Cosmological Dynamics and Double Screening of DBI-Galileon Gravity

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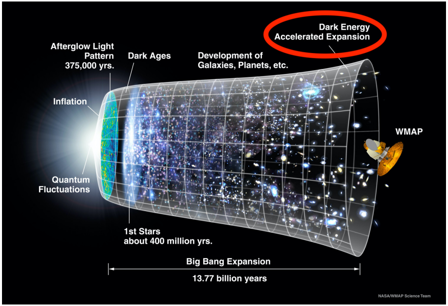
January 10, 2020

Phys.Rev.D **100** (2019) no.4, 044038

Outline

Introduction

Scalar field is one of the successful candidates for dark energy.



https://map.gsfc.nasa.gov/media/060915/index.html

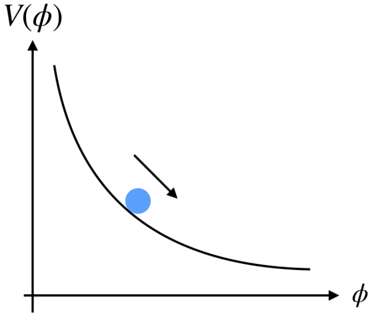
Candidates for dark energy:

- Cosmological constant
- Scalar field
- $f(R)$ gravity
- …

Introduction

Quintessence model:

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi G} - \frac{1}{2}(\partial\phi)^2 - V(\phi)\right]$$



When the scalar field is rolling slowly,

$$w_\phi = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)} \approx -1$$

However...

We have never detected the scalar field!

Degrees of freedom: $2+1$

Introduction

Q: How to hide the scalar field from observations?

A: Using screening mechanism

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Q: What is the screening mechanism?

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Q: How to hide the scalar field from observations?

A: Using screening mechanism

Q: What is the screening mechanism?

A: A mechanism which suppresses a fifth force comparing to the Newtonian force, i.e. $F_\phi/F_N \ll 1$.

fifth force?

Introduction

If a scalar field has interaction with matter field, we obtain a fifth force as

$$F^i_\phi = -\underbrace{\left(\frac{1}{A}\frac{\partial A}{\partial \phi}\right)}_{\text{coupling const.}}\partial^i \phi \quad ; \quad A(\phi) = \text{conformal factor}$$

$*$ we can prove by using conformal transformation on geodesic equation.

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Screening methods:

- range of interaction $\rightarrow$ mass of scalar field (chameleon mechanism)
- modified coupling constant $\rightarrow A(\phi) \propto \exp(\phi^2)$ (ex: symmetron mechanism)

Introduction

- profile of scalar field $\phi(r)$

$$\text{linear model:} \quad \Box\phi = 0 \quad \rightarrow \quad \phi(r) \propto \frac{1}{r}$$
$$\rightarrow \quad F_\phi^r \propto \frac{1}{r^2} \quad \text{(unscreened)}$$

Nonlinear models can provide a non-inverse r^2 fifth force which yield $F_\phi/F_N \ll 1$ at small r.

(ex: Vainshtein mechanism, kinetic screening, D-BIonic screening)

Motivation

"Double screening" (P. Gartia et al., 2016)

We can have both Vainshtein and kinetic screening mechanisms in one model.

$$\mathcal{L} = \underbrace{\overbrace{-\frac{1}{2}(\partial\phi)^2 - \frac{c_3}{\Lambda_v^3}\Box\phi(\partial\phi)^2}^{\text{Vainshtein}} - \frac{c_4}{4\Lambda_*^4}(\partial\phi)^4}_{\text{kinetic screening}} + \frac{g\phi}{M_{\rm PL}}T_m$$

$\Rightarrow$ It is also possible in cubic DBI galileon with some signs flipped.

Research question

What about cosmological dynamics of the DBI galileon model?

Outline

Cosmological dynamics of DBI galileon

DBI galileon (DBI + cubic galileon)

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}M_{\rm PL}^2 R + a_2\sqrt{1+2\lambda X} + a_3\ln(1+2\lambda X)\Box\phi\right] + S_m(A^2(\phi)g_{\mu\nu}, \psi_m)$$

where

- $X = -(\nabla\phi)^2/2$
- $\lambda < 0$: DBI galileon $\Rightarrow \sqrt{1+(\nabla\phi)^2}$
- $\lambda > 0$: DBIonic galileon $\Rightarrow \sqrt{1-(\nabla\phi)^2}$ required for screening mechanism
- scalar field has conformal interaction with matter $\Rightarrow$ fifth force

Cosmological dynamics of DBI galileon

We use dynamical system approach to study cosmological dynamics.

