photo credit: Yuya Makino

IceCube Upgrade: Science Goals, Installation, Early Data

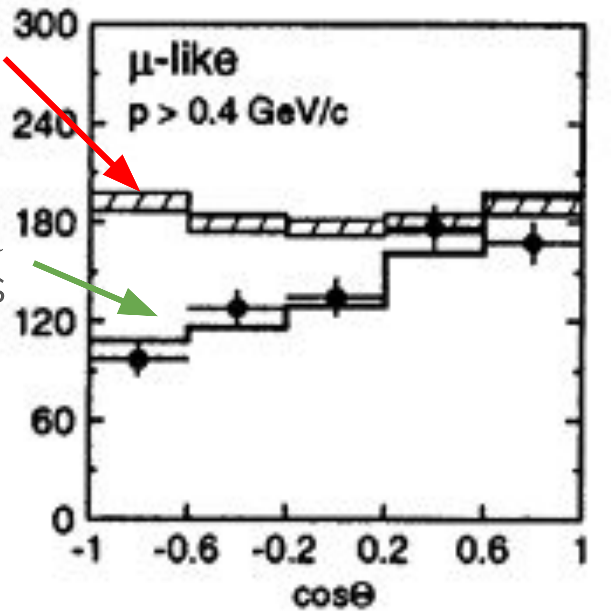
Delaney Butterfield
IceCube Summer School
June 2, 2026

A Brief History of Neutrinos

- 1931 - Pauli proposes neutral, invisible particle “neutron” responsible for missing energy in beta decays
- 1934 - Fermi proposes beta decay theory, introducing the “neutrino”
- 1956 - Reines & Cowan discover the neutrino at Savannah River Site with underground reactor experiment
- 1998 - Super-Kamiokande experiment finds neutrino flavors seen on Earth do not match expected flux predictions
    - Consistent with neutrino flavor oscillations

No $\nu_\mu \rightarrow \nu_\tau$ oscillations

With $\nu_\mu \rightarrow \nu_\tau$ oscillations



Y. Fukuda et al. 1998 Phys. Rev. Lett. 81, 1562

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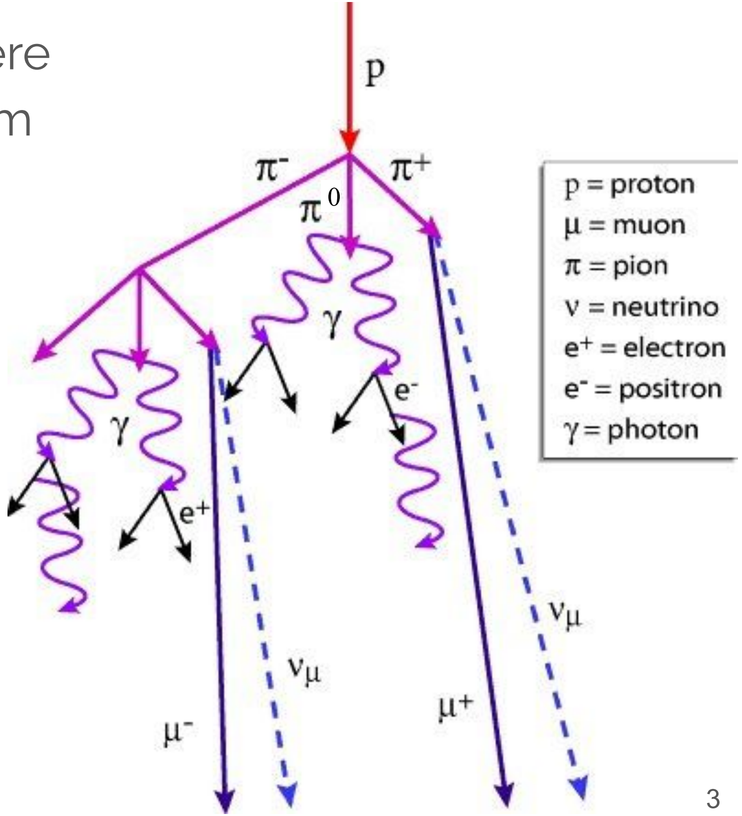
Atmospheric Neutrino Production

- Cosmic rays interact in the Earth's atmosphere
- Interactions produce particle showers ~15 km above sea level
  - Particles include charged pions and kaons, which decay into muons and neutrinos
- Neutrino production dominated by four primary interactions:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$$

$$\pi^- \rightarrow \mu^- + \overline{\nu}_\mu \qquad \mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu$$



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Neutrino Oscillations

- Neutrinos are created with definite flavor
  - Flavor basis: ν_e, ν_μ, ν_τ
- Neutrinos propagate with definite mass
  - mass basis: ν_1, ν_2, ν_3
- Mismatch between these causes flavor oscillations
- Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix relates the mass eigenstates to the flavor eigenstates via a rotation matrix

PMNS rotation matrix

Flavor states

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

Mass states

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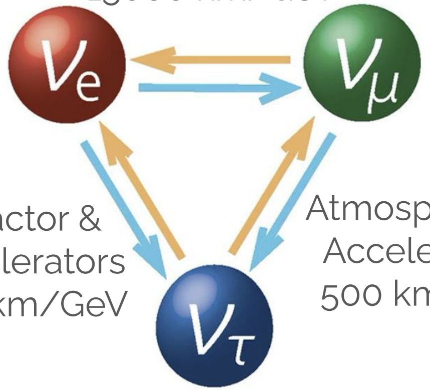
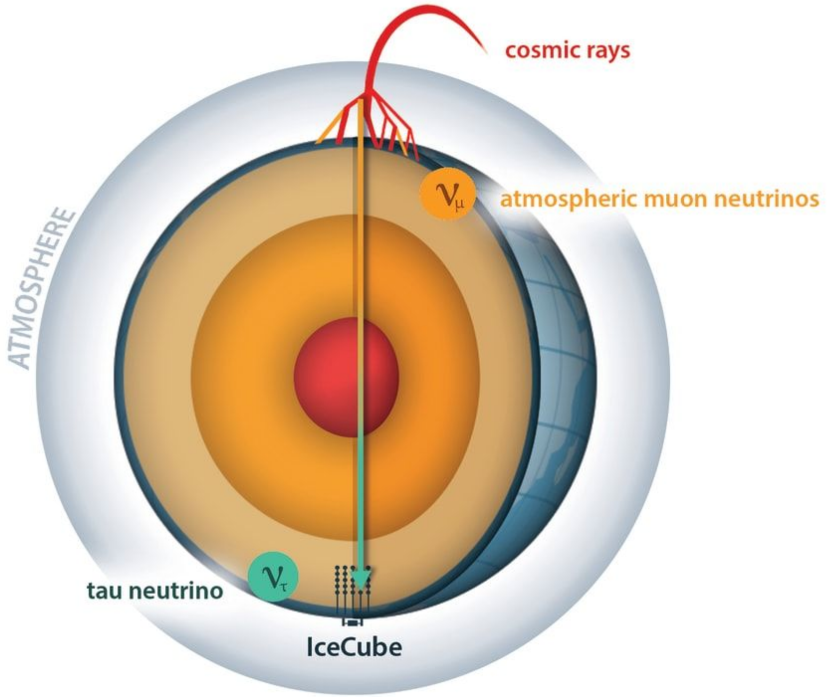
Neutrino Oscillations

