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# Sidereal Lorentz Invariance Violation

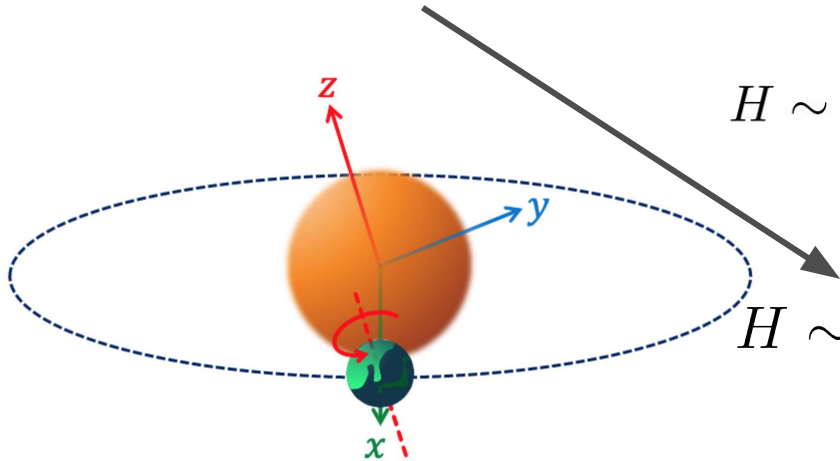
Andre Steklain  
Austin Schneider  
Barbara Skrzypek  
Jan Weldert

Maria Prado  
Qinrui Liu  
Tom Stuttard



# Lorentz Invariance Violation

- Introduce higher order operators that violate Lorentz invariance
- Recent IceCube studies examined rotation independent LIV (<https://arxiv.org/abs/1709.03434>)
- Sidereal effects are frame dependent
  - Coefficients of LIV operators change with direction
  - Last IceCube study with IC-40 (<https://arxiv.org/abs/1010.4096>)
- Consider the Earth's orientation wrt a global reference frame (neglecting boost factors)
- This adds directional dependence to the Hamiltonian



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

$$H \sim \frac{m^2}{2E} + \frac{1}{E} [(a_L)^\mu p_\mu - (c_L)^{\mu\nu} p_\mu p_\nu]_{ab}$$

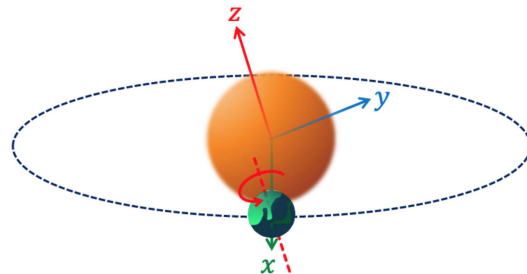
# Sidereal LIV formalism

- So far have adopted formalism from IC40 analysis
  - Considers dimension 3 (E independent) and dimension 4 operators (E<sup>1</sup> dependence) only
  - Standard oscillations neglected (only valid for E > 100 GeV)

$$P_{\nu_\mu \rightarrow \nu_\mu} = 1 - \sin^2 \left( L \left[ (A_s)_{\mu\tau} \sin(\alpha \mp \varphi_0) + (A_c)_{\mu\tau} \cos(\alpha \mp \varphi_0) \right] \right)$$

Baseline dependent

Periodic in RA



# Sidereal LIV formalism

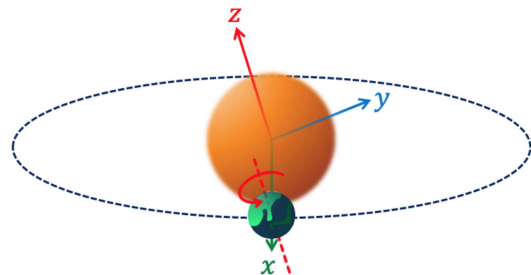
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**Amplitudes**