Using flat FLRW metric, the Friedmann equation is

$$3M_{\rm PL}^2 H^2 = \left(-\frac{a_2}{\sqrt{1+\lambda\dot{\phi}^2}} - 6a_3\lambda \frac{H\dot{\phi}^3}{1+\lambda\dot{\phi}^2} \right) + \rho_m + \rho_r \,,$$

Defining dimensionless dynamical variables as

- $x_1 \equiv \dfrac{\dot{\phi}}{H_0 M_{\rm PL}} \quad \propto$ kinetic energy of scalar field
- $x_2 \equiv \dfrac{H}{H_0} \quad \propto$ Hubble parameter
- $x_3 \equiv \dfrac{\rho_r}{3H^2 M_{\rm PL}^2} \quad \propto$ energy density of radiation

Cosmological dynamics of DBI galileon

Differentiating the dynamical parameters we find autonomous equations

$$\begin{aligned}
\frac{dx_1}{dN} &= -\frac{\left(\lambda x_1^2+1\right)}{\Delta x_2}\Big\{2g\Big[3\lambda x_2\Big(x_1^3-(\lambda x_1^2+1)x_2(x_3-1)\Big)+\sqrt{\lambda x_1^2+1}\Big] \\
&\quad +3\lambda x_1^2 x_2^2(x_3-3)+3x_1(x_1+2\lambda x_2)\sqrt{\lambda x_1^2+1}\Big\}\,, \\
\frac{dx_2}{dN} &= \frac{1}{\Delta x_2}\left\{g x_1^2\left[3\lambda x_2\left(x_1^3-(\lambda x_1^2+1)x_2(x_3-1)\right)+\sqrt{\lambda x_1^2+1}\right]\right. \\
&\quad +3\lambda x_1 x_2^2\left[-3x_1^3+2x_2(x_3+3)\right]-(\lambda x_1^2+1) \\
&\quad \left. +x_2\left[6x_1-\lambda x_2 x_3+3\lambda(x_1^3-x_2)\right]\sqrt{\lambda x_1^2+1}\right\}\,, \\
\frac{dx_3}{dN} &= -\frac{2x_3}{\Delta x_2^2}\left\{g x_1^2\left[3\lambda x_2\left(x_1^3-(\lambda x_1^2+1)x_2(x_3-1)\right)+\sqrt{\lambda x_1^2+1}\right]\right. \\
&\quad +3\lambda x_1 x_2^2[-x_1^3+2x_2(x_3-1)]-(\lambda x_1^2+1) \\
&\quad \left. +x_2\left[6x_1-\lambda x_2 x_3+\lambda(3x_1^3+x_2)\right]\sqrt{\lambda x_1^2+1}\right\}. \\
\text{where }\ \Delta &\equiv \lambda\left(3x_1(x_1^3-4x_2)+2\sqrt{\lambda x_1^2+1}\right)\,.
\end{aligned}$$

Fixed points: $dx_1/dN = dx_2/dN = dx_3/dN = 0.$

Cosmological dynamics of DBI galileon

Since $x_2 \propto H$ and $dx_2/dN = 0$, these fixed points give de Sitter spacetime.

$\lambda = -1$	x_1	x_2	x_3
(a)	0	$\frac{1}{\sqrt{3}}$	0
(b)	$\frac{1}{3}\sqrt{\frac{1}{2}\left(\sqrt{37}-1\right)}$	$\frac{1}{3}\sqrt{\frac{1}{2}\left(\sqrt{37}-1\right)}$	0
$\lambda = +1$	x_1	x_2	x_3
(c)	0	$\pm\frac{i}{\sqrt{3}}$	0
(d)	$\pm\frac{i}{3}\sqrt{\frac{1}{2}\left(\sqrt{37}-1\right)}$	$\mp\frac{i}{3}\sqrt{\frac{1}{2}\left(\sqrt{37}-1\right)}$	0

- DBIonic galileon ($\lambda = +1$) does not provide real fixed points.
- There exist two de Sitter solutions in DBI galileon ($\lambda = -1$).

$\therefore$ Only DBI galileon can provide the cosmological evolution.

Stability

Considering eigenvalues of each fixed point,

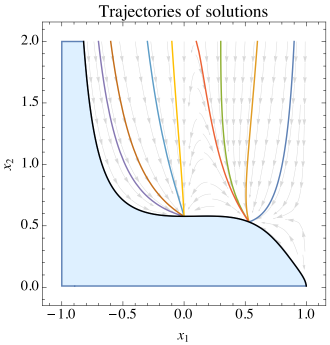
$$\delta x \propto e^{\mu N},$$

For negative eigenvalues μ, at large N, $\delta x \to 0$ (stable).

Eigenvalues:

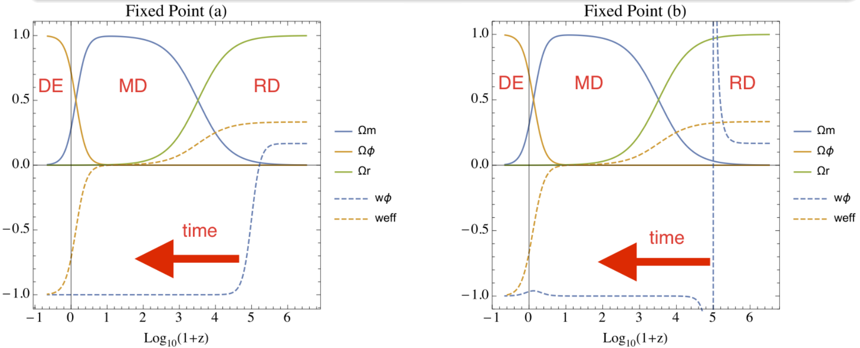
- FP (a): $-4\,, -3\,, -3$ (stable)
- FP (b): $-4\,, -3\,, -3$ (stable)

For nonzero conformal coupling, we find another fixed point. However, one of the eigenvalues is always positive (unstable).



