



# Freeze-in of WIMP dark matter

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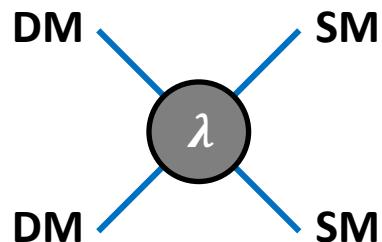
2023.5.9 @第二届地下和空间粒子物理与宇宙物理前沿问题研讨会

[With Xiaorui Wong, 2304.00908](#)

# Mystery of dark matter and a simple paradigm



Dark matter yield  $Y_X = n_X/s$



$$\frac{dY_X}{dz} = -\frac{s}{zH} \langle \sigma v_{\text{rel}} \rangle (Y_X^2 - Y_{\text{eq}}^2)$$

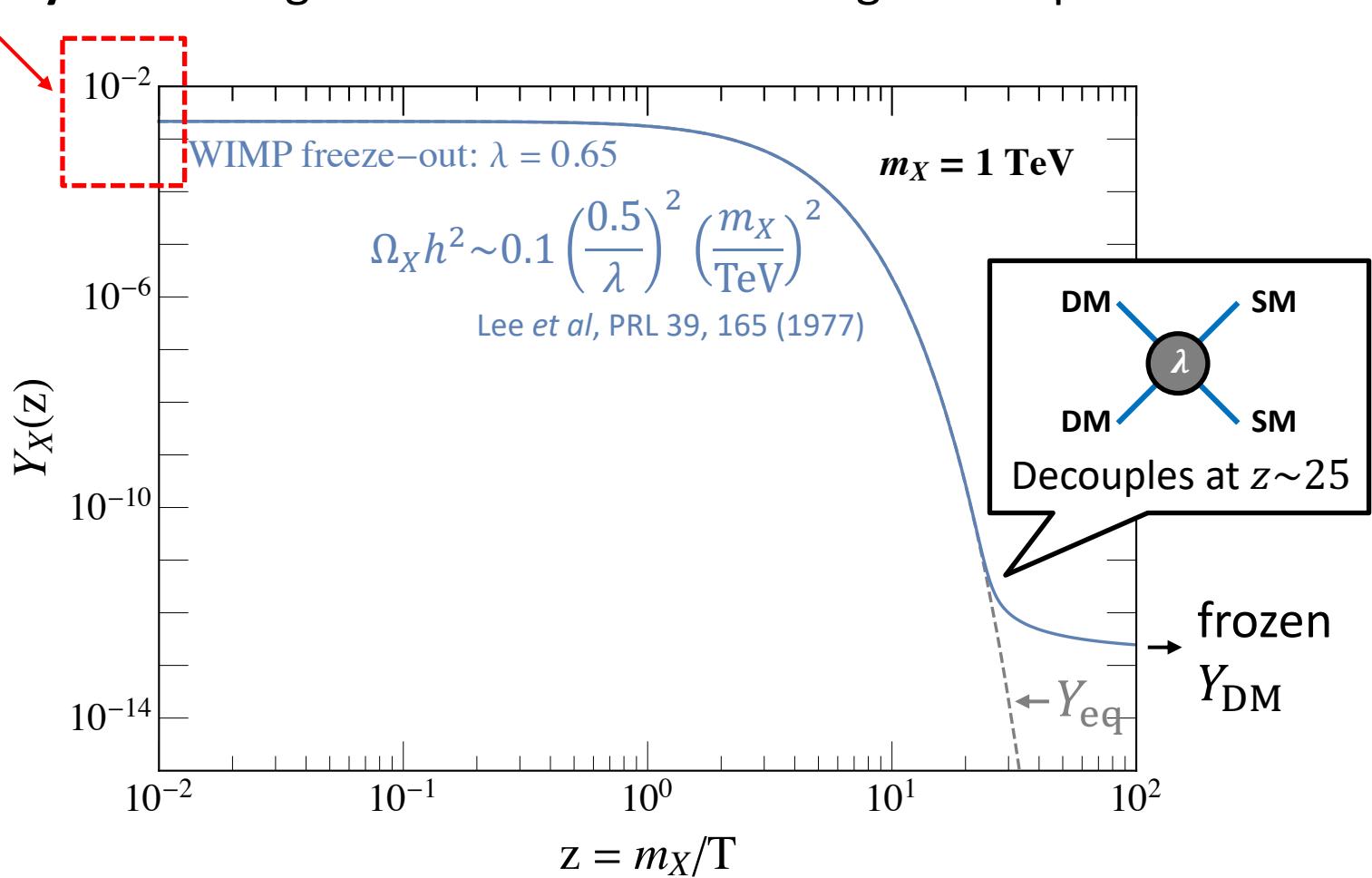
Entropy density      Hubble constant      Equilibrium distribution

$\sim \frac{\lambda^2}{32\pi m_X^2}$

Evolution:  $z \equiv \frac{m_X}{T} \uparrow$ . Goal: get correct  $Y_{\text{DM}} \sim \frac{0.8 \text{ eV}}{m_X}$  for  $z \gg 1$

