Non-thermally trapped inflation due to the tachyonic instability

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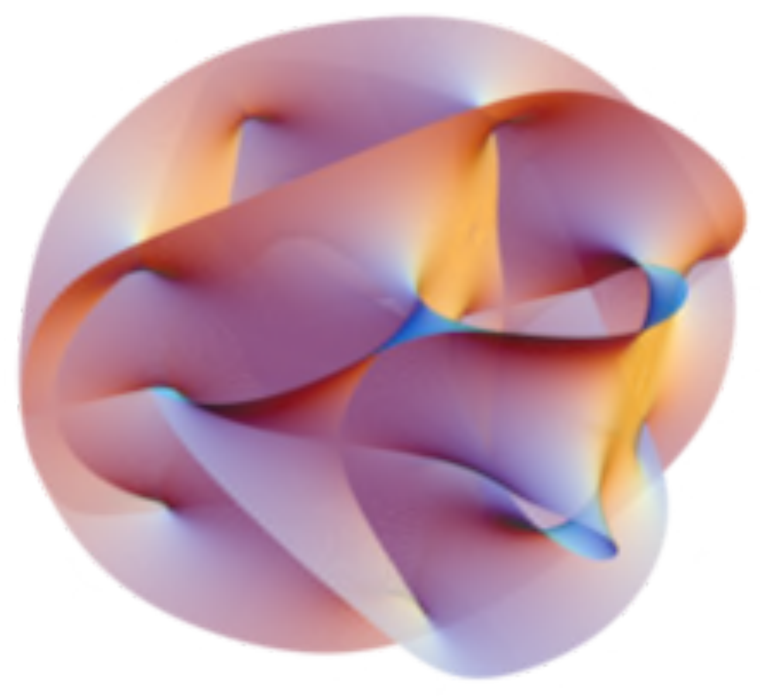
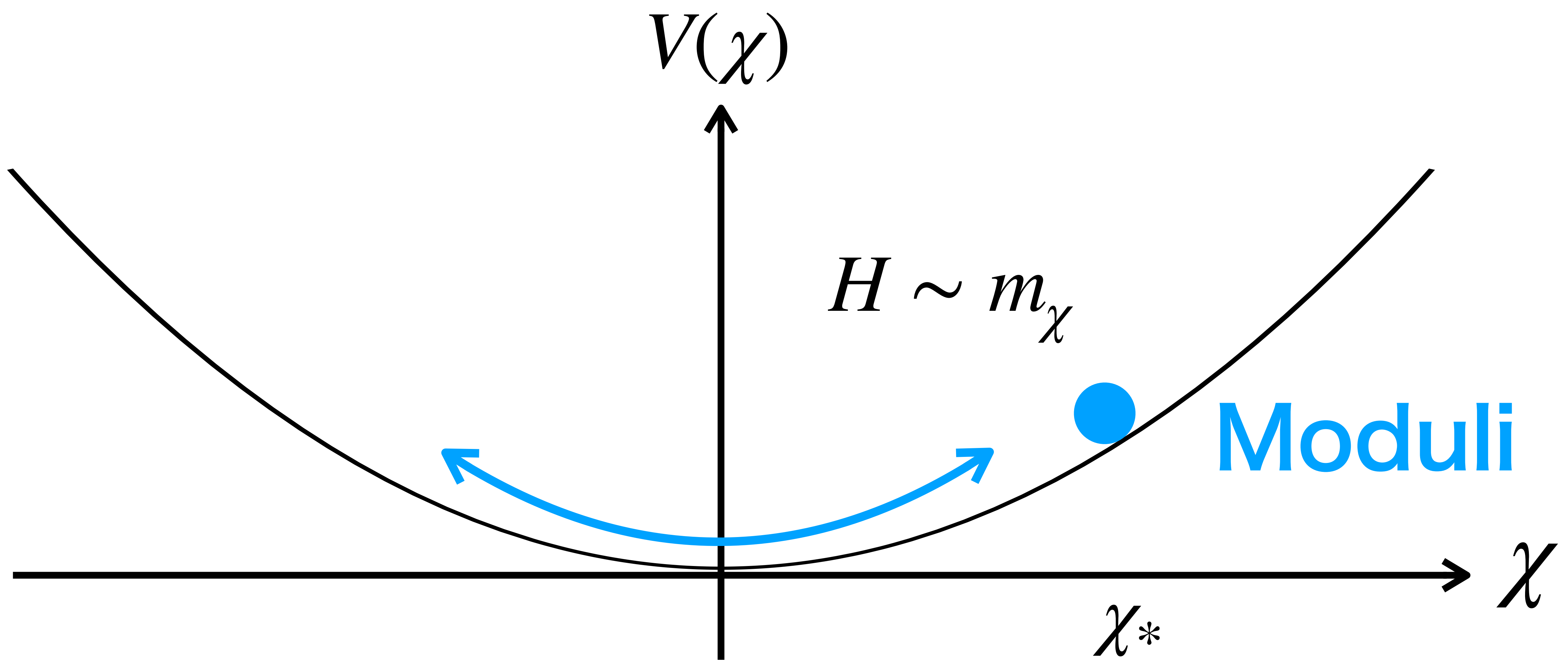
Collaborating with P. Agrawal, N. Kitajima, M. Reece, and F. Takahashi

1. Introduction



String theory



Low energy effective theory

Moduli easily dominate the universe soon after the oscillation.
If $m_\chi \lesssim O(10)\mathrm{TeV}$, they may decay during or after BBN.

Contradiction with the observation of light element abundances. Or, if stable, they overclose the universe.

Cosmological Moduli Problem

Solutions of the moduli problem

- Heavy moduli with $m_\chi \gtrsim O(10)\mathrm{TeV}$
- Adiabatic suppression mechanism — A. D. Linde (1996); K. Nakayama, F. Takahashi, T. T. Yanagida (1999)
- Thermal inflation — K. Yamamoto (1985), D. H. Lyth, E. D. Stewart (1996); T. Asaka, M. Kawasaki (1999)

