The Vev Flip-Flop: Dark Matter Decay between Weak Scale Phase Transitions

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Based on 1608.07578, MJB & Joachim Kopp

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- There is a phase in the early universe where this scalar has a vev, so the symmetry is broken and DM can decay
- At a lower temperature the symmetry is restored and DM is then stable

- Vev Flip-Flop: Model

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
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$$\mathcal{L}_{\rm Yuk} = y_\chi S_3^\dagger \overline{\chi}\Psi_3 + y_\chi' S_3^\dagger \overline{\chi}\Psi_3' + y_\Psi \epsilon^{ijk} S_3^i \overline{\Psi_3^j}(\Psi_3'^k)^c + h.c.$$

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$$y_\chi \sim y'_\chi \sim 10^{-7} \qquad\qquad y_\Psi \sim 1$$

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$$
\begin{aligned}
V(H,S_3) = &- \mu^2 H^\dagger H + \lambda (H^\dagger H)^2 \\
&- \mu_S^2 S_3^\dagger S_3 + \lambda_S (S_3^\dagger S_3)^2 + \lambda_3 (S_3^\dagger T^a S_3)^\dagger S_3^\dagger T^a S_3 \\
&+ \alpha H^\dagger H S_3^\dagger S_3 + \beta H^\dagger \tau^a H S_3^\dagger T^a S_3
\end{aligned}
$$

• Vev Flip-Flop: Effective Potential

$$V^{\text{eff}} = V^{\text{tree}} + V^{\text{1-loop}}$$

$$= V^{\text{tree}} + \sum_i \frac{n_i T}{2} \sum_{n=-\infty}^{+\infty} \int \frac{d^3\vec{k}}{(2\pi)^3} \log\left[\vec{k}^2 + \omega_n^2 + m_i^2(h,S)\right]$$

$$V^{\text{eff}} = V^{\text{tree}} + V^{\text{CW}} + V^{T} + V^{\text{daisy}}$$

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$$V^{\text{eff}} = V^{\text{tree}} + \underline{V^{\text{CW}}} + V^{T} + V^{\text{daisy}}$$

$$V^{\text{CW}}(h,S) = \sum_i \frac{n_i}{64\pi^2} m_i^4(h,S)\left[\log\frac{m_i^2(h,S)}{\Lambda^2} - \frac{3}{2}\right]$$

$$m_A^2(h,S) = -\mu_S^2 + \frac{1}{2}\alpha h^2 + \lambda_S S^2$$

$$m_{G^0}^2(h,S) = -\mu^2 + \lambda h^2 + \frac{1}{2}\alpha S^2$$

$$m_{W^\pm}^2(h,S) = \frac{1}{4}g^2(h^2 + 4S^2)$$

$$m_Z^2(h,S) = \frac{1}{4}(g^2 + g'^2)h^2$$

$$m_\gamma^2(h,S) = 0$$

$$m_t^2(h,S) = \frac{1}{2}y_t^2 h^2$$

$$i \in \{A, G^0, W^\pm, Z, \gamma, t, h - S, S^+ - S^- - G^+\}$$

Coleman & Weinberg, 1973

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$$V^{\text{ct}} = -\frac{h^2}{2}\left(\left.\frac{\partial^2 V^{\text{CW}}}{\partial h^2}\right|_{\text{min}} + \frac{3}{2v}\left(\left.\frac{\partial V^{\text{CW}}}{\partial h}\right|_{\text{min}} - v\left.\frac{\partial^2 V^{\text{CW}}}{\partial h^2}\right|_{\text{min}}\right)\right) + \\ + \frac{h^4}{4}\frac{1}{2v^3}\left(\left.\frac{\partial V^{\text{CW}}}{\partial h}\right|_{\text{min}} - v\left.\frac{\partial^2 V^{\text{CW}}}{\partial h^2}\right|_{\text{min}}\right)$$

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$$V^T(h,S) = \sum_i \frac{n_i T^4}{2\pi^2} \int_0^\infty dx\, x^2 \log\left[1 \pm \exp\left(-\sqrt{x^2 + m_i^2(h,S)/T^2}\right)\right]$$

Dolan & Jackiw, 1974

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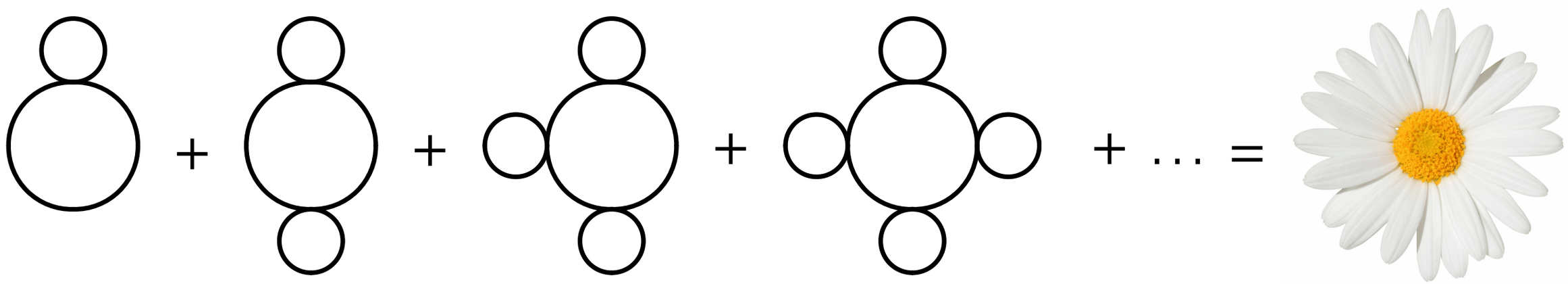

