Testing Lorentz violation in weak gravitational field

Zonghao Li and V. Alan Kostelecký
Indiana University, Bloomington
IU Center for Spacetime Symmetries

Based on: V. A. Kostelecký, Z. Li, PRD 103,024059(2021) and arXiv:2106.11293.

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Outline

- Lorentz violation in effective field theory
- Lorentz violation in weak gravitational field
- Experiment (1): free-dropping experiments
- Experiment (2): interferometer experiments
- Experiment (3): bound-state experiments

Outline

- **Lorentz violation and effective field theory**
- Lorentz violation in weak gravitational field
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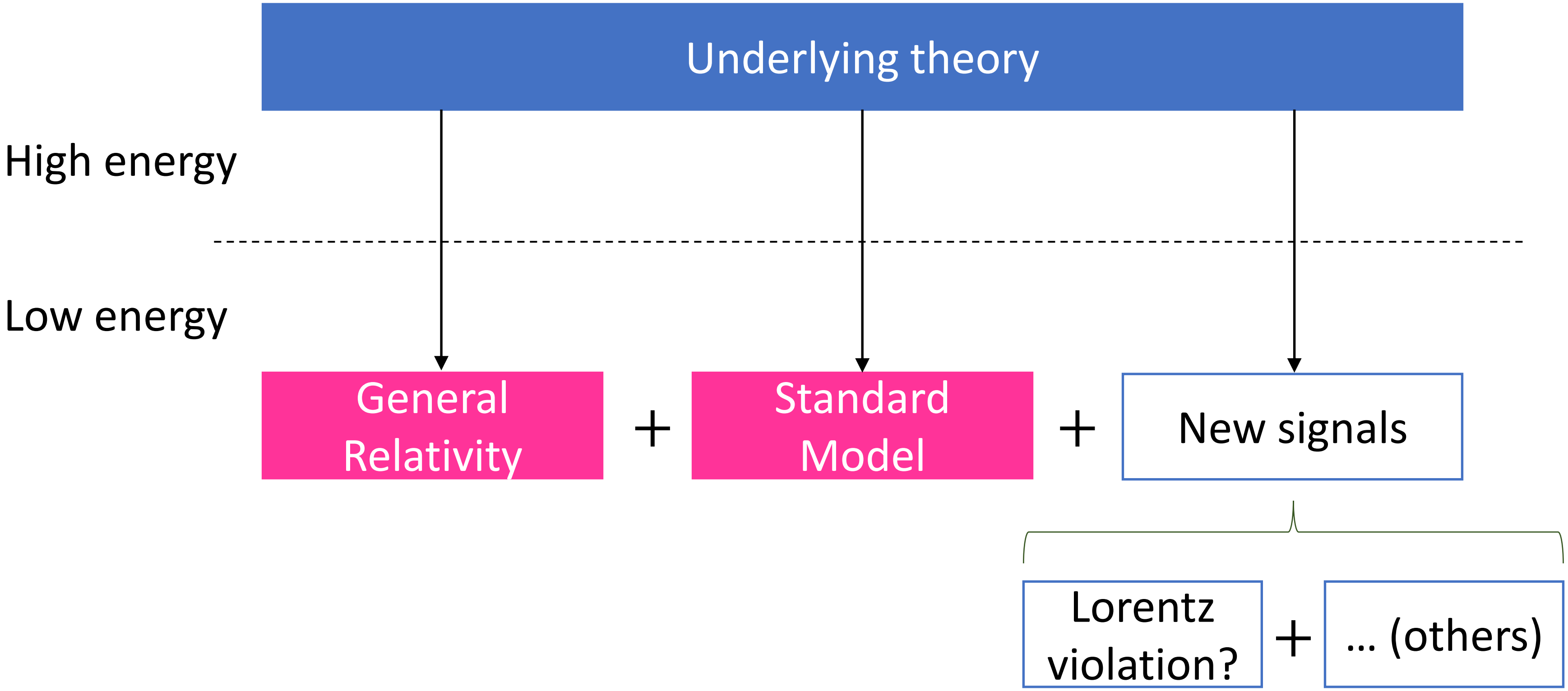
Unification of General Relativity and other forces

- Testing Lorentz violation can shed light on the underlying theory



Underlying theory

High energy

Low energy

General Relativity + Standard Model + New signals

Lorentz violation? + … (others)

Effective field theory (EFT)

- Lorentz violation studied in the context of effective field theory

EFT	**=**	**General Relativity coupled to Standard Model**	**+**	**All possible modifications**
$\mathcal{L}$	**=**	$\mathcal{L}_0$	**+**	$\mathcal{L}'$

Example: $\mathcal{L}' \supset (k_c^{(4)})^{\mu\nu}\partial_\mu\phi^\dagger\partial_\nu\phi$

$(k_c^{(4)})^{\mu\nu} \rightarrow$ background field

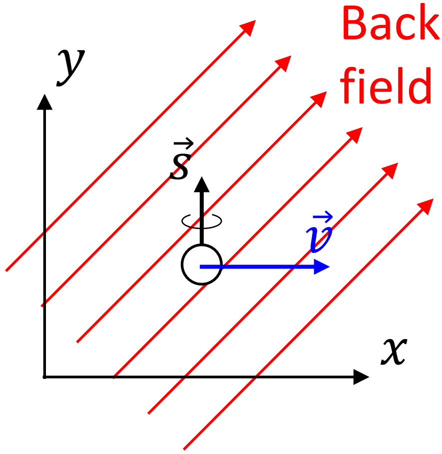
coefficients for Lorentz violation

coupling constants

control the size of Lorentz violation

$\phi \rightarrow$ dynamical scalar field

matter sector



Kostelecký, PRD 69,105009 (2004)
Edwards, Kostelecký, PLB 795,620 (2019)

Experiments to test Lorentz violation

Gravity sector:

- Gravitational waves
- Short-range gravity
- Atom interferometry
- Binary pulsars
- Gravimetry
- Cosmic ray
- Torsion pendulum

Photon sector:

- Astrophysical birefringence
- Astrophysical dispersion
- CMB polarization
- Laser interferometry
- Microwave, optical resonators
- Cavity oscillators
- Compton scattering

Electron and/or proton sectors:

- Penning trap
- Atom spectroscopy
- K/He magnetometer
- Atomic clock comparison
- 1S-2S transition
- Electron kinematics
- Nuclear binding energy

Neutrino sector:

- Neutrino oscillation
- Double beta decay
- Neutrino time-of-flight
- Čerenkov radiation
- Tritium decay

And more…

Kostelecky, Russell, *Data Tables for Lorentz and CPT Violation*, Rev.Mod.Phys. 83.11(2011) updated as arXiv:0801.0287v14(2021)

