# Searching for new physics in atmospheric neutrino oscillations with IceCube

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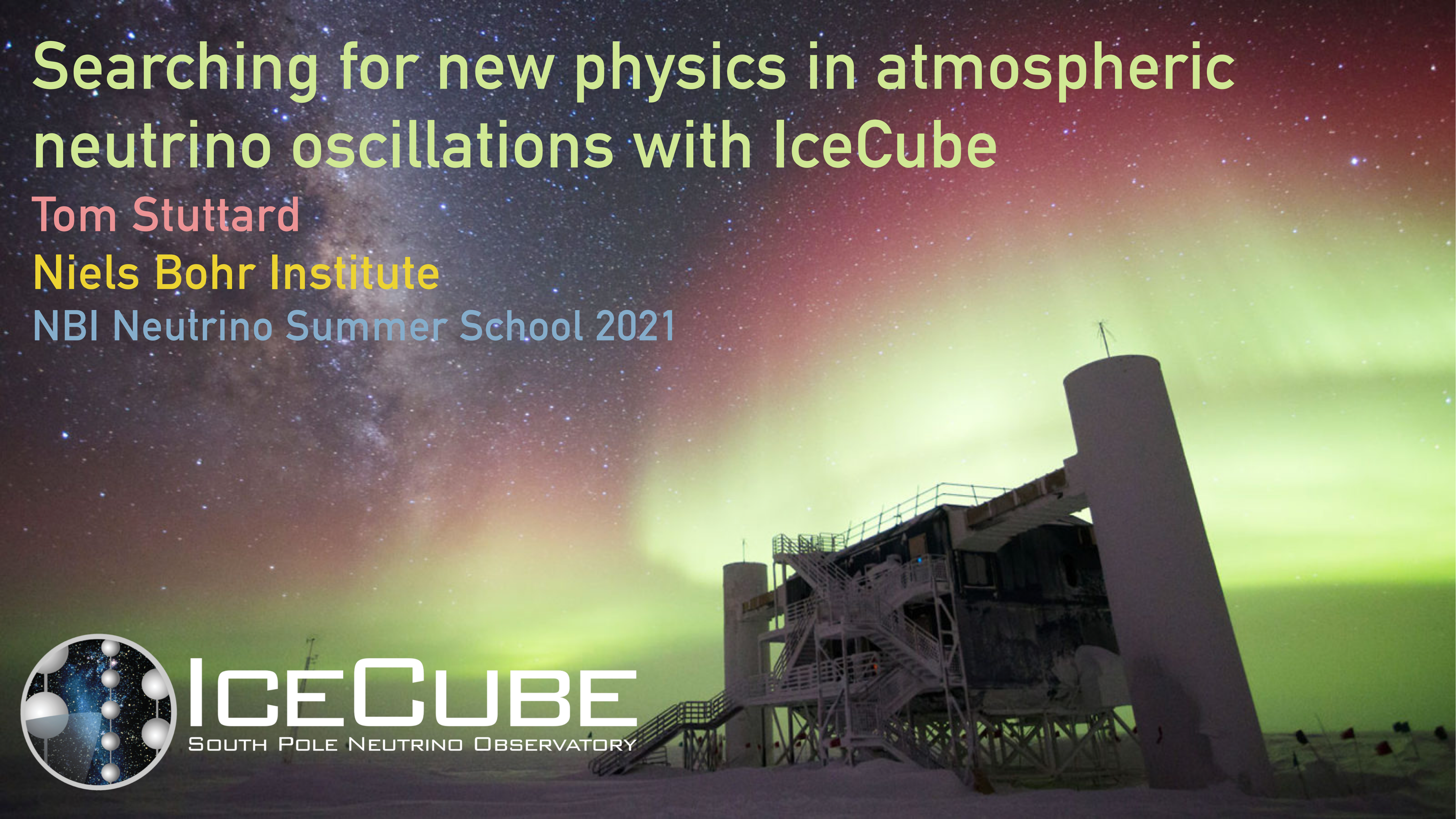
NBI Neutrino Summer School 2021

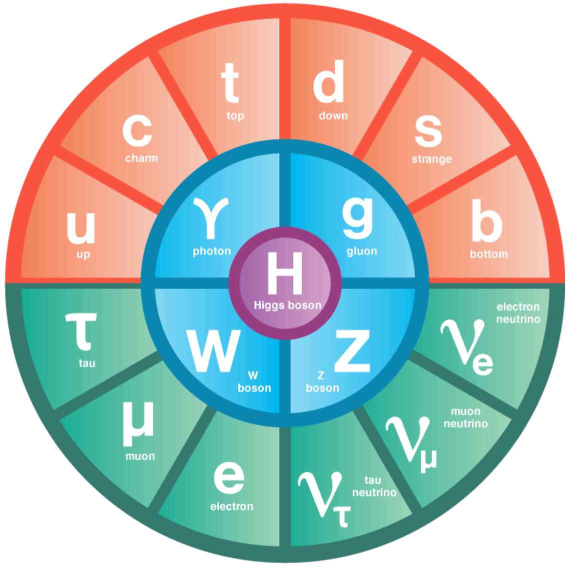


ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

# Why search for new physics?

- Our current understanding of the Universe described by:
  - Standard Model (SM)
  - Theory of General Relativity (GR)

- Despite the success of these theories, many open questions remain…



**Is gravity a quantum force?**

**What gives neutrinos mass?**

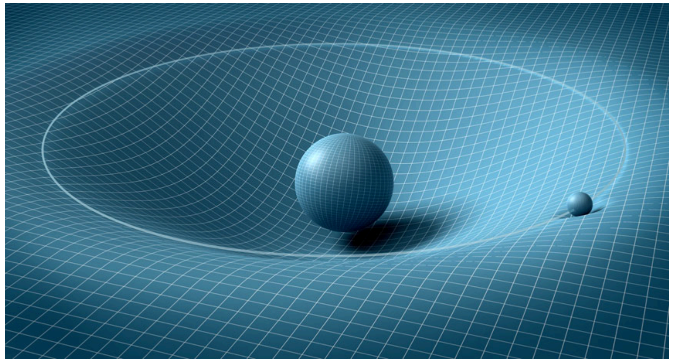
**Are there new particles/forces?**

**Why is gravity so weak?**

**What are Dark Matter/Energy?**

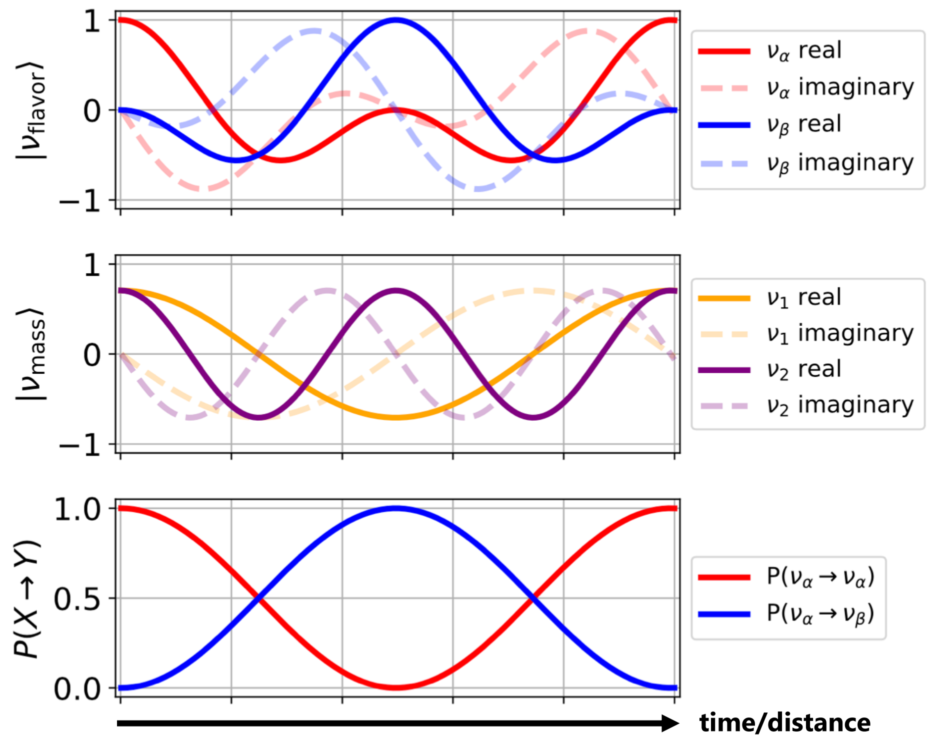
**Where is all the antimatter?**

**…**



# Why search for new physics in neutrino oscillations?

- Neutrinos propagate as a **superposition of ≥3 mass states**
  - Gives rise to oscillations
- **New physics can modify this superposition**
  - Results in modified/degraded oscillation effects
  - Neutrinos act as tiny quantum interferometers



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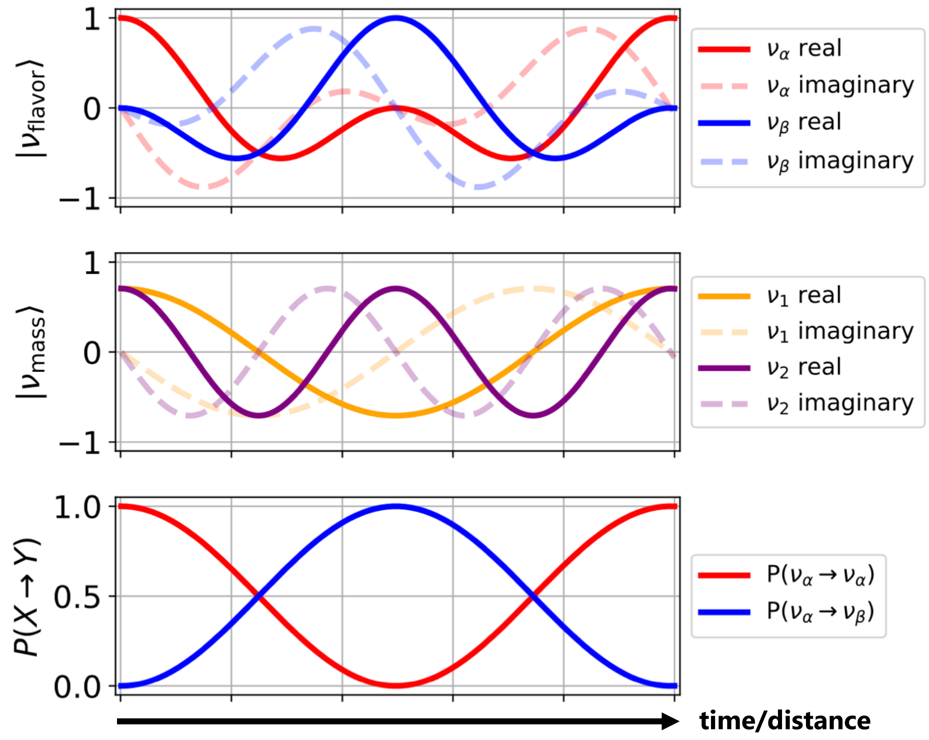
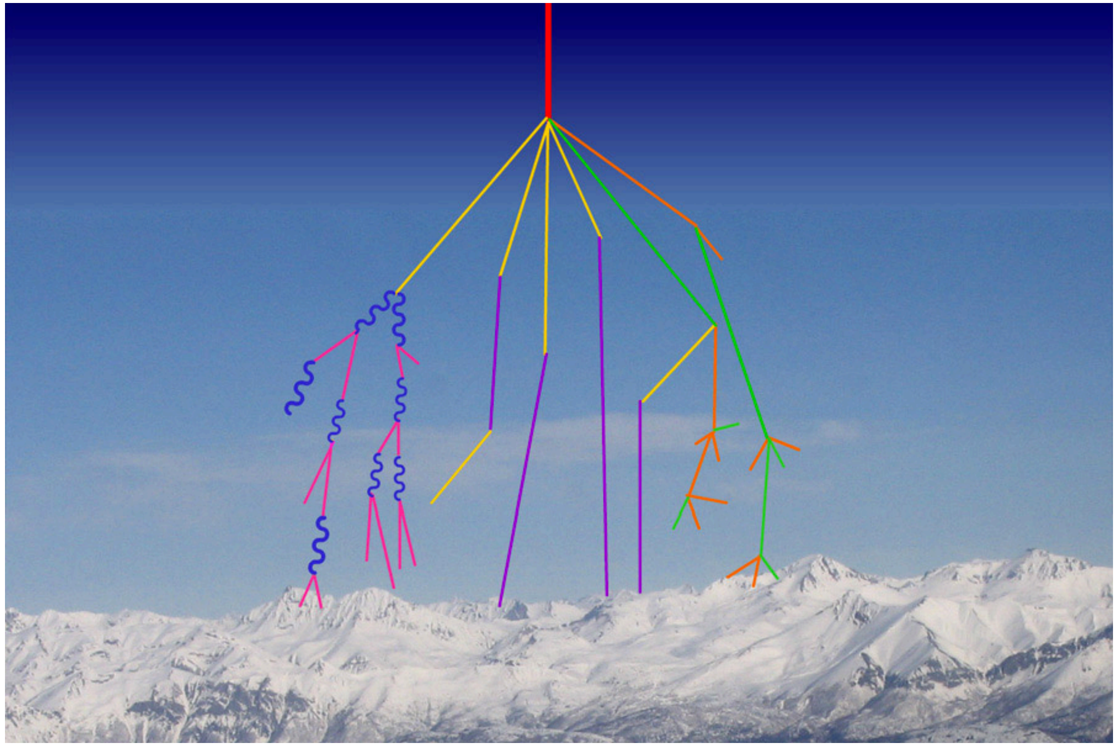
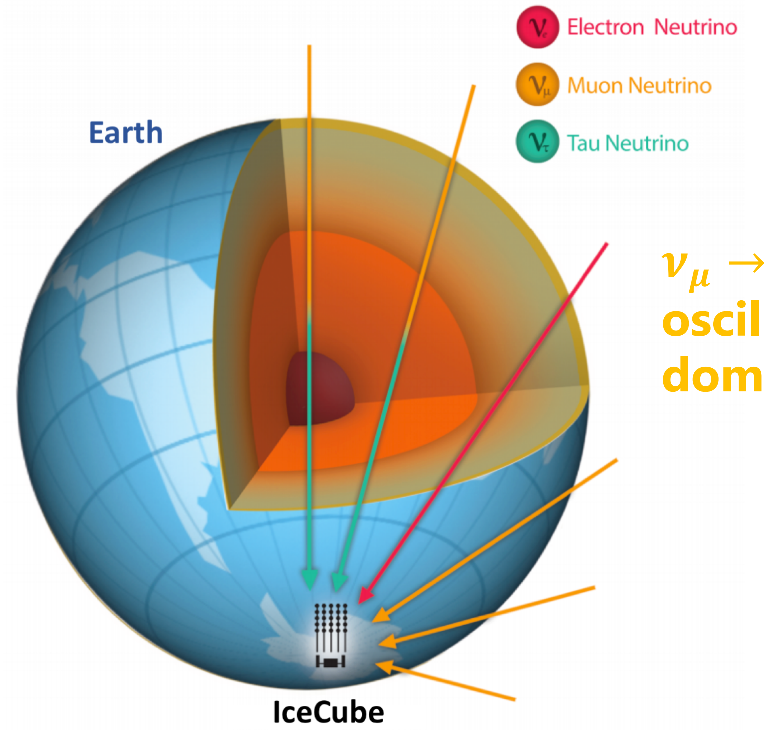


