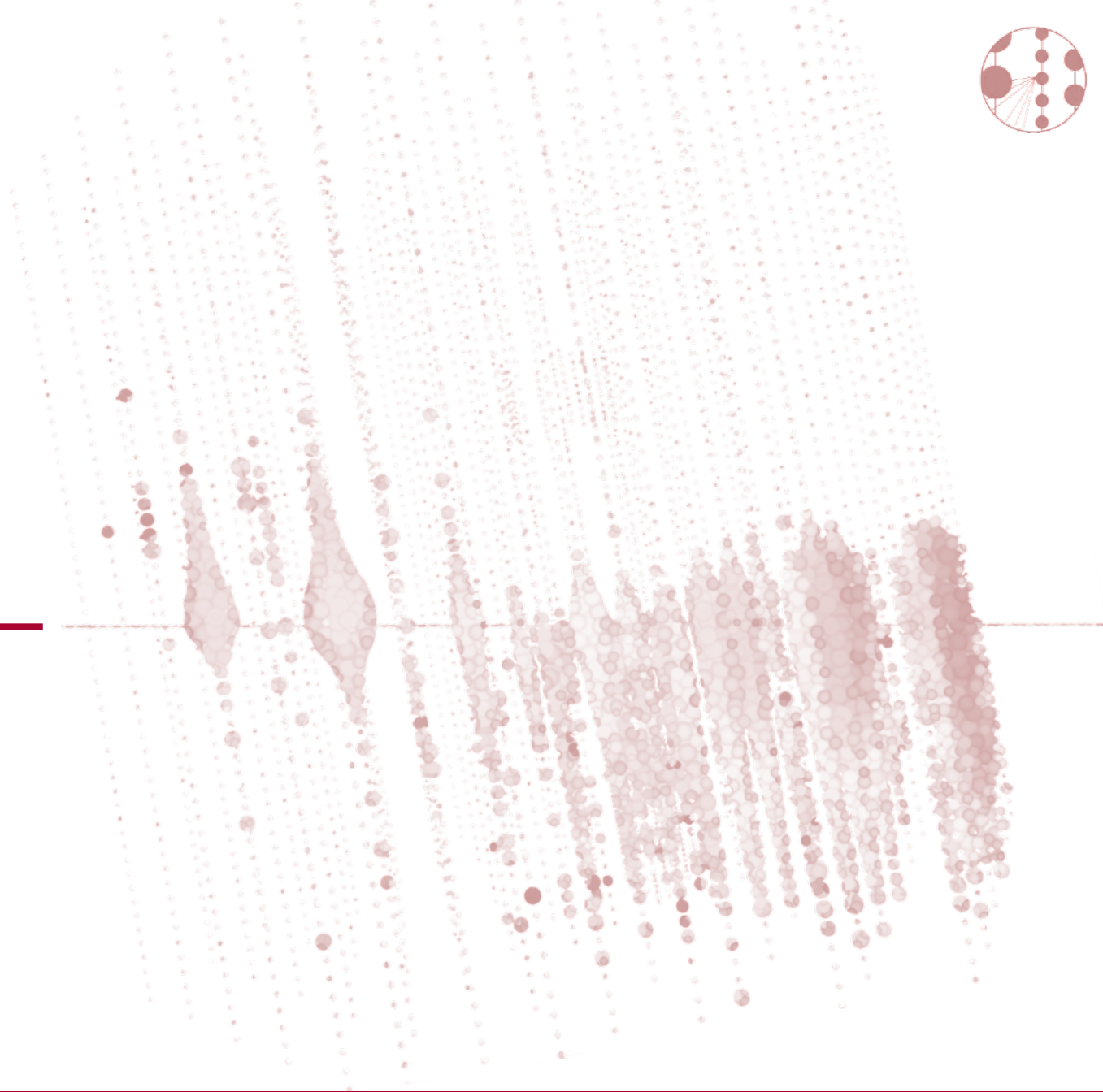# Neutrino Oscillations with IceCube & the IceCube Upgrade

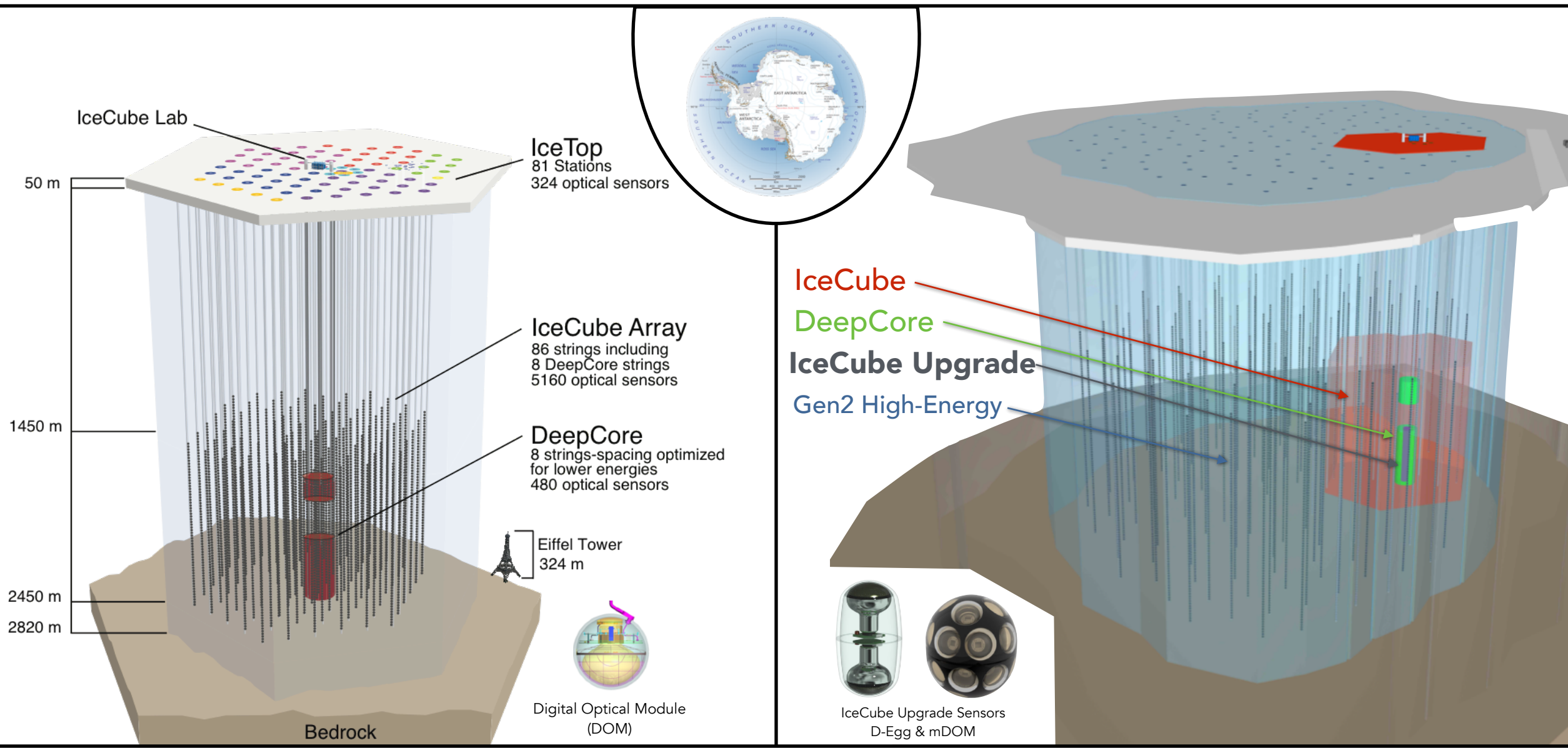D. Jason Koskinen - Niels Bohr Institute
for the IceCube Collaboration

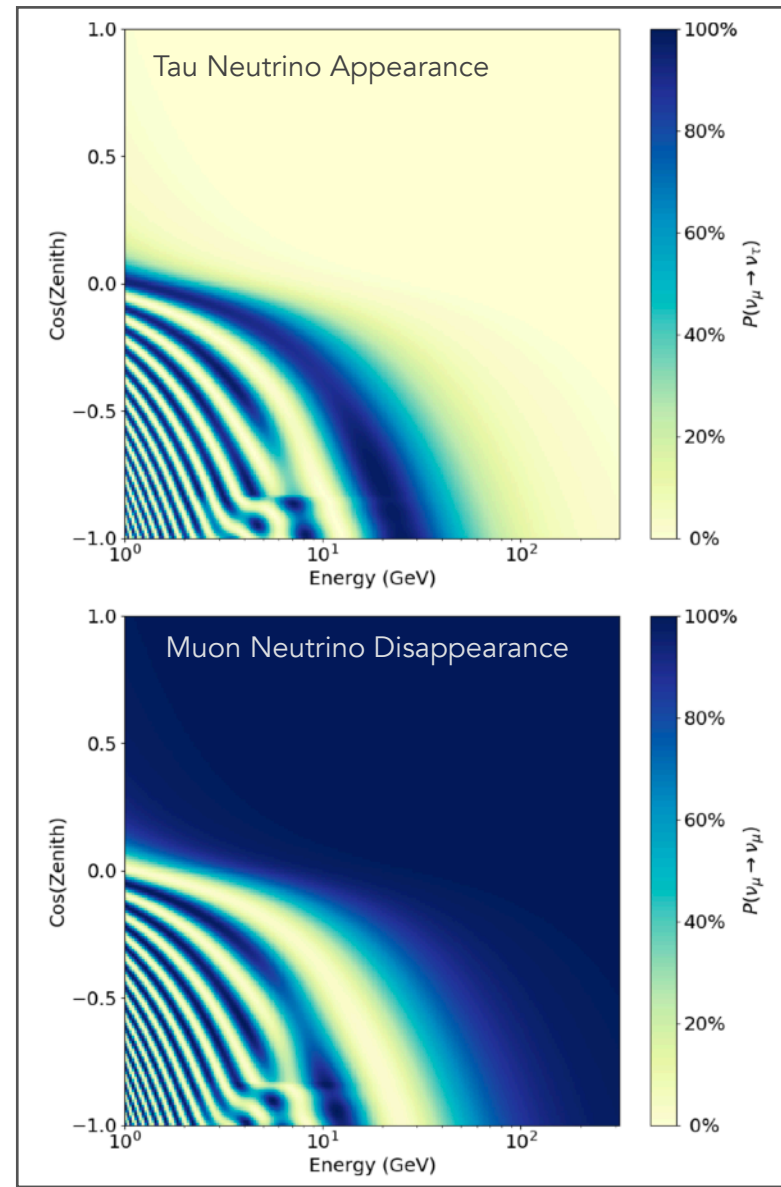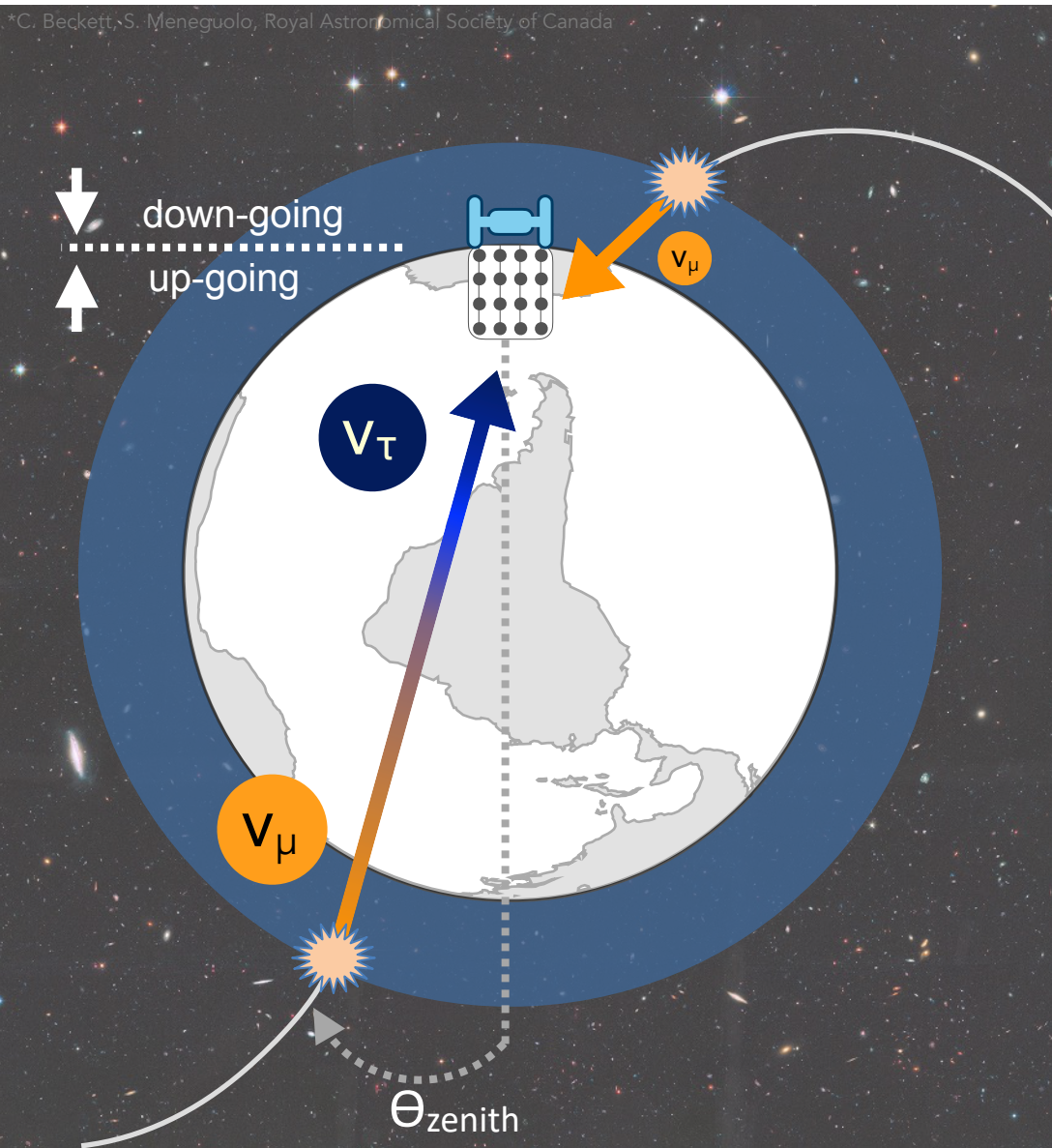TeV Particle Astrophysics (TeVPA 2022)
August 2022

