UNIVERSITY OF COPENHAGEN

Atmospheric neutrino oscillations in IceCube-DeepCore

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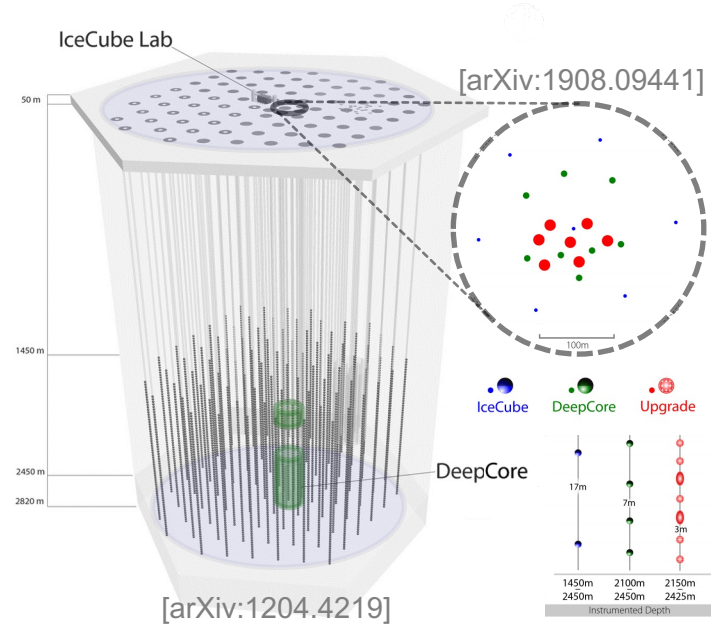
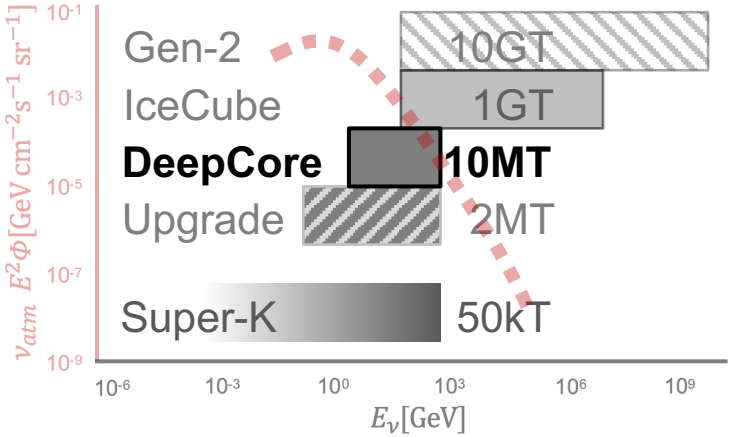
ICECUBE-DEEPCORE

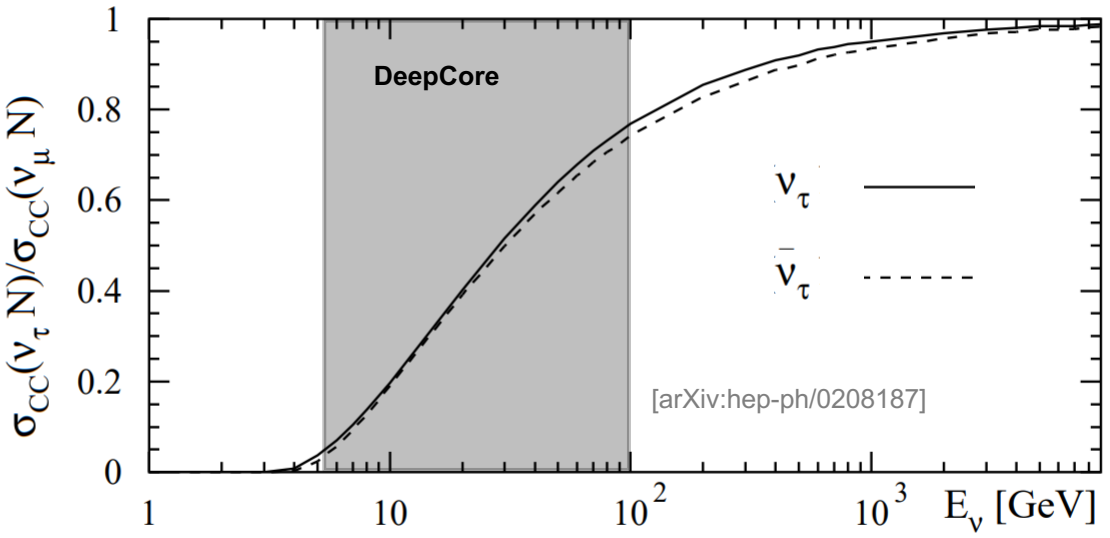
- ***IceCube** Neutrino Observatory*
  - Products of ν-N interactions radiate Cherenkov photons (no $\nu/\bar{\nu}$ ID)
  - 5160 optical sensors on 86 strings embedded within 1km^3 of ice
  - Down-facing 10” PMT in pressure sphere at depths 1450m - 2450m
- ***DeepCore** low-energy array*
  - Low-energy extension at 5x density in the cleanest ice (below 2100m)
  - Higher quantum efficiency PMTs in digital optical modules (DOMs)
  - mHz ν_{atm} rate (neutrino detection every 15 minutes)
- ***Upgrade** - **infill of DeepCore*** (2025-2026)
  - 700 new DOMs at 10x density on 7 strings in DeepCore region
  - New PMTs and first multi-directional modules (D-Eggs, mDOMs)
  - Overall 2x ν_τ rate and 3x ν_μ rate of DeepCore [arXiv:1908.09441]



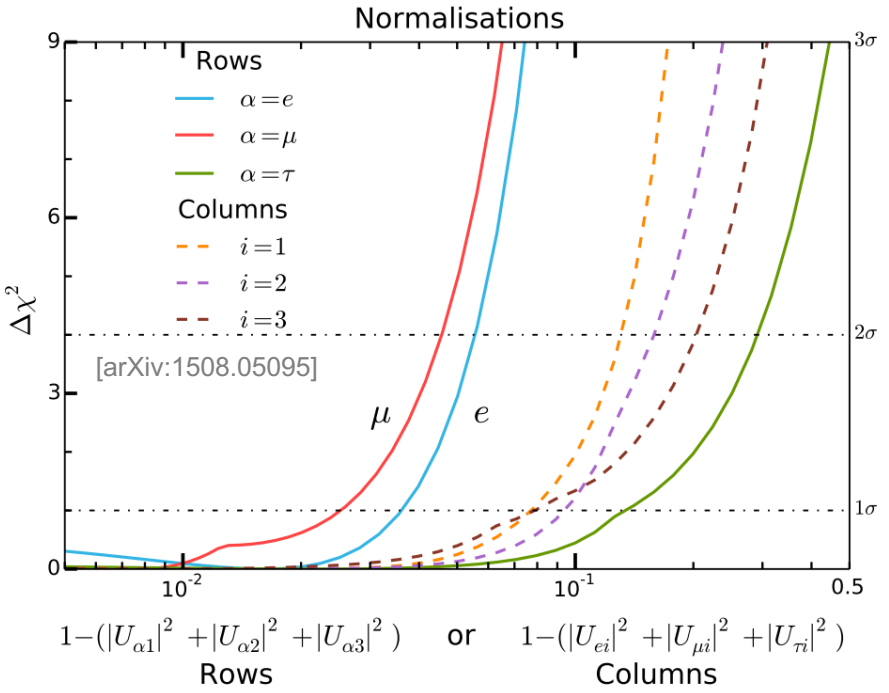


Sensitivity to ν_τ transitions

- ***High-statistics era for ν_τ physics***
  - Large Q^2 accesses CC to probe transitions to ν_τ
  - Only multi-channel experiment sensitive to N_{ν_τ}
  - 86% of ν_τ global data from DeepCore 3-year ν_{atm}



- ***Lepton flavour physics***
  - ν_τ PMNS elements least constrained
  - Major barrier to tests of PMNS unitarity

