2023年紫金山暗物质研讨会

Dilution of DM relic density caused by electroweak phase transition

arXiv:2207.14519, arXiv:2307.01072, Yang Xiao, Jin Min Yang, Yang Zhang

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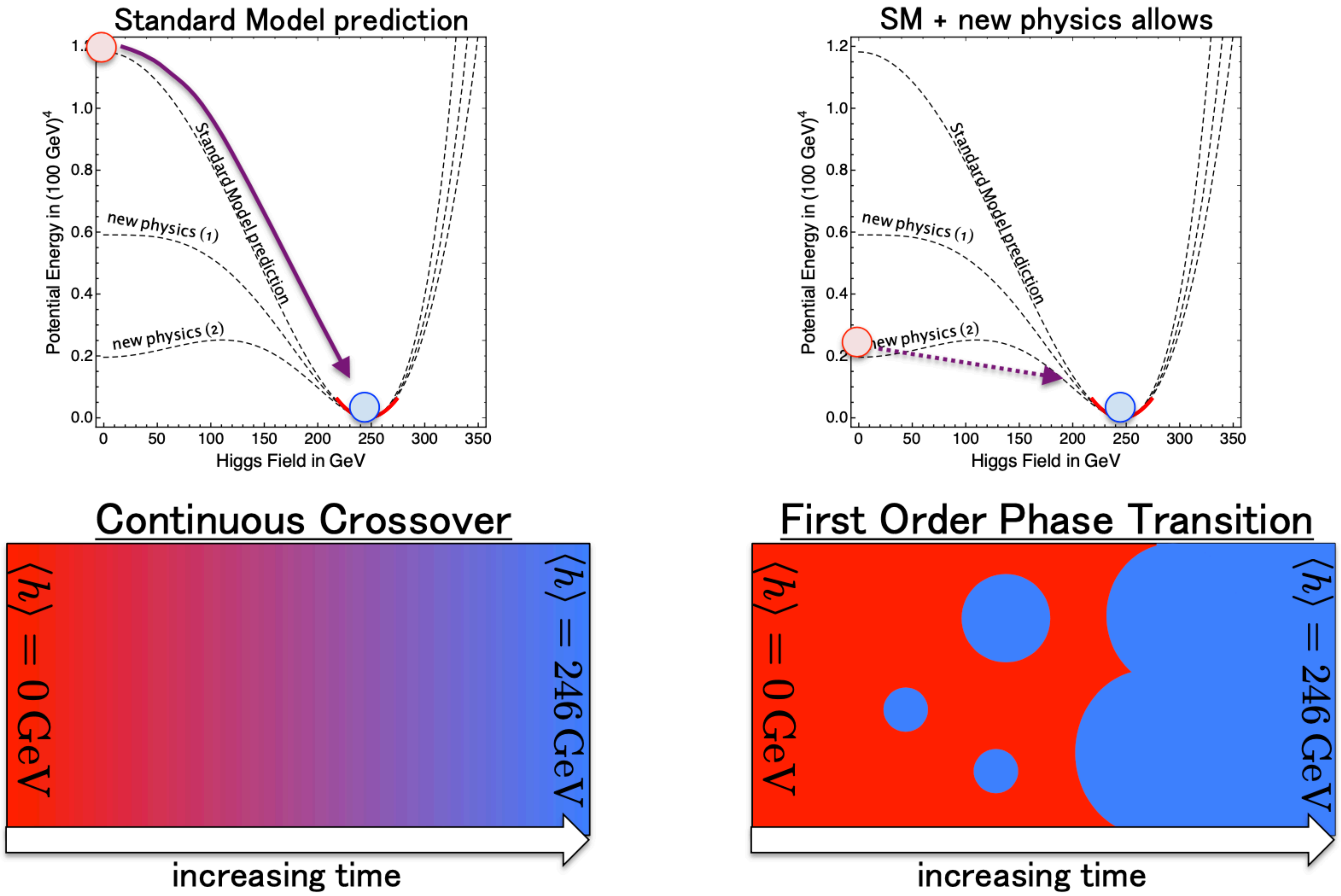
First-order phase transition



Slides from Liantao Wang's Talk, 2020

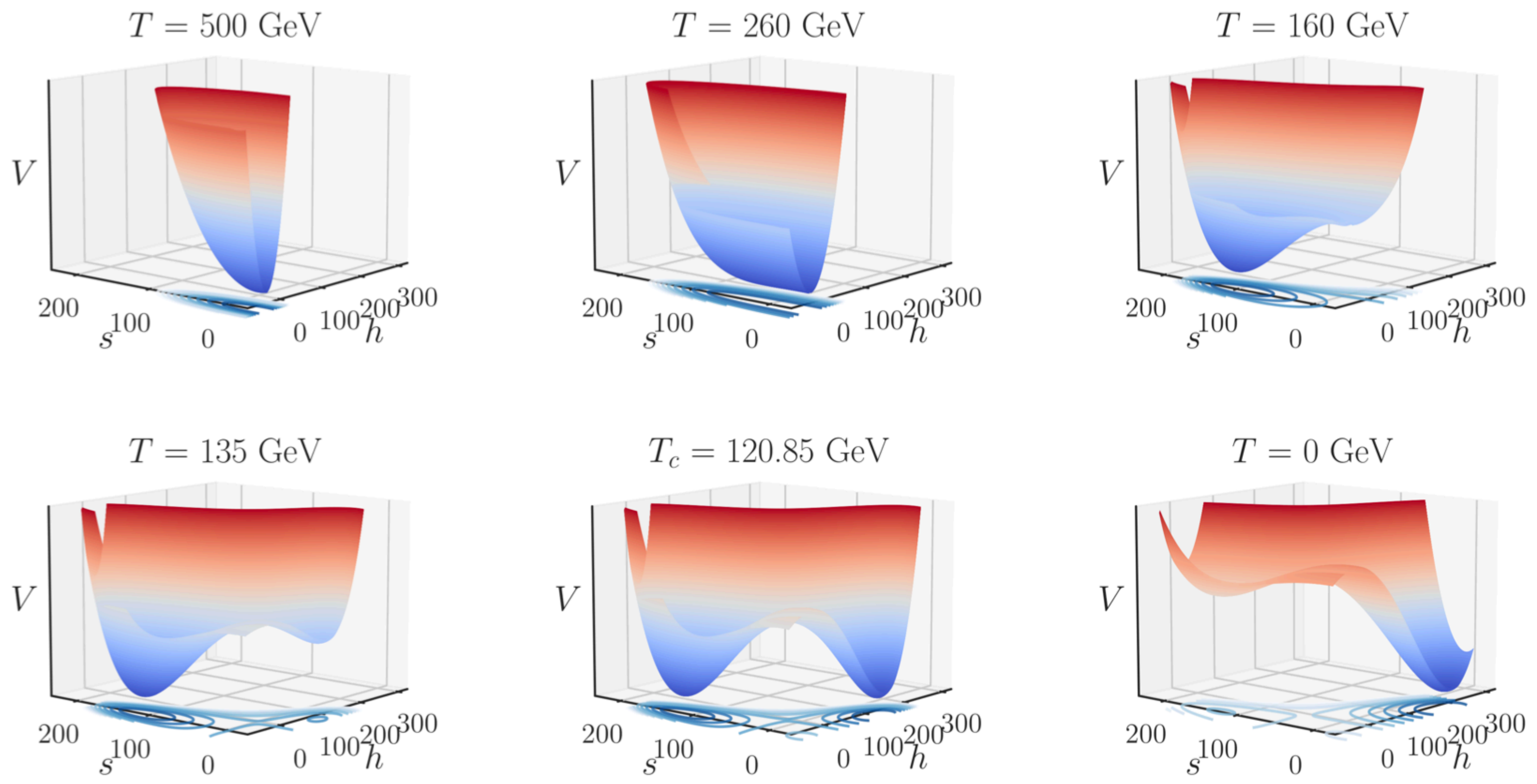
$$s = -\left(\frac{\mathrm{d}V}{\mathrm{d}T} + \frac{\mathrm{d}\phi}{\mathrm{d}T}\frac{\mathrm{d}V}{\mathrm{d}\phi}\right)$$

$$s_F(T_*) < s_T(T_*)$$

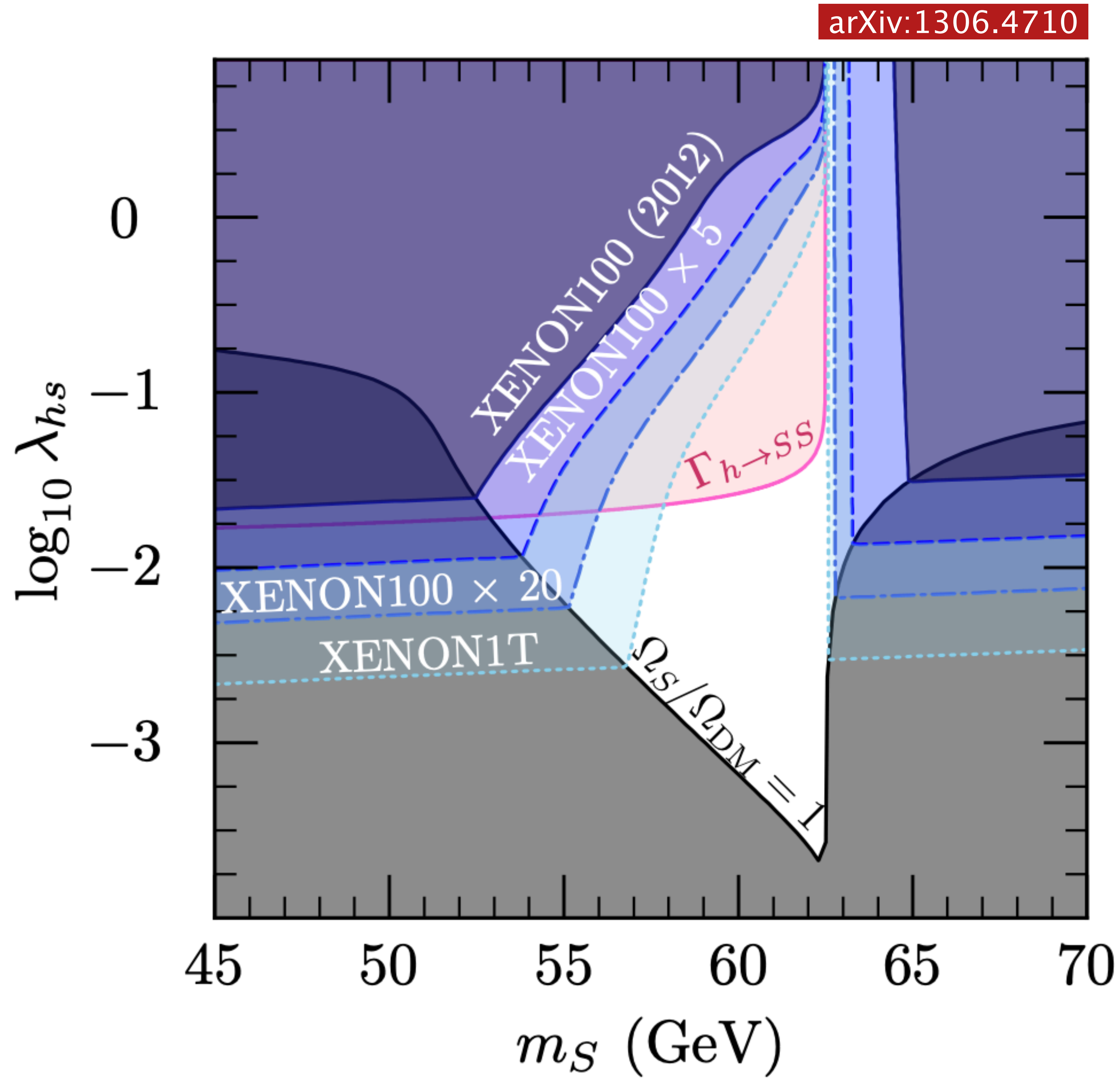
Entropy injection!

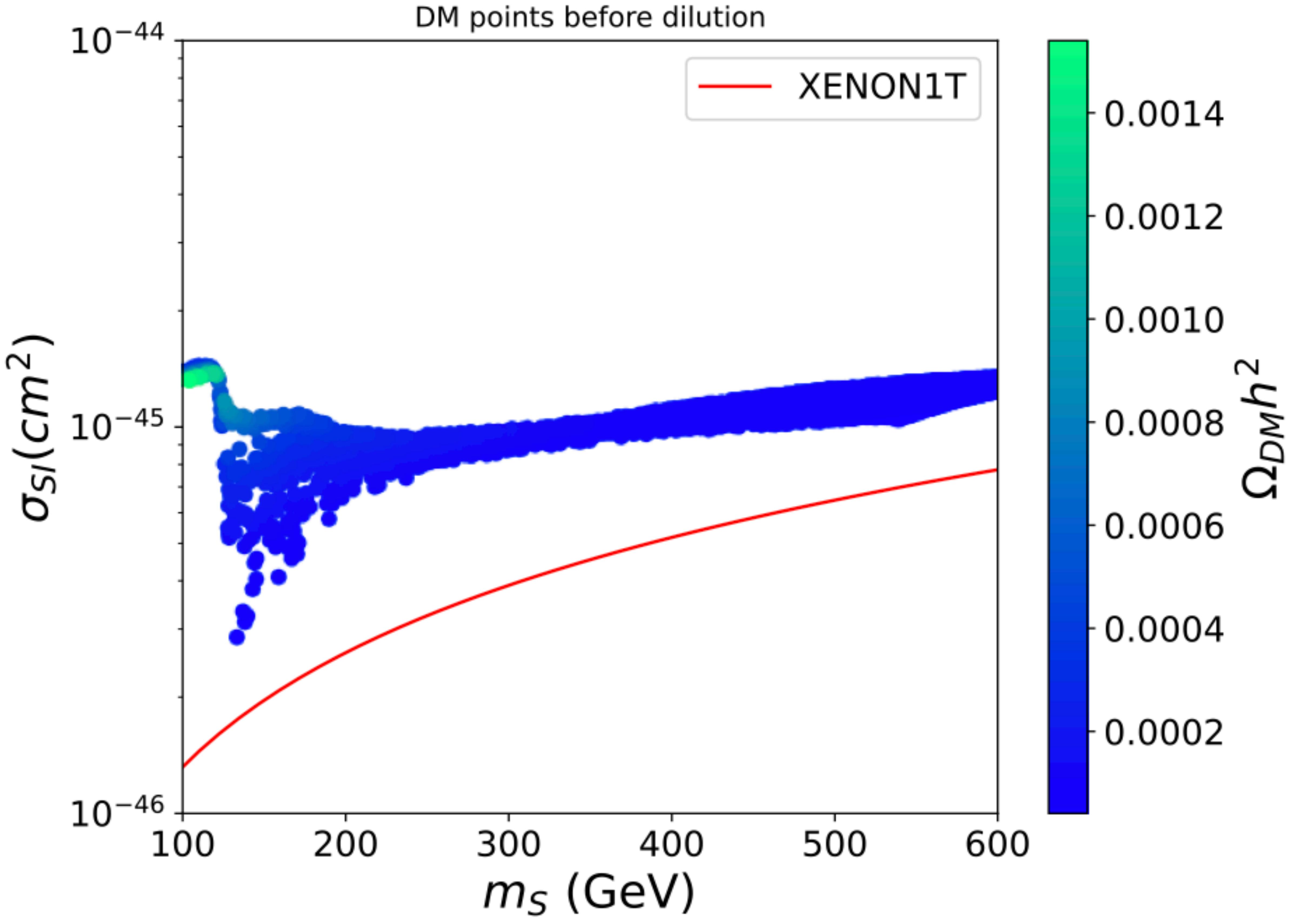
SM + $\mathbb{Z}_2$ singlet scalar DM

$$V_0(\phi_\mathrm{h},\phi_\mathrm{s}) = -\frac{\mu_\mathrm{h}^2}{2}\phi_\mathrm{h}^2 + \frac{\lambda_\mathrm{h}}{4}\phi_\mathrm{h}^4 - \frac{\mu_\mathrm{s}^2}{2}\phi_\mathrm{s}^2 + \frac{\lambda_\mathrm{s}}{4}\phi_\mathrm{s}^4 + \frac{\lambda_\mathrm{hs}}{4}\phi_\mathrm{h}^2\phi_\mathrm{s}^2$$



