Thermal productions of axion in DFSZ-type axion models

Kodai Sakurai (Tohoku U.)

In collaboration with

Fuminobu Takahashi (Tohoku U.)

[To be appeared in arXiv soon]

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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.

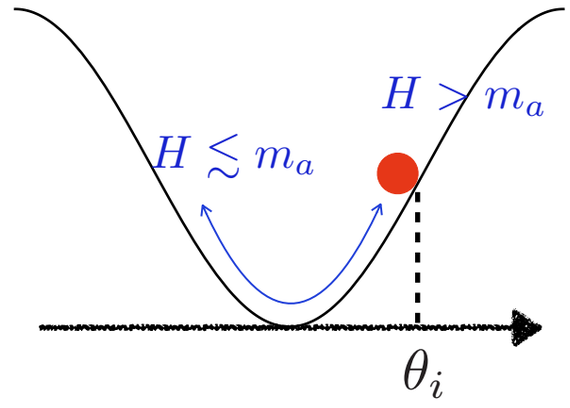
  - Mass scale, interactions

  - 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 ~~U(1)~~.



- It starts to oscillate when $m_a \gtrsim H$.

- The aboudance: $\Omega_a h^2 \sim 0.12 \left(\frac{\theta_i}{2}\right)^2 \left(\frac{m_a}{3.5\mathrm{keV}}\right)^{1/2} \left(\frac{f_a}{2\times 10^{10}\mathrm{GeV}}\right)^2$

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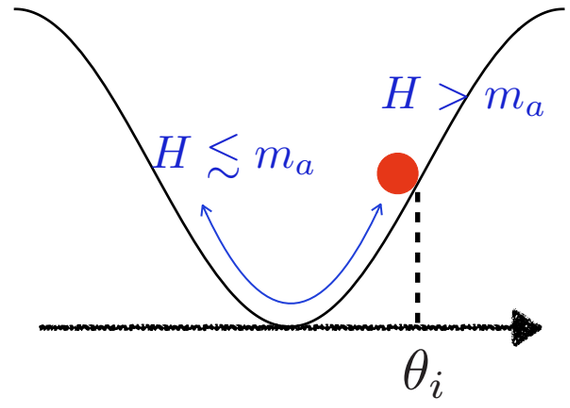

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Thermal productions

- Axion is thermalized (i.e., small f_a).
  - It is in thermal equilibrium.
  - It decouples from thermal plasma at a certain temperature.

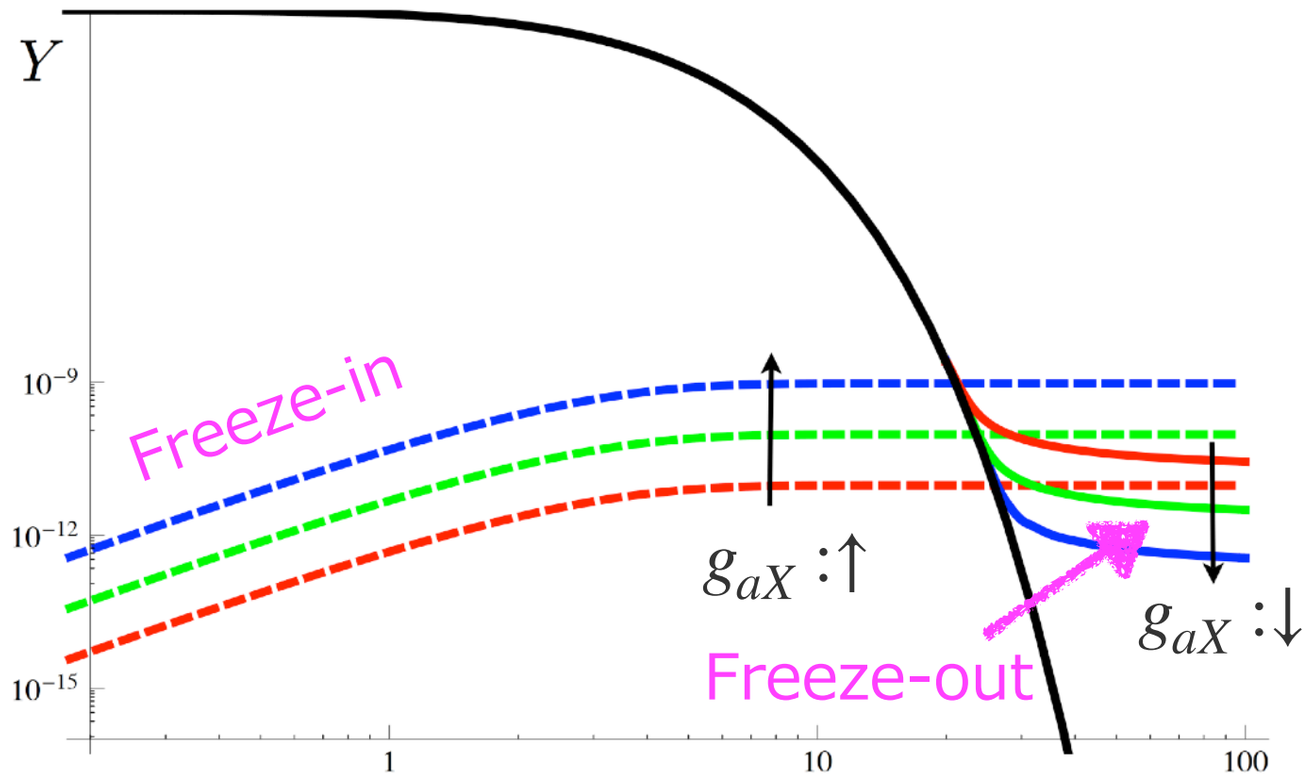
- Axion is not thermalized (i.e., large f_a). → Freeze-in mechanism

