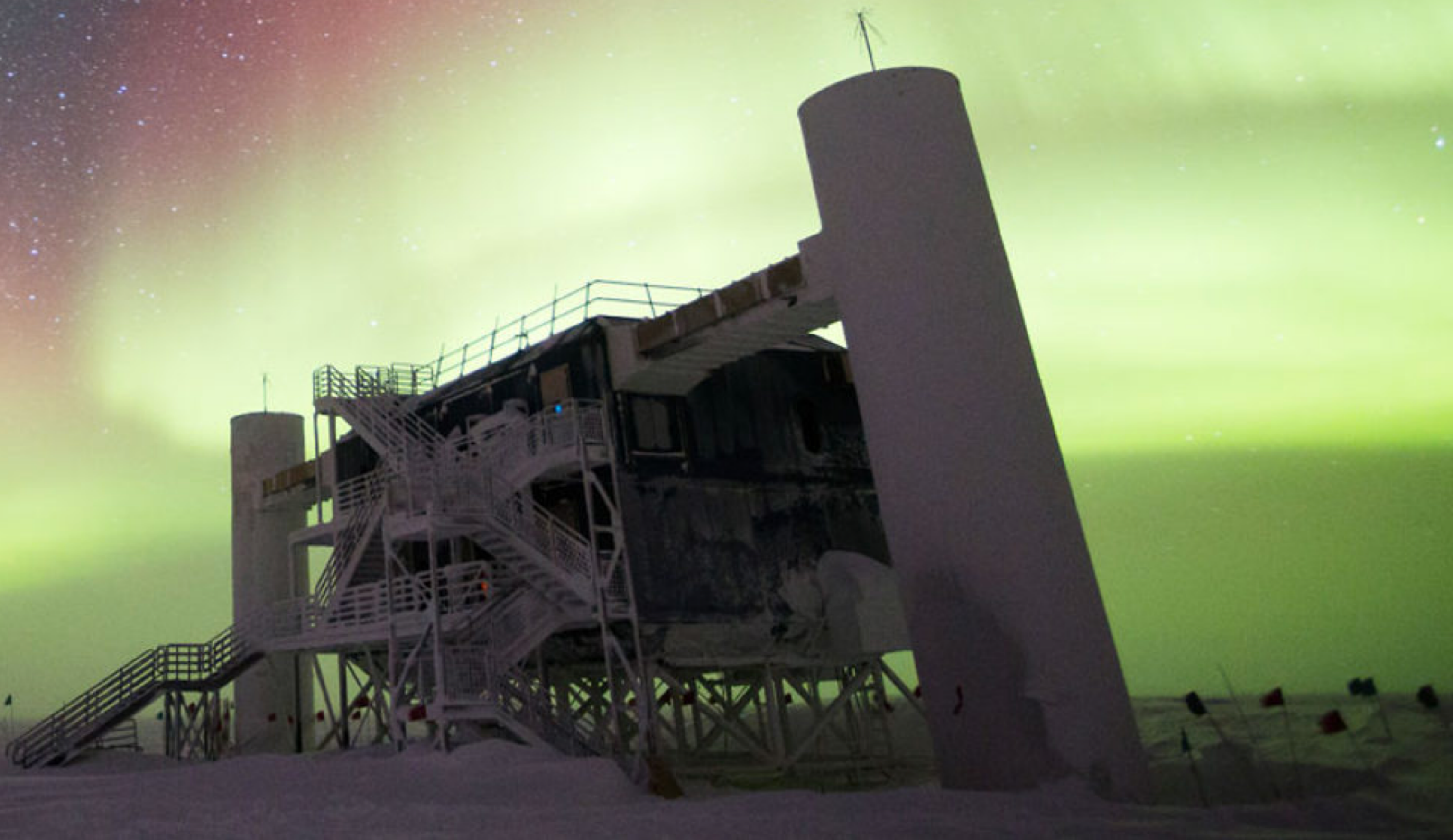
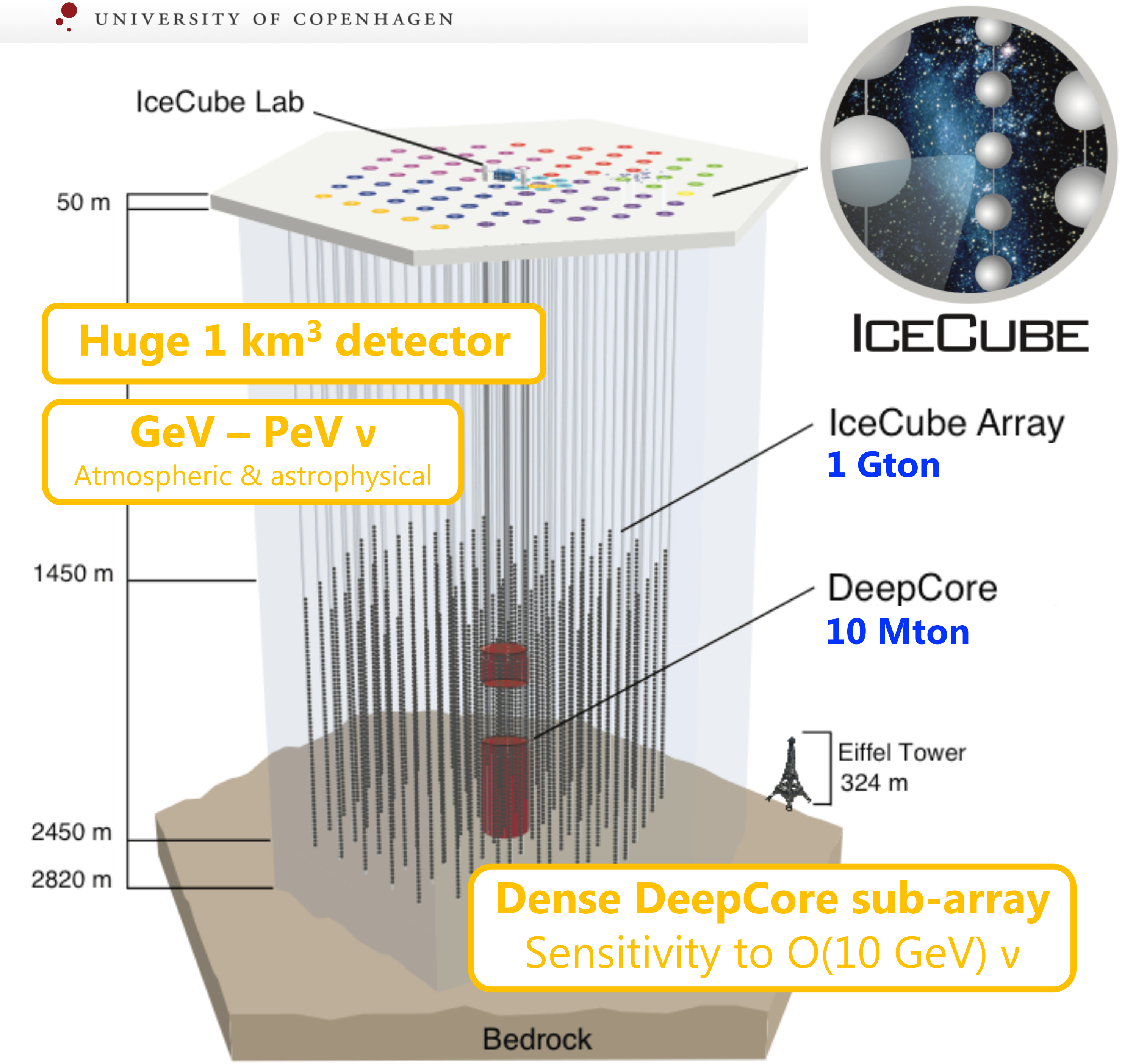
Environmental neutrino decoherence in atmospheric neutrinos // Neutrino oscillations with the IceCube Upgrade

Tom Stuttard on behalf of the IceCube Collaboration
Niels Bohr Institute

PPNT 2019, Uppsala



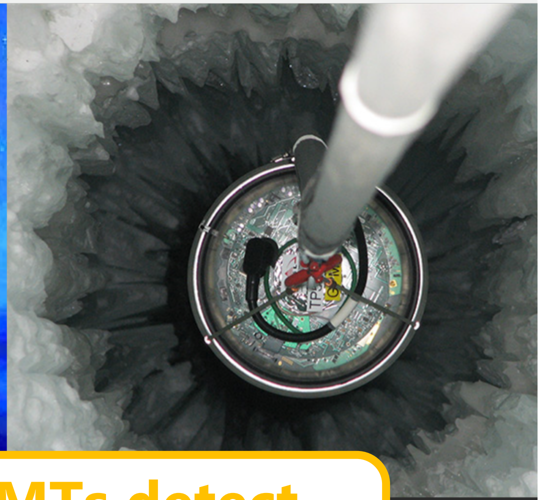
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY



Huge 1 km^3 detector

GeV – PeV ν
Atmospheric & astrophysical

Dense DeepCore sub-array
Sensitivity to O(10 GeV) ν



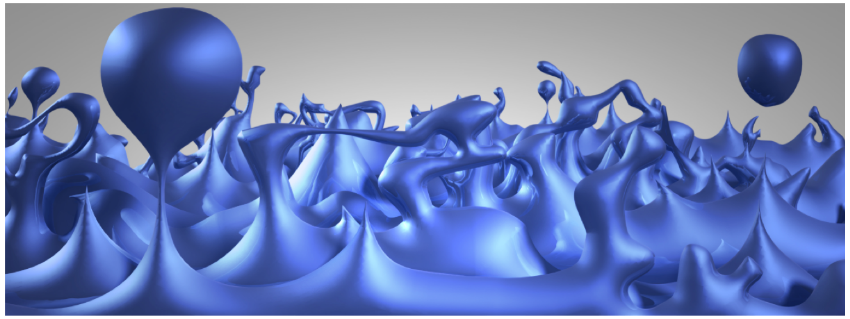
5160 PMTs detect Cherenkov photons

Environmentally-induced neutrino decoherence

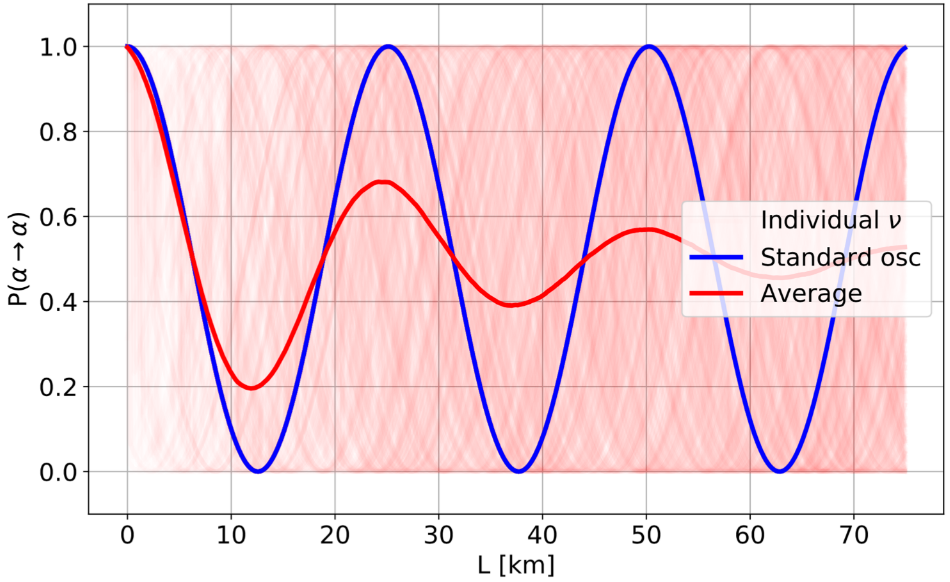
Environmentally-induced neutrino decoherence

- What if a neutrino experiences perturbations from the environment as it propagates?
  - e.g. fluctuating space-time (quantum gravity)

Credit: Chandra



- If perturbations are stochastic:
  → wavefunction phase shift
  → neutrino population loses coherence
  → damping of oscillation probability

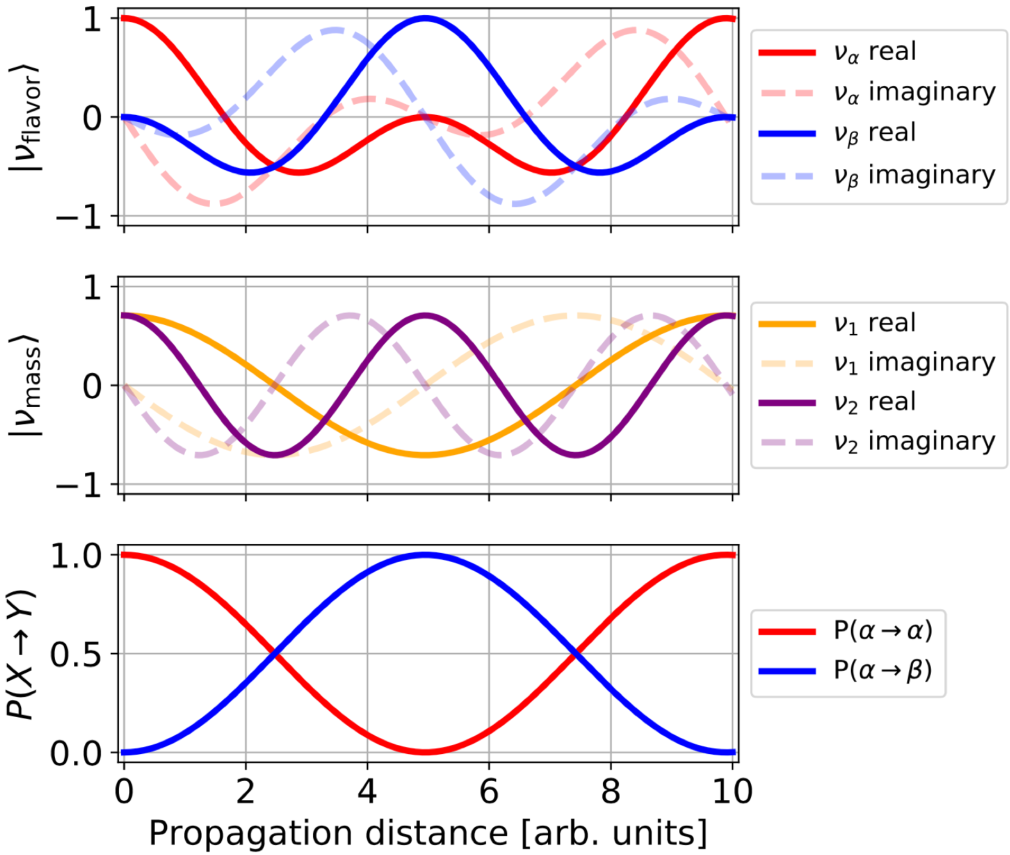


Perturbing neutrinos as they propagate

$$|\nu_i(L)\rangle = \exp\left\{-i\frac{m_i^2 L}{2E} + \phi\right\}|\nu_i(L=0)\rangle$$

- Want to test how neutrino responds to various types of perturbation
- Randomly inject desired perturbation into neutrino propagation model

