Non-Relativistic Quantum Gravity

Oriol Pujolàs

CERN

0906.3046, JHEP 0910 029
0909.3525, PRL xxx xxx
0912.0550, PLB xxx xxx
+ in progress

with **Diego Blas,**
Sergey Sibiryakov

Fundaments of Gravity

Munich, April 14 2010

Motivation

Great interest/merit of Hořava's proposal:

explicit construction of NR gravity theories, possibly renormalizable

many possible applications/implications

In this talk, focus on application as QG for our 3+1 world:

can any version of NR QG possibly be phenomenologically viable?

- no ghosts, no instabilities
- weakly coupled, if possible
- pass observational tests
- recovery of Lorentz invariance in IR

Plan

- Anisotropic Scaling.
- NR Gravity. A healthy extension.
- Stückelberg Formalism
- Phenomenology & bounds
- Open issues & applications

Anisotropic Scaling

Hořava's proposal: 'Anisotropic Scaling'

In the UV, $w^2 \sim k^{2z}$ $z > 1$

$$G = \frac{1}{w^2 - k^2 - a\,k^{2z}}$$ => Loops are less divergent (& no ghosts)

2 quick ways to see how Anisotropic Scaling assists renormalizability

Anisotropic Scaling

1) Dimensional analysis

Free Kinetic term: $\int dt\, d^3x \left\{ (\dot{\phi})^2 + \frac{\phi \Delta^z \phi}{M^{2(z-1)}} \right\}$ invariant under

$$x \mapsto b^{-1} x$$
$$t \mapsto b^{-z} t$$
$$\phi \mapsto b^{\frac{3-z}{2}} \phi$$

To this, we add interactions:

For $z = 2$, $[\phi] = 1/2 \Rightarrow \phi^{10}$ is marginal (renormalizable)

For $z = 3$, ϕ^n relevant (super-renormalizable)

$\phi^n \Delta^3 \phi$ marginal (renormalizable)

Note:

$\phi \Delta \phi$ relevant => generated => chance to recover Lorentz Inv

Anisotropic Scaling

1) Dimensional analysis

Free Kinetic term: $\int dt\, d^3x \left\{ (\dot{\phi})^2 + \frac{\phi \Delta^z \phi}{M^{2(z-1)}} \right\}$ invariant under

$$x \mapsto b^{-1} x$$
$$t \mapsto b^{-z} t$$
$$\phi \mapsto b^{\frac{3-z}{2}} \phi$$

To this, we add interactions:

For $z = 2$, $[\phi] = 1/2 \;\Rightarrow\; \phi^{10}$ is marginal (renormalizable)

For $z = 3$, ϕ^n relevant (super-renormalizable)

$\phi^n \Delta^3 \phi$ marginal (renormalizable)

E.g.,
$$L = \Lambda^2 \left[(\dot{\phi})^2 + c^2(\phi)\, \phi \Delta \phi + d^2(\phi)\, \frac{\phi \Delta^2 \phi}{M^2} + e^2(\phi)\, \frac{\phi \Delta^3 \phi}{M^4} \right]$$

is renormalizable.

$$c(\phi) = c_0 + c_1 \phi + \ldots$$

Anisotropic Scaling

1) Dimensional analysis

Free Kinetic term: $\int dt\, d^3x \left\{ (\dot{\phi})^2 + \frac{\phi \Delta^z \phi}{M^{2(z-1)}} \right\}$ invariant under

$$x \mapsto b^{-1} x$$
$$t \mapsto b^{-z} t$$
$$\phi \mapsto b^{\frac{3-z}{2}} \phi$$

To this, we add interactions:

For $z = 2,\quad [\phi] = 1/2 \;\Rightarrow\; \phi^{10}$ is marginal (renormalizable)

For $z = 3,\quad \phi^n$ relevant (super-renormalizable)

$\phi^n \Delta^3 \phi$ marginal (renormalizable)

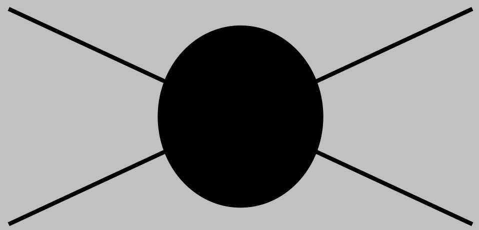
Note:

$(\ddot{\phi})^2$ irrelevant => not generated => no ghosts generated

Anisotropic Scaling

2) Power-counting argument

Count superficial degree of divergence of 1PI diagrams



$$\sim \left[\int dw\, d^3k \right]^L G(w,k)^I (k^{2z})^V$$

$$\delta \le (z+3)L - 2zI + 2zV = \boxed{(3-z)L + 2z}$$

$$(V - I + L = 1)$$

With $z=3$, all loop orders diverge equally -> Renormalizable

Anisotropic Scaling

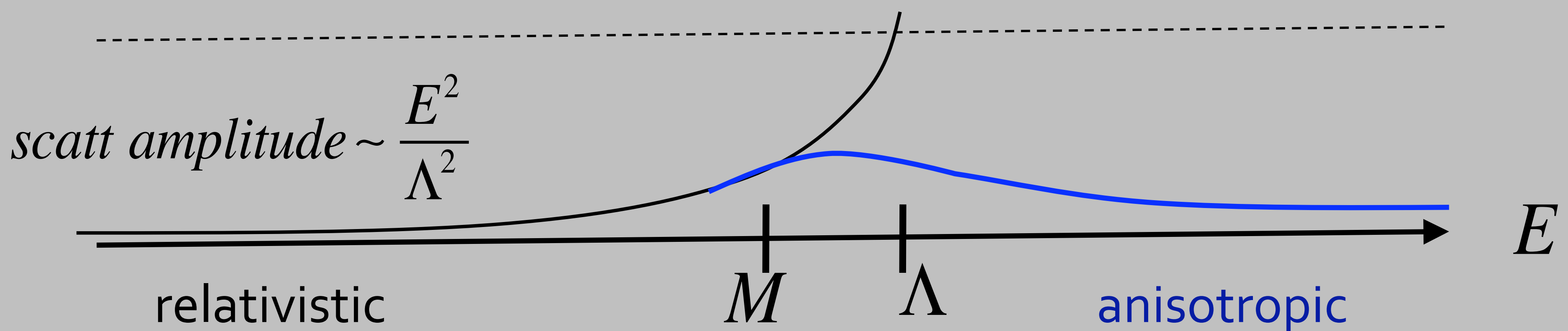
Hence, $$L = \Lambda^2\left[(\dot{\phi})^2 + c^2(\phi)\,\phi\Delta\phi + d^2(\phi)\,\frac{\phi\Delta^2\phi}{M^2} + e^2(\phi)\,\frac{\phi\Delta^3\phi}{M^4}\right]$$

is renormalizable.

$$c(\phi) = c_0 + c_1\phi + \ldots$$

Not only that…

It *may* be weakly coupled at all energy scales, if $M \leq \Lambda$



Anisotropic Scaling

Tree level Unitarity bound

disp relation $E = \mathcal{E}(p)$

Optical Thm:

$$2\mathrm{Im}\,\mathcal{M}(2\to 2) = \sum_n \left(\prod_{i=1}^{n}\int \frac{d^3 p_i}{2\mathcal{E}(p_i)}\right) |\mathcal{M}(2\to n)|^2\ \delta^4\left(\Sigma\, p_\mu\right)$$

$$\Rightarrow \qquad \left|\mathcal{M}(2\to 2)\right| \leqslant 16\pi\,\mathcal{E}'(p_0)\,\frac{E_0^2}{p_0^2}$$

Anisotropic Scaling

Tree level Unitarity bound

disp relation $E = \mathcal{E}(p)$

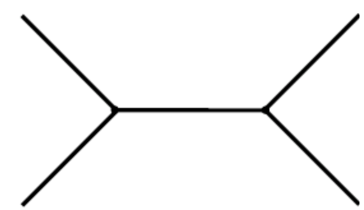
Optical Thm:

$$2\mathrm{Im}\,\mathcal{M}(2\to 2) = \sum_n \left(\prod_{i=1}^{n} \int \frac{d^3 p_i}{2\mathcal{E}(p_i)}\right) |\mathcal{M}(2\to n)|^2 \;\delta^4\left(\Sigma\, p_\mu\right)$$

$$\Rightarrow \qquad \left|\mathcal{M}(2\to 2)\right| \leqslant \left(\frac{E_0}{M_*}\right)^{3\frac{z-1}{z}}$$

Consider toy theory:

$$S = \alpha M_P^2 \int \mathrm{d}^4 x \left\{\left(\varphi + \sum_{n\geq 2} a_n \varphi^n\right)\left[-\Box + \frac{\Delta^3}{M_*^4}\right]\varphi\right\}$$



$$\sim \frac{E_0^2}{\alpha M_P^2} \leq \begin{cases} 1 & \text{for} \quad E_0 \leq M_* \\ \left(\frac{E_0}{M_*}\right)^2 & \text{for} \quad E_0 \geq M_* \end{cases} \Rightarrow M_* \leq \alpha M_P^2$$

Does the trick work for gravity ??

