Non-gravitational signals of dark energy under a gauge symmetry

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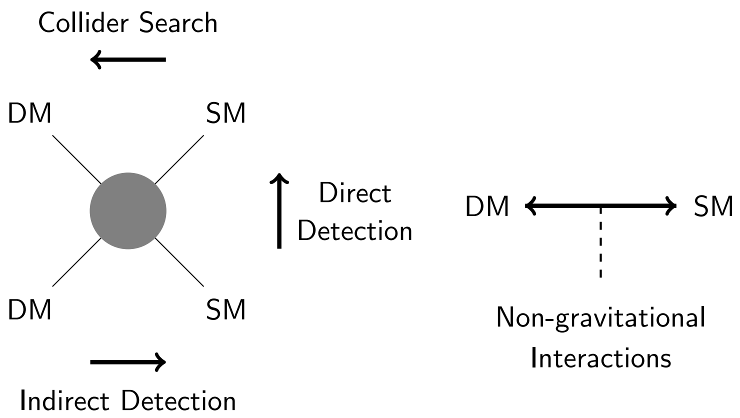
based on JCAP 02 (2023) 005 [arXiv:2208.09229]
JCAP 09 (2023) 017 [arXiv:2306.01291]
JCAP 03 (2024) 048 [arXiv:2312.09717]
with Kunio Kaneta, Hye-Sung Lee, and Jiheon Lee

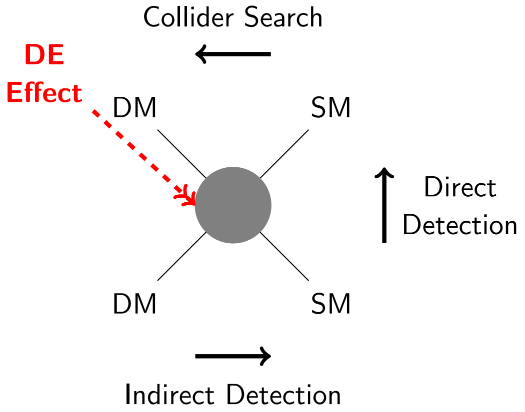
Overview

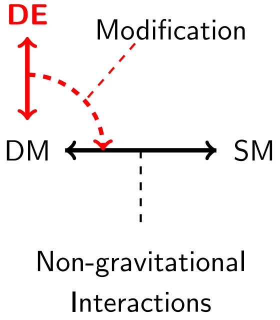
I. Introduction

Dark Matter Research



Implication of Dark Energy





In This Talk

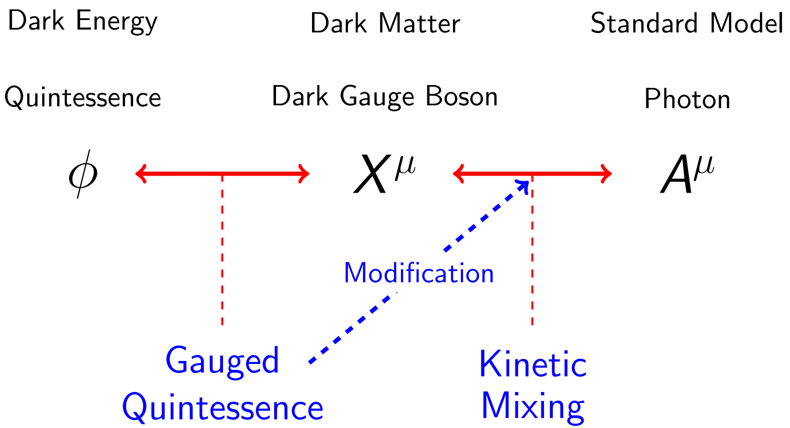
Dark Energy — Dark Matter

Quintessence — Dark Gauge Boson

ϕ ⟷ X^μ

Gauged Quintessence

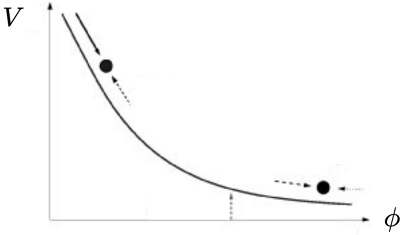
In This Talk


Dark Energy
Dark Matter
Standard Model
Quintessence
Dark Gauge Boson
Photon
ϕ
X^μ
A^μ
Modification
Gauged Quintessence
Kinetic Mixing

