NPhiS 2026

Unavoidable Impact of Cosmological Phase Transitions on Dark Matter

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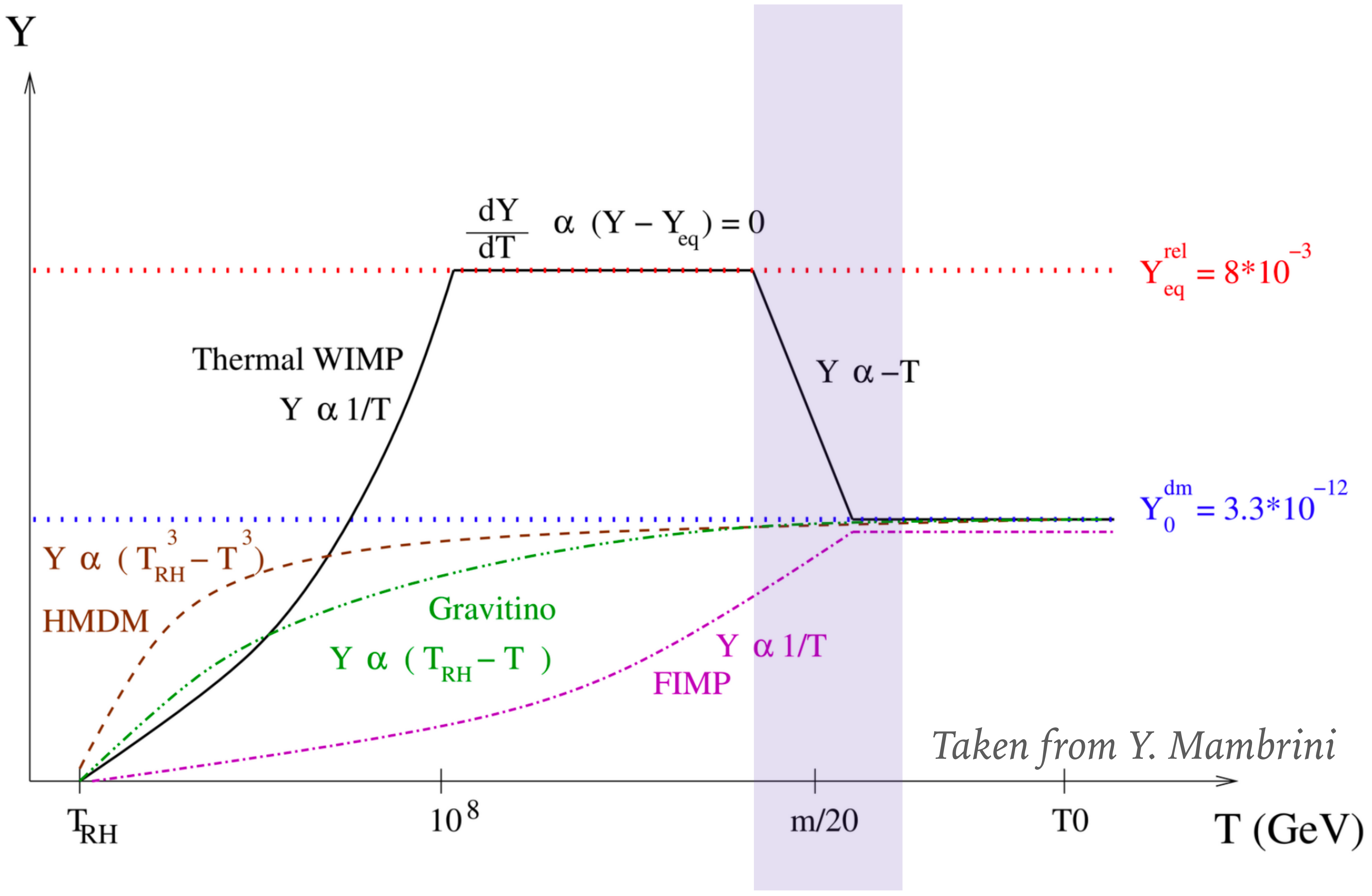
Outline

- Introduction
- Impact of Cosmological Phase Transitions on freeze-out DM
  - Yang Xiao, Jin Min Yang, YZ, JHEP 02 (2023) 008
  - Yang Xiao, Jin Min Yang, YZ, Sci.Bull. 68 (2023) 3158-3164
- Impact of Cosmological Phase Transitions on freeze-in DM
  - Yu Liu, Yang Xiao, Jin Min Yang, Bin Zhu, YZ, in progress
  - Guangshang Chen, Yang Xiao, Jin Min Yang, YZ, in progress
  - L. Bian, G. Chen, S. Li, H. Wang, Y. Xiao, J.M. Yang, YZ, arXiv:2601.15933
- Conclusions

1. Introduction: temperatures of EWPT and DM freeze-out/in

Event	time t	redshift z	temperature T
Inflation	10^{-34} s (?)	–	–
Baryogenesis	?	?	?
EW phase transition	20 ps	10^{15}	100 GeV
QCD phase transition	20 μs	10^{12}	150 MeV
Dark matter freeze-out	?	?	?
Neutrino decoupling	1 s	6×10^9	1 MeV
Electron-positron annihilation	6 s	2×10^9	500 keV
Big Bang nucleosynthesis	3 min	4×10^8	100 keV
Matter-radiation equality	60 kyr	3400	0.75 eV
Recombination	260–380 kyr	1100–1400	0.26–0.33 eV
Photon decoupling	380 kyr	1000–1200	0.23–0.28 eV
Reionization	100–400 Myr	11–30	2.6–7.0 meV
Dark energy-matter equality	9 Gyr	0.4	0.33 meV
Present	13.8 Gyr	0	0.24 meV



TeV ~ MeV

1. Introduction: DM density

- To compute the DM relic density, we solve the Boltzmann equation

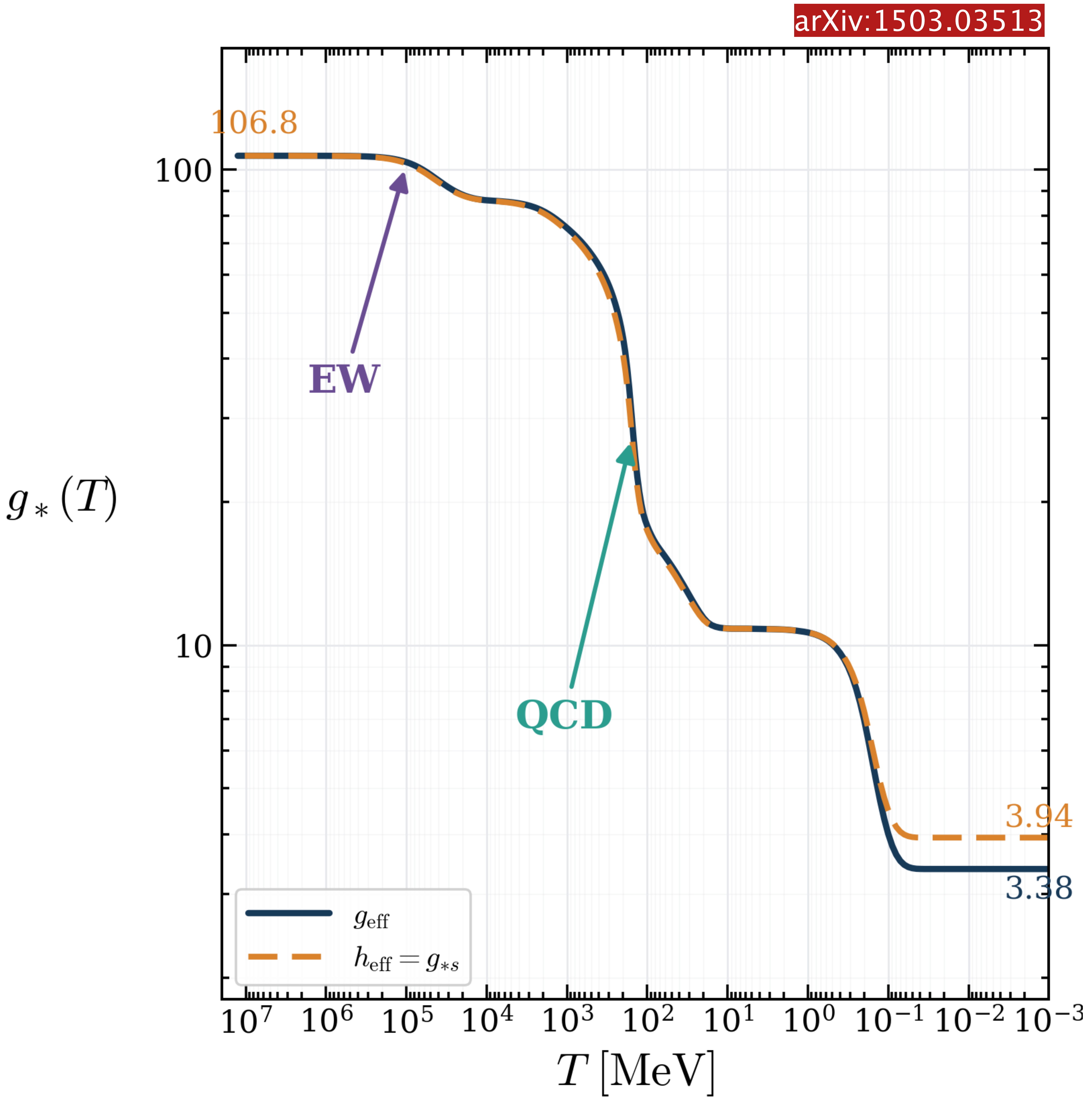
$$\frac{dY}{dx} = -\frac{\langle\sigma v\rangle s(x)}{Hx}\left[Y^2 - Y_{\rm eq}^2(x)\right]$$

where the entropy density plays a key role, given by

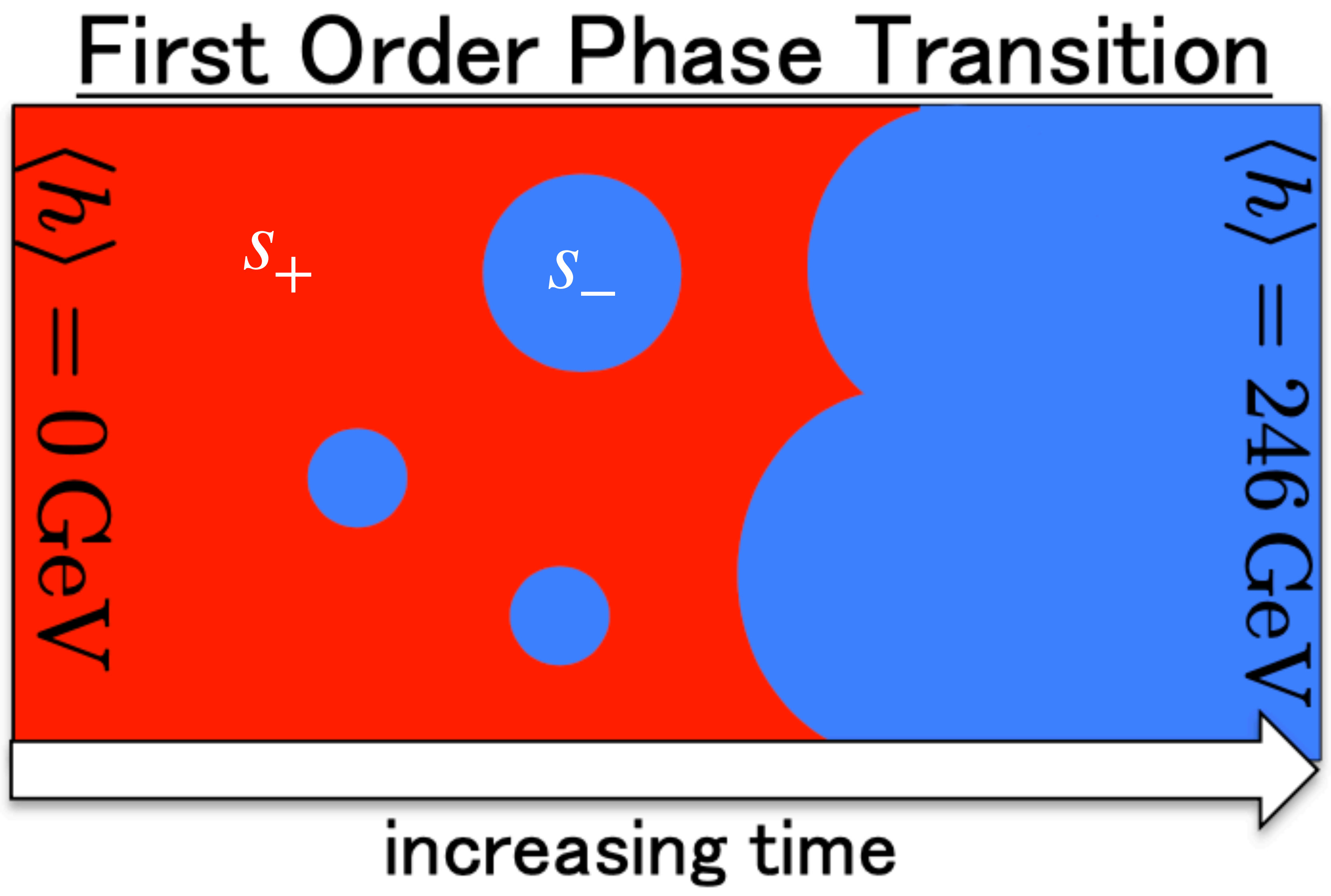
$$s = \frac{2\pi^2}{45} g_{*s} T^3$$

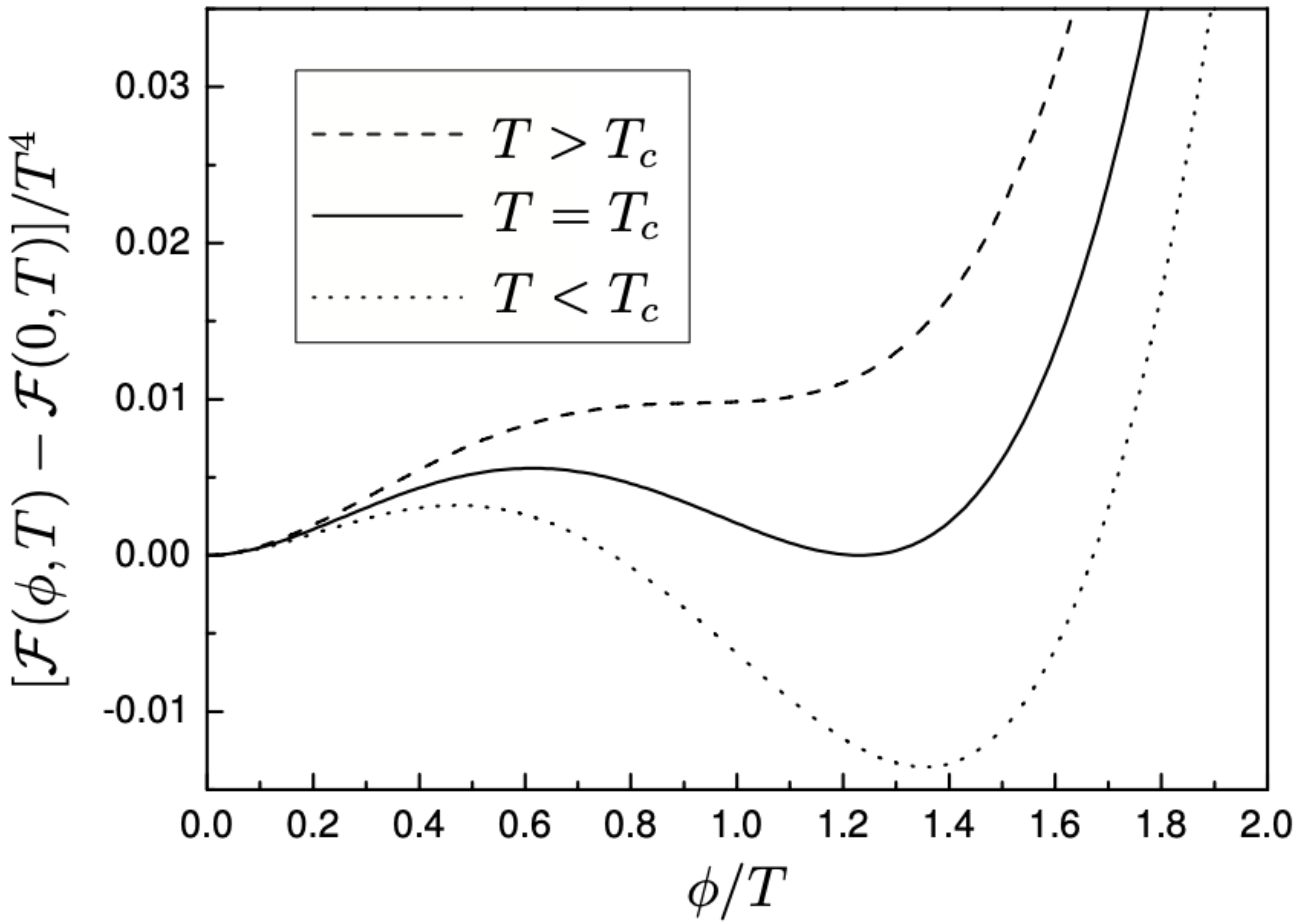
- In the SM, the effective entropy degrees of freedom are

$$g_s \equiv \sum_{i=\text{bosons}} \gamma_i \left(\frac{T_i}{T}\right)^3 + \frac{7}{8} \sum_{i=\text{fermions}} \gamma_i \left(\frac{T_i}{T}\right)^3$$



1. Introduction: entropy density in electroweak phase transitions





- In BSM with first order phase transition

$$s(T) = (1-f)s_+(T) + f\, s_-(T)$$

where f is the fraction of volume occupied by bubbles of true vacuum.

$$s = -\frac{\mathrm{d}\mathcal{F}}{\mathrm{d}T}, \qquad s_-(T_C) + > s_+(T_C)$$

1. Introduction: dilution of DM density

arXiv:1104.5034 , Daniel J. H. Chung, Andrew J. Long, Lian-Tao Wang

Suppose that a phase transition occurs after the time of the freeze out. The phase transition can affect $H(a)$ (though the energy density) in three ways: exotic energy, reheating, and decoupling.

$$H \approx H_R^{(U)}(x)\left[1+\frac{\epsilon_1}{2}x^4\,\kappa(x)+\frac{2}{3}\epsilon_2\Theta(x-(1+\delta))+\frac{\epsilon_{31}\Theta(x-(1+\delta))+\epsilon_{32}f\,(x)}{6}\right]$$

