Cosmology and Quantum Vacuum
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Can Scalaron be a Dark Matter candidate?

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The Final Frontier

GR is simple but successful theory.

But, we should consider the **alternative theories** seriously.

- We don't know the fundamental reason to choose Einstein-Hilbert action as gravitational theory.
- Studying the other possible theories helps us understand GR better.
- To learn from the experience of others:

``Vulcan" vs. GR (Peculiarities of Mercury's orbit)

We consider the gravitational theory beyond GR.

$\rightarrow$ **Modified Gravity theory** ~ GR + new DOF

It is important to study

- **How we can use the new DOF**
- **How predictions are different from those in GR**.

Into Darkness

The observation implies the existence of **Dark Energy & Dark Matter**.

DE = Energy to accelerate the expansion of the Universe.

- Type Ia supernova, CMB, BAO

DM = (Almost) Invisible matter besides ordinary matter

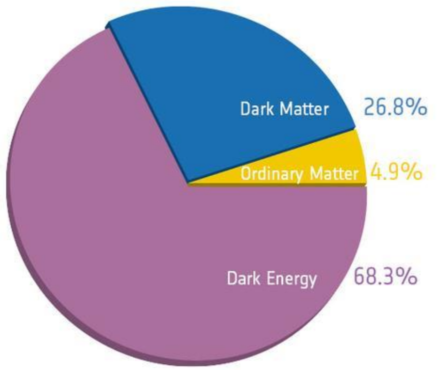
- Galaxy rotation curve, Gravitational Lensing

Note

DM = Cold Dark Matter (CDM), Ordinary Matter =SM

Questions:

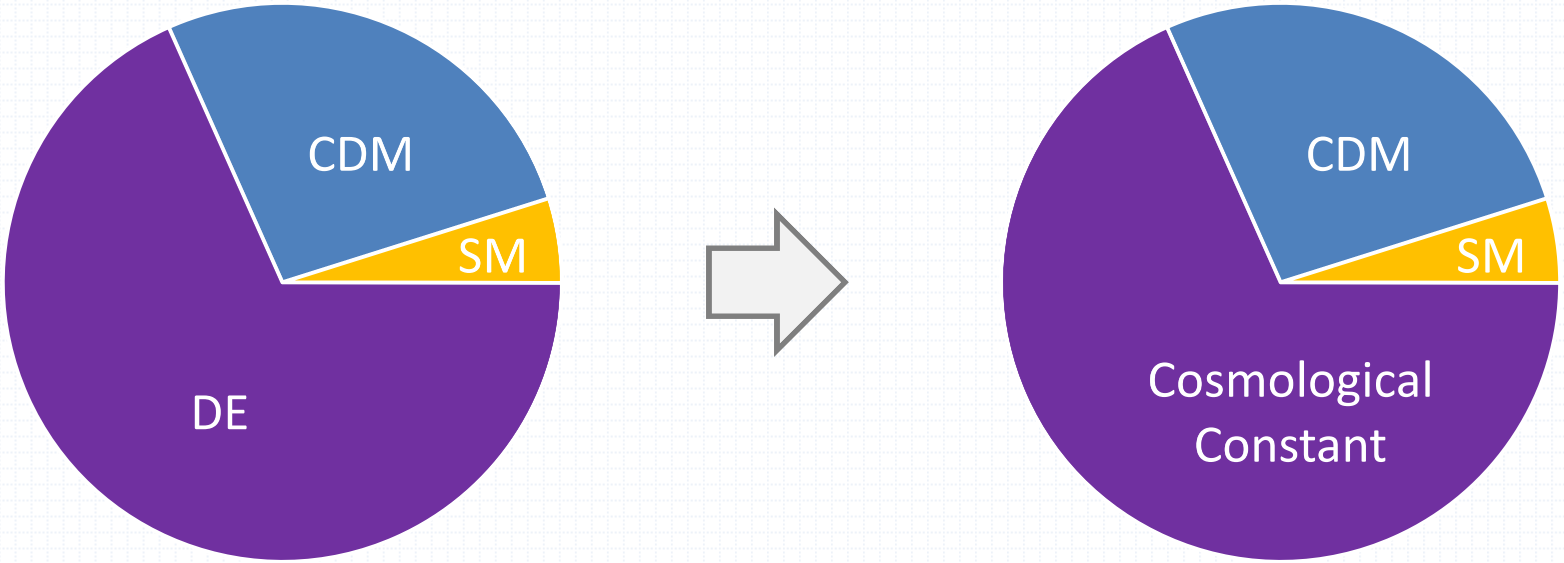
1. What is the Dark Energy?
2. What is the Dark Matter?