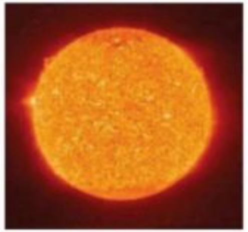
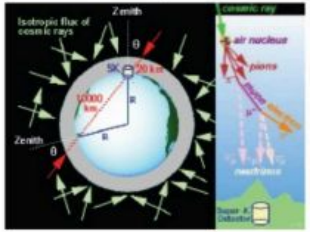
Solar & Reactors
15000 km/GeV



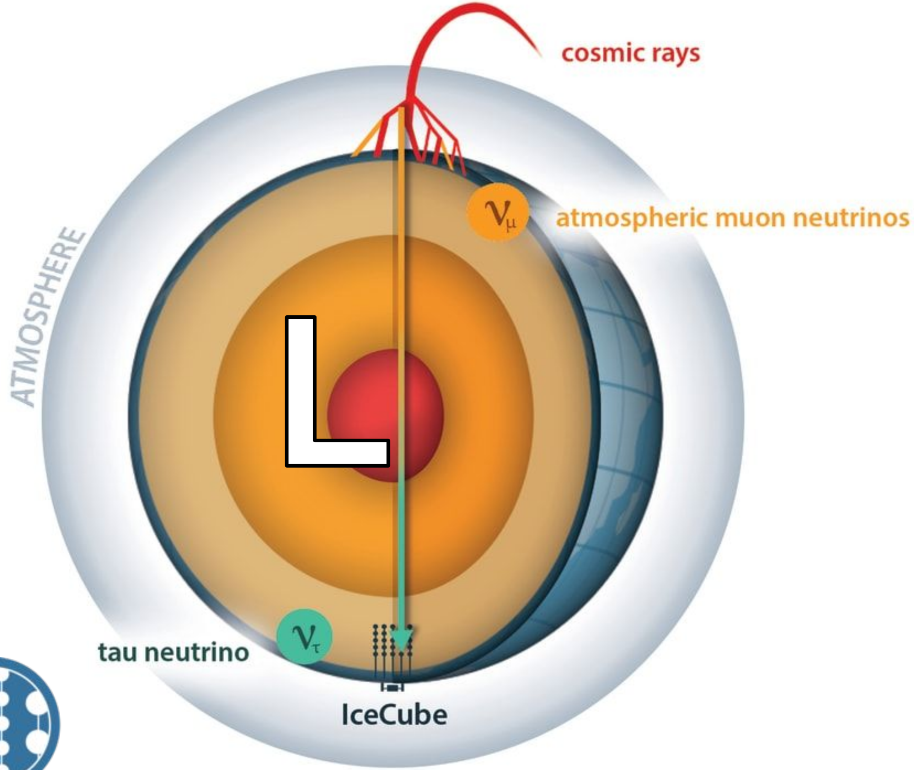
Reactor &
Accelerators
500 km/GeV

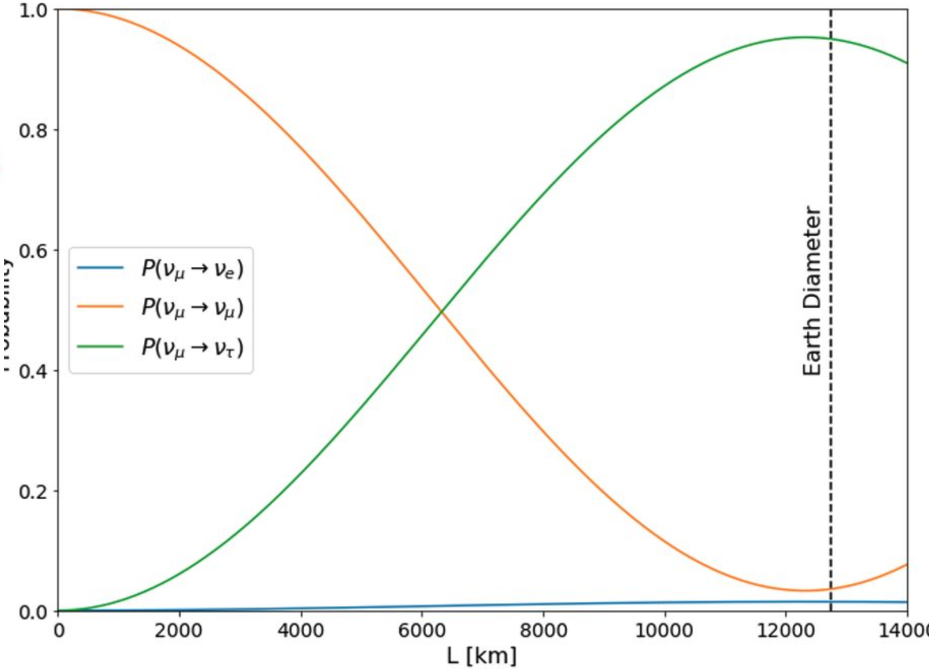
Atmospheric &
Accelerators
500 km/GeV



sun	reactors	atmosphere	accelerators
			
SuperK, SNO	Daya Bay, RENO, Double Chooz	IceCube, SuperK	MINOS, NOνA, DUNE, T2K

