[arXiv:2411.06457]

Freeze-in production of axions in DFSZ-type axion models

Kodai Sakurai (Tohoku U.)

In collaboration with

Fuminobu Takahashi (Tohoku U.)

Discreate 2024, Dec. 2th, 2024

Introduction

- Dark matter (DM) is one of the unsolved problems in the SM.

- Dark matter may be light and feeble interactions.
  - promising candidate: axions

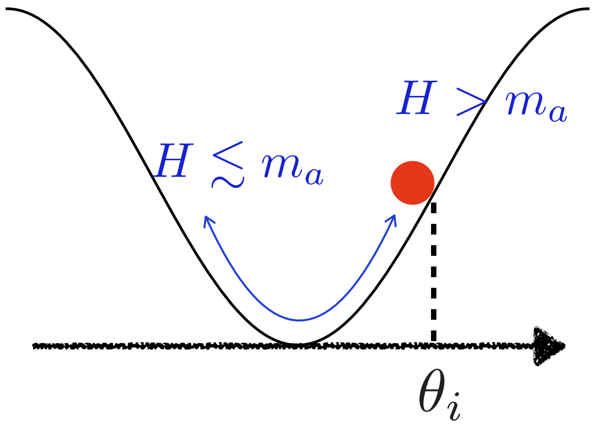
- Axions can solve DM and strong CP problems.

- The nature of the axion is unknown.
  - Mass scale, interactions
  - Production mechanisms → In this talk, we will discuss axion production from heavy Higgs bosons.

Axion productions in early Universe

Non-thermal productions (Misalignment mechanism)

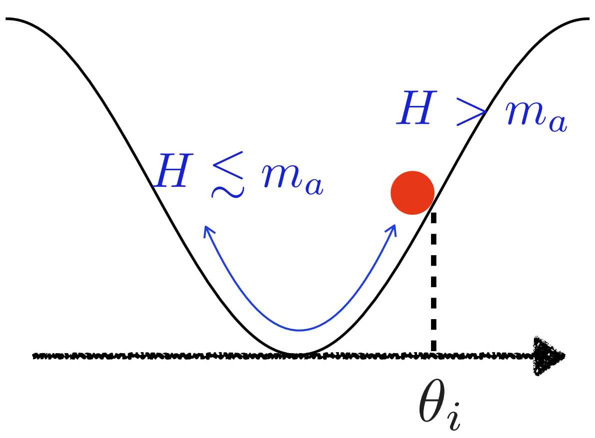
- Axion acquires potential due to the explicit ~~U(1)~~.
- It starts to oscillate when $m_a \gtrsim H$.



Axion productions in early Universe

Non-thermal productions (Misalignment mechanism)

- Axion acquires potential due to the explicit ~~U(1)~~.
- It starts to oscillate when $m_a \gtrsim H$.



Thermal productions

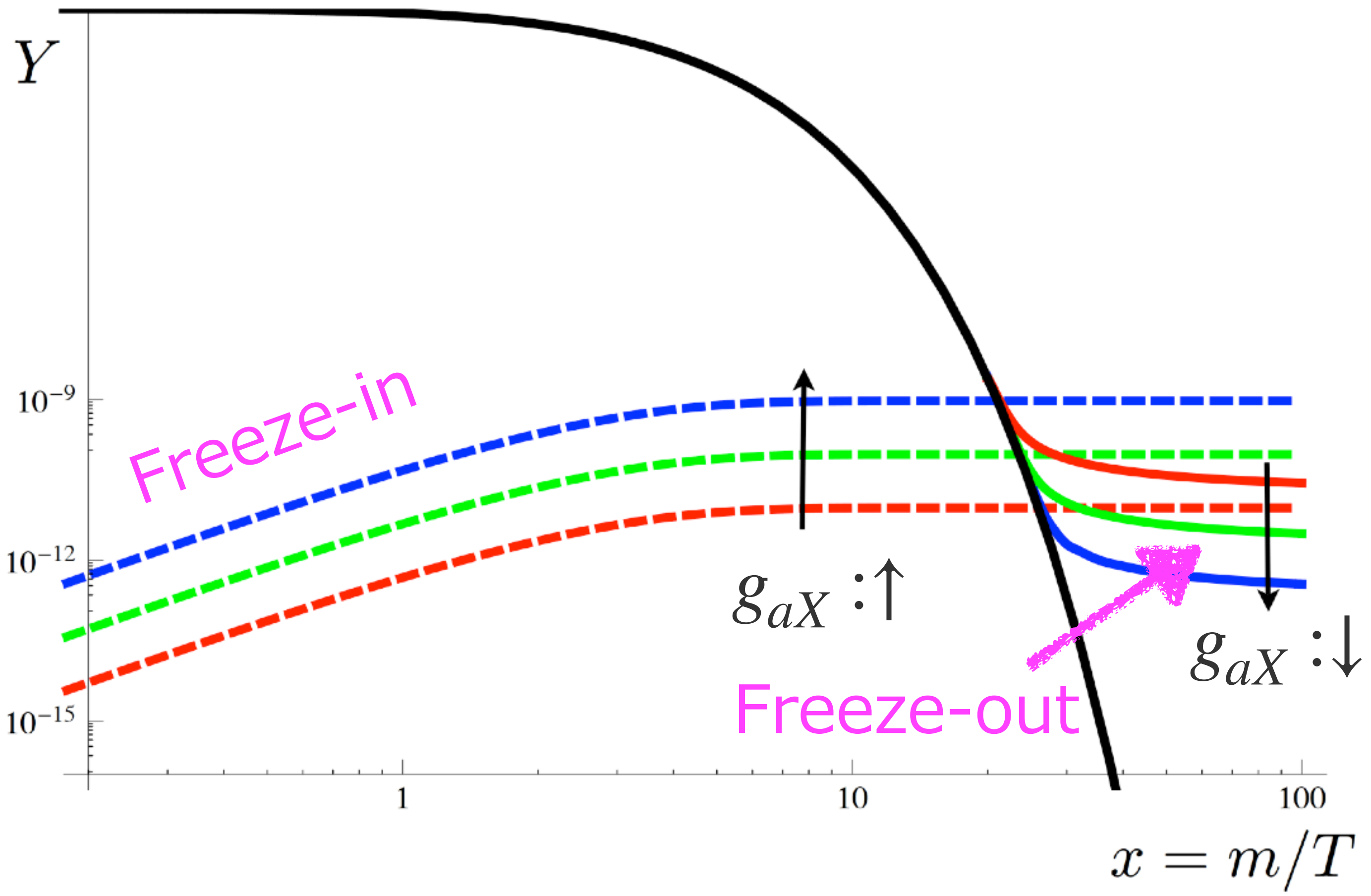
- Axion is thermalized (i.e., small f_a).
  - It is in thermal equilibrium.
  - It decouples from thermal plasma at a certain temperature.
- Axion is not thermalized (i.e., large f_a). → Freeze-in mechanism