$$A_s = \hat{N}^Y (a_L^X - 2Ec_L^{TX}) - \hat{N}^X (a_L^Y - 2Ec_L^{TY}),$$

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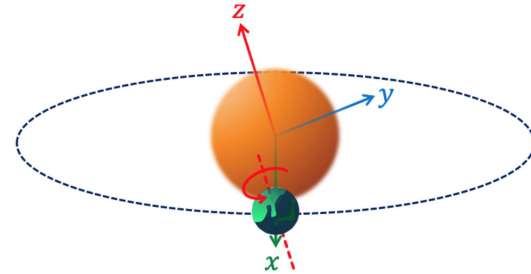
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**Neutrino direction vectors**

$$\hat{N}^X = \sin(\theta) \cos(\varphi)$$

$$\hat{N}^Y = \sin(\theta) \sin(\varphi)$$



# Sidereal LIV formalism

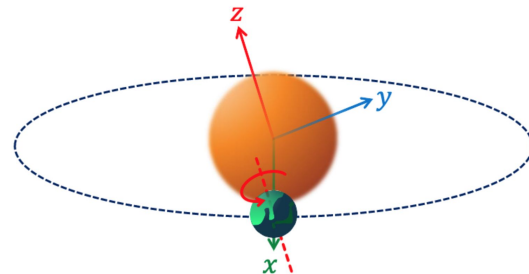
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Dimension 3 operator components (w.r.t. Earth's axis)



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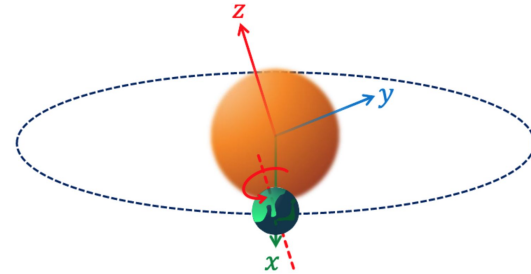
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Dimension 4 operator components (w.r.t. Earth's axis)



# Where to look for a signal

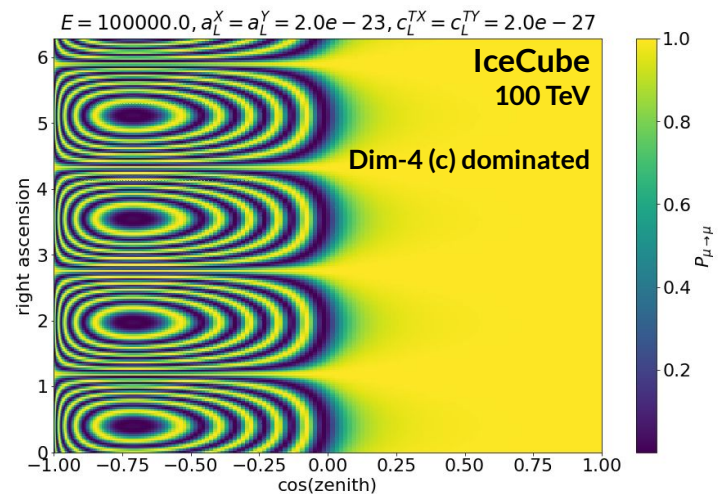
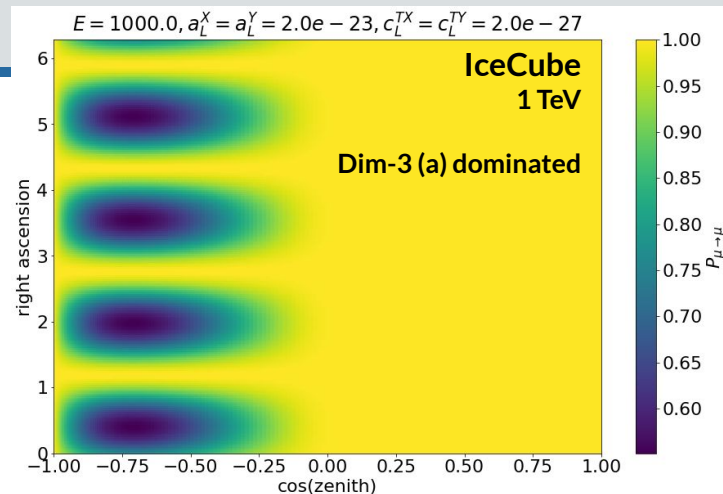
LIV effects depend on the right ascension (RA) and declination of the neutrino (e.g. travel direction w.r.t. celestial sphere)

