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Anomaly-free axion and heavy Higgs bosons in 3HDM

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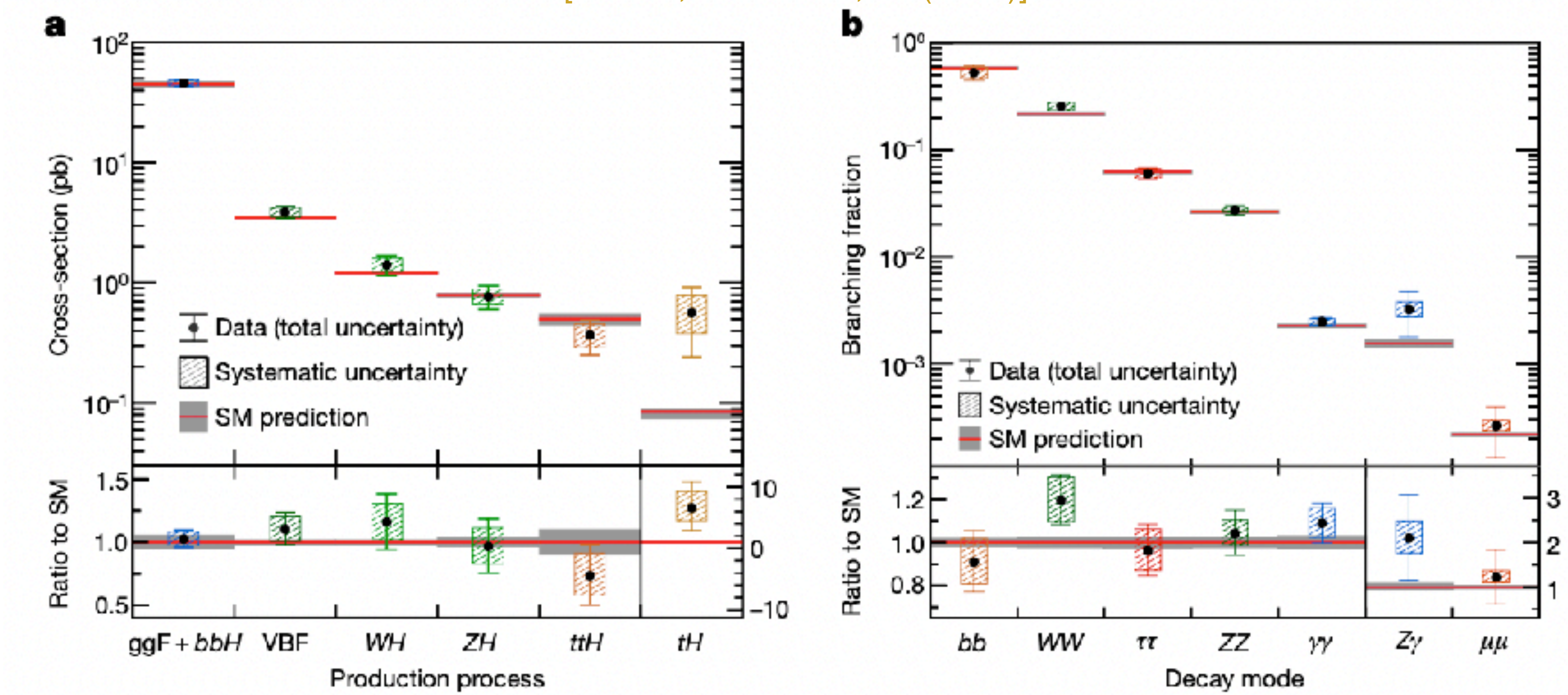
Current status of Higgs measurements

[ATLAS, Nature607, 52 (2022)]



- The data show success of the SM.
- However possibility of extended Higgs sector is not excluded at all.
  - E.g., Alignment limit, decoupling limit.

Probe of NP from Higgs sector

Higgs sector

$$\Phi + X \overset{?}{+} \ldots$$

X: Additional Higgs field

Dark matter
(WIMP, axion, dark photon, …)

Neutrino masses
(Type-II seesaw, radiative seesaw,…)

EW baryogenesis
(Phase transition, GWs, CPV,…)

Muon g-2, W-mass, …

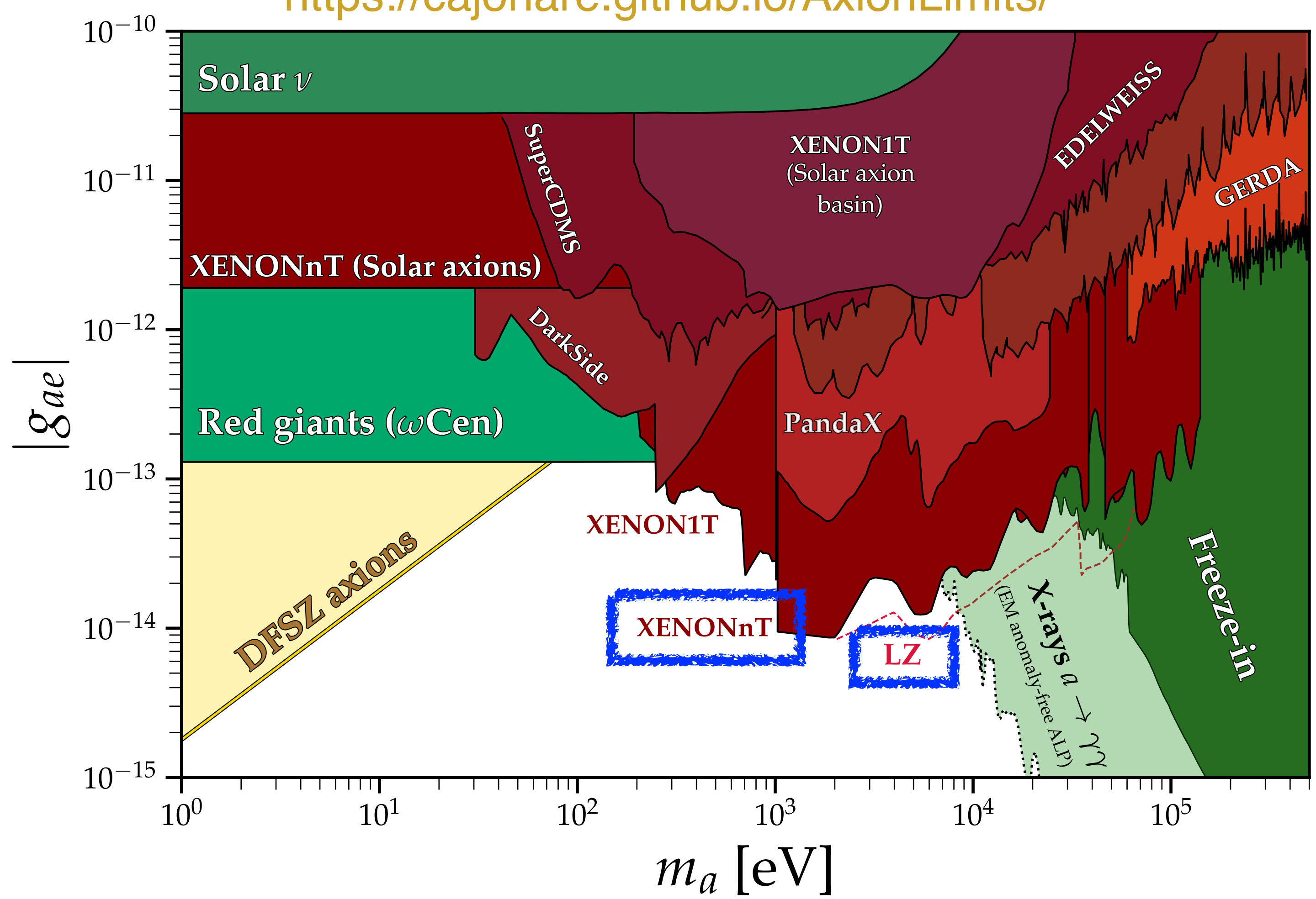
In this talk, we will discuss how axon DM can be embedded in the context of the extended Higgs model.

