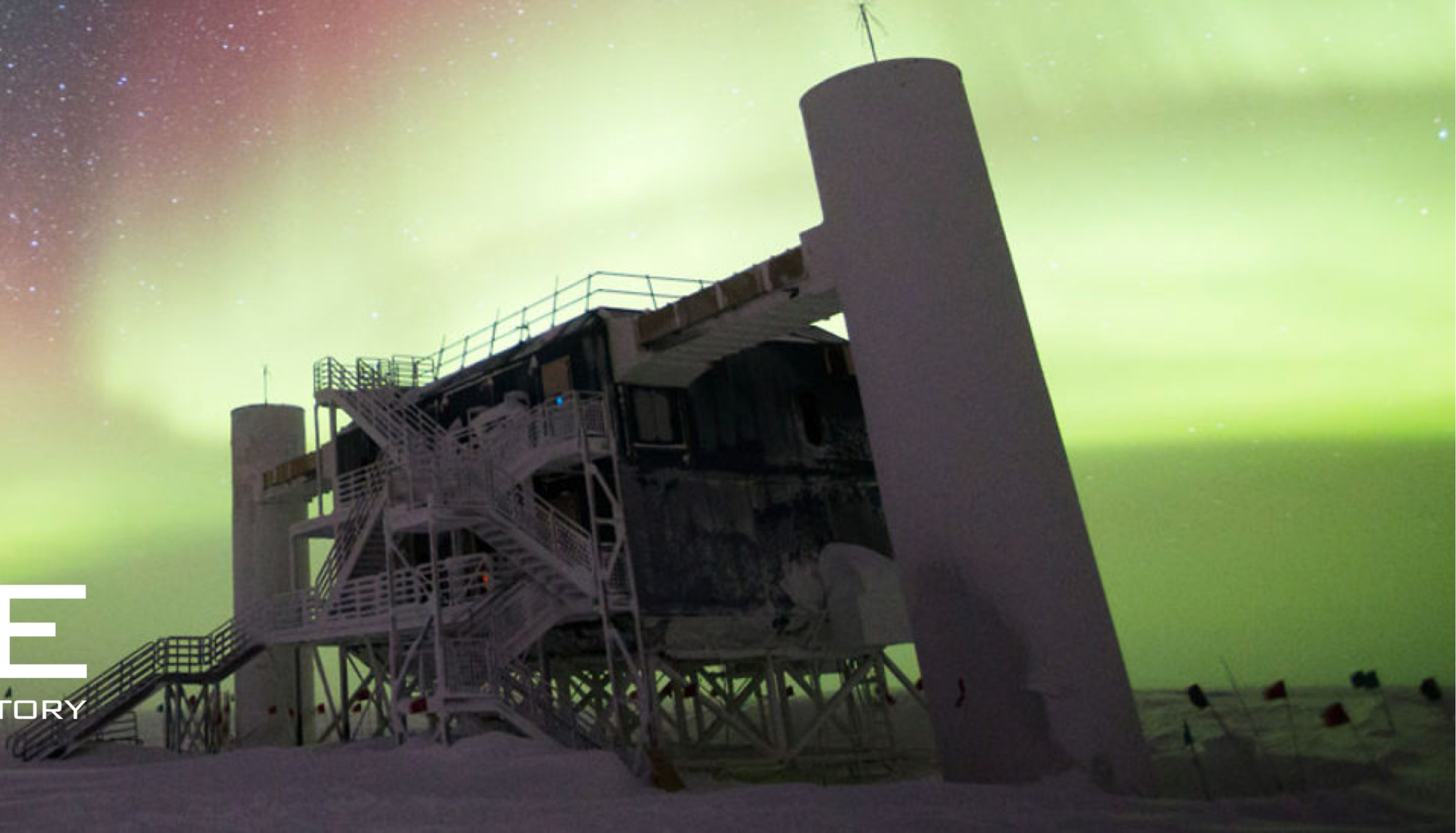
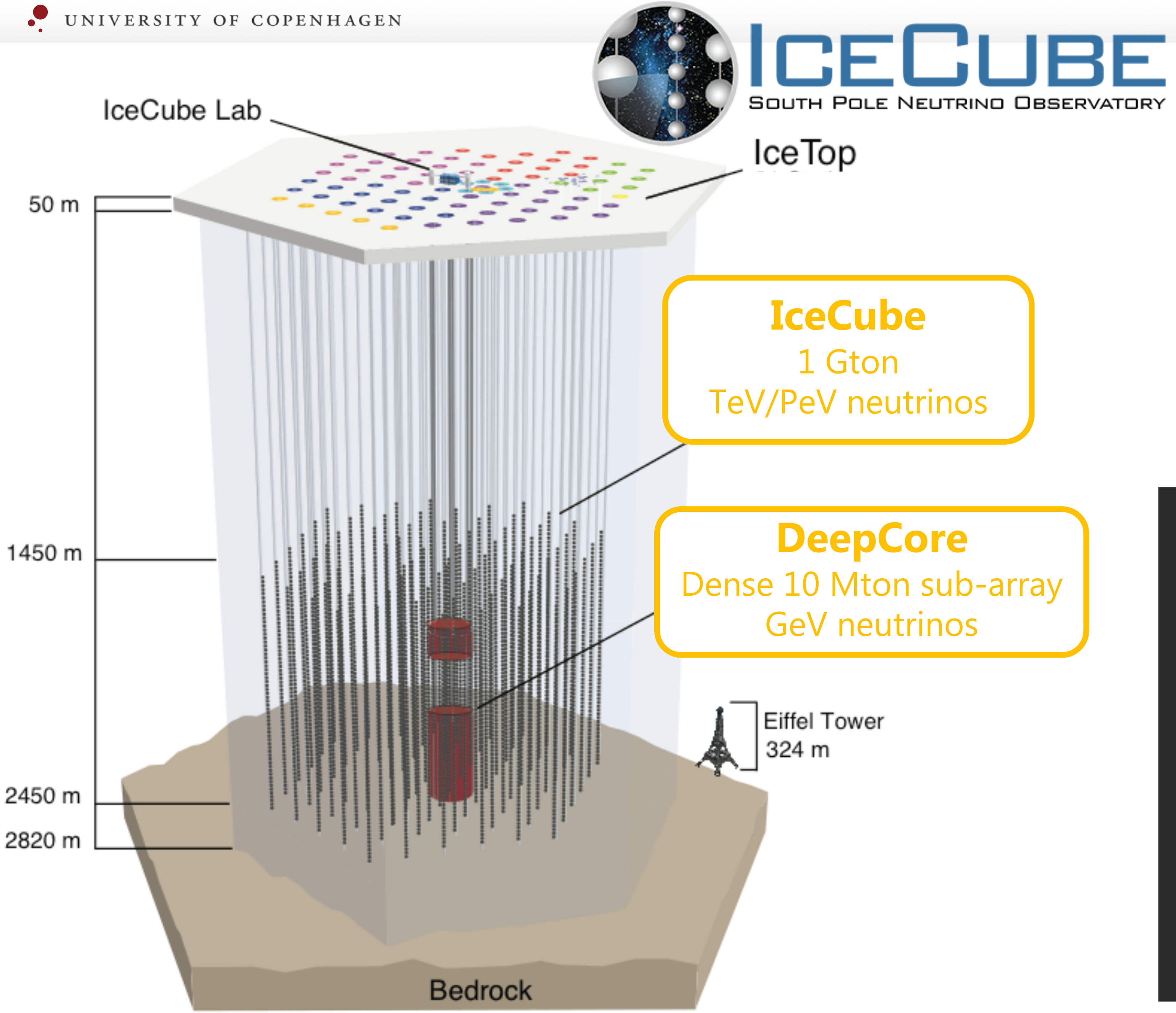
Neutrino oscillations with IceCube-DeepCore and the IceCube Upgrade

Tom Stuttard for the IceCube collaboration
Niels Bohr Institute
Snowmass 2021

CARLSBERG FOUNDATION
VILLUM FONDEN



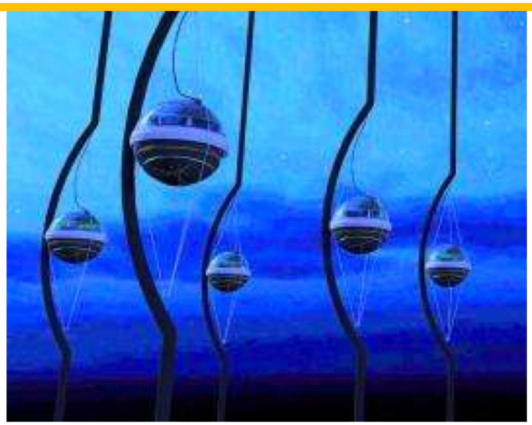
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY



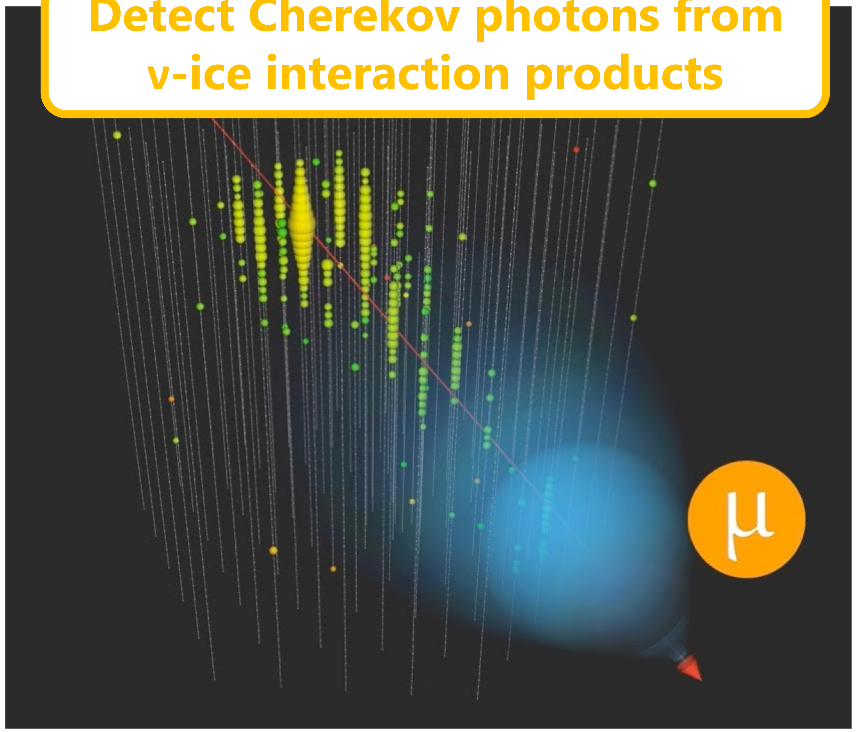
IceCube
1 Gton
TeV/PeV neutrinos

DeepCore
Dense 10 Mton sub-array
GeV neutrinos

5160 PMTs in glacial ice (natural detection medium)

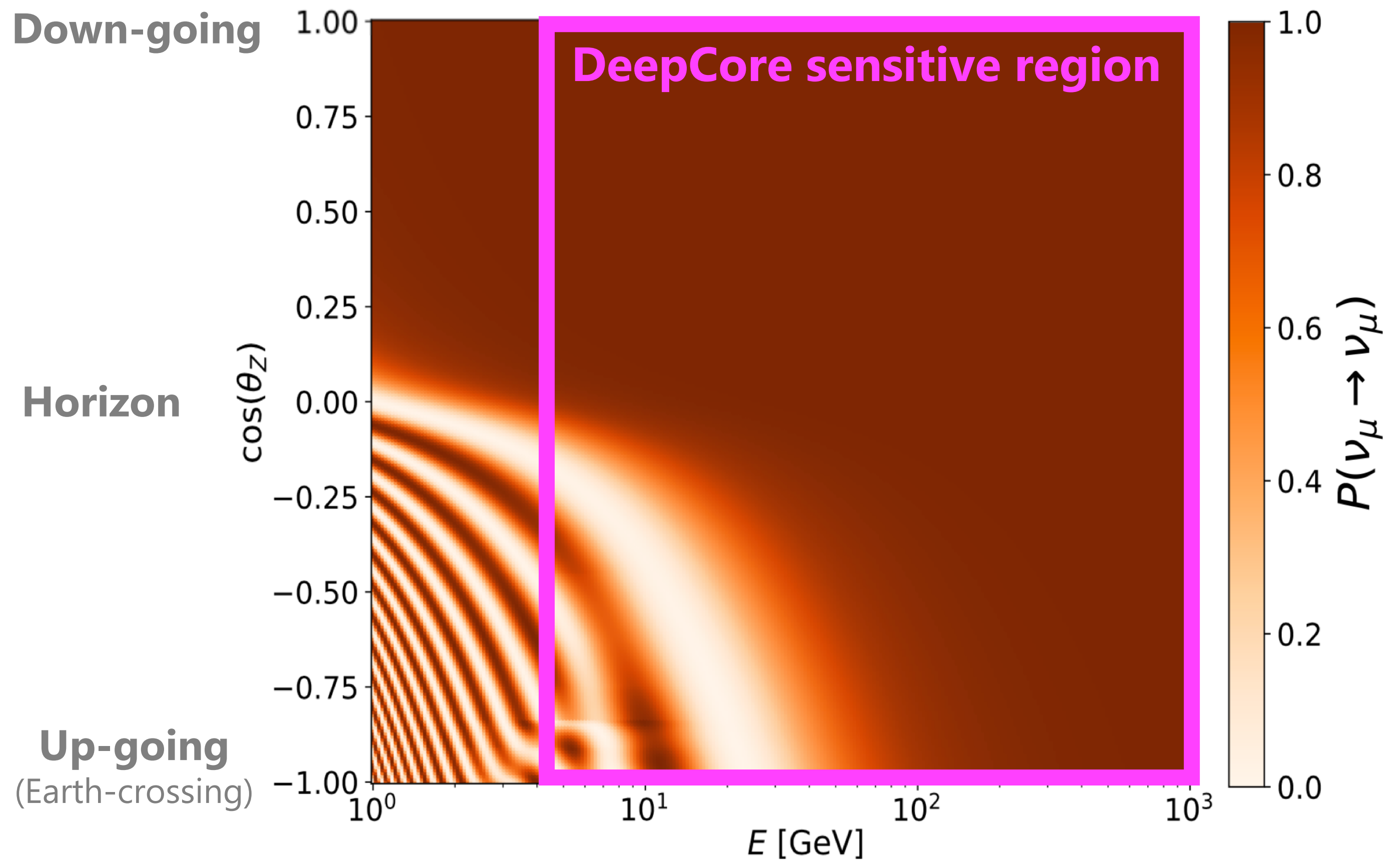


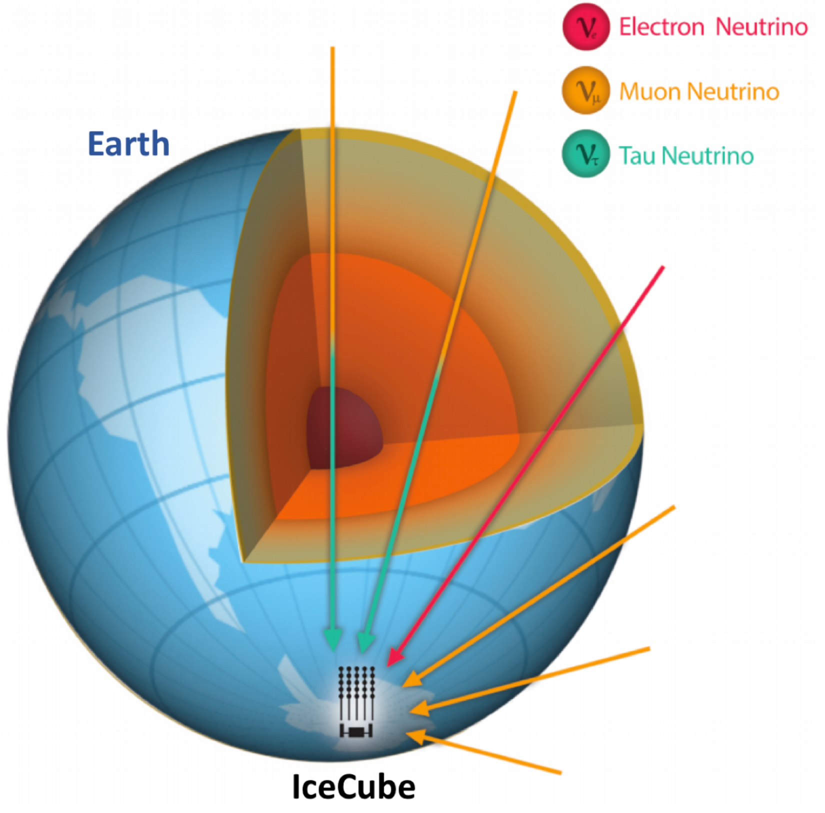
Detect Cherekov photons from ν-ice interaction products