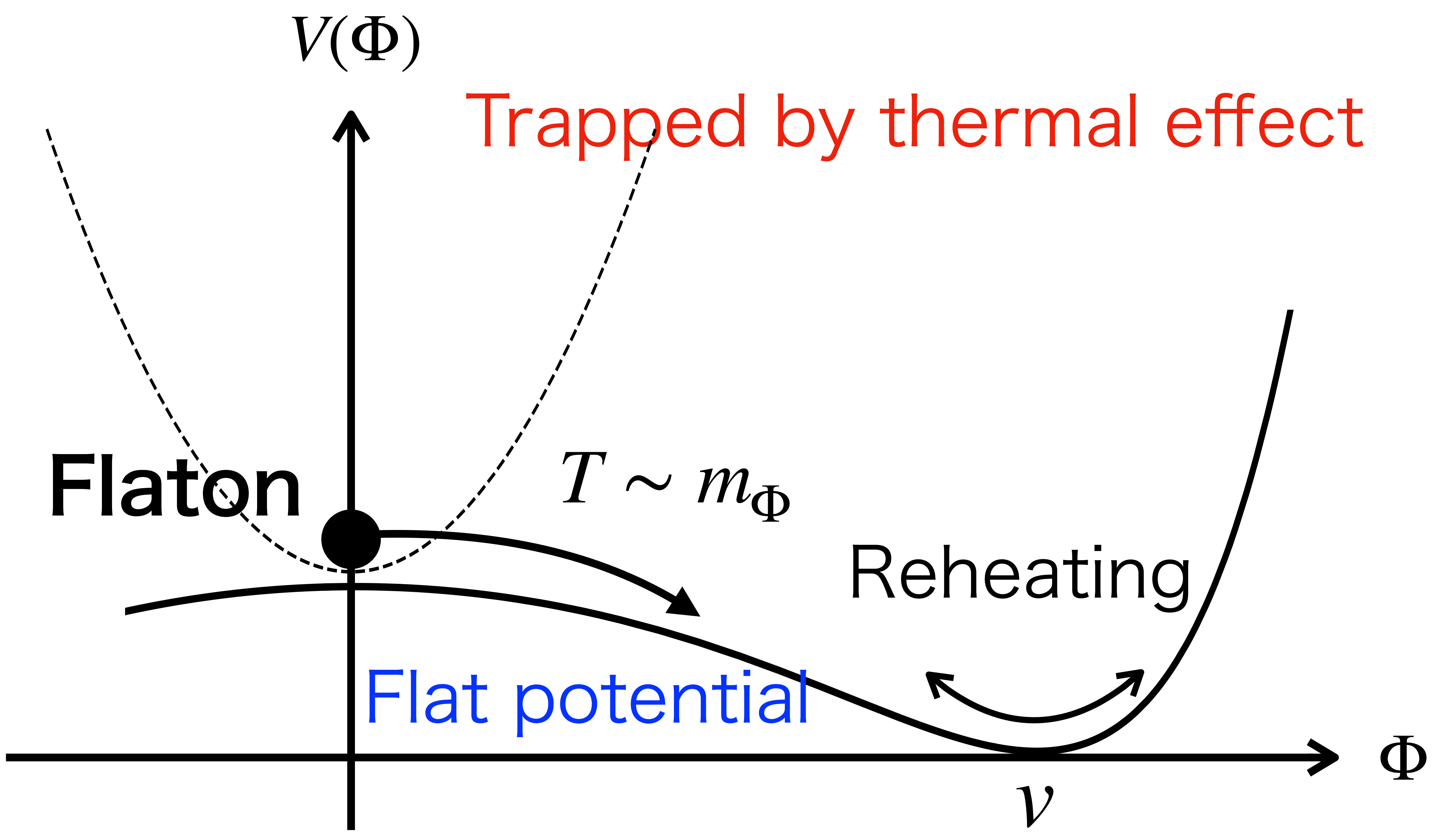
etc…

Features of thermal inflation:

1. Thermal trapping
2. Very flat potential

   i.e. light mass, m_ϕ, and

   very large VEV, v



The moduli abundance is diluted by large entropy production.

What we did

We propose a non-thermal inflation model in a hidden Abelian Higgs model with an axion coupled to dark photons.

Thermal inflation

- Driven by flaton field
- Thermally trapped by hot plasma
- Very flat potential required

Non-thermal inflation

- Driven by dark Higgs
- Non-thermally trapped by dark photons
- Flat potential not required
  Working for Mexican hat

We numerically check our scenario by lattice simulations, and investigate the possibility of solving the moduli problem and the experimental implications for dark photon searches.

2. Set up

Abelian Higgs model with an axion coupled to dark photons

$$\mathcal{L} = (D_\mu \Psi)^\dagger D^\mu \Psi - V_\Psi(\Psi, \Psi^\dagger) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V_\phi(\phi) - \frac{\beta}{4 f_\phi} \phi F_{\mu\nu} \tilde{F}^{\mu\nu}$$