~~Lorentz Invariance~~ => (part of the) gauge group broken

=> additional degrees of freedom

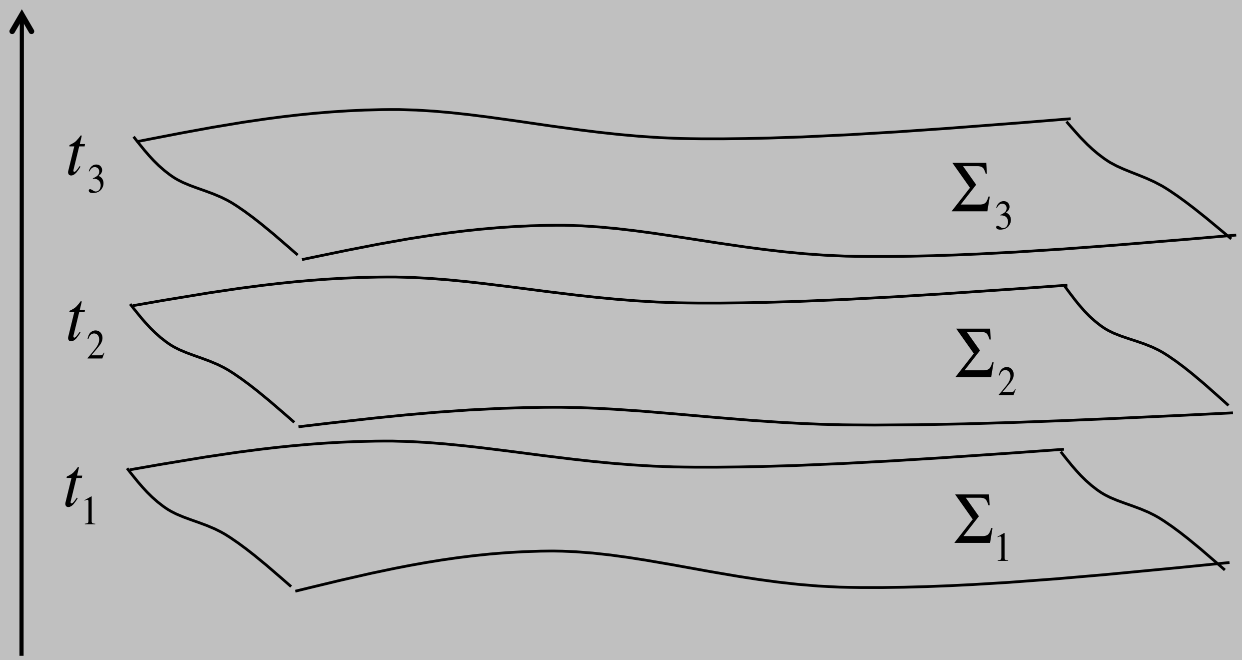
One needs to be extra-careful, or else extra d.o.f. pathological

Non-Relativistic Gravity

Hořava '09

Introduce preferred time coordinate t (back to "Absolute time")

Globally defined *Foliation* by spatial 3D surfaces:



Non-Relativistic Gravity

Hořava '09

Introduce preferred time coordinate t

3+1 split:
(ADM)

$$g_{\mu\nu} = \left(\begin{array}{c|c} N^2 - N^i N_i & N^i \\ \hline N^j & \gamma_{ij} \end{array}\right)$$

Foliation-preserving diffs

$$t \mapsto \hat{t}(t)$$

$$x \mapsto \hat{x}(t,x)$$

covariant objects:

$$\begin{cases} K_{ij} \equiv \dfrac{1}{2N}\left(\dot{\gamma}_{ij} - \nabla_i N_j - \nabla_j N_i\right) \\ a_i \equiv \dfrac{\partial_i N}{N}\,, \qquad R^{(3)}_{ijkl}[\gamma_{ij}]\ \ldots \end{cases}$$