UNIVERSITY OF COPENHAGEN

CARLSBERG FONDET

IceCube Lab

50 m

IceTop
81 Stations
324 optical sensors

IceCube Array
86 strings including
8 DeepCore strings
5160 optical sensors

1450 m

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

Eiffel Tower
324 m

2450 m

2820 m

Digital Optical Module
(DOM)

Bedrock

IceCube

DeepCore

IceCube Upgrade

Gen2 High-Energy

IceCube Upgrade Sensors
D-Egg & mDOM

UNIVERSITY OF
COPENHAGEN

*C. Beckett, S. Meneguolo, Royal Astronomical Society of Canada

down-going

up-going

ν_τ

ν_μ

ν_μ

θ_{zenith}

Tau Neutrino Appearance

Muon Neutrino Disappearance

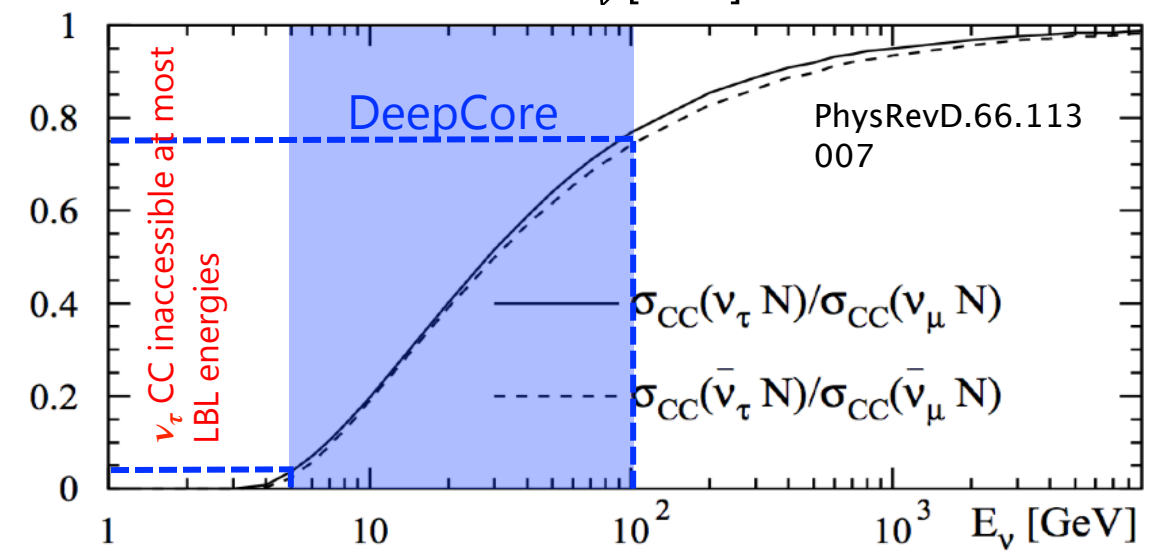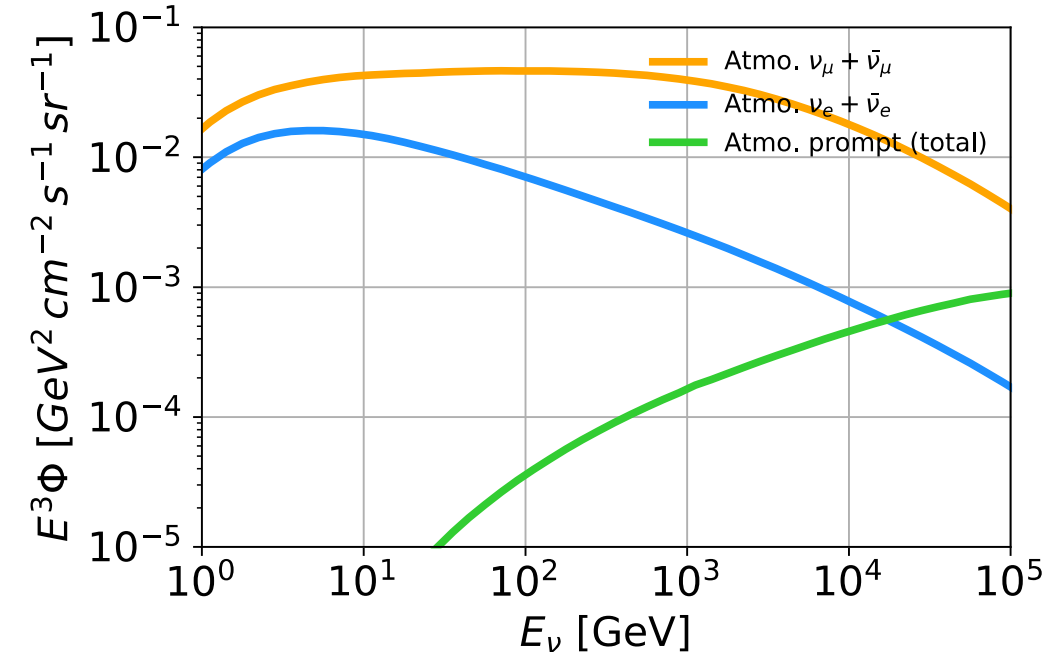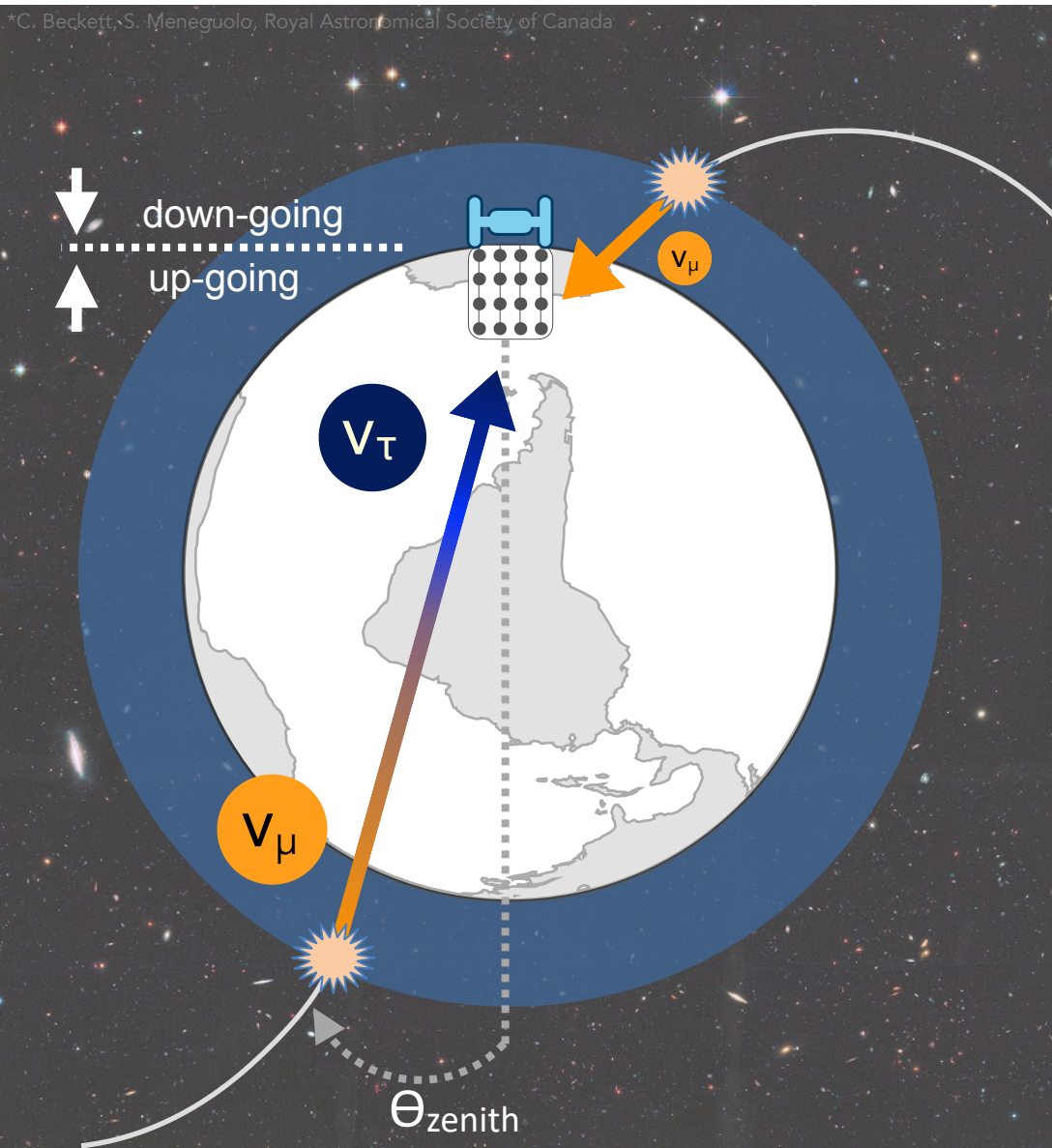Detection via Cherenkov emission from products of $\nu - N$ interactions

- Predominantly Deep Inelastic Scattering (DIS)
- "Tracks" from secondary μ
- "Cascades" from secondary e, τ, and hadrons
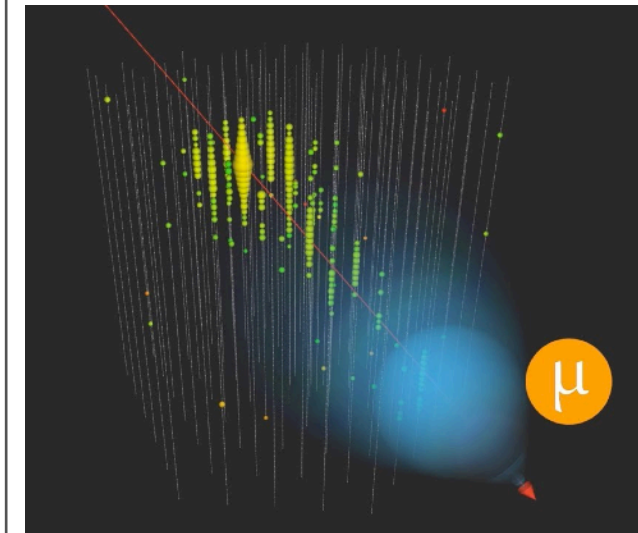
μ

