Freeze-in of WIMP dark matter

Ke-Pan Xie (谢柯盼)
Beihang University

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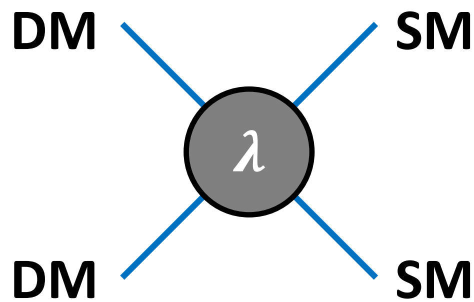
With Xiaorui Wong, 2304.00908

The most popular explanation for particle DM

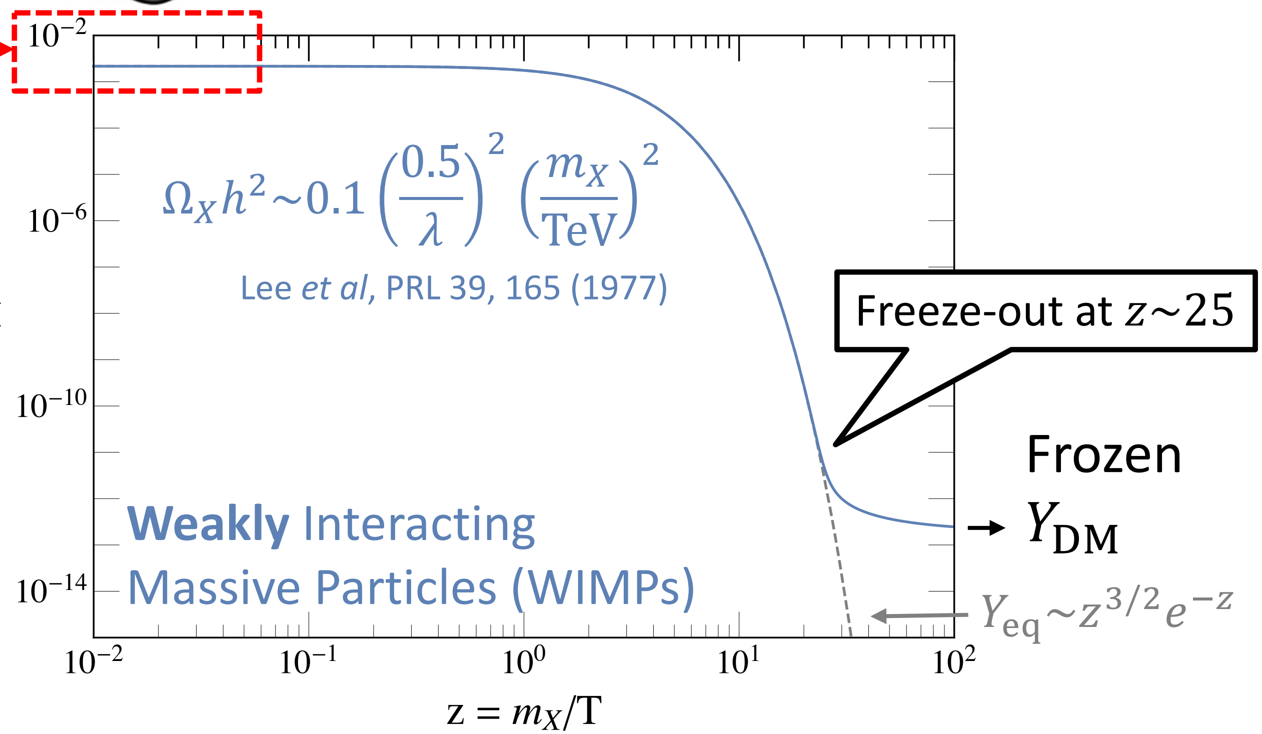


$$\langle \sigma v_{\rm rel} \rangle \sim \frac{\lambda^2}{32\pi m_X^2}$$

Initially in equilibrium

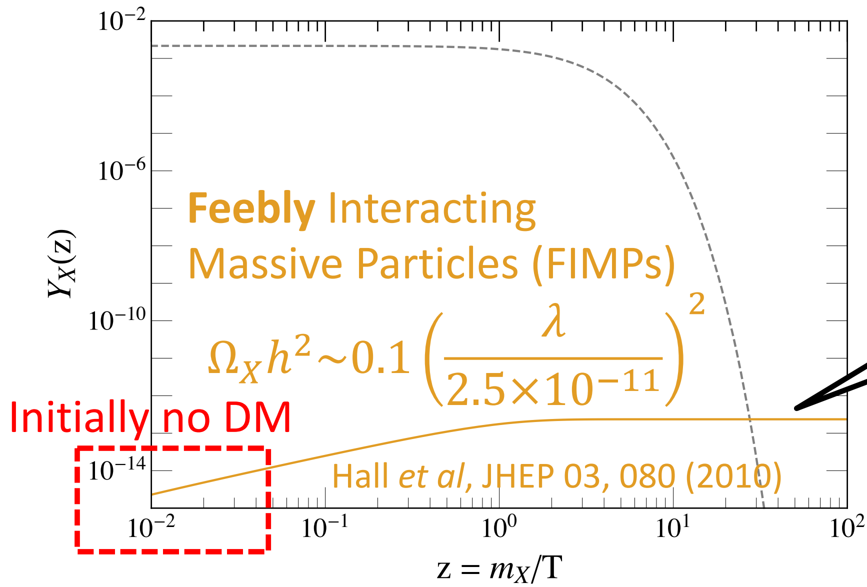
DM yield

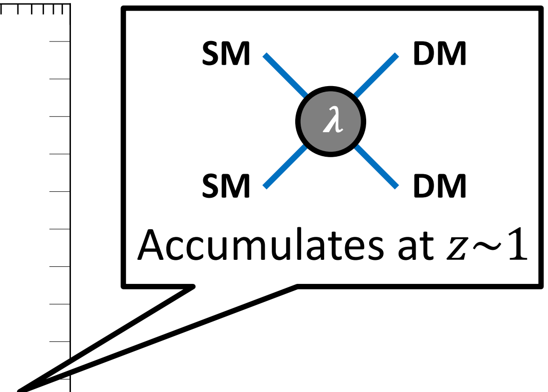
$$Y_X = \frac{n_X}{s}$$



Frozen $Y_{\rm DM}$

WIMP freeze-out and FIMP freeze-in





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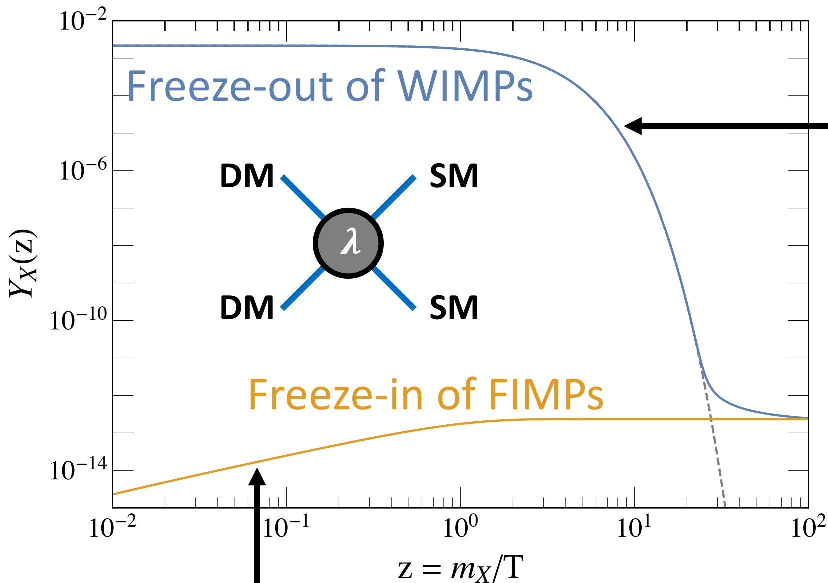
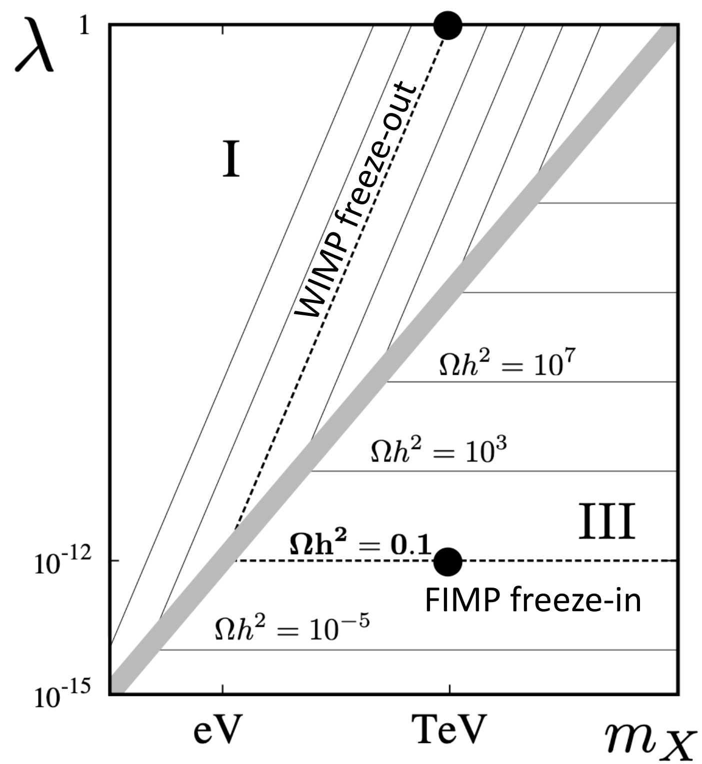


