Thermal QCD axions across thresholds

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arXiv:2108.04259 & **arXiv:2108.05371**

UNIVERSITÀ DEGLI STUDI DI PADOVA

Outline

01 Introduction
- Overview of axion physics
- Field basis to describe axion interactions
  - linearly
  - non-linearly

02 KSVZ axion scenario
- Heavy PQ fermion threshold
- QCD threshold

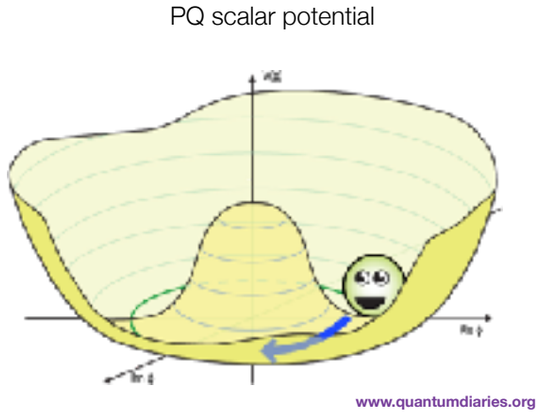
03 DFSZ axion scenario
- Heavy Higgs boson threshold
- Electroweak threshold
- QCD threshold

04 Hot axion relic and its implications

05 Conclusion

Axion

- Solution for the strong CP problem $\bar{\theta}_s G_{\mu\nu}\tilde{G}^{\mu\nu}$ $\lesssim 10^{-10}$



- Global Peccei-Quinn symmetry - Pseudo Nambu-Goldstone boson after spontaneous breaking at $\sim f_a$

- Mass and coupling proportional to f_a^{-1}

Axion interactions

[H. Gerogi et al, 86]

- Linearly realized

$$\varphi \equiv \frac{v_\varphi}{\sqrt{2}} e^{i c_\varphi \frac{a}{f_a}} \quad \Rightarrow \quad -\left(\frac{y_f v_\varphi}{\sqrt{2}}\right) \bar{f}_L e^{i c_\varphi \frac{a}{f_a}} f_R + \text{h.c.}$$

- Phase of PQ breaking scalars
- Tracking inherent axion coupling coefficients

- Non-Linearly realized

$$f_{L,R} \to e^{-i c_{L,R} \frac{a}{f_a}} f_{L,R} \quad \Rightarrow \quad \frac{\partial_\mu a}{f_a} \sum_{i=L,R} c_i \bar{f}_i f_i$$

- Axion shift symmetry
- PQ current ⇒ relevant to matching

Axion dependent rotation with $c_\varphi + c_L - c_R = 0$

field redefinition

[J.E. Kim, 1979] [M.A. Shifman, A.I. Vainshtein and V.I. Zakharov, 1980]

KSVZ axion scenario

- Ingredients: heavy colored PQ fermion (Ψ) & PQ singlet scalar (φ)

$$-y_\Psi \varphi^\dagger \bar{\Psi}_L \Psi_R + \mathrm{h.c.}$$

- Triangle diagram with Ψ-loop leads to

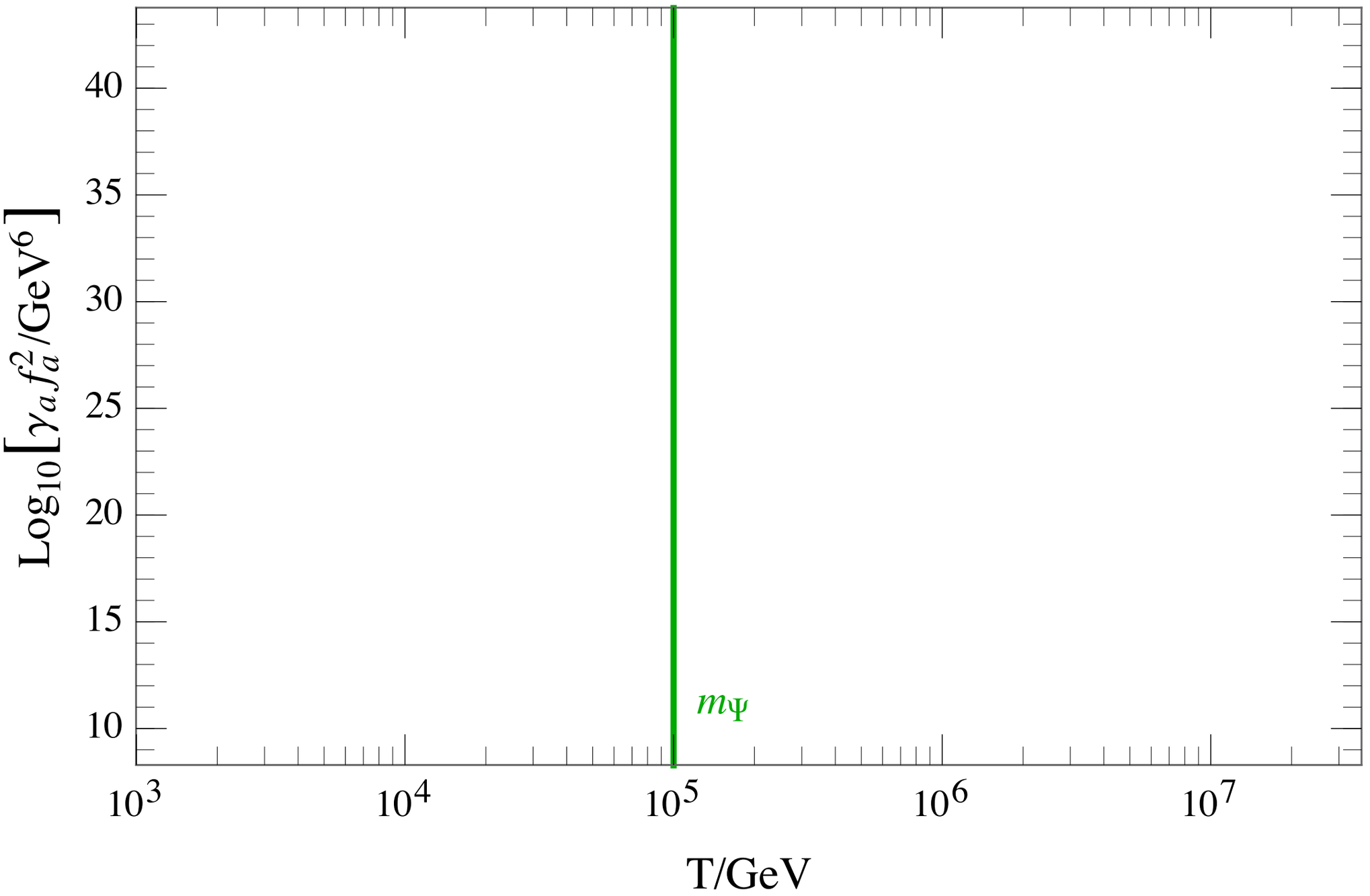
$$\frac{g_s^2}{32\pi^2}\frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

- Two thresholds

  @ *mass of* $\Psi \equiv m_\Psi$

  @ *QCD confinement*

Heavy PQ fermion threshold



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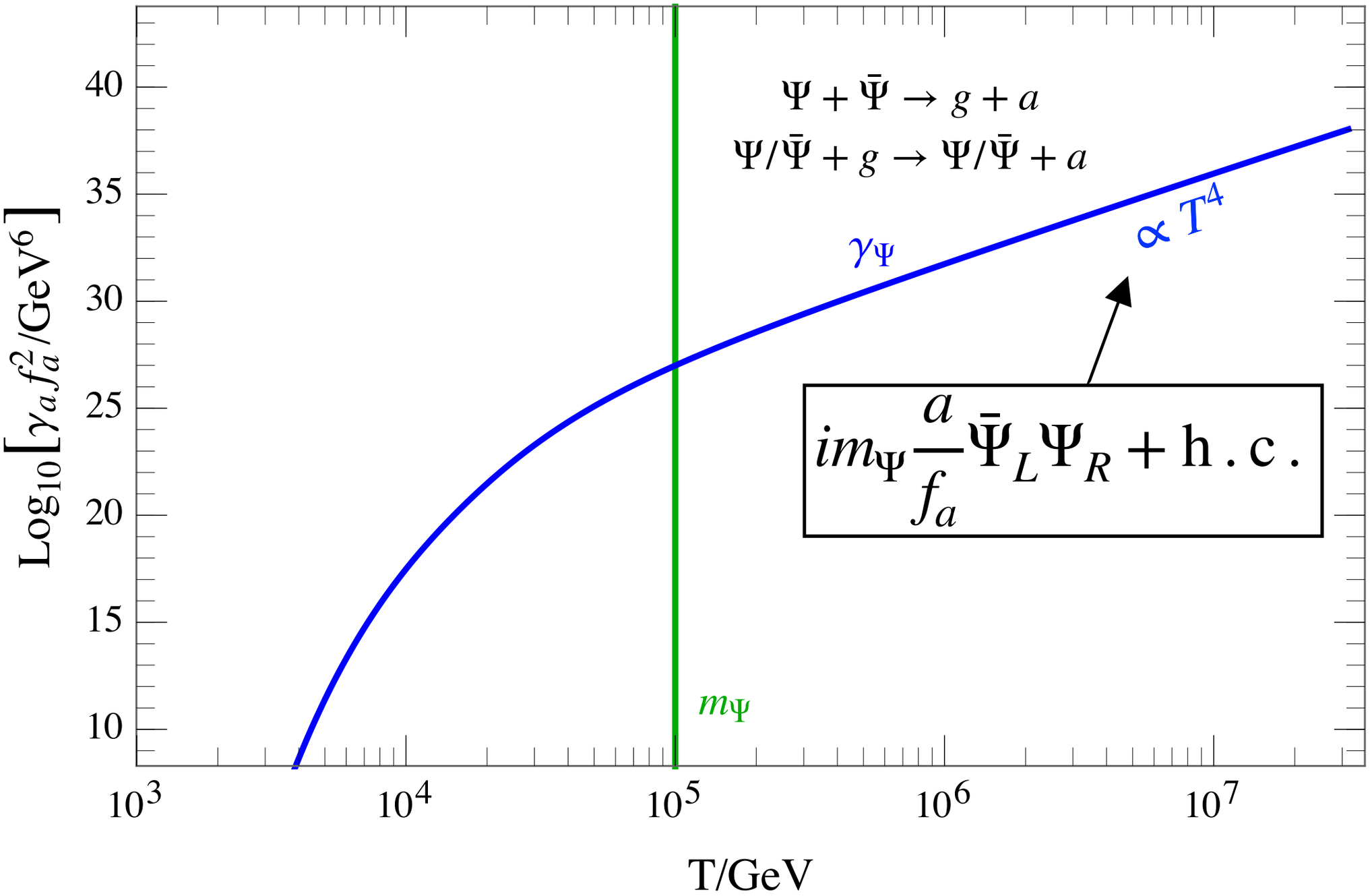
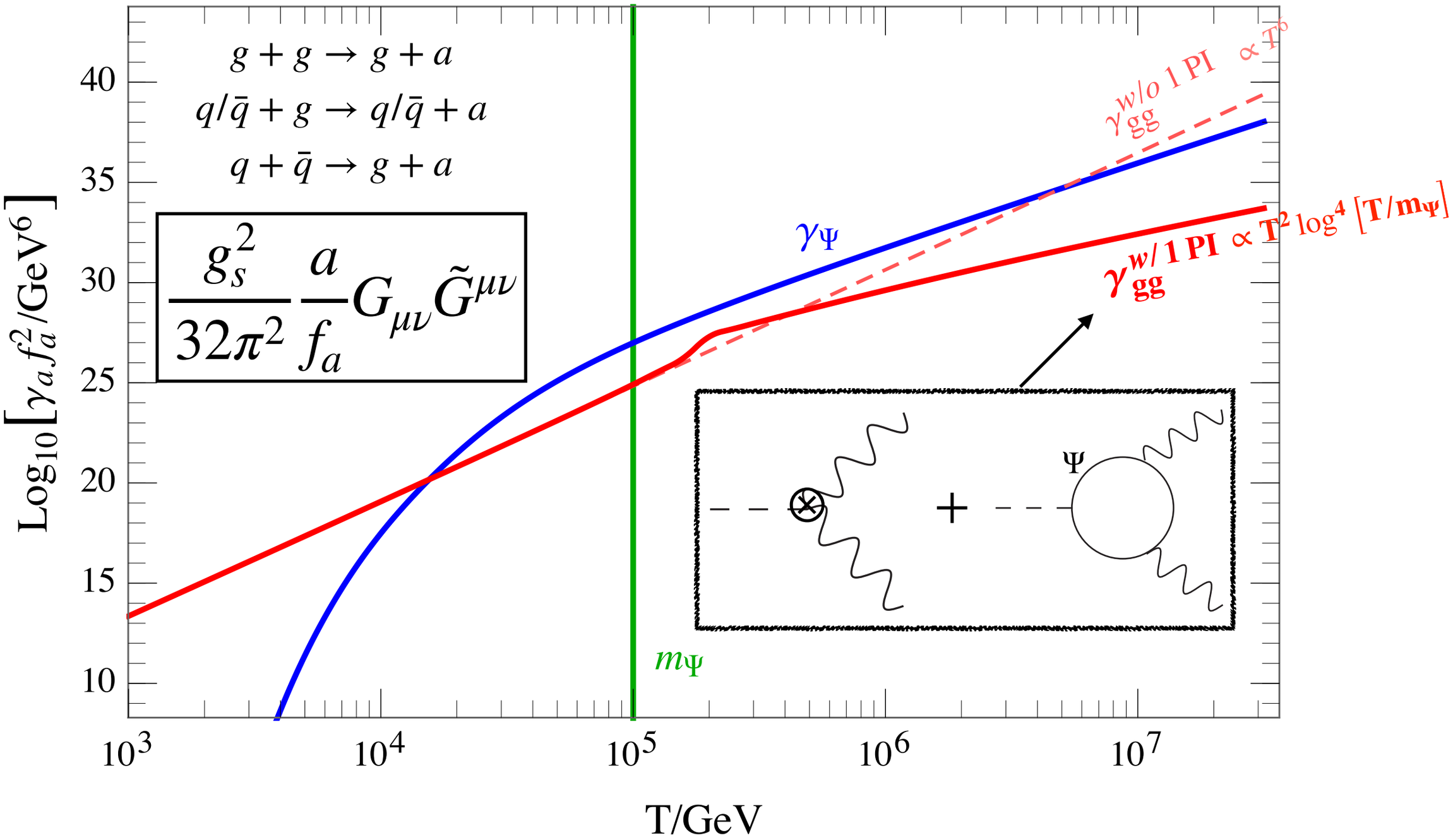
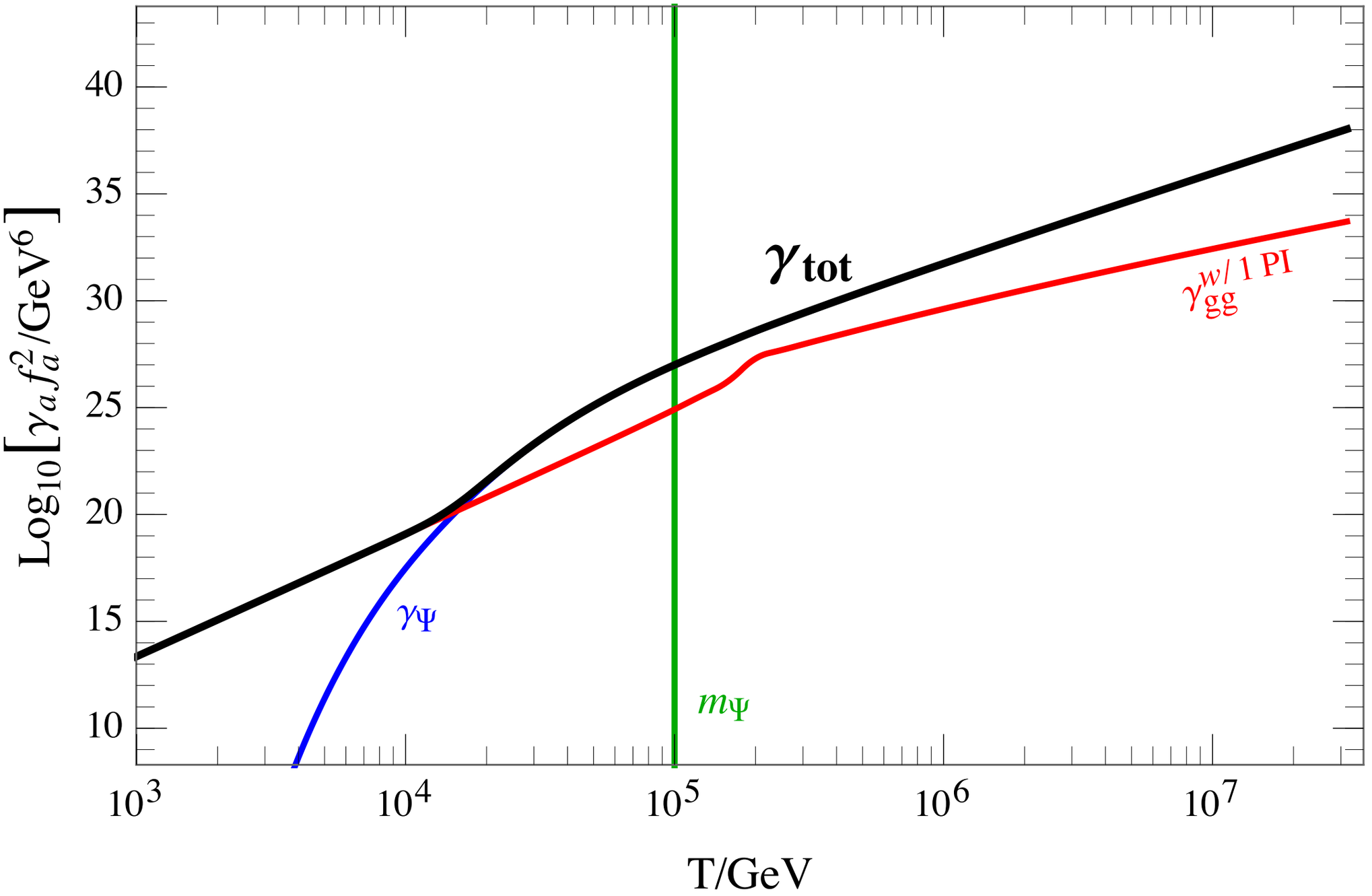


