Higgs Early Dark Energy by non-thermal trapping effect

Physics in LHC and Beyond
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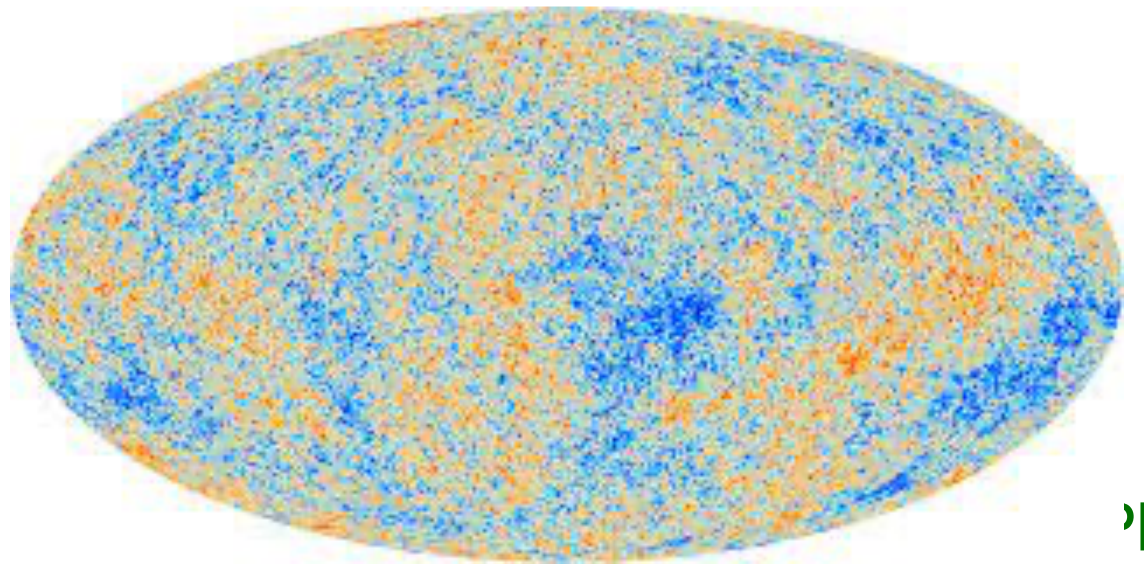
Based on arXiv: 2205(6?).XXXXX with F. Takahashi and W. Yin
cf) PRD 105 (2022) 10. [arXiv:2111.06696] with N. Kitajima and F. Takahashi

1. Introduction

The standard cosmology (ΛCDM) predicts the cosmic evolution which is consistent with observations.
However, there may be deviations from ΛCDM model.

Hubble (H_0) tension

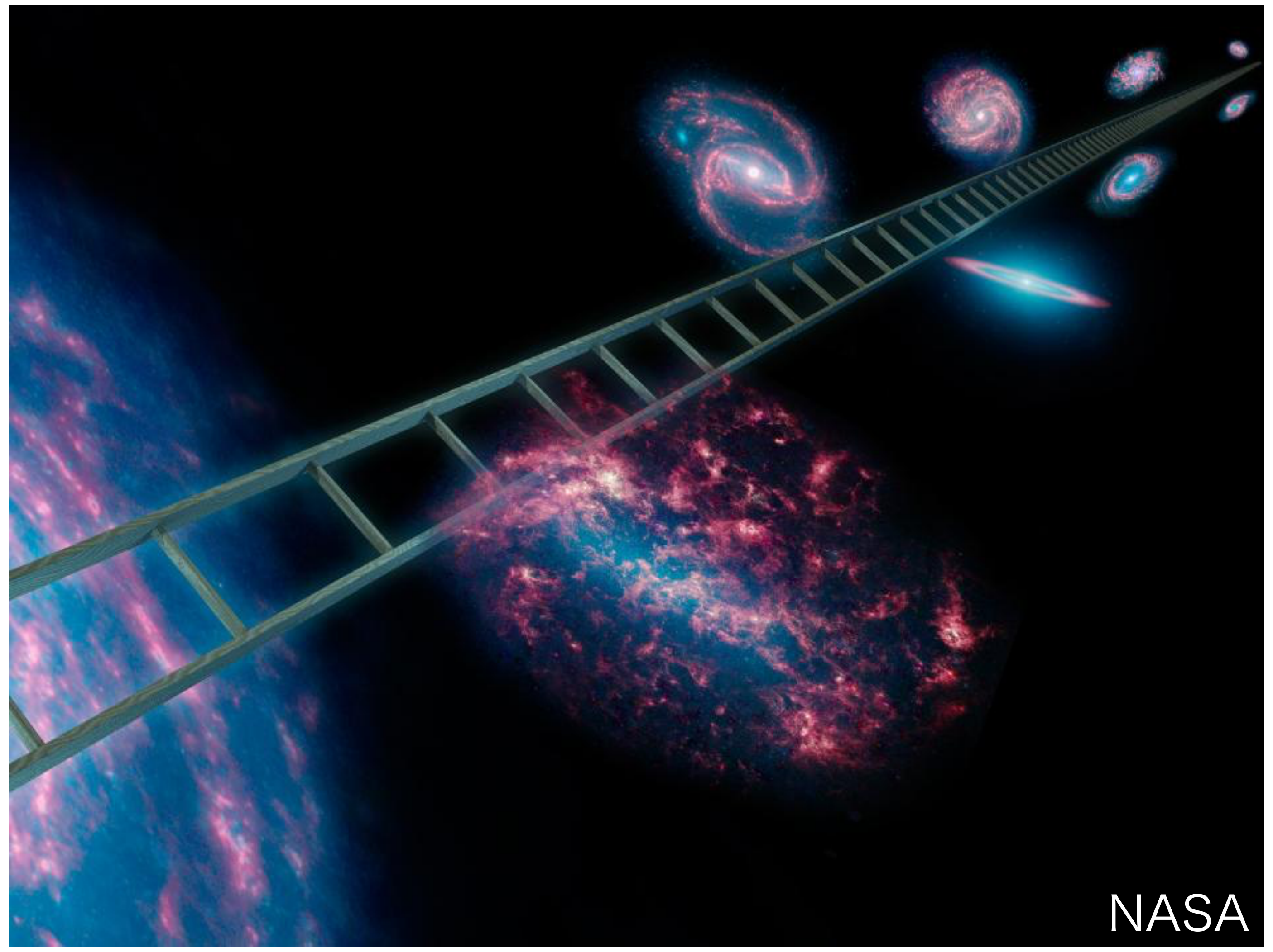


Planck collaboration

Direct measurement (CMB+ΛCDM)

$$H_0^{(\mathrm{direct})} = 67.27 \pm 0.60 \mathrm{km/s/Mpc}$$

Planck2018, 1807.06209



NASA

Indirect measurement w/ distance ladder

$$H_0^{(\mathrm{indirect})} = 73.04 \pm 1.04 \mathrm{km/s/Mpc}$$

A. Riess, et al. 2112.04510 (SNIa+Cepheid stars)

1. Introduction

The standard cosmology (ΛCDM) predicts the cosmic evolution which is consistent with observations.
However, there may be deviations from ΛCDM model.

Hubble (H_0) tension

Modified so that H_0 increases

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Direct measurement (CMB+ΛCDM)

$$H_0^{(\text{direct})} = 67.27 \pm 0.60 \text{km/s/Mpc}$$

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$\sim 5\sigma!$

New Physics??