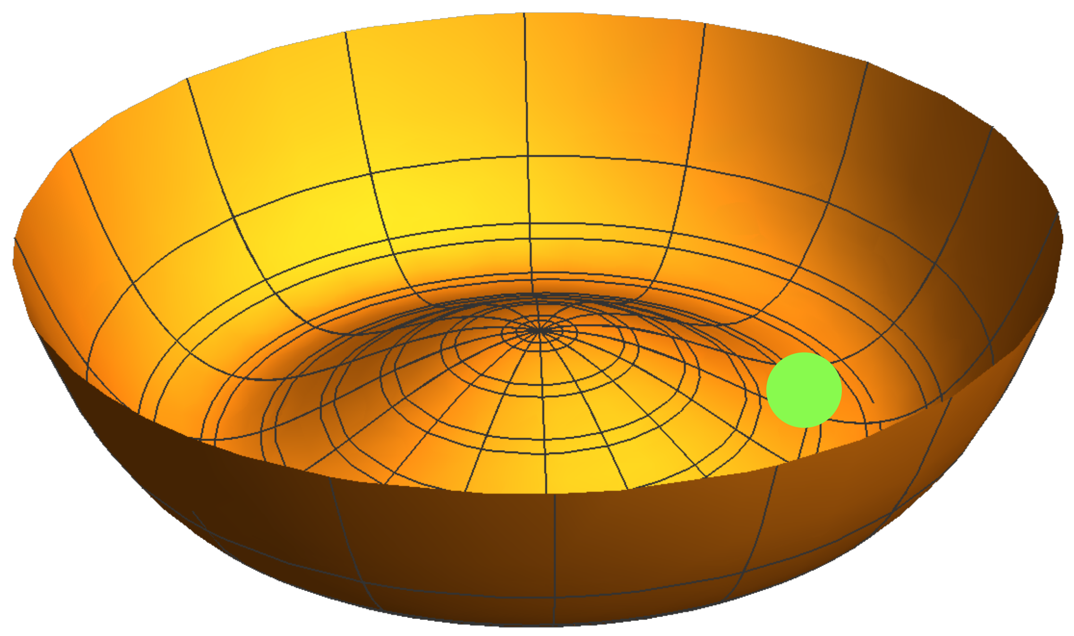
where $D_\mu = \partial_\mu - ieA_\mu$

Ψ : (dark) Higgs

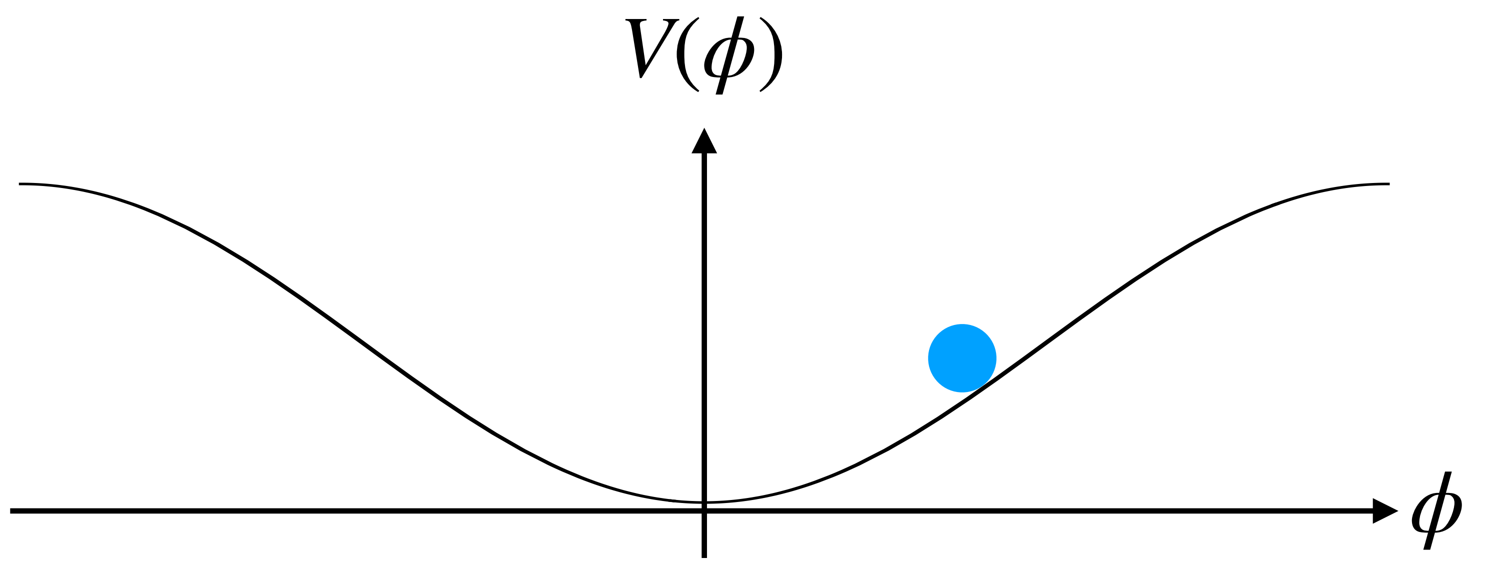
A_μ : dark photon

ϕ : axion

Higgs potential $V_\Psi(\Psi, \Psi^\dagger) = \frac{\lambda}{4}(|\Psi|^2 - v^2)^2$



Axion potential $V_\phi(\phi) = m_\phi^2 f_\phi^2 \left[1 - \cos\left(\frac{\phi}{f_\phi}\right)\right]$



2. Set up

Abelian Higgs model with an axion coupled to dark photons

$$\mathcal{L} = (D_\mu \Psi)^\dagger D^\mu \Psi - V_\Psi(\Psi, \Psi^\dagger) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V_\phi(\phi) - \frac{\beta}{4 f_\phi} \phi F_{\mu\nu} \tilde{F}^{\mu\nu}$$

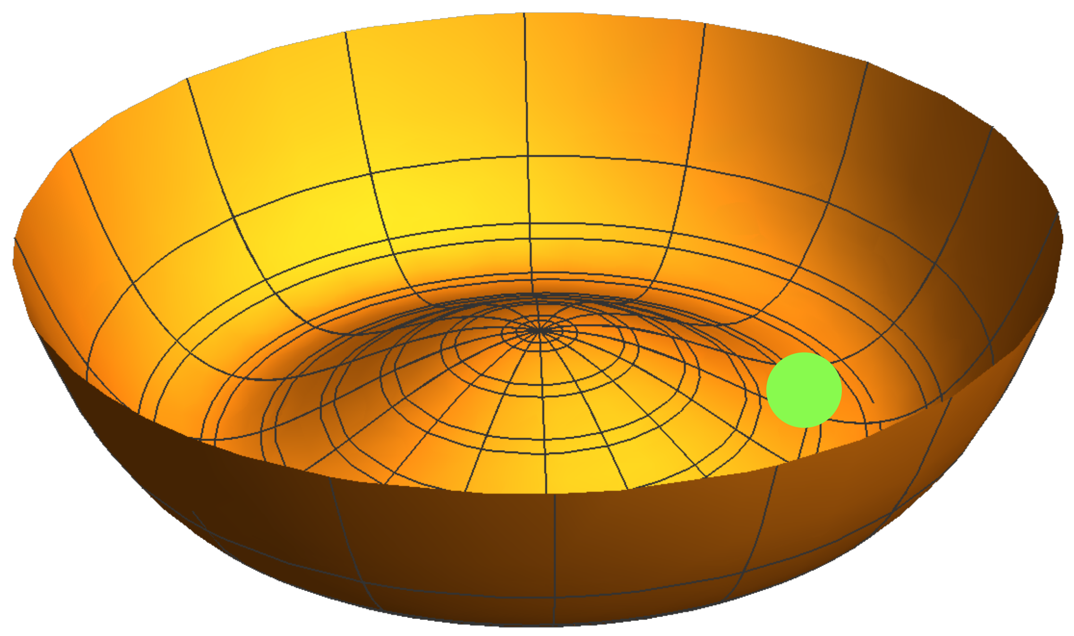
wh

$$(D_\mu \Psi)^\dagger D^\mu \Psi = |\partial_\mu \Psi|^2 + e^2 A_\mu A^\mu |\Psi|^2$$

Dark Higgs acquires an effective mass from dark photon production.

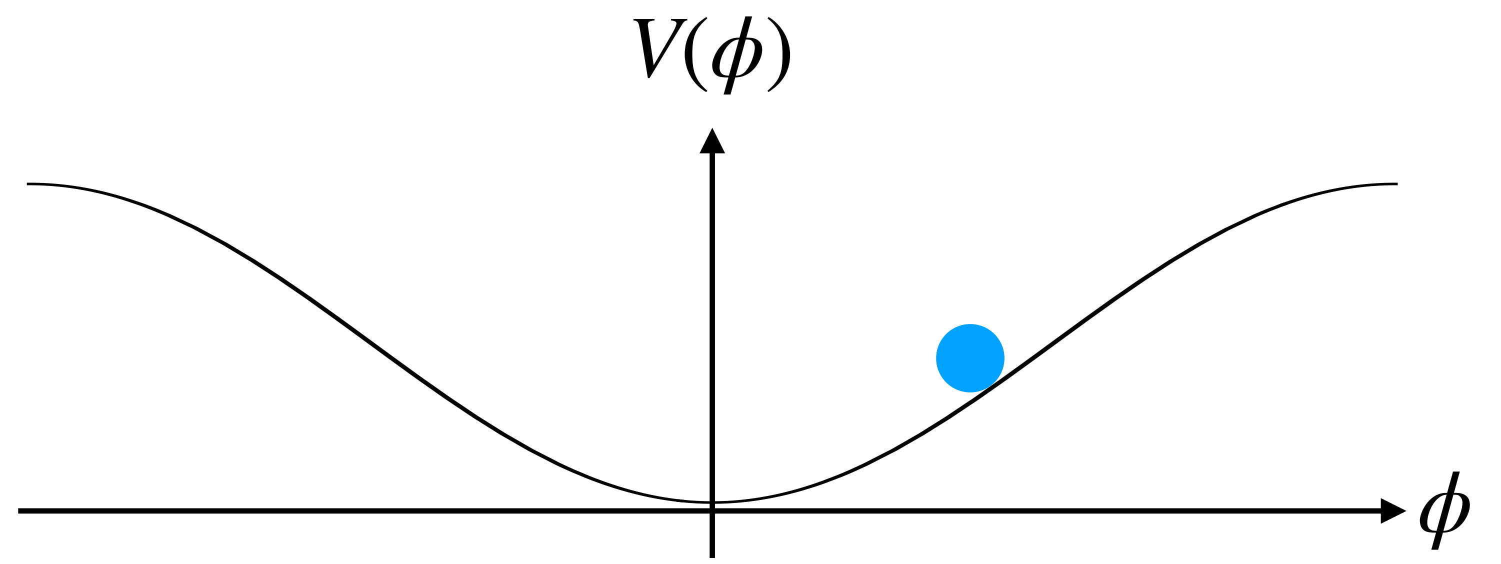
A_μ : dark photon

Higgs



Axion potential

$$V_\phi(\phi) = m_\phi^2 f_\phi^2 \left[1 - \cos\left(\frac{\phi}{f_\phi}\right)\right]$$