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

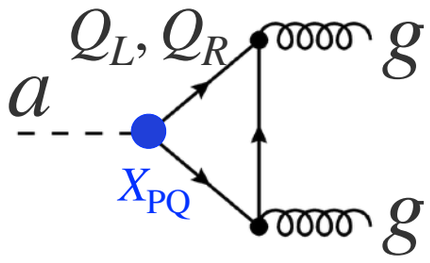
KSVZ-type model [Original model: J. E. Kim (1979); M. A. Shifman, A. I. Vainshtein, V. I. Zakharov (1980)]

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

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)]

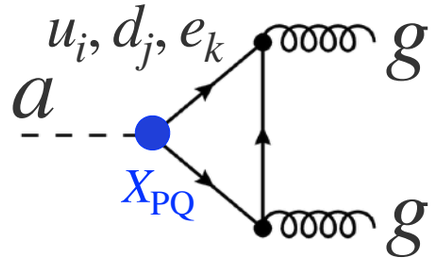
$$\mathscr{L}_{\rm DFSZ} \ni \kappa H_1^\dagger H_2 S^2 + y_u \bar{Q} H_2^c u_R + y_d \bar{Q} H_1 d_R + {\rm h.c.}$$

H_1 : SM Higgs doublet

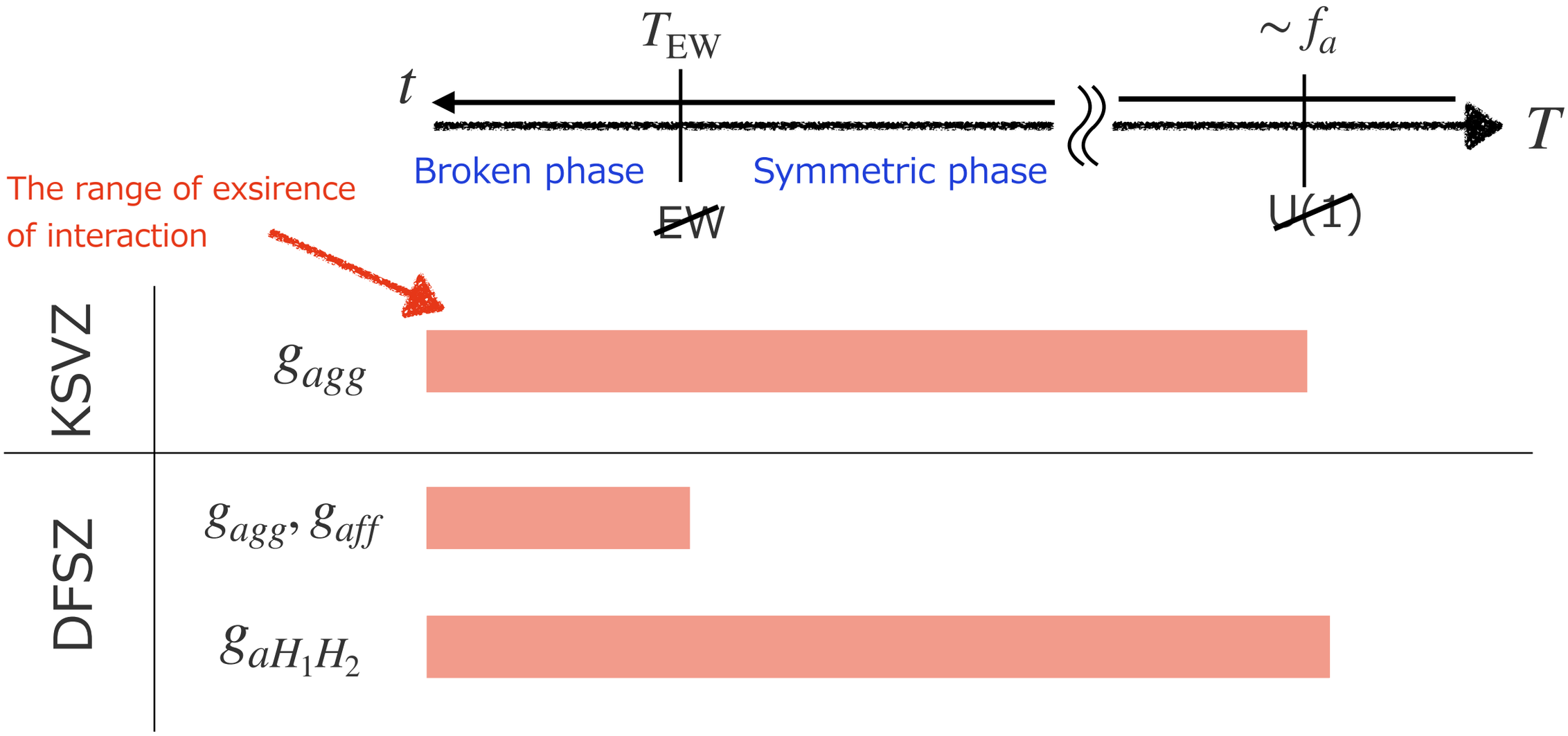
H_2 : extra Higgs doublet $\ni H, A, H^\pm$

S:extra singlet scalar

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



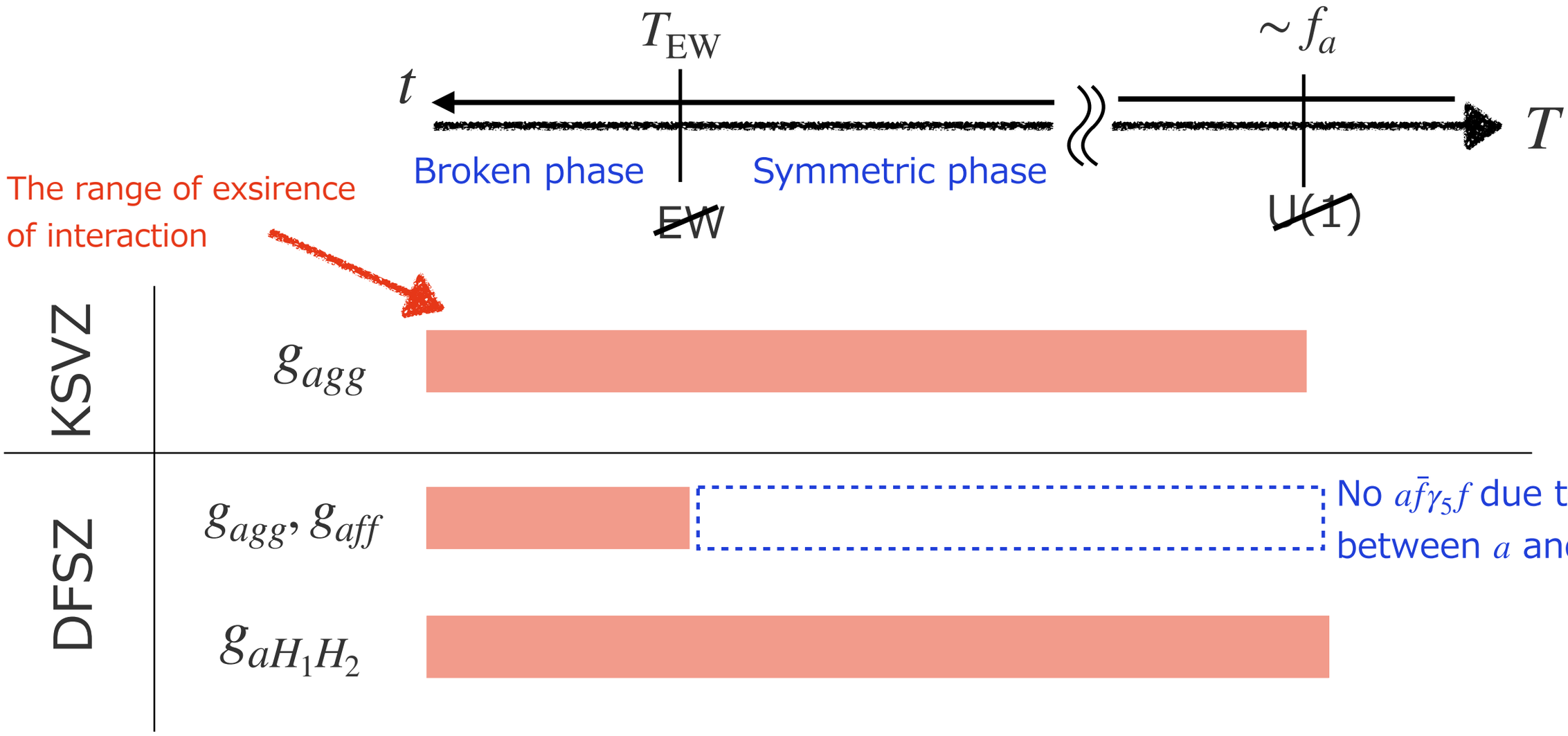
Thermal productions in KSVZ/DSFZ type models



