

Quantum Gravity Phenomenology Without Lorentz Invariance Violations

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Motivation

- Spacetime may have a non-trivial micro-structure at the Planck scale.
- Look for its consequences through LSV (\exists a preferred reference frame W^a).
- Why? Any spacetime granularity could be incompatible with the Lorentz length contraction.

Motivation

However...

- 1 There are very stringent bounds on LSV (Maccione *et al.*, 2009):

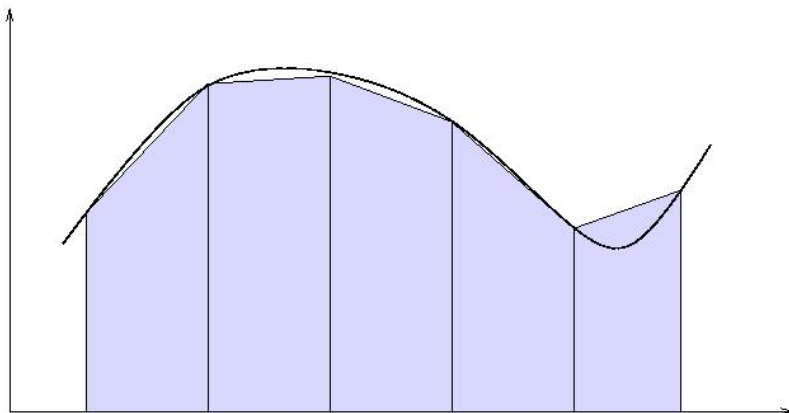
$$p_a p^a = -m^2 - \frac{\xi}{M_P} (W \cdot p)^3 + \dots; \quad |\xi| \leq 9 \times 10^{-10}.$$

- 2 Collins *et al.* (2004) showed that radiative corrections would magnify the effects of such granularity to a point where they are discarded by experiments. [Details](#)

We study how a LS granular structure can become manifest.

An analogy

There is no intuitive picture of how can a granular structure respect LS, we turn to an analogy.



The lesson from this analogy

- In flat regions of spacetime, the symmetry of the granular structure (LS) and the macroscopic symmetry coincide \Rightarrow the micro-structure cannot be detected through LSV.
- In regions where $R_{abcd} \neq 0$ the macroscopic symmetry deviate from LS \Rightarrow

Spacetime granularity could become manifest through couplings of matter fields and R_{abcd} .

Concrete coupling term

- R_{ab} is determined locally by $T_{ab} \Rightarrow$ coupling R_{ab} to the fields looks like a self-interaction \Rightarrow focus on R_{abcd} without R_{ab} , *i.e.*, W_{abcd} .
- We focus on fermionic fields ψ .
- We seek for coupling terms which are minimally suppressed by M_P .
- The most obvious coupling term is $(\gamma^a \equiv e_{\mu}^a \gamma^{\mu})$

$$W_{abcd} \bar{\psi} \gamma^a \gamma^b \gamma^c \gamma^d \psi \propto W_{abcd} \epsilon^{abcd} \bar{\psi} \gamma_5 \psi = 0.$$

- No more “obvious” dimension 5 coupling terms.

Concrete coupling term

- Let \mathcal{S} be the space of 2-forms which inherits a 'super-metric' $\mathcal{G}_{abcd} = \mathcal{G}_{[ab][cd]}$ from g_{ab} .
- Weyl is a map $\mathcal{S} \rightarrow \mathcal{S}$, we use $\lambda^{(s)}$ and the 2-forms $X_{ab}^{(s)}$ such that

$$\mathcal{W}_{ab}{}^{cd} X_{cd}^{(s)} = \lambda^{(s)} X_{ab}^{(s)}.$$

- The proposed coupling term is

$$\mathcal{L}_f = H_{ab} \bar{\psi} \gamma^a \gamma^b \psi, \quad H_{ab} = \sum_s \frac{\xi^{(s)}}{M_P} \lambda^{(s)} X_{ab}^{(s)}.$$

- H_{ab} depends on the (dynamical) gravitational environment.
- The proposal is covariant, super-renormalizable and H_{ab} vanishes when $R_{abcd} = 0$.

Refining the initial proposal

This coupling has some problems:

- 1 W_{ab}^{cd} is not hermitian (w.r.t. \mathcal{G}_{abcd}) \Rightarrow

$$\begin{aligned}(\mathcal{W}_+)_{ab}^{cd} &= W_{ab}^{cd} + W_{ab}^{\dagger cd}, \\(\mathcal{W}_-)_{ab}^{cd} &= \epsilon_{ab}^{ef} \left(W_{ef}^{\dagger cd} - W_{ef}^{cd} \right),\end{aligned}$$

where ϵ_{abcd} is the spacetime volume form.

- 2 $X_{ab}^{(s)}$ and $\epsilon_{ab}^{cd} X_{cd}^{(s)}$ always correspond to the same eigenvalue \Rightarrow Take the linear combinations $\Theta_{ab}^{(s)}$ s.t.

$$\epsilon^{abcd} \Theta_{ab}^{(s)} \Theta_{cd}^{(s)} = 0, \quad \mathcal{G}^{abcd} \Theta_{ab}^{(s)} \Theta_{cd}^{(s)} = \pm 1.$$

- 3 The model is invariant under $\Theta_{ab}^{(s)} \rightarrow -\Theta_{ab}^{(s)}$ and the physical setting is not \Rightarrow Quadratic coupling term.