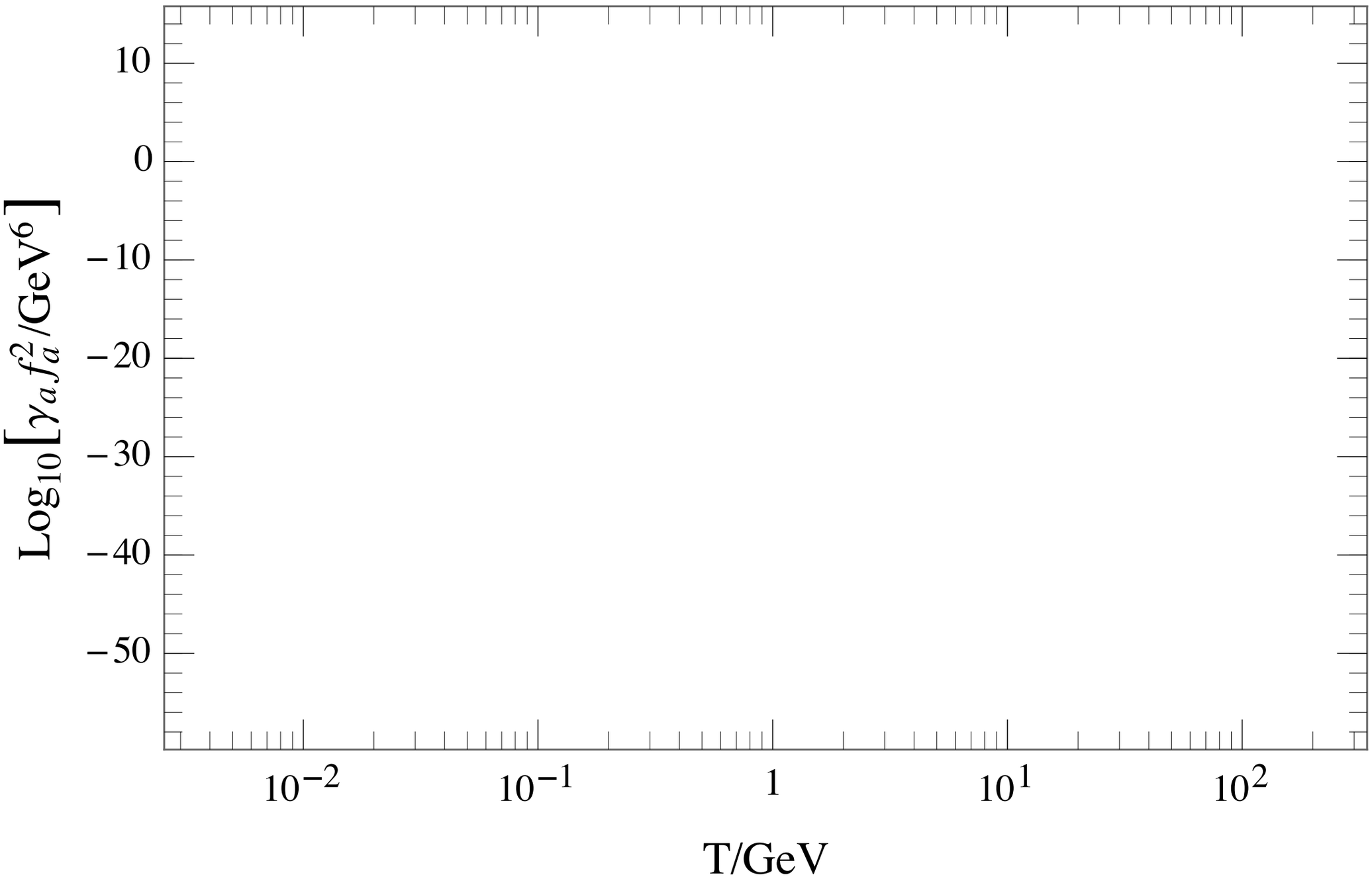
Heavy PQ fermion threshold



Heavy PQ fermion threshold



QCD threshold



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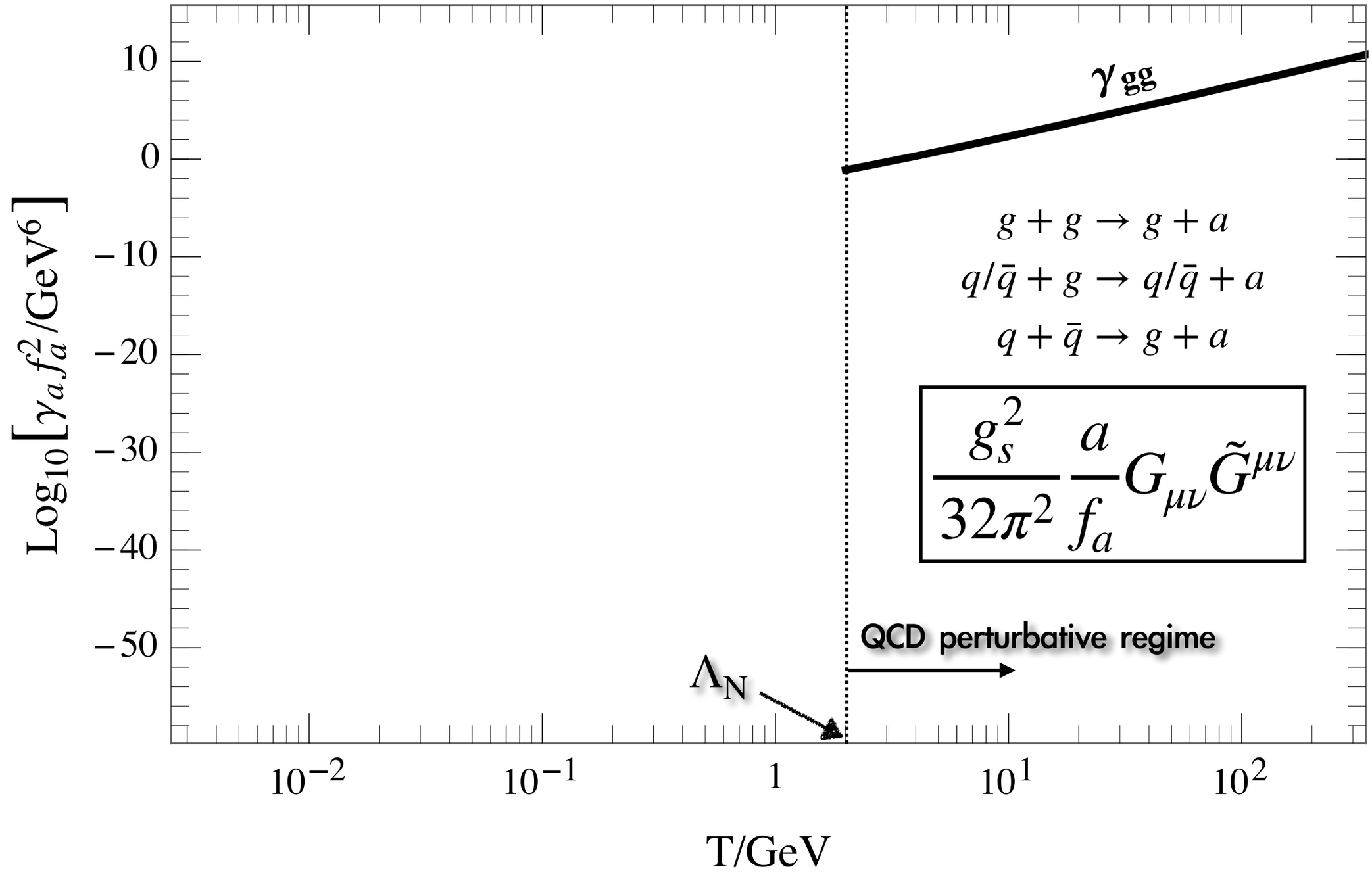
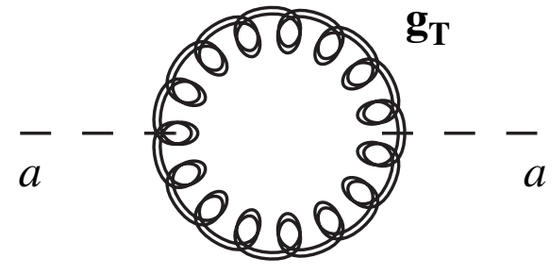


QCD threshold

- Long range nature ⇒ IR divergence
- At weak coupling regime, hard thermal loop approximation (i.e. Debye screening)
- Thermal field theory considered properly



$$g_T \rightarrow g_T + a$$

[A. Salvio et al, 2013]

γ_{gg}

$$g + g \rightarrow g + a$$
$$q/\bar{q} + g \rightarrow q/\bar{q} + a$$
$$q + \bar{q} \rightarrow g + a$$

$$\frac{g_s^2}{32\pi^2}\frac{a}{f_a}G_{\mu\nu}\tilde{G}^{\mu\nu}$$

10

−50

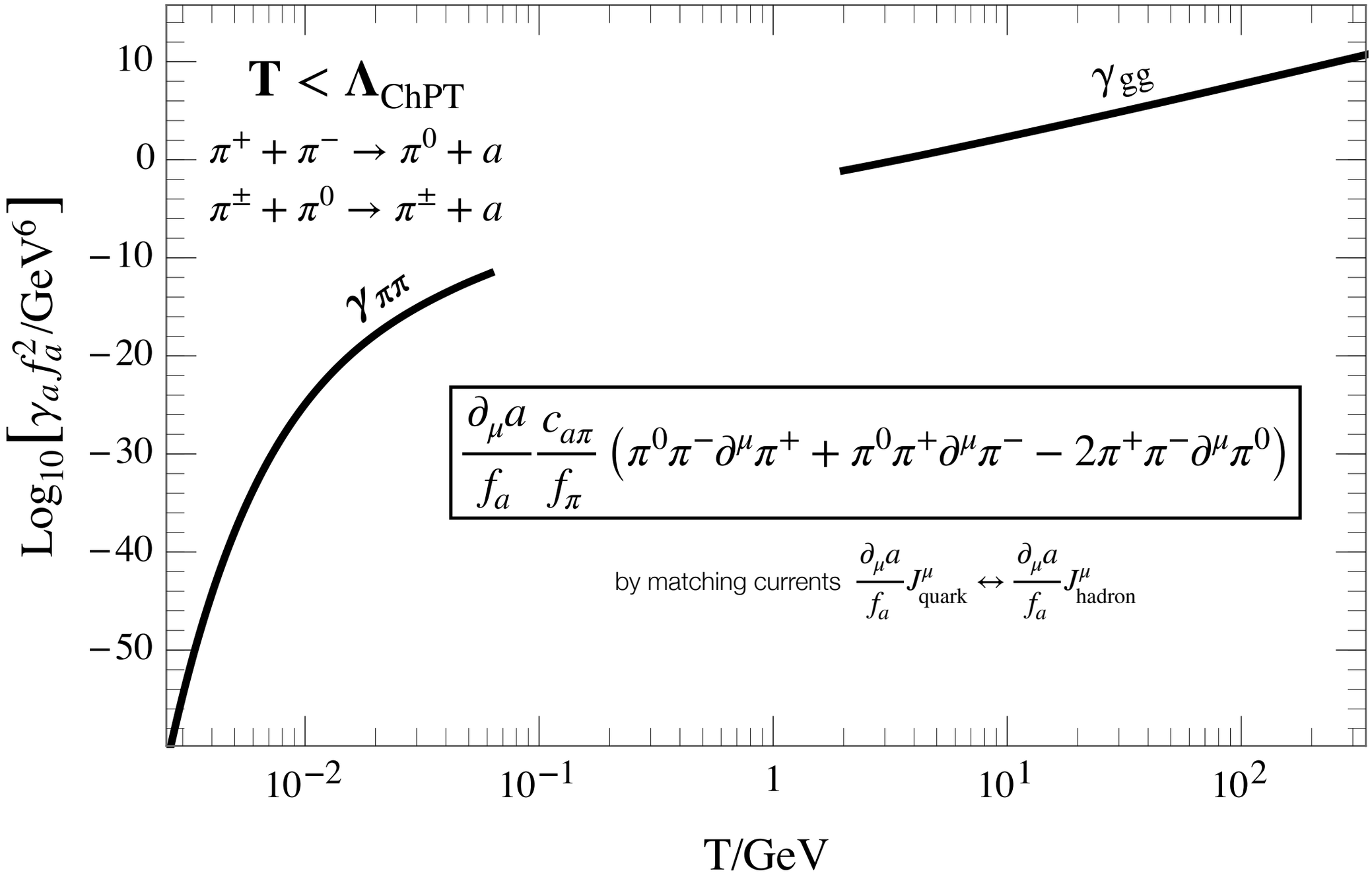
Λ_N

QCD perturbative regime

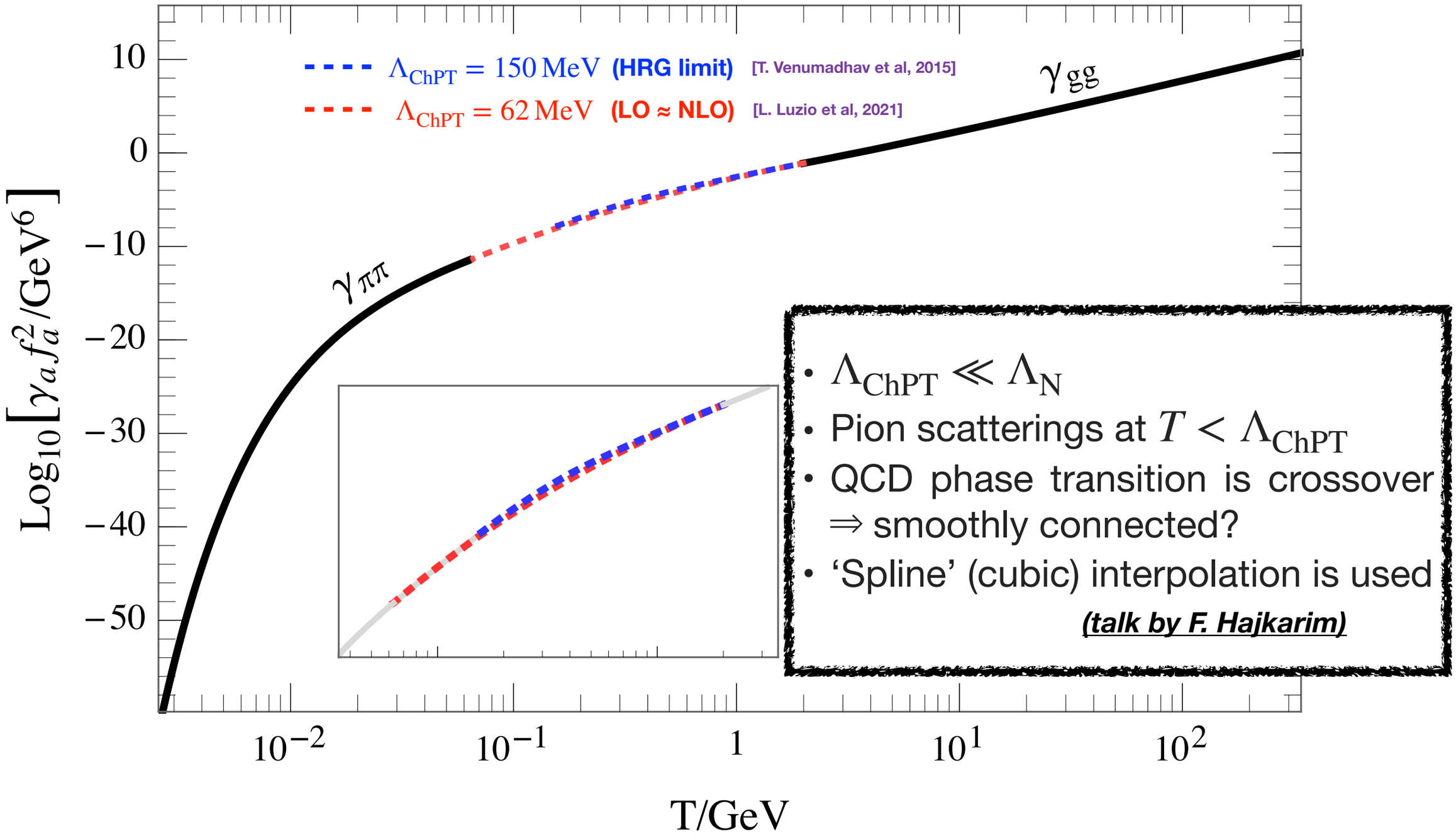
10^{-2} 10^{-1} 1 10^{1} 10^{2}

T/GeV

QCD threshold



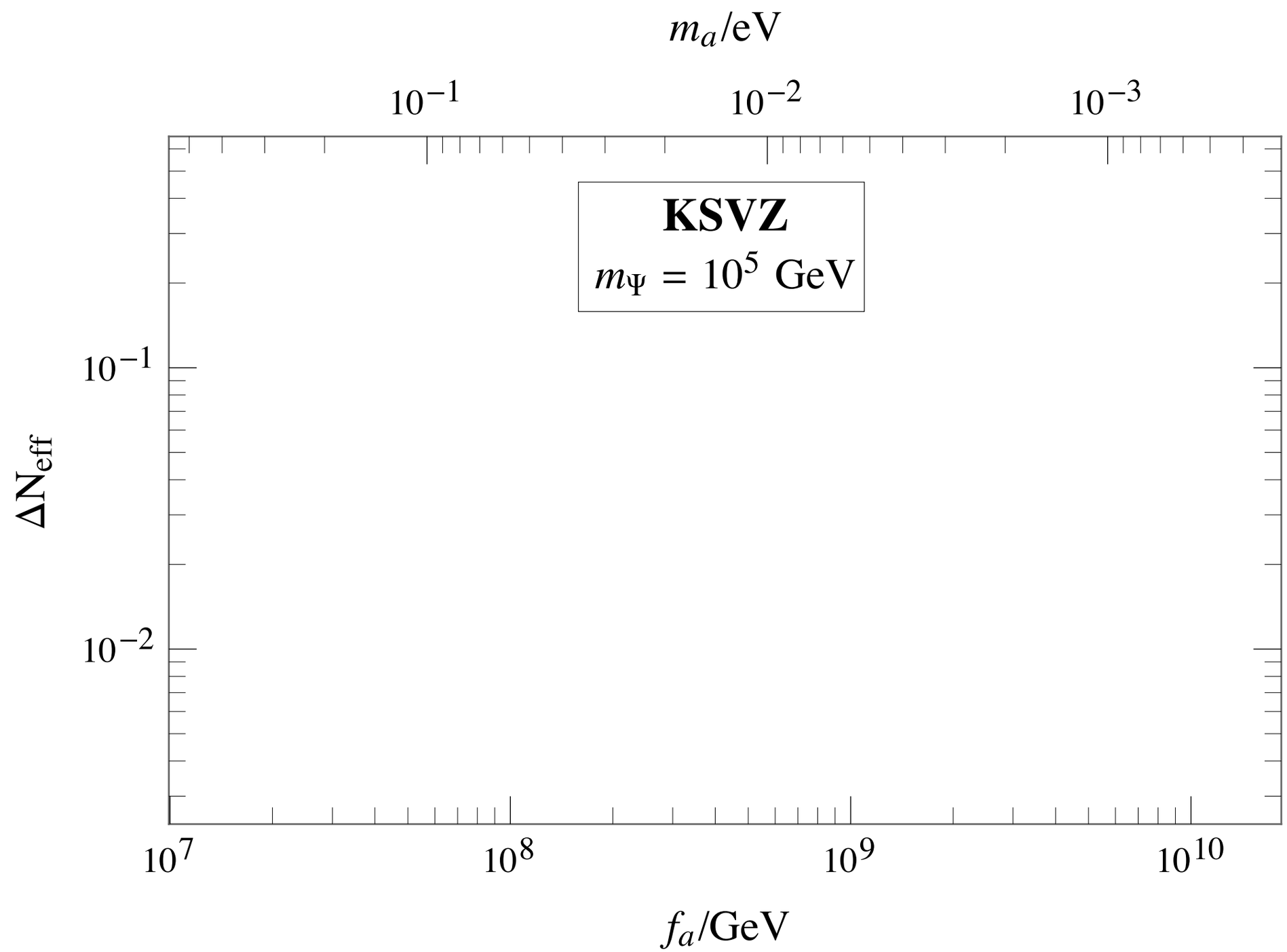
QCD threshold



- $\Lambda_{\rm ChPT} \ll \Lambda_{\rm N}$
- Pion scatterings at $T < \Lambda_{\rm ChPT}$
- QCD phase transition is crossover ⇒ smoothly connected?
- ‘Spline’ (cubic) interpolation is used

(talk by F. Hajkarim)

Hot KSVZ axion relic



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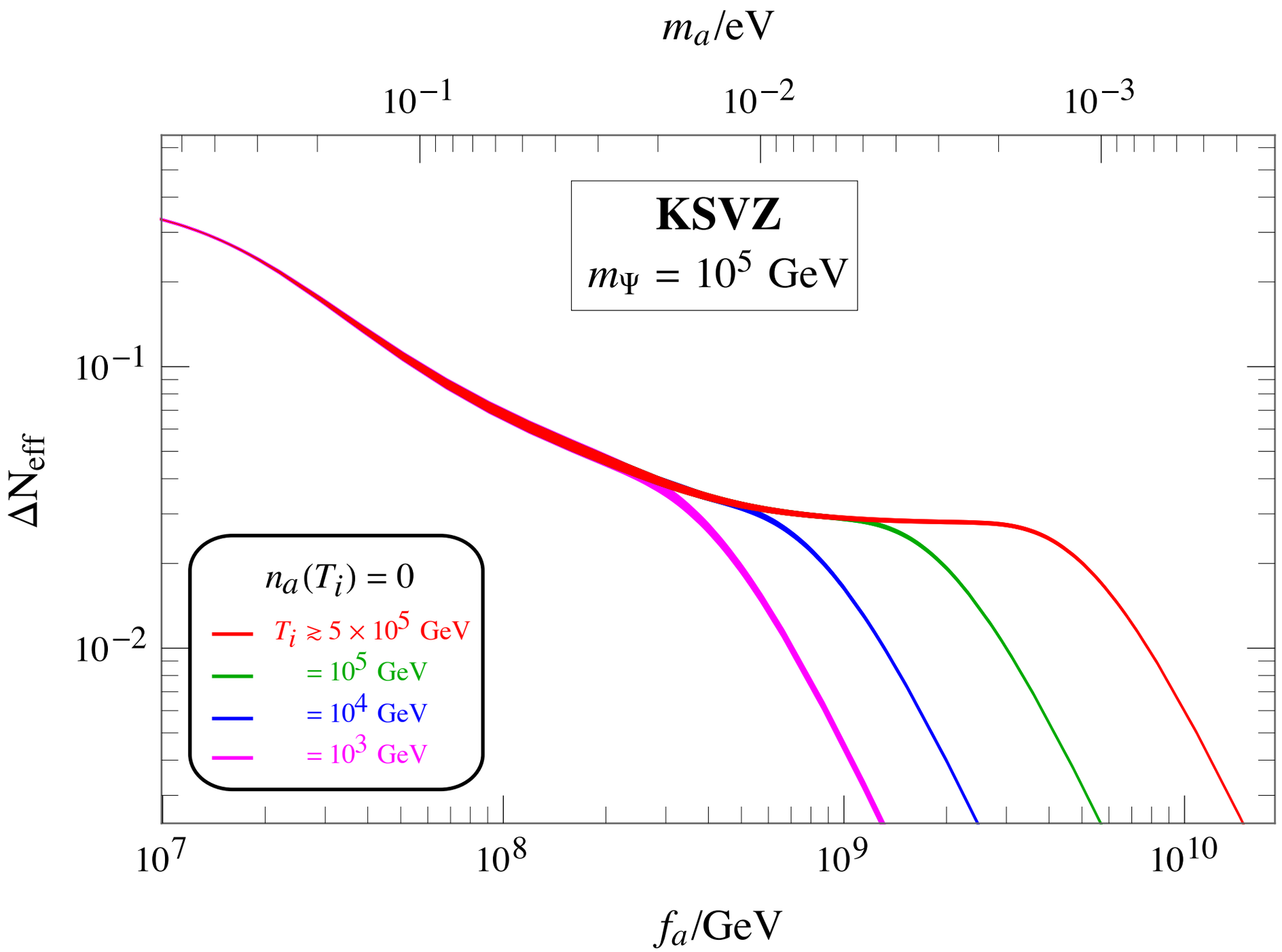

