

# THE ICECUBE UPGRADE

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# Infrastructure for Neutrino Astroparticle Physics

UU and SU prioritized infrastructure proposal to RFI

## The IceCube Upgrade

- New Ice Drill
- 7 New Strings, new module designs
- Upgrade detector calibration
  - > astrophysical neutrinos
- Lower energy threshold
  - > neutrino oscillation measurements

*This talk*

## The Radio Array

- ARIANNA / ARA -type surface array
- Detect ultrahigh energy neutrinos
  - > astrophysical flux at higher energy than IceCube
  - > cosmogenic neutrinos from GZK

*Allan Hallgren's talk*

# The IceCube Upgrade: Science Goals

Neutrino astronomy at high energy with recalibration and reanalysis of existing data

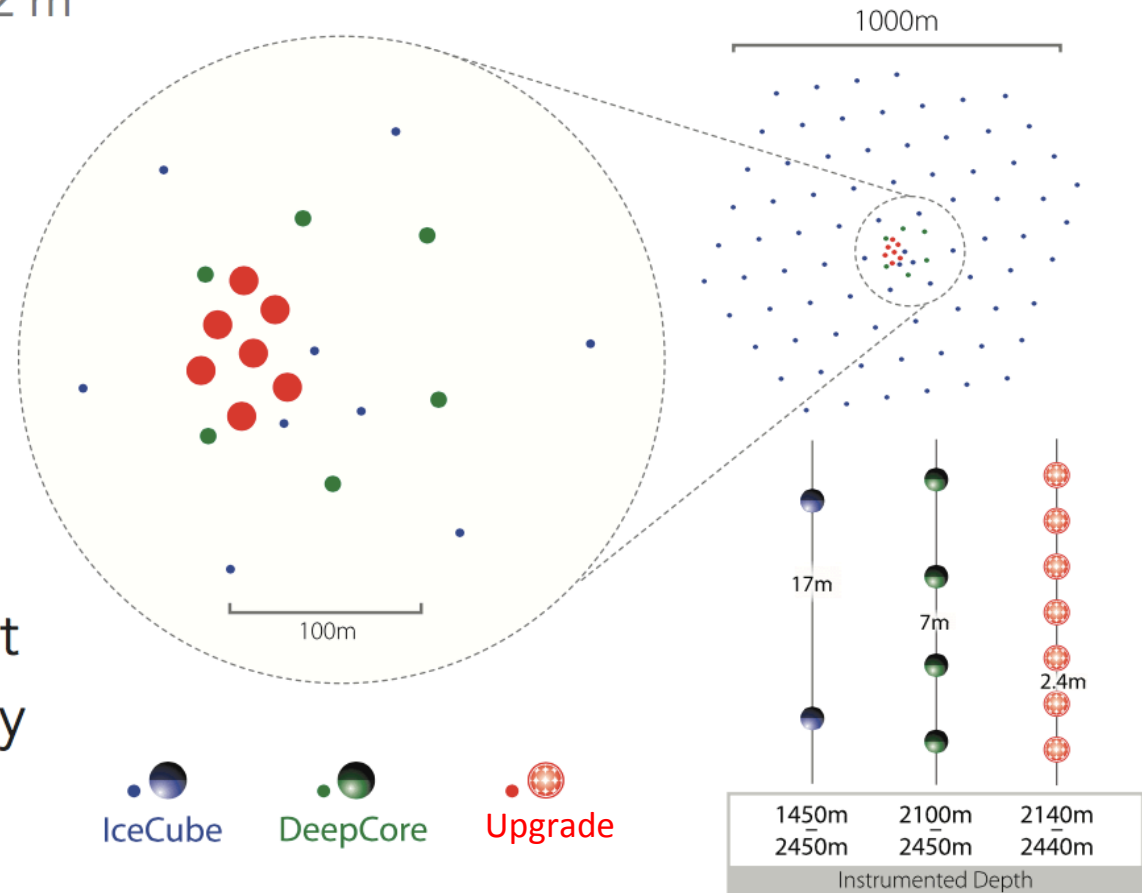
- Improved angular resolution and veto performance
- Tau neutrino identification
- Multi-messenger astronomy