UNIVERSITY OF
COPENHAGEN
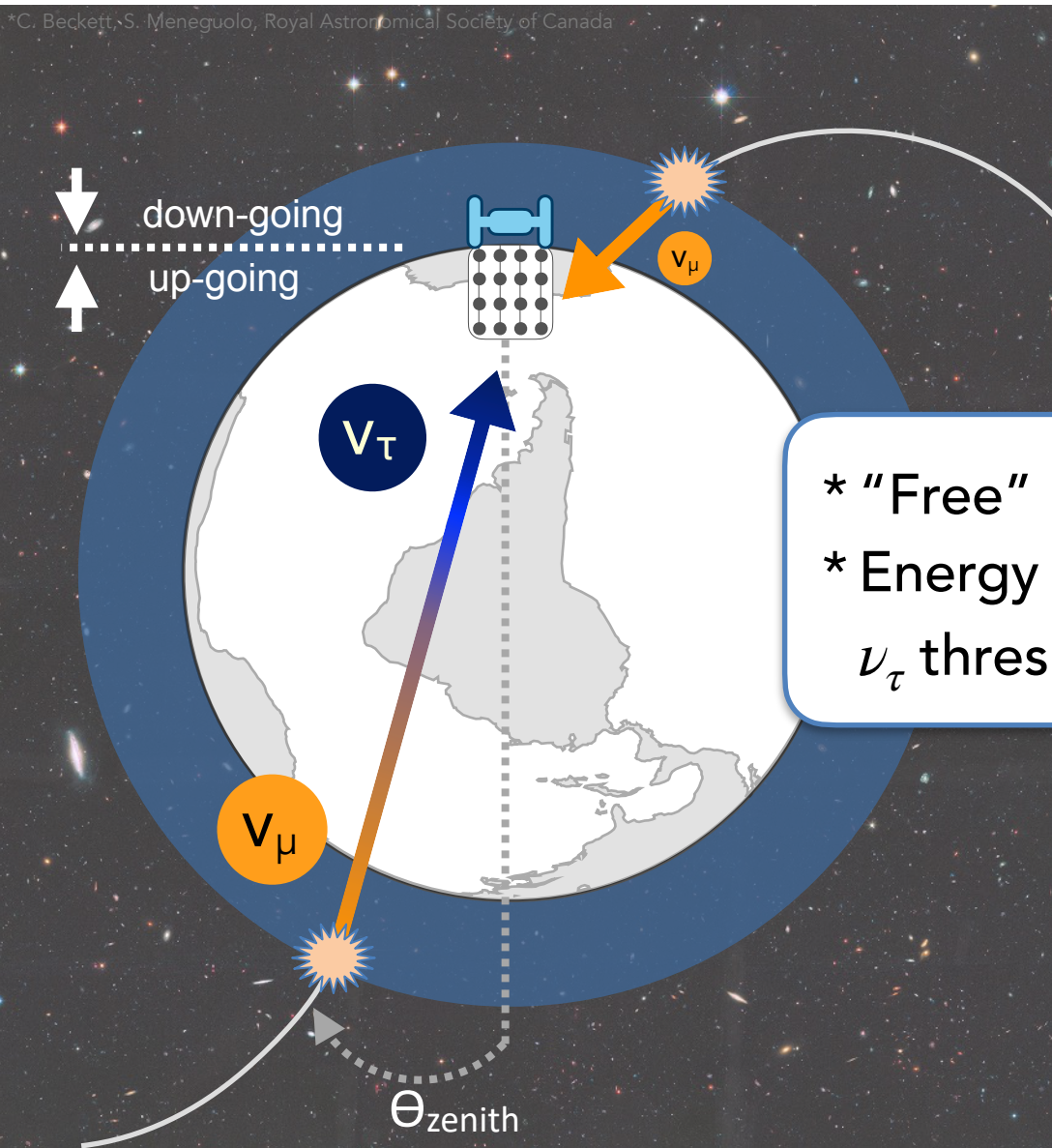

*C. Beckett, S. Meneguolo, Royal Astronomical Society of Canada

down-going

up-going

ν_μ

ν_τ

ν_μ

θ_{zenith}

Legend:
- Atmo. $\nu_\mu + \bar{\nu}_\mu$
- Atmo. $\nu_e + \bar{\nu}_e$
- Atmo. prompt (total)

$E^3\Phi$ $[GeV^2\ cm^{-2}\ s^{-1}\ sr^{-1}]$

E_ν [GeV]

ν_τ CC inaccessible at most LBL energies

DeepCore

PhysRevD.66.113007

$\sigma_{CC}(\nu_\tau N)/\sigma_{CC}(\nu_\mu N)$

$\sigma_{CC}(\bar{\nu}_\tau N)/\sigma_{CC}(\bar{\nu}_\mu N)$

E_ν [GeV]

UNIVERSITY OF
COPENHAGEN

* "Free" neutrino flux
* Energy sensitivity above charged current
 ν_τ threshold
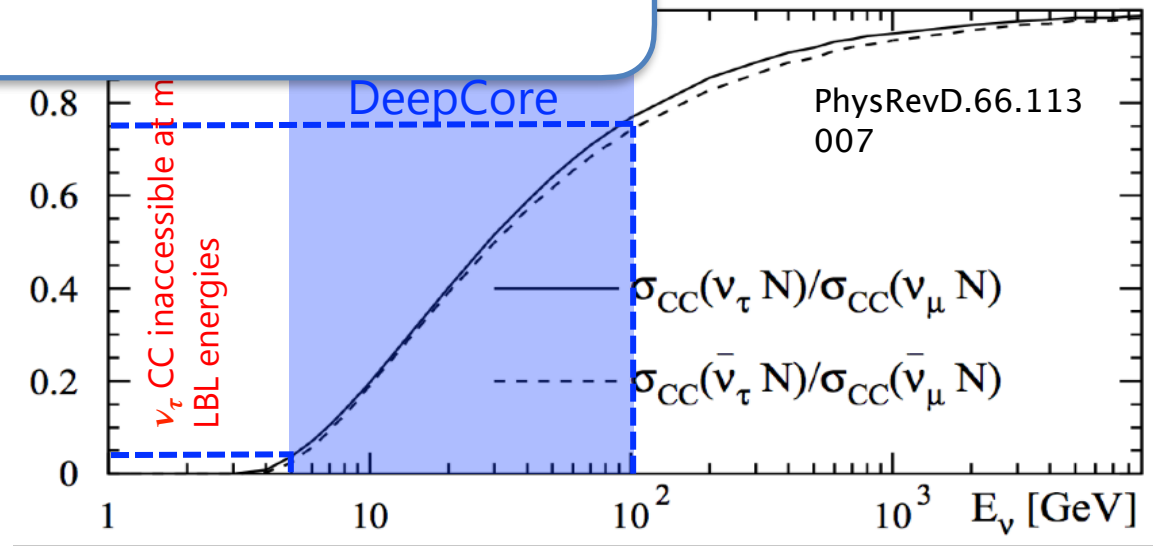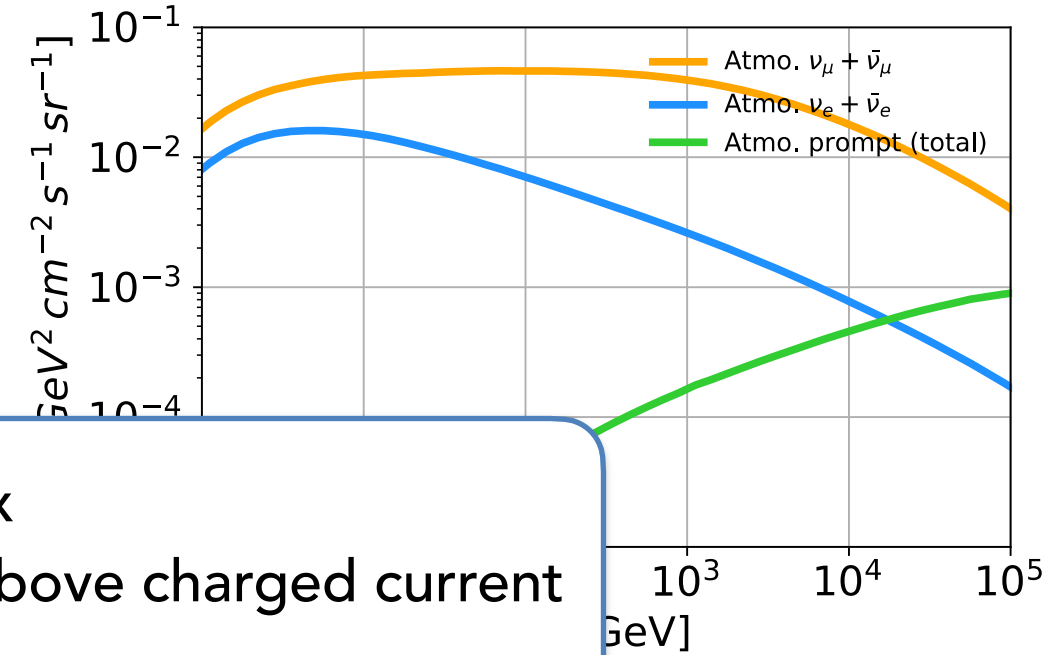
- ## Iterative approach to event selection

  - ### Backgrounds reduced by 6+ orders of magnitude*

    - Detector/electronics pure-noise
    - Atmospheric muons

  - ### Combination of straight cuts and boosted decision trees

  - ### Due to high event rates, the high fidelity reconstructions** are introduced near end of the selection chain
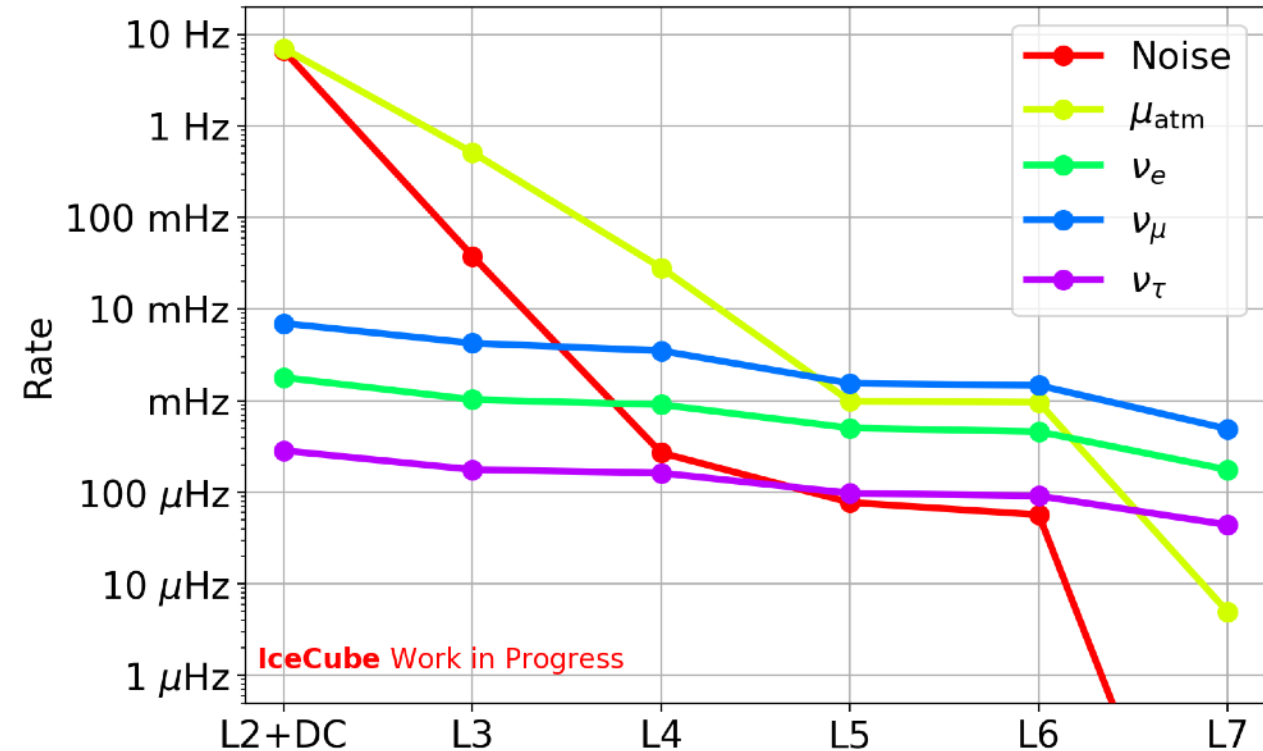