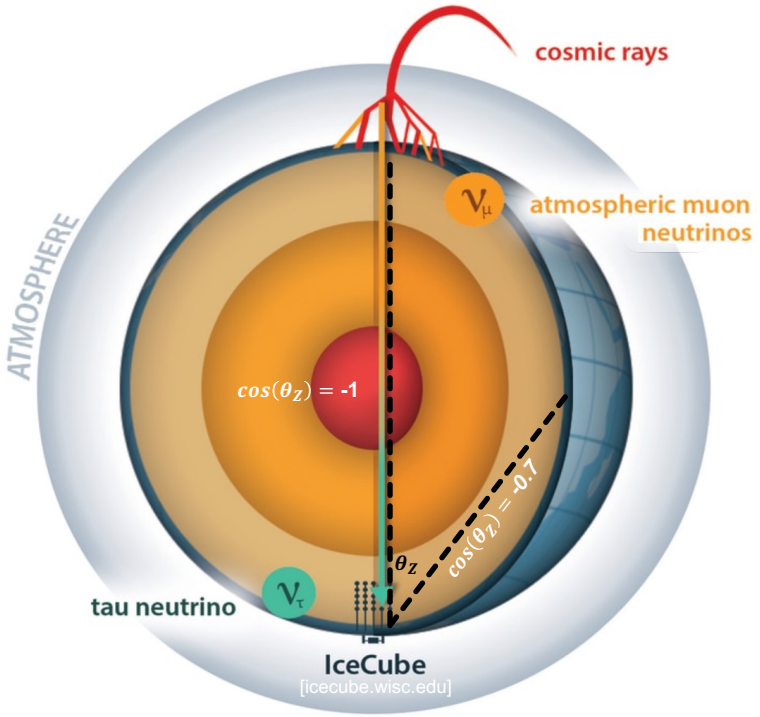


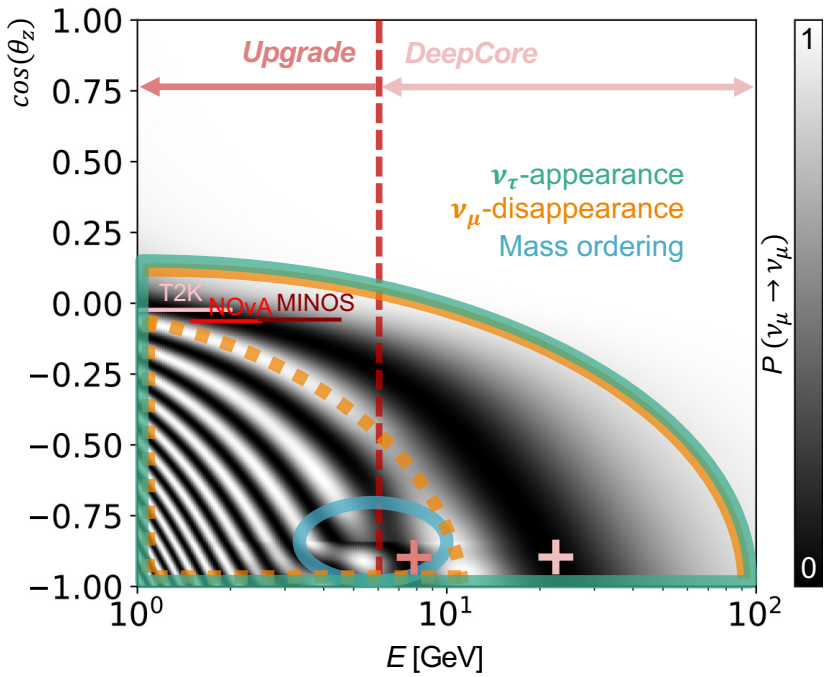
Atmospheric oscillations

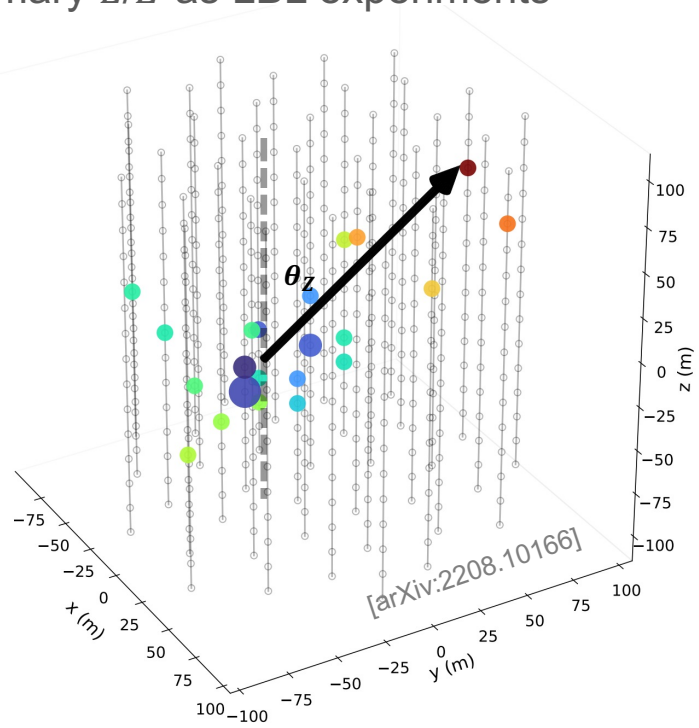
- ***Upgoing atmospheric muon neutrinos***
  - Maximum ~13,000km baseline, L
  - Near minimal ν_μ survival for ~25 GeV

High-energy long-baseline oscillations

- Interactions exceed $\nu_{\tau,CC}$ threshold ~4 GeV
- DeepCore optimum 25 GeV, sensitive to 5 GeV
- Accesses same primary L/E as LBL experiments



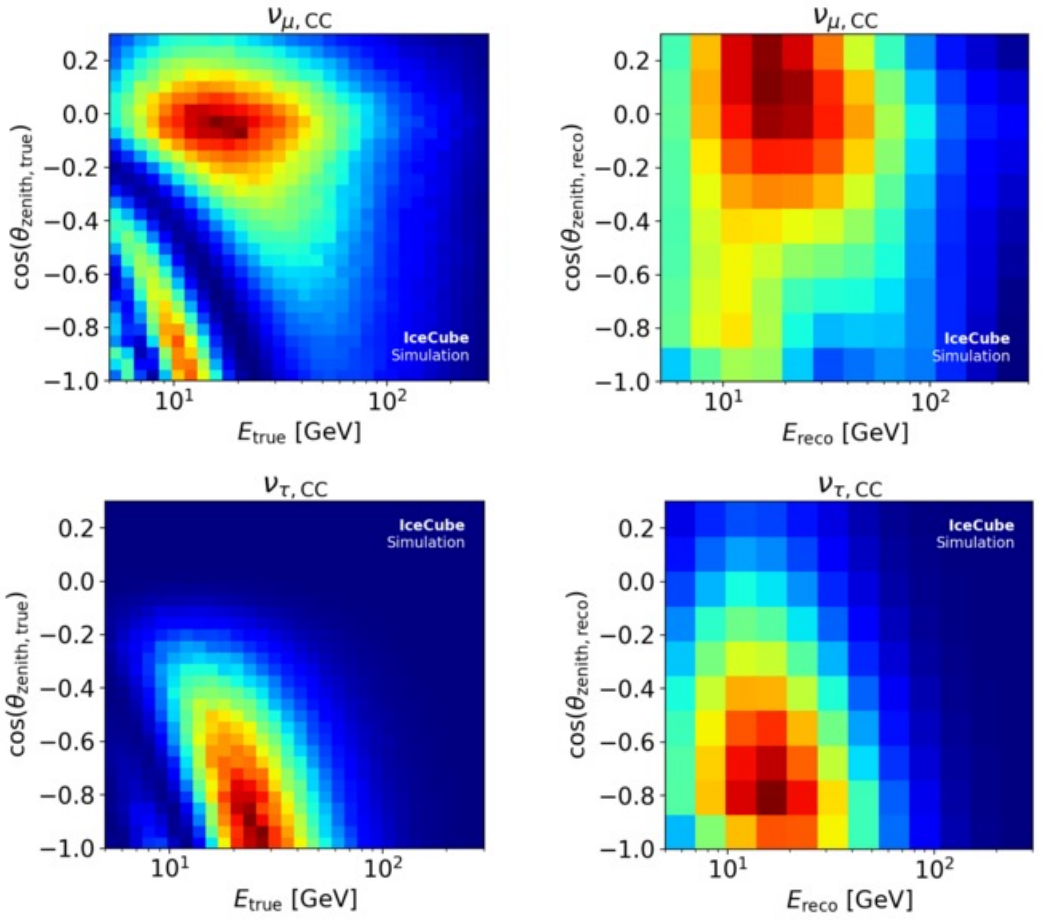




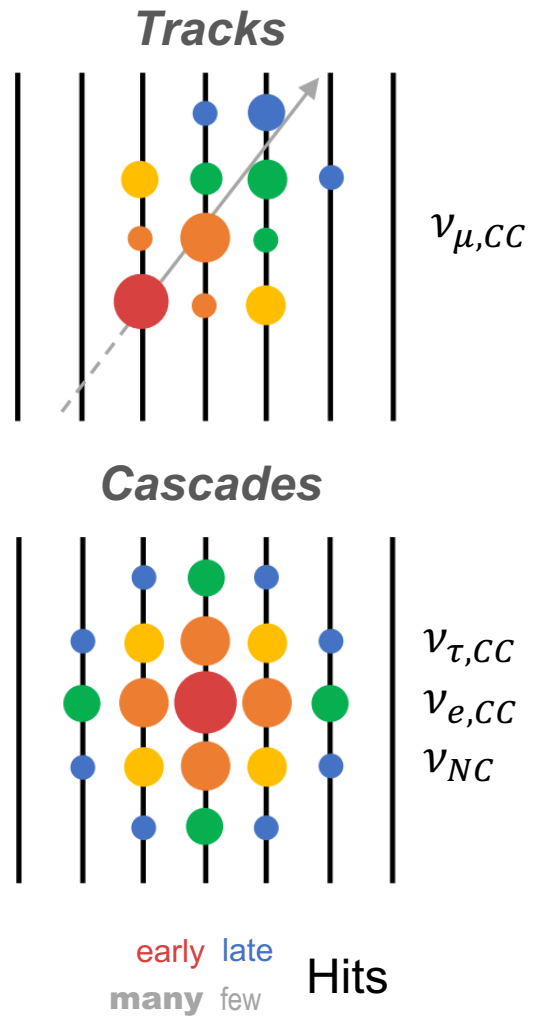
Oscillations analyses

- ***Atmospheric flux:***
  - Dominated by ν_μ
  - Negligible prompt ν_τ
- ***ν-N interactions:***
  - Predominantly DIS
  - Photons propagate in ice
- ***Hits to event classes:***
  - μ produces a ‘track’
  - e / τ / h produce a ‘cascade’
- ***Binned analysis:***
  - Energy, Zenith, PID
  - Fit using MC templates