Neutrino physics at low energy with new instrumentation

- Tau neutrino appearance and PMNS unitarity tests
- Precision measurements of  $\sin^2 \theta_{23}$  (incl. octant) and  $\Delta m^2_{32}$  at 10-20 GeV

# The IceCube Upgrade

- Seven new strings of multi-PMT mDOMs in the DeepCore region
  - Inter-string spacing of  $\sim 22$  m
- Suite of new calibration devices to boost IceCube calibration initiatives
- Improve scientific capabilities of IceCube at both high and low energy



# DOM (Digital Optical Module) – Upgrade Edition

IceCube DOM



5 160 currently operating in IC

(20% built in Sweden)

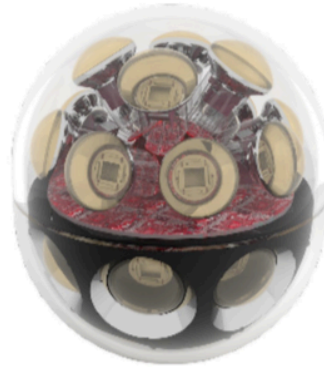
D-Egg



$4\pi$  sensitivity

Compact diam. reduces drilling costs

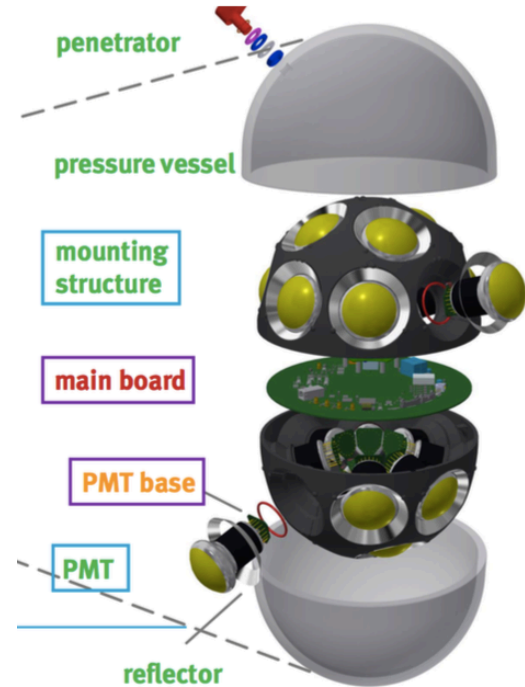
mDOM



$4\pi$  sensitivity

Directionality

Low noise via coincidence req.



# DOM (Digital Optical Module) – Upgrade Edition

IceCube DOM



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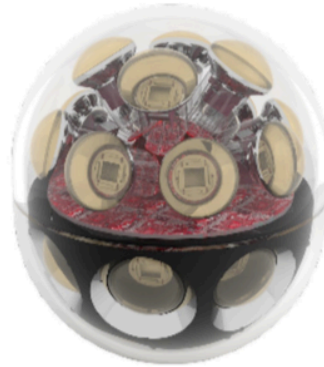
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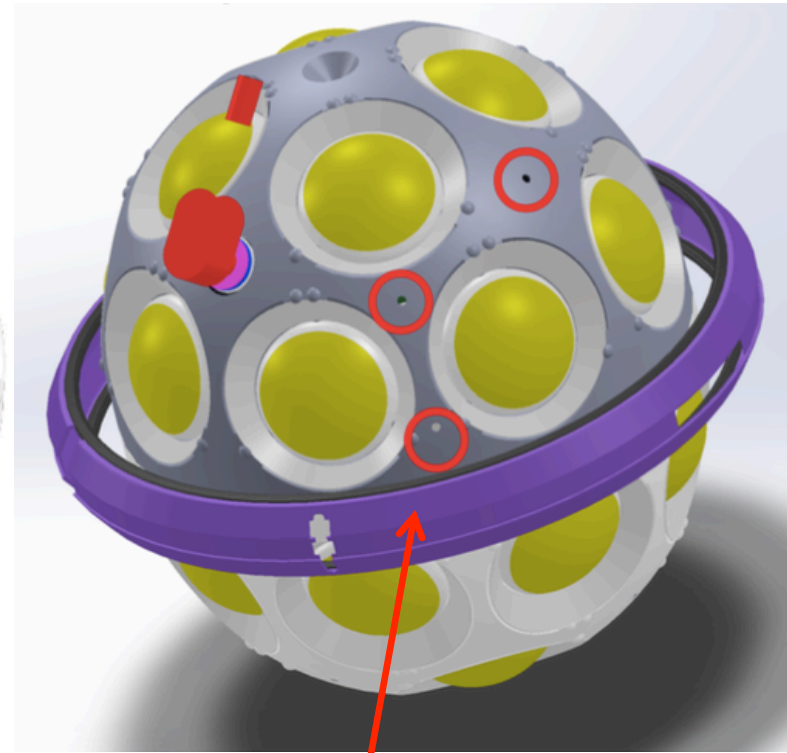
mDOM