No perturbations



2 flavor
θ=45°

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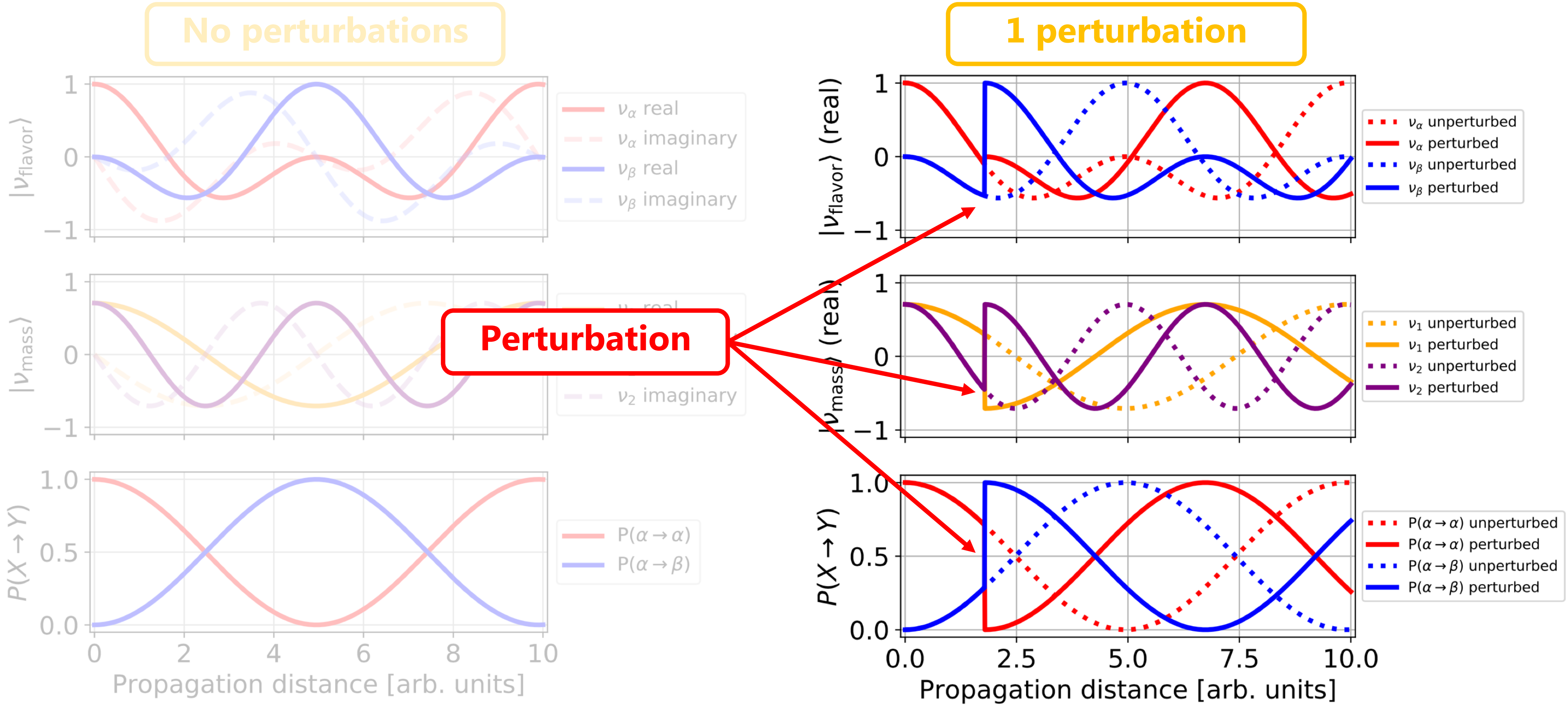

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***θ*=45°**

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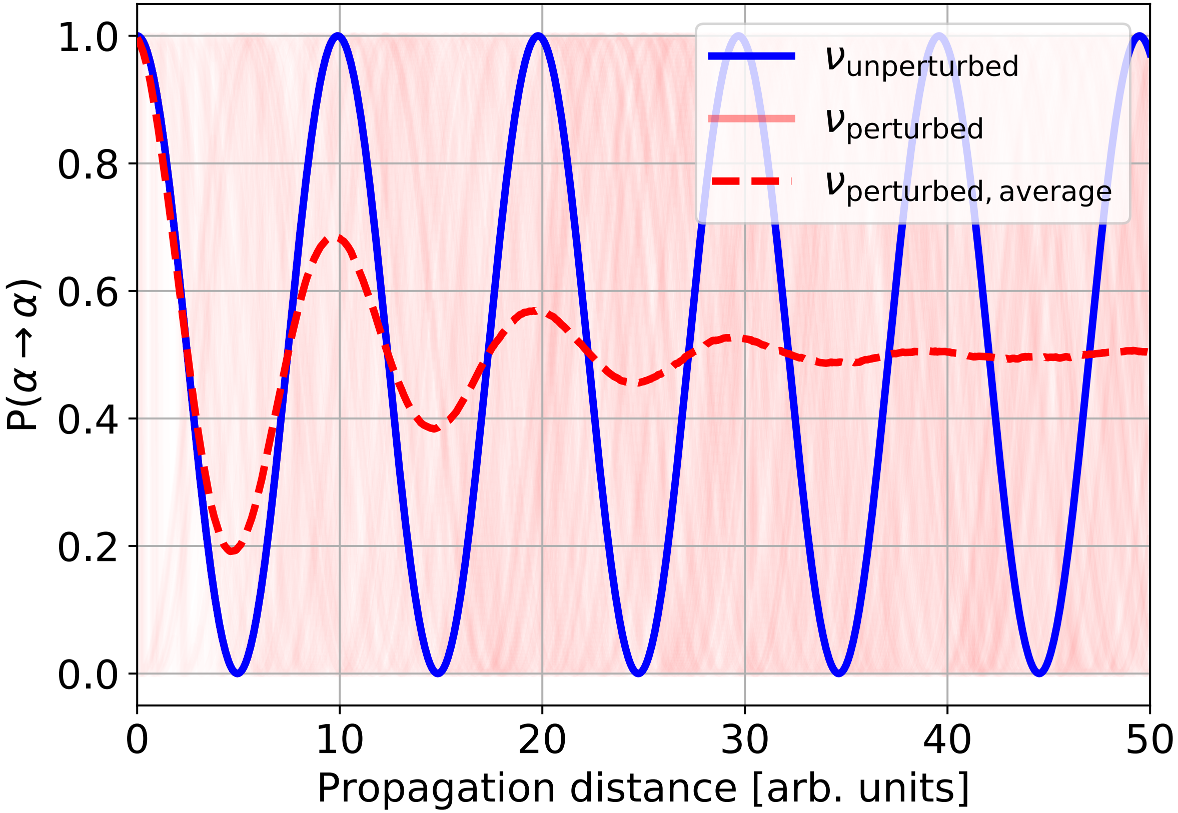
Many perturbations



Perturbation (→ out of phase) increasingly likely with distance

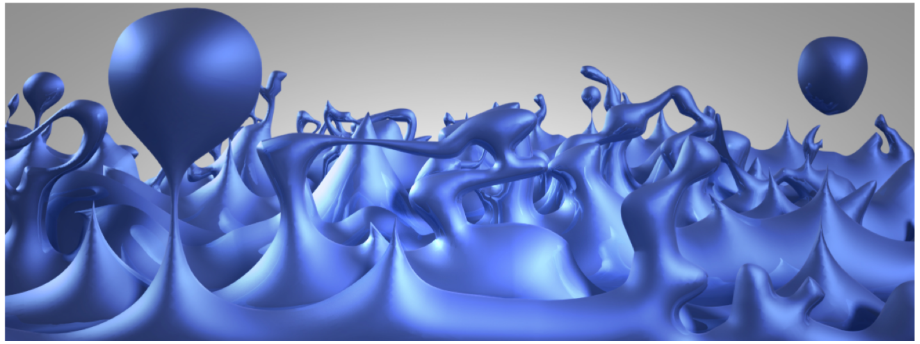
→ Damping of oscillation probability on average

2 flavor
***θ*=45°**

What perturbation?

- **Space-time foam**
  - **Quantum gravity → fluctuating space-time**
  - ➢ **Travel distance (light cone) fluctuates**
  - ➢ **Virtual back holes**
    - Decoherence from neutrino-black hole interactions
    - Flavor not expected to be conserved Anchordoqui et al, hep-ph/0506168

Credit: Chandra



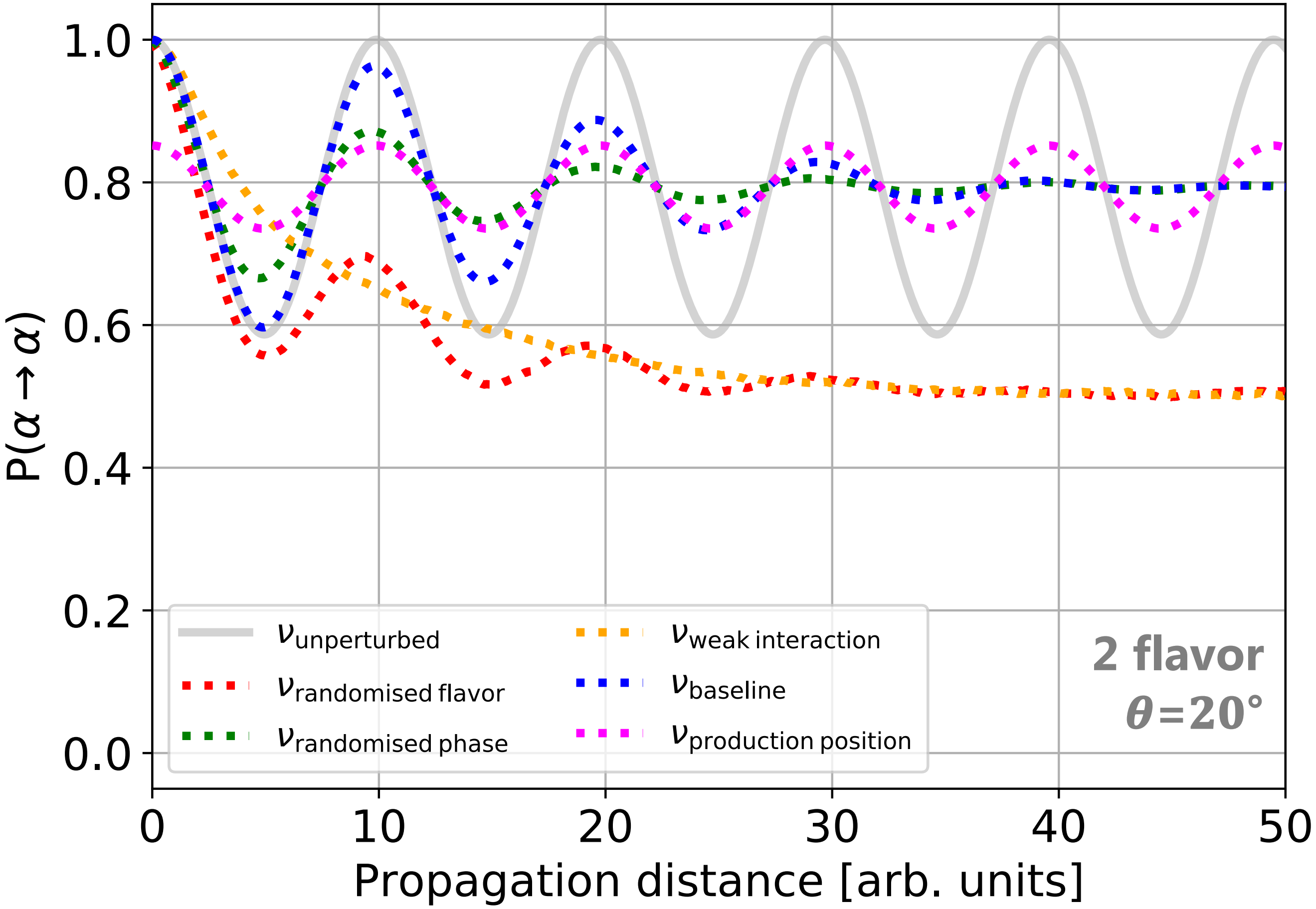
- **Wavefunction collapse**
  - Neutrino assumes definite state → discontinuity in wavefunction evolution
  - Occurs when neutrino is "measured", e.g. interacts (with Dark Matter? Graviton?)

- **Baseline variation**
  - Source-detector distance not constant (e.g. atmospheric neutrino production height)

Comparing perturbations

- Compare decoherence effect of various perturbation types

Survival probability w/ perturbations



No perturbation

Baseline/light cone fluctuation

Source position fluctuation

ν-BH interaction **(phase randomized)**

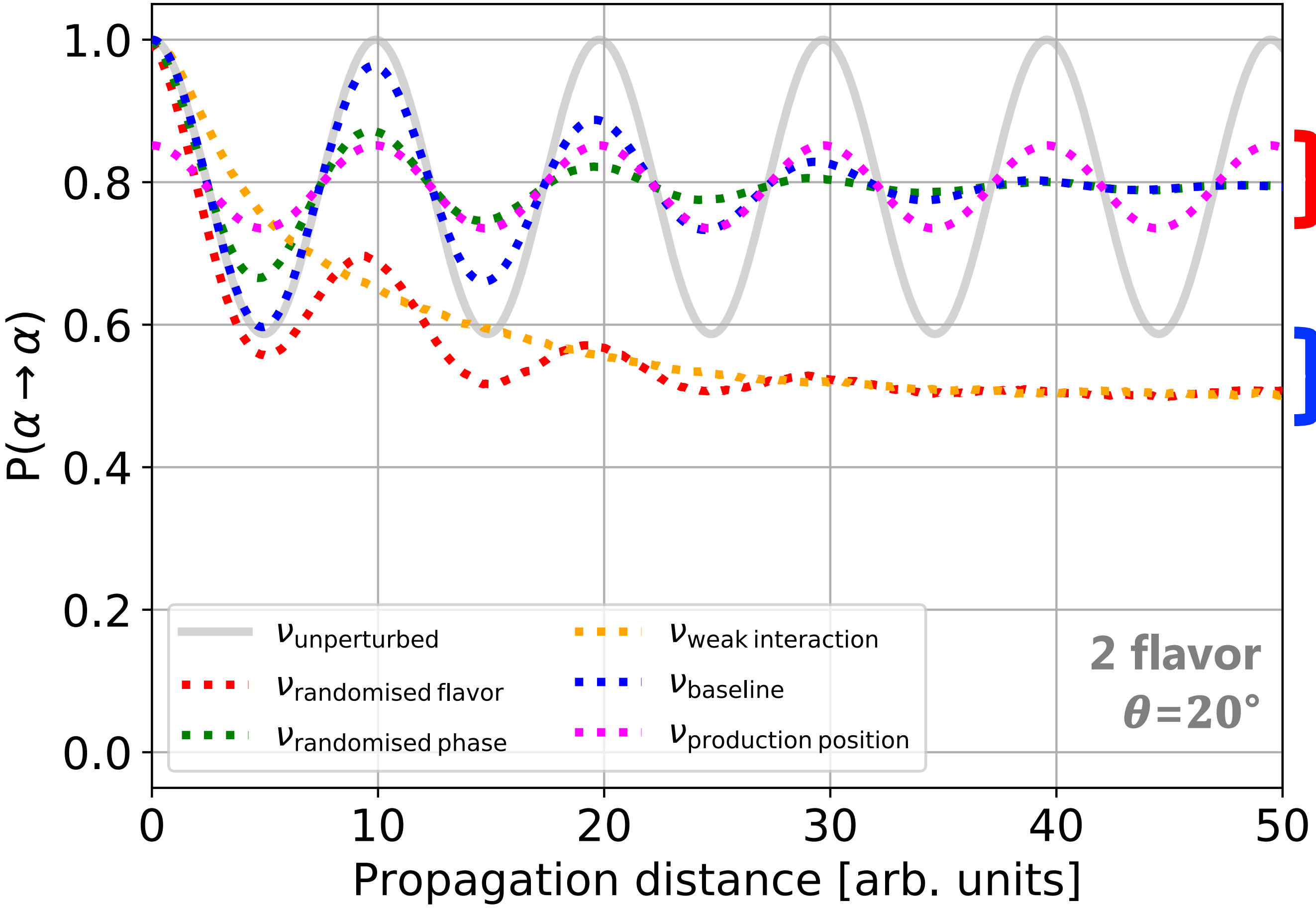
ν-BH interaction **(flavor randomized)**