ν_μ disappearance

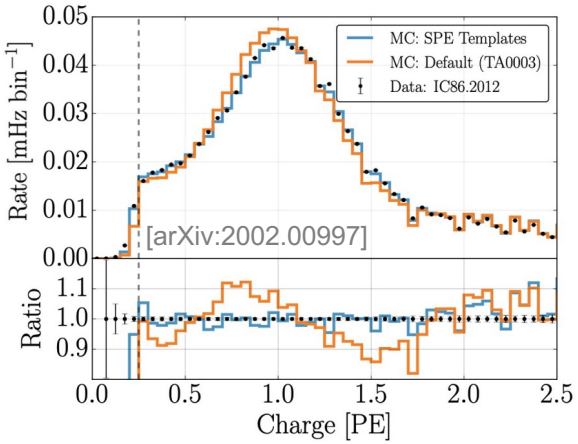


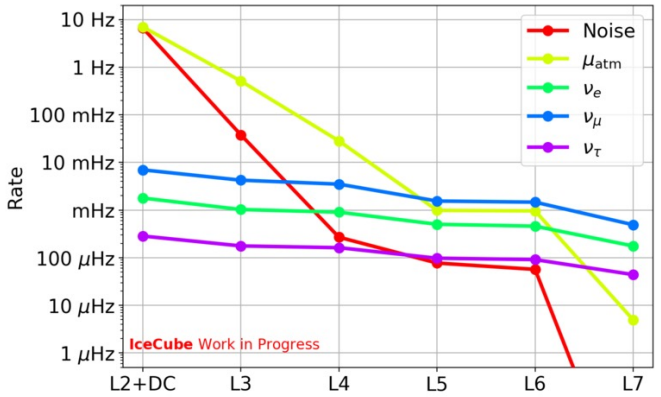
ν_τ appearance



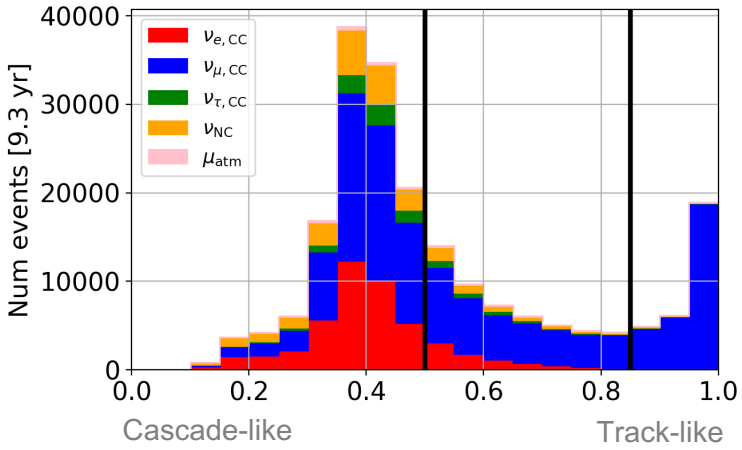
Next generation 8 year sample

- ***New developments***
  - Individual PMT pulse charge calibration
    → SPE identification and
    charge independent analysis
- ***Event selection***
  - Backgrounds reduced by factor of $O(10^6)$
    - Low-level muon filter & data-driven cuts
    - Noise cleaning & muon rejection LightGBM classifiers
- ***Reconstruction & PID***
  - High-fidelity reconstruction near end of the selection chain
    - Low-energy reconstructions: SANTA & RetroReco [arXiv:2203.02303]
  - Classifier discriminating $\nu_{\mu,CC}$ from all other topologies
    - Tracks versus cascades: XGBoost BDT





Current generation 9.3-year high-statistics event selection & PID

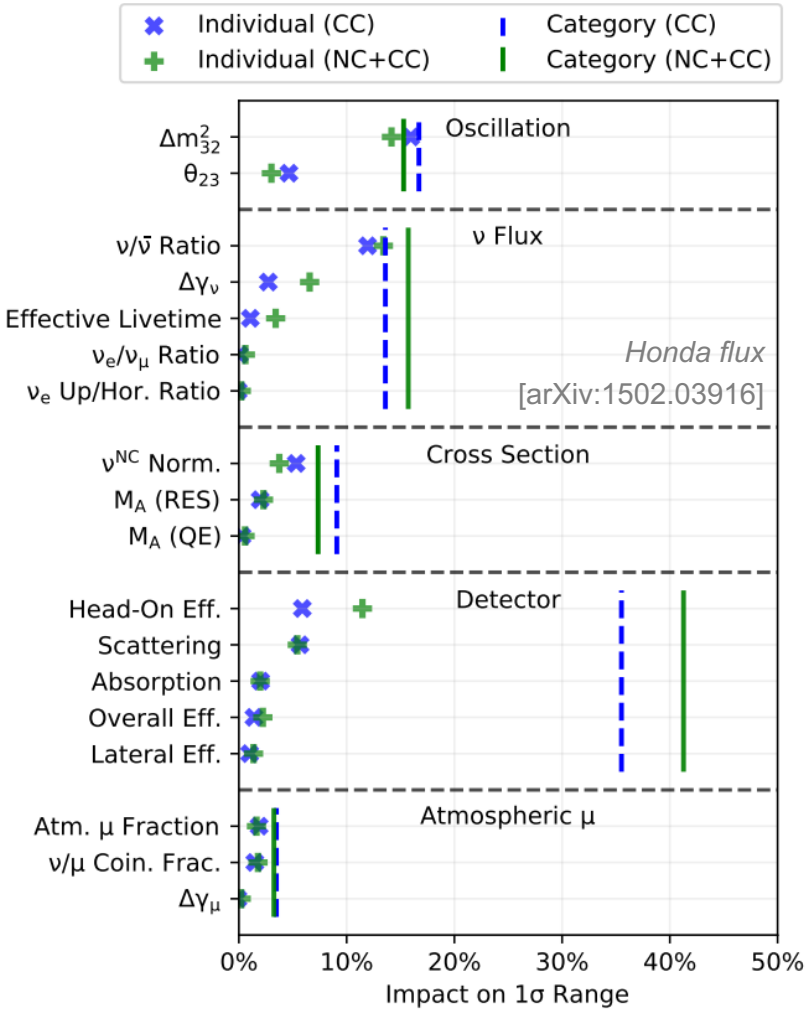


Systematic uncertainties

- ***Atmospheric flux using Matrix Cascade Equations*** [PoS(ICRC2015)1129] [arXiv:1806.04140]
  - Cosmic ray spectrum and hadronic model
  - Meson production, decay and (re)interaction & atmospheric density
- ***Cross-sections***
  - Axial mass uncertainties for quasi-elastic and resonance events
  - DIS transition from low-E (GENIE) to high-E (CSMS) & PDFs [arXiv:1510.05494] [arXiv:1106.3723]
- ***Ice & Detector properties***
  - Radioactive noise and individual charge calibration for every PMT
  - Optical properties across ice layers and refrozen drill column
  - Angular dependence of the DOMs' photon acceptance

~40 systematic uncertainties investigated
~1/2 included as nuisance parameters in fits of final analyses
Continuous 6D hypersurfaces fitted per analysis bin

DeepCore 3-year ν_τ appearance [arXiv:1901.05366]