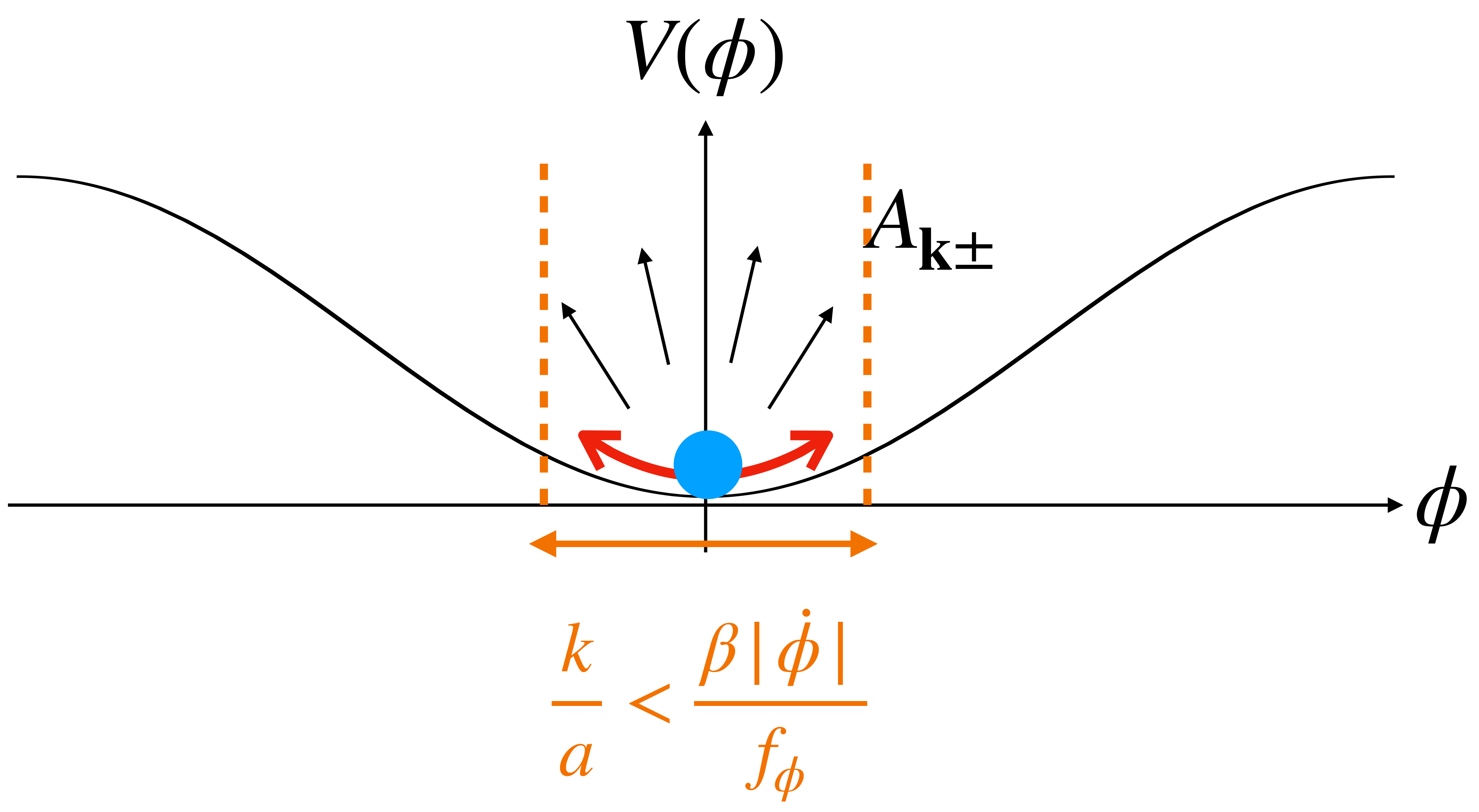
Tachyonic production of dark photon

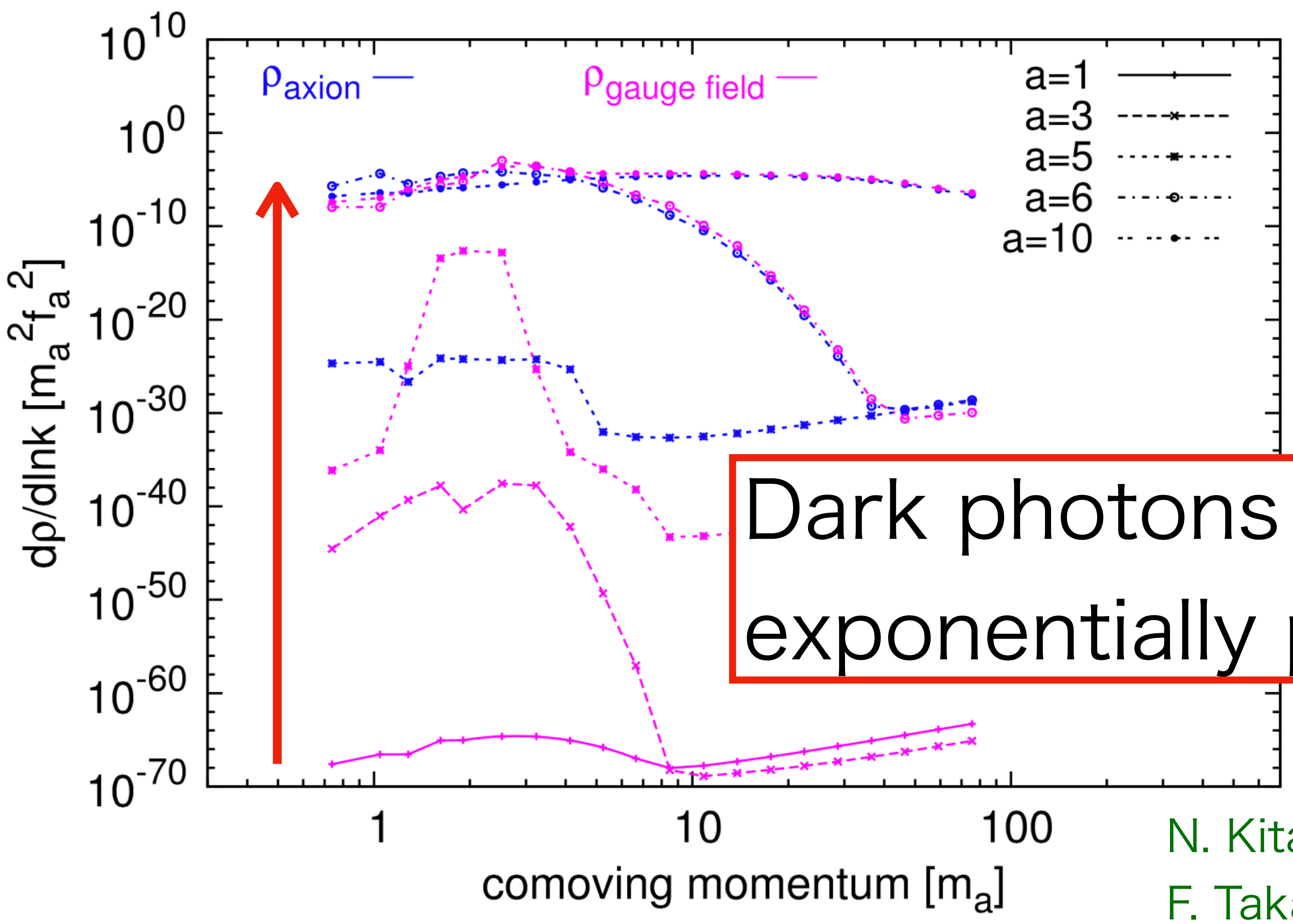
P. Agrawal, G. Marques-Tavares, W. Xue (2018) , N. Kitajima, T. Sekiguchi, F. Takahashi (2018),
P. Agrawal, N. Kitajima, M. Reece, T. Sekiguchi, F. Takahashi (2020)