- Correlation between axion mass and heavy Higgs boson masses.
- Axion couplings have the corrections from the mixing btw axion and heavy Higgs.

Axion in keV scale

- Axion has a good nature as DM.
    - Thermal production and/or non thermal production
    - The stability is explained by the lightness: $\Gamma(a \to \gamma\gamma) \simeq \frac{m_a^3}{64\pi} g_{a\gamma\gamma}$
- KeV scale is accessible by direct searches of DM experiments.

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

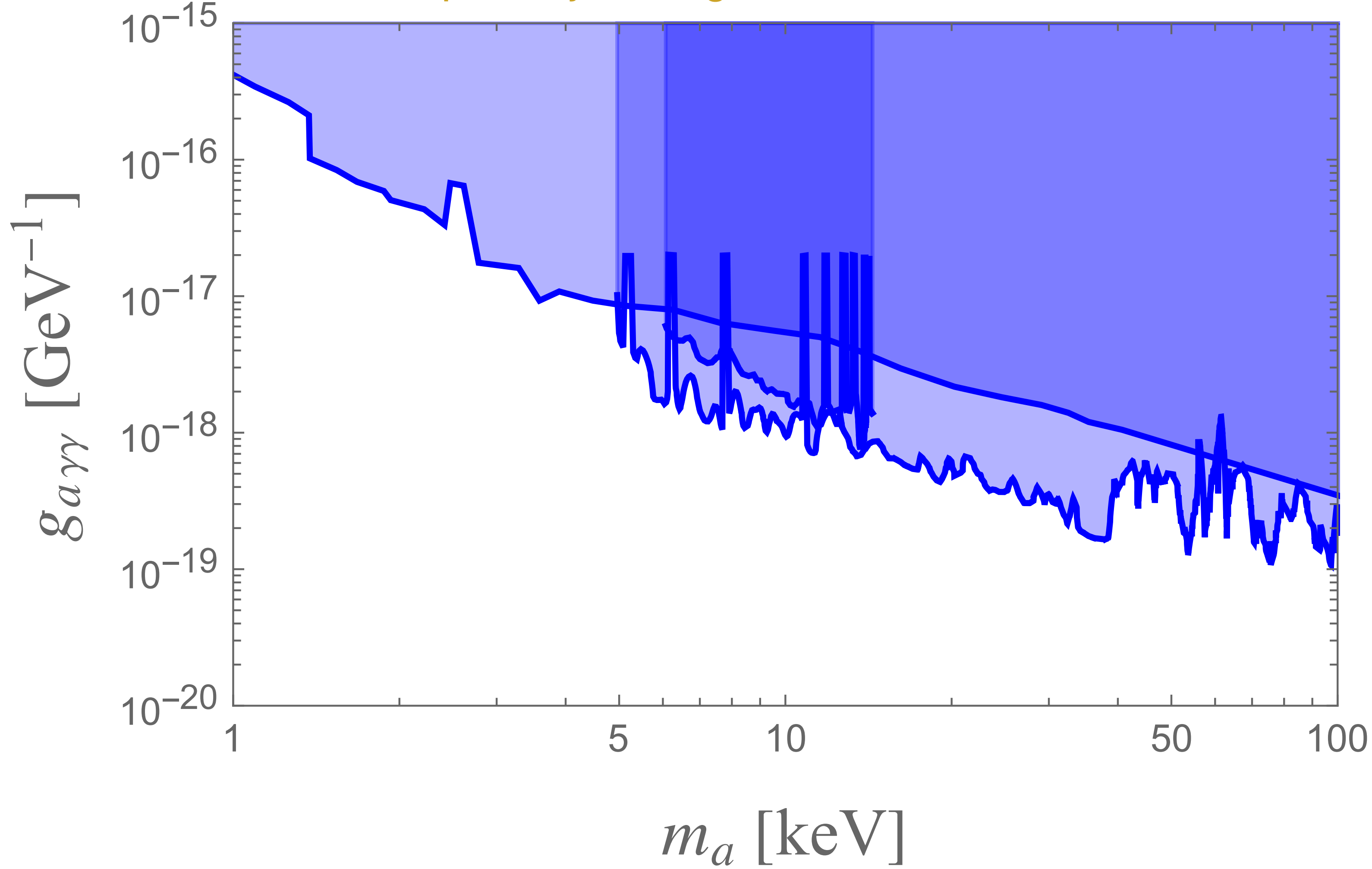


XENONnT (current) :
$g_{ae} \sim 10^{-14}$ at $m_a \sim 1\mathrm{keV}$

LZ (future) :
$g_{ae} \sim 10^{-14}$ at $m_a \sim \mathcal{O}(10)\mathrm{keV}$

X-ray constraint

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



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)

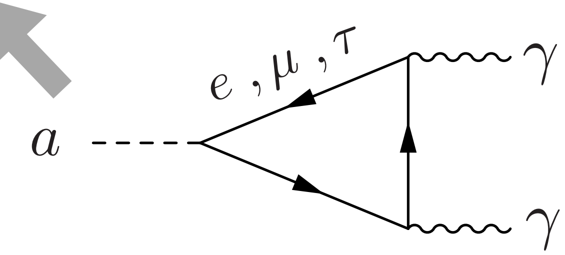
$$g_{a\gamma\gamma} \sim 10^{-18}\mathrm{GeV}^{-1}\left(\frac{10^{15}\mathrm{GeV}}{f_a}\right) \qquad g_{aee} = 5\times 10^{-19}\left(\frac{10^{15}\mathrm{GeV}}{f_a}\right)$$

