Scalaron DM in logarithmic F(R) gravity

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Introduction

F(R) gravity was proposed as a modified gravity theory at 1970.

Einstein-Hilbert → **F(R) gravity**

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

$$\kappa^2 = 8\pi G = 1/M_{pl}^2$$

The starobinsky inflation model ; $F(R) = R + f_{DE}(R) + \gamma R^2$

Dark Energy ($f_{DE}(R)$)

Inflation (γR^2)

I will show that the F(R) gravity can explain <u>inflation</u>, <u>dark energy</u> and also <u>dark matter</u>.

$F(R)$ gravity

Weyl transformation

$$g_{\mu\nu} \to \tilde{g}_{\mu\nu} = e^{2\sigma} g_{\mu\nu}$$

Jordan frame

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

Definition

$$\kappa^2 = 8\pi G = 1/M_{pl}^2$$

S_m; matter action

Einstein frame

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

Scalaron

$$\sigma \equiv \sqrt{1/6}\kappa\varphi$$

$$F'(R) = e^{2\sqrt{1/6}\kappa\varphi}$$

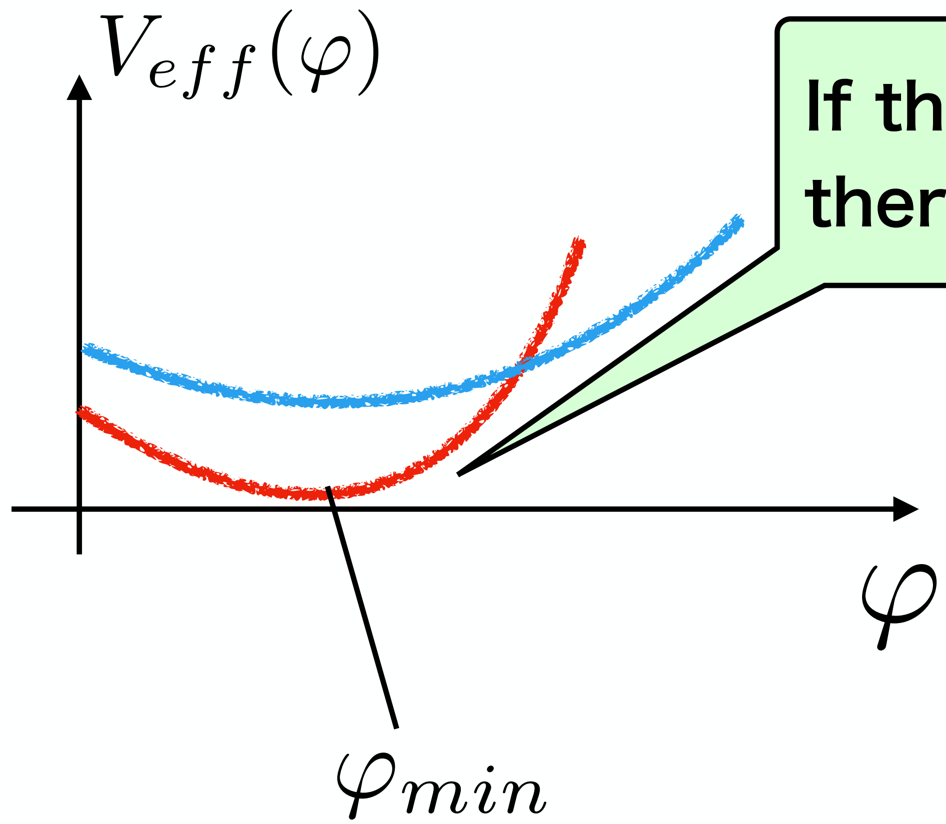
$$V(\varphi) = \frac{1}{2\kappa^2}\frac{RF'(R) - F(R)}{F'^2(R)}$$

T.Katsuragawa,S.Matsuzaki : 2018

F(R) gravity in Einstein frame contains scalar mode, we call this mode as scalaron.

We will discuss the scalaron as the candidate of DM

$$V_{eff}(\varphi) = \frac{1}{2\kappa^2 F'^2(R)}\left(RF'(R) - F(R) - \frac{1}{4}\tilde{T}^{\mu}_{\mu}\right)$$



If the effective potential has a minimum, there is a stable ground state for the scalaron field

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

The definition of the scalaron mass

The shape of the effective potential depends on the energy tensor for matters, so the scalaron mass also depends on the energy tensor.

$$\boxed{\text{(Scalaron's mass)}} = m_\varphi(\tilde{T}^{\mu}_{\mu})$$

↓

Chameleon mechanism

F(R) model

Logarithmic $F(R)$ gravity model

$$F(R) = R - \Lambda_{DE}\left[1 - \alpha\frac{R}{R_C}\ln\left(\frac{R}{R_C}\right)\right] + \kappa^2\gamma_0\left[1 + \gamma_1\ln\left(\frac{R}{R_0}\right)\right]R^2$$

Λ_{DE}; current cosmological constant

$\alpha, R_C, \gamma_0, \gamma_1, R_0$; free constant parameter

Our assumption

This logarithmic F(R) is motivated by quantum corrections of gravity.

