Phenomenological implications of anomaly-free axion for 3HDM

[arXiv:2203.17212]

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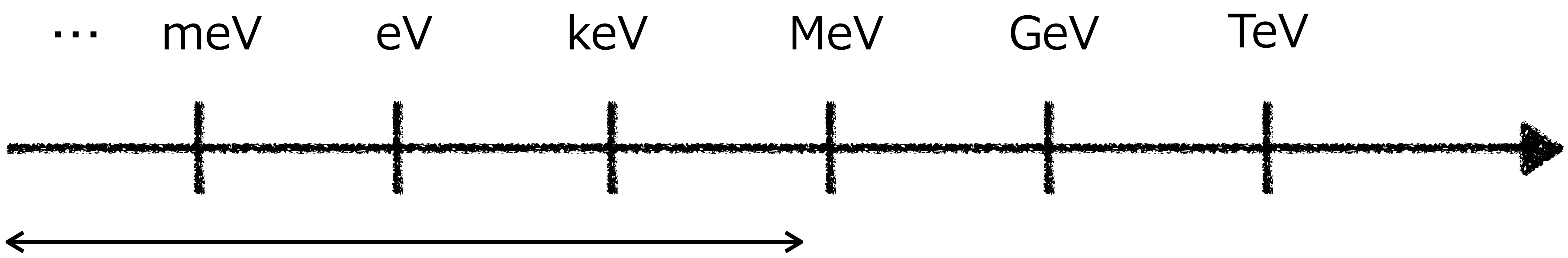
Axion/Axion like particles (ALPs)

- Dark matter (DM) is one of the most important unsolved problems in the SM.
- Axion/ALPs are prominent candidates of light DM.

- They emerge as pseudo Nambu Goldstone boson by spontaneous symmetry breaking of global U(1) symmetry.

- Mass range of axion is not fixed.



⋯ meV eV keV MeV GeV TeV

Axions can be DM if $\tau_a = 1/\Gamma_a \gtrsim 150\ \mathrm{Gyr}$

[K. Enqvist, S. Nadathur, et al., JCAP 04 (2020) 015]

$1\mathrm{Gyr} = 3.15 \times 10^{16}\mathrm{s}$

Axion-photon coupling

QCD axion has the anomalous photon coupling:

$$\mathcal{L} \ni \frac{\alpha}{8\pi}\frac{E}{N}\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

N : QCD anomaly coeefieicnt
E : EM anomaly coeefieicnt

<u>Experimental bounds for axion-pohoton couploing</u>

If $m_a \gtrsim 10\ \mathrm{eV}$, the constraint tighten.

