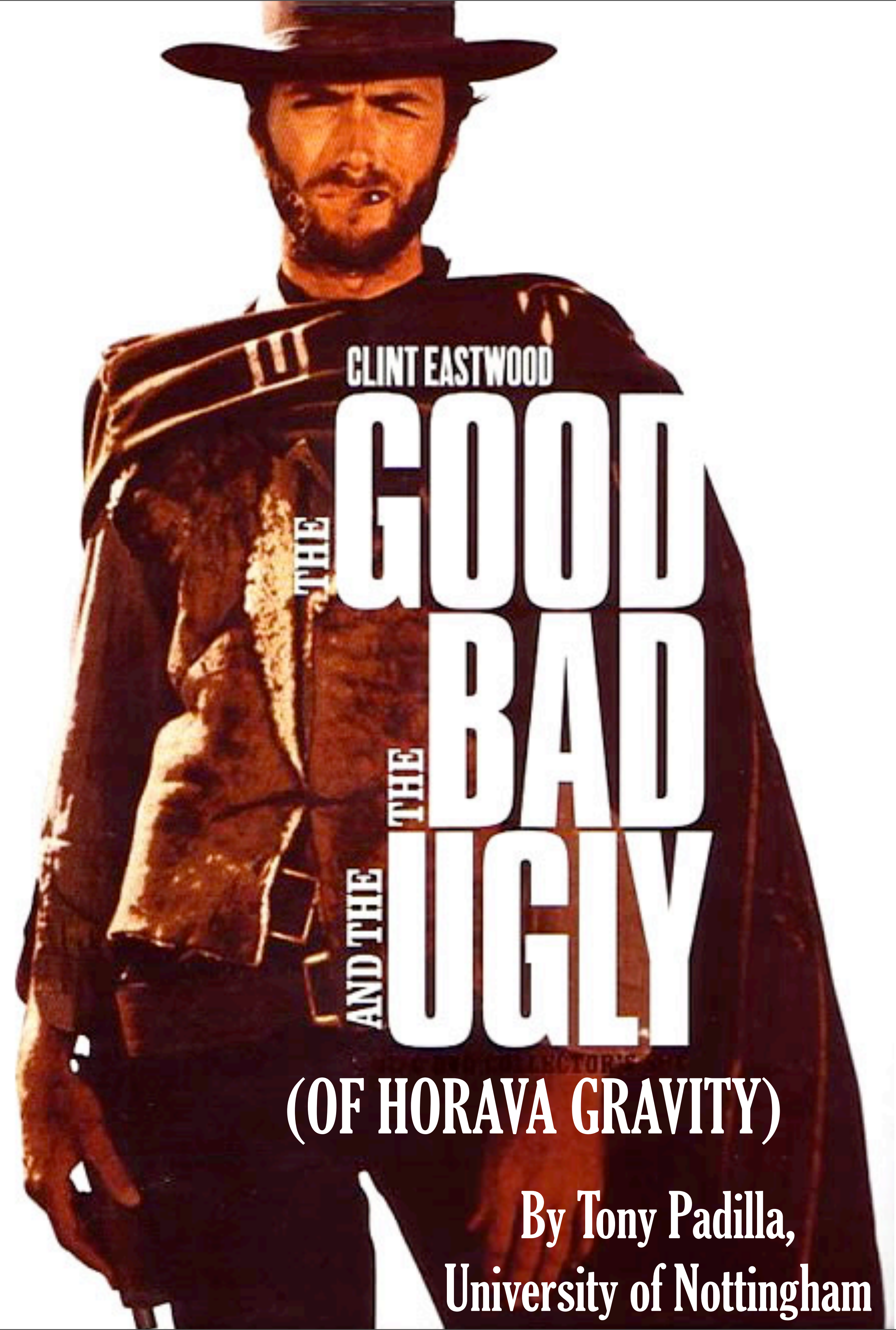

(OF HORAVA GRAVITY)

By Tony Padilla,
University of Nottingham

Outline

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The good: **Horava gravity as a quantum theory of gravity**

Horava PRD79:084008,2009, PRL102:161301,2009

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Charmousis, Niz, AP, & Saffin JHEP 0908:070,2009, Blas et al JHEP 0910:029,2009, Kimpton & AP 1003.5666 [hep-th]

