



# Freeze-in of WIMP dark matter

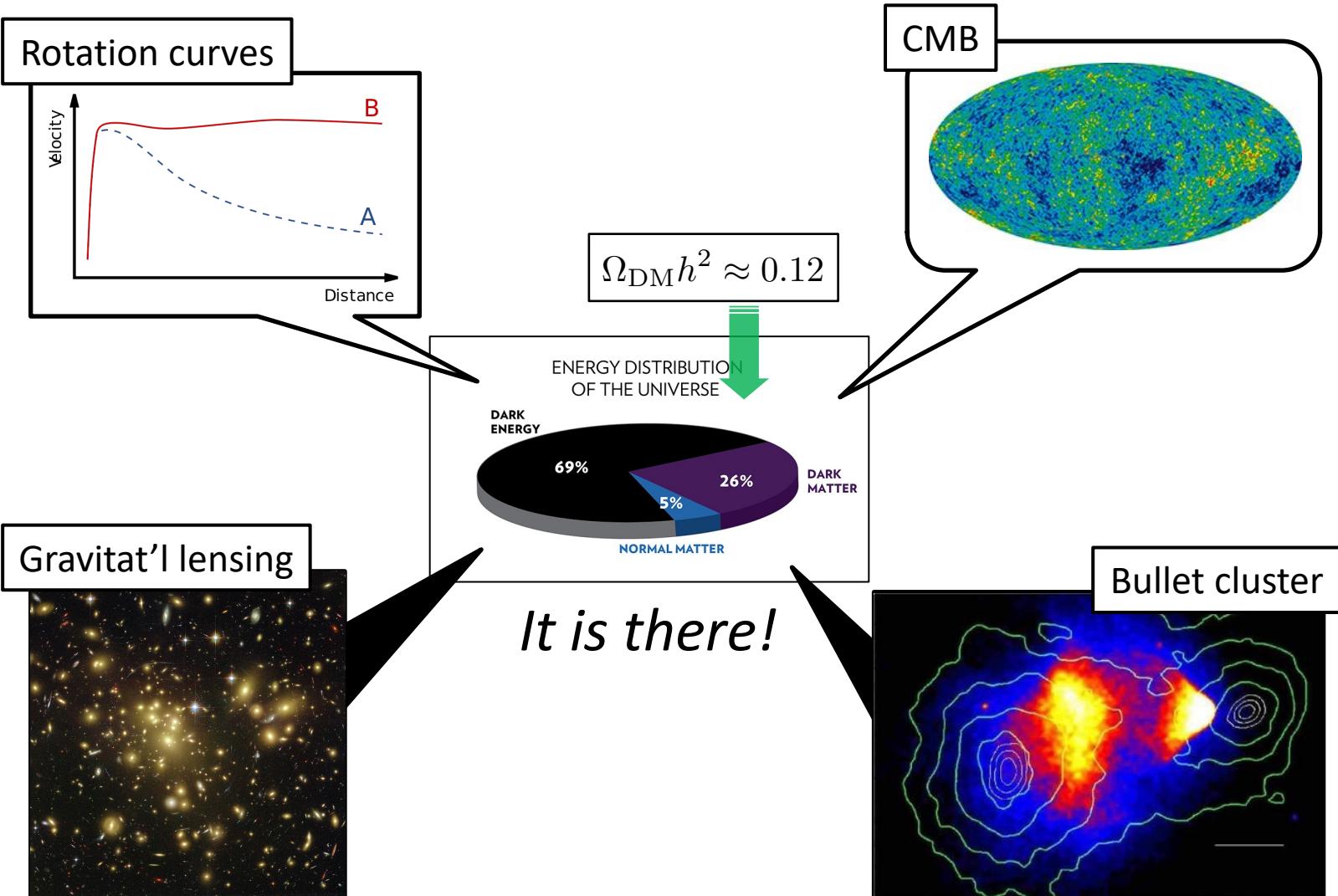
Ke-Pan Xie (谢柯盼)

Beihang University

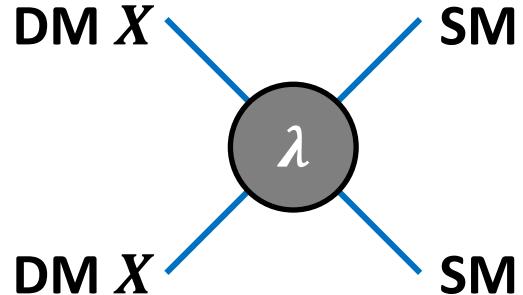
2023.3.23 @IHEP, CAS

With Xiaorui Wong, 2303.xxxxx

# The mystery of dark matter



# A paradigm for dark matter

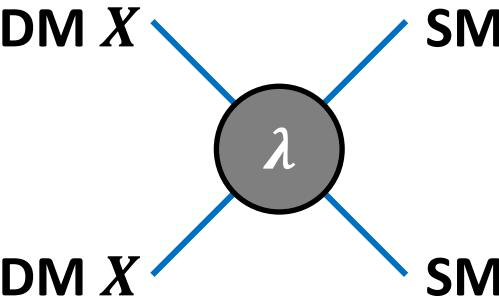


$$\langle \sigma v_{\text{rel}} \rangle \sim \frac{\lambda^2}{32\pi m_X^2} \left( \frac{K_1(z)}{K_2(z)} \right)^2$$

$\epsilon \in (0,1)$

$z \equiv \frac{m_X}{T}$

# A paradigm for dark matter


$$\langle \sigma v_{\text{rel}} \rangle \sim \frac{\lambda^2}{32\pi m_X^2} \left( \frac{K_1(z)}{K_2(z)} \right)^2$$
$$z \equiv \frac{m_X}{T}$$
$$\in (0,1)$$

The Boltzmann equation for yield  $Y_X = n_X/s$ :

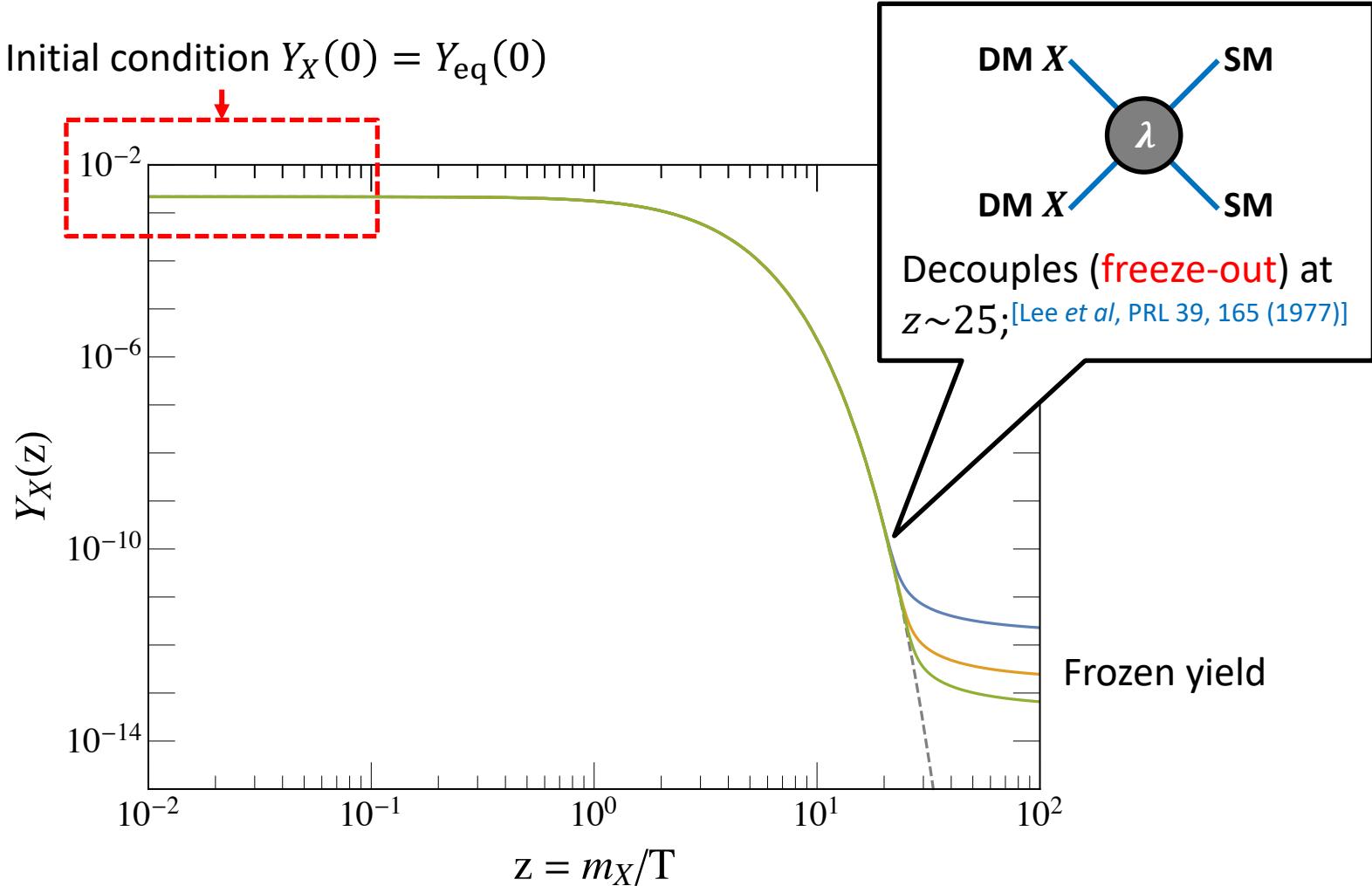
Entropy density    Equilibrium distribution