WIMPs: initially in equilibrium

DM scenario $\left(\frac{0.5}{\lambda}\right)^2\left(\frac{m_X}{\text{TeV}}\right)^2 \sim 1$

FIMPs: initially no abundance

DM scenario $\left(\frac{\lambda}{2.5\times10^{-11}}\right)^2 \sim 1$



"Phase diagram"

Hall *et al*, JHEP 03, 080 (2010)

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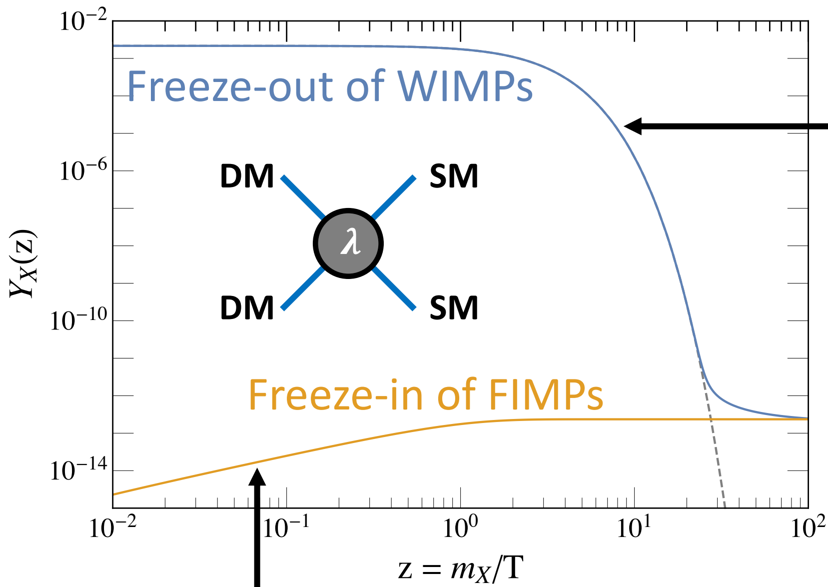

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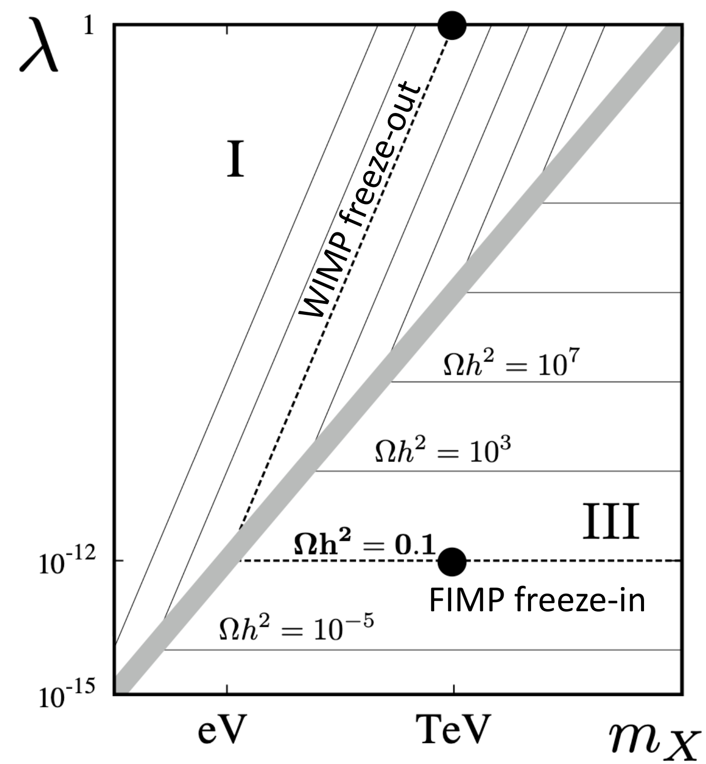

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FIMPs: initially no abundance

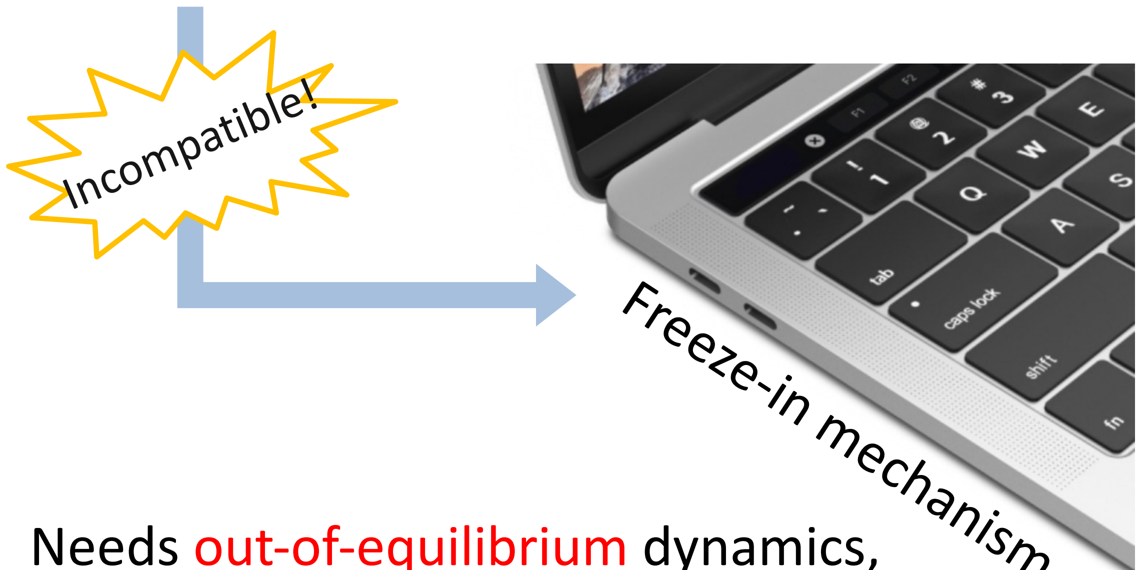
DM scenario $\left(\frac{\lambda}{2.5\times 10^{-11}}\right)^2 \sim 1$

This talk: **WIMP** can also **freeze-in**!

