Freezing-in a Hot Bath

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JHEP (110) 2022

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RWTH AACHEN UNIVERSITY
McGill

SOLVE A BOLTZMANN EQUATION

$$\dot{n}_\chi + 3Hn_\chi = C[f_\chi]$$

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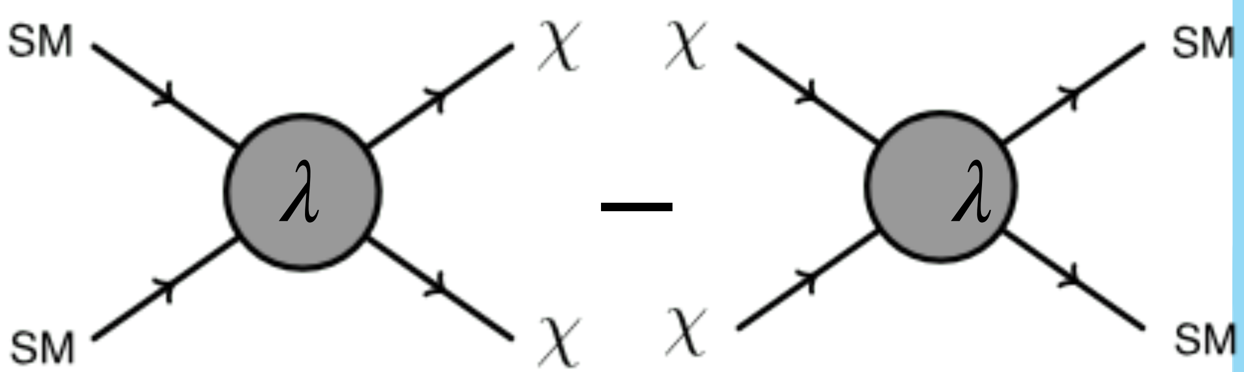
Collision term



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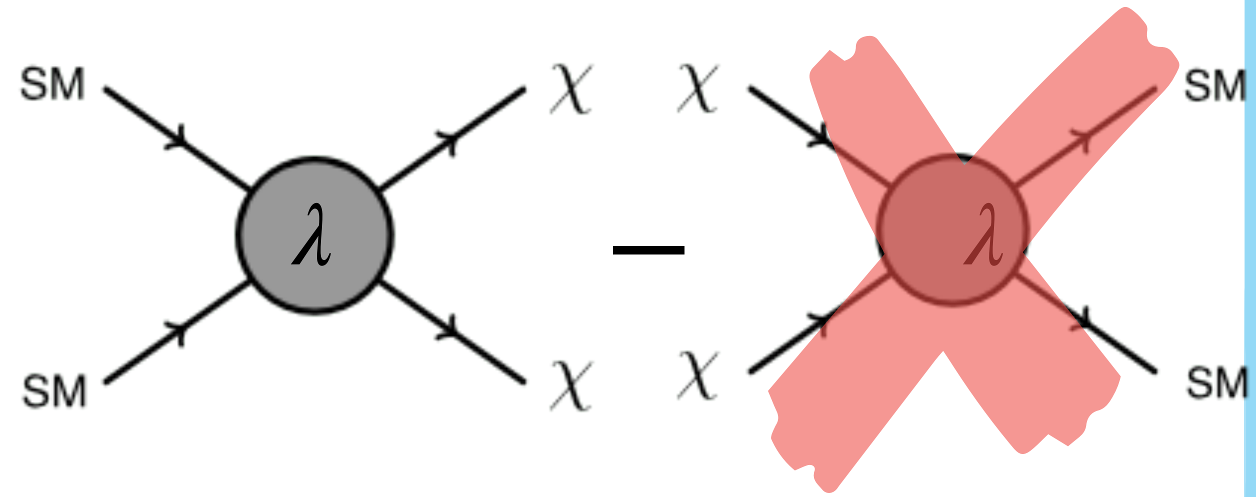

no back-reaction for freeze-in
since DM density is negligible

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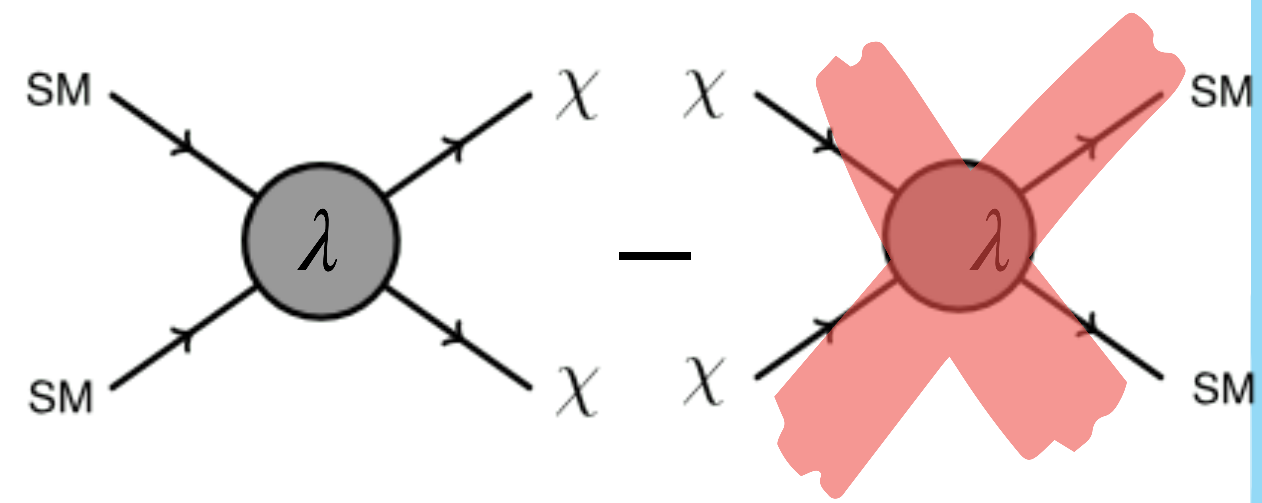
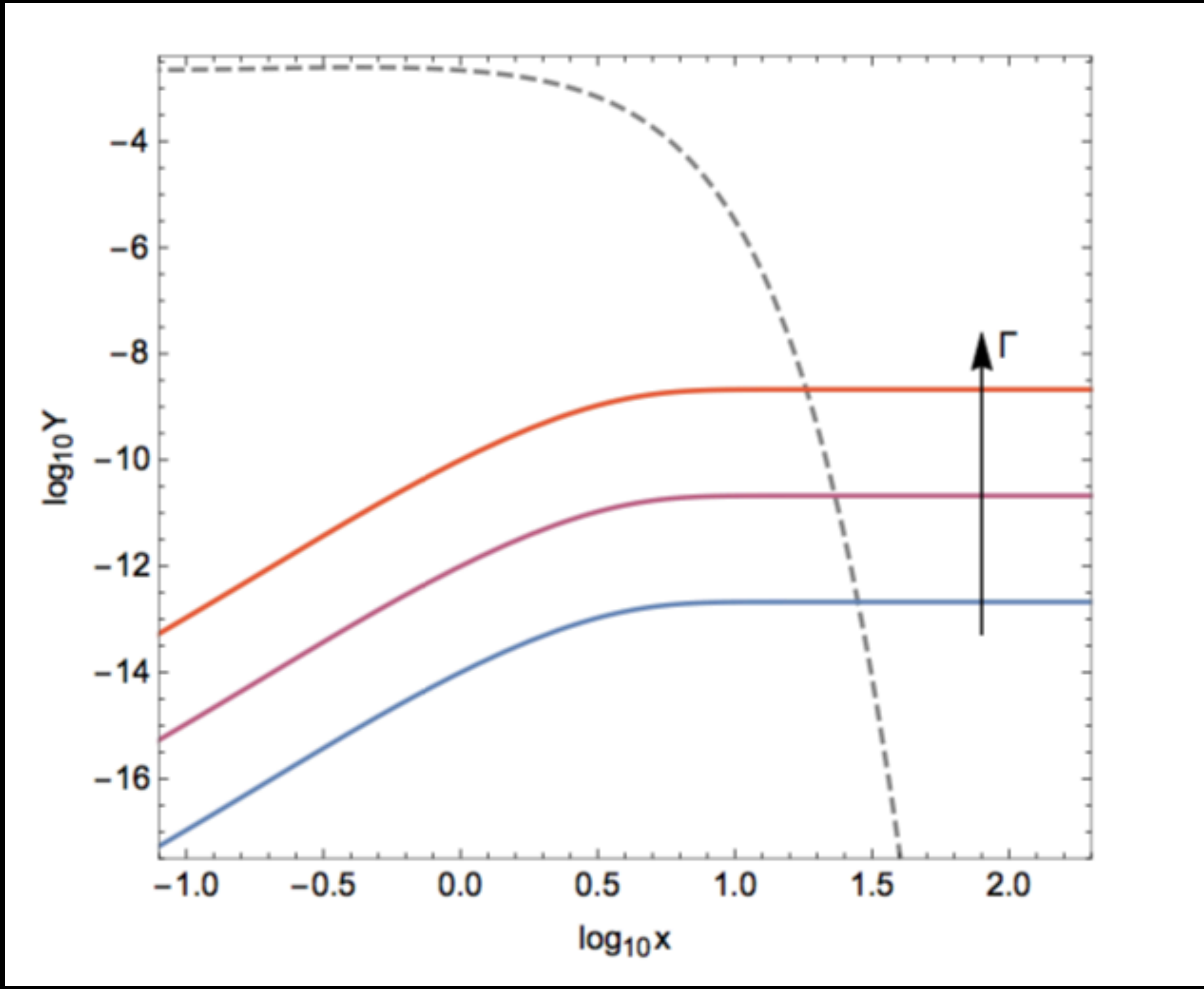
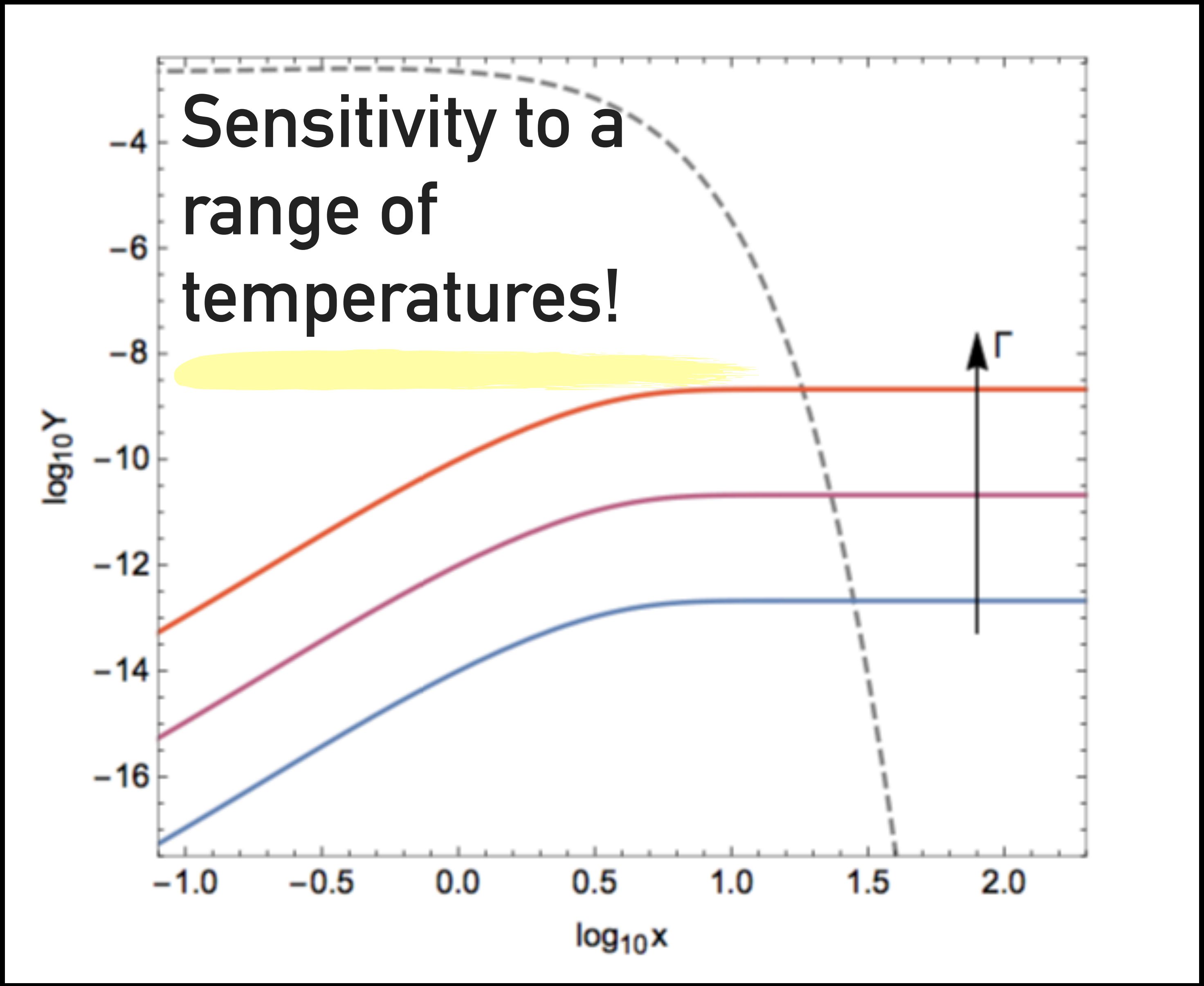


no back-reaction for freeze-in since DM density is negligible

$$\Rightarrow \frac{\mathrm{d}Y_\chi}{\mathrm{d}x} = \frac{s}{H\,x} \langle \sigma v \rangle_{\mathrm{SMSM} \to \chi\chi} \, Y^2_{\mathrm{SM,\,eq.}}$$



Γ
−4
−6
−8
−10
−12
−14
−16
$\log_{10}Y$
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
$\log_{10}x$