- 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



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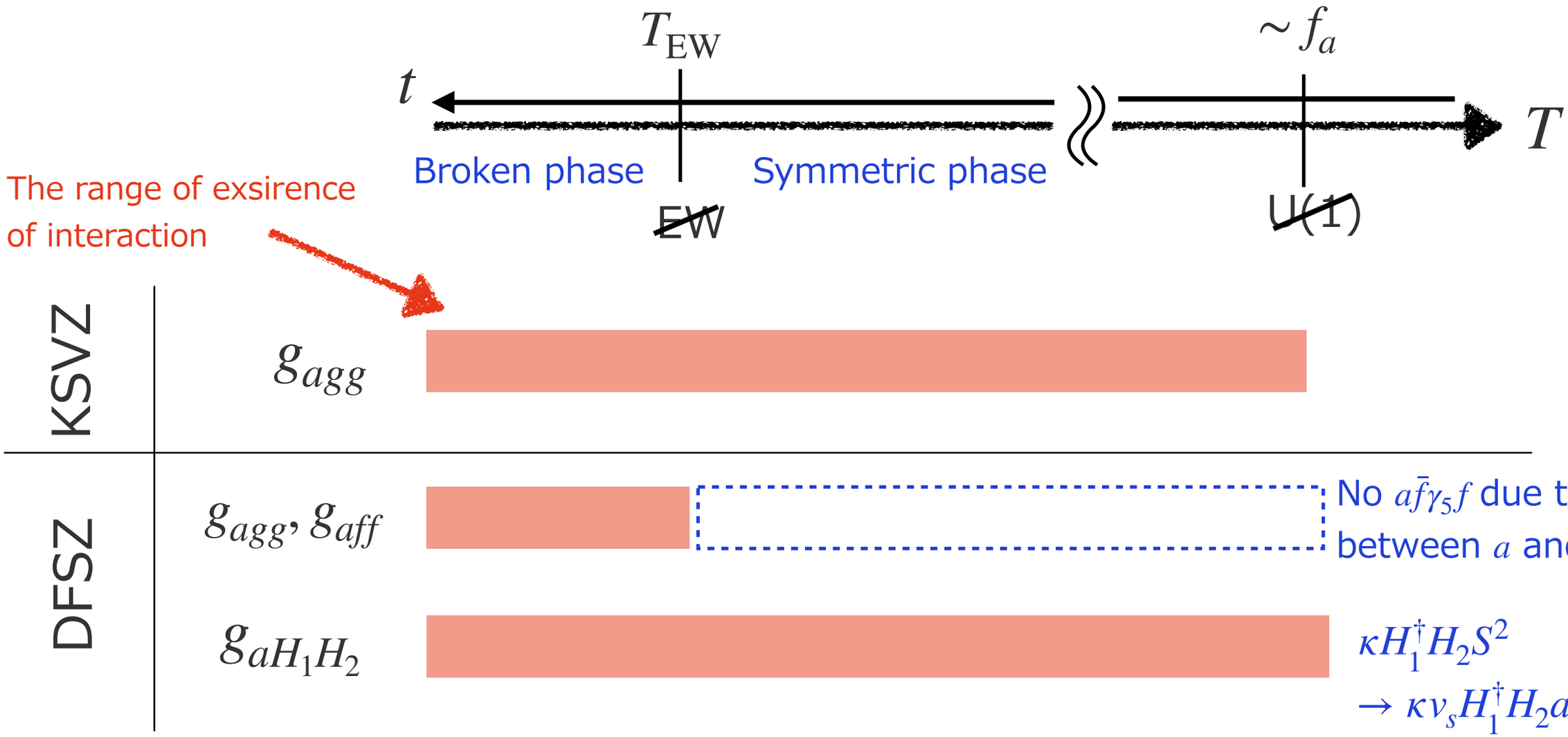

