Testing Gravity with the Standard-Model Extension (SME)

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Testing Gravity by Testing Local Lorentz Invariance

Open Problem $\Rightarrow$ General Relativity is a classical theory
$\Rightarrow$ not compatible with quantum physics

Expect particle physics and classical gravity to merge in a quantum theory of gravity at high energy scales

Effects of quantum gravity may involve Lorentz violation:

e.g., ideas from string theory, spontaneous Lorentz violation, vector-tensor models, modified gravity, anisotropy, etc.

Need a common theoretical framework for experimental tests

$\Rightarrow$ Talk will look at using the Standard-Model Extension (SME) to search for Lorentz violation in gravity experiments

Testing Lorentz Invariance

Theoretical effort in conjunction w/ many expt groups

SME Theory Group (~centered at Indiana University):

Alan Kostelecky	Stuart Samuel	Robert Bluhm
Rob Potting	Don Colladay	Neil Russell
Charles Lane	Ralf Lehnert	Matt Mewes
Brett Altschul	Quentin Bailey	Jay Tasson
Michael Berger	Mike Seifert	Agnes Roberts
Jorge Diaz	Arnaldo Vargas	Yuri Bonder
Rhondale Tso	Rui Xu	& others . . .

Review Articles:

R. Bluhm, Overview of the SME arXiv:hep-ph/0506054

R. Bluhm, Observational Constraints on Local Lorentz Invariance arXiv:1302.1150

Summary of Experimental Tests:

A. Kostelecky & Neil Russell, Data Tables for Lorentz & CPT Violation arXiv:0801.0287 (updated annually)

Theoretical Assumptions/Construction of the SME

➔ GR and Standard Model (SM) describe nature w/ high precision

$\Rightarrow$ framework must include both GR and SM

➔ Physics is observer and coordinate independent

$\Rightarrow$ use scalar Lagrangian-based effective field theory

The SME is the effective field theory containing GR & SM (including possible modifications) and all observer-independent interactions that break local Lorentz invariance (LLI)

$$\mathcal{L} = \frac{1}{16\pi G} R + \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{LV}} + \cdots$$

field operators
that break LLI

➔ Involves fixed background fields (SME coefficients)

$$\bar{a}_\mu, \bar{b}_\mu, \bar{c}_{\mu\nu}, \ldots, \bar{k}_{\mu\nu\ldots} \quad \rightarrow$$ coefficients of LLI-breaking operators

➔ Uses a vierbein formalism to include fermions & reveal LLI

$e_\mu{}^a \Rightarrow$ connects spacetime tensors to tensors in local Lorentz frame

$\Rightarrow$ also involves the spin connection & torsion

➔ SME with gravity involves two relevant symmetries

$$T^\mu = e^\mu{}_a T^a$$

$T^a \to \Lambda^a{}_b T^b \Rightarrow$ local Lorentz transfs

$T^\mu \to T^\mu + \mathcal{L}_\xi T^\mu \Rightarrow$ diffeomorphisms

$\Rightarrow$ SME terms breaking LLI also break diffeomorphisms

➔ SME coefficients suppressed by powers of large mass scale

$\longrightarrow$ Planck scale is the natural large mass scale

$$M_{\text{weak}}/M_{\text{Planck}} \simeq 3 \times 10^{-17}$$

$\bar{a}_\mu, \bar{b}_\mu, \bar{c}_{\mu\nu}, \ldots, \bar{k}_{\mu\nu\ldots} \longrightarrow$ SME coefficients are small

$\Rightarrow$ experiments can attain Planck-suppressed sensitivities

➔ Can restrict to extensions of special relativity

- $\Rightarrow$ Minkowski spacetime
  - → quark, lepton, gauge, Higgs sectors
  - → QED, nonrelativistic limits, . . .
- $\Rightarrow$ CPT violation implies Lorentz violation
  - → can use CPT expts to test LLI
- $\Rightarrow$ Experimental tests (ignoring gravitational effects)
  - → meson oscillations, neutrino oscillations, photon tests, g-2 expts, atomic clocks & traps, muon expts, hydrogen/antihydrogen, tests of CPT, etc.
  - → place tight bounds on Lorentz & CPT violation in particle, nuclear, atomic, astrophysical systems

Experiments put bounds on the SME coefficients

(See data tables in arXiv:0801.0287)

