Implications of anomaly-free axion to extra Higgs bosons in 3HDM

[arXiv:2203.17212]

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Contents

Beyond the Standard model

There are several unsolved problems in the standard model (SM):

Unsolved phenomena

- Dark matter (DM)
- Neutrino mass
- Baryon asymmetry
- …

Anomaly or excess

- W boson mass in CDF
- muon g-2
- XENON1T excess
- …

Mystery of the Higgs sector

- Numbers of Higgs fields
- Symmetry
- The relation with BSM phenomena and anomaly

Beyond the Standard model

There are several unsolved problems in the standard model (SM):

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Mystery of the Higgs sector

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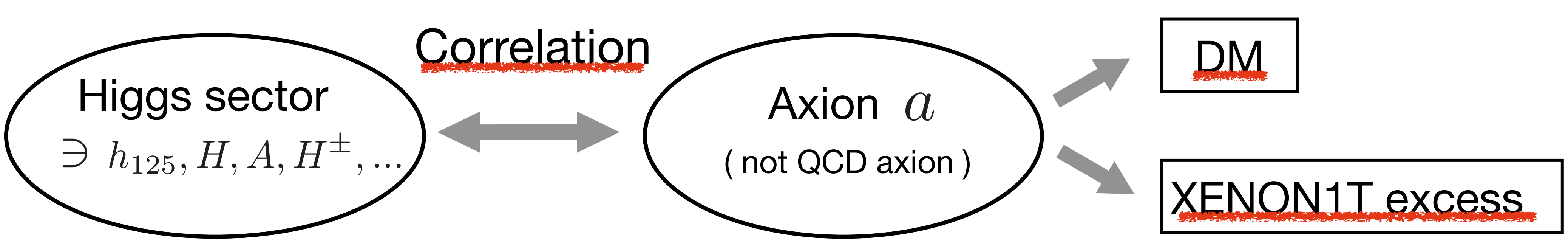
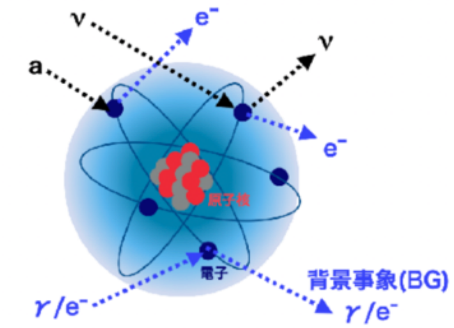
Our study:



[From slide of Kazama-san in ppp2020]

XENON1T excess [1/2]



- XENON 1T reported excess for electron recoil data in few keV region (2-3keV).

- Interpretations as New Physics
  - Solar axion
  - Bosonic DM (axion, dark photon)

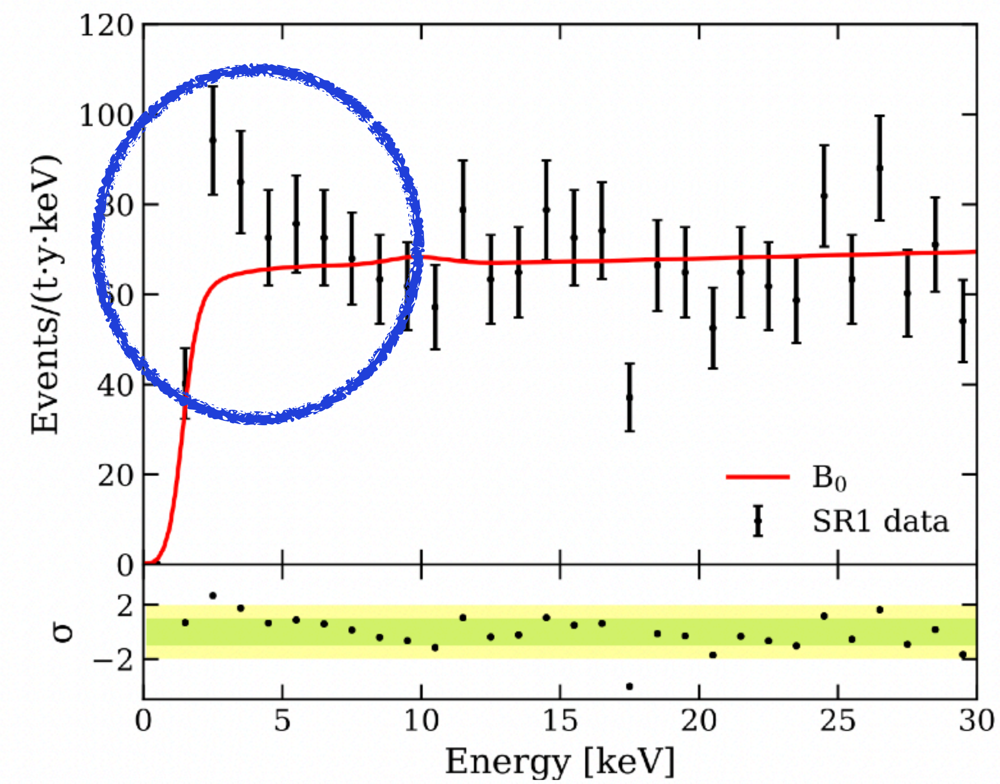
- Solar axions are produced through $g_{ae}, g_{a\gamma}, g_{an}$. Preferred parameter regions to explain the excess are evaluated.

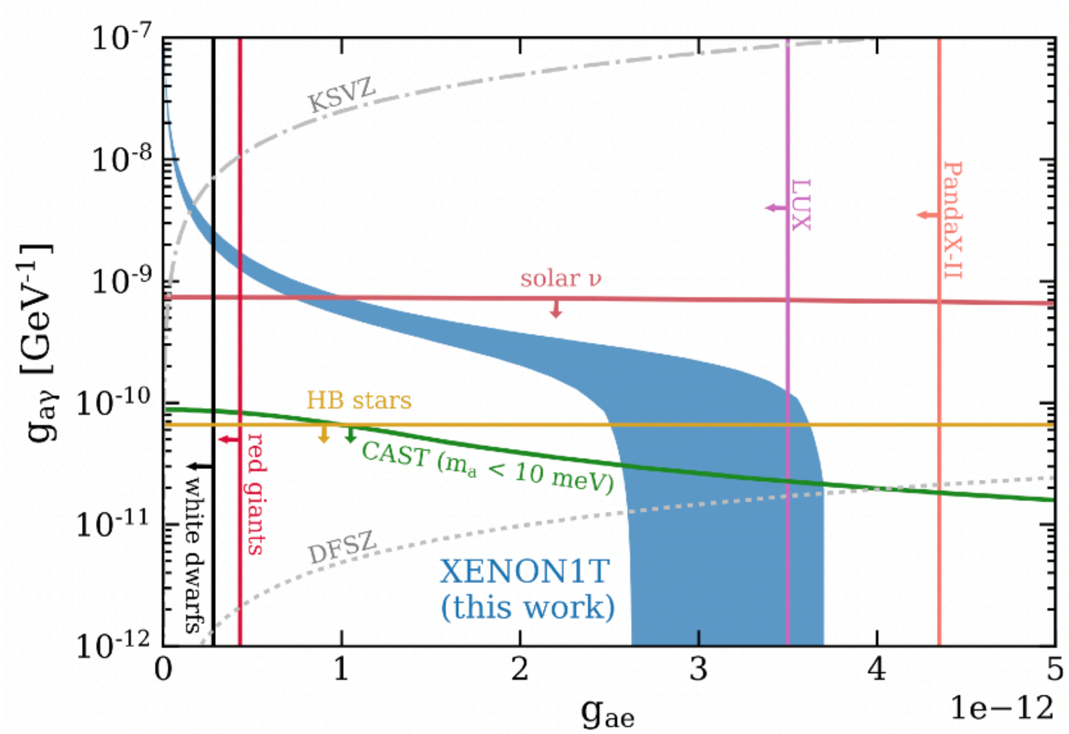
→ There is negative correlation between $g_{a\gamma}$ and g_{ae}.

→ The preferred parameter regions are already excluded Astropyical obseravations.

Bosonic DM may accommodate the excess.

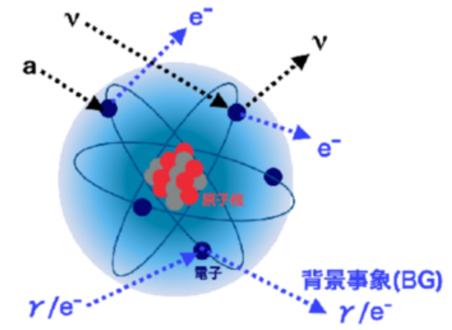
[XENON1T, 2006.09721]





XENON1T excess [2/2]

[From slide of Kazama-san in ppp2020]



- XENON 1T reported excess for electron recoil data in few keV region (2-3keV).

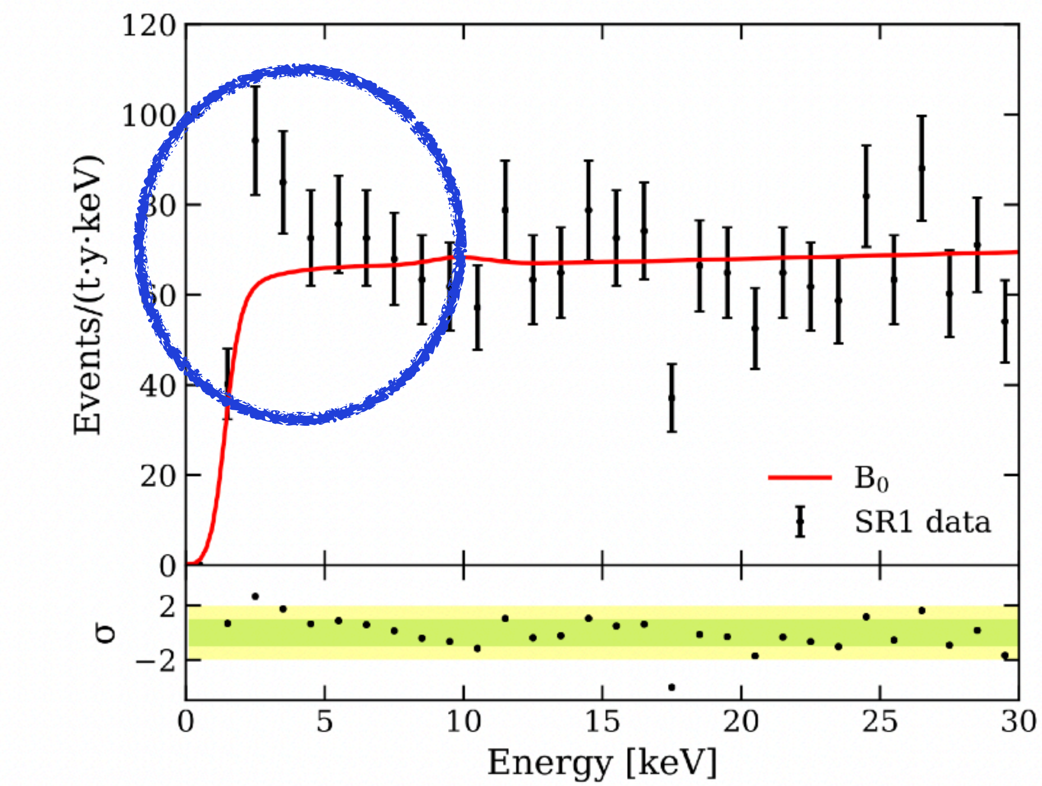
- Interpretations as New Physics
    - Solar axion
    - Bosonic DM (axion, dark photon)

