Gravity from Breaking of Local Lorentz Symmetry

Robertus Potting¹

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

Kostelecky and Potting, GRG '05, and paper in preparation

DISCRETE '08 Symposium on Prospects in the Physics of Discrete Symmetries IFIC, Valencia, December 2008



1 / 15

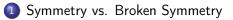
R. Potting (Algarve)

Gravity from Breaking of Local Lorentz S

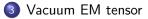
DISCRETE08

イロト イポト イヨト イヨト

Outline











2 / 15

э

DISCRETE08

< A

R. Potting (Algarve)

Gravity from Breaking of Local Lorentz S

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



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



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



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

- $C^{\mu
 u}$: tensor density; $\eta_{\mu
 u}$: flat background metric
- V: scalar potential built out of the 4 independent scalars $X_1 = C^{\mu\nu}\eta_{\nu\mu\nu} X_2 = (C \cdot \eta \cdot C \cdot \eta)^{\mu}_{\mu\nu\nu}$
- 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: $C^{\mu
u}=c^{\mu
u}+h^{\mu
u}$

٢

¹V.A. Kostelecky and R.P., GRG 37 (2005) 1675

R. Potting (Algarve)

Gravity from Breaking of Local Lorentz S DISCR

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

- $C^{\mu
 u}$: tensor density; $\eta_{\mu
 u}$: flat background metric
- V: scalar potential built out of the 4 independent scalars $X_1 = C^{\mu\nu}\eta_{\nu\mu\nu} X_2 = (C \cdot \eta \cdot C \cdot \eta)^{\mu}_{\mu\nu\nu\nu}$
- 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: $C^{\mu
u}=c^{\mu
u}+h^{\mu
u}$



4 / 15

(日) (同) (目) (日)

DISCRETE08

¹V.A. Kostelecky and R.P., GRG 37 (2005) 1675

R. Potting (Algarve)

Gravity from Breaking of Local Lorentz S

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
- $C^{\mu
 u}$: tensor density; $\eta_{\mu
 u}$: flat background metric
- V: scalar potential built out of the 4 independent scalars $X_1 = C^{\mu\nu}\eta_{\nu\mu}, X_2 = (C \cdot \eta \cdot C \cdot \eta)^{\mu}_{\mu,\dots}$
- 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: $C^{\mu\nu} = c^{\mu\nu} + h^{\mu\nu}$

¹V.A. Kostelecky and R.P., GRG 37 (2005) 1675

R. Potting (Algarve)

Image: A match the second s

gravitons as Nambu-Goldstone modes

$$L = rac{1}{2} C^{\mu
u} K_{\mu
ulphaeta} C^{lphaeta} + V(C^{\mu
u},\eta_{\mu
u})$$

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

- $K_{\mu\nu\alpha\beta}$: 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 $X_1 = C^{\mu\nu}\eta_{\nu\mu}, X_2 = (C \cdot \eta \cdot C \cdot \eta)^{\mu}_{\mu,\dots}$
- 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: $C^{\mu\nu} = c^{\mu\nu} + h^{\mu\nu}$

¹V.A. Kostelecky and R.P., GRG 37 (2005) 1675

R. Potting (Algarve)

Gravity from Breaking of Local Lorentz S

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 $X_1 = C^{\mu\nu}\eta_{\nu\mu}, X_2 = (C \cdot \eta \cdot C \cdot \eta)^{\mu}_{\mu,\dots}$
- 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: $C^{\mu\nu} = c^{\mu\nu} + h^{\mu\nu}$

¹V.A. Kostelecky and R.P., GRG 37 (2005) 1675

R. Potting (Algarve)

Gravity from Breaking of Local Lorentz S

< □ > < 同 > < 回 > < 回

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 $X_1 = C^{\mu\nu}\eta_{\nu\mu}, X_2 = (C \cdot \eta \cdot C \cdot \eta)^{\mu}_{\mu,\dots}$
- 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: $C^{\mu\nu} = c^{\mu\nu} + h^{\mu\nu}$

¹V.A. Kostelecky and R.P., GRG 37 (2005) 1675

A D N A B N A B N A

DISCRETE08

4 / 15

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 $X_1 = C^{\mu\nu}\eta_{\nu\mu}, X_2 = (C \cdot \eta \cdot C \cdot \eta)^{\mu}_{\mu,\dots}$
- 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: $C^{\mu
 u}=c^{\mu
 u}+h^{\mu
 u}$