e.g., for $m_a \sim 1\ \mathrm{keV}$

$$f_a \sim \frac{\alpha}{8\pi}\frac{1}{g_{a\gamma\gamma}}$$

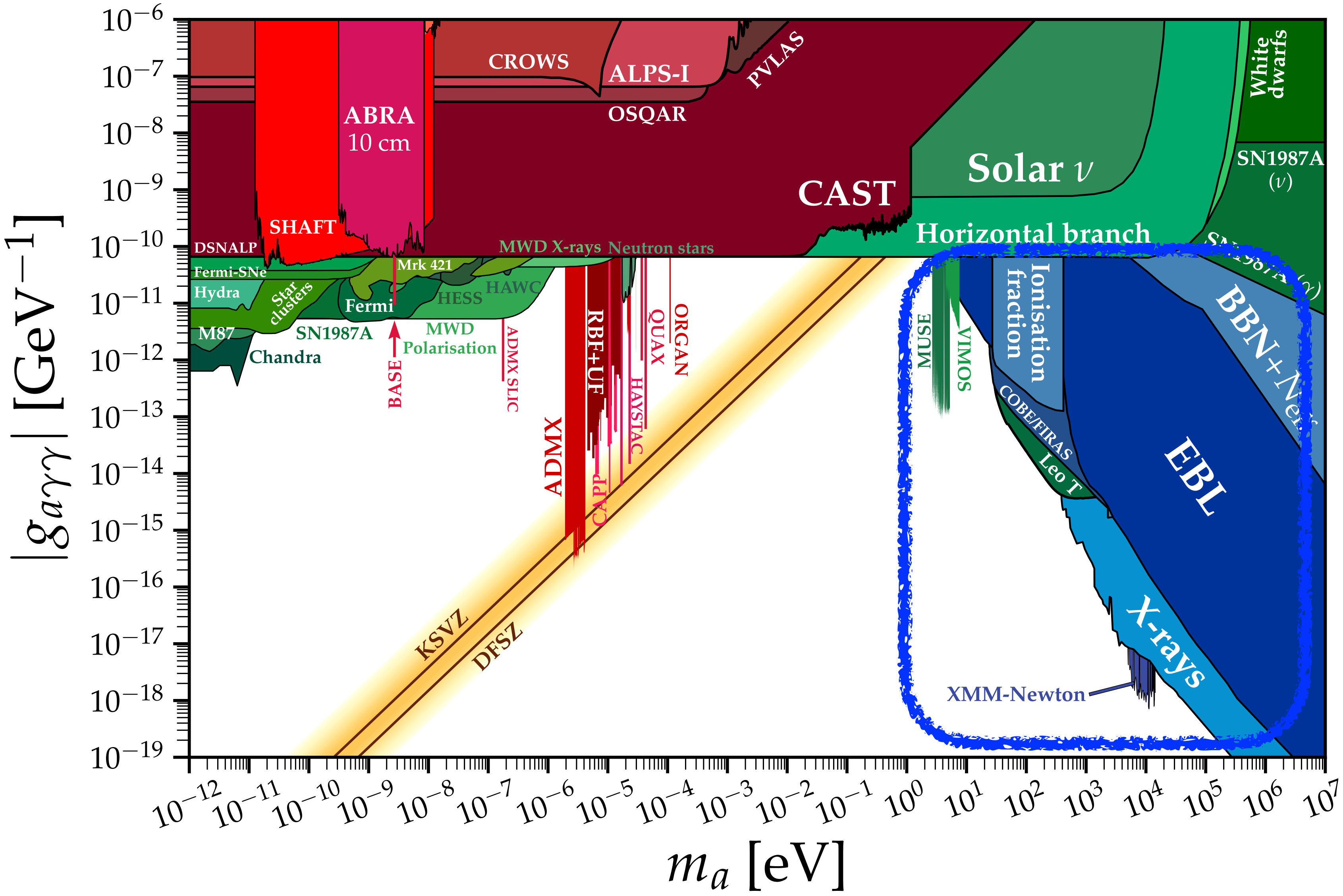
$$\simeq 1\times 10^{15}\mathrm{GeV}\left(\frac{10^{-19}\mathrm{GeV}^{-1}}{g_{a\gamma\gamma}}\right)$$

➡ $$g_{aee} \sim \frac{m_e}{f_a}$$

$$\simeq 10^{-19}$$

This is too small to be survyed by direct seaches.

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



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:

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

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

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

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

This can evade constraint from the X-ray.

Anomaly-free axion[2/3]

There are a lot of motivations to consider the anomalfy-free axion.

