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Neutrinos as Probes for Lorentz and CPT Symmetry

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Snowmass2021 - Letter of Interest

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Why Lorentz violation?

- Candidate descriptions of quantum gravity involve LV
- General theoretical framework: Standard-Model Extension
- Definite experimental signatures
- High-precision measurements allow experimental exploration

General theoretical framework: Standard-Model Extension

Colladay & Kostelecky, PRD 55, 6760 (1997)
Colladay & Kostelecky, PRD 58, 116002 (1998)
Kostelecky, PRD 69, 105009 (2004)

SME	=	standard model coupled to general relativity	+	all observer scalars that break Lorentz invariance

$$\mathcal{L} \supseteq \frac{i}{2} c_{\mu\nu} (\bar{\psi} \gamma^\mu \partial^\nu \psi) - \frac{1}{2} a_\mu (\bar{\psi} \gamma^\mu \psi) + \text{h.c.}$$

- standard field operators
- controlling coefficients
- observer scalars
- subset includes CPT violation
- well-defined experimental signatures

Neutrinos in the SME

Kostelecky & Mewes, PRD 69, 016005 (2004)

$$H_{\text{eff}} = \left(\begin{array}{c|c} h_0 & 0 \\ \hline 0 & h_0^* \end{array}\right) + \left(\begin{array}{c|c} \delta h_{\nu\nu} & \delta h_{\nu\bar{\nu}} \\ \hline \delta h_{\bar{\nu}\nu} & \delta h_{\bar{\nu}\bar{\nu}} \end{array}\right)$$

6x6 matrix

Neutrino block (minimal)

$$H^{\nu}_{ab} = |\boldsymbol{p}|\delta_{ab} + \frac{\boldsymbol{m}^2_{ab}}{2|\boldsymbol{p}|} + (a_L)^{\alpha}_{ab}\,\hat{p}_\alpha - (c_L)^{\alpha\beta}_{ab}\,\hat{p}_\alpha\,\hat{p}_\beta\,|\boldsymbol{p}|$$

$a,b{=}e,\mu,\tau;\ \hat{p}^\alpha{=}(1;\hat{\boldsymbol{p}})$

- unconventional energy dependence
- direction dependence
- sidereal time dependence
- CPT violation
- ν-$\bar{\nu}$ mixing
- for nonminimal terms

Kostelecky & Mewes, PRD 85, 096005 (2012)

in realistic effective field theory, CPT violation comes with Lorentz violation

SME neutrino sector

flavor mixing

- neutrino/antineutrino mixing
- neutrino-antineutrino mixing

oscillation free

- weak decays
- Cherenkov processes
- modified velocity

- oscillations
- astrophysical flavor ratios

Daya Bay, Double Chooz, DUNE, IceCube, LNSD, MINOS, MiniBooNE, NOvA, SNO, Super-Kamiokande, T2K

- single beta decay
- double beta decay
- time of flight
- astrophysical processes
- astrophysical dispersion

CUPID, EXO200, GERDA, KATRIN, NEMO3, SuperNEMO

LV Neutrino Oscillations

JSD, Kostelecky, Mewes, PRD 80, 076007 (2009)

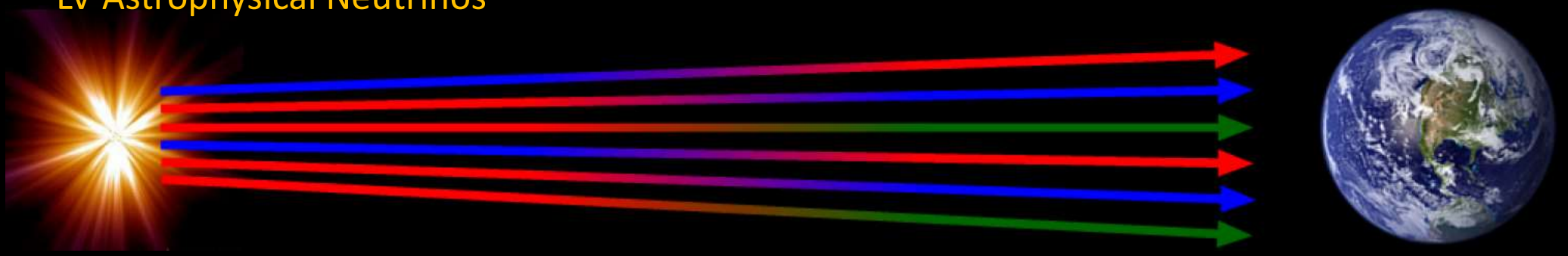
- Earth-based experiments, neutrino direction of propagation changes with frequency $\omega_\oplus = 2\pi/(23\ \mathrm{h}\ 56\ \mathrm{min})$