- Additionally, neutrinos:
    - Can **travel large distances** → weak signals can accumulate
    - Are **naturally available at high** (GeV-PeV) energies → access higher energy scale physics
    - Are **unaffected by EM and strong forces** → avoid diluting potential weak new physics

# Atmospheric neutrino oscillations

- Cosmic rays impacting the Earth’s atmosphere produce a **copious flux of high energy neutrinos**
- $\mathcal{O}$(mHz) neutrino rates detected by IceCube (GeV-PeV) → a $\nu$ every 15 mins!
- Neutrinos **oscillate as they cross the Earth** before detection





**$\nu_\mu \rightarrow \nu_\tau$ oscillations dominate**

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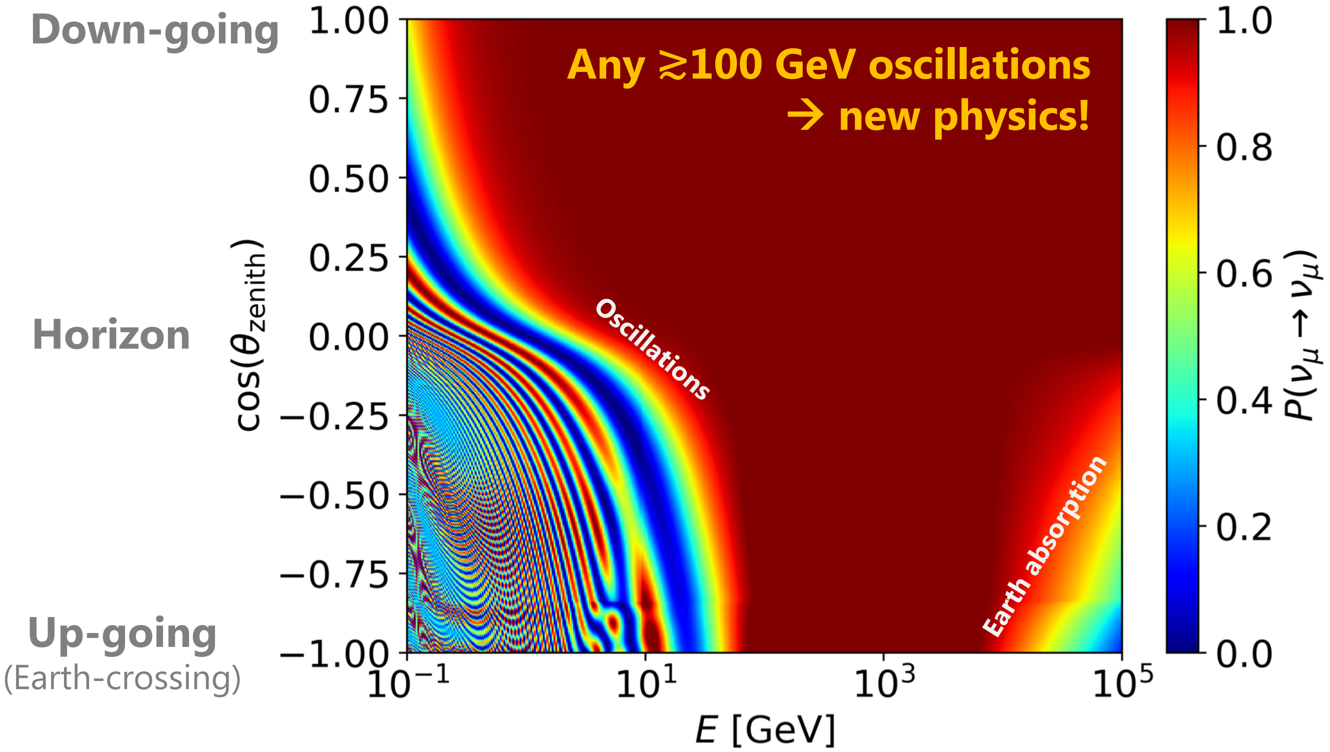

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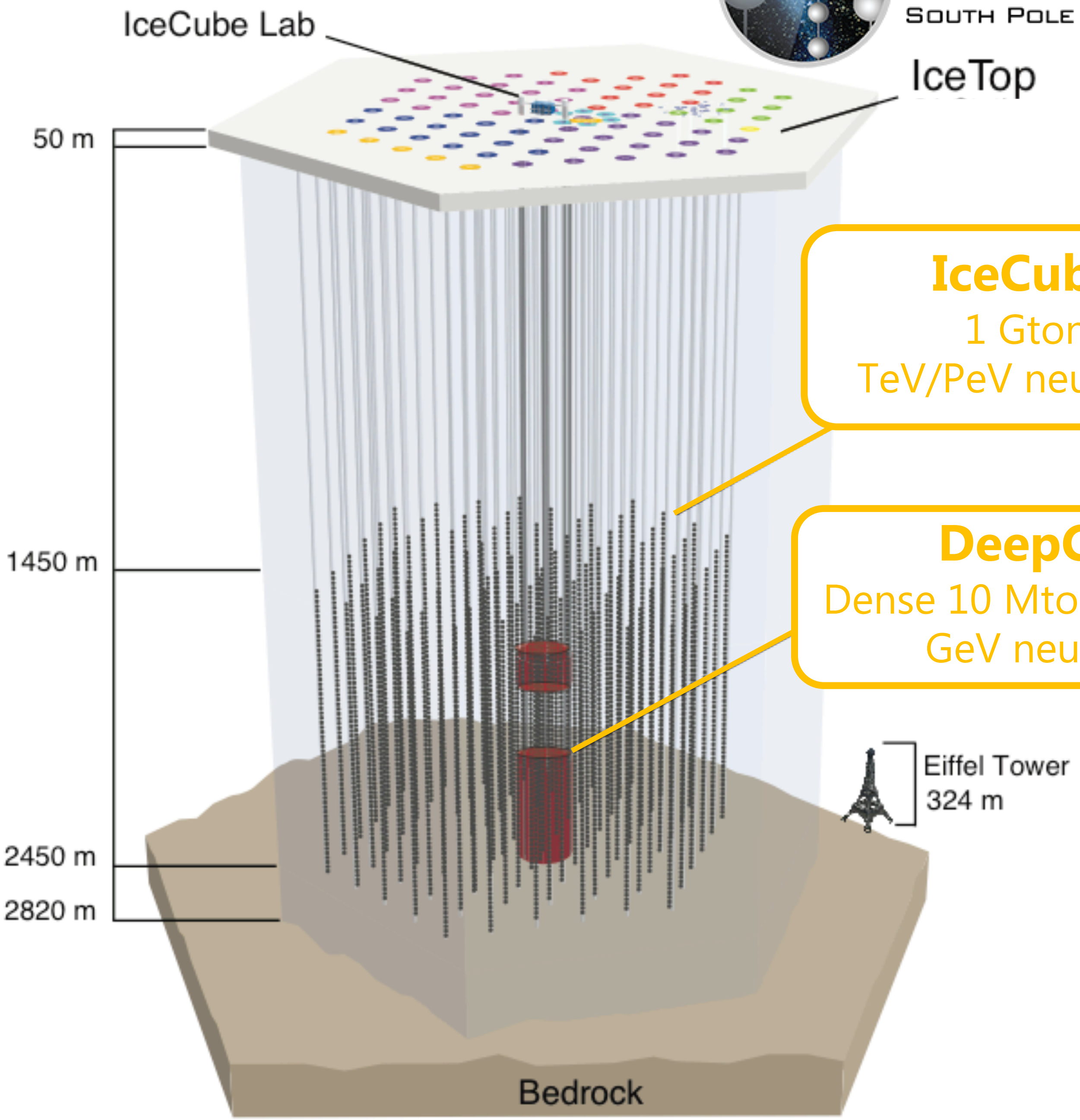
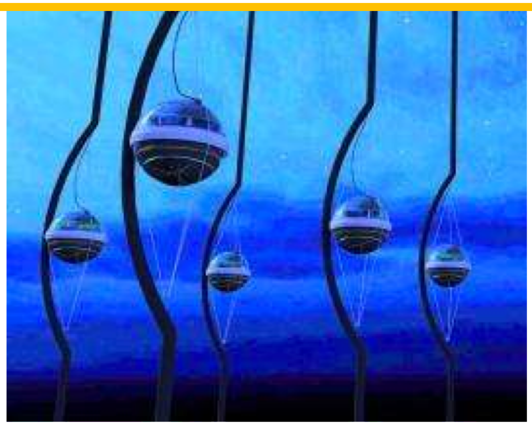


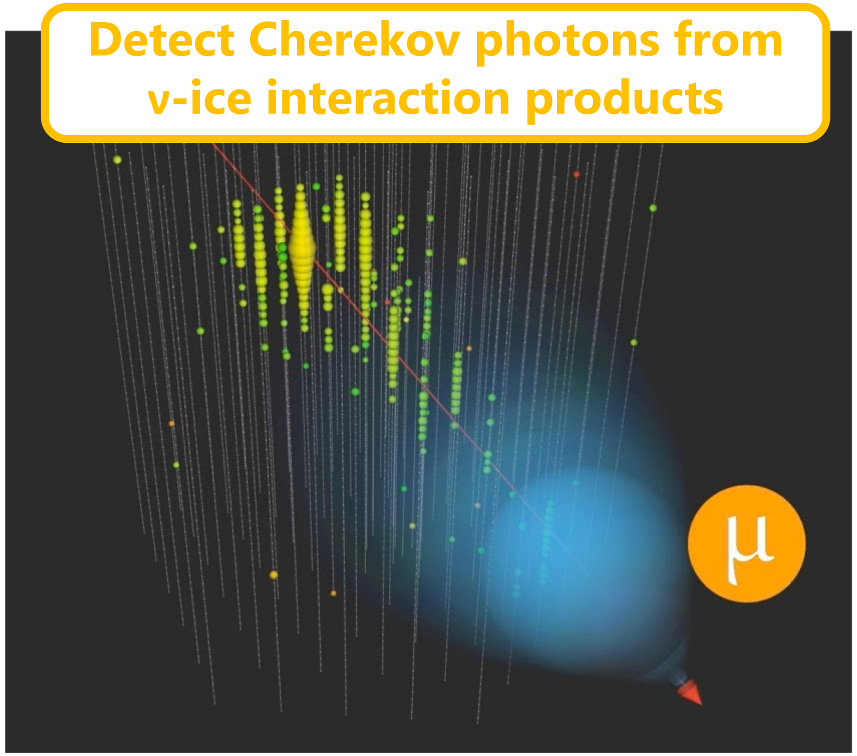
**IceCube**
1 Gton
TeV/PeV neutrinos

**DeepCore**
Dense 10 Mton sub-array
GeV neutrinos

**5160 PMTs in glacial ice (natural detection medium)**



**Detect Cherekov photons from ν-ice interaction products**



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5160 PMTs in glacial ice
(natural detection medium)

**See Jason Koskinen's talk yesterday for more details**

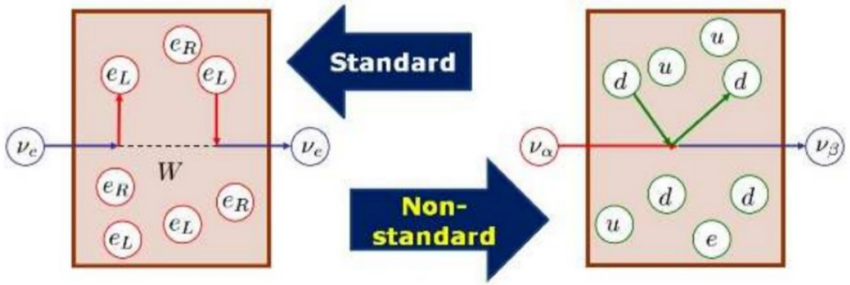
**For now, just need to know that IceCube is the world's highest energy, highest statistics atmospheric neutrino detector!**

# Non-Standard Interactions

# Non-Standard Interactions (NSI)

- **Neutrinos propagating in matter experience an effective potential**
  - Due to coherent CC forward scattering of $\nu_e$ with electrons → modified oscillations

- **New forces/interactions between neutrinos and electrons and/or quarks** could produce an additional potential



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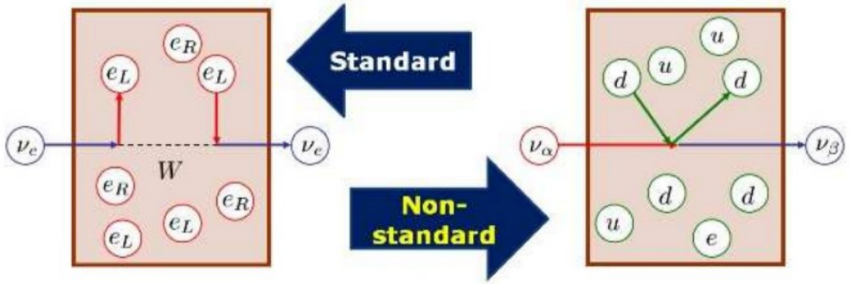


