Tests of fundamental symmetries with atmospheric neutrinos

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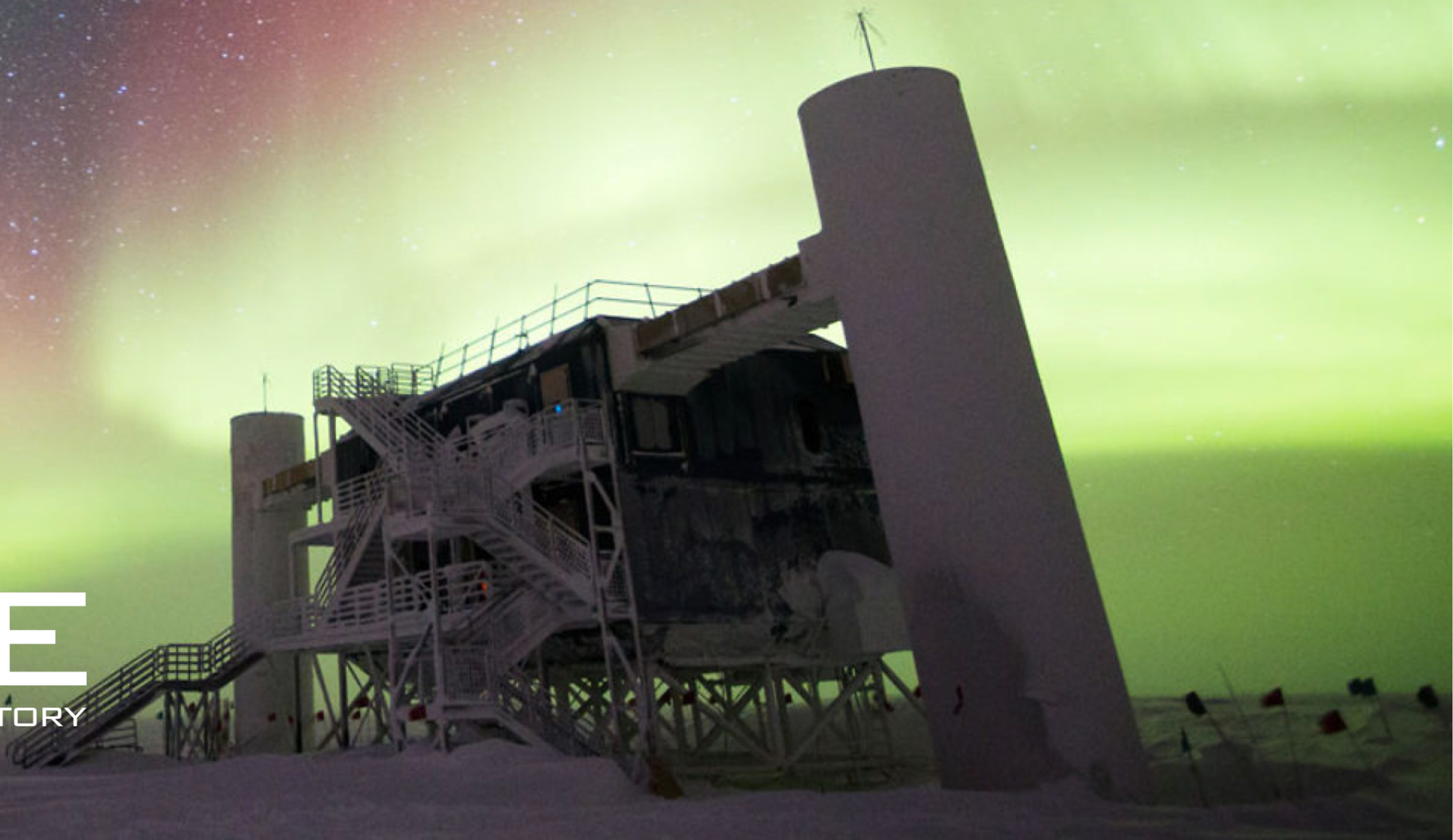
IceDUNE 2021

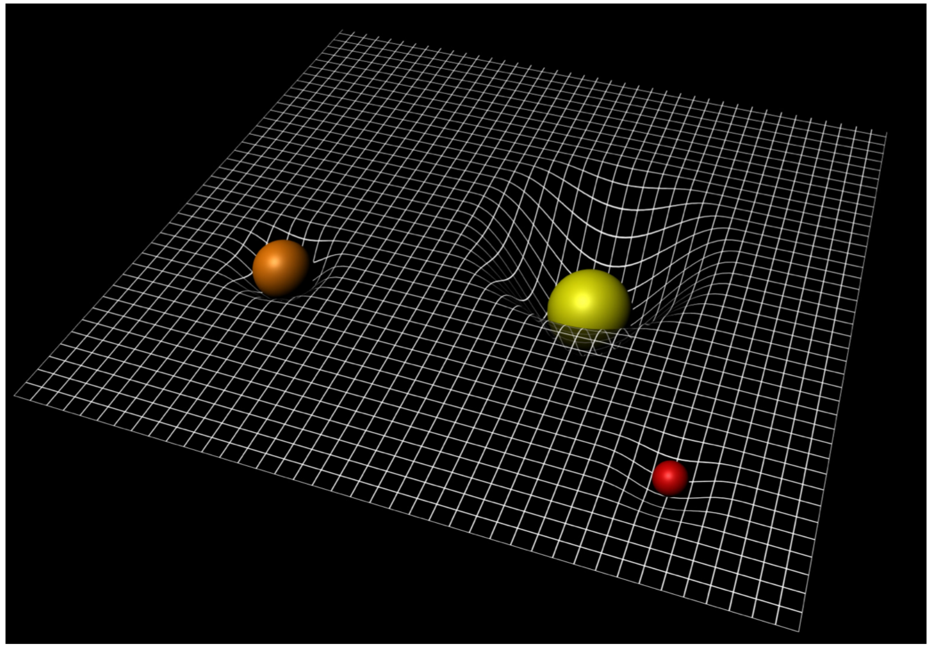
CARLSBERG FOUNDATION
VILLUM FONDEN

IceCube
South Pole Neutrino Observatory



The fundamental properties of Nature as we know it

- Our current understanding of the Universe (SM + GR) features various symmetries/rules
  - Lorentz invariance
  - CPT symmetry
  - Equivalence principal

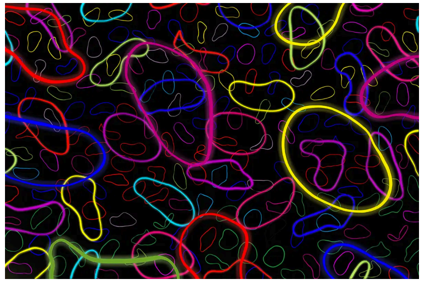


- Space-time is boring
  - Smooth and stable
  - Microscopically flat far from massive objects

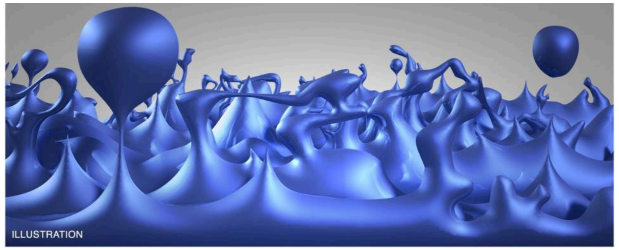
- Evolution of quantum states is boring
  - Deterministic, reversible and unitary in empty space

Physics at high energy scales

- New **high energy theories** proposed to solve shortcomings of the SM/GR
  - e.g. **quantum gravity** (QG)
  - E ~ 10^{19} GeV, L ~ 10^{-35} m (the **Planck scale**)



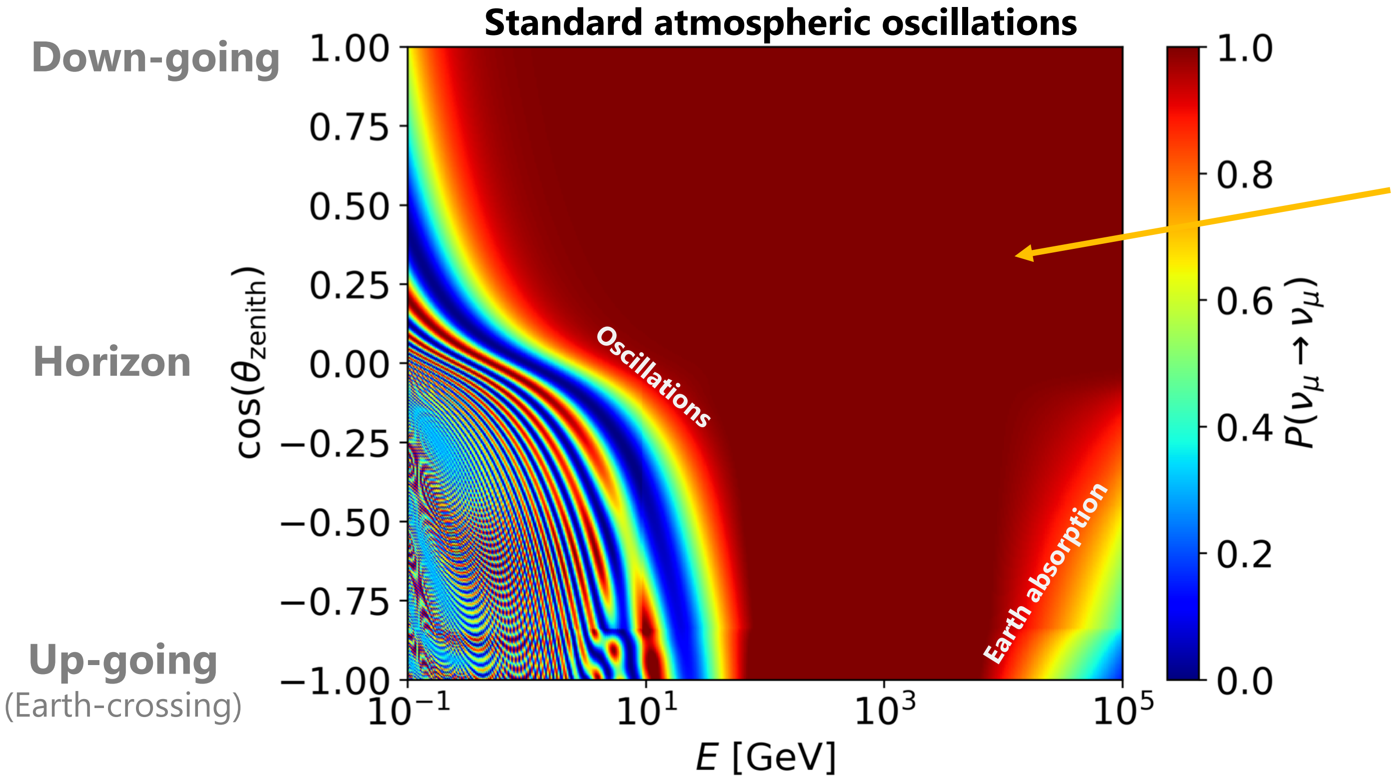
- SM is then a low energy limit of this new theory
- **Modifications of space-time** and **violations of fundamental properties/symmetries** often predicted in such high energy theories
  - These effects are suppressed at the "low" energies we observe



- Searching for these effects requires:
  - High energies → overcome suppression
  - Precision → effects are small
  - Large travel distances → accumulation of tiny effects of space-time defects

Atmospheric neutrino oscillations

- Neutrinos act as tiny quantum interferometers
  - Modifications to space-time interferes with superposition producing oscillations
- The high energies/baselines and copious, well understood flux of atmospheric neutrinos is a powerful testing ground for such effects



Any ≳100 GeV oscillations = new physics!