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The ugly: **The so-called "heathly" extension**

Blas et al 0909.3525 [hep-th], Papazoglou & Sotiriou PLB685:197-200,2010, Blas et al Phys.Lett.B688:350-355,2010, Kimpton & AP 1003.5666 [hep-th]

THE GOOD

THE TROUBLE WITH GRAVITY

Gravitational coupling constant has negative mass dimension

$$[G_n] = -2$$

Propagator scales schematically as

$$\frac{1}{k^2}$$

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Gravity is perturbatively non-renormalisable

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Non-renormalisable scalar field theory

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Coupling constant has negative mass dimension

$$[\phi] = 1 \implies [\lambda] = -2$$

Propagator scales as $\frac{1}{k^2}$

Theory is non-renormalisable.

Relativistic higher derivative corrections

Improves the UV behaviour of the propagator. Schematically

$$\frac{1}{k^2} \to \frac{1}{k^2} + \frac{1}{k^2}\lambda k^4 \frac{1}{k^2} + \frac{1}{k^2}\lambda k^4 \frac{1}{k^2}\lambda k^4 \frac{1}{k^2} + \ldots = \frac{1}{k^2 - \lambda k^4}$$

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Canonically normalise in UV $\quad \phi \to \dfrac{\hat{\phi}}{\sqrt{|\lambda|}}$

Get new coupling with non-negative mass dimension

$$\hat{\lambda} = \lambda^{-2} \qquad \implies [\hat{\lambda}] = 4$$

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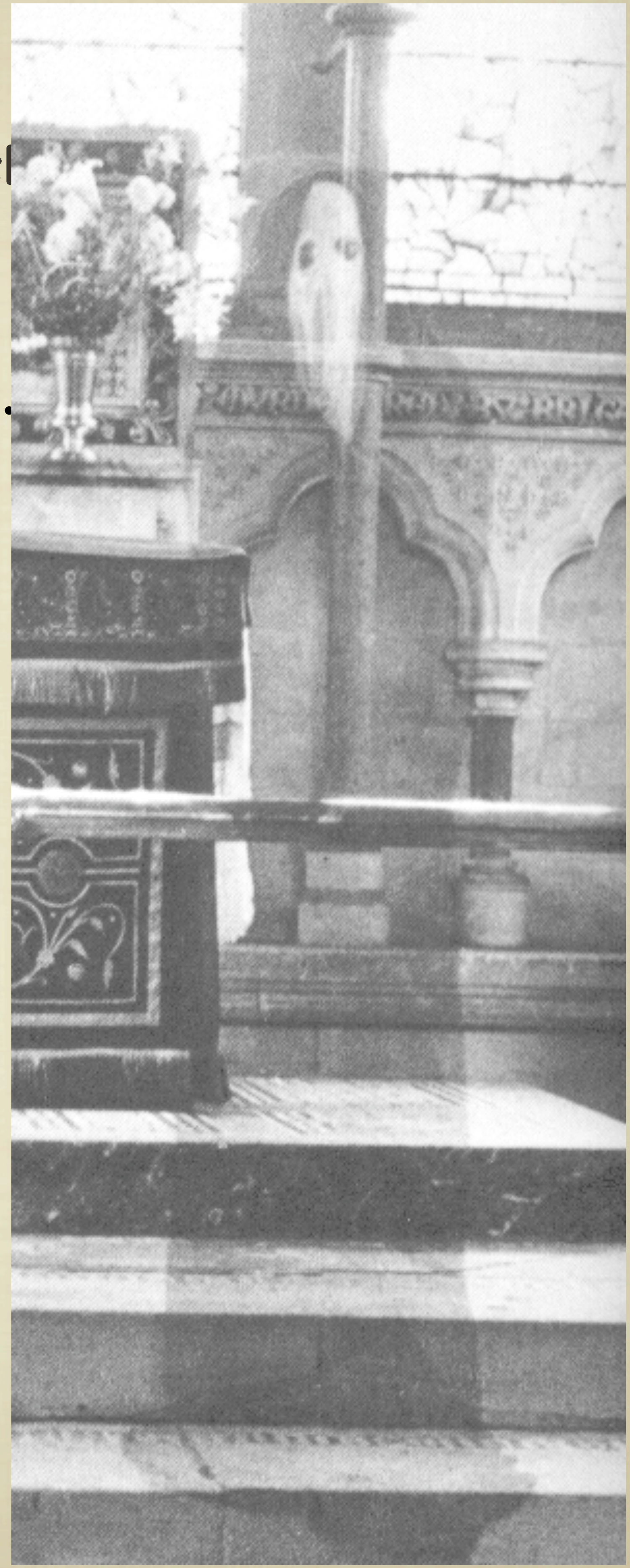

