University of Zurich[UZH]

Dynamic DM Production

Finite Temperature Effects and the Vev Flip Flop

Michael J. Baker

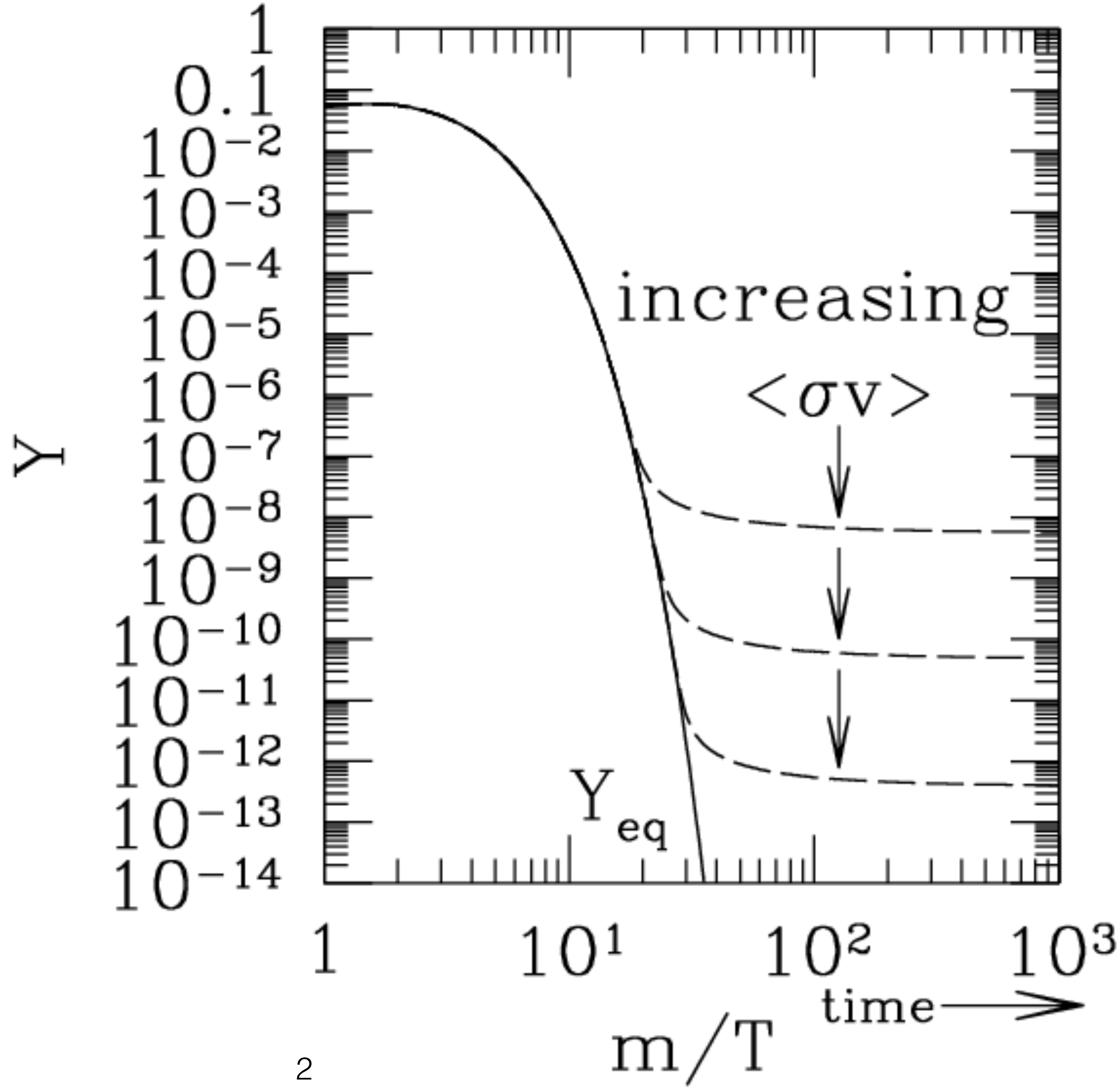
Blois, 06 June 2018

Based on 1608.07578 (PRL)
and 1712.03962 (JHEP)
MJB, M. Breitbach, L. Mittnacht, J. Kopp

• The thermal WIMP paradigm

1009.3690 — Gondolo & Gelmini

1) Assume a new, heavy particle is in thermal equilibrium in the early universe.



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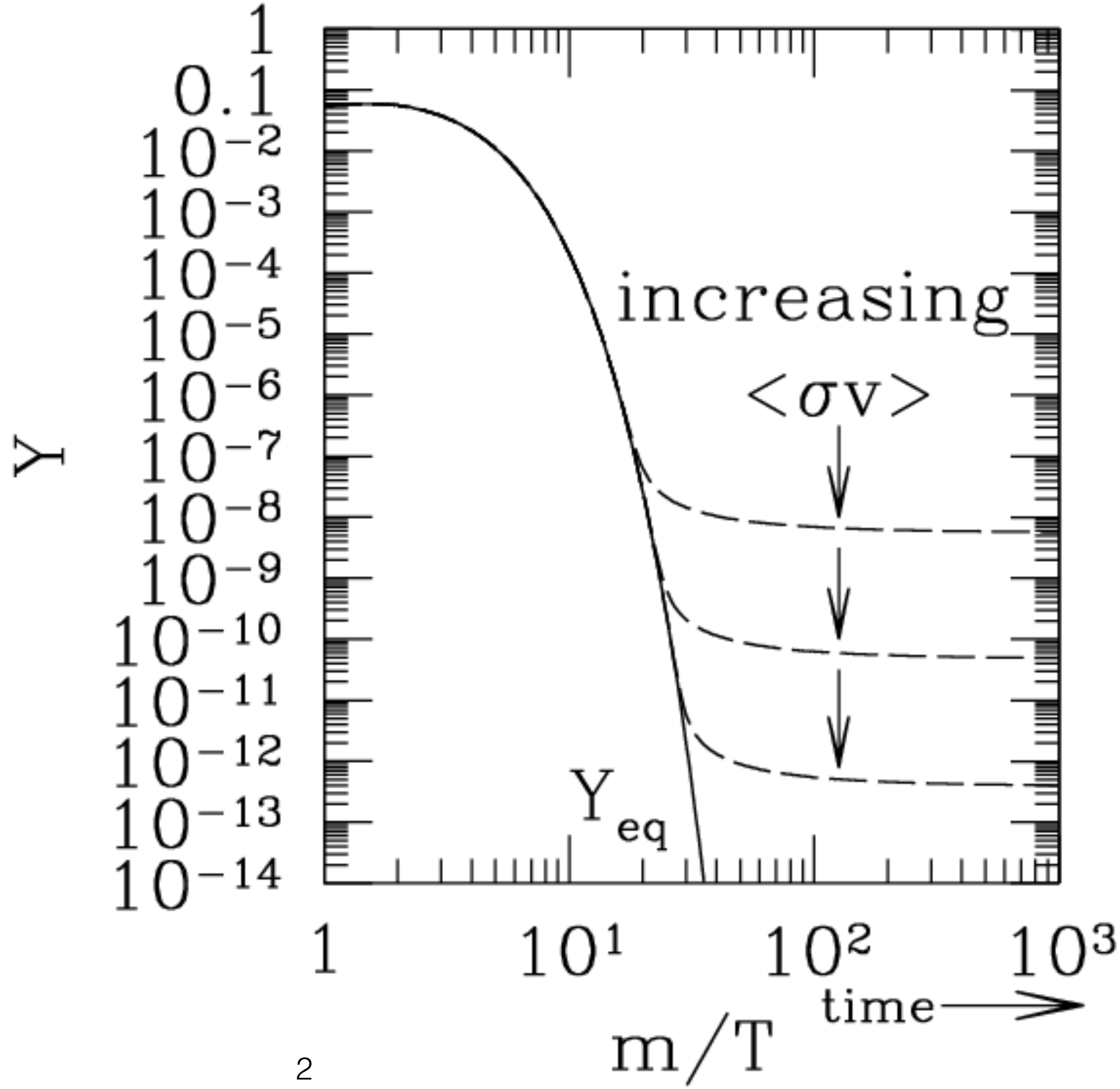
$$H \gtrsim \Gamma$$



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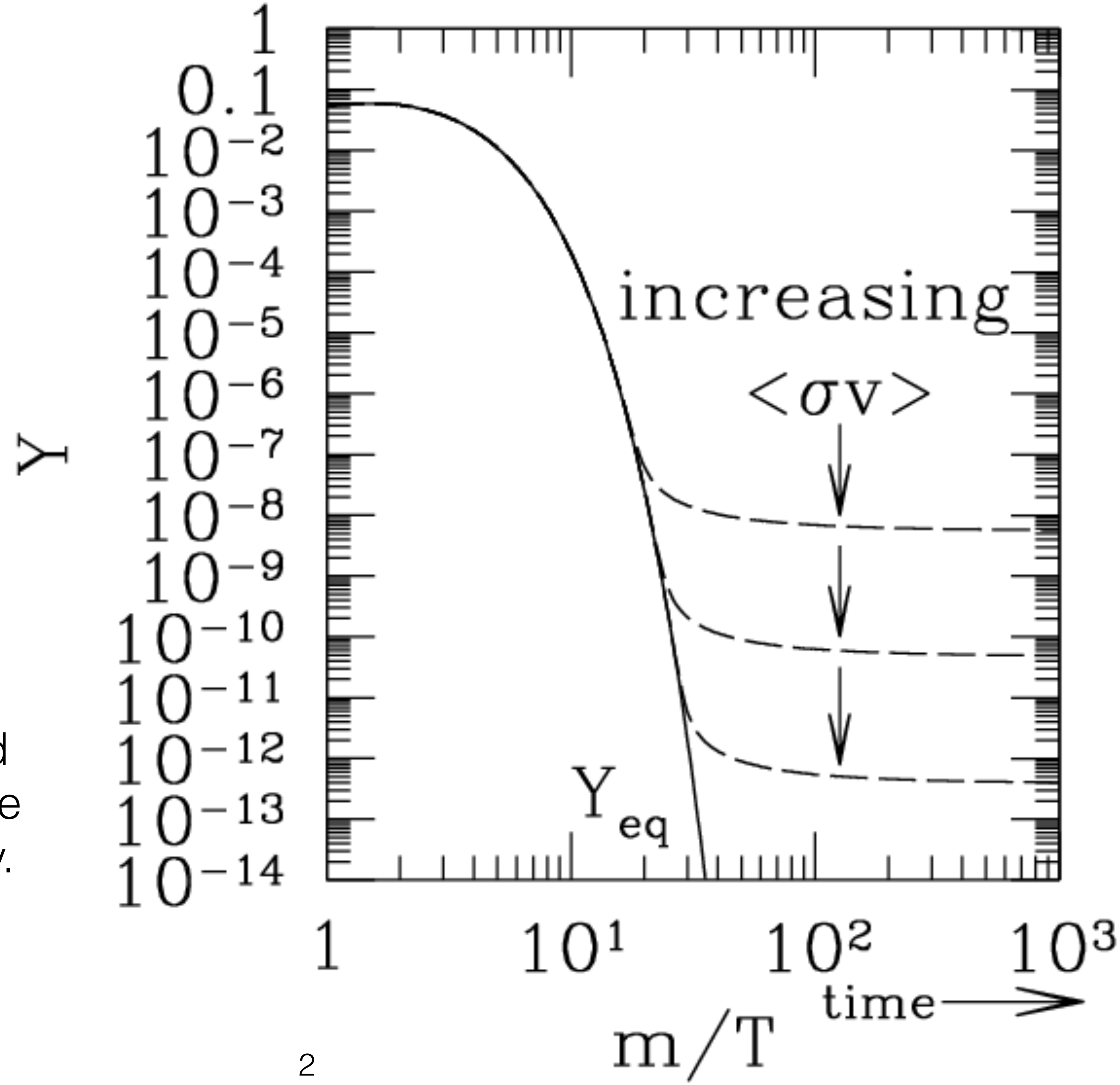
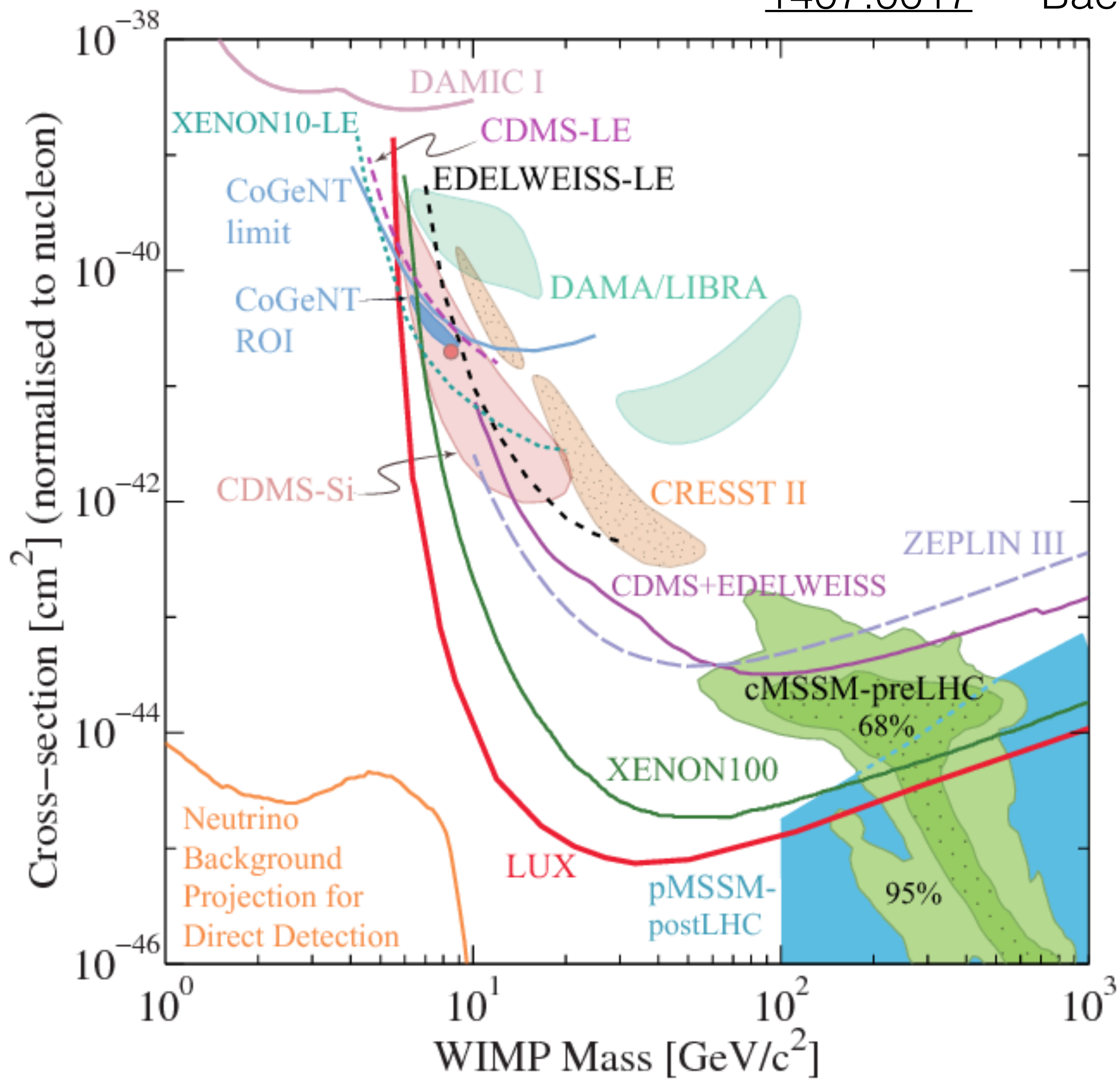
3) Weak scale masses and order one couplings give ~ observed relic density.



- The thermal WIMP paradigm

1407.0017 — Baer, Howard et al.



• Thermal Freeze-in

0911.1120 — Hall, Jedamzik, March-Russell & West

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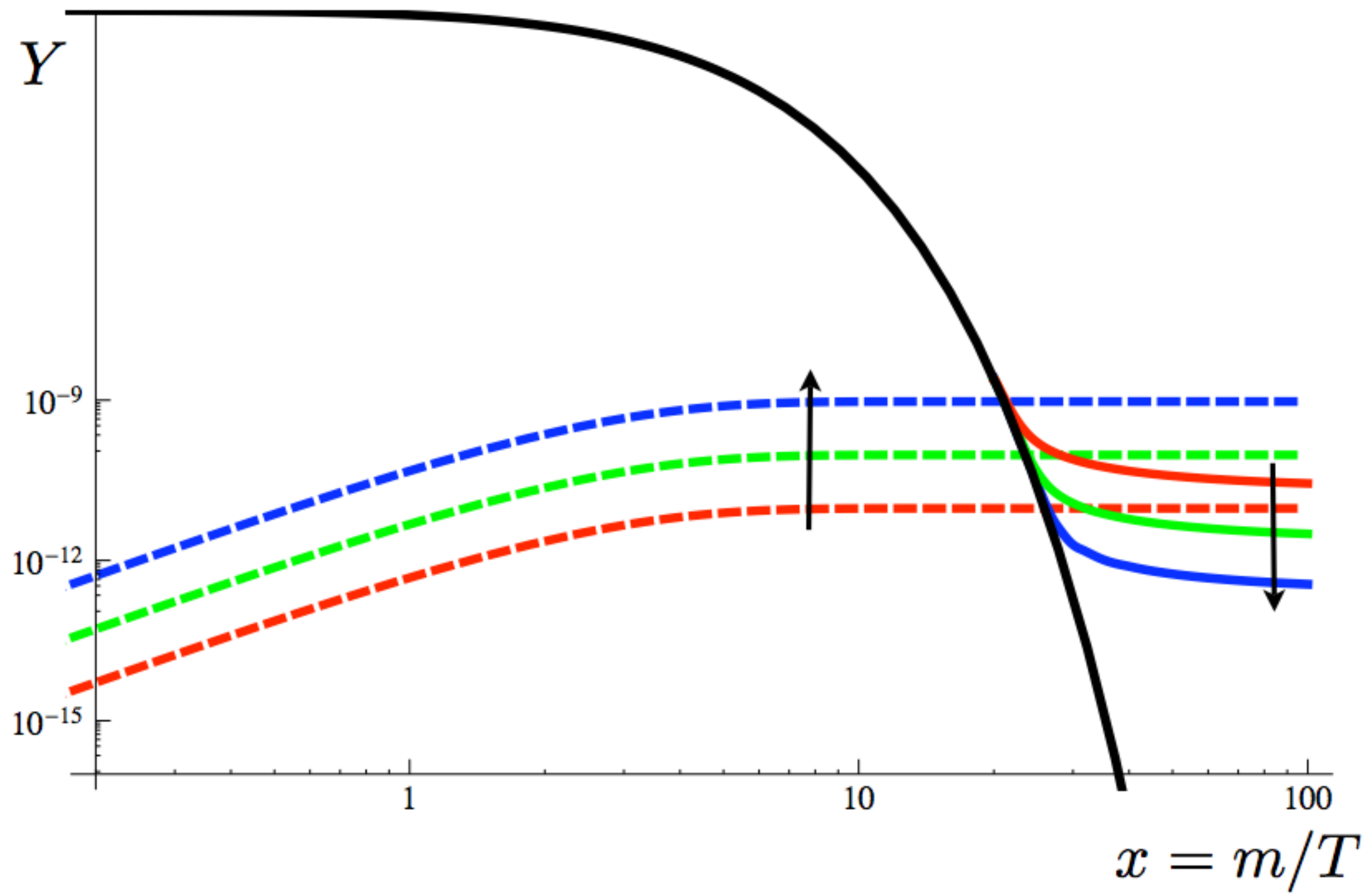