$$F(R) = R + f_{DE}(R) + \kappa^2\gamma(R)R^2$$

→ **logarithmic form**

It was found that this F(R) produces DE and inflation in

S.D.Odintsov,V.K.Oikonomou,L.Sebastiani : 2017

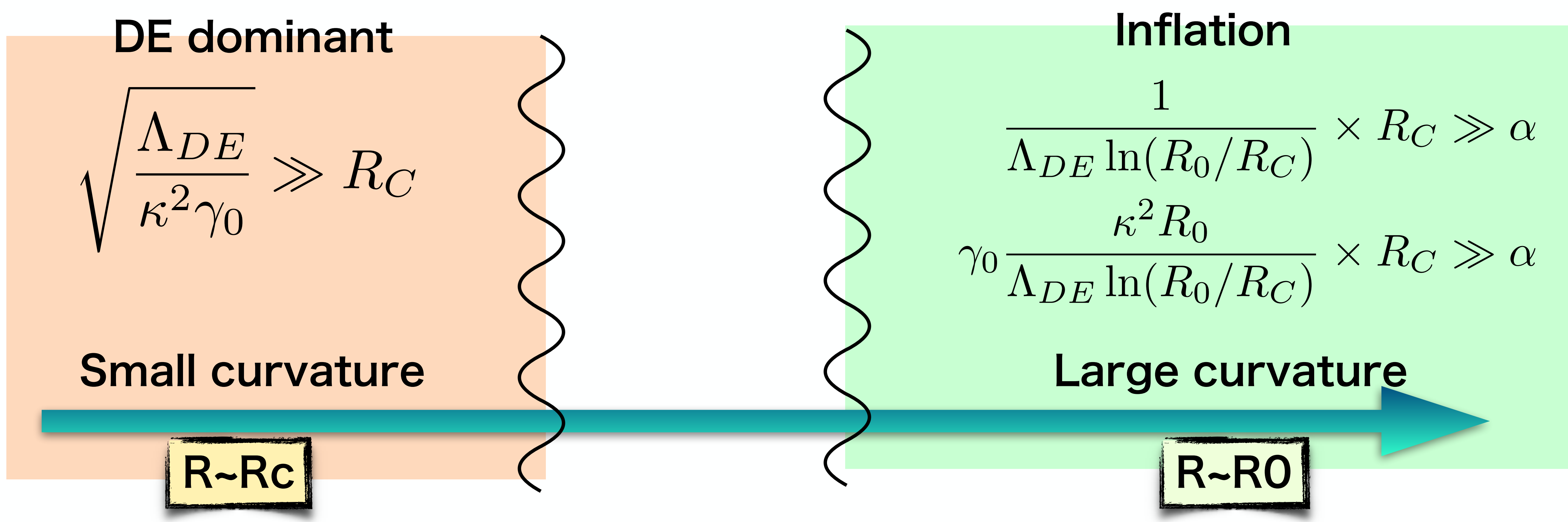
γ_0, γ_1, R_0 are constrained by inflation scenario
and
α and Rc are constrained by the condition that scalaron is DM candidate.

$$F(R) = R - \Lambda_{DE}\left[1 - \alpha \frac{R}{R_C}\ln\left(\frac{R}{R_C}\right)\right] + \kappa^2\gamma_0\left[1 + \gamma_1 \ln\left(\frac{R}{R_0}\right)\right]R^2$$

Our assumption

DE term

R^2 term



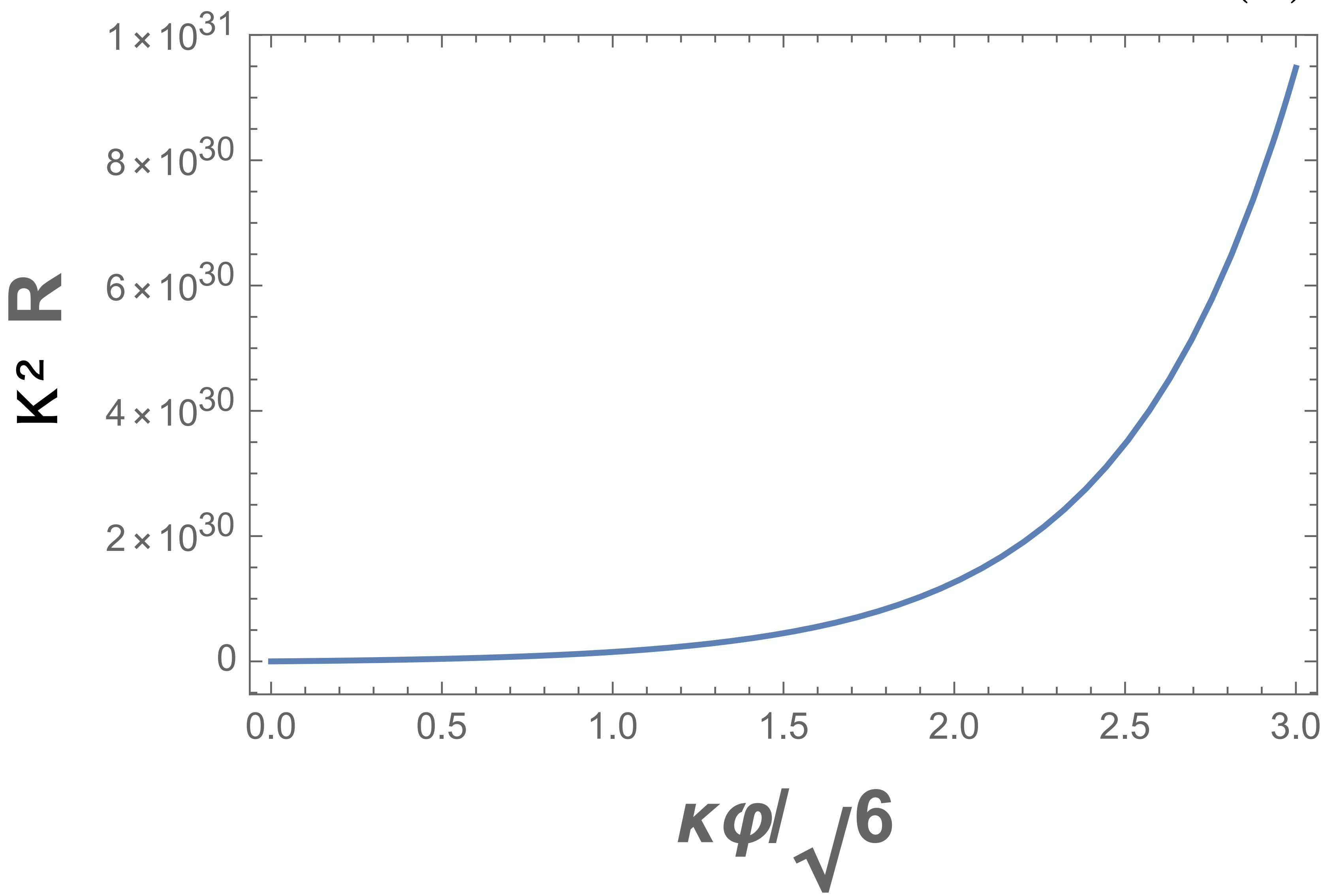
For a small curvature the R^2 term can be neglected.
For a large curvature the DE term can be neglected.