$$V^{\text{daisy}} = -\frac{T}{12\pi}\sum_i n_i \Big(\left[m_i^2(h,S) + \Pi_i(T)\right]^{\frac{3}{2}} - \left[m_i^2(h,S)\right]^{\frac{3}{2}} \Big)$$

$$\Pi_{S,A,S_R^+,S_I^+,S_R^-,S_I^-} = \frac{T^2}{6}\left(3g^2 + \alpha + 2\lambda_3 + 4\lambda_S\right)$$

Dolan & Jackiw, 1974

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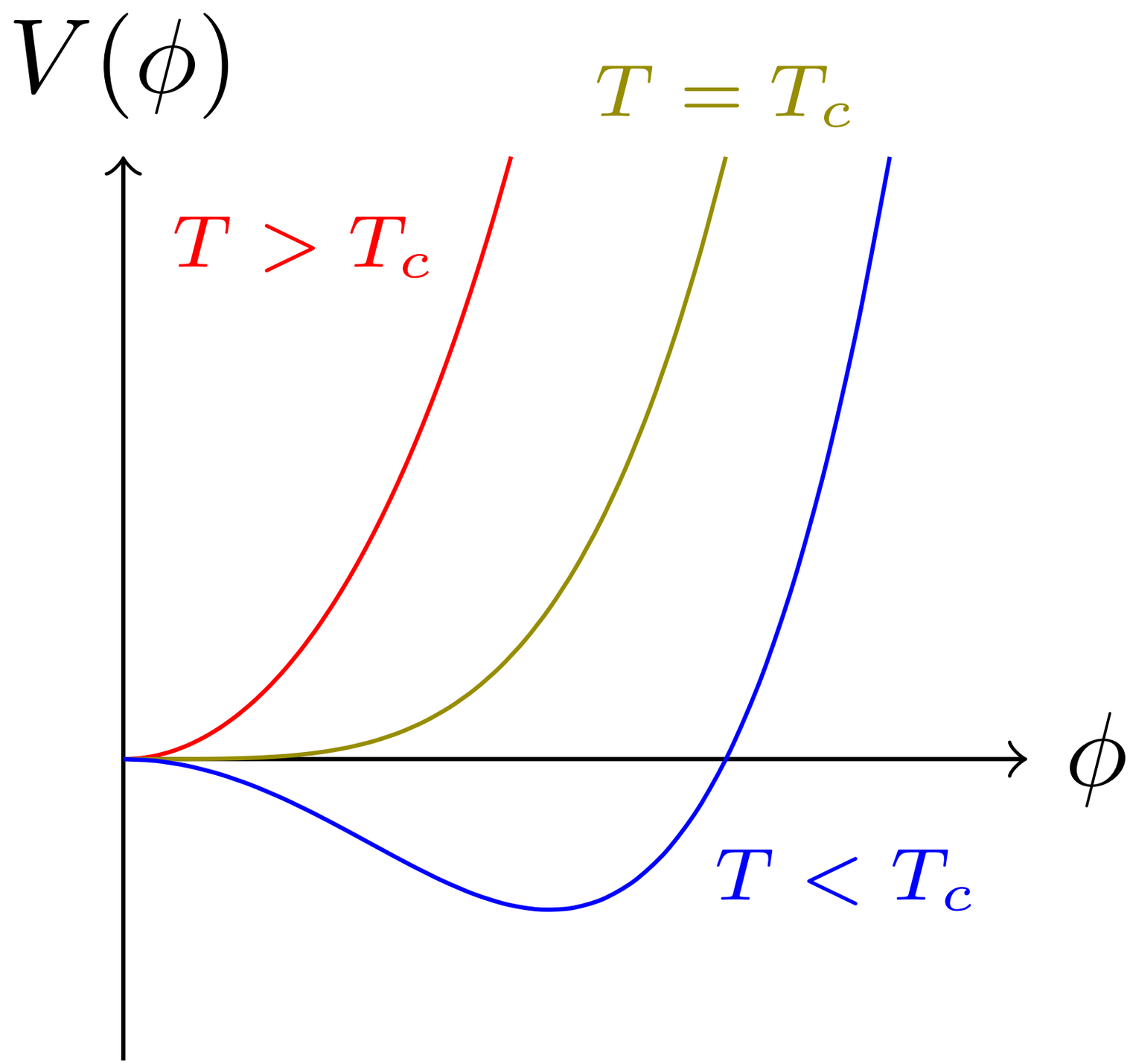