II. Gauged Quintessence

Quintessence

- Dynamic dark energy model proposed by Ratra and Peebles.
  [Bharat Ratra and P. J. E. Peebles PRD37(1988)3406]
- A scalar ϕ rolls down a potential slowly in the present universe.



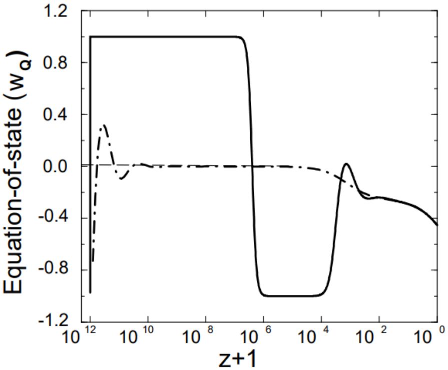
- Equation of state assuming slow roll condition $\frac{1}{2}\dot{\phi}^2 \ll V(\phi)$

$$w = \frac{p}{\rho} = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)} \approx -1$$

Tracking Behavior

- The initial value of ϕ does not really matter. Only the potential determines the the present time value of and its equation of state (addressing the cosmological coincidence problem).

[Steinhardt, Wang, Zlatev PRL82(1999)896]



Gauged Quintessence

- The gauged quintessence model includes complex scalar $\Phi = \phi e^{i\eta}/\sqrt{2}$ and $U(1)_{\rm dark}$ gauge boson $\mathbb{X}_\mu$. Φ is charged under the $U(1)_{\rm dark}$ gauge symmetry and ϕ behaves as dark energy.

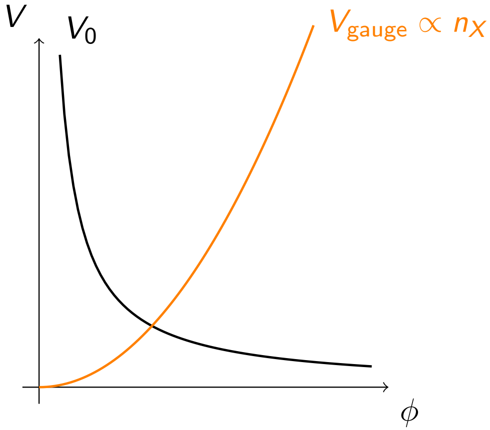
[KK, HL, JL, and **JY** JCAP02(2023)005]

- Under the unitary gauge, $\eta = 0$ and $X_\mu = \mathbb{X}_\mu + \frac{1}{g_X}\partial_\mu \eta$, the Lagrangian of gauged quintessence model is given by

$$\mathcal{L} \supset \sqrt{-g}\Big[-\frac{1}{2}(\partial_\mu\phi)(\partial^\mu\phi) - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - V_0(\phi) - \frac{1}{2}(g_X\phi)^2 X_\mu X^\mu \Big]$$

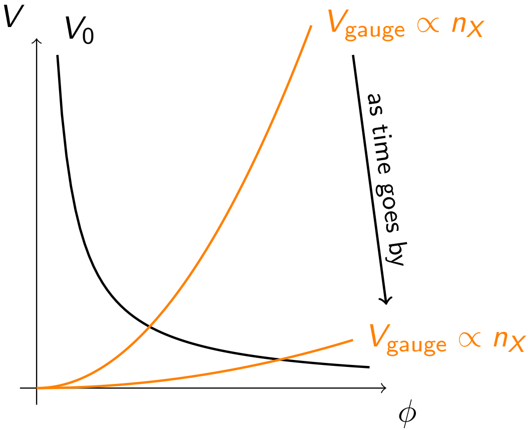
where g_X is the dark gauge coupling constant.