Atmospheric neutrino oscillations in DeepCore

- **mHz** atmospheric neutrino detection rate → a υ every 15 mins!
- Approx. **maximal $\nu_\mu \rightarrow \upsilon_\tau$ oscillations** for O(10 GeV) Earth-crossing υ
  - Same L/E as long baseline accelerator experiments



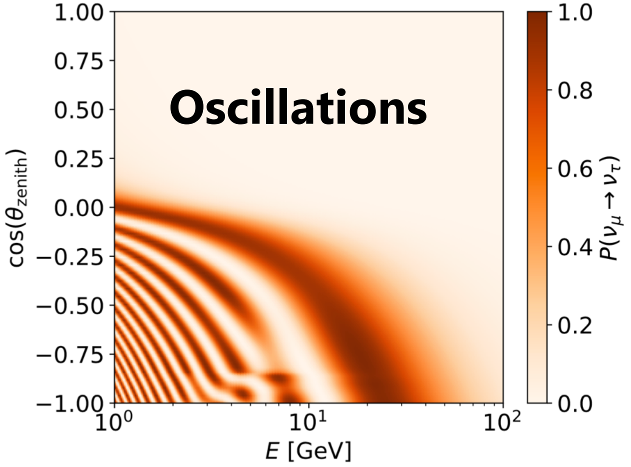


Measuring oscillations

- Simultaneously observe $\boldsymbol{\upsilon_\mu}$ **disappearance** and $\boldsymbol{\upsilon_\tau}$ **appearance**
  - Operating above ~4 GeV $\upsilon_{\tau,CC}$ threshold
- Measure 3D distortions in reconstructed [energy, zenith, PID]

Flux

+



+

Interactions

+

Detector

Measuring oscillations

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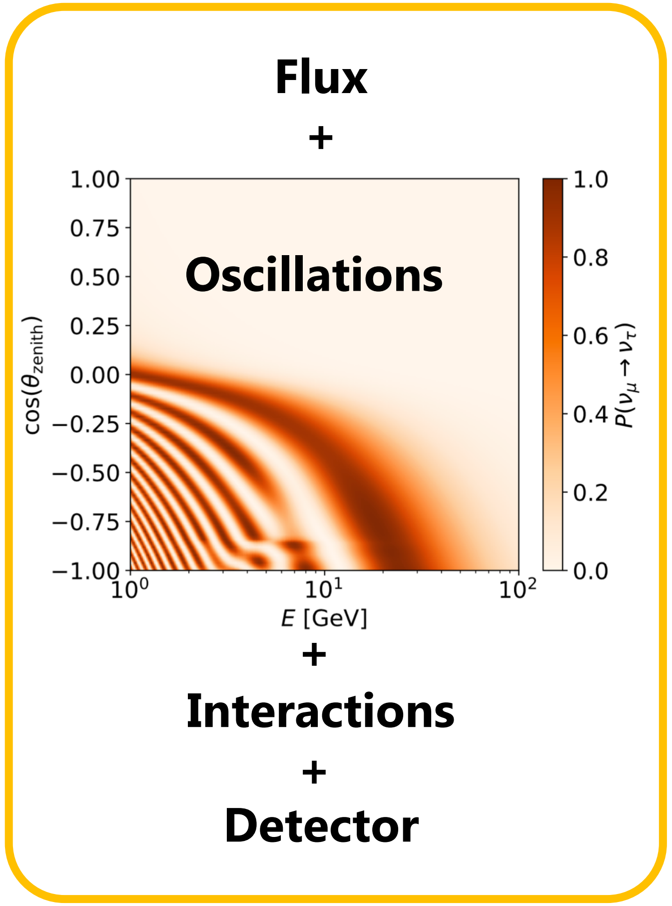

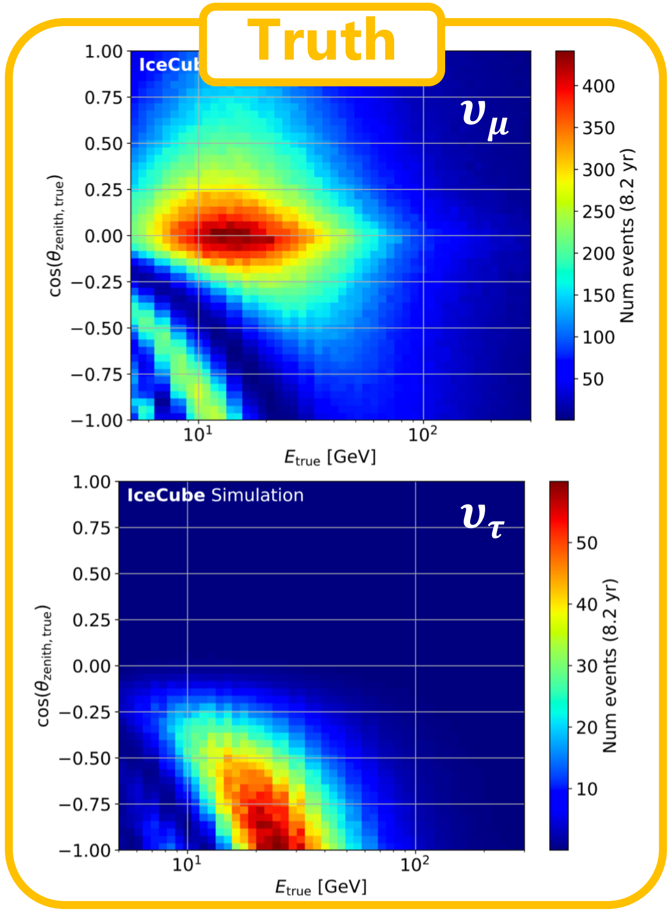

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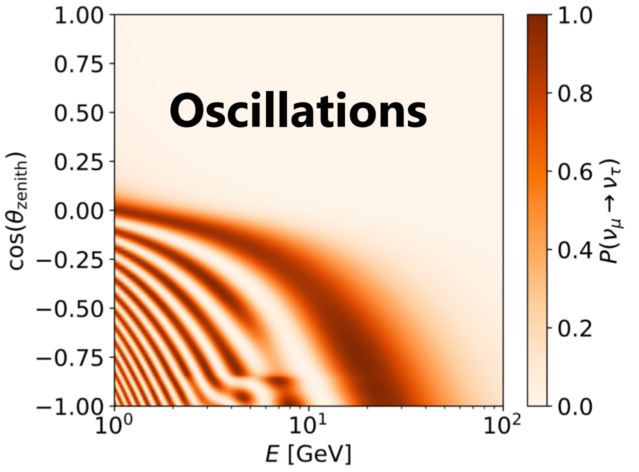

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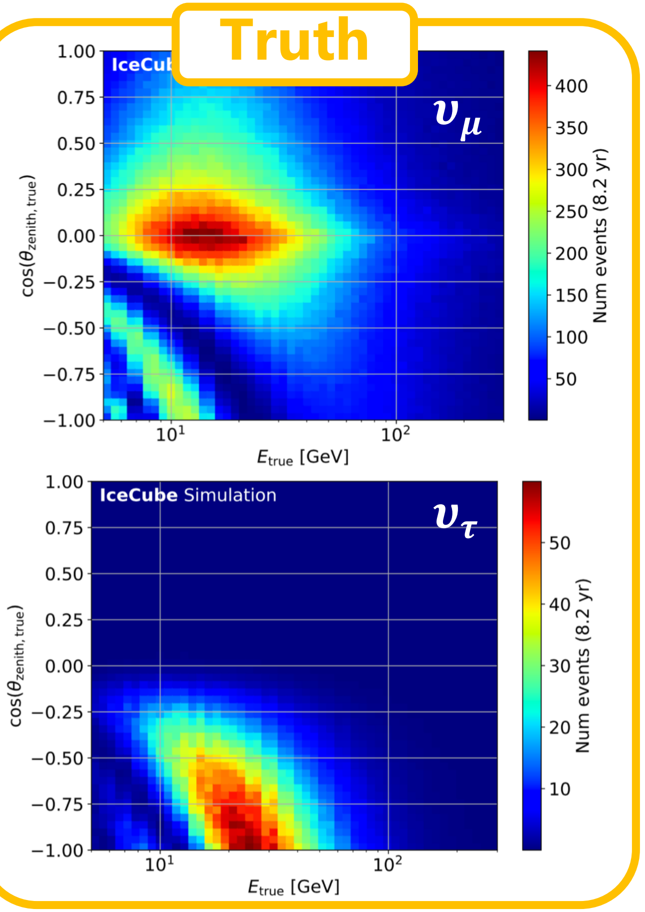
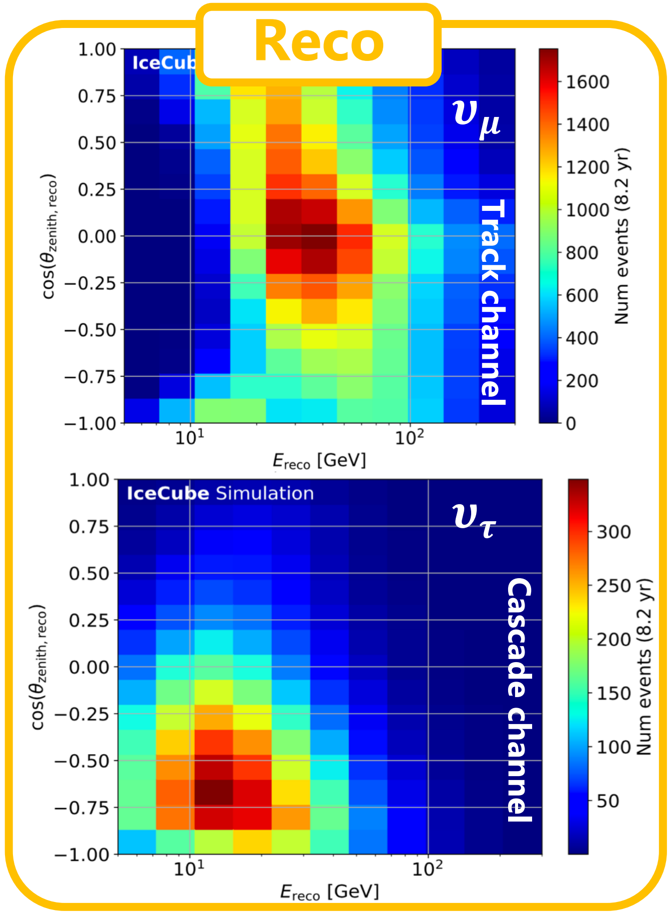
Interactions

