Title: Coming of Age for Horava Gravity: from Renormalizability to Black Holes

Date: Mar 22, 2012 01:00 PM

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Abstract: In this talk I will present evidence that accounting for the presence of hierarchies in string compactifications naturally leads to a UV sensitivity of dark matter in contrast to what is usually assumed. In particular, we will see that the existence of cosmological moduli may lead to a non-thermal history for the early universe and modifications in the primordial production of dark matter. If such a history were realized it would not only require probing new regions in dark matter searches, but also imply that a detection of dark matter would provide a direct probe on the early universe and the UV -- contrary to the thermal WIMP case. Regardless of the history of the early universe I will argue that if current string constructions are representative of more general models then all weak-scale dark matter would indeed be UV sensitive and would be a new prediction of string theory - falsifiable by experiment.

Coming of age for Hořava gravity: from renormalizability to black holes

Thomas P. Sotiriou
SISSA - International School for Advanced Studies

Brief review: T. P. Sotiriou, J. Phys. Conf. Ser. 283, 012034 (2011)
[arXiv: 1010.3218 [hep-th]]

Outline of the talk

The framework

Various versions of Horava-Lifshitz gravity

Consistency and IR viability

Properties and phenomenology

Open questions

Conclusions

Basic idea

Old problem: Can we make gravity renormalizable?

Possible solution: Add higher-order curvature invariants

- Higher order term contain higher order time derivatives
- This introduces ghosts!

Simple solution: give up Lorentz invariance. Then

- Higher order spatial derivatives without higher order time derivatives, i.e. no ghosts
- Renormalizable theory (at the power counting level)

Well, maybe not that simple...

Thomas P. Sotiriou - Perimeter Institute, March 22nd, 2012

Lifshitz scalar

Consider the action

$$S = \int dt dx^d \left(\dot{\phi}^2 - a_m \phi (-\Delta)^m \phi + g_n \phi^n \right)$$

It is then natural to choose the scaling dimensions

$$[dt] = [\kappa]^{-z} \qquad\qquad [dx] = [\kappa]^{-1}$$

which implies that

$$[\phi] = [\kappa]^{(d-z)/2} \qquad [a_m] = [\kappa]^{2(z-m)} \qquad [g_n] = [\kappa]^{d+z-n(d-z)/2}$$

So long as

$$z \geq d$$

the theory is power counting renormalizable.

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Lifshitz gravity

We first need to split spacetime into space and time by introducing a preferred foliation

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

Remaining symmetry: "foliation preserving diffeomorphisms"

- Time reparametrization: $t \to \tilde{t}(t)$
- Spacetime-dependent 3-diffeos: $x^i \to \tilde{x}^i(t, x^i)$

Most general action

$$S = \frac{M_{\rm pl}^2}{2}\int d^3x dt N\sqrt{g}\left\{K^{ij}K_{ij} - \lambda K^2 - V(g_{ij}, N)\right\}$$

P. Hořava, Phys. Rev. D 79, 084008 (2009)

General features

- The potential should be at least 6th order in spatial derivatives

$$V = -\xi R - \eta\, a_i a^i + \frac{1}{M_\star^2} L_4 + \frac{1}{M_\star^4} L_6 \qquad a_i = \partial_i \ln N$$

- There are 2 types of Lorentz-violating terms: those that come at lower order and those that come at higher order
- The theory propagates a scalar mode
- Generically there will be about 100 couplings!
- So far perfectly consistent and viable theory (with certain assumptions about matter coupling)

D. Blas, O. Pujolas and S. Sibiryakov, Phys. Rev. Let. 104, 181302 (2010)

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Reducing the number of couplings

Projectability: $N = N(t)$

- No terms with a_i

Detailed balance: $V = E^{ij}\mathcal{G}_{ijkl}E^{kl}$

$$E^{ij} = \frac{1}{\sqrt{g}}\frac{\delta W}{\delta g_{ij}} \qquad \mathcal{G}^{ijkl} = \frac{1}{2}\left(g^{ik}g^{jl} + g^{il}g^{jk}\right) - \lambda g^{ij}g^{kl}$$

- Only one 6th order term in the action!