Abandon Lorentz invariance

Space and time scale anisotropically $[t] = -z, [x] = -1$

$$-\frac{1}{2}(\partial\phi)^2 \to \frac{1}{2}\dot{\phi}^2 - \frac{1}{2}\phi(-\Delta)^z\phi$$

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For z=3, theory is now renormalisable

Restoring Lorentz invariance

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Add a relevant operator of the form

$$\mathcal{L}_{rel} = +\frac{1}{2}c^2\phi\Delta\phi$$

Good UV physics unaffected. Lorentz invariance restored in IR, with an emergent speed of light c

Horava gravity

Horava (0901.3775)

Works in just the same way

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Abandon Lorentz invariance -- choose a preferred time, t and make an ADM split

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Action constructed from the following covariant objects

$$g_{ij} \qquad K_{ij} = \frac{1}{2N}(\dot{g}_{ij} - 2\nabla_{(i}N_{j)})$$

Could also include $\dfrac{\nabla_i N}{N}$ -- the "ugly"

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z=3 theory is "power counting" renormalisable

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Compare with GR

$$\mathcal{L}_{GR} = \frac{1}{16\pi G_n c}\sqrt{g}N(K_{ij}K^{ij} - K^2 + c^2 R)$$

Assume λ flows to 1 in the IR -- would appear as if we recover GR with an emergent speed of light c!

THE BAD

The not so bad

Large number of allowed potential terms

$$V(g_{ij}) = \nabla_k R_{ij} \nabla^k R^{ij} + \ldots$$

Horava borrows the principle of "detailed balance" from condensed matter to limit the number -- ruled out phenomenologically (see Charmoussis, Niz, AP and Saffin, 0905.2579)

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For scalar break BACKGROUND lorentz invariance --not so bad

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1. They decouple.

2. They become strongly coupled.

Quick detour -- Massive photons

Massless U(1) gauge theory

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 - J^\mu A_\mu$$

Photon has just two degrees of freedom due to gauge invariance

$$A_\mu \to A_\mu + \partial_\mu \phi$$

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$$A_\mu \rightarrow A_\mu + \partial_\mu \phi$$

Give photon a mass

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{2}m^2 A_\mu^2 + J^\mu A_\mu$$

Gauge invariance lost -- photon picks up an extra degree of freedom

What happens as m->0?

Stuckelberg trick

Artificially restore gauge invariance by the field redefinition $A_\mu = \tilde{A}_\mu + \partial_\mu \phi$

$$\mathcal{L} = -\frac{1}{4}\tilde{F}_{\mu\nu}^2 - \frac{1}{2}m^2\tilde{A}_\mu^2 - \frac{1}{2}m^2(\partial\phi)^2 - m^2\partial_\mu\phi\tilde{A}^\mu + J^\mu(\tilde{A}_\mu + \partial_\mu\phi)$$

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New action manifestly invariant under

$$\tilde{A}_\mu \rightarrow \tilde{A}_\mu + \partial_\mu\chi, \qquad \phi \rightarrow \phi - \chi$$

Stuckelberg scalar reveals additional degree of freedom.

Canonically normalise the Stuckelberg field

$$\phi \to \frac{1}{m}\hat{\phi}$$

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Current-scalar interaction diverges as m->0

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Stuckelberg field becomes strongly coupled in massless limit!

Back to Horava gravity

Horava action takes the form $S = S_{GR} + S_{UV} + S_m$

$$S_{GR} = \frac{1}{\kappa}\int dt d^3x \sqrt{g} N (K_{ij}K^{ij} - K^2 + c^2 R)$$

$$S_{UV} = \frac{1-\lambda}{\kappa}\int dt d^3x \sqrt{g} N K^2 + \text{terms higher order in spatial derivatives}$$

$S_m =$ matter action

Note: matter action need only be invariant under reduced diffeos, so usual energy-momentum not necessarily conserved.