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]

$$\mathcal{L}_{\rm eff} \simeq -\underbrace{(q_e + q_\mu + q_\tau)}_{=0}\frac{\alpha_{\rm ew}}{4\pi f_a} aF_{\mu\nu}\tilde{F}^{\mu\nu} + \underline{\frac{\alpha_{\rm em} m_a^2}{48\pi f_a}\left(\frac{q_e}{m_e^2} + \frac{q_\mu}{m_\mu^2} + \frac{q_\tau}{m_\tau^2}\right)} aF_{\mu\nu}\tilde{F}^{\mu\nu}$$



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

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

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

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

Masses for axion and heavy Higgs bosons

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

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

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

Portal interaction

Soft U(1)$_F$ breaking terms

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

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

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

$$\boxed{g_{a\gamma} \simeq g_{a\gamma}^{ch} + g_{a\gamma}^{th} + g_{a\gamma}^{mix}}$$

[U(1) charge contributions] : $g_{a\gamma}^{\rm ch} \simeq \frac{\alpha_{\rm em}}{\pi f_a}\sum_\ell q_\ell = 0$

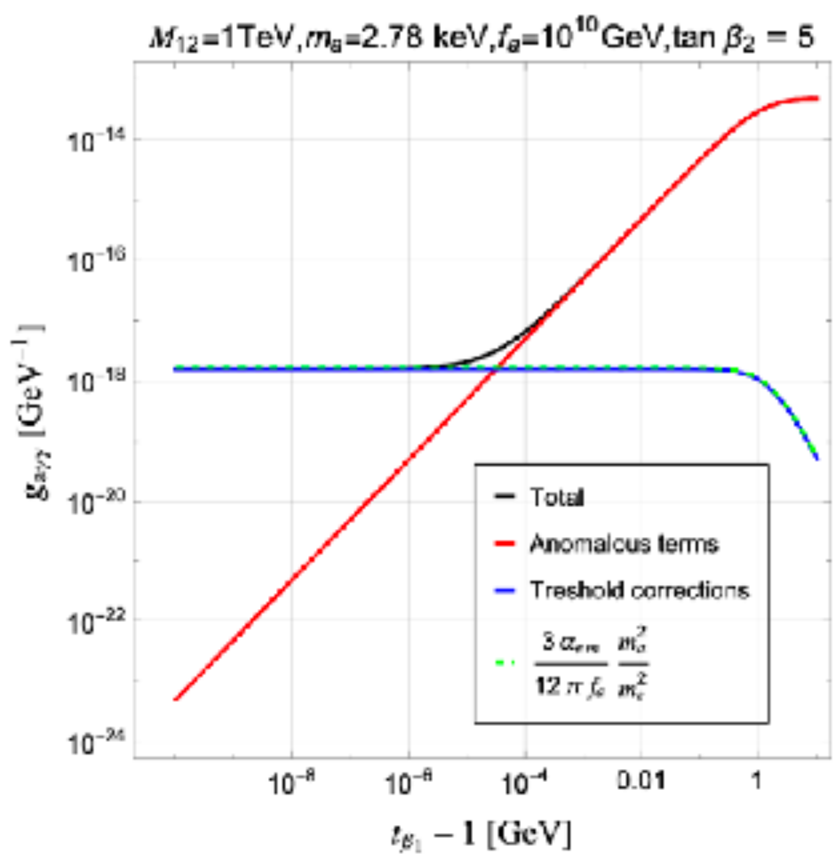
[Threshold corrections] : $g_{a\gamma}^{th} \simeq \frac{\alpha_{em}}{\pi v}\frac{m_a^2}{12}\frac{q_e}{m_e^2}$

[Mixing contributions] : It arises due to the mixing among *a* and *G₀*, *A1,2*.

(a-G mixing) ~ $\frac{\alpha_{em}}{\pi v}\sum_f N_c^f Q_f^2 X_f = 0$ (Due to shift symmetry) $X_f = -6I_f(c_{\beta_1}^2 - s_{\beta_1}^2)c_{\beta_2}^2$

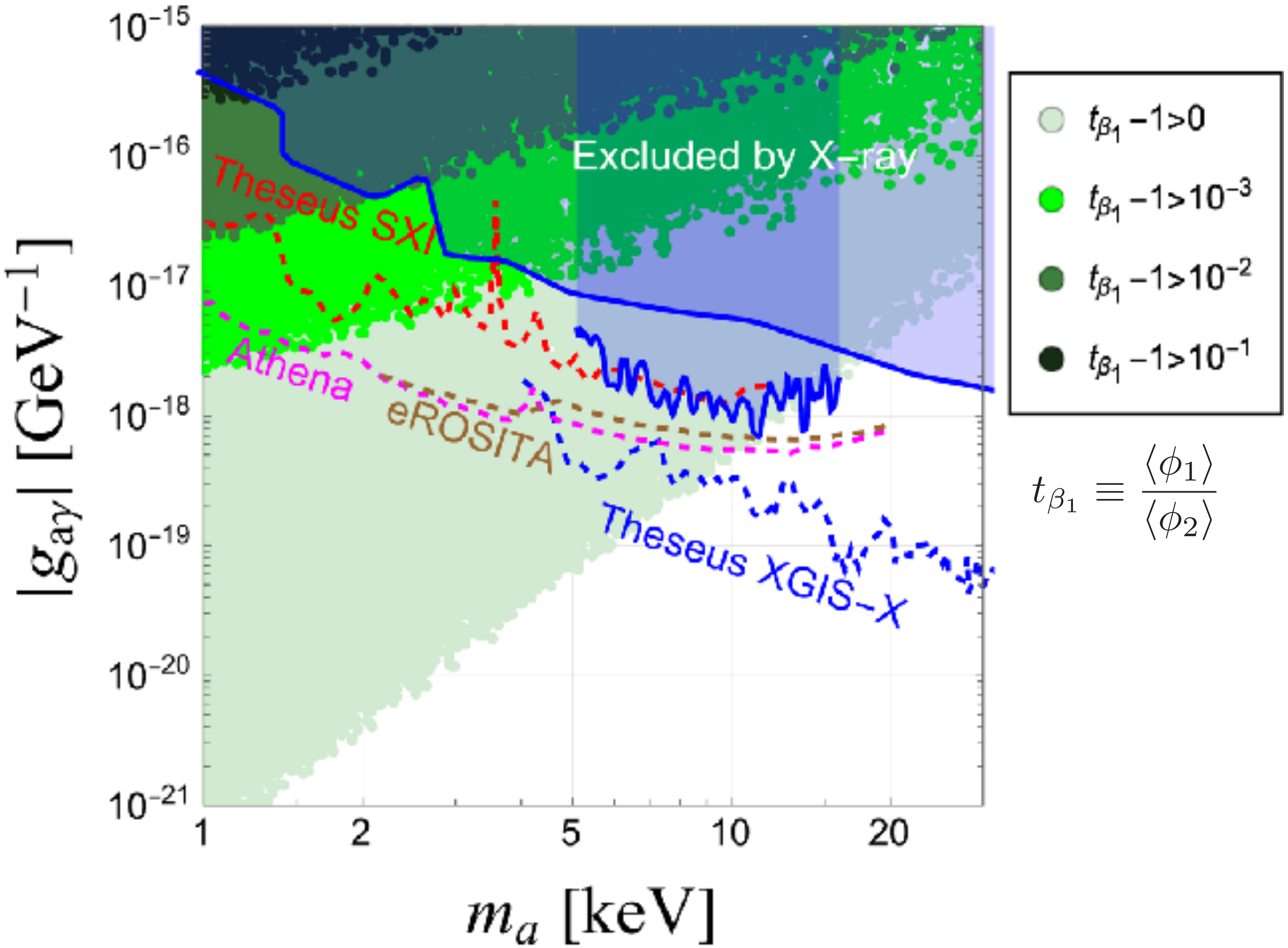
(a-A mixing) ~ $(c_{\beta_1}^2 - s_{\beta_1}^2)\frac{\alpha_{\rm EW}}{\pi v}\frac{m_{12}^2}{v f_a}$

