Nonlocal gravity

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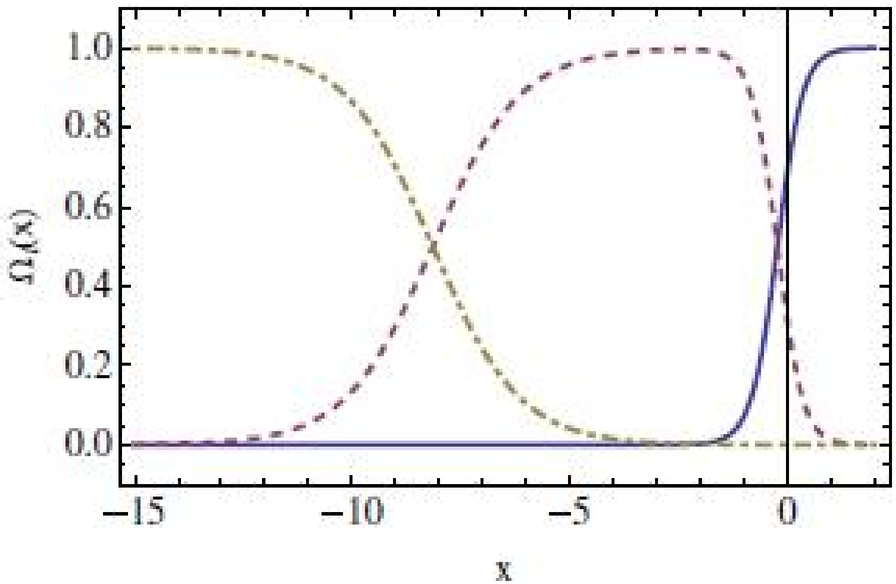
- Motivation to modify gravity: The late-time acceleration
- General result to explain the acceleration



Maggiore etal, PRD, 2014

- Coincidence problem

The following may be a better theory:

- The late-time acceleration
- Newtonian potential Psi=Phi exactly
- Except kappa=8PiG/c^2, only dimensionless parameters appear in the Lagrangian
- Pure geometric theory

For dimensionless parameters:

- Dimension analysis: [R]=length^{-2}
- If we use R^2, then we need length^2*R^2
- The coefficient length^2 can be a parameter (c/H0 etc), or a math operator (Box^{-1}, an integral operator)
- Box^{-1} ➔ nonlocal gravity

History of nonlocal gravity:

- Deser & Woodard, PRL, 2007 (not Psi=Phi)

$$\Delta \mathcal{L} \equiv \frac{1}{16\pi G} R\sqrt{-g} \times f\left(\frac{1}{\Box} R\right) ,$$

- Maggiore & Mancarella, PRD, 2014 (not dimensionless)

$$S_{\rm NL} = \frac{1}{16\pi G} \int d^{d+1}x\sqrt{-g}\left[R - \frac{d-1}{4d} m^2 R \frac{1}{\Box^2} R\right],$$

- And so on, but none of them satisfy previous 4 requirements

One attempt (Tian, PRD, 2018)

$$\mathcal{L}_G = \frac{1}{2\zeta}\left(R_{\mu\nu}\Box^{-1}R^{\mu\nu} - \frac{1}{2}R\Box^{-1}R\right),$$

- [zeta]=[kappa]
- -1/2 is for Psi=Phi, based on

$$ds^2 = -c^2(1 + 2\Phi/c^2)dt^2 + (1 - 2\Psi/c^2)d\mathbf{r}^2,$$

$$\Box^{-1}R^{\mu\nu} = 0 \text{ in the background}$$

- This assumption has been used in: Koivisto, PRD, 2008; Maggiore & Mancarella, PRD, 2014; Kehagias & Maggiore, JHEP, 2014; Conroy etal, CQG, 2015; etc.

How to set the background?