A relativistic version of HG

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(0906.1201)

Instead of N, N_i and g_{ij} write everything in terms of full spacetime metric $\gamma_{\mu\nu}$ and unit normal to spacelike surfaces n_μ

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Really a scalar-tensor theory of gravity

Just Stuckelberg

Restoring diffeo invariance by letting slices go from

$$t = \text{constant} \rightarrow \phi(x,t) = \text{constant}$$

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Perturbative analysis on Minkowski background suggests that Stuckelberg field becomes strong coupled at a scale

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Strongly coupled at nearly all scales close to "GR" limit!

It gets worse...

On a general background, Stuckelberg action is

$$\delta S_\chi = \Lambda^2_{naive} \int dt d^3x \; \frac{1}{L^2} \dot{\chi} \vec{v} \cdot \vec{\nabla} \chi + (\vec{\nabla}^2 \chi)^2 + \dot{\chi} (\vec{\nabla}^2 \chi)^2$$

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where $\phi = \bar{\phi} + \chi$, $\vec{v}$ is a unit vector,

and L measures the characteristic scale of the background

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Minkowski limit (L->infinity) "GR" limit $(\lambda \to 1)$	STRONGLY COUPLED ON ALL SCALES!!!!

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It might not be, in principle.

QED becomes strongly coupled in UV due to Landau pole, but still renormalisable

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Completely ignores Stuckelberg field

The Stuckelberg action looks nothing like a power counting renormalisable action (ie no z=3 scaling in UV)

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Effective degrees of freedom of GR not applicable

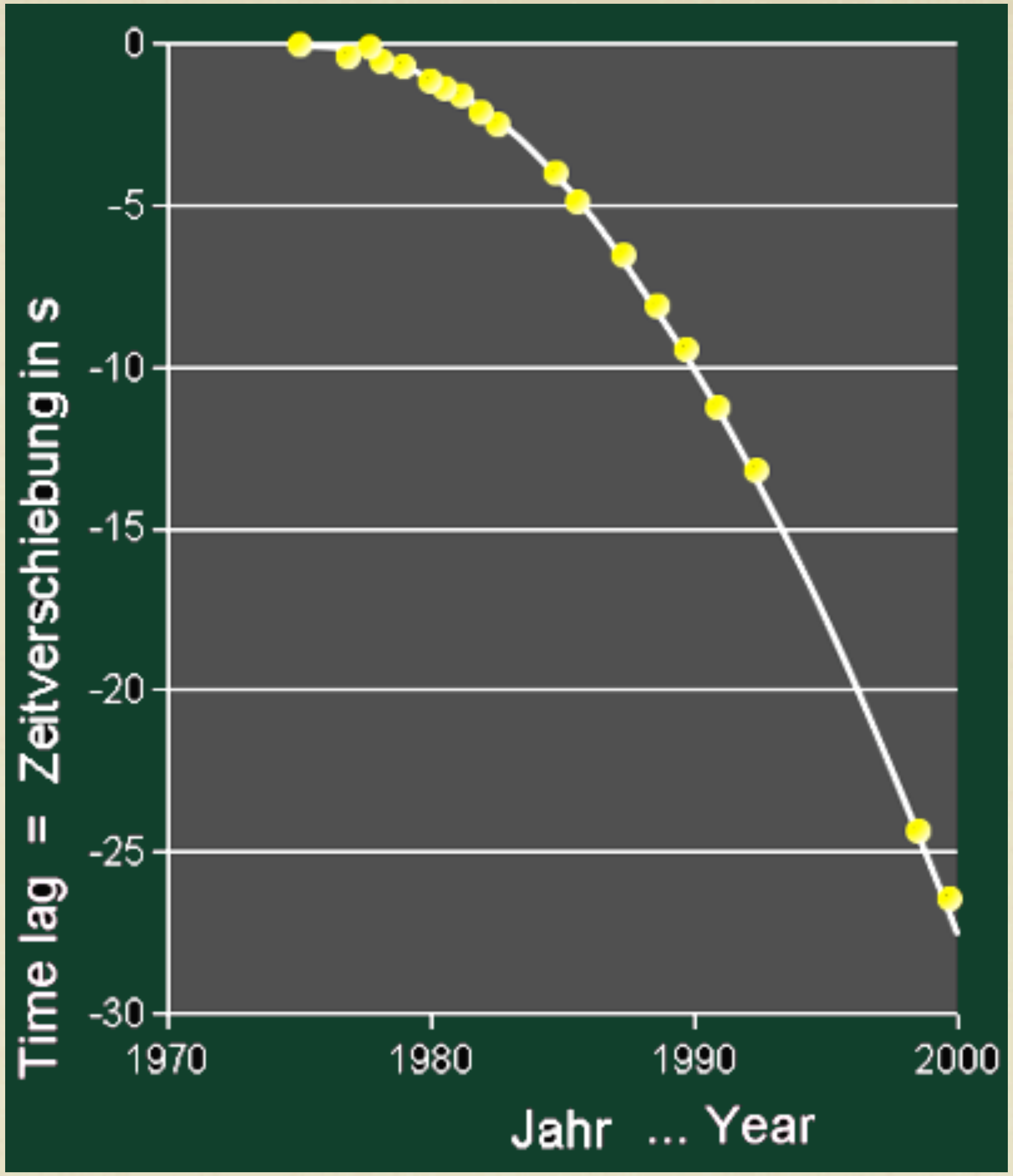
True d.o.fs are bound states of graviton and stuckelberg fields

