Lorentz violation, Horava gravity, Naturalness and all that

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IPMU meeting on Lorentz Violation

Plan

Part 1: Lorentz violation in Horava gravity. An attempt of preserving approximate Lorentz symmetry using the scale separation. Current status of the proposal. Based on 2010 paper with Y. Shang.

Part 2: Aether and one-loop effective action. Can one preserve the reparametrization invariance at loop level? (My collaborator, N. Afshordi, and I seem to have different views on that.)

Part 3: Re-profiling the terrestrial searches of Lorentz violation to searches of transient effects. Work in collaboration with Budker, Gawlik, Jackson-Kimball, Ledbetter, Pustelny. Future directions.

Questions for Part I

High-energy gravity is notorious for "bad behaviour" in UV. Specific form of explicit loss of LI in the UV (**Horava**, 2009) can be beneficial for rectifying this problem. *"Maybe gravity is asymptotically free"*

1. Is Horava theory just a nice tool, or can it be more than that? Can one make this theory consistent with stringent constraints on LV?

2. Status of $\Lambda_{HL} << M_{planck}$ proposal, (MP, Shang, 2010).

3. How to enforce $c_{gravity} \sim c_{matter}$? And how strictly should that be enforced?

Questions for Part II

Theories with LV can be covariantized by introducing dynamical spurions, or aether, which has to have self-interaction, and in general non-linear propagation/self-interaction terms. (In the context of Horava gravity emphasized by Blas, Pujolas, Sibiryakov).

1. How to construct a 1-loop effective action for such fields?

2. Do loops necessarily result in the loss of the reparametrization invariance for aether (reacting N. Afshordi's ideas)?

Questions for Part III

Several Labs around the world have searched for the breakdown of rotational invariance using atomic spins, torsion balances etc. (If there is aether, and you move over it, the rotational invariance is lost). In short, it is a search of some soft background that persists in time.

1. Can we extend the class of phenomena that are being searched for to include those that last a finite amount of time? *Transient LV*.

2. Macroscopic size monopoles, strings and domain walls (possibly clumps of DM) are some generic candidates. Do such experiments have capabilities to probe/set constraints on transients over and beyond cosmology?

3. How to implement such things in practice?

Lorentz violation at first glance

Suppose that our theory admits "external fields" with open Lorentz indices – I call them LV spurions – and physical fields couple to them,

Dimension 3 operators:

$$\mathcal{L}^{(3)}_{\rm QED} = -a_\mu \bar{\psi}\gamma_\mu\psi - b_\mu\bar{\psi}\gamma^\mu\gamma_5\psi - \frac{1}{2}H_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi - k_\mu\epsilon^{\mu\nu\alpha\beta}A_\nu\frac{\partial}{\partial x^\alpha}A_\beta,$$

Dimension 4 operators:

$$\mathcal{L}^{(4)}_{\rm QED} = -c_{\mu\nu}\bar{\psi}\gamma_\mu\partial_\nu\psi - d_{\mu\nu}\bar{\psi}\gamma_\mu\gamma_5\partial_\nu\psi - k_{\mu\nu\alpha\beta}F^{\mu\nu}F^{\alpha\beta},$$

a_μ, b_μ, k_μ, $H_{\mu\nu}$, *etc* are the LV spurions. They might result from some form of the spontaneous symmetry breaking (like in Jacobson and collaborators model of gravitational aether) or be a consequence of fundamental loss of LI in the UV (for example, a-la Horava-Lifshitz).

Lorentz violation at first glance

Effective field theory approach to LV is useful: allows to compare results of different experiments, and assign them a figure of merit in terms of sensitivity to spurions. Developed by A. Kostelecky and collaborators, with important contribution from S. Coleman and S. Glashow.

