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Conformal Supercooled Vector Dark Matter

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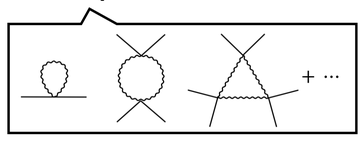
What is (Classical) Conformal?

Higgs potential terms in **SM**: $V_{\text{tree}}(H) = -\mu^2|\mathrm{H}|^2 + \lambda|\mathrm{H}|^4$ **Hierarchy Problem**

Only dim-four terms at tree level: $\lambda|\Phi|^4$ ✚ 1-loop correction



Coleman-Weinberg potential

$$V_{\text{eff}}(\phi) = V_{\text{tree}}(\phi) + \frac{B}{4}\phi^4\left(\log\frac{\phi}{w_0} - \frac{5}{6}\right)$$

keeps scale invariance ≈ classical conformal invariance

Count in Finite Temperature correction

$$V_T(\phi, T) \approx V_1(\phi) + c_\phi T^2\phi^2$$

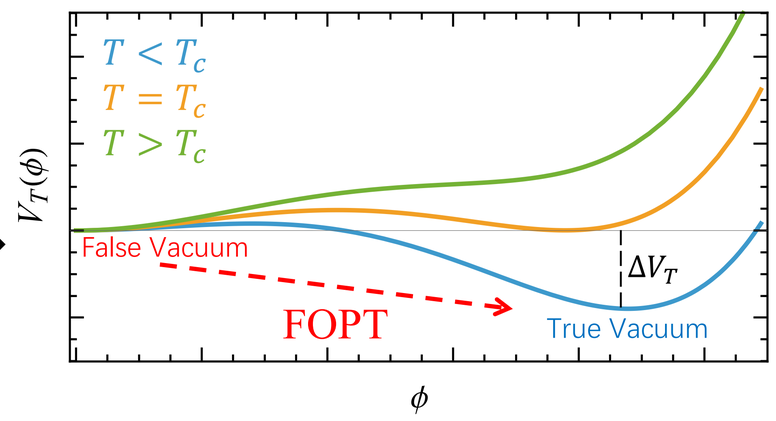
What is Super-cooling?

Before Conformal PT, DM & SM particles remain **massless**

Supercooling: conformal PT at a **very low temperature**

Mechanism of DM: **freeze-out** ❌ **freeze-in** ✅

First-order phase transition (FOPT):
The decay of the Universe between two minima (False Vacuum & Ture Vacuum) separated by a barrier
Proceeds with **Reheating of Universe**



1. Releases huge amount of entropy dilutes DM density $Y = \frac{n}{s}$
2. WIMPs gain mass $e^{-m_X/T}$ Boltzmann factor Prevents them from thermalizing.

Model Setup

$S = \begin{pmatrix} s_1 \\ s_2 \\ s_3 \end{pmatrix}$ SU(2) Spin 1 (adjoint) Rep

spontaneous symmetry breaking

$$V_{\text{CW}}(\phi) = \frac{B}{4}\phi^4(\log\frac{\phi}{w} - \frac{1}{4}) \qquad B = \frac{3g_X^4}{4\pi^2}$$

$S = \begin{pmatrix} \chi_1 \\ \chi_2 \\ s + w \end{pmatrix}$ Gauge Boson: $m_{A'} = 0$ $m_X = m_{X^\dagger} = g_X w$

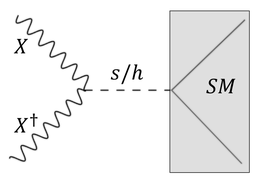
✚ WIMP

coupling with higgs $V_0 = \frac{\lambda_s}{4}|S|^4 + \frac{\lambda_{sh}}{2}|S|^2|H|^2 + \lambda_h|H|^4$

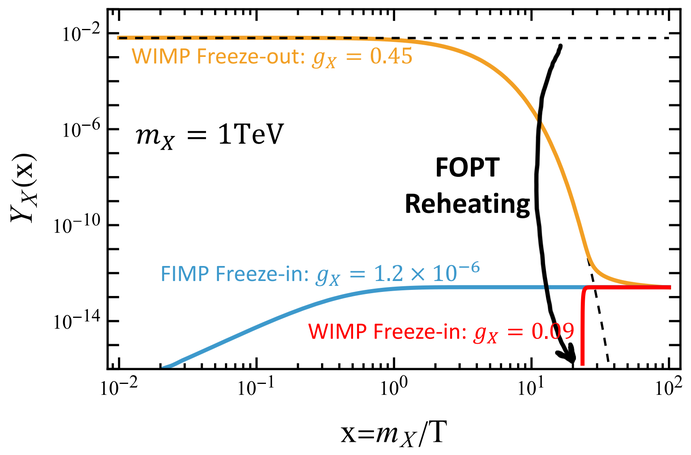
After spontaneous symmetry breaking

$$V(s,h) = \frac{B}{4}s^4\left(\log\frac{s}{w} - \frac{1}{4}\right) + \frac{\lambda_{sh}}{4}s^2h^2 + \frac{\lambda_h}{4}h^4$$

Mass eigenstate $\begin{pmatrix} h_M \\ s_M \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} h - v \\ s - w \end{pmatrix}$



Freeze-in of WIMP



$$\frac{dY_X}{dx} = -\sqrt{\frac{\pi g_{*,s}^2}{45\, g_*}}\frac{M_{pl}m_X}{x^2}\langle\sigma v\rangle(Y_X^2 - Y_{eq}^2)$$