+

Detector





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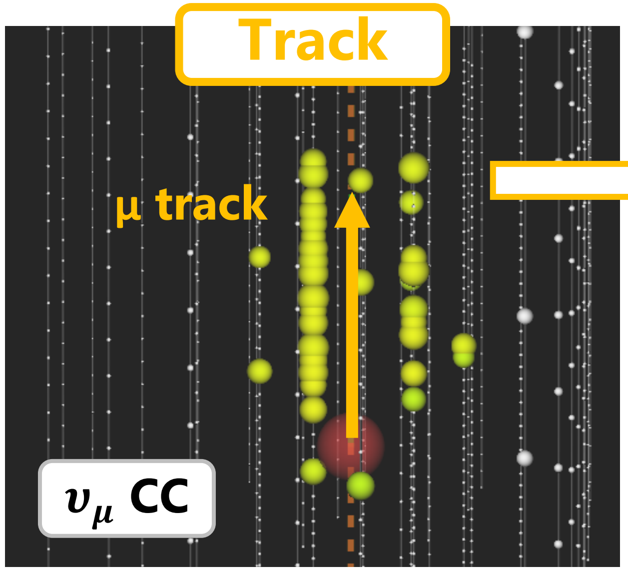
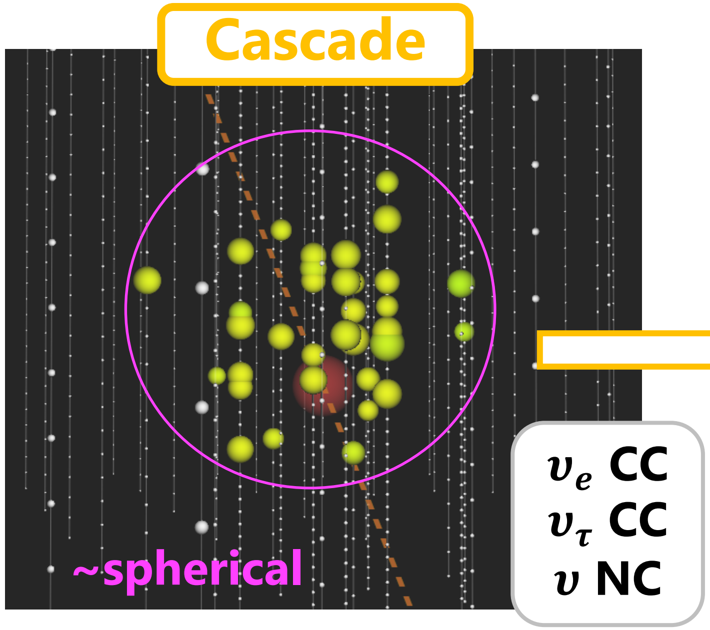
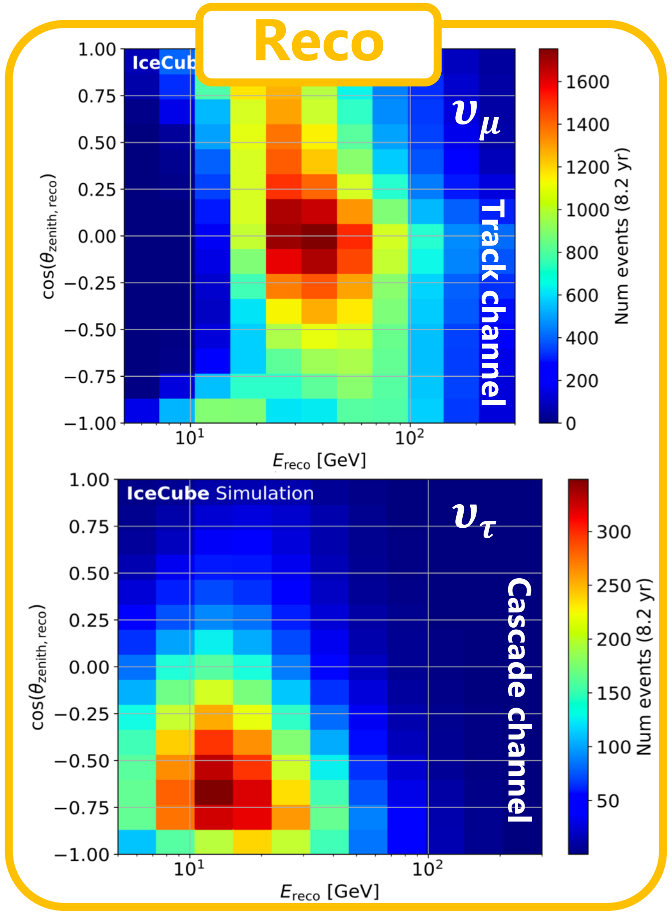
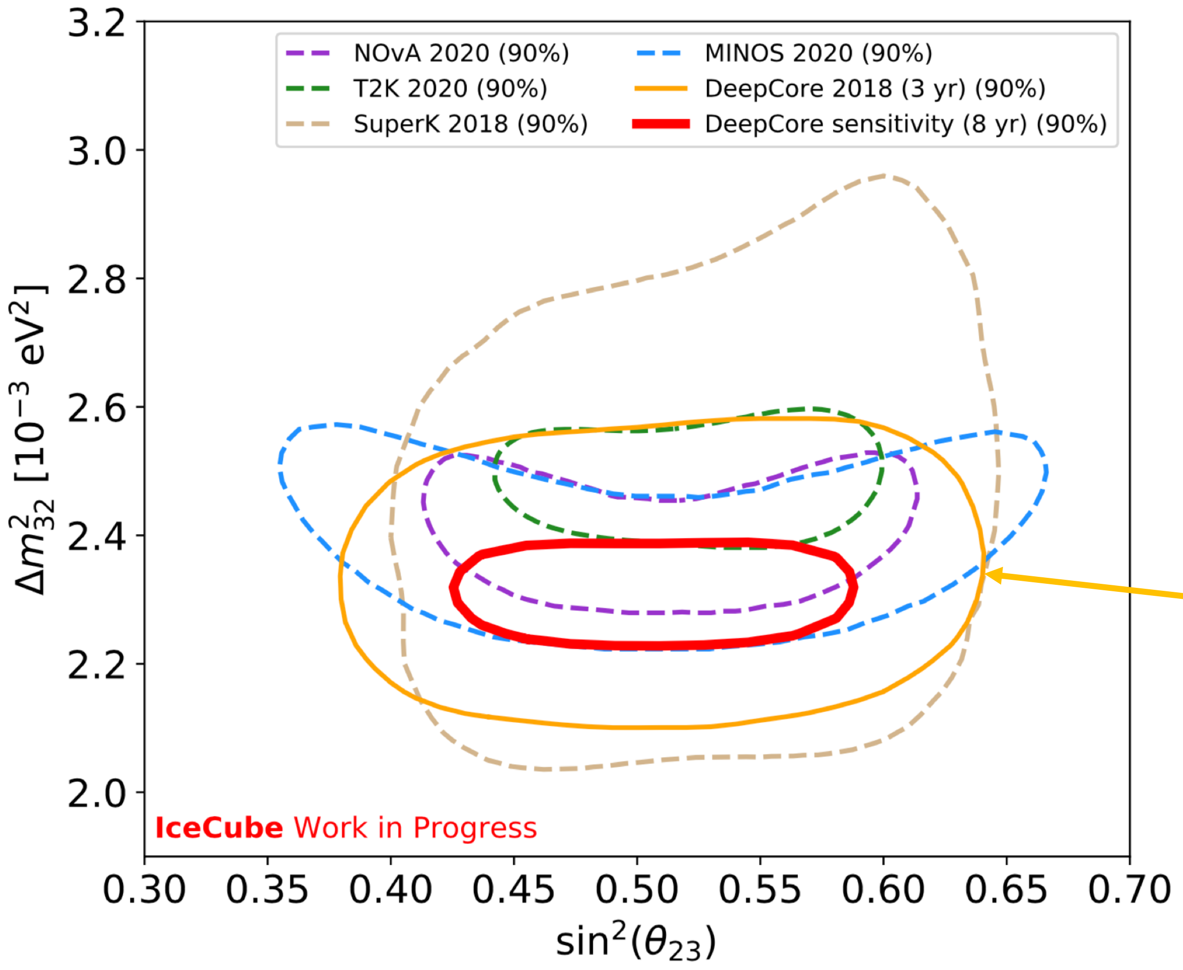




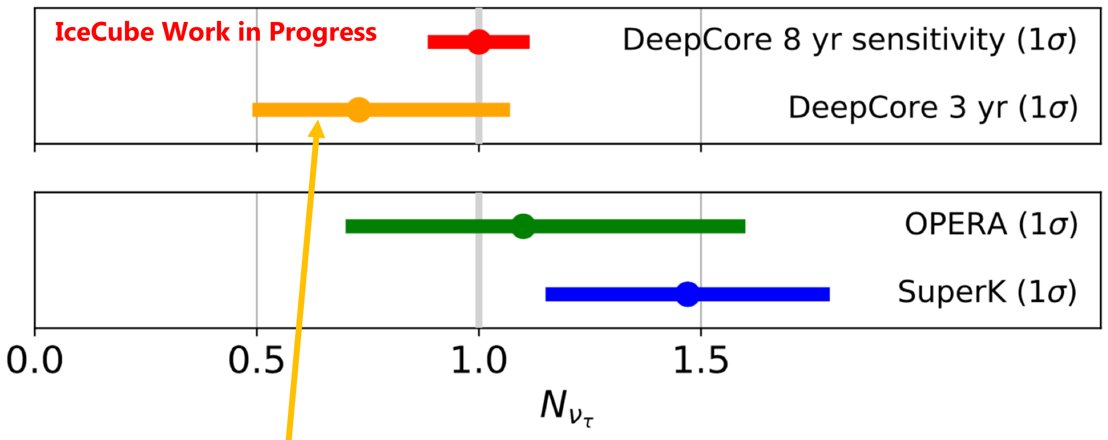


DeepCore oscillation results

Atmospheric oscillation parameters



ν_τ normalisation



Results with 3 years of data

PhysRevLett.120.071801, PhysRevD.99.032007

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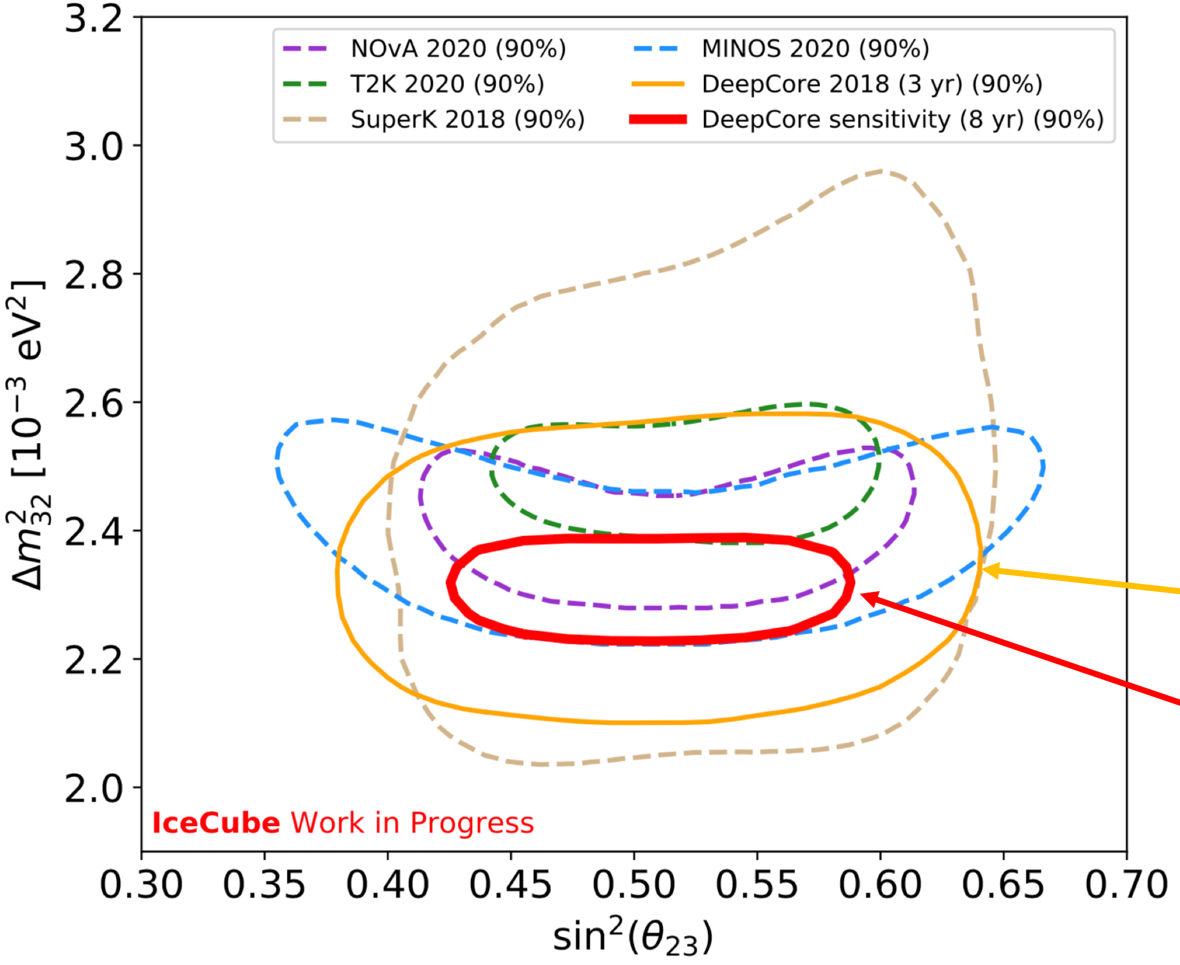

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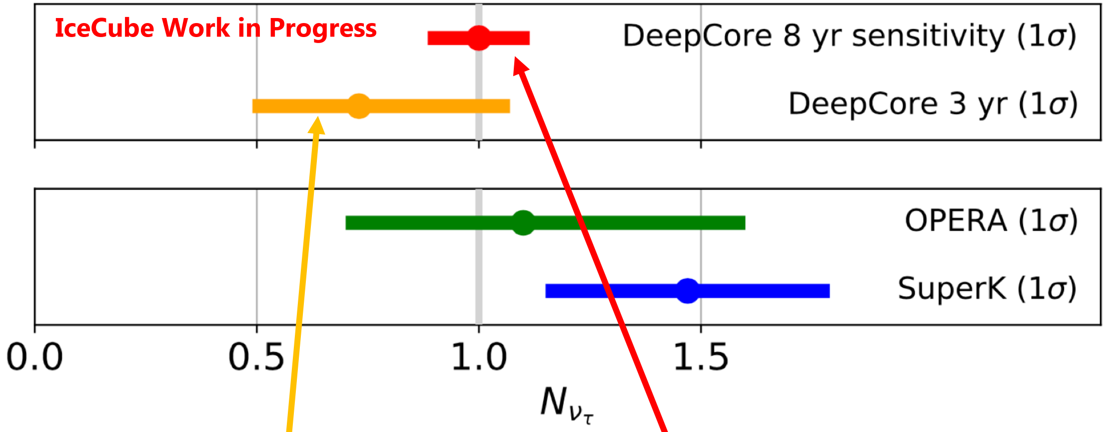


Results with 3 years of data

PhysRevLett.120.071801, PhysRevD.99.032007

Current 8 yr analysis sensitivity

$>$300,000 υ / 18,000 υ_τ

DeepCore oscillation results

Takeaway

DeepCore is sensitive to O(10 GeV) υ_μ disappearance and υ_τ appearance

High statistics 8 yr analyses underway

Coming soon:

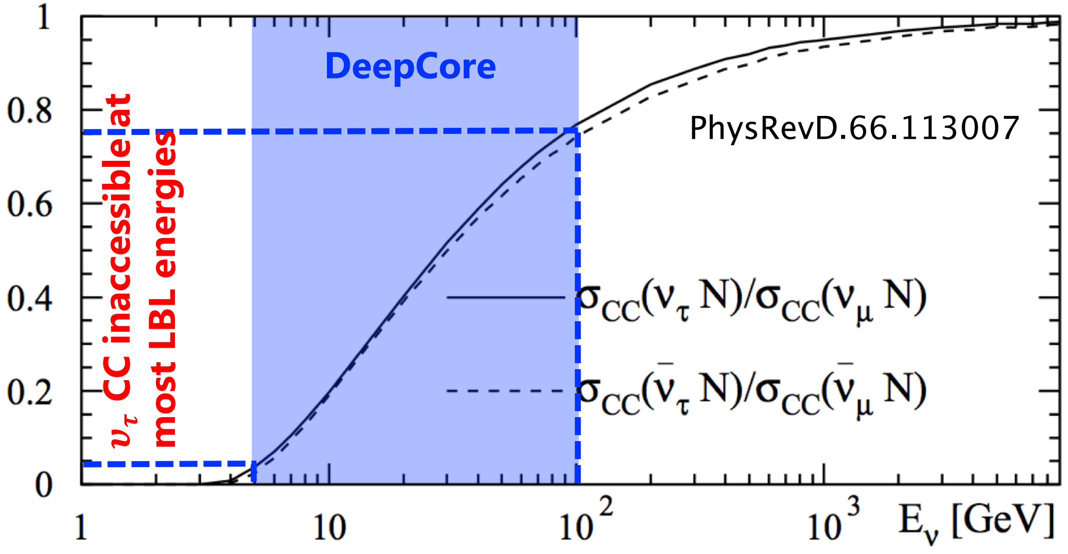
1) Comparable mixing angle and mass splitting precision to long baseline accelerators

