Dark Higgs early dark energy by axion-induced trapping effect

"What is DM?" symposium
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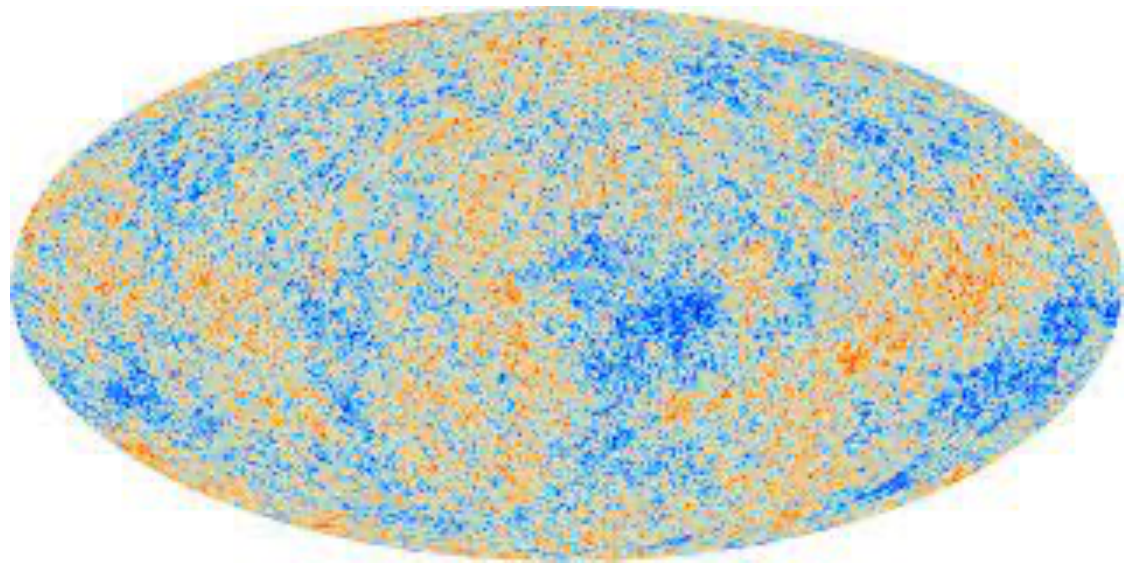
Based on arXiv: 2209.01107 with F. Takahashi and W. Yin (To be published in PRD)
PRD 105 (2022) 10. [arXiv:2111.06696] with N. Kitajima and F. Takahashi

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

Indirect measurement (CMB+ΛCDM)

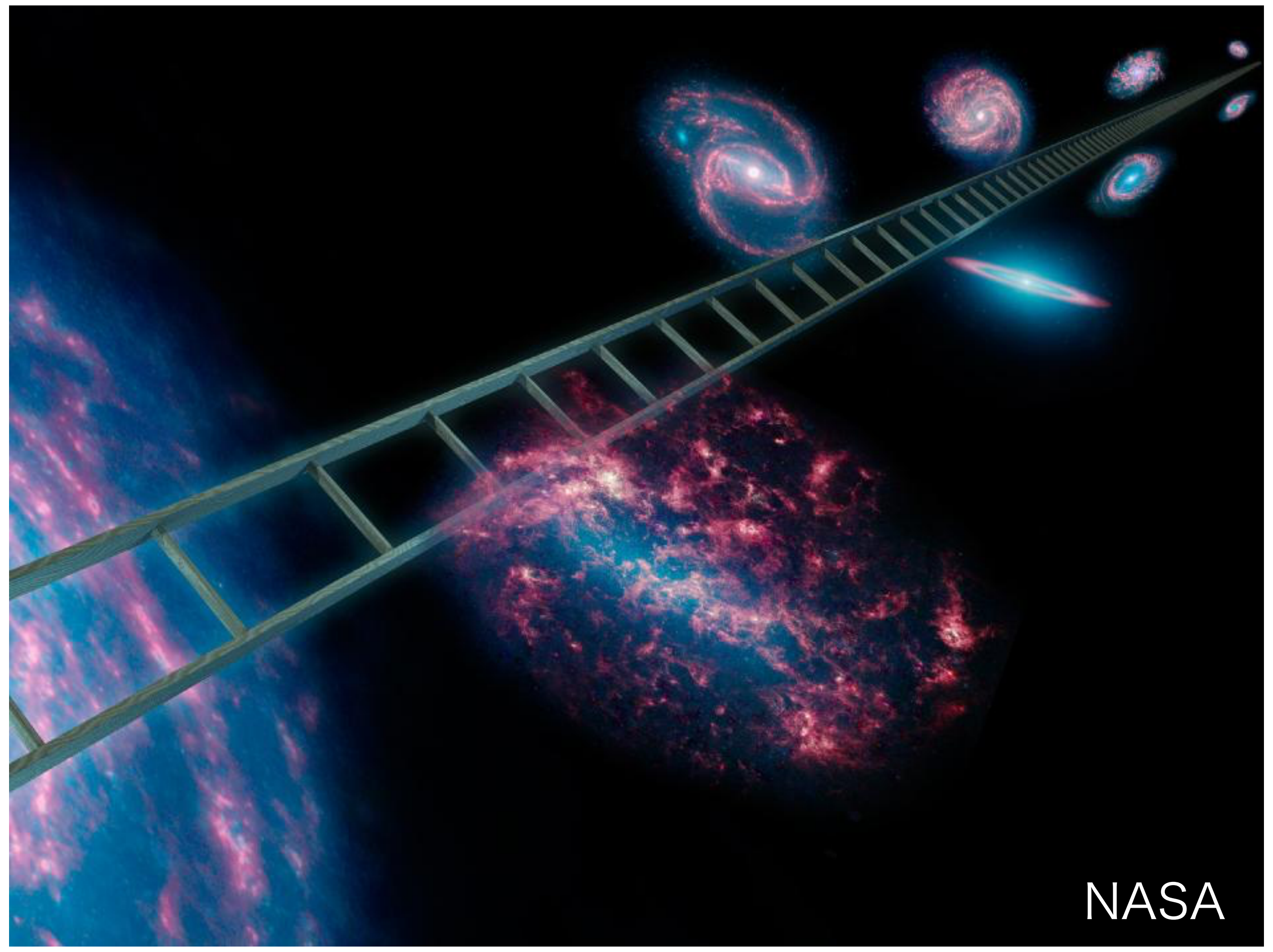
$$H_0^{(\text{indirect})} = 67.27 \pm 0.60 \text{km/s/Mpc}$$