(especially ν_τ)

$\mathcal{O}(1-10)$ mHz rates for IceCube (Upgrade)

Lorentz invariance violation

Lorentz invariance violation (LIV)

- **Lorentz invariance -** *Experimental results are independent of the orientation and velocity of the laboratory frame*

- LIV frequently predicted by high energy/GUT theories, e.g. quantum gravity, string theory, SUSY, …
  - LIV suppressed at energy scales we can currently access

- Example phenomenology:
  - Energy-dependent speed of light (modified dispersion relation)
  - Preferred direction of space-time

Standard Model Extension (SME)

- Effective field theory extending the SM to include all possible Lorentz invariance violating operators
  - Features both CPT preserving and violating operators

- Example neutrino Hamiltonian in SME:

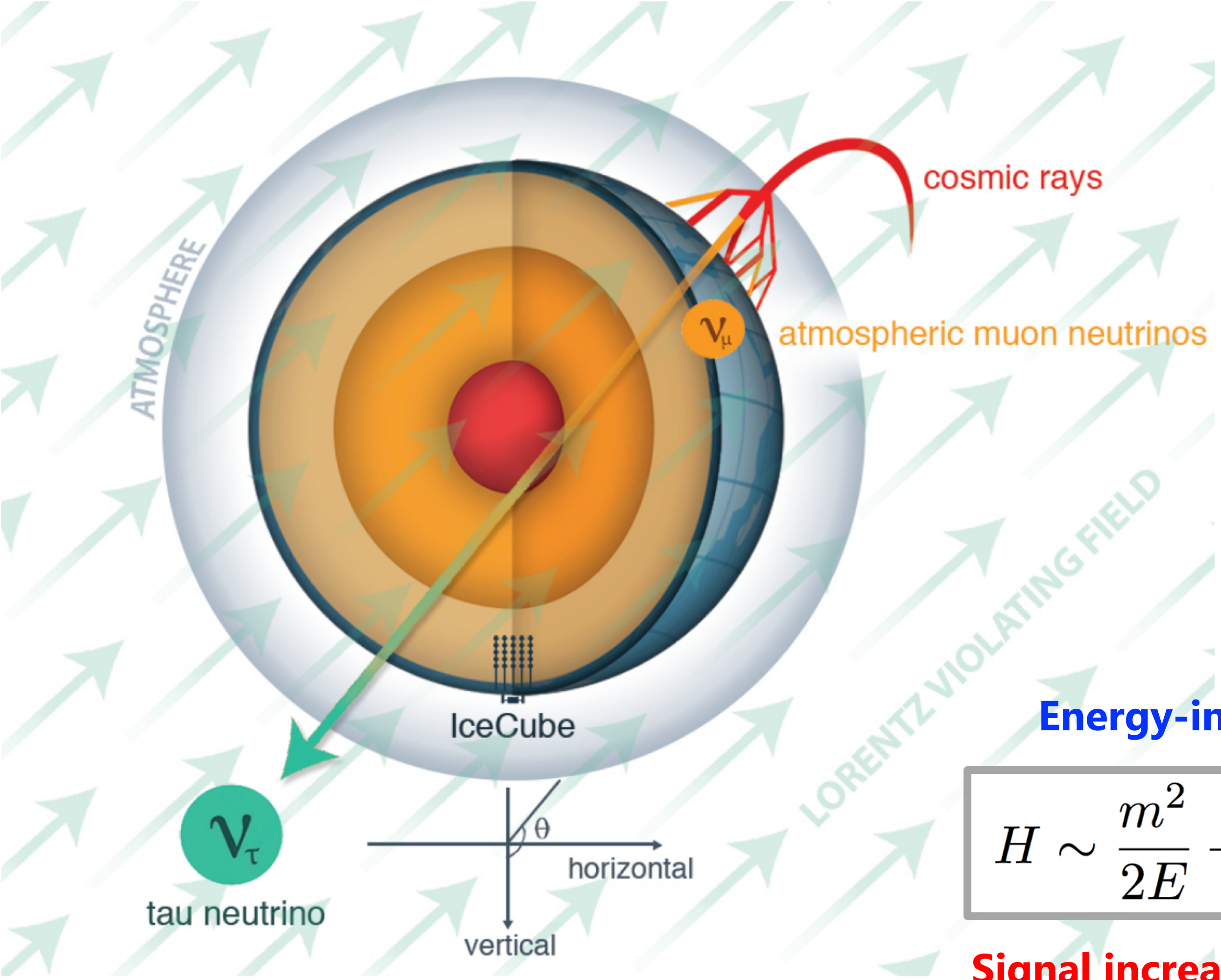
a = CPT odd
c = CPT even

$$H \sim \underbrace{\frac{m^2}{2E}}_{\text{Standard oscillations}} + \underbrace{\mathring{a}^{(3)} - E \cdot \mathring{c}^{(4)} + E^2 \cdot \mathring{a}^{(5)} - E^3 \cdot \mathring{c}^{(6)} \ldots}_{\text{LIV operators}}$$

- Many SME tests performed
  - Neutrino oscillations, accelerator, γ-ray, CRs, CMB, precision nuclear/atomic lab tests, …

Atmospheric neutrino tests

- Atmospheric neutrino flavour transitions modified by a LIV field



Signal is anomalous $\nu_\mu \rightarrow \nu_\tau$ transitions

(Only prompt and astrophysical ν_τ expected above 100 GeV in νSM)

Energy-independent signal for lowest order operator

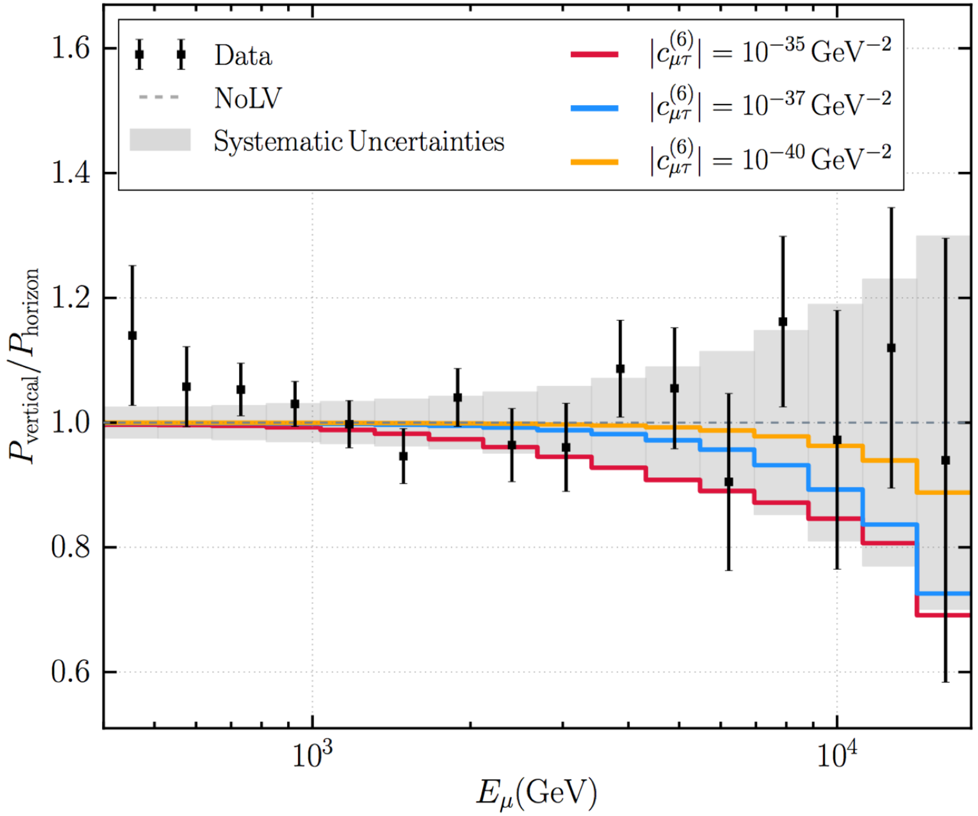
$$H \sim \frac{m^2}{2E} + \mathring{a}^{(3)} - E \cdot \mathring{c}^{(4)} + E^2 \cdot \mathring{a}^{(5)} - E^3 \cdot \mathring{c}^{(6)} \dots$$

Signal increases with energy for all higher order operators

Nature Physics 14, 961–966 (2018)

Atmospheric neutrino tests

- IceCube atmospheric neutrino LIV tests performed with 2 years of data
  - World’s most stringent constraints on higher order SME operators