- The third scenario based on the $2 \rightarrow 2$ annihilation

How to realize freeze-in for WIMPs?

Will be in equilibrium (very abundant) since λ is NOT feeble



Needs out-of-equilibrium dynamics,
especially **no DM** initially

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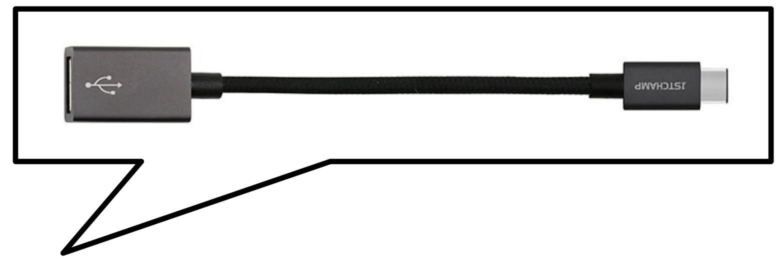
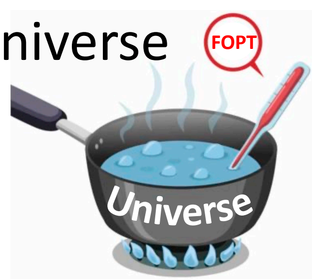


WIMP can **freeze-in**
if the early Universe
is boiling



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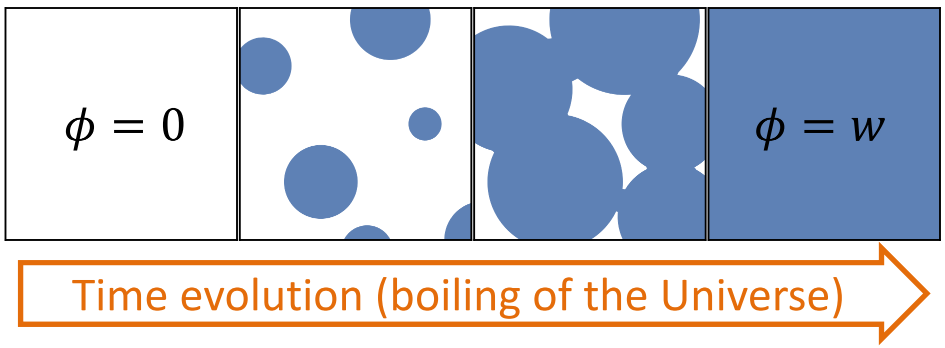
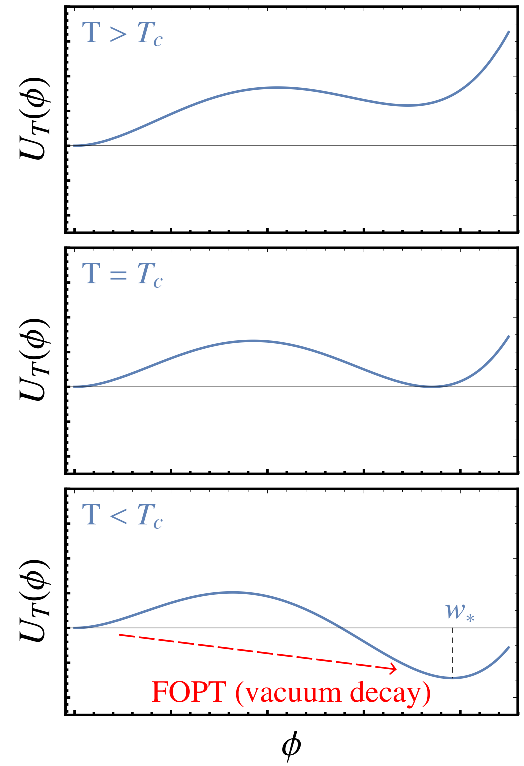
First-order phase transitions

FOPT: decay of the vacuum

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

Early Universe $\Rightarrow U_T(\phi, T)$





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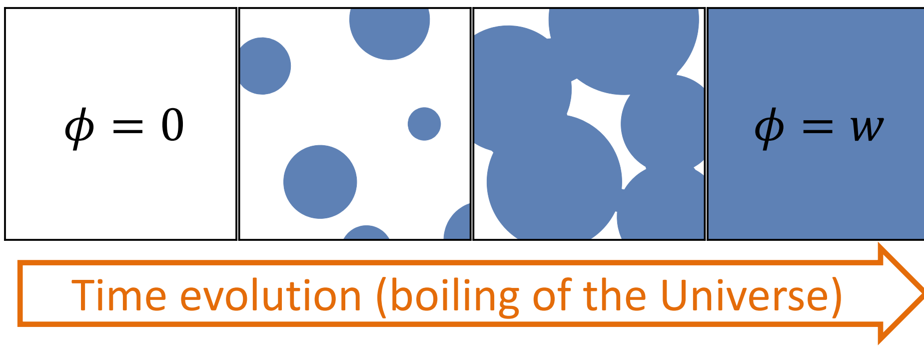
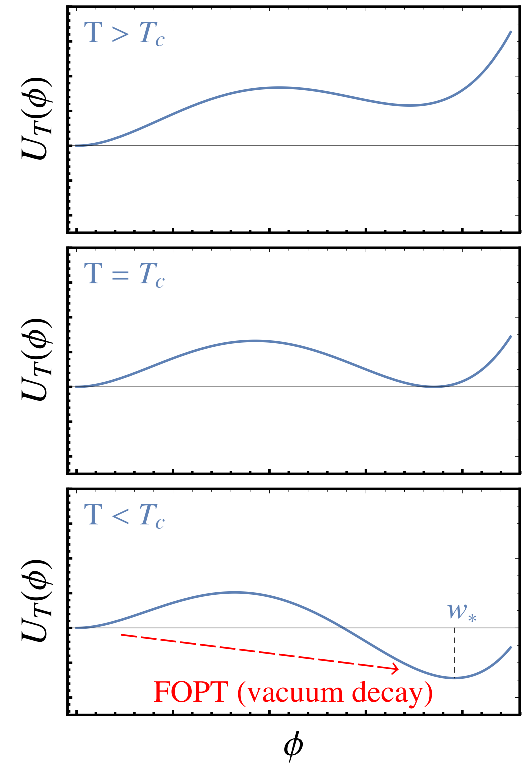




Vacuum energy ΔU released

- Cosmic temperature $T_1 \to T_2$
- Entropy injection $s_1 \to s_1\left(\frac{T_2}{T_1}\right)^3$

Dilution of DM $Y_X \to Y_X\left(\frac{T_1}{T_2}\right)^3$

Assume $\mathcal{L} \supset -\frac{\lambda_{\phi X}}{2}\phi^2|X|^2$

- Before transition $m_X = 0$
- After transition $m_X = \sqrt{\frac{\lambda_{\phi X}}{2}}w$

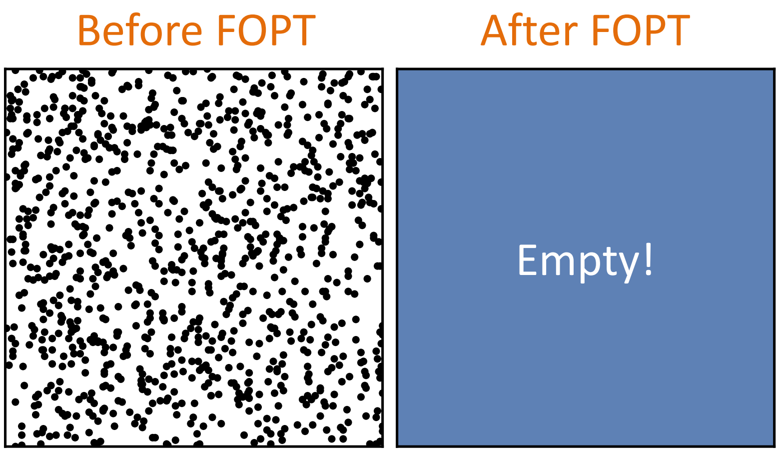
Jump of $z = \frac{m_X}{T} \Rightarrow 0 \to \mathcal{O}\left(\frac{w}{T_2}\right)$