Planck

It may be possible **to explain DE & DM in modified gravity**.

Λ-CDM model



Components : **GR** + **CC** + **SM** + **CDM**

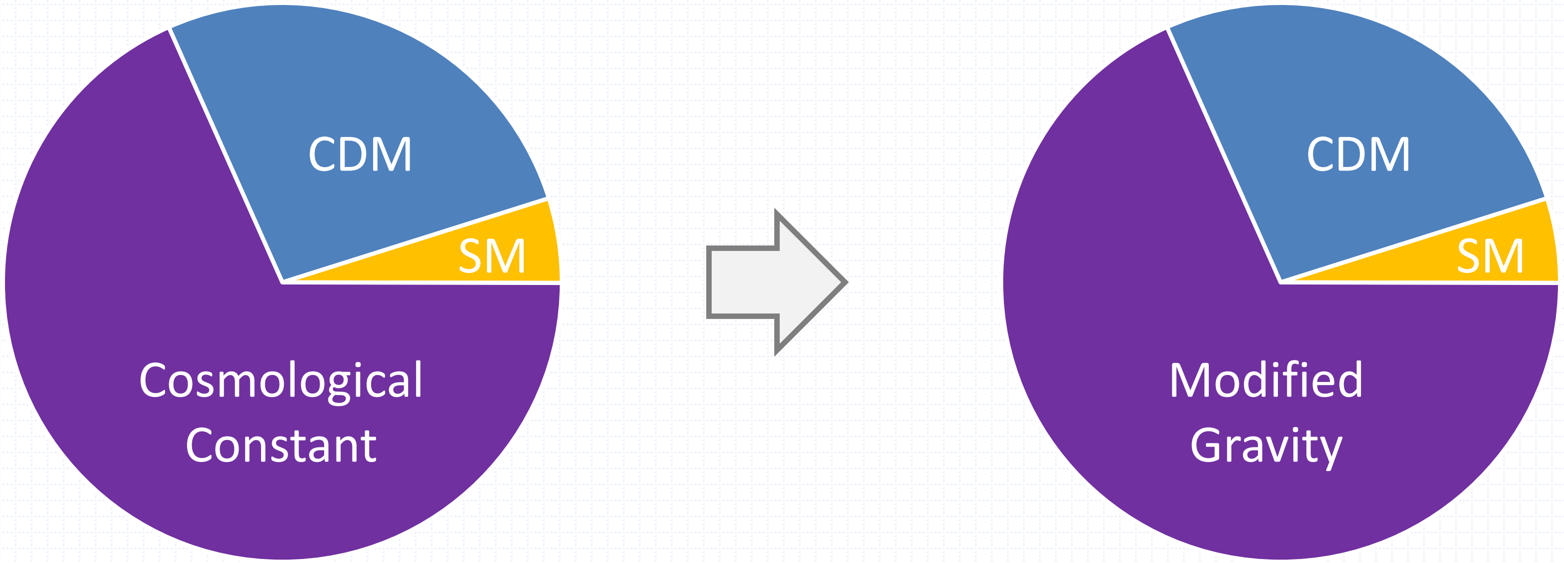
with

DE = Cosmological Constant

But, it suffers from quartic divergence

Λ = (Cut-off scale)^4 (cf. for $M_{pl} = 10^{19}$GeV, $\Lambda_{theo} \sim 10^{120}\Lambda_{obs}$)