Planck2018, 1807.06209

Direct measurement w/ distance ladder

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

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



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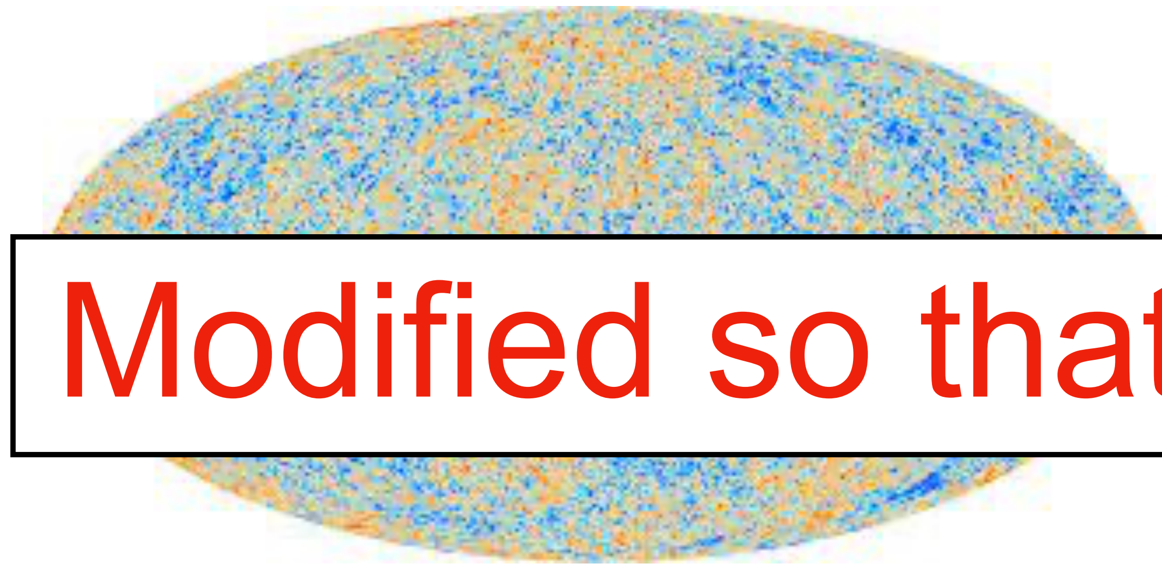
Hubble (H_0) tension



Modified so that H_0 increases

Planck collaboration

Indirect measurement (CMB+ΛCDM)

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

Planck2018, 1807.06209

$\sim 5\sigma !$

New Physics??

Direct measurement w/ distance ladder

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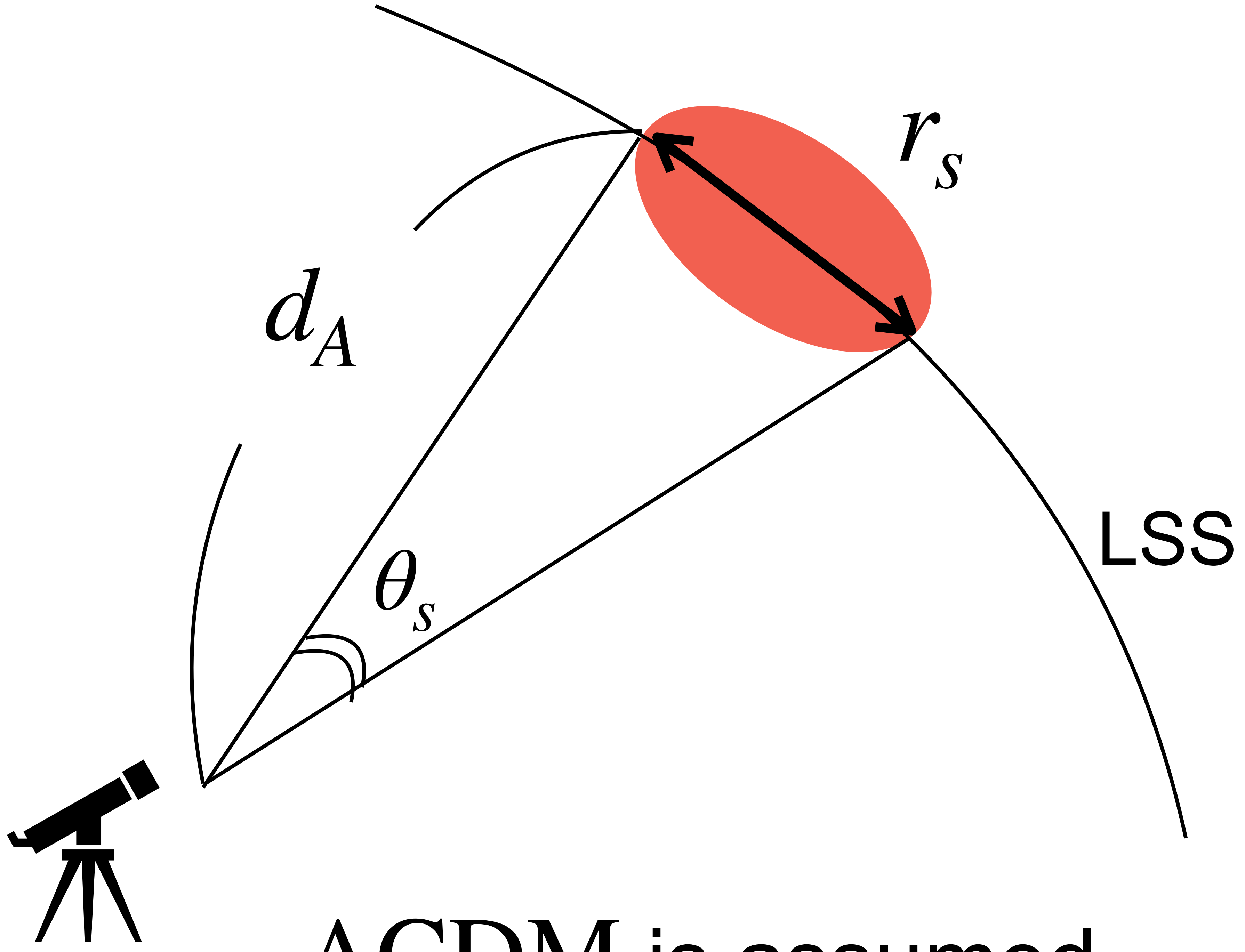
H_0 from CMB + cosmological model



Useful ruler: Sound horizon

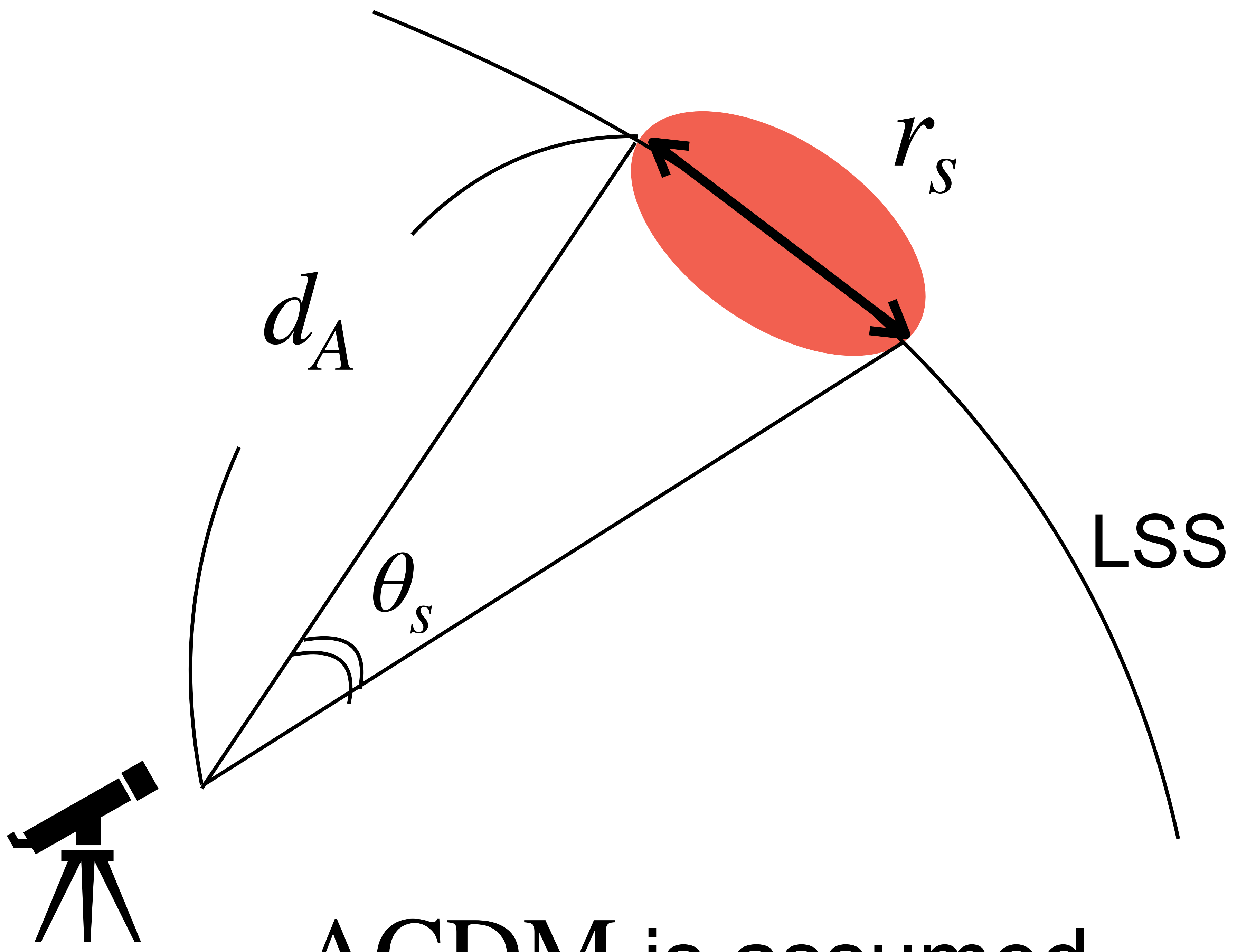
$$r_s \equiv \int_{z_{\rm rec}}^{\infty} dz \frac{c_s(z)}{H(z)}$$