Inflation

Large curvature $F(R) \sim R + \kappa^2 \gamma_0 \left[1 + \gamma_1 \ln \left(\frac{R}{R_0} \right) \right] R^2$

$$F'(R) = e^{2\kappa\varphi/\sqrt{6}} \quad \Rightarrow \quad R(\varphi) = \frac{e^{2\kappa\varphi/\sqrt{6}} - 1}{2\kappa^2\gamma_0\gamma_1 W\left(\frac{(e^{2\kappa\varphi/\sqrt{6}}-1)e^{1+1/\gamma 1}}{2R_0\kappa^2\gamma_0\gamma_1}\right)}$$

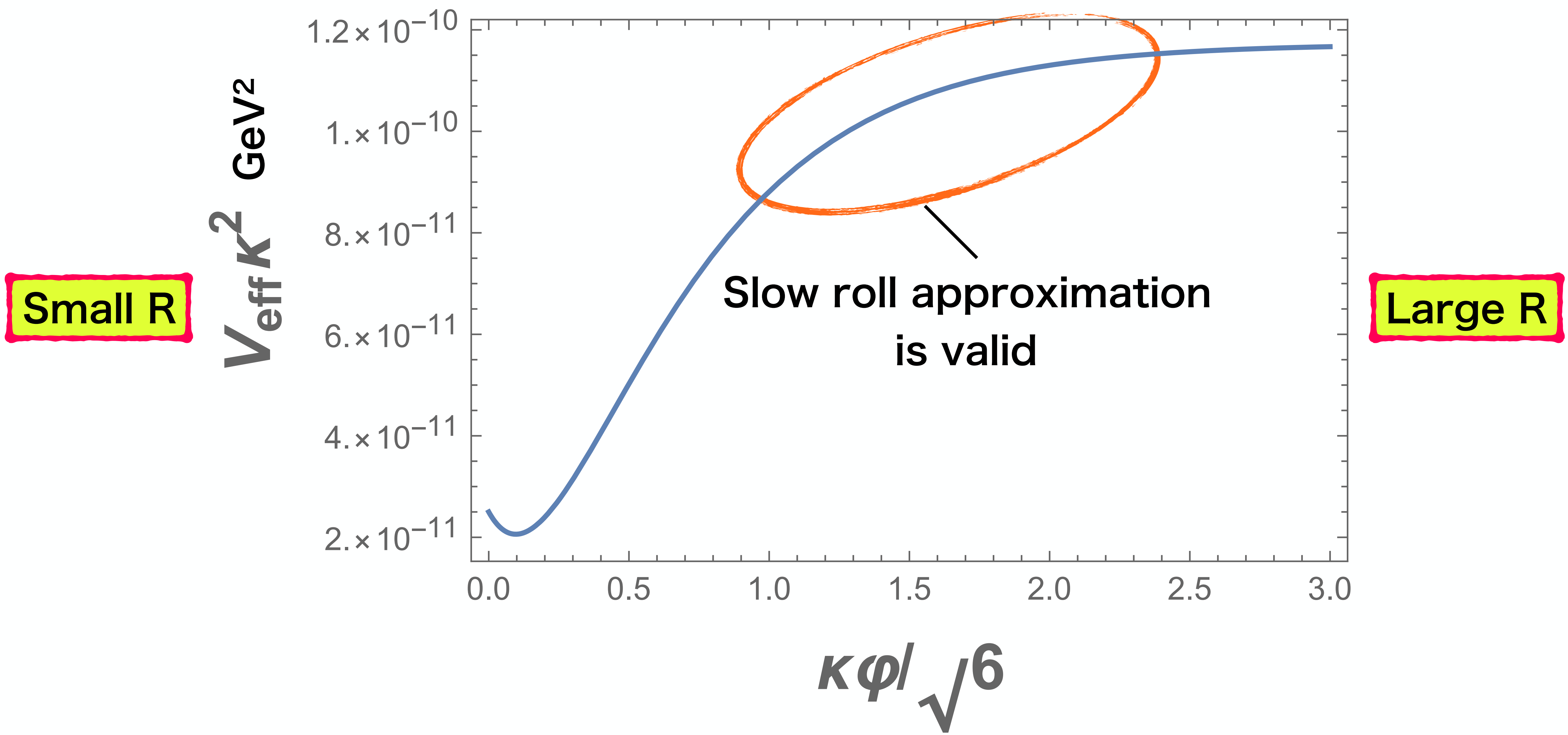
W : Lambelt W function, $z = W(z)e^{W(z)}$



The curvature R as a function of ϕ

Large curvature(2) $F(R) \sim R + \kappa^2\gamma_0\left[1+\gamma_1\ln\left(\frac{R}{R_0}\right)\right]R^2$

If R is large, F(R) is approximately given as above.



Potential for the scalaron

The potential drop down to the small curvature.

Inflation dominant (3) $F(R) \sim R + \kappa^2 \gamma_0 \left[1 + \gamma_1 \ln \left(\frac{R}{R_0} \right) \right] R^2$

By observation, any parameters
are suppressed as these.

the number of e-foldings ; $N = 55 \sim 65$

the curvature power spectrum ; $A_s = (1.881 \pm 0.014) \times 10^{-9}$

the spectral index ; $n_s = 0.968 \pm 0.006$

Planck 2015 results. XIII. Cosmological parameters

Any constant fee parameters are constrained as,

Jordan frame

$$\gamma_0 \simeq \frac{e^{-80}}{\gamma_1 R_0 \kappa^2}$$

$$\gamma_1 \ll 0.005$$

$$R_0 \simeq 1.8 \times 10^{85} \Lambda_{DE}$$

S.D.Odintsov,V.K.Oikonomou,L.Sebastiani : 2017

Einstein frame

γ_0	$(0.88 \sim 1.2) \times 10^9$
γ_1	$(1.0 \sim 1.4) \times 10^{-6}$
R_0	1.8

For consistent with Jordan frame,
we obtain above value.

Consistent for Odintsov's result,

γ_0	$(0.88 \sim 1.2) \times 10^9$
γ_1	$(1.0 \sim 1.4) \times 10^{-6}$
R_0	1.8

Tensor-to-scalar ratio ; $2.94 \times 10^{-3} \leq r = \dfrac{A_T}{A_S} \leq 4.10 \times 10^{-3}$

But, following cases are also permitted.