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Projectability and detailed balance

$$S_{db} = \frac{M_{\rm pl}^2}{2}\int d^3x dt N\sqrt{g}\Big\{K^{ij}K_{ij} - \lambda K^2 - \frac{\alpha^4}{M_{\rm pl}^4}C_{ij}C^{ij}$$
$$+\frac{2\alpha^2\beta}{M_{\rm pl}^3}\frac{\epsilon^{ijk}}{\sqrt{g}}R_{il}\nabla_j R^l{}_k - \frac{\beta^2}{M_{\rm pl}^2}R^{ij}R_{ij}$$
$$+\frac{\beta^2}{4}\frac{1-4\lambda}{1-3\lambda}R^2 + \frac{\beta^2\zeta}{1-3\lambda}R - \frac{3\beta^2\zeta^2}{1-3\lambda}M_{\rm pl}^2\Big\}$$

Problems (obvious and specific):

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- Parity violations necessary
- Scalar excitation does not have 6th order spatial derivatives (renormalizability compromised)
- Negative and large cosmological constant!

Can be fixed by adding more terms but then more couplings!

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Projectability without detailed balance

$$S_p = \frac{M_{\rm pl}^2}{2}\int d^3x dt N\sqrt{g}\Big\{K^{ij}K_{ij} - \lambda K^2 - g_0\, M_{\rm pl}^2 - g_1 R - g_2\, M_{\rm pl}^{-2}\, R^2$$
$$-g_3\, M_{\rm pl}^{-2}\, R_{ij}R^{ij} - g_4\, M_{\rm pl}^{-4}\, R^3 - g_5\, M_{\rm pl}^{-4}\, R(R_{ij}R^{ij})$$
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D. Vernieri and T. P. Sotiriou, Phys. Rev. D 85, 064003 (2012)

- 12 couplings
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- Same IR limit as the general theory, except CC
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For scalar perturbations, the quadratic action is

$$S^{(2)} = \frac{M_{\rm pl}^2}{2}\int dt d^3x \left\{\frac{2(1-3\lambda)}{1-\lambda}\dot{\zeta}^2 + 2\xi\left(\frac{2\xi}{\eta}-1\right)\zeta\partial^2\zeta\right\}$$

For the scalar field to be stable and not a ghost one needs

$$\lambda < \frac{1}{3} \quad \vee \quad \lambda > 1\,, \qquad\qquad 2\xi > \eta > 0$$

It looks OK!

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The scalar mode - projectable case

The projectable case corresponds to $\eta \to \infty$

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- instability when $\lambda > 1 \quad \vee \quad \lambda < 1/3$
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T. P. Sotiriou, M. Visser and S. Weinfurtner, JHEP 0910, 033 (2009)

However, there is a claim that the mode is stable around de Sitter space

Y.Huang, A. Wang and Q. Wu, Mod. Phys. Lett. A25, 2267 (2010)

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Strong coupling - projectable version

The IR part of the projectable theory get strongly coupled at

$$M_{\rm sc} \propto (|\lambda - 1|)^{3/2} M_{\rm pl}$$

which seems to be unacceptably low!

C. Charmousis, G. Niz, A. Padilla and P. M. Saffin, JHEP 08, 070 (2009)
D. Blas, O. Pujolas and S. Sibiryakov, JHEP 10, 029 (2009)
K. Koyama and F. Arroja, JHEP 1003, 061 (2010)

Is strong coupling a blessing in disguise?

- Fast running to IR fixed point
- Recovery of GR ala Vainshtein

S. Mukohyama, Class. Quant. Grav. 27, 223101 (2010)
K. Izumi and S. Mukohyama, Phys. Rev. D 84, 064025 (2011)
A. E. Gumrukcuoglu, S. Mukohyama and A. Wang, arXiv:1109.2609 [hep-th]

But what about perturbative arguments about renormalizability?

Strong coupling

In the more general theory strong coupling persists with

$$M_{\rm sc} = f(|\lambda - 1|, \eta) M_{\rm pl}$$

Can be a large energy scale, but problem with renormalizability!

A. Papazoglou and T. P. Sotiriou, Phys. Lett. B 685, 197 (2010)
I. Kimpton and A. Padilla, JHEP 1007, 014 (2010)

Strong coupling can be avoided if

$$M_{\rm sc} > M_\star$$

D. Blas, O. Pujolas and S. Sibiryakov, Phys.Lett. B 688, 350 (2010)

But then potential tension with observations!