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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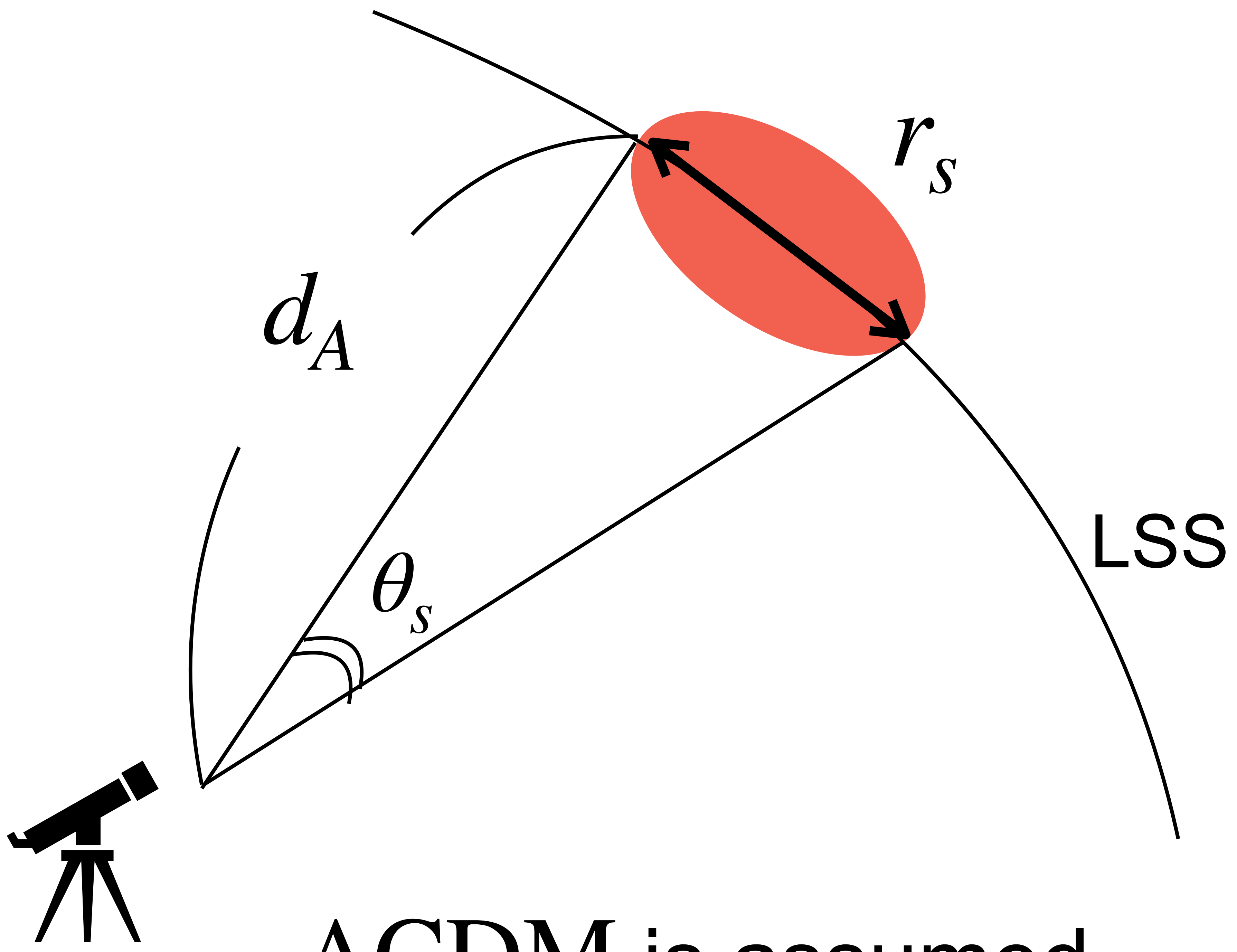
Observable

With late-time evolution left unchanged

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

H_0 from CMB + cosmological model



Useful ruler: Sound horizon

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

Early dark energy (EDE)

$$f_{\rm EDE} \equiv \rho_{\rm EDE}/\rho_{\rm tot}(z_c) \sim 10\,\%$$

$$z_c \sim 3500 - 4000$$

ΛCDM is assumed.