$4\pi$  sensitivity

Directionality

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LED flashers in all directions for precision calibration

# New Calibration with the IceCube Upgrade

Eff. scattering length for photons in ice  $\sim 20$  m

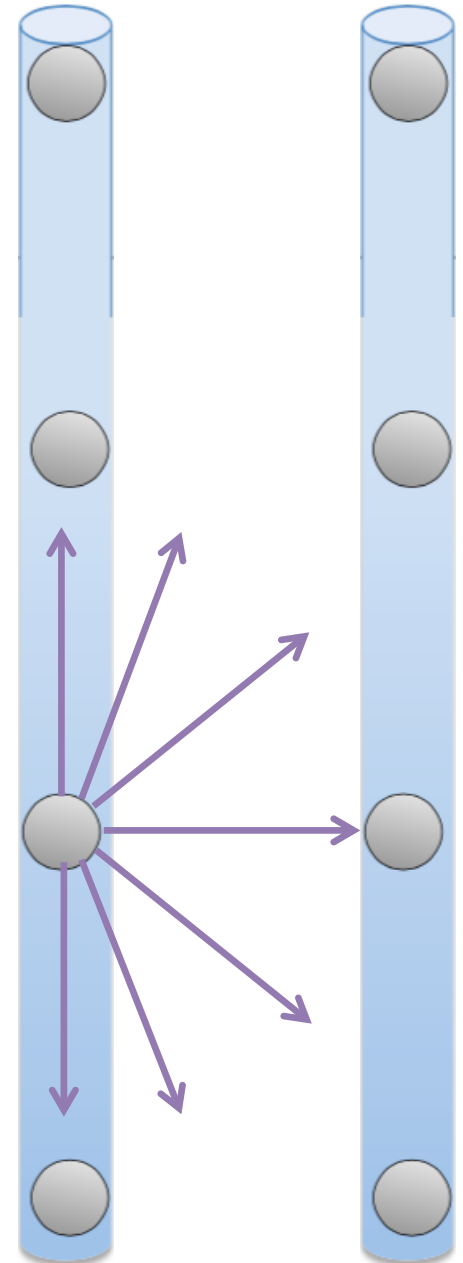
Detector inter-string spacing:

- IceCube: 125 m
  - DeepCore: 40 m
  - Upgrade: 20 m
- Probe  $L < \lambda_{\text{scatter}}$  for first time