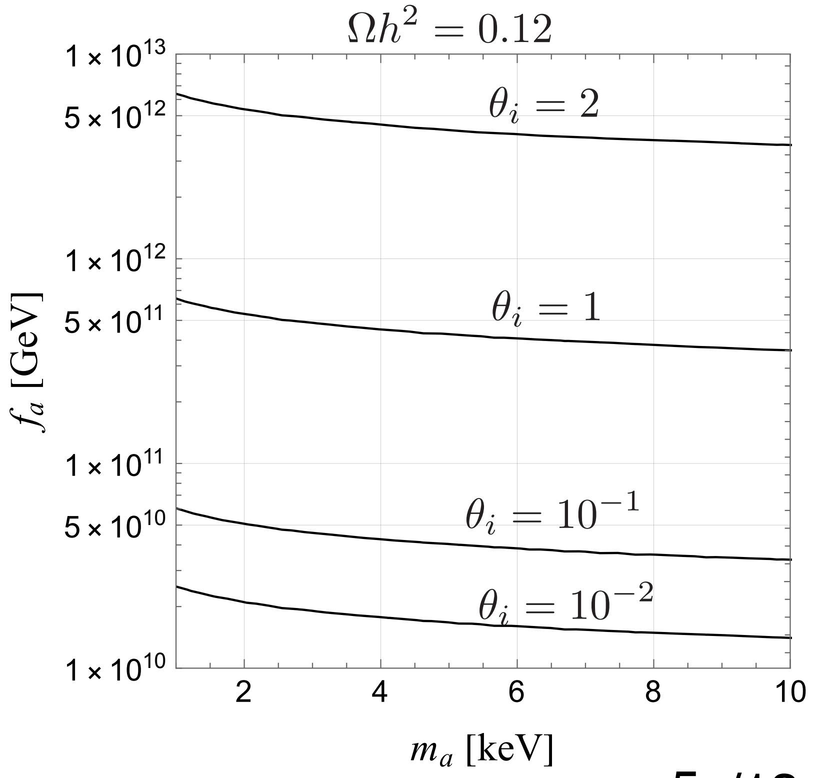
- It can be a good candidate for DM with the mass of order keV.

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

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

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

$$\Omega_a h^2 \sim 2.9 \times 10^{-20} f_a^2 \sqrt{m_a}\theta_i^2 F(\theta_i)$$



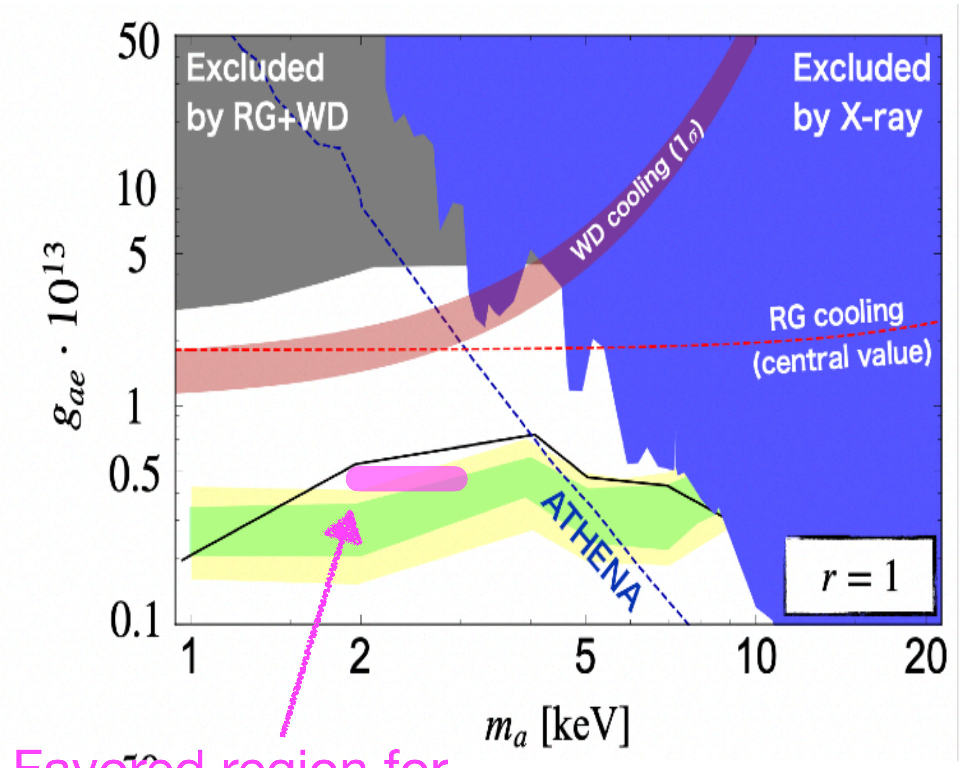
⇒ In the intermediate scale, the observed relic density can be satisfied by taking appropriate value of θ_i.

Anomaly-free axion[3/3]

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

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

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



Favored region for XENON 1T excess

- It can be tested by the future X-ray expereiments such as ATHENA if m_a is relatively lrarge.

