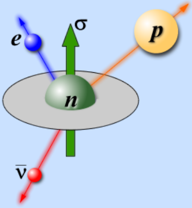
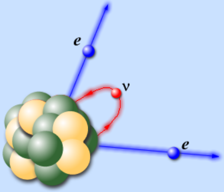
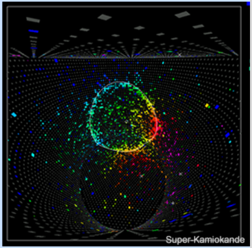
Defying Lorentz invariance with neutrinos

Jorge S. Diaz |

HEP CHILE, 07.01.2016

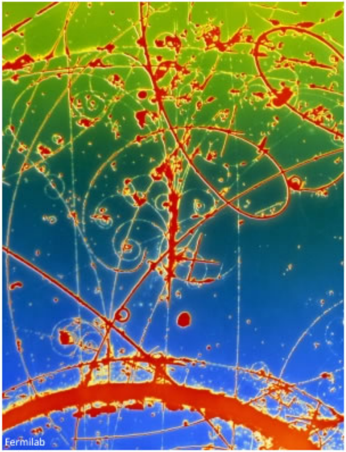






Outline

- Lorentz and CPT violation
- Searching for Lorentz and CPT violation
  - **neutrino oscillations**
  - **beta decays**
- Summary



Lorentz invariance

- Cornerstone of modern physics.
- Symmetry that underlies Special Relativity.
- Laws of physics are independent of speed and direction of propagation.
- Linked to CPT symmetry (relating properties of matter and antimatter).
- Established experiments indicate that nature is Lorentz invariant (so far).

Einstein & Lorentz (1921)

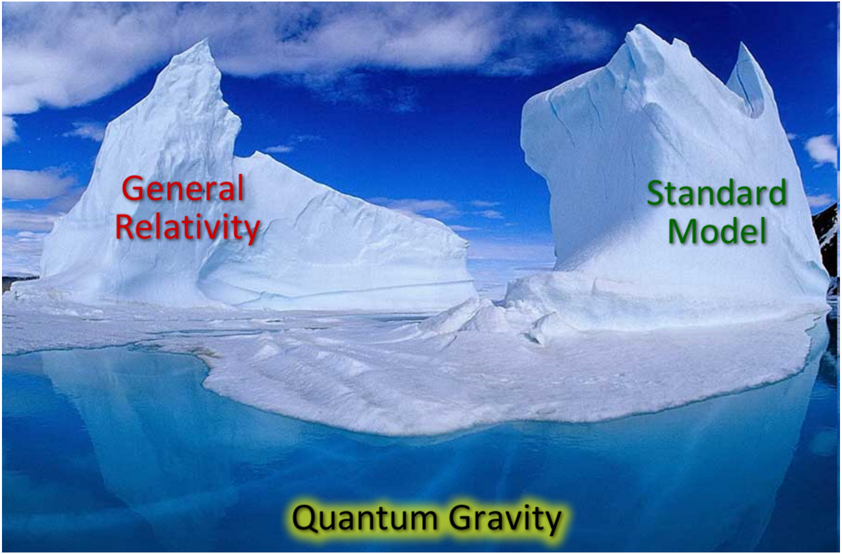
Lorentz violation

- Last 25 years, growing interest in the possibility that Lorentz symmetry may not be exact.
- Quantum gravity candidates involve the breaking of Lorentz symmetry.
- Lorentz symmetry is a basic building block of GR and the SM. Anything this fundamental should be tested.
- New era of high-precision measurements.

