[arXiv:2411.06457]

付加的ヒッグスボソンによるアクシオンの熱的生成

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Introduction

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

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

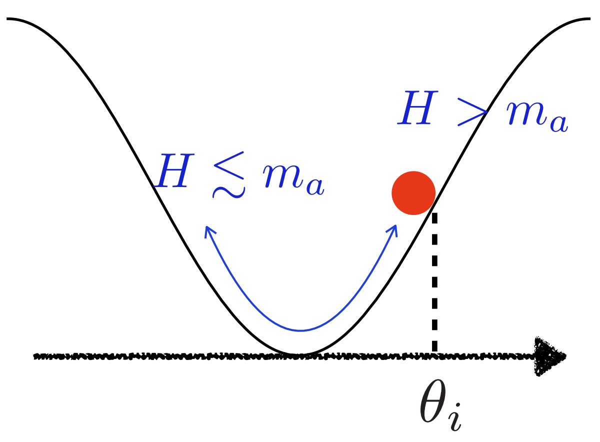
- Axions can solve DM and strong CP problems.

- 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 $\cancel{U(1)}$.
- It starts to oscillate when $m_a \gtrsim H$.



Thermal productions

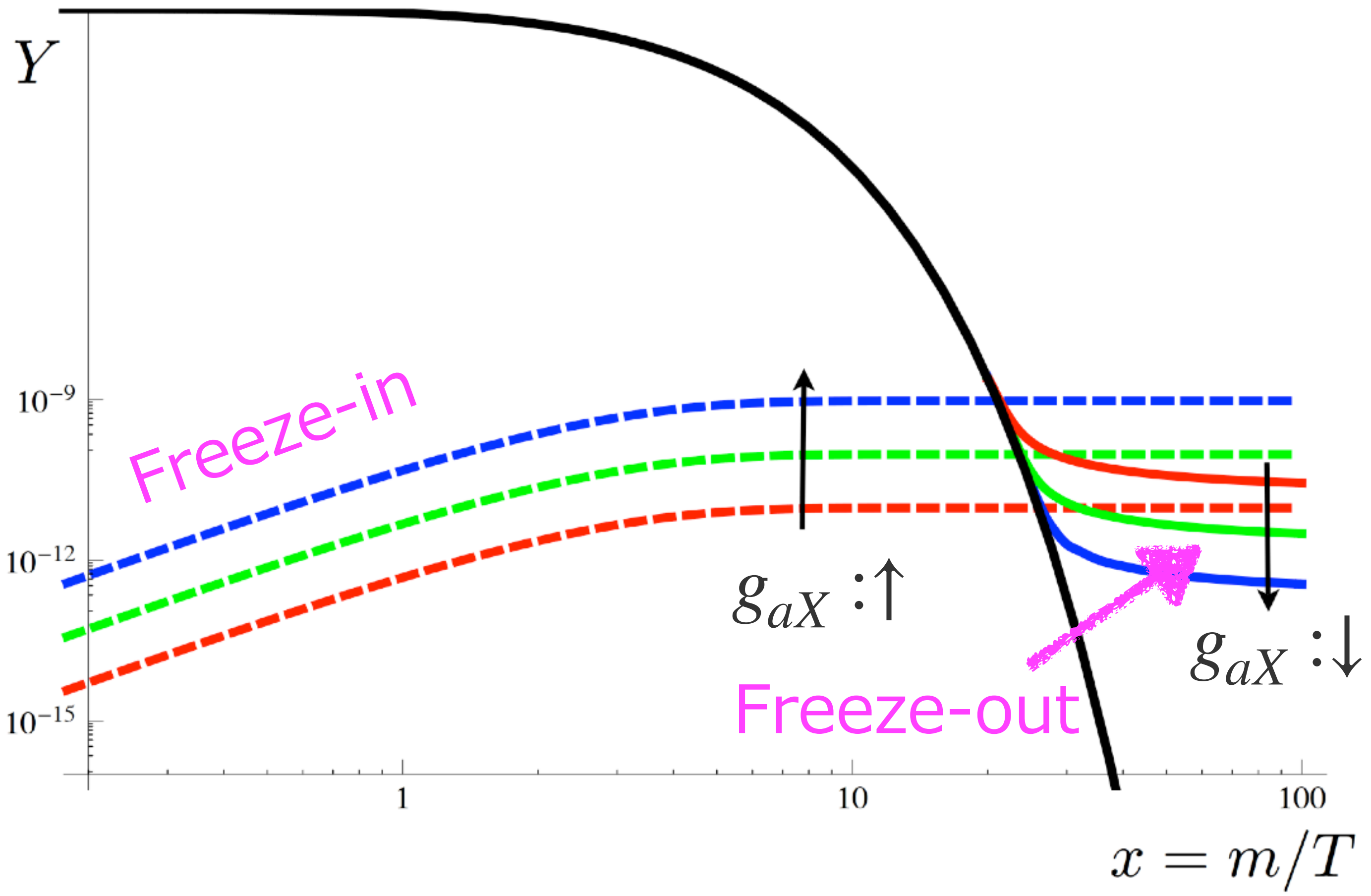
- Axion is thermalized (i.e., small f_a).
  - It is in thermal equilibrium.
  - It decouples from thermal plasma at a certain temperature.
- Axion is not thermalized (i.e., large f_a). → Freeze-in mechanism

