SCREENING THE STANDARD MODEL FROM GRAVITATIONAL LORENTZ VIOLATION

Chris Verhaaren

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With Zackaria Chacko, Rashmish Mishra, and Simon Riquelme

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 *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 *aether*
- If at some scale Λ_{LV} close to the Planck scale M_{Pl} the vector gets a *timelike* VEV, then boost symmetries will be *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*
  - Jacobson & Mattingly Phys. Rev. D 64 (2001)
- Preserves diffeomorphism invariance while breaking to a rotationally symmetric theory
- Completely general at 2-derivatives, captures *leading* low energy dynamics

Makes Aether Dynamical

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

Spontaneously Breaks LS

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

New Wave Modes

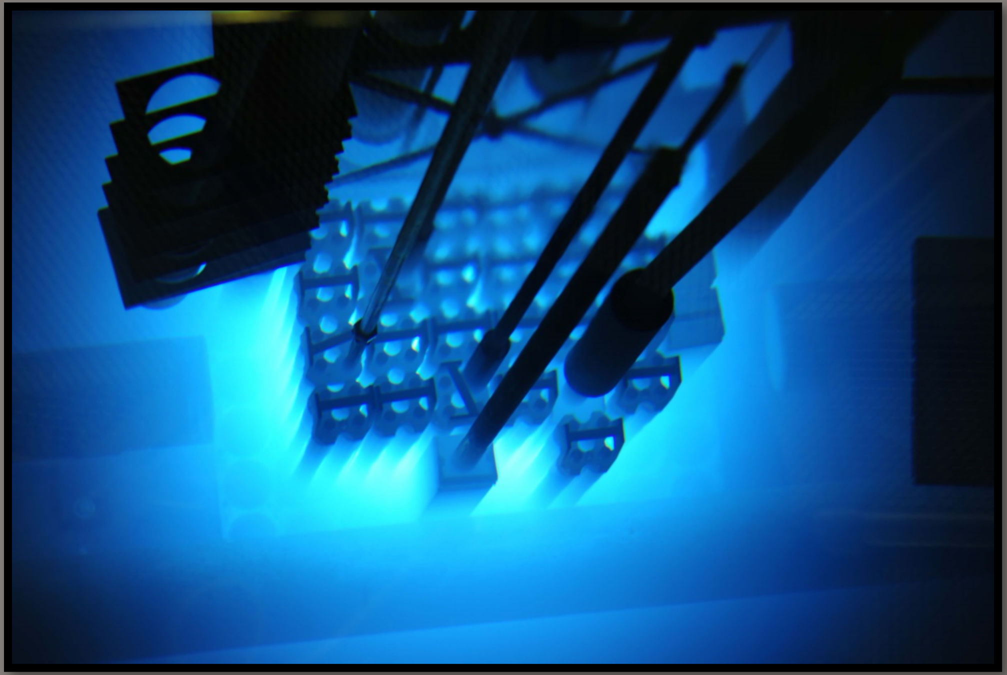
- The three Goldstones are organized as a spin 1 mode and spin 0 mode
- The speed of these waves may *not* be equal to light
- The usual gravitational tensor modes can also differ from 1

	Tensor	$\frac{1}{1-c_1-c_3}$
$c_i \ll 1$	Vector	$\frac{c_1}{c_1+c_4}$
$c_i \ll 1$	Scalar	$\frac{c_1+c_2+c_3}{c_1+c_4}$

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?*

Cherenkov 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*
- $U^\alpha = \Lambda_{\rm LV} u^\alpha$ with $\Lambda_{\rm LV} \lesssim M_{\rm Pl}$