A. Papazoglou and T. P. Sotiriou, Phys. Lett. B 685, 197 (2010)

Hierarchy of scales

- Recovering Lorentz invariance is out of the question...
- Absence of preferred frame effects in the Solar system leads to constraints of the order

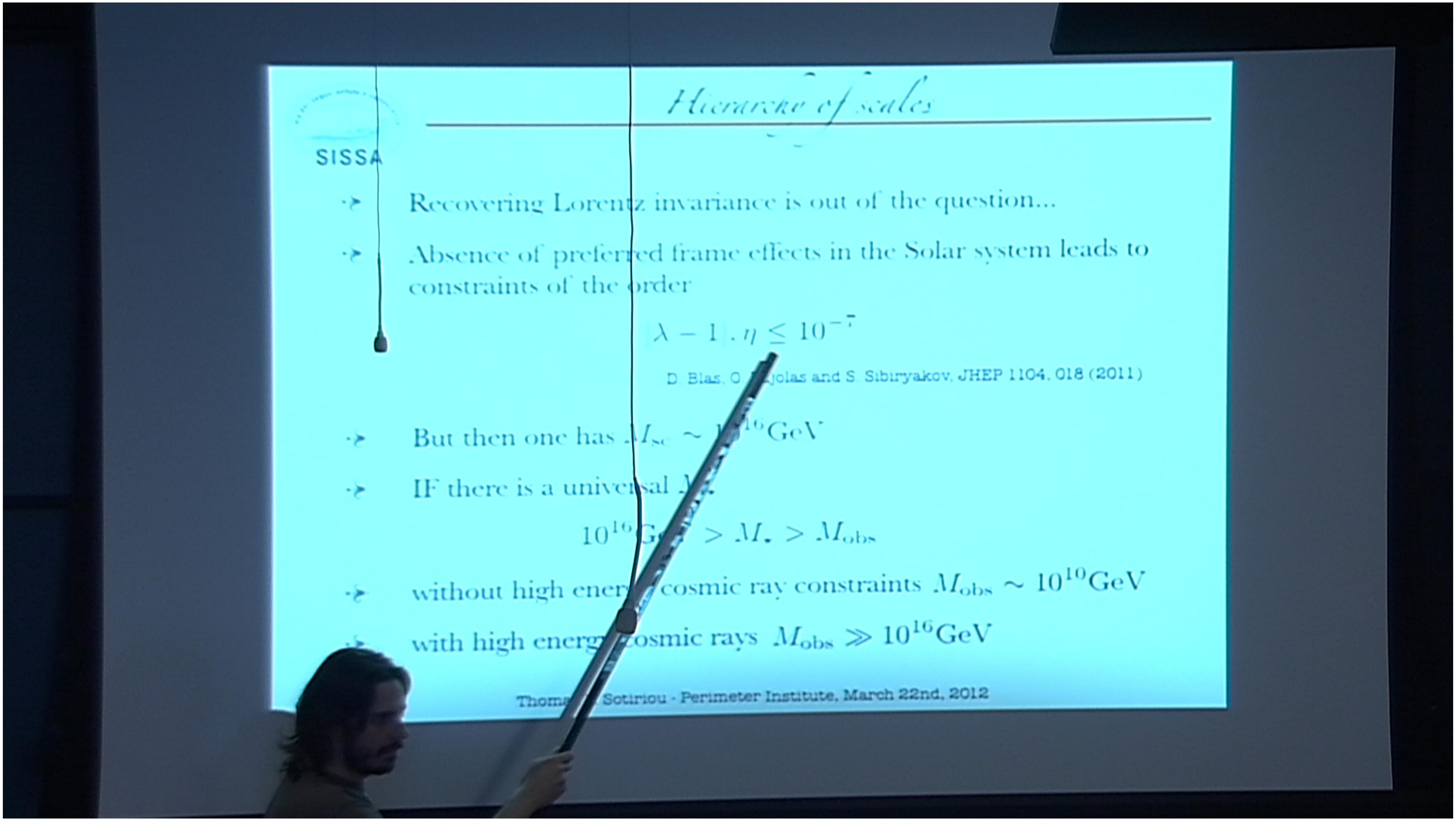
$$|\lambda - 1|, \eta \leq 10^{-7}$$

D. Blas, O. Pujolas and S. Sibiryakov, JHEP 1104, 018 (2011)

- But then one has $M_{\rm sc} \sim 10^{16}\text{GeV}$
- IF there is a universal $M_\star$

$$10^{16}\text{GeV} > M_\star > M_{\rm obs}$$

- without high energy cosmic ray constraints $M_{\rm obs} \sim 10^{10}\text{GeV}$
- with high energy cosmic rays $M_{\rm obs} \gg 10^{16}\text{GeV}$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Sotiriou - Perimeter Institute, March 22nd, 2012

Percolation of Lorentz violations

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But what about the matter sector and lower order operators?