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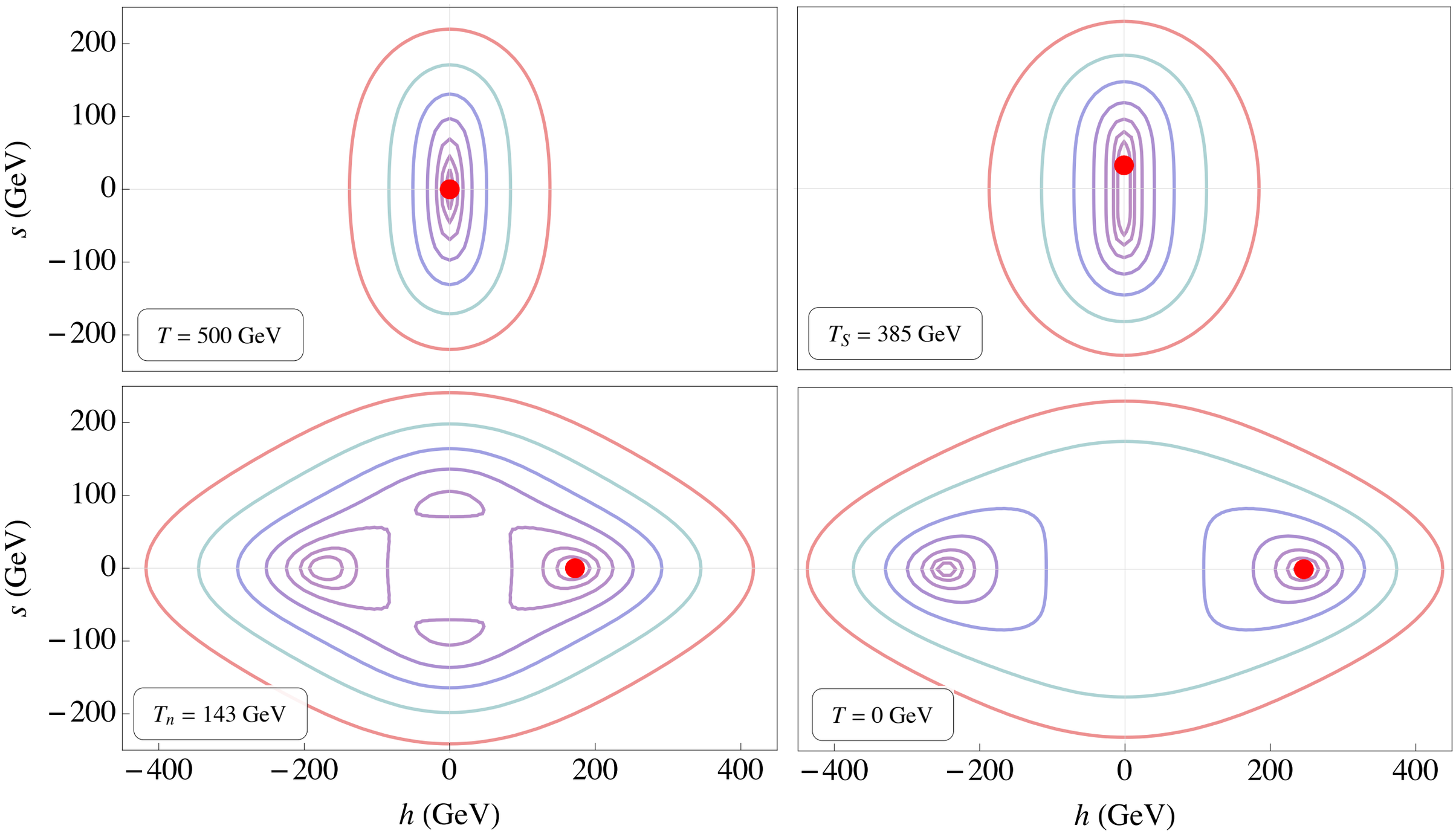