- The difference is 4 digit at $t_{\beta_1} \sim 2$.
- $g_{a\gamma}$ is suppressed by $t_{\beta_1} - 1$.



Comparison with X-ray bounds

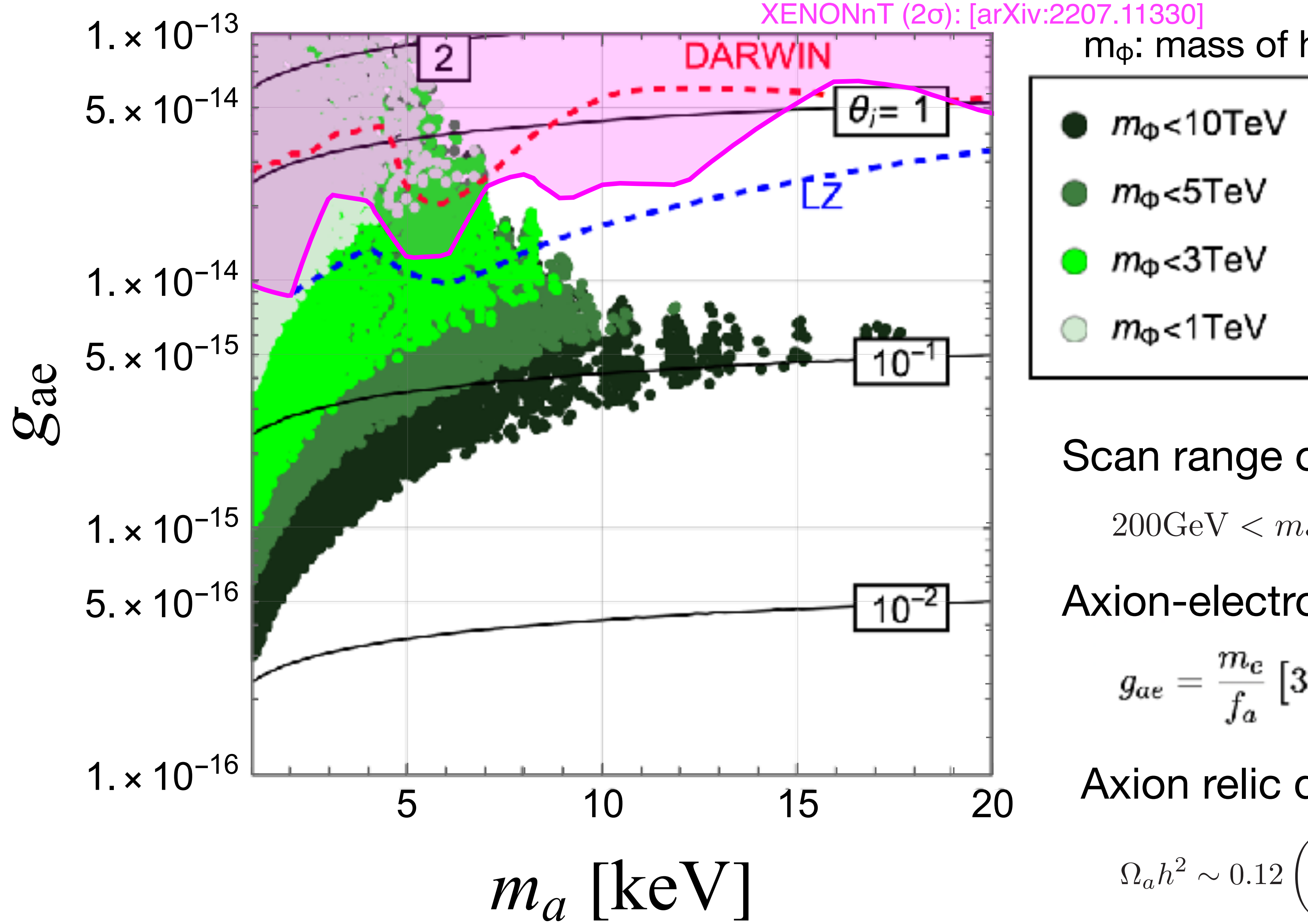
[KS, F. Takahashi]



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

- $g_{a\gamma}$ is constrained as usual axion if $t_{\beta 1}$-1~O(1).
- Only in the limit of $t_{\beta 1}$ —>1, threshold corrections dominates.
- $t_{\beta 1}$ <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:

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

Axion relic density:

$$\Omega_a h^2 \sim 0.12\left(\frac{\theta_i}{2}\right)^2\left(\frac{f_a}{2\times10^{11}\text{GeV}}\right)^2$$

- 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.

- We find that $g_{a\gamma}$ receive sizable corrections due to the mixing.

  $g_{a\gamma} \sim$ (Threshold corrections) [No extra CP-odd Higgs]

  $g_{a\gamma} \sim$ (Mixing corrections) [Additional CP-odd Higgs exists]

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

Buck up

Can two Higgs doublet models realize anomaly-free axion?

→ It wouldn't work.

