IceCube Upgrade: ν-oscillations' high-statistics era
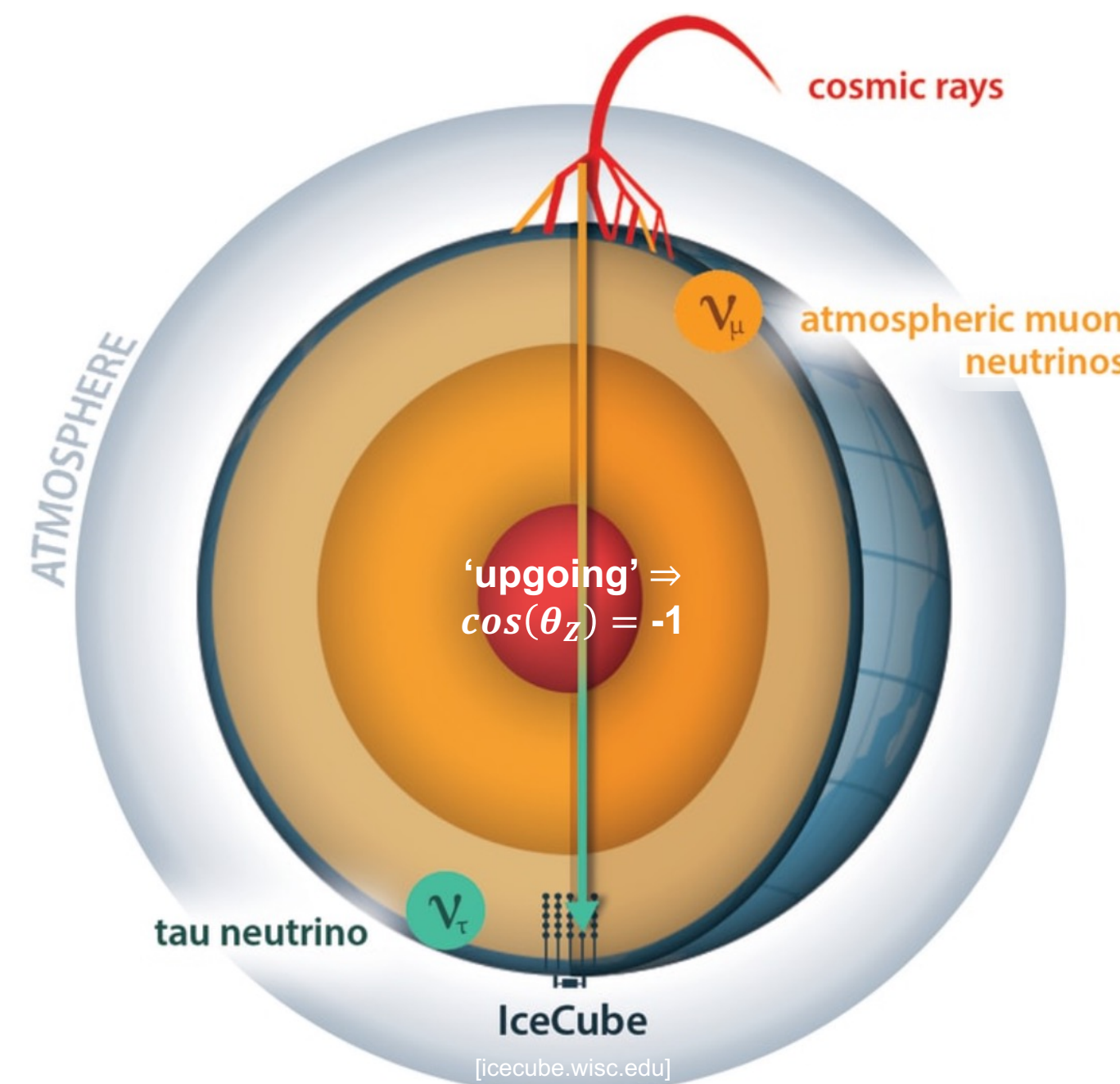
PHYSICS REACH

