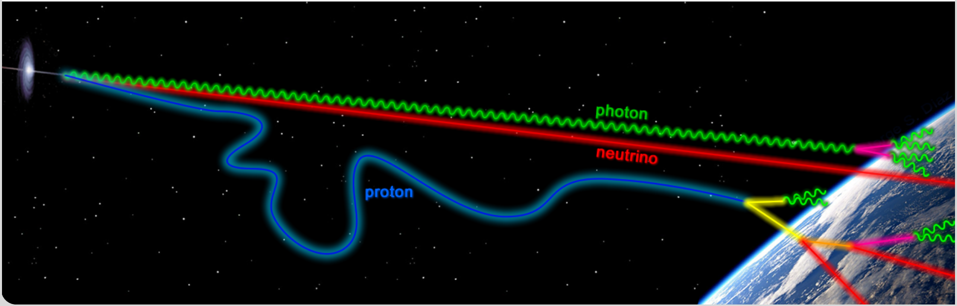
Astroparticle tests of Lorentz invariance

Jorge S. Diaz |

WIN 2015 - MPIK HEIDELBERG, 10.06.2015



Outline

- Lorentz symmetry and violation
- Tests of Lorentz and CPT invariance
  - **cosmic rays**
  - **gamma rays**
  - **neutrinos**
- 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)

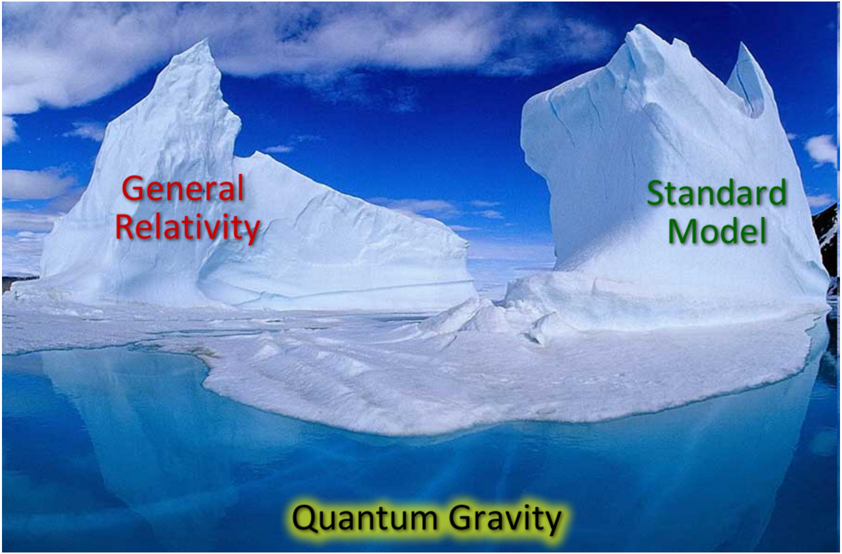
Lorentz violation

- Last 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.