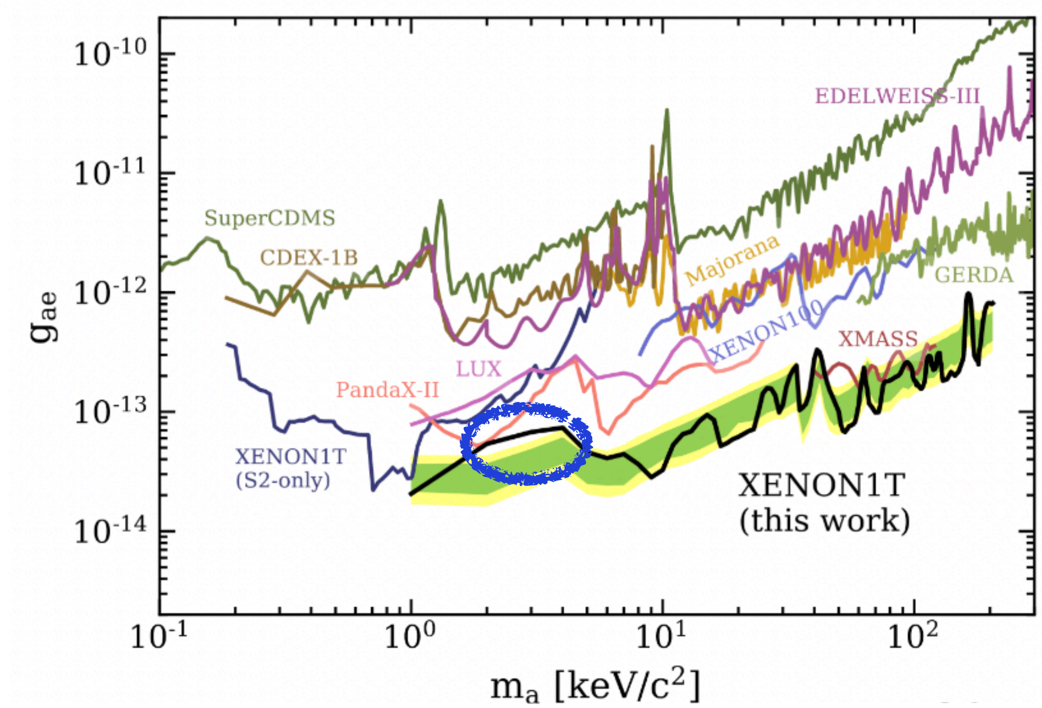
- Preferred value of axion coupling:

$$g_{aee} \sim \frac{m_e}{f_a}$$
$$\sim 10^{-14}$$

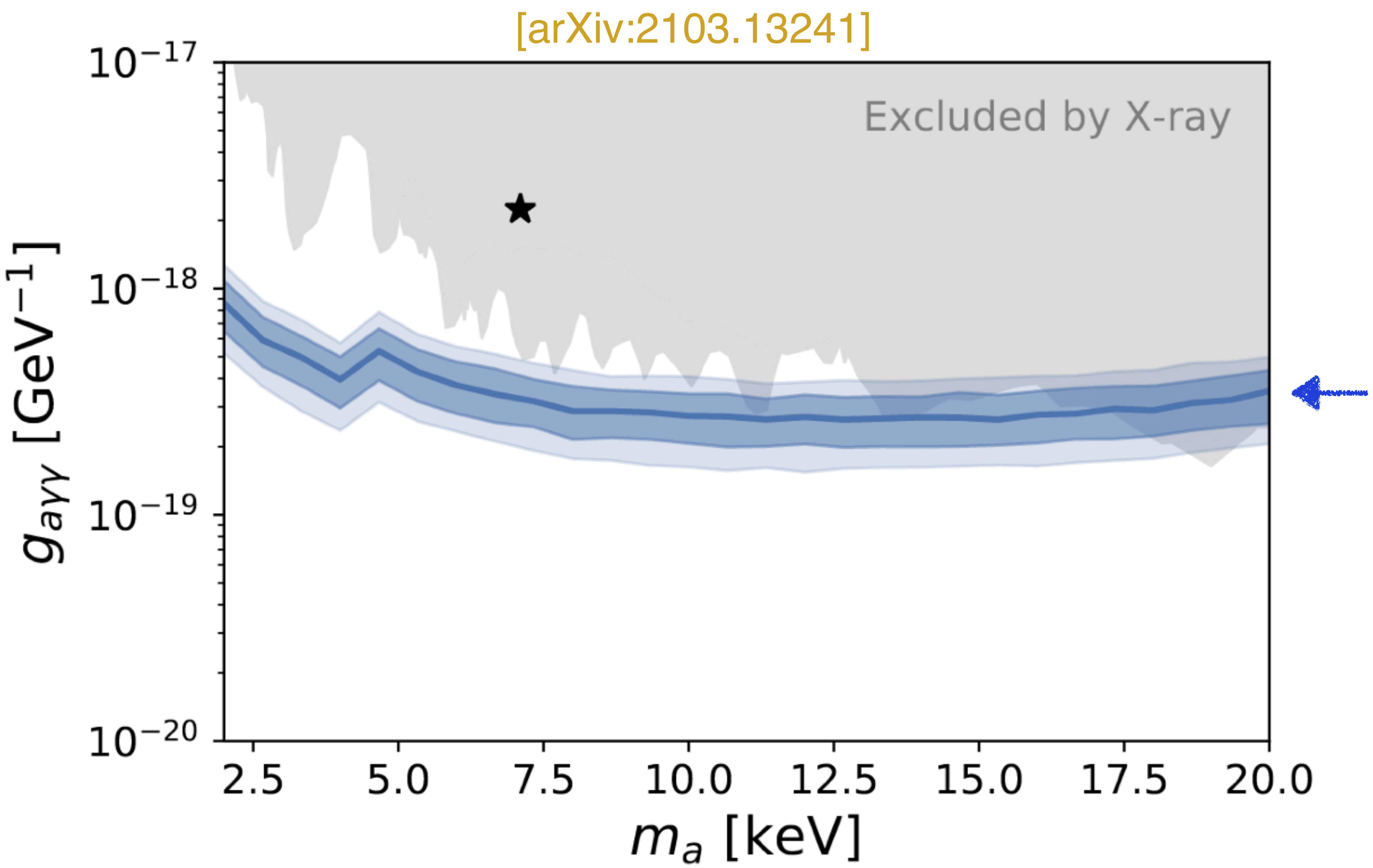
We need to consider if we can have the axion with the mass of O(1) keV and g_{ae}~10^{-14}

[XENON1T, 2006.09721]





Canonical axion case



Sensitivity of eROSITA
(future X-ray observatory)

$$\mathcal{L} = -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad g_{a\gamma\gamma} \equiv \frac{\alpha}{2\pi}\frac{C_{a\gamma}}{f_a}$$

$$f_a \sim \frac{\alpha}{8\pi}\frac{1}{g_{a\gamma\gamma}} \qquad (C_{a\gamma}=1)$$
$$\simeq 1\times 10^{15}\,\mathrm{GeV}\left(\frac{10^{-19}\,\mathrm{GeV}^{-1}}{g_{a\gamma\gamma}}\right)$$

$$\Rightarrow \quad g_{aee} \sim \frac{m_e}{f_a} \simeq 10^{-19}$$

This is too small for the required value of the XENON1T excess

Anomaly-free axion[1/3]

[K. Nakayama, F. Takahashi, T. Yanagida, Phys.Lett.B 734 (2014) 178]

- f_a can be O($10^{10\text{-}12}$)GeV while keeping the mass keV scale.
- It can be orignated from the SSB of $U(1)_F$.
- It does not has the anomalous photon coupling:

$$\mathcal{L}_{\rm eff} \simeq -(q_e + q_\mu + q_\tau)\frac{\alpha_{em}}{4\pi f_a} a F_{\mu\nu}\tilde{F}^{\mu\nu} \quad \Rightarrow \quad 0$$

(If $q_e + q_\mu + q_\tau = 0$)

$$+ \frac{\alpha_{em}}{48\pi f_a}\left(\frac{q_e}{m_e^2} + \frac{q_\mu}{m_\mu^2} + \frac{q_\tau}{m_\tau^2}\right) \times \left((\partial^2 a) F_{\mu\nu}\tilde{F}^{\mu\nu} + 2aF_{\mu\nu}\partial^2\tilde{F}^{\mu\nu}\right)$$

$$= m_a^2 a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\Rightarrow \quad g_{a\gamma\gamma} \simeq \frac{\alpha}{48\pi}\frac{q_e}{f_a}\frac{m_a^2}{m_e^2} \simeq 1\times 10^{-19}\left(\frac{q_e}{3}\right)\left(\frac{2\times 10^{10}\mathrm{GeV}}{f_a}\right)\left(\frac{m_a}{2\mathrm{keV}}\right)^2$$

This can evade constraint from the X-ray.

Anomaly-free axion[2/3]

Other features of anomaly-free axion.

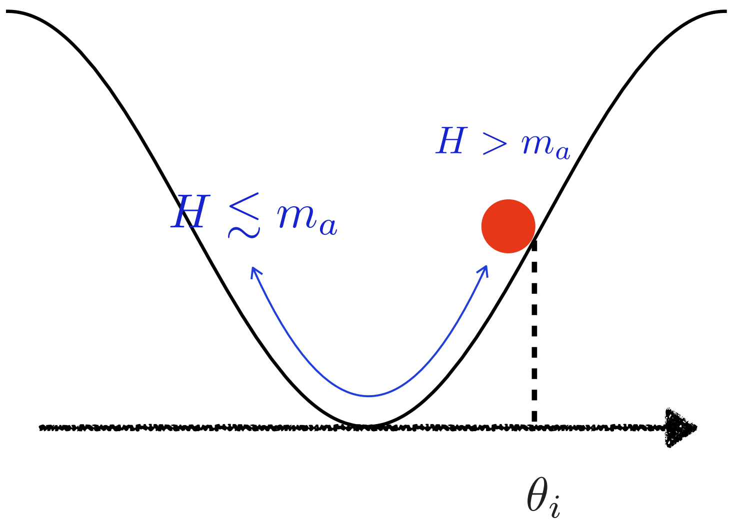
- It can be a good candidate for DM with the mass of order keV.

$$\Gamma(a \to \gamma\gamma) \simeq \frac{\alpha^2}{9216\pi^3}\frac{m_a^7}{f_a^2}\frac{q_e^4}{m_e^4}$$

$$\Rightarrow \tau_{a\to\gamma\gamma} \simeq 2\times 10^{32}\,\mathrm{sec.}\left(\frac{m_a}{2\,\mathrm{keV}}\right)^{-7}\left(\frac{f_a/q_e}{10^{10}\mathrm{GeV}}\right)^2$$

- Axion can be produced by the so-called misalignmet mechanism.

$$\Omega_a h^2 \sim 0.12\left(\frac{\theta_i}{2}\right)^2\left(\frac{q_e}{4}\right)^2\left(\frac{f_a/q_e}{10^{10}\mathrm{GeV}}\right)$$



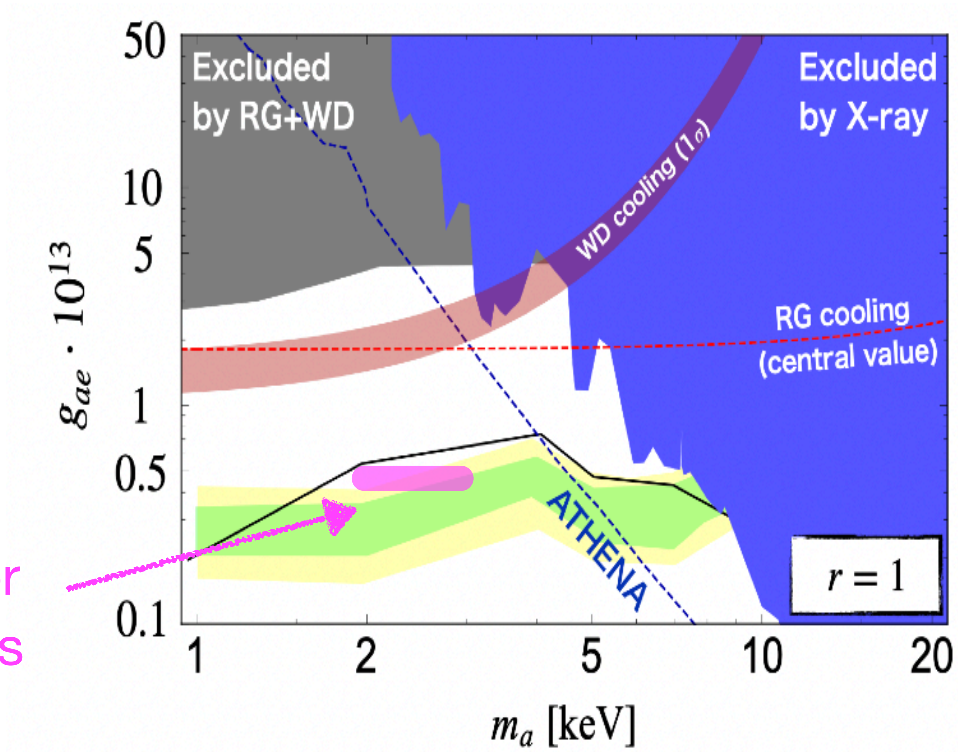
⇨ In the intermediate scale, the observed relic density can be satsfied without fintiuning of θ_i.