- NSI effects typically parameterised using a **modified potential matrix**

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

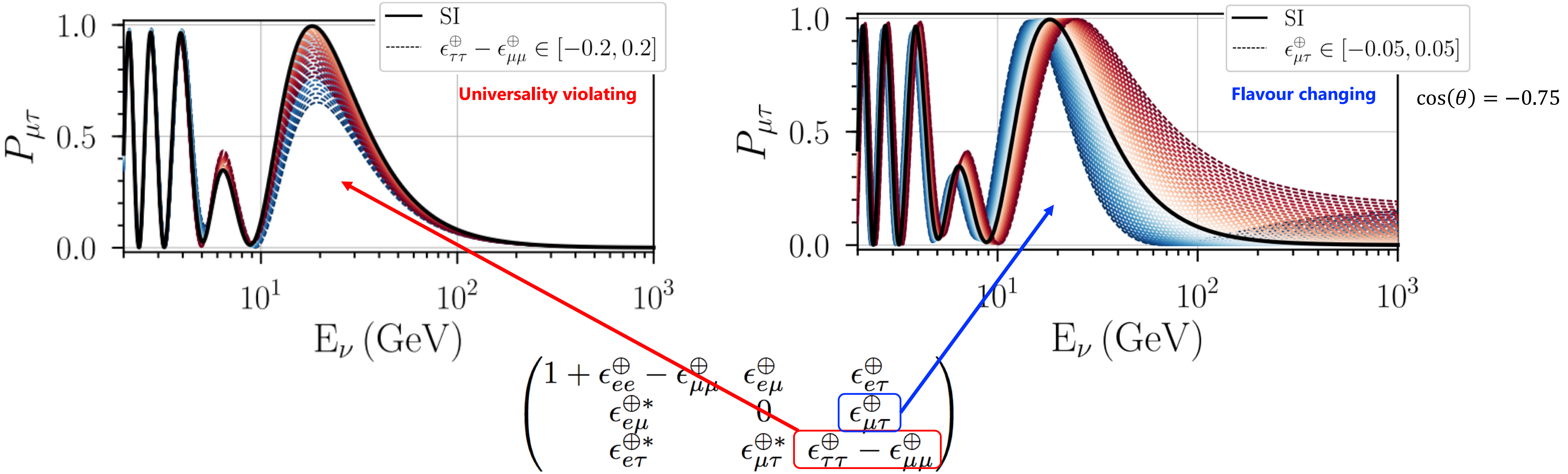
Lepton flavor violating

Lepton universality violating

# Atmospheric neutrino oscillations

- Effects of NSI depend on density of traversed matter
  - Largest signal expected for neutrinos crossing the Earth's core

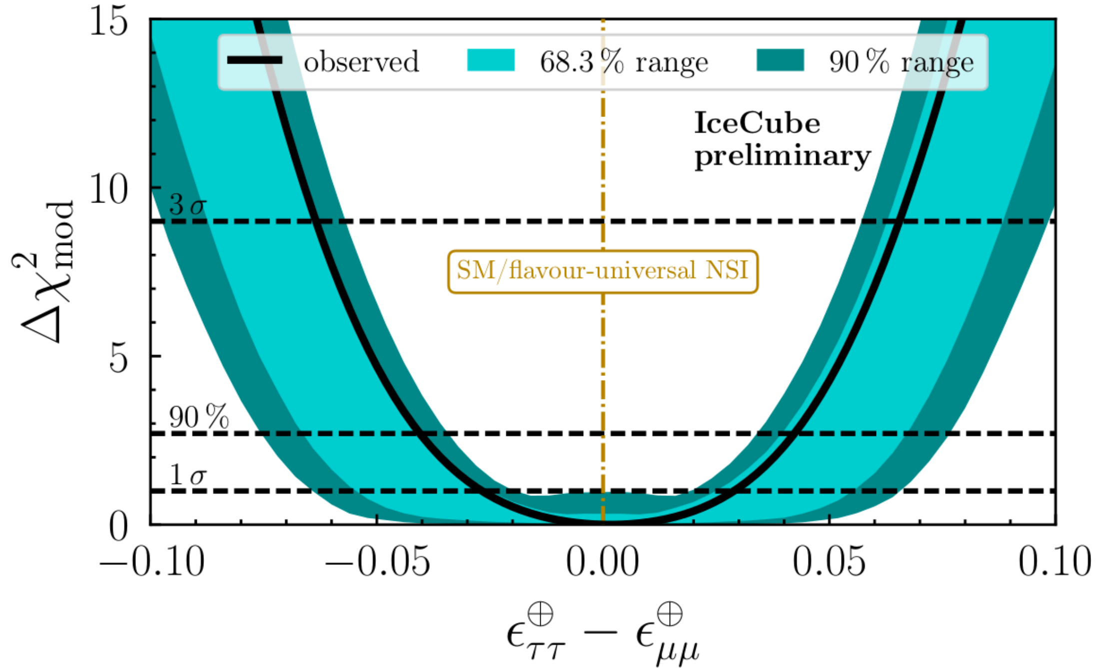
- Rich phenomenology depending on texture of NSI matrix
  - e.g. depending on underlying nature of new force

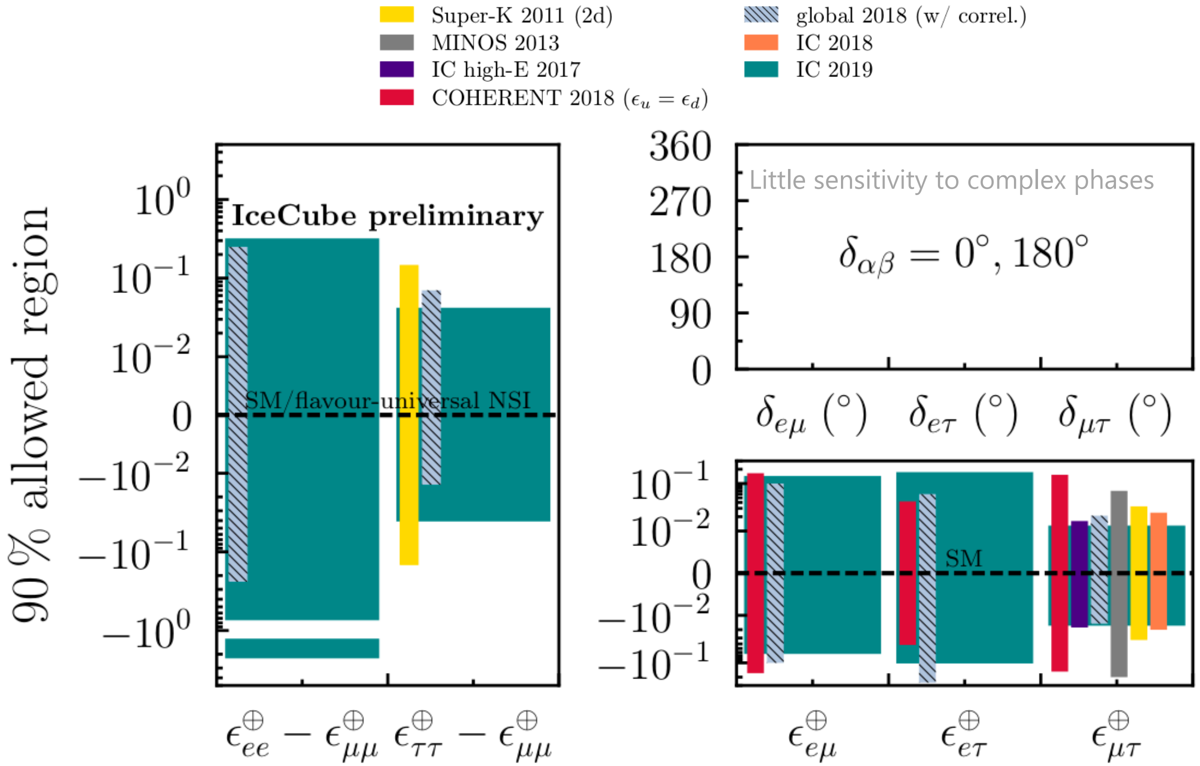


$$\begin{pmatrix} 1+\epsilon^\oplus_{ee}-\epsilon^\oplus_{\mu\mu} & \epsilon^\oplus_{e\mu} & \epsilon^\oplus_{e\tau} \\ \epsilon^{\oplus*}_{e\mu} & 0 & \boxed{\epsilon^\oplus_{\mu\tau}} \\ \epsilon^{\oplus*}_{e\tau} & \epsilon^{\oplus*}_{\mu\tau} & \boxed{\epsilon^\oplus_{\tau\tau}-\epsilon^\oplus_{\mu\mu}} \end{pmatrix}$$

# NSI constraints from IceCube

- **No evidence found of NSI** using 3 yrs of IceCube-DeepCore data
  - All matrix elements tested
  - Strongest constraints on $\mu/\tau$ sector
  - Little power to constrain real vs imaginary components (no $\nu/\bar{\nu}$ discrimination)



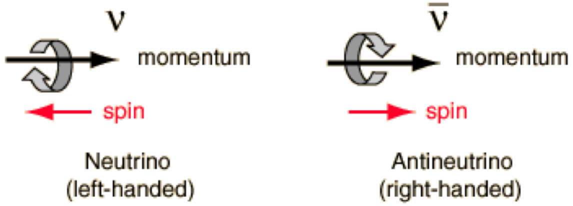


# Sterile neutrinos

**right-handed antineutrinos*

# Sterile neutrinos

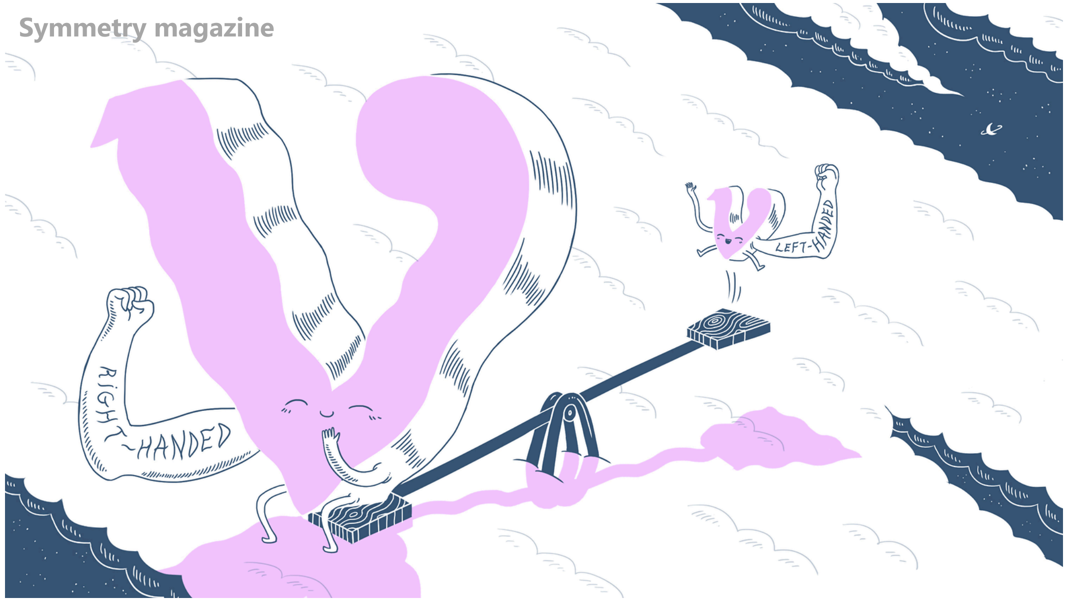
- **Only left-handed neutrinos*** are produced in weak interactions
  - Parity violation



- **Right-handed neutrinos** conjectured to exist, but **would only experience the gravitational force** (hence "sterile")

- Heavy sterile neutrinos can potentially explain the tiny but non-zero active neutrino masses via see-saw mechanisms

Symmetry magazine

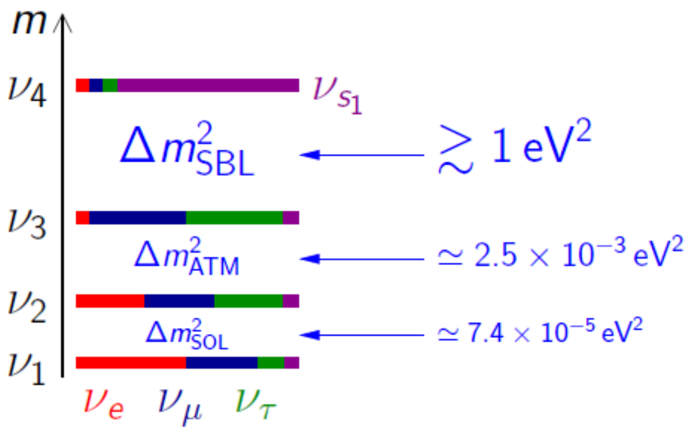


# Sterile neutrino searches

- **Cannot directly detect sterile neutrinos** in detectors
- Instead, search for **modified oscillations due to active-sterile mixing**