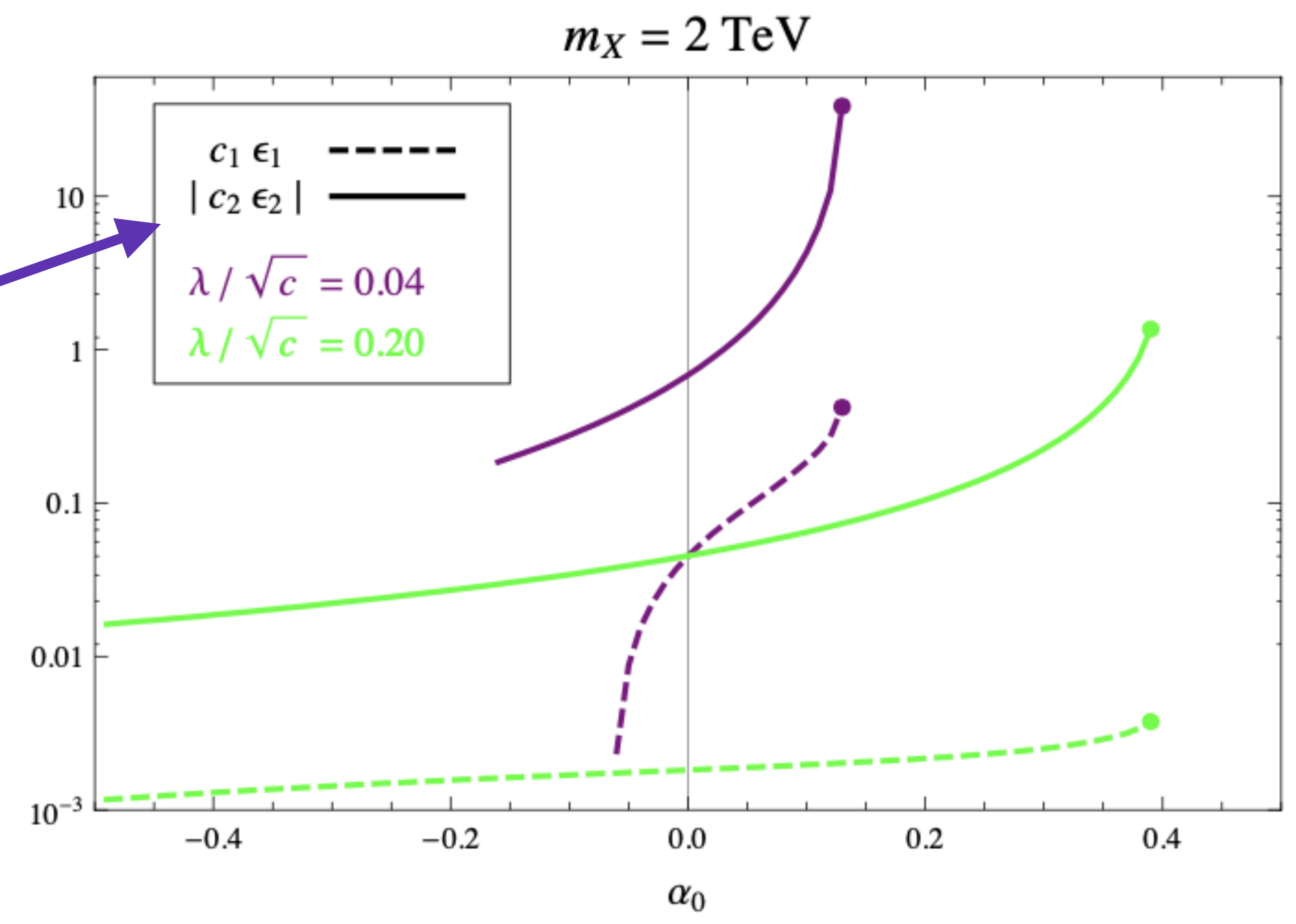
$$H_R^{(U)}(x)\equiv\frac{T_f^2}{3\,M_p\,x^2}\sqrt{\frac{\pi^2}{10}\,g_E(T_f)}\longrightarrow$$ *The "usual" Hubble parameter in the absence of the phase transition*

$$\epsilon_1\equiv\frac{\rho_{\rm ex}}{\frac{\pi^2}{30}g_E(T_f)\,T_f^4}=\text{fractional energy of the exotic during freeze out}$$

$$\epsilon_2\equiv(1+3\,\delta)\,\frac{\Delta s}{\frac{2\pi^2}{45}g_S(T_f)\,T_f^3}=\text{fractional entropy increase during PT}$$

$$\epsilon_{31}\equiv\frac{\frac{7}{8}N_{PT}}{g_E(T_f)}=\text{ fractional decoupling degrees of freedom during PT}$$

$$\epsilon_{32}\equiv\frac{\frac{7}{8}N}{g_E(T_f)}=\text{ fractional decoupling degrees of freedom}$$



Fractional shift in the DM relic abundance

1. Introduction: dilution of DM density

arXiv:0909.1317, Carroll Wainwright, Stefano Profumo

① **Supercooling stage**： false vacuum dominates the universe and the total entropy is conserved.

$$a_i^3 s_F(T_C) = a_*^3 s_F(T_*) \;\rightarrow\; \left(\frac{a_i}{a_*}\right)^3 = \frac{s_F(T_*)}{s_F(T_C)}$$

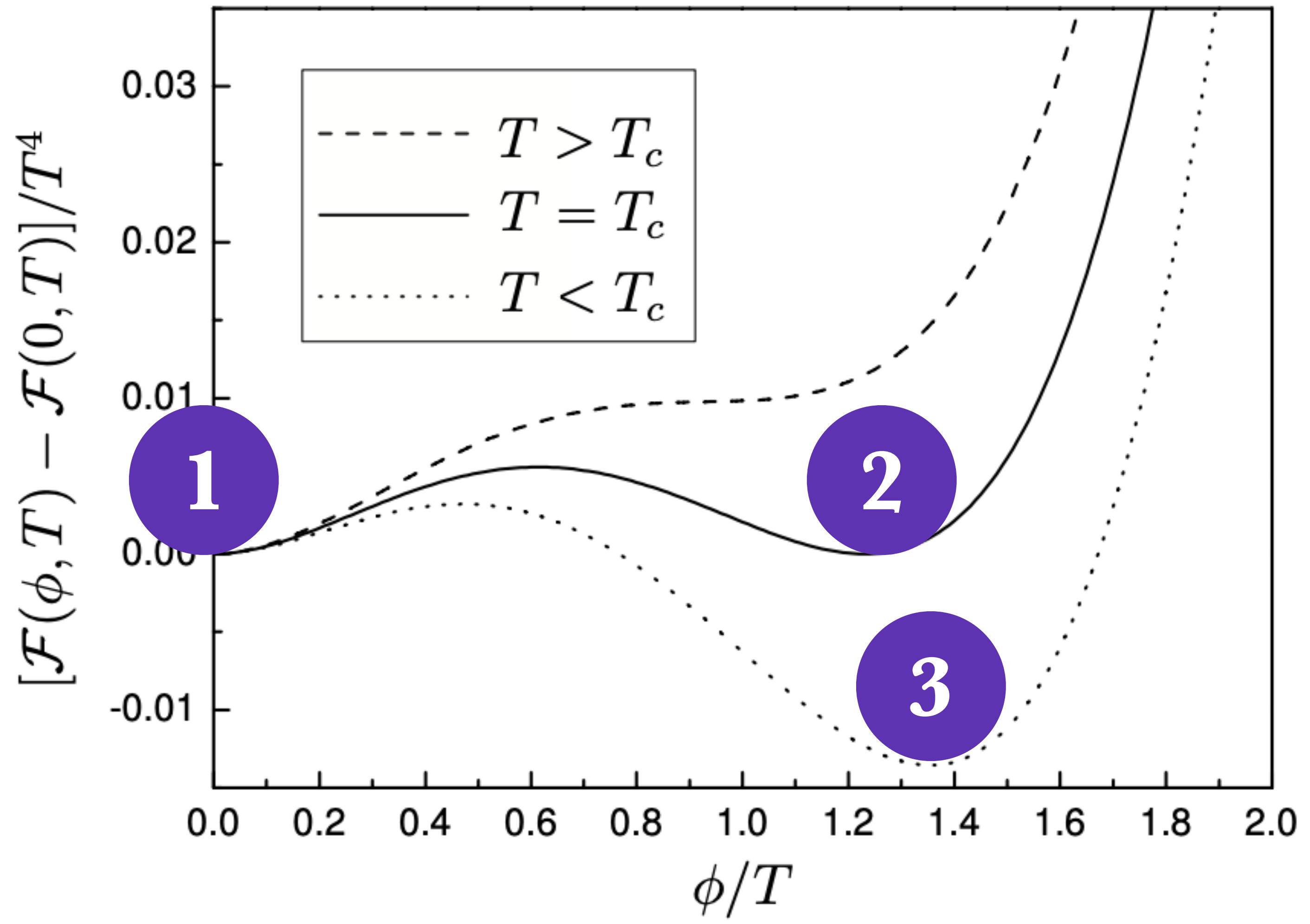
② **Reheating stage:** The latent heat is released and reheats the universe. The duration is short compared to the expansion rate, so the energy density ρ is conserved.

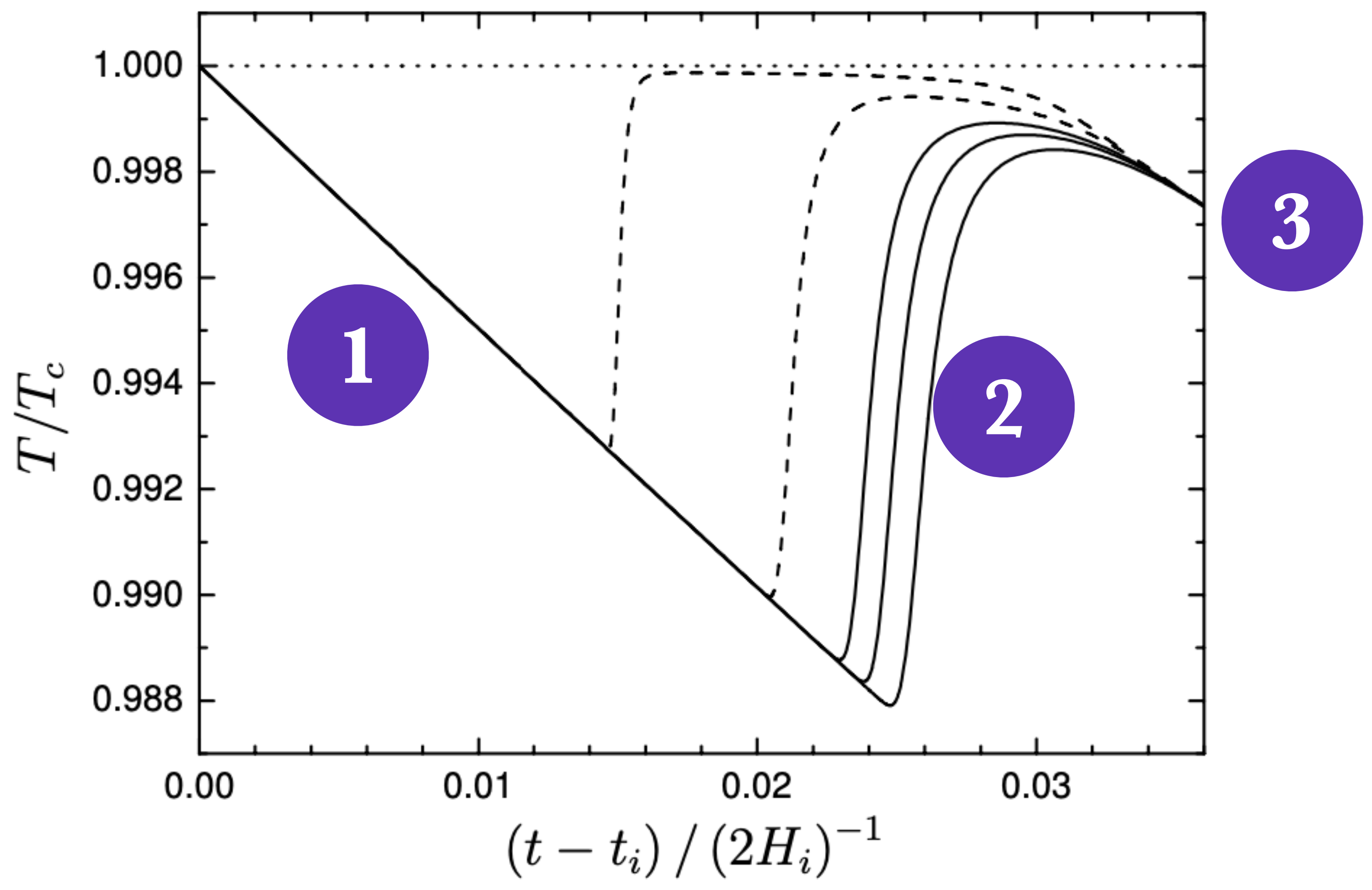
$$\rho_F(T_*) = \rho_{F/T}(T_R) \equiv f\,\rho_T(T_R) + (1-f)\rho_F(T_R) \;\rightarrow\; f = \frac{\rho_F(T_*) - \rho_F(T_R)}{\rho_T(T_R) - \rho_F(T_R)} = \frac{\rho_F(T_*) - \rho_F(T_R)}{L}$$

③ **Phase coexistence stage:** true vacuum vacuum dominates the universe and the total entropy is conserved again.

$$a_*^3[(1-f)s_F(T_R) + f\,s_T(T_R)] = a_f^3 s_T(T_F) \;\rightarrow\; \left(\frac{a_f}{a_*}\right)^3 = \frac{s_F(T_R) - f\,\Delta s(T_R)}{s_T(T_F)}$$

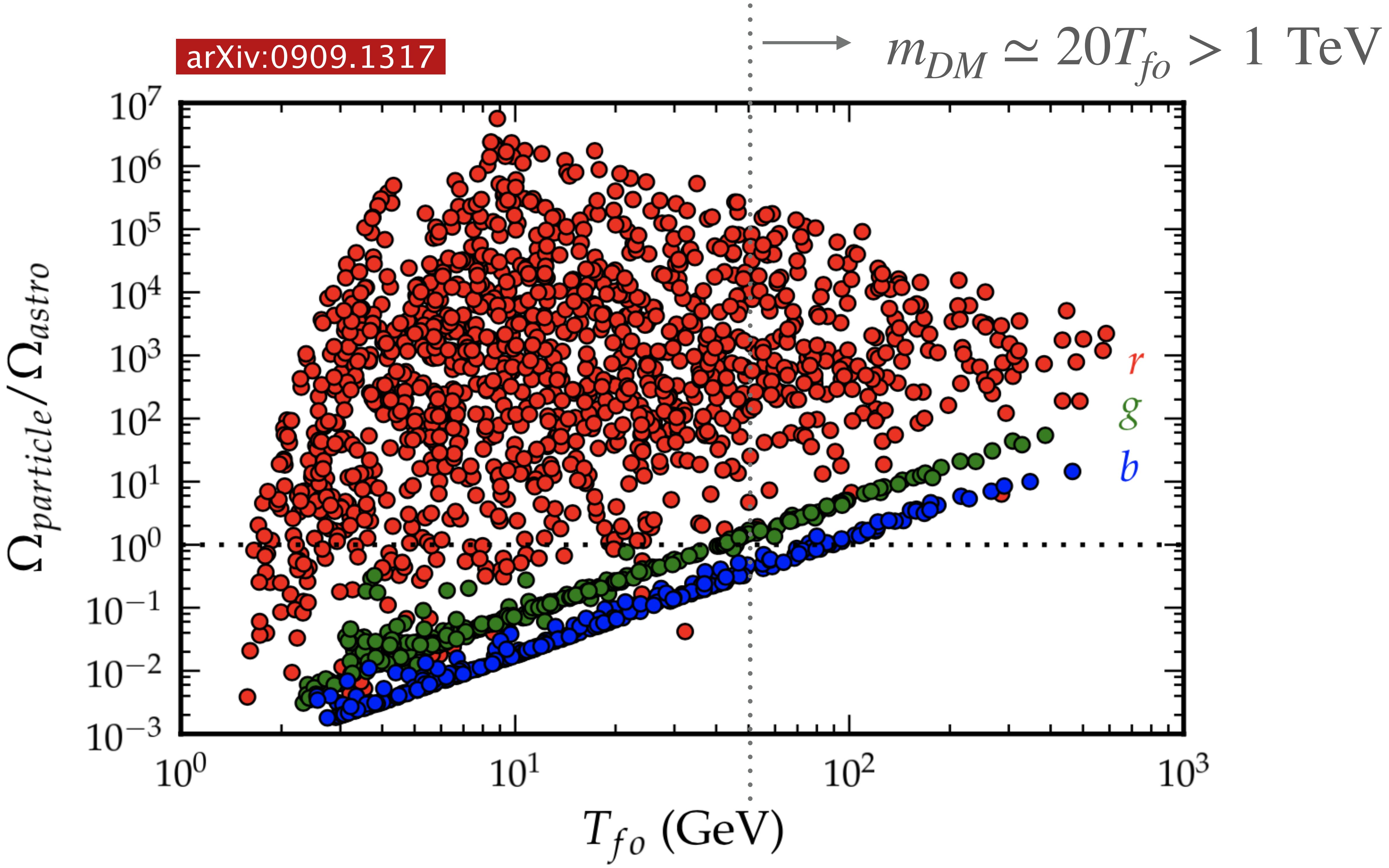
➤ The total dilution factor $d = \left(\frac{a_f}{a_i}\right)^3 = \frac{s_F(T_*)}{s_F(T_C)} \times \frac{s_F(T_R) - f\,\Delta s(T_R)}{s_T(T_F)}$

