Dark Energy as the weight of violating energy conservation

based on
arXiv:1604.04183
work in collaboration with D. Sudarsky and T. Josset

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Energy-Momentum is Conserved in General Relativity

$$R_{ab} - \frac{1}{2} R g_{ab} = \frac{8\pi G}{c^4} \langle T_{ab} \rangle$$

$$\Downarrow$$

$$\nabla^b \langle T_{ab} \rangle = 0$$

As a consequence of
diffeomorphism invariance
(general covariance)

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As a consequence of Bianchi identities

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Energy-Momentum can be (mildly) violated in **Unimodular Gravity**

$$S = \int \sqrt{|g|} R$$

$$g_{ab}\delta g^{ab} = 0$$

$$R_{ab} - \frac{1}{4} R g_{ab} = \frac{8\pi G}{c^4}\left(T_{ab} - \frac{1}{4} T g_{ab}\right)$$

Using Bianchi Identities

$$\frac{1}{4}\nabla_a R = \frac{8\pi G}{c^4}\left(\nabla^b \langle T_{ab}\rangle - \frac{1}{4}\nabla_a \langle T\rangle\right)$$

Integration constant

Vacuum fluctuations do not gravitate! S. Weinberg 1989

Integrating and replacing back into field equations

$$R_{ab} - \frac{1}{2} R g_{ab} + \left(\Lambda_{-\infty} + \frac{8\pi G}{c^4}\int_{\ell} J\right) g_{ab} = \frac{8\pi G}{c^4}\langle T_{ab}\rangle$$

$$J_a \equiv \nabla^b T_{ba}$$

Unimodular Gravity:

an effective low energy description where diffeomorphism invariance can be mildly broken

$$S = \int \sqrt{|g|}R$$

$$g_{ab}\delta g^{ab} = 0$$

General covariance can be broken down to 4-volume preserving diffeomorphism

$$\nabla_a \xi^a = 0$$

$$\xi^a = \epsilon^{abcd}\nabla_b \omega_{cd}$$

$$\delta S_m = \int T_{ab}\nabla^a \xi^b \sqrt{-g}dx^4 = \int J_a \xi^a \sqrt{-g}dx^4 = 0$$

$$J_a \equiv \nabla^b T_{ba}$$

$$dJ = 0 \qquad\qquad J_a = \nabla_a Q$$

Vacuum fluctuations do not gravitate!

S. Weinberg 1989

From Bianchi identities

$$\frac{1}{4}\nabla_a R = \frac{8\pi G}{c^4}\left(\nabla^b\langle T_{ab}\rangle - \frac{1}{4}\nabla_a\langle T\rangle\right)$$

$$R_{ab} - \frac{1}{2}R g_{ab} + \left(\Lambda_{-\infty} + \frac{8\pi G}{c^4}\int_\ell J\right) g_{ab} = \frac{8\pi G}{c^4}\langle T_{ab}\rangle$$

In the context of LFRW: Friedmann like equation

$$J_a \equiv \nabla^b T_{ba}$$

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2}\rho(t) + \frac{\Lambda^{\text{eff}}(t)c^2}{3}$$

$$\Lambda^{\text{eff}}(t) \equiv \Lambda_{-\infty} + \frac{8\pi G}{c^4}\int^t J$$

Models inspired by fundamental Planckian discreteness:

F. Dowker, J. Henson and R. D. Sorkin L. Philpott 2004 and 2009. Sorkin 1986

massless particle phase space distribution $\mu = \mu(x^a, p^a)$

LI diffusion eq. "swerves"

$$p^a \frac{\partial \mu}{\partial x^a} = -(k_1 + k_2) p^a \frac{\partial \mu}{\partial p^a} \mu + k_1 p^a p^b \frac{\partial^2 \mu}{\partial p^a \partial p^b}$$