If CPT is violated due to some unspecified dynamics at a very high scale, its more sensible that LI breaking is communicated via *higher-dimensional operators* (R.Myers, MP), *so that it can be decoupled from low-energy phenomenology if needed.*

As for example in the following dimension 5 operators:

$$\mathcal{L}_s = i\frac{\kappa}{M_{\rm Pl}}\bar{\Phi}(n\cdot\partial)^3\Phi \qquad \mathcal{L}_\gamma = \frac{\xi}{M_{\rm Pl}} n^a F_{ad} n\cdot\partial(n_b \tilde{F}^{bd})$$

$$\mathcal{L}_f = \frac{1}{M_{\rm Pl}}\bar{\Psi}\left(\eta_1 \not{n} + \eta_2 \not{n}\gamma_5\right)(n\cdot\partial)^2\Psi$$

Experimental constraints are strong

1. UV-enhanced operators are constrained by Cherenkov radiation in vacuum (Coleman, Glashow) and by the very existence of high-energy cosmic rays (Moore, Gagnon). Strong constraints on QED LV terms are derived by (e.g.) Jacobson, Liberati, Mattingly and others. The difference in the "speed of light" for different species is limited to better than 1 part per 10^{22}
2. By low-energy spin precession data, which constrain dim=5 LV at 10^{-8}-$10^{-7}/M_{Pl}$ level. New experiments at Princeton (group of M. Romalis) have improved these bounds by ~ two orders of magnitude.

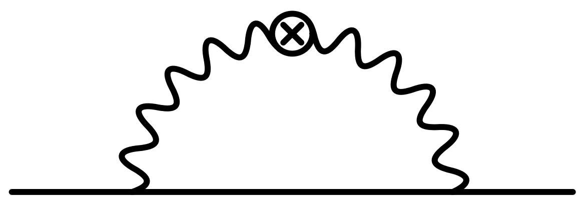
Given that there are strong constraints on LV in matter sector, one has to make sure that if gravity does violate LI, it does not get communicated into the matter sector easily.

Dimensional transmutation problem

Free particles are utopia. Real particles interact – at least gravitationally. It makes it difficult to "localize" LV to higher-dimensional operators.

Dimension 5 → Dimension 3

$$\frac{\xi}{M_{\mathrm{Pl}}} n^a F_{ad} n \cdot \partial (n_b \tilde{F}^{bd}) \rightarrow b_\mu \bar{\psi} \gamma^\mu \gamma_5 \psi$$



$$b_\mu \sim (\text{loop factor}) \times \xi \frac{\Lambda_{UV}^2}{M_{\mathrm{Pl}}}.$$

Another example, dim=6 LV in non-commutative QED:

$$\mathcal{L}_{\mathrm{eff}} = (\text{two loop factor}) \times \Lambda_{UV}^2 \theta^{\mu\nu} m_e \bar{\psi} \sigma_{\mu\nu} \psi$$

Very large dimension 3 operator will be induced if $\Lambda^2 \theta \sim O(1)$

Self-regulation + scale separation

Known examples of controlled dimensional transmutation use wide scale separation.

Consider two sectors coupled via irrelevant interaction: $\frac{1}{M^{n+k-4}} O_{\rm LV}^{(n)} O_{\rm SM}^{(k)}$ and let LI be broken in 1 sector by 100%. How much feedback do you have on another sector via loops?

$$\frac{1}{M} O_{\rm LV}^{(1)} O_{\rm SM}^{(4)} \to \frac{\Lambda_{\rm UV}^2}{M^2} O_{\rm SM,LV}^{(4)}$$

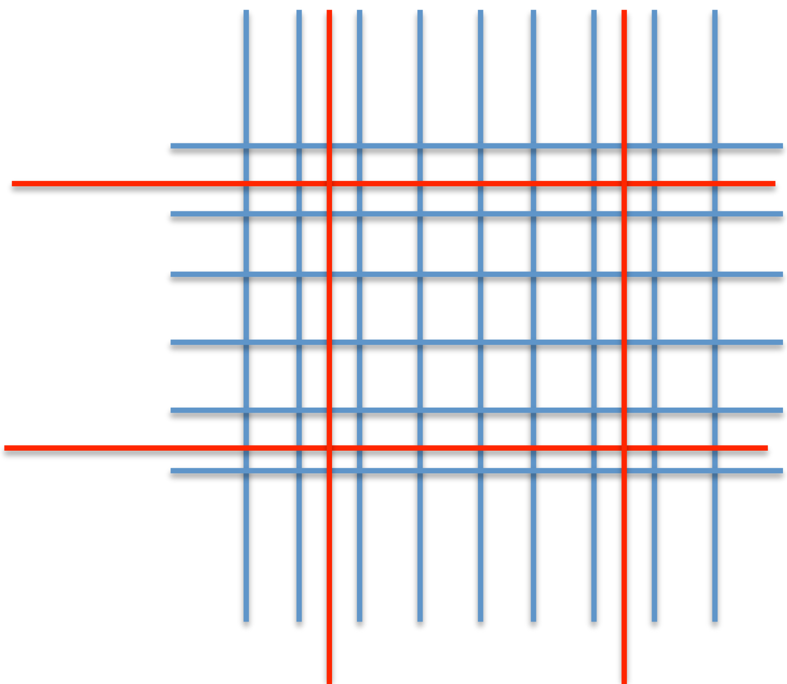
In HL theories *you do not have to cut loop integrals by hand* – instead they are self-regulated by Lifshitz propagators