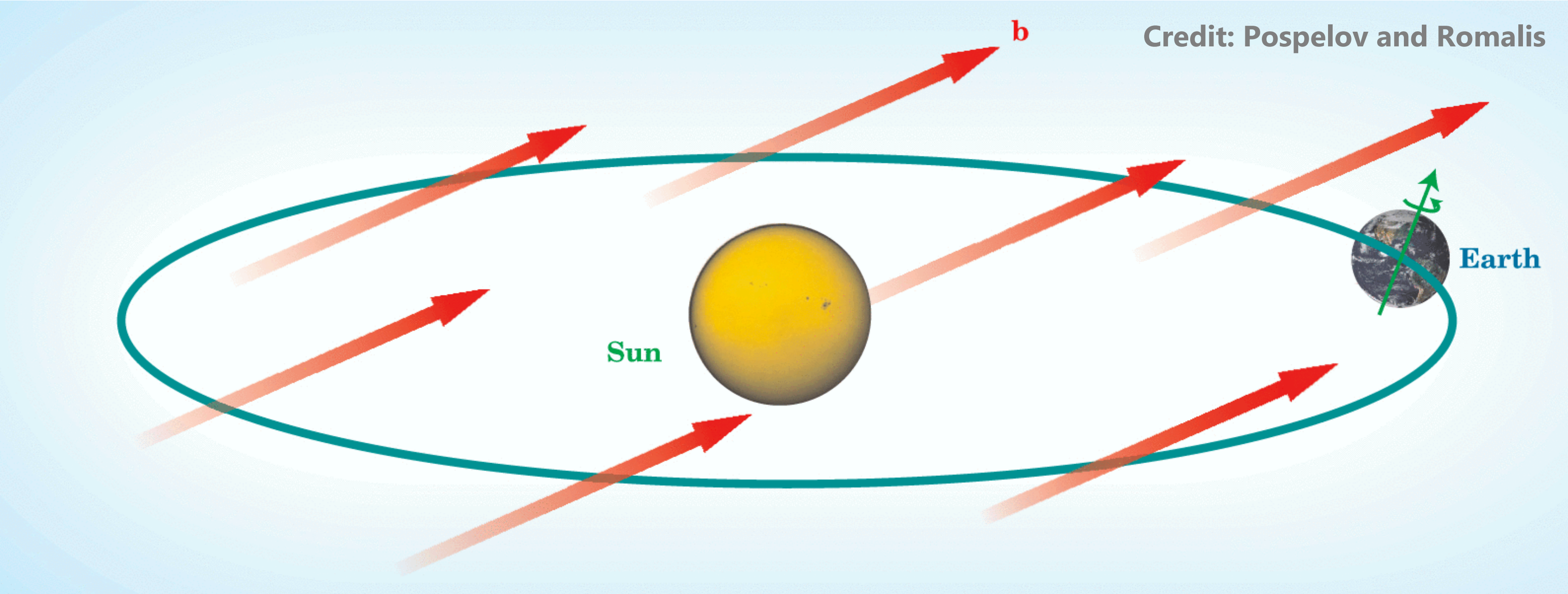


dim.	method	type	sector	limits	ref.
3	CMB polarization	astrophysical	photon	$\sim 10^{-43}$ GeV	[5]
	He-Xe comagnetometer	tabletop	neutron	$\sim 10^{-34}$ GeV	[10]
	torsion pendulum	tabletop	electron	$\sim 10^{-31}$ GeV	[12]
	muon g-2	accelerator	muon	$\sim 10^{-24}$ GeV	[13]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}(\mathring{a}^{(3)}_{\mu\tau})\rvert, \lvert\mathrm{Im}(\mathring{a}^{(3)}_{\mu\tau})\rvert$ $< 2.9 \times 10^{-24}$ GeV (99% C.L.) $< 2.0 \times 10^{-24}$ GeV (90% C.L.)	this work
4	GRB vacuum birefringence	astrophysical	photon	$\sim 10^{-38}$	[6]
	Laser interferometer	LIGO	photon	$\sim 10^{-22}$	[7]
	Sapphire cavity oscillator	tabletop	photon	$\sim 10^{-18}$	[8]
	Ne-Rb-K comagnetometer	tabletop	neutron	$\sim 10^{-29}$	[11]
	trapped Ca^+ ion	tabletop	electron	$\sim 10^{-19}$	[14]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}(\mathring{c}^{(4)}_{\mu\tau})\rvert, \lvert\mathrm{Im}(\mathring{c}^{(4)}_{\mu\tau})\rvert$ $< 3.9 \times 10^{-28}$ (99% C.L.) $< 2.7 \times 10^{-28}$ (90% C.L.)	this work
5	GRB vacuum birefringence	astrophysical	photon	$\sim 10^{-34}$ GeV^{-1}	[6]
	ultra-high-energy cosmic ray	astrophysical	proton	$\sim 10^{-22}$ to 10^{-18} GeV^{-1}	[9]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}(\mathring{a}^{(5)}_{\mu\tau})\rvert, \lvert\mathrm{Im}(\mathring{a}^{(5)}_{\mu\tau})\rvert$ $< 2.3 \times 10^{-32}$ GeV^{-1} (99% C.L.) $< 1.5 \times 10^{-32}$ GeV^{-1} (90% C.L.)	this work
6	GRB vacuum birefringene	astrophysical	photon	$\sim 10^{-31}$ GeV^{-2}	[6]
	ultra-high-energy cosmic ray	astrophysical	proton	$\sim 10^{-42}$ to 10^{-35} GeV^{-2}	[9]
	gravitational Cherenkov radiation	astrophysical	gravity	$\sim 10^{-31}$ GeV^{-2}	[15]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}(\mathring{c}^{(6)}_{\mu\tau})\rvert, \lvert\mathrm{Im}(\mathring{c}^{(6)}_{\mu\tau})\rvert$ $< 1.5 \times 10^{-36}$ GeV^{-2} (99% C.L.) $< 9.1 \times 10^{-37}$ GeV^{-2} (90% C.L.)	this work
7	GRB vacuum birefringence	astrophysical	photon	$\sim 10^{-28}$ GeV^{-3}	[6]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}(\mathring{a}^{(7)}_{\mu\tau})\rvert, \lvert\mathrm{Im}(\mathring{a}^{(7)}_{\mu\tau})\rvert$ $< 8.3 \times 10^{-41}$ GeV^{-3} (99% C.L.) $< 3.6 \times 10^{-41}$ GeV^{-3} (90% C.L.)	this work
8	gravitational Cherenkov radiation	astrophysical	gravity	$\sim 10^{-46}$ GeV^{-4}	[15]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}(\mathring{c}^{(8)}_{\mu\tau})\rvert, \lvert\mathrm{Im}(\mathring{c}^{(8)}_{\mu\tau})\rvert$ $< 5.2 \times 10^{-45}$ GeV^{-4} (99% C.L.) $< 1.4 \times 10^{-45}$ GeV^{-4} (90% C.L.)	this work

- SuperK results too, and new 8+ year IceCube measurement on the way

Sidereal effects

- LIV may result in preferred direction of Universe
  - Terrestrial physics would then depend on current orientation of Earth w.r.t. this direction
  - Expect sidereal variation in atmospheric neutrino flavour transitions



- Old (2010) IceCube search (PhysRevD.82.112003), not revisited since
- Synergy in testing with spatially separated detectors (e.g. IceCube + DUNE)

CPT violation

CPT violation (CPT-V)

- **CPT symmetry –** *Physics is unchanged under combined C (charge), P (parity) and T (time) transformations*

- CPT proven to hold in a local quantum field theory, if:
  - It is unitary
  - Lorentz invariance holds
  - Space-time is flat

All potentially violated by quantum gravity → CPT violation?

Information loss in virtual black holes

Fluctuating space-time metric

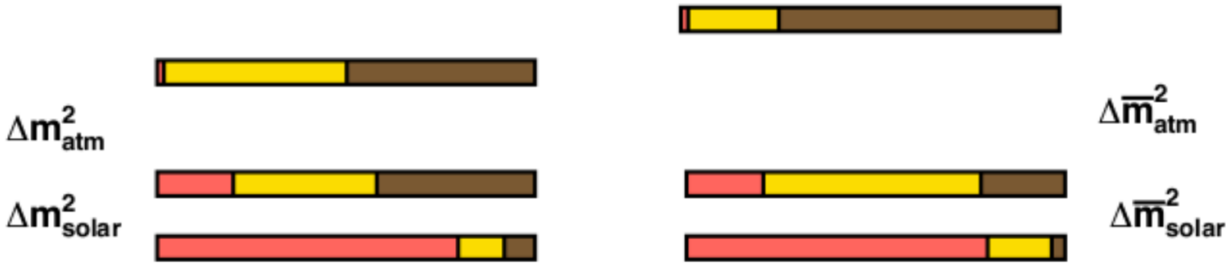
LIV

- Phenomenology: Differing particle vs antiparticle properties
  - e.g. mass, lifetime, …

CPT violation in neutrinos

- CPT-V could produce differing neutrino vs antineutrino mixing angles and/or mass splittings

Example (arXiv:1712.01714)

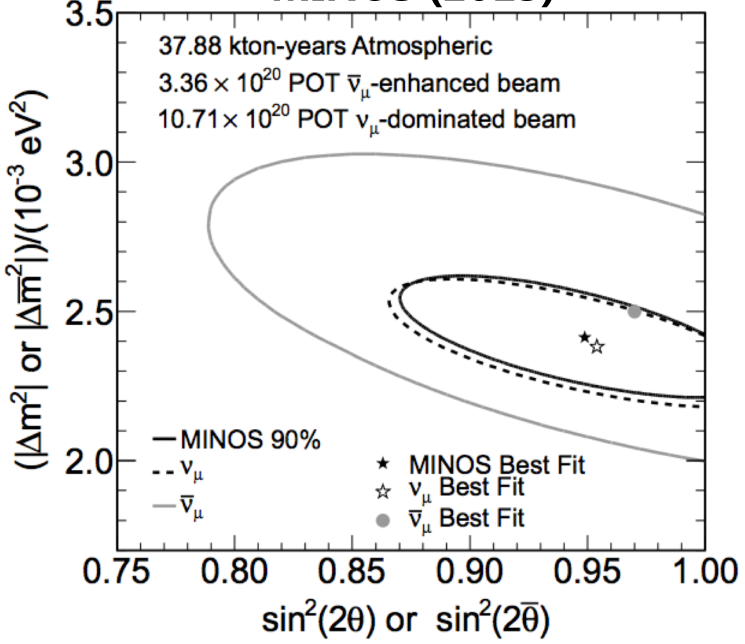


- Neutrino oscillations sensitive to very small (≪eV) mass differences

  → excellent CPT-V search channel

- Searches with SuperK, MINOS and global data
  - Sensitivity studies for DUNE, HyperK and ESSnuSB

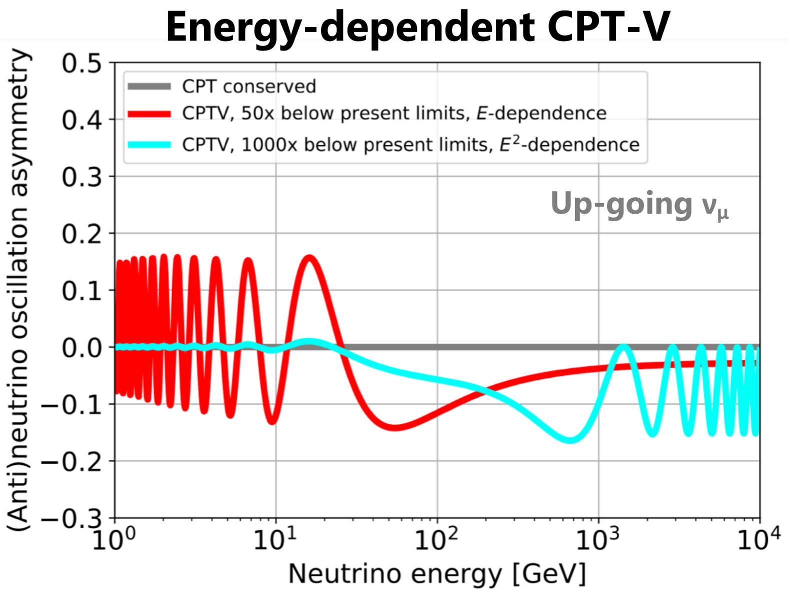
MINOS (2013)



Atmospheric neutrino CPT-V

- As for other Planck scale physics signals, CPT-V effects potentially suppressed at low energies, motivating:
  - High energy atmospheric neutrino tests (e.g. IceCube)
  - Tests of energy-dependent CPT-V phenomenology

Neither done so far



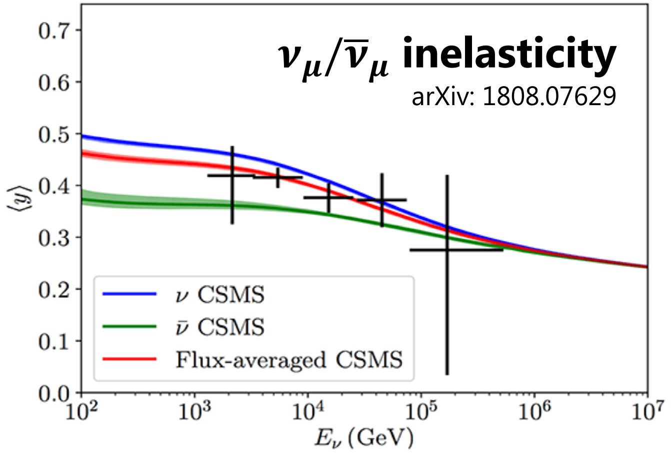
Atmospheric neutrino CPT-V

- As for other Planck scale physics signals, CPT-V effects potentially suppressed at low energies, motivating:
  - High energy atmospheric neutrino tests (e.g. IceCube)
  - Tests of energy-dependent CPT-V phenomenology

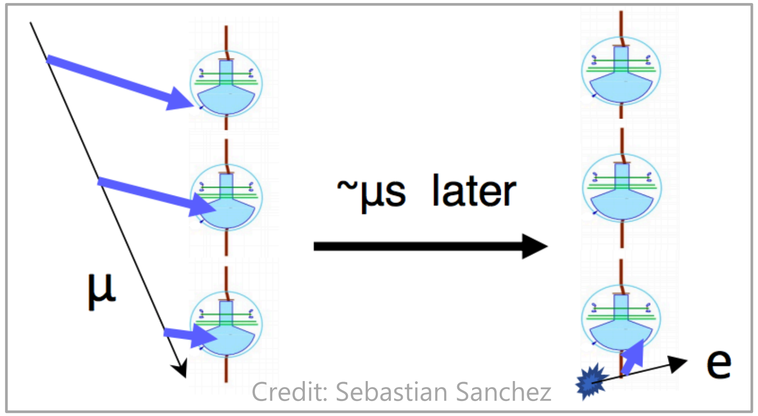
  } **Neither done so far**

- Can in principal statistically separate $\nu_\mu/\bar{\nu}_\mu$ samples using indirect information
  - Inelasticity
  - Michel electron tagging