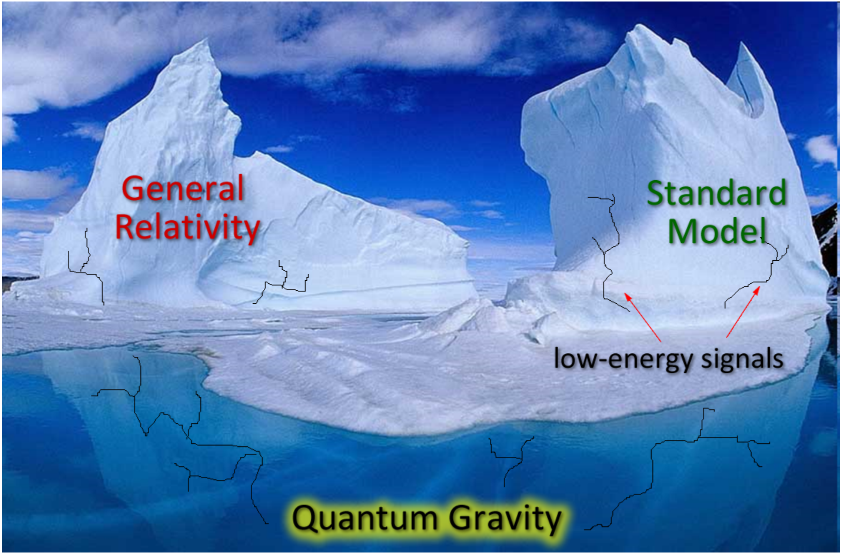
Lorentz violation

GR and the SM are expected to merge
at the Planck scale

Lorentz violation

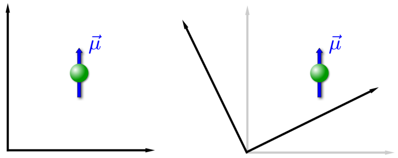


Lorentz violation



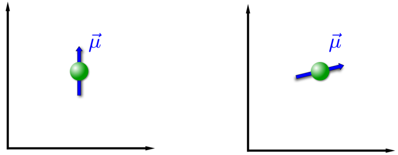
Lorentz transformations

Observer transformation



coordinate invariance

Particle transformation

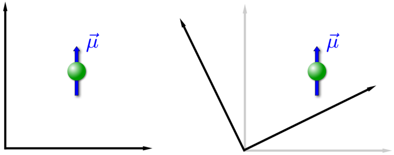


symmetry

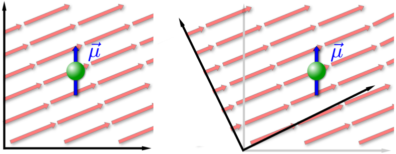
Lorentz transformations

Observer transformation

$$U = -\vec{\mu} \cdot \vec{B} = -\vec{\mu}' \cdot \vec{B}'$$

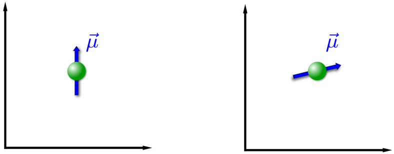


coordinate invariance



coordinate invariance

Particle transformation

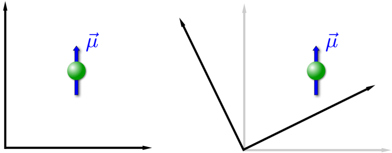


symmetry

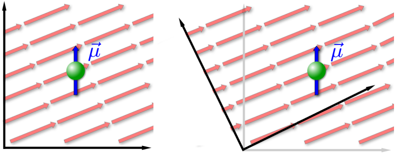
Lorentz transformations

Observer transformation

$$U = -\vec{\mu} \cdot \vec{B} = -\vec{\mu}' \cdot \vec{B}'$$



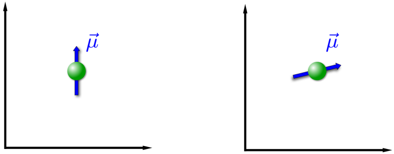
coordinate invariance



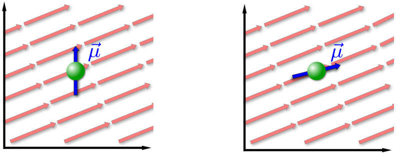
coordinate invariance

Particle transformation

$$U = -\vec{\mu} \cdot \vec{B} \neq -\vec{\mu}' \cdot \vec{B}$$



symmetry

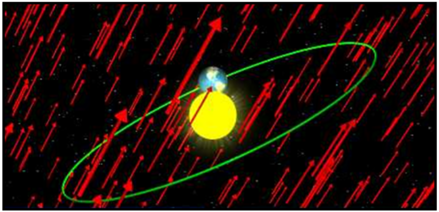


broken symmetry

Standard-Model Extension (SME)

SME $=$	**Standard Model coupled to General Relativity**	$+$	**all possible terms that break Lorentz symmetry**