Standard oscillations

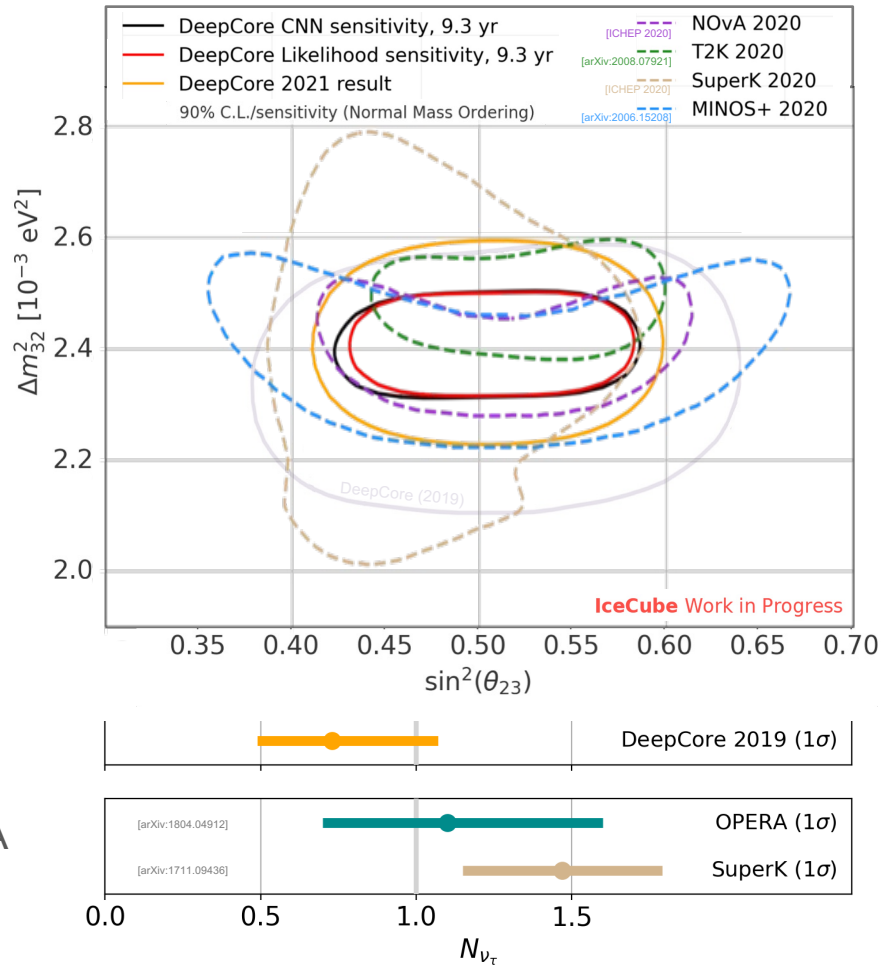
- ***DeepCore 3-year sample***
  - ν_μ disappearance (2017) [arXiv:1707.07081]
  - ν_τ appearance (2019) [arXiv:1901.05366]
- ***DeepCore 8-year sample***
  - ν_μ disappearance*
    - OscNext verification
      Fast reconstructions
      ~20k 'clean' tracks

      Corroborating full measurement
      Low photon scattering based reconstruction
      Result consistent with LBL experiments
      Best fit at near maximal mixing

$$\sin^2\theta_{23} = 0.505\,, \quad \Delta m^2_{32} = 2.41 \times 10^3 eV^2$$

    - OscNext-FLERCNN
      New classifiers and event selection
      ~200k tracks and cascades

      CNN reconstruction
      $O(10^3)$ times faster than SOTA likelihood-based methods



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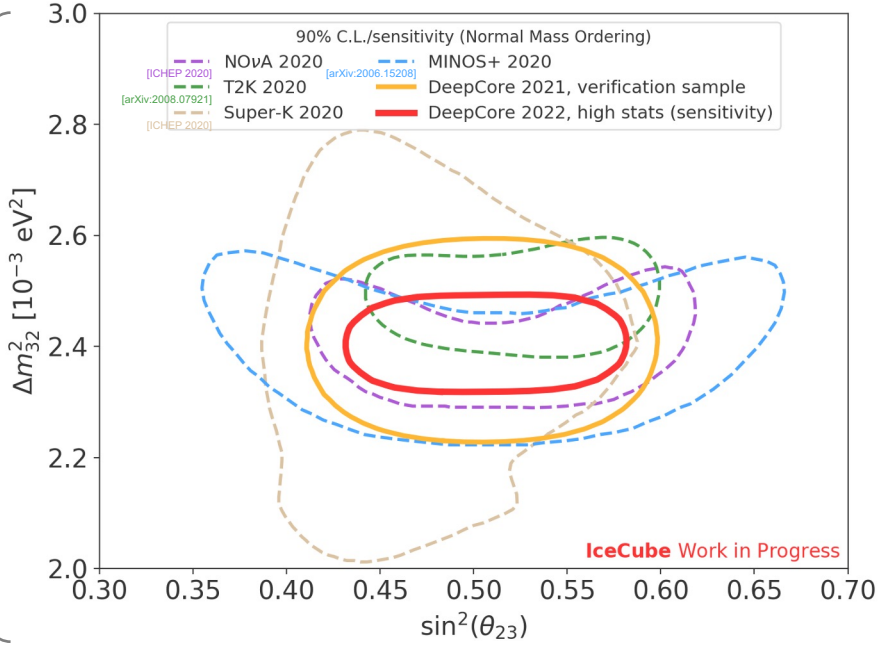
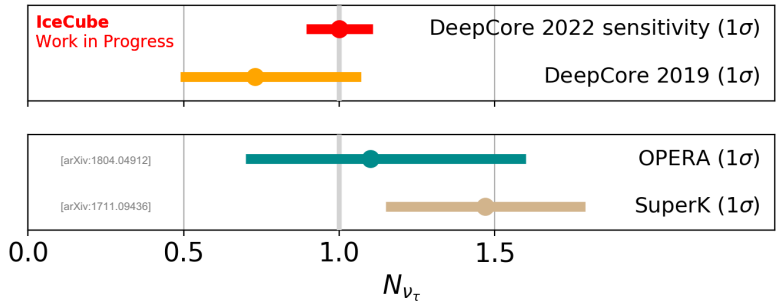
Standard oscillations

- ***DeepCore 3-year sample***
  - ν_μ disappearance (2017) [arXiv:1707.07081]
  - ν_τ appearance (2019) [arXiv:1901.05366]
- ***DeepCore 8-year sample***
  - ν_μ disappearance*
    - OscNext verification
    - OscNext-FLERCNN
  - ν_μ disappearance + ν_τ appearance*
    - OscNext high statistics
      Full 8D reconstruction
      ~200k tracks and cascades
  - Neutrino mass ordering*
  - Earth tomography*

Atmospheric oscillation parameters
Comparable mixing angle and mass splitting precision to LBL experiments



ν_τ normalisation
$\lesssim$15% precision in N_{ν_τ}
>2x current world best



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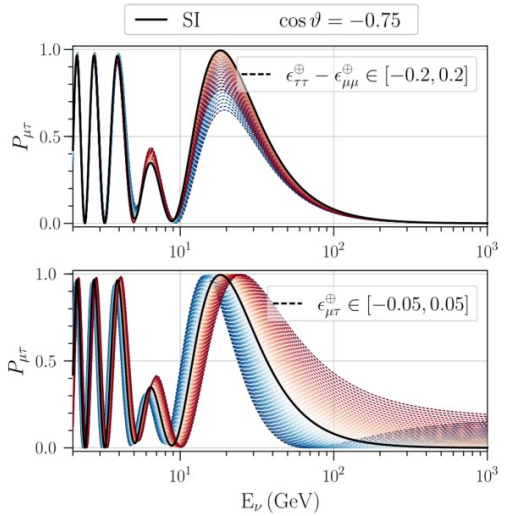
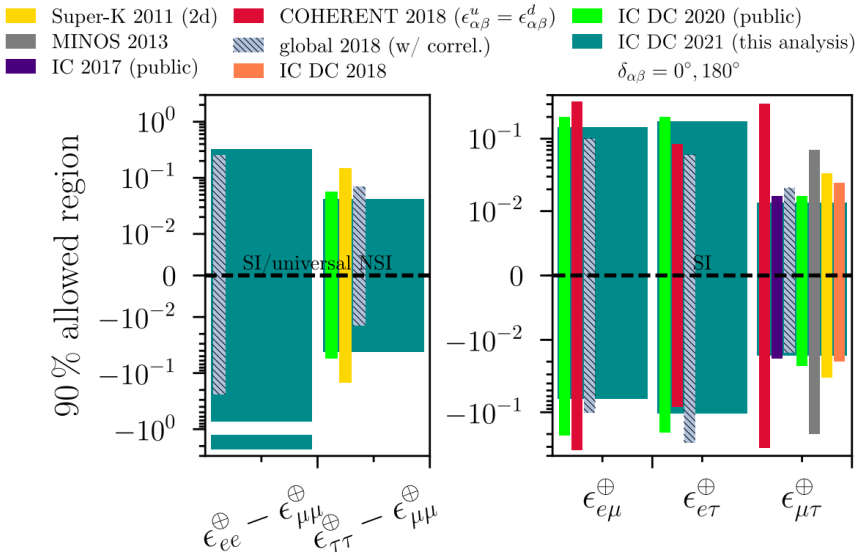
Non-standard interactions

- ***DeepCore 3-year sample*** [arXiv:2106.07755]
  - Matter effects
    - Coherent forward scattering sensitive to N_e in earth's core
  - New physics
    - Enhancement to SM matter effects through new heavy mediator
  - Experimental first
    - Constraining LFU violating and flavour changing simultaneously





$$H = \frac{1}{2E}\left[U_{\text{PMNS}}\begin{pmatrix}0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31}\end{pmatrix}U^{\dagger}_{\text{PMNS}} + a\begin{pmatrix}1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^{*}_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^{*}_{e\tau} & \varepsilon^{*}_{\mu\tau} & \varepsilon_{\tau\tau}\end{pmatrix}\right], \qquad a \equiv 2\sqrt{2}G_F N_e E$$