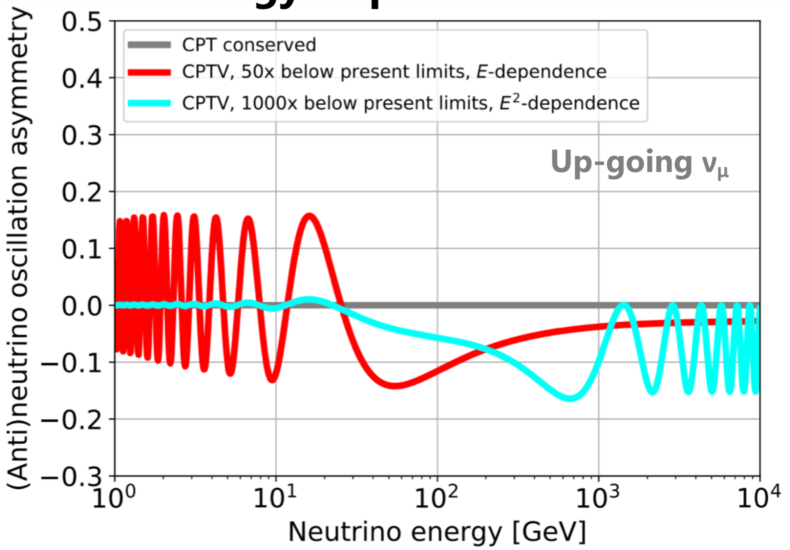
  } **IceCube Upgrade!**



Michel electron tagging



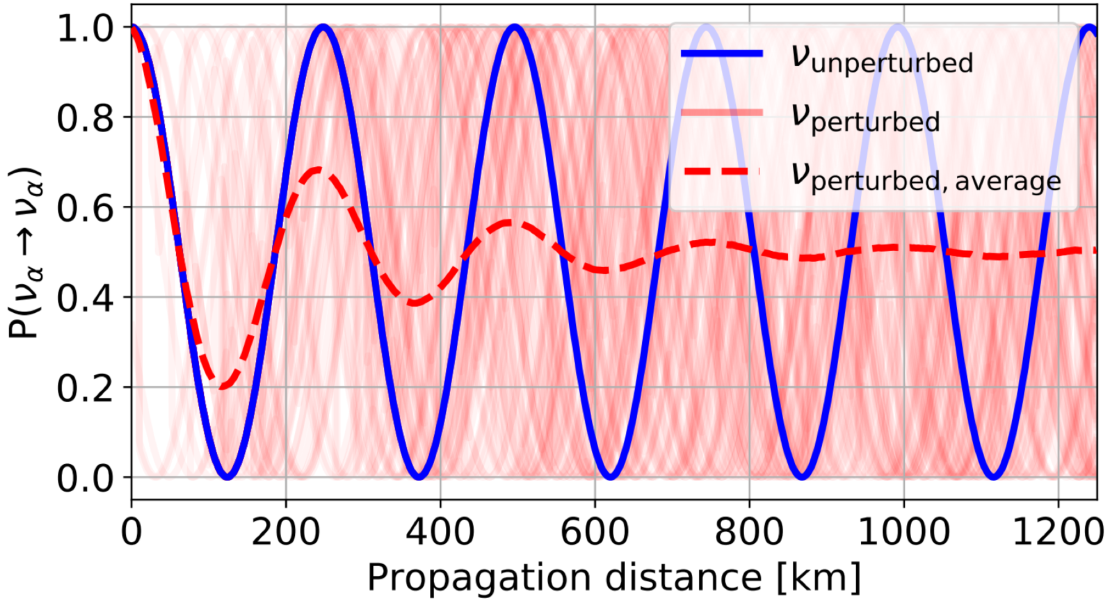
Energy-dependent CPT-V



Decoherence

Neutrino decoherence

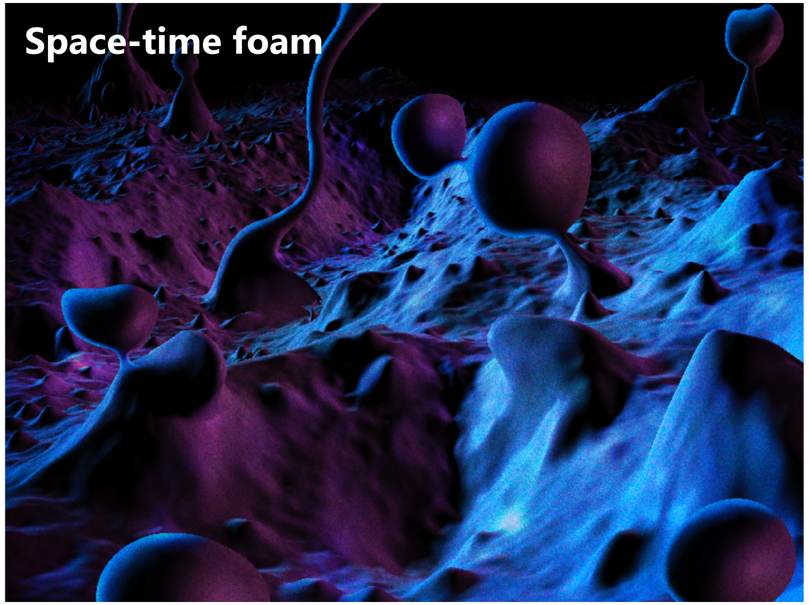
- Neutrino oscillations generally considered to be coherent
  - *The wavefunctions of two neutrinos of the same energy travelling the same path evolve identically*
- Not true for neutrinos propagating in a stochastic medium
  - Neutrino ensemble becomes increasingly out of phase over distance
  - Neutrino decoherence → damping of neutrino oscillations



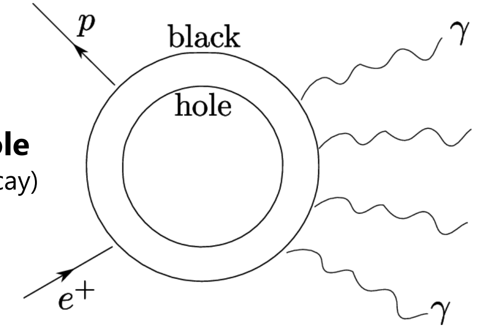
2-flavor toy model
(not realistic parameters)

What stochastic background?

- Quantum gravity → Planck scale space-time fluctuations: **space-time foam**
- Fluctuating space-time curvature → fluctuating travel time/distance between two points: **lightcone fluctuations**
  - Velocity fluctuations (stochastic LIV) also considered
- Also potential for **virtual black hole** (VBH) formation
  - QG analogue of vacuum polarisation
  - Space-time permeated with Planck scale black holes
  - Propagating neutrinos undergo stochastic (flavour violating?) interactions with VBH background



Virtual black hole
(inducing proton decay)



Decoherence formalism

- Neutrino decoherence generally treated as **open quantum system**
  - Neutrino and environment considered as single quantum system

- State evolution using **Lindblad master equation**:

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

$$\rho = \sum_j p_j \left|\psi_j\right\rangle \left\langle\psi_j\right|$$

State represented using **density matrices**

Standard oscillations

Decoherence operator

New physics here!

Decoherence formalism

- Neutrino decoherence generally treated as **open quantum system**
  - Neutrino and environment considered as single quantum system

- State evolution using **Lindblad master equation**:

$$\dot{\rho} = -i[H,\rho] - \mathcal{D}[\rho]$$

$$\mathcal{D}[\rho] = \begin{pmatrix} 0 & \Gamma_{21}\rho_{12} & \Gamma_{31}\rho_{13} \\ \Gamma_{21}\rho_{21} & 0 & \Gamma_{32}\rho_{23} \\ \Gamma_{31}\rho_{31} & \Gamma_{32}\rho_{32} & 0 \end{pmatrix}$$

Most studies use a general form for the decoherence operator, characterised by damping parameters, Γ

Decoherence formalism

- Neutrino decoherence generally treated as **open quantum system**
  - Neutrino and environment considered as single quantum system

- State evolution using **Lindblad master equation**:

$$\dot{\rho} = -i[H, \rho] - \mathcal{D}[\rho]$$

$$\mathcal{D}[\rho] = (D_{\mu\nu}\rho^{\nu})b^{\mu}$$

$$D = \begin{pmatrix} \Gamma_0 & \beta_{01} & \beta_{02} & \beta_{03} & \beta_{04} & \beta_{05} & \beta_{06} & \beta_{07} & \beta_{08} \\ \beta_{01} & \Gamma_1 & \beta_{12} & \beta_{13} & \beta_{14} & \beta_{15} & \beta_{16} & \beta_{17} & \beta_{18} \\ \beta_{02} & \beta_{12} & \Gamma_2 & \beta_{23} & \beta_{24} & \beta_{25} & \beta_{26} & \beta_{27} & \beta_{28} \\ \beta_{03} & \beta_{13} & \beta_{23} & \Gamma_3 & \beta_{34} & \beta_{35} & \beta_{36} & \beta_{37} & \beta_{38} \\ \beta_{04} & \beta_{14} & \beta_{24} & \beta_{34} & \Gamma_4 & \beta_{45} & \beta_{46} & \beta_{47} & \beta_{48} \\ \beta_{05} & \beta_{15} & \beta_{25} & \beta_{35} & \beta_{45} & \Gamma_5 & \beta_{56} & \beta_{57} & \beta_{58} \\ \beta_{06} & \beta_{16} & \beta_{26} & \beta_{36} & \beta_{46} & \beta_{56} & \Gamma_6 & \beta_{67} & \beta_{68} \\ \beta_{07} & \beta_{17} & \beta_{27} & \beta_{37} & \beta_{47} & \beta_{57} & \beta_{67} & \Gamma_7 & \beta_{78} \\ \beta_{08} & \beta_{18} & \beta_{28} & \beta_{38} & \beta_{48} & \beta_{58} & \beta_{68} & \beta_{78} & \Gamma_8 \end{pmatrix}$$

Decomposition in SU(N) basis also often used

Decoherence formalism

- Neutrino decoherence generally treated as **open quantum system**
  - Neutrino and environment considered as single quantum system

- State evolution using **Lindblad master equation**:

$$\dot{\rho} = -i[H, \rho] - \mathcal{D}[\rho]$$

- Energy-dependence typically added "by hand":

$$\Gamma(E) = \Gamma(E_0) \left(\frac{E}{E_0} \right)^n$$

w.r.t. arbitrary E (usually 1 GeV)