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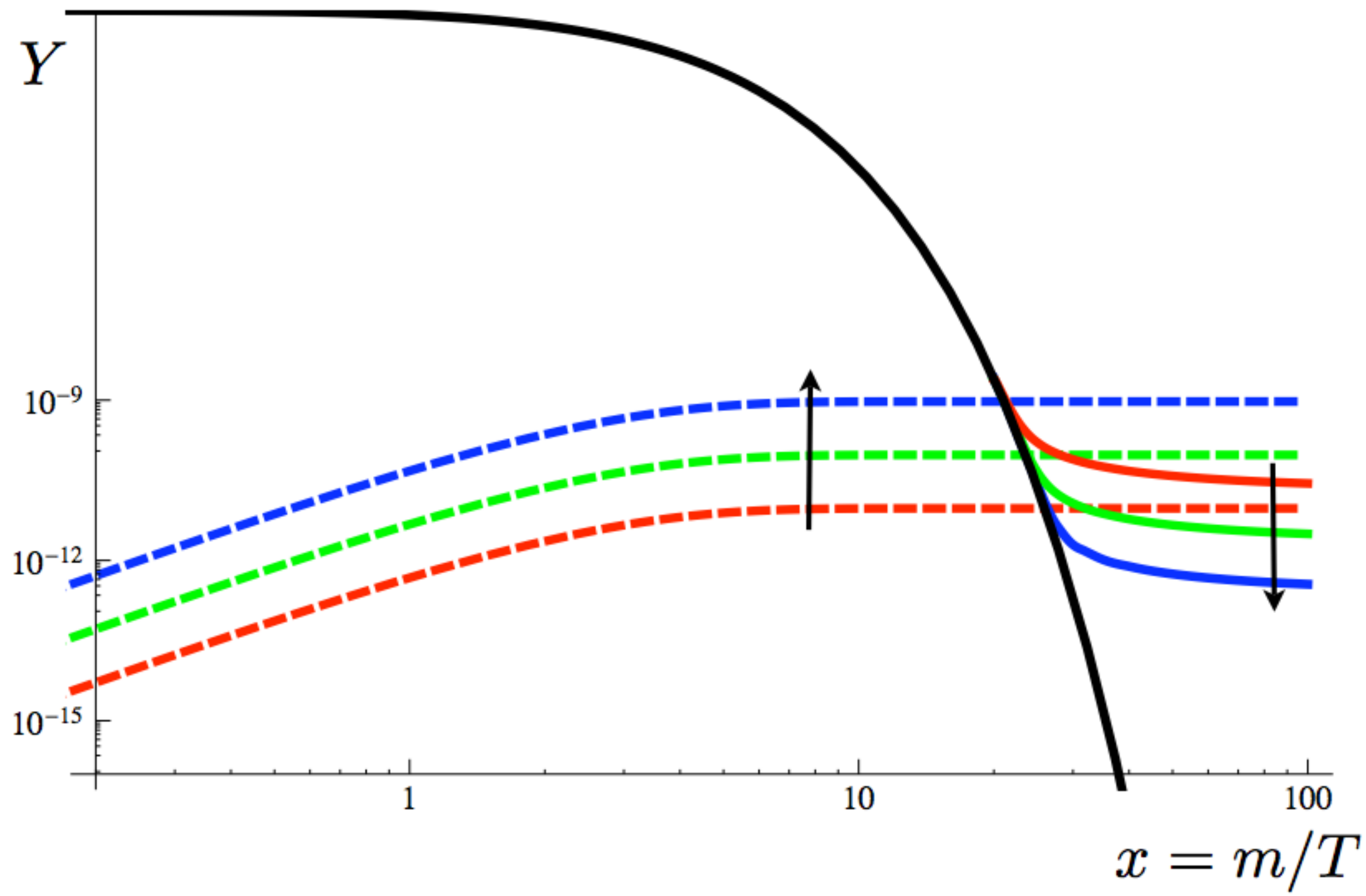

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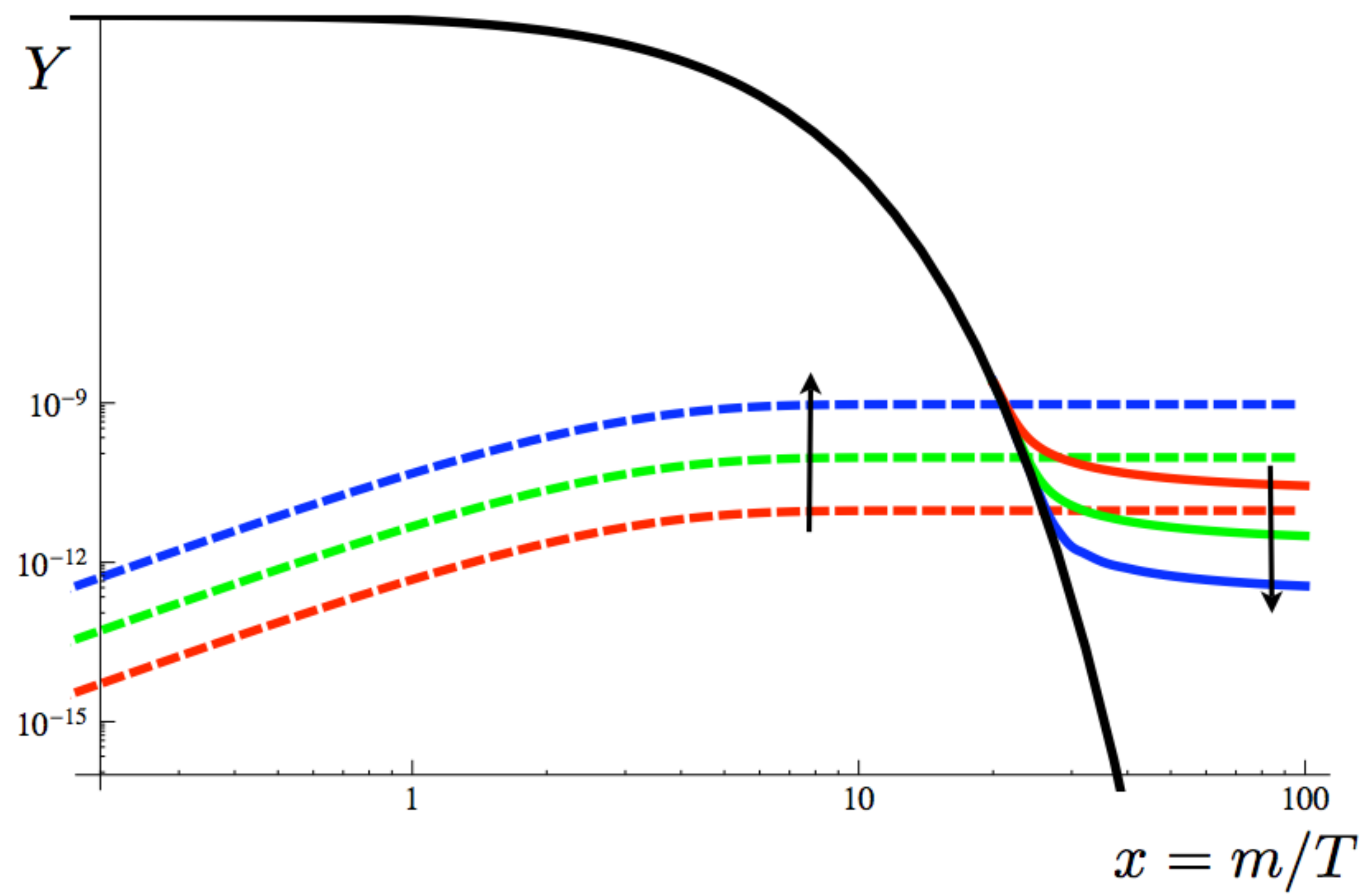
3) Whereas freeze-out is determined by physics at x ~ 20 - 30, freeze-in is determined at x ~ 2 - 5.



- Overview

In this talk we will discuss three BSM scenarios:

- Kinematically induced freeze-in
- Vev induced freeze-in
- Decaying dark matter

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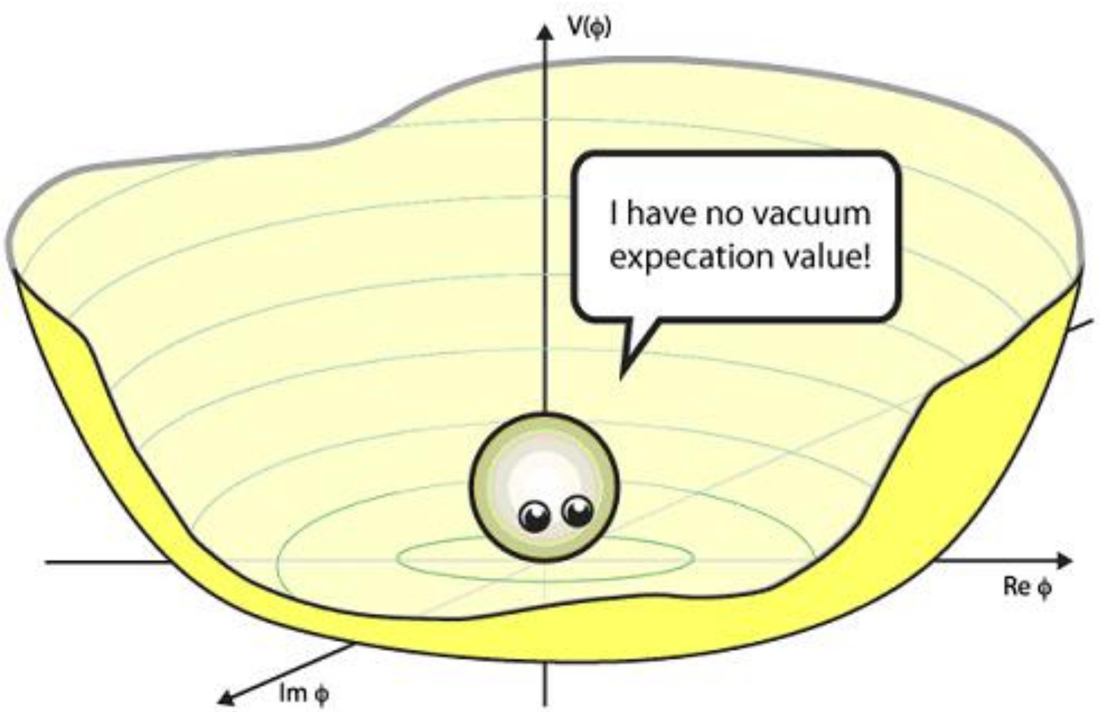
Our main tools will be:

- The effective potential at finite temperature
- Boltzmann equations

- The Standard Model Effective Potential

$$T \gg T_{\mathrm{EW}}$$



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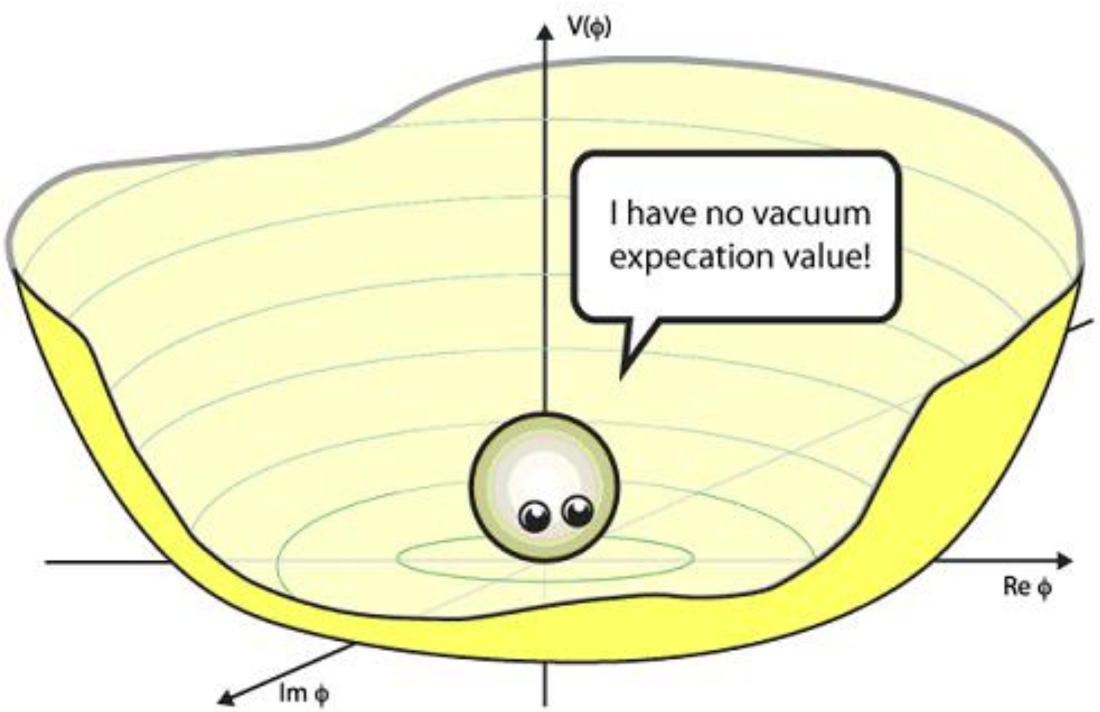
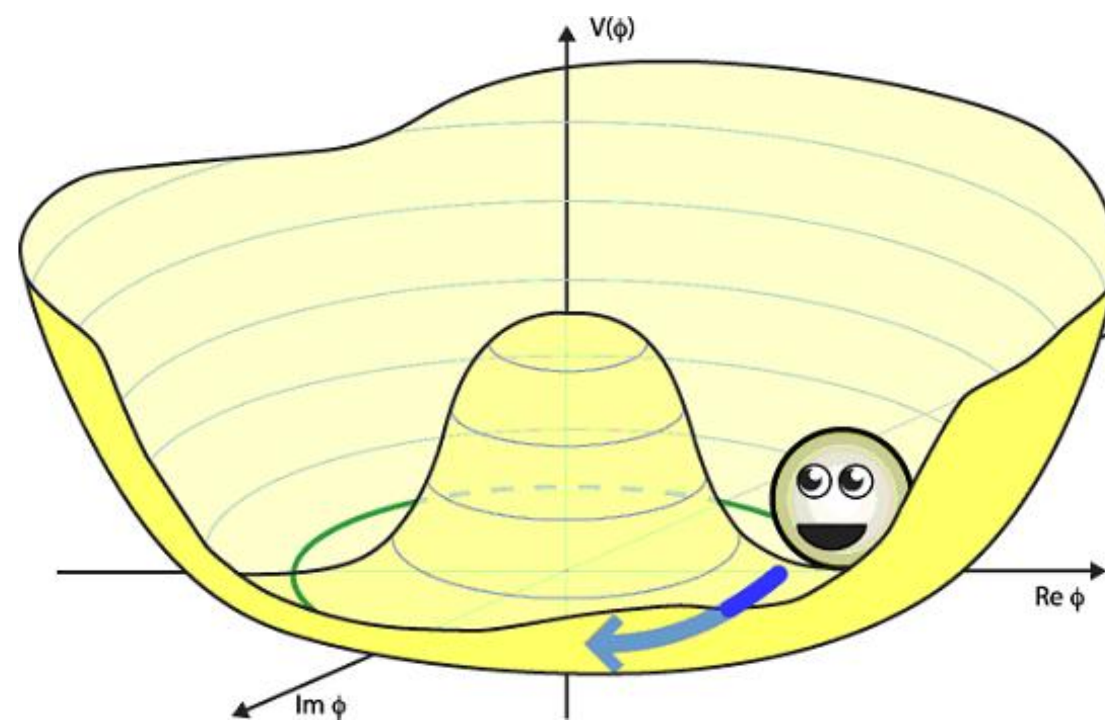


$T \sim 0$



Kinematically Induced Freeze-in

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Field	Spin	$\mathbb{Z}_2$	mass scale
S	0	$+1$	$m_S \sim 5\,\mathrm{GeV}$
χ	$\frac{1}{2}$	-1	$m_\chi \sim 50\,\mathrm{GeV}$
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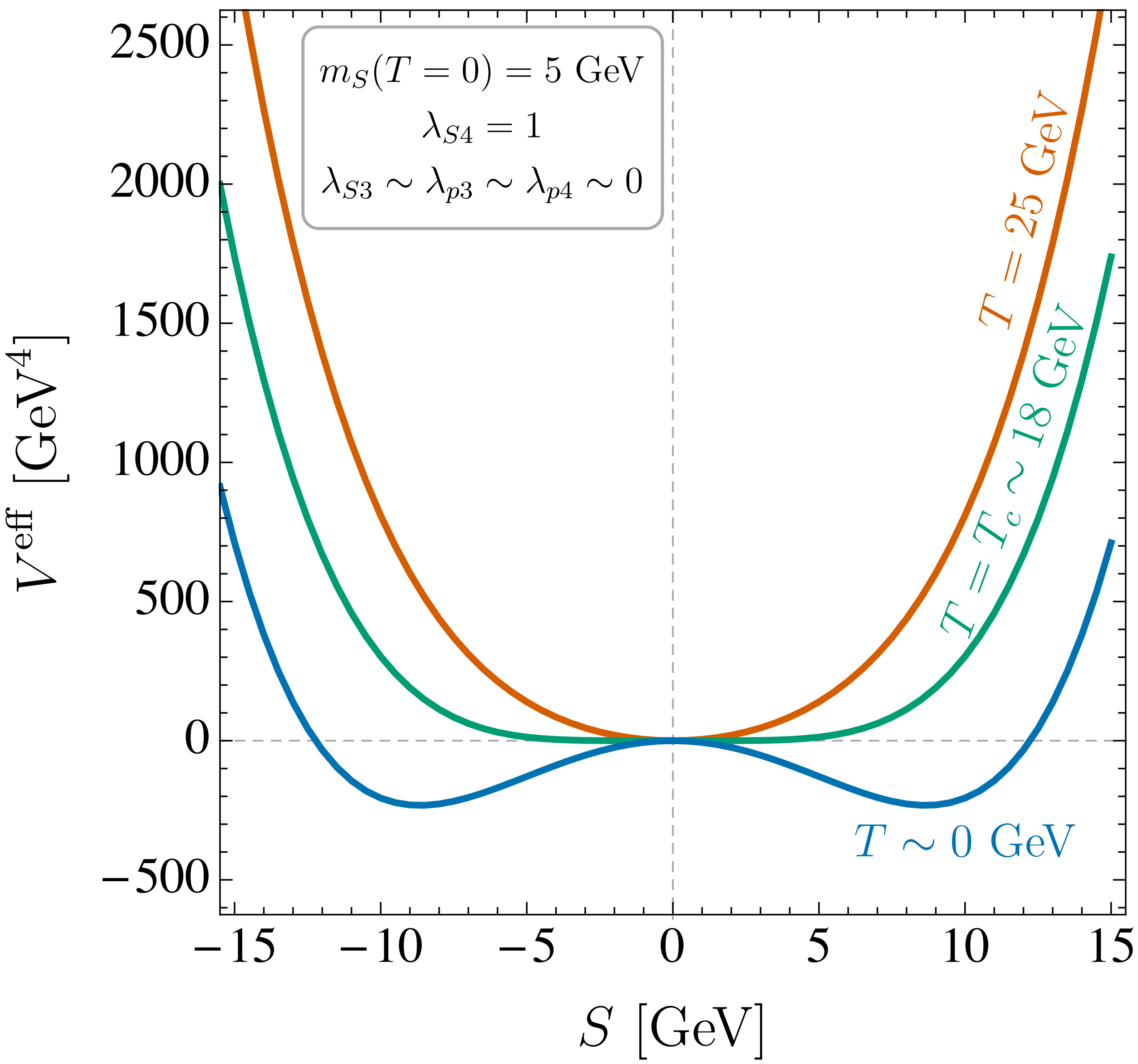
$\lambda_{S3} \sim 0 \qquad \lambda_{S4} \sim 1$