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

$$\frac{(\text{Late}) - (\text{Early})}{(\text{Early})} \sim 10\,\%$$

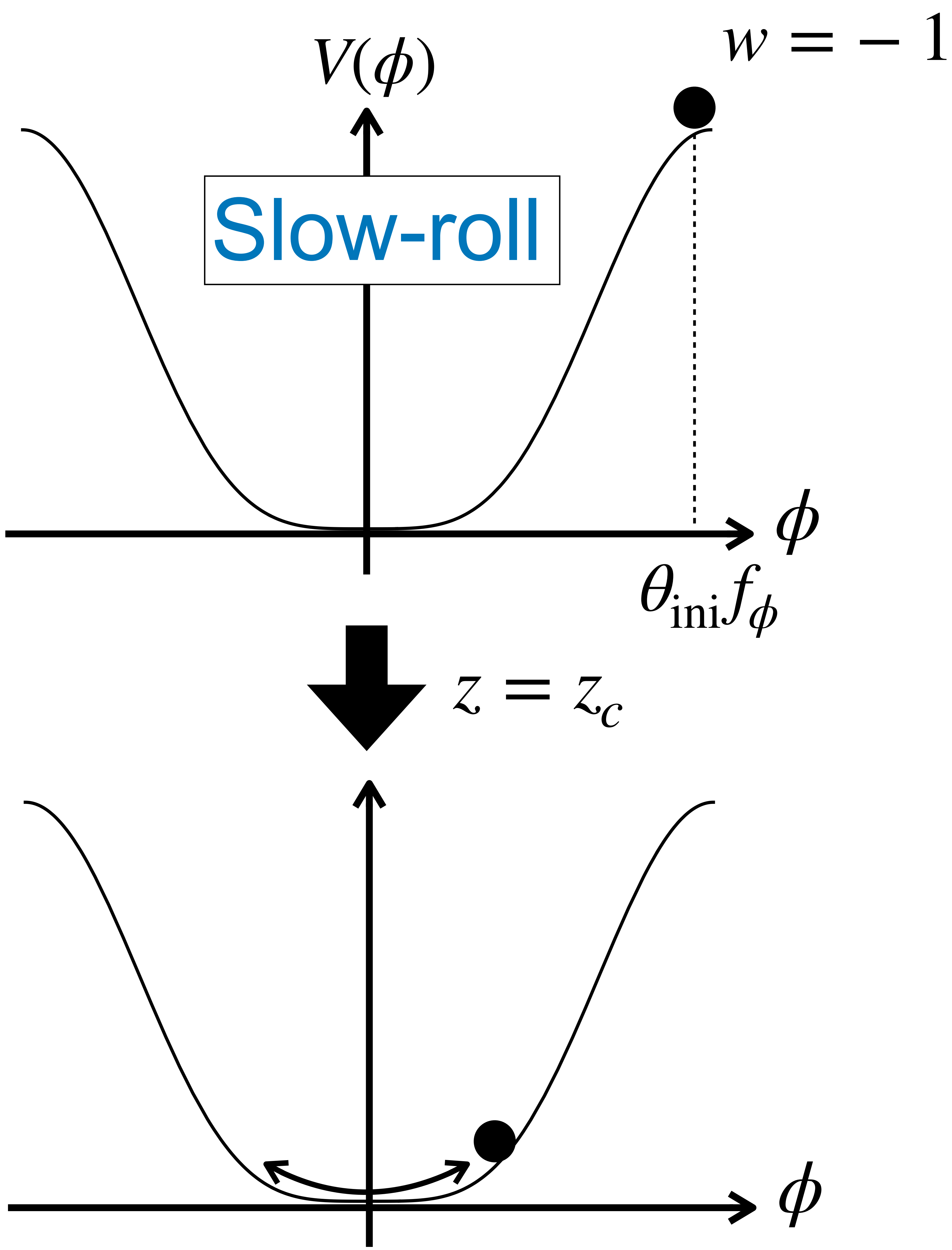
Observable

With late-time evolution left unchanged

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

Axion EDE

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

Kamionkowski , et al. 1409.0549

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

Late-time evolution is not affected.

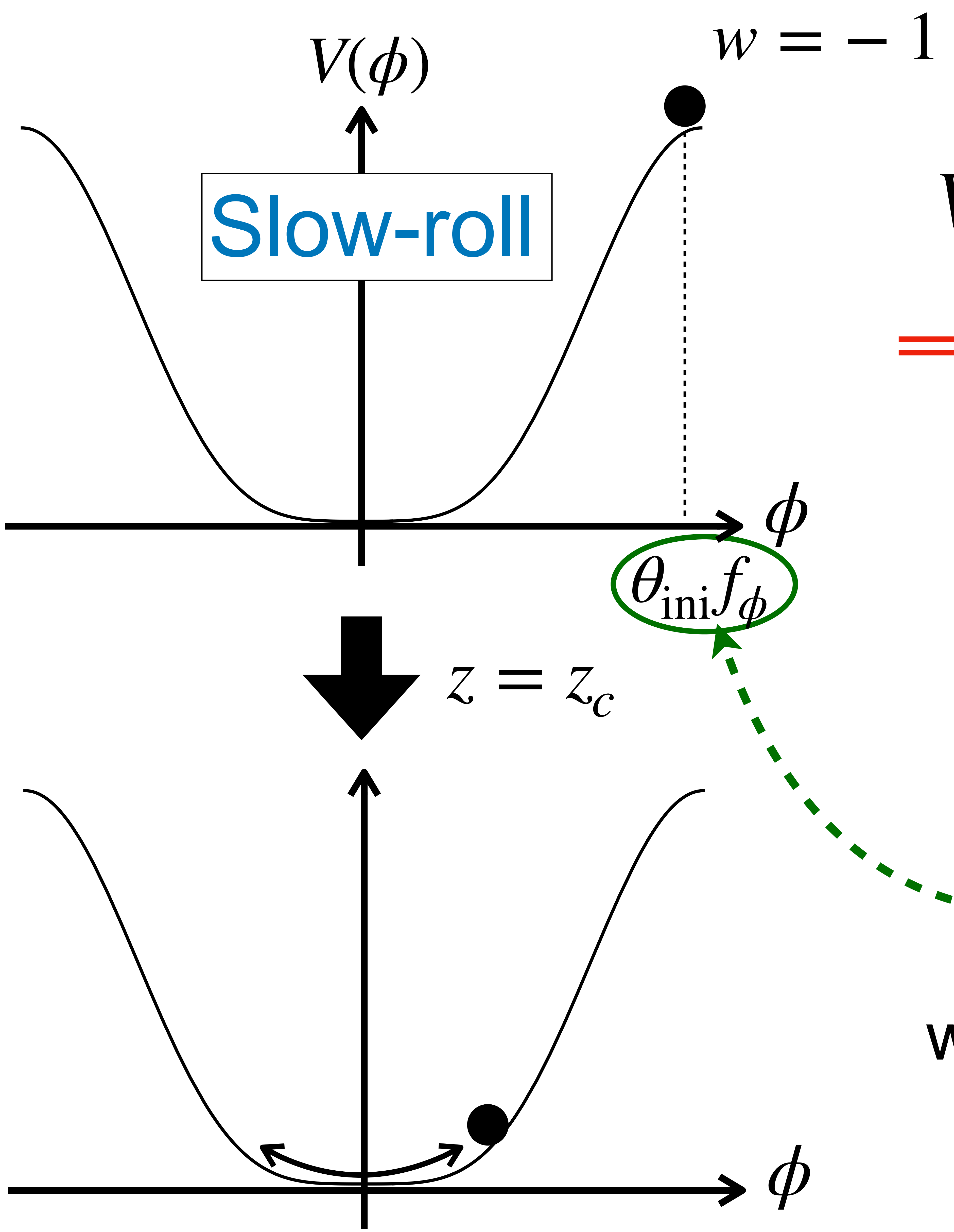
e.g. $n = 2, \quad \rho_a \propto a^{-4}$ (radiation)

$n = 3, \quad \rho_a \propto a^{-9/2}$

Axion EDE

Poulin, et al. (2019)

Pointed out by some literatures:
Berghaus and Karwal, 1911.06281. Alexander and McDonough, 1904.08912. Gonzalez, Hertzberg, and Rompineve, 2006.13959. Alexander, Bernardo, and Toomey, 2207.13086



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ϕ : axion
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Kamionkowski , et al. 1409.0549