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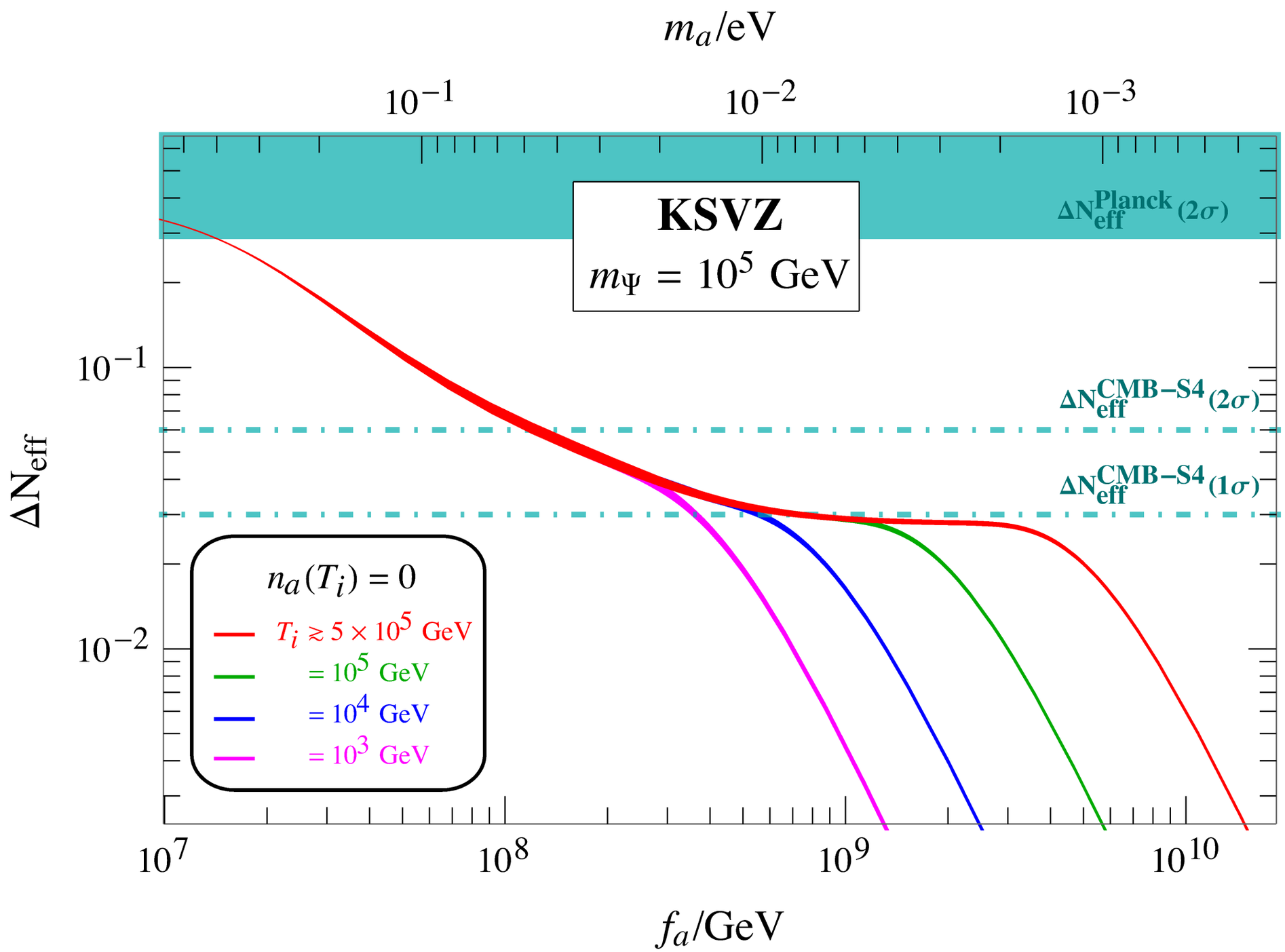

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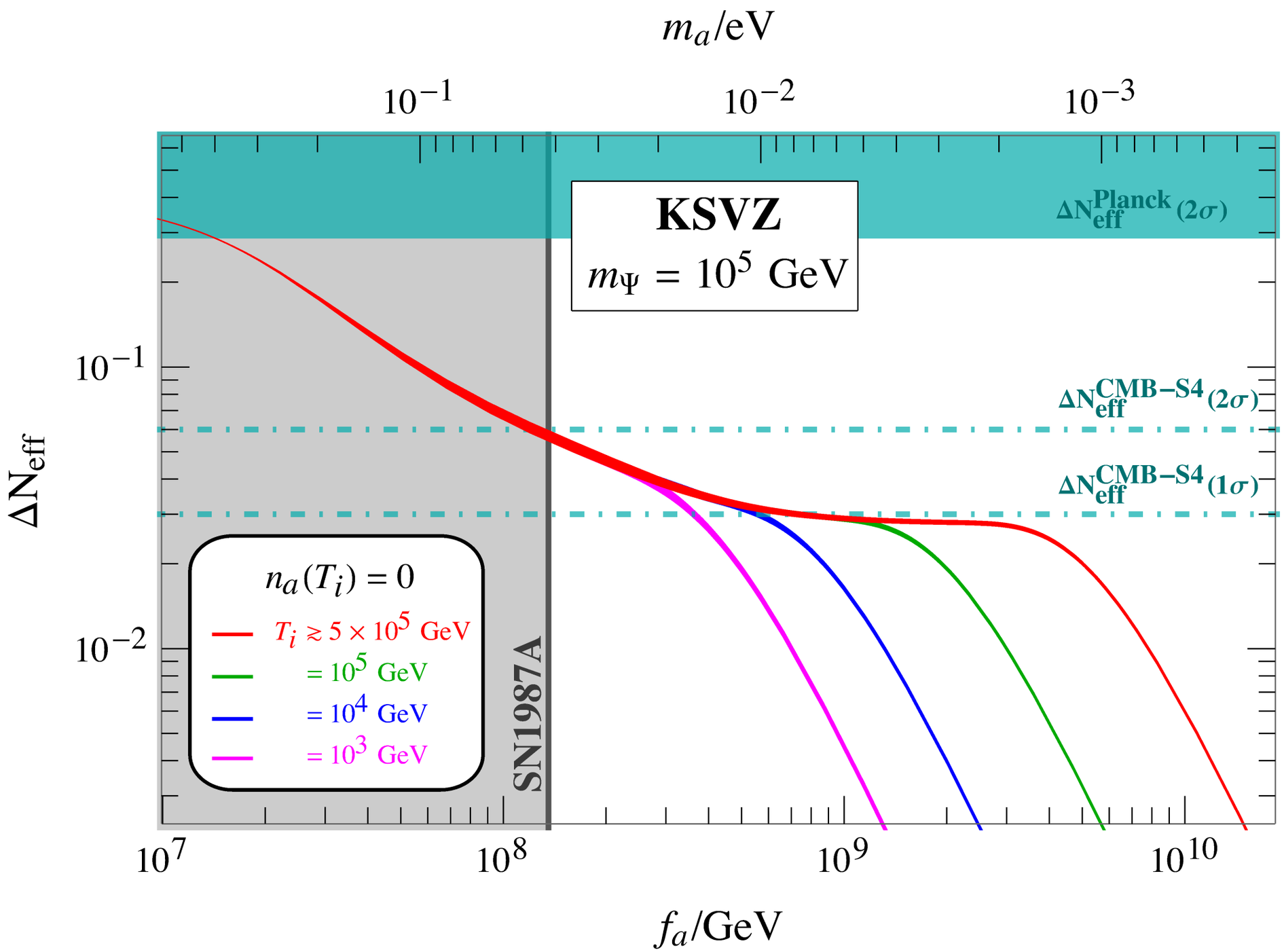


[M. Dine, W. Fischler and M. Srednicki, 1980] [A.R. Zhitnitsky, 1980]

DFSZ axion scenario

- Ingredients: extension of Higgs sector & PQ singlet scalar (φ)

$$-B\left(\frac{\varphi^\dagger}{v_\varphi/\sqrt{2}}\right)^n H_u^{\mathrm{T}} i\sigma^2 H_d + \mathrm{hc}\,.$$

- Anomalous couplings to SM gauge bosons + Couplings to SM fields

$$\frac{a}{f_a}\left(\frac{g_s^2}{32\pi^2}G_{\mu\nu}\tilde{G}^{\mu\nu}+\cdots\right) \qquad \frac{\partial_\mu a}{f_a}\left(\sum_f c_f \bar{f}\gamma^\mu f + \sum_i c_{H_i} H_i^\dagger i\overleftrightarrow{D}^\mu H_i\right)$$

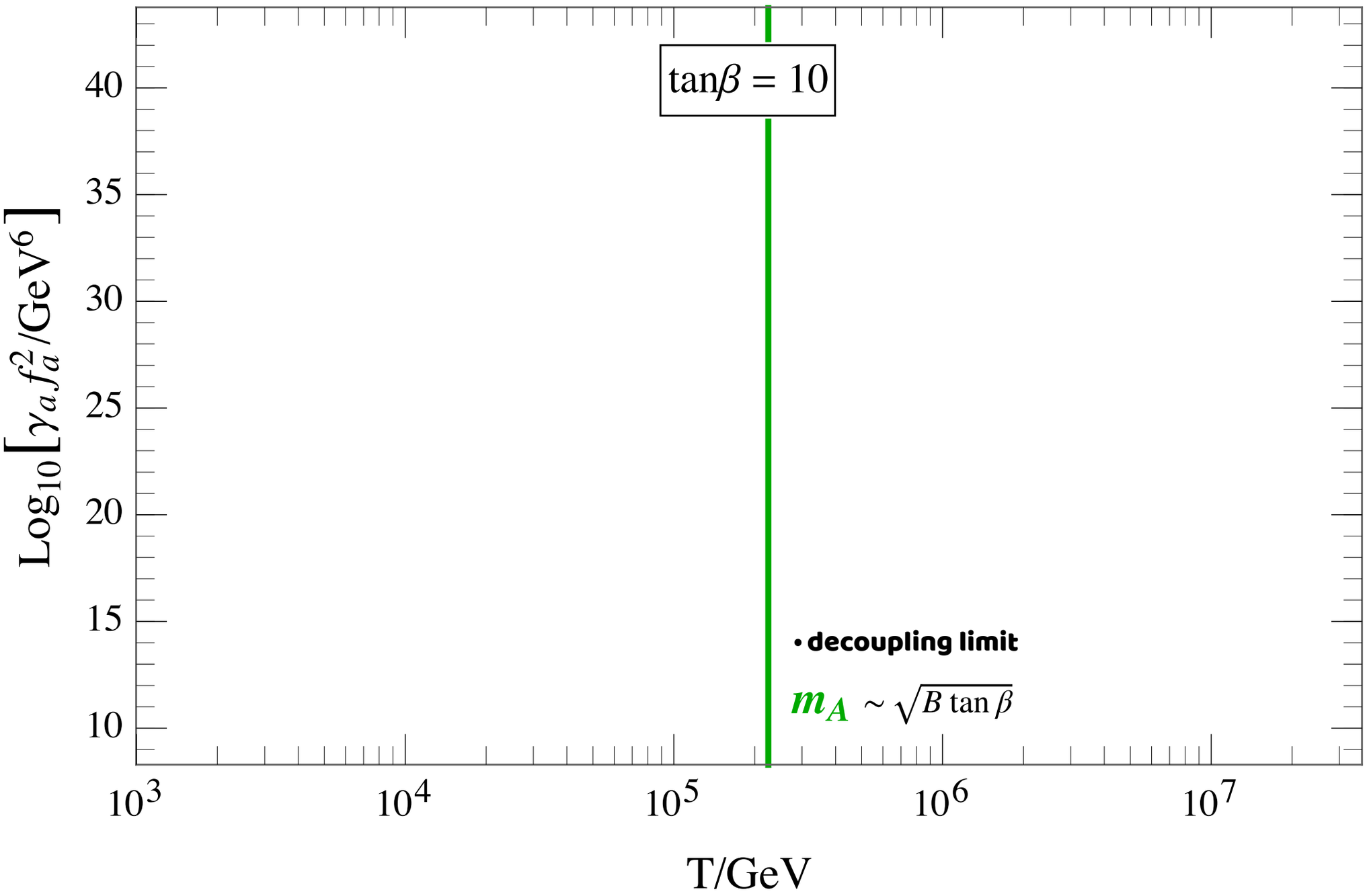
- Two + one thresholds

  @ *mass of heavy Higgs bosons* $\equiv m_A$ **($\gg \mathrm{v}_{\mathrm{EW}}$ in decoupling limit)**

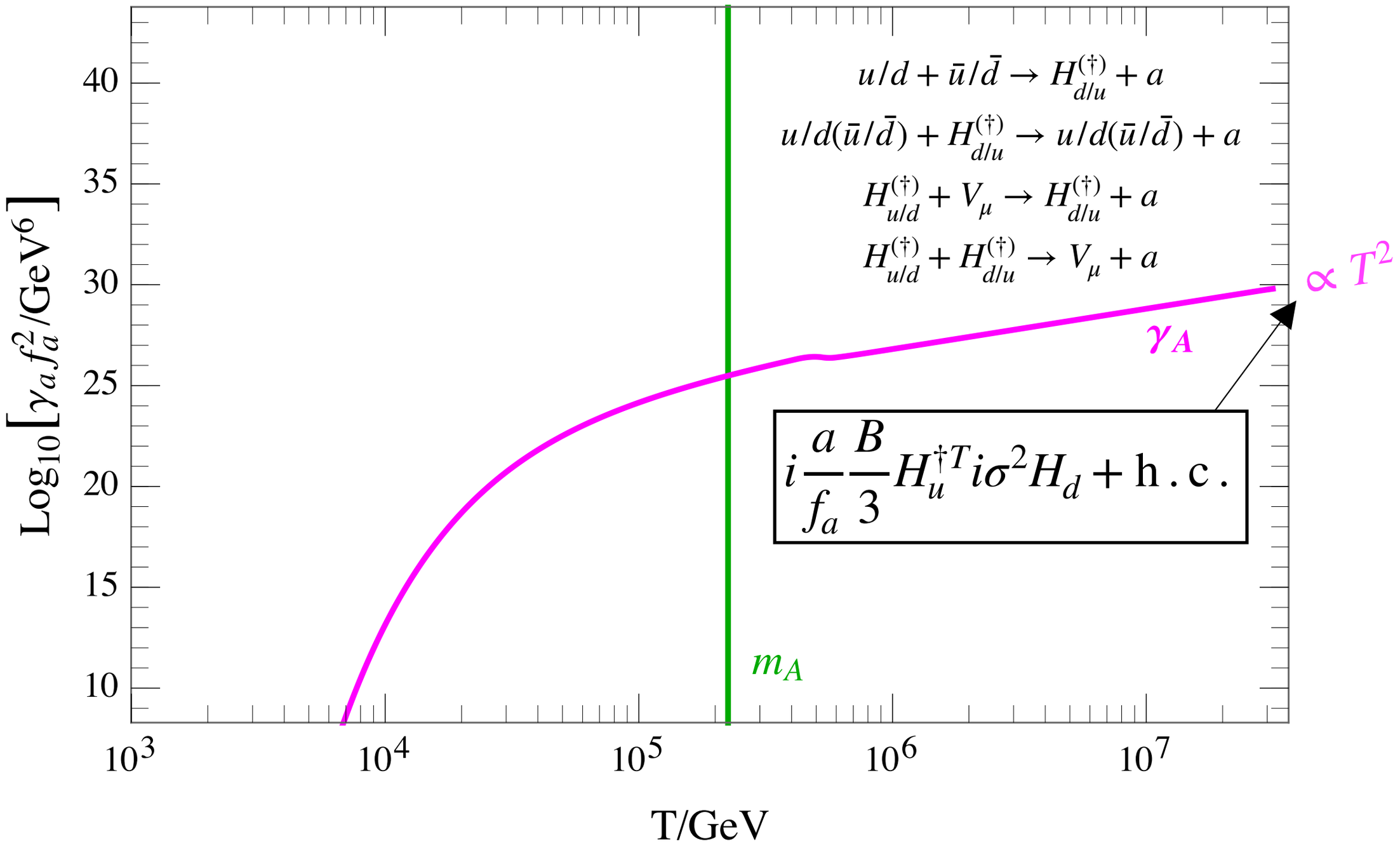
  @ *electroweak phase transition*

  @ *QCD confinement*

Heavy Higgs boson threshold



Heavy Higgs boson threshold



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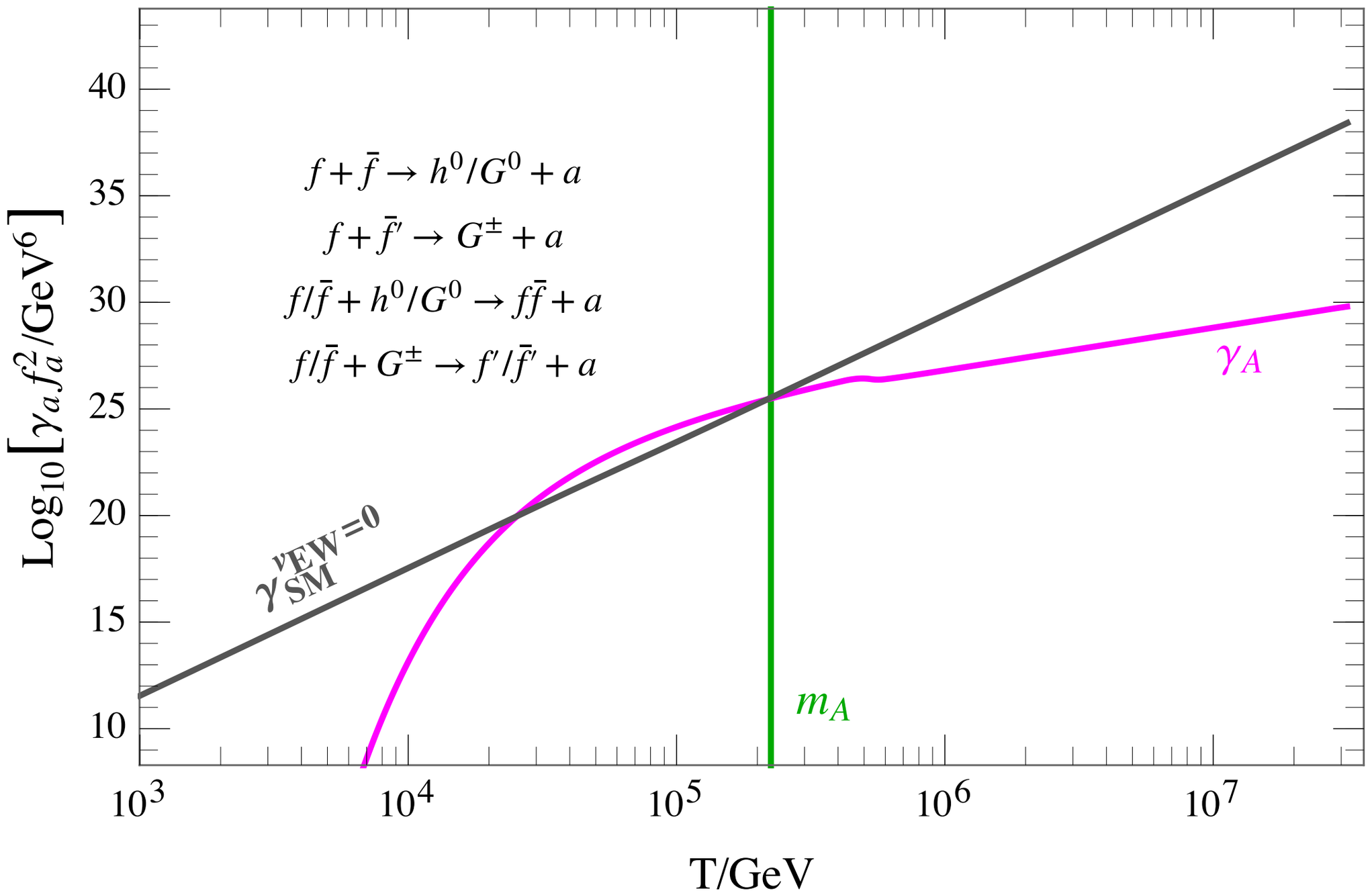