Potential



- $V_0 = \dfrac{M^{\alpha+4}}{\phi^\alpha}$
- $V_{\text{gauge}} \propto n_X$

Potential



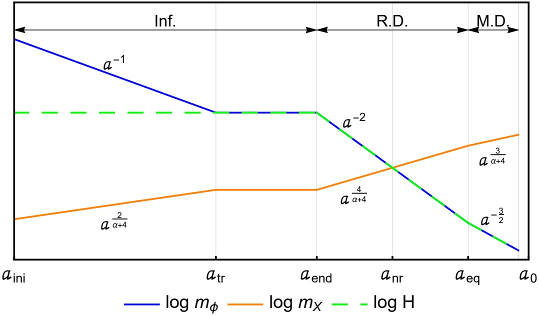
- $V_0 = \dfrac{M^{\alpha+4}}{\phi^{\alpha}}$
- $V_{\text{gauge}} \propto n_X$

Mass-varying Effect

- The masses of ϕ and X are given as

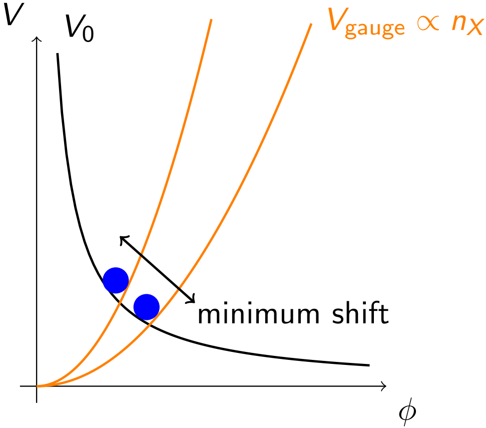
$$m_\phi^2 = \frac{\partial^2 V_{\rm eff}}{\partial \phi^2}, \quad m_X^2 = g_X^2 \phi^2$$

- Dynamic ϕ makes m_X vary over time.
- When the tracking and rolling of quintessence begin, m_X increases.



Mass-varying Effect

- If n_X is large, then ϕ can be trapped in the potential minimum.
- When ϕ is trapped in the potential minimum, m_X depends on n_X.



- n_X increases
  $\rightarrow m_X$ decreases
- n_X decreases
  $\rightarrow m_X$ increases

III. Production of Dark Gauge Boson

Kinetic Mixing

- To connect SM sector and dark sector, introduce the kinetic mixing.

$$\mathcal{L} \supset -\frac{\varepsilon}{2} F^{\mu\nu} X_{\mu\nu}$$

- Photon in the thermal bath obtains the effective mass m_γ.
- The diagonalization of mass terms of γ and X leads the effective kinetic mixing $\overline{\varepsilon}$ given as

$$|\overline{\varepsilon}|^2 = \varepsilon^2 \frac{m_X^4}{(m_X^2 - m_\gamma^2)^2 + (\omega D)^2}.$$

where ωD is the imaginary part of the effective photon mass.

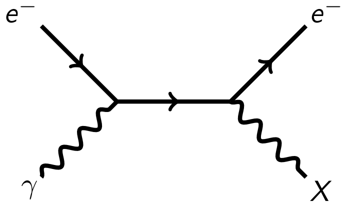
[Javier Redondo JCAP07(2008)008]

- Note that $\overline{\varepsilon}$ resonantly increases when $m_\gamma = m_X$.

Production of X

- Assuming m_X is small initially, X can be produced from the thermal bath via Compton-like scattering.