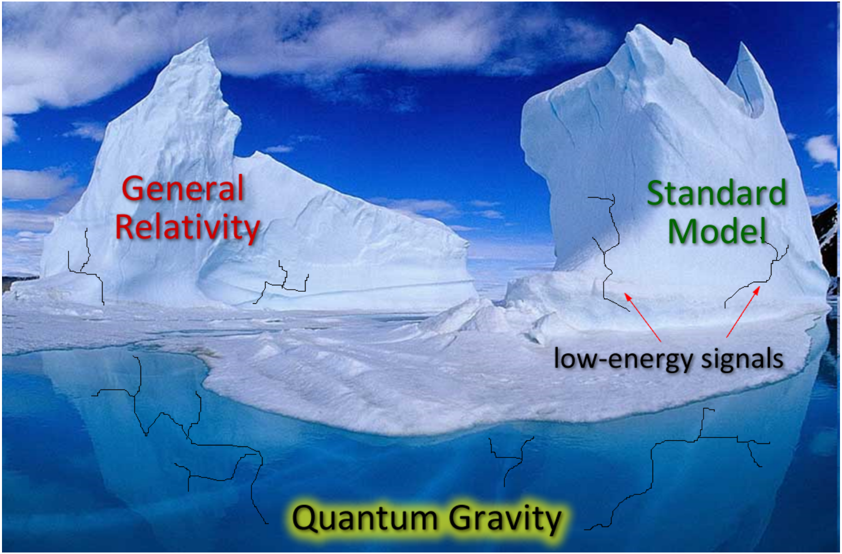
Lorentz violation

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

Lorentz violation

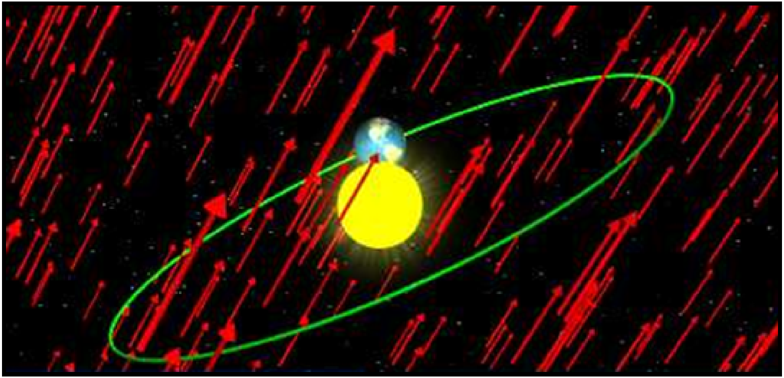


Lorentz violation



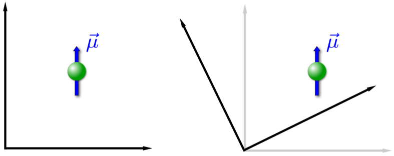
Lorentz violation

Does the universe have a preferred direction?



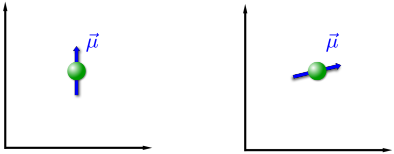
Lorentz transformations

Observer transformation



coordinate invariance

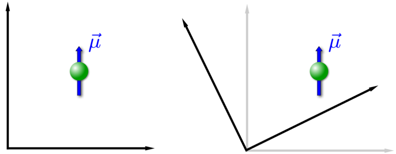
Particle transformation



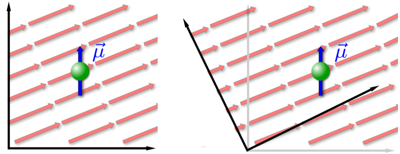
symmetry

Lorentz transformations

Observer transformation

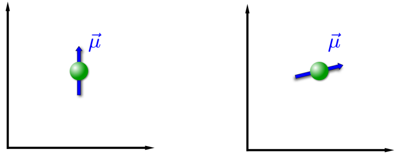


coordinate invariance



coordinate invariance

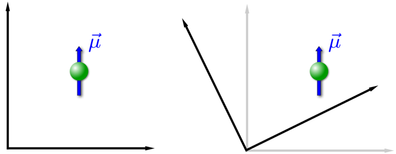
Particle transformation



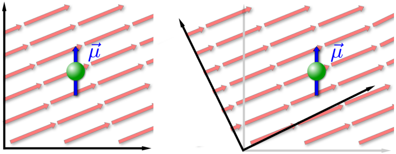
symmetry

Lorentz transformations

Observer transformation

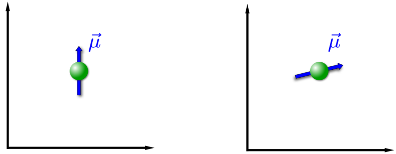


coordinate invariance

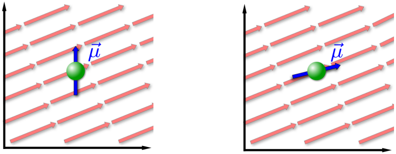


coordinate invariance

Particle transformation



symmetry

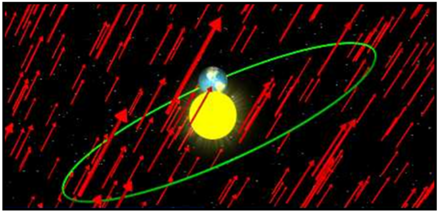


broken symmetry

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):

$$\mathcal{L}_{\text{LV}} \supset a_\mu(\overline{\psi}\gamma^\mu\psi) + b_\mu(\overline{\psi}\gamma_5\gamma^\mu\psi)$$

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

SME: theory & experiment playground

Karlsruhe Institute of Technology

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

Testing Lorentz invariance

- Cosmic rays
- Gamma rays
- Neutrinos

Lorentz-violating QED

Colladay & Kostelecký, PRD 58, 116002 (1998)

$$\mathcal{L}_{\text{LV QED}} = -\frac{1}{4} F_{\mu\nu}F^{\mu\nu} + \overline{\psi}(i\gamma^\mu D_\mu - m)\psi \quad \text{(QED)}$$
$$+\frac{1}{2} (k_{AF})_\kappa \epsilon^{\kappa\lambda\mu\nu} A_\lambda F_{\mu\nu} \quad \text{(cosmologically constrained)}$$
$$-\frac{1}{4} (k_F)_{\mu\nu\kappa\lambda} F^{\mu\nu} F^{\kappa\lambda} \quad \text{(this talk)}$$