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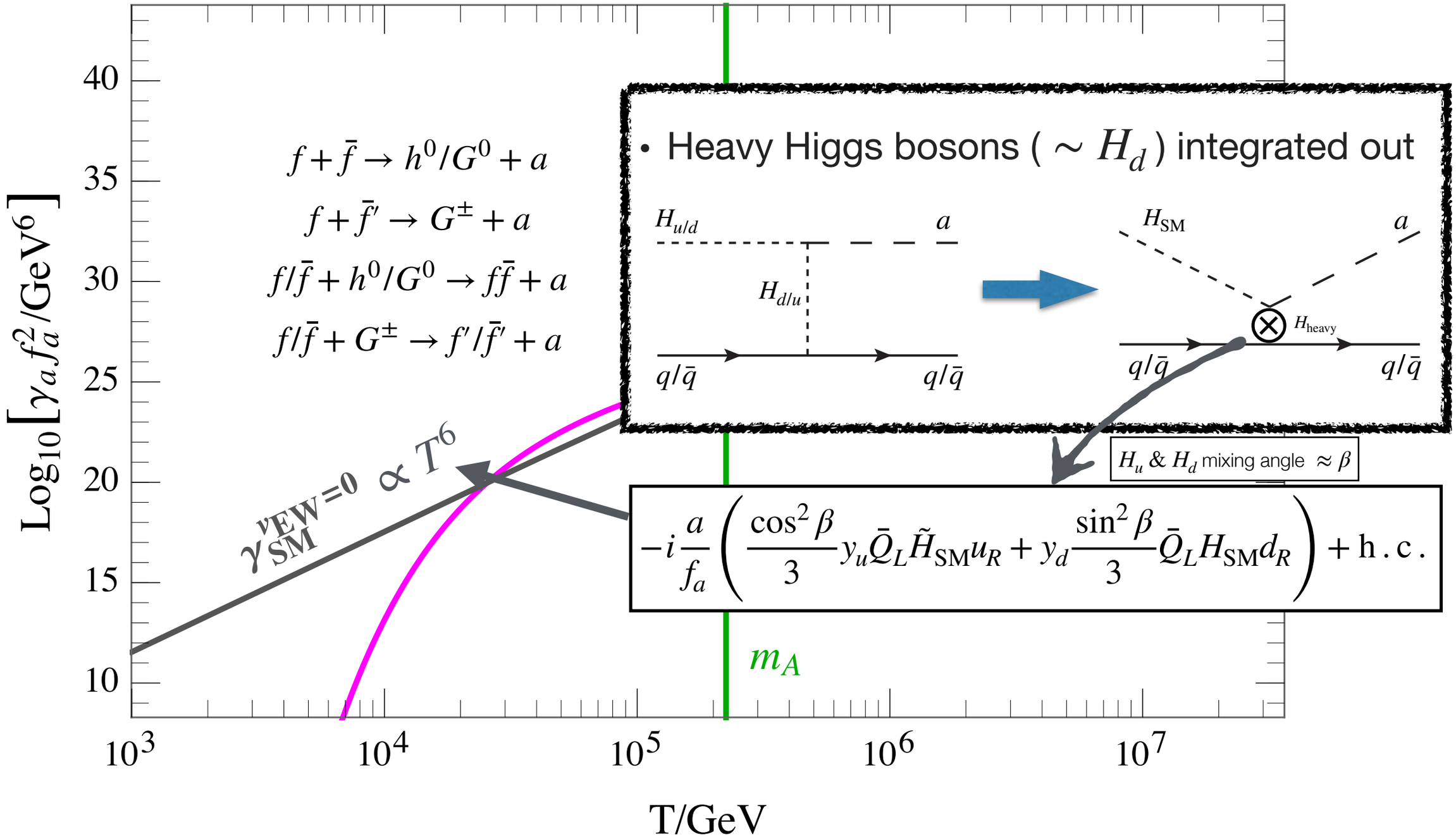

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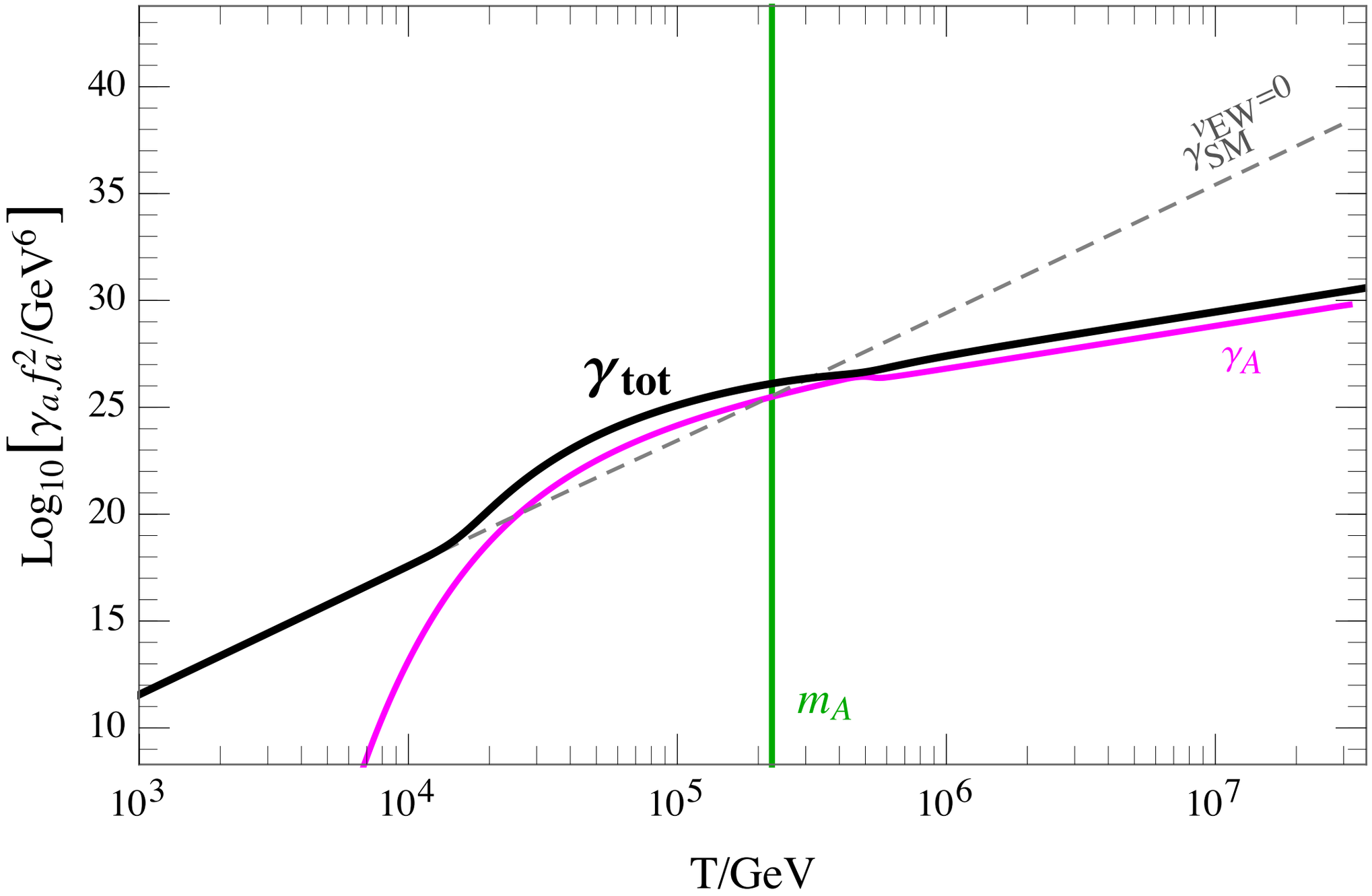
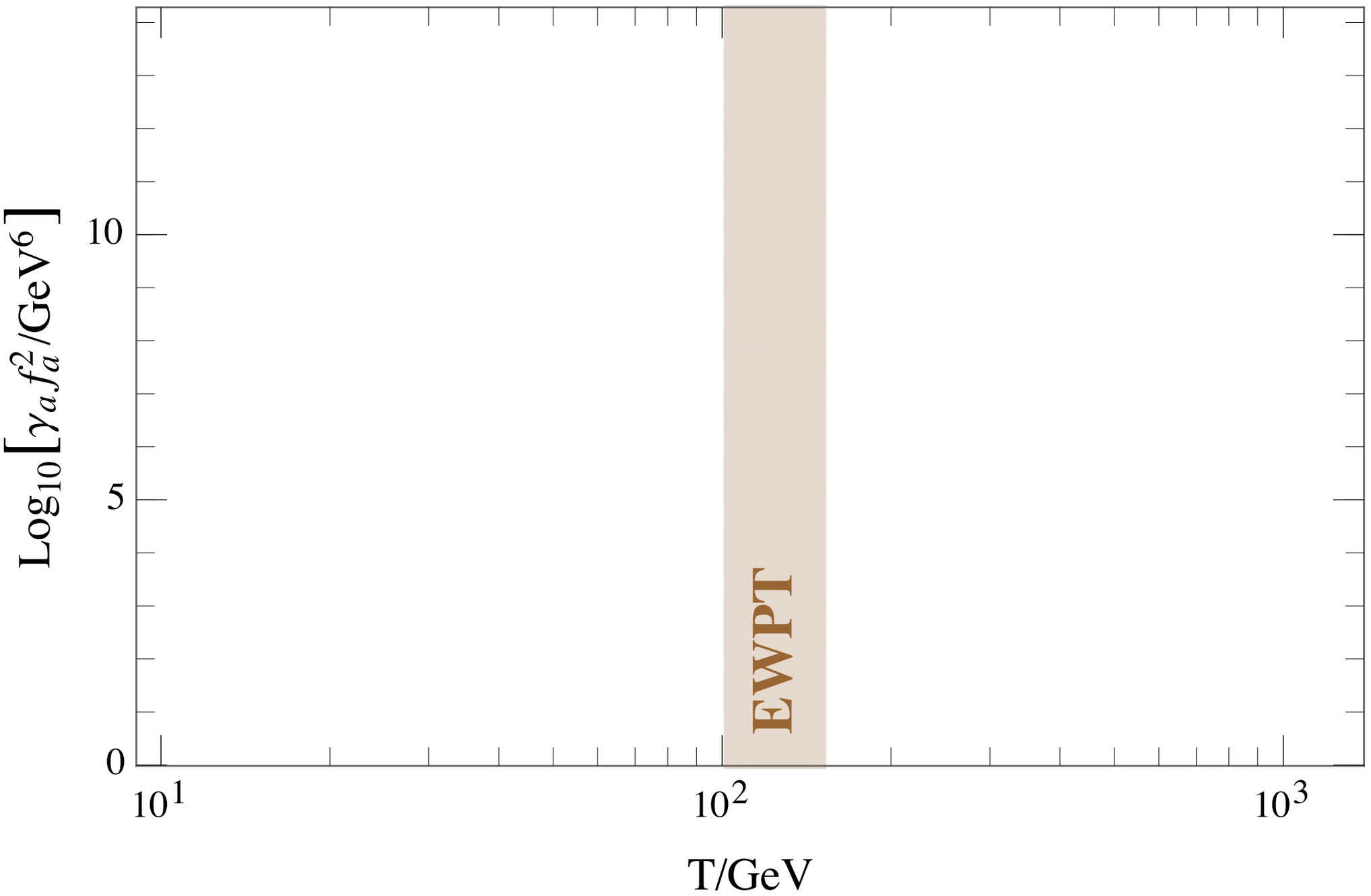


Electroweak threshold



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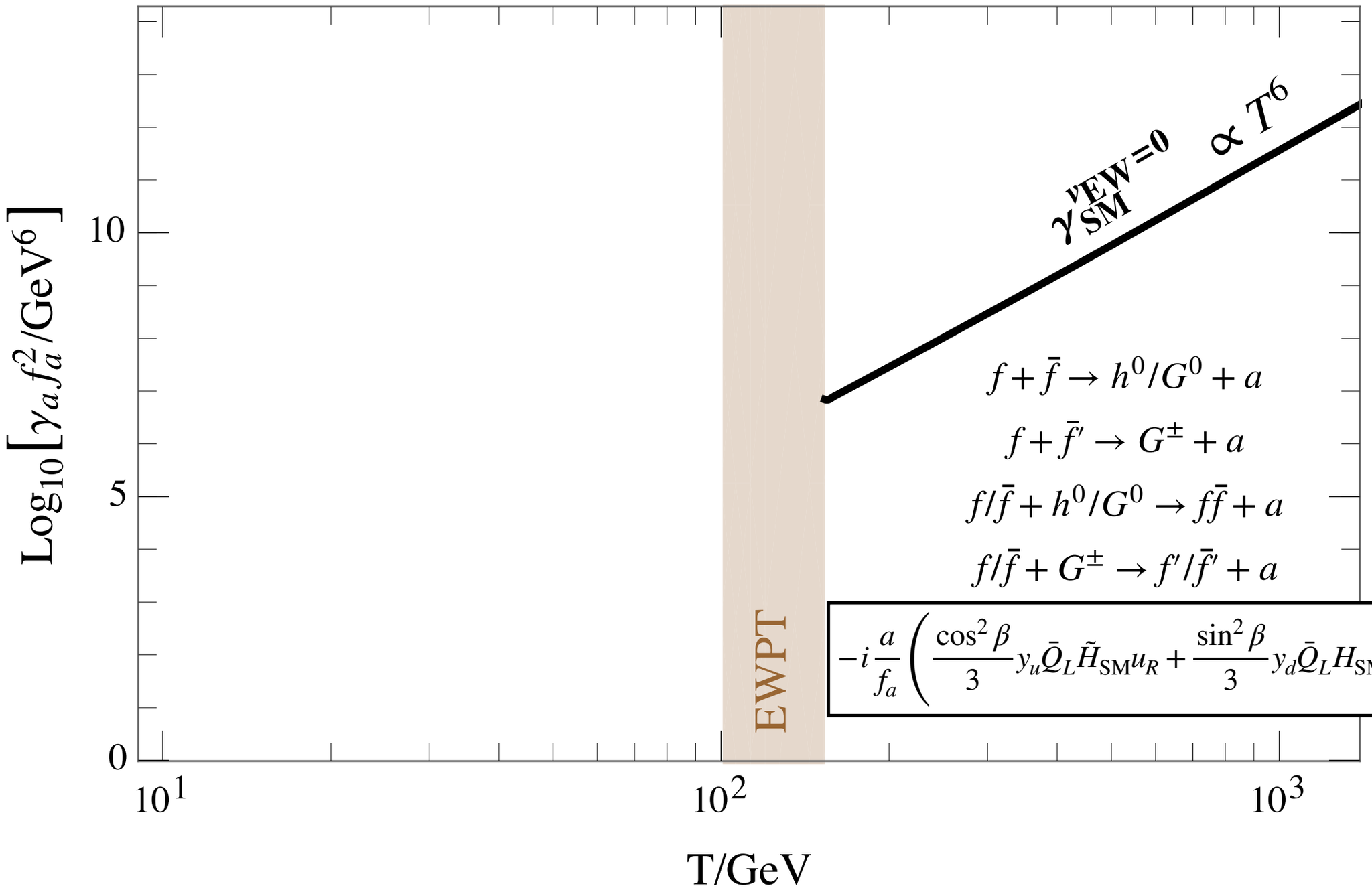

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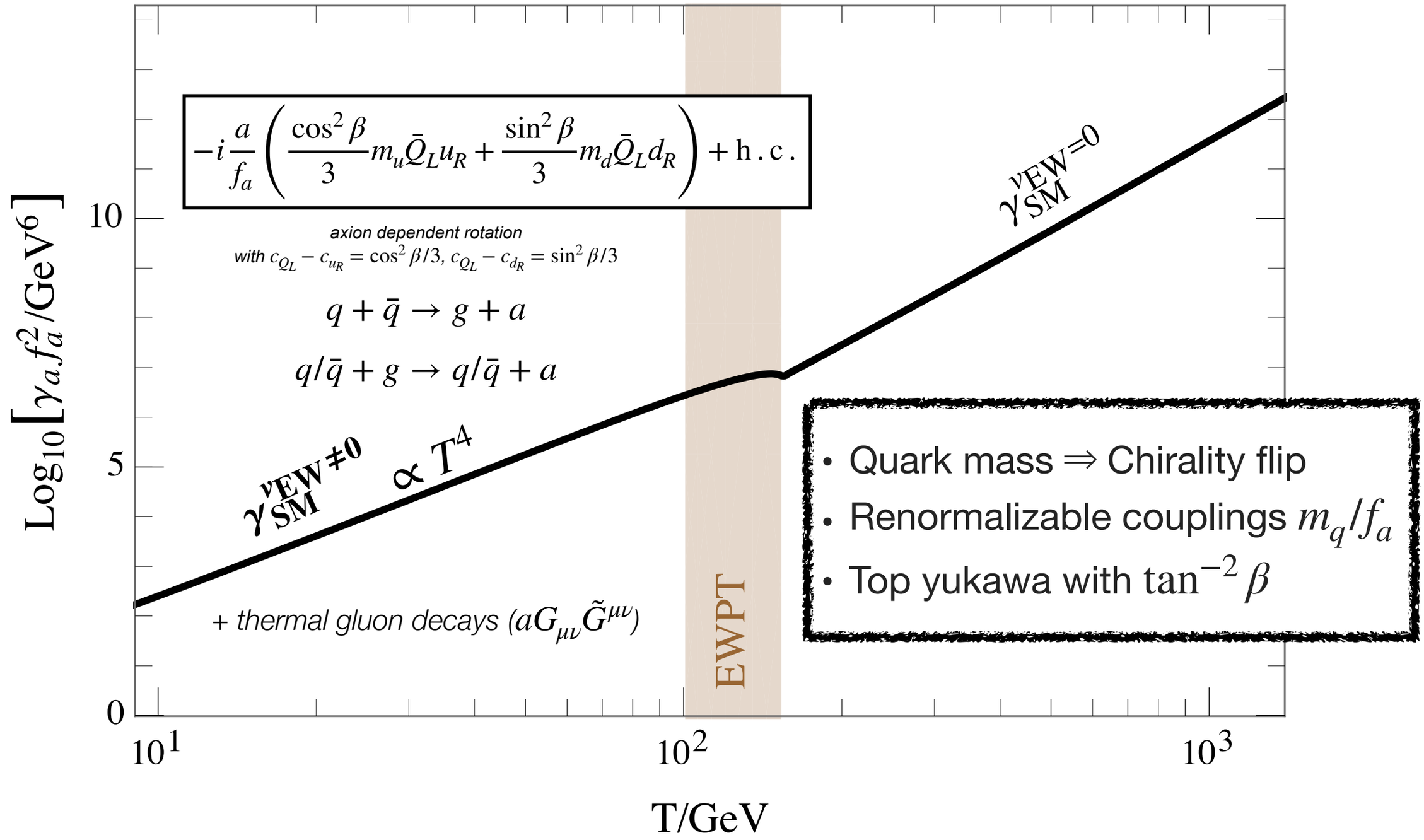
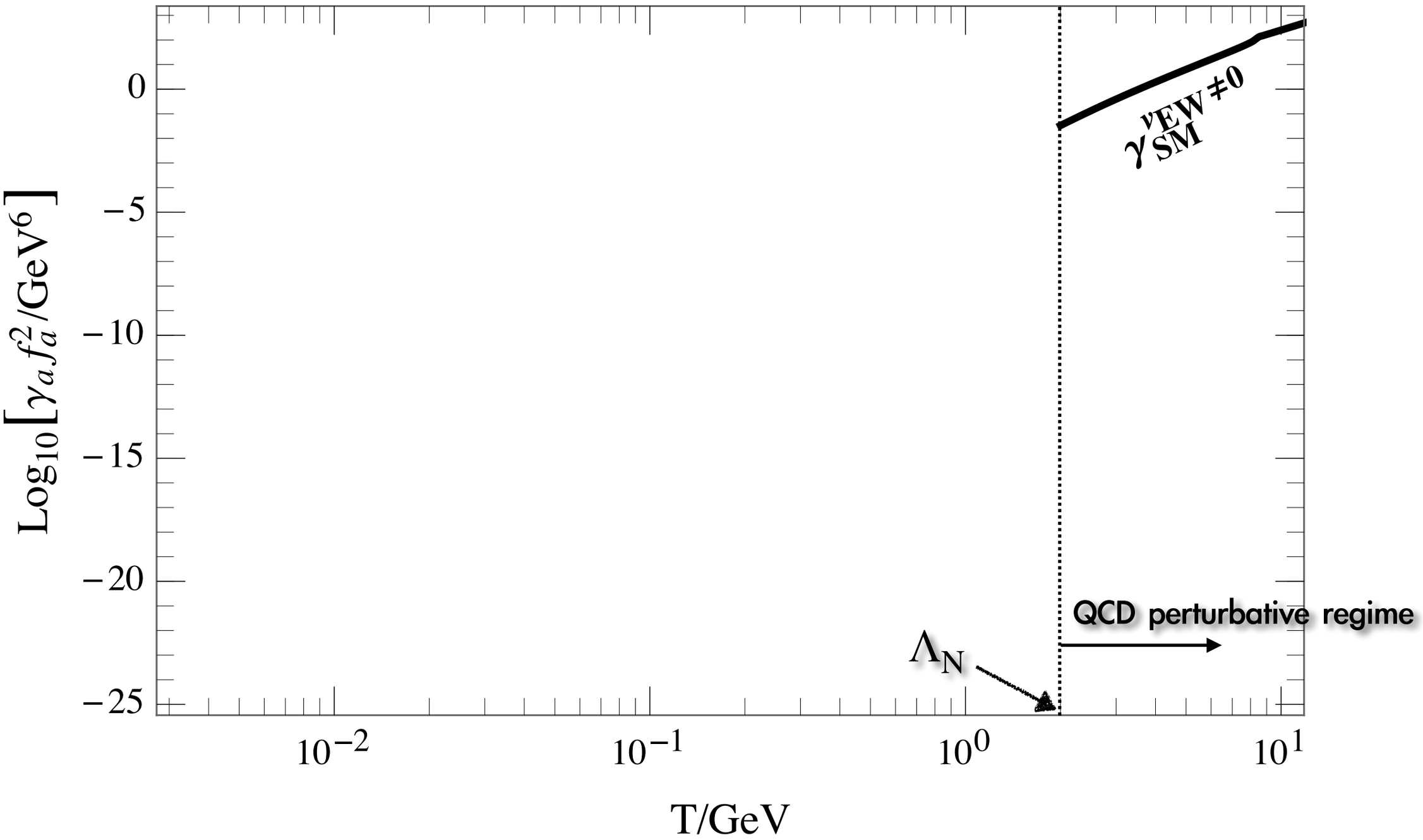


