A theory of Gravity from spontaneous Lorentz violation

Robertus Potting[1]

[1]CENTRA and Physics Departament
Faculdade de Ciências e Tecnologia
Universidade do Algarve
Faro, Portugal

XII Mexican Workshop on Particles and Fields, Mazatlán, 2009

Work in collaboration with V. Alan Kostelecký

Outline

Masslessness from symmetry or broken symmetry

Gauge Symmetries

Generator of unbroken gauge symmetry $\Rightarrow$ massless vector boson

Masslessness from symmetry or broken symmetry

Gauge Symmetries

Generator of unbroken gauge symmetry $\Rightarrow$ massless vector boson

General Relativity

Diffeomorphism invariance $\Rightarrow$ massless gravitons

Masslessness from symmetry or broken symmetry

Gauge Symmetries

Generator of unbroken gauge symmetry $\Rightarrow$ massless vector boson

General Relativity

Diffeomorphism invariance $\Rightarrow$ massless gravitons

Spontaneously Broken Global Symmetry

Spontaneously broken global symmetry $\Rightarrow$ massless Nambu-Goldstone boson

Bumblebee dynamics

photons as Nambu-Goldstone modes

$$L = -\frac{1}{4}(\partial_\mu B_\nu - \partial_\nu B_\mu)^2 + V(B_\mu B^\mu \pm b^2)$$

Bumblebee dynamics

photons as Nambu-Goldstone modes

$$L = -\frac{1}{4}(\partial_\mu B_\nu - \partial_\nu B_\mu)^2 + V(B_\mu B^\mu \pm b^2)$$

- potential V breaks $U(1)$ gauge invariance

Bumblebee dynamics

photons as Nambu-Goldstone modes

$$L = -\frac{1}{4}(\partial_\mu B_\nu - \partial_\nu B_\mu)^2 + V(B_\mu B^\mu \pm b^2)$$

- potential V breaks $U(1)$ gauge invariance
- potential V forces nonzero v.e.v. b_μ for B_μ: spontaneous breaking of Lorentz symmetry

Bumblebee dynamics

photons as Nambu-Goldstone modes

$$L = -\frac{1}{4}(\partial_\mu B_\nu - \partial_\nu B_\mu)^2 + V(B_\mu B^\mu \pm b^2)$$

- potential V breaks $U(1)$ gauge invariance
- potential V forces nonzero v.e.v. b_μ for B_μ: spontaneous breaking of Lorentz symmetry
- natural to expand $B_\mu = b_\mu + A_\mu$

Bumblebee dynamics

photons as Nambu-Goldstone modes

$$L = -\frac{1}{4}(\partial_\mu B_\nu - \partial_\nu B_\mu)^2 + V(B_\mu B^\mu \pm b^2)$$

- potential V breaks $U(1)$ gauge invariance
- potential V forces nonzero v.e.v. b_μ for B_μ: spontaneous breaking of Lorentz symmetry
- natural to expand $B_\mu = b_\mu + A_\mu$
- low-energy dynamics of fluctuations around v.e.v. equal to Maxwell theory in axial gauge

Bumblebee dynamics

photons as Nambu-Goldstone modes

$$L = -\frac{1}{4}(\partial_\mu B_\nu - \partial_\nu B_\mu)^2 + V(B_\mu B^\mu \pm b^2)$$

- potential V breaks $U(1)$ gauge invariance
- potential V forces nonzero v.e.v. b_μ for B_μ: spontaneous breaking of Lorentz symmetry
- natural to expand $B_\mu = b_\mu + A_\mu$
- low-energy dynamics of fluctuations around v.e.v. equal to Maxwell theory in axial gauge
- possible presence of background "vacuum charge"

Bumblebee dynamics

photons as Nambu-Goldstone modes

$$L = -\frac{1}{4}(\partial_\mu B_\nu - \partial_\nu B_\mu)^2 + V(B_\mu B^\mu \pm b^2)$$

- potential V breaks $U(1)$ gauge invariance
- potential V forces nonzero v.e.v. b_μ for B_μ: spontaneous breaking of Lorentz symmetry
- natural to expand $B_\mu = b_\mu + A_\mu$
- low-energy dynamics of fluctuations around v.e.v. equal to Maxwell theory in axial gauge
- possible presence of background "vacuum charge"
- non-linear dynamics of massive modes at high energies/temperatures

Bumblebee dynamics

photons as Nambu-Goldstone modes

$$L = -\frac{1}{4}(\partial_\mu B_\nu - \partial_\nu B_\mu)^2 + V(B_\mu B^\mu \pm b^2)$$

- potential V breaks $U(1)$ gauge invariance
- potential V forces nonzero v.e.v. b_μ for B_μ: spontaneous breaking of Lorentz symmetry
- natural to expand $B_\mu = b_\mu + A_\mu$
- low-energy dynamics of fluctuations around v.e.v. equal to Maxwell theory in axial gauge
- possible presence of background "vacuum charge"
- non-linear dynamics of massive modes at high energies/temperatures
- model can be coupled consistently to gravity Bluhm, Kostelecky (2004)

Linearized "Cardinal" dynamics (V.A. Kostelecky and R.P., GRG 37 (2005) 1675)

gravitons as Nambu-Goldstone modes

$$L = \frac{1}{2} C^{\mu\nu} K_{\mu\nu\alpha\beta} C^{\alpha\beta} + V(C^{\mu\nu}, \eta_{\mu\nu})$$

Linearized "Cardinal" dynamics (V.A. Kostelecky and R.P., GRG 37 (2005) 1675)

gravitons as Nambu-Goldstone modes

$$L = \frac{1}{2} C^{\mu\nu} K_{\mu\nu\alpha\beta} C^{\alpha\beta} + V(C^{\mu\nu}, \eta_{\mu\nu})$$

$$K_{\mu\nu\alpha\beta} = -\partial^2(\eta_{\mu\alpha}\eta_{\nu\beta} - \frac{1}{2}\eta_{\mu\nu}\eta_{\alpha\beta}) + \partial_\mu \eta_{\nu\alpha}\partial_\beta + \partial_\nu \eta_{\mu\alpha}\partial_\beta$$

Linearized "Cardinal" dynamics (V.A. Kostelecky and R.P., GRG 37 (2005) 1675)

gravitons as Nambu-Goldstone modes

$$L = \frac{1}{2} C^{\mu\nu} K_{\mu\nu\alpha\beta} C^{\alpha\beta} + V(C^{\mu\nu}, \eta_{\mu\nu})$$

$$K_{\mu\nu\alpha\beta} = -\partial^2(\eta_{\mu\alpha}\eta_{\nu\beta} - \frac{1}{2}\eta_{\mu\nu}\eta_{\alpha\beta}) + \partial_\mu\eta_{\nu\alpha}\partial_\beta + \partial_\nu\eta_{\mu\alpha}\partial_\beta$$