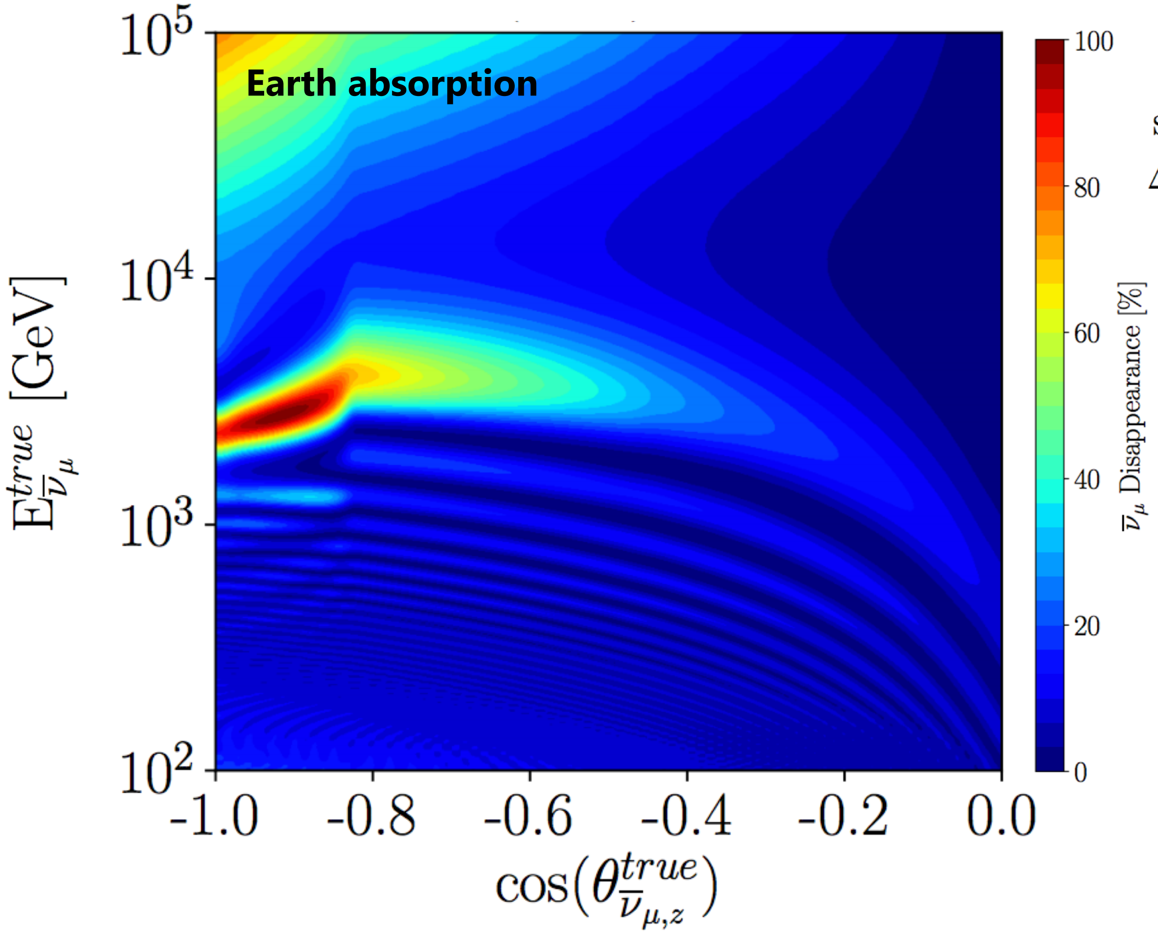
$$U_{\text{PMNS}}^{\text{Extended}} = \begin{pmatrix} \overbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}^{U_{\text{PMNS}}^{3\text{x}3}} & \begin{matrix} \cdots & U_{en} \\ \cdots & U_{\mu n} \\ \cdots & U_{\tau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

- Number of sterile neutrinos unknown → normally consider one new state
  - 3+1 models
- Huge range of masses theoretically allowed
  - Much recent focus on $\Delta m^2 \sim 1\ eV^2$ due to short baseline and reactor anomalies



# Sterile neutrinos in IceCube

- Two main sterile oscillation signals in atmospheric $\bar{\nu}_\mu$ disappearance:



3+1 ν
$\sin^2(2\theta_{24}) = 0.1$
$\Delta m^2_{41} = 1.0\,\mathrm{eV}^2$

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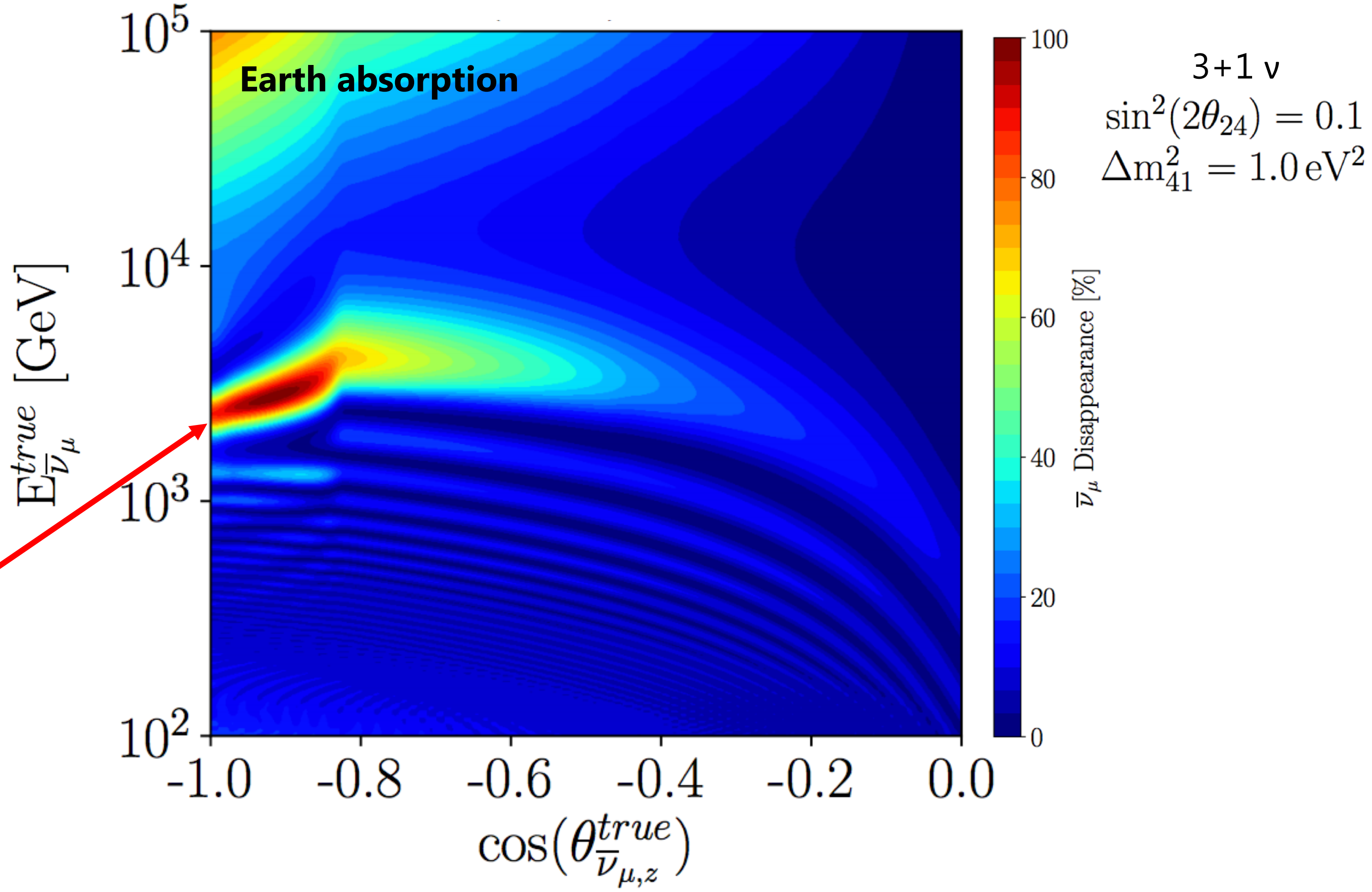

**1) Matter enhanced resonant disappearance when crossing core**

$E_\nu = TeV$
$\Delta m^2 \sim 1\ eV^2$

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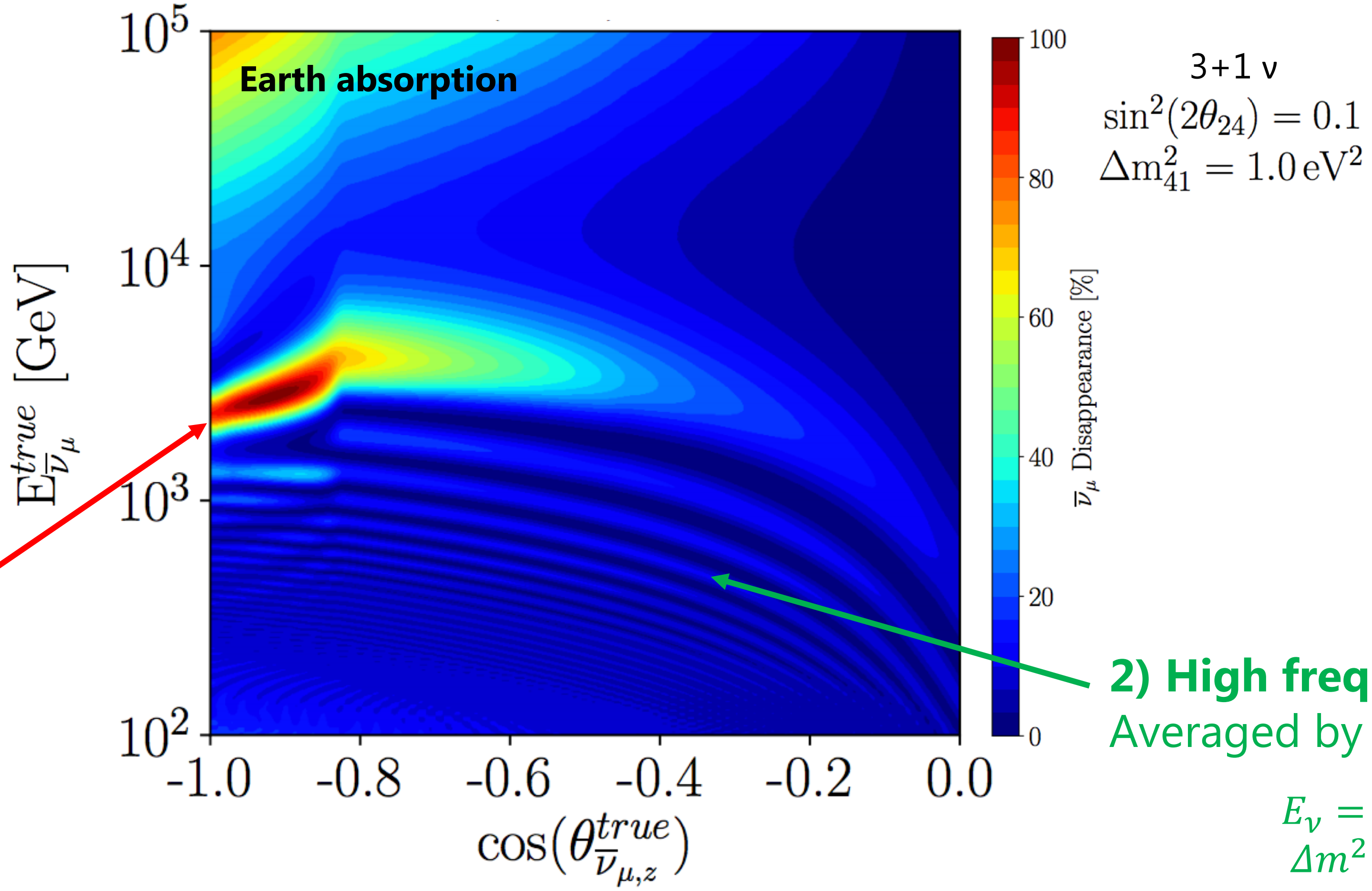


**1) Matter enhanced resonant disappearance when crossing core**

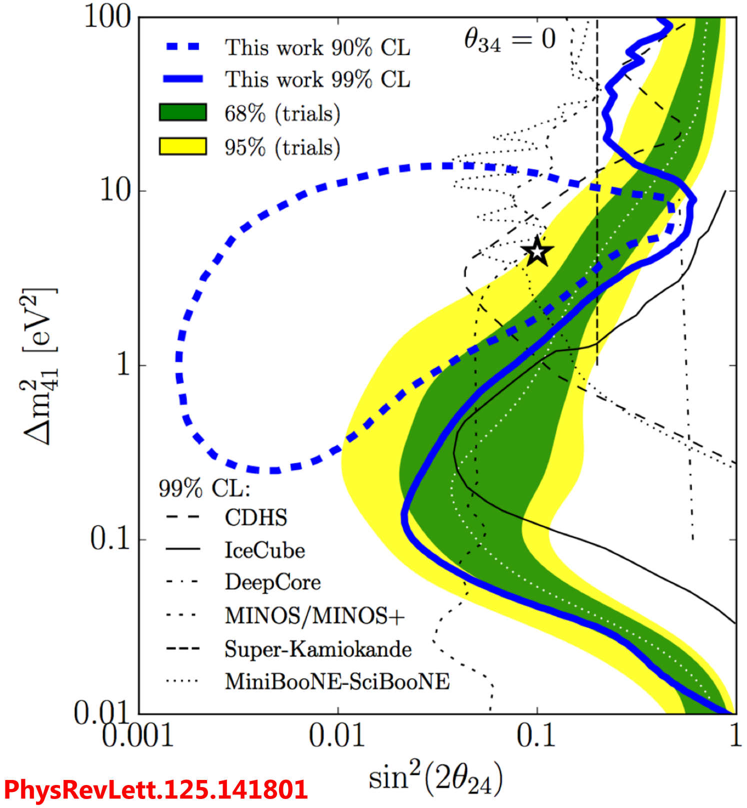
$E_\nu = TeV$
$\Delta m^2 \sim 1\ eV^2$

**2) High frequency oscillations**
Averaged by detector resolution

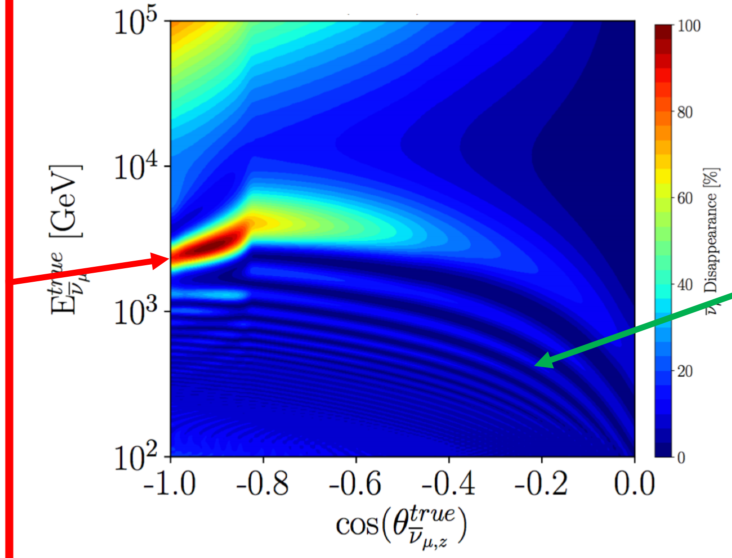
$E_\nu = GeV - TeV$
$\Delta m^2 \gtrsim 10\ eV^2$