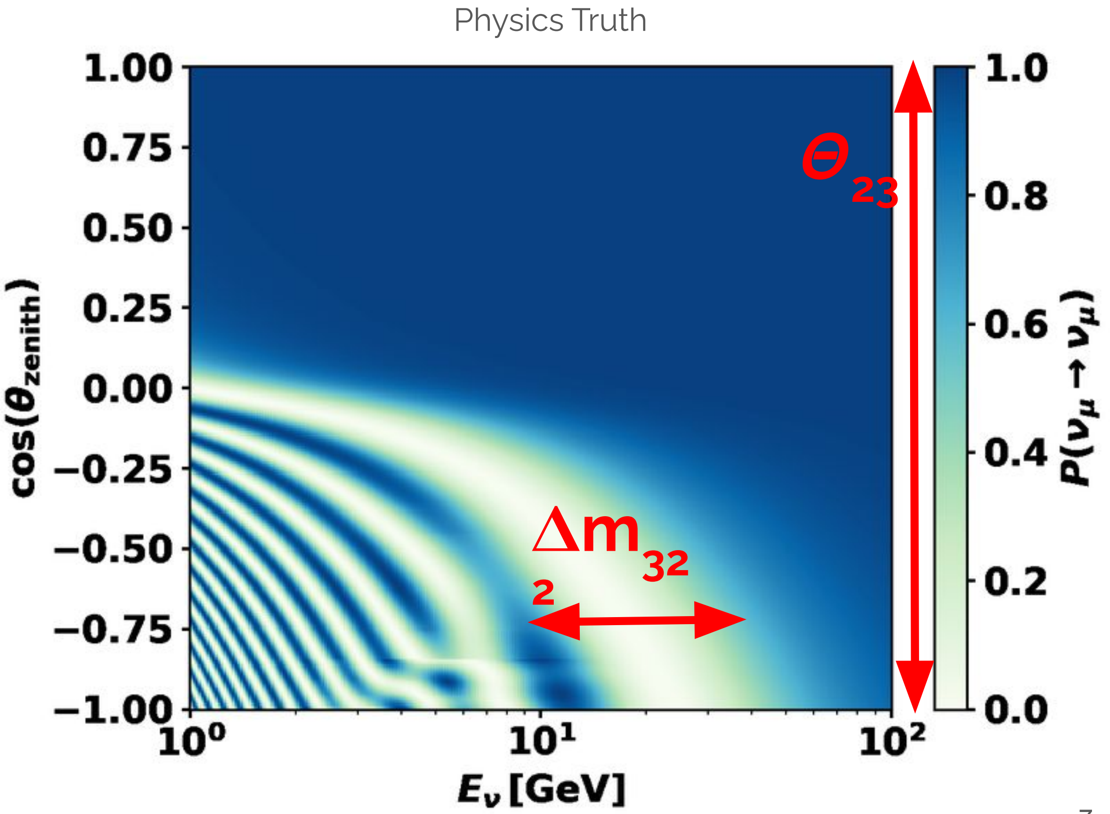
Neutrino Oscillations in IceCube

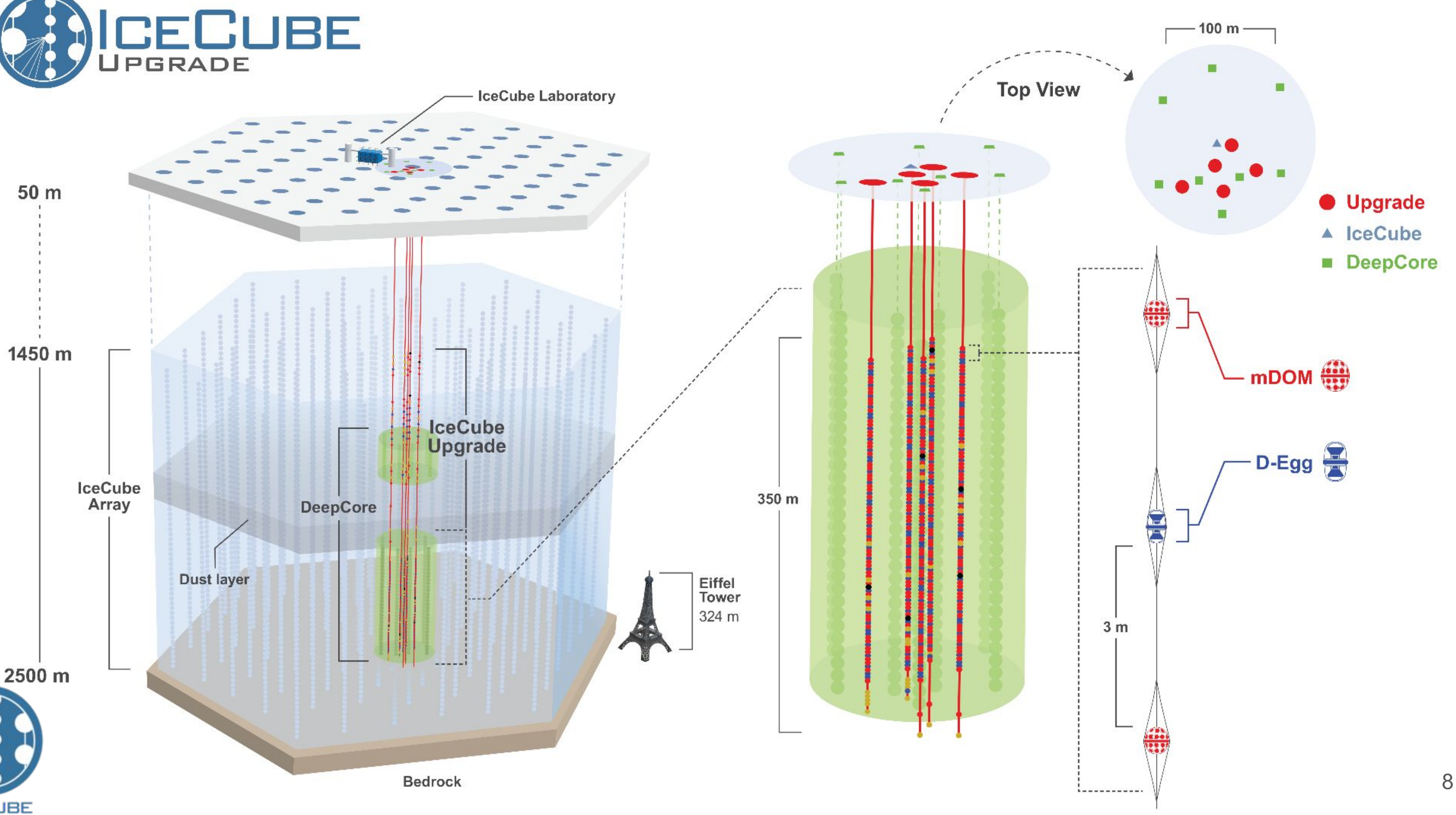




Neutrino Oscillations in IceCube

- Survival probability of muon neutrino follows banding pattern
- Width of banding pattern corresponds to Δm_{32}^2
- Amplitude of oscillations corresponds to θ_{23}
- Oscillation pattern is most prominent for neutrinos traveling through the earth below 10 GeV

