THE DARK SIDE OF THE UNIVERSE IN A NONLOCAL DE SITTER GRAVITY

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The Dark Side of the Universe

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Contents

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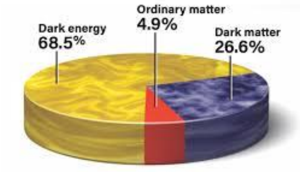
PLB 797 (2019) 134848; arXiv:1906.07560 [gr-qc].
JHEP 12 (2022) 054; arXiv:2206.13515 [gr-qc].
Symmetry **2024**, *16, 544; arXiv:2404.05848 [physics.gen-ph].*

1. Introduction

Standard Model of Cosmology (ΛCDM model)

Supposed that:

- General Relativity (GR) is classical theory of gravitation at all scales from the Solar system to the universe as a whole: $R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi G T_{\mu\nu}(DE + DM + OM)$.
- At the current cosmic time the universe consists of 68 % of dark energy (DE), 27 % of dark matter (DM) and only 5 % of ordinary matter (OM).
- DE = Λ, DM = CDM, ordinary matter = visible matter.
- DE causes accelerated expansion of the universe (1998), DM is responsible for galaxy dynamics (1930th).



1. Introduction

Standard Model of Cosmology

Problems:

- DE and DM are not yet discovered in any experiment.
- GR is not confirmed on galaxy and larger cosmic scales without assumption of DE and DM. GR – singularities, problems with quantization.

Possible solution:

- There is a sense to look for a modified (extended GR) gravity.

$$R_{\mu\nu} - \frac{1}{2} R \, g_{\mu\nu} + \ldots = 8\pi G \, T_{\mu\nu}(OM)$$

- There is no theoretical principle that could tell us in what direction to make modification of GR. Hence, many attempts!
- There are many directions to modify GR.

2. Nonlocal de Sitter gravity

- Einstein equation and Einstein-Hilbert action

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

$$S = \int d^4x \frac{\sqrt{-g}}{16\pi G} R + \int d^4x \sqrt{-g}\, \mathcal{L}(matter)$$

- What does mean modification of GR?

$$R \to f(R, \Lambda, R_{\mu\nu}, R^{\alpha}_{\mu\beta\nu}, \Box, \ldots), \quad \Box = \nabla^{\mu}\nabla_{\mu} = \frac{1}{\sqrt{-g}} \partial_{\mu} \sqrt{-g} g^{\mu\nu} \partial_{\nu}$$

2. Nonlocal de Sitter gravity

- $f(R)$ modified gravity

$$S = \int d^4x \frac{\sqrt{-g}}{16\pi G} f(R) + \int d^4x \sqrt{-g}\, \mathcal{L}(matter)$$

- nonlocal modified gravity

$$S = \int d^4x \frac{\sqrt{-g}}{16\pi G} f(R, \Lambda, \Box, \Box^{-1}, ...) + \int d^4x \sqrt{-g}\, \mathcal{L}(matter)$$

- Here we consider nonlocal approach to modification of GR.

2. Nonlocal de Sitter gravity

- Our nonlocal de Sitter gravity model

$$
\begin{aligned}
S &= \frac{1}{16\pi G}\int \Big(R - 2\Lambda + \sqrt{R-2\Lambda}\,\mathcal{F}(\Box)\,\sqrt{R-2\Lambda}\Big)\sqrt{-g}\,d^4x \\
&= \frac{1}{16\pi G}\int \sqrt{R-2\Lambda}\,F(\Box)\,\sqrt{R-2\Lambda}\Big)\sqrt{-g}\,d^4x
\end{aligned}
$$

where $\mathcal{F}(\Box) = \sum_{n=1}^{+\infty}\big(f_n\Box^n + f_{-n}\Box^{-n}\big)$, $F(\Box) = 1 + \mathcal{F}(\Box)$ and Λ is cosmological constant. Motivation: string theory (ordinary and p-adic), mimics od DE and DM.

- Simple and natural construction of nonlocal term:

$$R - 2\Lambda = \sqrt{R-2\Lambda}\,\sqrt{R-2\Lambda} \to \sqrt{R-2\Lambda}\,\mathcal{F}(\Box)\,\sqrt{R-2\Lambda}$$

- Invariance: $\sqrt{R-2\Lambda} \to -\sqrt{R-2\Lambda}$
- $F(\Box)$ is dimensionless nonlocal operator. Only one parameter, Λ.
- We consider nonlocal modification without matter sector, but we obtain effect of dark matter and dark energy at the cosmological scale. Also rotation curves of spiral galaxies.