2) $\lesssim$15% precision in υ_τ normalisation (>2x current world best)

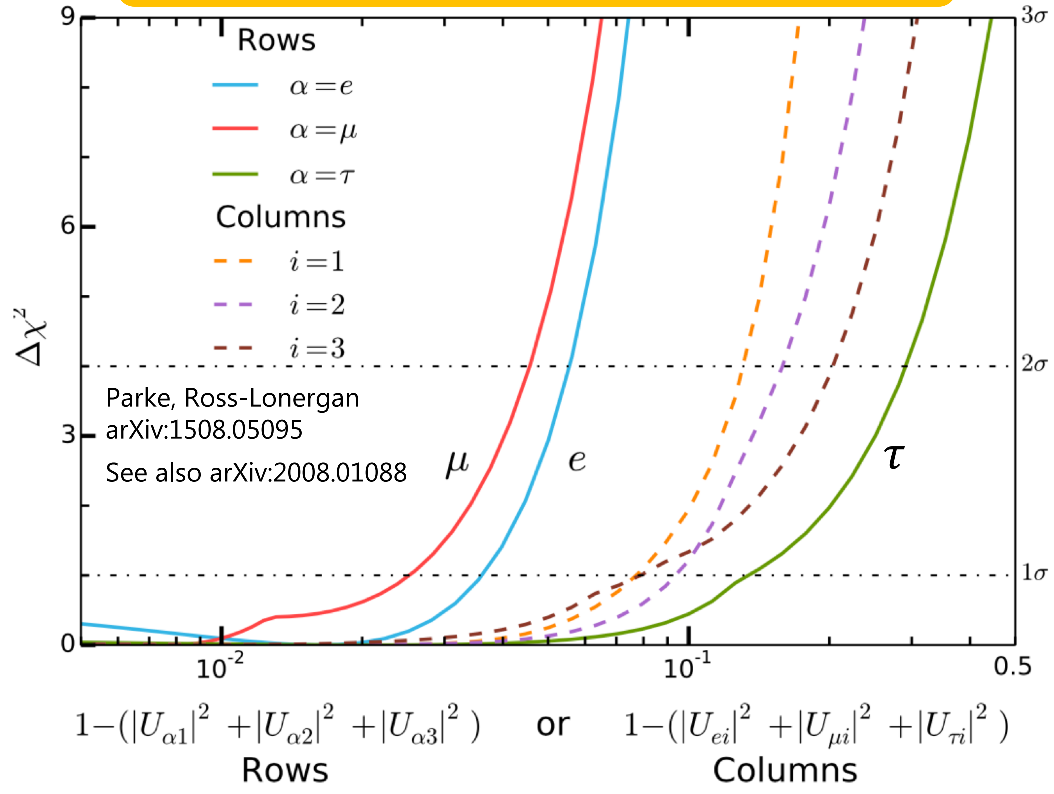
ν_τ measurements and PMNS unitarity

- Few experiments can detect ν_τ due to cross section suppression
- **ν_τ PMNS elements poorly measured**
- Major barrier to **PMNS unitarity** constraints

ν_τ CC cross section suppression



PMNS row/column norm constraints

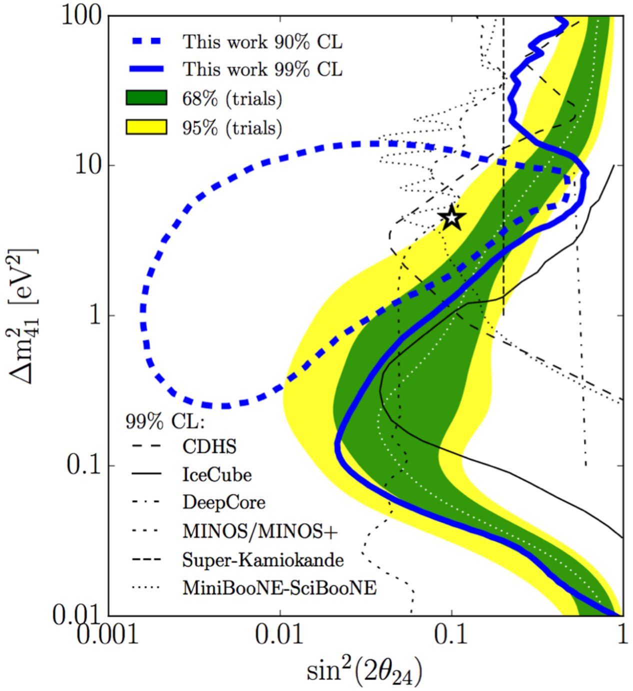


IceCube/DeepCore BSM oscillations

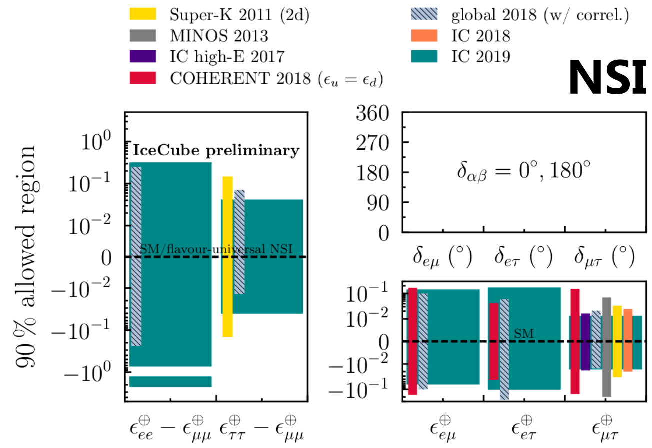
- Large range of energies, baselines, flavors and matter profiles
- → Often world leading sensitivity to BSM neutrino flavour transitions

- **Sterile neutrinos**
- **Non-standard interactions**
- **Lorentz invariance violation**
- **Decoherence**

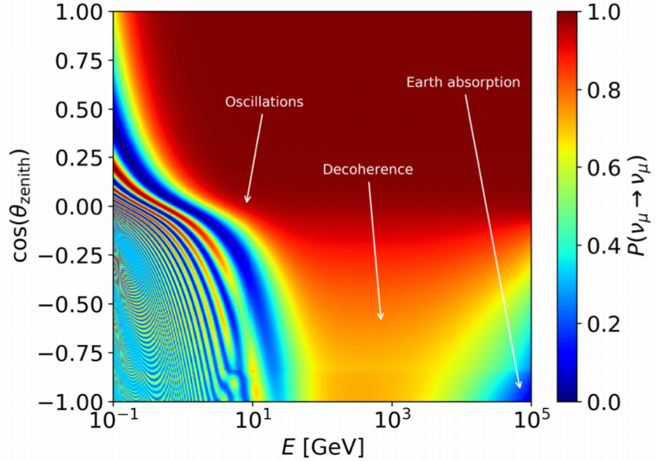
O(eV) steriles



NSI



Decoherence



- Multiple 8 yr analyses recently published or underway

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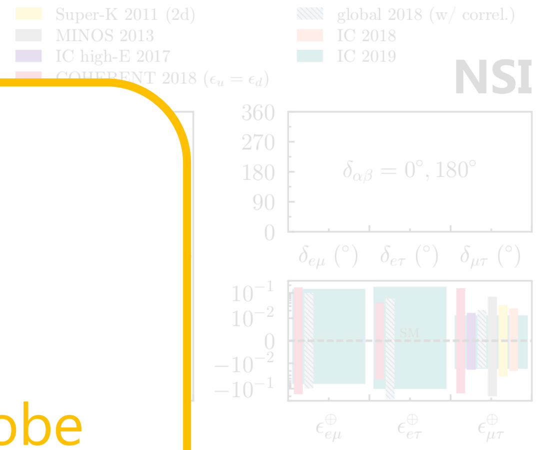
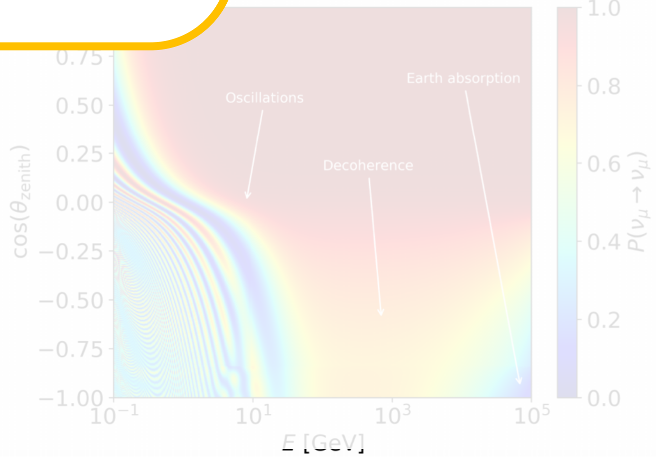




Takeaway

World class BSM physics reach

Coupled with υ_τ sensitivity → excellent power to probe beyond the standard 3υ paradigm

The IceCube Upgrade

- $30M extension to IceCube
  - Funded, deployment in 2022/3
- 700 multi-PMT sensors
  - Densely packed in 2 Mton core
- Improved detector/ice calibration