SM + $\mathbb{Z}_2$ singlet scalar DM





Dilution of DM density in the early universe

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.

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

The total dilution factor $d = \left(\frac{a_f}{a_i}\right)^3 = \frac{s_F(T_*)}{s_F(T_C)} \times \frac{(1-f)s_F(T_R) + f\,s_T(T_R)}{s_T(T_F)}$

Dilution of DM density in the early universe

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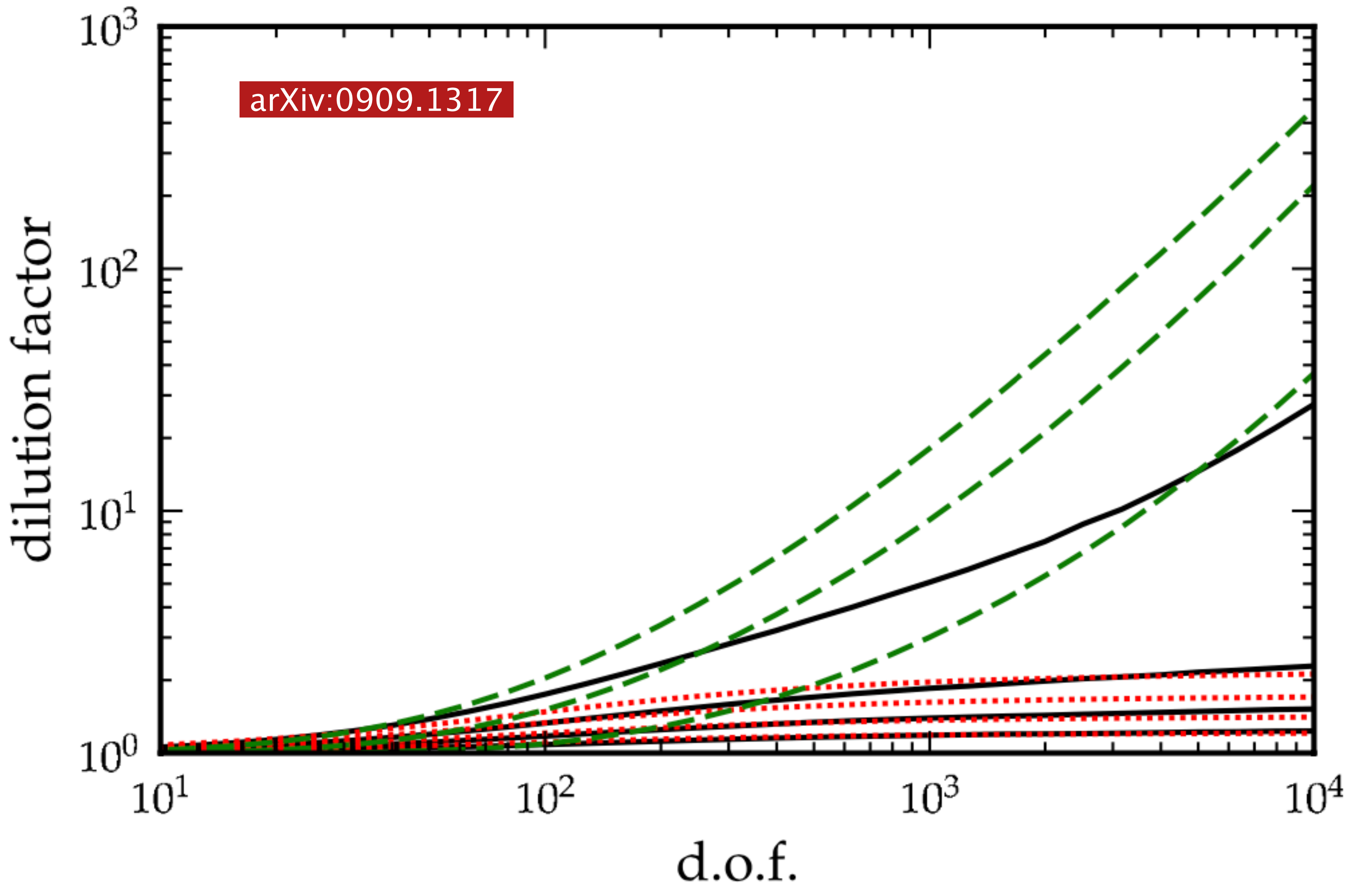


Assuming all particles acquire mass through a Higgs-like mechanism in which the mass terms are of the form