Isotropic nonbirenfringent Lorentz violation

$$(k_F)^\lambda{}_{\mu\lambda\nu} = \frac{\kappa}{2} \begin{pmatrix} 3 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

modified photon propagation and interactions

Lorentz-violating QED

Karlsruhe Institute of Technology

Colladay & Kostelecký, PRD 58, 116002 (1998)

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Isotropic nonbirenfringent Lorentz violation

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modified photon propagation and interactions

Direct experimental limit

$$|\kappa| < 10^{-10}$$

Reinhardt et al., Nature Phys. 3, 861 (2007)
Baynes et al., PRL 108, 260801 (2012)
Y. Michimura et al., PRL 110, 200401 (2013)

Indirect limit

$$|\kappa| < 10^{-11}$$

Hohensee et al., PRL 102, 170402 (2009)

Cosmic rays

Karlsruhe Institute of Technology

Vacuum Cherenkov radiation ($\kappa > 0$)

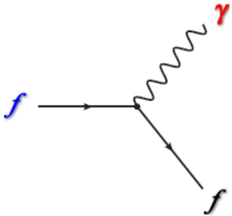
Klinkhamer & Schreck, PRD 78, 085026 (2008)

- energy-loss mechanism
- process allowed above threshold E_{th}
- observation of cosmic ray of energy E implies $E < E_{\text{th}}$
- Pierre Auger event $E = 2.12 \times 10^{11}$ GeV
- conservative limit (assume Fe nucleus)

$$\kappa < 6 \times 10^{-20}$$

- for structureless proton primary

$$\kappa < 2 \times 10^{-23}$$



Cosmic rays

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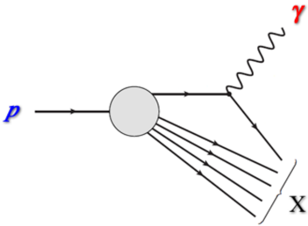
- limits still valid in parton-model approach



JSD & Klinkhamer, PRD (2015), arXiv:1504.01324

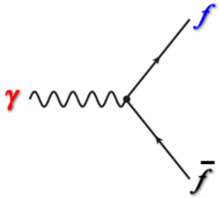
Gamma rays

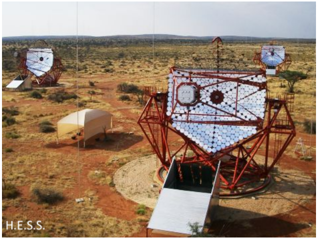
Photon decay ($\kappa < 0$)

Klinkhamer & Schreck, PRD 78, 085026 (2008)

- energy-loss mechanism
- process allowed above threshold ω_{th}
- observation of gamma ray of energy ω implies $\omega < \omega_{\text{th}}$
- H.E.S.S. event $\omega = 3 \times 10^4$ GeV
- lower limit

$$-9 \times 10^{-16} < \kappa$$





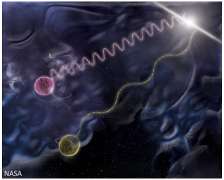
LV photons

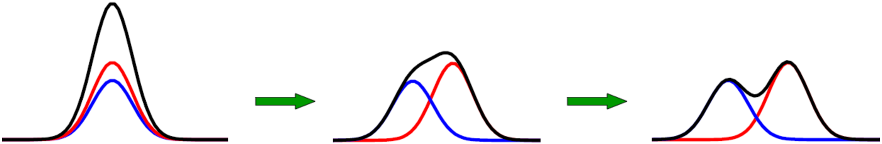
Dispersion measurements

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)

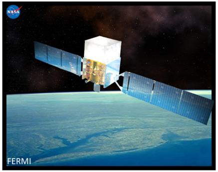
Time delay between photons of different energies

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





LV photons



Dispersion measurements

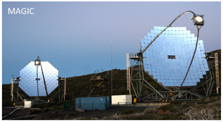
Kostelecký & Mewes, ApJ 689, L1 (2008)
Kostelecký & Mewes, PRD 80, 015020 (2009)
Ellis & Mavromatos, AP 43, 50 (2013)