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

$$
\begin{array}{cccc} & e & \mu & \tau \\ Q(e_i) = (& -a, & -b, & \underline{-b}) \end{array} \qquad Q(\ell_i) = (c, d, \underline{d})
$$

⇒ $$a + 2b = 0,$$
$$c + 2d = 0$$

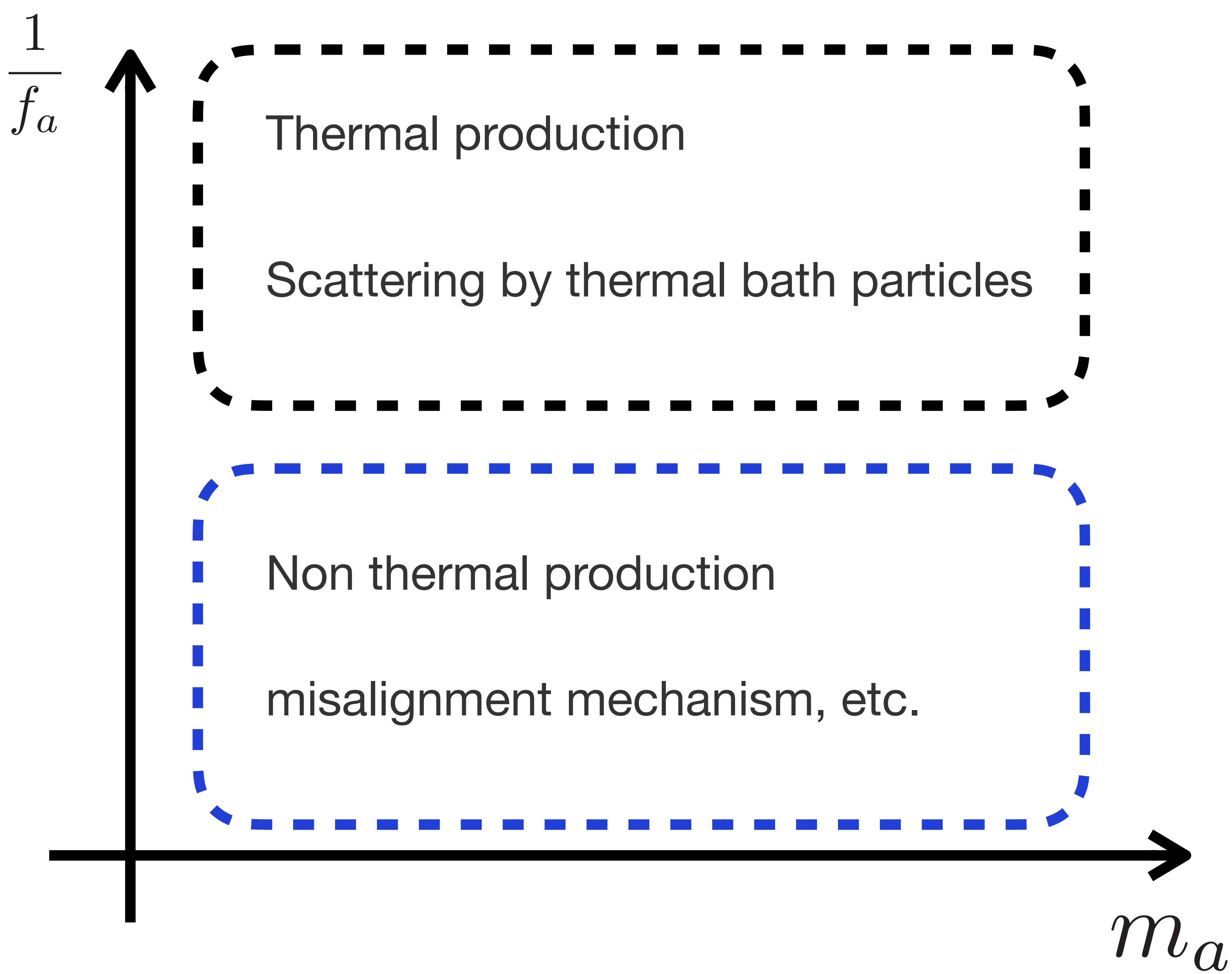
(Anomolous photon coupling is zero)

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

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

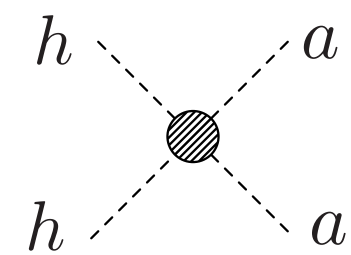
⇒ $g_{a\gamma}$ receives QCD corrections and a-π mixing, which gives O(1) contributions.

Axion production



- Thermal production

Ex.)

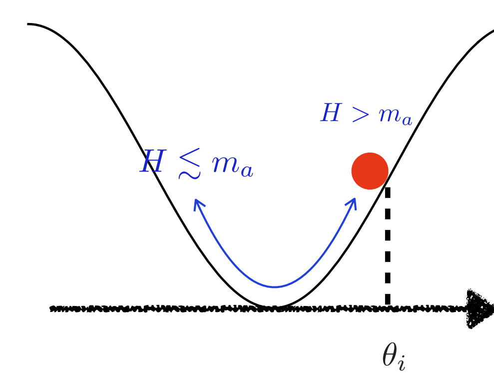


[e.g., M. Bauer, G. Rostagni, J. Spinner,PRD 107 (2023)]

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

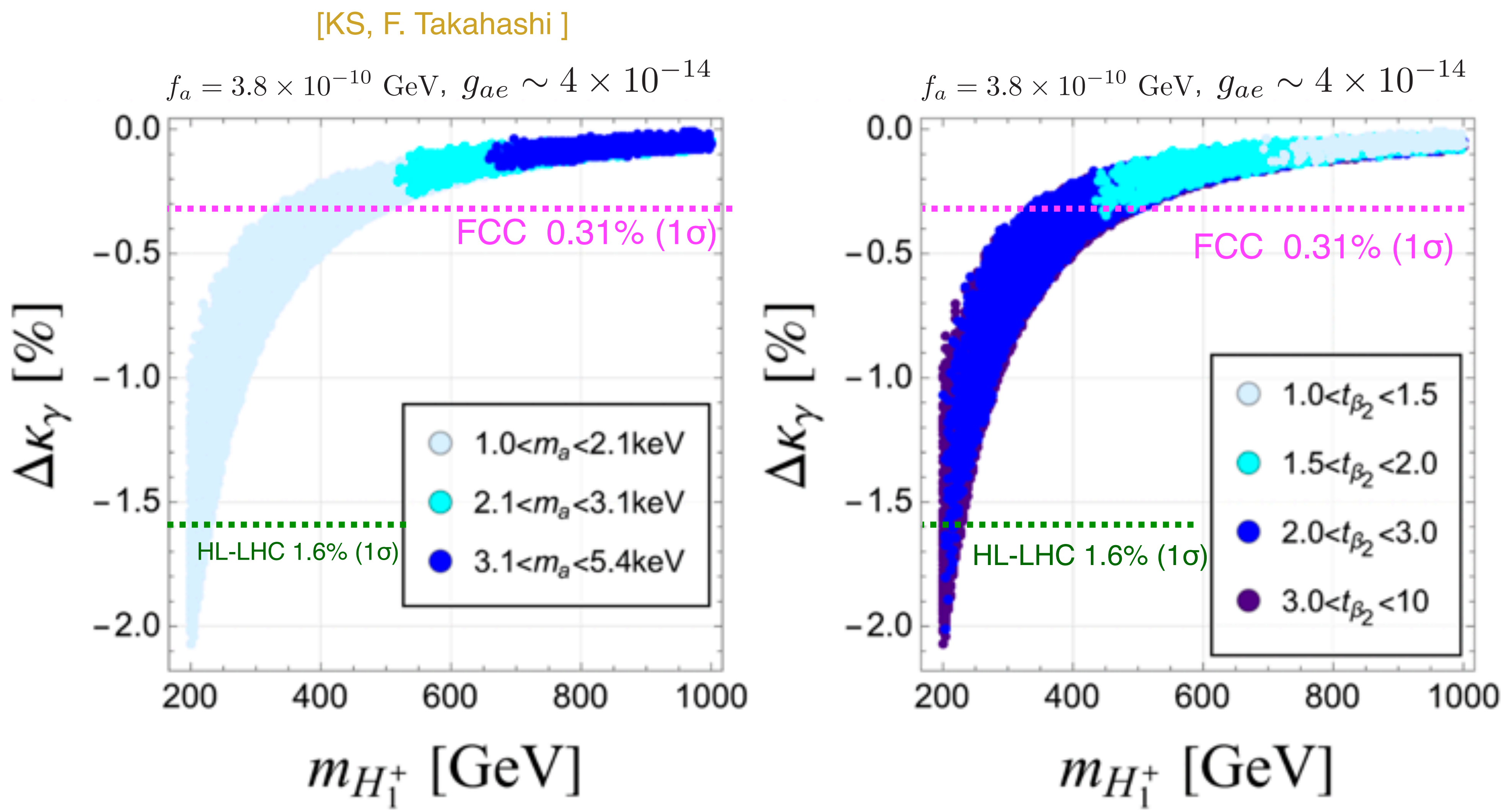
- Many parameter space is excluded by X-ray.