Non-Relativistic Gravity

Hořava '09

Action: $$S = M_P^2 \int d^3x\,dt\, N\sqrt{\gamma}\left[K_{ij}K^{ij} - \lambda (K_i^i)^2 - V\left(\gamma_{ij}, N\right)\right]$$

$$V\left(\gamma_{ij}, N\right) = R_{(3)} + \frac{R_{(3)}^2 + \ldots}{M_P^2} + \frac{R_{(3)}^3 + \ldots}{M_P^4}. \qquad (z = 3)$$

covariant objects:

$$\begin{cases} K_{ij} \equiv \dfrac{1}{2N}\left(\dot{\gamma}_{ij} - \nabla_i N_j - \nabla_j N_i\right) \\ a_i \equiv \dfrac{\partial_i N}{N}, \qquad R^{(3)}_{ijkl}[\gamma_{ij}] \ \ldots \end{cases}$$

Non-Relativistic Gravity

Hořava '09

Blas OP Sibiryakov '09

Action: $$S = M_P^2 \int d^3x dt\, N\sqrt{\gamma}\left[K_{ij}K^{ij} - \lambda (K_i^i)^2 - V\left(\gamma_{ij}, N\right)\right]$$

$$V\left(\gamma_{ij}, N\right) = R_{(3)} + \alpha a_i a^i + \frac{R_{(3)}^2 + a^4 + \dots}{M_P^2} + \frac{R_{(3)}^3 + a^6 + \dots}{M_P^4}.$$

covariant objects:

$$\begin{cases} K_{ij} \equiv \dfrac{1}{2N}\left(\dot{\gamma}_{ij} - \nabla_i N_j - \nabla_j N_i\right) \\ a_i \equiv \dfrac{\partial_i N}{N}, \qquad R^{(3)}_{ijkl}[\gamma_{ij}] \ \dots \end{cases}$$

Non-Relativistic Gravity

Hořava '09

Blas OP Sibiryakov '09

Action: $$S = M_P^2 \int d^3x\,dt\, N\sqrt{\gamma}\left[K_{ij}K^{ij} - \lambda (K_i^i)^2 - V\left(\gamma_{ij}, N\right)\right]$$

$$V\left(\gamma_{ij}, N\right) = \quad R_{(3)} + \alpha\, a_i a^i + \frac{R_{(3)}^2 + a^4 + \ldots}{M_P^2} + \frac{R_{(3)}^3 + a^6 + \ldots}{M_P^4}.$$

scalar mode: $$L_0^{(2)} = M_P^2\left[\frac{3\lambda - 1}{\lambda - 1}(\dot{\psi})^2 + \psi c_0^2 \Delta \left(\frac{1 + A_1 \frac{\Delta}{M} + \ldots + A_1 \frac{\Delta^4}{M^4}}{1 + B_1 \frac{\Delta}{M} + \ldots + B_2 \frac{\Delta^2}{M^2}}\right)\psi\right]$$

Original proposals	
$\alpha = 0$ 	$\alpha \to \infty$ Projectable, $N(t)$ 

$$c_0^2 = \frac{2 - \alpha}{\alpha}\frac{\lambda - 1}{3\lambda - 1} > 0$$

$$\boxed{\Rightarrow 0 < \alpha < 2}$$

Non-Relativistic Gravity

Hořava '09

Blas OP Sibiryakov '09

Action: $$S = M_P^2 \int d^3x\,dt\, N\sqrt{\gamma}\left[K_{ij}K^{ij} - \lambda (K_i^i)^2 - V\left(\gamma_{ij}, N\right)\right]$$

$$V\left(\gamma_{ij}, N\right) = \quad R_{(3)} + \alpha\, a_i a^i + \frac{R_{(3)}^2 + a^4 + \ldots}{M_P^2} + \frac{R_{(3)}^3 + a^6 + \ldots}{M_P^4}.$$

tensor modes: $$L_2^{(2)} = M_P^2\left[(\dot{h}_{TT})^2 + h_{TT}\left(1 + \tilde{A}_1\frac{\Delta}{M^2} + \tilde{A}_2\frac{\Delta^2}{M^4}\right)h_{TT}\right]$$

∃ choice of parameters
for which $z = 3$ in the UV

good UV behaviour *not* spoiled

Stückelberg formalism

Stückelberg formalism

Massive QED:

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

2 + 1 d.o.f.