$$m_i(\phi) = h_i \phi$$

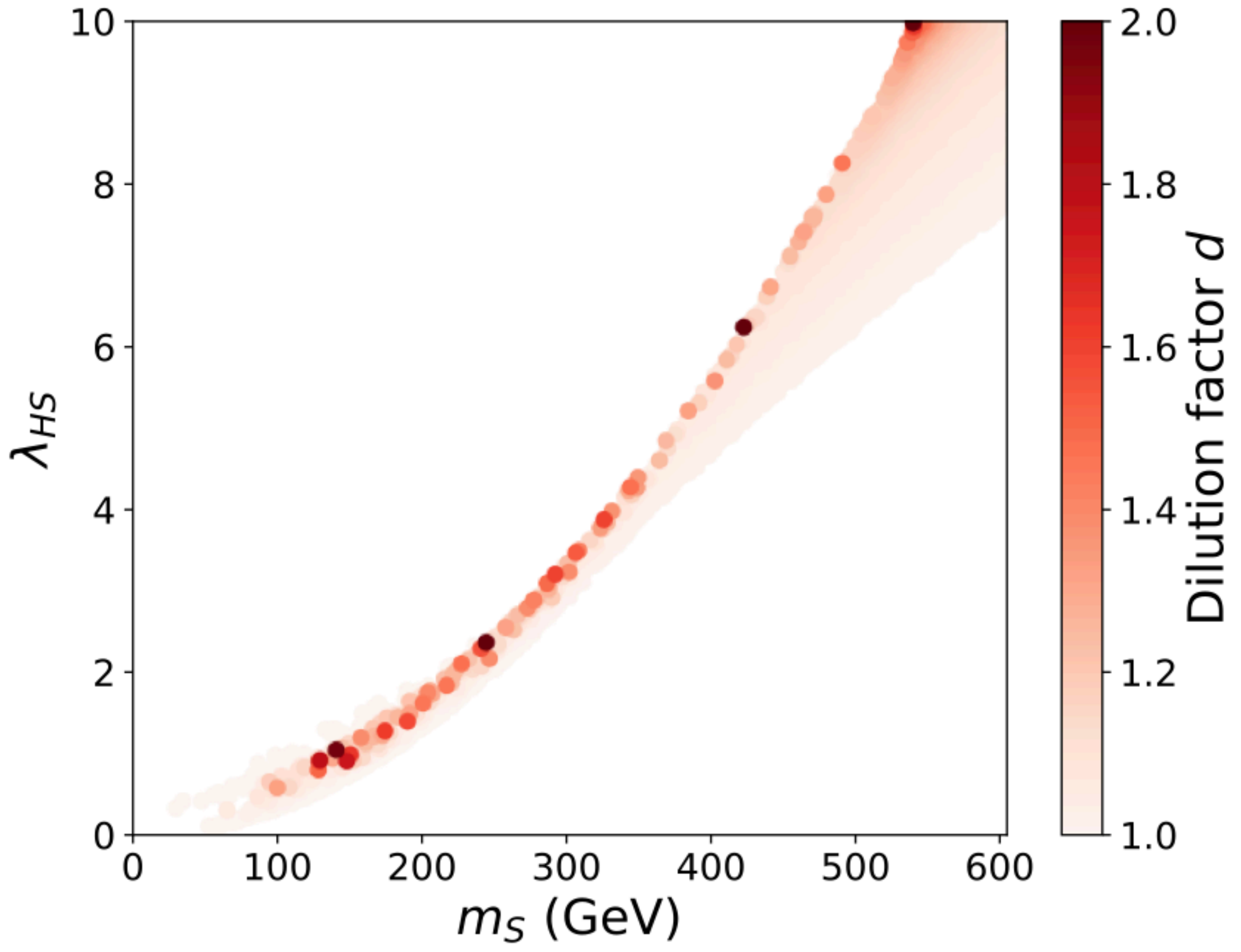
Purely bosonic models

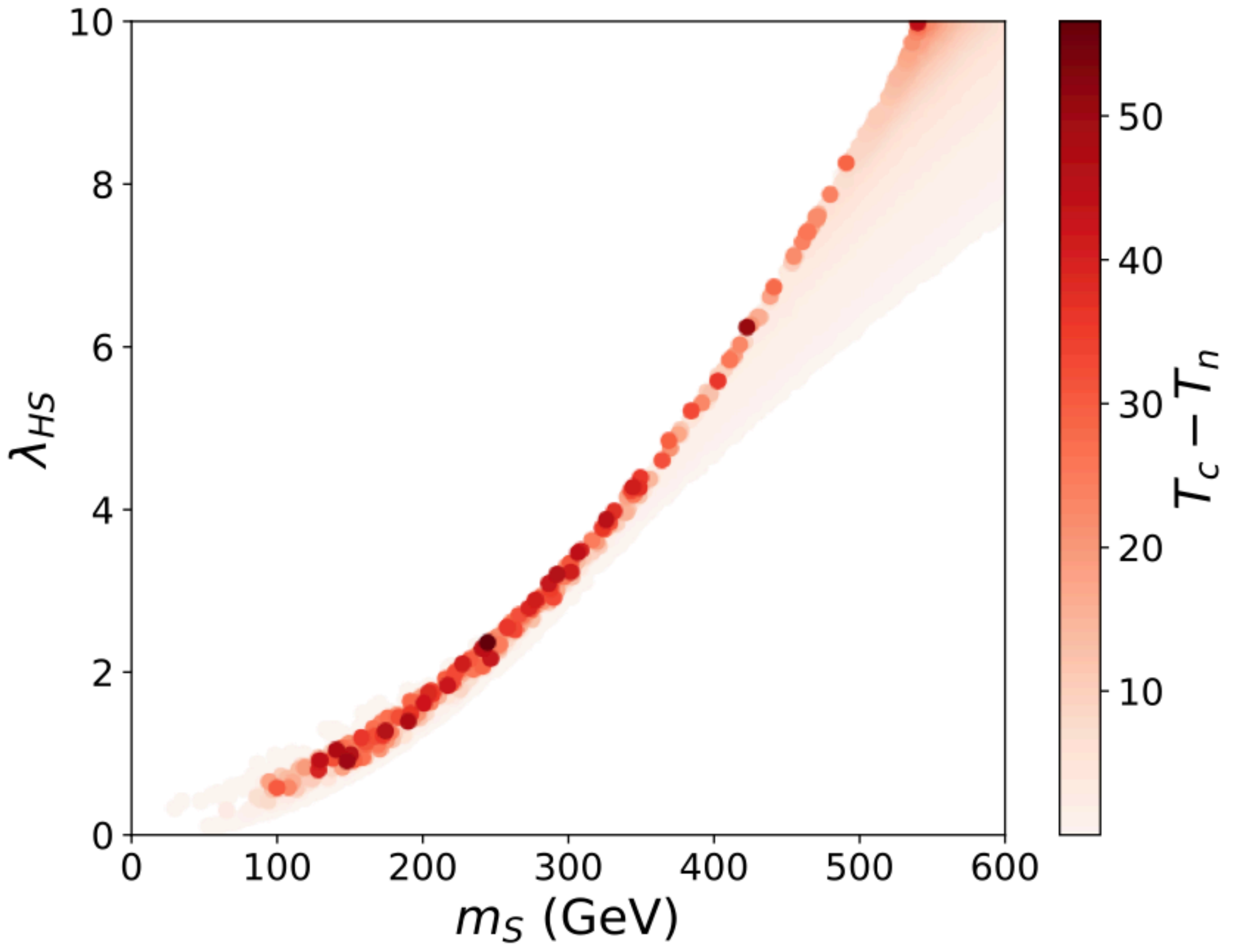
Boson-fermion models

Boson-fermion models

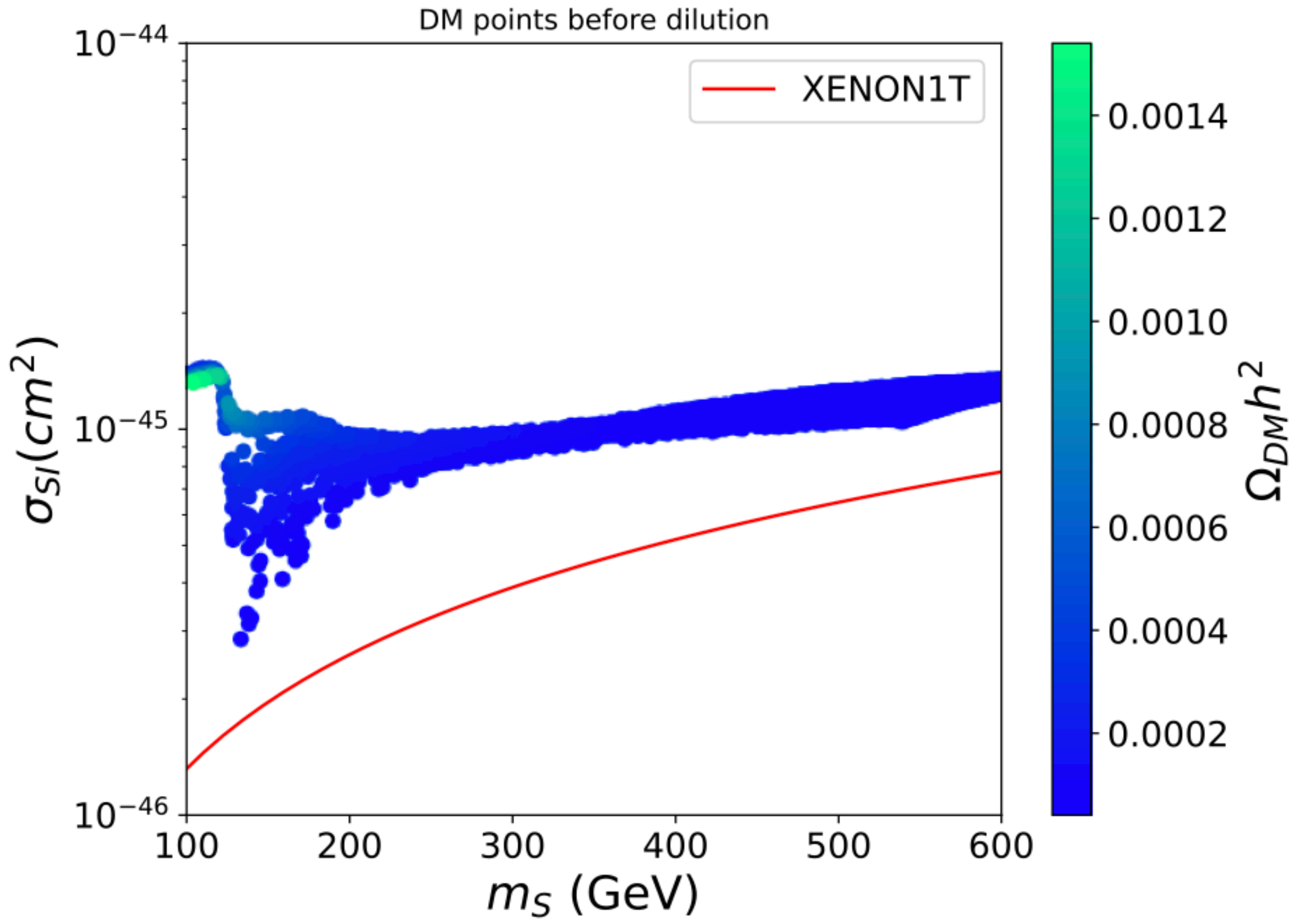
$$h_i = 0.5, 0.75, 1.0$$

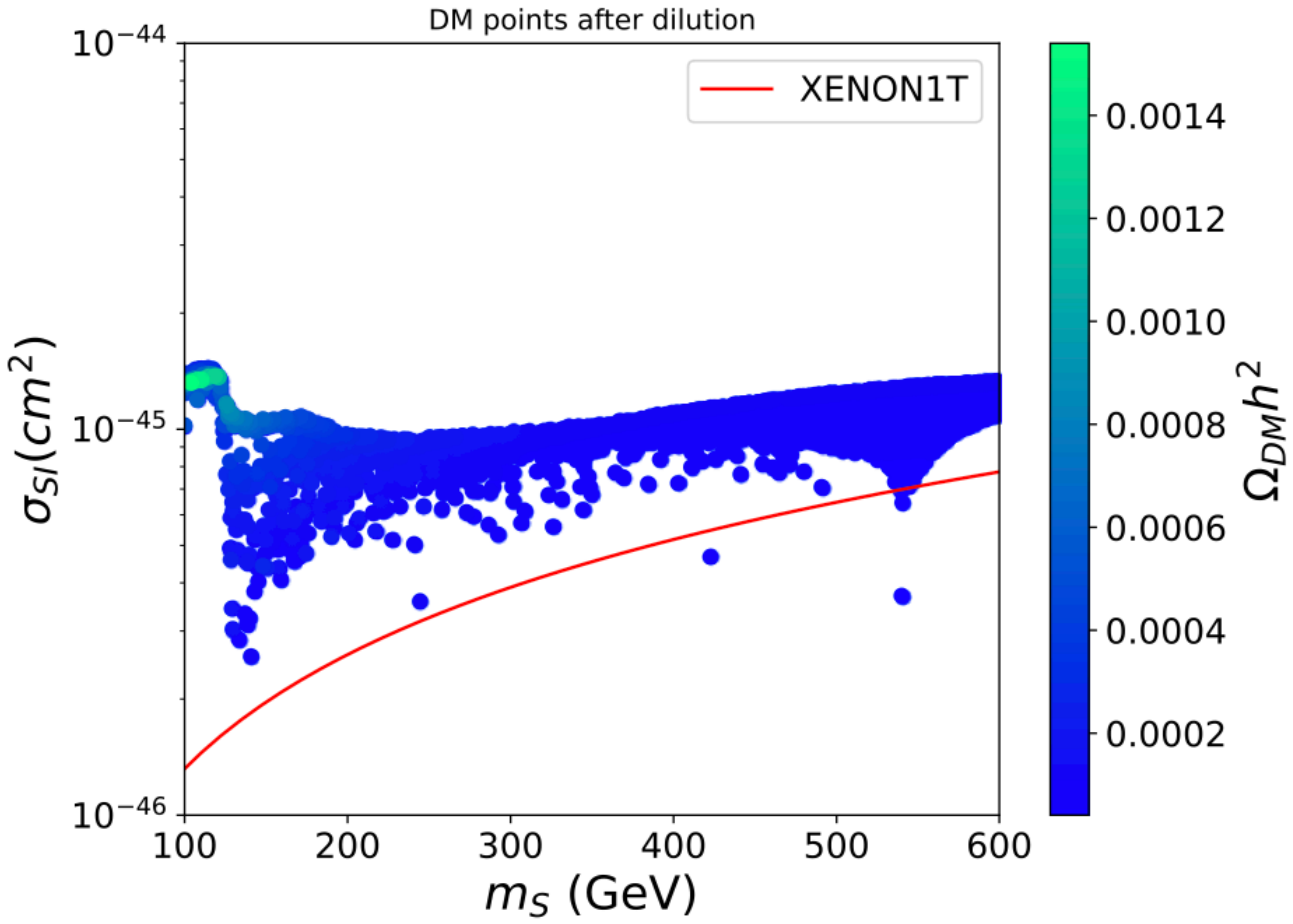
Dilution of DM density in SM + $\mathbb{Z}_2$ singlet scalar DM



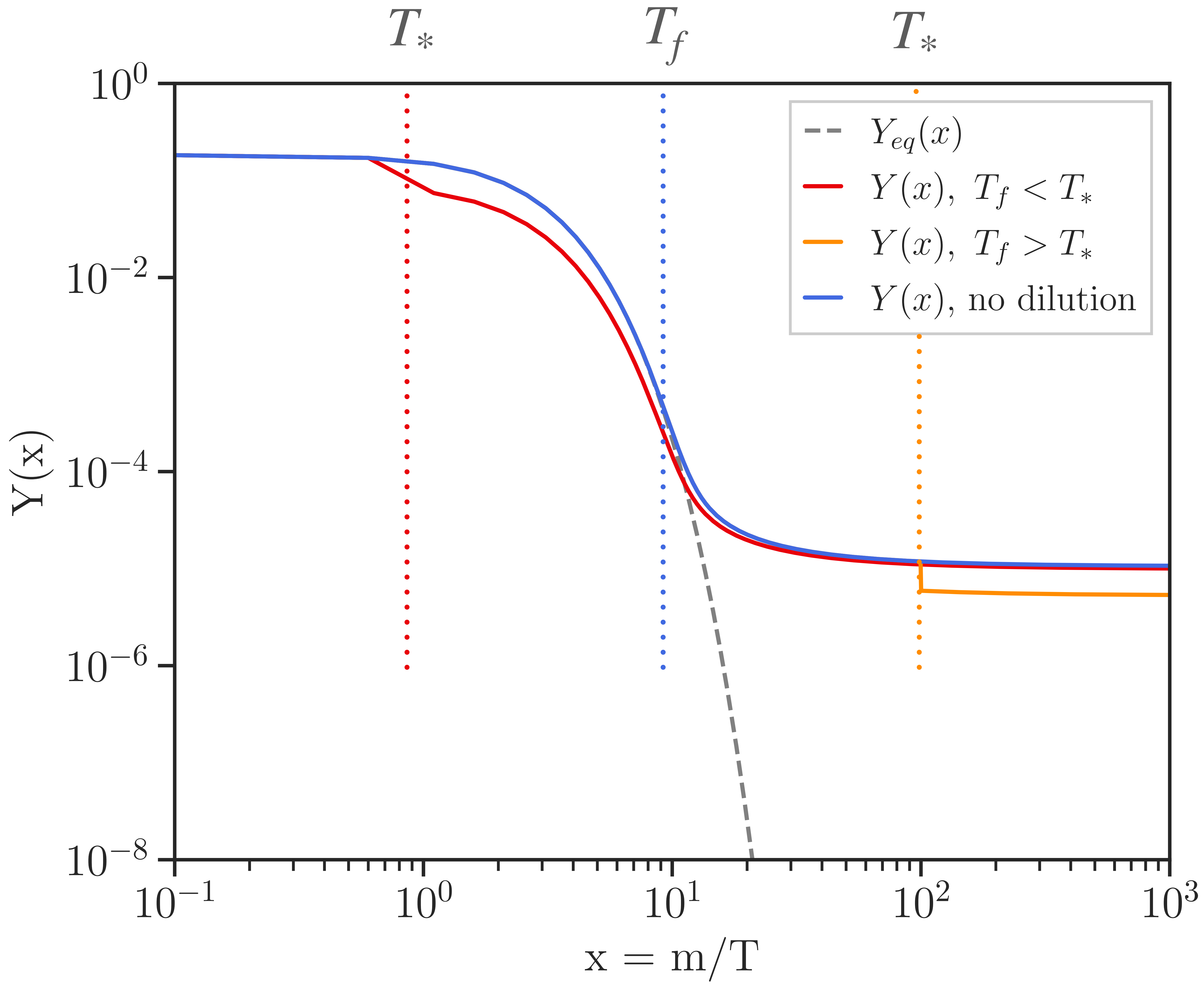


Dilution of DM density in SM + $\mathbb{Z}_2$ singlet scalar DM





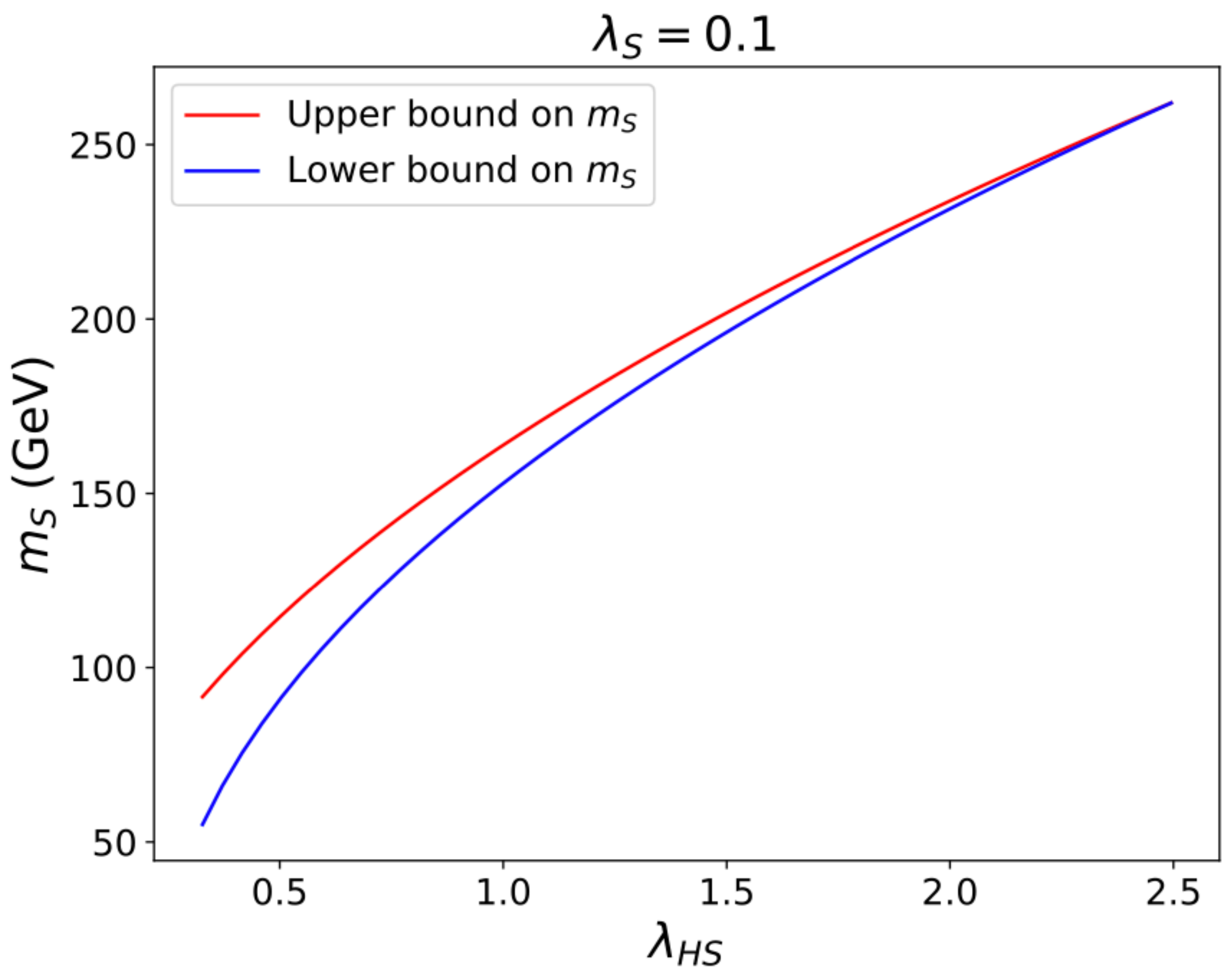
Dilution of DM density in the early universe