Modified Gravity for DE



Components : **Modified Gravity** + **SM** + **CDM**

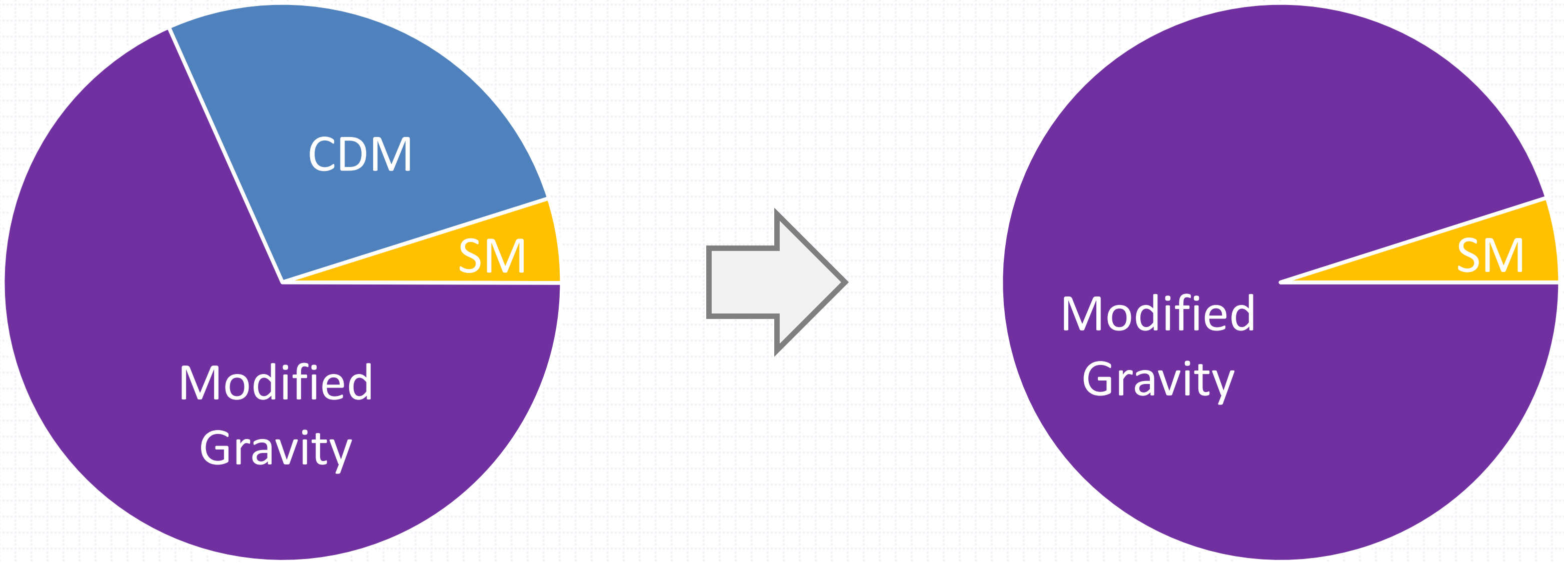
with

DE= Modification of gravity

We use the new DOF for DE.

→ Scalar-Tensor theory, F(R) gravity, Massive/Bi-gravity etc.

Modified Gravity for DE + DM ?



Components : **Modified Gravity** + **SM**

with

DE + CDM = Modification of gravity

We use the new DOF for DE and DM, simultaneously.

Note: New DOF as particle, not like MOND theory

Scalar field from F(R) gravity theory

Let's consider F(R) gravity

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

$$\xrightarrow{(1)} S = \frac{1}{2\kappa^2}\int d^4x\sqrt{-g}\left[F_A(A)R - \{F_A(A)A - F(A)\}\right]$$

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

$$V(\phi) = \frac{1}{2\kappa^2}\frac{F_A(A(\varphi))A(\varphi) - F(A(\varphi))}{F_A^2(A(\varphi))}\,,\ \tilde{g}_{\mu\nu} = \Omega^2 g_{\mu\nu}\,,\ \Omega^2 \equiv F_A(A) = \mathrm{e}^{2\sqrt{1/6}\kappa\varphi}$$

1. We rewrite the action by **introducing the auxiliary scalar field *A***. The equation of motion for *A* leads to *A*=*R*, and deformed action is equivalent to original one.
2. After the **Weyl transformation** of the metric, we finally obtain the EH action and minimally coupled scalar field *φ* (**Scalaron**).