Gauge invariance *restored* by introducing the Stückelberg field ϕ

$$A_\mu = \hat{A}_\mu - \partial_\mu \phi$$

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

The Lagrangian is invariant under

$$\hat{A}_\mu \to \hat{A}_\mu + \partial_\mu \varepsilon$$

$$\phi \to \phi + \varepsilon$$

Stückelberg formalism

Isolating the scalar mode: $S = S_{GR} + S[\phi;\alpha,\lambda ...]$ in covariant form

ϕ defines the Foliation structure: $\langle \phi \rangle = t$

Shortcut: unbroken $t \to \hat{t}(t)$ symmetry implies

Quantum Chrono-Dynamics (QCD) !!

$\boxed{\phi \to f(\phi) \quad \text{internal symmetry}}$

Invariants: $u_\mu \equiv \dfrac{\partial_\mu \phi}{\sqrt{(\partial\phi)^2}}$ and its derivatives

$$S[\phi] = M_P^2 \int d^4x \sqrt{-g} \left\{ (\lambda - 1)\left(\nabla_\mu u^\mu \right)^2 + \alpha \, (u^\nu \nabla_\nu u_\mu)^2 + ... \right\}$$

In the *unitary gauge* $(\phi = t)$ the action coincides with previous form

Stückelberg formalism

Eg, $(\lambda - 1)$ term is:

$$S[\phi] = (\lambda - 1) M_P^2 \int d^4x \sqrt{-g} \, \frac{1}{(\partial\phi)^2} \left(\Box\phi - \frac{\partial^\mu\phi \, \partial^\nu\phi}{(\partial\phi)^2} \nabla_\mu \nabla_\nu \phi \right)^2 + \ldots$$

Subtlety: higher covariant derivatives, yet no ghosts!

the e.o.m. contains, eg:

$$\left[g^{\mu\nu} - u^\mu u^\nu \right]\left[g^{\rho\sigma} - u^\rho u^\sigma \right] \nabla_\mu \nabla_\nu \nabla_\rho \nabla_\sigma \phi \ + \ldots = 0$$

Always reduce to purely spatial derivatives

in the preferred frame defined by $u_\mu \equiv \dfrac{\partial_\mu \phi}{\sqrt{(\partial\phi)^2}}$

Cauchy problem well posed with less initial data in the preferred frame

Similarly, pc-renormalizability not explicit (but present)

Stückelberg formalism

Around flat space and $\phi = t$, let us study the scalar mode $\phi = t + \chi(t,x)$

$$S[\chi] = M_P^2 \int d^4x \left[\alpha\,(\partial_i \dot{\chi})^2 - (\lambda - 1)\,(\Delta\chi)^2 \right]$$

Disp. relation at low energies $\quad w^2 = \dfrac{\lambda - 1}{\alpha} k^2 + \ldots$

Stückelberg formalism

Around flat space and $\phi = t$, let us study the scalar mode $\phi = t + \chi(t,x)$

$$S[\chi] = M_P^2 \int d^4x \left[\alpha (\partial_i \dot{\chi})^2 - (\lambda - 1)(\Delta\chi)^2 - (\lambda - 1)\dot{\chi}(\Delta\chi)^2 + \ldots \right]$$

Disp. relation at low energies $w^2 = \dfrac{\lambda - 1}{\alpha} k^2 + \ldots$

Naive strong coupling scale $\Lambda \approx \sqrt{|\lambda - 1|}\, M_P$

If High. deriv. terms suppressed by $M_* \leq \Lambda \quad \Rightarrow$ NO strong coupling!