- Different speeds for different fields in the IR, with logarithmic running!

R. Iengo, J. G. Russo and M. Serone, JHEP 0911, 020 (2009)

Possible ways out:

- Some extra symmetry, e.g. supersymmetry

S. Groot Nibbelink and M. Pospelov, Phys. Rev. Lett. 94, 081601 (2005)

- Assume Lorentz symmetry in matter and let the weak coupling to gravity (the Lorentz-violating sector) do the rest

M. Pospelov and Y. Shang, arXiv:1010.5249 [hep-th]

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Einstein-aether theory

T. Jacobson and D. Mattingly, Phys.Rev. D 64, 024028 (2001)

The action of the theory is

$$S_{æ} = \frac{1}{16\pi G_{æ}} \int d^4x \sqrt{-g}(-R - M^{\alpha\beta\mu\nu}\nabla_\alpha u_\mu \nabla_\beta u_\nu)$$

where

$$M^{\alpha\beta\mu\nu} = c_1 g^{\alpha\beta} g^{\mu\nu} + c_2 g^{\alpha\mu} g^{\beta\nu} + c_3 g^{\alpha\nu} g^{\beta\mu} + c_4 u^\alpha u^\beta g_{\mu\nu}$$

and the aether is implicitly assumed to satisfy the constraint

$$u^\mu u_\mu = 1$$

- Most general theory with a unit timelike vector field which is second order in derivatives
- Extensively tested and still viable

Thomas P. Sotiriou - Perimeter Institute, March 22nd, 2012

Imposing hypersurface orthogonality...

T. Jacobson, Phys. Rev. D 81, 101502 (2010)

Now assume

$$u_\alpha = \frac{\partial_\alpha T}{\sqrt{g^{\mu\nu}\partial_\mu T \partial_\nu T}}$$

and choose T as the time coordinate

$$u_\alpha = \delta_{\alpha T}(g^{TT})^{-1/2} = N\delta_{\alpha T}$$

Replacing in the action and defining one gets

$$S_{h.o.\,æ} = \frac{1}{16\pi G_H}\int dT d^3x\, N\sqrt{h}\,(K_{ij}K^{ij} - \lambda K^2 + \xi^{(3)}R + \eta a_i a^i)$$

with $a_i = \partial_i \ln N$ and the parameter correspondence

$$\frac{G_H}{G_{æ}} = \xi = \frac{1}{1-c_{13}} \qquad \lambda = \frac{1+c_2}{1-c_{13}} \qquad \eta = \frac{c_{14}}{1-c_{13}}$$

Imposing hypersurface orthogonality...

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$$S_{h.o.\,æ} = \frac{1}{16\pi G_H}\int dT d^3x\, N\sqrt{h}\,(K_{ij}K^{ij} - \lambda K^2 + \xi\, {}^{(3)}R + \eta a_i a^i)$$

with $a_i = \partial_i \ln N$ and the parameter correspondence

$$\frac{G_H}{G_æ} = \xi = \frac{1}{1-c_{13}} \qquad \lambda = \frac{1+c_2}{1-c_{13}} \qquad \eta = \frac{c_{14}}{1-c_{13}}$$

Covariantization and fine-tuning

T. P. Sotiriou, M. Visser and S. Weinfurtner, Phys. Rev. D 83, 124021 (2011)

Equivalence restricted to low energy action, but extendible

- Construct the most general action for ae-theory at a given order
- Lower order equivalence gives you the prescription of how to introduce the preferred foliation
- Go to the next order, identify the terms that match, set the rest of the couplings to zero/desired value
- Effectively, one can "covariantize" Horava gravity

But seen as a covariant theory, it would look severely fine tuned!

Pertinent questions

- Renormalization group flow: Do couplings get the values we want them to get?
- Quantization: some real quantum gravity predictions
- Causal structure: do we understand it?
- Black holes and singularities: are there black holes? Are singularities resolved?
- Matter coupling and relevant phenomenology
- Vacuum energy

Thomas P. Sotiriou - Perimeter Institute, March 22nd, 2012

Lower-Dimensional models

T. P. Sotiriou, M. Visser and S. Weinfurtner, Phys. Rev. D 83, 124021 (2011)

- 1+1 dimensions: No dynamics, identical to 1+1 ae-theory at all energies
- 2+1 dimensions: 1 scalar dof with same behaviour!