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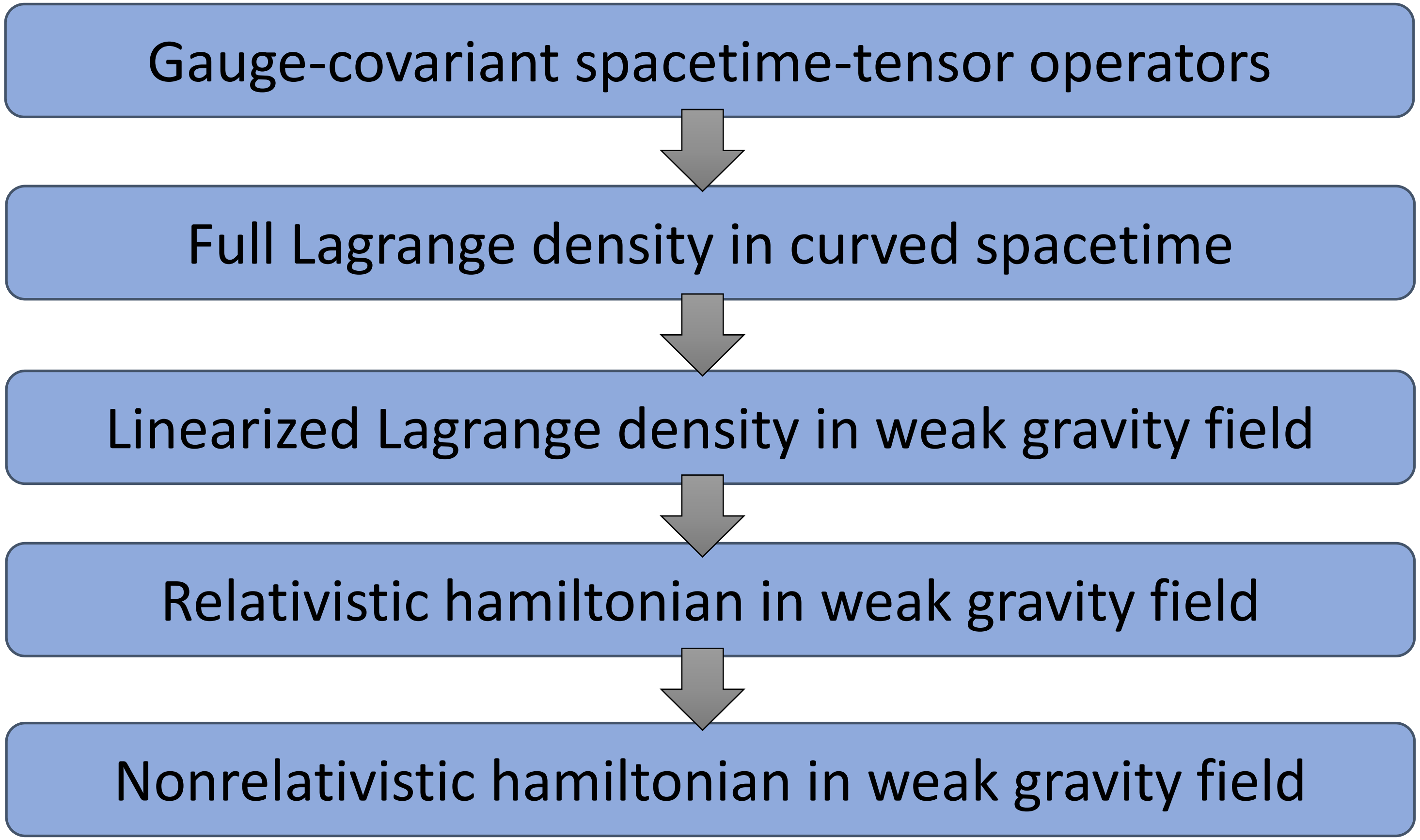
Framework



Gauge-covariant spacetime-tensor operators

Full Lagrange density in curved spacetime

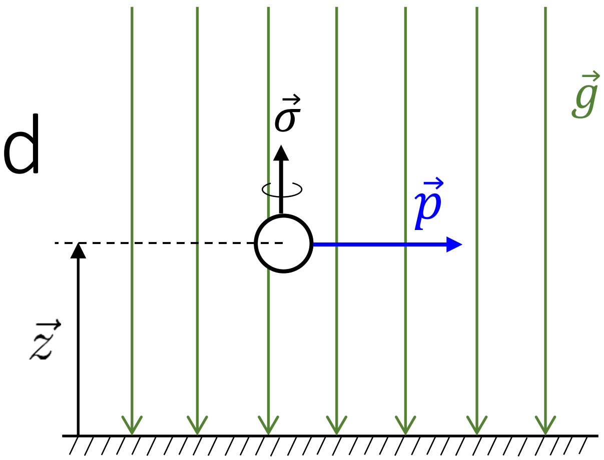
Linearized Lagrange density in weak gravity field

Relativistic hamiltonian in weak gravity field

Nonrelativistic hamiltonian in weak gravity field

Kostelecký, Li, PRD 99,056016(2019); PRD 103,024059(2021); arXiv:2106.11293

Nonrelativistic hamiltonian in the Earth’s gravitational field



- Conventional term: $H_0 = -m\vec{g}\cdot\vec{z}$
- Corrections from the EFT:

Spin-
Independent

$$\begin{aligned} H_\phi = {} & (k_\phi^{\rm NR})\vec{g}\cdot\vec{z} + (k_{\phi p}^{\rm NR})^j \tfrac{1}{2}(p^j\vec{g}\cdot\vec{z} + \vec{g}\cdot\vec{z}\,p^j) \\ & + (k_{\phi pp}^{\rm NR})^{jk} \tfrac{1}{2}(p^j p^k \vec{g}\cdot\vec{z} + \vec{g}\cdot\vec{z}\,p^j p^k) \end{aligned}$$

$$H_g = (k_g^{\rm NR})^j g^j + (k_{gp}^{\rm NR})^{jk} p^j g^k + (k_{gpp}^{\rm NR})^{jkl} p^j p^k g^l$$

Spin-
dependent

$$\begin{aligned} H_{\sigma\phi} = {} & (k_{\sigma\phi}^{\rm NR})^j \sigma^j \vec{g}\cdot\vec{z} + (k_{\sigma\phi p}^{\rm NR})^{jk} \tfrac{1}{2}\sigma^j (p^k\vec{g}\cdot\vec{z} + \vec{g}\cdot\vec{z}\,p^k) \\ & + (k_{\sigma\phi pp}^{\rm NR})^{jkl} \tfrac{1}{2}\sigma^j (p^k p^l \vec{g}\cdot\vec{z} + \vec{g}\cdot\vec{z}\,p^k p^l) \end{aligned}$$

$$\begin{aligned} H_{\sigma g} = {} & (k_{\sigma g}^{\rm NR})^{jk} \sigma^j g^k + (k_{\sigma gp}^{\rm NR})^{jkl} \sigma^j p^k g^l \\ & + (k_{\sigma gpp}^{\rm NR})^{jklm} \sigma^j p^k p^l g^m \end{aligned}$$

Kostelecký, Li, arXiv:2106.11293

TABLE III. Correspondence between nonrelativistic and linearized coefficients.