$$\frac{i}{\omega^2 - \mathbf{k}^2} \to \frac{i}{\omega^2 - \frac{\mathbf{k}^6}{\Lambda_{\rm HL}^4}}.$$

- Unlike Lee-Wick, such theories can have physical realizations.
- In NC field theories ~1/2 of loop integrals is convergent – but HL is much better because all of them can be convergent of log-divergent.

Self-regulation + scale separation: main idea

1. Break LI in some irrelevantly coupled/poorly probed sector such as gravity or axions etc. Preserve LI in the SM sector
2. Make the HL scale much *lower* than inverse coupling constant 1/M.
3. Leakage of LV into SM is proportional to Λ^2_{HL}/M^2 – will be under control if scales are widely separated.



Gravity "lattice" has much coarser graining $1/\Lambda_{HL}$ than matter field lattice with 1/M spacial cutoff. In Petr's terminology – "multicritical" Universe

What if $\Lambda_{HL} \sim M_{pl}$ or matter and gravity become "Lifshits" at a common scale?

1. If SM fields become Lifshits-type at some scale, then normal SM loops introduce difference in propagation speeds at > 0.1% level.

2. If matter kept "normal", then normal matter + HL gravity with $\Lambda_{HL} \sim \Lambda_{HL} \sim M_{planck}$ will induce same O(0.1%) differences in the propagations speeds because of the gravitational loops.

So, one needs either *new protection mechanism* or the *scale of non-linear behavior to be much lower the Planck scale*.

Toy examples

We checked this logic explicitly in

1. "Normal" fermion + HL axion coupled via $\partial_\alpha \phi / M \, \psi \gamma_\mu \gamma_5 \psi$

2. "Normal" photon + HL neutral fermion with dipole moment $\mu = 1/M$

In both examples the one-loop correction is explicitly calculated. In both cases $\Delta c_{SM} \sim (\Lambda^2_{HL}/M^2)\log(M/\Lambda_{HL})$.
It is under control if $\Lambda_{HL} \sim 10^{-9} M$

"Normal" matter + HL gravity with $\Lambda_{HL} << M_{planck}$

Application to Horava-Lifshitz gravity

Nonlinear terms in the action on top of EH

$$\mathcal{L}_{\text{Hořava}} = M_{\text{pl}}^2 \left(\cdots + \Lambda_{\text{HL}}^{-4} R_{ij} \Delta R^{ij} + \frac{a-3}{8} \Lambda_{\text{HL}}^{-4} R \Delta R + \frac{b}{2} \Lambda_{\text{HL}}^{-4} n \Delta^3 n - \frac{c}{2} \Lambda_{\text{HL}}^{-4} R \Delta^2 n \right)$$

We decompose gravity into 3 sectors of spins 2, 1, 0,

$$\begin{aligned}
\mathcal{L}_{\mathbf{2}} =& \frac{1}{4} \dot{h}_{ij}^{\text{TT}2} + \frac{1}{4} h^{\text{TT}ij} \Delta h_{ij}^{\text{TT}} + \frac{1}{4\Lambda_L^4} h_{ij}^{\text{TT}} \Delta^3 h^{\text{TT}ij} \,, \\
\mathcal{L}_{\mathbf{1}} =& -\frac{1}{2} \left(\dot{V}_i^{\text{T}} - n^{\text{T}i} \right) \Delta \left(\dot{V}^{\text{T}i} - n_i^{\text{T}} \right) \,, \\
\mathcal{L}_{\mathbf{0}} =& \frac{1-2\lambda}{2} \dot{\sigma}^2 - \frac{1}{2} \sigma \Delta \sigma - (\lambda - 1) \left(\Delta\varphi - \frac{1}{2} \dot{\tau} \right)^2 + \lambda \dot{\sigma} \left(2\Delta\varphi - \dot{\tau} \right) - 2n\Delta\sigma \\
& + \frac{a}{2\Lambda_L^4} \sigma \Delta^3 \sigma + \frac{b}{2\Lambda_{\text{HL}}^4} n \Delta^3 n + \frac{c}{\Lambda_{\text{HL}}^4} \sigma \Delta^3 n \,.
\end{aligned}$$