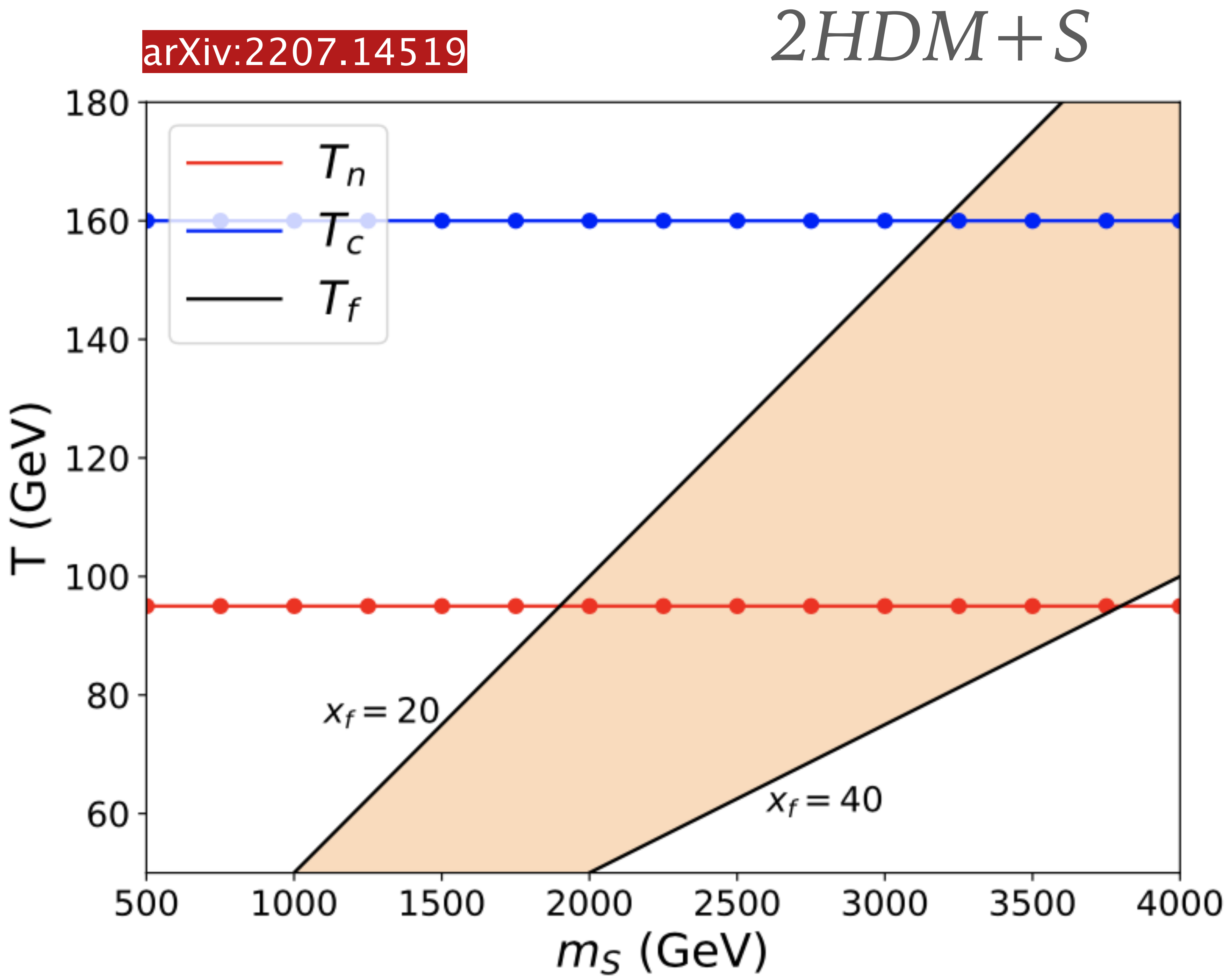




2. Impact on freeze-out DM: dilution of DM density

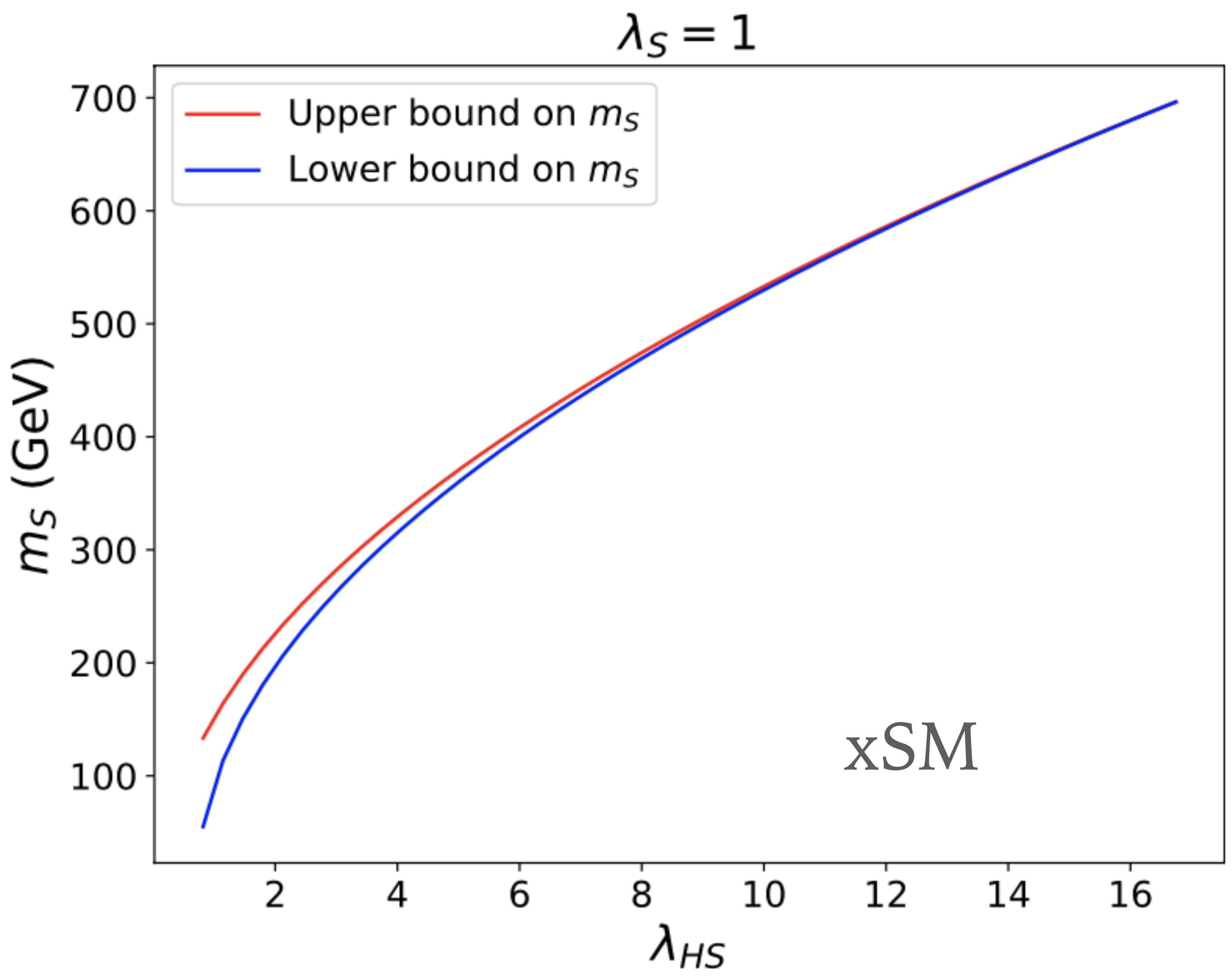
➤ The key requirement for dilution is that the first-order phase transition happens after DM freeze-out. Otherwise, the DM would be in thermal equilibrium after the phase transition and its number density would re-equilibrate to the other thermal species.

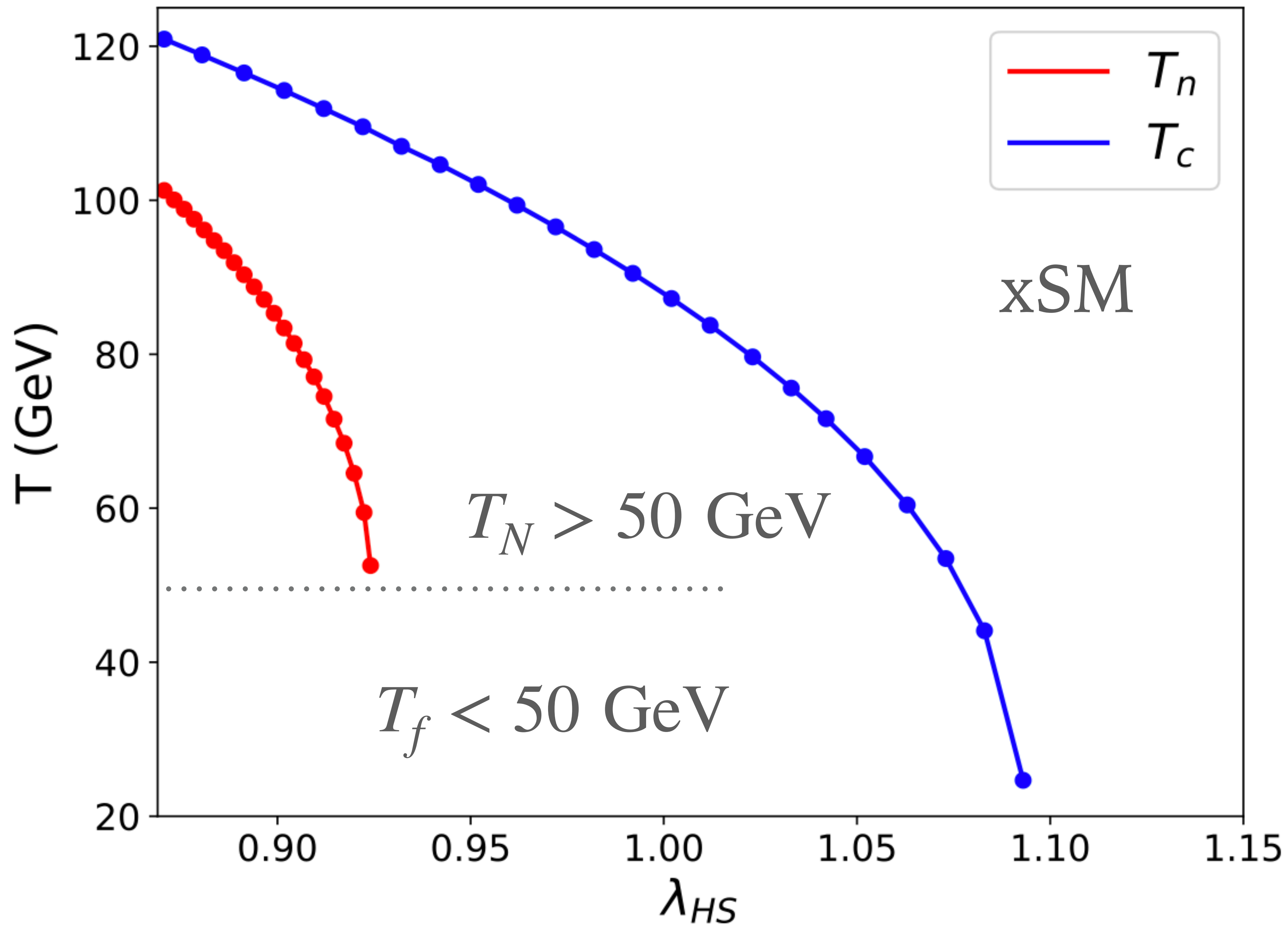




2. Impact on freeze-out DM: nucleation temperature T_N

- If a single scalar field acts as both the DM candidate and drives the first-order electroweak phase transition, the phase transition sets an upper limit for the dark matter, making it impossible for the phase transition to occur after freeze-out.

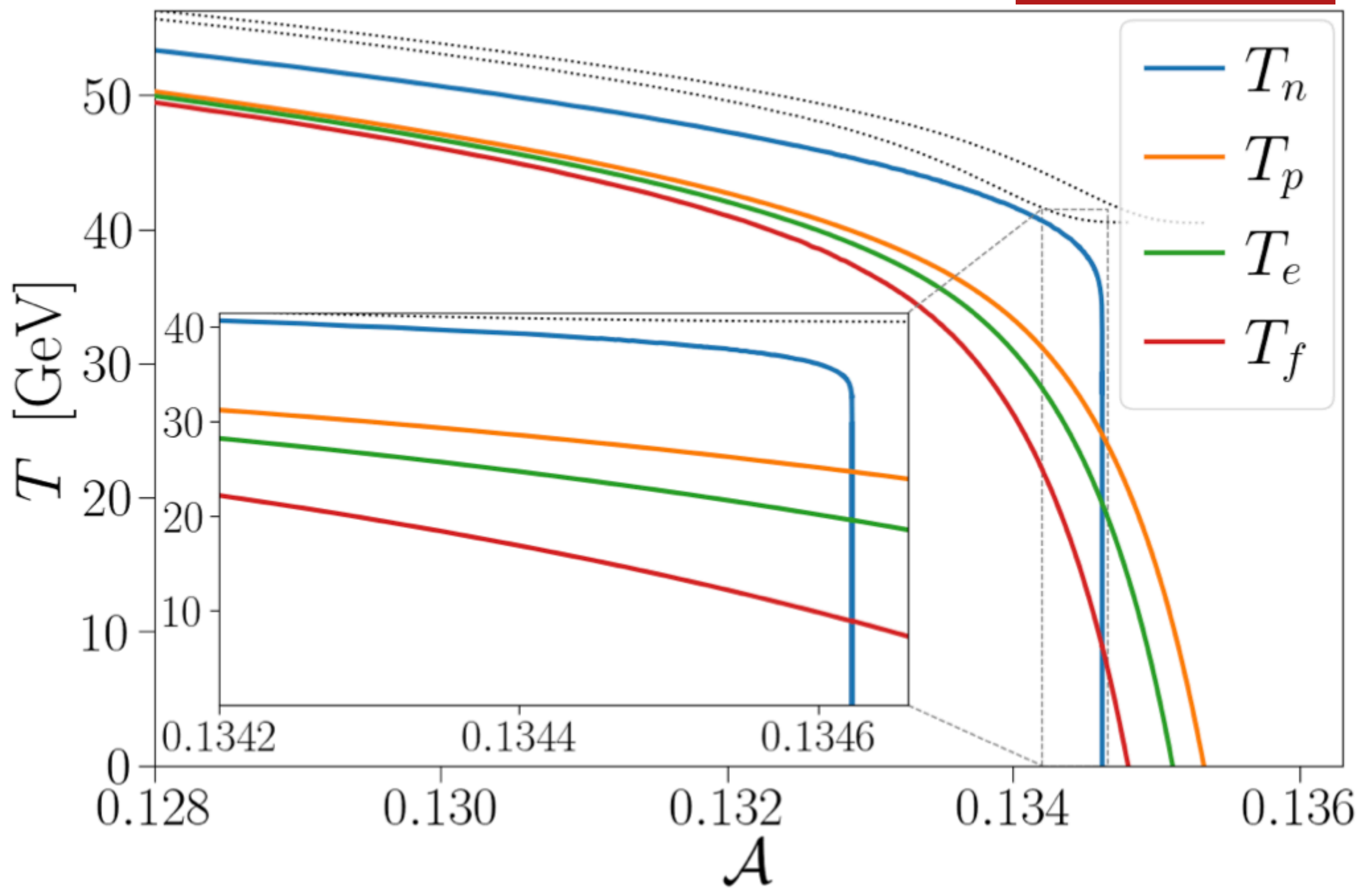


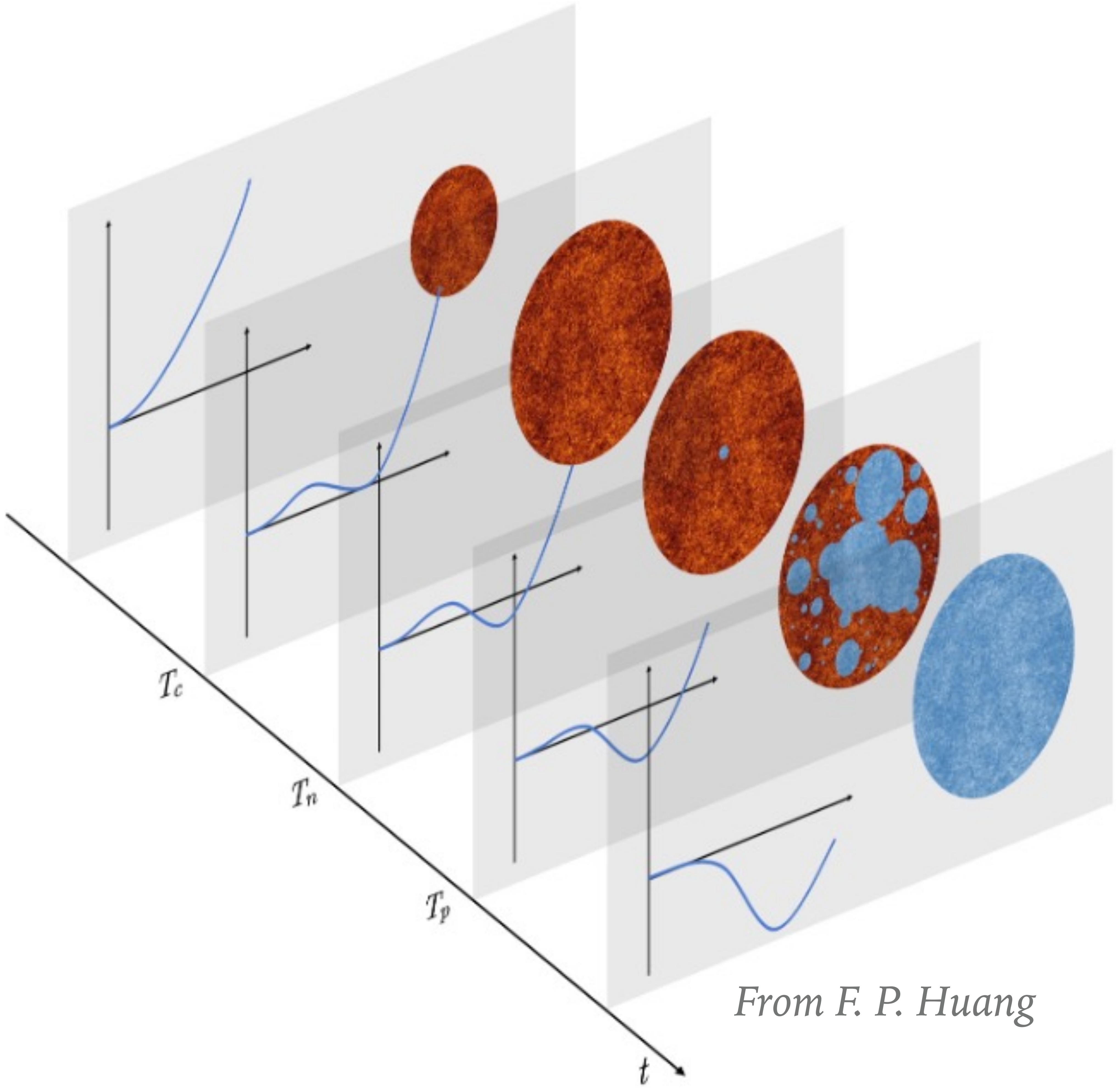


2. Impact on freeze-out DM: percolation temperature T_P

- Criterion of successful phase transition:
    - Existence of nucleation temperature T_N, $N(T) = 1$
    - Existence of percolation temperature, $P(T_{\rm per}) = 70\,\%$