- Quark mass ⇒ Chirality flip
- Renormalizable couplings m_q/f_a
- Top yukawa with $\tan^{-2}\beta$

QCD threshold



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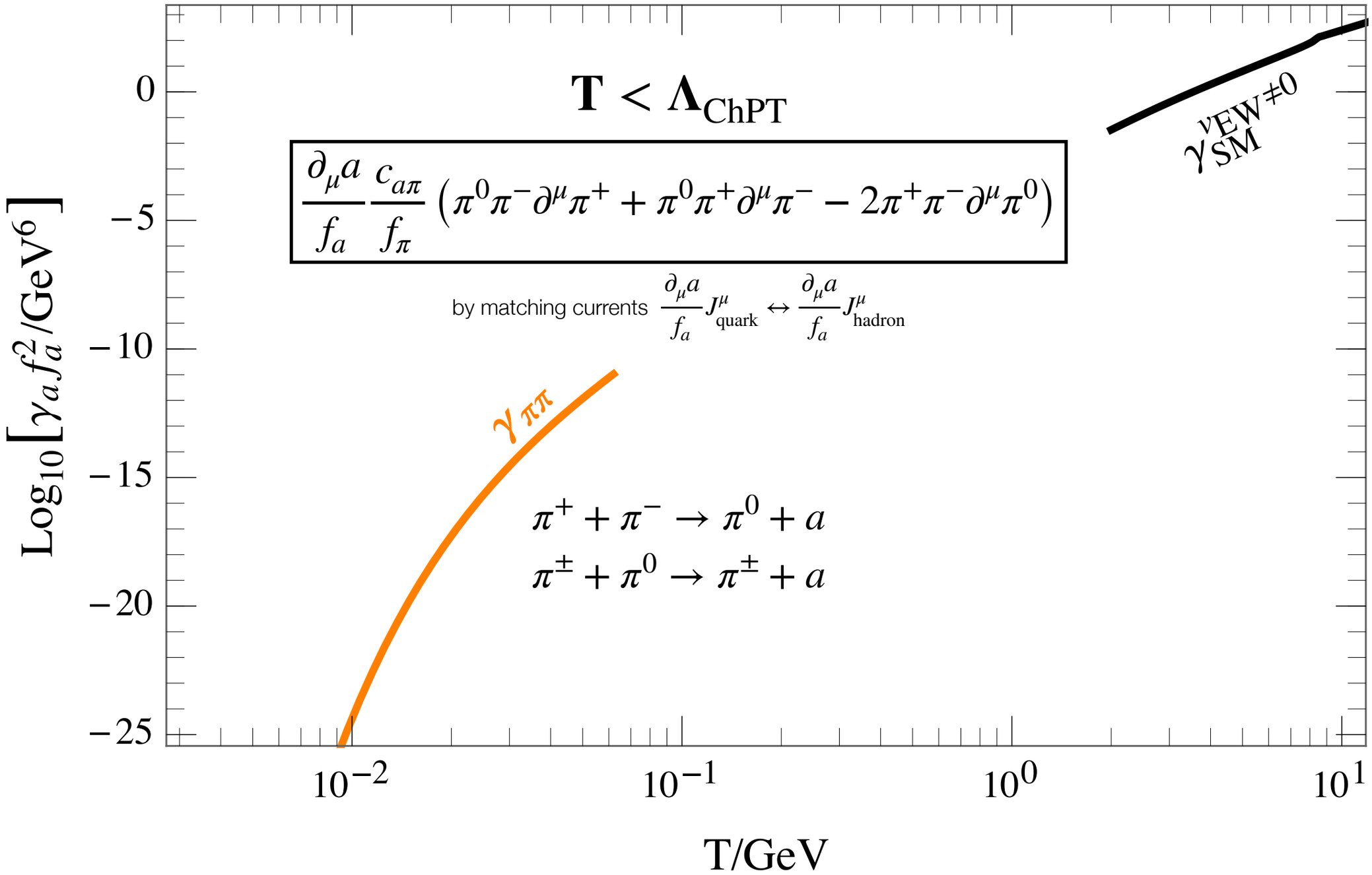

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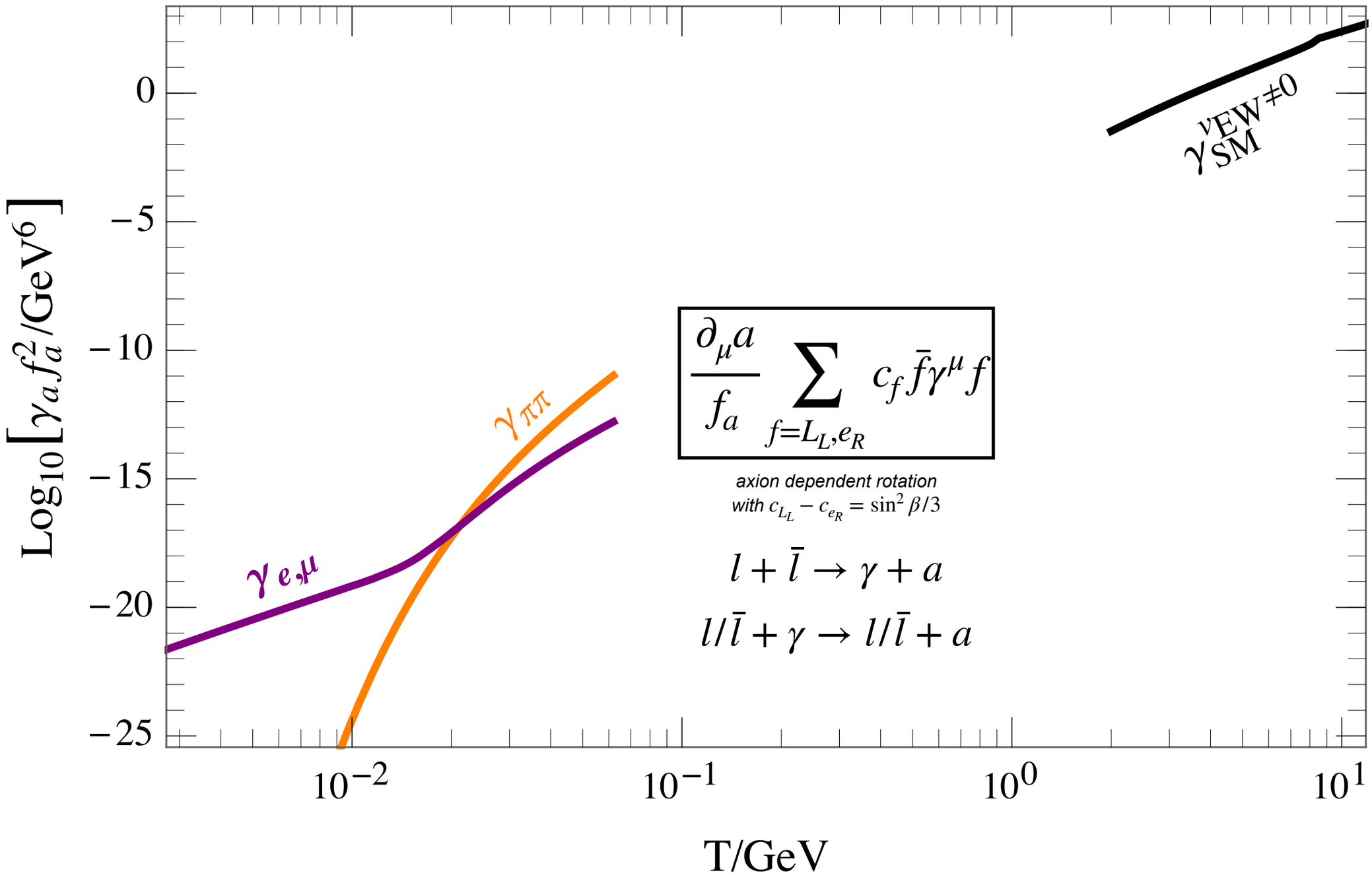

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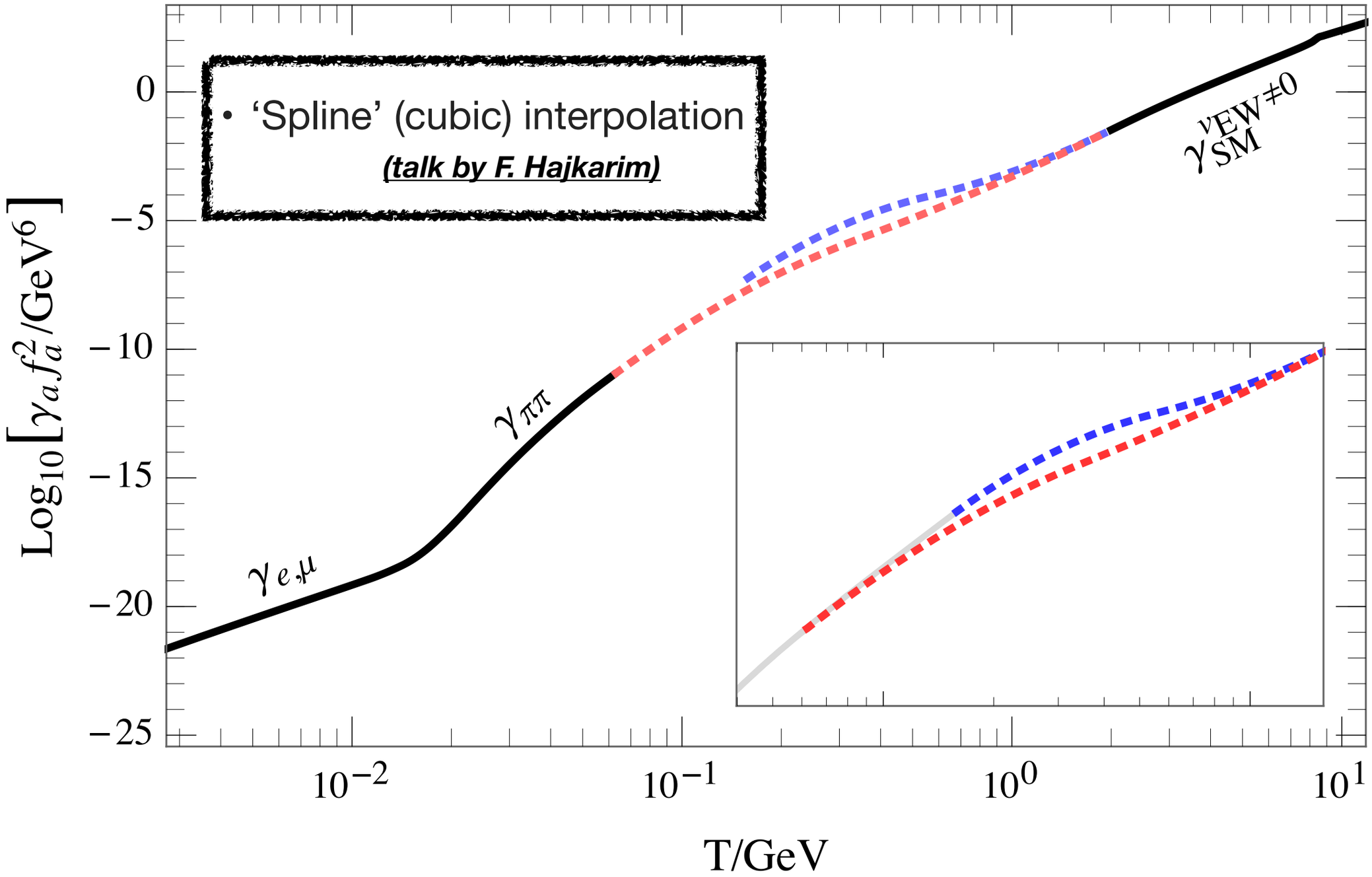
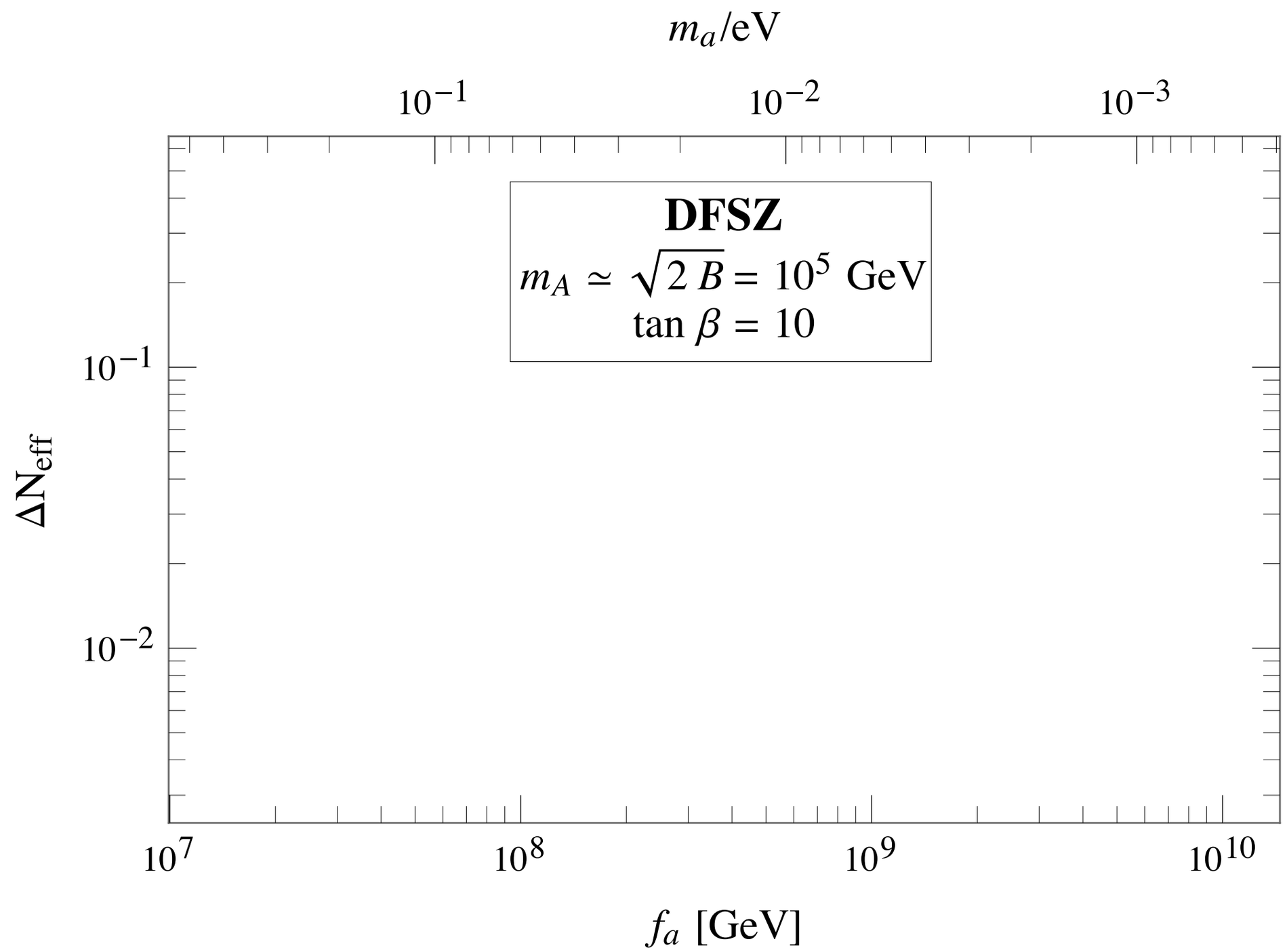


Hot DFSZ axion relic



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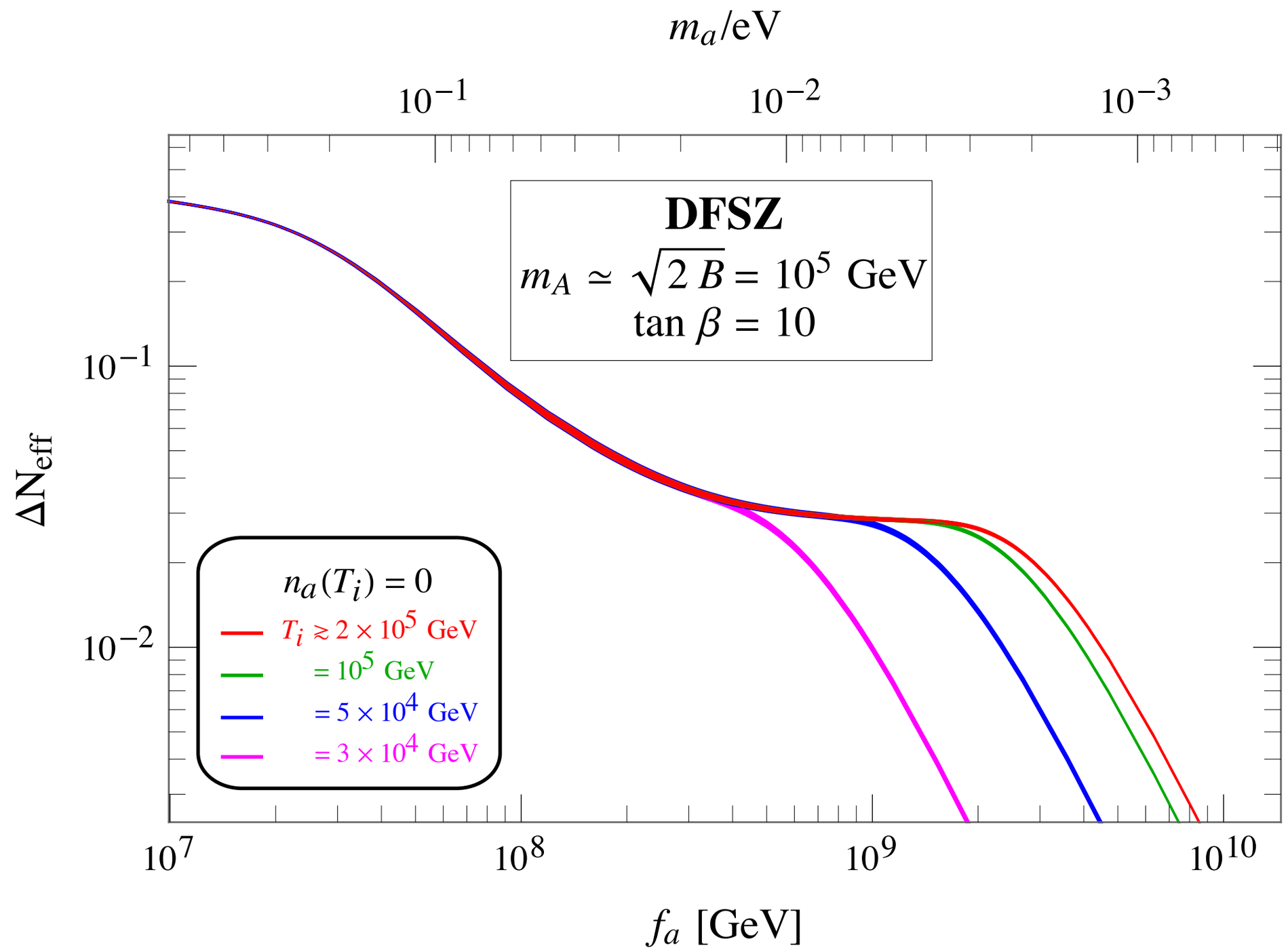

