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Electroweak Symmetry Breaking and WIMP-FIMP Dark Matter

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Electroweak Symmetry Breaking and WIMP-FIMP Dark Matter

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Abstract. Electroweak Symmetry Breaking (EWSB) is known to produce a massive universe that we live in. However, it also provides an important boundary for freeze-in or freeze-out of dark matter (DM) as processes contributing to DM relic differ across the boundary. We explore such possibilities in a two component DM framework, where a massive vector boson DM charged under $U(1)_X$ freezes-in and a scalar singlet DM freezes-out, that inherit the effect of EWSB for both the cases in a correlated way. Amongst different possibilities, we study two sample cases, first when both DM components necessarily (one of which) freezes in and (the other) freezes out from thermal bath *before* EWSB and the second, when both freeze-in and freeze-out occurs *after* EWSB. We find some prominent distinctive features in available parameter space of the model in these two cases, addressing relic density and recent most direct search constraints from XENON1T, some of which can be borrowed in a model independent way.

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In collaboration with
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Some acronyms

Standard Model: SM
Dark Matter: DM
Electroweak Symmetry Breaking: EWSB
Weakly Interacting Massive Particle: WIMP
Feebly Interacting Massive Particle: FIMP
Before EWSB: bEWSB
After EWSB: aEWSB
Vector Boson DM: VBDM
Boltzmann Equations: BEQ
Coupled Boltzmann Equations: cBEQ

EWSB and DM

EWSB is an important boundary for DM freeze-in/freeze-out for those connected to SM via Higgs portal

Because the processes are different !

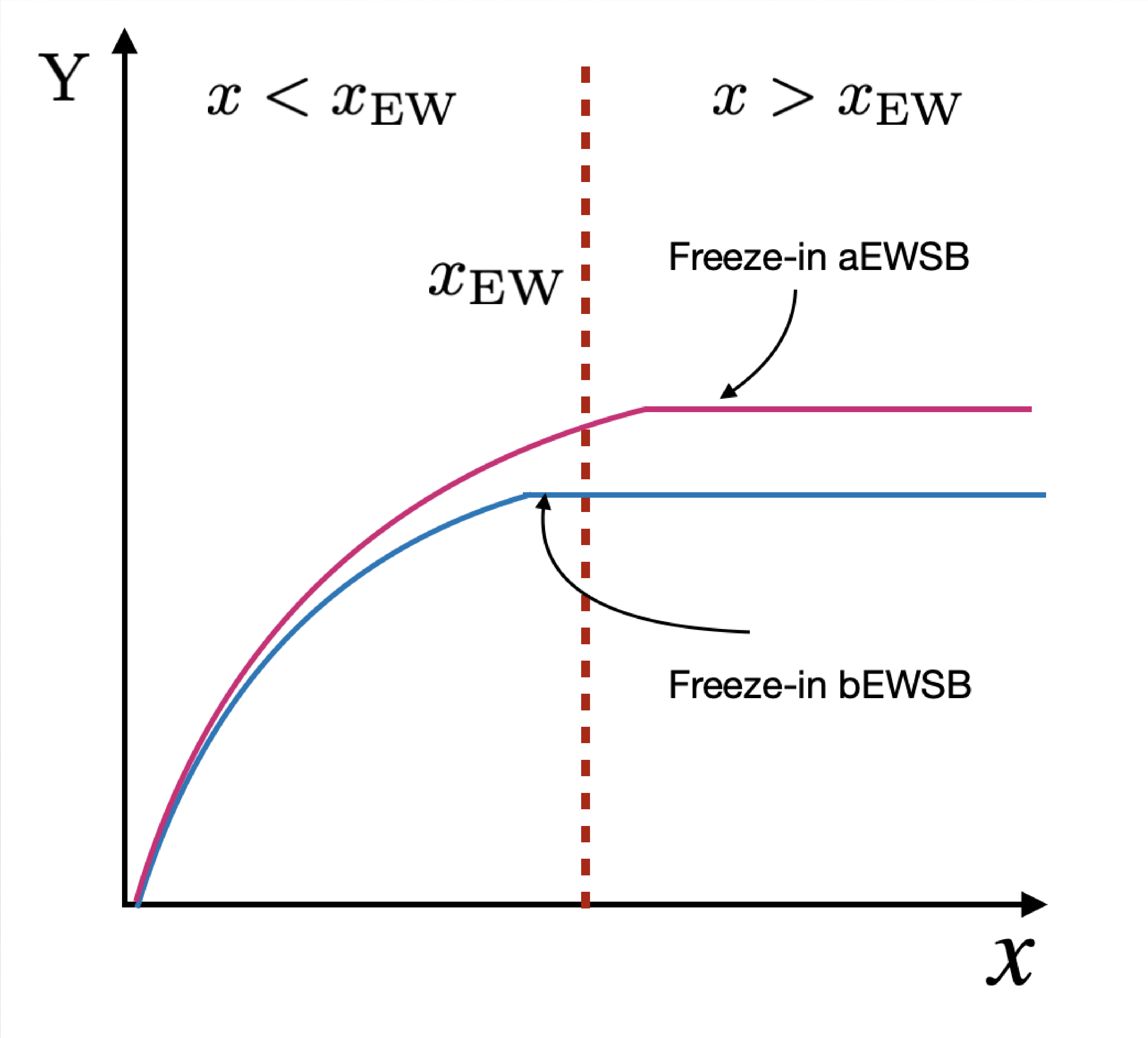
But we are usually agnostic about this issue

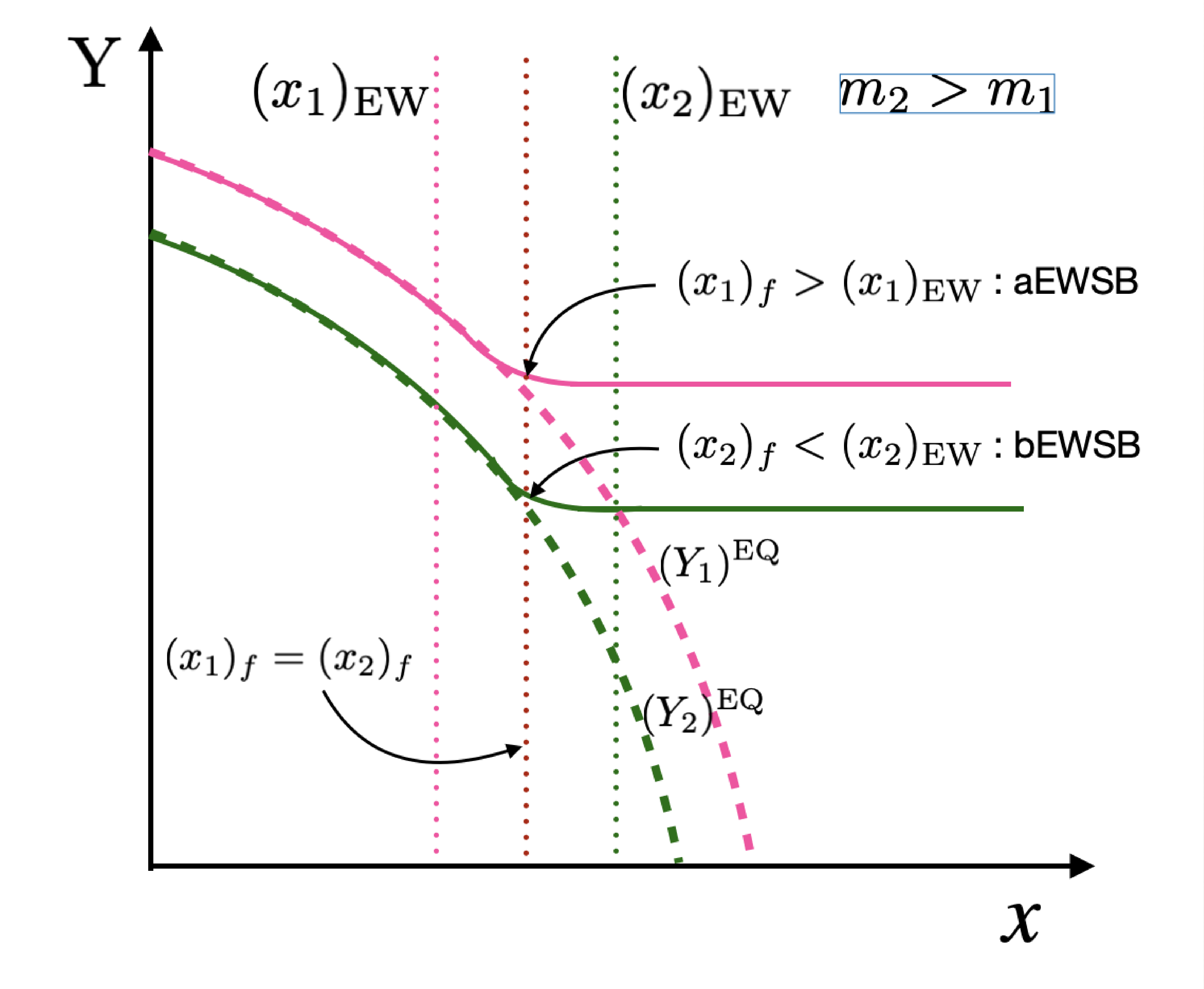
Is there a difference in the allowed parameter space of the model for freeze-in or freeze-out of DM before and after EWSB ?

A two component WIMP-FIMP model can elucidate the effects for both freeze-in and freeze-out in such cases

Could we then do a reverse job, that given a parameter space, can we say whether freeze-in or freeze-out occurs bEWSB or aEWSB ?

bEWSB and aEWSB



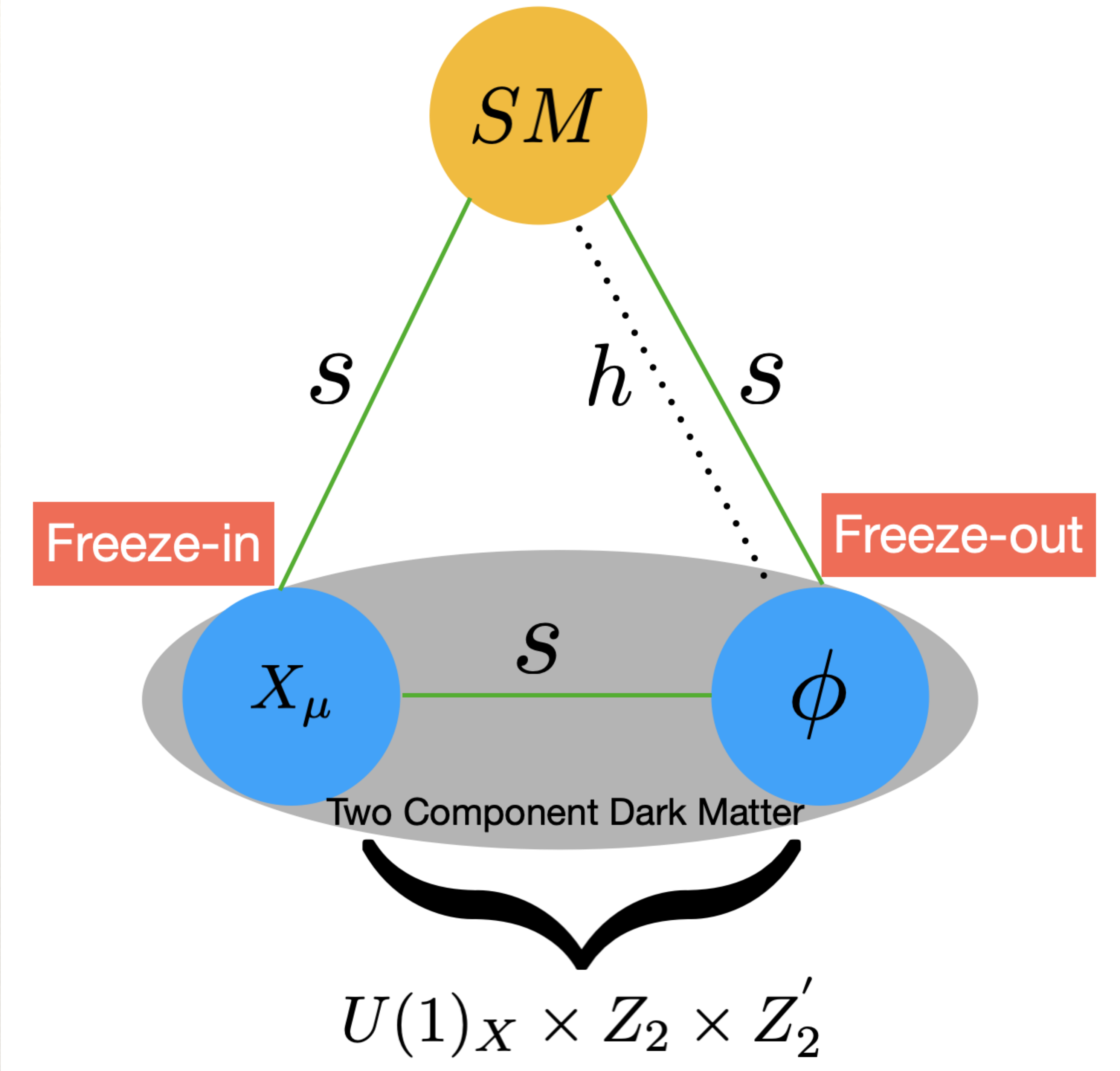


bEWSB: $T_F > T_{\mathrm{EWSB}} \implies x_F < x_{\mathrm{EW}}$

aEWSB: $T_F < T_{\mathrm{EWSB}} \implies x_F > x_{\mathrm{EW}}$

However, for freeze-out to render correct relic density, x_{FO} remains in the same ballpark $x_{\mathrm{FO}} \sim 20-25$ for both bEWSB and aEWSB. Inevitably, these two cases of freeze-out can only be possible for different DM masses, which changes x_{EW} to lie above or below x_{FO}, as depicted in the right panel of Fig. 3. We consider two DM species with $m_2 > m_1$; $\implies (x_2)_{\mathrm{EW}} > (x_1)_{\mathrm{EW}}$ (vertical dotted lines), by green and pink lines, which depicts freeze out bEWSB and aEWSB respectively from their equilibrium distributions shown by dashed lines.