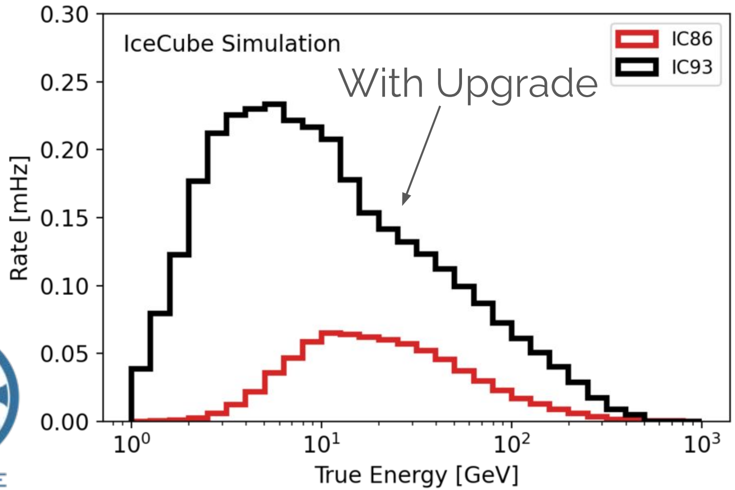


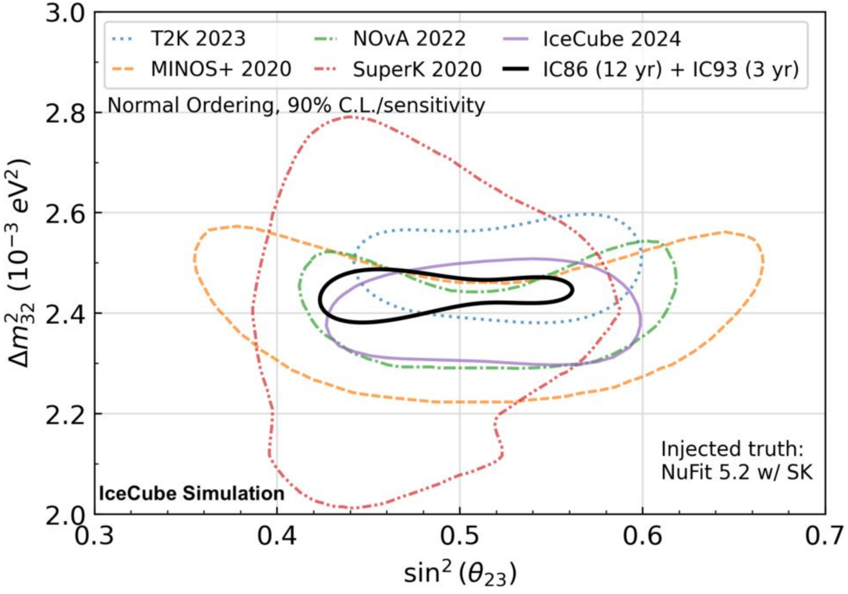

IceCube Laboratory
50 m
1450 m
2500 m
IceCube Array
Dust layer
DeepCore
IceCube Upgrade
Bedrock
Eiffel Tower
324 m
Top View
100 m
350 m
Upgrade
IceCube
DeepCore
mDOM
D-Egg
3 m

Science Goals of the Upgrade

- Aimed at neutrino oscillations physics, low energy neutrino astronomy, and ice modelling
- 2 MTons of instrumented volume
- Expect to see ~200,000 neutrino events in the first year of data taking

	Horizontal Spacing	Vertical Spacing	Targeted Energy Range
IceCube	125m	17m	> TeV
DeepCore	40-70m	7m	~10 GeV - 10 TeV
Upgrade	20-30m	3m	(O) GeV

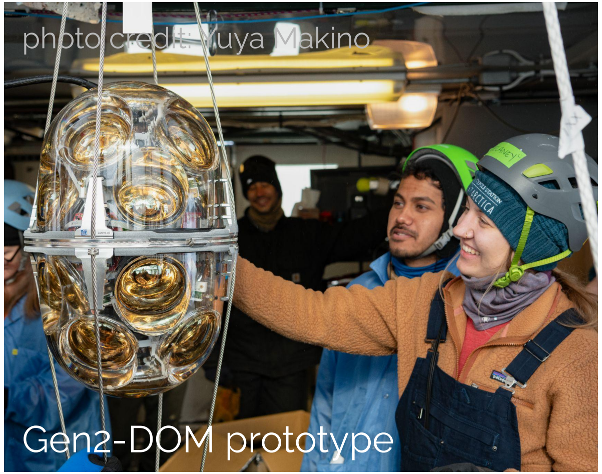


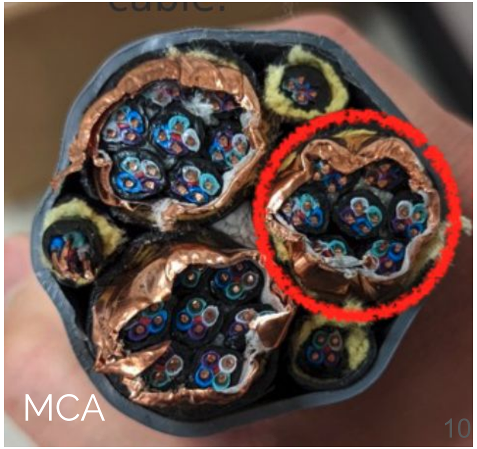


https://arxiv.org/abs/2509.13066

What's in the ice?