Freeze-in mechansim

[L. J. Hall, K. Jedamzik, J. Russell, et. al., JHEP 03 (2010)080]]

Assumptions

- Axion couple with bath particles in thermal plasma.
- It never reaches thermal equilibrium.



Features

- Axion is produced from the thermal plasma.
- The energy density increases as temperature decreases.
- The production of axion stops at $T \sim m_a$.

Concrete axion models

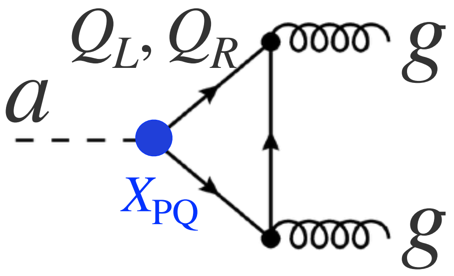
KSVZ-type model [Original model: J. E. Kim (1979); M. A. Shifman, A. I. Vainshtein, V. I. Zakharov (1980)]

$$\boxed{\mathscr{L}_{\mathrm{KSVZ}} \ni y_Q \bar{Q}_L Q_R S + \mathrm{h.c.}}$$

Q:extra vector like singlet fermions

S:extra singlet scalar: $S = \frac{1}{\sqrt{2}}(v_s + \rho)\exp(ia/v_S)$

- Extra fields (Q, S) are U(1) charged.
- Axion mainly couples with gluon. No Axion-fermion coupling at the tree-level.



DFSZ-type model [Original model: A. R. Zhitnitsky (1980); M. Dine, W. Fischler, M. Srednicki (1981)]

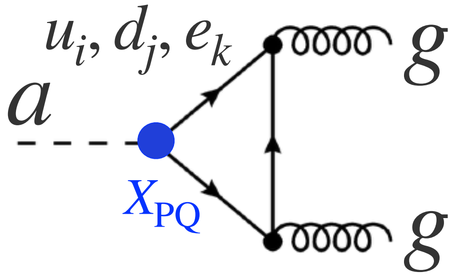
$$\boxed{\mathscr{L}_{\mathrm{DFSZ}} \ni \kappa H_1^\dagger H_2 S^2 + y_u \bar{Q} H_2^c u_R + y_d \bar{Q} H_1 d_R + \mathrm{h.c.}}$$