Freeze-out temperature:

$$T_f = m/x_f \simeq m/[20{,}40]$$

$$T_f \simeq [20{,}50] \text{ GeV for 1 TeV DM}$$

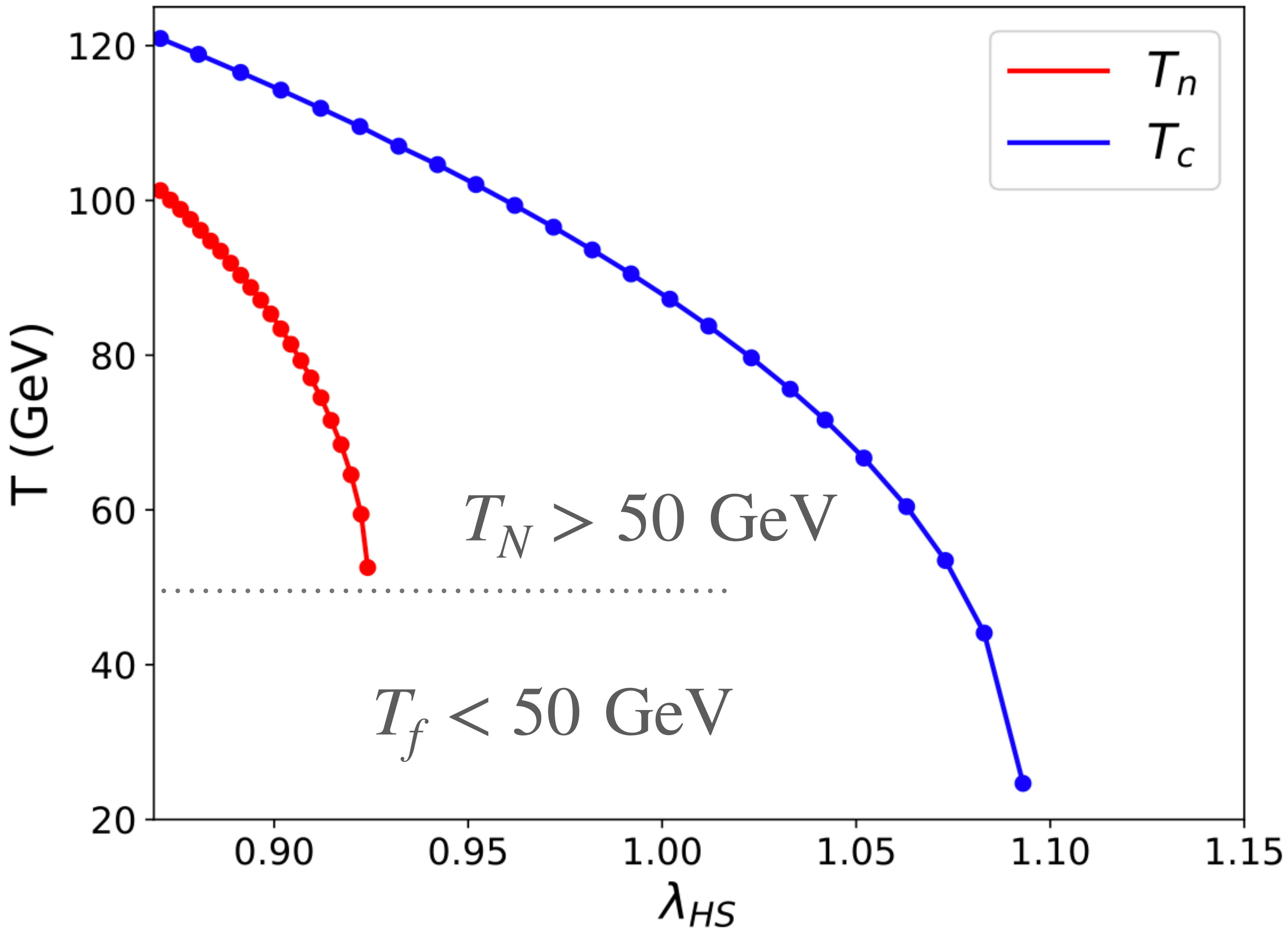


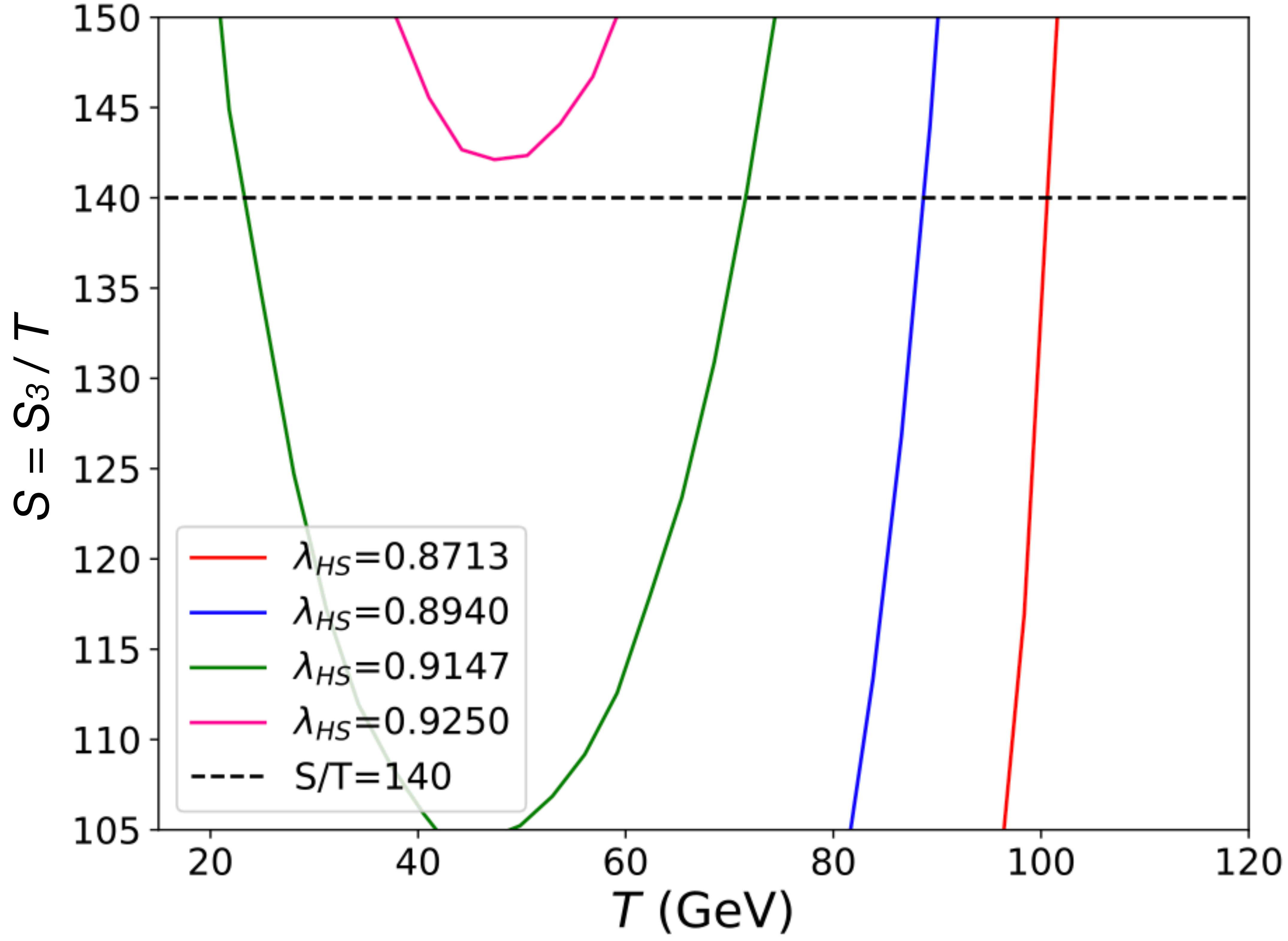
Dilution of DM density in the early universe

$$N(T) = \int_{t_{\rm tra}}^{t_{\rm nuc}} {\rm d}t \frac{\Gamma}{H^3} = \int_{T_{\rm nuc}}^{T_{\rm tra}} \frac{{\rm d}T}{T} \frac{\Gamma(T)}{H(T)^4} = 1.$$

$$\frac{\Gamma(T)}{H(T)^4} = \frac{T^4}{H(T)^4}\left(\frac{S}{2\pi}\right)^{\frac{3}{2}} e^{-S} = \left(\frac{90}{\pi^2 g_{\rm dof}}\right)^2 \frac{M_{\rm Pl}^4}{T^4}\left(\frac{S}{2\pi}\right)^{\frac{3}{2}} e^{-S} = 1$$

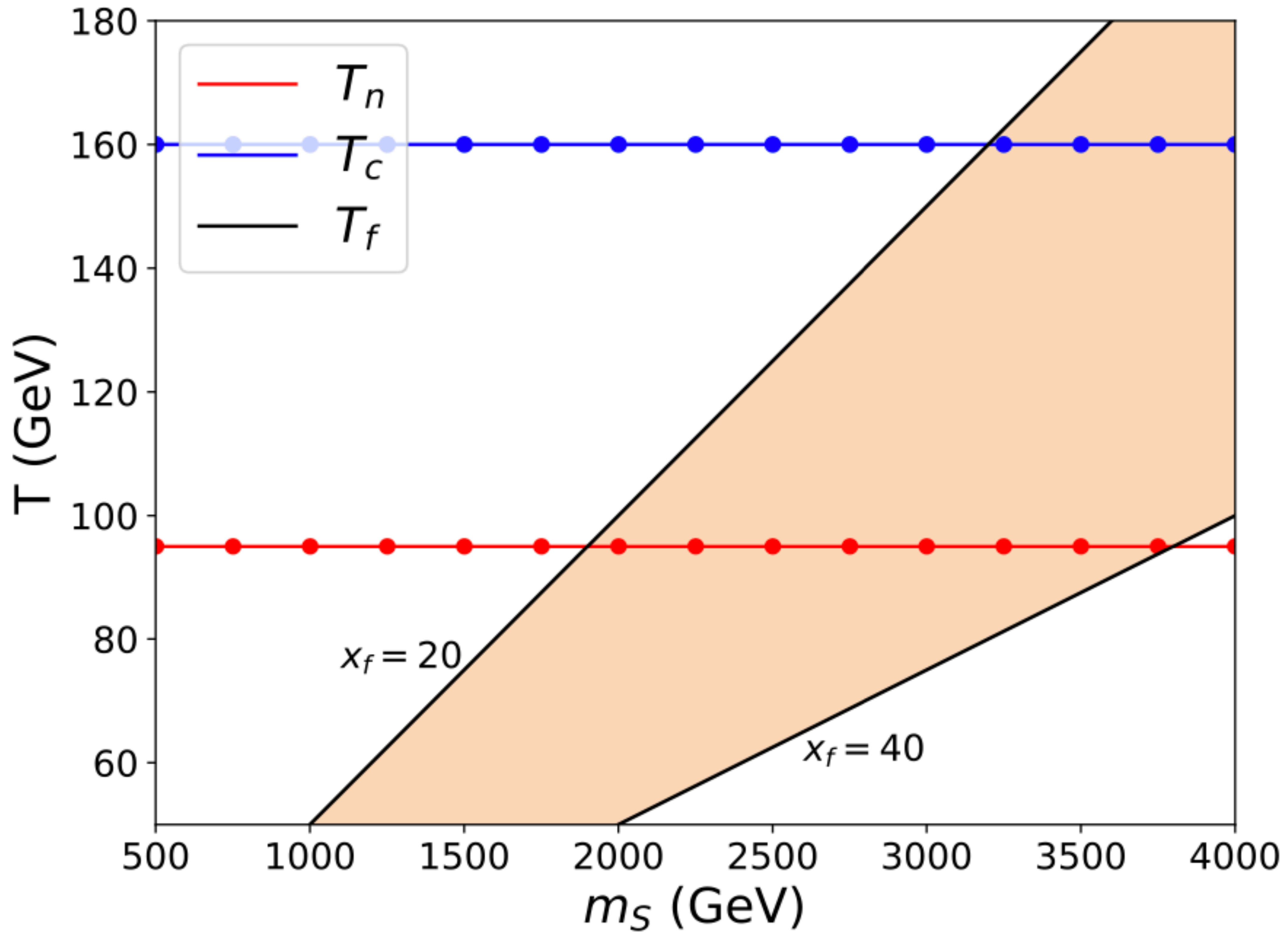
$$S = 4\log\frac{M_{\rm Pl}}{T} + \frac{3}{2}\log\frac{S}{2\pi} + 2\log\frac{90}{\pi^2 g_{\rm dof}} \approx 4\log\frac{M_{\rm Pl}}{T} \approx 130 \sim 140$$