*upcoming 9.3-year high-statistics event selection

**arXiv:2203.02303

UNIVERSITY OF COPENHAGEN

- ## Measure 3D distortions in reconstructed [energy, zenith, particle type]
  - Robust against systematic uncertainties
  - Particle identification discriminates $\nu_{\mu,CC}$ interactions vs all other flavors/channels
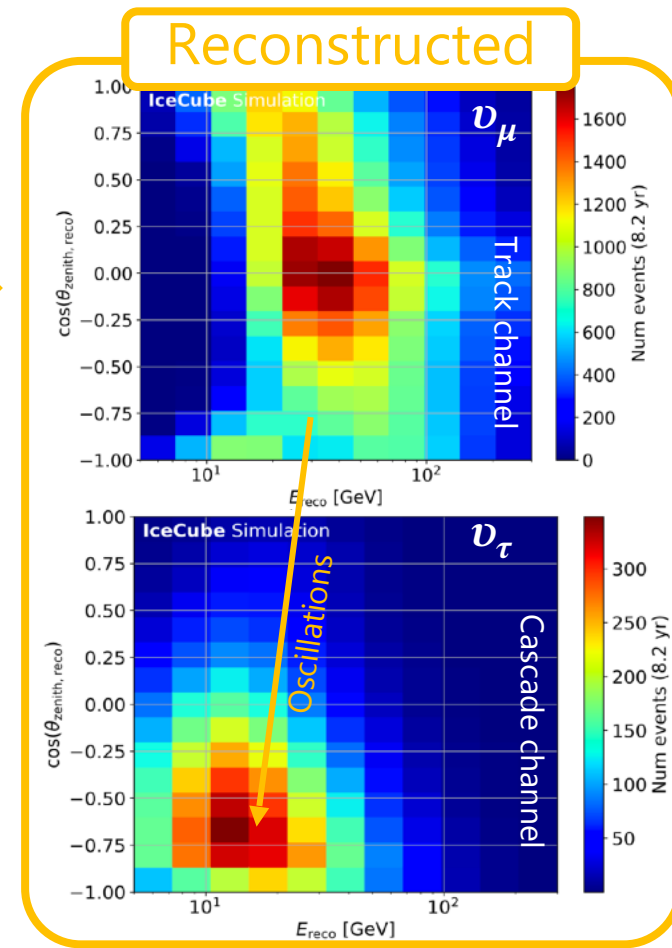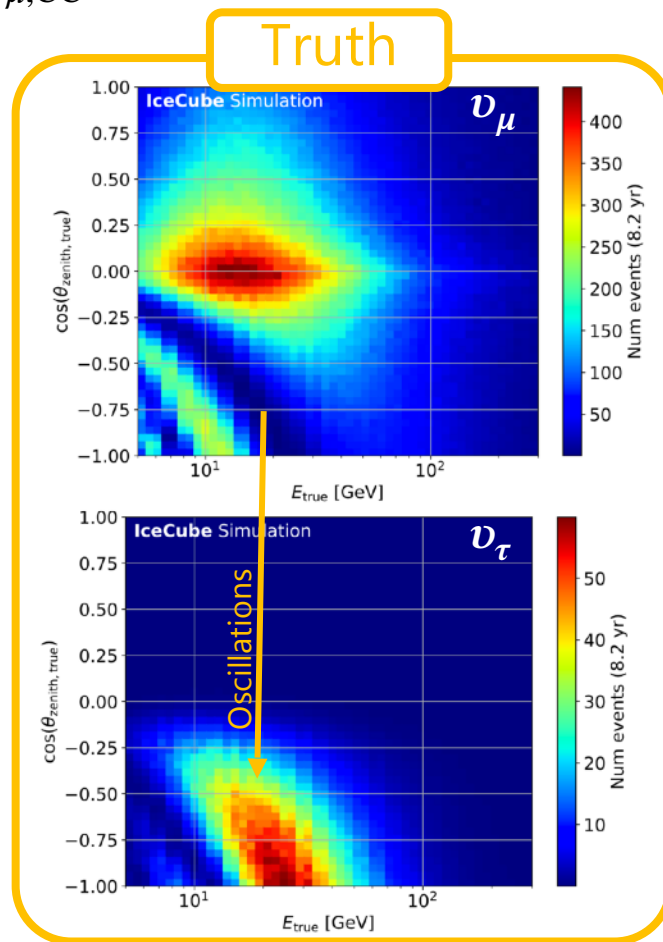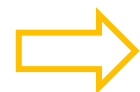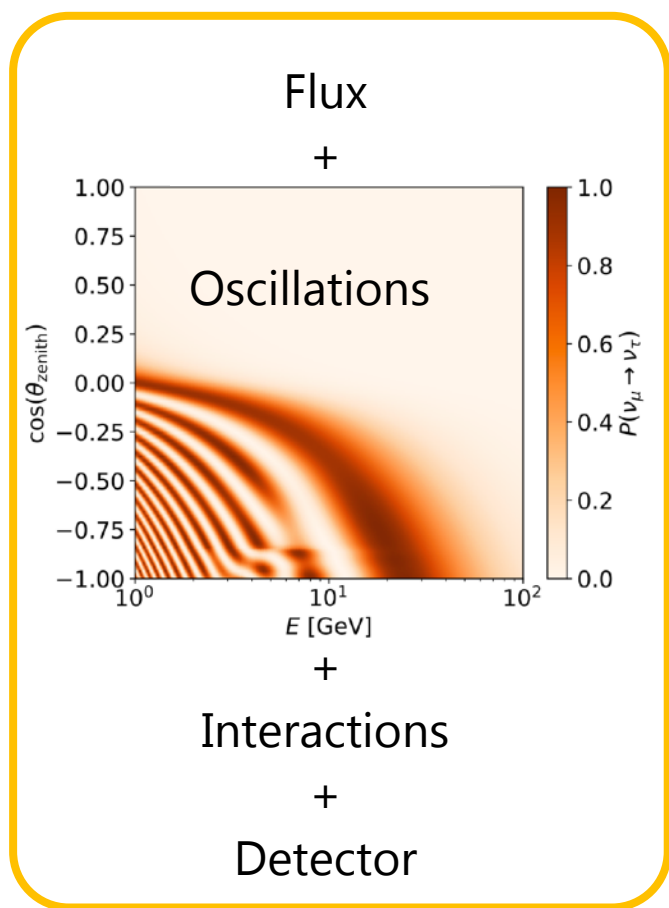
- ## Flux
  - Cosmic ray spectrum
  - Pion & Kaon uncertainties from production/decay/(re)interaction

- ## Cross Sections <small impact>
  - Axial mass uncertainties for QE and RES
  - Transition between GENIE lower energies (approx. 100 GeV) to CSMS* at higher energies

- ## Detector & Ice <large impact>
  - Optical property uncertainties from different ice layers and refrozen drill column
  - Angular dependence of photon acceptance on the digital optical module (DOM) photosensor

- ## ~40 systematic uncertainties are studied and approx. half are used in the final analyses fits

*arXiv:1106.3723
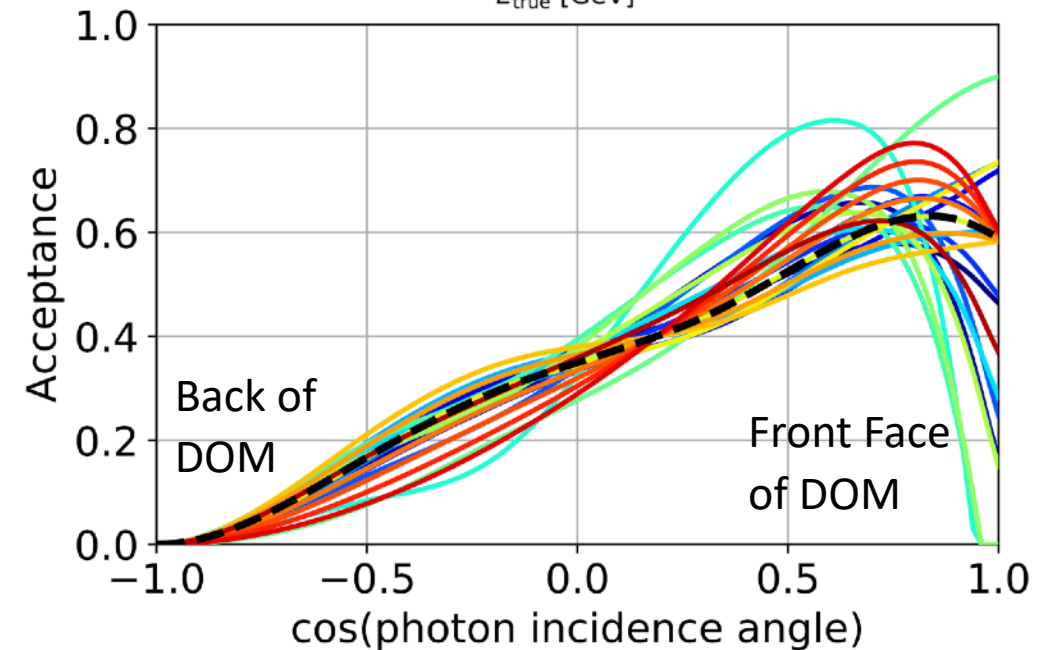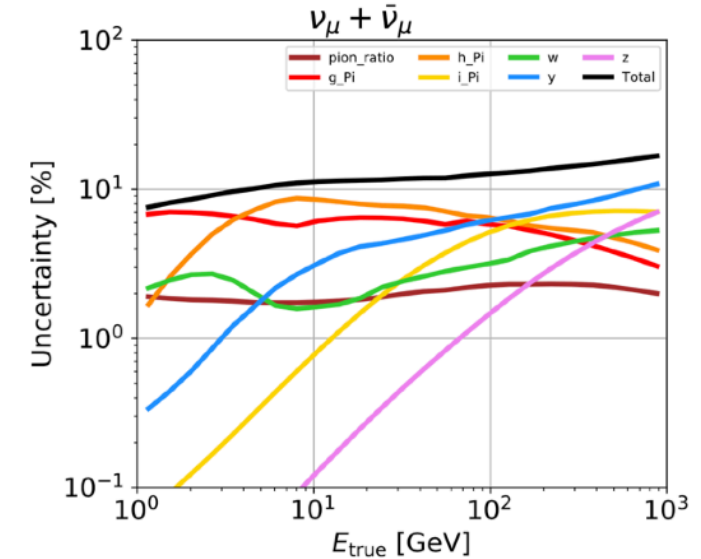
| Sub-sample	Full Sample
High quality events	High statistical power
~20k events	~200k events
Fast reconstructions • separate recos for energy and direction/vertex • can only be applied to certain high-quality events	Full 8d reconstruction • energy, direction, vertex fit simultaneously • can be applied to almost any event
Results available	**In progress**