H_1 : SM Higgs doublet

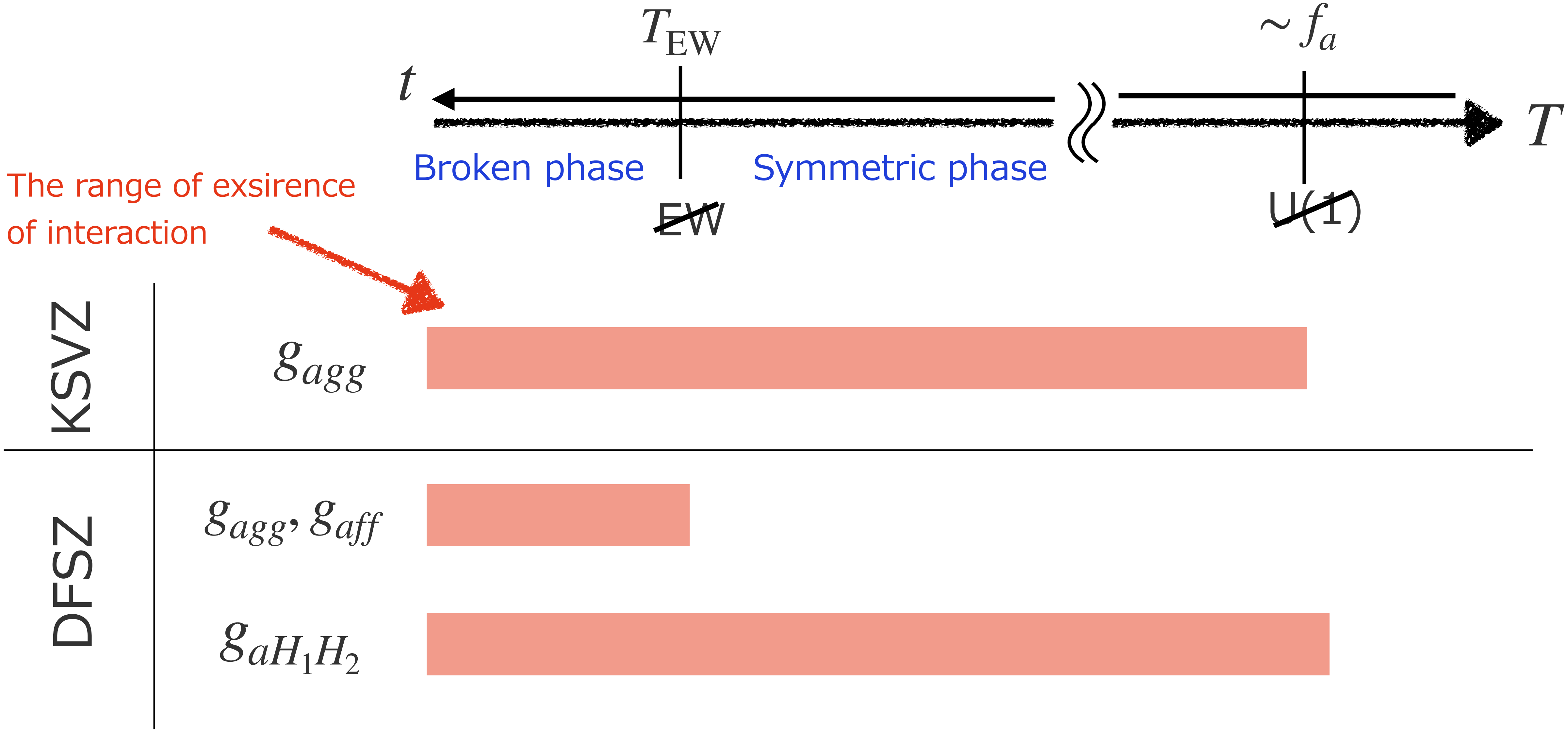
H_2 : extra Higgs doublet $\ni H, A, H^\pm$

S:extra singlet scalar

- Axion couple with Higgs bosons
- Axion-gluon couplings are realized by SM-fermions



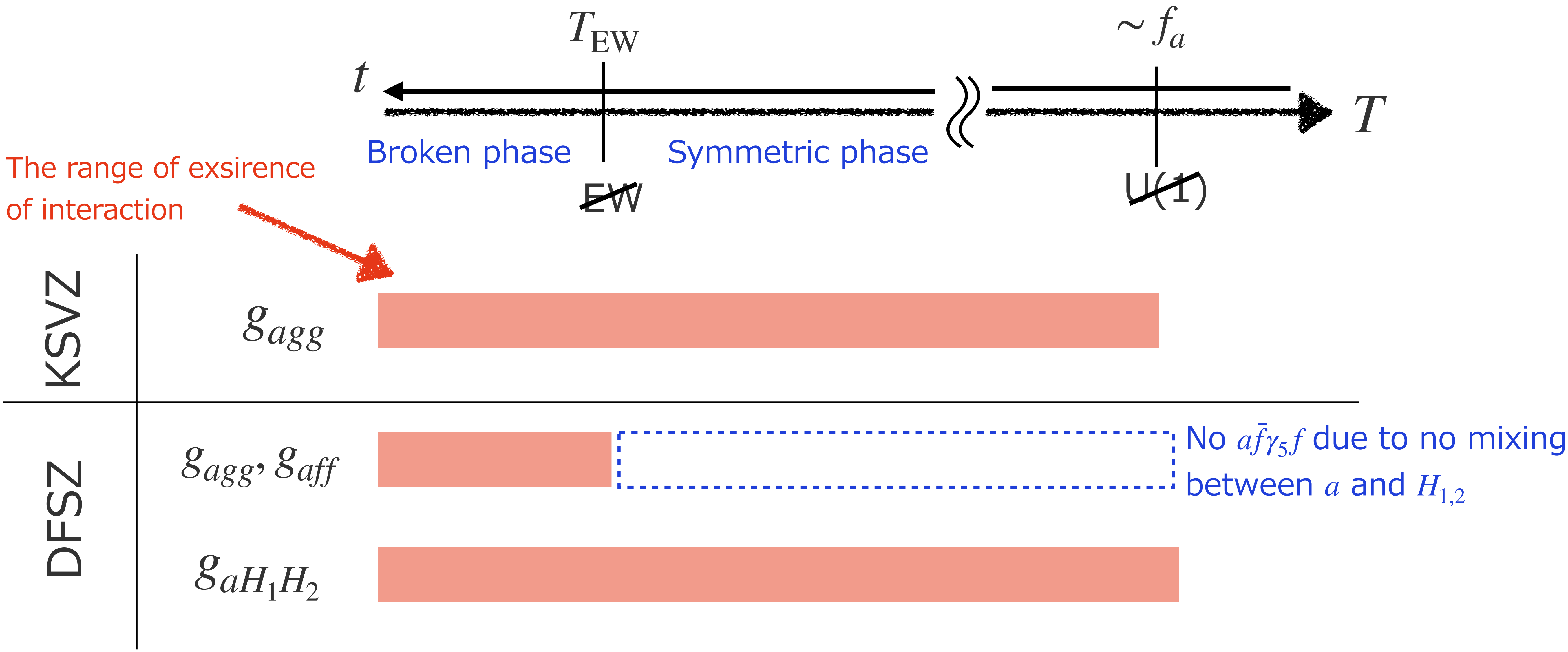
Thermal productions in KSVZ/DSFZ type models