Lorentz Invariance

$$\nabla^\mu T_{\mu\nu} = \nabla_\nu Q \equiv J_\nu$$

Endothermic case is allowed
$\Delta\Lambda > 0$

$$J = -(3k_1 + k_2) n^\gamma dt = -\xi_{\rm CS} \rho_0^\gamma \left(\frac{a_0}{a}\right)^3 dt$$

$$-10^{-21}\,{\rm s}^{-1} < \xi_{\rm CS} < 2\,10^{-21}\,{\rm s}^{-1}$$

From CMB thermality

F. Dowker, L. Philpott, R. D. Sorkin 2009.

$$\Delta\Lambda^{\rm eff}_{\rm CS} \approx -\frac{2\Omega_0^\gamma H_0 \xi_{\rm CS}}{\sqrt{\Omega_0^{\rm m}} c^2} z_{\rm dec}^{3/2} \approx -\frac{\xi_{\rm CS}}{6\,10^{-19}\,{\rm s}^{-1}} \Lambda^{\rm obs} \qquad z_{\rm dec} \approx 1100$$

Models inspired by fundamental Planckian discreteness:

F. Dowker, J. Henson and R. D. Sorkin L. Philpott 2004 and 2009.

“swerves”

$$\frac{d\mu}{dt} = -\frac{p^i}{E}\partial_i\mu - (k_1 + k_2)\,\frac{\partial\mu}{\partial E} + k_1 E\frac{\partial^2\mu}{\partial E^2}$$

$$J = -(3k_1 + k_2)n^\gamma dt = -\xi_{\rm CS}\rho_0^\gamma\left(\frac{a_0}{a}\right)^3 dt$$

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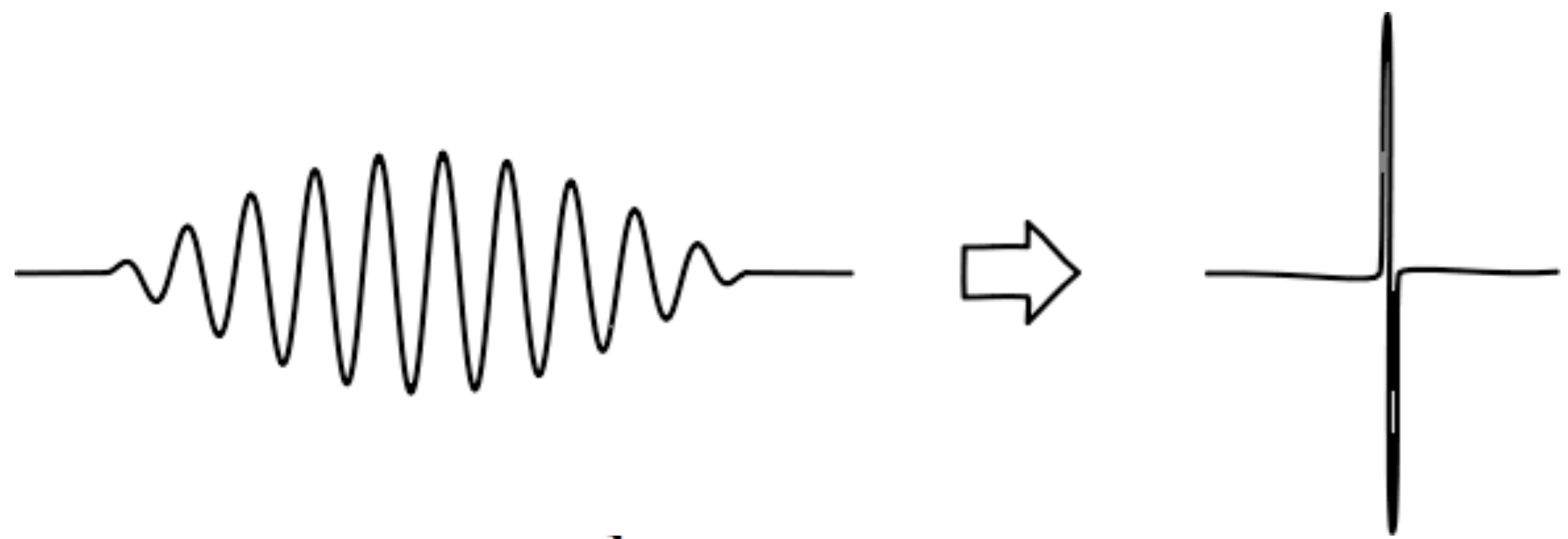
Modified theories of QM: proposals for solving the measurement problem