UNIVERSITY OF COPENHAGEN

- ## New measurement of ν_μ disappearance with 8 years of IceCube data

  - Uses a "golden" sub-sample of ~23,000 track-like events (10% of full data set)
  - Clean events with low levels of photon scattering → robust to ice modelling uncertainties
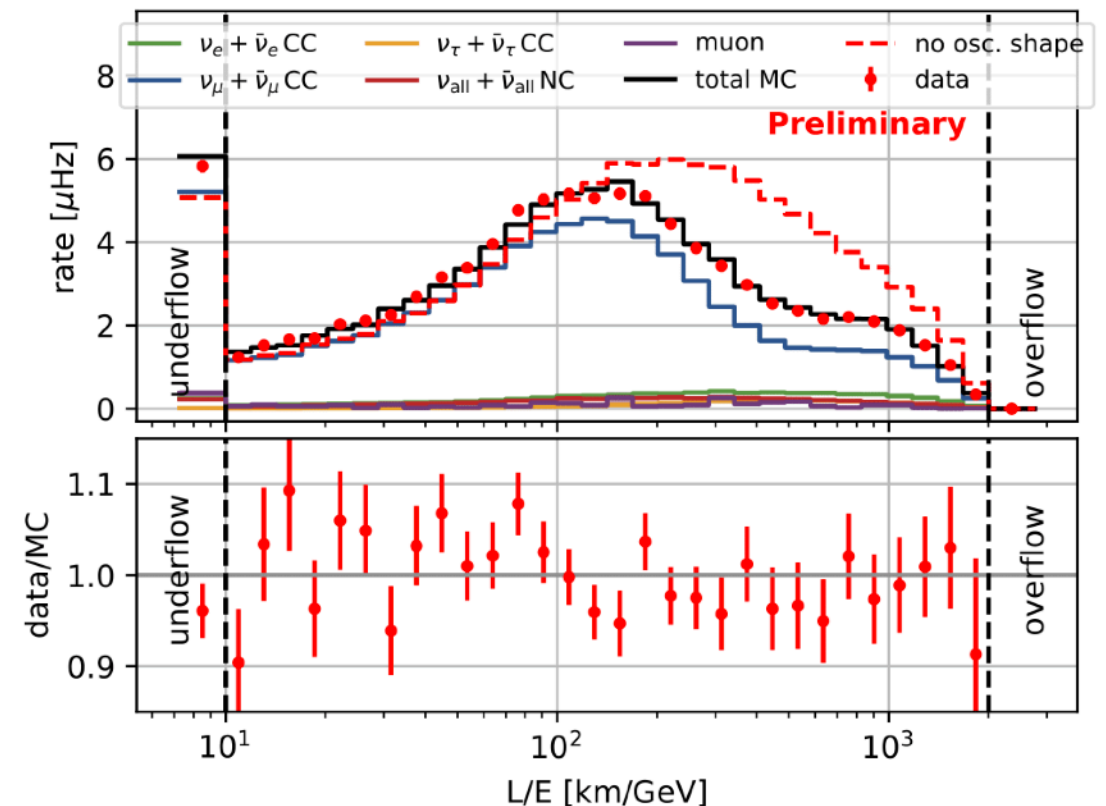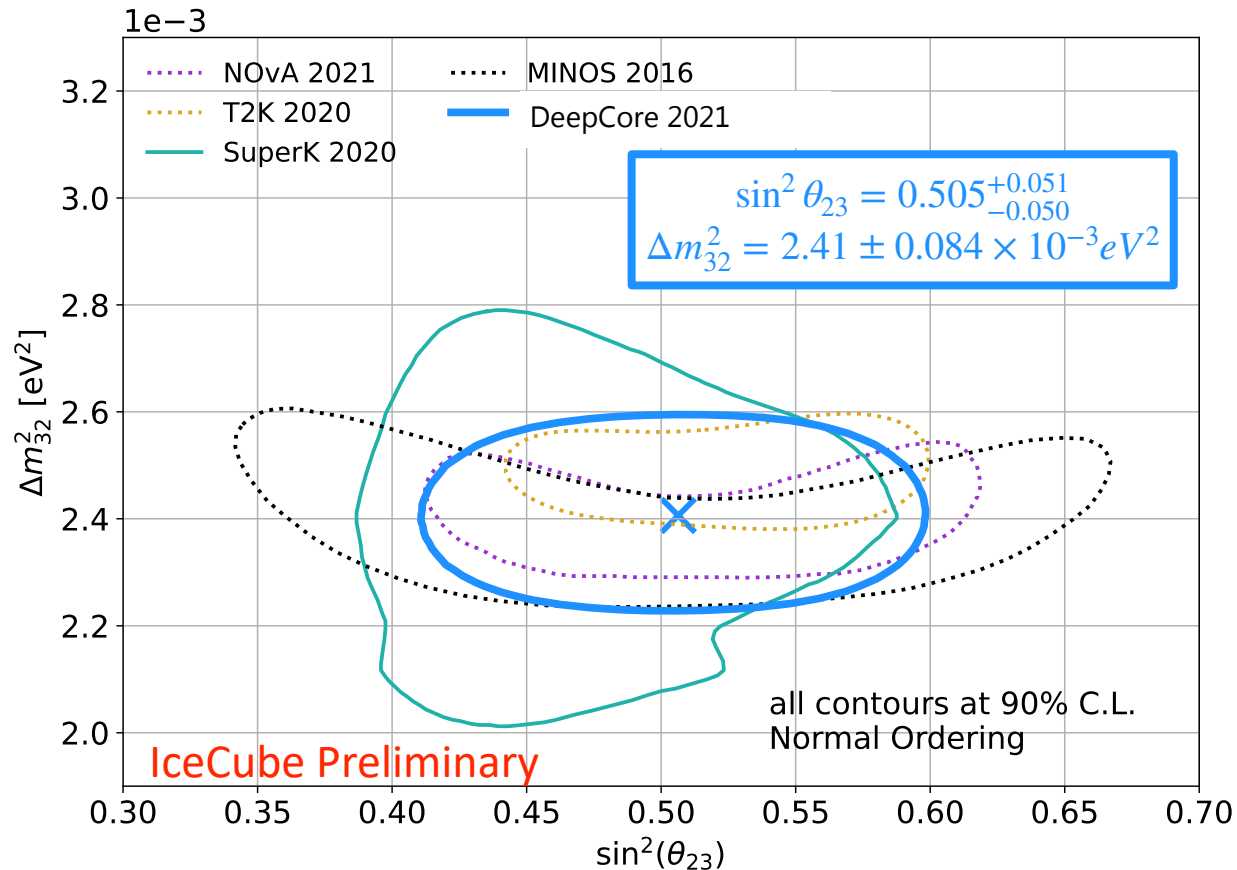
$$\sin^2\theta_{23} = 0.505^{+0.051}_{-0.050}$$
$$\Delta m^2_{32} = 2.41 \pm 0.084 \times 10^{-3}\,eV^2$$

all contours at 90% C.L.
Normal Ordering

IceCube Preliminary

- ## Suite of analyses underway with a new, high statistics data sample
  - All flavors, state-of-the-art reconstruction and background rejection

- ## Observe ν_μ disappearance and corresponding ν_τ appearance

Atmospheric mixing parameter sensitivity
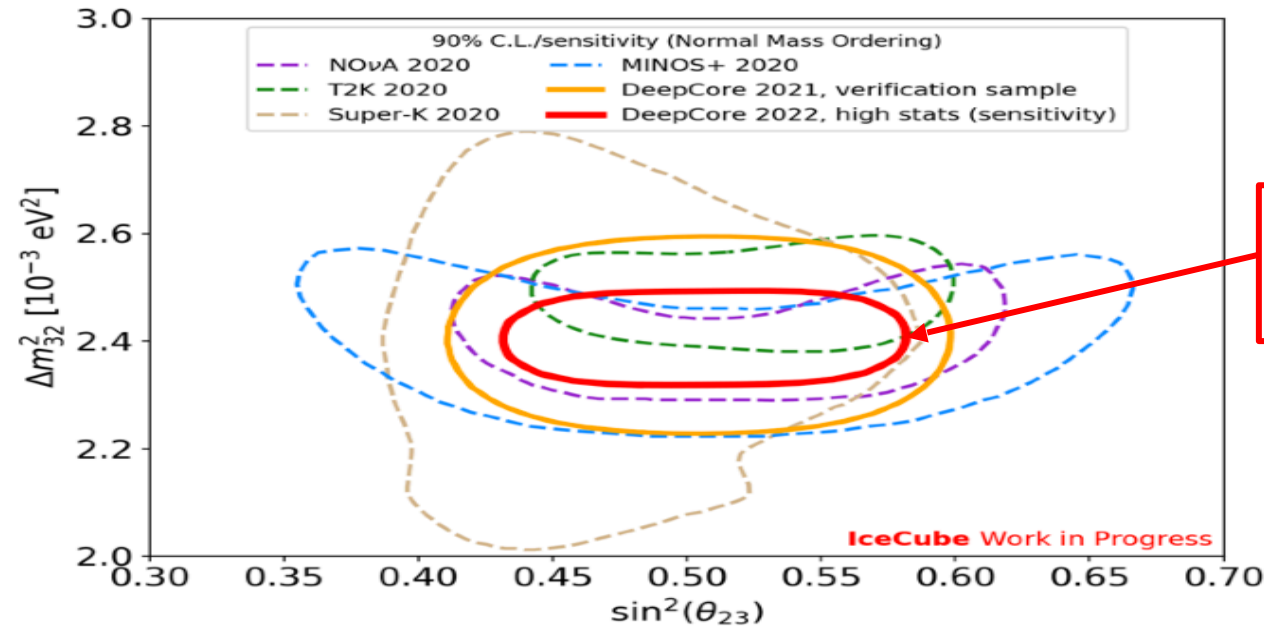
Sensitivity competitive with LBL accelerators

~210,000 neutrinos (0.7% background) → high stats and purity

Flavor
Eigenstate

Mass
Eigenstate

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \mathcal{U}_{\text{PMNS}} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

$$= \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

- Neutrino flavor eigenstates are related to mass eigenstates via the PMNS Unitary mixing matrix
- The 3 conventional angles (θ_{12}, θ_{13}, θ_{23}) fully describe the 3x3 mixing matrix **only if** the mixing matrix is unitary
- Tau neutrino appearance ($\nu_\mu \to \nu_\tau$) explicitly tests $U_{\tau 3}$ and whether the matrix is 3x3 unitary;
$|U_{e3}|^2 + |U_{\mu3}|^2 + |U_{\tau3}|^2 \neq 1$

- ## Suite of analyses underway with a new, high statistics data sample
  - All flavors, state-of-the-art reconstruction and background rejection

- ## Observe ν_μ disappearance and corresponding ν_τ appearance

Atmospheric mixing parameter sensitivity
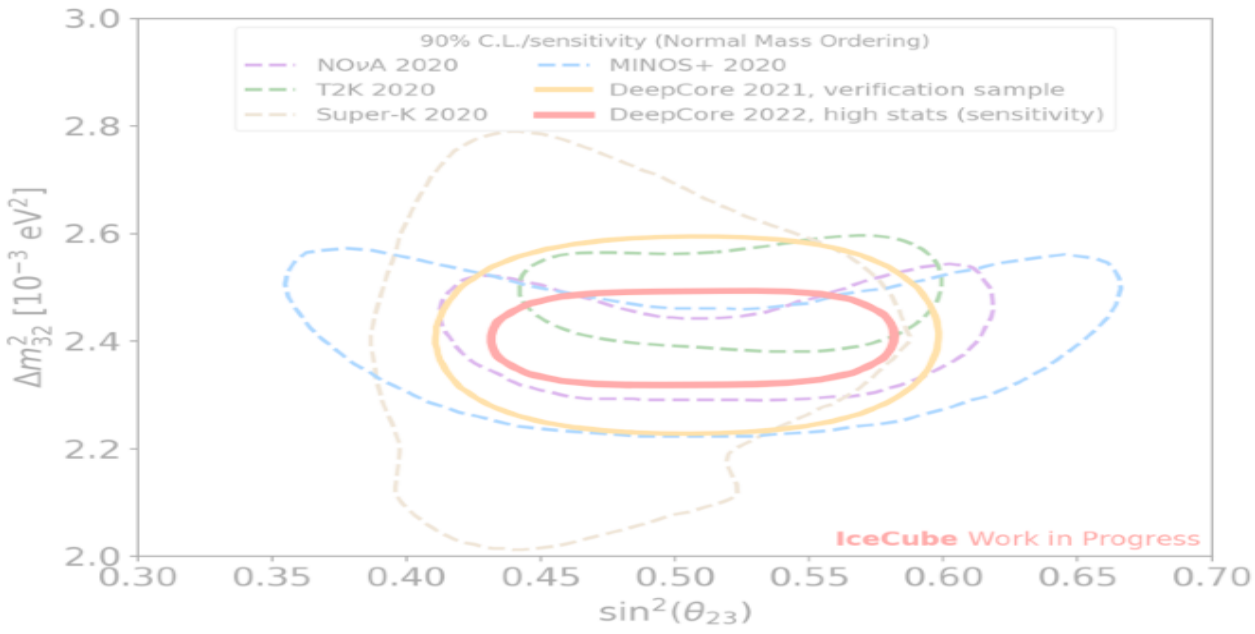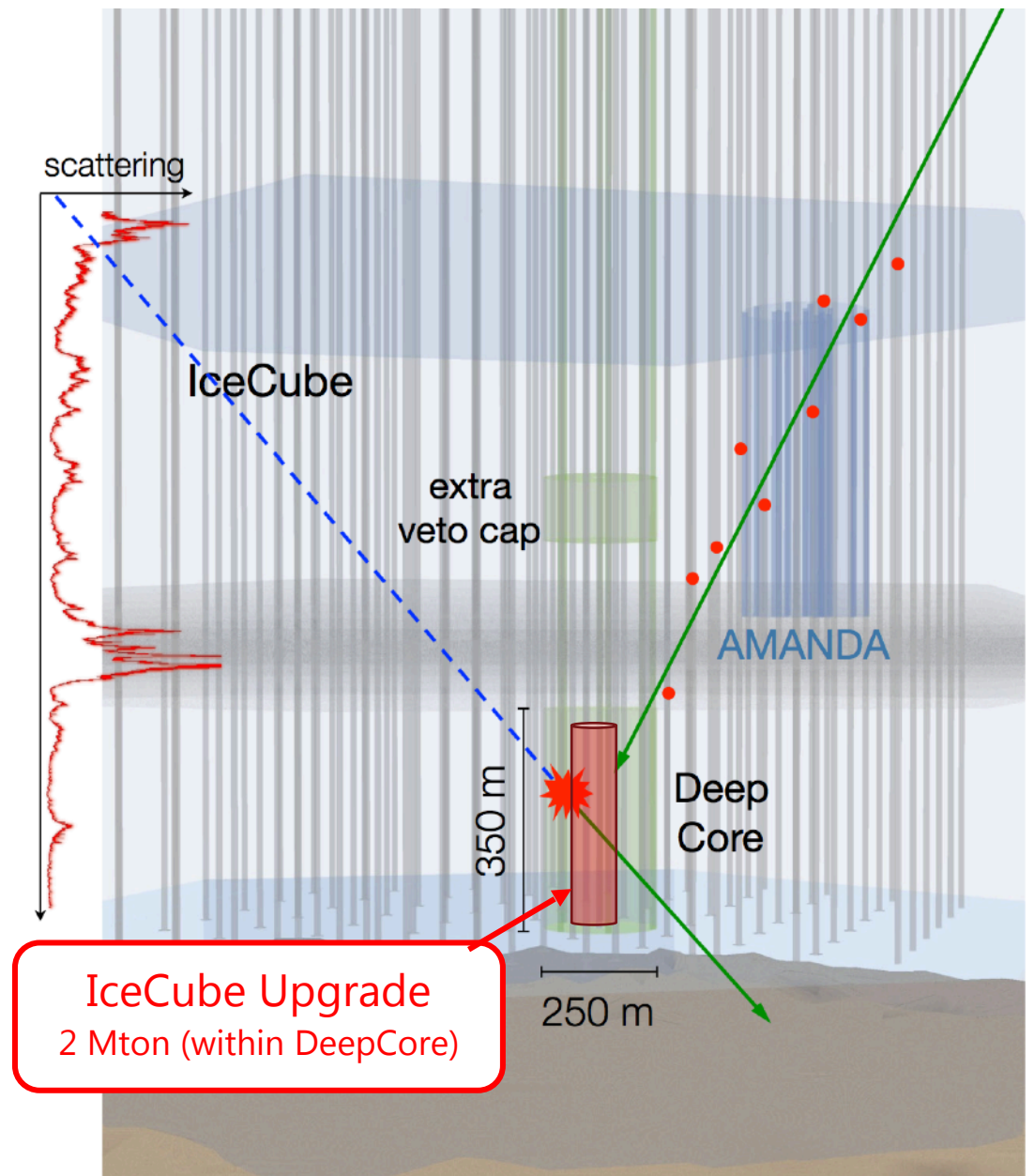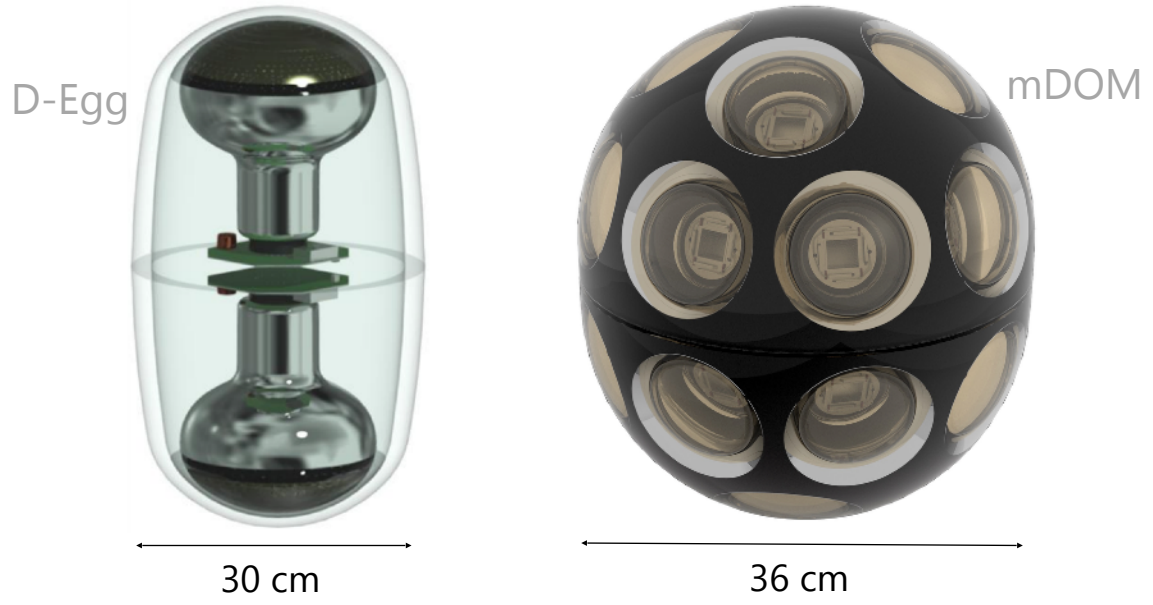
ν_τ normalization sensitivity
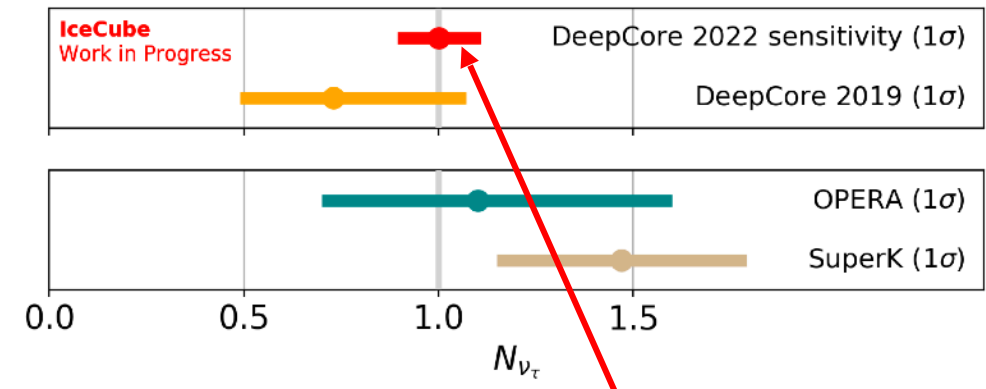
Expecting world-leading 11% precision