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

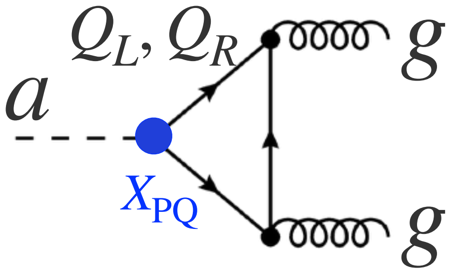
[Original model: J. E. Kim (1979); M. A. Shifman, A. I. Vainshtein, V. I. Zakharov (1980)]

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

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)]

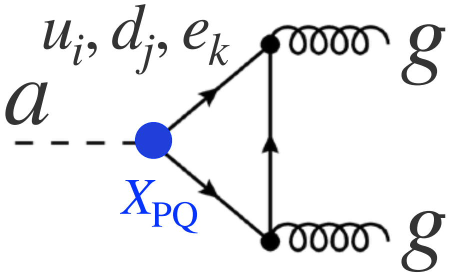
$$\boxed{\mathscr{L}_{\mathrm{DFSZ}} \ni \kappa H_1^\dagger H_2 S^2 + y_u \bar{Q} H_2^c u_R + y_d \bar{Q} H_1 d_R + \mathrm{h.c.}}$$

H_1 : SM Higgs doublet

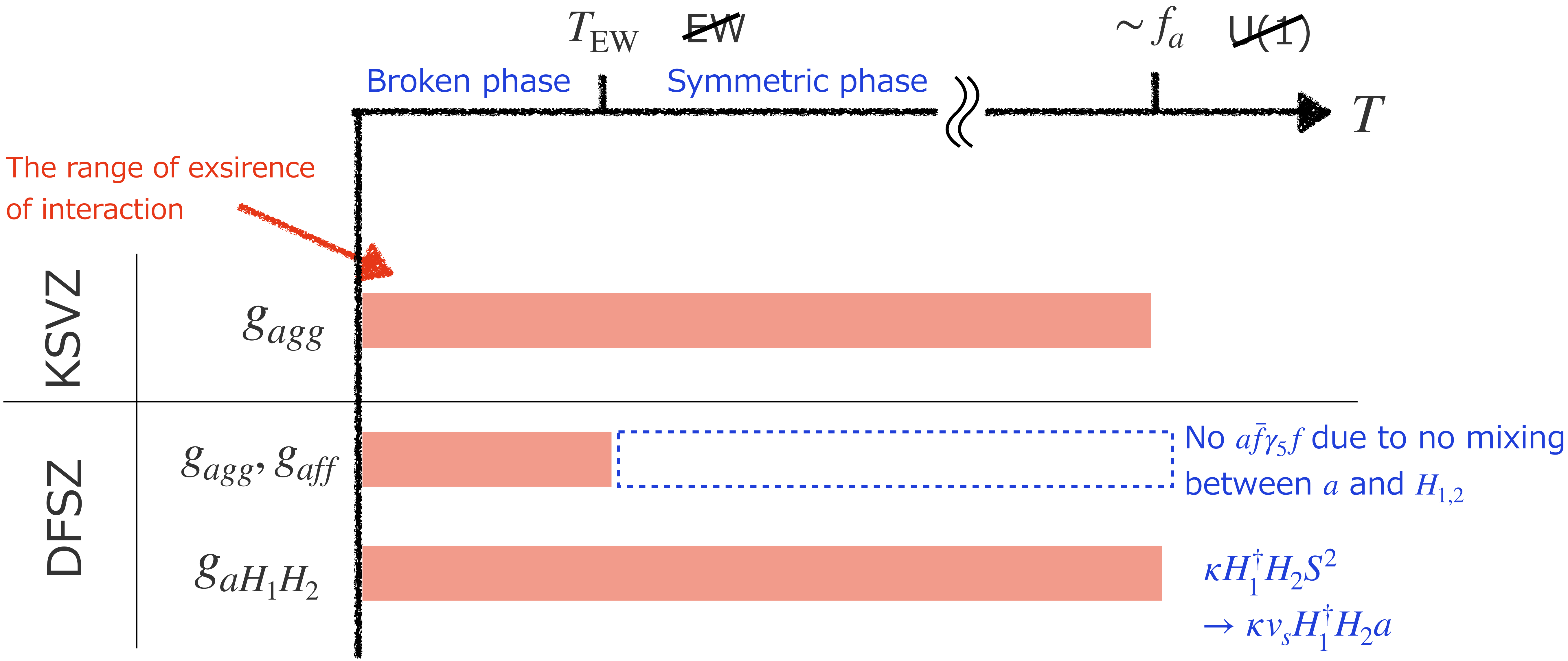
H_2 : extra Higgs doublet ∋ $H, A, H^\pm$

