Status of Hořava Gravity

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Introduction

- Lorentz invariance is an empirical fact, but is it necessary?
- Constraints on LV in gravity far weaker than in matter.

Motivations for considering LV in gravity sector

- **Concrete framework for testing LI:**
  Æ [Gasperini'87; Jacobson, Mattingly'00]
- **Cosmological problems:**
  alternative to inflation [Magueijo '08],
  dark energy [Afshordi '08], dark matter [Mukohyama'09]
- **Quantum gravity:**
  NCFT [Douglas, Nekrasov '01], Hořava gravity [Hořava '09]

Hořava gravity: a self-consistent Lorentz violating gravity theory

- P.C. renormalisable
- Low energy limit compatible with observations
- LV in gravity sector (even only in the UV) can still impact the matter sector in the IR [no time for this]

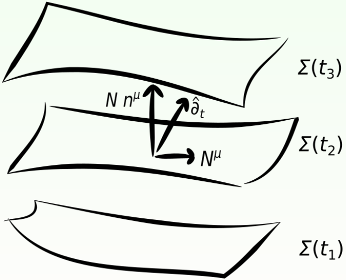
Symmetry

- Momentum dimensions from scaling: $[x] = -1$, $[t] = -3$.
- A compatible symmetry: foliation-preserving diffeos (FDiff)

$$t \to t'(t) \qquad \vec{x} \to \vec{x}'(t, \vec{x})$$

- ADM decomposition provides a natural parametrization

$$ds^2 = -N^2\, c^2 dt^2 + g_{ij}\, \left(dx^i + N^i dt\right) \left(dx^j + N^j dt\right)$$



Building blocks

$$\begin{array}{lcccc}
[\pounds_n] & = & 3 & \longleftrightarrow & \partial_t \\
[K_{ij}] & = & 3 & \longleftrightarrow & \dot{\phi} \\
[D_i] & = & 1 & \longleftrightarrow & \partial_i \\
[a_i] & = & 1 & \longleftrightarrow & \partial_i \phi \\
[R_{ij}] & = & 2 & \longleftrightarrow & \partial_i \partial_j \phi
\end{array}$$

$$K_{ij} \equiv \pounds_n g_{ij}$$

$$a_i \equiv \partial_i \log N$$

Non-projectable Hořava gravity
Building the Lagrangian

- $\underline{z = 3}$ Minimal model: All FDiff scalar terms up to $2\,z = 6$ spatial derivatives.

$$\mathcal{L}_{HG} = (1-\beta)K_{ij}K^{ij} - (1+\gamma)\,K^2 + \alpha\,a_i a^i + R + \frac{1}{M_*^2}\mathcal{L}_4 + \frac{1}{M_*^4}\mathcal{L}_6$$

with

$$\begin{aligned} \mathcal{L}_4 &= \alpha_1\,R\,D_i a^i + \alpha_2 D_i a_j D^i a^j + \beta_1 R_{ij}R^{ij} + \beta_2 R^2 + \ldots\,, \\ \mathcal{L}_6 &= \alpha_3 D_i D^i R\,D_j a^j + \alpha_4 D^2 a_i D^2 a^i + \beta_3 D_i R_{jk} D^i R^{jk} + \beta_4 D_i R D^i R + \ldots\,. \end{aligned}$$

[Blas, Pujolàs, Sibiryakov '09-'10]

- The preferred time coordinate: gauge symmetry is smaller. $t \to t'(t)$ not enough to remove 1 dof.
- 2 tensor gravitons + 1 scalar graviton.

Graviton propagation

- Dispersion relation for tensor perturbations

$$\omega_T^2 = \overbrace{\frac{1}{1-\beta}}^{c_T^2} k^2 - \beta_1 \frac{k^4}{M_*^2} - \beta_3 \frac{k^6}{M_*^4}$$

- Scalar perturbations $\omega_S^2 \sim f(k)/g(k)$, but in the UV it goes $\omega_S^2 \propto \frac{k^6}{M_*^4}$, and in IR

$$\omega_S^2 = \underbrace{\frac{(2-\alpha)(\gamma+\beta)}{\alpha(1-\beta)(2+3\,\gamma+\beta)}}_{c_S^2} k^2 + \mathcal{O}(k^4)$$

- At low energies ($k \ll M_*$), where higher derivative terms are suppressed, ∼GR is recovered for $\alpha = \beta = \gamma = 0$.

Constraints on the IR theory
Theoretical consistency

1. *Unitarity*: Scalar kinetic term should be positive:

$$\frac{2+3\,\gamma+\beta}{\gamma+\beta} > 0$$

2. *Perturbative stability*: Real propagation speeds $c_T^2, c_S^2 > 0$

$$0 < \alpha < 2\,, \qquad \beta < 1$$

3. *Perturbative regime in IR*: Theory strongly coupled above scale M_{SC}

$$M_{SC} \simeq \sqrt{\alpha}\, M_p \begin{cases} c_S^{3/2} & , c_S^2 < 1 \\ c_S^{-1/2} & , c_S^2 > 1 \end{cases}$$

[Kimpton, Padilla '10; AEG, Saravani, Sotiriou '17]

We assume that IR theory stays perturbative. If the UV terms become relevant at a lower scale, strong coupling does not kick in:

$$M_* < M_{SC}$$

[Blas, Pujolàs, Sibiryakov '10]

An upper bound on UV physics! We will come back to this relation later.

