Lorentz symmetry lies at the heart of relativity and is a feature of low-energy descriptions of nature. Minuscule Lorentz-violating effects arising in theories of quantum gravity offer a promising candidate signal for new physics at the Planck scale. A framework is presented for incorporating Lorentz violation into general relativity and other theories of gravity. Applying this framework yields a proof that explicit Lorentz symmetry breaking is incompatible with generic Riemann-Cartan geometries. The framework also enables the construction of all possible terms in the effective low-energy action for the underlying quantum gravity. These terms form the gravitationally coupled Standard-Model Extension (SME), which offers a comprehensive guide to searches for observable phenomena. The dominant and sub-dominant Lorentz-violating terms in the gravitational and QED sectors of the SME are discussed.

1. Introduction
Reconciling gravity with quantum mechanics to form a consistent theory of quantum gravity remains a major outstanding problem in theoretical physics. The difficulty of the problem is exacerbated by the lack of experimental guidance. Progress in physics is often made through the combination of theory and experiment working in tandem, but the natural scale for quantum gravity is the Planck scale, which lies some 17 orders of magnitude above our presently attainable energy scales. At first sight, this appears an insuperable barrier to the acquisition of experimental information about quantum gravity.

Remarkably, under suitable circumstances, some experimental information about quantum gravity can nonetheless be obtained. The point is that minuscule effects emerging from the underlying quantum gravity might be detected in sufficiently sensitive experiments. To be identified as definitive signals from the Planck scale, such effects would need to violate some established principle of low-energy physics. One promising class of potential effects is relativity violations, arising from breaking the Lorentz symmetry
that lies at the heart of relativity.\textsuperscript{1} Recent proposals suggest these effects could emerge from strings, loop quantum gravity, noncommutative field theories, or numerous other sources at the Planck scale.\textsuperscript{2}

Whatever the nature of the underlying quantum gravity, effective field theory is an appropriate tool for the general description of low-energy signals of Lorentz violation.\textsuperscript{3} To be realistic, a theory of this type must reproduce established physics. In Minkowski spacetime, nongravitational phenomena involving the basic particles and forces down to the quantum level are successfully described by the Standard Model (SM) of particle physics. Adding gravitational couplings and the Einstein-Hilbert action for general relativity yields the gravitationally coupled SM, which encompasses all known fundamental physics. This combined theory must therefore be a basic component of any realistic effective field theory.

In Minkowski spacetime, relativity violations can be incorporated as additional terms in the SM action describing arbitrary coordinate-independent Lorentz violation, and all dominant contributions at low energies are explicitly known.\textsuperscript{4} However, the inclusion of Lorentz violation in an effective field theory containing also the Einstein-Hilbert action and the gravitationally coupled SM is more challenging. The study of relativity violations in the corresponding spacetimes requires a framework allowing violations of local Lorentz invariance while preserving general coordinate invariance. Also, since physical matter is formed from leptons and quarks, the framework must be sufficiently supple to incorporate spinors.

This talk summarizes a suitable framework that meets all the above criteria, along with some key associated results. The framework described enables the construction of the general low-energy effective field theory, the Standard-Model Extension (SME), which serves as a comprehensive basis for theoretical and experimental studies of Lorentz violation in all gravitational and SM sectors. The talk is based on a selection of results obtained in Ref. 5, to which the reader is referred for more details.

2. Framework

The framework summarized here, appropriate for the comprehensive description of Lorentz violation, is founded on Riemann-Cartan geometry and the vierbein formalism.\textsuperscript{6} This formalism naturally distinguishes local Lorentz and general coordinate transformations and also allows the treatment of spinors. The basic gravitational fields are the vierbein $e_{\mu}^a$ and the spin connection $\omega_{\mu}^{ab}$, and the action of the local Lorentz group at
each spacetime point allows three rotations and three boosts independent
of general coordinate transformations. In this context, Lorentz violation
appears in a local Lorentz frame when a nonzero vacuum value exists for
one or more quantities carrying local Lorentz indices, called coefficients for
Lorentz violation.

As an illustrative example for the basic ideas of the framework, sup-
pose a nonzero timelike coefficient \( k_a = (k, 0, 0, 0) \) exists in a certain local
Lorentz frame at some point \( P \). Whenever particles (or localized fields)
have observable interactions with \( k_a \), physical Lorentz violation occurs. The
corresponding Lorentz transformations, called local particle Lorentz trans-
formations, act to boost or rotate particles in the fixed local frame at \( P \),
leaving \( k_a \) and any other background quantities unaffected. Note, however,
that the local Lorentz frame itself can be changed by local observer Lorentz
transformations, under which \( k_a \) behaves covariantly as a four-vector. Note
also that the physics is covariant under general coordinate transformations,
as desired, because a change of the observer’s spacetime coordinates \( x^\mu \)
duces a conventional general coordinate transformation on \( k_\mu = e_\mu^a k_a \).
The breaking of Lorentz symmetry is called explicit if \( k_\mu(x) \) is specified as
a predetermined external quantity, while it is spontaneous if instead \( k_\mu(x) \)
is determined through a dynamical procedure such as the development of
a vacuum value.