Model: VBDM+Scalar singlet



Possible two component DM cases

Vector DM	Scalar DM
Freezes out (WIMP)	Freezes out (WIMP)
Freezes in (FIMP)	Freezes in (FIMP)
Freezes out (WIMP)	Freezes in (FIMP)
Freezes in (FIMP)	Freezes out (WIMP)

Additional Fields: $\{X^\mu, S, \phi\}$

Symmetry: $U(1)_X \times Z_2 \times Z_2'$

Particles	Z_2	Z_2'	$U(1)_X$
$U(1)_X$ Gauge Boson X	$-$	$+$	$+1$
Complex scalar S	S^*	$+1$	$+1$
Real scalar ϕ	$+$	$-$	0
Complex scalar doublet H	$+$	$+$	0

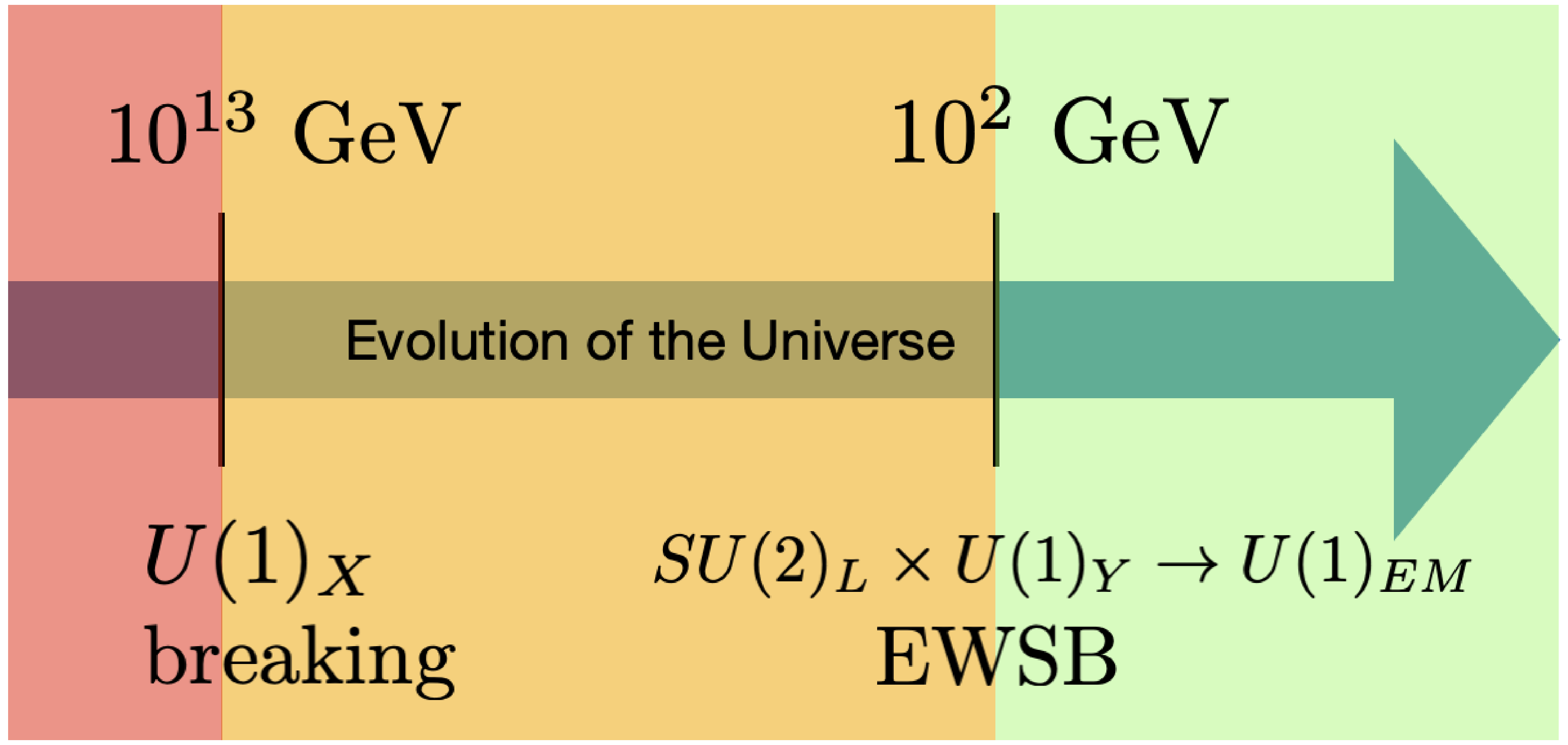
$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}|\partial_\mu \phi|^2 + |D_\mu S|^2 + \frac{1}{4}X^{\mu\nu}X_{\mu\nu} - V(H,\phi,S); \qquad (1)$$

where,

$$D_\mu = \partial_\mu + i g_X X_\mu; \quad X^{\mu\nu} = \partial^\mu X^\nu - \partial^\nu X^\mu; \text{ and}$$

$$\begin{aligned} V(H,S,\phi) &= -\mu_H^2(H^\dagger H) + \lambda_H (H^\dagger H)^2 + \frac{1}{2}\mu_\phi^2\phi^2 + \frac{1}{4}\lambda_\phi\phi^4 - \mu_S^2(S^*S) + \lambda_S(S^*S)^2 \\ &+ \frac{1}{2}\lambda_{\phi H}\phi^2(H^\dagger H) + \lambda_{HS}(H^\dagger H)(S^*S) + \frac{1}{2}\lambda_{\phi S}\phi^2(S^*S). \qquad (2) \end{aligned}$$

VBDM: FIMP+ Scalar: WIMP



Possible situations	X freezes-in	ϕ freezes-out
(i)	Before EWSB	Before EWSB
(ii)	Before EWSB	After EWSB
(iii)	After EWSB	Before EWSB
(iv)	After EWSB	After EWSB

$$m_X = g_X v_s ,$$

The $U(1)_X$ gauge coupling (g_X) which provides DM-SM interaction, is required to be feeble (roughly $g_X \sim 10^{-11}$) to keep it out of equilibrium. The DM yield that generates correct relic, is then proportional to the production cross section (or decay width). For $m_X \sim$ TeV, the $U(1)$ breaking scale turns out to be $v_s \sim 10^{13}$ GeV

These are the possibilities we study in details

bEWSB: physical states and parameters

As the phenomenology in this regime is dictated by interactions after spontaneous $U(1)_X$ breaking and bEWSB, we have

$$S = \frac{1}{\sqrt{2}}(v_s + s) \to \langle S \rangle = \frac{1}{\sqrt{2}} v_s, \quad \langle H \rangle = 0, \quad \langle \phi \rangle = 0. \tag{4.2}$$

The scalar potential in this limit reads:

$$V_{\text{scalar}} = \mu_H^2 (H^\dagger H) + \lambda_H (H^\dagger H)^2 + \frac{1}{2}\mu_\phi^2 \phi^2 + \frac{1}{4}\lambda_\phi \phi^4 - \frac{1}{2}\mu_S^2 (v_s + s)^2 + \frac{1}{4}\lambda_S (v_s + s)^4$$
$$+ \frac{1}{2}\lambda_{\phi H}(H^\dagger H)\phi^2 + \frac{\lambda_{HS}}{2}(H^\dagger H)(v_s + s)^2 + \frac{\lambda_{\phi S}}{4}\phi^2 (v_s + s)^2. \tag{4.3}$$

The physical scalars can be identified from extremization of the potential, which provides following relations between the neutral physical scalars and parameters of the model:

$$\frac{\partial V_{\text{scalar}}}{\partial H} = 0 \to \mu_H^2 = m_H^2 - \frac{\lambda_{HS}}{2} v_s^2;$$
$$\frac{\partial V_{\text{scalar}}}{\partial \phi} = 0 \to \mu_\phi^2 = m_\phi^2 - \frac{\lambda_{\phi S}}{2} v_s^2;$$
$$\frac{\partial V_{\text{scalar}}}{\partial s} = 0 \to \mu_S^2 = \lambda_S v_s^2. \tag{4.4}$$

bEWSB: processes relevant for DM

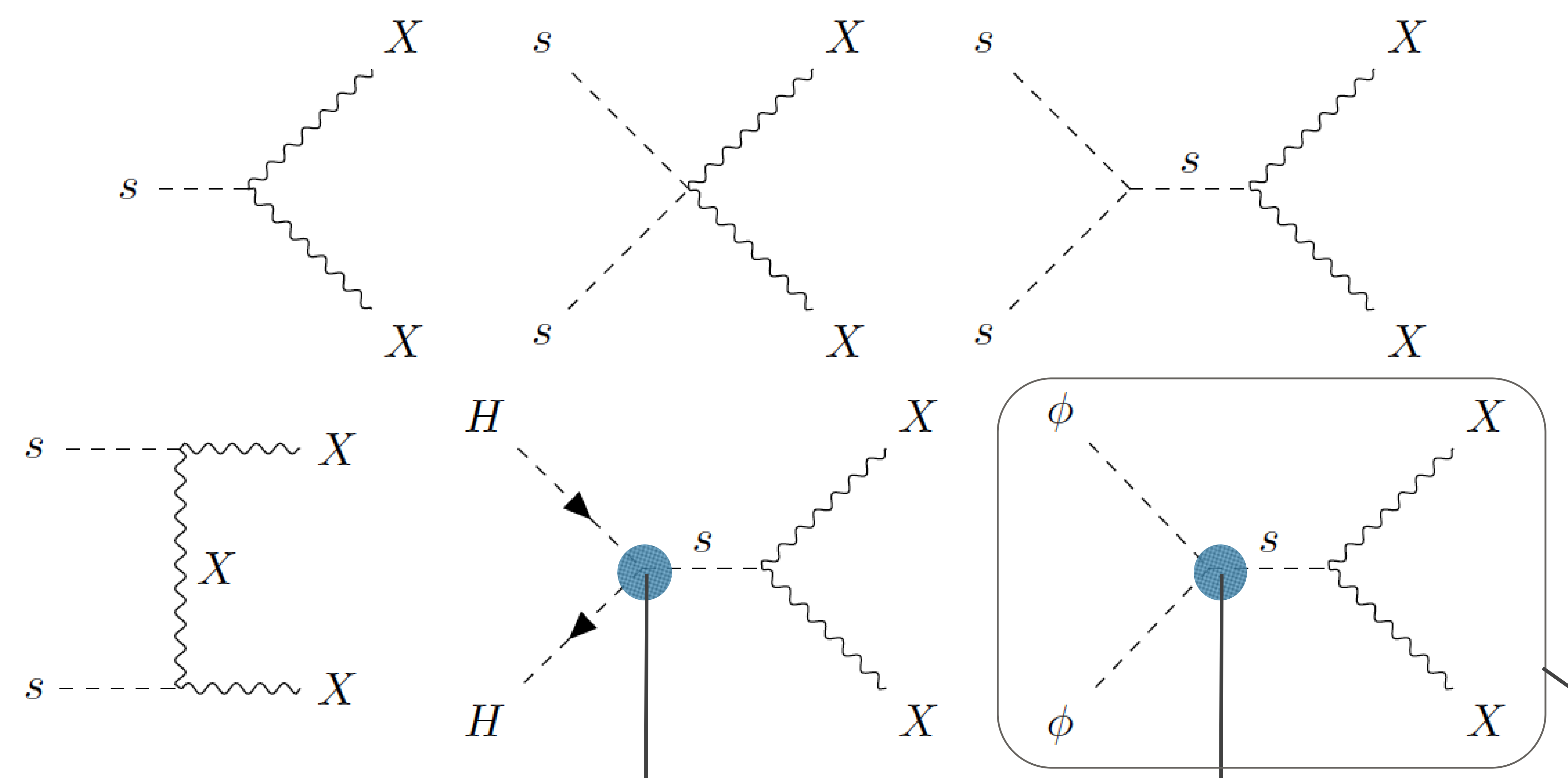


Figure 4. Feynman diagrams showing non-thermal production channels of X.