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

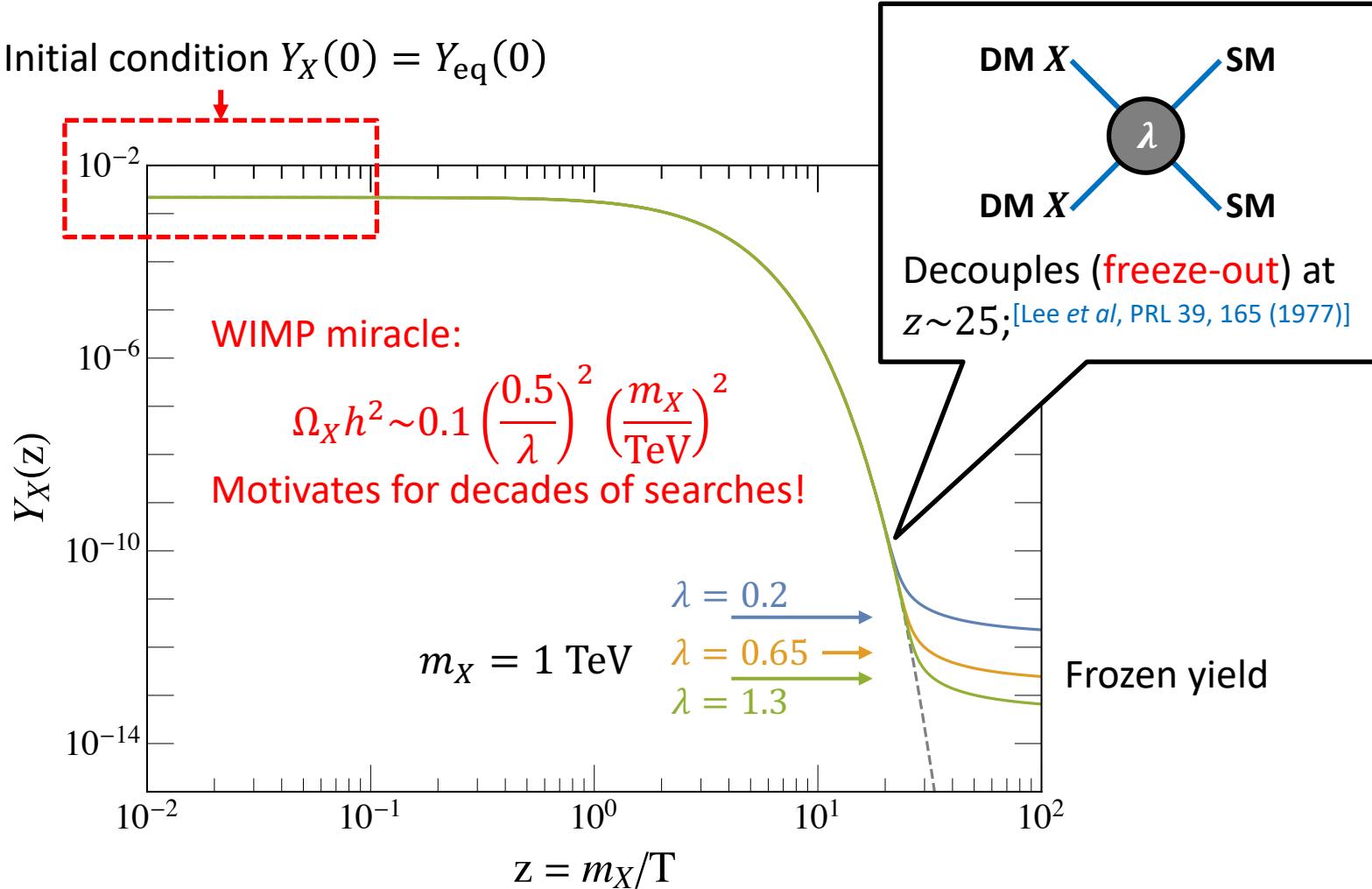
Hubble constant

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

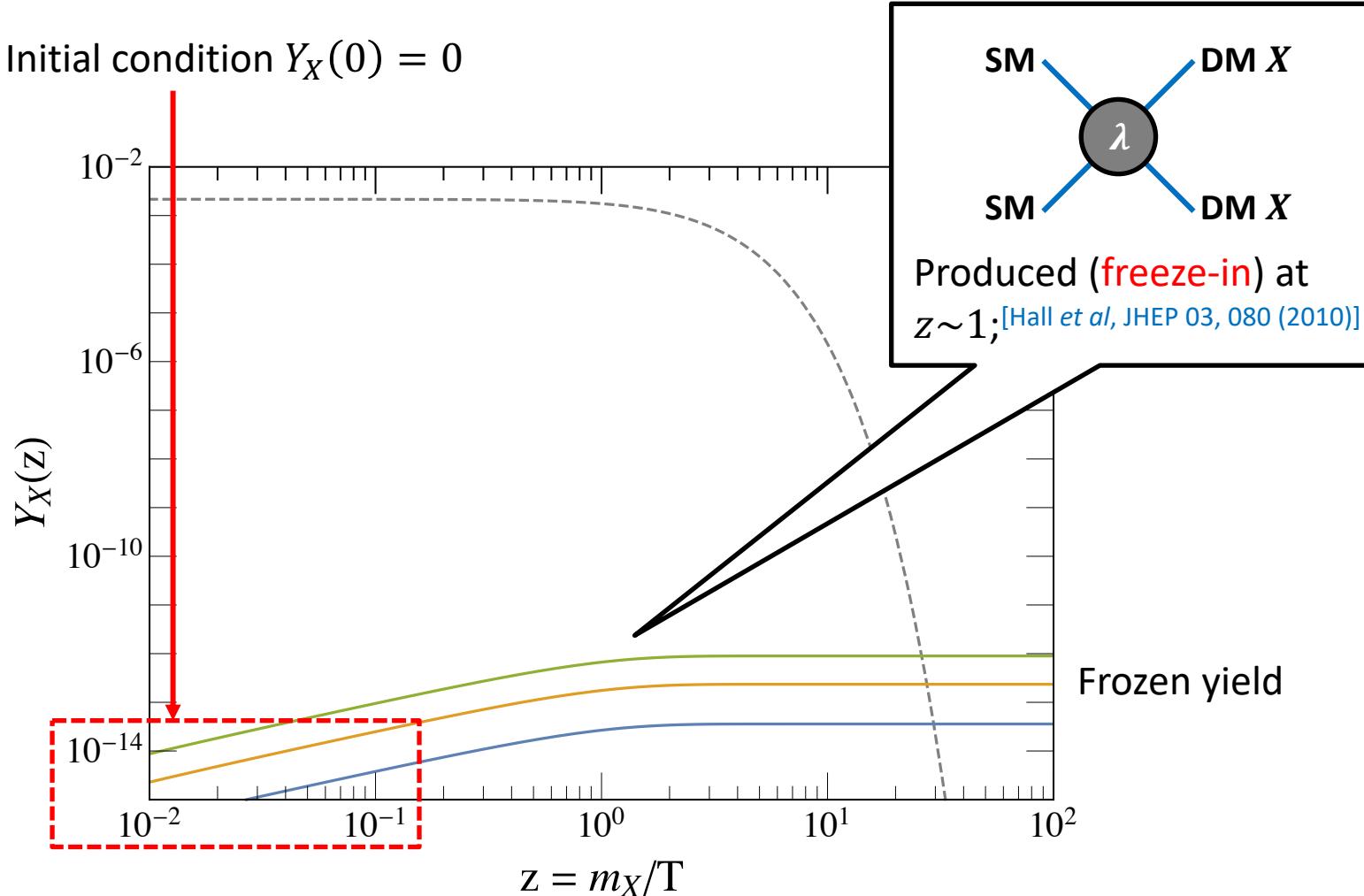
# Freeze-out of Weakly Interacting Massive Particles



