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Phenomenology of anomaly-free axion in three Higgs doublet model

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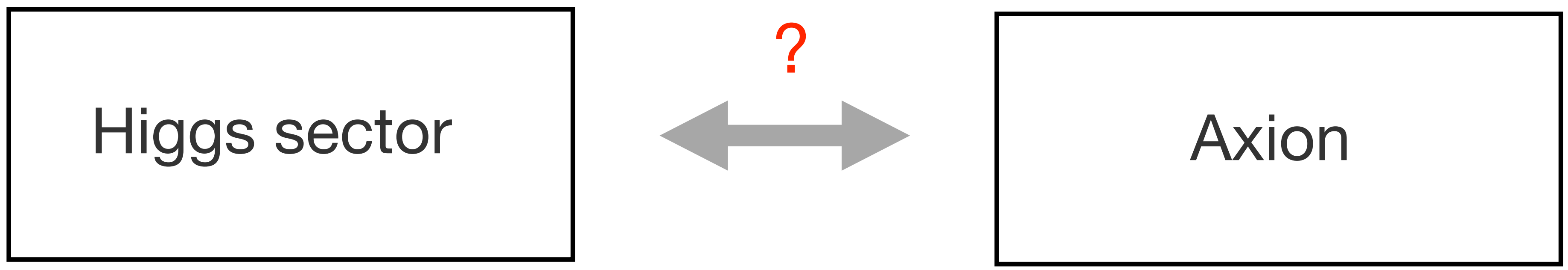
Motivations[1/2]

- Axion is one of the prominent candidates of Dark matter (DM).
  - Thermal production and/or non thermal production
  - The stability is explained by the lightness: $\Gamma(a \to \gamma\gamma) \simeq \frac{m_a^3}{64\pi} g_{a\gamma\gamma}$
  - Various experiments are running (e.g., cosmic rays, Beam dump,…)

- To pursue BSM problems, it is important to explore the shape of the Higgs sector.
  - Mystery of Higgs sector (No. of Higgs, symmetries,…)
  - The extended Higgs sector often appears in new physics models.

Motivations[2/2]



Relating 3HDM in HPNP2023:
[Pilaftsis, Ivanov, Song, Dey,...]

In this talk, we consider three Higgs doublet models with three B-L Higgs fields.

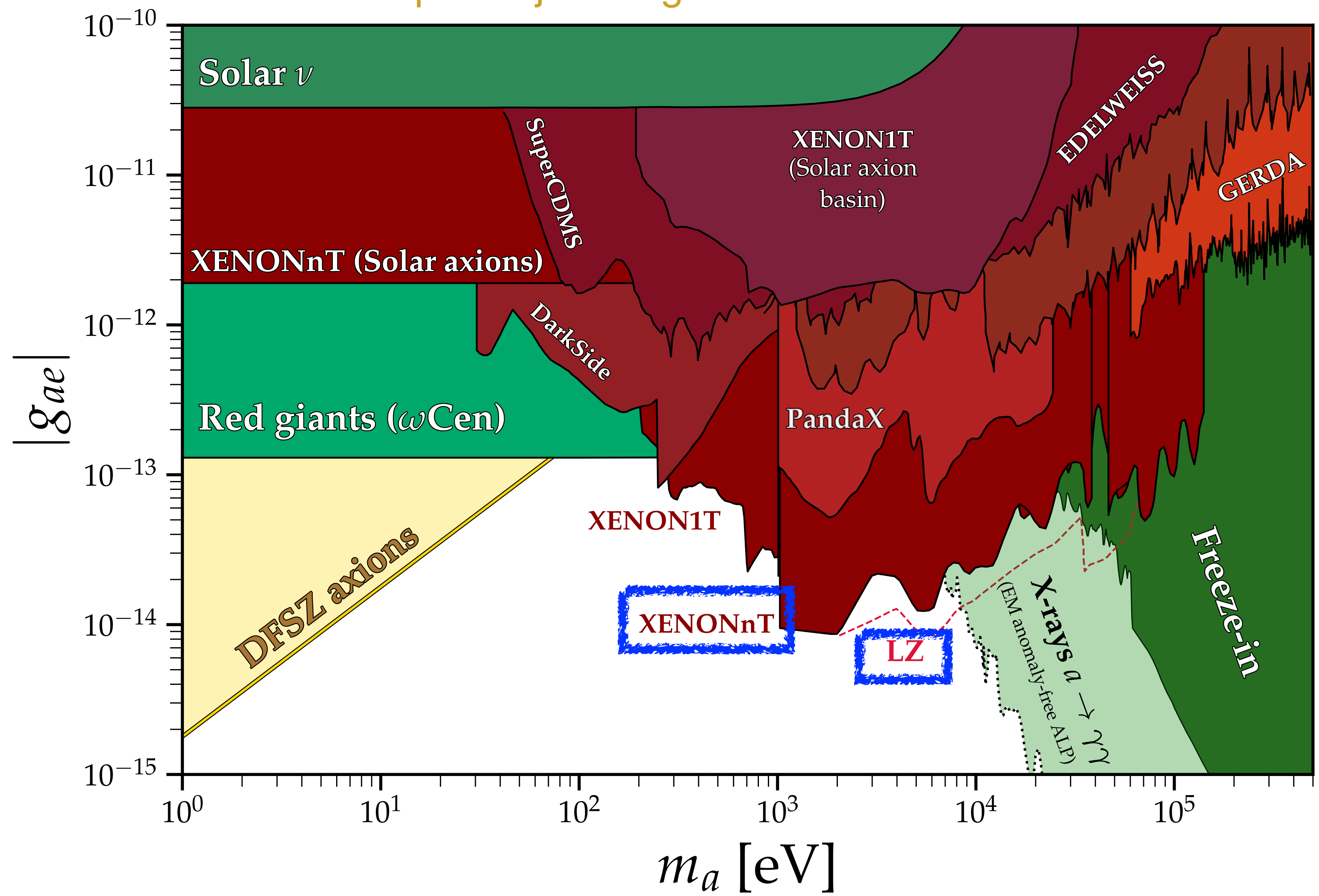
- the phenomenology of axion.

- how can we obtain the information of additional Higgs if the axion is detected?

Axion in keV scale

Axion can be tested by electron recoil event in DM direct detection experiments.

