Title: Infrared Modification of Gravity with Dynamical Torsion

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Abstract: Theories of gravity having connection as an independent dynamical variable can have a massive spin -2 particle together with the massless graviton in their spectrum. We study the potentiality of such models as a consistent infrared modification of gravity. It will be shown that these models are free from ghost like Boulware-Deser mode in the background of arbitrary torsionless Einstein manifolds. At least for weak for weak enough curvature the dangerous spin zero mode has a healthy kinetic energy in our backgrounds. vDVZ singularity seems to be a generic feature which may be cured by Vainshtein mechanism as in other infrared modified theories of gravity.

Infrared Modification of Gravity with Dynamical Torsion

S. Randjbar-Daemi
ICTP-Trieste/Italy

New prospects for solving the cosmological constant problem, Perimeter Institute, May 2009

Based on

- V. Parameswaran Nair , Valery Rubakov and S. R.D.
- arXiv:0811.3781

V. Nikiforava, V. Rubakov and S.R.D
to appear tomorrow!

Massive Spin-2

1. Motivation
2. Brief Remarks on Fierz-Pauli
3. Inclusion of Torsion
4. Massive Spin-2 in Curved Backgrounds
   (Arbitrary Einstein, dS and AdS spaces
   Higuchi bound)
5. Generalized FP in curved backgrounds
6. Unsolved Problems

Motivation

- Modification of gravity at large distances

  Motivated by the accelerated expansion of the universe.

- Acceleration may be due to an infrared modified gravity rather than to a new form of energy!

Massive Spin-2

- Massive gravitons?

A challenge for theory,
difficult to construct a consistent theory!

Massive Spin-2

- Any higher dimensional theory of gravity such as String Theory has infinite number of them.

- What we want is a theory in 4D with a finite number of interacting massive spin-2 particles.

- There is a Unique Non Interacting Theory

Fierz-Pauli (1939)

$$L_{EH}^{(2)}(h_{\mu\nu}) + \frac{\alpha}{4} h_{\mu\nu} h^{\mu\nu} + \frac{\beta}{4} (h^{\mu}_{\mu})^2$$

Consistent only if

$$\beta = -\alpha = m_G^2$$

Number Of Adjustments

- Actually since the only symmetries are global Poincare' even the coefficients in the Einstein Hilbert part are arbitrary.
- Absence of Ghosts and Tachyons in the Linear Theory fix them uniquely to the FP form
- P. van Nieuwenhuizen NPB 60 (1973) 478

5 massive d.o.f propagate

- No ghosts or tachyons.
- Zero mass limit does not produce GR in leading order approximation.
- Non linear terms must be taken into account.

A. I. Vainstein, Phys.Lett.39B (1972) 393

Curved Space (BD Ghost)

- No Coordinate Invariant non linear completion in D=4 is known.

$$S_m = M_{\rm Pl}^2 \int d^4x \sqrt{|g|} \left(R + \frac{m_g^2}{4} \left[h_{\mu\nu}^2 - (h_\mu^\mu)^2 \right] \right) ,$$

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

Buolware-Deser PRD6(1972)3368

Some other approaches

- Extra dimensions with brane worlds

Dvali, Gabadadze, Porrati' 01
de Rham et. al.' 07
Kaloper, Kiley' 07
Kobayashi' 07
etc.

- Lorentz-violating effective Lagrangians

V.R.'04
Dubovsky' 04
Dubovsky, Tinyakov, Tkachev' 05
Berezhiani, Comelli, Nesti, Pilo' 07
etc.

Non Metric Massive spin-2

- A Lorentz tensor t_{ijk} symmetric w.r.t the interchange of the i and j can also produce a spin-2 particle.

O(1,3) content

Impose two extra conditions:

$$\eta^{ij} t_{ijk} = 0$$

$$t_{ijk} + t_{jki} + t_{kij} = 0$$

Unconstrained Action

- Subject to these conditions t_{ijk} has 16 independent components, (still too many!)
- One way to construct a theory for such a field is to include torsion.
- We end up with torsion-gravity theories .
- An old idea!

Cartan, Kibble, Sciama, Hehl, ...