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

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

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

$$\Lambda_{\rm LV}^2 \sim 10^{-9} M_{\rm Pl}^2$$

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

$$E^2 = \vec{p}^2 + m^2 + f(\vec{p}^2)$$

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 κ_γ
  - $\kappa_\gamma > 0: \quad e^\pm \to e^\pm \gamma \qquad \kappa_\gamma < 0: \quad \gamma \to e^- e^+$
- 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

$$\Lambda_{\rm LV}^2 \sim 10^{-16} M_{\rm Pl}^2$$

Matter constraints

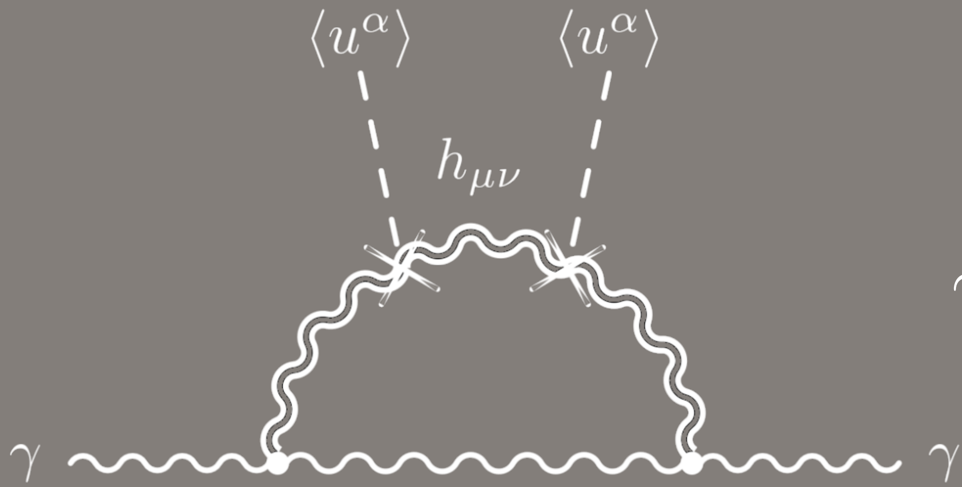
- The *lowest* dimension gauge invariant Lorentz violating fermion operator is $\kappa_f u^\mu u^\nu \overline{f} \gamma_\mu D_\nu F$
- The electron gives a constraint similar to the photon

$$\Lambda_{\mathrm{LV}}^2 \sim 10^{-15} M_{\mathrm{Pl}}^2$$

- 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



$$\sim \frac{1}{16\pi^2}\frac{\Lambda_{\rm LV}^2}{M_{\rm Pl}^2}$$

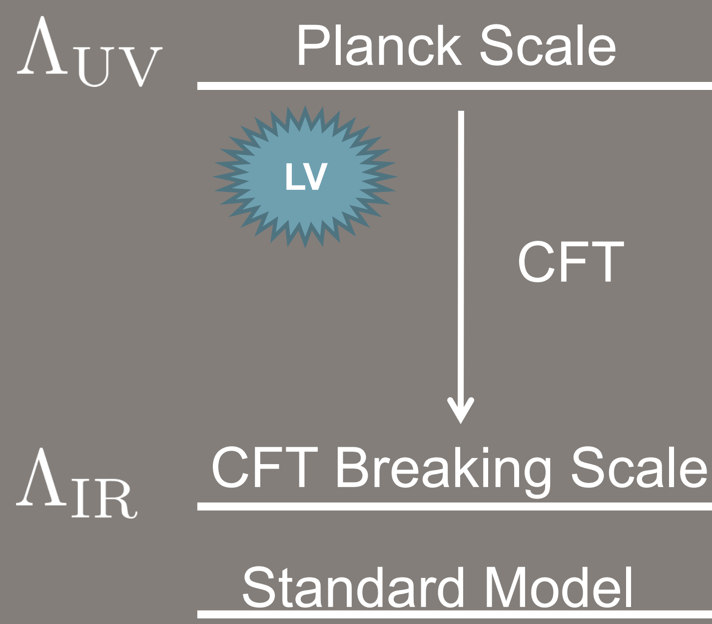
- With $\Lambda_{\rm LV} \sim M_{\rm Pl}$, or even with the gravity bound $\Lambda_{\rm LV}^2 \sim 10^{-9} M_{\rm Pl}^2$ the parameters are in *gross conflict* with experiment

