Thermal QCD axions across thresholds

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arXiv:2108.04259 & arXiv:2108.05371

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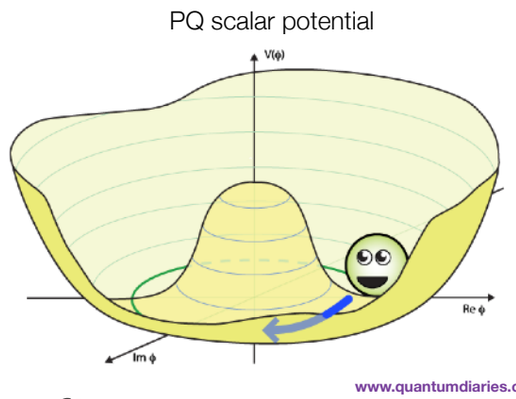
Outline

Axion

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



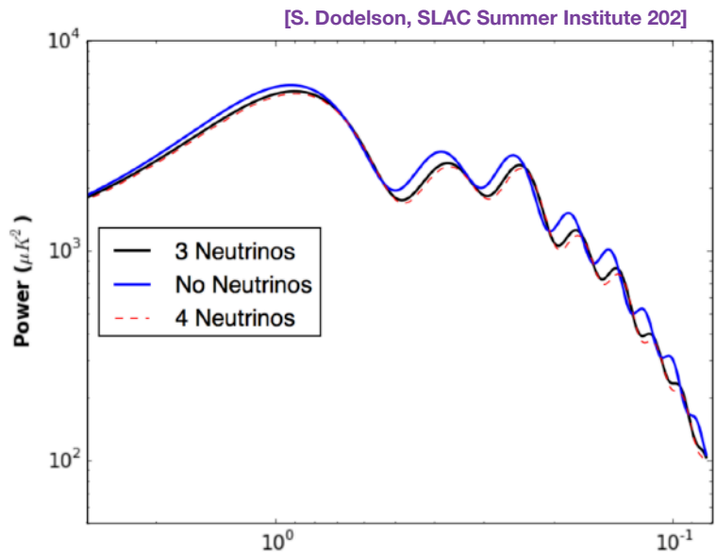
- Global Peccei-Quinn symmetry - Pseudo Nambu-Goldstone boson after spontaneous breaking at f_a
- Mass and coupling proportional to $1/f_a$
- Dark matter candidate; the misalignment mechanism (coherent oscillation)

$$\Omega_a h^2 \approx 0.12 \left(\frac{f_a}{9 \times 10^{11}\,\mathrm{GeV}} \right)^{1.165} F\theta_i^2$$

Axion dark radiation?

- QCD nature → Significant production of thermal axions
- Parametrized by $\Delta N_{\rm eff} \equiv N_{\rm eff} - N_{\rm eff}^{\rm SM}$

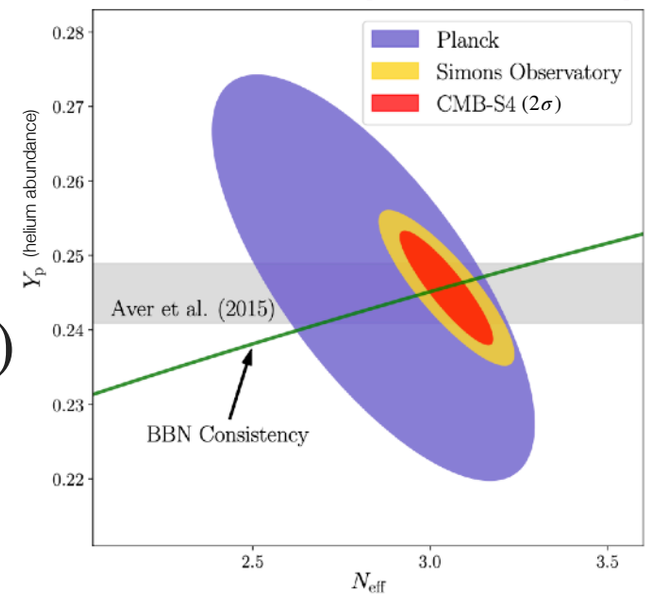
[S. Dodelson, SLAC Summer Institute 202]



- Effect on CMB spectrum
  (e.g. damping tails, changing the scale of matter-radiation equality, location of the first acoustic peak, etc)

- Current bound from Planck $N_{\rm eff} = 2.99 \pm 0.17$
- Future sensitivity from CMB-S4 $\Delta N_{\rm eff} = 0.03\ \ (0.06)$ for $1\sigma\ \ (2\sigma)$

[CMB-S4, arXiv:1907.04473]



Boltzmann equation

- Quantitative tool to track the abundance

$d = 4$ **axion production rate** $\propto T^{4-2n}$ with $d = n$ operator

$$\frac{dn_a}{dt} + 3Hn_a = \gamma_a \left(1 - \frac{n_a}{n_a^{\rm eq}}\right)$$

$$Y_a = \frac{n_a}{s},\ x = \frac{M}{T}$$

$$\rightarrow \frac{dY_a}{d\log x} = \left(1 - \frac{1}{3}\frac{d\log g_{*s}}{d\log x}\right)\frac{\gamma_a}{sH}\left(1 - \frac{Y_a}{Y_a^{\rm eq}}\right)$$

$$\Rightarrow \Delta N_{\rm eff} = \frac{4}{7}\left(\frac{11}{4}\right)^{4/3}\left[\frac{\frac{2\pi^4}{45\xi(3)}g_{*s}^{\rm SM}Y_a^{\infty}}{1 - \frac{2\pi^4}{45\xi(3)}Y_a^{\infty}}\right]$$

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

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

- 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

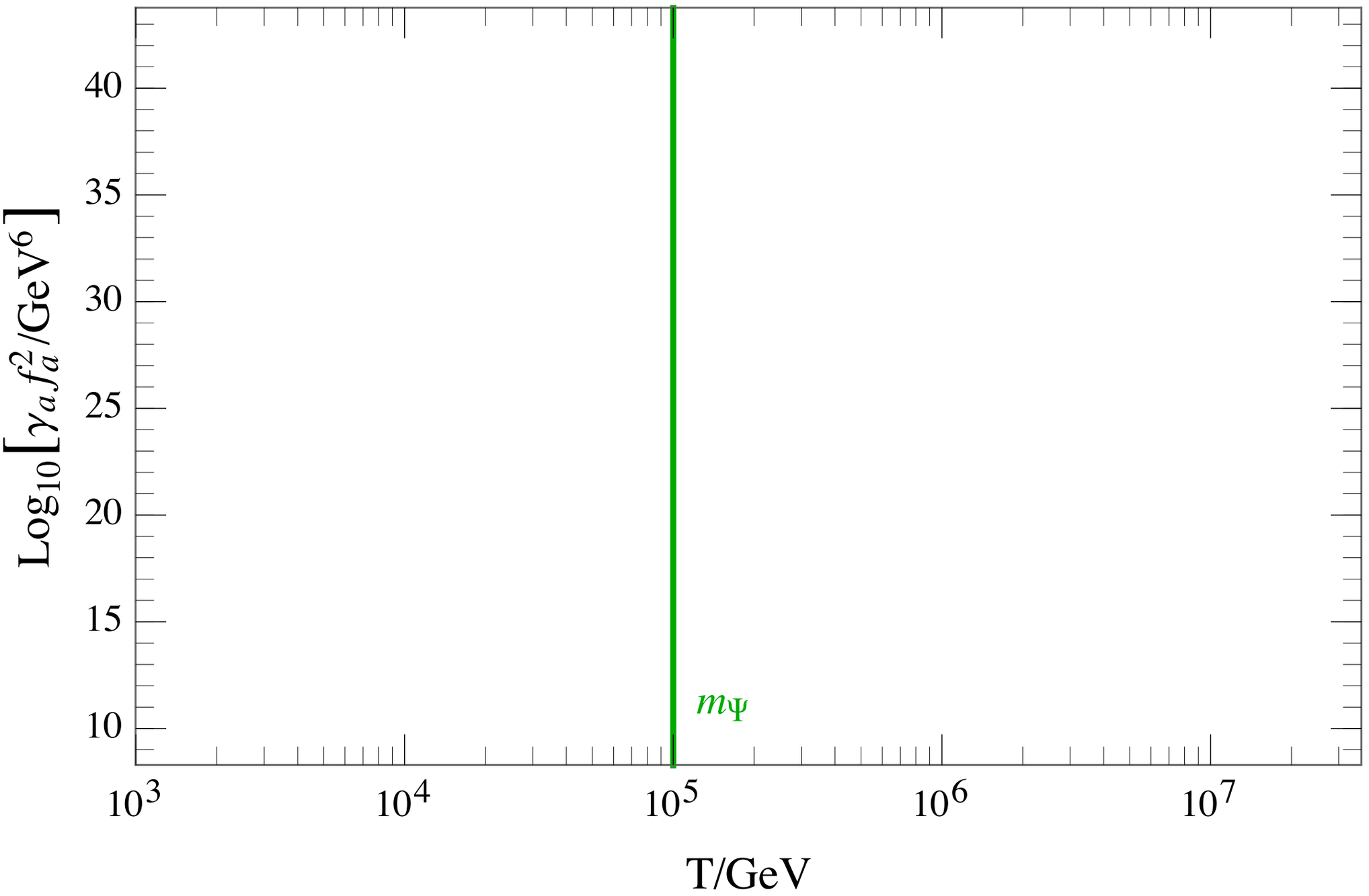
$$\frac{g_s^2}{32\pi^2}\frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

