Dark Matter in Modified Gravity?

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Introduction

What is Modified Gravity?

= Broader class of gravitational theory

General Relativity + Modification of GR

Modification leads to emergence of new DOF.

= Expressed in terms of new field
(new gravitational force = the fifth force)

Why Modified Gravity?

New field can generate the late-time accelerated expansion of the Universe.

= Dynamical dark energy

When the new field is quantized,
new particle shows up from modified gravity.

Then, a question naturally arises

"New particle derived from the modification of gravity can be a Dark Matter?"

Motivations

New Dark Matter Candidate

Viable modified gravity theories possess screening mechanism.

It suppresses the fifth force in order to avoid local tests of gravity although the new field acts as DE at cosmological scale.

Thus, new field depends on environment;
it is dynamical DE at cosmological scale,
while it is a DM candidate at smaller scales.

New Constraint on Modified Gravity

Many constraints on DM are known
(i.e. lifetime, relic abundance, direct search).

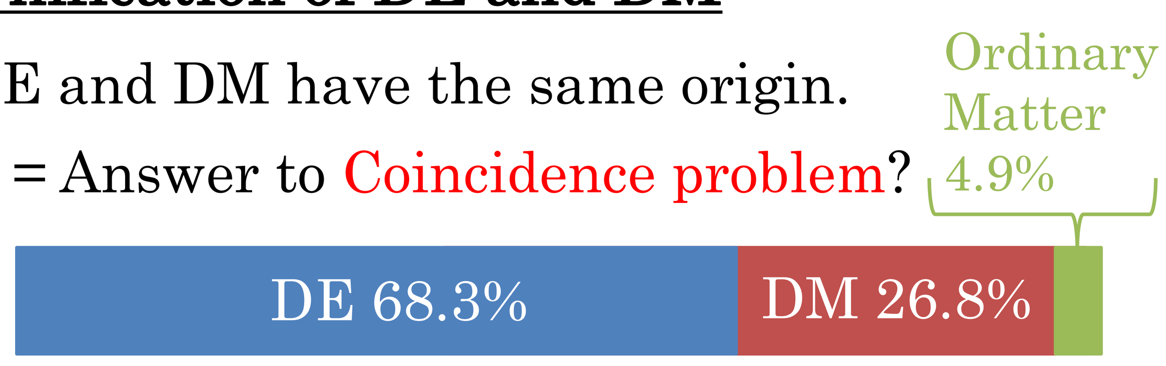
They can be converted into those on the modified gravity.

= To distinguish the modified gravities

Unification of DE and DM

DE and DM have the same origin.

= Answer to Coincidence problem?



One may predict the ratio of DE to DM w.r.t. current energy density.

Methods and Results

F(R) Gravity

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

Weyl transformation $\tilde{g}_{\mu\nu} = \Omega^2(x) g_{\mu\nu}$

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

Scalaron field $\varphi(x)$ appears.

Chameleon Mechanism

EOM of Scalaron $\tilde{\Box}\varphi = V'_{\text{eff}}(\varphi)$

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

Scalaron potential couples with $T_{\mu\nu}$

The mass $m_\varphi^2 = V''_{\text{eff}}(\varphi_{\text{min}})$ depends on the environment.

For large ρ, the scalaron becomes heavy.

Scalaron Coupling with SM

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

Dilatonic couplings show up.
= Suppressed by Planck mass

$$e^{\kappa\varphi} \sim 1 + \kappa\varphi$$

Weak coupling with SM particles

Particle Picture of Scalaron

$\varphi(x) =$ Background $\varphi_{\text{min}}(x)$ + Fluctuation $\hat{\varphi}(x)$

DE (classical) DM (particle)

We assume that the environment is described by the perfect fluid.

$$-T^{\mu}_{\mu} = \rho = \rho_{\text{EW}} \sim (100\,[\text{GeV}])^4$$

Constraint on F(R) Gravity

The Starobinsky model

$$F(R) \approx R - \beta R_c + \beta R_c \left(\frac{R}{R_c}\right)^{-2n} \quad \text{where } \beta R_c \approx 2\Lambda$$