A D N A B N A B N A

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 equations of motion:

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

constraints:

Lagrange multiplier terms force the constraints $h^{\mu}_{\mu} = 0 \qquad c^{\mu\nu}h_{\mu\nu} = 0 \qquad (c\eta c)^{\mu\nu}h_{\mu\nu} = 0 \qquad (c\eta c\eta c)^{\mu\nu}h_{\mu\nu} = 0$

Low-energy dynamics of $h_{\mu\nu}$ -fluctuations around v.e.v. equivalent to linearized general relativity in axial-type gauge, with possible Lorentz-violating source term from Lagrange multiplier terms



(日) (同) (三) (三)

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 equations of motion:

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

constraints:

Lagrange multiplier terms force the constraints $h^{\mu}_{\mu} = 0 \qquad c^{\mu\nu}h_{\mu\nu} = 0 \qquad (c\eta c)^{\mu\nu}h_{\mu\nu} = 0 \qquad (c\eta c\eta c)^{\mu\nu}h_{\mu\nu} = 0$

Low-energy dynamics of $h_{\mu\nu}$ -fluctuations around v.e.v. equivalent to linearized general relativity in axial-type gauge, with possible Lorentz-violating source term from Lagrange multiplier terms



(日) (同) (三) (三)

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 equations of motion:

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

constraints:

Lagrange multiplier terms force the constraints $h^{\mu}_{\mu} = 0 \qquad c^{\mu\nu}h_{\mu\nu} = 0 \qquad (c\eta c)^{\mu\nu}h_{\mu\nu} = 0 \qquad (c\eta c\eta c)^{\mu\nu}h_{\mu\nu} = 0$

Low-energy dynamics of $h_{\mu\nu}$ -fluctuations around v.e.v. equivalent to linearized general relativity in axial-type gauge, with possible Lorentz-violating source term from Lagrange multiplier terms



・ロト ・ 日 ・ ・ ヨ ・ ・ ヨ ・

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 equations of motion:

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

constraints:

Lagrange multiplier terms force the constraints $h^{\mu}_{\mu} = 0 \qquad c^{\mu\nu}h_{\mu\nu} = 0 \qquad (c\eta c)^{\mu\nu}h_{\mu\nu} = 0 \qquad (c\eta c\eta c)^{\mu\nu}h_{\mu\nu} = 0$

Low-energy dynamics of $h_{\mu\nu}$ -fluctuations around v.e.v. equivalent to linearized general relativity in axial-type gauge, with possible Lorentz-violating source term from Lagrange multiplier terms



(日) (同) (三) (三)



5 / 15

Counting degrees of freedom

Propagating massless degrees of freedom

• Can be considered Nambu-Goldstone modes of spontanously broken Lorentz generators:

$$h_{\mu
u} = \mathcal{E}_{\mu}{}^{lpha} c_{lpha
u} + \mathcal{E}_{
u}{}^{lpha} c_{\mulpha}$$

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



Counting degrees of freedom

Propagating massless degrees of freedom

• Can be considered Nambu-Goldstone modes of spontanously broken Lorentz generators:

$$h_{\mu
u} = \mathcal{E}_{\mu}{}^{lpha} c_{lpha
u} + \mathcal{E}_{
u}{}^{lpha} c_{\mulpha}$$

• Equations of motion imply masslessness $\partial^2 h_{\mu\nu} = 0$ and Lorenz conditions $\partial^{\mu} h_{\mu\nu} = 0$

• Number of propagating massless degrees of freedom: 6 - 4 = 2



6 / 15

DISCRETE08

Counting degrees of freedom

Propagating massless degrees of freedom

• Can be considered Nambu-Goldstone modes of spontanously broken Lorentz generators:

$$h_{\mu
u} = \mathcal{E}_{\mu}{}^{lpha} c_{lpha
u} + \mathcal{E}_{
u}{}^{lpha} c_{\mulpha}$$

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



DISCRETE08

Linear coupling to matter

Linear coupling to matter

 ${\cal L} \supset h^{\mu
u} au_{\mu
u}$

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

linear coupling to EM-tensor gives rise to linearized Einstein equation

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



7 / 15

э

DISCRETE08

・ロト ・ 日 ・ ・ ヨ ・ ・ ヨ ・

R. Potting (Algarve)

Gravity from Breaking of Local Lorentz S

Linear coupling to matter

Linear coupling to matter

 $\mathcal{L} \supset h^{\mu
u} au_{\mu
u}$

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

• linear coupling to EM-tensor gives rise to linearized Einstein equation

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



7 / 15

(日) (同) (三) (三) (三)