IceCube sees different declinations as different zenith angles

Muon neutrino survival probability depending on right ascension and zenith direction (directly translates to traveled distance and  $d$  for South Pole)

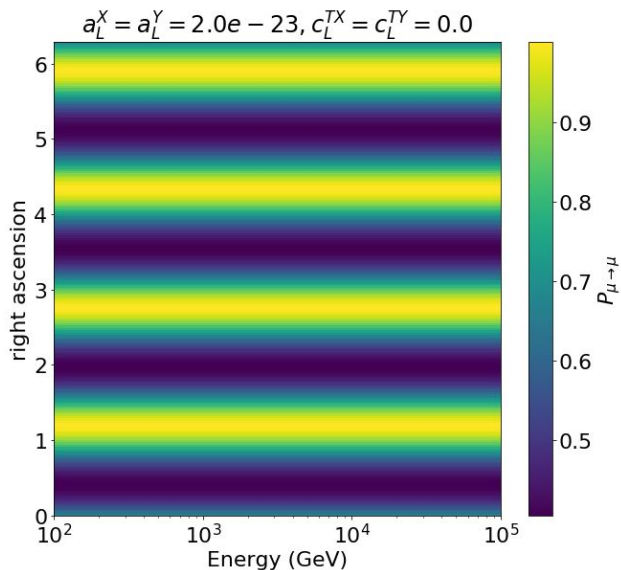
Need long baseline to see effect

→ Only for upgoing (coming from earth) events