NR coefficient	Linearized coefficient
$(k_\phi^{\rm NR})$	$2(m'^{\rm L})^{ss} - 2(a^{\rm L})^{tss} + 2m(e_h^{\rm L})^{tss} - 2m(c_h^{\rm L})^{ttss} + 2m^2(m_h^{(5){\rm L}})^{ttss} - 2m^2(a_h^{(5){\rm L}})^{tttss}$
$(k_{\phi p}^{\rm NR})^j$	$\frac{2}{m}(a^{\rm L})^{jss} - 2(e_h^{\rm L})^{jss} + 2(c_h^{\rm L})^{jtss} + 2(c_h^{\rm L})^{tjss} - 4m(m_h^{(5){\rm L}})^{jtss} + 2m(a_h^{(5){\rm L}})^{jttss} + 4m(a_h^{(5){\rm L}})^{tjtss}$
$(k_{\phi pp}^{\rm NR})^{jk}$	$-\frac{1}{m}[(c_h^{\rm L})^{jkss} + (c_h^{\rm L})^{kjss}] + 2(m_h^{(5){\rm L}})^{jkss} - 2(a_h^{(5){\rm L}})^{tjkss} - 2[(a_h^{(5){\rm L}})^{jktss} + (a_h^{(5){\rm L}})^{kjtss}]$ $-\delta^{jk}\big[\frac{1}{m^2}(m'^{\rm L})^{ss} + \frac{1}{m}(c_h^{\rm L})^{ttss} - (m_h^{(5){\rm L}})^{ttss} + 2(a_h^{(5){\rm L}})^{tttss}\big]$
$(k_{\sigma\phi}^{\rm NR})^j$	$-2(b^{\rm L})^{jss} + \epsilon^{jkl}(H^{\rm L})^{klss} - 2m(d_h^{\rm L})^{jtss} + m\epsilon^{jkl}(g_h^{\rm L})^{kltss} - 2m^2(b_h^{(5){\rm L}})^{jttss} + m^2\epsilon^{jkl}(H_h^{(5){\rm L}})^{klttss}$
$(k_{\sigma\phi p}^{\rm NR})^{jk}$	$2(d_h^{\rm L})^{jkss} - \epsilon^{jmn}(g_h^{\rm L})^{mnkss} + 4m(b_h^{(5){\rm L}})^{jktss} - 2m\epsilon^{jmn}(H_h^{(5){\rm L}})^{mnktss}$ $+\delta^{jk}\big[\frac{2}{m}(b^{\rm L})^{tss} + 2(d_h^{\rm L})^{ttss} + 2m(b_h^{(5){\rm L}})^{tttss}\big] - \epsilon^{jkl}\big[\frac{2}{m}(H^{\rm L})^{tlss} + 2(g_h^{\rm L})^{tltss} + 2m(H_h^{(5){\rm L}})^{tlttss}\big]$
$(k_{\sigma\phi pp}^{\rm NR})^{jkl}$	$-2(b_h^{(5){\rm L}})^{jklss} + \epsilon^{jmn}(H_h^{(5){\rm L}})^{mnklss} + \delta^{kl}\big[\frac{1}{m^2}(b^{\rm L})^{jss} + \frac{1}{2m}\epsilon^{jmn}(g_h^{\rm L})^{mntss} - (b_h^{(5){\rm L}})^{jttss} + \epsilon^{jkl}(H_h^{(5){\rm L}})^{mnttss}\big]$ $+\frac{1}{2}\Big[\Big(- \delta^{jk}\big[\frac{1}{m^2}(b^{\rm L})^{lss} + \frac{1}{2m^2}\epsilon^{lmn}(H^{\rm L})^{mnss} + \frac{2}{m}(d_h^{\rm L})^{tlss} + \frac{1}{m}(d_h^{\rm L})^{ltss} + \frac{1}{2m}\epsilon^{lmn}(g_h^{\rm L})^{mntss}$ $+4(b_h^{(5){\rm L}})^{ttlss} + (b_h^{(5){\rm L}})^{lttss} + \frac{1}{2}\epsilon^{lmn}(H_h^{(5){\rm L}})^{mnttss}\big] + \epsilon^{jkm}\big[\frac{2}{m}(g_h^{\rm L})^{tmlss} + 4(H_h^{(5){\rm L}})^{tmltss}\big]\Big) + (k \leftrightarrow l)\Big]$
$(k_g^{\rm NR})^j$	$\frac{1}{m}(H^{\rm L})^{tjss} + 2(e_{\partial h}^{\rm L})^{jss} - 2(c_{\partial h}^{\rm L})^{tjss} + (g_h^{\rm L})^{tjtss} + 2m(m_{\partial h}^{(5){\rm L}})^{tjss} - 2m(a_{\partial h}^{(5){\rm L}})^{ttjss} + m(H_h^{(5){\rm L}})^{tjttss}$
$(k_{gp}^{\rm NR})^{jk}$	$\frac{2}{m}(c_{\partial h}^{\rm L})^{jkss} - \frac{1}{m}(g_h^{\rm L})^{tkjss} - 2(m_{\partial h}^{(5){\rm L}})^{jkss} + 2(a_{\partial h}^{(5){\rm L}})^{tjkss} + 2(a_{\partial h}^{(5){\rm L}})^{jtkss} - 2(H_h^{(5){\rm L}})^{tkjtss}$ $-\epsilon^{jkl}[\frac{1}{2m^2}(b^{\rm L})^{lss} + \frac{1}{2m}(d_h^{\rm L})^{ltss} + \frac{1}{2}(b_h^{(5){\rm L}})^{lttss}] - \epsilon^{jkl}\epsilon^{lmn}[\frac{1}{4m^2}(H^{\rm L})^{mnss} + \frac{1}{4m}(g_h^{\rm L})^{mntss} + \frac{1}{4}(H_h^{(5){\rm L}})^{mnttss}]$
$(k_{gpp}^{\rm NR})^{jkl}$	$-\frac{1}{m}(a_{\partial h}^{(5){\rm L}})^{jklss} - \frac{1}{m}(a_{\partial h}^{(5){\rm L}})^{kjlss} + \frac{1}{m}(H_h^{(5){\rm L}})^{tljkss}$ $-\delta^{jk}\big[\frac{1}{m^2}(e_{\partial h}^{\rm L})^{lss} - \frac{1}{2m^2}(g_h^{\rm L})^{tltss} + \frac{1}{m}(a_{\partial h}^{(5){\rm L}})^{ttlss} - \frac{1}{m}(H_h^{(5){\rm L}})^{tlttss}\big]$ $+\epsilon^{jlm}[\frac{1}{2m^2}(d_h^{\rm L})^{mkss} + \frac{1}{m}(b_h^{(5){\rm L}})^{mtkss}] + \epsilon^{jlm}\epsilon^{mnr}[\frac{1}{4m^2}(g_h^{\rm L})^{nrkss} + \frac{1}{2m}(H_h^{(5){\rm L}})^{nrtkss}]$
$(k_{\sigma g}^{\rm NR})^{jk}$	$-2(d_{\partial h}^{\rm L})^{jkss} + \epsilon^{jmn}(g_{\partial h}^{\rm L})^{mnkss} - 2m(b_{\partial h}^{(5){\rm L}})^{jtkss} + m\epsilon^{jmn}(H_{\partial h}^{(5){\rm L}})^{mntkss}$ $-\delta^{jk}\big[\frac{1}{m}(m_5^{\rm L})^{ss} + (f_h^{\rm L})^{tss} + m(m_{5h}^{(5){\rm L}})^{ttss}\big] + \epsilon^{jkl}\big[\frac{1}{m}(a^{\rm L})^{lss} + (c_h^{\rm L})^{ltss} + m(a_h^{(5){\rm L}})^{lttss}\big]$
$(k_{\sigma gp}^{\rm NR})^{jkl}$	$2(b_{\partial h}^{(5){\rm L}})^{jklss} - \epsilon^{jmn}(H_{\partial h}^{(5){\rm L}})^{mnklss} + \epsilon^{jkl}\big[\frac{1}{2m^2}(m'^{\rm L})^{ss} + \frac{1}{2m^2}(a^{\rm L})^{tss} + \frac{1}{2m}(e_h^{\rm L})^{tss} + \frac{1}{2m}(c_h^{\rm L})^{ttss}$ $+\frac{1}{2}(m_h^{(5){\rm L}})^{ttss} + \frac{1}{2}(a_h^{(5){\rm L}})^{tttss}\big] + \delta^{jk}\big[\frac{2}{m}(d_{\partial h}^{\rm L})^{tlss} + 2(b_{\partial h}^{(5){\rm L}})^{ttlss}\big] + \delta^{jl}\big[\frac{1}{m}(f_h^{\rm L})^{kss} + 2(m_{5h}^{(5){\rm L}})^{ktss}\big]$ $-\epsilon^{jkm}\big[\frac{2}{m}(g_{\partial h}^{\rm L})^{tmlss} + 2(H_{\partial h}^{(5){\rm L}})^{tmtlss}\big] - \epsilon^{jlm}\big[\frac{1}{m}(c_h^{\rm L})^{mkss} + 2(a_h^{(5){\rm L}})^{mktss}\big]$
$(k_{\sigma gpp}^{\rm NR})^{jklm}$	$-\delta^{jm}\delta^{kl}\big[\frac{2}{m^2}(f_h^{\rm L})^{tss}\frac{1}{m}(m_{5h}^{(5){\rm L}})^{ttss}\big] - \delta^{jm}\frac{1}{m}(m_h^{(5){\rm L}})^{klss} + \delta^{kl}\big[\frac{1}{m^2}(d_{\partial h}^{\rm L})^{jmss} + \frac{1}{2m}\epsilon^{jnr}(H_{\partial h}^{(5){\rm L}})^{nrtmss}\big]$ $+\delta^{kl}\epsilon^{jmn}\big[\frac{1}{2m^2}(c_h^{\rm L})^{ntss} + \frac{1}{m}(a_h^{(5){\rm L}})^{nttss}\big] + \epsilon^{jmn}\frac{1}{m}(a_h^{(5){\rm L}})^{nklss}$ $-\frac{1}{2}\Big[\Big(\delta^{jk}\big[\frac{1}{m^2}(d_{\partial h}^{\rm L})^{lmss} + \frac{1}{2m^2}\epsilon^{lnr}(g_{\partial h}^{\rm L})^{nrmss} + \frac{2}{m}(b_{\partial h}^{(5){\rm L}})^{tlmss} + \frac{1}{m}(b_{\partial h}^{(5){\rm L}})^{ltmss} + \frac{1}{2m}\epsilon^{lnr}(H_{\partial h}^{(5){\rm L}})^{nrtmss}\big]$ $+\epsilon^{jkm}\big[\frac{1}{2m^2}(e_h^{\rm L})^{lss} + \frac{1}{2m^2}(c_h^{\rm L})^{tlss} + \frac{1}{m}(m_h^{(5){\rm L}})^{ltss} + \frac{1}{m}(a_h^{(5){\rm L}})^{tltss}\big] - \epsilon^{jkn}\frac{2}{m}(H_{\partial h}^{(5){\rm L}})^{tnlmss}\Big) + (k \leftrightarrow l)\Big]$