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



- general framework to search for Lorentz violation
- defined experimental signatures

example (from fermion sector):

$$\mathcal{L}_{\text{LV}} \supset a_\mu \left(\overline{\psi}\gamma^\mu\psi\right)$$

- Standard fields
- Controlling coefficients
- Observer scalars
- CPT violation included (no $m \neq \bar{m}$ terms)

SME: theory & experiment playground

Studies of CPT and Lorentz violation involve:

- beta decay
- neutrino oscillations
- oscillations and decays of K, B, D mesons
- particle-antiparticle comparisons
- matter interferometry
- birefringence and dispersion from cosmological sources
- clock-comparison measurements
- CMB polarization
- collider experiments
- electromagnetic resonant cavities
- equivalence principle
- gauge and Higgs particles
- high-energy astrophysical observations
- laboratory and gravimetric tests of gravity
- post-newtonian gravity in the solar system and beyond
- second- and third-generation particles
- space-based missions
- spectroscopy of hydrogen and antihydrogen
- spin-polarized matter

Neutrinos in the SME

Neutrinos in the SME

effective hamiltonian

Kostelecký & Mewes, PRD 69, 016005 (2004)

$$\boldsymbol{H}_{\text{eff}} = \left(\begin{array}{c|c} h_0 & 0 \\ \hline 0 & h_0^* \end{array}\right) + \left(\begin{array}{c|c} \delta h_{\nu\nu} & \delta h_{\nu\bar{\nu}} \\ \hline \delta h_{\bar{\nu}\nu} & \delta h_{\bar{\nu}\bar{\nu}} \end{array}\right) \qquad \leftarrow 6 \times 6 \text{ matrix}$$

Minimal* neutrino 3×3 block:

$$\boldsymbol{H}^{\nu}_{ab} = |\boldsymbol{p}|\delta_{ab} + \frac{\boldsymbol{m}^2_{ab}}{2|\boldsymbol{p}|} + (a_L)^{\alpha}_{ab}\,\hat{p}_{\alpha} - (c_L)^{\alpha\beta}_{ab}\,\hat{p}_{\alpha}\,\hat{p}_{\beta}\,|\boldsymbol{p}|, \qquad a,b=e,\mu,\tau;\ \hat{p}^{\alpha}=(1;\hat{\boldsymbol{p}})$$

Novel effects

- **unconventional energy dependence**
- **direction dependence**
- **sidereal time dependence**
- **CPT violation**
- $\nu - \bar{\nu}$ **mixing**

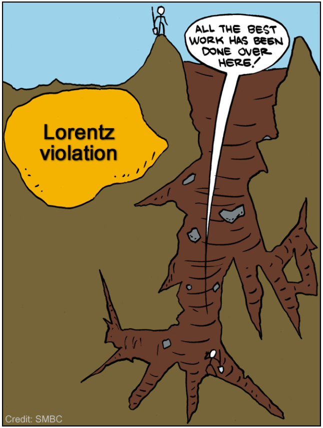
Higher derivatives appear by including operators of arbitrary dimension d

Kostelecký & Mewes, PRD 85, 096005 (2012)

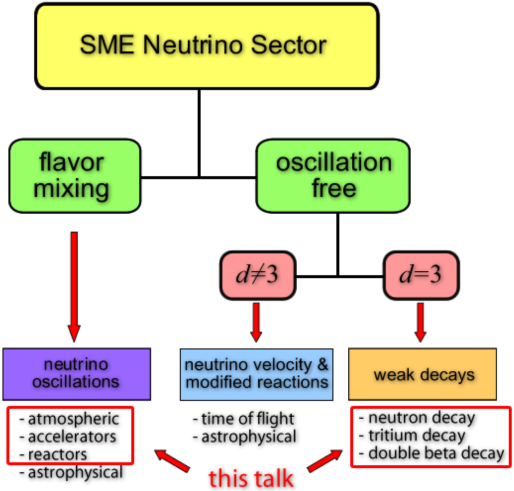
*: operators of dimension three and four only