Loss of predictive power, but is it really ruled out?

Yes!

Hulse-Taylor

Nobel prize 1993



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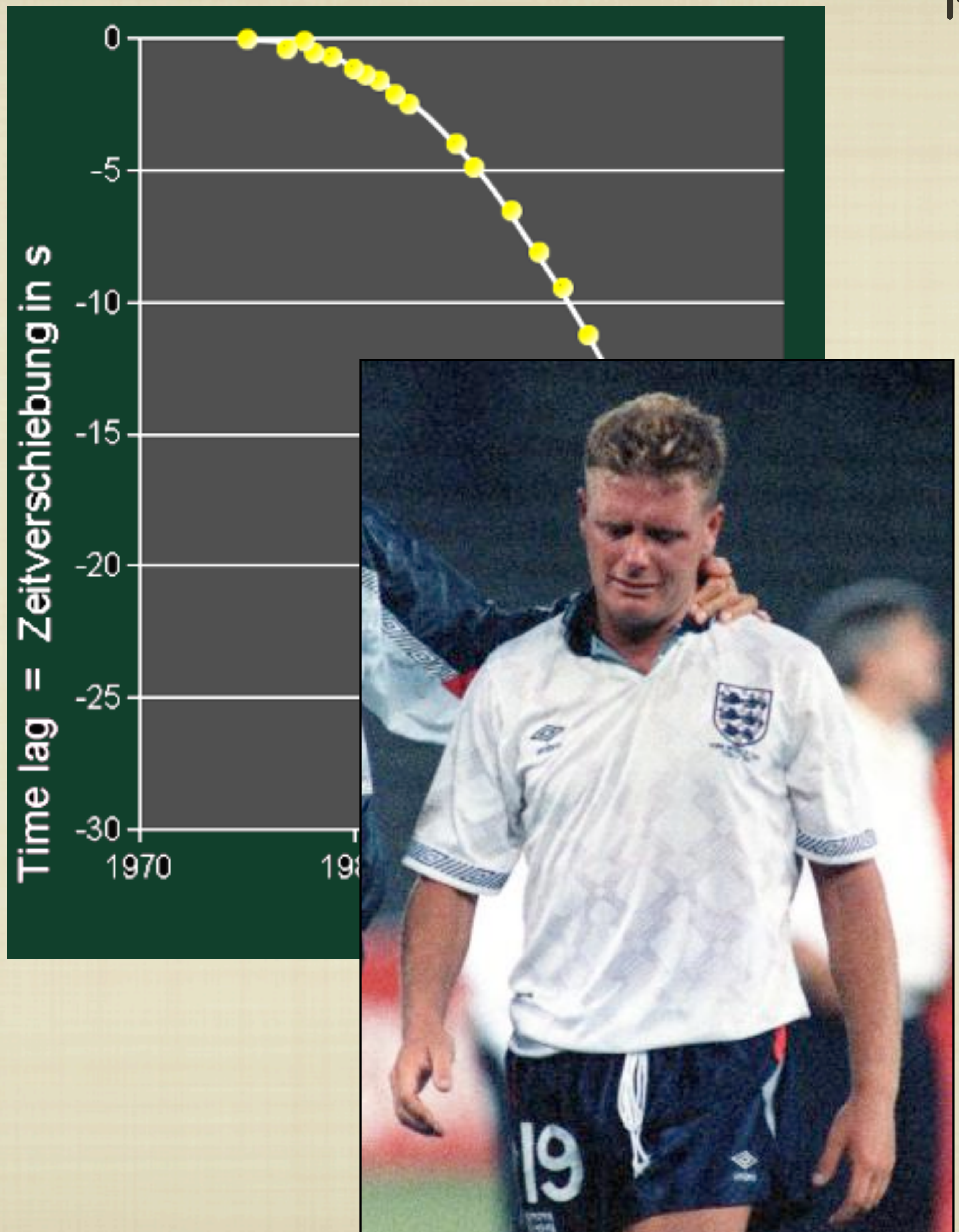