- multi-PMT optical modules
  - "mDOMs" → 24 3" PMTs
- Dual optical sensors in an Ellipsoid Glass for Gen2
  - "DEggs" → 2 8" PMTs
- Special devices
  - Calibration of ice properties
  - R&D of future optical modules
- Main cable assembly (MCA)
  - Newly designed for Upgrade
  - Can support 2 Mbaud communication rate





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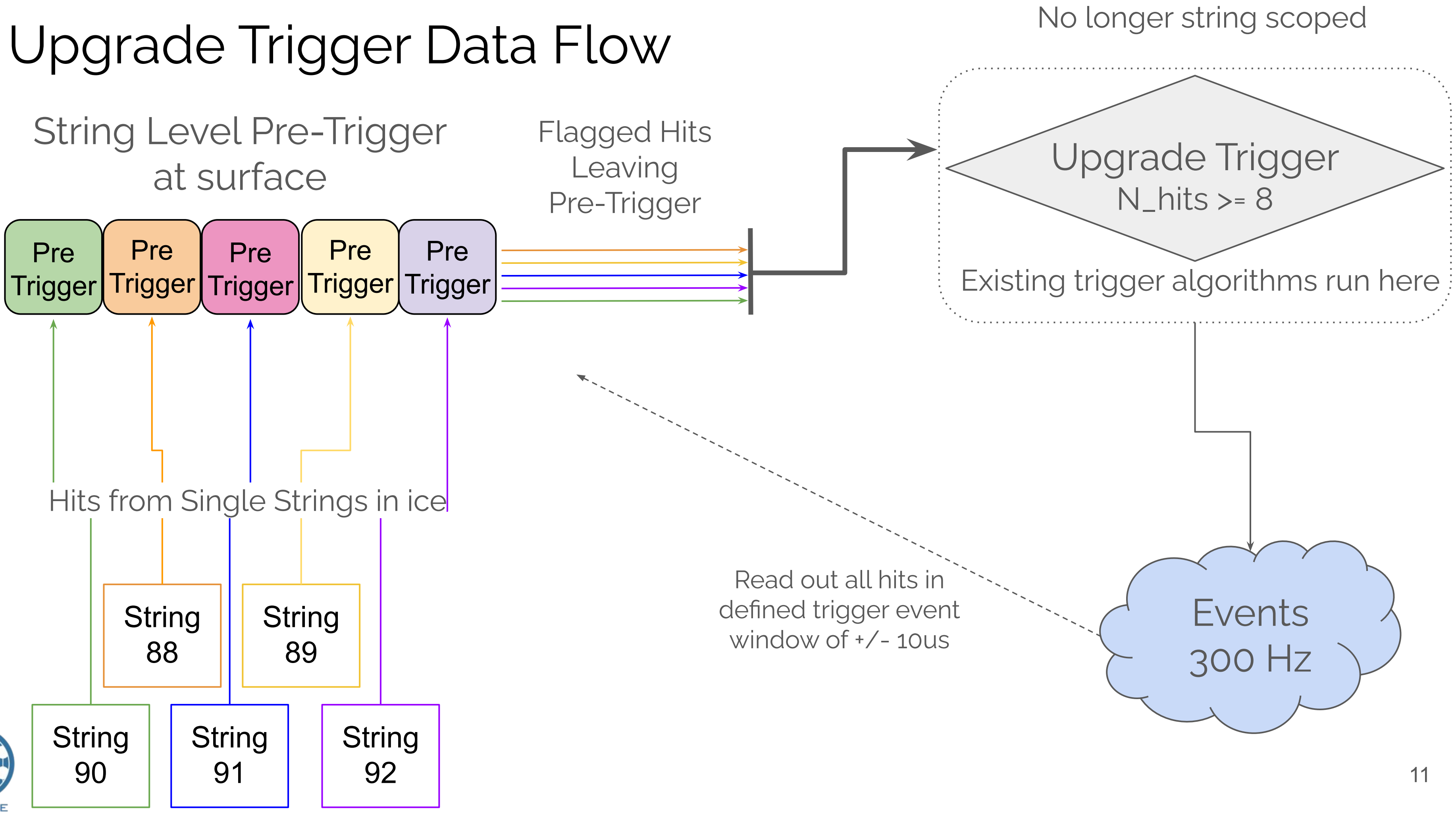
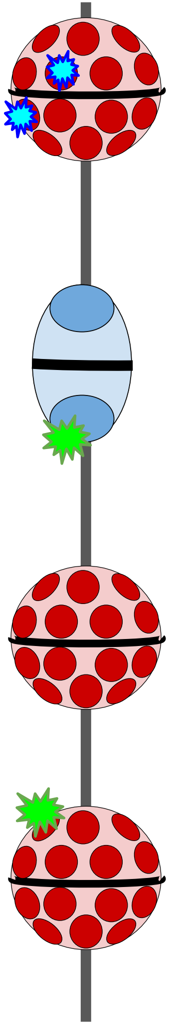
Upgrade Trigger Data Flow



