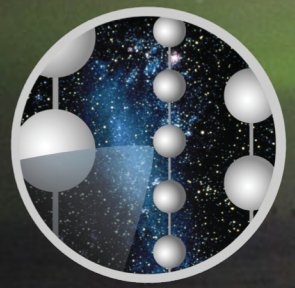
Neutrino oscillations and BSM physics with IceCube

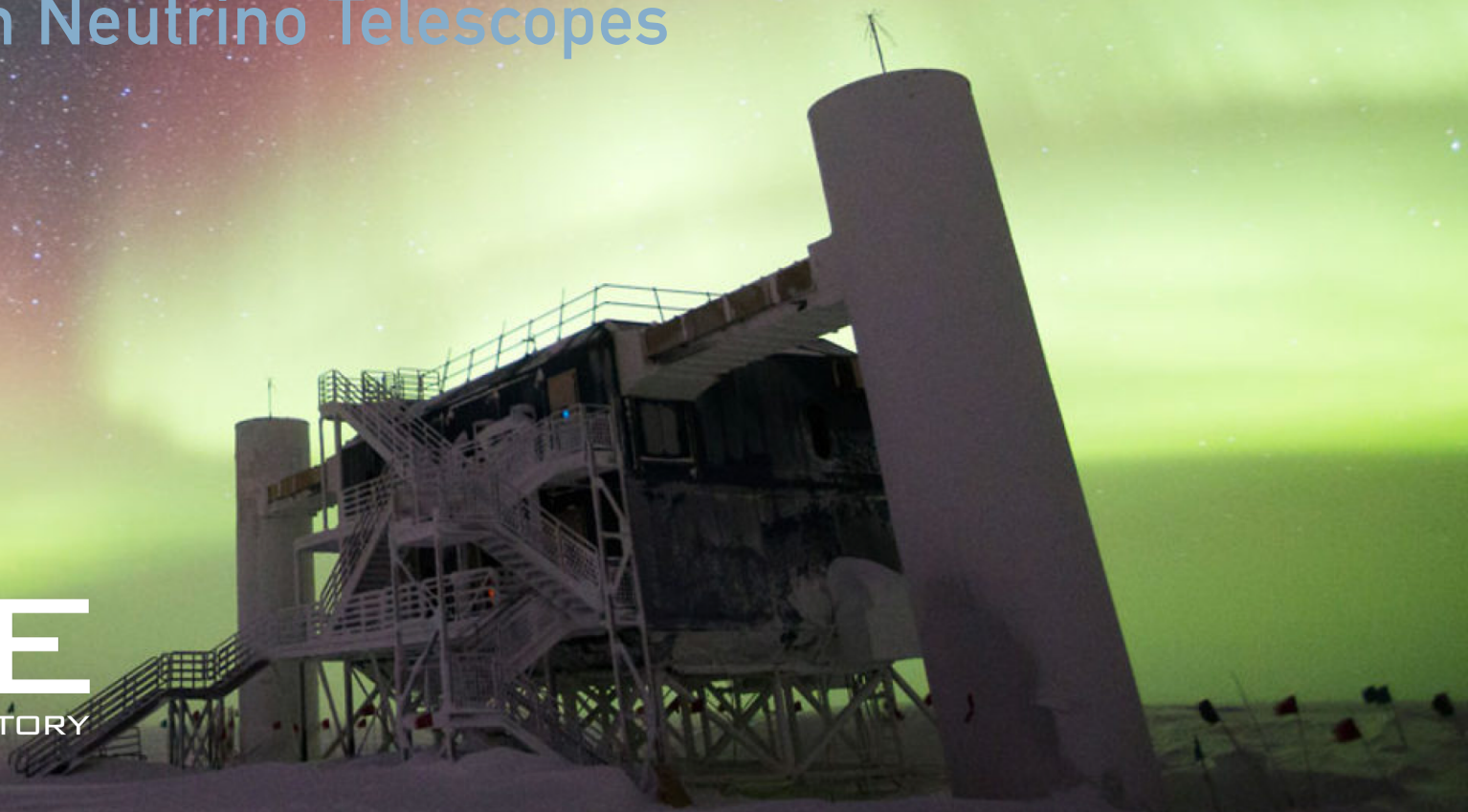
Tom Stuttard for the IceCube collaboration
Niels Bohr Institute

XIX International Workshop on Neutrino Telescopes

CARLSBERG FOUNDATION
VILLUM FONDEN



IceCube
South Pole Neutrino Observatory



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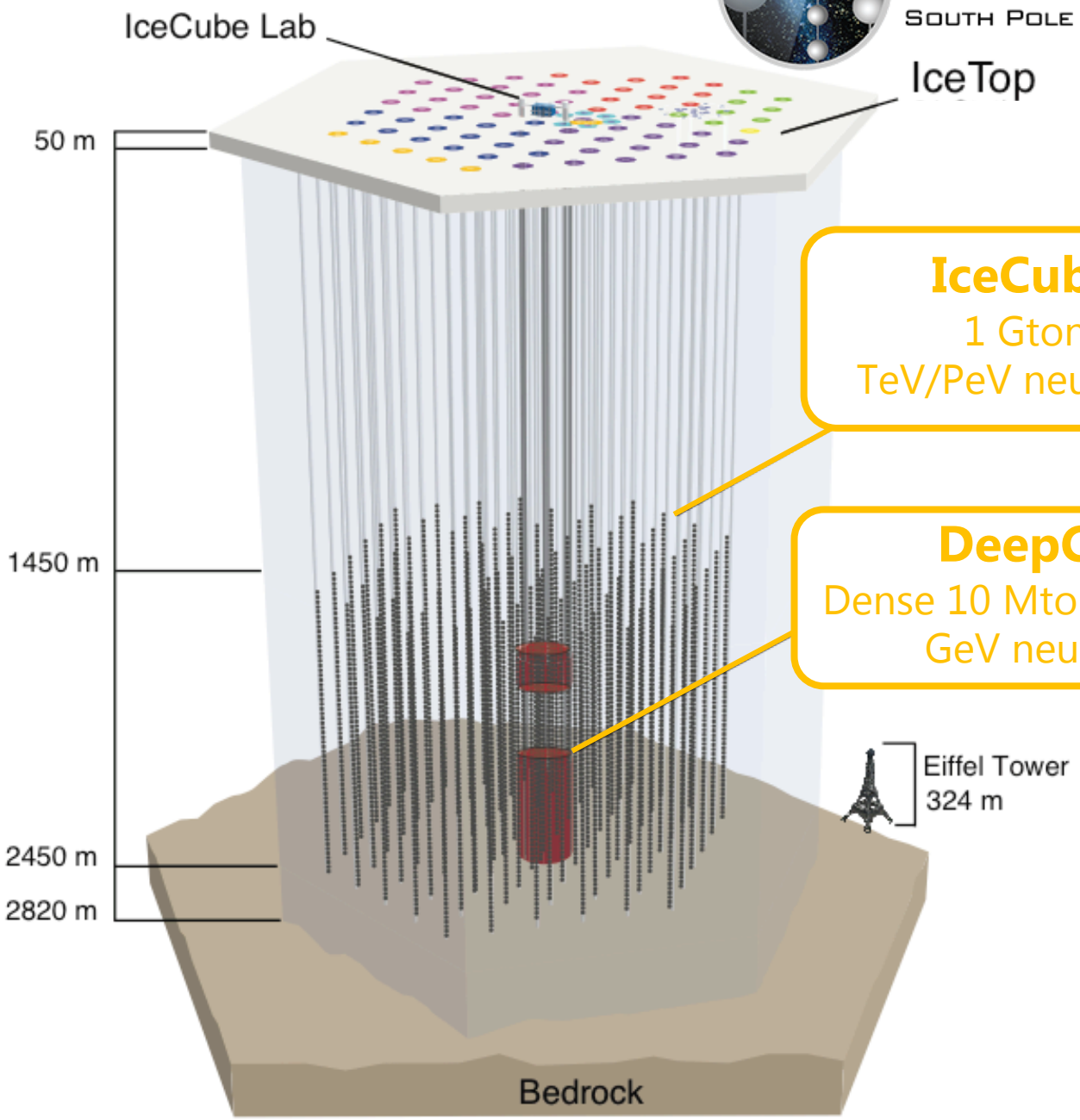
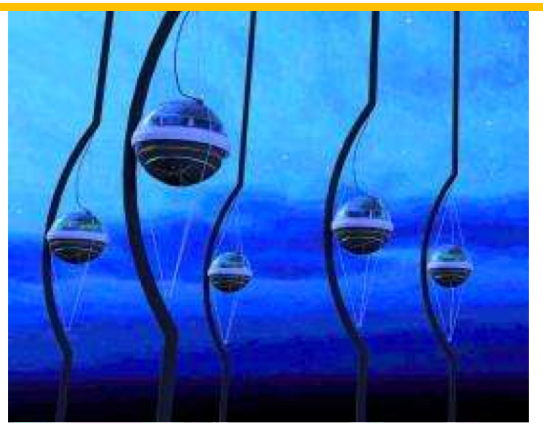


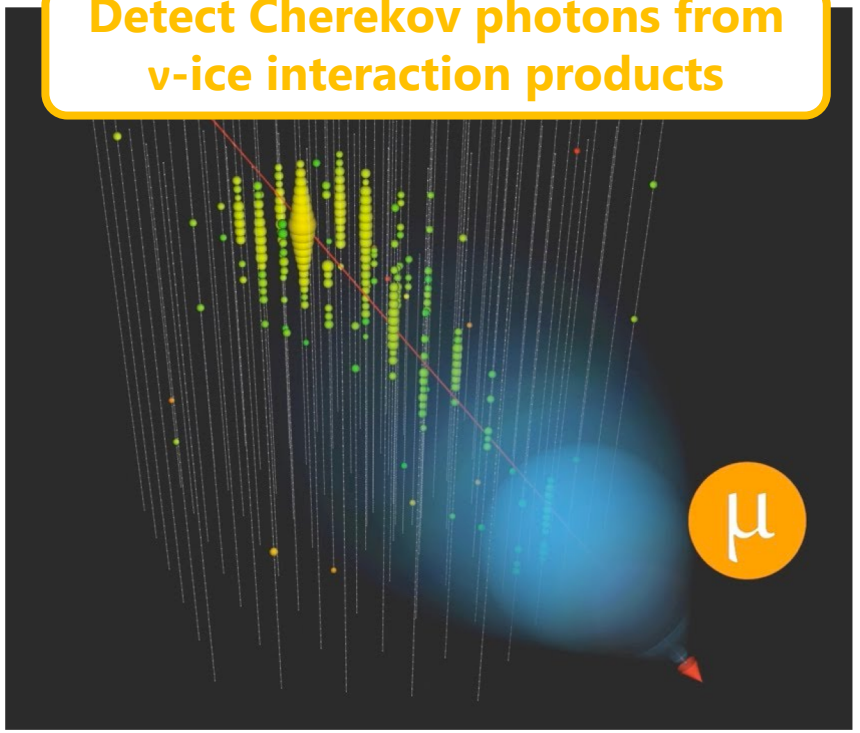
IceCube
1 Gton
TeV/PeV neutrinos

DeepCore
Dense 10 Mton sub-array
GeV neutrinos

5160 PMTs in glacial ice (natural detection medium)



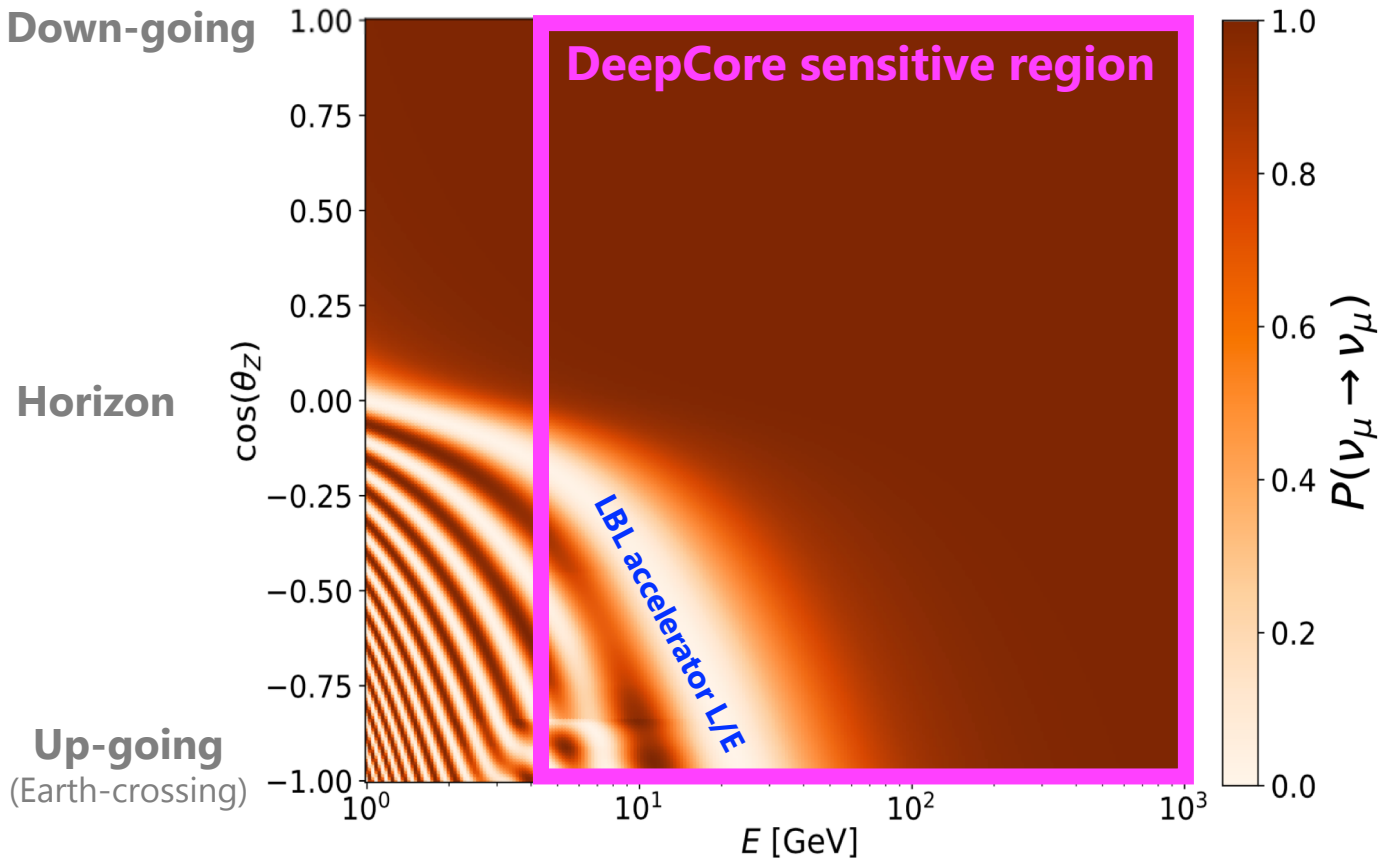
Detect Cherekov photons from ν-ice interaction products

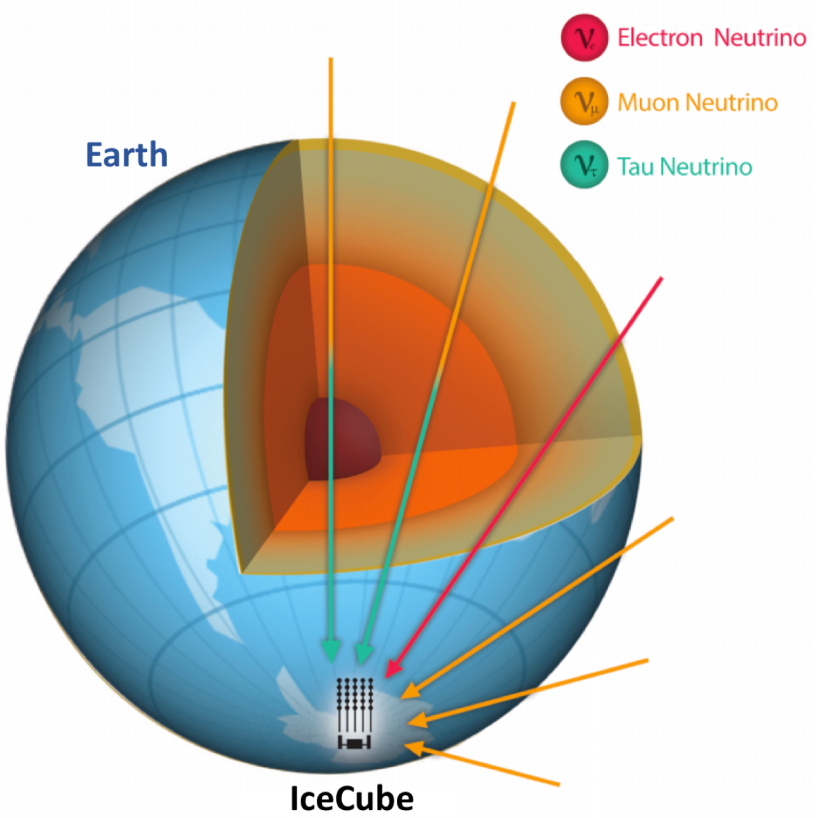


Neutrino oscillations

Atmospheric neutrino oscillations in DeepCore

- Near **maximal $\nu_\mu \rightarrow \nu_\tau$ oscillations** for O(10 GeV) Earth-crossing ν
- **mHz** atmospheric neutrino detection rate → **a ν every 15 mins!**



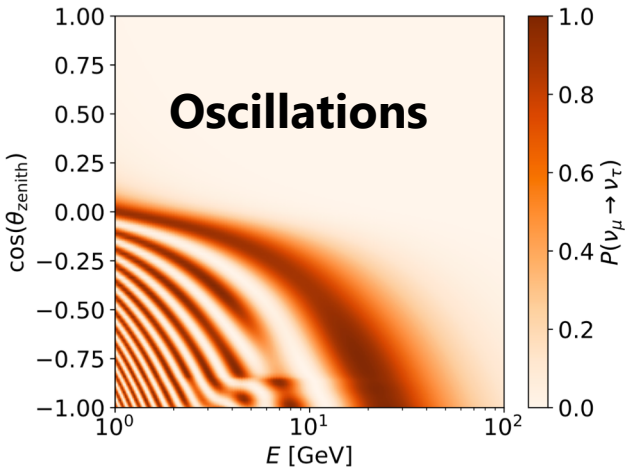


Measuring oscillations

- 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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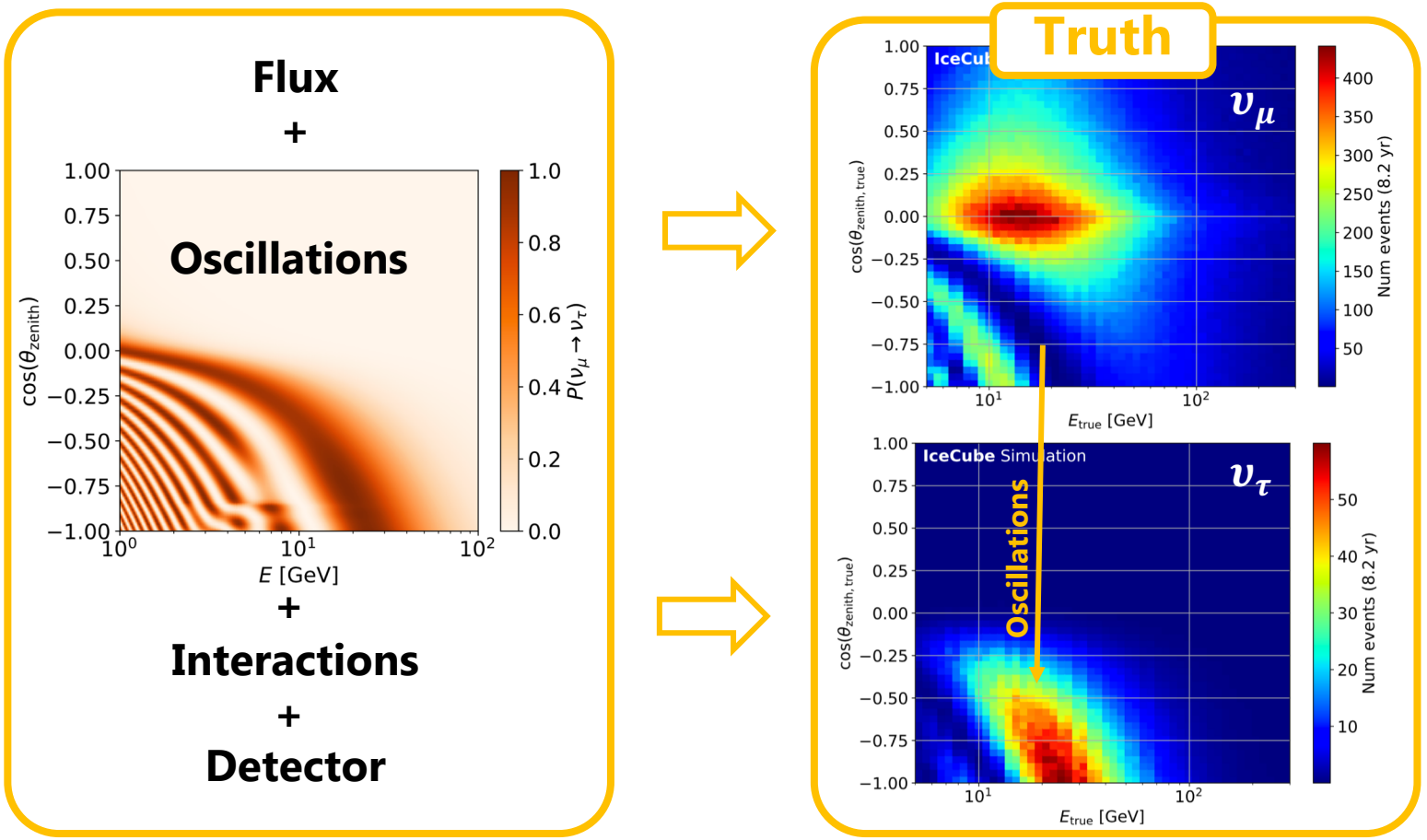