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:

- Is it possible to embady the anomaly-free axion in the UV complete models?
- How does the axion connect with a heavy new paricle above EW scale?

This talk:

- We consider the three Higgs doublet model with the U(1)_F symmetry.
- We investigate the viable parameter space to explain XENON1T excess for this model.
- We also discuss how the axion with keV mass correlates with the heavy additional Higgs boson.

Three Higgs doublet model with B-L Higgs boson [1/2]

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
Type-A	-3	3	0	0	1	-2	1	0	-1	-2	0	2	0	0
Type-B	-3	3	0	0	1	-2	1	-1	0	-2	2	0	0	0

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

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

$$-y_e\bar{L}_e\phi_2 e_R - y_\ell\bar{L}_\ell\phi_3\ell_R - y_{\ell'}\bar{L}_{\ell'}\phi_1\ell'_R + \text{h.c.}$$

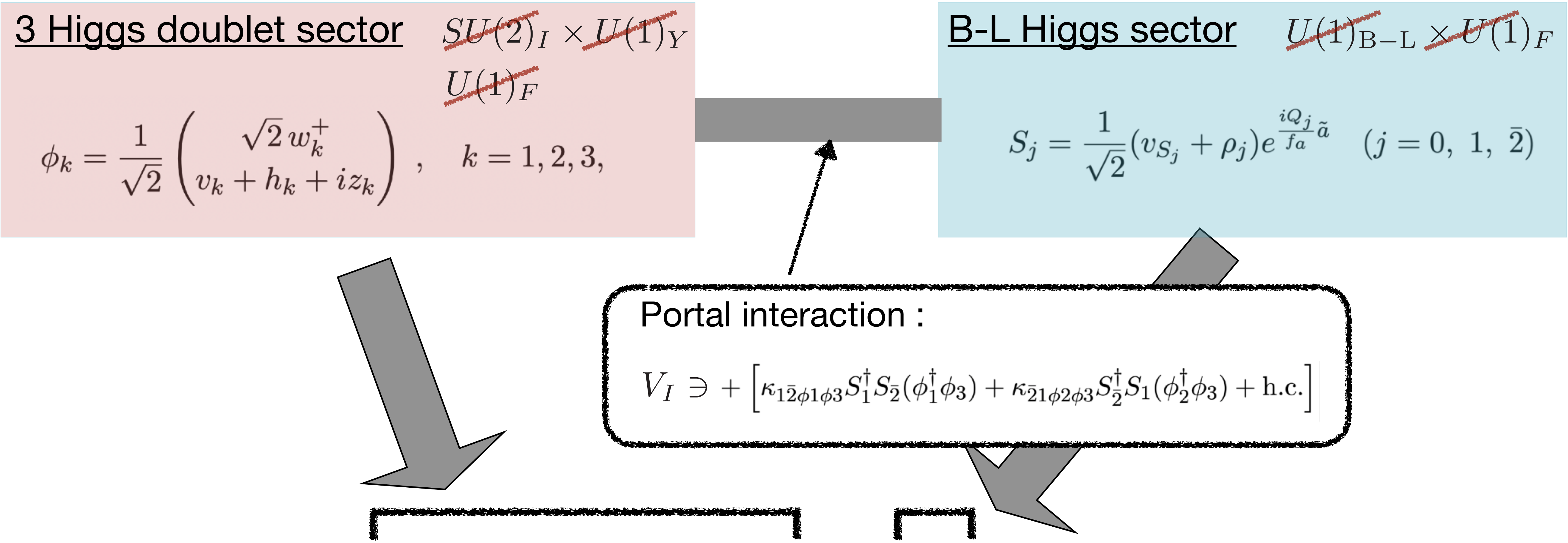
- Axion is indeed anomaly-free.

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

i.e., Anomalous photon coupling vanishes.