Indirect measurement w/ distance ladder

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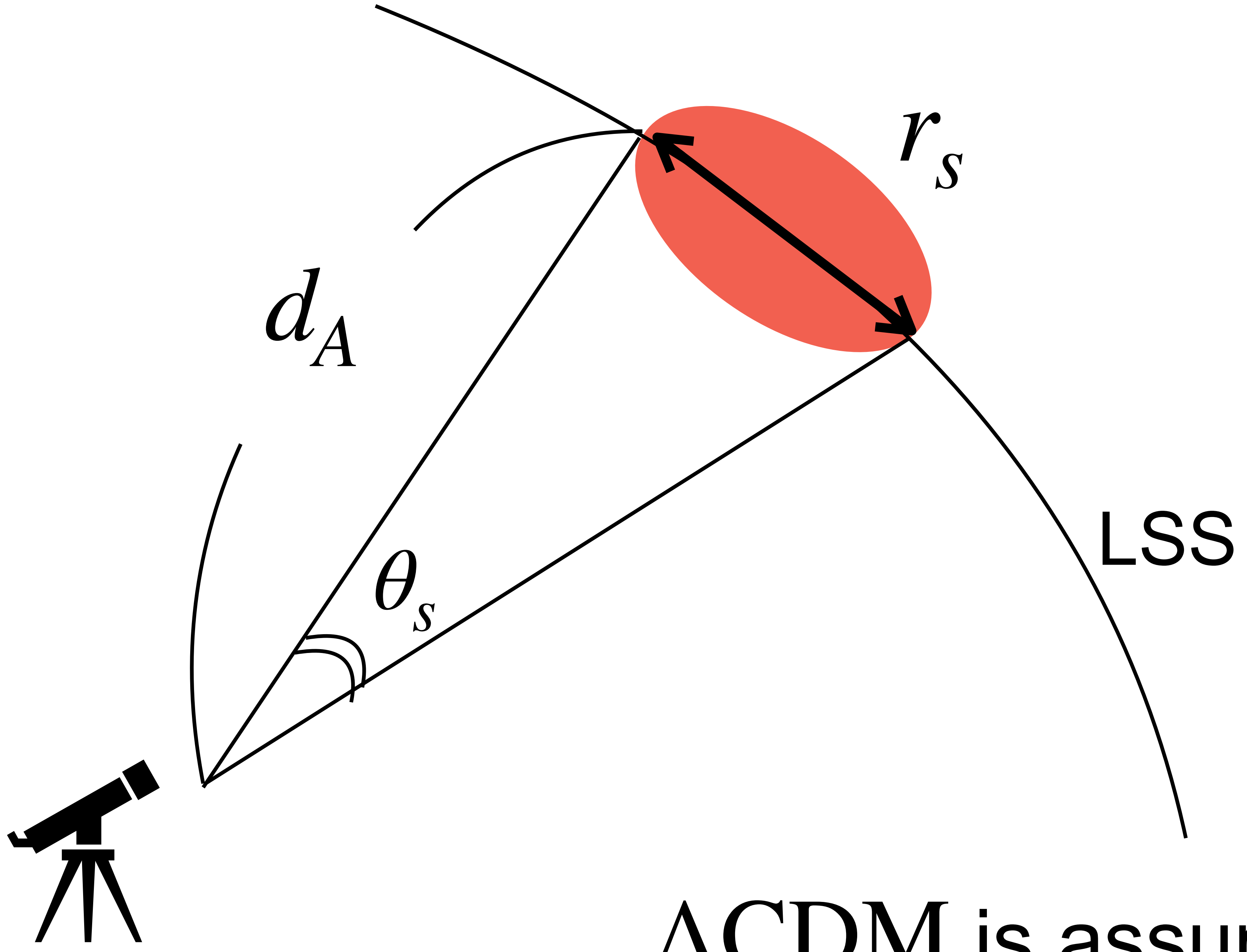
H_0 from CMB + cosmological model



Useful object : Sound horizon

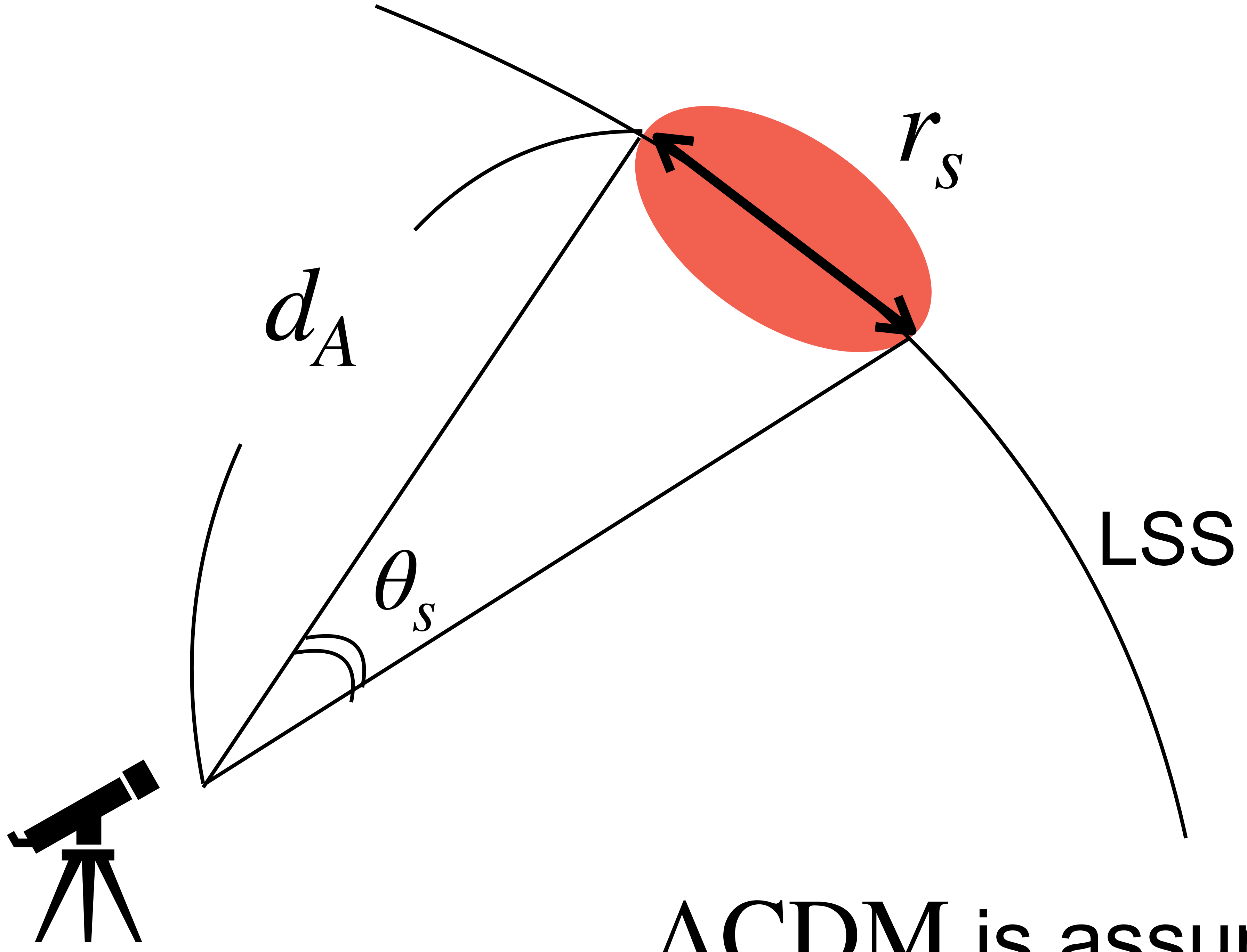
$$r_s \equiv \int_{z_{\rm rec}}^{\infty} dz \frac{c_s(z)}{H(z)}$$

ΛCDM is assumed.

$$\theta_s = \frac{r_s}{d_A} \simeq \frac{H_0 r_s}{\int_0^{z_{\rm rec}} dz[(1+z)^3\Omega_m + (1-\Omega_m)]^{-1/2}}$$

CMB data gives $\theta_s, \Omega_m, \Omega_b, \Omega_r \ldots$ and r_s is derived.