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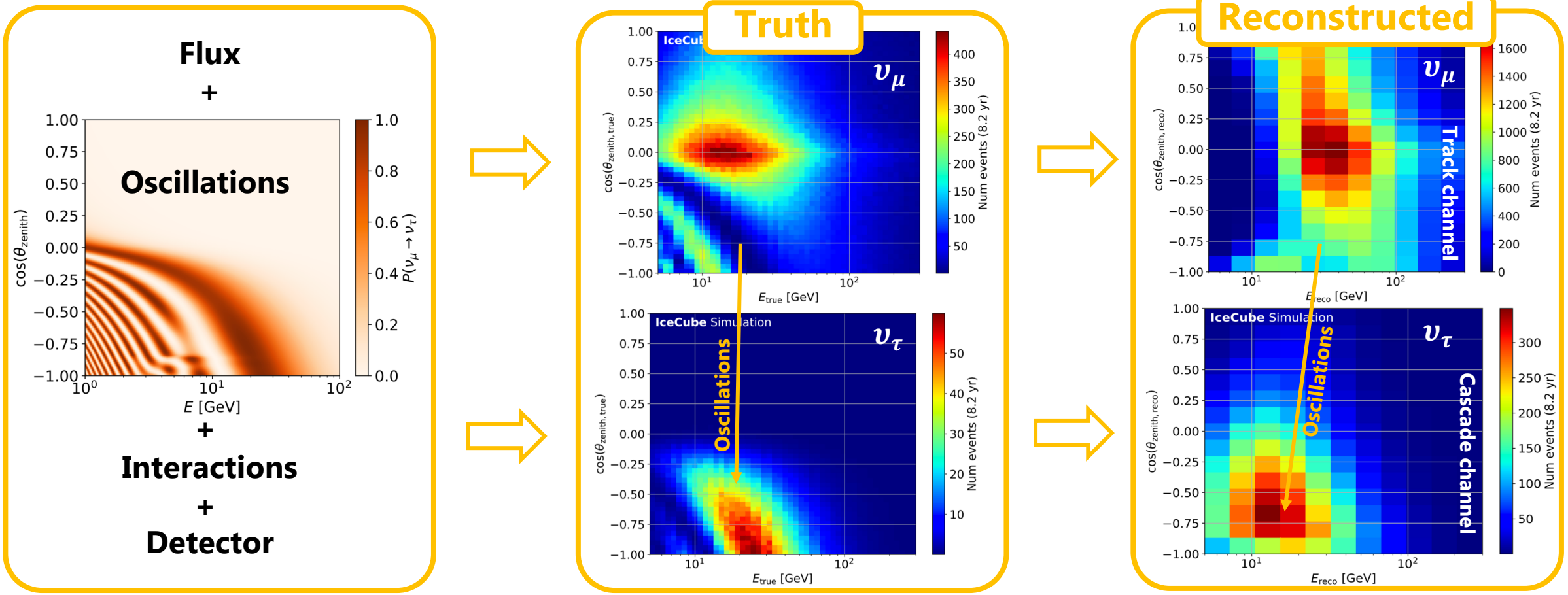

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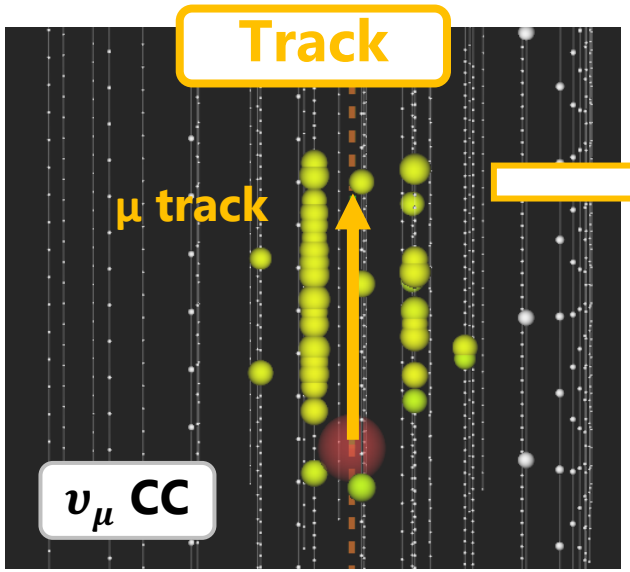
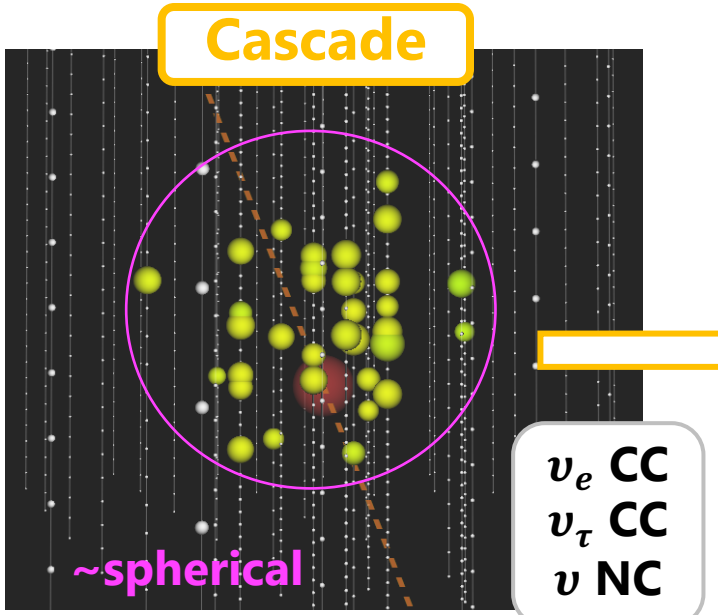
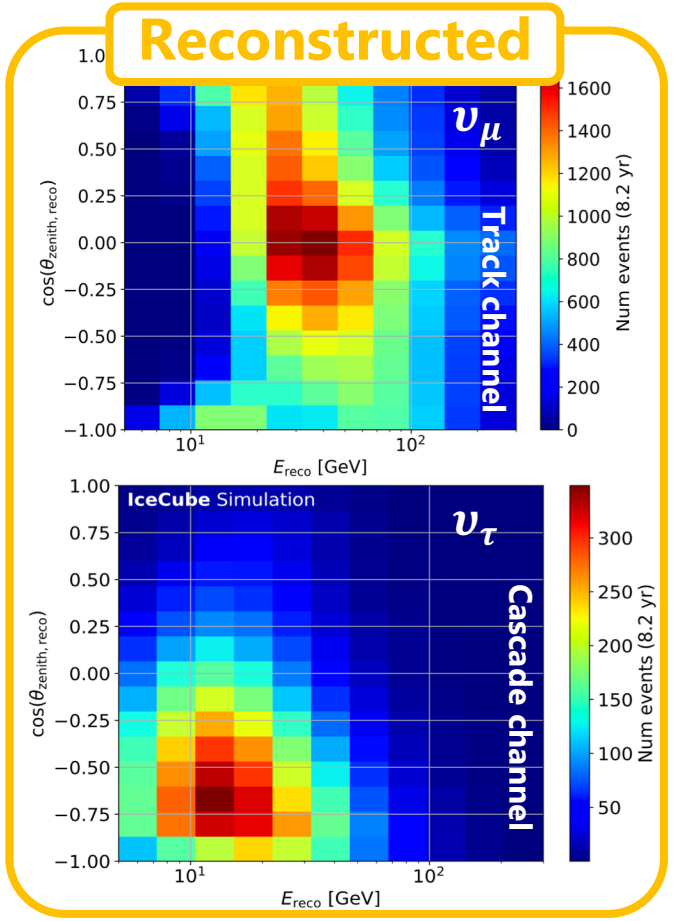


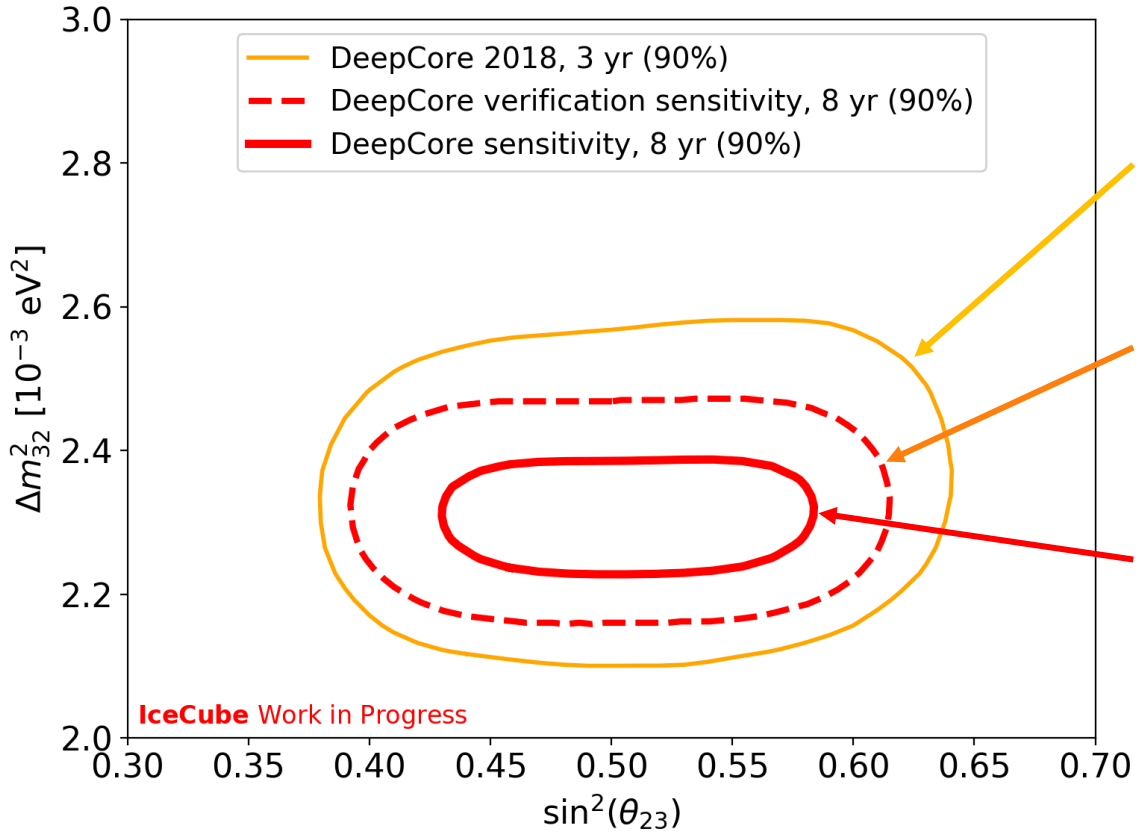
PID far less clear at low energy...





ν_μ disappearance

- New measurements of atmospheric neutrino oscillations imminent
  - Huge statistics → **8 yrs of data → 250,000 ν**
  - Major advances in calibration, machine learning, reconstruction, treatment of systematic uncertainties, etc



Current 3 yr result (PhysRevLett.120.071801)

New "golden events" 8 yr analysis (sensitivity)
Result imminent

New high statistics 8 yr analysis (sensitivity)
Unblinding shortly

ν_μ disappearance

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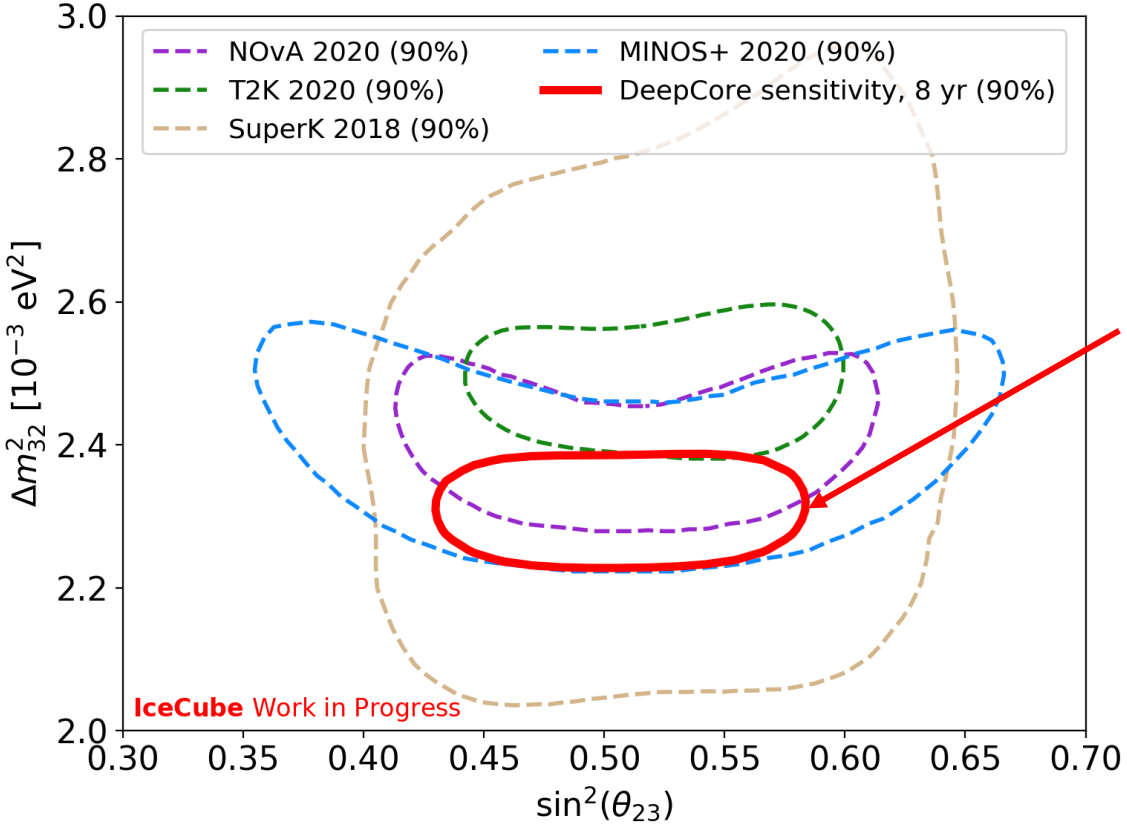


Sensitivity commensurate with long baseline accelerators for the first time

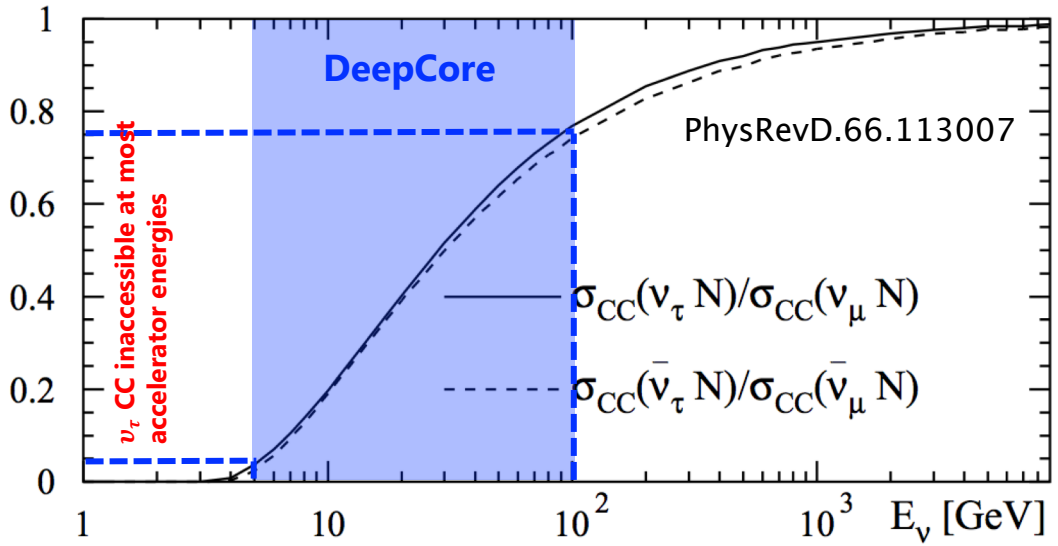
(DeepCore 2019 3 yr result best fit point assumed)

Also expect sensitivity to mass ordering via matter effects

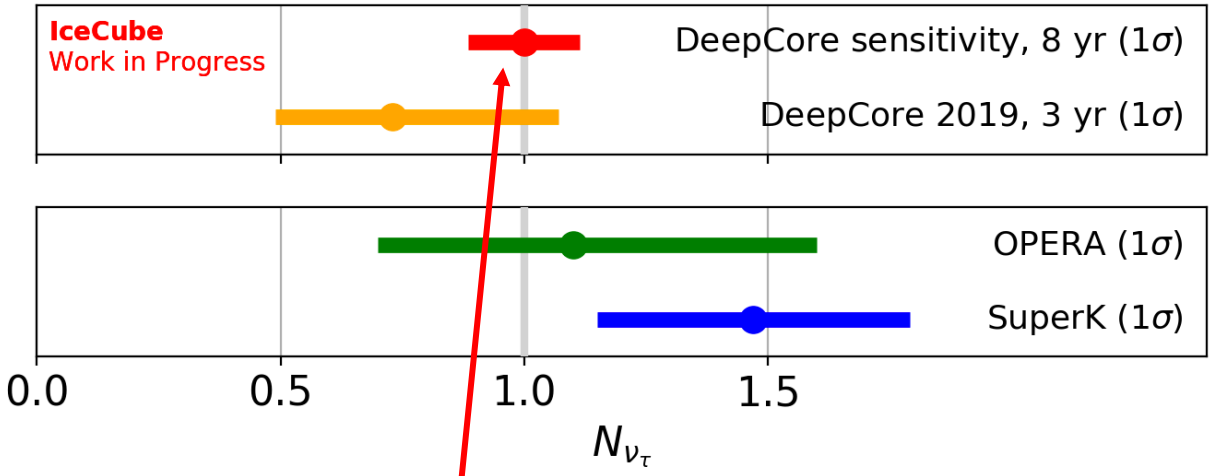
ν_τ appearance

- Measure ν_τ **appearance normalisation** w.r.t. unitary PMNS expectation
  - Large **volume + high energy** → overcome cross section suppression
  - Observe excess of cascade events corresponding to track deficit
- Crucial to tests of PMNS mixing matrix unitarity (τ-sector poorly constrained)