- For DFSZ type-model, axion is mainly produced from Higgs in sym. phase.
- Renormalizalbe int. generates IR dominant contributions for a production.

→ Axion production from heavy Higgs is important.

Thermal productions in KSVZ/DSFZ type models



$T_{\rm EW}$ $\sim f_a$

t T

Broken phase

Symmetric phase

~~EW~~

~~U(1)~~

The range of exsirence of interaction

KSVZ

g_{agg}

DFSZ

g_{agg}, g_{aff}

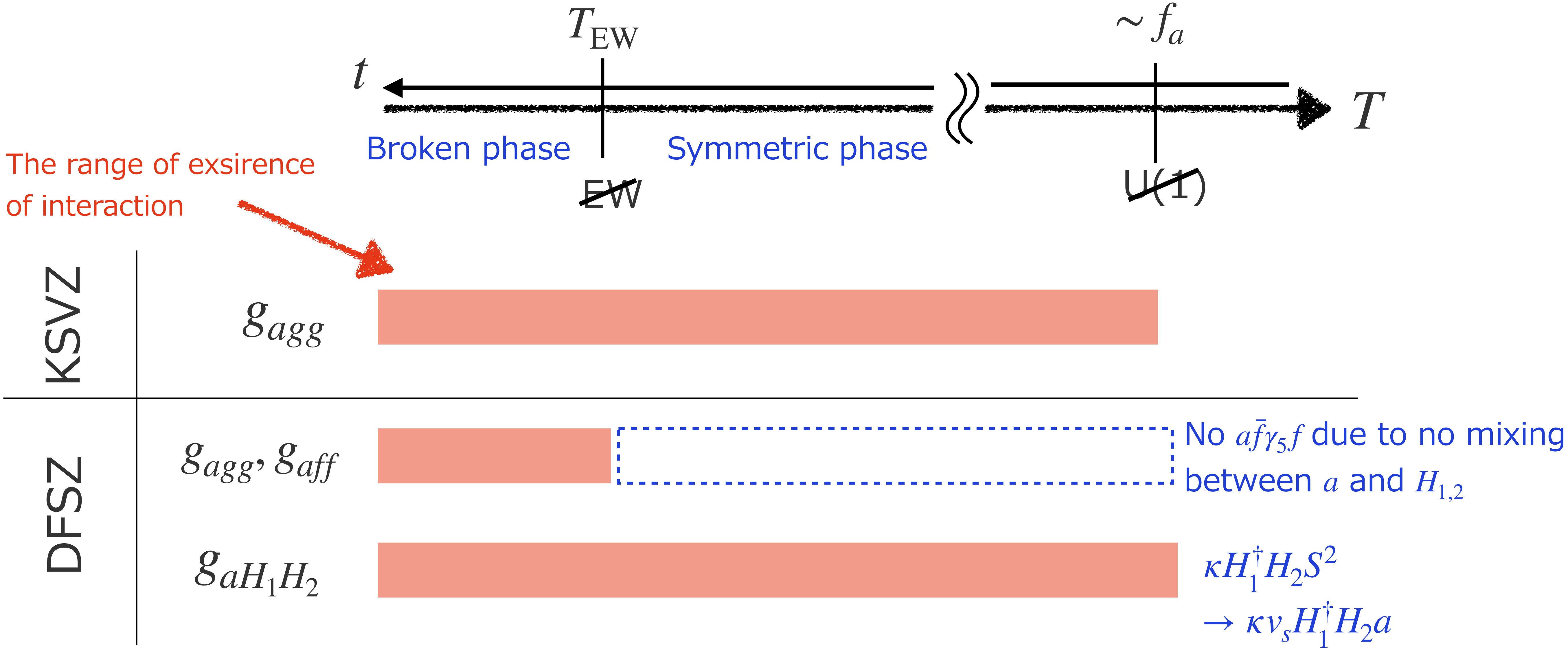
No $a\bar{f}\gamma_5 f$ due to no mixing between a and $H_{1,2}$

$g_{aH_1H_2}$

- For DFSZ type-model, axion is mainly produced from Higgs in sym. phase.
- Renormalizalbe int. generates IR dominant contributions for a production.