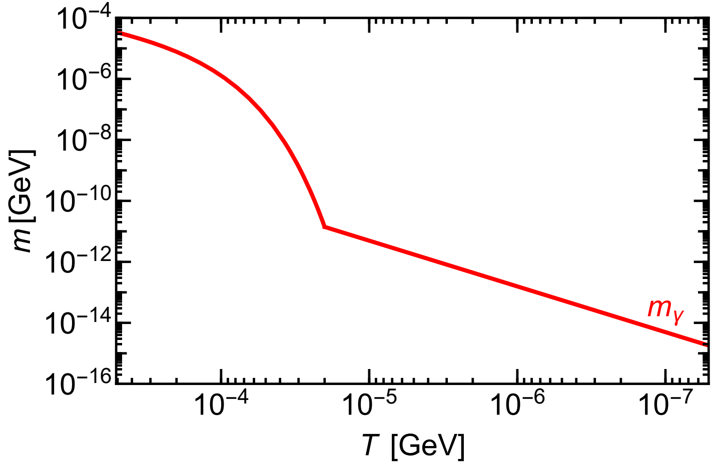
[Javier Redondo and Marieke Postma JCAP02(2009)005]



$$\Rightarrow \qquad \sigma \propto |\bar{\epsilon}|^2$$

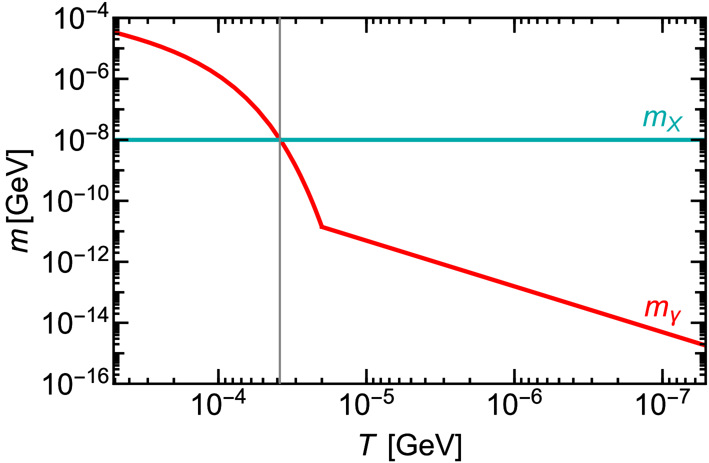
- The production of X dominantly occurs when the resonant condition $m_X = m_\gamma$ is satisfied.

$U(1)$ Model with Fixed Mass

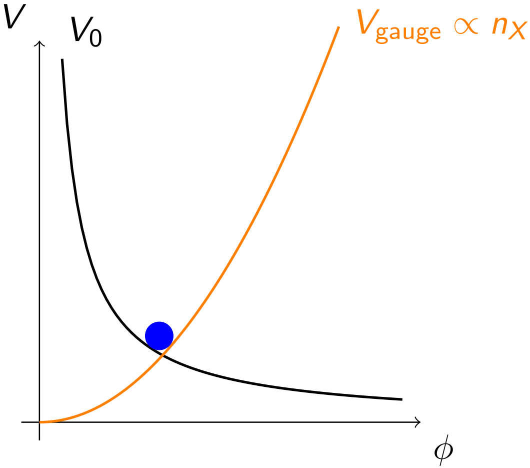


$U(1)$ Model with Fixed Mass

- Resonance occurs at a single moment.