Fix the gauge, $\mathcal{L}_{\text{GF}} = -\frac{1}{2\xi} (\partial^\mu \overline{h}_{\mu\nu} - \frac{1}{2} \partial_\nu \overline{h})^2$

and calculate all propagators and apply to photon vs scalar propagation speed.

TT gravitons are "safe" – only Logs
Annoying Λ^2 corrections from s = 1 sector

We were 50% successful

$$(\delta c^2)_{\rm photon} - (\delta c^2)_{\rm scalar} = -\frac{2}{3}\mathbb{L} - \frac{1}{3}\overline{\langle \sigma^2 + 2\sigma\tau \rangle} \cdot \mathbb{L}' - \frac{2}{3}\mathbb{Q}$$

$$= -\frac{\Lambda_{\rm HL}^2}{36\pi^2 M_{\rm pl}^2} \log\frac{\Lambda_{\rm UV}^2}{\Lambda_{\rm HL}^2} - \frac{3\lambda+1}{3(3\lambda-1)} \frac{\Lambda_{\rm HL}'^2}{24\pi^2 M_{\rm pl}^2} \log\frac{\Lambda_{\rm UV}^2}{\Lambda_{\rm HL}'^2} - \frac{\Lambda_{\rm UV}^2}{24\pi^2 M_{\rm pl}^2}$$

healthy pieces *needs treatment*

- *non-Lifshitz, GR-like propagators for vectors sources Λ^2*
- *Despite the fact that the sector of s=1 is gauge-dependent, the answer for Δc is not. Explicitly checked using R_ξ gauge, and then proven in general.*
- *The coefficient in front of the quadratic divergence is regularization dependent. (The referee was saying "choose DR and all your worries are gone")*
- *We need an extra term in the gravity action to make s=1 Lifshitz*

Proposal to modify Horava action

We need to make s=1 sector "Lifshitz". Otherwise we have $\left\langle v_i^{\mathrm{T}}\, v^{\mathrm{T}i} \right\rangle = -\frac{2}{\vec{k}^2}$,

One way to do it is to add some term(s) that are formally of higher dimension:

$$\mathcal{L}' = \frac{2}{\Lambda^2} \nabla^i K_{ij} \nabla^k K^{kj},$$

In components this will lead to

$$\mathcal{L}' = \frac{1}{2\Lambda^2} v_i^{\mathrm{T}} \Delta^2 v^{\mathrm{T}i} - \frac{2}{\Lambda^2} \chi \Delta \chi \,.$$

and excise $\Lambda_{\mathrm{UV}}{}^2$ divergence in any regularization scheme.

$$(\delta c^2)_{\mathrm{photon}} - (\delta c^2)_{\mathrm{scalar}} = -\frac{\Lambda_{\mathrm{HL}}^2}{12\pi^2 M_{\mathrm{pl}}^2} \left(1 + \frac{\sqrt{(1-2\lambda)\alpha^{-1}}}{2(2\lambda - 1)} \right) \log \frac{\Lambda_{\mathrm{UV}}^2}{\Lambda_{\mathrm{HL}}^2} - \frac{\Lambda^2}{12\pi^2 M_{\mathrm{pl}}^2} \log \frac{\Lambda_{\mathrm{UV}}^2}{\Lambda^2}$$

Making $\Lambda \sim \Lambda_{\mathrm{HL}}$ solves the problem (but we do not know if it adds more problems for gravity itself)

Comments on Dim=6 LV operators

- Unmodified, original proposal: Quadratic divergence can be either 1. *tuned away* or 2. *removed by DR*. But the momentum dependence will survive, and the new $O(p^2/M_{Pl}^2)$ terms in the dispersion relation of matter are generated.