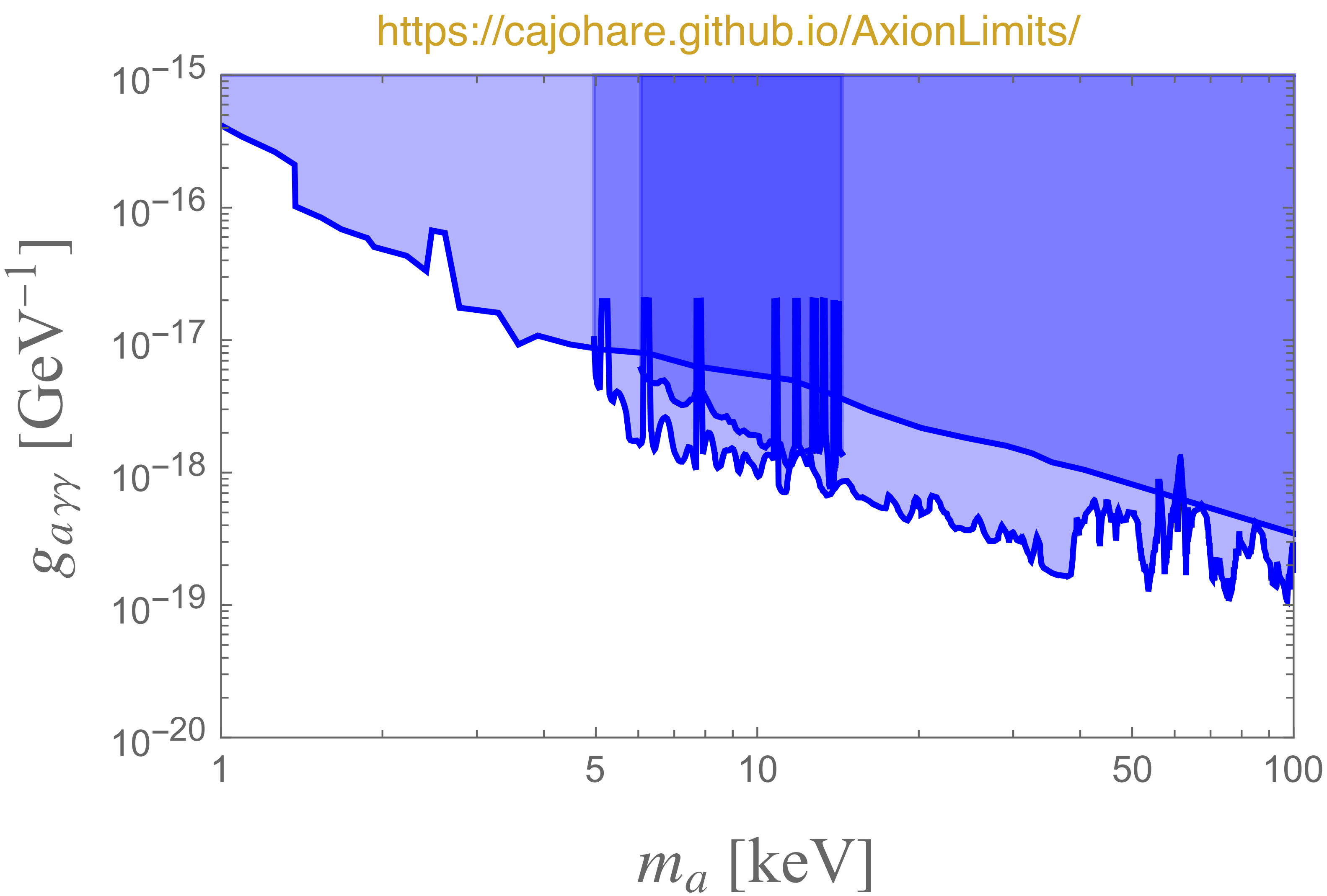
https://cajohare.github.io/AxionLimits/



XENONnT (current) : $g_{ae} \sim 10^{-14}$ at $m_a \sim 1\mathrm{keV}$

LZ (future) : The high mass region is covered.

X-ray constraint



DFSZ type-axion

$$g_{a\gamma\gamma} = \frac{\alpha_{em}}{2\pi f_a}\frac{E}{N} \qquad g_{aee} = q_e \frac{m_e}{f_a}$$

E: EM anomaly coefficient

N: QCD anomaly coefficient

q_e: PQ charge for electron

X-ray bounds (m_a ~ 5keV) →
$$g_{a\gamma\gamma} \sim 10^{-18}\mathrm{GeV}^{-1}\left(\frac{10^{15}\mathrm{GeV}}{f_a}\right) \quad g_{aee} = 5\times 10^{-19}\left(\frac{10^{15}\mathrm{GeV}}{f_a}\right)$$

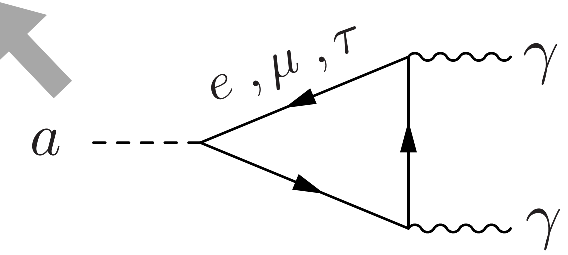
X-ray gives better sensitivity than DD exp.

Anomaly-free axion

[K. Nakayama, F. Takahashi, T. Yanagida, Phys.Lett.B 734 (2014) 178] [F. Takahashi, M. Yamada, W. Yin, Phys.Rev.Lett. 125 (2020) 161801]

$$\mathcal{L}_{\rm eff} \simeq -(q_e + q_\mu + q_\tau)\frac{\alpha_{\rm ew}}{4\pi f_a} a F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{\alpha_{\rm em} m_a^2}{48\pi f_a}\left(\frac{q_e}{m_e^2} + \frac{q_\mu}{m_\mu^2} + \frac{q_\tau}{m_\tau^2}\right) a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

= 0



Due to the suppression m_a^2/m_e^2, the X-ray constraint is relaxed.

$$g_{a\gamma\gamma} \simeq \frac{\alpha}{48\pi}\frac{q_e}{f_a}\frac{m_a^2}{m_e^2} \simeq 1\times 10^{-18}\left(\frac{q_e}{1}\right)\left(\frac{4.8\times 10^9\,\mathrm{GeV}}{f_a}\right)\left(\frac{m_a}{5\mathrm{keV}}\right)^2$$

$$g_{ae}^{\rm X-ray} \sim 1\times 10^{-13}\left(\frac{q_e}{1}\right)\left(\frac{4.8\times 10^9\,\mathrm{GeV}}{f_a}\right) > g_{ae}^{\rm LZ} \sim 10^{-15}$$ at $m_a = 5\mathrm{keV}$

→ Both X-ray and DD experiments can explore anomaly-free axion.

Three Higgs doublet models with B-L Higgs bosons

	Higgs doublet			B-L Higgs			SM leptons						SM quarks	
	ϕ_1	ϕ_2	ϕ_3	S_0	S_1	S_2	L_e	L_μ	L_τ	e_R	μ_R	τ_R	Q_L	q_R
$\mathrm{U}(1)_\mathrm{F}$ charge q	-3	3	0	0	1	-2	1	-1	0	-2	2	0	0	0

- Axion is indeed anomaly-free.

$$q_{L_e} + q_{L_\mu} + q_{L_\tau} = 0\,, \quad q_{e_R} + q_{\mu_R} + q_{\tau_R} = 0$$

i.e., Anomalous photon coupling vanishes.

- Three Φs are needed to write down the Yukawa interactions for each lepton generation:

$$\mathcal{L}_Y = -\, y_e \bar{L}_e \phi_2 e_R - y_\ell \bar{L}_\ell \phi_3 \ell_R - y_{\ell'} \bar{L}_{\ell'} \phi_1 \ell'_R + \mathrm{h.c.}$$

- Physical states: $H_{1,2,3},\ H^\pm_{1,2},\ A_{1,2},\quad a$

Can two Higgs doublet models realize anomaly-free axion?