Anomaly-free axion[3/3]

- It can explain the excess for the electron recoil events reported by the XENON1T.

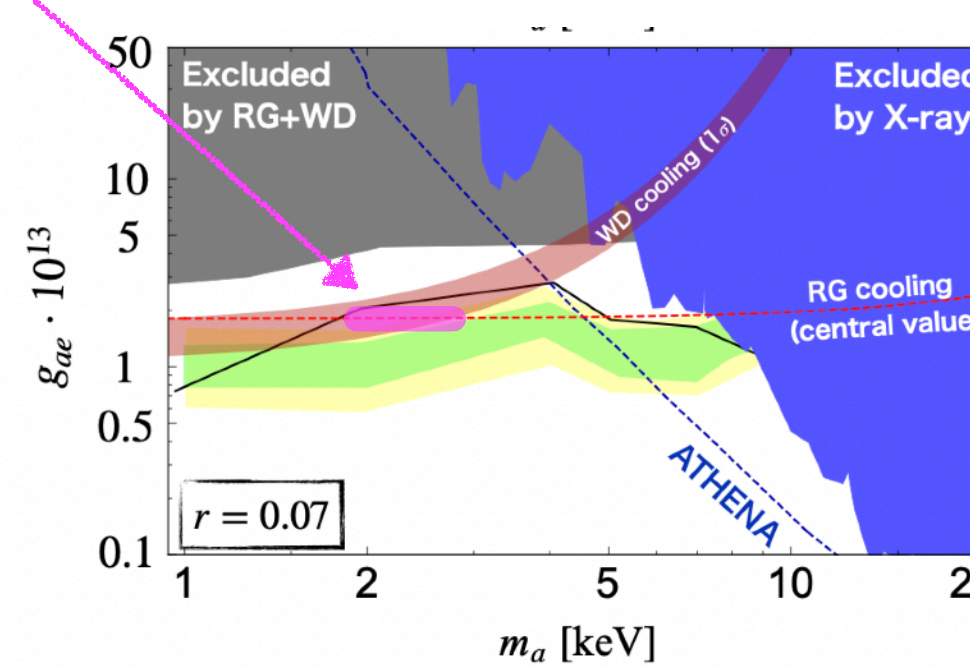
$$\frac{f_a}{q_e} \simeq 10^{10}\ \mathrm{GeV}\left(\frac{g_{ae}}{5\times 10^{-14}}\right)^{-1}$$

[F. Takahashi, M. Yamada, W. Yin, Phys.Rev.Lett. 125 (2020) 161801]



Favored region for XENON 1T excess

- If axion constitutes O(10)% of DM, it can accommodate aslo cooling anomaly.



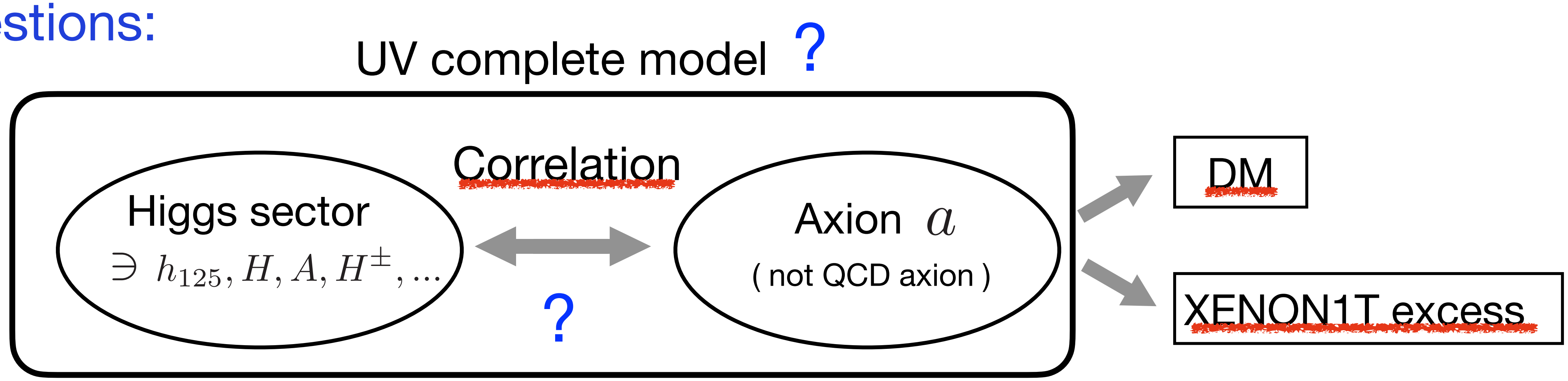
- It can be tested by future X-ray experiments such as ATHENA if m_a is relatively large.

$$r^{(\mathrm{th})} \equiv \Omega^{(\mathrm{th})}_{\mathrm{ALP}}/\Omega^{(\mathrm{obs})}_{\mathrm{DM}}$$

In this talk

These properties of the anomaly free-axion have been surveyed with the effective lagrangian for the axion in previous works.

Open questions:



This talk:

- We consider the thrree Higgs doublet models with the $U(1)_F$ symmetry.
- We inestigate the viable parameter space to explain to XENON1T excess for this model.
- We also disucss how the axion with keV mass and the heavy additional Higgs booss correlates

- Introduction
  - Motivation, Anomaly-free axion
- Model (Three Higgs doublet model)
- Numerical Results
  - Acomodation of XENON1T excess
  - Connection between axion and extra Higgs
- Summary

Why three Higgs doublet models?

- We parameterize U(1)$_F$ charge for the leptons as follows:

e_i: Righthanded leptons

ℓ_i: Lefthanded leptons

$$Q(e_i) = (\overset{e}{-a}, \overset{\mu}{-b}, \overset{\tau}{0}) \qquad Q(\ell_i) = (c, d, 0)$$

a,b,c,d: interger

(Anomolous photon coupling is zero)

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

- To have Yukawa interaction, we introduce Higgs doublet fields: $H(-a-c) \quad H(a+c) \quad H(0)$

$$\mathcal{L} \supset y_e \bar{e}_R \ell_1 H(-a-c) + y_\mu \bar{\mu}_R \ell_2 H(a+c) + y_\tau \bar{\tau}_R \ell_3 H(0) + \text{h.c.}$$

(If c=1)

$a =$ ~~0~~, ~~$+1$~~, $-1, \ +2, \ -2, \dots$ $\qquad b = -a, \ c = -d,$

Off-diagonal components are zero → $a \neq 0, \ a \neq c$

$a = -1$: One Higgs doublet $H(0)$ ← this does not contans extra Higgs

$a = 2$: Three Higgs doublet $H(-3), \ H(3), \ H(0)$ ← multi-Higgs doublet

We focus

Three Higgs doublet model with B-L Higgs boson [1/3]

- Symmetry

$$SU(2)_I \times U(1)_Y \times U(1)_{\mathrm{B-L}} \times U(1)_{\mathrm{F}}$$

Local (for $U(1)_{\mathrm{B-L}}$) and Global (for $U(1)_{\mathrm{F}}$)

$U(1)_F$

- Anomaly-free

$U(1)_{B-L}$

- To introduce B-L Higgs (singlet) boson.

- The CP-odd compontent is regarded as NGB which is identified as axion.

- fa can be taken around ~10^{10} GeV or above.

- Majorana mass for the righthanded neutrino can be generated by the SSB.

Three Higgs doublet model with B-L Higgs boson [2/3]

- Particle contents and charge assignment of the $U(1)_F$

		Higgs doublet			B-L Higgs			SM lepton/quark fields							
	$U(1)_F$ charge q	ϕ_1	ϕ_2	ϕ_3	S_0	S_1	$S_{\bar{2}}$	L_e	L_μ	L_τ	e_R	μ_R	τ_R	Q_L	q_R
(τ specific→)	Type-A	-3	3	0	0	1	-2	1	0	-1	-2	0	2	0	0
(μ specific→)	Type-B	-3	3	0	0	1	-2	1	-1	0	-2	2	0	0	0

- Yukawa lagrangian :

$$\mathcal{L}_Y = -(Y_u)_{ij}\bar{Q}_i\tilde{\phi}_3(u_R)_j - (Y_d)_{ij}\bar{Q}_i\phi_3(d_R)_j - y_e\bar{L}_e\phi_2 e_R - y_\ell \bar{L}_\ell\phi_3\ell_R - y_{\ell'}\bar{L}_{\ell'}\phi_1\ell'_R + \text{h.c.}$$

- $q_{L_e} + q_{L_\mu} + q_{L_\tau} = 0\,,\ \ q_{e_R} + q_{\mu_R} + q_{\tau_R} = 0$ i.e., Anomalous photon coupling vanishes.

- We have assumed that electrons are necessarily charged.

- $U(1)_{B\text{-}L}$ charge $Q_{B\text{-}L}(S_i) = +2$, $Q_{B\text{-}L}(\phi_i)$, $Q_{B\text{-}L}(L_\ell,\ \ell_R) = 0$

Three Higgs doublet model with B-L Higgs boson [2/3]

$$V = V_{\rm 3HDM}(\phi_i) + V_{\rm B-L}(s_k) + V_I(\phi_i, s_k)$$

$V_{\rm 3HDM}$: ~~$SU(2)_I$~~ $\times$ ~~$U(1)_Y$~~ , ~~$U(1)_F$~~ (Explicit)

$V_{\rm B-L}$: ~~$U(1)_{\rm B-L}$~~ $\times$ ~~$U(1)_F$~~ (Spontaneous)

V_I : Portal intereaction

$$\phi_k = \frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2}\, w_k^+ \\ v_k + h_k + i z_k \end{pmatrix}, \quad k = 1, 2, 3,$$

$$S_j = \frac{1}{\sqrt{2}}(v_{S_j} + \rho_j) e^{\frac{iQ_j}{f_a}\tilde{a}} \quad (j = 0,\ 1,\ \bar{2})$$

Physical states (Heavy Higss bosons in B-L Higgs sector are integrated out)

$$\begin{pmatrix} G^\pm \\ H_1^\pm \\ H_2^\pm \end{pmatrix} = \underbrace{R_+}_{\mathcal{O}_{\gamma_+}\mathcal{O}_\beta} \begin{pmatrix} w_1^\pm \\ w_2^\pm \\ w_3^\pm \end{pmatrix} \qquad \begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = \underbrace{R_S}_{\mathcal{O}_{\alpha_3}\mathcal{O}_{\alpha_2}\mathcal{O}_{\alpha_1}} \begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} \qquad \begin{pmatrix} G^0 \\ A_1 \\ A_2 \\ a \end{pmatrix} = \underbrace{R_P}_{\mathcal{O}_{\gamma_3}\mathcal{O}_{\gamma_2}\mathcal{O}_{\gamma_1}\mathcal{O}_\beta} \begin{pmatrix} z_1 \\ z_2 \\ z_3 \\ \tilde{a} \end{pmatrix}$$

$$\mathcal{O}_\beta = \begin{pmatrix} \cos\beta_2\cos\beta_1 & \cos\beta_2\sin\beta_1 & \sin\beta_2 \\ -\sin\beta_1 & \cos\beta_1 & 0 \\ -\cos\beta_1\sin\beta_2 & -\sin\beta_1\sin\beta_2 & \cos\beta_2 \end{pmatrix}$$

$\mathcal{O}_X$: 3×3 mixing matrix

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

H_1 : 125 GeV Higgs boson

$H_{2,3}$: CP-even Higgs boson

$H_{1,2}^\pm$: Charged Higgs boson

$A_{1,2}$: CP-odd Higgs boson

a : Anomaly-free axion

$G^0, G^\pm$: NGB for EWSB

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

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

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

]

