Quantum Gravity Phenomenology Without Lorentz Invariance Violations

Yuri Bonder

Instituto de Ciencias Nucleares
Universidad Nacional Autónoma de México

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In collaboration with P. Aguilar, A. Corichi and D. Sudarsky.

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):

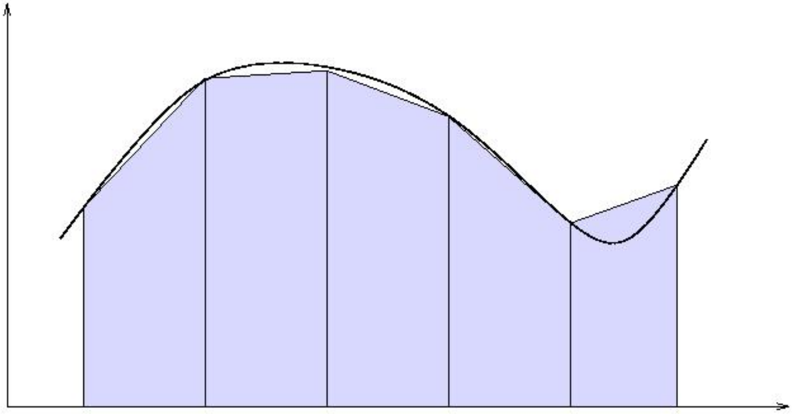
$$p_a p^a = -m^2 - \frac{\xi}{M_P}(W \cdot p)^3 + \cdots ; \quad |\xi| \leq 9 \times 10^{-10}.$$

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 ($\gamma^a \equiv e^a_\mu \gamma^\mu$)

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

- 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 $\mathcal{S} \to \mathcal{S}$, we use $\lambda^{(s)}$ and the 2-forms $X^{(s)}_{ab}$ such that

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

- The proposed coupling term is

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

- 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. $\mathcal{G}_{abcd}$) $\Rightarrow$

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

   where ϵ_{abcd} is the spacetime volume form.

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

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

3. The model is invariant under $\Theta^{(s)}_{ab} \to -\Theta^{(s)}_{ab}$ 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

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

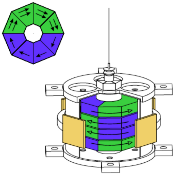
where the eigenvalues and eigenvectors of $\mathcal{W}_{\pm}$ are encoded in $\alpha^{(i)}$, $\beta^{(i)}$, $\vec{a}^{(i)}$ and $\vec{b}^{(i)}$. Details

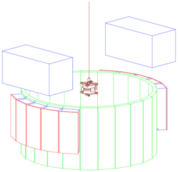
Experimental Outlook

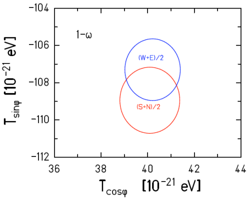
- Weyl is determined by tidal forces $\Rightarrow$ care when comparing experiments in different places.
- Only polarized probes are affected $\Rightarrow$ the setup has to be insensible to $\vec{B}$.
- The first bounds where obtained by using a Hughes-Drever experiment and the fact that the Sun gravitational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

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

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-tunning 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 $\vec{p}/c$:

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

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

$$
\begin{aligned}
H_{ab} &= \sum_{\alpha,\beta=\pm}\sum_{s,r} M^{(\alpha,\beta,s,r)}\Sigma_{ab}^{(\alpha,\beta,s,r)}, \\
M^{(\alpha,\beta,s,r)} &= \xi^{(\alpha,\beta,s,r)}\left(\frac{|\lambda^{(\alpha,s)}|^{1/2}}{M_P}\right)^{c^{(\alpha,s)}}\left(\frac{|\lambda^{(\beta,r)}|^{1/2}}{M_P}\right)^{c^{(\beta,r)}} \\
&\quad |\lambda^{(\alpha,s)}|^{1/4}|\lambda^{(\beta,r)}|^{1/4}, \\
\Sigma_{ab}^{(\alpha,\beta,s,r)} &= g^{cd}\mathcal{G}(\Theta^{(\alpha,s)},\Theta^{(\beta,r)})\Theta_{c[a}^{(\alpha,s)}\Theta_{b]d}^{(\beta,r)} + \cdots .
\end{aligned}
$$