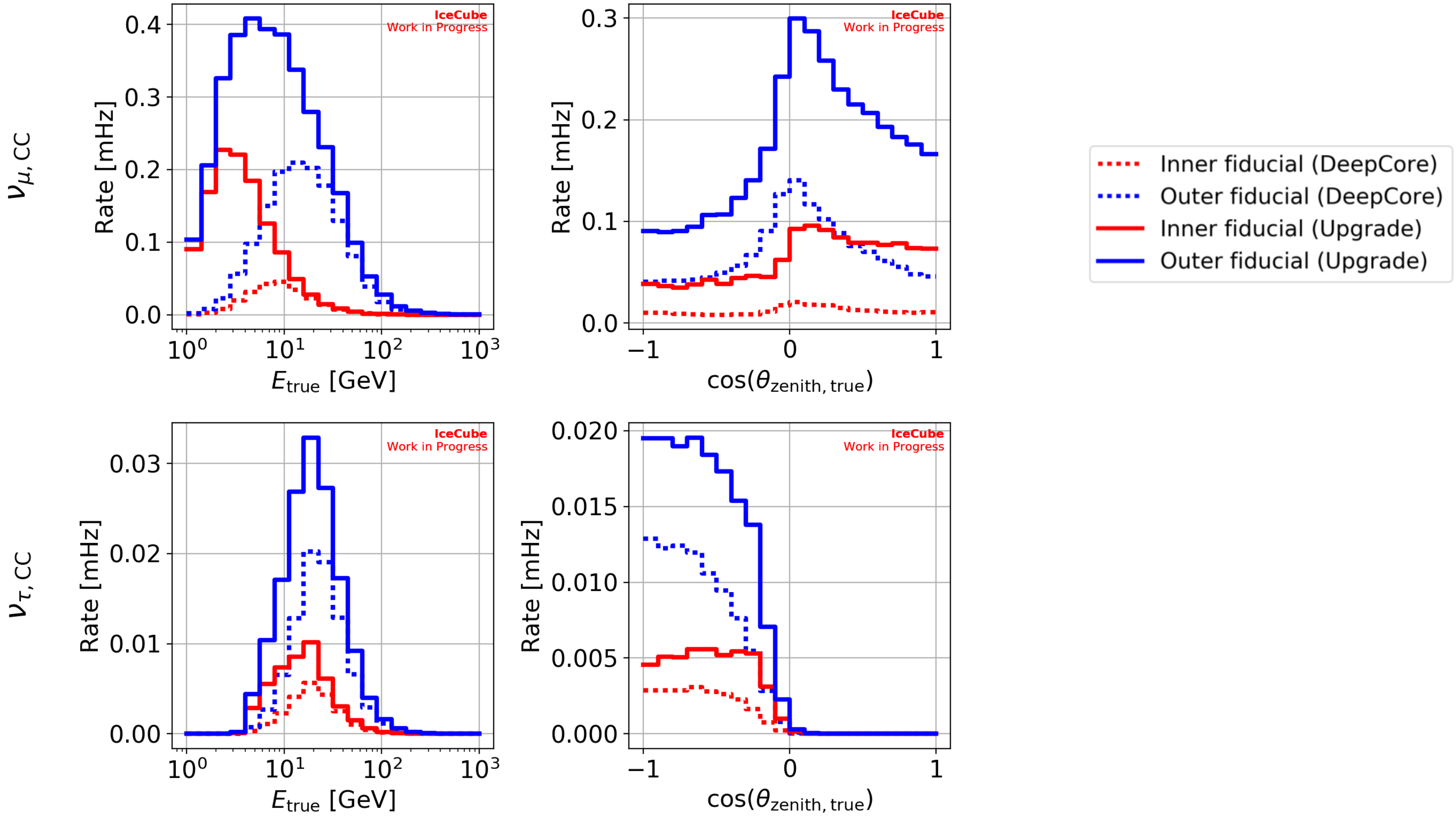
zenith angle reconstruction

energy reconstruction





More Events

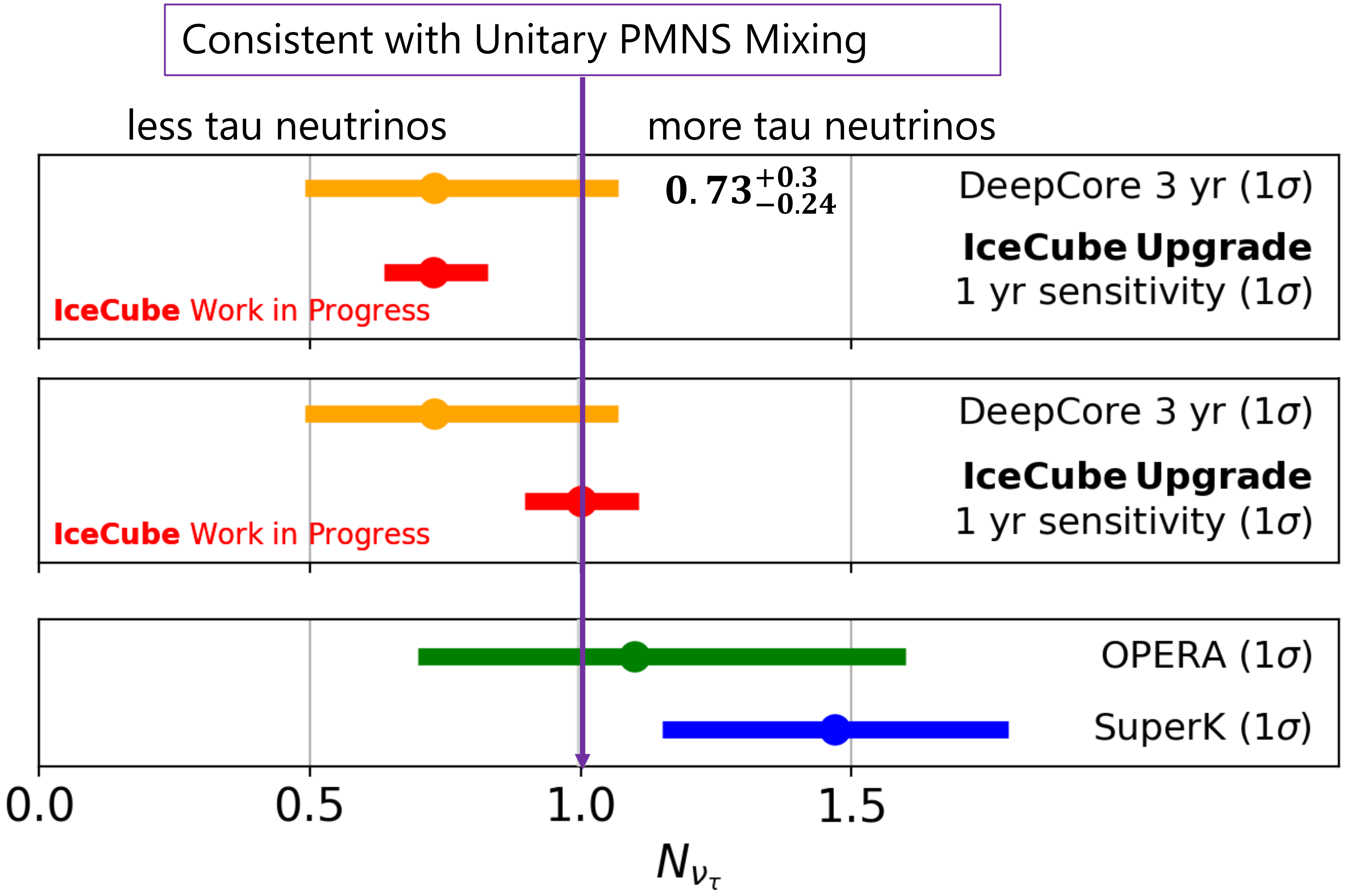


$\nu_{\mu,\mathrm{CC}}$
$\nu_{\tau,\mathrm{CC}}$
Rate [mHz]
E_{true} [GeV]
$\cos(\theta_{\mathrm{zenith,\,true}})$
IceCube
Work in Progress
Inner fiducial (DeepCore)
Outer fiducial (DeepCore)
Inner fiducial (Upgrade)
Outer fiducial (Upgrade)