ν_τ CC cross section suppression



ν_τ appearance sensitivity



New 8 yr analysis sensitivity → 11,000 ν_τ expected

12% precision expected → 2.5x current world best

ν_τ appearance

- Measure ν_τ appearance normalisation (w.r.t. unitary PMNS expectation)

Takeaway

DeepCore is sensitive to O(10 GeV) ν_μ disappearance and ν_τ appearance

High statistics 8 yr results imminent

Coming soon:

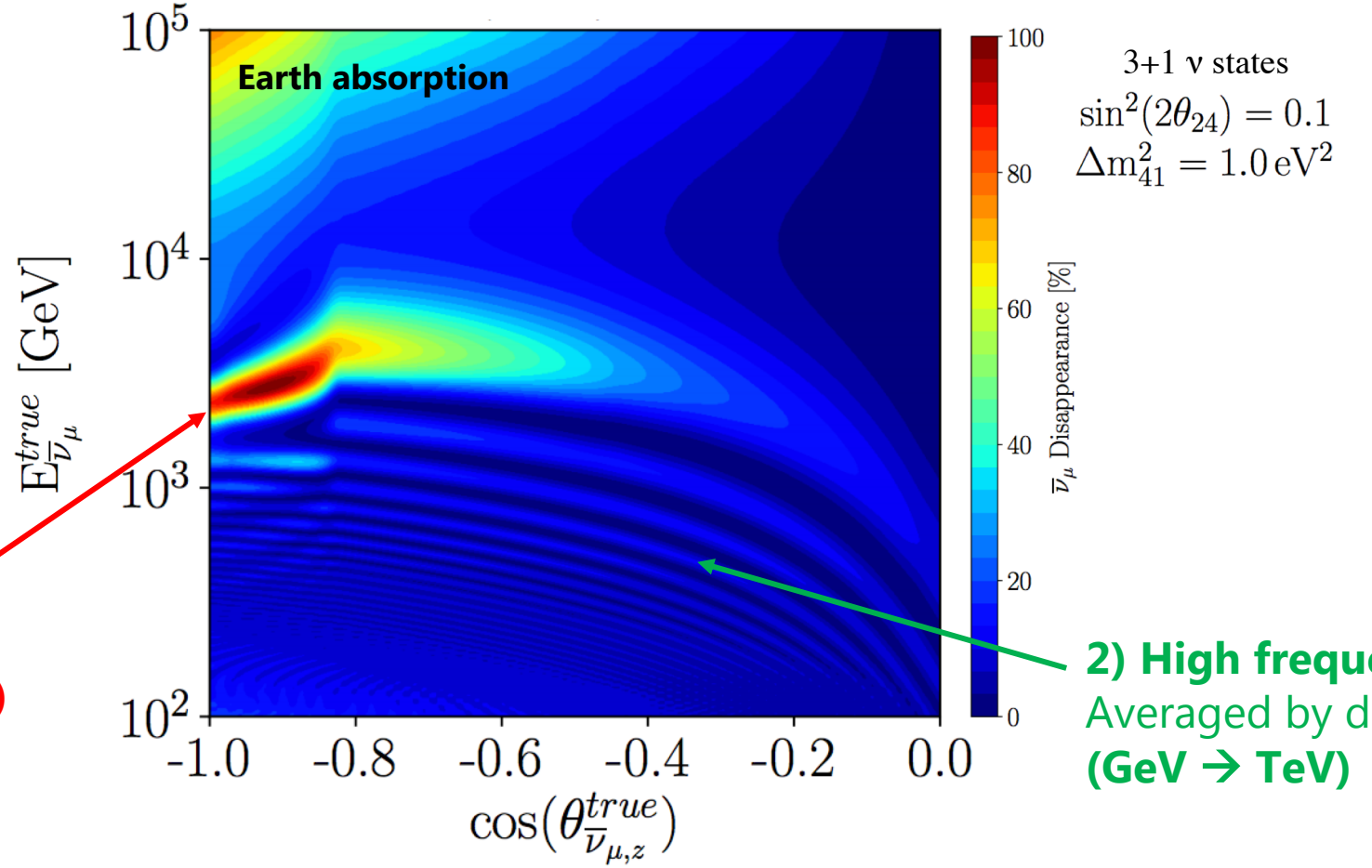
1) Comparable mixing angle and mass splitting precision to long baseline accelerators

2) 12% precision in ν_τ normalisation

BSM oscillations

Sterile neutrinos

- Neutrino oscillations modified by presence of additional sterile neutrino states
- Two main signals of eV steriles in atmospheric $\bar{\nu}_\mu$ disappearance:

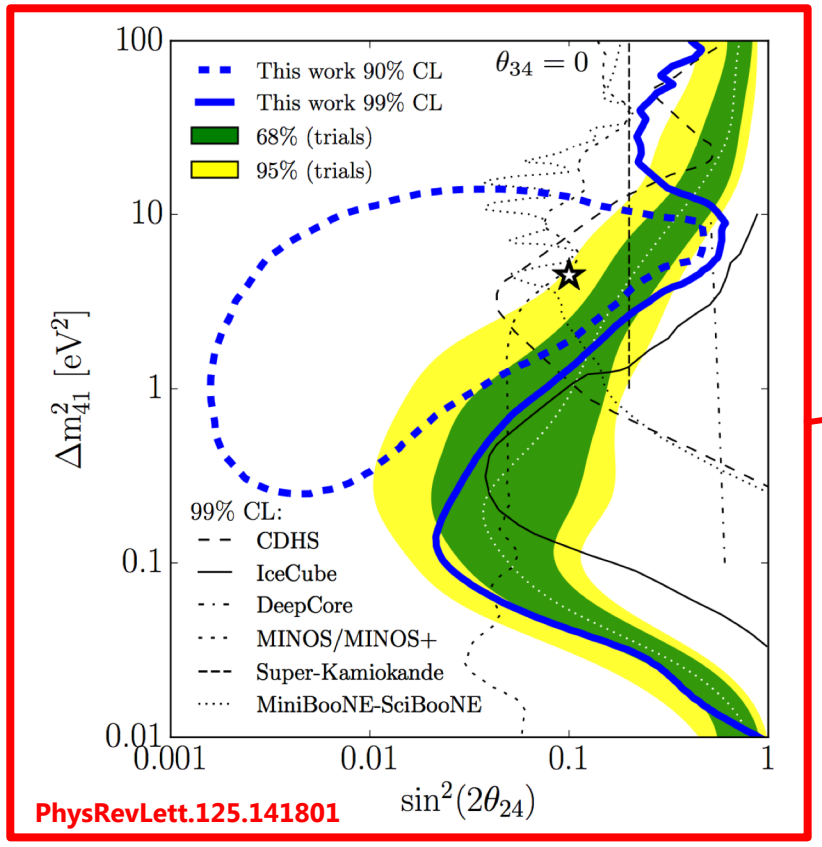


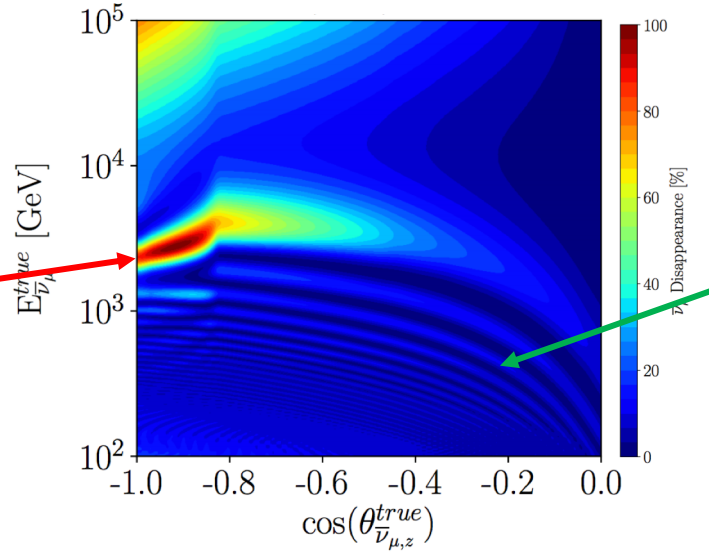
1) Matter enhanced resonant disappearance when crossing core (TeV)

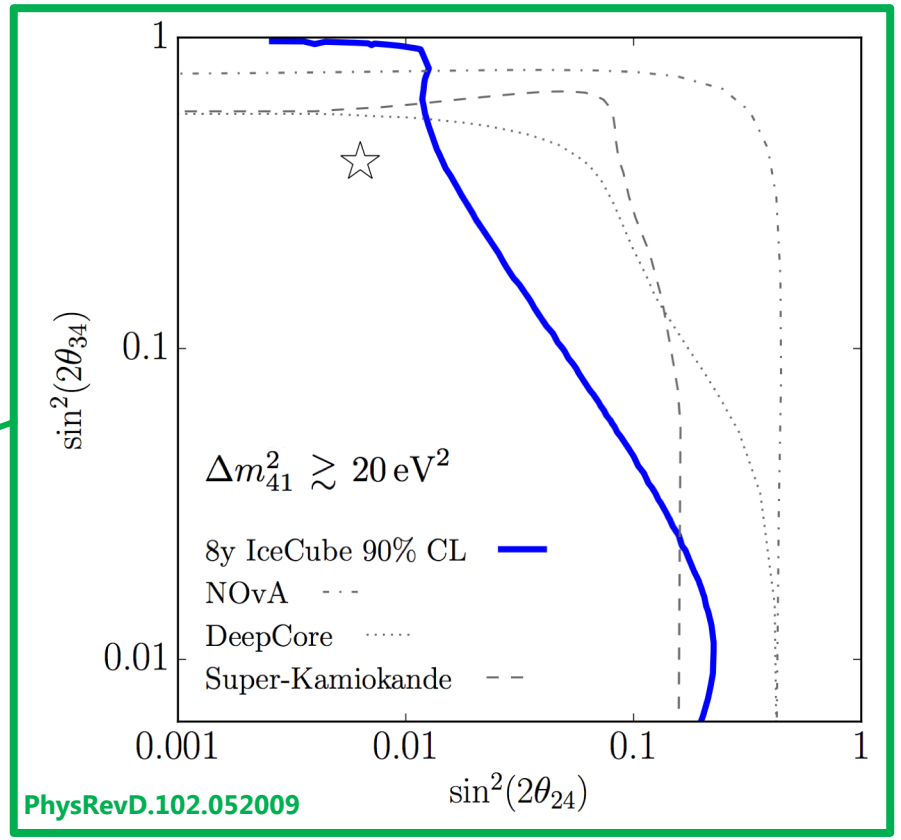
2) High frequency oscillations
Averaged by detector resolution
(GeV → TeV)

Sterile neutrinos

- Major 8 yr IceCube (high energy) results in both channels (300,000 ν_μ)
  - Consistent with no sterile → increased tension with short baseline anomalies



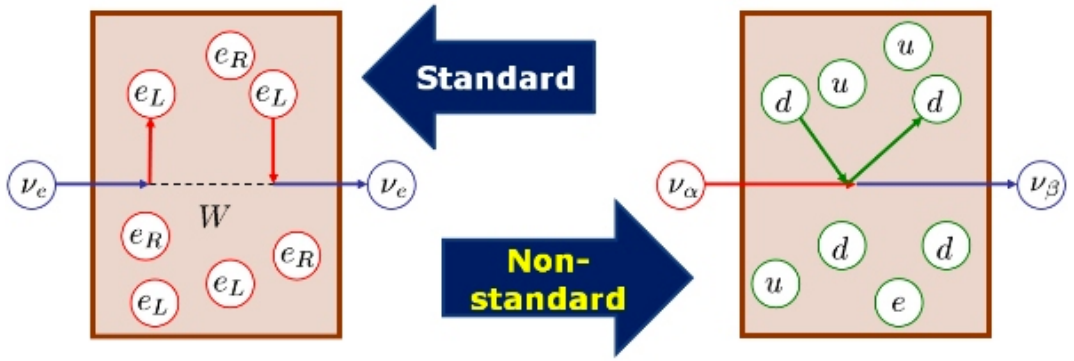




- 8 yr DeepCore (low energy) and sterile+decay results on the way

Non-Standard Interactions (NSI)

- New vector forces between neutrinos and matter → matter potential → modified oscillations as neutrinos cross the Earth



- Represent with effective matter Hamiltonian:

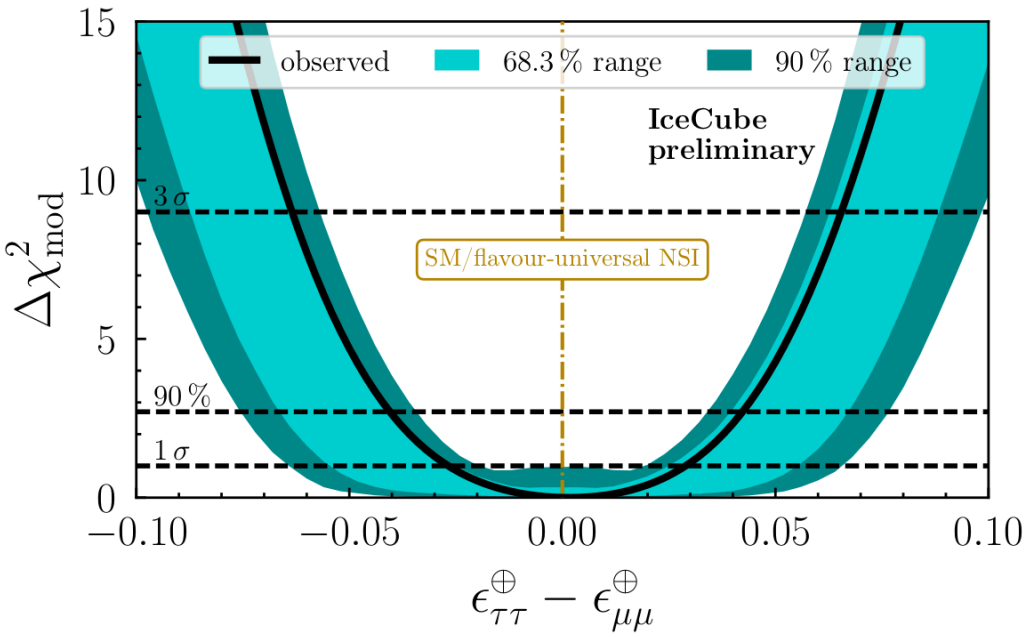
Lepton flavor violating

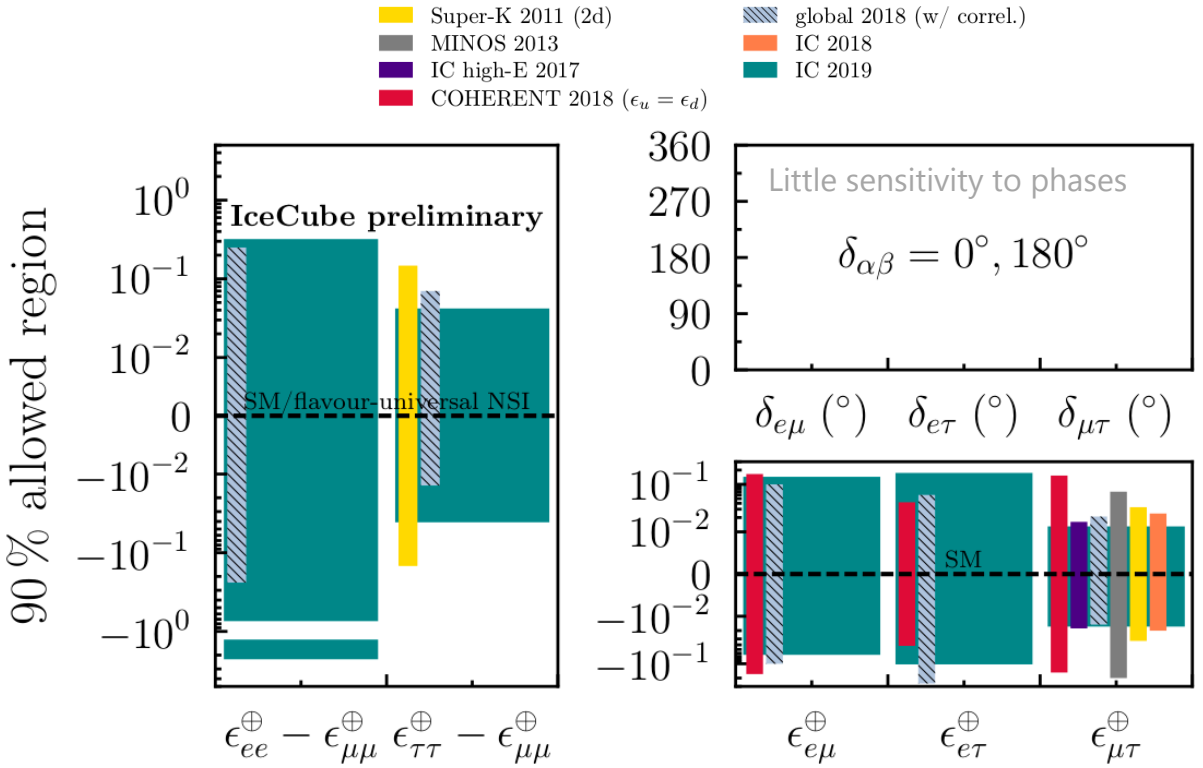
$$H_{\text{mat}}(x) = V_{\text{CC}}(x) \begin{pmatrix} 1 + \epsilon^{\oplus}_{ee} - \epsilon^{\oplus}_{\mu\mu} & \epsilon^{\oplus}_{e\mu} & \epsilon^{\oplus}_{e\tau} \\ \epsilon^{\oplus *}_{e\mu} & 0 & \epsilon^{\oplus}_{\mu\tau} \\ \epsilon^{\oplus *}_{e\tau} & \epsilon^{\oplus *}_{\mu\tau} & \epsilon^{\oplus}_{\tau\tau}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

Lepton universality violating

Non-Standard Interactions (NSI)

- Constraints on **all matrix elements** with 3 yrs DeepCore
  - **World best limits in multiple channels** → publication imminent
  - Also measurements in alternative "generalised matter potential" formulation





- 8 yr results with DeepCore (GeV) and IceCube (TeV) on the way

Non-Standard Interactions (NSI)

- Constraints on **all matrix elements** with 3 yrs DeepCore
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  - Al

