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Gravity and Cosmology 2018

Study on Chameleonic Dark Matter in F(R) Gravity

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Reference

"Dark matter in modified gravity?" Phys. Rev. D95 044040 (2017)

"Cosmic History of Chameleonic Dark Matter in F(R) Gravity" arXiv:1708.08702

In collaboration with
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Introduction

Many kinds of Modified Gravity have been investigated.

- UV modification
  - effective theory for quantum gravity
- IR modification
  - Dark energy instead of cosmological constant

- How to test modified gravity theories?
  - Cosmology
  - Astrophysics
  - Gravitational Waves
  - Dark matter

→ To explore new application of modified gravity from viewpoint of particle physics!

N.B.) NOT modified Newtonian dynamics, but particle DM

New Scalar Field in F(R) Gravity

F(R) Gravity is one of modified gravity theories.

F(R) gravity in Jordan Frame : $g_{\mu\nu}$

$$S = \frac{1}{2\kappa^2}\int d^4x\sqrt{-g}F(R)$$

cf.) EH-action

$$\int d^4x\sqrt{-g}R$$

Replace: $R \to F(R)$

Weyl trans.

$$\tilde{g}_{\mu\nu} = \Omega^2(x)g_{\mu\nu}\,,\ \ \Omega^2(x) = F_R(R) \equiv \mathrm{e}^{2\sqrt{1/6}\kappa\varphi(x)}$$

F(R) gravity in Einstein frame : $\tilde{g}_{\mu\nu}$

$$S = \int d^4x\sqrt{-\tilde{g}}\left[\frac{1}{2\kappa^2}\tilde{R} - \frac{1}{2}\tilde{g}^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi - V(\varphi)\right]$$

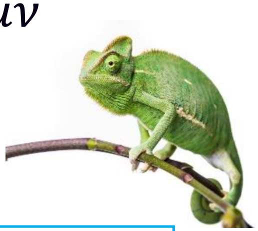
where $V(\varphi) = \dfrac{1}{2\kappa^2}\dfrac{F_R(R)R - F(R)}{F_R^2(R)}$

New scalar field $\varphi(x)$ appears (Scalaron)

Viable F(R) gravity possesses Chameleon mechanism

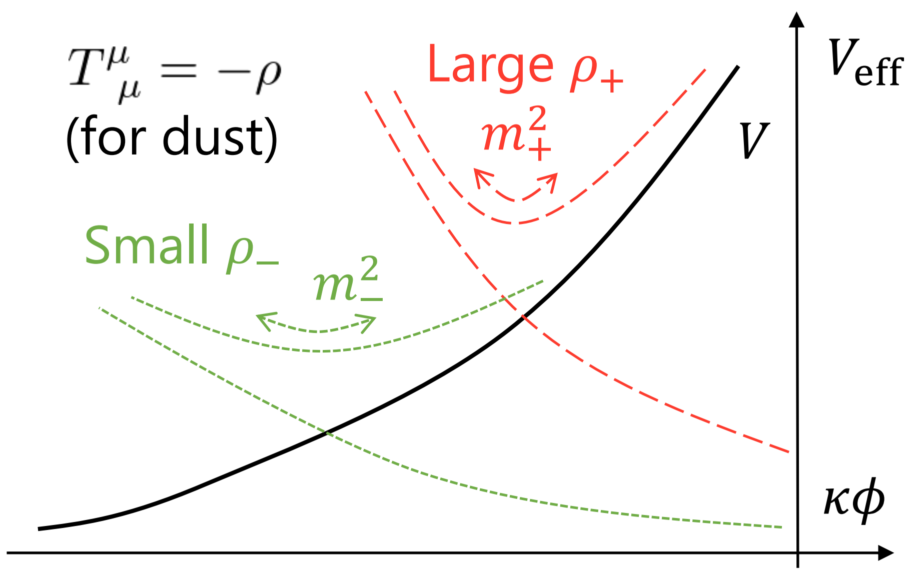
[Khoury and Weltman (2004)]