Most general action is 2+1 dimensions:

$$S = \frac{M_{\rm pl}^2}{2} \int d^2x\, dt\, N\sqrt{g}\Big\{K^{ij}K_{ij} - \lambda K^2 + \xi R + \eta\, a_i a^i + g_1\, R^2 + g_2\, \nabla^2 R + g_3\, (a^i a_i)^2 + g_4\, R a^i a_i + g_5 a^2 (\nabla\cdot a) + g_6 (\nabla \cdot a)^2 + g_7 (\nabla_i a_j)(\nabla^i a^j)\Big\}$$

A good toy model for some of the open questions

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A good toy model for some of the open questions

Black holes

Will there be black holes?

- There will be multiple horizons, which will not coincide with the metric horizon!
- These horizons will be penetrated by high momenta, so they are really artifacts of the low energy limit!

We looked (numerically) for black holes which are

- spherically symmetric and static,
- asymptotically flat,
- and have regular horizons

The exterior is not much different than that of GR black holes!

E. Barausse, T. Jacobson and T. P. Sotiriou, Phys. Rev. D 83, 124043 (2011)

Interior solution

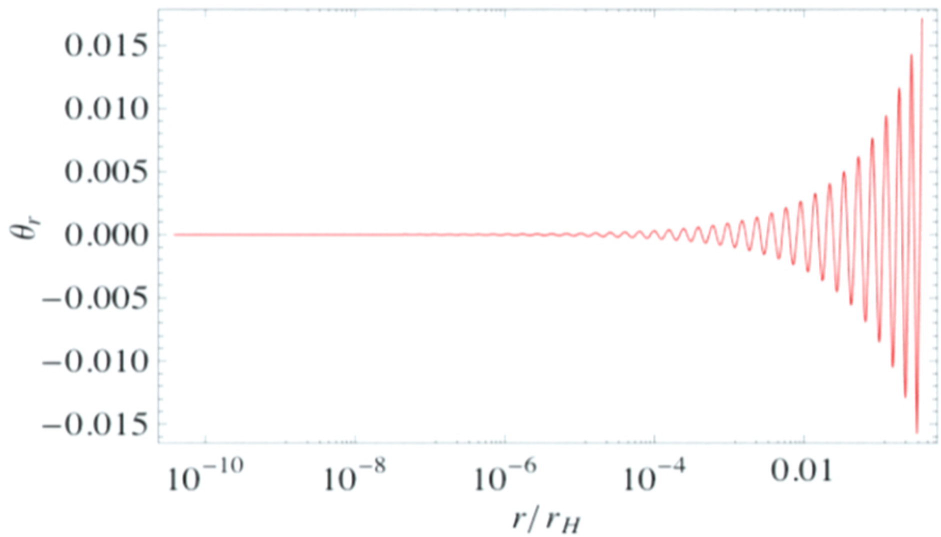
- Curvature singularity at the centre

We have also calculated the Lorentz factor of the aether as measured by the future directed observer orthogonal to $r = \text{const.}$ hypersurfaces

$$\gamma_r \equiv u^{\alpha}_{\text{obs}} u_{\alpha}$$

and the corresponding boost angle

$$\theta_r = \text{arccosh}\gamma_r$$



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Universal horizon?

- Signals cannot travel backwards in time
- Future and past direction are locally defined by the aether
- The aether is orthogonal to constant time hypersurfaces in the preferred foliation
- When the boost angle vanishes the aether is orthogonal to constant r hypersurfaces as well!
- Ultimate causal boundary for all signals!

The same result found perturbatively. However, this horizons seems to be unstable!