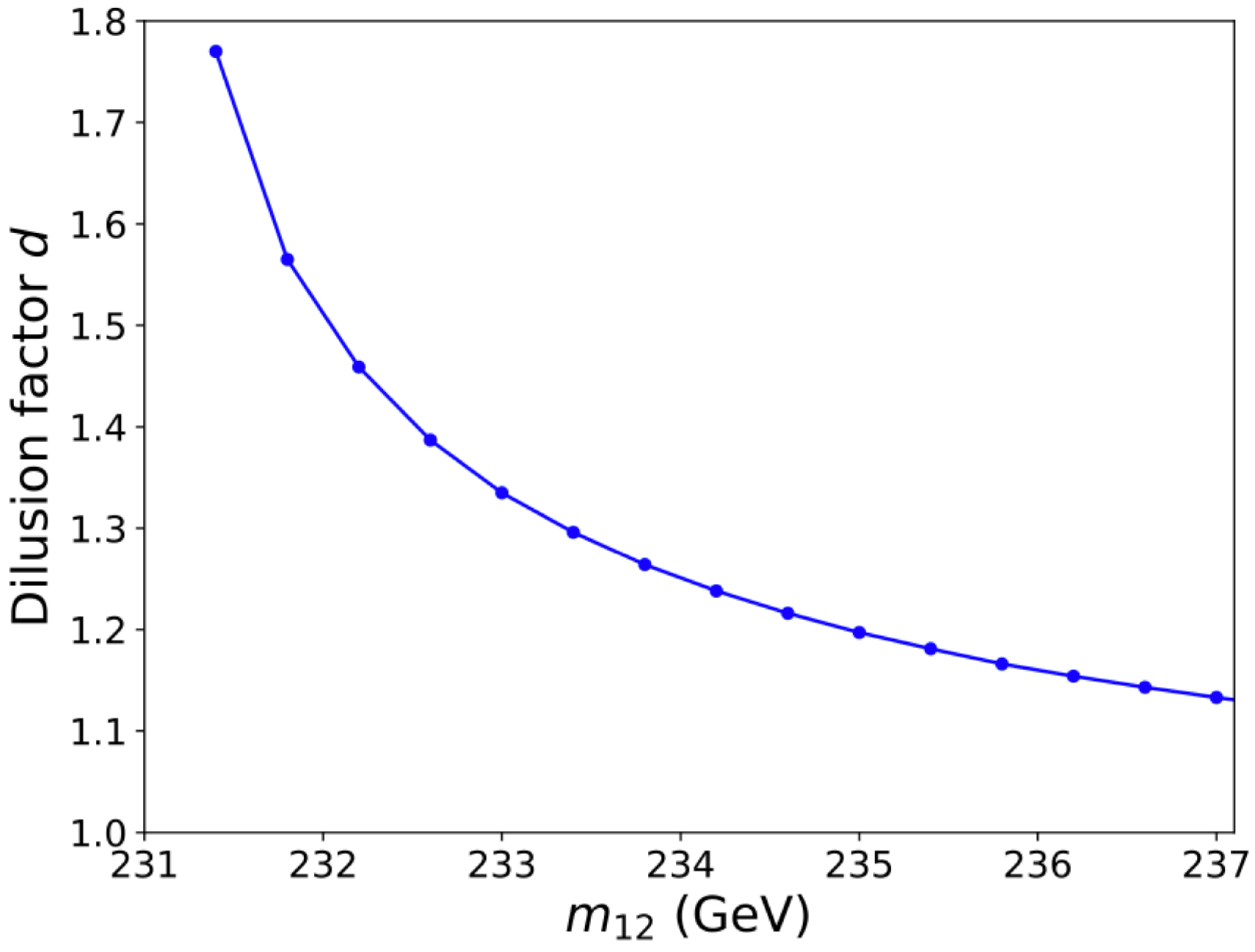




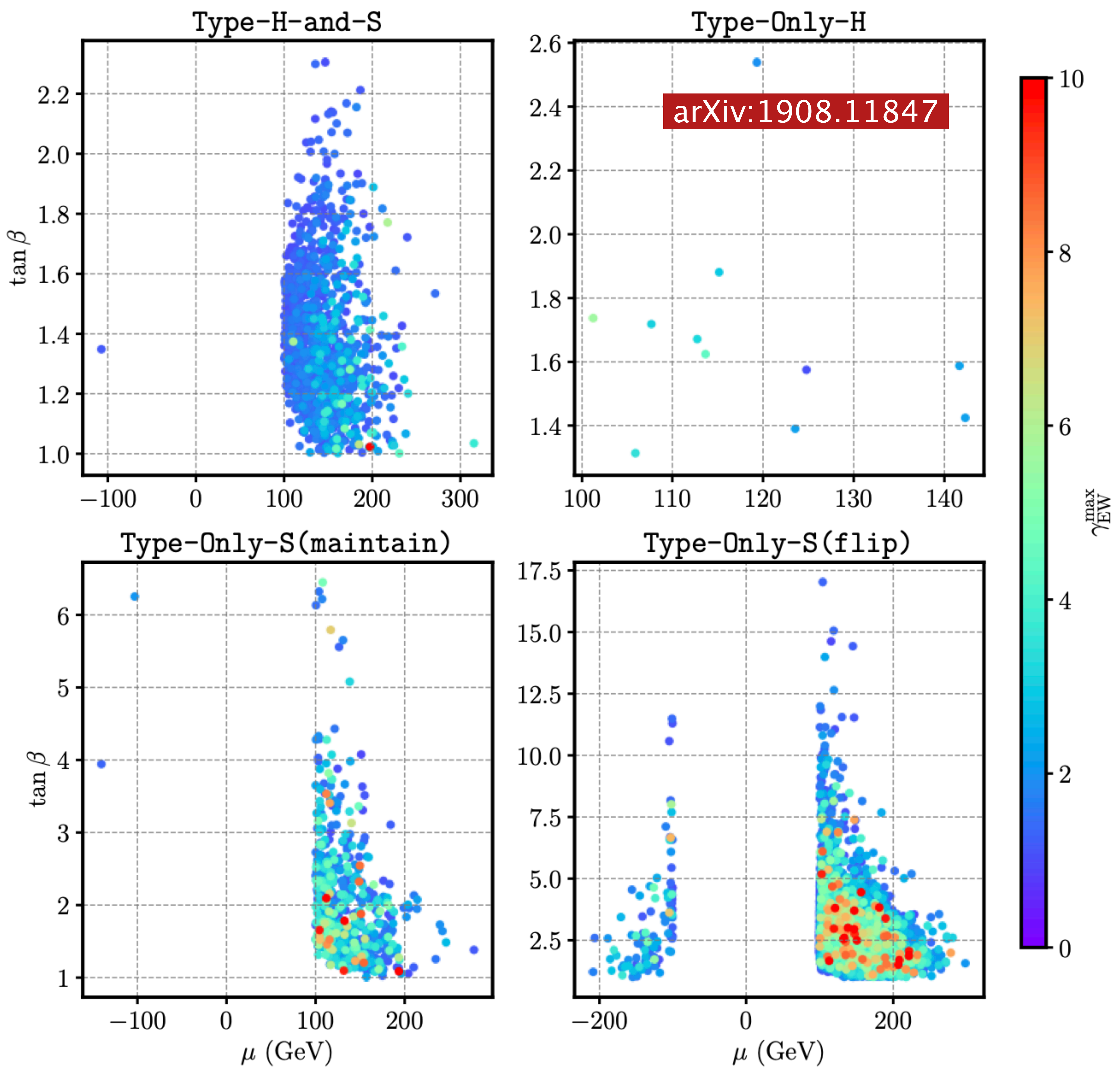
2HDM + singlet scalar DM

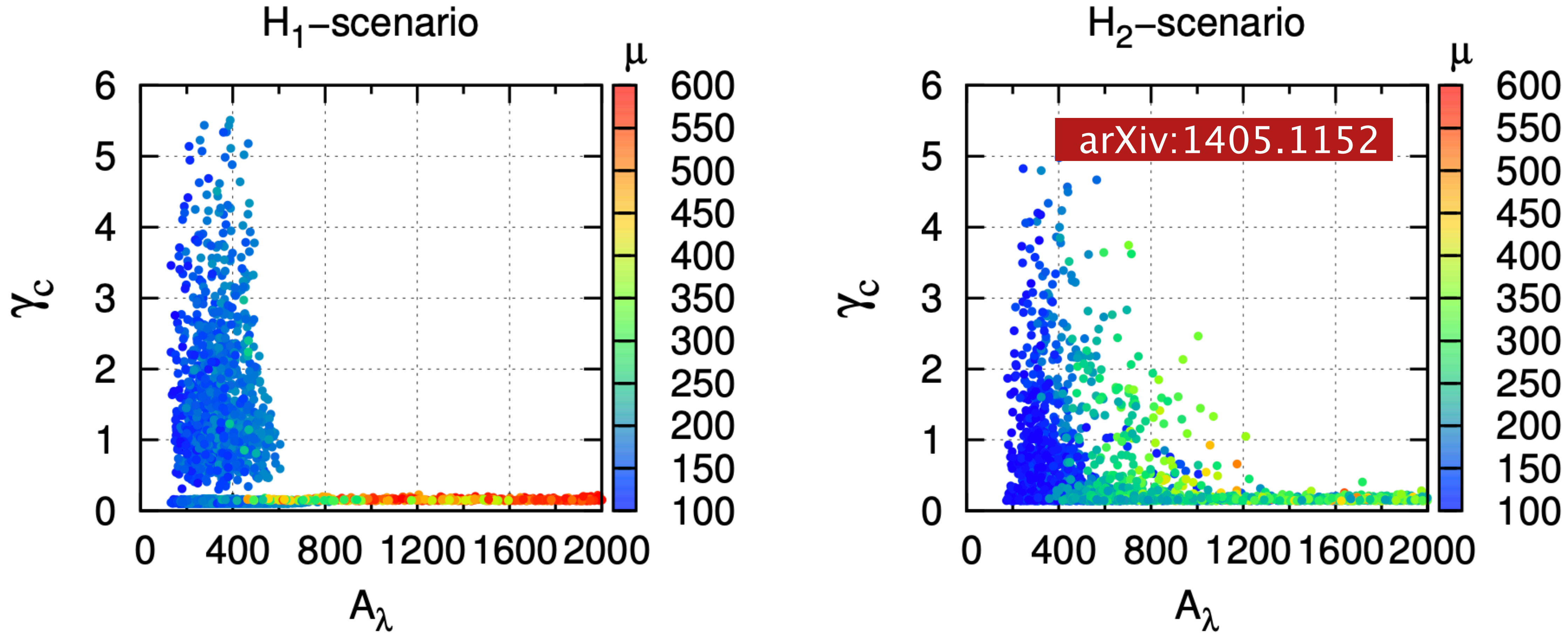
$$\begin{aligned}V_0^{\text{2HDM+S}} &= m_{11}^2(\Phi_1^\dagger\Phi_1) + m_{22}^2(\Phi_2^\dagger\Phi_2) - [m_{12}^2\Phi_1^\dagger\Phi_2 + h.c.] \\ &+ \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \frac{\lambda_3}{2}(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \frac{\lambda_4}{2}(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ &+ [\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + h.c.] + \frac{1}{2}S^2(\kappa_1\Phi_1^\dagger\Phi_1 + \kappa_2\Phi_2^\dagger\Phi_2) + \frac{m_0}{2}S^2 + \frac{\lambda_S}{4!}S^4.\end{aligned}$$

