Dark Photon DM from Quantum Fluctuations during Starobinsky Inflation

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Kasamaki and TM, arXiv 2607.29149

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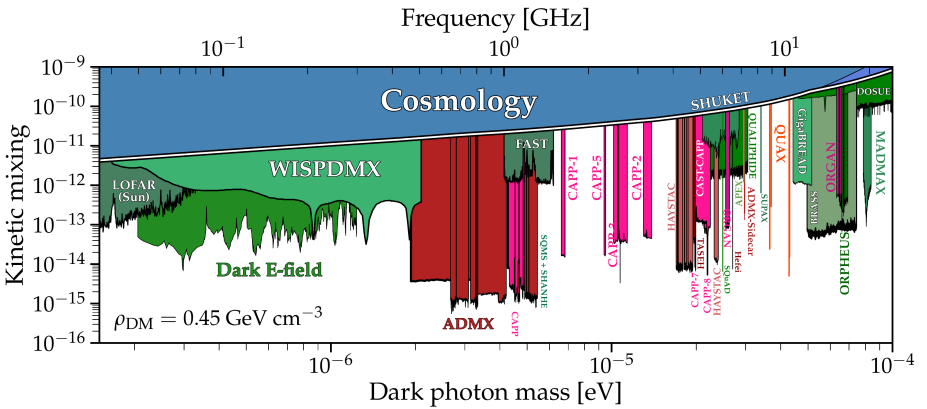
1. Introduction

I consider wave-like DM (particularly, dark photon)

$\Leftrightarrow$ Extensive efforts for its direct detection (particularly, using cavities), but no discovery yet

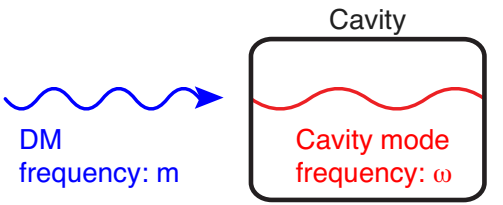


[Figure, with the use of AxionLimits]

Difficulty in detecting wave-like DM with haloscope experiments

- $\cdots$
- Scan over cavity frequency

Resonant enhancement of the cavity-mode excitation is required

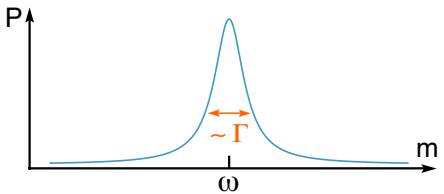


$\Rightarrow$ We have to scan over ω (because DM mass is unknown)

Power extracted from the cavity

$$P \propto (\text{DM-Cavity coupling}) \times \frac{\Gamma}{(\omega - m)^2 + \Gamma^2}$$

Γ: loss rate of cavity photon $\Leftrightarrow$ $Q \equiv \dfrac{\omega}{\Gamma} \gg 1$ ($\sim 10^5$ or larger)



$\Rightarrow$ DM mass probed: $\omega - \dfrac{\omega}{Q} \lesssim m \lesssim \omega + \dfrac{\omega}{Q}$

Scan is very time-consuming (since the DM mass is unknown)

$\Rightarrow$ We (i.e., theorists) should provide information about DM mass

Today, I will discuss: dark-photon DM mass

- I consider a scenario in which dark photon DM is produced as a quantum fluctuation during inflation
  [Graham, Mardon, Rajendran ('15)]
- I consider Starobinsky inflation