→ It wouldn't work.

- Two of three generations should have same $U(1)_F$ charge.

$$Q(e_i) = (\overset{e}{-a}, \overset{\mu}{-b}, \overset{\tau}{-b}) \qquad Q(\ell_i) = (c, d, d)$$

(Anomolous photon coupling is zero)

$$a + 2b = 0,$$
$$c + 2d = 0$$

- Axion necessarily couples with quarks. $H(-a-c) \quad H(\frac{a+c}{2})$

$$\mathcal{L} \ni y_e \bar{e}_R \ell_1 H(-a-c) + y_\mu \bar{\mu}_R \ell_2 H(\frac{a+c}{2}) + y_\tau \bar{\tau}_R \ell_3 H(\frac{a+c}{2})$$
$$+ y_U u_R Q H(\frac{a+c}{2}) + y_D d_R Q H(\frac{a+c}{2})$$

$g_{a\gamma}$ receives QCD corrections and a-π mixing, which gives O(1) contributions.

Masses for axion and heavy Higgs bosons

We assume $U(1)_F$ preserving Z_6. → One soft breaking parameter appears only in Higgs sector.

$$V(\phi_i, S_j) \ni \left[\kappa_1 S_1^\dagger S_{\bar{2}}(\phi_1^\dagger \phi_2) + \kappa_2 S_{\bar{2}}^\dagger S_1(\phi_2^\dagger \phi_3) + \text{h.c.}\right]$$

Portal interaction

$$-\left[m_{12}^2 \phi_1^\dagger \phi_2 + \text{h.c.}\right]$$

Soft $U(1)_F$ breaking terms

Mass of heavy Higgs: $(\Phi = H_{2,3} = H_{1,2}^\pm = A_{1,2})$

$$m_\Phi^2 \sim \frac{m_{12}^2 v^2}{v_1 v_2} + \lambda_i v^2$$

Mass of axion:

$$m_a^2 \sim \frac{m_{12}^2(\kappa_1 + \kappa_2) v_{S_1} v_{S_2}}{2m_{12}^2 + (\kappa_1 + \kappa_2) v_{S_1} v_{S_2}} \frac{v^2}{f_a^2}$$

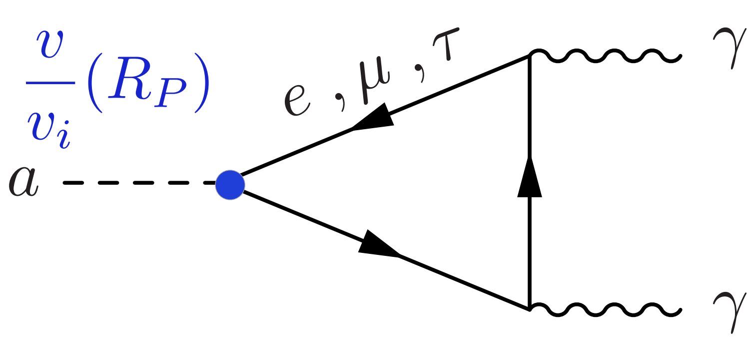
→ The mass of heavy Higgs bosons and axion are related.

Axion-photon coupling

$$g_{a\gamma} = \frac{\alpha_{em} m_a^2}{12\pi m_e^3} g_{ae} + \frac{\alpha_{em}}{\pi f_a} |q_e| \Delta,$$

Contributions from electron loop

Contributions from mixing among *a* and *CP-odd Higgs*



$$\begin{pmatrix} G^0 \\ A_1 \\ A_2 \\ a \end{pmatrix} = R_P \begin{pmatrix} z_1 \\ z_2 \\ z_3 \\ \tilde{a} \end{pmatrix}, \quad R_P = R_P(m_{12}^2, \kappa_i, f_a)$$

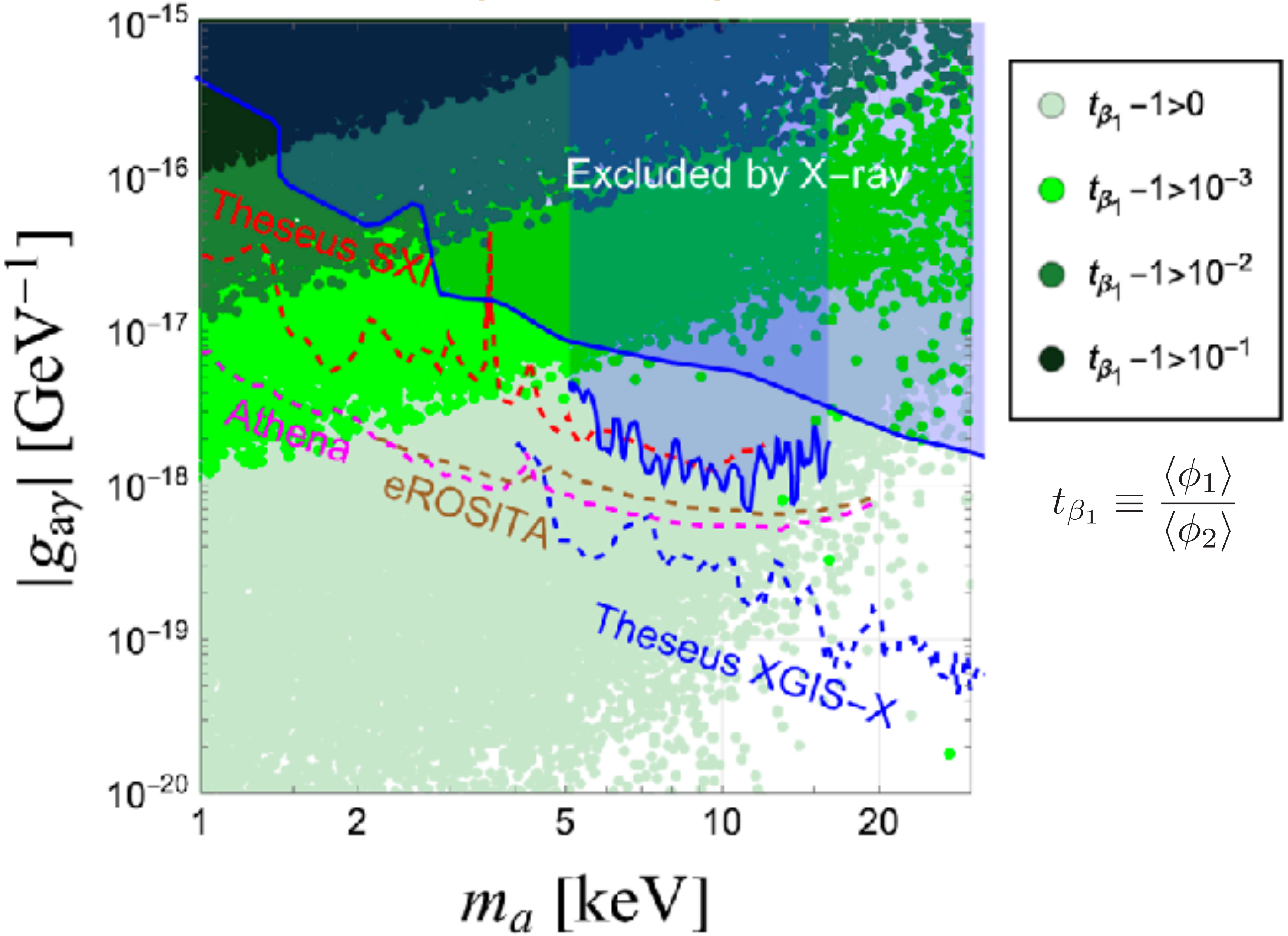
Even if the anomaly term is cancelled out, $g_{a\gamma}$ can be sizable due to the mixing.