→ Axion production from heavy Higgs is important.

Thermal productions in KSVZ/DSFZ type models



The range of exsirence of interaction

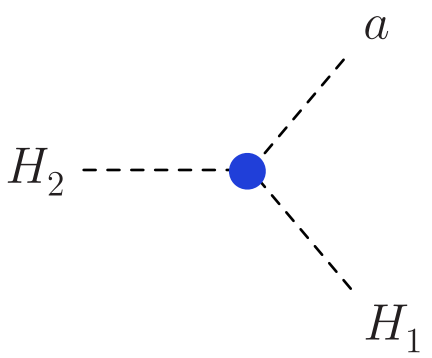
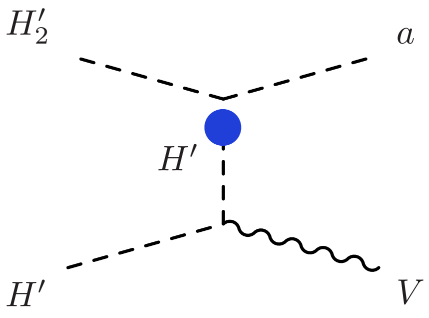
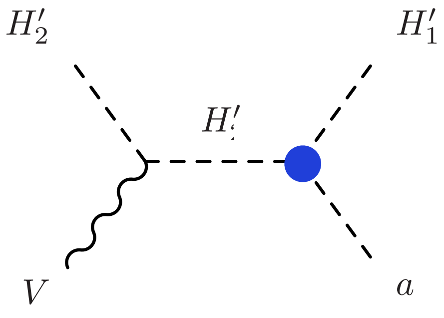
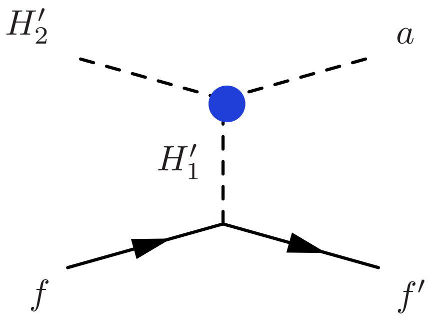
No $a\bar{f}\gamma_5 f$ due to no mixing between a and $H_{1,2}$

$\kappa H_1^\dagger H_2 S^2$
$\to \kappa v_s H_1^\dagger H_2 a$

- For DFSZ type-model, axion is mainly produced from Higgs in sym. phase.
- Renormalizalbe int. generates IR dominant contributions for a production.

→ Axion production from heavy Higgs is important.

Production processsces from heavy Higgs

Decay	
Scattering	  

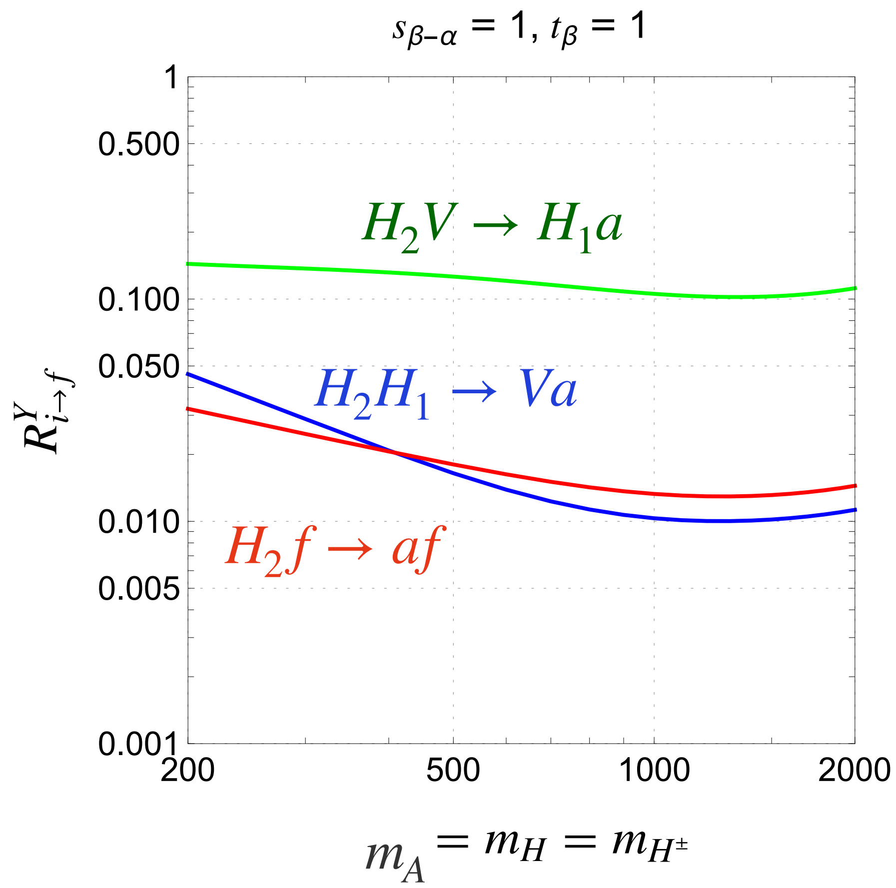
$$\mathscr{L} \ni \frac{m_A}{v_S} s_{2\beta} a H_2 H_1$$