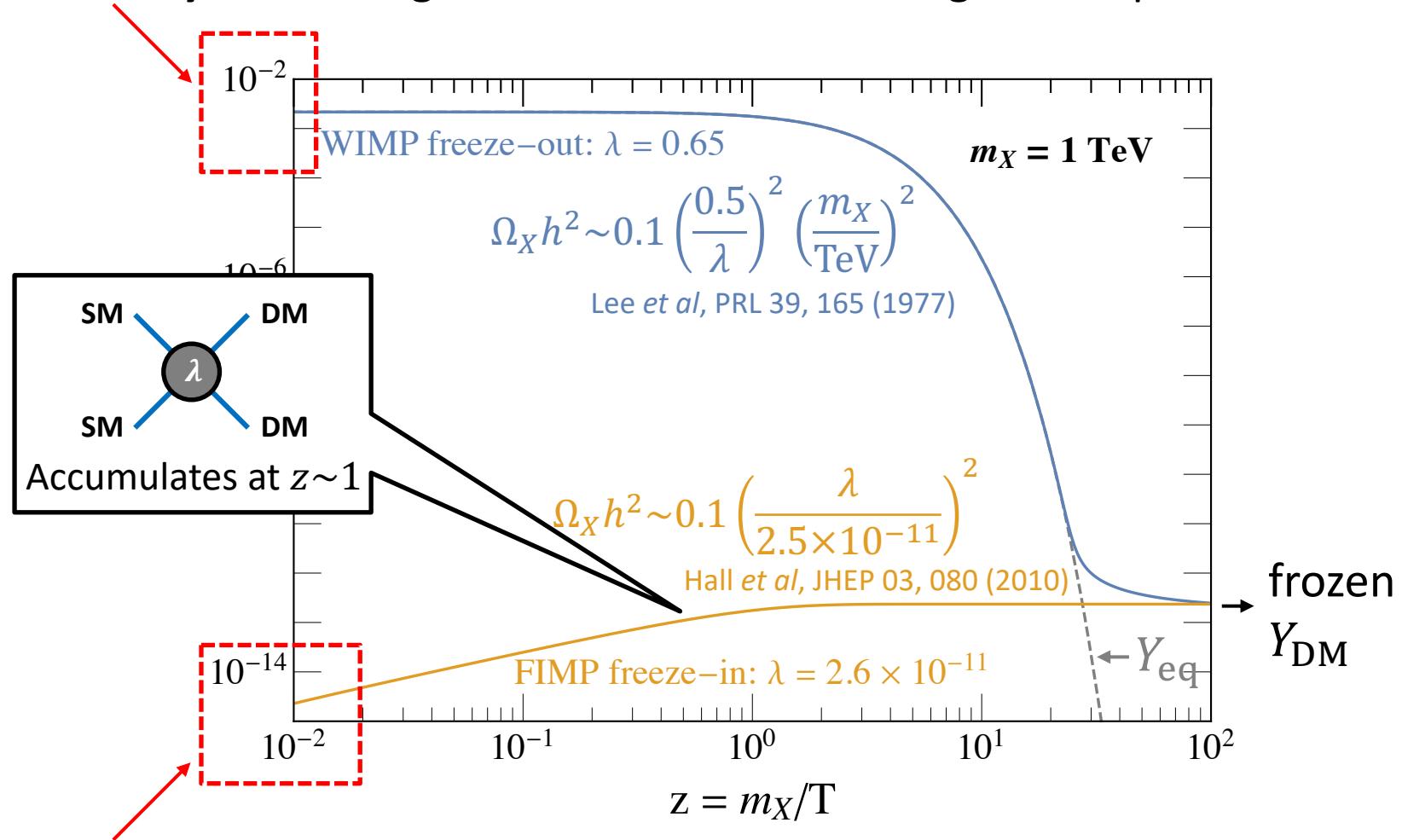
## Two popular solutions

Weakly Interacting Massive Particles: starting from equilibrium



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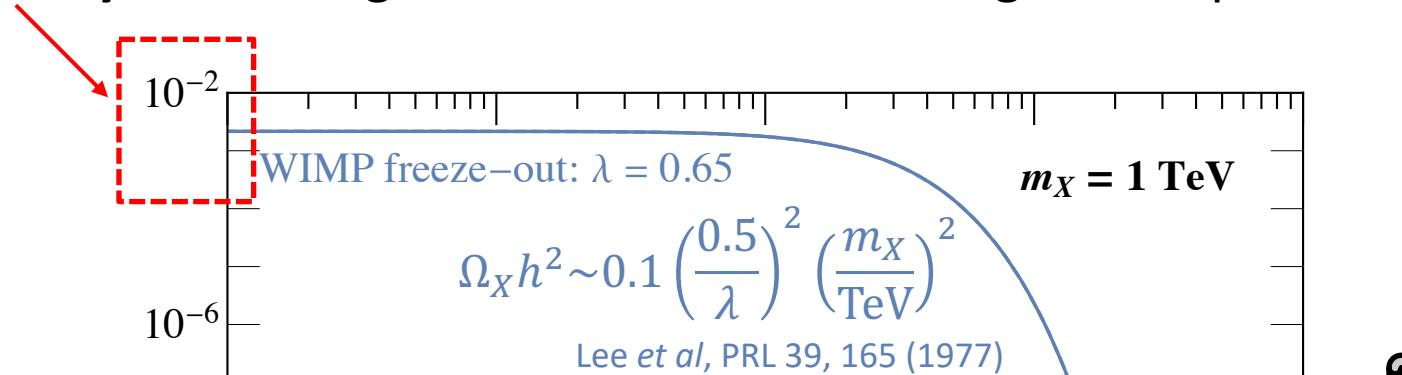
Weakly Interacting Massive Particles: starting from equilibrium



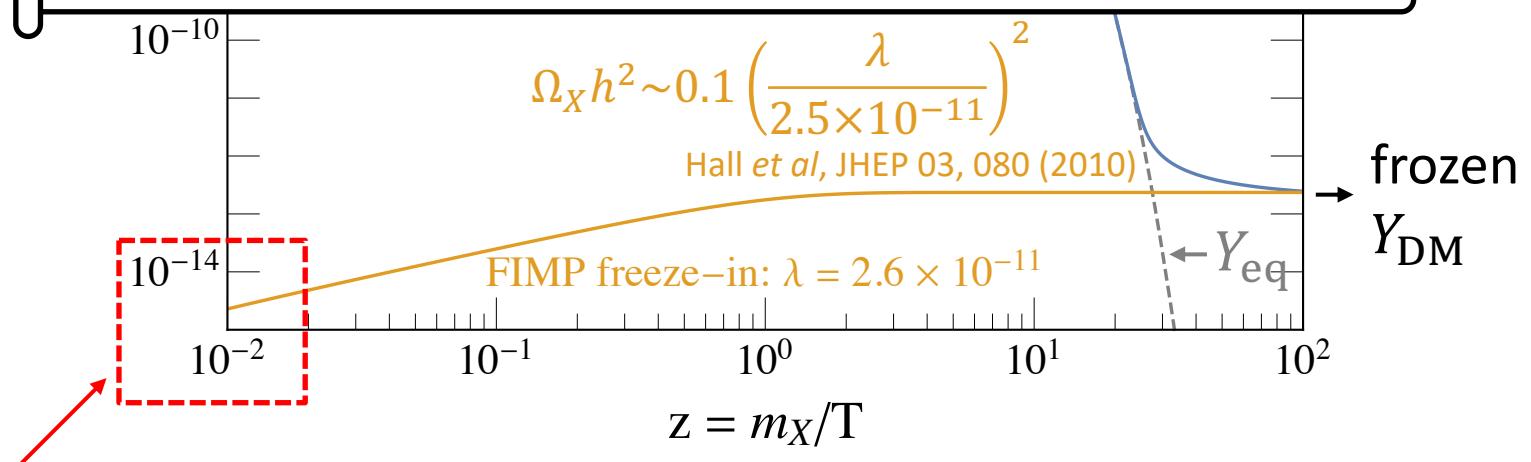
Feebly Interacting Massive Particles: starting from zero

## Two popular solutions

Weakly Interacting Massive Particles: starting from equilibrium



This talk: A third possibility, **WIMP freeze-in**

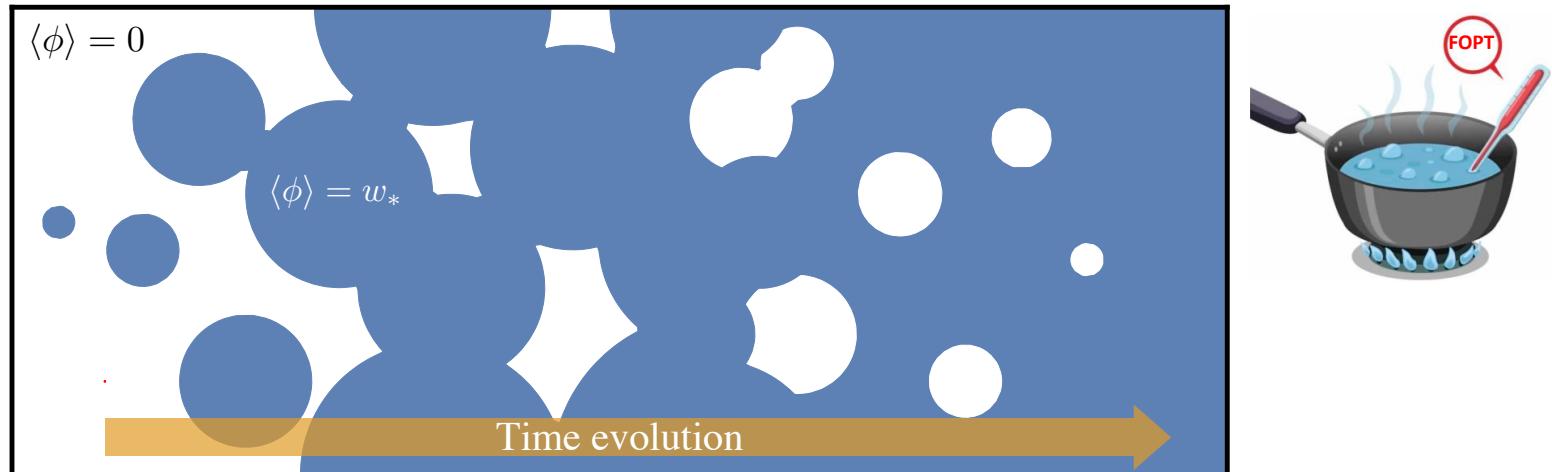
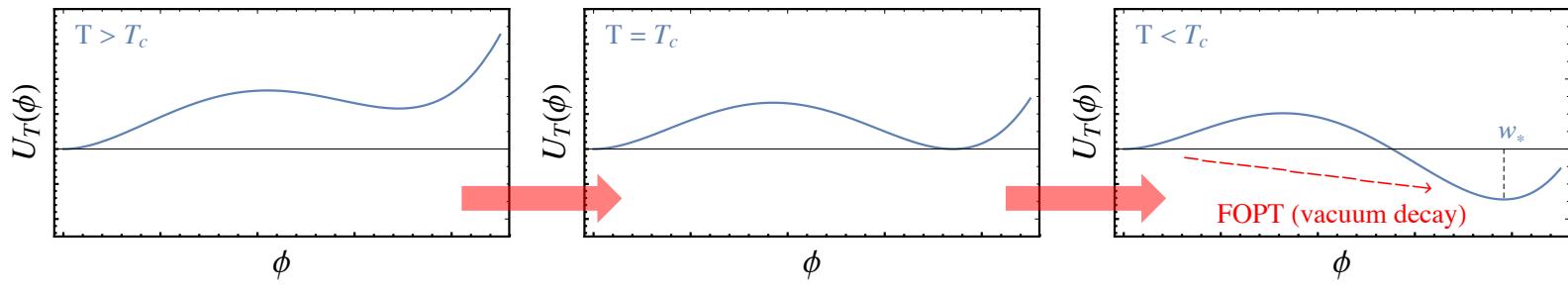