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

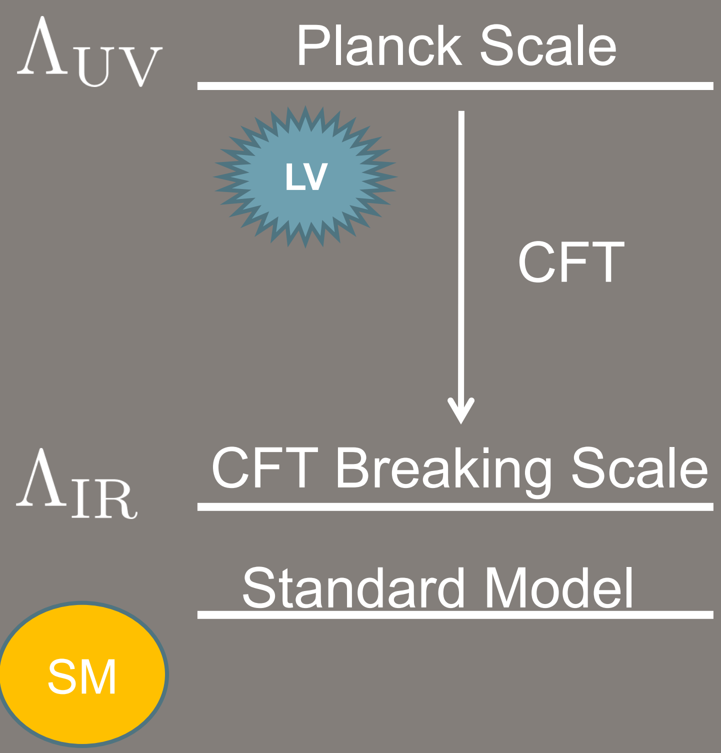
Use Strong Dynamics

- Consider a *strongly coupled* CFT, which spontaneously breaks at some scale Λ_{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*



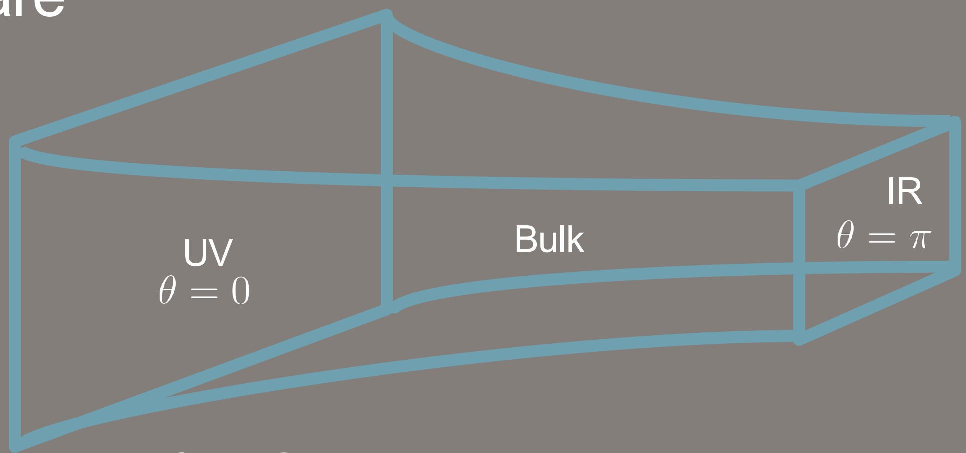
Use Strong Dynamics

- SM states are the *composites* of the CFT below $\Lambda_{\rm IR}$
- 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