DISCRETE08

R. Potting (Algarve)

Gravity from Breaking of Local Lorentz S

Linear coupling to matter

Linear coupling to matter

$${\cal L} \supset h^{\mu
u} au_{\mu
u}$$

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

$$K_{\mu
ulphaeta}h^{lphaeta}\equiv R^L_{\mu
u}= au_{\mu
u}$$



7 / 15

DISCRETE08

consistent coupling to total EM tensor

 require coupling to total EM tensor, including contribution of gravitational fluctuations

 $K_{\mu
ulphaeta}h^{lphaeta}= au_h^{(1)}{}_{\mu
u}$

- $au_h^{(1)}{}_{\mu
 u}$ corresponds to cubic term of total lagrangian
- cubic term yields new contribution to EM-tensor $au_h^{(2)}{}_{\mu\nu}$ \Rightarrow quartic term in Lagrangian
- etc., etc.
- This alternative non-geometrical "bootstrap" principle to deriving GR was proposed by Kraichnan, Feynman and others in 1950's



consistent coupling to total EM tensor

require coupling to total EM tensor, including contribution of gravitational fluctuations

$$K_{\mu
ulphaeta}h^{lphaeta}= au_{h}^{(1)}{}_{\mu
u}$$

- $\tau_{h}^{(1)}{}_{\mu\nu}$ corresponds to cubic term of total lagrangian
- cubic term yields new contribution to EM-tensor $\tau_h^{(2)}{}_{\mu\nu}$ \Rightarrow quartic term in Lagrangian
- etc., etc.
- This alternative non-geometrical "bootstrap" principle to deriving GR was proposed by Kraichnan, Feynman and others in 1950's



A B A B A
 A
 B
 A
 A
 B
 A
 A
 B
 A
 A
 B
 A
 A
 B
 A
 A
 B
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A

consistent coupling to total EM tensor

require coupling to total EM tensor, including contribution of gravitational fluctuations

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

- $\tau_{h}^{(1)}{}_{\mu\nu}$ corresponds to cubic term of total lagrangian
- cubic term yields new contribution to EM-tensor $\tau_h^{(2)}_{\mu\nu} \Rightarrow$ quartic term in Lagrangian
- etc., etc.
- This alternative non-geometrical "bootstrap" principle to deriving GR was proposed by Kraichnan, Feynman and others in 1950's



A B > A B > A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A
 A

consistent coupling to total EM tensor

require coupling to total EM tensor, including contribution of gravitational fluctuations

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

- $\tau_{h}^{(1)}{}_{\mu\nu}$ corresponds to cubic term of total lagrangian
- cubic term yields new contribution to EM-tensor $\tau_h^{(2)}{}_{\mu\nu} \Rightarrow$ quartic term in Lagrangian
- etc., etc.
- This alternative non-geometrical "bootstrap" principle to deriving GR was proposed by Kraichnan, Feynman and others in 1950's



consistent coupling to total EM tensor

require coupling to total EM tensor, including contribution of gravitational fluctuations

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

- $\tau_{h}^{(1)}{}_{\mu\nu}$ corresponds to cubic term of total lagrangian
- cubic term yields new contribution to EM-tensor $\tau_h^{(2)}{}_{\mu\nu} \Rightarrow$ quartic term in Lagrangian
- etc., etc.
- This alternative non-geometrical "bootstrap" principle to deriving GR was proposed by Kraichnan, Feynman and others in 1950's



consistent coupling to total EM tensor

require coupling to total EM tensor, including contribution of gravitational fluctuations

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

- $\tau_{h}^{(1)}{}_{\mu\nu}$ corresponds to cubic term of total lagrangian
- cubic term yields new contribution to EM-tensor $\tau_h^{(2)}{}_{\mu\nu} \Rightarrow$ quartic term in Lagrangian
- etc., etc.
- This alternative non-geometrical "bootstrap" principle to deriving GR was proposed by Kraichnan, Feynman and others in 1950's