2. Nonlocal de Sitter gravity

Action for a class of models:

$$S = \frac{1}{16\pi G}\int_M \Big(R - 2\Lambda + P(R)\mathcal{F}(\Box)Q(R)\Big)\sqrt{-g}\, d^4x$$

where $P(R)$ and $Q(R)$ are some differentiable functions of scalar curvature R.

Equations of motion (EoM):

$$\begin{aligned}
&G_{\mu\nu} + \Lambda g_{\mu\nu} - \frac{1}{2} g_{\mu\nu} P(R)\mathcal{F}(\Box)Q(R) + (R_{\mu\nu} - K_{\mu\nu})\,\Phi \\
&+ \frac{1}{2}\sum_{n=1}^{\infty} f_n \sum_{\ell=0}^{n-1} \big(g_{\mu\nu} g^{\alpha\beta}\partial_\alpha \Box^\ell P(R)\partial_\beta \Box^{n-1-\ell} Q(R) \\
&- 2\partial_\mu \Box^\ell P(R)\partial_\nu \Box^{n-1-\ell} Q(R) + g_{\mu\nu}\Box^\ell P(R)\Box^{n-\ell} Q(R)\big) = 0,
\end{aligned}$$

where $K_{\mu\nu} = \nabla_\mu\nabla_\nu - g_{\mu\nu}\Box$, $\Phi = P'(R)\mathcal{F}(\Box)Q(R) + Q'(R)\mathcal{F}(\Box)P(R)$, and $'$ denotes derivative on R.

A way to solve EoM

- $P(R) = Q(R) = \sqrt{R - 2\Lambda}$
- $\Box\sqrt{R-2\Lambda} = q\sqrt{R-2\Lambda}, \quad \Box^{-1}\sqrt{R-2\Lambda} = q^{-1}\sqrt{R-2\Lambda}, \quad q \neq 0$
  $\mathcal{F}(\Box)\,\sqrt{R-2\Lambda} = \mathcal{F}(q)\,\sqrt{R-2\Lambda}$
- Very simple form of EoM

$$(G_{\mu\nu} + \Lambda g_{\mu\nu})\,(1 + \mathcal{F}(q)) + \frac{1}{2}\mathcal{F}'(q) S_{\mu\nu}(\sqrt{R-2\Lambda}, \sqrt{R-2\Lambda}) = 0$$

where

$$S_{\mu\nu}(P,P) = g_{\mu\nu}\big(\nabla^{\alpha}P\,\nabla_{\alpha}P + P\Box P\big) - 2\nabla_{\mu}P\,\nabla_{\nu}P, \quad P = \sqrt{R-2\Lambda}$$

- Equations of motion are satisfied with conditions:
  $\mathcal{F}(q) = -1 \quad$ and $\quad \mathcal{F}'(q) = 0.$

3. Exact cosmological solutions

- The universe is homogeneous and isotropic space at cosmic scale with FLRW metric

$$ds^2 = -dt^2 + a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta\, d\phi^2\right)$$

k=0 (flat space), k= +1 (closed space), k=-1 (open space)

- We have to solve equation: $\Box\sqrt{R-2\Lambda} = q\sqrt{R-2\Lambda}$

$$\Box = -\frac{\partial^2}{\partial t^2} - 3H(t)\frac{\partial}{\partial t}, \quad H(t) = \frac{\dot{a}}{a},$$
$$R(t) = 6\left(\frac{\ddot{a}}{a} + \left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2}\right), \quad k \in \{0, +1, -1\}.$$

- Then $\mathcal{F}(\Box)\sqrt{R-2\Lambda} = \mathcal{F}(q)\sqrt{R-2\Lambda}$.

3. Exact cosmological solutions

- Equations of motion

$$(G_{\mu\nu} + \Lambda g_{\mu\nu})\,(1 + \mathcal{F}(q)) + \frac{1}{2}\mathcal{F}'(q) S_{\mu\nu}(\sqrt{R - 2\Lambda}, \sqrt{R - 2\Lambda}) = 0$$

have solutions if $\mathcal{F}(q) = -1, \quad \mathcal{F}'(q) = 0.$

- An example of nonlocal operator

$$\mathcal{F}(\Box) = e\Big(a\,\frac{\Box}{q}\,e^{(-\frac{\Box}{q})} + b\,\frac{q}{\Box}\,e^{(-\frac{q}{\Box})}\Big), \quad q = \zeta\Lambda \neq 0, \;\; a + b = -1$$

where ζ is dimensionless parameter depending of a concrete cosmological solution.