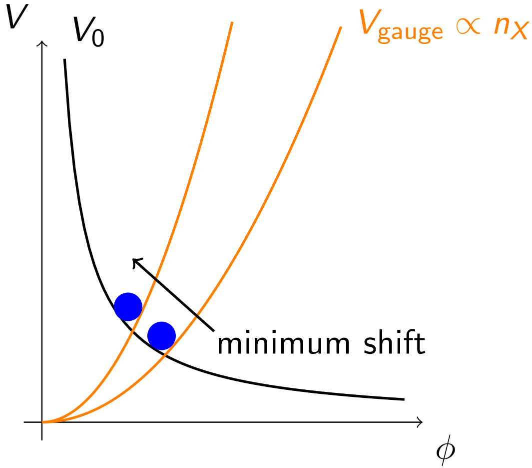


Trapped Scenario



ϕ can be trapped at the minimum

Trapped Scenario

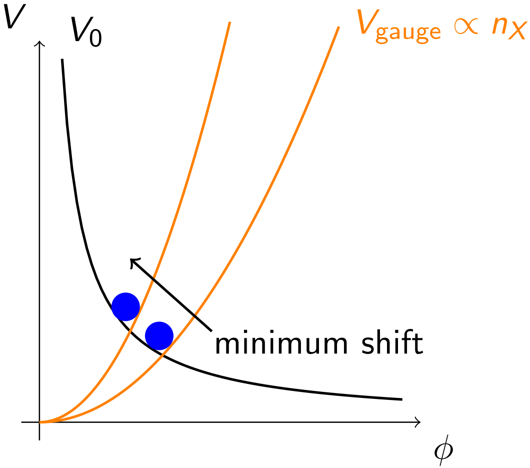


ϕ can be trapped at the minimum

↓

Production of X shifts the minimum

Trapped Scenario



ϕ can be trapped at the minimum

$\downarrow$

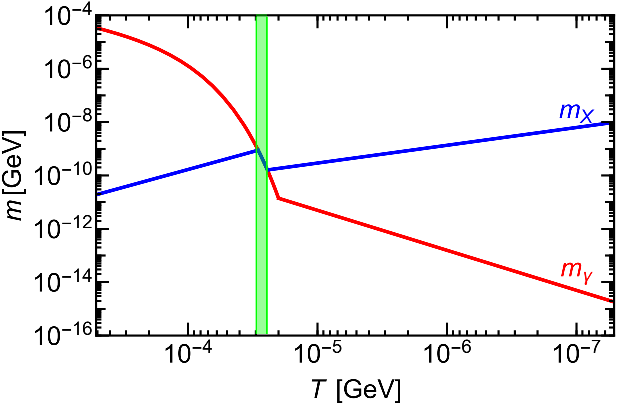
Production of X shifts the minimum

$\downarrow$

ϕ and m_X decrease

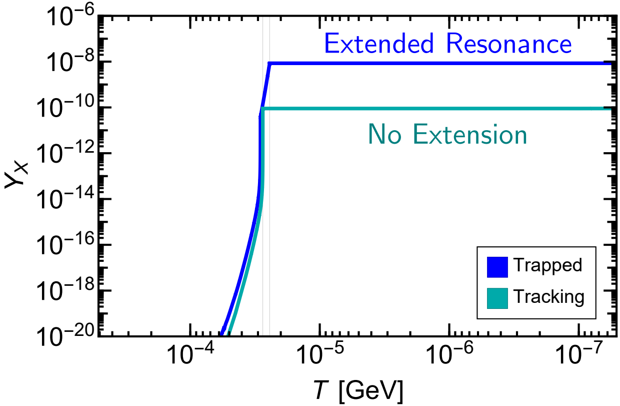
Extended Resonance

- Decreasing m_X can follow the behavior of m_γ.
- Resonance period is extended to a time interval.



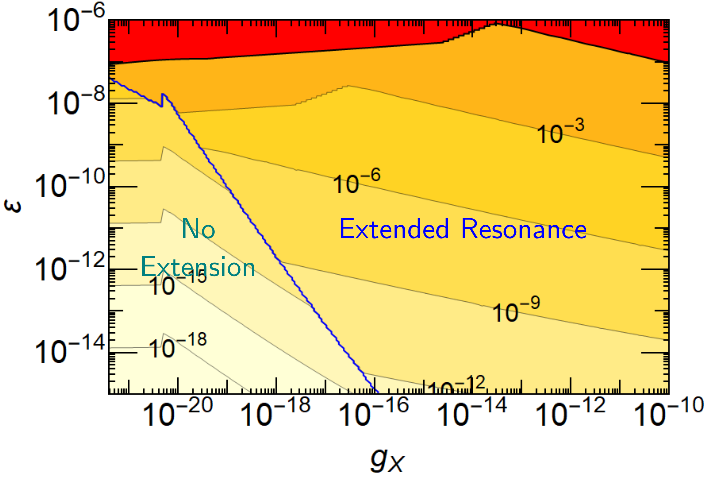
[KK, HL, JL, and **JY** JCAP03(2024)048]