H_0 from CMB + cosmological model



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Observable

With Late-time evolution left unchanged

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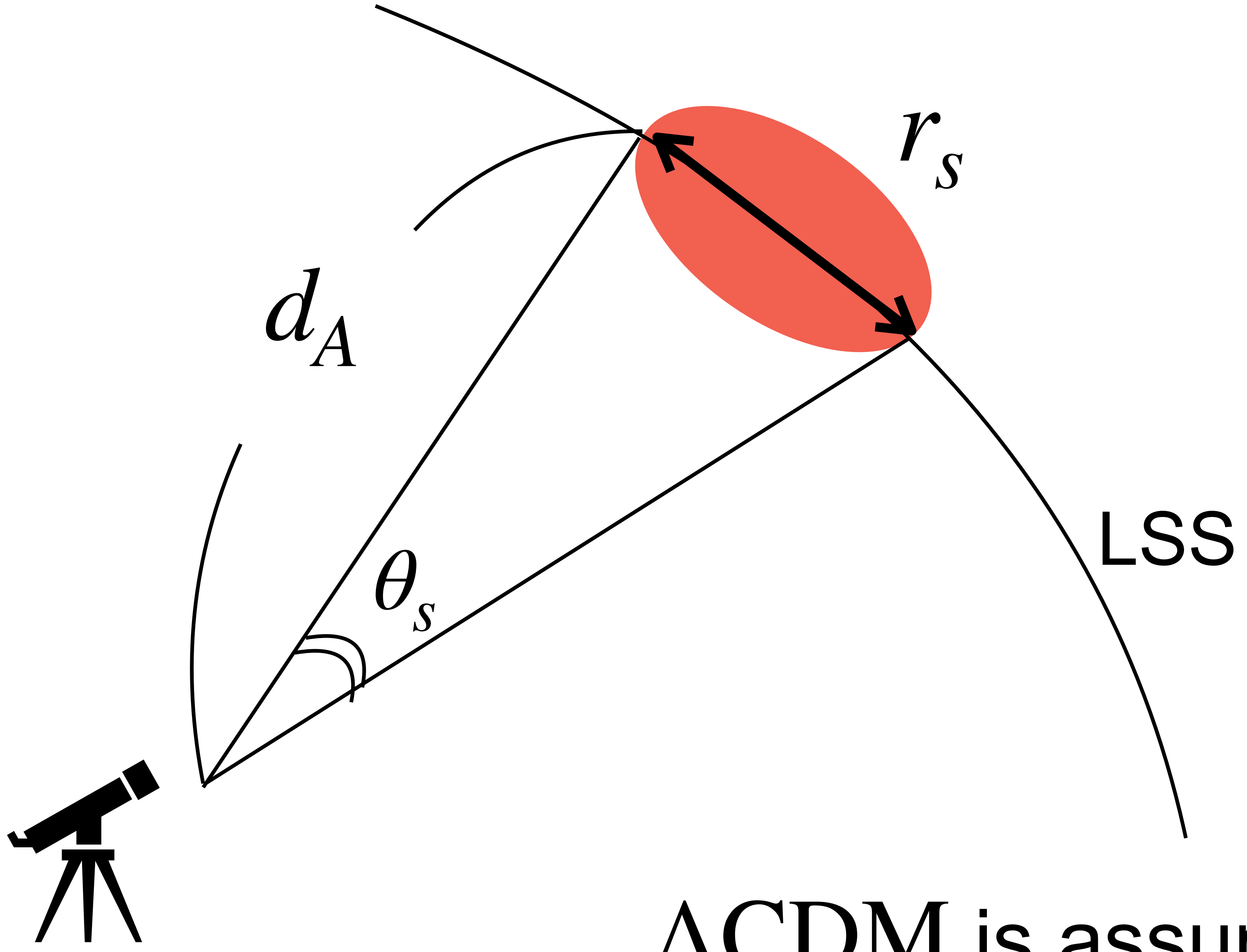
H_0 from CMB + cosmological model



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Early dark energy (EDE)

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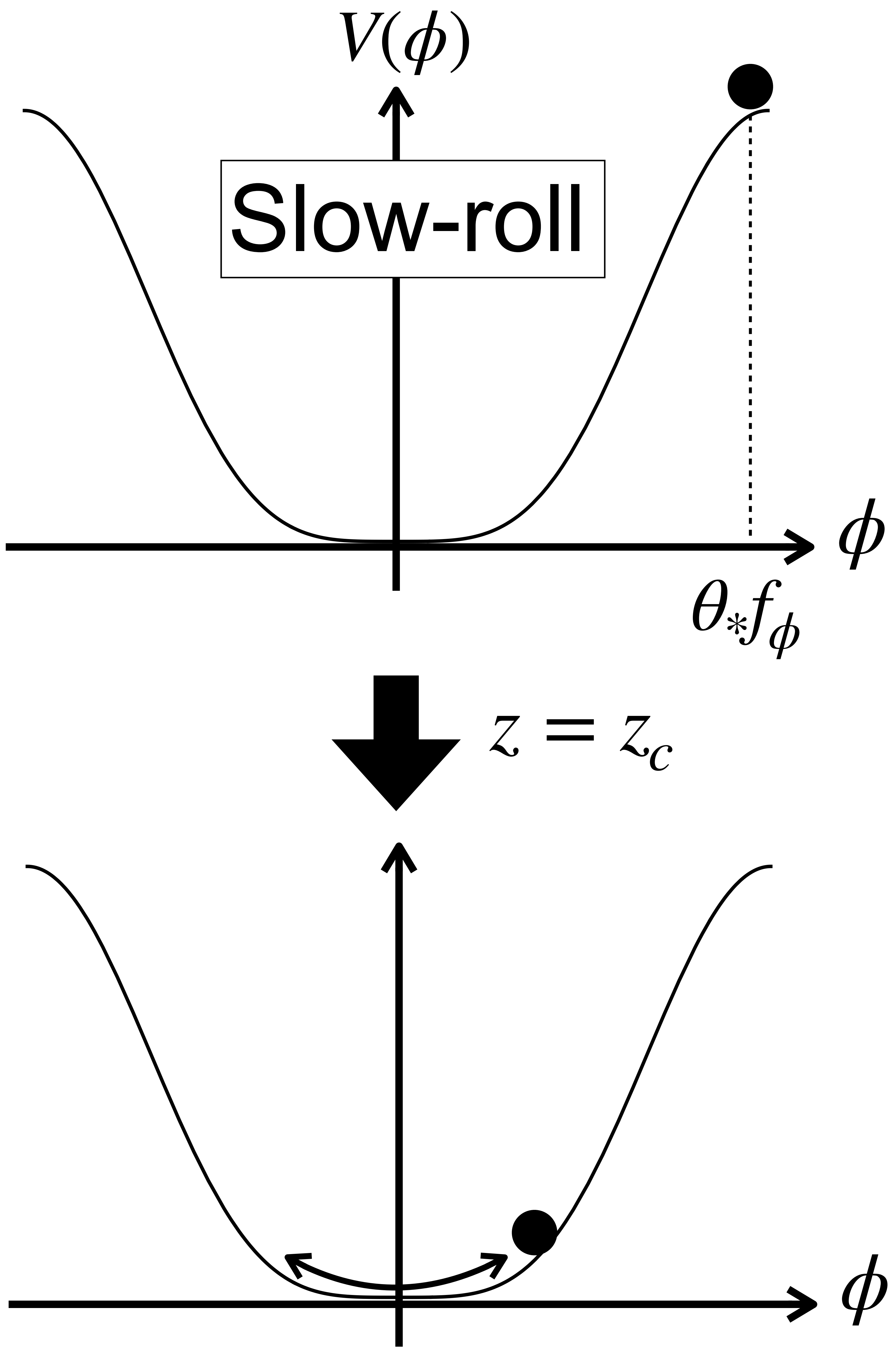
Example for EDE

V. Poulin, et al. (2019)



$$V(\phi) = m_\phi^2 f_\phi^2 \left(1 - \cos\frac{\phi}{f_\phi}\right)^n$$

ϕ : axion

f_ϕ : decay constant

M. Kamionkowski , et al. 1409.0549

$n \geq 2$ Diluted equal to or faster than radiation

Late-time evolution is not affected.