- Two thresholds

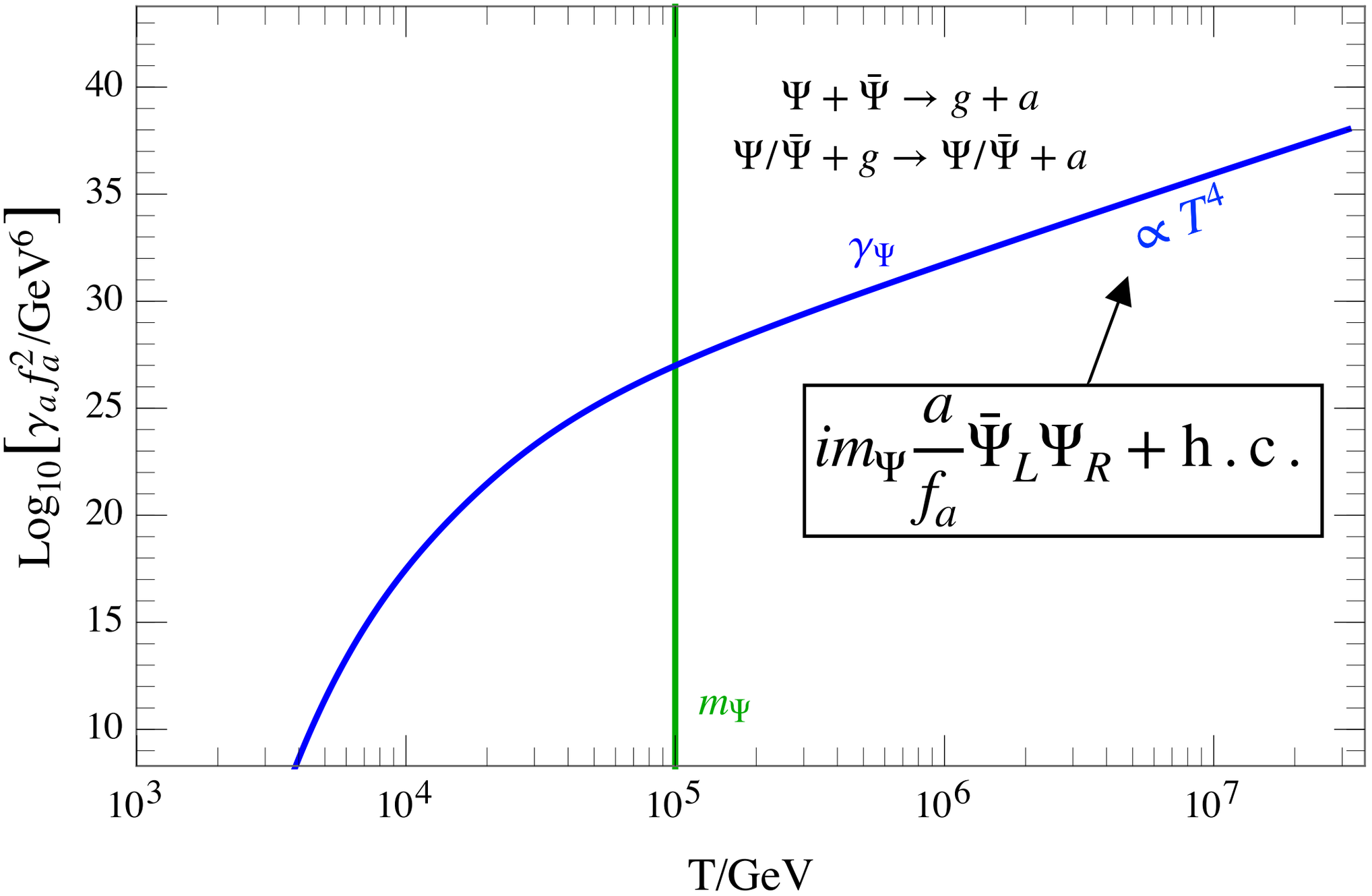
  @ *mass of* $\Psi \equiv m_\Psi$

  @ *QCD confinement*

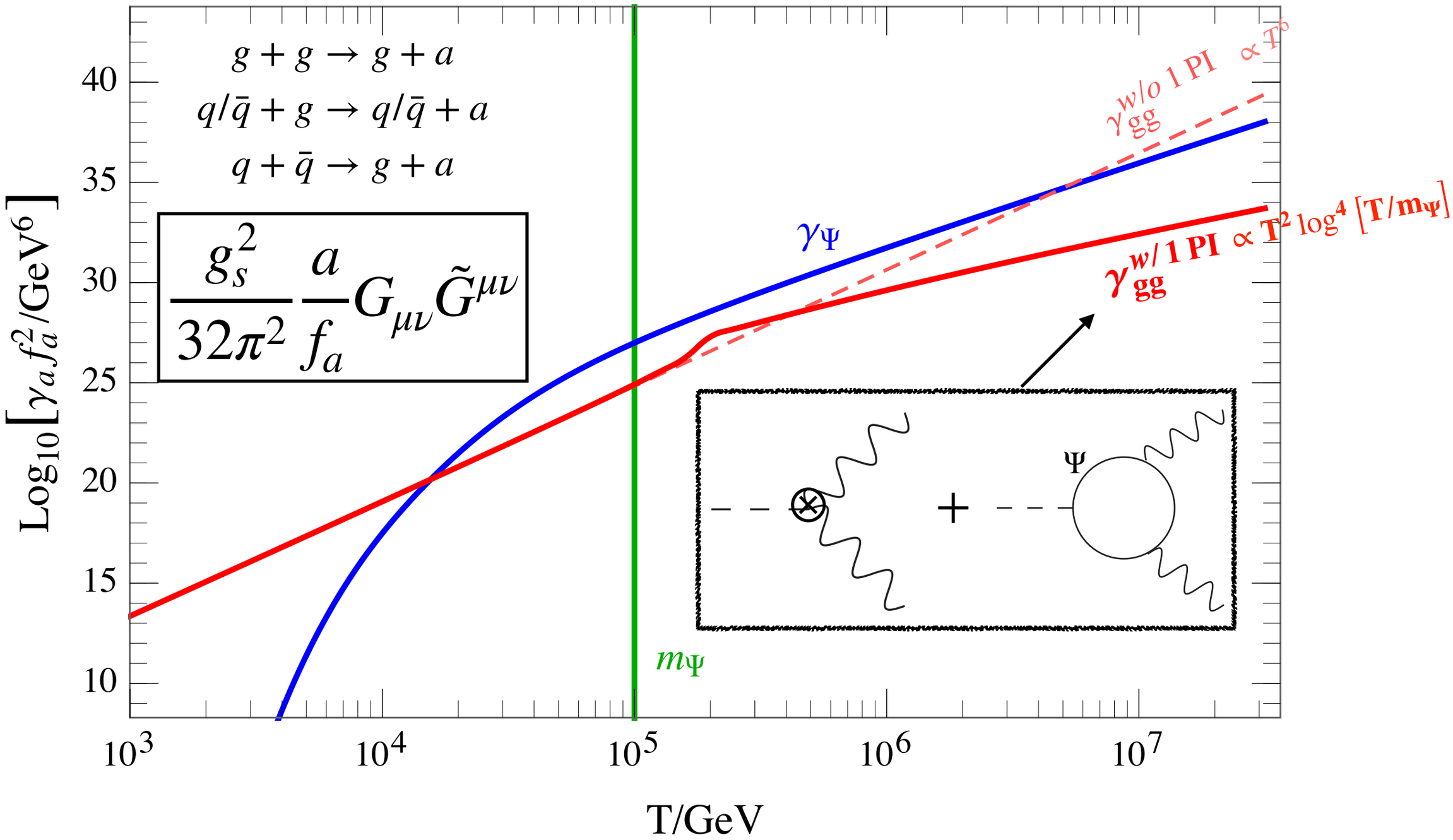
Heavy PQ fermion threshold



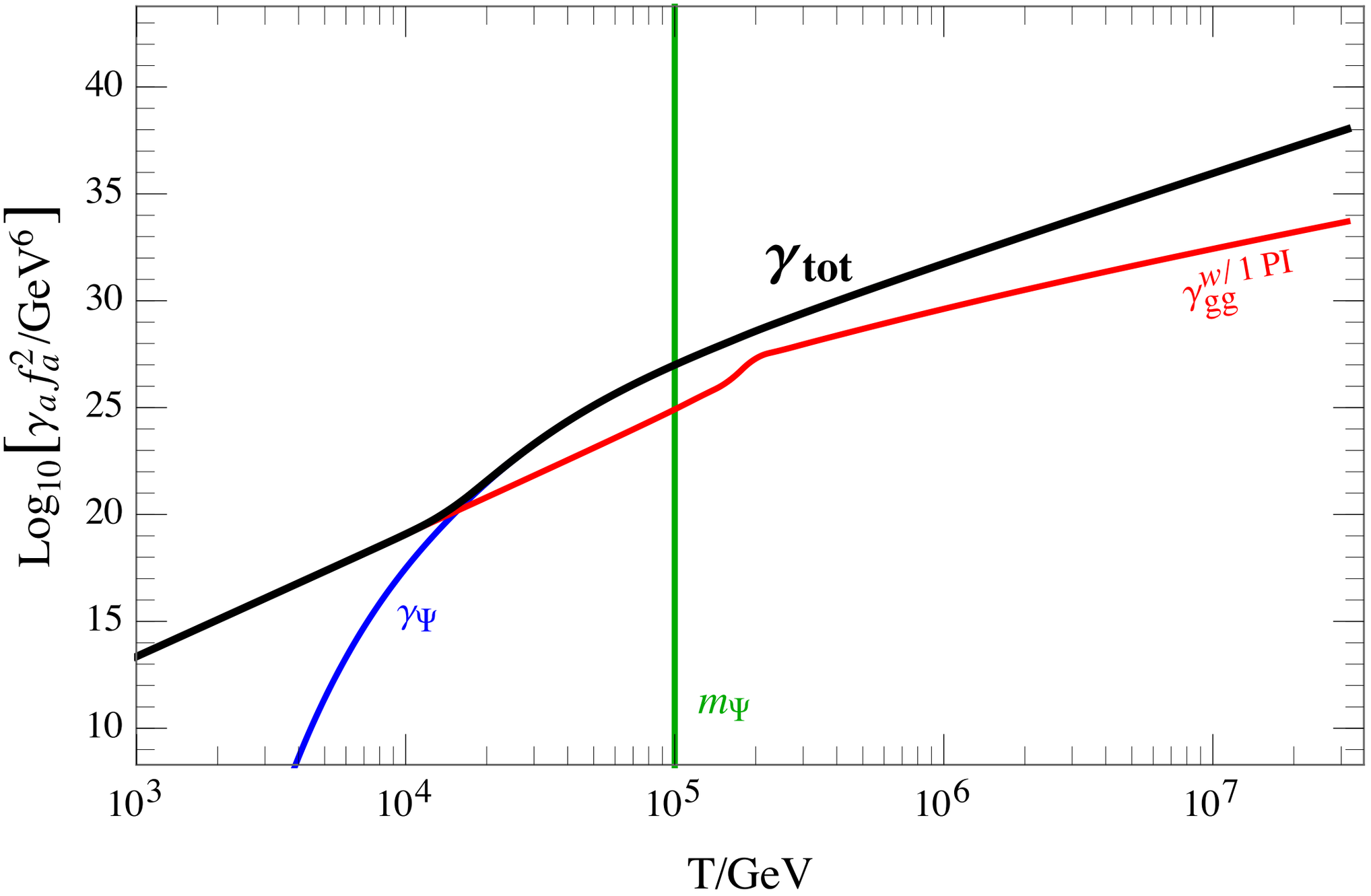
Heavy PQ fermion threshold



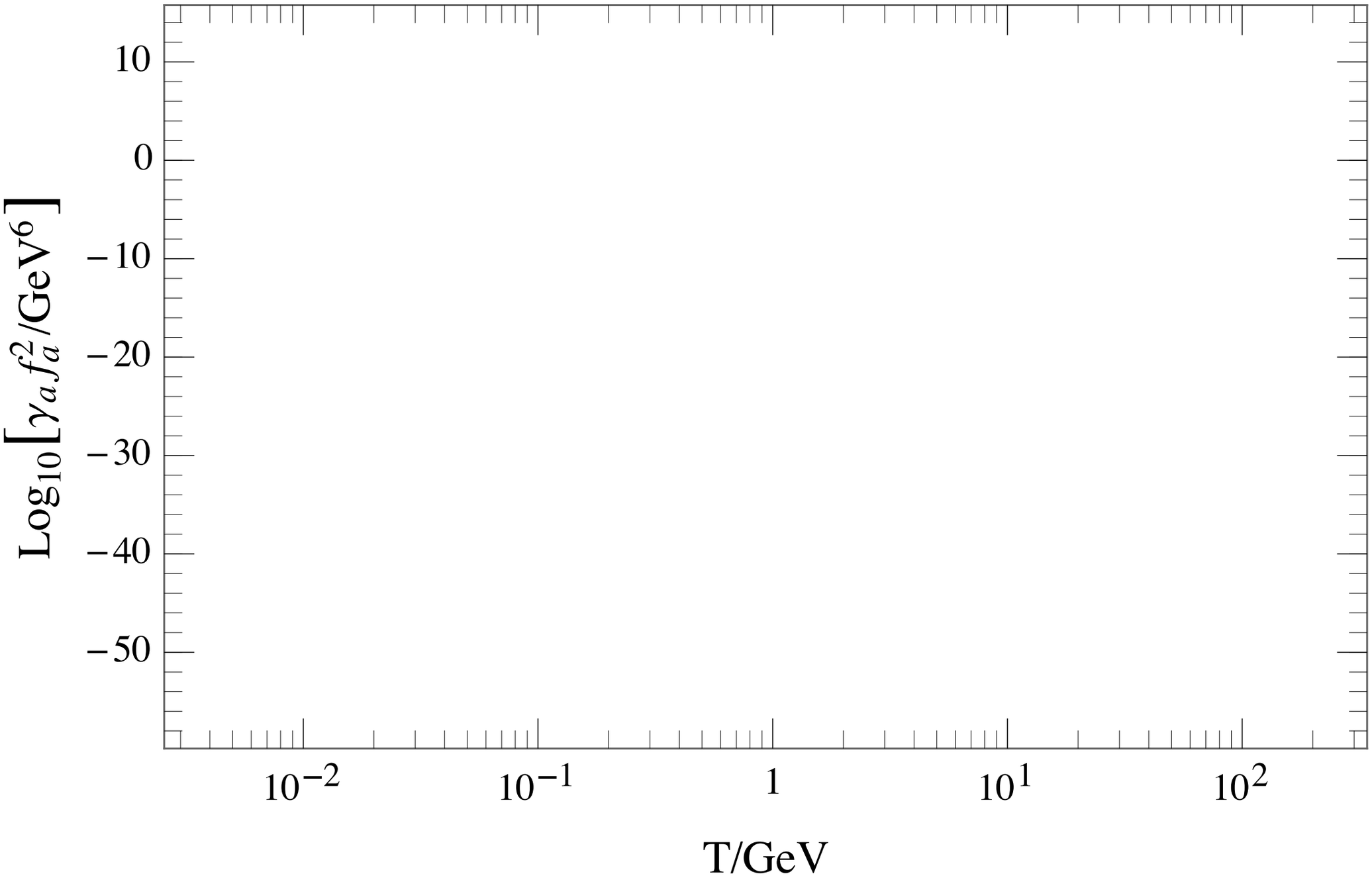
Heavy PQ fermion threshold



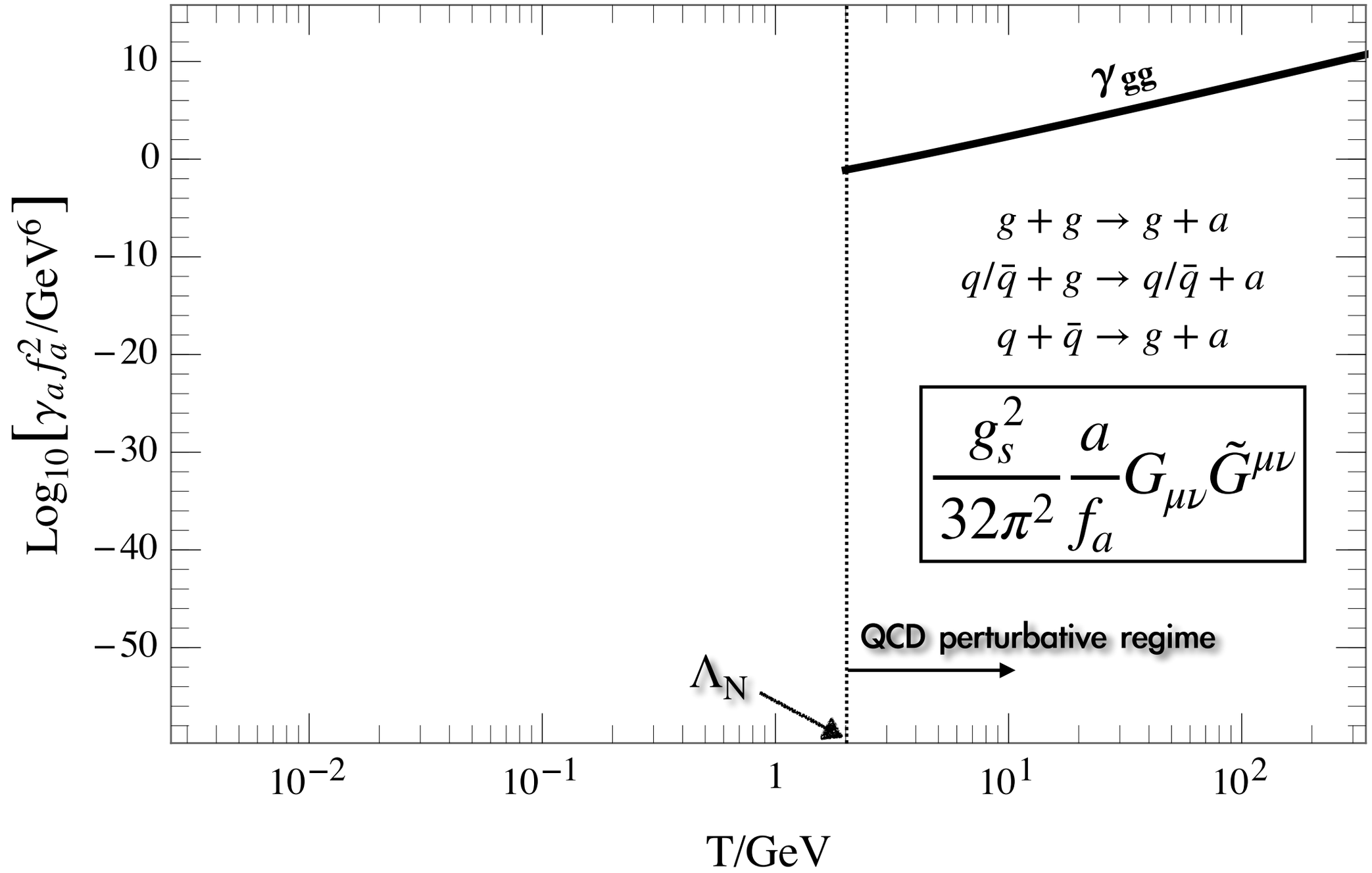
Heavy PQ fermion threshold



QCD threshold

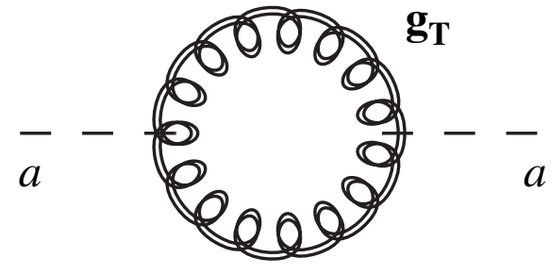


QCD threshold



QCD threshold

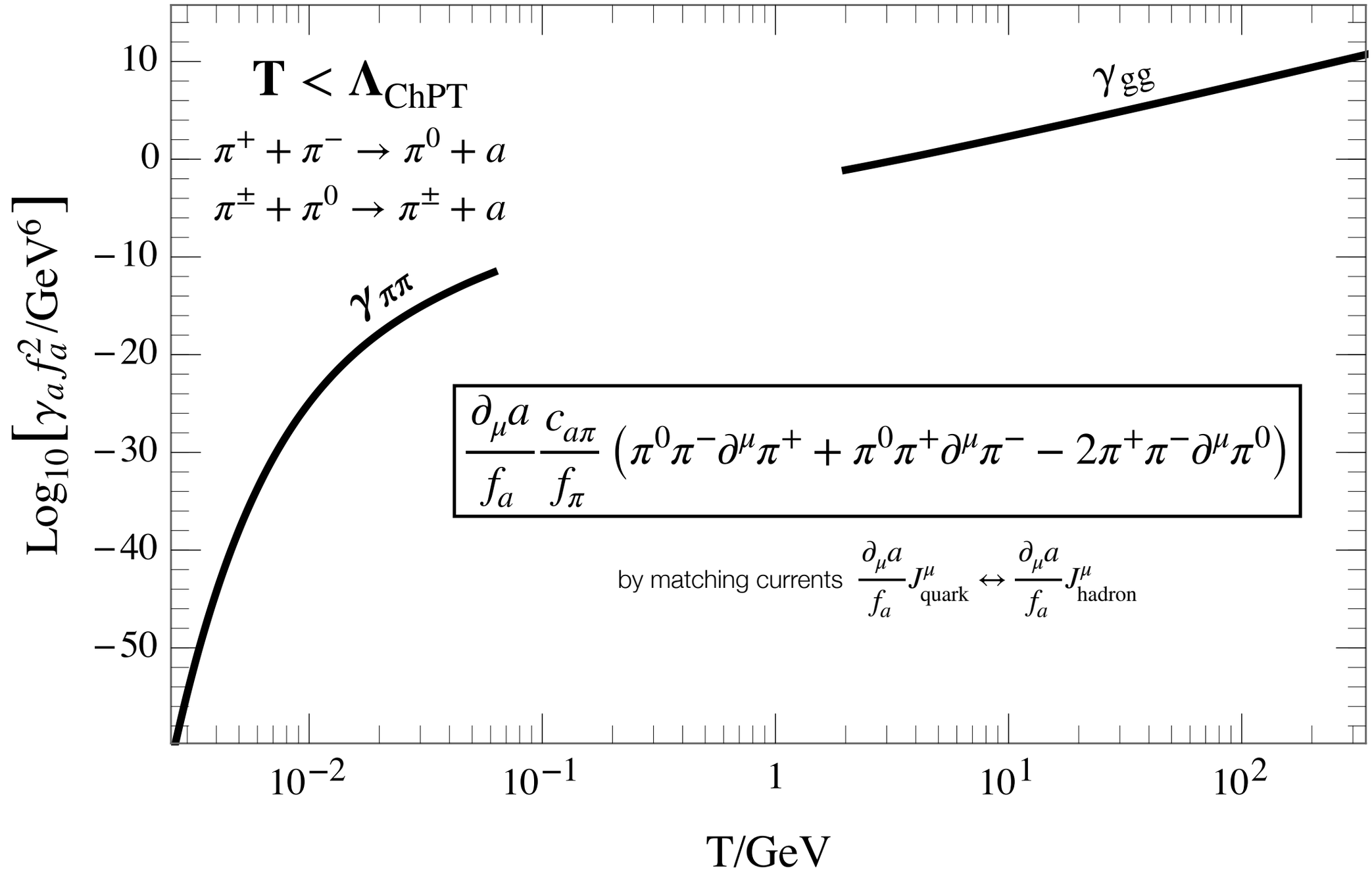
- Long range nature ⇒ IR divergence
- At weak coupling regime, hard thermal loop approximation (i.e. Debye screening)
- Thermal field theory considered properly



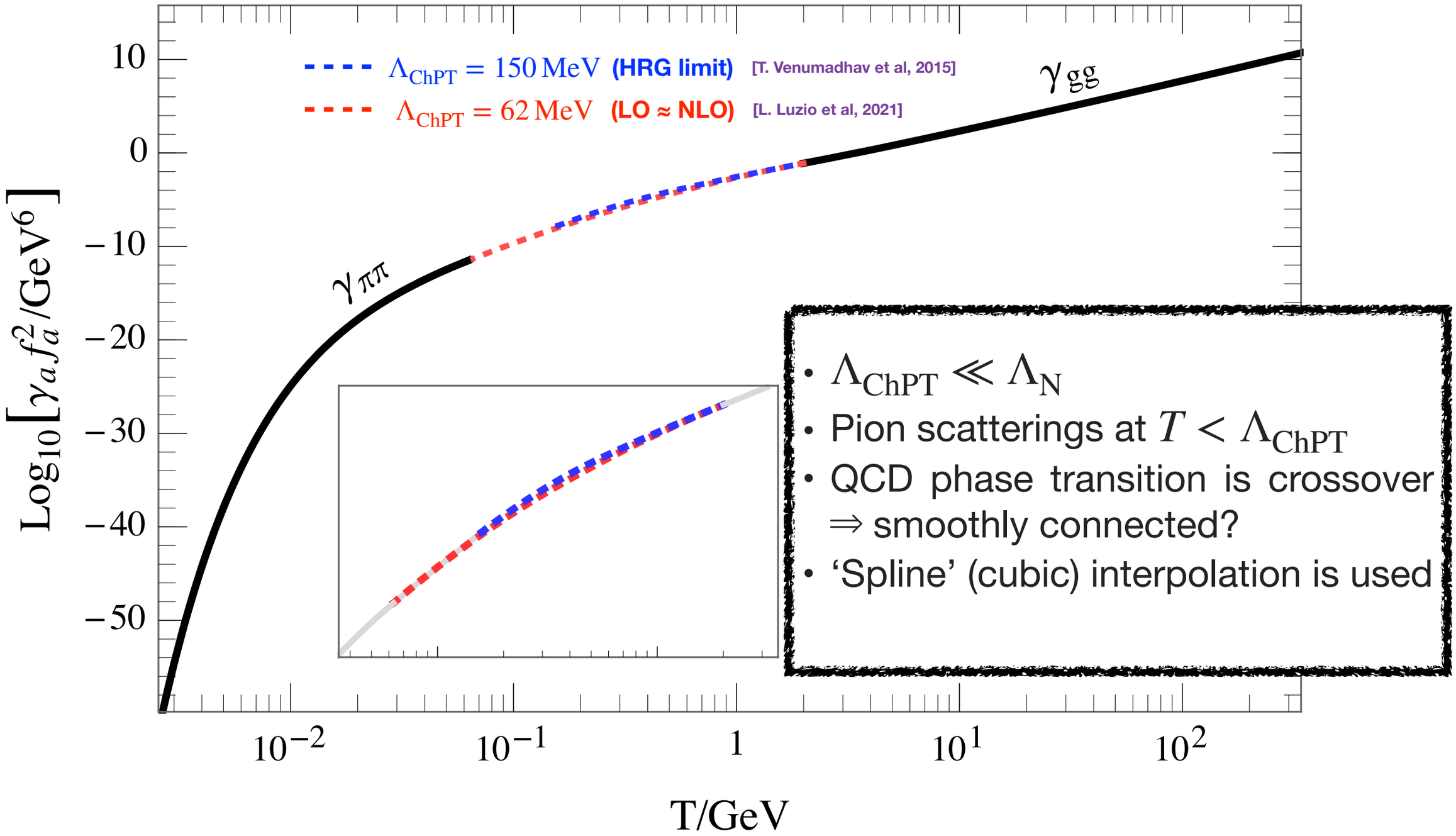
$$g_T \rightarrow g_T + a$$

[A. Salvio et al, 2013]

QCD threshold

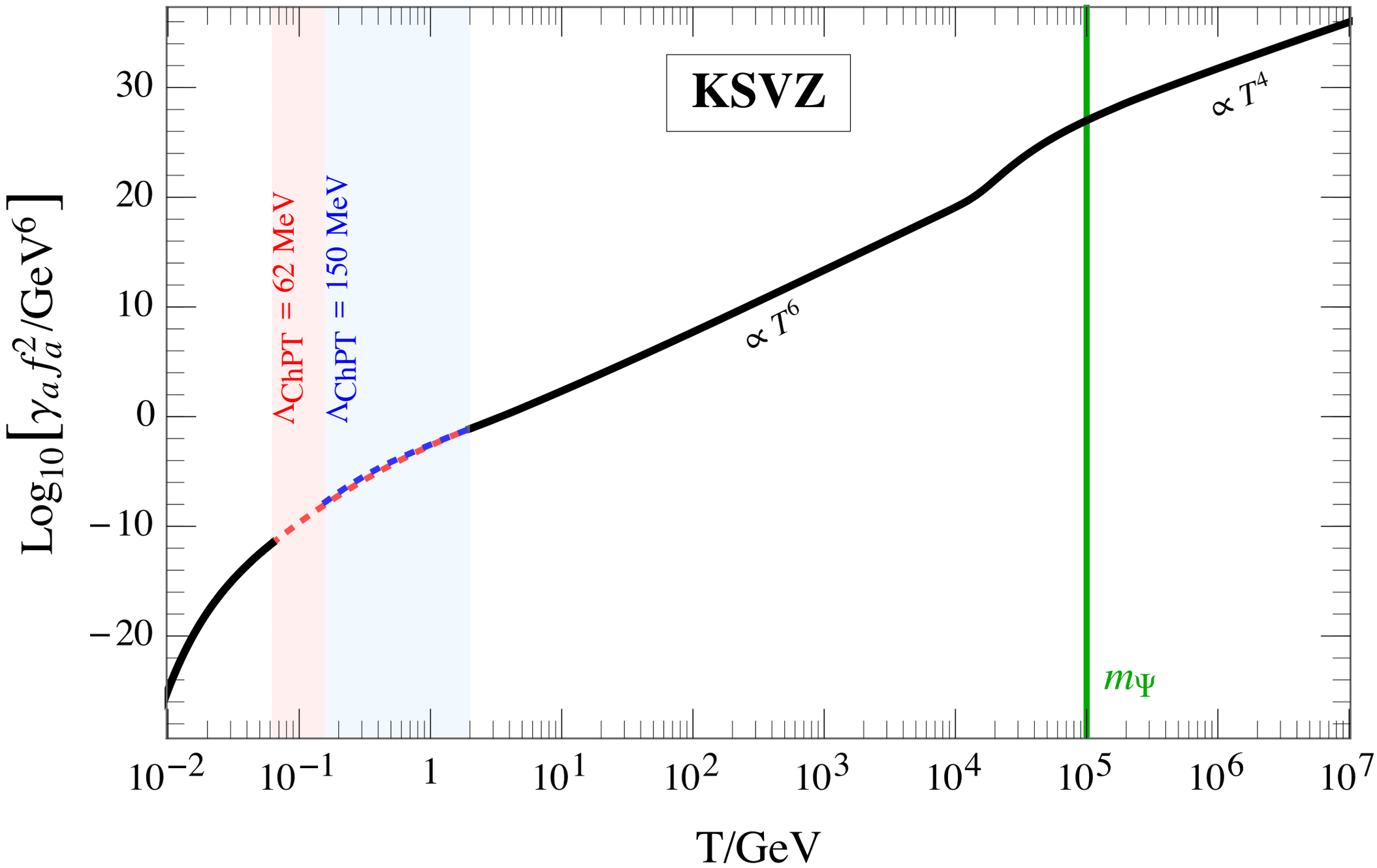


QCD threshold

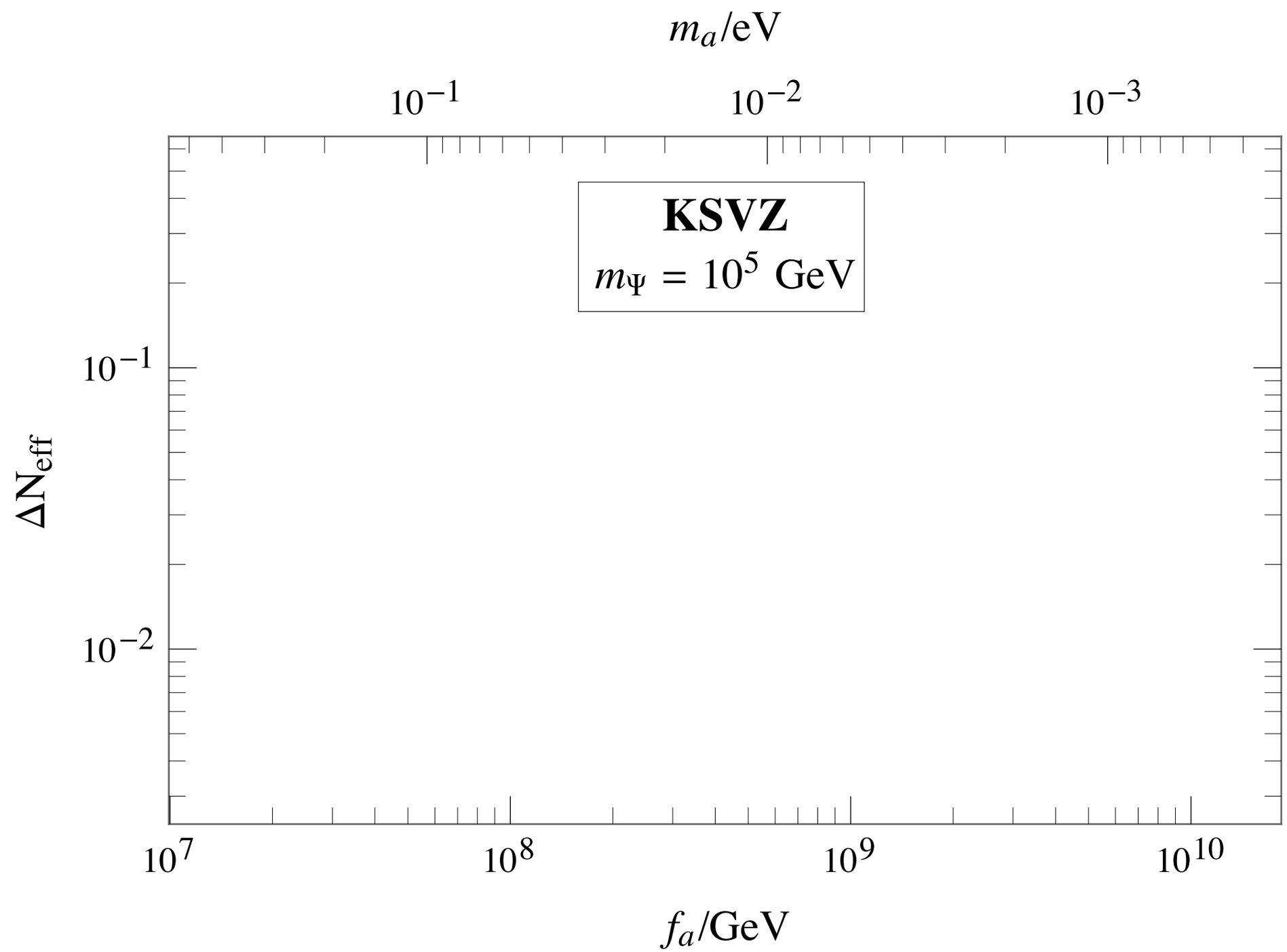


- $\Lambda_{\rm ChPT} \ll \Lambda_{\rm N}$
- Pion scatterings at $T < \Lambda_{\rm ChPT}$
- QCD phase transition is crossover ⇒ smoothly connected?
- ‘Spline’ (cubic) interpolation is used

KSVZ axion production rate



Hot KSVZ axion relic



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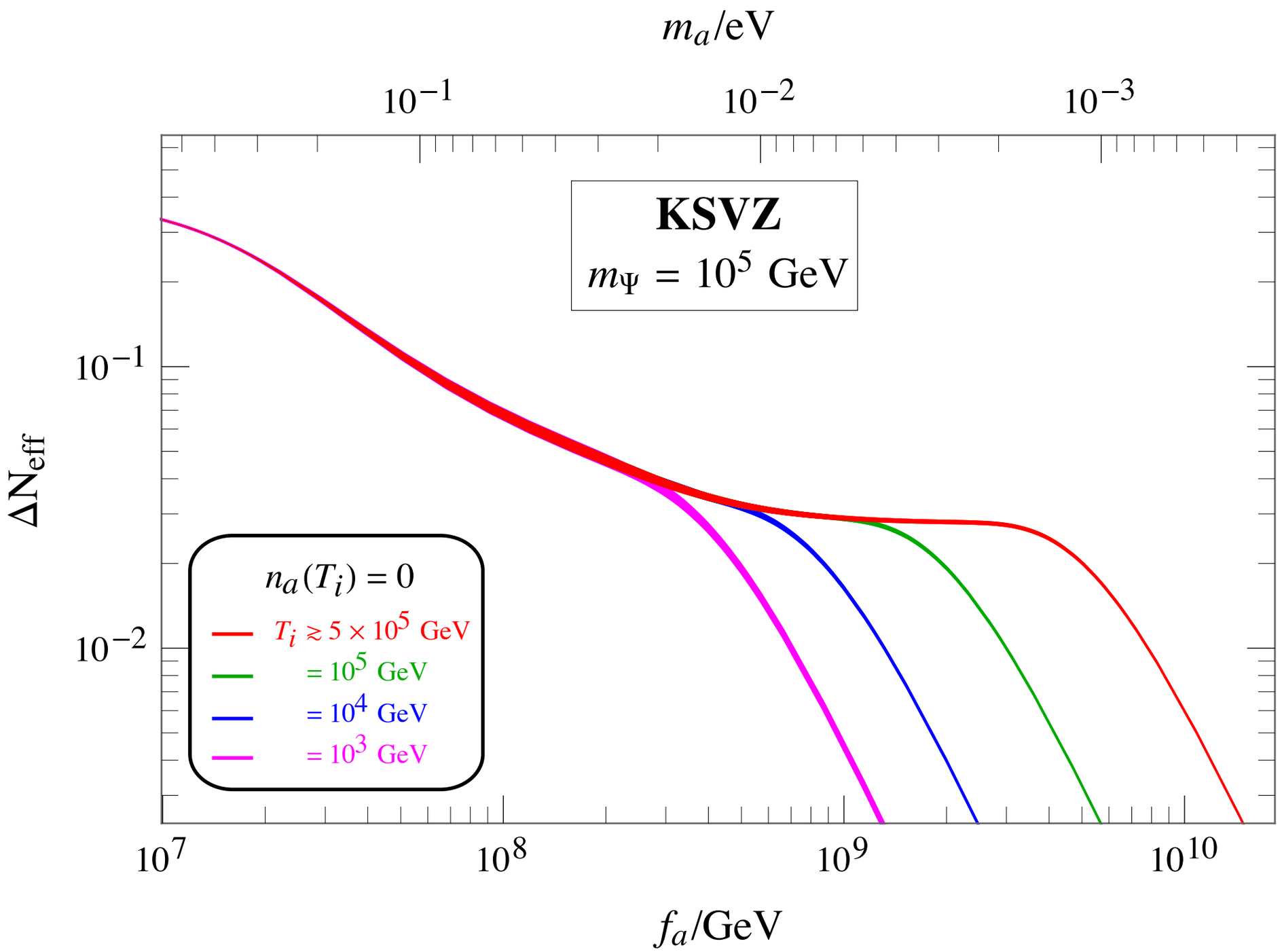

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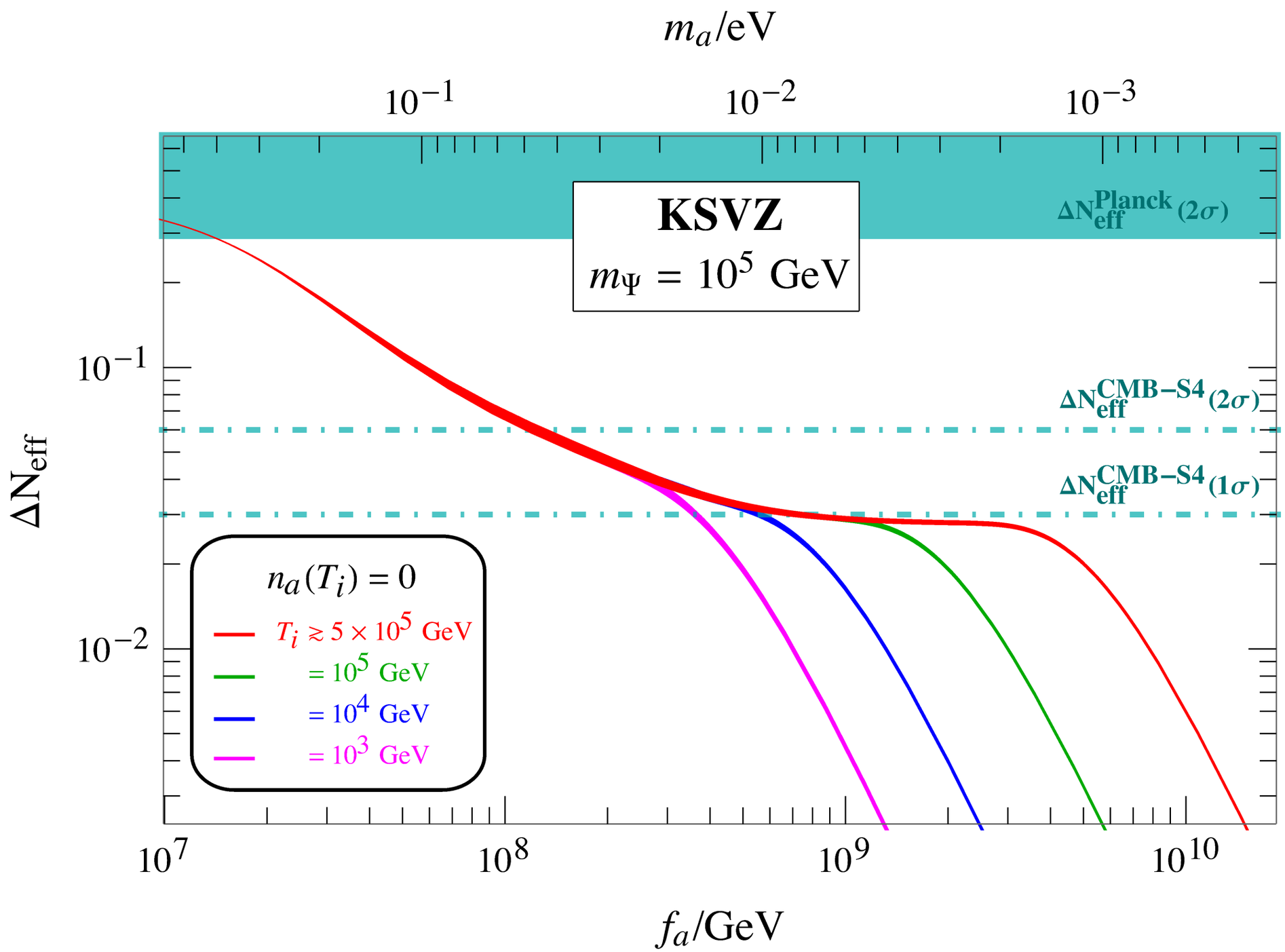