Equation of motion for massless dark photon

$$\mathcal{L}_{\rm int} = -\frac{\beta}{4 f_\phi}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\ddot{A}_{\boldsymbol{k},\pm} + H\dot{A}_{\boldsymbol{k},\pm} + \frac{k}{a}\left(\frac{k}{a} \mp \frac{\beta\dot{\phi}}{f_\phi}\right)A_{\boldsymbol{k},\pm} = 0$$



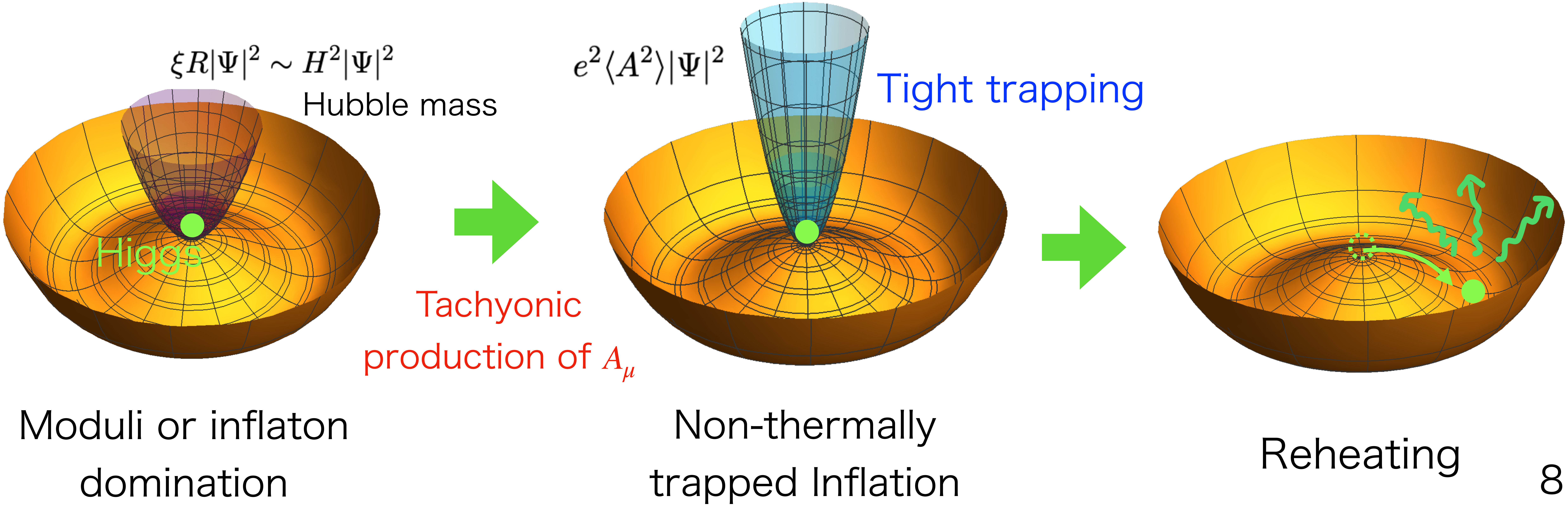


Dark photons are exponentially produced.

N. Kitajima, T. Sekiguchi, F. Takahashi (2018)

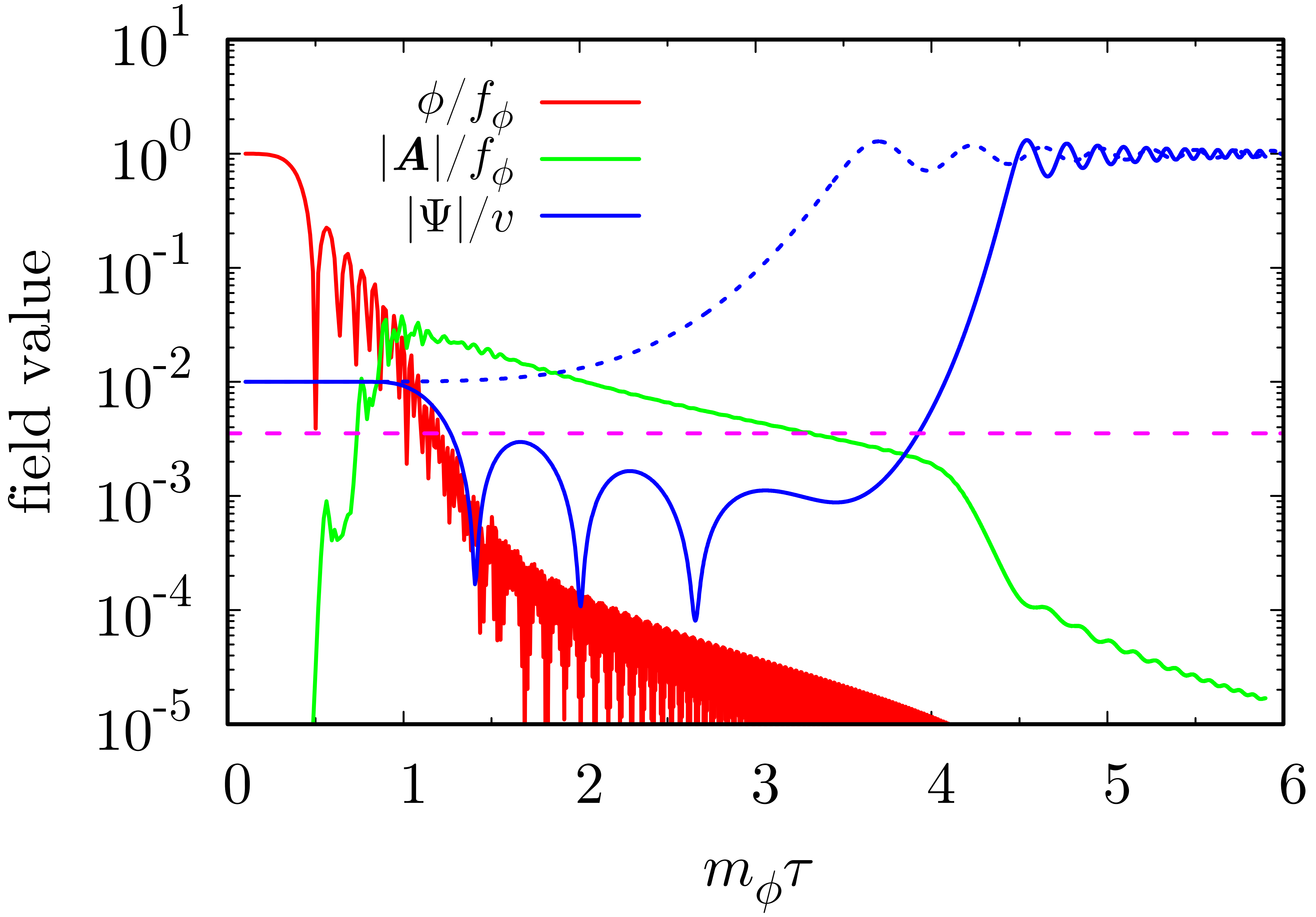
Our scenario

1. Dark photons are produced by tachyonic instability.
2. Vacuum energy of dark Higgs drives non-thermally trapped inflation.
3. Vacuum energy is converted into radiation (reheating).