$$\dot{\hat{\rho}} = -i[\hat{H}, \hat{\rho}] - \frac{1}{2}\sum_{\alpha}\lambda_{\alpha}[\hat{Q}_{\alpha}, [\hat{Q}_{\alpha}, \hat{\rho}]] \qquad \langle E \rangle \equiv \mathrm{Tr}[\hat{\rho}\hat{H}]$$

Continuous Spontaneous Localization (**GSL**)



Exothermic!

$\Delta\Lambda < 0$

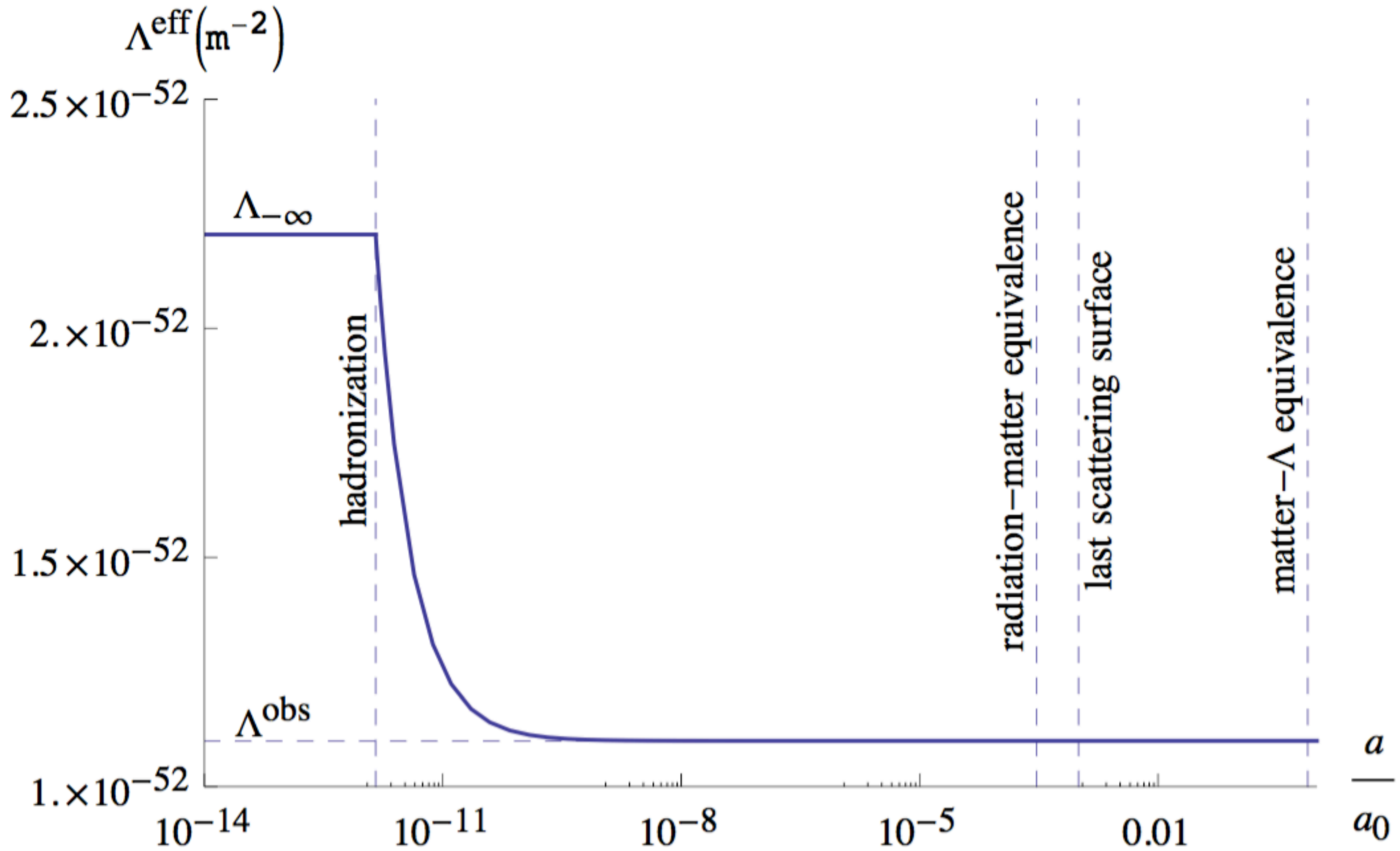
$$J = -\xi_{\rm CSL}\,\rho^{\rm b}\,dt$$