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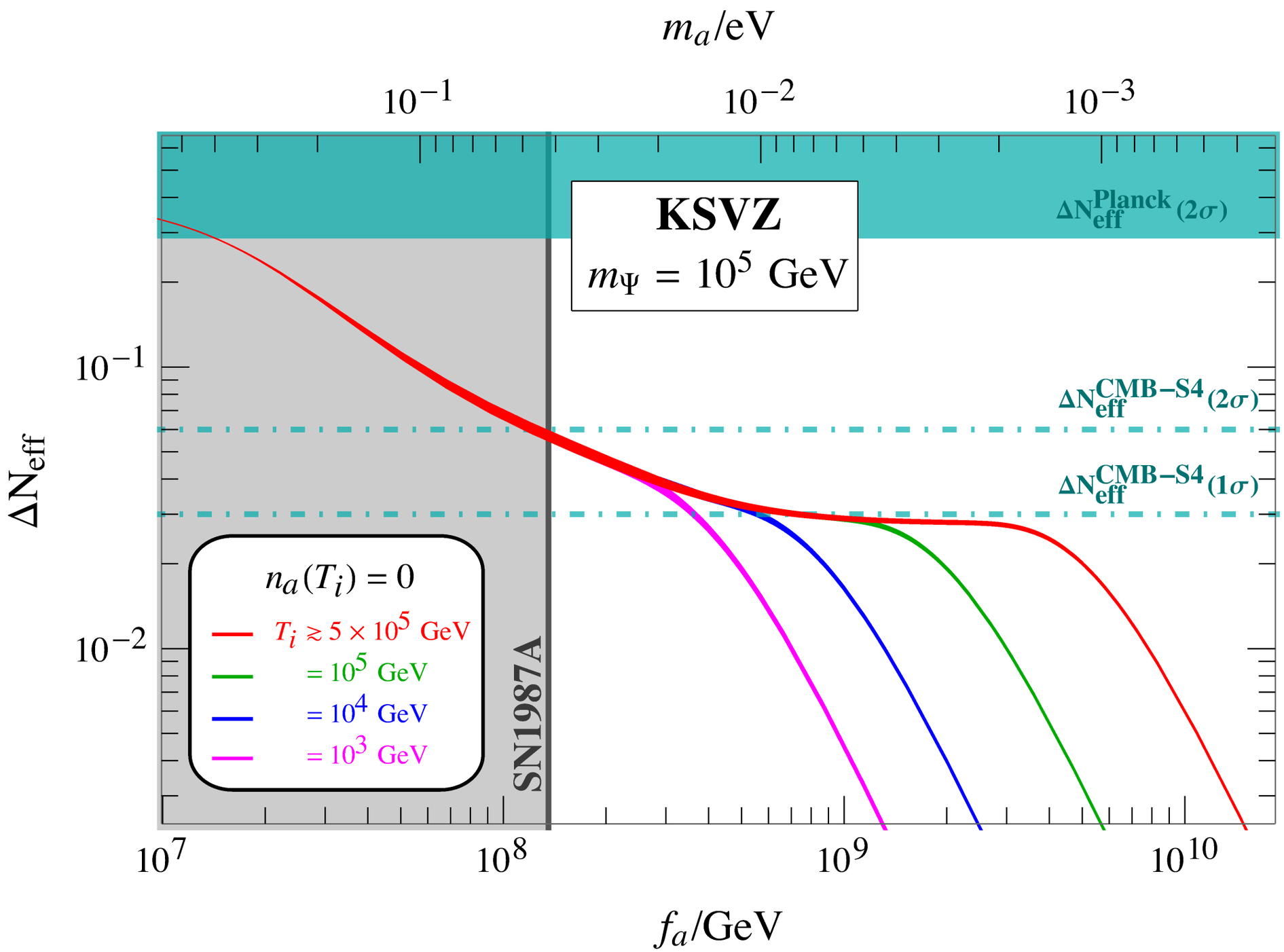
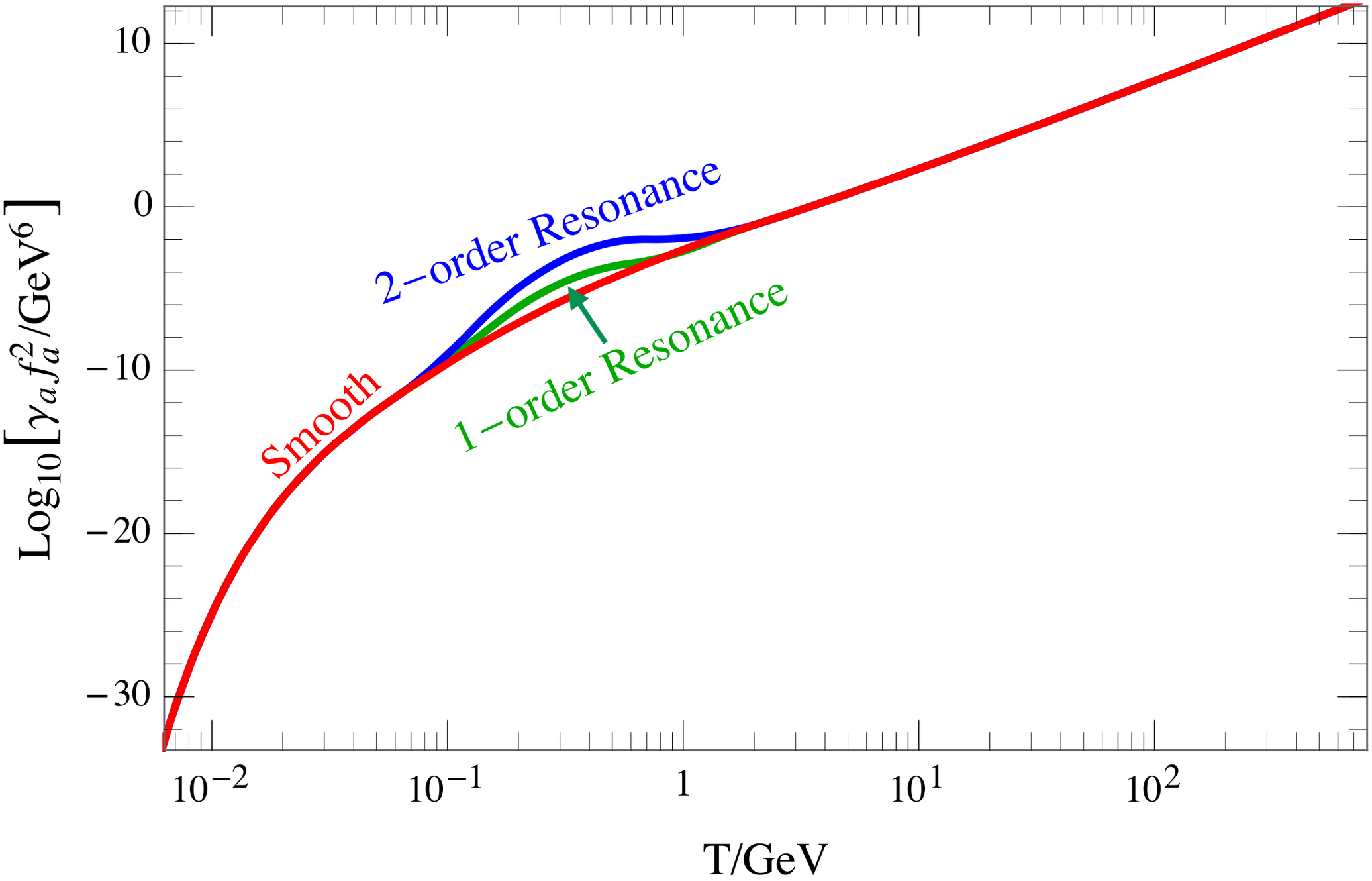


Issue on interpolation?



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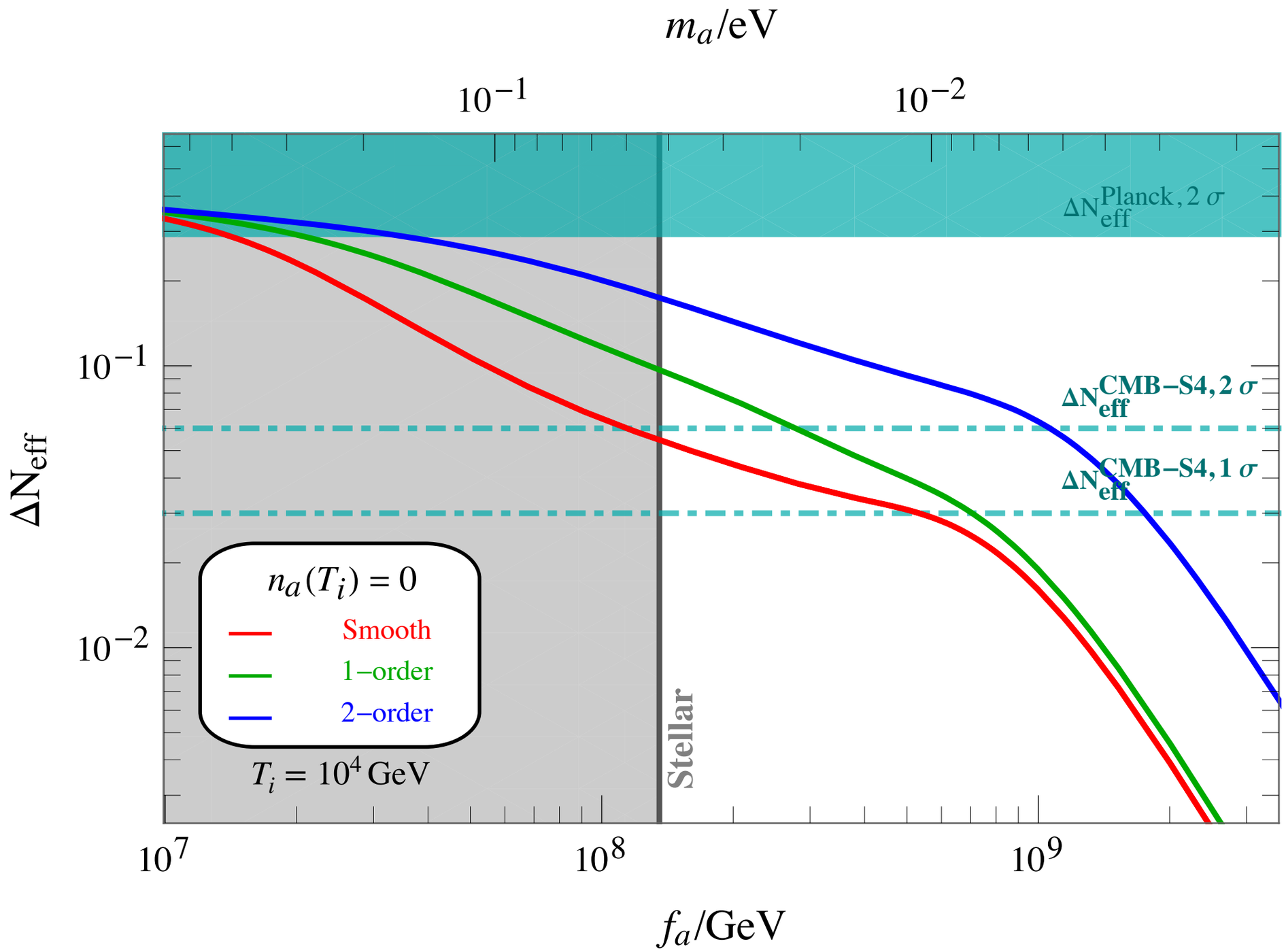


[M. Dine, W. Fischler and M. Srednicki, 1980] [A.R. Zhitnitsky, 1980]

