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Chameleonic Dark Matter and 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" Phys. Rev. D97, 064037 (2018)

Work in progress with

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Outline of Our Research

Modified gravity can explain DM as well as DE?

Modified gravity is one solution to answer DE problem.

- Can we explain other problems or mysteries in the same framework (theory or model) at the same time?

New field introduced by modification of gravity

- Dynamical DE （Cosmological "constant"→"Field" ）
- Background to explain accelerated expansion
  ＋ "Oscillation around background"
- When oscillation is quantized, we obtain particle picture
- Particle picture of new field ＝ New particle＝DM?

Difference from MOND-like theory

- Not a modification to explain only galaxy rotation curve
- "Particle DM" appears from the modified gravity

F(R) Gravity Theory

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

New scalar field "scalaron" $\varphi(x)$ appears from F(R)

Chameleon mechanism in F(R) gravity

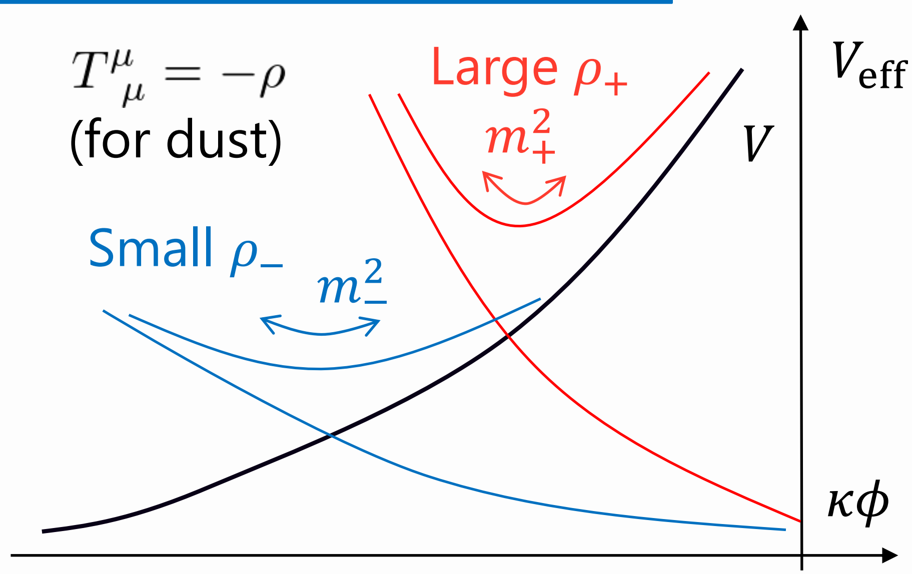
[Khoury and Weltman, (2004)] [Brax et. al (2008)]

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

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

Chameleon Mechanism

$T^\mu_{\ \mu} = -\rho$ (for dust)



Scalaron mass

$$m_\varphi^2 = V''_{\rm eff}(\varphi_{\rm min})$$

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

In low-density region, scalar field acts as DE.

Strategy and Issues

How to confirm scalaron can be DM?

Several suggestions in previous research

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

- Role of chameleon mechanism?
- Stability (Lifetime), Relic abundance, DM search experiments ?
- Constraint on F(R) gravity ?

Fundamental properties depend on “environment”

- To specify the situation which we consider
- To “reproduce” environment by hand (how to choose T_{μ}^{μ})

Scalaron changes in the cosmic history

- To discuss scalaron at a given epoch
- To “patchwork” independent results and examine the cosmic history of scalaron

Matter Coupling

Matter Sector

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

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

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

$$\mathrm{e}^{Q\kappa\varphi(x)} \to \mathrm{e}^{Q\kappa\varphi_{\mathrm{min}}}\mathrm{e}^{Q\kappa\varphi(x)}$$
$$\approx \mathrm{e}^{Q\kappa\varphi_{\mathrm{min}}} \cdot \left(1 + Q\kappa\varphi + \mathcal{O}(\kappa^2\varphi^2)\right)$$

Frame-deference   Coupling to matter

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

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

cf.) Coupling similar to Axion or Dilatonic DM

Coupling to SM Particles

Scalaron universally couples with SM particles

For massless vector field (Photon, Gluon)

$$\mathcal{L} = -\frac{3g_V^2}{4(4\pi)^2}\left(\frac{3}{2}\sqrt{\frac{1}{6}}\kappa\varphi\right) \mathrm{tr}\left[F_{\mu\nu}^2(V)\right] + \mathcal{O}(\kappa^2\varphi^2)$$