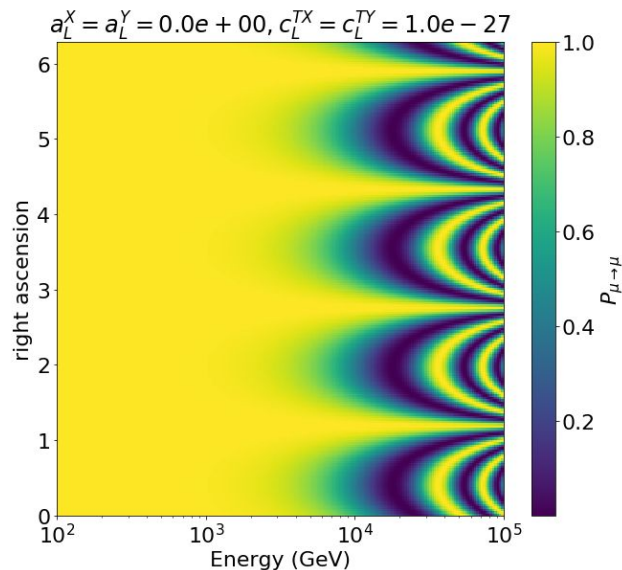




# Energy-dependence of a and c parameters



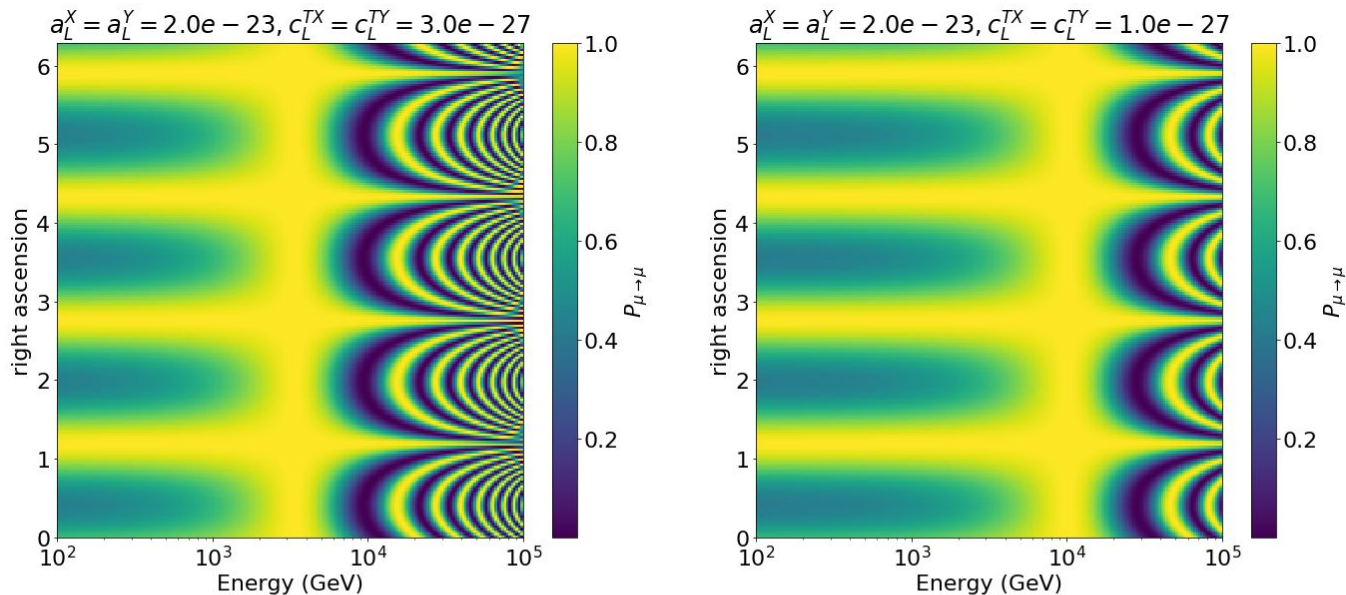
**Dim-3 only**  
→ E-independent signal



**Dim-4 only**  
→ Signal increases with E

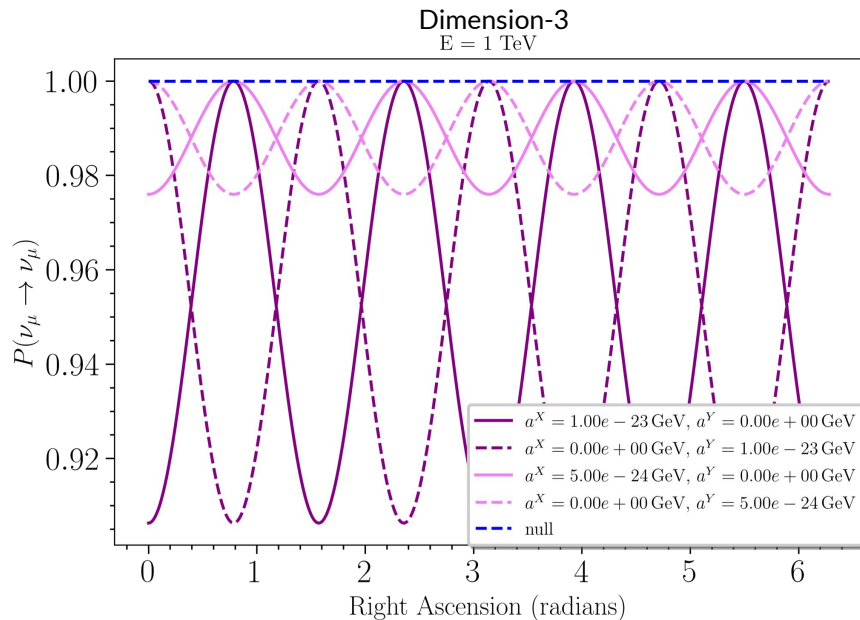
# Energy-dependence of a and c parameters