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

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

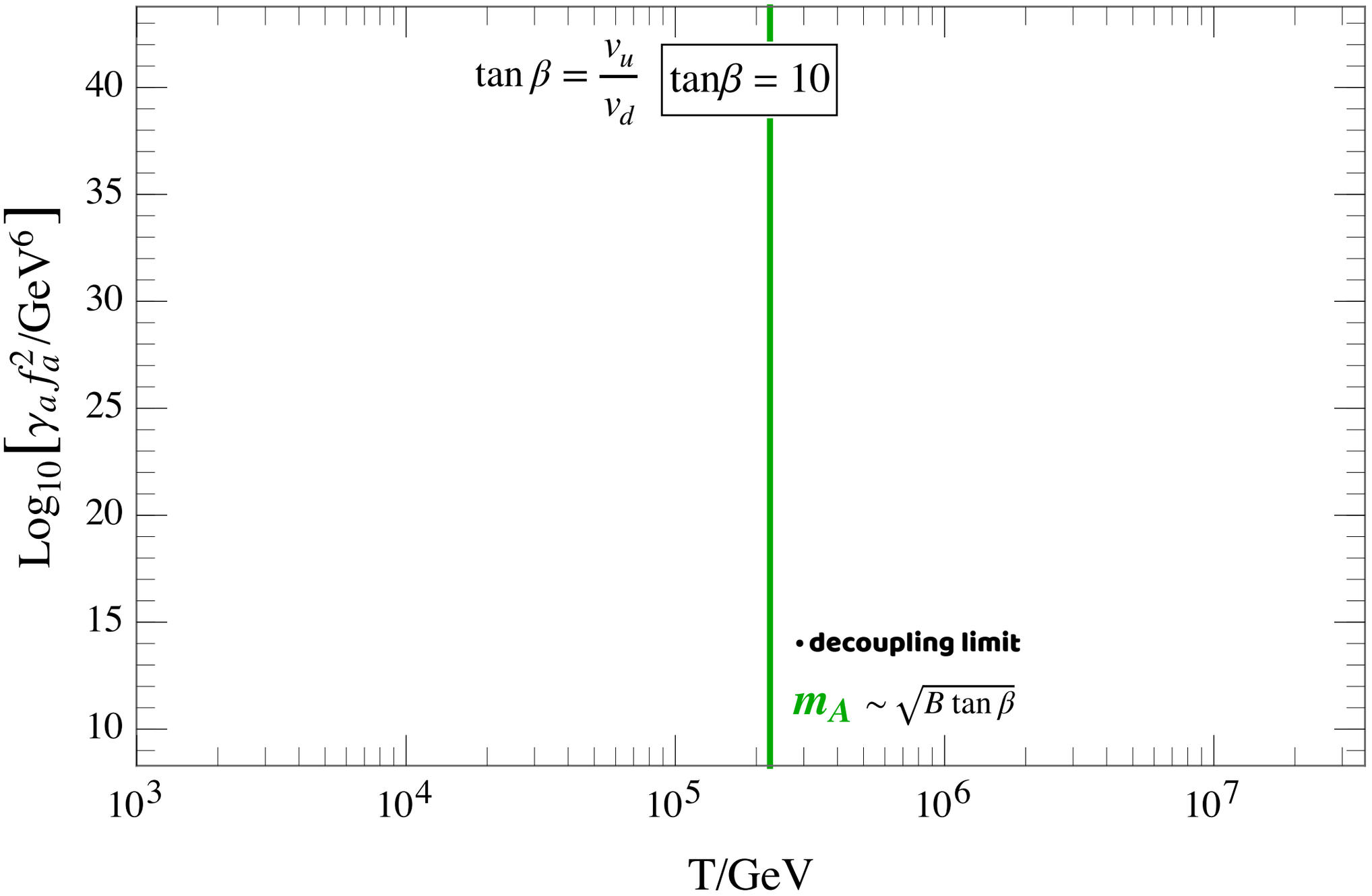
- Two + one thresholds

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

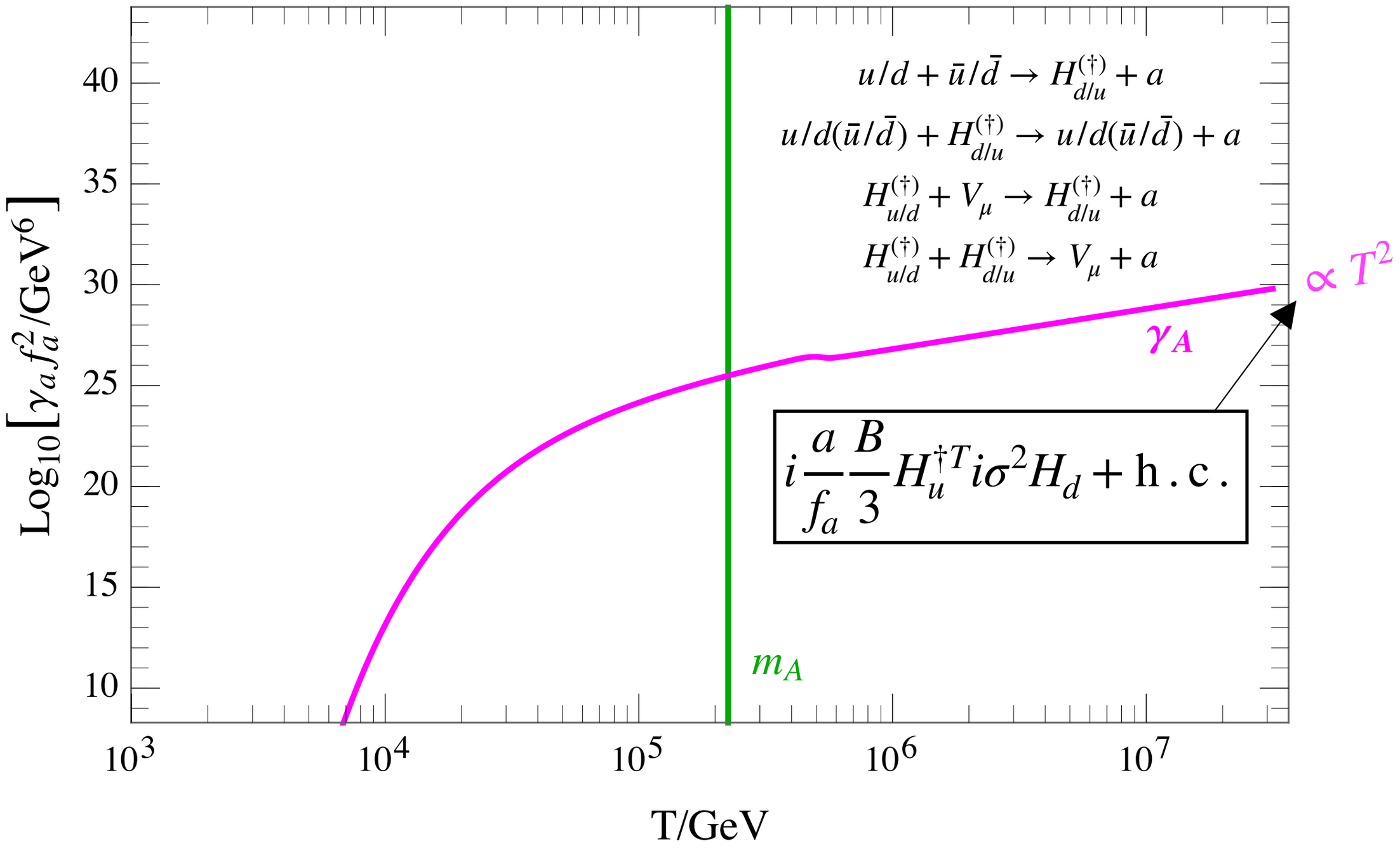
  @ *electroweak phase transition*

  @ *QCD confinement*

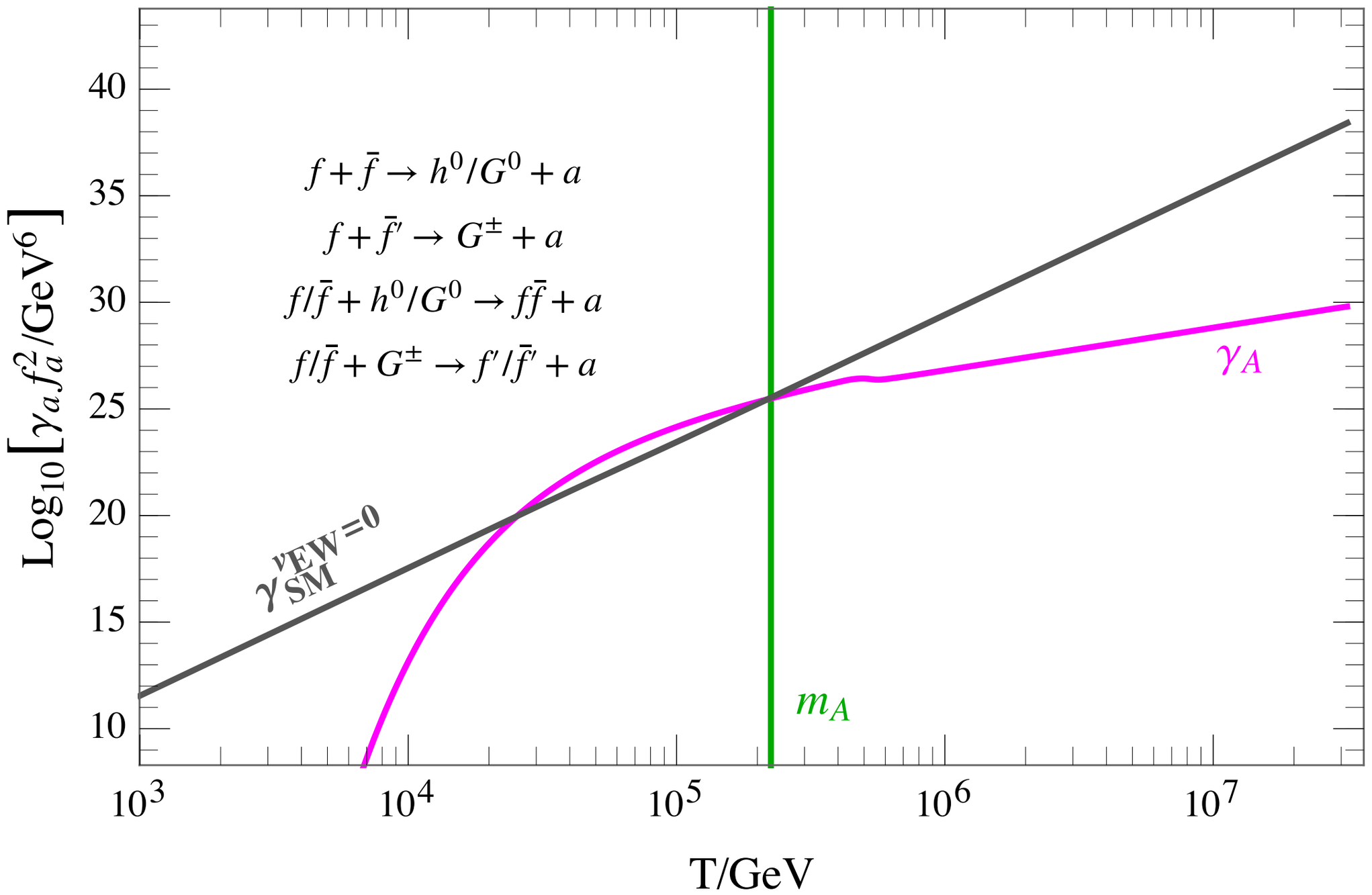
Heavy Higgs boson threshold



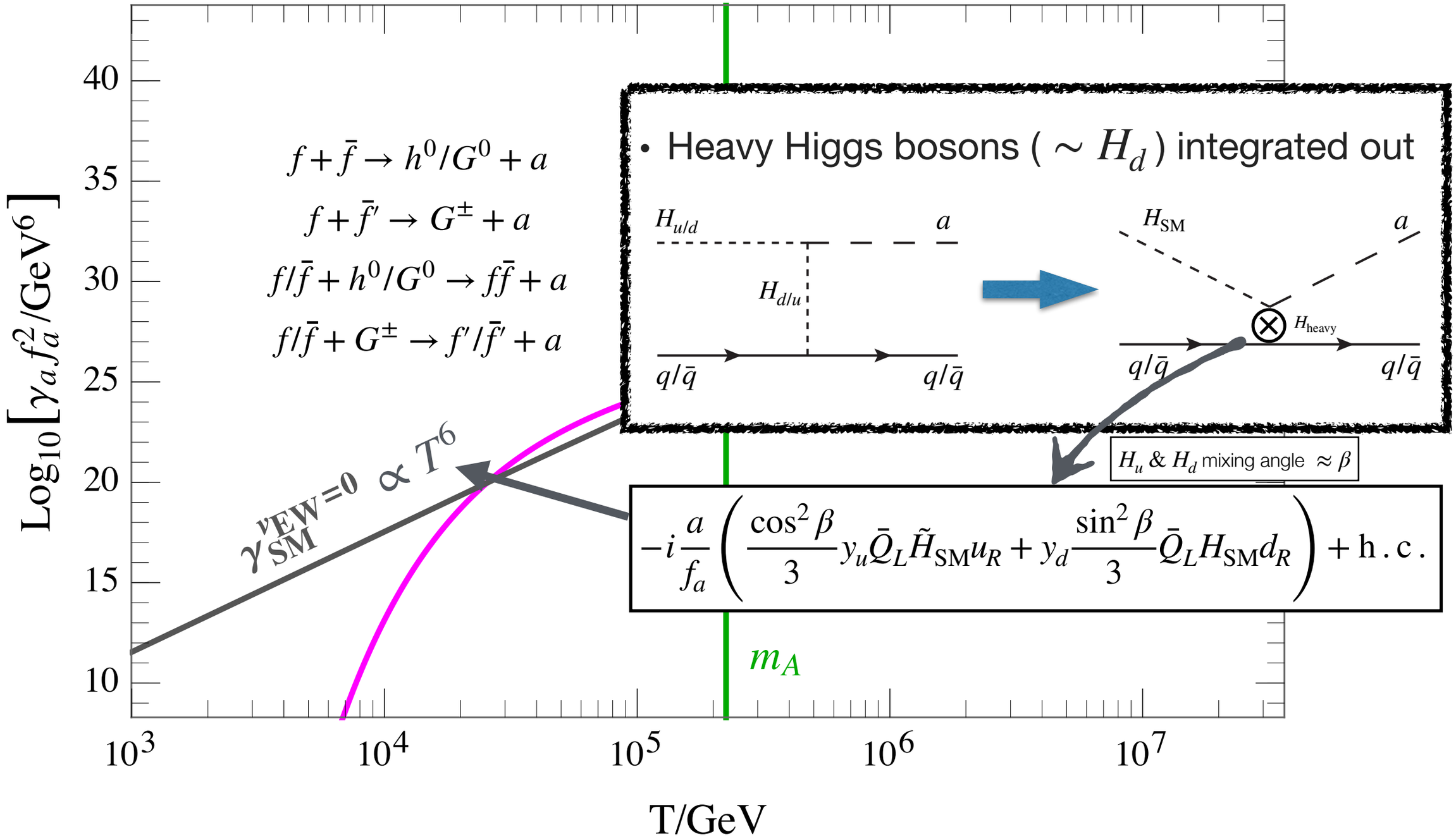
Heavy Higgs boson threshold



Heavy Higgs boson threshold



Heavy Higgs boson threshold



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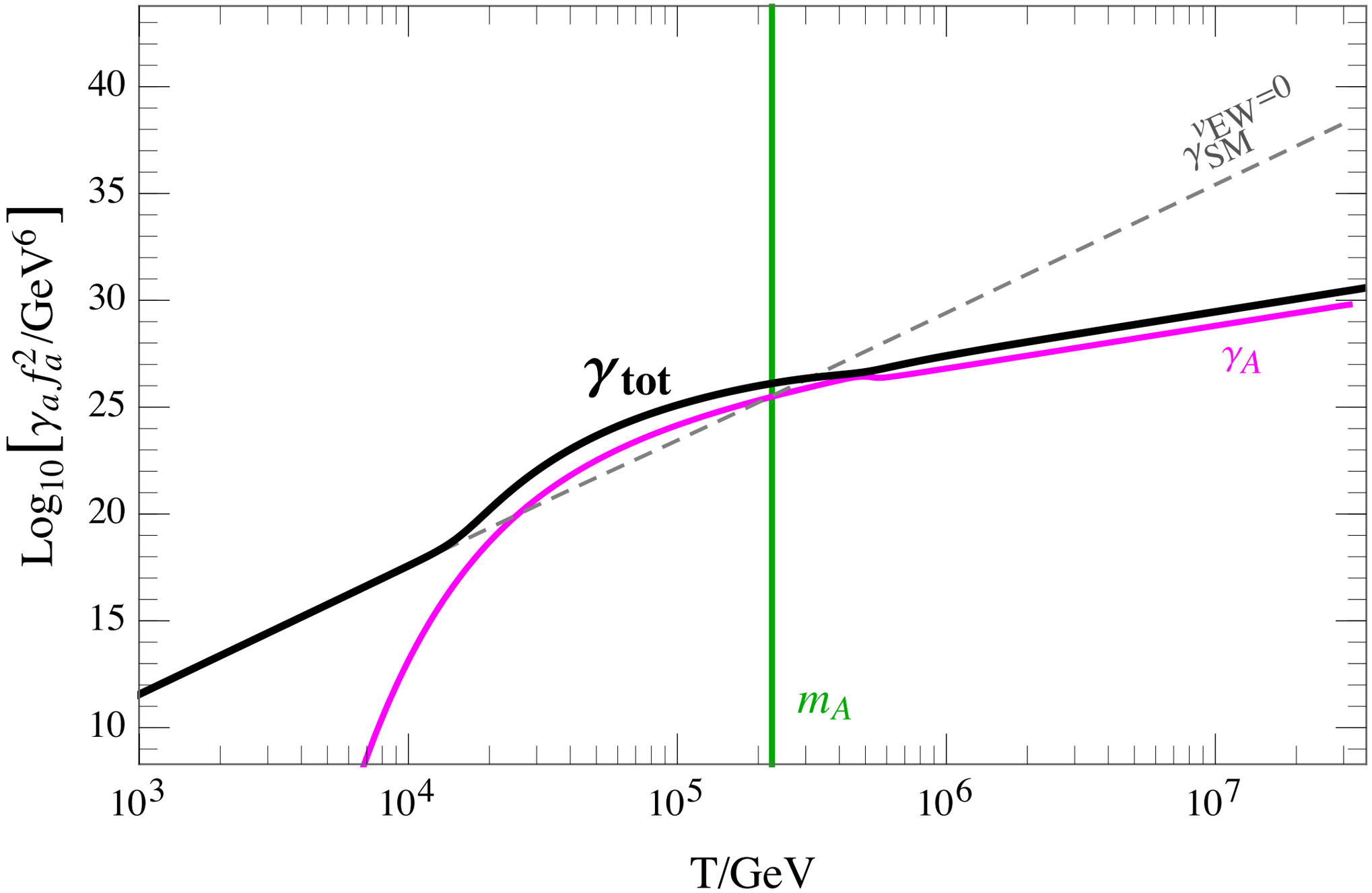
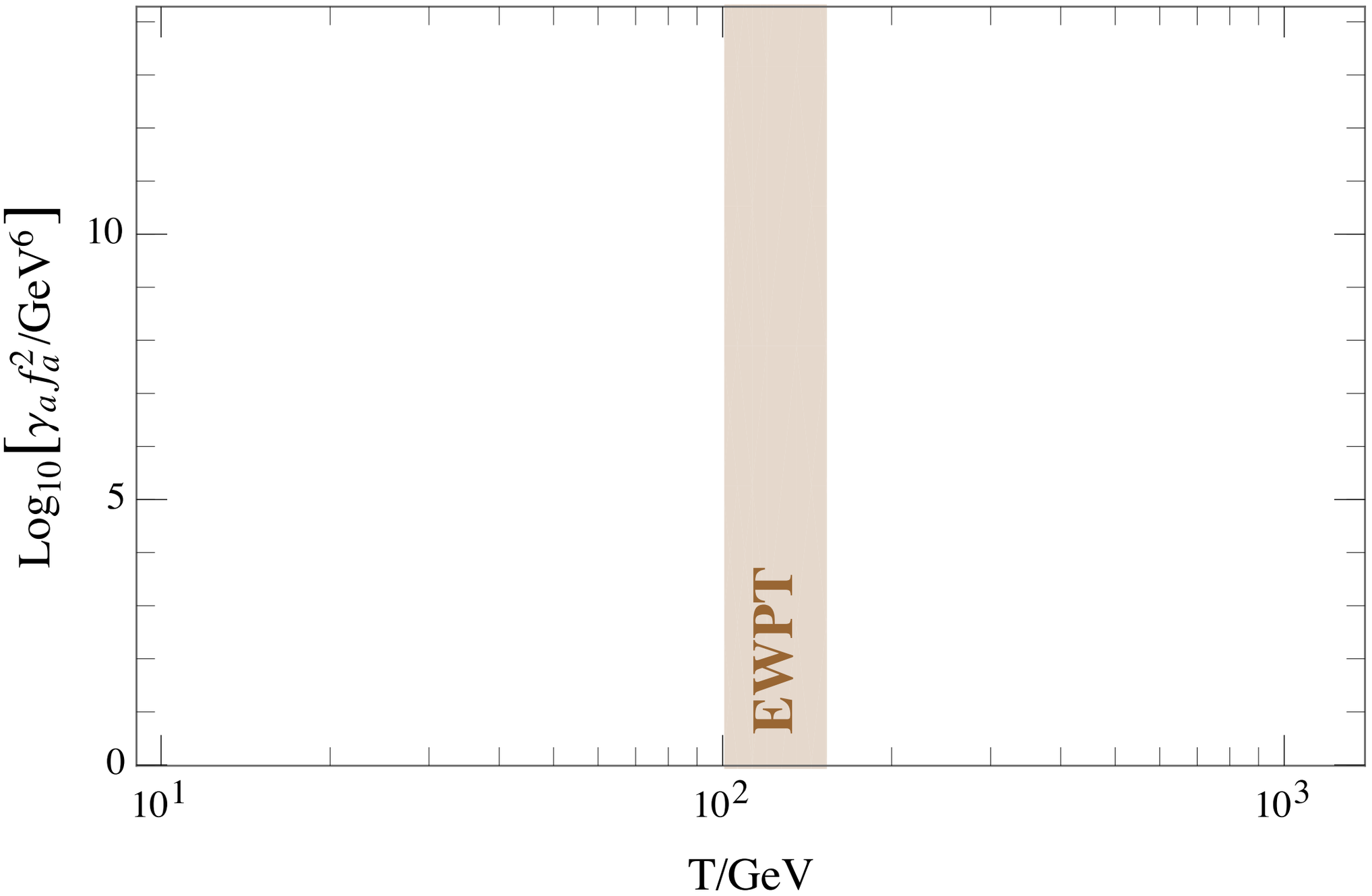
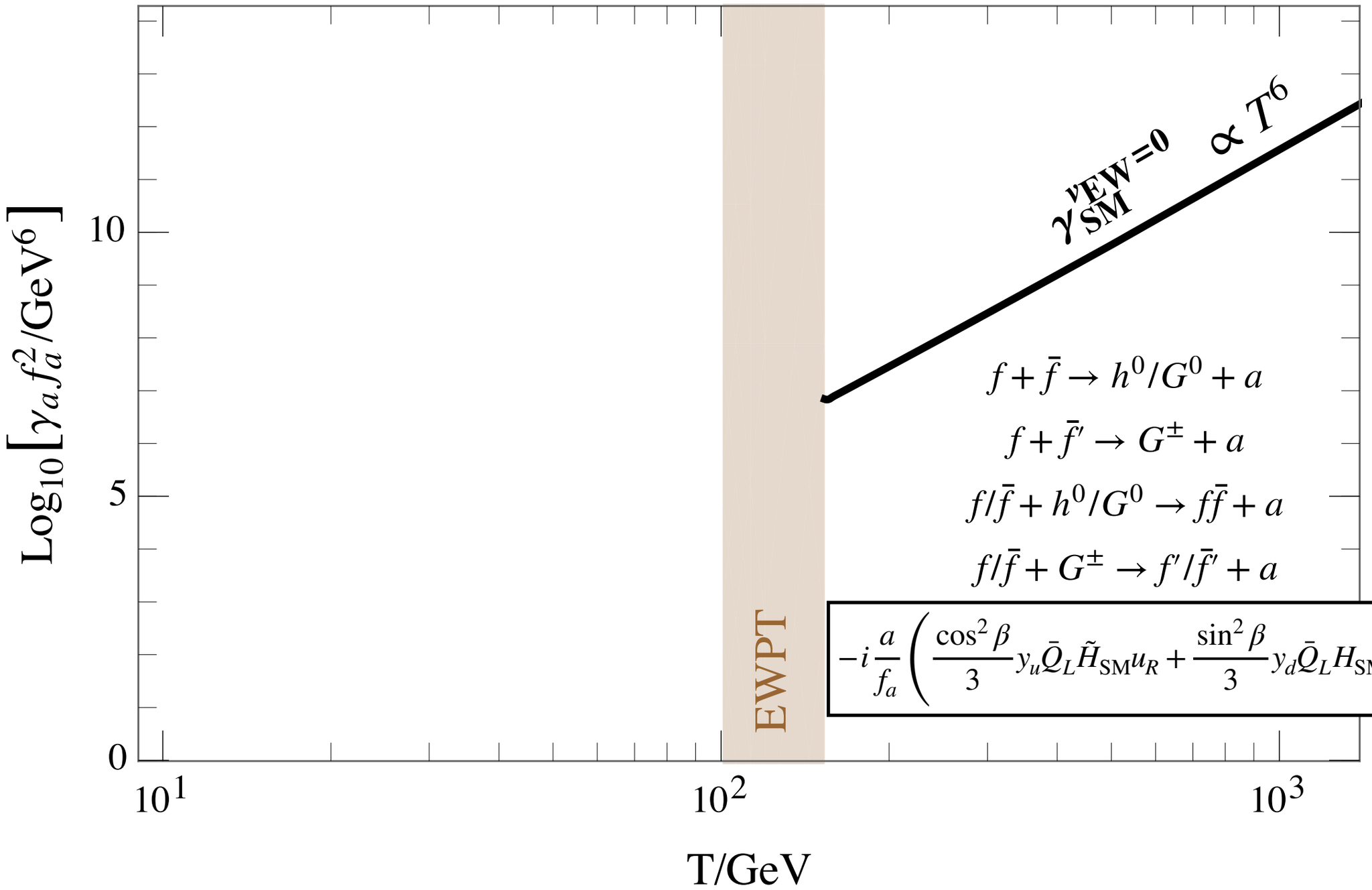