S:extra singlet scalar

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



Thermal productions in KSVZ/DSFZ type models



T_{EW} $\cancel{\mathrm{EW}}$

$\sim f_a$ $\cancel{U(1)}$

Broken phase

Symmetric phase

T

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 $H_{1,2}$

$g_{aH_1H_2}$

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

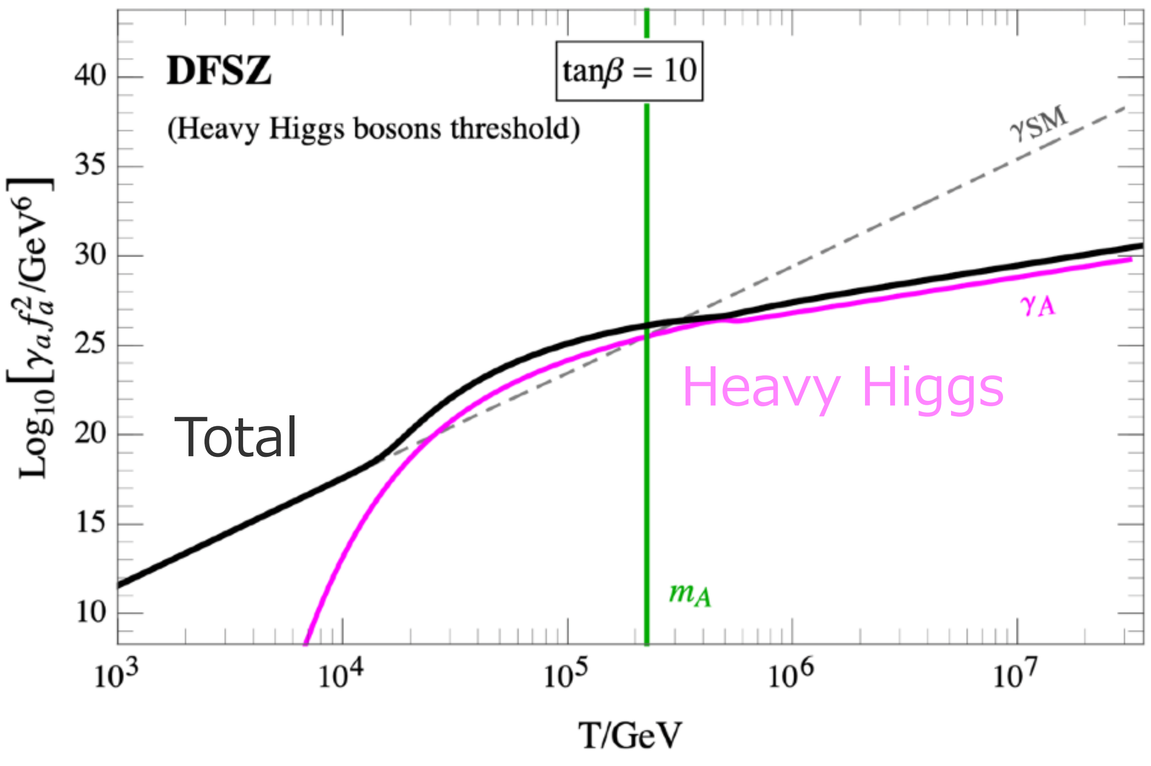
- For DFSZ type-model, axion is mainly produced from Higgs in sym. phase.
- Renormalizalbe int. generates IR dominant contributions for a production.