Feebly Interacting Massive Particles: starting from zero

# First-order phase transitions

FOPT: decay of the vacuum

$$\mathcal{L} \supset \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - U(\phi) \xleftarrow{\text{Thermal corrections}} U(\phi) \Rightarrow U_T(\phi, T)$$



“Boiling” of the Universe; bubble nucleation and expansion

# The basic idea

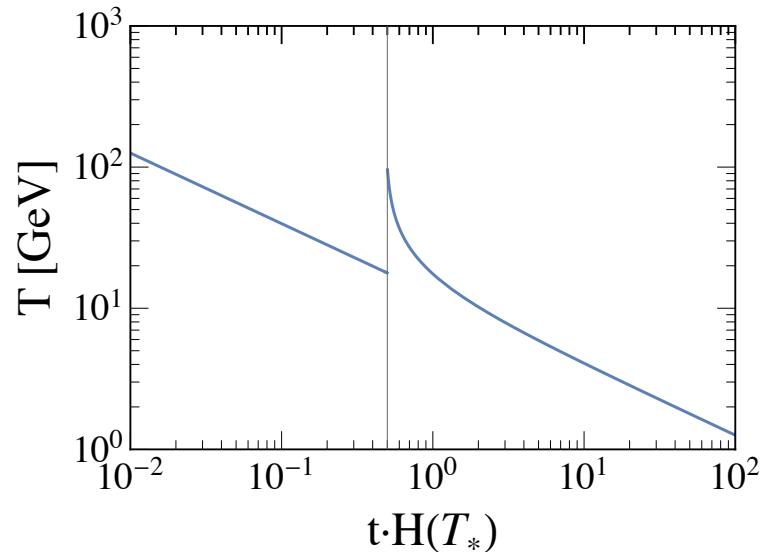
$$\mathcal{L} \supset -\lambda B^\dagger B X^\dagger X - \frac{\lambda_{\phi X}}{2} \phi^2 |X|^2;$$

Thermal bath particle

FOPT scalar

FOPT: two-fold

1. Change of VEV  $\langle \phi \rangle = 0 \rightarrow w_*$
2. Reheating  $T_1 \rightarrow T_2$



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Dark matter

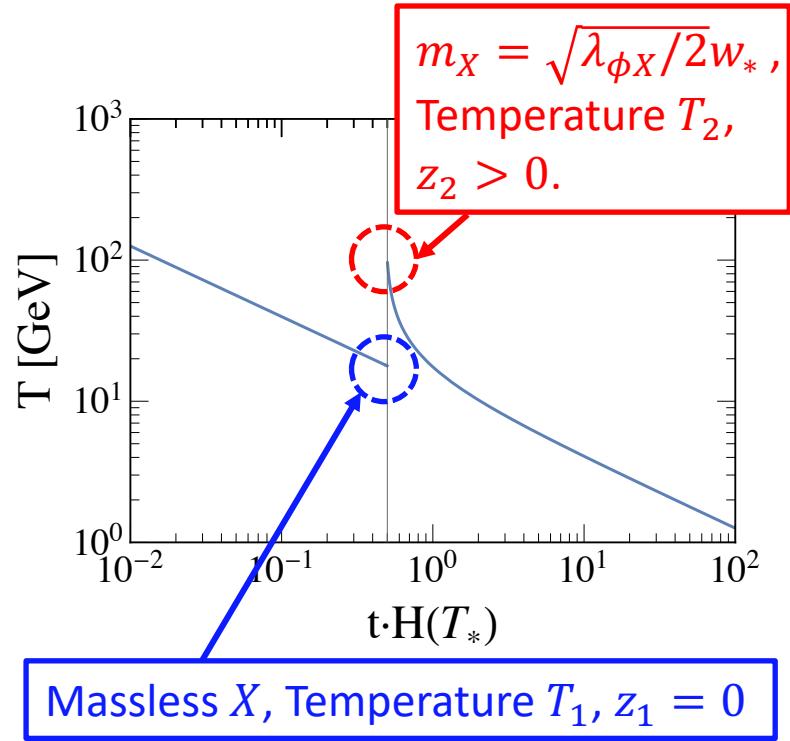
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$$\text{Dilution } Y_X(z_2) \approx \left(\frac{T_1}{T_2}\right)^3 \times Y_X(0)$$



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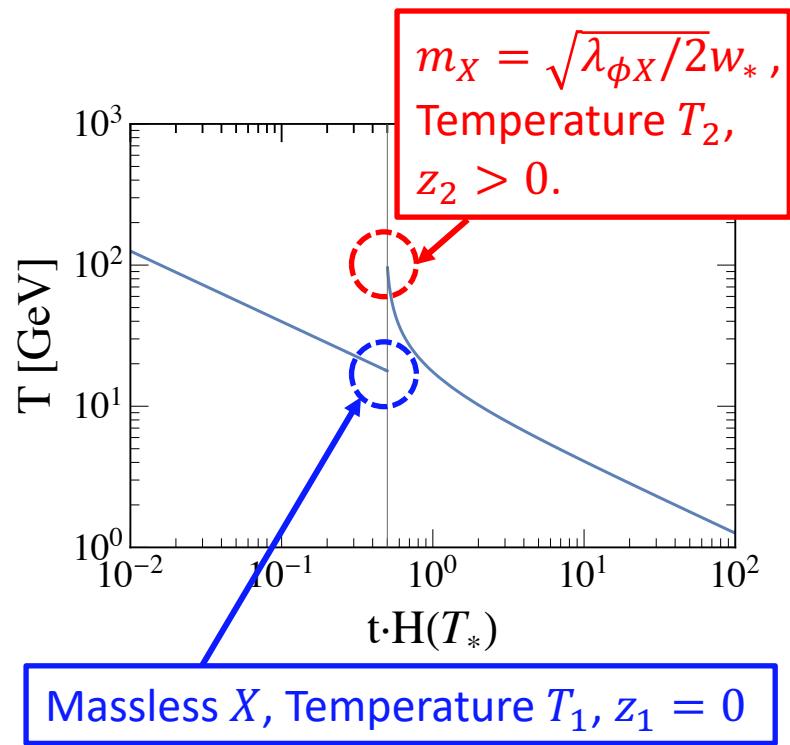
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After the (supercooled) FOPT:

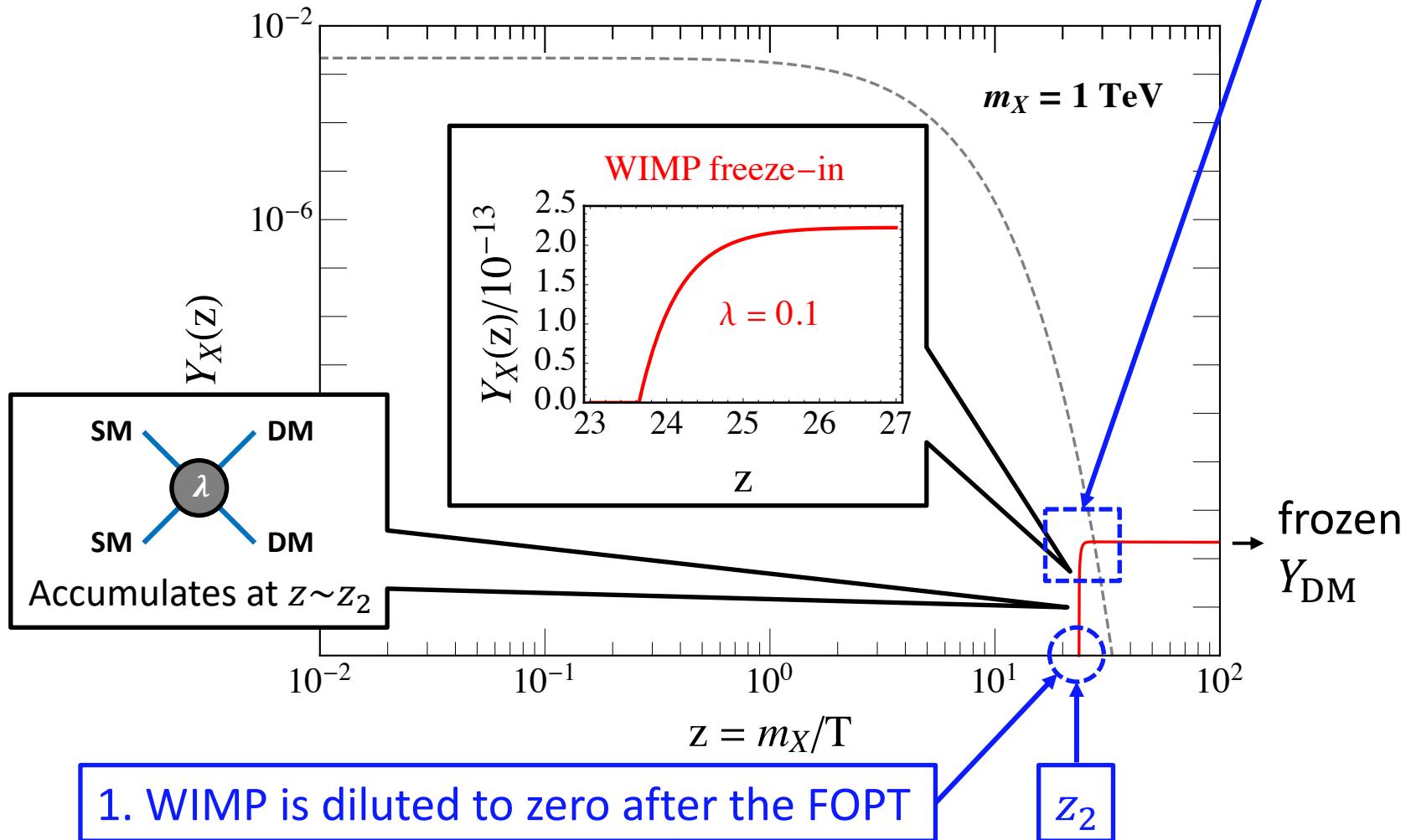
1. DM density is negligibly small;
2. DM cannot get back to equilibrium  
since  $z_2 = \frac{m_X}{T_2} \gg 1$ , even when  $\lambda$  is

**NOT feeble.**

Condition for  
freeze-in!

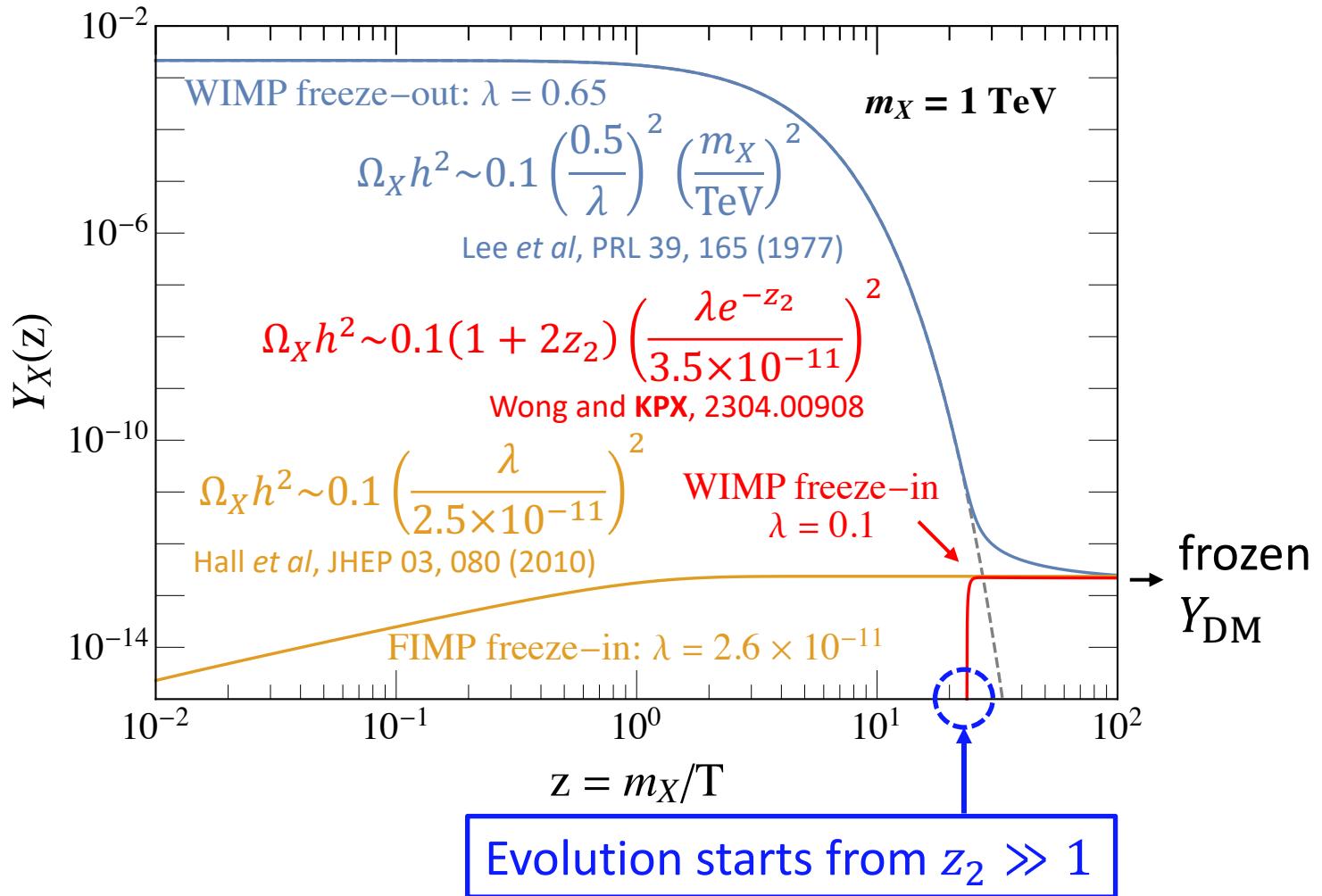
# Freeze-in of WIMPs [this talk]

2. WIMP cannot go back to equilibrium due to  $z_2 = m_X/T_2 \gg 1$



# Freeze-in of WIMPs [this talk]

A typical freeze-in scenario, but happens for WIMPs



# A realistic model with Higgs portal WIMP

SM + two singlet scalars [Kawana, PRD 105, 103515 (2022)]

$$V = \lambda_h |H|^4 + \frac{\lambda_\phi}{4} \phi^4 + \lambda_x |X|^4 + \frac{\lambda_{h\phi}}{2} \phi^2 |H|^2 + \frac{\lambda_{\phi x}}{2} \phi^2 |X|^2 + \lambda_{hx} |X|^2 |H|^2$$



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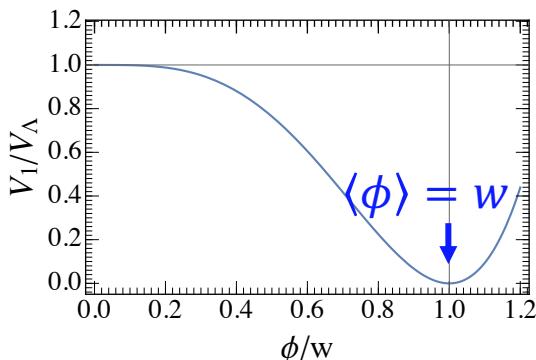
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Coleman-Weinberg potential [Coleman *et al*, PRD 7, 1888 (1973)]

$$V_1 \approx V_\Lambda + \frac{\lambda_{\phi s}^2 - 2y_\psi^4}{64\pi^2} \phi^4 \left( \log \frac{\phi}{w} - \frac{1}{4} \right);$$

Also contribution from fermion  $\mathcal{L}_I \supset -\frac{y_\psi}{\sqrt{2}} \phi \bar{\psi} \psi - y_\nu \bar{\ell}_L \tilde{H} \psi$