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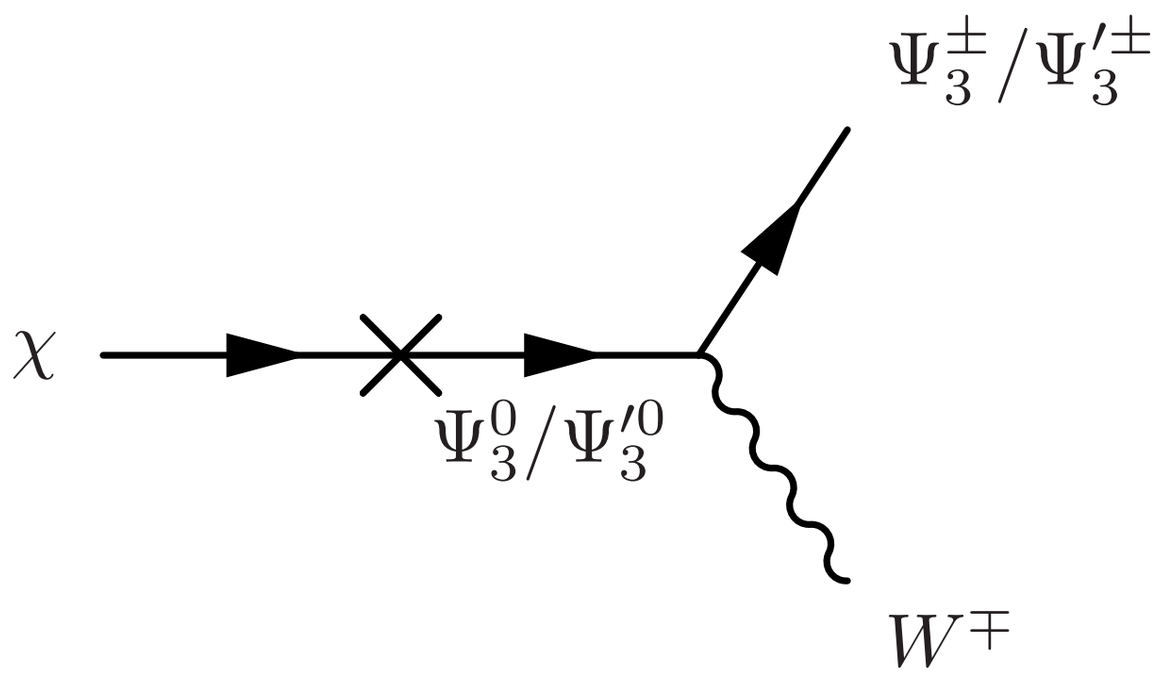

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Coupled Boltzmann equations

$$\dot{n}_\chi^j + 3Hn_\chi^j = -\frac{\Gamma}{\gamma^j}(n_\chi^j - n_\chi^{j,\mathrm{eq}})$$

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In practice we substitute

$$Y^j \equiv \frac{n^j}{s}, \qquad s = g_* \frac{2\pi^2}{45} T^3$$

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And find $\dot{T}$

$$\dot{\rho}_{\mathrm{SM}} = 4\rho_{\mathrm{SM}}\frac{\dot{T}}{T} = m_\chi \sum_j \frac{\Gamma}{\gamma^j}(n_\chi^j - n_\chi^{j,\mathrm{eq}}) - 4H\rho_{\mathrm{SM}}$$

$$\frac{dT}{dt} = \sum_j (n_\chi^j - n_\chi^{j,\mathrm{eq}})\frac{m_\chi \Gamma T}{4\gamma^j \rho_{\mathrm{SM}}} - HT$$

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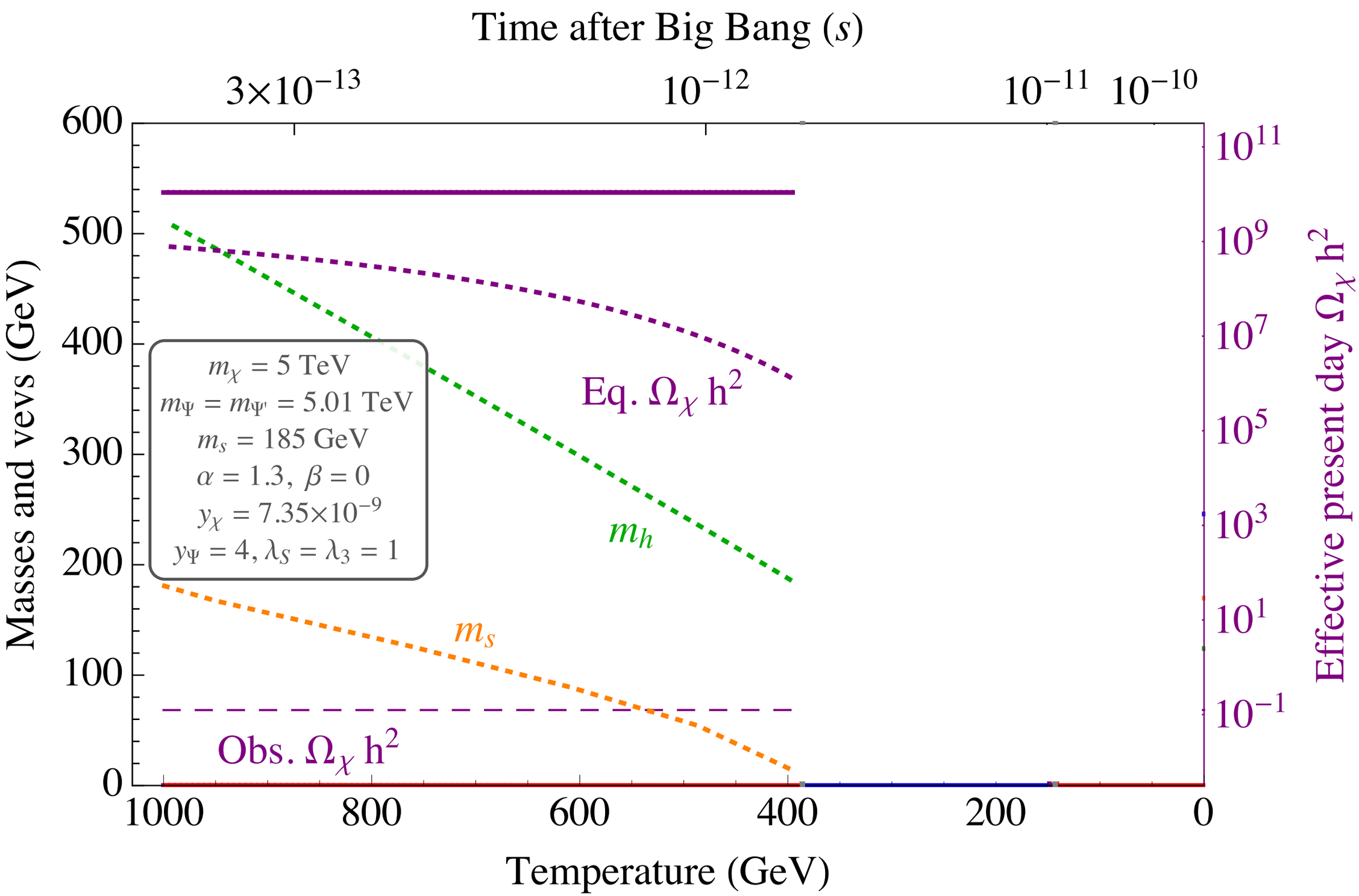