- Similarity with KSVZ axion with E=0. $g_{a\gamma} = \frac{\alpha_{\rm em}}{2\pi f_a}\left[\frac{E}{N} - 1.92(4)\right]$ [G. G. Cortona, et al., JHEP01(2016)034]

- In 3HDM, $g_{a\gamma\gamma}$ is not determined only by g_{ae}, we calculate it and evaluate the bounds by scanning parameters.

Axion photon couplings

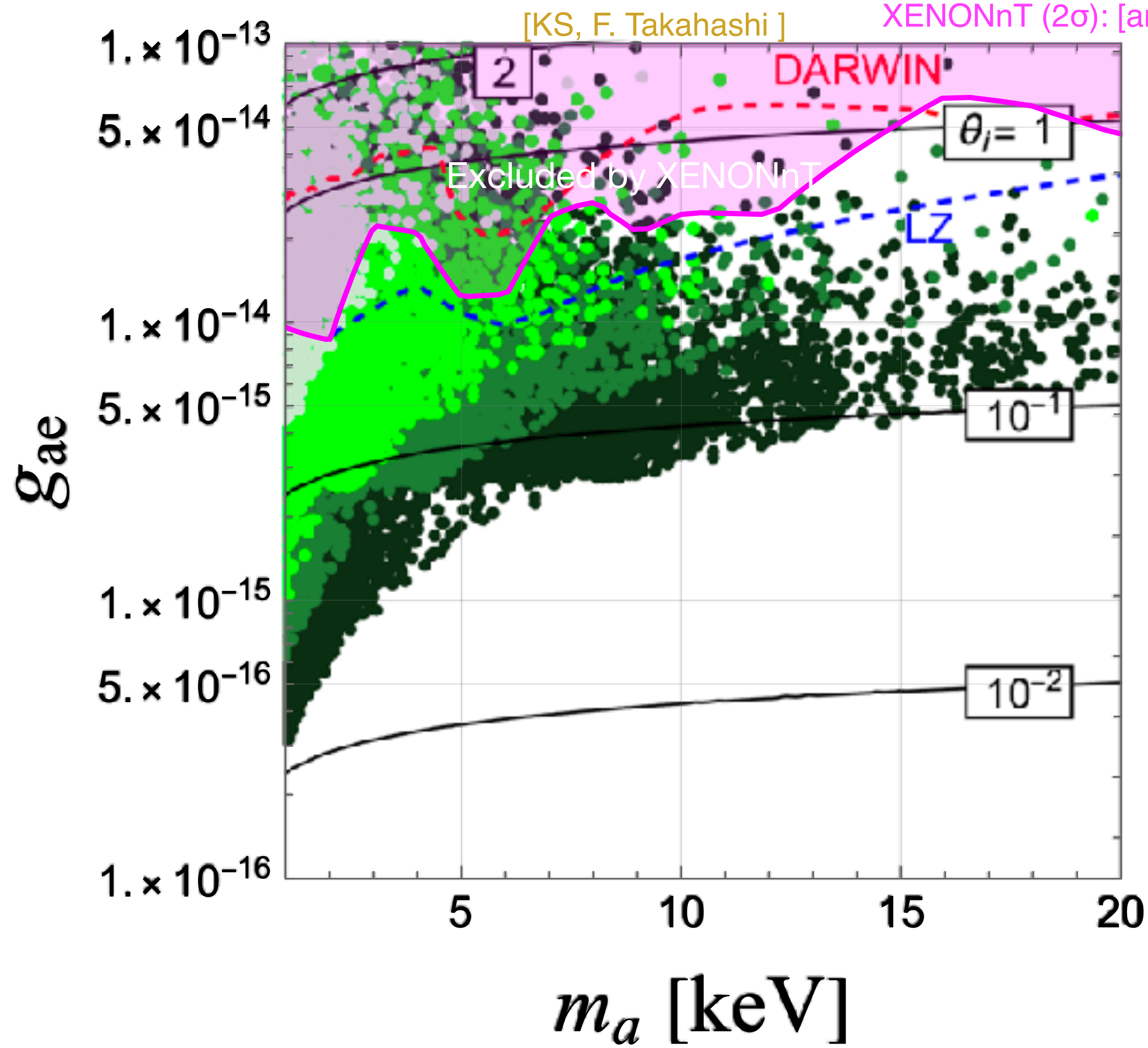
[KS, F. Takahashi]



$$t_{\beta_1} \equiv \frac{\langle \phi_1 \rangle}{\langle \phi_2 \rangle}$$

- $g_{a\gamma}$ is constrained as usual axion if $|\Delta|$~O(1).
- In the limit of $t_{\beta 1}$ —>1, $|\Delta|$ is close to 0 due to suppression of (R_p) .
- $t_{\beta 1}$ <1.1 is needed to evade current X-ray bounds.

Correlation between Higgs and axion



m_Φ: mass of heavy Higgs bosons

Scan range of m_Φ:

$$200\text{GeV} < m_\Phi < 10\text{TeV}$$

Axion-electron coupling:

$$g_{ae} = \frac{m_e}{f_a}\left[3(c^2_{\beta_1} - s^2_{\beta_1})c^2_{\beta_2} + 3\right]$$

Axion relic density:

$$\Omega_a h^2 \sim 0.12 \left(\frac{\theta_i}{2}\right)^2 \left(\frac{f_a}{2\times 10^{11}\text{GeV}}\right)^2$$

- We imposed the current X-ray bounds as well as various theoretical and exp. constraints.
- The heavy Higgs masses are correlated with the m_a and g_{ae}.

→If axion is detected by future experiments, the information of extra Higgs can be extracted.

Summary

- Anomaly-free axion can be probed by the future direct searches and future X-ray searches.