Extended Resonance Produce More X



$$Y_X = \frac{n_X}{s} \qquad \left(\begin{array}{rl} n_X : & \text{number density of dark gauge boson} \\ s : & \text{entropy density of the photon thermal bath} \end{array} \right)$$

Produced Y_X

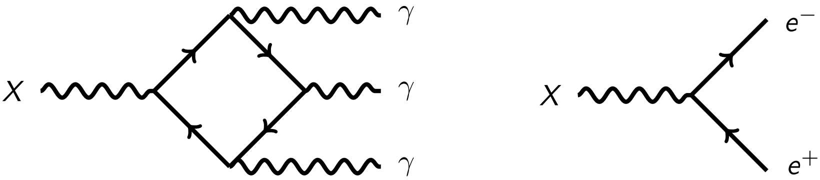


10−6
10−8
10−10
10−12
10−14
ε
10−20
10−18
10−16
10−14
10−12
10−10
gX
10−3
10−6
10−9
10−12
10−15
10−18
No Extension
Extended Resonance

IV. Decay Signal of Dark Gauge Boson

Decay Channels

$X \to \gamma\gamma\gamma \quad (m_X < 2m_e)$ $\qquad$ $X \to e^+e^- \quad (m_X > 2m_e)$



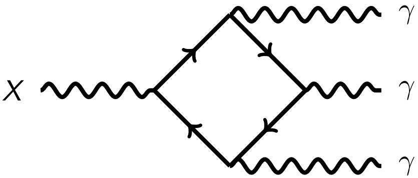
- If $m_X < 2m_e$, only $X \to \gamma\gamma\gamma$ channel is available.
- If $m_X > 2m_e$, both channels are available but $X \to e^+e^-$ channel highly dominates $X \to \gamma\gamma\gamma$.
- For the fixed mass case, only one of the channels is effective.
- Either $\gamma\gamma\gamma$ signal or e^+e^- signal can be detected.

Both Signals Are Available in Gauged Quintessence

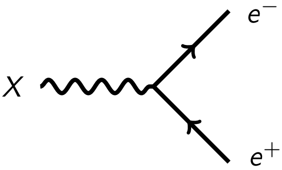
- After production, m_X increases over time.
- Early universe when $m_X < 2m_e$, $\gamma\gamma\gamma$ signal is produced.
- As time goes by m_X can become larger than $2m_e$, and then e^+e^- signal is produced.