- 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



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

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

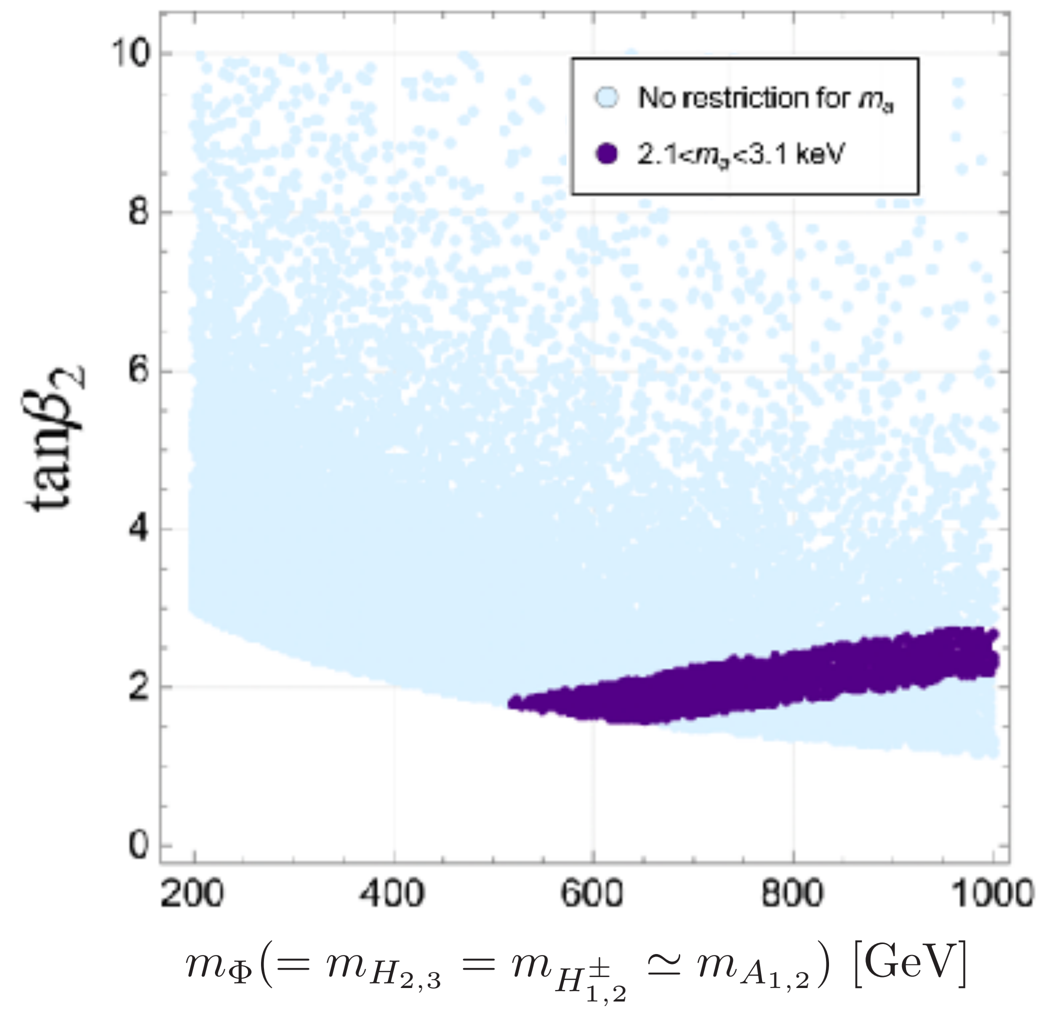
- The maximal size of deviation is around 2%. ← Perturvativity for the running coupling constants