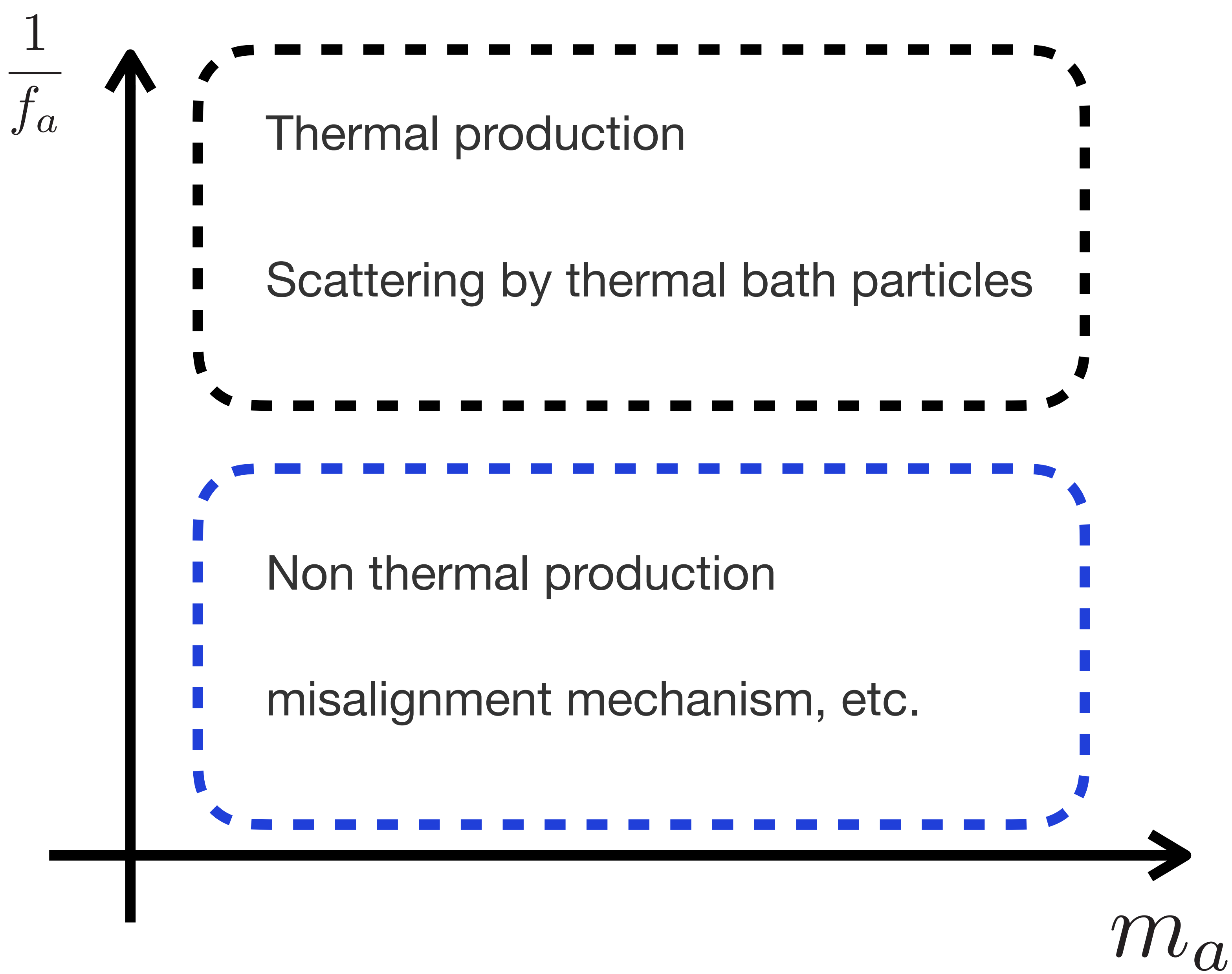
- We consider 3HDM as a possible UV completion to predict the anomaly-free axion.

- $g_{a\gamma}$ can be sizable due to mixing effects of heavy CP-odd Higgs states.

- Properties of the extra Higgs are related to those of axion.

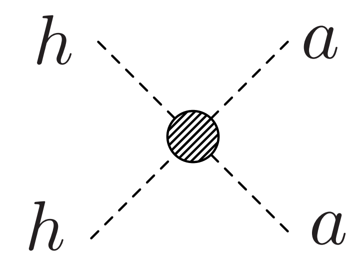
Buck up

Axion production



- Thermal production

Ex.)

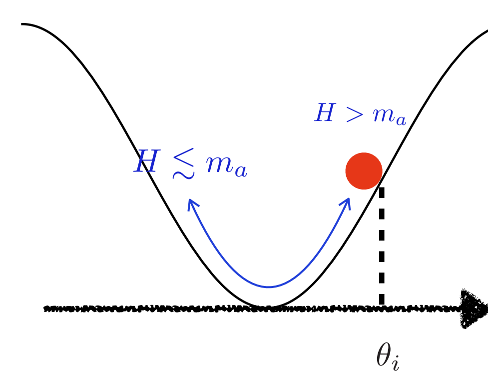


[e.g., M. Bauer, G. Rostagni, J. Spinner,PRD 107 (2023)]

- $\mathscr{M}_a \sim \frac{1}{f_a^n}$ (n=4 for $hh \to aa$)

- Many parameter space is excluded by X-ray.