For photon $F_{\mu\nu}(A) = \partial_\mu A_\nu - \partial_\nu A_\mu\,,\ g_A = e$

For gluon $F_{\mu\nu}(G) = \partial_\mu G_\nu - \partial_\nu G_\mu - ig_G[G_\mu, G_\nu]\,,\ g_G = g_s$

For massive vector field (Weak bosons)

$$\mathcal{L} = \frac{2\kappa\varphi}{\sqrt{6}} \cdot \frac{1}{2} m_V^2 \tilde{g}^{\mu\nu} A_\mu A_\nu + \mathcal{O}(\kappa^2\varphi^2)$$

For massive fermion field (Quarks, Leptons)

$$\mathcal{L} = \frac{\kappa\varphi}{\sqrt{6}} \cdot m_F \bar{\psi}'\psi' + \mathcal{O}(\kappa^2\varphi^2) \qquad \psi \to \psi' = \mathrm{e}^{-3/2\sqrt{1/6}\kappa\varphi}\psi$$

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)

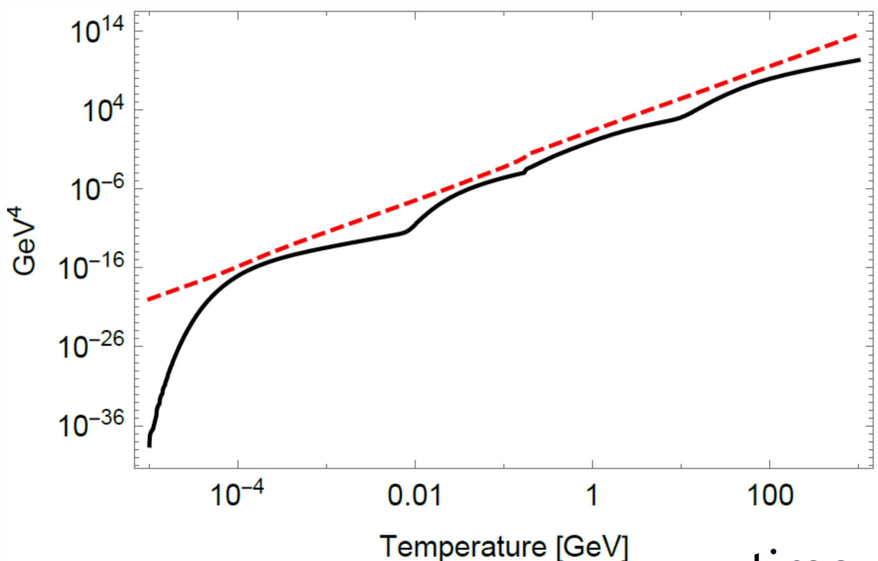
To construct the time evolution of $T^{\mu}_{\mu} = -(\rho - 3p)$

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

Trace of Energy-Momentum Tensor

For SM particles

$\rho - 3p$ and ρ



time

F(R) model for DE

We consider the Starobinsky model with R^2 correction

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 $R_c \sim \Lambda$ and $\alpha, \beta, n > 0$

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

$$F(R) \simeq R - \beta R_c + \beta R_c \left(\frac{R_c}{R}\right)^{2n} + \alpha R^2$$