Time Flow →

Early Universe $(m_X < 2m_e)$

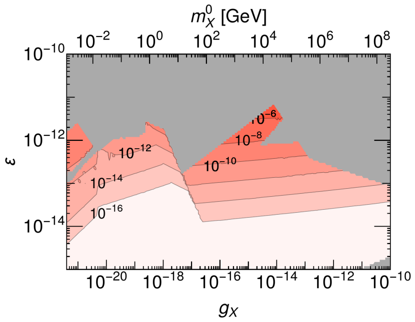


Late Universe $(m_X > 2m_e)$

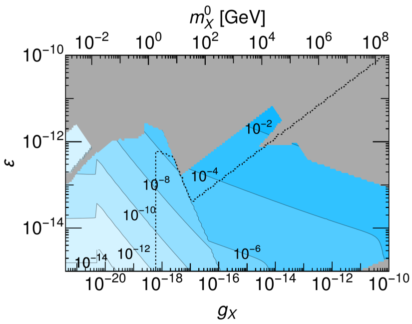


Produced Signals

$\rho^0_{\gamma\gamma\gamma}/\rho_{\rm crit}$



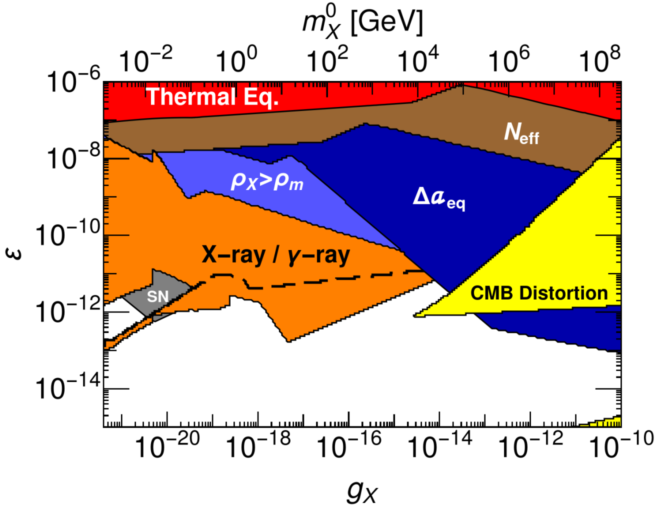
$\rho^0_{e^+e^-}/\rho_{\rm crit}$



- Both $\gamma\gamma\gamma$ signal and e^+e^- signal are sizable.

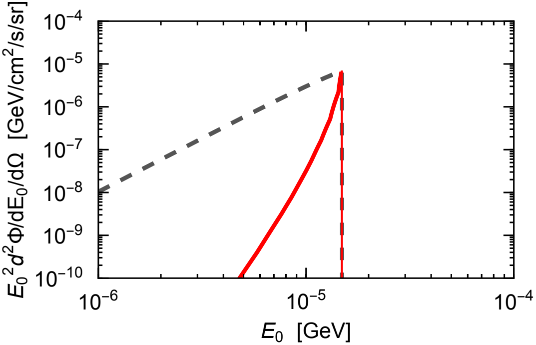
[KK, HL, JL, and **JY** JCAP03(2024)048]

Constraints



Characteristics of $\gamma\gamma\gamma$ Signals

- $\Gamma_{X\to\gamma\gamma\gamma}$ highly depends on m_X ($\propto m_X^9$).
- When the mass becomes larger, the decay rate increases, resulting in more energetic signals and the appearance of a steeper spectrum.



Gauged Quintessence   Fixed Mass

Characteristics of e^+e^- Signals

- Due to the kinematic threshold $m_X = 2m_e$, the decay occurs much later than the case of usual $U(1)$ model.
- Right after the threshold $m_X = 2m_e$ is overcame, $\Gamma_{X\to e^+e^-} \gg H$ is achieved.
- Then the decay extinguishes X and produce e^+e^- pair extremely quickly.
- The resulting e^+e^--pair is highly non-relativistic.

V. Summary

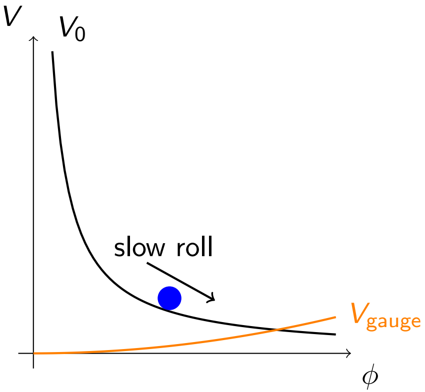
Summary

- Gauged Quintessence model is a $U(1)$ charged quintessence model.
- Gauged Quintessence can affect the dark sector signal.
- The production of dark gauge boson can be enhanced due to the extended resonance.
- Unlike the typical $U(1)$ model, both $\gamma\gamma\gamma$ signal and e^+e^- signal can be detected.
- $\gamma\gamma\gamma$ signal and e^+e^- signal have characteristic features.