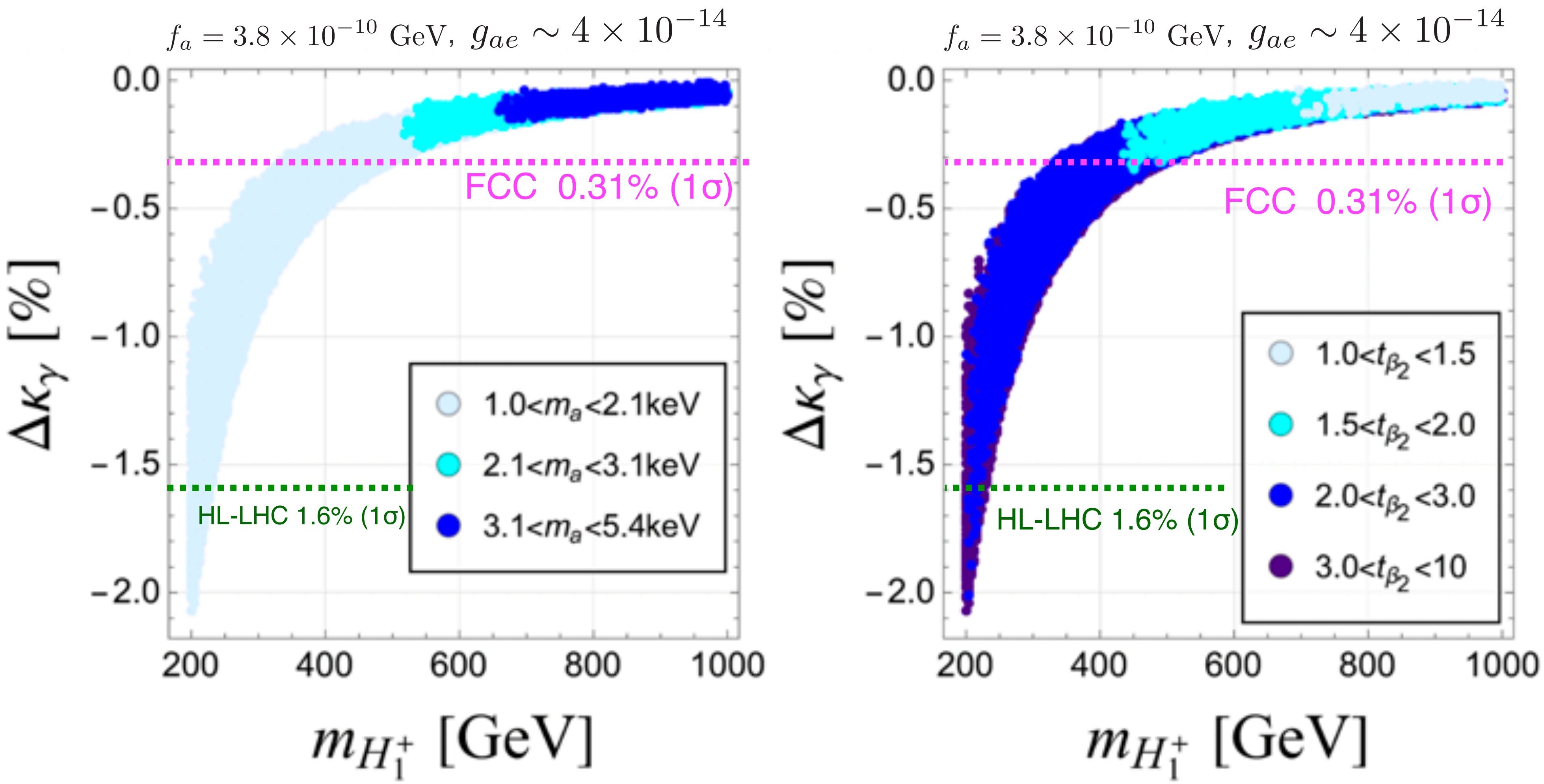
- Misalignment mechanism



$$\Omega_a h^2 \sim 0.12 \left(\frac{\theta_i}{2}\right)^2 \left(\frac{f_a}{2 \times 10^{11}\mathrm{GeV}}\right)^2$$

Correlation between axion mass and Higgs coupling

[KS, F. Takahashi]



$$\Delta\kappa_\gamma \equiv \sqrt{\frac{\Gamma^{\rm 3HDM}_{h\to\gamma\gamma}}{\Gamma^{\rm SM}_{h\to\gamma\gamma}}} - 1$$

$$t_{\beta_2} \equiv \frac{\langle\phi_1\rangle}{\langle\phi_3\rangle}$$

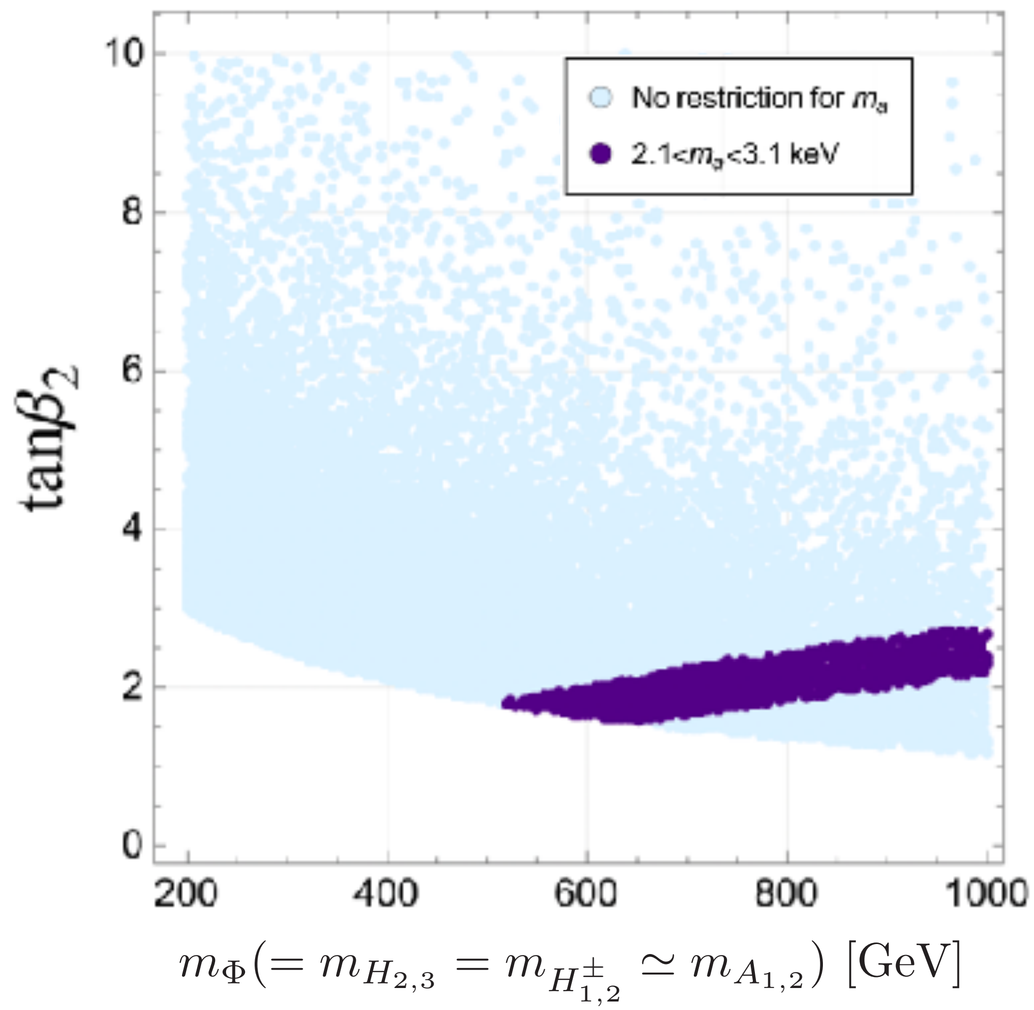
- The maximal size of deviation is around 2%. ← Perturvativity for the running coupling constants

- The keV scale axion can be tested by future colliders.

Correlations for the potential parameters

$$\tan\beta_1 \equiv \frac{v_2}{v_1} \;,\; \tan\beta_2 \equiv \frac{v_3}{\sqrt{v_1^2+v_2^2}}$$