Sensitivity to a range of temperatures!
Γ
log10Y
log10x
−4
−6
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−14
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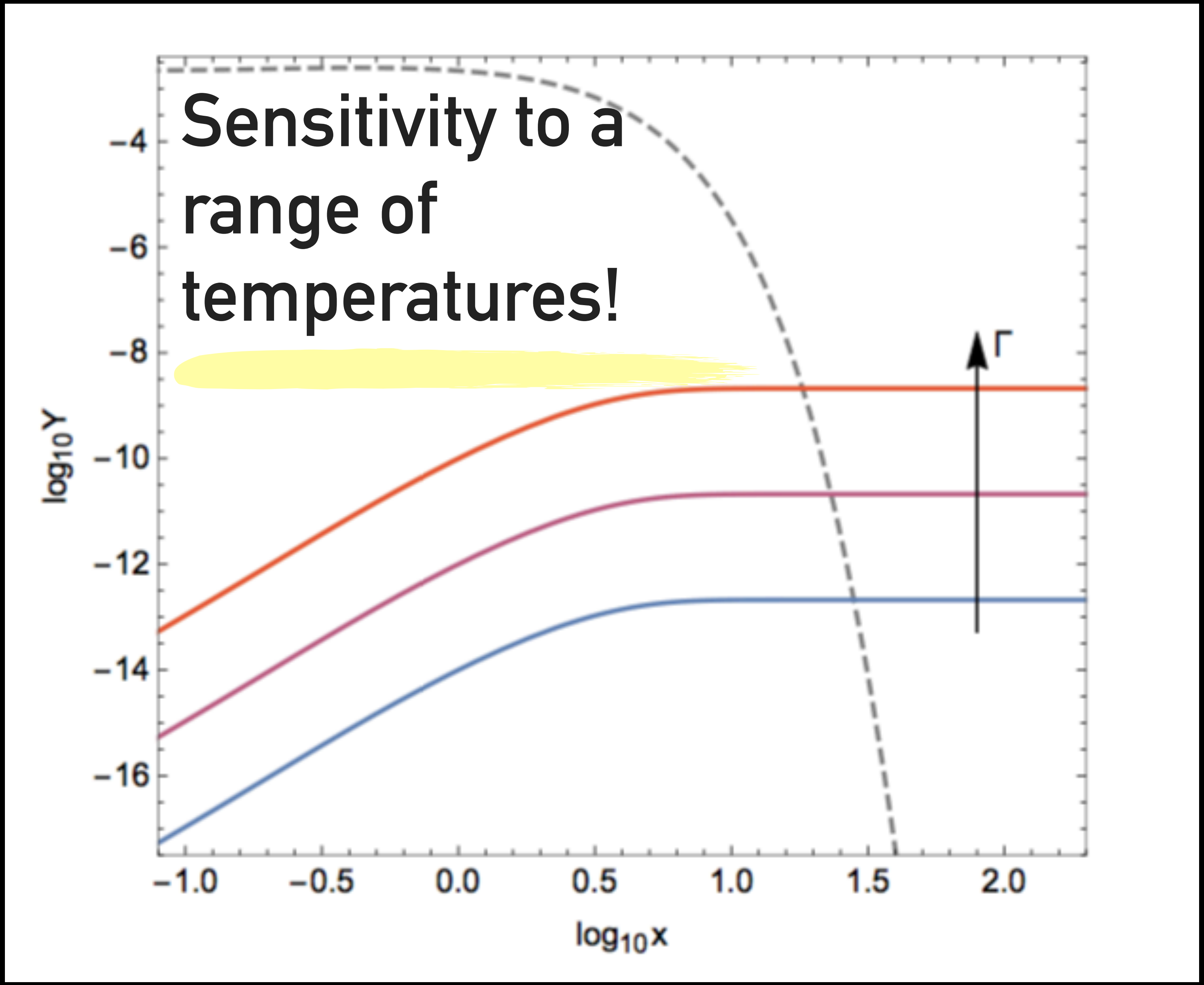
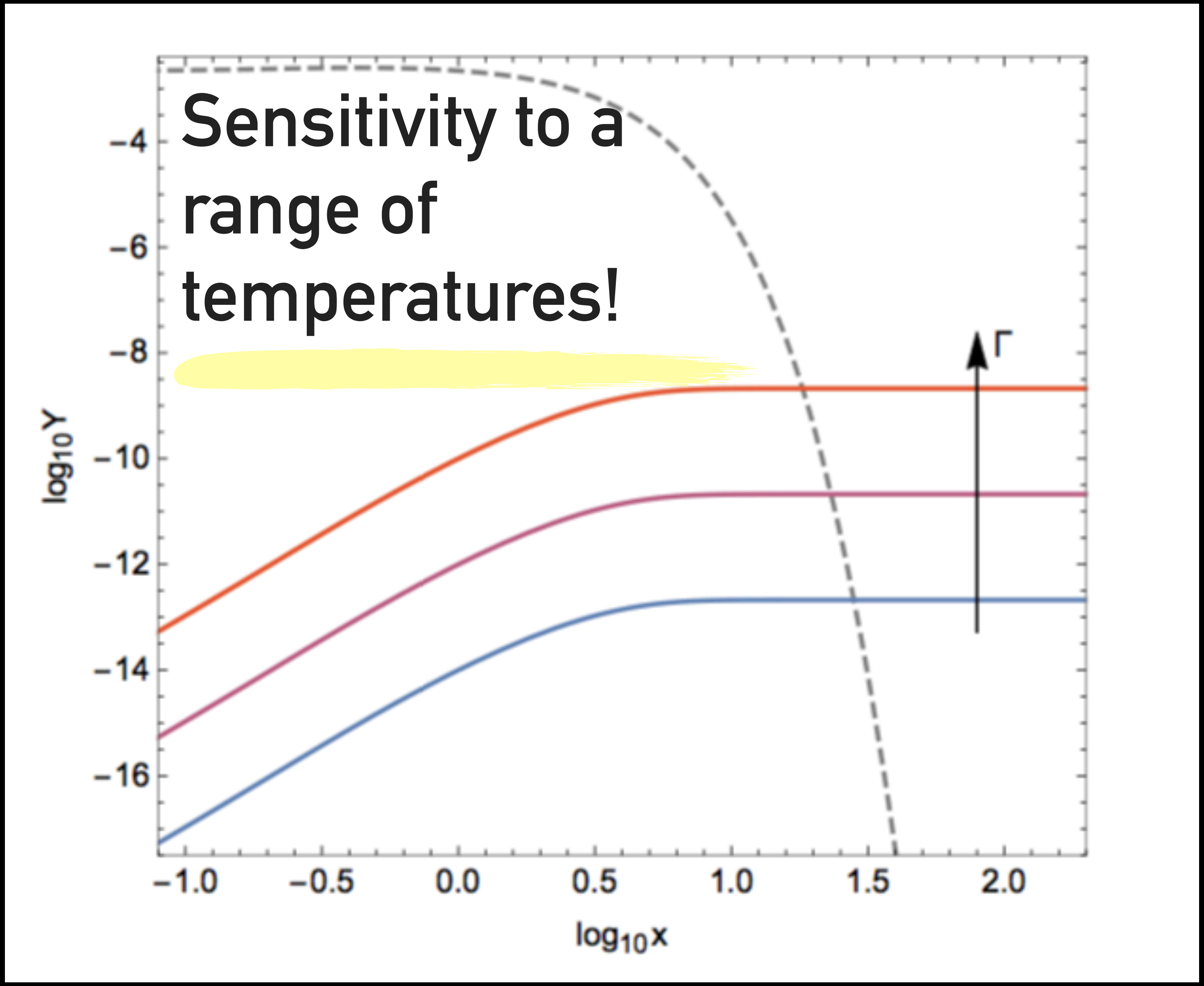
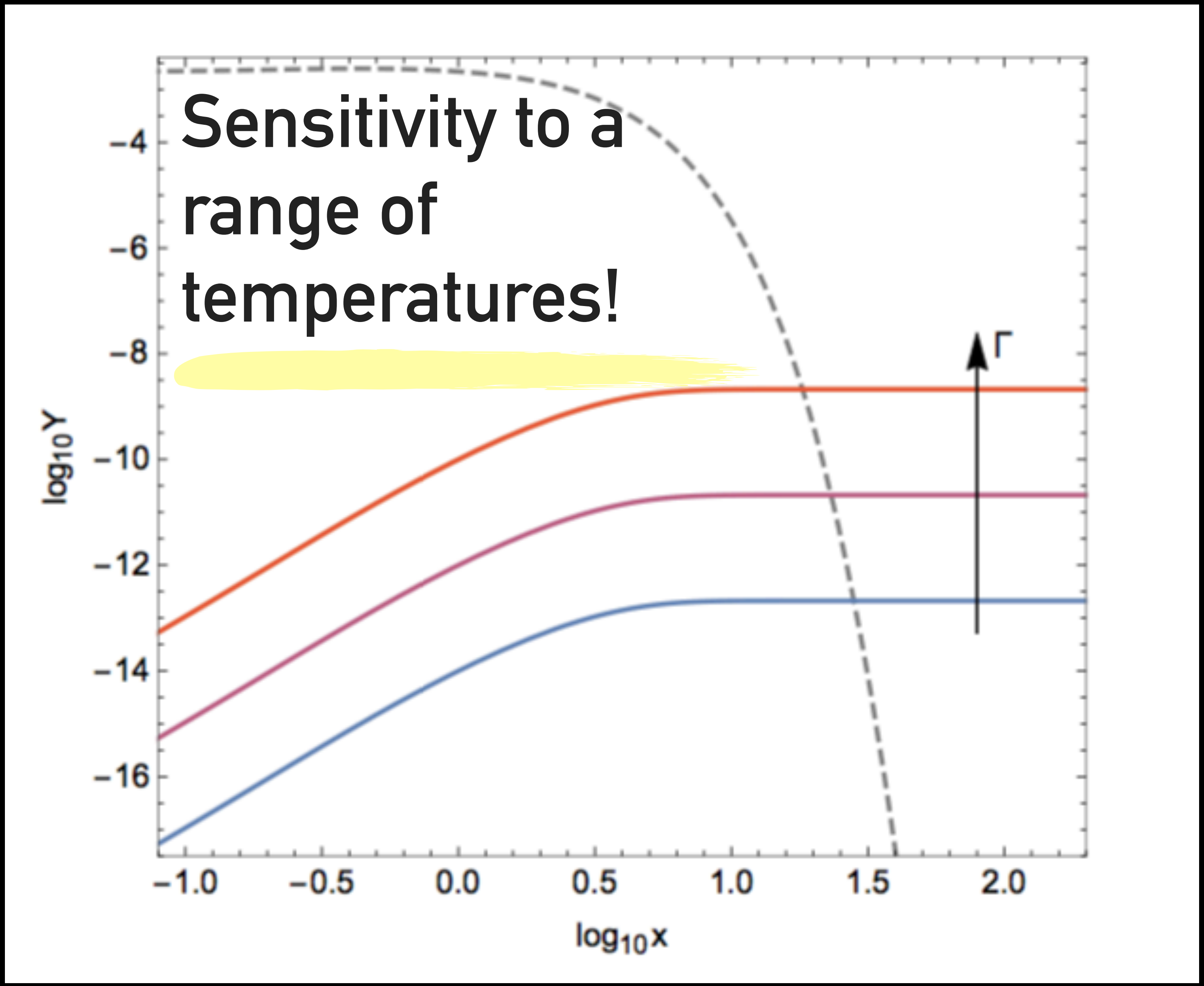


Need to account for:



Need to account for:

- spin statistics of relativistic quantum gases: result in a frame dependence



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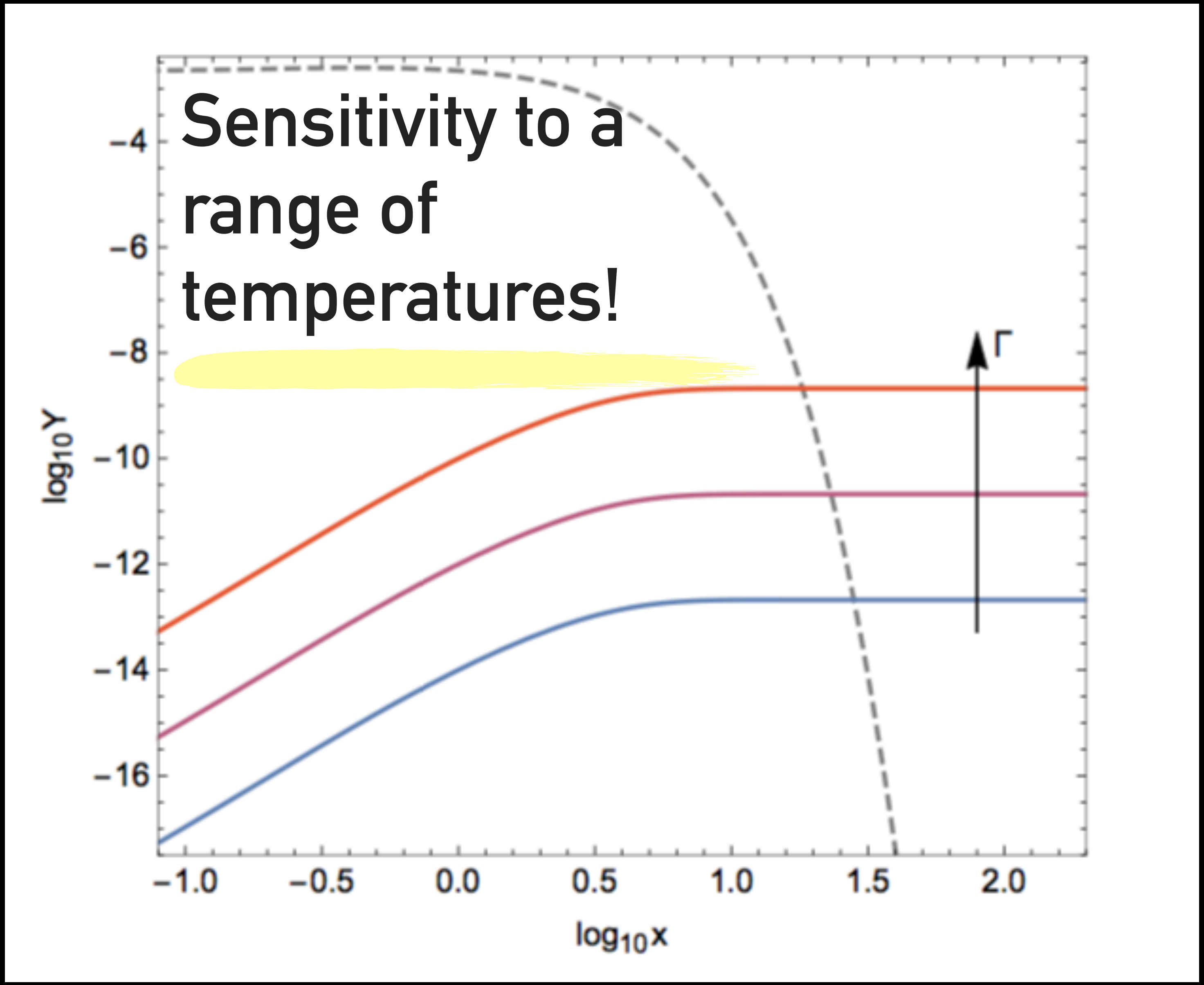

Need to account for:

- spin statistics of relativistic quantum gases: result in a frame dependence
- particle widths/masses in-medium
- relevant degrees of freedom (phase transitions…)

1.

REFORMULATE THE FIMP BOLTZMANN EQ TO CONSISTENTLY ACCOUNT FOR THESE EFFECTS

I.

REFORMULATE THE FIMP BOLTZMANN EQ TO CONSISTENTLY ACCOUNT FOR THESE EFFECTS

II.