where $\beta R_c \approx 2\Lambda$, $\beta \gtrsim \mathcal{O}(1)$

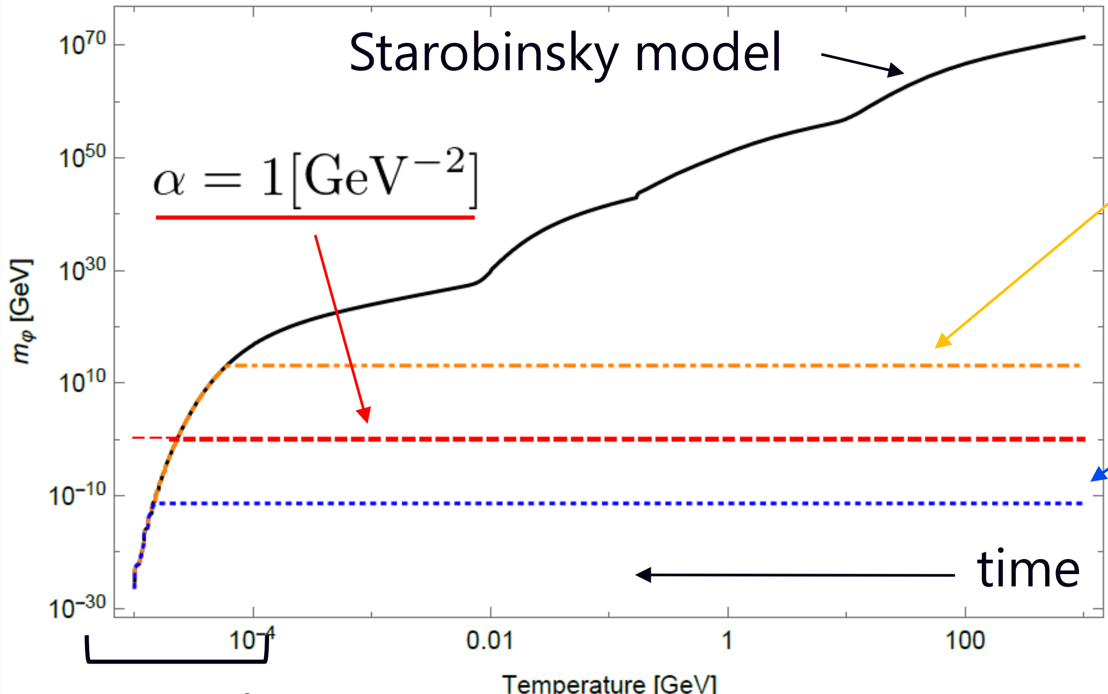
To convert it into scalaron potential $V(\varphi) = \frac{1}{2\kappa^2} \frac{F_R(R)R - F(R)}{F_R^2(R)}$

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.) $\beta R_c = 2\Lambda$



BBN (~100keV)

$\alpha = \frac{1}{6M^2}$, $M = 10^{13}[\mathrm{GeV}]$

Inflation

$\alpha = 10^{22}[\mathrm{GeV}^{-2}]$

bound from experiments

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

$m_\varphi^2 \sim \alpha^{-1}$ 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

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

Scalaron is very light in the current Universe.

cf.) Ultralight axion ($m \sim 10^{-23} \sim 10^{-22}$ [eV])

- "Ultralight scalaron" also solves the small-scale problems?

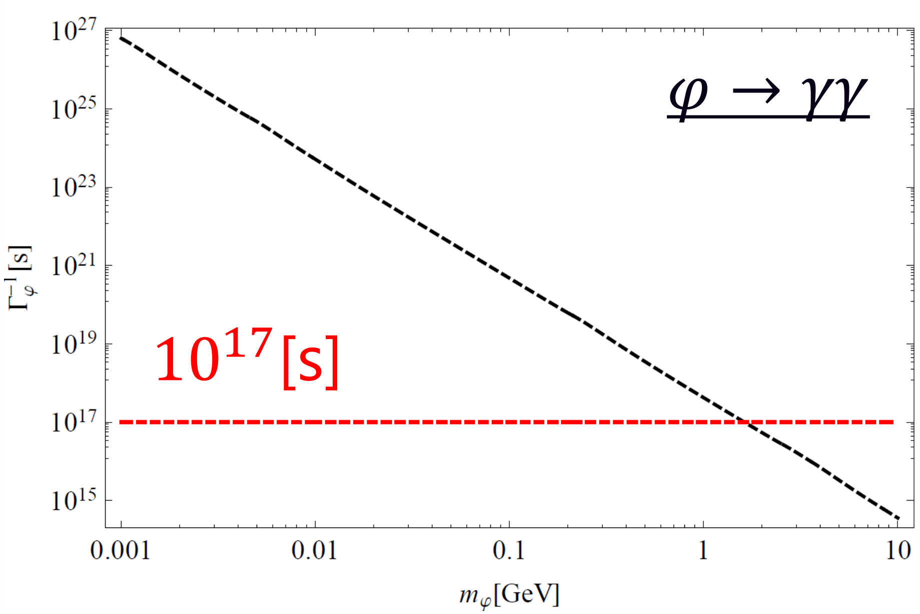
Scalaron can decay to other particles

- We need to check stability (long-lived?)