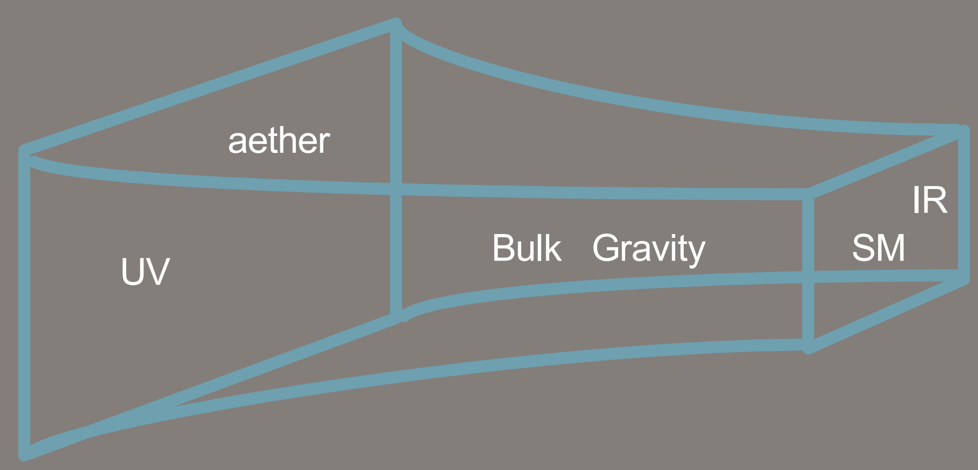


$$ds^2 = e^{-2kr_c|\theta|}\eta_{\mu\nu}dx^\mu dx^\nu + r_c^2 d\theta^2$$

RS Holography

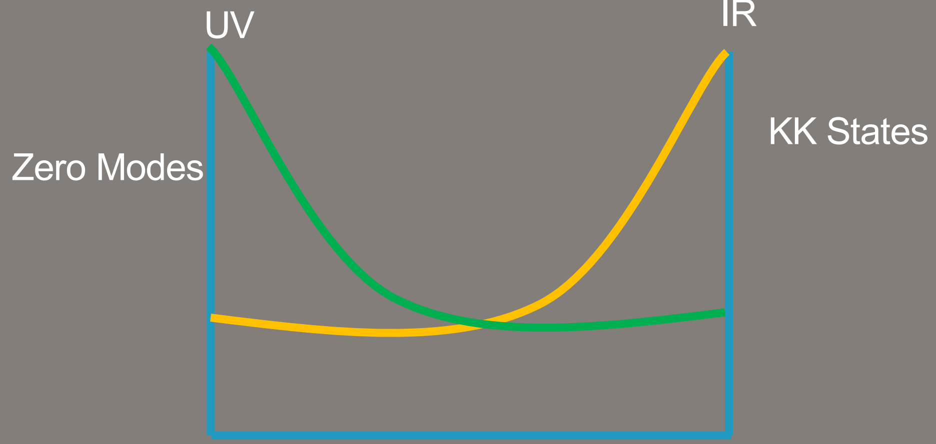
CFT		RS
UV Cutoff	$\Leftrightarrow$	UV Brane
SB Scale	$\Leftrightarrow$	IR Brane
RG Scale, μ	$\Leftrightarrow$	Warped Dimension, θ
Elementary Field	$\Leftrightarrow$	UV Field
Composite Field	$\Leftrightarrow$	IR Field