3. Exact cosmological solutions

- $a_1(t) = A\, t^{\frac{2}{3}}\, e^{\frac{\Lambda}{14} t^2}, \quad (k = 0,\ \Lambda \neq 0)$
- $a_2(t) = A\, e^{\frac{\Lambda}{6} t^2}, \quad (k = 0,\ \Lambda \neq 0)$
- $a_3(t) = A\, \cosh^{\frac{2}{3}} \left(\sqrt{\frac{3\Lambda}{8}}\, t\right), \quad (k = 0,\ \Lambda > 0)$
- $a_4(t) = A\, \sinh^{\frac{2}{3}} \left(\sqrt{\frac{3\Lambda}{8}}\, t\right), \quad (k = 0,\ \Lambda > 0)$
- $a_5(t) = A \left(1 + \sin\left(\sqrt{-\frac{3\Lambda}{2}}\, t\right)\right)^{\frac{1}{3}}, \quad (k = 0,\ \Lambda < 0)$
- $a_6(t) = A \left(1 - \sin\left(\sqrt{-\frac{3\Lambda}{2}}\, t\right)\right)^{\frac{1}{3}}, \quad (k = 0,\ \Lambda < 0)$
- $a_7(t) = A\, \sin^{\frac{2}{3}} \left(\sqrt{-\frac{3\Lambda}{8}}\, t\right), \quad (k = 0,\ \Lambda < 0)$
- $a_8(t) = A\, \cos^{\frac{2}{3}} \left(\sqrt{-\frac{3\Lambda}{8}}\, t\right), \quad (k = 0,\ \Lambda < 0)$
- $a_9(t) = A\, e^{\pm\sqrt{\frac{\Lambda}{6}}\, t}, \quad (k = \pm 1,\ \Lambda > 0)$
- $a_{10}(t) = A\, \cosh^{\frac{1}{2}} \left(\sqrt{\frac{3\Lambda}{2}}\, t\right), \quad (k = \pm 1,\ \Lambda > 0)$
- $a_{11}(t) = A\, \sinh^{\frac{1}{2}} \left(\sqrt{\frac{3\Lambda}{2}}\, t\right), \quad (k = \pm 1,\ \Lambda > 0)$
- + some anisotropic cosmological solutions. arXiv:2307.00621 [gr-qc].

4. Dark energy and dark matter: Case $a_1(t) = A\, t^{\frac{2}{3}}\, e^{\frac{\Lambda}{14} t^2}$

The Planck 2018 data for the ΛCDM universe are:

- $H_0 = (67.40 \pm 0.50)$ km/s/Mpc – Hubble parameter;
- $\Omega_m = 0.315 \pm 0.007$ – matter density parameter;
- $\Omega_\Lambda = 0.685$ – Λ density parameter;
- $t_0 = (13.801 \pm 0.024) \cdot 10^9$ yr – age of the universe;
- $w_0 = -1.03 \pm 0.03$ – ratio of pressure to energy density.
- $\Lambda = 3H_0^2 \Omega_\Lambda = 0.98 \cdot 10^{-35} s^{-2}$.

Solution $a_1(t) = A\, t^{\frac{2}{3}}\, e^{\frac{\Lambda}{14} t^2}, \quad (k = 0,\ \Lambda \neq 0)$

- mimics dark matter $t^{\frac{2}{3}}$ and dark energy $e^{\frac{\Lambda}{14} t^2}$
- $\Lambda_1 = 1.05 \cdot 10^{-35}\, s^{-2}$ from $H_0 = \frac{2}{3} t_0^{-1} + \frac{1}{7} \Lambda t_0$.
- $\bar{\rho}_1(t_0) = \frac{3}{8\pi G}\left(H_0^2 - \frac{\Lambda_1}{3}\right) = 2.26 \times 10^{-30}\ \frac{g}{cm^3}$.
- $\rho(t_0) = \frac{3}{8\pi G}\left(H_0^2 - \frac{\Lambda}{3}\right) = 2.68 \times 10^{-30}\ \frac{g}{cm^3}$.
- $\rho_c = \frac{3}{8\pi G} H^2(t_0) = 8.51 \times 10^{-30}\ \frac{g}{cm^3}$.
-

$$\Omega_{\Lambda_1} = \frac{\rho_{\Lambda_1}}{\rho_c} = 0.734, \quad \Omega_\Lambda = \frac{\rho_\Lambda}{\rho_c} = 0.685, \quad \Delta\Omega_\Lambda = \Omega_{\Lambda_1} - \Omega_\Lambda = 0.049$$

$$\Omega_m = \frac{\rho(t_0)}{\rho_c} = 0.315, \quad \Omega_{m_1} = \frac{\bar{\rho}_1(t_0)}{\rho_c} = 0.266, \quad \Delta\Omega_m = \Omega_m - \Omega_{m_1} = 0.049.$$