arXiv:2212.07559

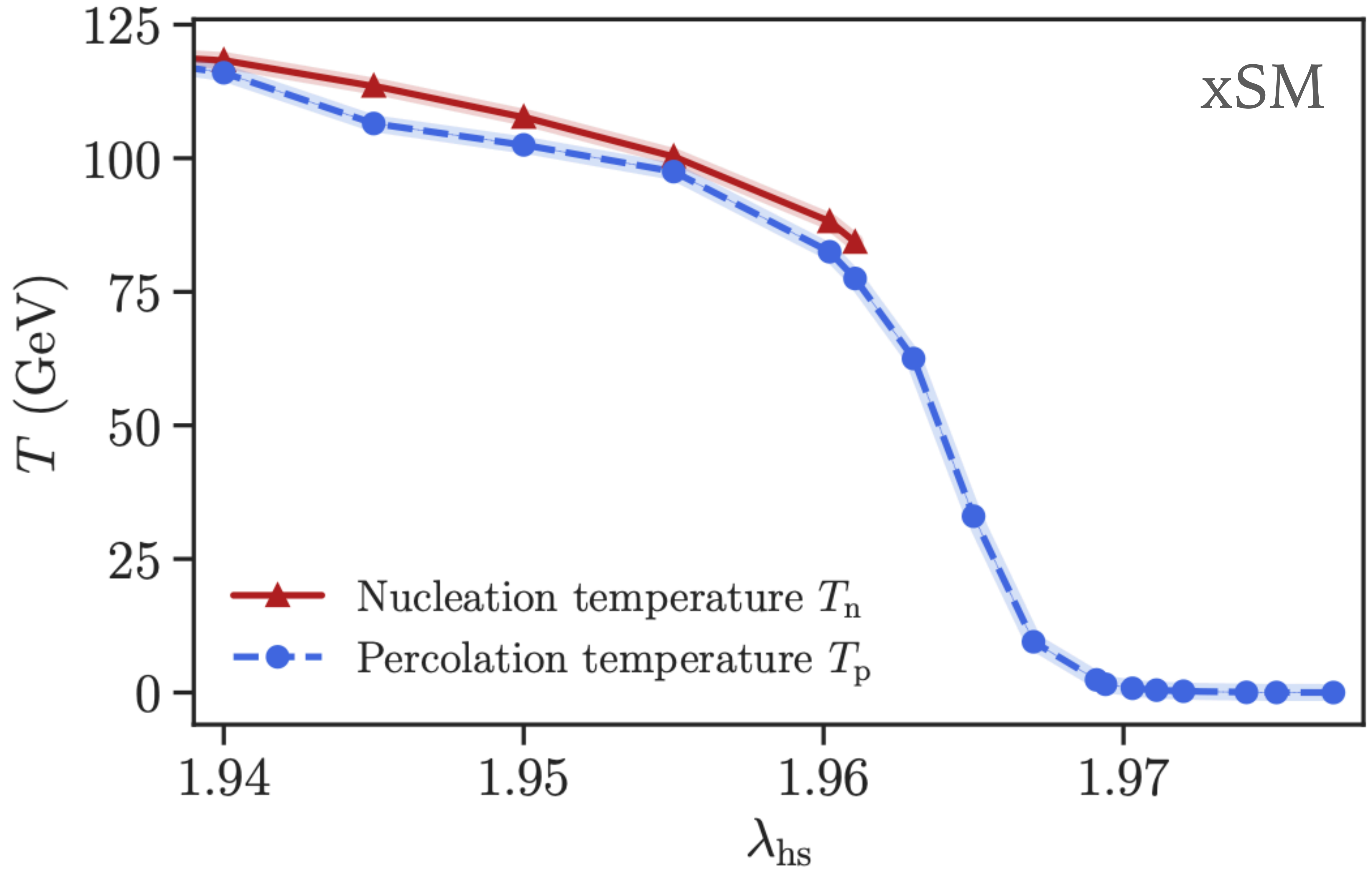


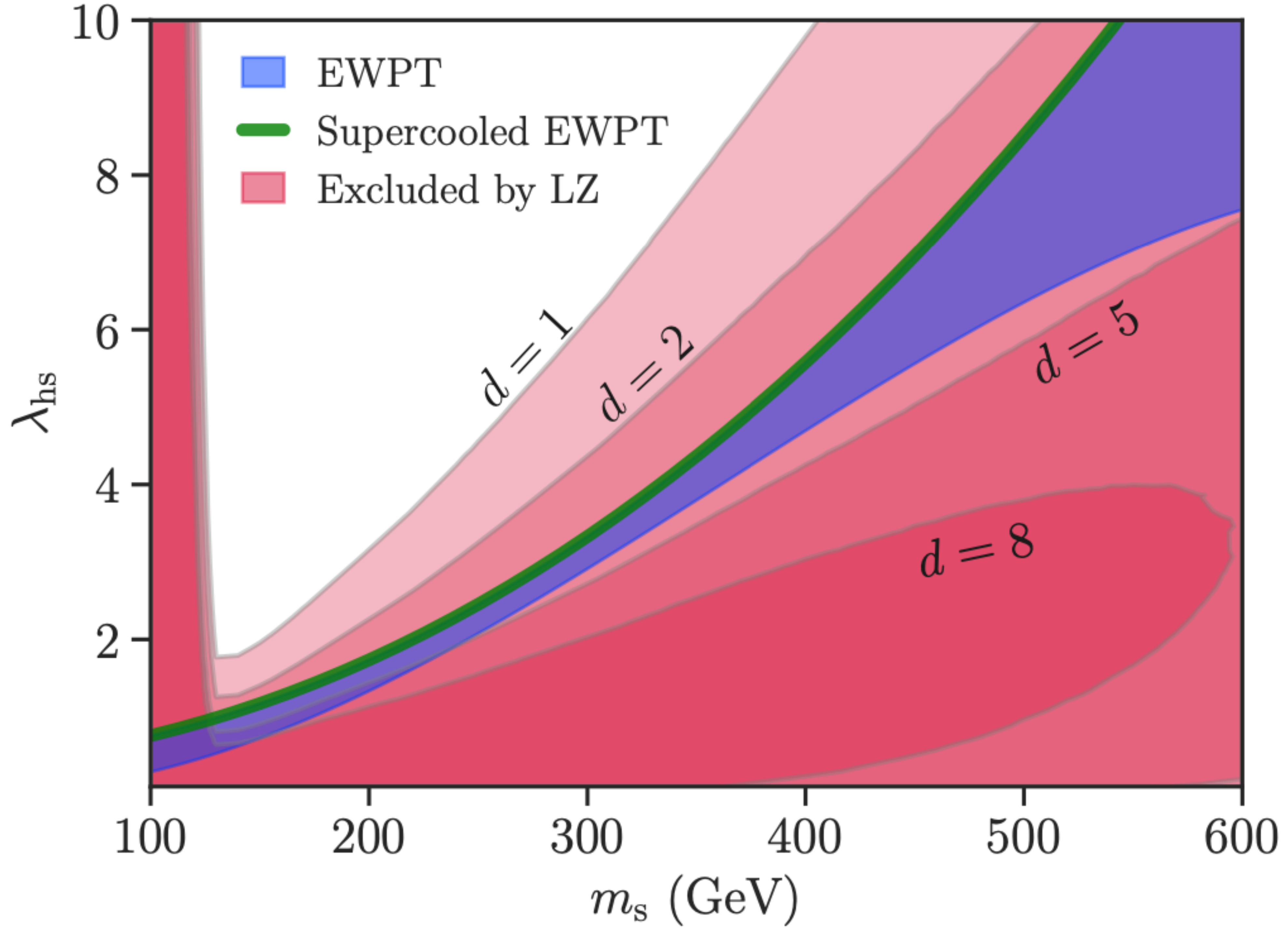


From F. P. Huang

2. Impact on freeze-out DM: percolation temperature T_P

- We find a parameter space with a very low percolation temperature where the phase transition takes place after DM freeze-out. This alters the dark matter relic density and enables it to avoid direct detection constraints.





3. Impact on freeze-in DM

Impact of Cosmological Phase Transitions on Freeze-Out Dark Matter

Very heavy DM, or fine-tuned parameter space

Impact of Cosmological Phase Transitions on Freeze-In Dark Matter

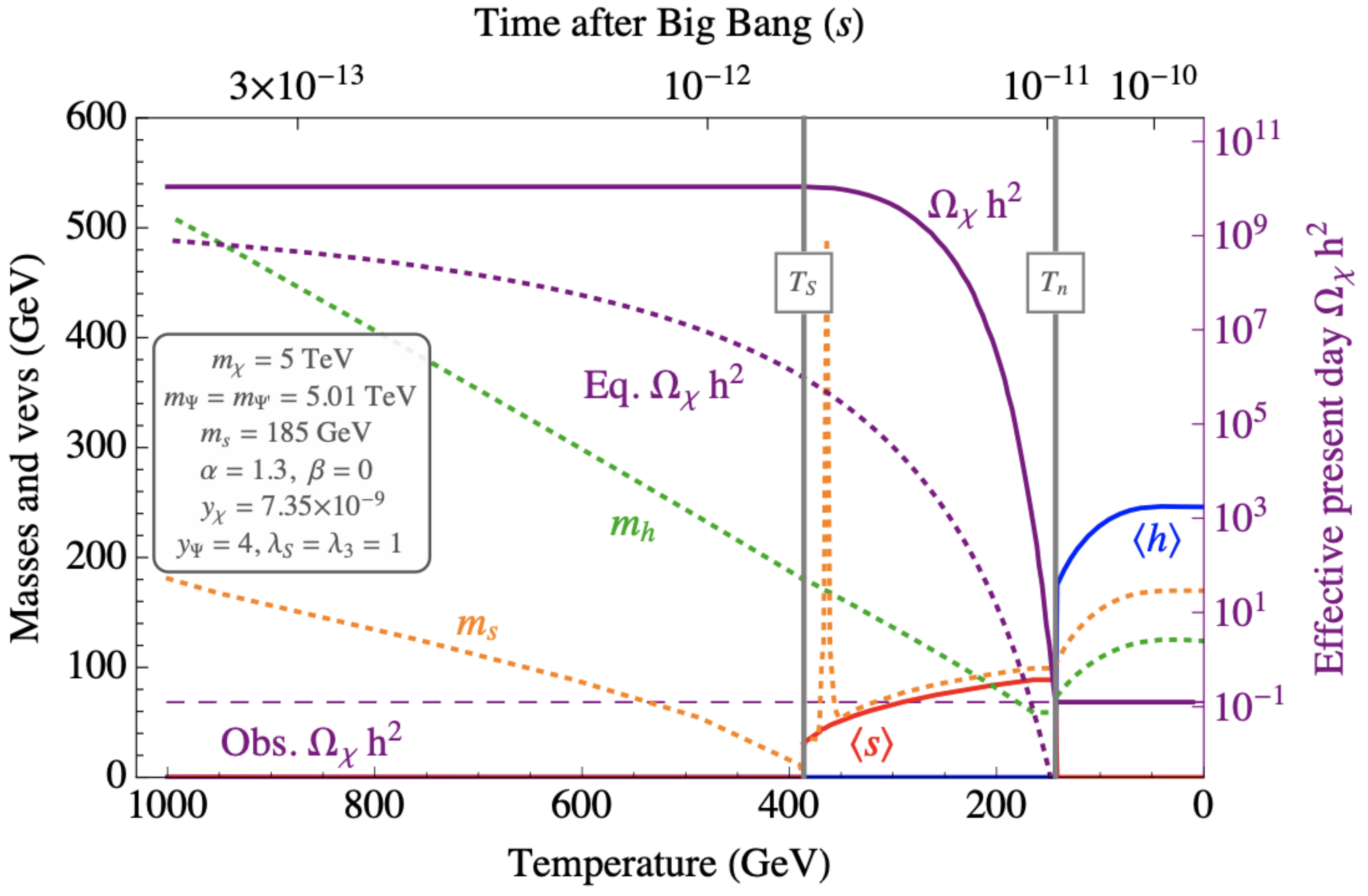
PT and DM can be strongly correlated

3. Impact on freeze-in DM: DM mechanisms associated with PT

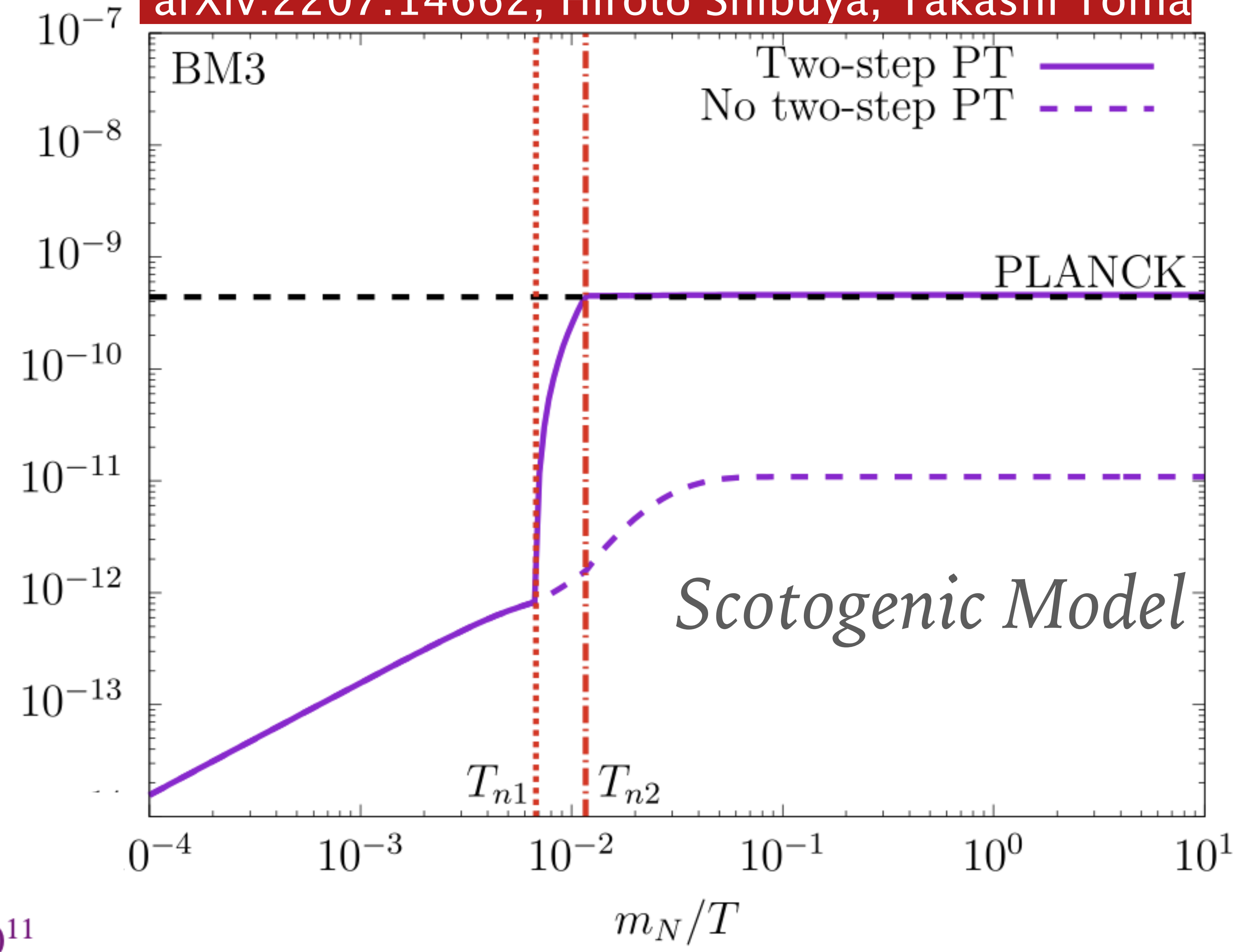
"VEV flip-flop" scenario

arXiv:1608.07578, Michael J. Baker, Joachim Kopp

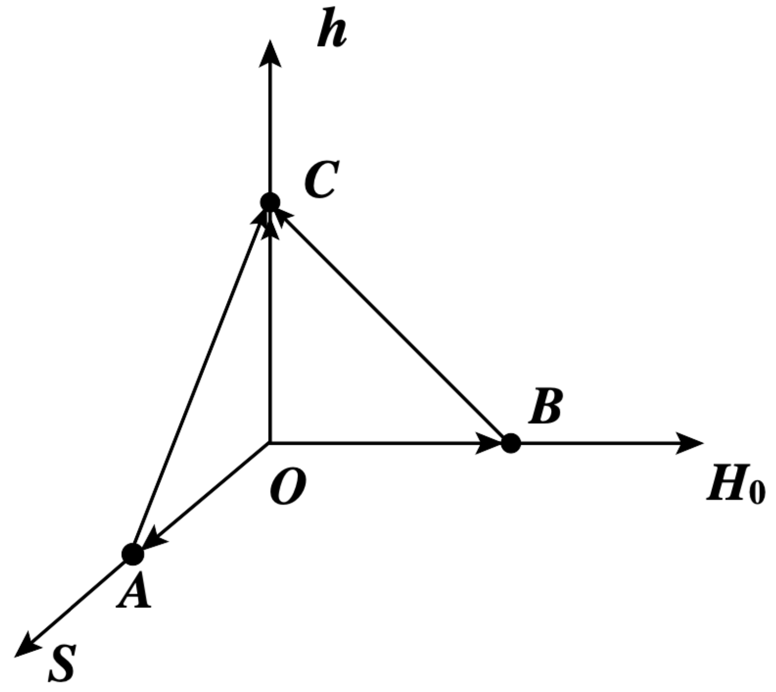
Field	Spin	SM	$\mathbb{Z}_3$	mass scale
χ	$\frac{1}{2}$	$(1,1,0)$	$\chi \to e^{2\pi i/3}\chi$	TeV
S_3	0	$(1,3,0)$	$S_3 \to e^{2\pi i/3}S_3$	100 GeV
Ψ_3	$\frac{1}{2}$	$(1,3,0)$	$\Psi_3 \to e^{-2\pi i/3}\Psi_3$	TeV
Ψ_3'	$\frac{1}{2}$	$(1,3,0)$	$\Psi_3' \to e^{-2\pi i/3}\Psi_3'$	TeV



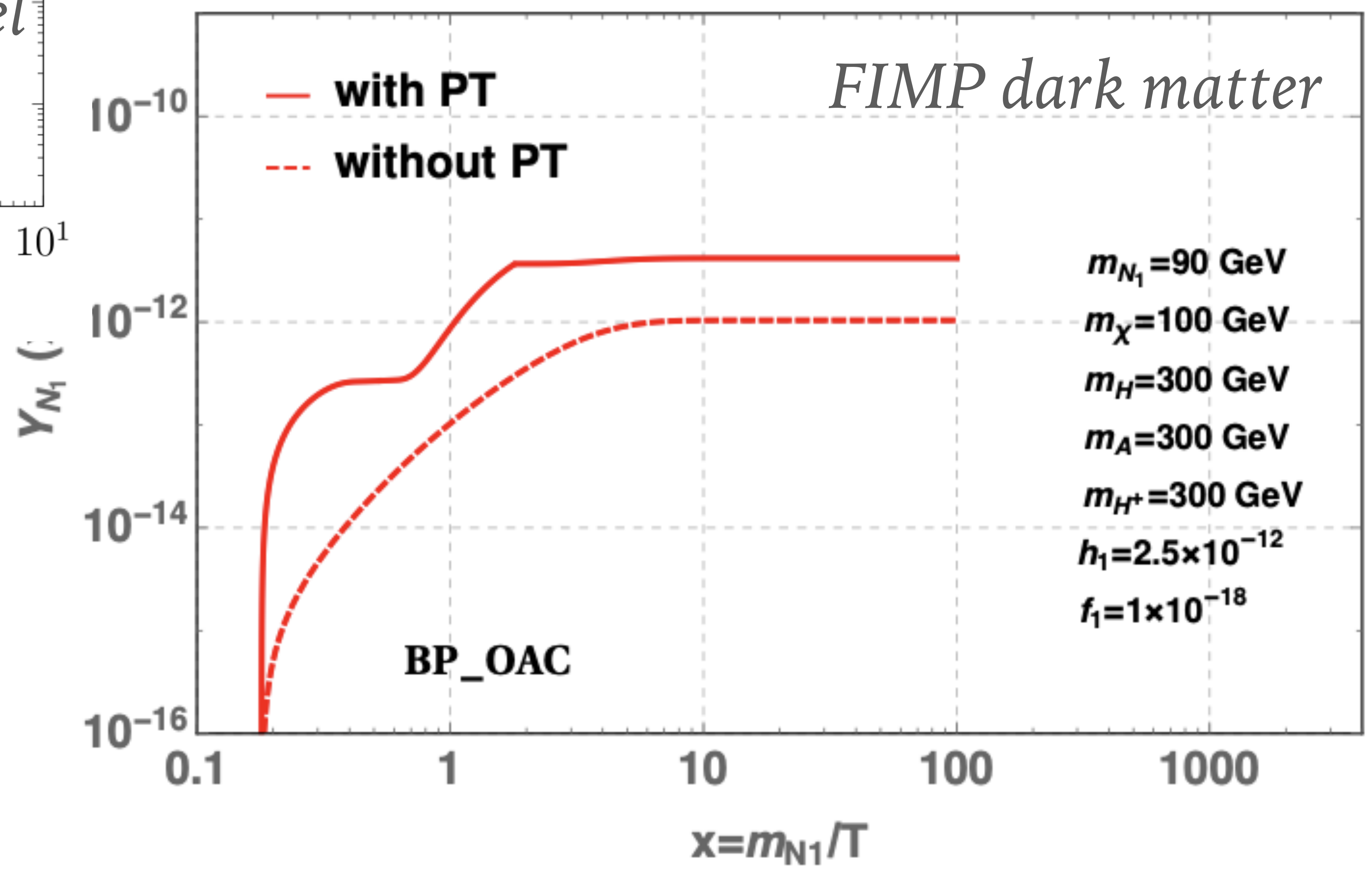
arXiv:2207.14662, Hiroto Shibuya, Takashi Toma



$$\left(\frac{a_f}{a_i}\right)^3 = \frac{s_+}{s_-} \approx 1 + \frac{\Delta s}{s_+} \approx 1.01$$



arXiv:1811.03279, Ligong Bian, Xuewen Liu



3. Impact on freeze-in DM: FIMP DM with a Z_2 symmetry

arXiv:1811.03279, Ligong Bian, Xuewen Liu
arXiv:2312.15752, Shuocheng Xu, Ruiyu Zhou, Wei Cheng, Xuewen Liu