Constraints on the IR theory

Observational constraints

4. *BBN*: Scalar graviton rescales gravitational constant differently in cosmology and Newtonian limit. Compared to GR, weak interactions freeze out later/earlier, modification in primordial helium abundance $\Delta Y_p = 0.08(G_C/G_N - 1)$ [Carroll, Lim'04]

$$\left|\frac{\alpha + 3\,\gamma + \beta}{2 + 3\,\gamma + \beta}\right| < \frac{1}{8}$$

5. *Gravi-Cherenkov*: Preventing UHECR from decaying into gravitons imposes

$$c_T^2 - 1 = \frac{\beta}{1-\beta} > -10^{-15}\,,$$

[Moore, Nelson '01]

For scalar modes, calculation in progress. Results for Æ suggest a subluminal margin of 10^{-15} is allowed [Elliott, Moore, Stoica '05]. For our purposes, $c_S^2 - 1 > 0$ should be sufficiently accurate.

6. *ppN*: Preferred-frame effect parameters $|\alpha_1| < 10^{-4},\ |\alpha_2| < 10^{-7}$ [Will'06]

$$\left|\frac{4(\alpha - 2\,\beta)}{1-\beta}\right| < 10^{-4}\,, \quad \left|\left(\frac{\alpha - 2\,\beta}{2\,\alpha}\right)\left(1 - \frac{(\alpha - 2\,\beta)(1+\beta+2\,\gamma)}{(1-\beta)(\beta+\gamma)}\right)\right| < 10^{-7}$$

- Most studies pre-LIGO focused on $\alpha = 2\,\beta$ plane.

7. *Binary pulsars*: Scalar graviton
$\Rightarrow$ increased orbital decay
due to dipolar radiation.

Situation pre-GW170817 $\longrightarrow$

[Yagi, Blas, Barausse, Yunes '14]

$[\alpha, \beta \lesssim 10^{-2},\ \gamma \lesssim 10^{-1}]$

On the $\alpha = 2\,\beta$ plane, binary pulsars provide the strongest constraints

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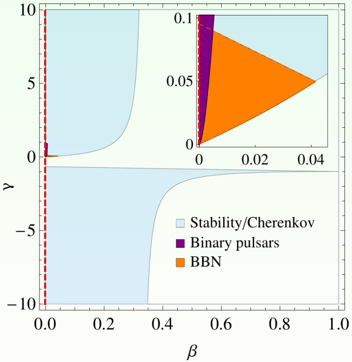

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Constraints on the IR theory

Aftermath of GW170817/GRB170817A

10 *GW*: GW with EM counterpart imposes a strong bound on c_T

$$-3 \times 10^{-15} \leq c_T - 1 \leq 7 \times 10^{-16}$$

[Abbott et al. '17]

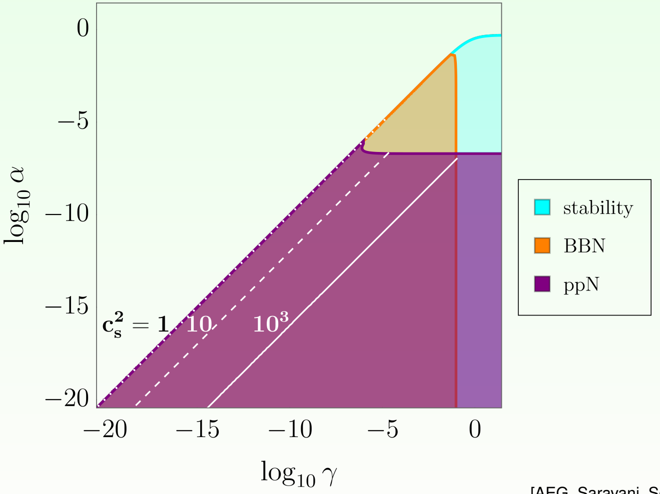
- For Hořava gravity this implies $|\beta| \lesssim 10^{-15}$
  [*c.f.* bounds from 2014, $\beta \lesssim 10^{-2}$]
- Although no direct impact on other bounds, the "conventional" $\alpha = 2\beta$ plane no longer relevant. Theory now confined to the $\beta = 0$ plane with a thickness of 10^{-15}.
- Bounds on modified dispersion:

$$\omega_T^2 = k^2 + \frac{1}{M_*^2} k^4 + \mathcal{O}(k^6)\,,$$

Mild lower bound from mergers: $M_* \gtrsim \mathrm{meV}$ [Yunes, Yagi, Pretorius'16]
Not competitive with sub-mm searches:

$M_* \gtrsim 10\,\mathrm{meV}$, see e.g.[Adelberger et al.'09]