The scalaron mass is given by

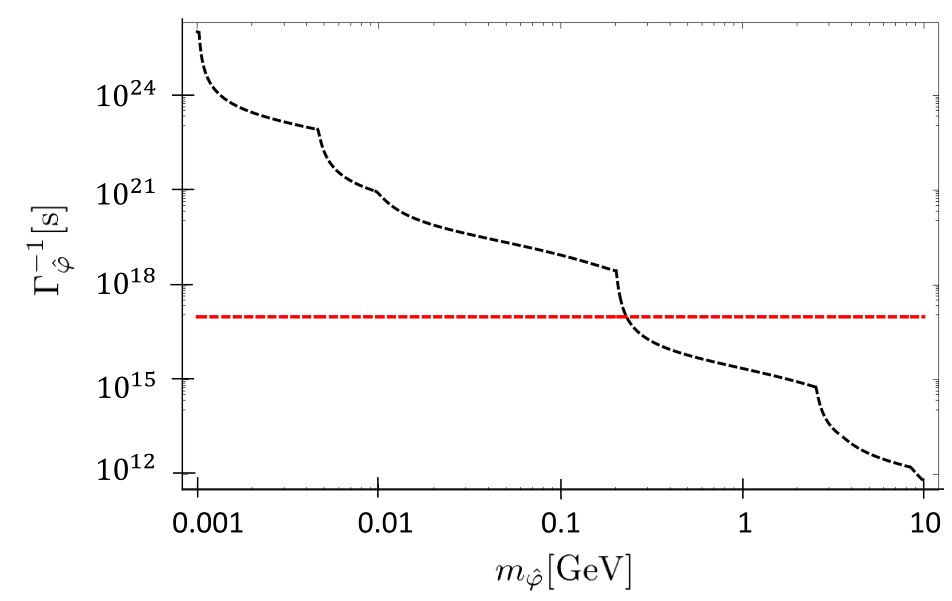
$$m_{\hat{\varphi}}^2 \approx \frac{2\Lambda}{6n(2n+1)\beta^2}\left(\frac{\kappa^2\beta}{2\Lambda}\rho_{\text{EW}}\right)^{2(n+1)}$$

Finally, we obtain

$\beta < 10^{-69}$ for n=1, $\beta < 10^{-59}$ for n=4

Lifetime of Scalaron

$10^{17}[\text{s}] \lesssim \Gamma_{\hat{\varphi}}^{-1} \rightarrow m_{\hat{\varphi}} \lesssim 0.23\,[\text{GeV}]$



Conclusions

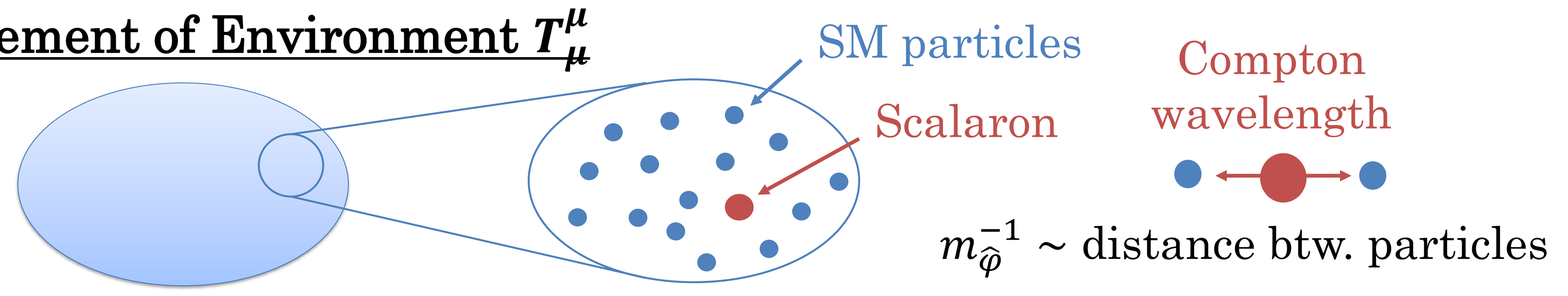
We studied the scalaron as a DM candidate derived from F(R) gravity.

We estimated the lifetime of scalaron based on QFT and obtained the constraint on β in the Starobinsky model.

β is extremely small although $\beta = O(1)$ for compatibility with DE.

= Scalaron is not DM. Or we need to reconsider assumptions in analysis.

Improvement of Environment T^{μ}_{μ}



We assumed perfect fluid around the scalaron.
In large scale, perfect fluid approximation is OK.

In microscopic scale, the approximation is invalid.
The chameleon mechanism may be weakened because the environment btw. particles is almost vacuum.

Literature Cited

1. T. Katsuragawa and S. Matsuzaki, "Modified Gravity Explains Dark Matter?", arXiv:1610.01016 [gr-qc].
2. S. Nojiri and S. D. Odintsov, "Can F(R)-gravity be a viable model: the universal unication scenario for inflation, dark energy and dark matter", arXiv:0801.4843 [astro-ph].

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