- $K_{\mu\nu\alpha\beta}$: ghost-free quadratic kinetic operator for spin 2

Linearized "Cardinal" dynamics (V.A. Kostelecky and R.P., GRG 37 (2005) 1675)

gravitons as Nambu-Goldstone modes

$$L = \frac{1}{2} C^{\mu\nu} K_{\mu\nu\alpha\beta} C^{\alpha\beta} + V(C^{\mu\nu}, \eta_{\mu\nu})$$

$$K_{\mu\nu\alpha\beta} = -\partial^2(\eta_{\mu\alpha}\eta_{\nu\beta} - \frac{1}{2}\eta_{\mu\nu}\eta_{\alpha\beta}) + \partial_\mu\eta_{\nu\alpha}\partial_\beta + \partial_\nu\eta_{\mu\alpha}\partial_\beta$$

- $K_{\mu\nu\alpha\beta}$: ghost-free quadratic kinetic operator for spin 2
- $C^{\mu\nu}$: tensor density; $\eta_{\mu\nu}$: flat background metric

Linearized "Cardinal" dynamics (V.A. Kostelecky and R.P., GRG 37 (2005) 1675)

gravitons as Nambu-Goldstone modes

$$L = \frac{1}{2} C^{\mu\nu} K_{\mu\nu\alpha\beta} C^{\alpha\beta} + V(C^{\mu\nu}, \eta_{\mu\nu})$$

$$K_{\mu\nu\alpha\beta} = -\partial^2(\eta_{\mu\alpha}\eta_{\nu\beta} - \frac{1}{2}\eta_{\mu\nu}\eta_{\alpha\beta}) + \partial_\mu \eta_{\nu\alpha}\partial_\beta + \partial_\nu \eta_{\mu\alpha}\partial_\beta$$

- $K_{\mu\nu\alpha\beta}$: ghost-free quadratic kinetic operator for spin 2
- $C^{\mu\nu}$: tensor density; $\eta_{\mu\nu}$: flat background metric
- V: scalar potential built out of the 4 independent scalars $X_1 = C^{\mu\nu}\eta_{\nu\mu}$, $X_2 = (C \cdot \eta \cdot C \cdot \eta)^\mu_\mu, \ldots$

Linearized "Cardinal" dynamics (V.A. Kostelecky and R.P., GRG 37 (2005) 1675)

gravitons as Nambu-Goldstone modes

$$L = \frac{1}{2} C^{\mu\nu} K_{\mu\nu\alpha\beta} C^{\alpha\beta} + V(C^{\mu\nu}, \eta_{\mu\nu})$$

$$K_{\mu\nu\alpha\beta} = -\partial^2(\eta_{\mu\alpha}\eta_{\nu\beta} - \tfrac{1}{2}\eta_{\mu\nu}\eta_{\alpha\beta}) + \partial_\mu \eta_{\nu\alpha}\partial_\beta + \partial_\nu \eta_{\mu\alpha}\partial_\beta$$

- $K_{\mu\nu\alpha\beta}$: ghost-free quadratic kinetic operator for spin 2
- $C^{\mu\nu}$: tensor density; $\eta_{\mu\nu}$: flat background metric
- V: scalar potential built out of the 4 independent scalars $X_1 = C^{\mu\nu}\eta_{\nu\mu}$, $X_2 = (C \cdot \eta \cdot C \cdot \eta)^\mu_\mu, \ldots$
- kinetic term invariant under $C^{\mu\nu} \to C^{\mu\nu} - \partial^\mu \Lambda^\nu - \partial^\nu \Lambda^\mu$; invariance broken by V!

Linearized "Cardinal" dynamics (V.A. Kostelecky and R.P., GRG 37 (2005) 1675)

gravitons as Nambu-Goldstone modes

$$L = \frac{1}{2} C^{\mu\nu} K_{\mu\nu\alpha\beta} C^{\alpha\beta} + V(C^{\mu\nu}, \eta_{\mu\nu})$$

$$K_{\mu\nu\alpha\beta} = -\partial^2(\eta_{\mu\alpha}\eta_{\nu\beta} - \frac{1}{2}\eta_{\mu\nu}\eta_{\alpha\beta}) + \partial_\mu\eta_{\nu\alpha}\partial_\beta + \partial_\nu\eta_{\mu\alpha}\partial_\beta$$

- $K_{\mu\nu\alpha\beta}$: ghost-free quadratic kinetic operator for spin 2
- $C^{\mu\nu}$: tensor density; $\eta_{\mu\nu}$: flat background metric
- V: scalar potential built out of the 4 independent scalars $X_1 = C^{\mu\nu}\eta_{\nu\mu}$, $X_2 = (C \cdot \eta \cdot C \cdot \eta)^\mu_\mu, \ldots$
- kinetic term invariant under $C^{\mu\nu} \to C^{\mu\nu} - \partial^\mu\Lambda^\nu - \partial^\nu\Lambda^\mu$; invariance broken by V!
- V acquires minimum for $C^{\mu\nu} = c^{\mu\nu} \equiv \langle C^{\mu\nu} \rangle \neq 0$: spontaneous breaking of Lorentz symmetry

Linearized "Cardinal" dynamics (V.A. Kostelecky and R.P., GRG 37 (2005) 1675)

gravitons as Nambu-Goldstone modes

$$L = \frac{1}{2} C^{\mu\nu} K_{\mu\nu\alpha\beta} C^{\alpha\beta} + V(C^{\mu\nu}, \eta_{\mu\nu})$$

$$K_{\mu\nu\alpha\beta} = -\partial^2(\eta_{\mu\alpha}\eta_{\nu\beta} - \frac{1}{2}\eta_{\mu\nu}\eta_{\alpha\beta}) + \partial_\mu \eta_{\nu\alpha}\partial_\beta + \partial_\nu \eta_{\mu\alpha}\partial_\beta$$

- $K_{\mu\nu\alpha\beta}$: ghost-free quadratic kinetic operator for spin 2
- $C^{\mu\nu}$: tensor density; $\eta_{\mu\nu}$: flat background metric
- V: scalar potential built out of the 4 independent scalars $X_1 = C^{\mu\nu}\eta_{\nu\mu}$, $X_2 = (C \cdot \eta \cdot C \cdot \eta)^\mu_\mu, \ldots$
- kinetic term invariant under $C^{\mu\nu} \to C^{\mu\nu} - \partial^\mu \Lambda^\nu - \partial^\nu \Lambda^\mu$; invariance broken by V!
- V acquires minimum for $C^{\mu\nu} = c^{\mu\nu} \equiv \langle C^{\mu\nu} \rangle \neq 0$: spontaneous breaking of Lorentz symmetry
- fluctuations around vev: $C^{\mu\nu} = c^{\mu\nu} + \tilde{C}^{\mu\nu}$