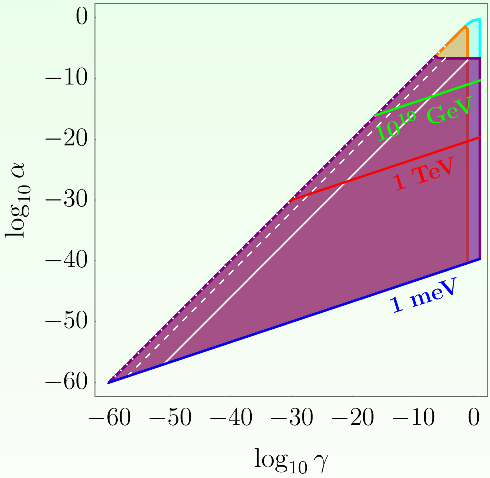
$\beta = 0$ surface



[AEG, Saravani, Sotiriou ’17]

Constraints on the IR theory

Including the strong coupling scale



- ***M_* linked to IR parameters***
  meV $< M_* < M_{SC}$
  $\Rightarrow$ Improving bounds on M_* would reduce the parameter space (or rule out the theory).
- Allowed parameter space is a finite region
- Post-GW bounds stronger, but c_S remains unconstrained. Even a mild constraint on c_S would rule out a vast portion of parameter space [scalar GW counterpart?].

[AEG, Saravani, Sotiriou ’17]

Conclusions

- Bounds presented here are independent of the model. We are testing the vacuum theory.
- The cancellation of ppN parameters for $\alpha = 2\,\beta$ is irrelevant in the aftermath of GW170817. Current bounds:

$$\alpha \lesssim 10^{-7}\;(\mathrm{ppN})\,,\qquad |\beta| \lesssim 10^{-15}\;(\mathrm{GW})\,,\qquad \gamma < 0.1\;(\mathrm{BBN})$$

- Relevant parameter range is $\beta = 0$ surface with a thickness of 10^{-15}
- Parameters further confined to a finite region, but c_S virtually unconstrained.
- New bounds on modified dispersions can impose further restrictions.
- Advantage: Information on UV scale from bounds on IR parameters!

Backup slides

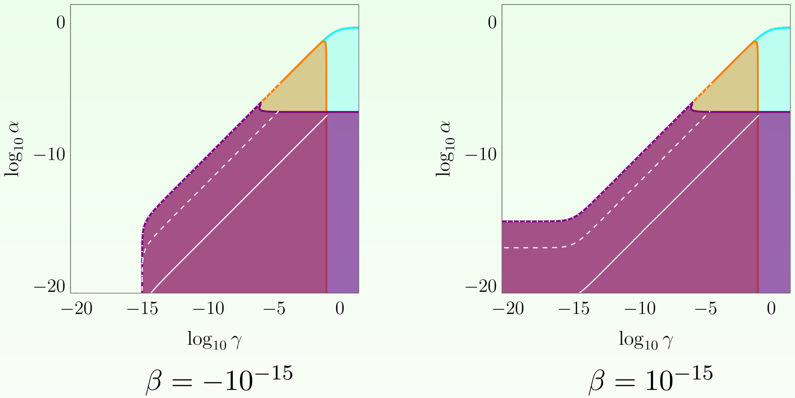
Is the $M_* < M_{SC}$ assumption necessary?

Why do we try to hide the strong coupling? Typical answer:
Potential renormalizability of Hořava gravity relies on power counting, and thus perturbative expansion. Strong coupling spoils it.

Does strong coupling imply loss of predictivity?

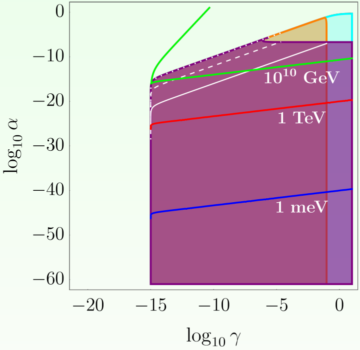
- Strong coupling at *intermediate scale*. Considering the running of coupling constants, theory can still be weakly coupled in UV e.g. [AEG, Mukohyama'11]
- If theory renormalizable, even in the SC regime, infinite # of coefficents in perturbative expansion will depend on finite # of parameters. $\Rightarrow$ SC does not imply loss of predictivity!
- This argument not verified as it requires non-perturbative tools/analyses

$\beta = \pm 10^{-15}$ surface

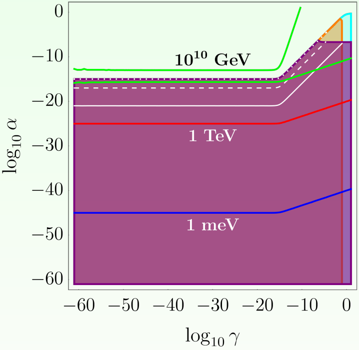


for $\beta \gg \alpha, \gamma \Longrightarrow c_S^2 \simeq \frac{\beta}{\alpha}$, i.e. independent of γ

$\beta = \pm 10^{-15}$ surface with M_{SC}



$\beta = -10^{-15}$



$\beta = 10^{-15}$