In general, the Lorentz-violating piece \( S_{LV} \) of the action for the effective
field theory contains terms of the form

\[
S_{LV} \supset \int d^4x \; e k_\mu J^\mu, \tag{1}
\]

where \( k_\mu \) is a coefficient for Lorentz violation in the covariant \( x \) representa-
tion of the observer Lorentz group. Also, \( J^\mu \) lies in the corresponding
contravariant representation and is a general-coordinate invariant formed
from the vierbein, spin connection, and SM fields. The form (1) of terms
in the effective action is independent of the origin of the Lorentz viola-
tion in the underlying quantum gravity, including whether the violation is
spontaneous or explicit.

3. Spontaneous and Explicit Lorentz Violation

With this framework established, various issues concerning observable
Lorentz violation can be addressed. One result is that explicit and
spontaneous Lorentz violations have distinct implications for the energy-
momentum tensor. To see this, first separate the action of the full effective
theory into a piece $S_{\text{Gravity}}$ involving only the vierbein and spin connection and the remainder, $S_{\text{matter}} = S_{\text{matter,0}} + S_{\text{matter,LV}}$, where $S_{\text{matter,LV}}$ contains all Lorentz violations involving matter. Any term in the latter therefore has the general form (1), where the operator $J^z$ is now taken to be formed from matter fields $f^y$ and their covariant derivatives.

For explicit Lorentz violation, consider a particular variation of $S_{\text{matter}}$ for which all fields and backgrounds are allowed to vary, including the coefficients for explicit Lorentz violation, but in which the dynamical fields $f^y$ satisfy equations of motion:

$$\delta S_{\text{matter}} = \int d^4x \ e(T^{\mu\nu}e^{\nu a}\delta e^a_\mu + \frac{1}{2}S^a_{\mu ab}\delta \omega^{ab}_\mu + eJ^z \delta k_x).$$  \hspace{1cm} (2)

This expression defines the energy-momentum tensor $T^{\mu\nu}$ and the spin-density tensor $S^a_{\mu ab}$, as usual. For infinitesimal local Lorentz transformations $\delta e^a_\mu$, $\delta \omega^{ab}_\mu$, $\delta k_x$, the variation (2) yields the condition

$$T^{\mu\nu} - T^{\nu\mu} - (D_\alpha - T^{\beta}_{\beta \alpha})S^{a\mu\nu} = -e^{\nu a}e^{\nu b}k_x(X_{[ab]})^x y J^y$$ \hspace{1cm} (3)

on the symmetry of the energy-momentum tensor $T^{\mu\nu}$, where $D_\mu$ is the covariant derivative, $T^{\lambda\mu}_{\mu\nu}$ is the torsion, and $(X_{[ab]})^x y$ is the representation for the local Lorentz generators. When instead the special variation (2) is induced by a diffeomorphism, the variations $\delta e^a_\mu$, $\delta \omega^{ab}_\mu$, $\delta k_x$ are Lie derivatives, yielding the covariant conservation law

$$(D_\mu - T^{\lambda\mu}_{\lambda\mu})T^{\nu\mu} + T^{\lambda\mu}_{\mu\nu}T^{\mu\nu}_{\lambda} + \frac{1}{2}R^{ab}_{\mu\nu}S^a_{\mu ab} = J^z D_\nu k_x,$$ \hspace{1cm} (4)

where $R^{ab}_{\mu\nu}$ is the curvature. In the limit of conventional general relativity, these equations reduce to the familiar expressions $T^{\mu\nu} = T^{\nu\mu}$ and $D_\mu T^{\nu\mu} = 0$. In the Minkowski-spacetime limit with Lorentz violation, known results also emerge.