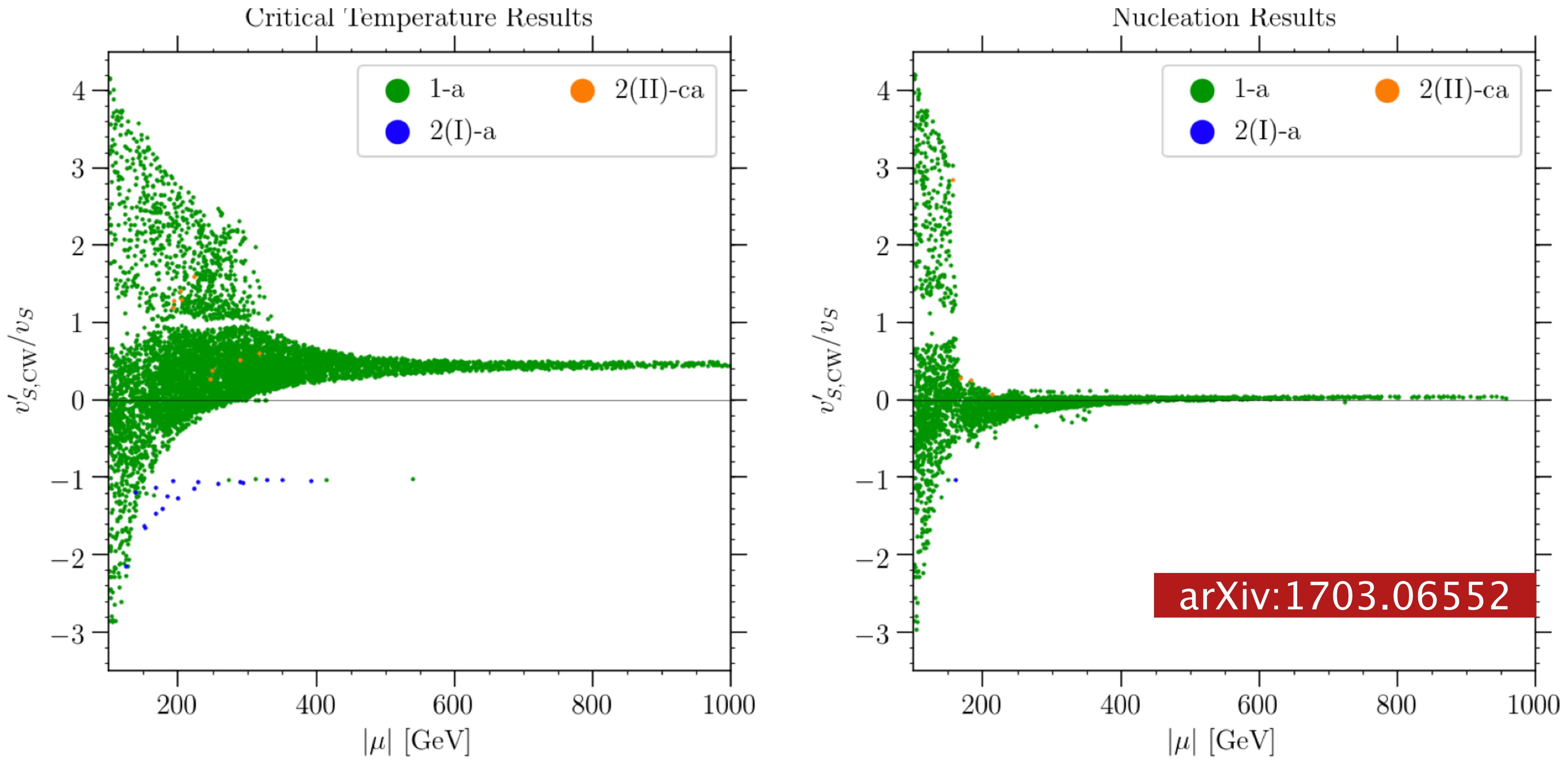




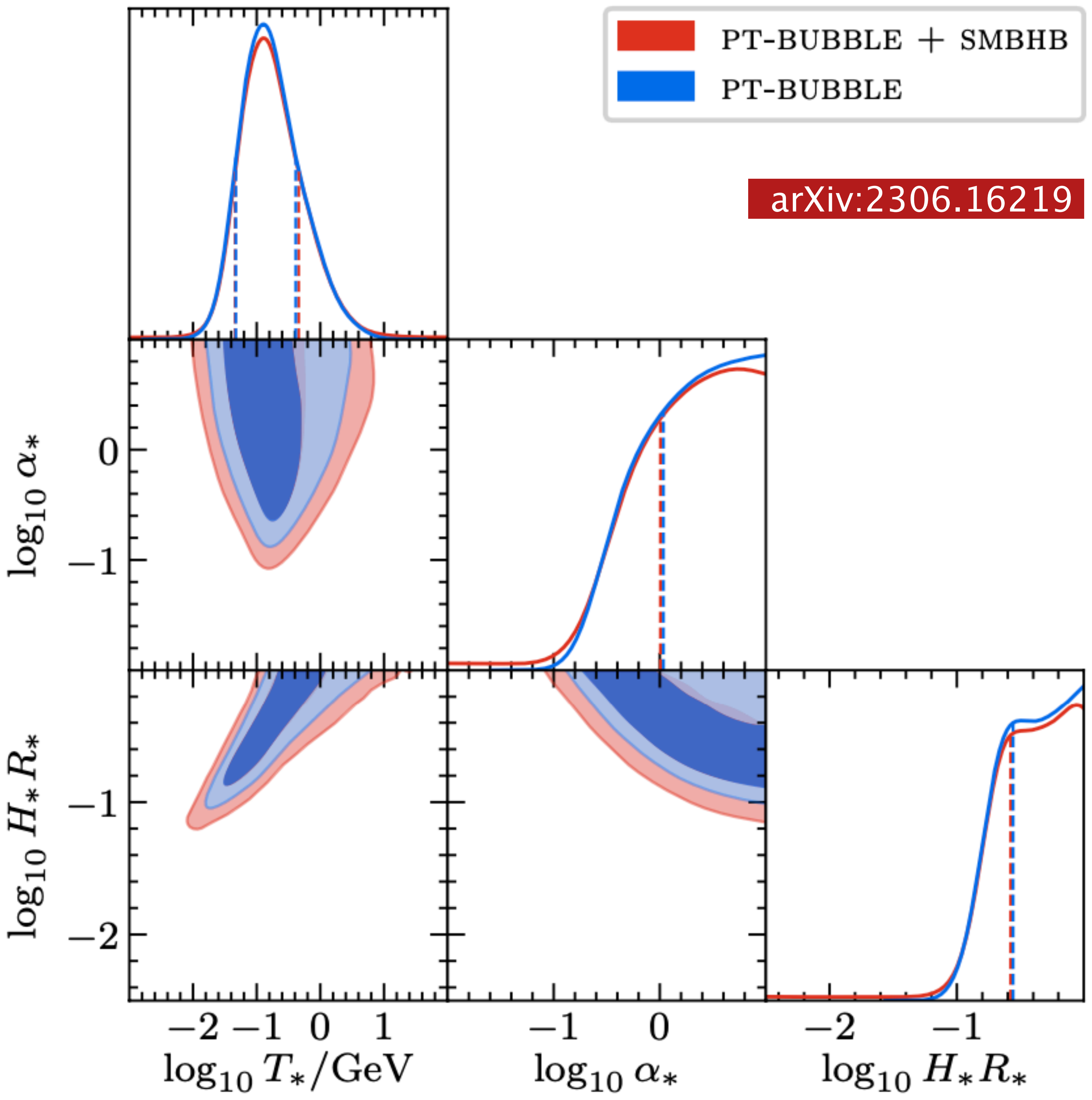
Next-to-Minimal Supersymmetric Standard Model

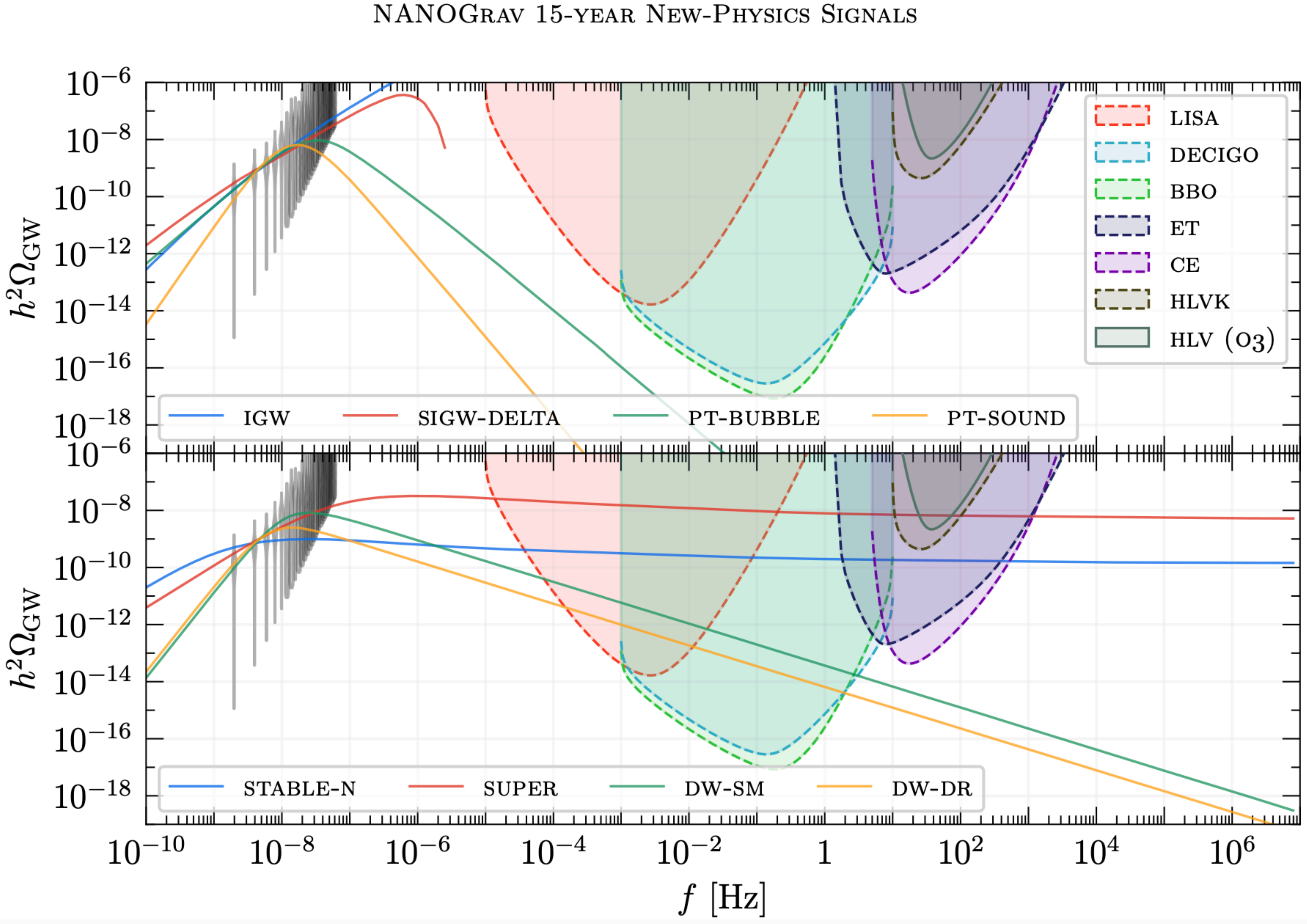






Nano-hertz Gravitational Waves



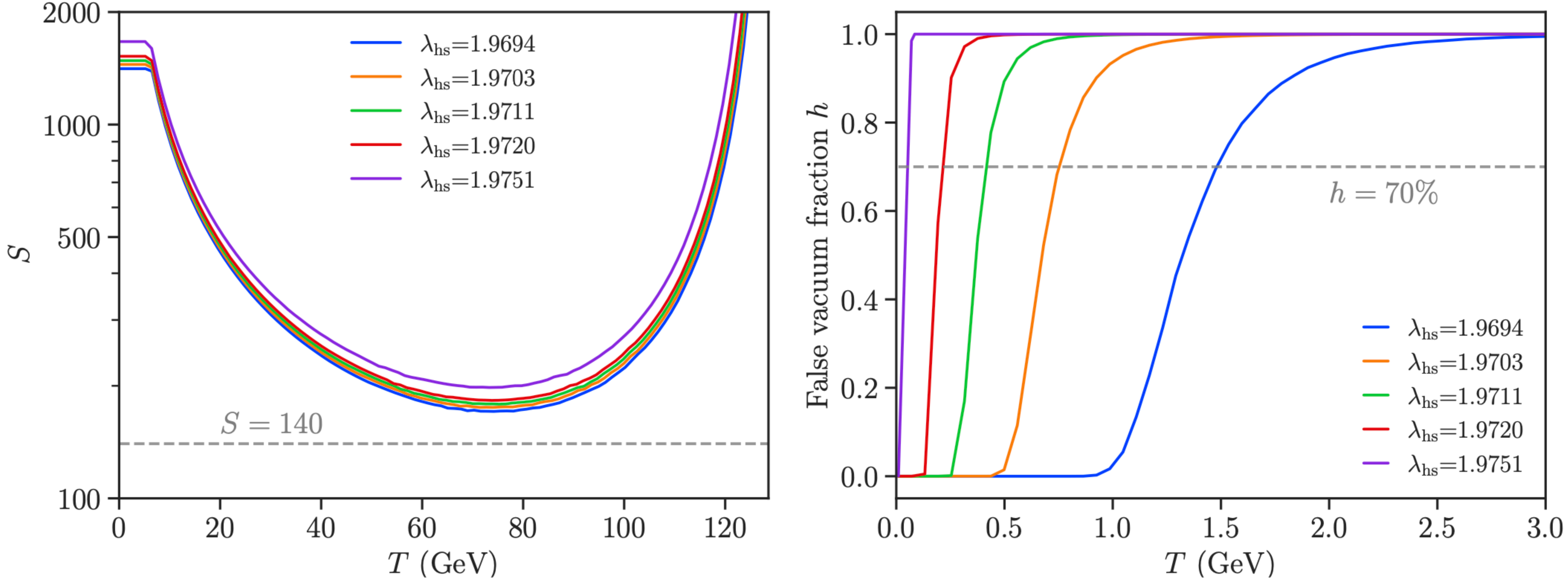


$$f_{b,s} \simeq 48.5\,\mathrm{nHz}\, g_*^{1/2}\left(\frac{g_{*,s}^{\mathrm{eq}}}{g_{*,s}}\right)^{1/3}\left(\frac{T_*}{1\,\mathrm{GeV}}\right)\frac{f_{b,s}^* R_*}{H_* R_*}$$

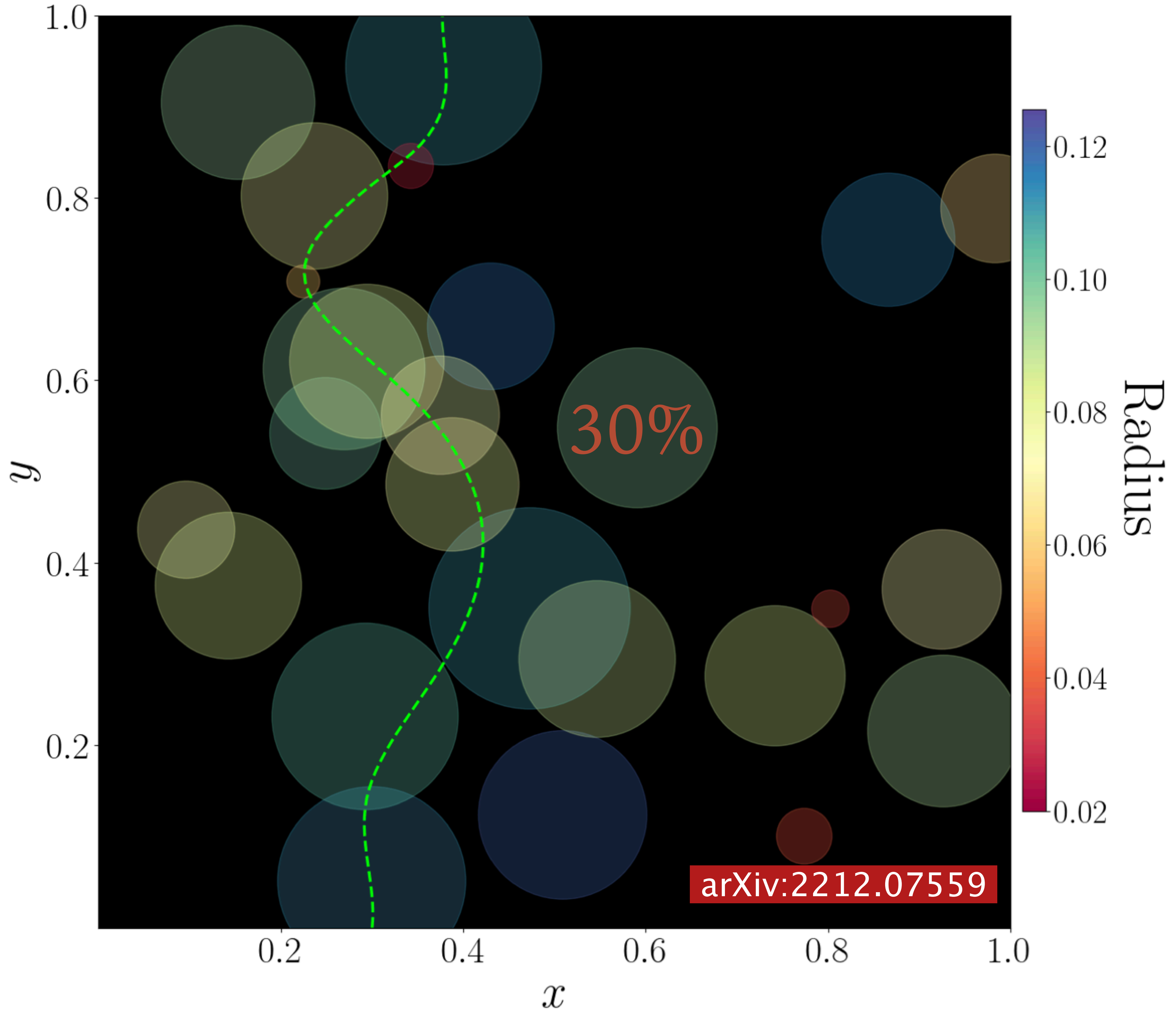
phase transition signal remain viable. A third option may consist in a strongly supercooled first-order electroweak phase transition (Kobakhidze et al. 2017).