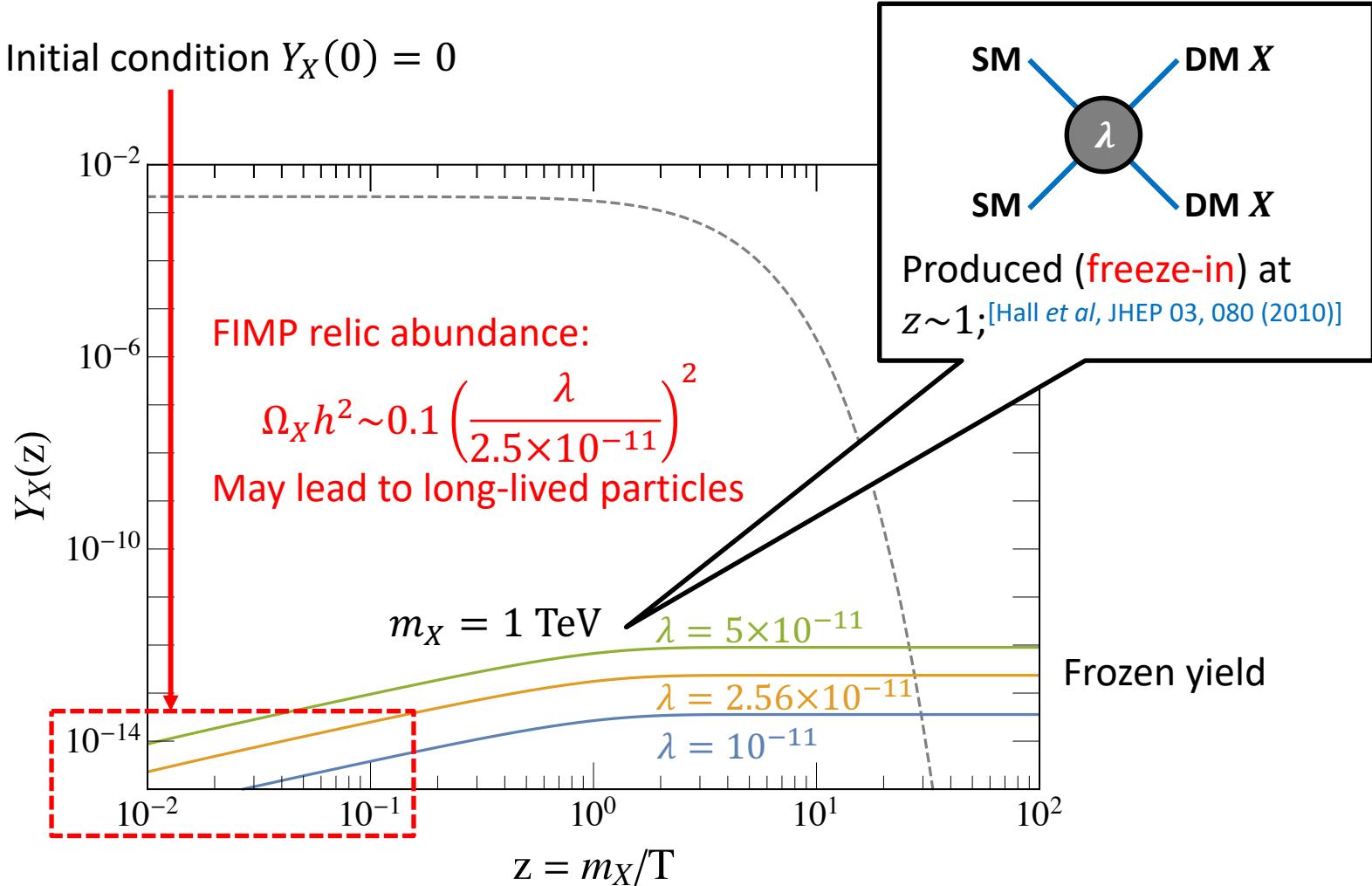
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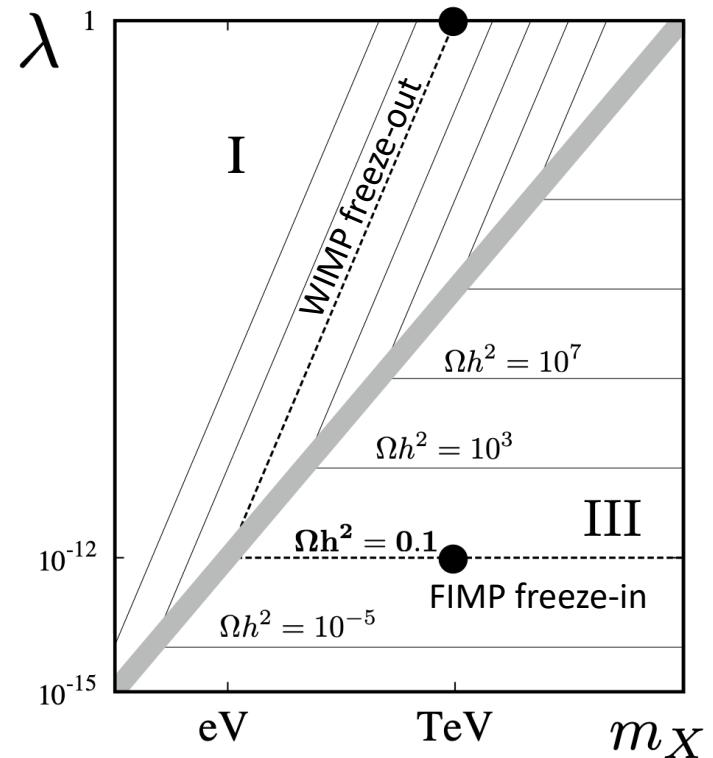
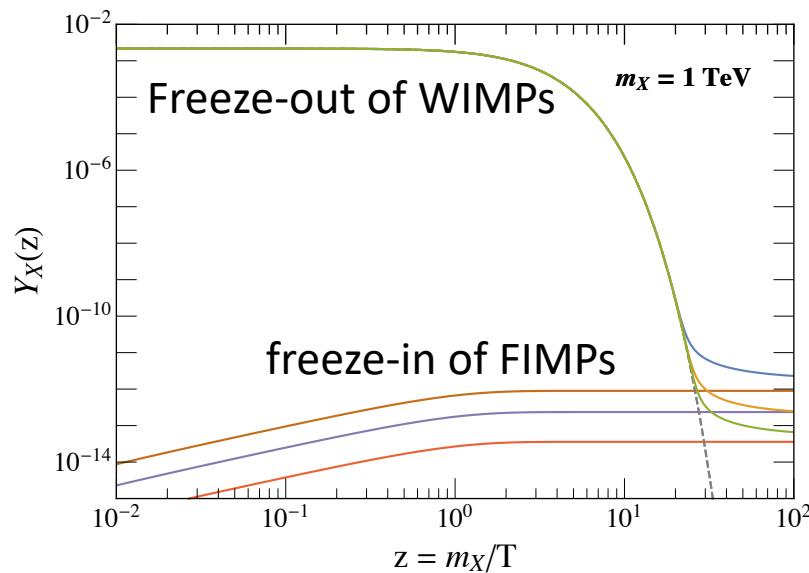
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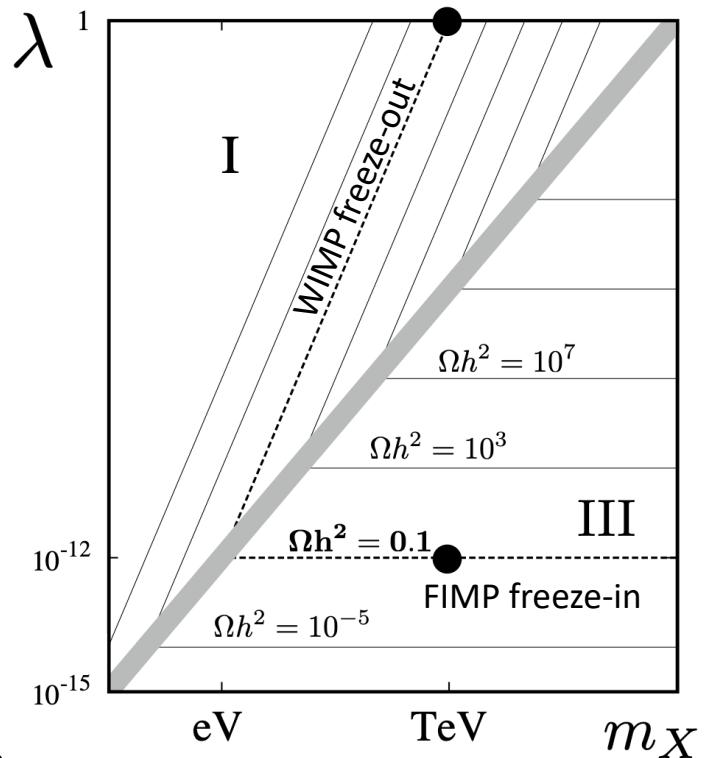
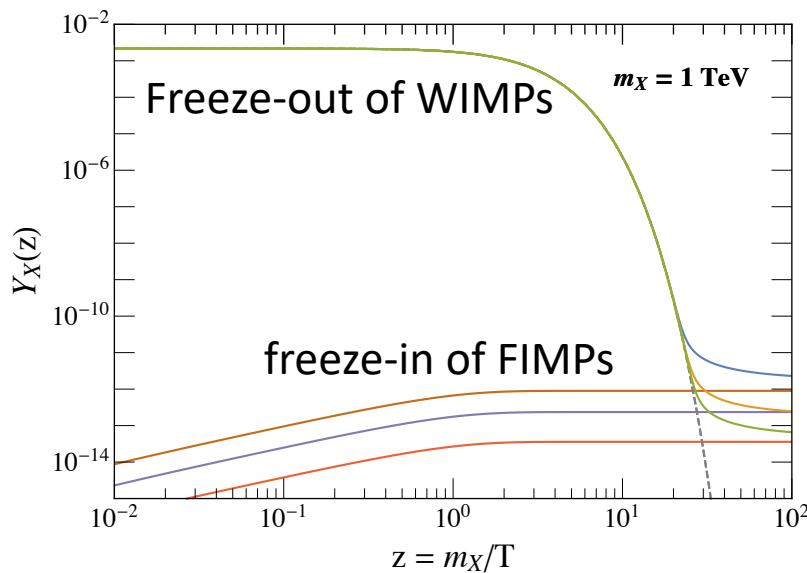


# Comparison of two classic scenarios



“Phase diagram”  
[Hall *et al*, JHEP 03, 080 (2010)]