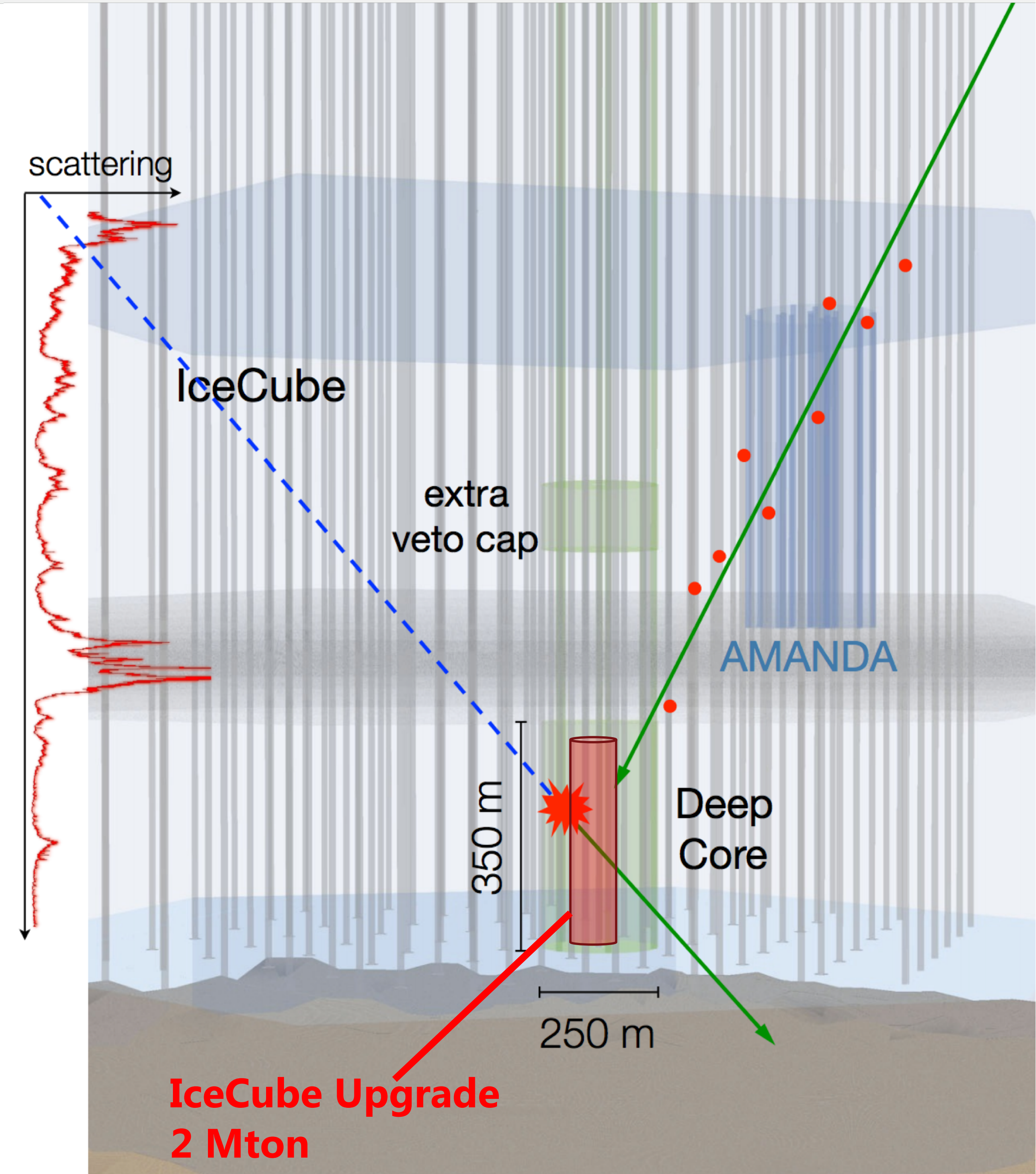
D-Egg

30 cm

mDOM

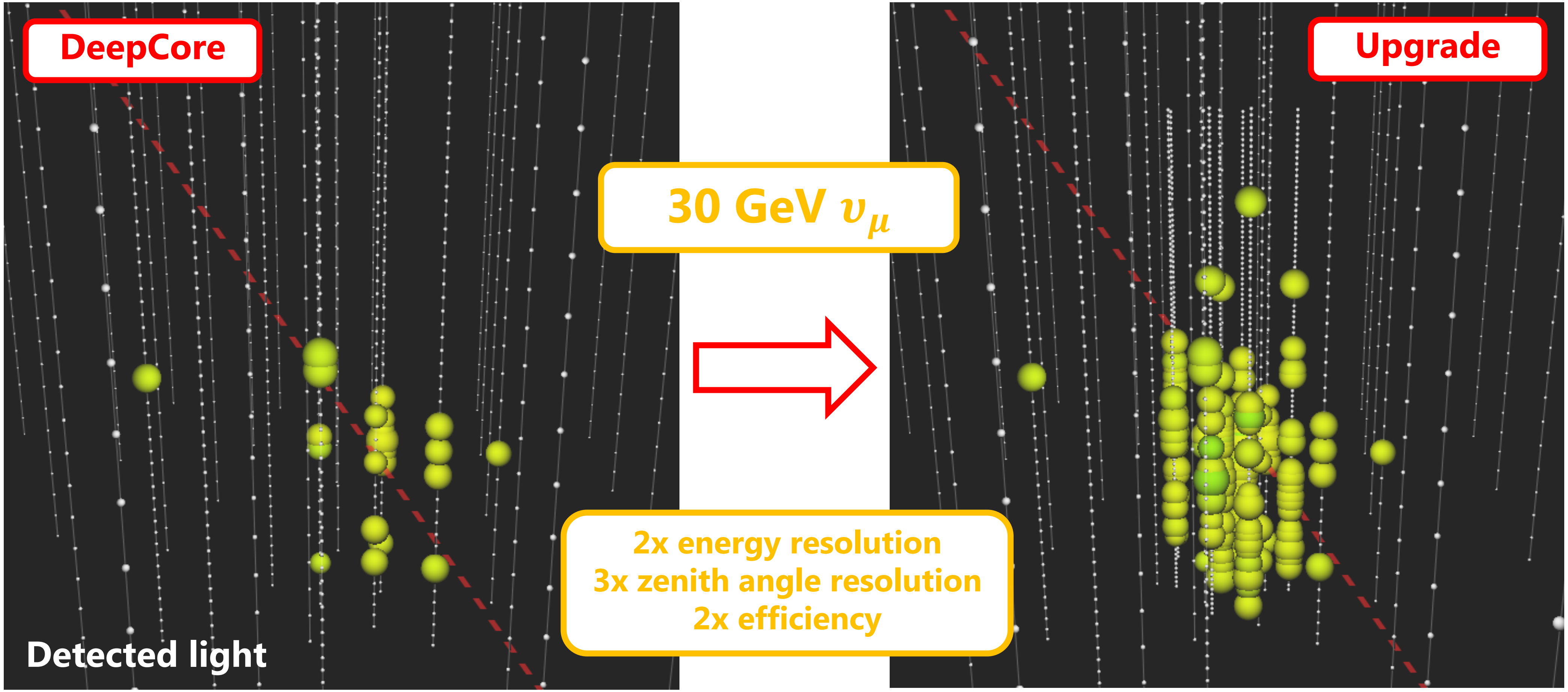
36 cm

arXiv:1908.09441



Increased photocathode density

- **Dense instrumentation** in 2 Mton core
  - Large increase in photocathode density → sensitive down to **1 GeV neutrinos**



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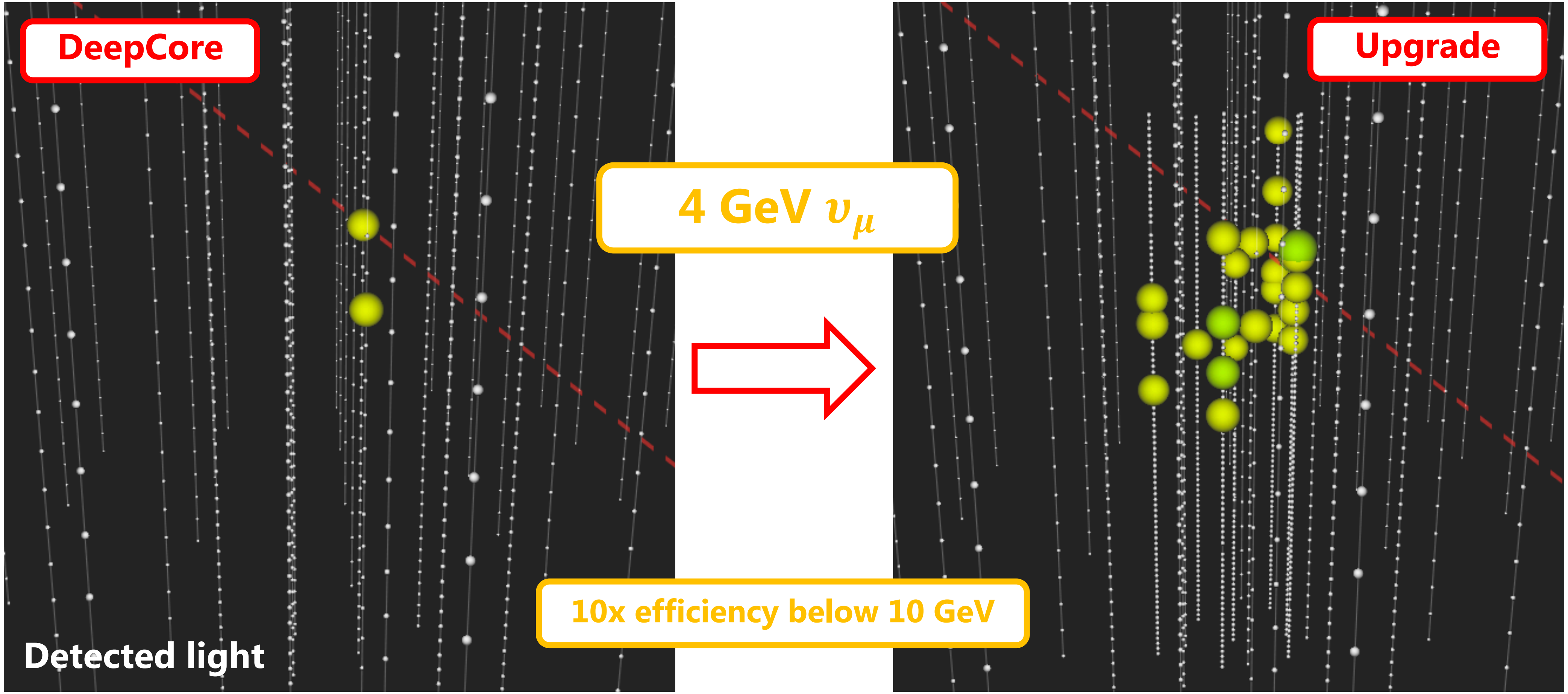

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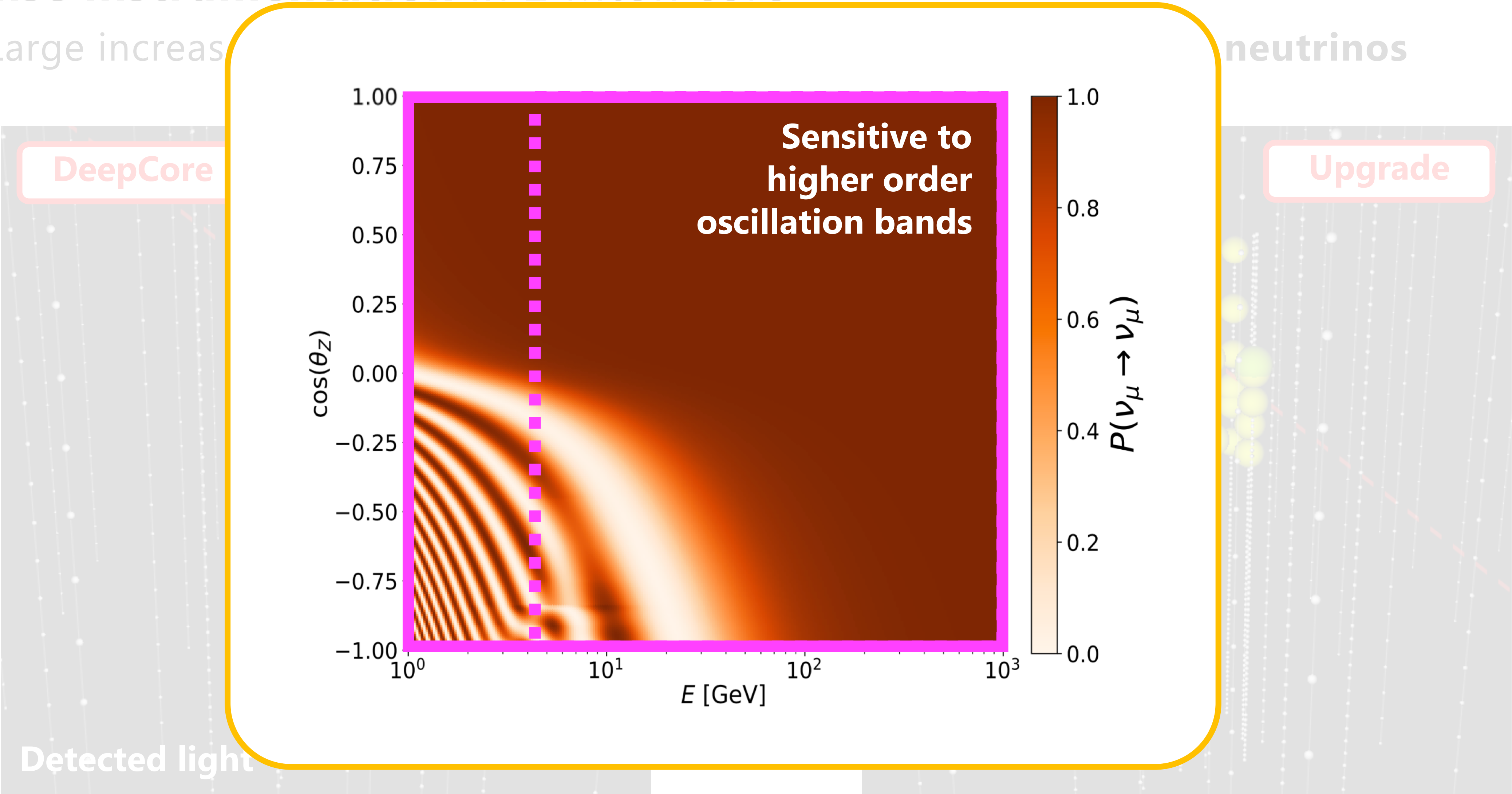
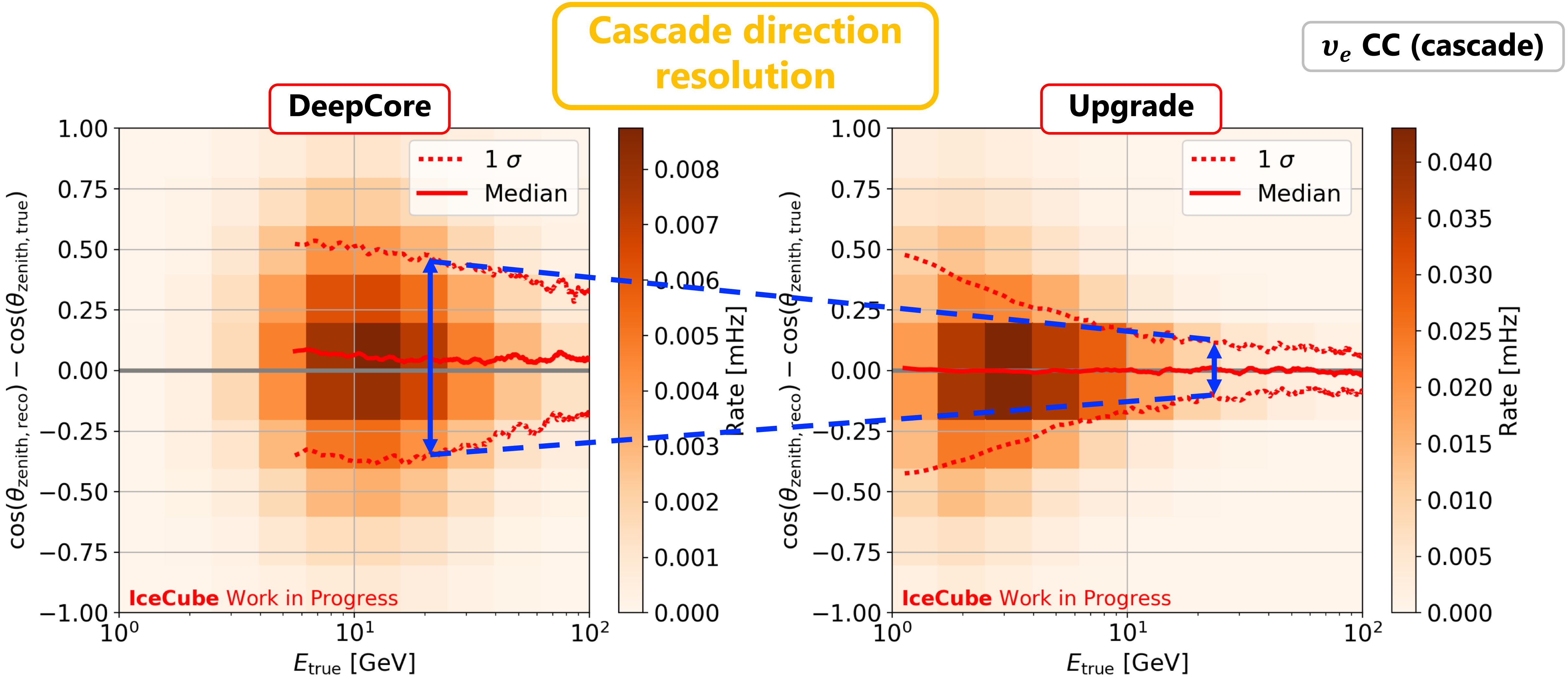