Wavefunction collapse **(weak interaction)**

"Toy" parameters for comparing on simple plot

Comparing perturbations

- Compare decoherence effect of various perturbation types



1) All cases produce decoherence

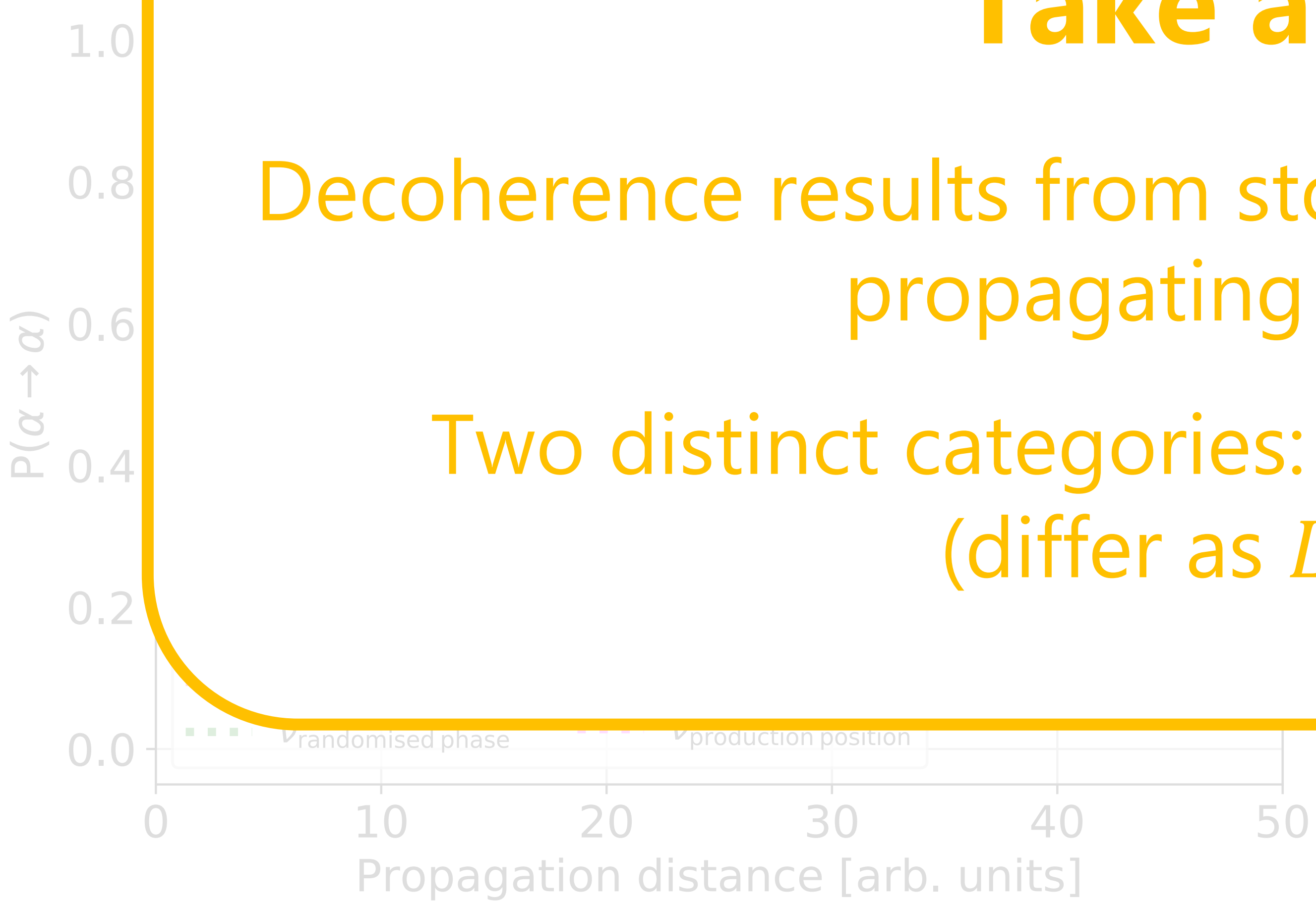
2) Two distinct categories observed…

$L \rightarrow \infty \Rightarrow$ **Oscillation average**
(mass basis decoherence)

$L \rightarrow \infty \Rightarrow$ **Equally populated flavors**
(flavor basis decoherence)

Comparing perturbations

- Compare decoherence effect of various perturbation types



Take away

Decoherence results from stochastic perturbations to propagating neutrino

Two distinct categories: mass vs flavor basis (differ as $L \rightarrow \infty$)

Neutrino decoherence as an open quantum system

$$\rho = \sum_i p_i \left|\psi_i\right\rangle \left\langle\psi_i\right|$$

density matrix

- Can treat neutrino + environment as **open quantum system**
  - Decoherence = **pure → mixed state**
  - Evolution of system given by Lindblad master equation

$$\dot{\rho} = \underbrace{-i[H,\rho]}_{\text{Standard oscillations}} \underbrace{-\mathcal{D}[\rho]}_{\text{Decoherence}}$$

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Perturbation-like decoherence

Farzan et al, arXiv:0805.2098

Damping strength parameters

Coherence length $= \frac{1}{\Gamma}$

(damped to e^{-1}**)**

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Lisi et al, hep-ph/0002053

- Phenomenological **energy-dependence**: $\Gamma_{ij}(E) = \Gamma_{ij}(E = E_0)\left(\frac{E}{E_0}\right)^n$

Usually 1 GeV

n = 2 predicted for quantum gravity

Ellis et al, arXiv:gr-qc/9602011, arXiv:hep-th/9704169

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- Define $\mathcal{D}[\rho]$ in **mass** or **flavour basis** depending on perturbation

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Lisi et al, hep-ph/0002053

5 free parameters

Decoherence strength x 3 (between pairs of states)

Basis

Energy-dependence

→ Implemented in nuSQuIDS

nce: $\Gamma_{ij}(E) = \Gamma_{ij}(E = E_0) \left(\frac{E}{E_0}\right)^n$

Usually 1 GeV

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density matrix

- Can treat neutrino + environment as **open quantum system**
  - Decoherence = **pure → mixed state**

/0002053

Take away

Neutrino decoherence from stochastic perturbations can be treated as open quantum system

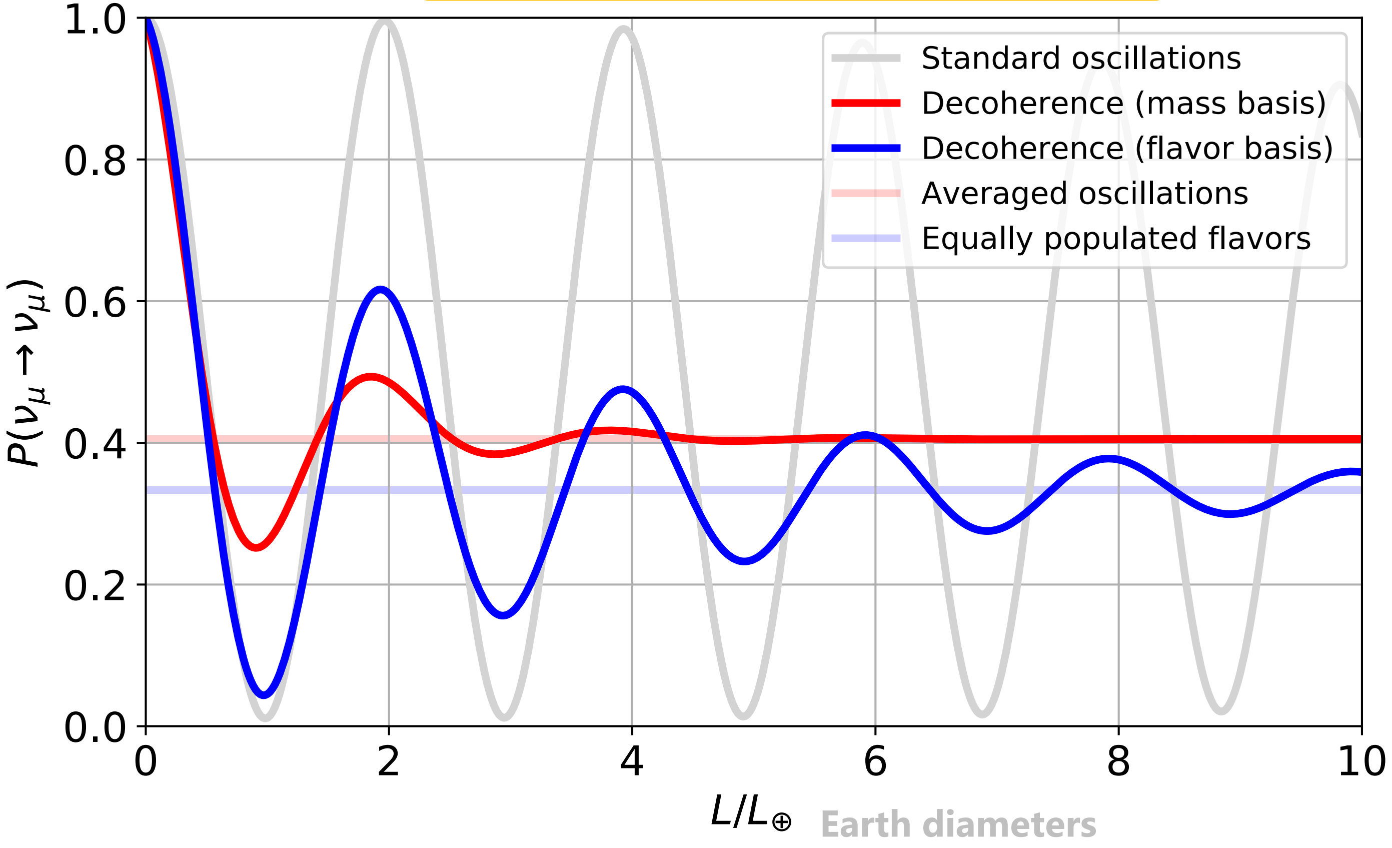
Model implemented in nuSQuIDS

- Define $\mathcal{D}[\rho]$ in **mass** or **flavour basis** depending on perturbation

Decoherence in atmospheric neutrinos

- Atmospheric neutrinos → **long baselines**, **high energies**
- Better understood than high energy astrophysical neutrinos

Atmospheric ν_μ survival



25 GeV
Vacuum
3 flavor
Coherence length = Earth diameter
n = 0

Mass basis → averaged oscillations at $L = \infty$

Flavor basis → 1:1:1 flavor ratio at $L = \infty$

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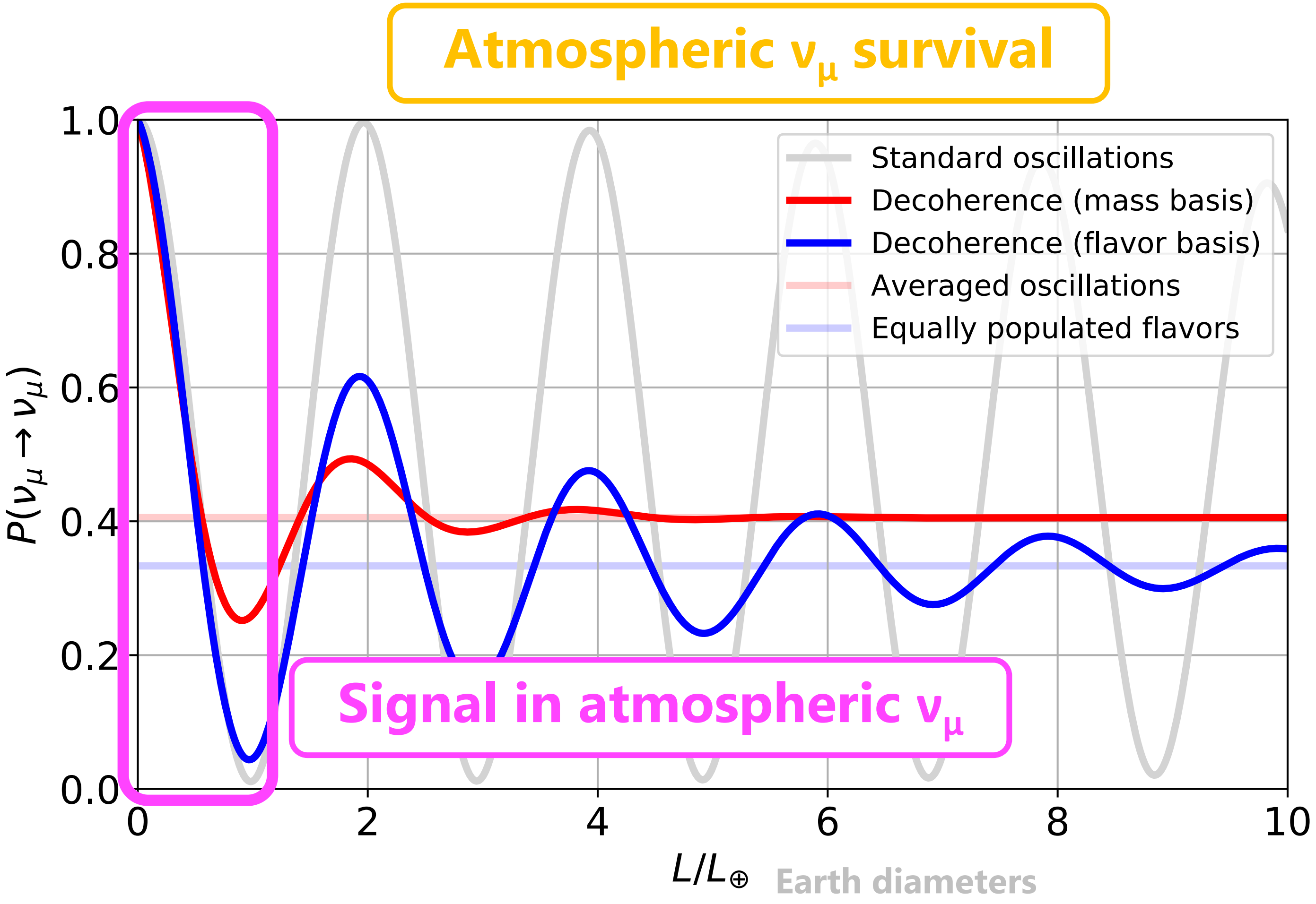
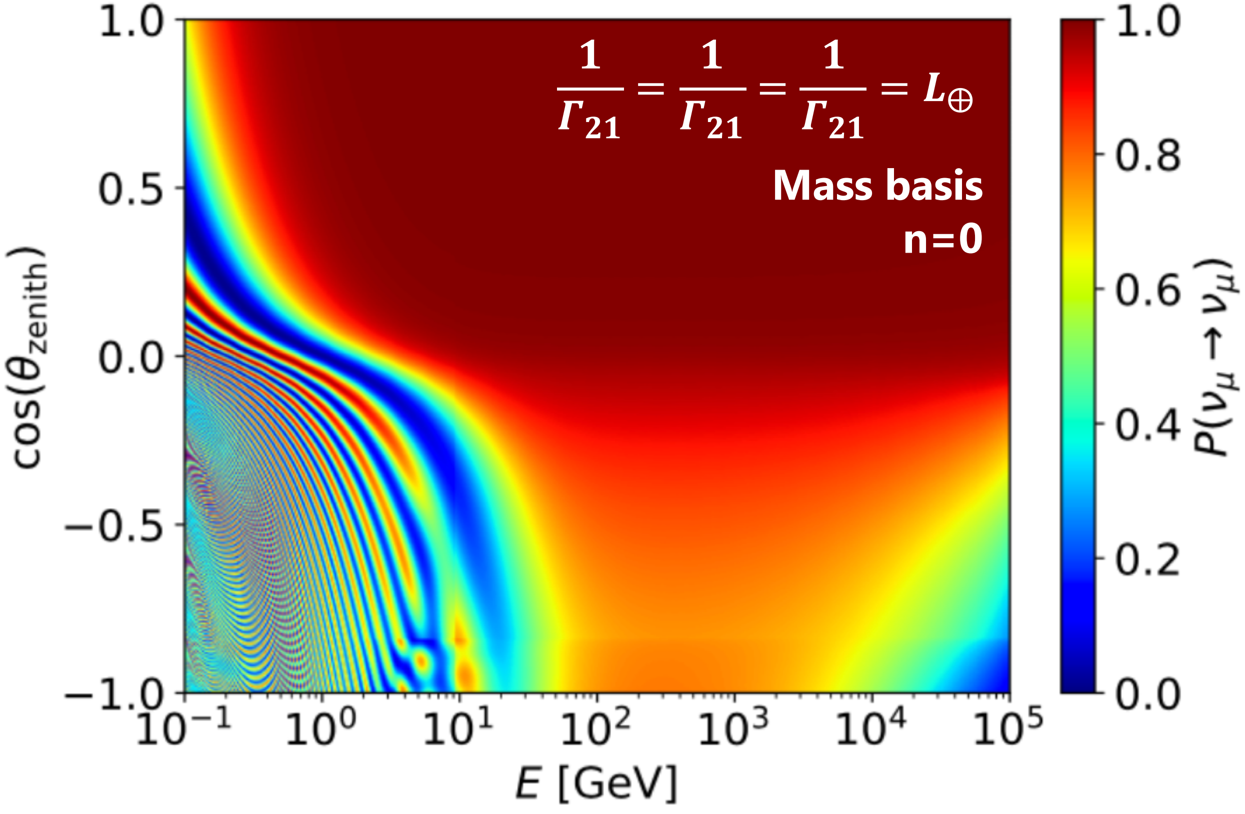