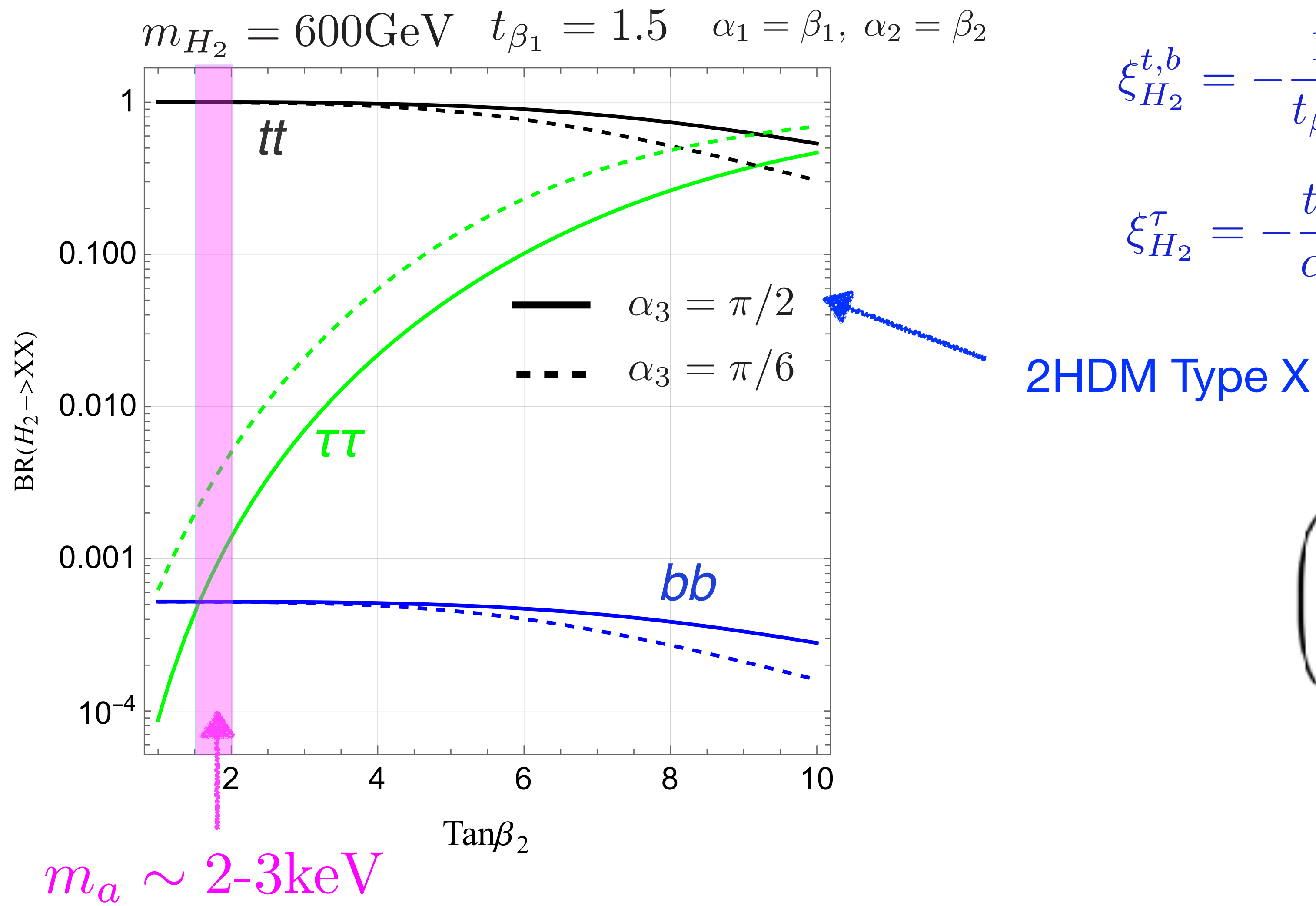
[KS, F. Takahashi]



→ m_Φ should be heavier than around 500 GeV if the mass of axion is fixed.

→ There is a correlation between m_Φ and $\tan\beta_{1,2}$ ➡ Characteristic decay pattern of Φ.

Predictions for decays of the heavy Higgs bosons



$$\xi^{t,b}_{H_2} = -\frac{1}{t_{\beta_2}} s_{\alpha_3}$$

$$\xi^{\tau}_{H_2} = -\frac{t_{\beta_1}}{c_{\beta_2}} c_{\alpha_3} + t_{\beta_2} s_{\alpha_3}$$

$$\begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = R_S \begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix}$$

$$R_S \equiv \mathcal{O}_{\alpha_3}\mathcal{O}_{\alpha_2}\mathcal{O}_{\alpha_1}$$

- BR(H_2 –> ττ) is relatively larger than the case of Type X 2HDM.

- If the axion is detected at a few keV, one can obtain predictions of a similar decay pattern of H_2 except for H_2 –> ττ .

Higgs potential

$$V = V_{3\mathrm{HDM}} + V_{\mathrm{B-L}} + V_I .$$

$$\begin{aligned} V_{3\mathrm{HDM}} = {} & m_{11}^2(\phi_1^\dagger\phi_1) + m_{22}^2(\phi_2^\dagger\phi_2) + m_{33}^2(\phi_3^\dagger\phi_3) \\ & +\lambda_1(\phi_1^\dagger\phi_1)^2 + \lambda_2(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_3^\dagger\phi_3)^2 \\ & +\lambda_4(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_5(\phi_1^\dagger\phi_1)(\phi_3^\dagger\phi_3) + \lambda_6(\phi_2^\dagger\phi_2)(\phi_3^\dagger\phi_3) \\ & +\lambda_7(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \lambda_8(\phi_1^\dagger\phi_3)(\phi_3^\dagger\phi_1) + \lambda_9(\phi_2^\dagger\phi_3)(\phi_3^\dagger\phi_2) \\ & + \left[\lambda_{10}(\phi_3^\dagger\phi_1)(\phi_3^\dagger\phi_2) + \mathrm{h.c.}\right] + V_{\mathrm{soft}} , \end{aligned}$$

$$V_{\mathrm{soft}} = -\left[m_{12}^2(\phi_1^\dagger\phi_2) + \mathrm{h.c.}\right]$$

$$\begin{aligned} V_I = {} & \sum_{m=0,1,\bar{2}} \sum_{n=1,2,3} \kappa_{m\phi n}|S_m|^2(\phi_n^\dagger\phi_n) \\ & + \left[\kappa_{1\bar{2}\phi1\phi3} S_1^\dagger S_{\bar{2}}(\phi_1^\dagger\phi_3) + \kappa_{\bar{2}1\phi2\phi3} S_{\bar{2}}^\dagger S_1(\phi_2^\dagger\phi_3) + \mathrm{h.c.}\right] \end{aligned}$$

$$\begin{aligned} V_{B-L} = {} & \sum_{i=0,1,\bar{2}} (\mu_i|S_i|^2 + \kappa_i|S_i|^4) + \kappa_{01}|S_0|^2|S_1|^2 + \kappa_{0\bar{2}}|S_0|^2|S_{\bar{2}}|^2 + \kappa_{1\bar{2}}|S_1|^2|S_{\bar{2}}|^2 \\ & + \kappa_{0110}|S_0^\dagger S_1|^2 + \kappa_{0\bar{2}\bar{2}0}|S_0^\dagger S_{\bar{2}}|^2 + \kappa_{1\bar{2}\bar{2}1}|S_1^\dagger S_{\bar{2}}|^2 , \end{aligned}$$

Yukawa interaction for the heavy Higgs

$$
\begin{aligned}
\mathcal{L}_Y^M \ni\ & \frac{\sqrt{2}}{v} V_{\rm CKM} \sum_{i=1}^{2} \xi^q_{H_i^\pm} H_i^\pm \left\{ \bar{u}(m_u P_L - m_d P_R) d + \text{h.c.} \right\} \\
& - \frac{m_q}{v} \sum_{i=1}^{3} \xi^q_{H_i} H_i \bar{q} q + i 2 I_q \frac{m_q}{v} \sum_{i=1}^{2} \xi^q_{A_i} A_i \bar{q} \gamma_5 q \\
& - \sqrt{2} \frac{m_l}{v} \sum_{i=1}^{2} \xi^l_{H_i^\pm} H_i^\pm \left\{ \bar{\nu}_L P_R l + \text{h.c.} \right\} - \frac{m_l}{v} \sum_{i=1}^{3} \xi^l_{H_i} H_i \bar{l} l \\
& - i \sum_l \frac{m_l}{v} \sum_{i=1}^{2} \xi^l_{A_i} A_i \bar{l} \gamma_5 l - i \sum_l g_{a\ell} a \bar{l} \gamma_5 l \ ,
\end{aligned}
$$