- A Feebly Interacting Massive Particle (FIMP) DM with a Z_2 symmetry:

$$\begin{aligned}-\mathcal{L} \supset\, & \mu_H^2|H|^2+\mu_\Phi^2\Phi^2+\mu_S^2S^2+\lambda_H|H|^4+\lambda_\Phi\Phi^4\\ &+\lambda_S S^4+\lambda_{SH}S^2|H|^2+\lambda_{H\Phi}|H|^2\Phi^2\\ &+\lambda_{S\Phi}S^2\Phi^2+\lambda_1\Phi S^3+\lambda_2\Phi^3 S,\end{aligned}$$

where S and Φ are Z_2-odd scalar singlets.

$$\begin{aligned}V_T(h,\Phi,T) =& \frac{\mu_H^2+c_h(T)}{2}h^2+\frac{\lambda_H}{4}h^4+\frac{\lambda_{H\Phi}}{2}h^2\Phi^2\\ &+\frac{2\mu_\Phi^2+c_\Phi(T)}{2}\Phi^2+\lambda_\Phi\Phi^4\end{aligned}$$

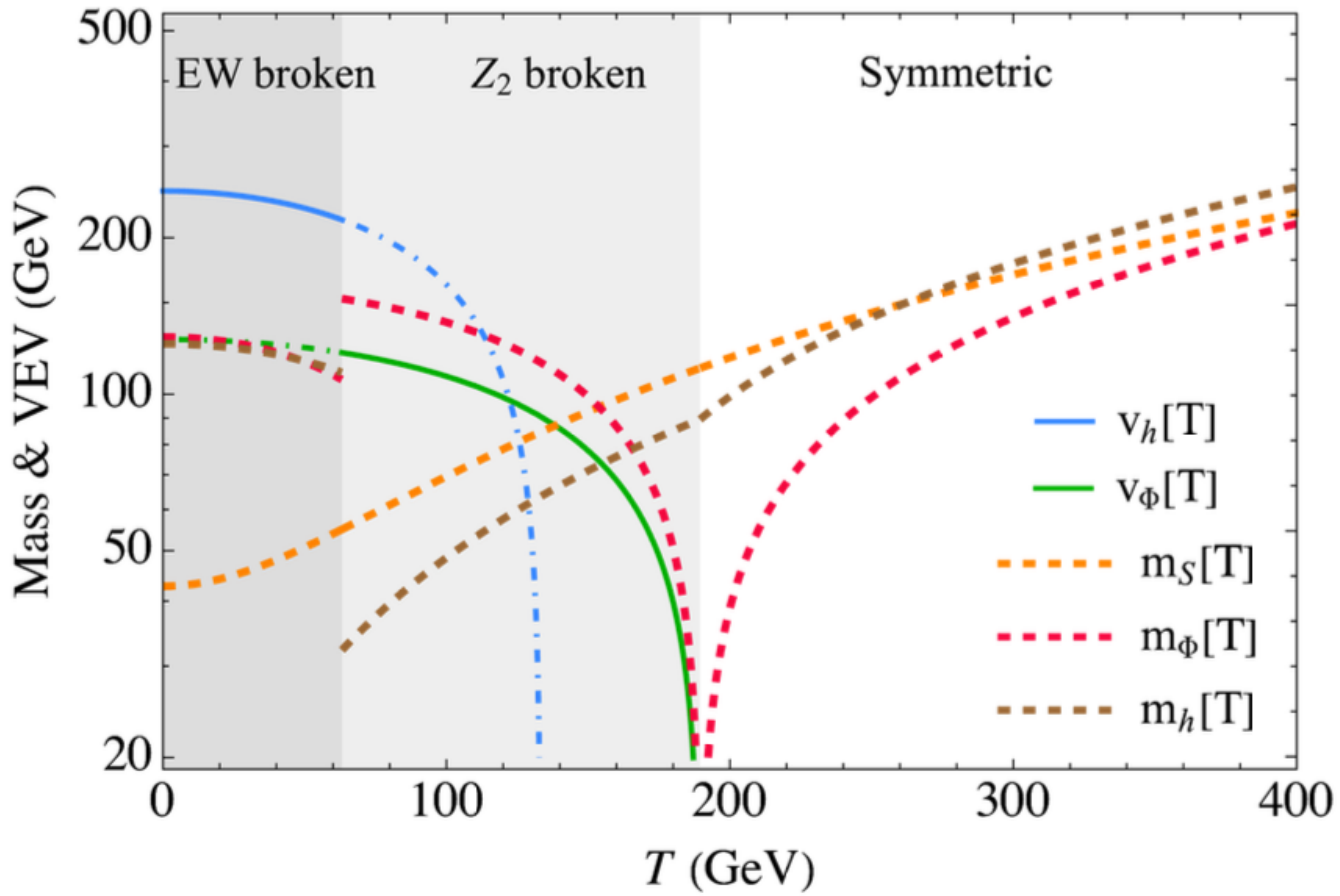
- S is considered as a FIMP DM.

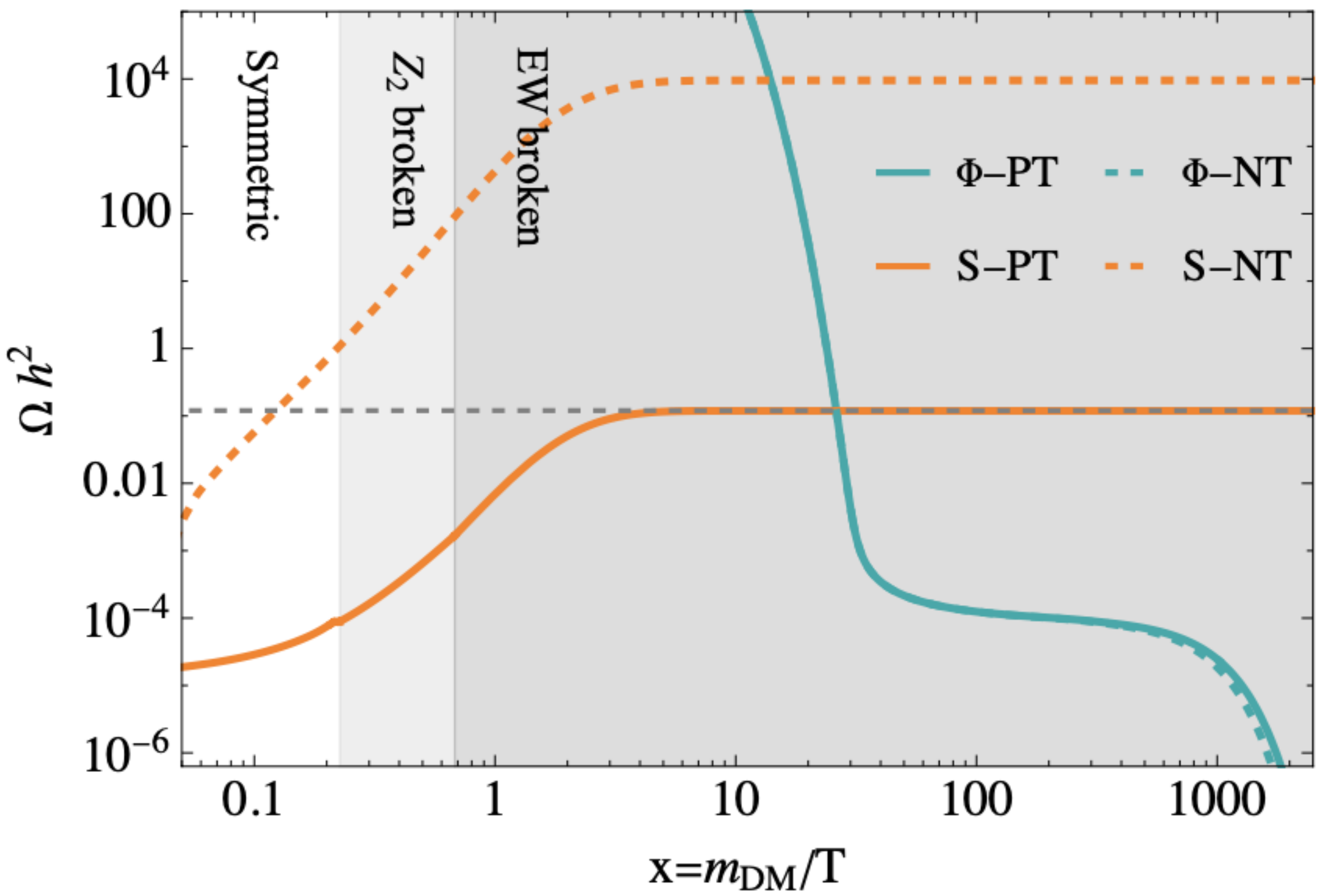
- Φ serves as the portal connecting the dark sector and the SM sector, i.e. the parent particle responsible for the production

- S does not acquire a VEV in the history.

3. Impact on freeze-in DM: FIMP DM with a Z_2 symmetry

arXiv:2312.15752, Shuocheng Xu, Ruiyu Zhou, Wei Cheng, Xuewen Liu





$$m_S^2 = 2\mu_S^2 + 2\lambda_{S\Phi} v_\Phi(T)^2 + \frac{1}{6}T^2(6\lambda_S + \lambda_{S\Phi}),$$

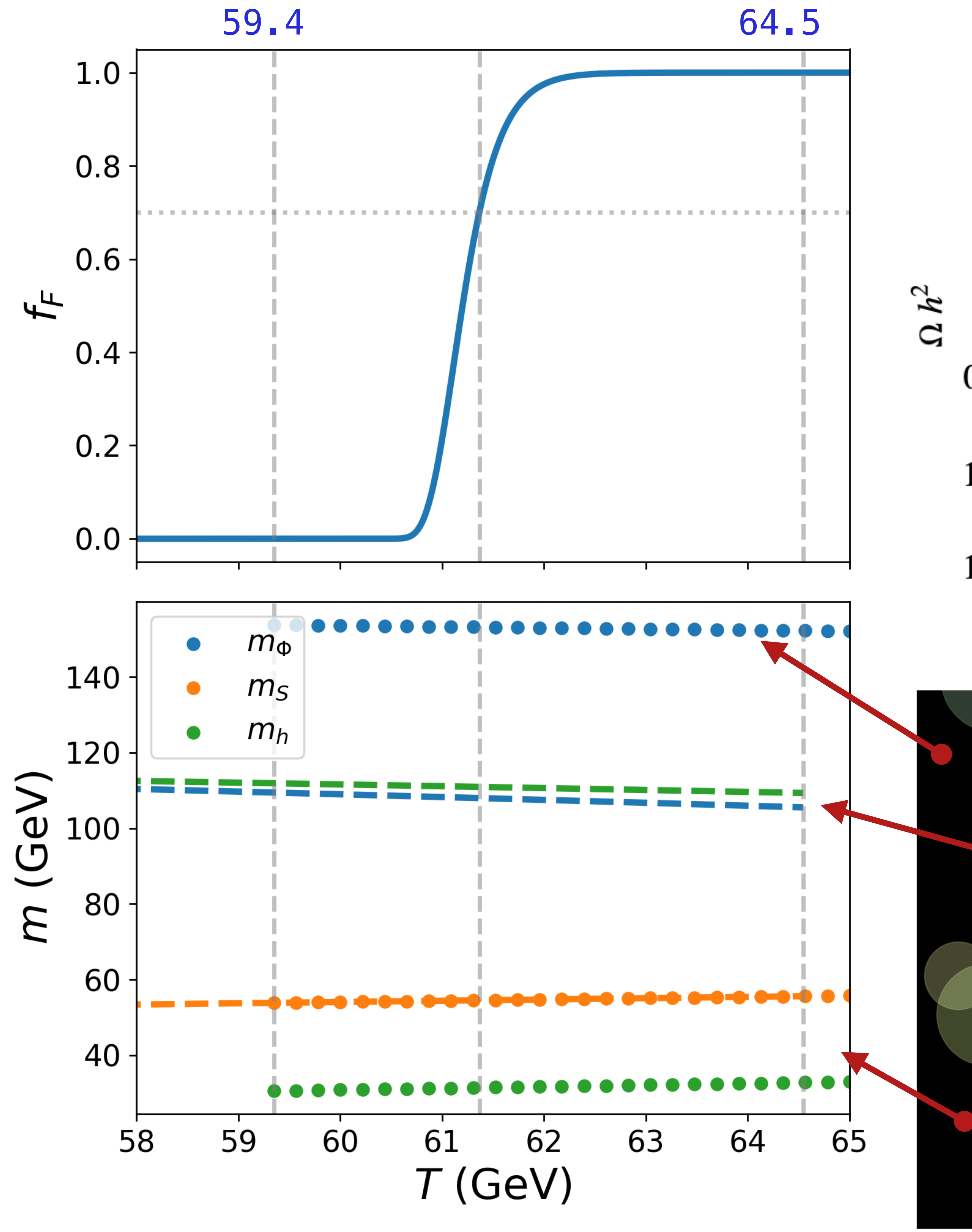
$$m_\Phi^2 = 2\mu_\Phi^2 + \lambda_{H\Phi} v_h(T)^2 + 12\lambda_\Phi v_\Phi(T)^2 + c_\Phi(T),$$

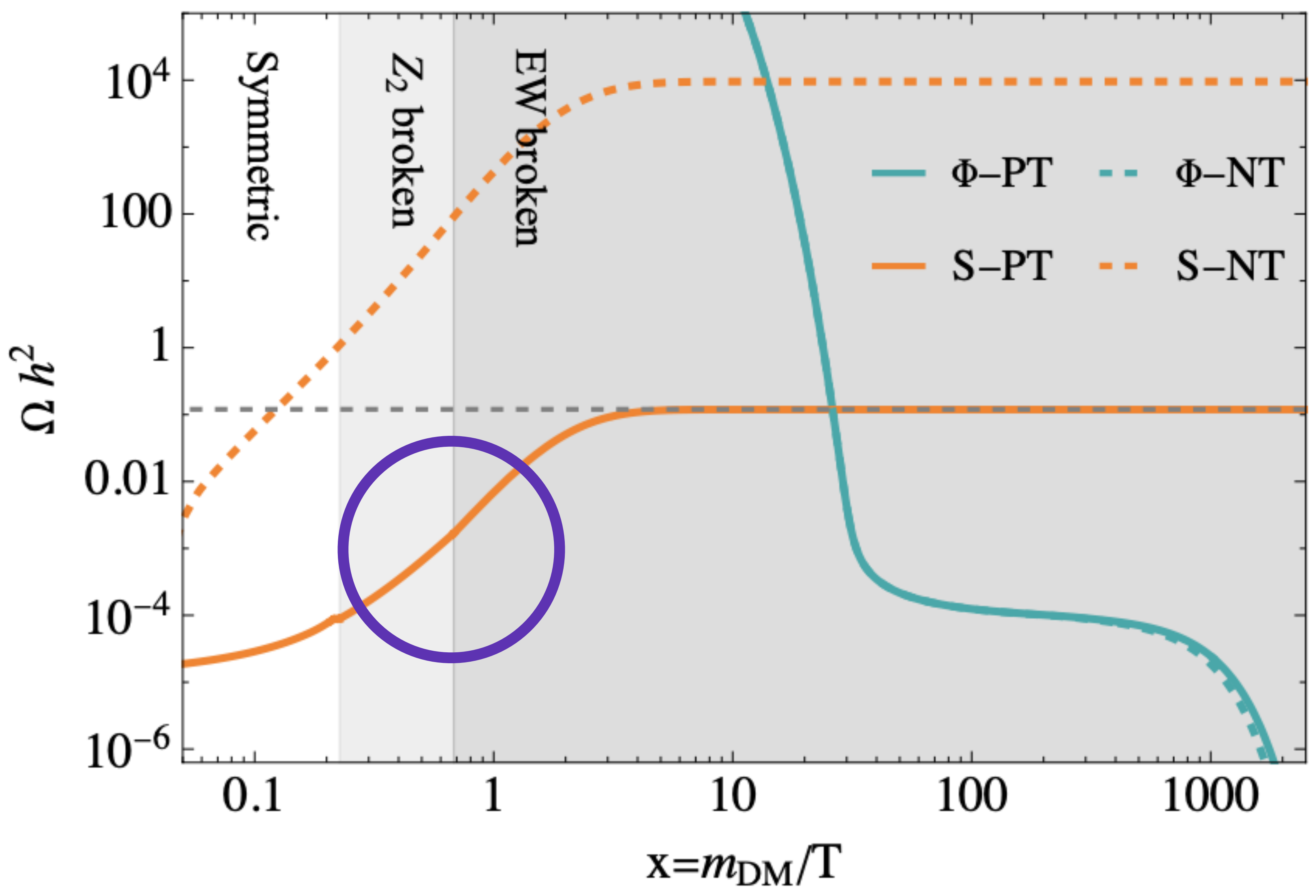
$$m_h^2 = \mu_H^2 + 3\lambda_H v_h(T)^2 + \lambda_{H\Phi} v_\Phi(T)^2 + c_h(T).$$

$$\begin{aligned}\frac{dY_\Phi}{dx} = &-\frac{2\pi^2}{45}\frac{m_{\rm Pl} m_{\rm DM}\sqrt{g_*(x)}}{1.66x^2}\langle\sigma v\rangle_{\Phi\Phi\to hh}\left(Y_\Phi^2 - Y_\Phi^{\rm eq2}\right)\\ &-\frac{3m_{\rm Pl}x\sqrt{g_*(x)}}{1.66m_{\rm DM}^2 g_s(x)}\langle\Gamma_{\Phi\to 3S}\rangle\left(Y_\Phi - Y_S^3\right)\\ &-\frac{2m_{\rm Pl}}{1.66m_{\rm DM}^2}\frac{x\sqrt{g_*(x)}}{g_s(x)}\langle\Gamma_{\Phi\to SS}\rangle\left(Y_\Phi^{\rm eq} - Y_S^2\right)\end{aligned}$$

$$\begin{aligned}\frac{dY_S}{dx} = &-\frac{2\pi^2}{45}\frac{m_{\rm Pl} m_{\rm DM}}{1.66x^2}\sqrt{g_*}\langle\sigma v\rangle_{\rm semi}\left(Y_S^2 - Y_\Phi^{\rm eq} Y_S\right)\\ &+\frac{4\pi^2}{45}\frac{m_{\rm Pl} m_{\rm DM}\sqrt{g_*}}{1.66x^2}\langle\sigma v\rangle_{\Phi\Phi}\left(Y_\Phi^{\rm eq2} - Y_S^2\right)\\ &+\frac{3m_{\rm Pl}x\sqrt{g_*(x)}}{1.66m_{\rm DM}^2 g_s(x)}\langle\Gamma_{\Phi\to 3S}\rangle\left(Y_\Phi - Y_S^3\right)\\ &+\frac{2m_{\rm Pl}}{1.66m_{\rm DM}^2}\frac{x\sqrt{g_*(x)}}{g_s(x)}\langle\Gamma_{\Phi\to 2S}\rangle\left(Y_\Phi^{\rm eq} - Y_S^2\right)\end{aligned}$$