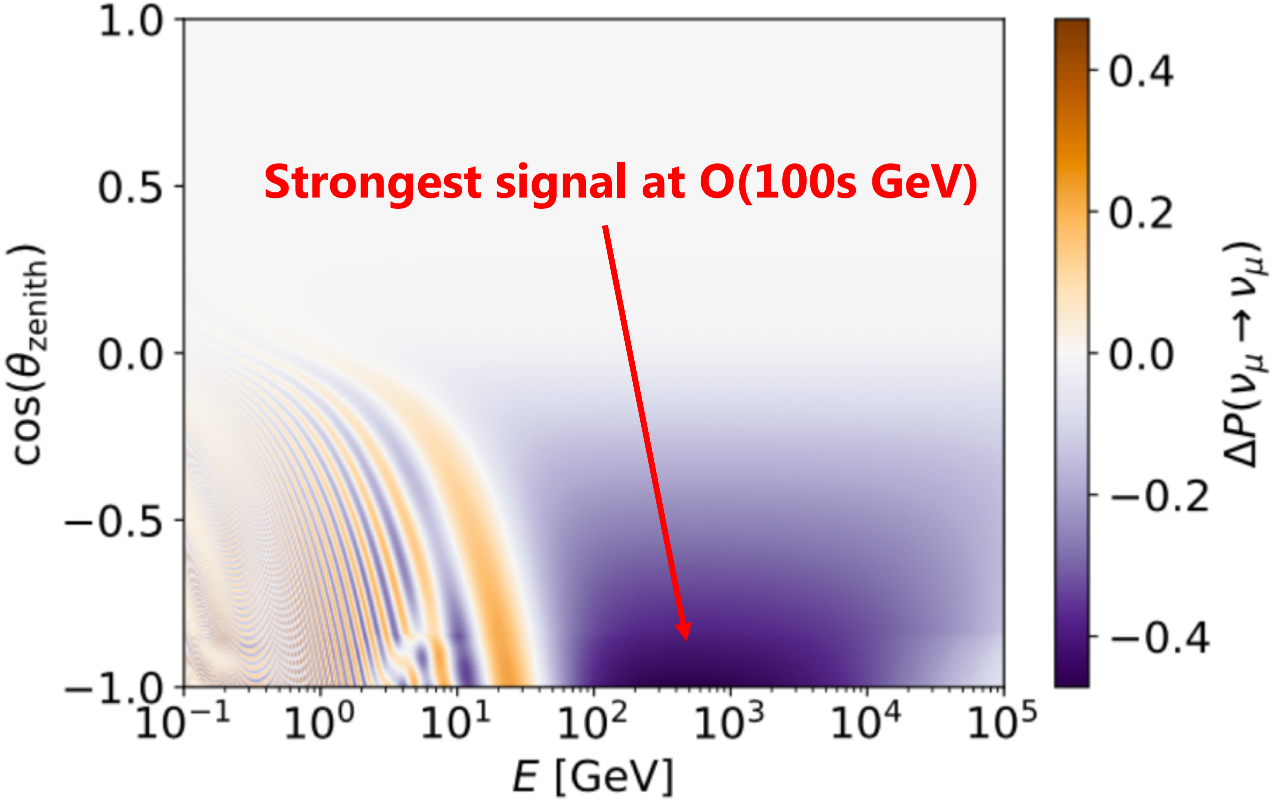
Atmospheric decoherence signal

- Calculate decoherence signal in dominant atmospheric ν_μ survival channel
  - Includes **matter effects** + **Earth absorption**

ν_μ survival probability



Decoherence – standard oscillations



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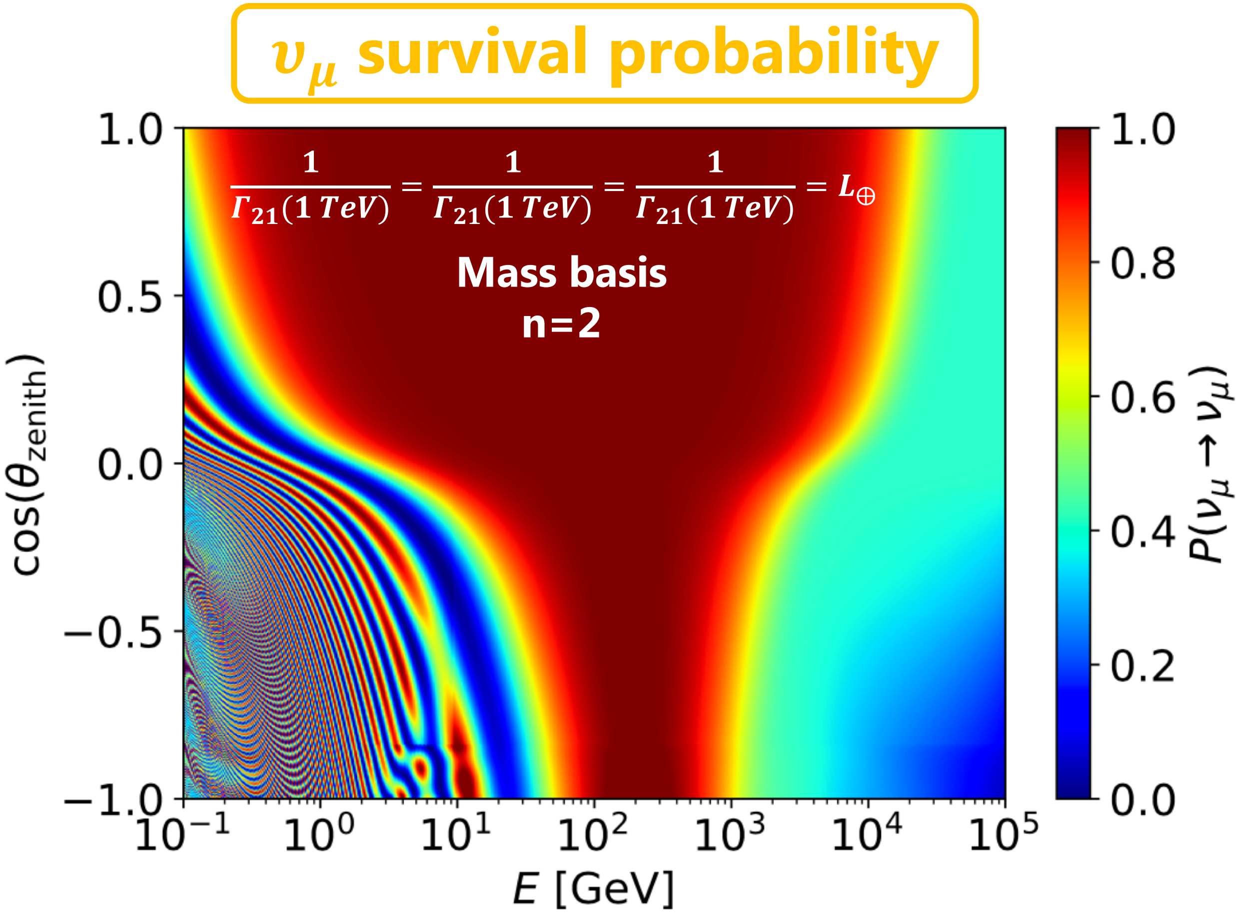
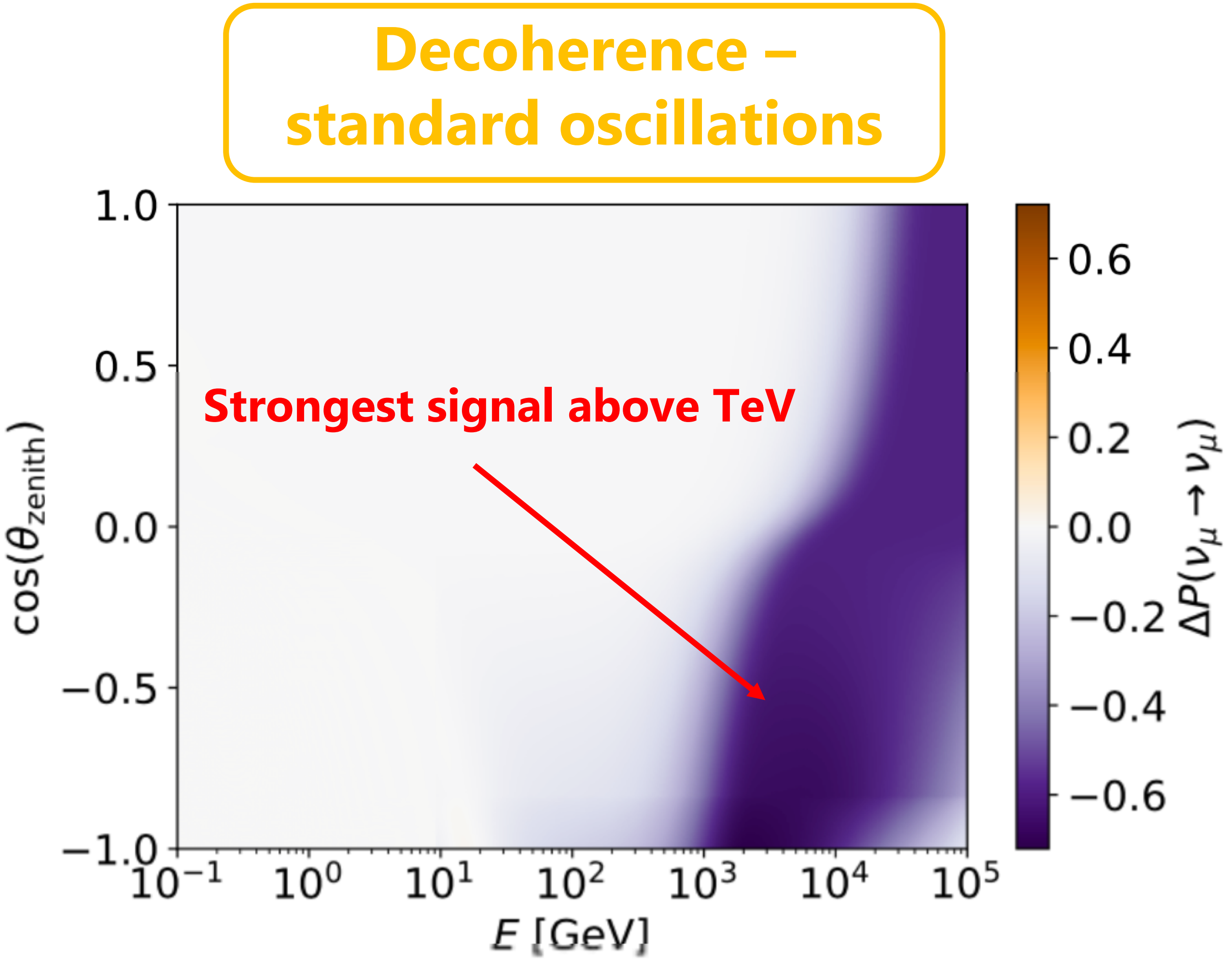




Planck scale decoherence

- **Experimental quantum gravity signature** is most compelling decoherence motivation

- Quantum gravity expected to be:
  - **Strong at Planck scale** (~10^{19} GeV)
  - **Suppressed at lower energies**

- Re-express Γ damping parameters w.r.t. Planck scale:

Anchordoqui et al, arXiV: hep-ph/0506168

$$\Gamma_{ij}(E) = \Gamma_{ij}(E = E_0) \left(\frac{E}{E_0} \right)^n \Rightarrow \Gamma(E) = \lambda_{\mathrm{Planck}} \frac{E^n}{M_{\mathrm{Planck}}^{n-1}}$$

One free parameter (dimensionless constant)

Planck scale decoherence

- **Experimental Quantum Gravity signature** is most compelling

Easier to understand in this form...