# Comparison of two classic scenarios and more...

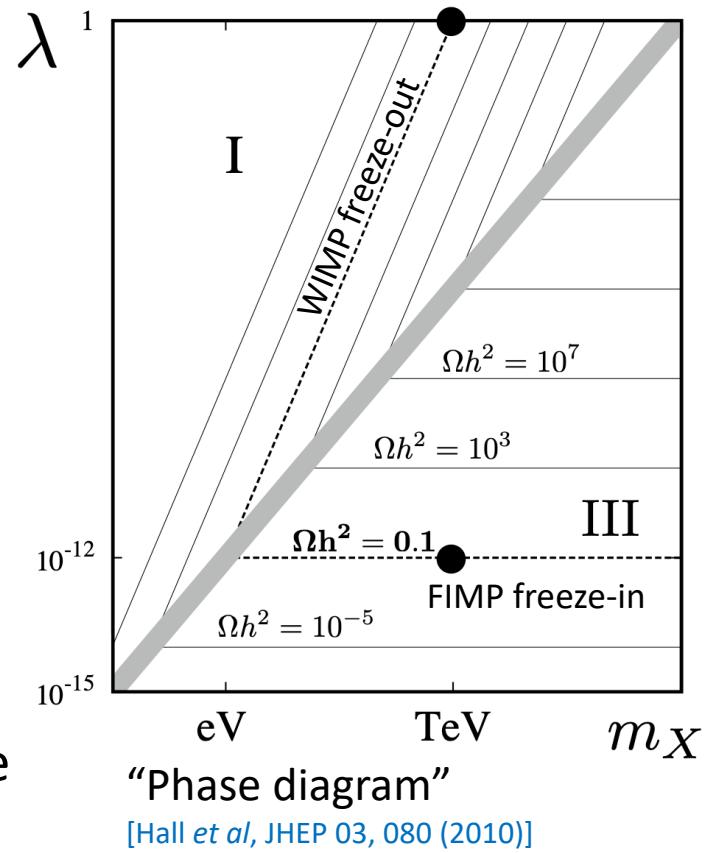
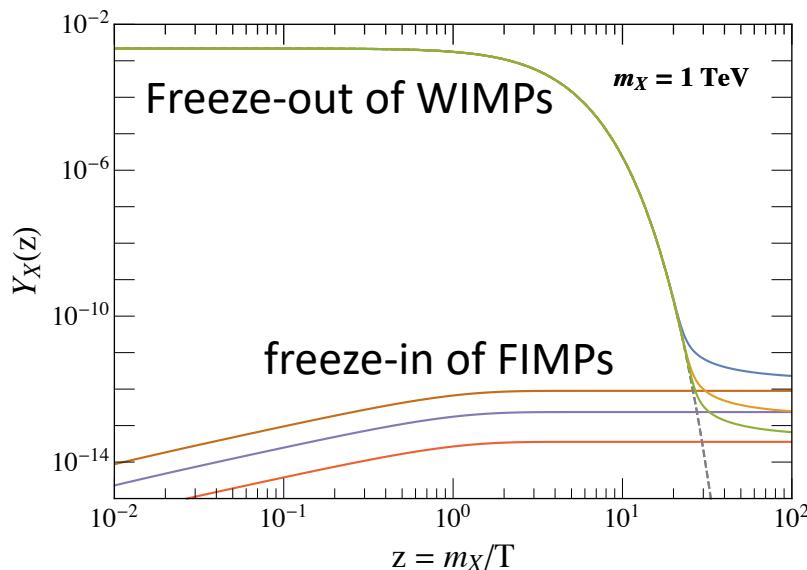


Can we have freeze-in of WIMPs?

- “WIMPs”: means interactions are initially in equilibrium;
- “Freeze-in”: means initial yield is negligibly small;

Compatible??

# Comparison of two classic scenarios and more...



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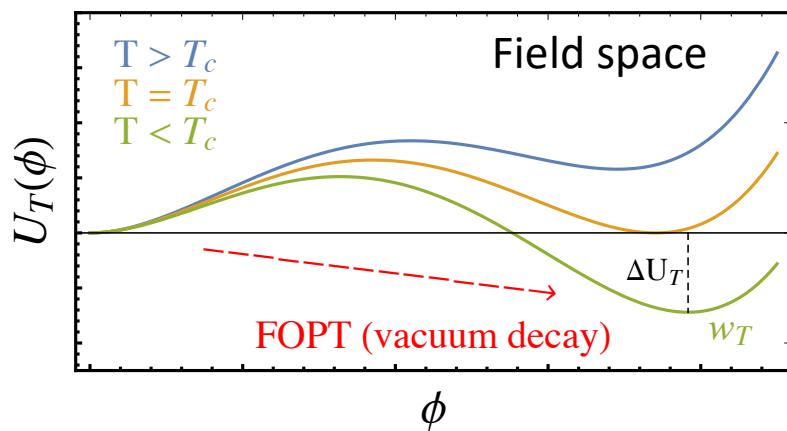
Yes, this can happen when the Universe is boiling!!

# First-order phase transitions

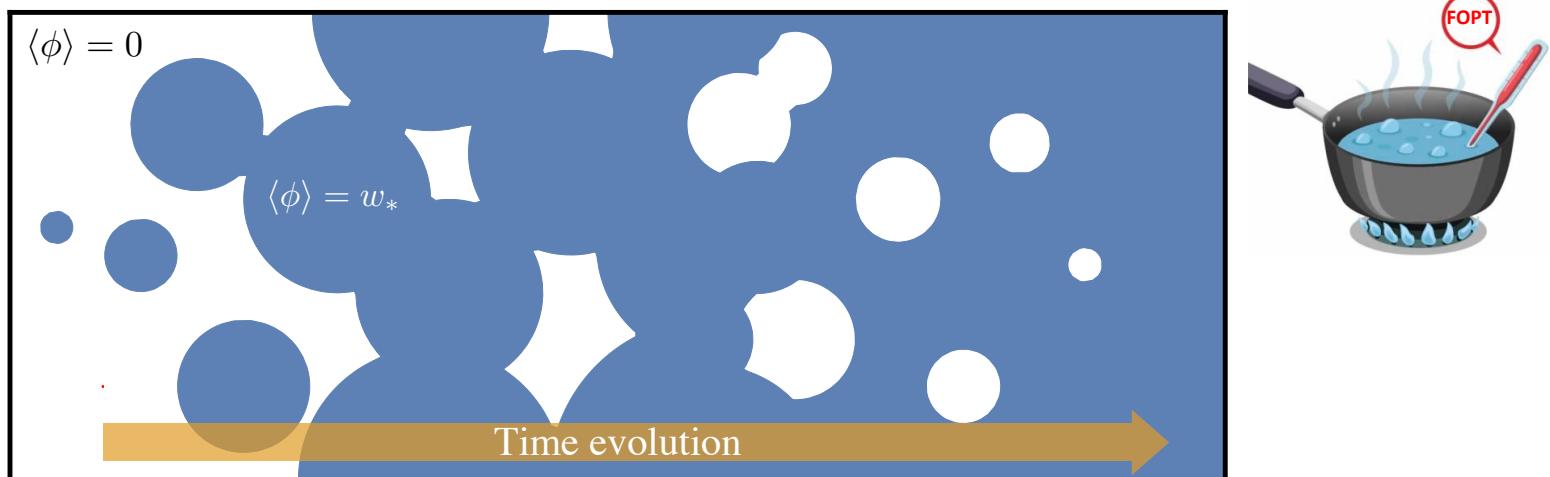
FOPT: decay of the vacuum

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - U(\phi)$$

Receives thermal corrections



“Boiling” of the Universe; bubble nucleation and expansion



# An illustrative model

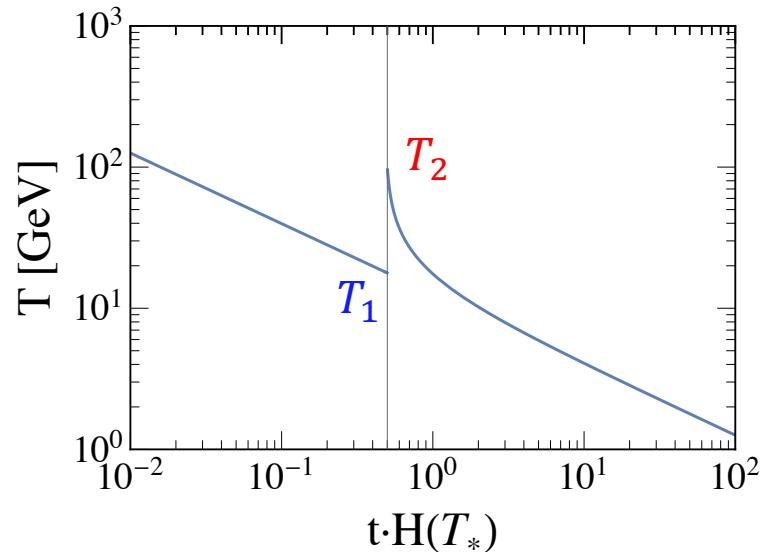
$$\mathcal{L} \supset -\lambda B^\dagger B X^\dagger X - \frac{\lambda_{\phi X}}{2} \phi^2 |X|^2;$$

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

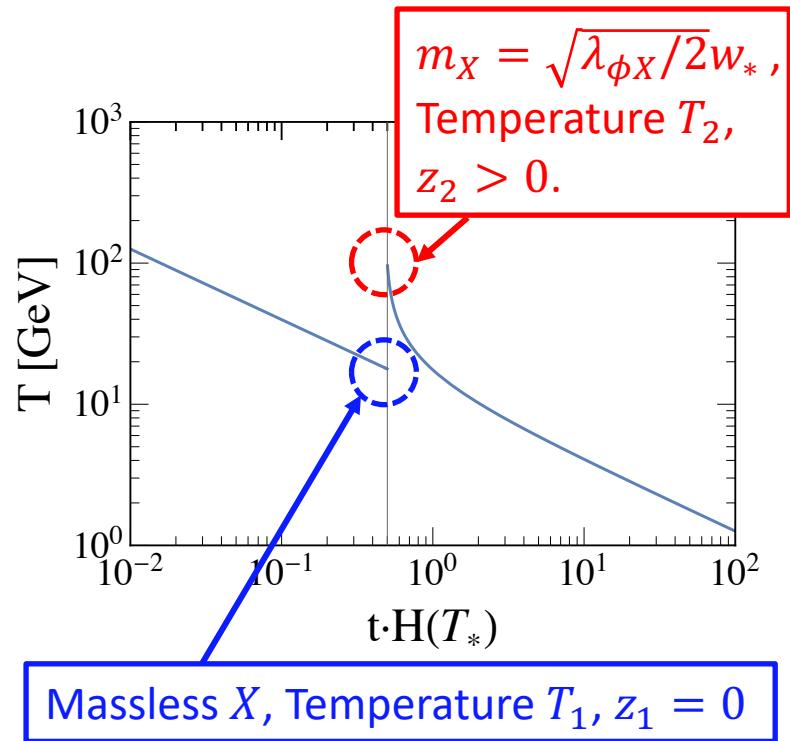
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$$\text{Dilution } Y_X(z_2) \approx \left(\frac{T_1}{T_2}\right)^3 \times Y_X(0)$$