We require

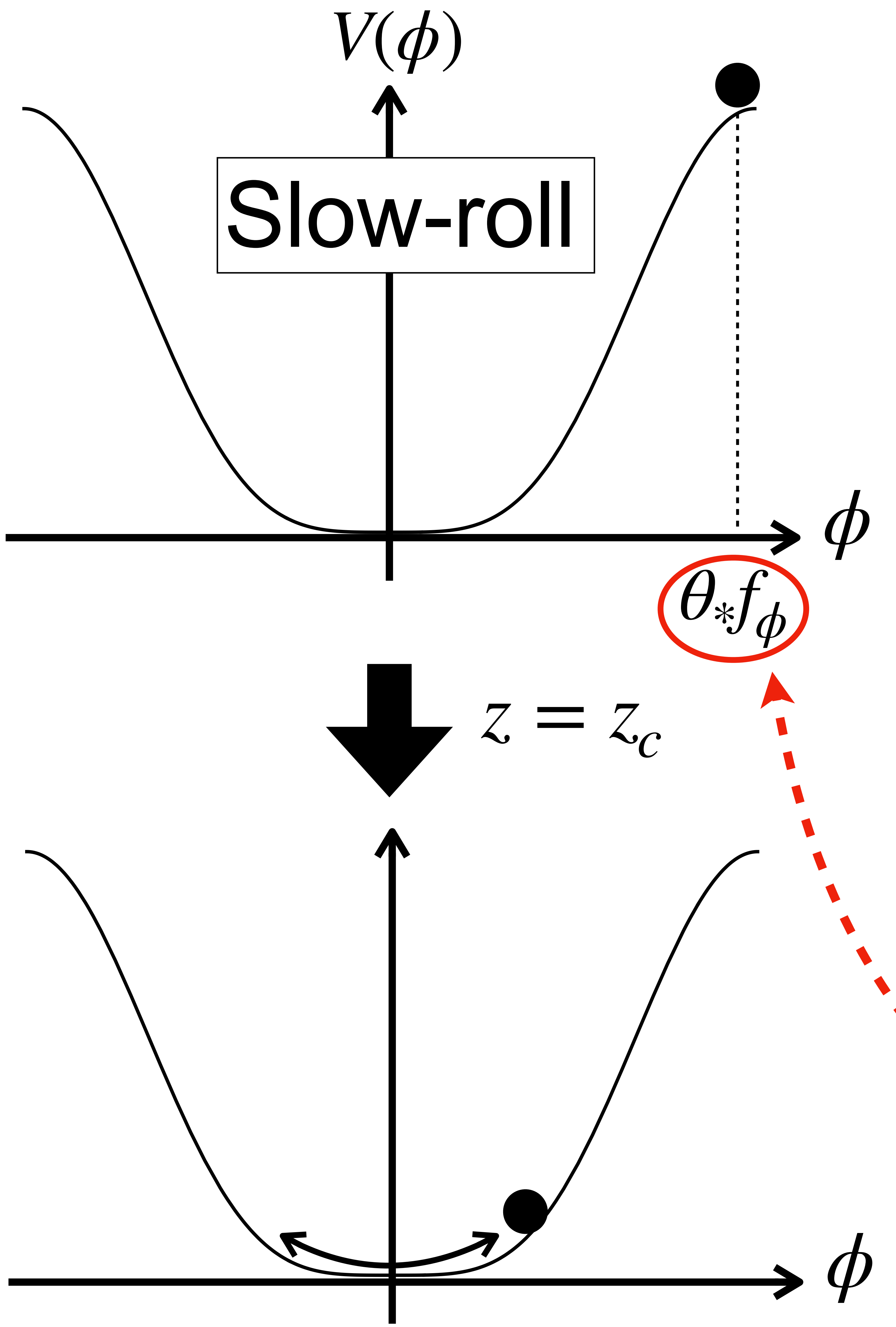
$$f_{\rm EDE} \equiv \frac{\rho_\phi}{\rho_{\rm tot}}(z_c) \simeq 0.05$$

$$z = z_c \simeq 5000$$

Example for EDE

V. Poulin, et al. (2019)

Can the potential shape be simpler?



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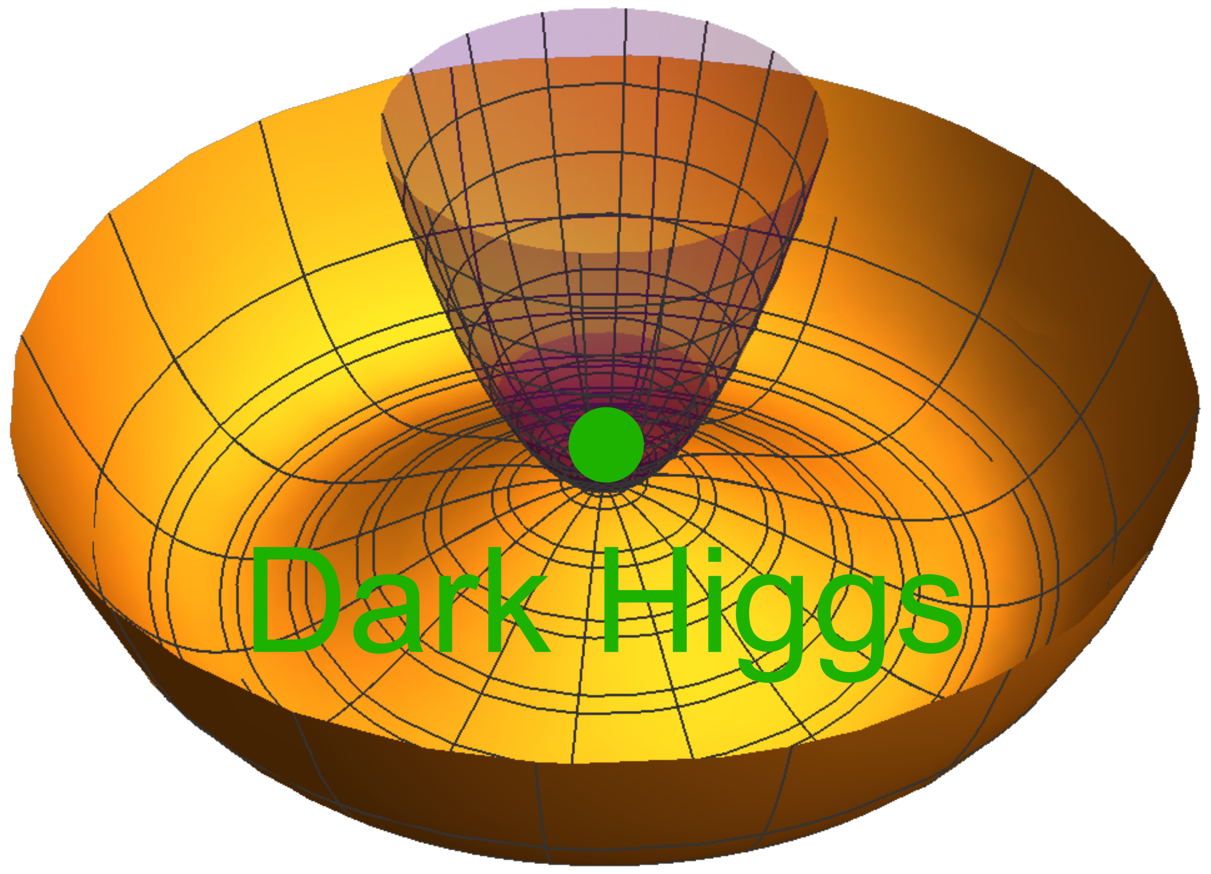
$|\pi - \theta_*| \ll 1$

What we did

<u>Our suggestions for simple EDE potential</u>

・Trapped scalar, not slow-rolling

The origin of this problem comes from slow-roll.
So, we consider trapped scalar field as EDE.



Thermal potential is difficult because the universe is already cold enough around $z \sim z_c$.

→Non-thermal trapping of dark Higgs N. Kitajima, **S.N.**, F. Takahashi (2022)

・How to dilute so as not to affect late-time universe

The dark Higgs decays into dark photons promptly at $z \sim z_c$.