→ Axion production from heavy Higgs is important.

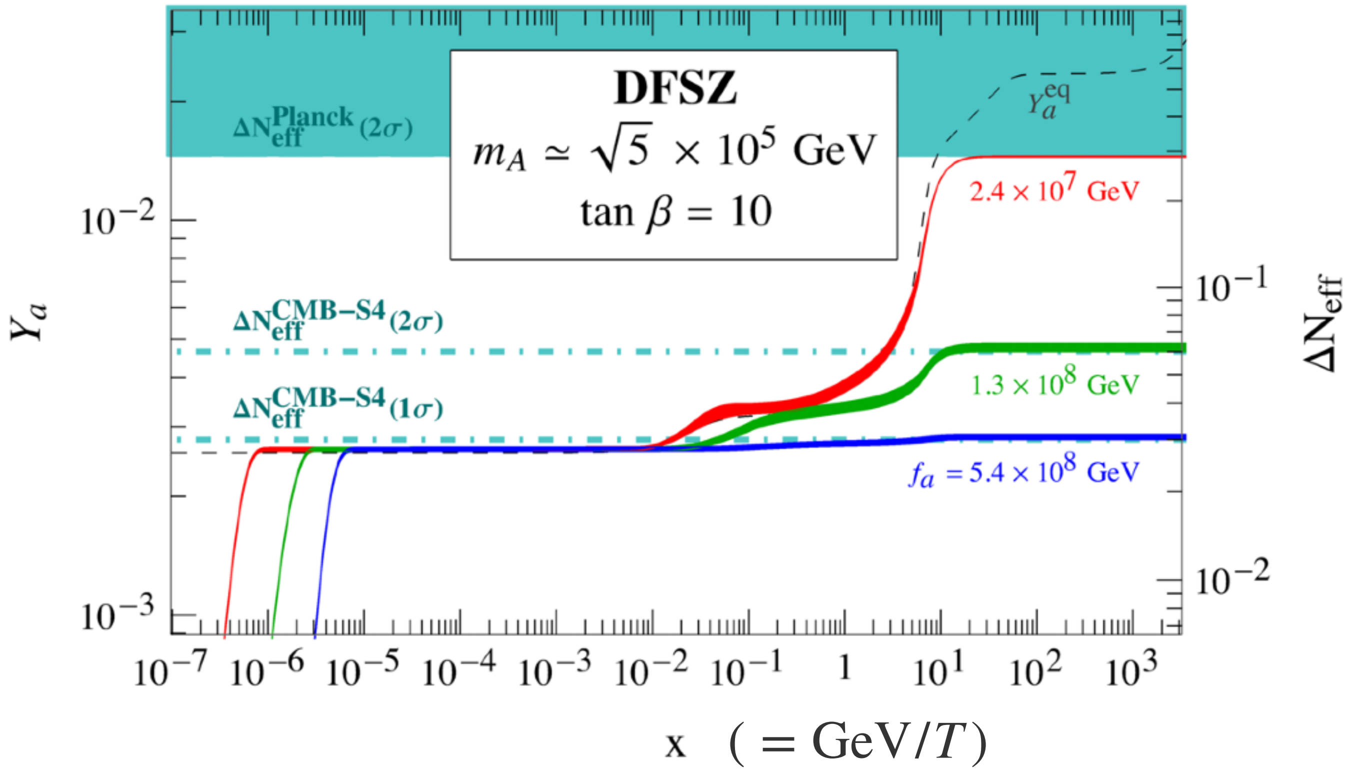
Thermal axion productions in DFSZ QCD axion model

[D'Eramo,Hajkarim,Yun,JCAP 10 (2021) 045]

Production rate γ_a



Comving number density $Y_a = n_a/s$



- Heavy Higgs contributions overcomes SM conttibutions when $T \sim m_A$.
- Number density of a is evaluated in the case that a is thermalized.

Our works

Previous works:

- The previous literature does not include contribution from **decays of heavy Higgs bosons**

  SM particle scatteings, heavy Higgs boson scattegings

- Axion is assumed to be thermalized.

Our works:

- We newly calcurate contributions from **decays of heavy Higgs bosons** for axion productions.

- We clarify that it is dominant contribution in **the axion freeze-in production**.

