Quantum gravity phenomenology

Testing *CPT*- and Lorentz invariance

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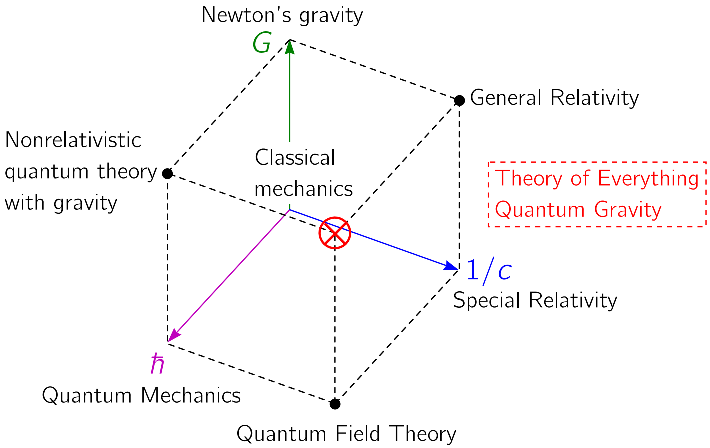
January 21, 2020

Outline

Lorentz symmetry violation

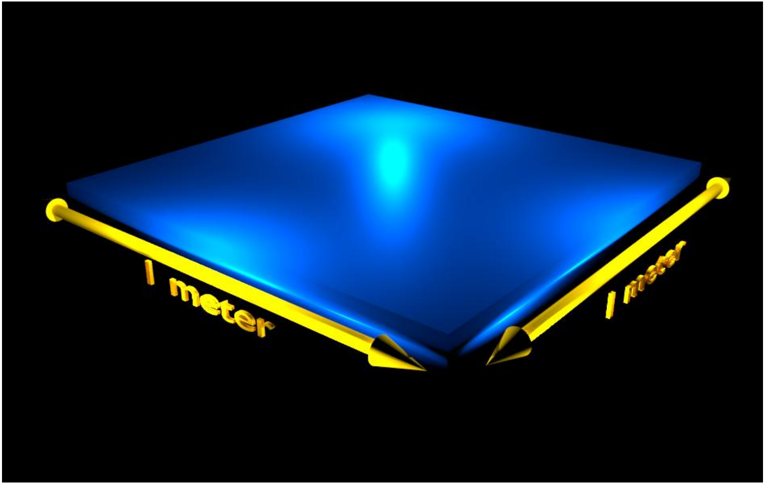


based on M. Bronshtein, A. Zelmanov

(cf. L.B. Okun, in *Multiple facets of quantization and supersymmetry*, M. Olshanetsky and A. Vainshtein, eds., hep-ph/0112339)

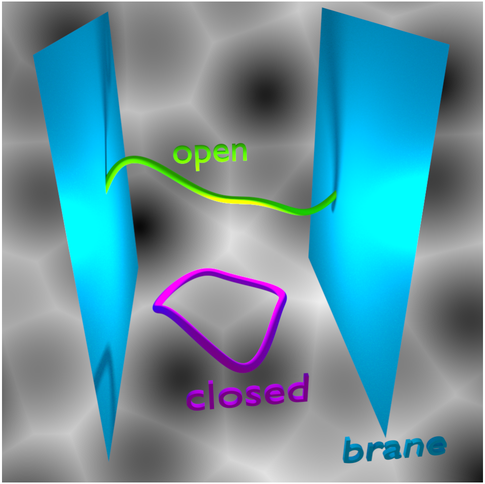
- Only prototype fundamental theories
- Main difficulty: no experimental signals
  $\Longrightarrow$ Better to look for possible experimental signals first!

The nature of spacetime



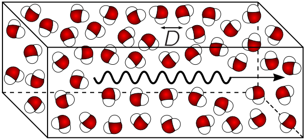
J.A. Wheeler, Annals Phys. **2**, 604 (1957); S.W. Hawking, Nucl. Phys. B **144**, 349 (1978); F.R. Klinkhamer and C. Rupp, Phys. Rev. D **70**, 045020 (2004), hep-th/0312032; S. Bernadotte and F.R. Klinkhamer, Phys. Rev. D **75**, 024028 (2007), hep-ph/0610216; MS, F. Sorba, and S. Thambyahpillai, Phys. Rev. D **88**, 125011 (2013), arXiv:1211.0084 [hep-th]; S. Hossenfelder, Adv. High Energy Phys. **2014**, 950672 (2014), arXiv:1401.0276 [hep-ph]; . . .

Lorentz violation from string theory

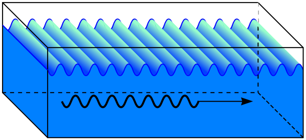


V.A. Kostelecký and S. Samuel, Phys. Rev. D **39**, 683 (1989); V.A. Kostelecký and R. Potting, Nucl. Phys. B **359**, 545 (1991);
V.A. Kostelecký and R. Potting, Phys. Rev. D **51**, 3923 (1995), hep-ph/9501341

Low-energy effective theory



High-energy particle



Low-energy particle

- Particle propagating through water
- Wavelength $\sim D$: complicated physics
- Wavelength $\gg D$: effective theory (optics in a medium)
- Expect modifications of

$$E(\vec{p}) = \sqrt{(c\vec{p})^2 + (mc^2)^2}$$

$$\omega(\vec{k}) = c|\vec{k}|$$

- Medium defines a Lorentz-violating background

Modified dispersion laws

- Modified dispersion laws:

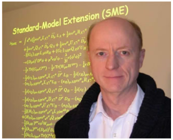
$$\omega^2\left[1 \pm \frac{\hbar\omega}{E_{\rm Pl}}\right] = c^2\vec{k}^{\,2}\,, \quad E^2 = (c\vec{p})^2 + (mc^2)^2 \pm \frac{c|\vec{p}|^{\,3}}{M_{\rm Pl}}\,.$$

G. Amelino-Camelia, J. R. Ellis, N.E. Mavromatos, D.V. Nanopoulos, and S. Sarkar, Nature **393**, 763 (1998), astro-ph/9712103; R. Aloisio, P. Blasi, P.L. Ghia, and A.F. Grillo, Phys. Rev. D **62**, 053010 (2000), astro-ph/0001258

- Problems:
  - Very special models
  - Description of kinematics, but not of *dynamics*
  - Theoretical issues hidden (unitarity?, microcausality?)
  - No observable physical effects(?)
- Framework based on an action: Standard-Model Extension

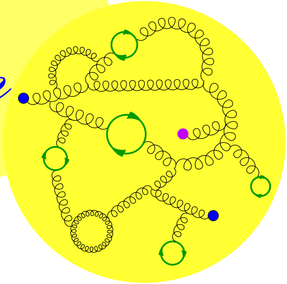
D. Colladay and V.A. Kostelecký, Phys. Rev. D **58**, 116002 (1998), hep-ph/9809521; V.A. Kostelecký, Phys. Rev. D **69**, 105009 (2004), hep-th/0312310

D. Colladay



V. A. Kostelecký

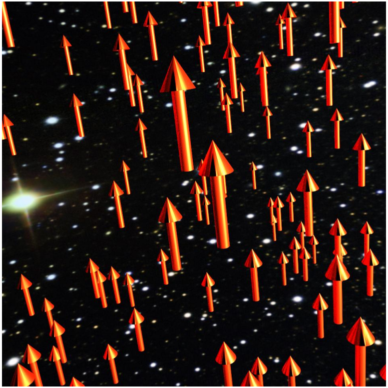
Standard-Model Extension



Lorentz-violating background field

$$\mathcal{L}_\gamma = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}(k_F)^{\mu\nu\varrho\sigma}F_{\mu\nu}F_{\varrho\sigma} + \ldots$$

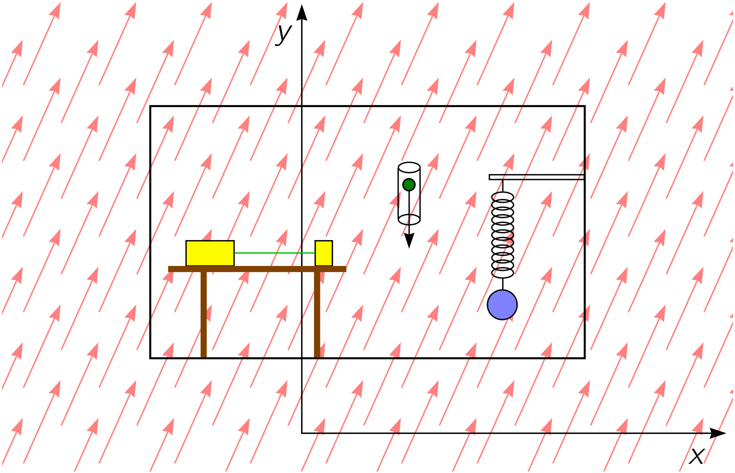
D. Colladay and V.A. Kostelecký, Phys. Rev. D **58**, 116002 (1998), hep-ph/9809521



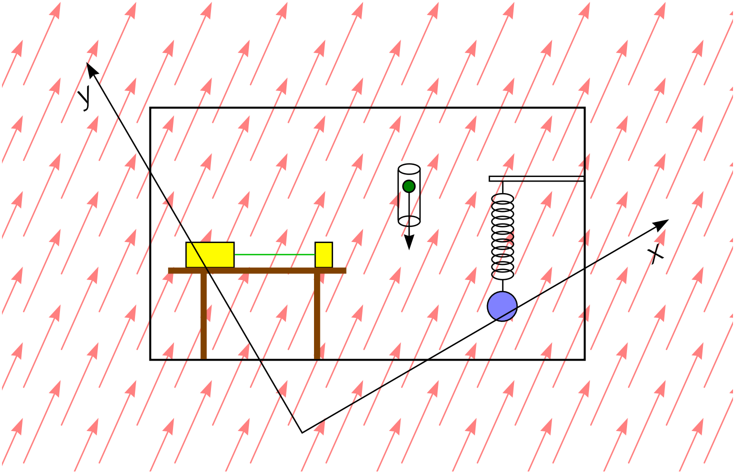
Behavior of background field:

- Tensor under observer (coordinate) Lorentz transformations
- Tensor under active Lorentz transformations (inverse of observer Lorentz transformations)
- Fixed under particle Lorentz transformations
- Low-energy effective description