Linearized "Cardinal" dynamics

At low energy, assume V can be approximated by sum of delta-functions that fix the 4 independent scalars: $V = \sum_{n=1}^{4} \frac{\lambda_n}{n} X_n$

Linearized "Cardinal" dynamics

At low energy, assume V can be approximated by sum of delta-functions that fix the 4 independent scalars: $V = \sum_{n=1}^{4} \frac{\lambda_n}{n} X_n$

equations of motion:

$$K_{\mu\nu\alpha\beta}\tilde{C}^{\alpha\beta} - \lambda_1\eta_{\mu\nu} - \lambda_2(\eta c\eta)_{\mu\nu} - \lambda_3(\eta c\eta c\eta)_{\mu\nu} - \lambda_4(\eta c\eta c\eta c\eta)_{\mu\nu} = 0$$

Linearized "Cardinal" dynamics

At low energy, assume V can be approximated by sum of delta-functions that fix the 4 independent scalars: $V = \sum_{n=1}^{4} \frac{\lambda_n}{n} X_n$

equations of motion:

$$K_{\mu\nu\alpha\beta}\tilde{C}^{\alpha\beta} - \lambda_1\eta_{\mu\nu} - \lambda_2(\eta c\eta)_{\mu\nu} - \lambda_3(\eta c\eta c\eta)_{\mu\nu} - \lambda_4(\eta c\eta c\eta c\eta)_{\mu\nu} = 0$$

constraints:

$$\tilde{C}^{\mu}_{\mu} = 0 \qquad c^{\mu\nu}\tilde{C}_{\mu\nu} = 0 \qquad (c\eta c)^{\mu\nu}\tilde{C}_{\mu\nu} = 0 \qquad (c\eta c\eta c)^{\mu\nu}\tilde{C}_{\mu\nu} = 0$$

Linearized "Cardinal" dynamics

At low energy, assume V can be approximated by sum of delta-functions that fix the 4 independent scalars: $V = \sum_{n=1}^{4} \frac{\lambda_n}{n} X_n$

equations of motion:

$$K_{\mu\nu\alpha\beta}\tilde{C}^{\alpha\beta} - \lambda_1\eta_{\mu\nu} - \lambda_2(\eta c\eta)_{\mu\nu} - \lambda_3(\eta c\eta c\eta)_{\mu\nu} - \lambda_4(\eta c\eta c\eta c\eta)_{\mu\nu} = 0$$

constraints:

$$\tilde{C}^{\mu}_{\mu} = 0 \qquad c^{\mu\nu}\tilde{C}_{\mu\nu} = 0 \qquad (c\eta c)^{\mu\nu}\tilde{C}_{\mu\nu} = 0 \qquad (c\eta c\eta c)^{\mu\nu}\tilde{C}_{\mu\nu} = 0$$

Low-energy dynamics of $\tilde{C}_{\mu\nu}$-fluctuations around vev equal to linearized general relativity (in axial-type gauge)!

Counting degrees of freedom

Propagating massless degrees of freedom

- Can be considered Nambu-Goldstone modes of spontanously broken Lorentz generators ${\mathcal{E}_\mu}^\alpha$:

$$\tilde{C}_{\mu\nu} = {\mathcal{E}_\mu}^\alpha c_{\alpha\nu} + {\mathcal{E}_\nu}^\alpha c_{\mu\alpha}$$

Counting degrees of freedom

Propagating massless degrees of freedom

- Can be considered Nambu-Goldstone modes of spontanously broken Lorentz generators $\mathcal{E}_\mu{}^\alpha$:

$$\tilde{C}_{\mu\nu} = \mathcal{E}_\mu{}^\alpha c_{\alpha\nu} + \mathcal{E}_\nu{}^\alpha c_{\mu\alpha}$$

- Equations of motion imply masslessness $\partial^2 \tilde{C}_{\mu\nu} = 0$ and Lorenz conditions $\partial^\mu \tilde{C}_{\mu\nu} = 0$

Counting degrees of freedom

Propagating massless degrees of freedom

- Can be considered Nambu-Goldstone modes of spontanously broken Lorentz generators $\mathcal{E}_\mu{}^\alpha$:

$$\tilde{C}_{\mu\nu} = \mathcal{E}_\mu{}^\alpha c_{\alpha\nu} + \mathcal{E}_\nu{}^\alpha c_{\mu\alpha}$$

- Equations of motion imply masslessness $\partial^2 \tilde{C}_{\mu\nu} = 0$ and Lorenz conditions $\partial^\mu \tilde{C}_{\mu\nu} = 0$
- Number of propagating massless degrees of freedom: $6 - 4 = 2$

Bootstrap in General Relativity

Write metric as Minkowski + fluctuations (gravitons):

$$g^{\mu\nu} = \eta^{\mu\nu} + h^{\mu\nu}$$

Bootstrap in General Relativity

Write metric as Minkowski + fluctuations (gravitons):

$$g^{\mu\nu} = \eta^{\mu\nu} + h^{\mu\nu}$$

Quadratic action for (free) gravitons: $\mathcal{L}^L_{GR} = \frac{1}{2} h^{\mu\nu} K_{\mu\nu\alpha\beta} h^{\alpha\beta}$

Bootstrap in General Relativity

Write metric as Minkowski + fluctuations (gravitons):

$$g^{\mu\nu} = \eta^{\mu\nu} + h^{\mu\nu}$$

Quadratic action for (free) gravitons: $\mathcal{L}^{L}_{GR} = \frac{1}{2} h^{\mu\nu} K_{\mu\nu\alpha\beta} h^{\alpha\beta}$

Linear coupling to matter EM

$$\mathcal{L} \supset h^{\mu\nu} \tau_{\mu\nu}$$

Bootstrap in General Relativity

Write metric as Minkowski + fluctuations (gravitons):

$$g^{\mu\nu} = \eta^{\mu\nu} + h^{\mu\nu}$$

Quadratic action for (free) gravitons: $\mathcal{L}^L_{GR} = \frac{1}{2} h^{\mu\nu} K_{\mu\nu\alpha\beta} h^{\alpha\beta}$

Linear coupling to matter EM

$$\mathcal{L} \supset h^{\mu\nu} \tau_{\mu\nu}$$

- $\tau_{\mu\nu}$: trace-inversed energy-momentum tensor

Bootstrap in General Relativity

Write metric as Minkowski + fluctuations (gravitons):

$$g^{\mu\nu} = \eta^{\mu\nu} + h^{\mu\nu}$$

Quadratic action for (free) gravitons: $\mathcal{L}^L_{GR} = \frac{1}{2} h^{\mu\nu} K_{\mu\nu\alpha\beta} h^{\alpha\beta}$