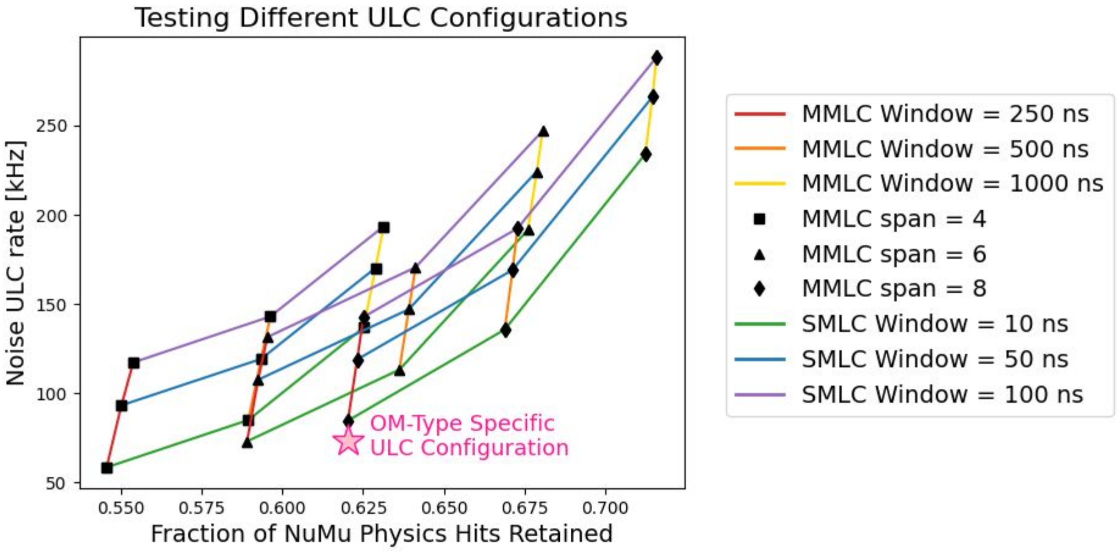
String Level Pre-Trigger

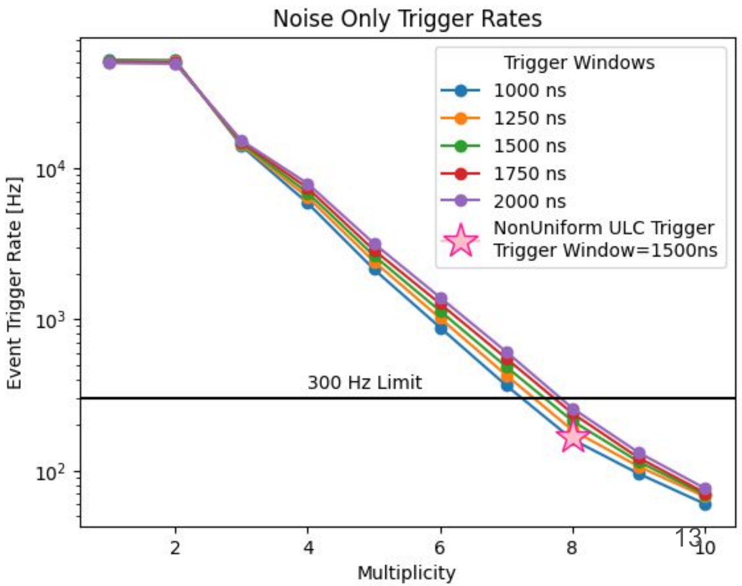
- Pre-Trigger identifies hits on single strings which meet “Upgrade Local Coincidence” (ULC) conditions
    - Single Module LC (SMLC) = 2 hits on different channels (pmts) on the same module
        - Within some module window Δt_{SMLC}
    - Multi Module LC (MMLC) = 2 hits on different modules on the same string
        - Within some MMLC window Δt_{MMLC} and vertical span
- Goal of Pre-Trigger: highest signal to noise ratio while being within bandwidth limits



Determining Pre-Trigger / Trigger Parameters

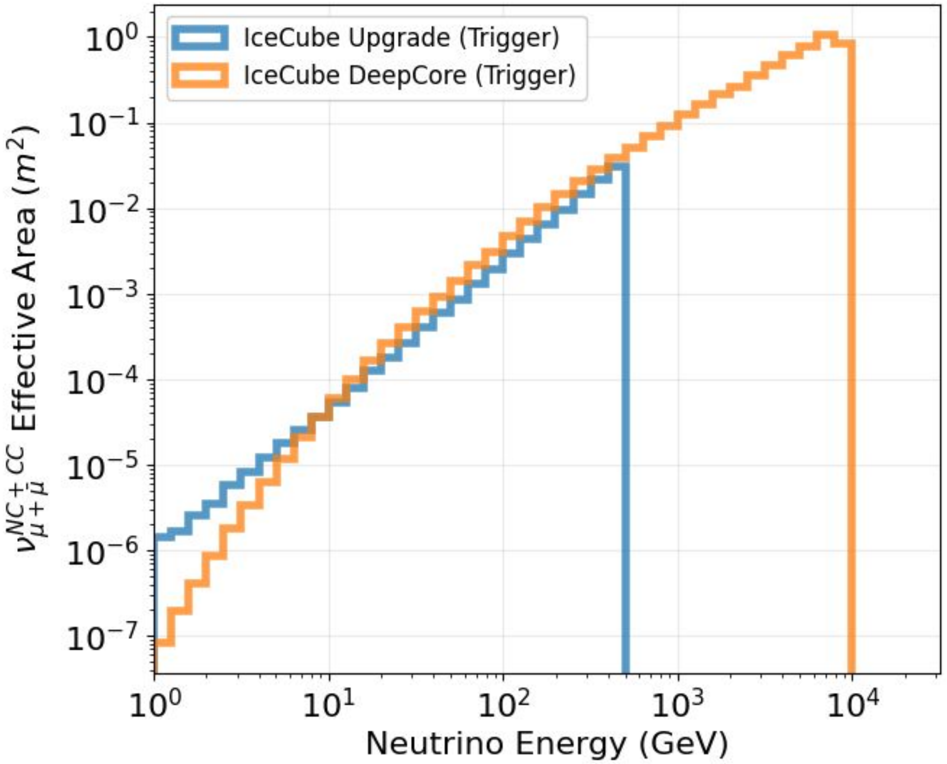
- Constrained by pDAQ functionality, developer availability, and timescale
- For First Light: want an algorithm that is simple but maximizes signal efficiency → "Upgrade SMT"





