Karlsruhe Institute of Technology

Tests of Lorentz and CPT invariance with neutrinos and photons

Jorge S. Diaz |

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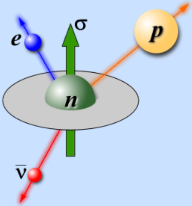
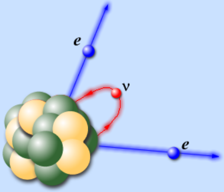
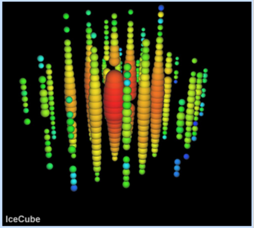
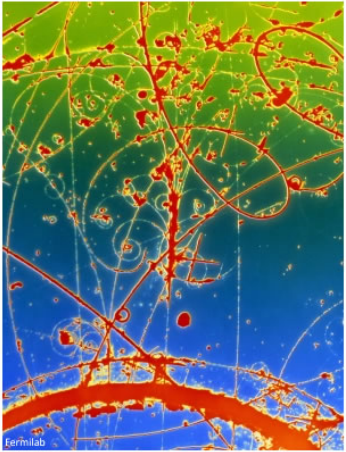






Outline

- Lorentz symmetry and violation
  - **Standard-Model Extension**
- Searching for Lorentz and CPT violation
  - **neutrino oscillations**
  - **high-energy neutrinos**
  - **high-energy photons**



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 20 years, growing interest in the possibility that Lorentz symmetry may not be exact.

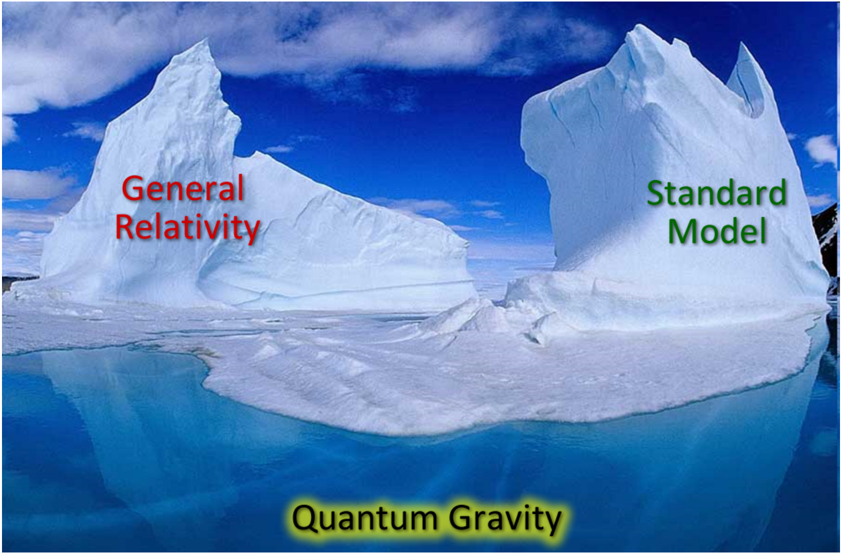
- Quantum gravity candidates involve the breaking of Lorentz symmetry.

- Lorentz symmetry is a basic building block of GR and the SM. Anything this fundamental should be tested.
- New era of high-precision measurements.