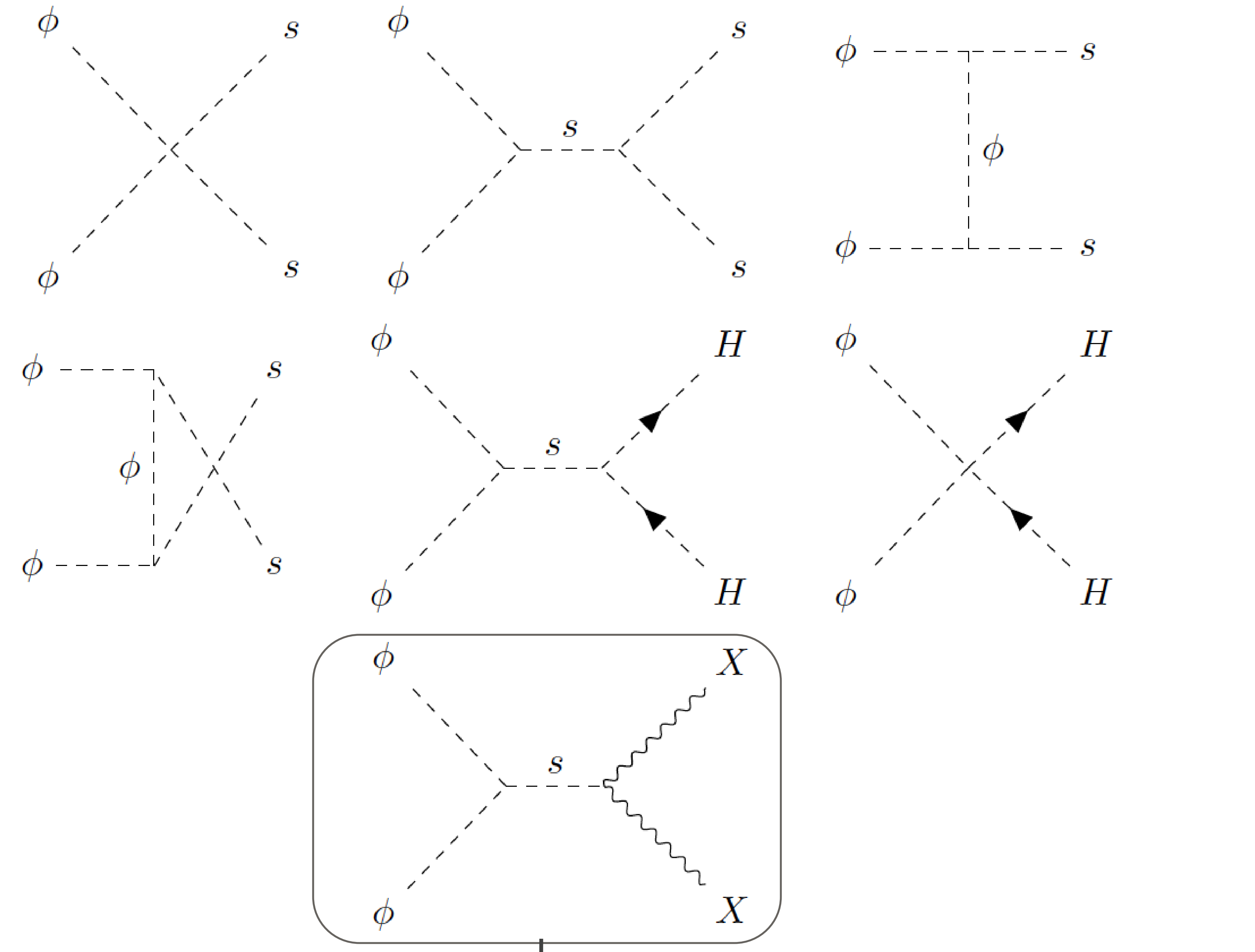


Figure 5. Feynman diagrams contributing to ϕ freeze out via $2 \to 2$ depletion processes.

$\underbrace{\lambda_{HS} \qquad \lambda_{\phi S}}_{\text{Tiny!}}$

DM-DM conversion

cBEQ: bEWSB

$$\frac{dY_X}{dx} = \frac{2\mathrm{M_{Pl}}}{1.66}\frac{x}{m_X^2}\frac{\sqrt{g_*(x)}}{g_s^*(x)}\langle\Gamma_{s\to XX}\rangle Y_s^{eq}$$
$$-\frac{4\pi^2\mathrm{M_{Pl}}\sqrt{\mathrm{g_*(x)}}}{45\times 1.66}\frac{m_X}{x^2}\left[\sum_{i=s,H}\langle\sigma v\rangle_{ii\to XX}(Y_X^2-(Y_i^{eq})^2)-\langle\sigma v\rangle_{\phi\phi\to XX}\left(Y_\phi^2-\frac{(Y_\phi^{eq})^2}{(Y_X^{eq})^2}Y_X^2\right)\right],$$
$$\frac{dY_\phi}{dx} = -\frac{2\pi^2\mathrm{M_{Pl}}\sqrt{\mathrm{g_*(x)}}}{45\times 1.66}\frac{m_\phi}{x^2}\left[\sum_{i=s,H}\langle\sigma v\rangle_{\phi\phi\to ii}(Y_\phi^2-(Y_\phi^{eq})^2)+\langle\sigma v\rangle_{\phi\phi\to XX}\left(Y_\phi^2-\frac{(Y_\phi^{eq})^2}{(Y_X^{eq})^2}Y_X^2\right)\right].$$

However, WIMP-FIMP conversion should be kept small, so that FIMP remains out of equilibrium

$$\frac{dY_X}{dx} = \frac{2\mathrm{M_{Pl}}}{1.66\sqrt{g_*^\rho(x)}}\frac{x}{m_X^2}\langle\Gamma_{s\to XX}\rangle Y_s^{eq}$$
$$+\frac{4\pi^2\mathrm{M_{Pl}}}{45\times 1.66}\frac{g_*^s(x)}{\sqrt{g_*^\rho(x)}}\frac{m_X}{x^2}\left(\sum_{i=s,H}\langle\sigma v\rangle_{ii\to XX}(Y_i^{eq})^2+\langle\sigma v\rangle_{\phi\phi\to XX}Y_\phi^2\right),$$
$$\frac{dY_\phi}{dx} = -\frac{2\pi^2\mathrm{M_{Pl}}}{45\times 1.66}\frac{g_*^s(x)}{\sqrt{g_*^\rho(x)}}\frac{m_\phi}{x^2}\sum_{i=s,H}\langle\sigma v\rangle_{\phi\phi\to ii}\left(Y_\phi^2-(Y_\phi^{eq})^2\right).$$

Drop DM-DM conversion from WIMP Equn.

cBEQ splits into two BEQs that can be addressed individually

bEWSB: constraints

- **Stabilty:**
In order to get the potential bounded from below, the quatric couplings of the potential $V_{\rm scalar}$ must have satisfy the following copositivity conditions as [98–100],

$$\begin{aligned} &\lambda_H \geq 0, \lambda_\phi \geq 0, \lambda_S \geq 0, \\ &\lambda_{\phi H} + 2\sqrt{\lambda_H \lambda_\phi} \geq 0, \lambda_{HS} + 2\sqrt{\lambda_H \lambda_S} \geq 0, \lambda_{\phi S} + 2\sqrt{\lambda_\phi \lambda_S} \geq 0 \end{aligned} \tag{4.5}$$

- **Perturbativity:**
In oder to maintain perturbativity of the theory, the quartic couplings of the scalar potential $V_{\rm scalar}$ and gauge couplings obey [53, 101],

$$\begin{aligned} &\lambda_H < 4\pi, \quad \lambda_S < 4\pi, \quad \lambda_\phi < 4\pi, \quad g_X < \sqrt{4\pi}, \\ &\lambda_{HS} < 4\pi, \quad \lambda_{\phi S} < 4\pi, \quad \lambda_{\phi H} < 4\pi\,. \end{aligned} \tag{4.6}$$

- **Tree level unitarity:**
Tree level unitarity of the theory, coming from all possible $2 \to 2$ scattering amplitude, can be ensured [53, 101, 102] via following constraints

$$\lambda_\phi < \frac{\pi}{3}, \; |\lambda_S| < 2\pi, \; |\lambda_H| < 2\pi, \; |\lambda_{\phi S}| < 8\pi, \; |\lambda_{HS}| < 8\pi, \; |\lambda_{\phi H}| < 8\pi\,. \tag{4.7}$$

- **Constraints on DM mass bEWSB:**
The possibility of freeze-in of X to complete bEWSB implies that the freeze-in scale, which is equivalent to the mass of DM m_X, has to be larger than $T_{\rm EW}$; then, $m_X \gtrsim 160$ GeV. Similarly, freeze-out of ϕ bEWSB forces the freeze-out temperature T_F to be larger than $T_{\rm EW}$, i.e, $T_F \gtrsim 160$ GeV. This condition automatically implies that $x_F = m_\phi/T_F$, which is typically ~ 25 for WIMP freeze-out, requires the following condition on WIMP and FIMP masses:

$$\boxed{\text{WIMP}: \; \mathrm{m}_\phi \gtrsim 4 \text{ TeV}; \quad \text{FIMP}: \; \mathrm{m}_\mathrm{X} \gtrsim 160 \text{ GeV}.} \tag{4.8}$$

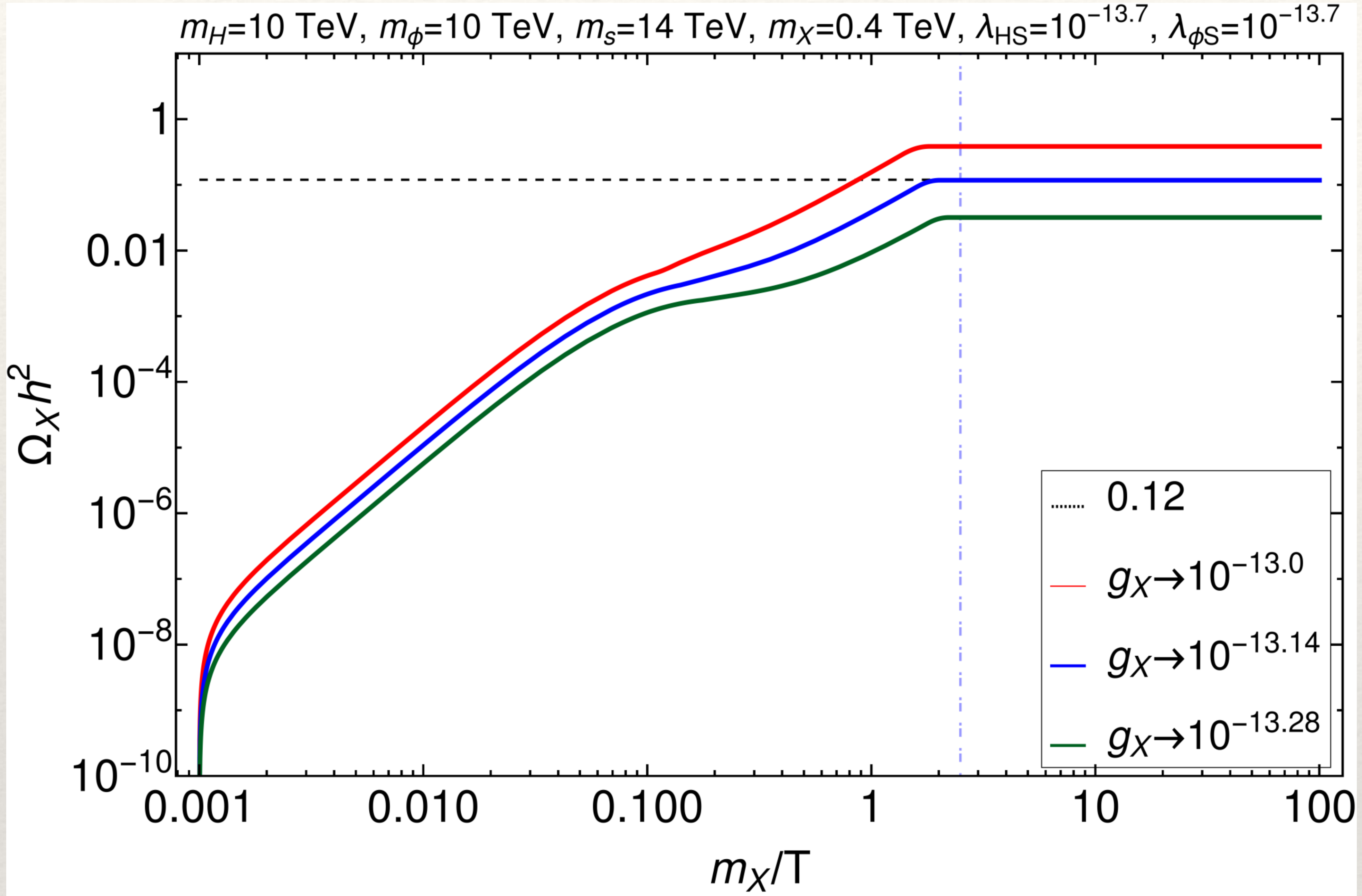
- **Direct detection (DD) constraints** : Although freeze out of ϕ occurs bEWSB, after EWSB ϕ will couple to SM particles yielding a possibility of direct search. The relevant couplings g_X and $\lambda_{\phi S}$ will be shown to be constrained ($\sim 10^{-12}$) both from the freeze-in requirements and direct search bounds. In addition to this, $\lambda_{\phi H} \sim 10^{-3}$ keeps the DD cross section safely below the experimental direct search bounds. We provide a detailed account for DD in the appendix C.