1-step bootstrap

• bootstrap can be done in one step using procedure invested by Deser

- uses trace-reverted field: $C^{\mu\nu} \rightarrow -C^{\mu\nu} + \frac{1}{2}\eta^{\mu\nu}C^{\alpha}_{\alpha}$
- employs first-order quadratic Lagrangian

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

final result for kinetic term

recursive process yields nonlinear bootstrapped kinetic action

$$S_{kin} = \int d^4 x (\eta + C)^{\mu
u} R_{\mu
u}(\Gamma)$$

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

R. Potting (Algarve)

Gravity from Breaking of Local Lorentz S

DISCRETE08 9 / 15

Bootstrap

1-step bootstrap

- bootstrap can be done in one step using procedure invested by Deser
- uses trace-reverted field: $C^{\mu\nu} \rightarrow -C^{\mu\nu} + \frac{1}{2}\eta^{\mu\nu}C^{\alpha}_{\alpha}$
- employs first-order quadratic Lagrangian

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

final result for kinetic term

recursive process yields nonlinear bootstrapped kinetic action

$$S_{kin} = \int d^4 x (\eta + C)^{\mu
u} R_{\mu
u}(\Gamma)$$

Thus $(\eta+{\sf C})^{\mu
u}$ is naturally interpreted as curved-space metric density.

Gravity from Breaking of Local Lorentz S

Bootstrap

1-step bootstrap

- bootstrap can be done in one step using procedure invested by Deser
- uses trace-reverted field: $C^{\mu\nu} \rightarrow -C^{\mu\nu} + \frac{1}{2}\eta^{\mu\nu}C^{\alpha}_{\alpha}$
- employs first-order quadratic Lagrangian

$$\mathcal{C}^{\mu
u}(\Gamma^{lpha}_{\mu
u,lpha}-\Gamma_{\mu,
u})+\eta^{\mu
u}(\Gamma^{lpha}_{\mu
u}\Gamma_{lpha}-\Gamma^{lpha}_{eta\mu}\Gamma^{eta}_{lpha
u})$$

final result for kinetic term

recursive process yields nonlinear bootstrapped kinetic action

$$S_{kin} = \int d^4 x (\eta + C)^{\mu\nu} R_{\mu\nu}(\Gamma)$$

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

R. Potting (Algarve)

Gravity from Breaking of Local Lorentz S

DISCRETE08 9 / 15

Bootstrap

1-step bootstrap

- bootstrap can be done in one step using procedure invested by Deser
- uses trace-reverted field: $C^{\mu\nu} \rightarrow -C^{\mu\nu} + \frac{1}{2}\eta^{\mu\nu}C^{\alpha}_{\alpha}$
- employs first-order quadratic Lagrangian

$$\mathcal{C}^{\mu
u}(\Gamma^{lpha}_{\mu
u,lpha}-\Gamma_{\mu,
u})+\eta^{\mu
u}(\Gamma^{lpha}_{\mu
u}\Gamma_{lpha}-\Gamma^{lpha}_{eta\mu}\Gamma^{eta}_{lpha
u})$$

final result for kinetic term

recursive process yields nonlinear bootstrapped kinetic action

$$S_{kin} = \int d^4 x (\eta + C)^{\mu
u} R_{\mu
u}(\Gamma)$$

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

R. Potting (Algarve)

Gravity from Breaking of Local Lorentz S

DISCRETE08 9 / 15

Bootstrap

1-step bootstrap

- bootstrap can be done in one step using procedure invested by Deser
- uses trace-reverted field: $C^{\mu\nu} \rightarrow -C^{\mu\nu} + \frac{1}{2}\eta^{\mu\nu}C^{\alpha}_{\alpha}$
- employs first-order quadratic Lagrangian

$$\mathcal{C}^{\mu
u}(\Gamma^{lpha}_{\mu
u,lpha}-\Gamma_{\mu,
u})+\eta^{\mu
u}(\Gamma^{lpha}_{\mu
u}\Gamma_{lpha}-\Gamma^{lpha}_{eta\mu}\Gamma^{eta}_{lpha
u})$$

final result for kinetic term

recursive process yields nonlinear bootstrapped kinetic action

$$S_{kin} = \int d^4 x (\eta + C)^{\mu
u} R_{\mu
u}(\Gamma)$$

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

R. Potting (Algarve)

Gravity from Breaking of Local Lorentz S

DISCRETE08 9 / 15

(日) (同) (三) (三)