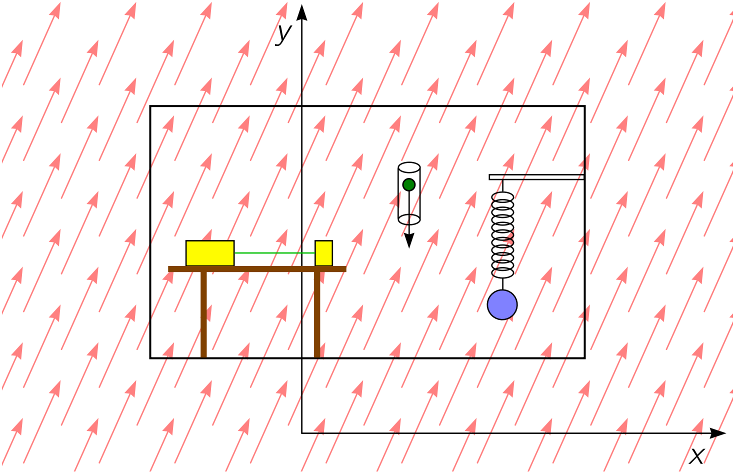
Observer Lorentz transformation



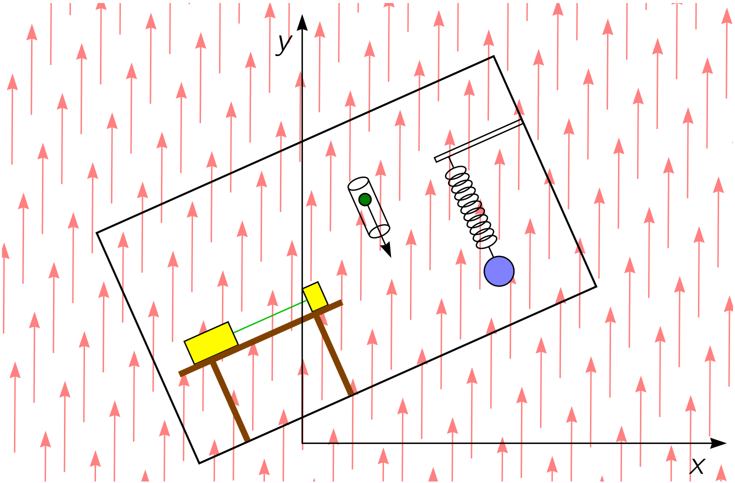
Observer Lorentz transformation



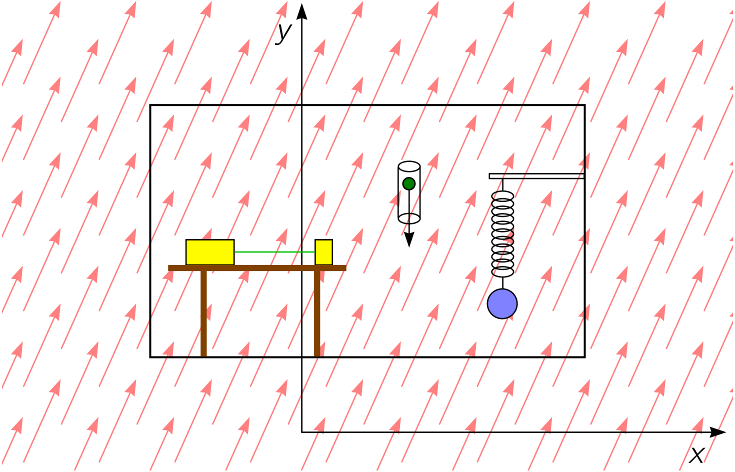
Active Lorentz transformation



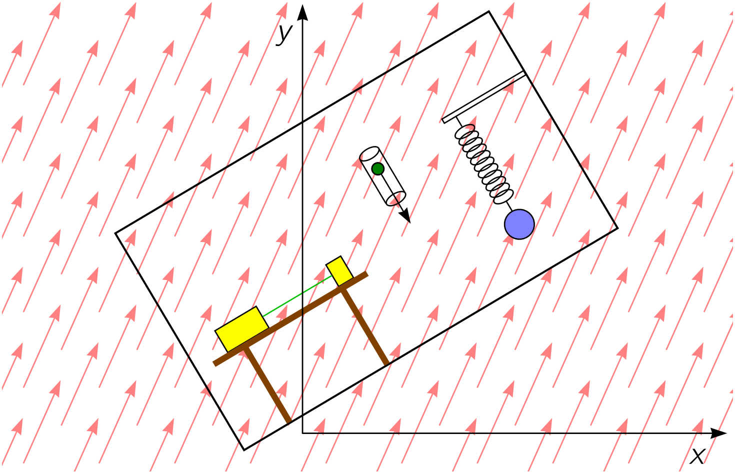
Active Lorentz transformation



Particle Lorentz transformation

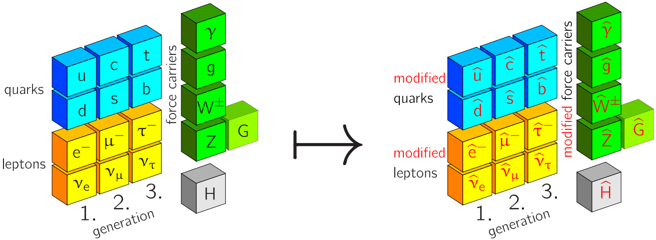


Particle Lorentz transformation



Standard-Model Extension (SME)

- SME describes possible Lorentz violation for Standard-Model particles + gravity



- All Lorentz-violating terms well organized
- *CPT*-violating contributions contained

O.W. Greenberg, Phys. Rev. Lett. **89**, 231602 (2002), hep-ph/0201258

- Besides modified energy-momentum relations:
  - Modified Dirac equation for electrons, quarks,
  - Modified Maxwell's equations for photons, etc.