β : Higgs mixing angle

$(H_1, H_2) = (h, A),\ (G^0, H)$

$(G^\pm, H^\pm)$

[Double a production is suppressed by $(m_A/v_S)^2$.]



$$R^Y_{H_2' X_1 \to X_2 a} \equiv \frac{Y_{H_2' X_1 \to X_2 a}}{Y_{H_2' \to H_1' a}}$$

- $Y^a_{\rm decay} \sim 10 Y^a_{\rm scattering}$

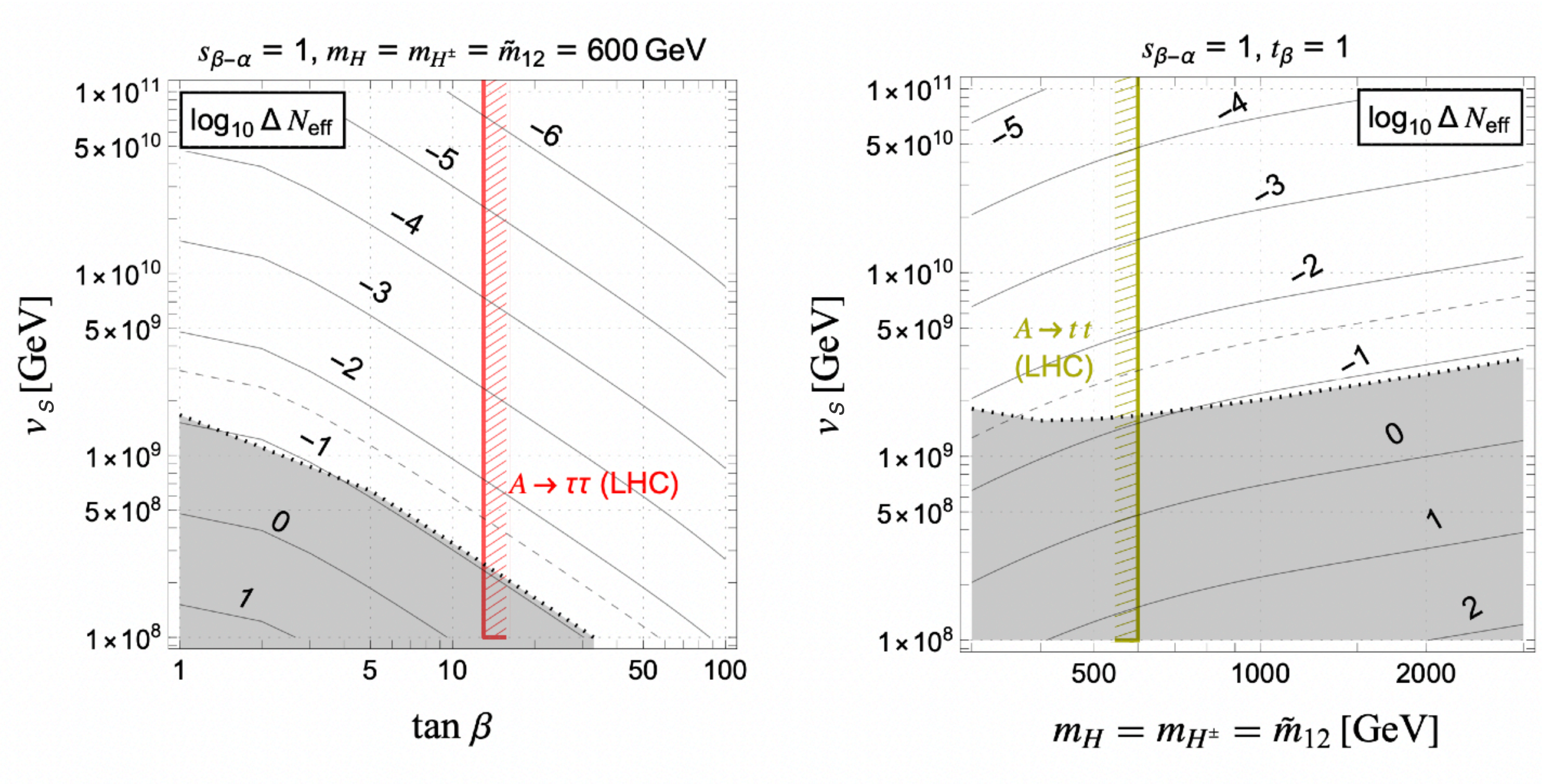
- Heavy Higgs boson decays are the main channels for the axion productions.