Linear coupling to matter EM

$$\mathcal{L} \supset h^{\mu\nu} \tau_{\mu\nu}$$

- $\tau_{\mu\nu}$: trace-inversed energy-momentum tensor
- linear coupling to EM-tensor gives rise to linearized Einstein equation

$$K_{\mu\nu\alpha\beta} h^{\alpha\beta} \equiv R^L_{\mu\nu} = \tau_{\mu\nu}$$

consistent coupling

consistent coupling to *total* EM tensor

consistent coupling

consistent coupling to *total* EM tensor

- require coupling to total EM tensor, including contribution of gravitational fluctuations (Gupta (1952); Kraichnan 1955; Feynman (1957);...)

$$K_{\mu\nu\alpha\beta}h^{\alpha\beta} = \tau_h^{(1)}{}_{\mu\nu}$$

consistent coupling

consistent coupling to *total* EM tensor

- require coupling to total EM tensor, including contribution of gravitational fluctuations (Gupta (1952); Kraichnan 1955; Feynman (1957);...)

$$K_{\mu\nu\alpha\beta}h^{\alpha\beta} = \tau_h^{(1)}{}_{\mu\nu}$$

- $\tau_h^{(1)}{}_{\mu\nu}$ is quadratic in $h^{\mu\nu}$, necessitating inclusion of cubic term in lagrangian

consistent coupling

consistent coupling to *total* EM tensor

- require coupling to total EM tensor, including contribution of gravitational fluctuations (Gupta (1952); Kraichnan 1955; Feynman (1957);...)

$$K_{\mu\nu\alpha\beta}h^{\alpha\beta} = \tau_h^{(1)}{}_{\mu\nu}$$

- $\tau_h^{(1)}{}_{\mu\nu}$ is quadratic in $h^{\mu\nu}$, necessitating inclusion of cubic term in lagrangian
- cubic term yields new contribution to EM-tensor $\tau_h^{(2)}{}_{\mu\nu} \Rightarrow$ quartic term in Lagrangian

consistent coupling

consistent coupling to *total* EM tensor

- require coupling to total EM tensor, including contribution of gravitational fluctuations (Gupta (1952); Kraichnan 1955; Feynman (1957);...)

$$K_{\mu\nu\alpha\beta} h^{\alpha\beta} = \tau_h^{(1)}{}_{\mu\nu}$$

- $\tau_h^{(1)}{}_{\mu\nu}$ is quadratic in $h^{\mu\nu}$, necessitating inclusion of cubic term in lagrangian
- cubic term yields new contribution to EM-tensor $\tau_h^{(2)}{}_{\mu\nu} \Rightarrow$ quartic term in Lagrangian
- etc., etc.

consistent coupling

consistent coupling to *total* EM tensor

- require coupling to total EM tensor, including contribution of gravitational fluctuations (Gupta (1952); Kraichnan 1955; Feynman (1957);...)

$$K_{\mu\nu\alpha\beta}h^{\alpha\beta} = \tau_h^{(1)}{}_{\mu\nu}$$

- $\tau_h^{(1)}{}_{\mu\nu}$ is quadratic in $h^{\mu\nu}$, necessitating inclusion of cubic term in lagrangian
- cubic term yields new contribution to EM-tensor $\tau_h^{(2)}{}_{\mu\nu} \Rightarrow$ quartic term in Lagrangian
- etc., etc.

consistent coupling

consistent coupling to *total* EM tensor

- require coupling to total EM tensor, including contribution of gravitational fluctuations (Gupta (1952); Kraichnan 1955; Feynman (1957);...)

$$K_{\mu\nu\alpha\beta}h^{\alpha\beta} = \tau_h^{(1)}{}_{\mu\nu}$$

- $\tau_h^{(1)}{}_{\mu\nu}$ is quadratic in $h^{\mu\nu}$, necessitating inclusion of cubic term in lagrangian
- cubic term yields new contribution to EM-tensor $\tau_h^{(2)}{}_{\mu\nu} \Rightarrow$ quartic term in Lagrangian
- etc., etc.

After resumming all terms one obtains Einstein-Hilbert action!

Cardinal bootstrap (V.A. Kostelecky and R.P., Phys. Rev. D (2009))

Deser's procedure

- bootstrap can be done in one step using procedure developed by Deser for GR

Cardinal bootstrap (V.A. Kostelecky and R.P., Phys. Rev. D (2009))

Deser's procedure

- bootstrap can be done in one step using procedure developed by Deser for GR
- use trace-reverted field: $\mathfrak{C}^{\mu\nu} = -C^{\mu\nu} + \frac{1}{2}\eta^{\mu\nu}C^{\alpha}_{\alpha}$

Cardinal bootstrap (V.A. Kostelecky and R.P., Phys. Rev. D (2009))

Deser's procedure

- bootstrap can be done in one step using procedure developed by Deser for GR
- use trace-reverted field: $\mathfrak{C}^{\mu\nu} = -C^{\mu\nu} + \frac{1}{2}\eta^{\mu\nu}C^{\alpha}_{\alpha}$
- can rewrite original linearized cardinal dynamics using Palatini formalism with auxiliary field $\Gamma^{\alpha}_{\mu\nu}$:

$$\mathcal{L}^L = \mathfrak{C}^{\mu\nu}(\Gamma^{\alpha}_{\mu\nu,\alpha} - \Gamma_{\mu,\nu}) + \eta^{\mu\nu}(\Gamma^{\alpha}_{\mu\nu}\Gamma_{\alpha} - \Gamma^{\alpha}_{\beta\mu}\Gamma^{\beta}_{\alpha\nu})$$

Cardinal bootstrap (V.A. Kostelecky and R.P., Phys. Rev. D (2009))

Deser's procedure

- bootstrap can be done in one step using procedure developed by Deser for GR
- use trace-reverted field: $\mathfrak{C}^{\mu\nu} = -C^{\mu\nu} + \frac{1}{2}\eta^{\mu\nu} C^{\alpha}_{\alpha}$
- can rewrite original linearized cardinal dynamics using Palatini formalism with auxiliary field $\Gamma^{\alpha}_{\mu\nu}$:

$$\mathcal{L}^L = \mathfrak{C}^{\mu\nu}(\Gamma^{\alpha}_{\mu\nu,\alpha} - \Gamma_{\mu,\nu}) + \eta^{\mu\nu}(\Gamma^{\alpha}_{\mu\nu}\Gamma_{\alpha} - \Gamma^{\alpha}_{\beta\mu}\Gamma^{\beta}_{\alpha\nu})$$