or

$$\Gamma(E) = \zeta_{\text{Planck}} \frac{E^n}{M_{\text{Planck}}^{n-1}}$$

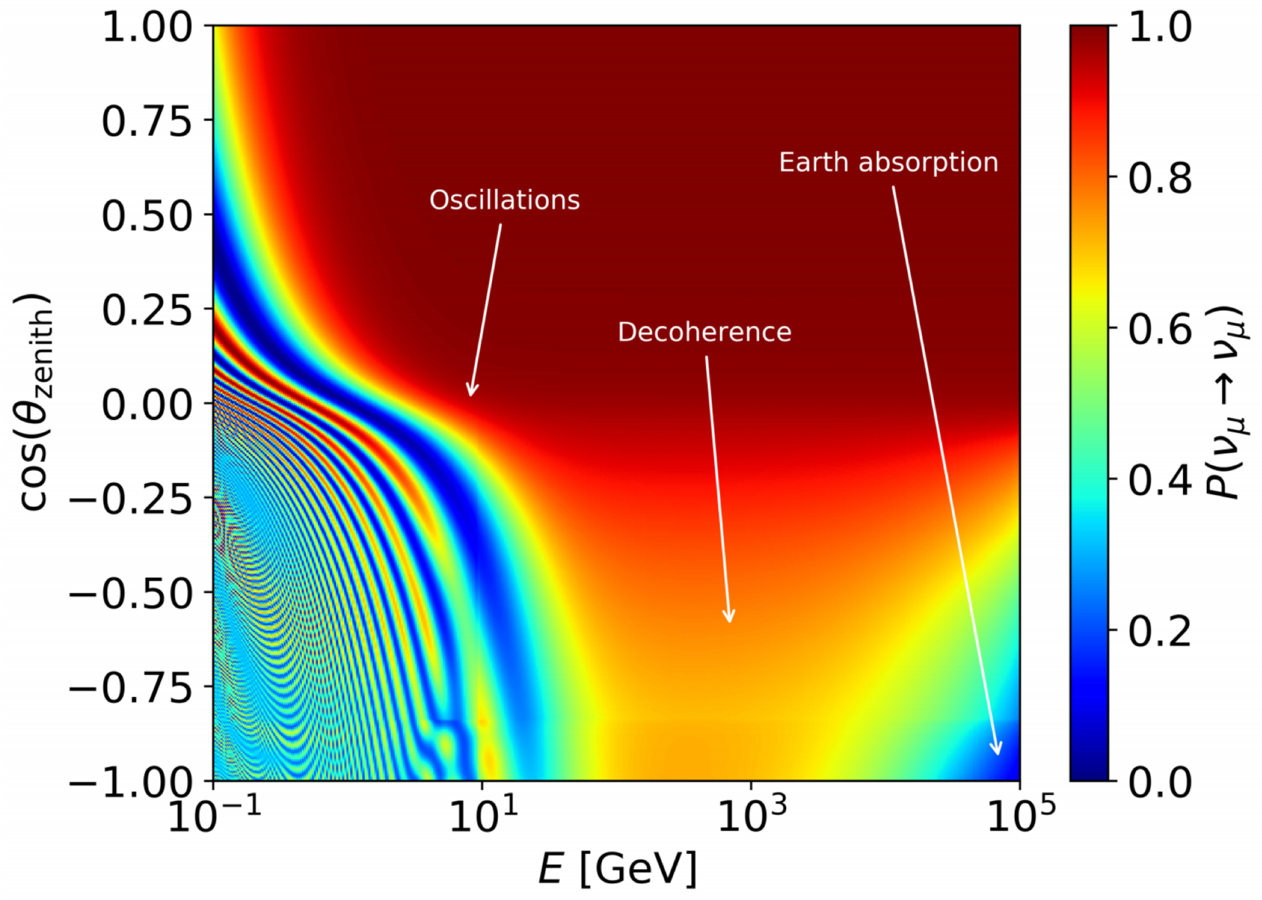
w.r.t. Planck scale

"Natural" expectation: $\zeta \sim \mathcal{O}(1)$

TS, M Jensen. PhysRevD.102.115003

Atmospheric neutrino signal

- Signal is damping of neutrino flavour transitions → increases with baseline



Example scenario 1:

Flavour violating ν-VBH interactions

Energy-independent

Signal across all E

(IceCube + DUNE synergy)

TS, M Jensen. PhysRevD.102.115003

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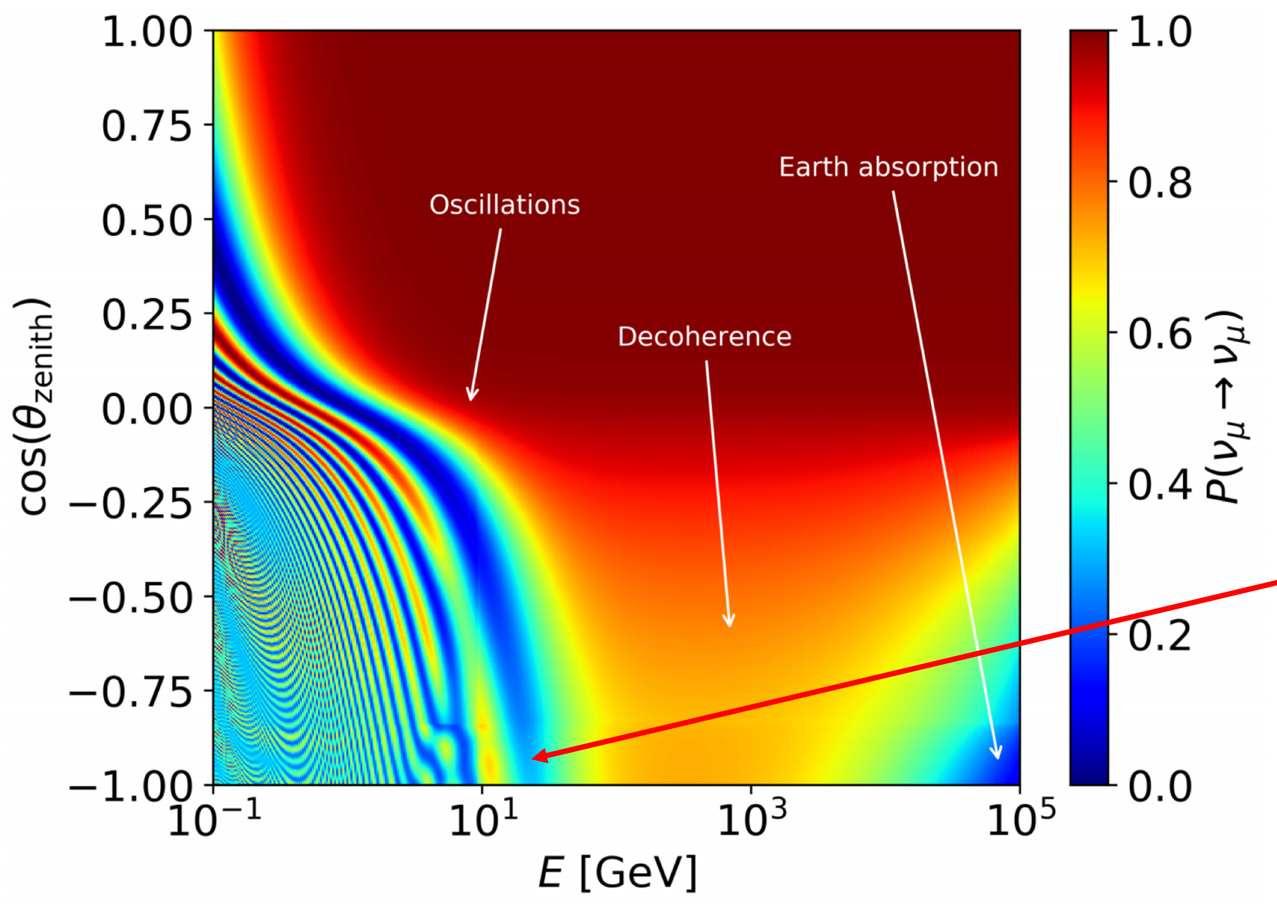

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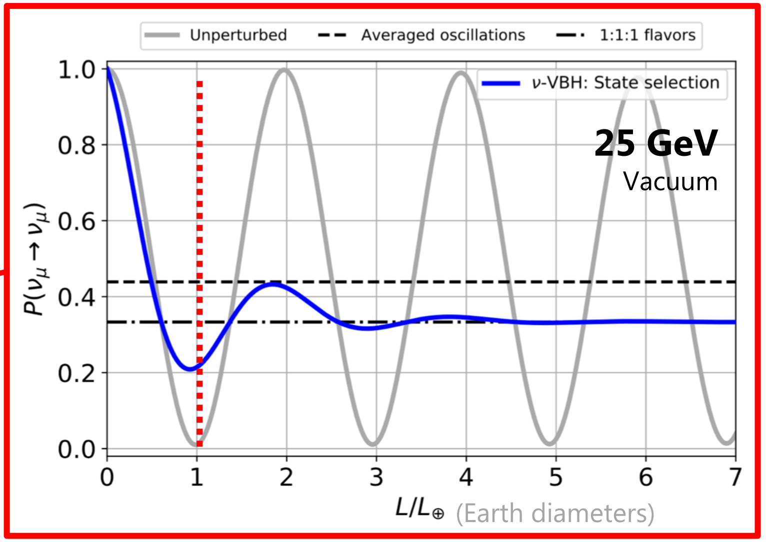

Standard oscillations for Earth crossing neutrinos weakened

TS, M Jensen. PhysRevD.102.115003

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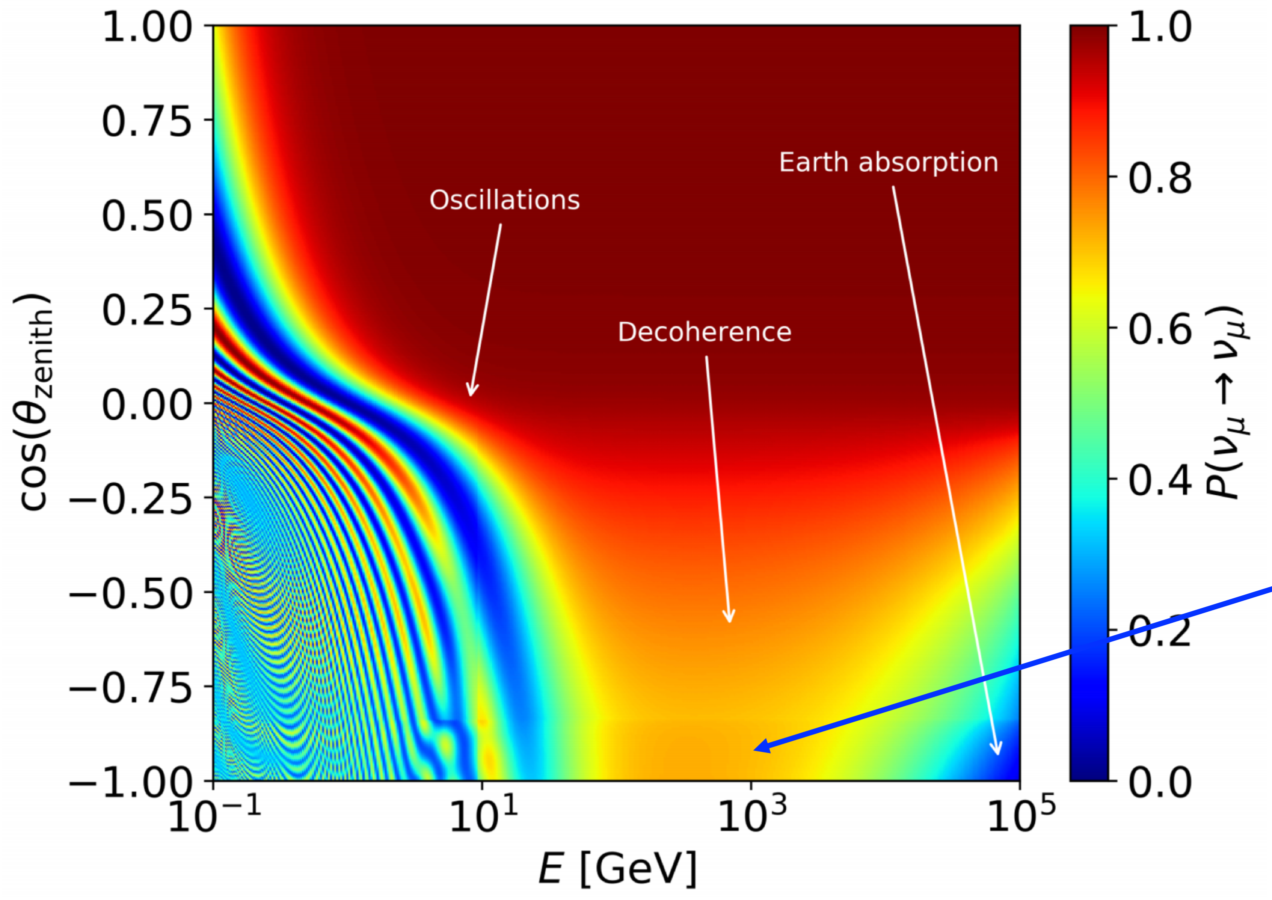