APPLY TO A SIMPLE MODEL TO STUDY THEIR RELEVANCE

GENERIC COLLISION TERM FOR FREEZE-IN

$$C[f_\chi] = \frac{1}{N_\psi} \int \frac{d^3p}{(2\pi)^3 2E} \int \frac{d^3\tilde{p}}{(2\pi)^3 2\tilde{E}} \int \frac{d^3k}{(2\pi)^3 2\omega} \int \frac{d^3\tilde{k}}{(2\pi)^3 2\tilde{\omega}} (2\pi)^4 \delta^{(4)}(\tilde{p} + p - \tilde{k} - k) \times \left[\left| \mathcal{M} \right|^2_{\psi\psi\to\chi\chi} f_\psi(\omega) f_\psi(\tilde{\omega}) \right]$$

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symmetry factor

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Lorentz Invariant Phase Space

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Energy-momentum conservation

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Energy conservation

Fiducial Maxwell-Boltzmann DM phase-space density

BOLTZMANN EQ. FOR FREEZE-IN:

$$\frac{\mathrm{d}Y_\chi}{\mathrm{d}x} = \frac{\langle \sigma v \rangle_{\chi\chi \to \psi\psi}}{xsH} \left(n_\chi^{\mathrm{MB}} \right)^2$$

Bringmann, **SH** et al: 2111.14871

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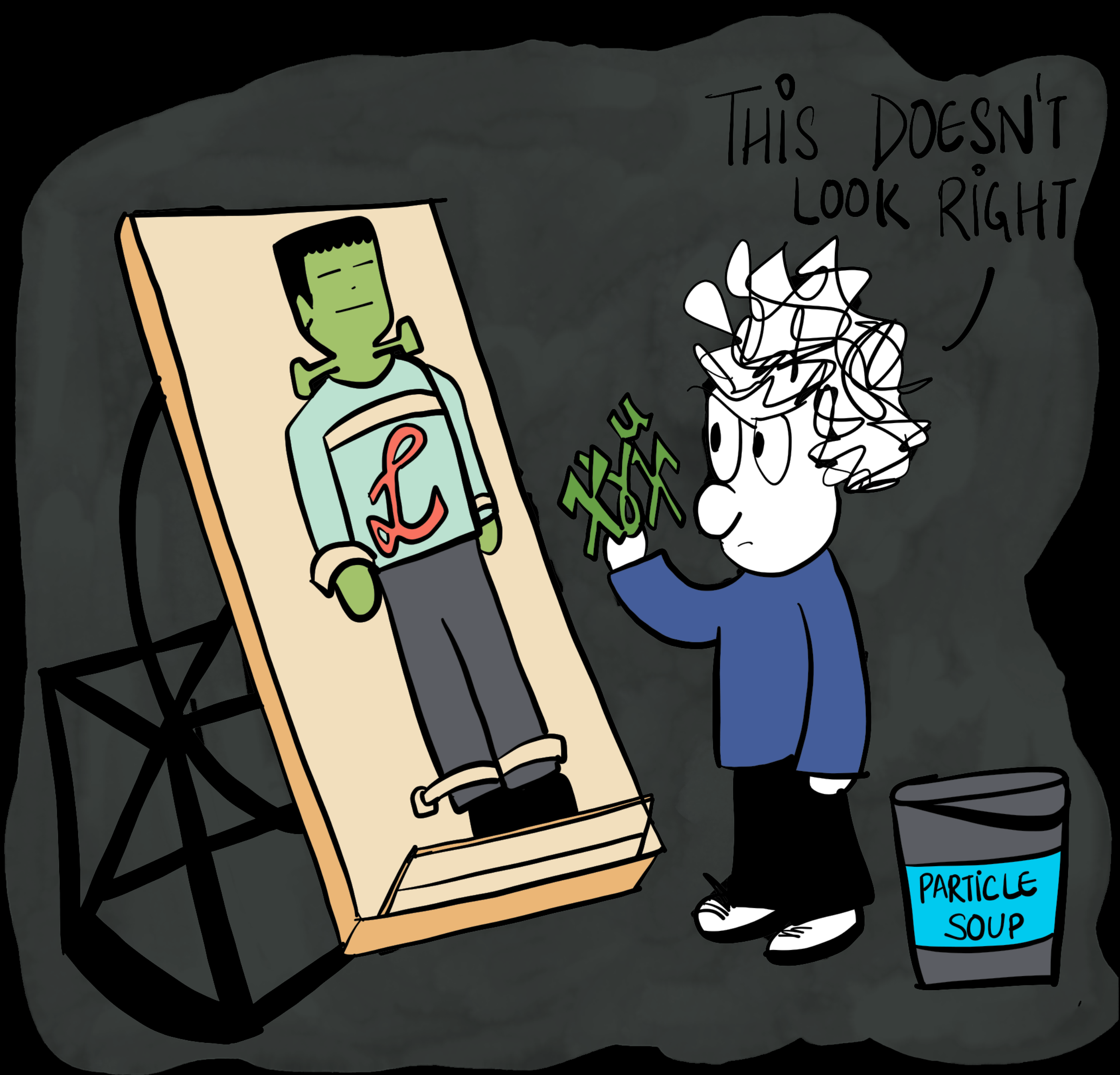
In-medium cross-section boosted to the CMS frame

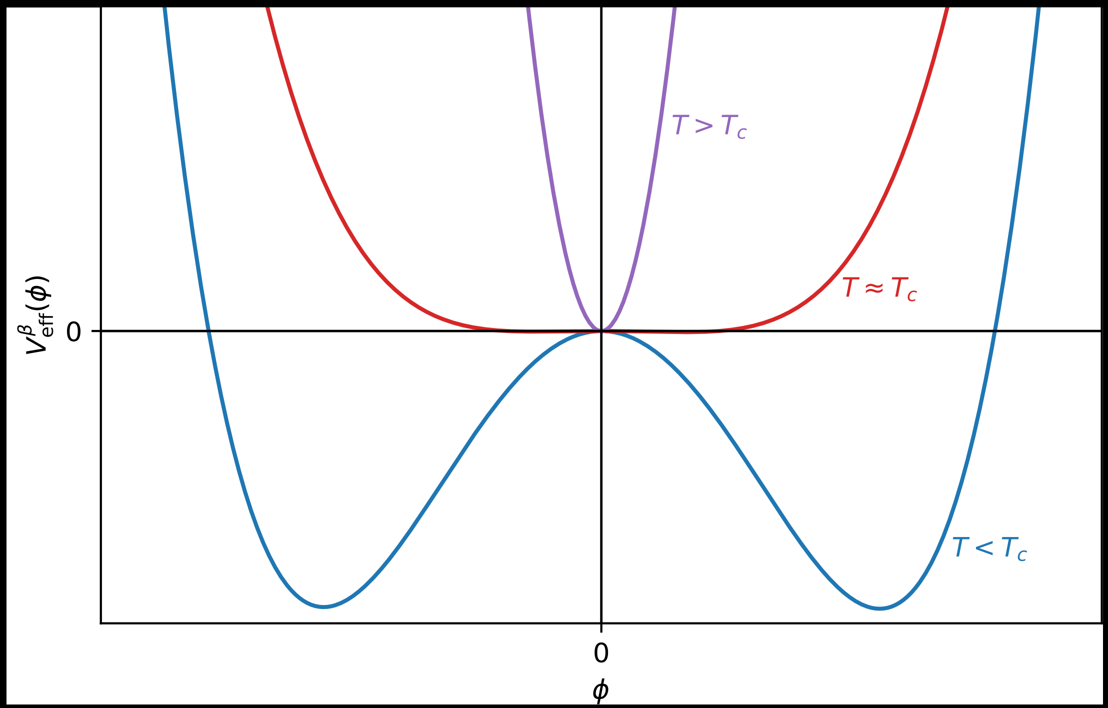
Bringmann, **SH** et al: 2111.14871

II. APPLICATION TO A MODEL

$$L \supset \frac{\lambda_{hs}}{2} |H|^2 S^2$$



ELECTROWEAK PHASE TRANSITION:



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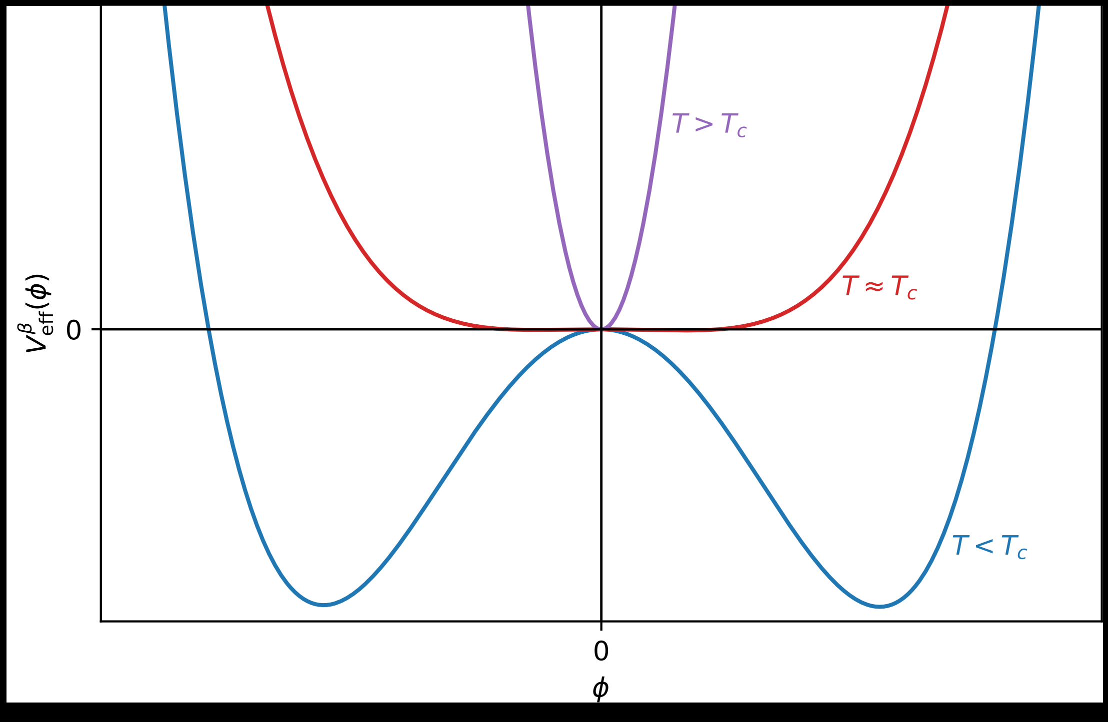
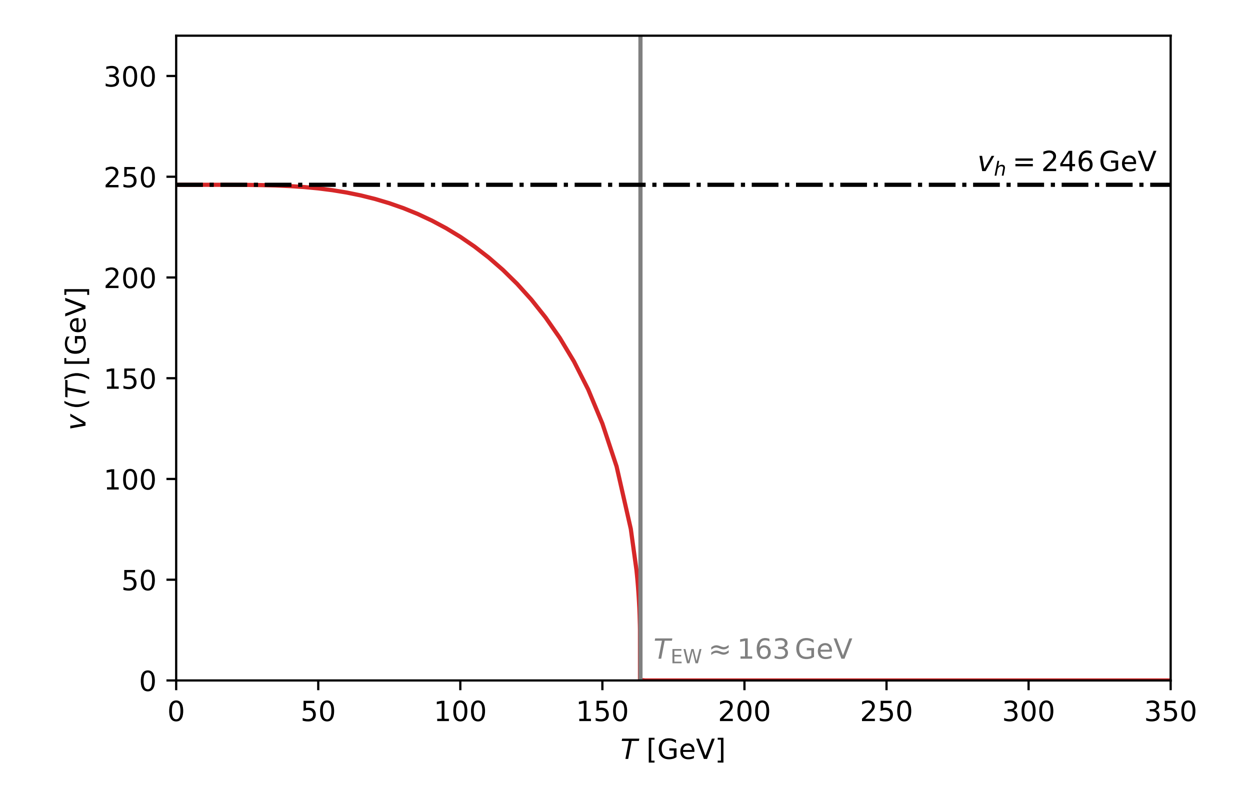
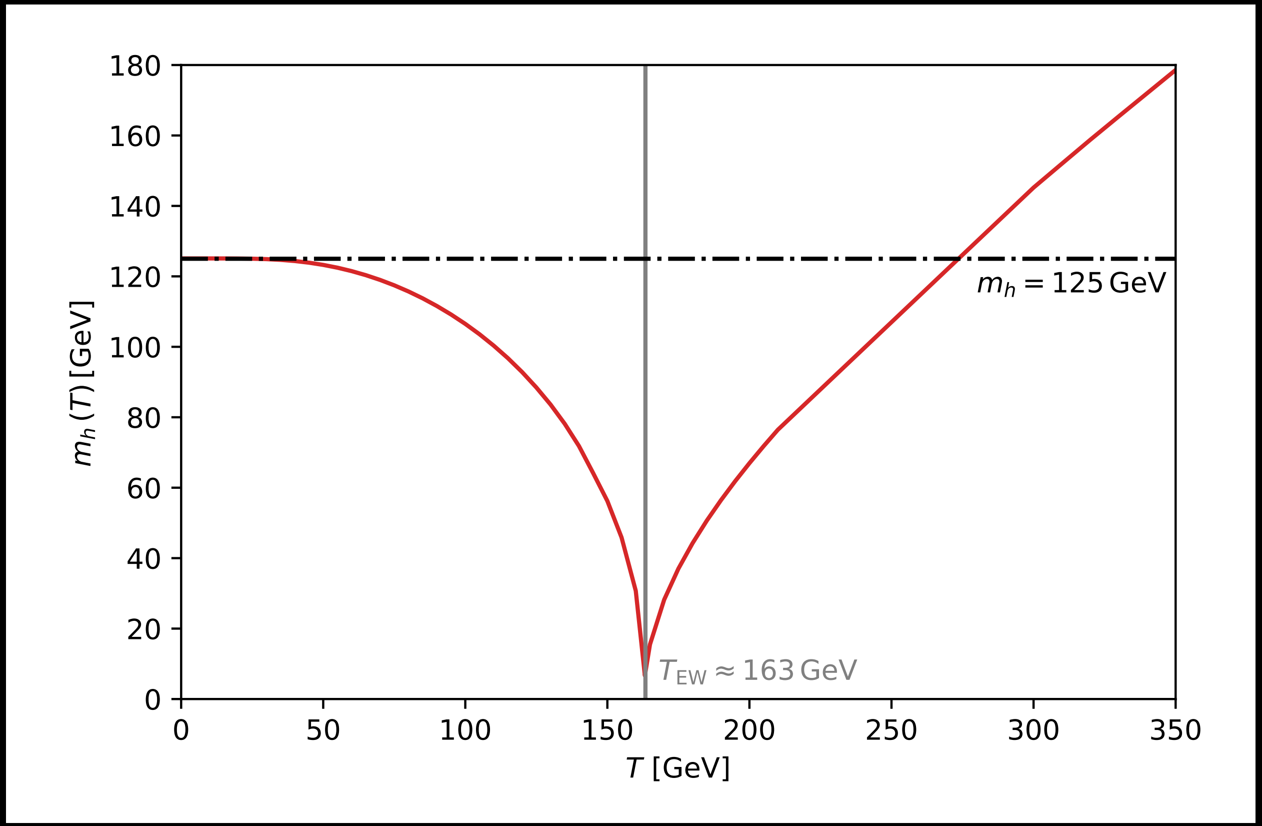
ELECTROWEAK PHASE TRANSITION:

- The **higgs mass** and **vev** are **temperature dependent**







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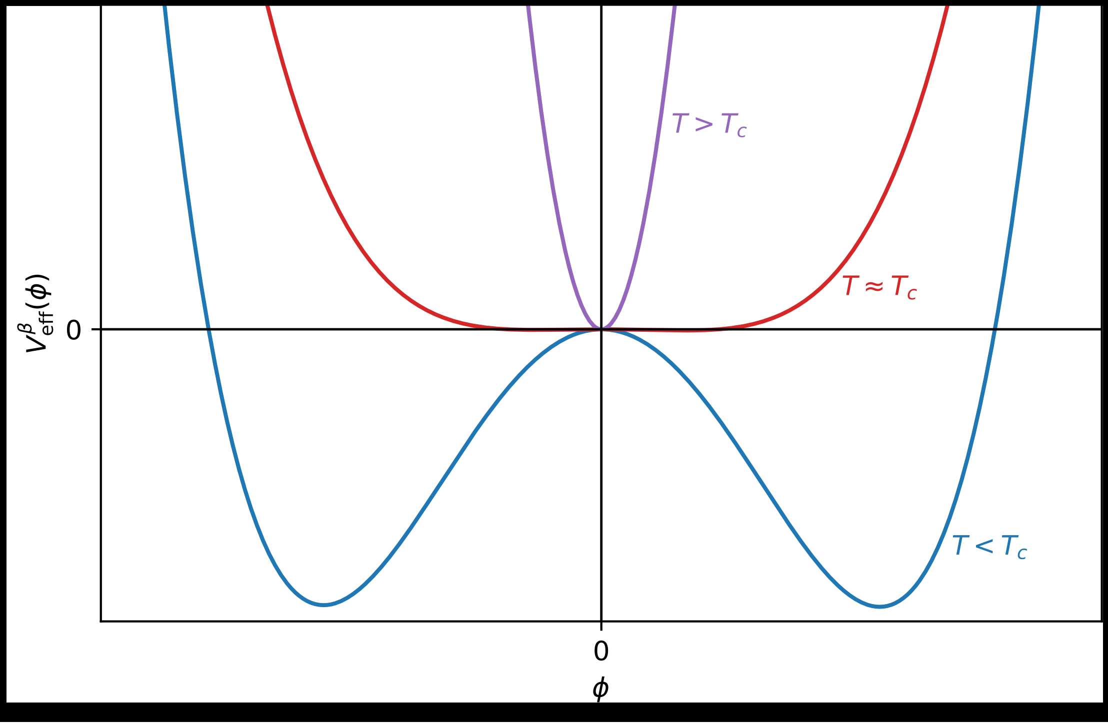
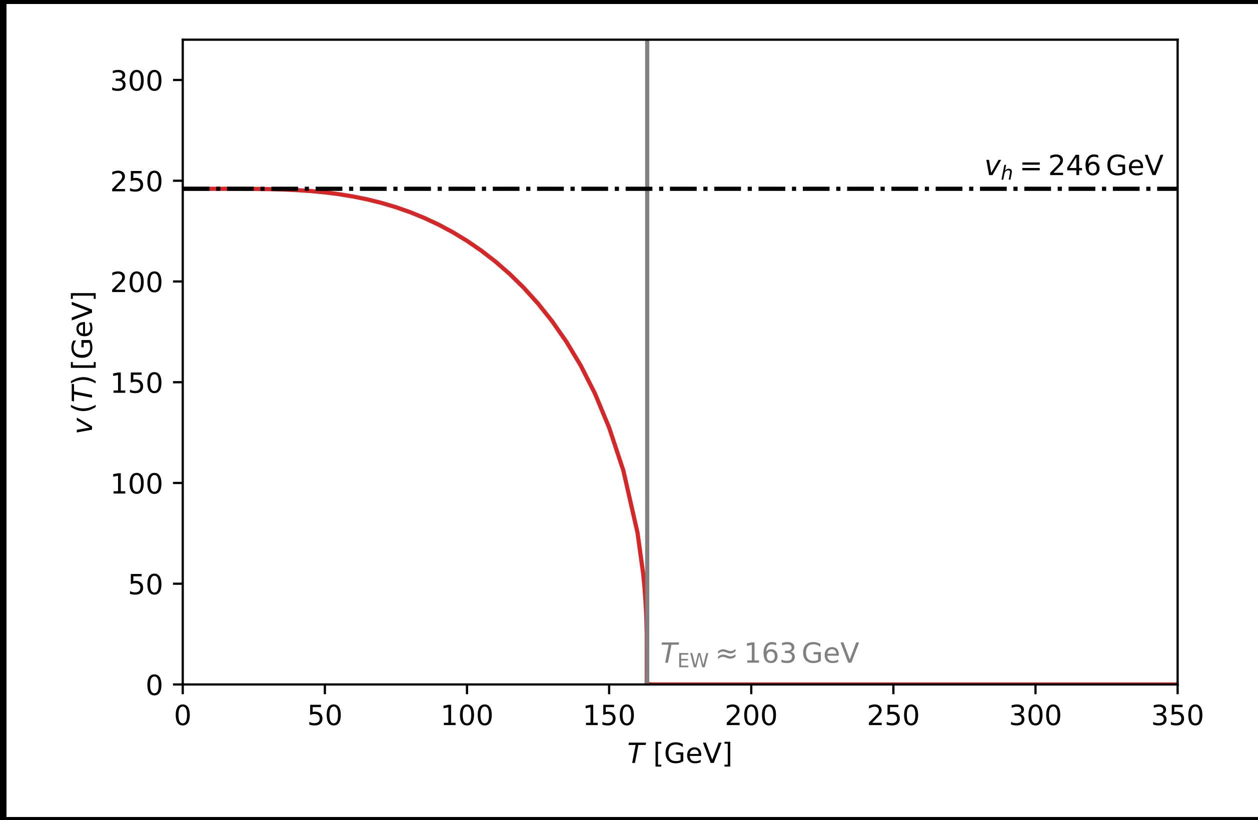
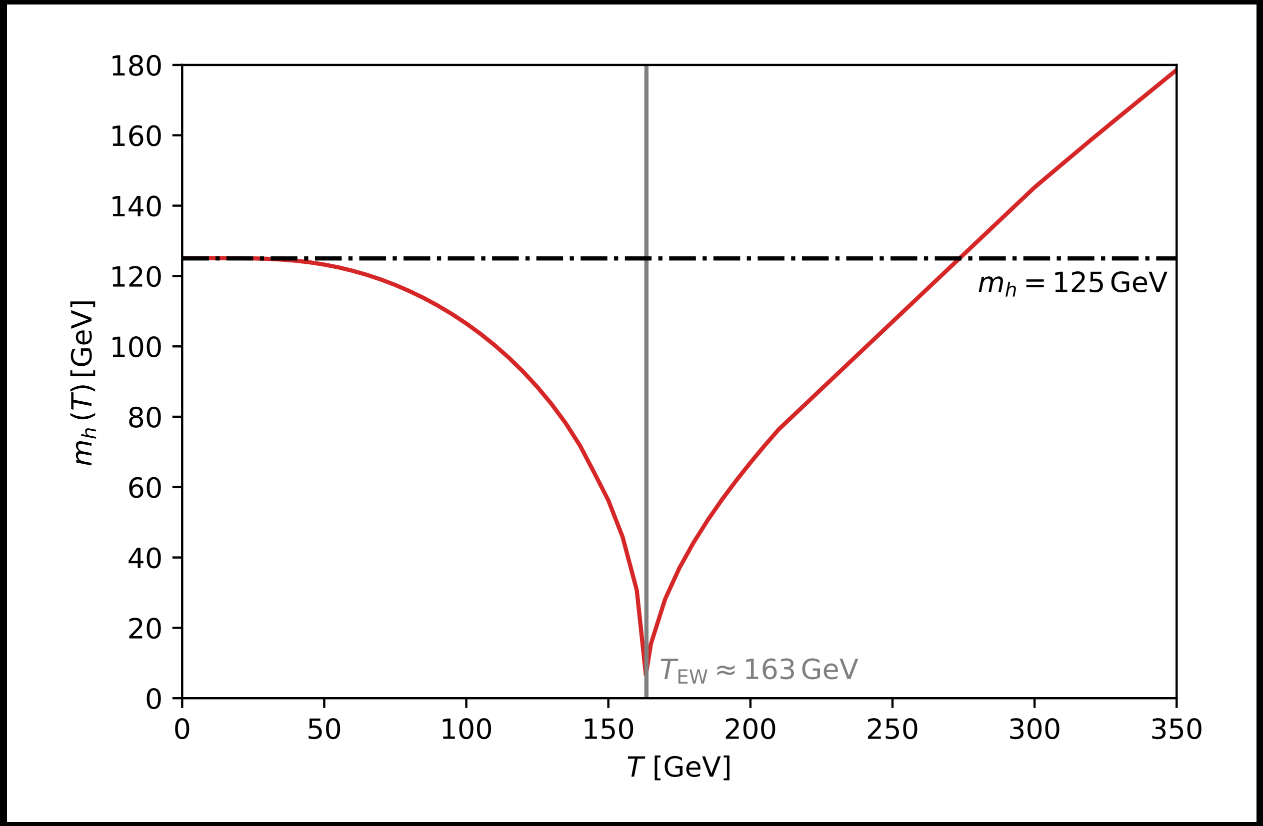
ELECTROWEAK PHASE TRANSITION:

- The **higgs mass** and **vev** are **temperature dependent**
- Coupling structure of the Lagrangian changes before/after PT







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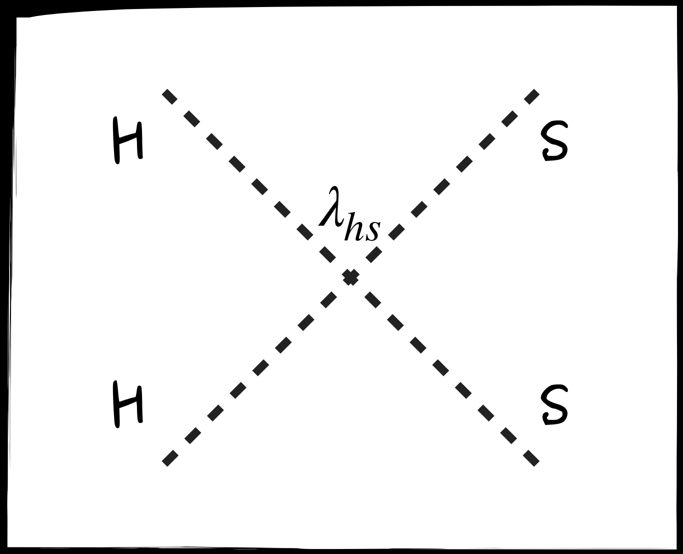
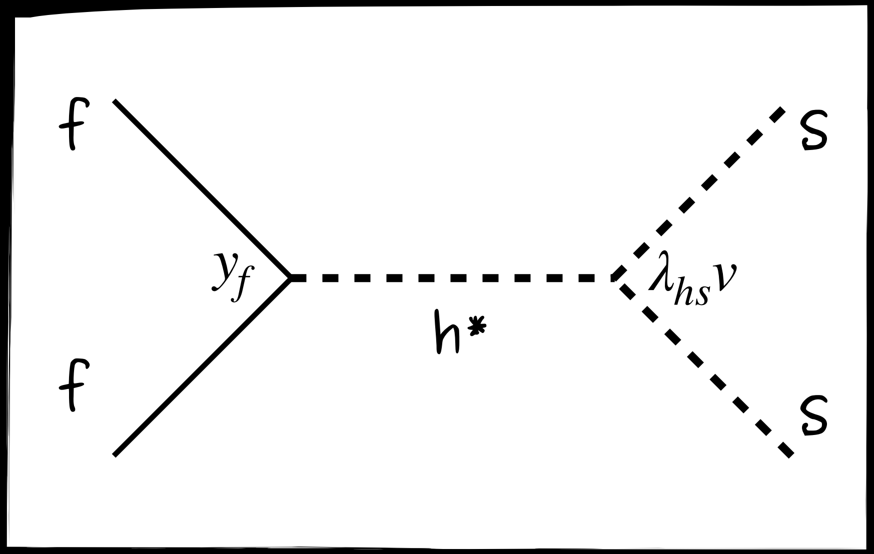
BEFORE EWPT