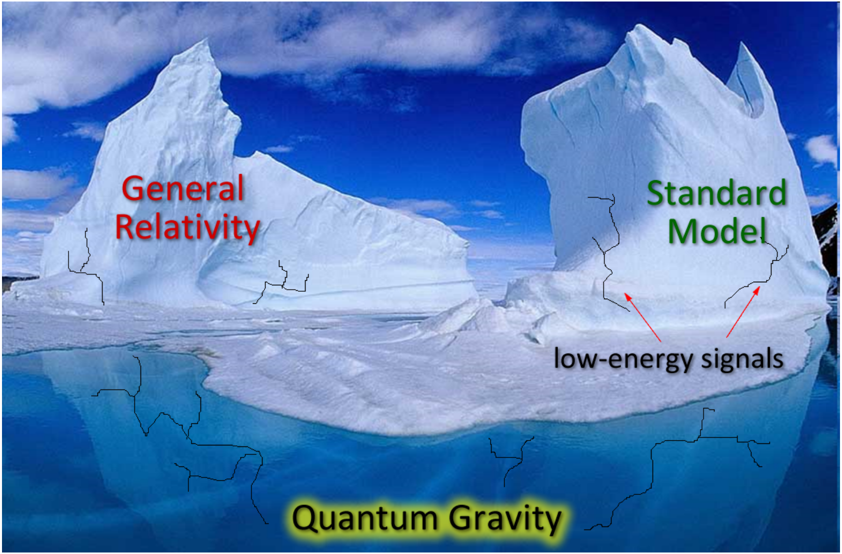
Lorentz violation

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

Lorentz violation

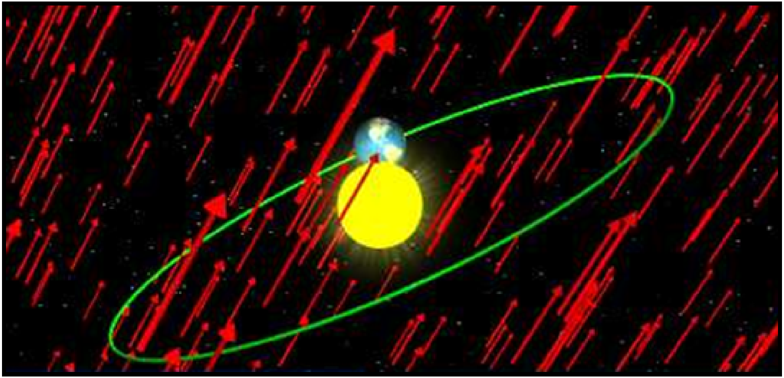


Lorentz violation



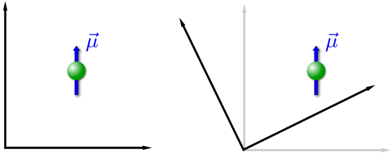
Lorentz violation

Does the universe have a preferred direction?



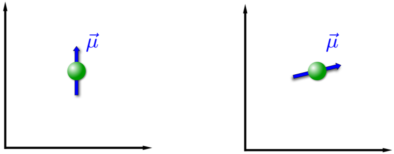
Lorentz transformations

Observer transformation



coordinate invariance

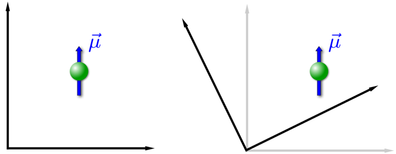
Particle transformation



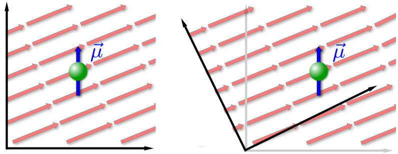
symmetry

Lorentz transformations

Observer transformation

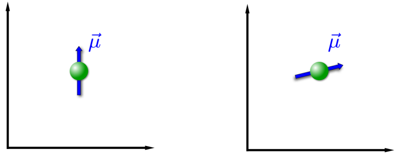


coordinate invariance



coordinate invariance

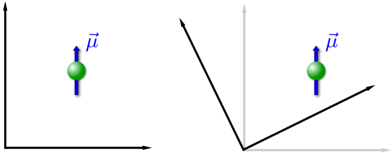
Particle transformation



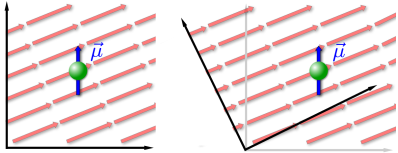
symmetry

Lorentz transformations

Observer transformation

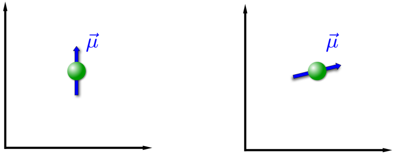


coordinate invariance

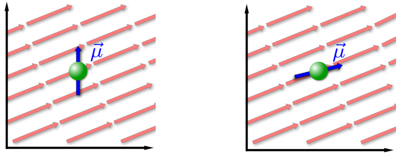


coordinate invariance

Particle transformation



symmetry

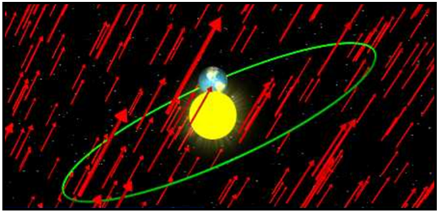


broken symmetry

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

KIT
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Studies of CPT and Lorentz violation involve:

- neutrino oscillations
- beta decay
- 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

SME: worldwide searches

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Neutrinos in the SME

Searching for Lorentz-violating neutrinos

Neutrinos in the SME

effective hamiltonian

Kostelecký & Mewes, PRD **69**, 016005 (2004)