Cardinal bootstrap (V.A. Kostelecky and R.P., Phys. Rev. D (2009))

Deser's procedure

- bootstrap can be done in one step using procedure developed by Deser for GR
- use trace-reverted field: $\mathfrak{C}^{\mu\nu} = -C^{\mu\nu} + \frac{1}{2}\eta^{\mu\nu} C^{\alpha}_{\alpha}$
- can rewrite original linearized cardinal dynamics using Palatini formalism with auxiliary field $\Gamma^{\alpha}_{\mu\nu}$:

$$\mathcal{L}^L = \mathfrak{C}^{\mu\nu}(\Gamma^{\alpha}_{\mu\nu,\alpha} - \Gamma_{\mu,\nu}) + \eta^{\mu\nu}(\Gamma^{\alpha}_{\mu\nu}\Gamma_{\alpha} - \Gamma^{\alpha}_{\beta\mu}\Gamma^{\beta}_{\alpha\nu})$$

1 step coupling

- Have to include coupling to energy-momentum tensor of $\mathcal{L}^L$ in self-consistent manner

Cardinal bootstrap (V.A. Kostelecky and R.P., Phys. Rev. D (2009))

Deser's procedure

- bootstrap can be done in one step using procedure developed by Deser for GR
- use trace-reverted field: $\mathfrak{C}^{\mu\nu} = -C^{\mu\nu} + \frac{1}{2}\eta^{\mu\nu} C^{\alpha}_{\alpha}$
- can rewrite original linearized cardinal dynamics using Palatini formalism with auxiliary field $\Gamma^{\alpha}_{\mu\nu}$:

$$\mathcal{L}^L = \mathfrak{C}^{\mu\nu}(\Gamma^{\alpha}_{\mu\nu,\alpha} - \Gamma_{\mu,\nu}) + \eta^{\mu\nu}(\Gamma^{\alpha}_{\mu\nu}\Gamma_{\alpha} - \Gamma^{\alpha}_{\beta\mu}\Gamma^{\beta}_{\alpha\nu})$$

1 step coupling

- Have to include coupling to energy-momentum tensor of $\mathcal{L}^L$ in self-consistent manner
- Use Rosenfeld method, promoting $\eta^{\mu\nu}$ to variable metric density and partial derivatives to $\eta^{\mu\nu}$-covariant ones.

Cardinal bootstrap

It follows: $-\frac{1}{2}\tau_{\mu\nu} = \frac{\delta \mathcal{L}^{L}}{\delta \eta^{\mu\nu}} = \Gamma^{\alpha}_{\mu\nu}\Gamma_{\alpha} - \Gamma^{\alpha}_{\beta\mu}\Gamma^{\beta}_{\alpha\nu} + \text{total derivative}$

Cardinal bootstrap

It follows: $-\frac{1}{2}\tau_{\mu\nu} = \frac{\delta \mathcal{L}^L}{\delta \eta^{\mu\nu}} = \Gamma^{\alpha}_{\mu\nu}\Gamma_{\alpha} - \Gamma^{\alpha}_{\beta\mu}\Gamma^{\beta}_{\alpha\nu} +$ total derivative

Full nonlinear action obtained by coupling nonderivative part of $\tau_{\mu\nu}$ as source for $\mathfrak{C}^{\mu\nu}$:

$$\mathcal{L} = \mathcal{L}^L + \mathfrak{C}^{\mu\nu}(\Gamma^{\alpha}_{\mu\nu}\Gamma_{\alpha} - \Gamma^{\alpha}_{\beta\mu}\Gamma^{\beta}_{\alpha\nu})$$

Cardinal bootstrap

It follows: $-\frac{1}{2}\tau_{\mu\nu} = \frac{\delta \mathcal{L}^L}{\delta \eta^{\mu\nu}} = \Gamma^\alpha_{\mu\nu}\Gamma_\alpha - \Gamma^\alpha_{\beta\mu}\Gamma^\beta_{\alpha\nu}$ + total derivative

Full nonlinear action obtained by coupling nonderivative part of $\tau_{\mu\nu}$ as source for $\mathfrak{C}^{\mu\nu}$:

$$\mathcal{L} = \mathcal{L}^L + \mathfrak{C}^{\mu\nu}(\Gamma^\alpha_{\mu\nu}\Gamma_\alpha - \Gamma^\alpha_{\beta\mu}\Gamma^\beta_{\alpha\nu})$$

final result for kinetic term

recursive process yields nonlinear "bootstrapped" action

$$\int d^4x \left(\mathfrak{C}^{\mu\nu}(\Gamma^\alpha_{\mu\nu,\alpha} - \Gamma_{\mu,\nu}) + (\eta + \mathfrak{C})^{\mu\nu}(\Gamma^\alpha_{\mu\nu}\Gamma_\alpha - \Gamma^\alpha_{\beta\mu}\Gamma^\beta_{\alpha\nu})\right)$$

$$\equiv \int d^4x (\eta + \mathfrak{C})^{\mu\nu} R_{\mu\nu}(\Gamma)$$

Cardinal bootstrap

It follows: $-\frac{1}{2}\tau_{\mu\nu} = \frac{\delta\mathcal{L}^L}{\delta\eta^{\mu\nu}} = \Gamma^\alpha_{\mu\nu}\Gamma_\alpha - \Gamma^\alpha_{\beta\mu}\Gamma^\beta_{\alpha\nu}$ + total derivative

Full nonlinear action obtained by coupling nonderivative part of $\tau_{\mu\nu}$ as source for $\mathfrak{C}^{\mu\nu}$:

$$\mathcal{L} = \mathcal{L}^L + \mathfrak{C}^{\mu\nu}(\Gamma^\alpha_{\mu\nu}\Gamma_\alpha - \Gamma^\alpha_{\beta\mu}\Gamma^\beta_{\alpha\nu})$$

final result for kinetic term

recursive process yields nonlinear "bootstrapped" action

$$\int d^4x \left(\mathfrak{C}^{\mu\nu}(\Gamma^\alpha_{\mu\nu,\alpha} - \Gamma_{\mu,\nu}) + (\eta + \mathfrak{C})^{\mu\nu}(\Gamma^\alpha_{\mu\nu}\Gamma_\alpha - \Gamma^\alpha_{\beta\mu}\Gamma^\beta_{\alpha\nu})\right)$$

$$\equiv \int d^4x (\eta + \mathfrak{C})^{\mu\nu} R_{\mu\nu}(\Gamma)$$

Thus $(\eta + \mathfrak{C})^{\mu\nu}$ is naturally interpreted as curved-space metric density!