Experimental searches

Complementarity between experiments

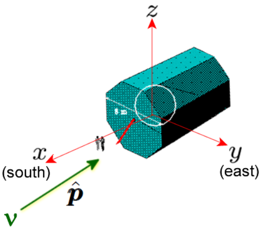


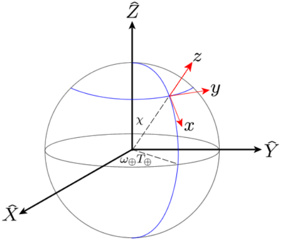
Credit: SMBC

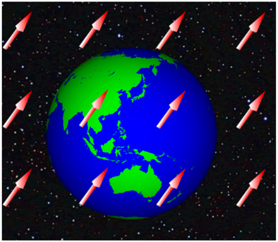


LV neutrino oscillations

Kostelecký & Mewes, PRD 70, 076002 (2004)
JSD, Kostelecký & Mewes, PRD 80, 076007 (2009)







Sidereal variation of the oscillation probability:

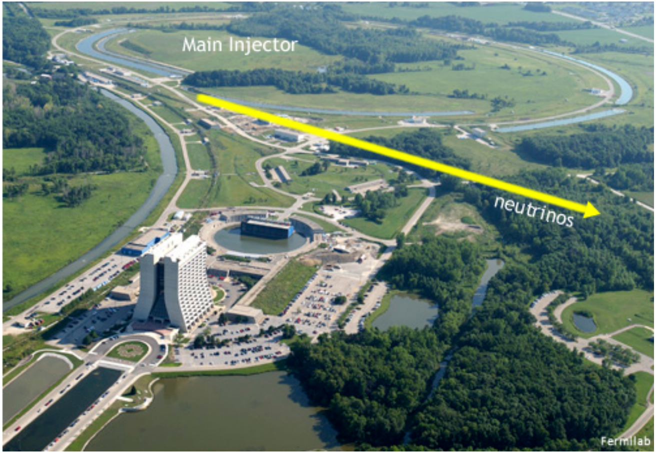
$$
\begin{aligned}
P_{\nu_b \to \nu_a} = (P_{\mathcal{C}})_{ab} &+ (P_{\mathcal{A}_s})_{ab} \sin \omega_\oplus T_\oplus + (P_{\mathcal{A}_c})_{ab} \cos \omega_\oplus T_\oplus \\
&+ (P_{\mathcal{B}_s})_{ab} \sin 2\omega_\oplus T_\oplus + (P_{\mathcal{B}_c})_{ab} \cos 2\omega_\oplus T_\oplus \\
&+ \ldots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

LV neutrino oscillations

Example: accelerator neutrinos

JSD, Kostelecký & Mewes, PRD 80, 076007 (2009)
MINOS, PRL 105, 151601 (2010)

$$P_{\nu_\mu\to\nu_\tau} = P^{(0)}_{\nu_\mu\to\nu_\tau} + P^{(1)}_{\nu_\mu\to\nu_\tau}$$



LV neutrino oscillations

PRL **105,** 151601 (2010) PHYSICAL REVIEW LETTERS week ending 8 OCTOBER 2010

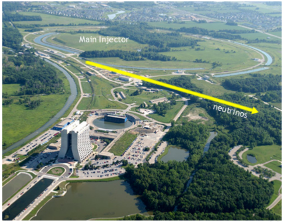
Search for Lorentz Invariance and *CPT* Violation with the MINOS Far Detector

(MINOS Collaboration)

In the SME, $P^{(1)}_{\mu\tau}$ is given by [8]

$$P^{(1)}_{\mu\tau} = 2L\{(P^{(1)}_{\mathcal{C}})_{\tau\mu} + (P^{(1)}_{\mathcal{A}_s})_{\tau\mu}\sin\omega_\oplus T_\oplus + (P^{(1)}_{\mathcal{A}_c})_{\tau\mu}\cos\omega_\oplus T_\oplus + (P^{(1)}_{\mathcal{B}_s})_{\tau\mu}\sin 2\omega_\oplus T_\oplus + (P^{(1)}_{\mathcal{B}_c})_{\tau\mu}\cos 2\omega_\oplus T_\oplus\}, \quad (1)$$

where $L = 735$ km is the distance from neutrino production in the NuMI beam to the MINOS FD [2], $T_\oplus$ is the local sidereal time (LST) at neutrino detection, and the coefficients $(P^{(1)}_{\mathcal{C}})_{\tau\mu}$, $(P^{(1)}_{\mathcal{A}_s})_{\tau\mu}$, $(P^{(1)}_{\mathcal{A}_c})_{\tau\mu}$, $(P^{(1)}_{\mathcal{B}_s})_{\tau\mu}$, and $(P^{(1)}_{\mathcal{B}_c})_{\tau\mu}$ contain the LV and CPTV information.