~9,700 $\nu_{\tau,CC}$ events expected

Signal is statistical excess of upgoing cascades with suppressed cross section

Tests PMNS unitarity and $\nu_{\tau,CC}$ cross section
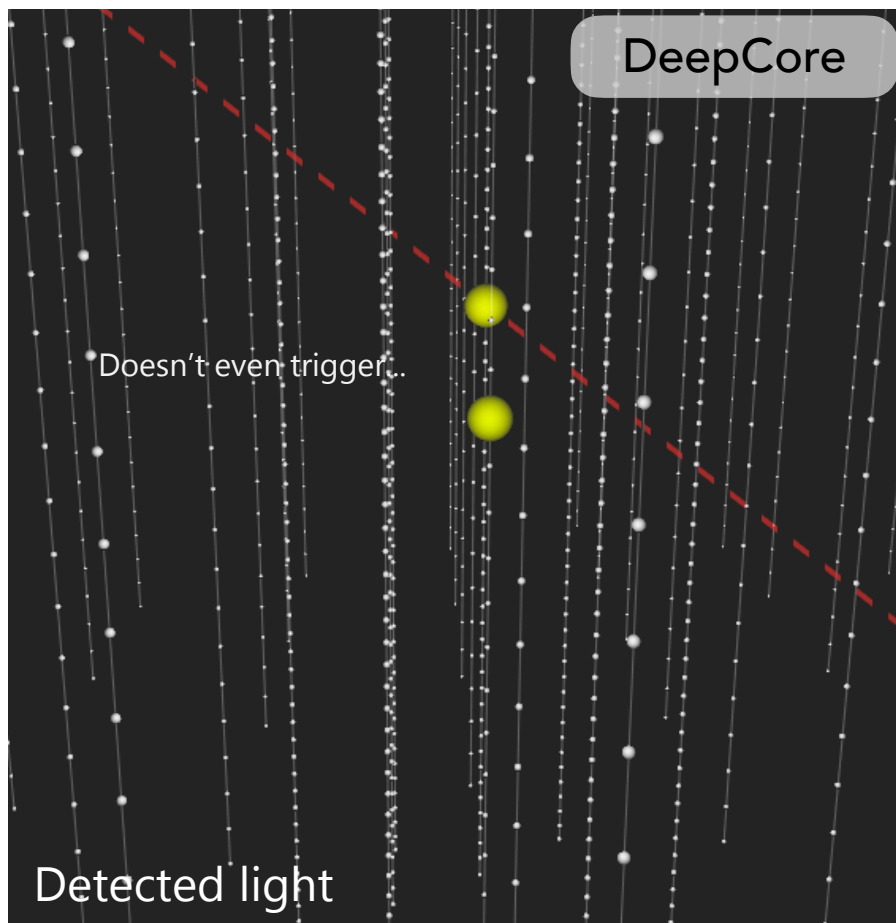
THE NEAR FUTURE

UNIVERSITY OF COPENHAGEN

- **Low-energy extension to IceCube**
  - Deployment in 2025/6
  - Reduce threshold to 1 GeV
- **700 multi-PMT sensors**
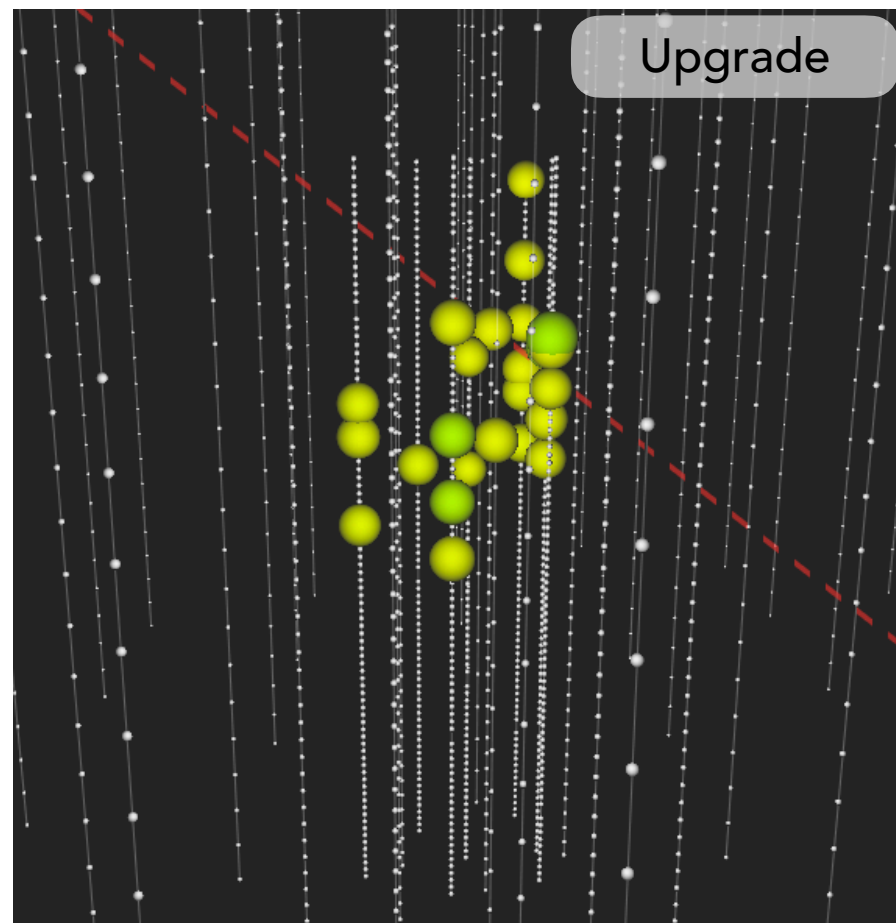- **Improved detector/ice calibration**

arXiv:1908.09441

D-Egg

mDOM

30 cm

36 cm

scattering

IceCube

extra veto cap

AMANDA

Deep Core

350 m

250 m

IceCube Upgrade
2 Mton (within DeepCore)

Dense instrumentation in 2 Mton core

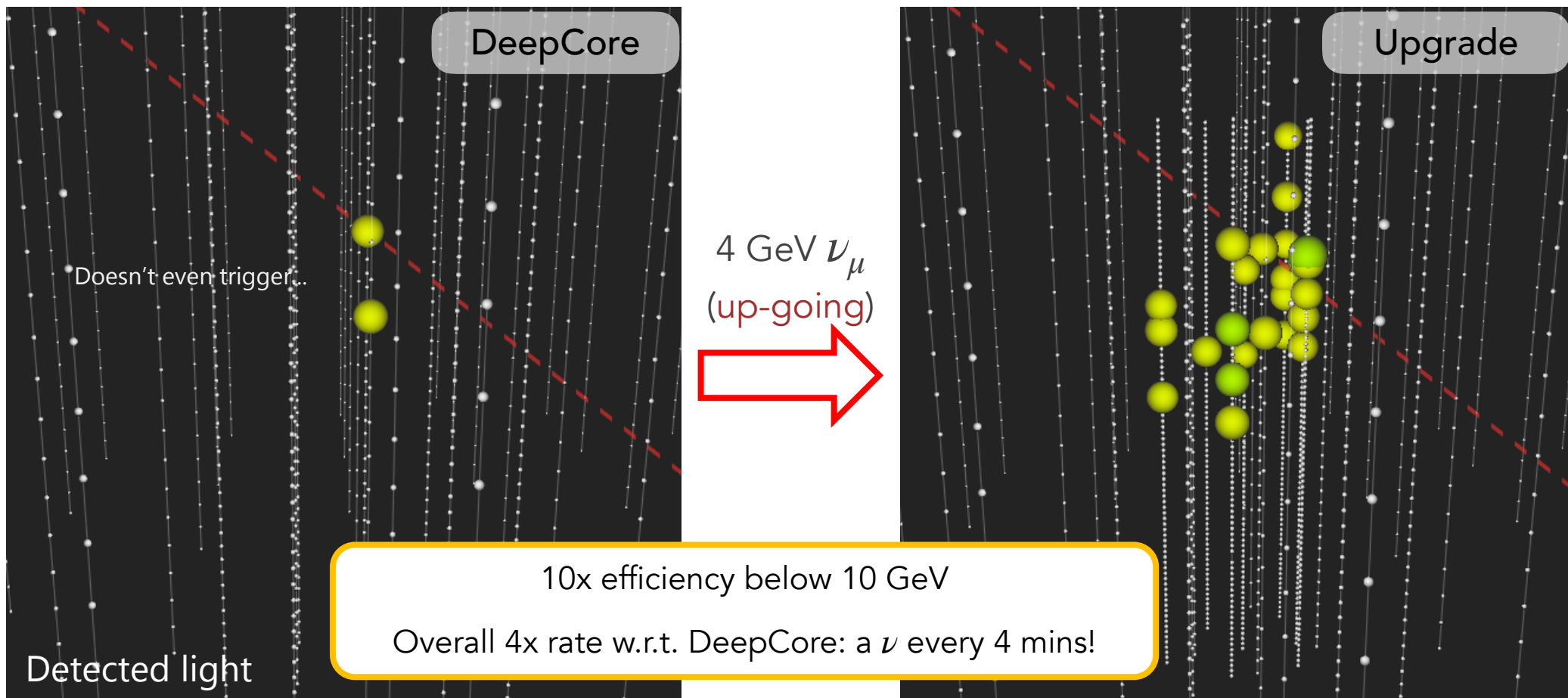- Large increase in photosensor density → sensitive down to ~1 GeV neutrinos

DeepCore

Doesn't even trigger...