For spontaneous Lorentz violation, the derivation can be adapted to obtain equations similar to (3) and (4), but with the terms involving $k_x$ replaced by zero. This is because all coefficients arising from spontaneous breaking are vacuum field values and therefore must obey equations of motion, so the variation $\delta k_x$ in Eq. (2) is absent. The result can also be understood geometrically. The spacetime geometry implies a set of identities, the Bianchi identities, that are tied to the equations of motion and hence imply certain conditions on the matter sources. However, for sources involving explicit Lorentz violation, these conditions are generically incompatible with covariant conservation laws for the matter. For example, in general relativity the Bianchi identities are $D_\mu G^{\mu\nu} = 0$, the Einstein equations are $G^{\mu\nu} = 8\pi G_N T^{\mu\nu}$, and substitution yields the condition $D_\mu T^{\mu\nu} = 0$, which
in the presence of explicit Lorentz violation is incompatible with the result (4). In contrast, spontaneous Lorentz violation yields consistent results, essentially because in this case the coefficients for Lorentz violation form an intrinsic part of the geometrical structure rather than being externally imposed.

4. Low-Energy Effective Action

A wide-ranging application of the general framework summarized here is the construction of all possible dominant terms in the low-energy effective action, independent of the structure of the underlying quantum gravity theory. The full SME effective action at low energies is a sum of partial actions,

\[ S_{\text{SME}} = S_{\text{gravity}} + S_{\text{SM}} + S_{\text{LV}} + \ldots \]  

Here, the term \( S_{\text{gravity}} \) represents the pure-gravity sector, involving the vierbein and the spin connection and including any Lorentz violation. The term \( S_{\text{SM}} \) is the SM action with gravitational couplings. The term \( S_{\text{LV}} \) contains all Lorentz-violating terms that involve matter fields and dominate at low energies, including minimal gravitational couplings. The ellipsis represents low-energy terms of higher suppression order, including operators of mass dimension greater than four, some of which violate Lorentz symmetry.

The pure-gravity action can be written

\[ S_{\text{gravity}} = \frac{1}{16\pi G_N} \int d^4 x \left( L_{\text{LI},\omega}^{\text{L}_{\mu}} + L_{\text{LV},\omega}^{\text{L}_{\mu}} + \ldots \right), \]  

where the Lorentz-invariant piece \( L_{\text{LI},\omega}^{\text{L}_{\mu}} \) and the Lorentz-violating piece \( L_{\text{LV},\omega}^{\text{L}_{\mu}} \) involve only \( e_\mu^a \) and \( \omega_\mu^{ab} \). The ellipsis represents possible dependence on nonminimal dynamical gravitational fields, such as the recently proposed cosmologically varying scalar fields that can lead to Lorentz violation. The Lorentz-invariant lagrangian \( L_{\text{LI},\omega}^{\text{L}_{\mu}} \) can be expanded as usual,

\[ L_{\text{LI},\omega}^{\text{L}_{\mu}} = eR - 2e\Lambda + \ldots, \]  

while the Lorentz-violating lagrangian \( L_{\text{LV},\omega}^{\text{L}_{\mu}} \) has the form

\[ L_{\text{LV},\omega}^{\text{L}_{\mu}} = e(k_T)^{\lambda_{\mu}} T_{\lambda_{\mu}} + e(k_R)^{\lambda_{\mu}} R_{\lambda_{\mu}} + \ldots \]  

The Lorentz-violating matter action \( S_{\text{LV}} \) can also be constructed as a series of terms involving both SM and gravitational fields. For illustrative purposes, attention here is restricted to the special limit of single-fermion
gravitationally coupled quantum electrodynamics (QED), for which only
the dominant and minimally coupled terms are considered. A discussion of
the full theory can be found in Ref. 5.

In this limit, the relevant U(1)-invariant action is a sum of partial actions
for the Dirac fermion $\psi$ and the photon $A_\mu$. The fermion partial action for
the QED extension can be written as

$$S_\psi = \int d^4x (\frac{1}{2}ie\bar{\psi}QD_\mu A_\mu - e\bar{\psi}M\psi),$$

(9)

where the symbols $\Gamma^a$ and $M$ are defined by

$$\Gamma^a \equiv \gamma^a - c_{\mu\nu}e^{\mu a}e^\nu_{\ b}\gamma^b - d_{\mu\nu}e^{\rho a}e^\rho_{\ b}\gamma^b
- e_{\mu}e^{\mu a} - if_{\mu}e^{\mu a}\gamma_5 - \frac{1}{2}g_{\lambda\mu\nu}e^{\rho a}e^\rho_{\ b}\sigma^{bc},$$

(10)

$$M \equiv m + im_5\gamma_5 + a_{\mu}e^{\mu a}\gamma^a + b_{\mu}e^{\mu a}\gamma_5\gamma^a + \frac{1}{2}H_{\mu\nu}e^{\rho a}e^\rho_{\ b}\sigma^{ab}.$$  

(11)

