Gravitational Experiments and Lorentz Violation

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outline

- introduction
  - motivation
  - Standard-Model Extension (SME)
- recent gravitational tests
- Lorentz violation in matter-gravity couplings\(^1,2\)
  - theoretical analysis
  - new sensitivities in gravitational experiments

1) Kostelecký, Tasson PRL ’09
2) Kostelecký, Tasson in preparation
motivation

• General Relativity and the Standard Model describe known physics.

• new physics at the Planck scale \(10^{19} \text{ GeV}\)

• options for probing such high energies
  – galaxy-sized accelerator
  – suppressed effects
    in sensitive experiments

Lorentz violation
  • can arise in theories of new physics
  • difficult to mimic with conventional effects
Standard-Model Extension (SME)

effective field theory which contains:

- General Relativity (GR)
- Standard Model (SM)
- arbitrary coordinate-independent Lorentz violation
  \[ L_{\text{SME}} = L_{\text{GR}} + L_{\text{SM}} + L_{\text{LV}} \]
- as a subset, other test frameworks

Lorentz-violating terms

- constructed from GR and SM fields
- parameterized by coefficients for Lorentz violation
- samples

Colladay & Kostelecký PRD ’97, ’98  Kostelecký PRD ’04
What is Lorentz violation?

consider the flat spacetime example $$\hat{A}b \circ 5^\circ 1 \hat{A}$$
under an observer Lorentz transformation (rotation)

physics is unchanged
What is Lorentz violation?

consider the flat spacetime example \( \hat{A}b \circ 5^\circ \hat{A} \)
under a particle Lorentz transformation (rotation)

Lorentz violation!
ongoing searches with...

$$L_{LV} = L_{pure\, gravity} + L_{fermion} + L_{photon} + \cdots$$
ongoing searches with...

\[ L_{LV} = L_{pure\, gravity} + L_{fermion} + L_{photon} + \cdots \]

Tests based on

**Physical Review D 74, 045001 (2006)**

**Signals for Lorentz violation in post-Newtonian gravity**

Quentin G. Bailey and V. Alan Kostelecký

*Physics Department, Indiana University, Bloomington, Indiana 47405, USA*

(Received 14 March 2006; published 1 August 2006)
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Results to date

**Physical Review Letters**

**PRL 99, 241103 (2007)**

**Testing for Lorentz Violation: Constraints on Standard-Model-Extension Parameters via Lunar Laser Ranging**

James B. R. Battat, John F. Chandler, and Christopher W. Stubbs

*Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138, USA*

(Received 6 September 2007; published 13 December 2007)
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Atom-Interferometry Tests of the Isotropy of Post-Newtonian Gravity

Holger Müller, 1,* Sheng-wei Chiow, 1 Sven Herrmann, 1 and Steven Chu 1, 2

Atom interferometry tests of local Lorentz invariance in gravity and electrodynamics


Many more tests proposed.
ongoing searches with...

\[ L_{LV} = L_{\text{pure gravity}} + L_{\text{fermion}} + L_{\text{photon}} + \cdots \]

Tests based on

Results to date

Many more tests proposed. See Mike Seifert’s talk.
Ongoing searches with...

\[ L_{LV} = L_{\text{pure gravity}} + L_{\text{fermion}} + L_{\text{photon}} + \cdots \]

- spin-polarized solids (Adelberger, Heckel, …)
- clock comparisons (Gibble, Hunter, Romalis, Walsworth, …)
- CMB analysis
- astrophysical photon decay
- cosmological birefringence
- pulsar-timing observations
- particle traps (Dehmelt, Gabrielse, …)
- resonant cavities (Lipa, Mueller, Peters, Schiller, Wolf, …)
- neutrino oscillations (LSND, MINOS, Super K, …)
- muons (Hughes, BNL g-2)
- meson oscillations (BABAR, BELLE, DELPHI, FOCUS, KTeV, OPAL, …)
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Constraints on Torsion from Bounds on Lorentz Violation

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^2 Physics Department, Northern Michigan University, Marquette, Michigan 49855, USA

PRL 100, 111102 (2008)
Ongoing searches with...

\[ L_{LV} = L_{pure\, gravity} + L_{fermion} + L_{photon} + \ldots \]

- spin-polarized solids (Adelberger, Heckel, ...)
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Ongoing searches with...

\[ L_{LV} = L_{pure gravity} + L_{fermion} + L_{photon} + \cdots \]

- spin-polarized solids (Adelberger, Heckel, ...)
- only \(~1/2\) of lowest order couplings explored
- use gravitational couplings and experiments to get more!

PRL 102, 010402 (2009)

PHYSICAL REVIEW LETTERS

Prospects for Large Relativity Violations in Matter-Gravity Couplings

V. Alan Kostelecký and Jay D. Tasson

Physics Department, Indiana University, Bloomington, Indiana 47405, USA

- resonant cavities (Lipa, Mueller, Peters, Schiller, Wolf, ...)
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gravitationally coupled fermions

\[ L_{\text{fermion}} = \frac{1}{2} i e^1_a \bar{A}(^a_i c^o \epsilon^o \epsilon^o \epsilon^b : : :) \bar{D} \bar{A} \]

\[ \bar{A}(m+a_1 e^1_a \epsilon^o \epsilon^a + : : :) \bar{A} \]

coefficients for Lorentz violation
• particle-species dependent

additional coefficients for LV, non-minimal torsion, ...