Outline

1. Introduction
2. Model (Based on Standard Inflation)
3. Case of Starobinsky Inflation
4. Summary

2. Model (Based on Standard Inflation)

Dark photon action

$$S_{\rm DP} = \int dt d^3x \sqrt{-g} \left(-\frac{1}{4} g^{\mu\nu} g^{\rho\sigma} F_{\mu\rho} F_{\nu\sigma} + \frac{1}{2} m^2 g^{\mu\nu} A_\mu A_\nu \right)$$

m: Dark photon mass

$g_{\mu\nu} = \text{diag}\,(1, -a^2, -a^2, -a^2)$

Longitudinal mode of dark photon plays the key role

$$\vec{\tilde{A}}(\vec{k}) \sim \tilde{A}_L(\vec{k}) \frac{\vec{k}}{k} \quad \Leftrightarrow \quad \tilde{A}_t(\vec{k}) = \frac{i\vec{k}\,\partial_t \vec{\tilde{A}}(\vec{k})}{k^2 + a^2 m^2} = \frac{ik}{k^2 + a^2 m^2}\,\partial_t \tilde{A}_L(\vec{k})$$

Action for longitudinal mode:

$$S_L = \int dt \frac{d^3k}{(2\pi)^3} a^3 \times \frac{1}{2a^2} \left(\frac{a^2 m^2}{k^2 + a^2 m^2} |\partial_t \tilde{A}_L|^2 - m^2 |\tilde{A}_L|^2 \right)$$

Behavior of the longitudinal mode (for $m \neq 0$):

- $\tilde{A}_L$ with $k \gg am$ behaves as an almost massless scalar

$$\tilde{\pi} \equiv \frac{m}{k}\tilde{A}_L \quad \Rightarrow \quad S_L \simeq \int dt \frac{d^3k}{(2\pi)^3} a^3 \times \frac{1}{2}\left(|\partial_t \tilde{\pi}|^2 - \frac{k^2}{a^2}|\tilde{\pi}|^2\right)$$

- Quantum fluctuation generated during inflation

$$\mathcal{P}_{\tilde{\pi}} \simeq \left(\frac{H_{\rm inf}}{2\pi}\right)^2 \quad \Rightarrow \quad \mathcal{P}_{\tilde{A}_L} \simeq \frac{k^2}{m^2}\left(\frac{H_{\rm inf}}{2\pi}\right)^2$$

- After the horizon exit, the dark photon field behaves as a classical wave

Final abundance of the relic dark photon density:

[Graham, Mardon, Rajendran ('15)]

$$\Omega_{\rm DM} h^2 \simeq 0.15 \times \left(\frac{m}{100\,\text{meV}}\right)^{1/2} \left(\frac{H_{\rm inf}}{10^{13}\,\text{GeV}}\right)^2$$

Relevant dark photon mass for $H_{\rm inf} \sim 10^{13}$ GeV

$m \sim O(100)$ meV: fully out of the reach of cavity haloscopes

$$f \simeq 24\,\text{THz} \times \left(\frac{m}{100\,\text{meV}}\right)$$

It is crucial that the dark photon is massive, even during inflation

$\Leftrightarrow$ Probably, Stueckelberg mechanism is the simplest option

3. Starobinsky Inflation

Gravity action for Starobinsky inflation:

$$S = -\frac{M_{\rm Pl}^2}{2}\int d^4x\sqrt{-\bar{g}}\left[\bar{R} - \frac{1}{6m_\phi^2}\bar{R}^2\right]$$

$\bar{g}_{\mu\nu}$ and $\bar{R}$: metric and Ricci scalar in the Jordan frame

Or equivalently:

$$S = -\frac{M_{\rm Pl}^2}{2}\int d^4x\sqrt{-\bar{g}}\left[\varphi\bar{R} + \frac{3}{2}m_\phi^2(\varphi-1)^2\right]$$

$\varphi = 1 - \dfrac{1}{3m_\phi^2}\bar{R}$: Auxiliary field

Weyl transformation to go to the Einstein frame: $g_{\mu\nu} = \varphi\bar{g}_{\mu\nu}$

$$S = -\frac{M_{\rm Pl}^2}{2}\int d^4x\sqrt{-g}\left[R - \frac{3}{2\varphi^2}\left\{g^{\mu\nu}(\partial_\mu\varphi)(\partial_\nu\varphi) + m_\phi^2(\varphi-1)^2\right\}\right]$$