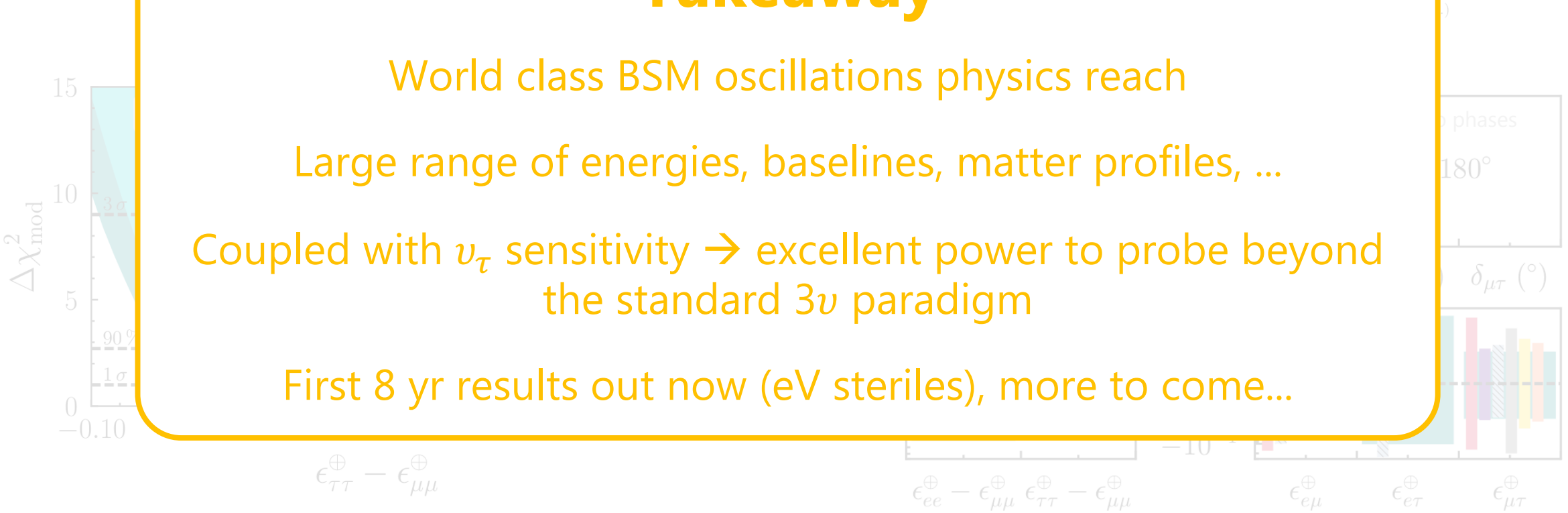
Takeaway

World class BSM oscillations physics reach

Large range of energies, baselines, matter profiles, …

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

First 8 yr results out now (eV steriles), more to come…



- 8 yr results with DeepCore (GeV) and IceCube (TeV) on the way

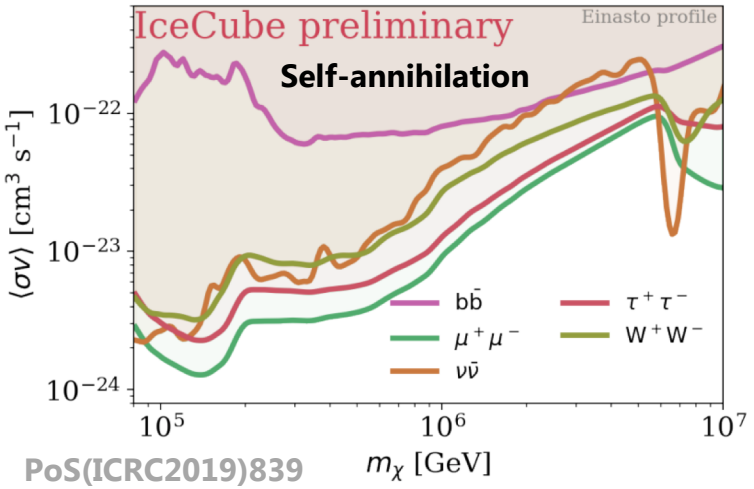
Dark Matter

Image credit: Juanan Aguilar

Dark matter: Galactic center

- Search for neutrinos from DM annihilation/decay in galactic center

High energy (HESE)
= higher DM mass



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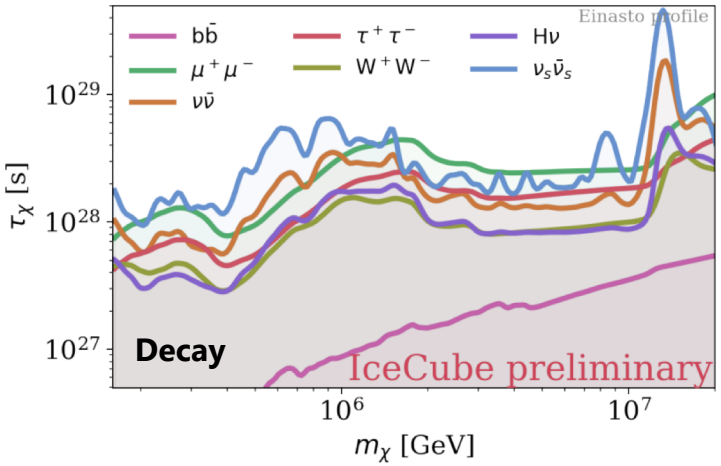
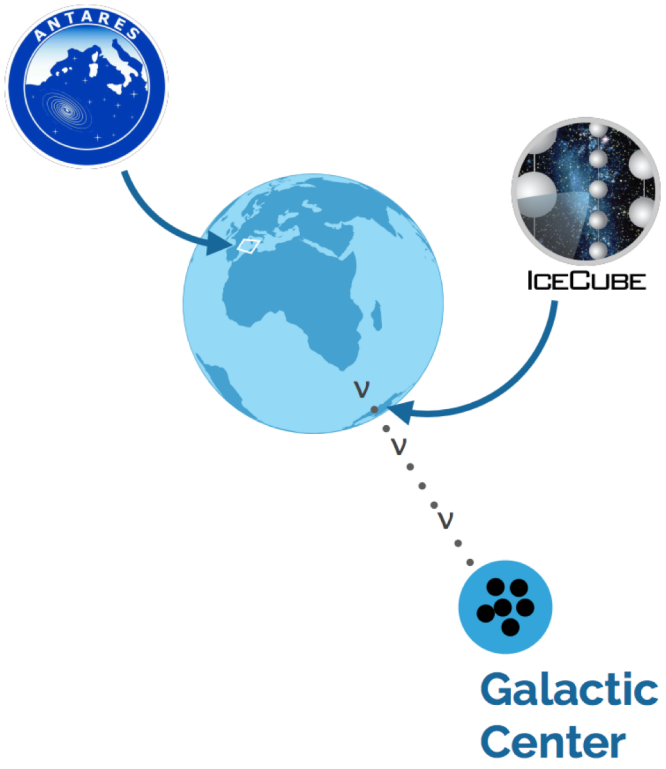
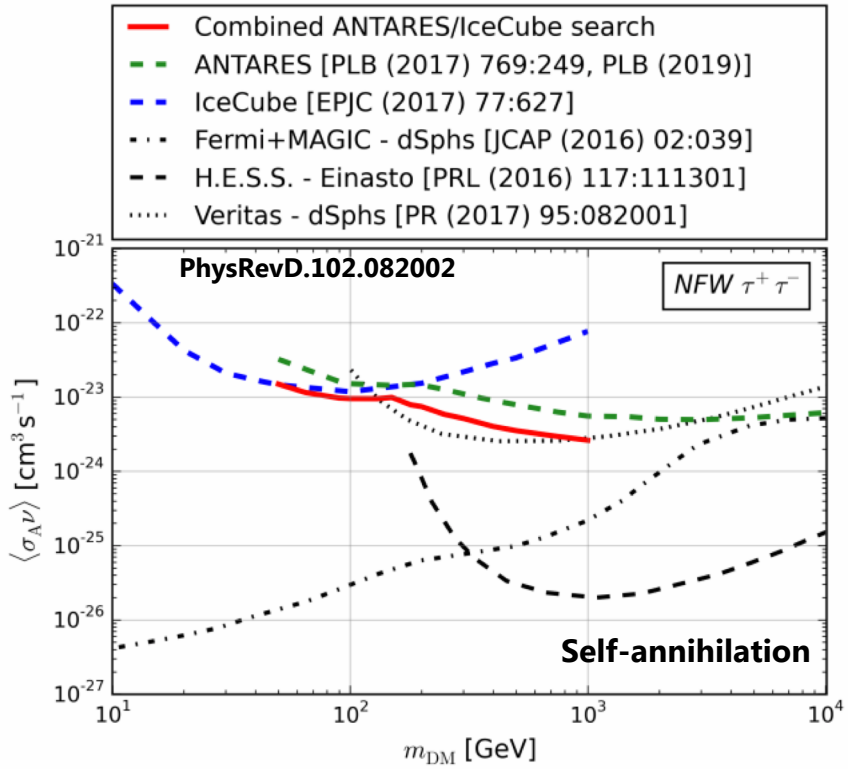




Low energy
= lower DM mass

DeepCore + ANTARES combined search



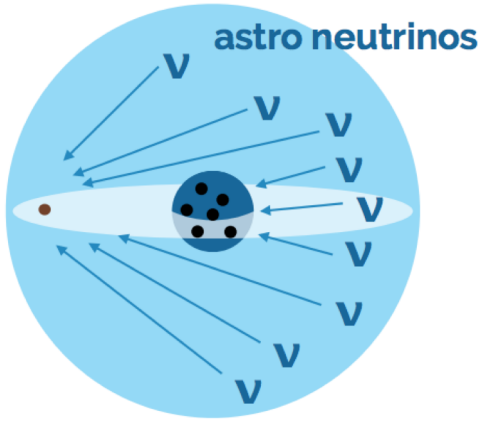
New 8 yr DeepCore result on the way

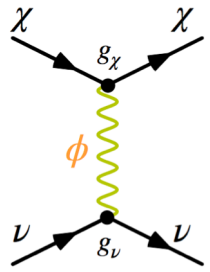
Image credit: Juanan Aguilar

Dark matter: Galactic center

- Search for neutrinos from DM annihilation/decay in galactic center

Or… Scattering of astrophysical neutrinos
Deficit from Galactic center





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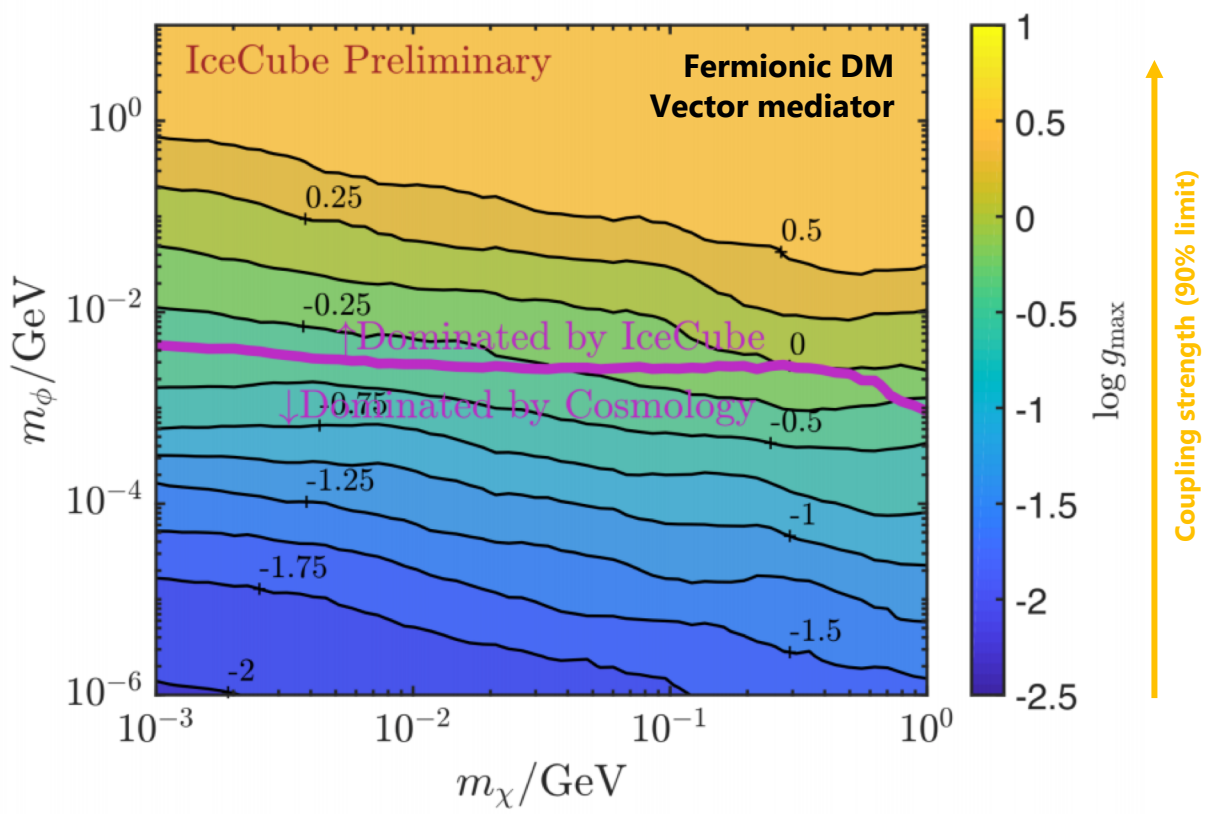
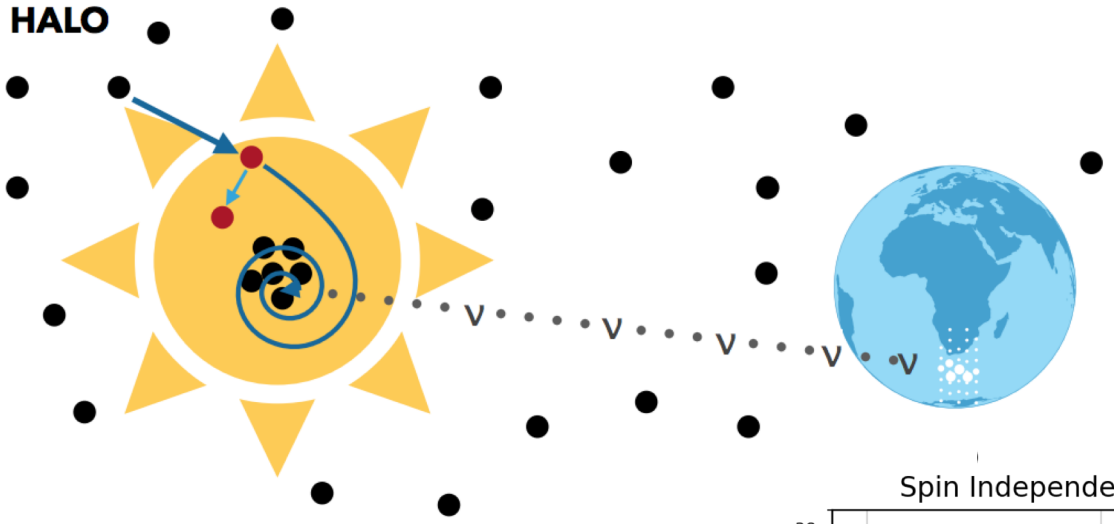
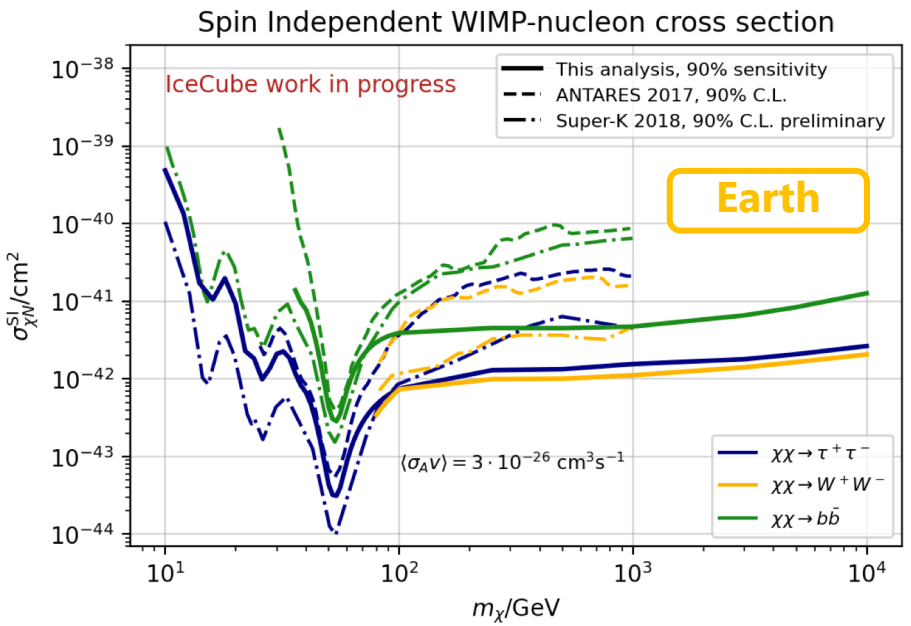


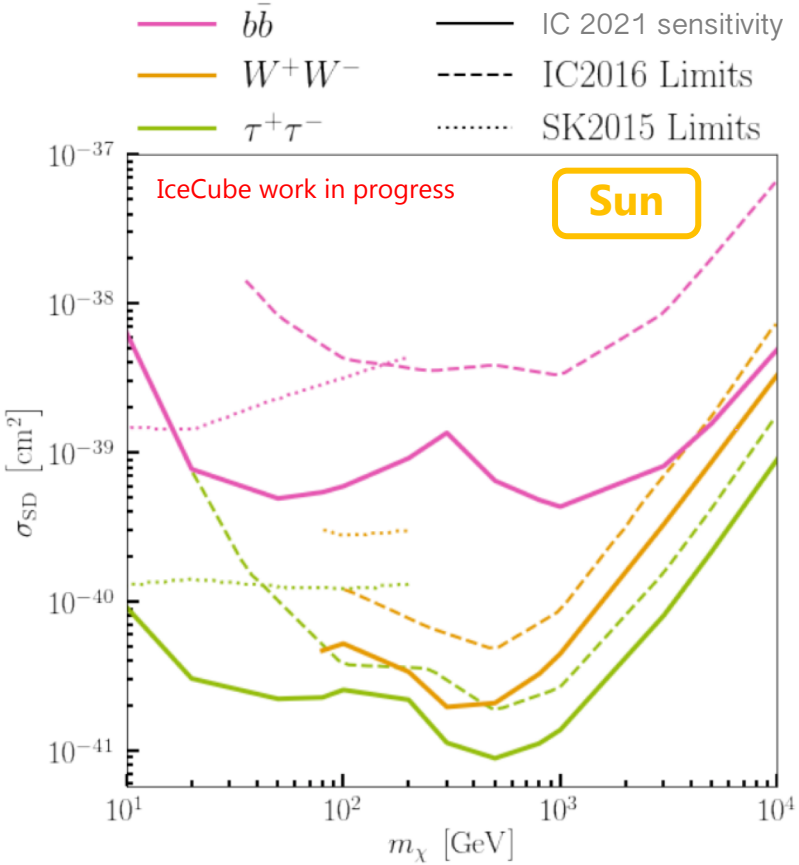
Image credit: Juanan Aguilar

Dark matter: Capture in Earth/Sun

- Search for neutrinos from annihilation of DM captured in Sun or Earth







New 8 yr analyses underway
Cover broad range of DM mass

See talk by J Lazar (23/02/2021, 12:05)

Image credit: Juanan Aguilar

Dark matter: Capture in Earth/Sun

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Takeaway

Broad indirect DM search potential

Galactic, Sun & Earth source, large range of E_ν (and thus m_χ)

No signal yet...