➔ Can restrict to extensions of general relativity

$\Rightarrow$ Riemann spacetime $\Rightarrow$ zero torsion limit

- $\rightarrow$ leading-order signals from dim=3,4 operators
- $\rightarrow$ suppressed higher-order signals for dim>4

$\Rightarrow$ some effects only emerge at higher orders

$\Rightarrow$ Weak-field limits can be constructed

- $\rightarrow$ Post-Newtonian approx
- $\rightarrow$ weak linearized approx

$\Rightarrow$ Experimental tests with gravity

- $\rightarrow$ solar system tests, lunar laser ranging, WEP tests, atom interferometers, Gravity Probe B, gravity waves, short-range tests, binary pulsars, cosmic rays, etc.

$\Rightarrow$ place bounds on violations of LLI & Einstein's GR

SME in Riemann Spacetime

For simplicity will focus on the pure-gravity sector of the SME

$$\mathcal{L} = \frac{1}{16\pi G}(R + \mathcal{L}_{\rm LV}) + \mathcal{L}_{\rm M}$$

→ Lorentz preserving matter sector

$$\mathcal{L}_{\rm LV} = \mathcal{L}_{\rm LV}^{(4)} + \mathcal{L}_{\rm LV}^{(5)} + \mathcal{L}_{\rm LV}^{(6)} + \cdots$$

dim=4,5,6,...

with Lorentz & diffeomorphism breaking terms

$$\mathcal{L}_{\rm LV}^{(4)} = -\bar{u}R + \bar{s}^{\mu\nu}R^T_{\mu\nu} + \bar{t}^{\kappa\lambda\mu\nu}C_{\kappa\lambda\mu\nu}$$

$$\mathcal{L}_{\rm LV}^{(5)} = (\bar{k}^{(5)})_{\alpha\beta\gamma\delta}R^{\alpha\beta\gamma\delta}$$

$$\mathcal{L}_{\rm LV}^{(6)} = \frac{1}{2}(\bar{k}_1^{(6)})_{\alpha\beta\gamma\delta\kappa\lambda}\{D^\kappa, D^\lambda\}R^{\alpha\beta\gamma\delta} + (\bar{k}_2^{(6)})_{\alpha\beta\gamma\delta\kappa\lambda\mu\nu}R^{\alpha\beta\gamma\delta}R^{\kappa\lambda\mu\nu}$$

$\Rightarrow$ need to address theoretical issues with gravity

Background Fields in Gravity

SME ➔ fixed background fields break diffeomorphisms

$$\bar{a}_\mu, \bar{b}_\mu, \bar{c}_{\mu\nu}, \ldots, \bar{k}_{\mu\nu\ldots} \quad \Rightarrow \text{ SME coeffs}$$

Have two cases to consider:

(1) Spontaneous diffeomorphism breaking

$$\frac{\delta S}{\delta \bar{k}_{\mu\nu\ldots}} = 0 \quad \Rightarrow \quad \bar{k}_{\mu\nu\ldots} = \langle k_{\mu\nu\ldots} \rangle \quad \rightarrow \text{ dynamical vacuum values}$$

(2) Explicit diffeomorphism breaking

$$\frac{\delta S}{\delta \bar{k}_{\mu\nu\ldots}} \neq 0 \quad \Rightarrow \quad \bar{k}_{\mu\nu\ldots} \quad \rightarrow \text{ nondynamical pre-existing background field}$$

$\Rightarrow$ to avoid potential conflicts with the Bianchi identities the SME assumes spontaneous diffeomorphism breaking

Spontaneous Lorentz & Diffeomorphism Breaking

Background fields are dynamically generated vacuum solutions

→ no pre-existing fields with spontaneous breaking

$$k_{\mu\nu\cdots} = \langle k_{\mu\nu\cdots} \rangle + \delta k_{\mu\nu\cdots}$$

→ also has excitations about the vacuum

$\bar{k}_{\mu\nu\cdots}$

includes Nambu-Goldstone (NG) and massive excitations

With NG modes included, diffeomorphism invariance still holds dynamically but is hidden in effective field theory

$\Rightarrow$ can still impose gauge fixing on the metric

$\Rightarrow$ SME maintains many features of GR

Expts search for effects of background vacuum fields

Post-Newtonian and Weak-Field Limits

$$\mathcal{L} = \frac{1}{16\pi G}(R + \mathcal{L}_{\rm LV}) + \mathcal{L}_{\rm M}$$ → gravity sector in Riemann spacetime