Bootstrap of matter tensor and scalar potential

Bootstrap can also be applied to scalar potential and matter EM tensor

- flat-space matter EM-tensor yields curved-space matter lagrangian with metric density $(\eta + \mathfrak{C})^{\mu\nu}$: $\mathcal{L}_{M,\mathfrak{C}} = \sqrt{|\eta + \mathfrak{C}|}\mathcal{L}^{L}_{M,\mathfrak{C}}|_{\eta\to\eta+\mathfrak{C}}$

Bootstrap of matter tensor and scalar potential

Bootstrap can also be applied to scalar potential and matter EM tensor

- flat-space matter EM-tensor yields curved-space matter lagrangian with metric density $(\eta + \mathfrak{C})^{\mu\nu}$: $\mathcal{L}_{M,\mathfrak{C}} = \sqrt{|\eta + \mathfrak{C}|}\mathcal{L}^{L}_{M,\mathfrak{C}}|_{\eta\to\eta+\mathfrak{C}}$
- procedure compatible with scalar potential depending only on $C^{\mu\nu}$ and background Minkowski metric $\eta_{\mu\nu}$

Bootstrap of matter tensor and scalar potential

Bootstrap can also be applied to scalar potential and matter EM tensor

- flat-space matter EM-tensor yields curved-space matter lagrangian with metric density $(\eta + \mathfrak{C})^{\mu\nu}$: $\mathcal{L}_{M,\mathfrak{C}} = \sqrt{|\eta + \mathfrak{C}|}\mathcal{L}^{L}_{M,\mathfrak{C}}|_{\eta\to\eta+\mathfrak{C}}$
- procedure compatible with scalar potential depending only on $C^{\mu\nu}$ and background Minkowski metric $\eta_{\mu\nu}$

Bootstrap of matter tensor and scalar potential

Bootstrap can also be applied to scalar potential and matter EM tensor

- flat-space matter EM-tensor yields curved-space matter lagrangian with metric density $(\eta + \mathfrak{C})^{\mu\nu}$: $\mathcal{L}_{M,\mathfrak{C}} = \sqrt{|\eta + \mathfrak{C}|}\mathcal{L}^{L}_{M,\mathfrak{C}}|_{\eta\to\eta+\mathfrak{C}}$
- procedure compatible with scalar potential depending only on $C^{\mu\nu}$ and background Minkowski metric $\eta_{\mu\nu}$

integrability conditions

- Bootstrap requires V satisfy integrability conditions

Bootstrap of matter tensor and scalar potential

Bootstrap can also be applied to scalar potential and matter EM tensor

- flat-space matter EM-tensor yields curved-space matter lagrangian with metric density $(\eta + \mathfrak{C})^{\mu\nu}$: $\mathcal{L}_{M,\mathfrak{C}} = \sqrt{|\eta + \mathfrak{C}|}\mathcal{L}^{L}_{M,\mathfrak{C}}|_{\eta\to\eta+\mathfrak{C}}$
- procedure compatible with scalar potential depending only on $C^{\mu\nu}$ and background Minkowski metric $\eta_{\mu\nu}$

integrability conditions

- Bootstrap requires V satisfy integrability conditions
- Conditions satisfied only by particular solutions, e.g.:

$$1, \qquad \mathfrak{X}_1, \qquad \mathfrak{X}_2 - \frac{\mathfrak{X}_1^2}{2}, \qquad \mathfrak{X}_3 - \frac{3\mathfrak{X}_1\mathfrak{X}_2}{4} + \frac{\mathfrak{X}_1^3}{8}, \qquad \ldots$$

$$(\mathfrak{X}_1 = \mathfrak{C}^{\mu\nu}\eta_{\nu\mu}, \mathfrak{X}_2 = (\mathfrak{C}\cdot\eta\cdot\mathfrak{C}\cdot\eta)^{\mu}_{\mu}, \ldots \text{ etc.})$$

Bootstrap of matter tensor and scalar potential

Bootstrap can also be applied to scalar potential and matter EM tensor

- flat-space matter EM-tensor yields curved-space matter lagrangian with metric density $(\eta + \mathfrak{C})^{\mu\nu}$: $\mathcal{L}_{M,\mathfrak{C}} = \sqrt{|\eta + \mathfrak{C}|}\mathcal{L}^{L}_{M,\mathfrak{C}}|_{\eta\to\eta+\mathfrak{C}}$
- procedure compatible with scalar potential depending only on $C^{\mu\nu}$ and background Minkowski metric $\eta_{\mu\nu}$

integrability conditions

- Bootstrap requires V satisfy integrability conditions
- Conditions satisfied only by particular solutions, e.g.:

$$1, \qquad \mathfrak{X}_1, \qquad \mathfrak{X}_2 - \frac{\mathfrak{X}_1^2}{2}, \qquad \mathfrak{X}_3 - \frac{3\mathfrak{X}_1\mathfrak{X}_2}{4} + \frac{\mathfrak{X}_1^3}{8}, \qquad \ldots$$

$$(\mathfrak{X}_1 = \mathfrak{C}^{\mu\nu}\eta_{\nu\mu}, \mathfrak{X}_2 = (\mathfrak{C}\cdot\eta\cdot\mathfrak{C}\cdot\eta)^{\mu}_{\mu}, \ldots \text{ etc.})$$

- Particular linear combination yields cosmological constant $\sqrt{|\eta + \mathfrak{C}|}$

Bootstrap of scalar potential

integrable scalar potentials

Particularly interesting: Scalar potentials of the form

$$V(\{\mathfrak{X}_i\}) = \frac{1}{2}\sum_{i,j} m_{ij}(\mathfrak{X}_i - \mathfrak{x}_i)(\mathfrak{X}_j - \mathfrak{x}_j) + \mathcal{O}(\mathfrak{X}_i - \mathfrak{x}_i)^3$$

with local minimum at $\mathfrak{X}_i = \mathfrak{x}_i$ $(i = 1 \ldots 4)$

- Represent possibly stable vacuum

Bootstrap of scalar potential

integrable scalar potentials

Particularly interesting: Scalar potentials of the form

$$V(\{\mathfrak{X}_i\}) = \frac{1}{2}\sum_{i,j} m_{ij}(\mathfrak{X}_i - \mathfrak{x}_i)(\mathfrak{X}_j - \mathfrak{x}_j) + \mathcal{O}(\mathfrak{X}_i - \mathfrak{x}_i)^3$$

with local minimum at $\mathfrak{X}_i = \mathfrak{x}_i$ $(i = 1 \ldots 4)$

- Represent possibly stable vacuum
- Integrability and stability highly nontrivial conditions