γ_0	$\dfrac{e^{-80}}{\kappa^2 \gamma_1 R_0}$
γ_1	$(1.0 \sim 1.4) \times 10^{-6} \times a^{-1}$
R_0	$1.8 \times a \gg 10^{-5}$

$$r = (2.2 \sim 4.1) \times 10^{-3}$$

γ_0	$\dfrac{e^{-80}}{\kappa^2 \gamma_1 R_0} \times a$
γ_1	$(1.0 \sim 1.4) \times 10^{-6}$
R_0	$1.8 \times a$

$$r = (2.9 \sim 4.1) \times 10^{-3}$$

Tensor-to-scalar ratio is suppressed as,

$$\rightarrow \quad r = (2.2 \sim 4.1) \times 10^{-3}$$

<u>May be any other case is exsist.</u>

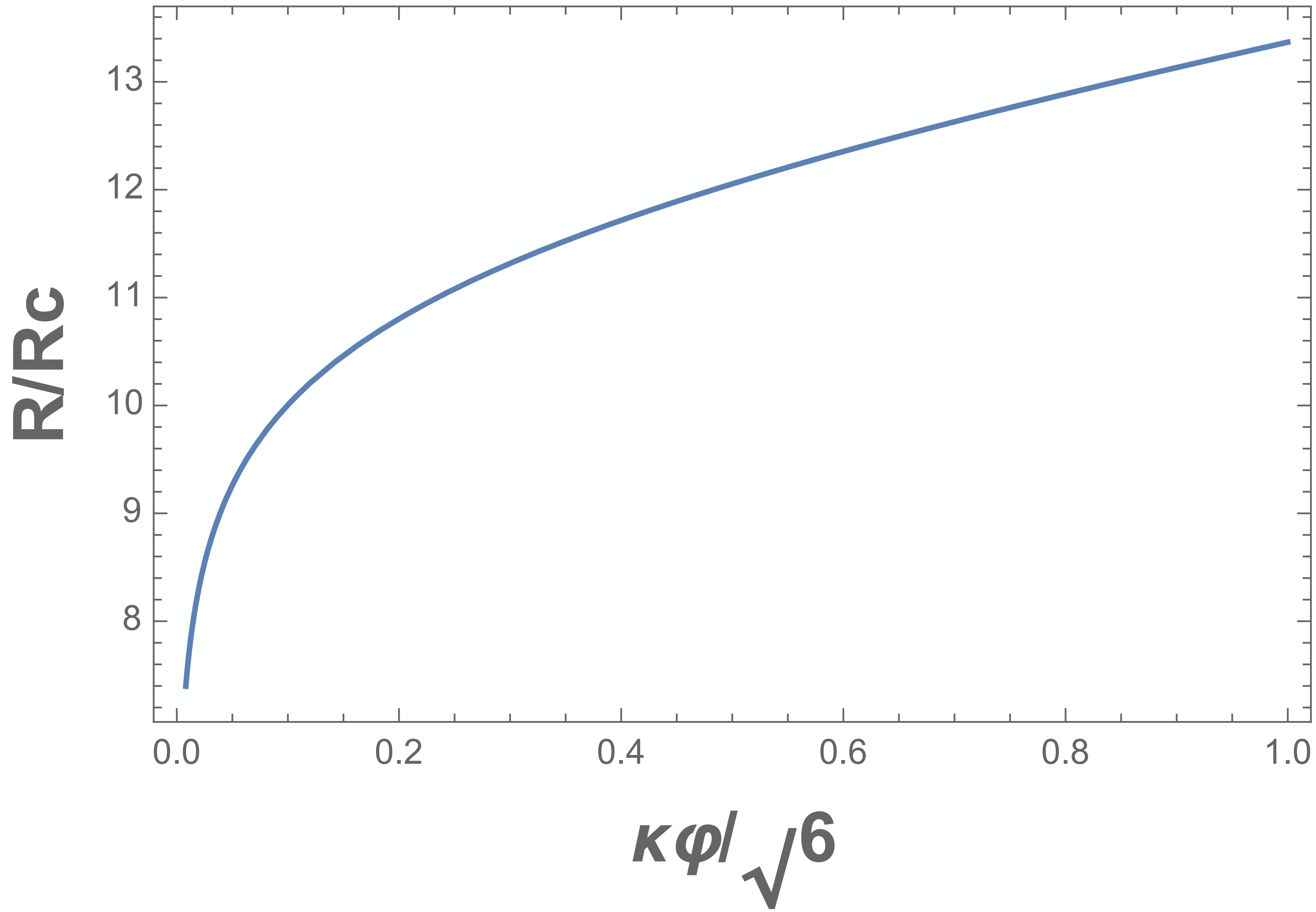
Dark Matter

DE dominant

$$F(R) \sim R - \Lambda_{DE}\left[1 - \alpha\frac{R}{R_C}\ln\left(\frac{R}{R_C}\right)\right]$$

$$F'(R) = e^{2\kappa\varphi/\sqrt{6}}$$

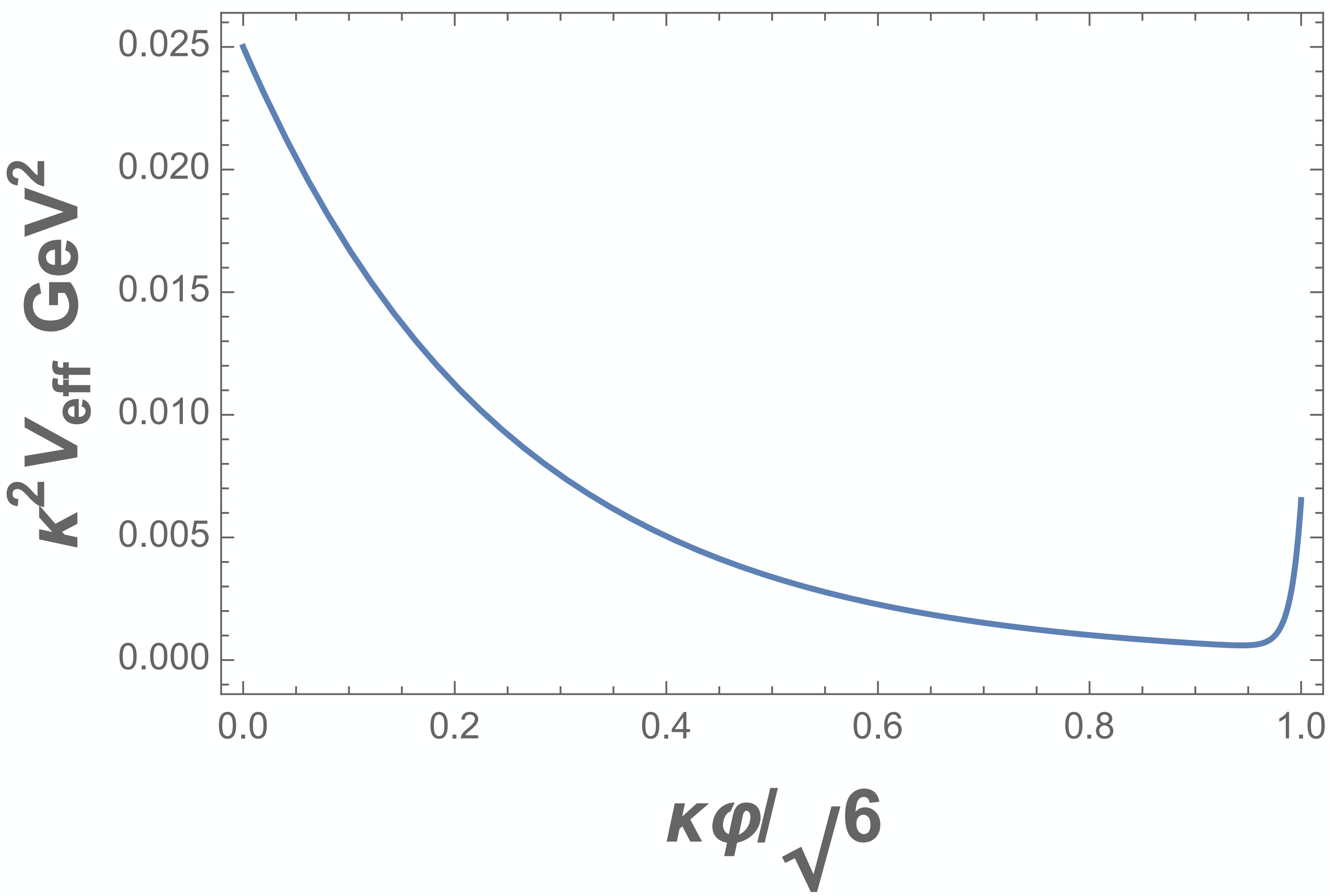
$$\Rightarrow \quad R(\varphi) = R_C \ln\left[\frac{R_C}{\alpha\Lambda_{DE}}\left(e^{2\kappa\varphi/\sqrt{6}} - 1 - \alpha\frac{\Lambda_{DE}}{R_C}\right)\right]$$