## Dim-3 and -4 combined



Changing dim-4 operator strength shifts signal in E

# Effect of X and Y components



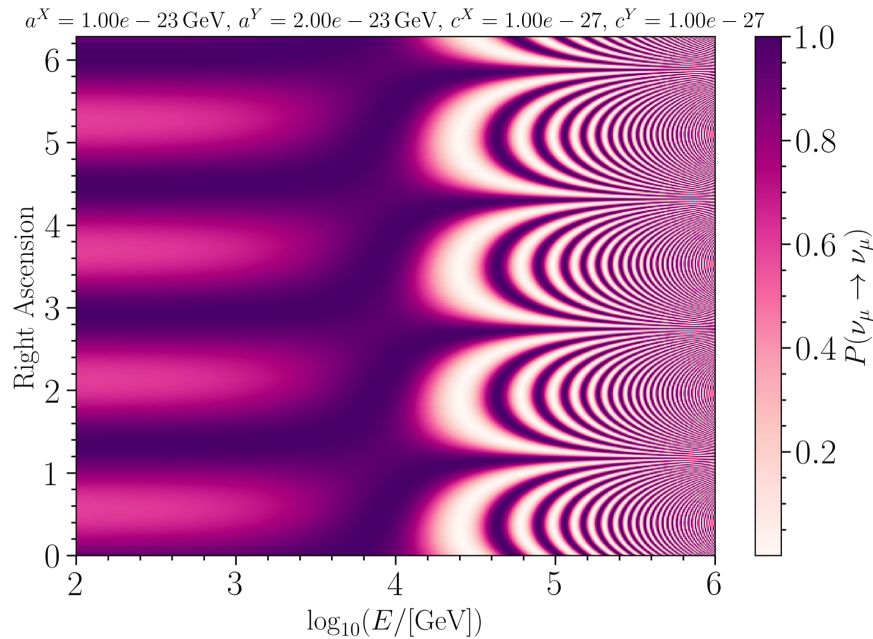
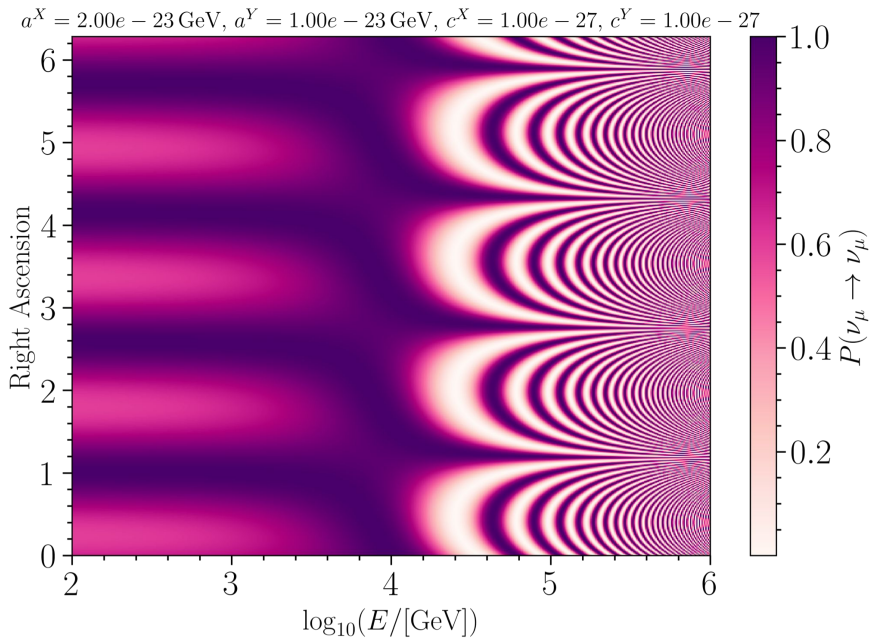
IceCube

