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Nonperturbative Effects of Modified Gravity

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OUTLINE

- Brane Induced Gravity

- Features
  - Breakdown of PT
  - vDVZ
  - Two Branches

- Nonperturbative solution (and possible tests)

- Implications
  - (De)coupling limit
  - Consistency of SA branch

Modification of Gravity

Motivation:

Accelerated expansion of the Universe

$$G_{\mu\nu} \ = \ T^{M}_{\mu\nu} + T^{DE}_{\mu\nu}$$

$$G_{\mu\nu} - M_{\mu\nu}(g) \ = \ T^{M}_{\mu\nu}$$

$$\uparrow$$

modification

Could also address the CC problem (higher codim setups)

Example:

Fierz Pauli

$$G_{\mu\nu} + m_g^2(h_{\mu\nu} - \eta_{\mu\nu}h) = T_{\mu\nu}$$

$$m_g \sim H_0 \sim 10^{-42GeV}$$

Immediate Problem!

5 degrees of freedom

massless $\longrightarrow$ 2 tensor,2 vector, 1 scalar

- vDVZ discontinuity

Brane Induced Gravity (DGP)

$$G_{\mu\nu} + m_c(K_{\mu\nu} - g_{\mu\nu}K) = T_{\mu\nu}$$

$$K_{\mu\nu} \sim \partial_y g_{\mu\nu} + \cdots$$

- Arises in higher dim theories

- Action Principle

$$S = \int d^4x\sqrt{g}R + m_c \int d^5x\sqrt{g_5}R_5 + \cdots$$

graviton has 2 kinetic terms

- Perturbative Spectrum (Minkowski background)

Propagator $\sim 1/(p^2 + m_c\sqrt{p^2})$

No massless graviton ($p^2 = 0$ residue vanishes)

Resonance graviton (lifetime $\sim m_c^{-1}$)

Potential on brane $\left| \begin{array}{ll} V(r) \sim 1/r & r \ll m_c^{-1} \\ V(r) \sim 1/r^2 & r \gg m_c^{-1} \end{array} \right.$

- Extrinsic curvature: non-local 4d interpretation

Breakdown of Perturbation Theory

Selfinteraction introduces inverse powers of m_c in a perturbative expansion in G_N

This leads to a premature breakdown of Perturbation Theory at scale $r_* = (r_M r_c^2)^{1/3}$

Sun: $r_* \sim Kpc$

Galaxy: $r_* \sim Mpc$

This is related to the vDVZ discontinuity

Way Out

Perturbation theory should be defined around a classical background created by a source

$R \neq 0$ outside the source up to distance r_* (unlike usual GR)

.

Clues from the equations

$$R = K_{\mu\nu}^2 - K^2$$

linear terms quadratic and higher

trace equation:

$$R + 3m_c K = -T$$

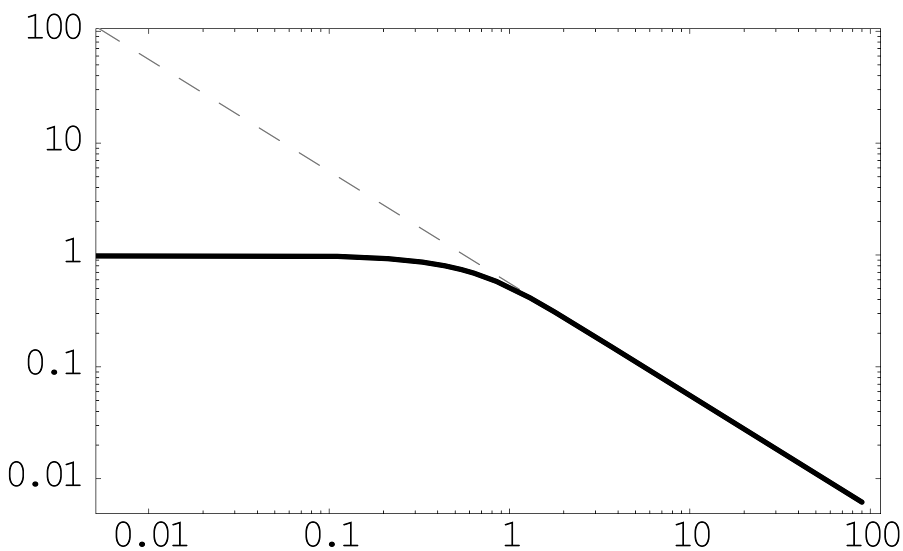
- $R \neq 0$ outside the source
- $R_{lin} = 0 \quad \rightarrow \quad h \sim T/m_c$
- Posible linearization artifacts