- Sidereal variation of the oscillation probability

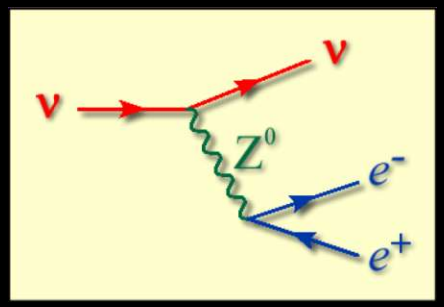
$$P_{\nu_b \to \nu_a} = (P_{\mathcal{C}})_{ab} + (P_{\mathcal{A}_s})_{ab} \sin \omega_\oplus T_\oplus + (P_{\mathcal{A}_c})_{ab} \cos \omega_\oplus T_\oplus + (P_{\mathcal{B}_s})_{ab} \sin 2\omega_\oplus T_\oplus + (P_{\mathcal{B}_c})_{ab} \cos 2\omega_\oplus T_\oplus + \ldots$$

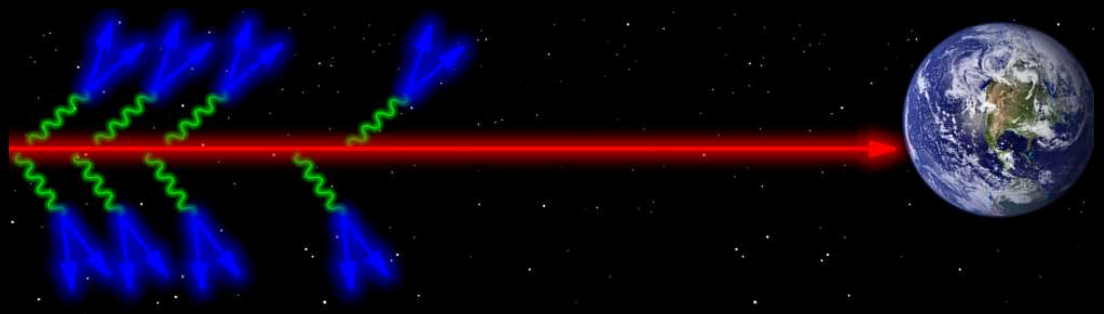
- Effects depend on experiment properties: energy, baseline, and beam direction

LV Astrophysical Neutrinos



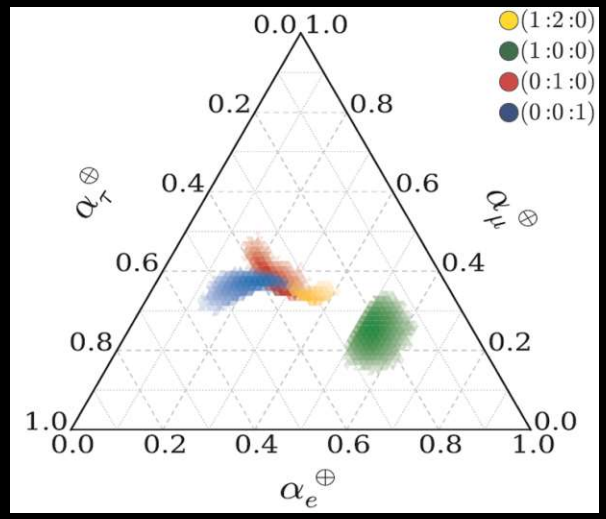
- unconventional processes





JSD, Kostelecky, Mewes, PRD 89, 043005 (2014)