AFTER EWPT



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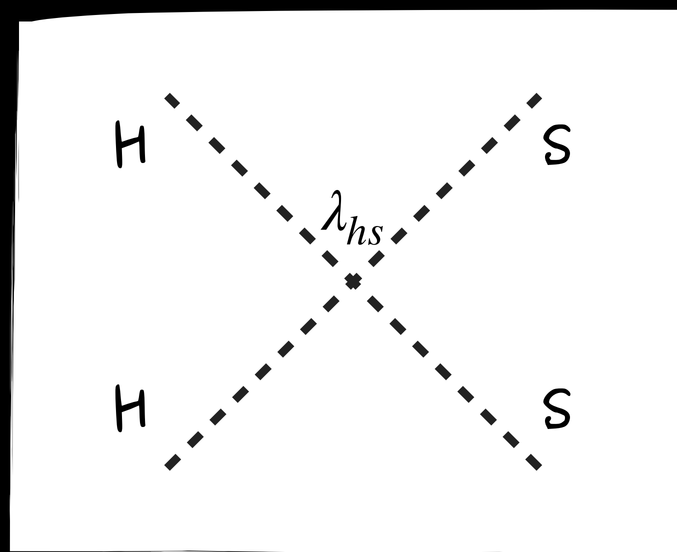
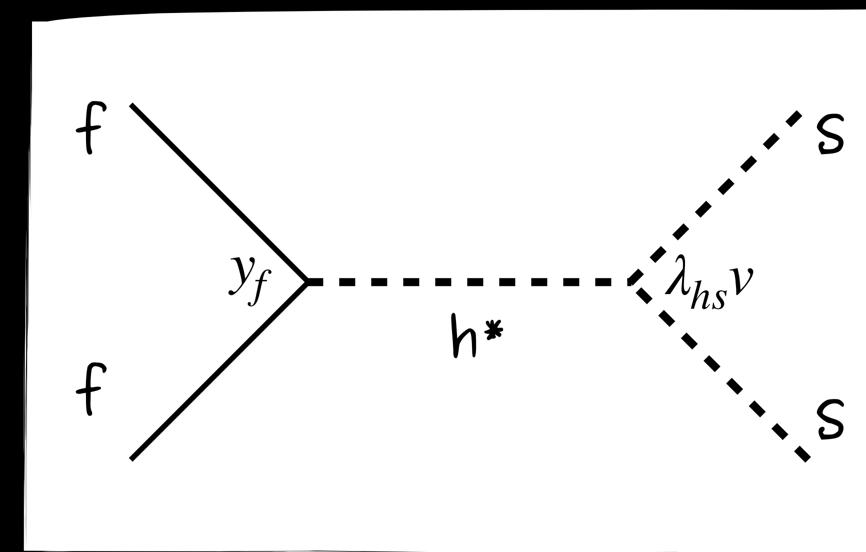


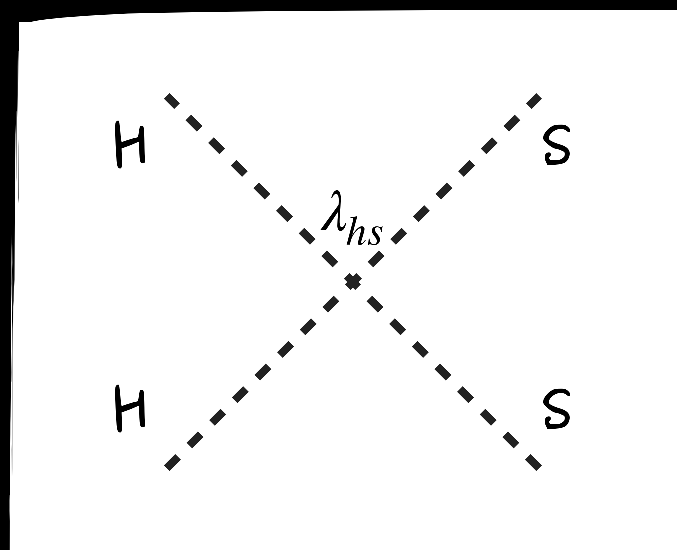
AFTER EWPT

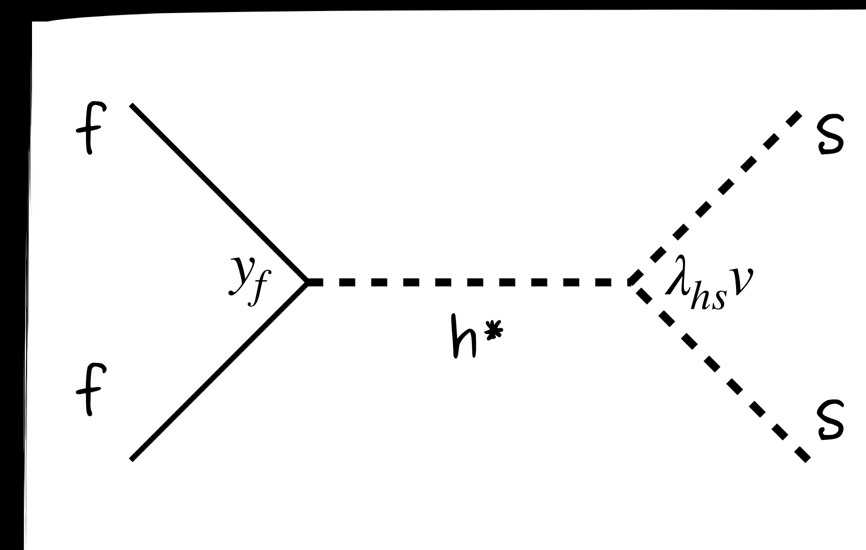


If we write this is in terms of scalar annihilation:

$$\sigma v_{ss\to h^*\to ff} \sim \frac{\lambda_{hs}^2 v_h}{\sqrt{s}} \frac{\Gamma_{h^*}(\sqrt{s})}{(s-m_h^2)^2 + m_h^2\Gamma_h^2}$$

BEFORE EWPT | **AFTER EWPT**





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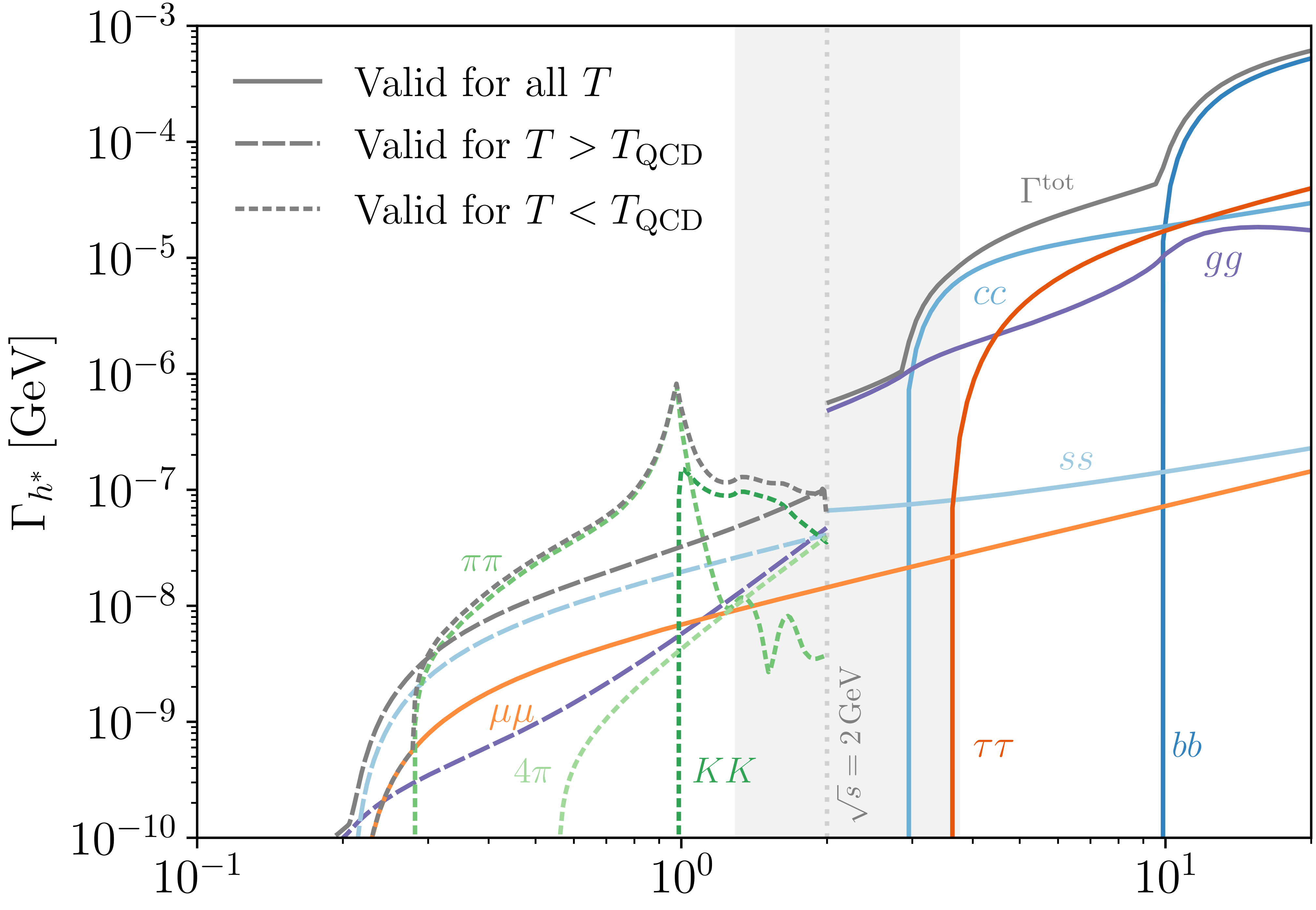
generically include NLO EW corrections!

QCD PHASE TRANSITION:



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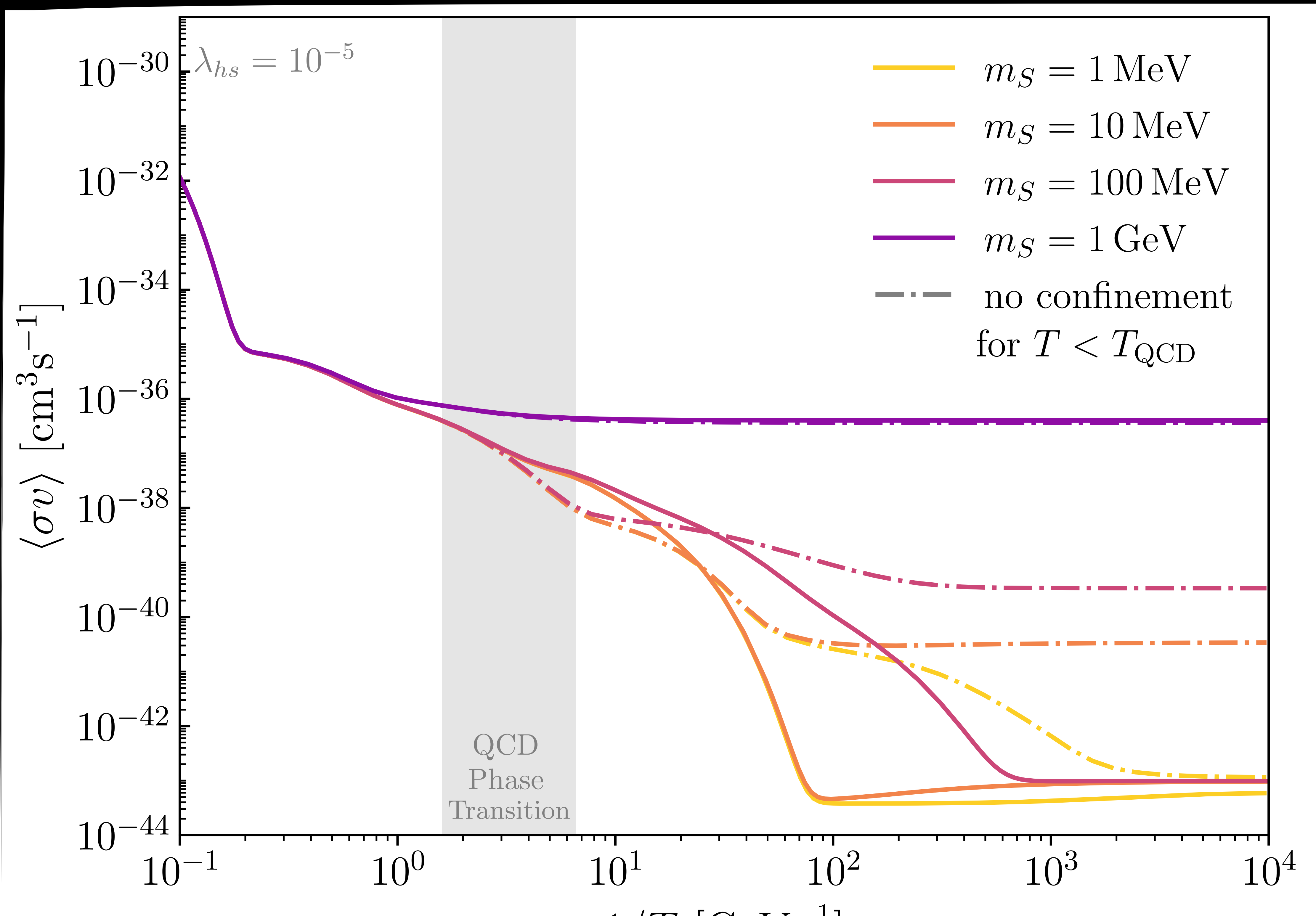
CROSS-SECTIONS:



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UNTIL NOW:

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1. FREEZE-IN IN TERMS OF DM ANNIHILATION CROSS SECTIONS INCLUDING IN-MEDIUM AND THERMAL EFFECTS

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3. CONSISTENTLY ACCOUNT FOR THE RELEVANT DEGREES OF FREEDOM

I.