Axion freeze-in production from heavy Higgs

Set up : DFSZ type-axion model

- Higgs potential:

$$\begin{aligned} V =\ & m_{11}^2(\phi_1^\dagger\phi_1) + m_{22}^2(\phi_2^\dagger\phi_2) - (m_{12}^2\phi_1^\dagger\phi_2 + \text{h.c.}) \\ & + \lambda_1(\phi_1^\dagger\phi_1)^2 + \lambda_2(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) \\ & - \left[m_{12}^2\phi_1^\dagger\phi_2\left(2i\frac{\tilde{a}}{v_s} - 2\frac{\tilde{a}^2}{v_s^2} + \dots\right) + \text{h.c.}\right], \end{aligned}$$

Two Higgs doublet models

Axion- Higgs interaction

$$\Phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix}\sqrt{2}w_1^+ \\ v_1 + h_1 + iz_1\end{pmatrix}, \qquad \Phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix}\sqrt{2}w_2^+ \\ v_2 + h_2 + iz_2\end{pmatrix}, \quad \Phi_\text{s} = (v_\text{S} + \rho)e^{i\frac{\tilde{a}}{v_\text{S}}}$$

Integrated out. $m_\rho \sim f_a$

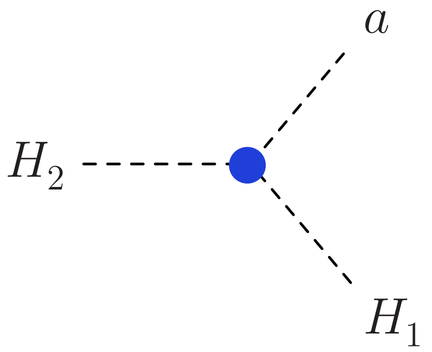
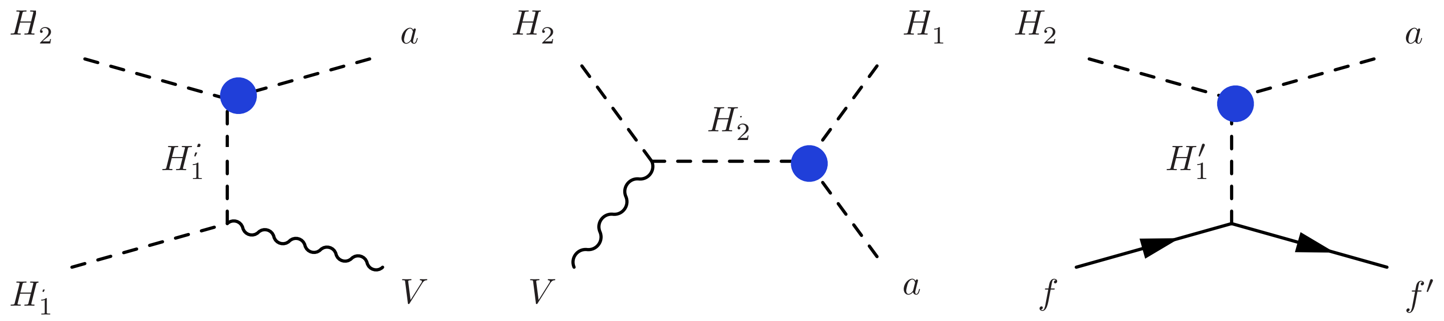
- Physical states:

H, *A*, H^+, H^- :additional Higgs bosons, *h* : SM-like Higgs boson, *a*:axion

- Assumptions for axion freeze-in productions:

  - $T_R > m_H$ ⟶ Heavy Higgs in thermal equilublium
  - $m_H > v_\text{EW}$ ⟶ Axion productions in symmetric phase