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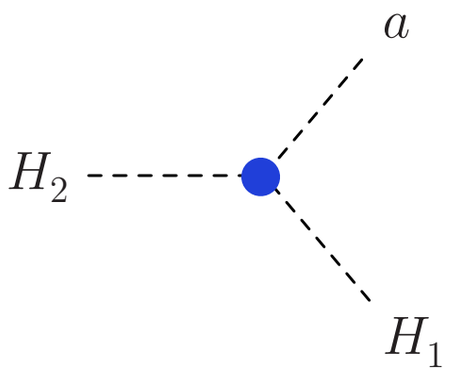
Thermal productions from heavy Higgs: set up

Assumptions

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

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

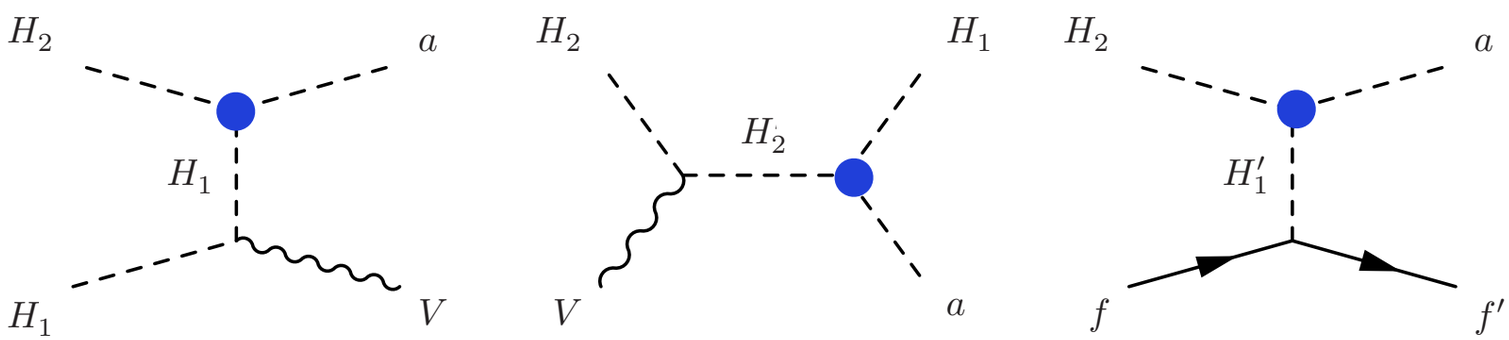
Decay:



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

β : Higgs mixing angle

Scattering:

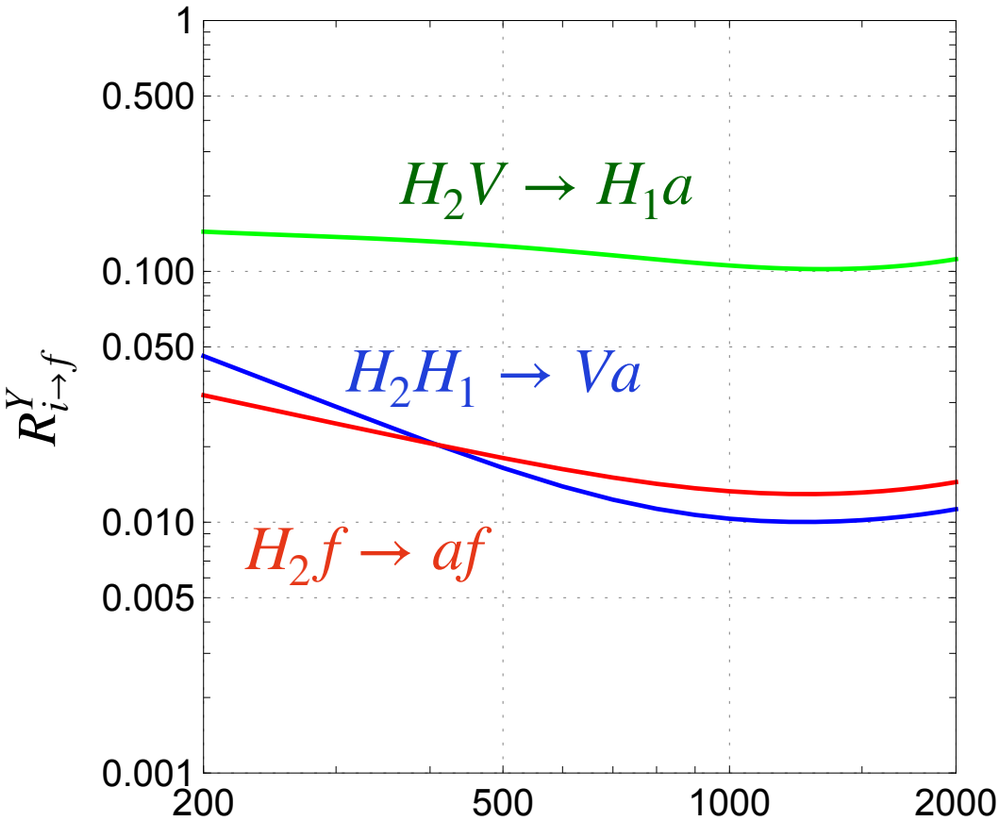


[Double a production is suppressed by $(m_A/v_S)^2$.]

Heavy Higgs decays vs scatterings

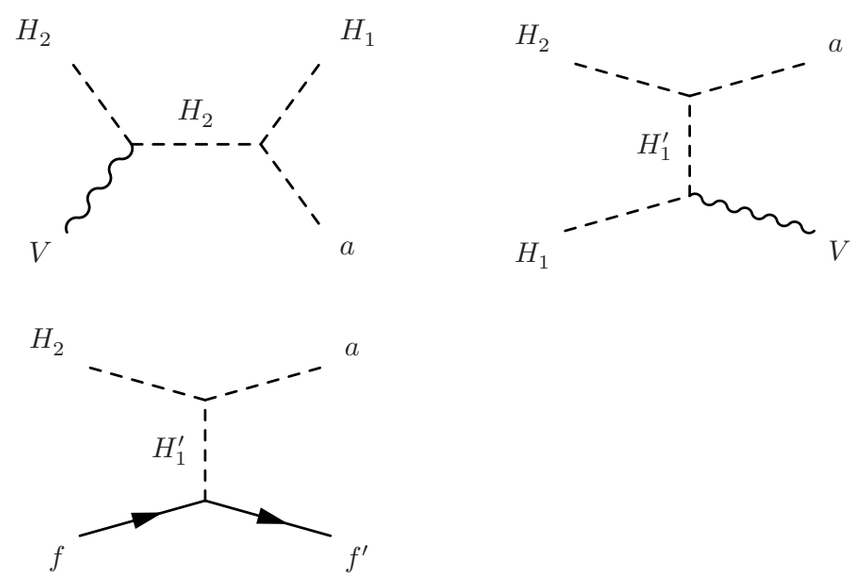
[KS, F. Takahashi, Preliminary]

$s_{\beta-\alpha} = 1,\ t_\beta = 1$



$m_A = m_H = m_{H^\pm}$

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



- $\sigma_{H_2V\to aH_1}, \sigma_{H_2H_1\to aV} \gtrsim \sigma_{H_2f\to af}$ because $H_2H_1 \to Va$ and $H_2V \to H_1a$ involve 16 channels.
- $\sigma_{H_2V\to aH_1} \gtrsim \sigma_{H_2H_1\to aV}$ because $H_2V \to H_1a$ is enhanced at $T \sim m_H$ via threshold effect.
- Heavy Higgs boson decays are the main channels for the axion productions.