More trouble

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Kimpton & AP (1003.5666)

Coupling to matter

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It follows that

$$h_{\alpha\nu} \nabla_\mu T^{\mu\nu} = 0, \qquad \frac{1}{\sqrt{-\gamma}} \frac{\delta S_m}{\delta \phi} = -\frac{n_\nu \nabla_\mu T^{\mu\nu}}{\sqrt{-(\nabla\phi)^2}}$$

Unit normal $n_\mu = \dfrac{\partial_\mu \phi}{\sqrt{-(\partial\phi)^2}}$ **Spatial metric** $h_{\mu\nu} = \gamma_{\mu\nu} + n_\mu n_\nu$

Violations of Equivalence Principle

Non-conserved sources can carry Stuckelberg "charge"

$$\Gamma \sim \frac{\nabla T^{\mu\nu}}{T^{\mu\nu}} < H_0$$

eg slowly varying point mass $T^{\mu\nu} = M \exp(-\Gamma t)\delta^3(\vec{x})\mathrm{diag}(1,0,0,0)$

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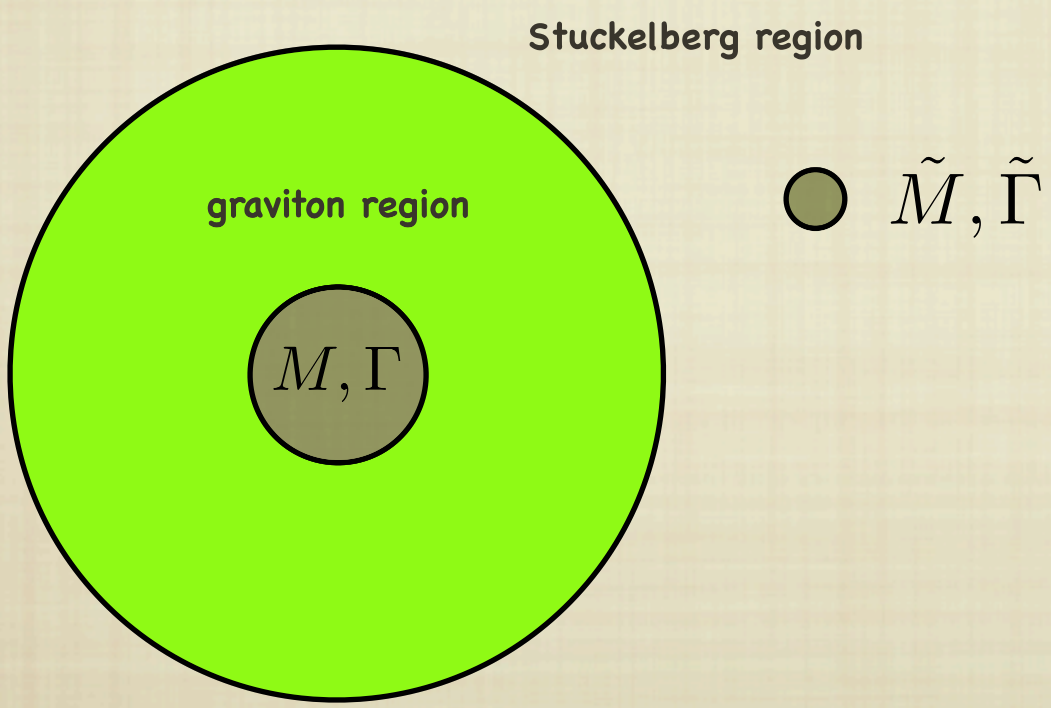