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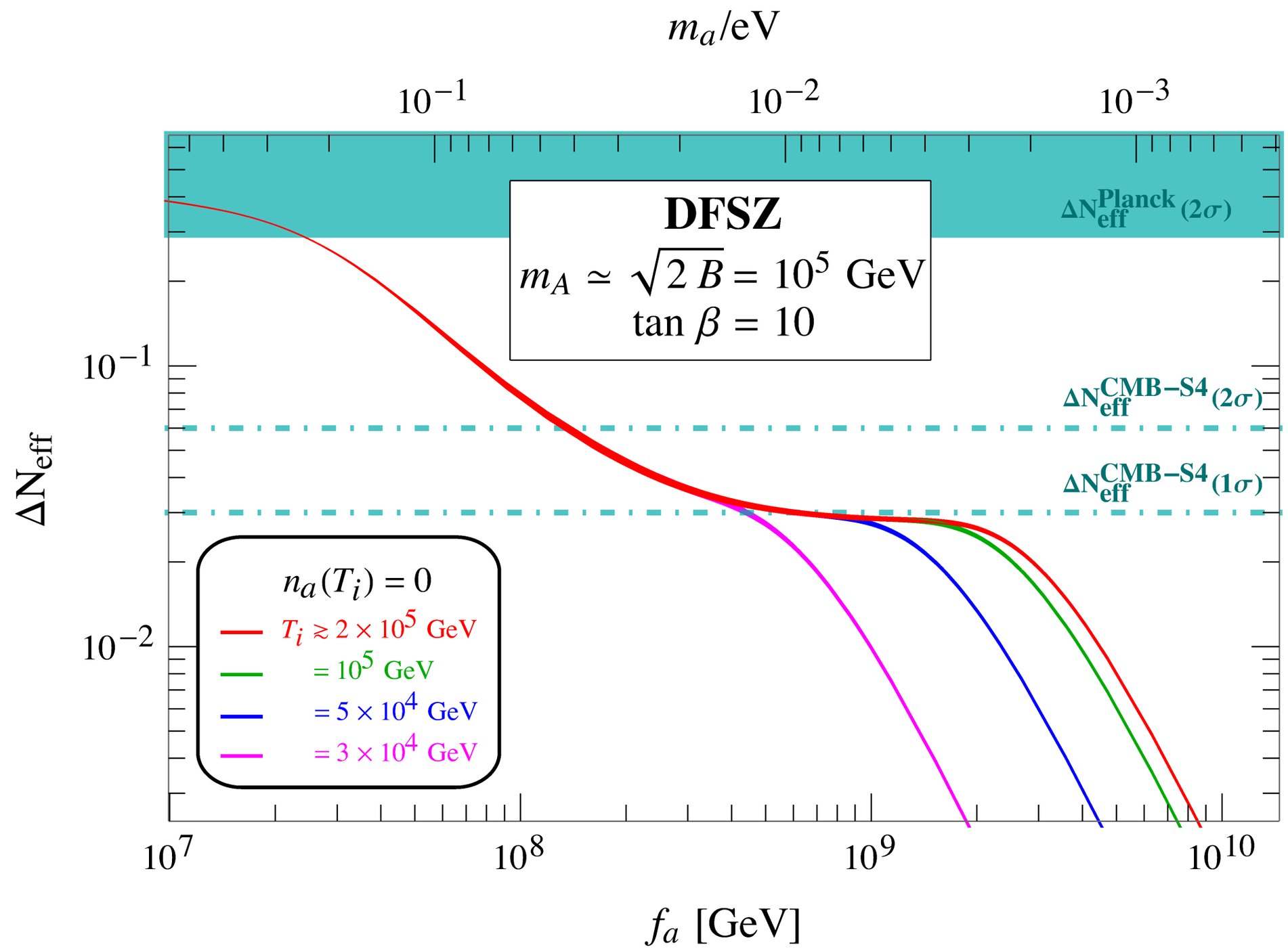

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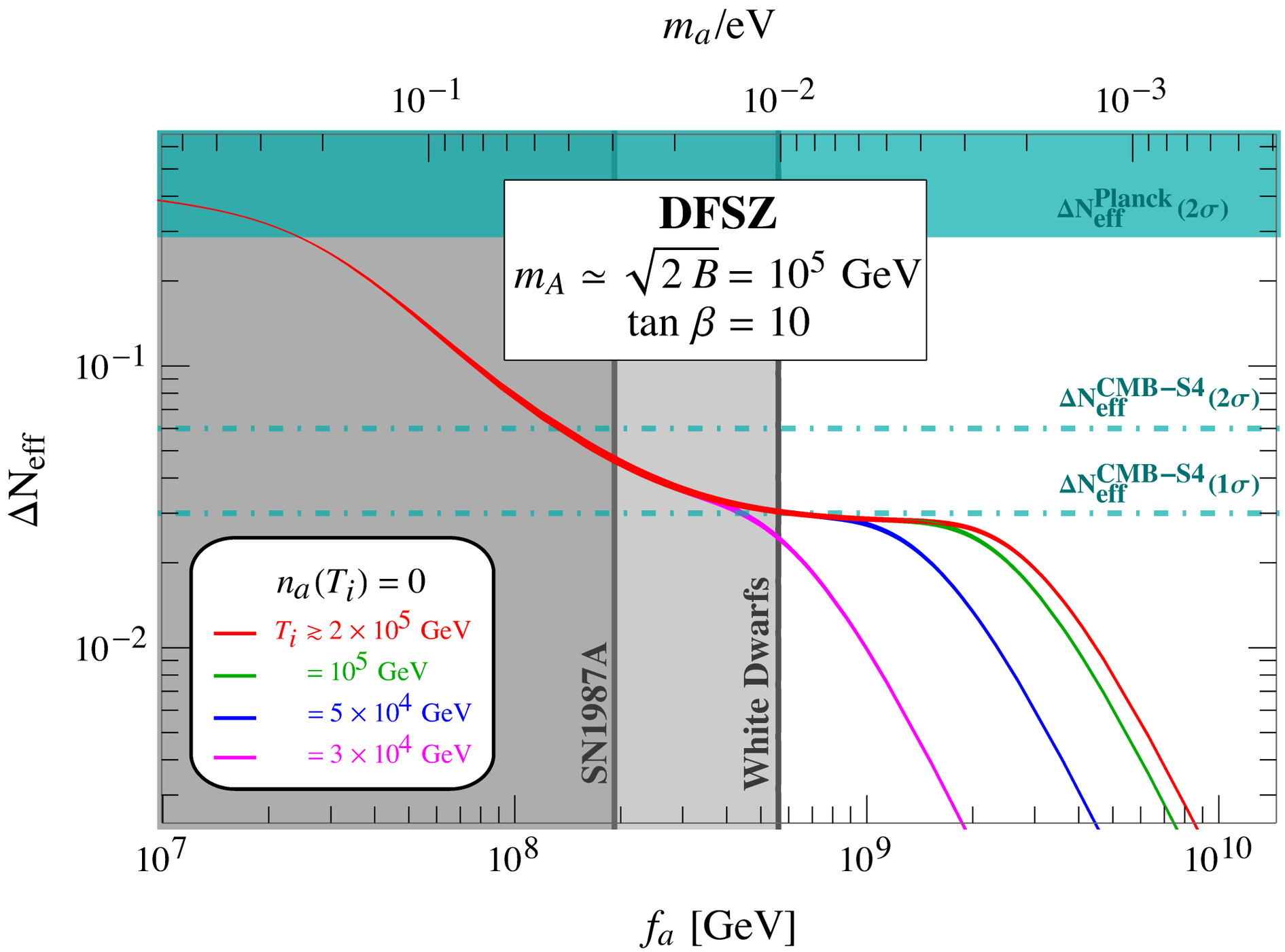


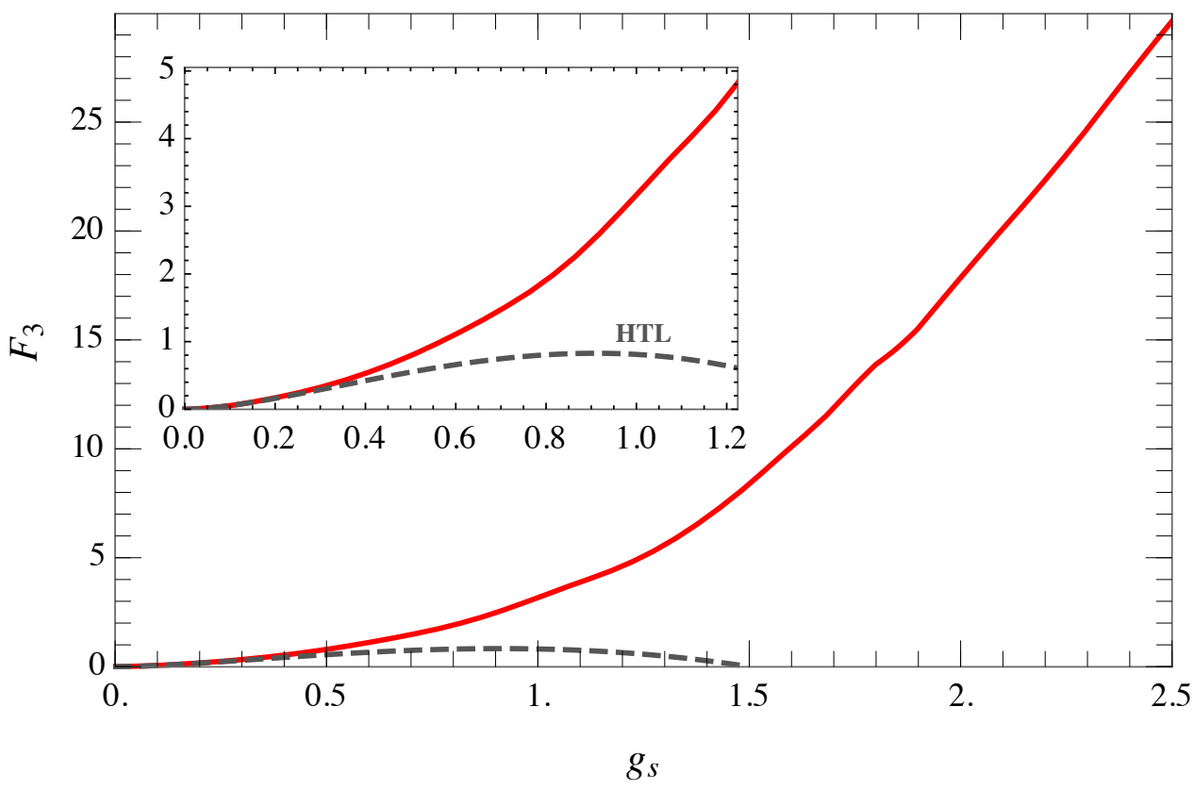
Conclusion

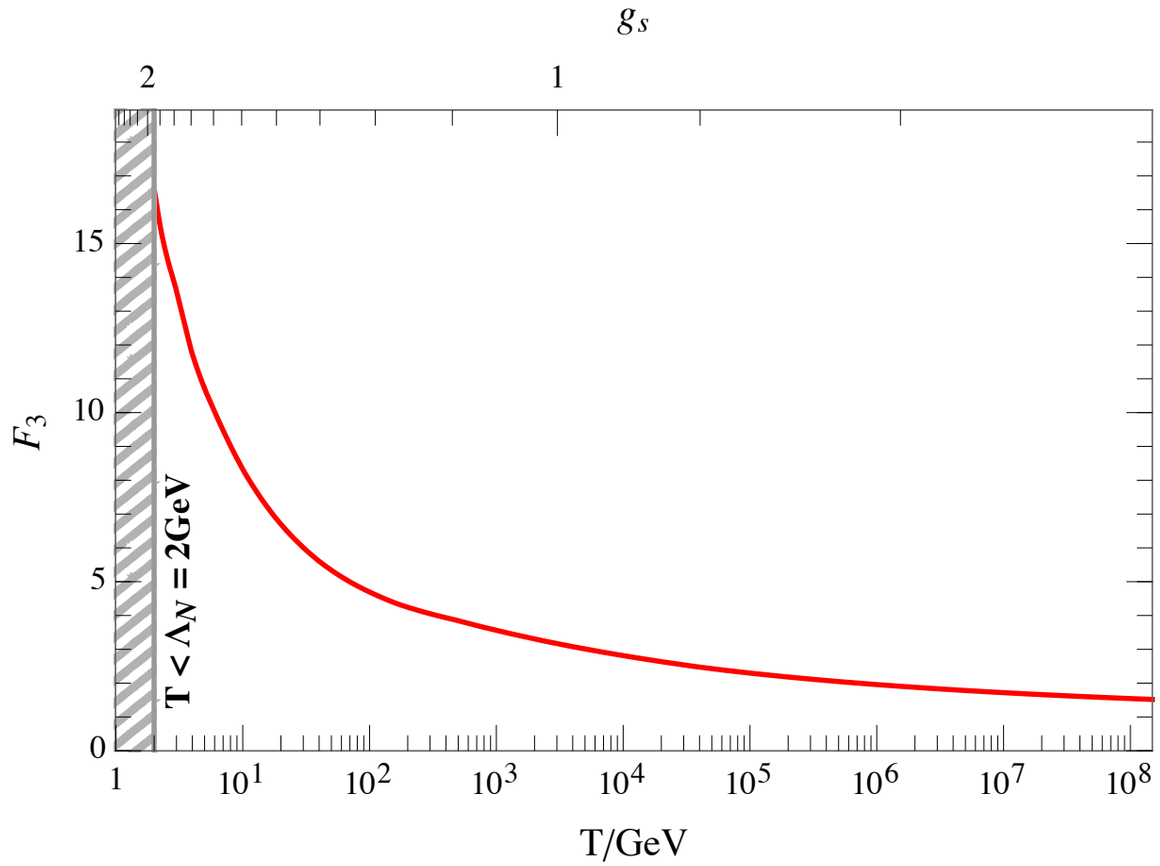
- We calculate the axion production rate in the full range for both of the typical QCD axion scenario: KSVZ & DFSZ
- Smoothly connected axion production rate in each threshold scales
- Future CMB sensitivity would give $f_a > \mathcal{O}(10^9)\,\mathrm{GeV}$
- Possibility to detect the KSVZ axion signal for $f_a \sim \mathcal{O}(10^8)\,\mathrm{GeV}$

Back up

[A. Salvio et al, 2013] [F. D'Eramo, F. Hajkarim, SY, 2021]