2. Non-thermal trapping effect

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

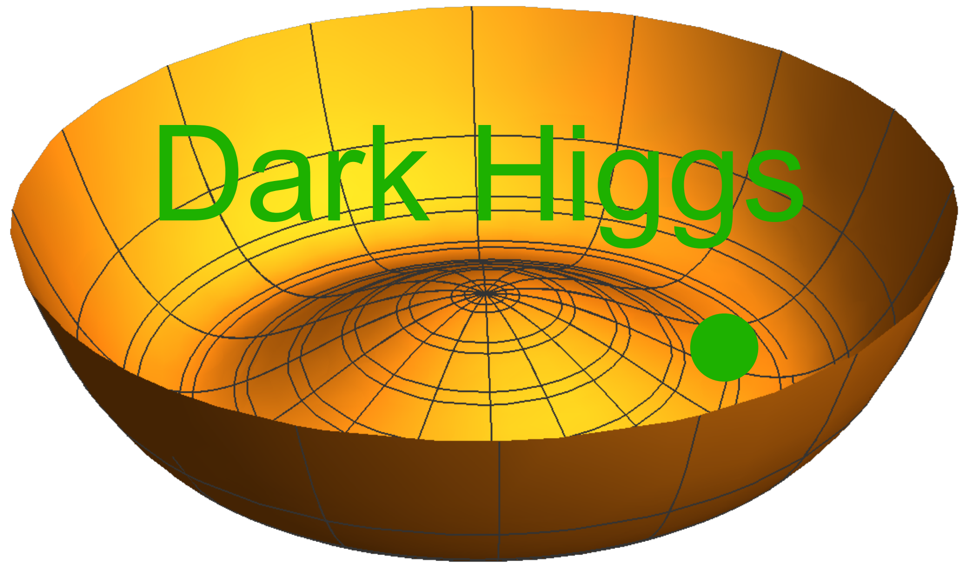
Ψ : dark Higgs

ϕ : axion

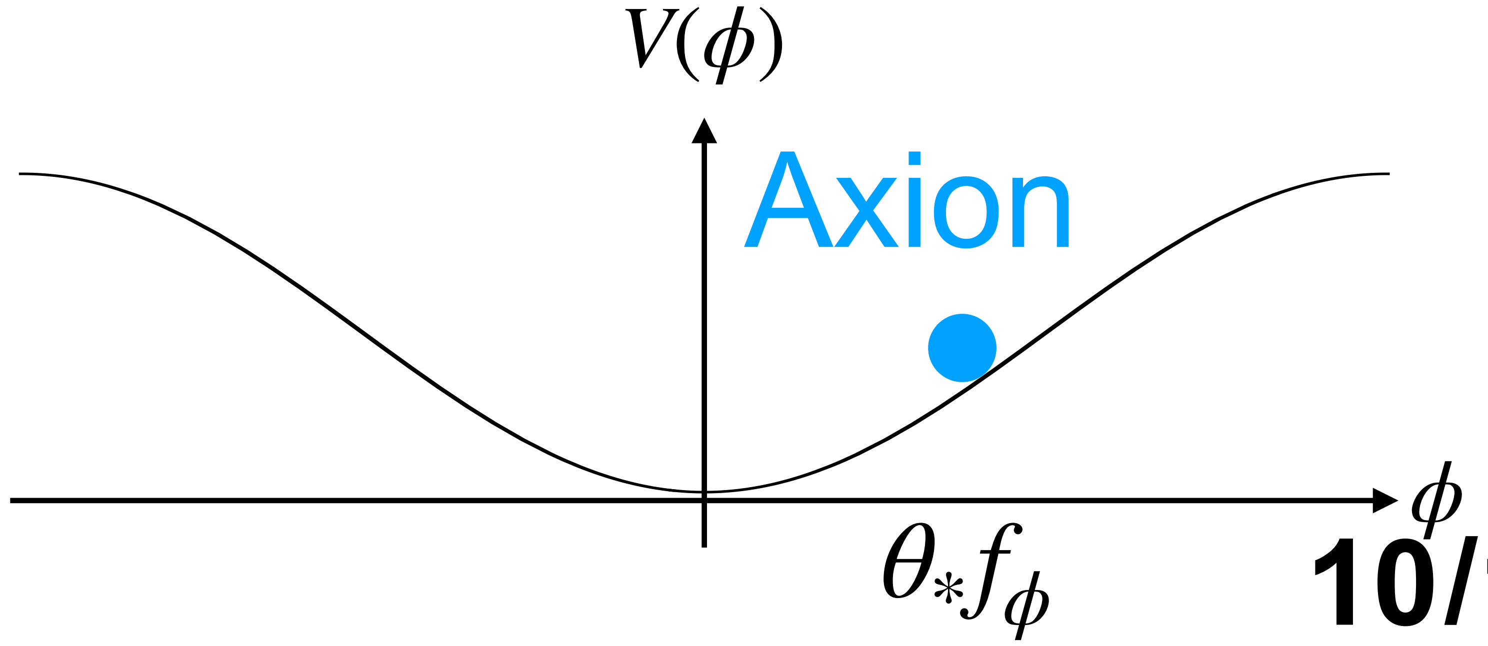
A_μ : dark photon

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

where $f_{\rm EDE} \equiv V_\Psi / \rho_{\rm tot}(z_c) \simeq 0.05$



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



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whe

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

Dark Higgs acquires an effective mass from dark photon production.