Suppression at lower energy scales

$$\frac{1}{\Gamma(E)} = \frac{L_{\text{Planck}}}{\lambda_{\text{Planck}}} \left(\frac{M_{\text{Planck}}}{E} \right)^n$$

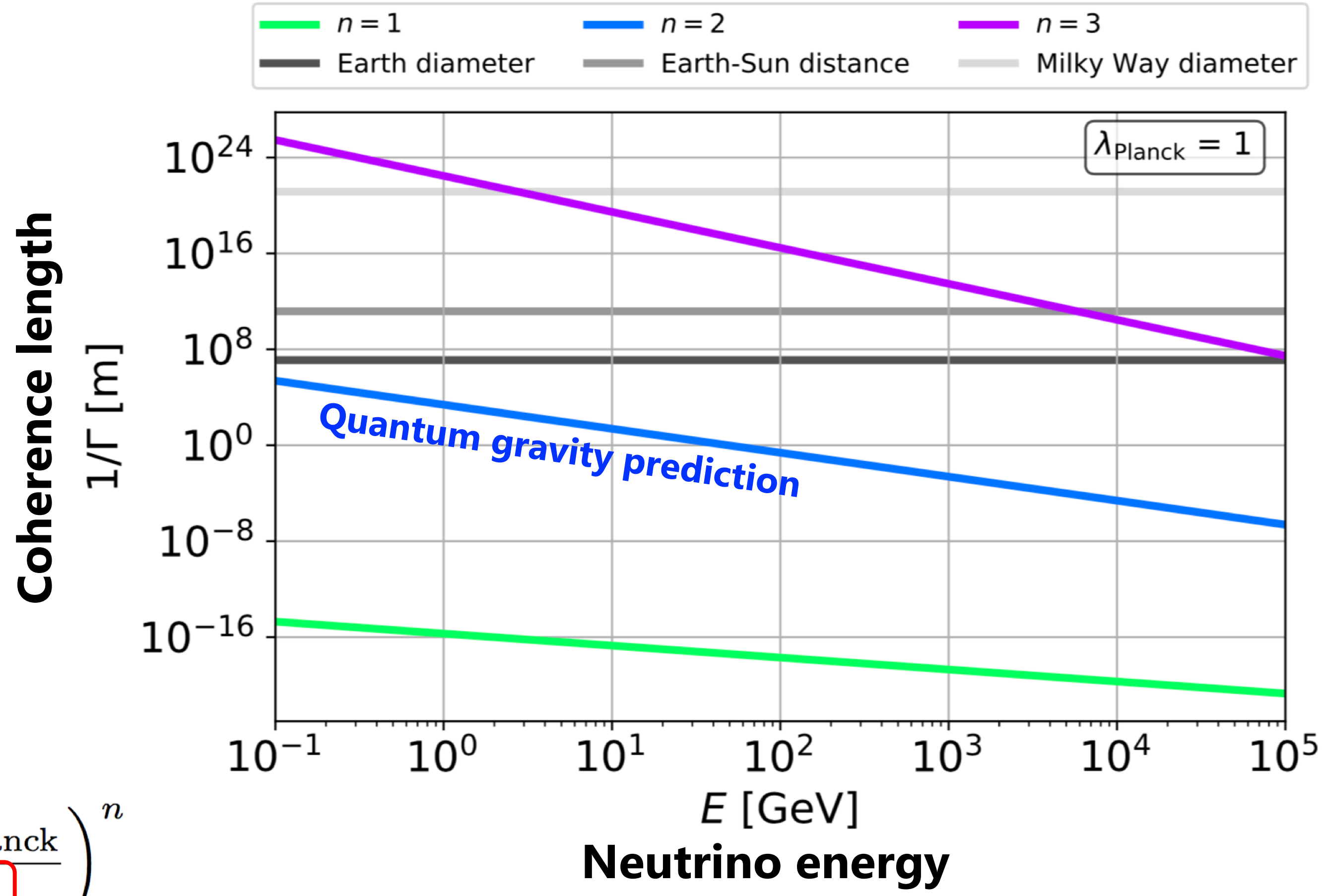
Coherence length

λ^{-1} = coherence length @ $E_\nu = M_{Planck}$ (in units of L_{Planck})

L_{Planck} ~ 10^{-35} m (Planck length)

Coherence length from Planck scale physics

- **"Naturalness" → λ ~ 1** ($E_\nu = M_{Planck}$ → coherence length = Planck length)
- What is "natural" **coherence length**?



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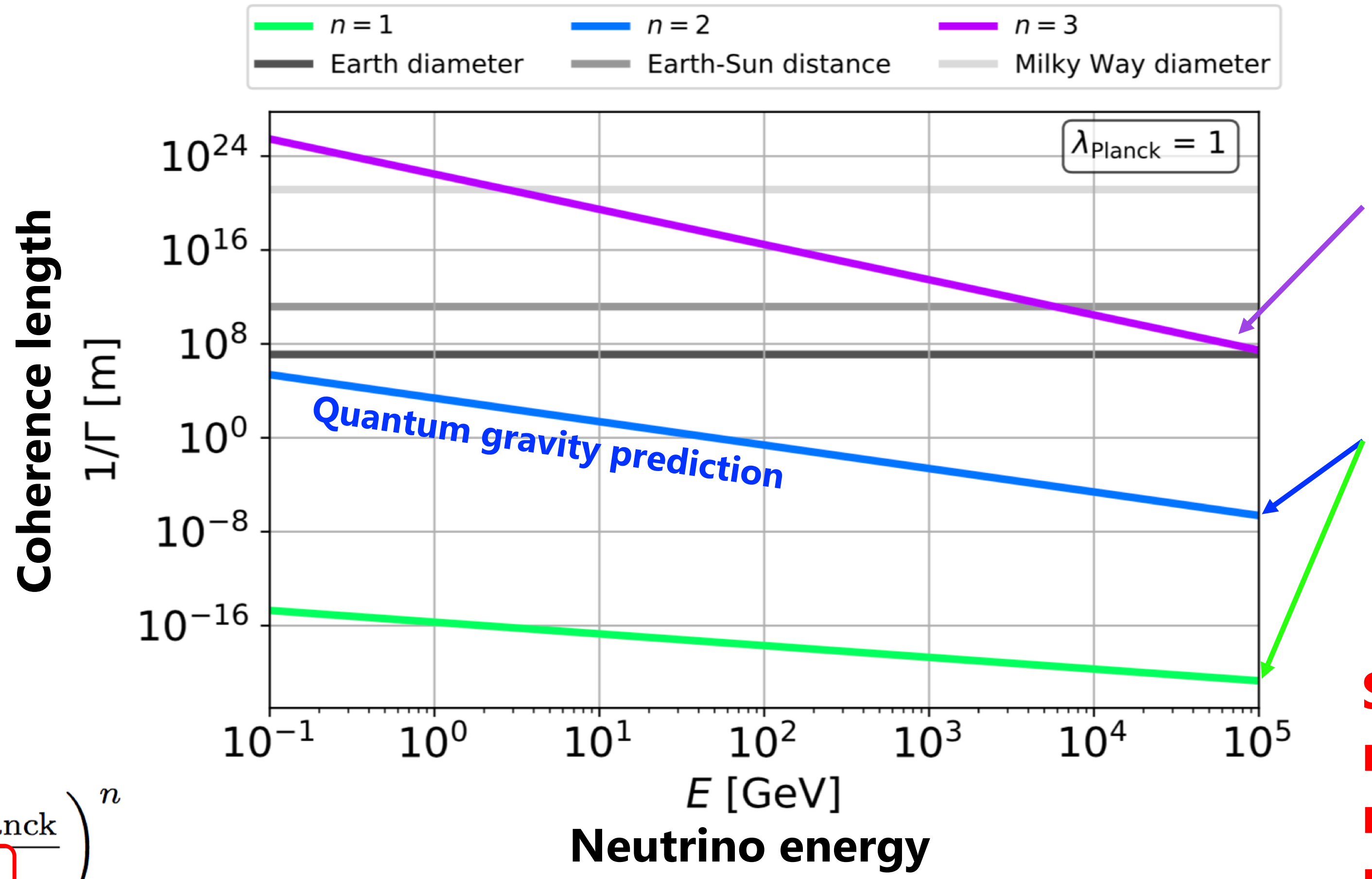


$$\frac{1}{\Gamma(E)} = L_{\text{Planck}} \left(\frac{M_{\text{Planck}}}{E} \right)^n$$

n=3 → need astrophysical distances for strong signal

n=1,2 → large decoherence effect at atmospheric distances

⇩

Sensitive to decoherence many orders of magnitude weaker than natural Planck scale!!!

Coherence length from Planck scale physics

- **“Naturalness” → λ ~ 1** ($E_\nu = M_{Planck}$ → coherence length = Planck length)
- What i…

Take away

Can express decoherence relative to Planck scale physics

Sensitivity to decoherence from Planck scale physics well below the natural scale can be achieved with atmospheric neutrinos

10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5}

E [GeV]

Neutrino energy

$$\frac{1}{\Gamma(E)} = L_{\text{Planck}} \left(\frac{M_{\text{Planck}}}{E} \right)^n$$

…tances

…ect at …ances

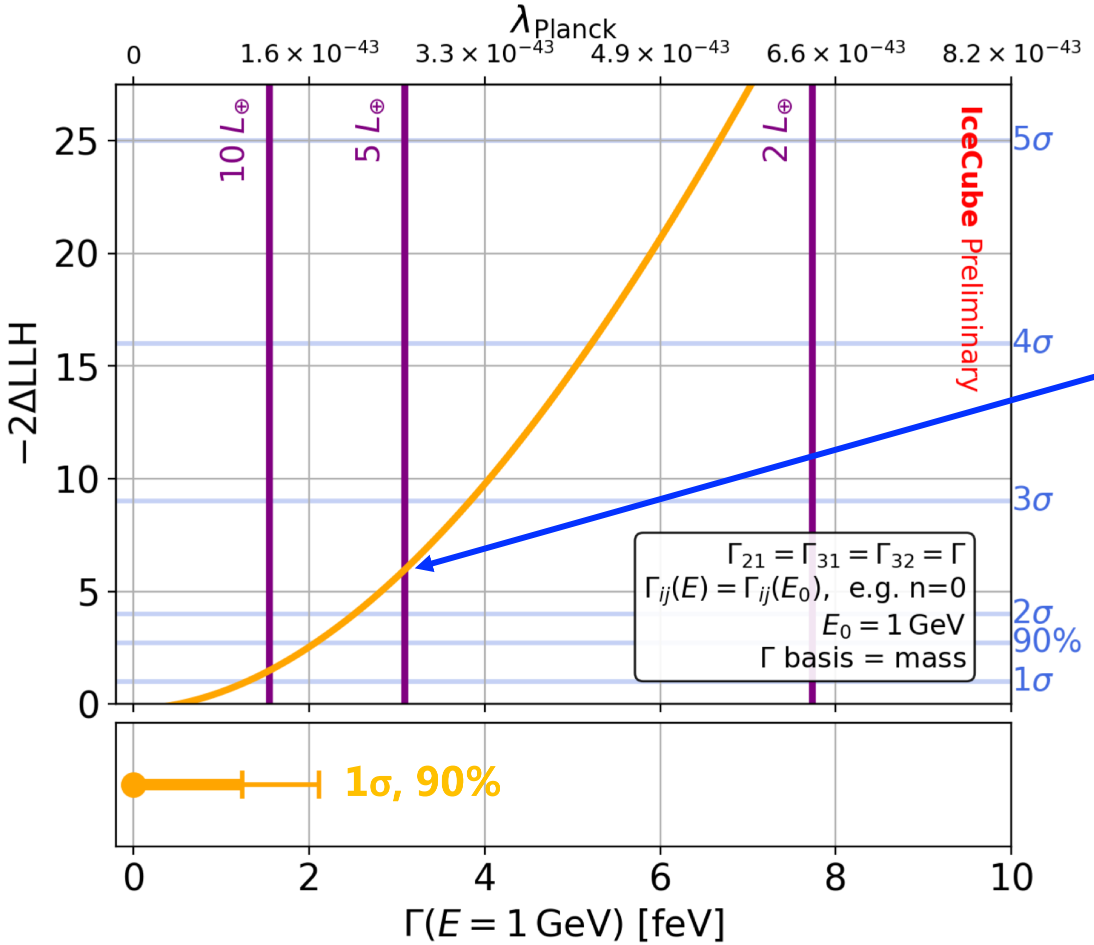
…decoherence many orders of magnitude weaker than natural Planck scale!!!

Measuring neutrino decoherence in DeepCore

- **Measuring neutrino decoherence** using 3 years of **DeepCore** data
  - Data sample, systematics, … as per 2019 ν_τ appearance PRD
  - **5 – 100 GeV** neutrinos

Sensitivity

n=0
(energy-independent)



Sensitive to energy-independent decoherence with coherence length of a few Earth diameters

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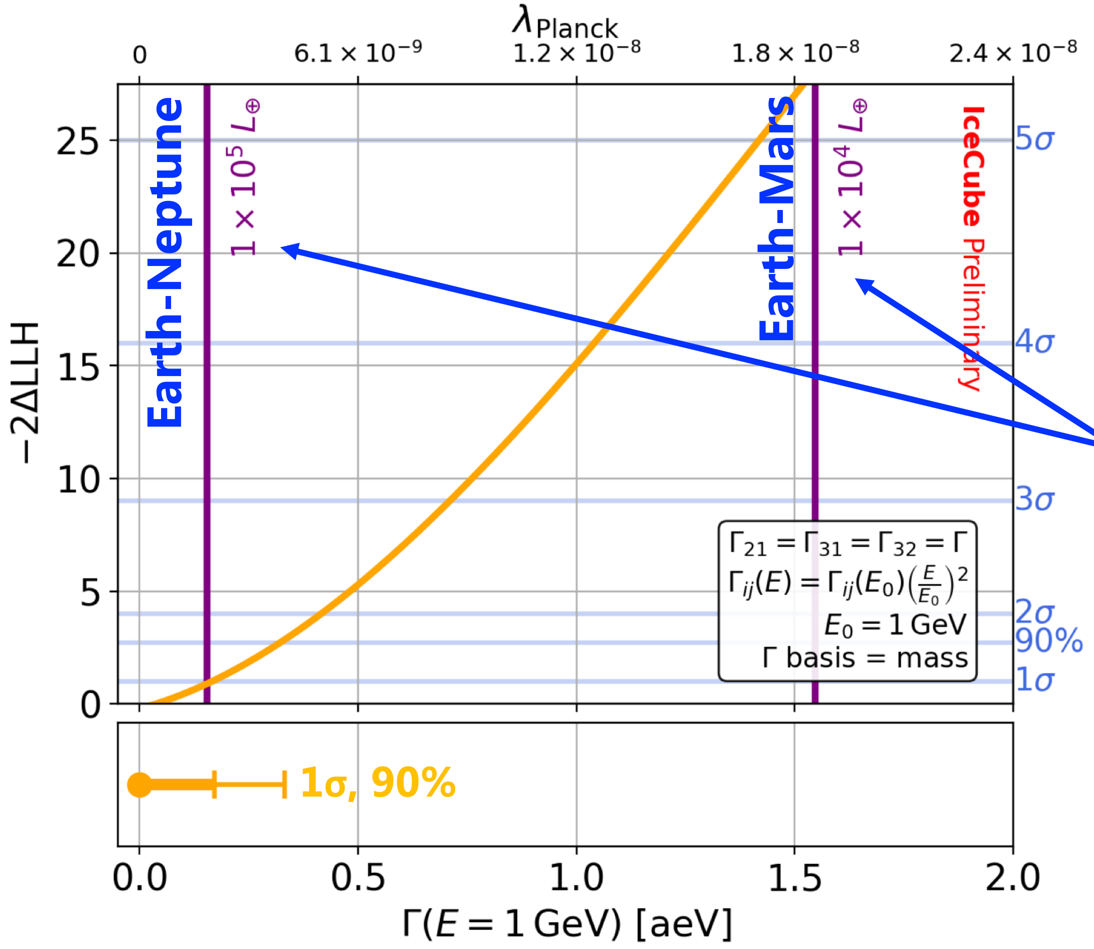
Sensitivity

n=2

(quantum gravity)