Realizing freeze-in with WIMPs in a strong FOPT

Freeze-in: needs zero DM abundance as <u>initial condition</u>

✗ Conventional WIMP: initially in equilibrium, very abundant

✓ Our scenario: preexisting DM is **diluted** to zero



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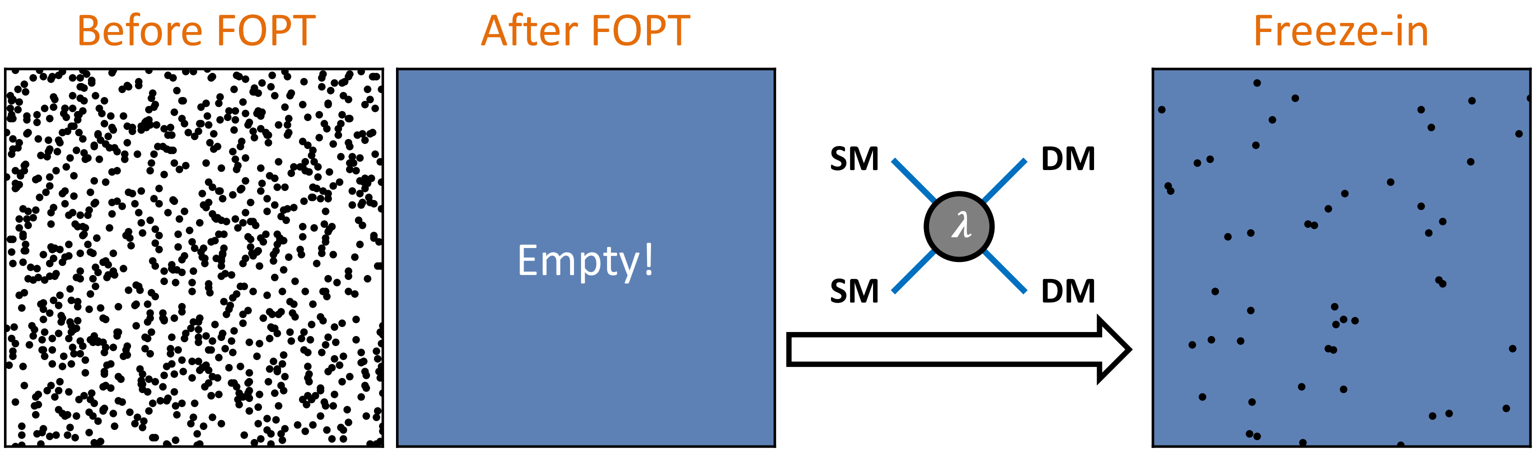
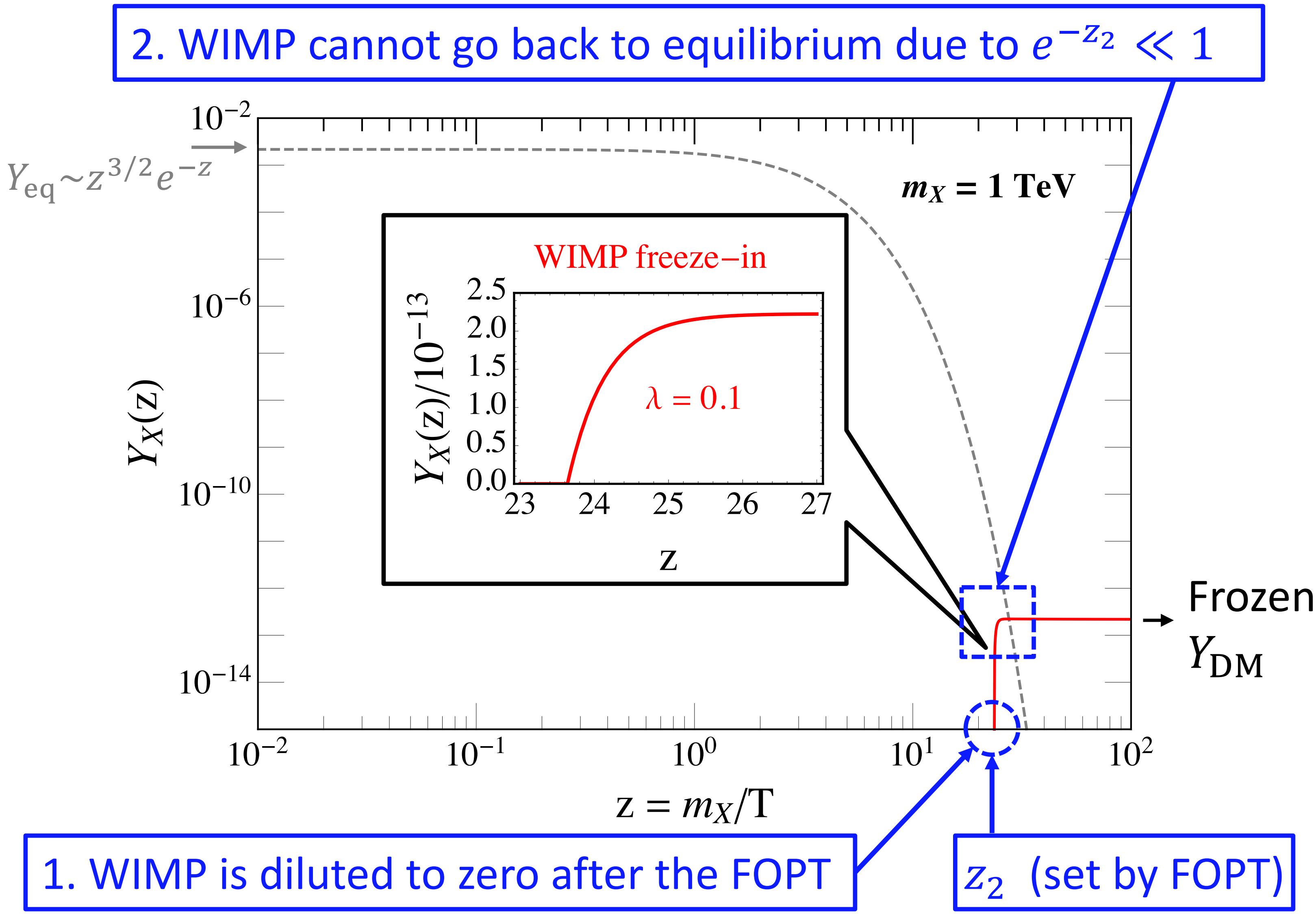