- 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*



Low Energy Fields

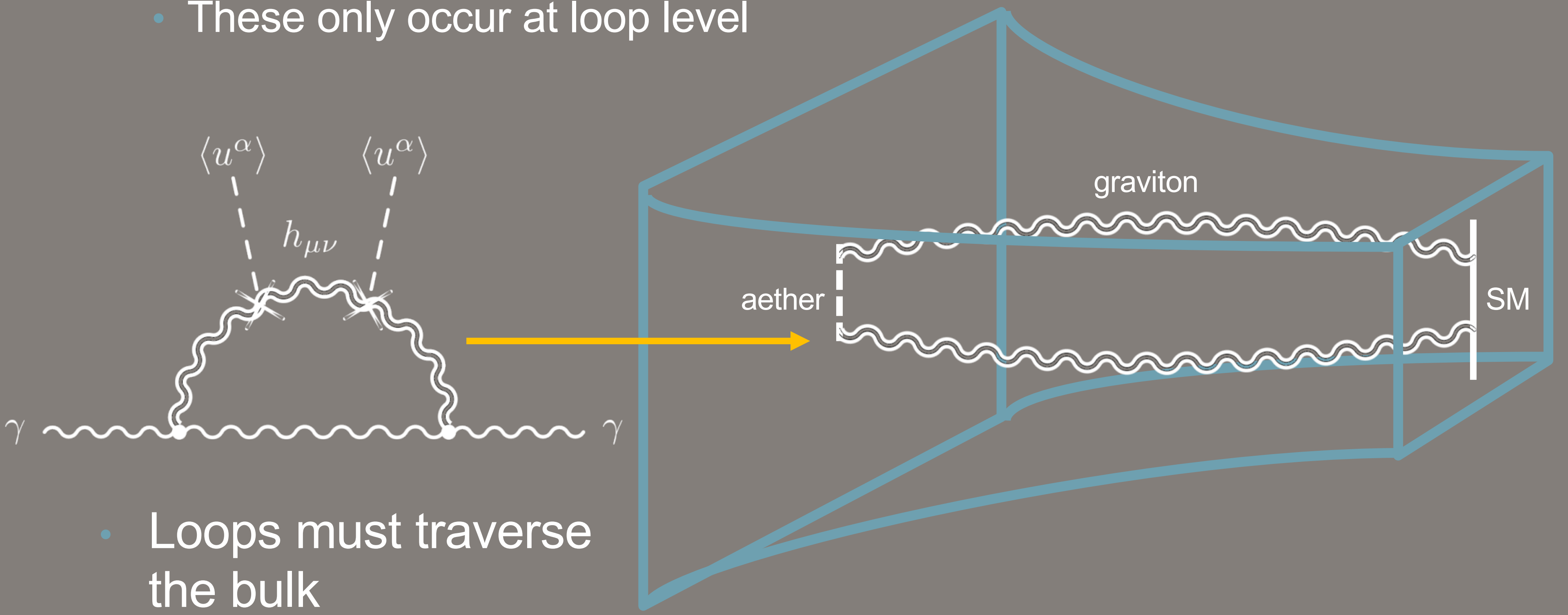
- We can capture the physics we care about by focusing on energies *below* the KK scale
- The low energy EFT has following the field content
  - Standard Model fields
  - The graviton
  - 3 LV Goldstone bosons
  - The radion, a graviscalar

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



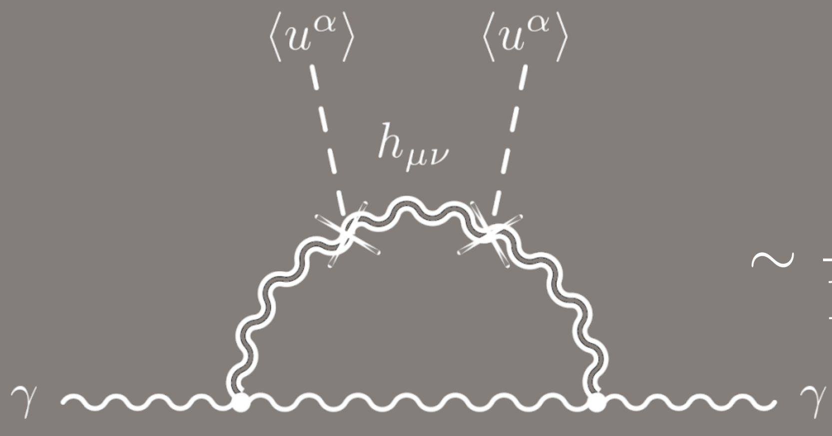
- Loops must traverse the bulk

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

$$\kappa_\gamma u^\mu u^\nu F_{\mu\alpha} F^\alpha{}_\nu$$

- 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



$$\sim \frac{1}{16\pi^2} \frac{M_{\mathrm{KK}}^2}{M_{\mathrm{Pl}}^2} \quad \Rightarrow \quad \kappa_\gamma \sim \frac{1}{16\pi^2} \frac{M_{\mathrm{KK}}^2 \Lambda_{\mathrm{LV}}^2}{M_{\mathrm{Pl}}^4}$$