- If quadratic divergencies are removed by the new physical term in the Lagrangian that makes s=1 sector Lifshitz, then dim=6 operators will acquire formfactor: momentum growth p^2/M_{Pl}^2 will be stabilized at $p^2 > \mathrm{Lambda}_{HL}^2$

Considered recently on pheno grounds by Liberati, Maccioni, Sotiriou

Unintended consequence of wide scale separation

- The evolution of the gravitational terms above Λ_{HL} is really *really* slow.

- Effective coupling constants $\alpha_{eff} \sim (\Lambda_{HL}/M_p)^2/4\pi$. This means that marginal terms in the Horava action evolve by O(1) at the UV scale such that $(\alpha_{eff}/4\pi)\ \mathrm{Log}(\Lambda_{UV}/\Lambda_{HL}) \sim 1$ or

$$\Lambda_{UV} \sim \Lambda_{HL} \times \exp(4\pi/\alpha_{eff}) \sim 10^{10}\ \mathrm{GeV} \times \exp(10^{20})$$

So, effectively gravity freezes above Λ_{HL}…..

What about graviton velocity?

- We do not have any symmetry reason why $c_{gravity} = c_{matter}$

- Corrections to IR-relevant terms in the gravitational action, such as sqrt(g)R ~ $h_{ij}\, \Delta\, h_{ij}$ are not going to be small at all! This terms determine the propagation speed of gravitational wave, that we cannot have arbitrary relative to *c* of matter.

- It looks entirely possible to have $c_{gravity} - c_{matter} \sim \Lambda_{UV}^4 / M_{Pl}^2 \Lambda_{HL}^2$ which may pose another huge tuning problem for HL gravity. Technical reason is that new Horava terms contribute not only to propagators (like in matter-gravity loops), but to vertices (triple graviton vertex) as well.

- May be additional protection mechanisms can be invoked (m-a-a-y be SUSY again, but I do not know how to implement it yet).

How well should $c_{graviton}$ match c_{matter} anyways?

- The bounds on the difference of matter/gravity propagation speed is highly asymmetric

$$-10^{-15} < c_{graviton} - c_{matter} < 0.01$$

(Moore, Nelson, 2000). The asymmetry comes from the Cerenkov radiation of gravitons. $dE/dt \sim G_N\, \omega_{max}{}^4 (n-1)^2$, as long as $n>1$.

Where n = c_matter/c_gravity ~ 1/(1-ε), and the conclusion is that ε has to be tiny, as $\omega_{max} \sim E_{max} \sim 10^{11}$ GeV.

In HL gravity n is modified differently,

$n \sim 1/(1 - \varepsilon + \omega^2/\Lambda_{HL}{}^2)$, and $n<1$ at $\omega < \Lambda_{HL}$. Therefore, if $\Lambda_{HL} < E_{max}$ all bounds are weakened by $(\Lambda_{HL}/E_{max})^4$, and strong constraints disappear, if say, $\Lambda_{HL} \sim 10^{-4} E_{max} \sim 10^7$ GeV, $\quad - 0.01 < c_{graviton} - c_{matter} < 0.01$

Part II: 1-loop effective action for aether

- Why does it matter? N. Afshordi (talks in 2012, this meeting) argues that cosmology in some sense impose stronger constraints on LV than anything else.

$$c_{\mu\nu}\overline{\psi}\partial_\mu\gamma_\nu\psi \longrightarrow \frac{\partial_\mu\phi\partial_\nu\phi}{\Lambda^4}\overline{\psi}\partial_\mu\gamma_\nu\psi \longrightarrow \Delta\mathcal{L}_{\phi,eff} \sim \frac{\Lambda_{UV}^4}{\Lambda^4}(\partial_\mu\phi\partial_\mu\phi)$$

If $d\phi/dt \neq 0$, and $d\phi/dt \sim (\rho_{cosm})^{1/2}$ then gigantic anisotropic contribution may develop.

On the other hand, if the "norm" of is fixed, then there is no problem, and also $d\phi/dt$ can be larger than $(\rho_{cosm})^{1/2}$

$$\mathcal{L}_\lambda = \lambda((\partial_\mu\phi\partial_\mu\phi) - \text{const}) \longrightarrow \lambda'((\partial_\mu\phi\partial_\mu\phi) - \text{const}'), \text{ and } T_{\mu\nu} \sim \Lambda g_{\mu\nu}$$

Lets' formulate everything in terms of $u_\mu = \frac{\partial_\mu\phi}{|\partial\phi|}$, where $|\partial\phi| = \sqrt{\partial_\mu\phi\partial_\mu\phi}$ which has symmetry $\phi \rightarrow c\,\phi$ symmetry, and see if 1-loop develops problems…. This is a sub-space of EA theories.