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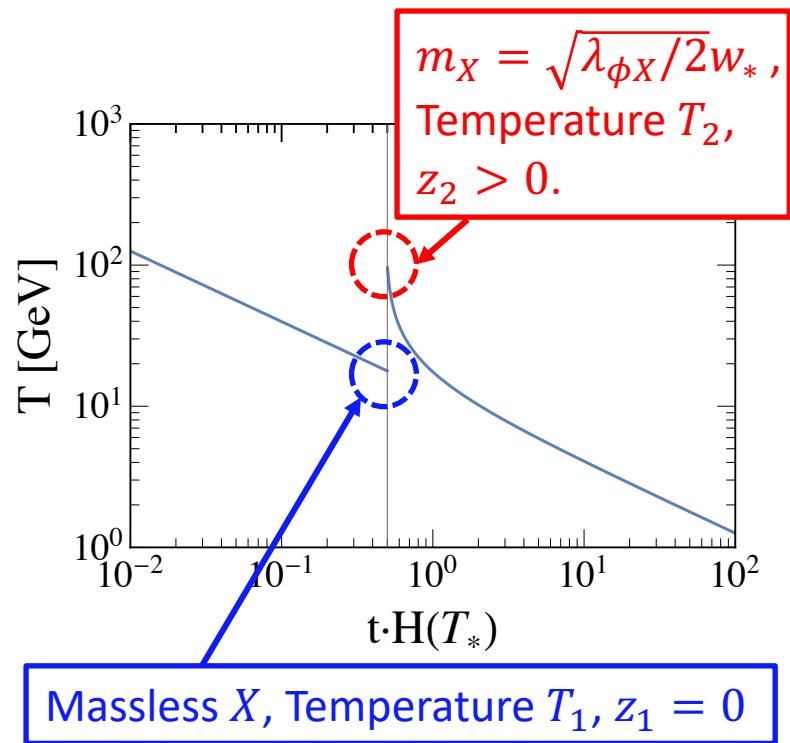
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Dark matter      ↓  
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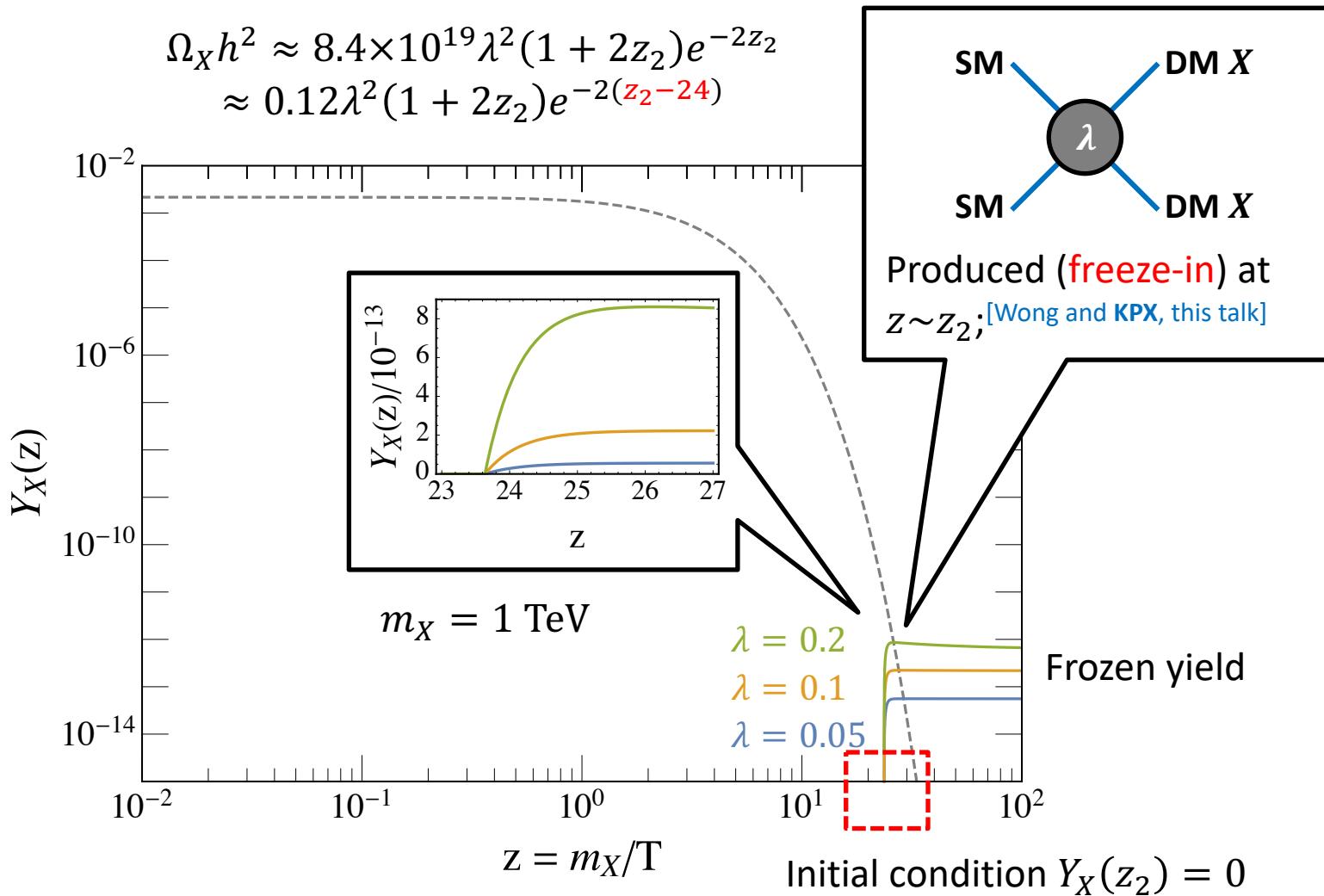
After the (supercooled) FOPT:

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

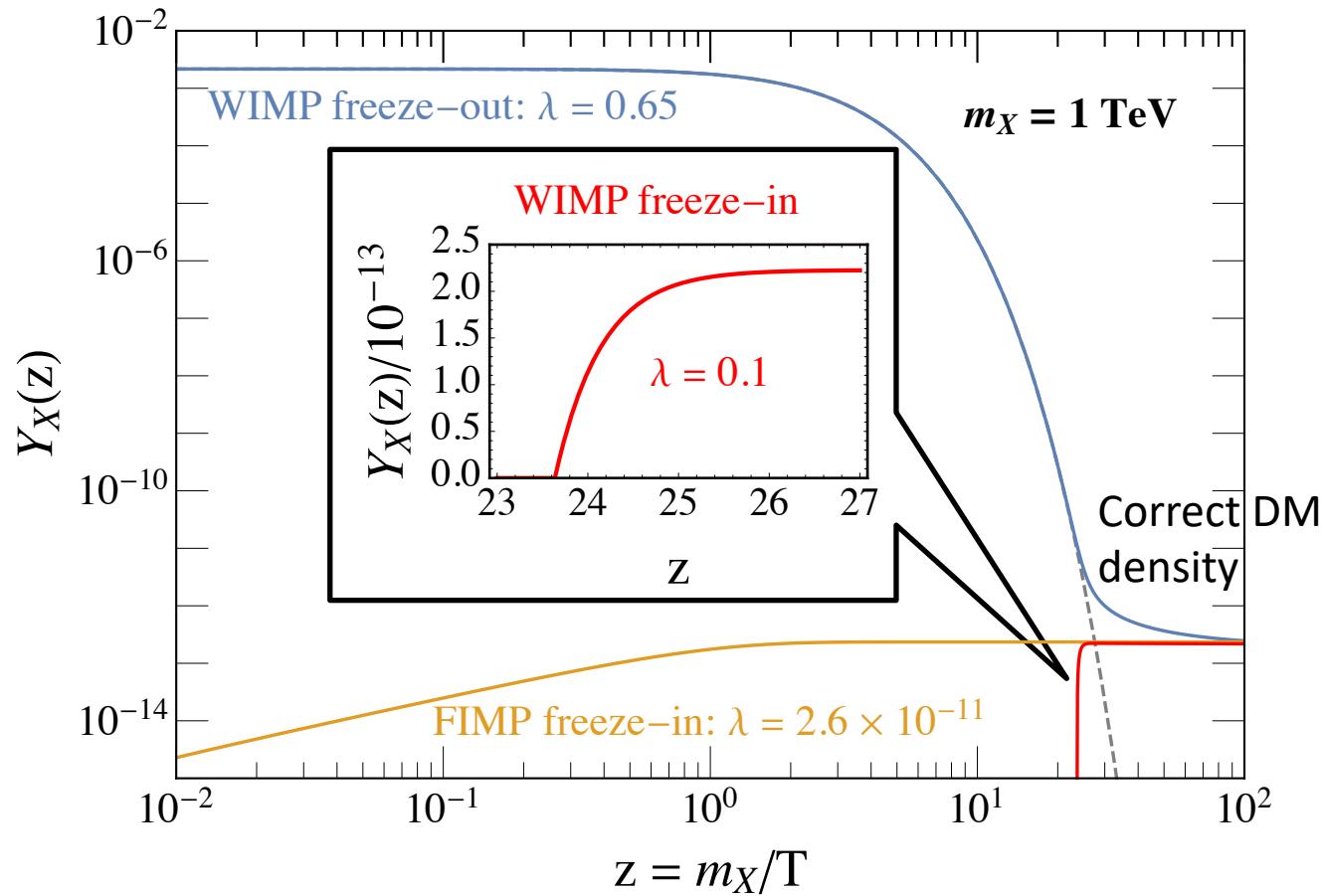
**NOT feeble.**

Condition for  
freeze-in!