Minimal Standard-Model Extension (SME)

- Low-energy effective photon sector

$$\mathcal{L}_\gamma = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}(k_F)^{\mu\nu\varrho\sigma}F_{\mu\nu}F_{\varrho\sigma} + \dots$$

- Fermion sector (minimally coupled)

$$\mathcal{L}_{\text{Dirac}} = \overline{\psi}\left(\frac{\mathrm{i}}{2}\gamma^\mu \overleftrightarrow{D_\mu} - m\right)\psi - a_\mu\overline{\psi}\gamma^\mu\psi - b_\mu\overline{\psi}\gamma_5\gamma^\mu\psi + c_{\mu\nu}\overline{\psi}\gamma^\mu\partial^\nu\psi + \dots$$

- Embed it into Standard Model

$$\mathcal{L}_{\text{quark}} = \frac{\mathrm{i}}{2}\overline{Q}_A\gamma^\mu\overleftrightarrow{D_\mu}Q_A + \dots - (a_Q)_{\mu,AB}\overline{Q}_A\gamma^\mu Q_B - (a_U)_{\mu,AB}\overline{U}_A\gamma^\mu U_B + \dots$$

$$\mathcal{L}_{\text{lepton}} = \frac{\mathrm{i}}{2}\overline{L}_A\gamma^\mu\overleftrightarrow{D_\mu}L_A + \dots - (a_L)_{\mu,AB}\overline{L}_A\gamma^\mu L_B - (a_R)_{\mu,AB}\overline{R}_A\gamma^\mu R_B + \dots$$

$$\mathcal{L}_{\text{gluon}} = -\frac{1}{2}\mathrm{Tr}(G^{\mu\nu}G_{\mu\nu}) - \frac{1}{2}(k_G)^{\mu\nu\varrho\sigma}\mathrm{Tr}(G_{\mu\nu}G_{\varrho\sigma}) + \dots$$

$$\mathcal{L}_{\text{Higgs}} = (D^\mu\phi)^\dagger D_\mu\phi + V(\phi) + \frac{1}{2}(k_{\phi\phi})^{\mu\nu}(D_\mu\phi)^\dagger D_\nu\phi - \frac{1}{2}(k_{\phi W})^{\mu\nu}\phi^\dagger W_{\mu\nu}\phi + \dots$$

$$\mathcal{L}_{\text{Yuk}} = -(G_U)_{AB}\overline{Q}_A\phi^c U_B + \dots - \frac{\mathrm{i}}{4}(H_U)_{\mu\nu,AB}\overline{Q_A}\phi^c[\gamma^\mu,\gamma^\nu]U_B + \dots$$

CPT violation

- Charge conjugation C

$$C|q,\vec{p},s_z\rangle = |-q,\vec{p},s_z\rangle$$

- Parity transformation P $(\vec{r}\mapsto -\vec{r})$

$$P|q,\vec{p},s_z\rangle = |q,-\vec{p},s_z\rangle$$

- Time reversal transformation T $(t\mapsto -t)$

$$T|q,\vec{p},s_z\rangle = |q,-\vec{p},-s_z\rangle$$

- CPT relates particle dynamics with antiparticle dynamics

$$CPT|q,\vec{p},s_z\rangle = |-q,\vec{p},-s_z\rangle$$

- All laws of nature are CPT-invariant
  - Locality, causality, Hermiticity
  - Energy bounded from below
  - Lorentz invariance
- CPT violation implies Lorentz violation
  O.W. Greenberg, Phys. Rev. Lett. **89**, 231602 (2002), hep-ph/0201258
- Odd number of Lorentz indices: CPT violation


J. Schwinger


W. Pauli

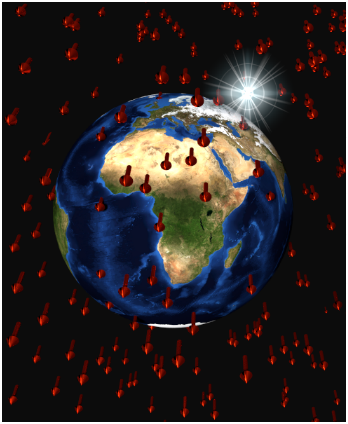

G. Lüders

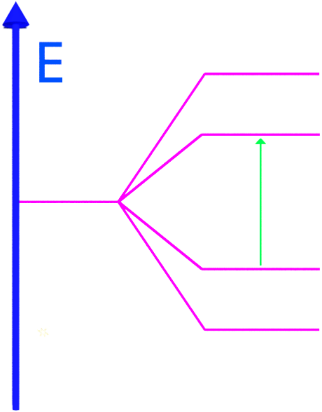

J.S. Bell

$$\mathcal{L}_{\text{Dirac}} \supset -a_\mu\overline{\psi}\gamma^\mu\psi + c_{\mu\nu}\overline{\psi}\gamma^\mu\partial^\nu\psi + \ldots$$