Flavour changing

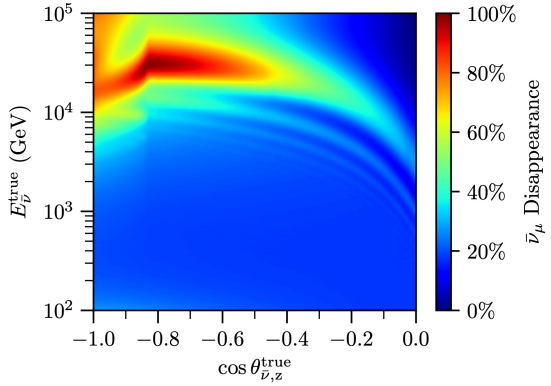
LFU violating

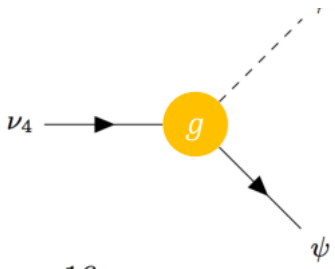
matter potential

electron density

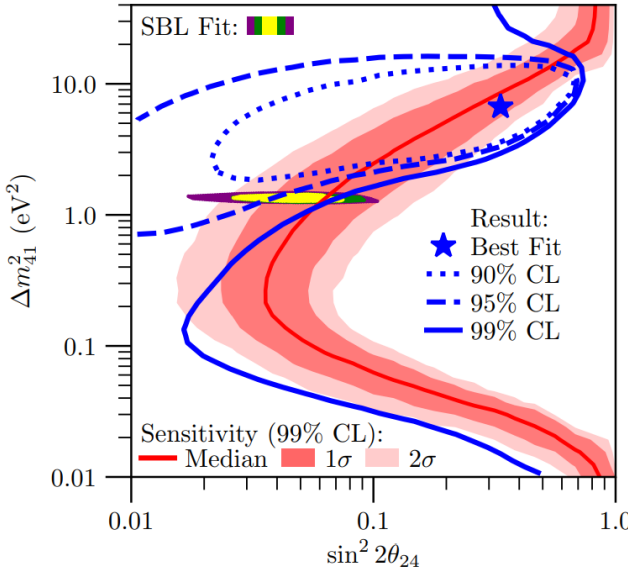
Unstable sterile neutrinos

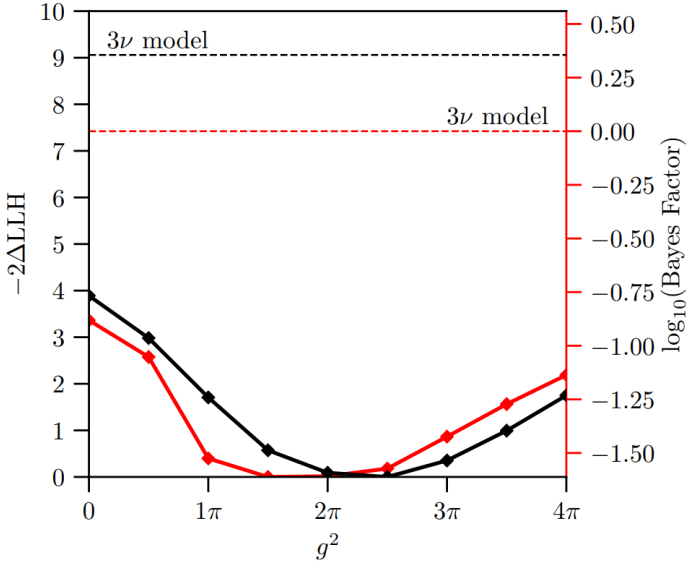
- ***DeepCore 8-year sample*** [arXiv:2204.00612]
  - Tension in global fits to eV steriles with SBL experiment anomalies
  - 3+1+decay model
    - ν_4 decay dampens oscillations
    - Tensions resolved if unstable ν_4 state decaying over LBLs
  - First unstable steriles search at IceCube





$$\tau = \frac{16\pi}{g^2 m_4}$$





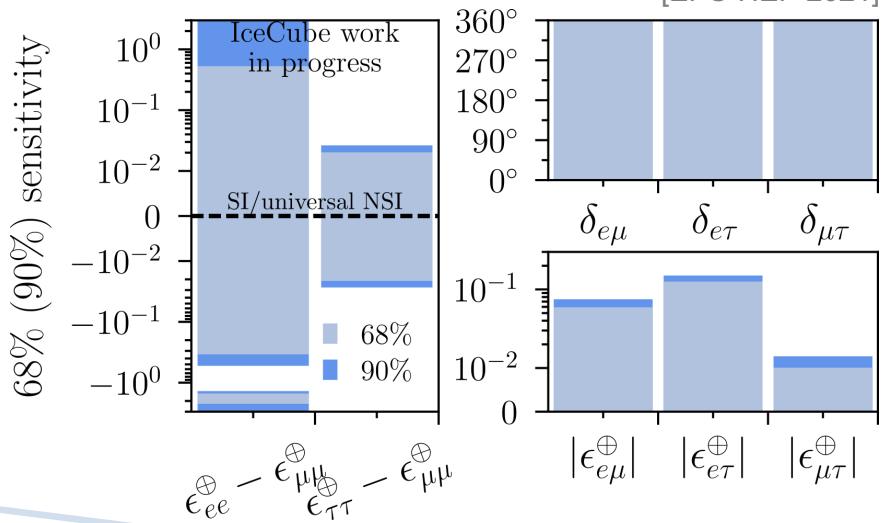
- Conclusions pending further study
  - No evidence of preference over standard 3ν paradigm
  - Weak preference over 3+1 scenario
  - Best fit lifetime: $\tau \sim 10^{-15}$s
  - Tension with SBL data remains

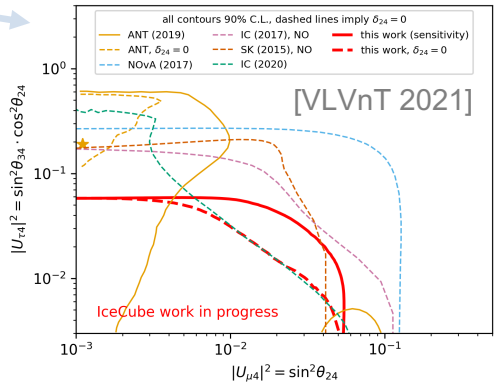
Beyond Standard Model

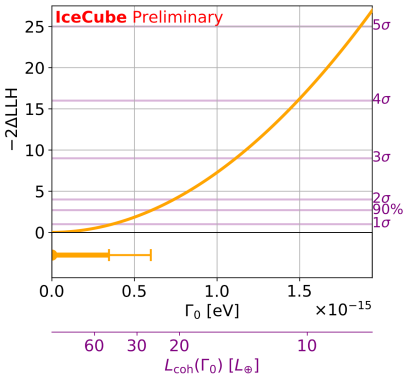
- ***DeepCore 3-year sample***
  - Non-Standard Interactions (2021) [arXiv:2106.07755]
  - 3+1 steriles O(eV) (2017) [arXiv:1702.05160]
- ***DeepCore 8-year sample***
  - Non-Standard Interactions*
  - Neutrino decoherence*
  - 3+1 steriles O(eV)*
  - 3+1+decay unstable sterile (2022) [arXiv:2204.00612]
- ***IceCube oscillations above 500GeV***
  - Neutrino decoherence*
  - Non-Standard Interactions (2022) [arXiv:2201.03566]
  - 3+1 steriles O(eV) (2020) [arXiv:2005.12942]
  - Lorentz invariance violation* (2017) [arXiv:1709.03434]

Broad BSM reach
Coupled with N_{ν_τ} sensitivity
→ Probe of 3ν paradigm

[EPS-HEP 2021]







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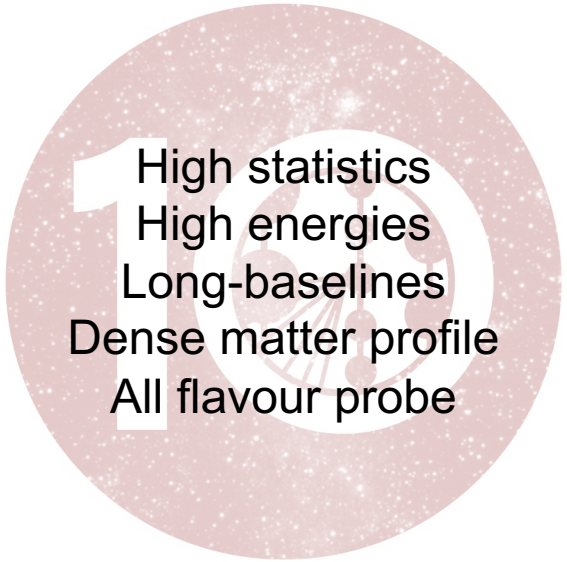
Summary