Kostelecký, Li, arXiv:2106.11293

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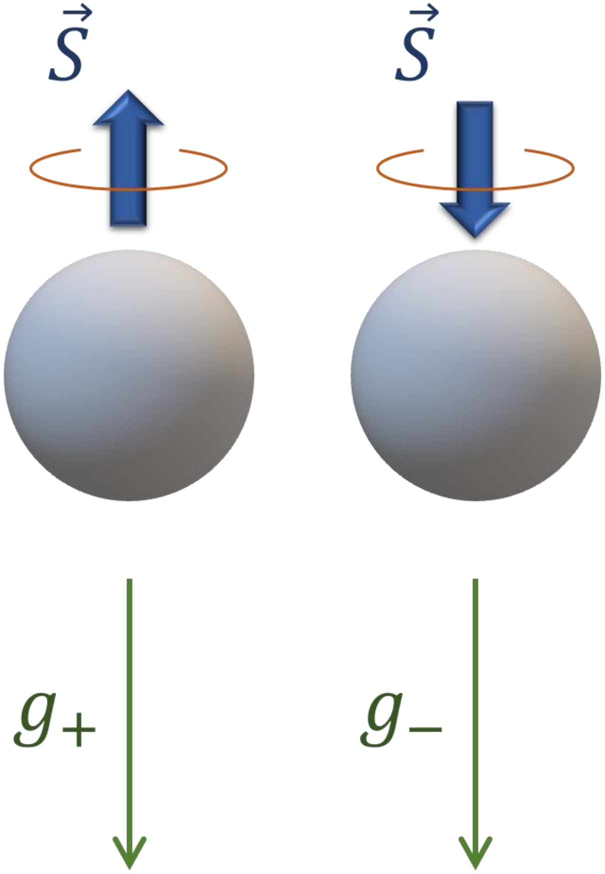
Free-dropping experiments

- Atoms with different spins
- Gravitational accelerations (g)
- Precision measurement

Sensitive to

- Weak equivalence principle (WEP)
- Spin-gravity coupling
- Lorentz violation



Dropping ^{87}Rb atoms

- ^{87}Rb with different spins
- Proton and electron sectors
- Sensitivity:

$$\Delta g/g \lesssim 10^{-7}$$

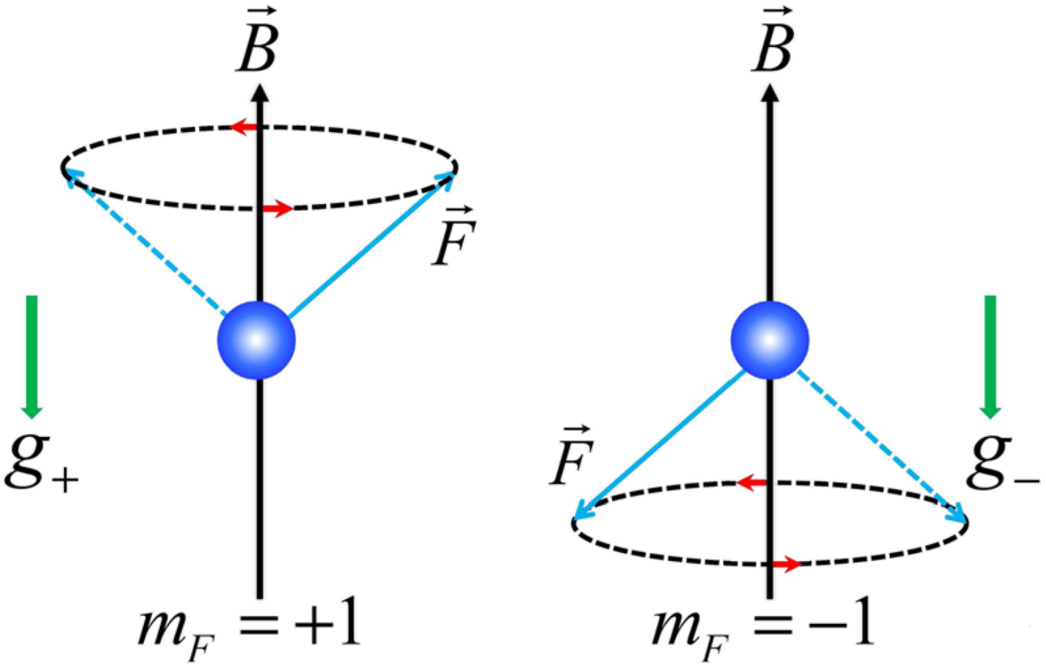


Image: Duan *et al.*, PRL'2016

- Constraints on coefficients for LV:

$$\left|(k^{\rm NR}_{\sigma\phi})^Z_p - 0.6(k^{\rm NR}_{\sigma\phi})^Z_e\right| < 2\times 10^{-5}\ {\rm GeV}$$

$$\left|(k^{\rm NR}_{\sigma\phi pp})^{ZJJ}_p + 0.3(k^{\rm NR}_{\sigma\phi pp})^{JJZ}_p\right| < 7\times 10^{-3}\ {\rm GeV}^{-1}$$

Duan *et al.*, PRL 117,023001(2016)
Kostelecký, Li, arXiv:2106.11293

Dropping ^{88}Sr and ^{87}Sr atoms

- ^{88}Sr: spin-0, bosonic
- ^{87}Sr: spin-9/2, fermionic
- Broadening of g for unpolarized ^{87}Sr
- Neutron sector
- Sensitivity: $\Delta g/g \lesssim 10^{-7}$

- Constraints on coefficients for LV:

$$\left|(k^{\mathrm{NR}}_{\sigma\phi})^{Z}_{n}\right| < 1\times 10^{-4}\ \mathrm{GeV}$$

$$\left|(k^{\mathrm{NR}}_{\sigma\phi pp})^{ZJJ}_{n} - 0.4(k^{\mathrm{NR}}_{\sigma\phi pp})^{ZZZ}_{n}\right| < 5\times 10^{-2}\ \mathrm{GeV}^{-1}$$

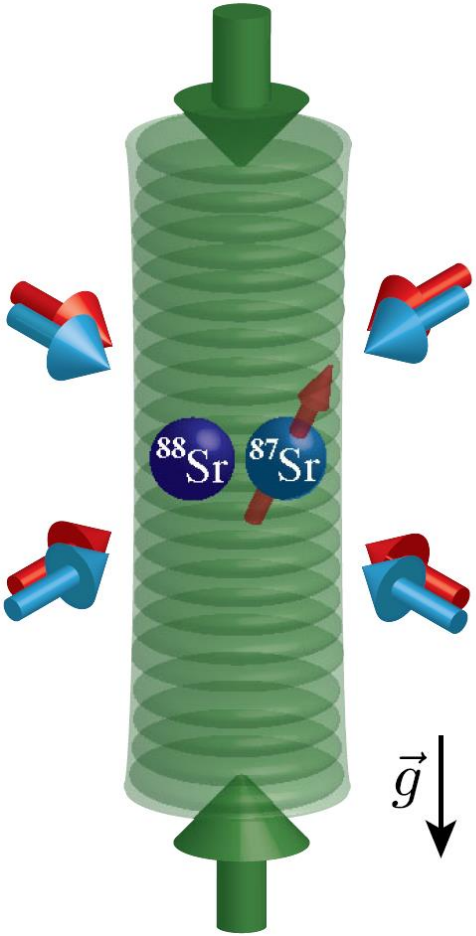


Image: Tarallo *et al.*, PRL’2014

Tarallo *et al.*, PRL 113,023005(2014)
Kostelecký, Li, arXiv:2106.11293

Dropping hydrogen and antihydrogen

- Symmetry between particles and antiparticles
- Plans proposed by many groups
- Contributions from the EFT:

spin

$$\frac{g_{\mathrm{eff}}}{g} = 1 - \frac{1}{m_H} \sum_{\omega} \left[(k_{\phi}^{\mathrm{NR}})_{\omega} + m_F (k_{\sigma\phi}^{\mathrm{NR}})_{\omega}^{z} \right]$$