Schwarschild Solution

Non-Perturbative solution

$$ds^2 = -e^{-\lambda}dt^2 + e^{\lambda}dr^2 + r^2 d\Omega^2 + e^{\sigma}dy^2 + \gamma dr dy$$

- No vDVZ
- $R \neq 0$ for $r < r_*$
- 5d $M_{eff} \sim M(r_M/r_c)^{1/3}$ (mass screening)
- Potential interpolates smoothly between $1/r$ and $1/r^2$ behavior



To be contrasted with previos perturbative solutions
Gruzinov, Porrati, Lue-Starkman, Tanaka

Tests: Perihelion Precession

Perturbative sol: Dvali Gruzinov Zaldarriaga
Lue Starkman

Non-perturbative solution: PP per orbit

$$\Delta\phi = 2\pi + 3\pi\frac{r_M}{r} \pm \frac{3}{4}\pi .84 \left(\frac{r}{r_*}\right)^{3/2} \left(\frac{r}{r_*}\right)^{0.04}$$

Earth-Moon

$r = 3.84 \times 10^{10}$ cm

$r_*^{Earth} \sim 6.59 \times 10^{12}$ cm

Additional $\pm 0.7 \times 10^{-12}$ (current 2.4×10^{-11})

Sun-Mars

$r = 2.28 \times 10^{13}$ cm

$r_*^{Sun} \sim 4.9 \times 10^{20}$ cm

Additional $\pm 1.3 \times 10^{-11}$ (current 9×10^{-11})

(De)coupling Limit

$$M_{Pl} \rightarrow \infty \qquad m_c \rightarrow 0 \qquad M \rightarrow \infty$$

$$\Lambda \equiv (M_{Pl} m_c^2)^{1/3} \qquad \frac{M}{M_{Pl}} \qquad \text{Fixed}$$

$$3\Box\pi = \frac{(\Box\pi)^2 - (\partial_\mu \partial_\nu \pi)^2}{\Lambda^3} \tag{1}$$

Wrong-sign kinetic term for π on SA background

Luty Porrati Rattazzi, Nicolis Rattzzi

(De)coupling Limit

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$$\tilde{R} + 3\Box\pi \;=\; \frac{(\Box\pi)^2 - (\partial_\mu\partial_\nu\pi)^2}{\Lambda^3} + \frac{\tilde{R}^2 - 3\tilde{R}^2_{\mu\nu}}{\Lambda^3} + \frac{\tilde{R}\Box\pi - 2\tilde{R}^{\mu\nu}\partial_\mu\partial_\nu\pi}{\Lambda^3}$$

$$\tilde{R}_{\mu\nu} = M_{Pl} R_{\mu\nu}$$

$$\tilde{h}_{\mu\nu} = \bar{h}_{\mu\nu} + \eta_{\mu\nu}\pi \qquad \to \qquad \bar{R} = \frac{\bar{R}^2 - 3\bar{R}^2_{\mu\nu}}{3\Lambda^3}$$

Consistency of Self-Accelerated Branch

Koyama, Gorbunov Koyama Sibiryakov
Charmousis Gregory Kaloper Padilla

Spectrum in SA background (dS brane)

- Continuum $m^2 > 9H^2/4$
- $m^2 = 2H^2$ Normalizable
- $m^2 = 0$ Non-normalizable

Empty brane: Effective action for $m^2 = 2H^2$

$$\begin{aligned} L_{eff} &= L_*(A_{\mu\nu}) - HA^{\mu\nu}(\nabla_\mu\nabla_\nu - \gamma_\mu\nu\Box - 3H^2\gamma_{\mu\nu})\varphi \\ &\quad -\frac{9}{4}H^2\varphi(\Box + 4H^2)\varphi \\ \delta A_{\mu\nu} &= (\nabla_m u\nabla_\mu + H^2\gamma_{\mu\nu})\alpha(x) \end{aligned}$$

Field Redefinition:

$$L_{eff} = L_*(B_{\mu\nu}) - \varphi H(\nabla_m u\nabla_n u - \gamma_{\mu\nu}\Box - 3H^2\gamma_{\mu\nu})B^{\mu\nu}$$

Source-free theory quantized without ghosts (as NL QED)

With sources: Amplitude has two solutions

- Doble pole at $m^2 = 2H^2$ + continuum
- Massless pole + continuum

However, in the presence of sources one should take into account screening effects found in the nonperturbative solution

Performing perturbations around that background may yield a consistent perturbative expansion

Further investigation is needed