Experiments

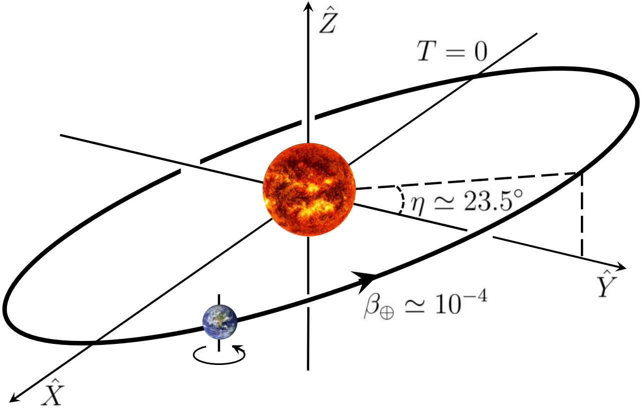
Sidereal variations





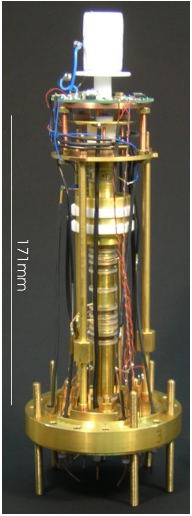
- Rotating laboratory frame on Earth
- Typical signal of Lorentz violation: Sidereal variations of atomic energy levels
- Problem: Noninertial coordinate frame!

Standard Sun-centered inertial reference frame

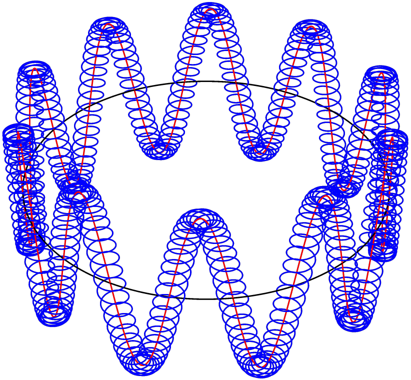


- Constraints compiled in V.A. Kostelecký and N. Russell, Data Tables for Lorentz and *CPT* Violation, Rev. Mod. Phys. **83**, 11 (2011) arXiv:0801.0287 [hep-ph]
- Start in 2008 (12 pages), presently version 13 (122 pages)

Penning traps: Classical treatment



MPI Heidelberg

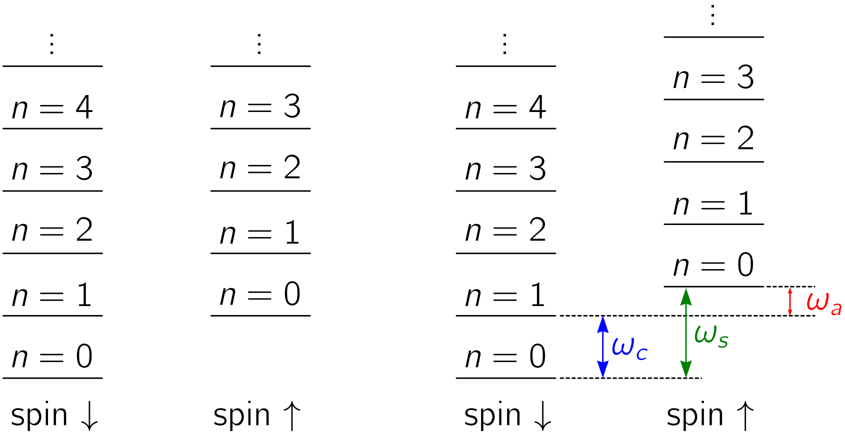


Classical trajectory of particle

L.S. Brown and G. Gabrielse, Rev. Mod. Phys. **58**, 233 (1986)

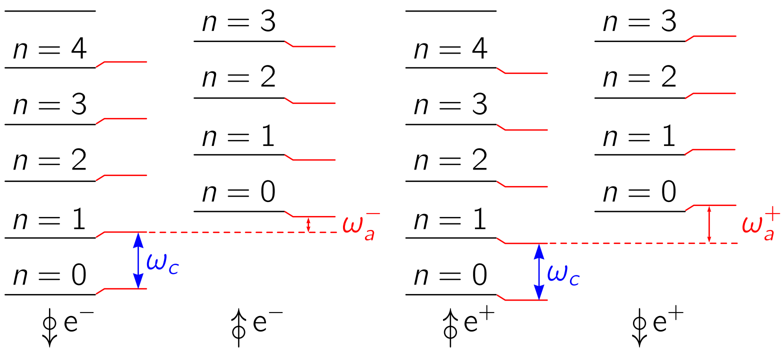
Penning traps: Quantum treatment

Solve Dirac equation for electron in uniform $\vec{B}$ field (Landau problem)



Modified energy levels

- Consider b_3^e: $\mathcal{L} = -b_\mu \overline{\psi} \gamma^5 \gamma^\mu \psi$

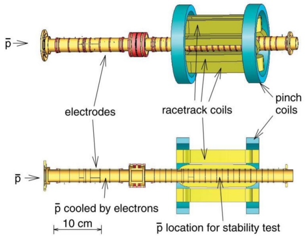


- Compare ω_a^- to ω_a^+ (also test of CPT invariance)
- Constrain Lorentz violation from the absence of a signal:

$$|\tilde{b}_X^e| < 1 \times 10^{-25}\,\mathrm{GeV}\,, \quad |\tilde{b}_X^{*,p}| < 9.7 \times 10^{-25}\,\mathrm{GeV}$$