Changing relative strength of X vs Y components of operators shifts phase of signal w.r.t. RA  
Makes sense → this corresponds to changing the preferred LIV direction

# Effect of X and Y Components - dimension 3

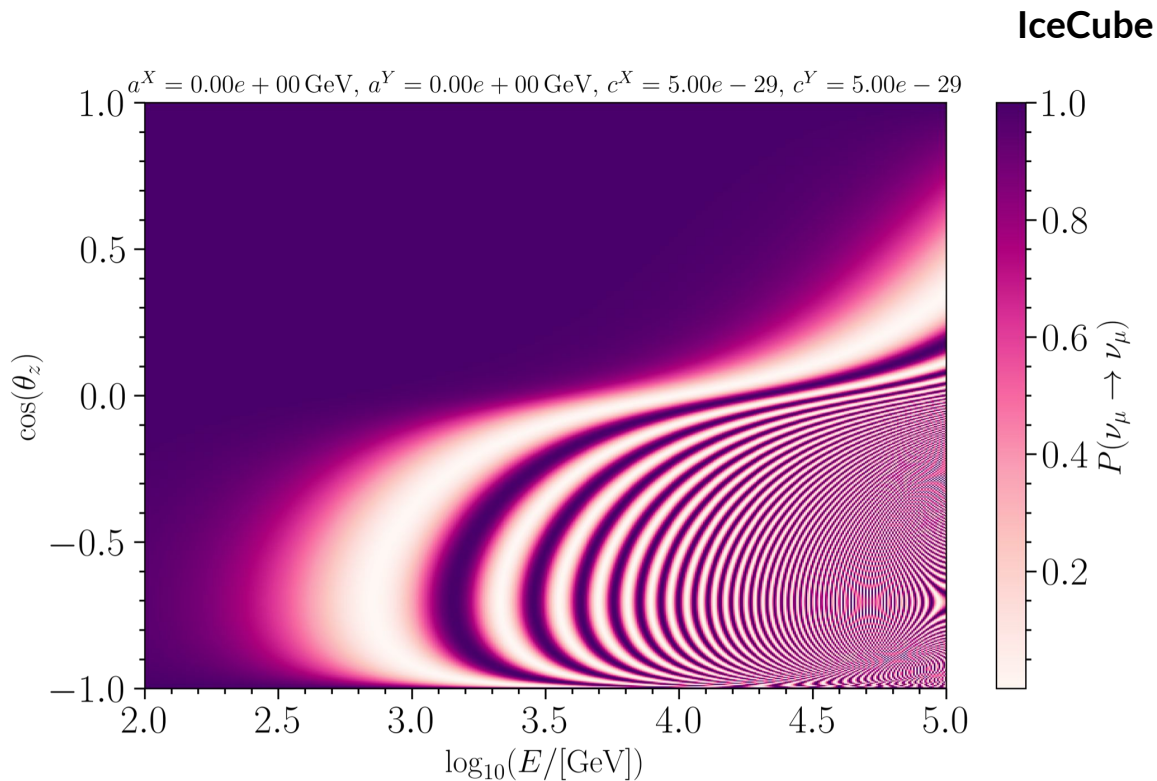
IceCube

Similar story in 2D



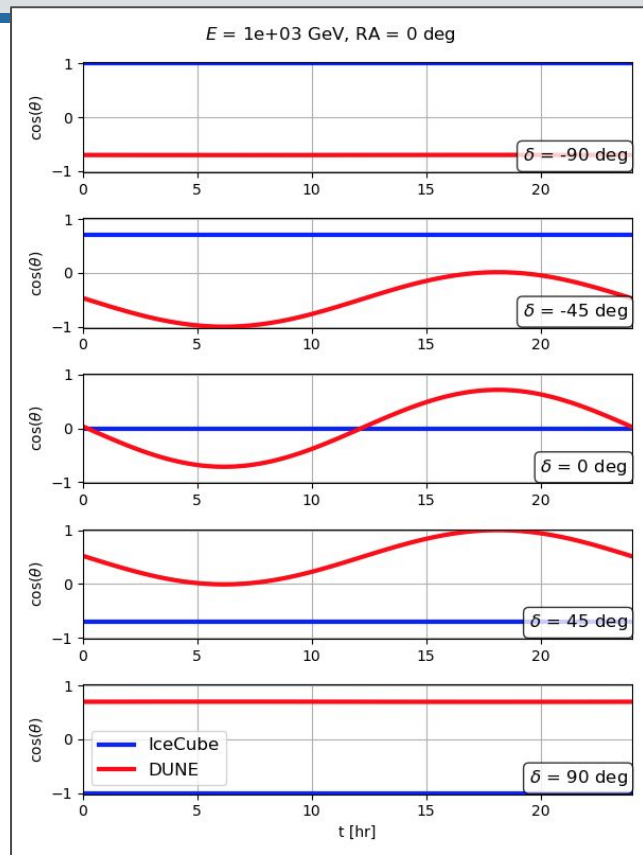
# Dimension-4 Oscillogram

- signal for  $a$  is flat in energy
- The dimension-4 operator,  $c$ , gives rise to oscillations that appear for upgoing neutrinos at low energies and then for most zenith angles at high energies