Atmospherics at IceCube
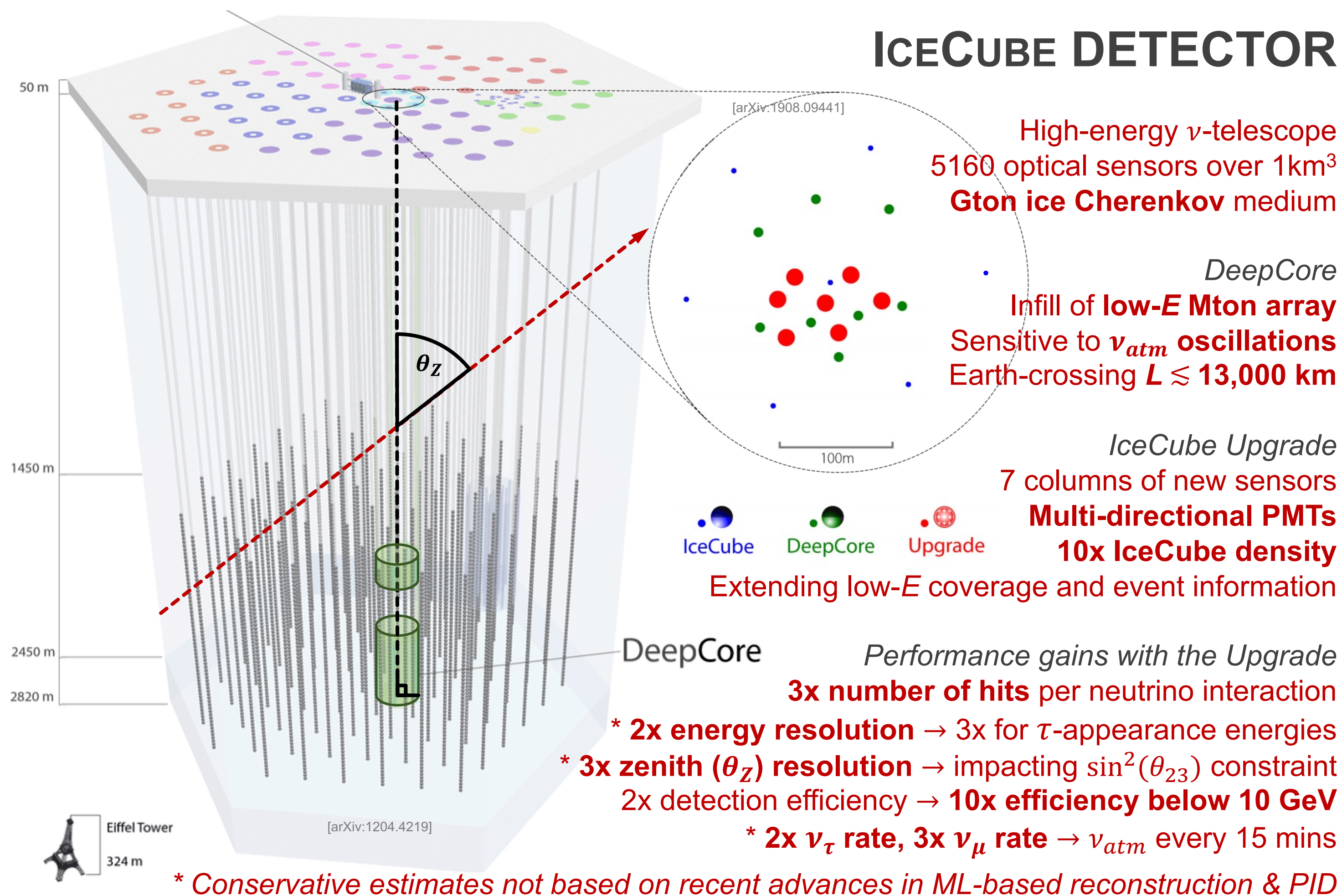- **86% of ν_τ global data** is from IceCube ν_{atm}
- Only **multi-channel experiment** sensitive to ν_τ-normalisation used to **probe unitarity**