Production processsces from heavy Higgs

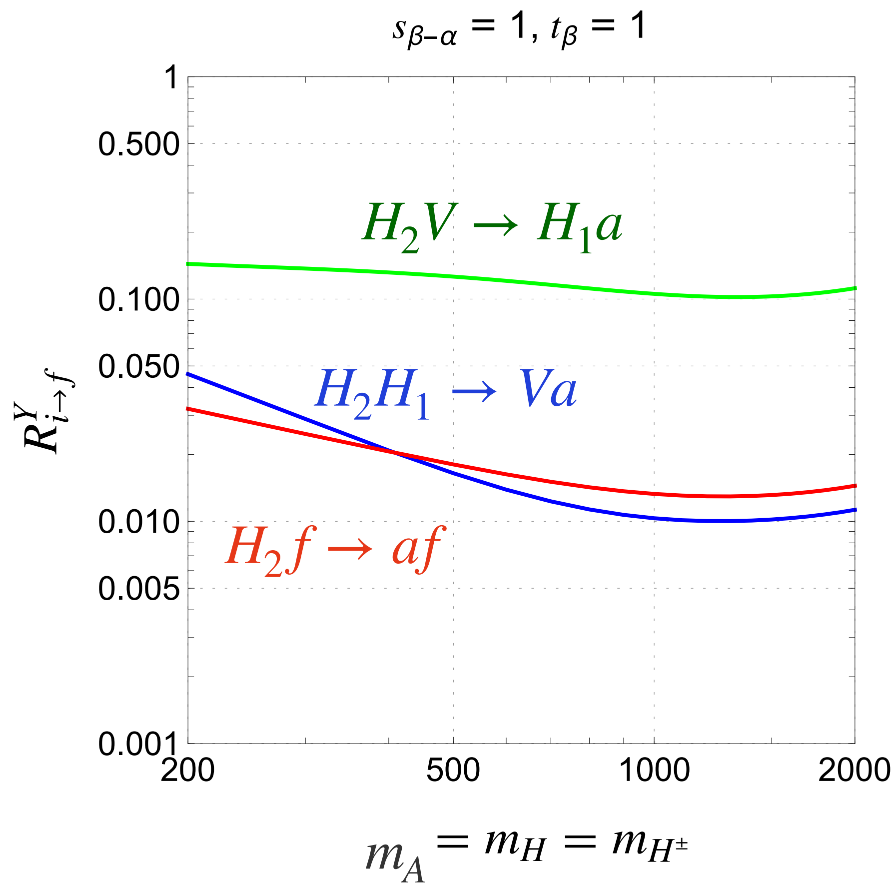
Decay	 $H_2 = H, A, H^+, H^-$ $H_1 = h, G, G^+, G^-$
Scattering	

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

β : Higgs mixing angle

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

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



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

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

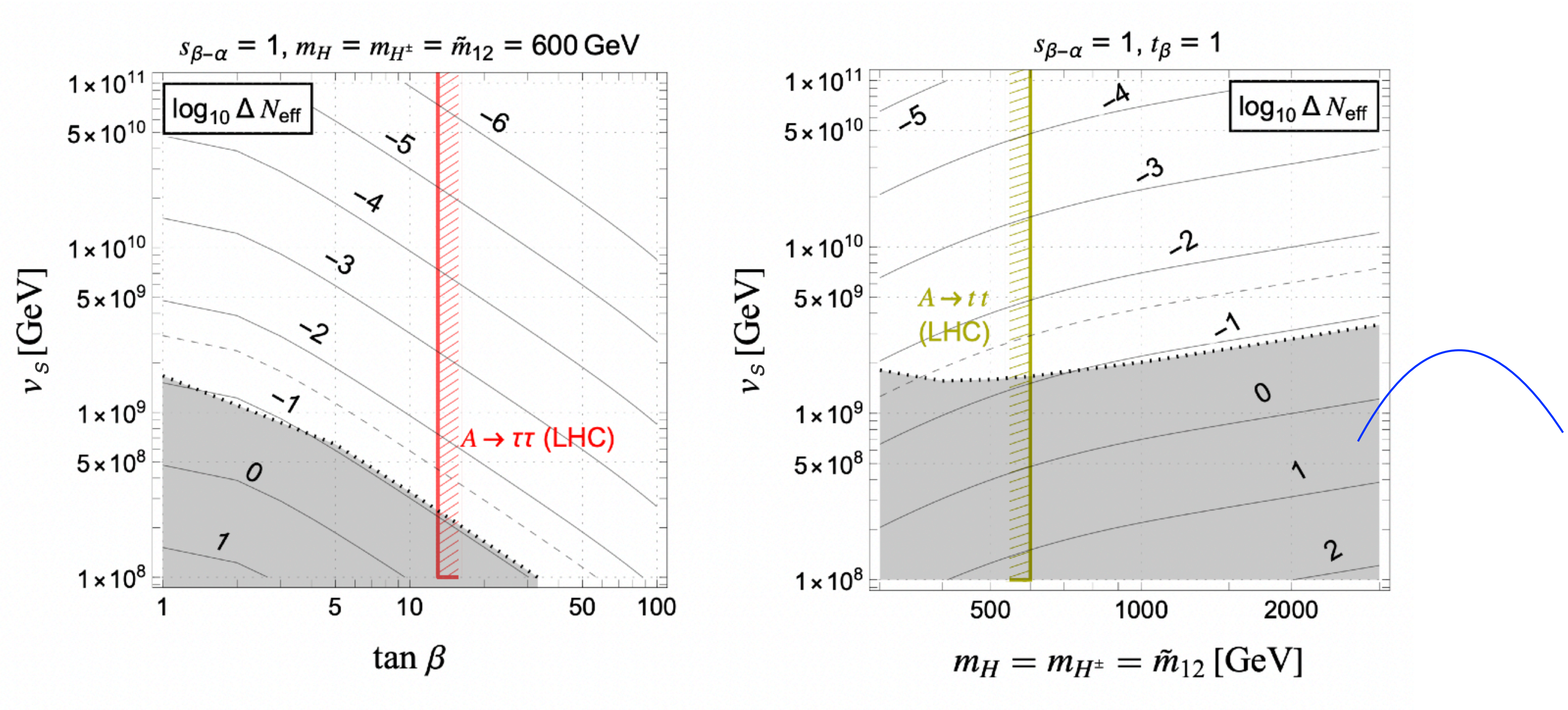
- Heavy Higgs boson decays are the main channels for the axion productions.