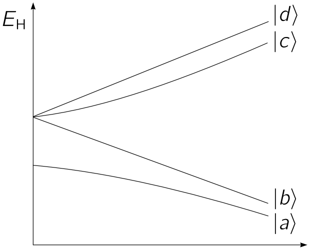
Y. Ding, Symmetry **11**, 1220 (2019), arXiv:1910.00456; C. Smorra *et al.*, BASE Collaboration, Nature **575**, 310 (2019)

Tests with anti-hydrogen



Penning trap + Ioffe-Pritchard trap

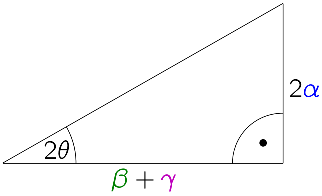
G. Gabrielse *et al.*, Phys. Rev. Lett. **98**, 113002 (2007)



$\alpha \gg \beta + \gamma$ L-S coupling

$\alpha \ll \beta + \gamma$ Paschen-Back effect

$$H_s = \alpha \vec{\sigma}_{\mathrm{e}} \cdot \vec{\sigma}_{\mathrm{p}} + \beta \sigma_{\mathrm{e},3} - \gamma \sigma_{\mathrm{p},3}, , \quad |s_{\mathrm{e}-}, s_{\mathrm{p}}\rangle$$

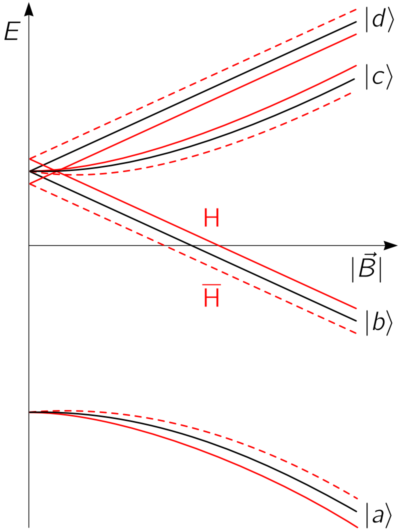


$$|d\rangle = |\uparrow,\uparrow\rangle$$
$$|c\rangle = \sin\theta|\downarrow,\uparrow\rangle + \cos\theta|\uparrow,\downarrow\rangle$$
$$|b\rangle = |\downarrow,\downarrow\rangle$$
$$|a\rangle = \cos\theta|\downarrow,\uparrow\rangle - \sin\theta|\uparrow,\downarrow\rangle$$

For anti-hydrogen: Same $\vec{B}$ field with spins reversed (CPT test)

Energy shifts by Lorentz violation

Consider b_3^p: $\mathcal{L} = -b_\mu \overline{\psi}\gamma^5\gamma^\mu\psi$



- For hydrogen (red):

$$\Delta E_d = -b_3^p + \dots$$

$$\Delta E_c = b_3^p \cos 2\theta + \dots$$

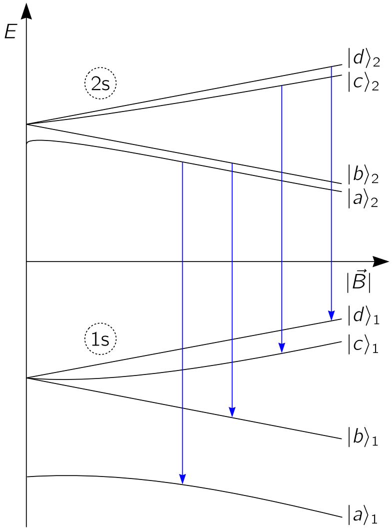
$$\Delta E_b = b_3^p + \dots$$

$$\Delta E_a = -b_3^p \cos 2\theta + \dots$$

- For anti-hydrogen (red, dashed):

$$b_3^p \mapsto -b_3^p$$

1s-2s transitions



- $|d\rangle_2 \mapsto |d\rangle_1$: no Lorentz-violating signal at leading order
- $|c\rangle_2 \mapsto |c\rangle_1$: has unsuppressed signal, as mixing angles θ_n differ
  - Optimum for $|\vec{B}| \approx 0.01\,\mathrm{T}$
  - Advantage over $|d\rangle_2 \mapsto |d\rangle_1$: $\approx 10^5$
- Problems:
  - Dependence on magnetic field
  - Zeeman splitting (broadening)
- Nevertheless, searches performed for $\mathcal{L} = c_{\mu\nu}\overline{\psi}\gamma^\mu \mathrm{i}\partial^\nu\psi$

$$c^e_{(TX)} = (3.1 \pm 1.9) \times 10^{-11}$$

$$0.92 c^e_{(TY)} + 0.40 c^e_{(TZ)} = (2.6 \pm 5.3) \times 10^{-11}$$

A. Matveev *et al.*, Phys. Rev. Lett. 110, 230801 (2013)

Constraints from hyperfine splitting

- Consider hyperfine transition between $|c\rangle$ and $|d\rangle$
  - Independent of magnetic field
  - No Zeeman splitting
- Unsuppressed signal for Lorentz violation