IR FREEZE-IN

$(T_{\rm RH} \gg T_{\rm EW})$

CROSS-SECTIONS:

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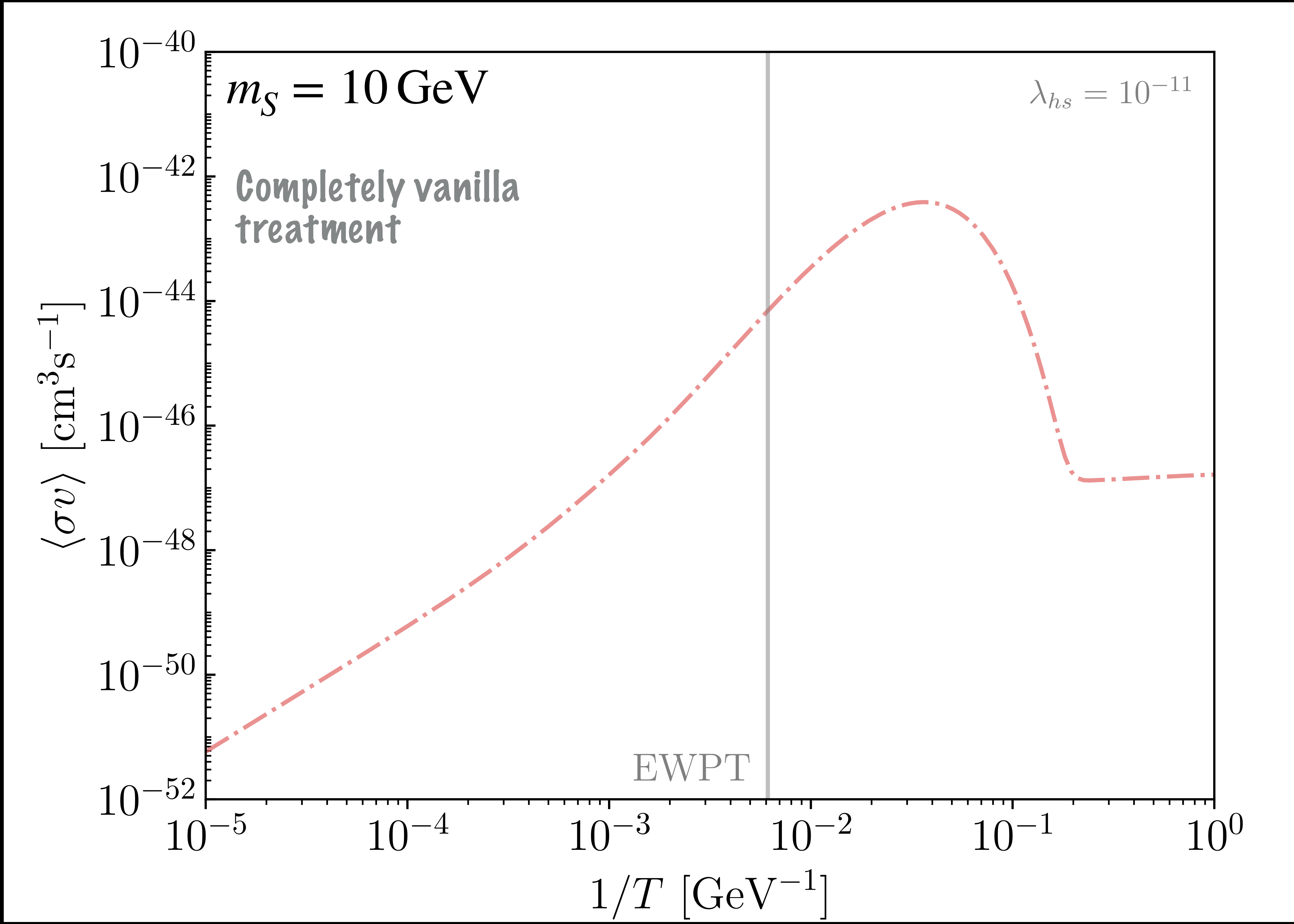

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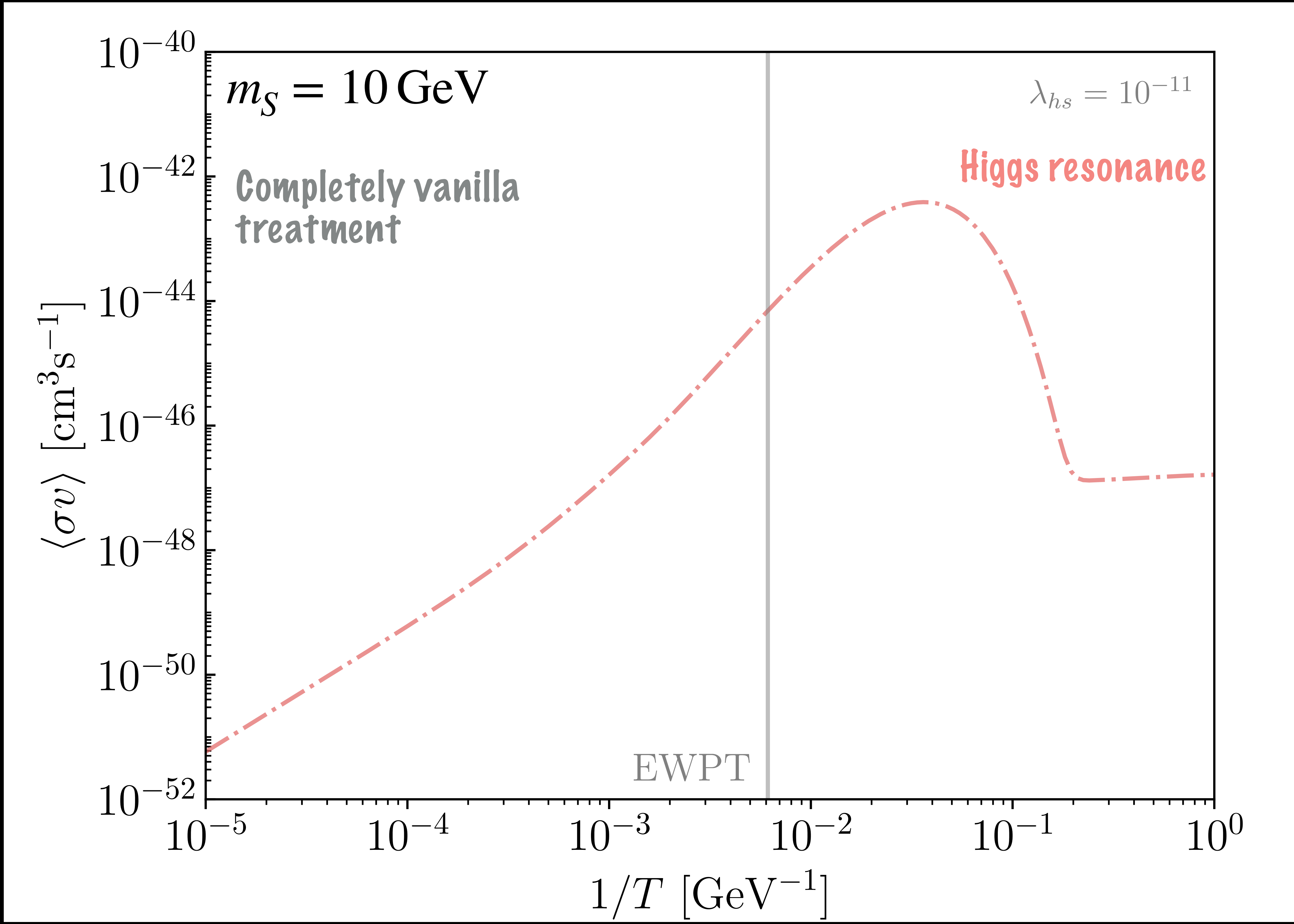

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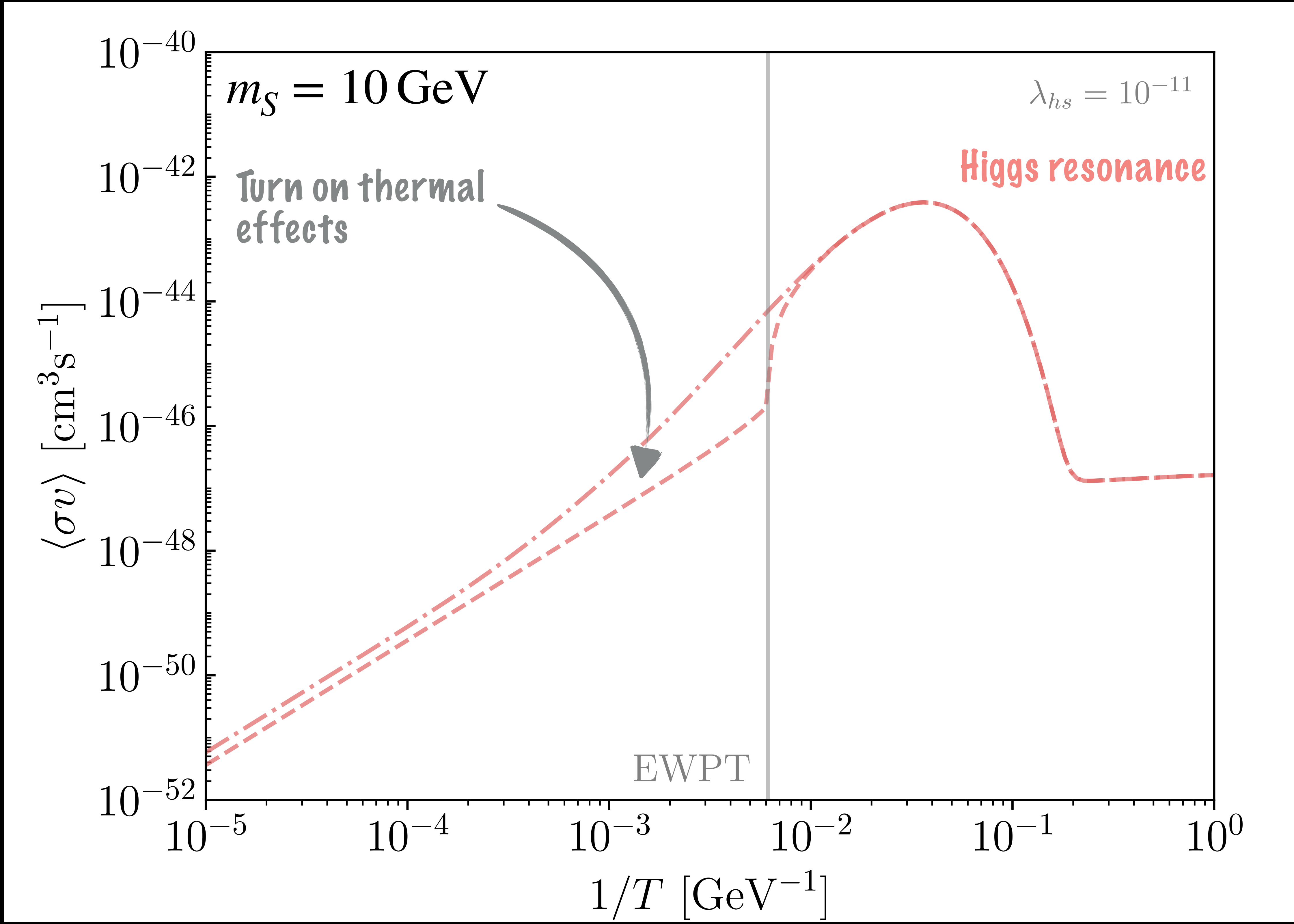

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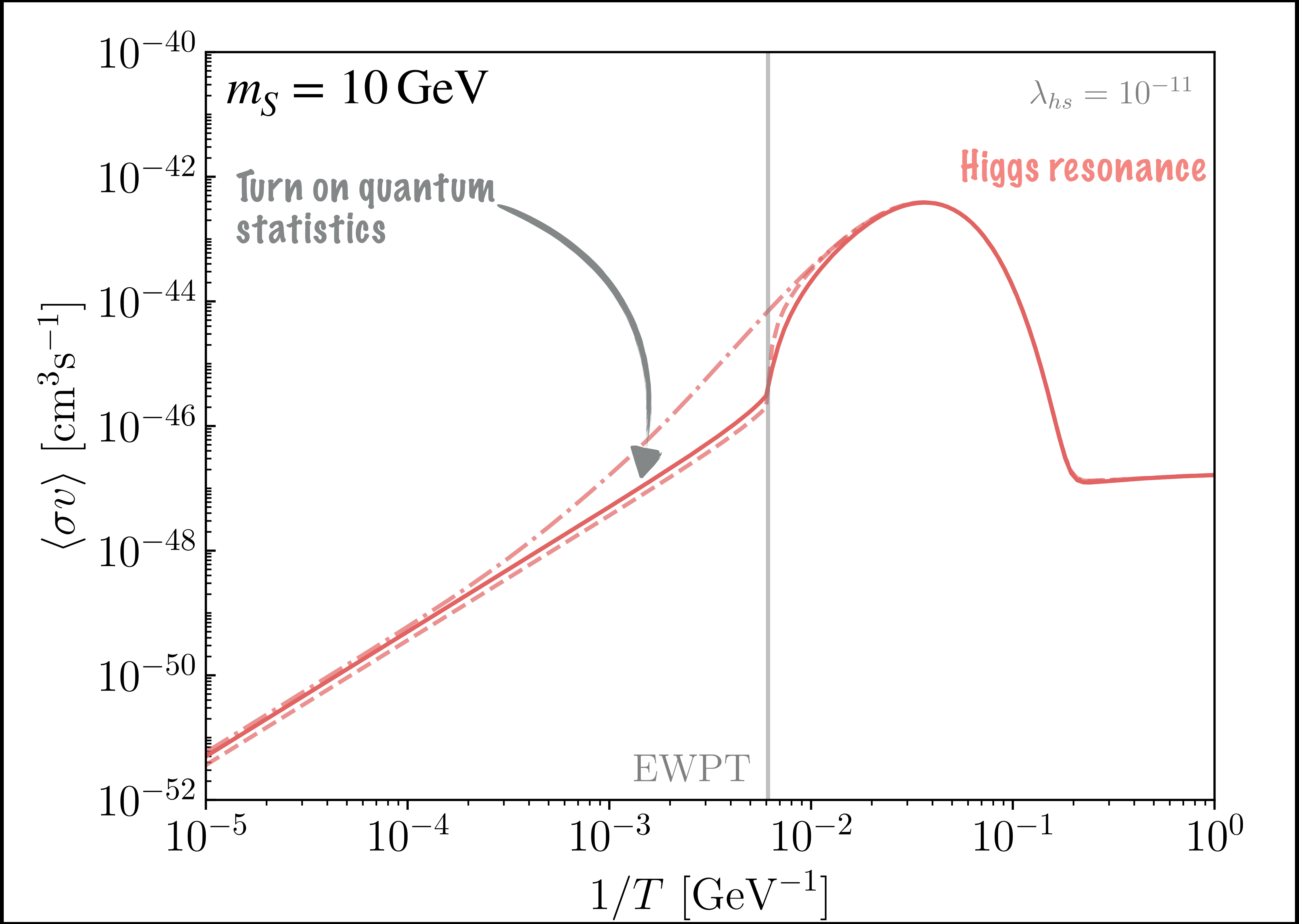