3. Impact on freeze-in DM: Phases coexistence

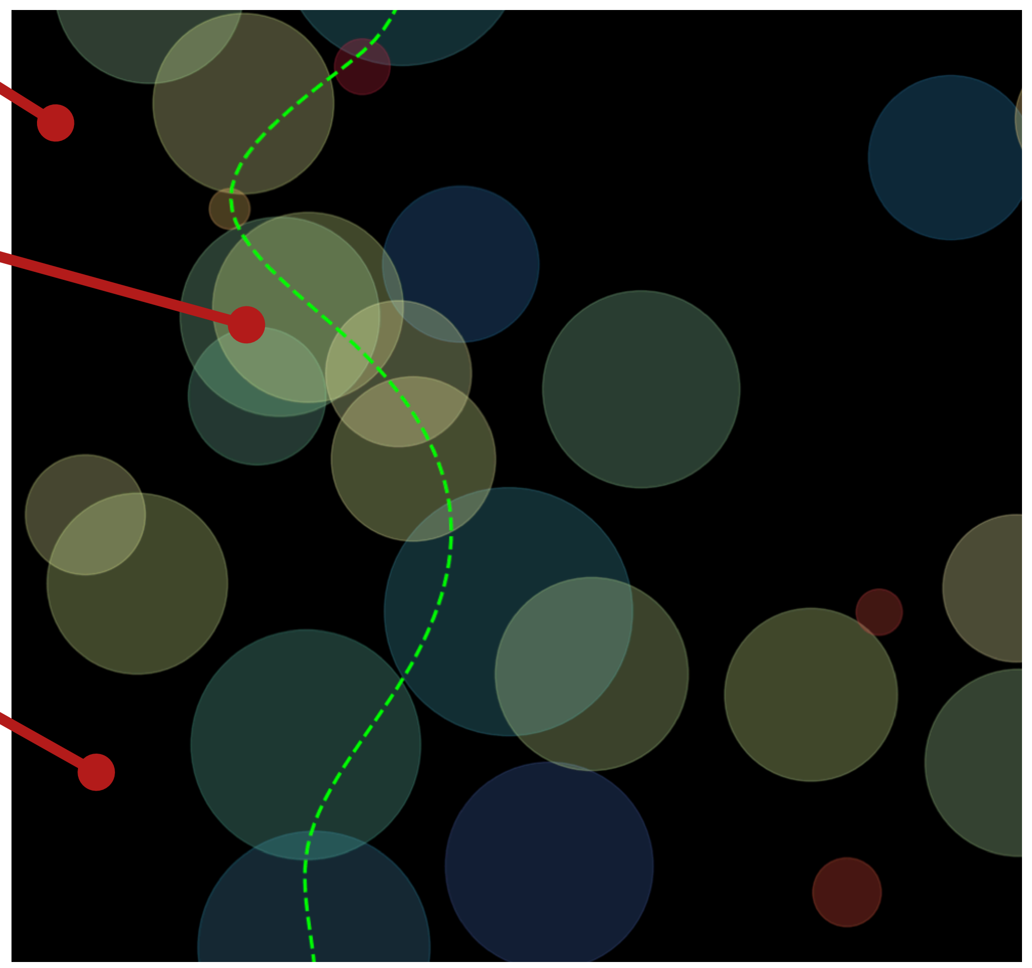


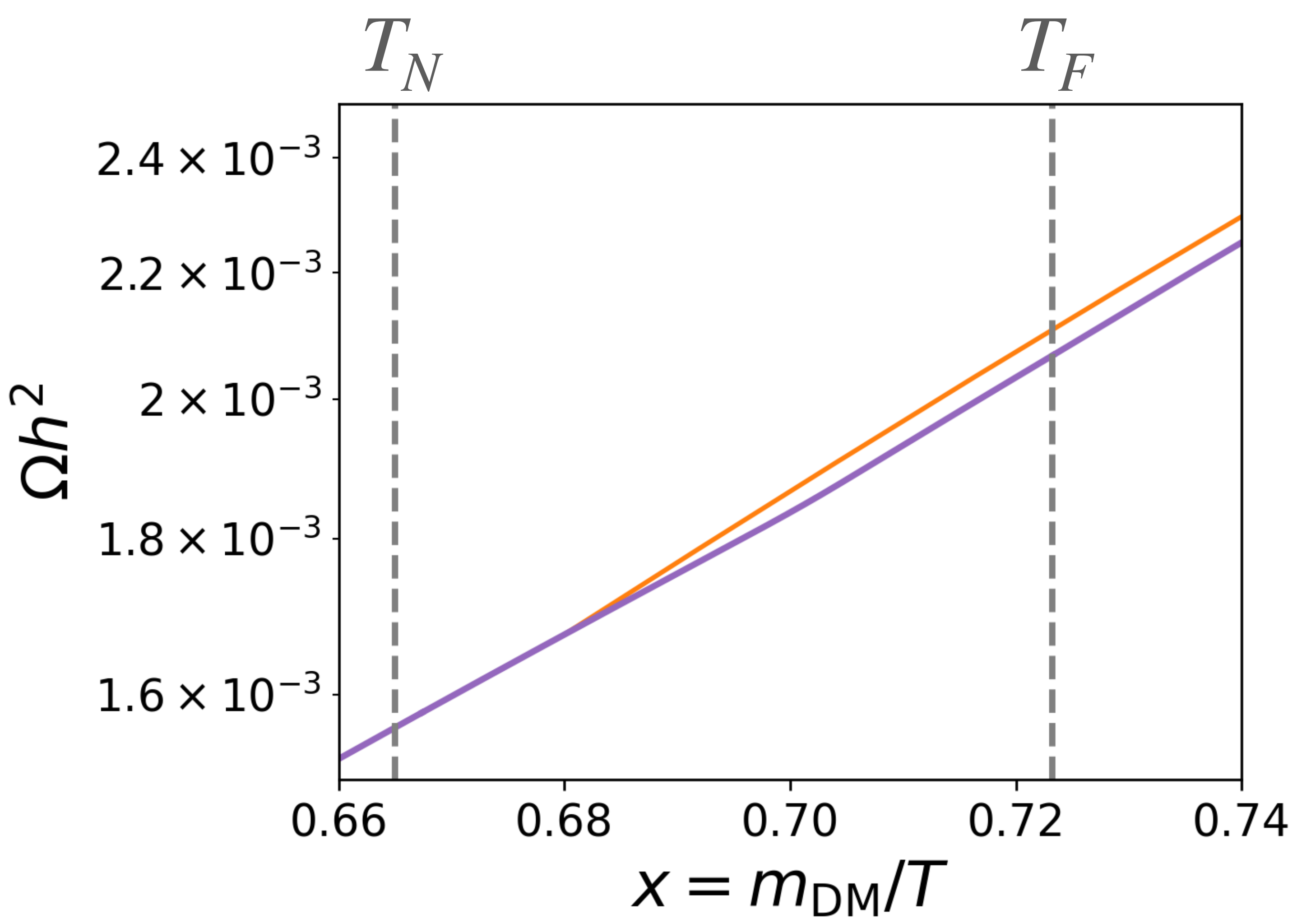


Phases Coexistence

$$\Omega_{\rm DM}h^2 = 0.1193 \rightarrow 0.1170$$

$$\delta = -2\,\%$$

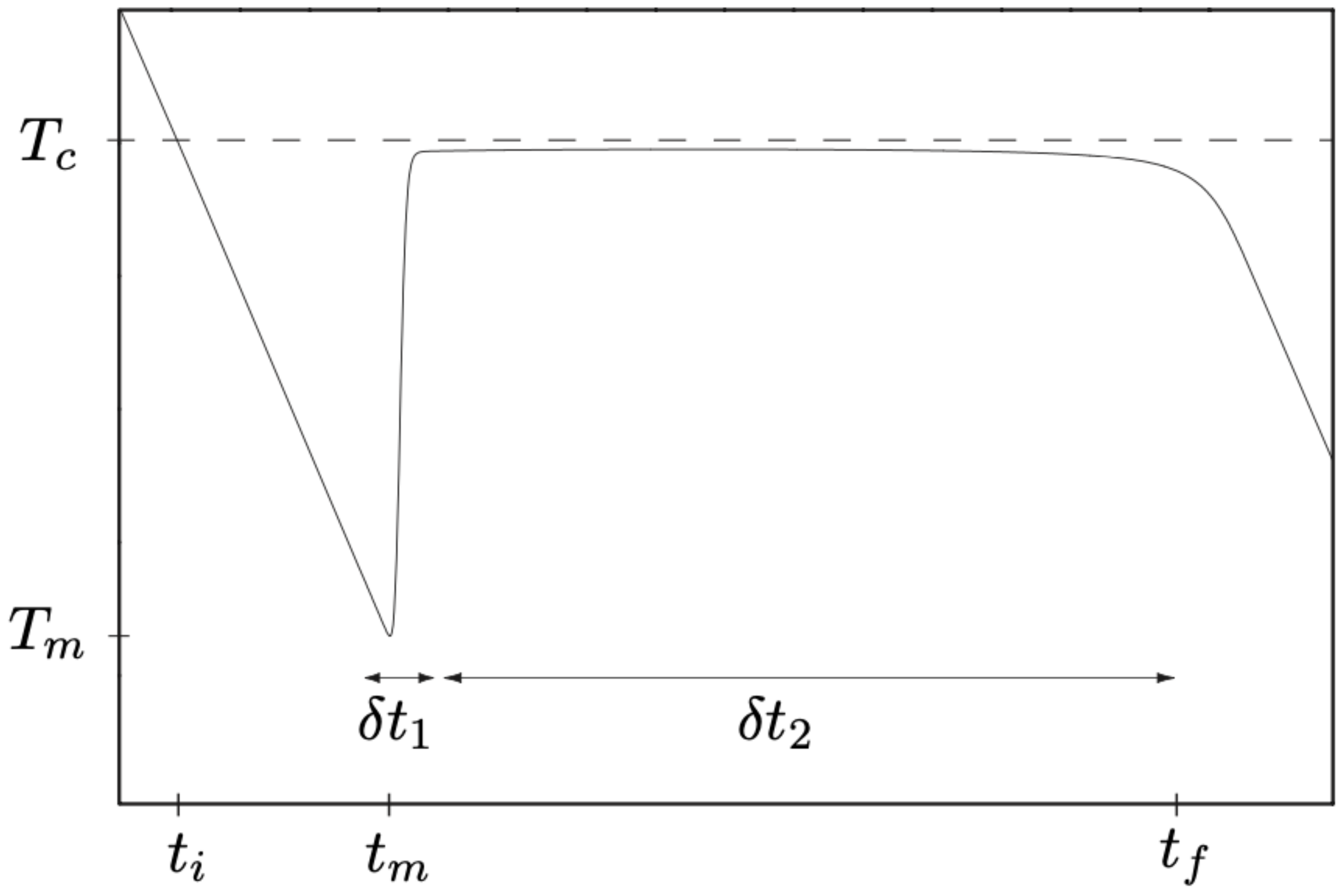




3. Impact on freeze-in DM: Reheating

- After successful percolation, the latent heat is liberated and reheats the system.
  ① The Universe first supercools below the critical temperature.
  ② Bubbles of the new phase nucleate and expand.
  ③ Latent heat is released into the plasma.
  ④ The plasma reheats toward the critical temperature.
  ⑤ Cosmic expansion takes over again and the temperature continues to decrease.

arXiv:0312305
arXiv:0712.1031



3. Impact on freeze-in DM: Reheating

- If there is little supercooling, $T_C \simeq T_N$, consider that the phase transition develops entirely at T_C,

$$s(T,f) \equiv s_+(T) - \Delta s(T) f = s_+(T) + \Delta F'(T) f \,.$$

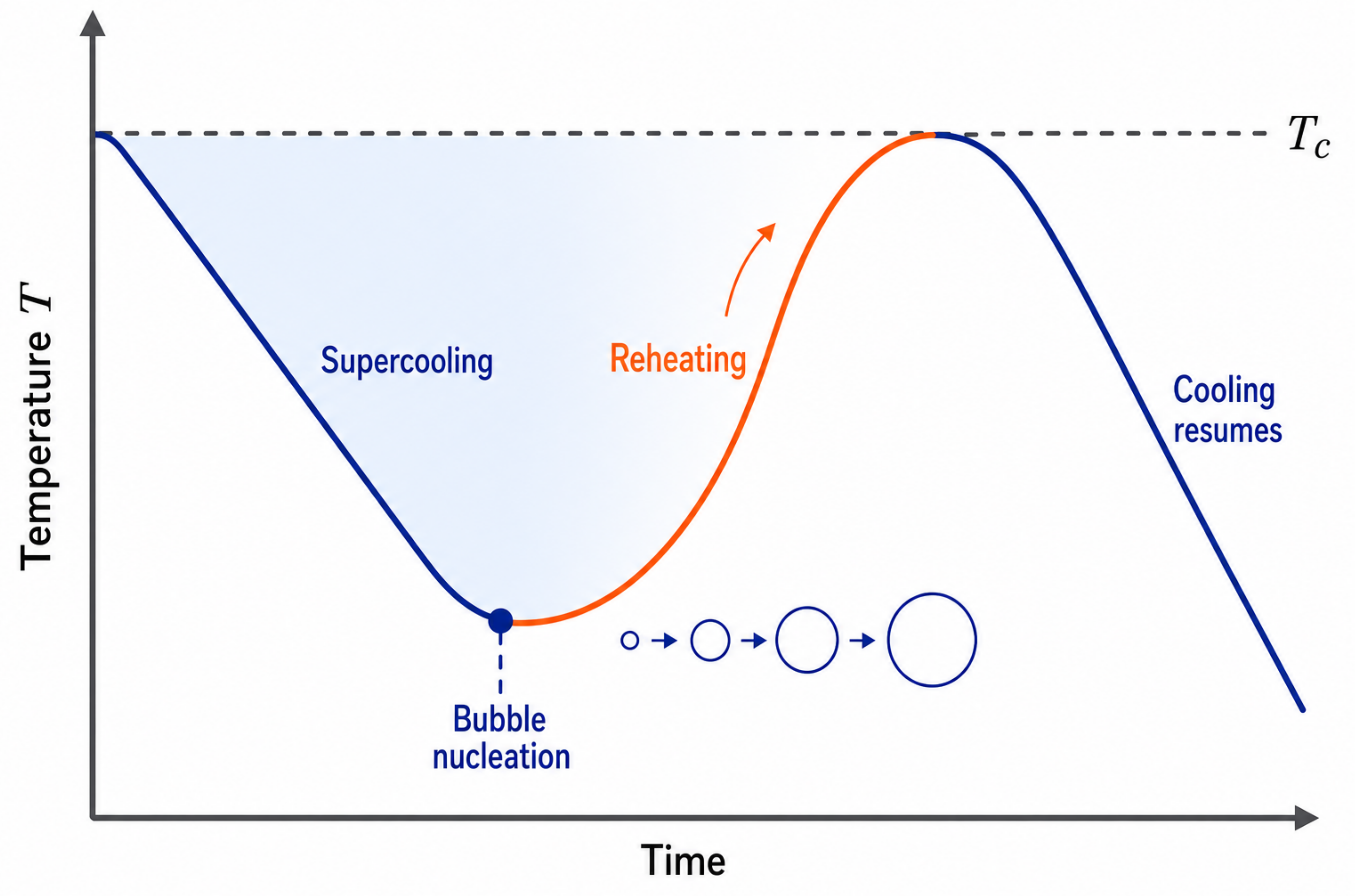
- The total comoving entropy is approximately conserved here,

$$s(T,f)a^3 = s_+(T_c)a_i^3, \quad s_+(T) = \frac{2\pi^2}{45} g_* T^3 \,.$$

- It gives the relation

$$T^3 = \frac{-\Delta F'(T)}{2\pi^2 g_*/45} f + \frac{T_c^3 a_i^3}{a^3} \,.$$

- We can solve it iteratively from T_C.



Integrated in the upcoming PhaseTracer release.

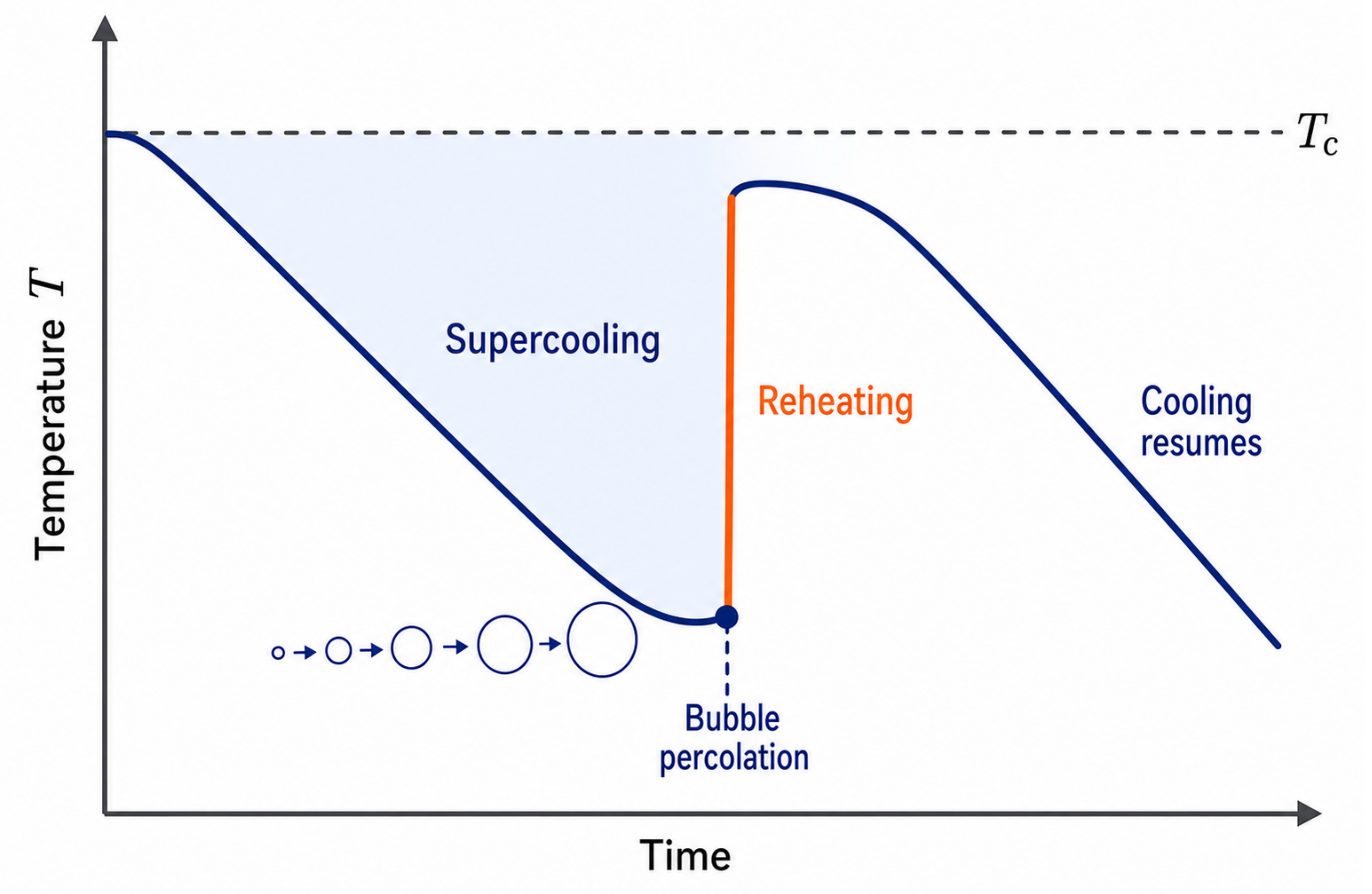
3. Impact on freeze-in DM: Phase transition in FIMP DM with a Z_2 symmetry

- For strongly supercooled phase transitions, reheating is assumed to occur rapidly during percolation.
- The released latent energy is converted into radiation:

$$\rho_R(T_{\rm reh}) = \rho_R(T_p) + \Delta\rho(T_p) = \left[1 + \alpha(T_p)\right] \rho_R(T_p)$$

- Using $\rho_R(T) = \dfrac{\pi^2}{30} g_*(T) T^4$, we get

$$T_{\rm reh} = \left[\frac{g_*(T_p)}{g_*(T_{\rm reh})}\left(1 + \alpha(T_p)\right)\right]^{1/4} T_p$$



Integrated in the upcoming PhaseTracer release.

