SCREENING THE STANDARD MODEL FROM GRAVITATIONAL LORENTZ VIOLATION

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It’s **Halloween**…

• A time for exhibiting what some find frightening
  • And seeing that it’s not so scary after all

• In that vein, let’s talk about

  **Lorentz Violation** (LV)
Why Violate Lorentz Symmetry?

- We don’t have a complete theory of gravity and quantum mechanics
- We may have to give up foundational assumptions of one or the other
- Every assumption should be tested by experiment
Sensible Symmetry Breaking

• Lorentz symmetry can be broken several ways

• Let’s focus on the motivated subset that preserve rotational invariance and CPT

• The bounds on rotationally invariant models
  • Constrained by the matter sector
    • Bounds are pretty tight
  • Constrained by gravitational processes
    • Bounds are much weaker
Which Bounds Are Fundamental?

- If gravity is Lorentz Violating the gravitational bounds are inescapable.
  - These are the weakest bounds.
- Quantum effects communicate the LV from gravity to matter, seeming to put the gravitational and matter bounds on equal footing.
- Maybe there is some reason why the matter sector appears to be Lorentz symmetric even with LV gravity.
The Punchline

- We construct a model with direct LV in gravity.
- However, quantum corrections to LV operators in the matter sector are suppressed.
- This gives a useful framework for constructing LV theories that are consistent with data.
A Preferred Frame

• Suppose we fill spacetime with a dynamical vector field, an \textit{aether}.

• If at some scale $\Lambda_{LV}$ close to the Planck scale $M_{Pl}$ the vector gets a \textit{timelike} VEV, then boost symmetries will be \textit{spontaneously broken}.

• Goldstone’s theorem ensures a massless degree of freedom for each broken generator.
Einstein-Aether Theory

- Einsteinian gravity + a timelike vector field of unit norm
- Preserves diffeomorphism invariance while breaking to a rotationally symmetric theory
- Completely general at 2-derivatives, captures leading low energy dynamics

\[ S_{AE} = \int \frac{d^4 x \sqrt{-g}}{16\pi G_4} \left[ R - \mathcal{L}_u + \lambda (u^\alpha u_\alpha + 1) \right] \]

\[ \mathcal{L}_u = \left( c_1 g^{\alpha\beta} g_{\mu\nu} + c_2 \delta^\alpha_\mu \delta^\beta_\nu + c_3 \delta^\alpha_\nu \delta^\beta_\mu - c_4 u^\alpha u^\beta g_{\mu\nu} \right) \nabla_\alpha u^\mu \nabla_\beta u^\nu \]
New Wave Modes

- The three Goldstones are organized as a spin 1 mode and spin 0 mode
- The speed of these waves may not be equal to light
- The usual gravitational tensor modes can also differ from 1

<table>
<thead>
<tr>
<th></th>
<th>Tensor</th>
<th>Vector</th>
<th>Scalar</th>
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<tbody>
<tr>
<td>$c_i \ll 1$</td>
<td>$\frac{1}{1-c_1-c_3}$</td>
<td>$\frac{c_1}{c_1+c_4}$</td>
<td>$\frac{c_1+c_2+c_3}{c_1+c_4}$</td>
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Evaluation So Far

- A preferred frame breaking of LS passes some basic checks for a physical theory.
- What other checks remain?
- Experimental tests of Lorentz symmetry
  - In the gravity sector
  - In the matter sector
- What are the bounds?
When a particle with electric charge travels through a dielectric medium faster than the phase velocity of light it emits radiation.

Suppose particles could go faster than gravity or aether modes.

Such particles would emit gravitational radiation until they slowed to the speed of gravity/aether.

We’ve seen energetic cosmic rays from far away.

So, gravity/aether speeds must exceed or equal light.
PPN Bounds

- Paremeterized Post-Newtonian coefficients detail how a general theory of gravity differs from Newtonian gravity.
- PPN coefficients $\alpha_{1,2}$ determine preferred frame effects.
- In the EA theory, $\alpha_i \sim c_i$ for small $c_i$.
- There exist choices for the $c_i$ such that the PPN coefficients vanish exactly, but this does not seem generic.
- Excluding such choices, the $c_i$ must allow

$$\alpha_1 \lesssim 10^{-4}, \quad \alpha_2 \lesssim 10^{-9}$$

- Orbital Polarization
- Spin Precession of Millisecond Pulsars
Canonical Fields

- How big do we expect the $c_i$ to be?
- Rewrite the action with the aether canonically normalized