Axion freeze-in 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]



$$\Gamma_a \gtrsim H$$

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

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

→ Axion could be tested by future CMB mesurments.

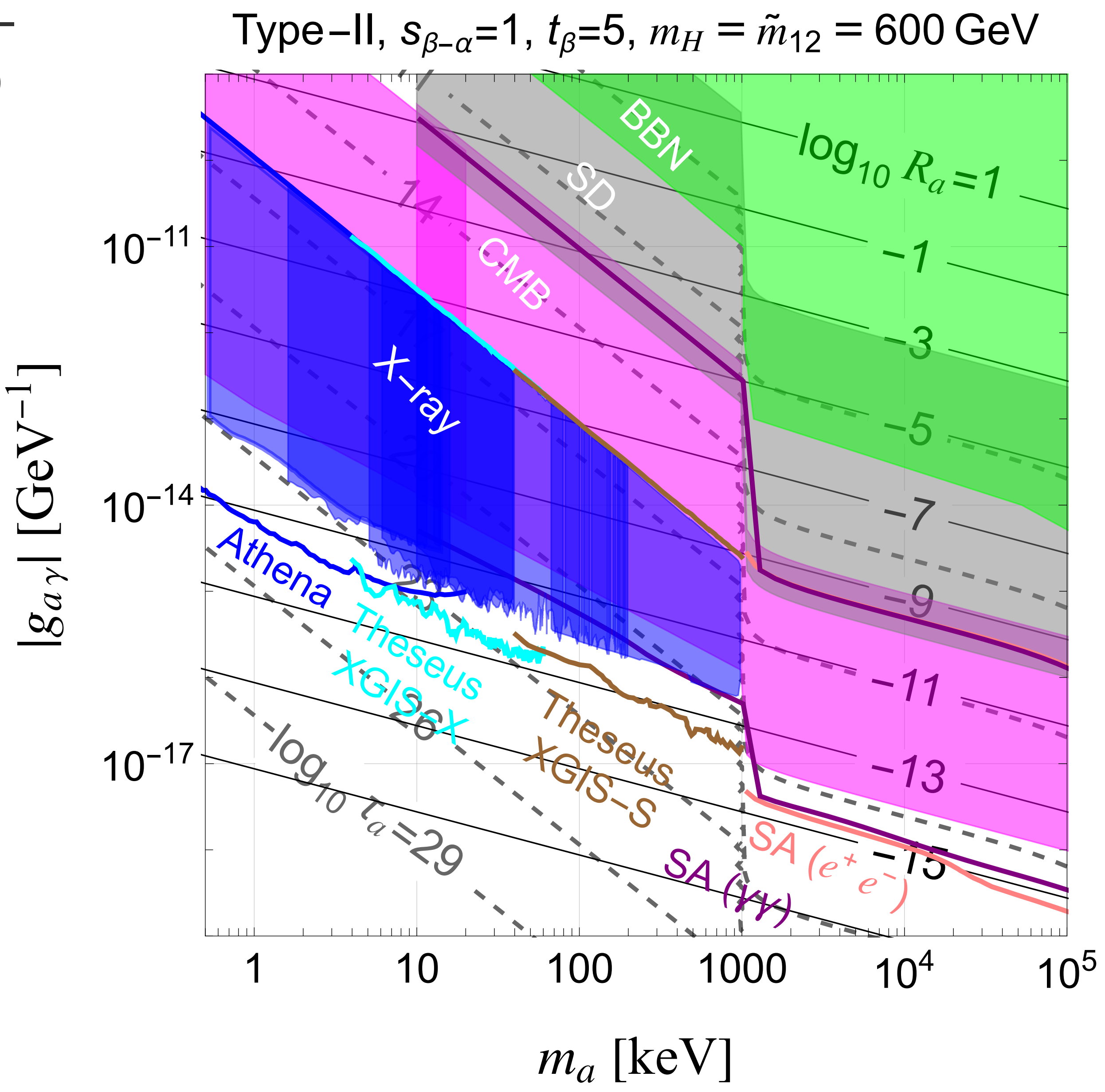
→ This gives compementary bounds with direct searches of *A*.