Canonically normalized inflaton field:

$$\varphi = \exp\left(\sqrt{\frac{2}{3}}\frac{\phi}{M_{\rm Pl}}\right)$$

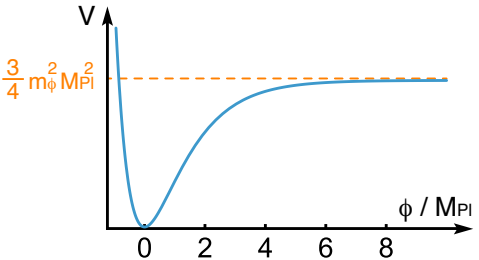
Action in the Einstein frame

$$S_{\rm tot} = \int d^4x\sqrt{-g}\left[-\frac{M_{\rm Pl}^2}{2}R + \frac{1}{2}g^{\mu\nu}(\partial_\mu\phi)(\partial_\nu\phi) - V_\phi\right]$$

Inflaton potential

$$V_\phi = \frac{3}{4}m_\phi^2 M_{\rm Pl}^2\left[1 - \exp\left(-\sqrt{\frac{2}{3}}\frac{\phi}{M_{\rm Pl}}\right)\right]^2$$

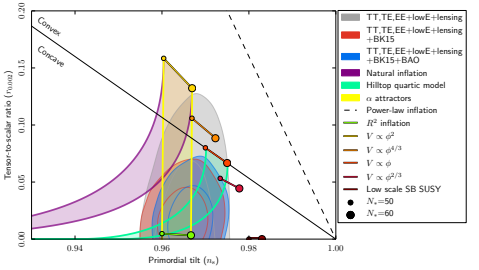
Inflaton potential



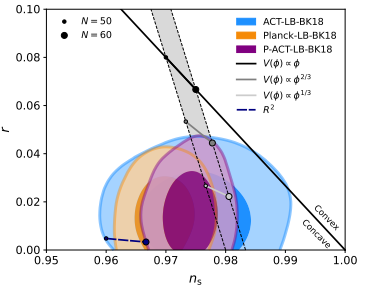
- Slow-roll inflation occurs at $\phi \to +\infty$
- Density perturbations are consistent with observations
- m_ϕ: inflaton mass

$$V_\phi \simeq \frac{1}{2} m_\phi^2 \phi^2 + O(\phi^3)$$

Starobinsky inflation vs. CMB observations



[Planck Collaboration ('18)]



[ACT Collaboration ('25)]

⇔ I will not discuss the possible tension with the ACT result

Effect of the Weyl transformation onto the dark photon:

$$g_{\mu\nu} = \varphi \bar{g}_{\mu\nu} = \Omega^2 \bar{g}_{\mu\nu} \ \text{ with } \ \Omega \equiv \varphi^{1/2} = \exp\left(\sqrt{\frac{1}{6}}\frac{\phi}{M_{\rm Pl}}\right)$$

$$S_{\rm DP} = \int dt d^3x \sqrt{-g}\left(-\frac{1}{4} g^{\mu\nu} g^{\rho\sigma} F_{\mu\rho} F_{\nu\sigma} + \frac{1}{2}\,\Omega^{-2}\, m^2 g^{\mu\nu} A_\mu A_\nu\right)$$

Longitudinal-mode action (for $k \gg a\hat{m}$):

$$S_L \simeq \int dt \frac{d^3k}{(2\pi)^3} a^3 \times \frac{1}{2a^2}\left(\frac{a^2 \widehat{m}^2}{k^2}|\partial_t \tilde{A}_L|^2 - \widehat{m}^2 |\tilde{A}_L|^2\right)$$

$$\widehat{m} \equiv \Omega^{-1} m$$

$\Rightarrow$ Kinetic function for A_L varies during inflation

Fluctuation amplitude (after inflation)