Separating fast and slow degrees of freedom

- The [simplified] aether Lagrangian is

$$S = \int d^4x[c_1(\partial_\mu u_\mu)^2 + c_2((u\cdot\partial)u_\mu)^2]$$

As usual, I separate things into "slow" and "fast" degrees of freedom, keep bilinear terms in ϕ_f, and full dependence on slow field. But in analogy with Euler-Heisenberg L, I take $\left|\partial\phi_s\right|$ = const

$$u_\mu = \frac{\partial_\mu\phi_s + \partial_\mu\phi_f}{|\partial\phi_s + \partial\phi_f|} = u^s_\mu + \frac{\partial_\nu\phi_f}{|\partial\phi_s|}\left(g_{\mu\nu} - u^s_\mu u^s_\nu\right) + \ldots$$

And $$\mathcal{L}_{\phi_s,\phi_f} = c_1\left[\frac{\partial_\mu\partial_\nu\phi_f}{|\partial\phi_s|}\left(g_{\mu\nu} - u^s_\mu u^s_\nu\right)\right]^2 + c_2\left[(u^s\cdot\partial)\frac{\partial_\nu\phi_f}{|\partial\phi_s|}(g_{\mu\nu} - u^s_\mu u^s_\nu)\right]^2$$

Does the resulting action in ϕ_s preserves the rescaling symmetry?

How reparametrization invariance can be preserved at one loop level

- Absorb some background $\frac{\partial_\mu \phi_f}{|\partial \phi_s|} \to \tilde{\phi}_f, \text{ if } |\partial \phi_s| = \text{const}$

fields into fast degrees of freedom, and then quantize (similar to back. g)

$$\frac{\partial_\mu \phi_f}{|\partial \phi_s|} \to \tilde{\phi}_f, \text{ if } |\partial \phi_s| = \text{const}$$

Bilinear terms in the new fast field is only u^{slow} dependent

$$\mathcal{L}_{\phi_s,\phi_f} \longrightarrow \mathcal{L}(u_s, \tilde{\phi}_f) = \tilde{\phi}_f (c_1 \Pi_{\alpha\beta} + c_2 u^s_\alpha u^s_\beta) \Pi_{\mu\nu} \partial_\alpha \partial_\beta \partial_\mu \partial_\nu \phi_f$$

This way the rescaling $\phi^s \to \phi^s C$ is preserved. So, in this [admittedly restricted] analysis I do not see any "drama" for aether developing

One can avoid "background gauge", and integrate out ϕ_f directly. Then one should remember "the measure" that Niayesh introduced in FI, and

$$\mathcal{L}_{\text{eff}} = (\Lambda'_{UV})^4 \log(|\partial \phi_s|)\Big|_{\text{measure}} - (\Lambda''_{UV})^4 \log(|\partial \phi_s|)\Big|_{\text{integation out of } \phi_{\text{f}}} = 0 \text{ if } \Lambda'_{UV} = \Lambda''_{UV}$$

So, I find that the loss of reparam. invariance does not have to happen

Part III: “LV” and transient effects

Suppose we are immensely ambitious and want not just “set limits on” LV, but have a decent shot at discovering something like LV, if it really exists…

You would need two things: 1. Some very sensitive [preferably lab-based] experiments. 2. Extreme cooperation from Mother Nature.

Most advanced in terms of the reach to LV parameters Lab experiments on LV typically test for the breakdown of rotational invariance. This was pioneered by Drever, Hughes (1980s). You look for $H_{eff} = b_{LV}$ Spin*direction, and best experiments probe $b_{LV} < 10^{-24}$ eV, which is still ~ 9 orders of magnitude short of Hubble scale.