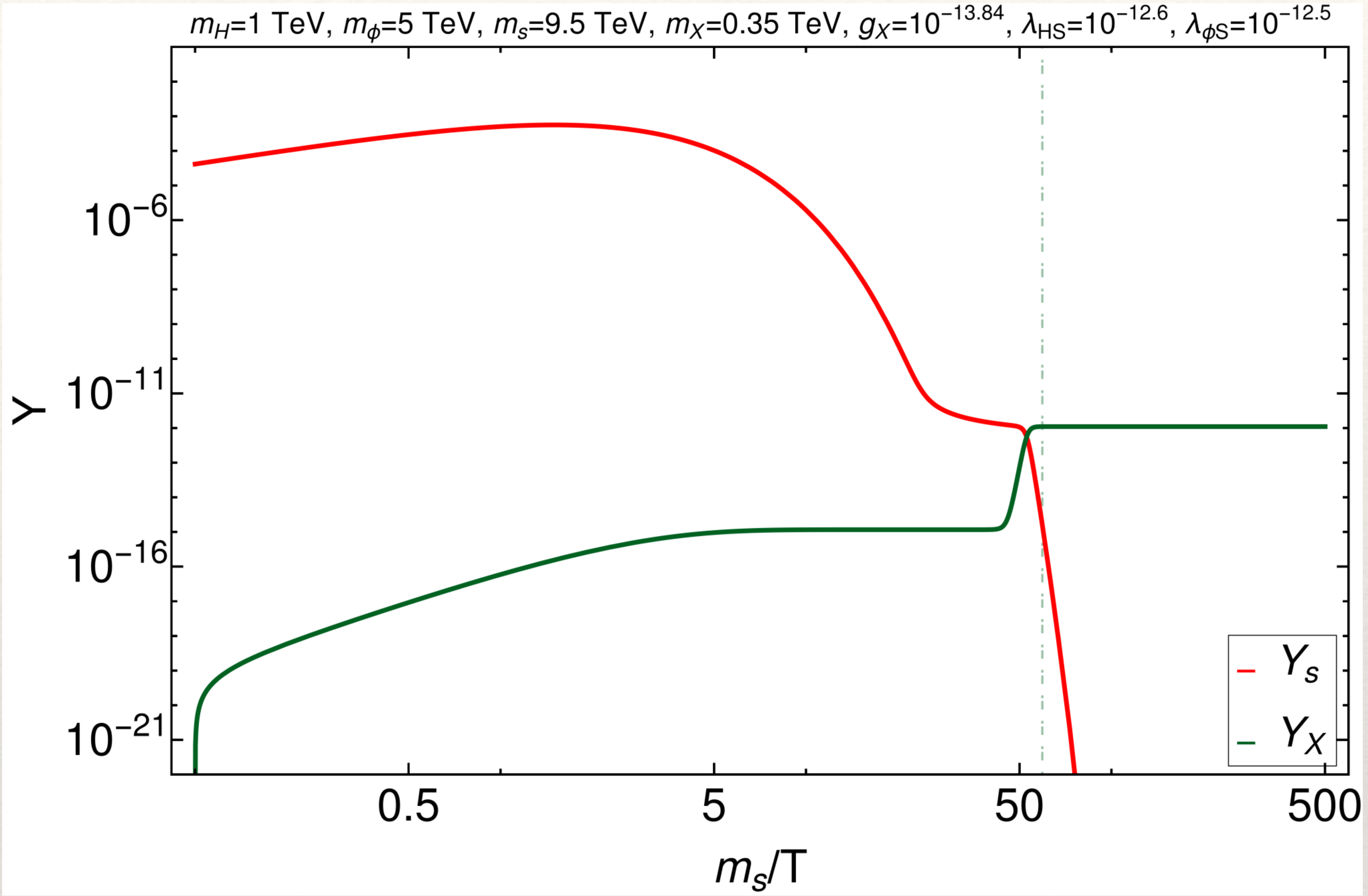
- **Collider constraints** : Immaterial to freezes-out/in bEWSB or aEWSB, there is a possibility of mixing of Higgs with the complex scalar s aEWSB depending on the mass hierarchy of s and X (we will elaborate on this point in next section). Higgs-complex scalar singlet mixing has a strong bound from LHC [103], where the mixing angle θ is restricted as,

$$|\sin\theta| \lesssim 0.3 \tag{4.9}$$

which in turn puts constraint on the portal coupling λ_{HS}. Collider bound on scalar singlet WIMP DM mass m_ϕ is mild [104, 105], while no significant bound on FIMP mass can be obtained.

bEWSB: Freeze-in (decay and late decay)





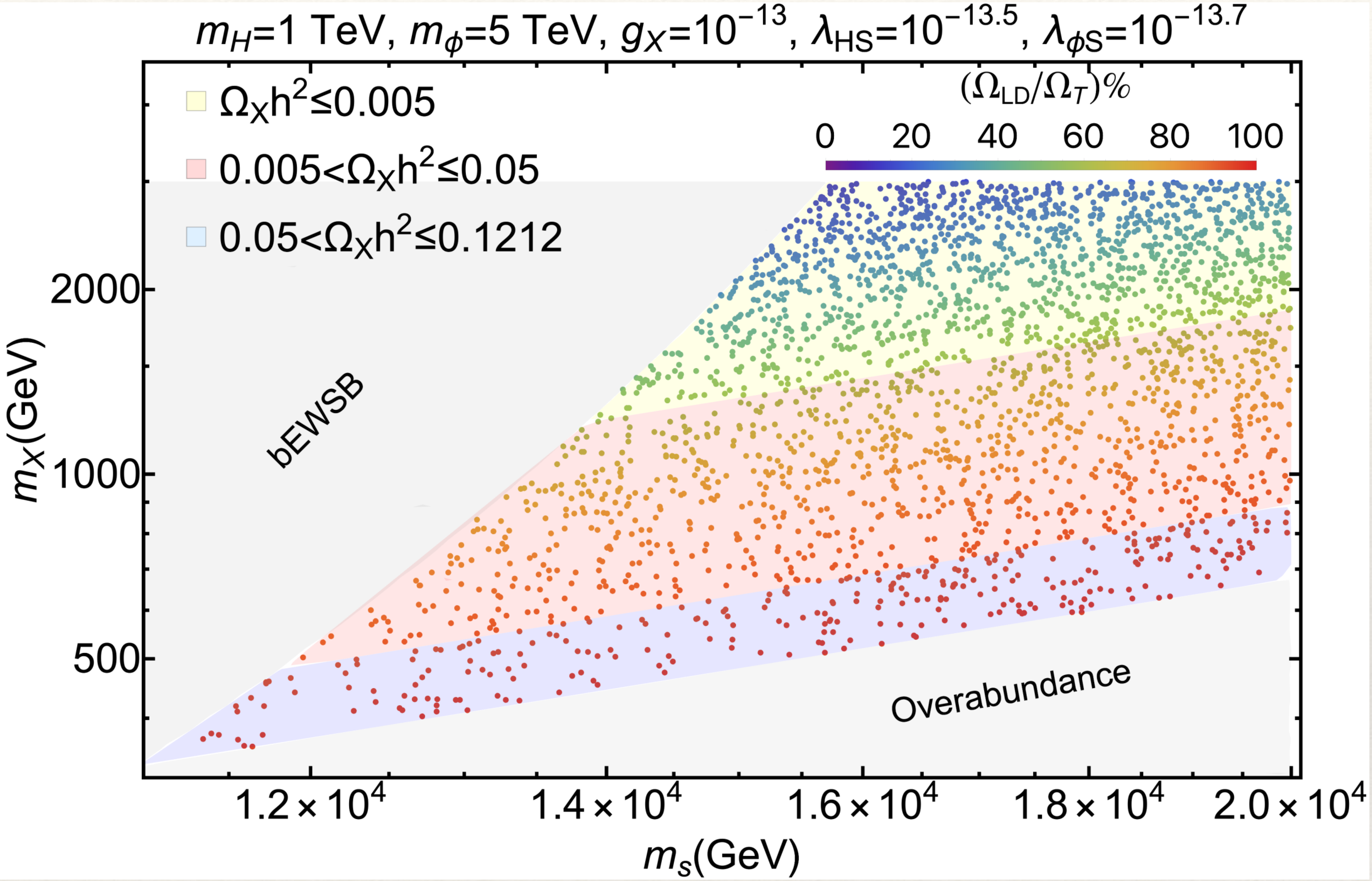
$$\frac{dY_X}{dx} = \frac{45}{3.32\pi^4}\frac{g_s \mathrm{M_{Pl}} \mathrm{m_s^2} \Gamma_{\mathrm{s}\to\mathrm{XX}}}{m_X^4}\left(\frac{x^3 K_1\left[\frac{m_s}{m_X}x\right]}{g_*^s(x)\sqrt{g_*^\rho(x)}}\right. \qquad \eta(x,x_D) = \alpha(x,x_D)g_*^s(x)\sqrt{g_*^\rho(x)}, \quad \alpha(x,x_D) = \left[\frac{g_*^s(x_D)}{g_*^s(x)}\right]^{1/3}\left[\frac{g_*^\rho(x_D)}{g_*^\rho(x)}\right]^{1/4}.$$

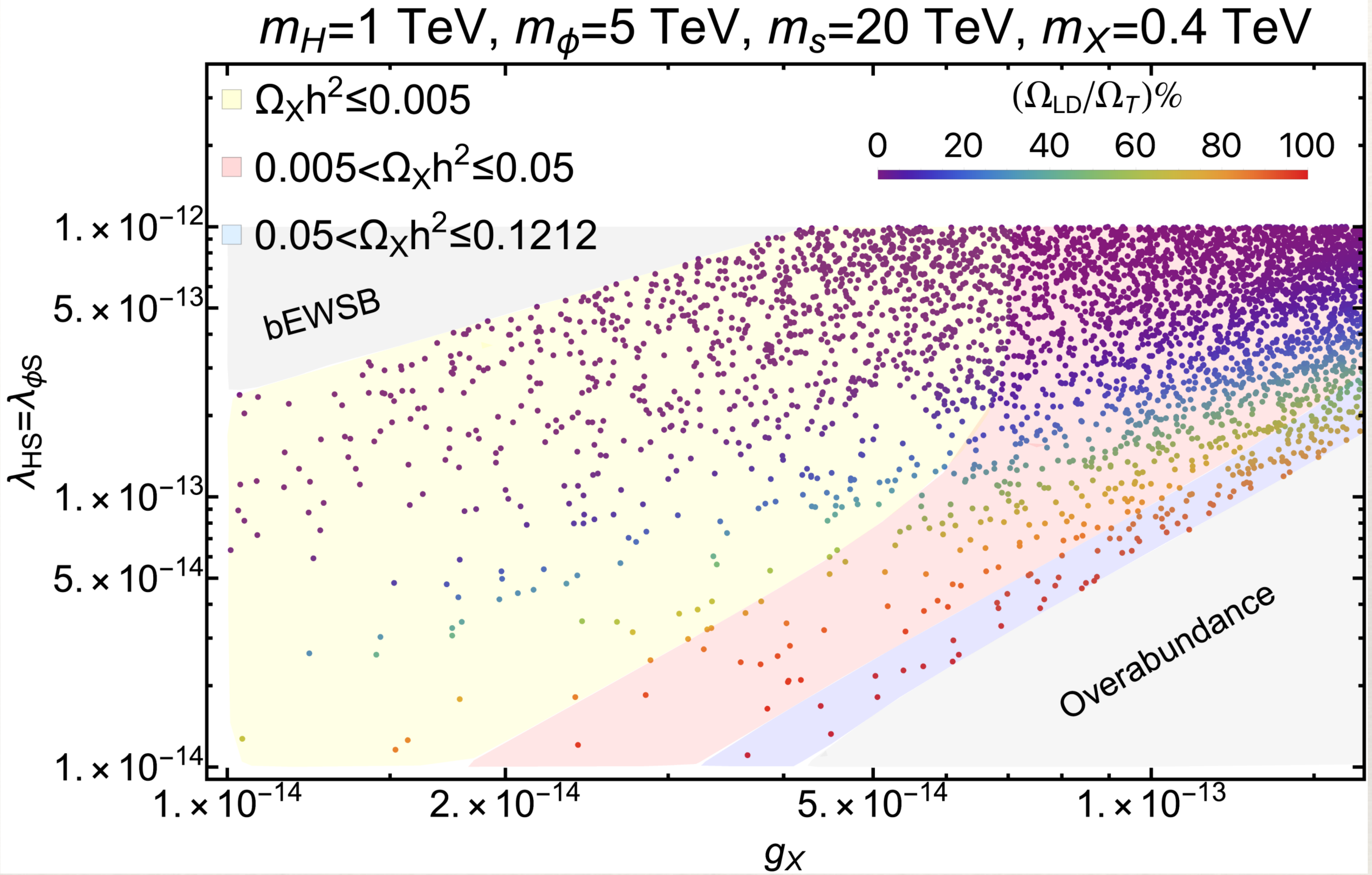
$$+\, e^{-\frac{0.602\mathrm{M_{Pl}}\Gamma_{\mathrm{s}\to\mathrm{XX}}}{m_X^2\sqrt{g_*^\rho(x)}}(x^2-x_D^2)}\frac{x^2 x_D}{\eta(x,x_D)}K_1\left[\alpha(x,x_D)\frac{m_s}{m_X}\frac{x^2}{x_D}\right]e^{\frac{m_s}{m_X}\left(\alpha(x,x_D)\frac{x^2}{x_D}-x_D\right)}\Theta(x-x_D)\Bigg)$$

$$+\,\frac{4\pi^2 \mathrm{M_{Pl}}}{45\times 1.66}\frac{g_*^s(x)}{\sqrt{g_*^\rho(x)}}\frac{m_X}{x^2}\left(\sum_{i=s,H}\langle\sigma v\rangle_{ii\to XX}(Y_i^{eq})^2 + \langle\sigma v\rangle_{\phi\phi\to XX}Y_\phi^2\right).$$