- ***Oscillations in DeepCore***
  - Complimentary of and competitive with accelerator experiments
  - Offers leading constraints on (non-)unitarity through ν_τ-normalisation
  - Extensive BSM program with complementary studies are higher energies
- ***Next generation of analysis***
  - 8 years of detector live-time → $O(10^5)\,\nu_{\mathrm{atm}}$ interactions
  - New calibration, simulation, reconstruction, PID, systematics and analysis software
  - Charge-independent samples, off-signal regions, data-driven background classification
- ***Next generation of detector***
  - The Upgrade greatly enhances DeepCore's oscillations sensitivity and statistical power
  - Conservative estimates predict world-leading results within 1 year of data-taking
  - Set to inherit new SOTA reconstruction & PID (FreeDOM, DynEdge) and ice-modelling (Birefringence)

[arXiv:2208.10166] [Neutrino 2022] [GraphNet Git] [arXiv:2107.08692]

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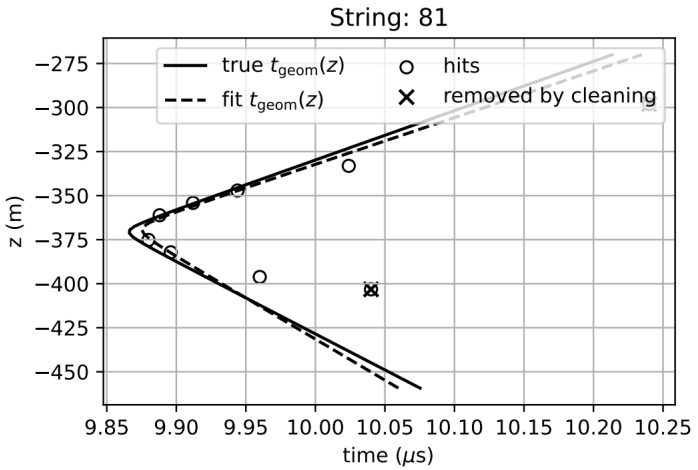
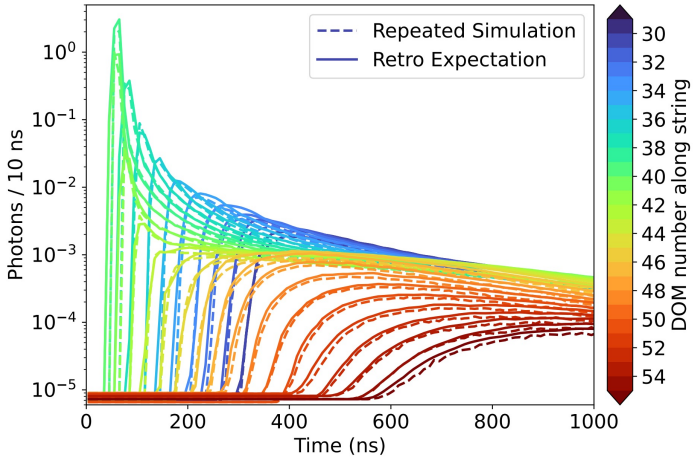
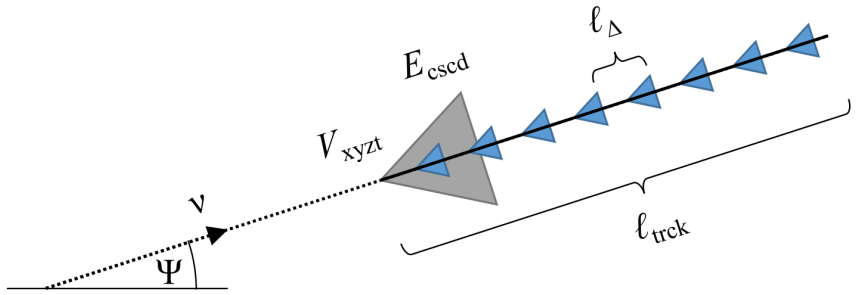
Low-energy reconstruction

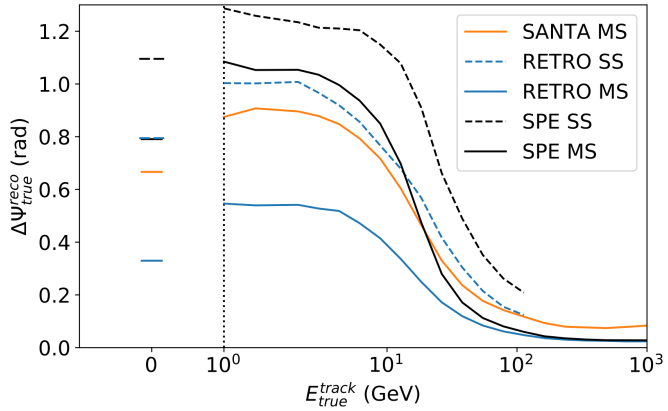
- ***SANTA – removing indirect light***
  - Fast directional reconstruction fitting light cone to DOM hits along a string
  - Hits not consistent with fitted light cone rejected as scattered light
- ***RetroReco – reverse table reconstruction***
  - Reverse simulated photon emission used to approximate LLH tables
  - Provides use of scattered and unscattered light in 8D event model





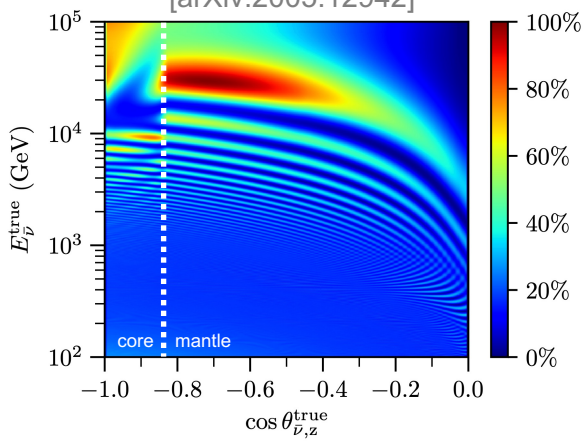


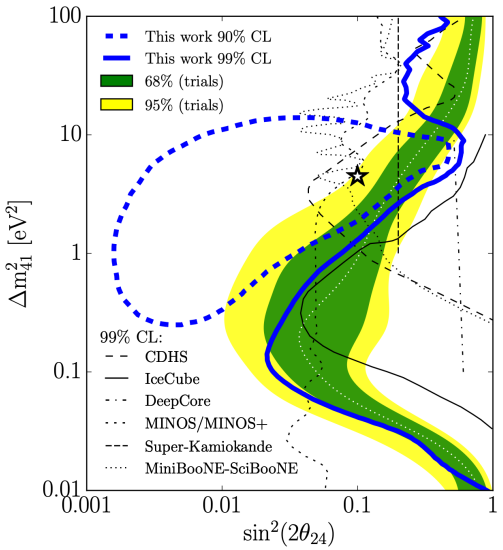
[arXiv:2203.02303]



Oscillations above 500GeV

[arXiv:2005.12942]