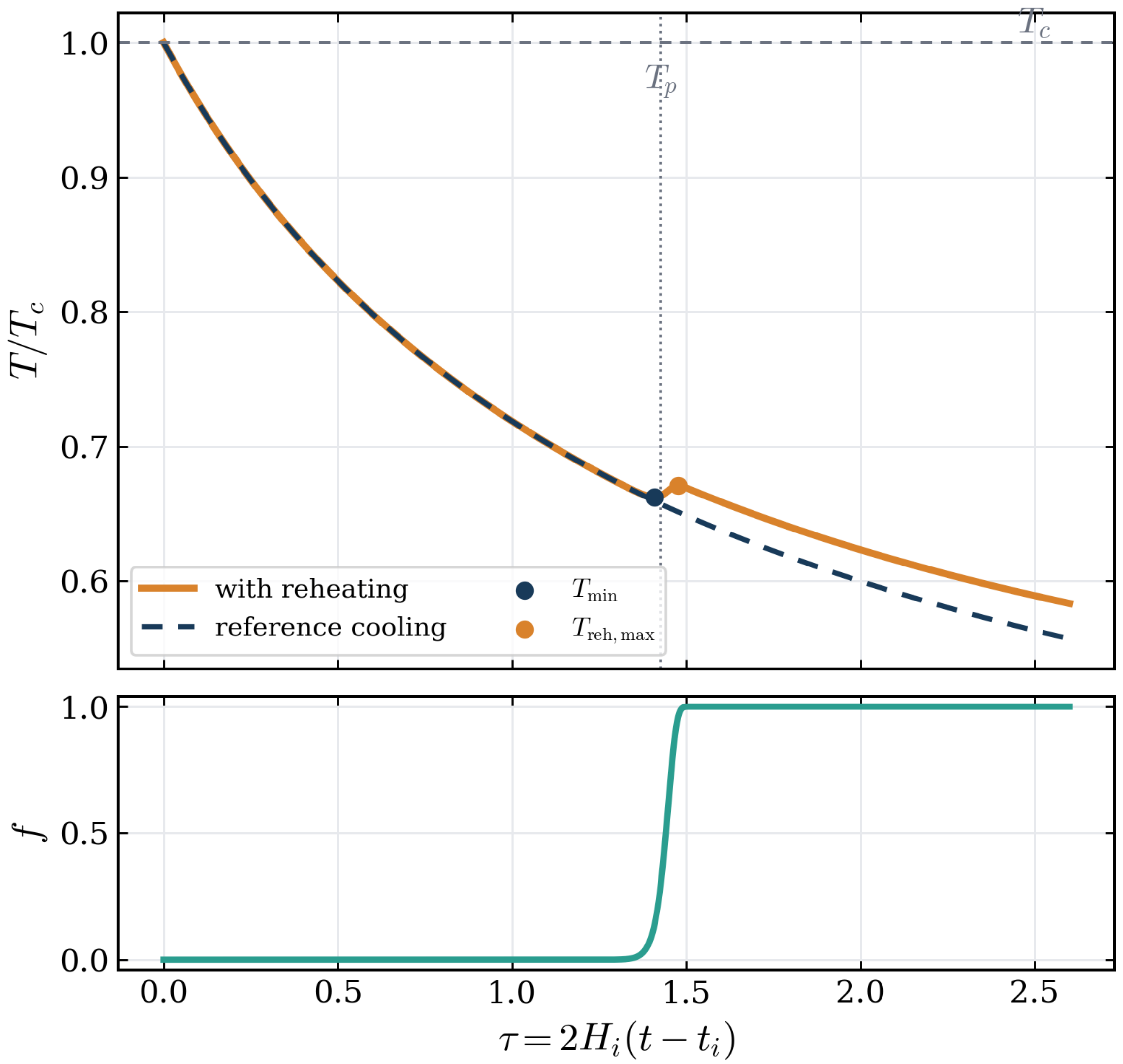
3. Impact on freeze-in DM: Phase transition in FIMP DM with a Z_2 symmetry

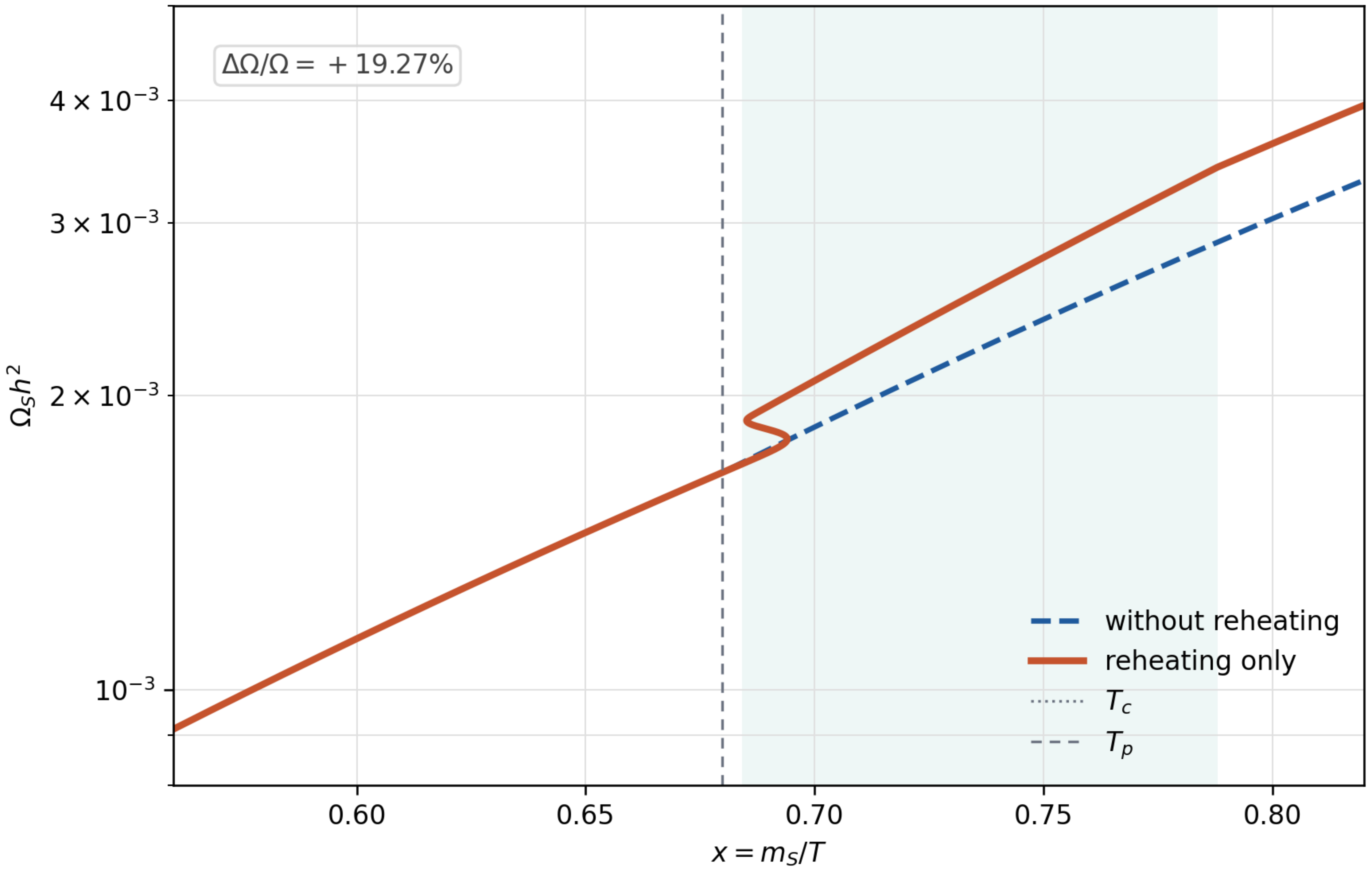
- For this benchmark point, reheating raised the temperature by 0.8 GeV.

Reheating

$$\Omega_{\rm DM}h^2 = 0.1170 \to 0.1398$$

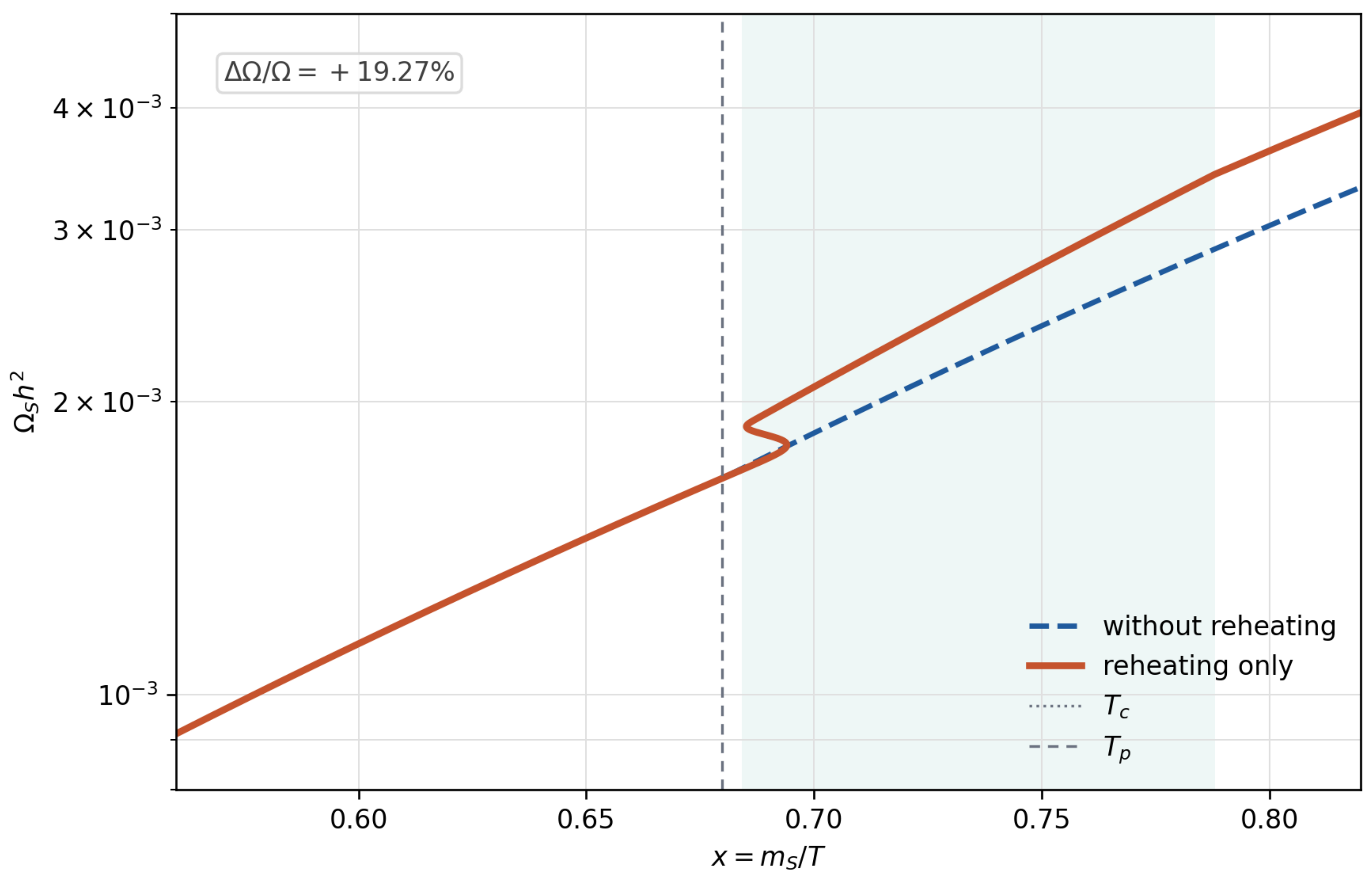
$$\delta = +19\,\%$$

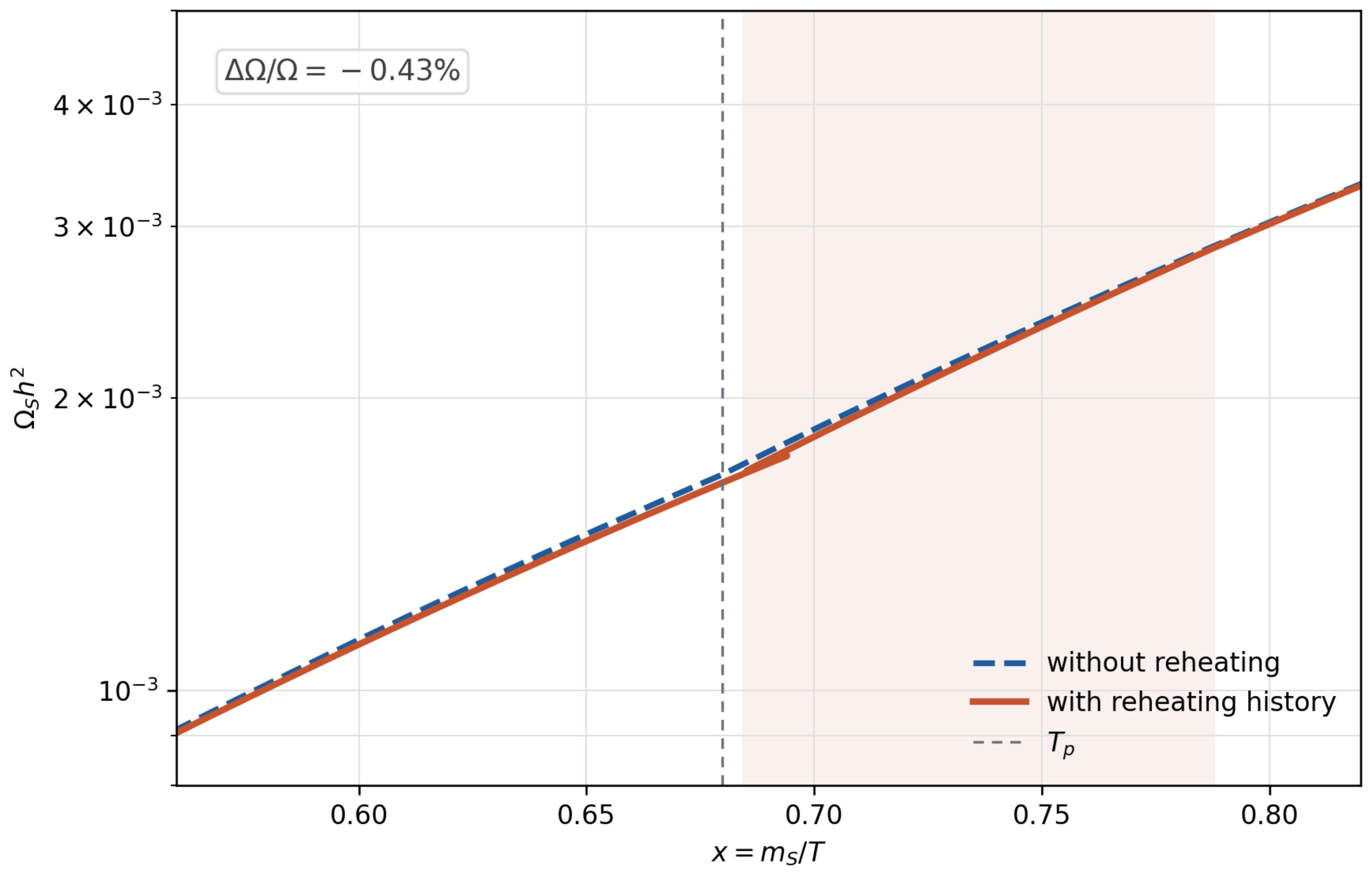




3. Impact on freeze-in DM: Phase transition in FIMP DM with a Z_2 symmetry

- The total dilution factor $d = \left(\dfrac{a_f}{a_i}\right)^3 = \dfrac{s_F(T_*)}{s_F(T_C)} \times \dfrac{s_F(T_R) - f\,\Delta s(T_R)}{s_T(T_F)}$