Digression: Full 2-point Function

- Beginning from the 5D action

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

- The classical solution for the metric is

$$ds^2 = e^{-2kr_c|\theta|}\eta_{\mu\nu}dx^\mu dx^\nu + r_c^2 d\theta^2, \qquad -\pi \le \theta < \pi\,,$$

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

- In the RS-gauge fluctuations of the metric evolve according, with $p^2 \equiv \omega^2 - \vec{p}^2$, to

Brane Source terms

$$\left[\partial_\theta^2 + p^2 r^2 e^{2kr\theta} - 4k^2r^2 + 4kr\delta(\theta) - 4kr\delta(\theta-\pi)\right]\widehat{h}_{\mu\nu} = -2\delta(\theta)\widehat{\Sigma}^{\rm UV}_{\mu\nu} - 2\delta(\theta-\pi)\widehat{\Sigma}^{\rm IR}_{\mu\nu}$$

Full 2-point function

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

$$h^{(\mathrm{S,V,T})} = -\widehat{\Sigma}_{\mathrm{UV}}^{(\mathrm{S,V,T})}\widehat{g}(\theta,0,p)^{(\mathrm{S,V,T})} - \widehat{\Sigma}_{\mathrm{IR}}^{(\mathrm{S,V,T})}\widehat{g}(\theta,\pi,p)^{(\mathrm{S,V,T})}$$

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

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

$$\partial_\theta \widehat{g}(0,\theta',p)^{(\mathrm{S,V,T})} = -2kr\widehat{g}(0,\theta',p)^{(\mathrm{S,V,T})} + \frac{rp^2}{2k}\frac{\mathcal{N}^{(\mathrm{S,V,T})}}{\mathcal{D}^{(\mathrm{S,V,T})}}\widehat{g}(0,\theta',p)^{(\mathrm{S,V,T})},$$

$$\partial_\theta \widehat{g}(\pi,\theta',p)^{(\mathrm{S,V,T})} = -2kr\widehat{g}(\pi,\theta',p)^{(\mathrm{S,V,T})}$$

- The solutions are only distinguished by the LV boundary conditions. The $\mathcal{N}^{(\mathrm{S,V,T})}$ and $\mathcal{D}^{(\mathrm{S,V,T})}$ 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

$$\widehat{g}(\theta,\pi,p)^{(\mathrm{S,V,T})} = \frac{2\varpi^2 k e^{-2kr\theta}\mathcal{D}^{(\mathrm{S,V,T})}}{rp^2\left[(1-\varpi^2)\mathcal{D}^{(\mathrm{S,V,T})} - \mathcal{N}^{(\mathrm{S,V,T})}\right]} \qquad \varpi \equiv e^{-kr_c\pi}$$