Projectable Horava ($\alpha \to \infty$): $c^2 < 0$

slow instabilities $\Rightarrow \Lambda \simeq (100m)^{-1} \Rightarrow$ either $\begin{cases} \text{strong coupl} \\ \text{or ruled out} \end{cases}$

(Arroja Koyama, Blas OP Sibiryakov)

Stückelberg formalism

Reparametrization symmetry $\phi \to f(\phi)$

The conserved current $\nabla^{\mu} J_{\mu} = 0$

is purely spatial $u^{\mu} J_{\mu} = 0$ (no charge density)

Infinitessimal form of the symmetry is $\chi \to \chi + f(t)$

At least one power of momentum in front of χ everywhere

Stückelberg formalism

Coupling to matter

Chronon field, $\chi = \phi - t$, couples to matter through

$$\boxed{L^{\chi-matter} = \chi \nabla^i j_i}$$

any vector constructed from matter

(Dictated by reparametrization invariance, $\chi \rightarrow \chi + f(t)$)

In principle, non-Universal coupling => violations of Equivalence Pple

However, ~~EP~~ suppressed because derivative coupling

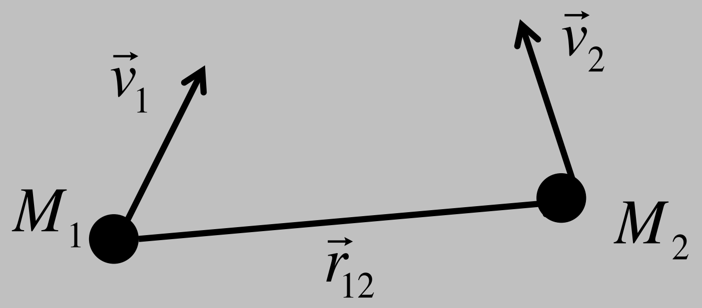
Stückelberg formalism

Chronon-force

If chronon couples Universally, then $j_i = T_{0i}$

(because matter couples to effective metric $\tilde{g}_{\mu\nu} = g_{\mu\nu} + \beta u_\mu u_\nu$)

Velocity-dependent force, $$V = \beta^2 \frac{M_1 M_2}{r_{12}} \left[v_1 \cdot v_2 - (v_1 \cdot \hat{r}_{12})(v_2 \cdot \hat{r}_{12}) \right]$$



Phenomenology

Phenomenology

The model reduces to a Scalar-tensor theory

the scalar displays
- Lorentz breaking
- derivative coupling
- mixing with gravity

$$S = \int d^4x \sqrt{-g} \left(M_P^2 R + \Lambda^2 L^{(\phi)}\left[\partial_\mu \phi \ , ...\right] + L^{(matter)}\left[\psi, g_{\mu\nu}, \partial_\mu \phi\right]\right)$$

-> Both lower and upper bounds on Λ

Note: $\Lambda \ll M_P$

not a fine-tuning

Phenomenology is very similar to
- ghost condensation
- Einstein-aether (gauged gh condens)

Blas OP Sibiryakov '09

Jacobson '10

Newtonian potential *vs* cosmology

By mixing with graviton, ϕ couples to matter so as to renormalize G_N

$$\phi_N = -G_N \frac{M}{r}; \qquad G_N = \frac{1}{8\pi M_P^2} \frac{1}{1-\alpha/2}$$

$$H^2 = \frac{8\pi}{3} G_{\mathrm{cosmo}} \rho; \qquad G_{\mathrm{cosmo}} = \frac{1}{8\pi M_P^2} \frac{1}{1-3(\lambda-1)/2}$$

Observational bound (BBN):

$$\left| \frac{G_{\mathrm{cosmo}}}{G_N} - 1 \right| < 0.13 \qquad \Rightarrow \qquad \alpha, (\lambda - 1) \lesssim 0.1$$

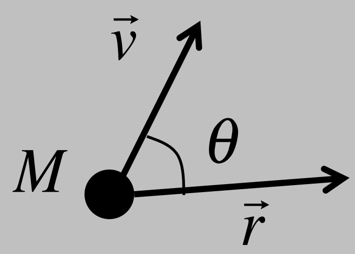
Limits from PPN expansion

(PPN = "Parameterized Post-Newtonian" expansion)

$\alpha_1^{PPN}, \alpha_2^{PPN}$ parameterize preferred-frame effects

velocity with repect to preferred frame

eg



$$\rightarrow \quad \phi_N = -\frac{G_N M}{r}\left(1 + \frac{\alpha_2^{PPN}}{2} v^2 \sin^2\theta\right)$$

Observational bounds:

$\alpha_2^{PPN} \leq 10^{-7}$ (alignment of solar spin axis w.r.t. ecliptic)

$\alpha_1^{PPN} \leq 10^{-4}$ (Lunar ranging, binary pulsars)

Limits from PPN expansion

(PPN = "Parameterized Post-Newtonian" expansion)