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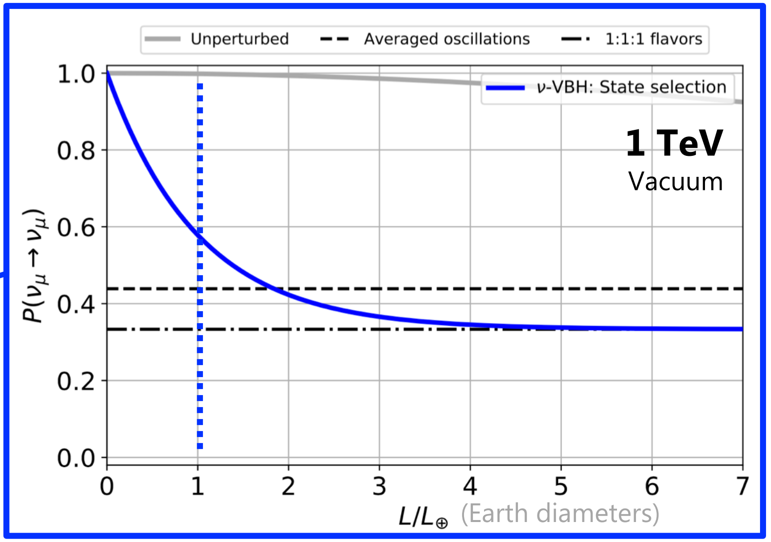

Flavour transitions outside of standard oscillation region

TS, M Jensen. PhysRevD.102.115003

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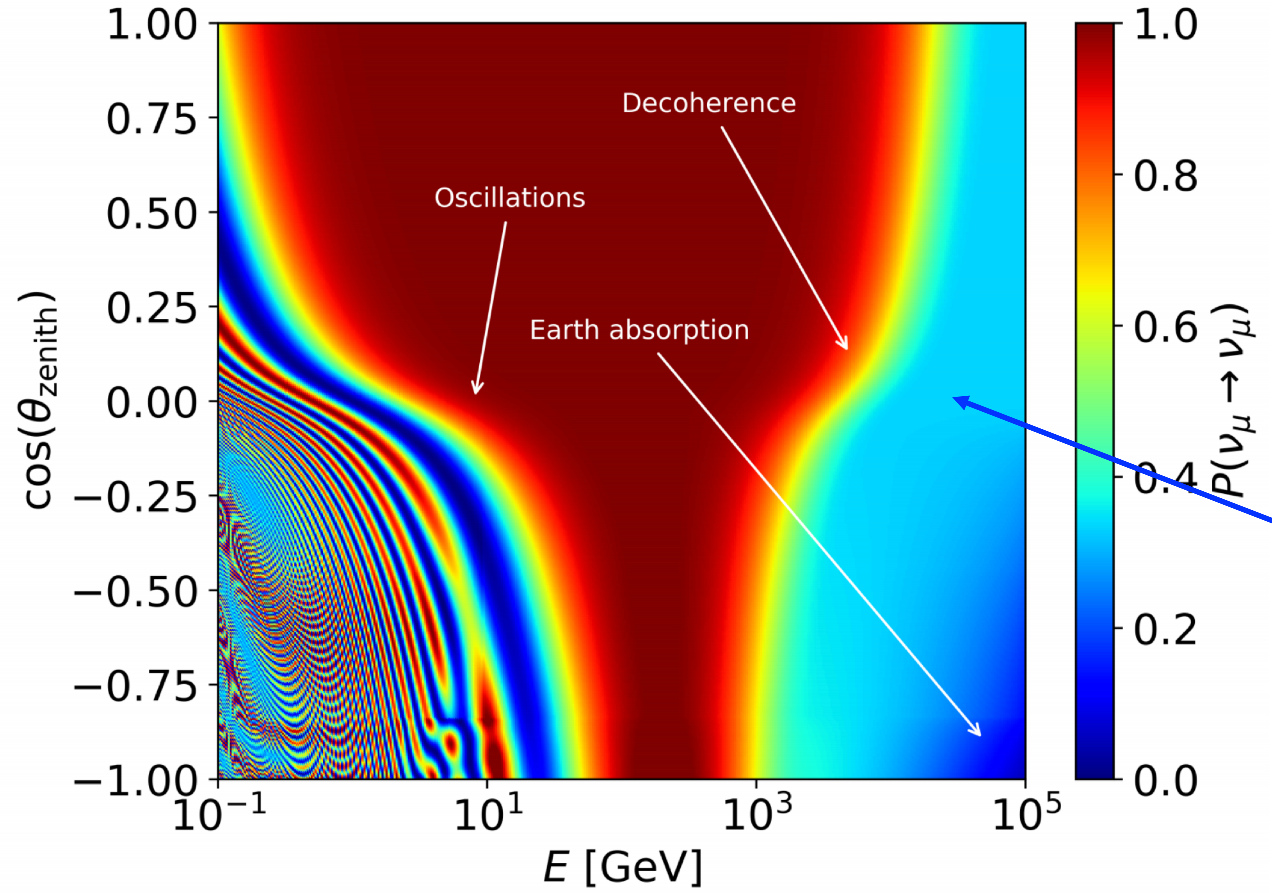
- Signal is damping of neutrino flavour transitions → increases with baseline



Example scenario 2:

Flavour violating ν-VBH interactions

E² energy-dependence

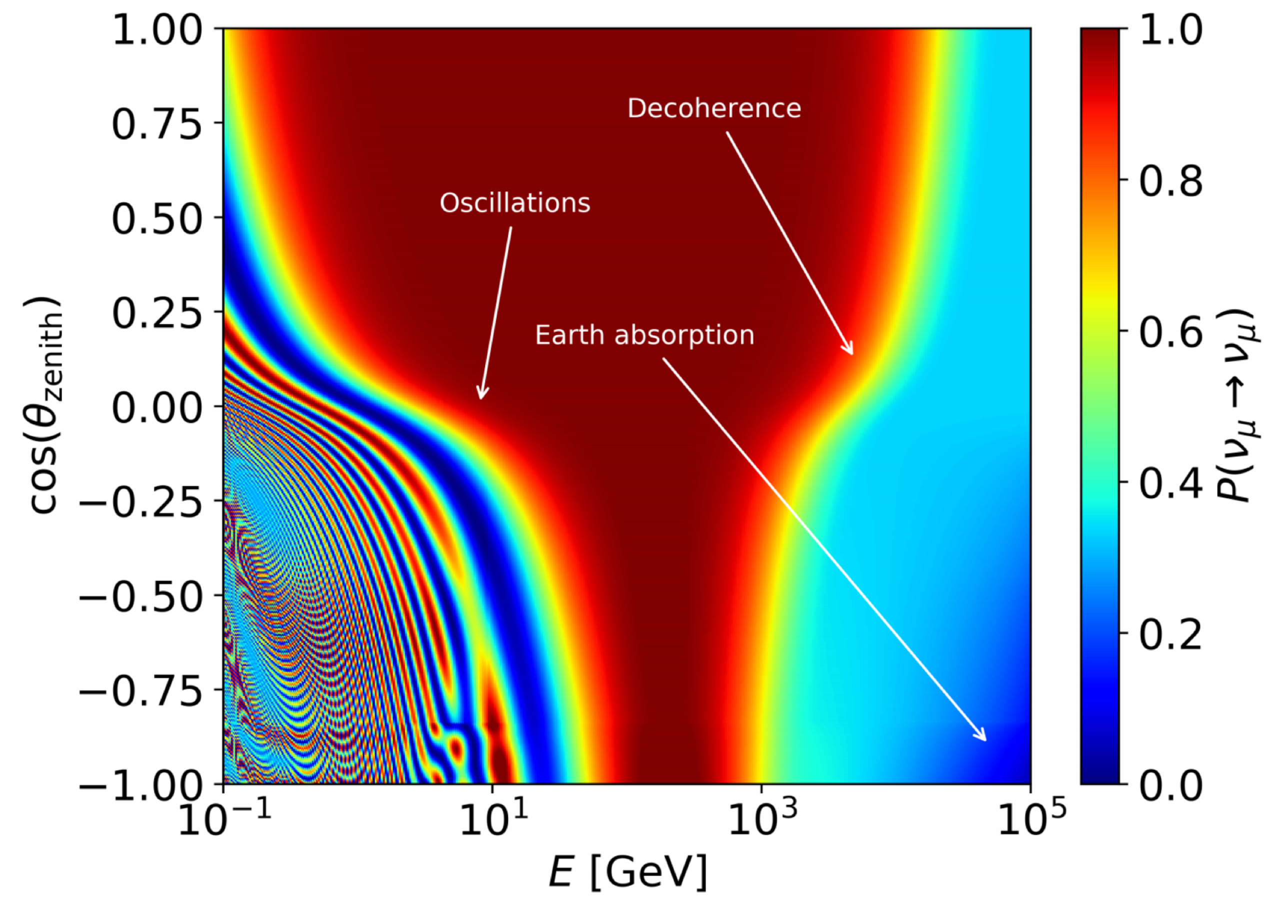
High-energy flavour transitions outside of standard oscillation region, even for smaller baselines

Saturates at $\upsilon_e : \upsilon_\mu : \upsilon_\tau = 1:1:1$

TS, M Jensen. PhysRevD.102.115003

Atmospheric neutrino signal

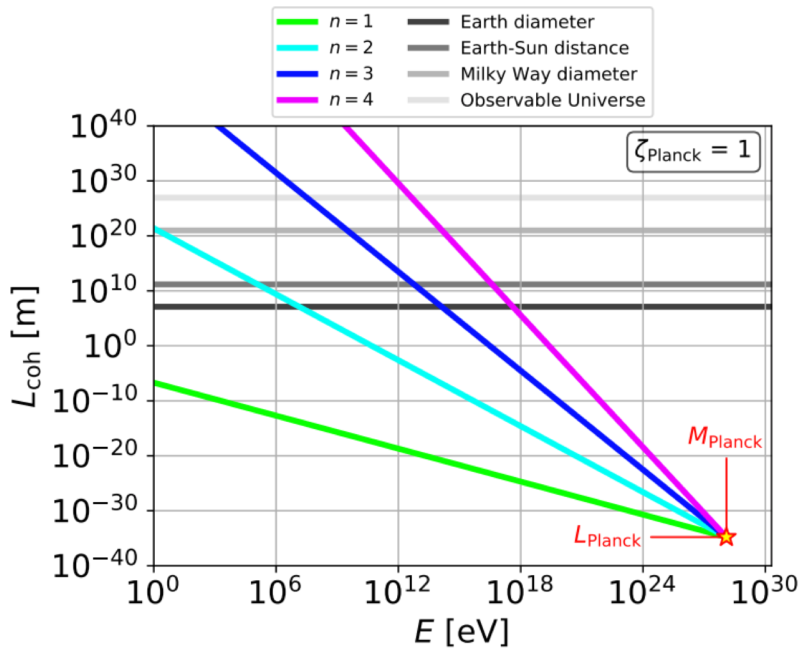
- Signal is damping of neutrino flavour transitions → increases with baseline



Example scenario 2:

Flavour violating ν-VBH interactions

E^2 energy-dependence



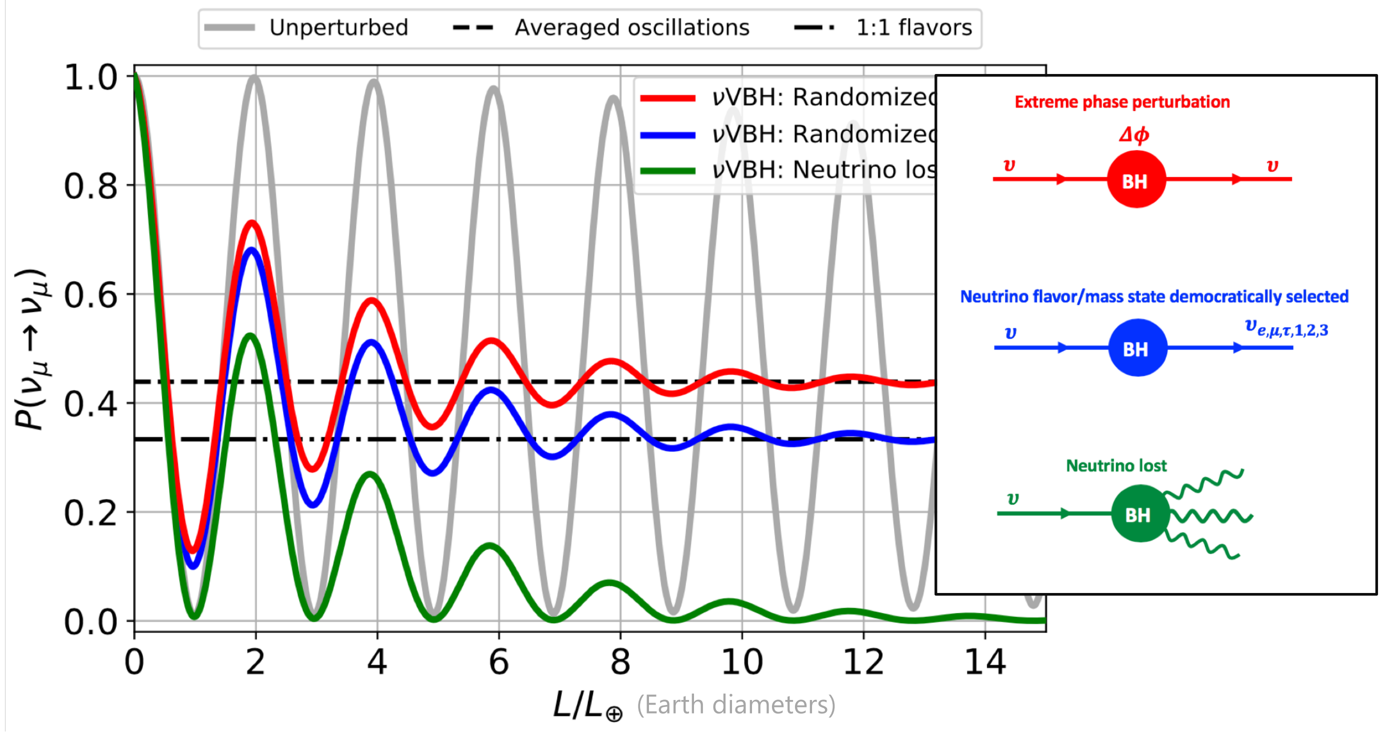
Sensitivity to "natural" Planck scale effects for $E^{\lesssim 3}$-dependence!

TS, M Jensen. PhysRevD.102.115003
TS, arXiv:2103.15313

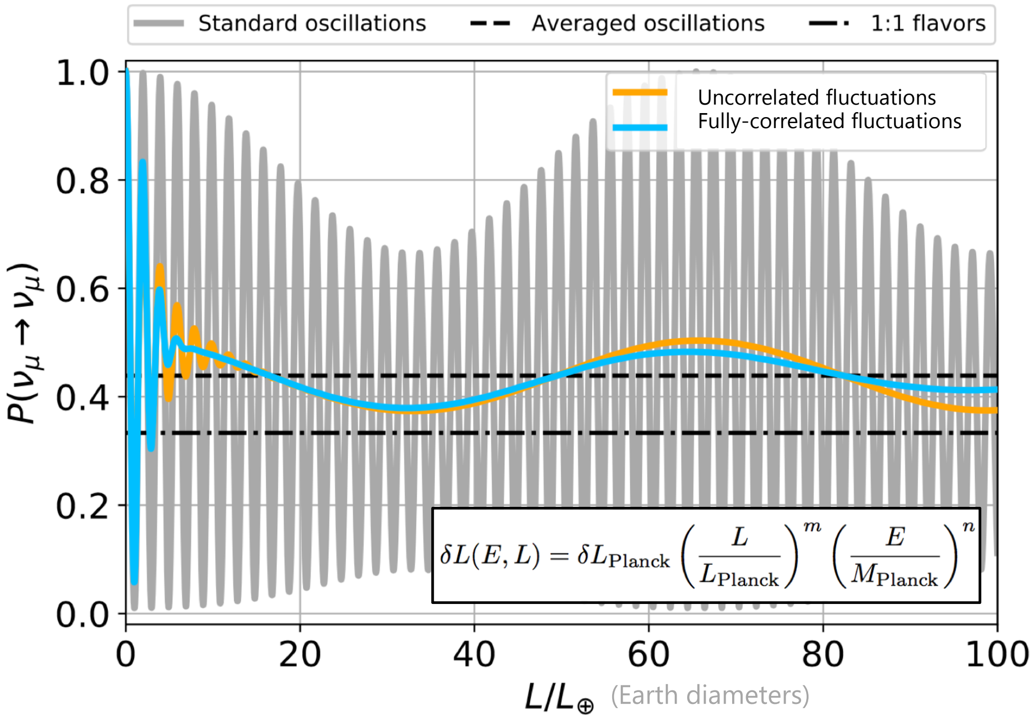
Other scenarios

- Rich decoherence phenomenology depending on underlying microphysics
  - Final flavour, large baseline limit, atmospheric vs solar frequency relative damping, unitarity and energy- and distance-dependence depend on operator/scenario tested

ν – virtual black hole interactions

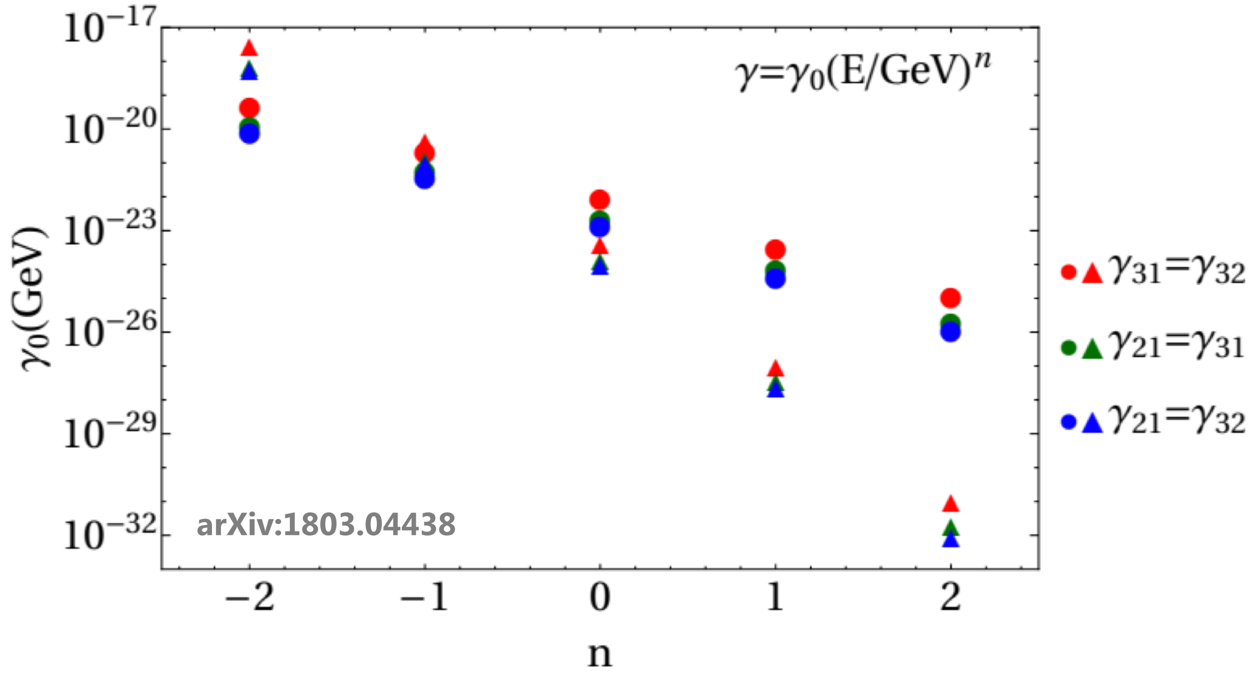


Lightcone fluctuations



Status of atmospheric neutrino searches

- Searches performed with both SuperK and IceCube
  - Most sensitive using 1 yr IceCube + 3 yr DeepCore public datasets
  - Coloma, Lopez-Pavon, Martinez-Soler, Nunokawa



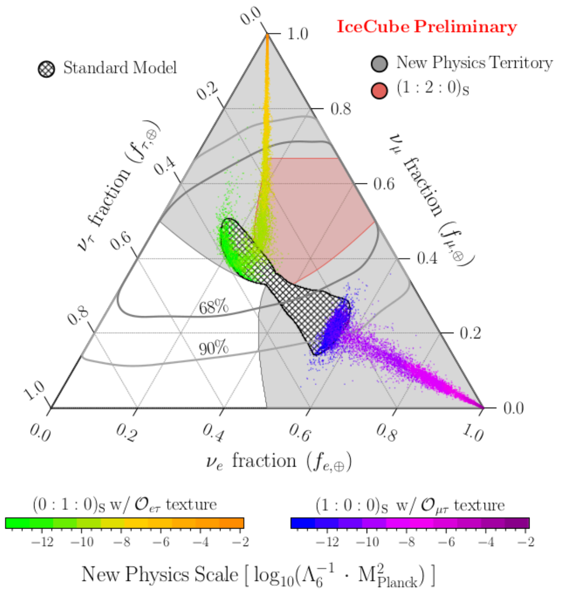
- 8+ yr IceCube collaboration searches underway
  - Testing both specific models and general operators

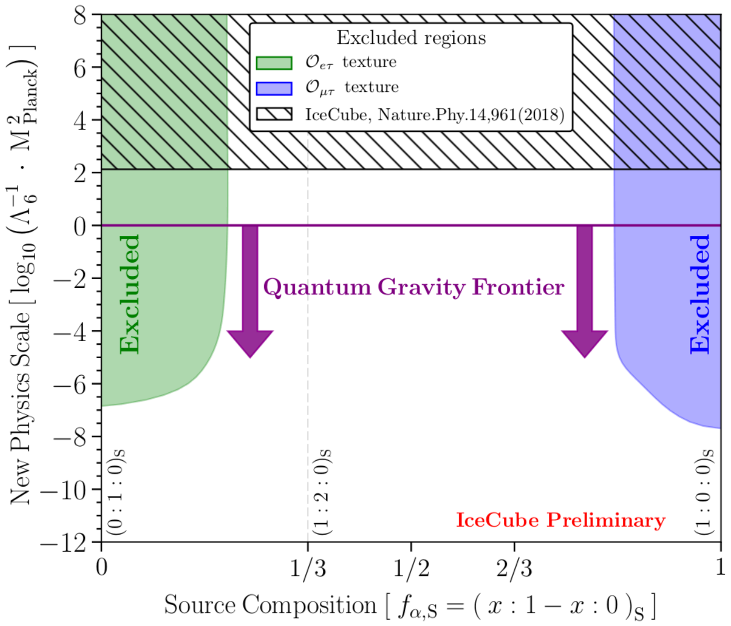
Wrapping up

Why not astrophysical neutrinos?