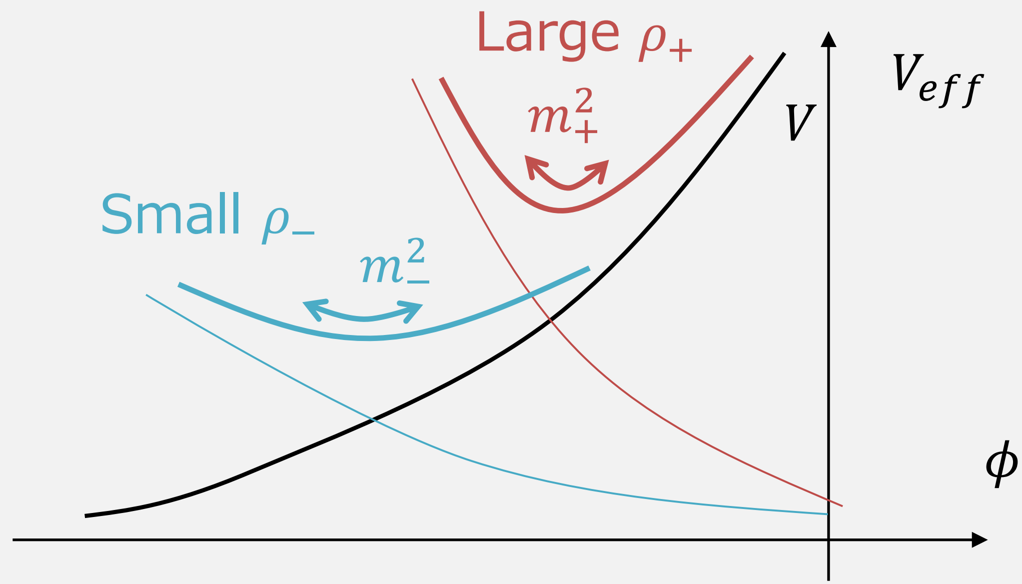
Chameleon Mechanism

Scalaron couples to trace of energy-momentum tensor

$$\tilde{\Box}\phi = \partial_\phi V(\phi) - \rho\frac{\kappa}{\sqrt{6}}e^{-4\sqrt{1/6}\kappa\phi}\ ,\ \ \rho = -g_{\mu\nu}T^{\mu\nu}$$

Effective potential of Scalaron is

$$V'_{eff} = \partial_\phi V(\phi) - \frac{\kappa}{\sqrt{6}}e^{-4\sqrt{1/6}\kappa\phi}\rho\ ,\ \ m_\phi^2 = \partial_\phi^2 V_{eff}|_{\phi=\phi_{min}}$$



Environment dependence

The mass depends on matter fields surrounding the Scalaron
→ Screening in **environment-dependent** way

- In bulk of the Universe,
the Scalaron is very light comparable to cosmological constant.

- In the Solar-system or galaxies, the Scalaron is very heavy.
Then, the Compton wavelength is short,
and Scalaron is screened.

Chameleon in the twilight
of the Universe

Dark Matter from F(R) gravity

Recall the properties of Scalaron

- Heavy around the Galaxy or the Earth.
- Interaction to SM particle is suppressed $\mathbf{e}^{\kappa\varphi} \sim 1 + \kappa\varphi,\ \kappa = \frac{1}{M_{pl}}$

It suggests that the Scalaron could be a DM.

→ **Can F(R) gravity explain DM problem?**

[Nojiri and Odintsov (2008), Choudhury et al. (2015)]

We do not require the beyond SM, but beyond GR.

→ One modification for Two physics (DE and DM)

To study the Scalaron as DM candidate, we need to reveal

- Mass and Coupling to SM particles
- Life time (or Decay width)
- Creation process and Relic abundance in the Universe etc.

Coupling to Matter : Massless vector

Massless vector field $A_\mu(x)$

$$\mathcal{L}_V\left(g^{\mu\nu}, A_\mu\right) = -\frac{1}{4} g^{\alpha\mu} g^{\beta\nu} F_{\alpha\beta} F_{\mu\nu}$$
$$= -\frac{1}{4} \mathrm{e}^{4\sqrt{1/6}\kappa\varphi} \tilde{g}^{\alpha\mu} \tilde{g}^{\beta\nu} F_{\alpha\beta} F_{\mu\nu}$$

Field strength is invariant under the Weyl trans.

$$F_{\mu\nu} = \nabla_\mu A_\nu - \nabla_\nu A_\mu = \partial_\mu A_\nu - \partial_\nu A_\mu$$

Coupling does not appear

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

Scalaron does not directly couple to photon.