Bootstrap of scalar potential

integrable scalar potentials

Particularly interesting: Scalar potentials of the form

$$V(\{\mathfrak{X}_i\}) = \frac{1}{2}\sum_{i,j} m_{ij}(\mathfrak{X}_i - \mathfrak{x}_i)(\mathfrak{X}_j - \mathfrak{x}_j) + \mathcal{O}(\mathfrak{X}_i - \mathfrak{x}_i)^3$$

with local minimum at $\mathfrak{X}_i = \mathfrak{x}_i$ $(i = 1\ldots 4)$

- Represent possibly stable vacuum
- Integrability and stability highly nontrivial conditions
- Limit $m_{ij} \to \infty$ corresponds to bootstrap of linearized limit

$$V^L = \lambda_1(\mathfrak{X}_1 - \mathfrak{x}_1) + \lambda_2(\mathfrak{X}_2 - \frac{\mathfrak{X}_1^2}{2} - \mathfrak{x}_2 + \frac{\mathfrak{x}_1^2}{2}) + \ldots$$

Vacuum energy-momentum tensor

Bootstrapped Lagrangian

$$(\eta + \mathfrak{C})^{\mu\nu} R_{\mu\nu}(\Gamma) - \sqrt{-|\eta + \mathfrak{C}|}\, V(\mathfrak{X}_1, \mathfrak{X}_2, \mathfrak{X}_3, \mathfrak{X}_4) + L_{matter}(\mathfrak{C}, \eta, \phi_i, \partial_\mu \phi_i)$$

Vacuum energy-momentum tensor

Bootstrapped Lagrangian

$$(\eta + \mathfrak{C})^{\mu\nu} R_{\mu\nu}(\Gamma) - \sqrt{-|\eta + \mathfrak{C}|}\, V(\mathfrak{X}_1, \mathfrak{X}_2, \mathfrak{X}_3, \mathfrak{X}_4) + L_{matter}(\mathfrak{C}, \eta, \phi_i, \partial_\mu \phi_i)$$

Linearized equations of motion

$$K_{\mu\nu\alpha\beta} h^{\alpha\beta} = (\eta_{\mu\nu}\partial_1 + 2\eta_{\mu\alpha} c^{\alpha\beta} \eta_{\beta\nu}\partial_2 + \ldots) V + \tau^{(m)}_{\mu\nu}(\eta, \phi_i, \partial_\mu \phi_i)$$

$$\partial_n \equiv \frac{\partial}{\partial X_n} \qquad X_n = (C \cdot \eta)^n \qquad (n = 1 \ldots 4)$$

Vacuum energy-momentum tensor

Bootstrapped Lagrangian

$$(\eta + \mathfrak{C})^{\mu\nu} R_{\mu\nu}(\Gamma) - \sqrt{-|\eta + \mathfrak{C}|}\, V(\mathfrak{X}_1, \mathfrak{X}_2, \mathfrak{X}_3, \mathfrak{X}_4) + L_{matter}(\mathfrak{C}, \eta, \phi_i, \partial_\mu \phi_i)$$

Linearized equations of motion

$$K_{\mu\nu\alpha\beta} h^{\alpha\beta} = (\eta_{\mu\nu}\partial_1 + 2\eta_{\mu\alpha} c^{\alpha\beta} \eta_{\beta\nu} \partial_2 + \ldots) V + \tau^{(m)}_{\mu\nu}(\eta, \phi_i, \partial_\mu \phi_i)$$

$$\partial_n \equiv \frac{\partial}{\partial X_n} \qquad X_n = (C \cdot \eta)^n \qquad (n = 1 \ldots 4)$$

"vacuum energy-momentum tensor"

$$T^{(vac)}_{\mu\nu} = \tau^{(vac)}_{\mu\nu} - \frac{1}{2} \eta_{\mu\nu} \left(\tau^{(vac)}\right)^{\alpha}_{\alpha}.$$

Vacuum energy-momentum tensor

Bootstrapped Lagrangian

$$(\eta + \mathfrak{C})^{\mu\nu} R_{\mu\nu}(\Gamma) - \sqrt{-|\eta + \mathfrak{C}|}\, V(\mathfrak{X}_1, \mathfrak{X}_2, \mathfrak{X}_3, \mathfrak{X}_4) + L_{matter}(\mathfrak{C}, \eta, \phi_i, \partial_\mu \phi_i)$$

Linearized equations of motion

$$K_{\mu\nu\alpha\beta} h^{\alpha\beta} = (\eta_{\mu\nu}\partial_1 + 2\eta_{\mu\alpha} c^{\alpha\beta}\eta_{\beta\nu}\partial_2 + \ldots) V + \tau^{(m)}_{\mu\nu}(\eta, \phi_i, \partial_\mu \phi_i)$$

$$\partial_n \equiv \frac{\partial}{\partial X_n} \qquad X_n = (C \cdot \eta)^n \qquad (n = 1 \ldots 4)$$

"vacuum energy-momentum tensor"

$$T^{(vac)}_{\mu\nu} = \tau^{(vac)}_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}\left(\tau^{(vac)}\right)^{\alpha}_{\alpha}.$$

where

$$\tau^{(vac)}_{\mu\nu} = (\eta_{\mu\nu}\partial_1 + 2\eta_{\mu\alpha} C^{\alpha\beta}\eta_{\beta\nu}\partial_2 + \ldots) V$$

Vacuum energy-momentum tensor (cont.)

Explicit solutions

- Explicit solutions of linearized equations of motion can be obtained for $h^{\mu\nu}$ with nonzero vacuum energy-momentum tensor

Vacuum energy-momentum tensor (cont.)

Explicit solutions

- Explicit solutions of linearized equations of motion can be obtained for $h^{\mu\nu}$ with nonzero vacuum energy-momentum tensor
- Initial/boundary values can be defined on suitable initial timelike/spacelike spacetime slices (4 independent functions)

Vacuum energy-momentum tensor (cont.)

Explicit solutions

- Explicit solutions of linearized equations of motion can be obtained for $h^{\mu\nu}$ with nonzero vacuum energy-momentum tensor
- Initial/boundary values can be defined on suitable initial timelike/spacelike spacetime slices (4 independent functions)

Conservation and initial conditions

If matter EM tensor conserved independently, same is true for vacuum EM tensor

Vacuum energy-momentum tensor (cont.)

Explicit solutions

- Explicit solutions of linearized equations of motion can be obtained for $h^{\mu\nu}$ with nonzero vacuum energy-momentum tensor
- Initial/boundary values can be defined on suitable initial timelike/spacelike spacetime slices (4 independent functions)

Conservation and initial conditions

If matter EM tensor conserved independently, same is true for vacuum EM tensor

then

Vacuum energy-momentum tensor (cont.)