Axion production from heavy Higgs decays

$$\boxed{m_a \lesssim 0.1\mathrm{eV}}$$

$$\Delta N_{\rm eff} = \left.\frac{\rho_a}{\rho_\nu^{(1)}}\right|_{\rm MeV} \sim \mathcal{O}(1) * Y_a$$

[KS, F. Takahashi]



$$Y_a^D \simeq 4\frac{45 m_{\rm pl}}{1.66\cdot 4\pi^4 g_*^{3/2}}\frac{\Gamma_{H\to aG^0}}{m_A^2}\int_{x_{\rm min.}}^{x_{\rm max.}} x^3 K_1(x)\, dx\ , \quad \Gamma(H\to aG^0) \simeq \frac{1}{16\pi}\frac{m_A^3}{v_a^2}s_{2\beta}^2$$

- $\Delta N_{\rm eff}$ can be $\mathcal{O}(0.01)$ at $v_s \sim \mathcal{O}(10^9)$GeV.

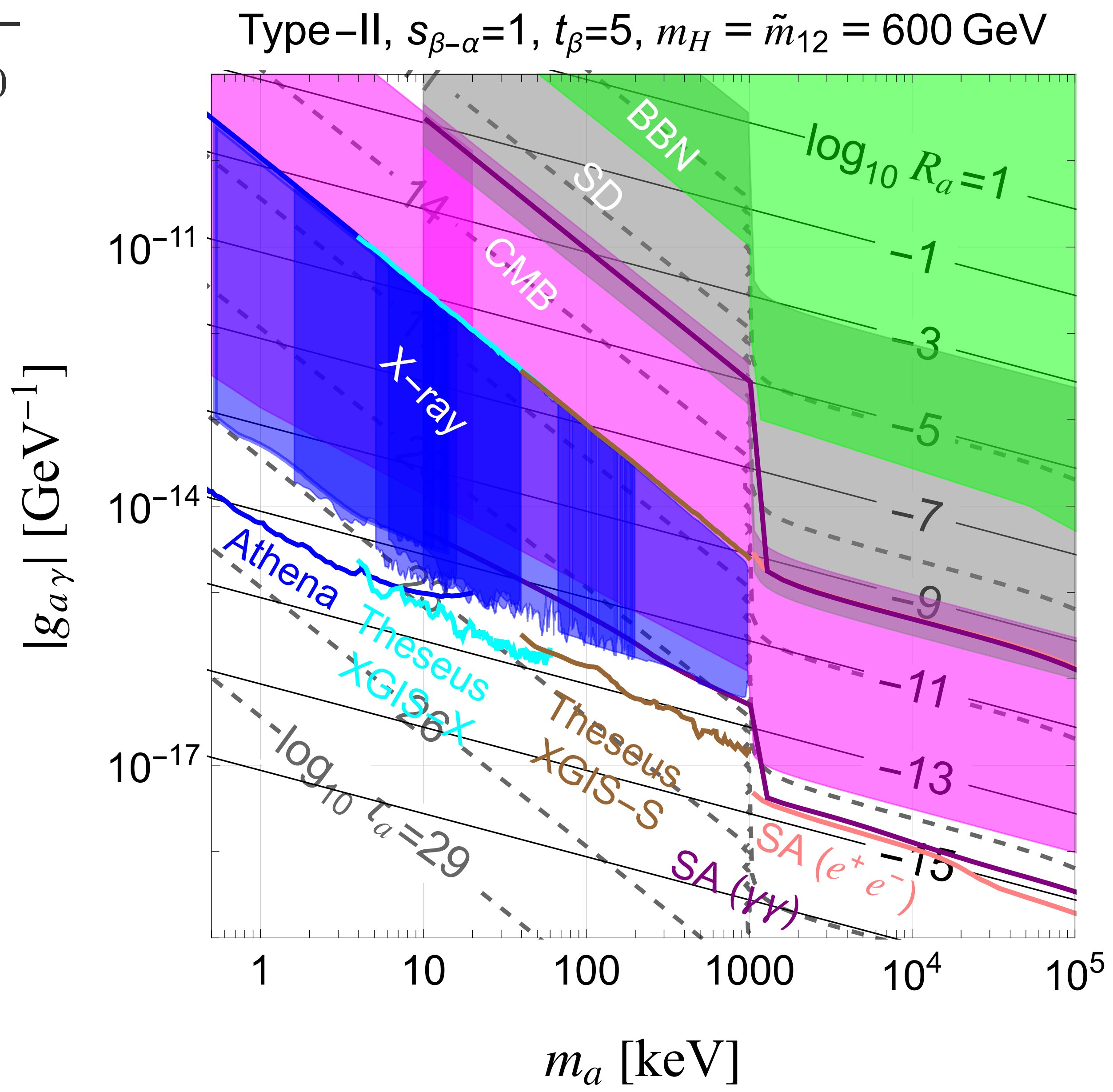
→ Axion production can be

Cosmological bounds for the keV scale axion

$$\boxed{1\mathrm{keV} \lesssim m_a \lesssim 0.1\mathrm{GeV}}$$

$$R_a = \frac{\rho_{\mathrm{a}}^{\tau_a \to \infty}}{\rho_{\mathrm{DM},0}}$$

[KS, F. Takahashi, Preliminary]



- Deacying axion is constrained by the X-ray and CMB, etc.

- The two bound constrains $g_{a\gamma}$ and R_a.

(X-ray): $R_a \lesssim 10^{-12}$

(CMB): $R_a \lesssim 10^{-14}$

- More heaviear mass of extra Higgs make the bound strong.