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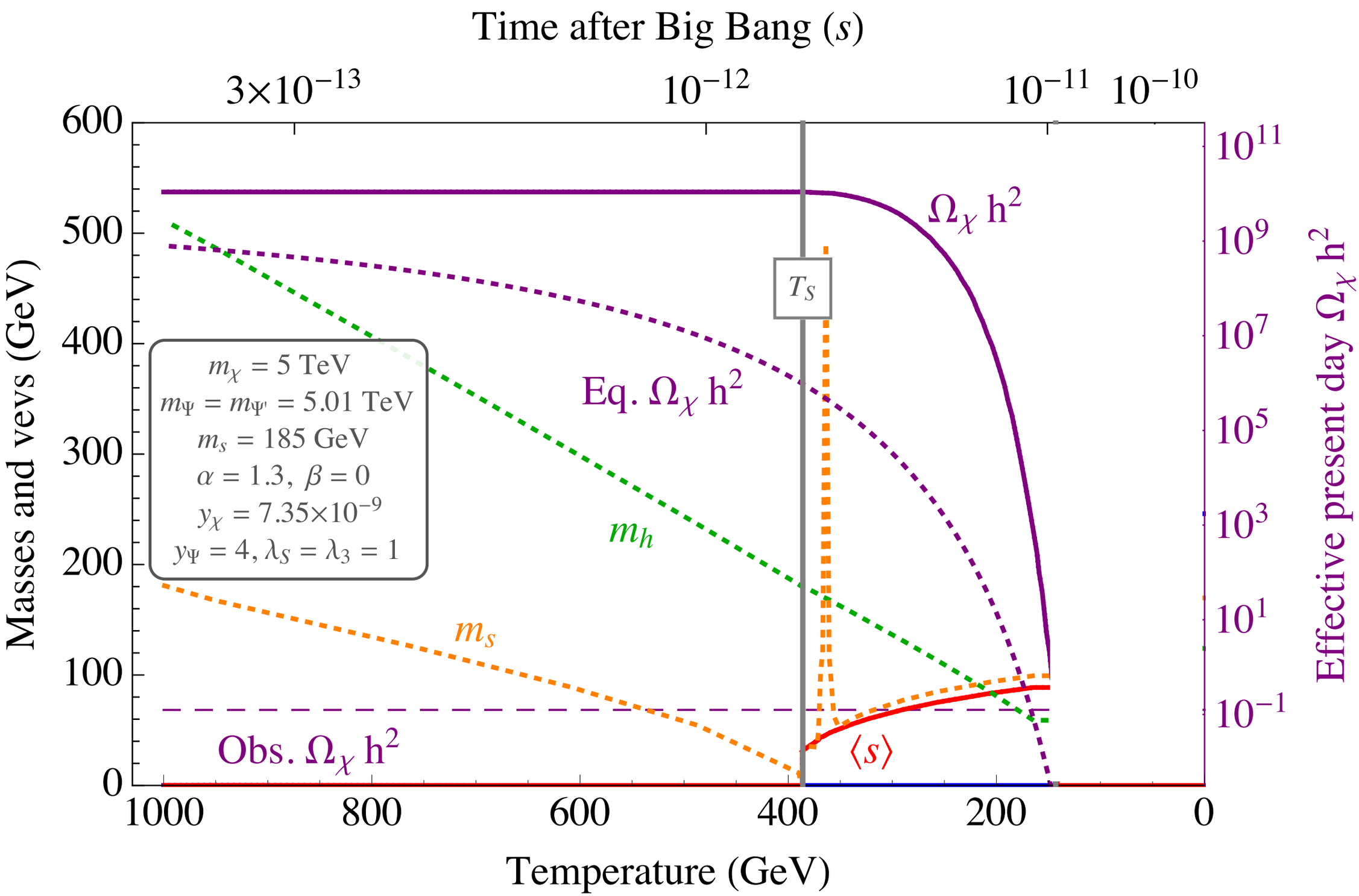