Fundamental Fields

- Vierbein e^i_μ
- Connection $A_{ij\mu} = -A_{ji\mu}$
- Curvature $F_{ijmn} =$

$$e^\mu_m e^\nu_n (\partial_\mu A_{ij\nu} - \partial_\nu A_{ij\mu} + A_{ik\mu} A^k{}_{j\nu} - A_{ik\nu} A^k{}_{j\mu})$$

Invariants

$$F_{jl} = \eta^{ik} F_{ijkl},$$

$$F = \eta^{jk} F_{jk},$$

$$\varepsilon \cdot F = \varepsilon_{ijkl} F^{ijkl}$$

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Torsion

- Define

$$C_{ijk} = e^{\mu}_{j} e^{\nu}_{k} (\partial_{\mu} e_{i\nu} - \partial_{\nu} e_{i\mu})$$

- Torsion

$$T_{ijk} = A_{ijk} - A_{ikj} - C_{ijk}$$

O(1,3) pieces

$$T_{ijk} = \frac{2}{3}(t_{ijk} - t_{ikj}) + \frac{1}{3}(\eta_{ij}v_k - \eta_{ik}v_j) + \varepsilon_{ijkl}a^l$$

$$S = \int d^4x \; e \; L, \qquad e = \det e^i_\mu$$

$$L = L_F + L_T,$$

$$L_T = \alpha t_{ijk} t^{ijk} + \beta v_i v^i + \gamma a_i a^i$$

Gravitational Action

$$L_F = c_1 F + c_2 + c_3 F_{ij} F^{ij}$$

$$+ c_4 F_{ij} F^{ji} + c_5 F^2$$

$$+ c_6 (\varepsilon_{ijkl} F^{ijkl})^2 + b F_{ijkl} F^{ijkl},$$

Ghost and Tachyon Free Classes

- Tachyon and ghost cancellations in flat backgrounds require restrictions on the parameters.

- In flat space only the $c_2 = 0$ has been studied

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K. Hayashi and T. Shirafuji

Prog. Theor. Phys. **64**, 866 (1980)

64, 1435 (1980)

64, 2222 (1980).

E. Sezgin and P. van Nieuwenhuizen,

Phys. Rev. D **21**, 3269 (1980).

There are 10 parameters

- We shall work with a 6-parameter family by choosing:

$$b = c_3 + c_4 + 3c_5 = 0$$

$$\alpha = -\beta = \frac{4\gamma}{9}$$

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Reduced Lagrangian

$$L_T = \alpha(t_{ijk}t^{ijk} - v_i v^i + \frac{9}{4}a_i a^i) \ ,$$

$$L_F = c_1 F + c_2 +$$

$$c_3 F_{ij} F^{ij} + c_4 F_{ij} F^{ji}$$

$$+ c_5 F^2 + c_6 (\varepsilon_{ijkl} F^{ijkl})^2 ,$$

Field equations

- Gravitational

$$\frac{\delta S}{\delta e^i_m} = 0$$

- Torsion

$$\frac{\delta S}{\delta A^i_{j\mu}} = 0$$

Gravitational Equations

$$c_1 F_{ji} + c_3(F^m{}_i F_{mj} - F_j{}^{mn}{}_i F_{mn}) +$$

$$c_4(F^m{}_i F_{jm} - F_j{}^{mn}{}_i F_{nm}) + 2c_5 F_{ji} F$$

$$+2c_6 \varepsilon_{kmnj} F^{kmn}{}_i (\varepsilon_{rpqs} F^{rpqs}) +$$

$$(D^k + v^k) F_{ijk} + H_{ij} - \frac{1}{2}\eta_{ij} L = 0$$

where

$$F_{ijk} = \alpha\left[(t_{ijk} - t_{ikj}) - (\eta_{ij}v_k - \eta_{ik}v_j) - \frac{3}{4}\varepsilon_{ijkl}a^l\right]$$

$$H_{ij} = T_{mni}F^{mn}{}_j - \frac{1}{2}T_{jmn}F_i{}^{mn}$$

- We shall not need H

Gravitational Equations

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We shall not need H

Torsion equation

$$\frac{\delta S}{\delta A^{i}_{j\mu}} = 0$$

$$\{c_i\}(DF)_{ijk} + (\text{torsion})_{ijk} = 0$$

Vanishing Torsion Backgrounds

- Grav.Equ. + Torsion Equ.