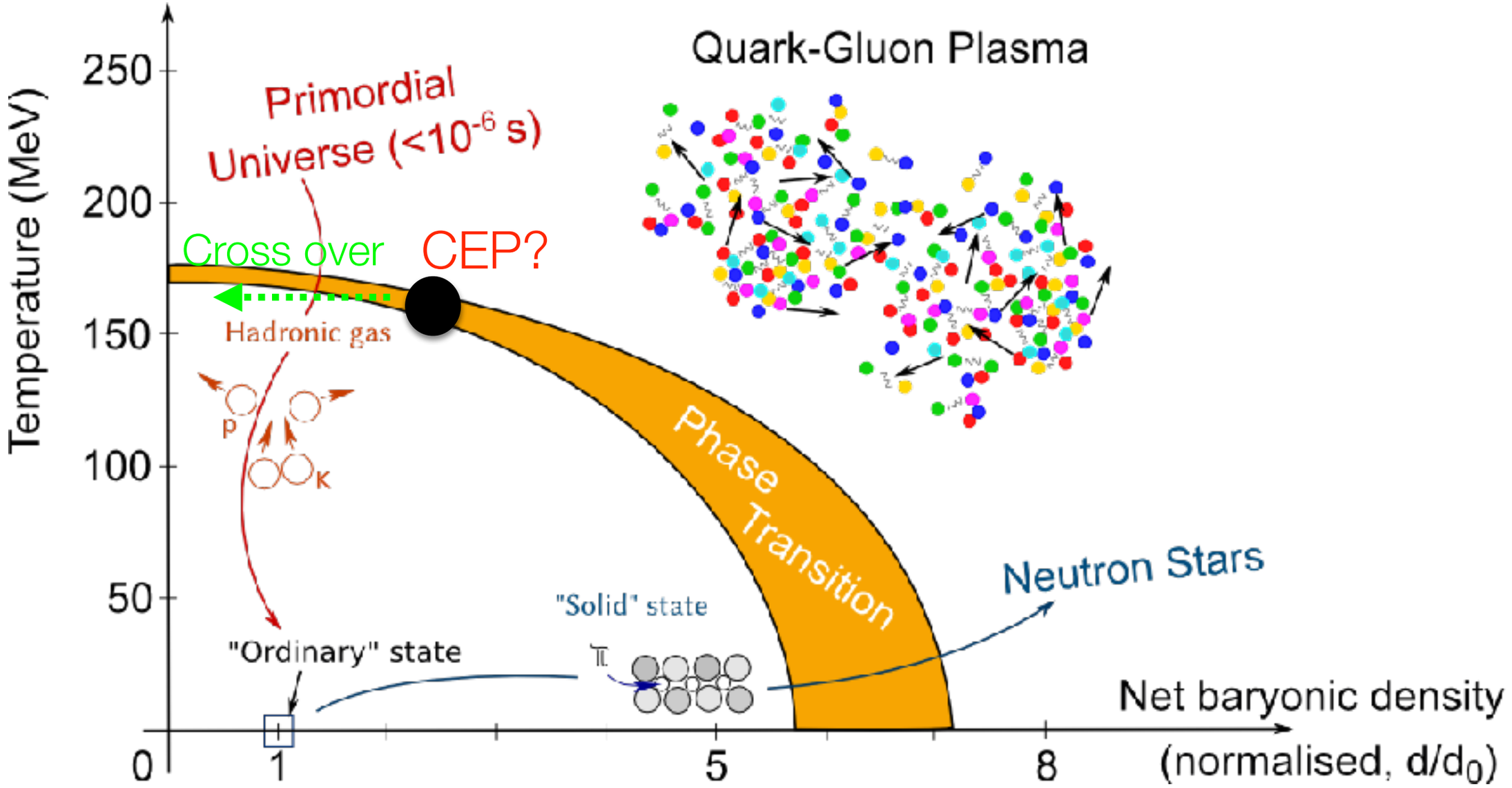
Control function for gluon scatterings



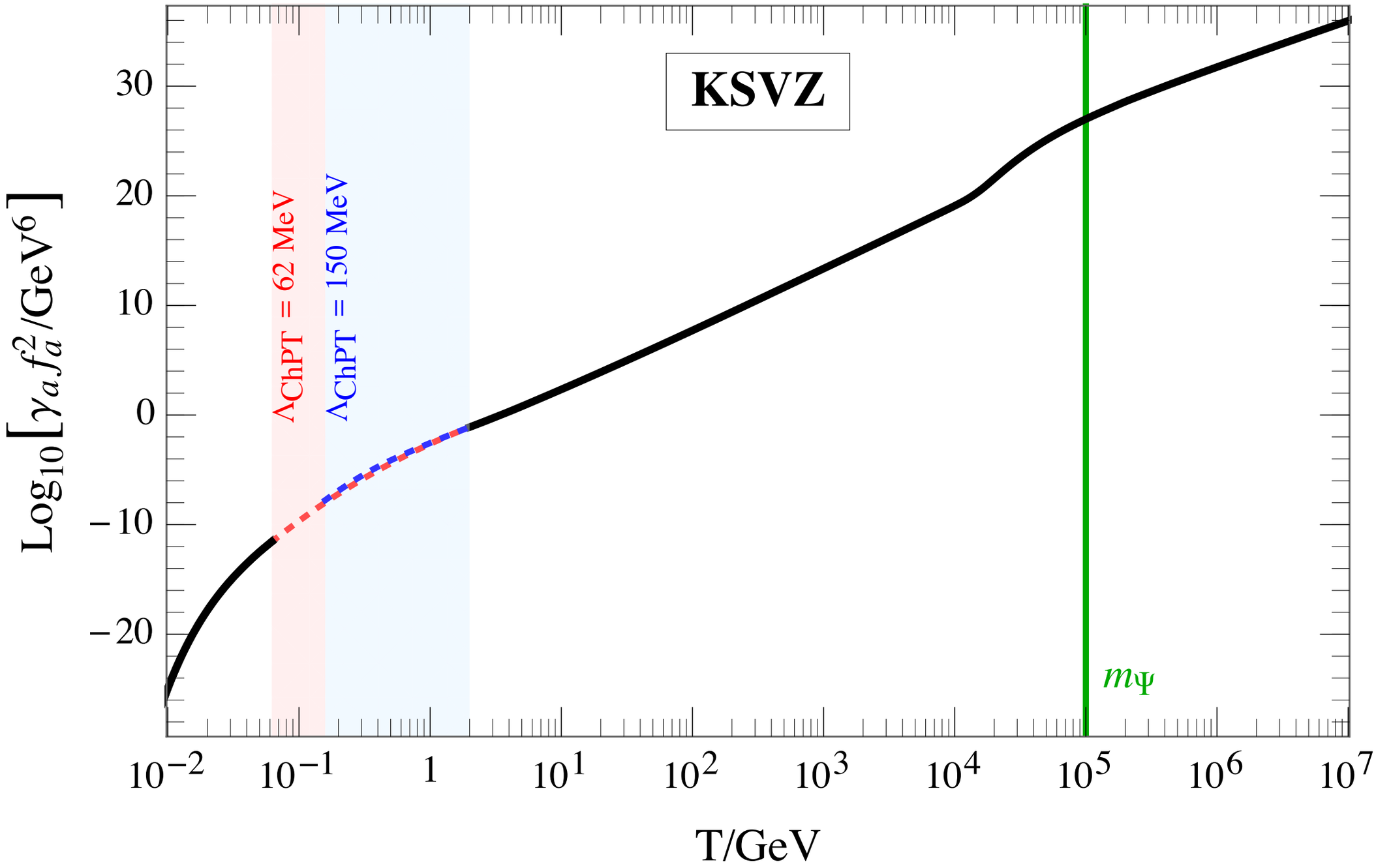


QCD phase diagram

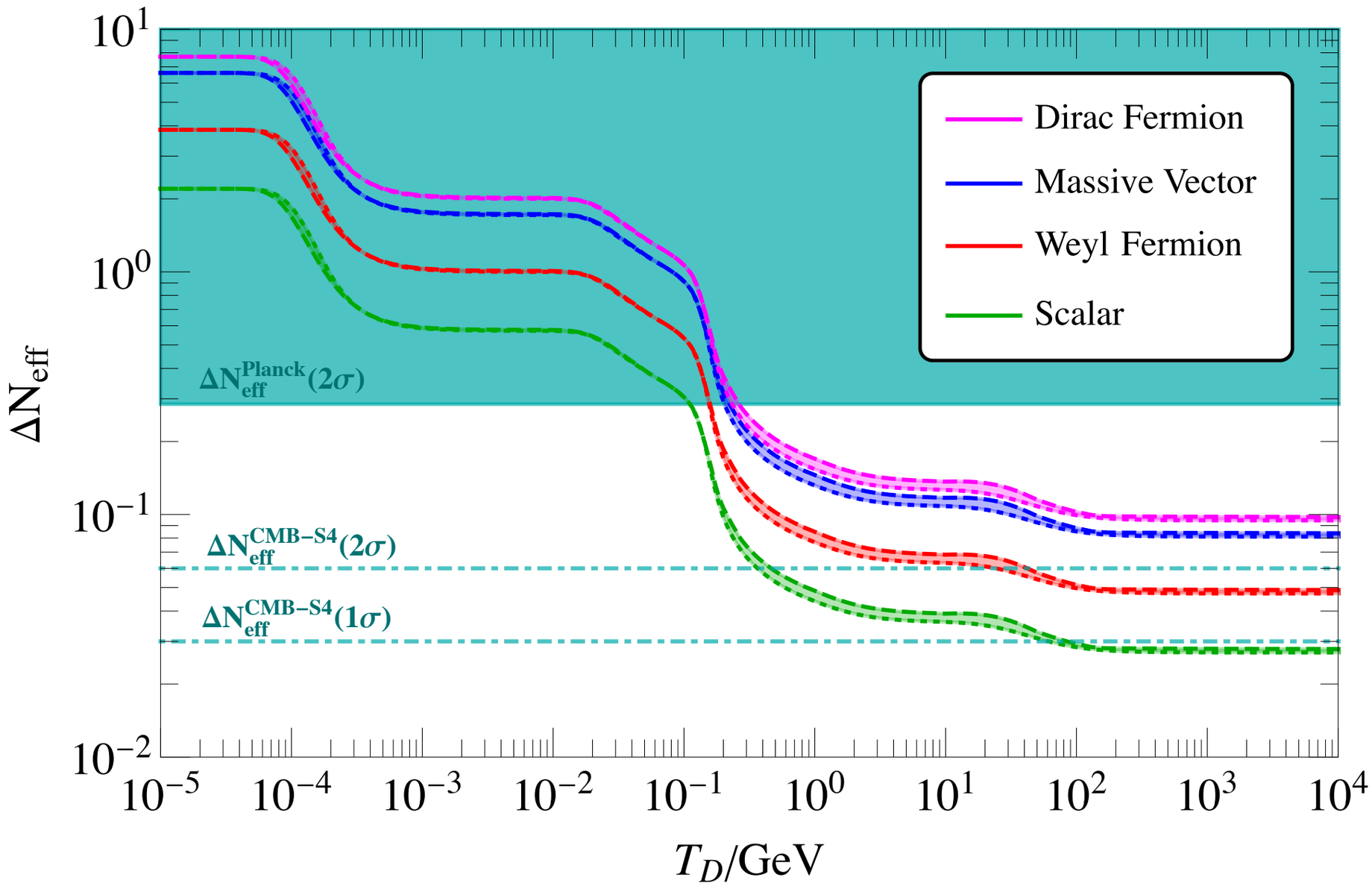
[A. Maire, 2015]



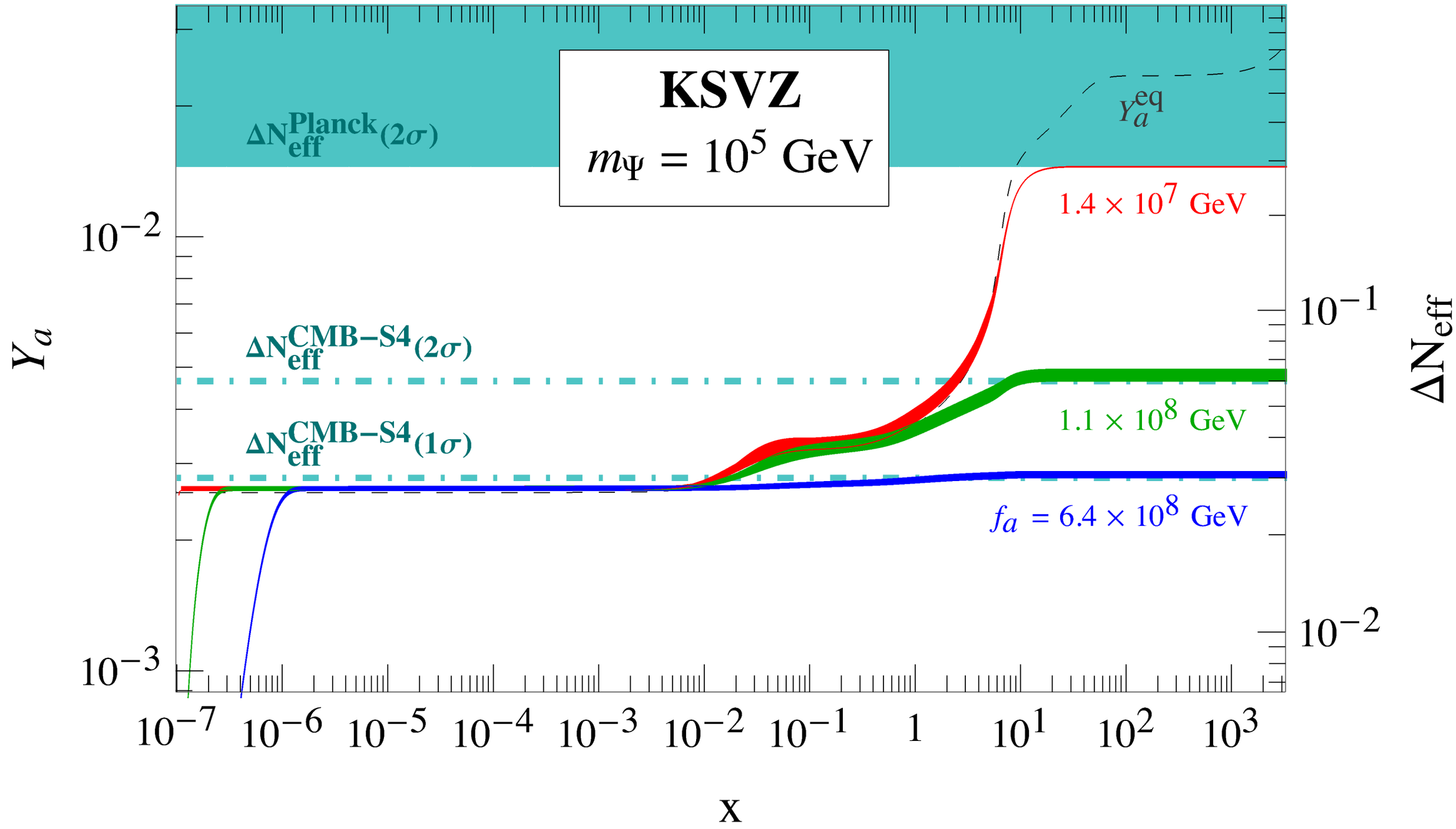
KSVZ axion production rate



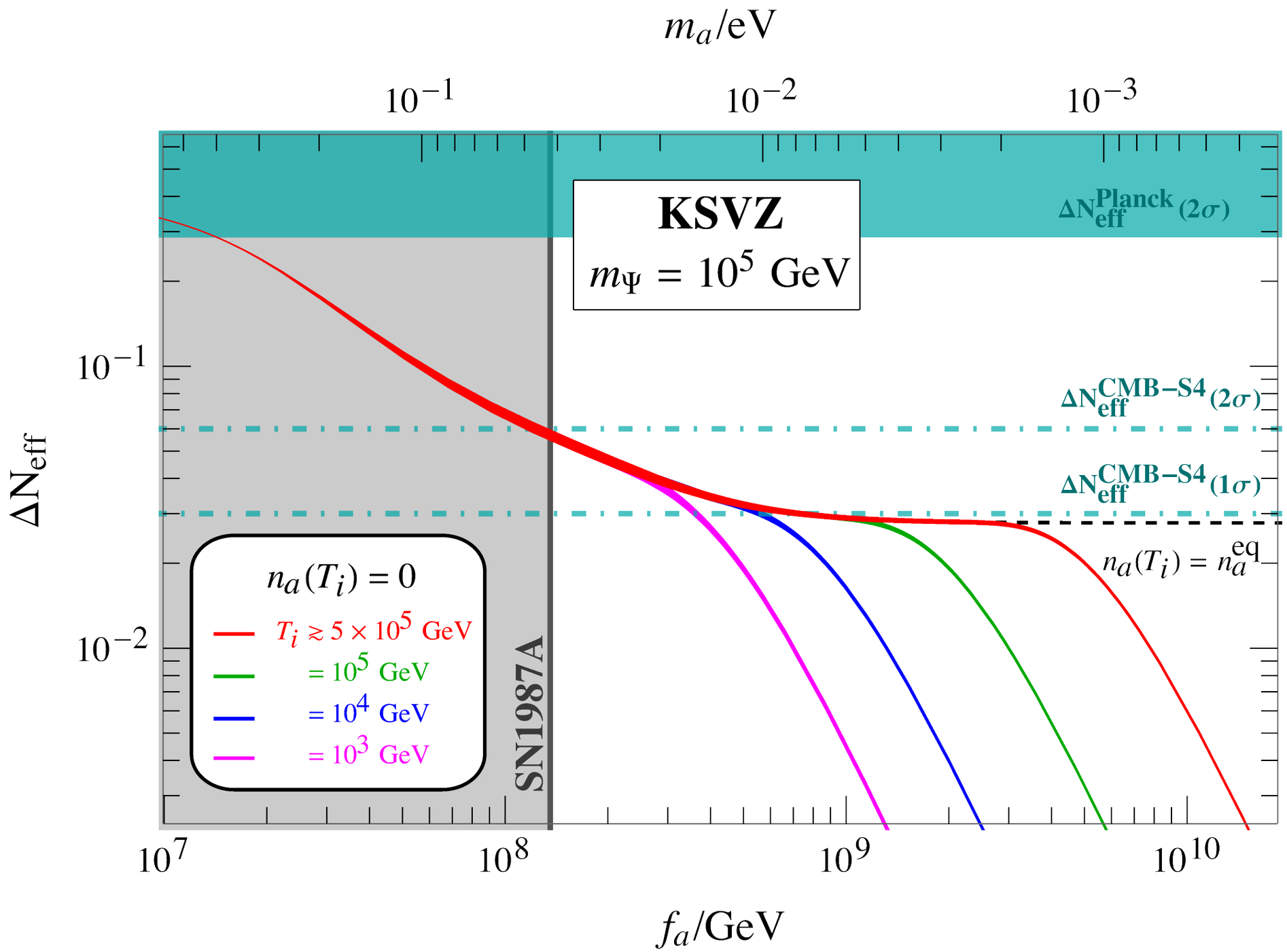
$\Delta N_{\rm eff}$ VS $T_{\rm D}$



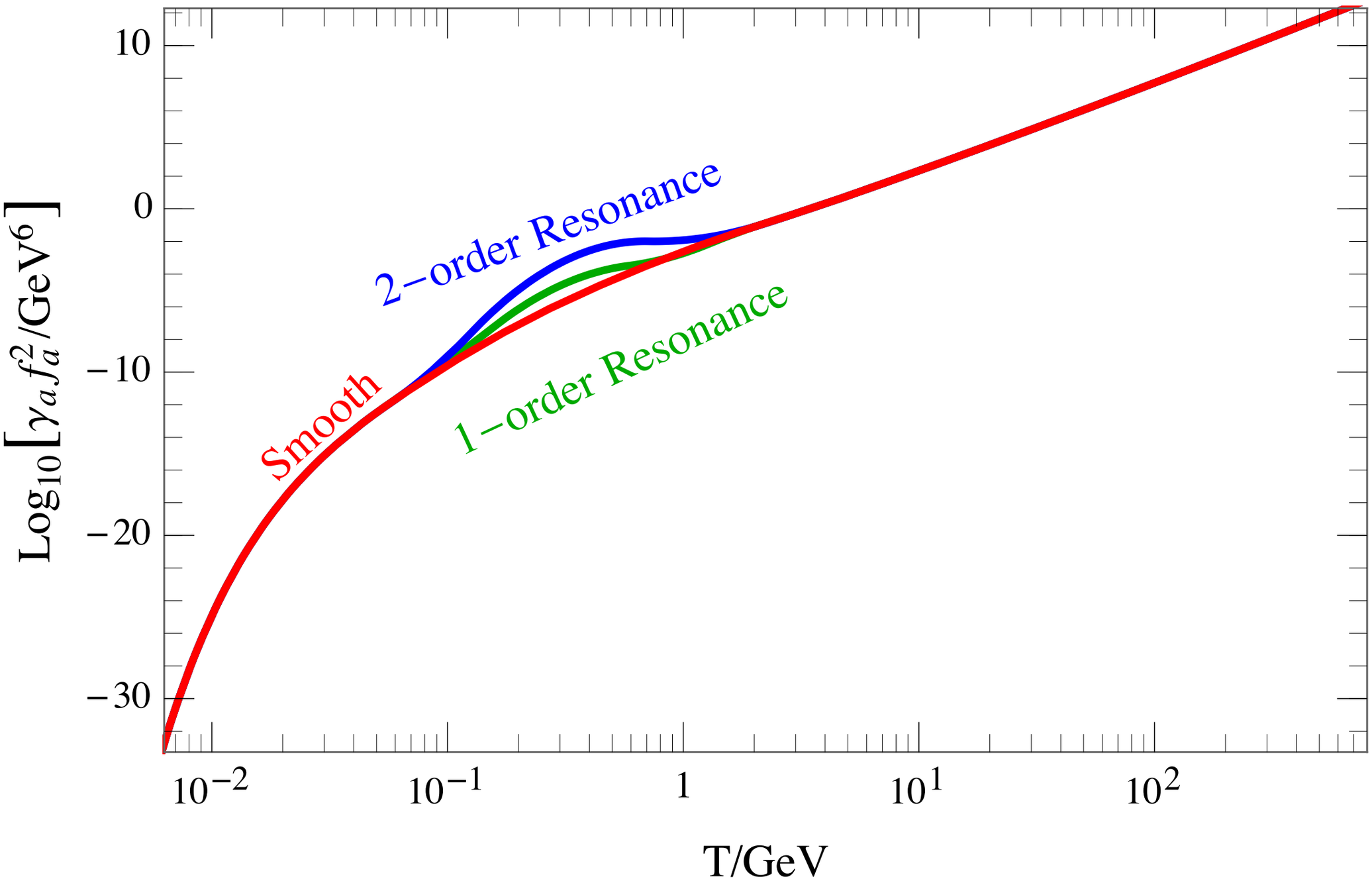
Evolution of KSVZ axion relic density



Hot KSVZ axion relic



Issue on interpolation?