$$U^\alpha = \Lambda_{LV} u^\alpha \text{ with } \Lambda_{LV} \lesssim M_{Pl}$$

$$S_{AE} = \int d^4 x \sqrt{-g} M_{Pl}^2 \left[ R - \frac{\mathcal{L}_U}{\Lambda_{LV}^2} + \frac{\lambda}{\Lambda_{LV}^2} (U^\alpha U_\alpha + \Lambda_{LV}^2) \right]$$

$$\mathcal{L}_U = \left( c_1 g^{\alpha \beta} g_{\mu \nu} + c_2 \delta^\alpha_{\mu} \delta^\beta_{\nu} + c_3 \delta^\alpha_{\nu} \delta^\beta_{\mu} - \frac{c_4}{\Lambda_{LV}^2} U^\alpha U^\beta g_{\mu \nu} \right) \nabla_\alpha U^\mu \nabla_\beta U^\nu$$

- The natural size of the $c_i$ is $c_{1,2,3} \sim \frac{\Lambda_{LV}^2}{M_{Pl}^2}, \quad c_4 \sim \frac{\Lambda_{LV}^4}{M_{Pl}^4}$
- PPN constraints imply

$$\Lambda_{LV}^2 \sim 10^{-9} M_{Pl}^2$$
Standard Model Matter Bounds

- The *most constraining* interactions of the aether to matter come from photons, electrons, and neutrinos.
- In general, these are many *orders of magnitude* more stringent than the gravitational bounds.
  - We can examine electrons and photons very precisely and see just how much they violate Lorentz symmetry.
- The tightest bounds come from modified dispersion relations:
  \[ E^2 = \not{p}^2 + m^2 + f(\not{p}^2) \]
Photon Bounds

- The gauge invariant, but Lorentz violating operator of lowest dimension is
  \[ \kappa_\gamma u^\mu u^\nu F_{\mu \alpha} F^{\alpha \nu} \]
- Only allowing even factors of the aether is equivalent to preserving CPT symmetry
- Two processes bound \( \kappa_\gamma \)
  - \( \kappa_\gamma > 0 \): \( e^\pm \rightarrow e^\pm \gamma \)
  - \( \kappa_\gamma < 0 \): \( \gamma \rightarrow e^- e^+ \)
- Both are forbidden by LS dispersion relations
- From dispersion bounds, \( -2 \times 10^{-16} < \kappa_\gamma < 2 \times 10^{-20} \)
- The canonical normalized aether implies that
  \[ \Lambda_{LV}^2 \sim 10^{-16} M_{Pl}^2 \]
Matter constraints

- The lowest dimension gauge invariant Lorentz violating fermion operator is
  \[ \kappa_f \bar{u}^\mu u^\nu \bar{f} \gamma_\mu D_\nu F \]
- The electron gives a constraint similar to the photon
  \[ \Lambda_{LV}^2 \sim 10^{-15} M_{Pl}^2 \]
- The \( \kappa_{\gamma,e} \) must be much smaller than the \( c_i \)
Quantum Corrections

- Suppose we *naively* set the $\kappa_{\gamma,e}$ parameters to zero
- Radiative corrections, like graviton loops generate *large* contributions to the 2-point function

\[ \sim \frac{1}{16\pi^2} \frac{\Lambda_{LV}^2}{M_{Pl}^2} \]

- With $\Lambda_{LV} \sim M_{Pl}$, or even with the gravity bound $\Lambda_{LV}^2 \sim 10^{-9} M_{Pl}^2$ the parameters are in *gross conflict* with experiment
A Natural Separation of Scales

• Suppose a mechanism that *naturally* suppresses the communication of Lorentz violating effects to the matter sector

• Then the comparatively weak bounds on the gravitational sector could be the *leading* constraints on the theory
Use Strong Dynamics

- Consider a *strongly coupled* CFT, which spontaneously breaks at some scale $\Lambda_{\text{IR}}$.
- The CFT couples to gravity, which *sources LV*.
- *Assume* that the CFT operators that manifest LV are irrelevant at low energies.
- The strong coupling makes the LV effects small very *fast*.

\[
\Lambda_{\text{UV}} \quad \text{Planck Scale} \\
\Lambda_{\text{IR}} \quad \text{CFT Breaking Scale} \\
\]