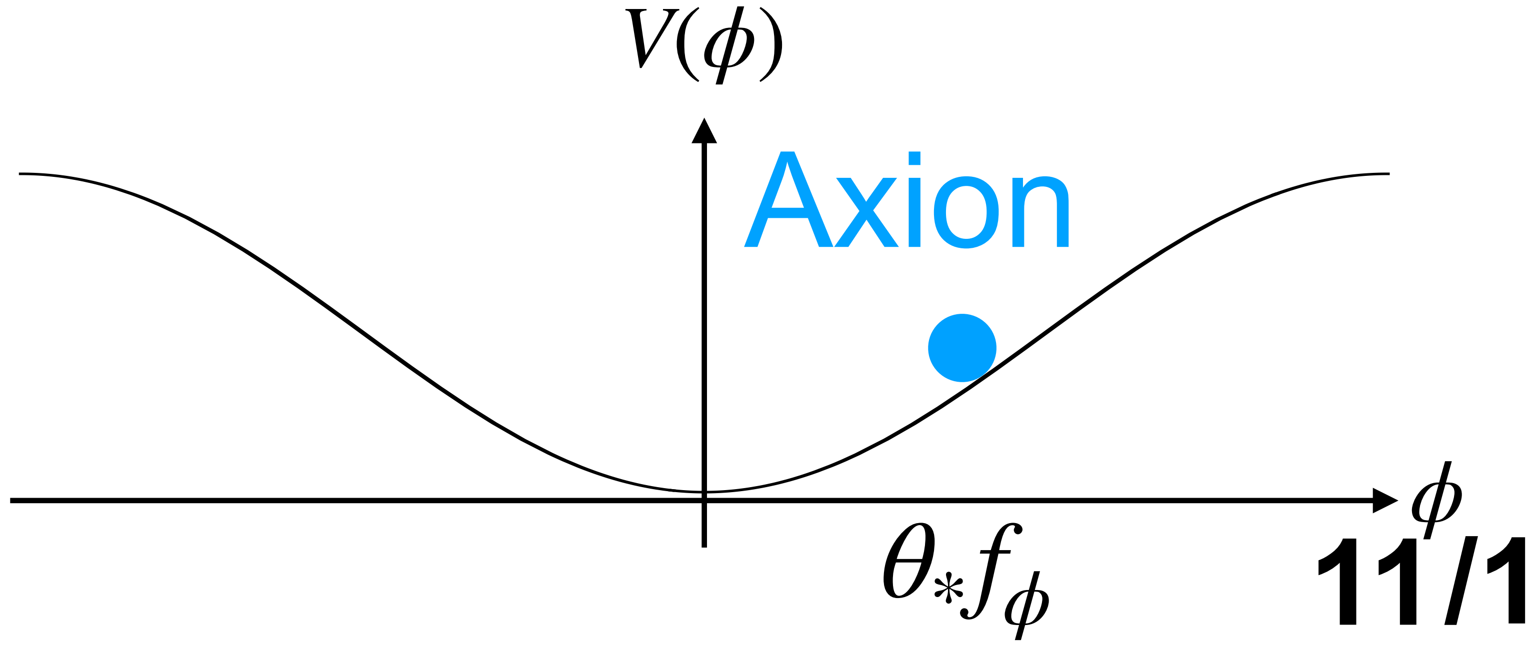
A_μ : dark photon

Higgs p

4

where $f_{\mathrm{EDE}} \equiv V_\Psi / \rho_{\mathrm{tot}}(z_c) \simeq 0.05$

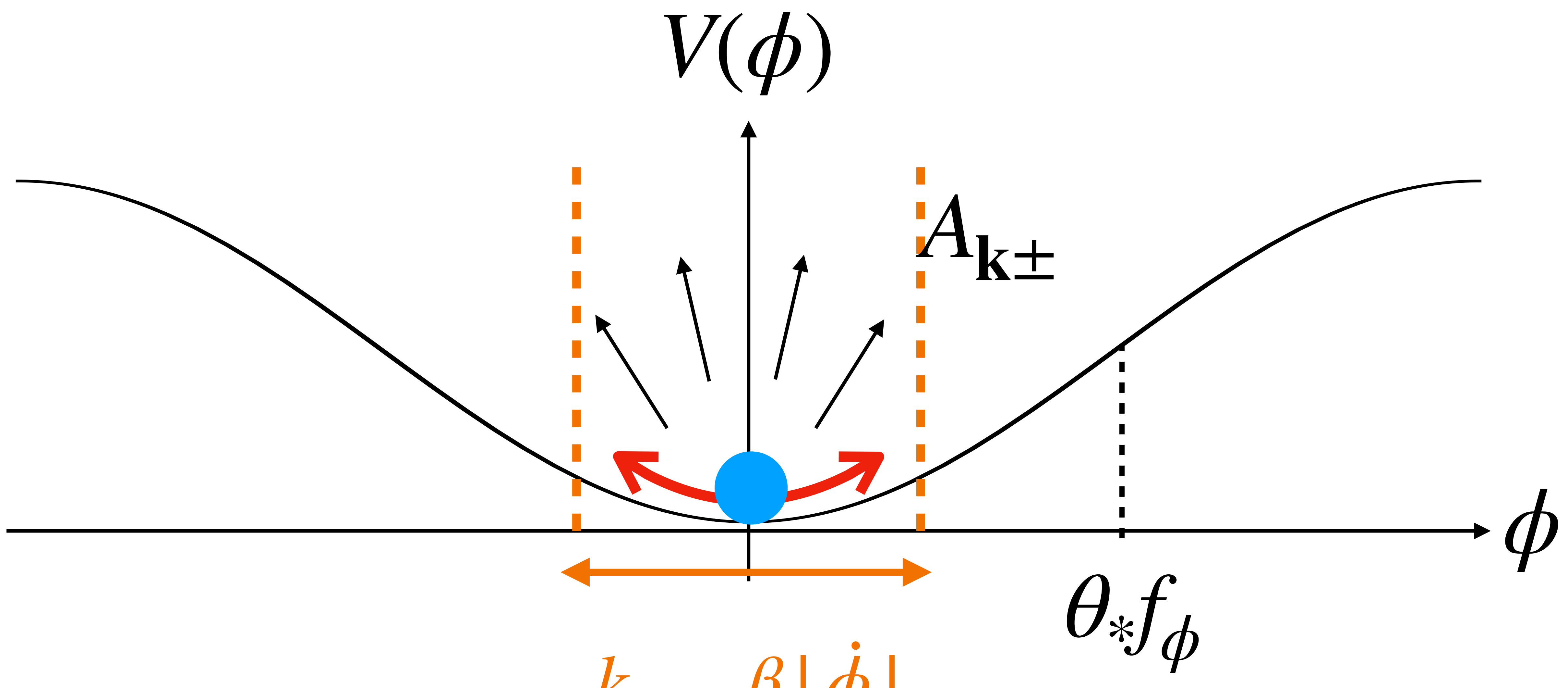
Axion potential $V_\phi(\phi) = m_\phi^2 f_\phi^2 \left[1 - \cos\left(\frac{\phi}{f_\phi}\right)\right]$



Equation of motion for massless dark photon

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

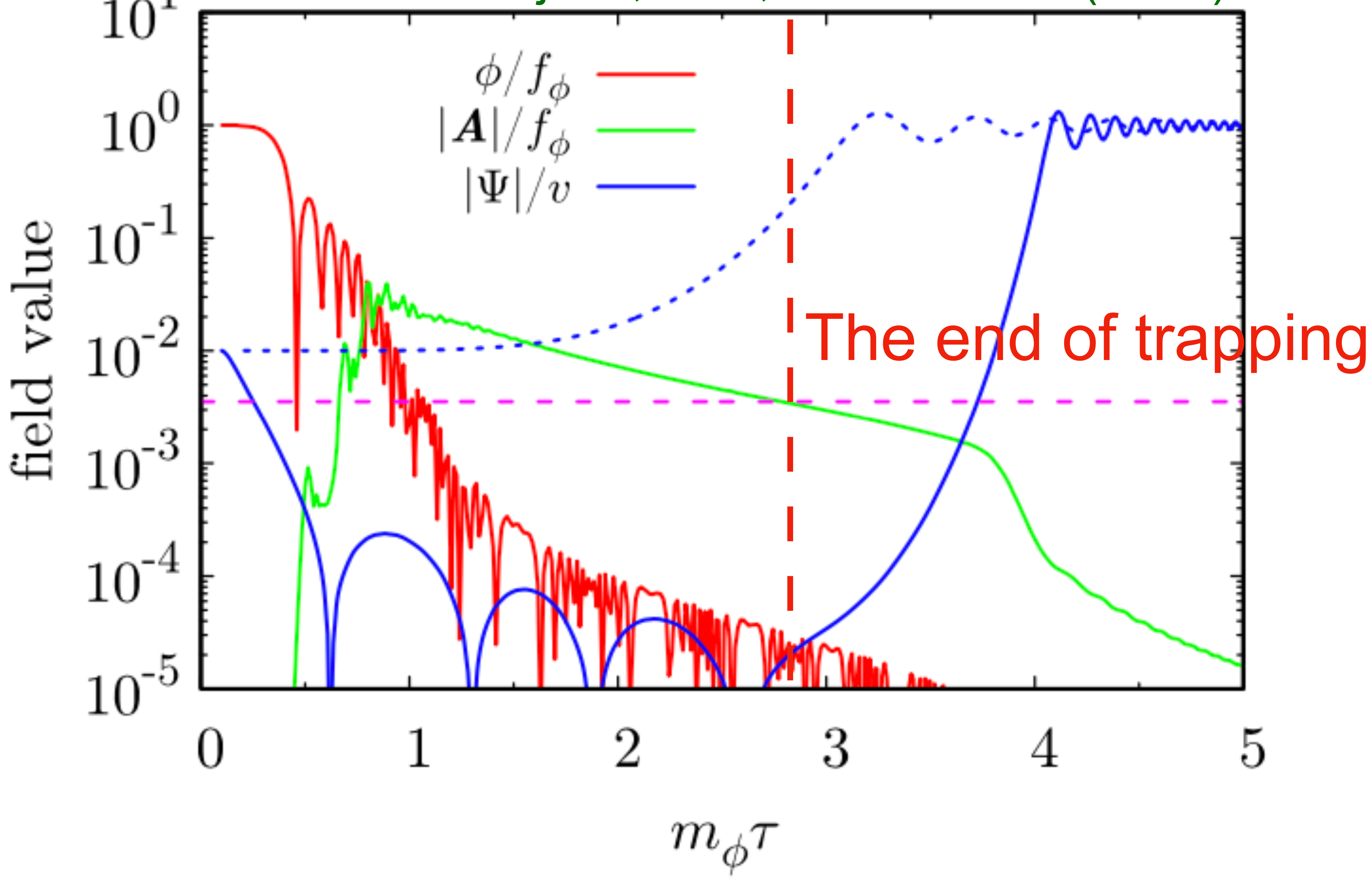
$$\ddot{A}_{\boldsymbol{k},\pm} + H\dot{A}_{\boldsymbol{k},\pm} + \frac{k}{a}\underline{\underline{\left(\frac{k}{a} \mp \frac{\beta\dot{\phi}}{f_\phi}\right)}} A_{\boldsymbol{k},\pm} = 0$$



$$\frac{k}{a} < \frac{\beta|\dot{\phi}|}{f_\phi}$$ ($\beta \sim O(10)$ needed)