- unconventional flavor ratios

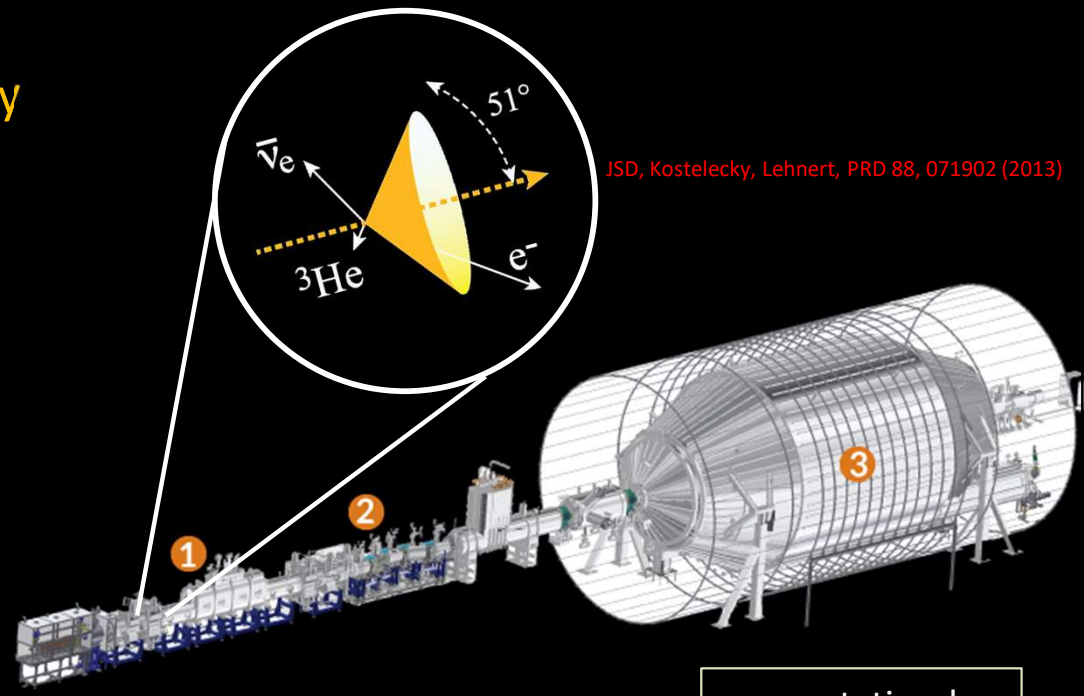


Argüelles, Katori, Salvado, PRL 89, 161303 (2015)

LV Neutrinos in Single and Double Beta Decay

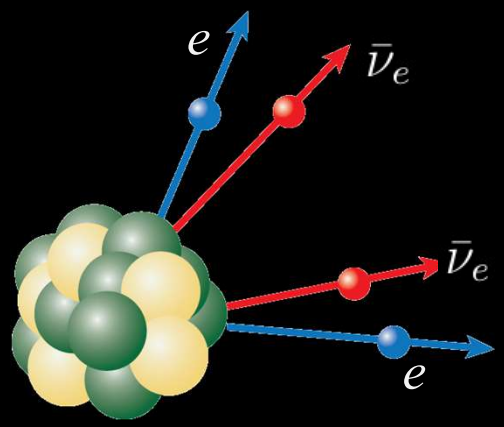
- End-point harmonic shift

$$\frac{d\Gamma}{dT} = B + C[(T_0 + k(t) - T)^2 - \frac{1}{2}m_\nu^2]$$

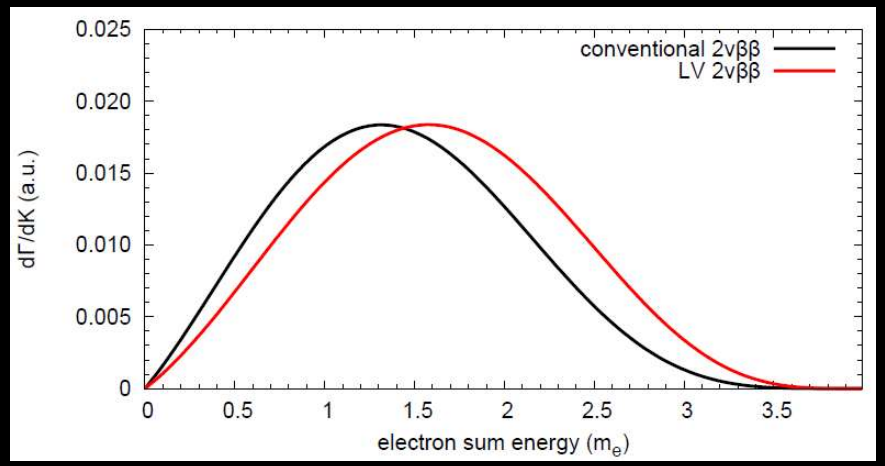


JSD, Kostelecky, Lehnert, PRD 88, 071902 (2013)

- 2νββ spectral distortion



JSD, PRD 89, 036002 (2014)



presentation by Kathrin Valerius in this workshop

Summary

- Predicted the key experimental signatures of Lorentz and CPT violation in
  - neutrino oscillations
  - astrophysical neutrinos
  - single & double beta decays
- Many effects of Lorentz violation **remain unexplored**
- Both low- and high-energy experiments **crucial** to study spacetime symmetries
- **Multi-year efforts** needed to take advantage of unique neutrino opportunities

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