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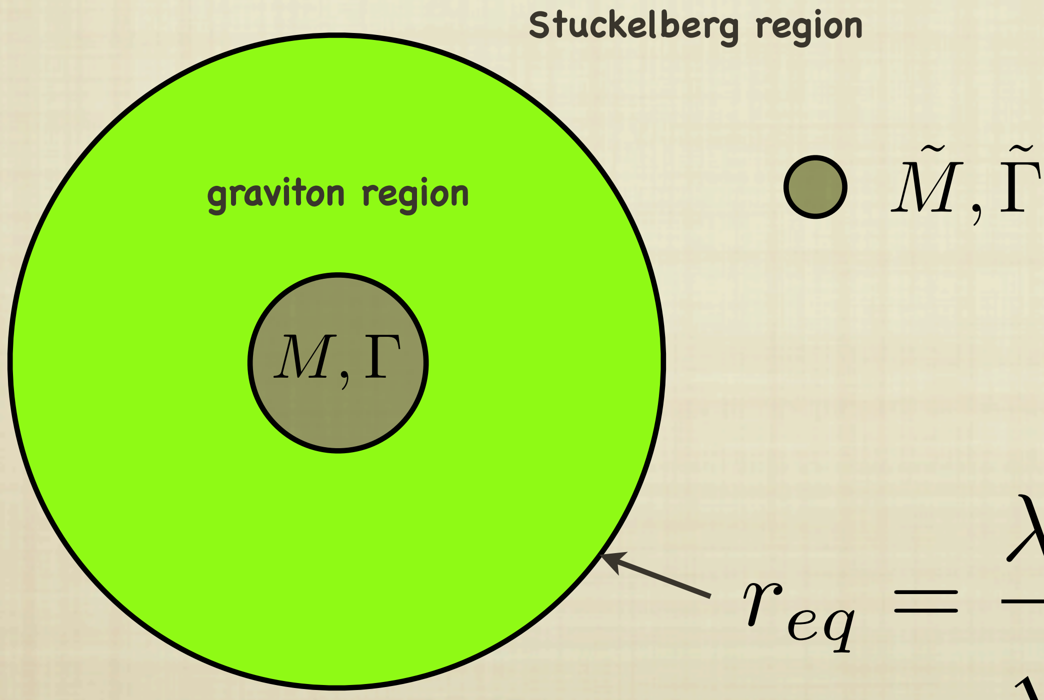

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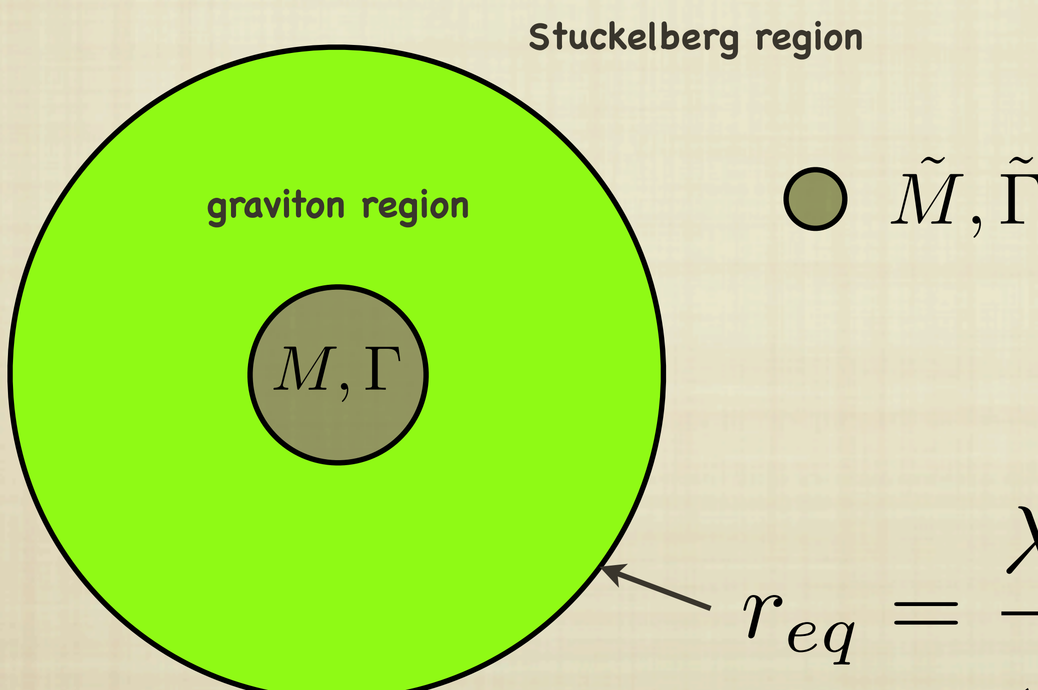