1-step bootstrap

- bootstrap can be done in one step using procedure invested by Deser
- uses trace-reverted field: $C^{\mu\nu} \rightarrow -C^{\mu\nu} + \frac{1}{2}\eta^{\mu\nu}C^{\alpha}_{\alpha}$
- employs first-order quadratic Lagrangian

$$\mathcal{C}^{\mu
u}(\Gamma^{lpha}_{\mu
u,lpha}-\Gamma_{\mu,
u})+\eta^{\mu
u}(\Gamma^{lpha}_{\mu
u}\Gamma_{lpha}-\Gamma^{lpha}_{eta\mu}\Gamma^{eta}_{lpha
u})$$

final result for kinetic term

recursive process yields nonlinear bootstrapped kinetic action

$$S_{kin} = \int d^4 x (\eta + C)^{\mu
u} R_{\mu
u}(\Gamma)$$

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

(日) (同) (三) (三)

Bootstrap of matter EM tensor and scalar potential

matter energy-momentum tensor

- Bootstrap can also be applied to flat-space matter Lagrangian
- Result: curved-space matter lagrangian, with metric density (η + C)^{μν}
 Example: L_{EM} = -¹/_{4√|η+C|}(η + C)^{αγ}(η + C)^{βδ}F_{αβ}F_{γδ}

scalar potential V

- Assume flat-space V built out of independent scalars X_1 , X_2 , X_3 , X_4
- Bootstrap requires V satisfy integrability conditions
- Conditions satisfied only by particular solutions, e.g.:

Bootstrap of matter EM tensor and scalar potential

matter energy-momentum tensor

- Bootstrap can also be applied to flat-space matter Lagrangian
- Result: curved-space matter lagrangian, with metric density $(\eta + C)^{\mu
 u}$
- Example: $L_{EM} = -\frac{1}{4\sqrt{|\eta+C|}}(\eta+C)^{\alpha\gamma}(\eta+C)^{\beta\delta}F_{\alpha\beta}F_{\gamma\delta}$

scalar potential V

- Assume flat-space V built out of independent scalars X_1 , X_2 , X_3 , X_4
- Bootstrap requires V satisfy integrability conditions
- Conditions satisfied only by particular solutions, e.g.:

Bootstrap of matter EM tensor and scalar potential

matter energy-momentum tensor

- Bootstrap can also be applied to flat-space matter Lagrangian
- Result: curved-space matter lagrangian, with metric density $(\eta + C)^{\mu
 u}$

• Example:
$$L_{EM} = -rac{1}{4\sqrt{|\eta+C|}}(\eta+C)^{lpha\gamma}(\eta+C)^{eta\delta}F_{lphaeta}F_{\gamma\delta}$$

scalar potential V

- Assume flat-space V built out of independent scalars X_1 , X_2 , X_3 , X_4
- Bootstrap requires V satisfy integrability conditions
- Conditions satisfied only by particular solutions, e.g.:

Bootstrap of matter EM tensor and scalar potential

matter energy-momentum tensor

- Bootstrap can also be applied to flat-space matter Lagrangian
- Result: curved-space matter lagrangian, with metric density $(\eta + C)^{\mu
 u}$

• Example:
$$L_{EM} = -rac{1}{4\sqrt{|\eta+C|}}(\eta+C)^{lpha\gamma}(\eta+C)^{eta\delta}F_{lphaeta}F_{\gamma\delta}$$

scalar potential V

- Assume flat-space V built out of independent scalars X_1 , X_2 , X_3 , X_4
- Bootstrap requires V satisfy integrability conditions
- Conditions satisfied only by particular solutions, e.g.:

Bootstrap of matter EM tensor and scalar potential

matter energy-momentum tensor

- Bootstrap can also be applied to flat-space matter Lagrangian
- Result: curved-space matter lagrangian, with metric density $(\eta + C)^{\mu
 u}$

• Example:
$$L_{EM} = -rac{1}{4\sqrt{|\eta+C|}}(\eta+C)^{lpha\gamma}(\eta+C)^{eta\delta}F_{lphaeta}F_{\gamma\delta}$$

scalar potential V

- Assume flat-space V built out of independent scalars X_1 , X_2 , X_3 , X_4
- Bootstrap requires V satisfy integrability conditions
- Conditions satisfied only by particular solutions, e.g.:

Bootstrap of matter EM tensor and scalar potential

matter energy-momentum tensor

- Bootstrap can also be applied to flat-space matter Lagrangian
- Result: curved-space matter lagrangian, with metric density $(\eta + C)^{\mu
 u}$

• Example:
$$L_{EM} = -rac{1}{4\sqrt{|\eta+C|}}(\eta+C)^{lpha\gamma}(\eta+C)^{eta\delta}F_{lphaeta}F_{\gamma\delta}$$

scalar potential V

- Assume flat-space V built out of independent scalars X_1 , X_2 , X_3 , X_4
- Bootstrap requires V satisfy integrability conditions
- Conditions satisfied only by particular solutions, e.g.:

Bootstrap of matter EM tensor and scalar potential

matter energy-momentum tensor

- Bootstrap can also be applied to flat-space matter Lagrangian
- Result: curved-space matter lagrangian, with metric density $(\eta + \mathcal{C})^{\mu
 u}$

• Example:
$$L_{EM} = -rac{1}{4\sqrt{|\eta+C|}}(\eta+C)^{lpha\gamma}(\eta+C)^{eta\delta}F_{lphaeta}F_{\gamma\delta}$$

scalar potential V

- Assume flat-space V built out of independent scalars X_1 , X_2 , X_3 , X_4
- Bootstrap requires V satisfy integrability conditions
- Conditions satisfied only by particular solutions, e.g.:

1,
$$X_1$$
, $X_2 - \frac{X_1^2}{2}$, $X_3 - \frac{3X_1X_2}{4} + \frac{X_1^3}{8}$,

Bootstrap of scalar potential

integrable scalar potentials

Particularly interesting: Scalar potentials of the form

$$V(\{X_i\}) = \frac{1}{2} \sum_{i,j} m_{ij}(X_i - x_i)(X_j - x_j) + \mathcal{O}(X_i - x_i)^3$$

with local minimum at $X_i = x_i$ (i = 1...4)

- Represent possibly stable vacuum
- Integrability and stability highly nontrivial conditions (work in progress)
- Expect limit $m_{ij}
 ightarrow \infty$ to correspond to bootstrap of linearized limit

$$V^{L} = \lambda_{1}X_{1} + \lambda_{2}(X_{2} - \frac{X_{1}^{2}}{2}) + \lambda_{3}(X_{3} - \frac{3X_{1}X_{2}}{4} + \frac{X_{1}^{3}}{8}) + \dots$$

R. Potting (Algarve)

Gravity from Breaking of Local Lorentz S

DISCRETE08 11 / 15

Bootstrap of scalar potential

integrable scalar potentials

Particularly interesting: Scalar potentials of the form

$$V(\{X_i\}) = \frac{1}{2} \sum_{i,j} m_{ij}(X_i - x_i)(X_j - x_j) + \mathcal{O}(X_i - x_i)^3$$

with local minimum at $X_i = x_i$ (i = 1...4)

- Represent possibly stable vacuum
- Integrability and stability highly nontrivial conditions (work in progress)
- Expect limit $m_{ij}
 ightarrow \infty$ to correspond to bootstrap of linearized limit

$$V^{L} = \lambda_{1}X_{1} + \lambda_{2}(X_{2} - \frac{X_{1}^{2}}{2}) + \lambda_{3}(X_{3} - \frac{3X_{1}X_{2}}{4} + \frac{X_{1}^{3}}{8}) +$$

R. Potting (Algarve)

Gravity from Breaking of Local Lorentz S

DISCRETE08 11 / 15

Bootstrap of scalar potential

integrable scalar potentials

Particularly interesting: Scalar potentials of the form

$$V(\{X_i\}) = \frac{1}{2} \sum_{i,j} m_{ij}(X_i - x_i)(X_j - x_j) + \mathcal{O}(X_i - x_i)^3$$

with local minimum at $X_i = x_i$ (i = 1...4)

- Represent possibly stable vacuum
- Integrability and stability highly nontrivial conditions (work in progress)
- Expect limit $m_{ij}
 ightarrow \infty$ to correspond to bootstrap of linearized limit

$$V^{L} = \lambda_{1}X_{1} + \lambda_{2}(X_{2} - \frac{X_{1}^{2}}{2}) + \lambda_{3}(X_{3} - \frac{3X_{1}X_{2}}{4} + \frac{X_{1}^{3}}{8}) + \dots$$