$\lambda_{p3} \sim 0 \qquad \lambda_{p4} \sim 10^{-3}$

- The Effective Potential - Second Order PT



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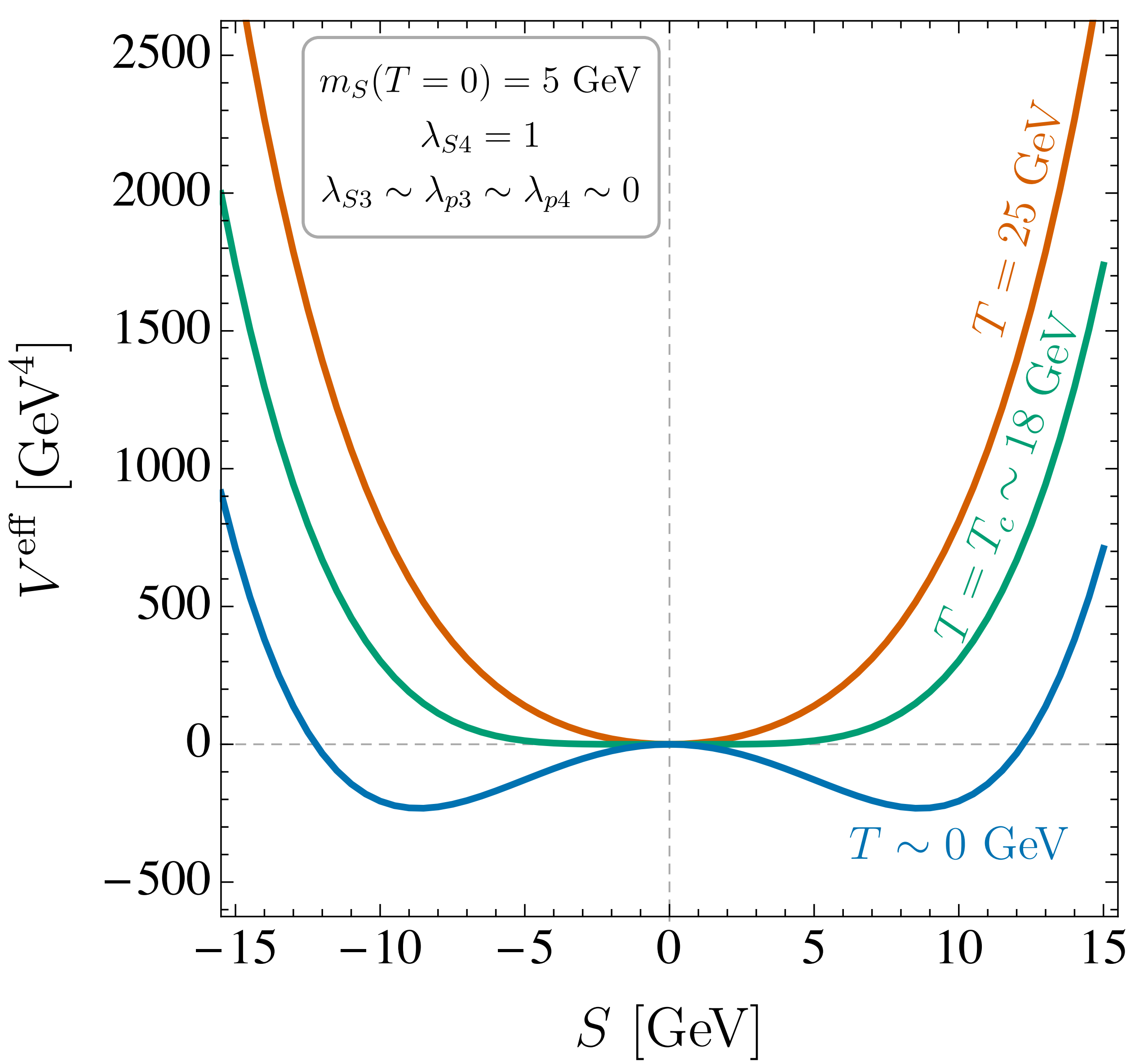

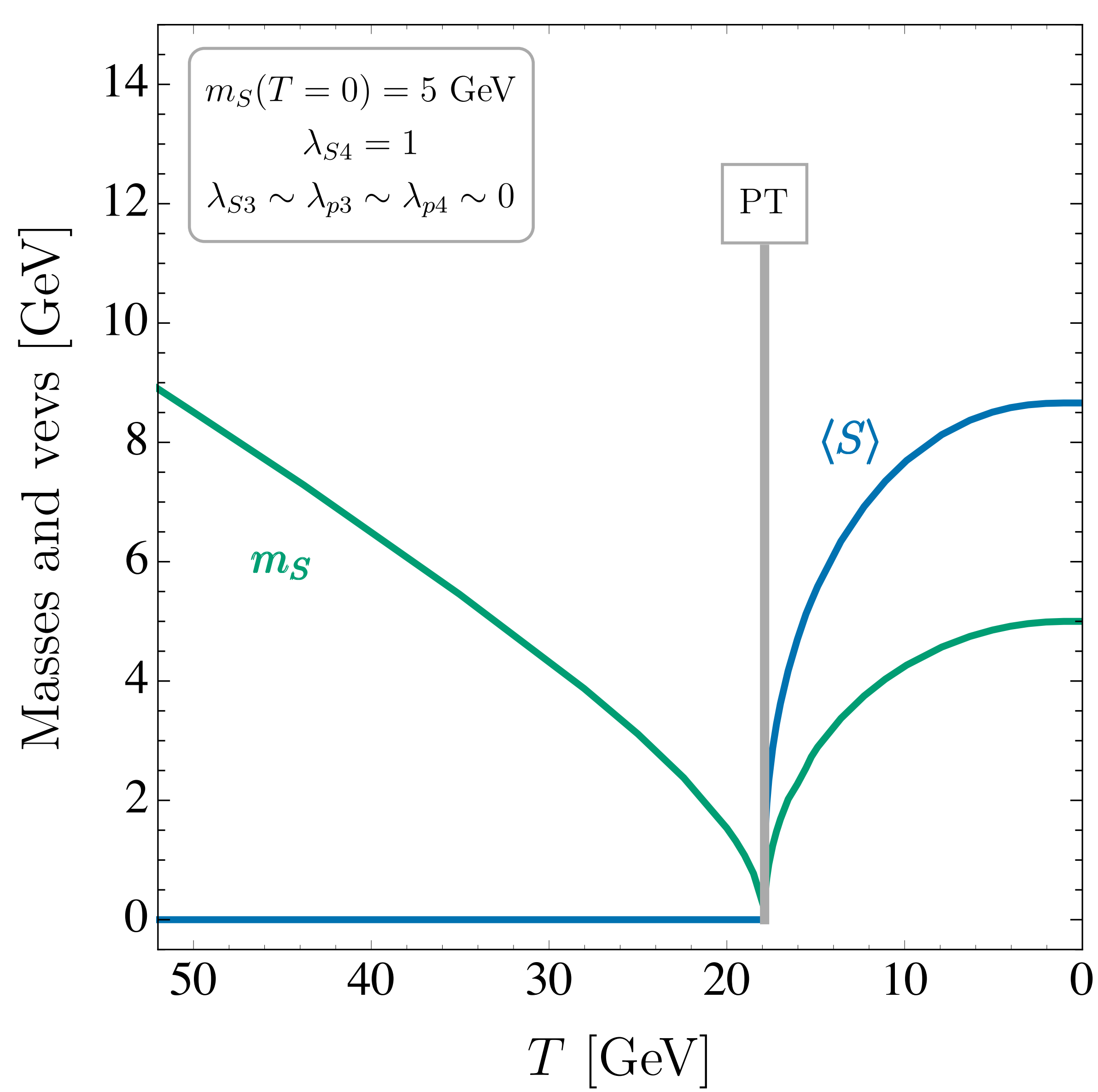

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$$y_{\psi\chi} \sim 10^{-12}$$

$$y_\chi \sim 0$$

$$y_\psi \sim 0.01$$

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$y_\chi \sim 0$

$y_\psi \sim 0.01$ we'll assume ψ stays in thermal equilibrium

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Assume χ begins with negligible abundance

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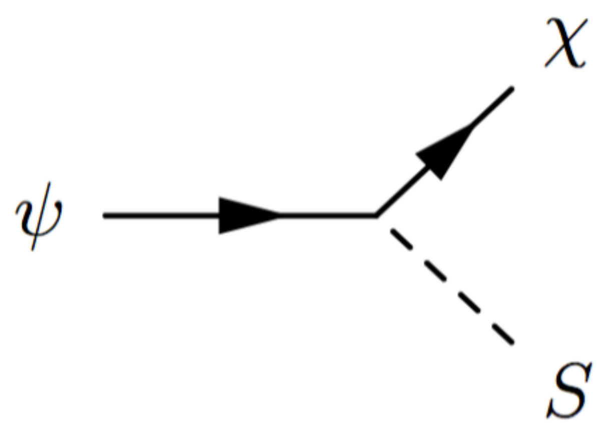

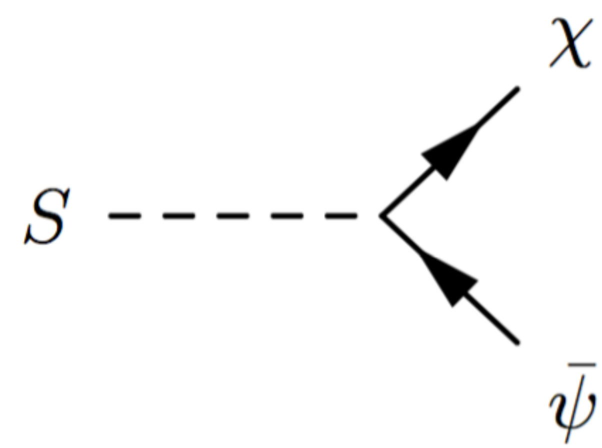

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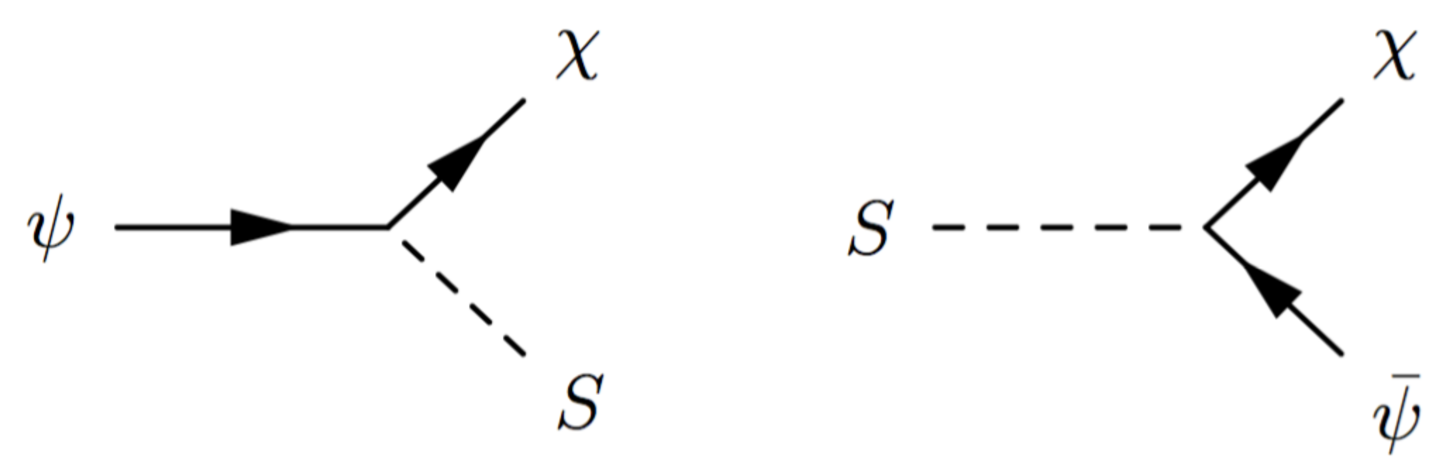

$m_\psi > m_\chi + m_S(T)$

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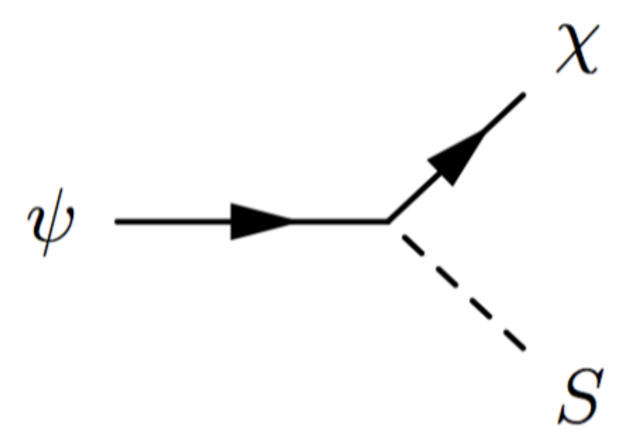

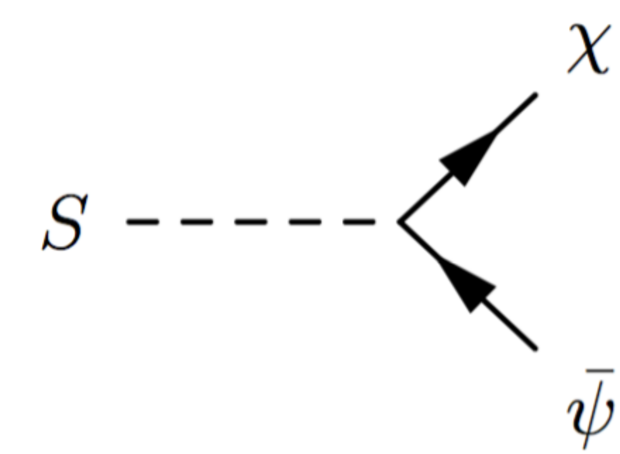

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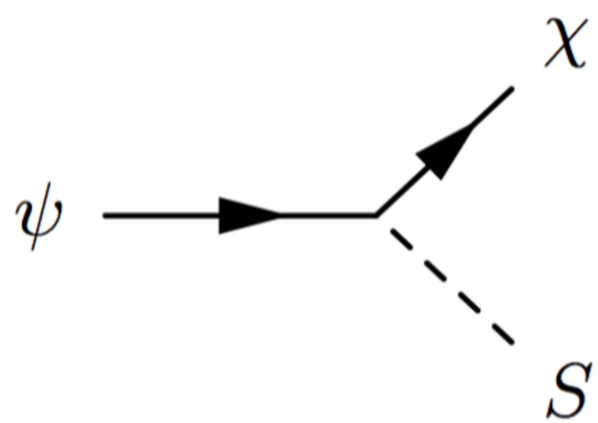

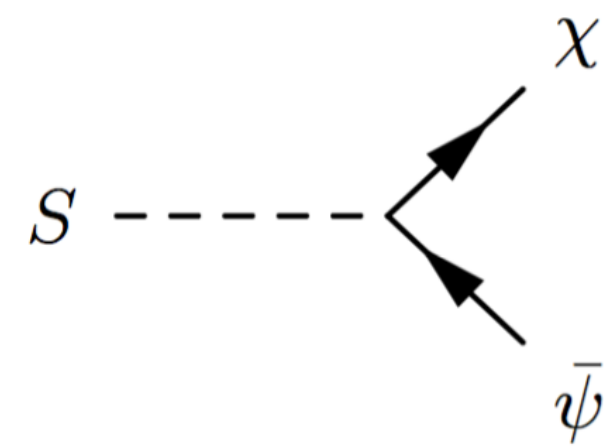

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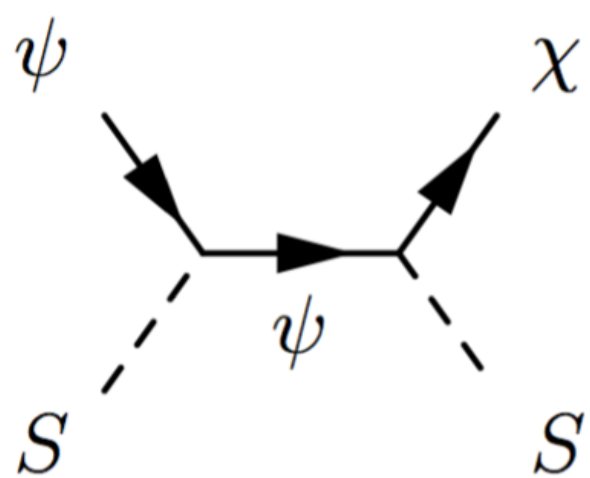

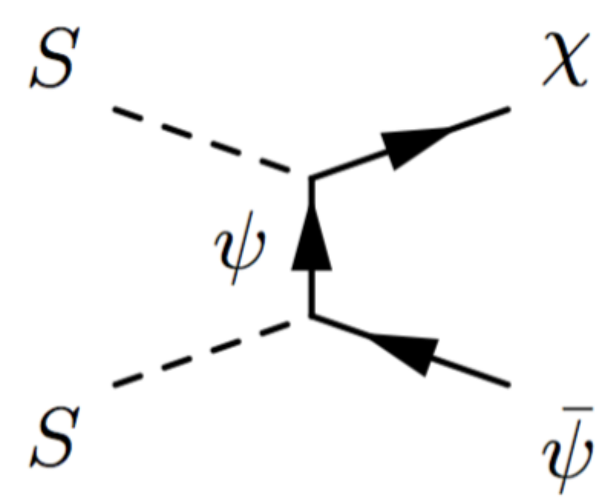

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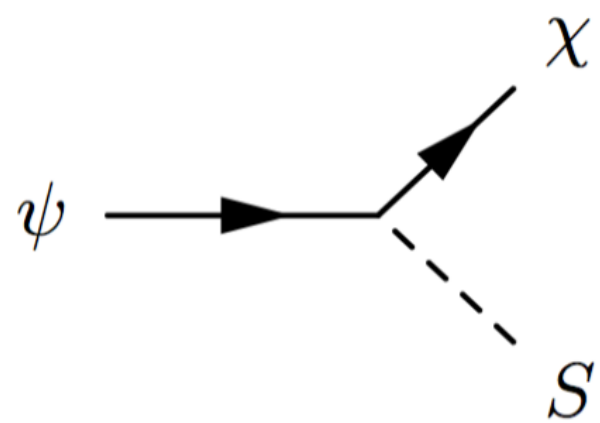

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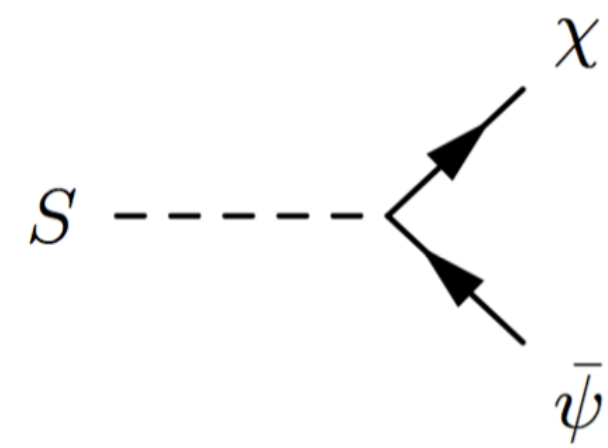

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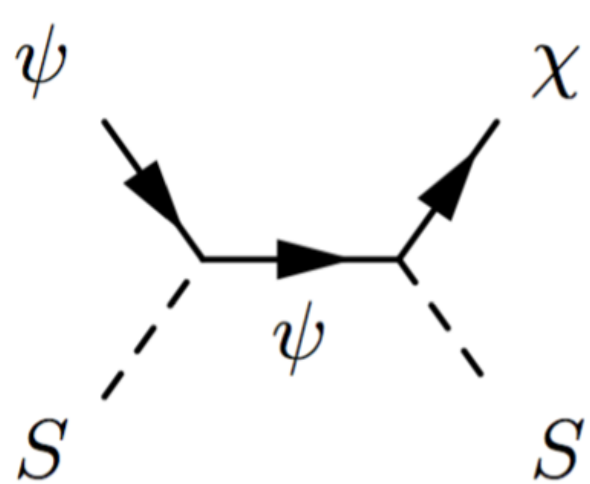