- GRB 080916C (Fermi)

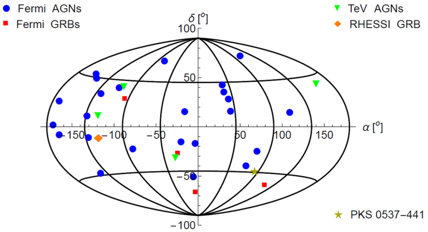
$$\sum_{jm} Y_{jm}(147^\circ, 120^\circ) c^{(8)}_{(I)jm} < 2.6 \times 10^{-23}\ \text{GeV}^{-4}$$

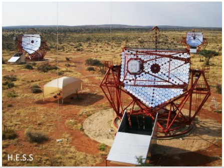
- Markarian 501 (MAGIC)

$$\sum_{jm} Y_{jm}(50.2^\circ, 253^\circ) c^{(6)}_{(I)jm} = 3^{+1}_{-2} \times 10^{-22}\ \text{GeV}^{-2}$$



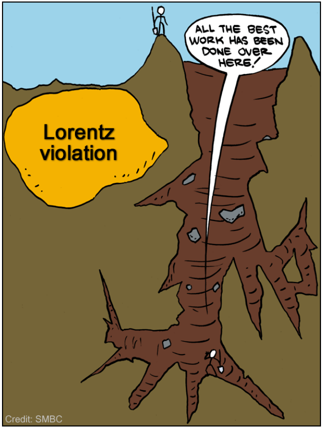
Kislat & Krawczynski, arXiv:1505.02669

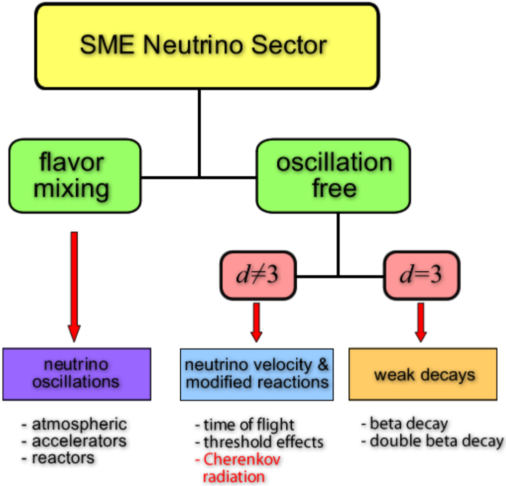




Neutrinos

Complementarity between experiments





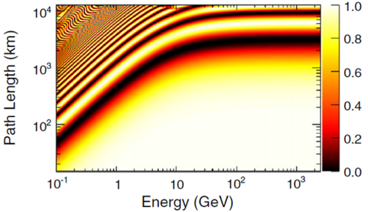
LV neutrino oscillations

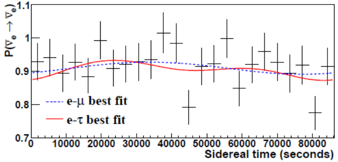
Experimental searches

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)

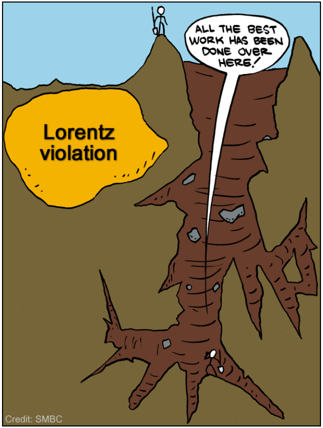


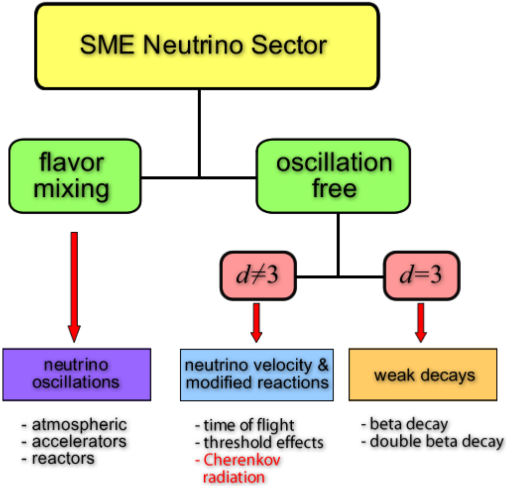


Double Chooz (2012)