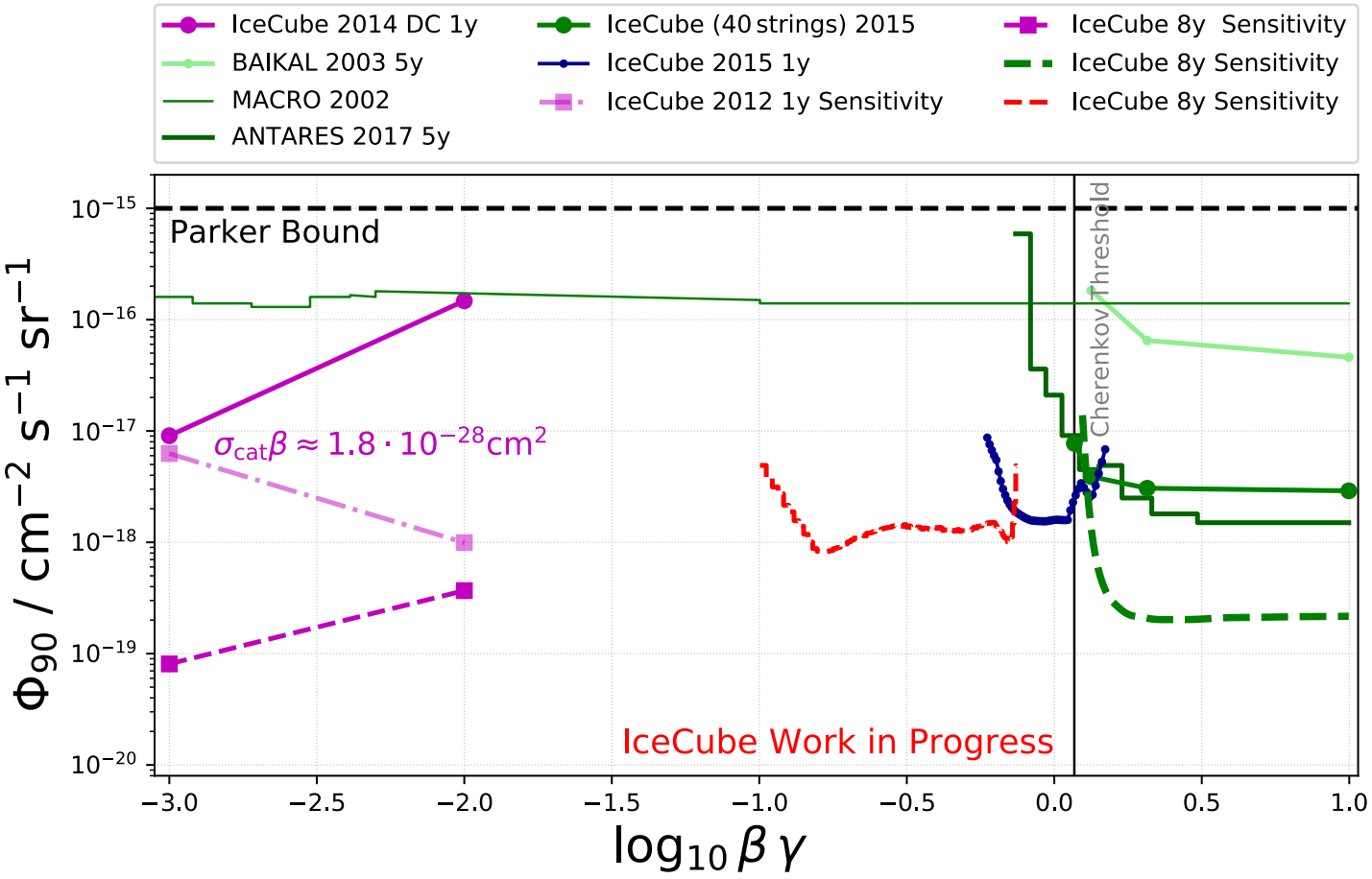
8 yr analyses underway → major sensitivity gains

New 8 yr analyses underway
Cover broad range of DM mass

Magnetic monopoles

Monopoles

- Isolated magnetic charge, predicted by many GUT models
- Search for direct signals of astrophysical monopoles crossing IceCube



Signal in IceCube depends on monopole velocity

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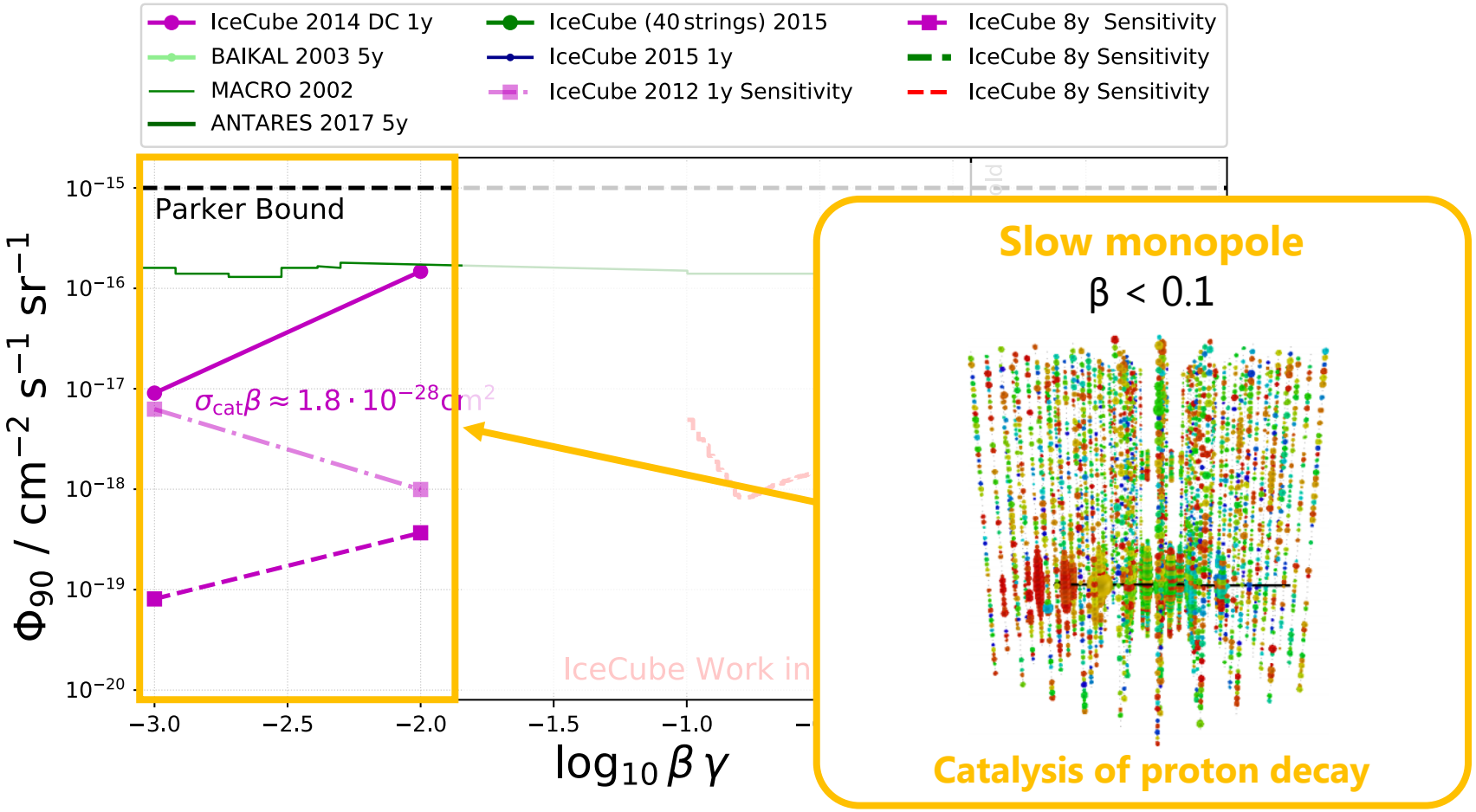

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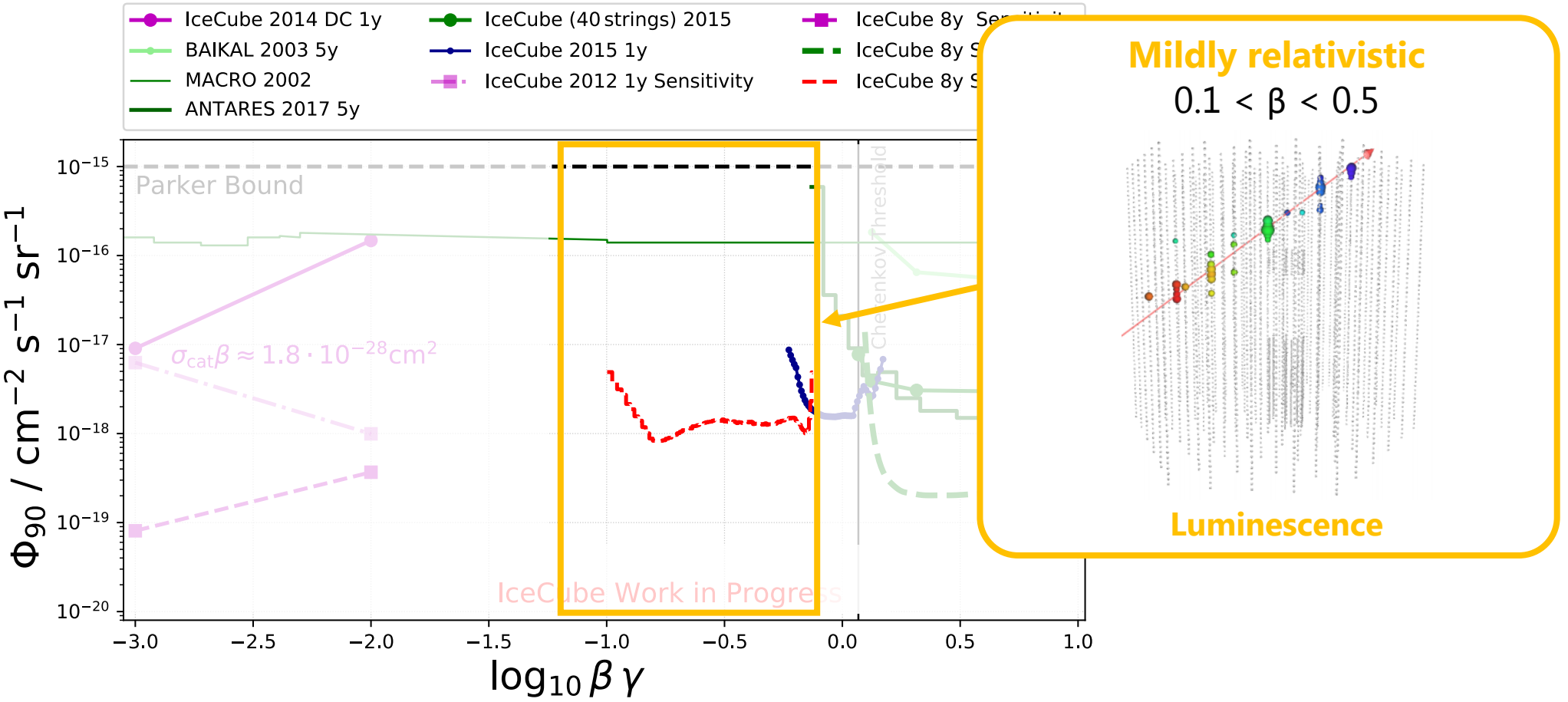

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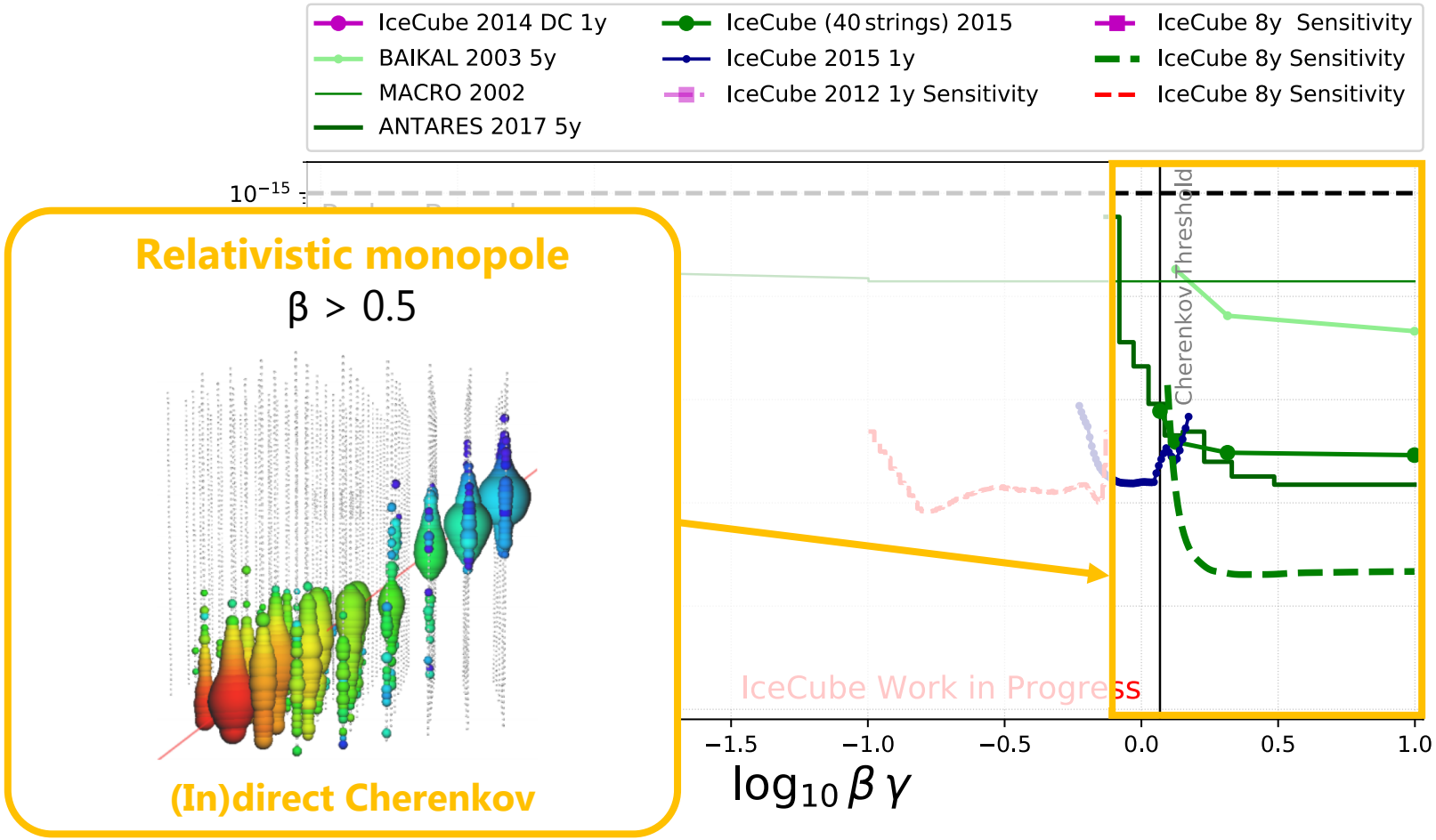

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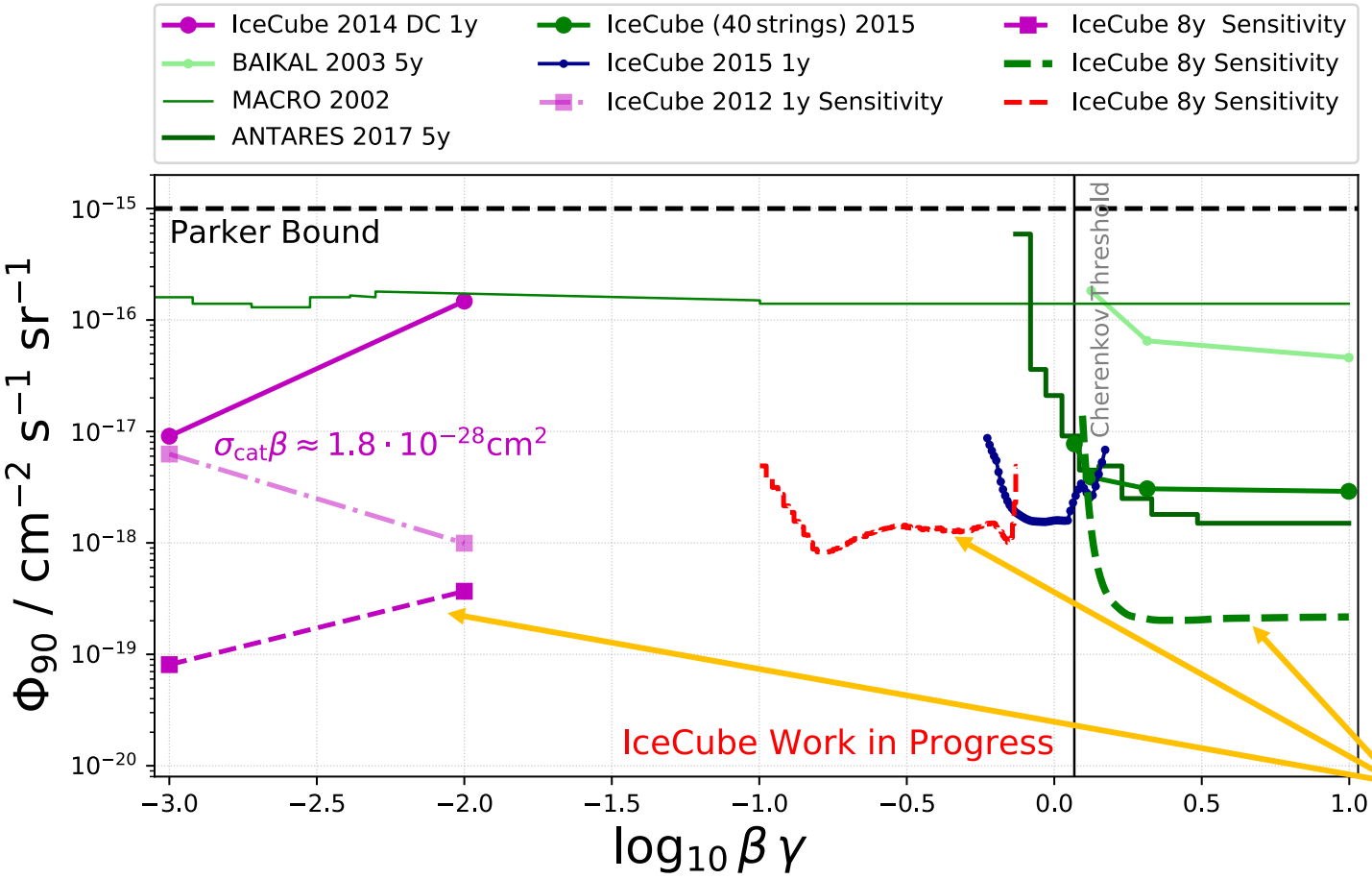
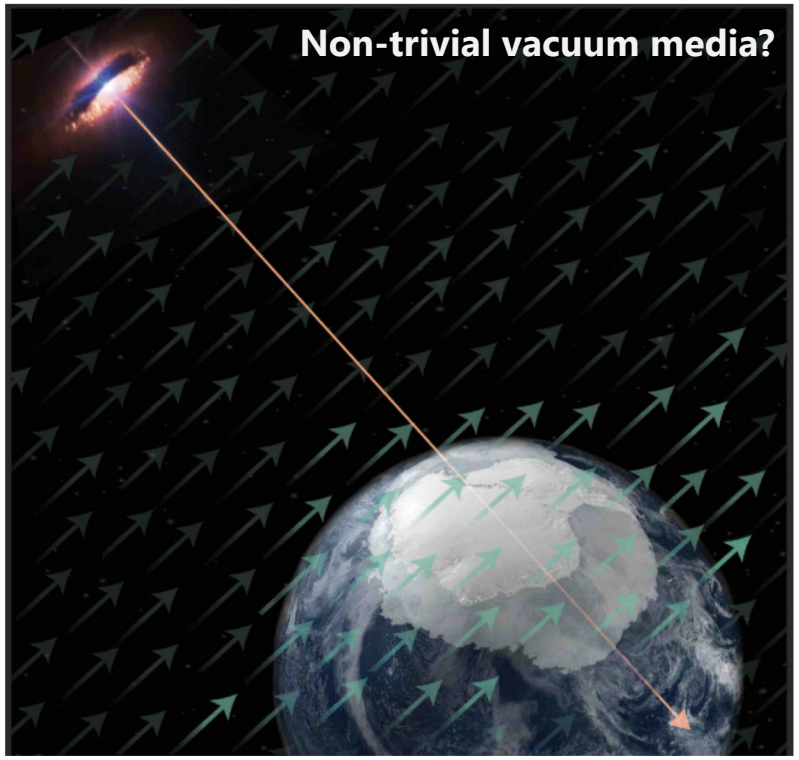