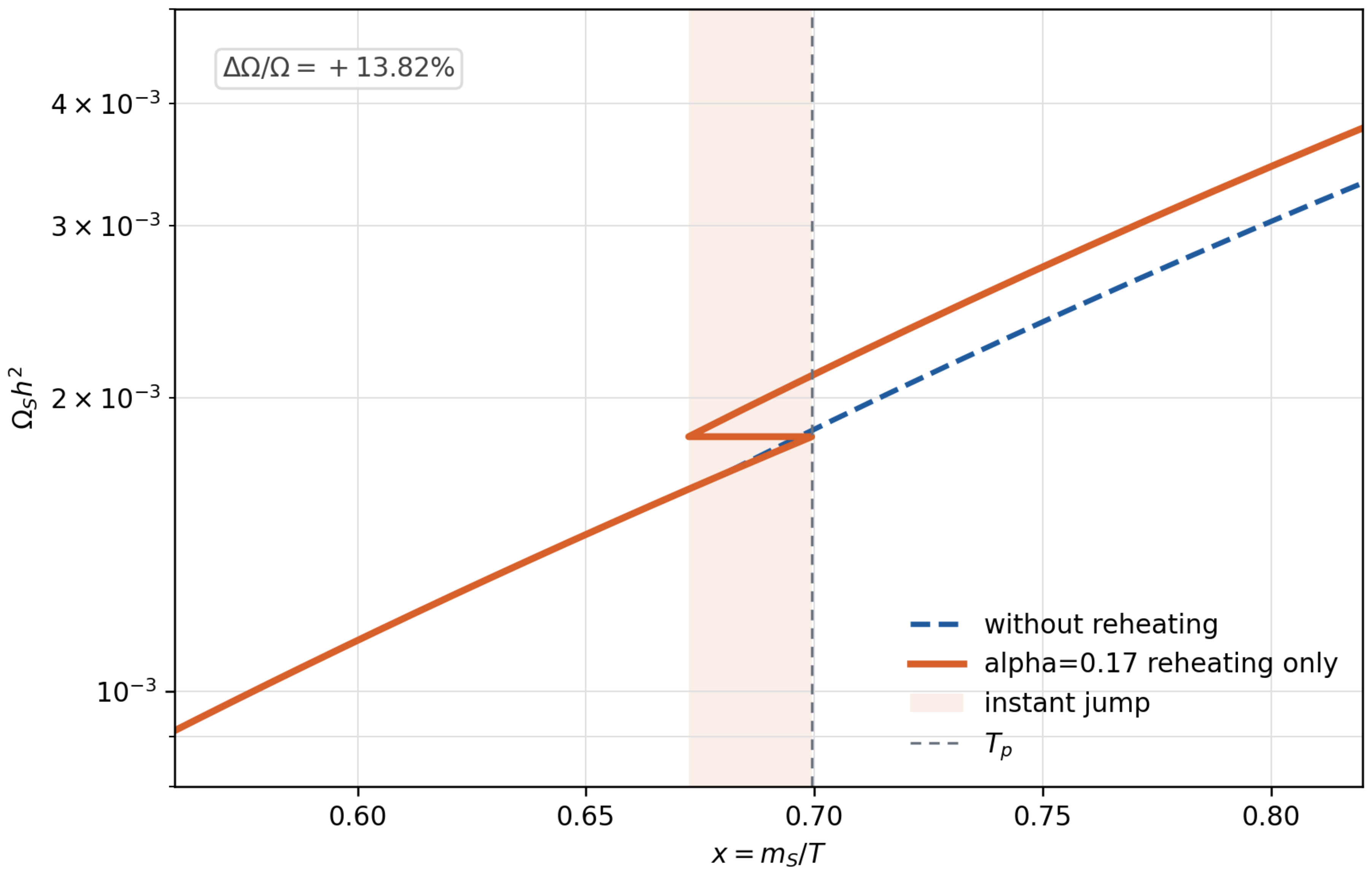


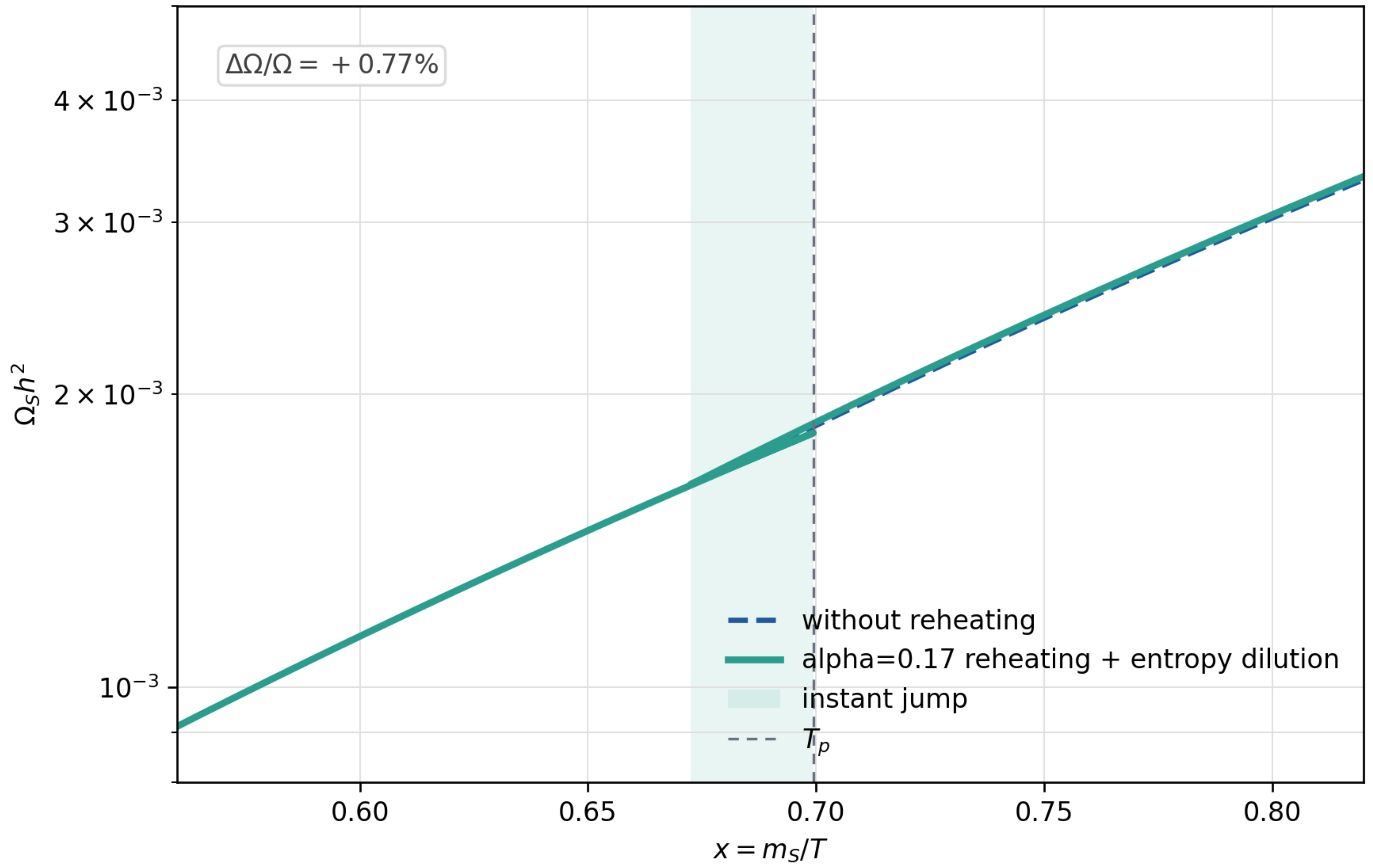
$$\Omega_{\rm DM}h^2 = 0.1193 \xrightarrow[\delta=-2\,\%]{\textit{Phases Coexistence}} 0.1170 \xrightarrow[\delta=+19\,\%]{\textit{Reheating}} 0.1398 \xrightarrow[\delta=-17\,\%]{\textit{Dilution}} 0.1167$$

$\delta = -0.4\,\%$

3. Impact on freeze-in DM: Phase transition in FIMP DM with a Z_2 symmetry

- Using $T_{\rm reh} = \left[\dfrac{g_*(T_p)}{g_*(T_{\rm reh})}\left(1+\alpha(T_p)\right)\right]^{1/4} T_p$ for strongly supercooled phase transition:





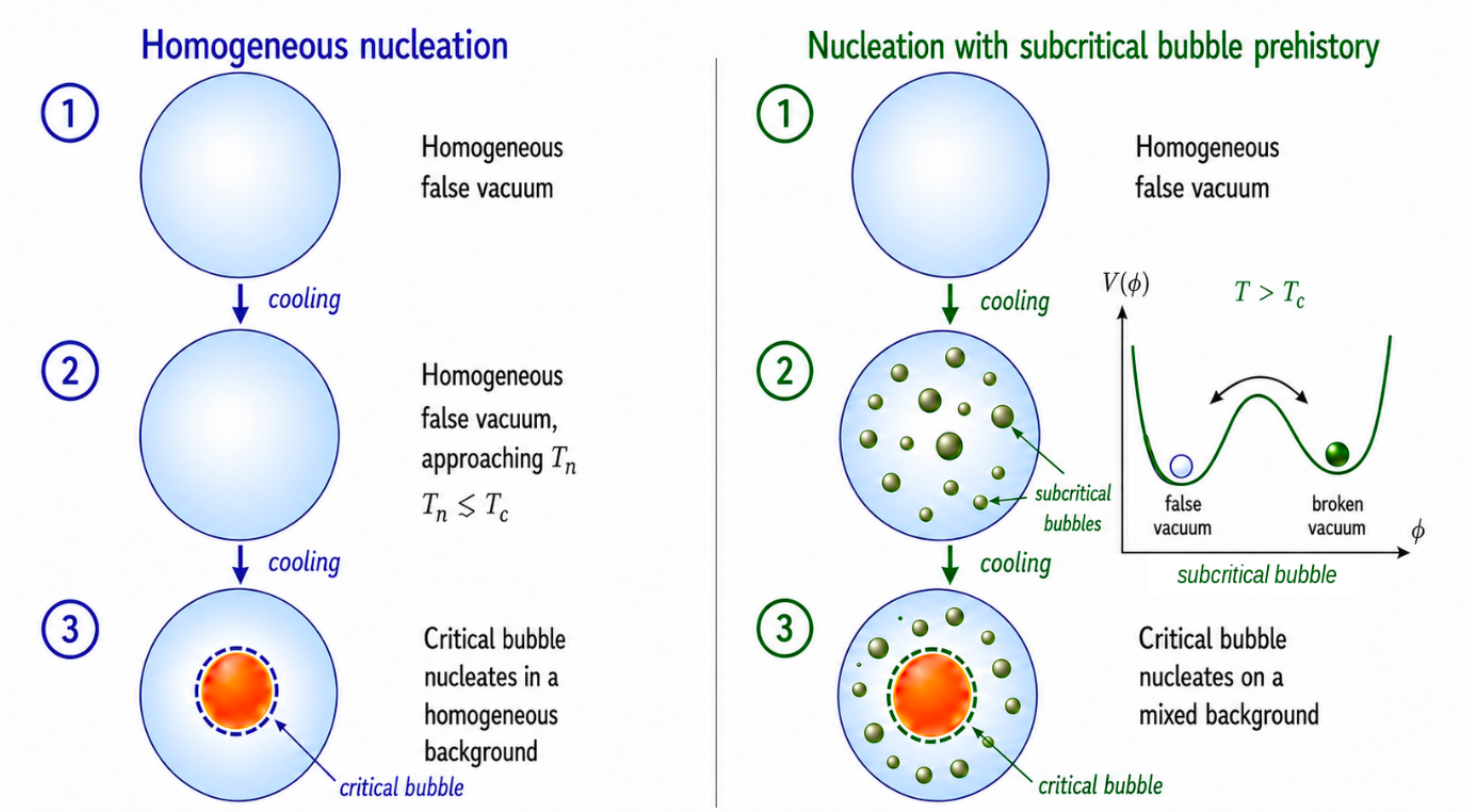
$$\Omega_{\rm DM}h^2 = 0.1193 \xrightarrow[\delta=-2\,\%]{\textit{Phases Coexistence}} 0.1170 \xrightarrow[\delta=+14\,\%]{\textit{Reheating}} 0.1334 \xrightarrow[\delta=-11\,\%]{\textit{Dilution}} 0.1181$$

$\delta = -0.7\,\%$

3. Impact on freeze-in DM: Subcritical bubble

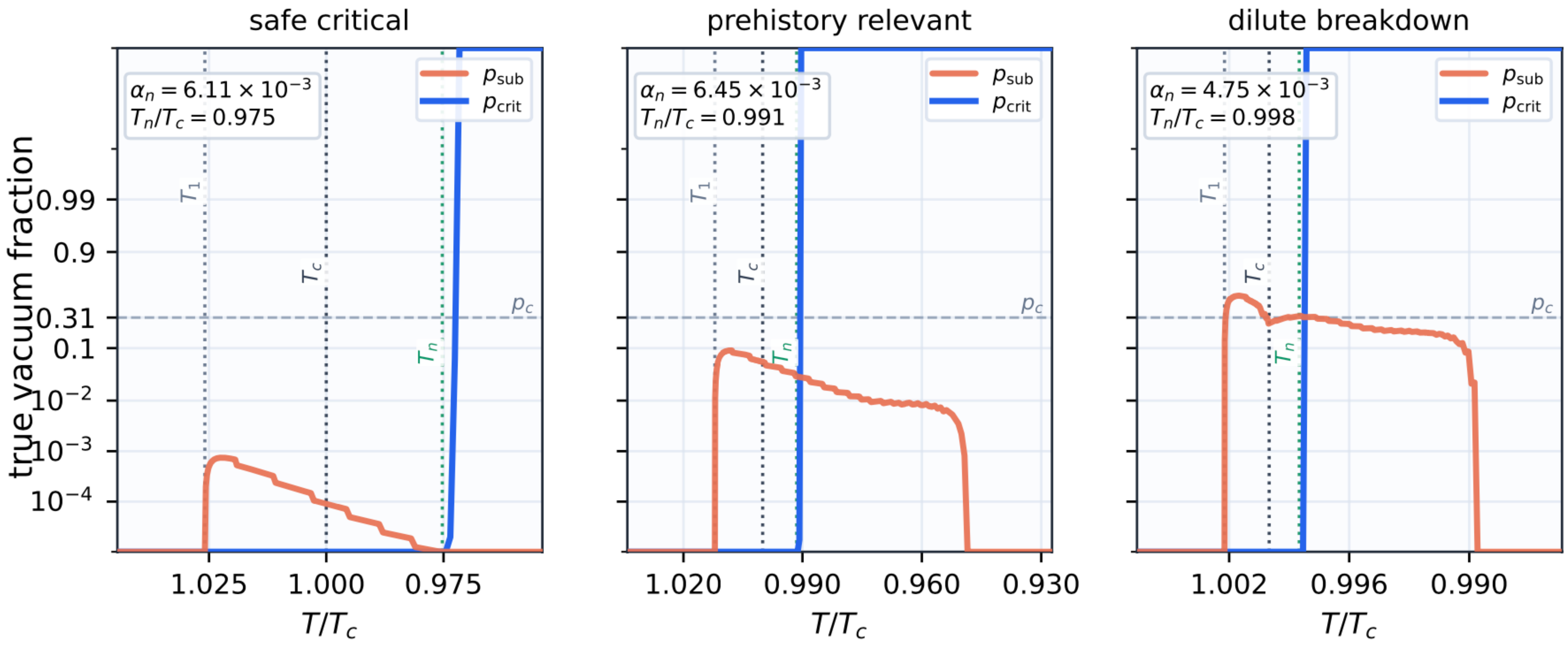
Guangshang Chen, Yang Xiao, Jin Min Yang, YZ, in progress

- ➤ For weak transitions, temperature evolution is further influenced by subcritical bubbles.
- The standard framework for first-order phase transitions involves nucleation and expansion of critical bubbles in a homogeneous false-vacuum background.
- However, thermal fluctuations may drive the field over the potential barrier toward the broken phase, whereas reverse fluctuations and thermal noise eliminate such domains before they grow critical. Consequently, short lived subcritical bubbles constantly form and vanish in the pre-nucleation regime.



$$\frac{\partial n}{\partial t}+3Hn=-\frac{\partial n}{\partial R}\frac{dR}{dt}+\frac{V_f}{V}\Gamma_{f\to t}-\frac{V_t^{(R)}}{V}\Gamma_{t\to f}-\frac{V_t^{(R)}}{V}\Gamma_{\mathrm{TN}}.$$

3. Impact on freeze-in DM: Subcritical bubble



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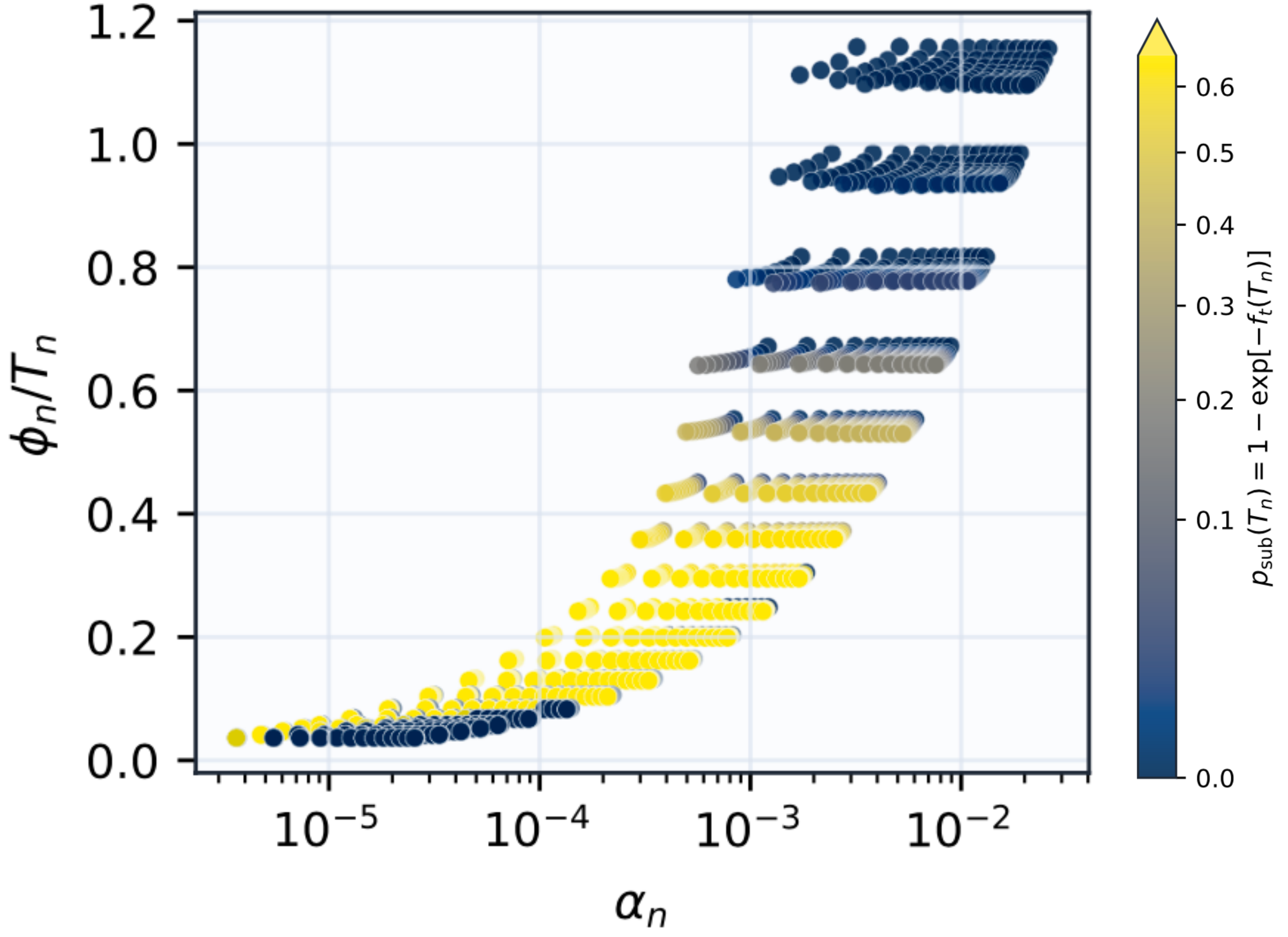

- ➤ The subcritical bubbles modify the initial conditions for the subsequent dynamics
- Inhomogeneous nucleation may modify the resulting GW spectrum

  See arXiv:2601.15933

- Variations in the vacuum fraction alter the temperature evolution and further affect the evolution of dark matter.
- The presence of subcritical bubbles around critical bubbles influences filtered dark matter production.

4. Conclusions

- The effects arise from inherent processes during phase transitions, rather than those unique to specific transition scenarios. These influences are inevitable if the phase transition temperature is close to the DM freeze temperature.
- For freeze-out DM, studying the impact of the phase transition on the relic density requires the phase transition to occur before freeze-out. Thus, it only affects very heavy dark matter, or fine-tuned parameter space.
- For freeze-in DM, in addition to the effect on mass, the electroweak phase transition also influences the dark matter density through the reheating process and phases coexistence.
- Subcritical bubbles can further modify the impact of weak phase transitions on DM.