# Freeze-in of WIMPs



# Comparison



# A realistic model

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

Classically conformal potential:

$$V = \lambda_h |H|^4 + \frac{\lambda_\phi}{4} \phi^4 + \frac{\lambda_s}{4} S^4 + \frac{\lambda_{h\phi}}{2} \phi^2 |H|^2 + \frac{\lambda_{hs}}{2} |H| S^2 + \frac{\lambda_{\phi s}}{4} \phi^2 S^2;$$

↑      ↑      ↑

SM Higgs doublet   FOPT scalar   **dark matter candidate**   **Portal couplings**

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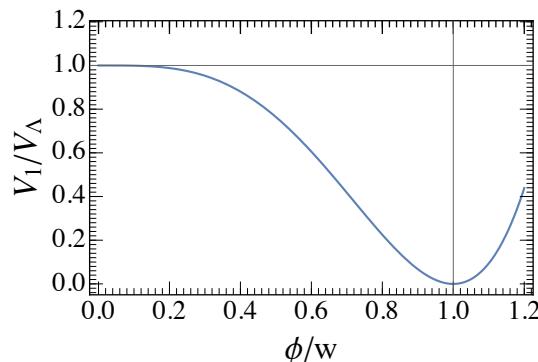
↑      ↑      ↑

SM Higgs doublet   FOPT scalar   dark matter candidate   Portal couplings

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

$$V_1 \approx V_\Lambda + \frac{\lambda_{\phi s}^2}{256\pi^2} \phi^4 \left( \log \frac{\phi}{w} - \frac{1}{4} \right);$$

- $\langle \phi \rangle = w$ ; vacuum energy  $V_\Lambda = \frac{\lambda_{\phi s}^2}{1024\pi^2} w^4$ ;



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↑      ↑      ↑      brace

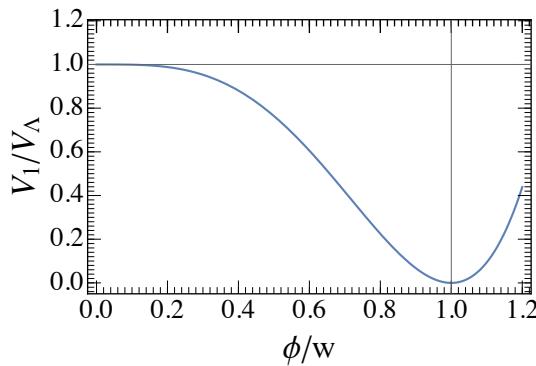
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Triggers EW symmetry breaking:  $\lambda_{h\phi} = -\frac{m_h^2}{w^2}$



- $V \rightarrow -\frac{m_h^2}{2} |H|^2 + \lambda_h |H|^4$
- $\langle h \rangle = v_{EW} = 246 \text{ GeV}; m_h = 125 \text{ GeV}.$

$$\bullet \text{ DM mass } m_S = \sqrt{\frac{\lambda_{\phi s} w^2 + \lambda_{hs} v_{EW}^2}{2}}.$$

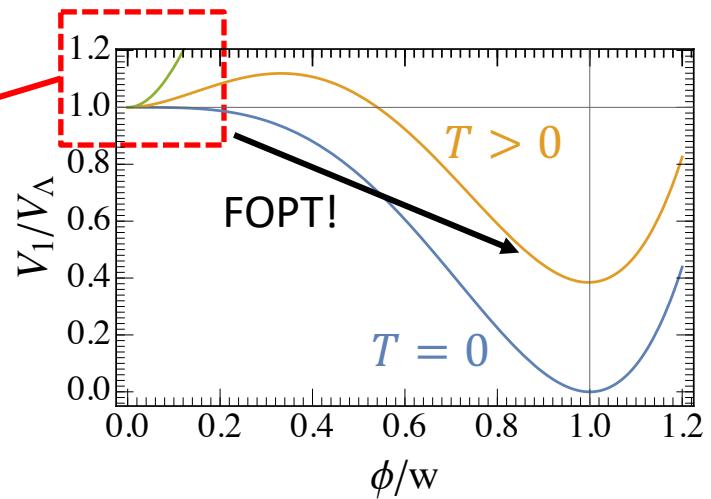
# At finite temperature

The Universe trapped at the origin

$$V_T \approx \frac{\lambda_{\phi s} T^2}{48} \phi^2;$$

Decay probability  $\Gamma \sim T^4 e^{-S_3/T}$ ;

$\frac{S_3}{T} \sim \lambda_{\phi s}^{-3/2}$ . [Iso et al, PRL 119, 141301 (2017)]



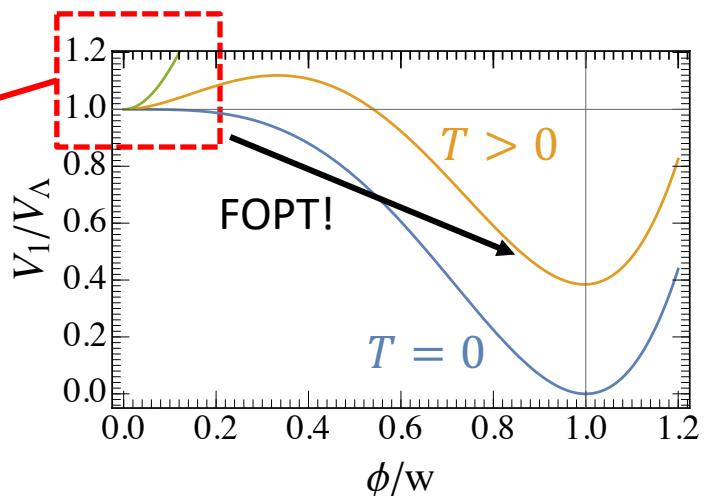
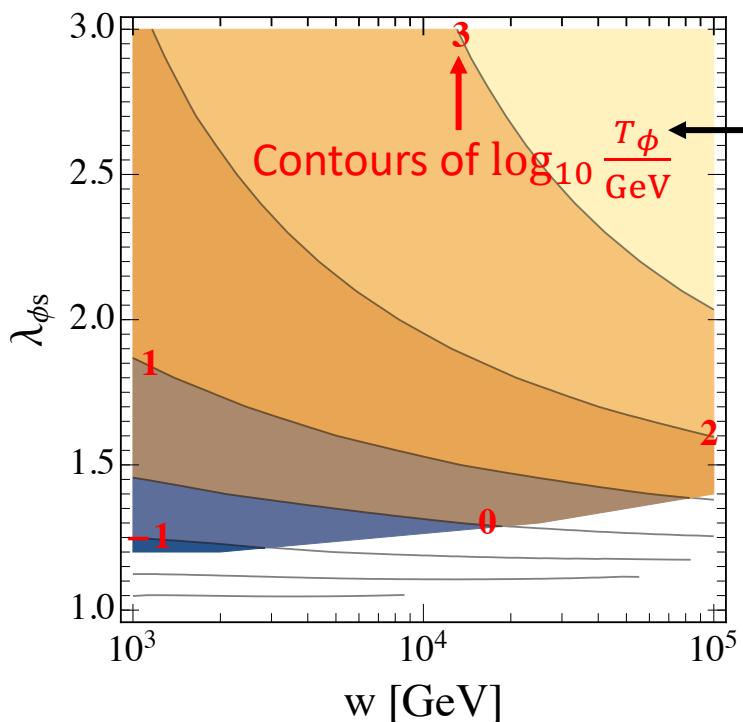
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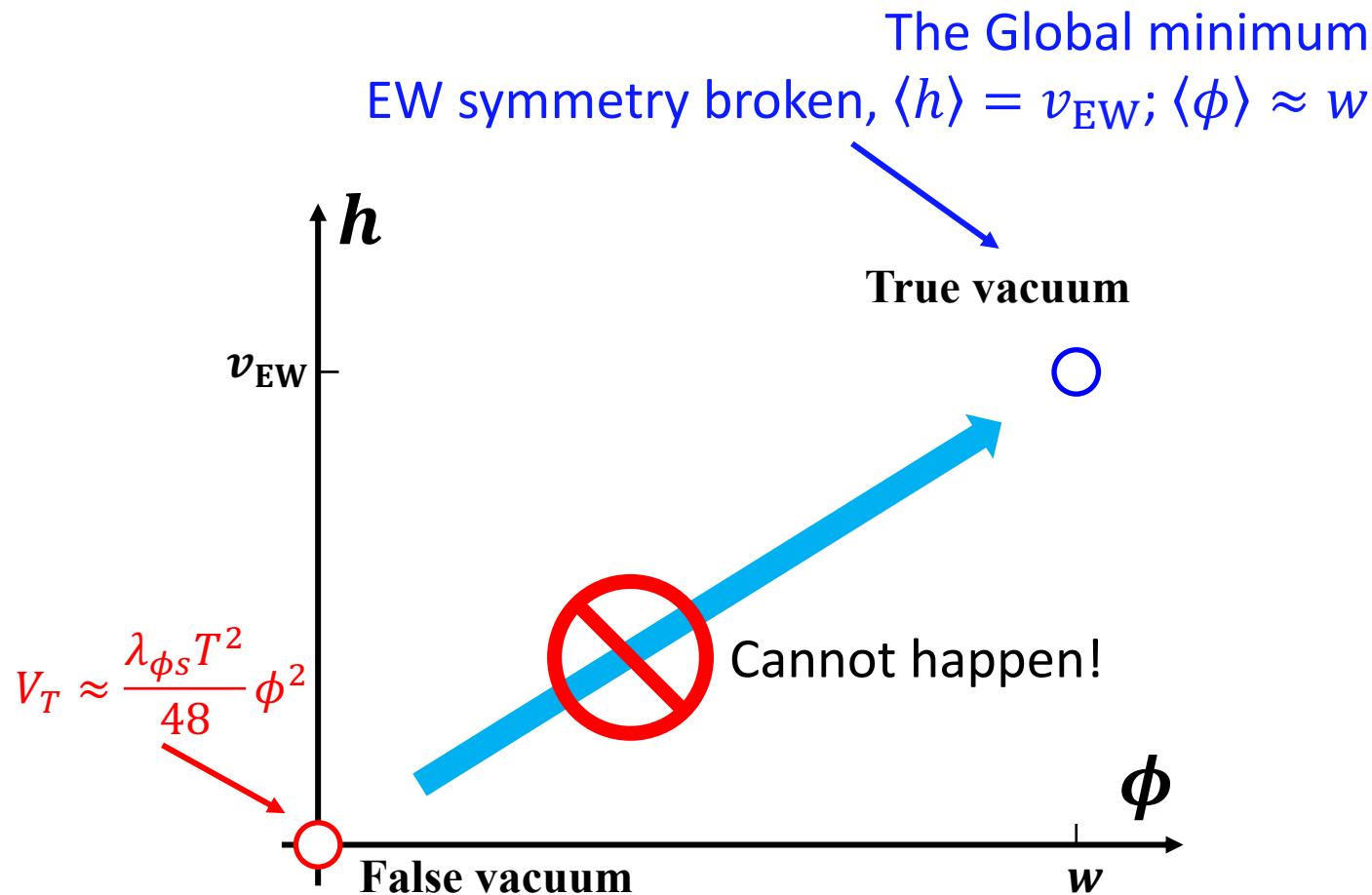