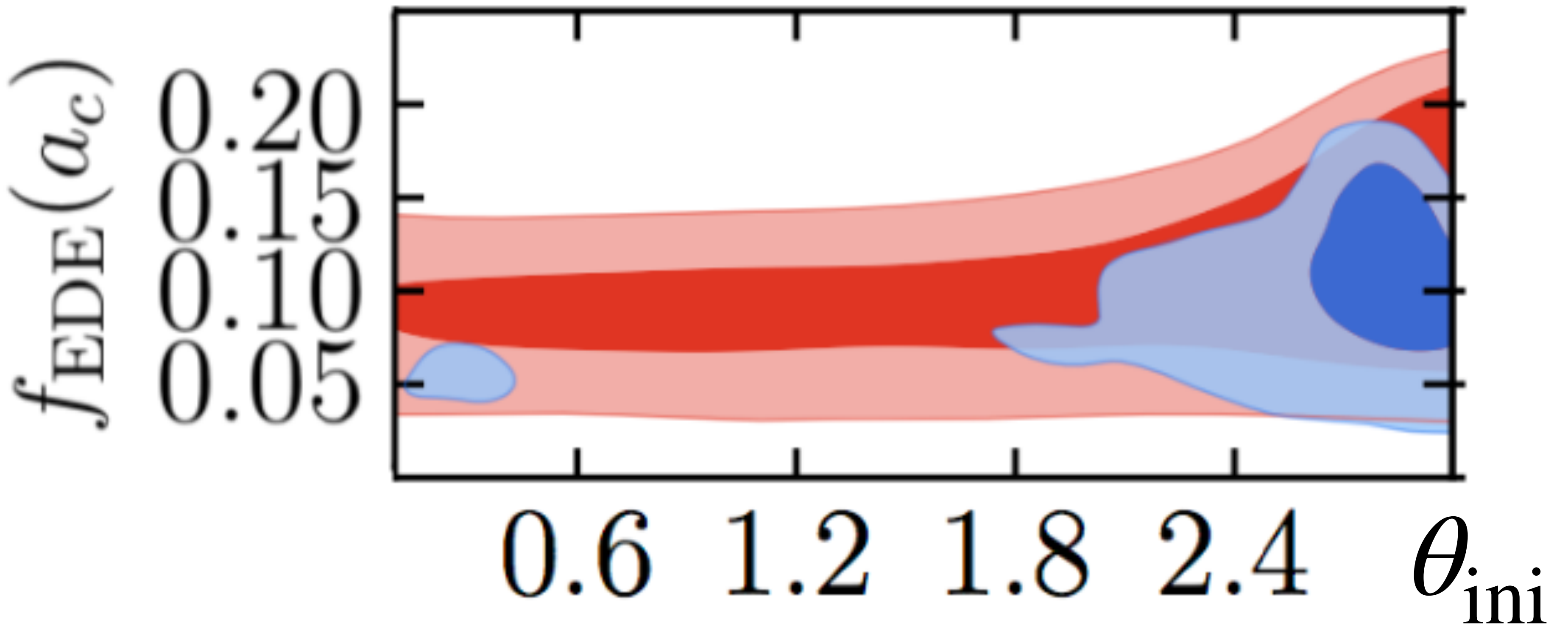
Contrived shape

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

Late-time evolution is not affected.

$\theta_{\rm ini} \gtrsim 2.7$

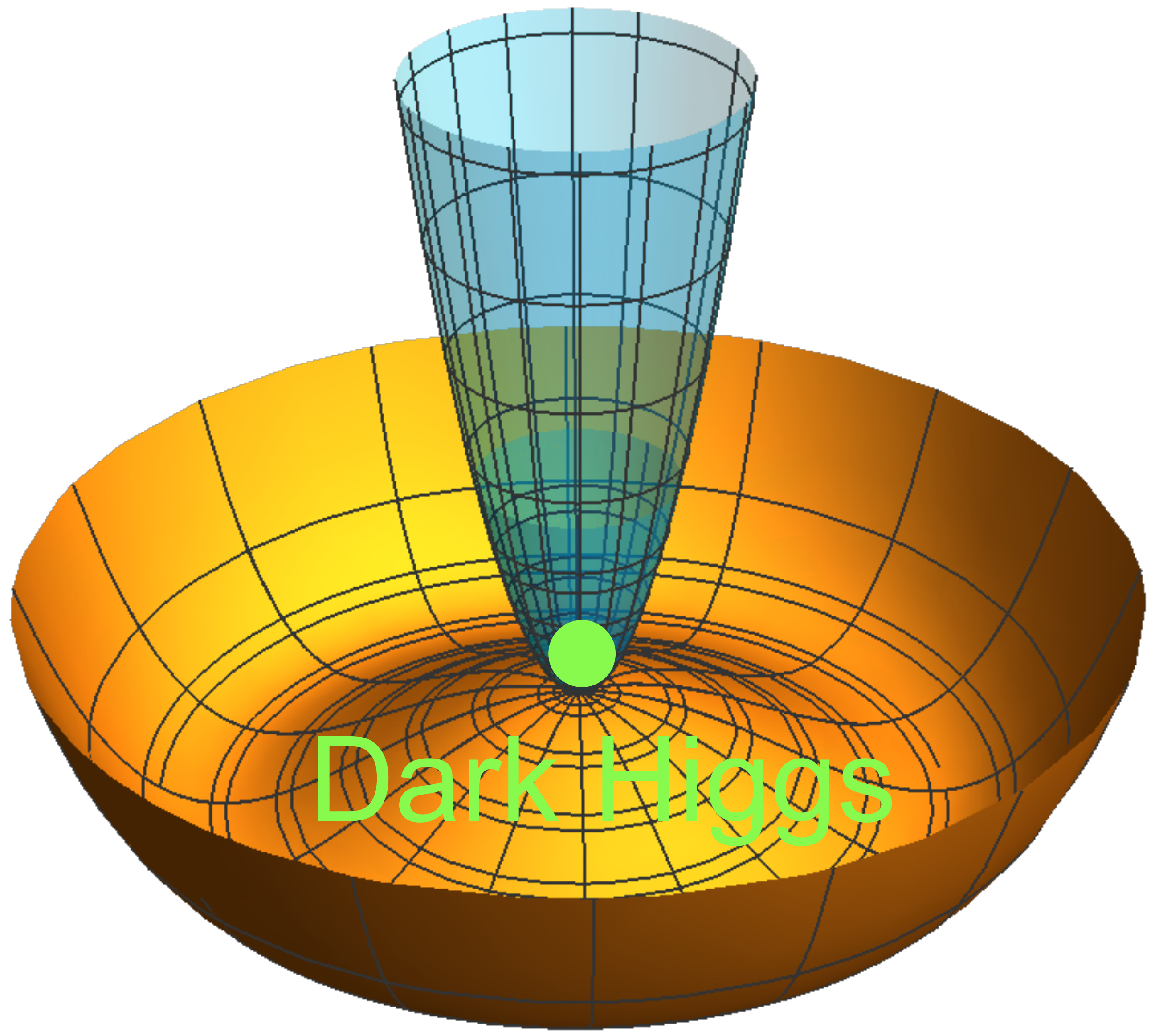
w/ CMB polarization



Poulin, et al. (2020)

What we did

We consider a trapped dark Higgs as EDE, and the dark Higgs promptly decays into dark photons.



→ The dark Higgs EDE potential shape is arbitrary or simple.

To that end, a non-thermal trapping is required.

We identify a viable parameter region consistent with successful EDE scenario.