arXiv:1908.09441

Major resolution improvement

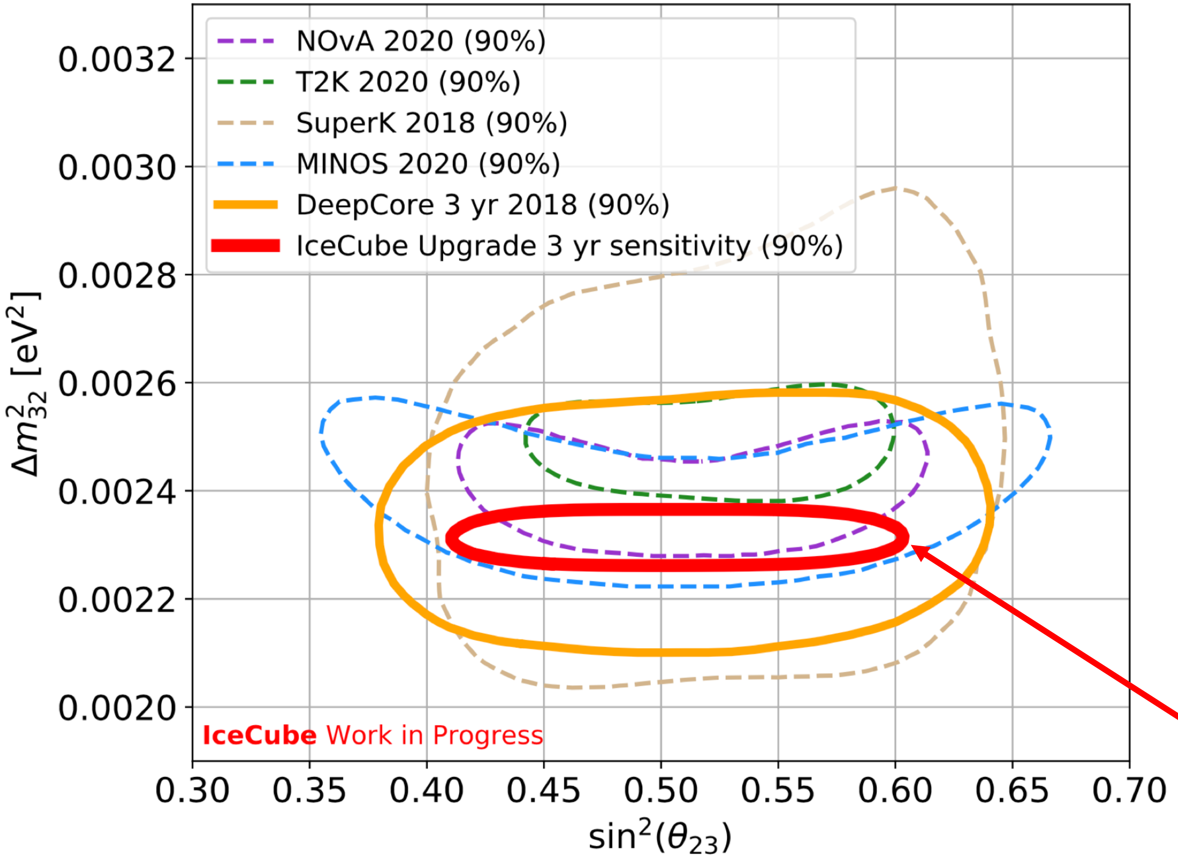


3x improvement @ ν_τ appearance energies

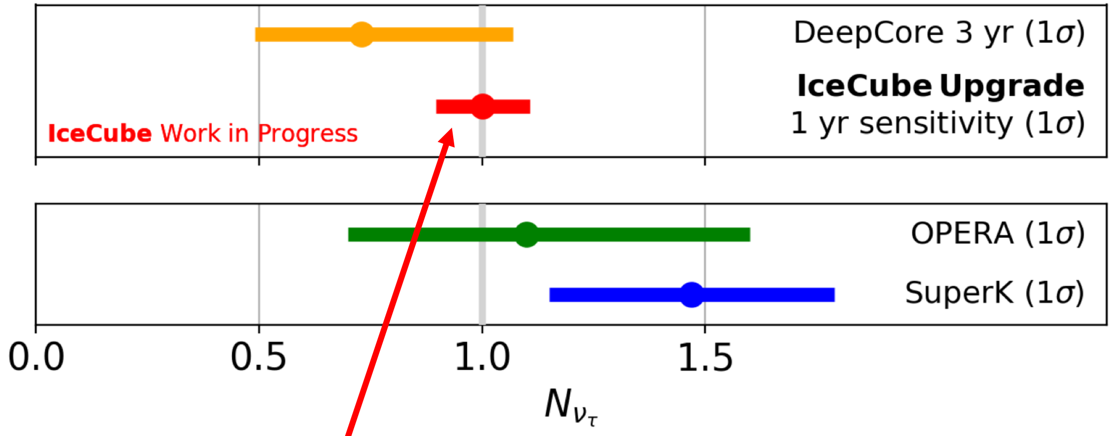
arXiv:1908.09441

IceCube Upgrade oscillation sensitivity

Atmospheric oscillation parameters



υ_τ normalisation



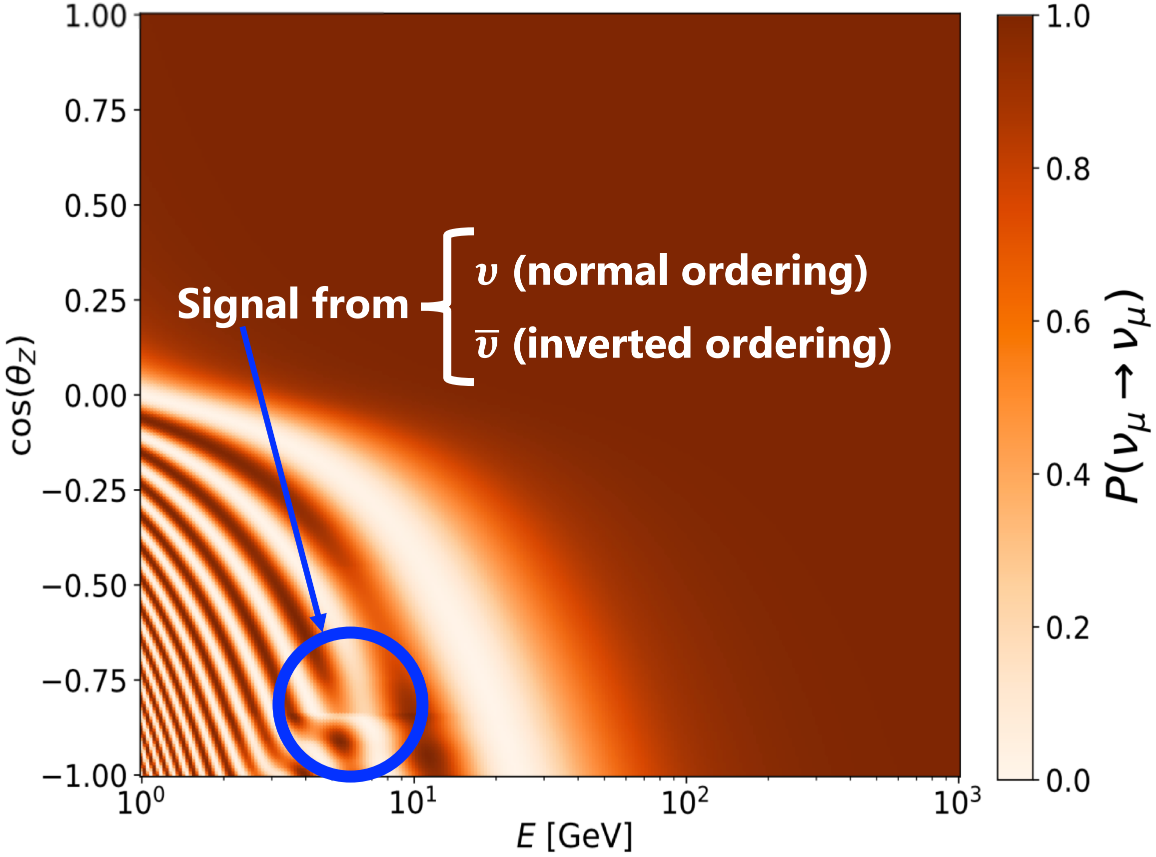
10% υ_τ norm in 1 yr (6% in 3 yrs)

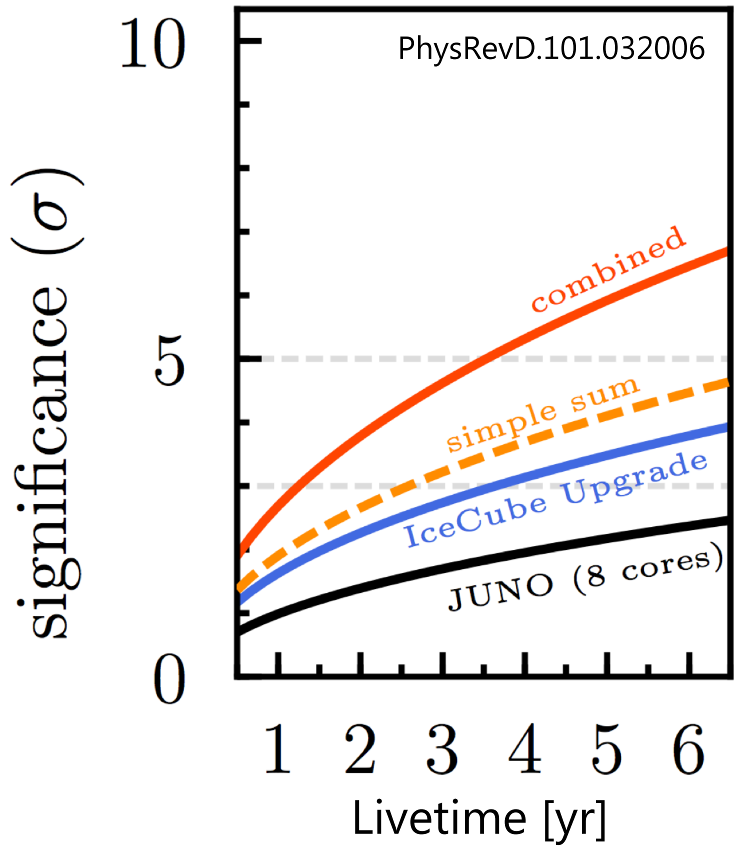
Strong sensitivity in 3 yrs or less

Conservative projections Still to add: track reconstruction, new calibration, DeepCore fiducial volume

Neutrino mass ordering (NMO)

- Strong sensitivity to NMO via matter effects at ~6 GeV
  - Can also exploit synergy from joint fit with JUNO





Neutrino mass ordering (NMO)

- Sensitivity to NMO via matter effects at ~6 GeV
- Powerful synergy from joint fit with JUNO

Takeaway

IceCube Upgrade will provide next-generation standard and BSM oscillation physics by mid-2020s

Major advances in world leading ν_τ capabilities

New opportunities afforded by precision detector we are only beginning to explore

(NMO, $\nu/\bar{\nu}$ discrimination, τ-ID, PMNS element fit, HNL double-bangs, ...?)

Summary

IceCube Oscillation LoIs:
Low energy (std + BSM): SNOWMASS21-NF1_NF0_Tom_Stuttard-058.pdf
High energy (BSM): SNOWMASS21-NF3_NF2_Ben_Jones-046.pdf

- Strong IceCube oscillation program
  - World-leading υ_τ and BSM capabilities
  - High statistics, energy, baselines, matter densities, …
- New 8 year oscillation results due soon
  - Comparable to current long baseline precision in atmospheric parameter space
  - >2x improvement in υ_τ appearance precision c.f. current world best
  - Many new BSM measurements
- Next-generation oscillation physics with the IceCube Upgrade in mid-2020s
  - Will be major contributor to the global search beyond the standard 3υ paradigm
- Further ahead: IceCube-Gen2 high energy array extension

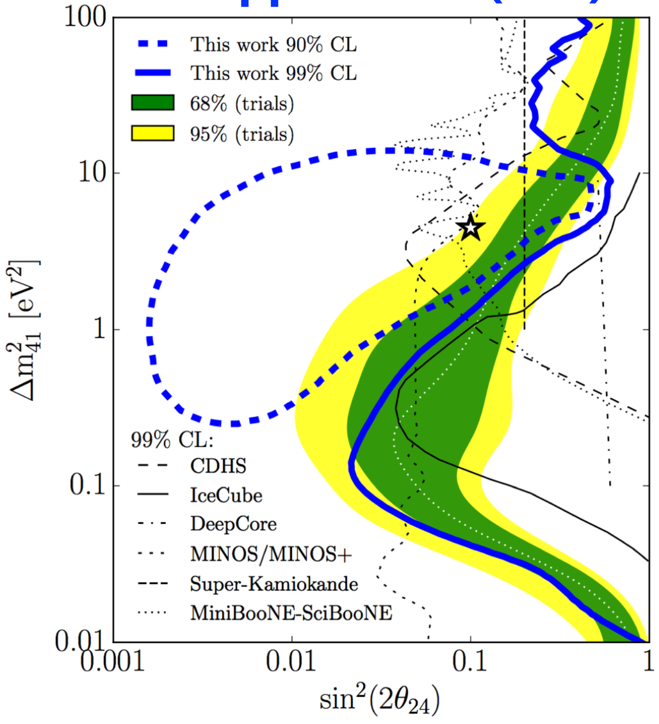
Backup slides

arXiv:2005.12942
arXiv:2005.12943
PhysRevD.95.112002

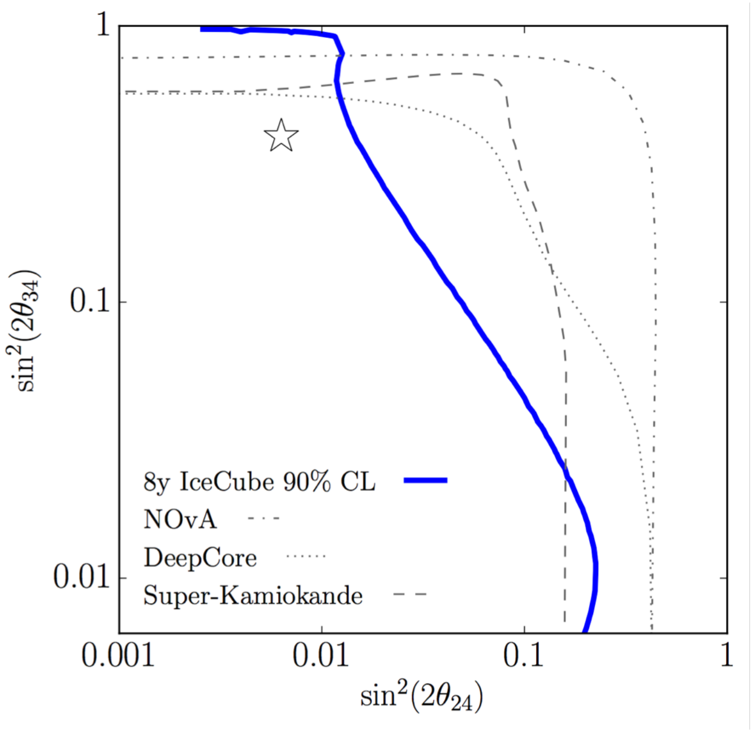
Sterile neutrinos

Sensitive to O(eV) steriles via:

1) Matter-enhanced resonant disappearance (TeV)



2) Modified GeV oscillations



Recent 8 year results (+ new DeepCore result coming soon)