Stability in Late-time Universe

Scalaron lifetime in the late-time Universe

Scalaron mainly decays into diphotons
because scalaron mass becomes smaller and smaller.



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

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

cf.) in galaxy at present

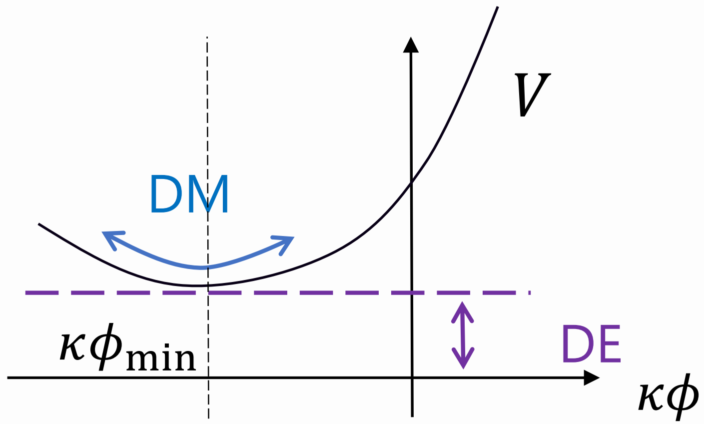
$$m_\varphi = 10^{-24} \sim 10^{-23}[\mathrm{eV}]$$

Scalaron is stable in current Universe

- Stability in early Universe is controlled by parameter α
- What about relic density?

How to estimate relic abundance of scalaron?

Non-thermal production



cf.) Coherent oscillation of Axion

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

To assume harmonic oscillation of scalaron at present

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

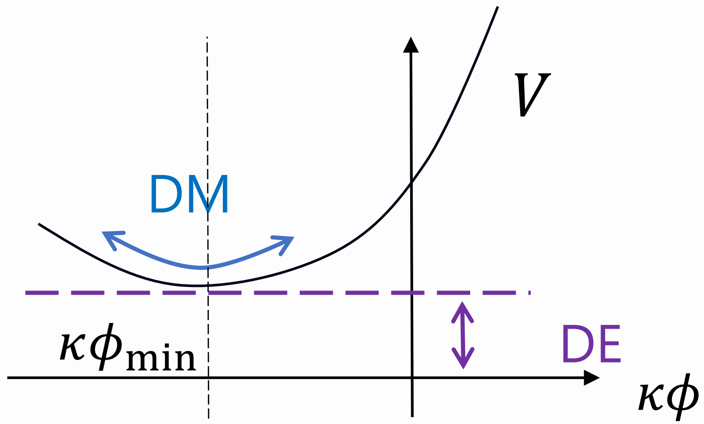
Amplitude $\ll 1$ $\qquad$ $V'(\varphi_{\rm min}) = 0$

Scalaron energy is (approximately) decomposed

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

How to estimate relic abundance of scalaron?

Non-thermal production cf.) Coherent oscillation of Axion



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

harmonic oscillation approximation

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

$V(\varphi_{\rm min}) = \frac{\Lambda}{\kappa^2}$ 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, $\kappa\varphi_0 < 1$
- Need all cosmic history to predict precise DM density
  (= Origin of oscillation? Initial condition/value of scalaron?)

Summary and Discussion

We studied scalaron as new DM candidate

Interaction to SM particles

- Very weak and suppressed by Planck mass scale
- No thermal production (out of thermal equilibrium)

Chameleonic properties

- Mass changes according to cosmic environment
- Very light in current Universe, heavy in early Universe

Stability and Lifetime

- Decaying modes to SM particles
- Long enough to be DM candidate at late-time

Relic Abundance

- Estimation based on coherent oscillation
- Possibility to address the coincidence problem

Summary and Discussion

Remaining Issues

Lifetime

- Scalaron in early Universe → Can be heavy?
- To survive in early Universe (<1[s])→ Constraints in each epoch
- To include the particle physics beyond SM
- Not perfect fluid, but Lagrangian based on QFT

Relic Abundance

- Origin of coherent oscillation? → In early Universe?
- Time evolution of "field" → Damping harmonic oscillation?
- Validity of particle picture? → Behaves as dust?

Unification of Dark Sector

- Coupling b/w two dark components is introduced
- Interacting DE model [Farrar and Peebles (2004)]
- How to embed our scenario into interacting DE model?