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

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



3 Higgs doublet sector $\cancel{SU(2)}_I \times \cancel{U(1)}_Y$ $\cancel{U(1)}_F$

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

B-L Higgs sector $\cancel{U(1)}_{\mathrm{B-L}} \times \cancel{U(1)}_F$

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

Portal interaction :

$$V_I \ni + \left[\kappa_{1\bar{2}\phi_1\phi_3} S_1^\dagger S_{\bar{2}} (\phi_1^\dagger \phi_3) + \kappa_{\bar{2}1\phi_2\phi_3} S_{\bar{2}}^\dagger S_1 (\phi_2^\dagger \phi_3) + \mathrm{h.c.} \right]$$

Mass eigenstates: $\underbrace{H_{1,2,3},\ H^\pm_{1,2},\ A_{1,2},}\ \ \underbrace{a}$

H_1 : 125 GeV Higgs boson

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

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

$H^\pm_{1,2}$: Charged Higgs boson

a : Anomaly-free axion

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

Axion mass and heavy Higgs boson masses

We asume U(1)$_F$ breaks into Z$_6$. → One soft breaking parameter only appears in 3HDM sector.

3 Higgs doublet sector $\cancel{SU(2)_I} \times \cancel{U(1)_Y}$

$\cancel{U(1)_F}$

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

B-L Higgs sector $\cancel{U(1)_{\rm B-L}} \times \cancel{U(1)_F}$

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

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

Portal interaction :

$$V_I \ni + \left[\kappa_{1\bar{2}\phi 1 \phi 3} S_1^\dagger S_{\bar{2}} (\phi_1^\dagger \phi_3) + \kappa_{\bar{2}1\phi 2\phi 3} S_{\bar{2}}^\dagger S_1 (\phi_2^\dagger \phi_3) + {\rm h.c.} \right]$$

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$_\Phi$ and m$_a$ relate through the soft breaking parameter and the portal couplings.