Neutrinos

Complementarity between experiments

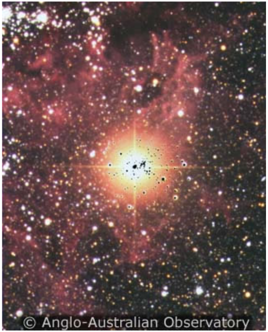




LV neutrino velocity

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

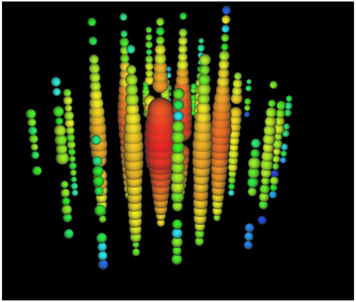
LV modified reactions

- observation of TeV-PeV neutrinos

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

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

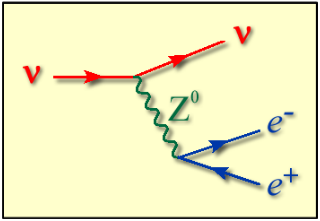
JSD, Kostelecký & Mewes, PRD 89, 043005 (2014)


IceCube Collaboration

- **energy loss as Cherenkov radiation**

$$\nu \to \nu + e^- + e^+$$

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



LV modified reactions

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

characteristic distortion distance:

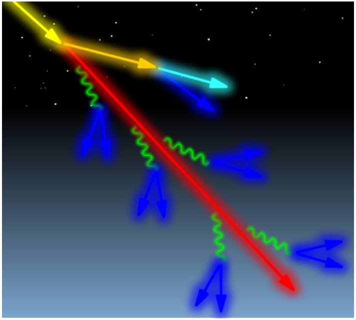
$$D(E) = -\frac{E}{(dE/dx)}$$

since we *do* observe PeV neutrinos

propagation distance		distortion distance
L	$<$	$D(E)$

Conservative approach:
suppose PeV events are atmospheric

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



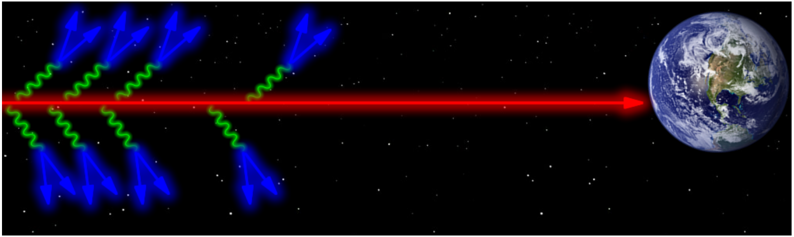
Lower bounds:

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

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:

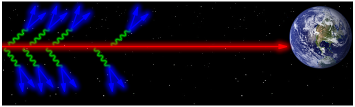
$$-\sum_{djm} |\boldsymbol{p}|^{d-2}\, Y_{jm}(\hat{\boldsymbol{p}})\, \left(c^{(d)}_{\text{of}}\right) \lesssim 2m_e^2$$

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)

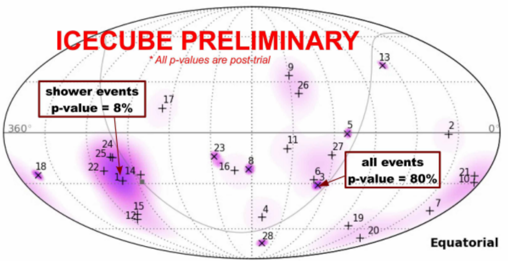


d	j	Lower bound	Coefficient	Upper bound
4	0	$-4 \times 10^{-19} <$	$(c_{\text{of}}^{(4)})_{00}$	
4	1	$-1 \times 10^{-17} <$	$(c_{\text{of}}^{(4)})_{10}$	$< 4 \times 10^{-17}$
		$-3 \times 10^{-17} <$	$\text{Re}(c_{\text{of}}^{(4)})_{11}$	$< 2 \times 10^{-17}$
		$-2 \times 10^{-17} <$	$\text{Im}(c_{\text{of}}^{(4)})_{11}$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

Astrophysical Cherenkov threshold

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

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



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

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

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

KIT
Karlsruhe Institute of Technology

- Tests of Lorentz invariance constitute a **worldwide effort** across multiple disciplines

- Neutrinos and photons are **remarkably sensitive** to key observable effects of Lorentz violation using
  - cosmic rays
  - high-energy photons (X-rays, gamma rays)
  - neutrinos

- Many effects of Lorentz violation **remain unexplored**

- Interesting prospects for **low- and high-energy experiments**

- Rich research area for **theory-experiment collaboration**