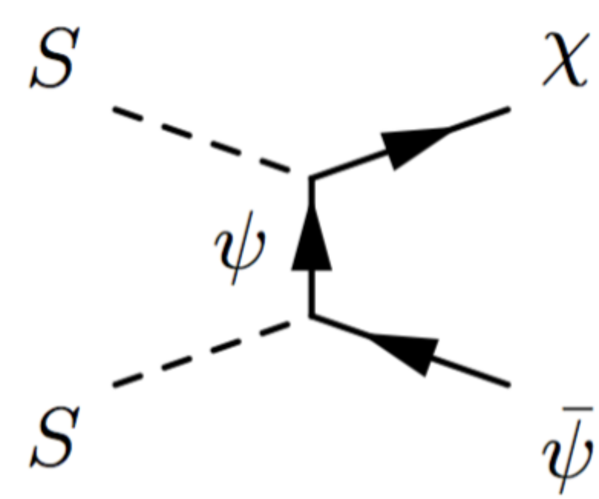

$$T \gtrsim m_\chi$$

- Freeze-in - Boltzmann Equations

$$\frac{dY_\chi}{dx} = \frac{g_{B_1} m_{B_1}^2}{2\pi^2} \frac{m_\chi}{H(x)s(x)x^2} \Gamma(B_1 \to \chi B_2)\, K_1\!\left(\frac{m_{B_1} x}{m_\chi}\right)$$

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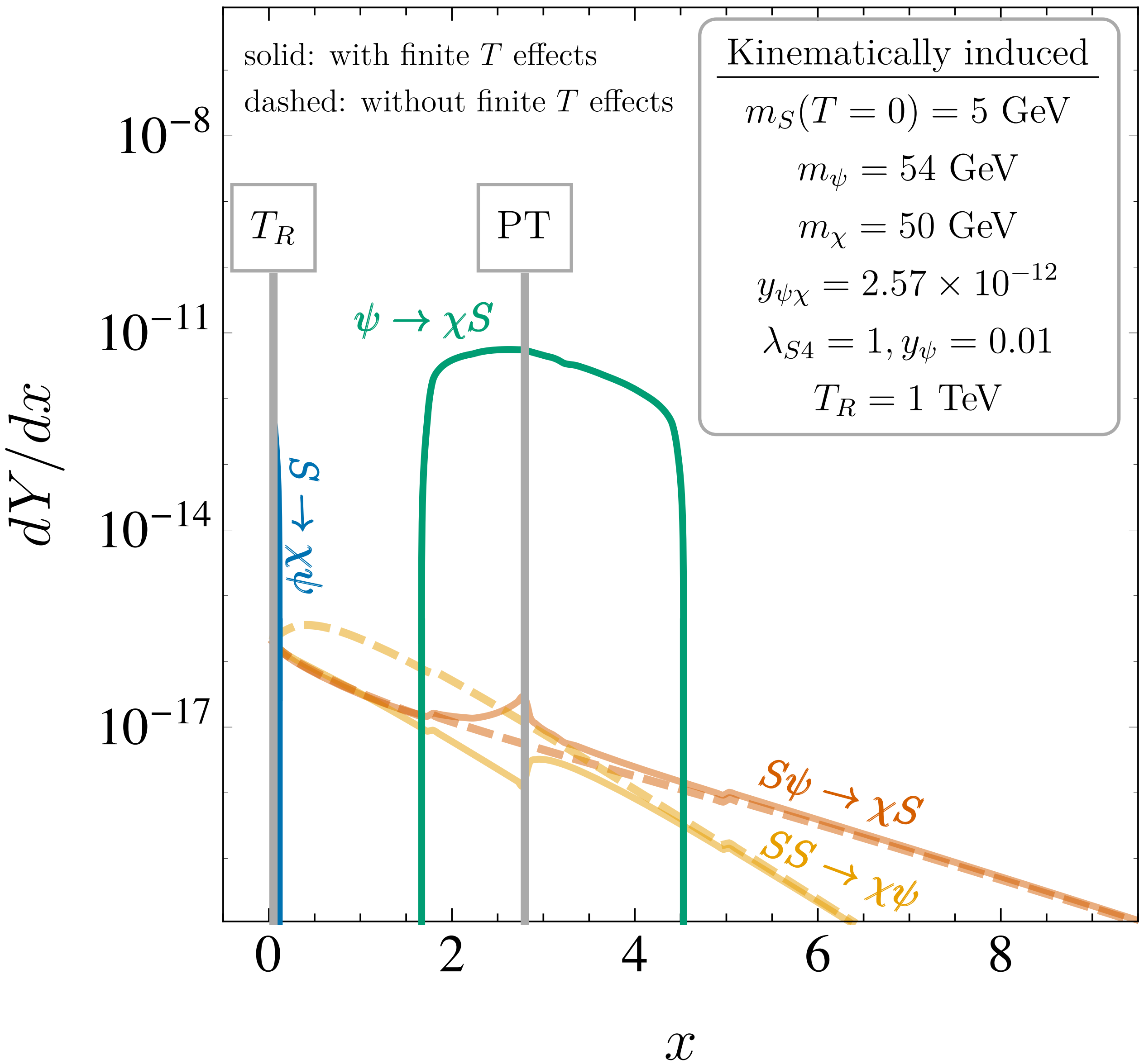
$$\frac{dY_\chi}{dx} = \frac{g_{B_1} g_{B_2}}{32\pi^4} \frac{m_\chi}{H(x)s(x)x^2} \int_{(m_{B_1}+m_{B_2})^2}^{\infty} ds\, 4p_{B_1 B_2}^2 \sigma(B_1 B_2 \to \chi B_3)\, K_1\left(\frac{x\sqrt{s}}{m_\chi}\right)$$

- Kinematically Induced Freeze-in - Results



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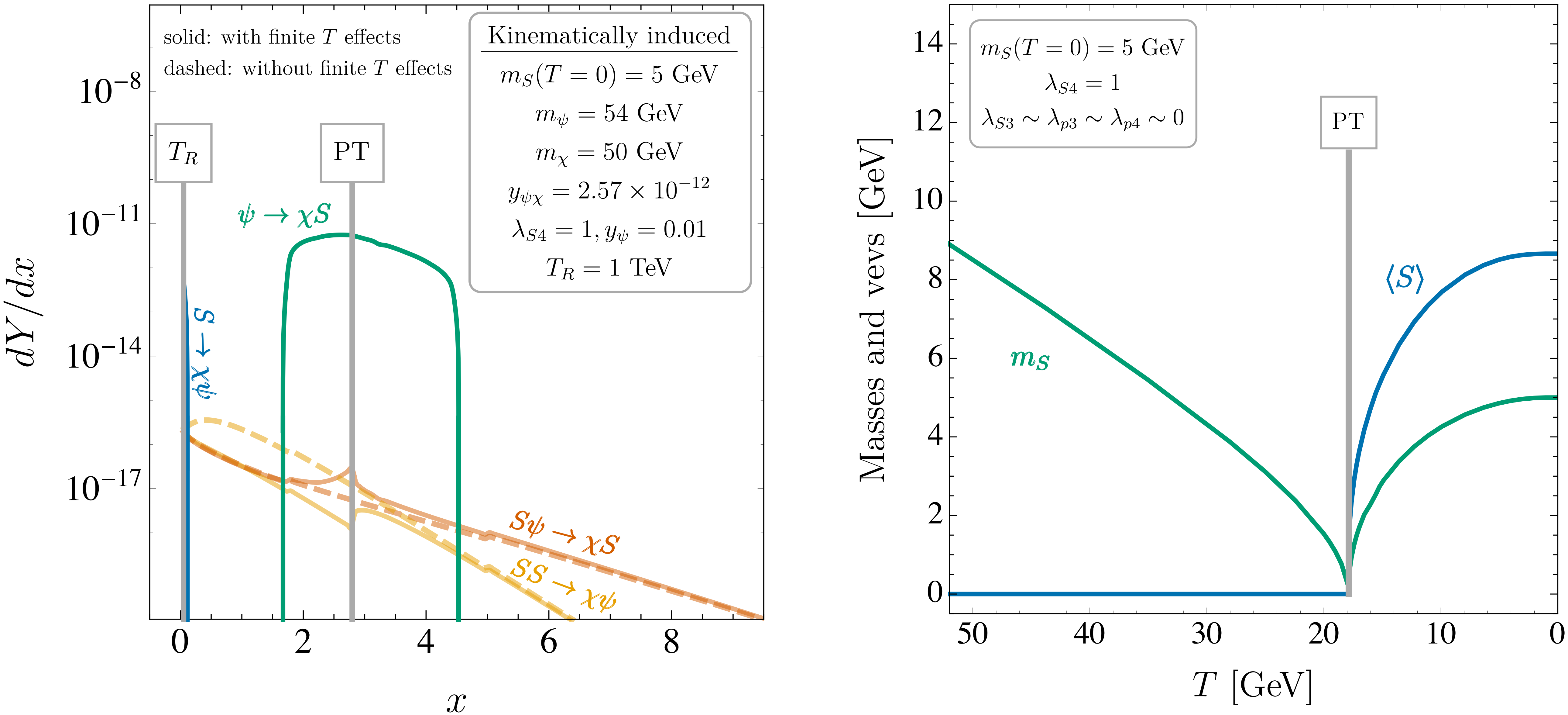

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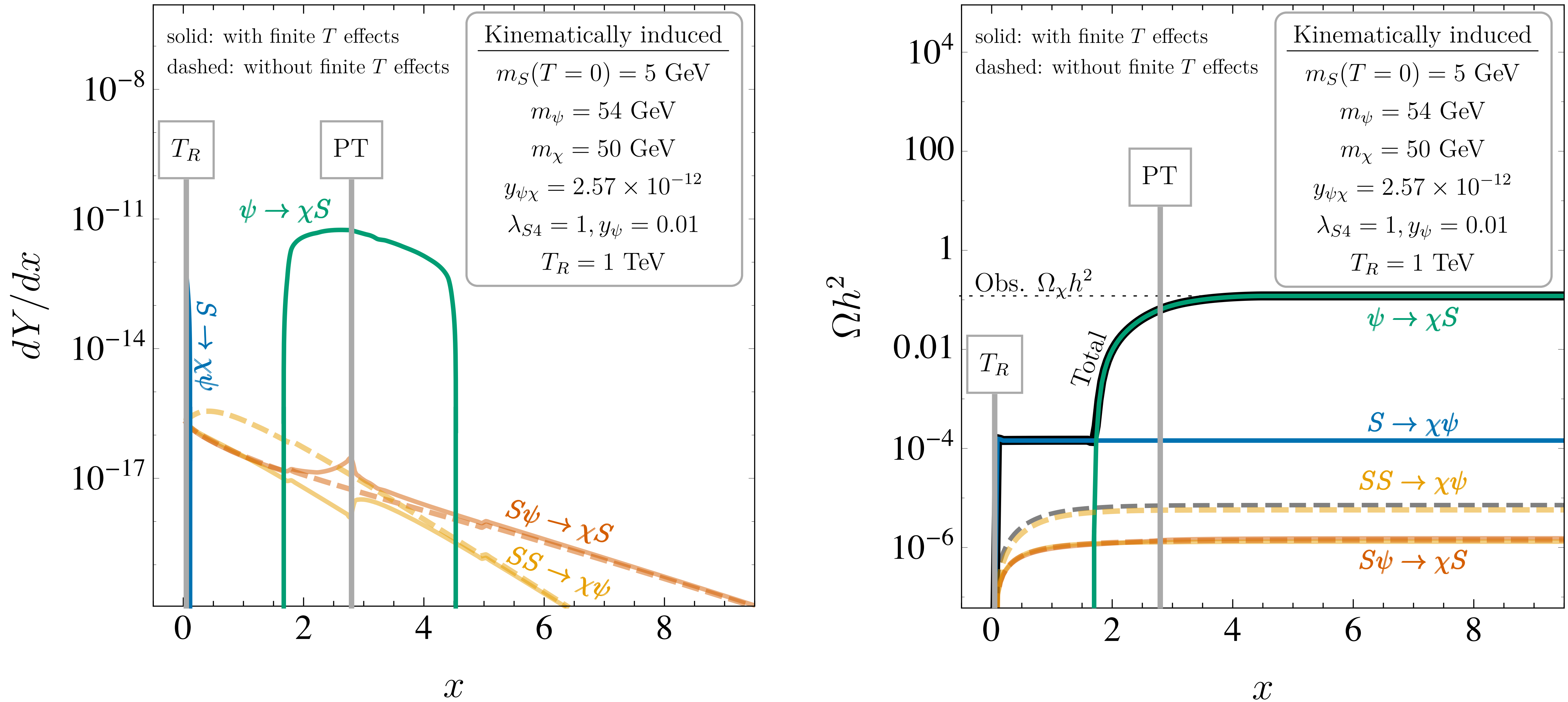

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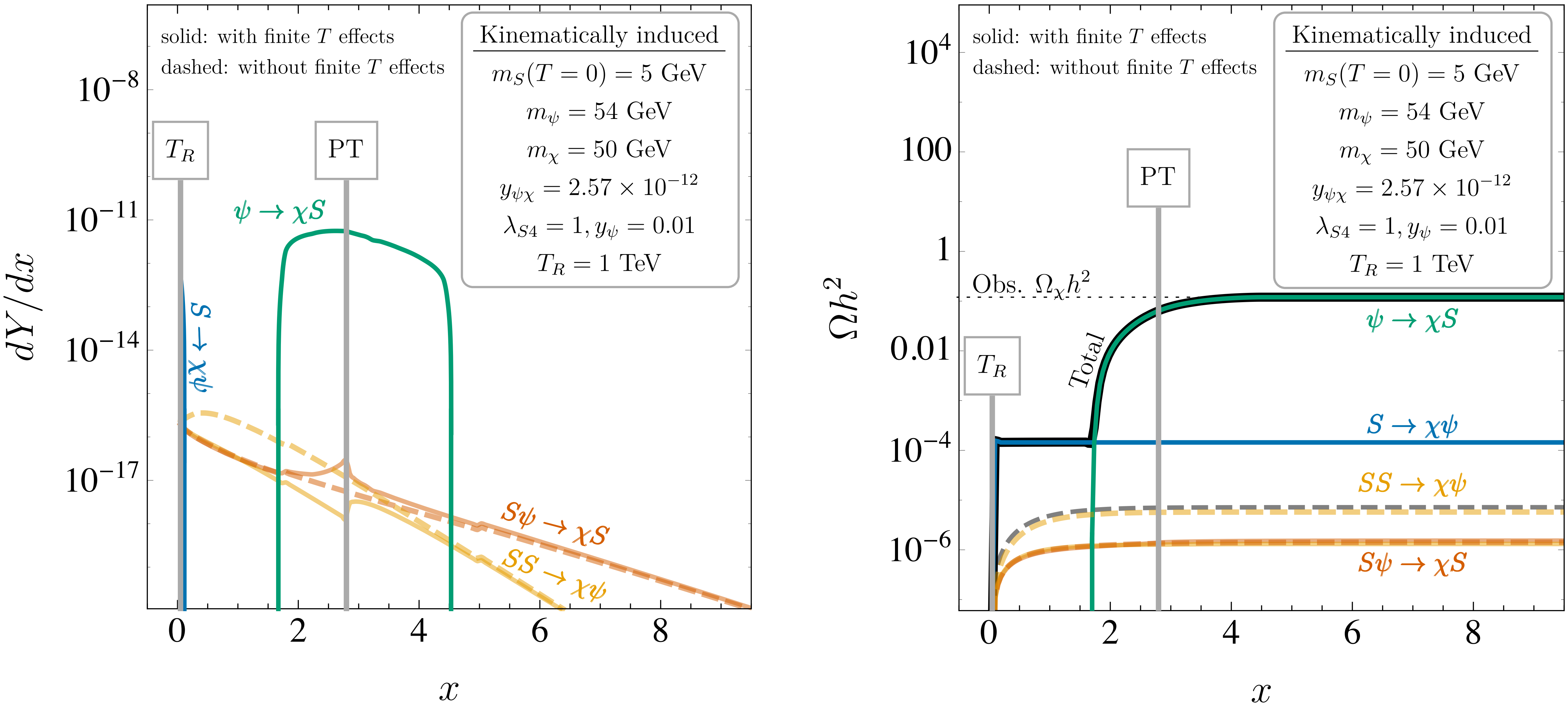

Thermal effects increase relic abundance by orders of magnitude

Vev Induced Freeze-in

- Vev Flip-Flop: Phase Transitions

Brief (1 slide) aside on phase transitions…

- Vev Flip-Flop: Phase Transitions

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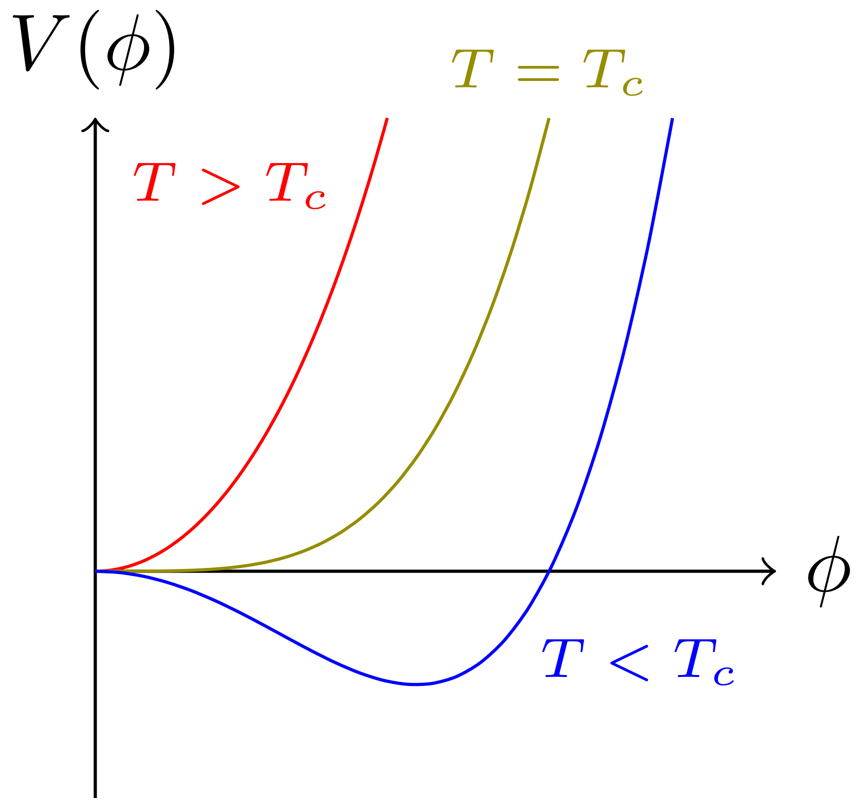
Second Order Phase Transitions