$\omega = e^-, p$ for hydrogen

$\omega = e^+, \bar{p}$ for antihydrogen

S. Aghion *et al.*, Nat. Commun. 5,4538(2014)
C. Amole *et al.*, Phys. Rev. Lett. 112,121102(2014)
P. Indelicato *et al.*, Nat. Commun. 4,1787(2013)
Kostelecký, Li, arXiv:2106.11293

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Colella-Overhauser-Werner (COW) experiment

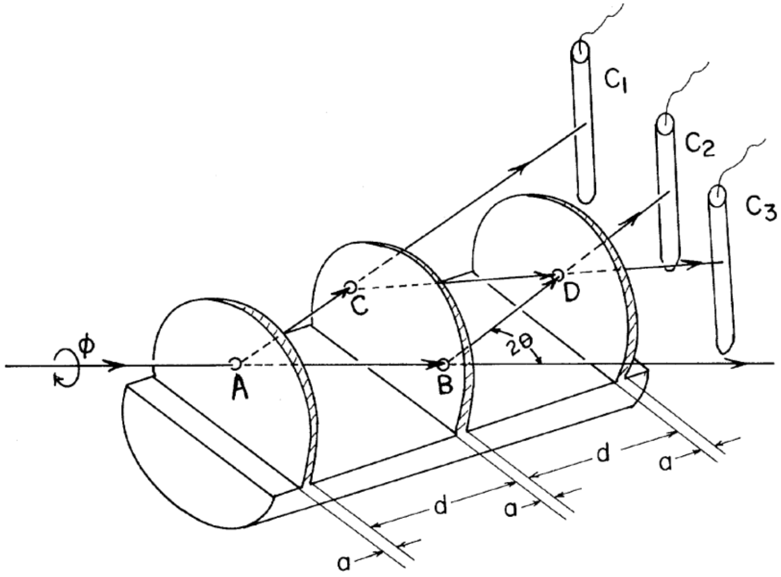

Image: Colella, Overhauser, Werner, PRL'1975

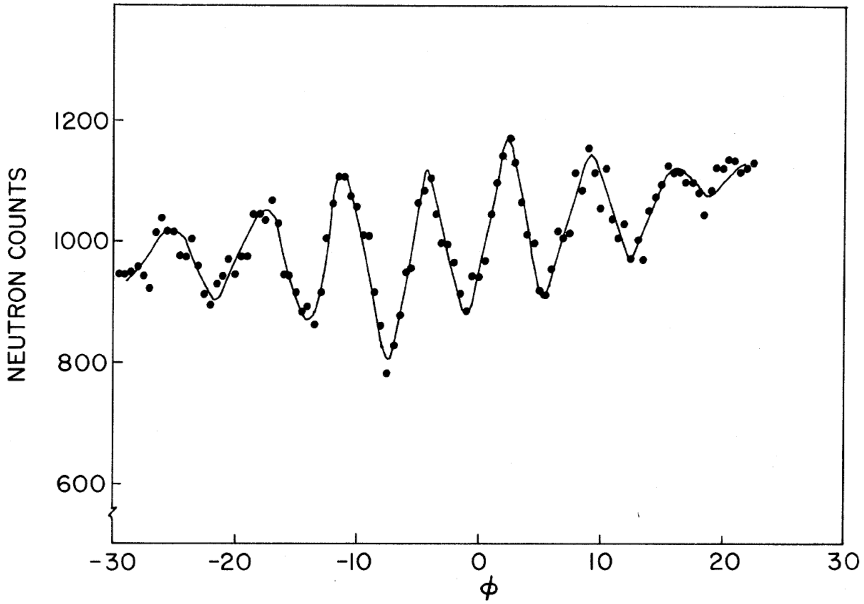

Image: Colella, Overhauser, Werner, PRL'1975

- Gravity-induced phase shift depending on coefficients for LV
- Sensitivity and constraints on coefficients for LV:

$$\Delta g/g = \boxed{-(k_\phi^{\mathrm{NR}})_n/m_n} \qquad |(k_\phi^{\mathrm{NR}})_n| < 1 \times 10^{-1}\ \mathrm{GeV}$$

↑

Spin-independent

Colella, Overhauser, Werner, PRL 34,23(1975)
Kostelecký, Li, arXiv:2106.11293

Neutron spin-echo experiment

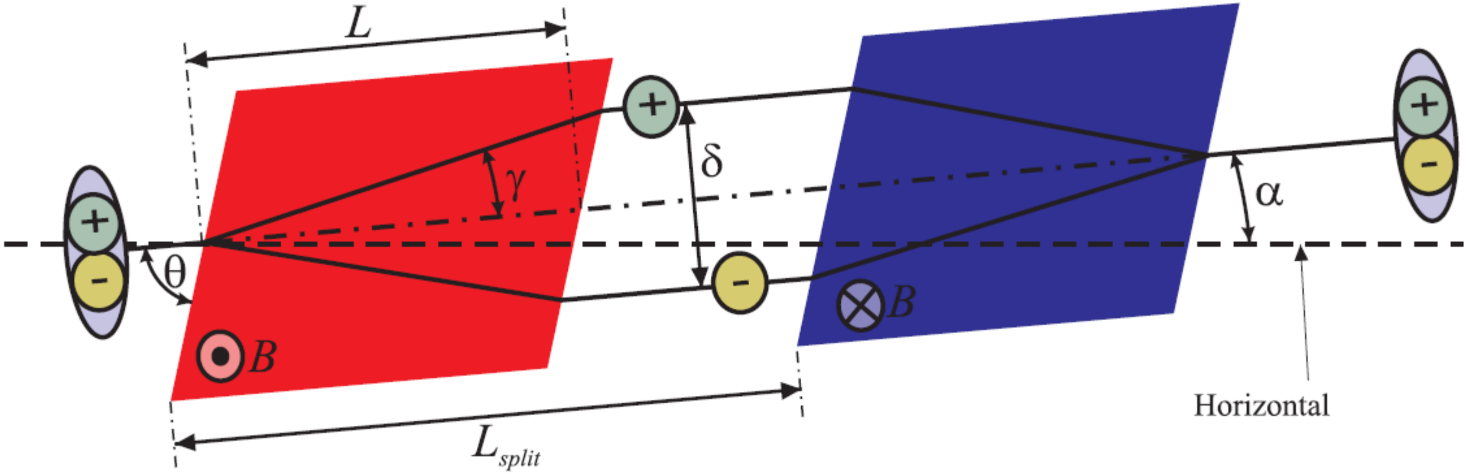

Image: V.-O. de Haan *et al.*, PRA'2004

- Similar method using neutrons and magnetic fields
- Sensitivity and constraints on coefficients for LV:

$$g_{n,\hat{s}^j} = g\left[1 - \frac{(k_\phi^{\rm NR})_n}{m_n} - \frac{(k_{\sigma\phi}^{\rm NR})_n^j \hat{s}^j}{m_n}\right]$$

$$(k_\phi^{\rm NR})_n + (k_{\sigma\phi}^{\rm NR})_n^j \underset{\substack{\uparrow \\ \text{Initial spin}}}{\hat{s}^j} < 2.5 \times 10^{-2} {\rm GeV}$$