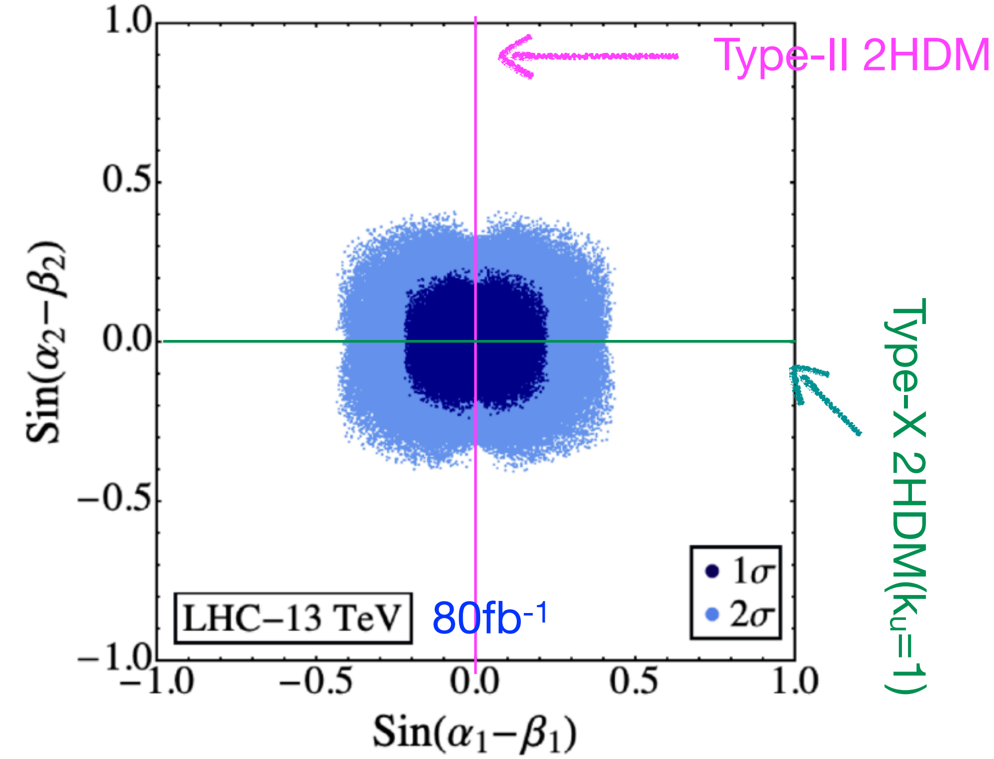
Higgs signal strength

Measurements of Higgs signal strength indicate (near) alignment limit.

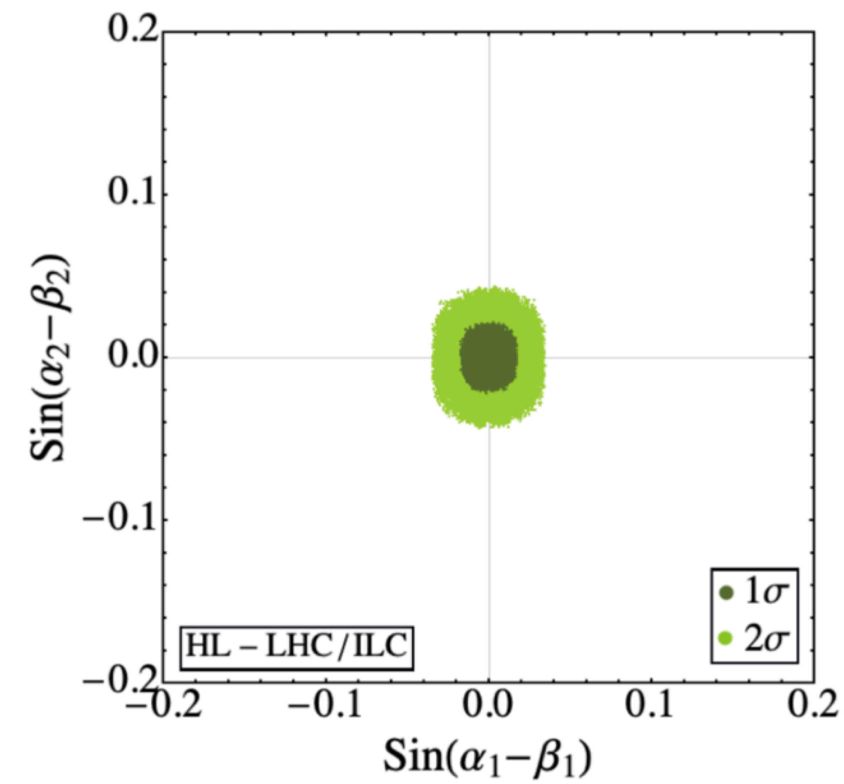
e.g.) 3HDM Type Z (u:ϕ_3, d:ϕ_2, ℓ:ϕ_1)

$$\kappa_u = \frac{\sin\alpha_2}{\sin\beta_2},$$
$$\kappa_d = \frac{\sin\alpha_1\cos\alpha_2}{\sin\beta_1\cos\beta_2},$$
$$\kappa_\ell = \frac{\cos\alpha_1\cos\alpha_2}{\cos\beta_1\cos\beta_2}$$

[D. Das, I. Saha, PRD100 (2019)]



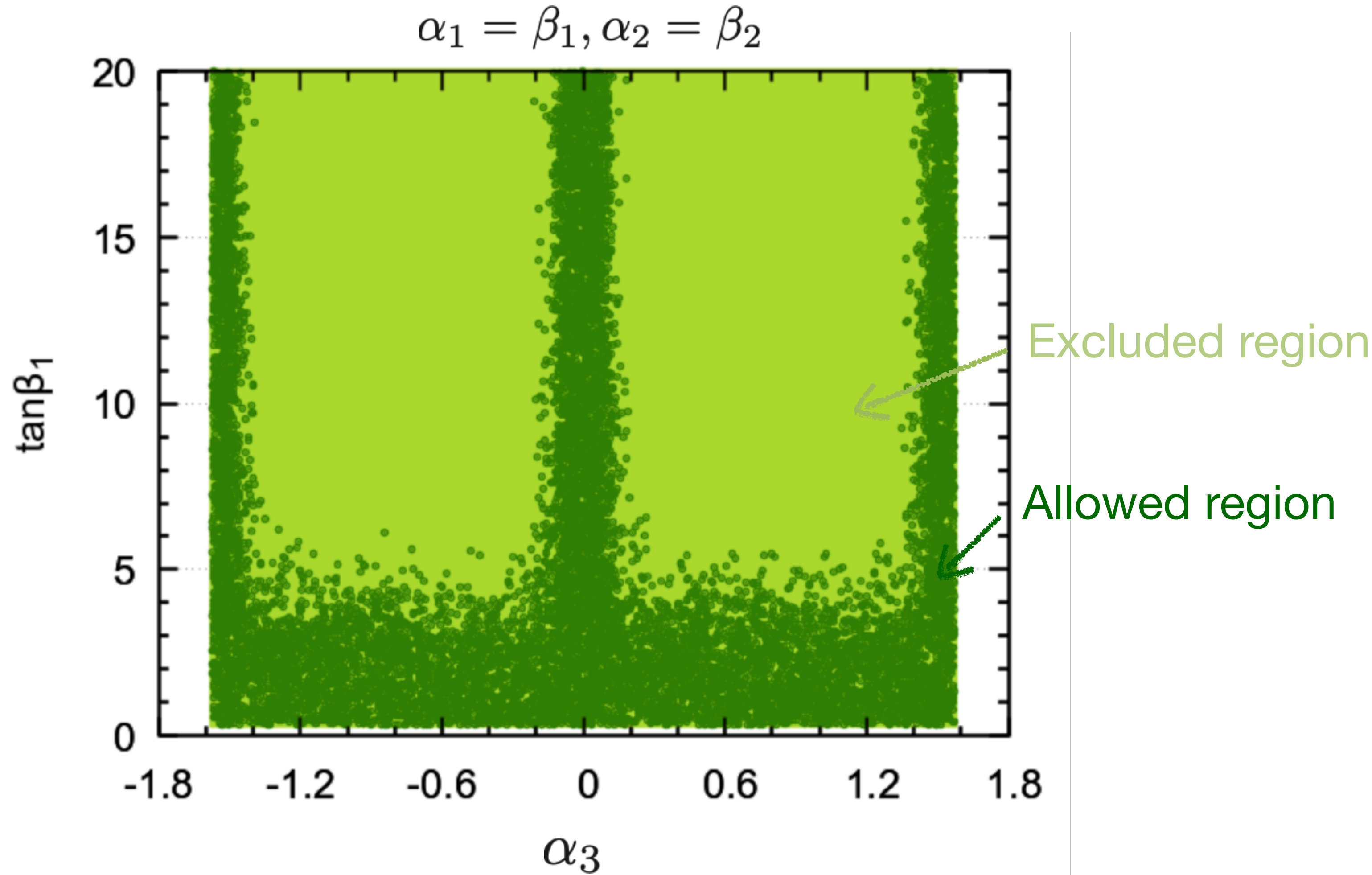
c.f.) 3HDM Type A (u:ϕ_3, d:ϕ_3, e:ϕ_2, μ:ϕ_3, τ:ϕ_1) [our case]



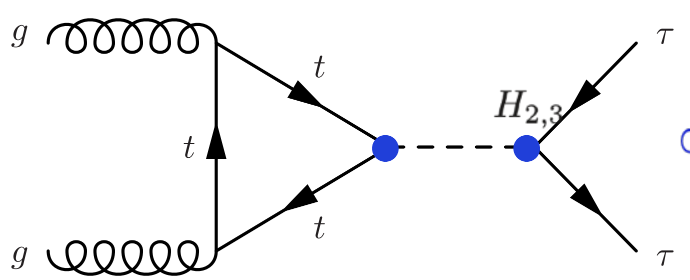
➡ To avoid the constraint, we basically take the alignment limit in our analysis.

Direct searches for additional Higgs bosons

e.g.) 3HDM Type Z (u:ϕ_3, d:ϕ_2, ℓ:ϕ_1) [2106.11977]



- The most severe constraint comes from $H_{2,3} \to \tau\tau$.



$\propto \xi^t_{H_i} \xi^\tau_{H_i}$

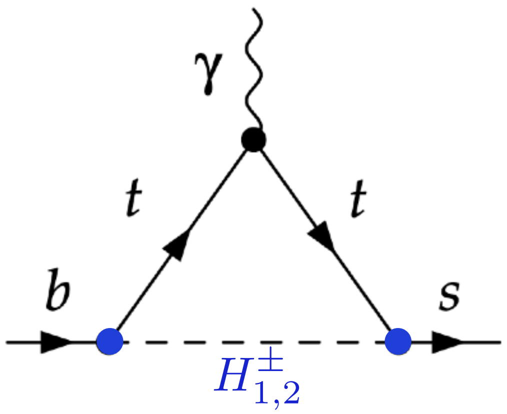
$$\xi^t_{H_2} = -\frac{1}{t_{\beta_2}} s_{\alpha_3} \qquad \xi^\tau_{H_2} = -\frac{t_{\beta_1}}{c_{\beta_2}} c_{\alpha_3} + t_{\beta_2} s_{\alpha_3}$$

$$\xi^t_{H_3} = \frac{1}{t_{\beta_2}} c_{\alpha_3} \qquad \xi^\tau_{H_3} = -t_{\beta_2} c_{\alpha_3} - \frac{t_{\beta_1}}{c_{\beta_2}} s_{\alpha_3}$$

⇒ $\sigma(pp \to H_{2,3} \to \tau\tau)$ can be sizable in case of $\alpha_3 \neq 0, \pm\frac{1}{2}$

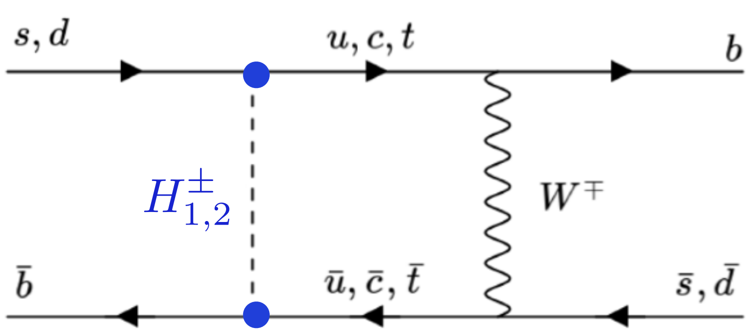
Constraint from flavor physics

- $B \to X_s \gamma$



\+ (*W* boson loop diagrams)