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

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

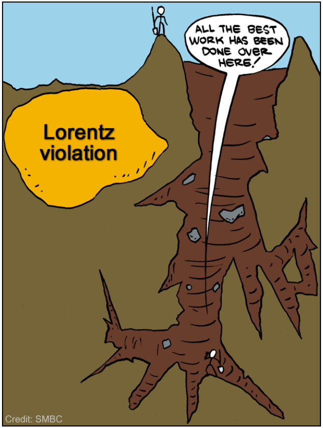
- **unconventional energy dependence**
- **direction dependence**
- **sidereal time dependence**
- **CPT violation**
- **ν-$\bar{\nu}$ mixing**

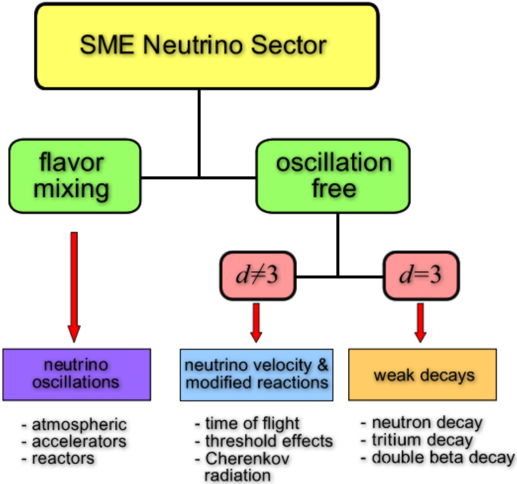
Higher derivatives appear by including operators of arbitrary dimension d

Kostelecký & Mewes, PRD **85**, 096005 (2012)

Experimental searches

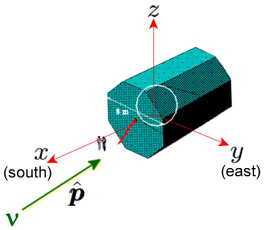
Complementarity between experiments

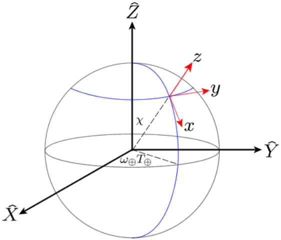


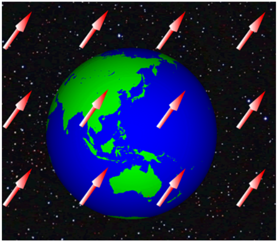


LV neutrino oscillations

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

LV as a perturbation over mass-driven oscillations

- characterize effective hamiltonian

JSD, Kostelecký & Mewes, PRD **80**, 076007 (2009)

$$\boldsymbol{H}_{\text{eff}} = \boldsymbol{H}_0 + \delta\boldsymbol{H}$$

- perturbation theory $\rightarrow$ construct 6×6 time-evolution operator

$$\boldsymbol{S}(t) = e^{-i\boldsymbol{H}_{\text{eff}}t} = \boldsymbol{S}^{(0)}(t) + \boldsymbol{S}^{(1)}(t) + \boldsymbol{S}^{(2)}(t) + \cdots$$

- derive oscillation probabilities ($A, B = e, \mu, \tau, \bar{e}, \bar{\mu}, \bar{\tau}$)

$$P_{\nu_B \rightarrow \nu_A}(t) = \left|\boldsymbol{S}^{(0)}(t) + \boldsymbol{S}^{(1)}(t) + \boldsymbol{S}^{(2)}(t) + \cdots\right|^2$$

LV neutrino oscillations

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$$P_{\nu_B\rightarrow\nu_A}(t) = \left|\boldsymbol{S}^{(0)}(t) + \boldsymbol{S}^{(1)}(t) + \boldsymbol{S}^{(2)}(t) + \cdots\right|^2$$

Neutrino Osc.	Antineutrino Osc.	Neutrino-antineutrino Osc.
$P^{(0)}_{\nu_b\rightarrow\nu_a}$	$P^{(0)}_{\bar{\nu}_b\rightarrow\bar{\nu}_a}$	–
$P^{(1)}_{\nu_b\rightarrow\nu_a}$	$P^{(1)}_{\bar{\nu}_b\rightarrow\bar{\nu}_a}$	–
$P^{(2)}_{\nu_b\rightarrow\nu_a}$	$P^{(2)}_{\bar{\nu}_b\rightarrow\bar{\nu}_a}$	$P^{(2)}_{\nu_b\rightarrow\bar{\nu}_a}$

LV neutrino oscillations

Example: ν_μ disappearance

JSD, Kostelecký & Mewes, PRD **80**, 076007 (2009)