$$\mathcal{P}_{A_L}(k \ll aH) \simeq \Omega^2(t_k)\frac{k^2}{m^2}\left(\frac{H(t_k)}{2\pi}\right)^2\left[1+O(\epsilon^{1/2})\right]$$

t_k: time of the horizon exit of the mode-k

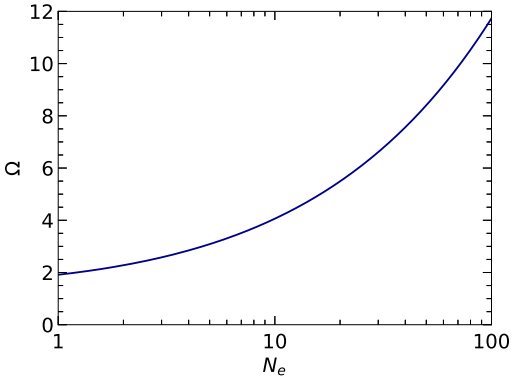
$$\Rightarrow\ \Omega_{\rm DM}h^2 \simeq 0.15\times\left(\frac{m}{10\,\mu{\rm eV}}\right)^{1/2}\left(\frac{H(t_{k_*})}{10^{13}\,{\rm GeV}}\right)^2\left(\frac{\Omega(t_{k_*})}{10}\right)^2$$

k_*: k of the mode that reenters the horizon at $H=m$

We performed a precise calculation of the relic density

- Evolution of the power spectrum during and after inflation is numerically studied
- Higher order slow-roll corrections are considered

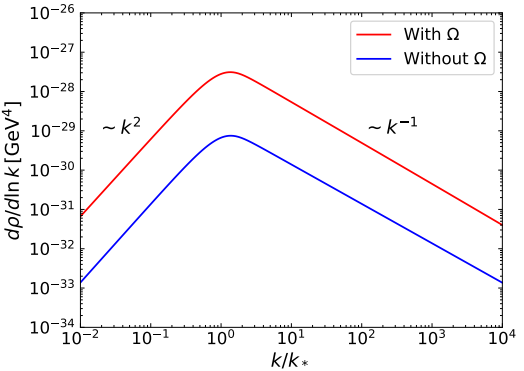
Ω as a function of e-folding number during inflation



$$\Leftrightarrow \quad \Omega \simeq \sqrt{\frac{4}{3}N_e}$$

$\Rightarrow$ We found $N_e(t_{k_*}) \simeq 30$, and $\Omega^2(t_{k_*}) \simeq 40$

Energy spectrum at the radiation-matter equality (example)



$\Rightarrow$ Mode with $k \sim k_*$ dominates

For the precise calculation of $\Omega_{\rm DM}$, reheating is important

- N_e depends on the reheating temperature
- Inflaton decays into dark radiation

Decay into SM particles (maybe Higgs?)

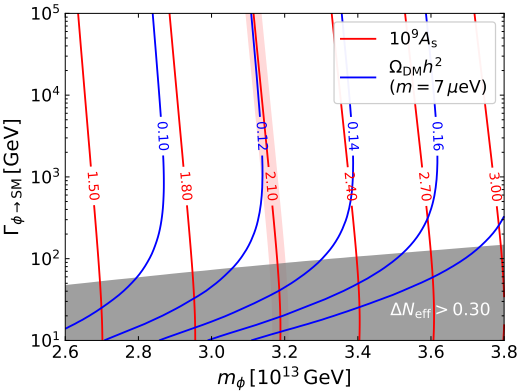
$$\mathcal{L}_{\rm int} = \xi |H|^2 \bar{R} \quad \Rightarrow \quad \Gamma_{\phi \to HH} = \frac{(1-6\xi)^2}{48\pi} \frac{m_\phi^3}{M_{\rm Pl}^2}$$

$\Leftrightarrow$ Preheating occurs if $\xi \gtrsim 1.8$

Decay into dark photon (which becomes dark radiation)

$$\mathcal{L}_{\rm int} = \frac{1}{2} \Omega^{-2}(\phi)\, m^2 A_\mu A^\mu \quad \Rightarrow \quad \Gamma_{\phi \to AA} = \frac{1}{192\pi} \frac{m_\phi^3}{M_{\rm Pl}^2}$$