$x_0 \sim 10^1$ $Y(x_0) \ll Y_{eq}$

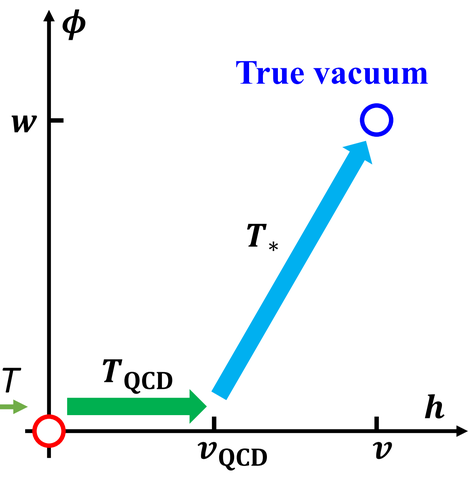
Also see
Hambye *et al*, JHEP 08 (2018) 188;
Wong *et al*, PRD 108 (2023) 5 055035
…

How PT happens?

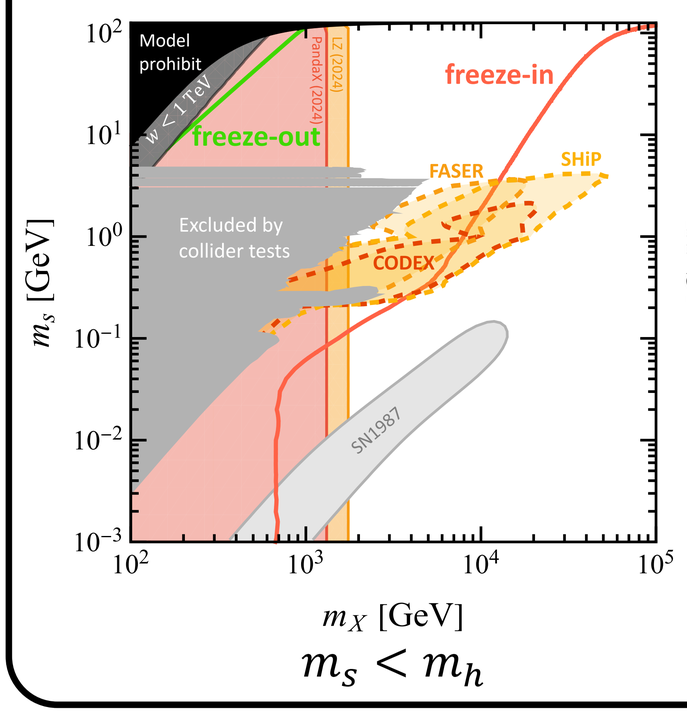
decay rate sufficiently low until $T_{QCD} \approx 85$ MeV

QCD condensation $\langle\bar{q}q\rangle \neq 0$
⇩ $-y_q h\langle\bar{q}q\rangle/\sqrt{2}$
$\langle h\rangle = v_{\text{QCD}} \approx 100$ MeV

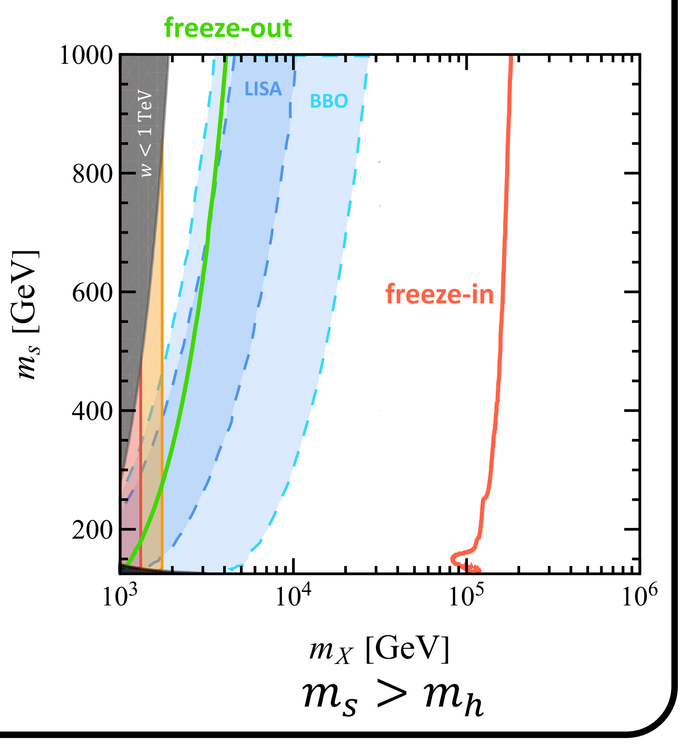
joint QCD-EW PT



Results



$m_s < m_h$



$m_s > m_h$

Conclusion

Dark SU(2) in Spin 1 Rep with **2 WIMPs** X & $X^\dagger$
Based on Classical Conformal / Log potential
Conformal FOPT can be super-cool
produce Reheating of Universe

Phenomenology:

1. Freeze-out: at $m_s < m_h$ completely excluded
   at $m_s > m_h$ can be excluded by future GW excess detected
2. **Freeze-in**: at $m_s < m_h$ can be excluded by future long-lived decay experiment
   at $m_s > m_h$ Not excluded at present