Standard oscillations measurements
- ν_τ-appearance: $N_{\nu_\tau} \neq 1 \Rightarrow$ **non-unitary mixing** $\Rightarrow$ BSM, steriles, non-standard interactions
- ν_μ-disappearance: Constraints on atmospheric oscillation mass splitting & mixing angle

cosmic rays

ν_μ atmospheric muon neutrinos

ATMOSPHERE

'upgoing' $\Rightarrow$ $cos(\theta_z) = -1$

tau neutrino ν_τ

IceCube
[icecube.wisc.edu]

ν_e *electron neutrino* ν_μ *muon neutrino* ν_τ *tau neutrino*

IceCube DETECTOR

[arXiv:1908.09441]

High-energy ν-telescope
5160 optical sensors over 1km³
Gton ice Cherenkov medium

DeepCore
Infill of **low-E Mton array**
Sensitive to ν_{atm} **oscillations**
Earth-crossing $L \lesssim 13{,}000$ km

IceCube Upgrade
7 columns of new sensors
Multi-directional PMTs
10x IceCube density
Extending low-E coverage and event information

IceCube DeepCore Upgrade

θ_z

50 m

1450 m

2450 m

2820 m

DeepCore

Performance gains with the Upgrade
3x number of hits per neutrino interaction
* **2x energy resolution** → 3x for τ-appearance energies
* **3x zenith (θ_z) resolution** → impacting $sin^2(\theta_{23})$ constraint
2x detection efficiency → **10x efficiency below 10 GeV**
* **2x ν_τ rate, 3x ν_μ rate** → ν_{atm} every 15 mins

* Conservative estimates not based on recent advances in ML-based reconstruction & PID

Eiffel Tower
324 m
[arXiv:1204.4219]

100m

OSCILLATIONS

Near maximal $\nu_\mu \to \nu_\tau$ oscillations for $O(10$ GeV) Earth-crossing ν_{atm}

IceCube's baselines **access high-E** oscillations with $Q^2 \gtrsim 2m_\tau$ for ν_τ CC

The Upgrade will access features of ν_{atm} oscillations at high-(L/E) for the first time

Constrains Δm_{23}^2 & $sin^2(\theta_{23})$ with rich, higher-order oscillations space

$P(\nu_\mu \to \nu_e)$ matter effects **sensitive to mass-ordering**, signal in ν or $\bar{\nu} < 10$GeV