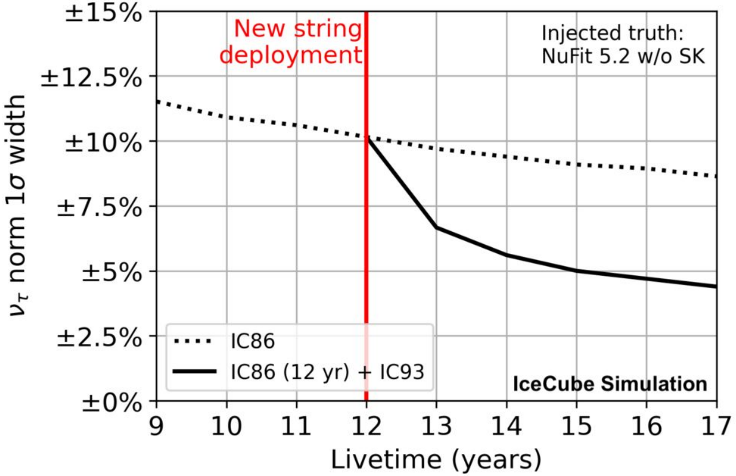
Pre-Trigger → Upgrade Event Trigger

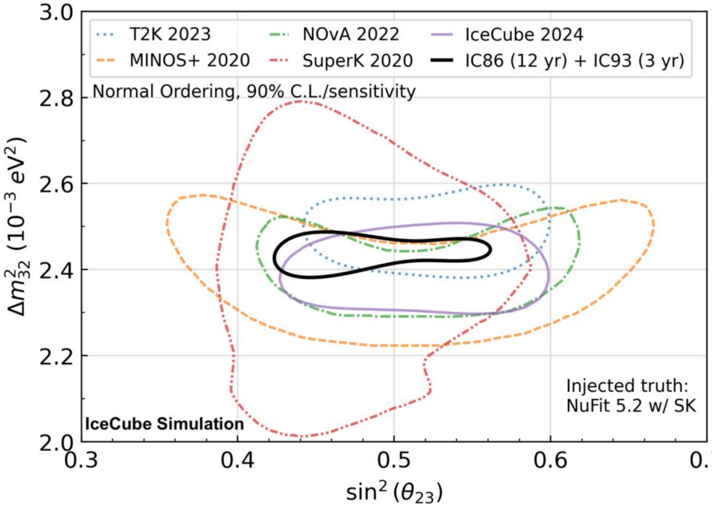
- Event trigger for entire Upgrade array:
  - N_hits >= 8 Upgrade local coincidence hits within 1750ns
- Heavily noise dominated at this level
- Important to consider both signal efficiency and manageable noise rates
- In current pre-trigger configuration:
  - 62% of signal hits pass ULC conditions
  - ~150 Hz of noise only events
- Offers significant improvement in effective area at low energies
  - Expect trigger to be efficient at capturing reconstructable events at low energies



Future Upgrade Analyses

- Science goals focused on neutrino oscillations and low energy astrophysics
- Improving low energy event reconstruction and particle identification will reduce uncertainties and shrink oscillations parameters contour





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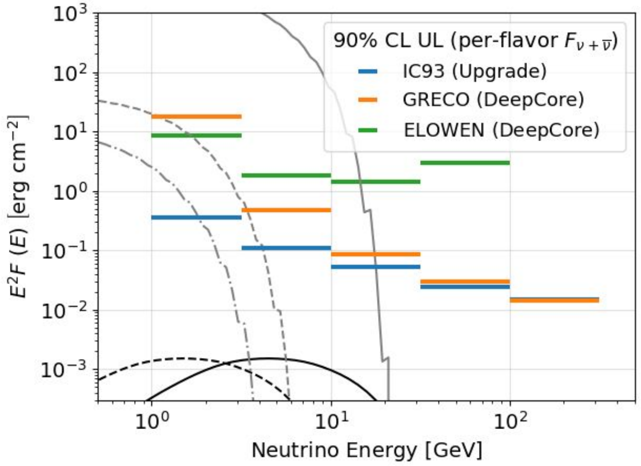
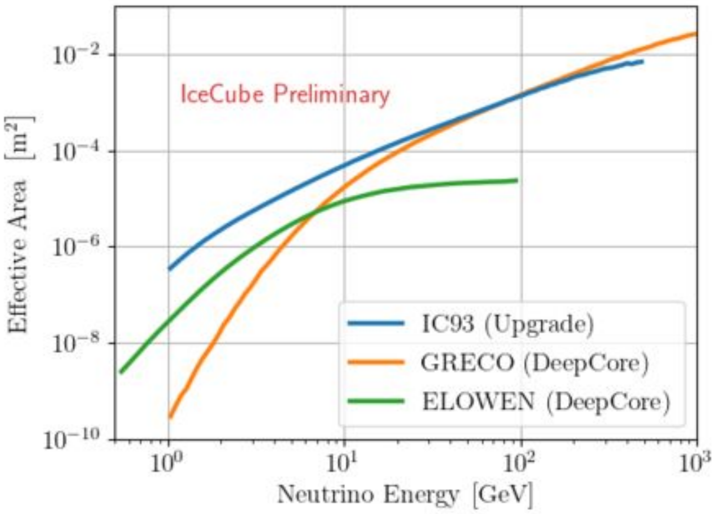
Future Upgrade Analyses

- Science goals focused on neutrino oscillations and low energy astrophysics
- Added strings and increased photocathode area extend effective area and sensitivity to lower energies





Kobayashi, PoS-ICRC2025-1076

Upgrade Deployment Season

Preparing for Deployment

- South Pole is a harsh environment → want to iron out the procedures ahead of time so less problem solving on the ice
  - Spoiler: still a lot of problem solving done on the ice

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South Pole Deployment & Early Data Taking

- 5 strings installed and commissioned!
- Performed acceptance testing of all optical sensors and other devices at the South Pole
- Commissioning and test data taking has been ongoing since detector completion
    - Preparing for physics data taking starting in November!


photo credit: Colton Hill

photo credit: Yuya Makino

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Drilling 2600m into the ice

- Upgrade strings are 2450-2600m deep in the ice
- Before installation, drill team uses an Enhanced Hot Water Drill to melt a column of water, which we then install our strings into
- Takes ~3-5 days to drill start to finish!

video credit: Colton Hill

Installation

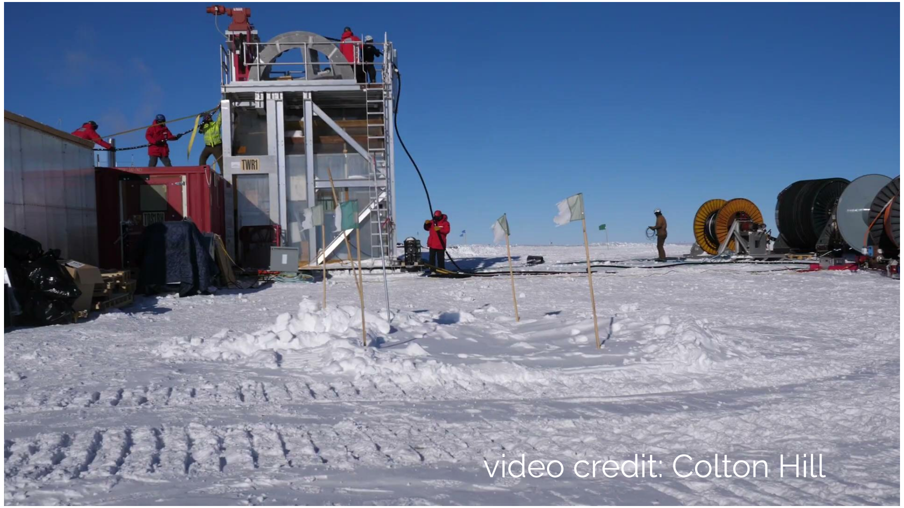
- Spent ~1 week preparing for installation
  - Stocking the TOS with rigging equipment
  - Loading the DHF with mDOMs & DEggs
  - Working towards testing all devices
- Installing over 100 devices per string
- Each module requires individual rigging along the MCA
- Each string took ~24 hours
  - Two 12 hour shifts - day & night