Potential of scalar field $V(\varphi)$ couples with trace of $T_{\mu\nu}$



$$\tilde{\Box}\varphi = \partial_\varphi V_{\text{eff}}(\varphi)\,,\ \ V_{\text{eff}}(\varphi) = V(\varphi) - \frac{1}{4}e^{-4\sqrt{1/6}\kappa\varphi}T^{\mu}_{\ \mu}$$

Chameleon Mechanism



Scalaron mass

$$m_\varphi = V''_{\text{eff}}(\varphi_{\min})$$

In high-density region, scalar field is heavy and suppressed.

The fifth force is screened in Solar System

Dark Matter in F(R) Gravity ?

At classical level, scalar field is responsible for DE.

→ Particle picture of scalaron field?

→ "chameleon" particle [Burrage and Sakstein (2017)]

Scalaron's properties

- SM singlet scalar field from modified gravity
- Massive because of chameleon mechanism
- Very weak interaction suppressed by $M_{\rm pl}$

Scalaron can be a DM candidate?

[Nojiri and Odintsov (2008)], [Cembranos (2009)] etc.

Scalaron Field	=	Background	+	Oscillation
		Dark Energy		Particle Picture = Dark Matter

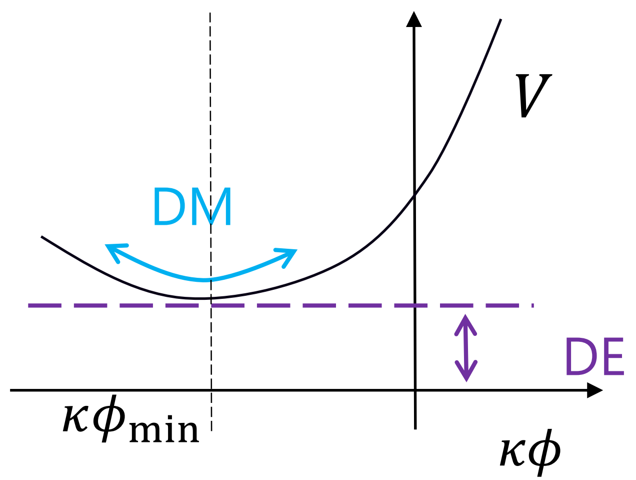
Chameleonic DM and Coincidence Problem

Scalar field with chameleon mechanism

- "Chameleonic" Dark Matter
- Environment-dependence (choice of T_{μ}^{μ})
- Scalaron mass is NOT constant, but determined by other ordinary matters
- Depends on cosmic history (time-dependent mass)

Scalar field for two dark components

- Unified treatment of DM & DE in one theory
- To estimate DM-DE ratio, and address coincidence problem
- To expect DM and DE densities are of same order



Cosmic Environment in Early Universe

To construct the time evolution of $T^{\mu}_{\mu} = -(\rho - 3p)$.

$$V_{\text{eff}}(\varphi) = V(\varphi) + \frac{1}{4} e^{-4\sqrt{1/6}\kappa\varphi}(\rho - 3p)$$

Trace of Energy-Momentum Tensor

$$\rho - 3p = \frac{gT^4}{2\pi^2} x^2 \int_0^\infty d\xi \frac{\xi^2}{\sqrt{\xi^2 + x^2}} \frac{1}{\mathrm{e}^{\sqrt{\xi^2+x^2}} \pm 1} \qquad x = \frac{m}{T},\ \xi = \frac{p}{T}$$

At high temp. (relativistic)

$$\rho - 3p \approx \frac{g}{24} m^2 T^2 \begin{cases} 2 \text{ for bosons} \\ 1 \text{ for fermions} \end{cases}$$

At low temp. (non-relativistic)

$$\rho - 3p \approx \rho \approx mg \left(\frac{mT}{2\pi} \right)^{3/2} \mathrm{e}^{-m/T}$$