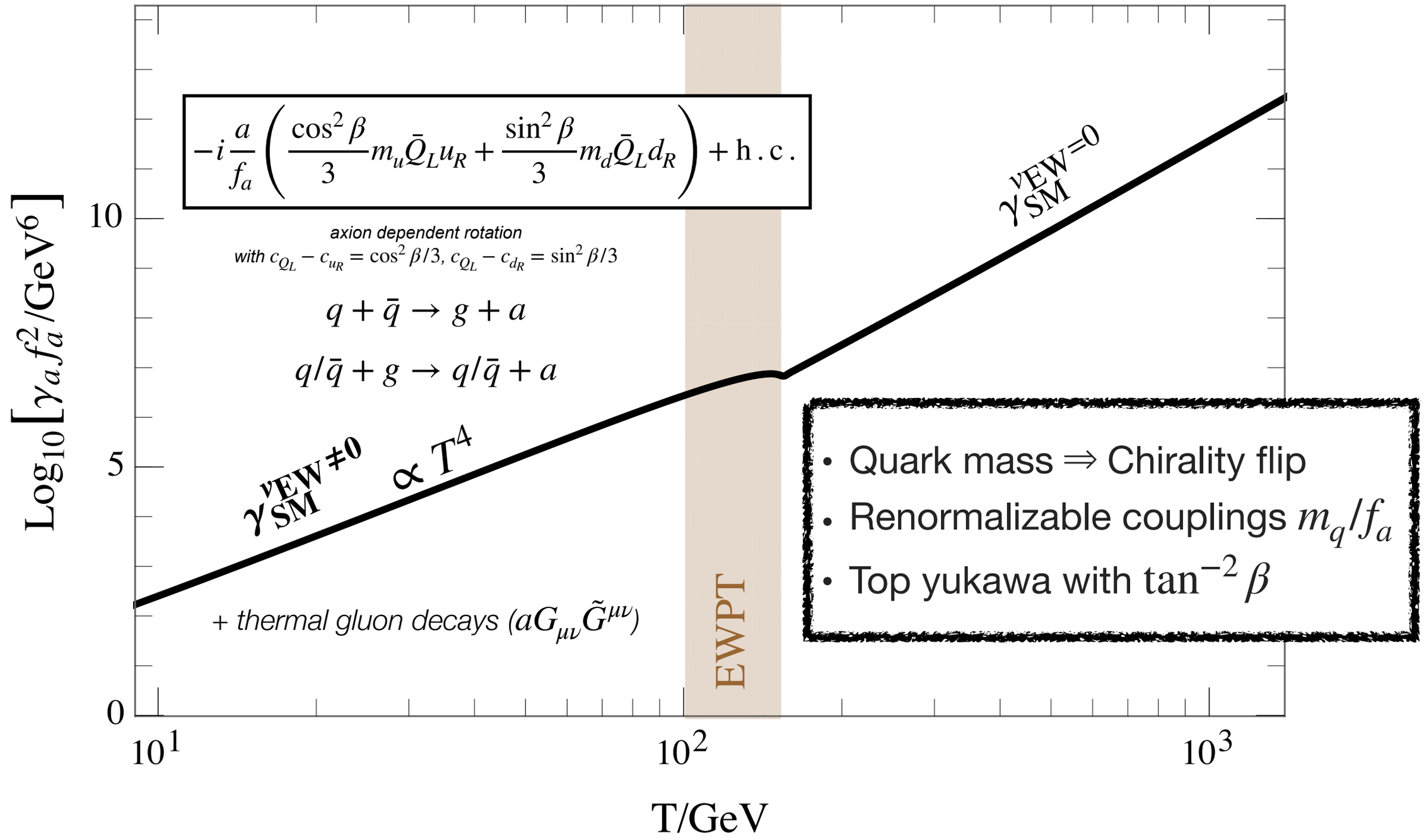
Electroweak threshold



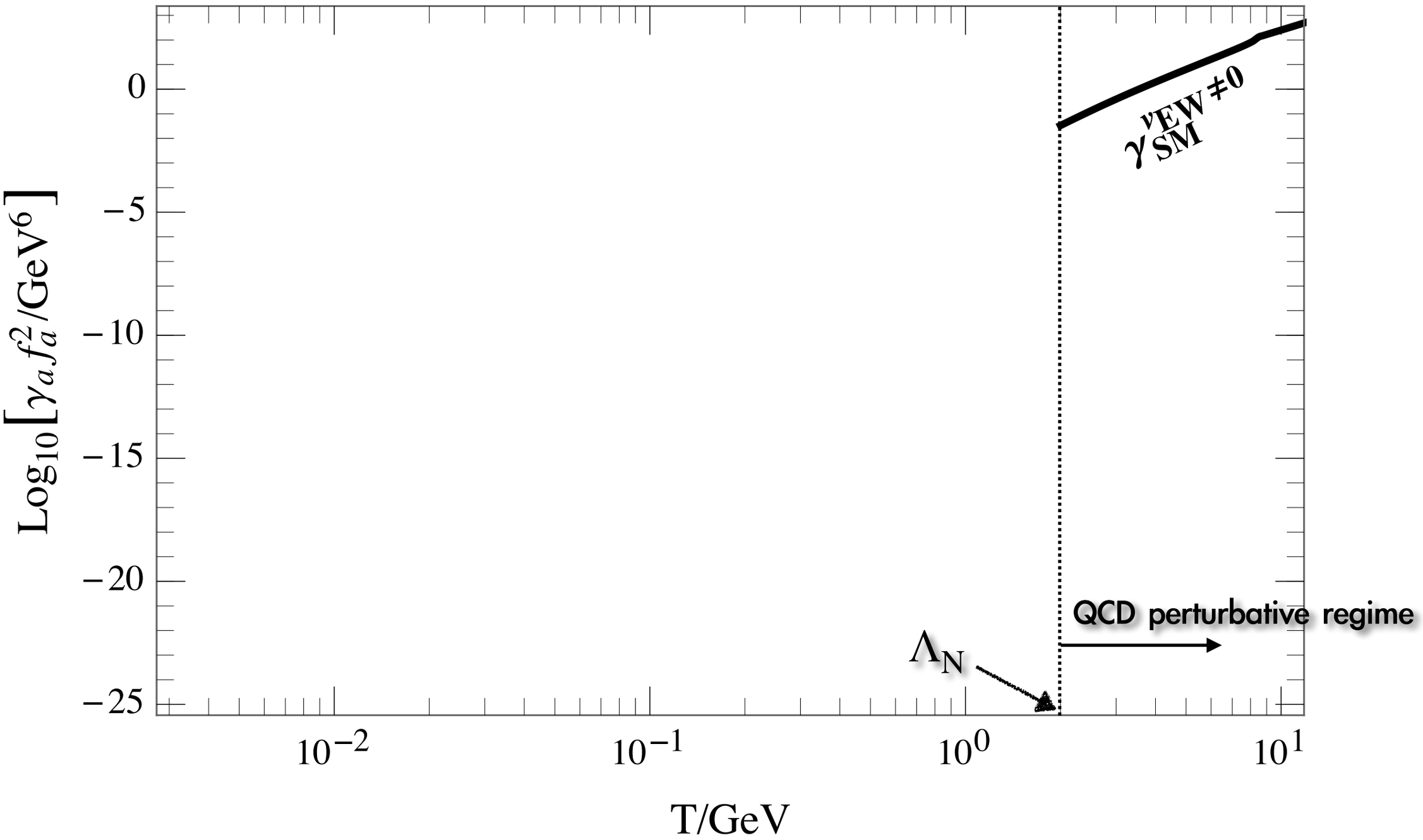
Electroweak threshold



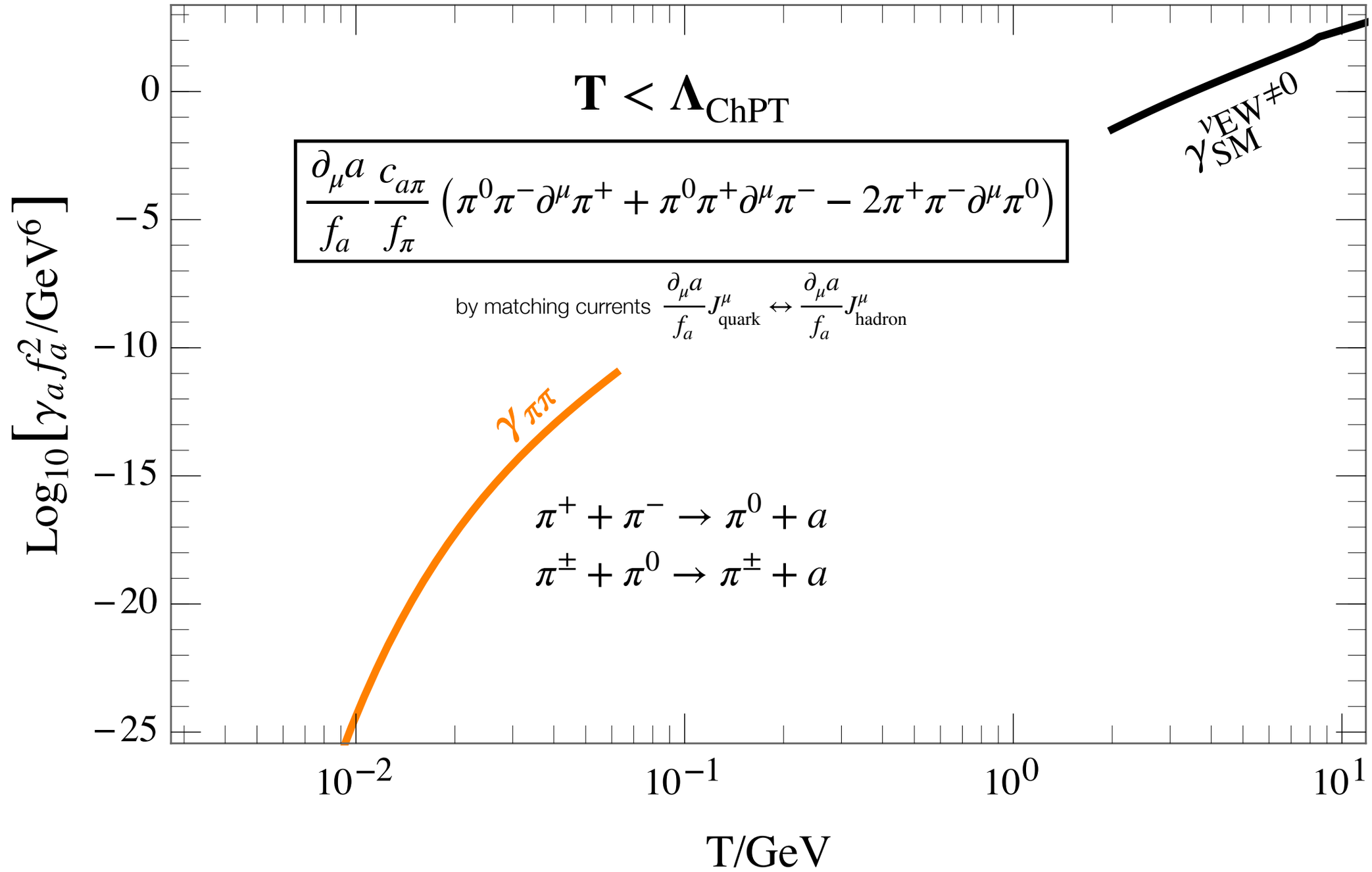
Electroweak threshold



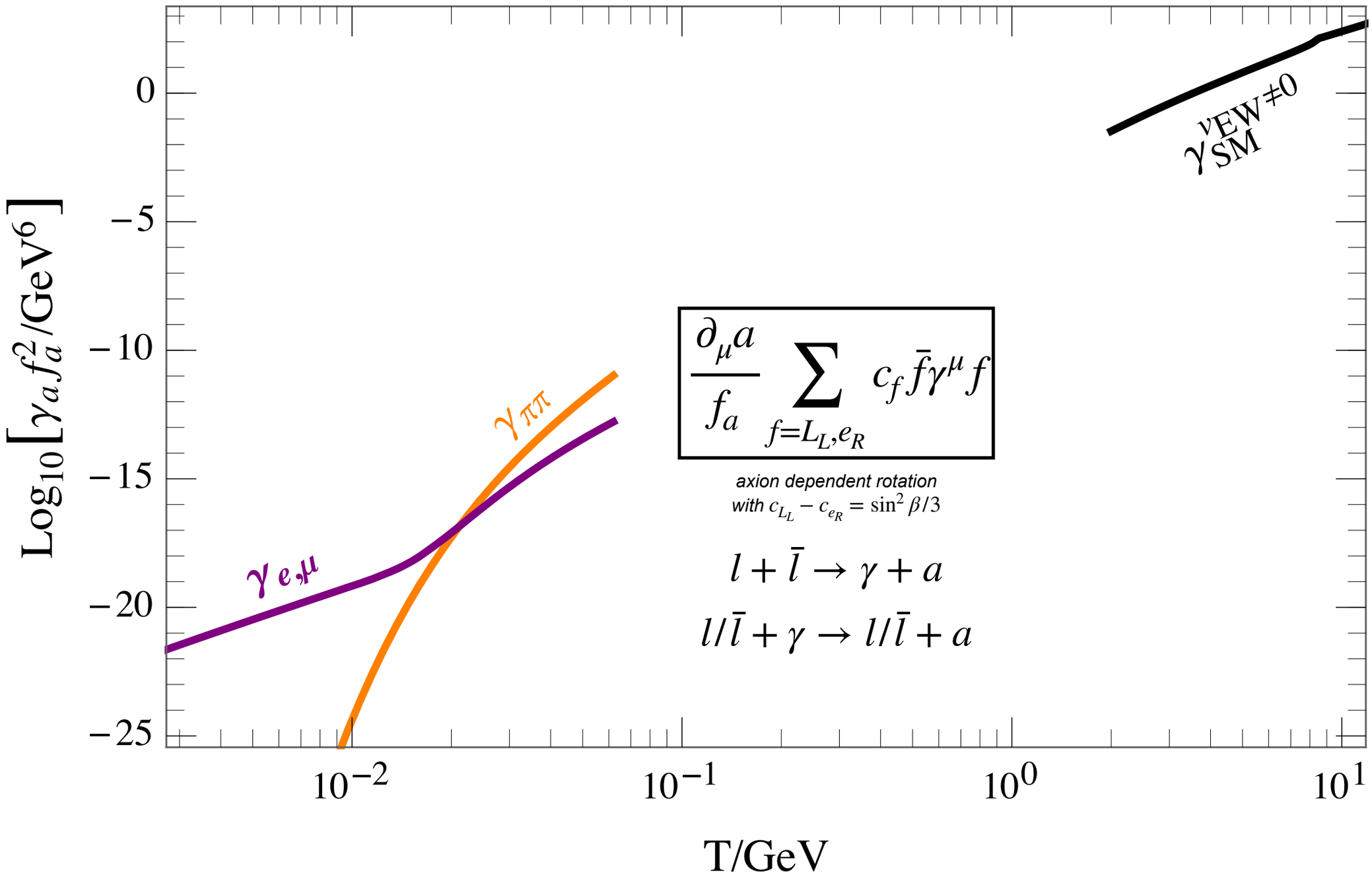
QCD threshold



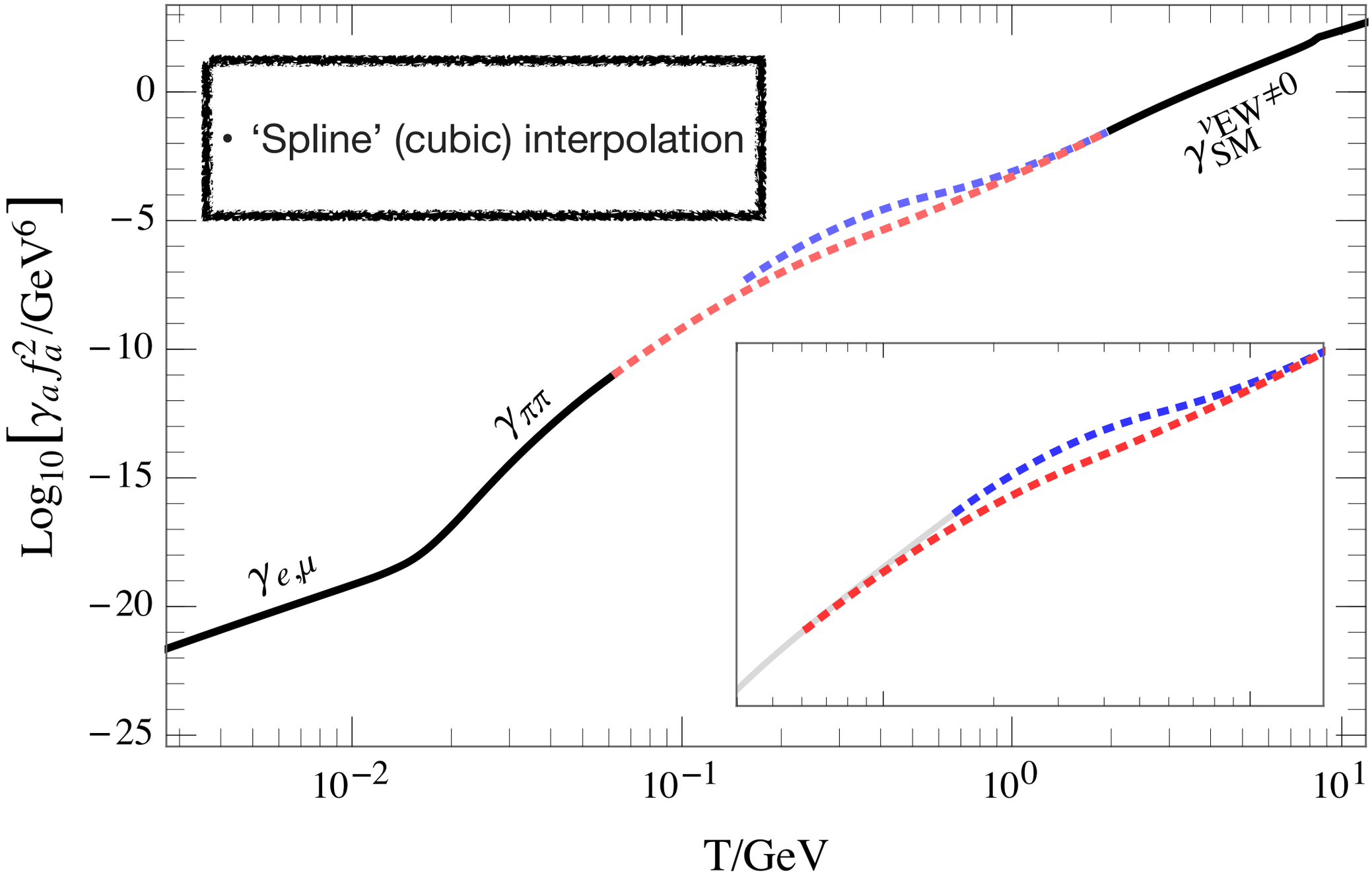
QCD threshold



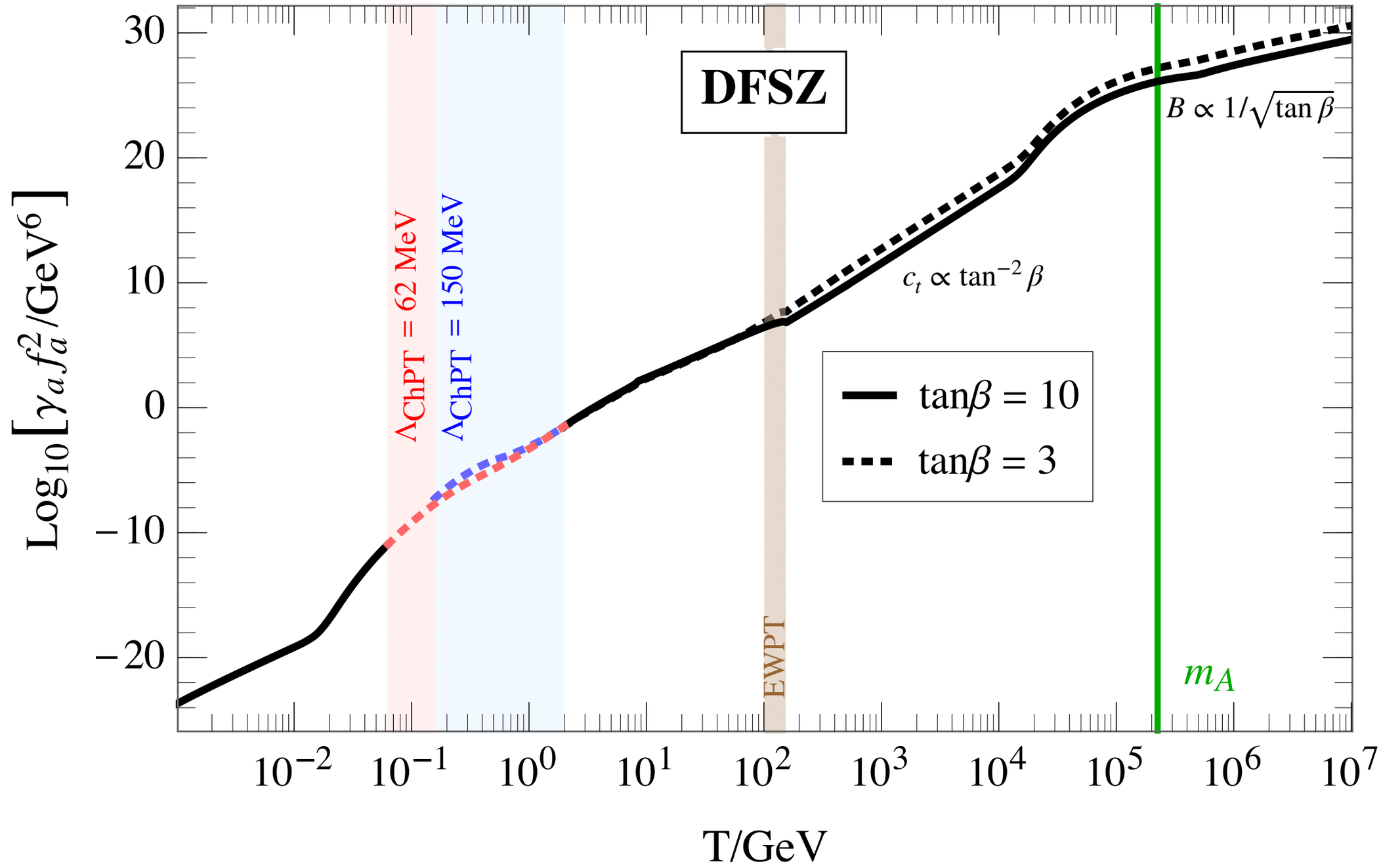
QCD threshold



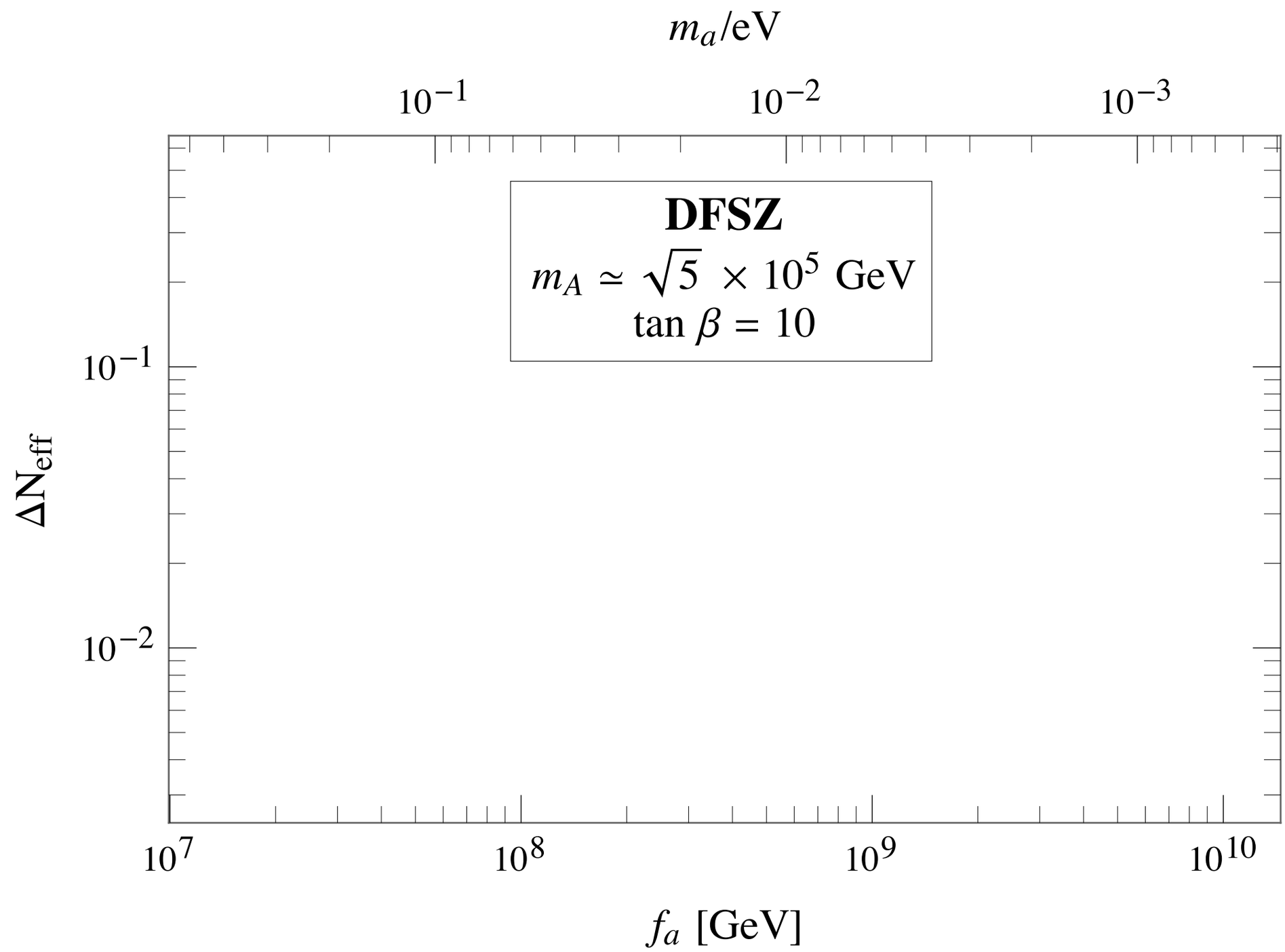
QCD threshold



DFSZ axion production rate



Hot DFSZ axion relic for $\tan\beta = 10$



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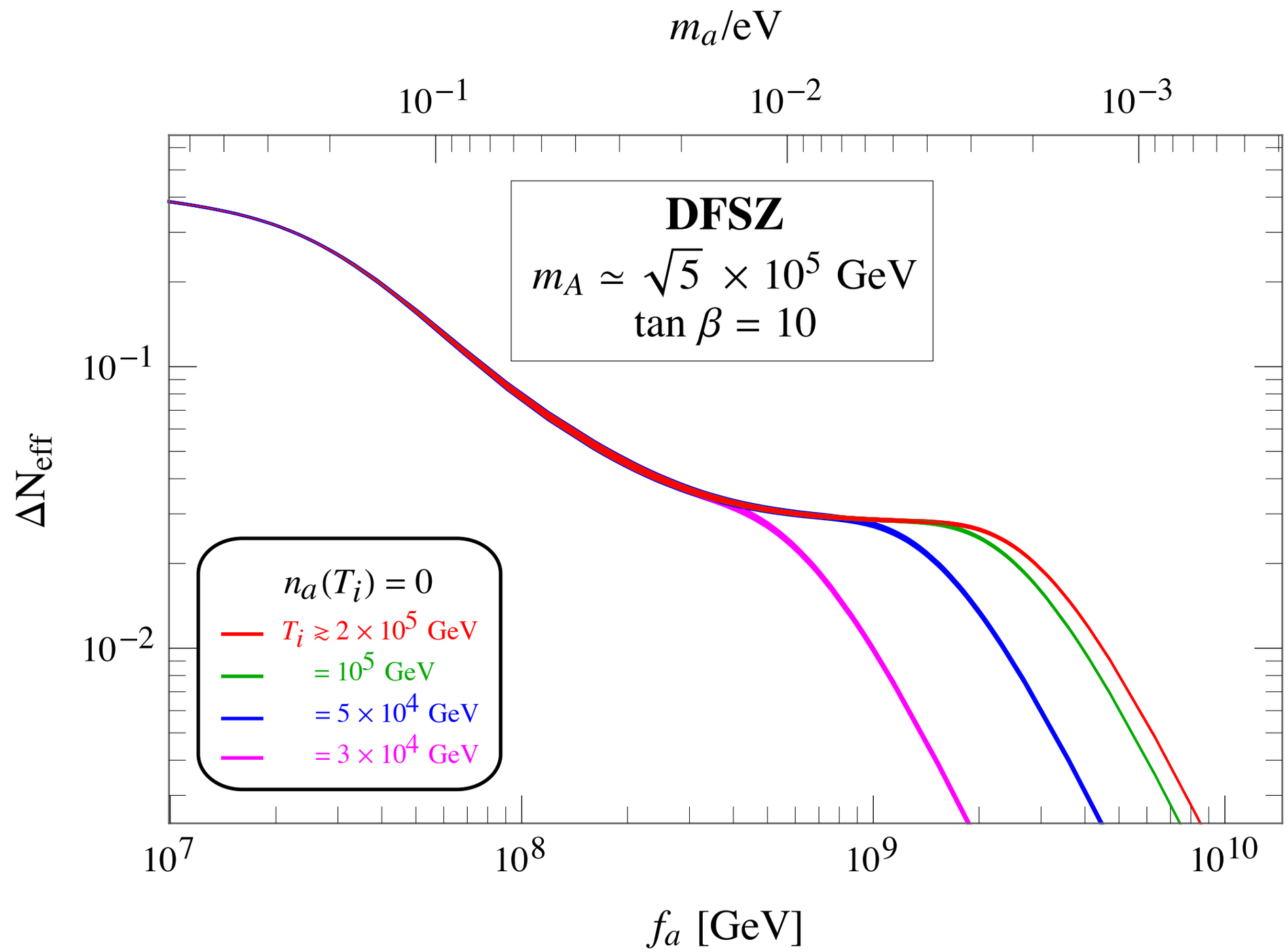

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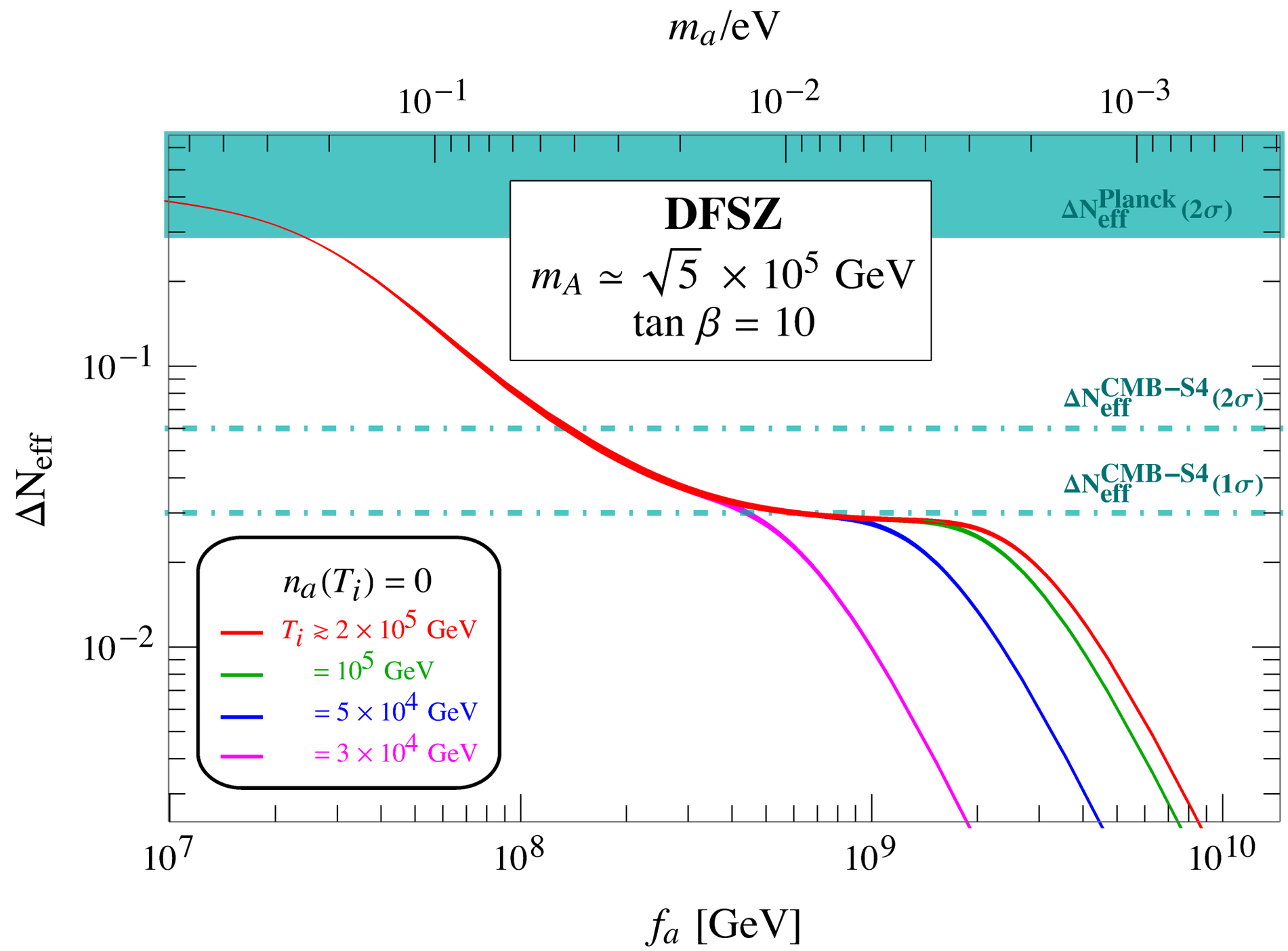
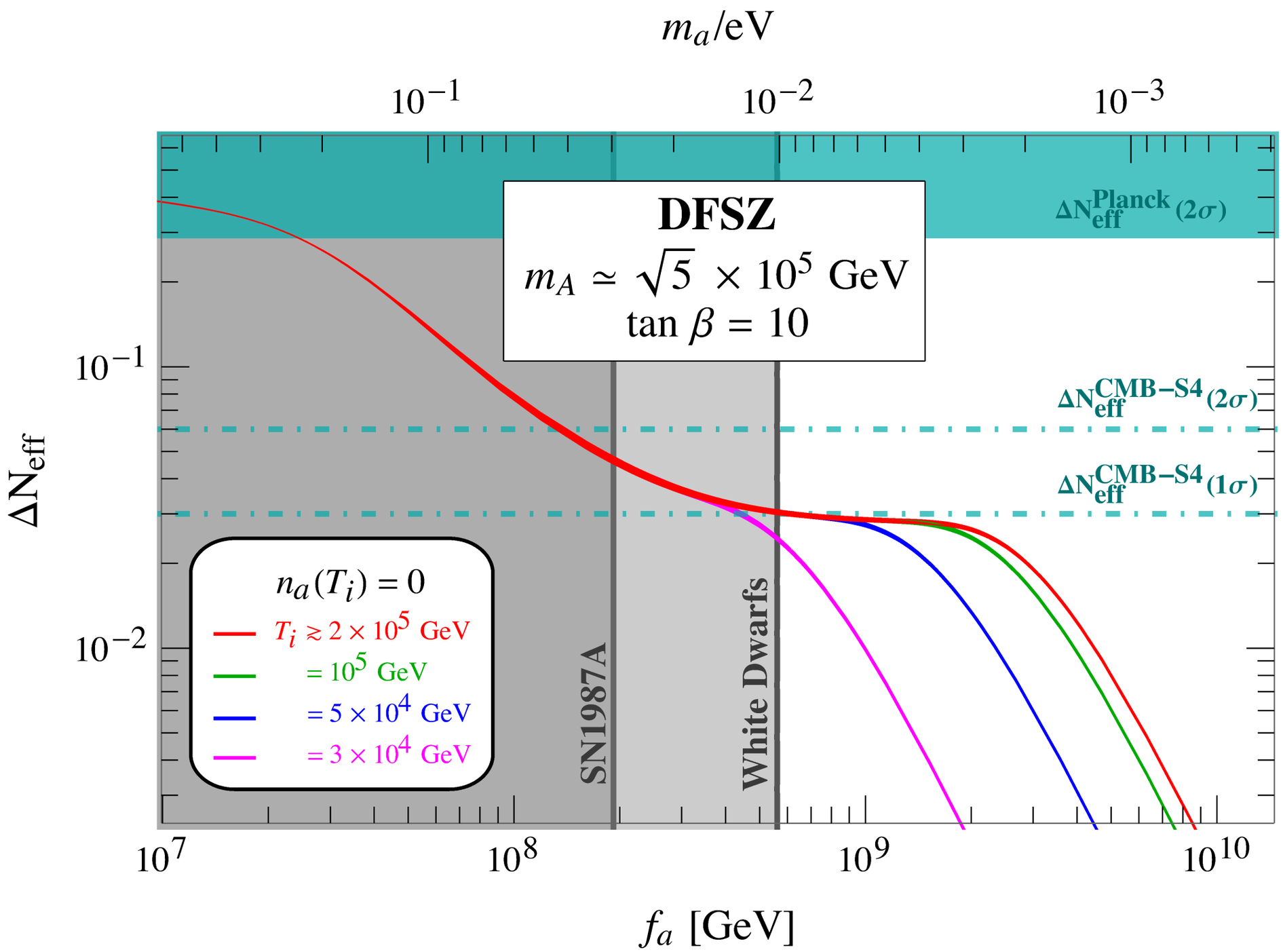
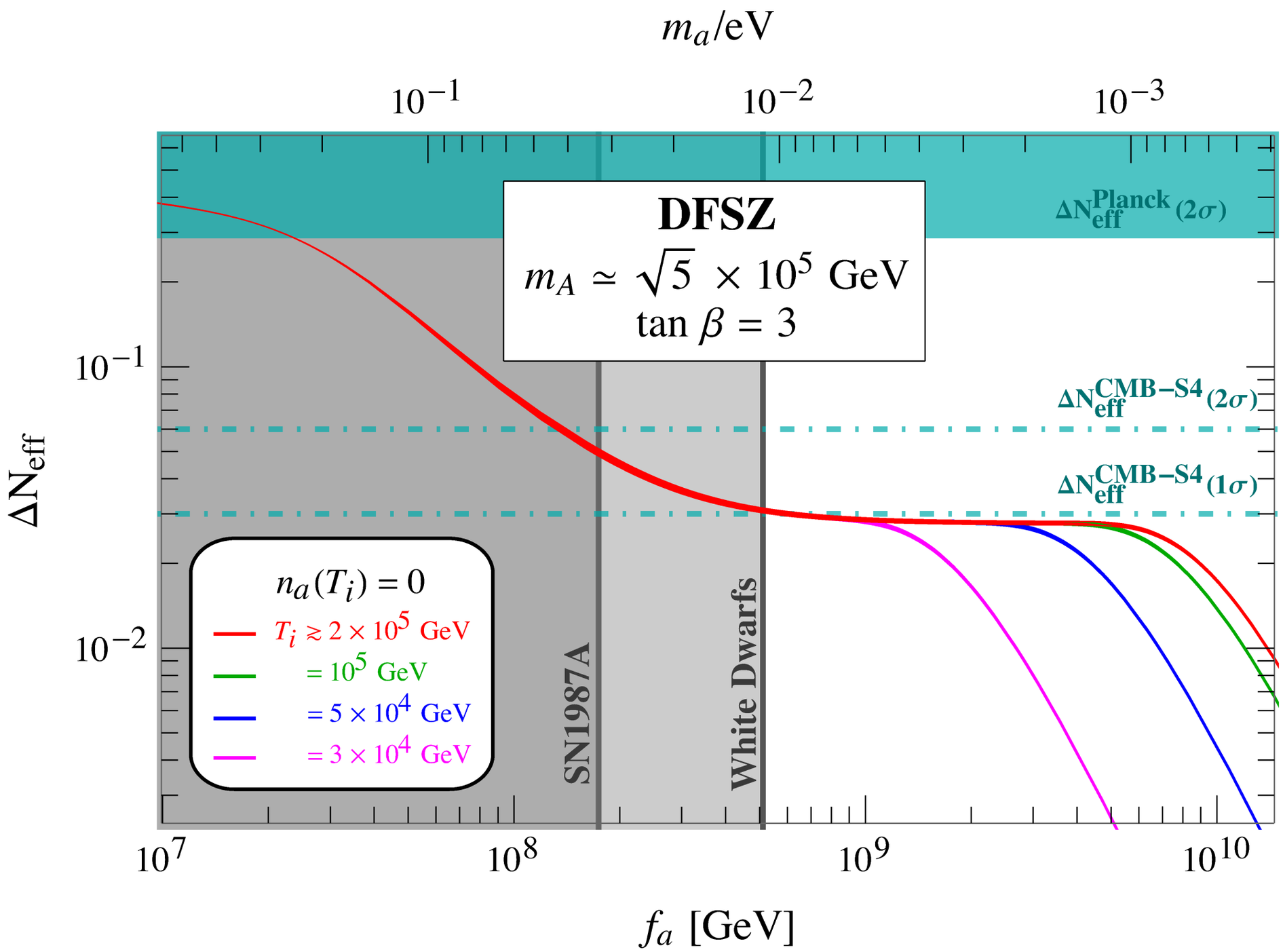