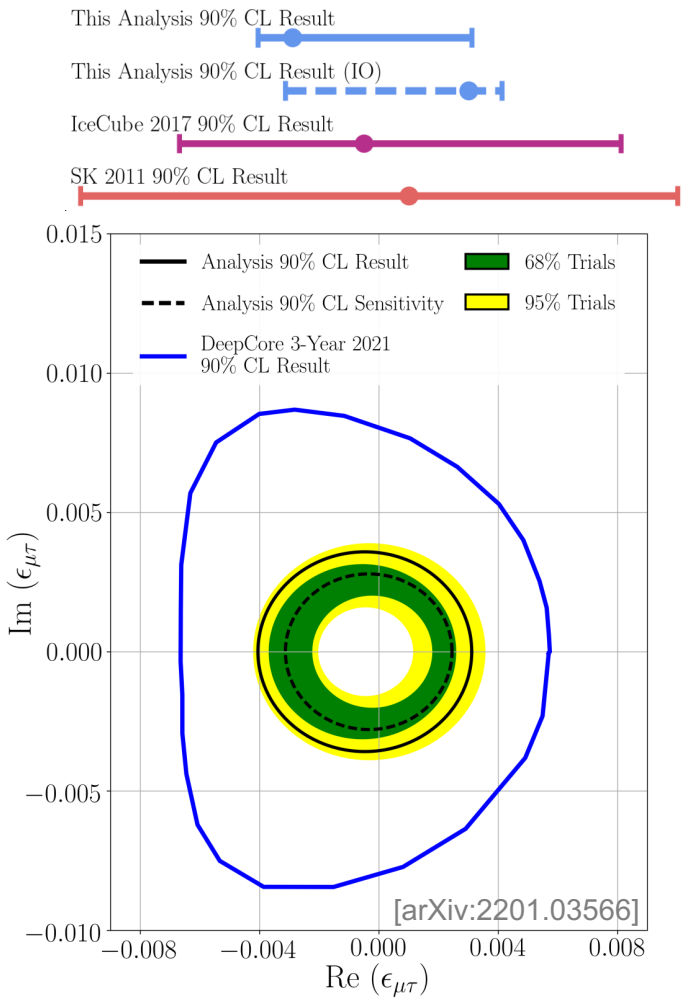




IceCube 8-year sample
~300k tracks (0.5 – 10 TeV)
Complementary to DeepCore

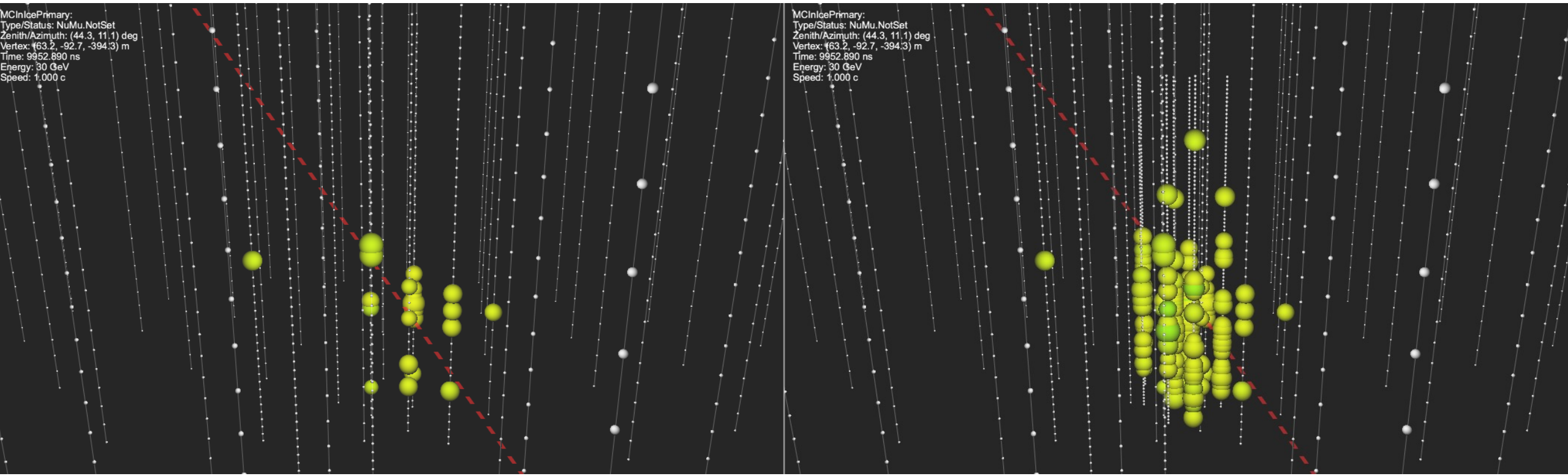
- ***3+1 steriles 0(eV)***
  - Test for matter-enhanced oscillation
  - Mass splitting between $0.01\ \text{eV}^2 - 100\ \text{eV}^2$
  - Best fit: $\sin^2(2\theta_{24}) = 0.10,\ \Delta m^2_{41} = 4.5\text{eV}^2$
  - Consistent with no sterile neutrino hypothesis

- ***Non-Standard interactions***
  - Probing Re and Im components of $\epsilon_{\mu\tau}$
  - Strongest constraint on any NSI parameter from any oscillation channel to date
  - Results consistent with no NSI



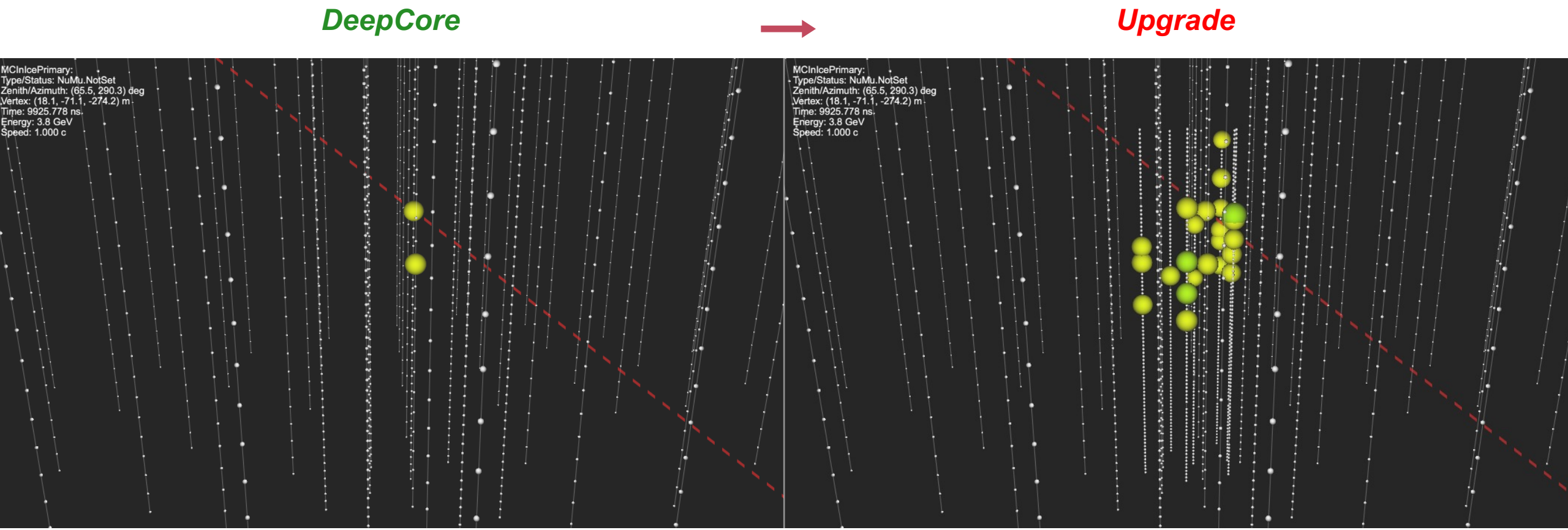
Earth crossing ν_τ appearance

DeepCore → ***Upgrade***



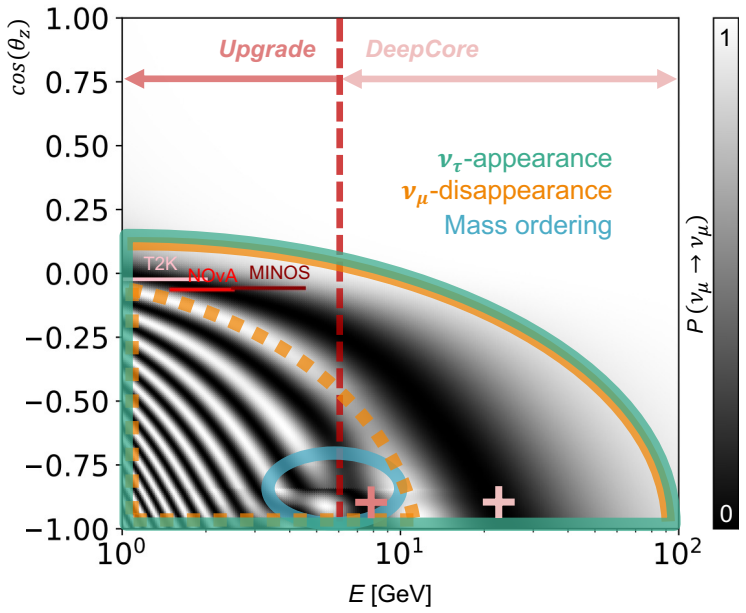
- The same simulated 30 GeV $\nu_\mu \rightarrow \mu$-track as viewed by each setup

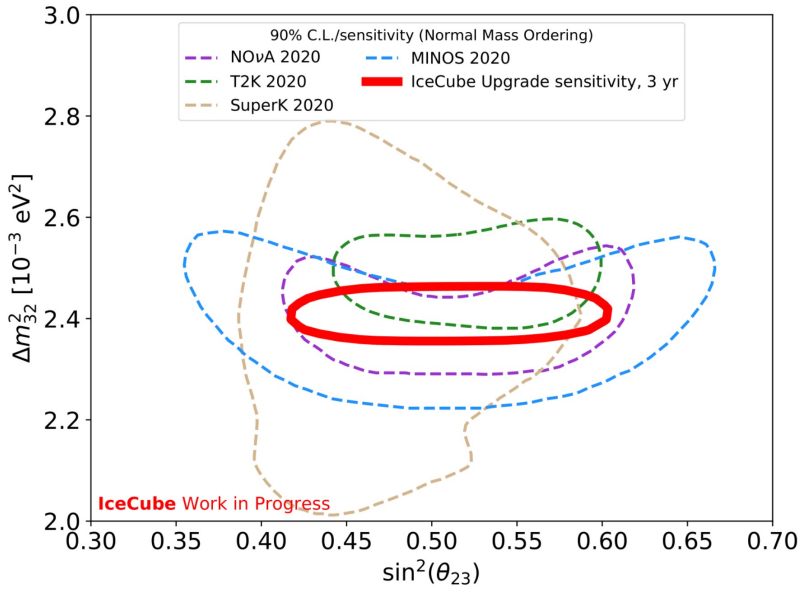
Matter effects for NMO

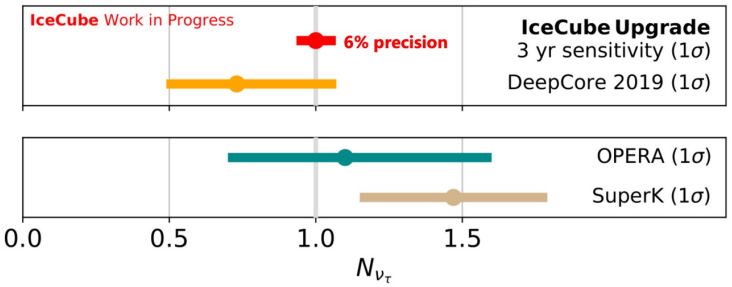


- The same simulated 3.8 GeV $\nu_\mu \rightarrow \mu$-track as viewed by each setup