Coupling to Matter : Massless fermion

Massless fermion field $\psi(x)$

$$\mathcal{L}_F\left(\gamma^\mu,\psi\right) = i\bar{\psi}(x)\gamma^\mu\nabla_\mu\psi(x)$$
$$\gamma^\mu(x) = e_a{}^\mu(x)\gamma^a\,,\ \{\gamma^\mu,\,\gamma^\nu\} = 2g^{\mu\nu}$$

Action in the Einstein frame

$$S = \int de^4x\sqrt{-\tilde{g}}\,\mathrm{e}^{-4\sqrt{1/6}\kappa\varphi}\mathcal{L}_F\left(\gamma^\mu,\psi\right)$$
$$= \int d^4x\sqrt{-\tilde{g}}\left[\mathcal{L}_F\left(\tilde{\gamma}^\mu,\psi\right) + \mathcal{L}_{F-\varphi}\left(\tilde{\gamma}^\mu,\psi,\varphi\right)\right]$$
$$\mathcal{L}_{F-\varphi} = \left(\mathrm{e}^{-3\sqrt{1/6}\kappa\varphi} - 1\right)i\bar{\psi}\tilde{\gamma}^\mu\tilde{\nabla}_\mu\psi - \frac{3i}{2}\sqrt{\frac{1}{6}}\kappa\mathrm{e}^{-3\sqrt{1/6}\kappa\varphi}\left(\partial_\mu\varphi\right)\bar{\psi}\tilde{\gamma}^\mu\psi$$

Coupling appears

$$S_{F-\varphi} = \int d^4x\sqrt{-\tilde{g}}\mathcal{L}_{F-\varphi}\left(\tilde{g}^{\mu\nu},\psi,\varphi\right)$$
$$= \int d^4x\sqrt{-\tilde{g}}\left[-\frac{3i\kappa}{\sqrt{6}}\varphi\bar{\psi}\tilde{\gamma}^\mu\tilde{\nabla}_\mu\psi - \frac{3i\kappa}{2\sqrt{6}}\left(\partial_\mu\varphi\right)\bar{\psi}\tilde{\gamma}^\mu\psi\right] + \mathcal{O}(\kappa^2\varphi^2)$$

Coupling to Matter : Higgs and Massive Felds

Higgs field $H(x)$ with potential $V(H)$

$$
\begin{aligned}
\mathcal{L}_H\left(g^{\mu\nu}, H\right) &= -\, g^{\mu\nu}\left(D_\mu H\right)^\dagger\left(D_\nu H\right) - V(H^\dagger H) - \bar{\psi}_i Y_{ij}\psi_j H \\
&= -\, \mathrm{e}^{2\sqrt{1/6}\kappa\varphi}\tilde{g}^{\mu\nu}\left(D_\mu H\right)^\dagger\left(D_\nu H\right) - V(H^\dagger H) - \bar{\psi}_i Y_{ij}\psi_j H
\end{aligned}
$$

After SSB, via the Higgs mechanism, massless vector and fermion fields acquire the mass, which comes from covariant derivative and Yukawa term, respectively.

For, massive vector field

$$
\mathcal{L}_{V-\mathrm{mass}}\left(g^{\mu\nu}, A_\mu\right) = -\, \frac{1}{2} m_V^2 \mathrm{e}^{2\sqrt{1/6}\kappa\varphi}\tilde{g}^{\mu\nu} A_\mu A_\nu
$$

$$
\begin{aligned}
S &= \int d^4x\sqrt{-\tilde{g}}\,\mathrm{e}^{-4\sqrt{1/6}\kappa\varphi}\mathcal{L}_{V-\mathrm{mass}}\left(g^{\mu\nu}, A_\mu\right) \\
&= \int d^4x\sqrt{-\tilde{g}}\left[\mathcal{L}_{V-\mathrm{mass}}\left(\tilde{g}^{\mu\nu}, A_\mu\right) + \mathcal{L}_{V-\varphi}\left(\tilde{g}^{\mu\nu}, A_\mu, \varphi\right)\right]
\end{aligned}
$$

$$
\mathcal{L}_{V-\varphi}\left(\tilde{g}^{\mu\nu}, A_\mu, \varphi\right) = -\frac{1}{2} m_V^2\left(\mathrm{e}^{-2\sqrt{1/6}\kappa\varphi} - 1\right)\tilde{g}^{\mu\nu} A_\mu A_\nu
$$