Deploy improved calibration devices with wide range of accessible angles

Vertical measurements – characterize “hole” ice

Improved modeling of light propagation in the ice



# Improved Angular Resolution: Cascade Events

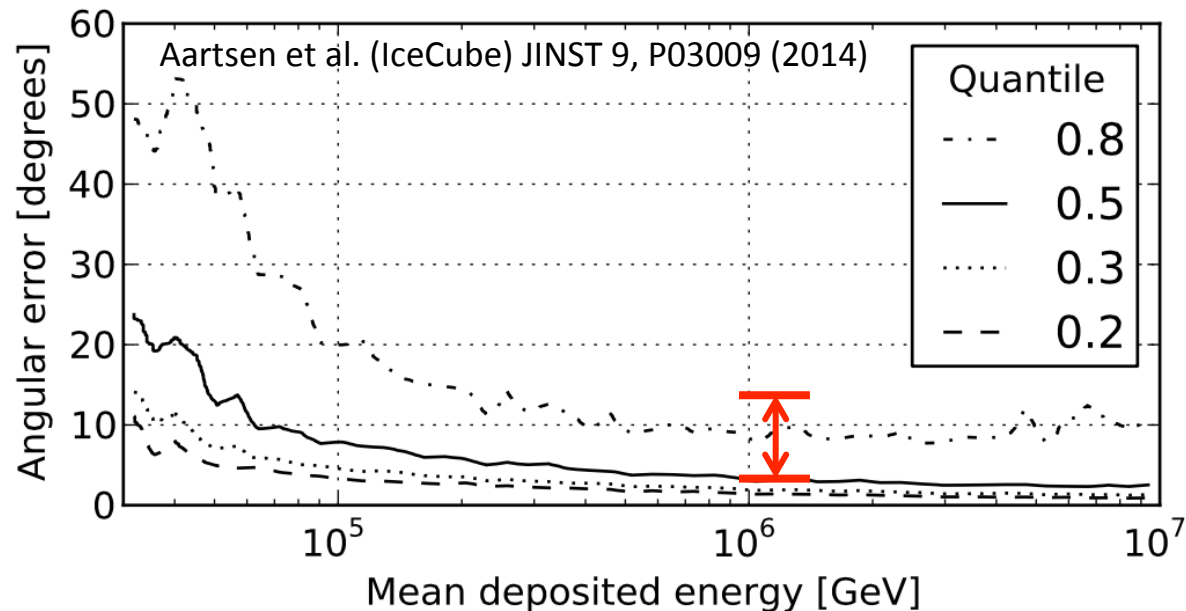
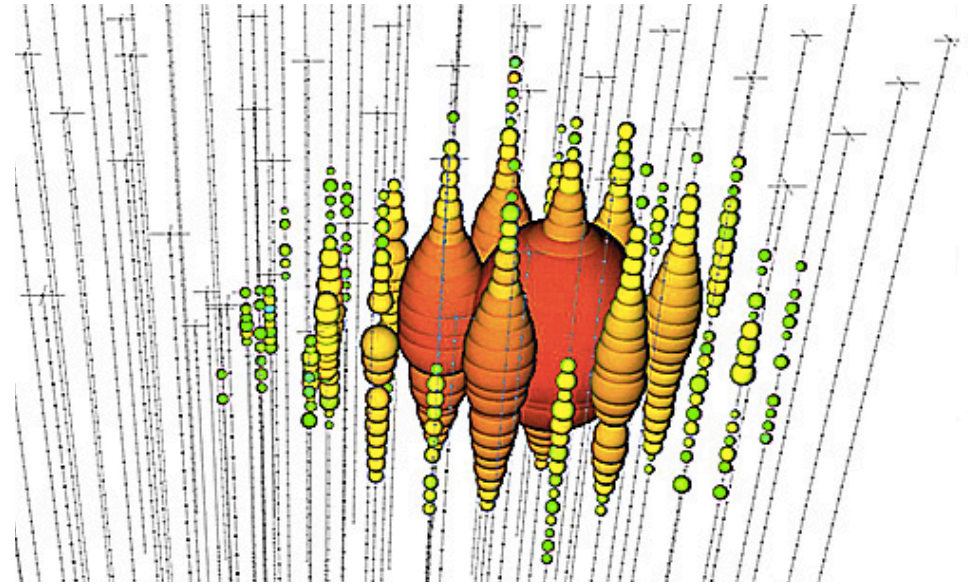
“Bert” – 1<sup>st</sup> PeV neutrino

100 000 photoelectrons detected

directional unc.: 13°

Statistical error for PeV events is  $\sim 2^\circ$

Systematic uncertainties on modeling of light propagation in ice leads to  $\sim 15^\circ$  errors





# Improved Angular Resolution: Track Events

Statistical angular uncertainty for HE tracks:  $\sim 0.1^\circ$

Systematic uncertainty for HE tracks from ice model uncertainties:  $\sim 0.6^\circ$

Confident identification of counterparts is limited by angular resolution uncertainty (source confusion: multiple possible sources within error box)