Explicit solutions

- Explicit solutions of linearized equations of motion can be obtained for $h^{\mu\nu}$ with nonzero vacuum energy-momentum tensor
- Initial/boundary values can be defined on suitable initial timelike/spacelike spacetime slices (4 independent functions)

Conservation and initial conditions

If matter EM tensor conserved independently, same is true for vacuum EM tensor

then

Choosing $T_{\mu\nu}^{(vac)}$ to be zero at suitable initial timelike/spacelike spacetime slices ensures it is zero at all spacetime

Quantum effective action

Quantum effective action

- Kinetic term not protected by gauge invariance

Quantum effective action

Quantum effective action

- Kinetic term not protected by gauge invariance
- One can expect quantum corrections will render kinetic term non-gauge invariant (Krauss & Tomboulis 2002)

Quantum effective action

Quantum effective action

- Kinetic term not protected by gauge invariance
- One can expect quantum corrections will render kinetic term non-gauge invariant (Krauss & Tomboulis 2002)
- In general the 4 auxiliary modes can become propagating

Quantum effective action

Quantum effective action

- Kinetic term not protected by gauge invariance
- One can expect quantum corrections will render kinetic term non-gauge invariant (Krauss & Tomboulis 2002)
- In general the 4 auxiliary modes can become propagating
- Yields Lorentz-violating corrections to Lagrangian (Carroll et.al. (2009))

Renormalization

Fixed points of Renormalization Group

- Interesting to consider behaviour of theory under (Wilson) renormalization group

Renormalization

Fixed points of Renormalization Group

- Interesting to consider behaviour of theory under (Wilson) renormalization group
- A related vector model with spontaneous Lorentz violation, the bumblebee, has been shown to have Gaussian fixed point that is UV stable in certain directions of linearized RG flow (Altschul & Kostelecky, 2005)

Renormalization

Fixed points of Renormalization Group

- Interesting to consider behaviour of theory under (Wilson) renormalization group
- A related vector model with spontaneous Lorentz violation, the bumblebee, has been shown to have Gaussian fixed point that is UV stable in certain directions of linearized RG flow (Altschul & Kostelecky, 2005)
- These relevant directions of RG flow correspond to asymptotically free theory with nonpolynomial interactions, similar to behaviour found by Halpern & Huang (1995) for scalar fields

Renormalization

Fixed points of Renormalization Group

- Interesting to consider behaviour of theory under (Wilson) renormalization group
- A related vector model with spontaneous Lorentz violation, the bumblebee, has been shown to have Gaussian fixed point that is UV stable in certain directions of linearized RG flow (Altschul & Kostelecky, 2005)
- These relevant directions of RG flow correspond to asymptotically free theory with nonpolynomial interactions, similar to behaviour found by Halpern & Huang (1995) for scalar fields
- Stable minima of these bumblebee potentials are necessarily Lorentz violating

Renormalization

Fixed points of Renormalization Group

- Interesting to consider behaviour of theory under (Wilson) renormalization group
- A related vector model with spontaneous Lorentz violation, the bumblebee, has been shown to have Gaussian fixed point that is UV stable in certain directions of linearized RG flow (Altschul & Kostelecky, 2005)
- These relevant directions of RG flow correspond to asymptotically free theory with nonpolynomial interactions, similar to behaviour found by Halpern & Huang (1995) for scalar fields
- Stable minima of these bumblebee potentials are necessarily Lorentz violating
- Similar analysis for cardinal model very interesting but challenging

Conclusions

- Construction of alternative theory of gravity possible

Conclusions

- Construction of alternative theory of gravity possible
- Massless gravitons can be interpreted as Nambu-Goldstone modes of spontaneously broken Lorentz symmetry

Conclusions

- Construction of alternative theory of gravity possible
- Massless gravitons can be interpreted as Nambu-Goldstone modes of spontaneously broken Lorentz symmetry
- Nonlinear lagrangian from requirement of consistent coupling to total energy-momentum tensor

Conclusions

- Construction of alternative theory of gravity possible
- Massless gravitons can be interpreted as Nambu-Goldstone modes of spontaneously broken Lorentz symmetry
- Nonlinear lagrangian from requirement of consistent coupling to total energy-momentum tensor
- Low-energy Lagrangian corresponds to Einstein-Hilbert action

Conclusions

- Construction of alternative theory of gravity possible
- Massless gravitons can be interpreted as Nambu-Goldstone modes of spontaneously broken Lorentz symmetry
- Nonlinear lagrangian from requirement of consistent coupling to total energy-momentum tensor
- Low-energy Lagrangian corresponds to Einstein-Hilbert action
- Full Lagrangian includes 4 massive graviton modes

Conclusions

- Construction of alternative theory of gravity possible
- Massless gravitons can be interpreted as Nambu-Goldstone modes of spontaneously broken Lorentz symmetry
- Nonlinear lagrangian from requirement of consistent coupling to total energy-momentum tensor
- Low-energy Lagrangian corresponds to Einstein-Hilbert action
- Full Lagrangian includes 4 massive graviton modes
- Integrability conditions for potential very restrictive

Conclusions

- Construction of alternative theory of gravity possible
- Massless gravitons can be interpreted as Nambu-Goldstone modes of spontaneously broken Lorentz symmetry
- Nonlinear lagrangian from requirement of consistent coupling to total energy-momentum tensor
- Low-energy Lagrangian corresponds to Einstein-Hilbert action
- Full Lagrangian includes 4 massive graviton modes
- Integrability conditions for potential very restrictive
- Formalism gives rise to "vacuum energy-momentum tensor"

Conclusions

- Construction of alternative theory of gravity possible
- Massless gravitons can be interpreted as Nambu-Goldstone modes of spontaneously broken Lorentz symmetry
- Nonlinear lagrangian from requirement of consistent coupling to total energy-momentum tensor
- Low-energy Lagrangian corresponds to Einstein-Hilbert action
- Full Lagrangian includes 4 massive graviton modes
- Integrability conditions for potential very restrictive
- Formalism gives rise to "vacuum energy-momentum tensor"
- Quantum effective action can turn auxiliary modes propagating at low energy

Future work

- Classification of all integrable and bootstrapped potentials

Future work

- Classification of all integrable and bootstrapped potentials
- What is the behaviour of the theory at high energies/temperatures?

Future work

- Classification of all integrable and bootstrapped potentials
- What is the behaviour of the theory at high energies/temperatures?
- Behaviour under Renormalization Group?

Future work

- Classification of all integrable and bootstrapped potentials
- What is the behaviour of the theory at high energies/temperatures?
- Behaviour under Renormalization Group?
- Cosmological implications of vacuum energy-momentum tensor?

Future work

- Classification of all integrable and bootstrapped potentials
- What is the behaviour of the theory at high energies/temperatures?
- Behaviour under Renormalization Group?
- Cosmological implications of vacuum energy-momentum tensor?
- Extension of cardinal model: extra massless modes (ex. combination with bumblebee)?