Cosmological bounds for the keV scale axion

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

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

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

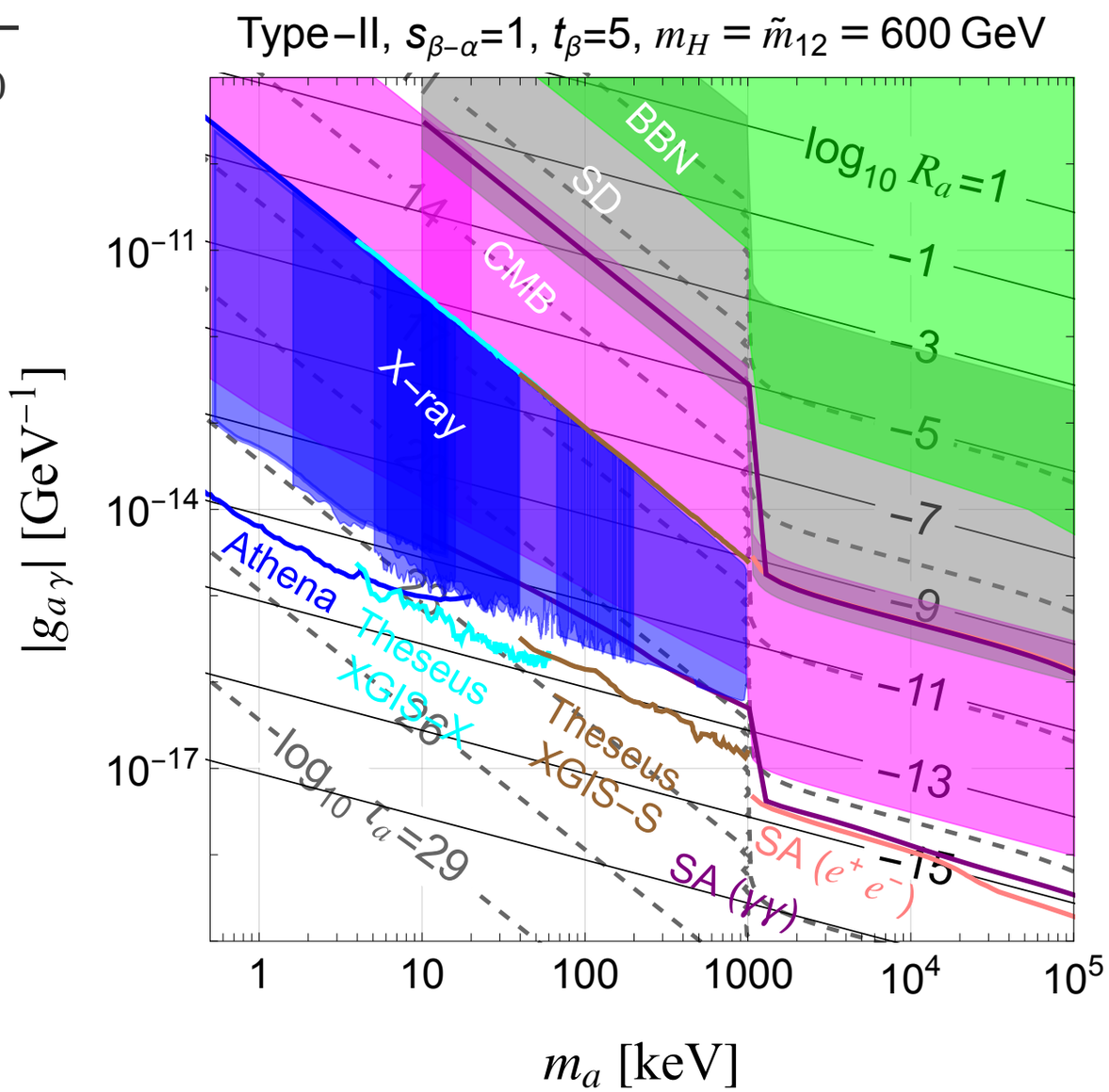
- The two bound constrains $g_{a\gamma}$ and R_a.