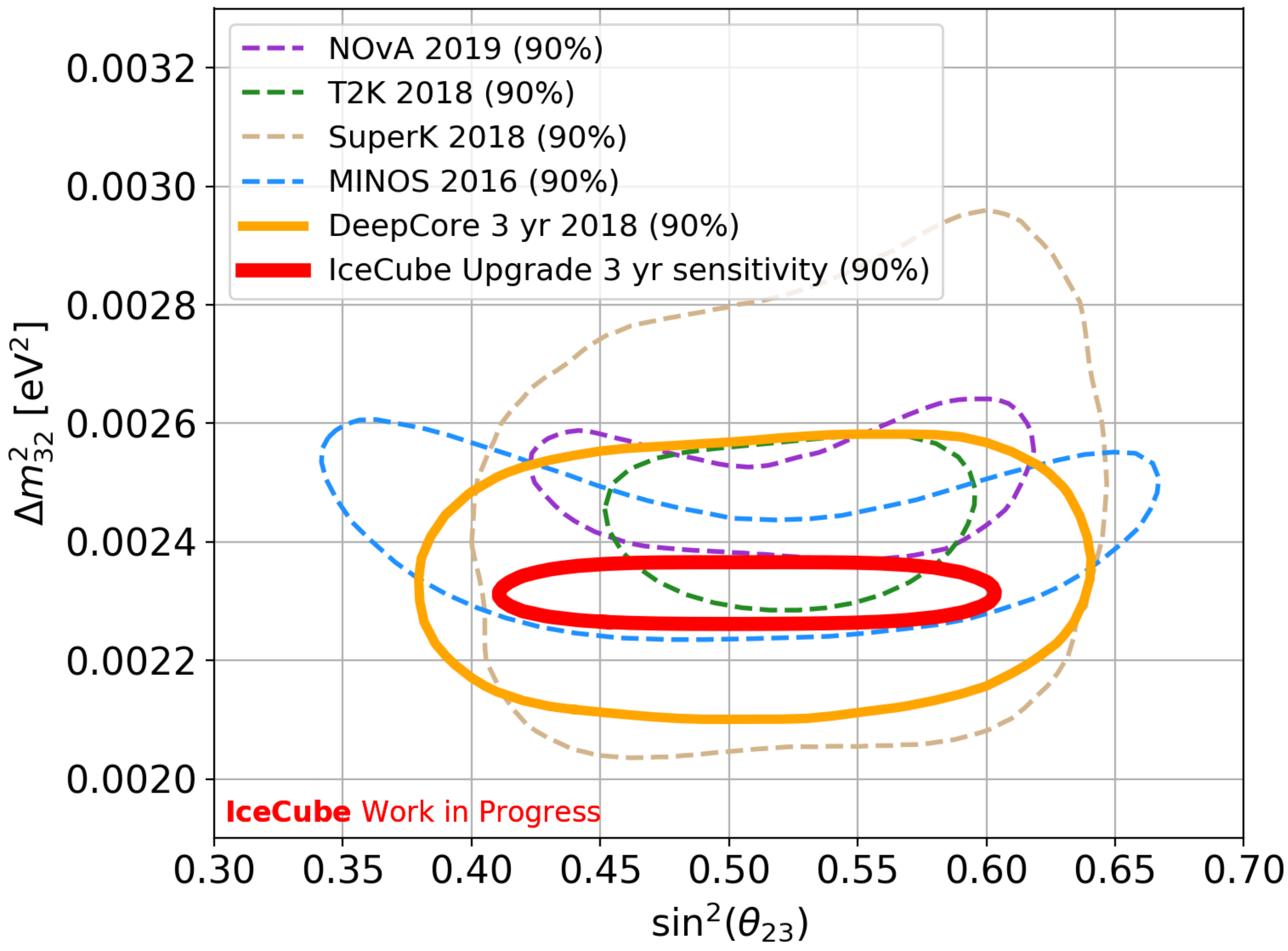
Tau-neutrino Appearance Sensitivity

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

- Conservative assumption of inner fiducial volume event only analysis

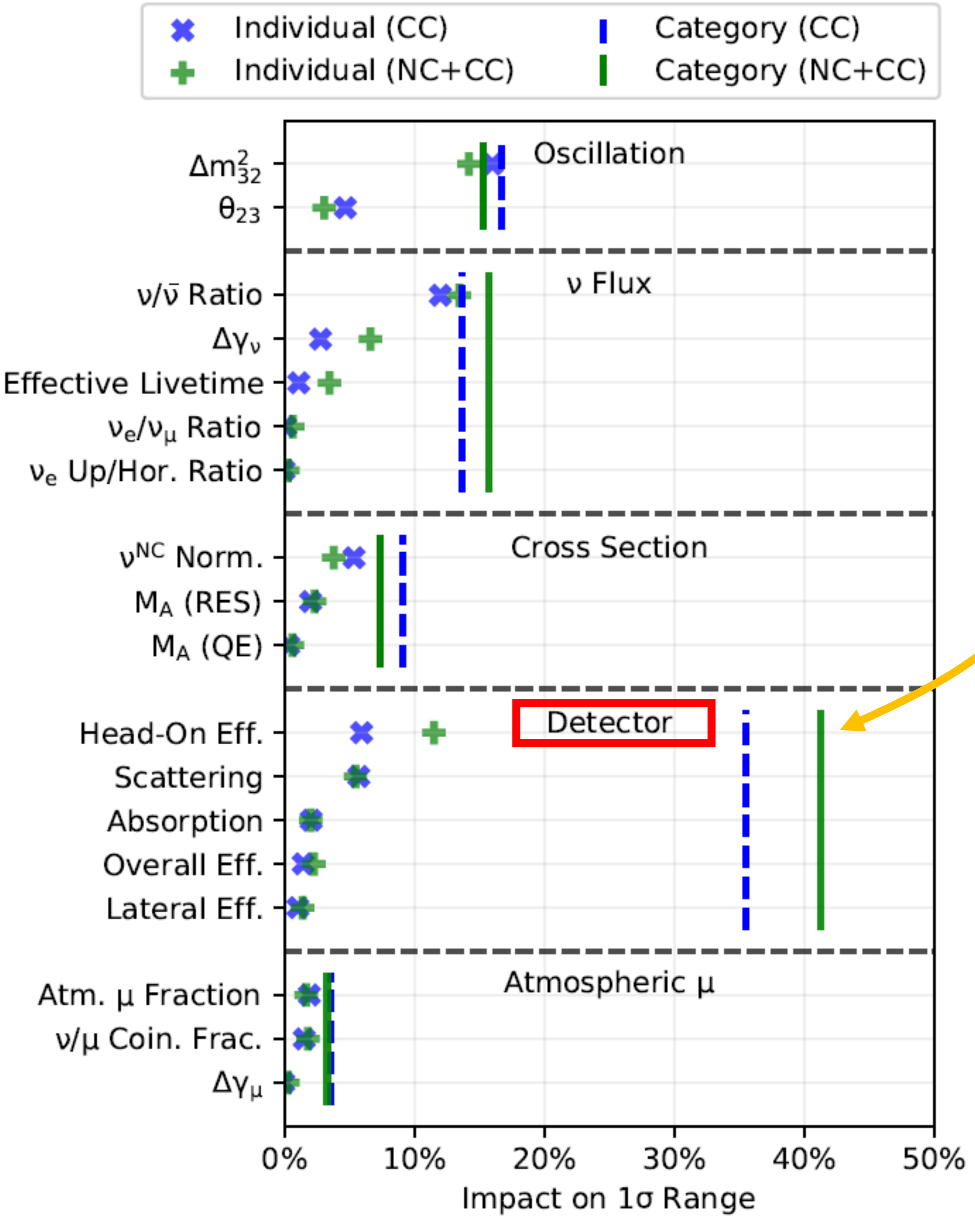


Muon-neutrino Disappearance Sensitivity



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

Systematics Uncertainty



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