V.-O. de Haan *et al.*, PRA 89,063611(2004)
Kostelecký, Li, arXiv:2106.11293

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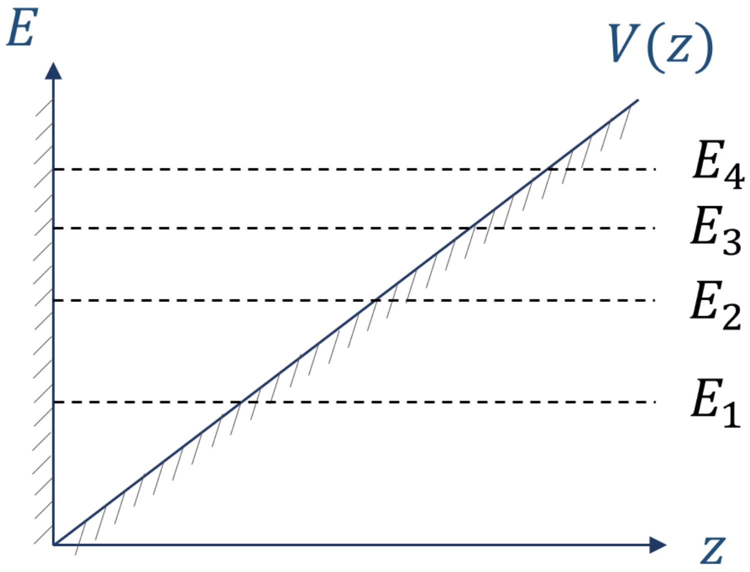
Bound states of neutrons in the Earth’s gravitational field

Linear potential



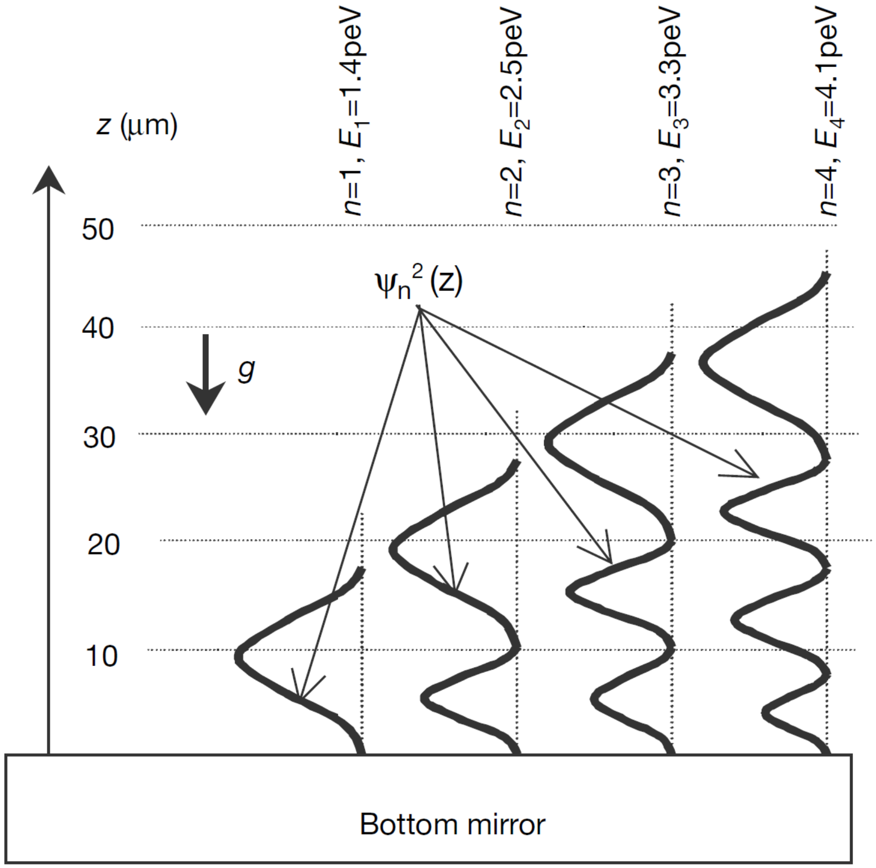
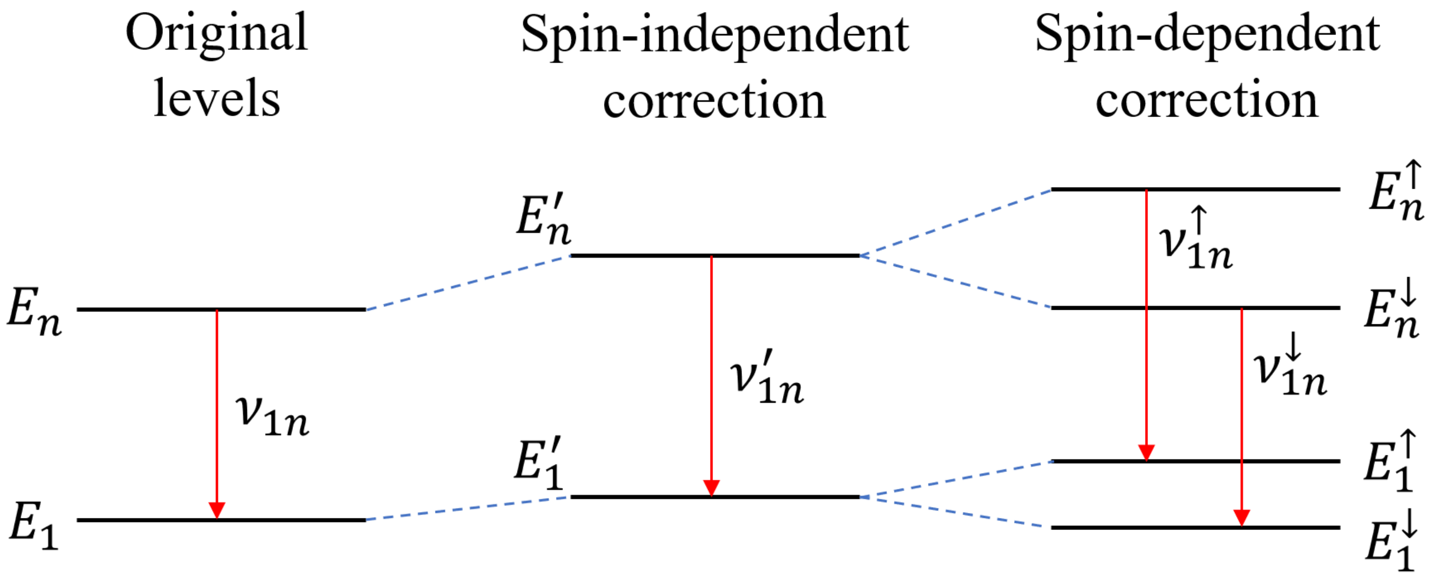


Image: Nesvizhevsky *et al.*, Nature’2002

Nesvizhevsky *et al.*, Nature 415,297(2002)

Transition frequencies



- Corrections:

$$\Delta E_n - \Delta E_1 = -\frac{2}{3}\,\frac{\overset{\text{Spin-independent}}{\overset{\downarrow}{(k_{\phi}^{\mathrm{NR}})_n}} \pm \overset{\text{Spin-dependent}}{\overset{\downarrow}{\sqrt{\left[(k_{\sigma\phi}^{\mathrm{NR}})_n^j\right]^2}}}}{m}(E_n - E_1)$$

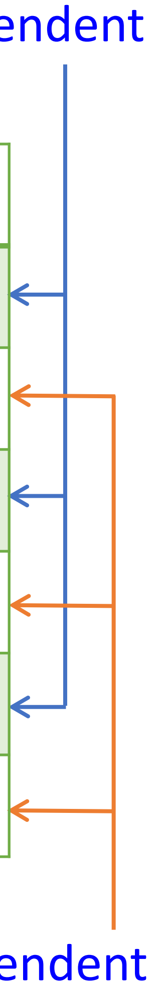
- Constraints on coefficients for LV:

$$\left|(k_{\phi}^{\mathrm{NR}})_n\right| < 1.3 \times 10^{-2}\ \mathrm{GeV} \qquad \sqrt{\left[(k_{\sigma\phi}^{\mathrm{NR}})_n^j\right]^2} < 7.8 \times 10^{-3}\ \mathrm{GeV}$$

Cronenberg *et al.*, Nat.Phys. 14,1022(2018)
Kostelecký, Li, arXiv:2106.11293

Constraints on coefficients for LV from various types of experiments

		Free-dropping	Interferometer	Bound-state
Proton sector	$(k_{\phi}^{\mathrm{NR}})_p$			
	$(k_{\sigma\phi}^{\mathrm{NR}})_p^J$	10^{-5}		
Neutron sector	$(k_{\phi}^{\mathrm{NR}})_n$		10^{-2}	10^{-2}
	$(k_{\sigma\phi}^{\mathrm{NR}})_n^J$	10^{-4}	10^{-2}	10^{-2}
Electron sector	$(k_{\phi}^{\mathrm{NR}})_e$			
	$(k_{\sigma\phi}^{\mathrm{NR}})_e^J$	10^{-5}		