- $B_s - \bar{B}_s$ mixing

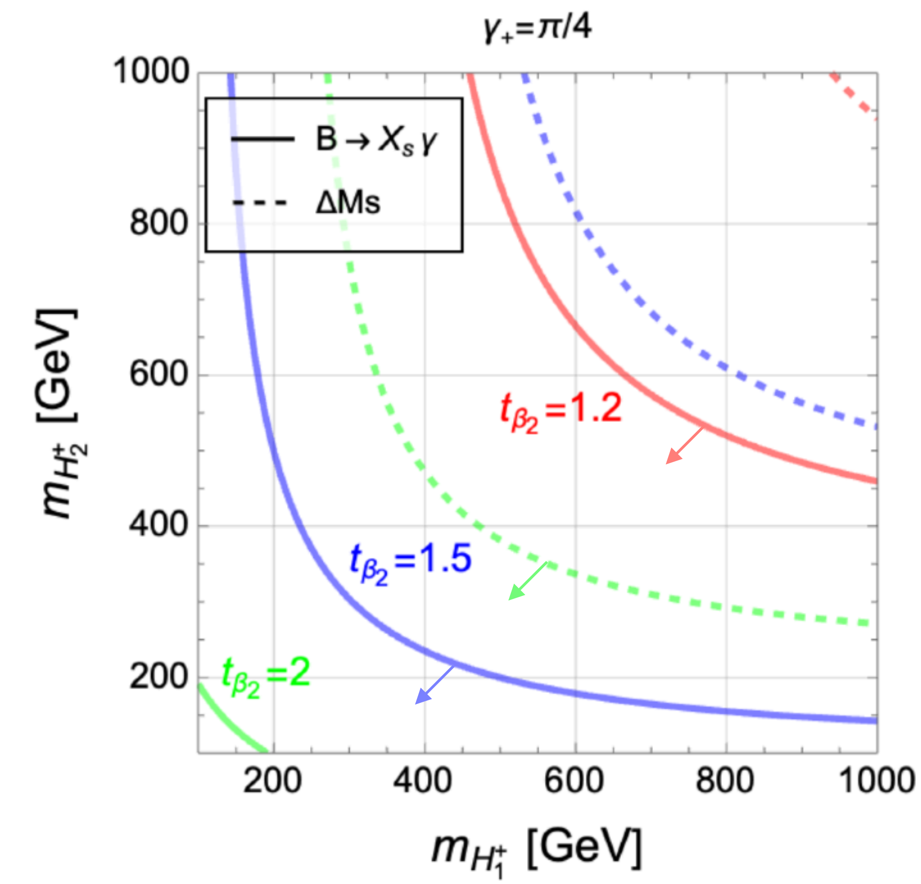


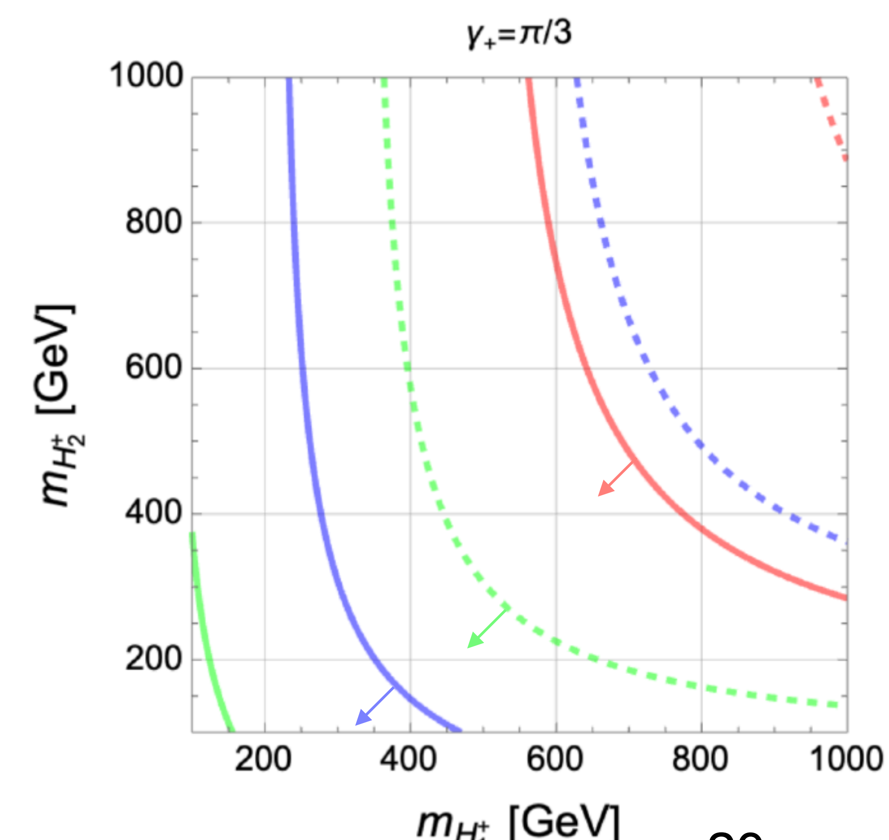
\+ (*W* boson loop diagrams)

$H^{\pm}$ couplings: $\xi^q_{H_1^+} = -\frac{s_{\gamma_+}}{t_{\beta_2}}, \ \xi^q_{H_2^+} = \frac{c_{\gamma_+}}{t_{\beta_2}}$ (Type-I like)

for Type A, B

- The constant of $B_s - \bar{B}_s$ mixing is tighter than $B \to X_s \gamma$.
- $t_{\beta_2} \gtrsim 1$ for $m_{H^{\pm}_{1,2}} \lesssim 1\text{TeV}$





Source of axion mass

- Axion obtains the mass from the explicit breaking term from the $U(1)_F$.
- The soft breaking terms of $U(1)_F$ are classified by the conserving discrete symmetries

Z_6: $\phi_1^\dagger(-3)\phi_2(3)$

Z_3: $\phi_{1,2}^\dagger(\mp 3)\phi_3(0),\ S_2^\dagger(-2)S_1(1)$

➡ We focus on $U(1)_F$ preserving Z_6

<u>3 Higgs doublet sector:</u> $V_{\rm 3HDM}$

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

<u>B-L Higgs sector:</u> $V_{\rm B-L}$

No soft term

Portal interaction :

$$V_I \ni -m'_{ij} e^{\pm 3i\frac{\tilde{a}}{f_a}}(\phi_i^\dagger\phi_j)$$

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

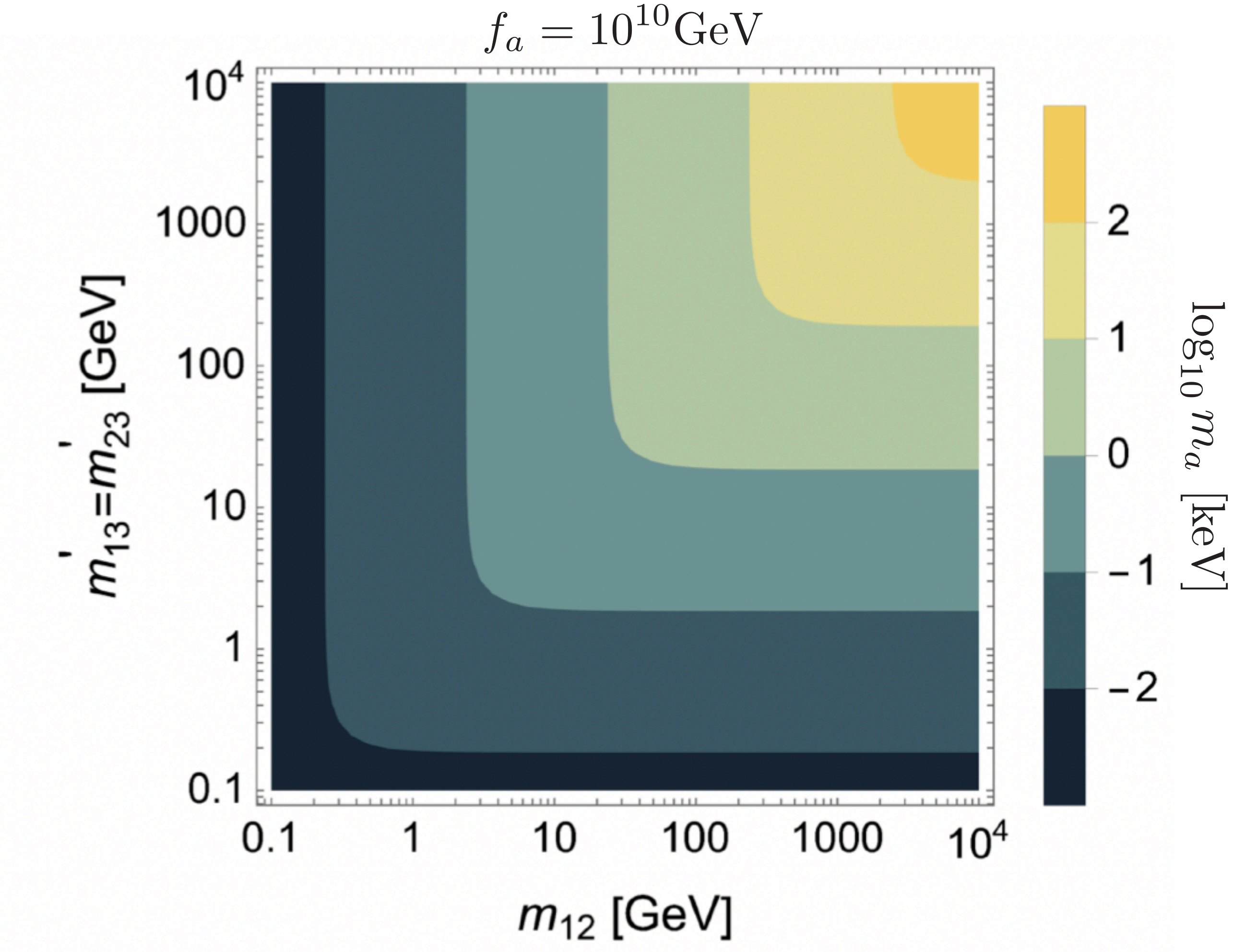
$$m_\Phi^2 \sim \frac{m_{12}^2 v^2}{v_1 v_2} + \lambda_i v^2$$

Mass of axion:

$$m_a^2 \sim m_{12}^2 \frac{v^2}{f_a^2}$$

➡ m_Φ and m_a relates through the soft breakig parameters and the portal couplings.

Axion mass



$$V_I \ni -m'_{ij} e^{\pm 3i \frac{\tilde{a}}{f_a}} (\phi_i^\dagger \phi_j)$$

$$m_a \simeq \begin{cases} 18 c_{\beta_2}^2 m_{12}^2 \frac{v^2}{f_a^2} \left[\left(1 - \frac{\sqrt{2}}{t_{\beta_2}} \frac{m_{12}^2}{m_{13}'^2} \right) - 9 c_{\beta_2}^2 \frac{v^2}{f_a^2} \left(1 - \frac{3\sqrt{2}}{t_{\beta_2}} \frac{m_{12}^2}{m_{13}'^2} \right) \right] & (m_{12}^2 \sim v^2 \ll m_{13}'^2) \\ 9 s_{\beta_2} m_{13}'^2 \frac{v^2}{f_a^2} \left[\sqrt{2} c_{\beta_2} - \frac{m_{13}'^2}{m_{12}^2} s_{\beta_2} \right] & (m_{13}'^2 \sim v^2 \ll m_{12}^2) \end{cases}$$

- When $m_{12}, m'_{13,23} \sim 100\mathrm{GeV}$, axion can be keV sclale for $f_a = 10^{10}\mathrm{GeV}$.
- Both of the soft parameters are needed to be large in incleasing m_a .