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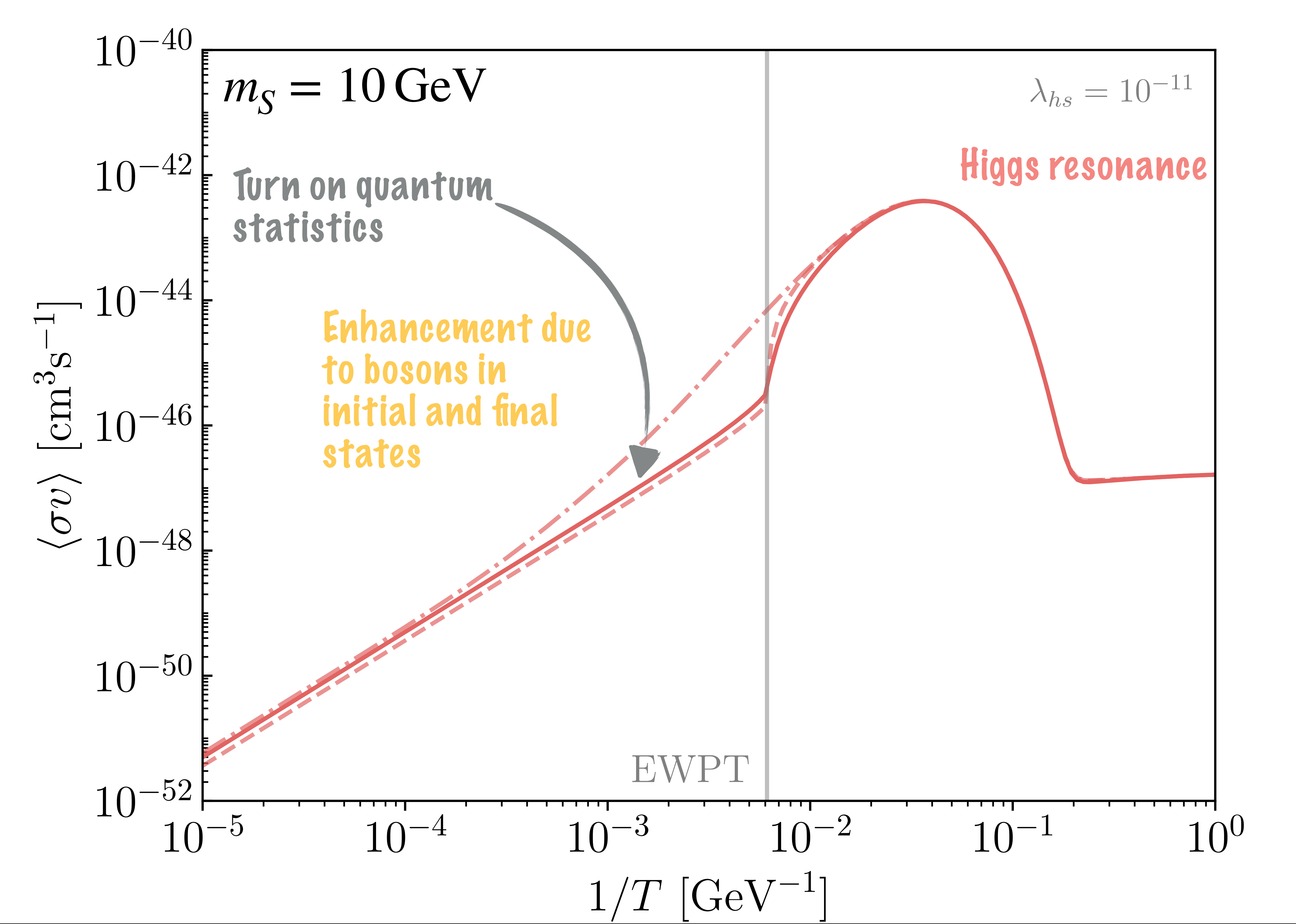

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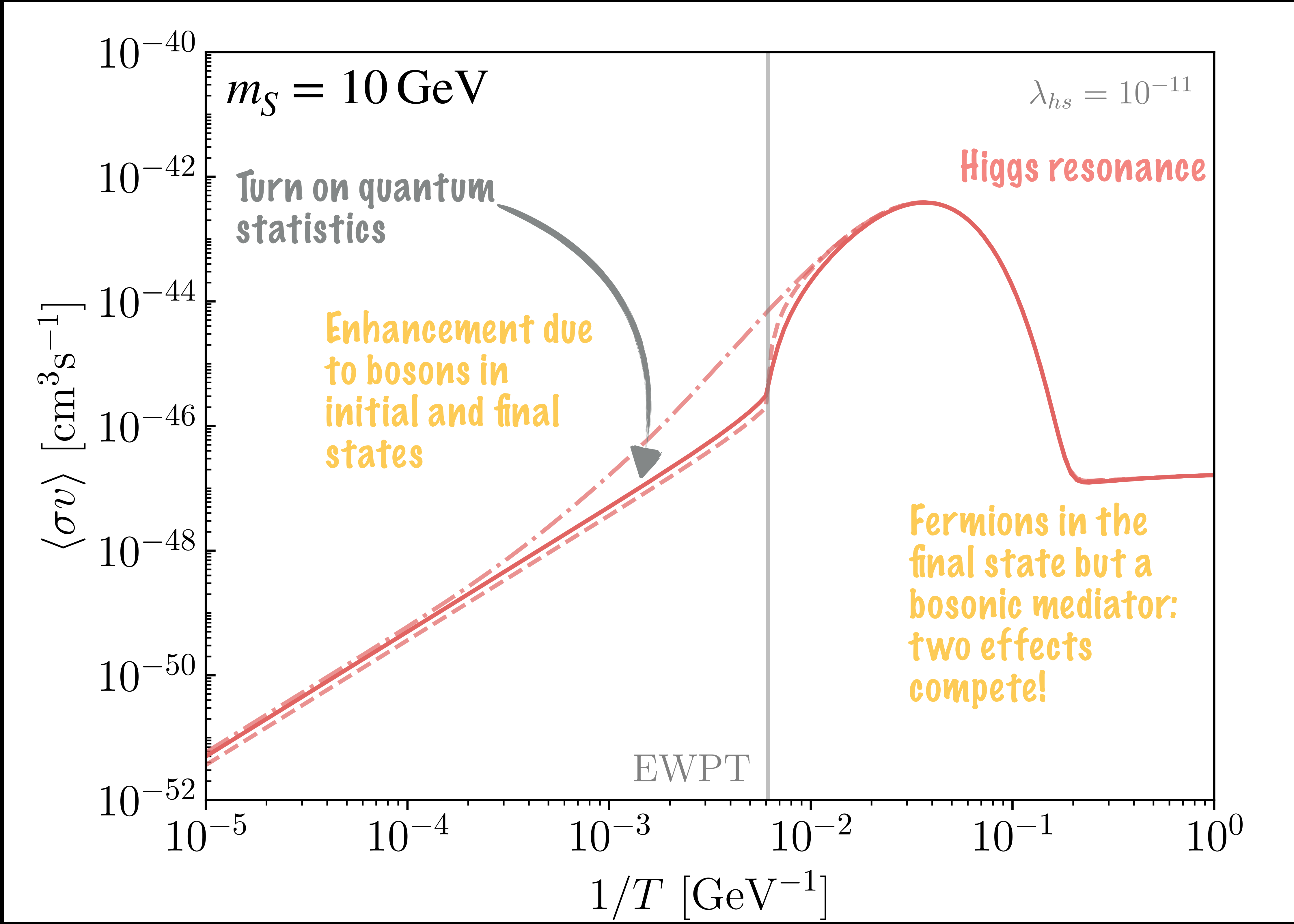

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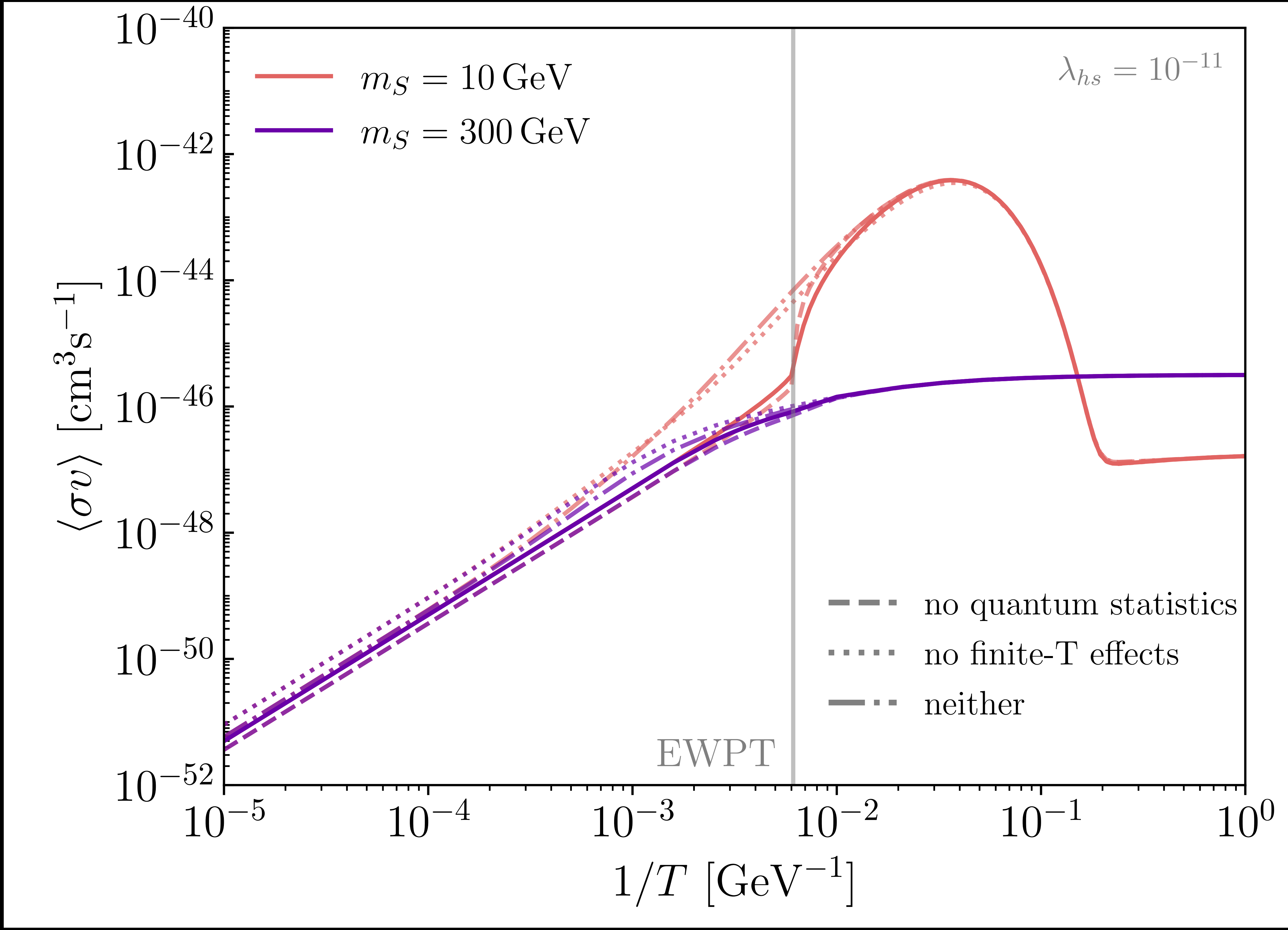

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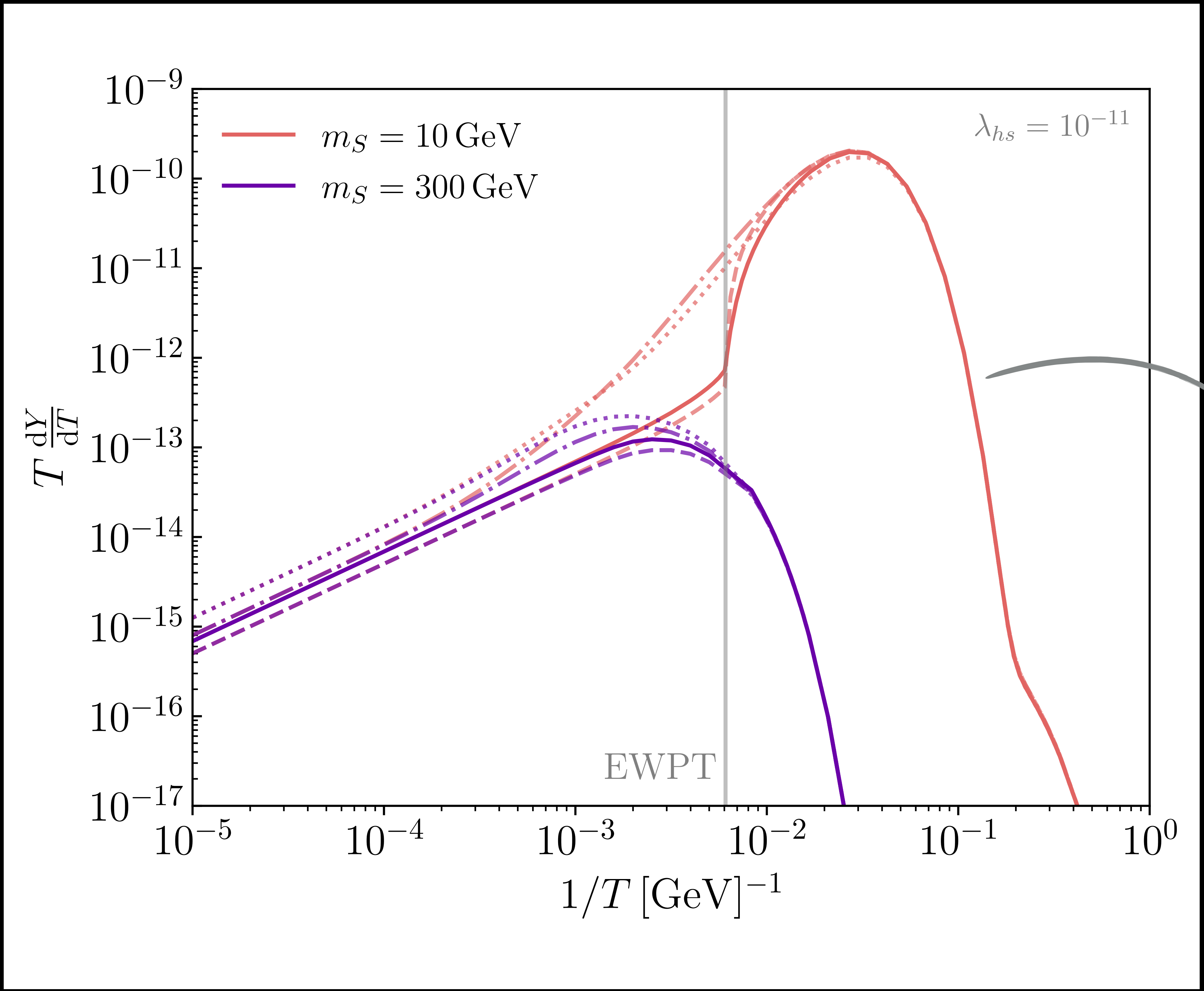