Freeze-in: during evolution, DM is never in equilibrium

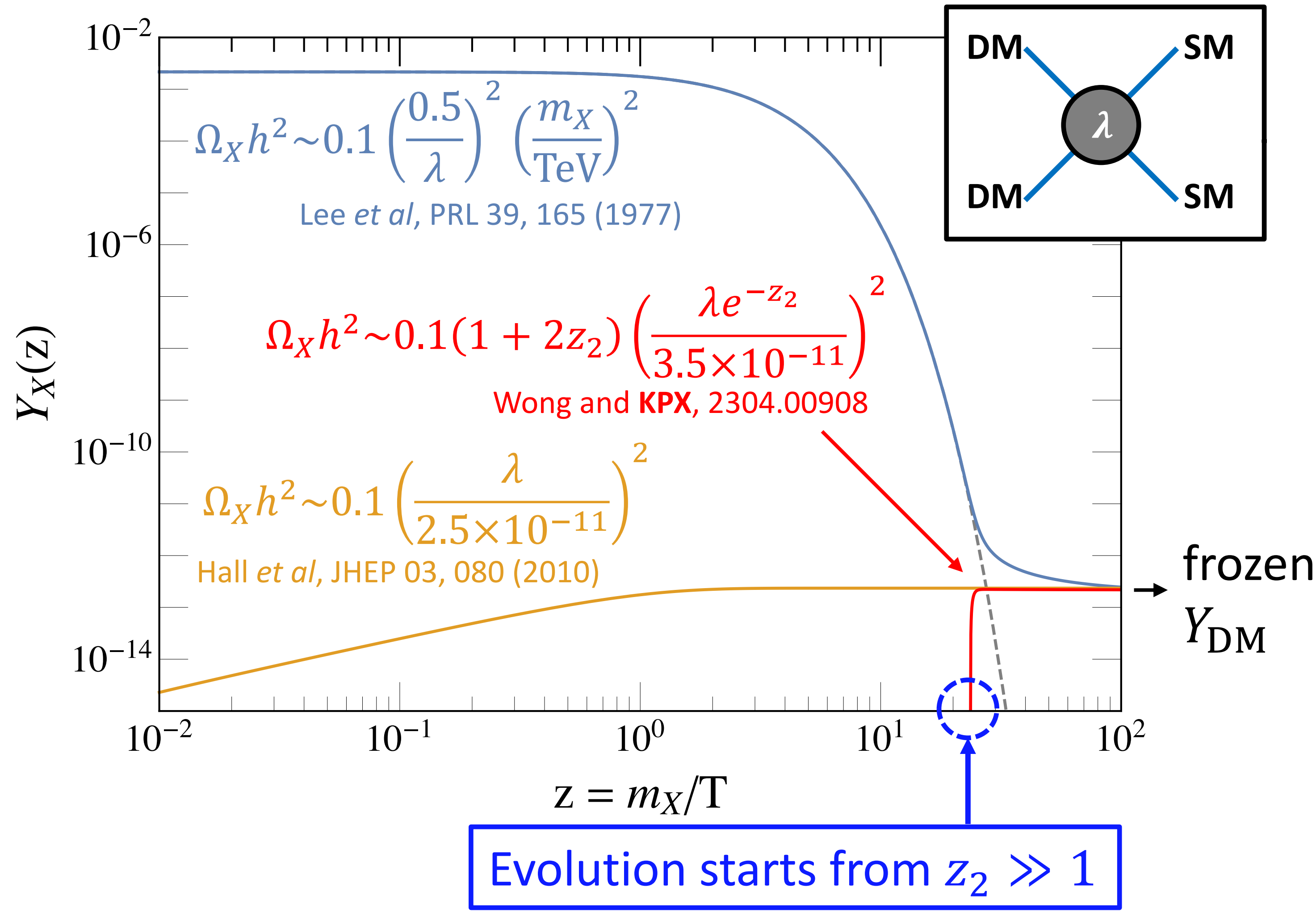
- ✗ Conventional WIMP: be back to equilibrium **rapidly**, since λ is NOT feeble,
- ✓ Our scenario: cannot get back to equilibrium because of the **Boltzmann suppression** $e^{-\frac{m_X}{T_2}} \equiv e^{-z_2}$ (if $z_2 \sim \frac{w}{T_2} \gg 1$)

Freeze-in of WIMPs in a boiling Universe



Comparison of three scenarios

A typical freeze-in scenario, but happens for WIMPs



A realistic model with Higgs portal WIMP

SM + <u>two singlet scalars</u>[Kawana, PRD 105, 103515 (2022)]

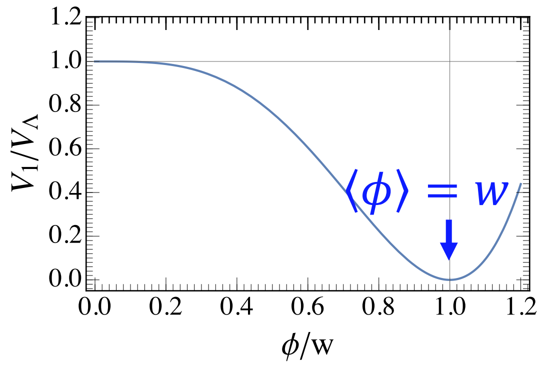
$$V = \lambda_h |H|^4 + \frac{\lambda_\phi}{4}\phi^4 + \lambda_x |X|^4 + \underbrace{\frac{\lambda_{h\phi}}{2}\phi^2|H|^2 + \frac{\lambda_{\phi x}}{2}\phi^2|X|^2 + \lambda_{hx}|X|^2|H|^2}_{\text{Portal couplings}}$$

SM Higgs FOPT scalar **dark matter candidate**

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 $\mathcal{L}_\mathrm{I} \supset -\frac{y_\psi}{\sqrt{2}}\phi\bar{\psi}\psi - y_\nu \bar{\ell}_L \tilde{H}\psi$



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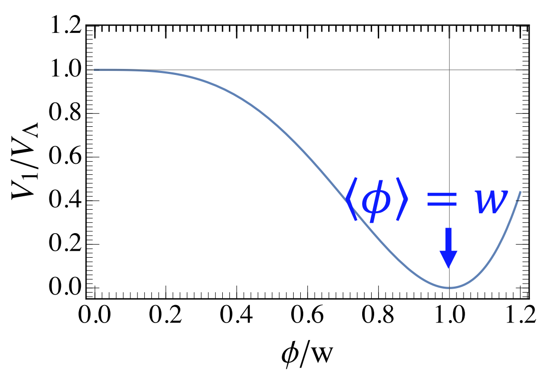


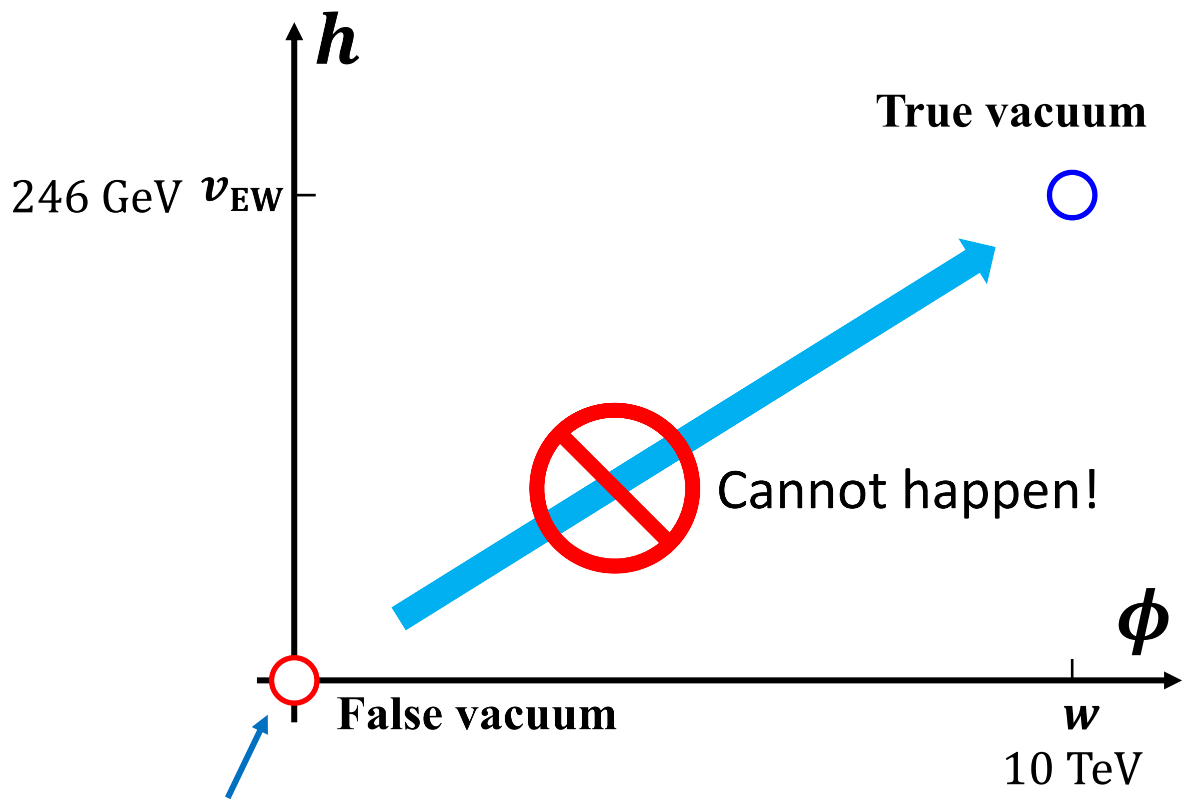
Triggers EW symmetry breaking: $\lambda_{h\phi} = -\frac{m_h^2}{w^2}$