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

$$\begin{aligned}
P^{(0)}_{\nu_\mu \to \nu_\tau} &= \sin^2 2\theta_{23} \sin^2 \left(1.27 \Delta m^2_{\text{atm}} L/E\right) \\
P^{(1)}_{\nu_\mu \to \nu_\tau} &= 2L \Big\{ (P_{\mathcal{C}})_{\tau\mu} + (P_{\mathcal{A}_s})_{\tau\mu} \sin \omega_\oplus T_\oplus + (P_{\mathcal{A}_c})_{\tau\mu} \cos \omega_\oplus T_\oplus \\
&\quad + (P_{\mathcal{B}_s})_{\tau\mu} \sin 2\omega_\oplus T_\oplus + (P_{\mathcal{B}_c})_{\tau\mu} \cos 2\omega_\oplus T_\oplus \Big\}
\end{aligned}$$

LV neutrino oscillations

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JSD, Kostelecký & Mewes, PRD **80**, 076007 (2009)

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

$$(P_{\mathcal{B}_s})_{\tau\mu} = \tfrac{1}{2}\,\text{Re}(\mathcal{B}_s^{(1)})_{\mu\tau}\sin\left(2.54\Delta m^2_{\text{atm}} L/E\right)$$

LV neutrino oscillations

Example: ν_μ disappearance

JSD, Kostelecký & Mewes, PRD **80**, 076007 (2009)

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

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P^{(1)}_{\nu_\mu\to\nu_\tau} &= 2L\Big\{(P_{\mathcal{C}})_{\tau\mu} + (P_{\mathcal{A}_s})_{\tau\mu} \sin\omega_\oplus T_\oplus + (P_{\mathcal{A}_c})_{\tau\mu} \cos\omega_\oplus T_\oplus \\
&\qquad + (P_{\mathcal{B}_s})_{\tau\mu} \sin 2\omega_\oplus T_\oplus + (P_{\mathcal{B}_c})_{\tau\mu} \cos 2\omega_\oplus T_\oplus\Big\}
\end{aligned}$$

$$(P_{\mathcal{B}_s})_{\tau\mu} = \tfrac{1}{2}\,\text{Re}(\mathcal{B}_s^{(1)})_{\mu\tau} \sin\left(2.54\Delta m^2_{\text{atm}} L/E\right)$$

$$\begin{aligned}
(\mathcal{B}_s^{(1)})_{\mu\tau} &= N^X N^Y E\left((c_L)^{XX}_{\mu\tau} - (c_L)^{YY}_{\mu\tau}\right) \\
&\qquad - \left(N^X N^X - N^Y N^Y\right) E\,(c_L)^{XY}_{\mu\tau}
\end{aligned}$$

LV neutrino oscillations

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

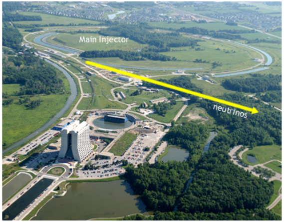
Search for Lorentz Invariance and *CPT* Violation with the MINOS Far Detector

(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.



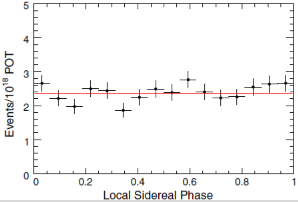


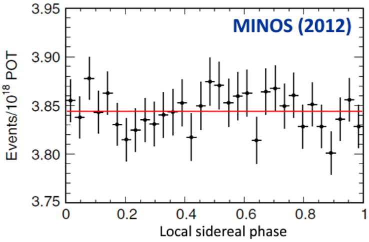
TABLE III. 99.7% C.L. limits on SME coefficients for $\nu_\mu \to \nu_\tau$; $(a_L)^{\alpha}_{\mu\tau}$ have units [GeV]; $(c_L)^{\alpha\beta}_{\mu\tau}$ are unitless.

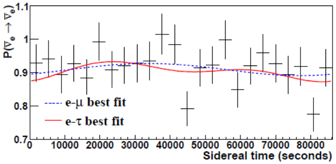
Coeff.	Limit	Coeff.	Limit
$(a_L)^X_{\mu\tau}$	5.9×10^{-23}	$(a_L)^Y_{\mu\tau}$	6.1×10^{-23}
$(c_L)^{TX}_{\mu\tau}$	0.5×10^{-23}	$(c_L)^{TY}_{\mu\tau}$	0.5×10^{-23}
$(c_L)^{XX}_{\mu\tau}$	2.5×10^{-23}	$(c_L)^{YY}_{\mu\tau}$	2.4×10^{-23}
$(c_L)^{XY}_{\mu\tau}$	1.2×10^{-23}	$(c_L)^{YZ}_{\mu\tau}$	0.7×10^{-23}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