For massless particles $\rho - 3p = 0$ (Radiation)

Model of F(R) Gravity

Starobinsky model with R^2 correction

$$F(R) = R - \beta R_c \left[1 - \left(1 + \frac{R^2}{R_c^2}\right)^{-n}\right] + \alpha R^2$$

where $R_c \sim \Lambda$ is constant curvature, and $\alpha, \beta, n > 0$

$$F(R) = R - \beta R_c \left[1 - \left(1 + \frac{R^2}{R_c^2}\right)^{-n}\right]$$

Viable F(R) gravity model for DE

[Starobinsky (2007)]

$$\alpha R^2$$

to cure singularity problem

[Frolov (2008)]
[Kobayashi and Maeda (2008)]
[Dev et al. (2008)]

In large-curvature limit $R > R_c$ (chameleon mechanism works in high-density region),

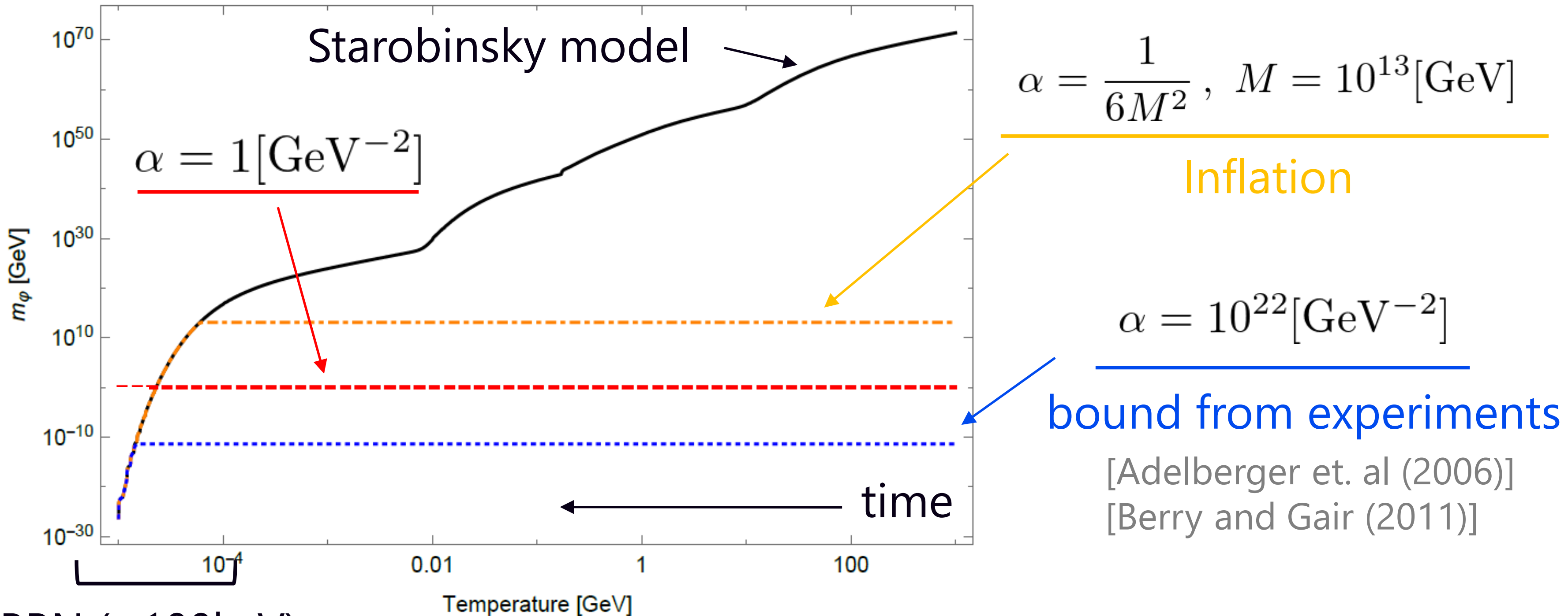
$$F(R) \approx R - \underline{\beta R_c} + \beta R_c \left(\frac{R}{R_c}\right)^{-2n} + \alpha R^2 \qquad \frac{\beta R_c \approx 2\Lambda}{\beta \gtrsim \mathcal{O}(1)}$$