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

Major systematics for oscillation analysis

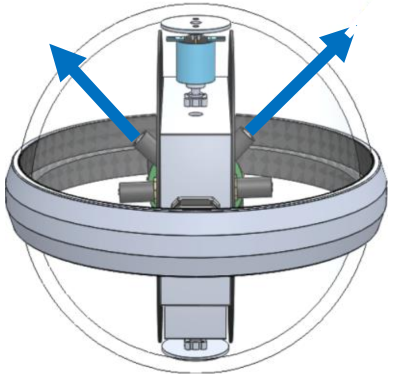
Calibration of **bulk ice**

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

Major systematics for high energy cascade/tau analysis

Upgrade Calibration

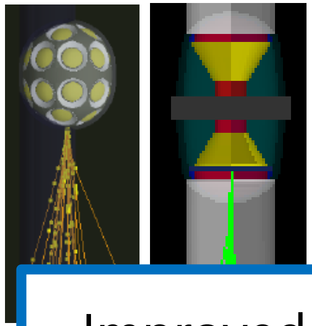
Pencil beam
(beaming light source)

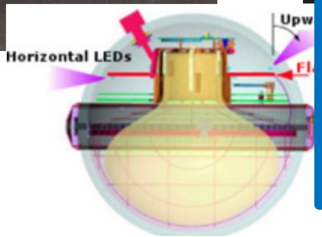


POCAM Poster3-114
(isotropic light source)