Barman et al in JCAP 02 (2020) 029

bEWSB: under abundance for FIMP

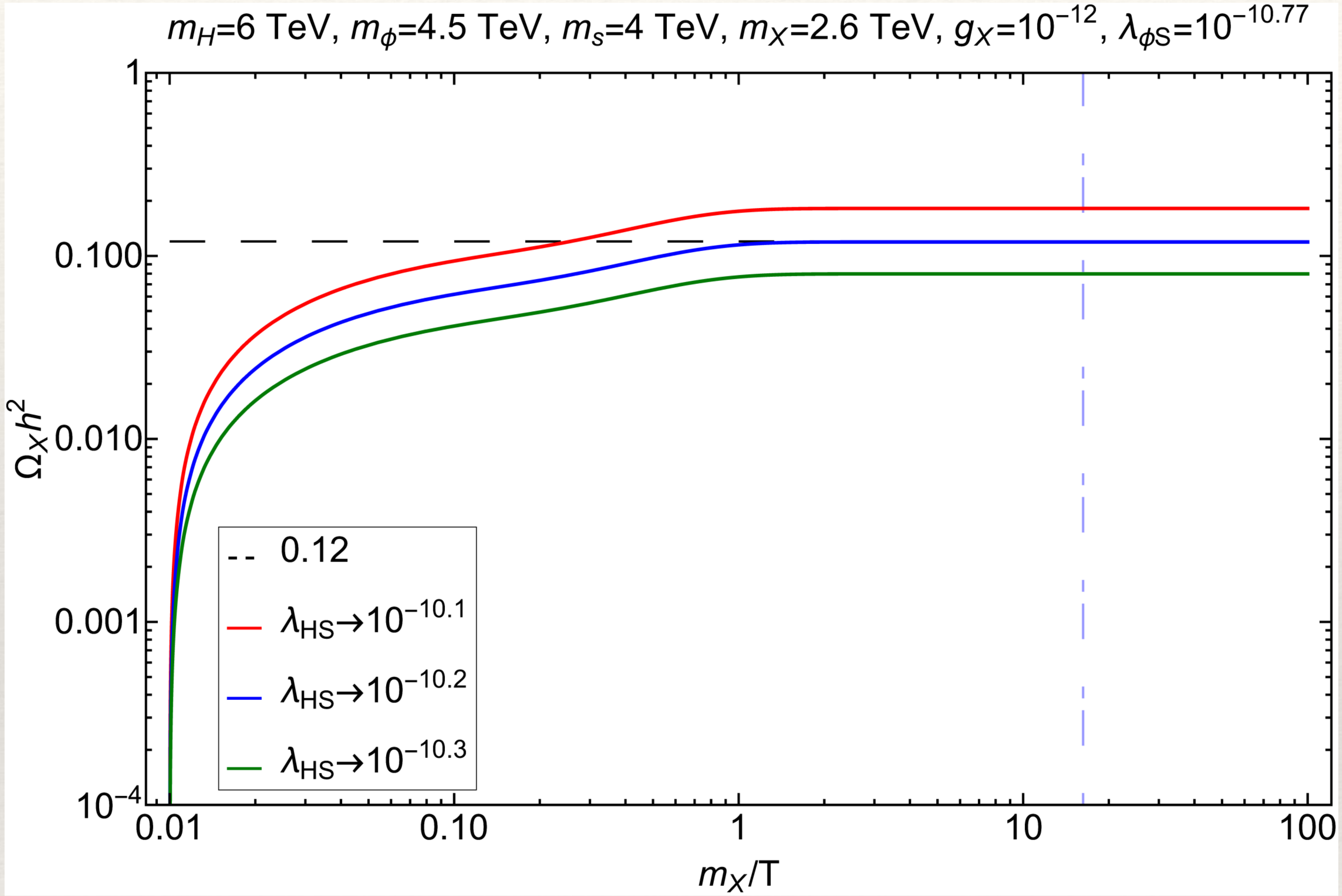


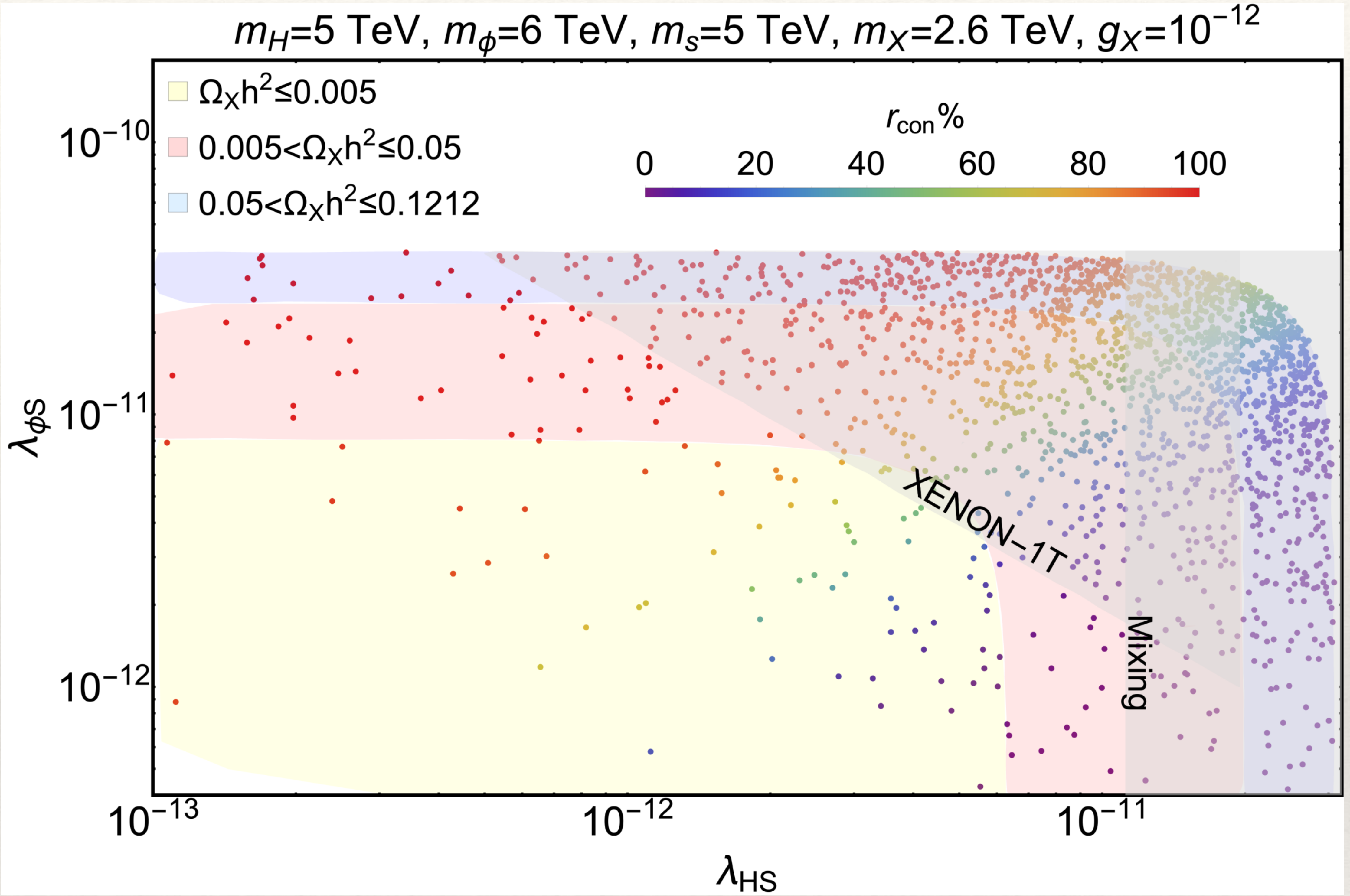


$$m_S > 2m_X;\ S \to XX$$

No direct search or Higgs Mixing bound !