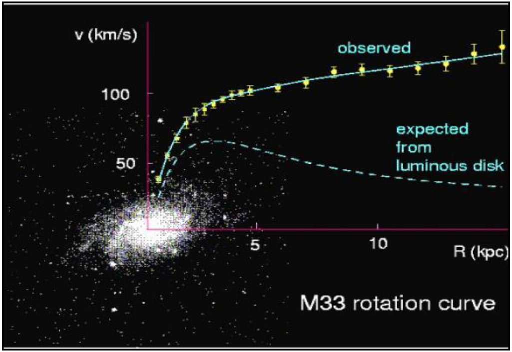
4. Dark energy and dark matter: Case $a_1(t) = A\, t^{\frac{2}{3}}\, e^{\frac{\Lambda}{14} t^2}$

Effective energy density and pressure:

- $\bar\rho = \frac{2t^{-2} + \frac{9}{98}\Lambda^2 t^2 - \frac{9}{14}\Lambda}{12\pi G}\,, \quad \bar p = -\frac{\Lambda}{56\pi G}\big(\frac{3}{7}\Lambda t^2 - 1\big).$
- $\bar w = \frac{\bar p}{\bar\rho} \to -1 \quad \text{when} \quad t \to \infty$
- $t \to 0:\ \bar\rho \to \infty, \quad \bar p \to \frac{\Lambda}{56\pi G}.$
- One can also compute time (t_m) when the Hubble parameter has minimum value H_m, i.e. $t_m = 21.1 \cdot 10^9$ yr and $H_m = 61.72$ km/s/Mpc.
- Beginning of the universe expansion acceleration was at $t_a = 7.84 \cdot 10^9$ yr, or in other words at 5.96 billion years ago.

5. Rotation curves for spiral galaxies

- Dark matter ?



5. Rotation curves for spiral galaxies

$$ds^2 = -A(r)dt^2 + B(r)dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\varphi^2, \qquad (c = 1).$$

Equation that should be solved

$$\Box u(r) = \frac{1}{B(r)}\left(\triangle u(r) + \frac{1}{2}\left(\frac{A'(r)}{A(r)} - \frac{B'(r)}{B(r)}\right)u'(r)\right) = qu(r), \quad u(r) = \sqrt{R - 2\Lambda}$$

$$R = \frac{2}{r^2} - \frac{1}{B(r)}\Big(\frac{2}{r^2} + \frac{2A'(r)}{rA(r)} - \frac{A'(r)^2}{2A(r)^2} - \frac{2B'(r)}{rB(r)} - \frac{A'(r)B'(r)}{2A(r)B(r)} + \frac{A''(r)}{A(r)}\Big)$$

$$\triangle = \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2\frac{\partial}{\partial r}\right] = \frac{\partial^2}{\partial r^2} + \frac{2}{r}\frac{\partial}{\partial r}$$

5. Rotation curves for spiral galaxies

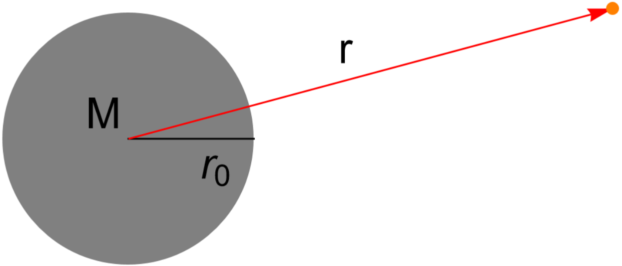


Figure: We consider the Schwarzschild-de Sitter metric of nonlocal $\sqrt{dS}$ gravity at the distances far from a spherically symmetric massive body.