Fermilab

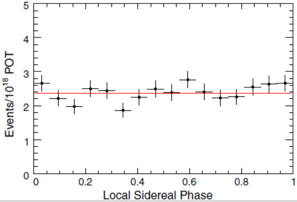


TABLE III. 99.7% C.L. limits on SME coefficients for $\nu_\mu \to \nu_\tau$; $(a_L)^\alpha_{\mu\tau}$ have units [GeV]; $(c_L)^{\alpha\beta}_{\mu\tau}$ are unitless.

Coeff.	Limit	Coeff.	Limit
$(a_L)^X_{\mu\tau}$	5.9×10^{-23}	$(a_L)^Y_{\mu\tau}$	6.1×10^{-23}
$(c_L)^{TX}_{\mu\tau}$	0.5×10^{-23}	$(c_L)^{TY}_{\mu\tau}$	0.5×10^{-23}
$(c_L)^{XX}_{\mu\tau}$	2.5×10^{-23}	$(c_L)^{YY}_{\mu\tau}$	2.4×10^{-23}
$(c_L)^{XY}_{\mu\tau}$	1.2×10^{-23}	$(c_L)^{YZ}_{\mu\tau}$	0.7×10^{-23}
$(c_L)^{XZ}_{\mu\tau}$	0.7×10^{-23}	...	...

LV neutrino oscillations

Example: reactor antineutrinos

JSD, Katori, Spitz & Conrad, PLB 727, 412 (2013)

$$P_{\bar{\nu}_e\to\bar{\nu}_e} = P^{(0)}_{\bar{\nu}_e\to\bar{\nu}_e} - P^{(2)}_{\bar{\nu}_e\to\nu_x}$$

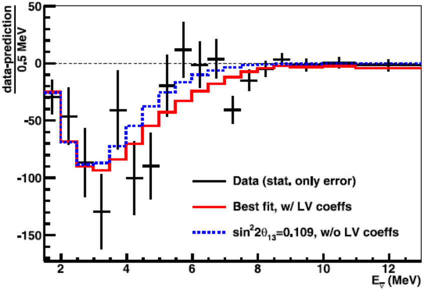
Credit: QuantumDiaries.org

LV neutrino oscillations

JSD, Katori, Spitz & Conrad, PLB 727, 412 (2013)

Chooz nuclear power station next to the *Meuse* river (France)

Double Chooz Collaboration



upper limits (90% CL)

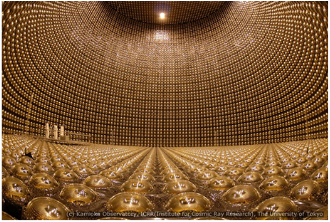
–	$\lvert\tilde{g}^{ZT}_{e\bar{e}}\rvert < 9.7 \times 10^{-18}$	$\lvert\tilde{g}^{ZZ}_{e\bar{e}}\rvert < 3.3 \times 10^{-17}$
–	$\lvert\tilde{g}^{ZT}_{\mu\bar{\mu}}\rvert < 2.3 \times 10^{-16}$	$\lvert\tilde{g}^{ZZ}_{\mu\bar{\mu}}\rvert < 8.1 \times 10^{-16}$
–	$\lvert\tilde{g}^{ZT}_{\tau\bar{\tau}}\rvert < 2.3 \times 10^{-16}$	$\lvert\tilde{g}^{ZZ}_{\tau\bar{\tau}}\rvert < 8.1 \times 10^{-16}$
$\lvert\widetilde{H}^{Z}_{e\bar{\mu}}\rvert < 1.4 \times 10^{-19}$	$\lvert\tilde{g}^{ZT}_{e\bar{\mu}}\rvert < 2.7 \times 10^{-17}$	$\lvert\tilde{g}^{ZZ}_{e\bar{\mu}}\rvert < 9.3 \times 10^{-17}$
$\lvert\widetilde{H}^{Z}_{e\bar{\tau}}\rvert < 1.4 \times 10^{-19}$	$\lvert\tilde{g}^{ZT}_{e\bar{\tau}}\rvert < 2.7 \times 10^{-17}$	$\lvert\tilde{g}^{ZZ}_{e\bar{\tau}}\rvert < 9.3 \times 10^{-17}$
$\lvert\widetilde{H}^{Z}_{\mu\bar{\tau}}\rvert < 1.7 \times 10^{-18}$	$\lvert\tilde{g}^{ZT}_{\mu\bar{\tau}}\rvert < 4.4 \times 10^{-16}$	$\lvert\tilde{g}^{ZZ}_{\mu\bar{\tau}}\rvert < 1.5 \times 10^{-15}$