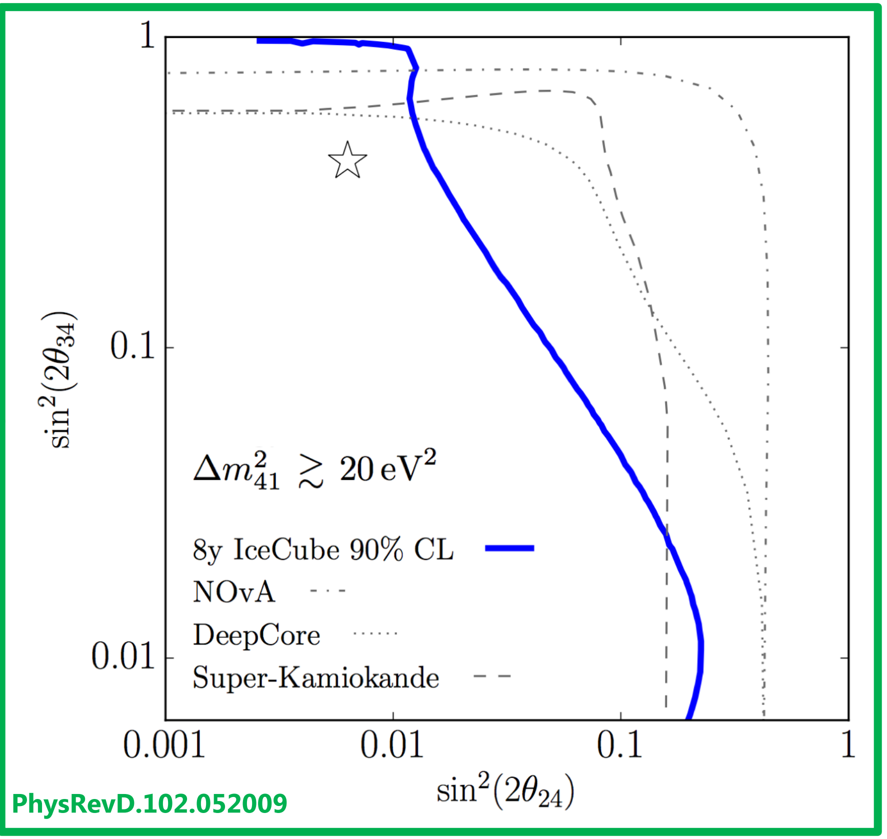
# IceCube searches

- IceCube searches performed for both channels
  - 8 yrs of data, 300,000 $\nu_\mu/\bar{\nu}_\mu$



PhysRevLett.125.141801





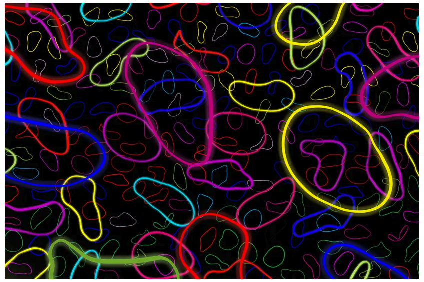
PhysRevD.102.052009

- **Consistent with no sterile →** major tension with short baseline anomalies

# Planck scale physics

# Physics at high energy scales

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



- SM is then a low energy limit of this new theory

# Physics at high energy scales

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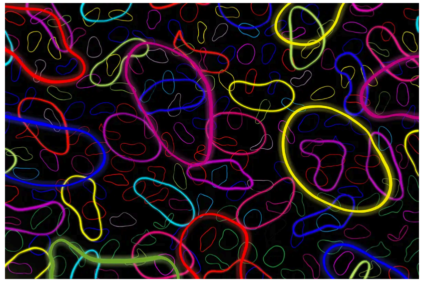
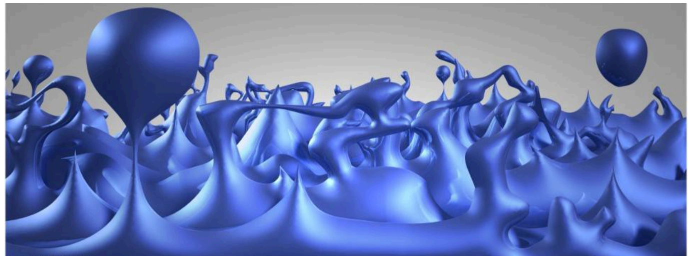


- SM is then a low energy limit of this new theory

- **Modifications of space-time** and **violations of fundamental properties/symmetries** often predicted in such high energy theories
  - Lorentz invariance violation?
  - CPT violation?
  - Neutrino decoherence?



- These effects are **suppressed at the “low” energies** we observe
  - Need high neutrino energies and statistics to search for these effects

# Lorentz invariance violation

# Lorentz invariance violation (LIV)

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

- LIV **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:

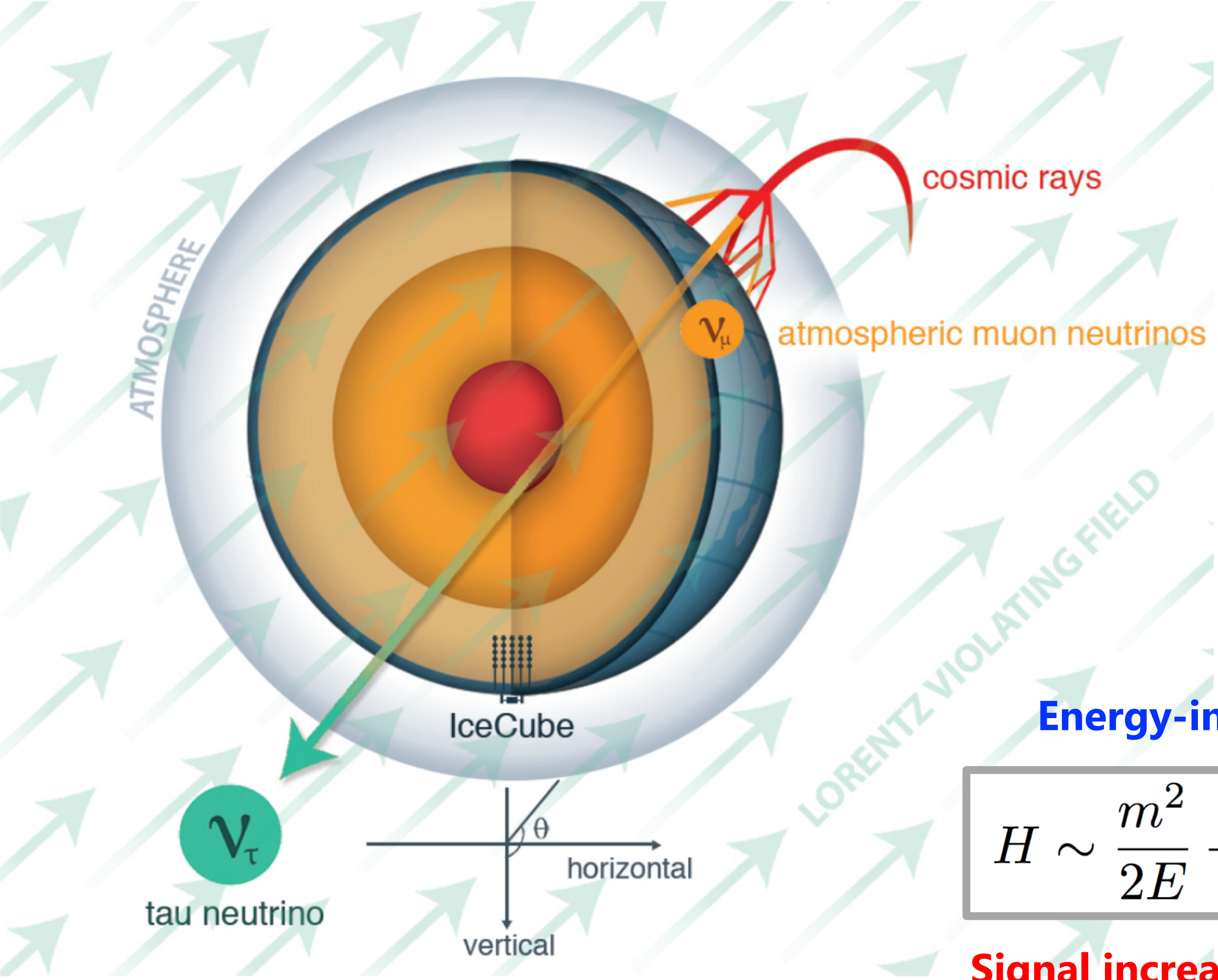
a = CPT odd
c = CPT even

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

- Many SME tests performed
  - Neutrino oscillations, accelerator, $\gamma$-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 $\nu_\tau$ expected above 100 GeV in νSM)

**Energy-independent signal for lowest order operator**

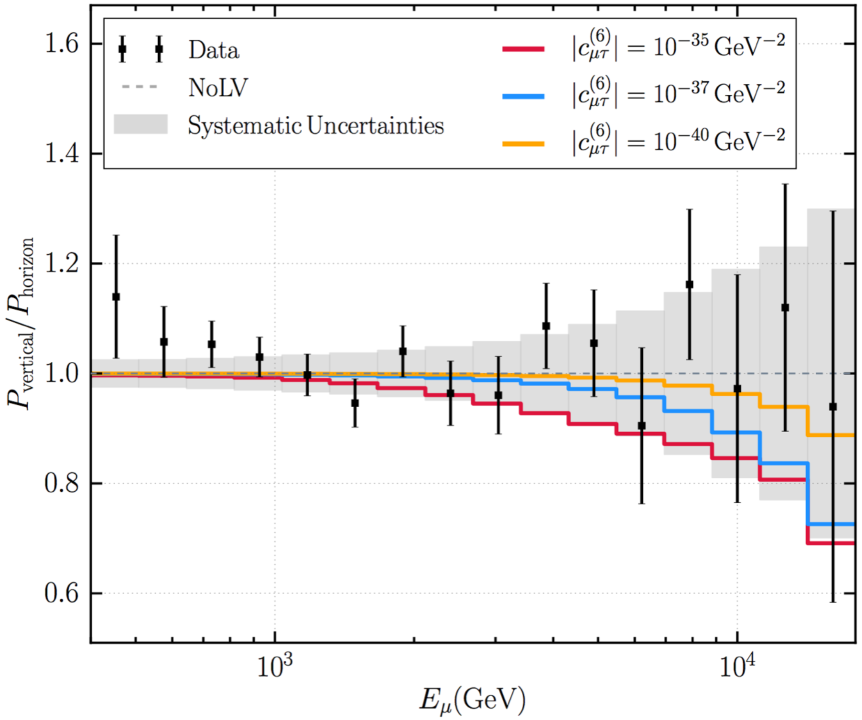
$$\boxed{H \sim \frac{m^2}{2E} + \boxed{\mathring{a}^{(3)}} - \boxed{E \cdot \mathring{c}^{(4)} + E^2 \cdot \mathring{a}^{(5)} - E^3 \cdot \mathring{c}^{(6)} \ldots}}$$

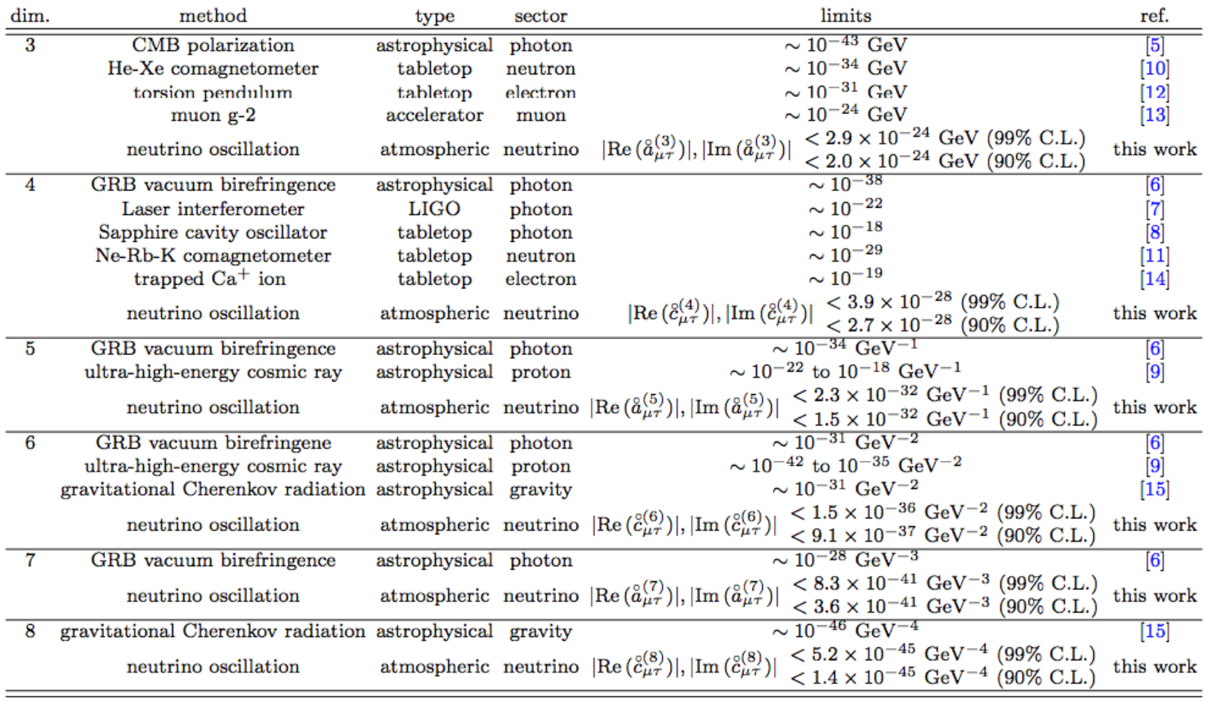
**Signal increases with energy for all higher order operators**

Nature Physics 14, 961–966 (2018)

# IceCube search

- LIV search performed using IceCube data
  - Signal is disappearance of high energy neutrinos as they cross the Earth
  - Only isotropic effects considered
- No LIV effects observed
  - World's most stringent constraints on higher order SME operators