Tachyonic production

N. Kitajima, **S.N.**, F. Takahashi (2022)

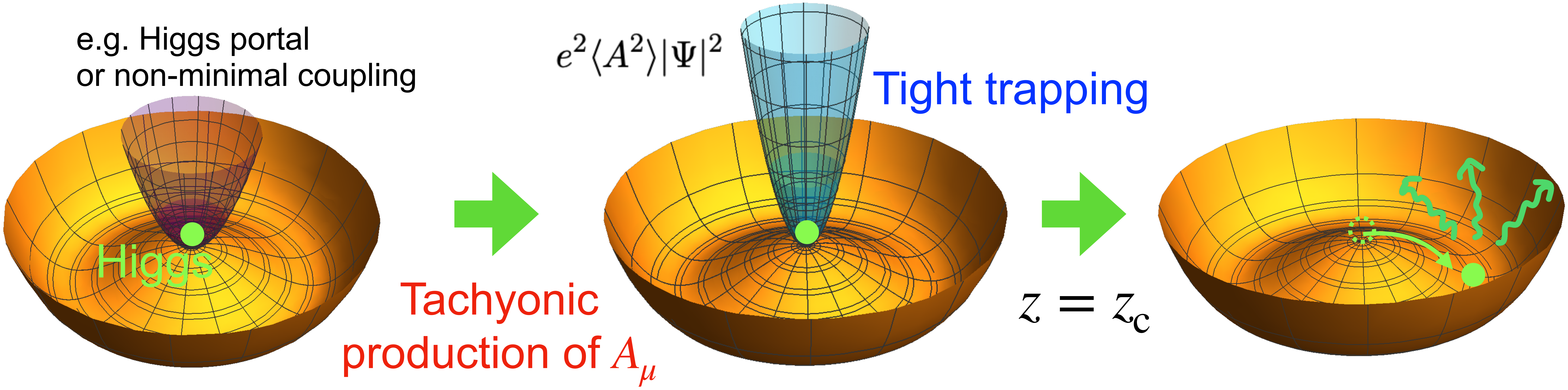


P. Agrawal, G. Marques-Tavares, W. Xue (2018) , N. Kitajima, T. Sekiguchi, F. Takahashi (2018), P. Agrawal, N. Kitajima, M. Reece, T. Sekiguchi, F. Takahashi (2020)

Non-thermal trapping

Summary of our scenario

1. Dark photons are produced by tachyonic instability
   (Note: the axion becomes dark matter at the same time).
2. Dark Higgs is non-thermally trapped until $z = z_c \simeq 5000$.
3. It promptly decays into dark photons.



Initially trapped regime

Non-thermally trapped EDE

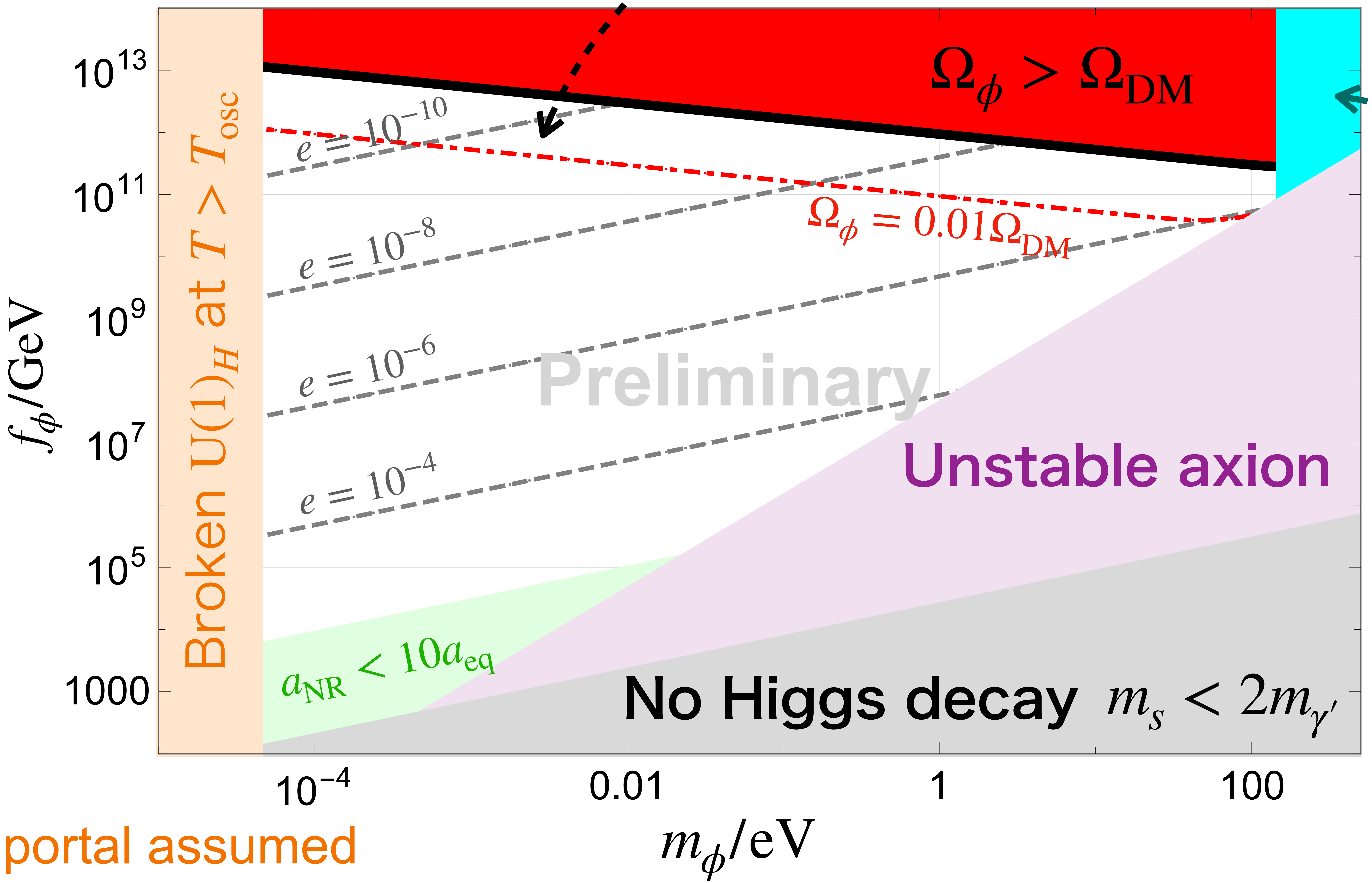
Decay into dark photons

3. Allowed region

Some tuning of e is needed for successful EDE and DM.