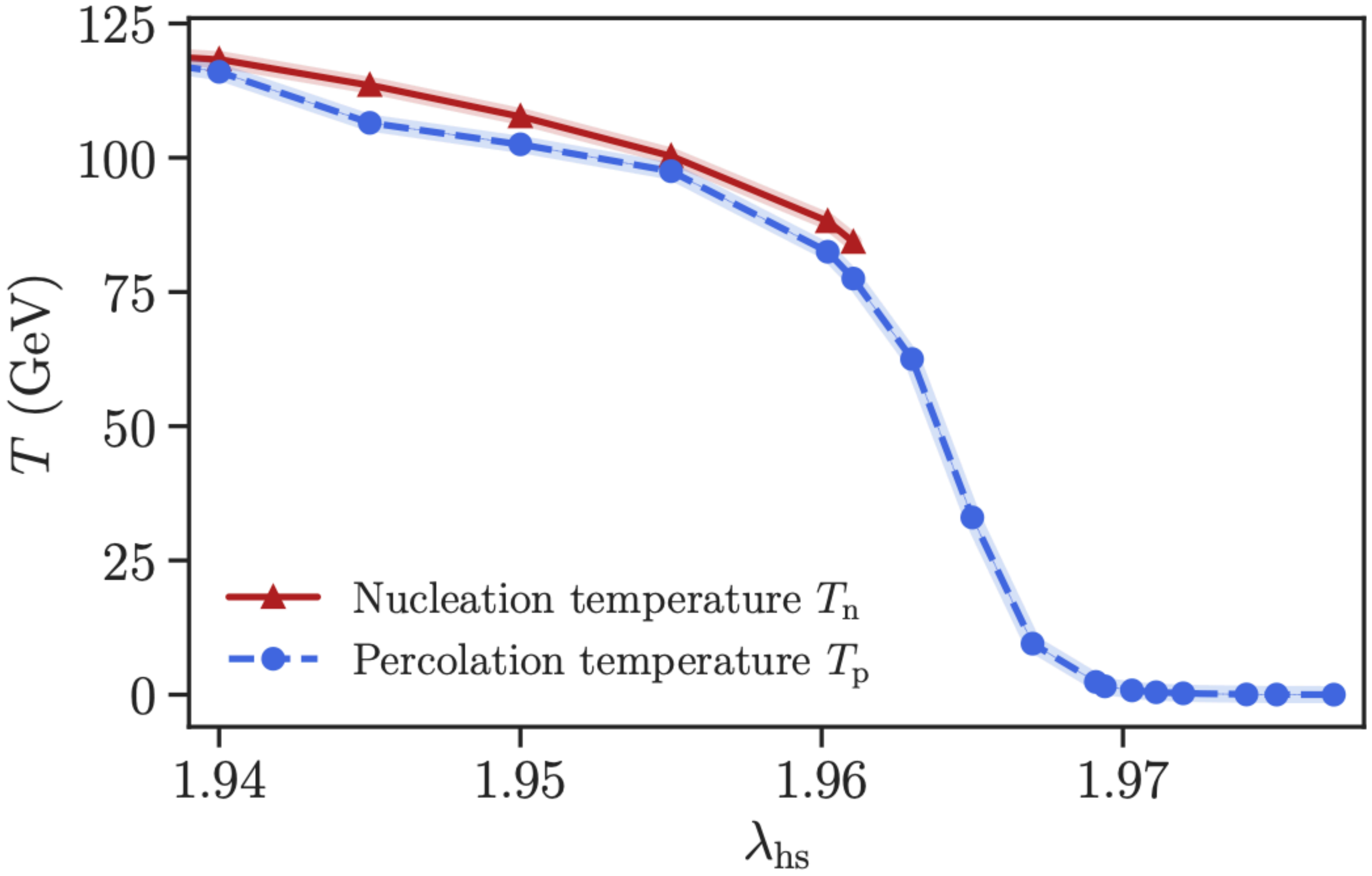
Strongly supercooled FOPT

$$h(t) = \exp[-\int_{t_{\mathrm{initial}}}^{t} \Gamma(t')V(t',t)\mathrm{d}t']$$

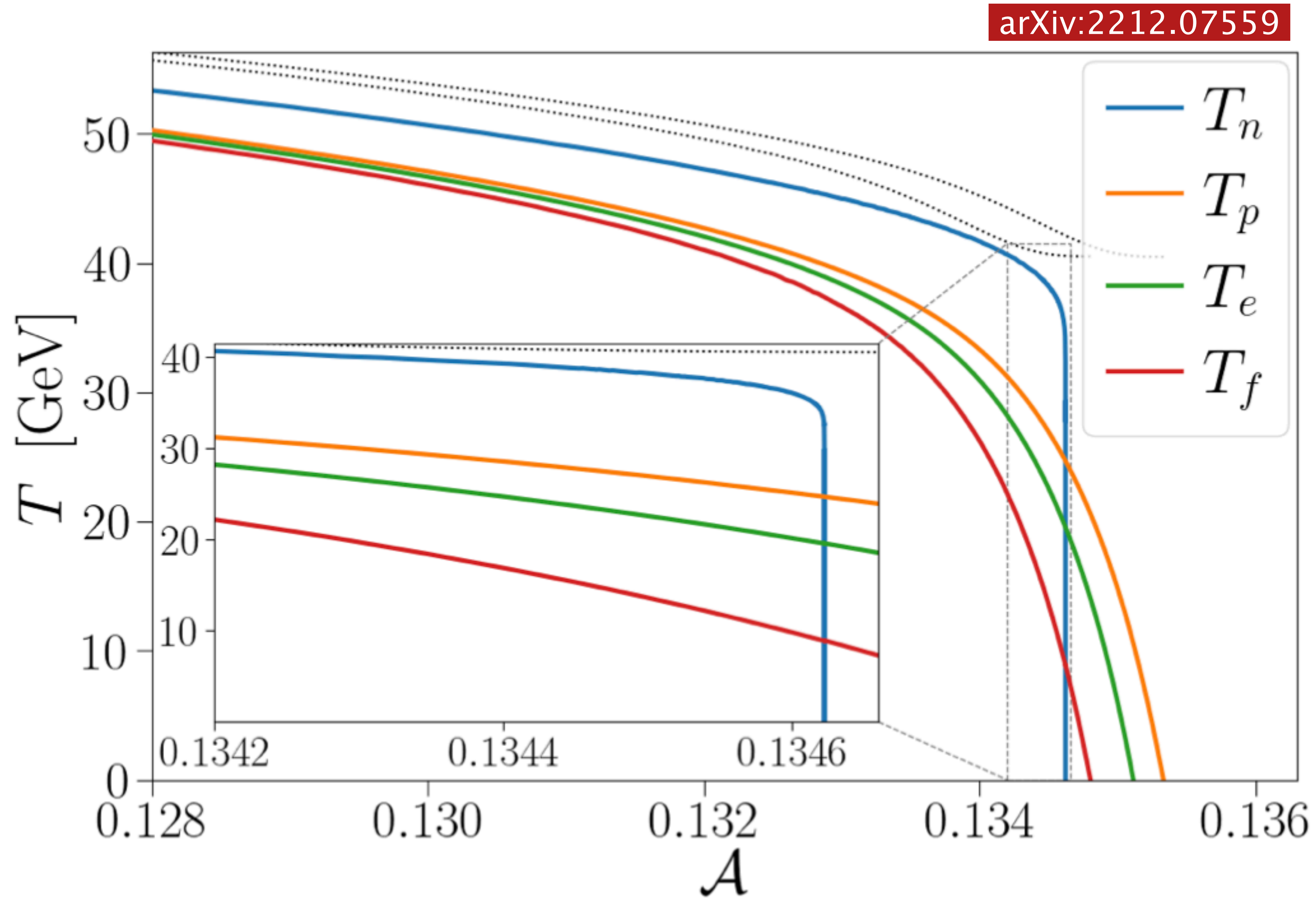


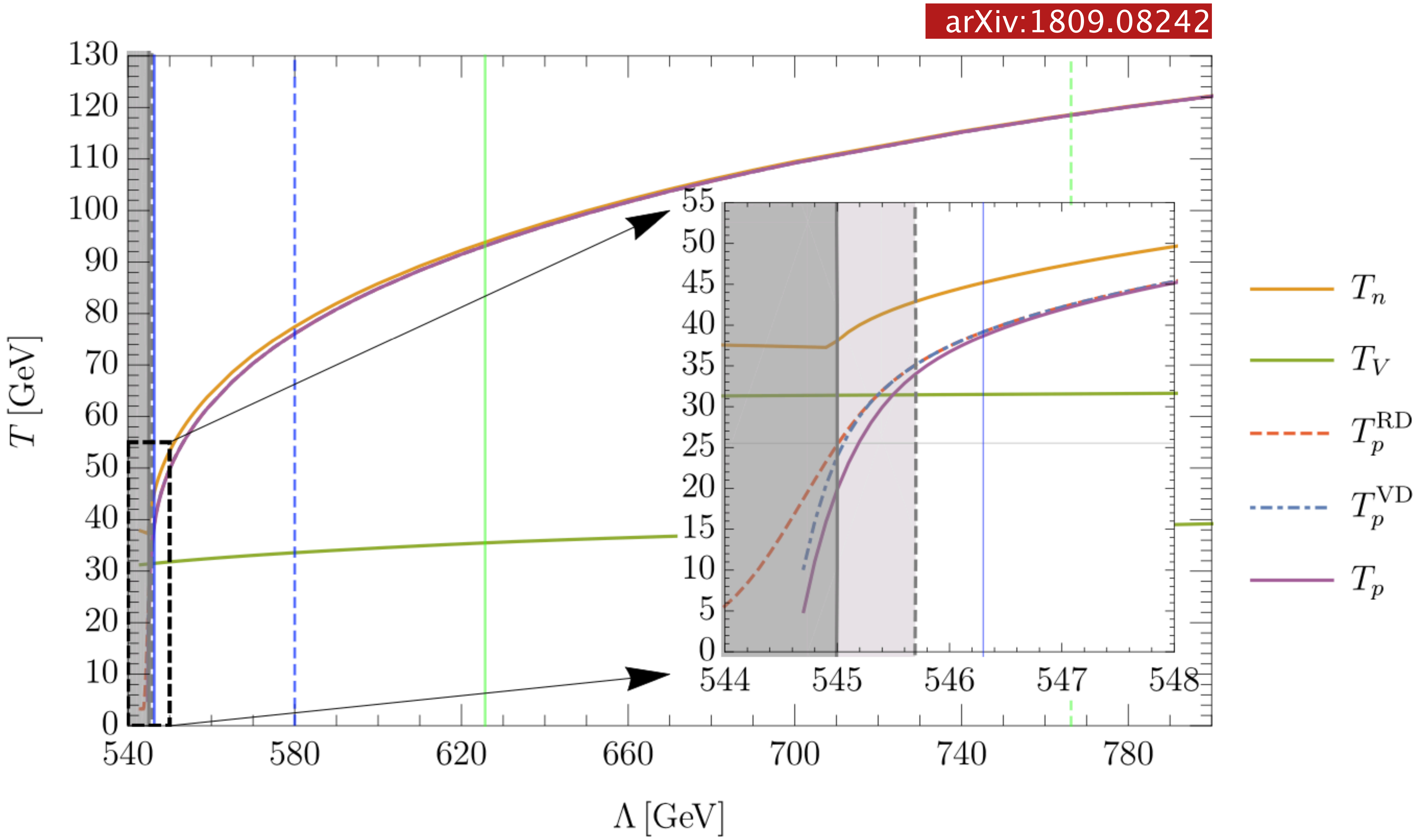
Strongly supercooled FOPT





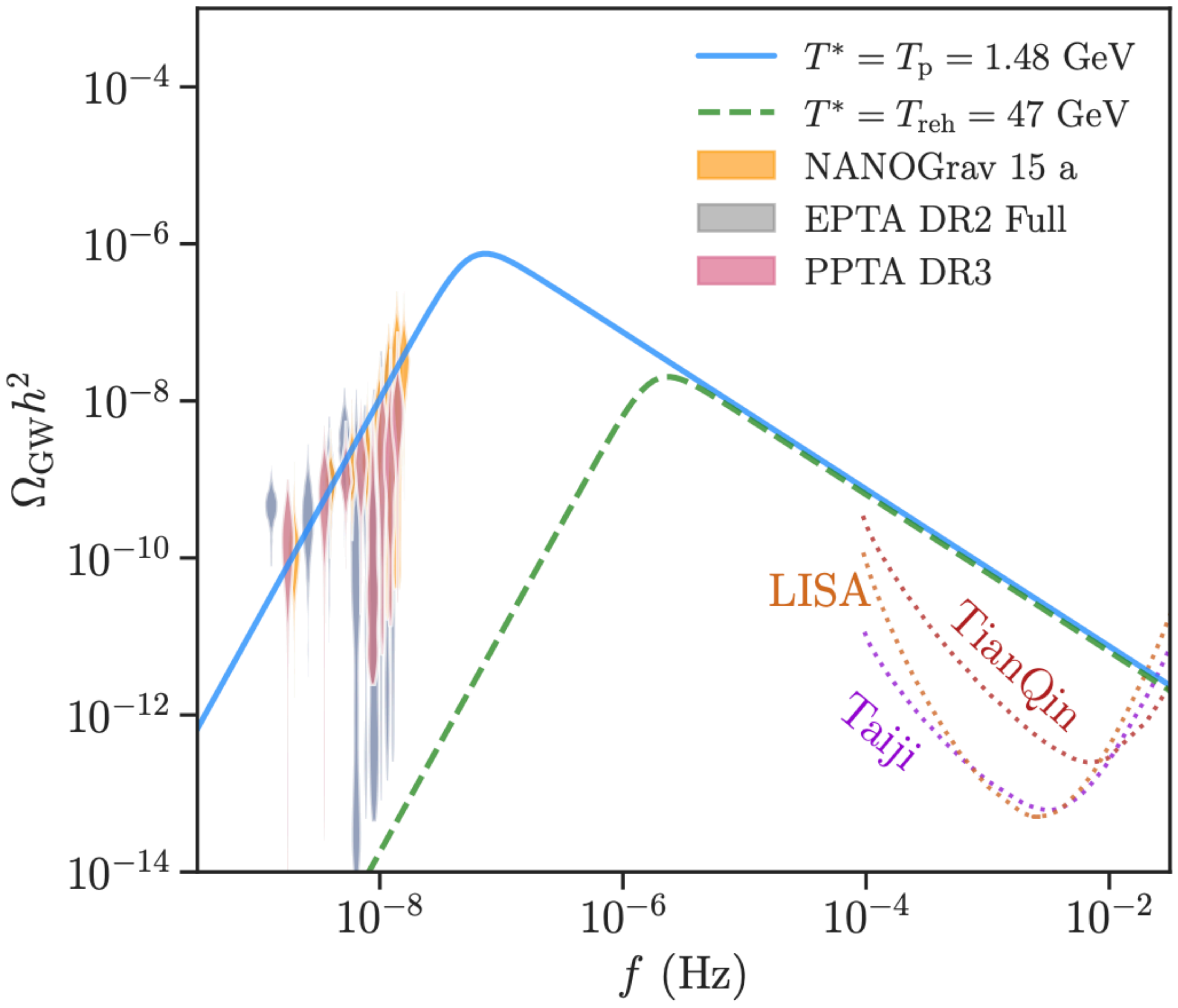
Strongly supercooled FOPT



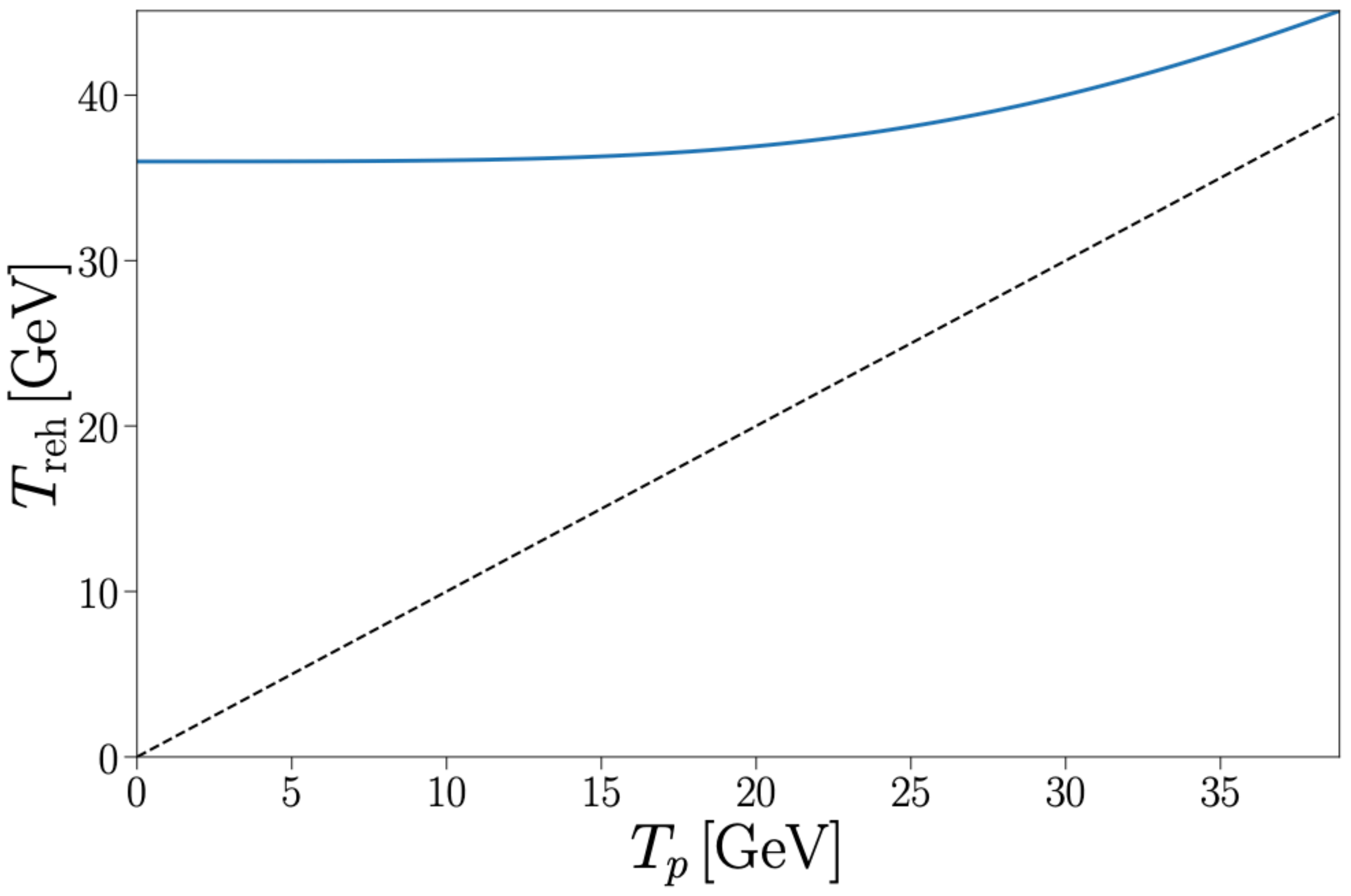


$$T_{\mathrm{reh}} \simeq (1+\alpha)^{1/4} \sim \left(M^4/T_P^4\right)^{1/4} T_P = M$$

Strongly supercooled FOPT

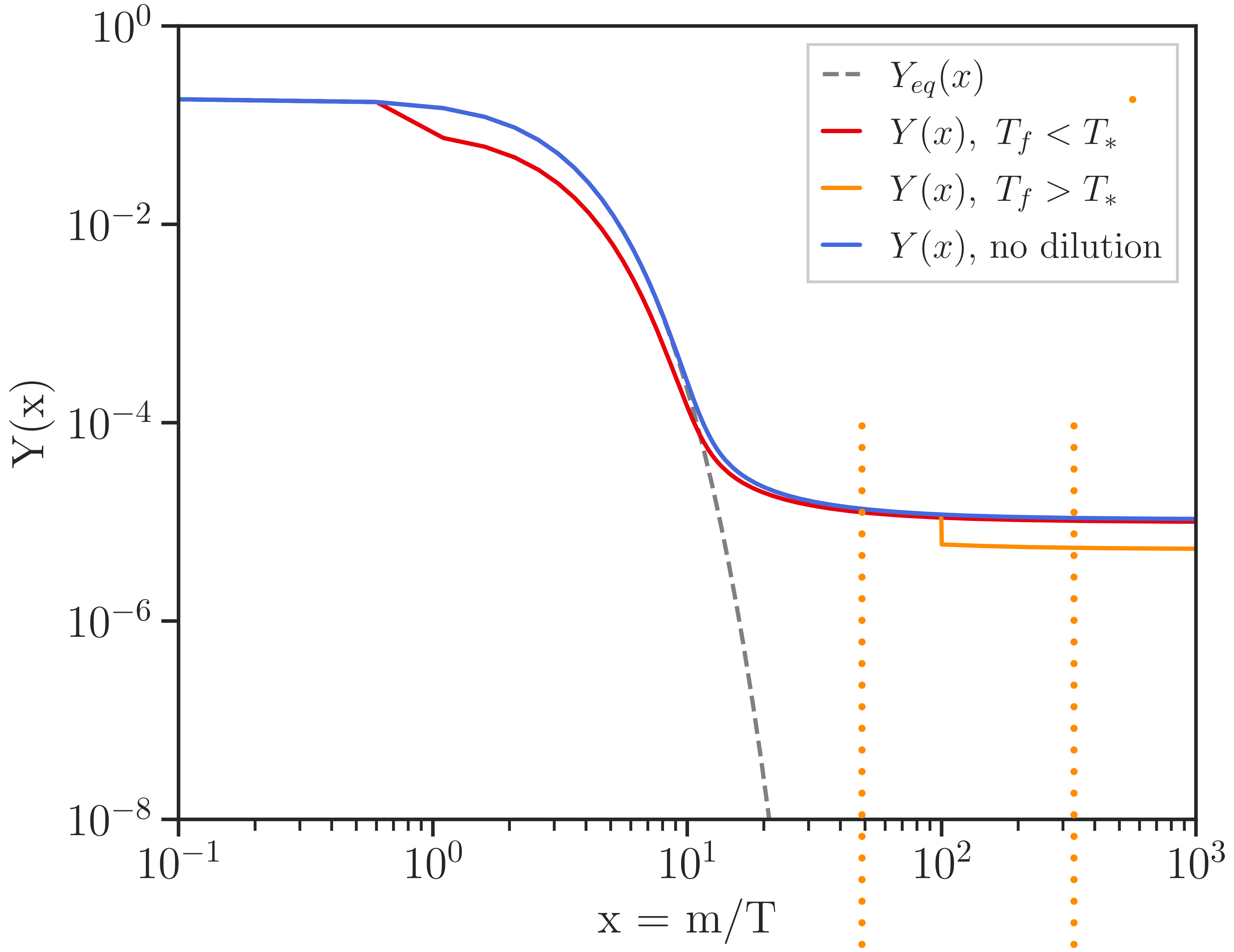


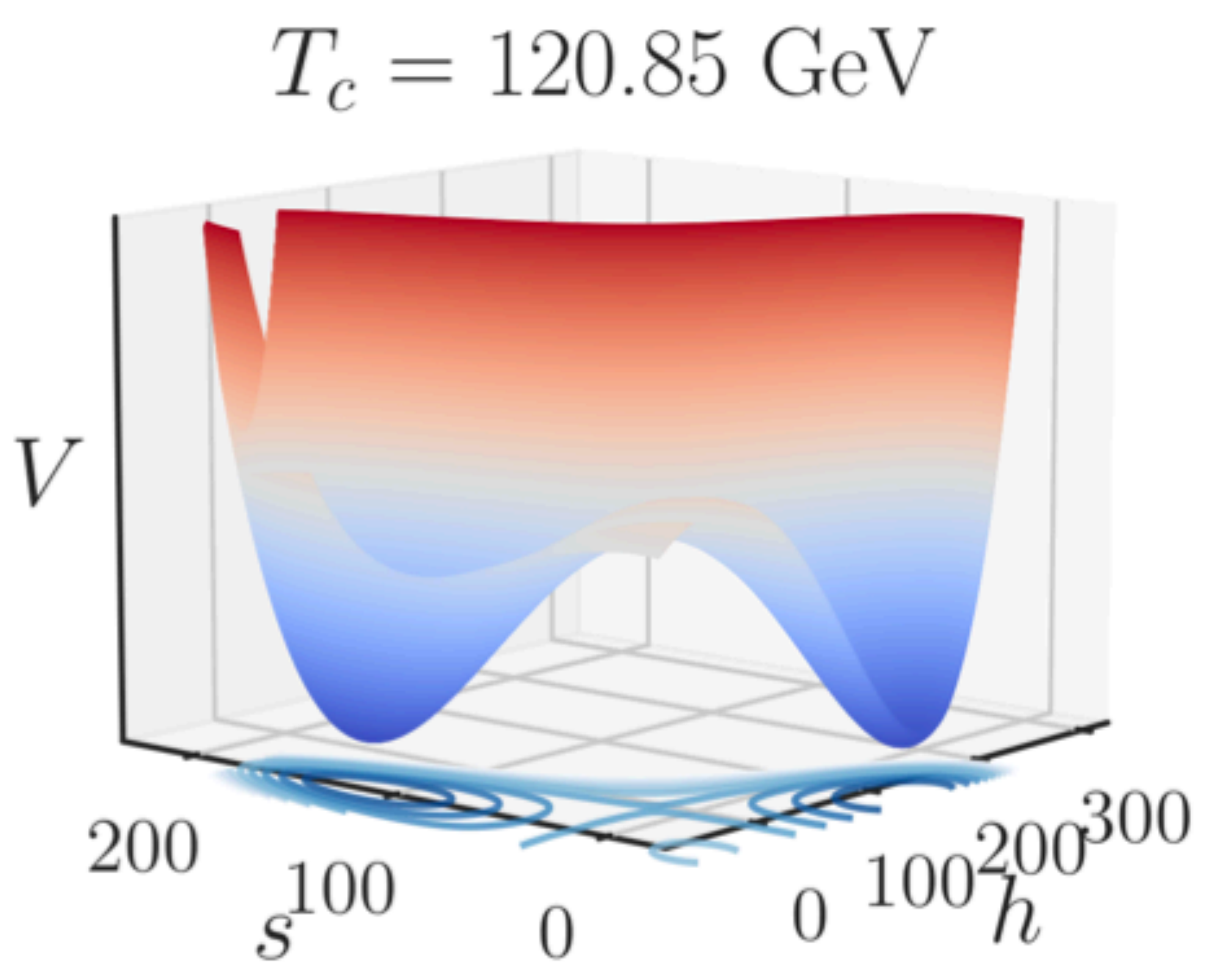
arXiv:2306.17239



$$T_{reh} \sim \left(\frac{M^4}{T_p^4}\right)^{\frac{1}{4}} T_p = M.$$

Strongly supercooled FOPT





$(v_h = 0, v_s \simeq 100 \text{ GeV})$ $(v_h \simeq 246 \text{ GeV}, v_s = 0)$

$T_{\rm reh}$ T_*

Summary

- Inspired by the nano-hertz gravitational wave signal, we have discovered that in the DM model, the critical temperature of a strongly supercooled phase transition can be lower than 1 GeV. However, this scenario poses a challenge in terms of reheating.
- The critical temperature of the strongly supercooled phase transition has the potential to be lower than the freeze-out temperature of the dark matter. As a result, there is a possibility of dilution in the relic density of DM.
- In the case of supercooling, certain quantities need to be recalculated.

谢 谢！