Detected light

4 GeV ν_μ
(up-going)

Upgrade

- # Dense instrumentation in 2 Mton core

  - Large increase in photosensor density $\rightarrow$ sensitive down to ~1 GeV neutrinos

DeepCore

Doesn't even trigger...

Detected light

4 GeV ν_μ
(up-going)

Upgrade

10x efficiency below 10 GeV

Overall 4x rate w.r.t. DeepCore: a ν every 4 mins!

- **Conservative** experimental choices still illustrate potential of IceCube Upgrade for physics

  - ~6% N_{ν_τ} resolution with 1-year of data
  - Excludes improvements from new reconstruction techniques, improved detector systematic uncertainties, better flux treatment, and no combination of 10+ years of DeepCore data
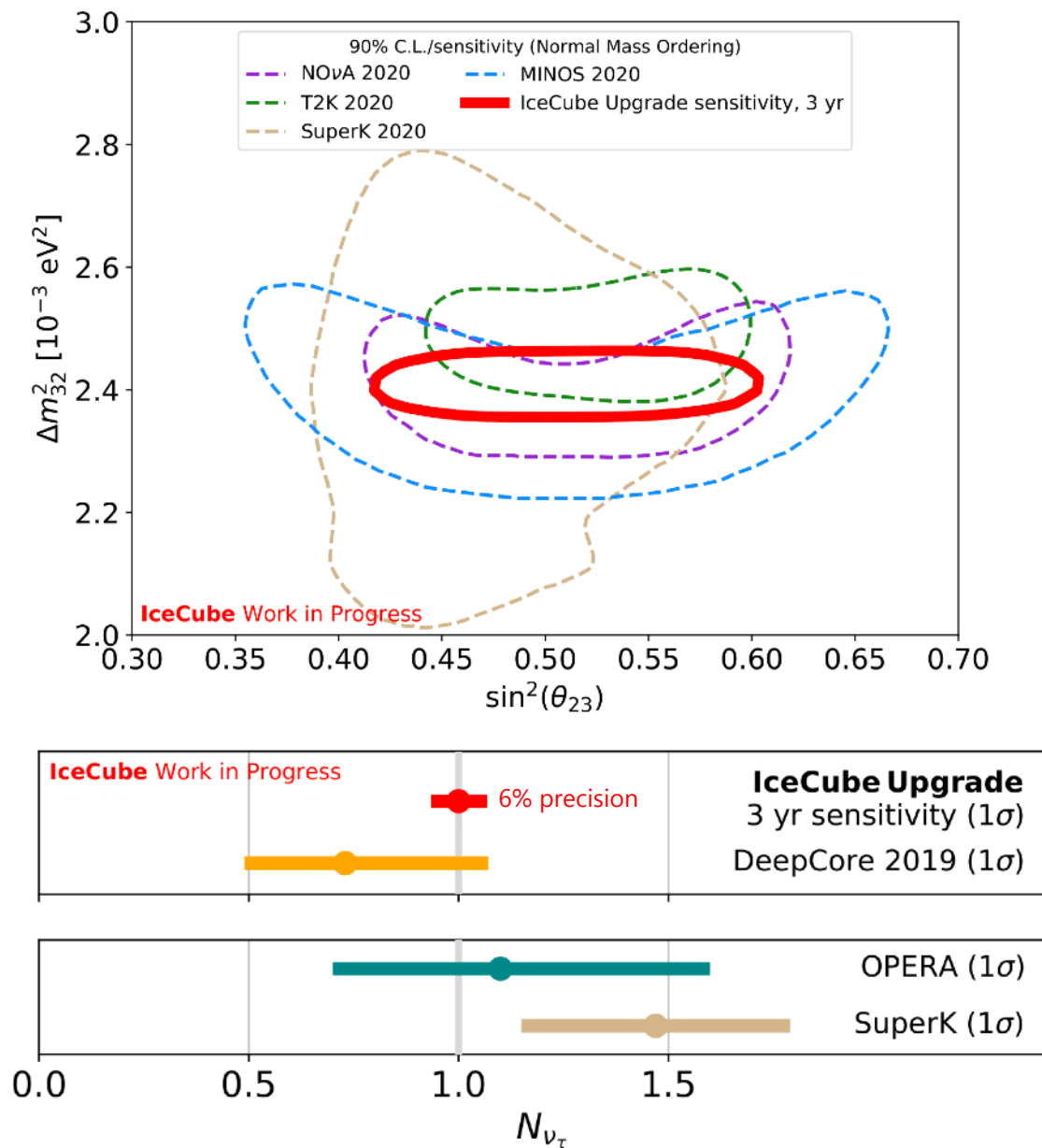
- Unique view of oscillations which complement (and will be competitive) with neutrino beam experiments

- Leading ν_τ appearance measurement(s) & constraints for (non)unitarity through N_{ν_τ}

- IceCube Upgrade is on path to improve calibration techniques and expand GeV capabilities

BACKUP

- Previous analyses - forward light propagation

- Upcoming analysis - backwards light propagation

- Future analysis & IceCube Upgrade - likelihood free inference, convolution neural network, graph neural network

  - Faster reconstructions will provide better event selections… positive feedback loop
  - Better reconstruction resolutions are always better
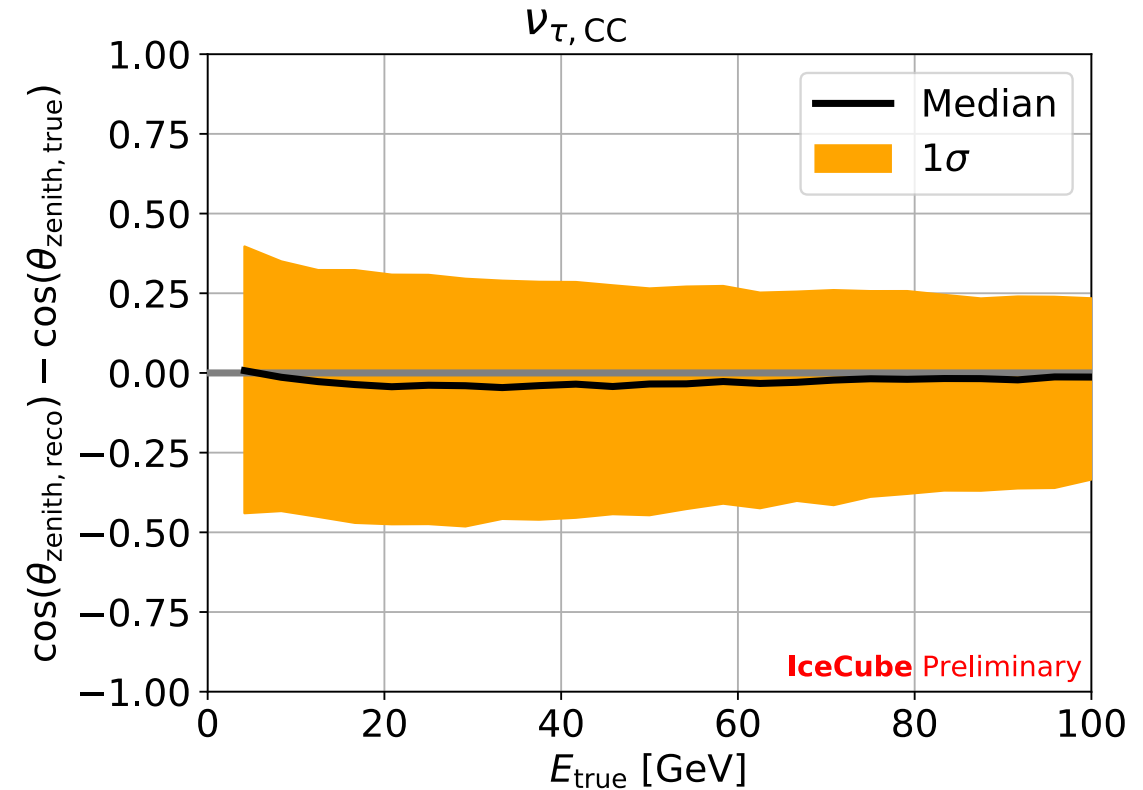
- ~40 systematic uncertainties evaluated for upcoming analysis
  - Many have a negligible impact on oscillation measurements and are dropped
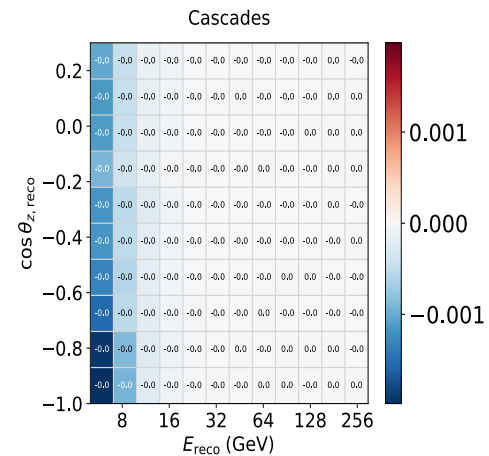 - The non-negligible systematics can be **very** non-negligible
    - e.g. DOM efficiency, hole ice photon scattering, spectral index
  - Shown here are a subset of systematics checked
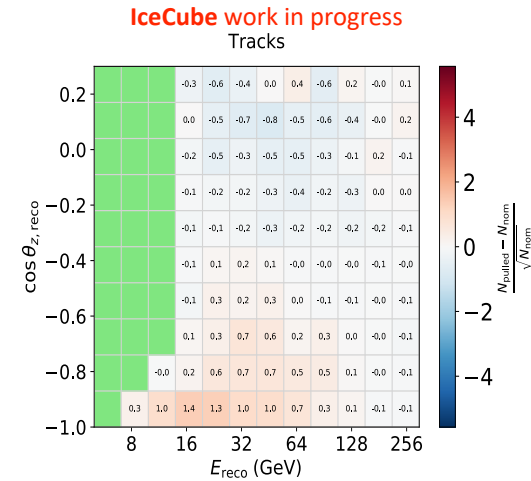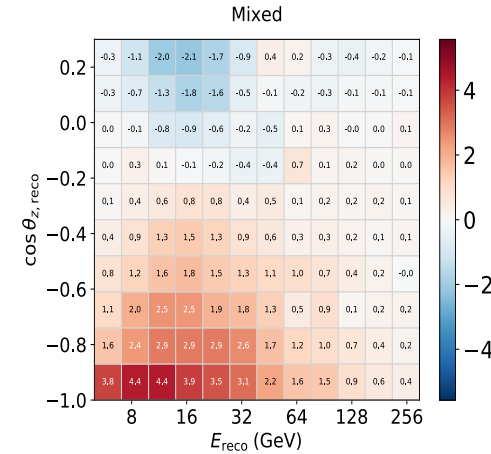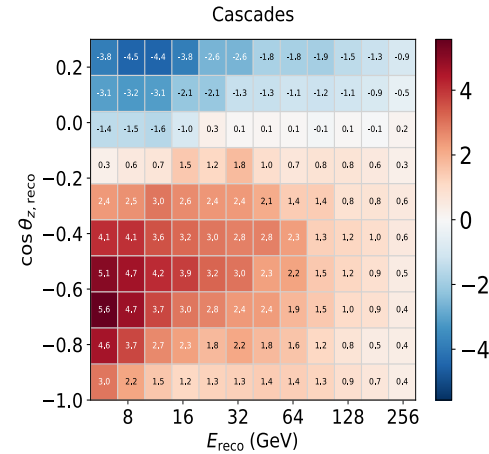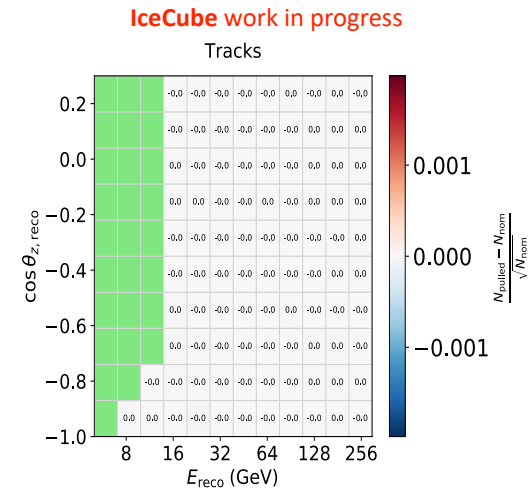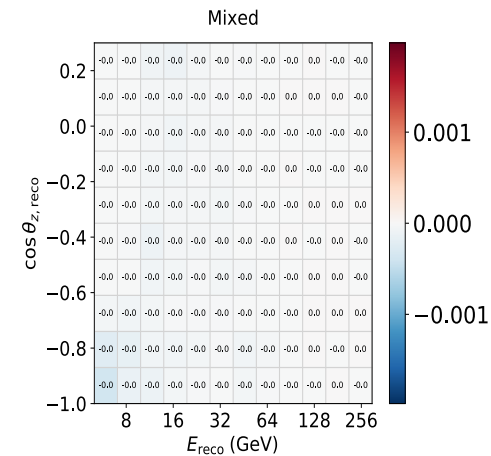
*arXiv:astro-ph/0611266