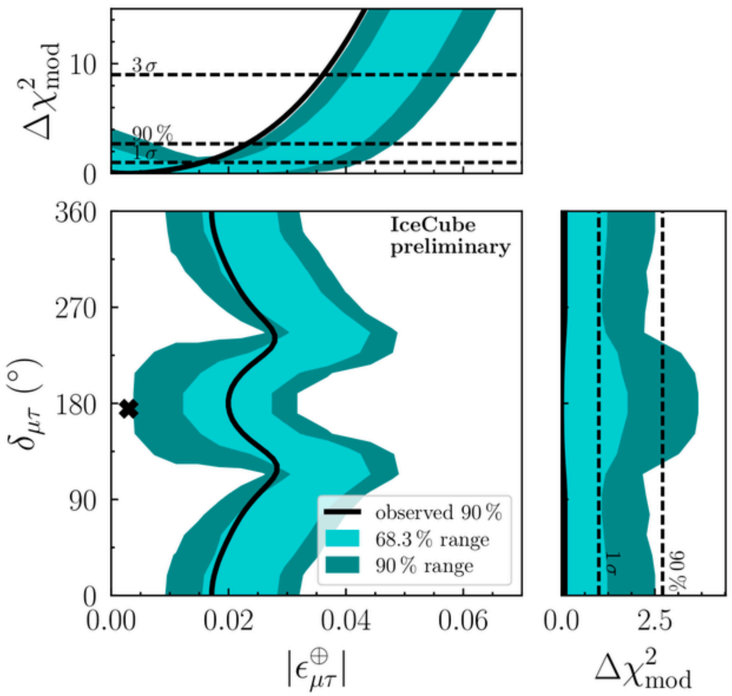
Non-Standard Interactions (NSI)

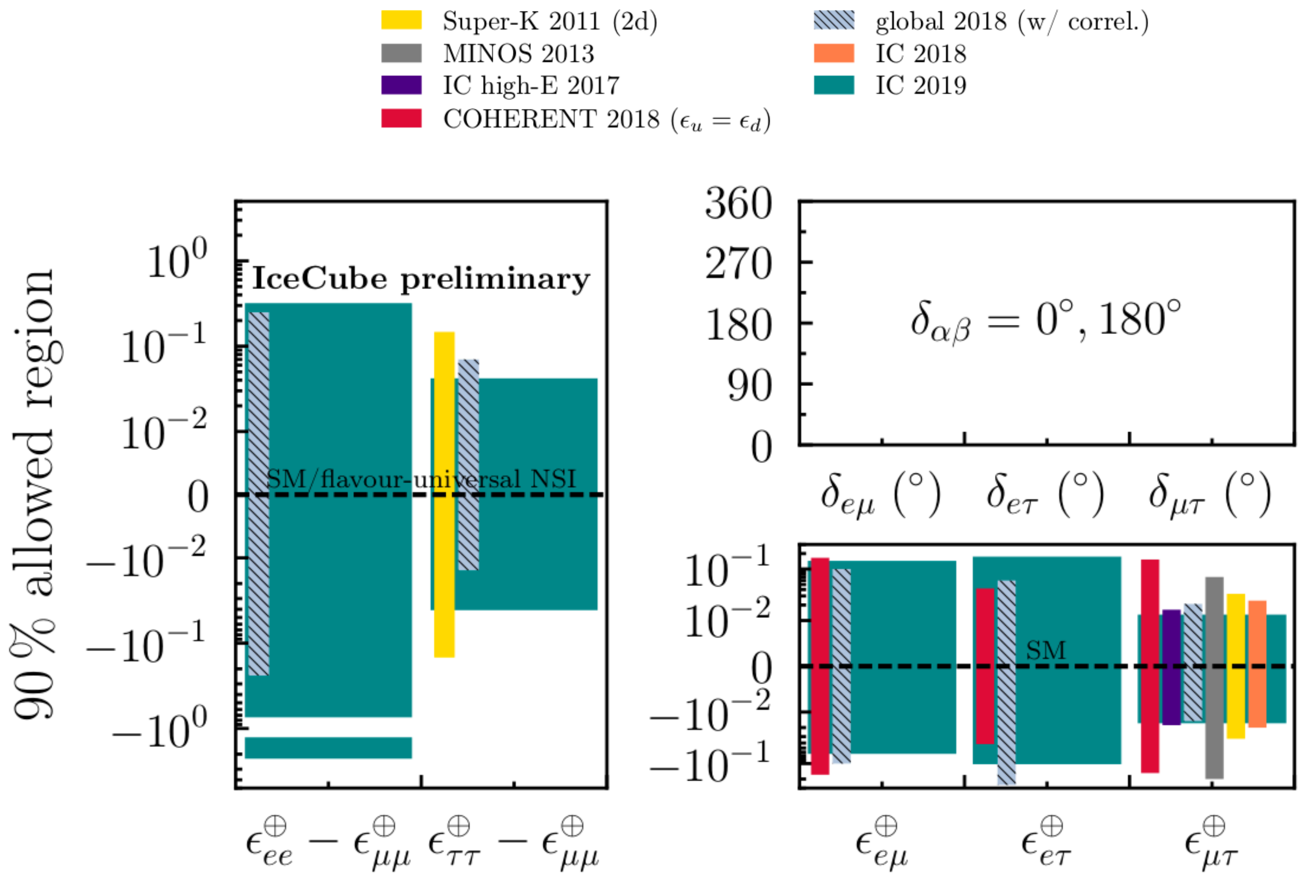
$$H_{\text{mat}}(x) = V_{\text{CC}}(x)\begin{pmatrix} 1+\epsilon^{\oplus}_{ee}-\epsilon^{\oplus}_{\mu\mu} & \epsilon^{\oplus}_{e\mu} & \epsilon^{\oplus}_{e\tau} \\ \epsilon^{\oplus *}_{e\mu} & 0 & \epsilon^{\oplus}_{\mu\tau} \\ \epsilon^{\oplus *}_{e\tau} & \epsilon^{\oplus *}_{\mu\tau} & \epsilon^{\oplus}_{\tau\tau}-\epsilon^{\oplus}_{\mu\mu} \end{pmatrix}$$

Sensitive to NSI matter effects for core-crossing neutrinos

Measurements in many channels

($\upsilon_e + \upsilon_\mu$ flux, all-flavour detection)



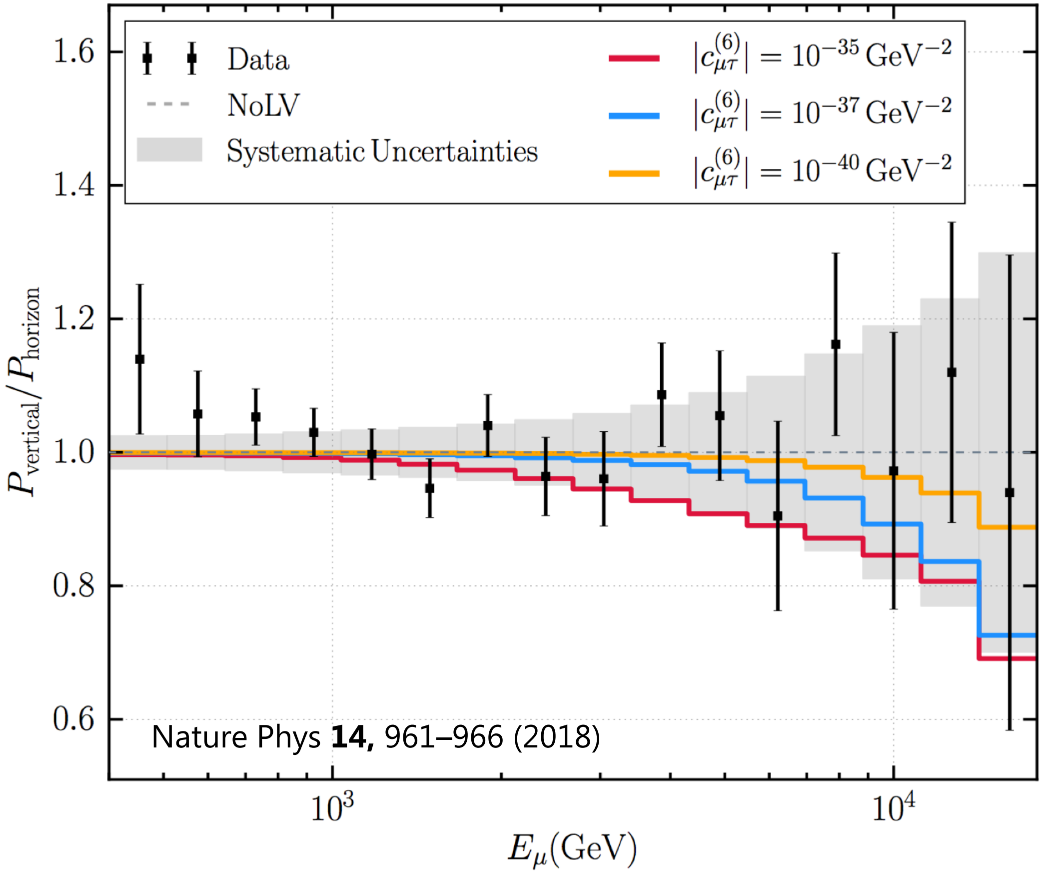


3 yr result paper shortly, 8 yr results on the way

Lorentz invariance violation

Limits on higher order terms in Hamiltonian
Standard Model Extension (SME)

$$H \sim \frac{m^2}{2E} + \mathring{a}^{(3)} - E \cdot \mathring{c}^{(4)} + E^2 \cdot \mathring{a}^{(5)} - E^3 \cdot \mathring{c}^{(6)} \dots$$



2 yr limits published, 8 yr analysis underway

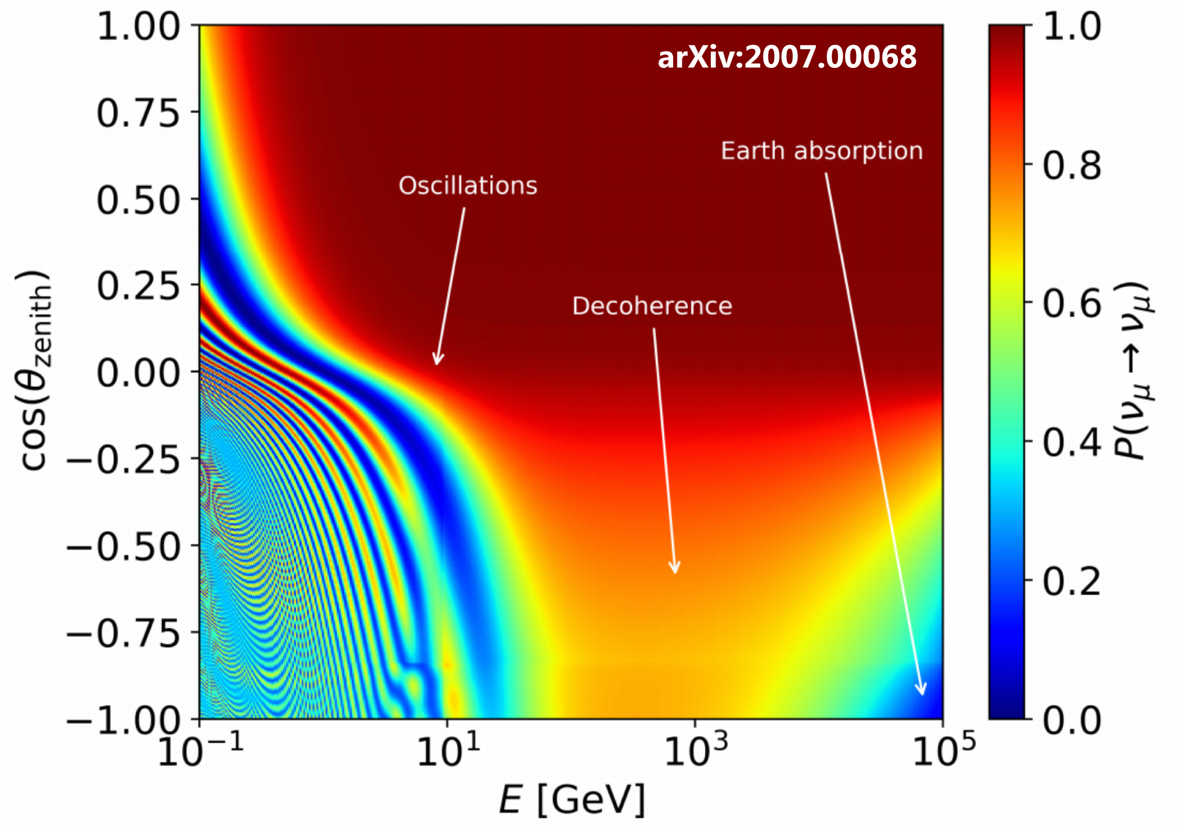
Neutrino decoherence

$$\dot{\rho} = -i[H,\rho] - \mathcal{D}[\rho] \qquad \Gamma(E) = \Gamma(E_0)\left(\frac{E}{E_0}\right)^n$$