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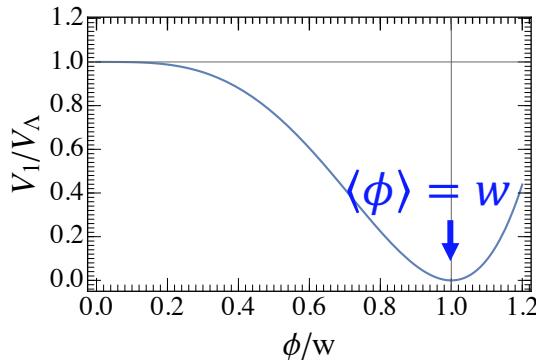
↑      ↑      ↑      dark matter candidate      brace

SM Higgs   FOPT scalar   dark matter candidate      Portal couplings

Coleman-Weinberg potential [Coleman *et al*, PRD 7, 1888 (1973)]

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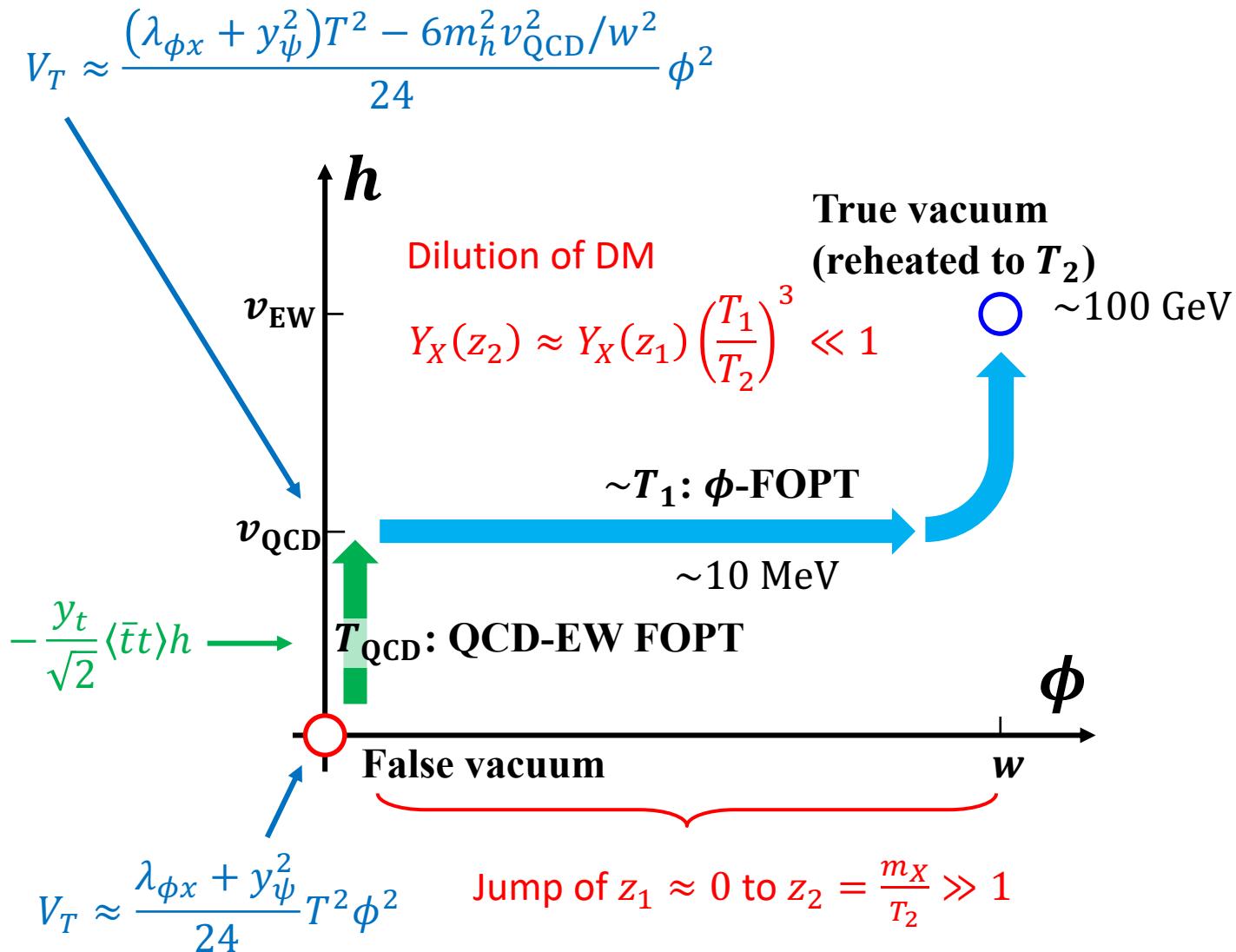
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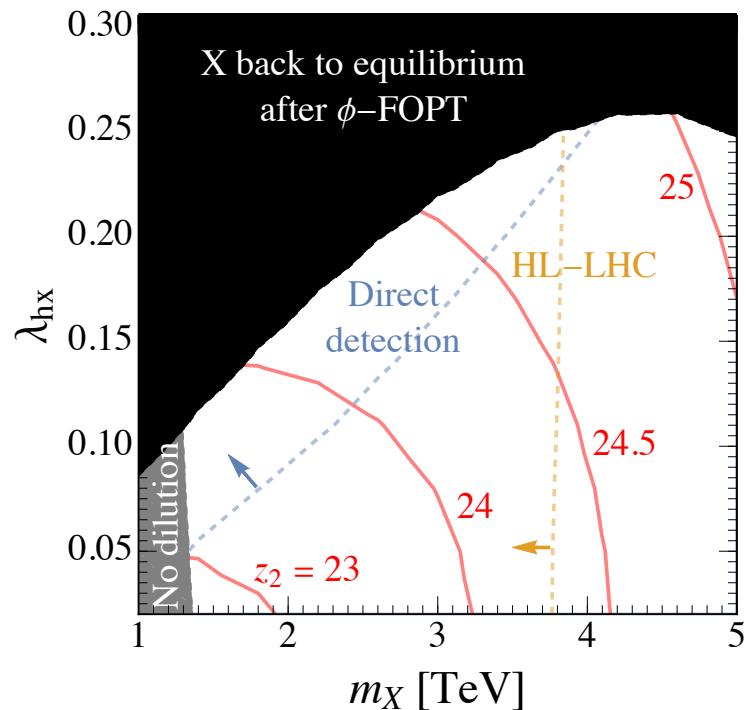
Triggers EW symmetry breaking:  $\lambda_{h\phi} = -\frac{m_h^2}{w^2}$

- $V \rightarrow -\frac{m_h^2}{2} |H|^2 + \lambda_h |H|^4$
- $\langle h \rangle = v_{EW} = 246 \text{ GeV}; m_h = 125 \text{ GeV}$
- DM mass  $m_X = \sqrt{\frac{\lambda_{\phi X} w^2 + \lambda_{hx} v_{EW}^2}{2}}$