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

Correlations for the potential parameters

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

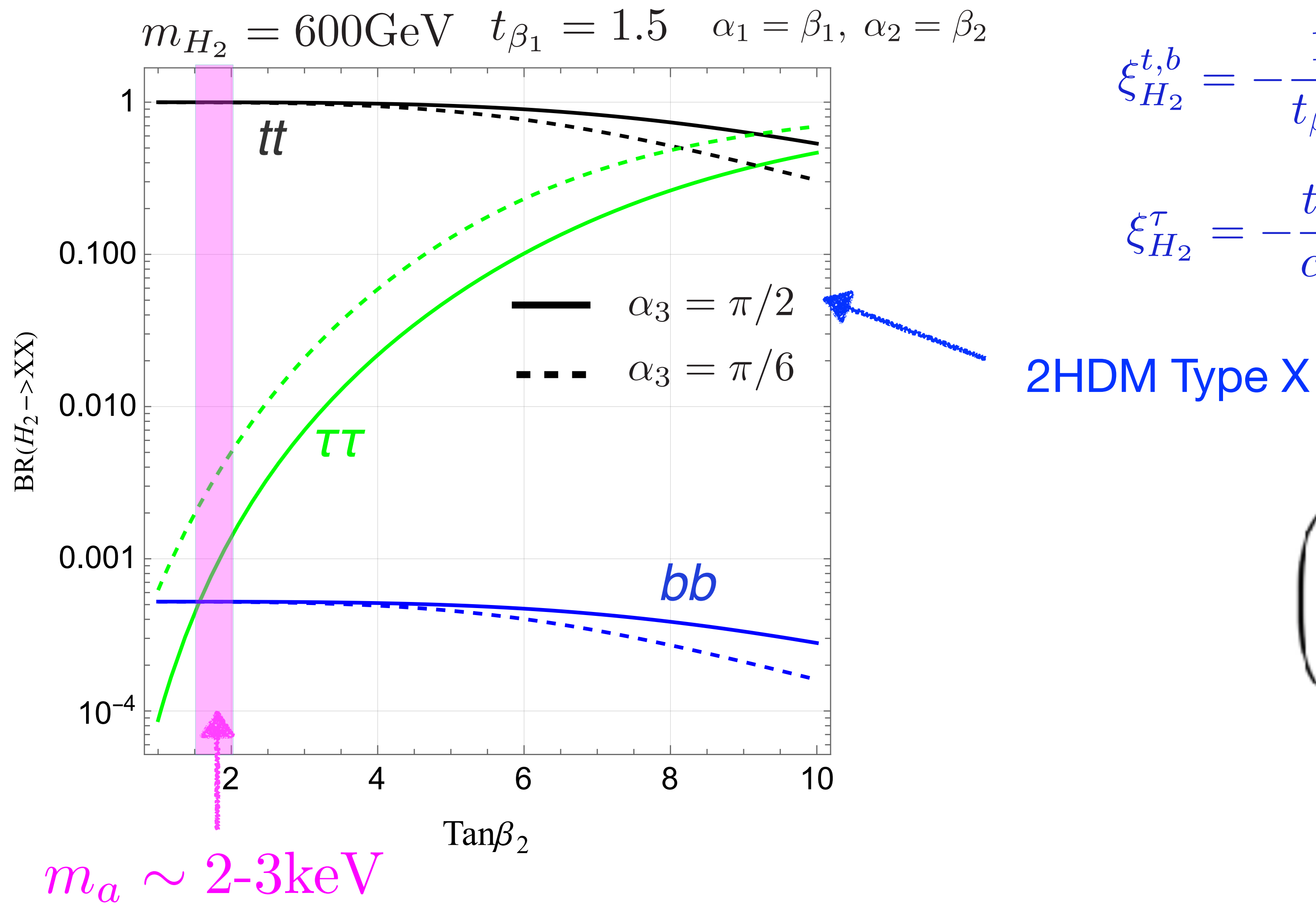
[KS, F. Takahashi]



→ 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



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

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

$$\begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = \underbrace{R_S}_{\equiv \mathcal{O}_{\alpha_3}\mathcal{O}_{\alpha_2}\mathcal{O}_{\alpha_1}} \begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix}$$

- BR($H_2 \to \tau\tau$) 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 $H_2 \to \tau\tau$.

Higgs potential

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

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

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

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

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

Yukawa interaction for the heavy Higgs

$$\mathcal{L}_Y^M \ni \frac{\sqrt{2}}{v} V_{\rm CKM} \sum_{i=1}^{2} \xi^q_{H_i^\pm} H_i^\pm \left\{ \bar{u}(m_u P_L - m_d P_R) d + \text{h.c.} \right\}$$

$$- \frac{m_q}{v} \sum_{i=1}^{3} \xi^q_{H_i} H_i \bar{q} q + i 2 I_q \frac{m_q}{v} \sum_{i=1}^{2} \xi^q_{A_i} A_i \bar{q} \gamma_5 q$$

$$- \sqrt{2} \frac{m_l}{v} \sum_{i=1}^{2} \xi^l_{H_i^\pm} H_i^\pm \left\{ \bar{\nu}_L P_R l + \text{h.c.} \right\} - \frac{m_l}{v} \sum_{i=1}^{3} \xi^l_{H_i} H_i \bar{l} l$$

$$-i \sum_l \frac{m_l}{v} \sum_{i=1}^{2} \xi^l_{A_i} A_i \bar{l} \gamma_5 l - i \sum_l g_{a\ell} a \bar{l} \gamma_5 l \ ,$$

$\xi^f_{H_i^+}$	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	$\frac{c_{\alpha_2} c_{\alpha_3}}{s_{\beta_2}}$	$\frac{1}{s_{\beta_1} c_{\beta_2}}(-s_{\alpha_1} s_{\alpha_2} c_{\alpha_3} - c_{\alpha_1} s_{\alpha_3})$	$\frac{c_{\alpha_2} c_{\alpha_3}}{s_{\beta_2}}$	$\frac{1}{c_{\beta_1} c_{\beta_2}}(-c_{\alpha_1} s_{\alpha_2} c_{\alpha_3} + s_{\alpha_1} s_{\alpha_3})$

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

$v_3 = v \sin\beta_2$

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: $\begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = \underbrace{R_S}_{\mathcal{O}_{\alpha_3}\mathcal{O}_{\alpha_2}\mathcal{O}_{\alpha_1} \to \mathcal{O}_{\alpha_3}\mathcal{O}_{\beta}} \begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix}$

[c.f.) 2HDM

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

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

]

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:

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

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

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

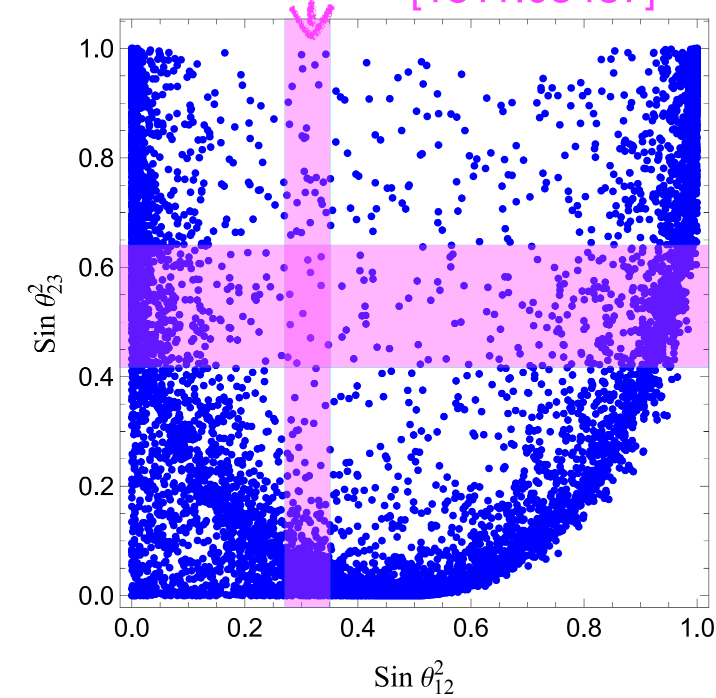
- Neutrino mass and mixing ($m_D = \text{diag}(y_1, y_2, y_3)\frac{v_3}{\sqrt{2}}$)