Boltzmann suppression due to $(n_S^{\mathrm{MB}})^2$

ABUNDANCE: WHAT WE EXPECT

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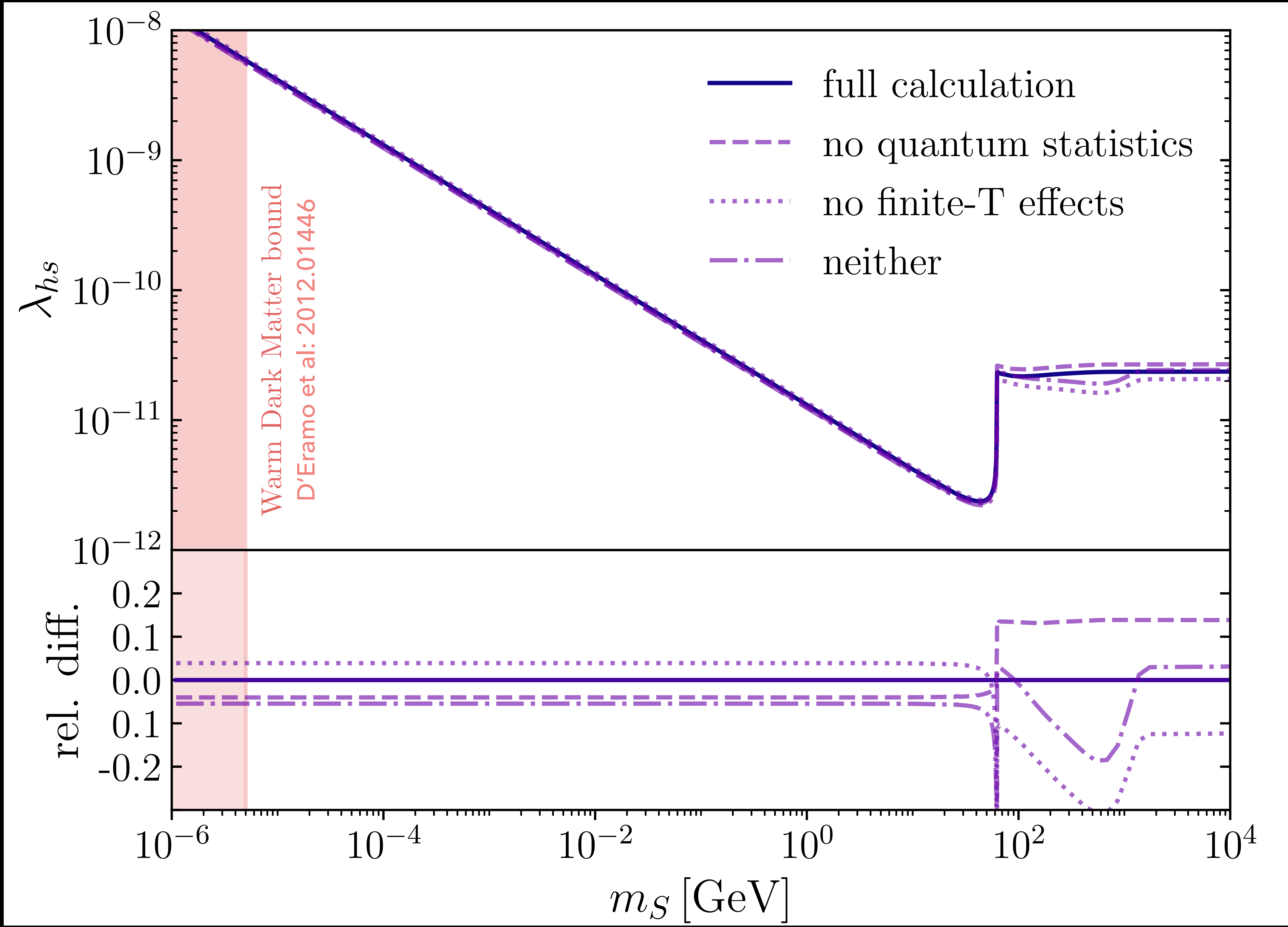
- For $m_S > m_h/2$, production close to or before the electroweak phase transition, sizeable effects

λ_{hs} FOR $\Omega_S h^2 = 0.12$:



I.

UV FREEZE-IN

$(T_{\mathrm{RH}} \ll T_{\mathrm{EW}})$

BACKGROUND:

Lower bound on the reheating temperature $\sim$ 5 MeV

If $T_{\rm RH} \ll m_h$, interaction described by a dim-5 operator: $\mathscr{L} \supset \frac{1}{\Lambda} f\bar{f} S^2$

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QCD phase transition is relevant!

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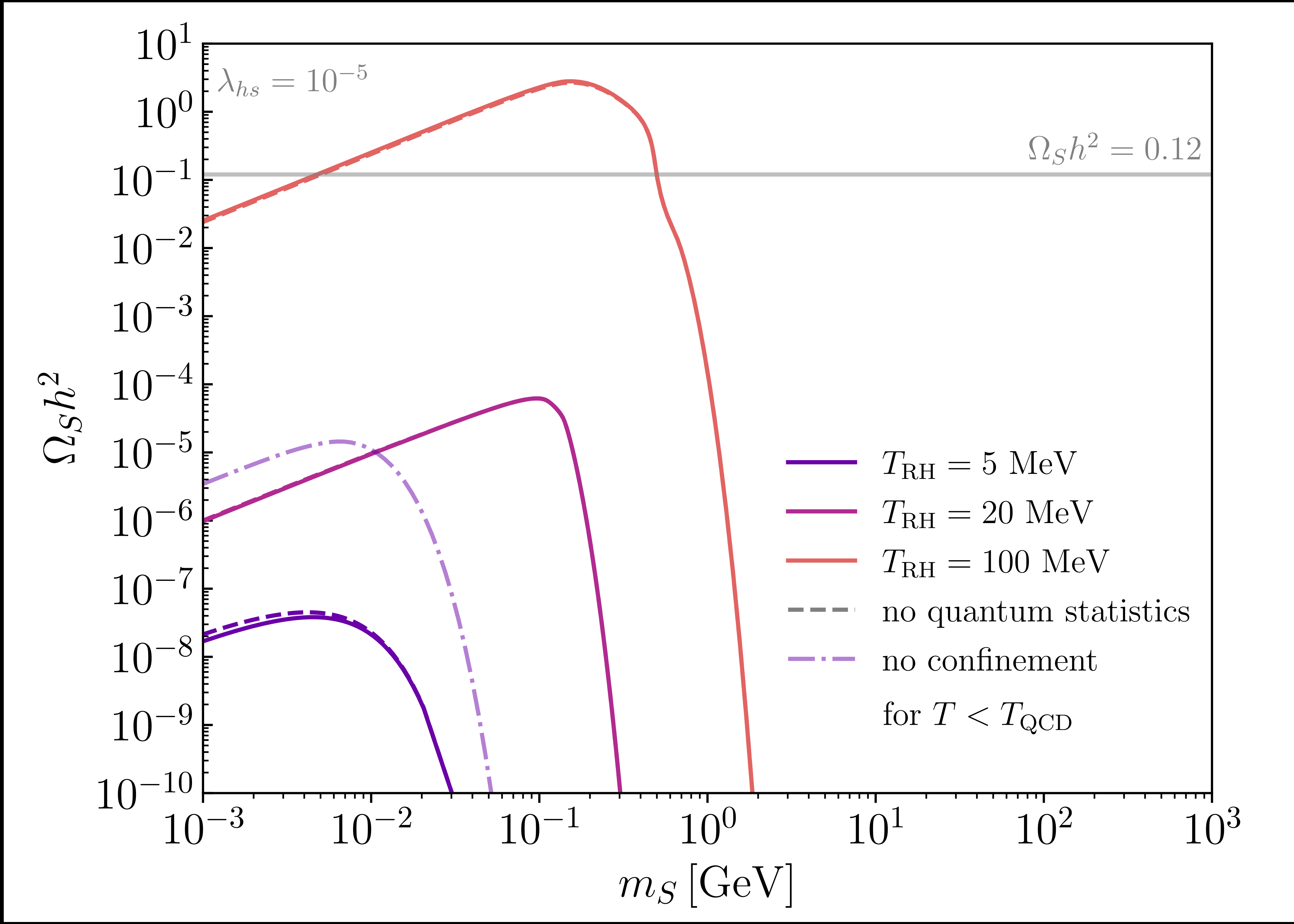

$\lambda_{hs} = 10^{-5}$
$\Omega_S h^2 = 0.12$
$\Omega_S h^2$
m_S [GeV]
$T_{\rm RH} = 5$ MeV
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for $T < T_{\rm QCD}$

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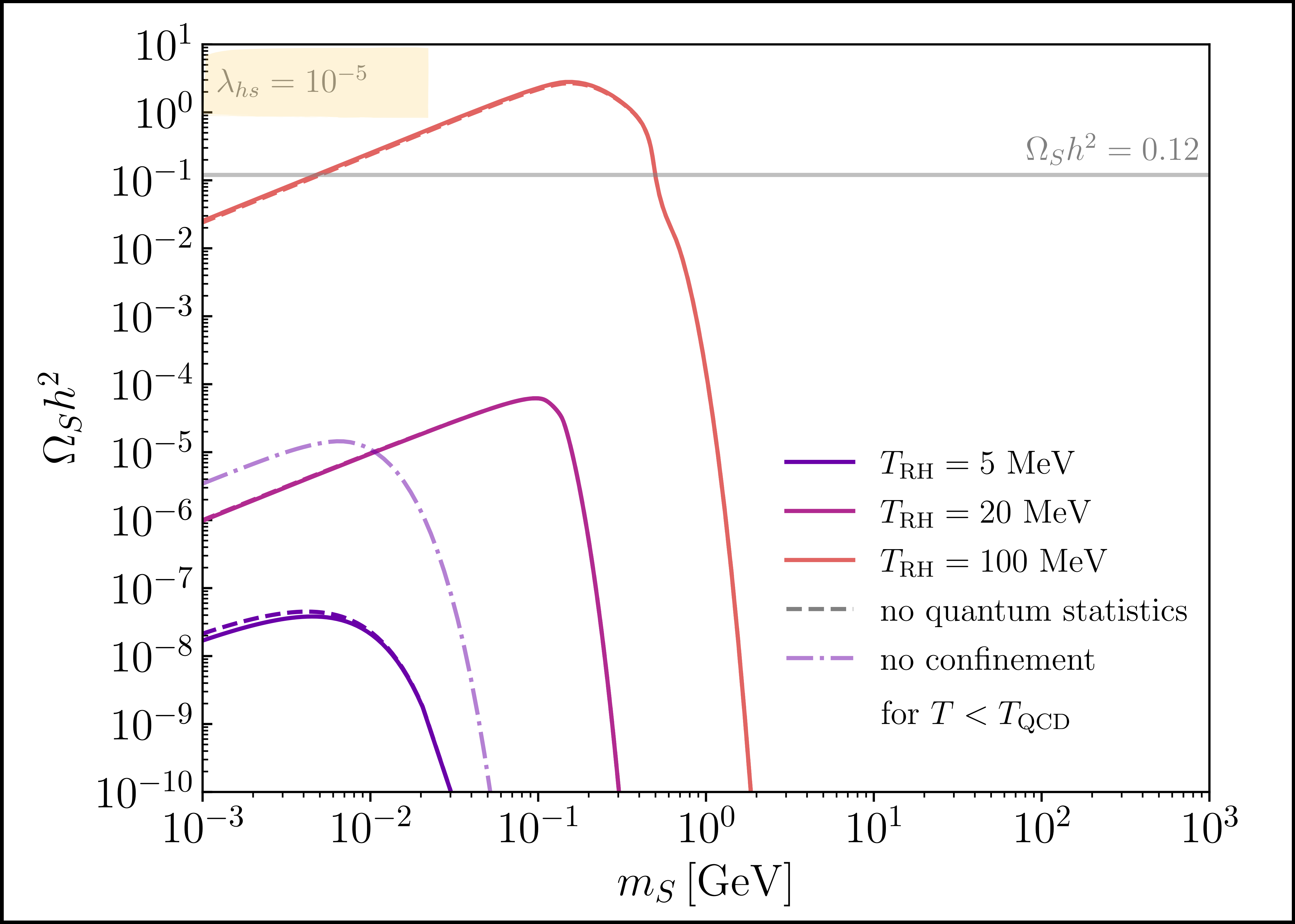

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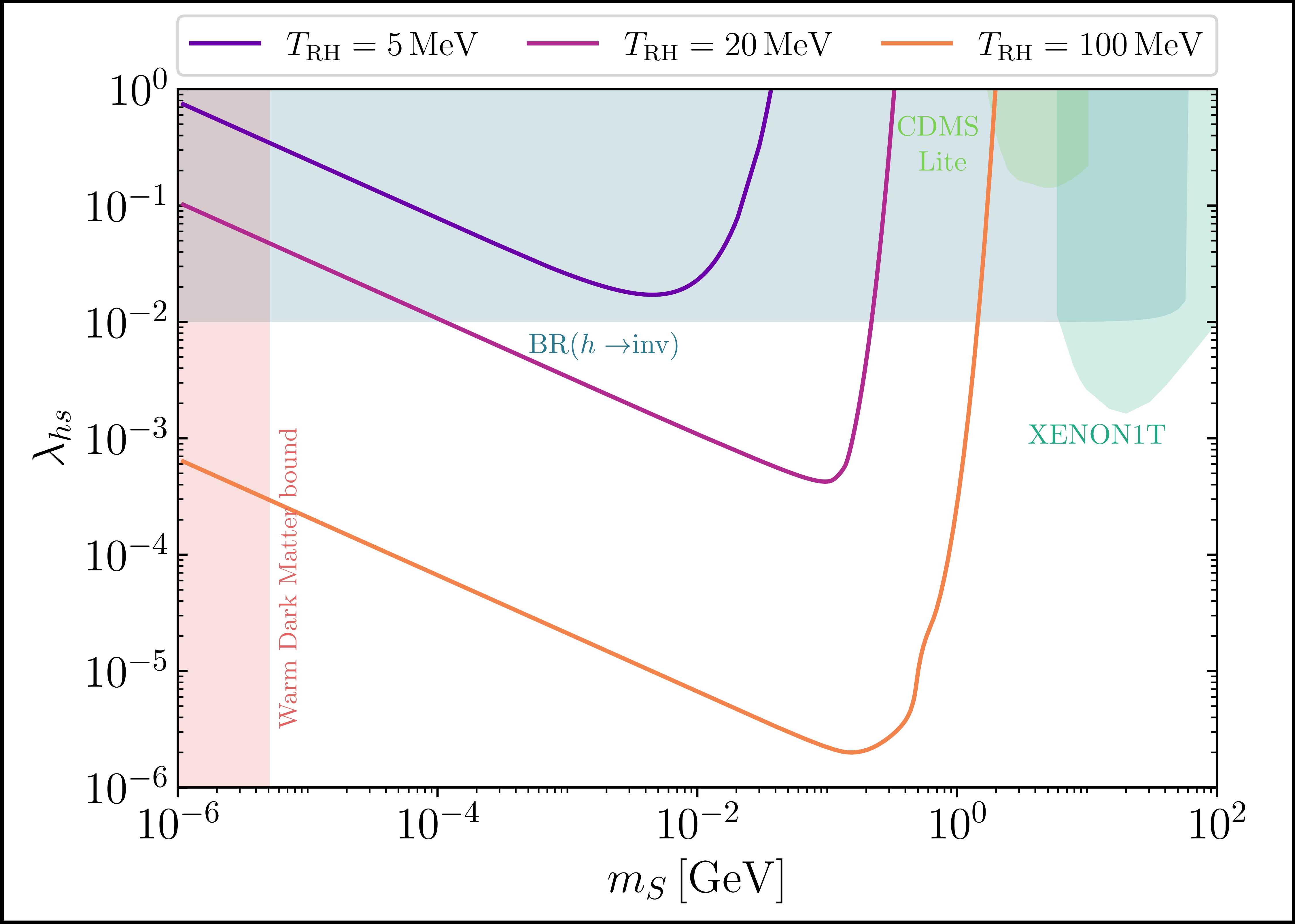

ALL OF THIS AND MORE NOW IN DARKSUSY!

https://darksusy.hepforge.org

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FREEZE-IN MODELS ARE EXPERIMENTALLY TESTABLE