Coupling to Matter : Massive Felds

Coupling appears

$$S_{V-\varphi} = \int d^4x \sqrt{-\tilde{g}} \mathcal{L}_{V-\varphi}\left(\tilde{g}^{\mu\nu}, A_\mu, \varphi\right)$$
$$= \int d^4x \sqrt{-\tilde{g}} \left[\frac{\kappa m_V^2}{\sqrt{6}} \varphi \tilde{g}^{\mu\nu} A_\mu A_\nu \right] + \mathcal{O}(\kappa^2 \varphi^2)$$

For massive fermion field

$$\mathcal{L}_{F-\mathrm{mass}}\left(\psi\right) = -m_F \bar{\psi}\psi$$
$$S = \int d^4x \sqrt{-\tilde{g}}\, \mathrm{e}^{-4\sqrt{1/6}\kappa\varphi} \mathcal{L}_{V-\mathrm{mass}}\left(g^{\mu\nu}, A_\mu\right)$$
$$= \int d^4x \sqrt{-\tilde{g}} \left[\mathcal{L}_{F-\mathrm{mass}}\left(\psi\right) + \mathcal{L}_{F-\varphi}\left(\psi, \varphi\right)\right]$$
$$\mathcal{L}_{F-\varphi}\left(\psi, \varphi\right) = -m_F \left(\mathrm{e}^{-4\sqrt{1/6}\kappa\varphi} - 1\right) \bar{\psi}\psi$$

Coupling appears

$$S_{F-\varphi} = \int d^4x \sqrt{-\tilde{g}} \mathcal{L}_{F-\varphi}\left(\psi, \varphi\right)$$
$$= \int d^4x \sqrt{-\tilde{g}} \left[\frac{4\kappa m_F}{\sqrt{6}} \varphi \bar{\psi}\psi \right] + \mathcal{O}(\kappa^2 \varphi^2)$$

Scalaron indirectly couples to photon via the loop.

Particle Picture and Effective Action

We regard an excitation of scalaron field as a particle.

$$\varphi = \varphi_{min} + \hat{\varphi}\,, \ \ |\hat{\varphi}| \ll |\varphi_{min}|$$

We assume that matter sector can be divided into two parts:

$$T^{\mu}_{\ \mu} = \langle T^{\mu}_{\ \mu} \rangle + \epsilon \hat{T}^{\mu}_{\ \mu}\,, \ \ |\epsilon| \ll 1$$

$\langle T^{\mu}_{\mu} \rangle$: Matter fields of environment

$\hat{T}^{\mu}_{\mu}$: Matter fields as particle = SM

Background solution is determined by $\langle T^{\mu}_{\mu} \rangle$

$$\hat{\Box}\varphi_{min} \approx V'(\varphi_{min}) + \frac{\kappa}{\sqrt{6}} \mathrm{e}^{-4\sqrt{1/6}\kappa\varphi_{min}} \langle T^{\mu}_{\ \mu} \rangle$$