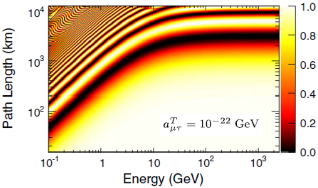
LV neutrino oscillations

Example: atmospheric neutrinos

Super-Kamiokande, PRD 91, 052003 (2015)

$$P_{\nu_\mu\to\nu_\mu} = P^{(0)}_{\nu_\mu\to\nu_\mu} + P^{(1)}_{\nu_\mu\to\nu_\mu}$$





	LV parameter	Limit at 95% C.L.
$e\mu$	$\mathrm{Re}(a^T)$	1.8×10^{-23} GeV
	$\mathrm{Im}(a^T)$	1.8×10^{-23} GeV
	$\mathrm{Re}(c^{TT})$	8.0×10^{-27}
	$\mathrm{Im}(c^{TT})$	8.0×10^{-27}
$e\tau$	$\mathrm{Re}(a^T)$	4.1×10^{-23} GeV
	$\mathrm{Im}(a^T)$	2.8×10^{-23} GeV
	$\mathrm{Re}(c^{TT})$	9.3×10^{-25}
	$\mathrm{Im}(c^{TT})$	1.0×10^{-24}
$\mu\tau$	$\mathrm{Re}(a^T)$	6.5×10^{-24} GeV
	$\mathrm{Im}(a^T)$	5.1×10^{-24} GeV
	$\mathrm{Re}(c^{TT})$	4.4×10^{-27}
	$\mathrm{Im}(c^{TT})$	4.2×10^{-27}

LV neutrino oscillations

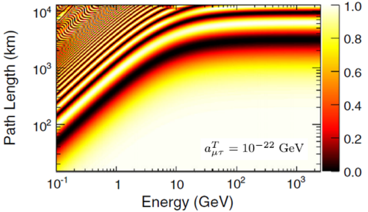
Karlsruhe Institute of Technology

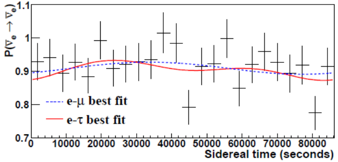
Experimental searches

Kostelecký & Mewes, PRD 70, 076002 (2004)
JSD, Kostelecký & Mewes, PRD 80, 076007 (2009)

- **LSND** PRD 72, 076004 (2005)
- **MINOS** PRL 101, 151601 (2008)
- **IceCube** PRD 82, 112003 (2010)
- **MINOS** PRL 105, 151601 (2010)
- **MINOS** PRD 85, 031101 (2012)
- **Double Chooz** PRD 86, 112009 (2012)
- **MiniBooNE** PLB 718, 1303 (2013)
- Rebel & Mufson AP 48, 78 (2013)
- Conrad, JSD, Katori, Spitz PLB 727, 412 (2013)
- **Super-Kamiokande** PRD 91, 052003 (2015)
- . . .

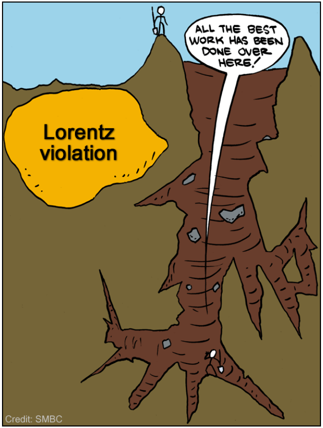
Super-Kamiokande (2015)