- Using 'Barr blocks'* for hadroproduction flux-related uncertainties
  - ~18 total

- Matrix Cascade Equation (MCEq)** for flux
  - Fast and amenable to different cosmic ray spectra & hadronic interaction models
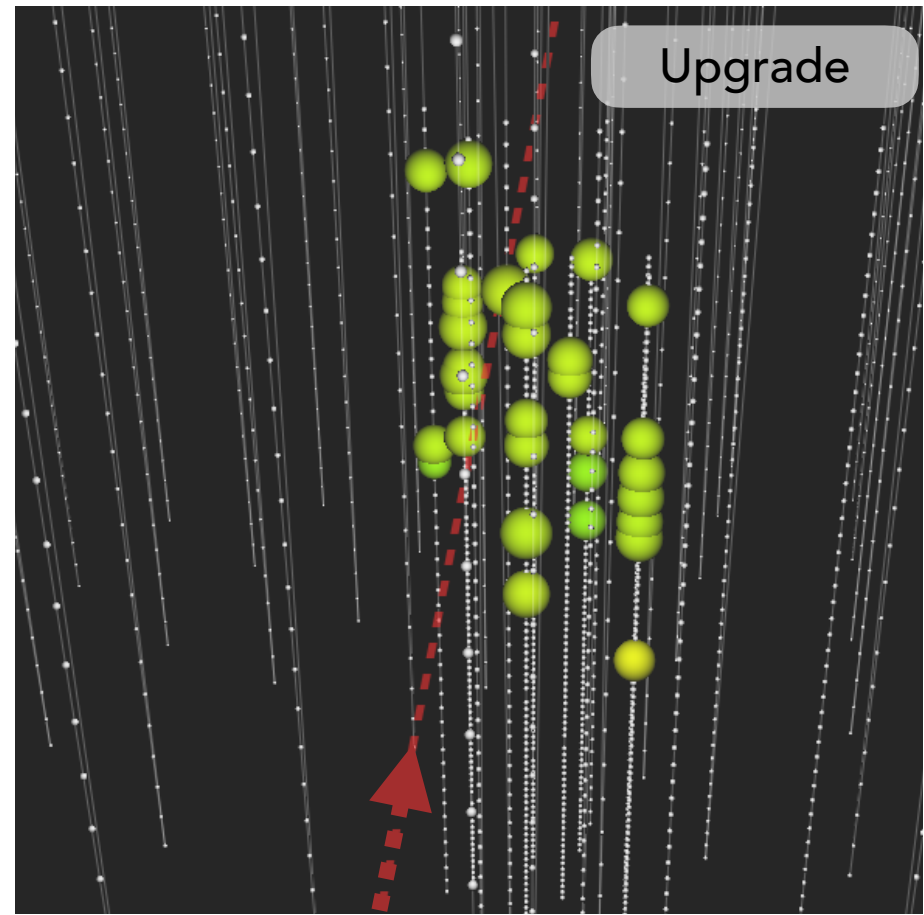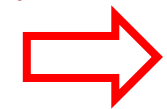 - Correlated treatment of evolving flux particle interactions & decays

$$\frac{d\Phi}{dX} = [\hat{\Lambda}_{int} + \hat{\Lambda}_{dec}\rho^{-1}]\Phi$$

**arXiv:1503.00544

UNIVERSITY OF
COPENHAGEN

- Dense instrumentation within inner core

DeepCore

Upgrade

$29\ \mathrm{GeV}\ \nu_\tau$
(up-going)

Detected Light
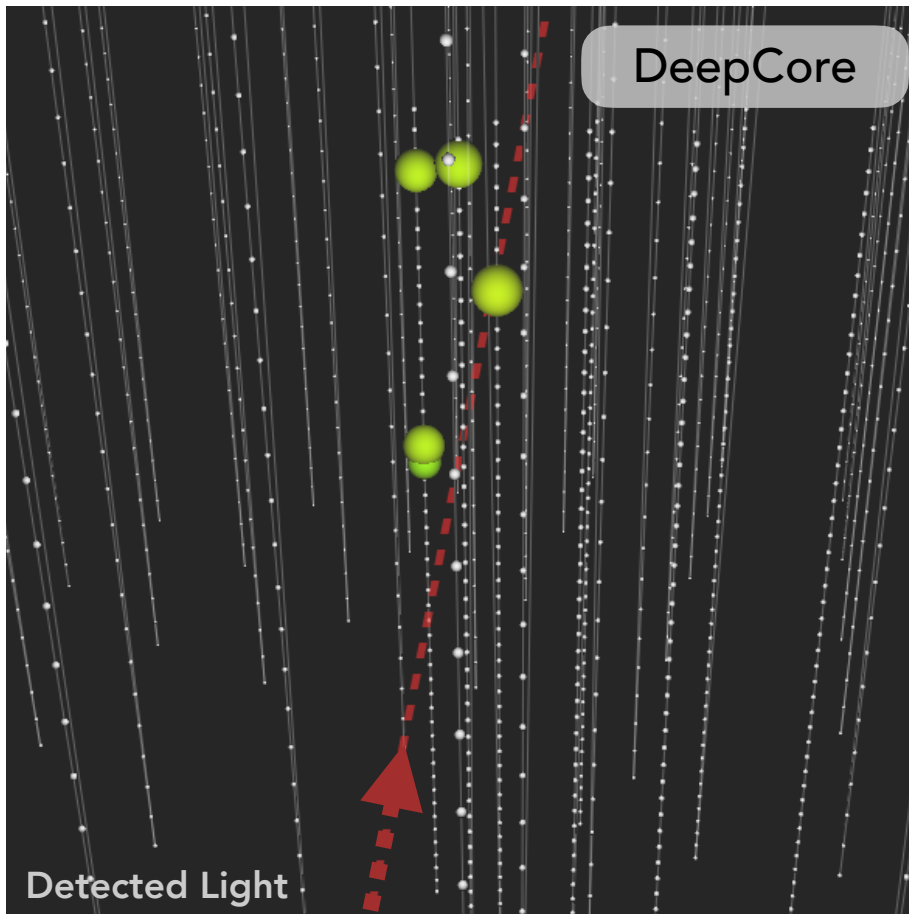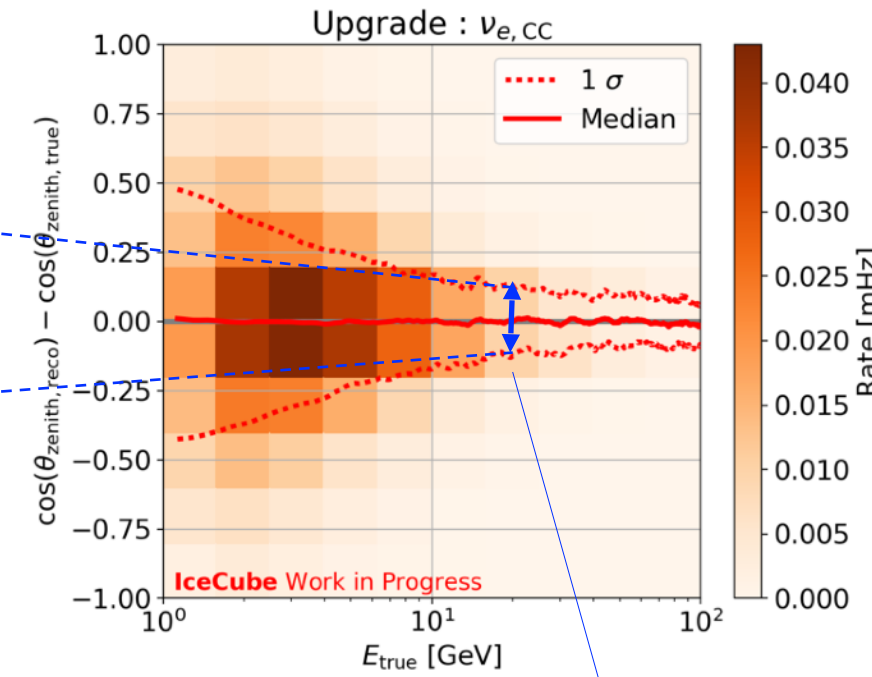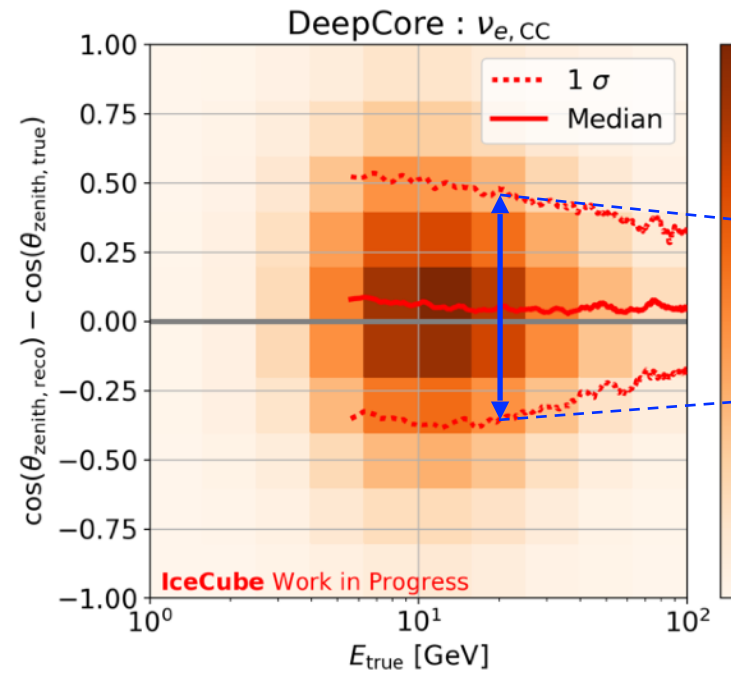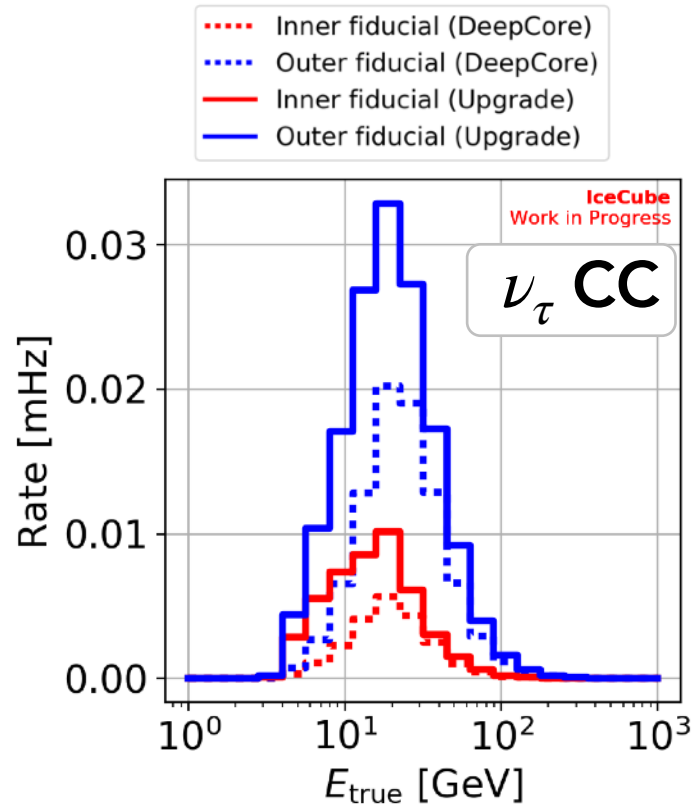
*ν_e CC and ν_τ CC both appear as cascades. ν_e are an easier proxy for cascade reconstruction development.

3x improvement in cascade resolution @ ν_τ appearance energies