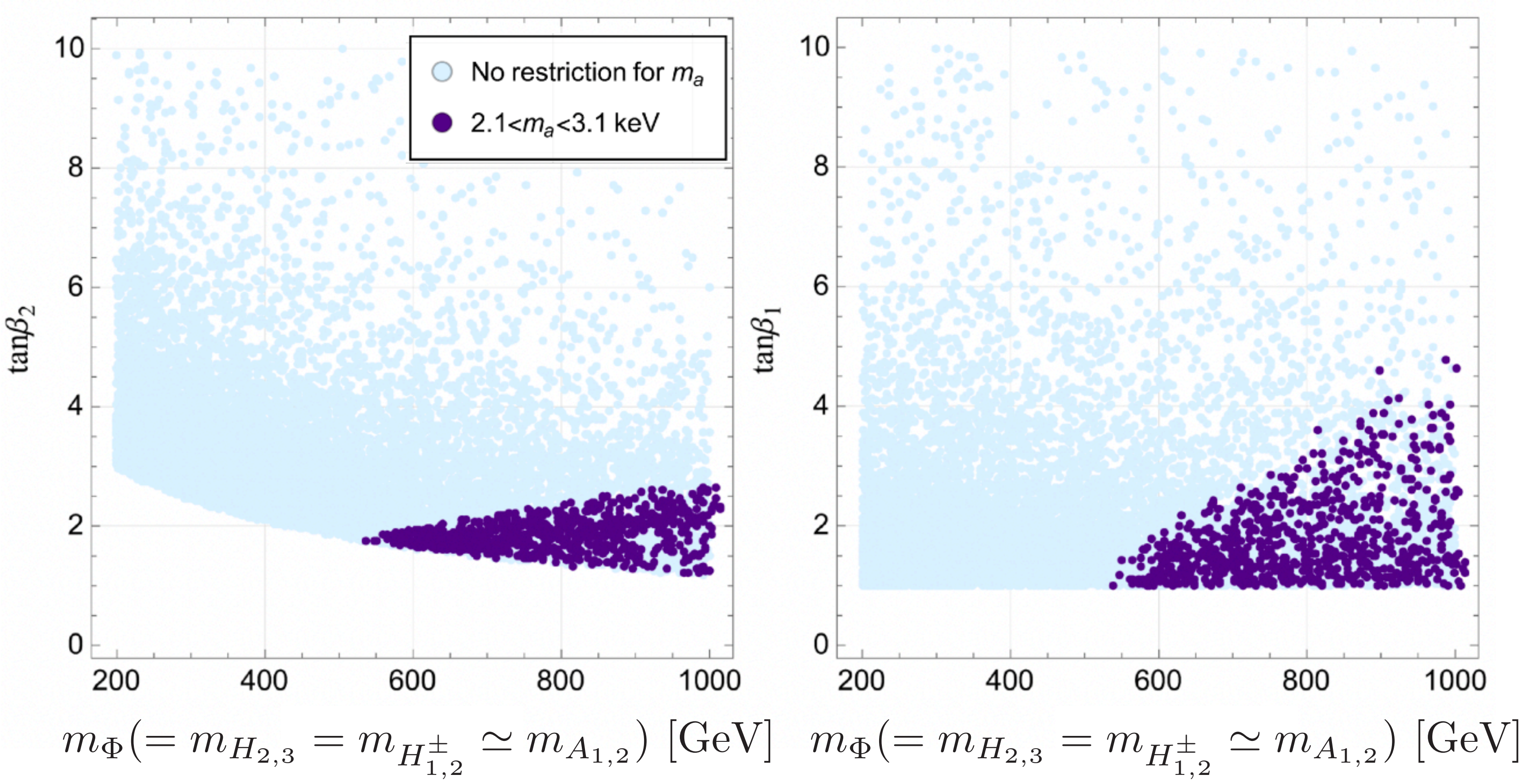
Accommodation of XENON 1T excess

Constraints:

- Thoretical bounds:
  - Perturvativity for the running coupling constants (up to $\Lambda = f_a$)
  - Potential bounded from below