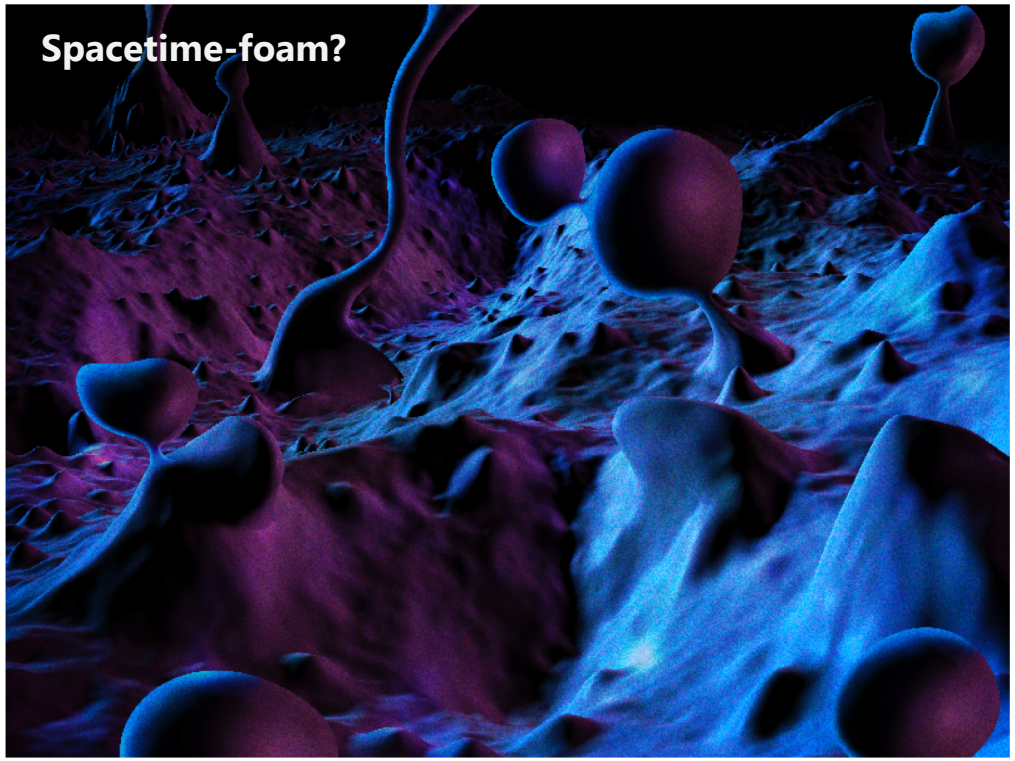
New 8 yr results in all channels coming soon
Large sensitivity gains

Planck scale physics

Planck scale physics

- **New physics expected at the Planck scale → quantum gravity?**
  - Space-time defects/fluctuations → modified neutrino propagation/oscillations





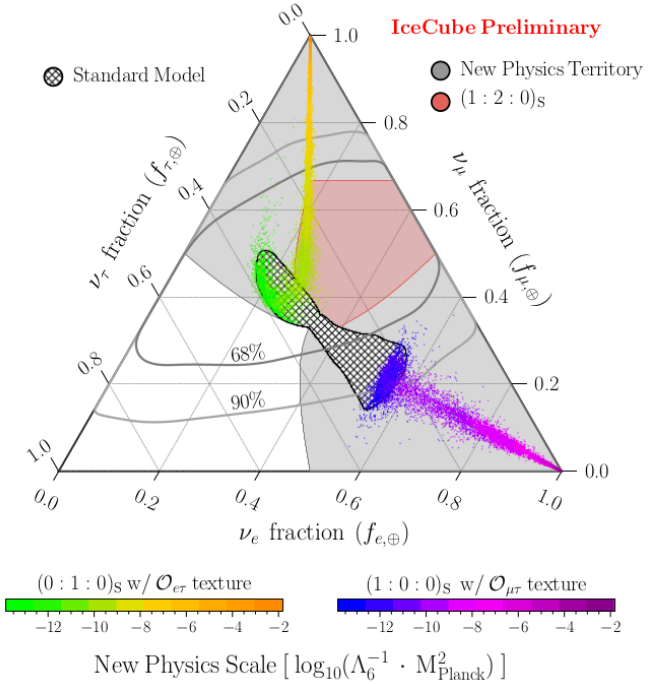
- Large particle energies and propagation distances can yield measurable effects
  - Astrophysical and atmospheric neutrinos

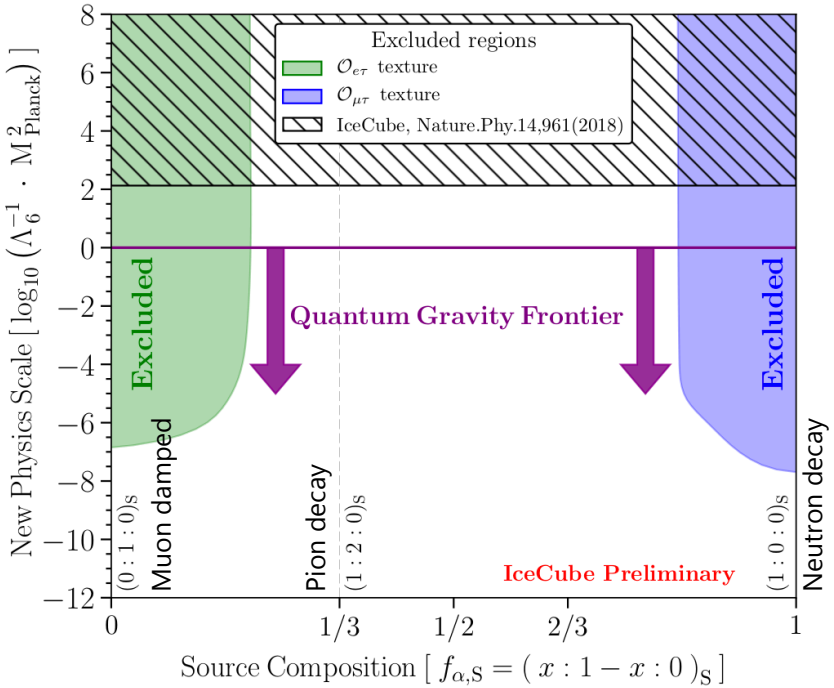
Planck scale physics: Lorentz invariance violation

- Generic search for new Lorentz invariance violating couplings
  - Modelled as energy-suppressed effective operators: SM Extension (SME)

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

- Diffuse astrophysical flavour triangle measurements exclude Planck scale physics for some operator and source flavour composition scenarios

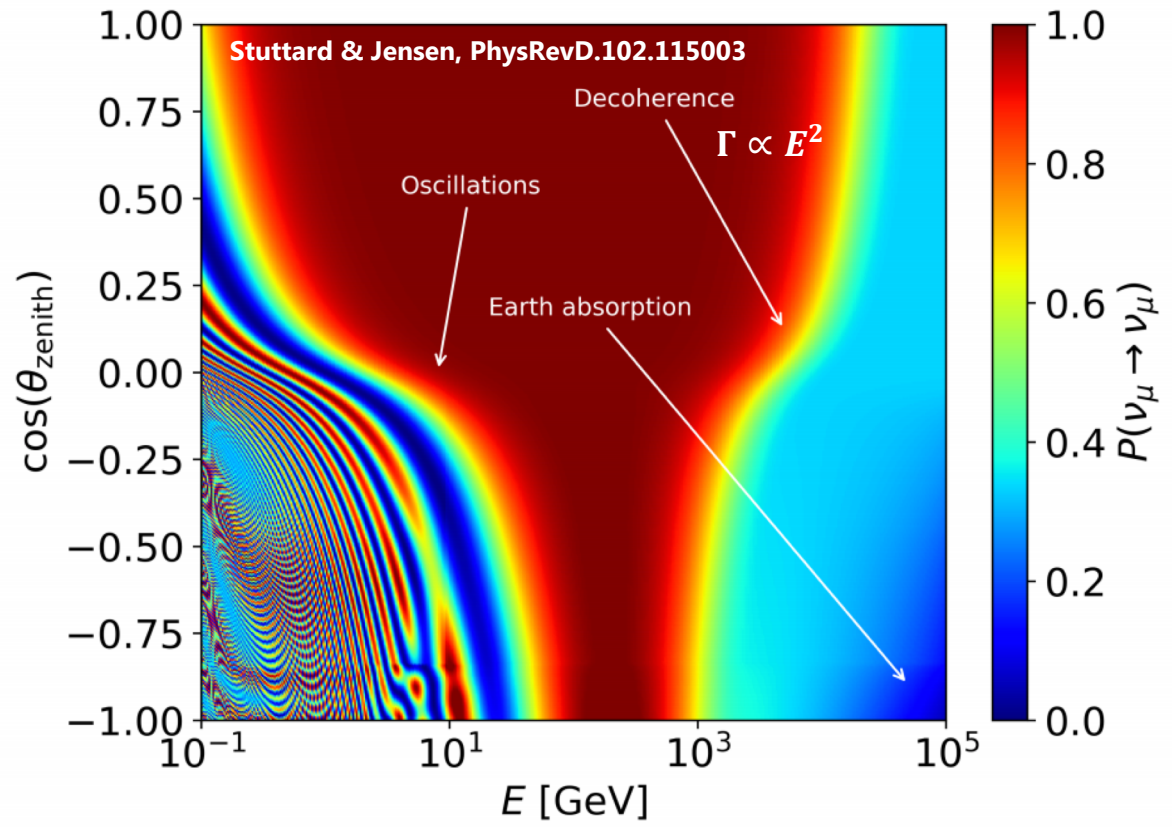


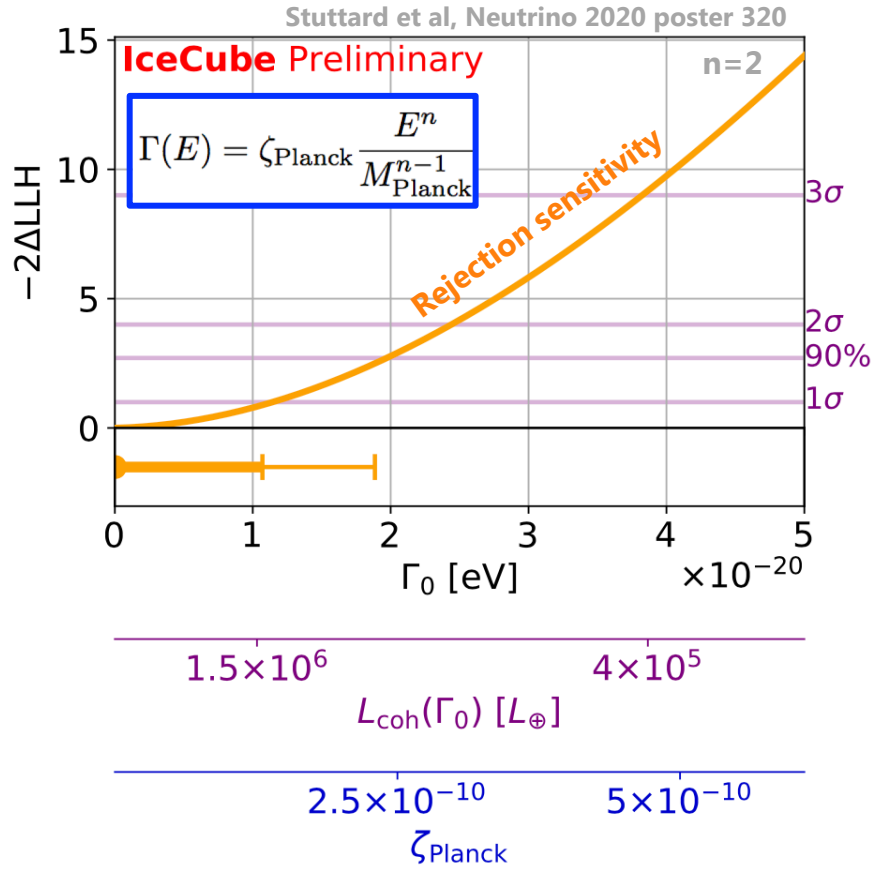


Paper soon...

Planck scale physics: Neutrino decoherence

- Fluctuating space-time → loss of neutrino coherence → damped oscillations
- Particularly strong signal from neutrino-virtual black hole interactions
  - Atmospheric neutrino analysis unblinding soon → Planck scale sensitivity





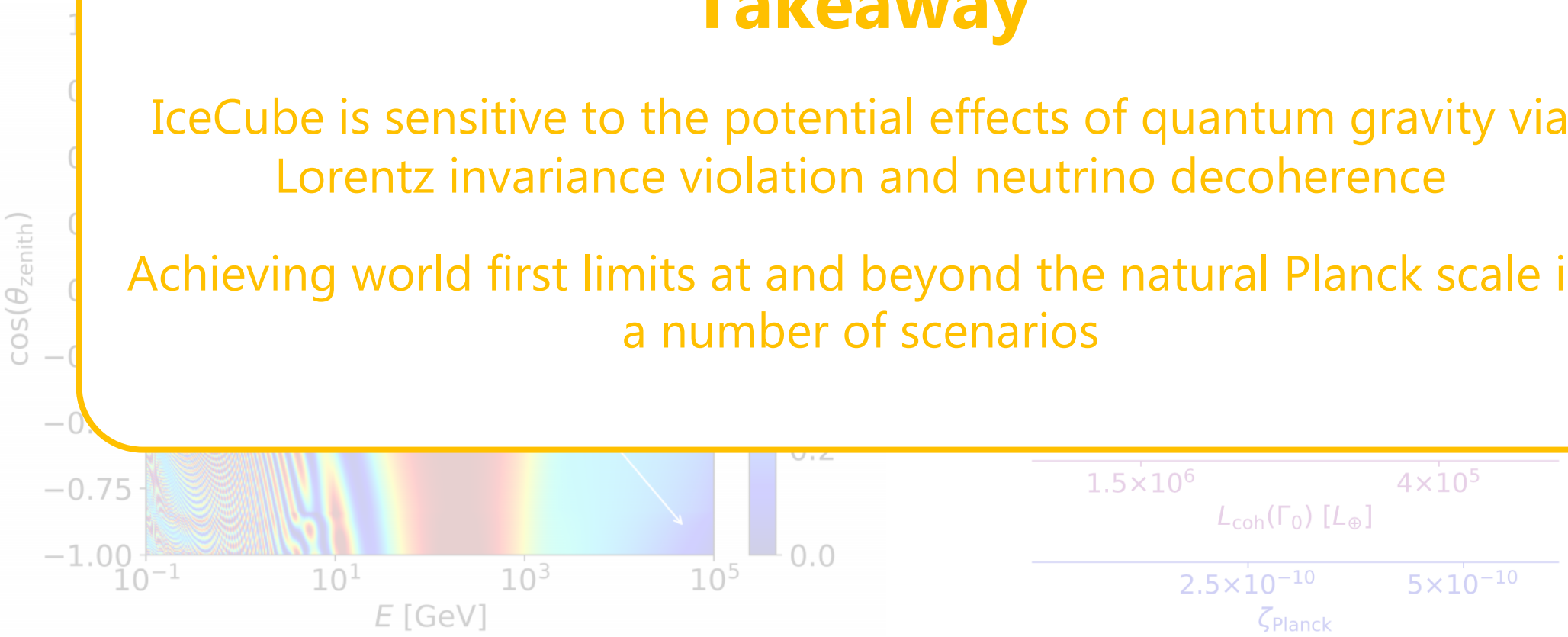
Planck scale physics: Neutrino decoherence

- Fluctuating space-time → loss of neutrino coherence → damped oscillations
- Particularly strong signal from neutrino-virtual black hole interactions
  - A

Takeaway

IceCube is sensitive to the potential effects of quantum gravity via Lorentz invariance violation and neutrino decoherence

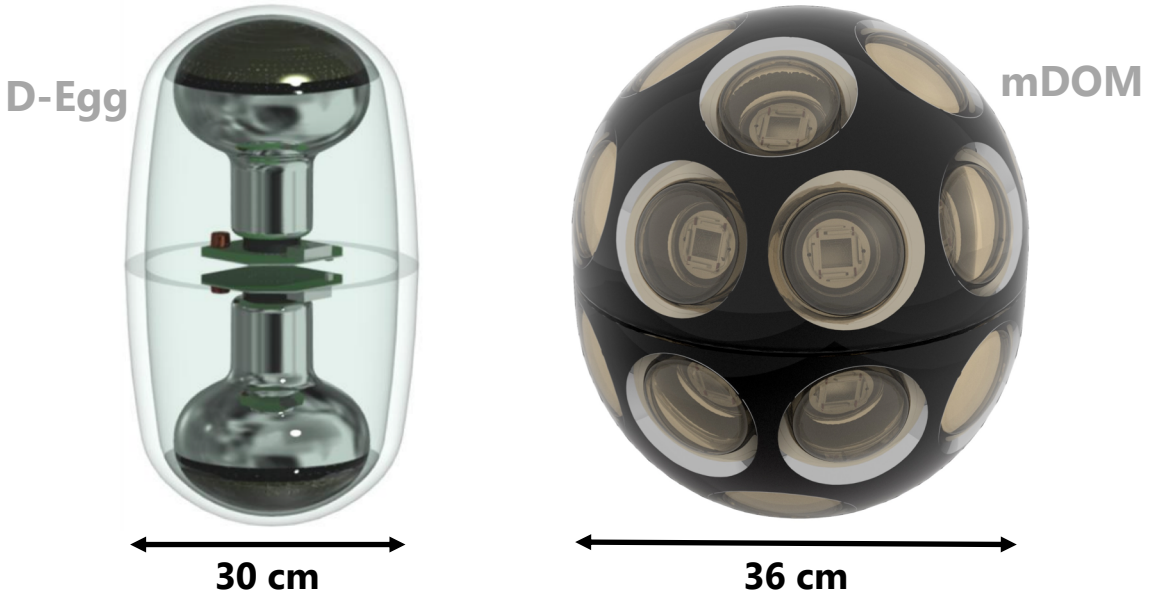
Achieving world first limits at and beyond the natural Planck scale in a number of scenarios

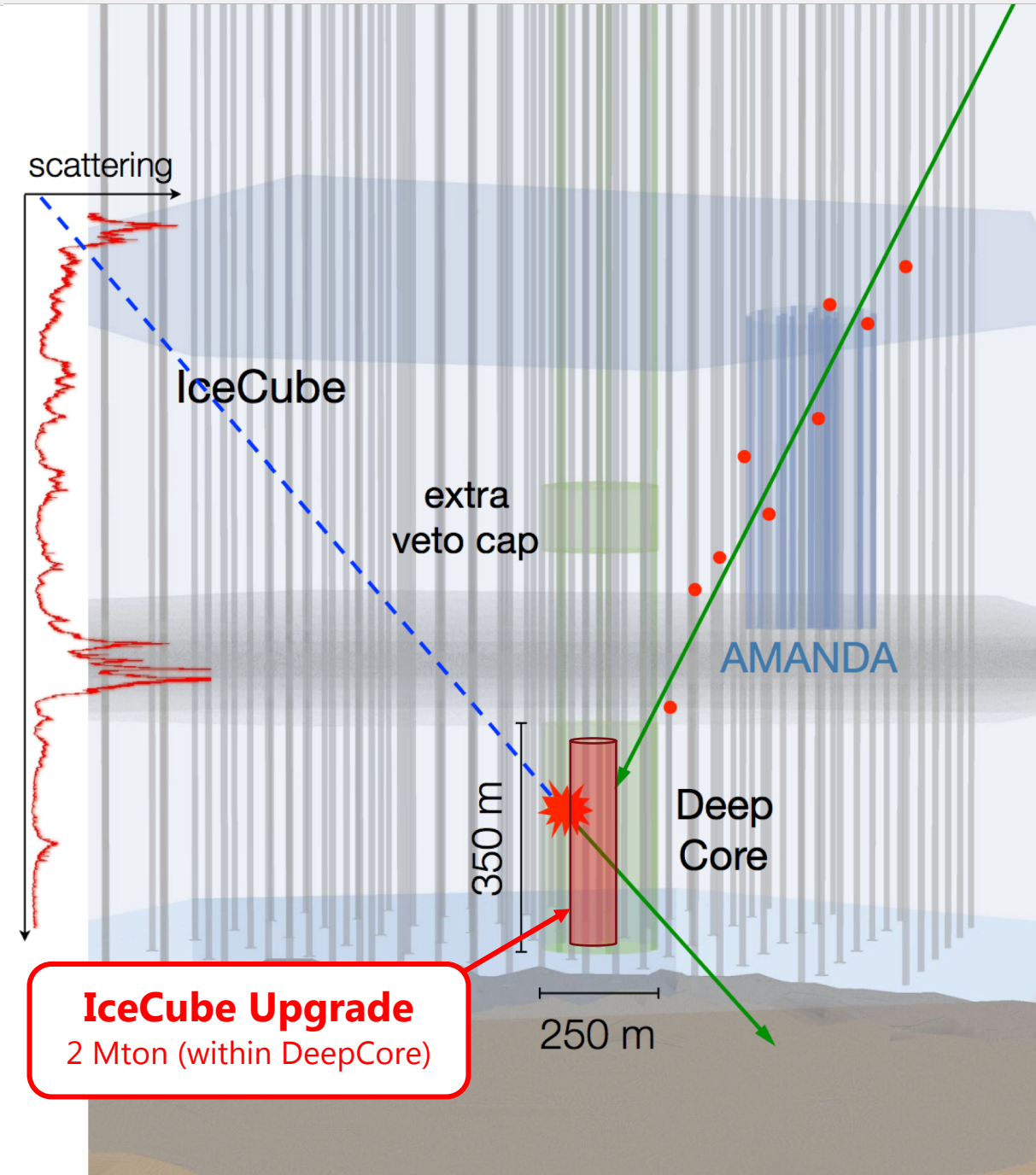


The future

The IceCube Upgrade

- $30M extension to IceCube
  - Funded, planned deployment in 2022/3
  - Schedule under review due to COVID-19
- 700 multi-PMT sensors
  - Densely packed in 2 Mton core
- Improved detector/ice calibration