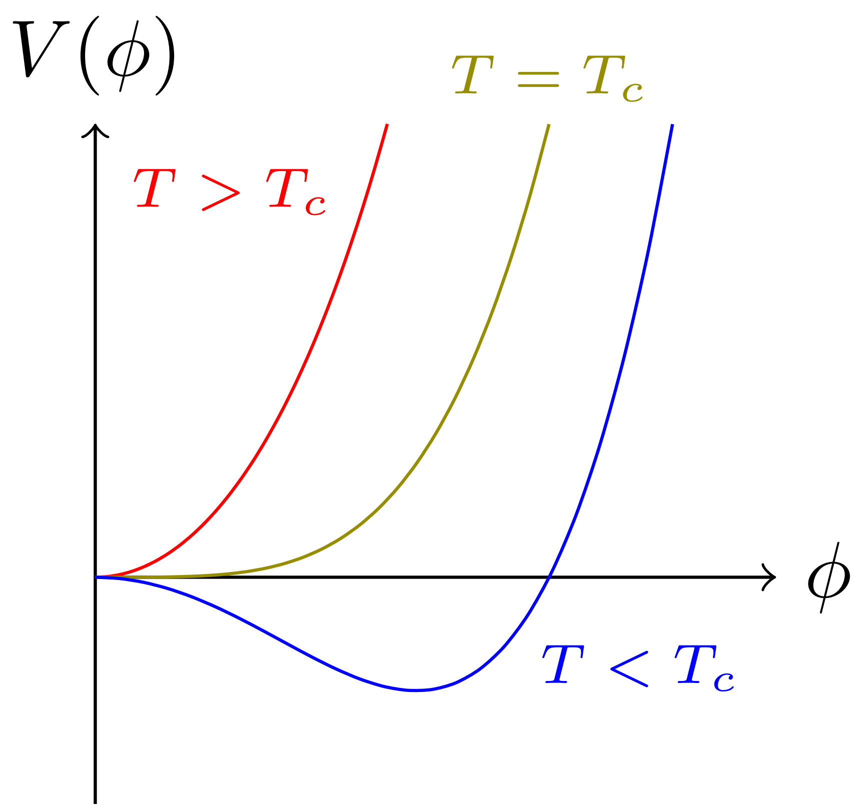


$$T_{\text{PT}} = T_c$$

- Vev Flip-Flop: Phase Transitions

Brief (1 slide) aside on phase transitions…

<u>Second Order Phase Transitions</u>



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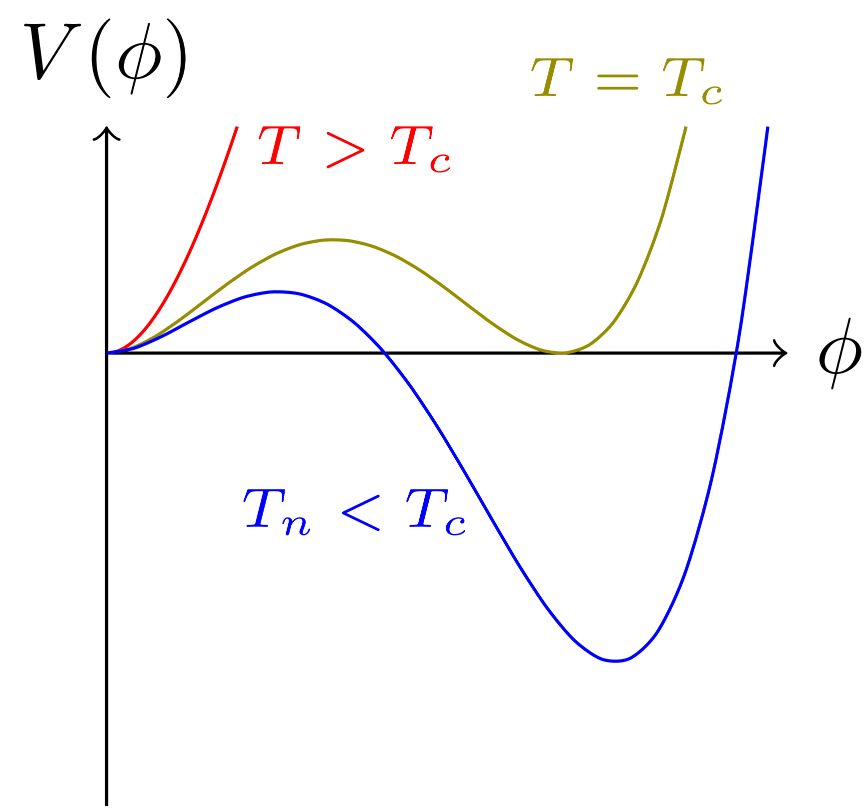
<u>First Order Phase Transitions</u>



$$T_n < T_c$$

- Vev Induced Freeze-in

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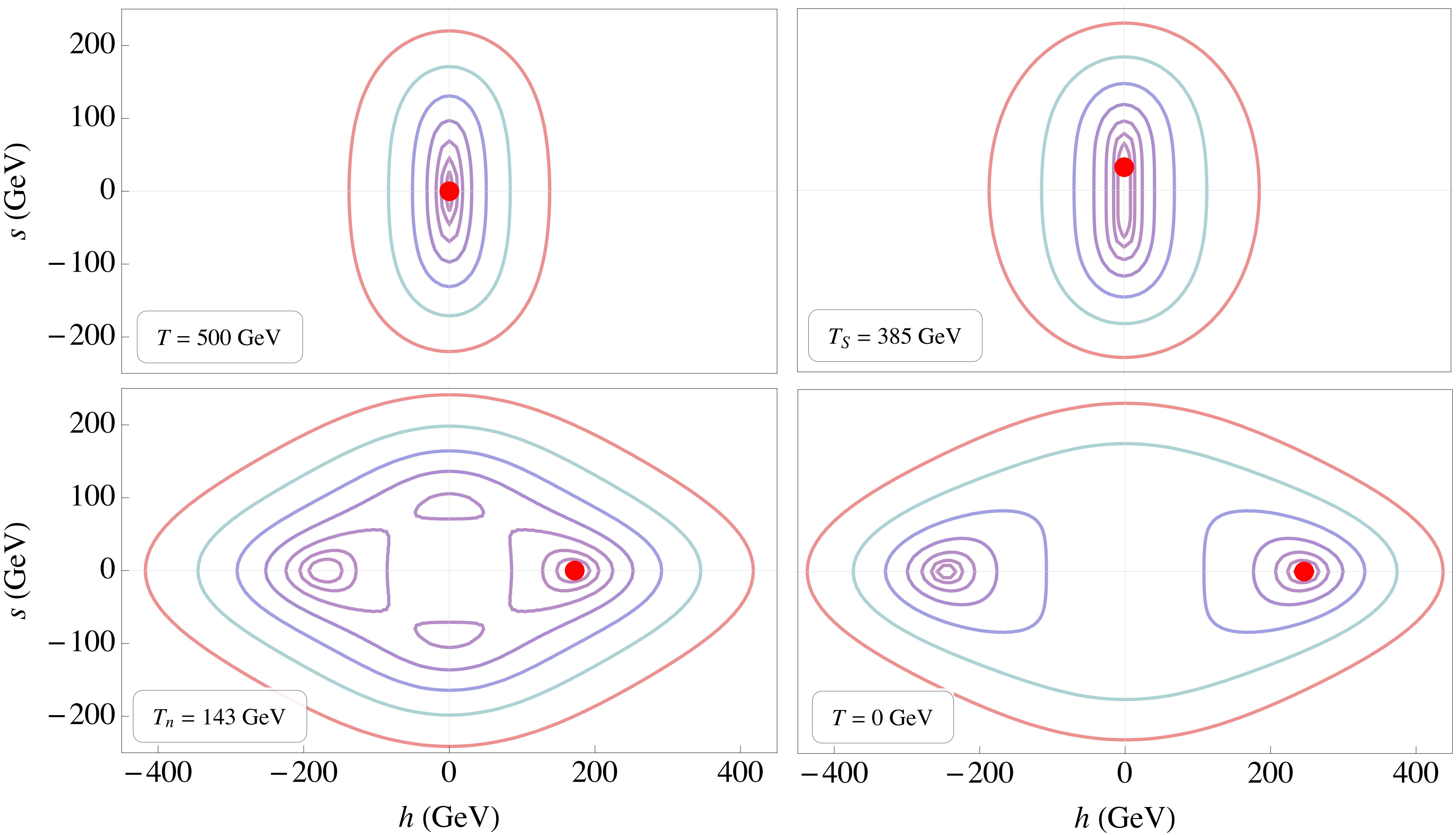
$$\lambda_{p3} \sim 0 \qquad \lambda_{p4} \sim 1$$

- Vev Flip-Flop: Effective Potential



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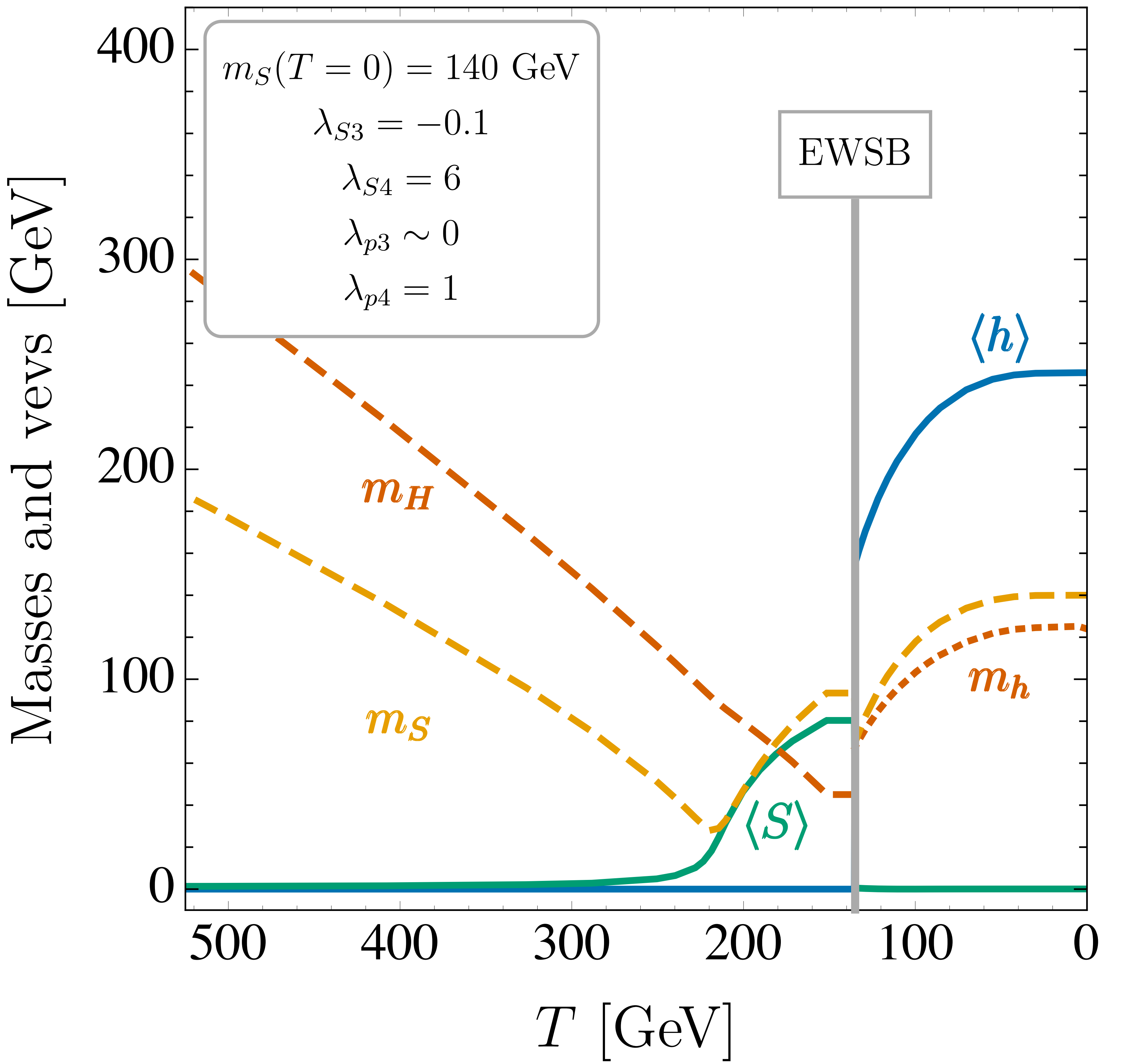

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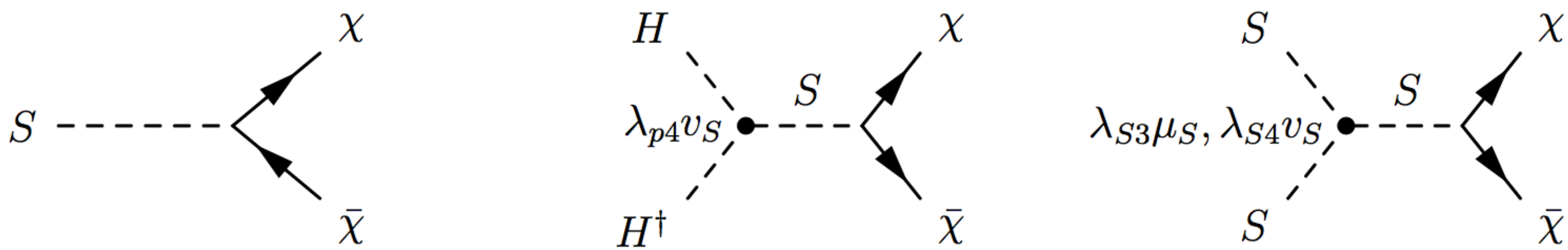

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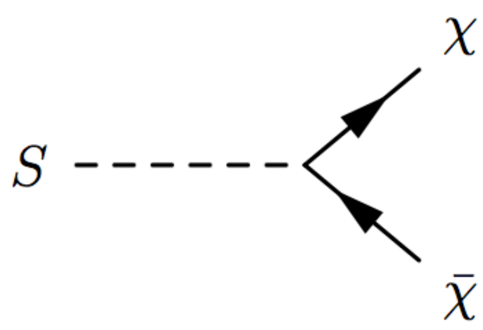

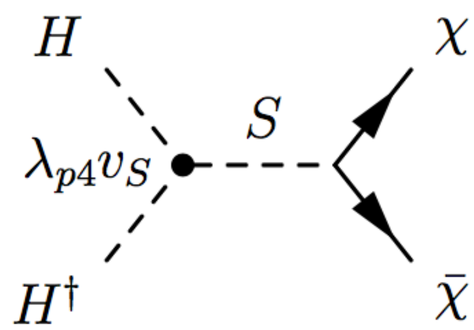

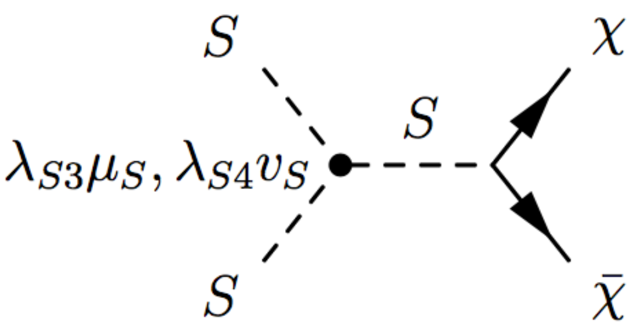

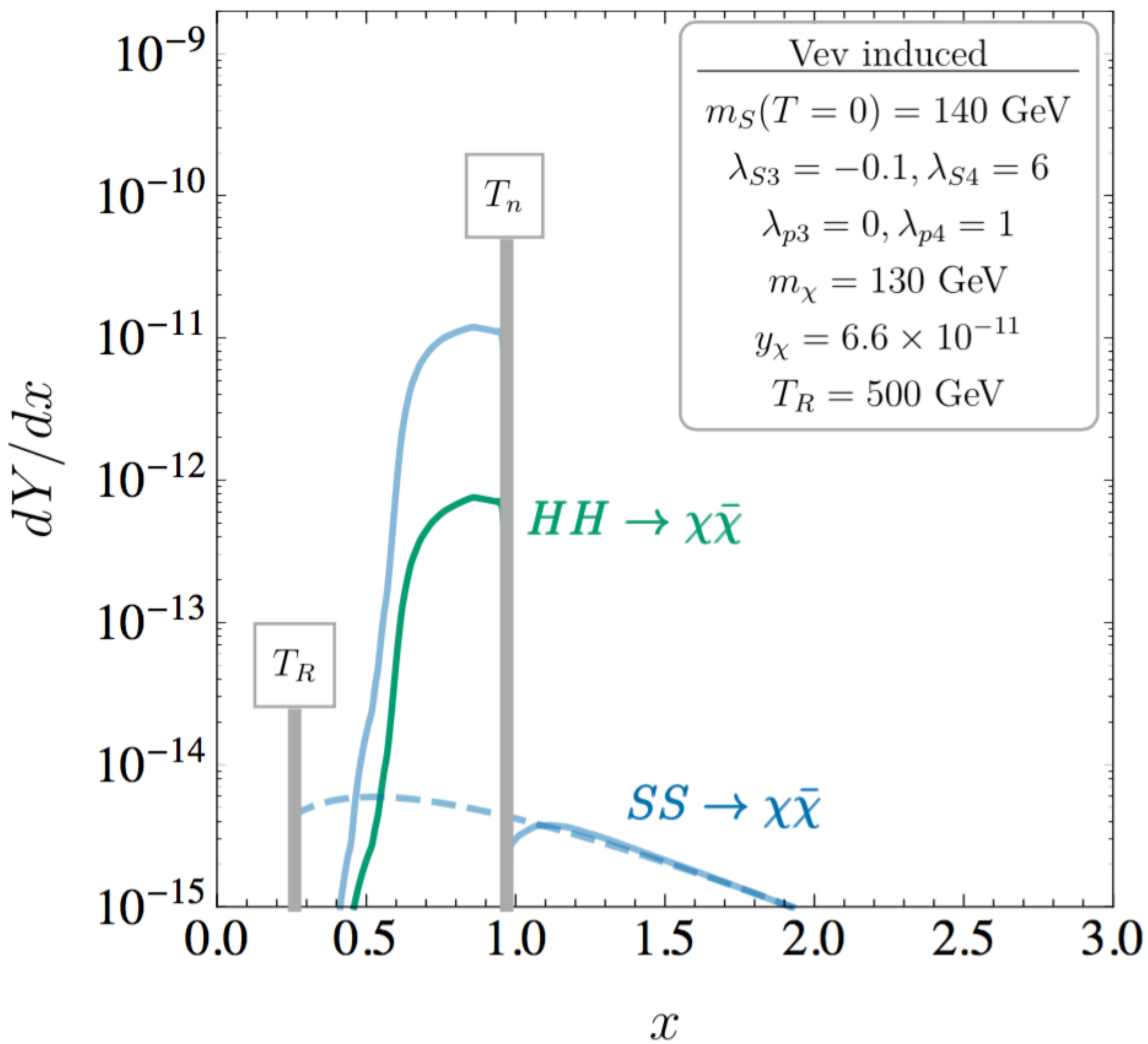

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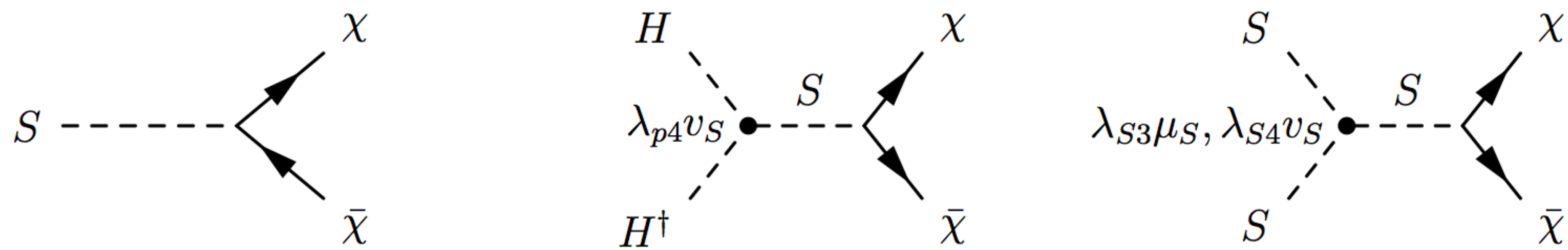