Upgrade   DeepCore

ν_τ-appearance
ν_μ-disappearance
Mass ordering

T2K NOνA MINOS
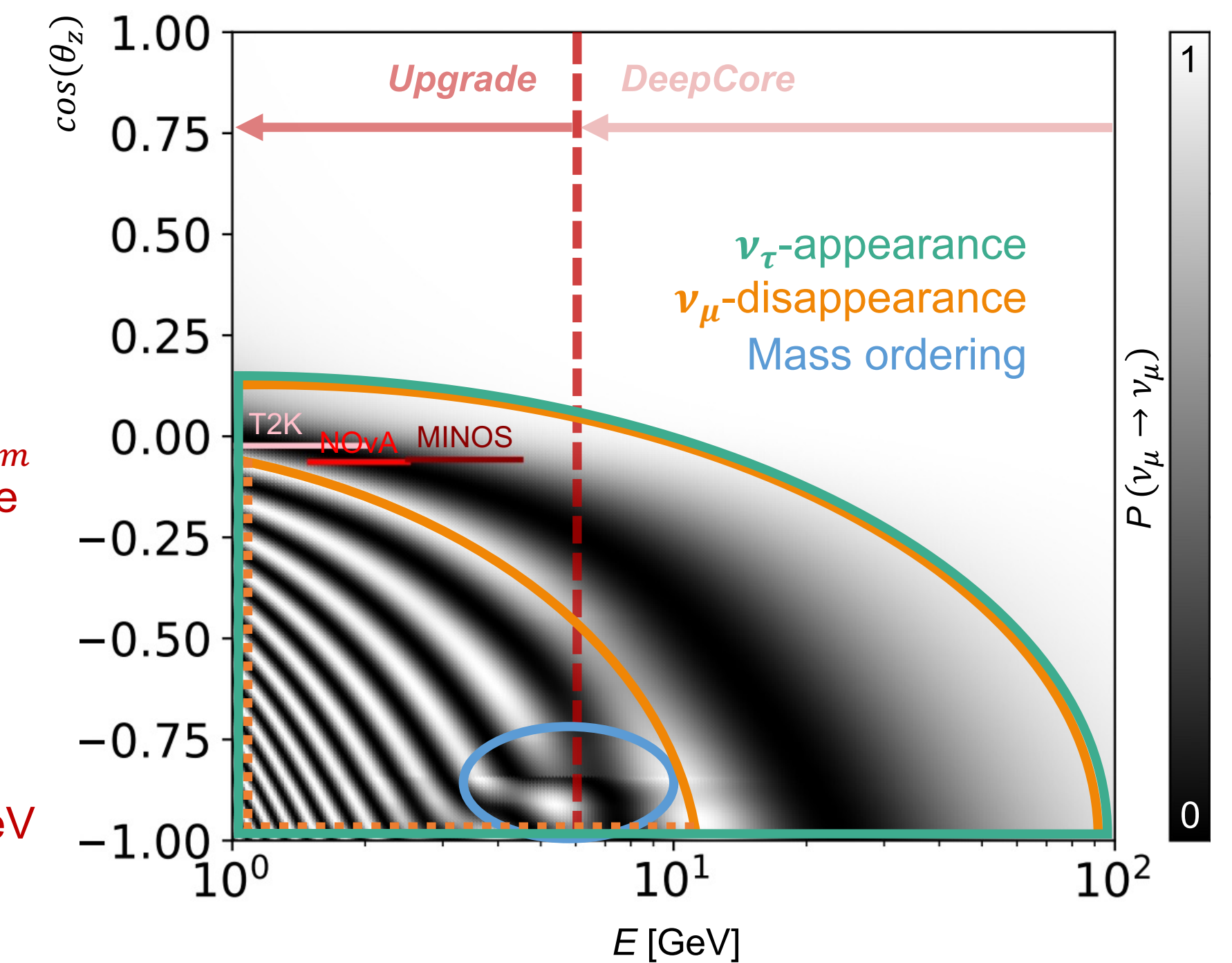
PROJECTIONS

Fits of standard oscillations to 3-year Upgrade-only expectation performed:

Sample, systematics & selection
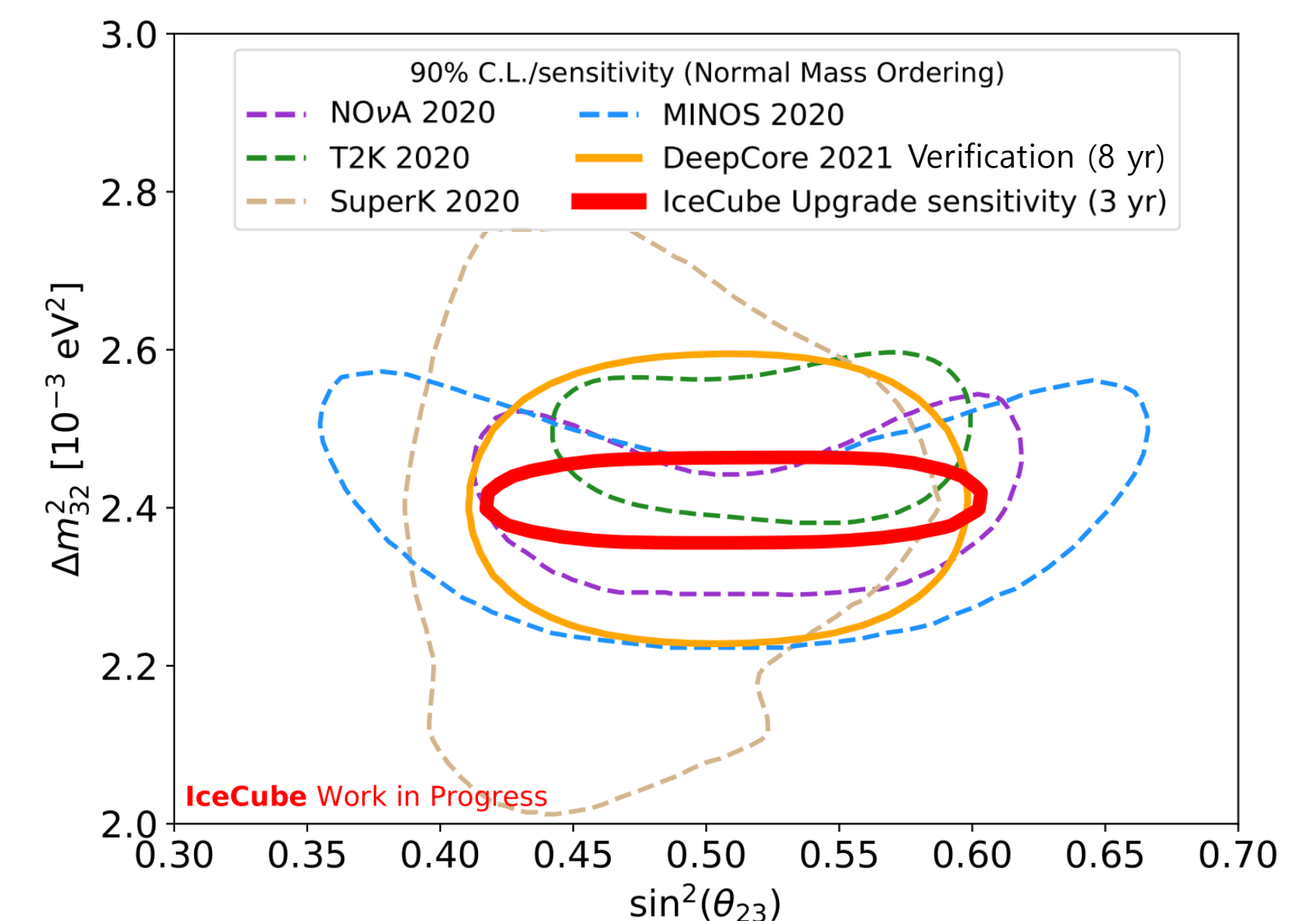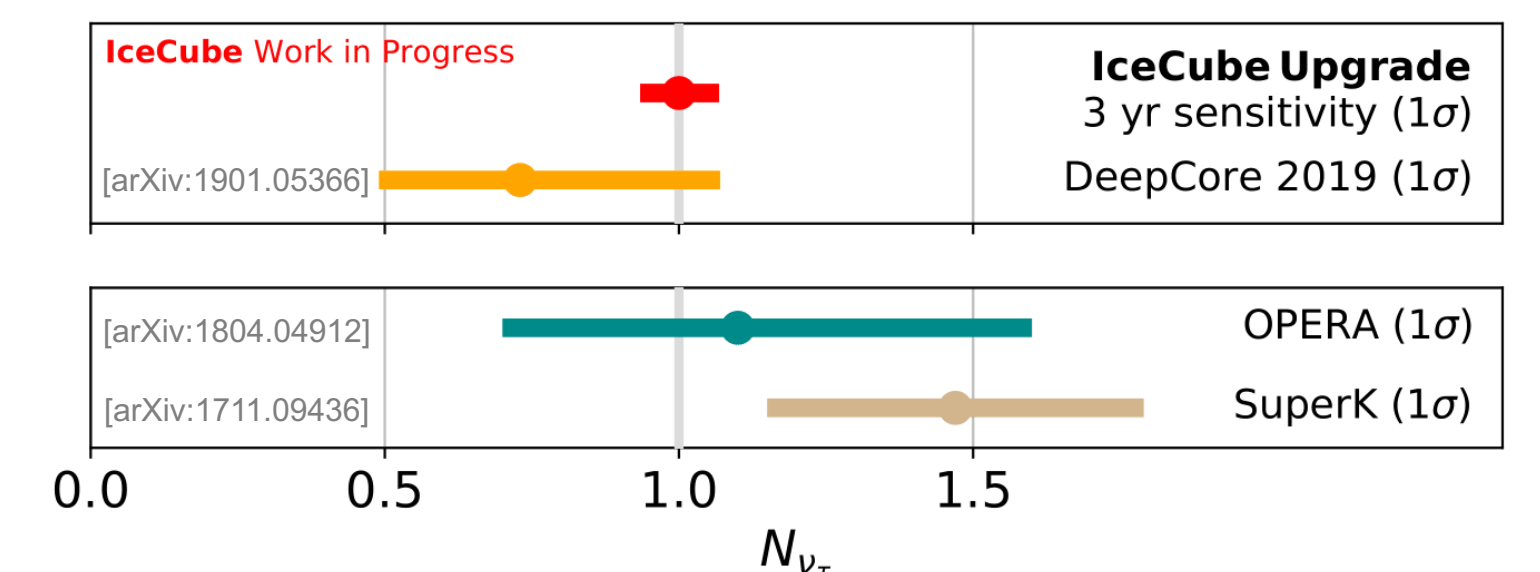- MCEq ν_{atm} flux + GENIE sample
- Events limited to Upgrade volume
- No noise or μ_{atm} contamination
- DeepCore detector systematics
- Adapted DeepCore event selection