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.

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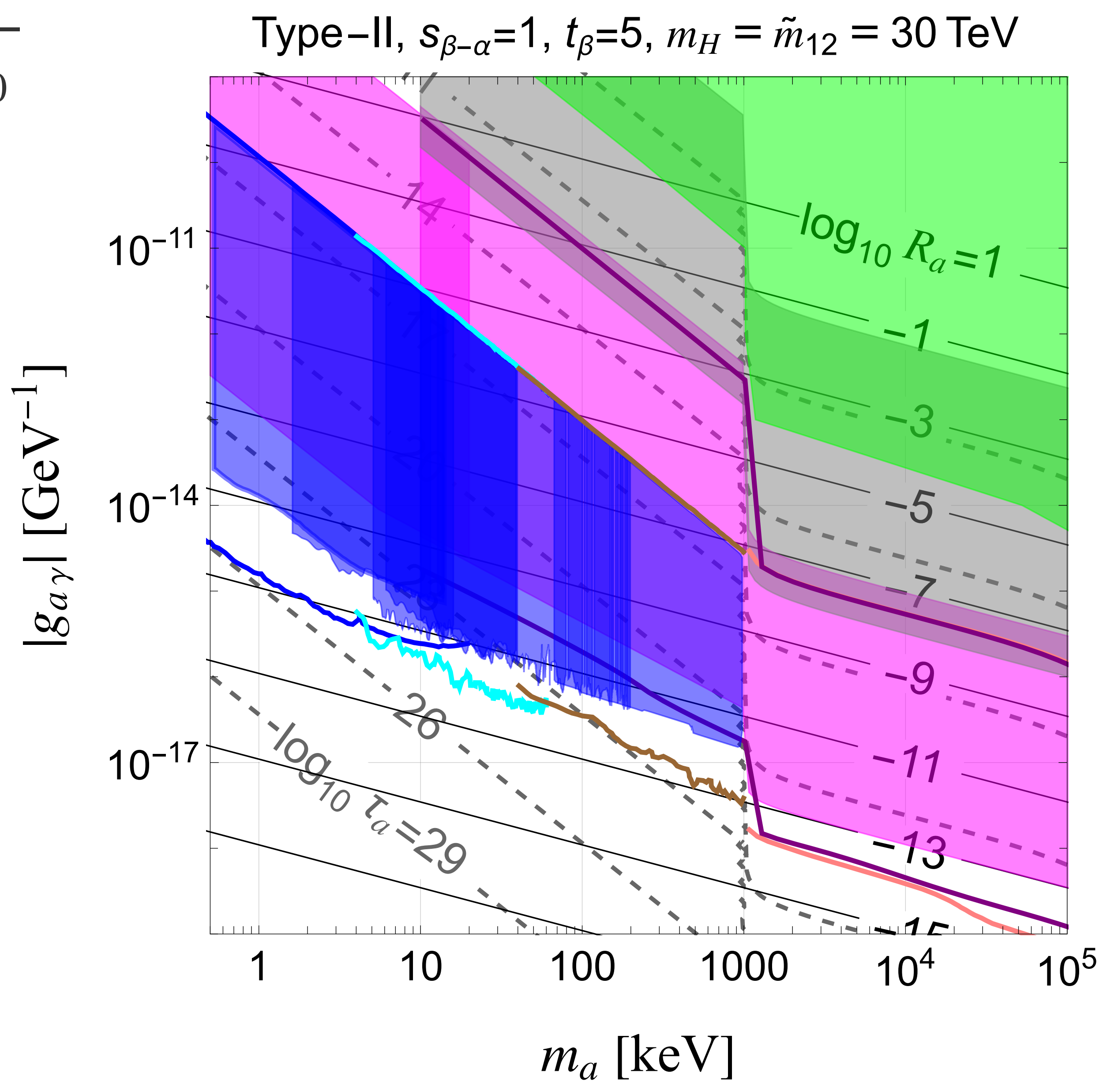

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Summary

- 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, which is overlooked in the previous literature.

- 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.).