bEWSB: freeze-in in absence of decay

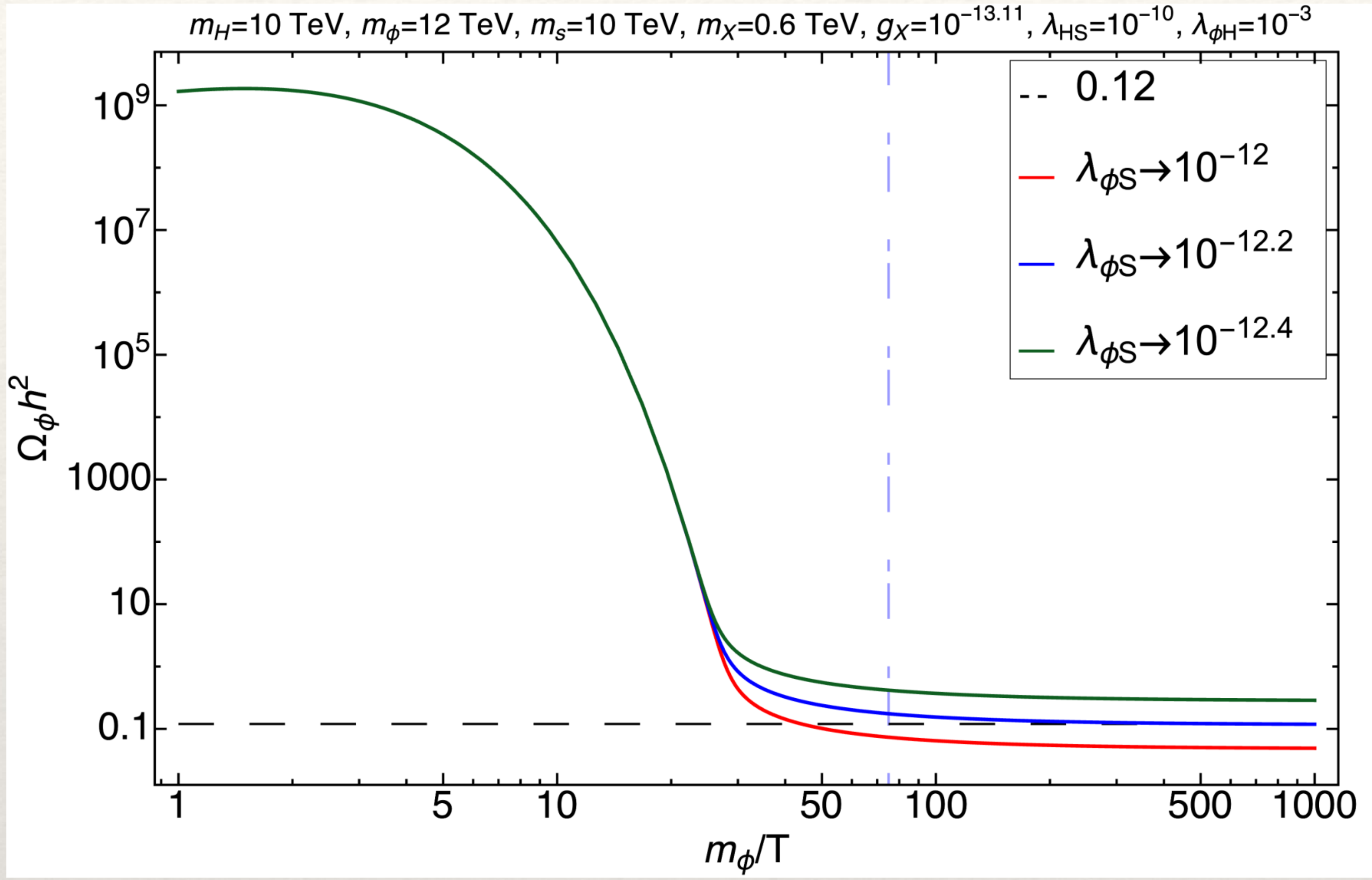


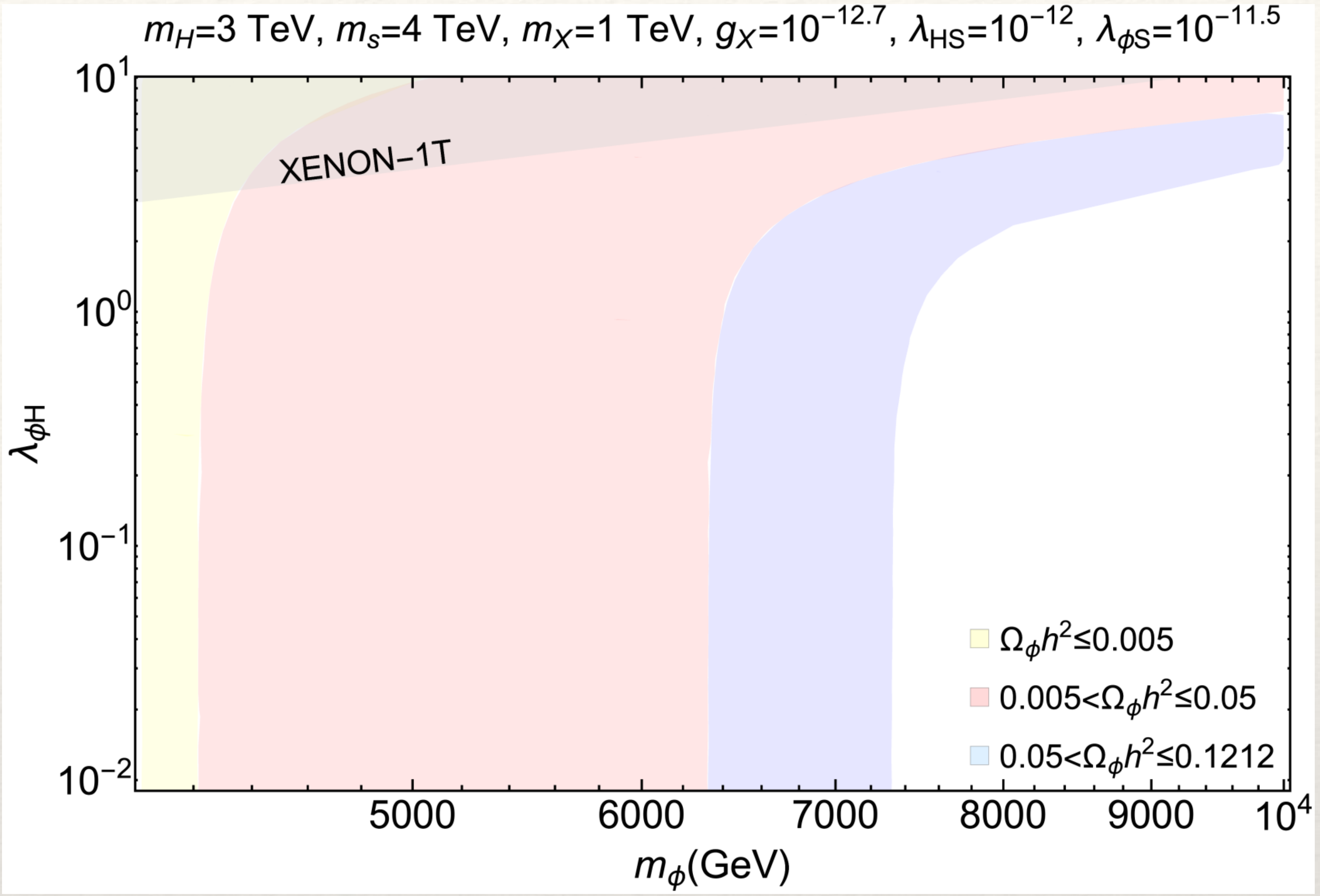


$$m_S < 2m_X;\ S \nrightarrow XX$$

Higgs mixing and direct search bound severely constrains allowed parameter space

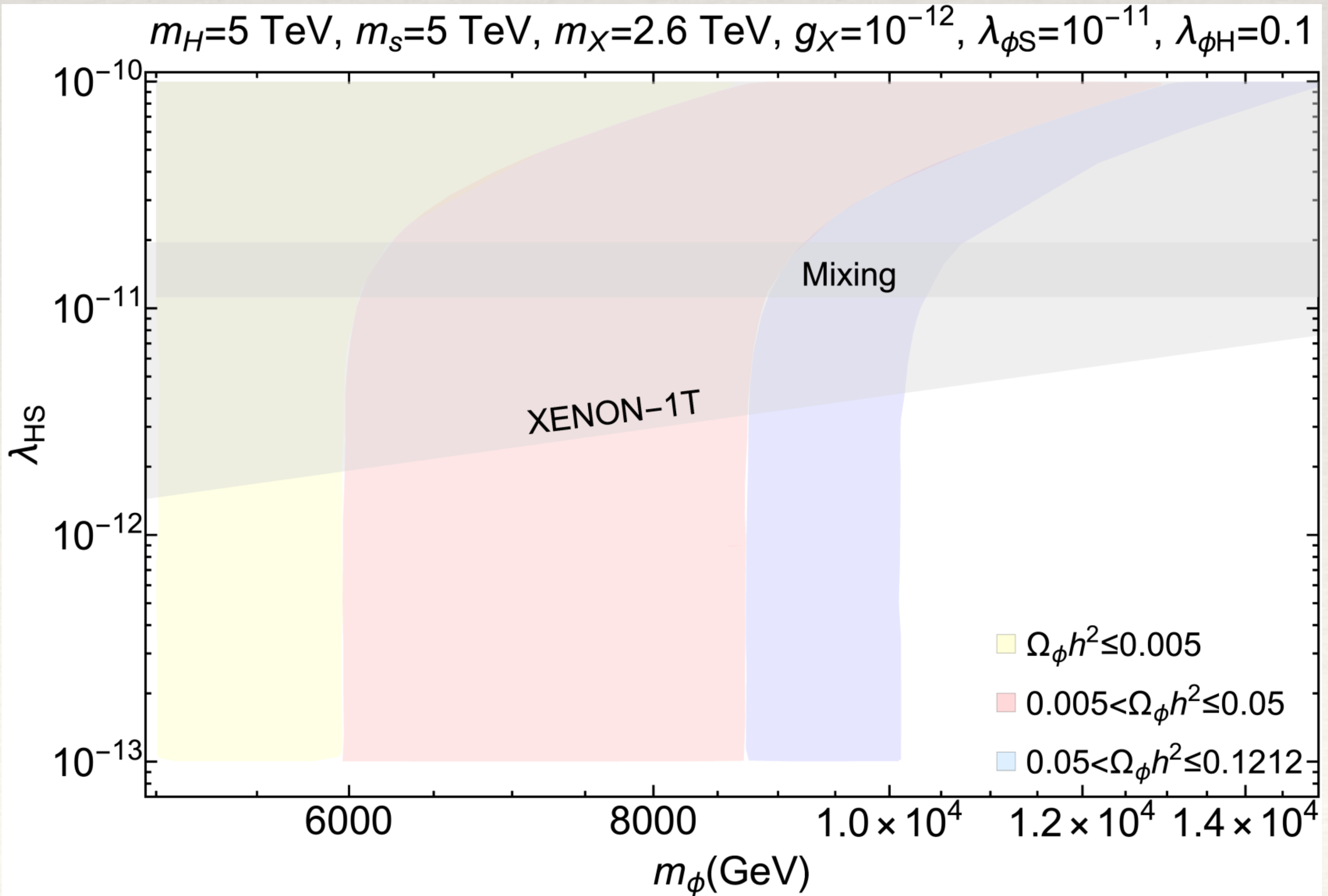
bEWSB: Freeze-out

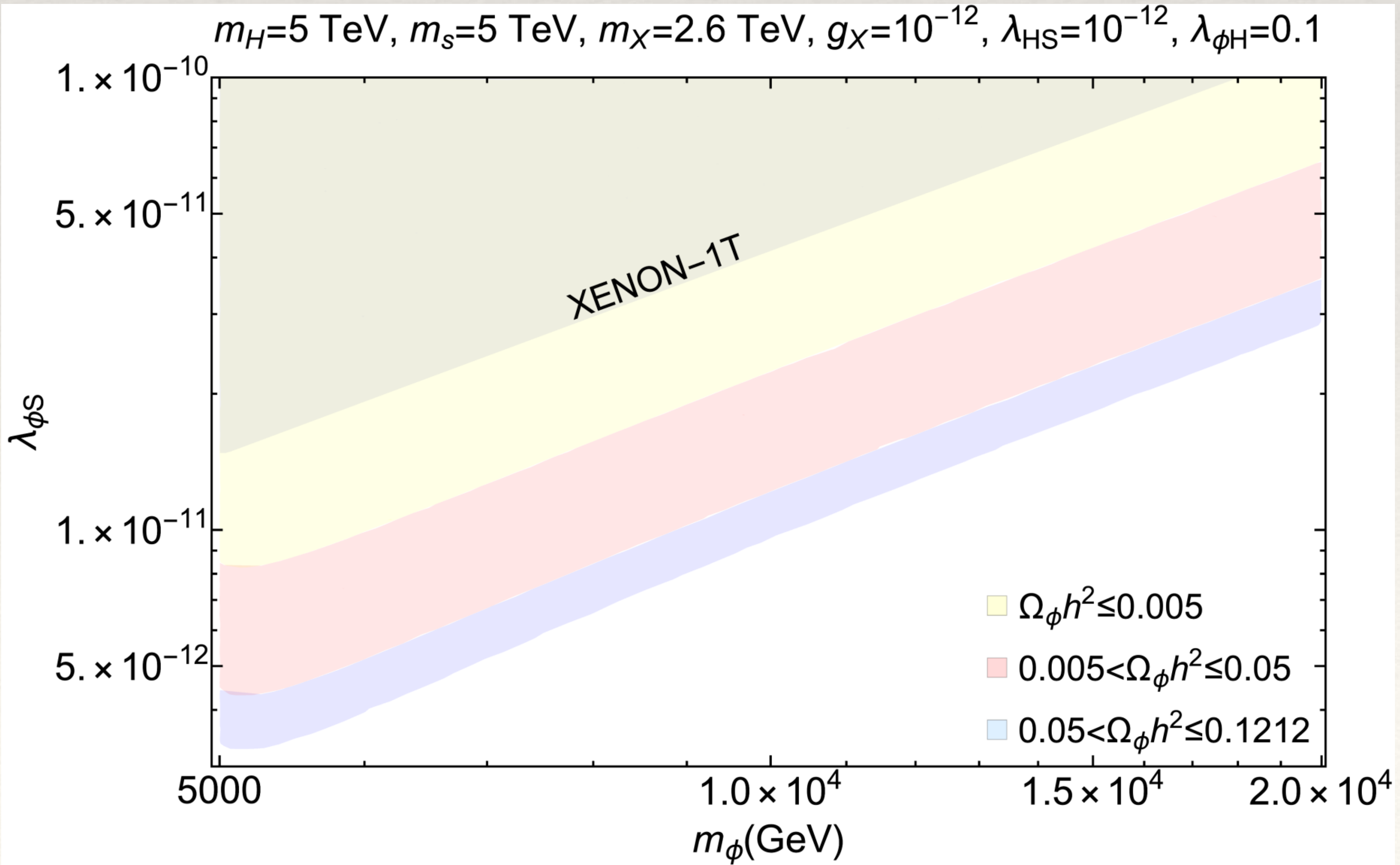




In presence of decay

$$m_S > 2m_X;\ S \to XX$$





In absence of decay

$$m_S < 2m_X;\ S \nrightarrow XX$$

bEWSB: Benchmark points

Benchmark points	m_H, m_ϕ, m_s, m_X (TeV)	$g_X, \lambda_{HS}, \lambda_{\phi S}, \lambda_{\phi H}$	$\Omega_\phi h^2$	$\Omega_X h^2$	$\frac{\Omega_\phi}{\Omega_T}\%$	$\frac{\Omega_X}{\Omega_T}\%$	$\sigma^{\rm SI}_{\phi_{eff}}$ (cm^2)
BP1	3, 7, 4, 1	$3.16\times10^{-13}, 1.14\times10^{-12}, 4.69\times10^{-12}, 0.5$	0.1151	0.0055	95.44	4.56	2.53×10^{-45}
BP2	3, 7, 5, 1	$6.31\times10^{-13}, 7.23\times10^{-12}, 9.61\times10^{-12}, 0.5$	0.0890	0.0313	73.98	26.02	7.4×10^{-45}
BP3	3, 7, 4, 0.9	$1.26\times10^{-12}, 4.6\times10^{-12}, 3.55\times10^{-11}, 0.5$	0.0155	0.1050	12.86	87.14	7.52×10^{-46}