$\phi$ -FOPT temperature



$\left. \right\} \Gamma \sim T^4 e^{-S_3/T}$  too small,  
The  $\phi$ -FOPT cannot happen!!

# If the $\phi$ -FOPT cannot happen



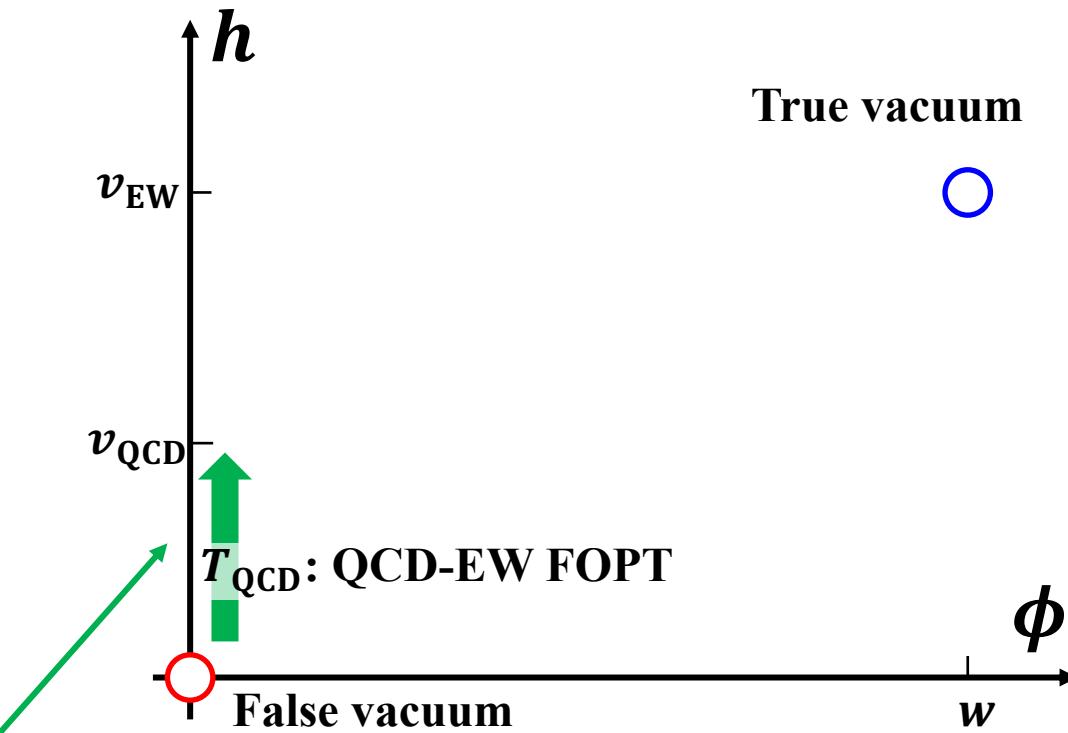
The local minimum:  $\langle h \rangle = \langle \phi \rangle = 0$ ; EW symmetry preserved

- $m_S = 0$ , dark matter massless

# Then the QCD phase transition first happens!

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)]

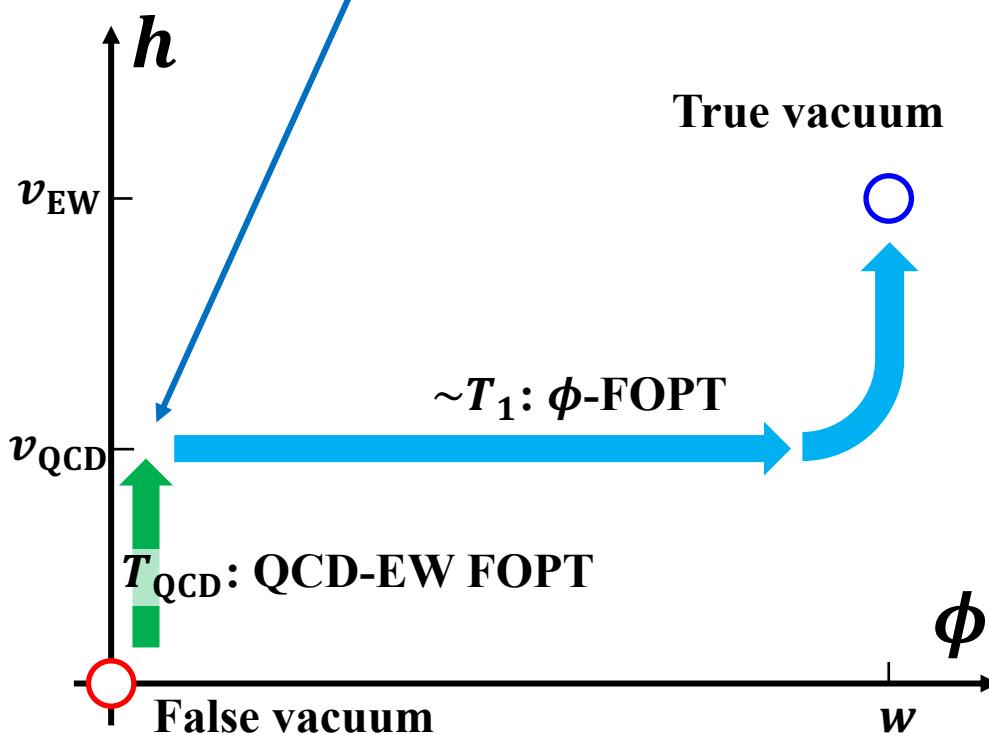


Quark Yukawa  $-\frac{y_t}{\sqrt{2}} \bar{t} t h$  induces  $-\frac{y_t}{\sqrt{2}} \langle \bar{t} t \rangle h$  -- linear term

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

And then  $\phi$ -FOPT occurs

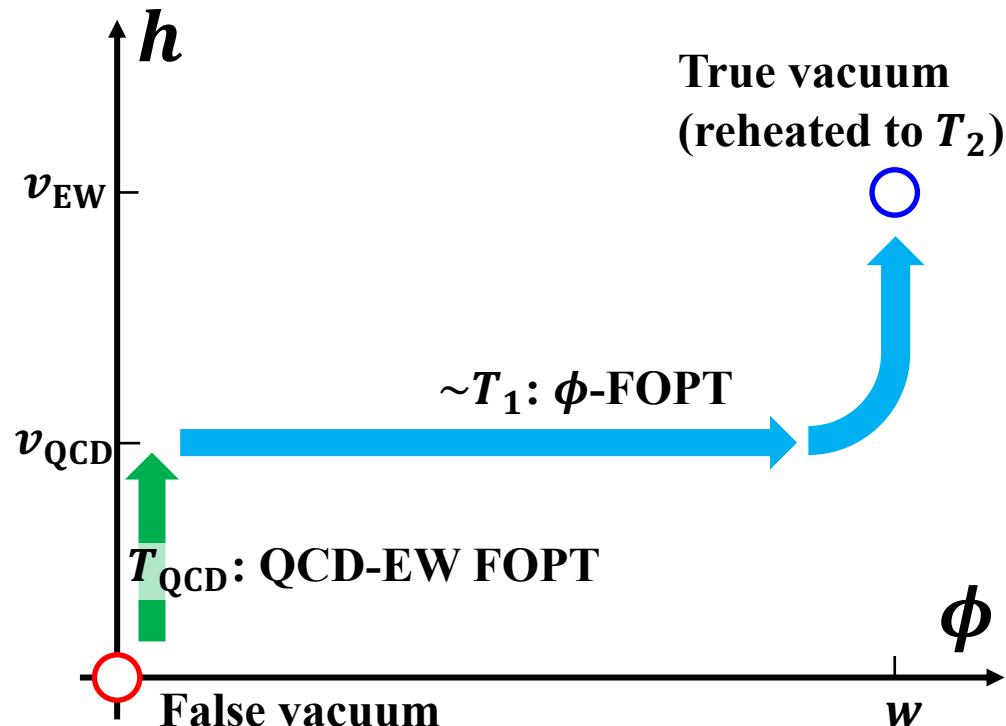
$$V_T \approx \frac{\lambda_{\phi s} T^2 + 12\lambda_{h\phi} v_{\text{QCD}}^2}{48} \phi^2 \quad \lambda_{h\phi} = -\frac{m_h^2}{w^2}$$