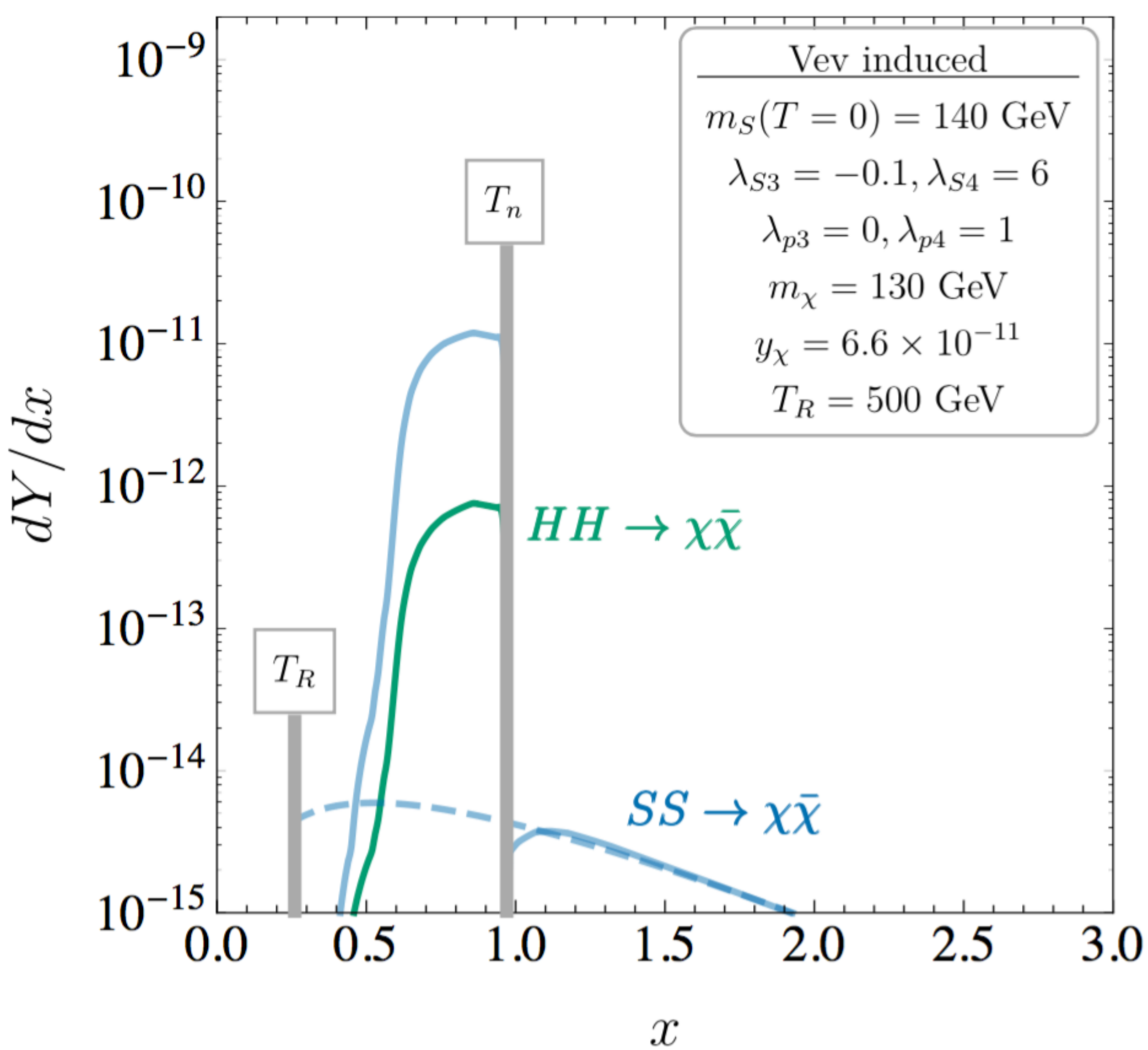

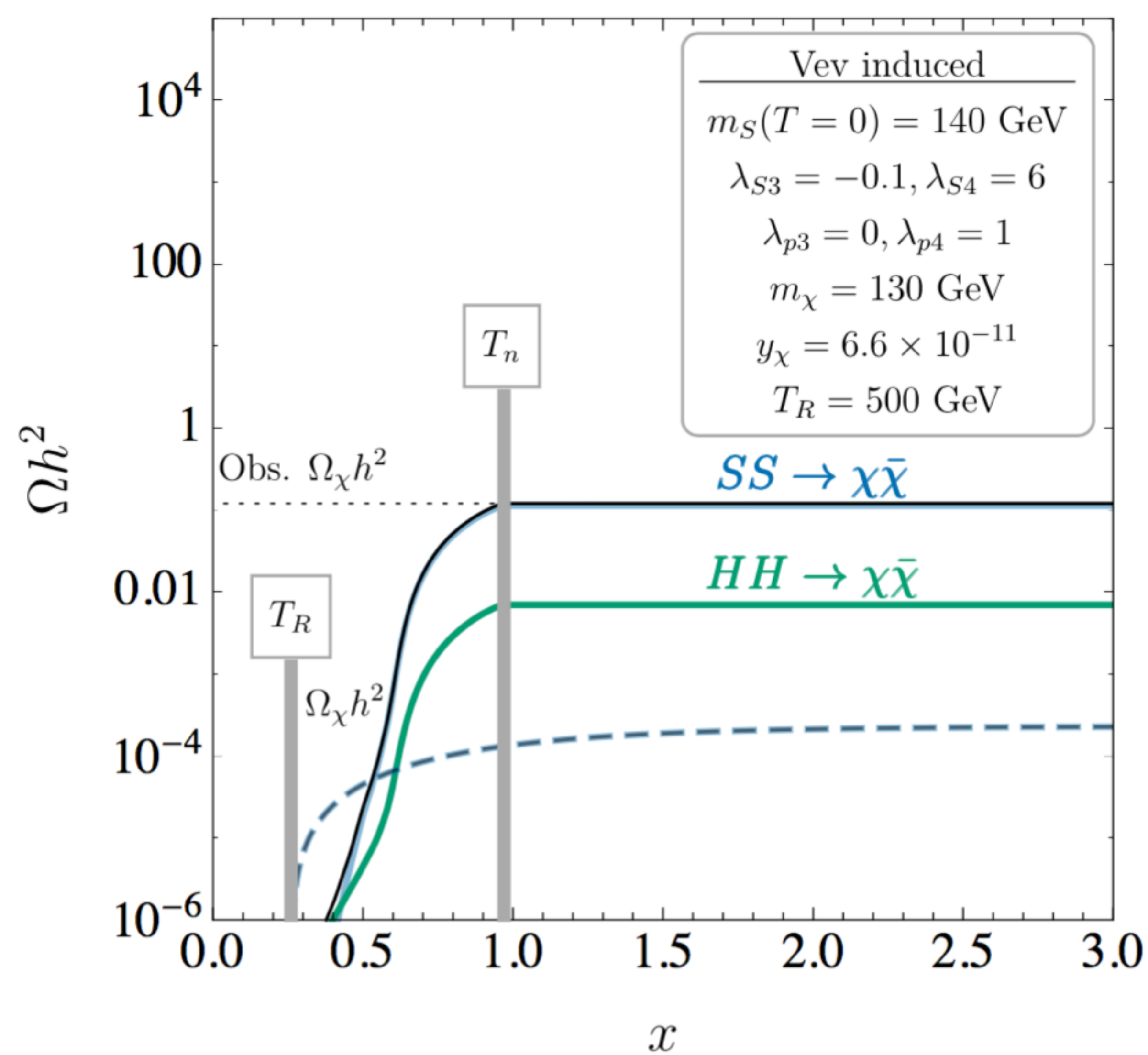

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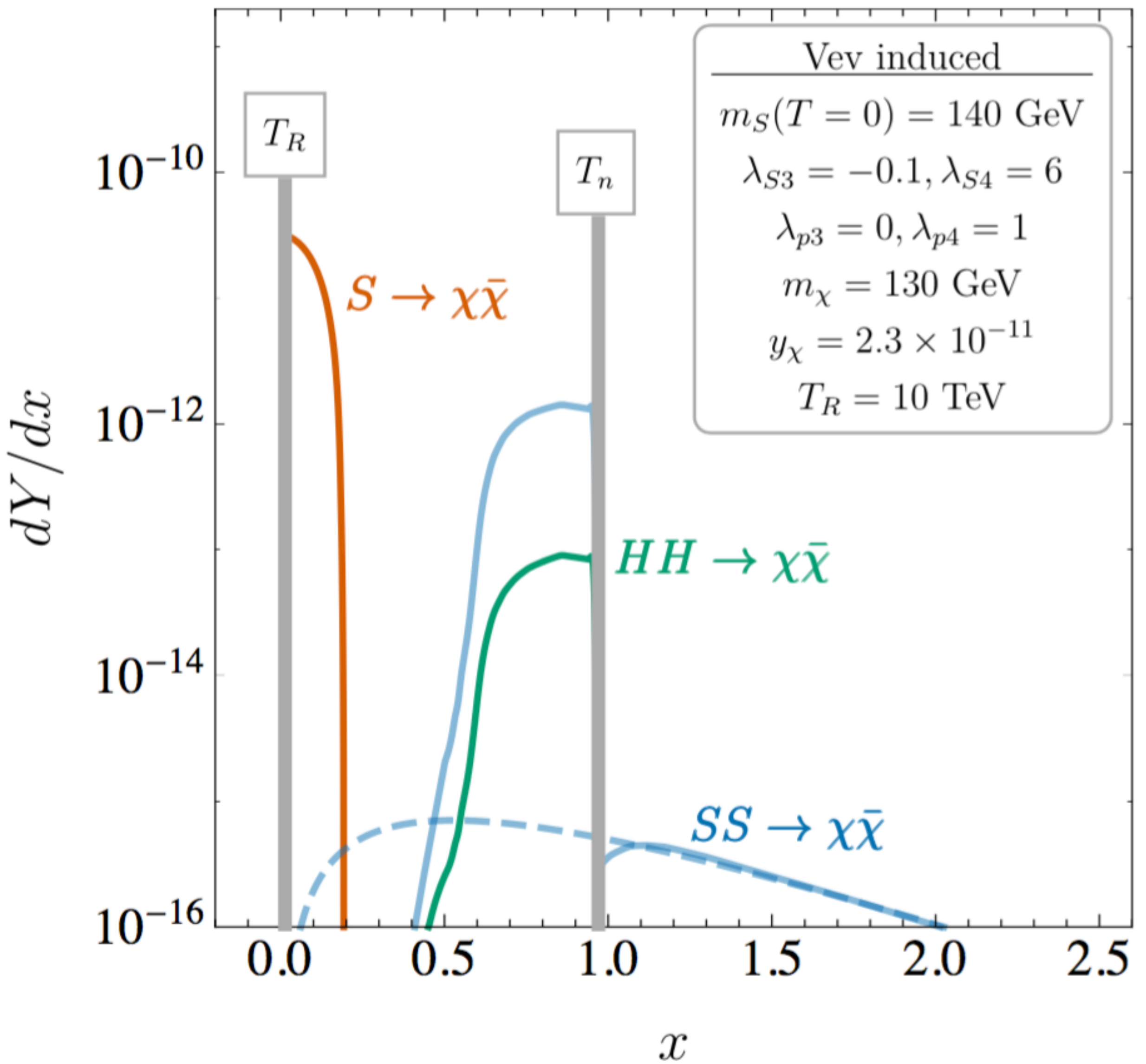

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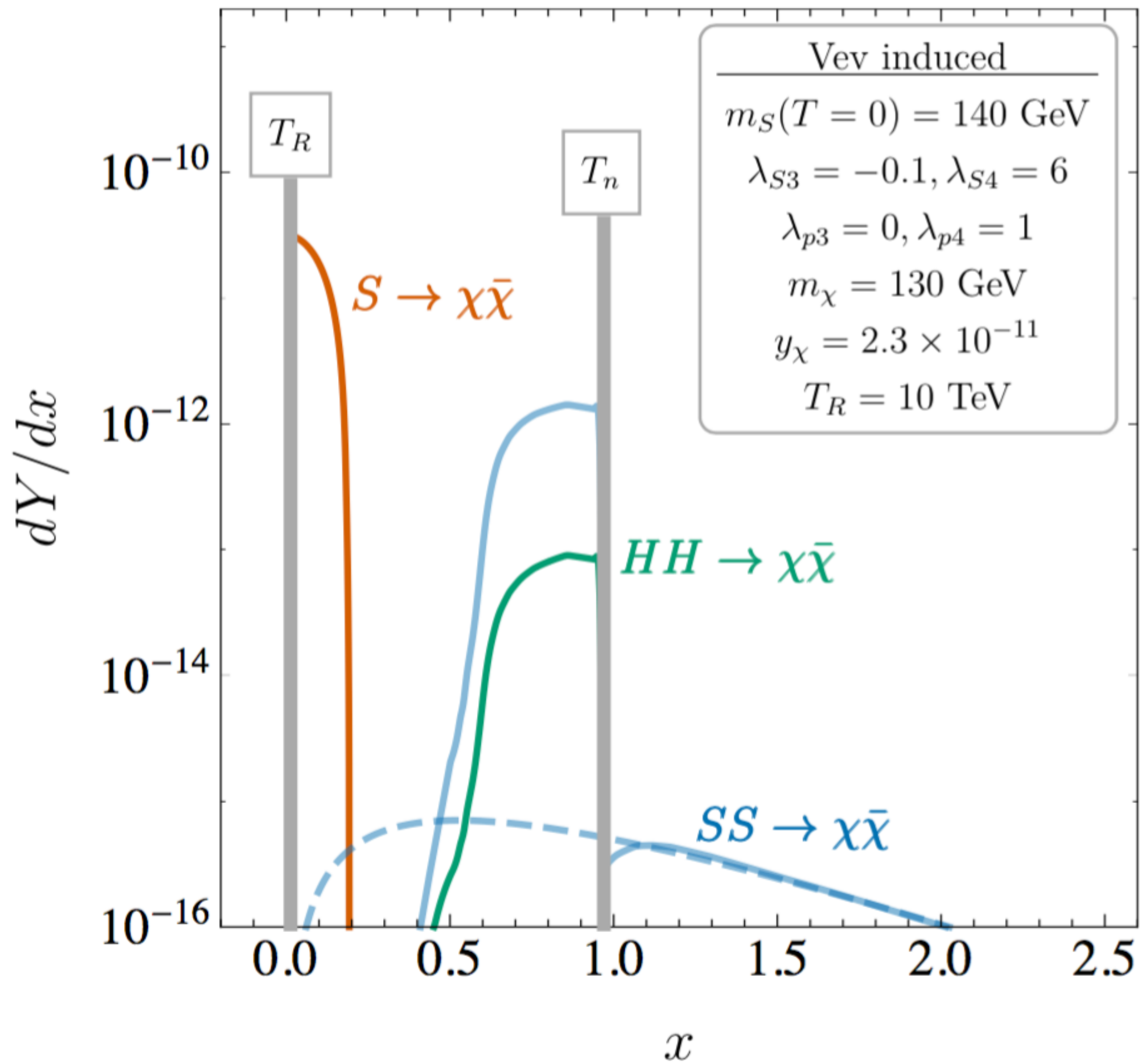