Hot DFSZ axion relic for $\tan\beta = 10$



Hot DFSZ axion relic for $\tan\beta = 3$



Flavor-violating couplings

✦ Explicit charge assignments

e.g., through the Froggatt-Nielsen mechanism

"Flaxion" **[Y. Ema et al, 2016]**

"Axiflavon" **[L. Calibbi et al, 2016]**

⋮

✦ Radiatively induced

[K. Choi, S. Im, C. Park, SY, 2017]

[M. Chala, 2020]

[K. Choi et al, 2021]

⋮

◉ Scatterings

$$q_i + \bar{q}_j \to g + a$$

$$q_i\left(\bar{q}_j\right) + g \to q_j\left(\bar{q}_i\right) + a$$

⋮

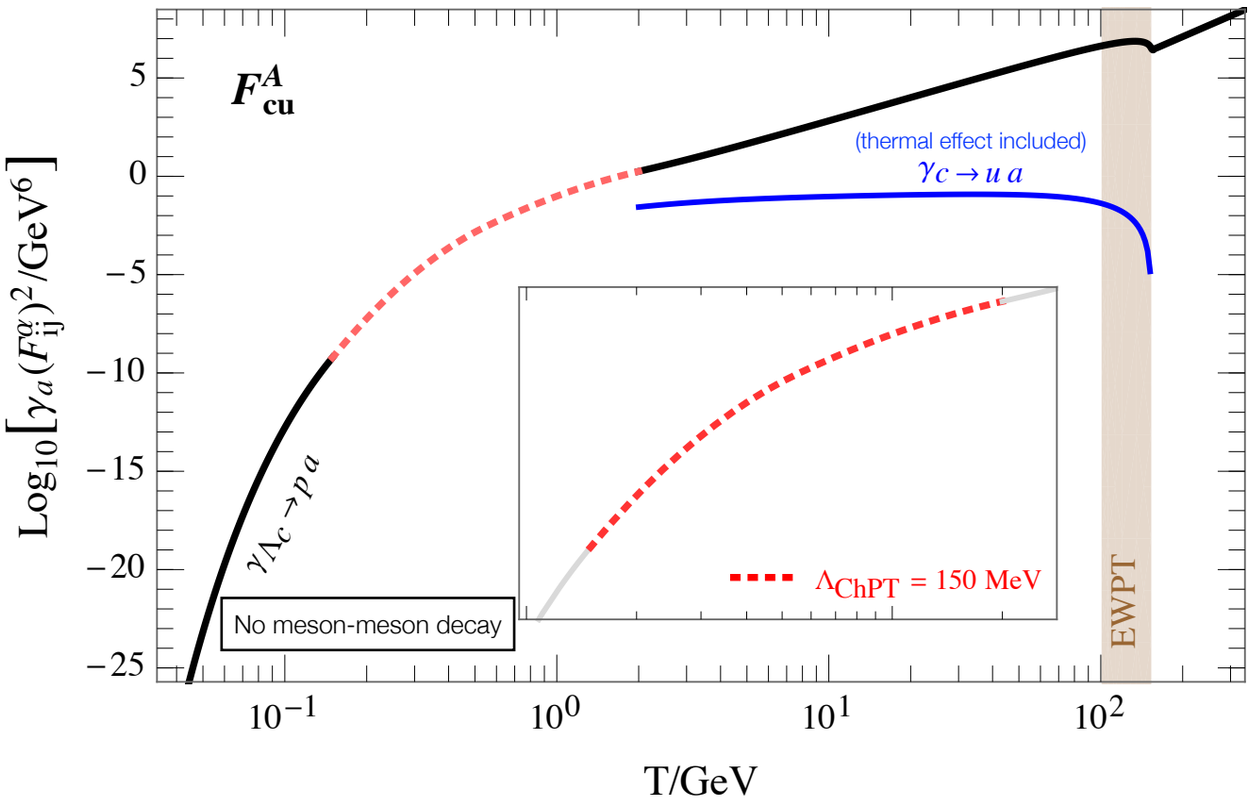
◉ **Decay**

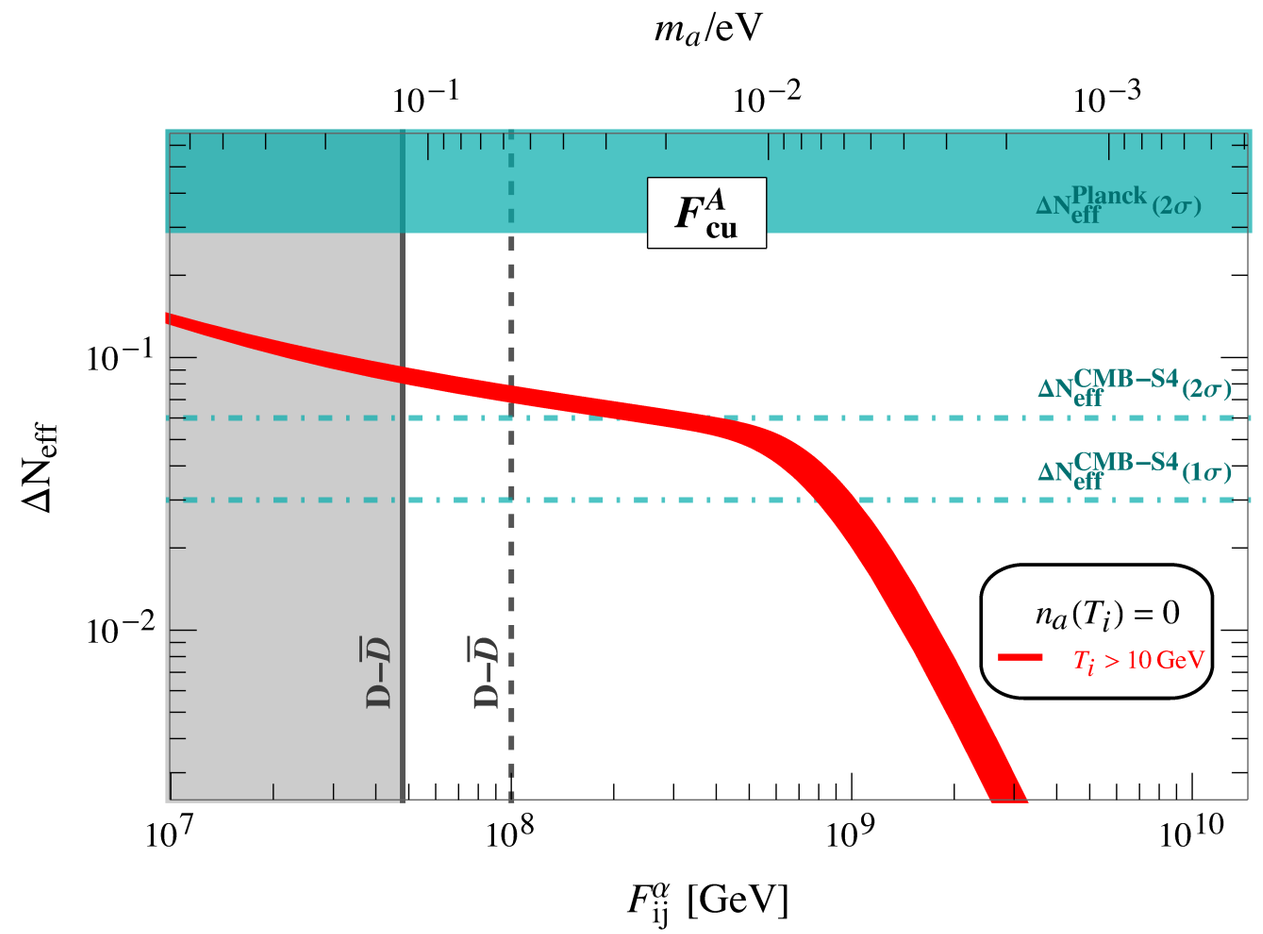
$$q_i\left(\bar{q}_j\right) \to q_j\left(\bar{q}_i\right) + a$$

[F. D'Eramo, SY, in progress]

c-u axial current

- $\frac{\partial_\mu a}{F_{cu}^{\mathrm{A}}}\,\bar{u}\gamma^\mu\gamma^5 c$

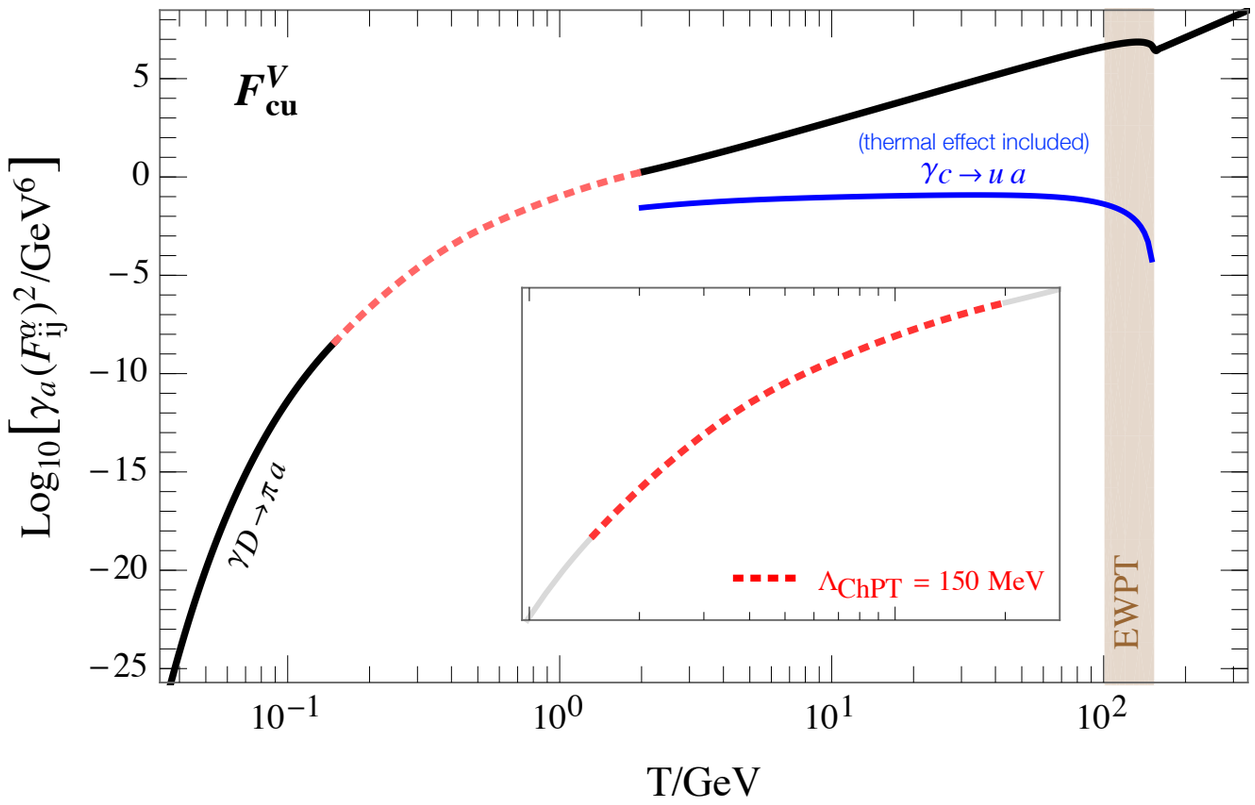


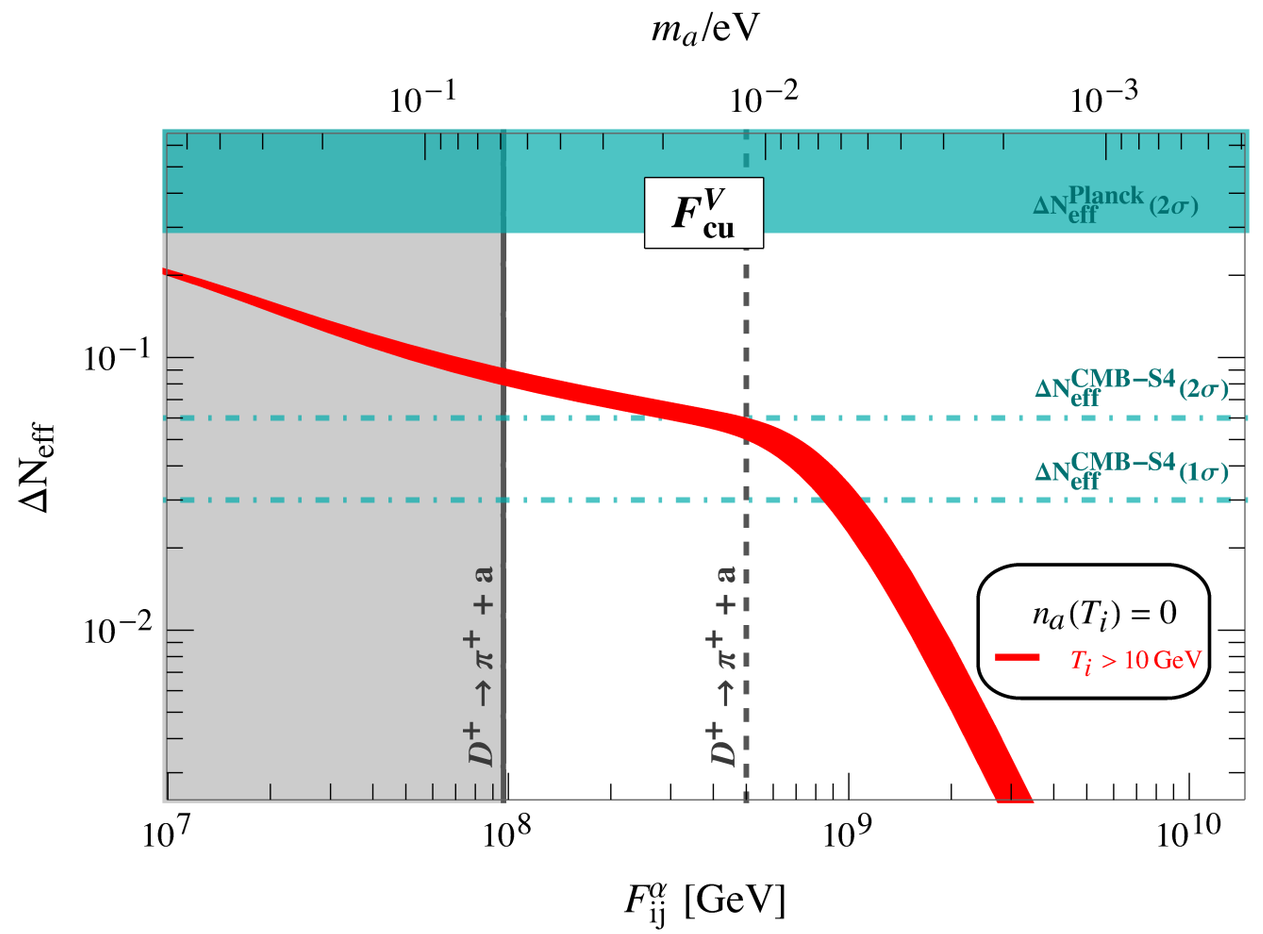


[F. D'Eramo, SY, in progress]

c-u vector current

- $\dfrac{\partial_\mu a}{F_{cu}^{\rm V}}\,\bar{u}\gamma^\mu c$



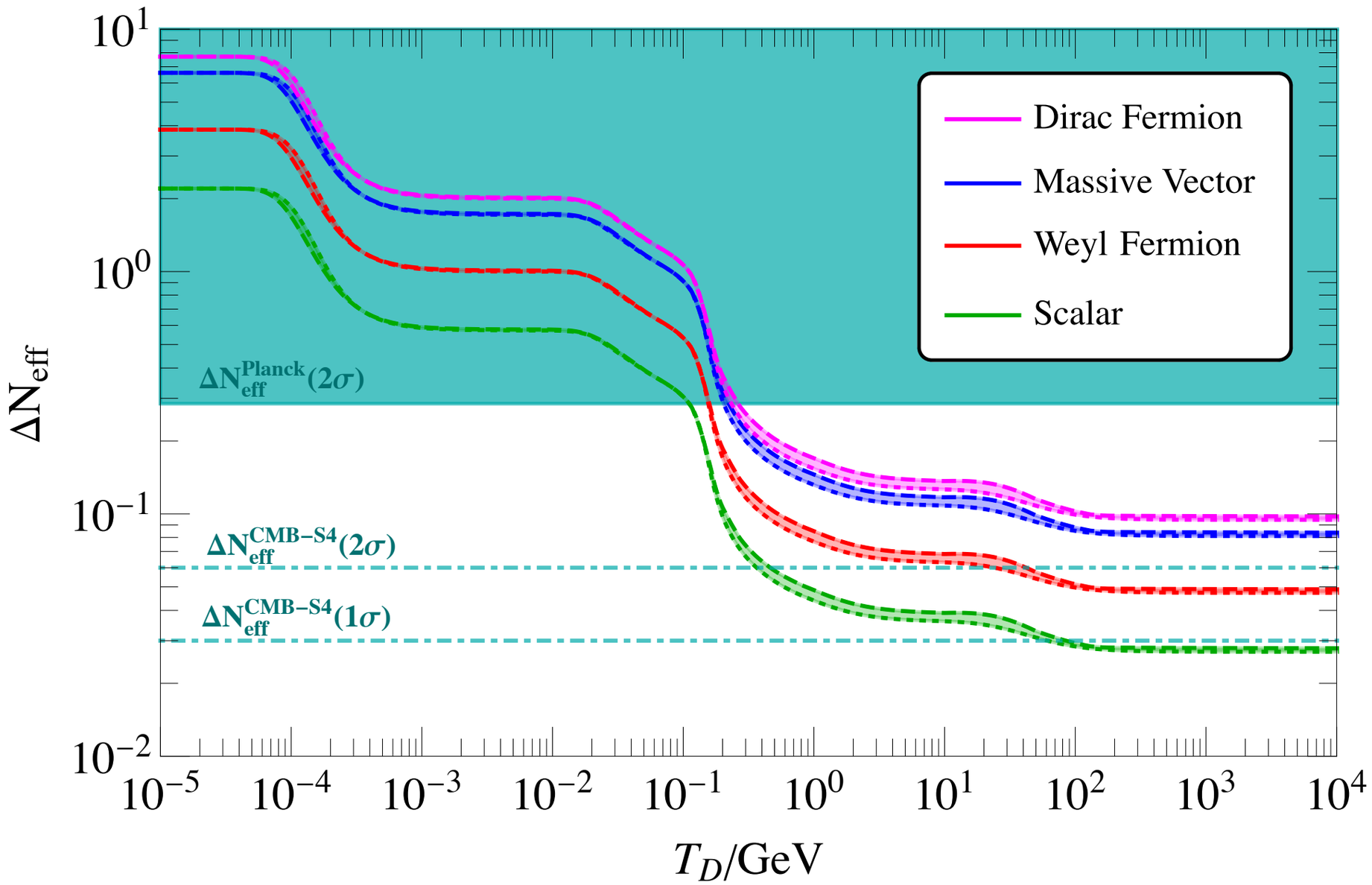


Conclusion

- 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 $f_a \sim \mathcal{O}(10^8)\,\mathrm{GeV}$