Barrier vanishes at  $T_1 = v_{\text{QCD}} \sqrt{-\frac{12\lambda_{h\phi}}{\lambda_{\phi s}}}$ ! Then  $\phi$ -FOPT

# Providing the environment for WIMP freeze-in

At  $T_1$ :  $\phi$ -FOPT; large vacuum energy  $V_\Lambda$  released; reheat the Universe to  $T_2 \gg T_1$     Dilution of preexisting  $S$

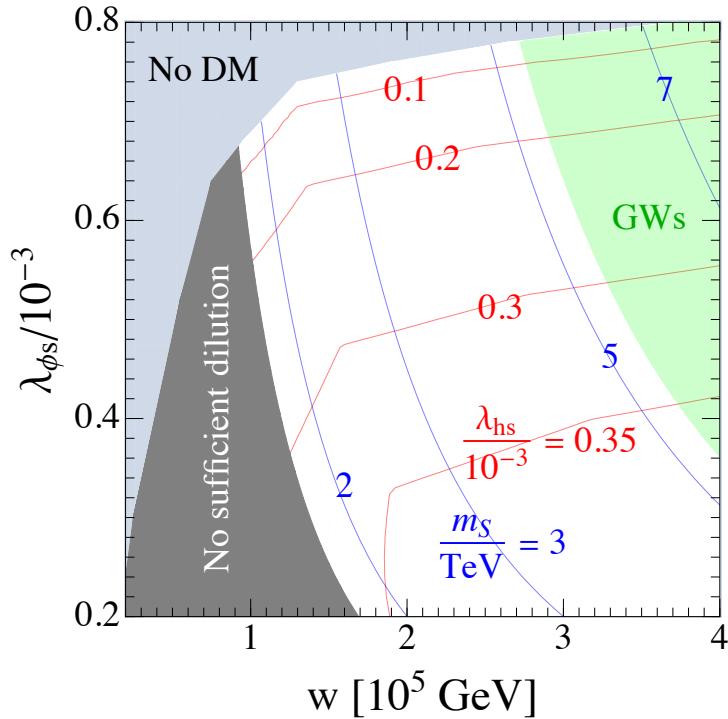


Before the  $\phi$ -FOPT:  $m'_S = v_{\text{QCD}} \sqrt{\lambda_{\phi s}/2}$ ;

After the  $\phi$ -FOPT:  $m_S = \sqrt{(\lambda_{\phi s} w^2 + \lambda_{hs} v_{\text{EW}}^2)/2}$ ;

Jump of  $z = \frac{m_S}{T}$

# Scanning over the parameter space

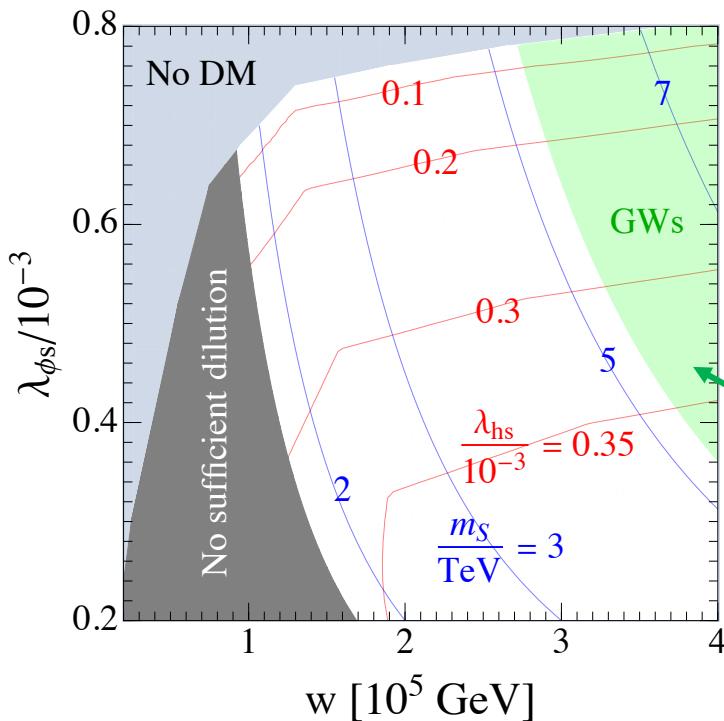


## WIMP dark matter $S$

Produced via **freeze-in**:  $hh \rightarrow SS$ ;  
 $\phi\phi \rightarrow SS$ ; happens for  $z \sim 17$

- Direct detection  $\sigma_{\text{SI}} < 10^{-53} \text{ cm}^2$
- $\text{Br}(h \rightarrow \phi\phi) \sim 10^{-4} - 10^{-5}$ ;

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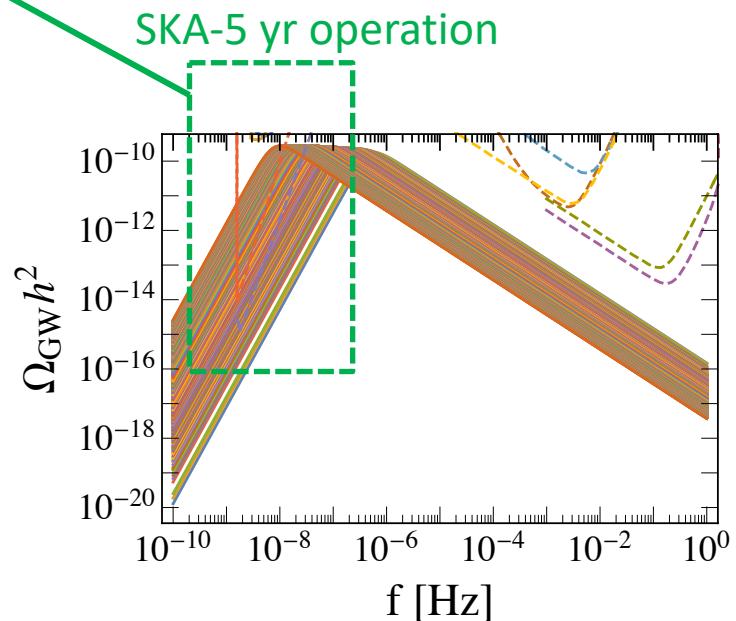


Gravitational waves  $f \sim 10^{-8} \text{ Hz}$   
Pulsar timing array (PTA) detection  
**\*Phenomenology specifically for this minimal model**

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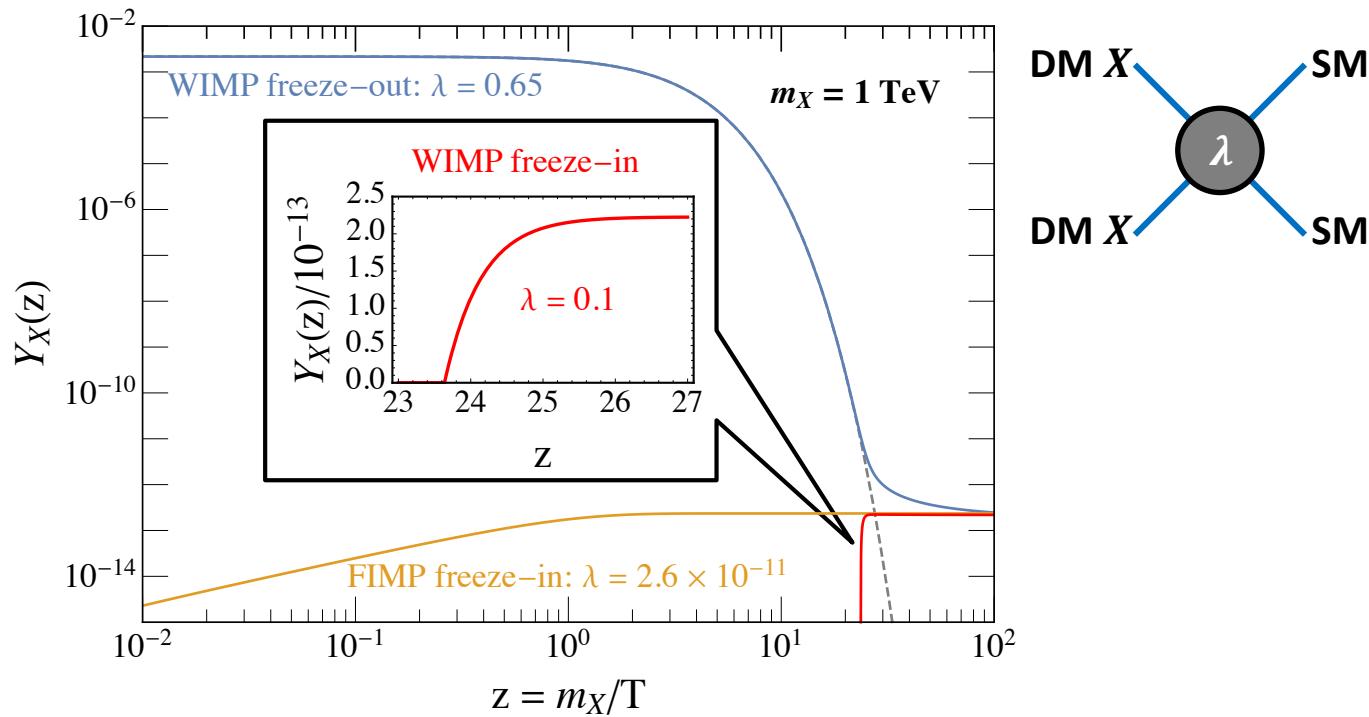
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# Conclusion

A novel dark matter scenario based on the  $2 \rightarrow 2$  process  
Very general, could be applied to a lot of new physics models



# Thank you!