LV

CFT

Standard Model
Use Strong Dynamics

- SM states are the *composites* of the CFT below $\Lambda_{\text{IR}}$
- At these low energies, the theory *appears* Lorentz invariant to very high precision
- Sounds good, but *hard to verify* by direct calculation
- How can we check this *qualitative* picture?
AdS/CFT

- The AdS/CFT correspondence relates *strongly coupled* conformal 4D theories without gravity to weakly coupled 5D theories in Anti-de Sitter space including gravity.
- A ‘brane truncated’ slice of Anti-de Sitter space may be interpreted as a strongly coupled theory with a *nearly conformal* phase that spontaneously breaks below some scale.
- Warped extra dimensions are a *geometric* way to separate scales.

\[ ds^2 = e^{-2kr_c|\theta|} \eta_{\mu\nu} dx^\mu dx^\nu + r_c^2 d\theta^2 \]
Fix the aether to the UV brane
Fix the SM fields to the IR brane
5D gravity communicates the Lorentz violation to the matter sector
5D to 4D Effective Theory

- Only gravity resides in the 5D bulk
- At energies below the KK scale, only the massless ‘zero-modes’ are present
- The KK states have small overlap with the UV brane
- Their communication of LV is suppressed

![Diagram](image.png)
Low Energy Fields

- We can capture the physics we care about by focusing on energies below the KK scale

- The low energy EFT has following the field content
  - Standard Model fields
  - The graviton
  - 3 LV Goldstone bosons
  - The radion, a graviscalar
Lorentz Violation in Gravity

• The EFT is 4D, so the bounds on the 4D Einstein-Aether apply without modification
  • Well…, the Aether scalar mode mixes with the Radion
  • We will return to this issue later

• The communication of LV from Gravity to the SM is greatly modified
Lorentz Violation in the Matter Sector

- The *meaningful* constraints come from modified dispersion relations
  - These only occur at loop level

- Loops must traverse the bulk
Estimating the Diagrams

- We *estimate* these loops to compare with experiment.
- Use the 4D EFT and insert 2 instances of the aether VEV.
  - Remember, an even number of aether VEV insertions is equivalent to preserving CPT symmetry.
- The divergence is *cut off* at the KK scale.
  - Above this scale we resolve the 5th dimension.
  - CFT compositeness scale is dual to the KK scale.

\[
\kappa_{\gamma} \gamma^{\mu} \gamma^{\nu} F_{\mu \alpha} F_{\nu}^{\alpha} \\
\sim \frac{1}{16\pi^2} \frac{M_{KK}^2}{M_{Pl}^2} \Rightarrow \kappa_{\gamma} \sim \frac{1}{16\pi^2} \frac{M_{KK}^2 \Lambda_{LV}^2}{M_{Pl}^4}
\]
Digression: Full 2-point Function

• Beginning from the 5D action

\[ S = \int d^4x \, d\theta \frac{\sqrt{-G}}{16\pi G_5} \left\{ R_5 - 2\Lambda \right\} + \int_{\theta=0} d^4x \sqrt{-g_{\text{UV}}} \{ \mathcal{L}_{\text{UV}} - \sigma_{\text{UV}} \} + \int_{\theta=\pi} d^4x \sqrt{-g_{\text{IR}}} \{ \mathcal{L}_{\text{IR}} - \sigma_{\text{IR}} \}, \]

• The classical solution for the metric is

\[ ds^2 = e^{-2kr_c|\theta|} \eta_{\mu\nu} dx^\mu dx^\nu + r_c^2 d\theta^2, \quad -\pi \leq \theta < \pi, \]

\[ \Lambda = -6k^2, \quad \sigma_{\text{UV}} = -\sigma_{\text{IR}} = \frac{3k}{4\pi G_5}, \]

• In the RS-gauge fluctuations of the metric evolve according, with \( p^2 \equiv \omega^2 - p^2 \), to

\[ \left[ \partial_\theta^2 + p^2 r^2 e^{2kr\theta} - 4k^2 r^2 + 4kr \delta(\theta) - 4kr \delta(\theta - \pi) \right] \tilde{h}_{\mu\nu} = -2\delta(\theta) \tilde{\Sigma}_{\mu\nu}^{\text{UV}} - 2\delta(\theta - \pi) \tilde{\Sigma}_{\mu\nu}^{\text{IR}}, \]
Full 2-point function