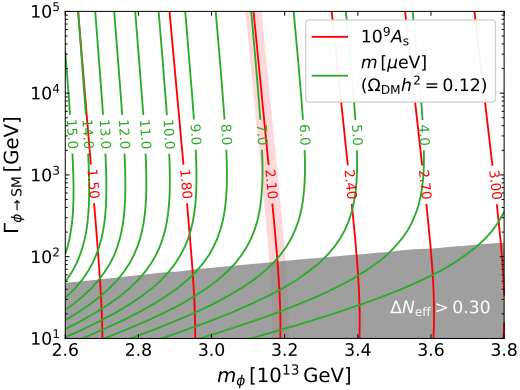
$\Omega_{\rm DM}$ on m_ϕ vs. $\Gamma_{\phi\to{\rm SM}}$ plane (treating $\Gamma_{\phi\to{\rm SM}}$ as a free parameter)



$\Leftrightarrow$ Scalar amplitude: $A_{\rm s} = (2.100 \pm 0.030) \times 10^{-9}$

[Planck Collaboration ('18)]

Dark photon mass (in units of μeV), realizing $\Omega_{\rm DM}h^2 = 0.12$

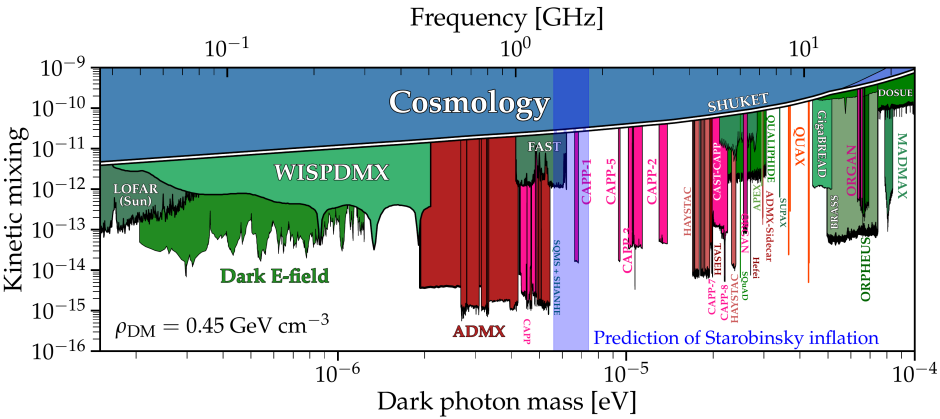


$\Rightarrow$ Dark photon mass suggested from Starobinsky inflation

$5.6\ \mu\mathrm{eV} < m < 7.4\ \mu\mathrm{eV}$

Dark photon mass suggested from Starobinsky inflation

$$5.6\ \mu\text{eV} < m < 7.4\ \mu\text{eV} \quad \Rightarrow \quad 1.4\ \text{GHz} < f < 1.8\ \text{GHz}$$



[Figure, with the use of AxionLimits]

4. Summary

We studied dark photon DM production in Starobinsky inflation

- $5.6\ \mu\text{eV} < m < 7.4\ \mu\text{eV}$
- Our formalism for the Weyl rescaling applies to many models

Future directions

- Study in other inflation models

  $\Leftrightarrow$ ACT-motivated models, $\cdots$

- Dark photon DM search for $f \gtrsim O(1)$ GHz

  $\Leftrightarrow$ Superconducting qubits, Rydberg atoms, $\cdots$

  [Chen, Fukuda, Inada, TM, et al. ('22); Chigusa, Kasamaki, Kusano, TM, et al. ('25)]