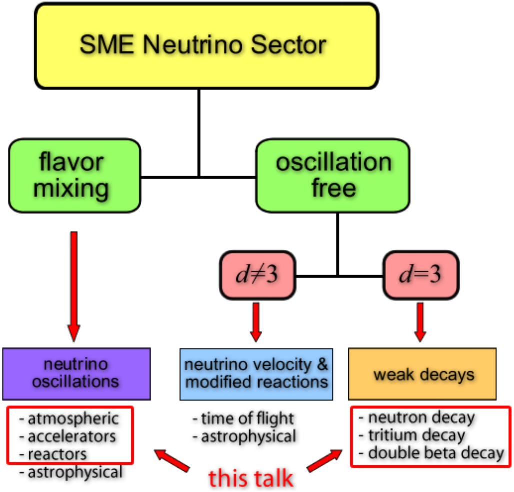
Double Chooz (2012)

Experimental searches



Credit: SMBC

Complementarity between experiments

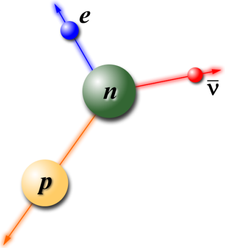


LV beta decay

Theoretical considerations:

JSD, Kostelecký & Lehnert, PRD 88, 071902 (2013)
JSD, Adv.HEP 2014, 305298 (2014)

- antineutrino spinors get modified
- modified antineutrino phase space
- coefficients: $(a_{\text{of}}^{(3)})_{jm}$



$$d\Gamma \propto E\omega \left\{ 1 + a\frac{\boldsymbol{p}\cdot\widetilde{\boldsymbol{q}}}{E\omega} + A\,\frac{\hat{\boldsymbol{n}}\cdot\boldsymbol{p}}{E} + B\,\frac{\hat{\boldsymbol{n}}\cdot\widetilde{\boldsymbol{q}}}{\omega} + D\,\frac{\hat{\boldsymbol{n}}\cdot(\boldsymbol{p}\times\widetilde{\boldsymbol{q}})}{E\omega} \right\} \frac{d^3p}{2E}\,\frac{d^3q}{2\omega}\;\delta(E+\omega-E_0)$$

Observable effects

- spectrum distortion: $(a_{\text{of}}^{(3)})_{00}$
- modified angular correlations: $(a_{\text{of}}^{(3)})_{10}$, $(a_{\text{of}}^{(3)})_{11}$

LV in W boson

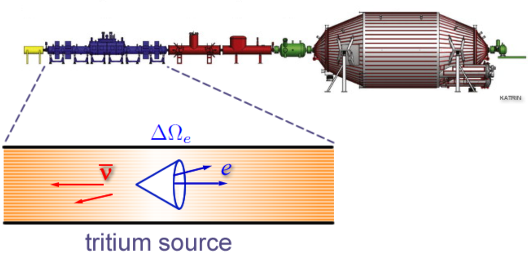
Vos et al., PRC 92, 052501 (2015)
Vos et al., PRC 91, 038501 (2015)
Vos et al., Rev. Mod. Phys. (2015)
Vos et al.,PLB 729, 112 (2014)
Noordmans et al.,PRD 89, 101702 (2014)
Noordmans, PRC 87, 055502 (2013)
Altschul, PRD 88, 076015 (2013)
Dijck et al., PRD 88, 07190 (2013)
Noordmans et al., PRL 111, 171601 (2013)
Müller et al., PRD 88, 071901 (2013)

LV tritium decay

Endpoint measurements

JSD, Kostelecký & Lehnert, PRD 88, 071902 (2013)
JSD, Adv.HEP 2014, 305298 (2014)

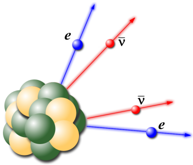
$$\frac{d\Gamma}{dE} \propto \int_{\Delta\Omega_e} E|\boldsymbol{p}|\, d\Omega_e\, \frac{d^3q}{2\omega}\, \delta(E+\omega-E_0)$$



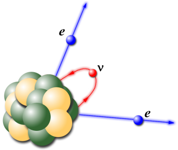
- Mainz
- Troitsk
- KATRIN

LV double beta decay

JSD, Kostelecký & Lehnert, PRD 88, 071902 (2013)
JSD, PRD 89, 036002 (2014)



$$\Gamma \propto \int \overline{|\mathcal{M}^{2\nu}|^2} F(Z,E_1)F(Z,E_2) \times \delta(E_1+E_2+\omega_1+\omega_2-\Delta M) \times \frac{d^3p_1}{2E_1}\frac{d^3p_2}{2E_2}\frac{d^3q_1}{2\omega_1}\frac{d^3q_2}{2\omega_2}$$