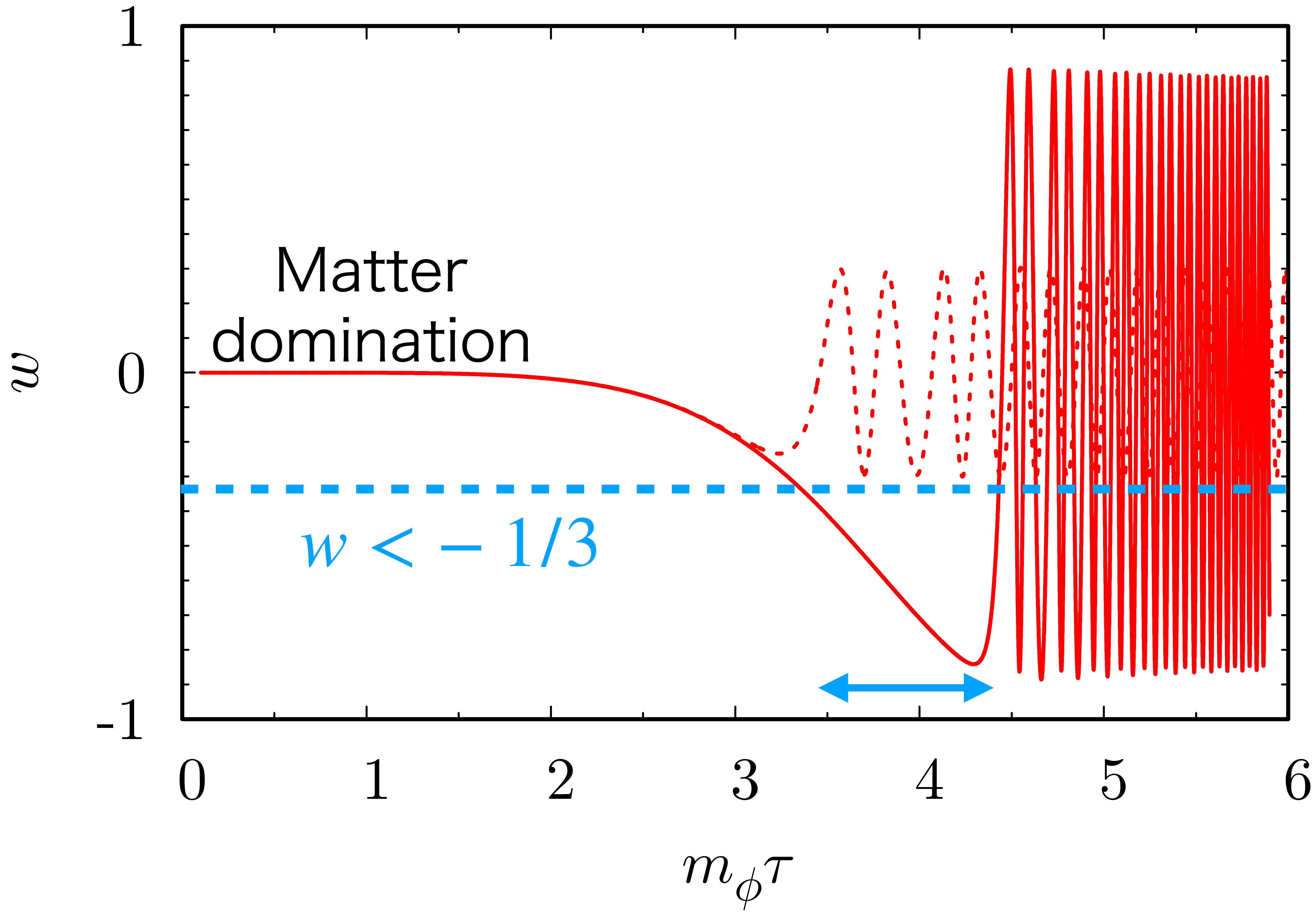


3. Results of lattice simulations

Field values



Equation of state $w \equiv p_{\rm tot}/\rho_{\rm tot}$

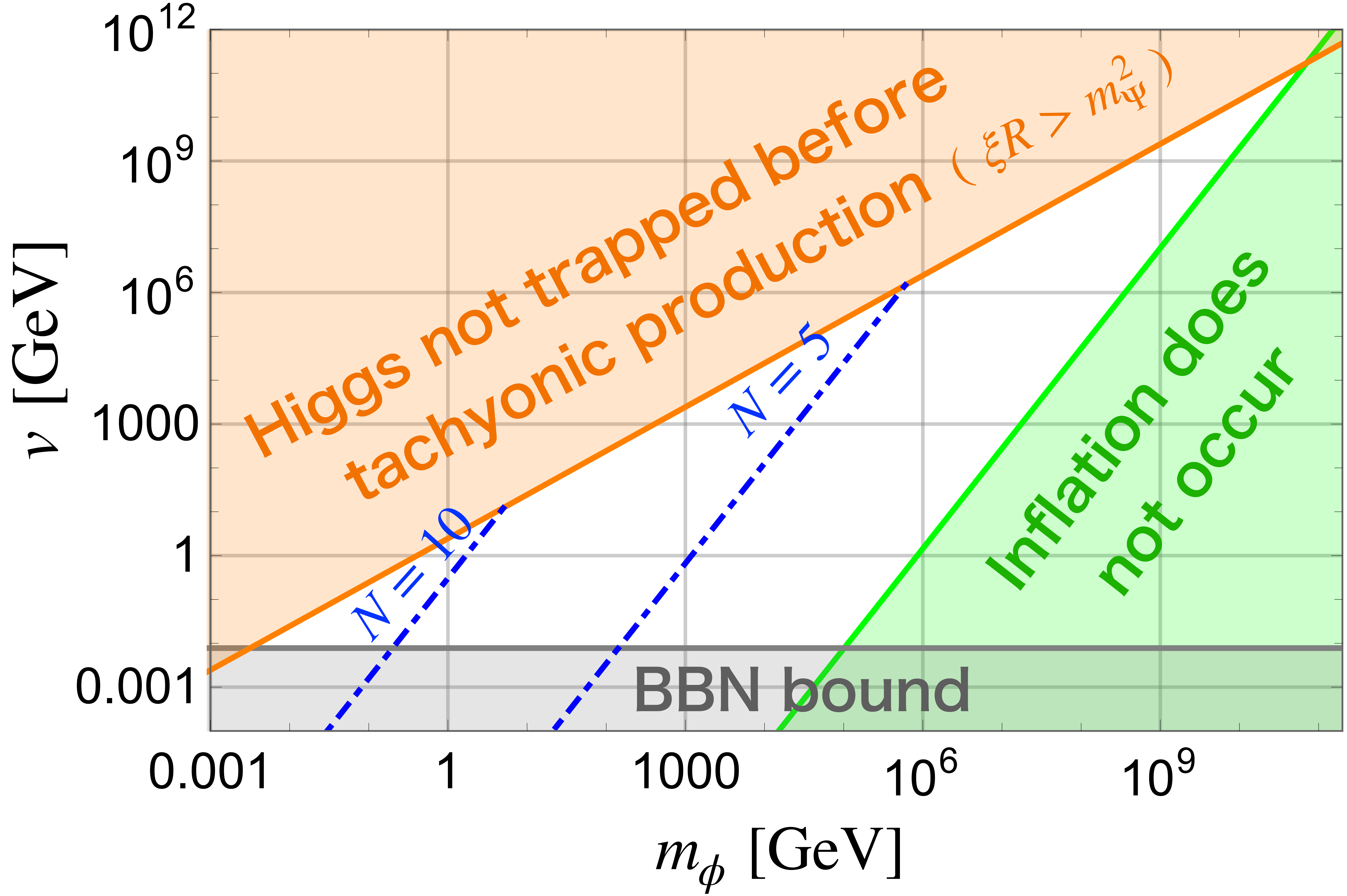


Parameters $f_\phi = 5 \times 10^{17}\mathrm{GeV}$ $m_\phi = 5 \times 10^{8}\mathrm{GeV}$ $v = f_\phi$

$\beta = 30$ $e = 2m_\phi/f_\phi$ $\lambda = 10^{-4} m_\phi^2/f_\phi^2$

We choose parameters so that inflation ends very soon.