2. Trapped dark Higgs EDE

SN, Takahashi, Yin, 2209.01107

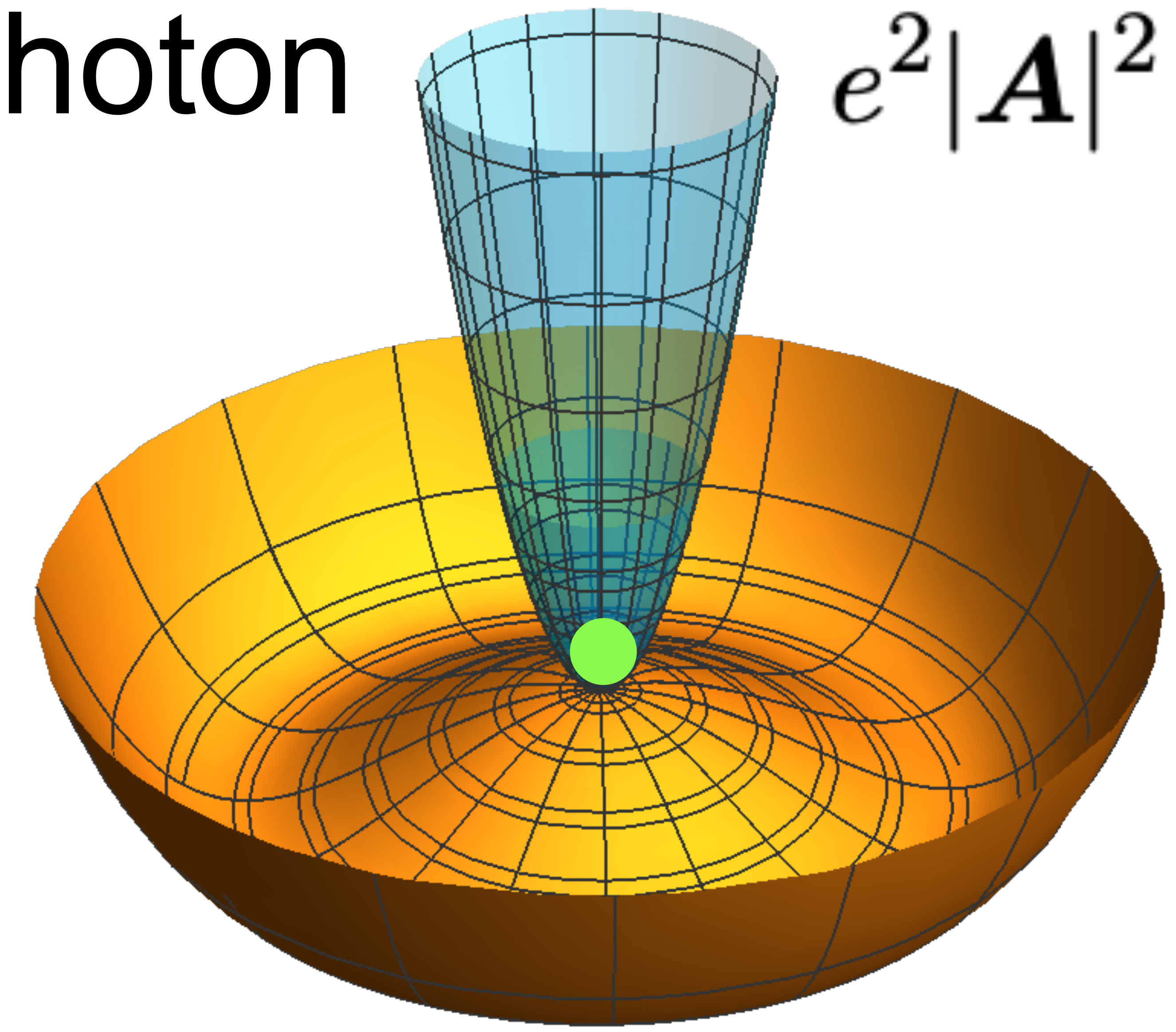
Abelian (dark) Higgs model

$$\mathcal{L} = (D_\mu \Psi)^\dagger D^\mu \Psi - V(\Psi, \Psi^\dagger) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

where $D_\mu = \partial_\mu - ieA_\mu$ Ψ : dark Higgs A_μ : dark photon

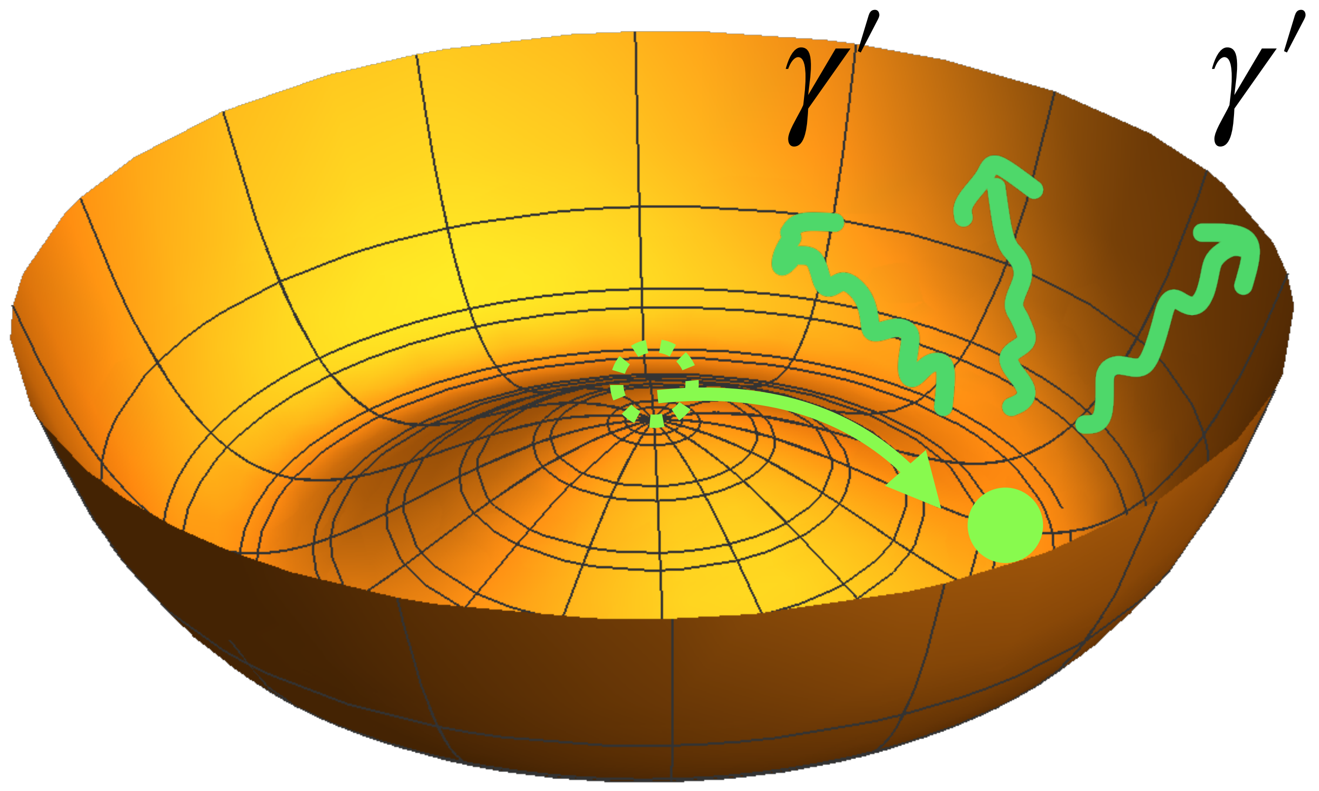
$$V_\Psi(\Psi, \Psi^\dagger) = \frac{\lambda}{4}(|\Psi|^2 - v^2)^2 \supset -m_\Psi^2 |\Psi|^2$$