LV neutrino oscillations

Experimental searches

- **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** arXiv:1410.4267
- …



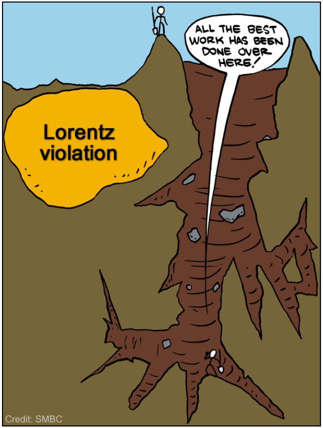


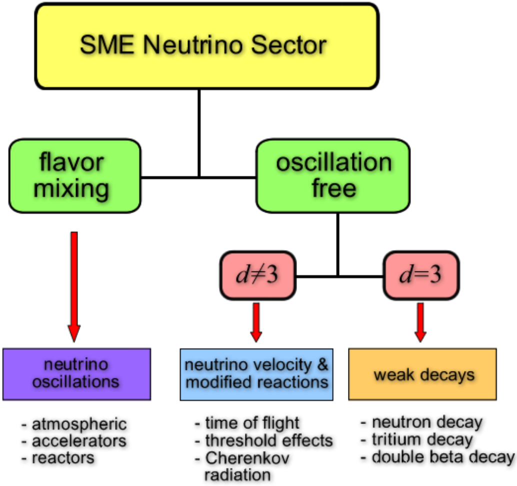
Double Chooz (2012)

Experimental searches

Karlsruhe Institute of Technology

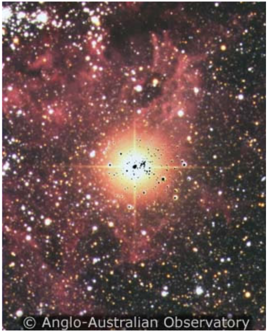
Complementarity between experiments





LV neutrino velocity

Kostelecký & Mewes, PRD **85**, 096005 (2012)



- Sensitive to **oscillation-free** effects
- Neutrino velocity can depend on:
  - **energy:** E
  - **sidereal time:** $\omega_\oplus T_\oplus$
  - **direction of propagation:** ${}_0\mathcal{N}_{jm}$
  - **particle or antiparticles**
- Physical effects
  - $v \neq 1 \rightarrow$ unconventional reactions
  - dispersion
- For beam experiments:

$$v \approx 1 - \frac{m^2}{2E^2} + \sum_{djm} (d-3) E^{d-4} e^{im\omega_\oplus T_\oplus} {}_0\mathcal{N}_{jm} \left[(a_{\text{of}}^{(d)})_{jm} - (c_{\text{of}}^{(d)})_{jm} \right]$$

Effects of **dimension-three operators** ($d = 3$) not observable

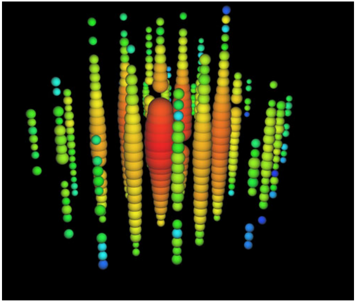
LV modified reactions

- observation of TeV-PeV neutrinos

- dispersion relation for high-energy neutrinos (neglecting CPT-odd terms)

$$E(\boldsymbol{p}) = |\boldsymbol{p}| - \sum_{djm} |\boldsymbol{p}|^{d-3}\, Y_{jm}(\hat{\boldsymbol{p}}) (c_{\text{of}}^{(d)})_{jm}$$

JSD, Kostelecký & Mewes, PRD 89, 043005 (2014)

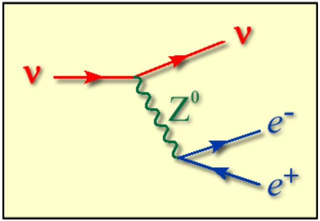


IceCube Collaboration

- **energy loss as Cherenkov radiation**

$$\boldsymbol{\nu} \rightarrow \boldsymbol{\nu} + \boldsymbol{e}^{-} + \boldsymbol{e}^{+}$$

$$i\mathcal{M} = \frac{-i\sqrt{2} G_F M_Z^2}{(k+k')^2 - M_Z^2} \overline{\nu}(p')\gamma^\alpha \nu(p)$$
$$\times\, \overline{u}(k)\gamma_\alpha (2\sin^2\theta_W - P_L) v(k')$$