[► Details](#)

Experimental Outlook

- Locally, this coupling looks like a LV term that has been studied in the SME.
- Using the non-relativistic Hamiltonian of the SME (Kostelecký and Lane, 1999) we obtain

$$\mathcal{H}_{NR} = \sum_{i=1}^3 \left(\frac{\xi_A^{(i)}}{M_P} \alpha^{(i)} \vec{\sigma} \cdot \vec{a}^{(i)} + \frac{\xi_B^{(i)}}{M_P} \beta^{(i)} \vec{\sigma} \cdot \vec{b}^{(i)} \right),$$

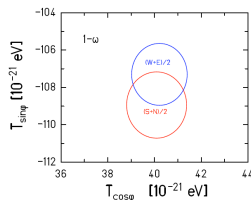
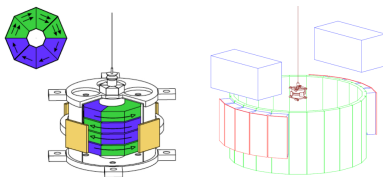
where the eigenvalues and eigenvectors of \mathcal{W}_{\pm} are encoded in $\alpha^{(i)}$, $\beta^{(i)}$, $\vec{a}^{(i)}$ and $\vec{b}^{(i)}$. [► Details](#)

Experimental Outlook

- Weyl is determined by tidal forces \Rightarrow care when comparing experiments in different places.
- Only polarized probes are affected \Rightarrow the setup has to be insensible to \vec{B} .
- The first bounds were obtained by using a Hughes-Drever experiment and the fact that the Sun gravitational effect on Earth varies with a yearly period.

Experimental Outlook

- The Eöt-Wash Group (Heckel *et al.*, 2006) developed polarized probes that are insensible to \vec{B} and they performed an experiment to test the model (Terrano *et al.*, 2011), obtaining bounds for some of the parameters of the electron sector. [► Details](#)



Summary

- It is possible to study phenomenologically some implications of a Lorentz respectful micro-structure of spacetime.
- A concrete and well-defined phenomenological proposal is made involving non-trivial coupling of Weyl and fermions.
- The proposal has been confronted with experiments.
- Other consequences? Neutrinos?

Spacetime granularity and LSV

- Consider Yukawa theory $\mathcal{L}_{int} = g\phi\bar{\psi}\psi$ in spacetime s.t.
 - 1 It is granular.
 - 2 The granularity determines a preferential frame W^a .
- Assuming \nexists field's modes shorter than the size of the granularity $l_{gran} \sim l_P \Rightarrow$ momentum cutoff $\Lambda \propto l_{gran}^{-1}$.
- For simplicity, this cutoff is implemented in the frame associated with W^a by

$$\frac{1}{p^2 - M^2 + i\epsilon} \rightarrow \frac{f[|\vec{p}(W)|/\Lambda(W)]}{p^2 - M^2 + i\epsilon},$$

where $f(0) = 1$ and $f(x \geq 1) = 0$.

Spacetime granularity and LSV

- The scalar self-energy takes the form

$$\Pi(p) = \xi p^a p^b W_a W_b + \Pi^{(LS)}(p) + \mathcal{O}(p^4/\Lambda^4),$$

where $\Pi^{(LS)}$ is the standard self-energy and

$$\xi = \frac{g^2}{6\pi^2} \left[1 + 2 \int_0^\infty dx x (f'(x))^2 \right].$$

- ξ is independent of Λ and $\xi \geq g^2/6\pi^2$.
- Unless there is an extremely unnatural fine-tuning when performing renormalization, the speed of light becomes particle dependent to a point that is experimentally discarded.

The weak gravity regime

- We consider gravity in the linearized regime and neglect $\mathcal{O}(c^{-2})$.
- If the gravitational source has a Newtonian potential Φ_N and momentum density \vec{p}/c :

$$A_{ij} = \partial_i \partial_j \Phi_N, \quad B_{ij} = 2\partial_{(i}(\text{curl}\vec{\pi})_{j)}/c,$$

where

$$\vec{\pi} = G \int \frac{\vec{p}(\vec{x}', t)}{|\vec{x} - \vec{x}'|} d^3x'.$$

- The eigenvalues and eigenvectors of Weyl can be encoded in $\alpha^{(i)}$, $\beta^{(i)}$, $\vec{a}^{(i)}$ and $\vec{b}^{(i)}$ s.t.

$$\mathbf{A}\vec{a}^{(i)} = \alpha^{(i)}\vec{a}^{(i)}, \quad \mathbf{B}\vec{b}^{(i)} = \beta^{(i)}\vec{b}^{(i)}.$$

Bounds

$$H_{ab} = \sum_{\alpha, \beta = \pm} \sum_{s, r} M^{(\alpha, \beta, s, r)} \Sigma_{ab}^{(\alpha, \beta, s, r)},$$

$$M^{(\alpha, \beta, s, r)} = \xi^{(\alpha, \beta, s, r)} \left(\frac{|\lambda^{(\alpha, s)}|^{1/2}}{M_P} \right)^{c^{(\alpha, s)}} \left(\frac{|\lambda^{(\beta, r)}|^{1/2}}{M_P} \right)^{c^{(\beta, r)}} \\ |\lambda^{(\alpha, s)}|^{1/4} |\lambda^{(\beta, r)}|^{1/4},$$

$$\Sigma_{ab}^{(\alpha, \beta, s, r)} = g^{cd} \mathcal{G}(\Theta^{(\alpha, s)}, \Theta^{(\beta, r)}) \Theta_{c[a}^{(\alpha, s)} \Theta_{b]d}^{(\beta, r)} + \dots$$