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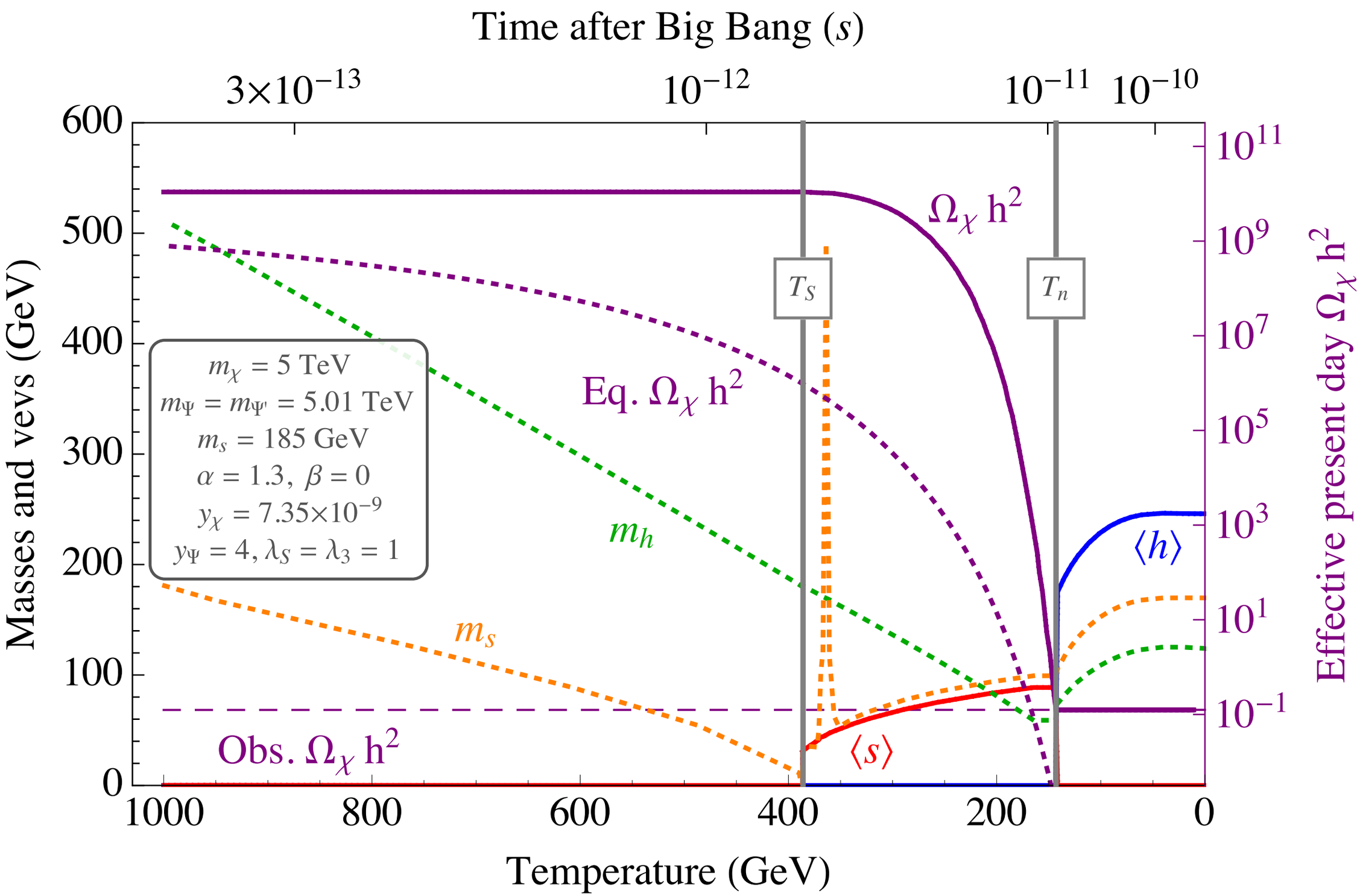
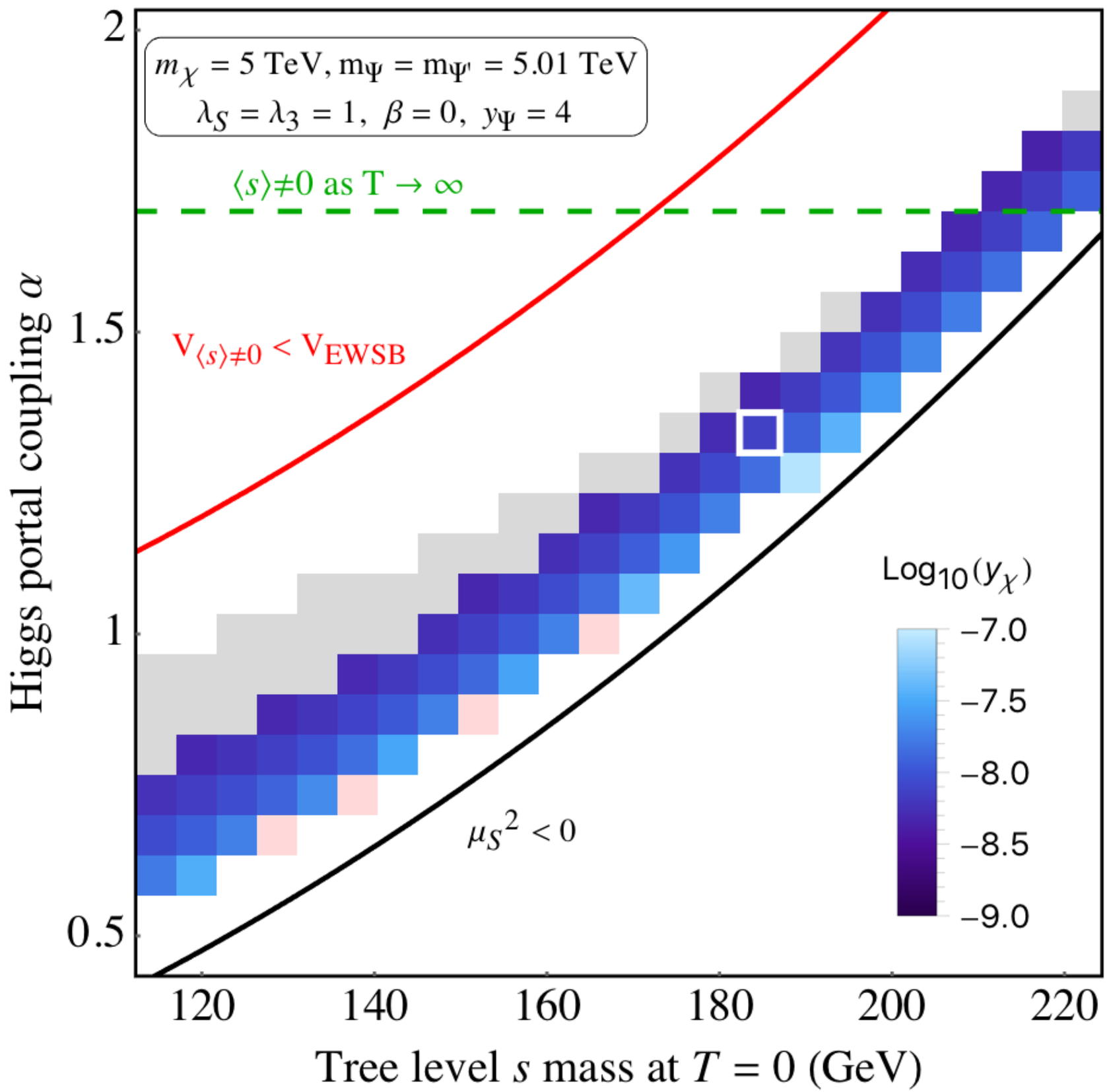