Table 3. Some benchmark points satisfying total relic density bound and the other experimental constraints. For all these points, WIMP freeze-out and FIMP freezes in bEWSB.

aEWSB: processes for DM

s, h mixes to produce h_1, h_2

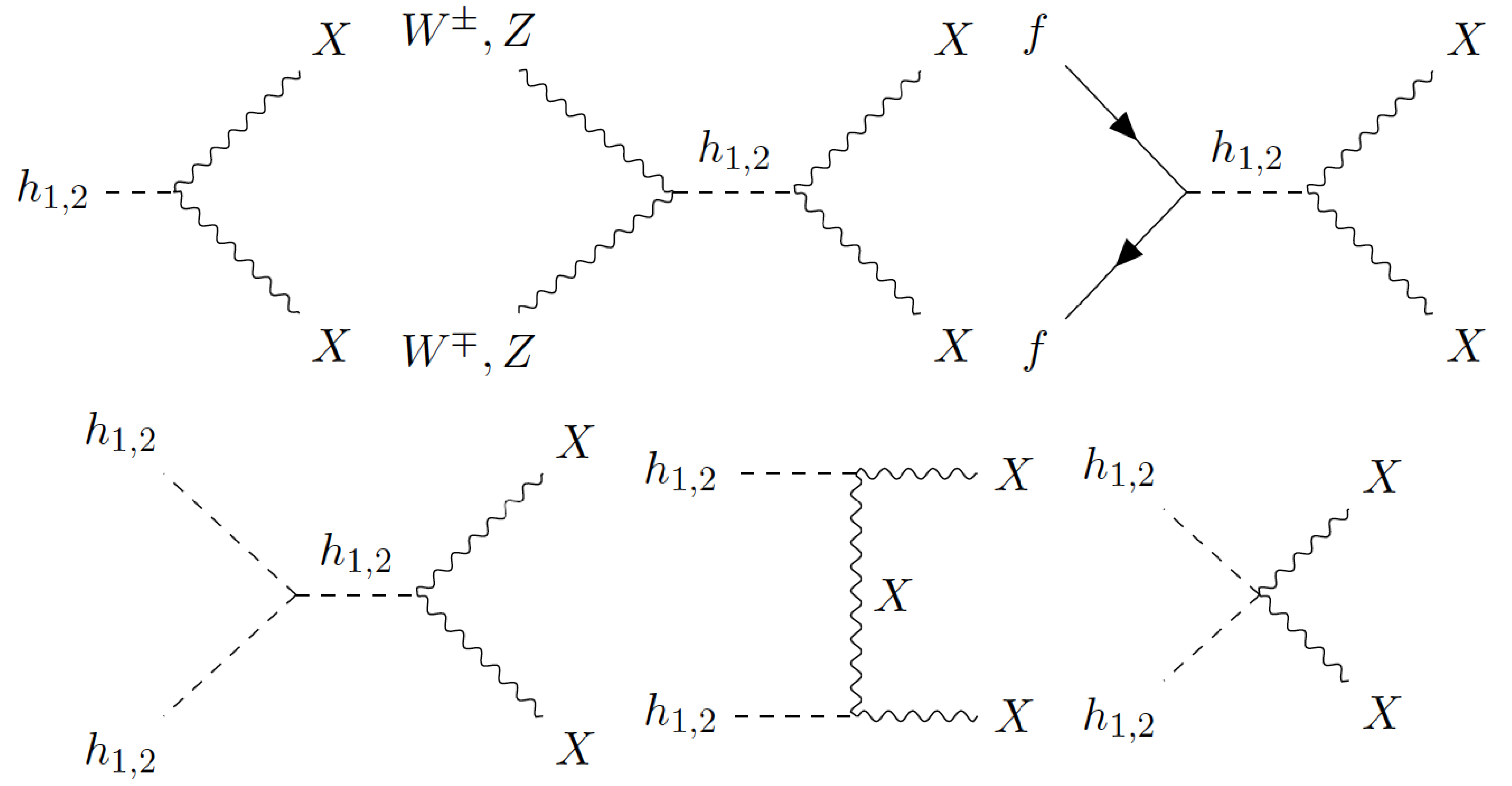


Figure 17. Feynman diagrams showing non-thermal production channels of X after EWSB

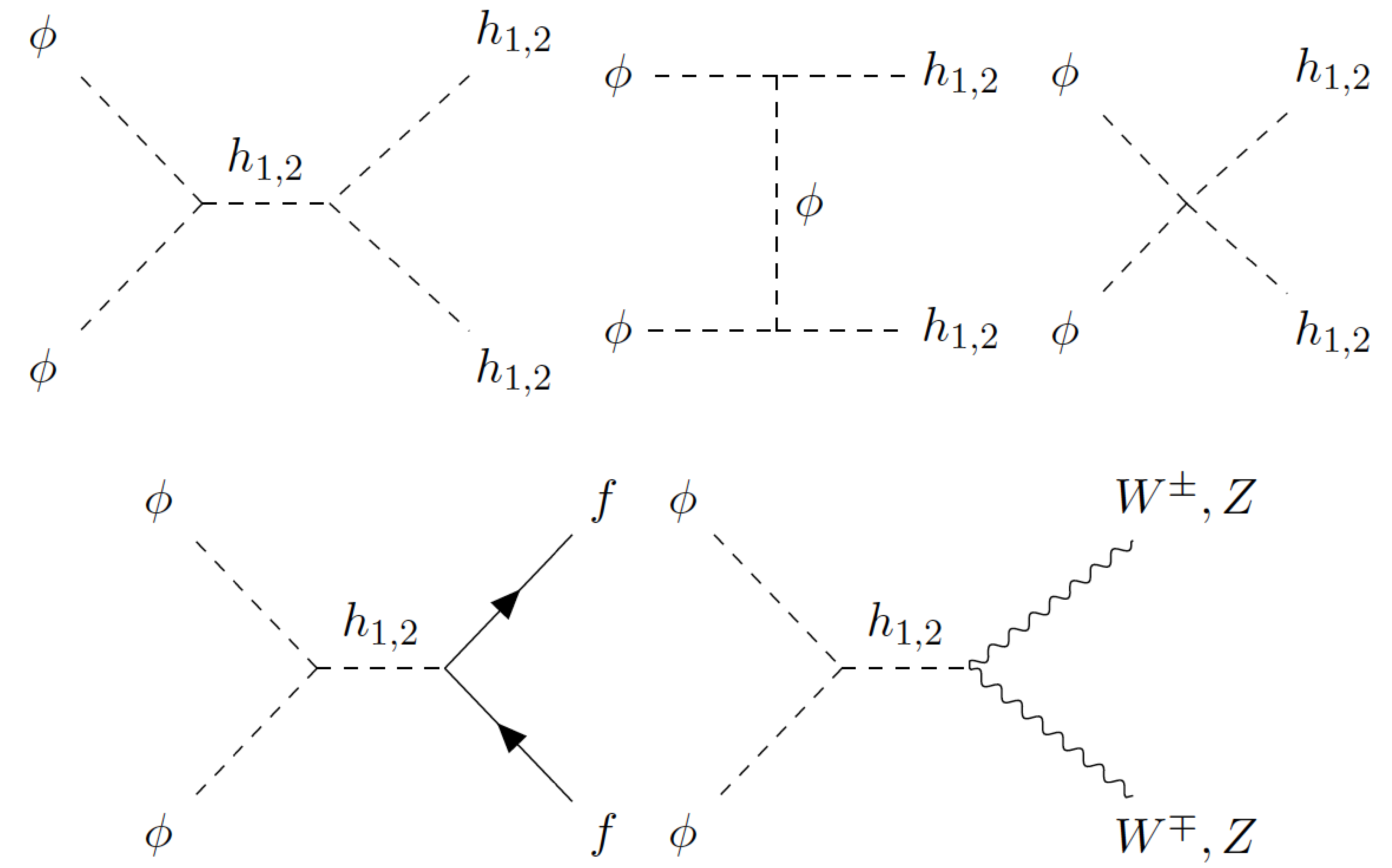
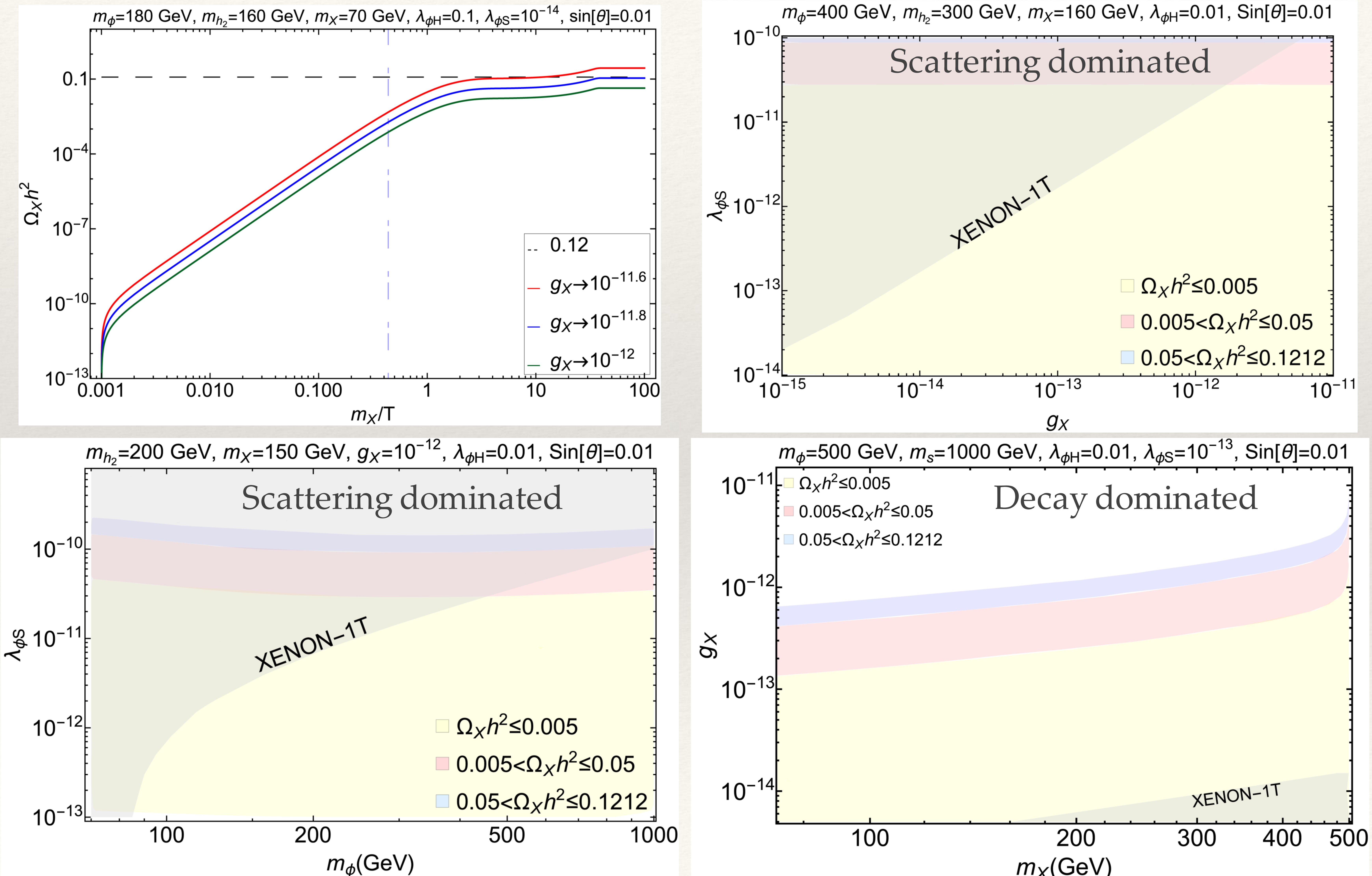