$$c_1 R_{ij} = \frac{\lambda}{2}\eta_{ij} - 3c_5 W_{iklj} R^{kl}$$

$$\nabla^i W_{ijkl} = 0$$

Einstein Manifolds

$$R_{ijkl} = \Lambda(\eta_{ik}\eta_{jl} - \eta_{il}\eta_{jk}) + W_{ijkl},$$

$$R_{ij} = 3\Lambda\eta_{ij}, \qquad R = 12\Lambda,$$

$$\Lambda = -\frac{c_2}{6c_1}$$

Spectrum around flat space
Vanishing source for Torsion

$$h_{ij} = \frac{1}{c_1}\frac{1}{k^2}\left(\tau_{ij} - \frac{1}{2}\eta_{ij}\tau\right) - \frac{\tilde{\alpha}}{\alpha c_1}\frac{1}{k^2+m^2}\left(\tau_{ij} - \frac{1}{3}\eta_{ij}\tau\right)$$

$$m^2 = \frac{\tilde{\alpha} c_1}{3\alpha c_5}$$

$$\tilde{\alpha} = \alpha + \frac{2}{3}c_1$$

$$c_5 < 0$$

Full Expression

$$S_{int} = \int d^4k \left\{ \frac{1}{72\tilde{\alpha}} \frac{\bar{S}S}{k^2 + m_0^2} + \frac{2}{c_1}\frac{1}{k^2}\bar{\tau}_{ij}\left(\tau^{ij} - \frac{1}{2}\eta^{ij}\tau\right) \right.$$
$$\left. - \frac{2\tilde{\alpha}}{\alpha c_1}\frac{1}{k^2 + m^2}\left[\bar{\sigma}_{ij}\left(\sigma^{ij} - \frac{1}{3}\eta^{ij}\sigma\right) + 2\frac{k^i k_m}{m^2}\bar{\sigma}_{ij}\left(\sigma^{jm} - \frac{1}{3}\eta^{jm}\sigma\right)\right]\right\}$$

$$m_0^2 = \frac{\tilde{\alpha}}{16c_6}$$

$$\alpha < 0\,, \qquad \tilde{\alpha} > 0$$

Curved Backgrounds

- The axial vector field decouples from the rest, Its longitudinal part propagates with a mass squared

$$\frac{c_5 \varkappa}{8 c_6}$$

$$\varkappa = 2\Lambda + \frac{\tilde{\alpha}}{2c_5}$$

Fierz-Pauli

- Define

$$u_{ij} = F_{(1)ij} - \frac{1}{6}\eta_{ij}F_{(1)}$$

- The remaining equations become

$$\nabla^2 u_{ij} - \nabla^k\nabla_i u_{kj} - \nabla^k\nabla_j u_{ki} + \nabla_i\nabla_j u + \eta_{ij}\left(\nabla^k\nabla^l u_{kl} - \nabla^2 u\right) + 6\Lambda\left(u_{ij} - \frac{1}{2}\eta_{ij}u\right)$$
$$-\left(2\Lambda + \frac{2\varkappa c_1}{3\alpha}\right)(u_{ij} - \eta_{ij}u) + \left(1 - \frac{2\varkappa c_5}{\alpha}\right)W_{ilkj}u^{lk} = 0$$

FP in flat background

$$\nabla^2 u_{ij} - \nabla^k \nabla_i u_{kj} - \nabla^k \nabla_j u_{ki} + \nabla_i \nabla_j u + \eta_{ij} \left(\nabla^k \nabla^l u_{kl} - \nabla^2 u \right.$$

$$+ 6\Lambda \left(u_{ij} - \frac{1}{2} \eta_{ij} u \right)$$

$$^2 = 4\Lambda \left(1 + \frac{c_1}{3\alpha}\right) + \frac{\tilde{\alpha} c_1}{3\alpha c_5}$$

$$- \left(2\Lambda + \frac{2\varkappa c_1}{3\alpha} \right) (u_{ij} - \eta_{ij} u)$$

$$+ \left(1 - \frac{2\varkappa c_5}{\alpha} \right) W_{ilkj} u^{lk} = 0$$

dS or AdS backgrounds

- W=0 and we obtain FP with a mass term

$$M^2 = 4\Lambda\left(1+\frac{c_1}{3\alpha}\right)+\frac{\tilde{\alpha}c_1}{3\alpha c_5}$$
$$= 4\Lambda + \frac{16c_6}{3\alpha c_5}M_0^2 c_1$$

- This satisfies the Higuchi bound if the background is dS.

$$M_2^2 > 4\Lambda$$

A. Higuchi, Nucl. Phys. B **325**, 745 (1

M. Porrati, JHEP **04**, 058 (2002), [hep-th/01121

Counting d.o.f

- Back to general Einstein manifolds:
  Take trace and divergence of FP

$$u = \frac{2\varkappa c_5 - \alpha}{\tilde{M}^2 \varkappa c_1} W_{imkn} \nabla^i \nabla^n u^{mk}$$

$$\tilde{M}^2 \nabla^i (u_{ij} - \eta_{ij} u) = \left(1 - \frac{2\varkappa c_5}{\alpha}\right) W_{jikl} \nabla^k u^{il}$$

$$\tilde{M}^2 = M^2 - 2\Lambda$$

- Note that for dS or AdS, W=0 and these reduce to the usual constraints for the FP field.