If $\kappa\varphi_{min} \ll 1$, excitation $\hat{\varphi}$ satisfies

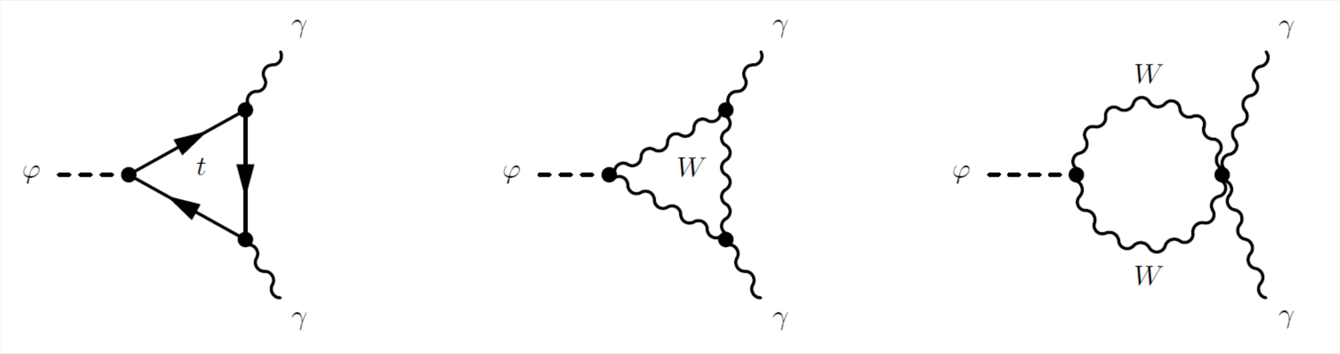
$$\tilde{\Box}\hat{\varphi} \approx \tilde{V}'(\hat{\varphi}) + \epsilon \frac{\kappa}{\sqrt{6}} \mathrm{e}^{-4\sqrt{1/6}\kappa\hat{\varphi}} \hat{T}^{\mu}_{\ \mu}\,, \ \ \tilde{V}(\hat{\varphi}) = \frac{1}{2} m_{\varphi}^2 \hat{\varphi}^2 + \frac{1}{3!} V'''_{eff}(\varphi_{min}) \hat{\varphi}^3 \cdots$$

Decay Width

Scalaron can decay to photon through loop diagram.

$$\mathcal{L}_{eff} = \frac{\beta(e)}{4e}\frac{\varphi}{f_\varphi}F_{\mu\nu}^2, \ \beta(e) = \sum_f \frac{e^3}{(4\pi)^2} Q_f^2 N_c^{(f)}$$

Main contributions to $\varphi \to \gamma\gamma$



$$\Gamma_{\varphi\to\gamma\gamma} = \frac{\alpha_{em}}{256\pi^3}\frac{m_\varphi^3}{f_\varphi^2}\left|3\cdot\left(\frac{2}{3}\right)^2\cdot\left(\frac{4}{3}\right) + (-7)\right|^2, \ f_\varphi^{-1} \sim \frac{\epsilon}{M_p}$$ (Decay constant)

Life time > 10^{17}[s] (age of Universe) → $m_\varphi \lesssim 1\times\epsilon^{-2}[\mathrm{GeV}]$

Constraint to F(R) gravity

If we regard the scalaron as DM candidate, **constraint to F(R) model can be obtained by converting that to DM**.

→ From the lower bound of life time, we obtain the upper bound of scalaron mass, which constrains the model of F(R).

As a trial, we consider the environment in the early Universe:

1. At classical level, EW phase transition $\langle T \rangle \sim (100\ GeV)^4$
2. At quantum level, $\hat{T}$ = SM particles

And, we use the Starobinski model

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

In large curvature limit $R \gg R_c \sim R_0 (\Leftrightarrow \kappa\varphi_{min} \ll 1)$, the scalaron mass is

$$m_\varphi^2 = \frac{R_c}{6n(2n+1)\beta} \left(\frac{\kappa^2}{R_c} \langle T^\mu{}_\mu \rangle \right)^{2(n+1)}$$

Work in Progress

As an effective theory, ϵ is considered to be ratio between the scales of gravitational physics and particle physics.

→ We assume $\epsilon = {}^{M_{EW}}/_{M_P} = 10^{-18}$

We find $\beta < 10^{-53}$ for n=4 ($\beta R_c \approx 2\Lambda$).

But, it should be $O(1)$ for compatibility with DE...