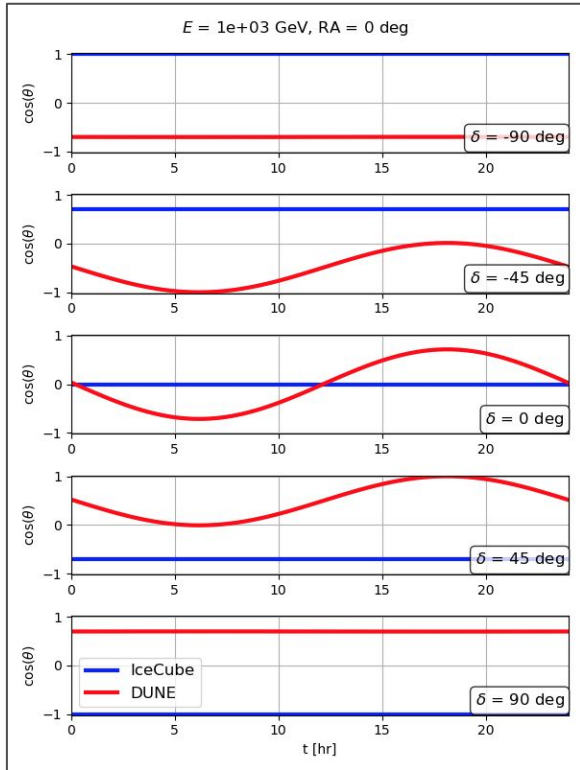
# Including DUNE

- LIV oscillations depend on the following neutrino properties:
  - $E$  (dimension  $>3$  only)
  - $L$
  - $RA$
  - $\delta$
- For IceCube,  $\delta$  completely defines  $\cos\theta$  and thus  $L$ 
  - Since IceCube is located on the Earth's axis
- For DUNE,  $\delta \rightarrow L$  is time-dependent due to Earth's rotation
- $\rightarrow$  The same LIV physics produces different signals in IceCube and DUNE