- $\cdots$

Backup: Dark Photon Energy Density

Volume-averaged energy density (after inflation, i.e., $\Omega = 1$)

$$\tilde{\rho}(k,t) = \frac{d\rho}{d\ln k} = \frac{1}{2a^2}\left(\frac{a^2m^2}{k^2+a^2m^2}\left|\dot{\mathcal{A}}_L(k,t)\right|^2 + m^2\left|\mathcal{A}_L(k,t)\right|^2\right)$$

Mode function $\mathcal{A}_L$

- $\partial_t^2\mathcal{A}_L = -F(t)\partial_t\mathcal{A}_L - \omega^2(t)\mathcal{A}_L$

  $F(t) \equiv \dfrac{3k^2+a^2(t)m^2}{k^2+a^2(t)m^2}H(t), \quad \omega(t) \equiv \sqrt{\dfrac{k^2}{a^2(t)}+m^2}$

- $\mathcal{A}_L \xrightarrow{k\ll aH} \Omega(t_k)\dfrac{k}{m}\left(\dfrac{H(t_k)}{2\pi}\right)\left[1+O(\epsilon^{1/2})\right]$

- $\dot{\mathcal{A}}_L \xrightarrow{k\ll aH} 0$

Case 1: $\omega \ll H$

- $\partial_t^2 \mathcal{A}_L + F(t)\partial_t \mathcal{A}_L \simeq 0$

  $\Rightarrow\ \partial_t \mathcal{A}_L \simeq 0$

  $\Rightarrow\ \mathcal{A}_L$ is (approximately) constant

Case 2: $\omega \gg H$

- $\mathcal{A}_L$ rapidly oscillates with frequency ω

  $\Rightarrow\ \mathcal{A}_L \simeq \bar{\mathcal{A}}_L(t)\cos(\omega t - \varphi)$

  $\Rightarrow\ \bar{\mathcal{A}}_L(t)$ gradually decreases with time

Case 2-a: $k \gg aH$ and $k \gg am$ (relativistic case)

$$\partial_t^2 \mathcal{A}_L + 3H\partial_t \mathcal{A}_L + \frac{k^2}{a^2}\mathcal{A}_L \simeq 0$$

$$\Rightarrow \ \mathcal{A}_L \propto a^{-2}$$

$$\Rightarrow \ \tilde{\rho} \propto a^{-4}$$

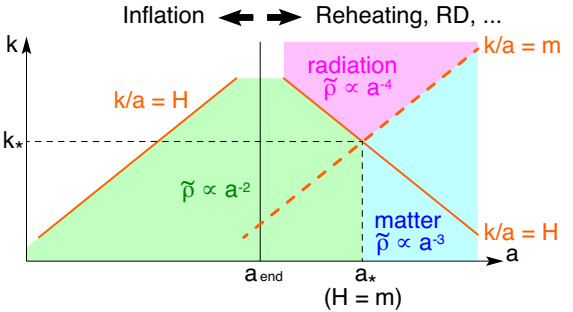
Case 2-b: $m \gg H$ and $m \gg a^{-1}k$ (non-relativistic case)

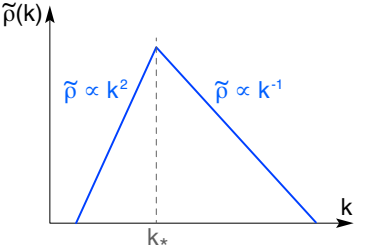
$$\partial_t^2 \mathcal{A}_L + H\partial_t \mathcal{A}_L + m^2 \mathcal{A}_L \simeq 0$$

$$\Rightarrow \ \mathcal{A}_L \propto a^{-1/2}$$

$$\Rightarrow \ \tilde{\rho} \propto a^{-3}$$

Energy spectrum





$\Rightarrow$ $\tilde{\rho}$ is dominated by the mode with $k \sim k_*$

$$k_* \simeq 1.5\ \mathrm{kpc}^{-1} \times \left(\frac{m}{10\ \mu\mathrm{eV}} \right)^{1/2}$$