$$z_{\rm h} \approx 7\,10^{11}$$

$$\Delta\Lambda^{\rm eff}_{\rm CSL} \approx -\frac{3\Omega_0^{\rm b} H_0 \xi_{\rm CSL}}{\sqrt{\Omega_0^{\rm r}}c^2} z_{\rm h} \approx -\frac{\xi_{\rm CSL}}{4.3\,10^{-31}\,{\rm s}^{-1}}\Lambda^{\rm obs}$$

$$3.3\,10^{-42}{\rm s}^{-1} < \xi_{\rm CSL} < 2.8\,10^{-29}{\rm s}^{-1}$$

Modified theories of QM: exothermic case $\Delta\Lambda < 0$



The energy-momentum conservation violations have negligible effects on matter's equations of state

$$\rho^\gamma(a) = \rho^\gamma_{\mathrm{h}} \frac{a^4_{\mathrm{h}}}{a^4} \left[1 + \frac{1}{2} \frac{\rho^b_{\mathrm{h}}}{\rho^\gamma_{\mathrm{h}}} \frac{\xi_{\mathrm{CSL}}}{H_{\mathrm{h}}} \left(\frac{a^3}{a^3_{\mathrm{h}}} - 1 \right) \right]^{\frac{2}{3}}$$

$$\frac{\rho^\gamma_{\mathrm{eq}} a^4_{\mathrm{eq}}}{\rho^\gamma_{\mathrm{h}} a^4_{\mathrm{h}}} - 1 \approx \frac{\Omega^{\mathrm{b}}_0}{2(z_{\mathrm{eq}} \Omega^{\mathrm{m}}_0)^{3/2}} \frac{\xi_{\mathrm{CSL}}}{H_0} < 10^{-17}$$

$$z_{\mathrm{eq}} \sim 3000$$

assuming kinetic excess energy is transferred to photons

Breaking diffeomorphism invariance down to **volume preserving diffeomorphism:** standard in QFT on curved spacetimes

Hadamard regularization

$$\nabla^a \langle T_{ab} \rangle_{\rm NO} = \nabla_b Q$$

GR compatible stress tensor satisfying Wald axioms

$$\langle T_{ab} \rangle_{\rm GR} \equiv \langle T_{ab} \rangle_{\rm NO} - Q g_{ab}$$

trace anomaly for CFT's!

Unimodular gravity compatible stress tensor

$$\langle T_{ab} \rangle_{\rm Unimed} \equiv \langle T_{ab} \rangle_{\rm NO}$$

NO trace anomaly! Diffeos broken down to volume preserving ones

Conclusions:

We are proposing a new perspective on the dark energy puzzle in cosmology, that identifies potential violations of energy-momentum conservation in the past (that could also be postulated on a simply phenomenological ground) as a source of dark energy today.

The associated violation of full diffeormorphism invariance is a consequence of the effective nature of the low energy description. A fundamental description of the physics leading to these must be generally covariant.

Thank you very much!

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