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

Thermal history (1)

Thermal barrier forbids the direct tunneling

- The Universe is supercooled

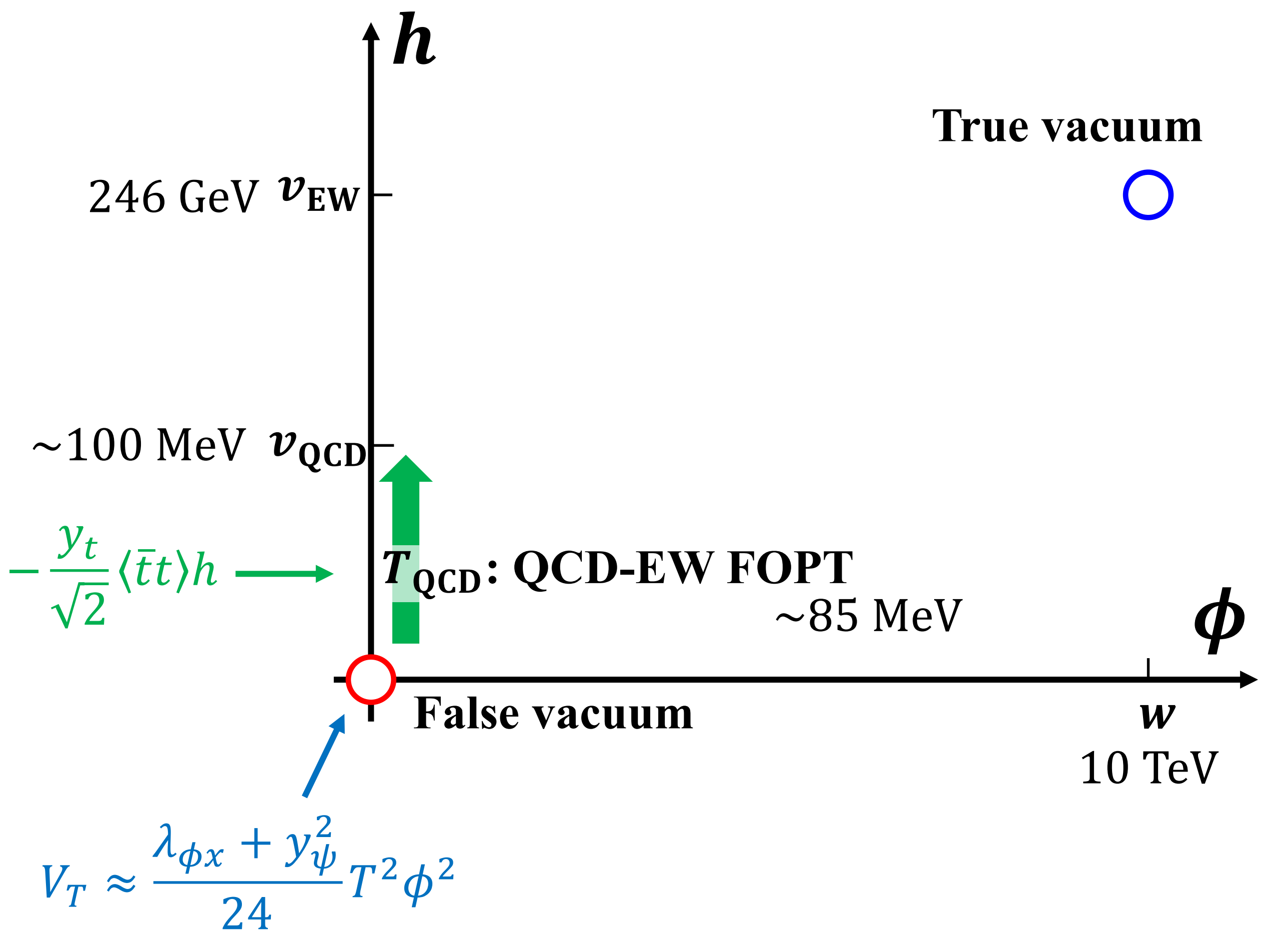


$$V_T \approx \frac{\lambda_{\phi x} + y_\psi^2}{24} T^2 \phi^2$$

Thermal history (2)

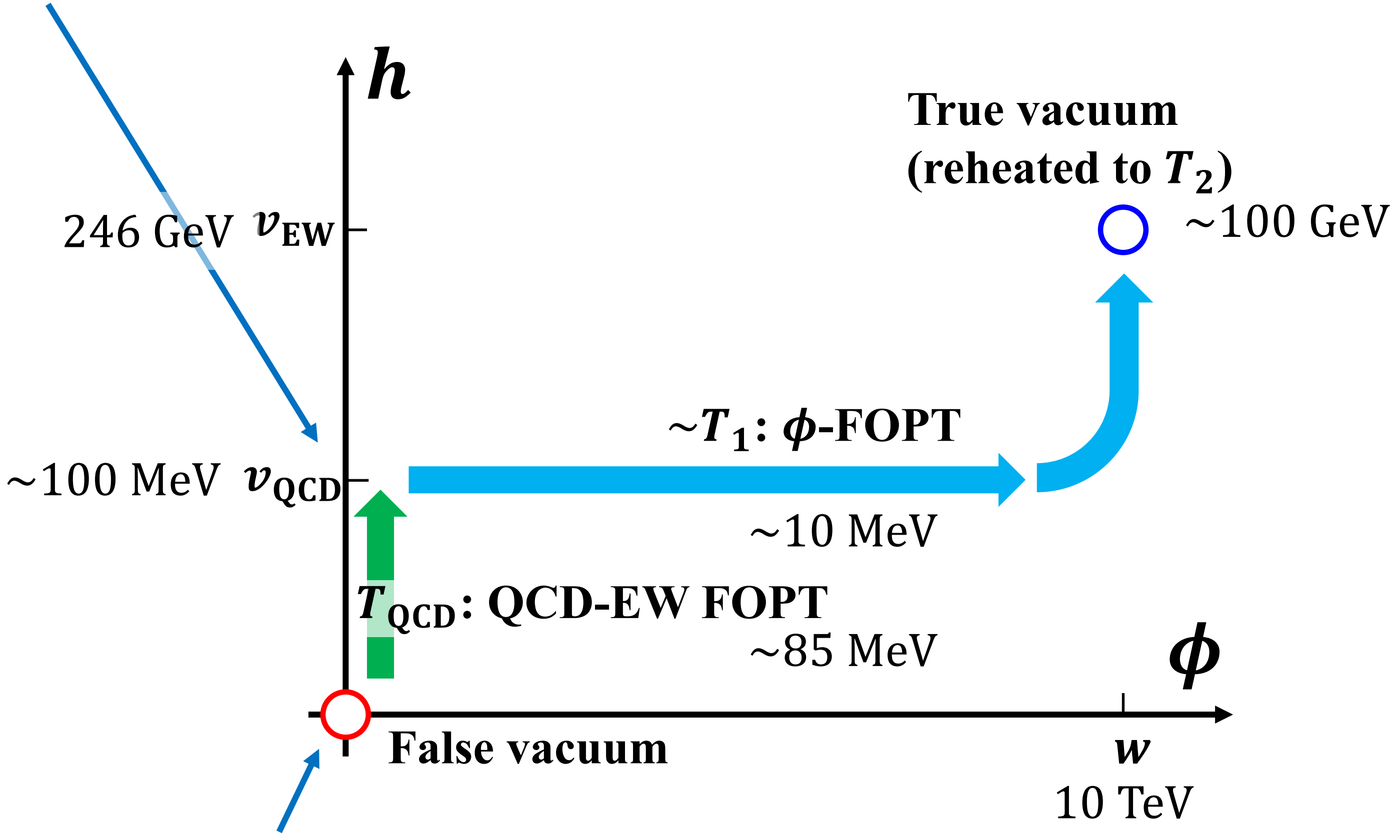
QCD FOPT with 6-flavor massless quarks[Pisarski *et al*, PRD 29, 338 (1984)]