Contours of the e-folding number

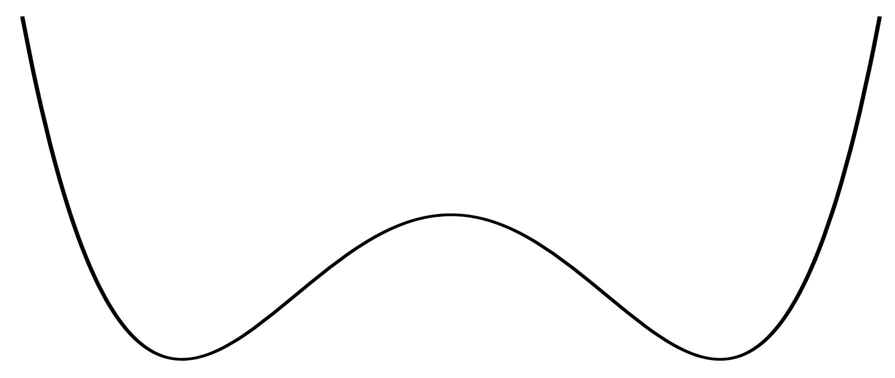


Parameters

$f_\phi = 5 \times 10^{17}\,\mathrm{GeV}$

$\beta = 30 \quad e = 0.1$

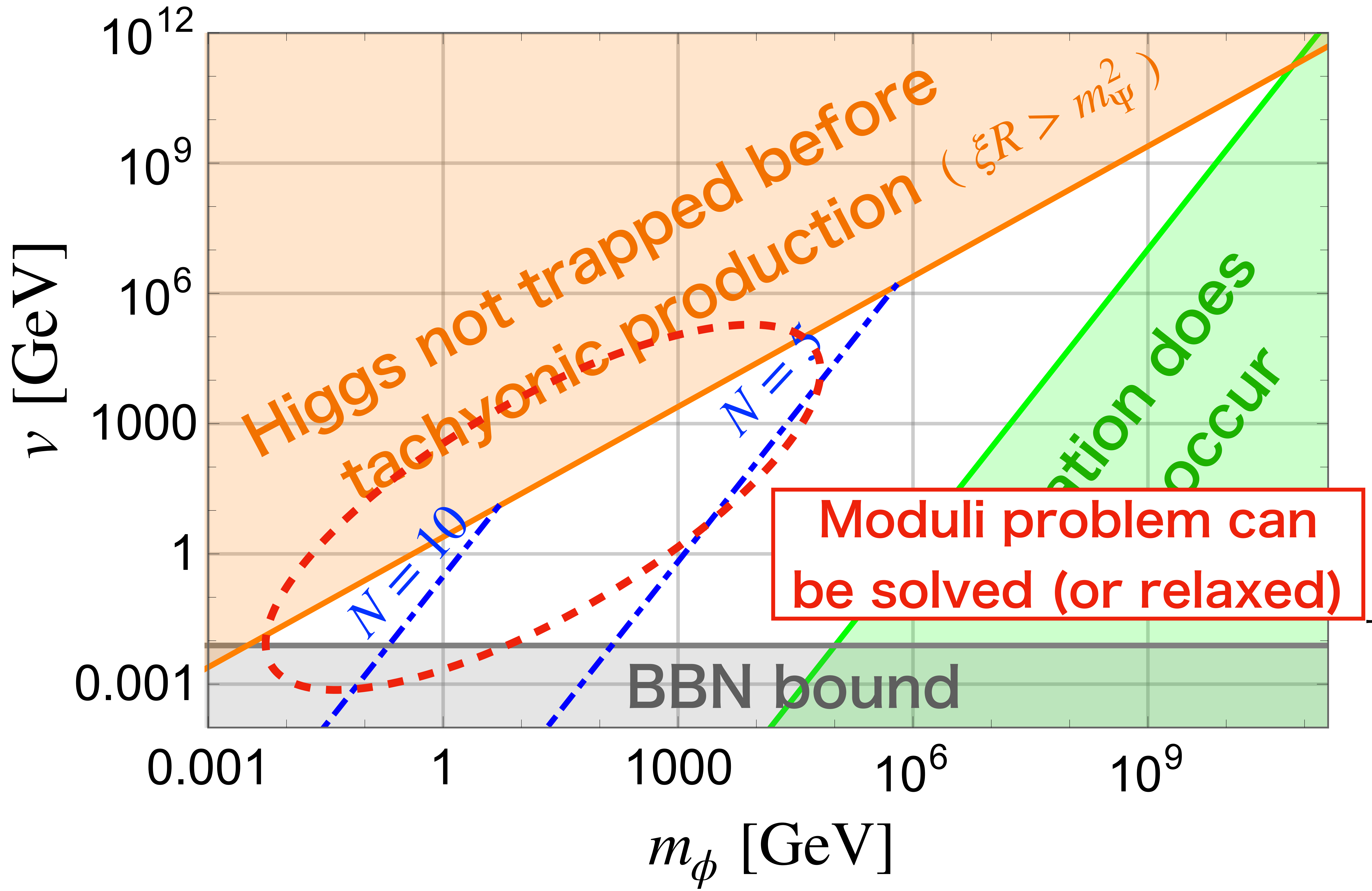
$\lambda = 1 \quad \xi = 1$



The number of e-folds :

$$N \equiv \log \frac{a_{\mathrm{end}}}{a_{\mathrm{begin}}}$$

Viable parameter and the e-folding



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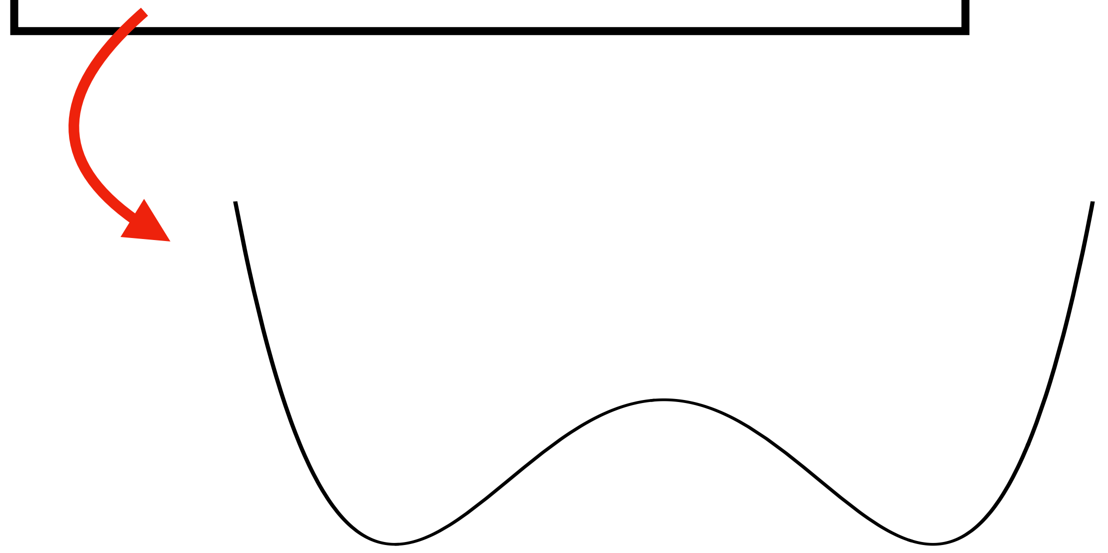