Numerical results

Numerical solutions for DBI galileon with zero conformal coupling



- The fixed point (a) gives $x_1 = 0$, which is similar to the cosmological constant.
- For the fixed point (b), the kinetic term still exists.

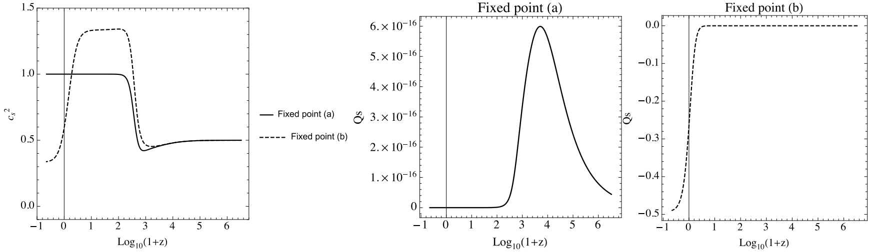
Both fixed points give cosmological evolution successfully.

Ghost and Laplacian instability

To avoid the ghost and Laplacian instability, we require

$$S_s^{(2)} = \int d^4x a^3 Q_s \left[\dot{\zeta}^2 - \frac{c_s^2}{a^2}(\partial\zeta)^2\right] \quad \Rightarrow \quad Q_s > 0\,, \quad c_s^2 > 0$$

Using numerical results we find



- both fixed points have $c_s^2 > 0$.
- the fixed point (b) has $Q_s < 0$ at late-time, thus only the fixed point (a) can avoid the ghost instability.

Outline

Screening mechanism

The fifth force from conformal interaction is given by

$$F_\phi^r \equiv -\frac{A_{,\phi}}{A}\frac{d\phi}{dr} = -\frac{g}{M_{\rm PL}}\frac{d\phi}{dr}\,. \quad g : \text{conformal coupling}$$

Screening mechanism

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From equation of motion,

$$\nabla_\mu\left(\frac{1}{\sqrt{1+2\lambda X}}\nabla^\mu\phi\right) + \frac{1}{\Lambda^3}\nabla_\mu\left(\frac{1}{1+2\lambda X}\left(\nabla^\mu\phi\Box\phi - \nabla_\nu\phi\nabla^\mu\nabla^\nu\phi\right)\right) = \frac{g}{M_{\rm PL}}\rho_m ,$$

Using flat static spherically symmetric metric, we find

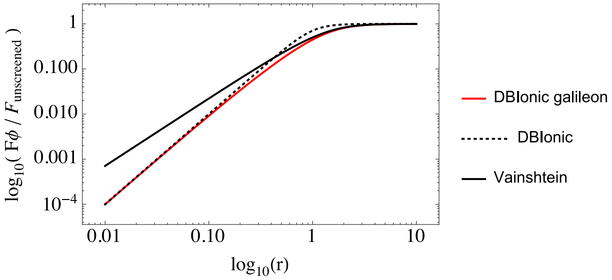
$$\phi'(r) = \sqrt{\frac{2\tilde{A}^2}{\frac{4\tilde{A}r}{\Lambda^3} + r^4 + 2\tilde{A}^2\lambda + \sqrt{r^8 + 8\tilde{A}r^5/\Lambda^3}}} , \qquad \tilde{A} \equiv \frac{gM}{4\pi M_{\rm PL}}$$

In the limit $r \to 0$, $\phi'(r) \simeq \sqrt{\frac{1}{\lambda}} \Rightarrow \therefore \lambda$ must be positive.

$\therefore$ Only DBIonic galileon has screening mechanism.

Screening mechanism

Defining $F_{\text{unscreened}} \equiv 2g^2 F_N$,



- at large distances $\Rightarrow$ Vainshtein mechanism
- at short distances $\Rightarrow$ DBIonic (kinetic) screening.

$\therefore$ DBIonic galileon possesses double (two) screening mechanisms.

Outline

Summary

We study cosmological dynamics and screening mechanism of the DBI galileon (DBI + cubic galileon) model

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}M_{\rm PL}^2 R + a_2\sqrt{1+2\lambda X} + a_3 \ln(1+2\lambda X)\Box\phi\right] + S_m(A^2(\phi)g_{\mu\nu}, \psi_m)$$

- only DBI galileon ($\lambda < 0$) can provide cosmological evolution successfully.
- only DBIonic galileon ($\lambda > 0$) has screening mechanisms (Vainshtein and DBIonic).

We are still looking for a model which can unifies both situations.

Thank you very much for your attention!