# Thermal history



# Viable parameter space

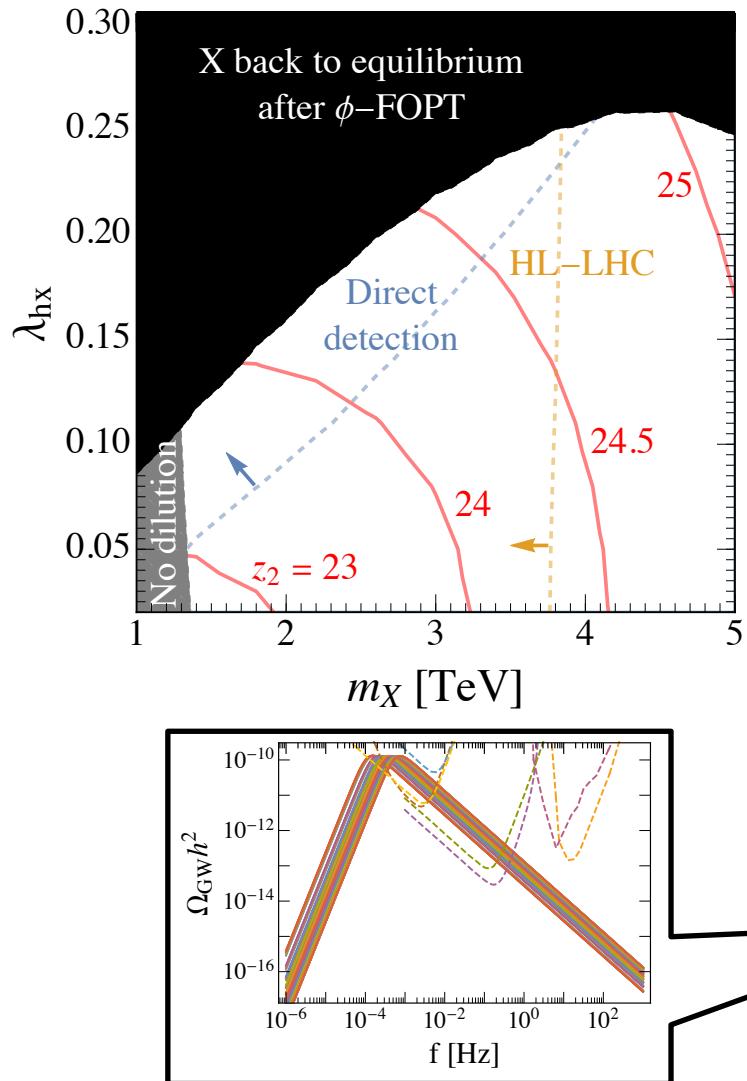


## WIMP dark matter $X$

Produced via **freeze-in**:  $hh \rightarrow XX^\dagger$ ,  
 $\phi\phi \rightarrow XX^\dagger$

- Direct detection  $\sigma_{\text{SI}} \sim 10^{-48} \text{ cm}^2$
- $\text{Br}(h \rightarrow \phi\phi) \sim 4\% - 9\%$ ;

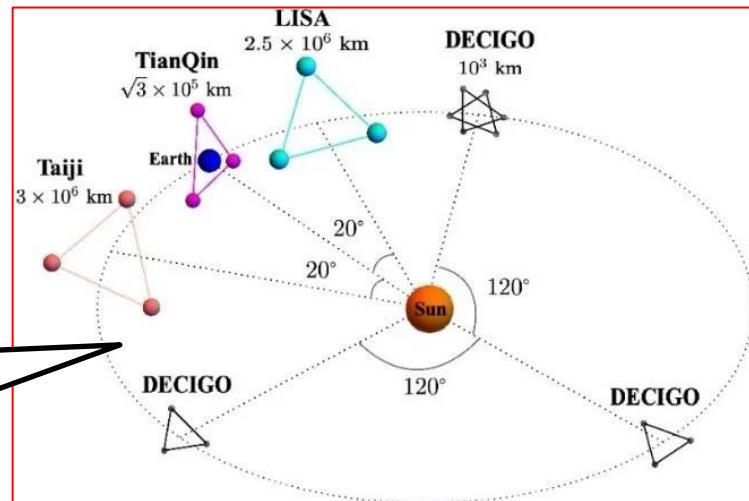
# Viable parameter space



## WIMP dark matter $X$

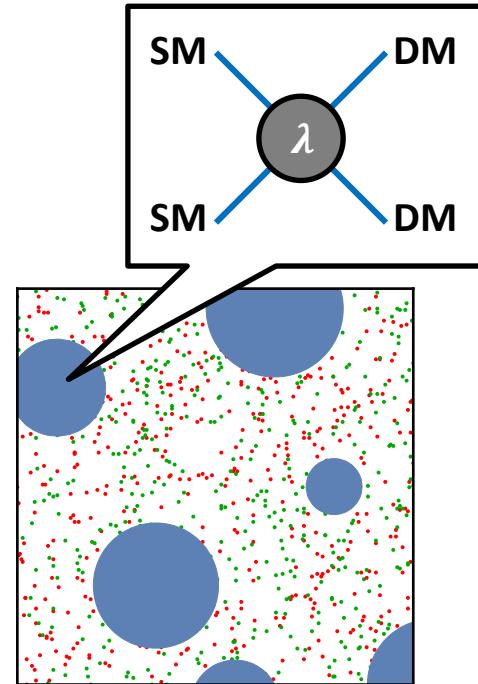
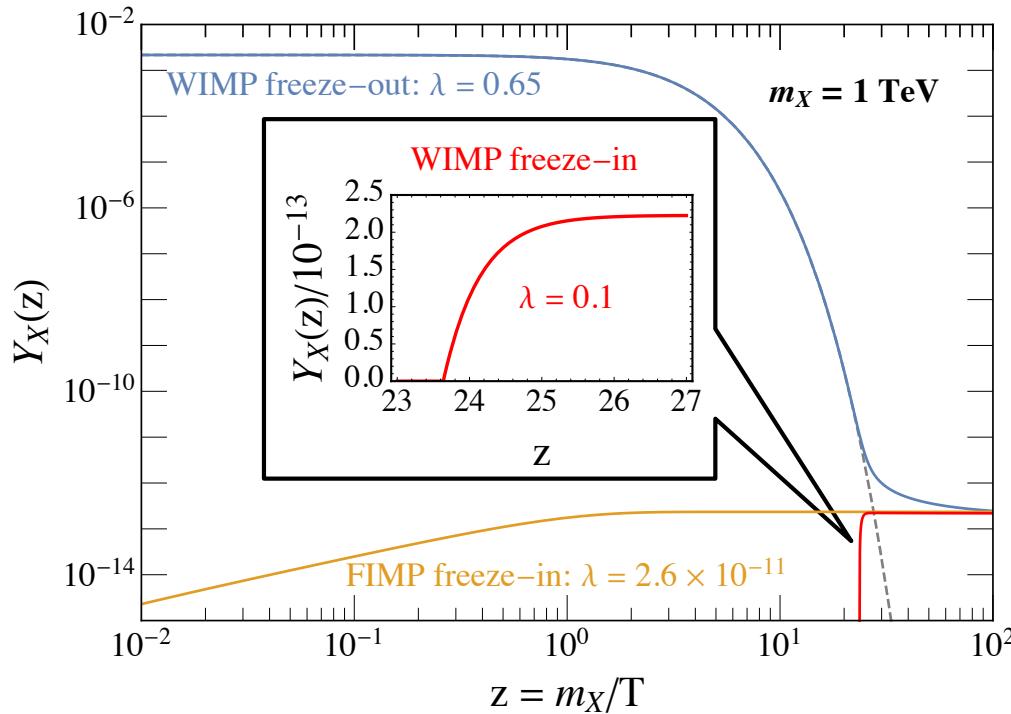
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- Gravitational waves  $f \sim 10^{-3} \text{ Hz}$ , LISA, TianQin, Taiji, ...