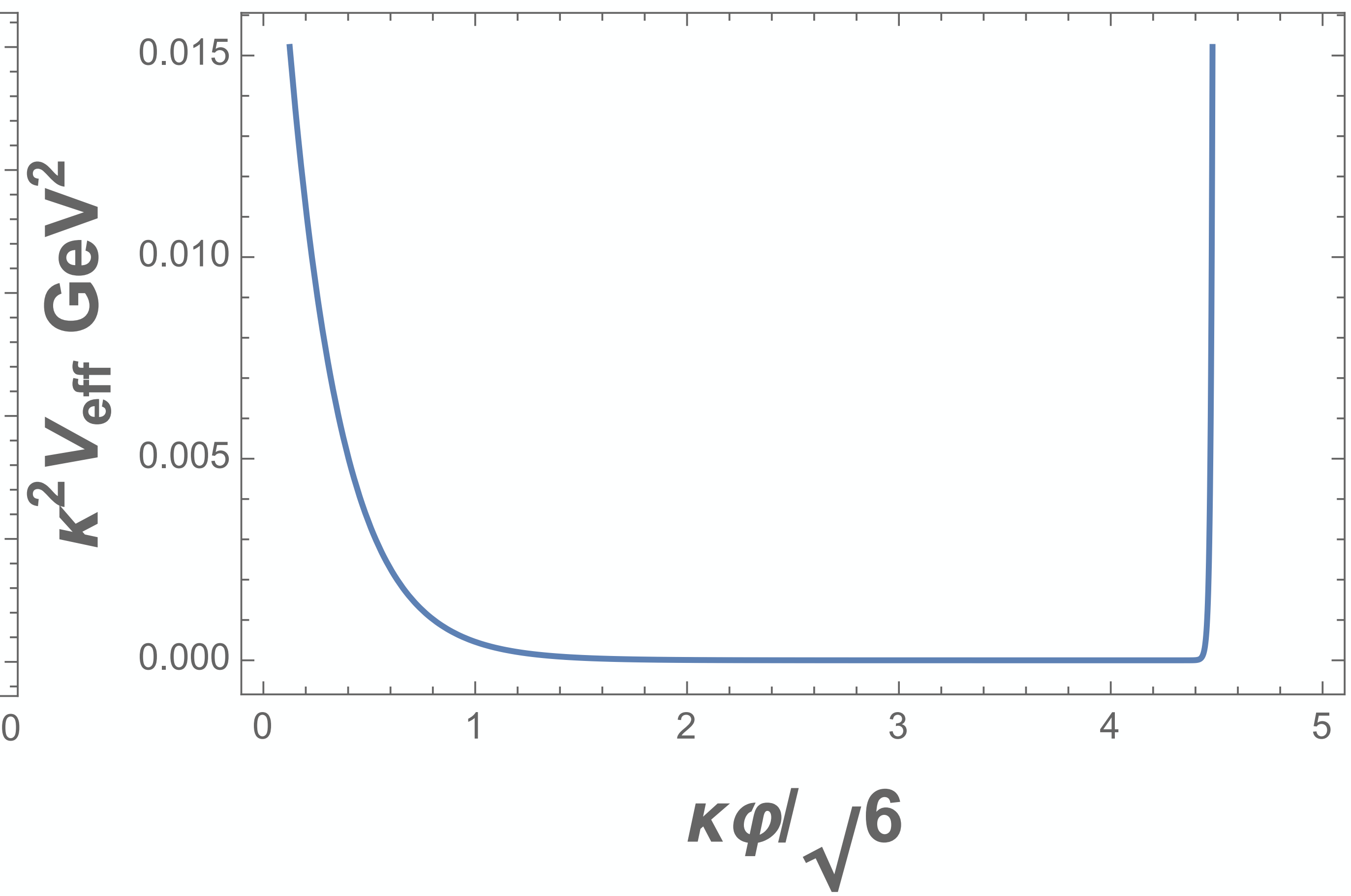
Curvature R depends on ϕ

DE dominant(2) $F(R) \sim R - \Lambda_{DE}\left[1 - \alpha\frac{R}{R_C}\ln\left(\frac{R}{R_C}\right)\right]$

$$V_{eff}(\varphi) = \frac{1}{2\kappa^2 F'^2(R)}(RF'(R) - F(R) - \frac{1}{4}\tilde{T}^{\mu}_{\mu})$$