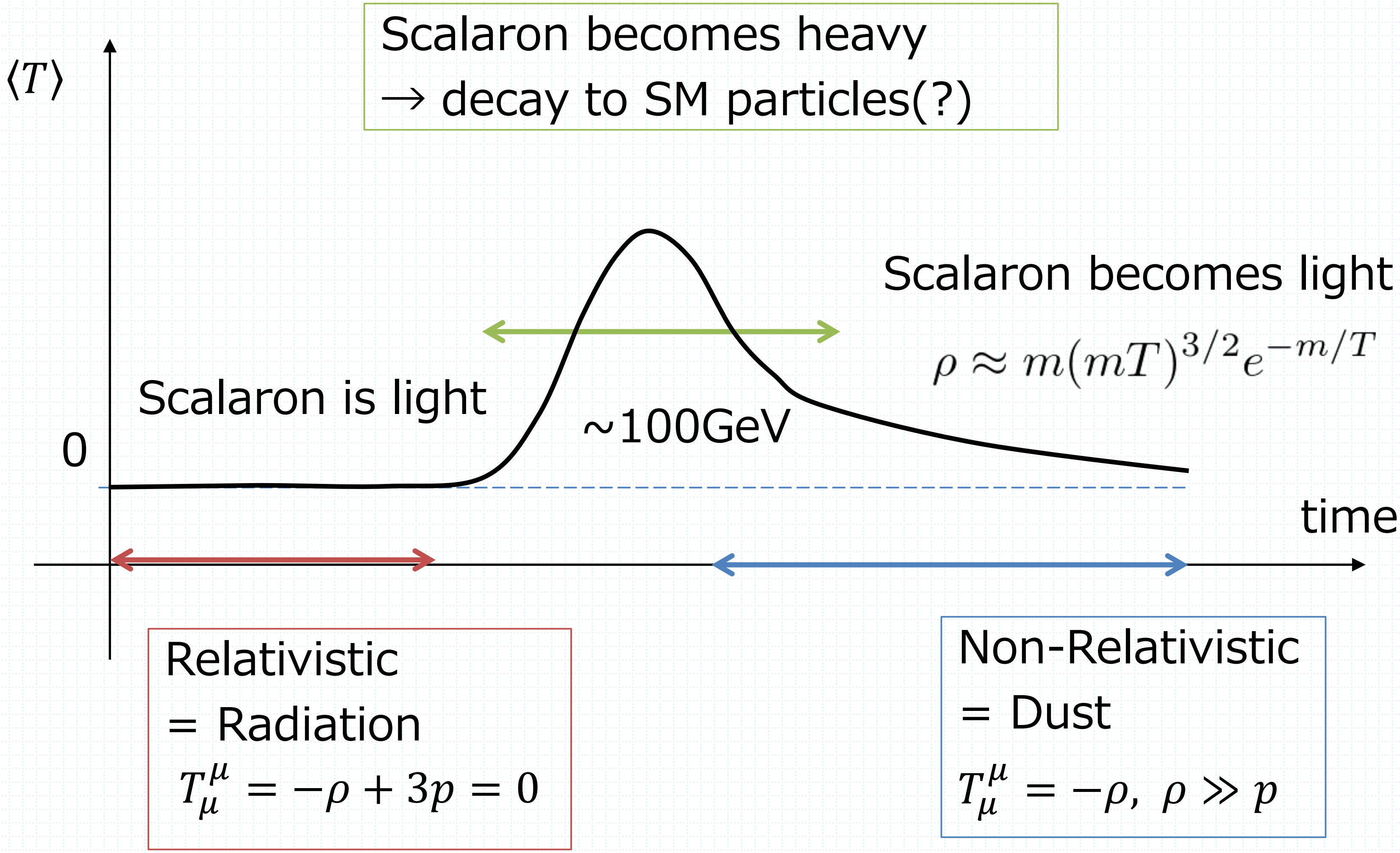
Other environments?

- If all matters are relativistic, $\langle T \rangle = 0$ as perfect fluid (radiation).
- If so, the chameleon mechanism doesn't work, and we cannot use the large-curvature approximation.
- Then, scalaron mass ~ Λ, which satisfies the constraint.
- Precise estimation of $\langle T \rangle$ (Tiny but non-zero value?)

Validity of the constraint?

- Scalaron mass changes in the cosmic history.
- We can get the constraint at a particular time (non-local).

Trace of energy-momentum tensor



Summary

- Scalaron field from F(R) gravity has a properties which required as DM candidate.
- The effective action is considered to study the scalaron in particle physics.
- Scalaron depends on assumptions about the environment, which should be treated carefully.
- We estimated the constraint to parameter in the Starobinski model from the life time of the scalaron.

Many applications

1. Is it possible to construct the new F(R) model to explain DE and DM?
2. We can use the effective action for other phenomena if we choose the other $\langle T \rangle$ (e.g. $\langle T \rangle \sim 10^{-24}[gcm^{-3}]$ for galaxy)

Many problems remains

→ Thermal history, Relic density, Self-interacting DM etc.