Start with $\mathcal{L}_{\rm LV}^{(4)} = -uR + s^{\mu\nu}R^T_{\mu\nu} + t^{\kappa\lambda\mu\nu}C_{\kappa\lambda\mu\nu}$

and let
$$u = \bar{u} + \tilde{u}$$
$$s^{\mu\nu} = \bar{s}^{\mu\nu} + \tilde{s}^{\mu\nu}$$
$$t^{\kappa\lambda\mu\nu} = \bar{t}^{\kappa\lambda\mu\nu} + \tilde{t}^{\kappa\lambda\mu\nu}$$

tildes denote excitations about vacuum solutions

Eliminate NG and massive excitations in weak-field limit

$\Rightarrow$ applying Bianchi identities & diffeomorphism invariance

Left with $\mathcal{L}_{\rm LV}^{(4)} = -\bar{u}R + \bar{s}^{\mu\nu}R^T_{\mu\nu} + \bar{t}^{\kappa\lambda\mu\nu}C_{\kappa\lambda\mu\nu}$

all excitations now in metric field

Post-Newtonian expansion for the metric

$$g_{0j} = -\bar{s}^{0j}U - \bar{s}^{0k}U^{jk} - \tfrac{7}{2}(1 + \tfrac{1}{28}\bar{s}^{00})V^j + \tfrac{3}{4}\bar{s}^{jk}V^k - \tfrac{1}{2}(1 + \tfrac{15}{4}\bar{s}^{00})W^j$$
$$+ \tfrac{5}{4}\bar{s}^{jk}W^k + \tfrac{9}{4}\bar{s}^{kl}X^{klj} - \tfrac{15}{8}\bar{s}^{kl}X^{jkl} - \tfrac{3}{8}\bar{s}^{kl}Y^{klj}$$

$$g_{jk} = \delta^{jk} + (2 - \bar{s}^{00})\delta^{jk}U + (\bar{s}^{lm}\delta^{jk} - \bar{s}^{jl}\delta^{mk} - \bar{s}^{kl}\delta^{jm} + 2\bar{s}^{00}\delta^{jl}\delta^{km})U^{lm}$$

Potentials for a perfect fluid

$$U = G\int d^3x' \frac{\rho(\vec{x}', t)}{R},$$

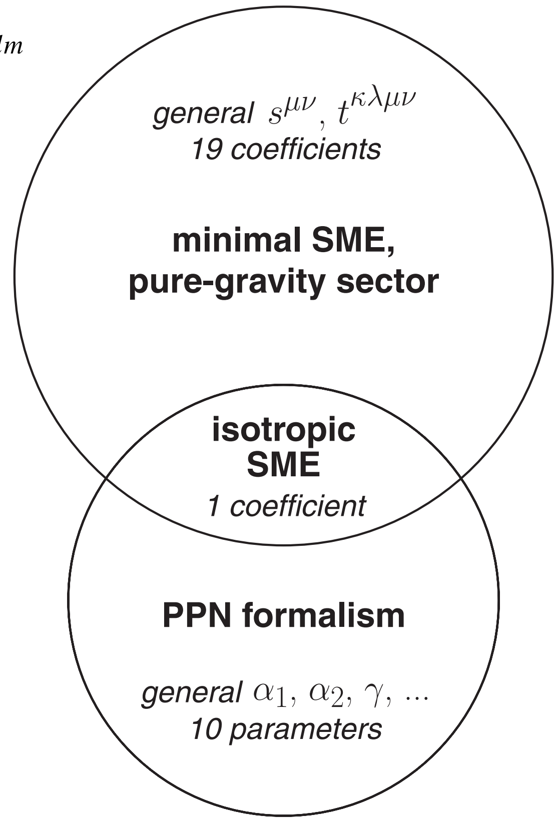
$$U^{jk} = G\int d^3x' \frac{\rho(\vec{x}', t)R^jR^k}{R^3},$$

$$V^j = G\int d^3x' \frac{\rho(\vec{x}', t)v^j(\vec{x}', t)}{R},$$

$$W^j = G\int d^3x' \frac{\rho(\vec{x}', t)v^k(\vec{x}', t)R^kR^j}{R^3},$$

$$X^{jkl} = G\int d^3x' \frac{\rho(\vec{x}', t)v^j(\vec{x}', t)R^kR^l}{R^3},$$

$$Y^{jkl} = G\int d^3x' \frac{\rho(\vec{x}', t)v^m(\vec{x}', t)R^mR^jR^kR^l}{R^5}$$