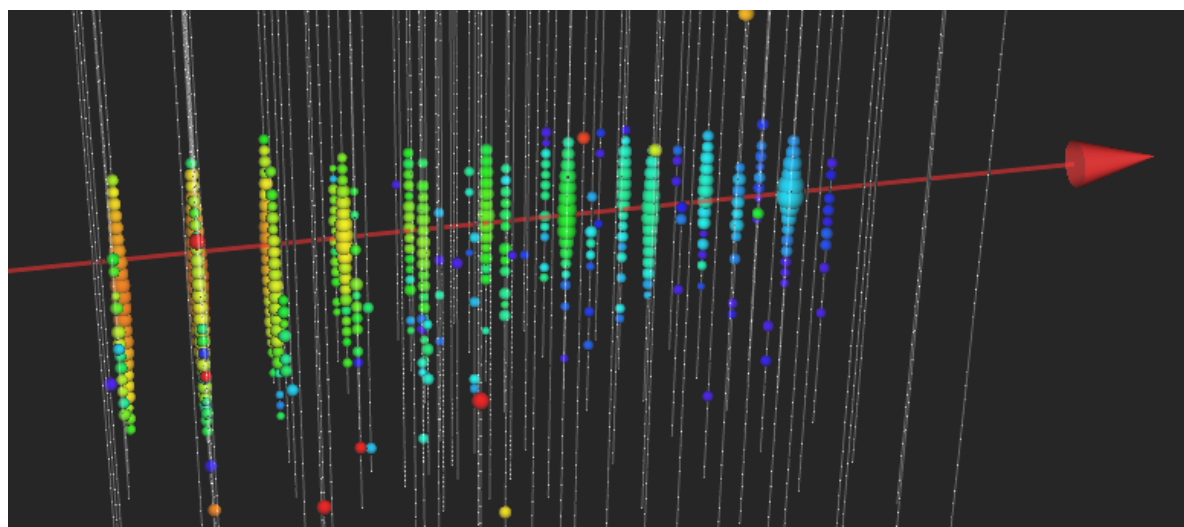
2017 Sept. 22:

IC-170922 Public alert event (GCN)

$> 100$  TeV neutrino

$\sim 2^\circ \times 1^\circ$  err. region 90% CL

Fermi / MAGIC detections of flaring Blazar galaxy at same time and well within dir. uncertainty



# Tau Appearance and PMNS Unitarity

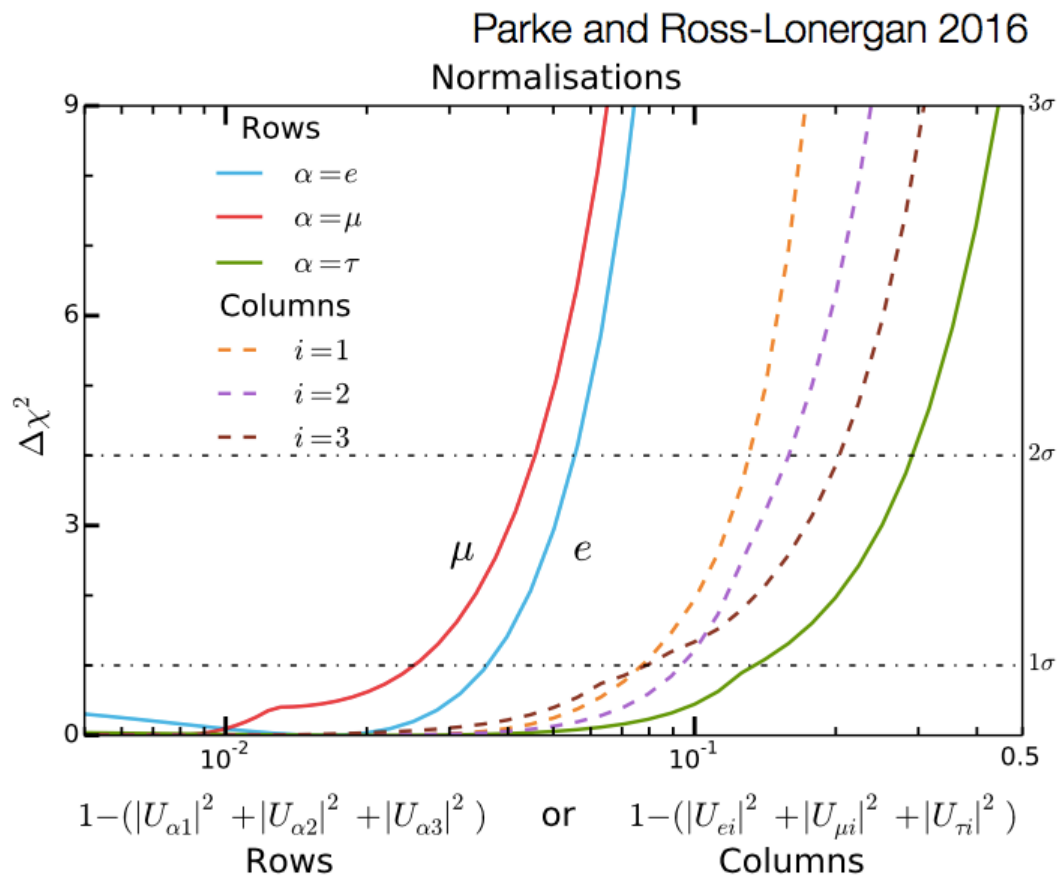
Direct tests of unitarity of the PMNS mixing matrix are limited by imprecision of tau neutrino appearance data