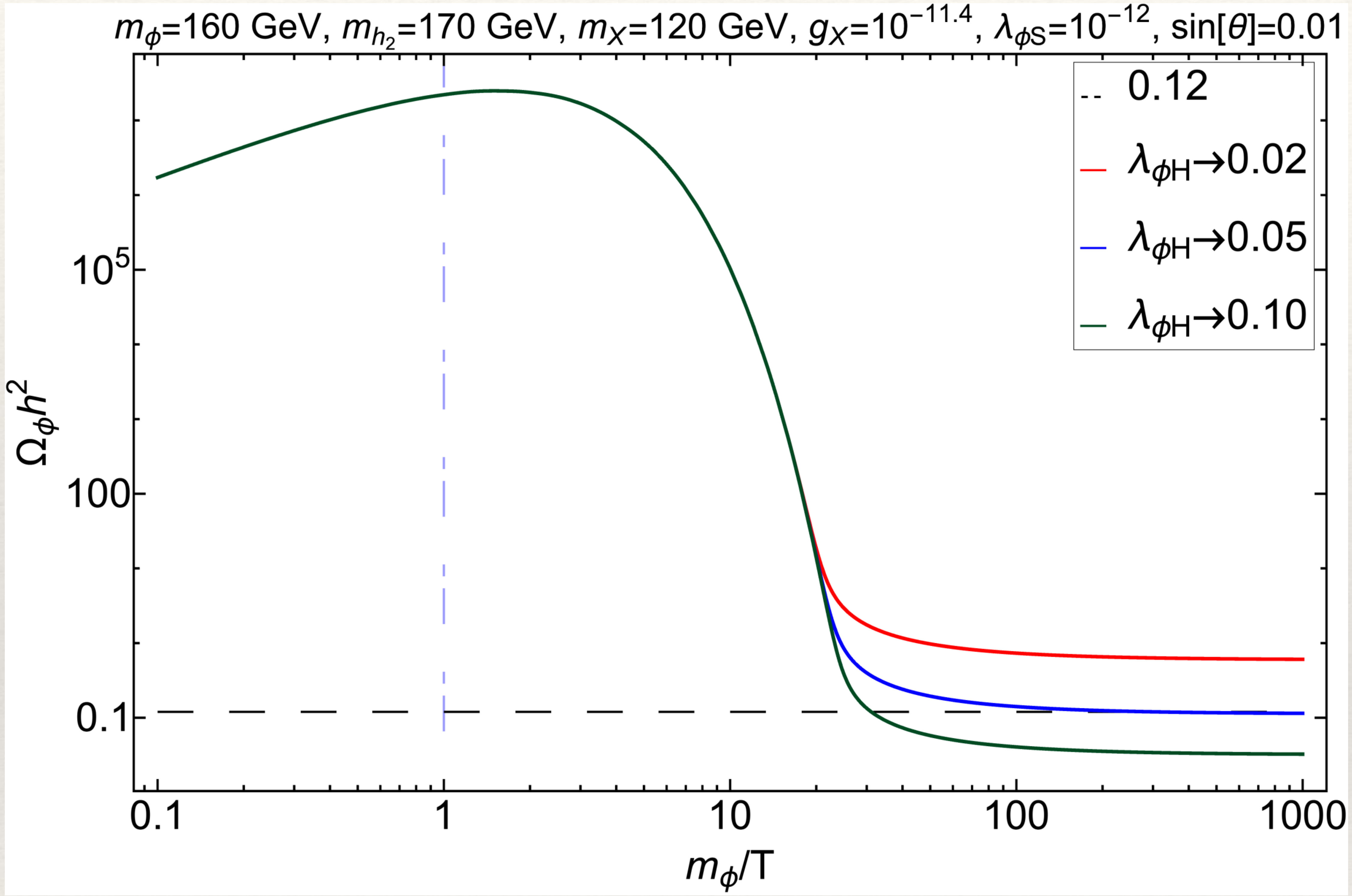
Figure 18. Feynman diagrams showing annihilation channels of ϕ after EWSB

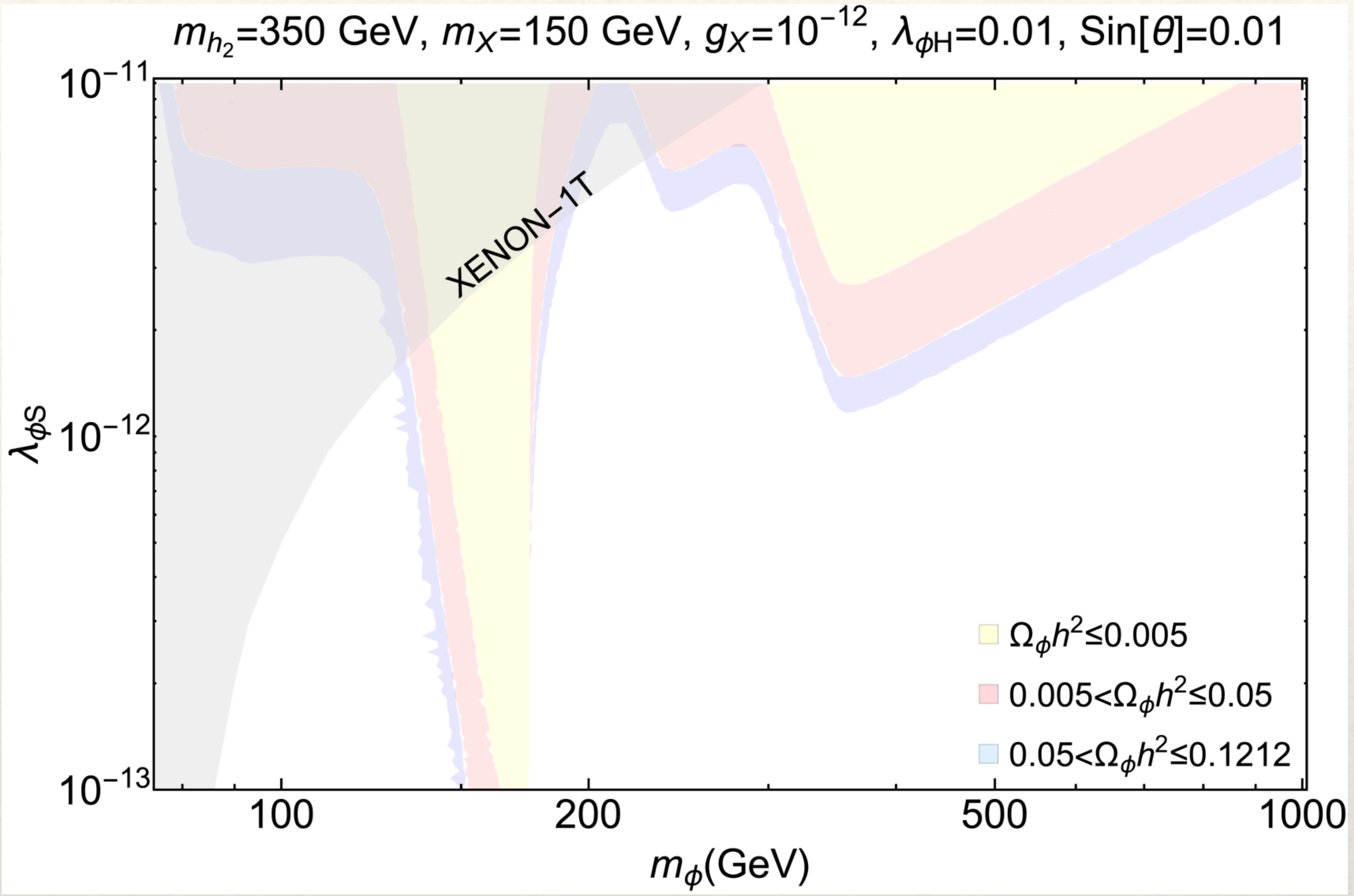
aEWSB: freeze in

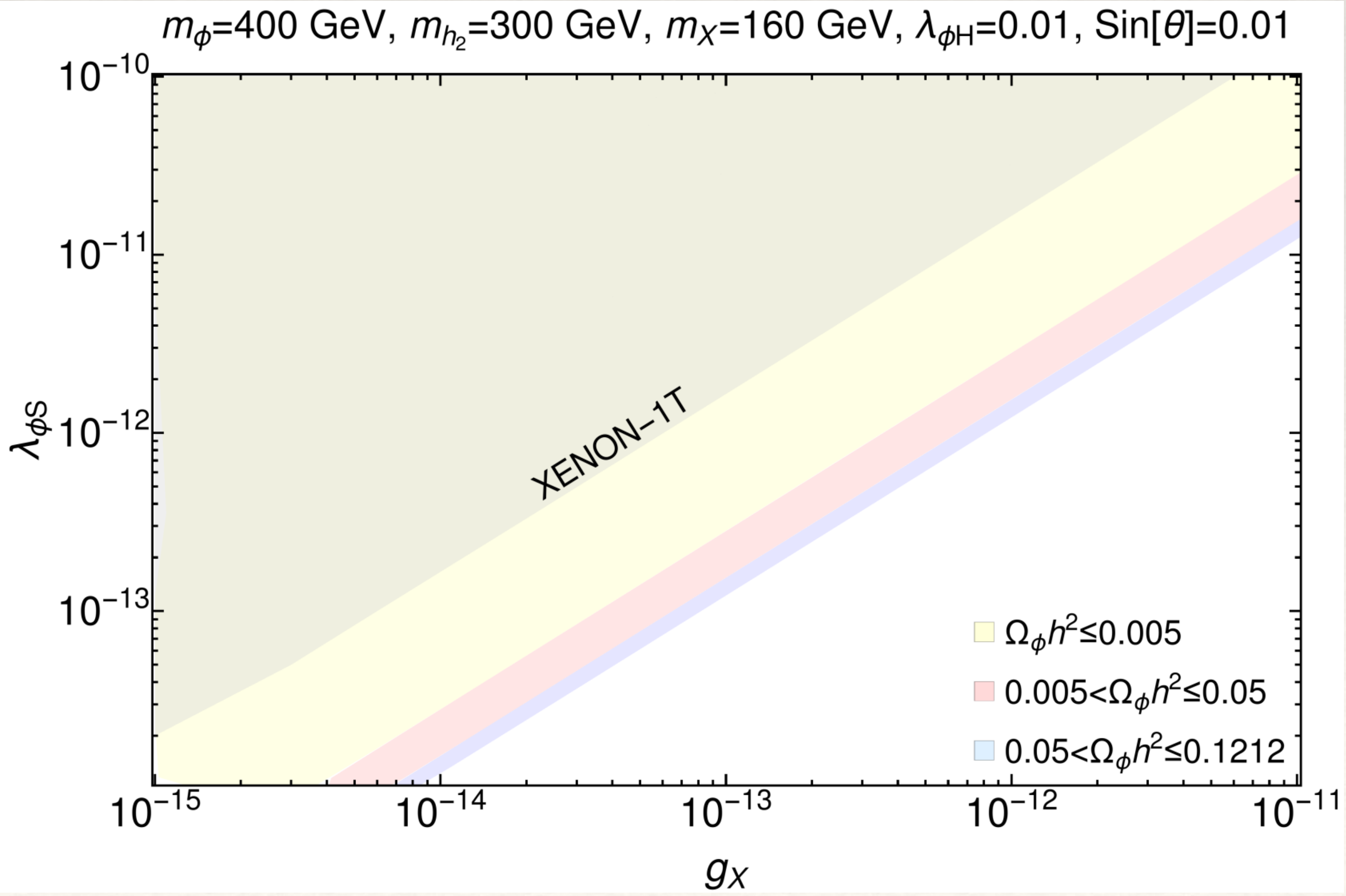


Direct search constraints play a crucial role even in decay dominated case unlike bEWSB case

aEWSB: freeze out







h_2 resonance at $m_\phi = \frac{m_{h_2}}{2}$ and $m_\phi > m_{h_2}$ regions are allowed by direct search.

aEWSB: benchmark points

Benchmark points	m_ϕ, m_{h_2}, m_X (GeV)	$g_X, \lambda_{\phi H}, \lambda_{\phi S}, \sin\theta$	$\Omega_\phi h^2$	$\Omega_X h^2$	$\frac{\Omega_\phi}{\Omega_T}$ (%)	$\frac{\Omega_X}{\Omega_T}$ (%)	$\sigma^{\rm SI}_{\phi_{eff}}$ (cm^2)
AP1	200,150,70	$6.31\times10^{-13}, 10^{-3}, 6.31\times10^{-13}, 10^{-2}$	0.1140	0.0049	95.88	4.12	7.31×10^{-49}
AP2	200,270,130	$2.48\times10^{-12}, 10^{-2}, 1.12\times10^{-11}, 10^{-2}$	0.0666	0.0524	55.97	44.03	1.01×10^{-46}
AP3	350,300,100	$1.91\times10^{-12}, 10^{-2}, 10^{-11}, 10^{-2}$	0.0013	0.1195	1.08	98.92	5.85×10^{-49}

Table 5. Some benchmark points which satisfy present relic and direct search bound for aEWSB freeze-out.

Summary

- We show that relic density allowed parameter space differs for DMs connected to SM via Higgs portal for freeze-in or freeze-out bEWSB or aEWSB.
- We show this for a two component DM where a vector boson DM freezes in and a scalar single freezes out. The model best encapsulates such distinction due to the fact that both DMs are connected to SM by Higgs/scalar portal. Also VBDM inherits another symmetry breaking scale on top of EWSB.
- For freeze-out to occur bEWSB, the DM needs to be heavy, for freeze-out after aEWSB the mass can be much smaller ~TeV and can be accessible for collider search. While the one that freezes out bEWSB, leaves the scope of direct search only.
- For FIMP produced from the decay of a particle in thermal bath, even the late decay to occur bEWSB, makes the particle converted to DM completely bEWSB and *do not allow it to mix with SM Higgs* and therefore leaves little scope for direct search.
- In a WIMP-FIMP model, the conversion is limited to be small enough to keep the FIMP out of equilibrium, thus allowing a significant contribution to FIMP production from WIMP, but the depletion of WIMP is mostly unaffected by the conversion.