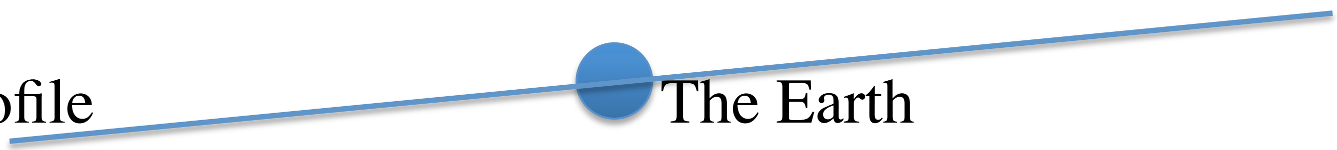
Recent experimental developments come hand-in-hand with the increase in accuracy of atomic magnetometers that can surpass 1 fT/(Hz)$^{1/2}$. *Are we using these experimental capabilities to the fullest?*

The idea of “transient LV”

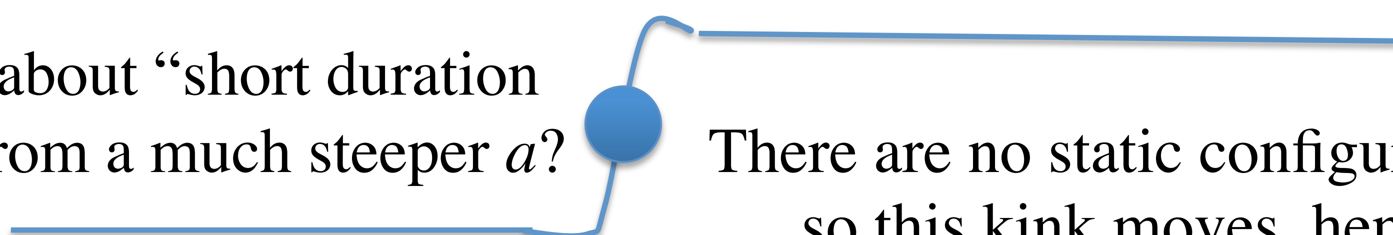
Typical “LV” experiment looks for $b_\mu \bar{\psi}\gamma^\mu\gamma_5\psi$
that one can generalize as interaction os a spin i to with the gradient of the scalar field a,

$$f_i^{-1}\partial_\mu a \bar{\psi}_i \gamma_\mu \gamma_5 \psi_i$$

a-profile



What about “short duration LV” from a much steeper a?



There are no static configurations, so this kink moves, hence *transient*

The Universe is filled with some substances DE, DM, and such field configurations may contribute. “LV” experiments can search for macroscopic size domain wall, strings, monopoles etc.

How do you know if you ran through a wall?

MP, Pustelny, Ledbetter, Jackson-Kimball, Gawlik, Budker, PRL 2013

- Many models of "New Physics" predict stable topological defects (domain walls, strings, monopoles). Physicists tend to discuss small size of these objects, e.g. $1/M_{GUT}$ across. But the spatial extent could be much larger, if a theory admits light excitations.
- If such objects are "scattered" in our galaxy, their velocity in the Solar system rest frame ~ 10^{-3} c, and the overall energy density must satisfy, $\rho_{\textbf{Domain walls}} < \rho_{\textbf{Dark Matter, Dark energy}}$
- Crucially, if such a defect passes through the Earth, how would you know?

You need a time-synchronized network of sensitive probes that can detect the event in different locations. Domain walls will be an especially suitable "target".

Signal of axion-like domain wall

Consider a very light complex scalar field with Z_N symmetry:

$$\mathcal{L}_\phi = |\partial_\mu \phi|^2 - V(\phi); \quad V(\phi) = \frac{\lambda}{S_0^{2N-4}} \left| 2^{N/2}\phi^N - S_0^N \right|^2$$

Theory admits several distinct vacua, $\phi = 2^{-1/2} S \exp(ia/S_0)$

$$S = S_0; \;\; a = S_0 \times \left\{ 0; \; 2\pi \times \frac{1}{N}; \; 2\pi \times \frac{2}{N}; \ldots \; 2\pi \times \frac{N-1}{N} \right\}$$

Reducing to the one variable, we have the Lagrangian

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - V_0 \sin^2\left(\frac{Na}{2S_0}\right)$$

that admits domain wall solutions

$$a(z) = \frac{4S_0}{N} \times \arctan\left[\exp(m_a z)\right]; \quad \frac{da}{dz} = \frac{2S_0 m_a}{N\cosh(m_a z)}$$

$$\rho_{\rm DW} \le \rho_{\rm DM} \Longrightarrow \frac{S_0}{N} \le 0.4 \text{ TeV} \times \left[\frac{L}{10^{-2}\text{ ly}} \times \frac{\text{neV}}{m_a}\right]^{1/2}$$