Bootstrapped Lagrangian

 $(\eta + C^{\mu\nu}R_{\mu\nu}(\Gamma) - \sqrt{-|\eta + C|}V(X_1, X_2, X_3, X_4) + L_{matter}(C, \eta, \phi_i, \partial_\mu\phi_i)$

Linearized equations of motion

$$K_{\mu\nu\alpha\beta}h^{\alpha\beta} = (\eta_{\mu\nu}\partial_1 + 2\eta_{\mu\alpha}c^{\alpha\beta}\eta_{\beta\nu}\partial_2 + ...)V + \tau^{(m)}_{\mu\nu}(\eta,\phi_i,\partial_\mu\phi_i)$$
$$\partial_n \equiv \frac{\partial}{\partial X_n} \qquad X_n = (C \cdot \eta)^n \qquad (n = 1...4)$$

"vacuum energy-momentum tensor"

$$T_{\mu\nu}^{(\textit{vac})} = \tau_{\mu\nu}^{(\textit{vac})} - \frac{1}{2}\eta_{\mu\nu} (\tau^{(\textit{vac})})_{\alpha}^{\alpha}.$$

where

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

R. Potting (Algarve)

Bootstrapped Lagrangian

 $(\eta + C^{\mu\nu}R_{\mu\nu}(\Gamma) - \sqrt{-|\eta + C|}V(X_1, X_2, X_3, X_4) + L_{matter}(C, \eta, \phi_i, \partial_\mu\phi_i)$

Linearized equations of motion

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

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

"vacuum energy-momentum tensor"

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

where

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

R. Potting (Algarve)

Bootstrapped Lagrangian

 $(\eta + C^{\mu\nu}R_{\mu\nu}(\Gamma) - \sqrt{-|\eta + C|}V(X_1, X_2, X_3, X_4) + L_{matter}(C, \eta, \phi_i, \partial_\mu\phi_i)$

Linearized equations of motion

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

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

"vacuum energy-momentum tensor"

$$T^{(extsf{vac})}_{\mu
u} = au^{(extsf{vac})}_{\mu
u} - rac{1}{2}\eta_{\mu
u}ig(au^{(extsf{vac})}ig)^lpha_lpha.$$

where

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

R. Potting (Algarve)

Bootstrapped Lagrangian

 $(\eta + C^{\mu\nu}R_{\mu\nu}(\Gamma) - \sqrt{-|\eta + C|}V(X_1, X_2, X_3, X_4) + L_{matter}(C, \eta, \phi_i, \partial_\mu\phi_i)$

Linearized equations of motion

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

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

"vacuum energy-momentum tensor"

$$T^{(\mathrm{vac})}_{\mu
u} = au^{(\mathrm{vac})}_{\mu
u} - rac{1}{2}\eta_{\mu
u} ig(au^{(\mathrm{vac})}ig)^lpha_lpha.$$

where

$$\tau_{\mu\nu}^{(\mathsf{vac})} = (\eta_{\mu\nu}\partial_1 + 2\eta_{\mu\alpha}C^{\alpha\beta}\eta_{\beta\nu}\partial_2 + ...)V$$

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

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



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

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



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

ther

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



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



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

• 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"



• • • • • • • • • • • • •

DISCRETE08

- 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"



DISCRETE08

- 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"



(日) (周) (王) (王)

- 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"



(日) (周) (王) (王)

- 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"



(**D**) (**A B**) (**A**) (**A**

- 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"



(**D**) (**A B**) (**A**) (**A**

- 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"



14 / 15

DISCRETE08

• Classify all integrable and bootstrapped potentials

- Effect of "massive modes": near singularities, or at high temperature?
- Quantum theory ?
- Cosmological implications of vacuum energy-momentum tensor? Dark energy?



- 4 周 ト - 4 日 ト - 4 日 ト

- Classify all integrable and bootstrapped potentials
- Effect of "massive modes": near singularities, or at high temperature?
- Quantum theory ?
- Cosmological implications of vacuum energy-momentum tensor? Dark energy?



- Classify all integrable and bootstrapped potentials
- Effect of "massive modes": near singularities, or at high temperature?
- Quantum theory ?
- Cosmological implications of vacuum energy-momentum tensor? Dark energy?



- Classify all integrable and bootstrapped potentials
- Effect of "massive modes": near singularities, or at high temperature?
- Quantum theory ?
- Cosmological implications of vacuum energy-momentum tensor? Dark energy?



15 / 15

DISCRETE08