covariant derivative for spacetime as well as U(1)

Idea:
• new gravitational couplings provide new LV sensitivity
• explore \( a_1 \) coefficient unobservable in flat spacetime

Kostelecký, Tasson PRL '09

1) Kostelecký PRD '04
gravitationally coupled fermions

\[ L_{\text{fermion}} = \frac{1}{2} i e^a \bar{A} (e^a c^a e^b \bar{A} + \cdots) \bar{D}_1 \bar{A} \]

coefficients for Lorentz violation
- particle-species dependent

additional coefficients for LV, non-minimal torsion, …

\[ \overleftrightarrow{D}_\mu \] covariant derivative for spacetime as well as U(1)

Idea:
- new gravitational couplings provide new LV sensitivity
- explore \( a_1 \) coefficient unobservable in flat spacetime

Kostelecký, Tasson PRL ’09

What is the form of \( a_1 \)? Where does it come from?

1) Kostelecký PRD ’04
Lorentz-symmetry breaking

• explicit
  – Lorentz violation is a predetermined property of the spacetime
  – inconsistent with Riemannian geometry

• spontaneous
  – LV arises dynamically
  – consistent with geometry
  – possible in numerous underlying theories: string theory, quantum gravity …

• upon investigating spontaneous breaking we find

\[ a_1 = \bar{a}_1 + \frac{1}{2} \mathcal{R} a \cdot h_1 \cdot i + \frac{1}{4} \mathcal{R} a \cdot h \cdot i \]

characterize couplings in dynamical theories
countershaded Lorentz violation

\[ a_1 = \bar{a}_1 + \frac{1}{2} R a_1 \ h_1 \ i \ \frac{1}{4} R a_1 \ h. \]

- \( \bar{a}_1 \) for matter is unobservable in flat-spacetime tests
- Observable \( \bar{a}_1 \) effects are suppressed by the gravitational field
- \( \bar{a}_1 \) could be large (~1eV) relative to existing matter-sector bounds
  c.f. \( b < 10^{-30} \) GeV
path to experimental analysis

\[ L_{\text{fermion}} \] expand to desired order in LV and gravity
\[ \downarrow \text{field redefinition} \]
\[ L'_{\text{fermion}} \]
\[ \downarrow \text{Euler-Lagrange eq.} \]
\[ H_{\text{Relativistic}} \rightarrow \text{relativistic quantum experiments} \]
\[ \downarrow \text{Foldy-Wouthuysen expansion} \]
\[ H_{\text{NonRel}} \rightarrow \text{non-relativistic quantum experiments} \]
\[ \downarrow \text{inspection} \]
\[ L_{\text{Classical}} \rightarrow \text{non-relativistic quantum experiments} \]
\[ \text{classical experiments} \]
relativistic hamiltonian

\[ H_{\text{rel}} = \frac{1}{2} \left( h_{jk} + h_{00, jk} \right) + i h_{j0} \partial_j + \frac{1}{2} m h_{00} \partial_j + \frac{1}{2} \left( \partial_j \partial^j + 5 \right) \partial_0 + i \frac{1}{2} \left( h_{jk} \partial_j + h_{00, jk} \right) \]

\[ + \frac{1}{2} \left( i \left( h_{j0} \partial_j + h_{00, j0} \right) \right) + \frac{1}{2} \left( h_{jk} \partial_j + h_{00, jk} \right) \partial_0 \]
Experimental implications

\[ F_3 = m^T g_i \ 2g \circ \ a_t^T + \frac{m^T}{m_s} a_t^S + \cdots \]

S and T denote composite coefficients for source and test respectively.

- Gravimeter tests
- Tests of Weak Equivalence
  - Laboratory
  - Space based
- Lunar laser ranging
- Exotic tests
  - Charged matter
  - Antimatter
  - Higher generation matter
- Light-travel tests
- ...
experimental implications

\[ F_3 = \sum_i m^T g_i \ 2g \mathring{a}_t^T + \frac{m^T}{m^S} a_t^S + \cdots \]

\[ a_1^T = \sum_{w=p;n;e} N^w a_1^w \]

- gravimeter tests
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S and T denote composite coefficients for source and test respectively.
Sun-centered frame

- standard frame for reporting SME bounds

- boost and rotation of test \[ \rightarrow \text{annual & sidereal variations} \]
lab tests
differential acceleration for test-particles A and B

• monitor acceleration of one particle over time → gravimeter
• monitor relative behavior of particles → EP test
• frequency and phase distinguish from other effects
experimental sensitivities

• one bound\textsuperscript{1} based on torsion-pendulum data\textsuperscript{2}
\[ |\alpha \bar{a}_T^e + \alpha \bar{a}_T^p - 0.8\alpha \bar{a}_T^n | < 1 \times 10^{-11} \text{ GeV} \]

• excellent prospects for remaining 11 coefficients in current and future experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\alpha \bar{a}_T^w$, actual</th>
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\[\] = crude estimate for existing experiment
\{} = crude estimate for future experiment

1) Kostelecký, Tasson PRL ’09 2) Schlamminginger et al. PRL ’08
experimental sensitivities

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Summary

Lorentz violation introduces qualitatively new signals in gravitational experiments

- several experiments performed
- much remains unexplored
- comparatively large
- detectable in current and planned tests
- multiple tests needed for maximum independent sensitivities