Comparison with PPN

For dim=4 terms:

$$\mathcal{L}_{\rm LV}^{(4)} = -\bar{u}R + \bar{s}^{\mu\nu} R^T_{\mu\nu} + \bar{t}^{\kappa\lambda\mu\nu} C_{\kappa\lambda\mu\nu}$$

absorb in G

expts sensitive to these coeffs

no sensitivity found (t puzzle)

Coefficient	Sensitivity
$\overline{s}^{XY}$	10^{-10}
$\overline{s}^{XZ}$	10^{-11}
$\overline{s}^{YZ}$	10^{-11}
$\overline{s}^{XX} - \overline{s}^{YY}$	10^{-10}
$\overline{s}^{XX} + \overline{s}^{YY} - 2\overline{s}^{ZZ}$	10^{-10}
$\overline{s}^{TT}$	10^{-5}
$\overline{s}^{TX}$	10^{-8}
$\overline{s}^{TY}$	10^{-8}
$\overline{s}^{TZ}$	10^{-8}

Experiments include
- → binary pulsars
- → lunar laser ranging
- → atom interferometry
- → cosmic rays
- → Gravity Probe B
- → solar system tests

⇒ bounds given with respect to sun-centered celestial coords

For dim=5,6 terms:

$\Rightarrow$ a variety of expt tests can be made as well

e.g.,gravity wave event GW150914 places limits on Lorentz-violating dispersion effects

Coefficient	Constraint
$\lvert k^{(5)}_{(V)00}\rvert$	$< 6\times 10^{-14}$ m
$\lvert k^{(5)}_{(V)10}\rvert$	$< 4\times 10^{-14}$ m
$\lvert k^{(5)}_{(V)11}\rvert$	$< 1\times 10^{-13}$ m
$\lvert k^{(5)}_{(V)20}\rvert$	$< 3\times 10^{-14}$ m
$\lvert k^{(5)}_{(V)21}\rvert$	$< 7\times 10^{-14}$ m
$\lvert k^{(5)}_{(V)22}\rvert$	$< 4\times 10^{-13}$ m
$\lvert k^{(5)}_{(V)30}\rvert$	$< 3\times 10^{-14}$ m
$\lvert k^{(5)}_{(V)31}\rvert$	$< 4\times 10^{-14}$ m
$\lvert k^{(5)}_{(V)32}\rvert$	$< 2\times 10^{-13}$ m
$\lvert k^{(5)}_{(V)33}\rvert$	$< 1\times 10^{-12}$ m
$\lvert k^{(6)}_{(E)40}\rvert$, $\lvert k^{(6)}_{(B)40}\rvert$	$< 1\times 10^{-6}$ m^2
$\lvert k^{(6)}_{(E)41}\rvert$, $\lvert k^{(6)}_{(B)41}\rvert$	$< 3\times 10^{-7}$ m^2
$\lvert k^{(6)}_{(E)42}\rvert$, $\lvert k^{(6)}_{(B)42}\rvert$	$< 6\times 10^{-8}$ m^2
$\lvert k^{(6)}_{(E)43}\rvert$, $\lvert k^{(6)}_{(B)43}\rvert$	$< 2\times 10^{-8}$ m^2
$\lvert k^{(6)}_{(E)44}\rvert$, $\lvert k^{(6)}_{(B)44}\rvert$	$< 1\times 10^{-8}$ m^2

gives bounds on dim=5,6 coeffs

other experiments with dim>4
- $\rightarrow$ cosmic rays
- $\rightarrow$ torsion pendula
- $\rightarrow$ tungsten oscillators

$\Rightarrow$ decomposition using spin-weighted spherical harmonics

Conclusions

SME provides a comprehensive theoretical framework for testing local Lorentz symmetry in particle physics & gravity

No violations of local Lorentz invariance observed to date

➔ many SME coefficients remain unbounded
➔ new & improved tests continue to be made

Comprehensive tables of expt bounds are maintained online
arXiv:0801.0287 (see version 9 for 2016)

$\Rightarrow$ extensive references for theoretical & experimental papers can be found in the data tables as well