Neutrino masses

If we introduce righthanded 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:

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

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

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

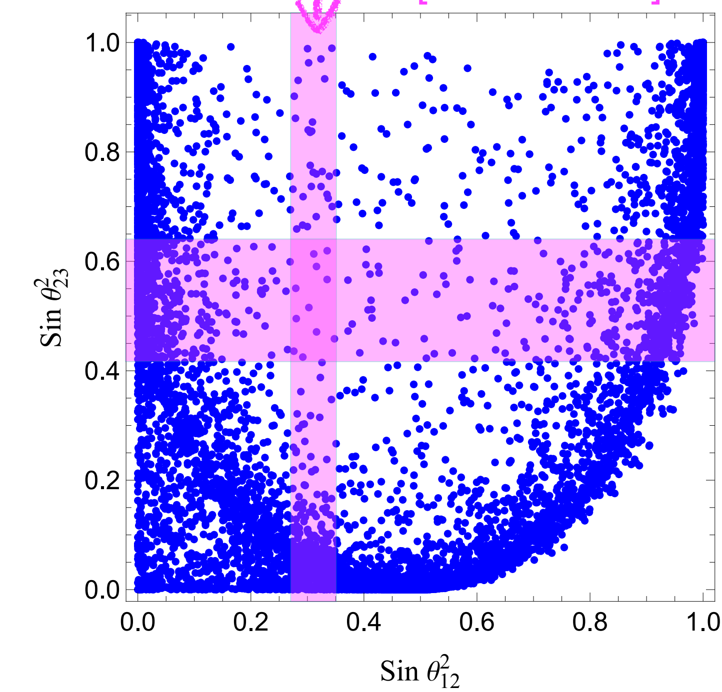
- Neutrino mass and mixing ($m_D = \text{diag}(y_1, y_2, y_3)\frac{v_3}{\sqrt{2}}$)

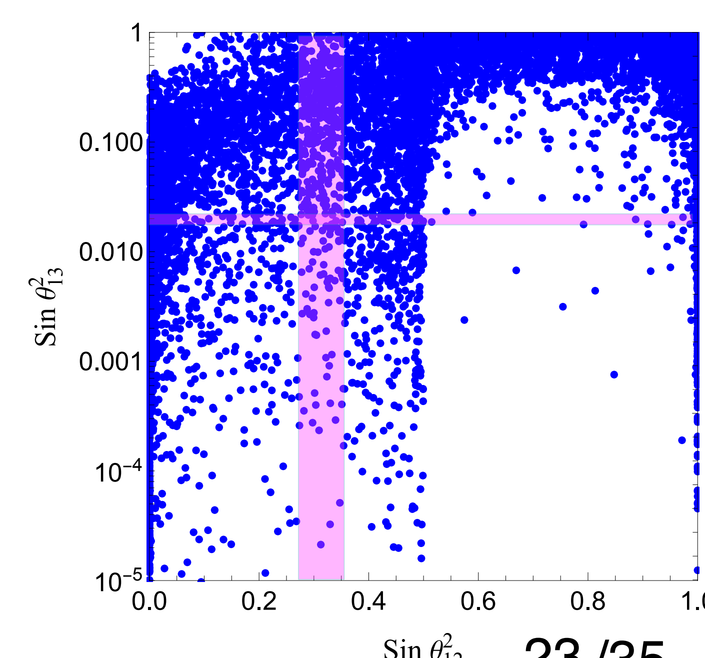
$$m_\nu \simeq m_D^T M_N^{-1} m_D \quad \propto \frac{y_i^2 v^2}{v_S} \quad \sim 0.1\text{eV}\left(\frac{y_i}{0.01}\right)^2 \left(\frac{10^{10}\text{GeV}}{v_S}\right)$$

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

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

Global fit oscillation data (3σ) [1811.05487]





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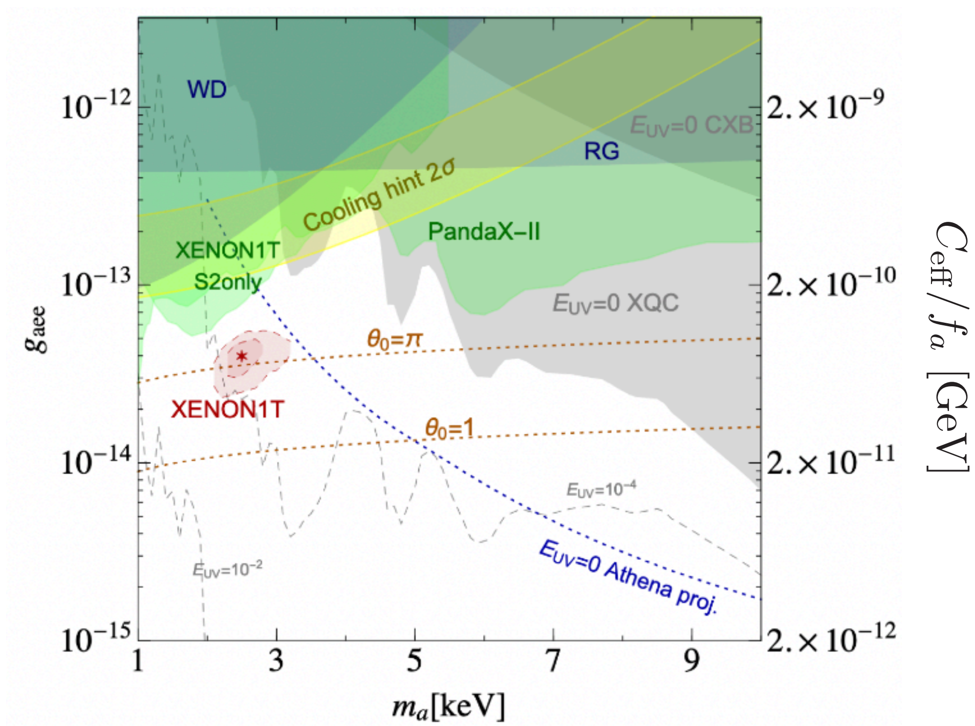
The anomaly-free axion can acomodate XENON 1T excess?

We discuss the if the anomalfy-free axion can acomodate XENON 1T excess in considering expereimental constraint and theoretical constraints.

- Favored region for the XENON1T excess:

$$2.1\ \mathrm{keV} \lesssim m_a \lesssim 3.1\ \mathrm{keV}$$
$$2 \times 10^{-14} \lesssim g_{aee} \lesssim 6 \times 10^{-14}$$

[I. M. Bloch, A. Caputo, et. al., 2006.14521]



- We scan input parameters to seek the viable parameter space.

- Constraints:
  - Thoretical bounds:
    - Perturvativity for the running coupling constants (up to $\Lambda = f_a$) → $m_\Phi \simeq M_{ij}^{(\prime)}$
    - Potential bounded from below

$$V_I \ni -m'_{ij} e^{\pm 3i\frac{\tilde{a}}{f_a}} (\phi_i^\dagger \phi_j)$$

$$M_{13}'^2 = \frac{m_{13}'^2}{c_{\beta_1} c_{\beta_2} s_{\beta_2}}, \quad M_{23}'^2 = \frac{m_{23}'^2}{s_{\beta_1} c_{\beta_2} s_{\beta_2}}$$

  - Experimental bounds:
    - Higgs signal strength → Alignment limit $\alpha_1 = \beta_1,\ \alpha_2 = \beta_2$
    - *B* meson decay, mixing → $\tan\beta_2 \gtrsim 1$
    - S,T parameters

Axion mass

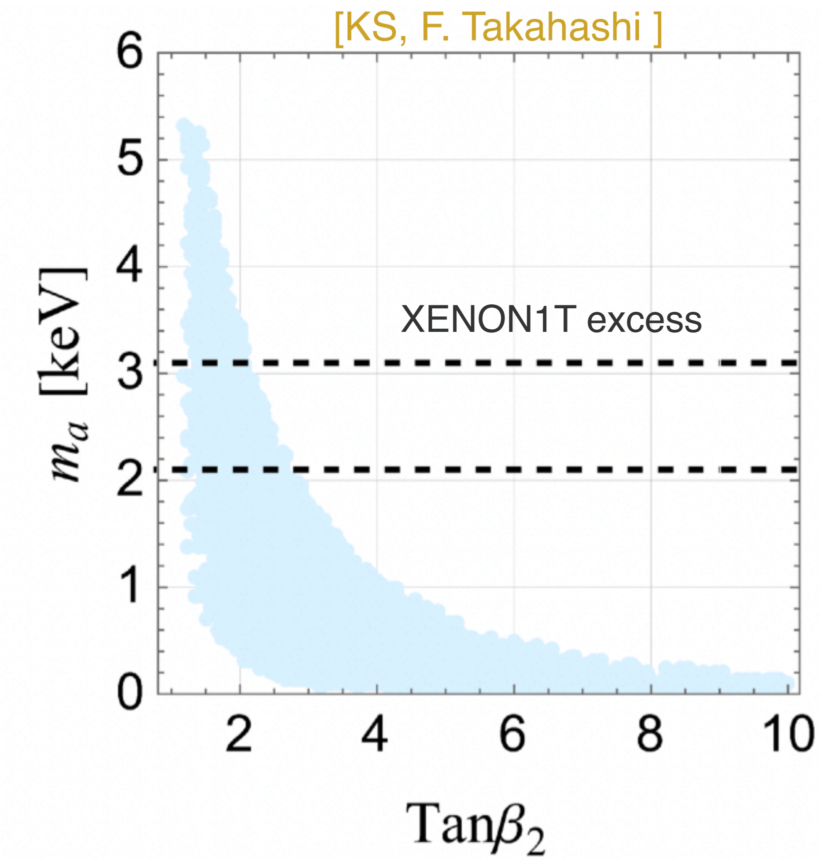
- Negative corrections for *tanβ₂* (also for *tanβ₁*)

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

The only source of the $U(1)_F$ breaking.

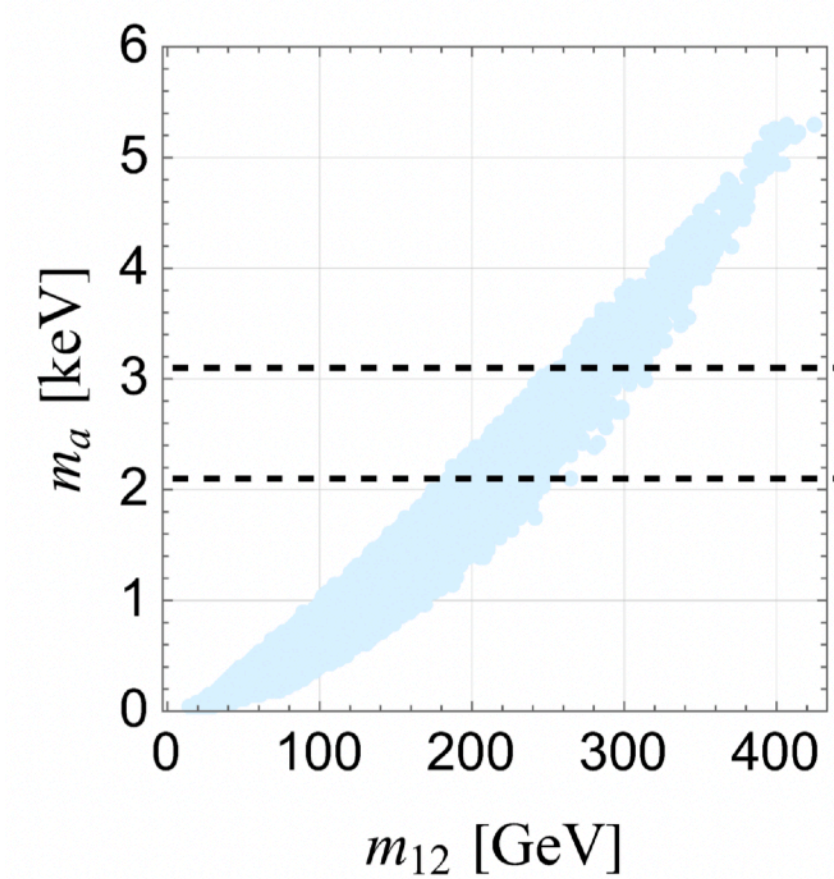
$$v_1 = v\cos\beta_1\cos\beta_2\,,\quad v_2 = v\sin\beta_1\cos\beta_2\,,\quad v_3 = v\sin\beta_2$$

In $\tan\beta_2 \gg 1$, the effect of $U(1)_F$ breaking is suppressed.