LV modified reactions

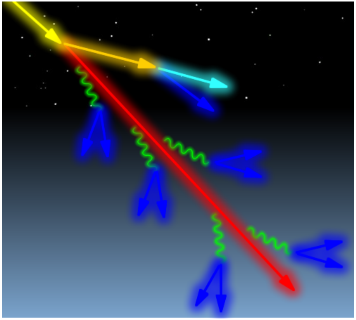
JSD, Kostelecký & Mewes, PRD 89, 043005 (2014)

characteristic distortion distance:

$$D(E) = -\frac{E}{(dE/dx)}$$

since we *do* observe PeV neutrinos

$$\text{propagation distance } L < \text{distortion distance } D(E)$$



Conservative approach:

suppose PeV events are atmospheric

$$L \approx 1000\,\text{km} < D(E)$$

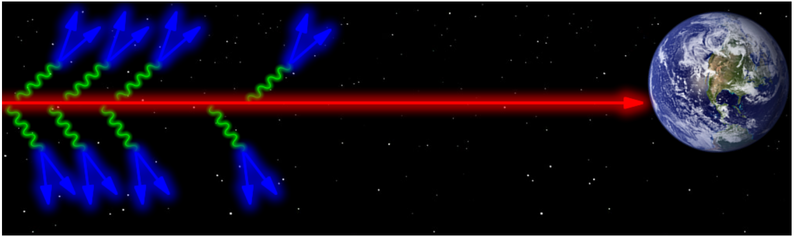
Lower bounds:

Coefficient	Atmospheric Čerenkov
$\mathring{c}^{(4)}$	$> -3 \times 10^{-13}$
$\mathring{c}^{(6)}$	$> -3 \times 10^{-25}$ GeV^{-2}
$\mathring{c}^{(8)}$	$> -2 \times 10^{-37}$ GeV^{-4}
$\mathring{c}^{(10)}$	$> -2 \times 10^{-49}$ GeV^{-6}

LV modified reactions

if PeV events are astrophysical:

JSD, Kostelecký & Mewes, PRD 89, 043005 (2014)



$\rightarrow$ neutrinos will lose energy falling below threshold

threshold condition:

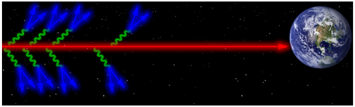
$$-\sum_{djm} |\boldsymbol{p}|^{d-2}\, Y_{jm}(\boldsymbol{p})\, \left(c^{(d)}_{\text{of}}\right) \lesssim 2m_e^2$$

Lower bounds:

Coefficient	Astrophysical	Čerenkov
$\mathring{c}^{(4)}$	$> -5 \times 10^{-19}$	
$\mathring{c}^{(6)}$	$> -5 \times 10^{-31}$	GeV^{-2}
$\mathring{c}^{(8)}$	$> -5 \times 10^{-43}$	GeV^{-4}
$\mathring{c}^{(10)}$	$> -5 \times 10^{-55}$	GeV^{-6}

LV modified reactions

JSD, Kostelecký & Mewes, PRD 89, 043005 (2014)

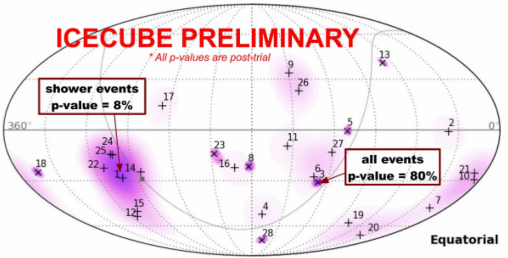


d	j	Lower bound	Coefficient	Upper bound
4	0	$-4\times10^{-19} <$	$(c_{\text{of}}^{(4)})_{00}$	
4	1	$-1\times10^{-17} <$	$(c_{\text{of}}^{(4)})_{10}$	$< 4\times10^{-17}$
		$-3\times10^{-17} <$	$\text{Re}(c_{\text{of}}^{(4)})_{11}$	$< 2\times10^{-17}$
		$-2\times10^{-17} <$	$\text{Im}(c_{\text{of}}^{(4)})_{11}$	$< 2\times10^{-17}$
4	2	$-1\times10^{-17} <$	$(c_{\text{of}}^{(4)})_{20}$	$< 7\times10^{-17}$
		$-2\times10^{-17} <$	$\text{Re}(c_{\text{of}}^{(4)})_{21}$	$< 3\times10^{-17}$
		$-2\times10^{-17} <$	$\text{Im}(c_{\text{of}}^{(4)})_{21}$	$< 5\times10^{-17}$
		$-5\times10^{-17} <$	$\text{Re}(c_{\text{of}}^{(4)})_{22}$	$< 2\times10^{-17}$
		$-3\times10^{-17} <$	$\text{Im}(c_{\text{of}}^{(4)})_{22}$	$< 4\times10^{-17}$
6	0	$-3\times10^{-31} <$	$(c_{\text{of}}^{(6)})_{00}$	
6	1	$-2\times10^{-28} <$	$(c_{\text{of}}^{(6)})_{10}$	$< 9\times10^{-28}$
		$-6\times10^{-28} <$	$\text{Re}(c_{\text{of}}^{(6)})_{11}$	$< 5\times10^{-28}$
		$-3\times10^{-28} <$	$\text{Im}(c_{\text{of}}^{(6)})_{11}$	$< 3\times10^{-28}$
6	2	$-4\times10^{-28} <$	$(c_{\text{of}}^{(6)})_{20}$	$< 7\times10^{-27}$
		$-1\times10^{-27} <$	$\text{Re}(c_{\text{of}}^{(6)})_{21}$	$< 2\times10^{-27}$
		$-1\times10^{-27} <$	$\text{Im}(c_{\text{of}}^{(6)})_{21}$	$< 3\times10^{-27}$
		$-5\times10^{-27} <$	$\text{Re}(c_{\text{of}}^{(6)})_{22}$	$< 6\times10^{-28}$
		$-1\times10^{-27} <$	$\text{Im}(c_{\text{of}}^{(6)})_{22}$	$< 4\times10^{-27}$
		$\vdots$		