# Conclusion

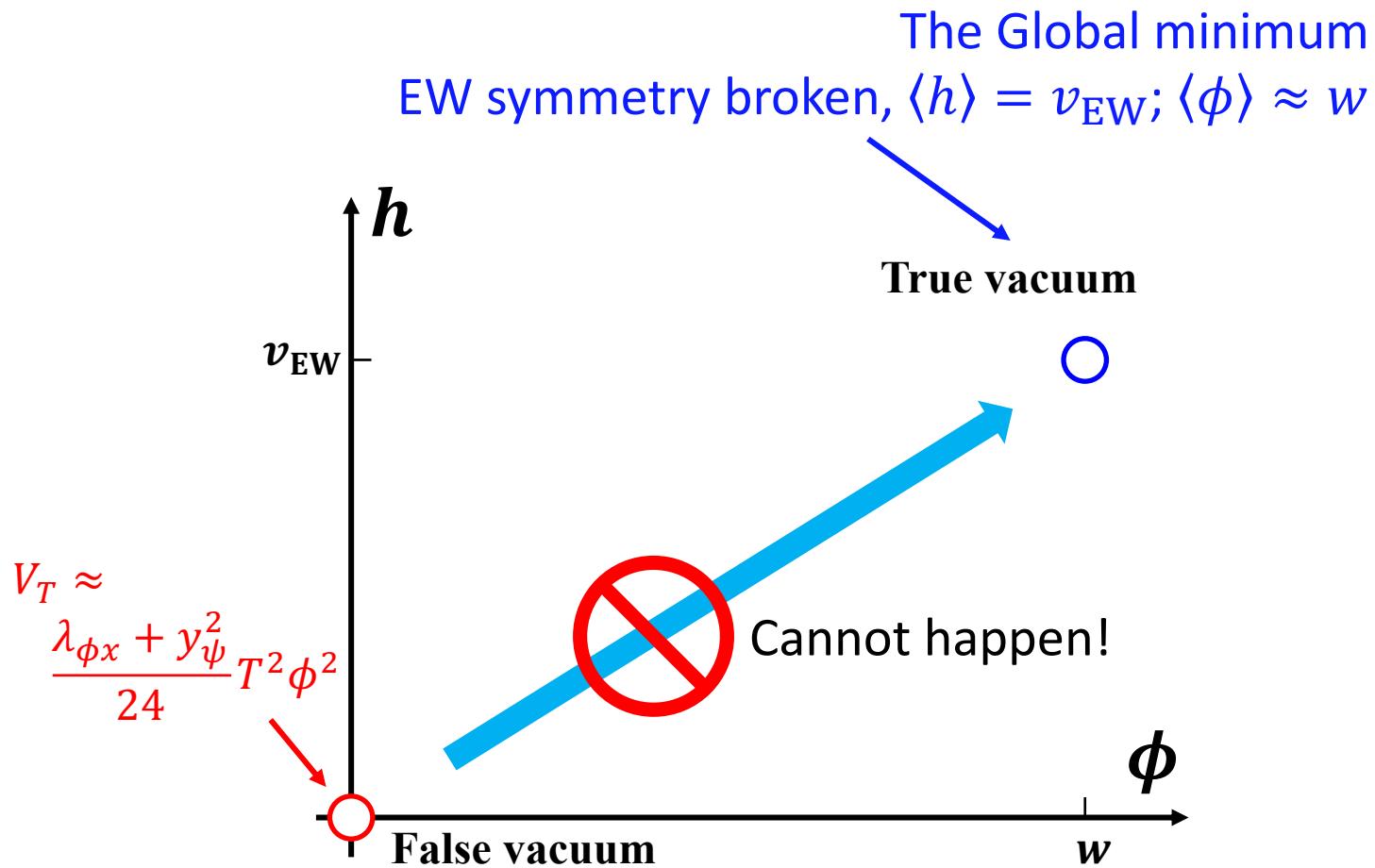
A novel dark matter scenario based on the  $2 \rightarrow 2$  process



- Generally applied to a lot of new physics models;
- Phenomenology: correlation with **WIMP searches & gravitational waves**

Thank you!

## Backup: thermal history (1)



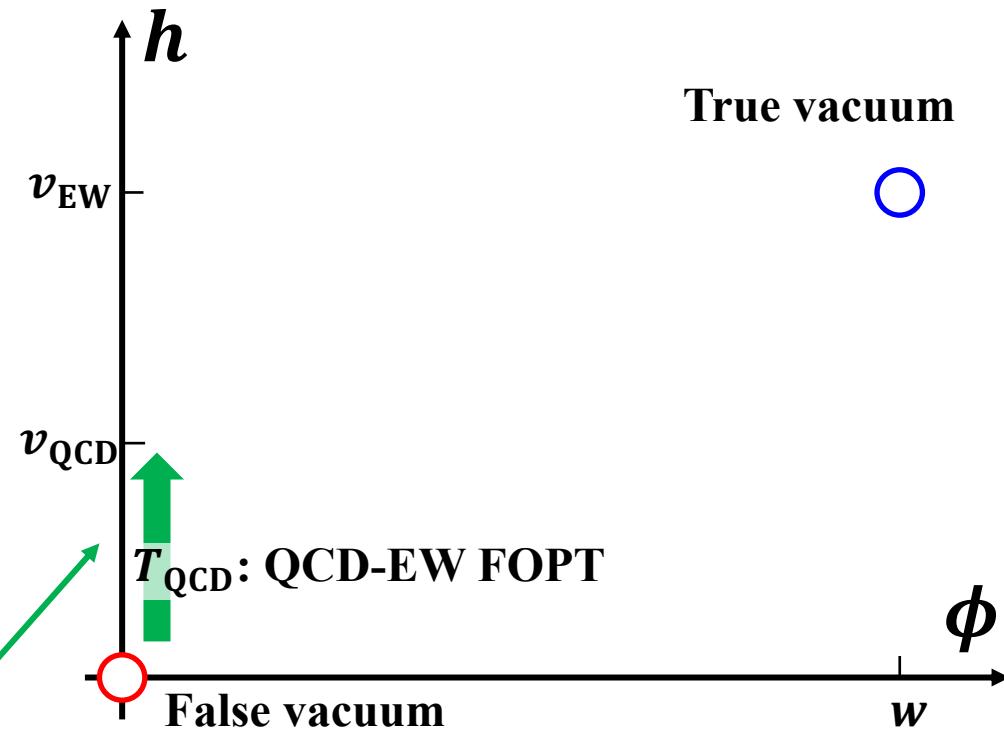
The local minimum:  $\langle h \rangle = \langle \phi \rangle = 0$ ; EW symmetry preserved

- $m_X = 0$ , dark matter massless

## Backup: thermal history (2)

At  $T_{\text{QCD}} \approx 85$  MeV: QCD confinement [Braun et al, JHEP 06, 024 (2006)]

- A FOPT --  $N_f = 6$  massless quarks [Pisarski et al, PRD 29, 338 (1984)]

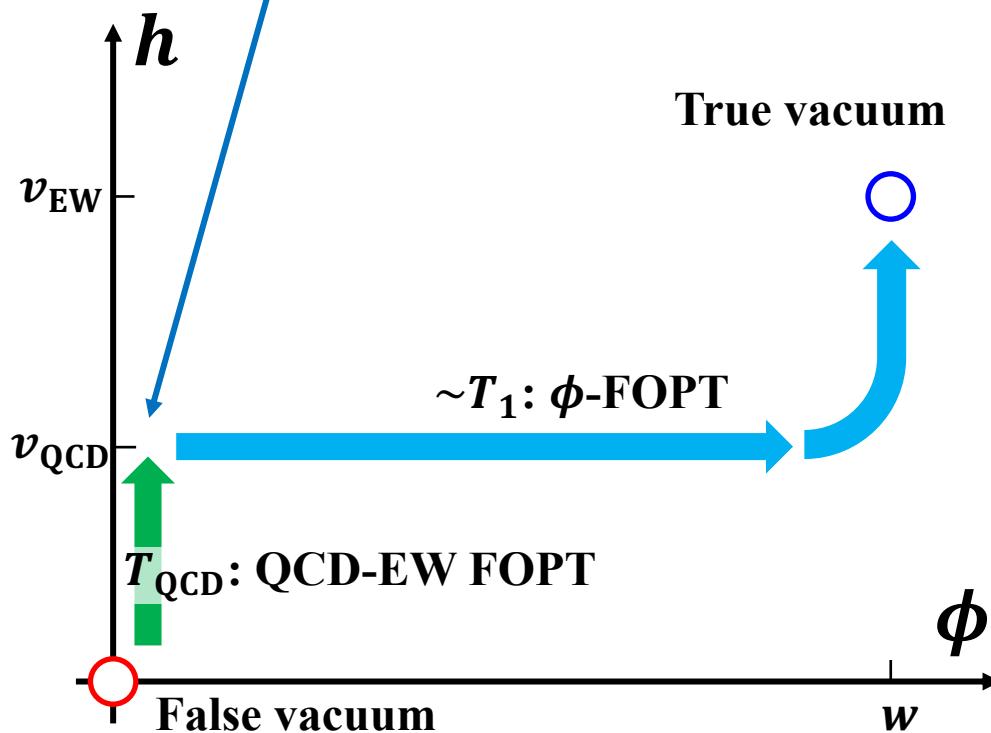


Quark Yukawa  $-\frac{y_t}{\sqrt{2}} \bar{t} t h$  induces  $-\frac{y_t}{\sqrt{2}} \langle \bar{t} t \rangle h$  -- linear term

- Triggers  $\langle h \rangle = v_{\text{QCD}} = (y_t \langle \bar{t} t \rangle / \sqrt{2} \lambda_h)^{1/3} \sim 100$  MeV;