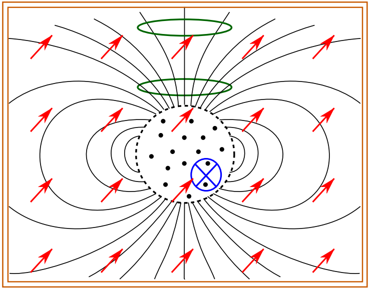
$$\delta\omega|_{\mathrm{LV,H}} = -2b_3^p\,, \quad \delta\omega|_{\mathrm{LV,\overline{H}}} = 2b_3^p$$

- With frequency resolution of $1\,\mathrm{mHz}$: sensitivity for b_3^p at $10^{-27}\,\mathrm{GeV}$

He/Xe magnetometer

Nonrelativistic limit of b coefficients in neutron sector:

$$\mathcal{L} = -b_\mu \overline{\psi}\gamma^5\gamma^\mu\psi\,, \quad V = -\vec{b}^n \cdot \vec{\sigma}$$



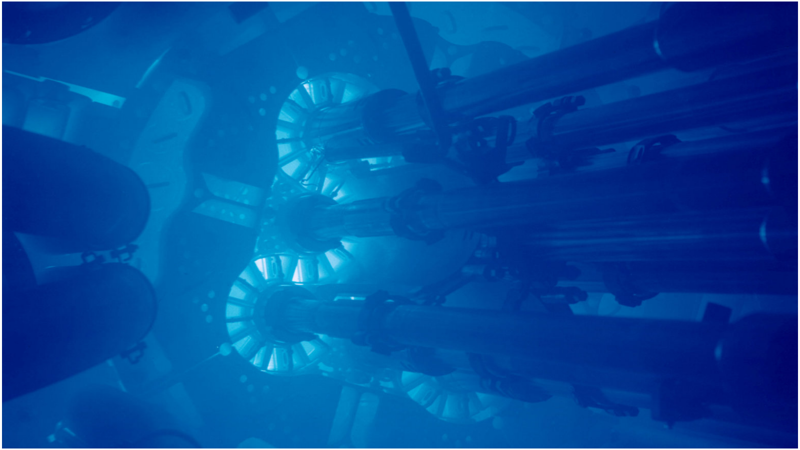
- Magnetically shielded room
- Homogeneous magnetic field $B_0 \approx 400\,\mathrm{nT}$
- Polarize $^3\mathrm{He}$ and $^{129}\mathrm{Xe}$ nuclear spins in spherical glass shell
- Spin precession produces oscillation of magnetic flux: measurement by SQUIDS
- Look for sidereal variation of weighted phase difference

$$\Delta\Phi \equiv \Phi_{\mathrm{He}} - \frac{\gamma_{\mathrm{He}}}{\gamma_{\mathrm{Xe}}}\Phi_{\mathrm{Xe}} = \Delta\Phi_{\mathrm{known}}(t) + \Delta\Phi_{\mathrm{LV}}(t)$$

$$\tilde{b}^n_\perp < 1.3 \times 10^{-33}\,\mathrm{GeV}$$

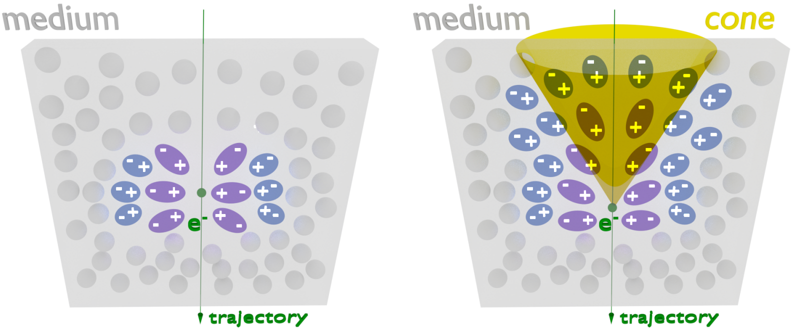
F. Allmendinger *et al.*, Phys. Rev. Lett. 112, 110801 (2014), arXiv:1312.3225

Cherenkov radiation in media



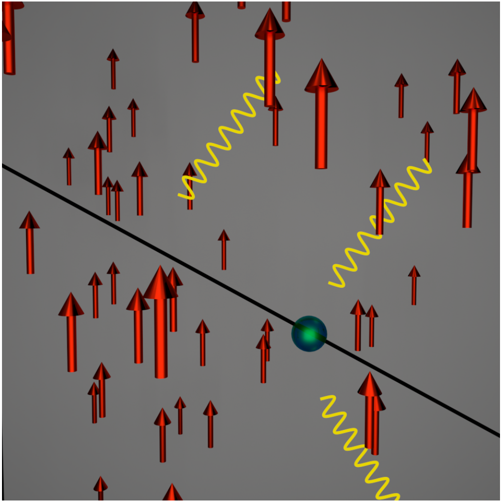
Idaho National Laboratory's Advanced Test Reactor core
(Argonne National Laboratory; Wikipedia)