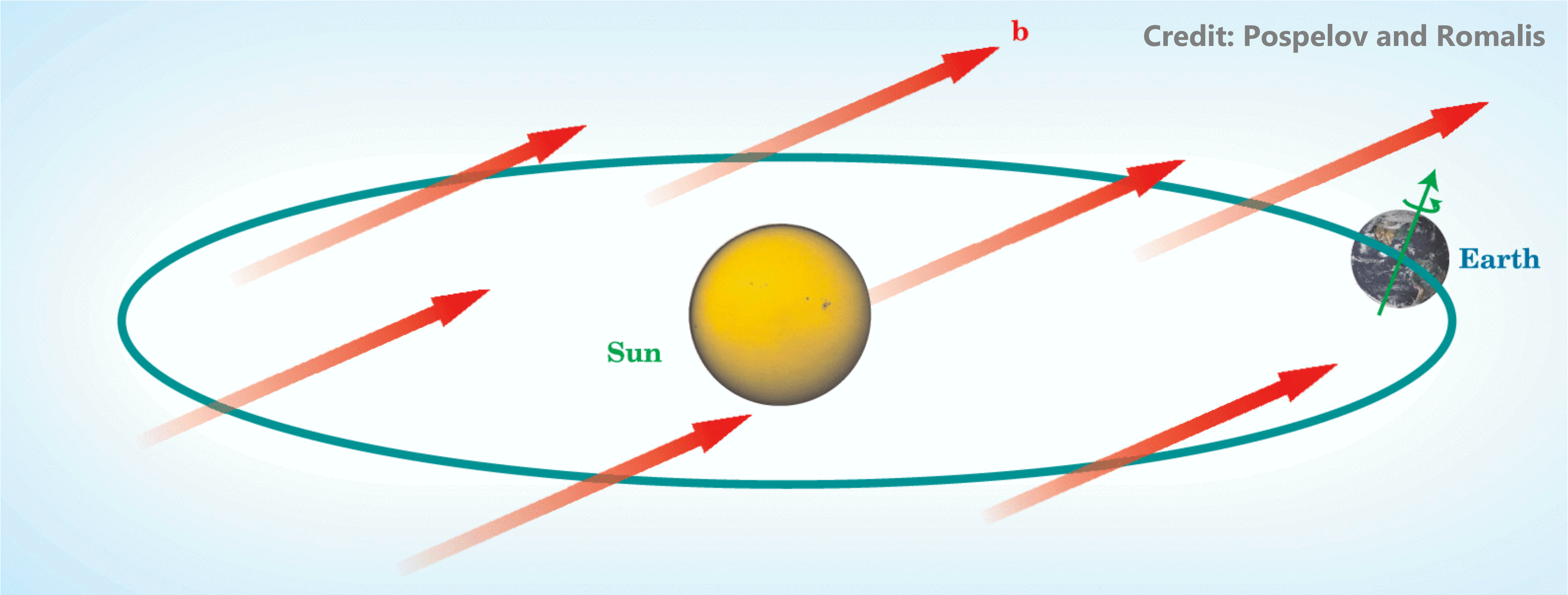




| dim. | method | type | sector | limits | ref. |
|---|---|---|---|---|---|
| 3 | CMB polarization | astrophysical | photon | $\sim 10^{-43}$ GeV | [5] |
| | He-Xe comagnetometer | tabletop | neutron | $\sim 10^{-34}$ GeV | [10] |
| | torsion pendulum | tabletop | electron | $\sim 10^{-31}$ GeV | [12]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

# 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



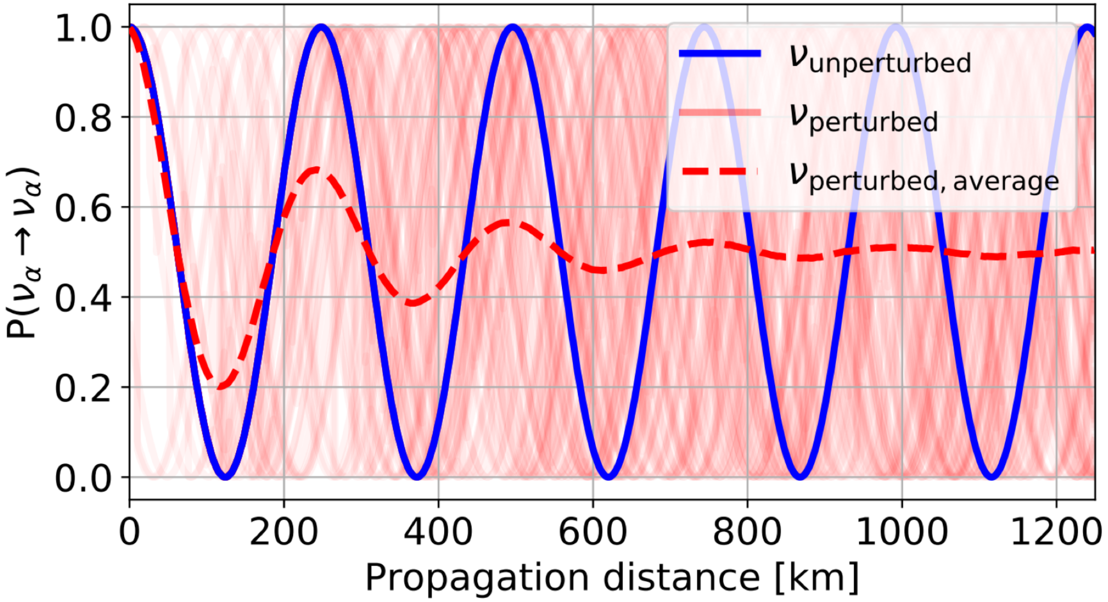
Credit: Pospelov and Romalis

- Old (2010) IceCube search (PhysRevD.82.112003), an update is overdue!

# Neutrino 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**

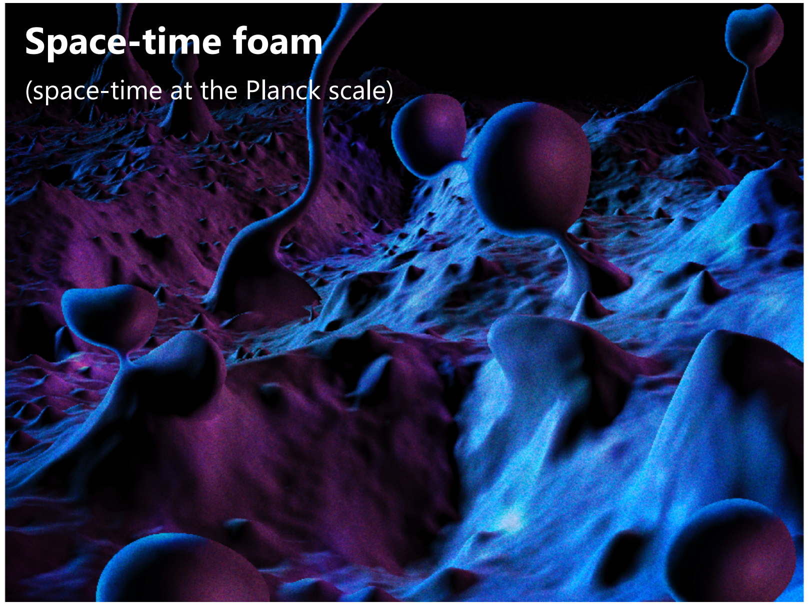
(not realistic parameters)

# 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
  - Quantum gravity analogue of vacuum polarisation
  - Space-time permeated with Planck scale black holes
  - Propagating neutrinos undergo stochastic (flavour violating?) interactions with VBH background

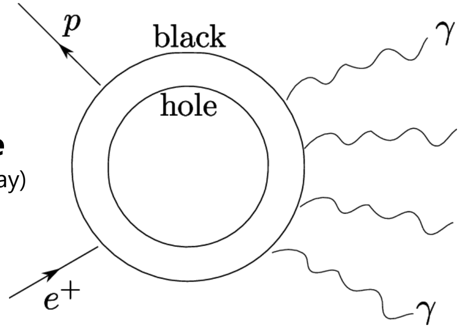


**Space-time foam**

(space-time at the Planck scale)

**Virtual black hole**

(here 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**

**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**:

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

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

**Most studies use a general form for the decoherence operator, characterised by damping parameters, $\Gamma$**

# 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":

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

or

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

**w.r.t. arbitrary $E_0$ (usually 1 GeV)**

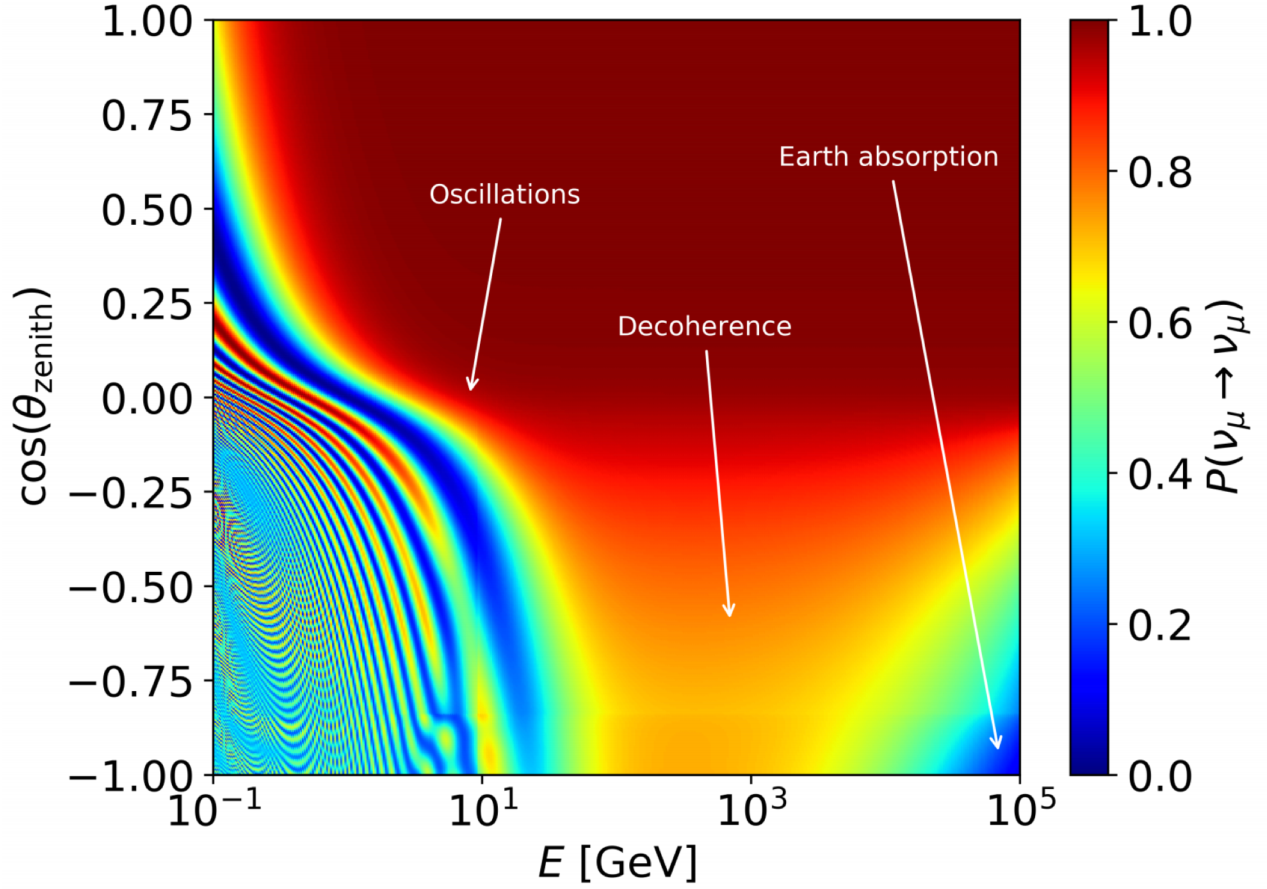
**w.r.t. Planck scale**

"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**

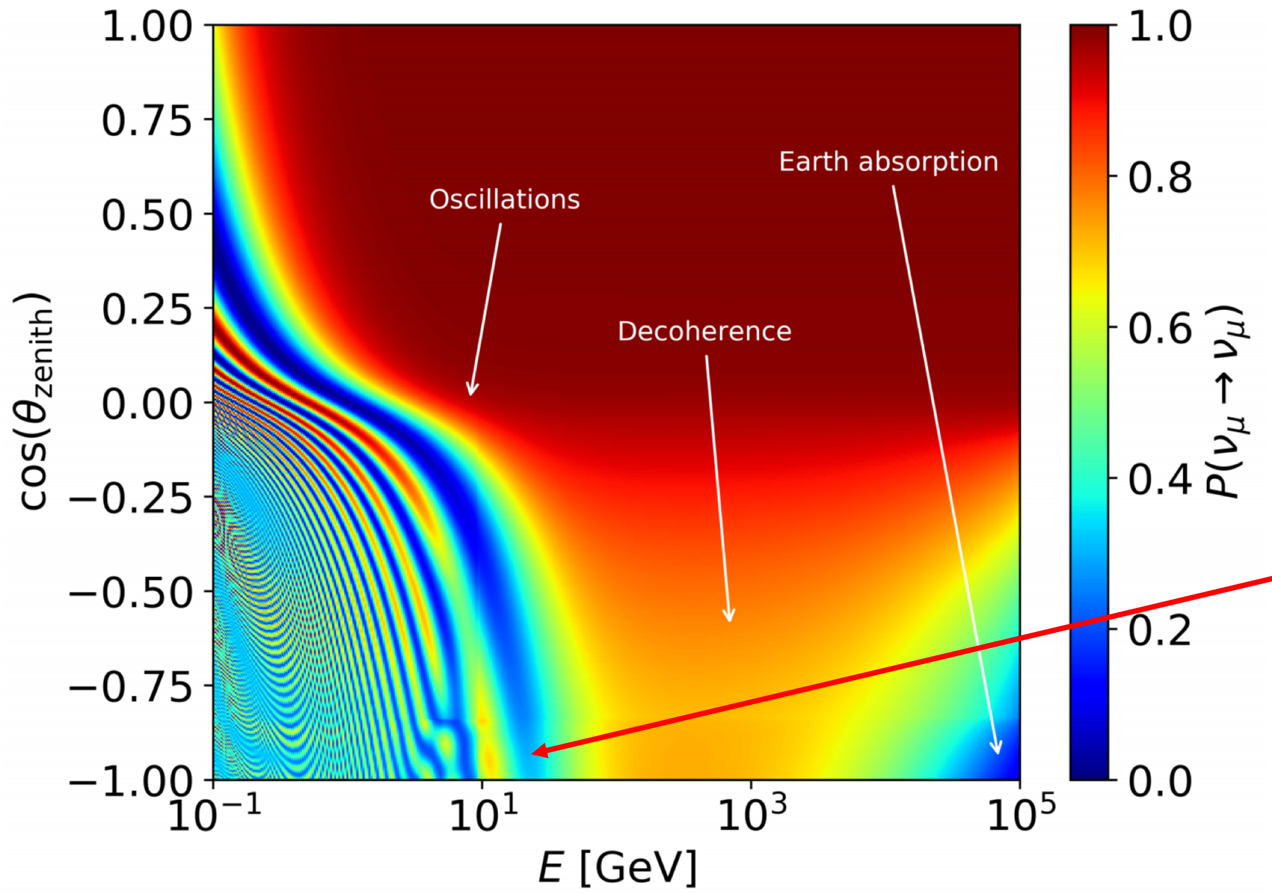
**Signal across all E**

(IceCube + DUNE synergy)