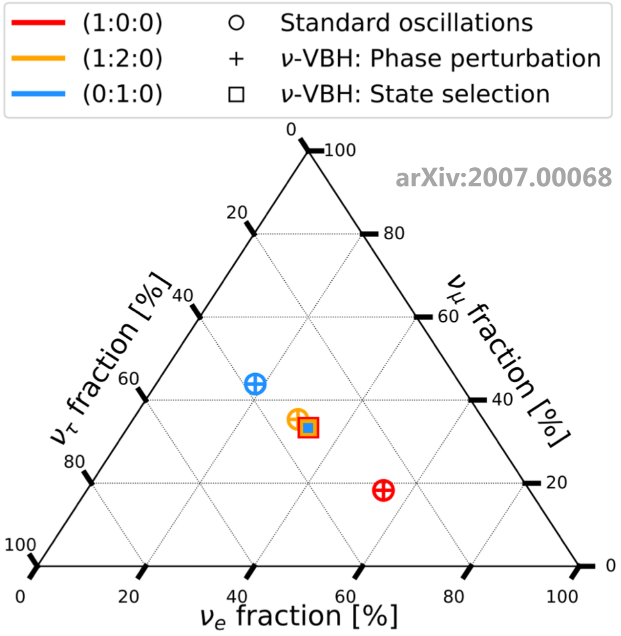
- The extremely high energies and baselines of the diffuse astrophysical neutrino flux is also a great testing ground for new physics
- However, poorly understood flux, incoherent nature of sources and low statistics make atmospheric neutrinos preferable in many cases

LIV





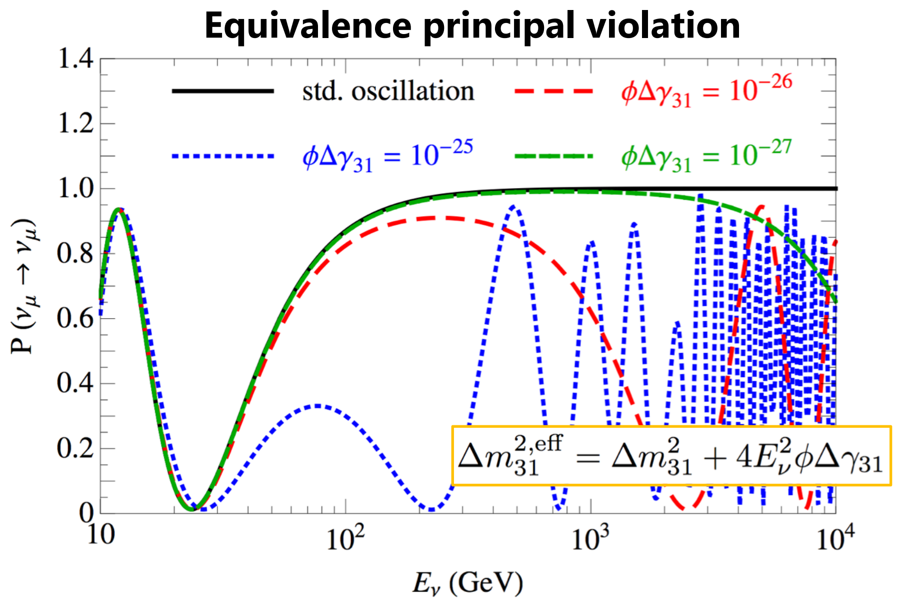
Decoherence

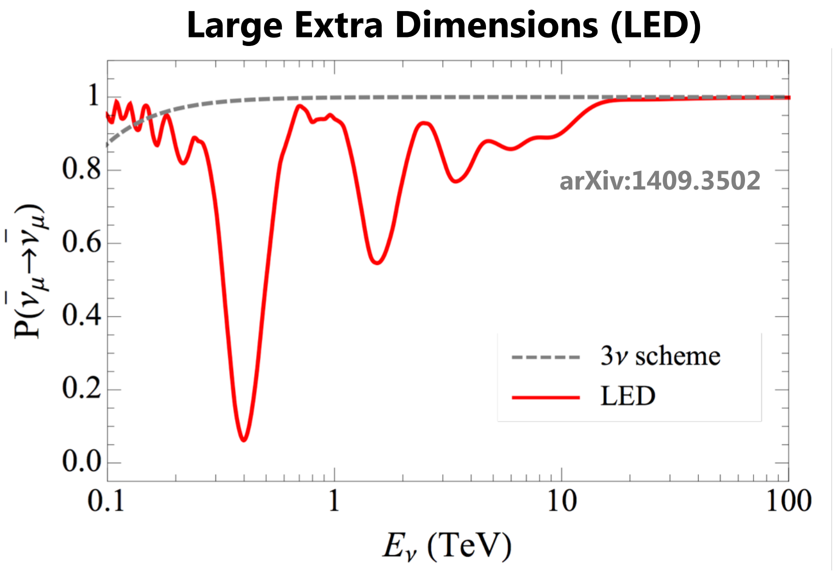


Other related topics

- Equivalence principal violation
  - Inertial mass ≠ gravitational mass
- Extra dimensions
  - RH neutrinos access in compactified dimensions
- Proton decay
  - Baryon number violation
- Quantum mechanical tests
  - Leggett-Garg Inequality, …
- ….

arXiv:1404.3608



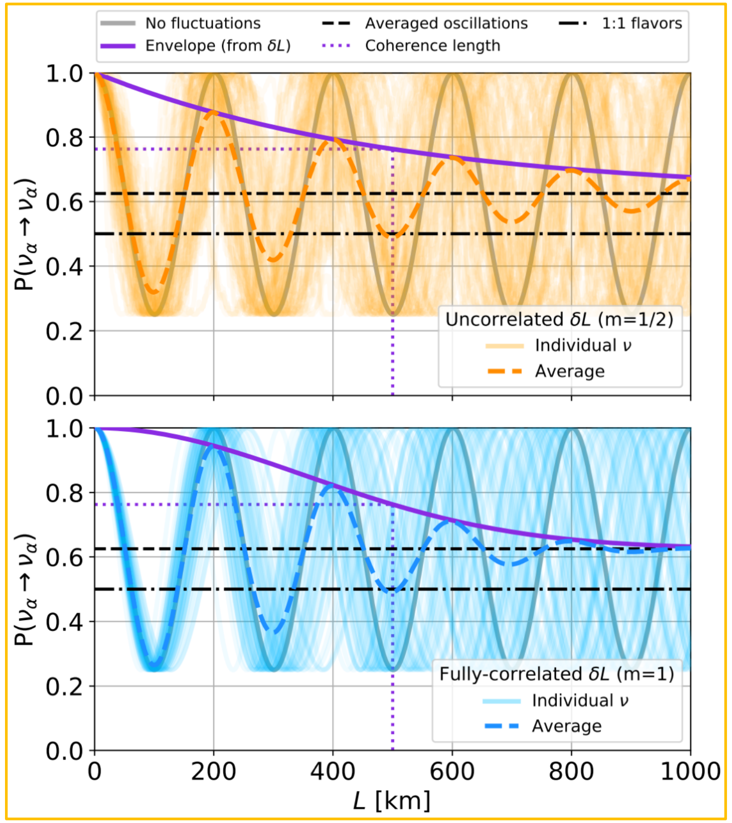


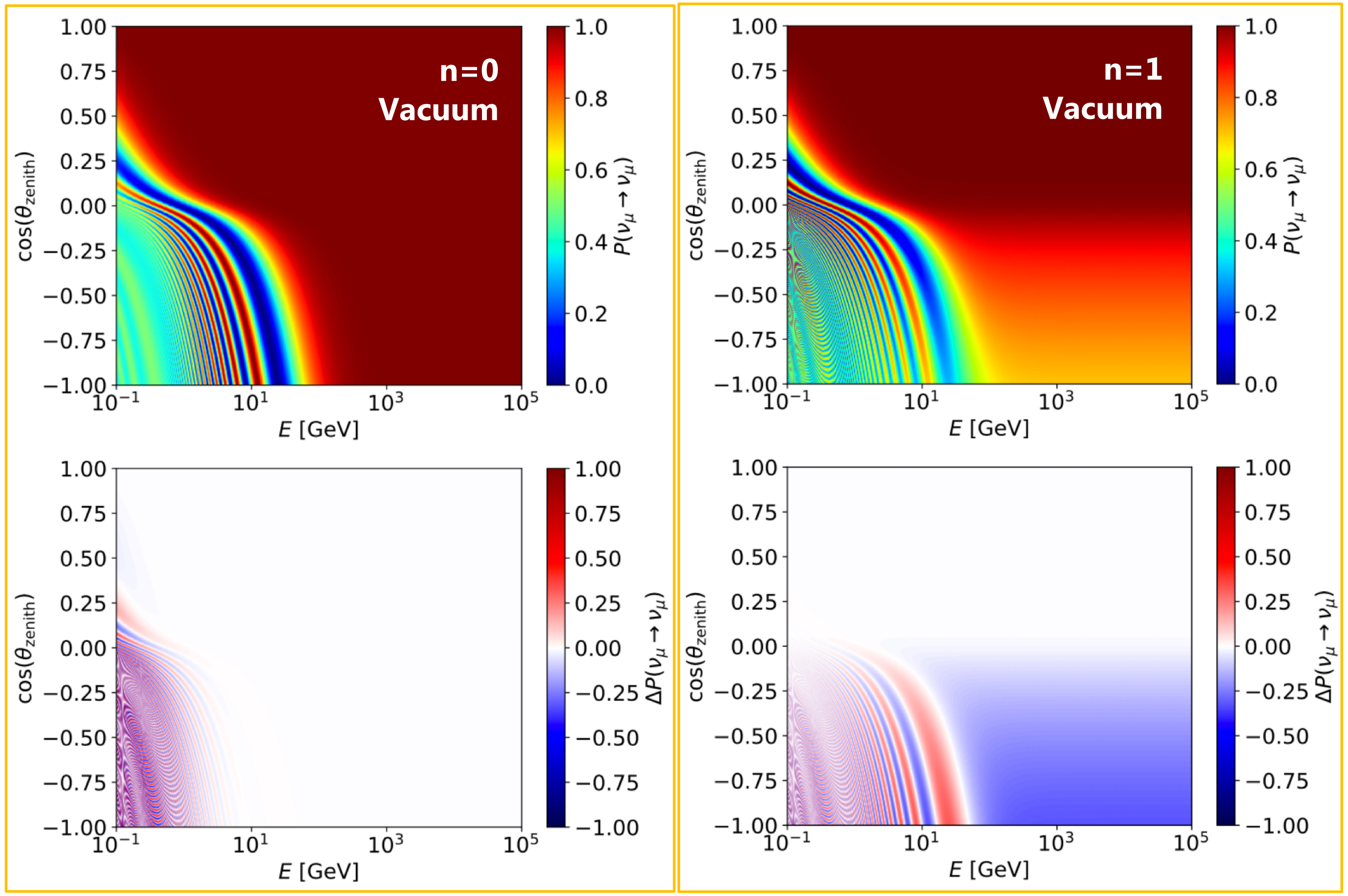
Summary

- Many fundamental properties of SM and GR potentially violated in high energy theories such as quantum gravity
  - Suppression at low energies
- Potentially produce sub-dominant modifications to neutrino oscillations
- The high energy, large baseline, high statistics oscillation measurements enabled by atmospheric neutrinos are ideally suited to these searches
  - Some of the strongest tests of Planck scale physics
- Underdeveloped field → plenty of scope for new measurements
- Broad signal energy range → DUNE+IceCube synergy

Back up

Lightcone fluctuations





$$\delta L(E,L) = \delta L_{\text{Planck}} \left(\frac{L}{L_{\text{Planck}}}\right)^{m} \left(\frac{E}{M_{\text{Planck}}}\right)^{n}$$

$$\mathcal{D}[\rho] = \frac{2m(\delta L_0)^2 L^{2m-1}}{L_0^{2m}} \left(\frac{E}{E_0}\right)^{2n} \begin{pmatrix} 0 & \frac{\rho_{21}}{(\eta\lambda_{21})^2} & \frac{\rho_{31}}{(\eta\lambda_{31})^2} \\ \frac{\rho_{21}}{(\eta\lambda_{21})^2} & 0 & \frac{\rho_{32}}{(\eta\lambda_{32})^2} \\ \frac{\rho_{31}}{(\eta\lambda_{31})^2} & \frac{\rho_{32}}{(\eta\lambda_{32})^2} & 0 \end{pmatrix}$$

arXiv:2103.15313