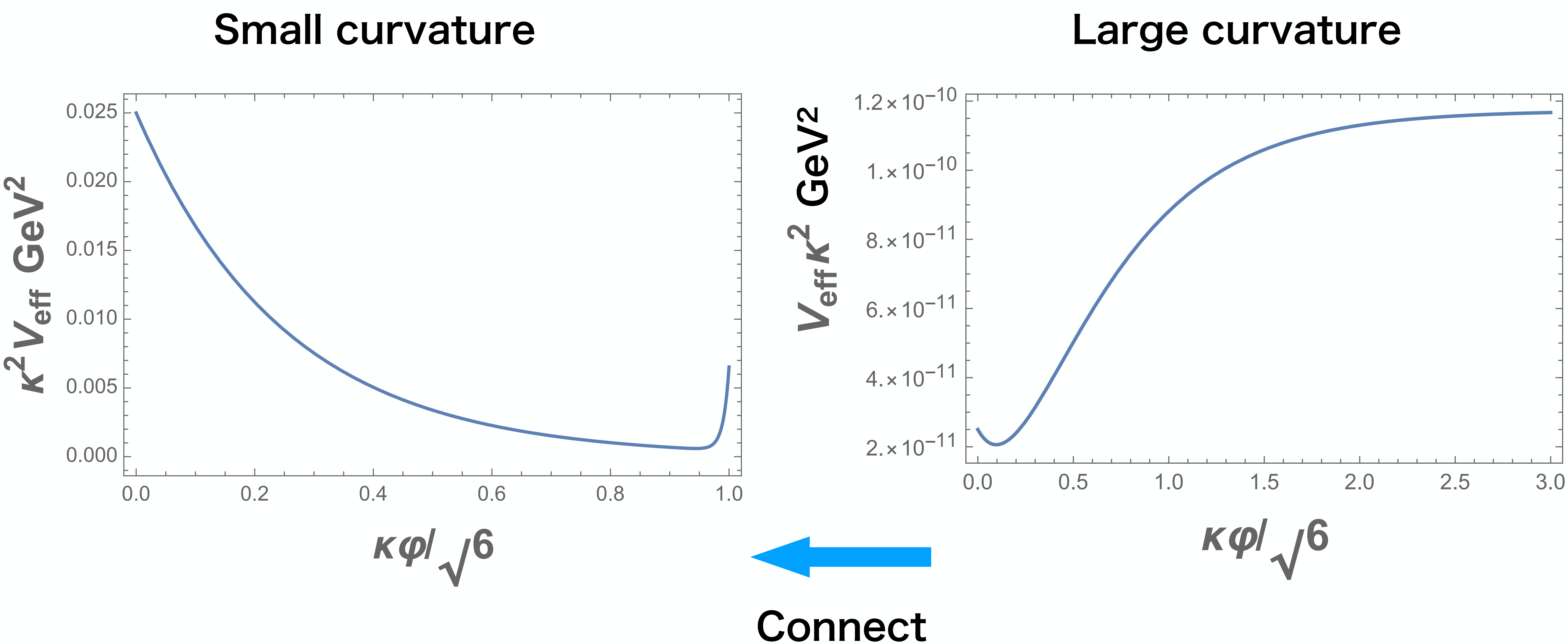
α<<Rc/Λde



α>>Rc/Λde

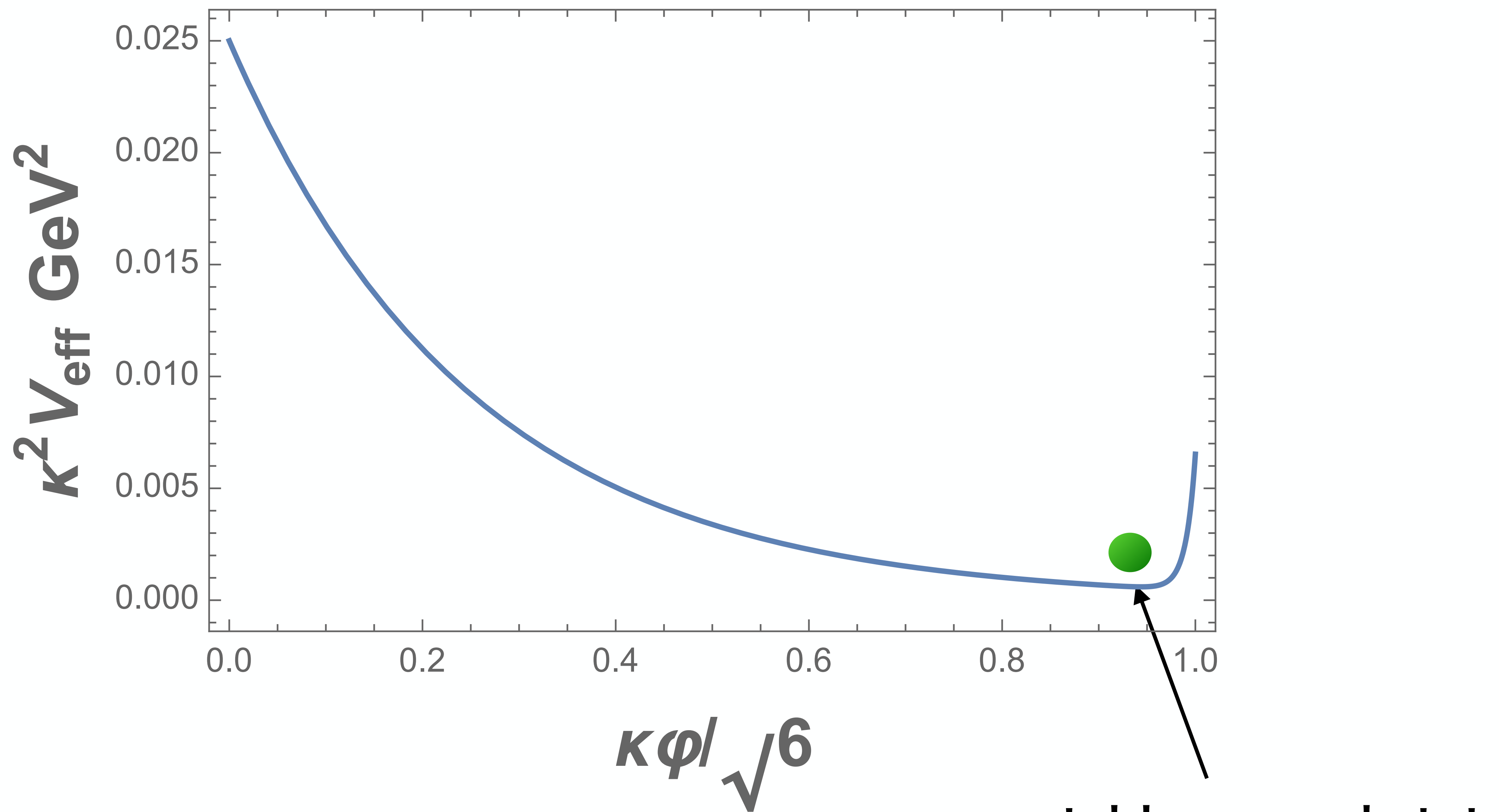
We consider only Rc/Λ>>α case because of large curvature constraint,