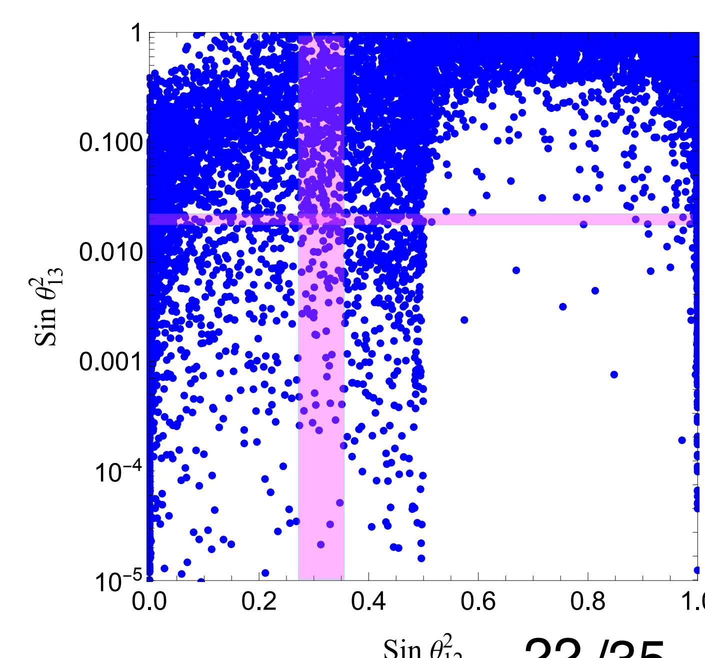
$$m_\nu \simeq m_D^T M_N^{-1} m_D \quad \propto \frac{y_i^2 v^2}{v_S} \quad \sim 0.1\text{eV}\left(\frac{y_i}{0.01}\right)^2 \left(\frac{10^{10}\text{GeV}}{v_S}\right)$$

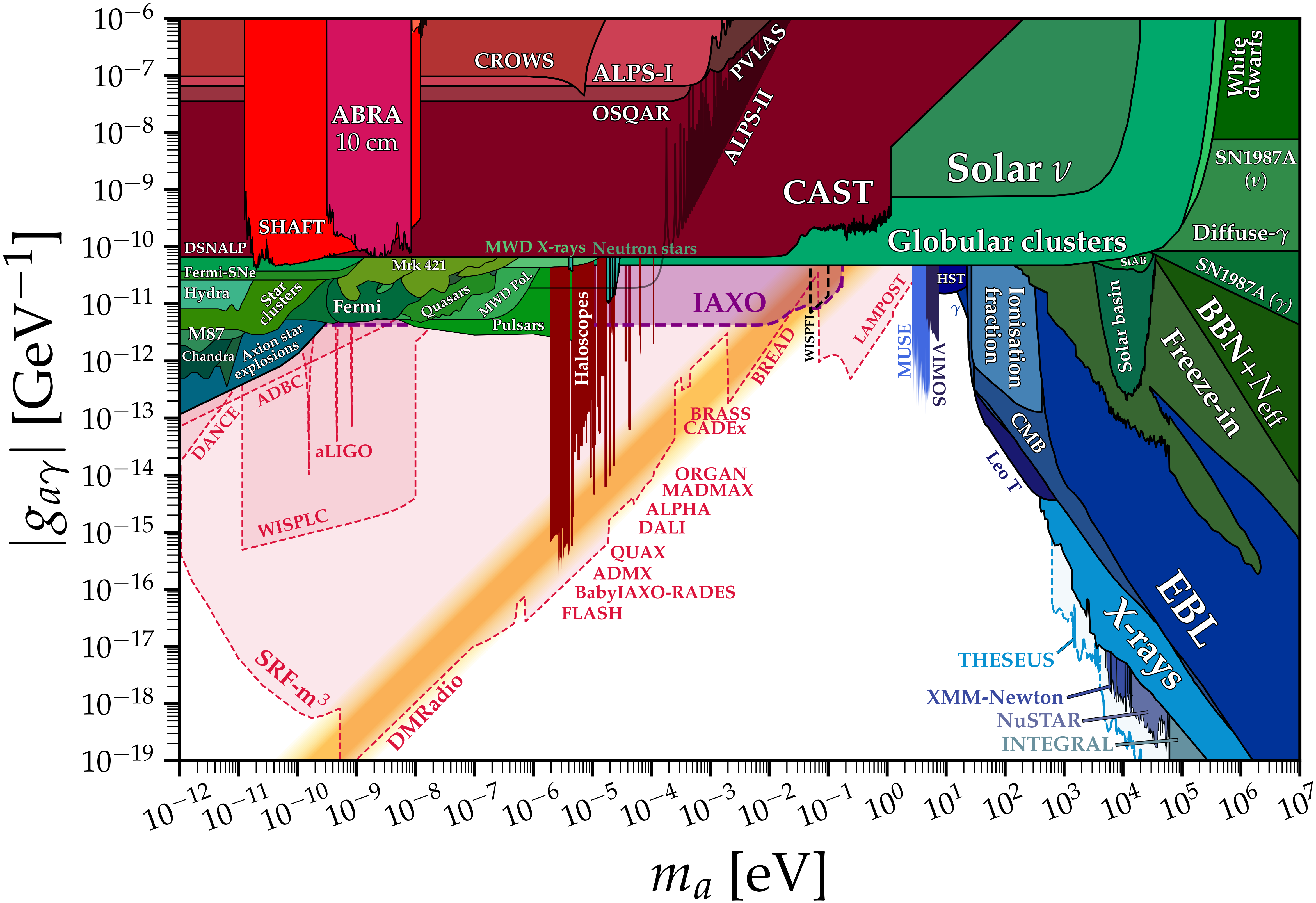
$$U_{PMNS}^\dagger m_\nu U_{PMNS} = \text{diag}(m_1, m_2, m_3)$$

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

Global fit oscillation data (3σ)
[1811.05487]







$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]
CROWS
ALPS-I
OSQAR
PVLAS
ALPS-II
ABRA
10 cm
SHAFT
CAST
Solar ν
Globular clusters
White dwarfs
SN1987A (ν)
Diffuse-γ
SN1987A (γ)
BBN+$N_{\rm eff}$
Freeze-in
Solar basin
StAB
DSNALP
Fermi-SNe
Hydra
Star clusters
Fermi
Mrk 421
Quasars
MWD Pol.
MWD X-rays
Neutron stars
Pulsars
M87
Chandra
Axion star explosions
Haloscopes
IAXO
WISPFI
LAMPOST
BREAD
MUSE
VIMOS
HST
γ
Ionisation fraction
CMB
Leo T
EBL
X-rays
THESEUS
XMM-Newton
NuSTAR
INTEGRAL
DANCE
ADBC
aLIGO
WISPLC
SRF-m^3
DMRadio
BRASS
CADEx
ORGAN
MADMAX
ALPHA
DALI
QUAX
ADMX
BabyIAXO-RADES
FLASH