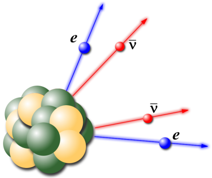
$$\Gamma \propto \int \overline{|\mathcal{M}^{0\nu}|^2} F(Z,E_1)F(Z,E_2) \times \delta(E_1+E_2-\Delta M)\frac{d^3p_1}{2E_1}\frac{d^3p_2}{2E_2}$$

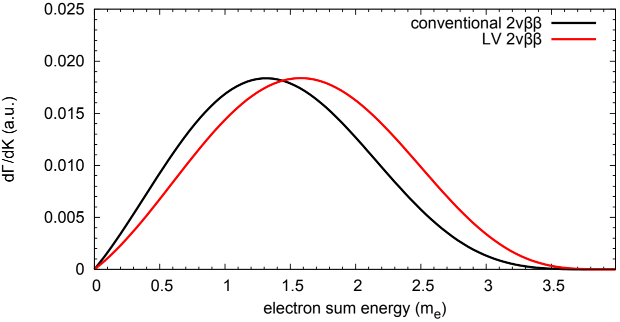
LV double beta decay: $2\nu\beta\beta$

Isotropic spectral distortion

JSD, Kostelecký & Lehnert, PRD 88, 071902 (2013)
JSD, PRD 89, 036002 (2014)

- directionality is irrelevant
- unconventional energy dependence modifies the sum electron spectrum





LV double beta decay: $0\nu\beta\beta$

Half-life gets modified

JSD, Kostelecký & Lehnert, PRD 88, 071902 (2013)
JSD, PRD 89, 036002 (2014)

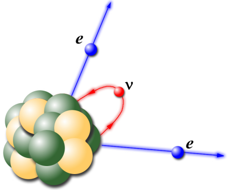
- neutrino propagator modifies the effective mass

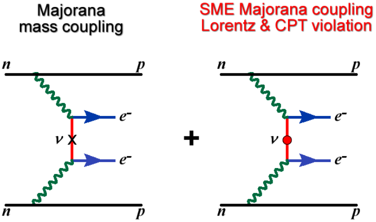
$$\boxed{\frac{1}{T_{1/2}} = G(Z,Q)\,|M^{0\nu}|^2\,m^2}$$

$$m^2 \rightarrow m^2 + m\frac{g}{R} + \left(\frac{g}{R}\right)^2$$

R: nuclear radius

- **neutrinoless double beta decay can occur for massless neutrinos**





LV double beta decay: $0\nu\beta\beta$

Karlsruhe Institute of Technology

$\beta\beta$ angular correlation

JSD, PRD 89, 036002 (2014)

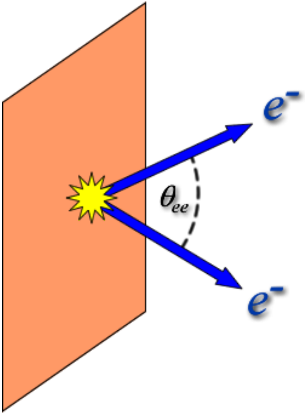
- unique sensitivity for experiments with tracking system
- angular correlation

$$\frac{d\Gamma}{dx_1 dx_2} = \frac{\Gamma}{4}(1 - K\, x_1 x_2)$$

- forward-backward asymmetry

$$\mathcal{A} = \frac{N_+ - N_-}{N_+ - N_-} \propto K,$$

with $N_\pm$ events with $\theta_{ee} \gtrless 90^\circ$



Majorana-mass case: $\mathcal{A}$ is constant

LV case: $\mathcal{A}$ depends on location and can vary sidereal time

Summary

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- We have determined the **key experimental signatures** of Lorentz and CPT violation in
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  - astrophysical neutrinos
  - single & double beta decays ← this talk
- Many effects of Lorentz violation **remain unexplored**
- Interesting prospects for **low- and high-energy experiments**
- Rich and active research area for **theory-experiment collaboration**

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> *"Today we say that the law of relativity is supposed to be true at all energies, but someday somebody may come along and say how stupid we were."*
>
> R.P. Feynman