$\xi^f_{H_i^+}$	q	e	ℓ	ℓ'
H_1^+	$-\frac{1}{t_{\beta_2}} s_{\gamma_+}$	$\frac{1}{t_{\beta_1}} \frac{c_{\gamma_+}}{c_{\beta_2}} + t_{\beta_2} s_{\gamma_+}$	$-\frac{1}{t_{\beta_2}} s_{\gamma_+}$	$-t_{\beta_1} \frac{c_{\gamma_+}}{c_{\beta_2}} + t_{\beta_2} s_{\gamma_+}$
H_2^+	$\frac{1}{t_{\beta_2}} c_{\gamma_+}$	$-t_{\beta_1} c_{\gamma_+} + \frac{1}{t_{\beta_2}} \frac{s_{\gamma_+}}{c_{\beta_2}}$	$\frac{1}{t_{\beta_2}} c_{\gamma_+}$	$-t_{\beta_2} c_{\gamma_+} - t_{\beta_1} \frac{s_{\gamma_+}}{c_{\beta_2}}$

$\xi^f_{A_i,a}$	q	e	ℓ	ℓ'
A_1	$\frac{1}{s_{\beta_2}} (R_P)_{23}$	$\frac{1}{s_{\beta_1} c_{\beta_2}} (R_P)_{22}$	$\frac{1}{s_{\beta_2}} (R_P)_{23}$	$\frac{1}{c_{\beta_1} c_{\beta_2}} (R_P)_{21}$
A_2	$\frac{1}{s_{\beta_2}} (R_P)_{33}$	$\frac{1}{s_{\beta_1} c_{\beta_2}} (R_P)_{32}$	$\frac{1}{s_{\beta_2}} (R_P)_{33}$	$\frac{1}{c_{\beta_1} c_{\beta_2}} (R_P)_{31}$
a	$\frac{1}{s_{\beta_2}} (R_P)_{43}$	$\frac{1}{s_{\beta_1} c_{\beta_2}} (R_P)_{42}$	$\frac{1}{s_{\beta_2}} (R_P)_{43}$	$\frac{1}{c_{\beta_1} c_{\beta_2}} (R_P)_{41}$

$\xi^f_{H_i}$	q	e	ℓ	ℓ'
H_1	$\frac{s_{\alpha_2}}{s_{\beta_2}}$	$\frac{s_{\alpha_1} c_{\alpha_2}}{s_{\beta_1} c_{\beta_2}}$	$\frac{s_{\alpha_2}}{s_{\beta_2}}$	$\frac{c_{\alpha_1} c_{\alpha_2}}{c_{\beta_1} c_{\beta_2}}$
H_2	$\frac{c_{\alpha_2} s_{\alpha_3}}{s_{\beta_2}}$	$\frac{1}{s_{\beta_1} c_{\beta_2}} (c_{\alpha_1} c_{\alpha_3} - s_{\alpha_1} s_{\alpha_2} s_{\alpha_3})$	$\frac{c_{\alpha_2} s_{\alpha_3}}{s_{\beta_2}}$	$\frac{1}{c_{\beta_1} c_{\beta_2}} (-s_{\alpha_1} c_{\alpha_3} - c_{\alpha_1} s_{\alpha_2} s_{\alpha_3})$
H_3	$\frac{c_{\alpha_2} c_{\alpha_3}}{s_{\beta_2}}$	$\frac{1}{s_{\beta_1} c_{\beta_2}} (-s_{\alpha_1} s_{\alpha_2} c_{\alpha_3} - c_{\alpha_1} s_{\alpha_3})$	$\frac{c_{\alpha_2} c_{\alpha_3}}{s_{\beta_2}}$	$\frac{1}{c_{\beta_1} c_{\beta_2}} (-c_{\alpha_1} s_{\alpha_2} c_{\alpha_3} + s_{\alpha_1} s_{\alpha_3})$

$$v_1 = v \cos\beta_1 \cos\beta_2 \ , \qquad v_2 = v \sin\beta_1 \cos\beta_2 \ ,$$

$$v_3 = v \sin\beta_2$$

Alignment limit

- The alignment limit in 3HDM is defined by [D. Das, I. Saha, PRD100 (2019)]

$$\alpha_1 = \beta_1, \;\; \alpha_2 = \beta_2$$

- Higgs coupling: $\kappa_V^{H_1} = c_{\alpha_2} c_{\alpha_1 - \beta_1} c_{\beta_2} + s_{\alpha_2} s_{\beta_2} \quad \to \quad 1$

- Mixing matrix: $\begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = R_S \begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix}$

  $R_S = \mathcal{O}_{\alpha_3} \mathcal{O}_{\alpha_2} \mathcal{O}_{\alpha_1}$

  $\to \mathcal{O}_{\alpha_3} \mathcal{O}_{\beta}$

[c.f.) 2HDM

$\sin(\beta - \alpha) = 1 \quad \to \alpha = \beta + \frac{\pi}{2}$

$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} -\sin\beta & -\cos\beta \\ \cos\beta & -\sin\beta \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$]

Neutrino masses

If we introduce right-handed neutrinos N_i, we can explain the neutrino mass by the seesaw mechanism.

- $U(1)_F$ charge: $Q(N_i) = (1, -1, 0)$ ← Same assignment as e_{Ri}
  (Type A)

- Lagrangian for neutrinos:

$$-\mathcal{L} = y_1 \bar{L}_e N_1 \tilde{\phi}_3 + y_2 \bar{L}_\tau N_2 \tilde{\phi}_3 + y_3 \bar{L}_\mu N_3 \tilde{\phi}_3 + \frac{1}{2}(M_N)_{ij} \bar{N}_i^c N_j + \text{h.c.}$$

$$(y^N)_{ij} \bar{N}_i^c N_j S_{0,1,\bar{2}}$$

$$(M_N)_{ij} \sim \begin{pmatrix} \langle S_{\bar{2}} \rangle & \langle S_0 \rangle & 0 \\ \langle S_0 \rangle & 0 & \langle S_1 \rangle \\ 0 & \langle S_1 \rangle & \langle S_0 \rangle \end{pmatrix} \quad \text{If} \quad y^N \sim \mathcal{O}(1)$$

- Neutrino mass and mixing ($m_D = \text{diag}(y_1, y_2, y_3)\frac{v_3}{\sqrt{2}}$)

$$m_\nu \simeq m_D^T M_N^{-1} m_D \quad \propto \frac{y_i^2 v^2}{v_S} \quad \sim 0.1\text{eV}\left(\frac{y_i}{0.01}\right)^2 \left(\frac{10^{10}\text{GeV}}{v_S}\right)$$

$$U_{PMNS}^\dagger m_\nu U_{PMNS} = \text{diag}(m_1, m_2, m_3)$$

Large neutrino mixings are checked by scanning $\{y_i,\ (M_N)_{ij}\}$.

Global fit oscillation data (3σ) [1811.05487]