Spin-independent

Spin-dependent

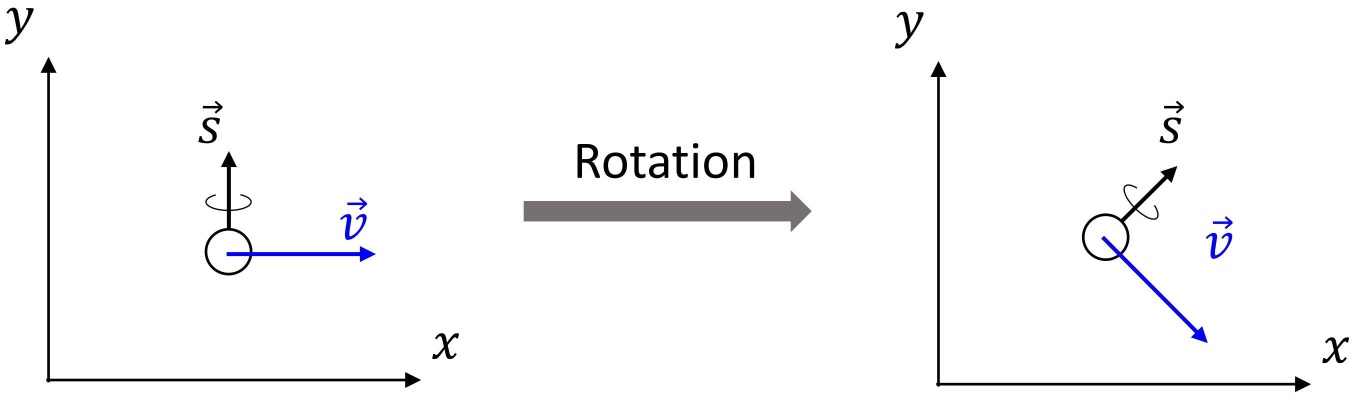
Kostelecký, Li, arXiv:2106.11293

Summary

- The unification of General Relativity and other forces
  may lead to small deviations from Lorentz symmetry.
- An effective field theory is developed to study Lorentz violation (LV).
- The general form of Lorentz-violating terms in curved spacetime
  and the limits in the Earth's gravitational field
  are obtained for the first time.
- Three types of experiments,
  free-dropping, interferometer, and bound-state experiments,
  are analyzed to extract first constraints
  on certain coefficients for LV and spin-gravity coupling.
- More experiments are needed for complete coverage of the coefficients.

Local Lorentz symmetry and diffeomorphism symmetry

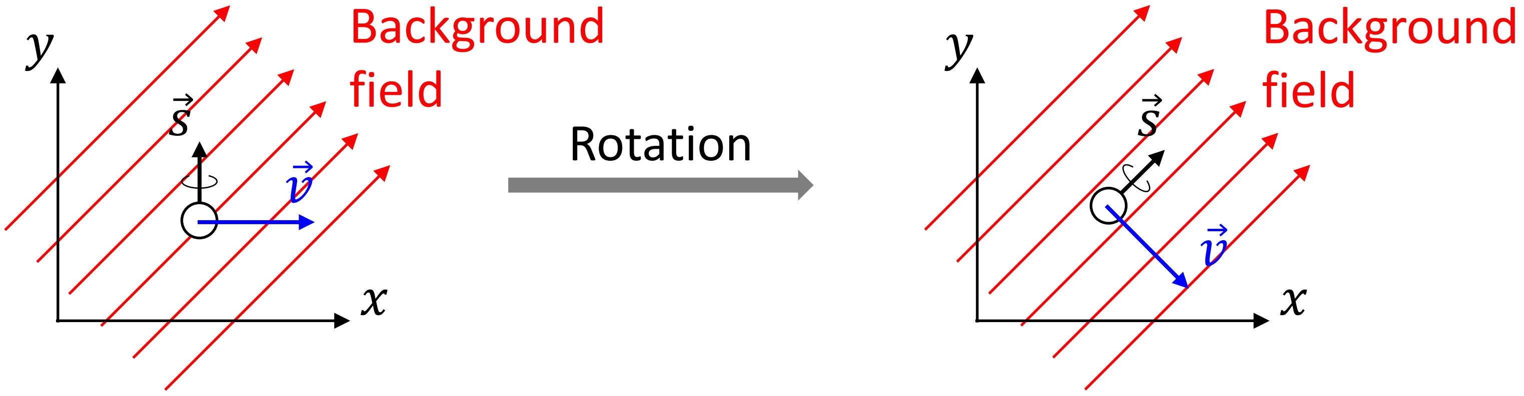
- Experimental results are independent of the orientation and velocity of the laboratory
- Local Lorentz transformation: 3 rotations and 3 boosts in tangent space
- Diffeomorphism: isomorphism of manifolds
- Fundamental symmetries in physics
- Must be precisely tested in experiments



Rotation

Lorentz violation (LV)

- Particle Lorentz transformation (violation):

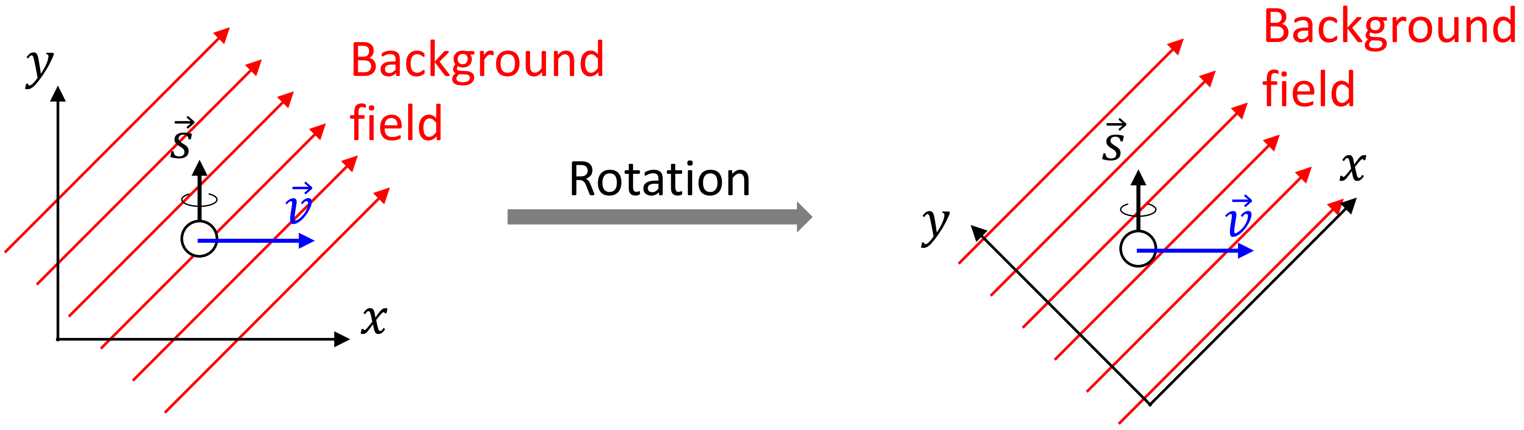


Background field

Rotation

Background field

- Observer Lorentz transformation (invariance):



Background field

Rotation

Background field

Sun-centered frame and sidereal dependence

- Coefficients for LV are normally assumed approximately constant in the Sun-centered frame.

Z axis: aligns with the rotational axis of the Earth
X axis: points from the Sun to the Earth at 2000 vernal equinox
Y axis: forms a right-handed system with X and Z axes
T axis: origin set at the 2000 vernal equinox

- Experimental results depend on the sidereal time.