Sensitive to decoherence with coherence lengths of interplanetary distances at accelerator energies

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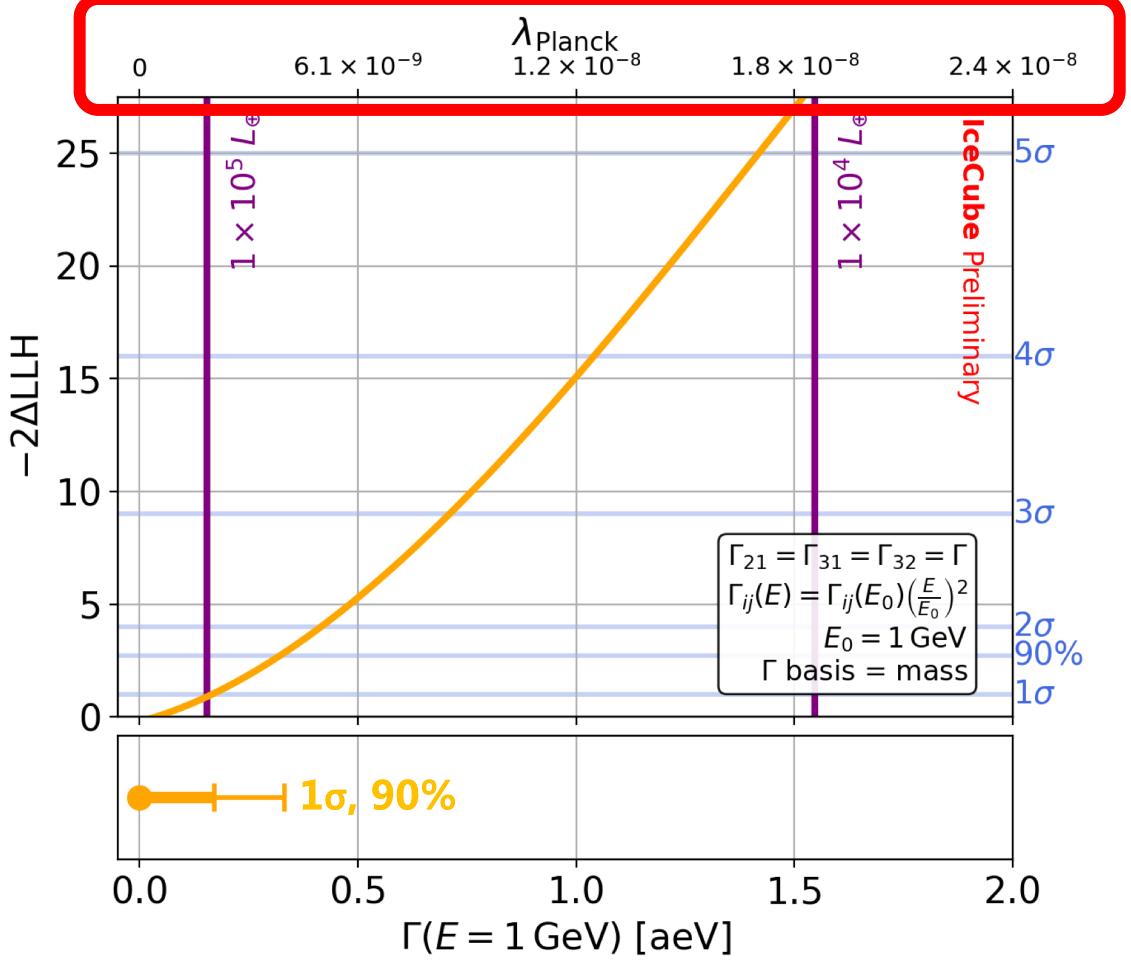


Sensitive to decoherence 8 orders of magnitude weaker than the natural Planck scale expectation!!

→ Planck scale neutrino coherence length of ~10^7 L_{Planck}

Neutrino decoherence in DeepCore

Take away

Measurement of atmospheric neutrino decoherence underway using 3 years of DeepCore data

Sensitive to decoherence from quantum gravity 8 orders of magnitude weaker than natural Planck scale!

Even more sensitive 8 yr DeepCore (low energy) and IceCube (high energy) measurements to follow

Neutrino decoherence in DeepCore

Look out for:

Phenomenology paper (this month)

DeepCore 3yr decoherence measurement (soon)

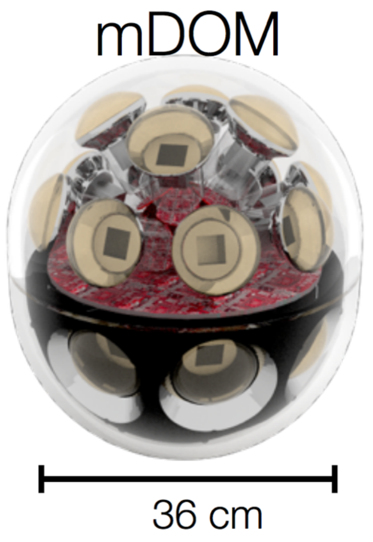
Decoherence nuSQuIDS model → open source (soon)

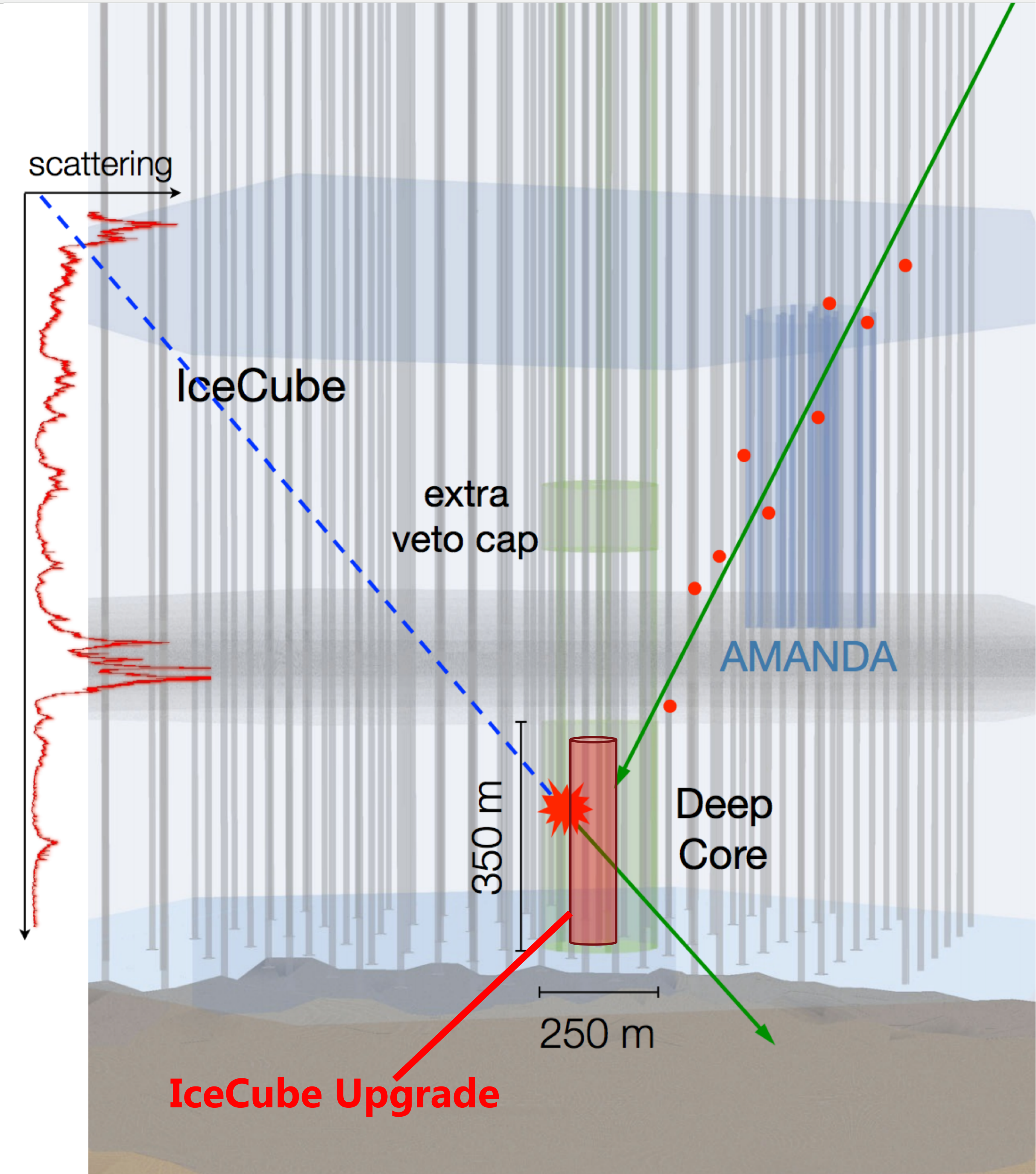
If you have ideas for perturbations to test, come find me!

Neutrino oscillations @ The IceCube Upgrade

The IceCube Upgrade

- NSF have funded a **$30M extension to IceCube**
  - Deployment in 2022/3
  - 700 multi-PMT sensors
  - Improved ice calibration
- Primary physics goal is **precision ν_τ appearance measurement**



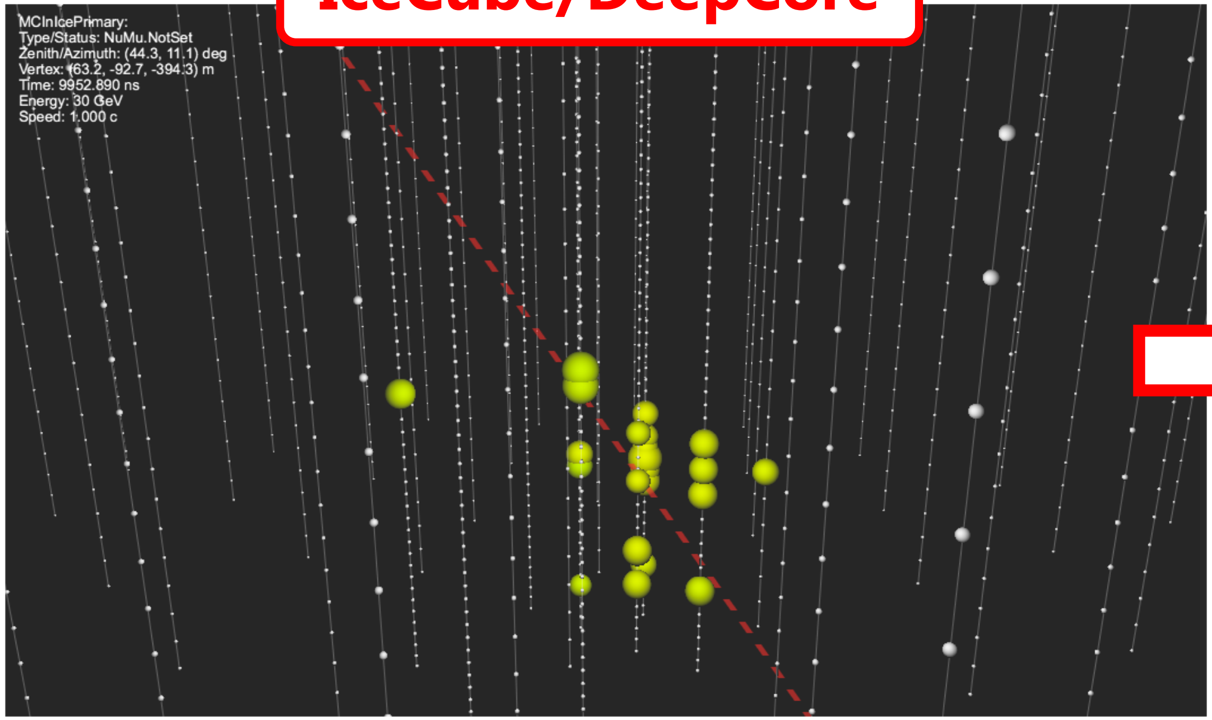


A low energy neutrino detector

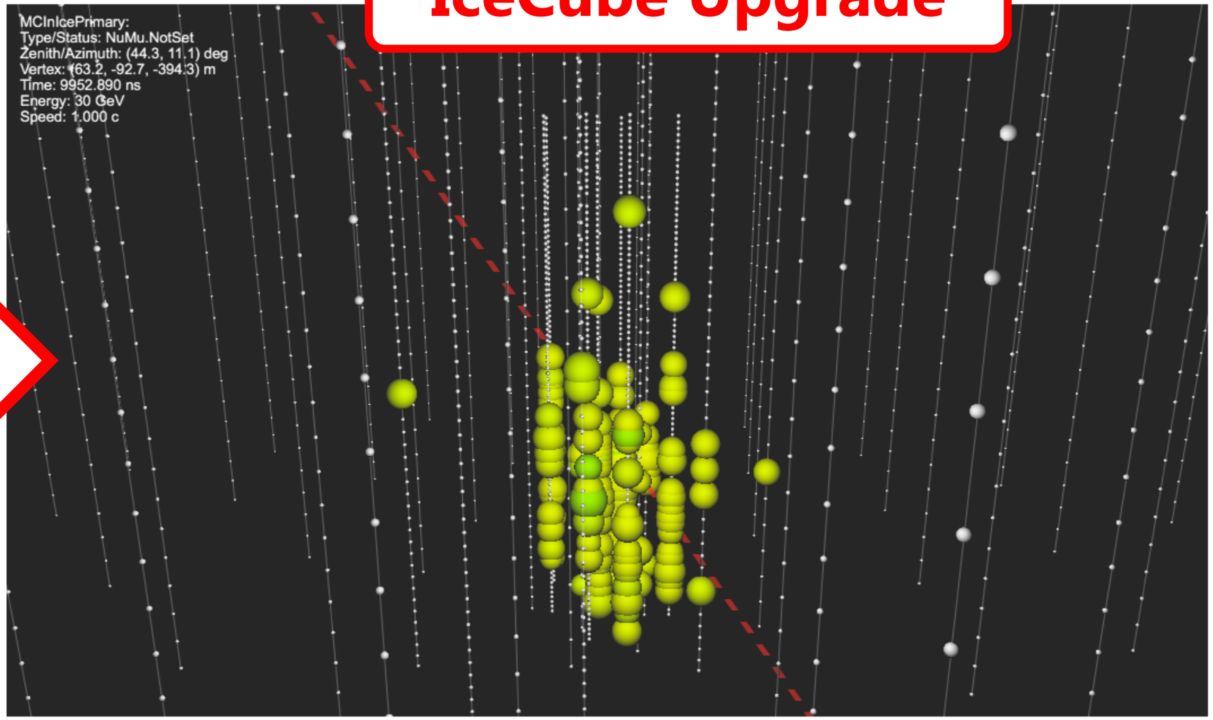
- **Dense instrumentation** in 2 Mton core
  - Large increase in photocathode density → sensitive to **1 GeV neutrinos**