$\alpha_1^{PPN}, \alpha_2^{PPN}$ parameterize preferred-frame effects

Limits from PPN expansion

(PPN = "Parameterized Post-Newtonian" expansion)

$\alpha_1^{PPN}, \alpha_2^{PPN}$ parameterize preferred-frame effects

In our model, $\alpha_1^{PPN} = -4\alpha$ $\quad \alpha_2^{PPN} = \dfrac{\alpha^2/2}{\lambda - 1} \sim \alpha$

$$\Rightarrow \quad \alpha, (\lambda - 1) \lesssim 10^{-7} \qquad \Rightarrow \boxed{\Lambda \lesssim 10^{15} GeV}$$

since $\Lambda = \sqrt{\alpha}\, M_P$

Lower bounds on Λ

Within gravitational sector:

Table-top tests of Newton's law -> $\Lambda > 0.1 eV$

Assuming that UV scale M_* is *the same* in the Matter sector:

$$w^2 = c^2k^2 + \cancel{\frac{k^3}{M_{*3}}} + \frac{k^4}{M_{*4}^2} + \ldots$$

From GRB and AGN observations, $M_* \geq 10^{10} \div 10^{11}\ GeV$

$$\Rightarrow \quad 10^{10 \div 11} GeV \lesssim \Lambda \lesssim 10^{15} GeV$$

in the simplest model

Conclusions

So far:

$\exists$ 1 formulation that is
free from instabilities, strong coupling or other basic pathologies

At low energies:

Lorentz-breaking scalar-tensor theory

Deviations from GR are small, theory can be weakly coupled

Observational bounds leave a window for UV scale

$$10^{10 \div 11} GeV \lesssim \Lambda \lesssim 10^{15} GeV$$

Conclusions

So far:

$\exists$ 1 formulation that is
free from instabilities, strong coupling or other basic pathologies

Response to criticism:

- Papazoglou & Sotiriou '09

1) strong coupling claimed

absent if $M_{\substack{high \\ deriv}} \leq \Lambda_{\substack{naive \\ strong\ c}}$

2) fine tuning? Not so.

(marginal/irrelevant operators)

Conclusions

So far:

$\exists$ 1 formulation that is
free from instabilities, strong coupling or other basic pathologies

Response to criticism:

- Papazoglou & Sotiriou '09 ✔

- Kimpton & Padilla '10 Strong coupling re-claimed

" $\exists$ a decoupling limit that spoils UV scaling "

$\exists$ *other dec. lims. that do not spoil scaling*.

(In the appropriate limit, mixing with metric is important)

Non-Relativistic Gravity

Action: $$S = M_P^2 \int d^3x\,dt\, N\sqrt{\gamma}\left[K_{ij}K^{ij} - \lambda (K_i^i)^2 - V\left(\gamma_{ij}, N\right)\right]$$

$$V\left(\gamma_{ij}, N\right) = \quad R_{(3)} + \alpha\, a_i a^i + \frac{R_{(3)}^2 + a^4 + \ldots}{M_P^2} + \frac{R_{(3)}^3 + a^6 + \ldots}{M_P^4}.$$

scalar mode:

$$L_0^{(2)} = M_P^2\left[\frac{3\lambda - 1}{\lambda - 1}(\dot{\psi})^2 + \psi c_0^2 \Delta\left(\frac{1 + A_1\frac{\Delta}{M} + \ldots + A_1\frac{\Delta^4}{M^4}}{1 + B_1\frac{\Delta}{M} + \ldots + B_2\frac{\Delta^2}{M^2}}\right)\psi\right]$$

Conclusions

So far:

$\exists$ 1 formulation that is
free from instabilities, strong coupling or other basic pathologies

Response to criticism:

- Papazoglou & Sotiriou '09 ✔

- Kimpton & Padilla '10 ✔

-Henneaux, Kleinschmidt & Lucena-Gomez'09 ✔

(also Pons & Talavera'10)

does not apply to extended model (nonlinear in lapse, N)

Outlook

Many open questions :

- Recovery of Lorentz Invariance (matter sector): fine tuning avoidance

- Is it really renormalizable / UV complete ??

  Is the $\phi \to f(\phi)$ symmetry non-anomalous?
  Absence of Landau poles?
  Generalized 2^{nd} law of thermodynamics obeyed?

- Is it consistent with all observations ?

  Any stronger bounds?