Installation

video credit: Coll

After Installation

- String drop → instrumented region is over 1000m below the surface of the ice
    - Need to drop the string into final position
    - Sometime we turn on a handful of devices and take data during the drop for calibration purposes → “Drop Ops”
- Unspool MCA from reel, tie off string, drag cable



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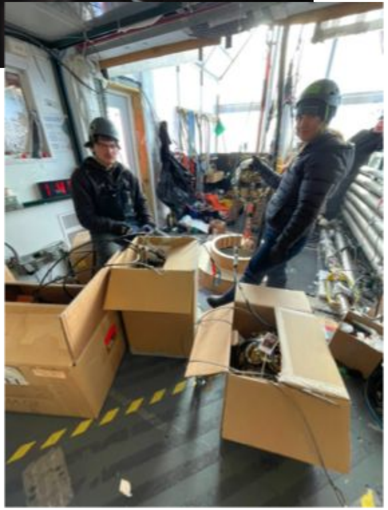
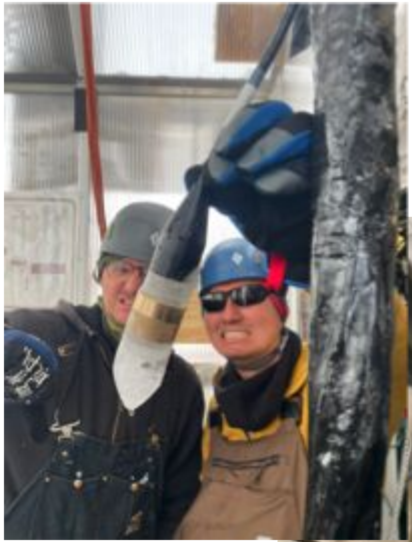
Some of the previously mentioned on-ice problem solving…





Commissioning the Detector

- At Pole: measure current, capacitance, etc immediately after deployment and connecting the MCA
  - Monitor freeze-in, checks to see if we lost any devices, test comms
- After Pole: continue to monitor freeze-in, take test data, run communications tests
- We don't turn on the detector and magically get perfect physics data!
- Requires a lot of fine tuning settings, running calibrations, taking test data, etc.
- Some discrepancies between expected noise rates from lab measurements and in-situ rates
  - Expected ~8-10 kHz of noise from mDOMs → in-situ rates ~2 kHz
  - Expected ~1.8-3 kHz of noise from mDOMS → in situ rates ~700 Hz

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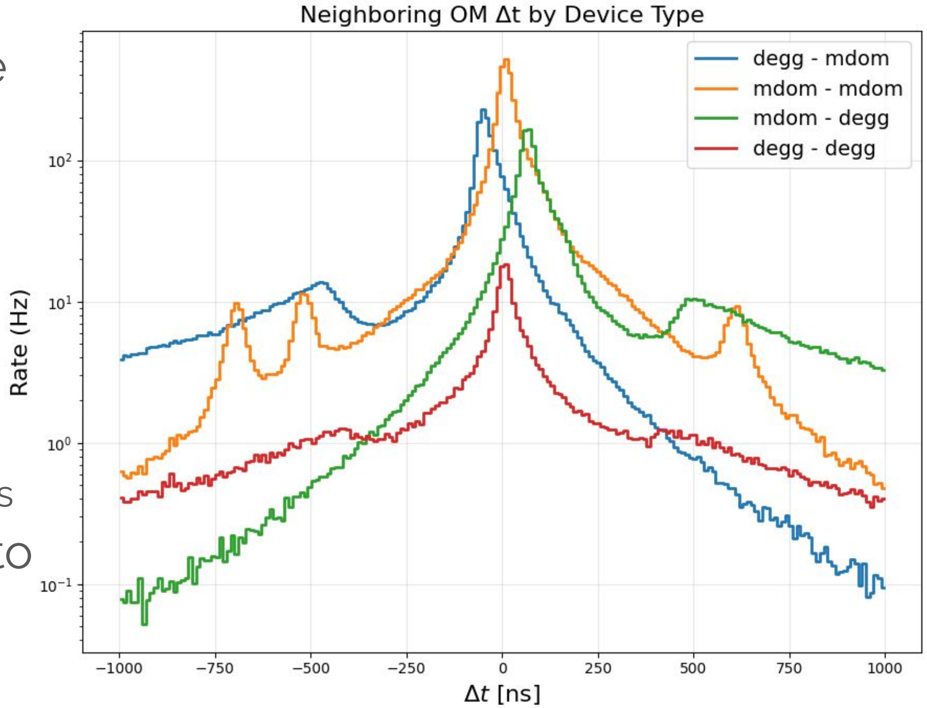
What's next for the Upgrade?

- Continue to take test data to validate the detector
- Reoptimize trigger settings for lower than expected noise rates
- Run calibrations
  - Using special devices for ice calibrations
  - Use flashers to calibrate geometries
  - Run DOM calibrations to fine tune settings
- Aiming for a November 1st run start to take physics data!



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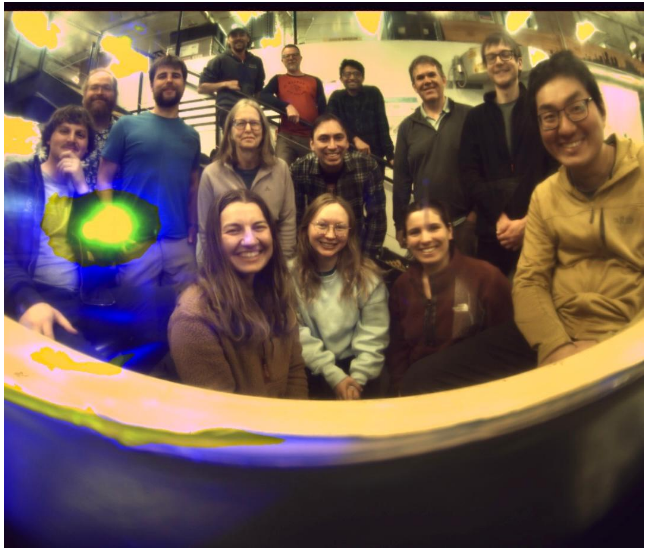

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