5. Rotation curves for spiral galaxies

After linearization (weak field approximation):

$$A(r) = 1 - \frac{\mu}{r} - \frac{\Lambda r^2}{3} + \frac{\delta}{\sqrt{q} r}\left(1 + e^{-\sqrt{q}\, r}\right) - \frac{2\delta}{q r^2}\left(1 - e^{-\sqrt{q}\, r}\right), \quad q = \zeta \Lambda$$

Finally:

$$v(r) = c\sqrt{\frac{GM}{c^2 r} - \frac{\Lambda r^2}{3} + \frac{\delta}{\sqrt{q} r}\left(\frac{2}{\sqrt{q} r} - \frac{1}{2}\right) - \delta\left(\frac{1}{2} + \frac{3}{2\sqrt{q} r} + \frac{2}{q r^2}\right) e^{-\sqrt{q}\, r}}.$$

5. Rotation curves for spiral galaxies

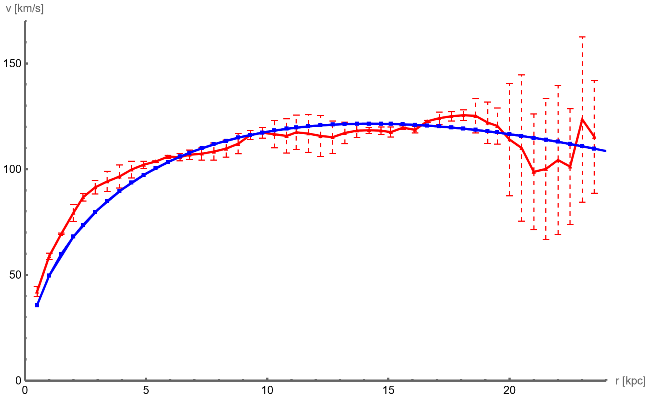


Figure: Rotation curve for the galaxy M33. Red points are measured observational values and blue line is computed $v(r)$ by our Formula, where $\delta = 5.7 \times 10^{-6}$, $\zeta = 3.62 \times 10^{10}$, $\Lambda = 10^{-52}\ \mathrm{m}^{-2}$, and $M = 1.5 \times 10^{3} M_{\odot}$.

5. Rotation curves for spiral galaxies

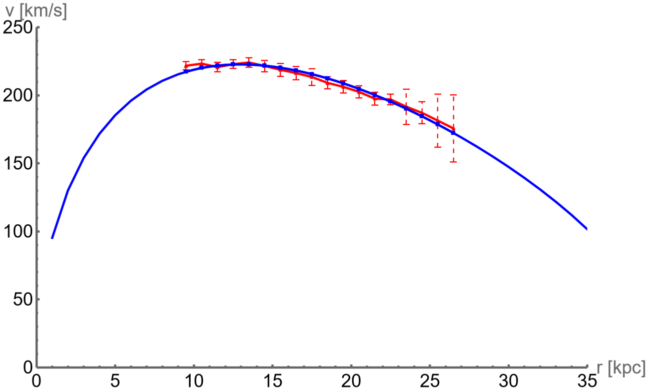


Figure: Rotation curve for the Milky Way galaxy. Red points are measured observational values and blue line is computed $v(r)$ by our Formula, where $\delta = 1.9 \times 10^{-5}$, $\zeta = 4.4 \times 10^{10}$, $\Lambda = 10^{-52}\mathrm{m}^{-2}$, and $M = 4.28 \times 10^{6} M_{\odot}$.

5. Conclusion

- We introduced and analyzed nonlocal de Sitter gravity model $\sqrt{dS}$

$$S = \frac{1}{16\pi G} \int_M \Big(R - 2\Lambda + \sqrt{R - 2\Lambda}\, \mathcal{F}(\Box)\, \sqrt{R - 2\Lambda} \Big) \sqrt{-g}\; d^4 x$$

  as very simple and interesting model in several aspects.
- Model set up and EoM are relatively very simple.
- We found 11 exact cosmological (flat, closed and open) solutions. Some of them are nonsingular bounce, and also cyclic.
- All solutions are new and do not exist in the local de Sitter case.
- The most interesting is exact vacuum cosmological solution

$$a(t) = A\, t^{\frac{2}{3}} e^{\frac{\Lambda}{14} t^2}, \quad \Lambda \neq 0, \;\; k = 0$$

  which mimics dark matter and dark energy. Computed cosmological parameters are in good agreement with observations.
- We also get description of galaxy rotation curves without dark matter.
- The next step is testing this model at other space-time scales and phenomena.

Some more references

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THANK YOU FOR YOUR ATTENTION!