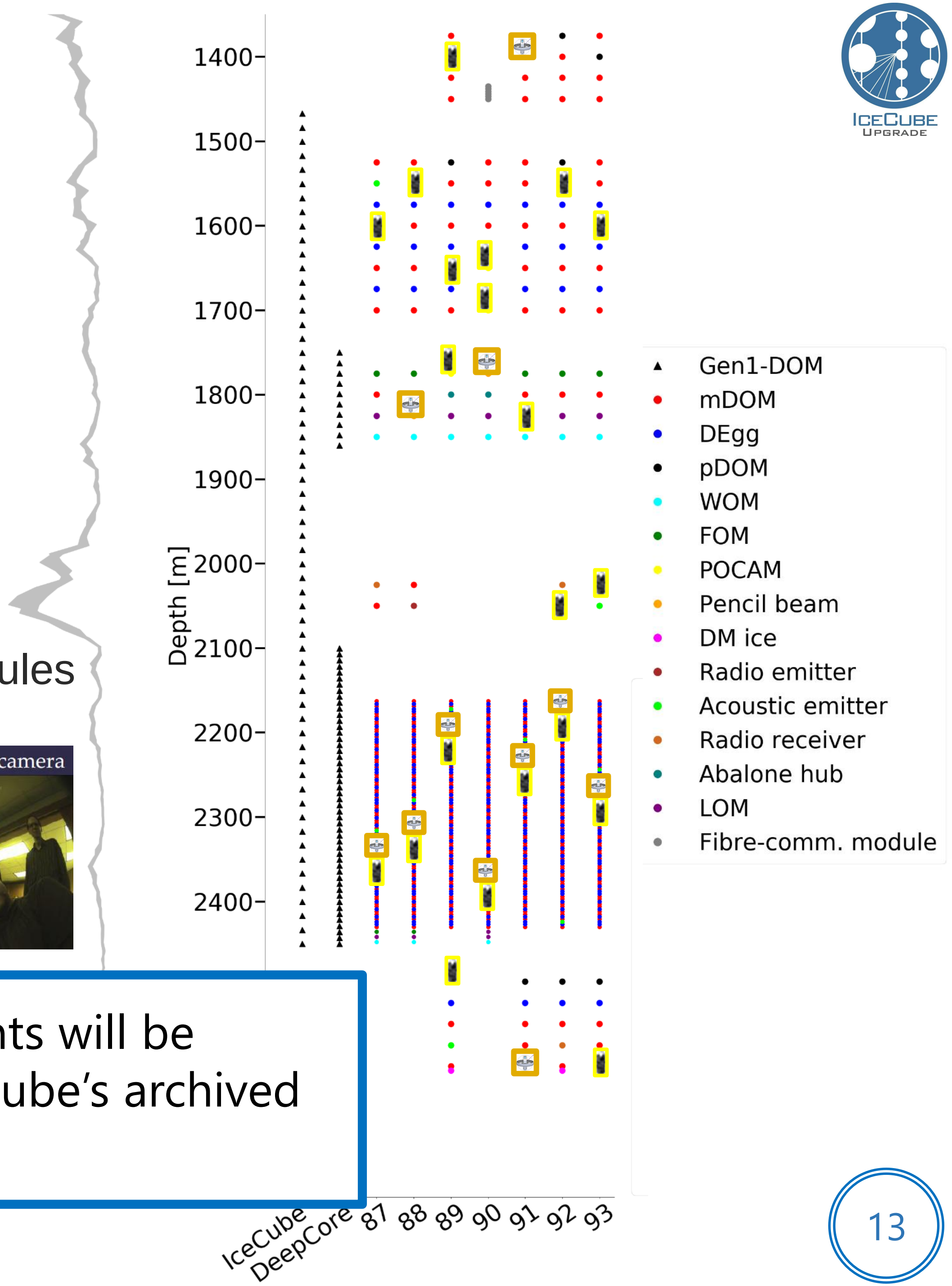
IceCube DOMs with new electronics (pDOM)
Poster3-123

LEDs in modules
Poster3-117





Cameras in modules
Poster3-118



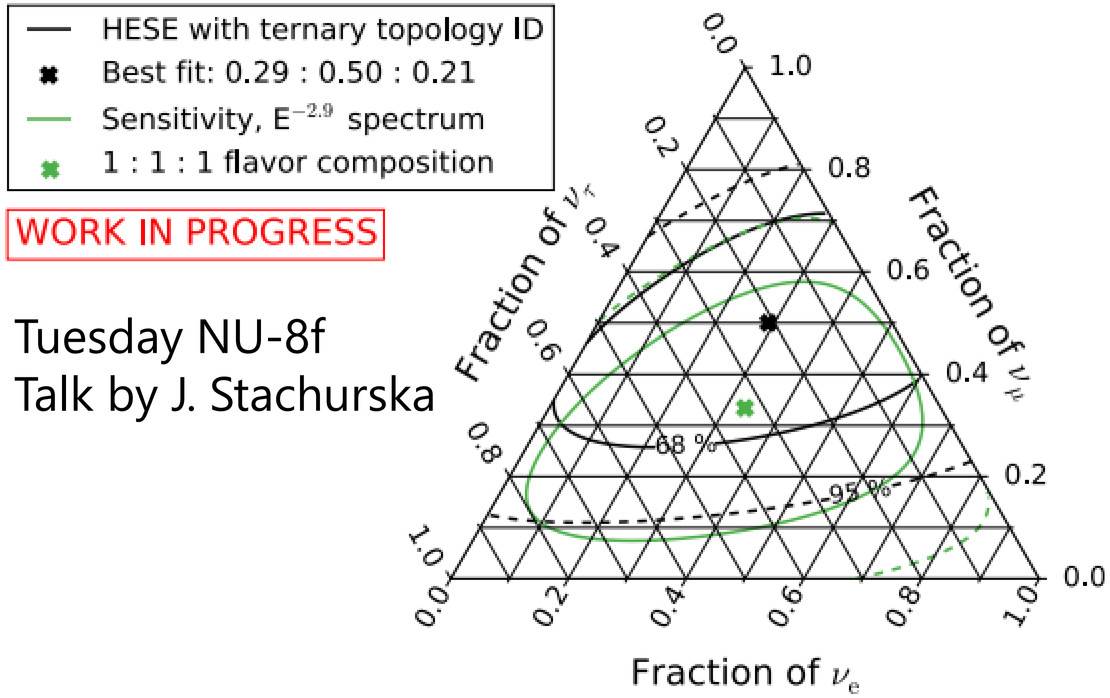
Improved calibration constants will be applied over 10 years of IceCube's archived sample