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



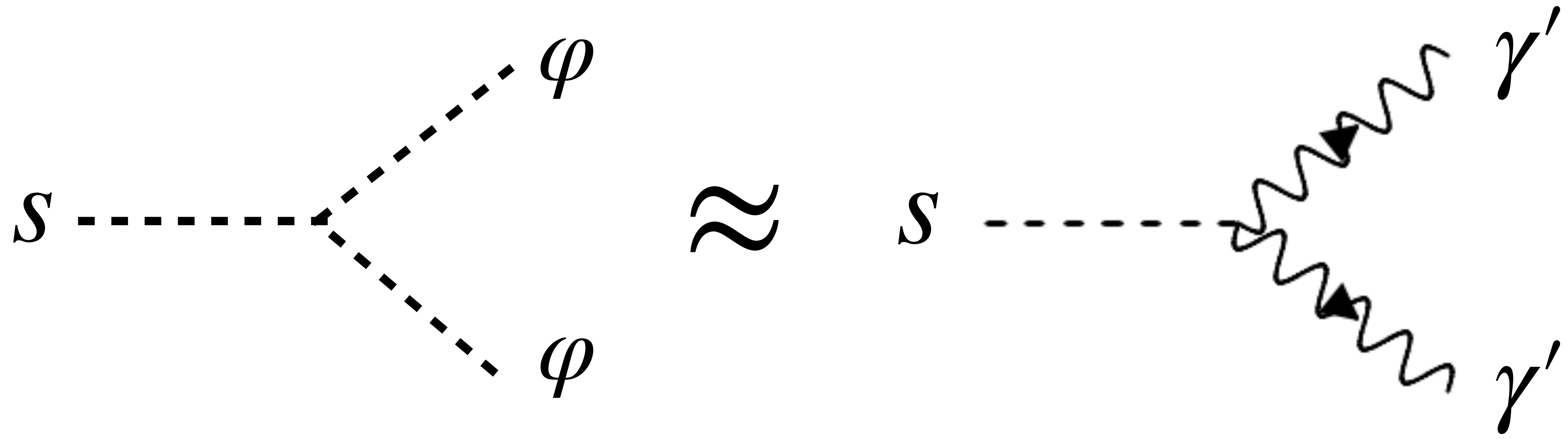
Dark Higgs acquires an effective mass if dark photon exists.

For EDE scenario to work successfully, the dark Higgs must decay quickly to dark photons.



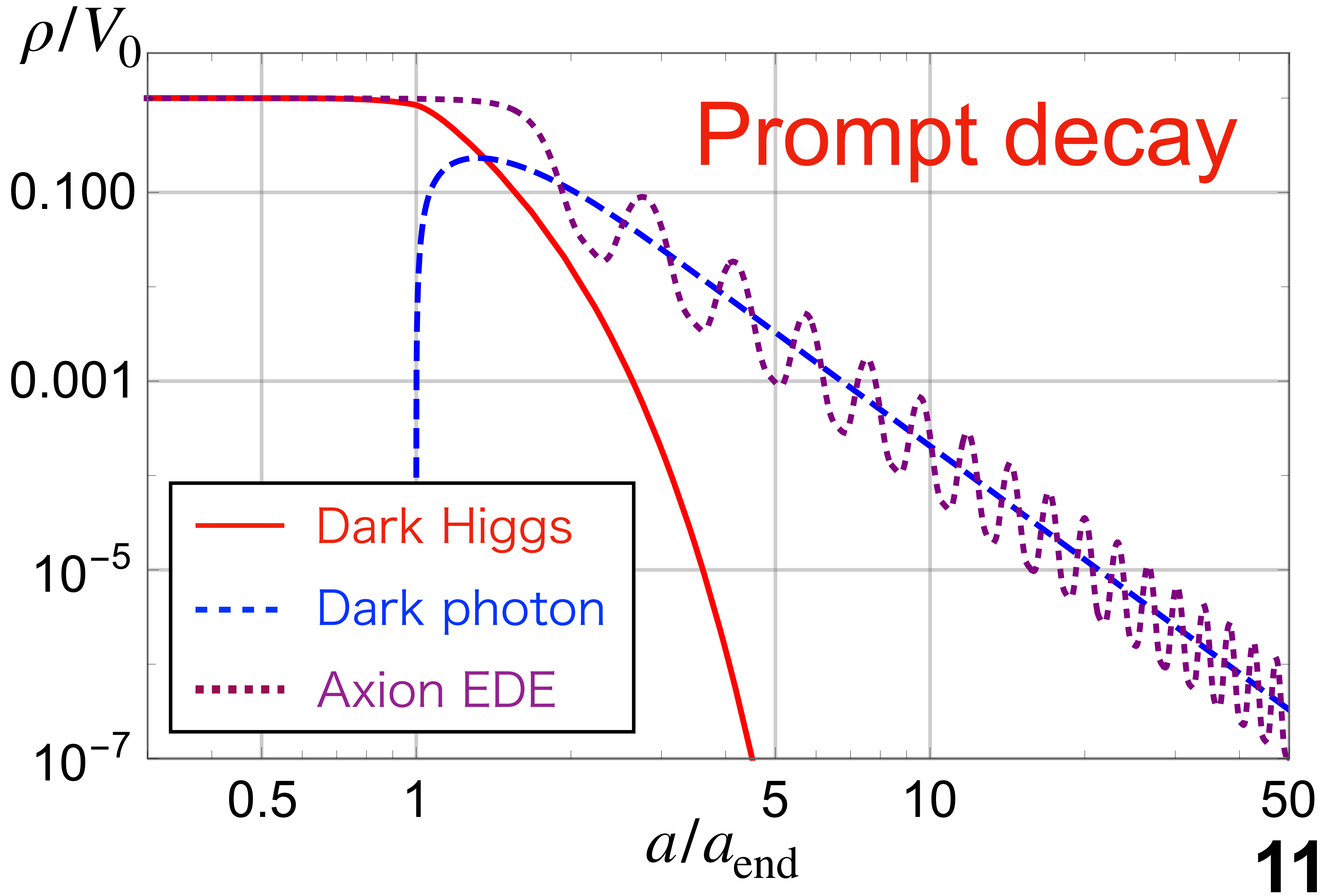
Assuming $2m_{\gamma'} \lesssim m_s \leftrightarrow 2\sqrt{2}e \lesssim \sqrt{\lambda},$

$$\mathcal{L} \supset |\partial_\mu \Psi|^2 \supset \frac{s}{\sqrt{2}v}(\partial_\mu \varphi)^2 \qquad \Psi = \left(v + \frac{s}{\sqrt{2}}\right) e^{i\varphi/\sqrt{2}v}$$



$$\Gamma_s(s \to \gamma'\gamma') \simeq \frac{\lambda m_s}{64\pi} \simeq 4.0\text{meV} \cdot \lambda^{5/4}$$

$\gg H(z_c)$ for $\lambda = O(1)$



3. Non-thermal dark photon production

Kitajima, **SN**, Takahashi (2022)

We consider an axion coupled to the dark photon.