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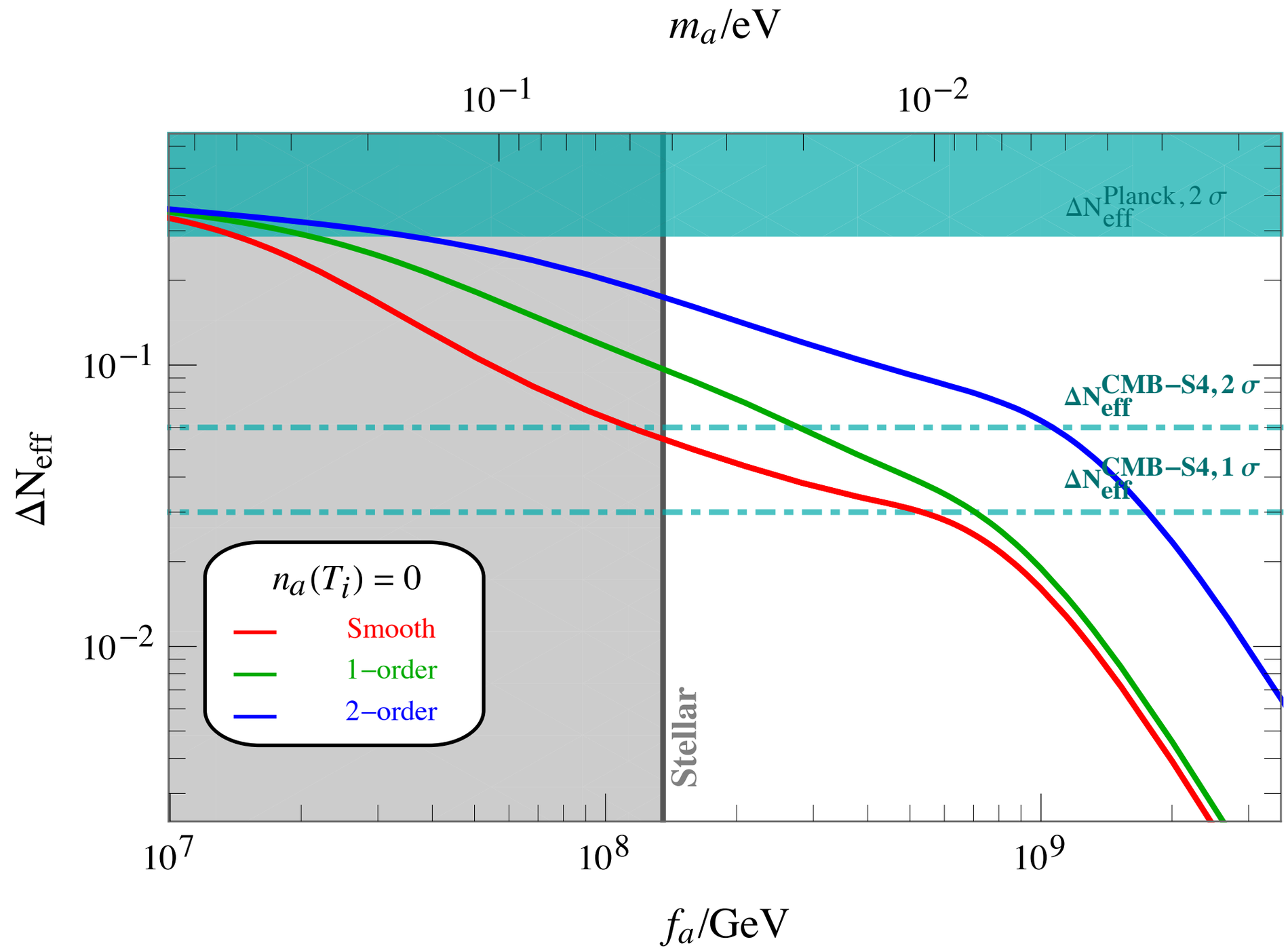
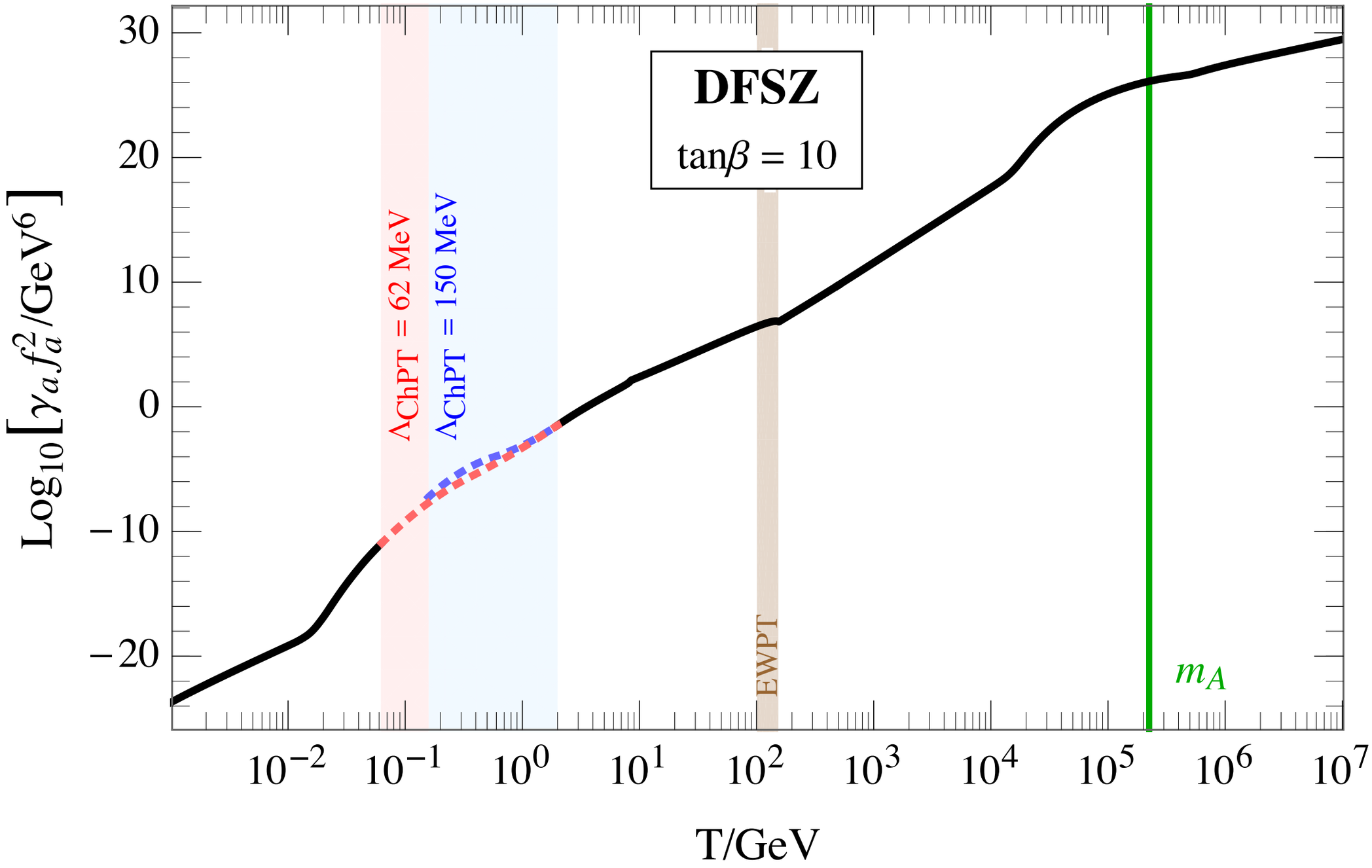
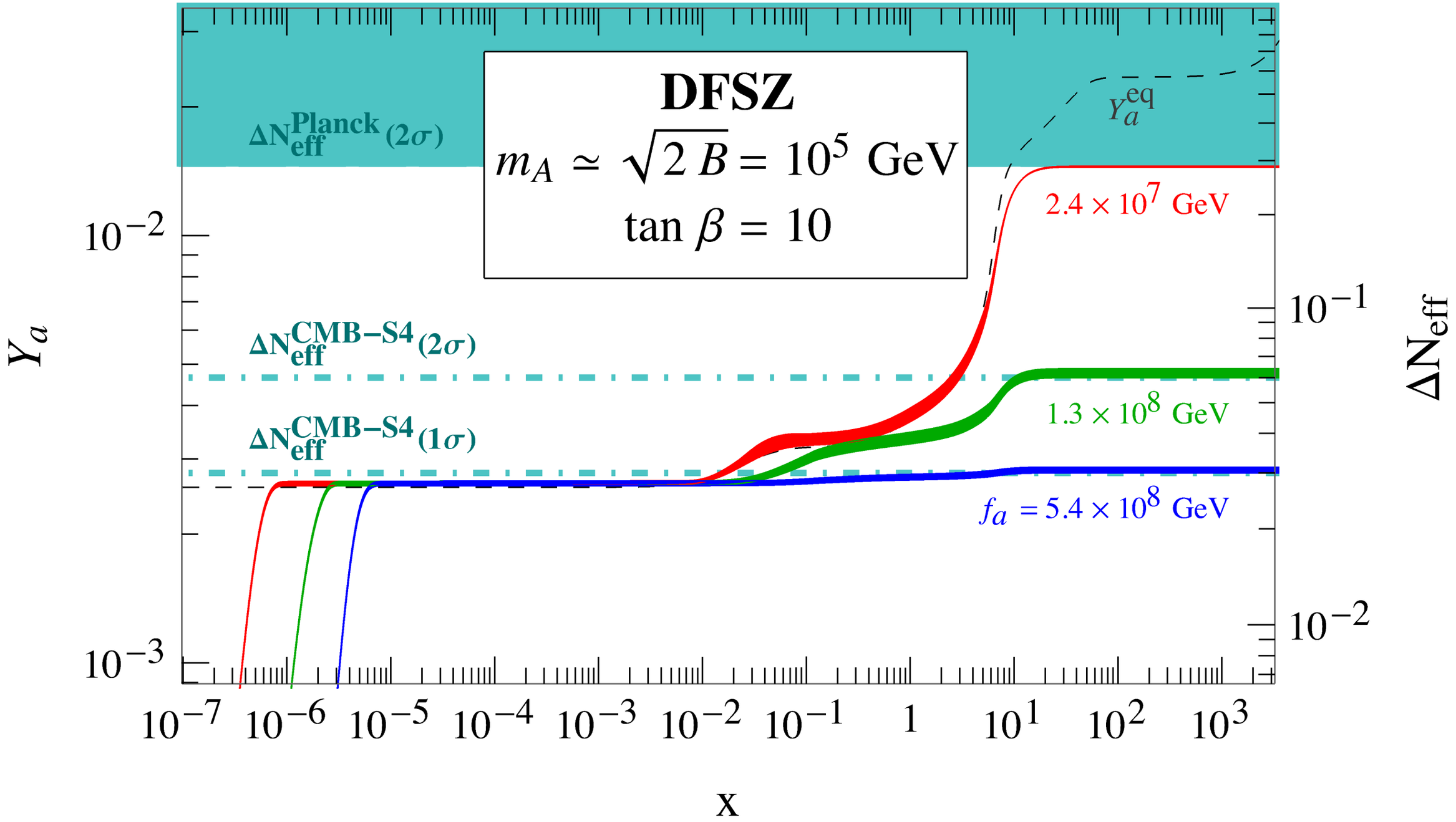


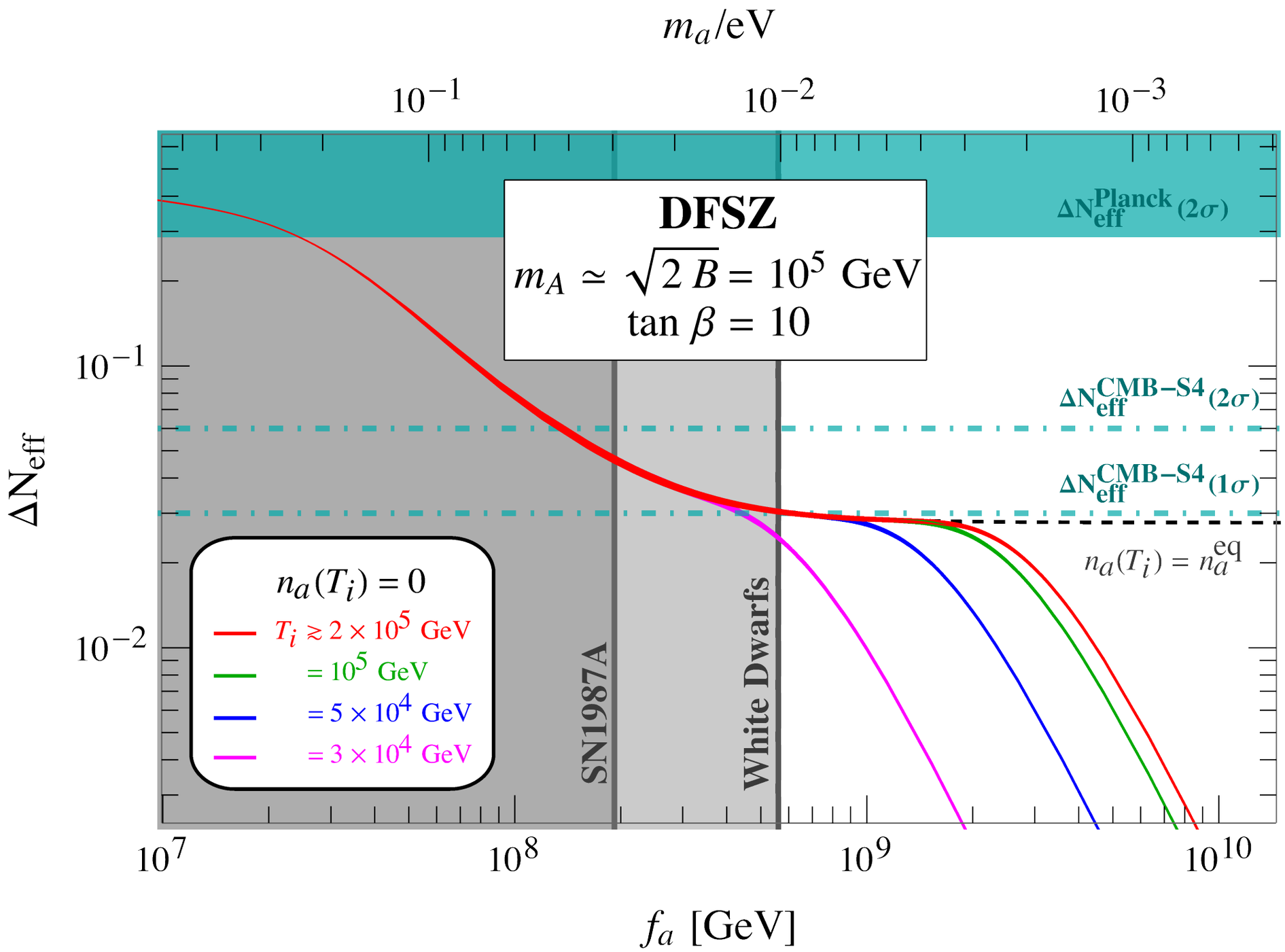
DFSZ axion production rate



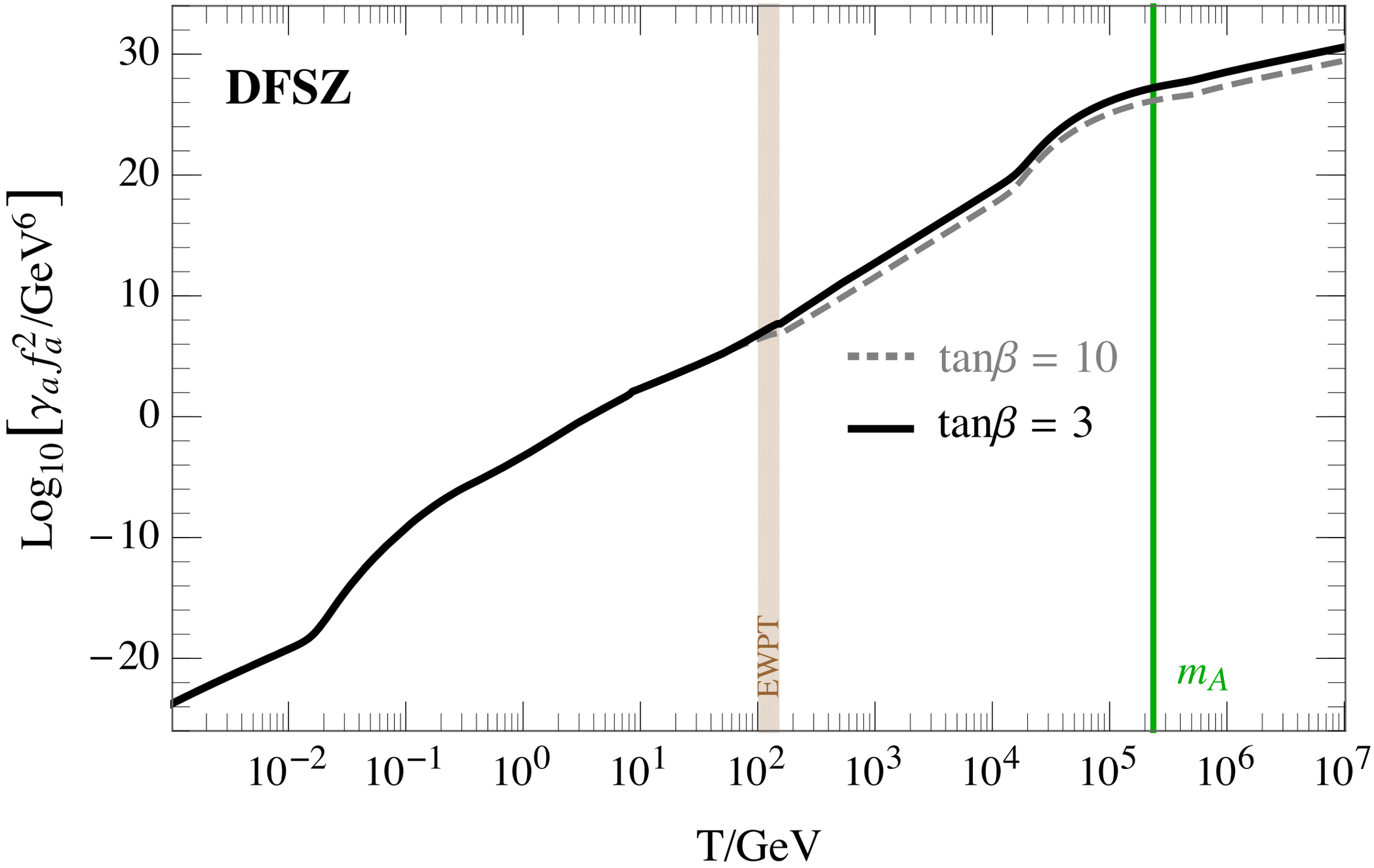
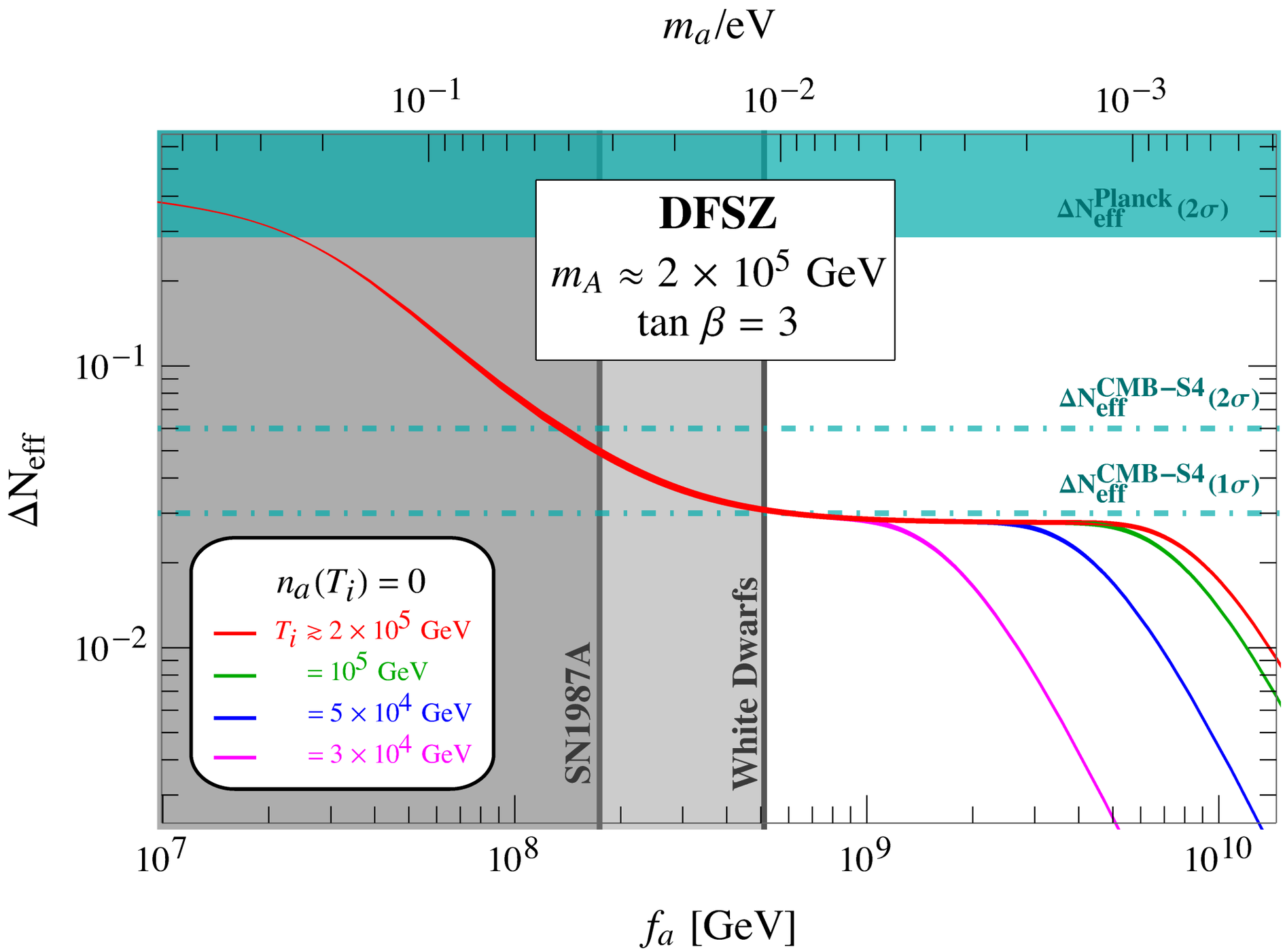
Evolution of DFSZ axion relic density



Hot DFSZ axion relic



DFSZ axion production rate



Hot DFSZ axion relic