**TS, M Jensen. PhysRevD.102.115003**

# Atmospheric neutrino signal

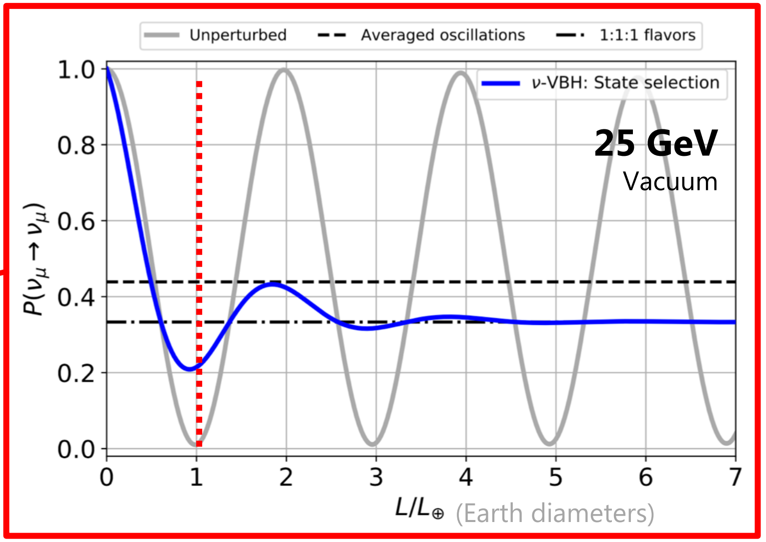
- Signal is damping of neutrino flavour transitions → increases with baseline



*Example scenario 1:*

**Flavour violating ν-VBH interactions**

**Energy-independent**

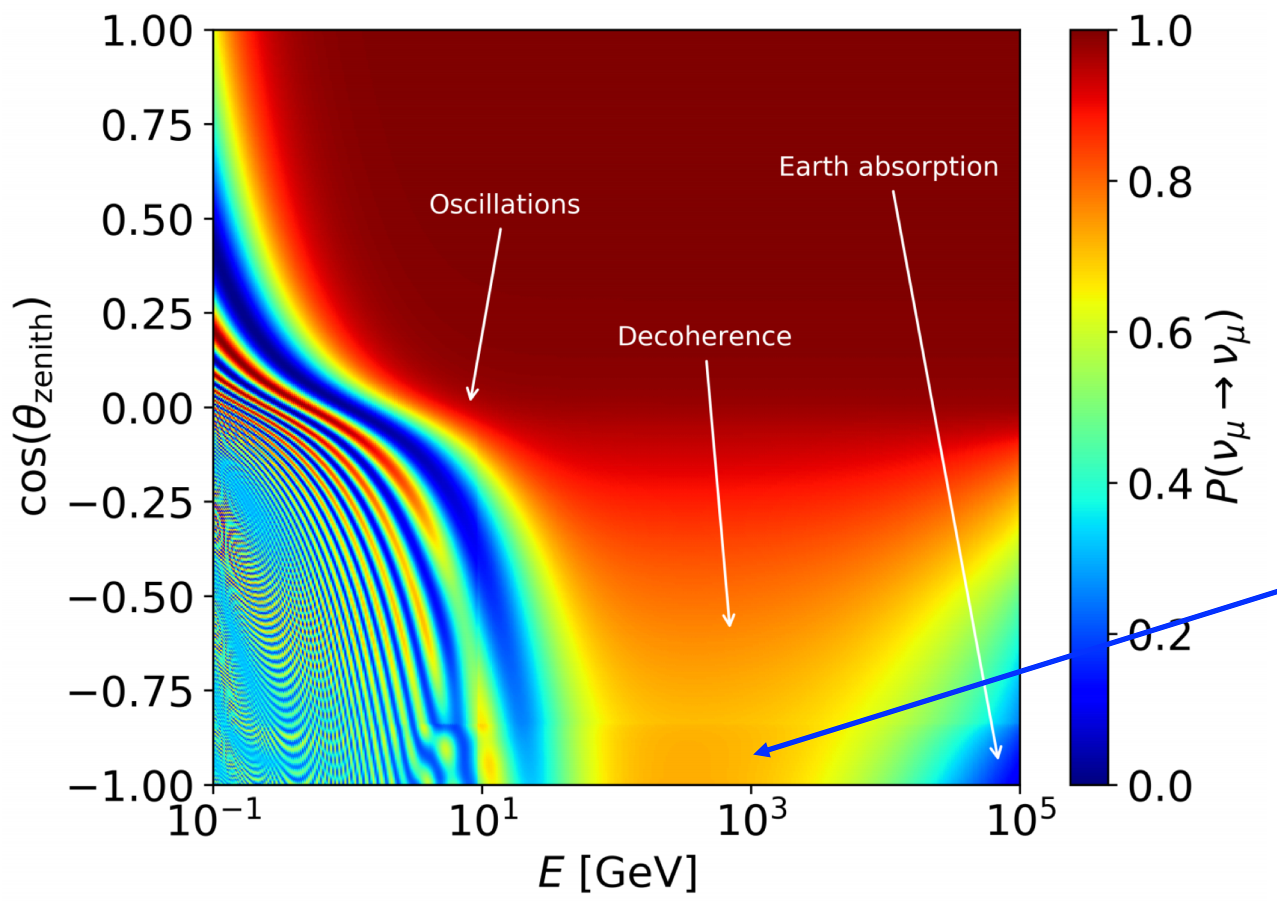


**Standard oscillations for Earth crossing neutrinos weakened**

TS, M Jensen. PhysRevD.102.115003

# Atmospheric neutrino signal

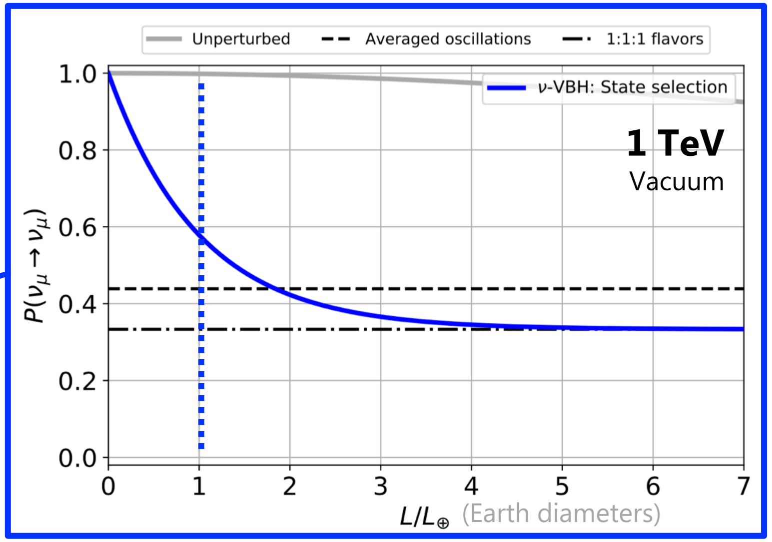
- Signal is damping of neutrino flavour transitions → increases with baseline



*Example scenario 1:*

**Flavour violating ν-VBH interactions**

**Energy-independent**

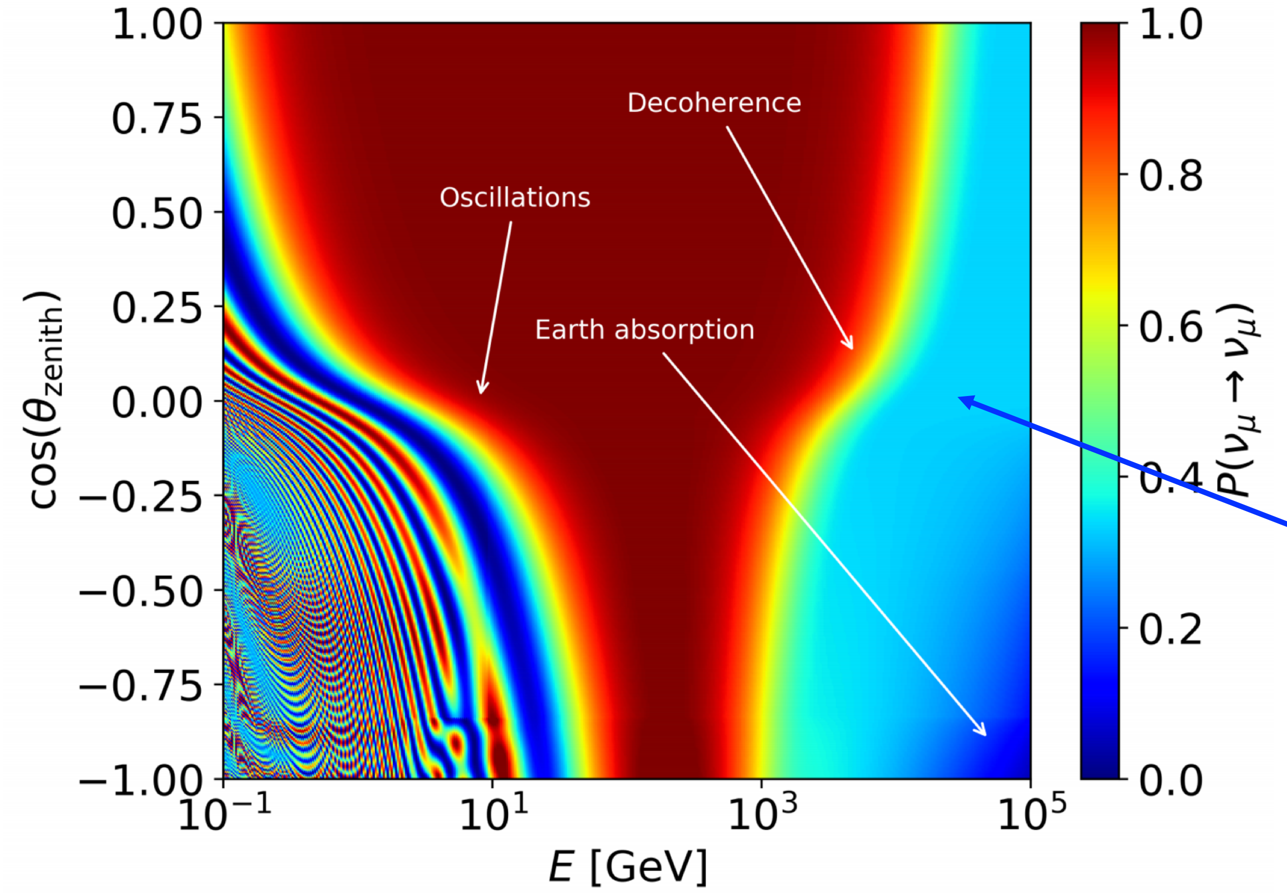


**Flavour transitions outside of standard oscillation region**

**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**

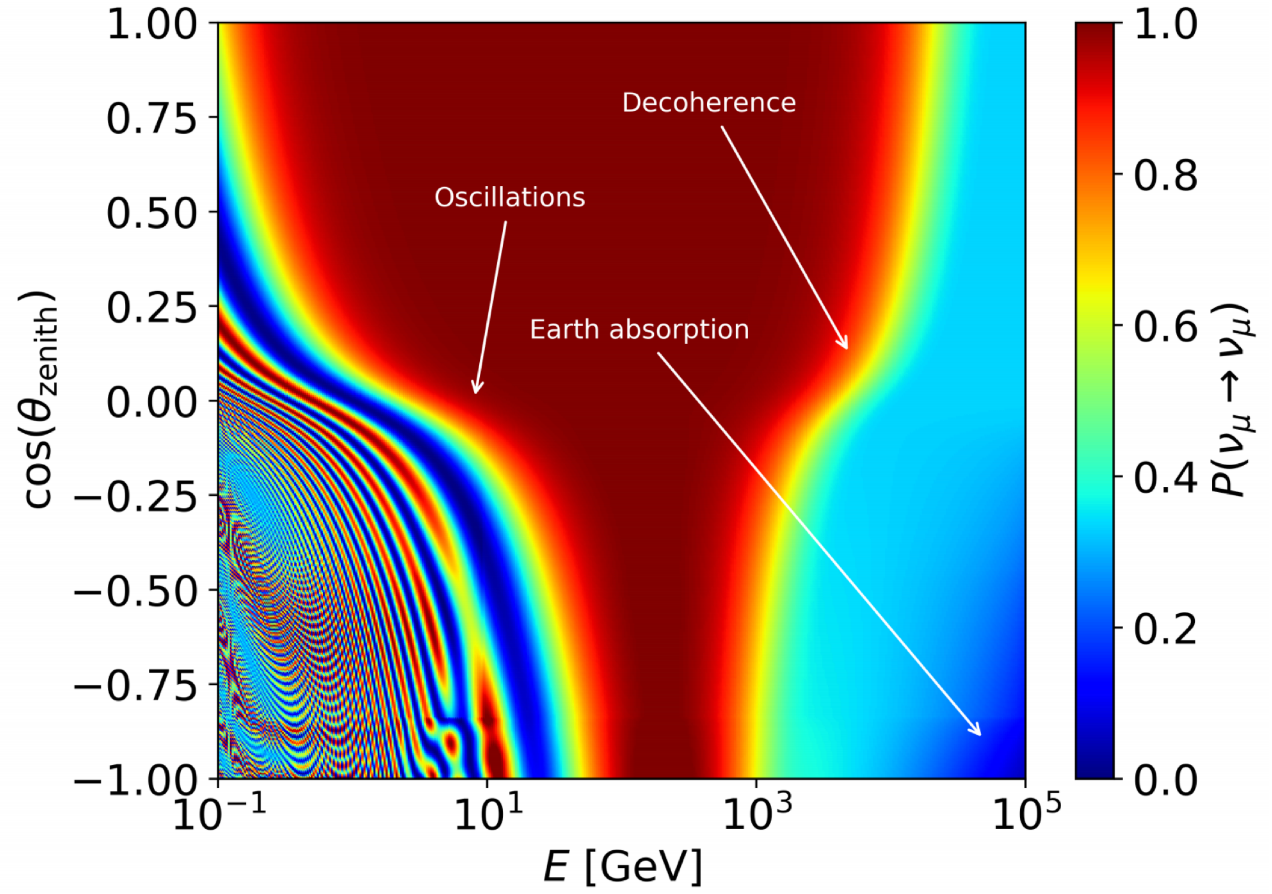
**High-energy flavour transitions outside of standard oscillation region, even for smaller baselines**