- Experimental bounds:
  - Higgs signal strength
  - *B* meson decay, mixing
  - S,T 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]



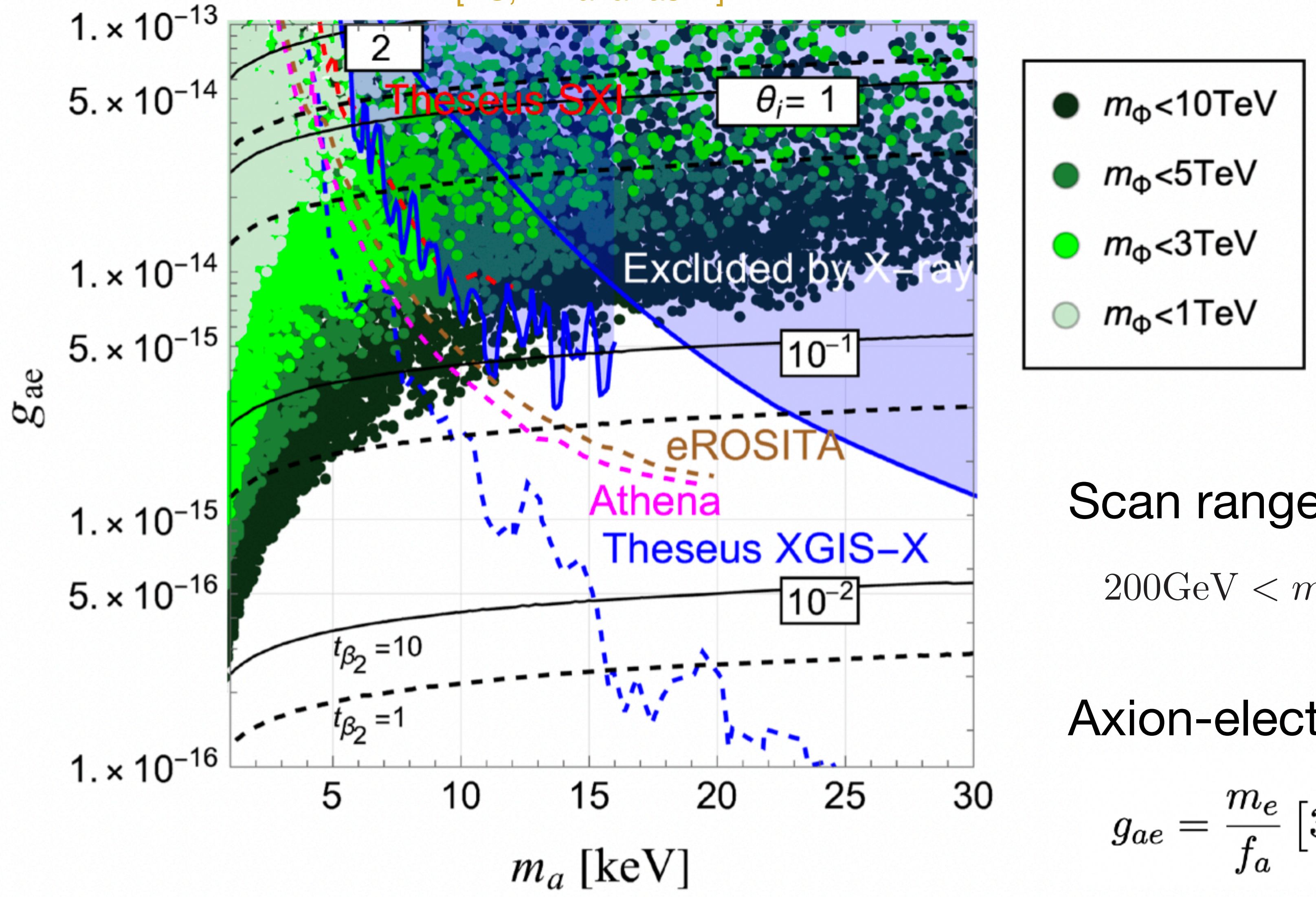
XENON1T excess:

$$\left[\begin{array}{l} 2.1\ \mathrm{keV} \lesssim m_a \lesssim 3.1\ \mathrm{keV} \\ g_{ae} = 4\times 10^{-14} \quad \longleftrightarrow \quad f_a \simeq 3.8\times 10^{10} \end{array}\right.$$

→ 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.

Correlation between axion coupling and heavy Higgs mass



[KS, F. Takahashi]

Scan range of mΦ:

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

Axion-electron coupling:

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

mΦ correlates with not only the mass of axion but also the axion-electron coupling.

➡ If *a* is discovered in the future X-ray search, we can obtain the information of mΦ.

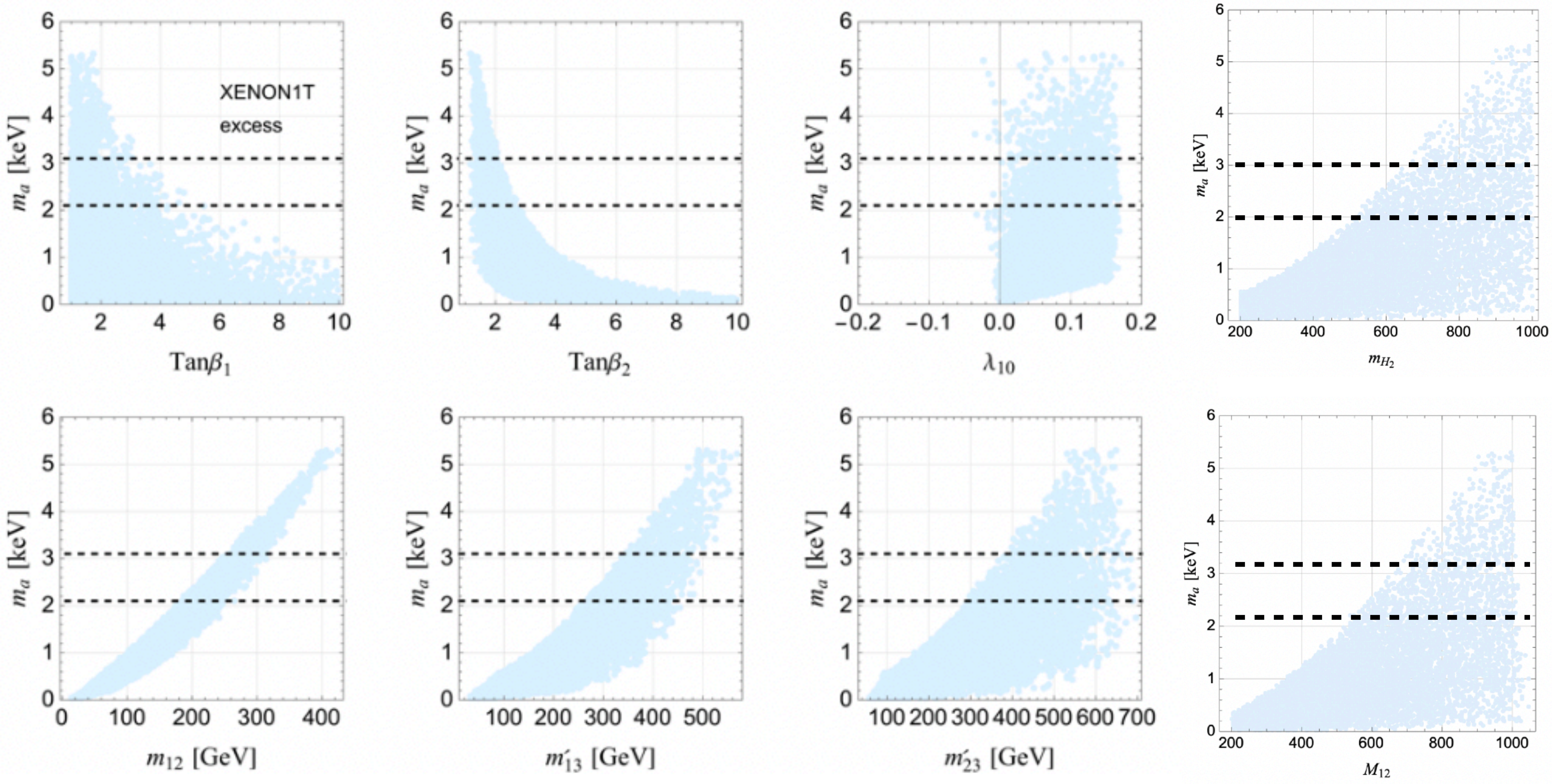
Summary

We discussed anomaly-free axion in the framework of the three Higgs doublet model (3HDM).

- Motivation for anomaly-free axion:
    - It can be DM with mass of keV scale and the decay constant at intermesiate scale.
    - It can explain the XENON 1T excess while satisfying the constraint from X-ray.
- The results:
    - Anomaly-free axion correlates with the heavy Higgs bosons in 3HDM.
    - The scenario to explain XENON1T excess predicts a correlation between $t_{\beta 1, \beta 2}$, and the mass of additional Higgs bosons.

Buck up

Parameter dependence for axion mass



Higgs potential

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

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

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

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

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

Yukawa interaction for the heavy Higgs

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

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

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

$$v_3 = v \sin\beta_2$$

Physical states after EWSB

- Mass eigenstates

$$\begin{pmatrix} G^\pm \\ H_1^\pm \\ H_2^\pm \end{pmatrix} = R_+ \begin{pmatrix} w_1^\pm \\ w_2^\pm \\ w_3^\pm \end{pmatrix} \qquad \begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = R_S \begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} \qquad \begin{pmatrix} G^0 \\ A_1 \\ A_2 \\ a \end{pmatrix} = R_P \begin{pmatrix} z_1 \\ z_2 \\ z_3 \\ \tilde{a} \end{pmatrix}$$

- Model input parameters (17)

$$v\ ,\ t_{\beta_1}\ ,\ t_{\beta_2}\ ,\ \alpha_i\ ,\ m_{H_i}\ ,\ \gamma_+\ ,\ m_{H_1^\pm}\ ,\ m_{H_2^\pm}\ ,\ M_{12}\ ,\ M'_{13}\ , M'_{23}\ ,\ \lambda_{10}\ ,\ f_a$$

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

- Symmetry

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

$U(1)_F$

- Axion can be anomaly-free

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

- B-L Higgs (singlet) bosons are introduecd.

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

- f_a can be taken around 10^{10} GeV.

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

- large neutrino mixing is obtained by introducing several B-L Higgs fields.