The number of e-folds :

$$N \equiv \log \frac{a_{\rm end}}{a_{\rm begin}}$$

4. Experimental implications

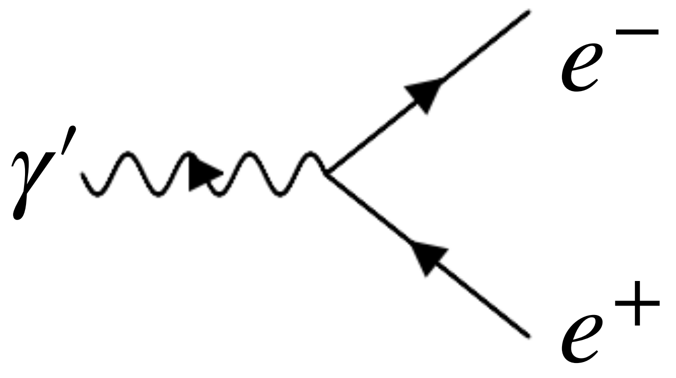
Reheating process

Assuming the kinetic mixing between

$\mathrm{U}(1)_Y$ gauge boson and dark photon :

$$\mathcal{L} \supset -\frac{\epsilon}{2} B_{\mu\nu} F^{\mu\nu}$$

・Dominant decay :



・Reheating temperature:

$$T_{\rm reh} \simeq \begin{cases} 0.26 \text{ GeV} \left(\frac{\epsilon}{10^{-8}}\right) \left(\frac{m_{\gamma'}}{1 \text{ GeV}}\right)^{1/2} & (\Gamma_{\gamma' \to e^+ e^-} < H_{\rm end}) \\ 2.2 \text{ GeV} \lambda^{1/4} \left(\frac{e}{0.1}\right)^{-1} \left(\frac{m_{\gamma'}}{1 \text{ GeV}}\right) & (\Gamma_{\gamma' \to e^+ e^-} > H_{\rm end}). \end{cases}$$

4. Experimental implications

Parameters

$m_\phi = 10\text{GeV}$ $e = 0.1$

$\lambda = 1$ $\xi = 1$

Reheating process

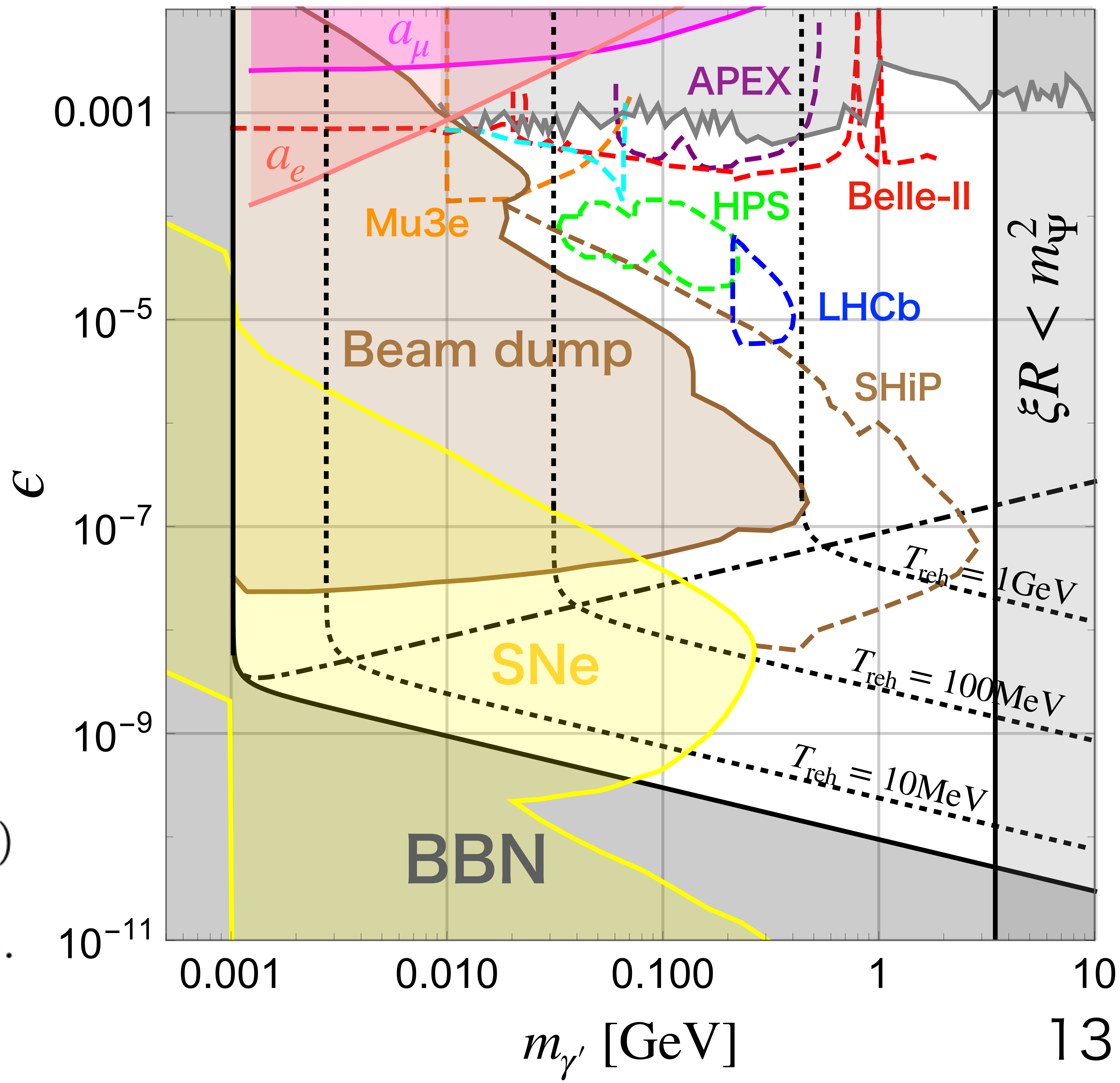
Assuming the kinetic mixing between $\mathrm{U}(1)_Y$ gauge boson and dark photon :

$$\mathcal{L} \supset -\frac{\epsilon}{2} B_{\mu\nu} F^{\mu\nu}$$

- Dominant decay : $\gamma' \to e^- e^+$

- Reheating temperature:

$$T_{\rm reh} \simeq \begin{cases} 0.26\ \text{GeV} \left(\frac{\epsilon}{10^{-8}}\right) \left(\frac{m_{\gamma'}}{1\ \text{GeV}}\right)^{1/2} & (\Gamma_{\gamma' \to e^+ e^-} < H_{\rm end}) \\ 2.2\ \text{GeV} \lambda^{1/4} \left(\frac{e}{0.1}\right)^{-1} \left(\frac{m_{\gamma'}}{1\ \text{GeV}}\right) & (\Gamma_{\gamma' \to e^+ e^-} > H_{\rm end}). \end{cases}$$



Summary

・We proposed non-thermally trapped inflation in a hidden Abelian Higgs model with axion coupled to dark photons.

・Very strong non-thermal trapping enables a large entropy to be produced even in an ordinary Mexican hat potential.

・We confirmed that the non-thermal inflation occurs by lattice simulations.

・Our scenario predicts dark photons which can be searched for by future collider or fixed target experiments.