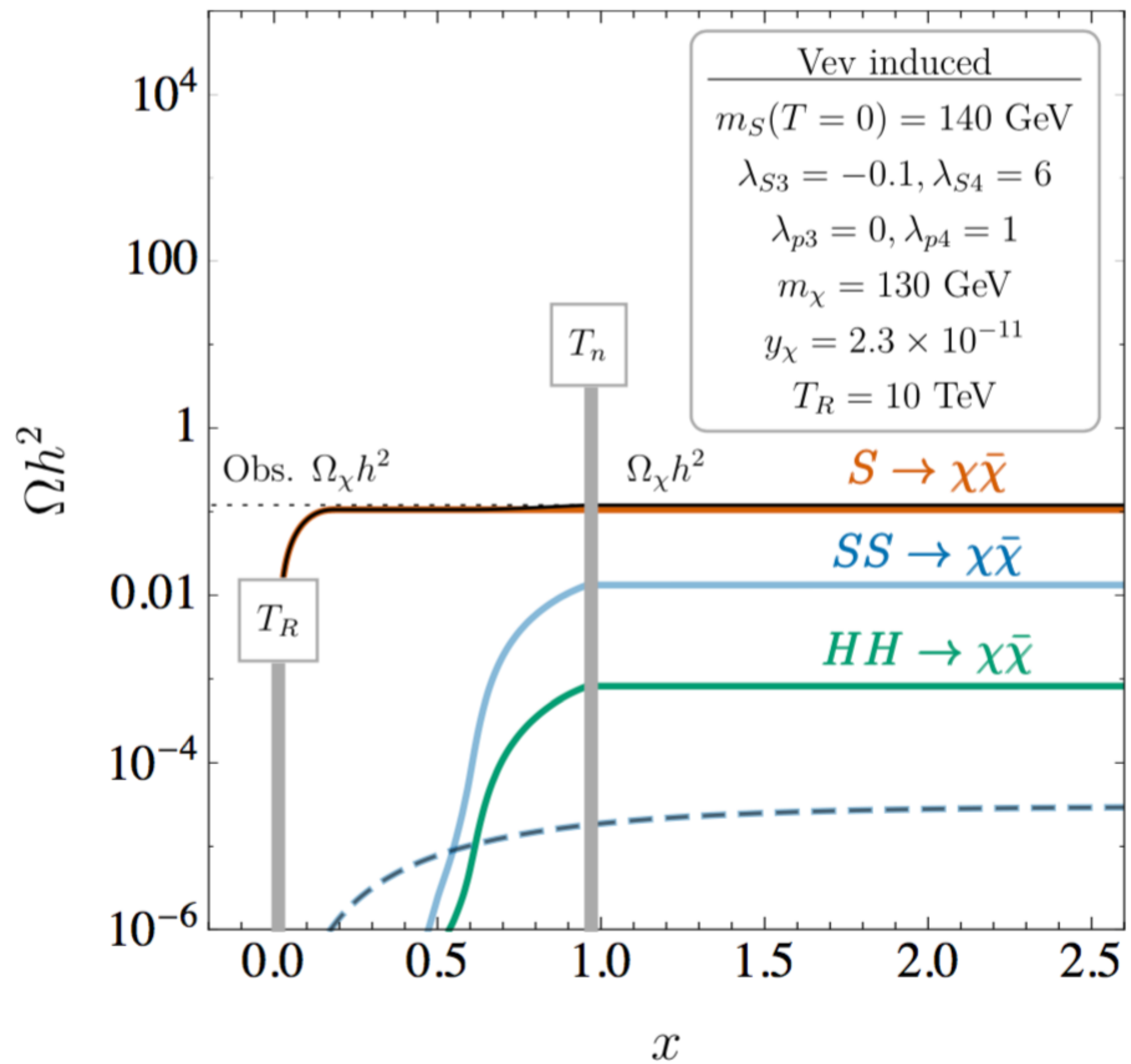

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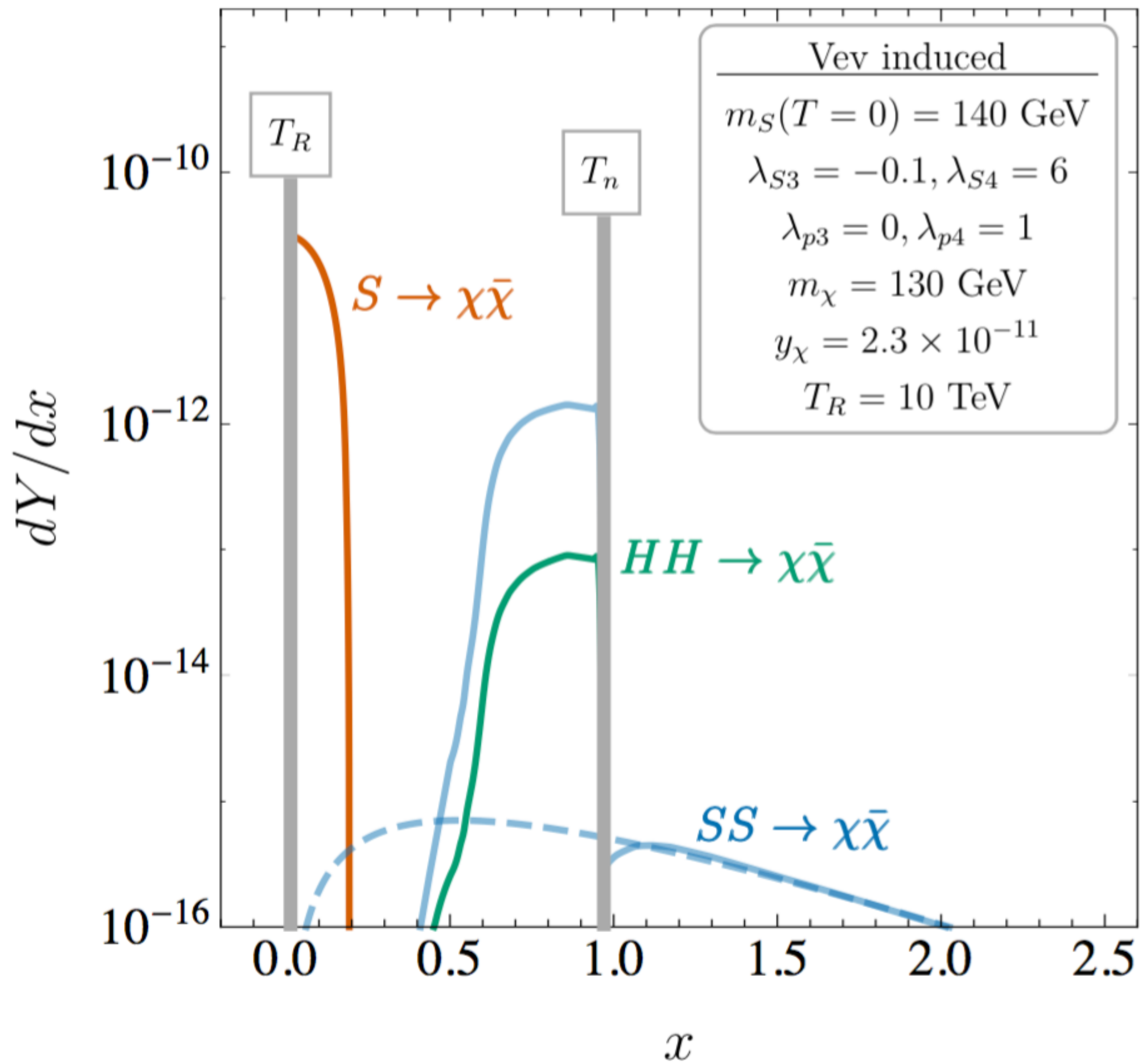
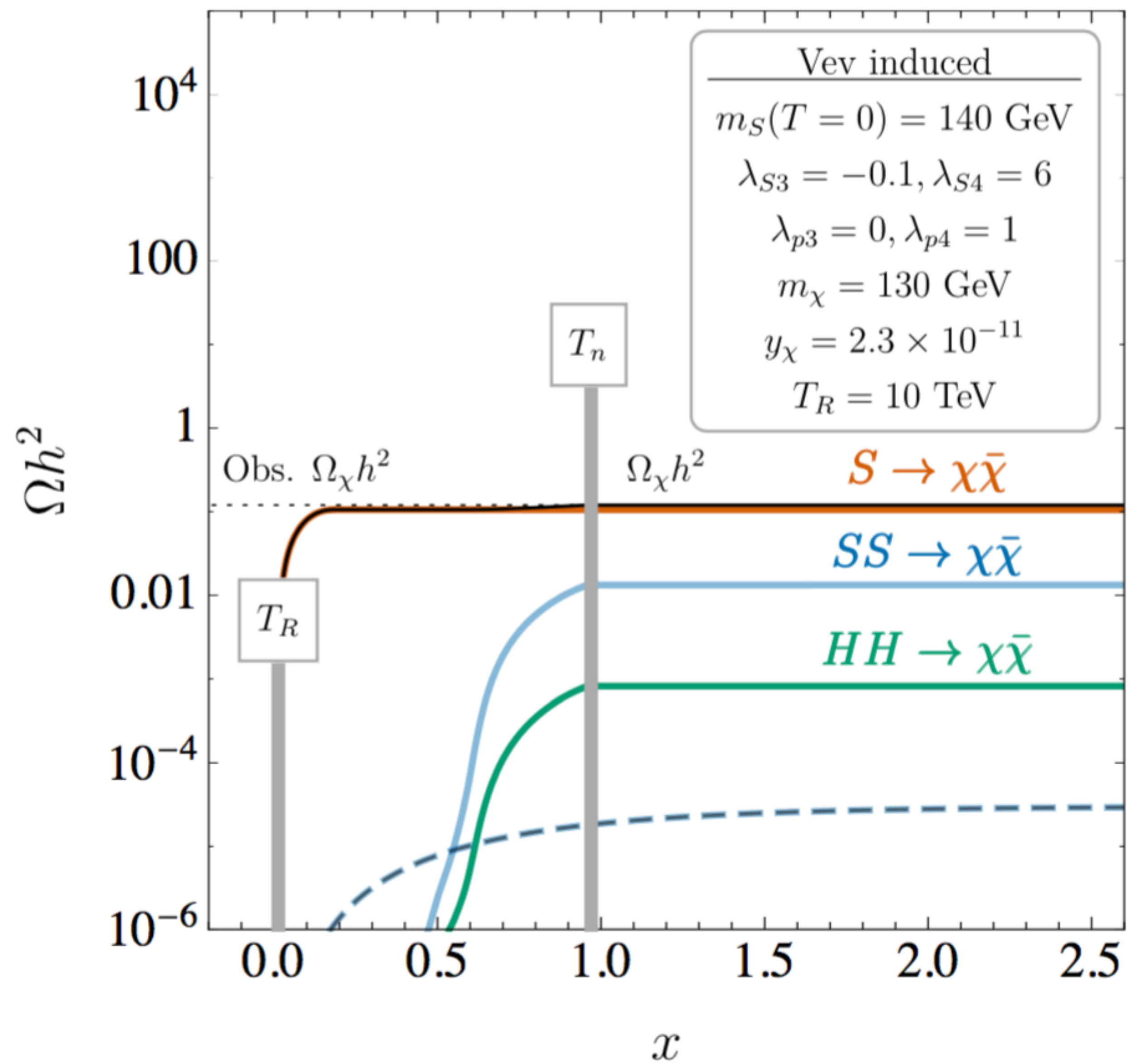




Thermal effects increase relic abundance by orders of magnitude

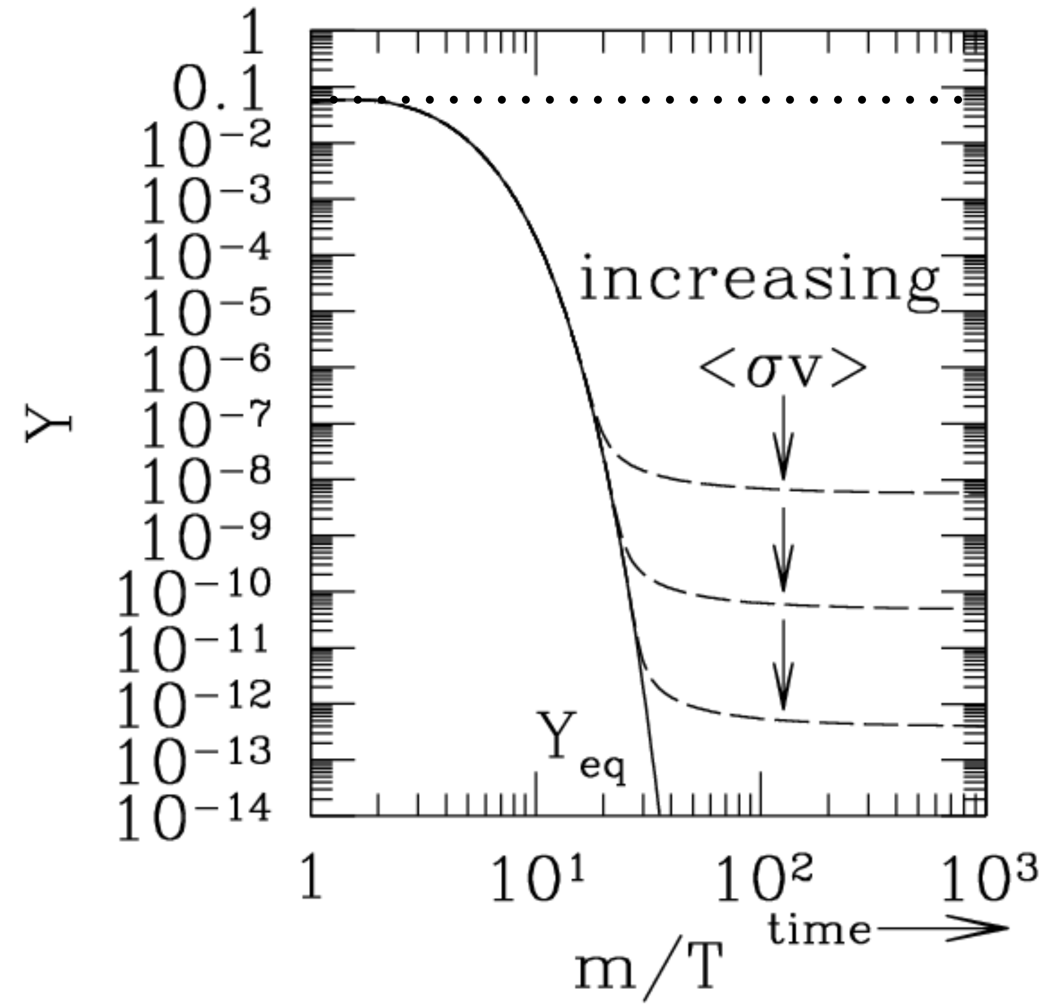
Decaying Dark Matter

- 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	0	$(1,3,0)$	$S \to e^{2\pi i/3}S$	100 GeV
Ψ	$\frac{1}{2}$	$(1,3,0)$	$\Psi \to e^{-2\pi i/3}\Psi$	TeV
Ψ'	$\frac{1}{2}$	$(1,3,0)$	$\Psi' \to e^{-2\pi i/3}\Psi'$	TeV

- Vev Flip-Flop: Dark Matter Decay

We now assume χ is overproduced in the early universe



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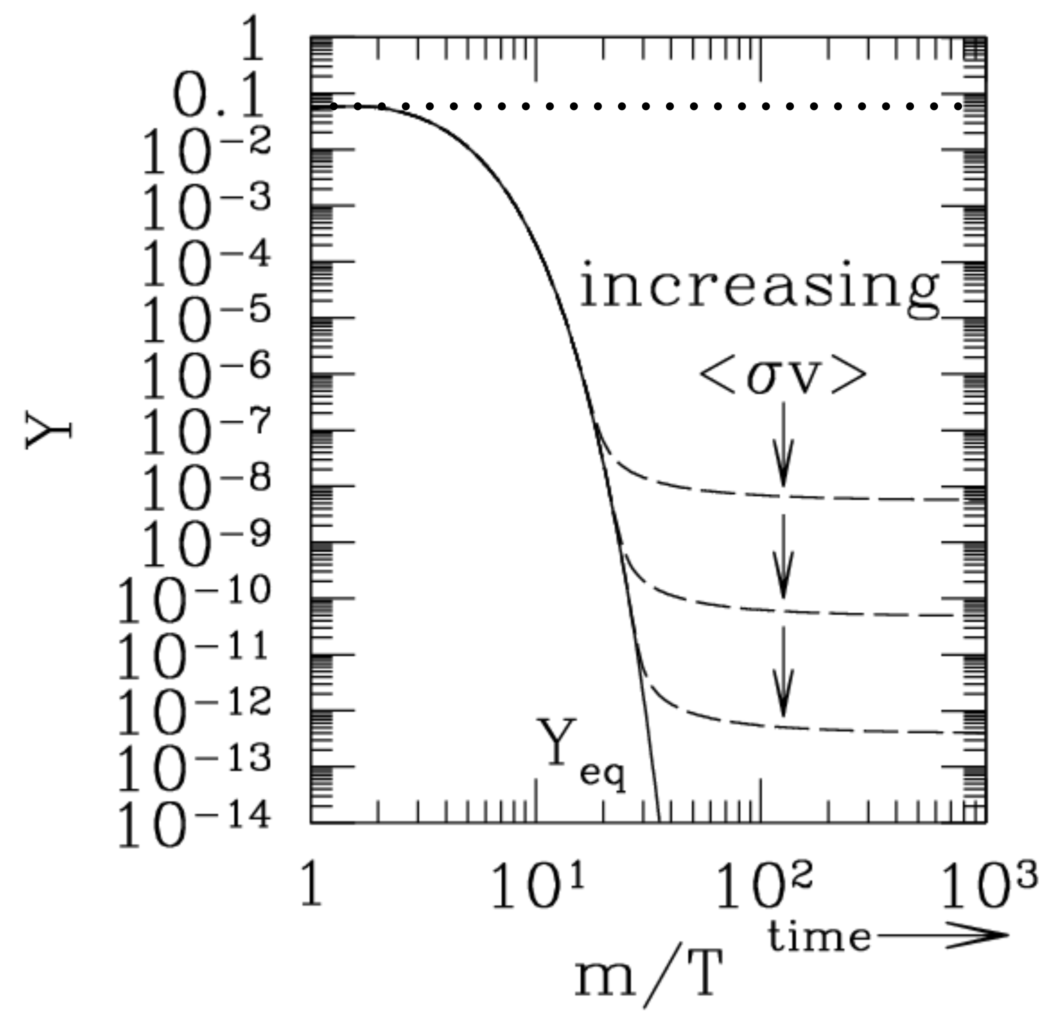

$$\mathcal{L} \supset y_\chi S \overline{\chi} \Psi + y'_\chi S \overline{\chi} \Psi'$$

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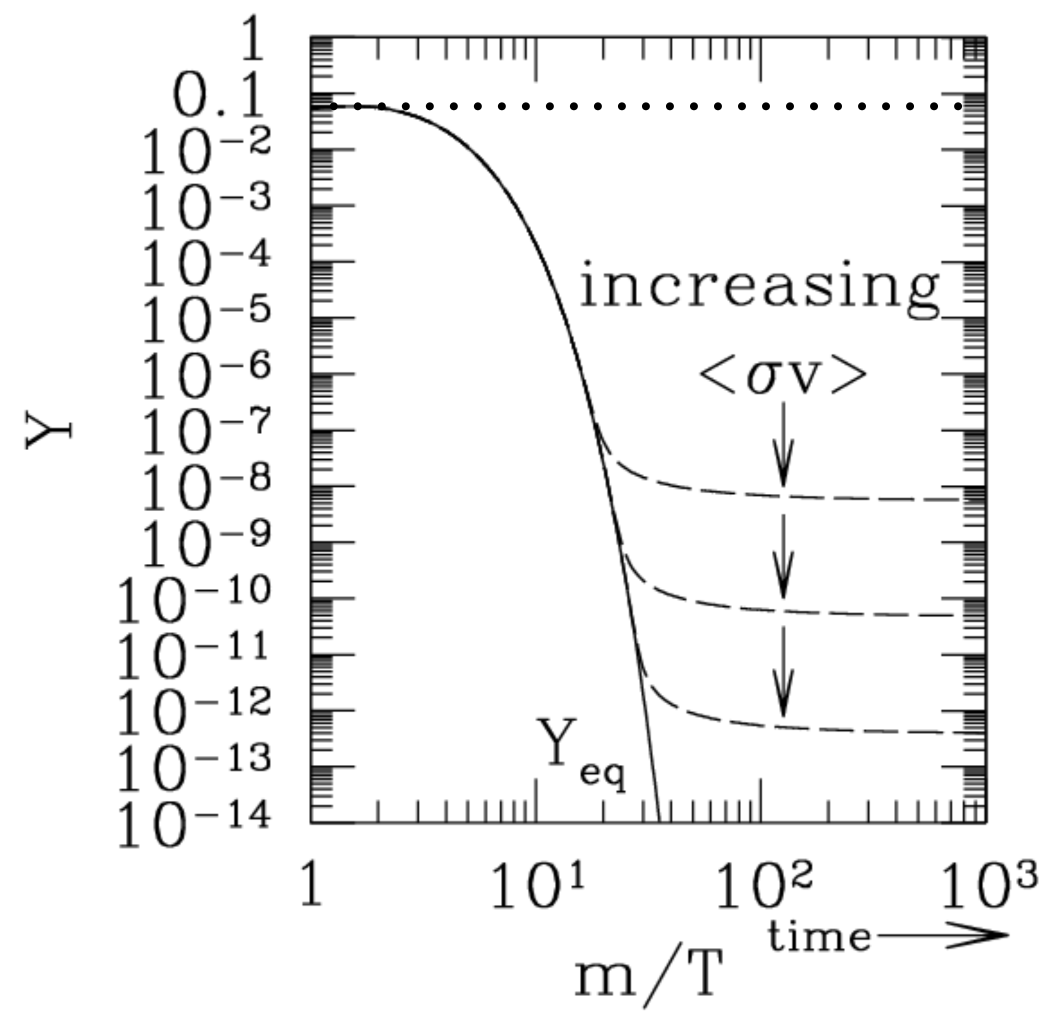

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$$\langle S \rangle \neq 0 \implies \mathcal{L} \supset y_\chi \langle S \rangle \overline{\chi} \Psi + y'_\chi \langle S \rangle \overline{\chi} \Psi'$$

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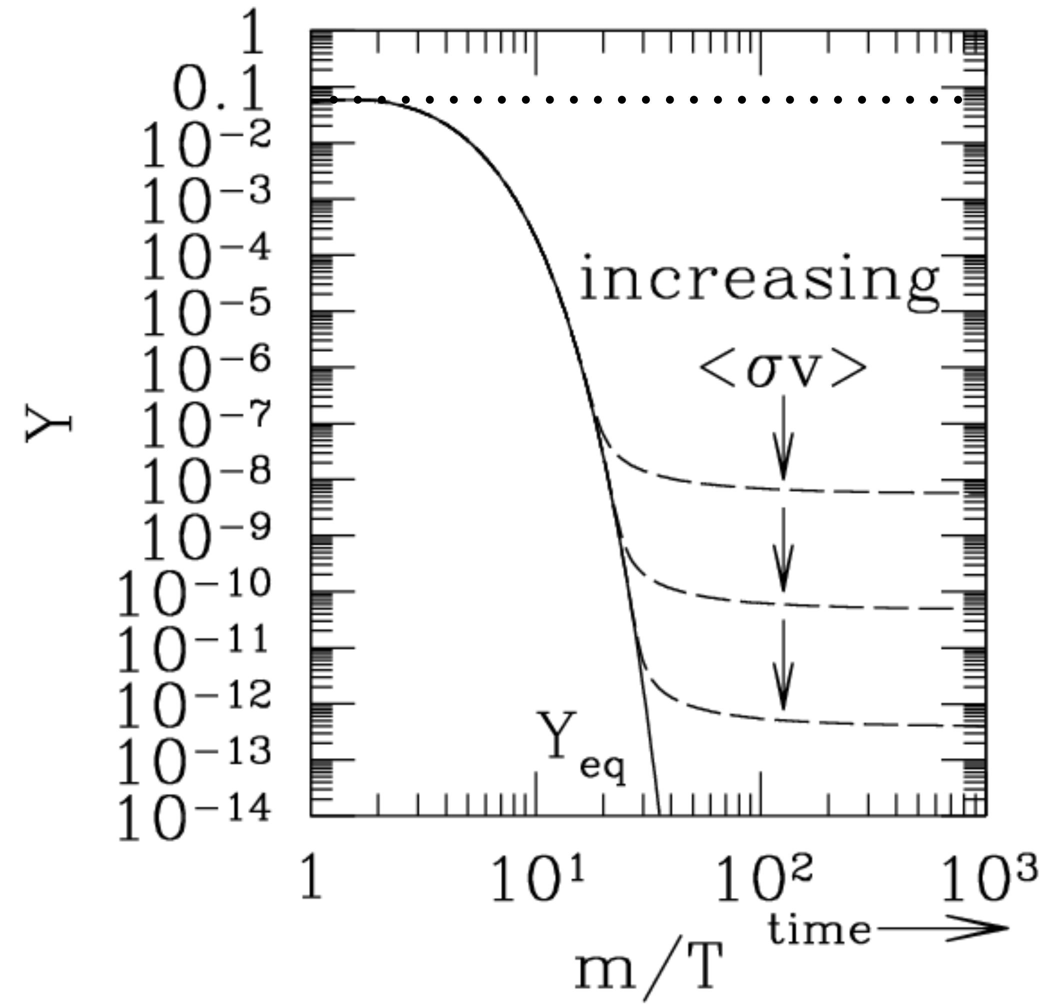

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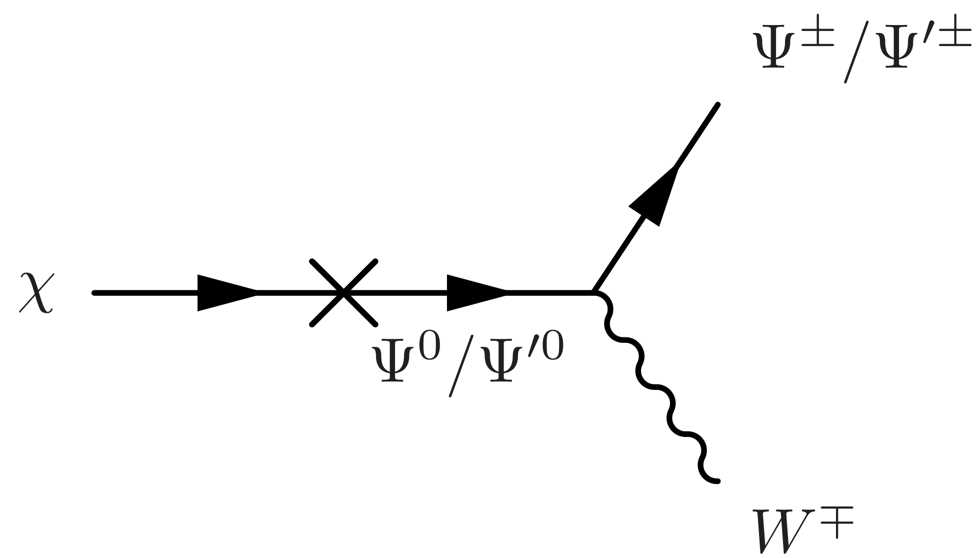