- Vev Flip-Flop: Parameter Space



• Vev Flip-Flop: Possible tests

Direct and Indirect Detection

Detection of χ hindered by small couplings

Best prospect from subdominant population of $s, \Psi_3^0, \Psi_3'^0$

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Drell-Yan production of $s^\pm$ pairs, followed by $s^\pm \to s + W^{*\pm}$

Small mass splitting implies soft decay products

Mono-X is several orders of magnitude too weak

Possibilities in disappearing charged tracks

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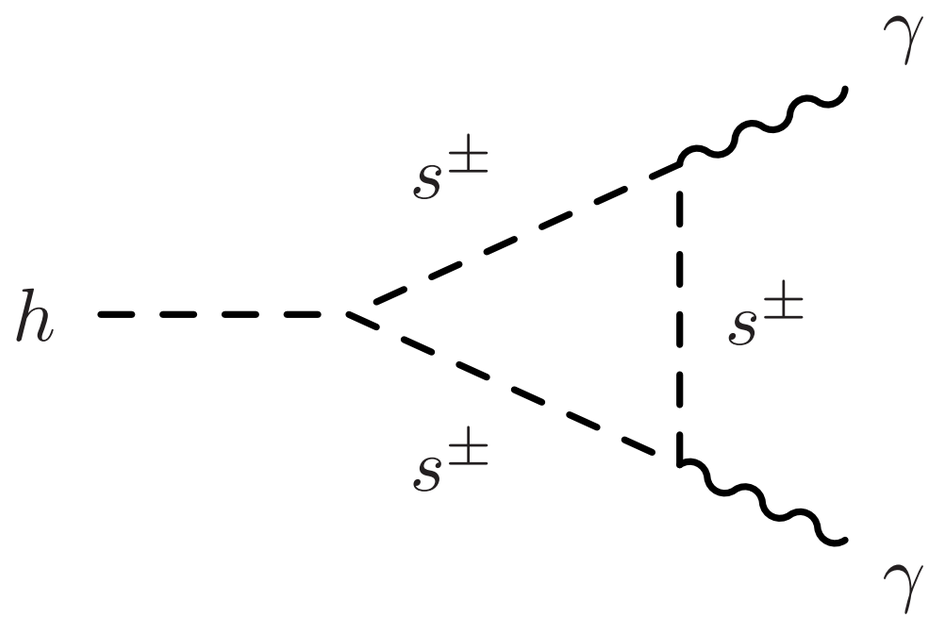