D. Blas and S. Sibiryakov, Phys. Rev. D 84, 124043 (2011)

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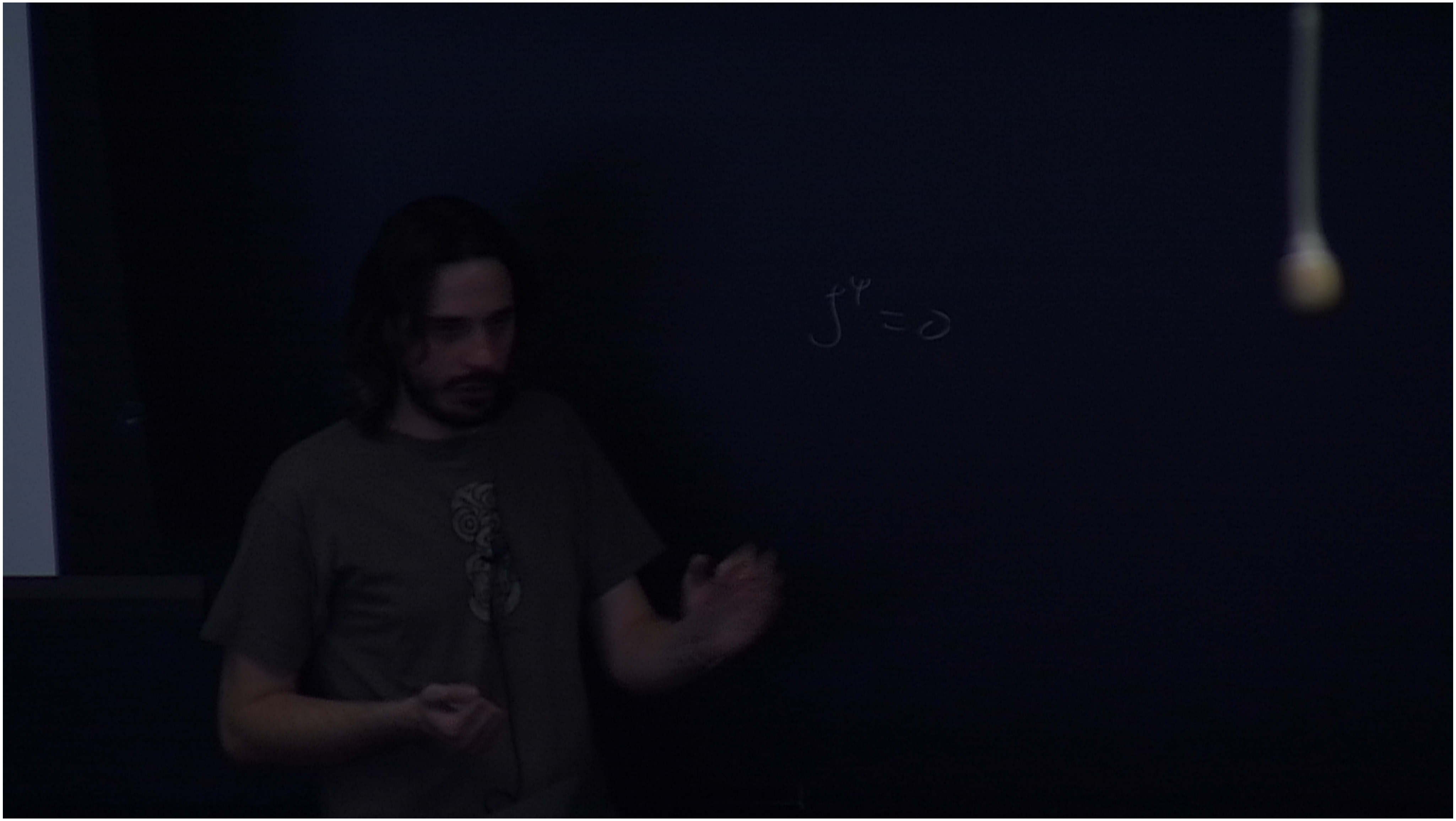
Conclusions and Prospects

- A well-defined QG candidate that makes testable predictions
- Major IR viability issues resolved (at least in some versions)
- Not so easy and fast to make progress, unknown territory
- Some very interesting predictions. I did not mention:
  - Cosmology: scale invariant spectrum, no horizon problem, ...

    S. Mukohyama, Class. Quant. Grav. 27, 223101 (2010)
  - Possible contact with discrete QG (CDT)

    P. Hořava, Phys. Rev. Lett. 102, 161301 (2009)
    T. P. Sotiriou, M. Visser and S. Weinfurtner, Phys. Rev. Lett. 107, 131303 (2011)
- Major challenges ahead: renormalization group flow, quantization
- What about quantum predictions?

Thomas P. Sotiriou - Perimeter Institute, March 22nd, 2012


$J^\psi = 0$