Astrophysical Cherenkov threshold

$$-\sum_{djm} |\boldsymbol{p}|^{d-2}\, Y_{jm}(\boldsymbol{p})\, (c_{\text{of}}^{(d)})_{jm} \lesssim 2m_e^2$$

two-sided bounds can be obtained from several events distributed in the sky



Photons in the SME

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} F^{\mu\nu} (\hat{k}_F)_{\mu\nu\lambda\rho} F^{\lambda\rho} + \frac{1}{2} \epsilon^{\mu\nu\lambda\rho} A_\nu (\hat{k}_{AF})_\mu F_{\lambda\rho},$$

LV photons

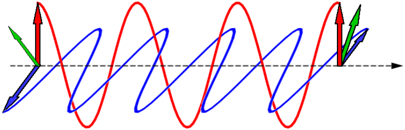
Colladay & Kostelecký, PRD 58, 116002 (1998)
Kostelecký & Mewes, PRL 87, 251304 (2001)
Kostelecký & Mewes, PRD 66, 056005 (2002)
Kostelecký & Mewes, PRD 80, 015020 (2009)
Stecker, AP 35, 95 (2011)

Polarimetry measurements

- speed of normal modes

$$v = 1 - \varsigma^0 \pm \sqrt{(\varsigma^1)^2 + (\varsigma^3)^2 + (\varsigma^3)^2}$$

- $\varsigma^0, \varsigma^1, \varsigma^3, \varsigma^3$ affect vacuum propagation
- isotropic and direction-dependent effects
- $\varsigma^1, \varsigma^3, \varsigma^3$ vacuum birefringence



- most stringent limits on relativity violations Kostelecký & Mewes, PRL 110, 201601 (2013)

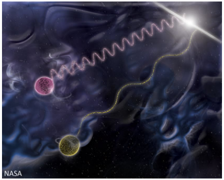
LV photons

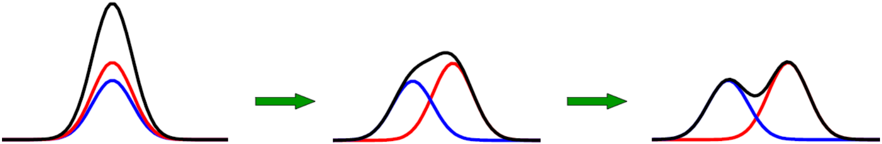
Dispersion measurements

G. Amelino-Camelia et al., Nature 393, 763 (1998)
Kostelecký & Mewes, ApJ 689, L1 (2008)
Kostelecký & Mewes, PRD 80, 015020 (2009)
Vasileiou et al., PRD 87, 122001 (2013)

Time delay between photons of different energies

$$\Delta t \approx \left(E_2^{d-4} - E_1^{d-4}\right) \int_0^z \frac{(1+z')^{d-4}}{H_{z'}}\, dz' \times \sum_{jm} Y_{jm}(\hat{p})\, c_{(I)jm}^{(d)}$$





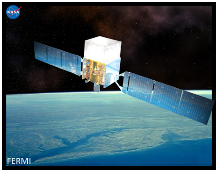
LV photons

Dispersion measurements

Kostelecký & Mewes, ApJ 689, L1 (2008)
Kostelecký & Mewes, PRD 80, 015020 (2009)
Ellis & Mavromatos, AP 43, 50 (2013)