Cherenkov radiation in media

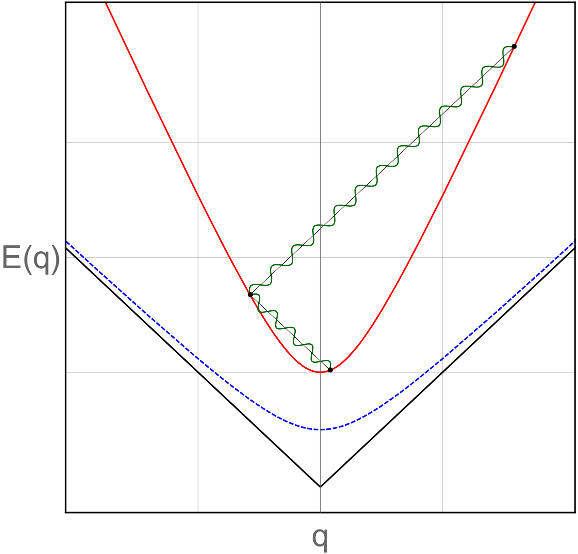


- Experimental discovery: Cherenkov, Vavilov (1934)
- Theoretical explanation: Frank, Tamm (1937)
- Book reference: J.V. Jelley, *Čerenkov Radiation and Its Applications* (Pergamon Press, London, 1958)

Cherenkov-type process in vacuo



Modified fermions: spin-degenerate case



Threshold analysis

- Consider operator $\mathcal{L} = c_{\mu\nu}\overline{\psi}\gamma^{\mu}\mathrm{i}\partial^{\nu}\psi$
- Vacuum Cherenkov threshold energy

$$q_{\mathring{c}}^{\mathrm{th}} = \frac{1}{2}\sqrt{\frac{3}{2}}\frac{m_{\psi}}{\sqrt{-\mathring{c}}}$$

- Simplified analysis based on Pierre-Auger event of $E = 212\,\mathrm{EeV}$

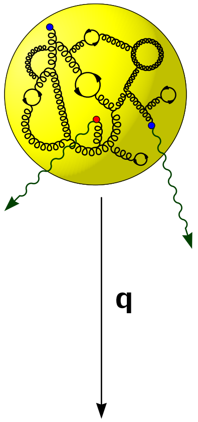
J. Abraham *et al.* [Pierre Auger Collaboration], Astropart. Phys. 27, 155 (2007)

- u and d quarks of proton carrying 10% of E

$$\mathring{c}^{\mathrm{u}} > -3 \times 10^{-23}$$

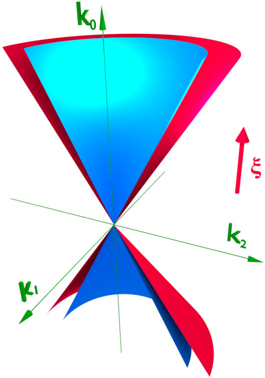
MS, Phys. Rev. D **96**, 095026 (2017), arXiv:1702.03171 [hep-ph]

- To be refined by using parton model



Consistency of Standard-Model Extension

Many sectors tested for . . .



- Microcausality
  - $[A_\mu(x), A_\nu(y)] = 0$ (photons)
  - $\{\psi(x), \overline{\psi}(y)\} = 0$ (fermions)

  outside of *modified* light cones
- Unitarity (reflection positivity, validity of optical theorem)
- Renormalizability (operators of dimensions 3, 4)
- Consistent cross sections

$\Longrightarrow$ Quantum Field Theory very robust with respect to presence of background fields!

V.A. Kostelecký and R. Lehnert, Phys. Rev. D **63**, 065008 (2001) [hep-th/0012060]; F.R. Klinkhamer and MS, Nucl. Phys. B **848**, 90 (2011) arXiv:1011.4258 [hep-th]; MS, Phys. Rev. D **86**, 065038 (2012), arXiv:1111.4182 [hep-th]; . . .

For higher-dimensional operators: MS, Phys. Rev. D **89**, 105019 (2014), arXiv:1312.4916 [hep-th]; MS, Phys. Rev. D **90**, 085025 (2014), arXiv:1403.6766 [hep-th]; R. Casana, M.M. Ferreira, Jr., A.R. Gomes, and P.R.D. Pinheiro, Phys. Rev. D **80**, 125040 (2009), arXiv:0909.0544 [hep-th]; C.M. Reyes, Phys. Rev. D **87**, 125028 (2013), arXiv:1307.5340 [hep-th]; . . .

Outlook

- (Minimal) Lorentz violation tightly constrained by experiment

Matter			
	Electron	Proton	Neutron
$\tilde{b}_X$	10^{-31} GeV	10^{-33} GeV	10^{-33} GeV
$\tilde{c}_{TX}$	10^{-18} GeV	10^{-20} GeV	10^{-17} GeV
$\tilde{d}_{XY}$	10^{-26} GeV	—	10^{-27} GeV
Photons			
$k^{(3)}_{(V)00}$	10^{-43} GeV		
$(\tilde{\kappa}_{e-})^{XY}$	10^{-22}		
$(\tilde{\kappa}_{o+})^{XY}$	10^{-14}		
Neutrinos			
	electron-muon	electron-tau	mu-tau
$\mathrm{Re}(a_L)^X$	10^{-20} GeV	10^{-19} GeV	10^{-23} GeV
$\mathrm{Re}(c_L)^{XY}$	10^{-21}	10^{-17}	10^{-23}

V.A. Kostelecký and N. Russell, Rev. Mod. Phys. **83**, 11 (2011), arXiv:0801.0287 [hep-ph] and references therein

- Space for higher-dimensional operators
- Feedback on fundamental theories of quantum gravity

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