→ If axion is produced from heavy Higgs boson, comosorogical bounds depends on the properties of the heavy Higgs bosons.

Cosmological bounds for the keV scale axion

$\boxed{1\text{keV} \lesssim m_a \lesssim 0.1\text{GeV}}$

$$R_a = \frac{\rho_a^{\tau_a \to \infty}}{\rho_{\text{DM},0}}$$

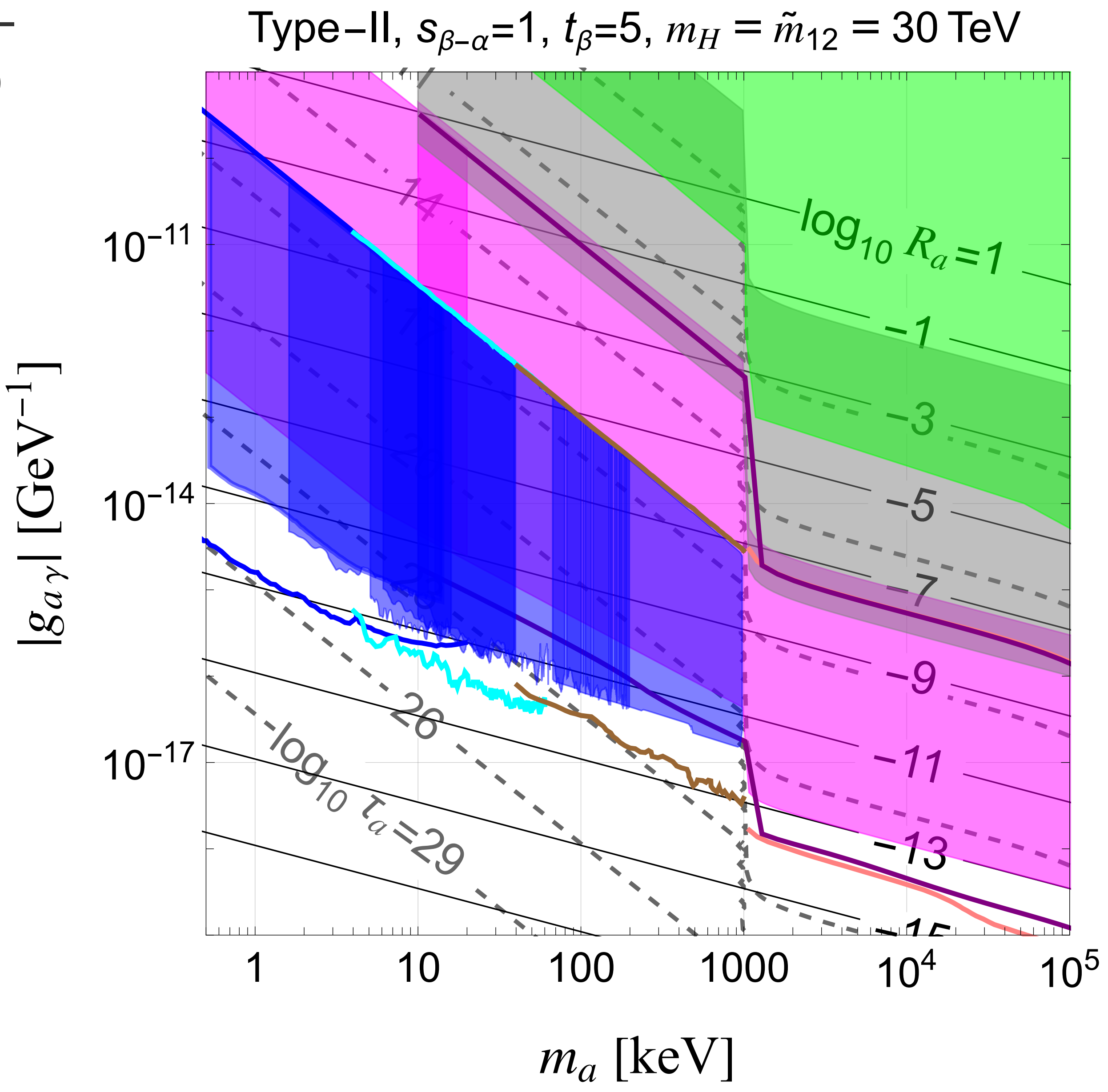
- Deacying axion is constrained by the X-ray and CMB, etc.

- The two bound constrains $g_{a\gamma}$ and R_a.

(X-ray): $R_a \lesssim 10^{-12}$

(CMB): $R_a \lesssim 10^{-14}$

- More heaviear mass of extra Higgs make the bound strong.



[KS, F. Takahashi, Preliminary]

→ If axion is produced from heavy Higgs boson, comosorogical bounds depends on the properties of the heavy Higgs bosons.

Summary

- We have discussed axion thermal productions from the heavy Higgs bosons in DFSZ type axioin models.

- We find that the amount of axion produced from the heavy Higgs decays is lager than that of heavy Higgs scatterings.

- the axion energy density depends on the model parameters of the Higgs sector. The Higgs sector can be explored by the cosmorogical observations (Xray, CMB, N_{eff} etc.).