- It looks like that the r.h.s. of u contains two derivatives of the fields.

- A closer examination shows that it contains only one time derivative!

An Action Integral for u

$$S = S_{inv} + S_m + S_W$$

- Where S_{inv} is the linearized

  Einstein-Hilbert action for u

$$S_m = -\frac{\tilde{M}^2}{2} \int d^4x \sqrt{-g}\,(u_{ij}u^{ij} - u^2)$$

$$S_W = s \int d^4x \sqrt{-g}\, W_{iklj} u^{kl} u^{ij}$$

$$s = 1 - \frac{2\varkappa c_5}{\alpha}$$

Gauge Invariance?

- Substitute $$u_{ij} = \bar{u}_{ij} + \nabla_i \zeta_j + \nabla_j \zeta_i$$

- Since S_{inv} is invariant under

g.c.t it will not depend on ζ_j

$$S_m = -\frac{\tilde{M}^2}{2} \int d^4x\sqrt{-g}\,\left(u_{ij}u^{ij} - u^2\right)$$

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- Since S_{inv} is invariant under

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- However, S_m and S_W will depend
- on ζ_j

Stückelberg trick

Arkani-Hamed, Georgi, Schwartz' 03
Creminelli, Nicolis, Papucci, Trincherini' 05
Deffayet, Rombouts' 05

- Introduce new fields

$$u_{ij} = \bar{u}_{ij} + \nabla_i \xi_j + \nabla_j \xi_i + \nabla_i \nabla_j \phi$$

- The total action will be invariant under two independent gauge transformations

1. $\bar{u}_{ij} \rightarrow \bar{u}_{ij} + \nabla_i \zeta_j + \nabla_j \zeta_i \,, \qquad \xi_i \rightarrow \xi_i - \zeta_i$

2. $\xi_i \rightarrow \xi_i + \nabla_i \psi \,, \qquad \phi \rightarrow \phi - 2\psi$

Counting the number of d.o.f

10+ 4 + 1 = 15 fields

4 + 1 = 5 gauge invariances

$15 - 2 \times 5 = 5$ propagating degrees of freedom, right number for massive spin-2 field.

- Only if the action is second order in derivatives! Fails for FP!!

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It works in our case!!

- Higher derivative terms for ϕ cancel out everywhere!

- A healthy Kinetic term for ϕ

$$S_\phi = -\frac{3}{4}\tilde{M}^2\left(\tilde{M}^2 - 2\Lambda\right)\int d^4x\sqrt{-g}\;\nabla_i\phi\nabla^i\phi$$

Mixing

$$S_W(\bar{u},\xi,\phi) = s\int d^4x\sqrt{-g}W^{iklj}\left\{2\bar{u}_{ij}(2\nabla_k\xi_l + \nabla_k\nabla_l\phi)\right.$$

$$\left. - W_{iklm}(\nabla^m\phi\nabla^j\phi + 4\nabla^m\phi\xi^j + 2\xi_j\xi^j) + \ldots\right\}$$

In sufficiently weak background fields,

$$|W_{ijkl}| \ll \tilde{M}^2$$

the mass term S_m dominates

Schwarzchild Background

$$|W_{ijkl}| \sim R_S/r^3$$

$$r \lesssim r_3 = \left(\frac{R_S}{m^2}\right)^{1/3}$$

smallest of all Vainshtein radii in the Fierz–Pauli

generic value

$$r_V = r_5 = \left(\frac{R_S}{m^4}\right)^{1/5}$$

Vainshtein mechanism?

- Non linearity for $r \lesssim r_3 = \left(\frac{R_S}{m^2}\right)^{1/3}$?

- Does Vainshtein mechanism cure potential ghost?

We do not know.....

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A lot to be understood

- Solutions.
  - Is vDVZ problem cured by Vainshtein mechanism? Or one has to fine tune parameters to make massive spin-2 mode weakly interacting with matter?
  - Consistency with tests of GR
  - Do black holes have tensor hair?
- Further consistency checks
  - General backgrounds
  - Strong coupling scale in effective low energy theory
- Cosmology
- ...