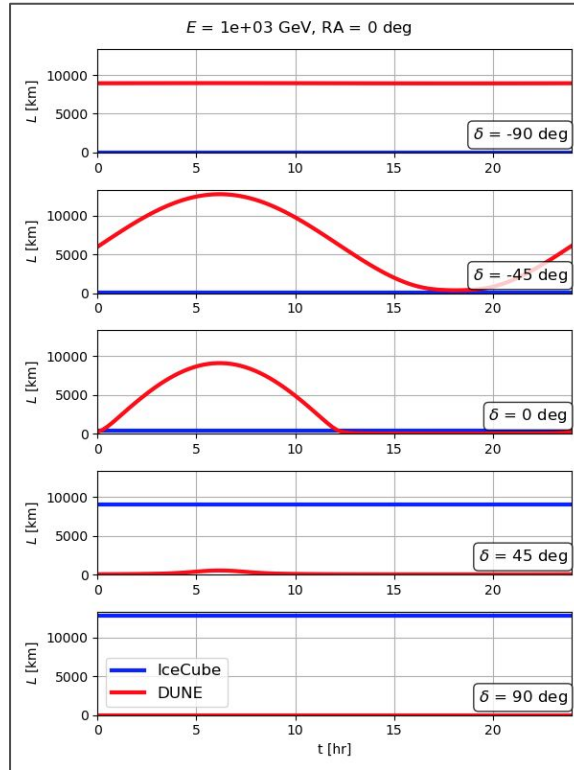


# Including DUNE

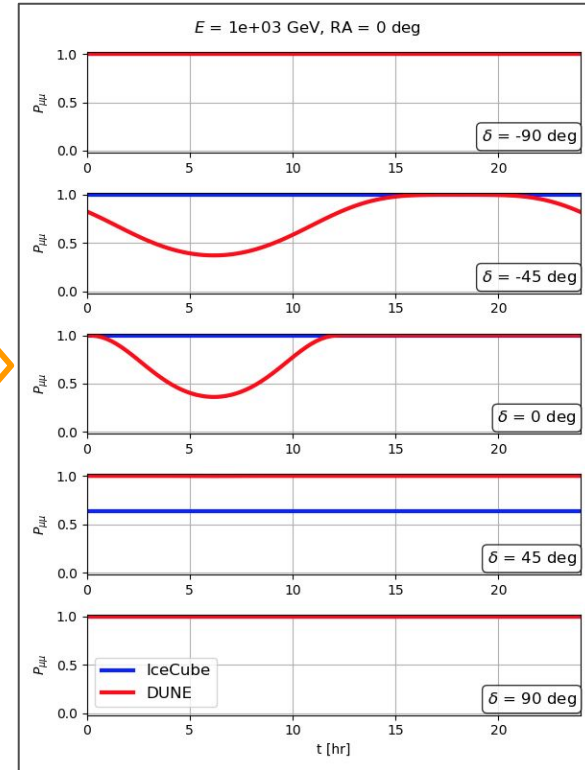
cos(zenith)



L



$P_{\mu\mu}$



# Summary

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- Investigating phenomenology of directional LIV in IceCube and DUNE
  - Focussed on dim-3 and -4 operators
- Effects depend on neutrino E and L, direction w.r.t. LIV frame, and detector location
- Clear synergies between IceCube and DUNE
  - Signals across broad E range
  - Time-dependence of signal in DUNE, not in IceCube → two different signals to cross-check
- Next steps:
  - Implement model as Hamiltonian and integrate into a full oscillation solver
  - Find “money plots” for how best to visualise time-dependence synergy
  - Combine with fluxes, effective areas to estimate signals in IceCube and DUNE
  - Document study in overleaf
- Our code is here: [https://github.com/ts4051/IceDUNE LIV](https://github.com/ts4051/IceDUNE_LIV)



# Useful references

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- Recent IceCube studies examined rotation independent LIV (<https://arxiv.org/abs/1709.03434>)
  - Energy / Zenith study with dimension 3+ operators
- Last IceCube study of sidereal effects (IC-40) (<https://arxiv.org/abs/1010.4096>)
  - Minimal SME study in right ascension
- Review of Lorentz and CPT violation phenomenology in the neutrino sector (<https://arxiv.org/abs/hep-ph/0309025>)
  - Formal look at the theory
- Lorentz violation in MiniBooNE (<https://arxiv.org/abs/1206.6915>)
  - Slightly nicer breakdown of the theory
- Existing constraints (<https://arxiv.org/abs/0801.0287>)