Outlook

"Lorentz Fine-Tuning Problem":

c is species- dependent

Generically, RG flow generates $c_i - c_j \neq 0$

But $c_i - c_j$ experimentally constrained $\leq 10^{-20}$

Severe fine-tuning

Collins Perez Sudarsky Urrutia Vucetich 04

Iengo Russo Serone 09

Would be trivial in a single species theory

$$L = (\dot{\phi})^2 + c^2 \phi \Delta \phi + \frac{\phi \Delta^2 \phi}{M^2} + \ldots$$

relevant operator

Outlook

"Lorentz Fine-Tuning Problem":

Possible Way out: SUSY (~~Lorentz~~ SUSY = SUSY / boosts)

No Dim ≤ 4 ~~Lorentz~~ operators in ~~Lorentz~~ MSSM !

Groot-Nibbelink
Pospelov '04

$$\{Q,\bar{Q}\} = \sigma^0 E + c\,\sigma^i P_i$$

$$\Rightarrow c_i - c_j \propto \frac{M_{SUSY}^2}{M_*^2}$$

$\Rightarrow M_{SUSY} \leq 10^{-10} M_*$ is enough

$\Rightarrow$ SUSY at $1GeV - 10^2 TeV$??

Outlook

Renormalizability?

Second 'kosher' property (in addition to power-counting)

Detailed Balance: $$V(\gamma_{ij}) = \left|\frac{\delta W}{\delta \gamma_{ij}}\right|^2$$

(broken softly,
otherwise $\Lambda < 0$)

$W[\gamma_{ij}] =$ action for (euclidean) 3D Topologically Massive Gravity (TMG)

'Quantum inheritance' + TMG is renormalizable -> actual renormalizability?

-> Supersymmetrizable ?

-> Generalization to scalar-tensor TMG?

-> Parity broken ??

Outlook

Applications

Outlook

Applications 1) Black Holes

BH notion really **not present** (no light-cone structure)

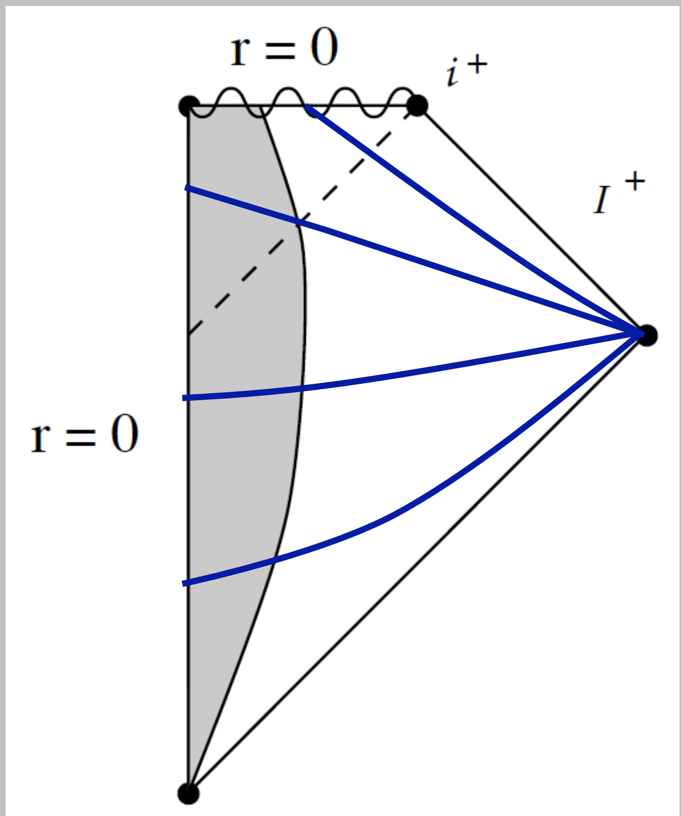
Still, approximate notion @ low energies should exist

-> meaning of BH entropy?

Theory contains instantaneous propagation of signals

-> access to BH interior ?

-> enough for info. paradox ?



Kiritsis' talk

BHs in Einstein Aether

Outlook

Applications 2) Cosmology

bouncing cosmologies *Kiritsis' talk*

inflation

generation of scale-invariant perturbations

alignment between CMB and preferred frame

Armendariz-Picon, Farina & Garriga

3) 'Resolution' of singularities

Thank you!