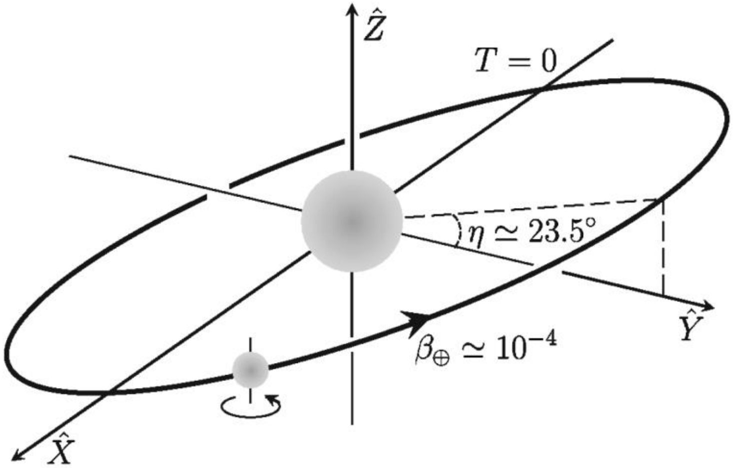


Image: Kostelecky, Russell, Rev.Mod.Phys. 83.11(2011)

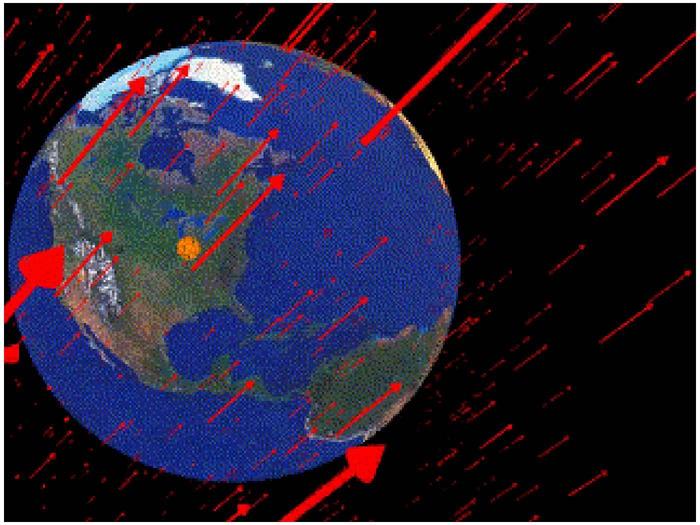
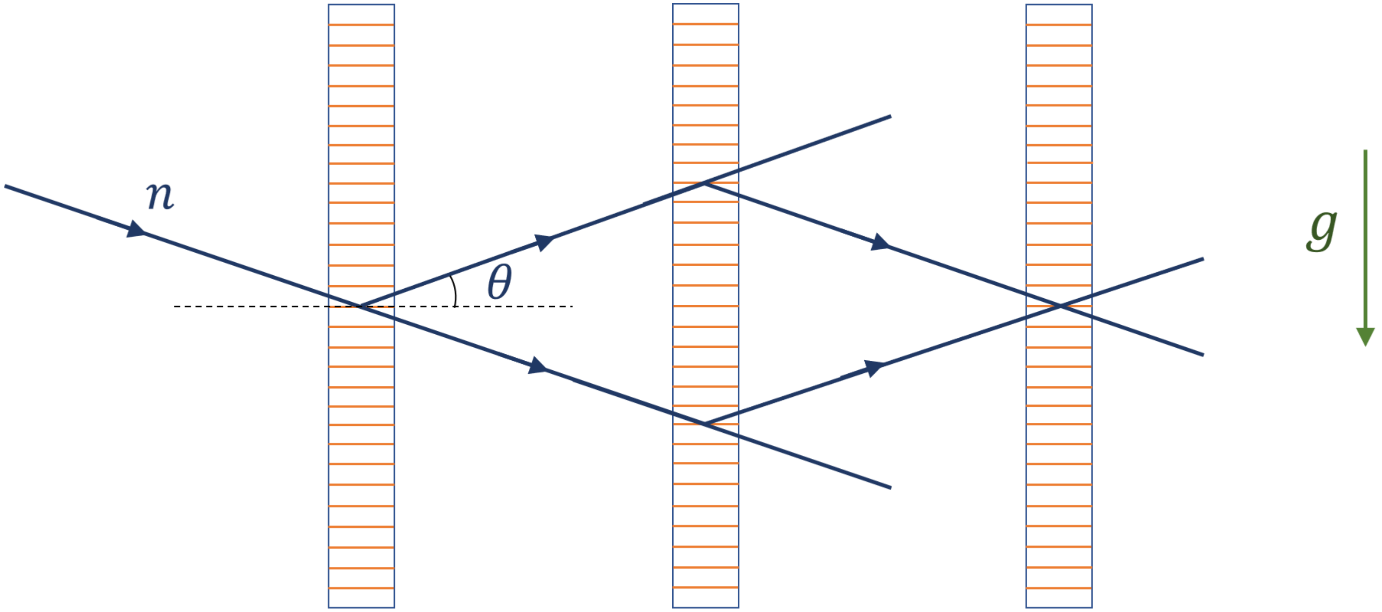


Image: www.physics.indiana.edu/~kostelec

COW experiment



- Phase shift depending on coefficients for LV
- Sensitivity and constraints on coefficients for LV:

$$\Delta g/g = -(k_\phi^{\mathrm{NR}})_n/m_n \qquad |(k_\phi^{\mathrm{NR}})_n| < 1\times 10^{-1}\ \mathrm{GeV}$$

$\uparrow$

Spin-independent

Kostelecký, Li, arXiv:2106.11293

Critical heights

- Relation with energy:

$$mgz_n = E_n$$

- Corrections from the EFT:

$$z'_n = \left(1 + \frac{(k_{\phi}^{\mathrm{NR}})_n}{3m} \pm \frac{\sqrt{\left[(k_{\sigma\phi}^{\mathrm{NR}})_n^j\right]^2}}{3m}\right) z_n$$

Spin-independent Spin-dependent

- Constraints on coefficients for LV:

$$\left|(k_{\phi}^{\mathrm{NR}})_n\right| < 8.2 \times 10^{-1}\ \mathrm{GeV}$$

$$\sqrt{\left[(k_{\sigma\phi}^{\mathrm{NR}})_n^j\right]^2} < 5.4 \times 10^{-1}\ \mathrm{GeV}$$

Experimental setup

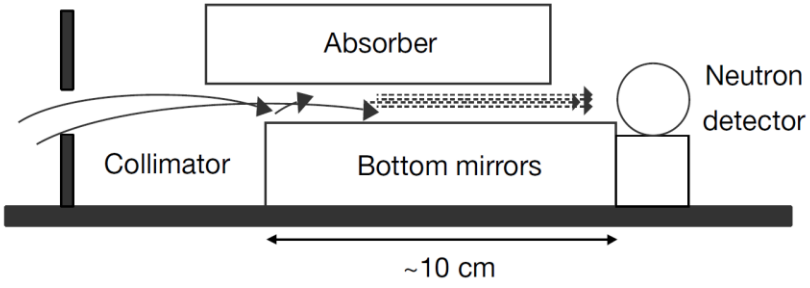


Image: Nesvizhevsky *et al.*, Nature'2002

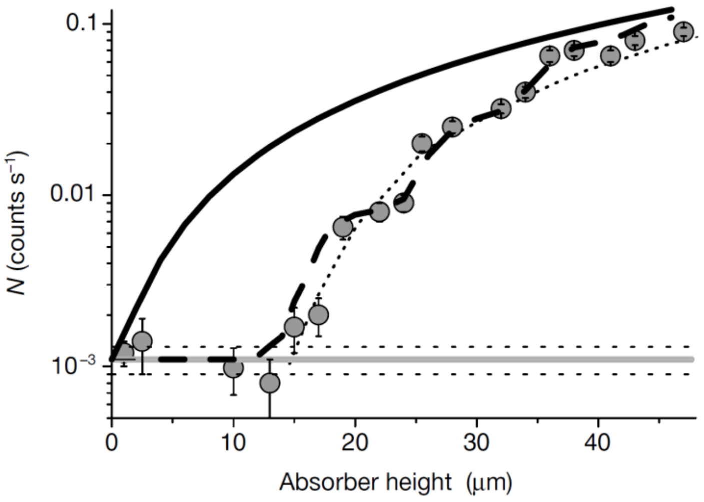


Image: Nesvizhevsky *et al.*, Nature'2002

Nesvizhevsky *et al.*, Nature 415,297(2002)
Kostelecký, Li, arXiv:2106.11293