- QCD phase transition triggers EW phase transition



Thermal history (3)

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



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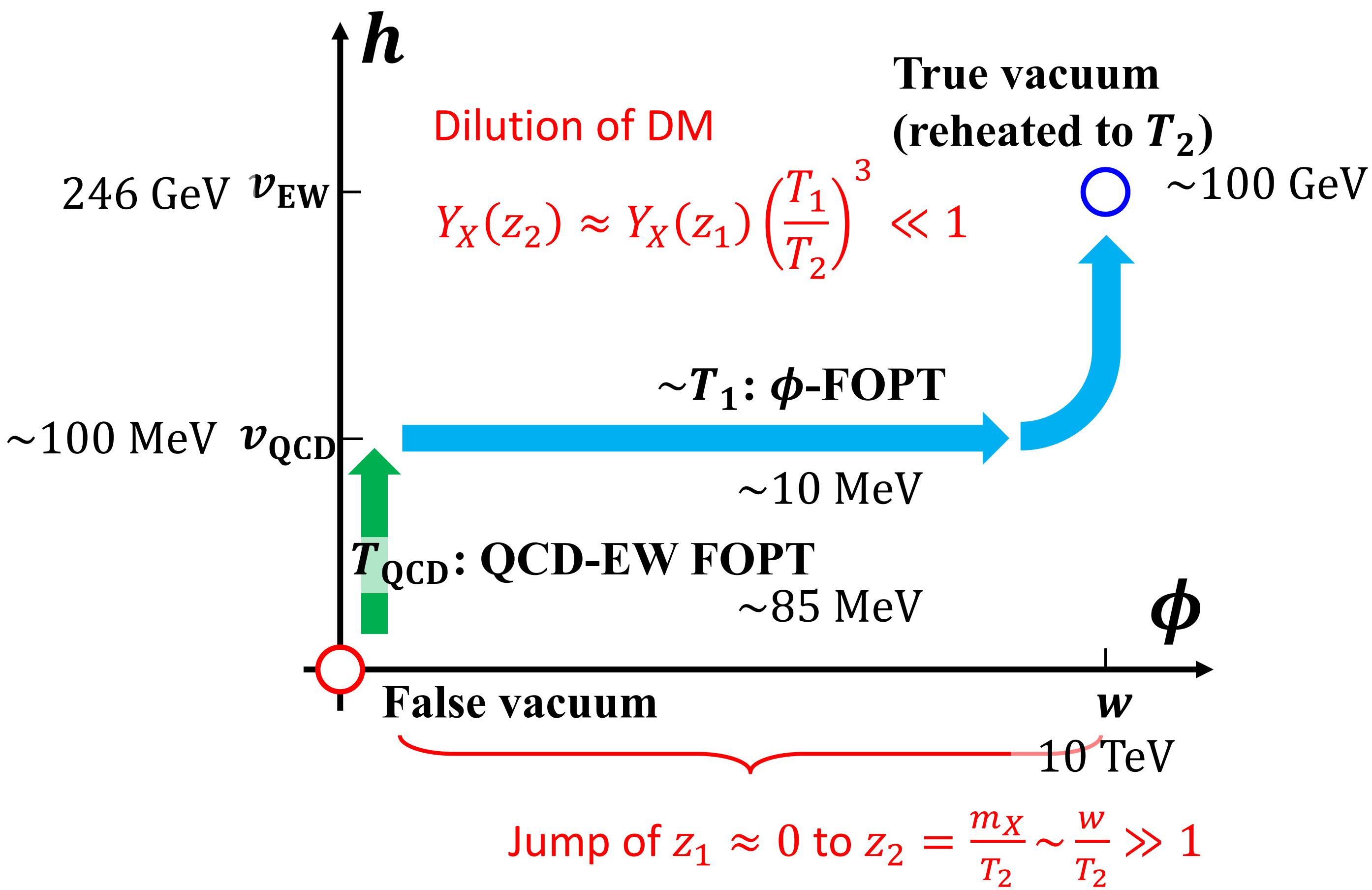
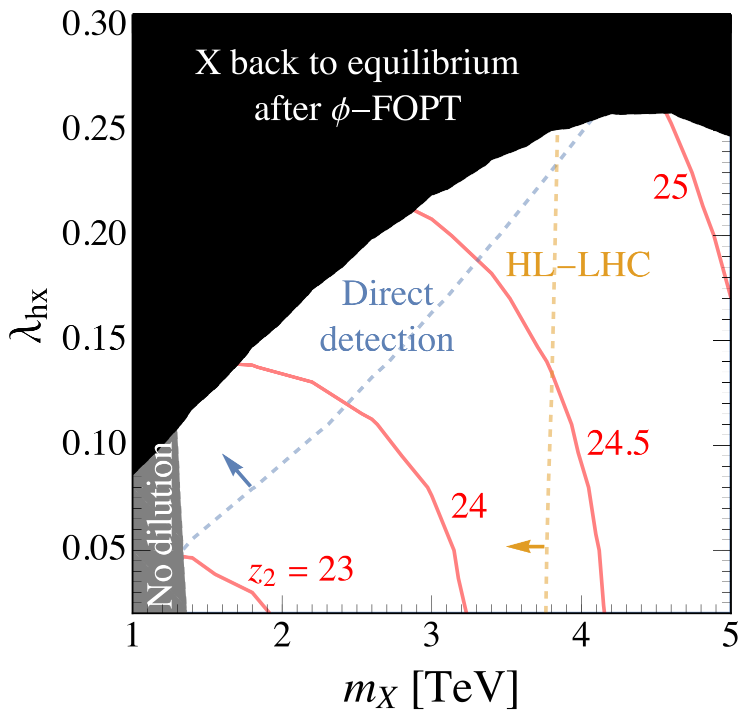
Satisfying conditions of WIMP freeze-in

Satisfying the two conditions of WIMP freeze-in

- Dilution & large z_2

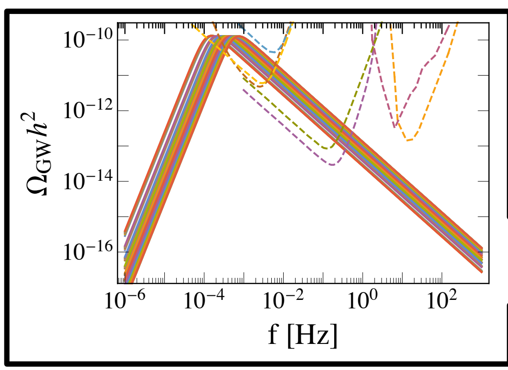


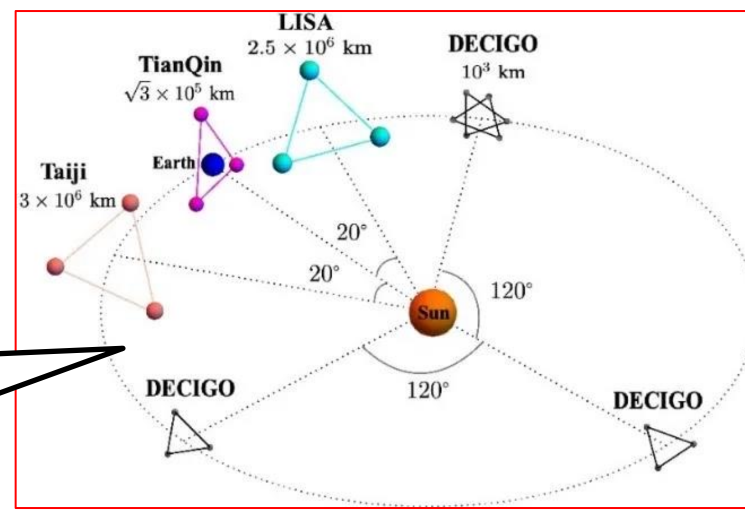
Viable parameter space



Higgs portal WIMP X, but **freeze-in**: $hh \to XX^\dagger$; $\phi\phi \to XX^\dagger$