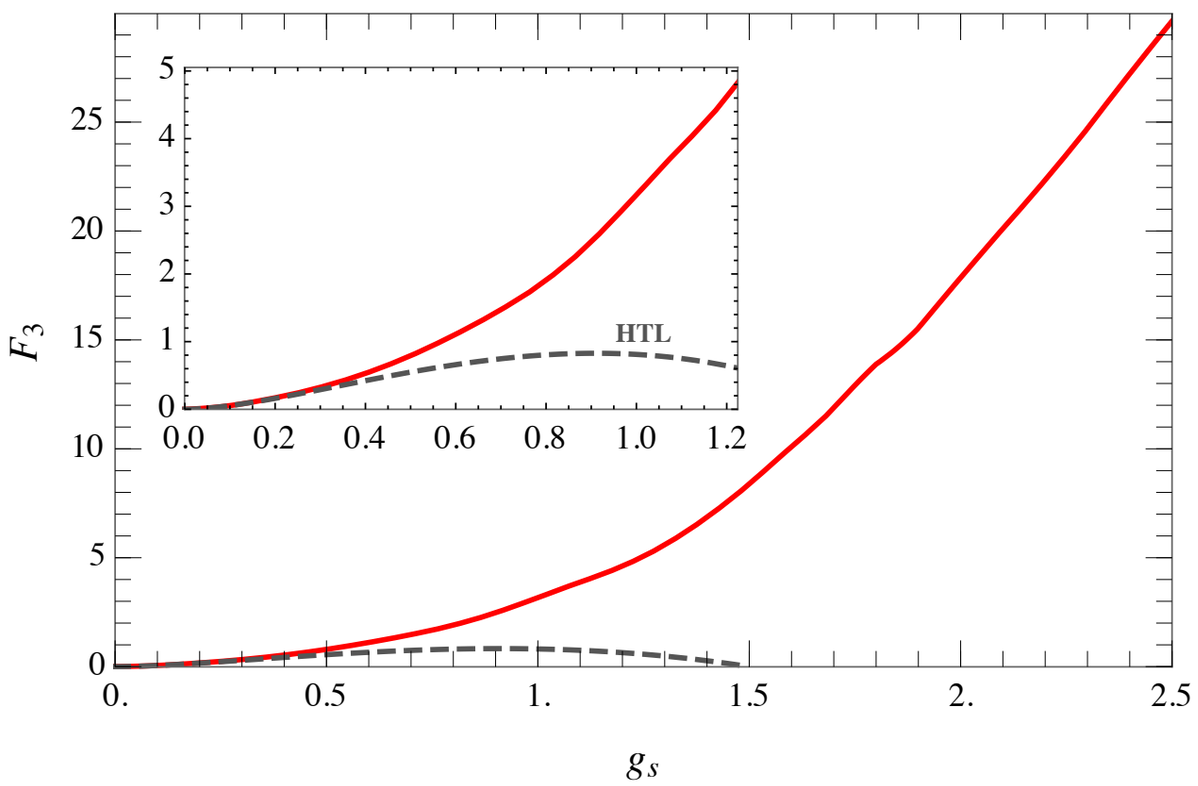
Back up

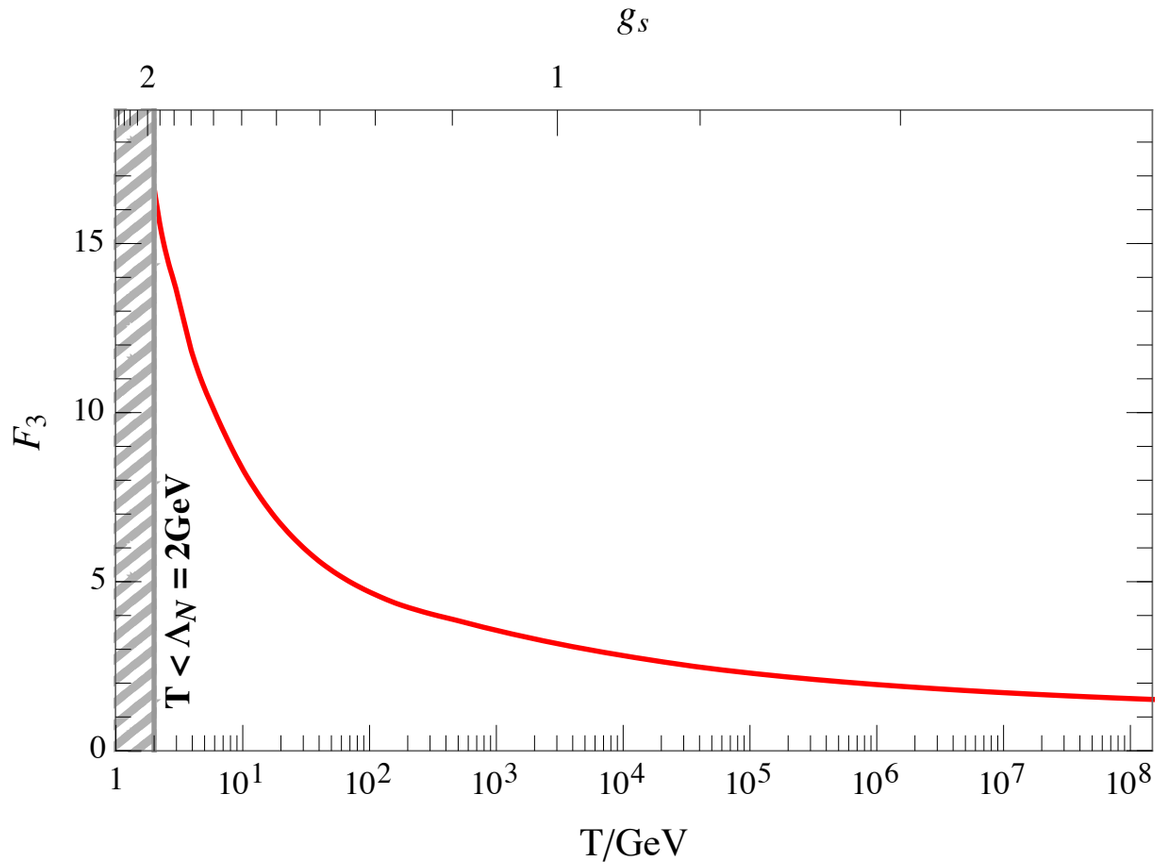
$\Delta N_{\rm eff}$ VS $T_{\rm D}$



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

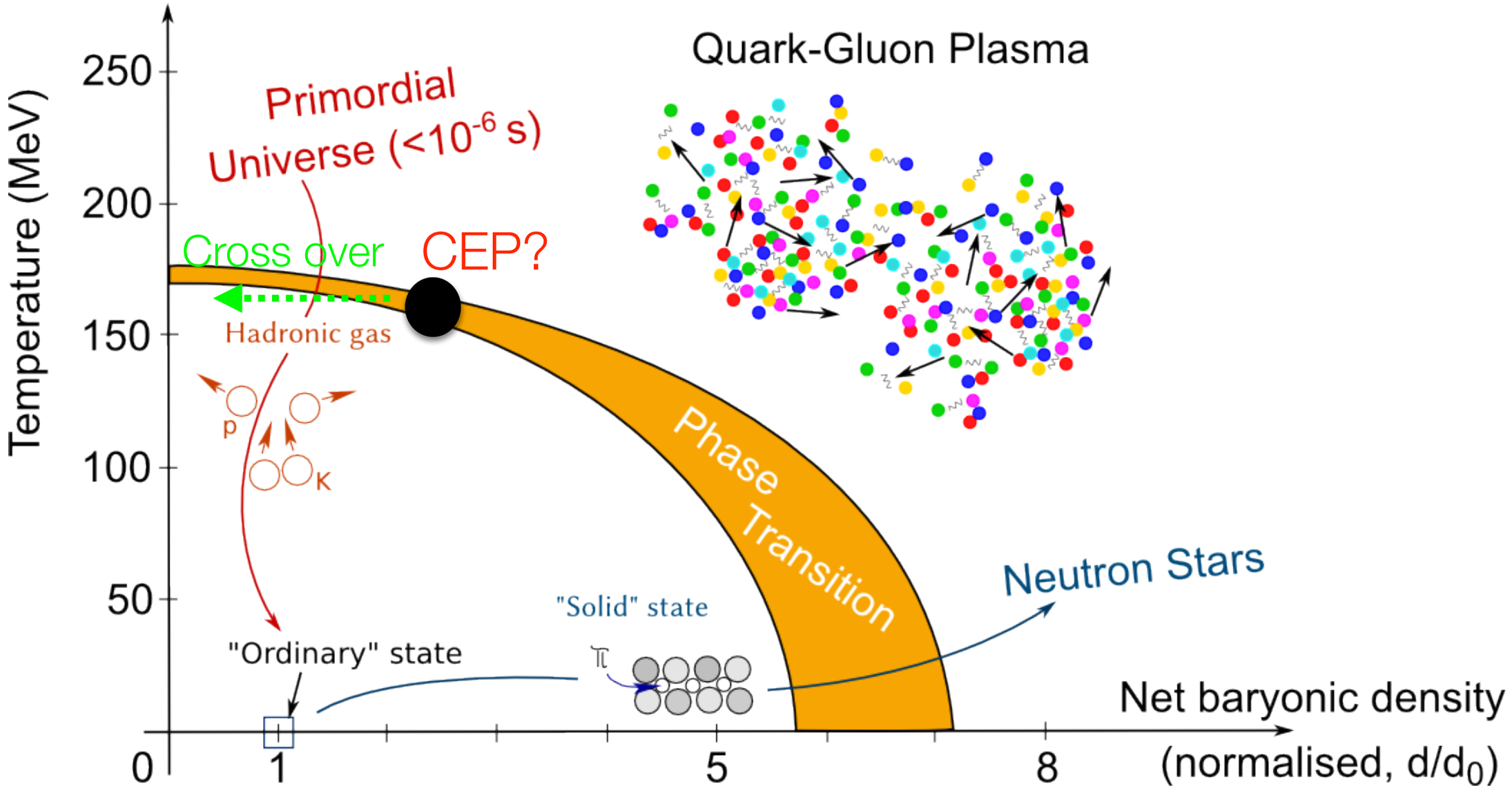
Control function for gluon scatterings



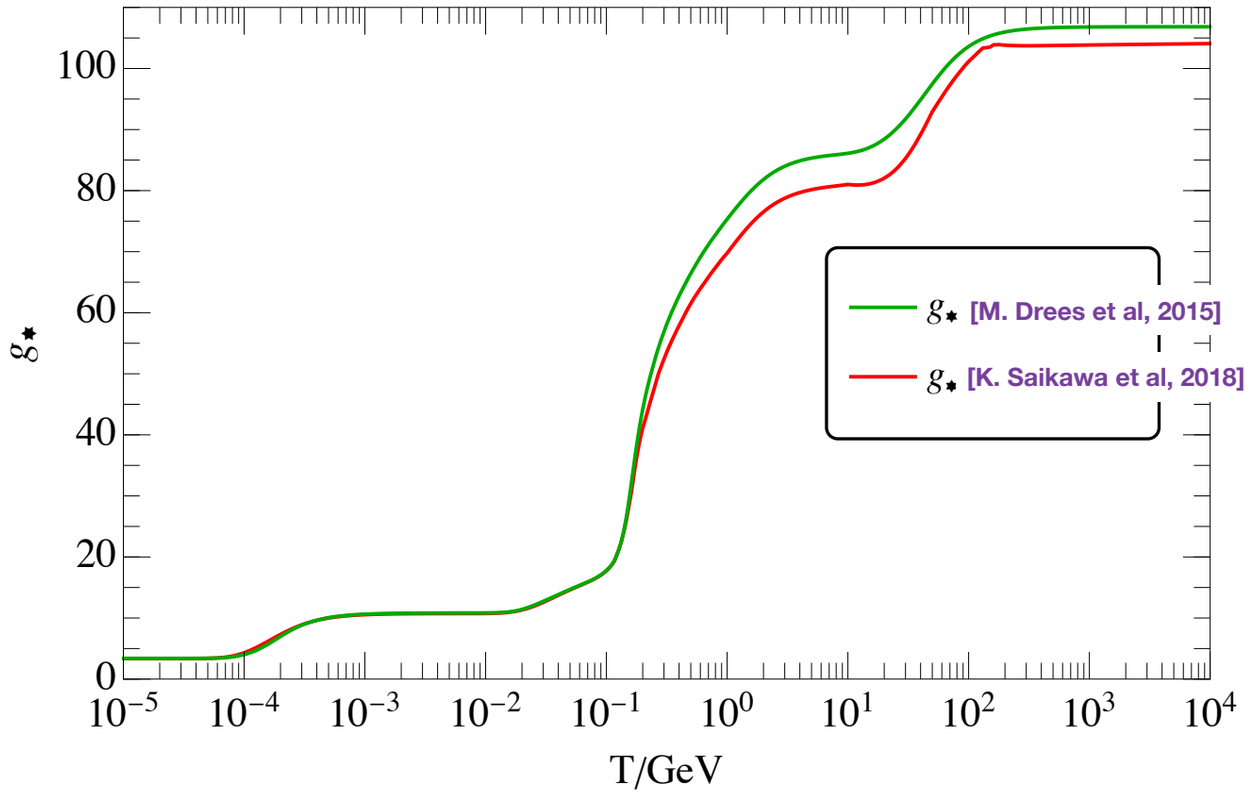


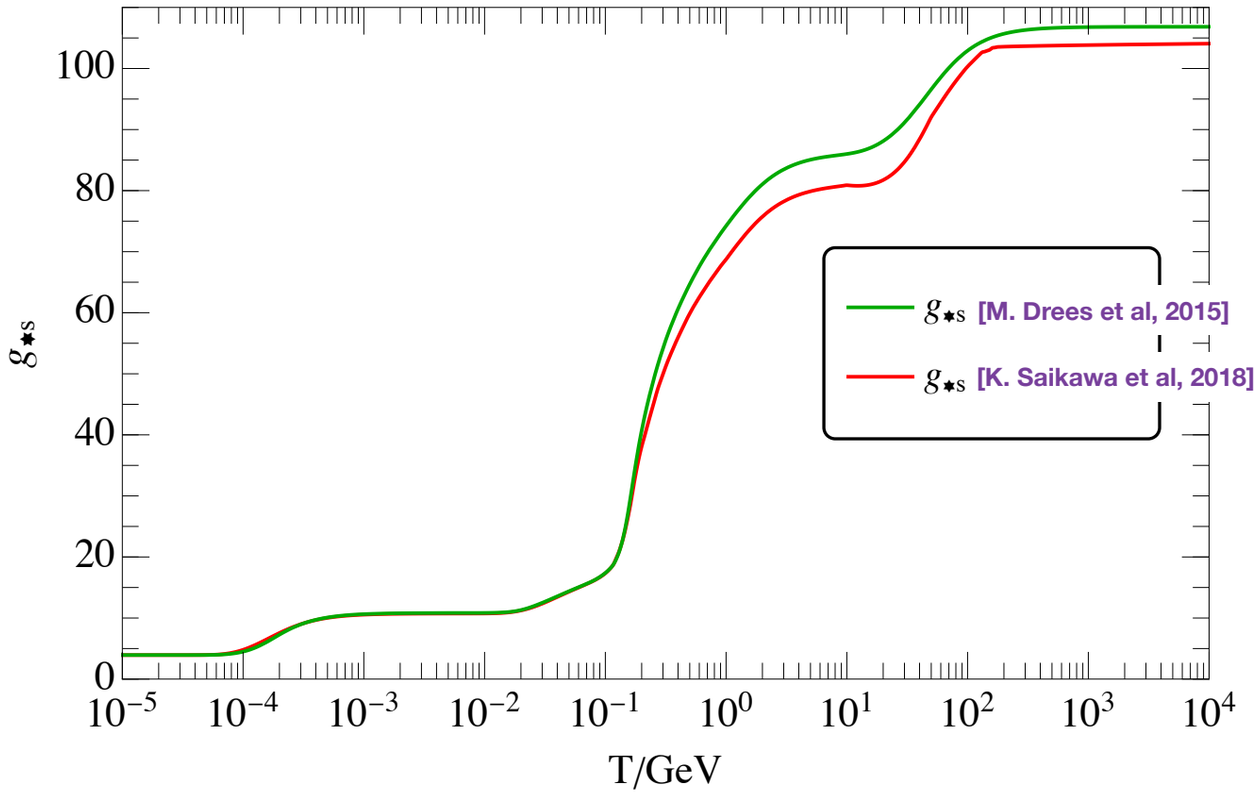
QCD phase diagram

[A. Maire, 2015]