- Cosmological evolution may give the nonlocal field a nonzero value in the solar system scales.
- Belgacem, Finke, Frassino, and Maggiore, JCAP, 2019 proved this with the McVittie metric.
- And then, Deser2007 and Maggiore2014 (RR model) theories are ruled out by the time-varying G observations. (Belgacem2019)

theory: $|\dot{G}_{\text{eff}}/G_{\text{eff}}| = \mathcal{O}(H_0)$.

observations: $|\dot{G}/G| < 10^{-12}\ \text{yr}^{-1} \approx 0.01 H_0$

Revisit Tian2018 model

$$\mathcal{L}_G = \frac{1}{2\zeta}\left(R_{\mu\nu}\Box^{-1}R^{\mu\nu} - \frac{1}{2}R\Box^{-1}R\right),$$

$$\mathrm{d}s^2 = -c^2(1+2\Phi/c^2)\mathrm{d}t^2 + (1-2\Psi/c^2)\mathrm{d}\mathbf{r}^2,$$

$$U_{00} = f_{10}c^2 + f_{11}(\mathbf{r})c^2, \qquad U_{0i} = 0, \qquad U_{\mu\nu} \equiv \Box^{-1}R_{\mu\nu}$$

$$U_{ij} = \delta_{ij}f_{20} + \delta_{ij}f_{21}(\mathbf{r}),$$

- Results:

Psi=Phi

$$G_{\rm eff} = \frac{\zeta c^4}{8\pi[-(f_{10}+f_{20})^2 + f_{10} - f_{20} + 1]},$$

$$|\dot{G}_{\rm eff}/G_{\rm eff}| = \mathcal{O}(H_0).$$

Newtonian approximation in nonlocal Gauss-Bonnet gravity

Capozziello etal, PLB, 20

$$\mathcal{L}_G = \frac{1}{2\kappa}(R - \alpha\mathcal{G}\Box^{-1}\mathcal{G}),$$

[alpha]=length^4

$$\mathcal{G} = R^2 - 4R_{\mu\nu}R^{\mu\nu} + R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}.$$

$$ds^2 = -c^2(1 + 2\Phi/c^2)dt^2 + a^2(1 - 2\Psi/c^2)d\mathbf{r}^2,$$

$$U = U_0(t) + U_1(\mathbf{r}, t), \qquad U \equiv \Box^{-1}\mathcal{G}$$

$$H_0/c \approx \partial/(c\partial t) \ll \partial/(a\partial x)$$

$$\gamma \equiv \frac{\Psi}{\Phi} = \frac{c^4/(8\alpha) + 8H^4 + 8H^2\ddot{A} + C_1 H/a^3}{c^4/(8\alpha) - 24H^4 + 24H^2\ddot{A} + 16\ddot{A}^2 - 3C_1 H/a^3}, \quad \ddot{A} \equiv \ddot{a}/a.$$

$$G_{\rm eff} = \frac{\kappa c^4}{4\pi(\gamma r_1 + r_2)}. \quad r_1 = \frac{2H^2}{\ddot{A}} + 2 - \frac{48\alpha C_1 H^3}{\ddot{A}a^3c^4} + \frac{384\alpha H^2\ddot{A}}{c^4} + \frac{16\alpha C_1 H}{a^3c^4} - \frac{384\alpha H^6}{\ddot{A}c^4} + \frac{512\alpha H^4}{c^4},$$

$$r_2 = -\frac{2H^2}{\ddot{A}} - \frac{16\alpha C_1 H^3}{\ddot{A}a^3c^4} - \frac{128\alpha H^6}{\ddot{A}c^4} - \frac{192\alpha H^4}{c^4}.$$

- Generally, $|\dot{G}_{\rm eff}/G_{\rm eff}| = \breve{\mathcal{O}}(H_0)$. $\Psi \neq \Phi$.
- In the de Sitter phase, Psi=Phi and G_eff is constant.

Summary

- The RT model (Maggiore, PRD, 2014) is the only viable nonlocal gravity theory when confronting observations for now. (Belgacem etal, JCAP, 2019; Tian & Zhu, PRD, 2019)
- Nonlocal gravity may cannot achieve the initial four requirements (Psi=Phi, dimensionless…), and may cannot solve the coincidence problem.

Thanks