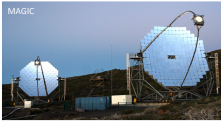
- GRB 080916C (Fermi)

$$\sum_{jm} Y_{jm}(147^\circ, 120^\circ)\, c^{(8)}_{(I)jm} < 2.6\times10^{-23}\ \text{GeV}^{-4}$$

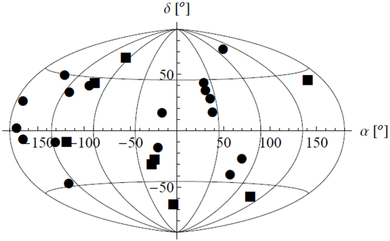


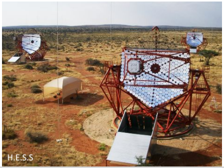
- Markarian 501 (MAGIC)

$$\sum_{jm} Y_{jm}(50.2^\circ, 253^\circ)\, c^{(6)}_{(I)jm} = 3^{+1}_{-2}\times10^{-22}\ \text{GeV}^{-2}$$



Krawczynski et al, arXiv:1307.6946



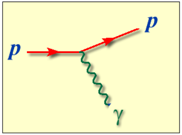


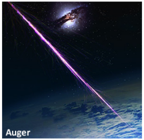
LV photons

Other tests

- **vacuum Cherenkov**
  high-energy cosmic rays

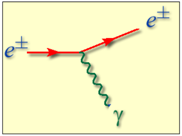
Altschul, PRL 98, 041603 (2007)
Kaufhold & Klinkhamer, PRD 76, 025024 (2007)
Klinkhamer & Risse, PRD 77, 016002 (2008)
Klinkhamer & Schreck, PRD 78, 085026 (2008)

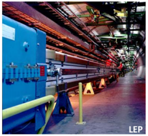




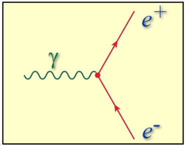
- **vacuum Cherenkov**
  electron energy-loss
  measurements in colliders

Hohensee et al., PRD 80, 036010 (2009)
Altschul, PRD 82, 016002 (2010)





- **photon decay**
  high-energy cosmic photons



Modified dispersion relations

Limitations of modified dispersion relations $E^2 = m^2 + \boldsymbol{p}^2 + \boldsymbol{f}(\boldsymbol{p}, E_{\text{QG}})$

- may be incompatible with any quantum field theory
- may not represent physical effects
- involve kinematics but neglect dynamics
- only include isotropic effects
- example: group velocity

$$v = 1 - \frac{m^2}{2\boldsymbol{p}^2} + \boldsymbol{\xi} \left(\frac{|\boldsymbol{p}|}{E_{\text{QG}}} \right)^{\alpha}, \; \alpha=0,1,2$$

In the SME

- **precisely how dispersion relations get modified**
- **field-theory calculations possible** (Feynman diagrams)
- **anisotropic effects appear**
- example: neutrino group velocity

$$v = 1 - \frac{m^2}{2\boldsymbol{p}^2} + \sum_{dmj} (d-3)|\boldsymbol{p}|^{d-4}\, \boldsymbol{Y_{jm}(\hat{p})} \left[(a^{(d)})_{jm} - (c^{(d)})_{jm} \right]$$

Summary

- Tests of Lorentz invariance constitute a **worldwide effort** across multiple disciplines
- Neutrinos and photons are **remarkably sensitive** to key observable effects of Lorentz violation
- Many effects of Lorentz violation **remain unexplored**
- Interesting prospects for **low- and high-energy experiments**
- Rich research area for **theory-experiment collaboration**

"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

Invitation

Karlsruhe Institute of Technology

IUCSS

Program

Registration

Travel

Organizers:

Ralf Lehnert
IUCSS
rlehnert@gmail.com

Mike Snow
Indiana University
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Second IUCSS Summer School on the

Lorentz- and CPT-violating Standard-Model Extension

June 12-18, 2015

Indiana University, Bloomington

The Second IUCSS Summer School on the Standard-Model Extension (SME) will be held in the Physics Department at Indiana University, Bloomington from Friday June 12 to Thursday June 18, 2015. The School is aimed primarily at students and researchers in theory and experiment who seek a pedagogical introduction to the SME framework.

The School format will include lectures and discussion periods. The lectures will cover theoretical, phenomenological, and experimental topics in Lorentz and CPT violation, beginning at the introductory level and advancing to the cutting edge of this active field. The discussion periods will provide opportunities to consolidate and explore in greater depth the lecture material. The School will also include a poster session for participants to showcase their own work.

http://www.indiana.edu/∼lorentz/sme2015/