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

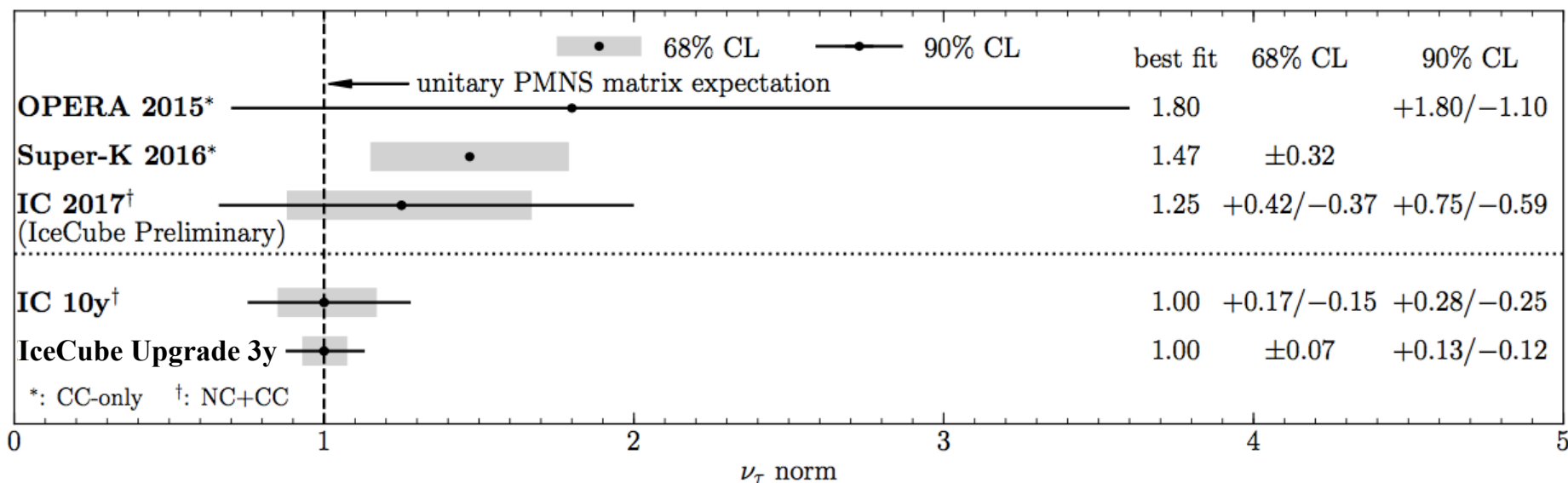
30% deviations in tau row allowed at  $2\sigma$  CL by world data

Tau lepton mass suppresses CC cross section – appearance measurements difficult in long-baseline experiments

Advantage with atmospheric neutrino experiments



# Tau Appearance and PMNS Unitarity



3yr DeepCore analysis (IC2017) already competitive with 15yr Super-K result

Analysis improvements and additional data will yield world-leading result

Upgrade required to achieve precision better than 10%

# The IceCube Upgrade

## Objectives:

- Atmospheric tau neutrino appearance – test unitarity of PMNS matrix
- New ice calibration will enable re-analysis of 10 years collected data
- Multi-messenger astronomy goal: identify sources of astro.  $\nu$  flux

A “Mid-Scale” NSF proposal. Must be stand-alone science project, targeting the upgrade of an existing detector.

Naturally opens a path toward a much larger extension of IceCube array in the future, IceCube-Gen2.