- Positive corrections for m_{12} (also for m'_{13}, m'_{23})

$$m_a^2 \sim m_{12}^2\frac{v^2}{f_a^2}$$



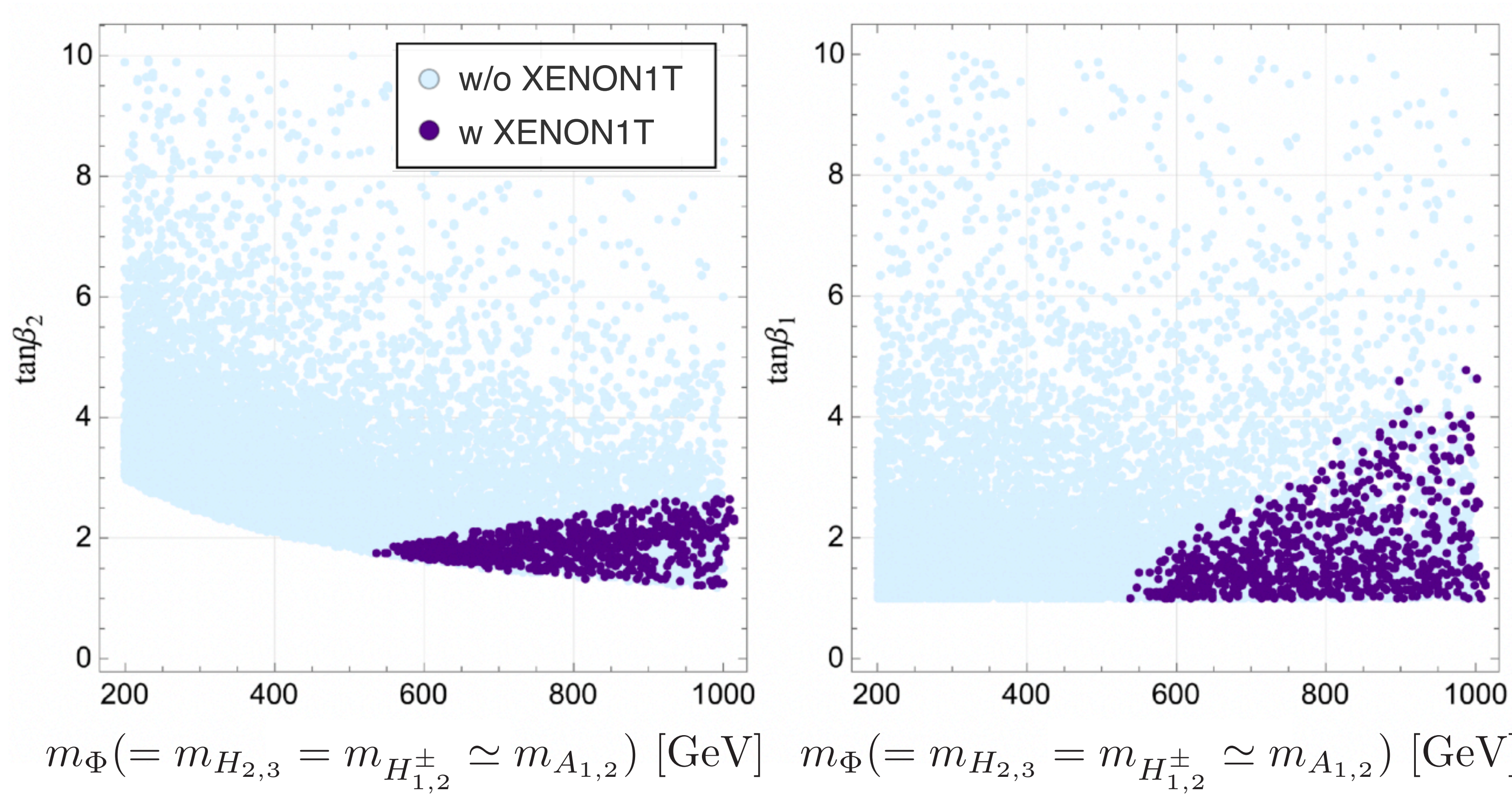
- Favored region for XENON1T excess restricts the range of these parameters.

$$1 \lesssim \tan\beta_2 \lesssim 3\,,\qquad 180{\rm GeV} \lesssim m_{12} \lesssim 320{\rm GeV}$$

Accommodation of XENON 1T excess

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

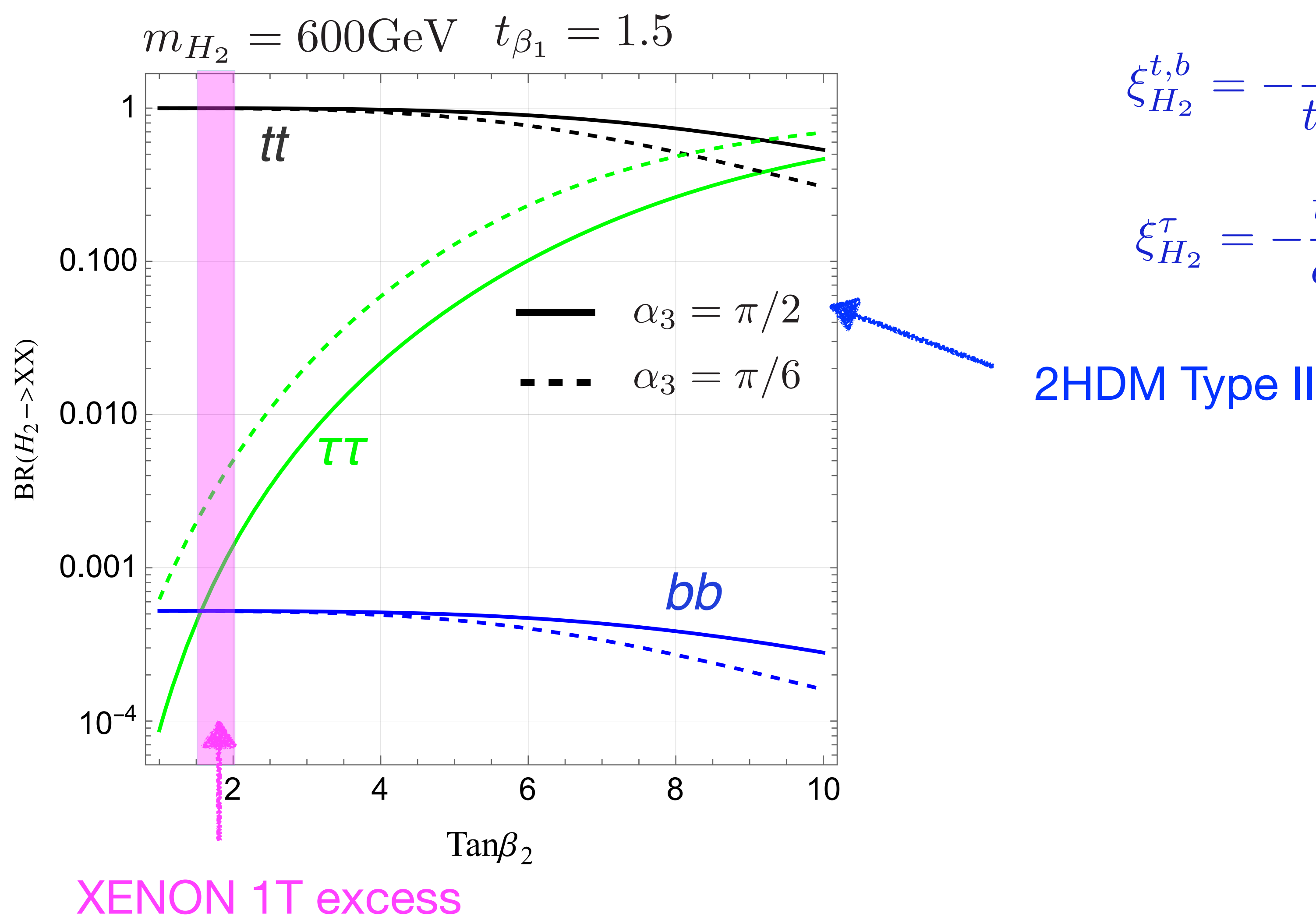
[KS, F. Takahashi]



→ m_Φ should be heavier than around 500 GeV for the scenario to explain XENON1T excess.

→ 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



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

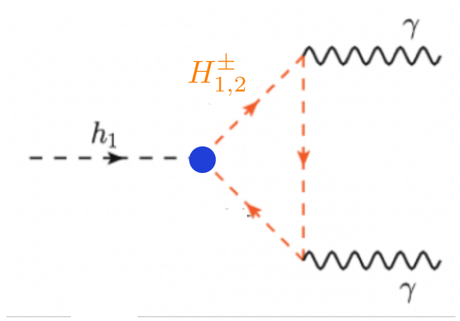
$$\xi_{H_2}^{\tau} = -\frac{t_{\beta_1}}{c_{\beta_2}} c_{\alpha_3} + t_{\beta_2} s_{\alpha_3}$$

- BR($H_2 \to \tau\tau$) is relatively larger than the case of Type II 2HDM.

- The XENON1T scenario predicts a similar decay pattern of H2 except for $H_2 \to \tau\tau$.

Predictions for the Higgs couplings

- For h—>γγ , $H^{\pm}_{1,2}$ contributes.



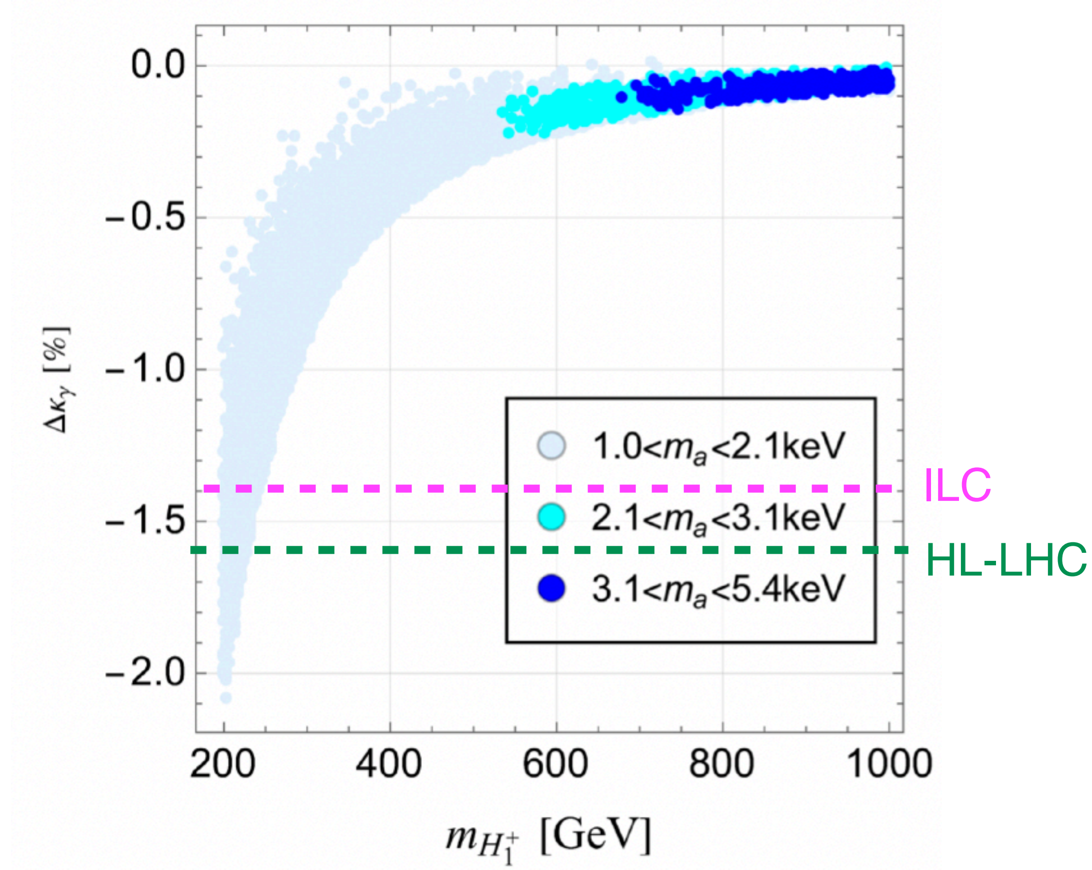
$$\lambda_{H_1 H_i^\pm H_i^\pm} v = m_{H_1}^2 + 2(m_{H_i^\pm}^2 - M_{12}^2)$$