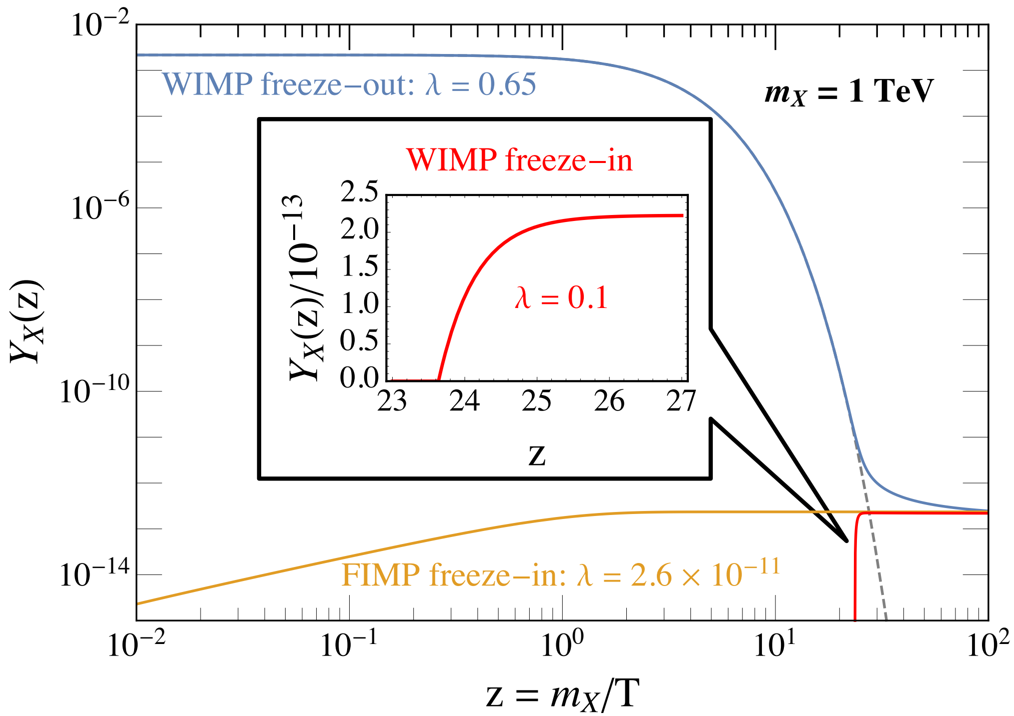
- Direct detection $\sigma_{SI} \sim 10^{-48}$ cm^2 (smaller than standard WIMP)
- $\mathrm{Br}(h \to \phi\phi) \sim 4\% - 9\%$;
- Gravitational waves $f \sim 10^{-3}$ Hz, LISA, TianQin, Taiji, …

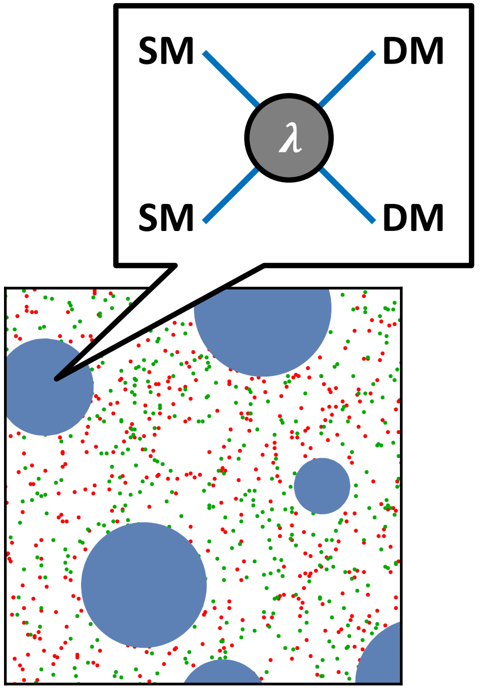




Conclusion

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





- Generally applied to a lot of new physics models;
- Phenomenology: Correlation between WIMP searches & gravitational waves

Thank you!

Backup: guide for model building (1)

Dark matter

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

Thermal bath particle FOPT scalar

Minimal setup:

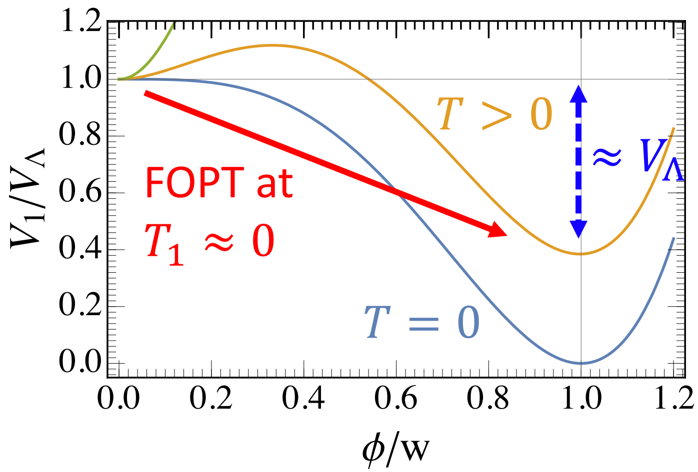
$$B = \frac{\phi}{\sqrt{2}} \text{ and hence } \lambda_{\phi X} = \lambda$$

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

One-loop level: Coleman-Weinberg potential

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

$\Omega_X h^2$ determined by λ and λ_B



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

$$z_2 \equiv \frac{m_X}{T_2}$$

Backup: guide for model building (2)

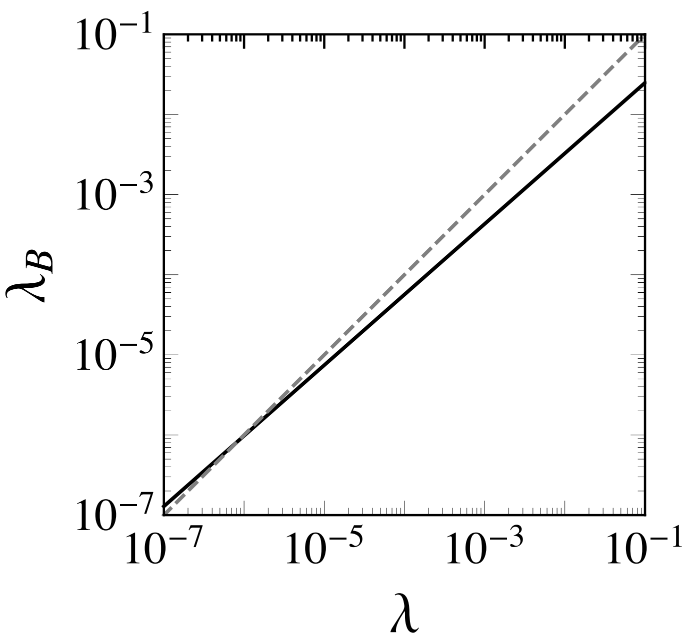
Dark matter

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

Thermal bath particle

Classically conformal principle

$\Omega_X h^2$ determined by λ and λ_B



$\Omega_{\rm DM} h^2 = 0.12$--

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