30 GeV ν_μ

IceCube/DeepCore



IceCube Upgrade



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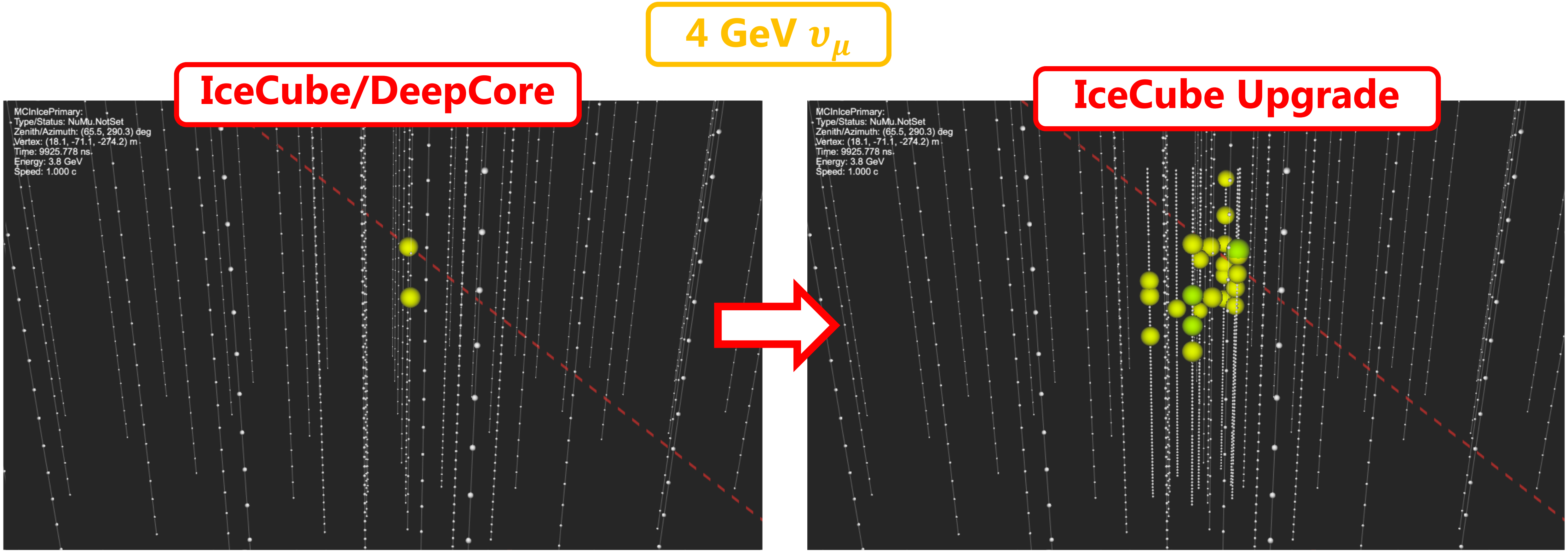
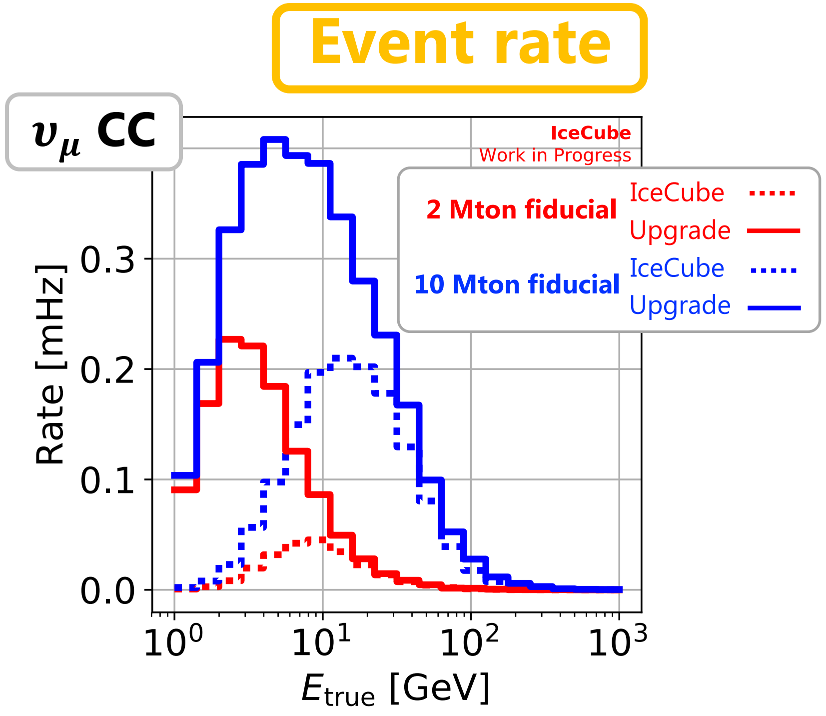
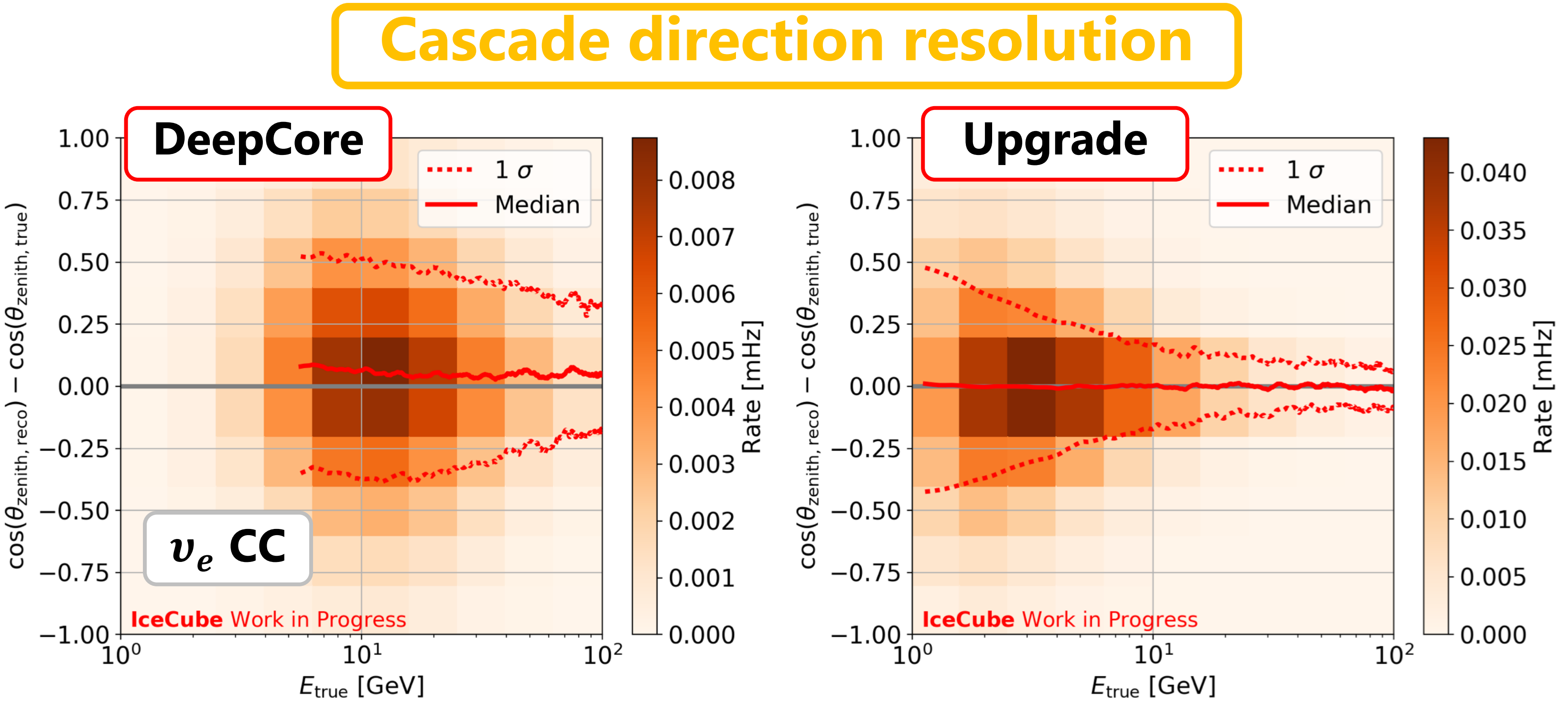


Upgrade performance

- Major improvement in detection rate and energy/direction resolution





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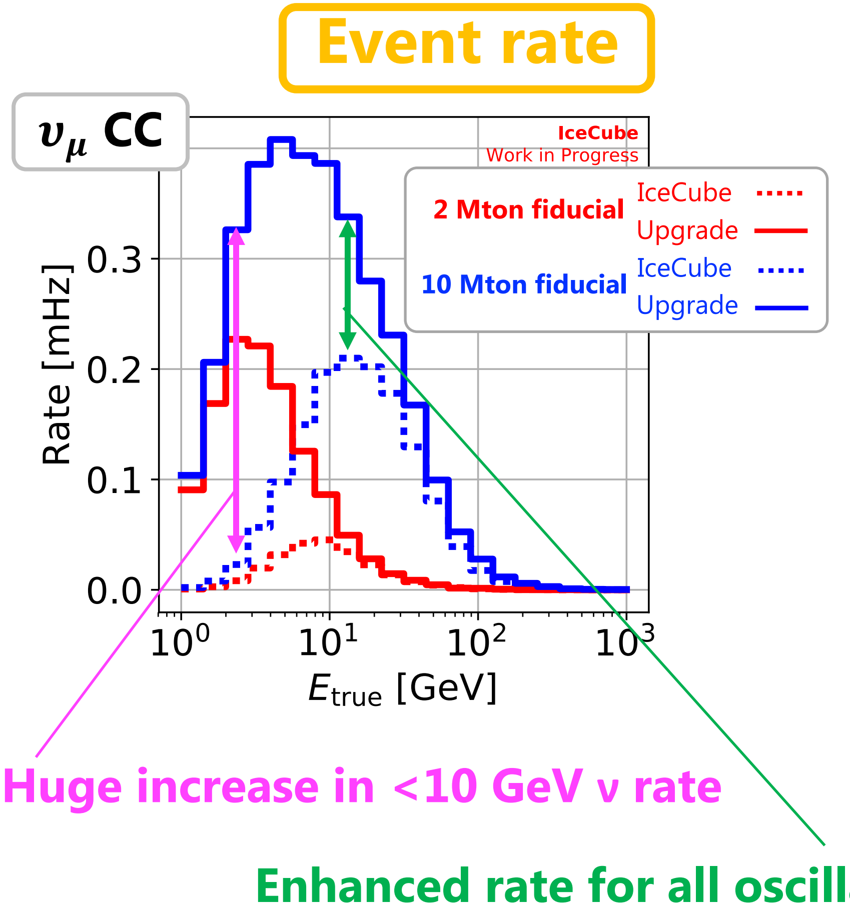
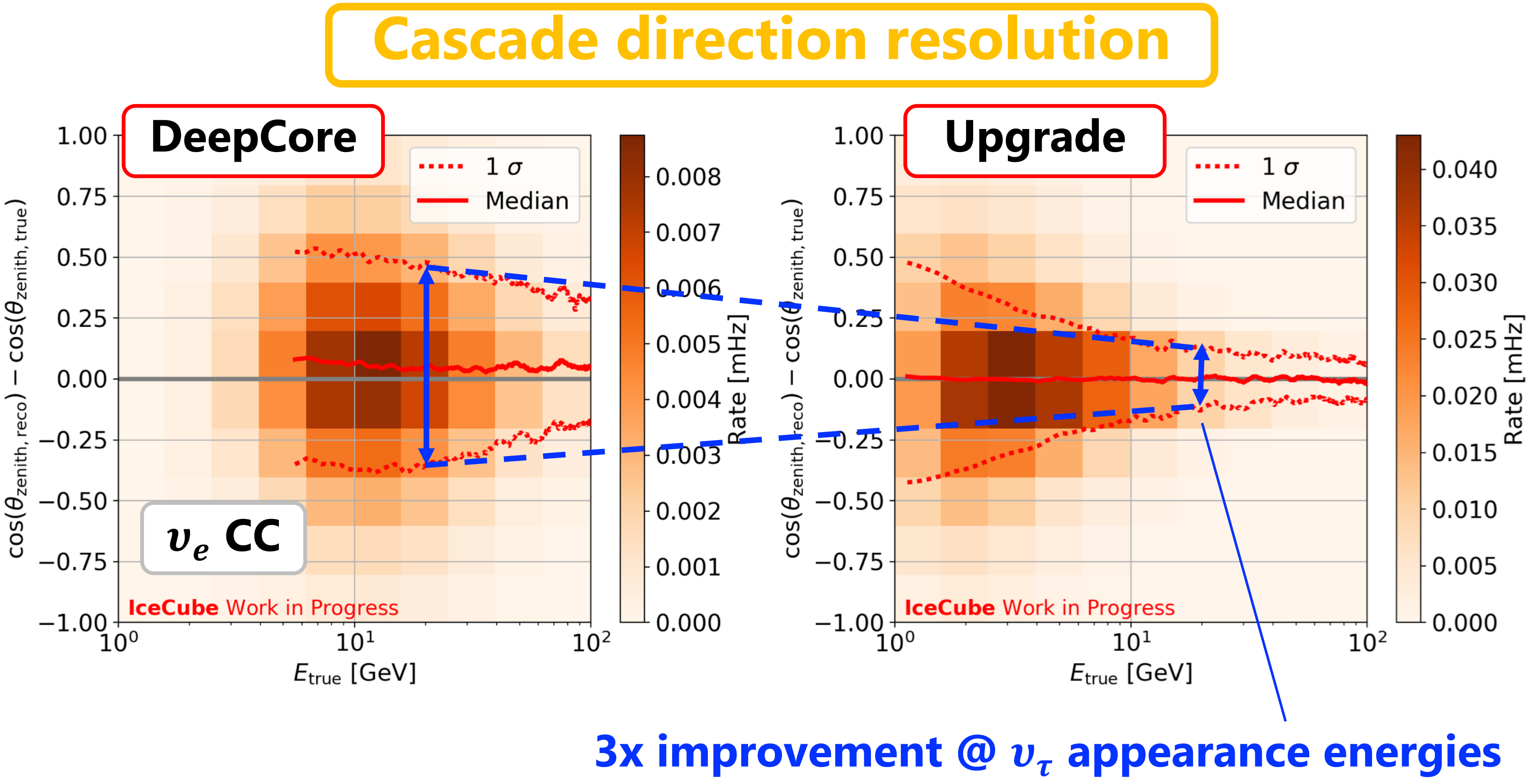