Upgrade standard oscillations



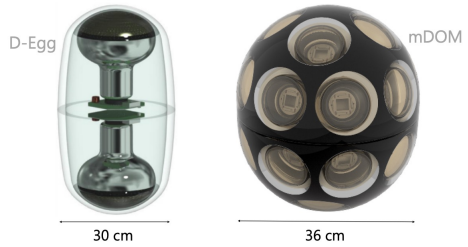




World-leading N_{ν_τ} sensitivity in one year

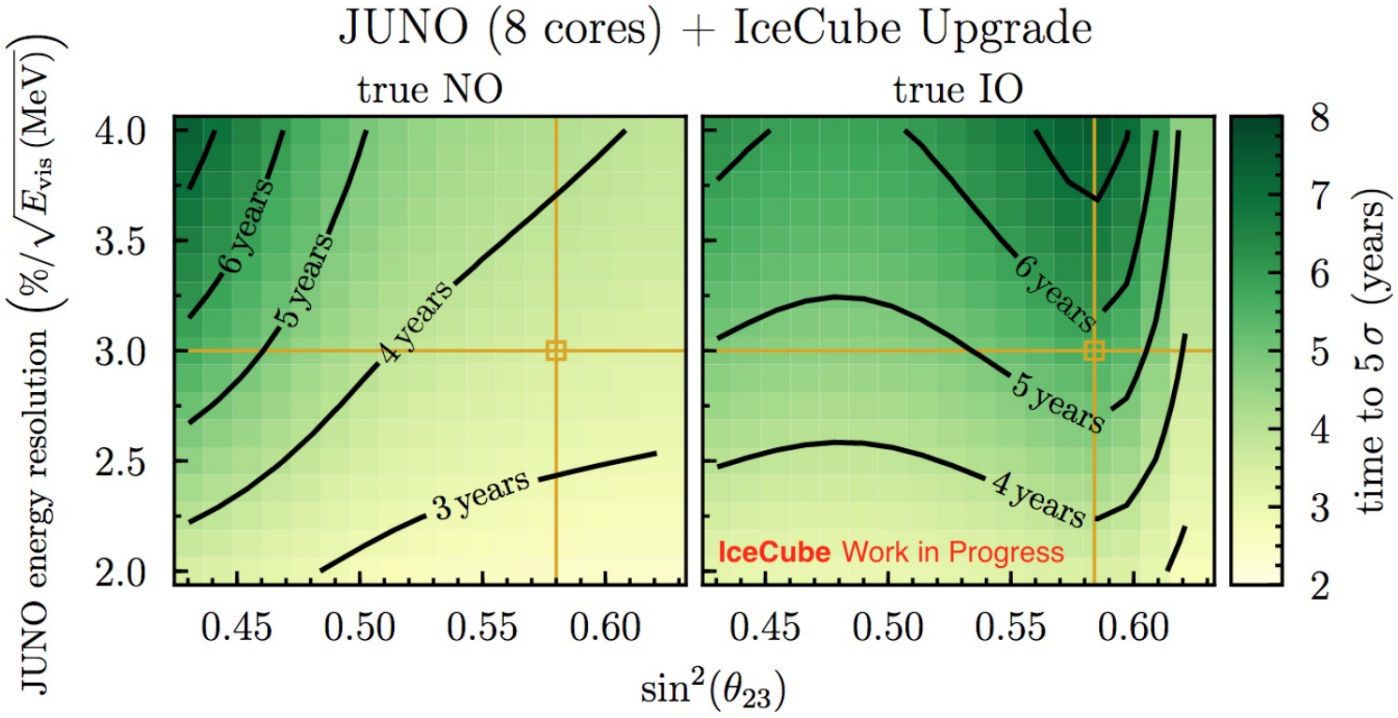
Competitive mass splitting and mixing angle in three years

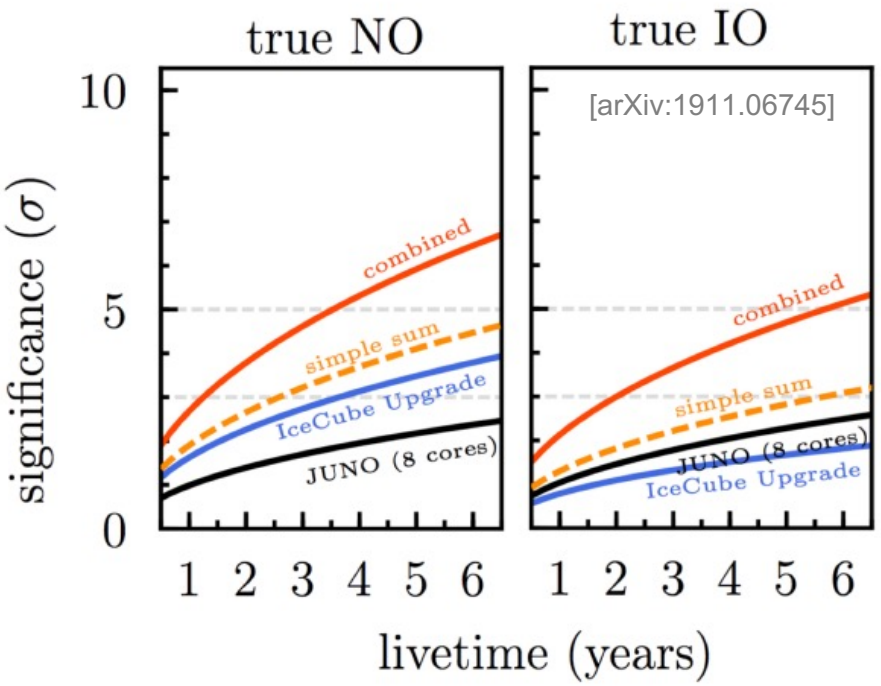
- Huge boost in statistical power from more than doubled ν_{atm} rate
- Accessing dominant upgoing oscillation signal at lower energies
- Conservative treatment for parameterised reconstruction and PID
- Sensitivities based on fits to 3-year live-time Upgrade only volume projections



Upgrade complementarity

[doi:10.1088/1742-6596/1468/1/012169]



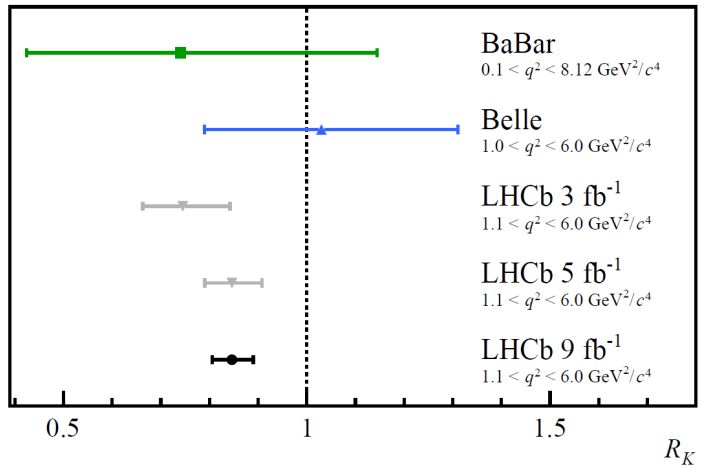


- Live-time for JUNO+Upgrade to obtain 5σ sensitivity of NMO as f(true $\sin^2\theta_{23}$) and JUNO's $\sigma(E)$
- Yellow squares mark nominal values, contours trace parameter combinations required time in years

DeepCore complementarity

- ***New physics with leptons / flavour universality***
  - $(g-2)_\mu$ points to lepton sensitive NP (4.2σ)
  - LHCb flavour anomalies → P_5' ⇒ 3.3σ, R_K ⇒ 3.1σ
    - Singling out muons' via C_9
    - Leptoquarks or new heavy mediator?
    - Ongoing $b \to s\,\tau^+\tau^-$ and LFV measurements with τ channels
- ***IceCube's role***
  - LBL ν_μ and SBL ν_e experiments lead the way in neutral lepton sector
  - Entering precision era of neutrino oscillations physics
  - DeepCore provides unique probe of PMNS unitarity
    - Crucial to global fits of ν_τ matrix elements
    - Constraining multi-channel NSI, 4th generation neutrinos and modified mixing

[CERN seminar - LHCb]



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