$\theta_* = 1,\ \beta = 25,\ \lambda = 1,\ f_{\mathrm{EDE}} = 0.05,\ z_c = 5000$

$\rightarrow m_s \sim 1\mathrm{eV}$



DDM lifetime
$(a \rightarrow \gamma'\gamma')$
$\tau_{\mathrm{DM}} \gtrsim 175\mathrm{Gyr}$

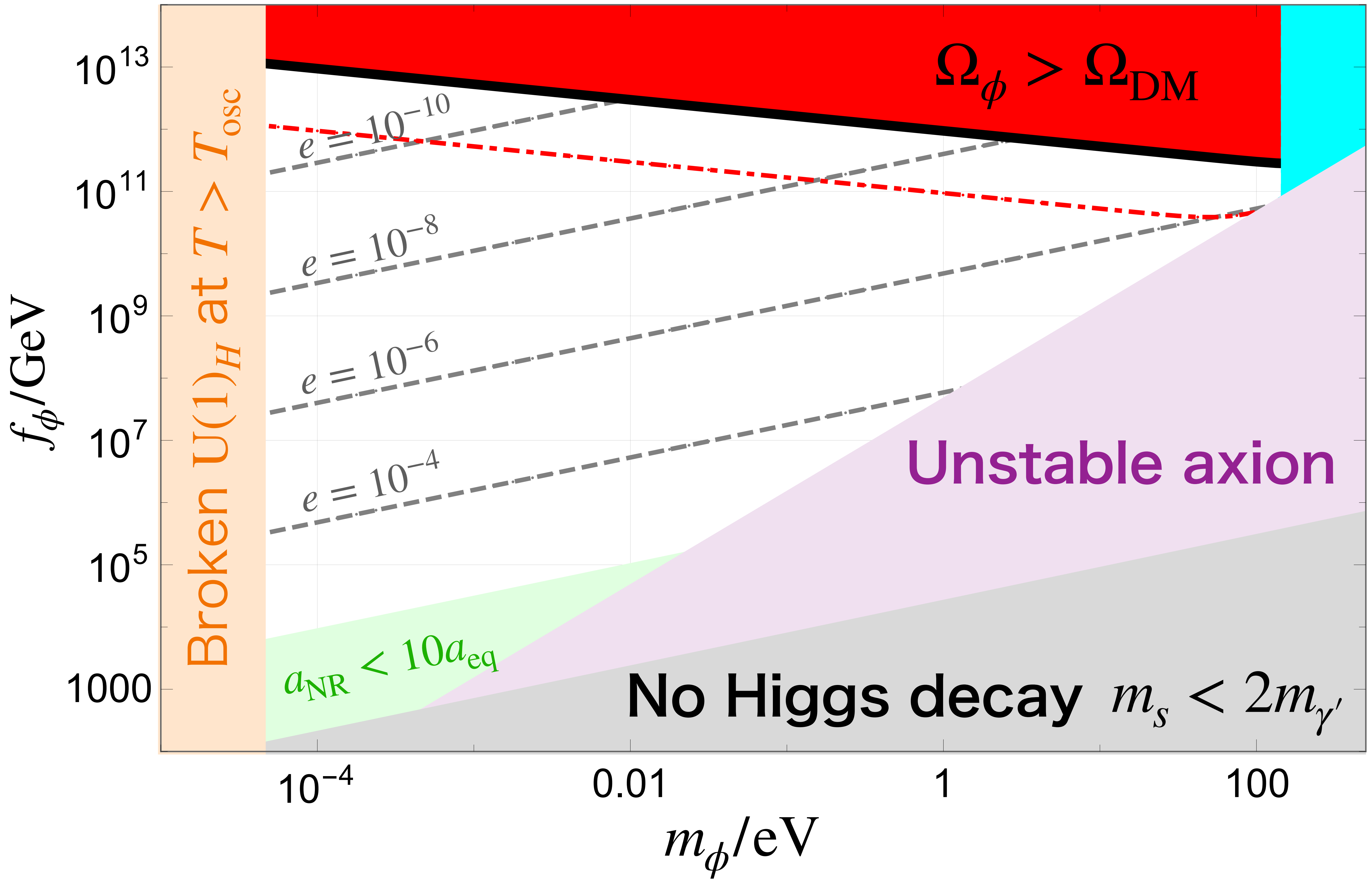
Higgs portal assumed

Summary

• H_0 tension is being revealed by recent development of observation. We propose a new EDE model as a possible solution.

• The Higgs EDE can be triggered by axion dark matter which is strongly coupled to dark photons.

• H_0 tension can be alleviated in a vast parameter region (some tuning of e for successful EDE and DM).



Back Up

Initial trapping regime

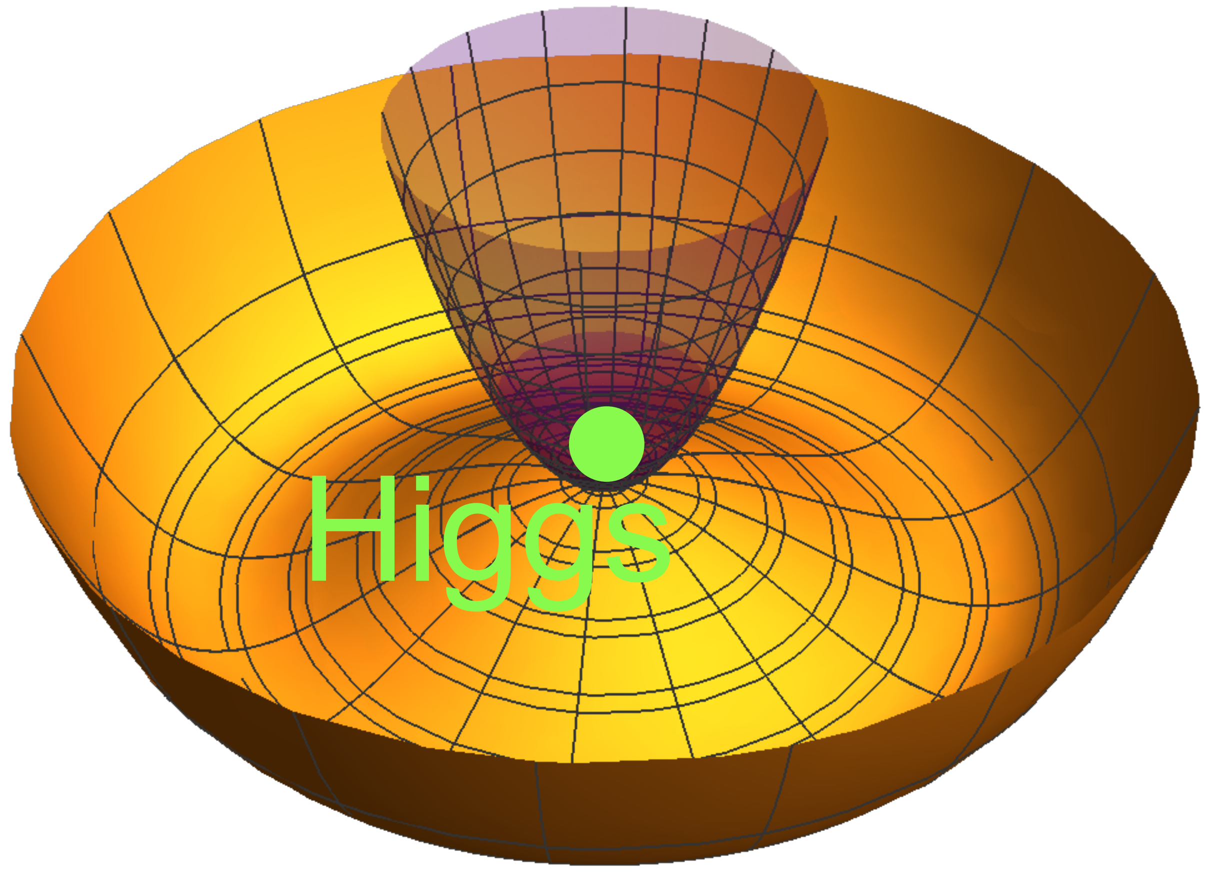
Enough tachyonic instability requires the absence of dark photon mass.

e.g. Higgs portal coupling

$$L = -\lambda_{H\Psi} H H^\dagger |\Psi|^2$$

The dark Higgs acquires thermal mass, $m_{\rm th} \sim \sqrt{\lambda_{H\Psi}} T_{\rm osc}$ at the axion oscillation.

$$V_{\rm eff} = \frac{\lambda}{4} v^4 + \underbrace{\left(m_{\rm th}^2 - \frac{\lambda}{2} v^2 \right)}_{> 0} |\Psi|^2 + \dots$$



We can also consider non-minimal coupling to gravity, but it is somewhat weak.

Sensitivity for axion search experiment

Assuming axion-photon coupling

For $\lambda = 1,\ \beta = 25,\ \theta_* = 1$