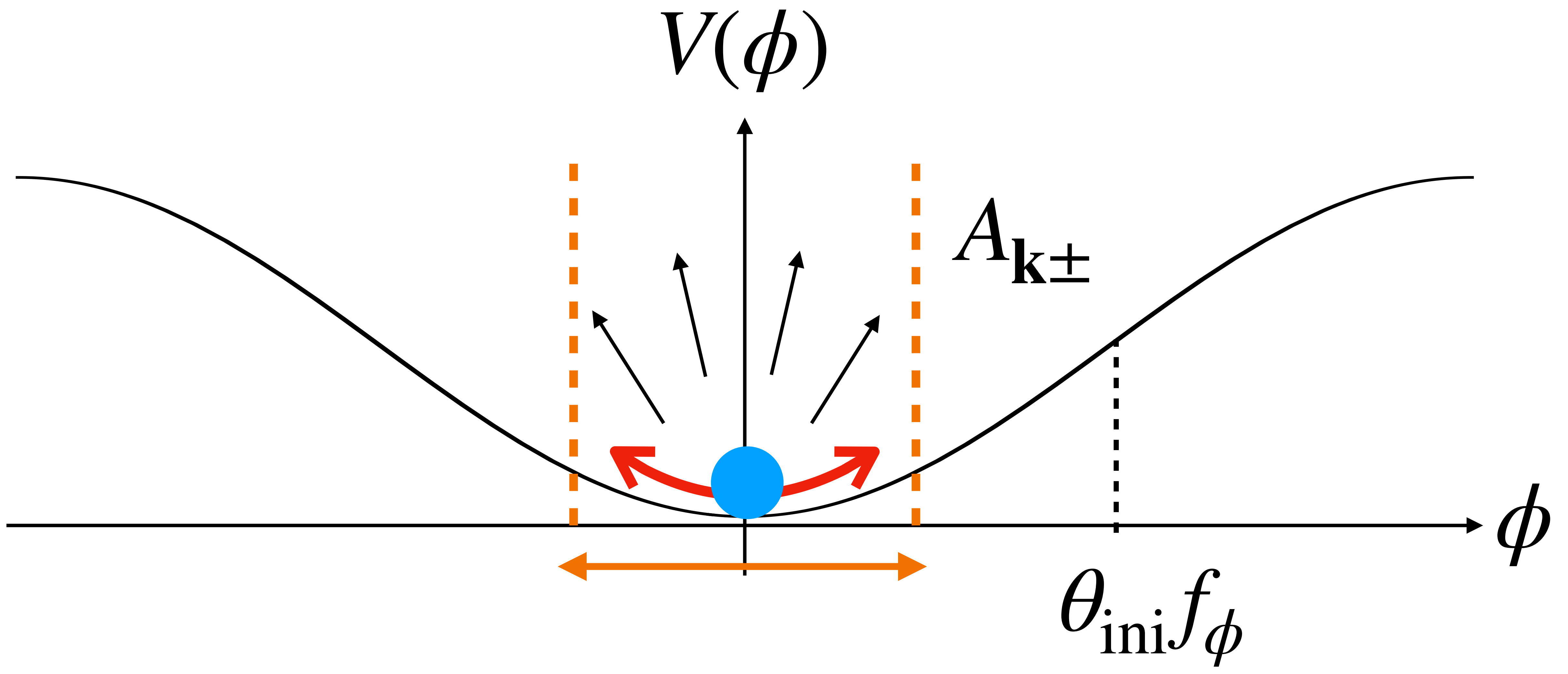
$$\mathcal{L}_\phi = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - m_\phi^2 f_\phi^2\left(1-\cos\frac{\phi}{f_\phi}\right) - \frac{\beta}{4f_\phi}\phi F_{\mu\nu}F^{\mu\nu}$$

where $\beta = \frac{c_{\gamma'} e^2}{8\pi^2}$

EOM for massless dark photon

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

$$\frac{k}{a} < \frac{\beta|\dot{\phi}|}{f_\phi}$$



Tachyonic production

Kitajima, Sekiguchi, Takahashi (2018),
Agrawal, Kitajima, Reece, Sekiguchi, Takahashi (2020)

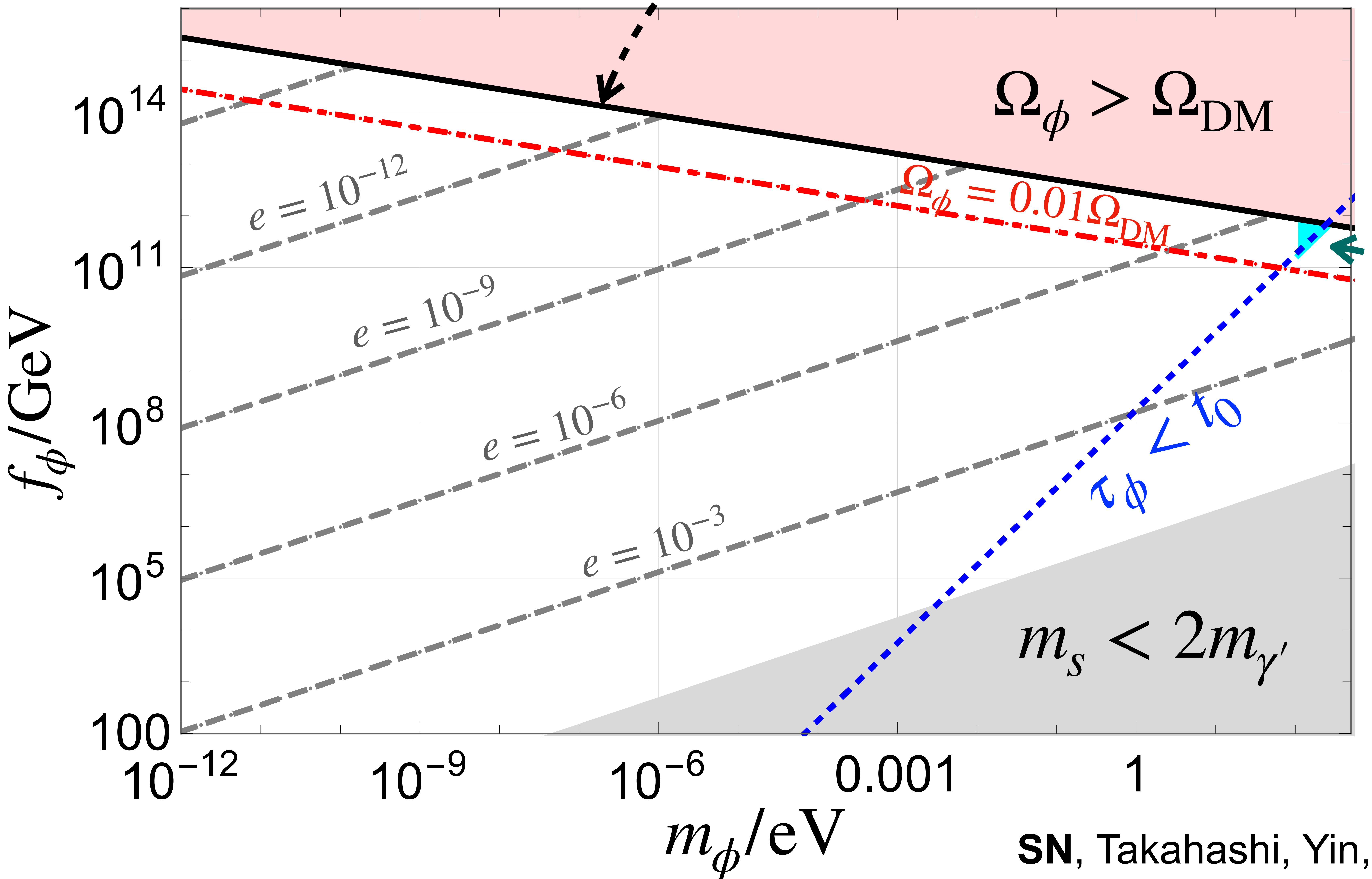
The axion also becomes DM.

Allowed region

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

$\theta_* = 1,\ \beta = 100,\ \lambda = 1,\ f_{\rm EDE} = 0.1,\ z_c = 3500$

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



DDM lifetime ($\phi \to \gamma'\gamma'$)

$\tau_{\rm DM} \gtrsim 246\mathrm{Gyr}$

Alvi, et al. 2205.05636

SN, Takahashi, Yin, 2209.01107

Summary

- H_0 tension is being revealed by recent development of observation.

- In our dark Higgs EDE model, the dark Higgs promptly decays into dark photons, and we don’t need any contrived potential.

- The axion produces the dark photons which traps the dark Higgs, and the remnant of axion can become DM for $m_\phi \lesssim 100\mathrm{eV}$ and $f_\phi \gtrsim 10^{12}\mathrm{GeV}$.

Thanks so much!