  (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]



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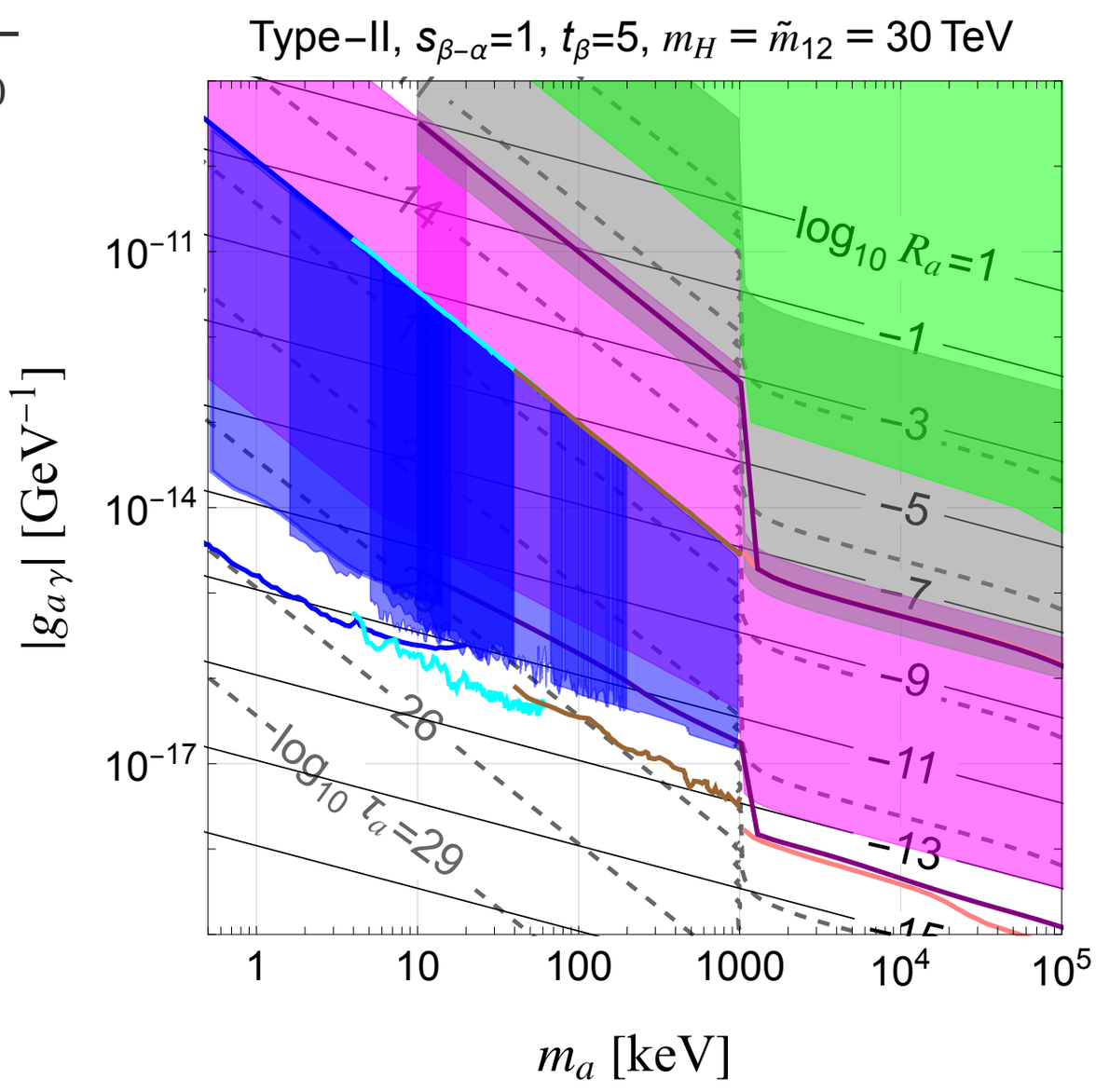

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Summary

- Production mechanisms between KSVZ model and DFSZ model are different.

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

- Larger mass of heavy Higgs increase the axion energy density. Various cosmorogical bounds(Xray, CMB, etc.) are severe.