Parameterised reconstruction & PID
- Reconstruction tuned to ν_e cascade with DeepCore ν_μ/ν_e relative $\sigma(\cos\theta_z)$
- DeepCore PID up-scaled such that 50% of ν_μ CC at 10GeV are tagged as tracks

ν_τ-appearance → N_{ν_τ} **6% precision** *
>4-fold improvement on current world best

ν_μ-disappearance → Limits on Δm_{32}^2 & $sin^2(\theta_{23})$ **competitive with long-baseline accelerator experiments** *

IceCube Work in Progress
[arXiv:1901.05366]
IceCube Upgrade
3 yr sensitivity (1σ)
DeepCore 2019 (1σ)

[arXiv:1804.04912] OPERA (1σ)
[arXiv:1711.09436] SuperK (1σ)

N_{ν_τ}

90% C.L./sensitivity (Normal Mass Ordering)
- NOνA 2020
- T2K 2020
- SuperK 2020
- MINOS 2020
- DeepCore 2021 Verification (8 yr)
- IceCube Upgrade sensitivity (3 yr)

IceCube Work in Progress

Δm_{32}^2 [10^{-3} eV²]
$sin^2(\theta_{23})$

[1] IceCube collab. 'Measurement of At…' (2017) [arXiv:1707.07081]
[2] IceCube collab. 'Measurement of At…' (2019) [arXiv:1901.05366]
[3] IceCube collab. 'An Absence of Neutri…' (2015) [arXiv:1204.4219]
[4] IceCube collab. 'The IceCube Neutrino…' (2016) [arXiv:1612.05093]
[5] A Ishihara. 'The IceCube Upgrade: Design…' (2019) [arXiv:1908.09441]
[6] R. Abraham et al. 'Tau neutrinos in the Next…' (2022) [arXiv:2203.05591]
[7] IceCube-Gen2 collab. 'Combined sens…' (2019) [arXiv:1911.06745]
[8] S. Ellis et al. 'Current and Future Neut…' (2020) [arXiv:2008.01088]

CARLSBERG FONDET

James Vincent Mead

Niels Bohr Institute