- Has the formal solution for Tensor, Vector, and Scalar parts

\[ h^{(S,V,T)} = -\sum_{UV} \hat{g}(\theta, 0, p)^{(S,V,T)} - \sum_{IR} \hat{g}(\theta, \pi, p)^{(S,V,T)} \]

- Where \( \hat{g}(\theta, \theta', p)^{(S,V,T)} \) is the Green's function satisfying

\[
\left[ \frac{\partial^2}{\partial \theta^2} + p^2 r^2 e^{2kr\theta} - 4k^2 r^2 \right] \hat{g}(\theta, \theta', p)^{(S,V,T)} = \delta(\theta - \theta'),
\]

\[
\partial_\theta \hat{g}(0, \theta', p)^{(S,V,T)} = -2kr \hat{g}(0, \theta', p)^{(S,V,T)} + \frac{rp^2}{2k} \mathcal{G}^{(S,V,T)} \hat{g}(0, \theta', p)^{(S,V,T)},
\]

\[
\partial_\theta \hat{g}(\pi, \theta', p)^{(S,V,T)} = -2kr \hat{g}(\pi, \theta', p)^{(S,V,T)}
\]

- The solutions are only distinguished by the LV boundary conditions. The \( \mathcal{G}^{(S,V,T)} \) and \( \mathcal{D}^{(S,V,T)} \) encapsulate the LV for each mode
Confirm the EFT validity

- With the full 2 point function in hand we can verify that the EFT has captured the relevant physics

- Putting a leg on the IR brane we find the leading, in $p^2/k^2$, behavior

$$\hat{g}(\theta, \pi, p)^{(S,V,T)} = \frac{2\omega^2 k e^{-2kr\theta} D^{(S,V,T)}}{r p^2 \left[ (1 - \omega^2) D^{(S,V,T)} - N^{(S,V,T)} \right]} \quad \omega \equiv e^{-kr e^{\pi}}$$

- There is unsuppressed LV, which can be shown to yield the dispersion relations found in the EFT

- Above the KK scale, no leading order LV

$$\hat{g}(\theta, \pi, iq)^{(S,V,T)} = -\frac{1}{iqr} e^{-\frac{1}{2} rk(\pi+\theta)} \exp \left[ -\frac{q}{k} \left( e^{kr \pi} - e^{kr \theta} \right) \right]$$

- Exponential suppression cuts off the integrals
What about the Radion?

- The radion couples to the trace of the IR brane stress tensor with IR scale suppressed coupling.
- It also mixes with the Aether, does this lead to a huge new source of LV?
- No, the mixing is exponentially suppressed, leading to Planck suppressed communication of LV.
- Just as other Gravity modes
Constraints

- Recall that \(-2 \times 10^{-16} < \kappa_{\gamma} < 2 \times 10^{-20}\)
- The gravity constraint is \(\frac{\Lambda_{LV}^2}{M_{Pl}^2} \sim 10^{-9}\)
- Then \(M_{KK} \lesssim 10^{-5} M_{Pl} \sim 10^{14} \text{ GeV}\)
- For \(\Lambda_{LV} \sim M_{Pl}\) we have \(M_{KK} \lesssim 10^{10} \text{ GeV}\)
- Well above scales probed by flavor bounds \(\sim 10^8 \text{ GeV}\)
Some Summary

• The Standard Model exists as composites of strongly coupled quasi-conformal sector
• Gravity is sensitive to the LV, but graviton loops are cut off at the IR scale
• The leading signal of LV come from the purely gravitational effects
• Indications of the composite structure at colliders give a lower bound on the IR scale
Conclusions

• Lorentz symmetry may not be fundamental, but rather an *emergent* symmetry at low energies

• The experimental bounds are quite tight in the matter sector, but less so in gravity

• We have shown that the Standard Model can be *screened* from Lorentz violation in the gravity sector

• In our model, after satisfying the gravity constraints, the matter sector is effectively *unconstrained*
Conclusions

• In effect, we have used strong dynamics to ‘hide’ Lorentz violation from the low energy experiments using Standard Model fields

• We can estimate the size of these effects through the AdS/CFT correspondence

• Predictions from 5D confirm our CFT intuition

• This framework gives a *sane* way to study Lorentz violating extensions of the Standard Model