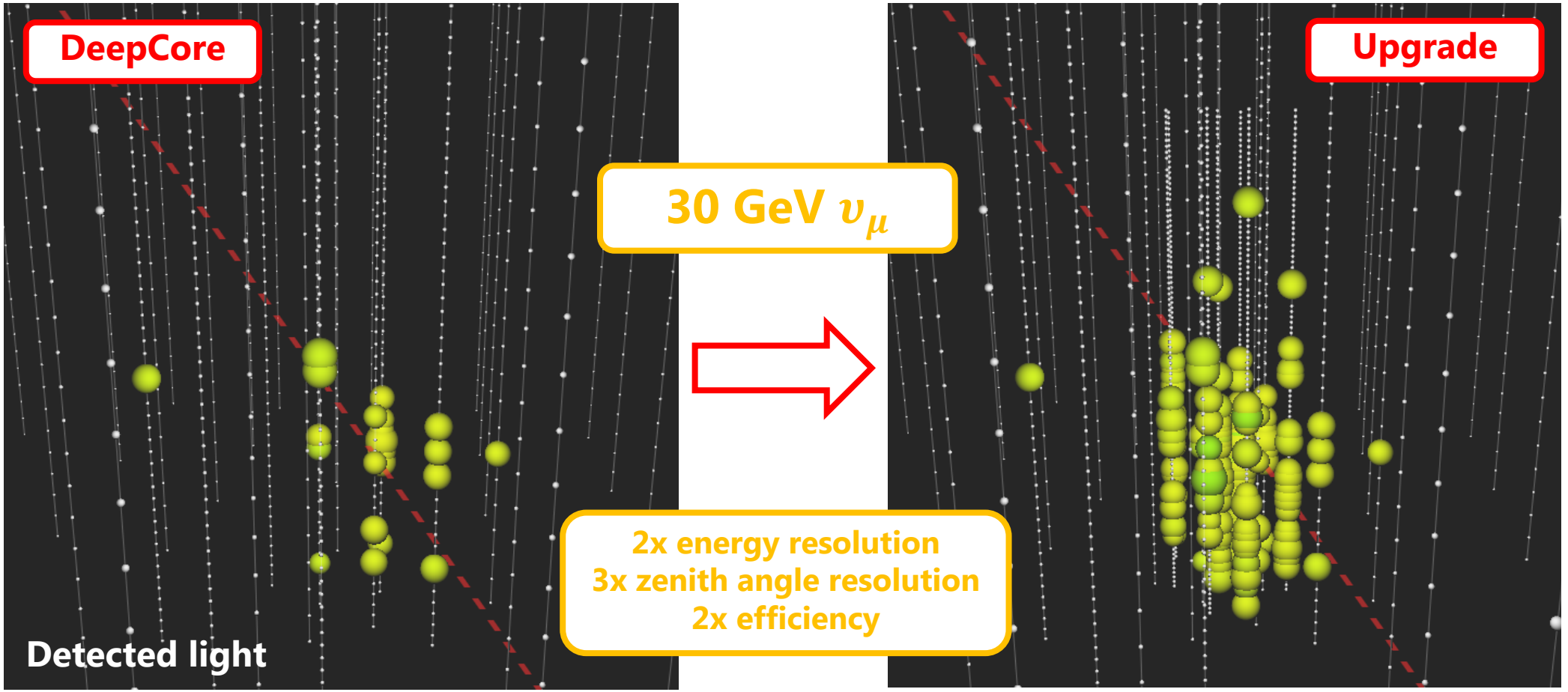




arXiv:1908.09441

A next-generation low-energy neutrino detector

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



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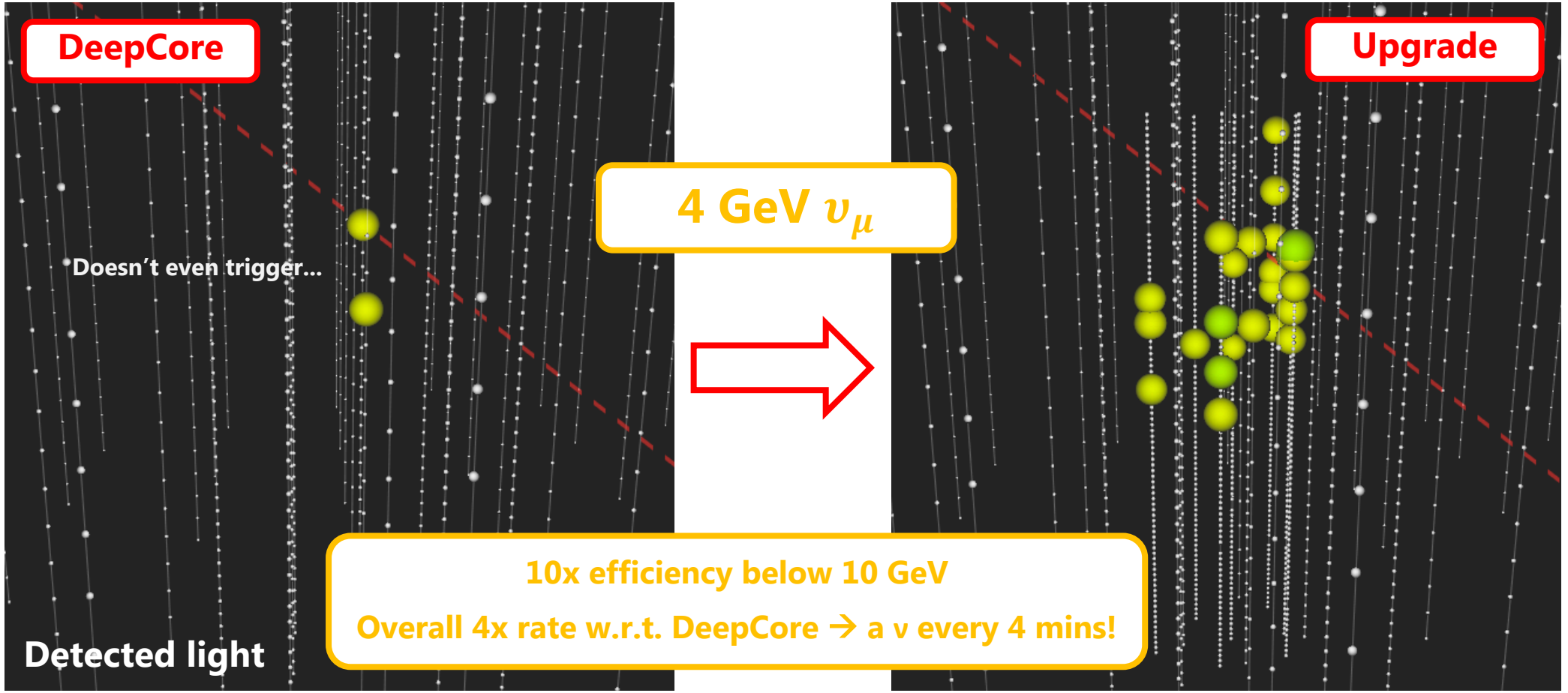
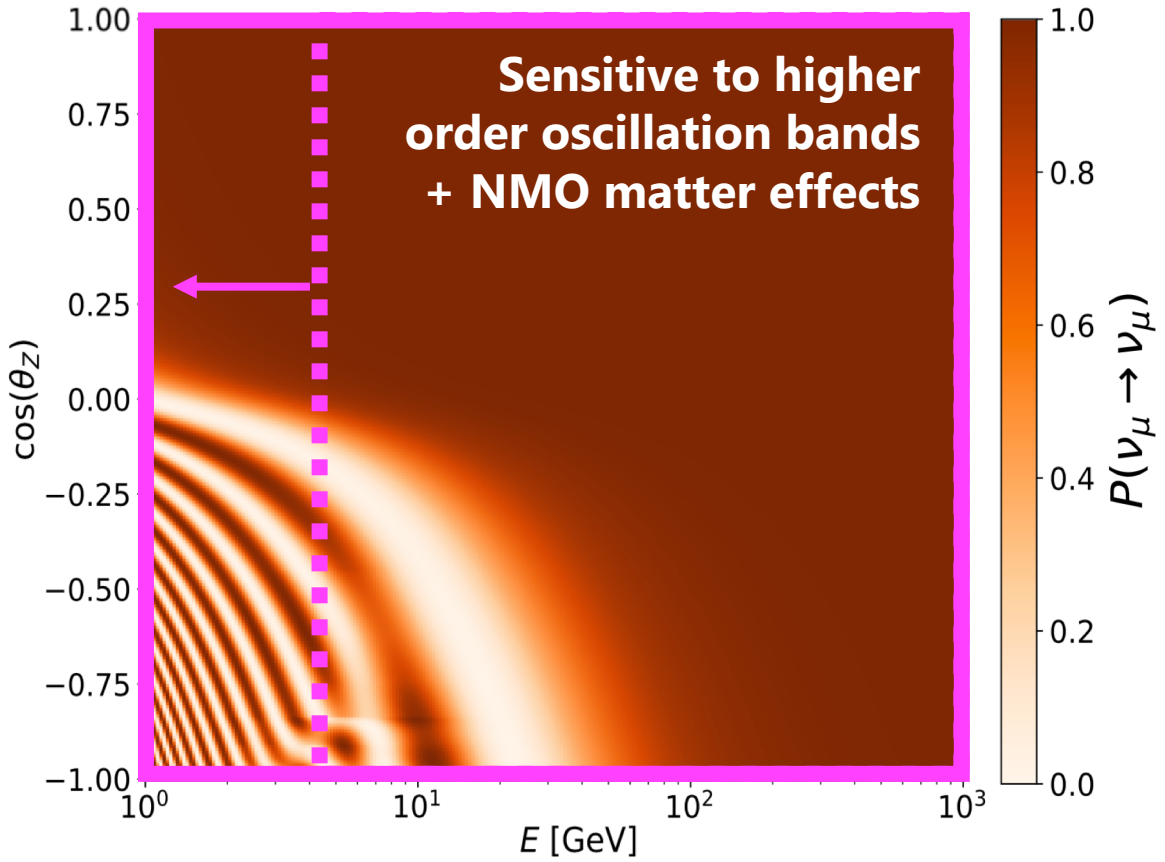


A next-generation low-energy neutrino detector

- **Dense instrumentation** in 2 Mton core
  - Large increas… neutrinos



DeepCore

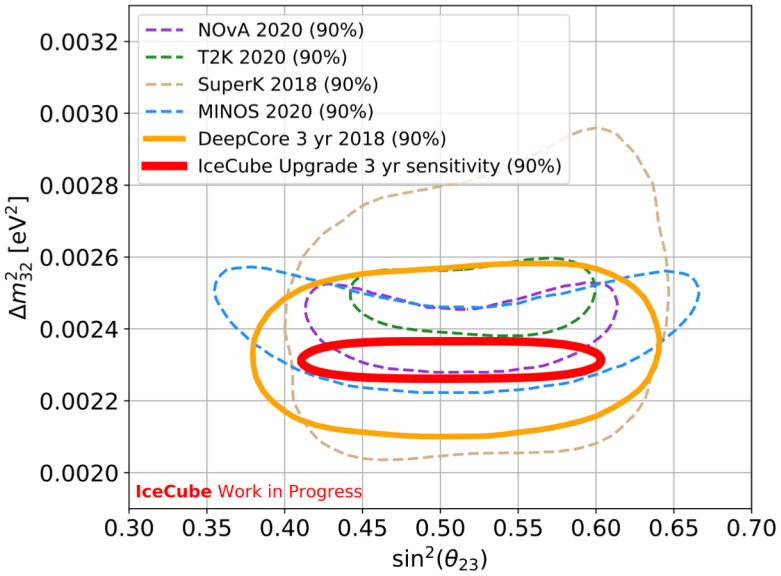
Upgrade

Detected ligh…

IceCube Upgrade oscillation sensitivity

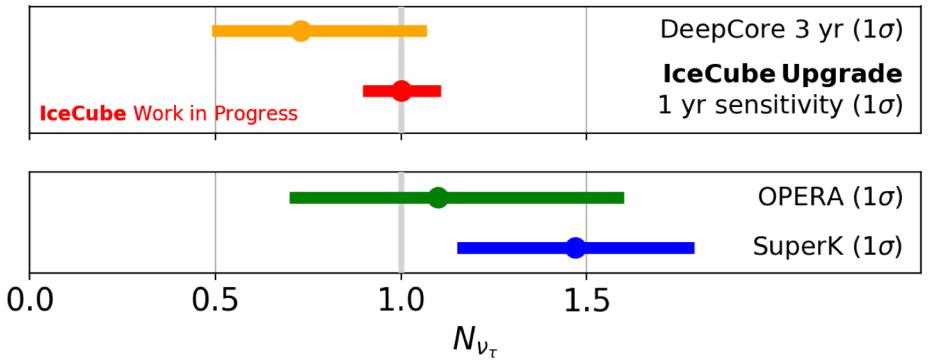
arXiv:1908.09441
arXiv:1911.06745

Atmospheric oscillation parameters



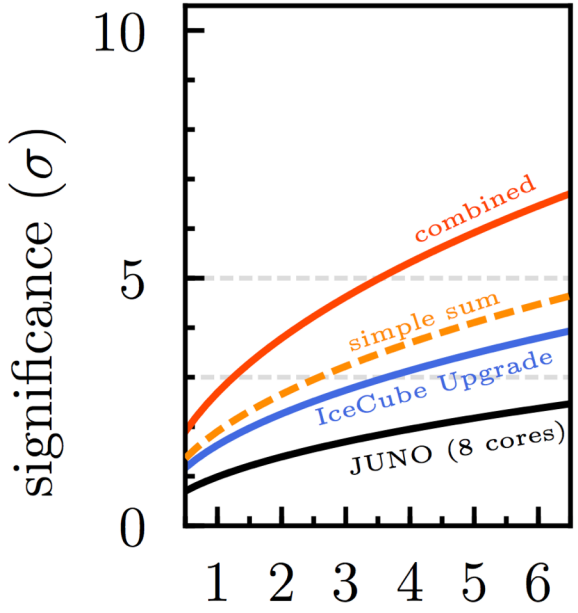
Strong sensitivity in 3 yrs or less

υ_τ normalisation



10% υ_τ norm in 1 yr
(6% in 3 yrs)

Mass ordering



Strong NMO sensitivity expected
Alone or in combined fit with JUNO

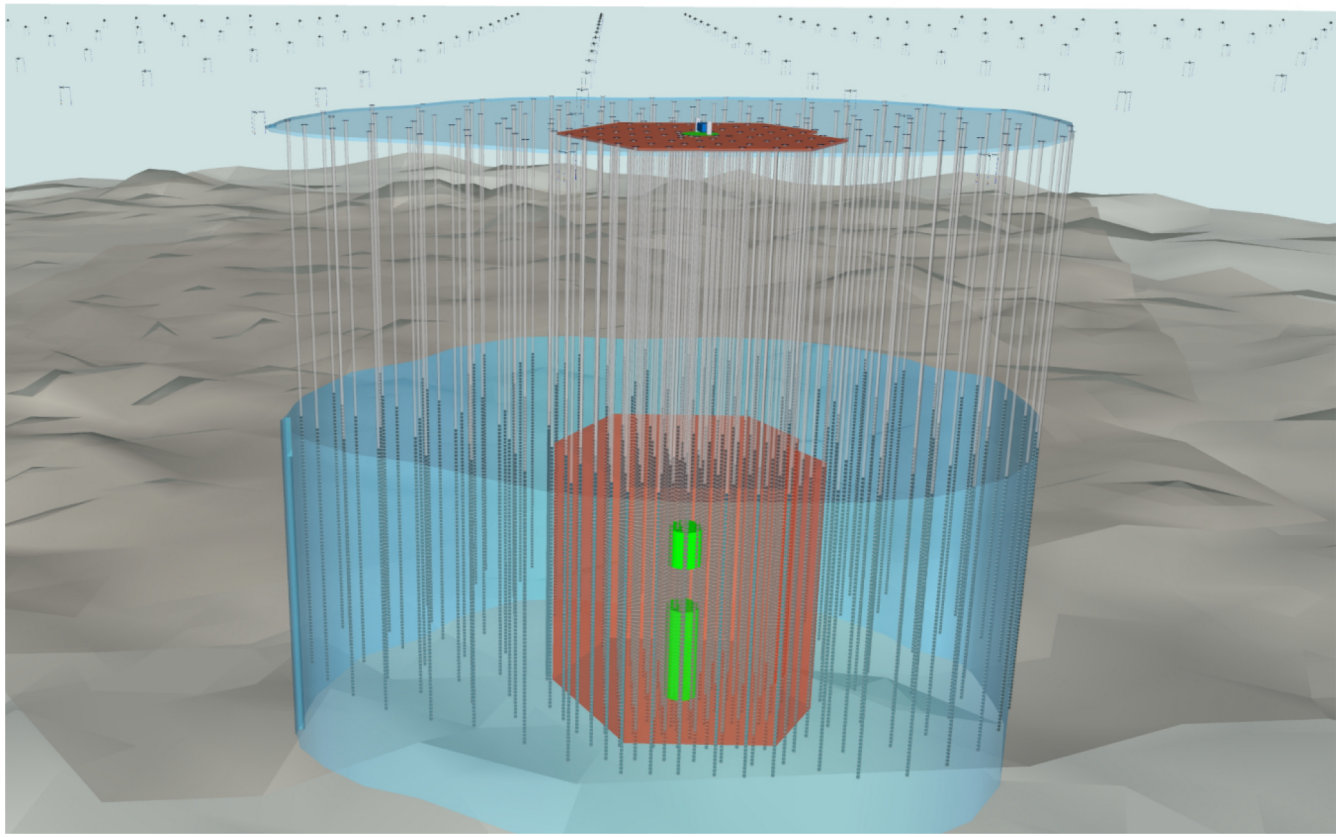
Very conservative projections - update underway