## Backup: thermal history (3)

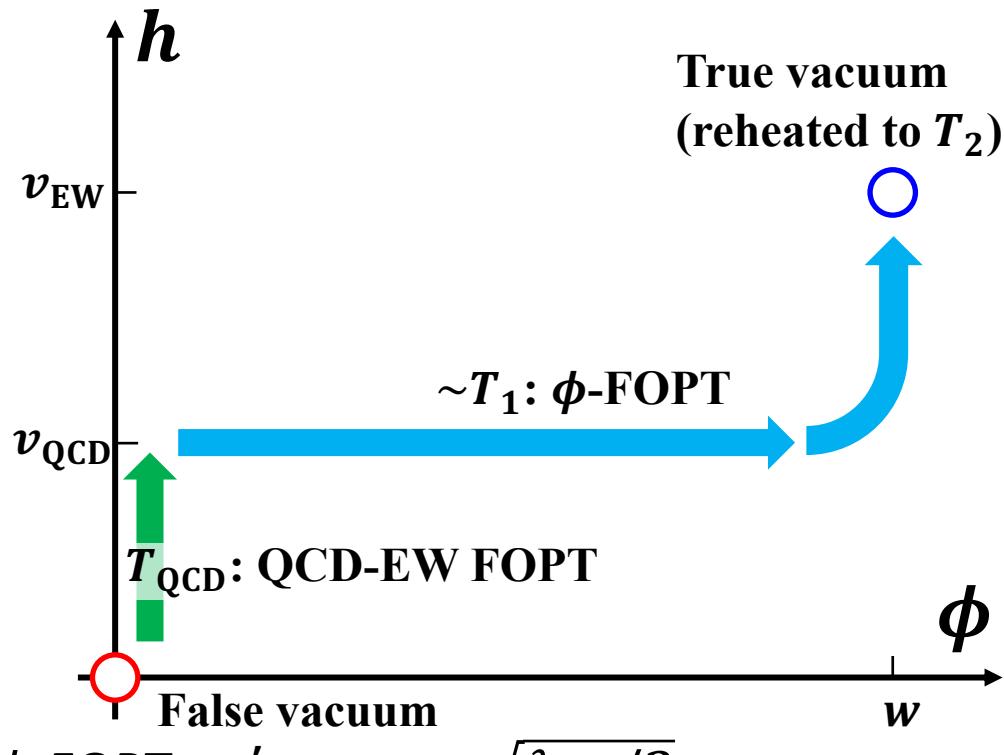
$$V_T \approx \frac{(\lambda_{\phi x} + y_\psi^2)T^2 + 6\lambda_{h\phi} v_{\text{QCD}}^2}{24} \phi^2 \quad \lambda_{h\phi} = -\frac{m_h^2}{w^2}$$



Barrier vanishes at  $T_1 = v_{\text{QCD}} \sqrt{-\frac{6\lambda_{h\phi}}{\lambda_{\phi x} + y_\psi^2}}$ ; Then  $\phi$ -FOPT!

## Backup: thermal history (4)

At  $T_1$ :  $\phi$ -FOPT; large vacuum energy  $V_\Lambda$  released; reheat the Universe to  $T_2 \gg T_1$      $T_1 \sim 10$  MeV;  $T_2 \sim 100$  GeV  
Dilution of preexisting  $X$



Before the  $\phi$ -FOPT:  $m'_X = v_{\text{QCD}} \sqrt{\lambda_{\phi X}/2}$ ;

After the  $\phi$ -FOPT:  $m_X = \sqrt{(\lambda_{\phi X} w^2 + \lambda_{hX} v_h^2)/2}$ ;

$$\text{Jump of } z = \frac{m_X}{T}$$

# Backup: guide for model building (1)

$$\mathcal{L} \supset -\lambda B^\dagger B X^\dagger X - \frac{\lambda_{\phi X}}{2} \phi^2 |X|^2;$$

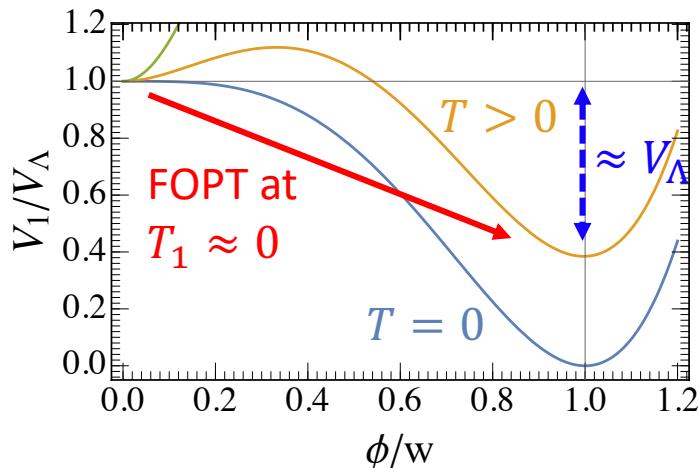
Dark matter  
Thermal bath particle      FOPT scalar

Minimal setup:  
 $B = \frac{\phi}{\sqrt{2}}$  and hence  $\lambda_{\phi X} = \lambda$

Classically conformal principle  $V_{\text{tree}} = \lambda_\phi \phi^4 / 4$

One-loop level: Coleman-Weinberg potential

$$V_1(\phi) = V_\Lambda + \frac{\lambda_B^2}{64\pi^2} \phi^4 \left( \log \frac{\phi}{w} - \frac{1}{4} \right)$$



- $m_X^2 = \frac{\lambda}{2} w^2$
  - $V_\Lambda = \frac{\lambda_B^2}{256\pi^2} w^4$
  - $\frac{\pi^2}{30} g_* T_2^4 \approx V_\Lambda$
  - $\Omega_X h^2 \approx 0.1(1 + 2z_2) \left( \frac{\lambda e^{-z_2}}{3.5 \times 10^{-11}} \right)^2$
- $\Omega_X h^2$  determined by  $\lambda$  and  $\lambda_B$
- $$z_2 \equiv \frac{m_X}{T_2}$$

## Backup: guide for model building (2)

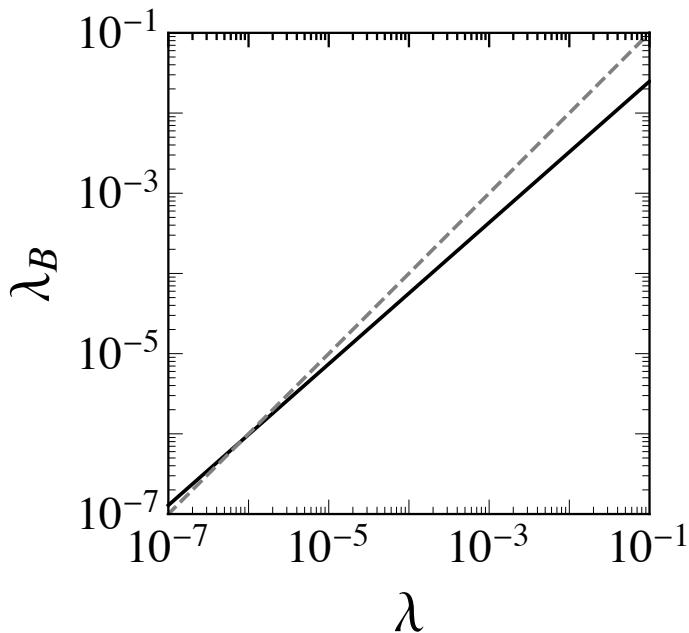
**Dark matter**

$$\mathcal{L} \supset -\frac{\lambda}{2} \phi^2 X^\dagger X - \frac{\lambda}{2} \phi^2 |X|^2; \quad V_1(\phi) = V_\Lambda + \frac{\lambda_B^2}{64\pi^2} \phi^4 \left( \log \frac{\phi}{w} - \frac{1}{4} \right).$$

Thermal bath particle

Classically conformal principle

$\Omega_X h^2$  determined by  $\lambda$  and  $\lambda_B$



$\Omega_{\text{DM}} h^2 = 0.12--$   
Numerical:  $\lambda_B \approx 0.189 \lambda^{0.881}$

Minimal setup:  $\lambda_B \approx \lambda$   
 $\Rightarrow \lambda \sim 10^{-6};$

If  $\lambda \sim 0.1$  (WIMP)  
 $\Rightarrow \lambda_B \approx 0.024;$   
 $\Rightarrow$  additional fermions included