Damping of oscillations over long baselines

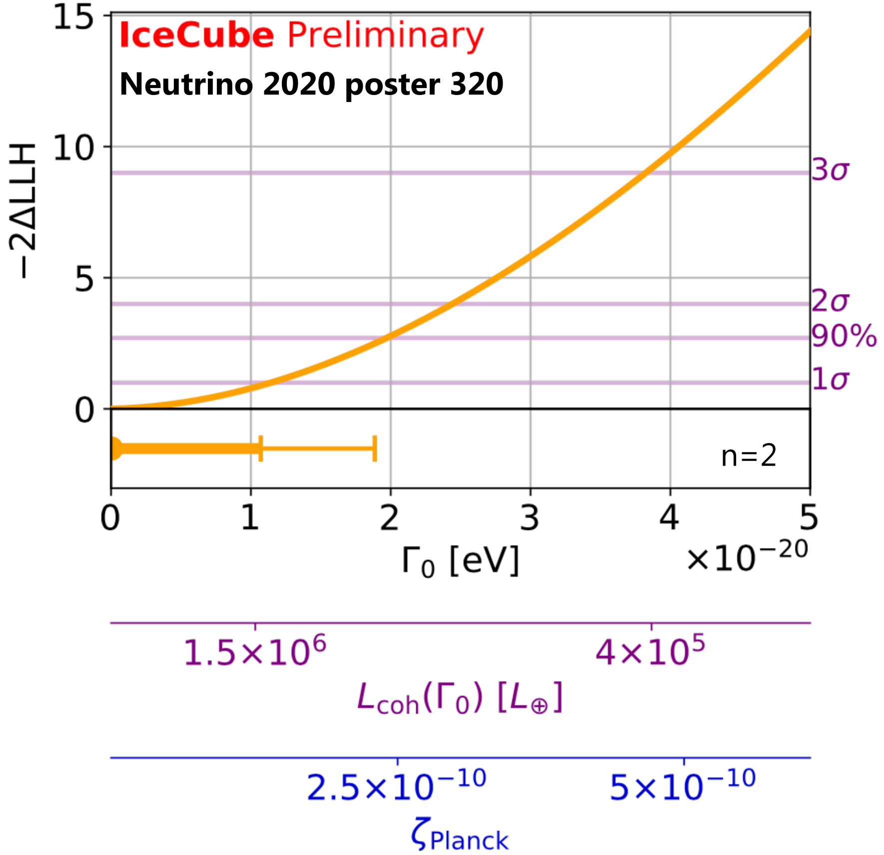
Quantum gravity probe

Sensitive to Planck-scale physics at high energy

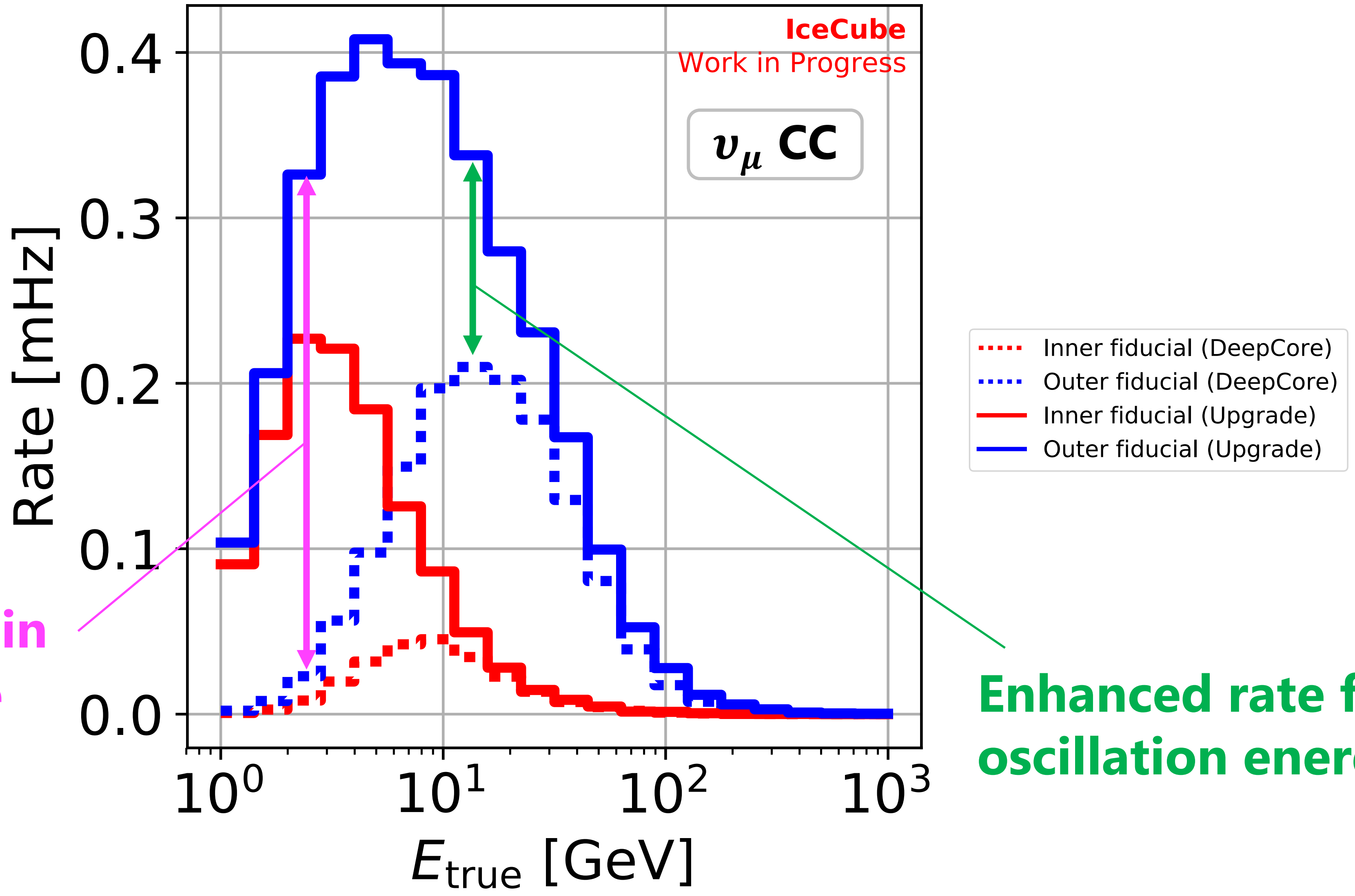


8 yr results underway

IceCube is ideal detector - order of magnitude improvement over current limits expected



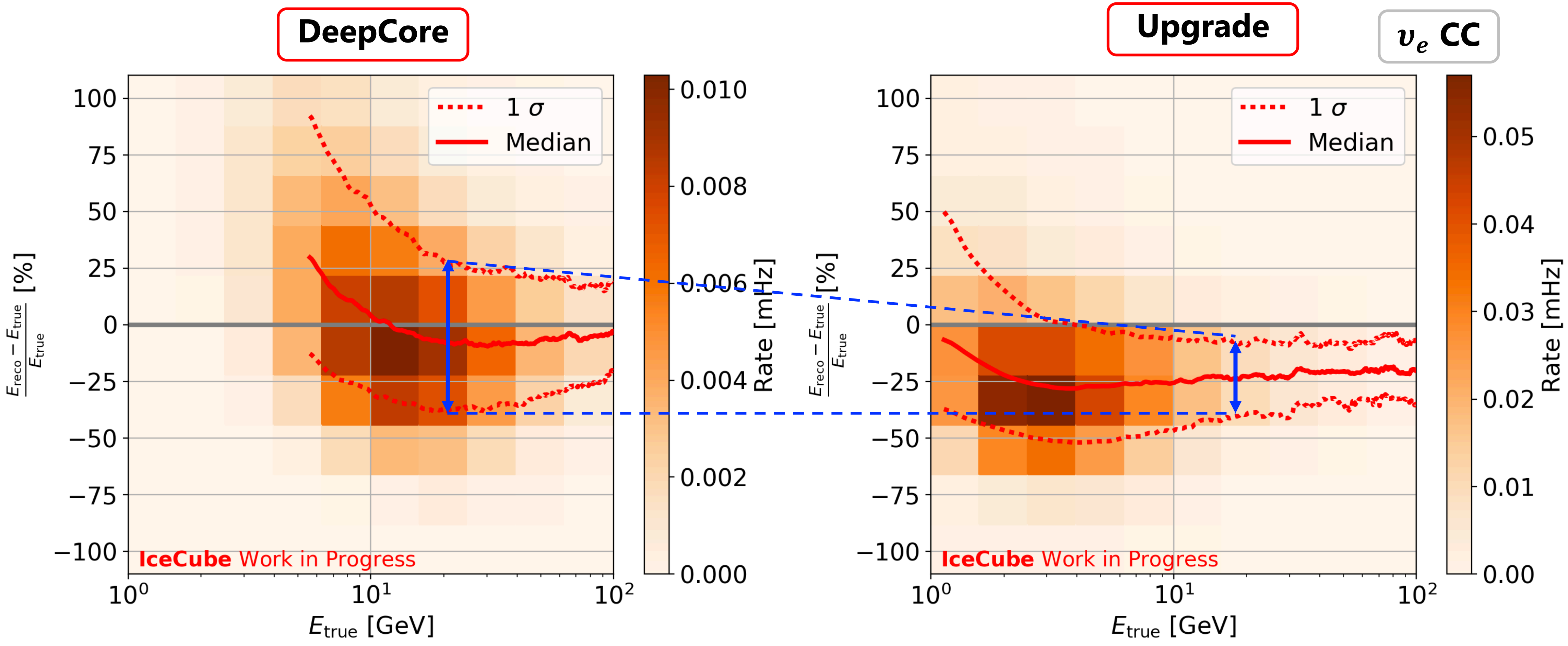
Upgrade detection efficiency



Huge increase in <10 GeV ν rate

Enhanced rate for all oscillation energies

Upgrade energy resolution



2x improvement @ ν_τ appearance energies

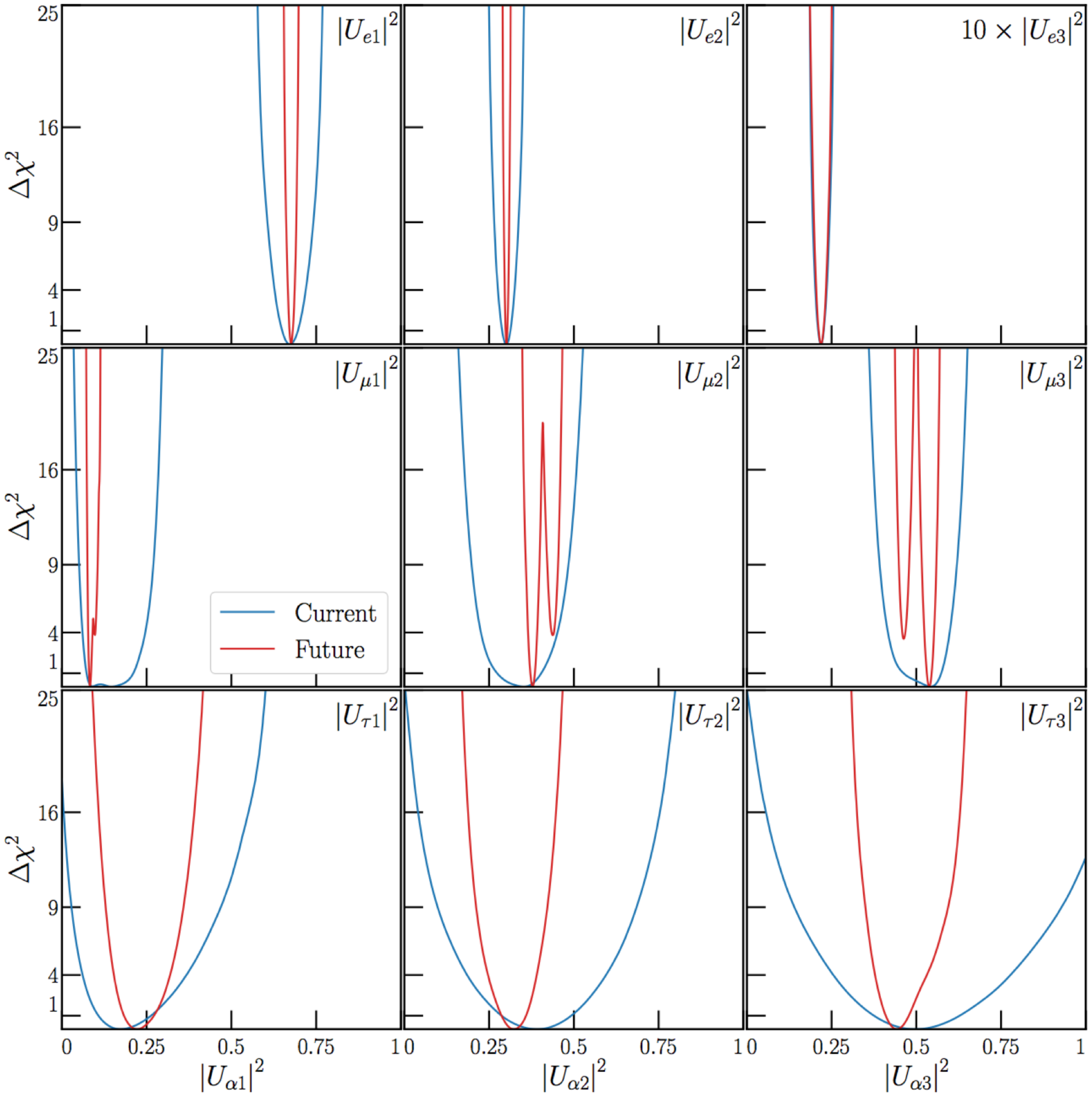
PMNS elements measured

Parke, Ross-Lonergan, arXiv:1508.05095

Experiment	Measured quantity with unitarity	Without unitarity	Normalisation
Reactor SBL ($\overline{\nu}_e \to \overline{\nu}_e$)	$4\lvert U_{e3}\rvert^2 \left(1-\lvert U_{e3}\rvert^2\right) = \sin^2 2\theta_{13}$	$4\lvert U_{e3}\rvert^2 \left(\lvert U_{e1}\rvert^2 + \lvert U_{e2}\rvert^2\right)$	$\left(\lvert U_{e1}\rvert^2 + \lvert U_{e2}\rvert^2 + \lvert U_{e3}\rvert^2\right)^2$
Reactor LBL ($\overline{\nu}_e \to \overline{\nu}_e$)	$4\lvert U_{e1}\rvert^2\lvert U_{e2}\rvert^2 = \sin^2 2\theta_{12}\cos^4\theta_{13}$	$4\lvert U_{e1}\rvert^2\lvert U_{e2}\rvert^2$	$\left(\lvert U_{e1}\rvert^2 + \lvert U_{e2}\rvert^2 + \lvert U_{e3}\rvert^2\right)^2$
SNO (ϕ_{CC}/ϕ_{NC} Ratio)	$\lvert U_{e2}\rvert^2 = \cos^2\theta_{13}\sin^2\theta_{12}$	$\lvert U_{e2}\rvert^2$	$\lvert U_{e2}\rvert^2 + \lvert U_{\mu 2}\rvert^2 + \lvert U_{\tau 2}\rvert^2$
SK/T2K/MINOS ($\nu_\mu \to \nu_\mu$)	$4\lvert U_{\mu 3}\rvert^2 \left(1-\lvert U_{\mu 3}\rvert^2\right) =$ $4\cos^2\theta_{13}\sin^2\theta_{23}\left(1-\cos^2\theta_{13}\sin^2\theta_{23}\right)$	$4\lvert U_{\mu 3}\rvert^2 \left(\lvert U_{\mu 1}\rvert^2 + \lvert U_{\mu 2}\rvert^2\right)$	$\left(\lvert U_{\mu 1}\rvert^2 + \lvert U_{\mu 2}\rvert^2 + \lvert U_{\mu 3}\rvert^2\right)^2$
T2K/MINOS ($\nu_\mu \to \nu_e$)	$4\lvert U_{e3}\rvert^2\lvert U_{\mu 3}\rvert^2 = \sin^2 2\theta_{13}\sin^2\theta_{23}$	$-4\,\mathrm{Re}\{U_{e3}^* U_{\mu 3}\left(U_{e1}^* U_{\mu 1} + U_{e2}^* U_{\mu 2}\right)\}$	$\lvert U_{e1}U_{\mu 1}^* + U_{e2}U_{\mu 2}^* + U_{e3}U_{\mu 3}^*\rvert^2$
SK/OPERA ($\nu_\mu \to \nu_\tau$)	$4\lvert U_{\mu 3}\rvert^2\lvert U_{\tau 3}\rvert^2 = \sin^2 2\theta_{23}\cos^4\theta_{13}$	$-4\,\mathrm{Re}\{U_{\tau 3}^* U_{\mu 3}\left(U_{\tau 1}^* U_{\mu 1} + U_{\tau 2}^* U_{\mu 2}\right)\}$	$\lvert U_{\mu 1}U_{\tau 1}^* + U_{\mu 2}U_{\tau 2}^* + U_{\mu 3}U_{\tau 3}^*\rvert^2$

PMNS element constraints

arXiv:2008.01088



Systematic uncertainties