Scalaron Mass in Early Universe

Mass

$$m_\varphi^2 = \frac{R_c}{6n(2n+1)\beta}\left[\left(-\frac{\kappa^2 T}{R_c}\right)^{-2(n+1)} + \frac{\alpha R_c}{n(2n+1)\beta}\right]^{-1}\frac{1}{1-2\alpha\kappa^2 T}$$

For $n = 1, \beta = 2, R_c = \Lambda$ cf.) $\beta R_c = 2\Lambda$



[Adelberger et. al (2006)]
[Berry and Gair (2011)]

BBN (~100keV)

$m_\varphi^2 \sim \alpha^{-1}$ in early Universe cf.) R^2-inflation

Scalaron Mass in Current Universe

Scalaron mass in the current Universe.

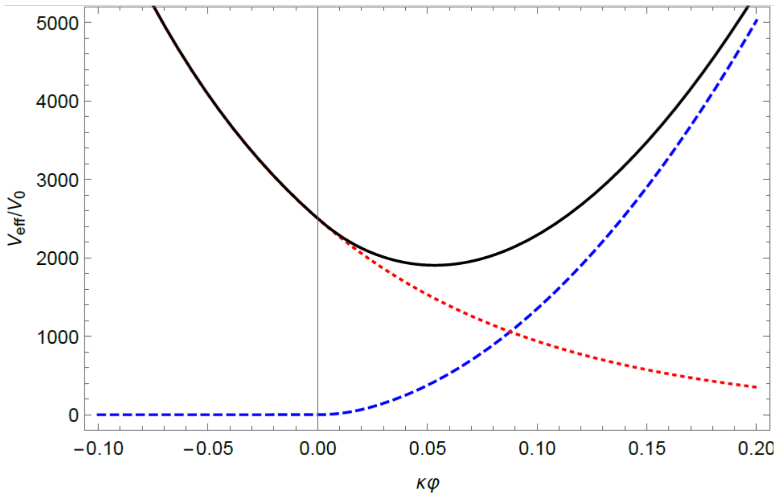
As an example, we study the environment in the galaxy

Typical density

$$-T^{\mu}_{\ \mu} = \rho \sim 3\text{–}5 \times 10^{-25}[\mathrm{g/cm^3}]$$

Scalaron mass

$$m_\varphi = 10^{-24} \sim 10^{-23}[\mathrm{eV}]$$



Scalaron is very light in the current Universe.

Ultralight axion $m \sim 10^{-23} \sim 10^{-22}$ [eV] for problems in small-scale structure [Hu, Barkana, Gruzinov (2000)]

→ “Ultralight scalaron” also solves the problems?

Matter Coupling to SM Particles

Matter Sector

exponential form $\mathrm{e}^{Q\kappa\varphi}$

$$S_{\text{Matter}} = \int d^4x \sqrt{-g}\mathcal{L}\left(g^{\mu\nu}, \Psi\right)$$
$$= \int d^4x \sqrt{-\tilde{g}}\, \underline{\mathrm{e}^{-4\sqrt{1/6}\kappa\varphi(x)}\mathcal{L}\left(\mathrm{e}^{2\sqrt{1/6}\kappa\varphi(x)}\tilde{g}^{\mu\nu}\right.}, \left.\Psi\right)$$

$$\varphi \to \varphi_{\min} + \varphi$$

$$\mathrm{e}^{Q\kappa\varphi(x)} \to \mathrm{e}^{Q\kappa\varphi_{\min}}\mathrm{e}^{Q\kappa\varphi(x)}$$
$$\approx \underbrace{\mathrm{e}^{Q\kappa\varphi_{\min}}}_{\text{Frame-deference}} \cdot \left(1 + \underbrace{Q\kappa\varphi + \mathcal{O}(\kappa^2\varphi^2)}_{\text{Coupling to matter}}\right)$$