$$R_C/\Lambda_{DE} \gg \alpha\ln(R_0/R_C)$$



Small curvature
Large curvature
$\kappa^2 V_{eff}$ GeV^2
0.025
0.020
0.015
0.010
0.005
0.000
0.0
0.2
0.4
0.6
0.8
1.0
$\kappa\varphi/\sqrt{6}$
$V_{eff}\kappa^2$ GeV^2
1.2×10^{-10}
$1.\times10^{-10}$
$8.\times10^{-11}$
$6.\times10^{-11}$
$4.\times10^{-11}$
$2.\times10^{-11}$
0.0
0.5
1.0
1.5
2.0
2.5
3.0
$\kappa\varphi/\sqrt{6}$
Connect

DE dominant(3) $F(R) \sim R - \Lambda_{DE}\left[1 - \alpha\frac{R}{R_C}\ln\left(\frac{R}{R_C}\right)\right]$

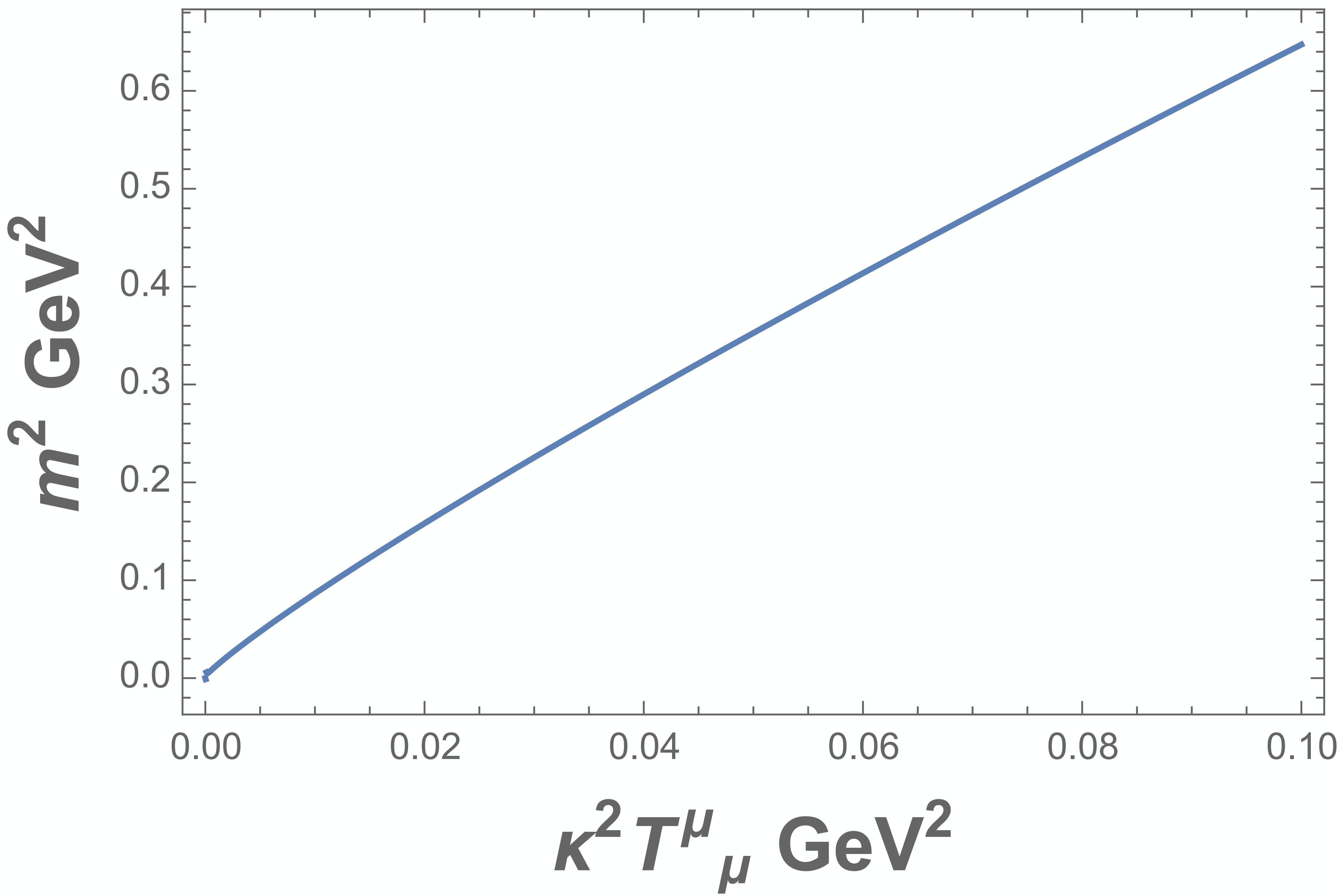


α<<Rc/Λde

In this case, the potential has stable ground state.
We regards the scalaron as a massive particle.

The mass depends on the energy tensor, $m_\varphi^2 \simeq \frac{8R_C}{3\Lambda_{DE}}\frac{\kappa^2 T^\mu_\mu}{\alpha}$

DE dominant (4) $F(R) \sim R - \Lambda_{DE}\left[1 - \alpha \frac{R}{R_C} \ln\left(\frac{R}{R_C}\right)\right]$