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

**TS, M Jensen.** PhysRevD.102.115003

# Atmospheric neutrino signal

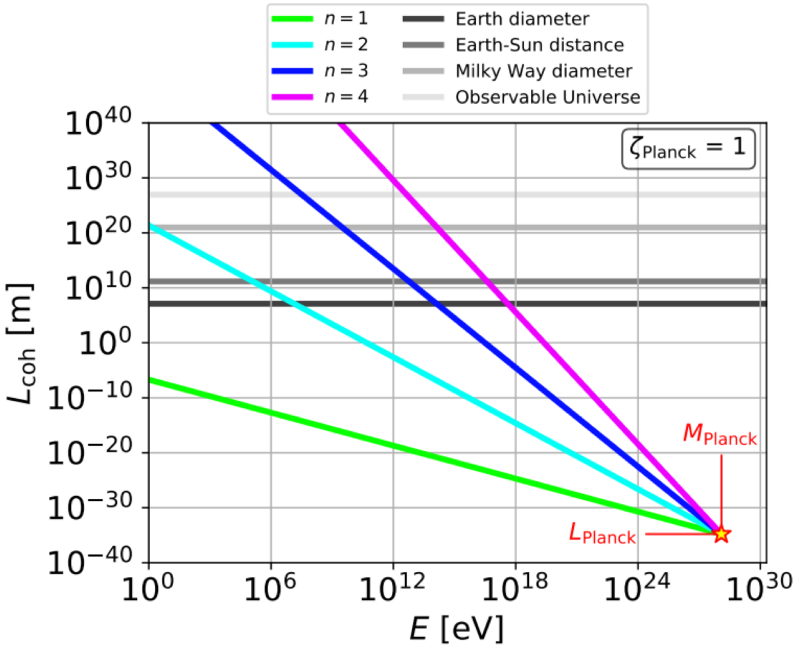
- Signal is damping of neutrino flavour transitions → increases with baseline



*Example scenario 2:*

**Flavour violating ν-VBH interactions**

**$E^2$ energy-dependence**



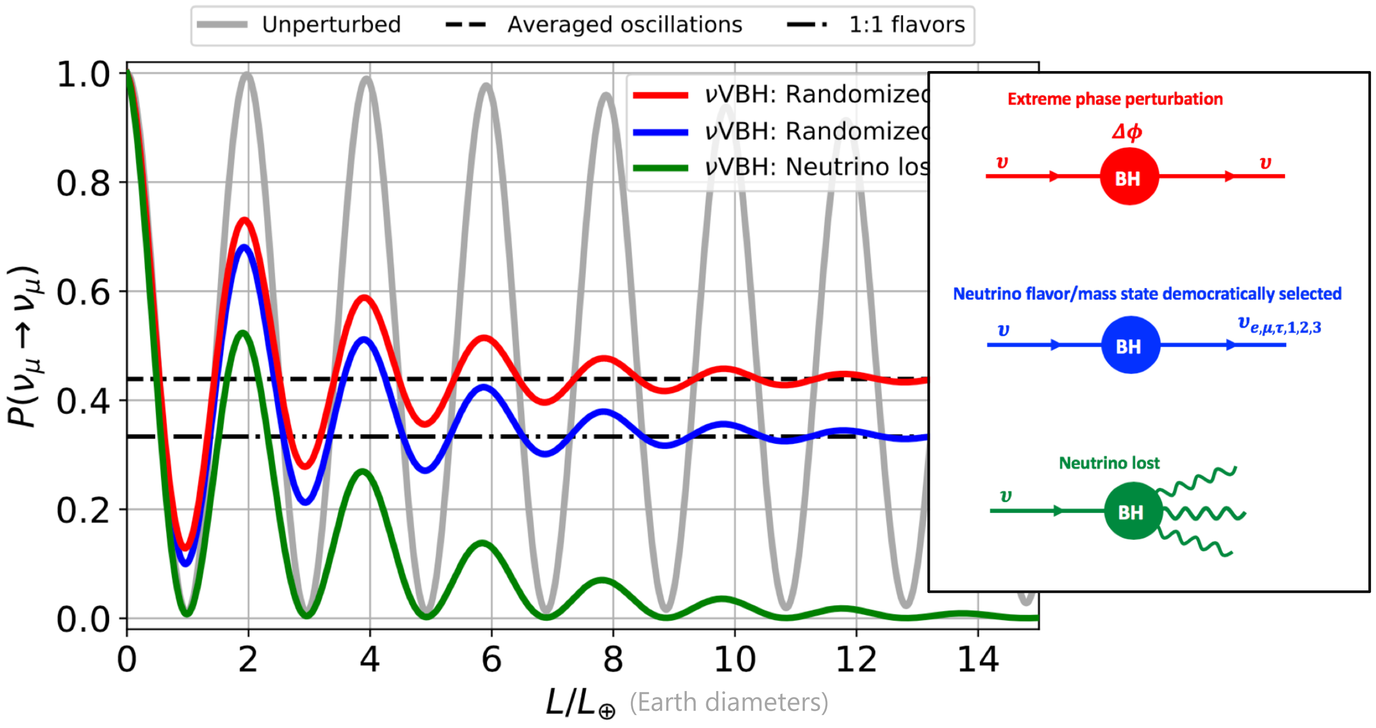
**Sensitivity to "natural" Planck scale effects for $E^{\lesssim 3}$-dependence!**

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

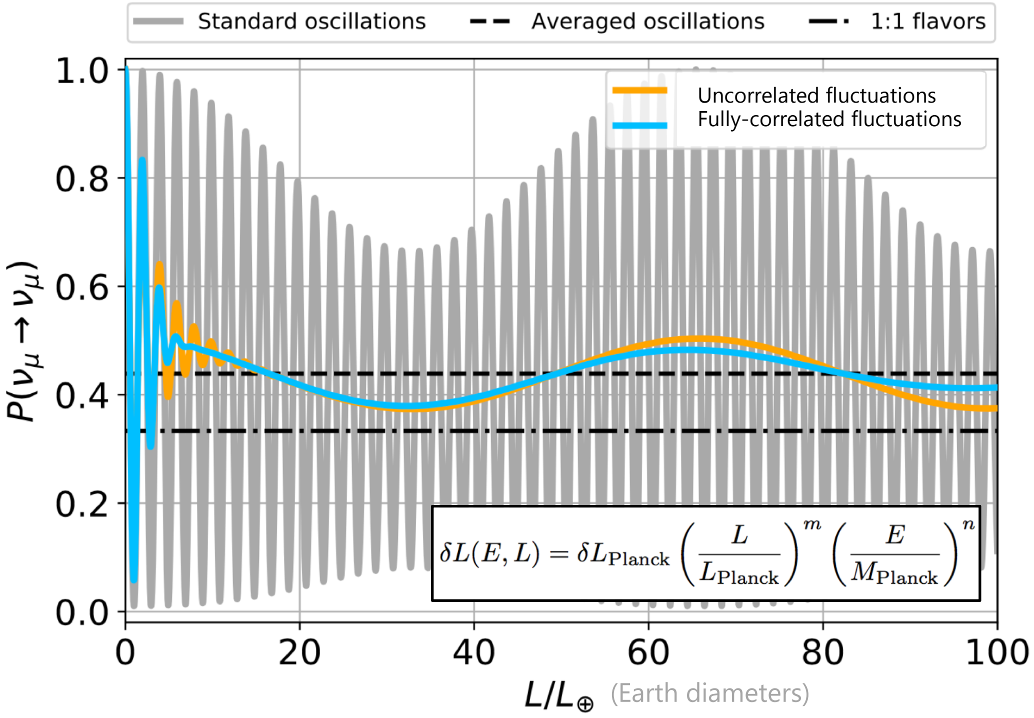
# Other scenarios

- 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

**$\nu$ – virtual black hole interactions**



**Lightcone fluctuations**



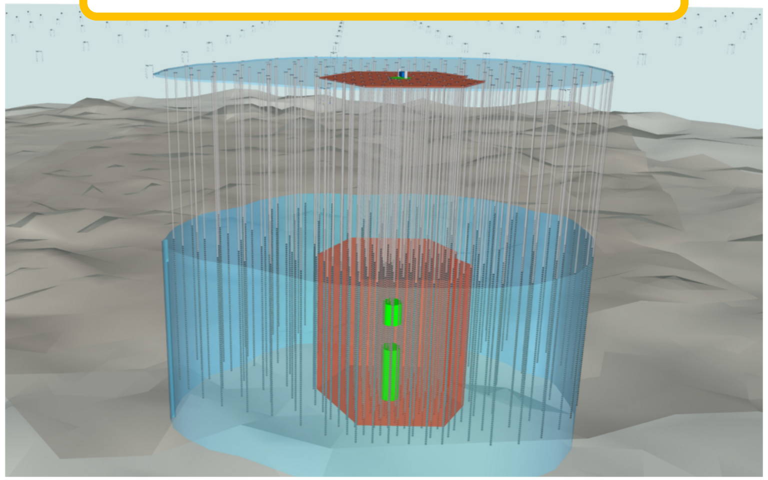
New IceCube searches in progress…

# Wrapping up

# Summary & outlook

- Many open questions remain in fundamental physics…
- Neutrino oscillations are sensitive to the possible answers to many of these questions
- Atmospheric neutrino oscillation measurements with IceCube offer world leading new physics sensitivity
  - High energies, baselines, matter density and statistics…
- No signal found yet…
  - But, new generation of measurements on the way…
  - And, the future is bright in the IceCube Upgrade and Gen2…

**IceCube Gen2: ~10 km$^3$**

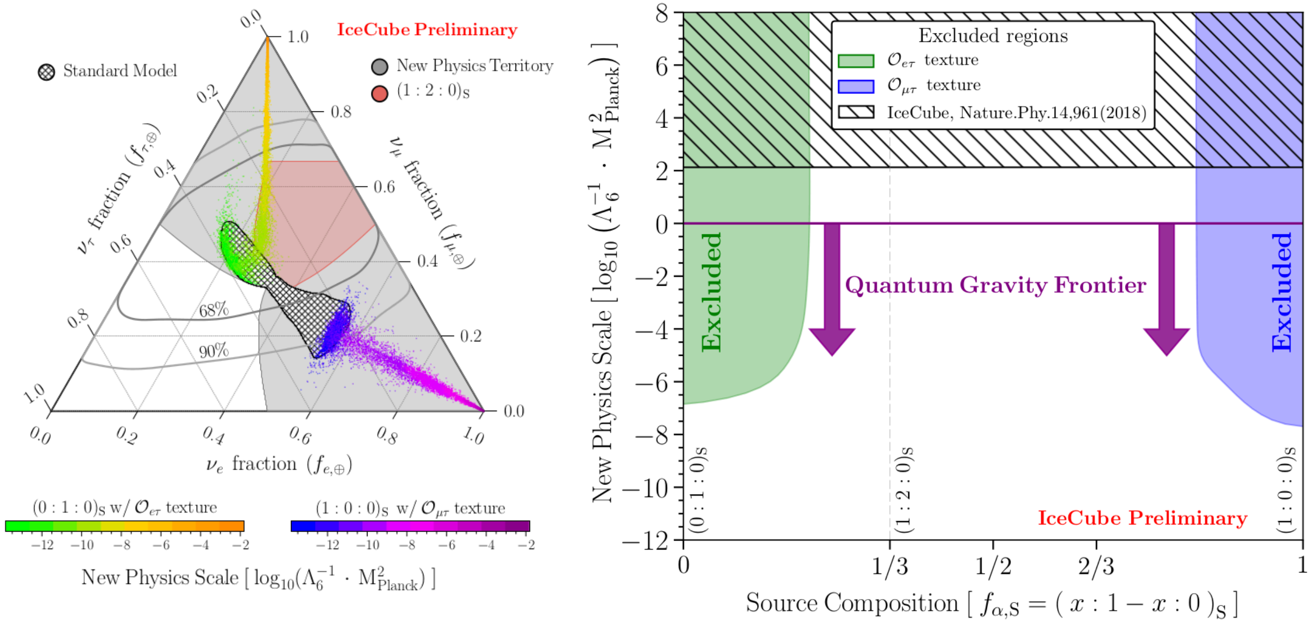


# Thank you!

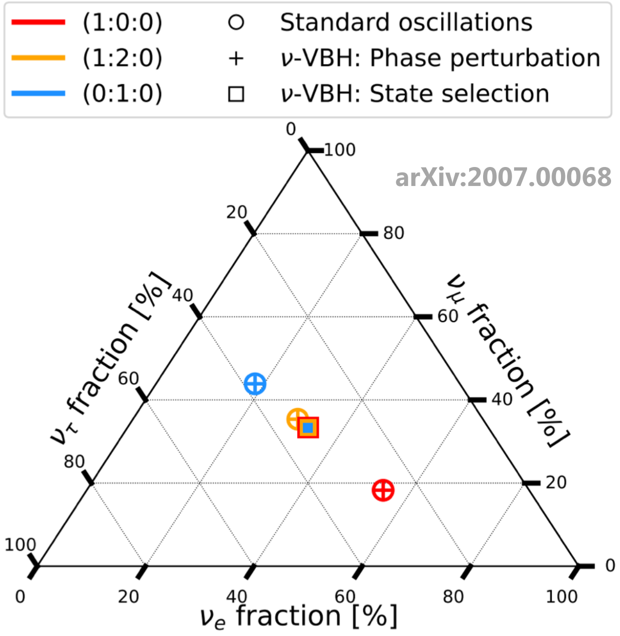
# Why not astrophysical neutrinos?

- 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**



arXiv:2007.00068