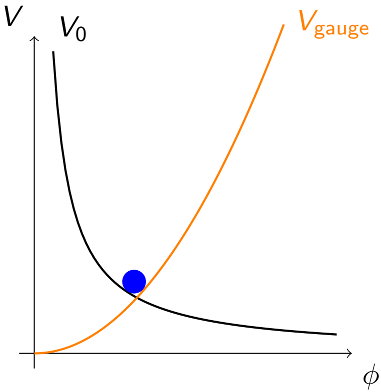
Thank you for listening

Back-up Slides

Two Behaviors of m_X

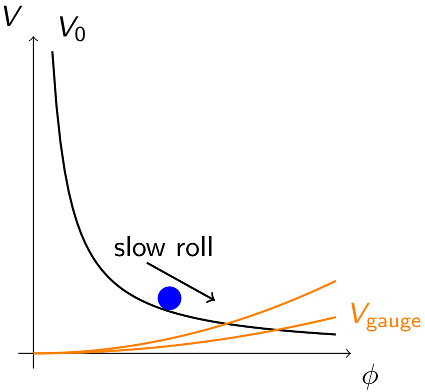


Rolling Scenario



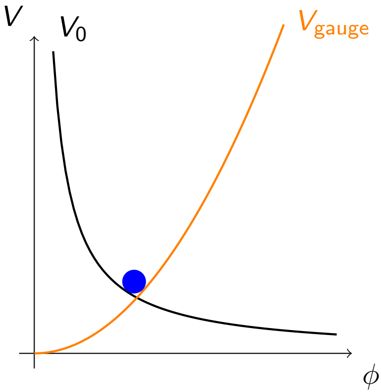
Trapped Scenario

Two Behaviors of m_X



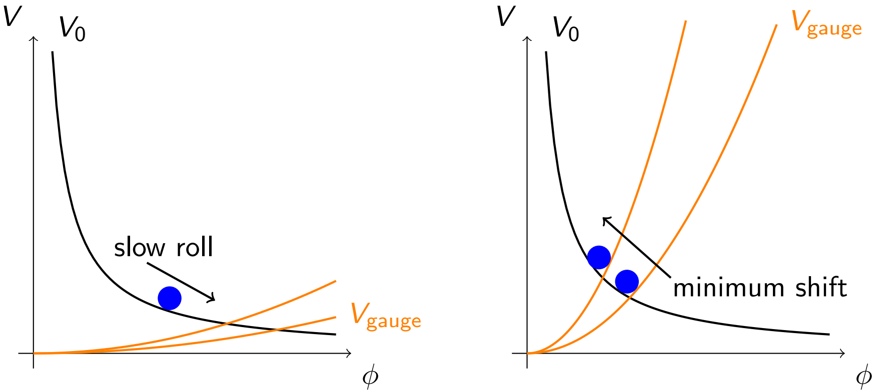
Rolling Scenario

ϕ and m_X increase



Trapped Scenario

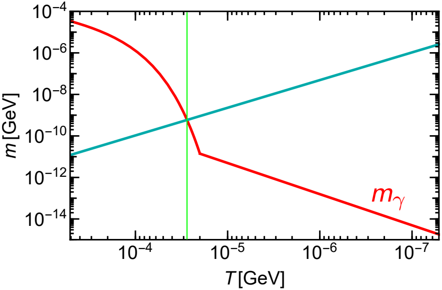
Two Behaviors of m_X



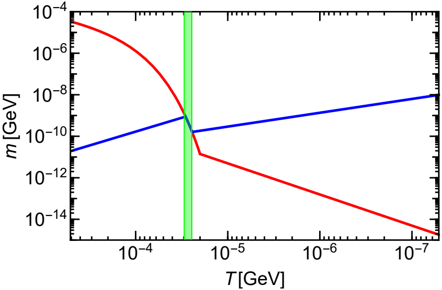
Rolling Scenario
ϕ and m_X increase

Trapped Scenario
ϕ and m_X decrease

Extended Resonance



Rolling Scenario
Resonance at a single instant



Trapped Scenario
Resonance within a time interval