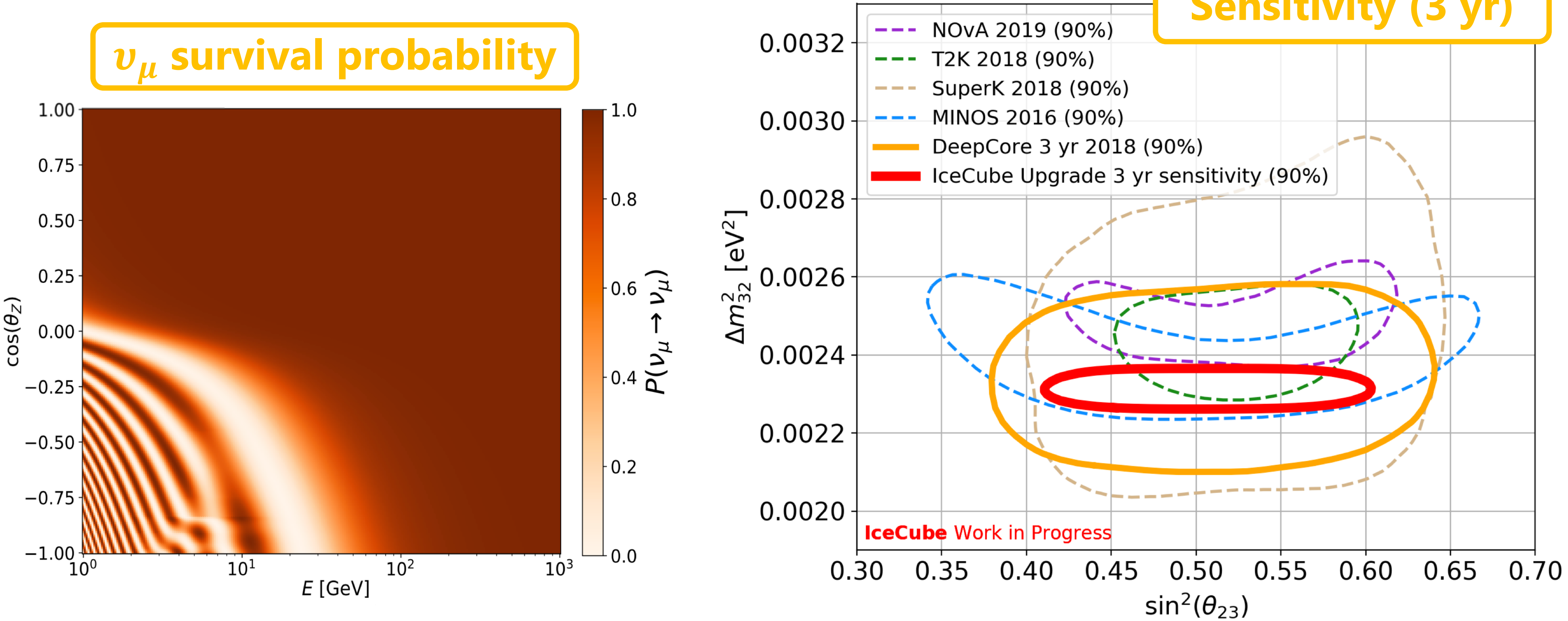
arXiv:1908.09441

ν_μ disappearance

- **3 year Upgrade ν_μ disappearance sensitivity** estimated
- Comparable to current long baseline precision

ν_μ survival probability

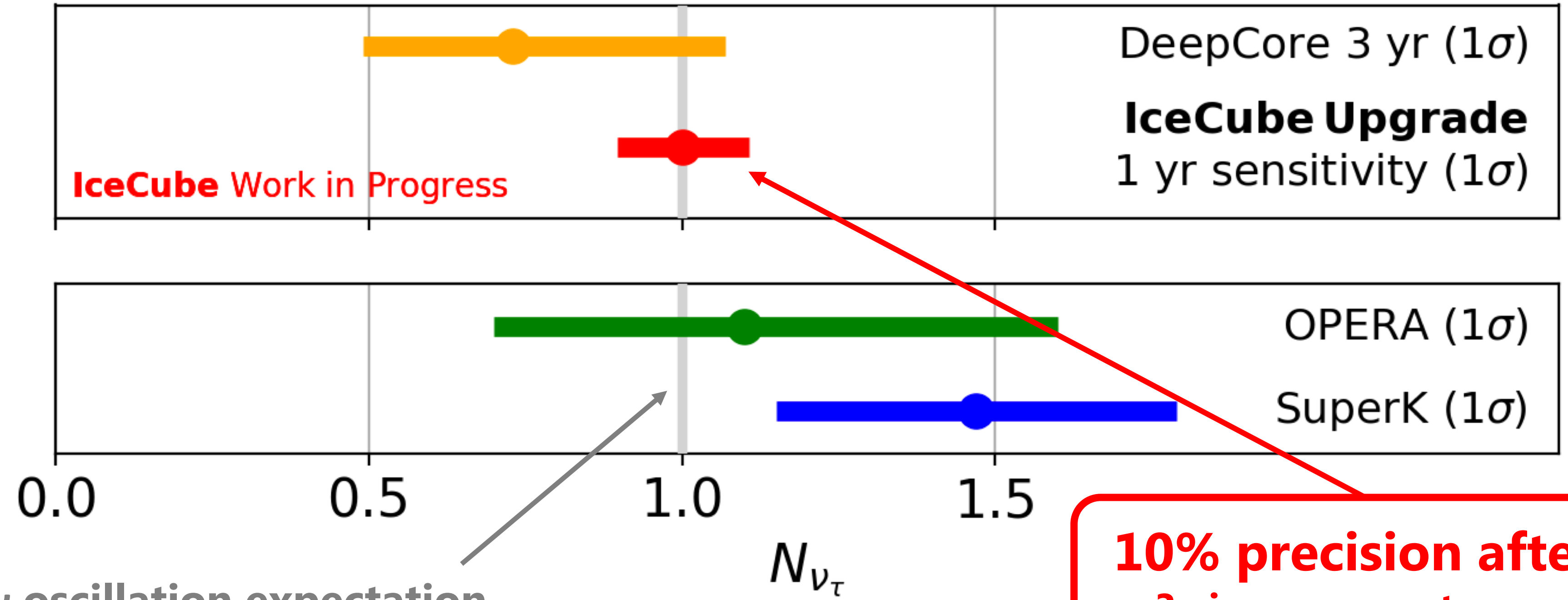
Sensitivity (3 yr)



arXiv:1908.09441

ν_τ appearance

- **Poor precision in ν_τ sector is major barrier to testing PMNS unitarity**
  - Difficult measurement (CC cross section suppression, poor PID)
- Need new ν_τ measurements
- IceCube Upgrade will provide **world leading ν_τ appearance sensitivity**



Standard 3ν oscillation expectation

ν_τ normalisation

10% precision after just 1 year

>3x improvement on current world best

arXiv:1908.09441

Take away

IceCube Upgrade will provide huge leap in low energy neutrino statistics and resolutions

10% υ_τ appearance precision after only 1 year

υ_μ disappearance competitive with long baseline beam experiments

Also: neutrino mass ordering, BSM oscillations, Dark Matter, …

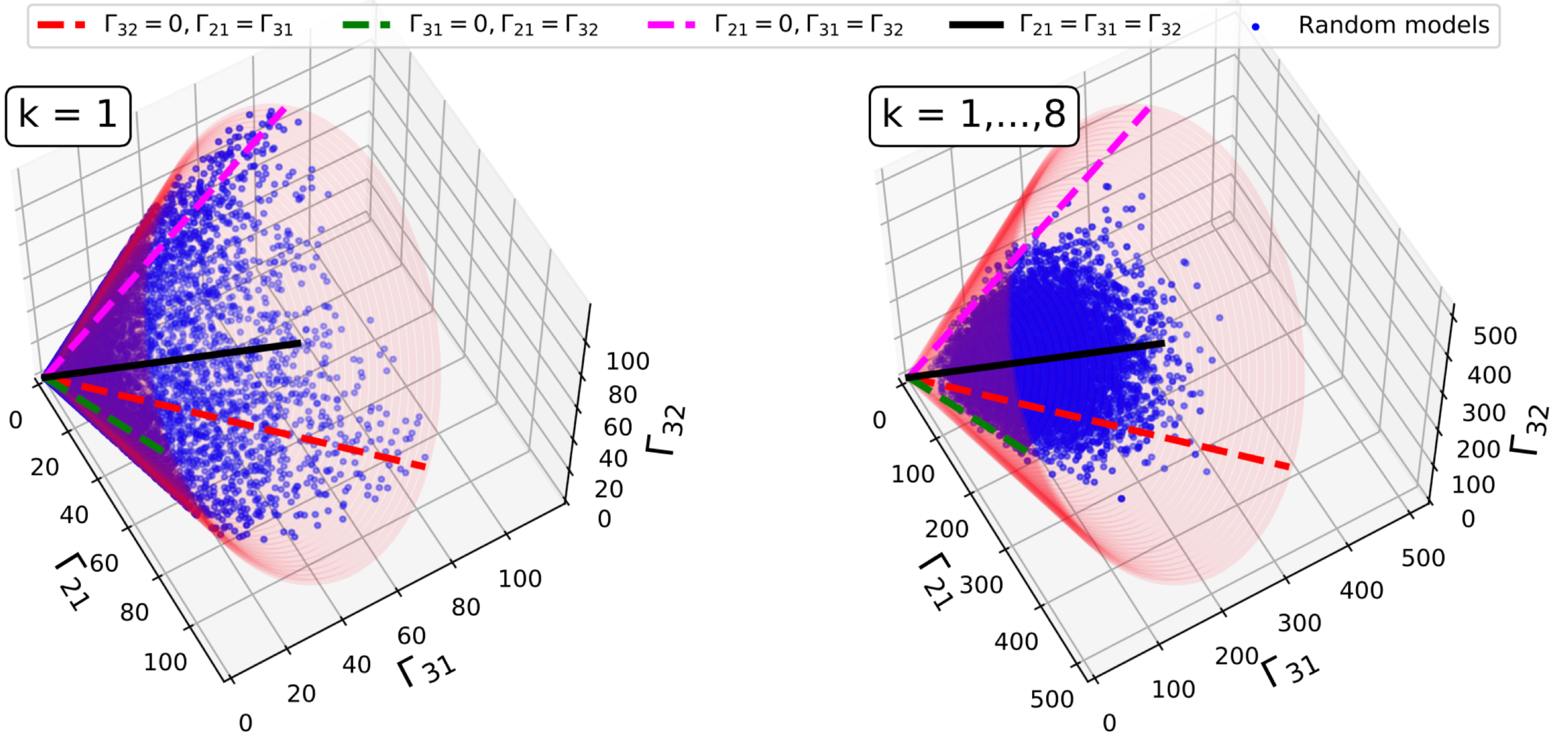
Backup

Decoherence parameter interdependence

$$\Gamma_{ij} = \Gamma_{ji} = \sum_{k=1}^{8} \left(D_k^{(i,i)} - D_k^{(j,j)} \right)^2$$

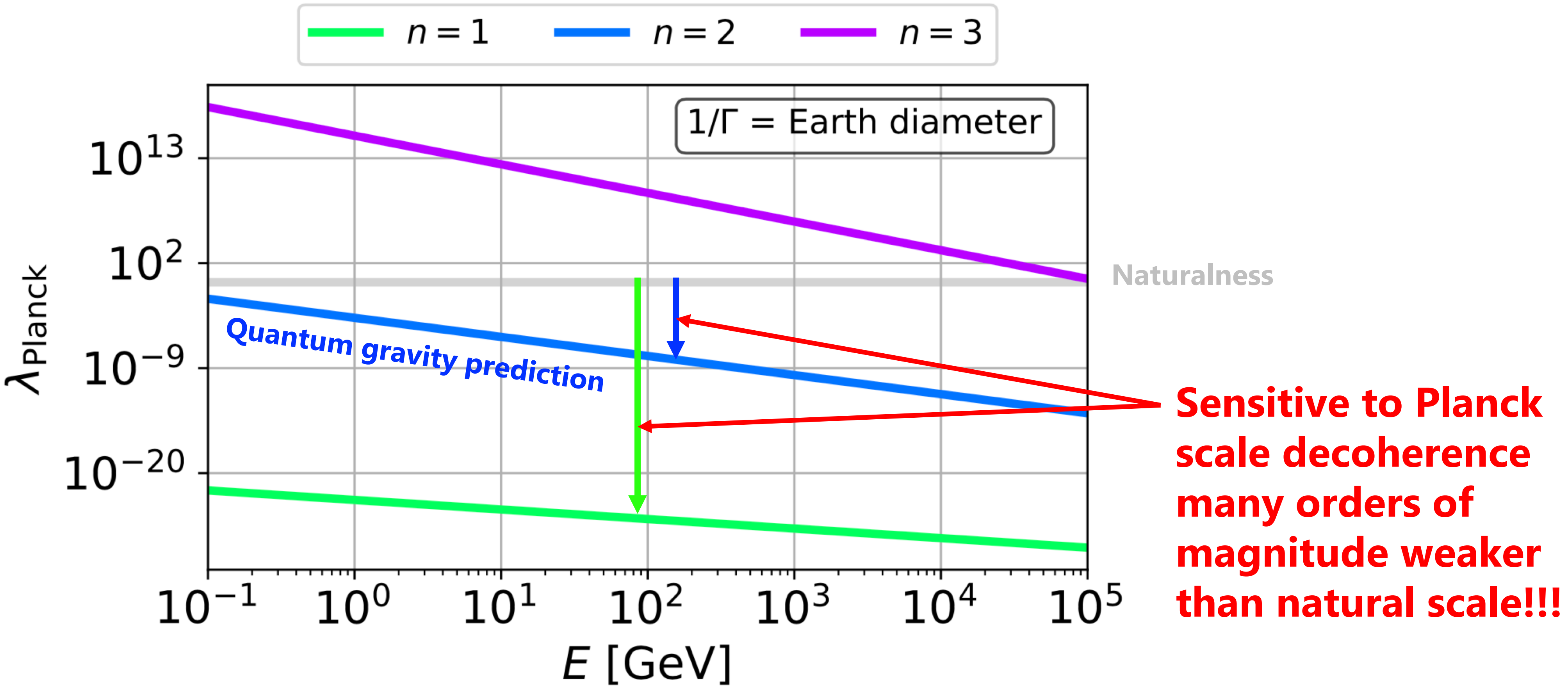
- $\mathbf{\Gamma}$ parameters not independent
  - Conical bound
  - Allowed values depend on number of operators

$$\sqrt{\Gamma_{ij}} = \sqrt{\Gamma_{il}} \pm \sqrt{\Gamma_{jl}}$$



Planck scale constraining power with atmospheric neutrinos

- Ignore naturalness → **test atmospheric neutrino sensitivity to λ_{Planck}**



Neutrino energy

$$\frac{1}{\Gamma(E)} = \frac{L_{\text{Planck}}}{\lambda_{\text{Planck}}} \left(\frac{M_{\text{Planck}}}{E} \right)^n$$

PMNS unitarity

- ν_τ sector poorly constrained
  - Parke, Ross-Lonergan, arXiv:1508.05095