Frame-deference Coupling to matter

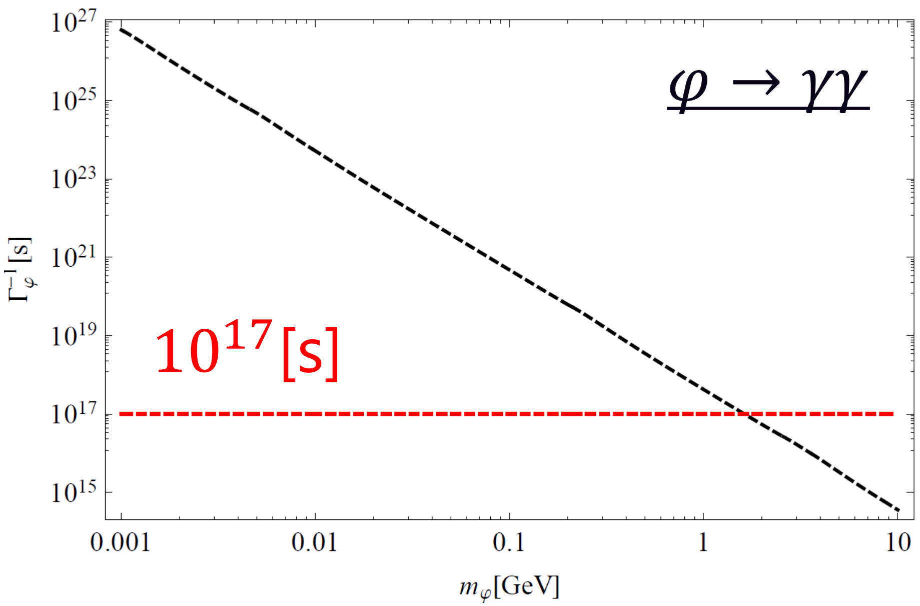
Massless vector field: $\mathcal{L} \supset g^2 \dfrac{\varphi}{M_{\text{pl}}} F_{\mu\nu}^2$ (induced from anomaly)

Massive fields: $\mathcal{L} \supset m^2 \dfrac{\varphi}{M_{\text{pl}}} \bar{\psi}\psi\,,\ m^2 \dfrac{\varphi}{M_{\text{pl}}} \tilde{g}^{\mu\nu} A_\mu A_\nu$

cf.) Coupling similar to Axion or Dilatonic DM

Scalaron Lifetime at late-time Universe

At late-time, the scalaron mainly decays into diphotons because scalaron mass becomes smaller in the cosmic history.