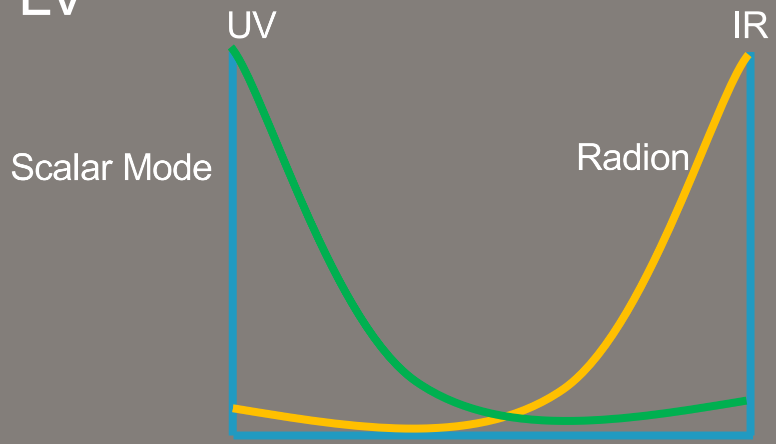
- There is unsuppressed LV, which can be shown to yield the dispersion relations found in the EFT
- Above the KK scale, no leading order LV

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

- 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

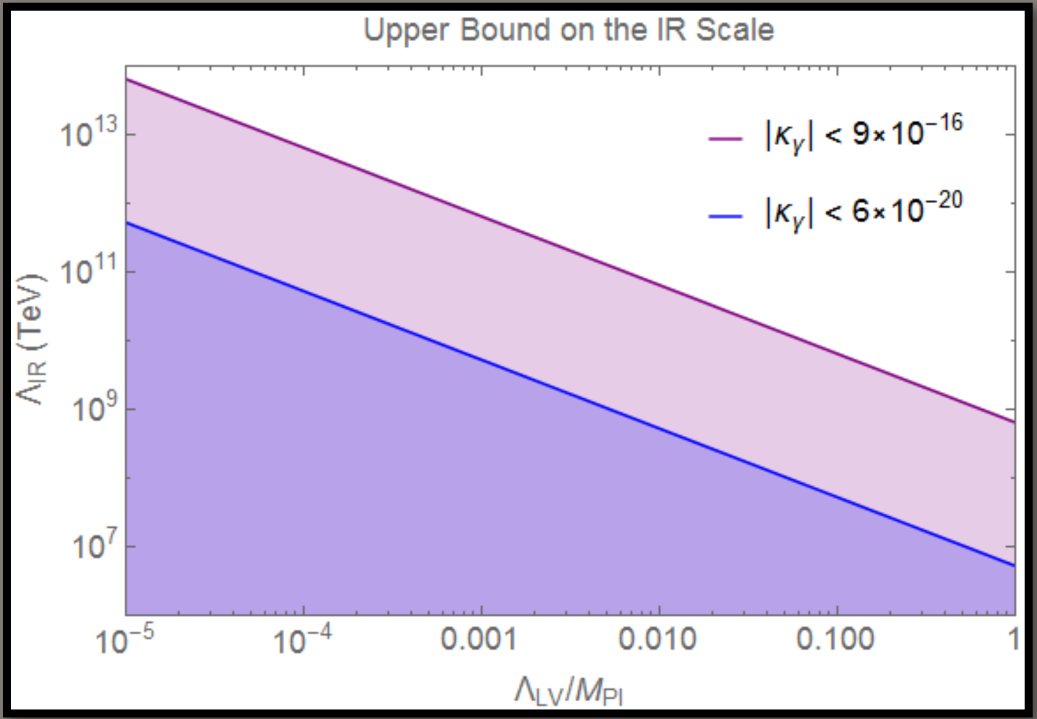


Constraints

- Recall that $-2 \times 10^{-16} < \kappa_\gamma < 2 \times 10^{-20}$
- The gravity constraint is $\dfrac{\Lambda_{\mathrm{LV}}^2}{M_{\mathrm{Pl}}^2} \sim 10^{-9}$
- Then $M_{\mathrm{KK}} \lesssim 10^{-5} M_{\mathrm{Pl}} \sim 10^{14}\,\mathrm{GeV}$
- For $\Lambda_{\mathrm{LV}} \sim M_{\mathrm{Pl}}$ we have

  $$M_{\mathrm{KK}} \lesssim 10^{10}\,\mathrm{GeV}$$

- Well above scales probed by flavor bounds $\sim 10^8\,\mathrm{GeV}$



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