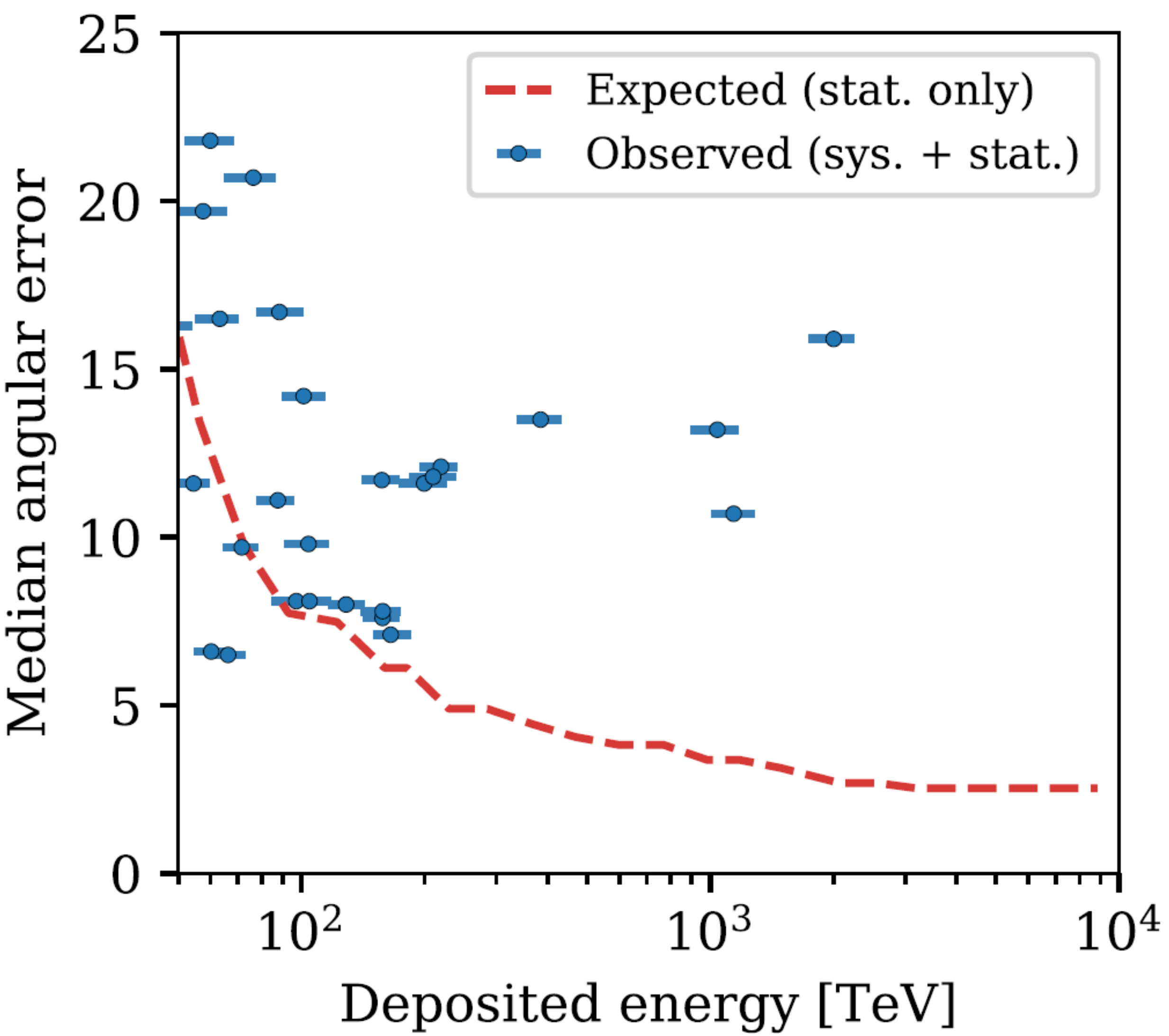
Calibration of IceCube Main Array

- 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



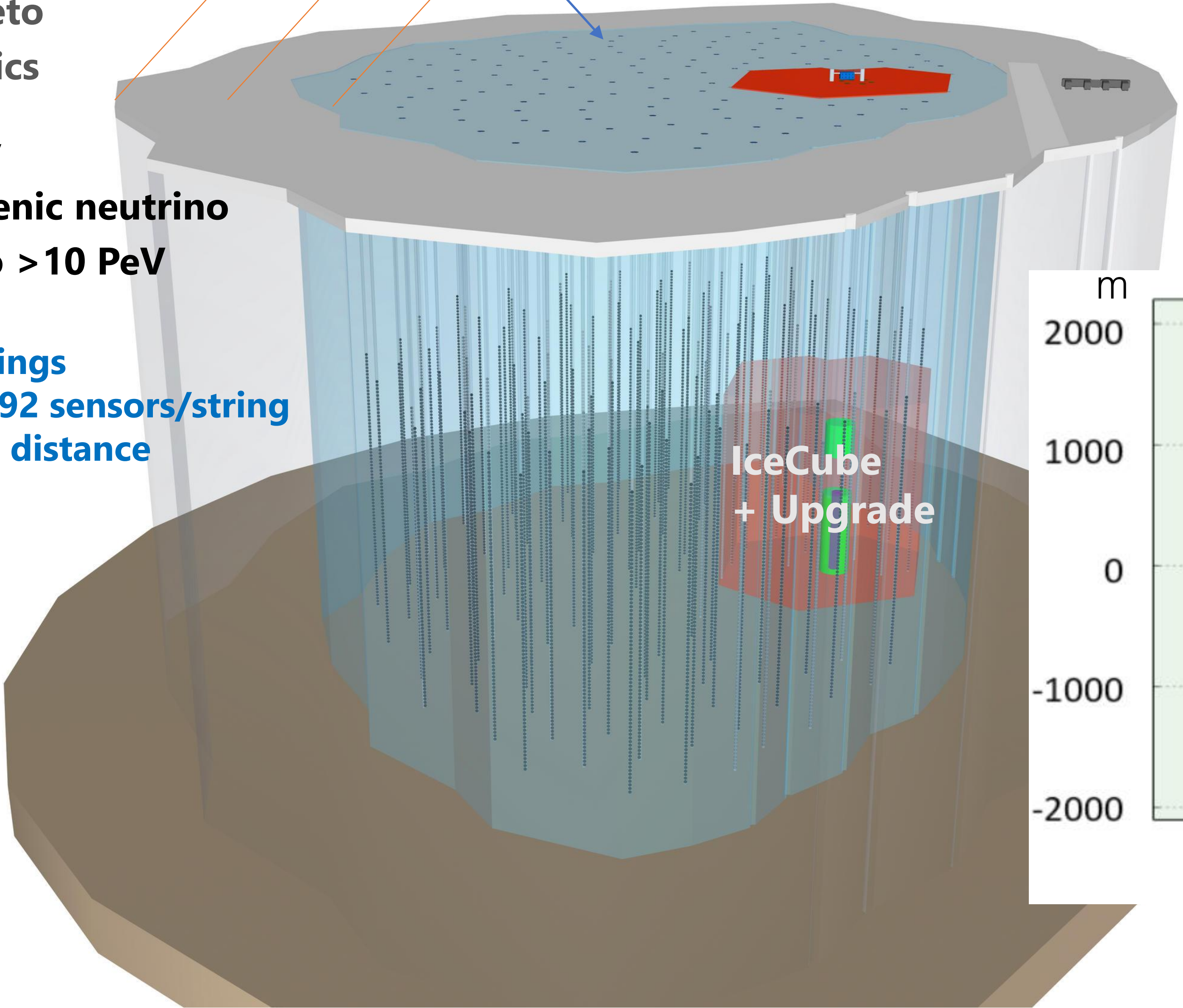


IceCube-Gen2 Facility

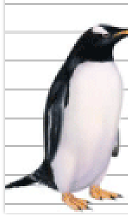
Surface array
- muon veto
- CR physics