The first term of Eq. (10) and the first two terms of Eq. (11) are con-
tentional, while the others involve Lorentz violation controlled by the co-
efficients $a_{\mu}$, $b_{\mu}$, $c_{\mu\nu}$, $d_{\mu\nu}$, $e_{\mu}$, $f_{\mu}$, $g_{\lambda\mu\nu}$, $H_{\mu\nu}$, which typically vary with
position. The covariant derivative $D_\mu$ in Eq. (9) is a combination of the
space-time covariant derivative and the usual U(1) covariant derivative:

$$D_\mu \psi \equiv \partial_\mu \psi + \frac{1}{4}i\omega_{\mu}^{\ ab}\sigma_{ab}\psi - iqA_\mu \psi.$$  

(12)

In the photon sector, the partial action is

$$S_A = \int d^4x (\mathcal{L}_F + \mathcal{L}_A),$$

(13)

where

$$\mathcal{L}_F = -\frac{1}{4}eF_{\mu\nu}F^{\mu\nu} - \frac{1}{4}e(k_F)_{\kappa\lambda\mu\nu}F^{\kappa\lambda}F^{\mu\nu},$$

(14)

$$\mathcal{L}_A = \frac{1}{4}e(k_{AF})^\kappa e_{\kappa\lambda\mu\nu}A^{\lambda}F^{\mu\nu} - e(k_A)^\kappa A^\kappa.$$  

(15)

The electromagnetic field strength $F_{\mu\nu}$ is defined by the locally U(1)-
invartant form

$$F_{\mu\nu} \equiv D_\mu A_\nu - D_\nu A_\mu + T^{\lambda}_{\mu\nu}A_\lambda \partial_\mu A_\nu - \partial_\nu A_\mu.$$  

(16)

The Lorentz violation in this sector is controlled by the coefficients
$(k_F)_{\kappa\lambda\mu\nu}$, $(k_{AF})_{\mu}$, and $(k_A)_{\mu}$.

In Minkowski spacetime, the coefficients for Lorentz violation in the
SME predict a plethora of experimental signals for relativity violations, even
when attention is limited to spacetime-constant coefficients for operators
of mass dimension four or less. Experimental tests in this limit to date
include ones with photons,\textsuperscript{8,9} electrons,\textsuperscript{10,11,12} protons and neutrons,\textsuperscript{13,14} mesons,\textsuperscript{15} muons,\textsuperscript{16} neutrinos,\textsuperscript{17,18} and the Higgs.\textsuperscript{19}

In the full SME effective action including the gravitational couplings, the Lorentz-violating terms create spacetime anisotropies and spacetime-dependent rescalings of the coupling constants in the field equations, which in turn induce further potentially significant physical effects. The Lorentz-violating behaviors of gravity modes and fundamental particles vary with momentum magnitude and orientation, spin magnitude and orientation, and particle species. Established results for post-newtonian physics, gravitational waves, black holes, cosmologies, and other standard scenarios typically acquire corrections depending on coefficients for Lorentz violation.

In the gravitational sector, substantial deviations from conventional physics due to Lorentz violation are likely only in regions of large gravitational fields, such as near black holes or in the early Universe. Nonetheless, observable effects may emerge under suitable circumstances. For example, searches for Lorentz violation are feasible in laboratory and space-based experiments studying post-newtonian gravitational physics,\textsuperscript{20} including the classic tests of gravitational physics, of the inverse square law, and of gravitomagnetic effects. Similarly, spacetime anisotropies in the equations for gravitational waves\textsuperscript{21} can be sought in Earth- or space-based experiments. Comparisons of the speeds of neutrinos, light, and gravitational waves which can differ in the presence of Lorentz violation, may also eventually be feasible by observing certain violent astrophysical processes. On a larger scale, anisotropic Lorentz-violating corrections generated for the conventional homogeneous FRW cosmologies have the potential to generate a realistic anisotropic cosmology with detectable effects. One possible class of Lorentz-violating cosmological signals would be alignment anomalies on large angular scales, which have been reported in the WMAP data\textsuperscript{22} but are absent in standard cosmologies.\textsuperscript{23} Certain coefficients for Lorentz violation can also contribute to an effective cosmological constant, dark matter, and dark energy. For instance, the small nonzero cosmological constant may be partially or entirely tied to small Lorentz violation and may also vary with spacetime position.

5. Summary

The gravitationally coupled SME discussed in this talk is the full low-energy effective field theory for gravitation and other fundamental interactions.\textsuperscript{5} It offers a comprehensive basis for the study and analysis of experimental
tests of Lorentz symmetry, independent of the underlying quantum gravity. The detailed exploration of the associated theoretical and experimental implications is an open challenge of considerable interest, with the potential to uncover experimental signals from the underlying Planck-scale theory.

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