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EP violations can be large in Stuckelberg region

$$\sim \frac{\Gamma_1 - \Gamma_2}{\Gamma_1 + \Gamma_2}$$

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small Γ's Requires high scale of Lorentz violation -- problems for "healthy" extension

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Expect typical Γ to be suppressed by some power of the Lorentz symmetry breaking scale M_{UV}

THE UGLY

Horava gravity

Horava (0901.3775)

Works in just the same way

Abandon Lorentz invariance -- choose a preferred time, t and make an ADM split

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

Full diffeomorphism invariance broken. Replaced by "foliation preserving" diffeos

$$x^i \to \tilde{x}^i = \tilde{x}^i(x,t), \qquad t \to \tilde{t} = \tilde{t}(t)$$

Action constructed from the following covariant objects

$$g_{ij} \qquad K_{ij} = \frac{1}{2N}(\dot{g}_{ij} - 2\nabla_{(i}N_{j)})$$

Could also include $\dfrac{\nabla_i N}{N}$ **-- the "ugly"**

Why is strong coupling so bad...for renormalisability?

It might not be, in principle.

QED becomes strongly coupled in UV due to Landau pole, but still renormalisable

But...

Renomalisability of Horava gravity is based on dubious power counting argument. Relies on a wrongly inferred schematic form for the perturbative degrees of freedom

ie schematically $R_{ij} \rightsquigarrow \vec{\nabla}^2 h_{ij}$ in Horava action

Completely ignores Stuckelberg field

The Stuckelberg action looks nothing like a power counting renormalisable action (ie no z=3 scaling in UV)

"Healthy" Horava gravity

Blas et al 0909.3525 [hep-th]

Extend the original Horava action

$$\mathcal{L} = \frac{1}{\kappa}\sqrt{g}N(K_{ij}K^{ij} - \lambda K^2 + c^2 R) + \kappa\sqrt{g}N\nabla_k R_{ij}\nabla^k R^{ij} + \dots$$
$$+\frac{1}{\kappa}\sqrt{g}N\left[\alpha a_i a^i + \kappa(A_1 a_i \nabla^2 a^i + A_2 a_i a_j R^{ij} + \dots)\right.$$
$$\left. +\kappa^2(B_1 a_i \nabla^4 a^i + B_2 a_i a^i a_j a_k R^{jk} + \dots)\right]$$

where $a_i = \dfrac{\nabla_i N}{N}$

Alters UV scaling of Stuckelberg mode

“Healthy” Horava gravity

Dispersion relation for scalar/Stuckelberg mode

$$w^2 = c_s^2 k^2 + \frac{k^4}{M_A^2} + \frac{k^6}{M_B^4}$$

Low energy speed of sound $c_s^2 = \dfrac{\lambda - 1}{\alpha}$

Higher order Lorentz violation scales

$$M_A \sim \left(\frac{\alpha}{A}\right)^{1/2} M_{pl}, \qquad M_B \sim \left(\frac{\alpha}{B}\right)^{1/4} M_{pl}$$

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*** z=3 anisotropic scaling in UV ***

$$w^2 \propto k^6$$

Power counting renormalisability in Stuckelberg sector?

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Papazoglou & Sotiriou PLB685:197-200,2010,
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"Healthy" model challenged by EP tests

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Thanks!

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Initially, harder to rule out phenomenologically!

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Strong coupling as sound speed -> 0 (Blas et al 0906.3046, Koyama & Arroja 0910.1998)