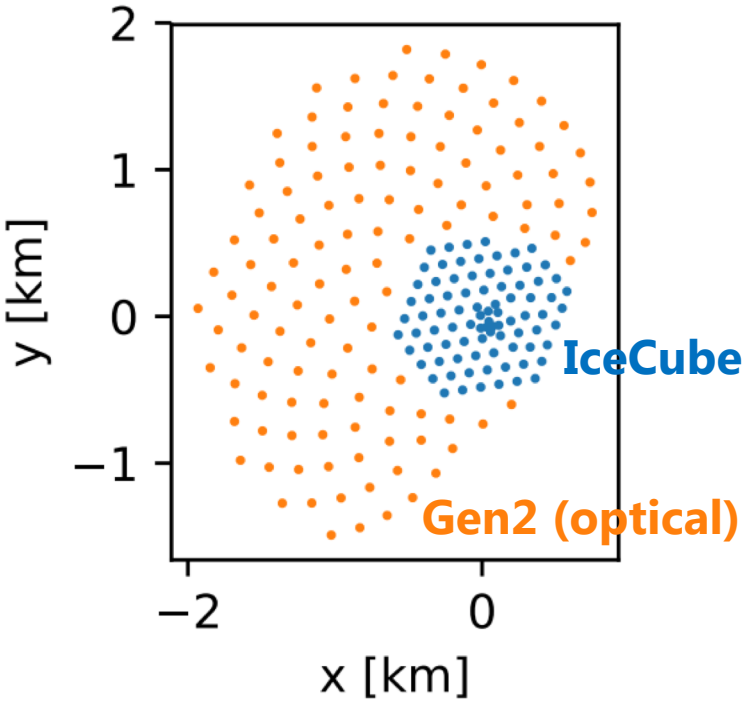
Coming soon: track reconstruction, new calibration, DeepCore fiducial volume, 10 yr DeepCore data, ...

arXiv:2008.04323

IceCube-Gen2

- Proposed 8 Gton upgrade to in-ice detector (2033)
- Addition of radio array increases energy reach by orders of magnitude
- Next-generation high energy neutrino astronomy and particle physics





Summary

- Neutrino telescopes are potent and unique particle physics laboratories

- Strong IceCube oscillation program
  - World-leading υ_τ and BSM capabilities
  - High statistics, energy, baselines, matter densities, …

- Broad BSM reach: DM, monopoles, quantum gravity…

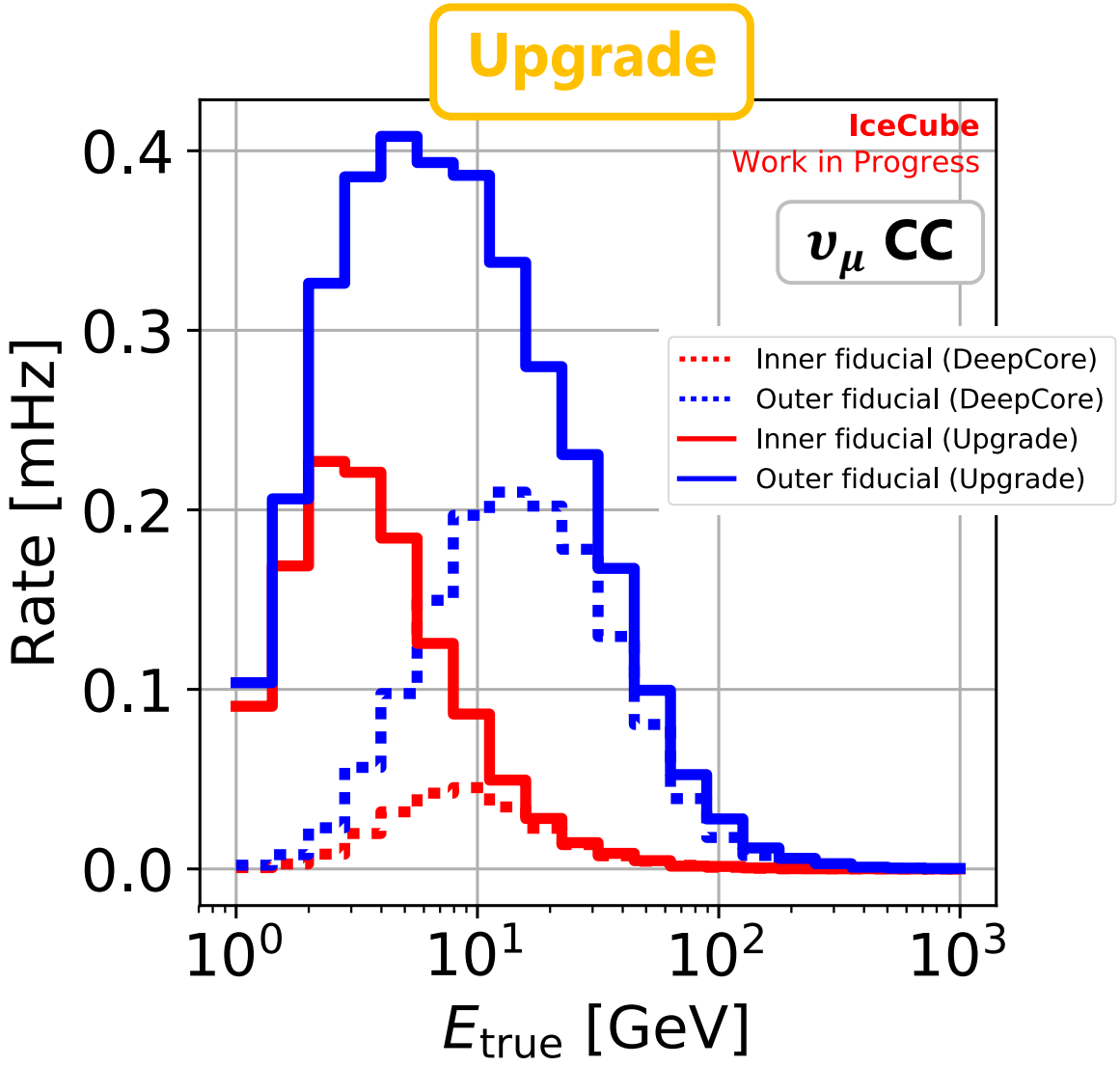
- Many new high stats 8+ yr measurements either recently or imminently unblinding → a lot to look forward to!

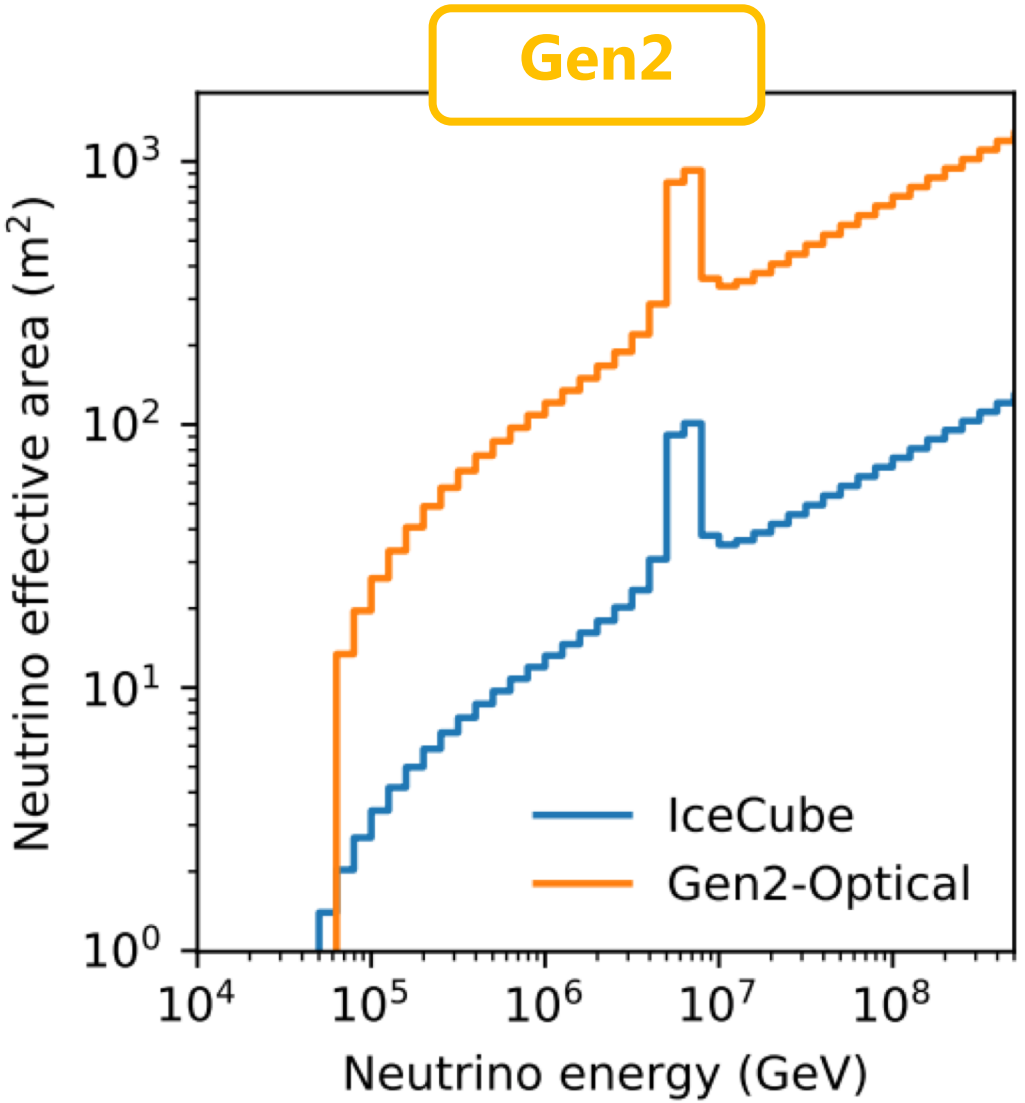
- Next-gen low energy physics soon with the IceCube Upgrade

- Ambitious plans for next-gen high energy with IceCube-Gen2 + radio

Thank you

Next-gen detection efficiency



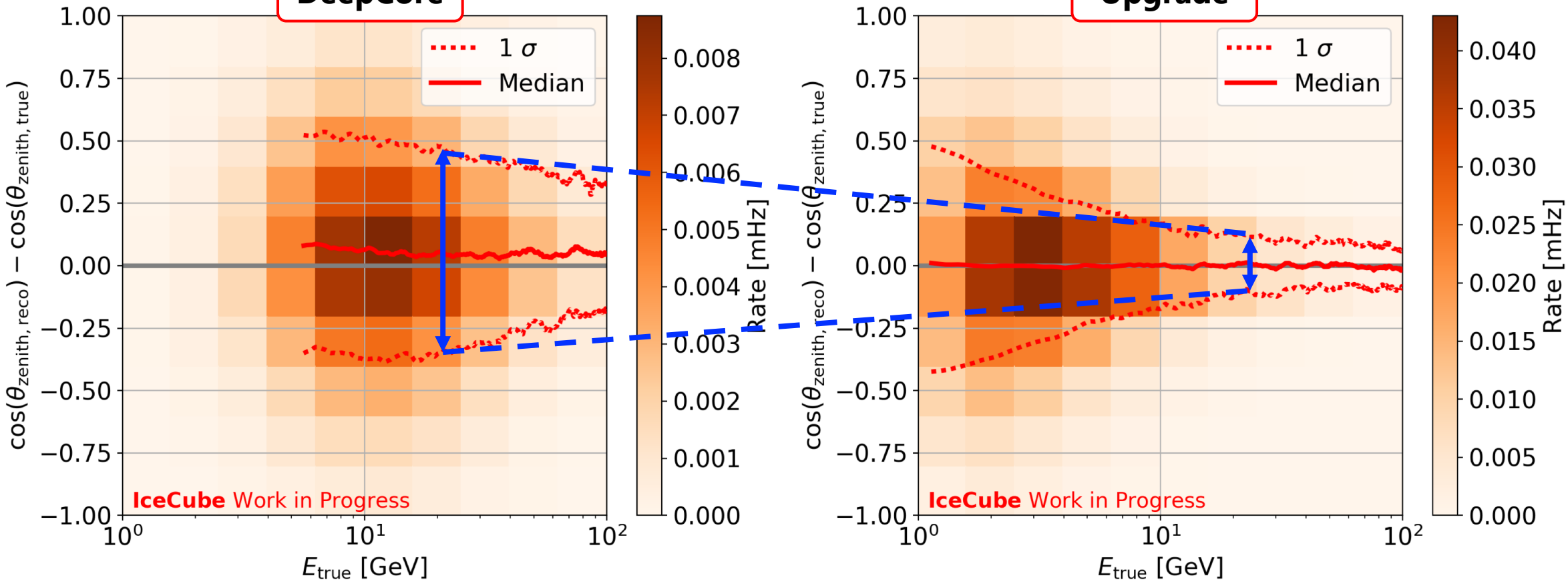


arXiv:1908.09441

Upgrade zenith angle resolution

Cascade zenith angle resolution

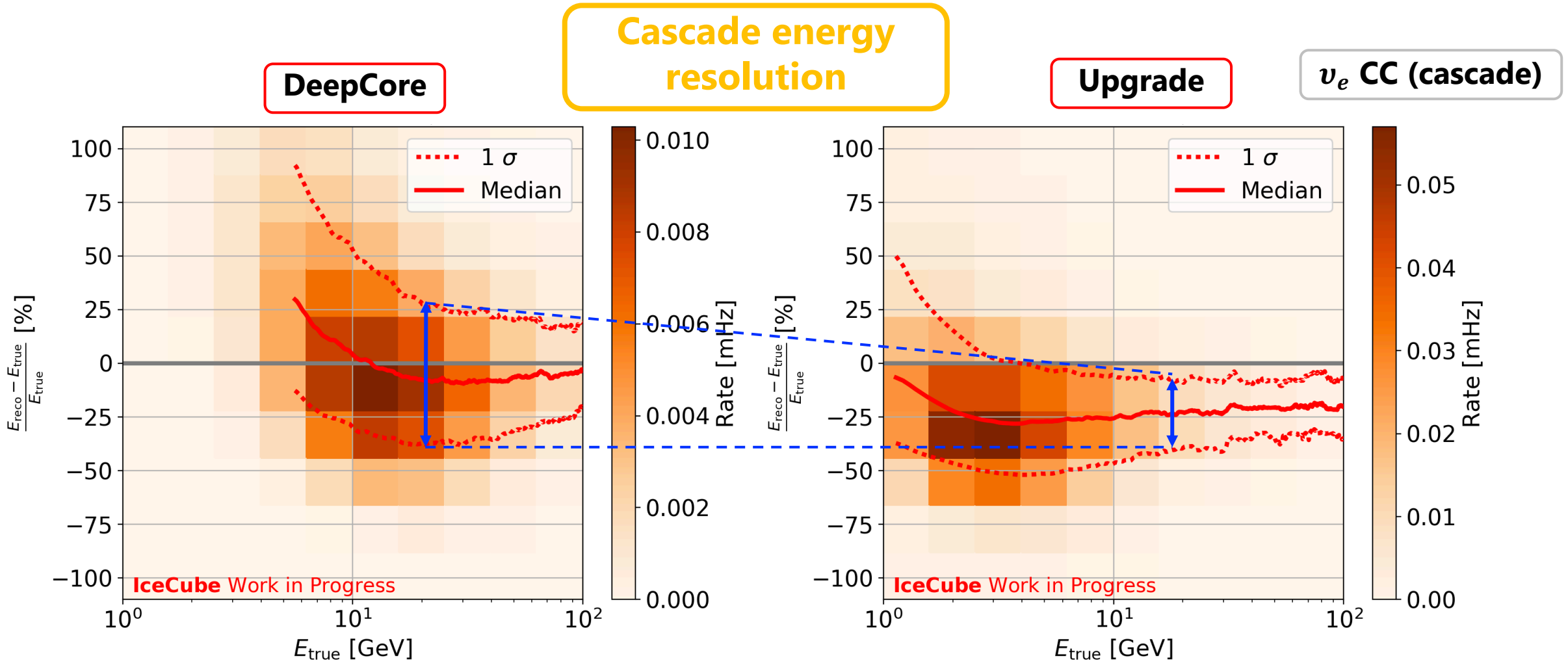
ν_e **CC (cascade)**



3x improvement @ ν_τ appearance energies

arXiv:1908.09441

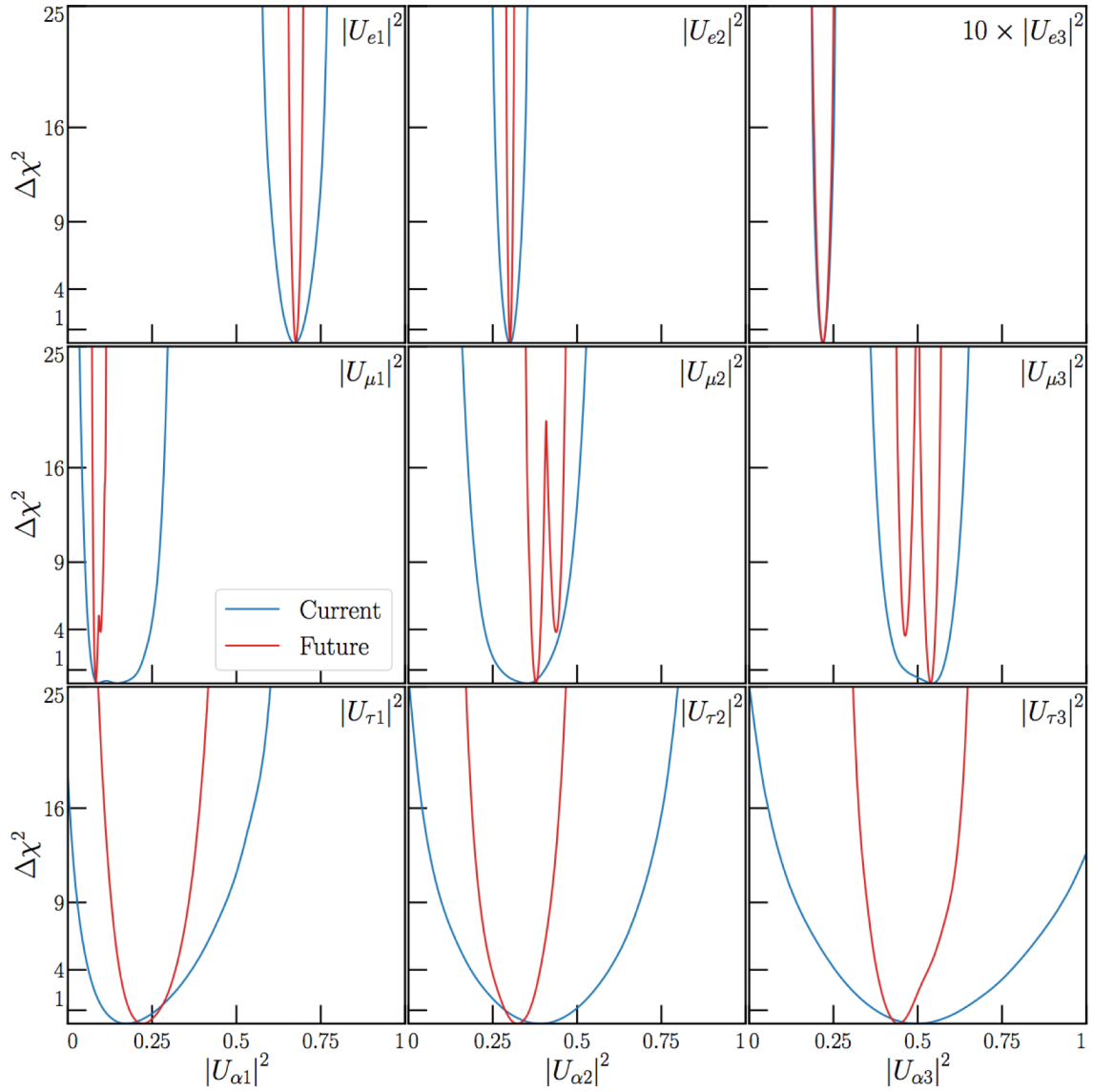
Upgrade energy resolution



2x improvement @ ν_τ appearance energies

PMNS matrix element constraints

arXiv:2008.01088



τ-sector poorly constrained
Need ν_τ appearance measurements