$$\Gamma(h \to \gamma\gamma) = \frac{v^2}{16\pi m_h}|F^{\gamma\gamma}|^2$$

$$|F^{\gamma\gamma}|^2 = (|F_W^{\gamma\gamma}| - |F_f^{\gamma\gamma}| - |F_{S_3}^{\gamma\gamma}|)^2$$

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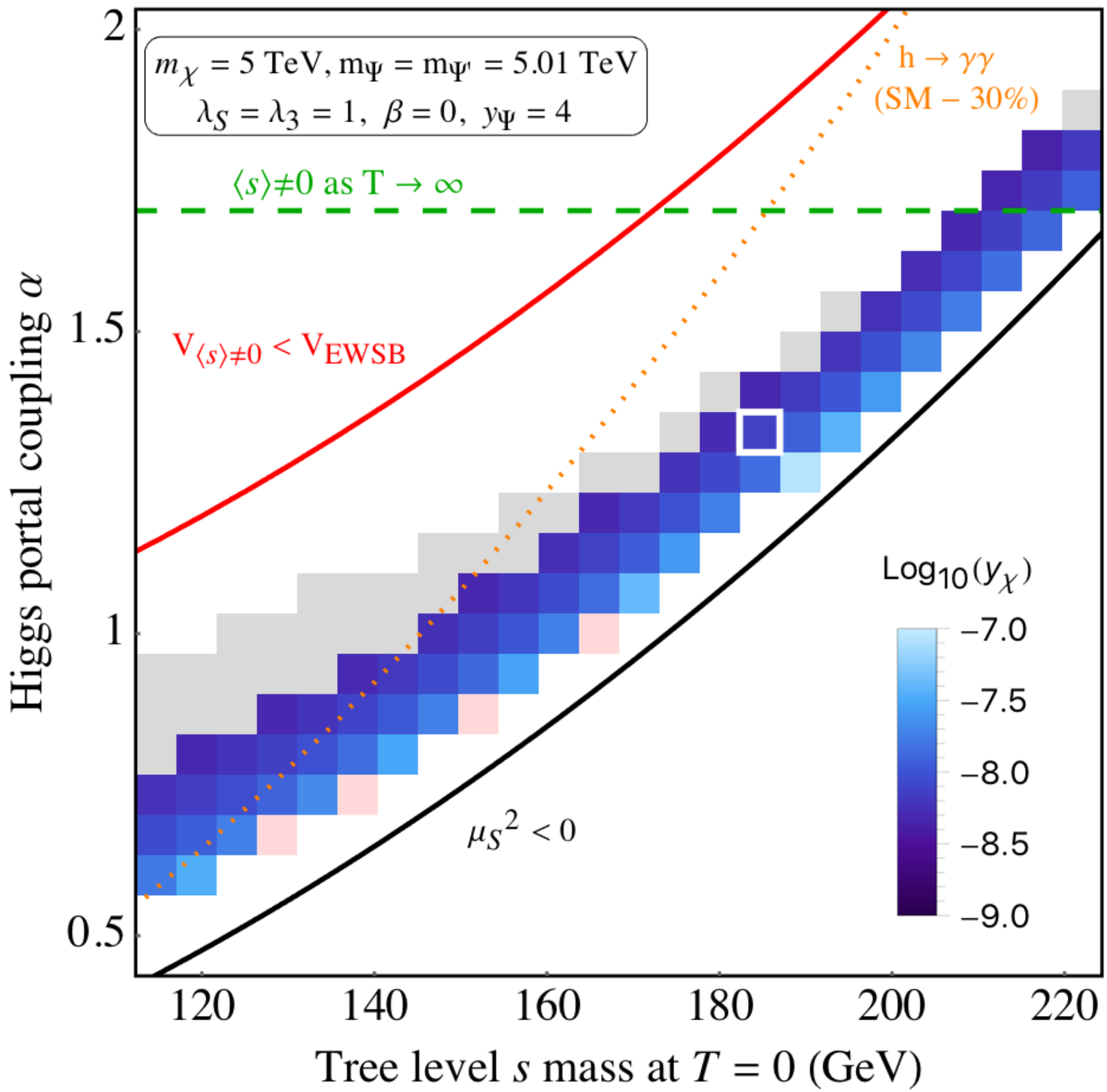

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- Outlook:
  - More realisations,
  - LHC phenomenology,
  - gravitational wave signals,
  - baryogenesis,…