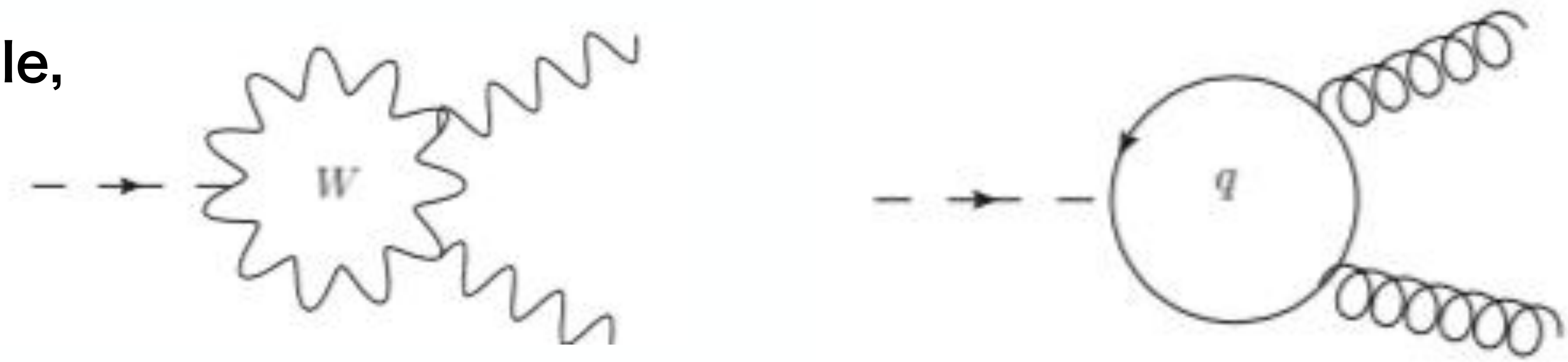
Scalaron mass is monotonically increasing as a function of the trace of the energy tensor

Life time of scalaron

Scalaron's decay rate

The scalaron decays to two photons or two gluons through massive fermion and gauge boson loops.

For example,



T.Katsuragawa,S.Matsuzaki : 2017

Scalaron life time has to be longer than the age of the universe.

$$\tau_\varphi > \tau_{\rm uni} \sim 10^{17}{\rm s}$$

The upper bound for the scalaron mass as $m_\varphi \leq 0.23{\rm GeV}$

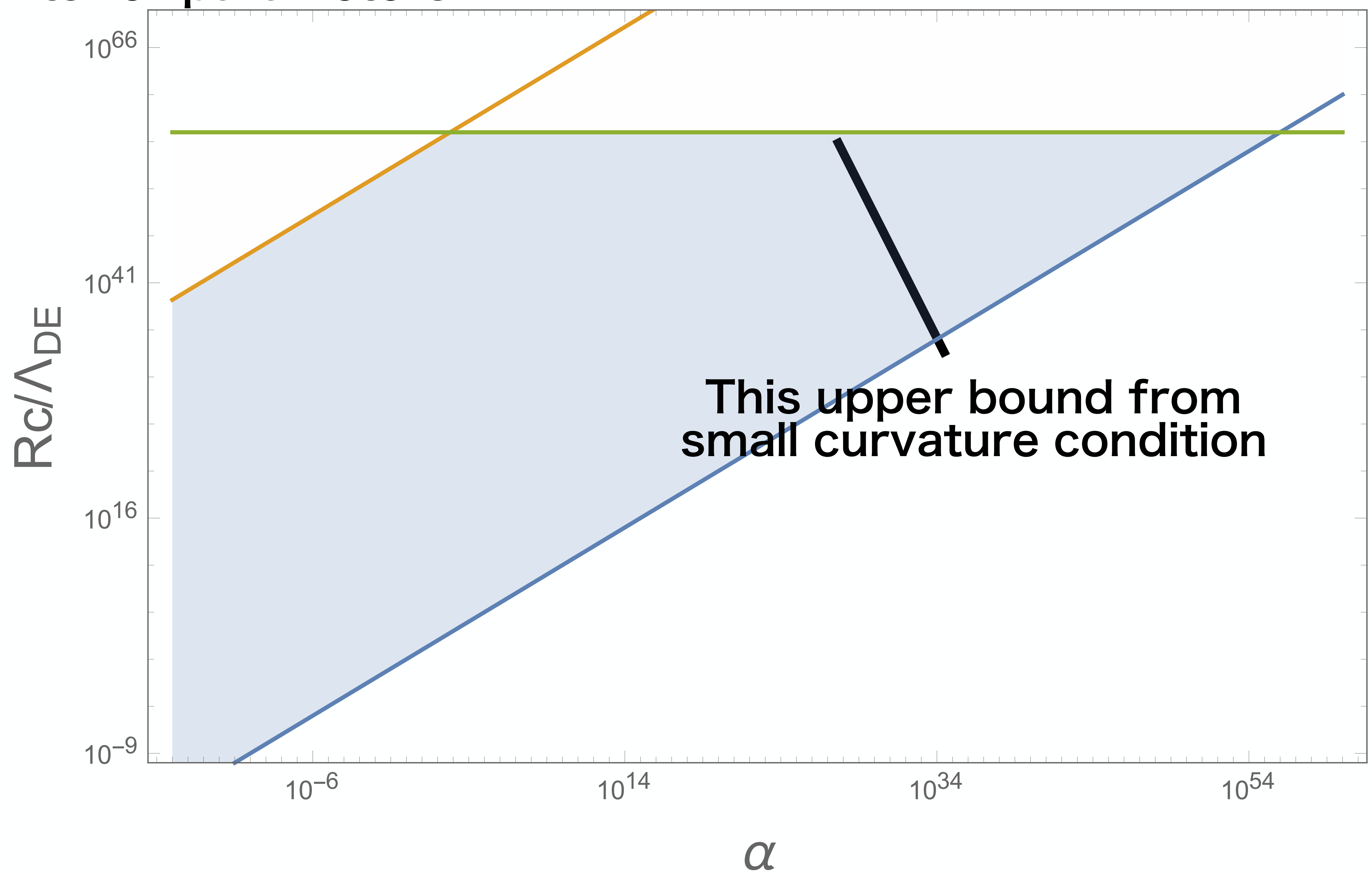
T.Katsuragawa,S.Matsuzaki : 2018

We consider solar system energy scale.

$$T^\mu_\mu = \rho_\odot \sim 10^{-17}{\rm GeV}^4$$

→ We obtain the constraint for α and R_C.

Constraints for parameters



Allowed region is illustrated by colored area.

$$\frac{R_C}{\Lambda_{DE}} \times 6.4 \times 10^{-55} \leq \alpha \ll \frac{R_C}{\Lambda_{DE}} \times \frac{1}{\ln(R_0/R_C)} \qquad R_C \ll \sqrt{\frac{\Lambda_{DE}}{\kappa^2 \gamma_0}}$$

Scalaron life time **Large curvature constraint** **Small curvature constraint**

Summary

- We study a logarithmic F(R) model in the Einstein frame.
- The logarithmic model in the Einstein frame describes the inflation.
- We obtain the constraints for γ_0, γ_1, R_0 by inflationary scenario.
- We show that the scalaron can be DM candidate.
- We obtain the constraints for R_C, α by the life time of scalaron.

Next step

- We calculate the constraints for inflation scenario more precisely.
- We calculate the relic abundance of scalaron more precisely.

Thank you