If on top of that *a*-field has the axion-type couplings, there will be a magnetic-type force on the spin inside the wall, $H_{\rm int} = \sum_{i=e,n,p} 2 f_i^{-1} \nabla a \cdot \mathbf{s}_i$

Network of Magnetometers

- For alkali magnetometers, the signal is

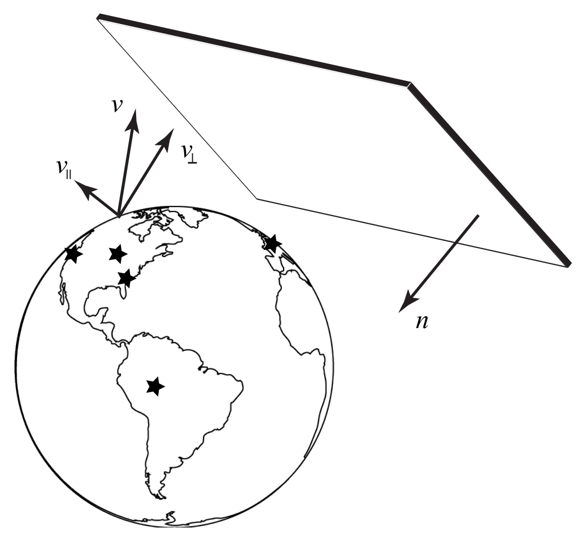
$$\mathcal{S} \simeq \frac{0.4\,\mathrm{pT}}{\sqrt{\mathrm{Hz}}} \times \frac{10^9\,\mathrm{GeV}}{f_{\mathrm{eff}}} \times \frac{S_0/N}{0.4\,\mathrm{TeV}} \times \left[\frac{m_a}{\mathrm{neV}}\frac{10^{-3}}{v_\perp/c}\right]^{1/2}$$

$$\leq \frac{0.4\,\mathrm{pT}}{\sqrt{\mathrm{Hz}}} \times \frac{10^9\,\mathrm{GeV}}{f_{\mathrm{eff}}} \times \left[\frac{L}{10^{-2}\ \mathrm{ly}}\frac{10^{-3}}{v_\perp/c}\right]^{1/2},$$

- For nuclear spin magnetometers, the tipping angle is

$$\Delta\theta = \frac{4\pi S_0}{v_\perp N f_{\mathrm{eff}}} \simeq 5\times 10^{-3}\,\mathrm{rad}\times\frac{10^9\,\mathrm{GeV}}{f_{\mathrm{eff}}}\times\frac{10^{-3}}{v_\perp/c}\times\frac{S_0/N}{0.4\,\mathrm{TeV}}$$

- It is easy to see that one would need >5 stations. 4 events would determine the geometry, and make predictions for the 5th, 6th etc…



* *Nobody has ever done this before*

Future direction

- Generalization to other types of defects, i.e. *strings and monopoles*.
- Working out a plausible theoretical framework that creates enough topological defects around us.
- Generalization to other types of interaction. Going from spin to frequency, means switching from *magnetometers* to *atomic clocks*.
- Involve networks of gravitational wave detectors. E.g. *LIGO* can be used because a transient event will create strain – detectable signal. Morphology of the signal is different – more work required.
- Experimental developments: GNOME proposal (Global Network of Magnetometers for studies of Exotic physics).

Conclusion

1. Wide separation of M_{Planck} and Λ_{HL} looks to me as the most promising and generic way of "sheltering" LV in the gravitational sector. This idea goes beyond HL gravity and can be applied to other models. Two naturalness problems remain in HL gravity: A. Vector modes are non-Lifshits – they furnish sensitivity to scales beyond, and we proposed how to "tame" them. B. Problem of $c_{graviton} = c_{matetr}$ remains

2. Radiative corrections in the aether sector is important to analyze, in order to see whether the reparametrisation invariance can be preserved at loop level. I see the way how 1-loop corrections can be made to respect $\phi \rightarrow$ const ϕ.

3. Transient effects (due to possible cosmological presence of macroscopic size topological defects) can be searched for with a slight "re-profiling" of the current LV experiments. [Modulo funding] a network of synchronized magnetomers is going to be created.