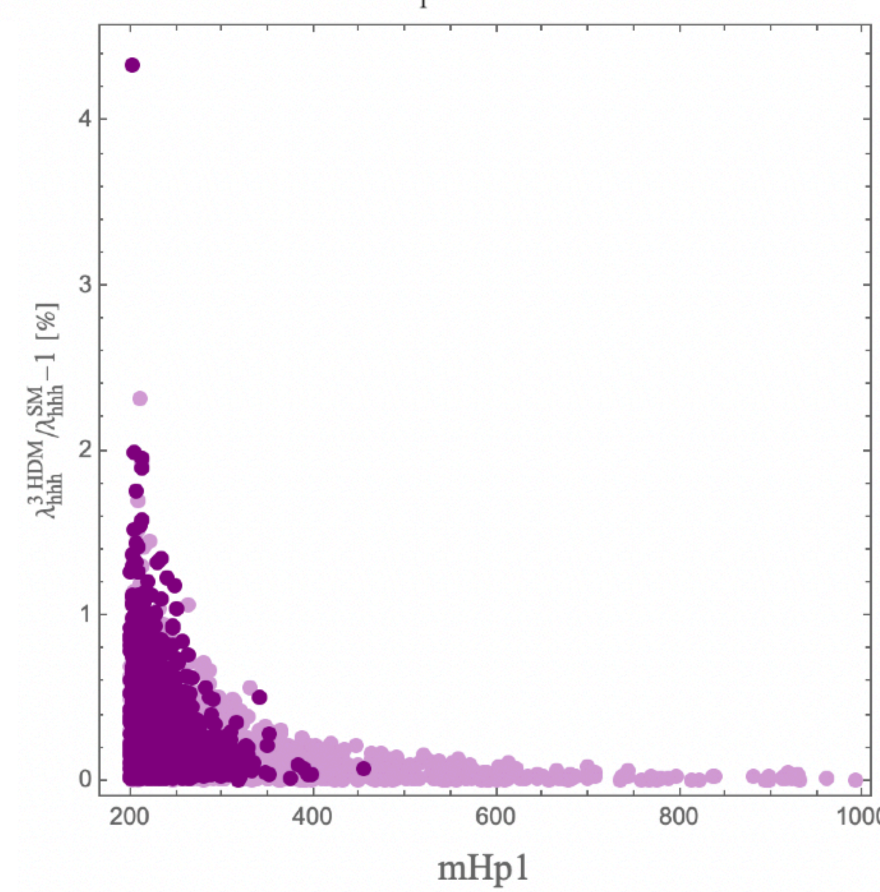
- $\Delta\kappa_\gamma \lesssim 2\%$ due to perturbativity for running couplngs

- $\Delta\kappa_\gamma \neq 0$ in $200\text{GeV} \lesssim m_{H_1^\pm} \lesssim 300\text{GeV}$ due to the constraint from B_s-B_s mixing.

- λ_{hhh} is evaluated from the effective potential method. The maximal deviation is 4.3%.

[KS, F. Takahashi]





If we find sizable deviations in future colliders,
3HDM with B-L Higgs can be excluded.

Correlation between axion coupling and heavy Higgs mass [1/2]

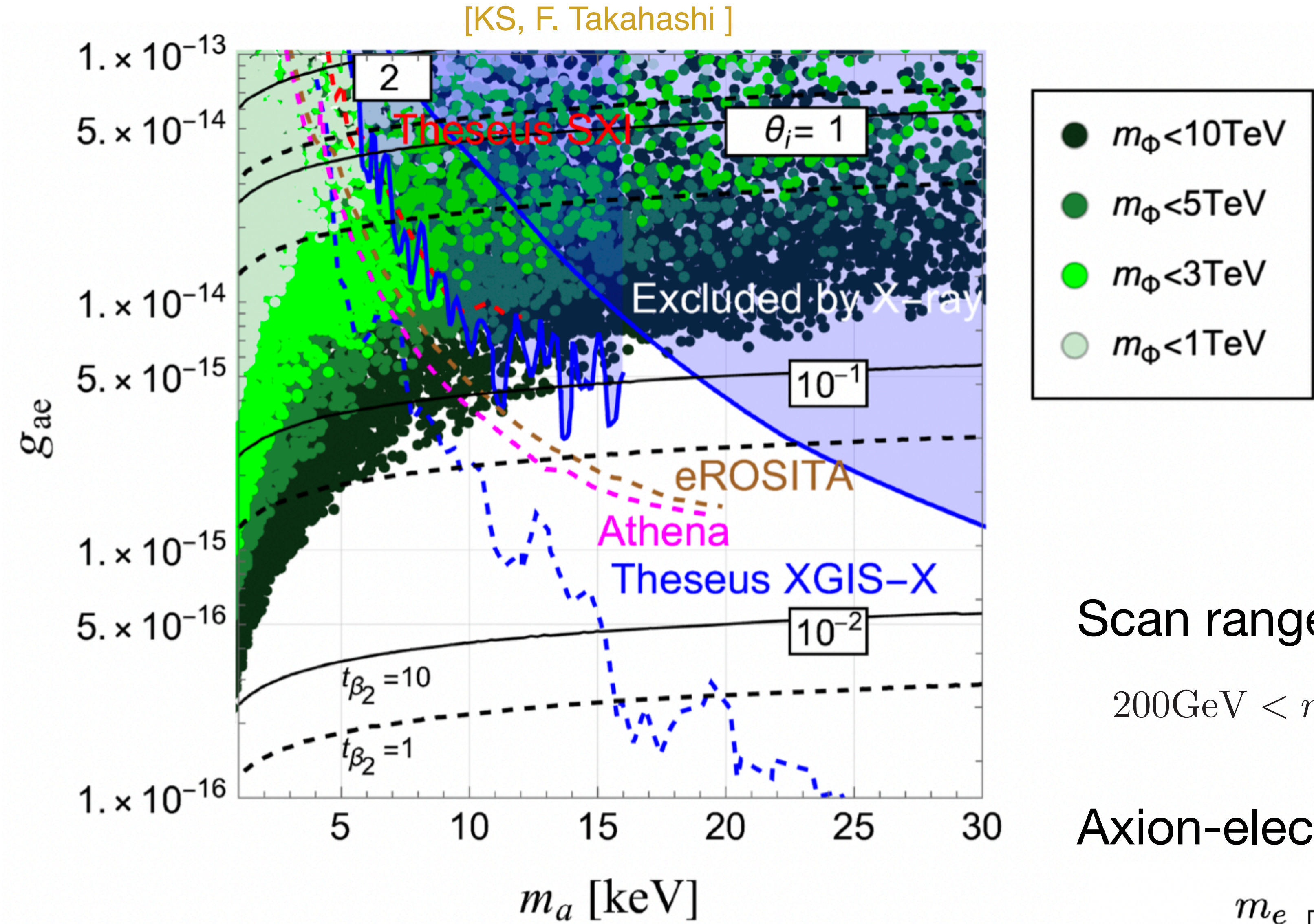
- An interesting aspect of considering the keV scale axion is testability in future X-ray observations (ATHENA, THESEUS, eROSITA, etc.).

- In this analysis, we vary f_a to survey the correlation between g_{ae} and heavy Higgs bosons:

$$1 \times 10^{10}\mathrm{GeV} \lesssim f_a \lesssim 5 \times 10^{12}\mathrm{GeV}$$

- We discuss the implications for the heavy Higgs bosons in case that the axion is detected (or hints are indicated) in the future X-ray observations.

Correlation between axion coupling and heavy Higgs mass [1/2]



Scan range of m$_\Phi$:

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

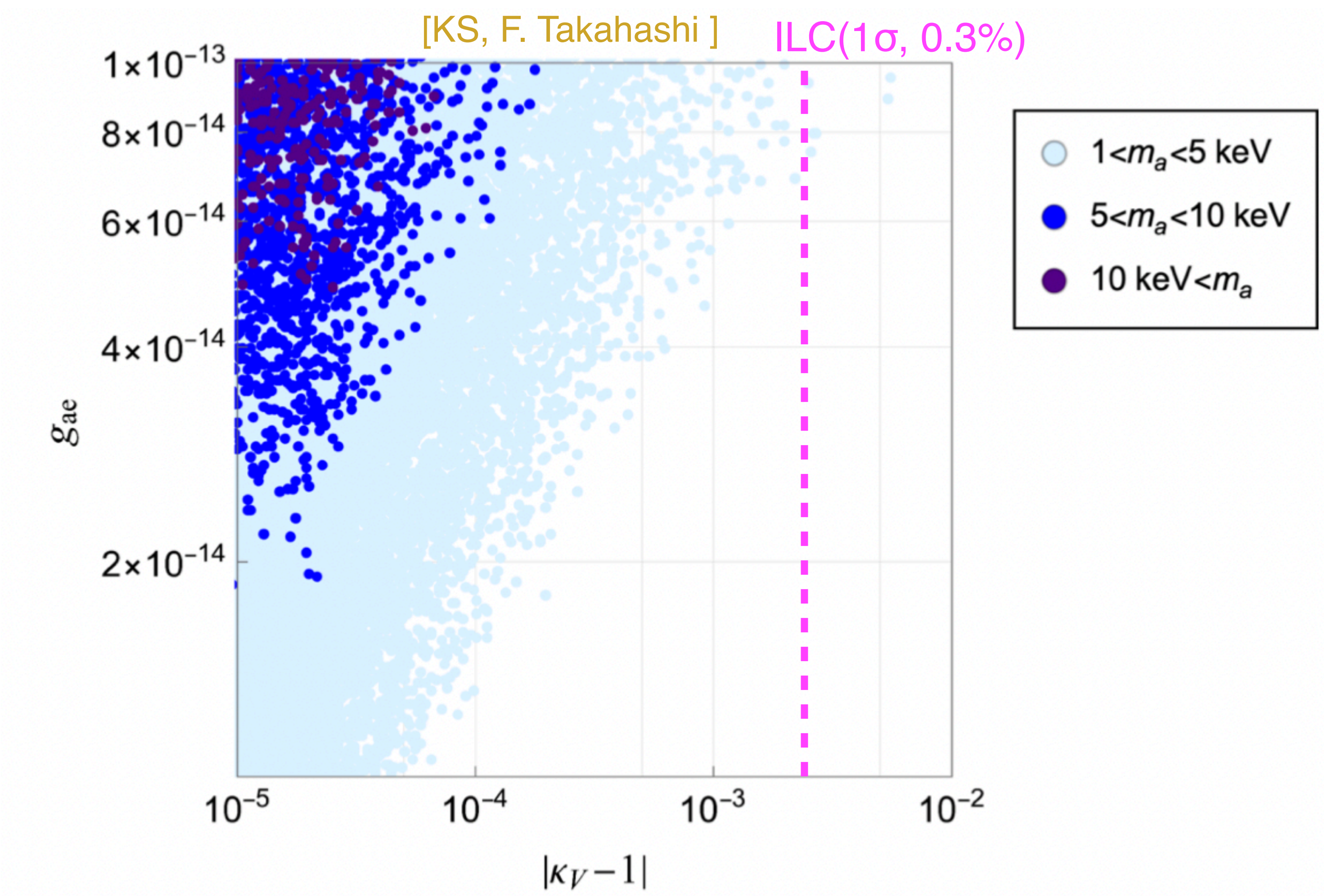
Axion-electron coupling:

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

→ m$_\Phi$ correlates with not only the mass of axion but also the axion-electron coupling.

→ If the axion is discovered (or some hint is indicated), we obtain the information of m$_\Phi$.

Correlation between axion coupling and Higgs coupling



$$\kappa_V \equiv \frac{g_{hZZ}^{3HDM}}{g_{hZZ}^{SM}} - 1$$

- The maximal size of deviation does not exceed 1%. ⟵ Perturvativity for the running coupling constants

- $m_a \gtrsim 5\mathrm{keV}$ can be searched by future X-ray observations such as ATHENA, THESEUS, etc.

  - The predicted deviation is almost zero.

  - The keV scale axion can be excluded by $\Delta\kappa_Z \gtrsim 1\%$ in future colliders.

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Summary

$\Rightarrow 0$

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

$= m_a^2 a F_{\mu\nu}\tilde{F}^{\mu\nu}$

3HDM with B-L Higgs

Higgs sector $\ni h_{125}, H, A, H^\pm, \ldots$

Correlation

Anomaly-free axion

Axion a (not QCD axion)

DM

XENON1T excess