Lifetime $\Gamma_\varphi^{-1} \geq 10^{17}[\mathrm{s}]$

$\to m_\varphi \leq O(1)[\mathrm{GeV}]$

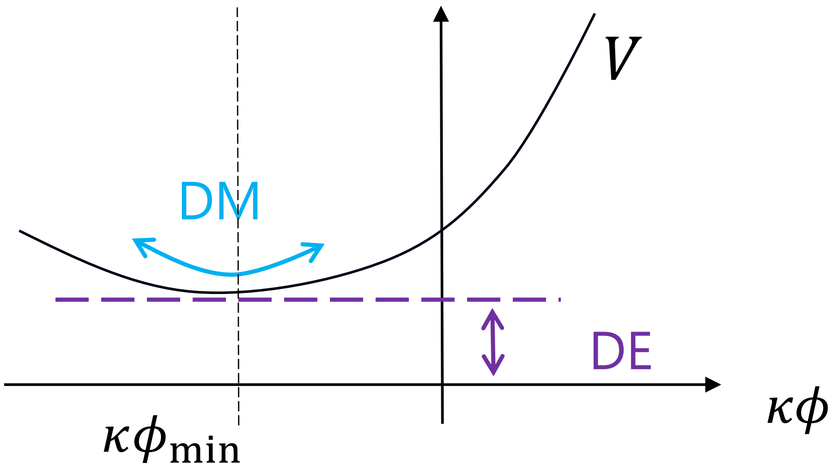
cf.) in galaxy at present

$$m_\varphi = 10^{-24} \sim 10^{-23}[\mathrm{eV}]$$

cf.) Scalaron can be heavy in early Universe because it is in very short time

→ Small effect to total lifetime

Scalaron Relic Density



$$\rho = \frac{1}{2}\dot{\varphi}^2 + V(\varphi)$$

To estimate scalaron energy density at current Universe

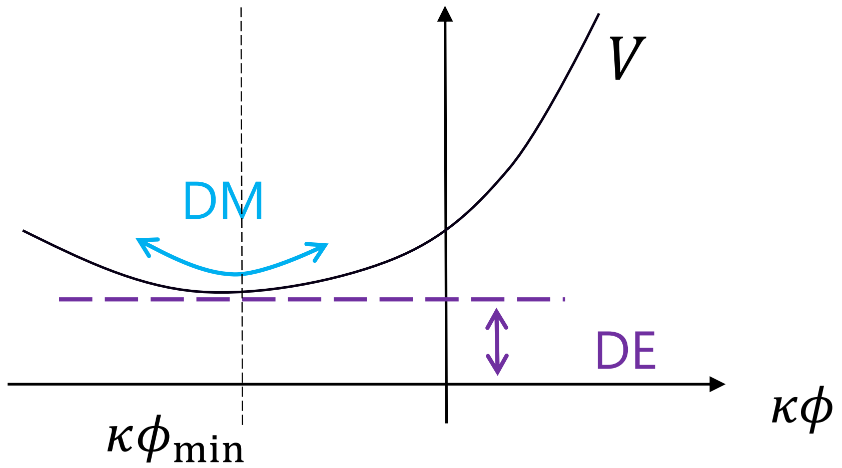
To assume harmonic oscillation approximation is valid.

$$\kappa\varphi \approx \underbrace{\kappa\varphi_0}_{\text{Amplitude} \ll 1} \cos(mt) + \kappa\varphi_{\rm min}\,, \quad V(\varphi) \approx V(\varphi_{\rm min}) + \frac{1}{2}m^2(\varphi - \varphi_{\rm min})^2$$

$V'(\varphi_{\rm min}) = 0$

We obtain $\rho \approx \frac{1}{2}m^2\varphi_0^2 + V(\varphi_{\rm min})$

Scalaron Relic Density



$$\rho = \frac{1}{2}\dot{\varphi}^2 + V(\varphi)$$

harmonic oscillation approximation

$$\rho \approx \frac{1}{2}m^2\varphi_0^2 + V(\varphi_{\mathrm{min}})$$

$V(\varphi_{\mathrm{min}}) = \frac{\Lambda}{\kappa^2}$ for scalaron potential energy to be DE

$m_\varphi > 3H_0$ for scalaron to harmonically oscillate at present

If we input DM:DE≈3:7, we get $\kappa\varphi_0 < 0.3$

- Consistent with approximation, $\kappa\varphi_0 < 1$
- We need all cosmic history to predict precise DM density (= initial condition/value of scalaron)

Summary and Discussion

We studied scalaron as new dark matter candidate.

- Mass changes according to cosmic environment
- Very light in current Universe, possibly heavy in early Universe
- Long lifetime to be DM candidate at late-time
- Possibility to address the coincidence problem

Constraints on this scenario from (in-)direct detection

- Heavy scalaron at galactic center decays to photons?
- To discriminate from axion?
- Non-constant mass or chameleon mechanism are keys

Analysis in the early Universe

- Conditions for scalaron to survive in the early Universe?
- To include other BSM? (inflation, Particle creation etc.)
- Depends on our understanding of cosmic history