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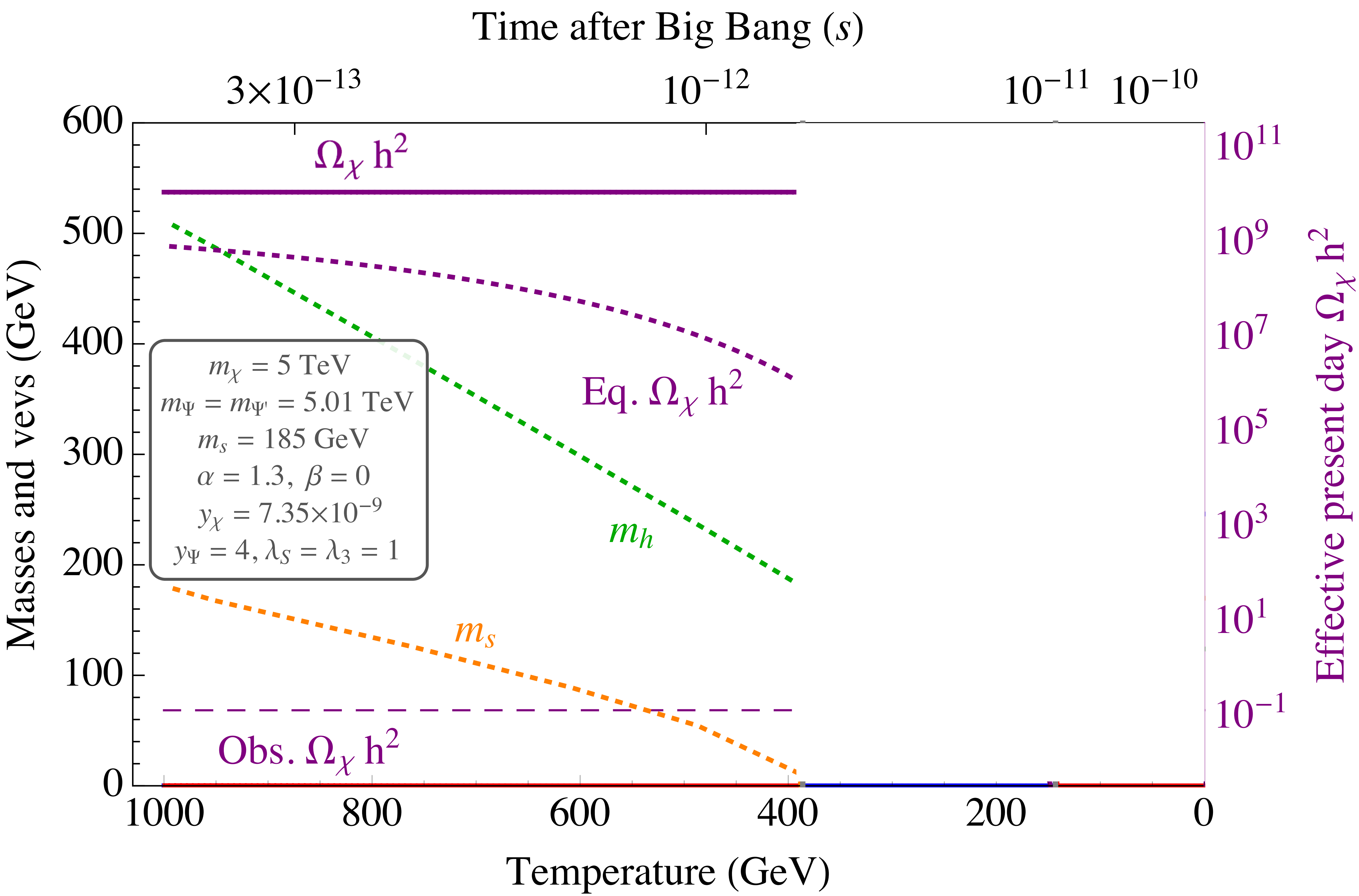

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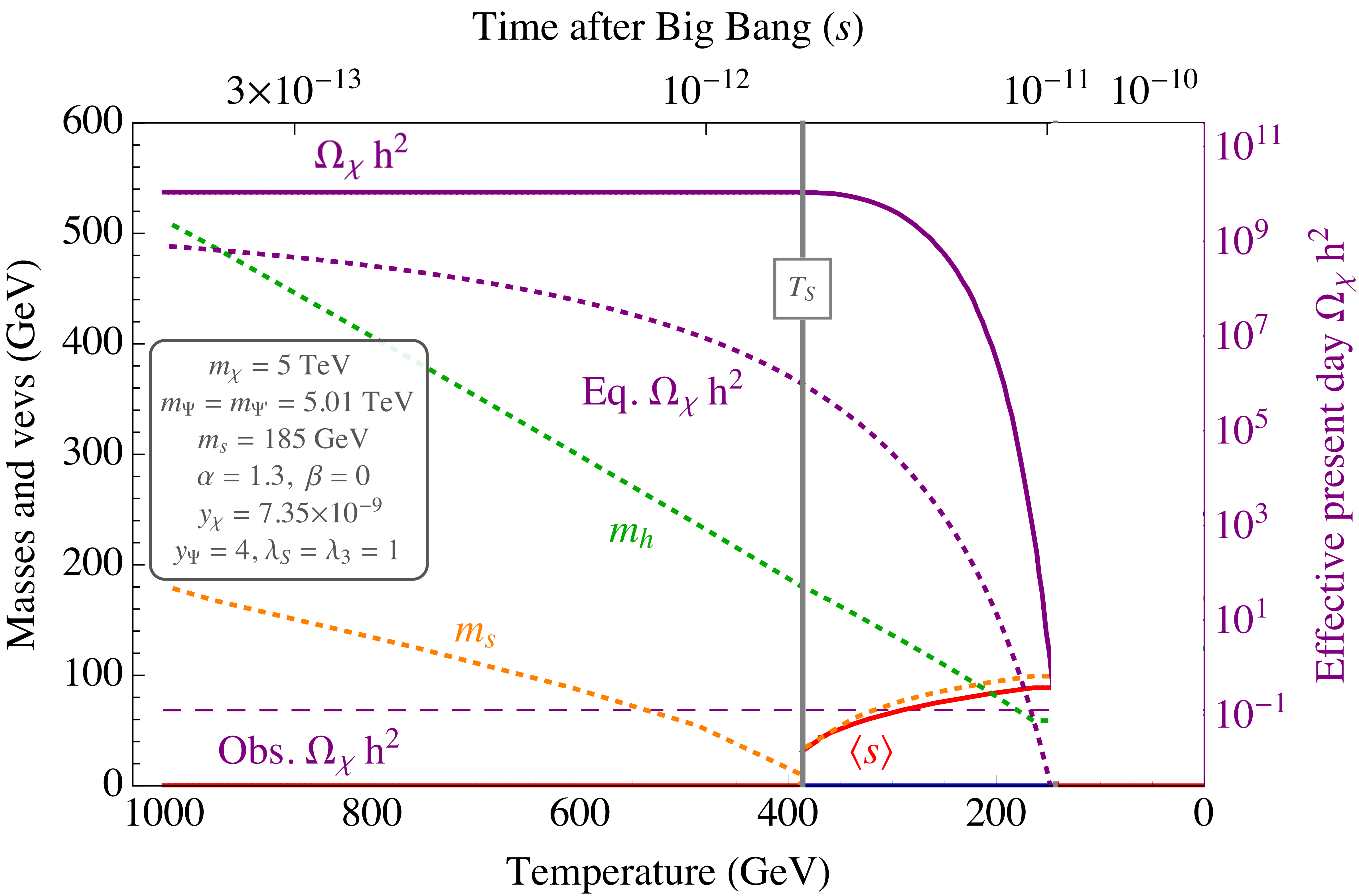

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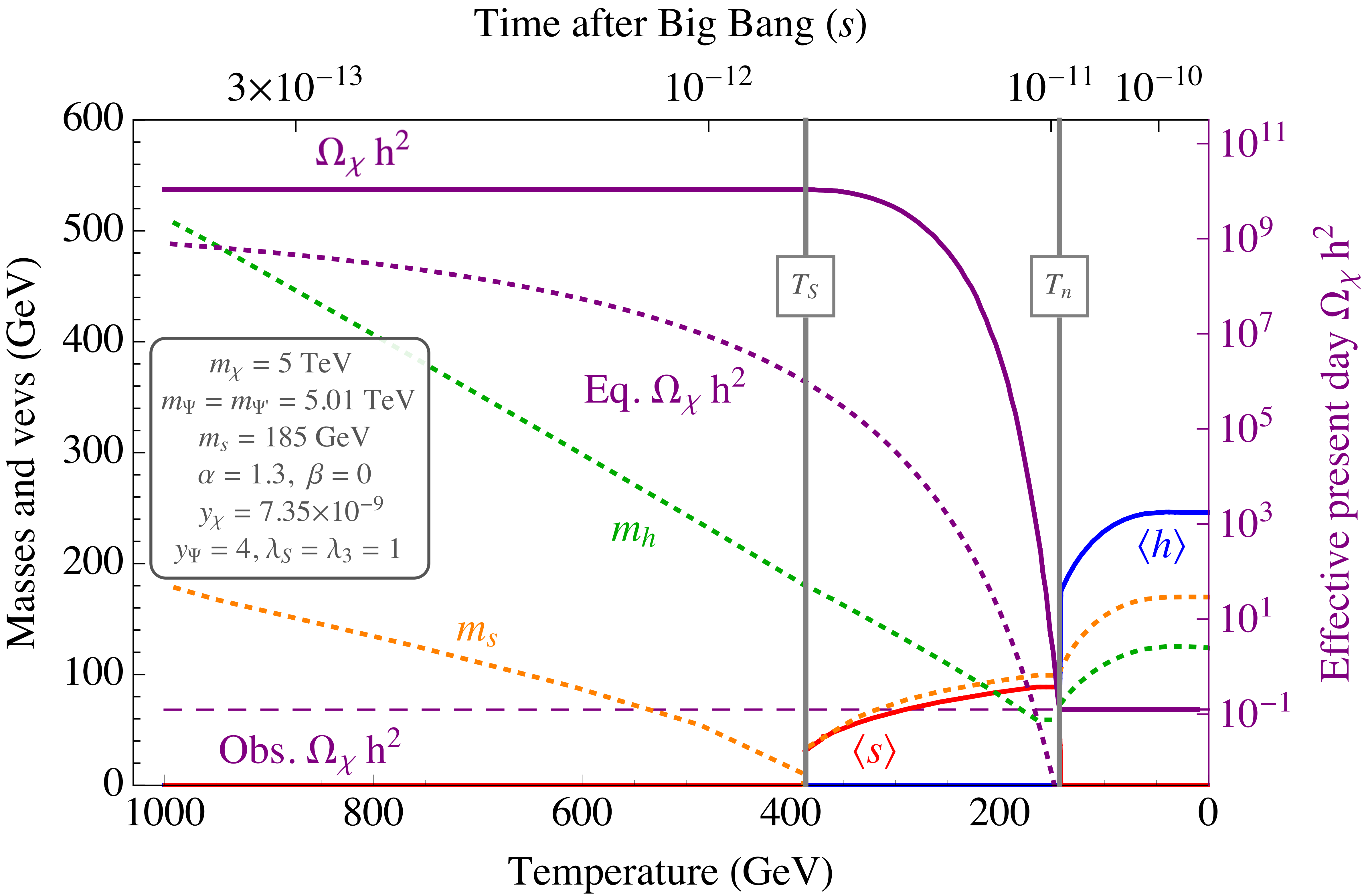

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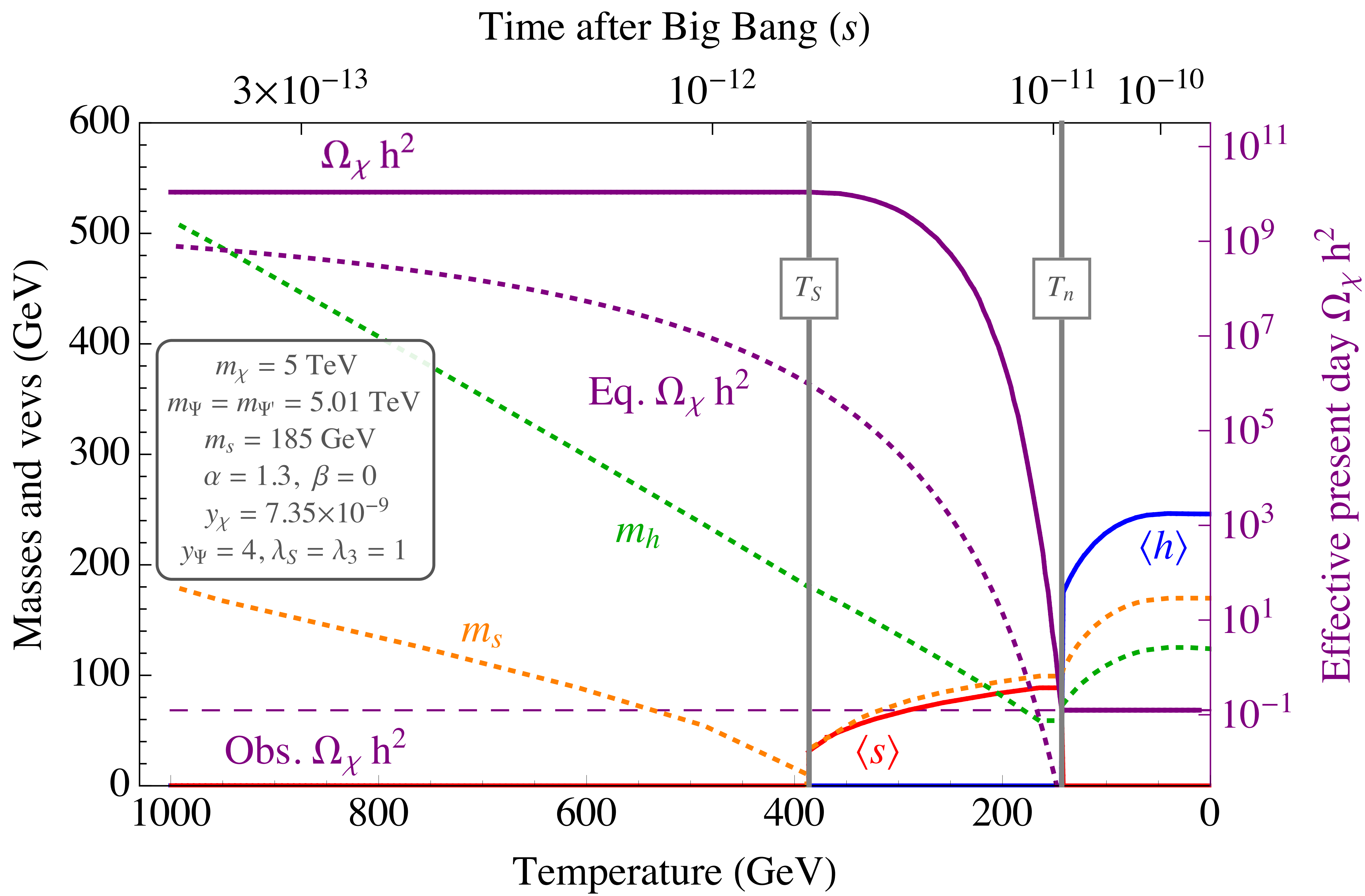
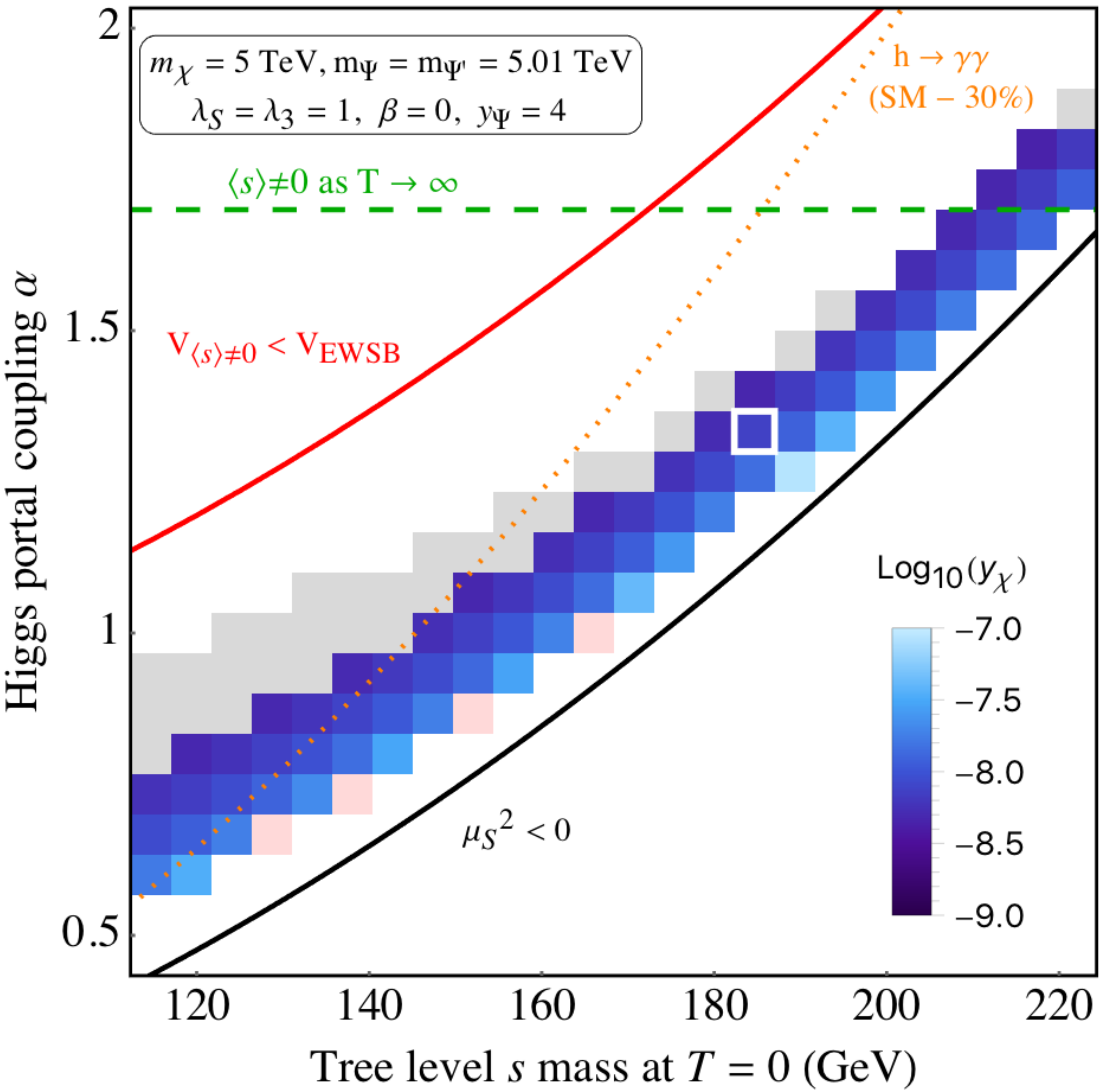


New production mechanism, determined by finite temperature effects

- Vev Flip-Flop: Parameter Space



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

- Vev Flip-Flop: Possible tests

Direct and Indirect Detection

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Detection of χ hindered by small couplings

Best prospect from subdominant population of s, Ψ^0, Ψ'^0

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Small mass splitting implies soft decay products

Mono-X is several orders of magnitude too weak

Possibilities in disappearing charged tracks