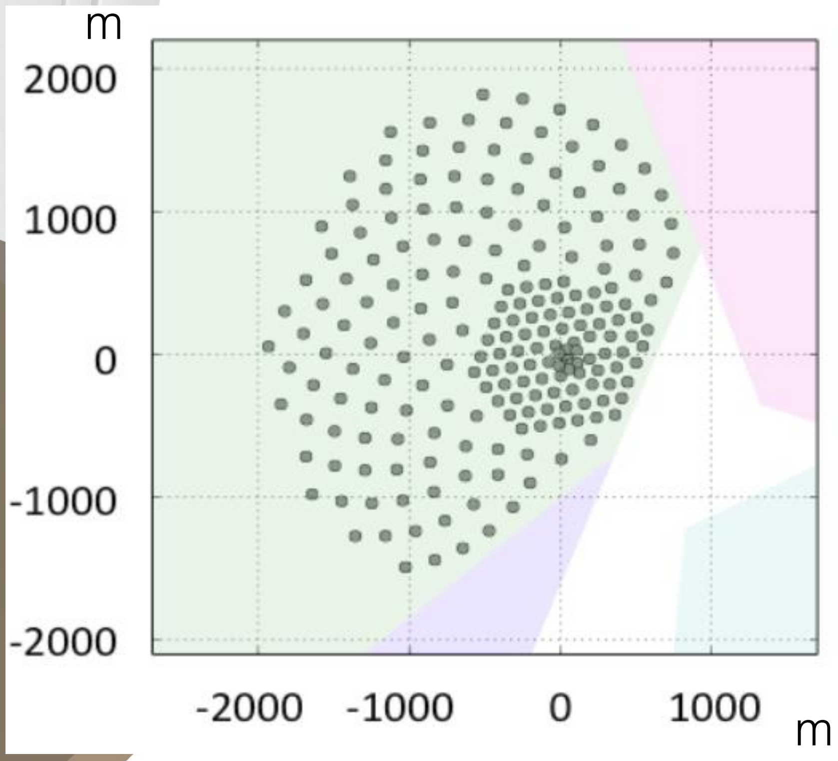
Radio array
- cosmogenic neutrino
- neutrino >10 PeV

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

12cm

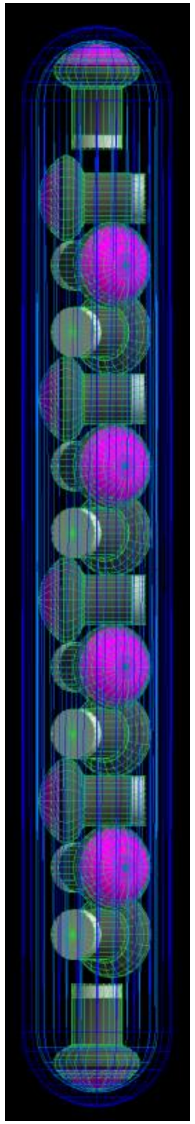
New R&D sensors are also to be studied in the Upgrade array

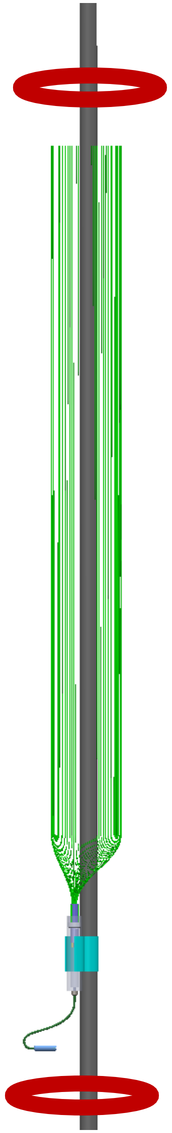
Why we want sensors fit into narrow holes?

- Significant cost/time saving in Gen2 drilling!
  - If hole diameter becomes 1/3

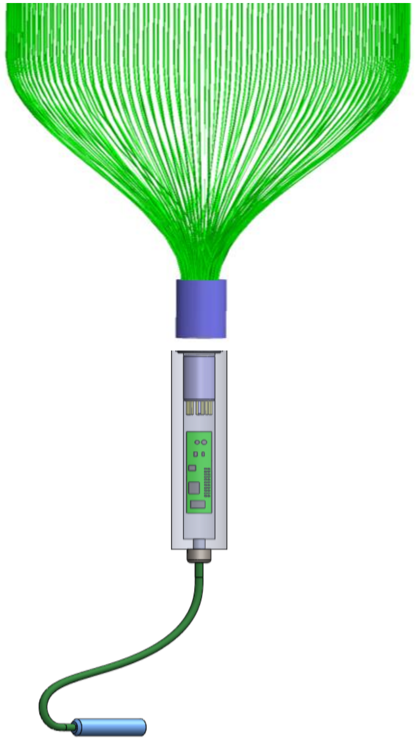
  ➡ drilling time/cost becomes 1/10

LOM





FOM



WOM

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