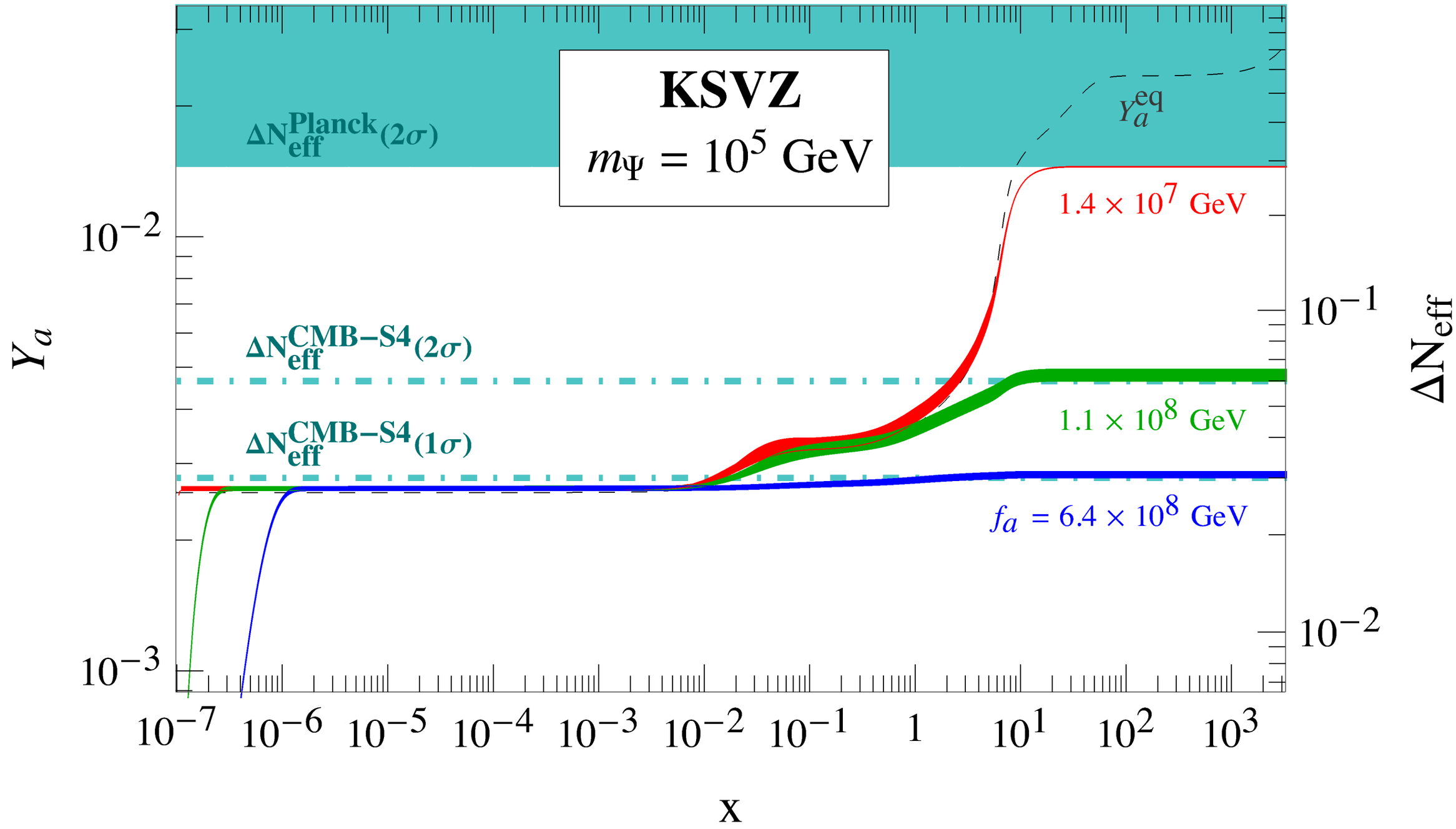


Cosmological profile

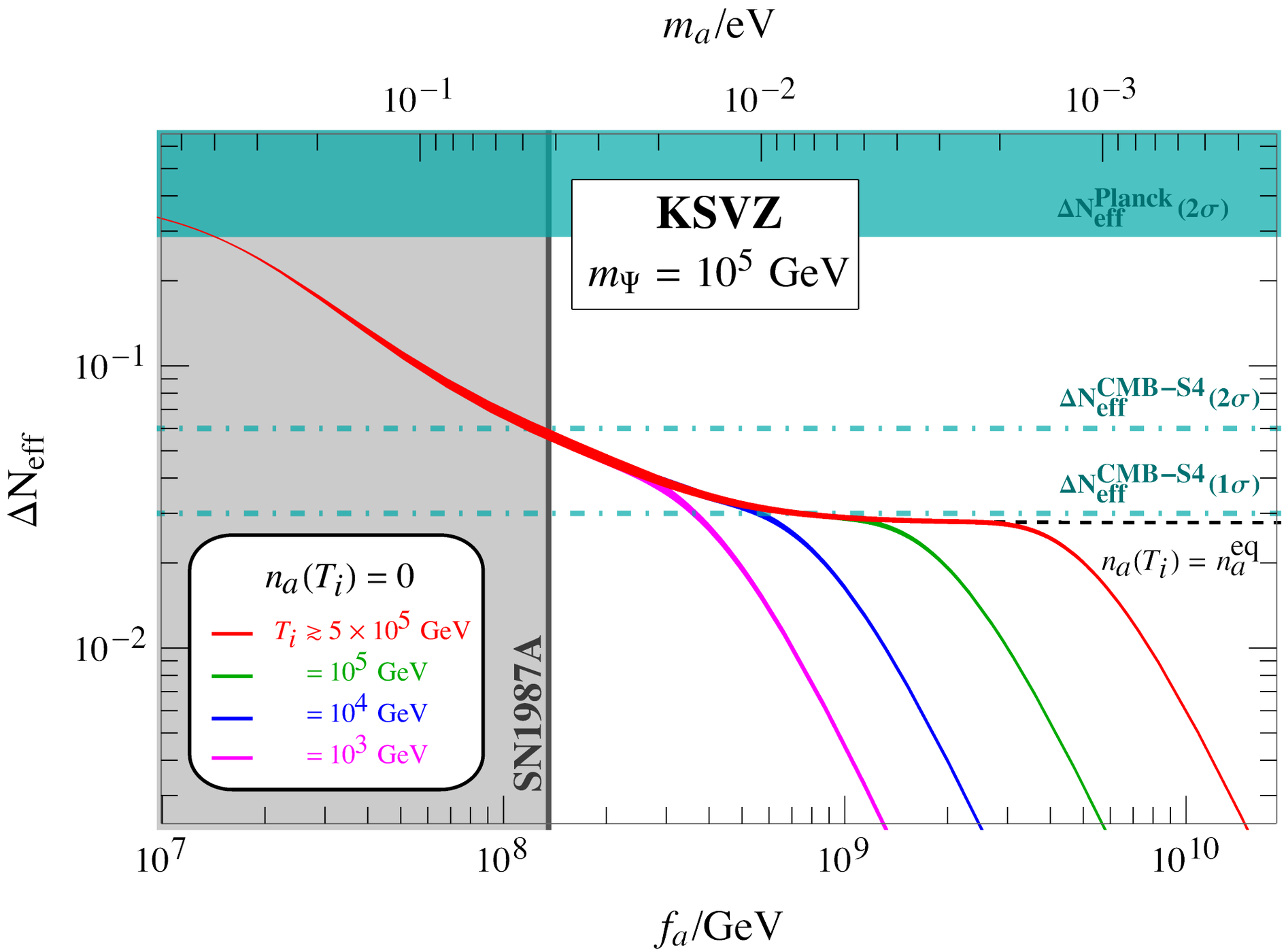




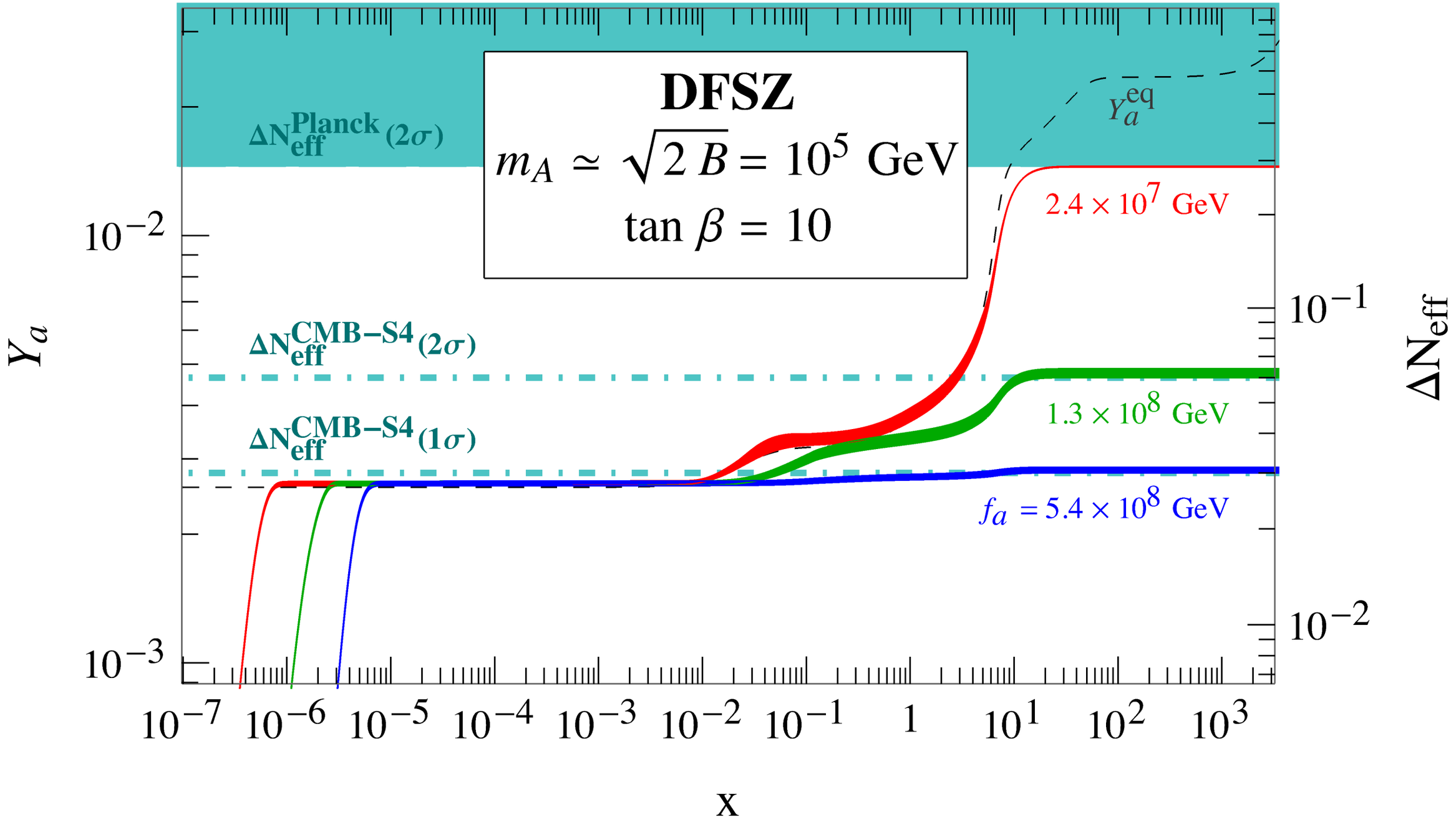
Evolution of KSVZ axion relic density



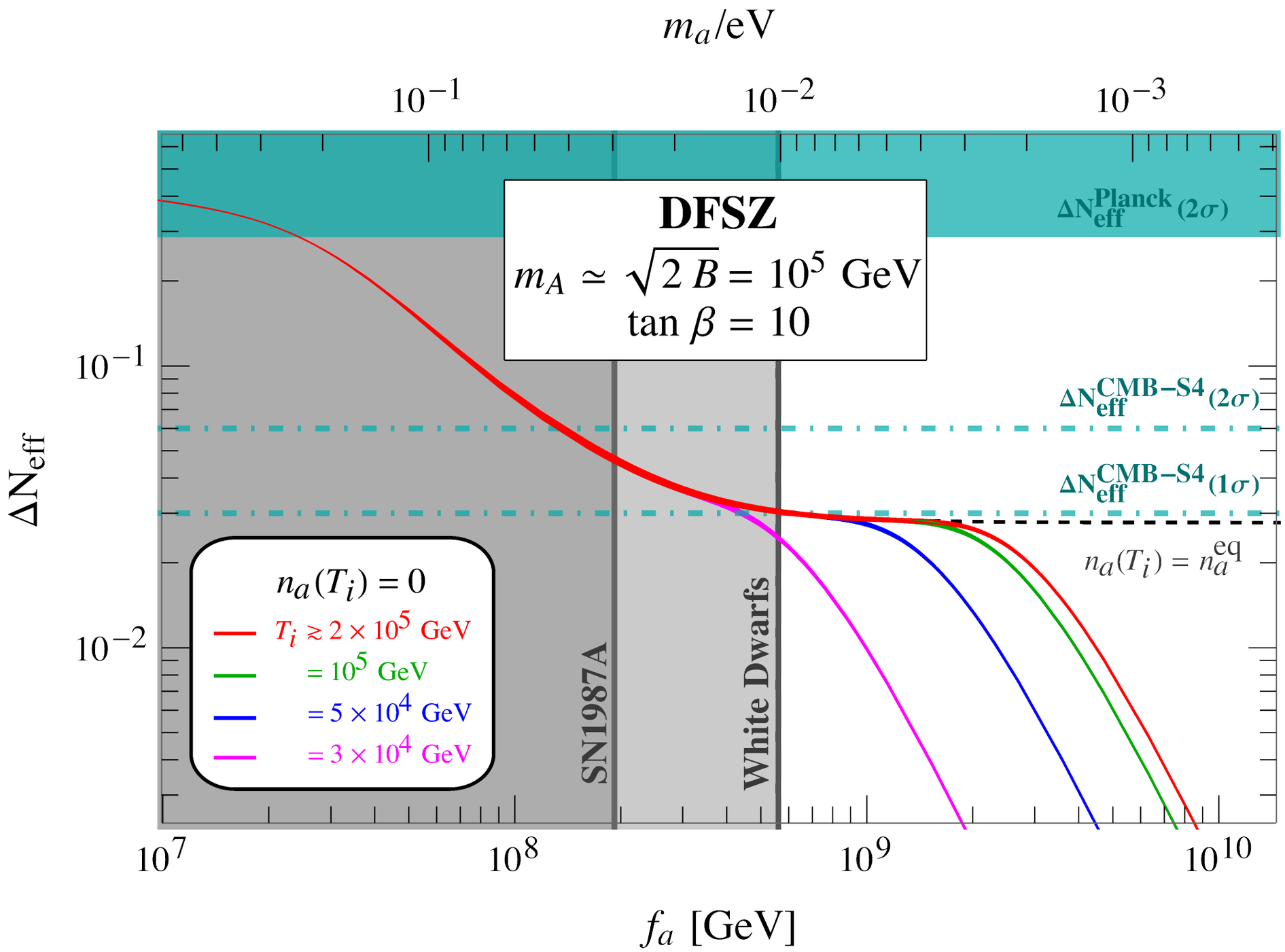
Hot KSVZ axion relic



Evolution of DFSZ axion relic density

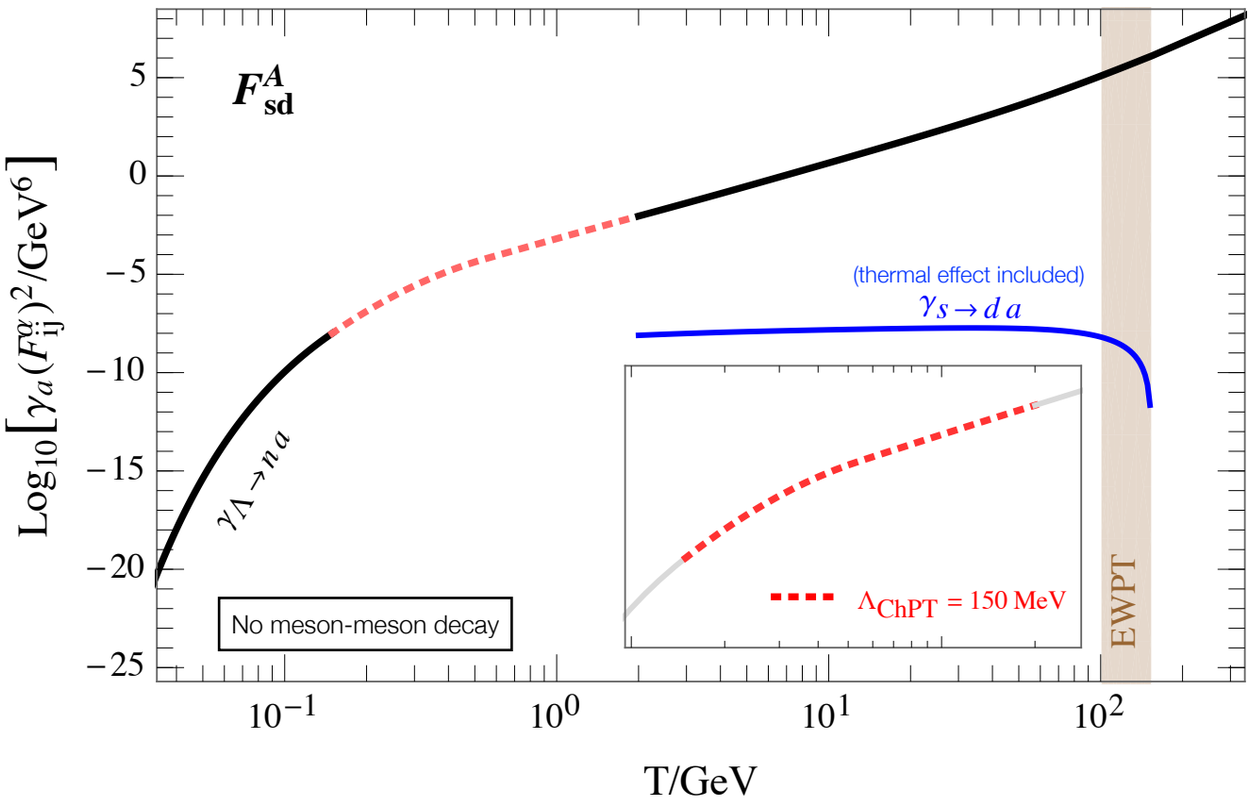


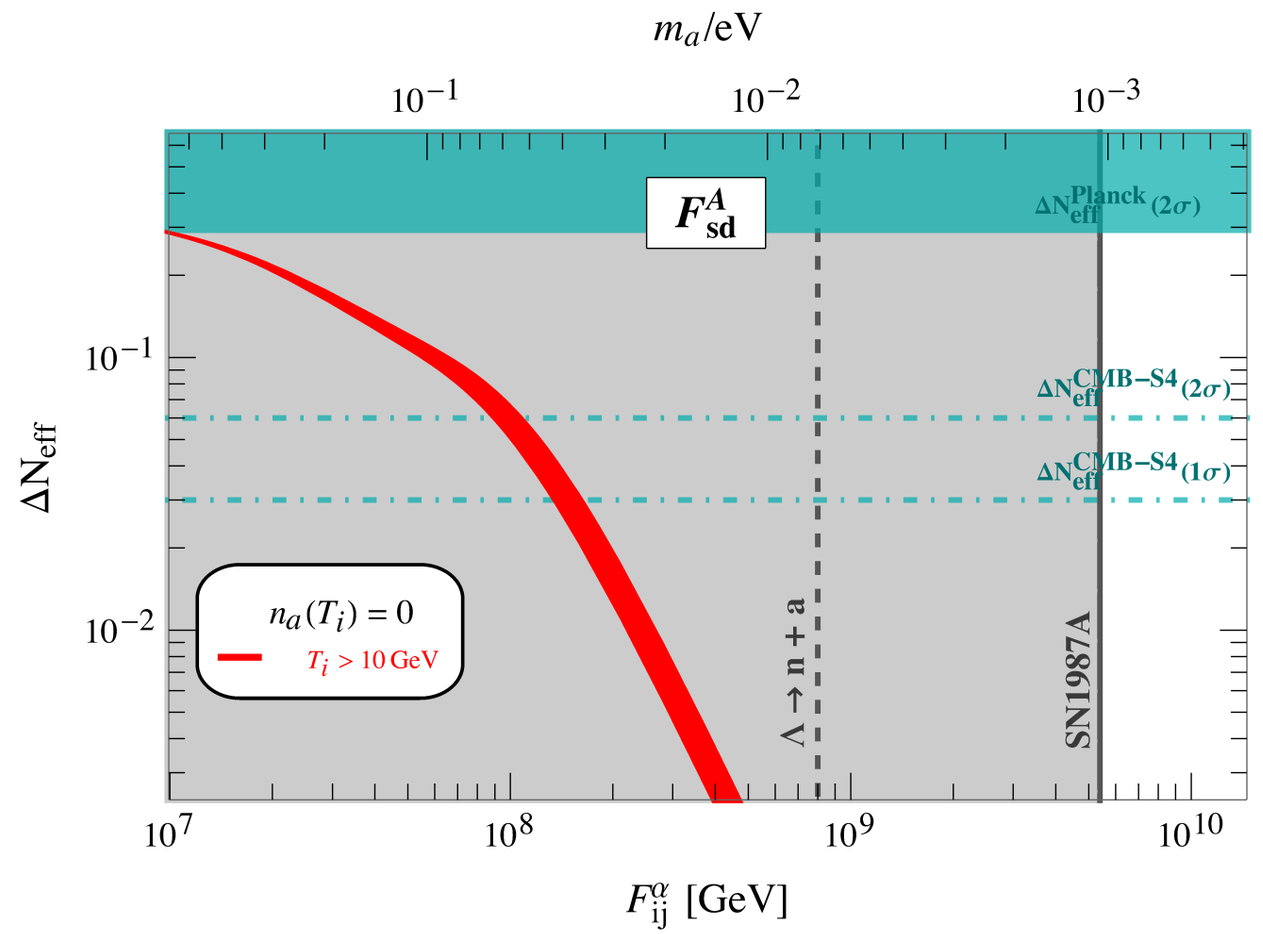
Hot DFSZ axion relic



s-d axial current

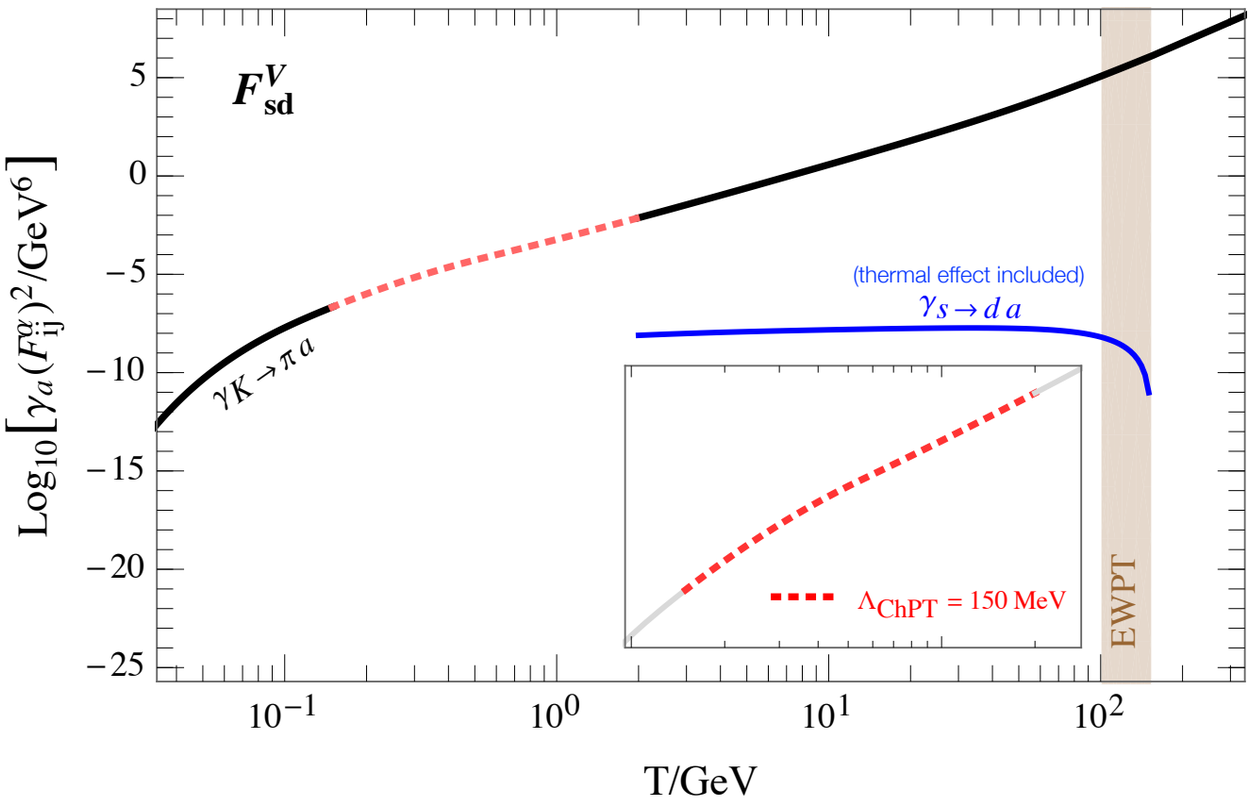
- $\frac{\partial_\mu a}{F_{sd}^{\mathrm{A}}}\,\bar{d}\gamma^\mu\gamma^5 s$

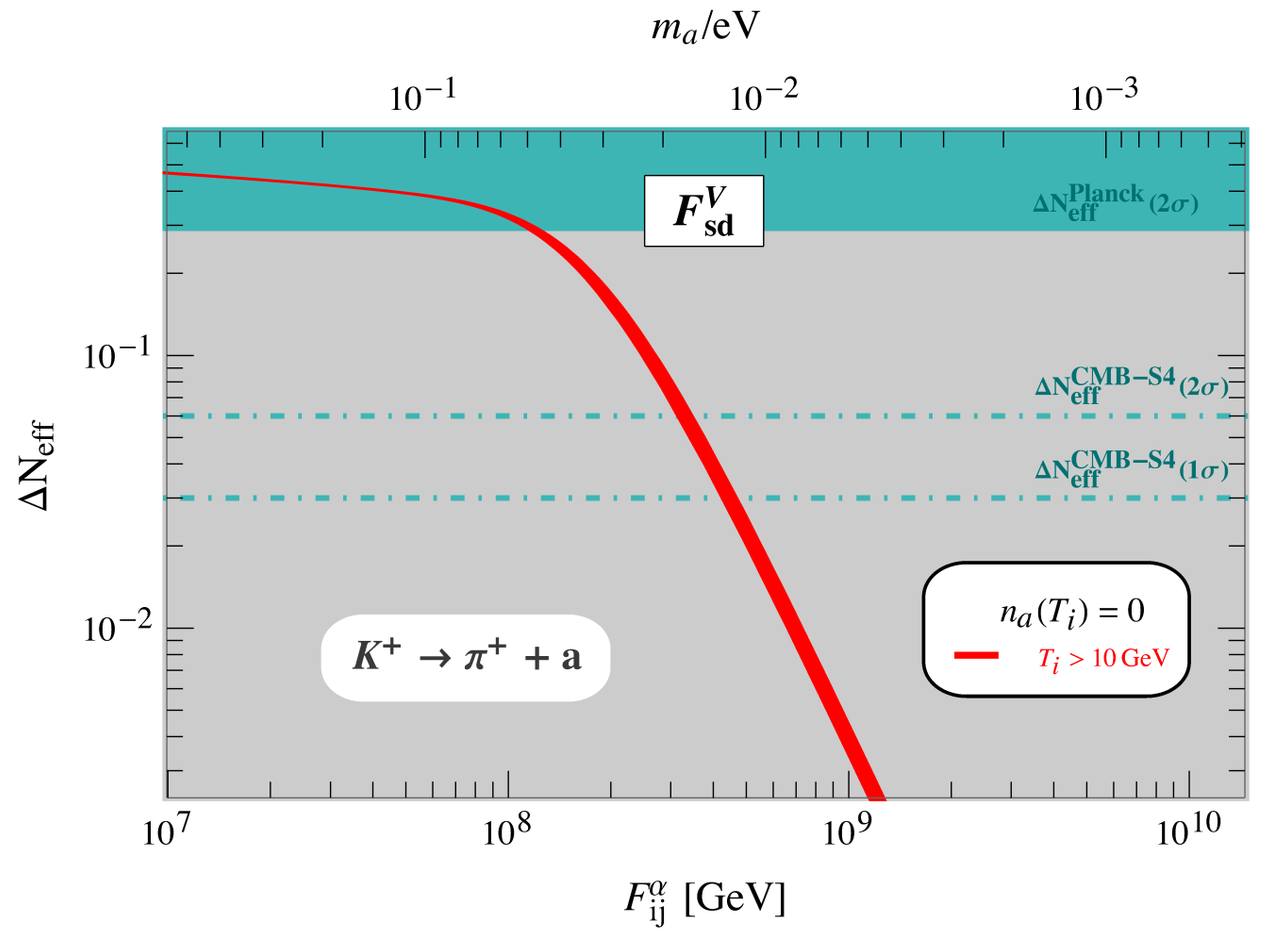




s-d vector current

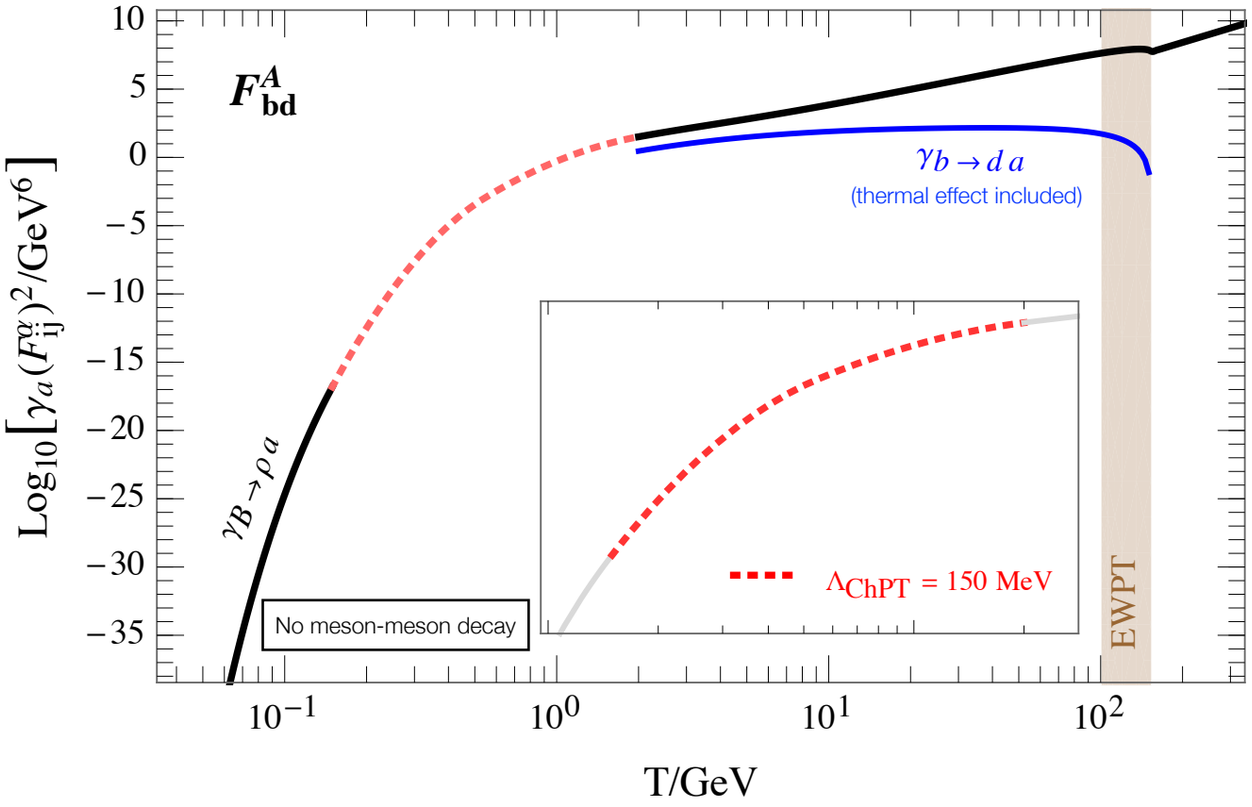
- $\frac{\partial_\mu a}{F_{sd}^{\mathrm{V}}}\,\bar{d}\gamma^\mu s$

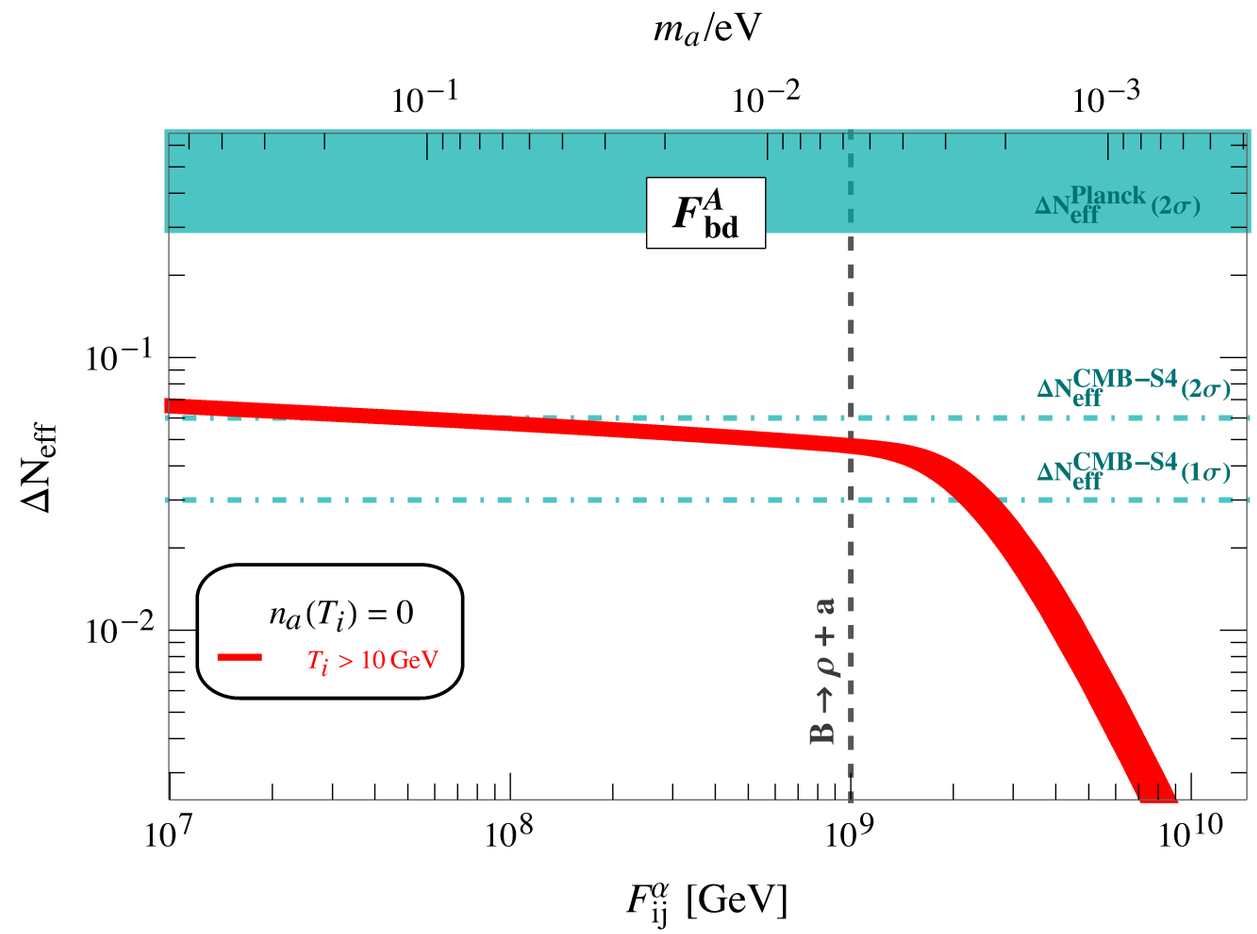




b-d axial current

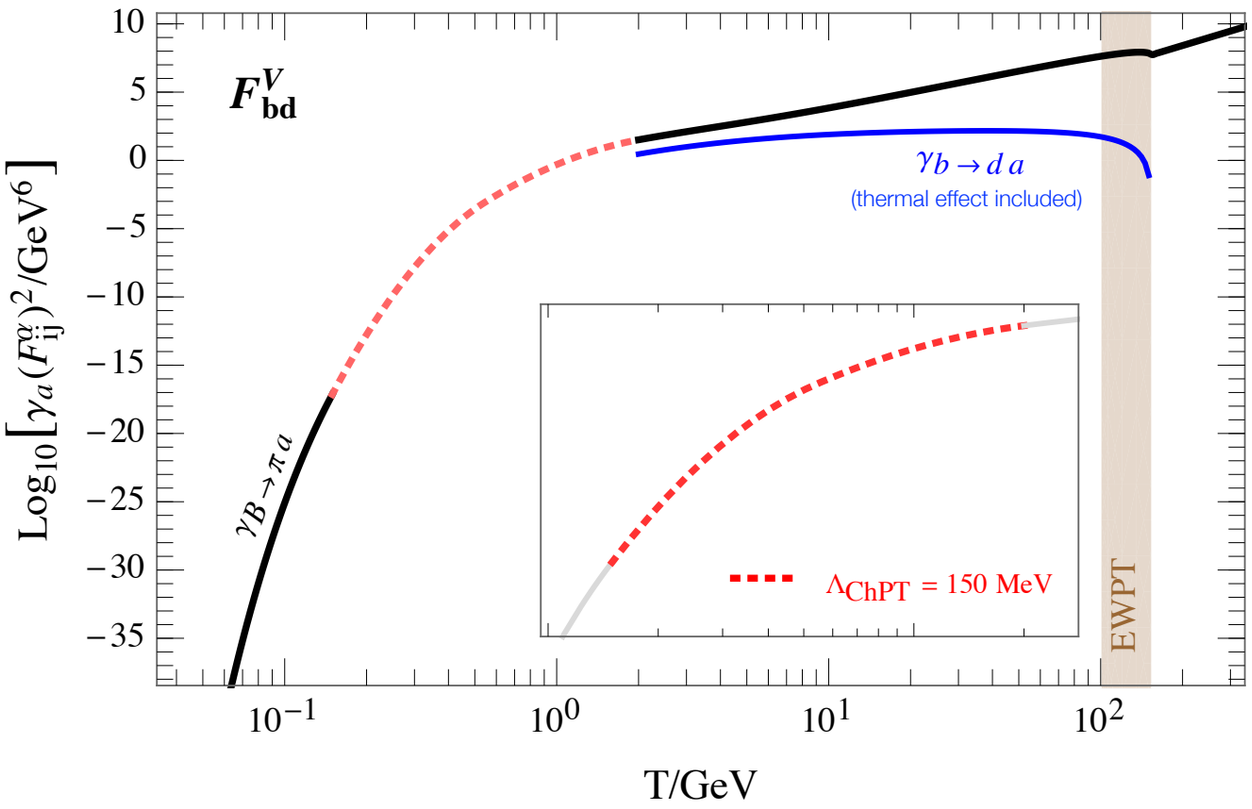
- $\frac{\partial_\mu a}{F_{bd}^{\mathrm{A}}}\,\bar{d}\gamma^\mu\gamma^5 b$

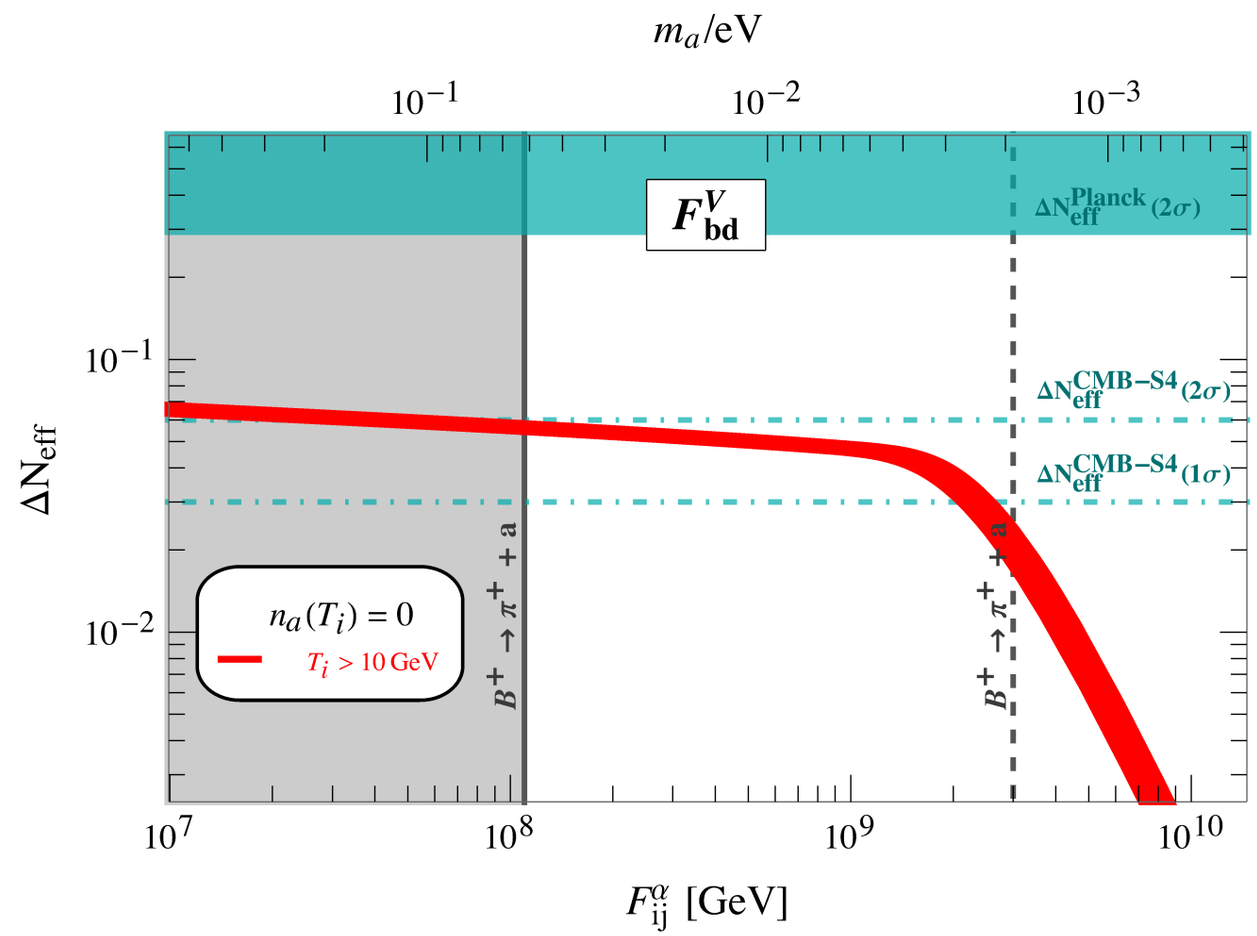




b-d vector current

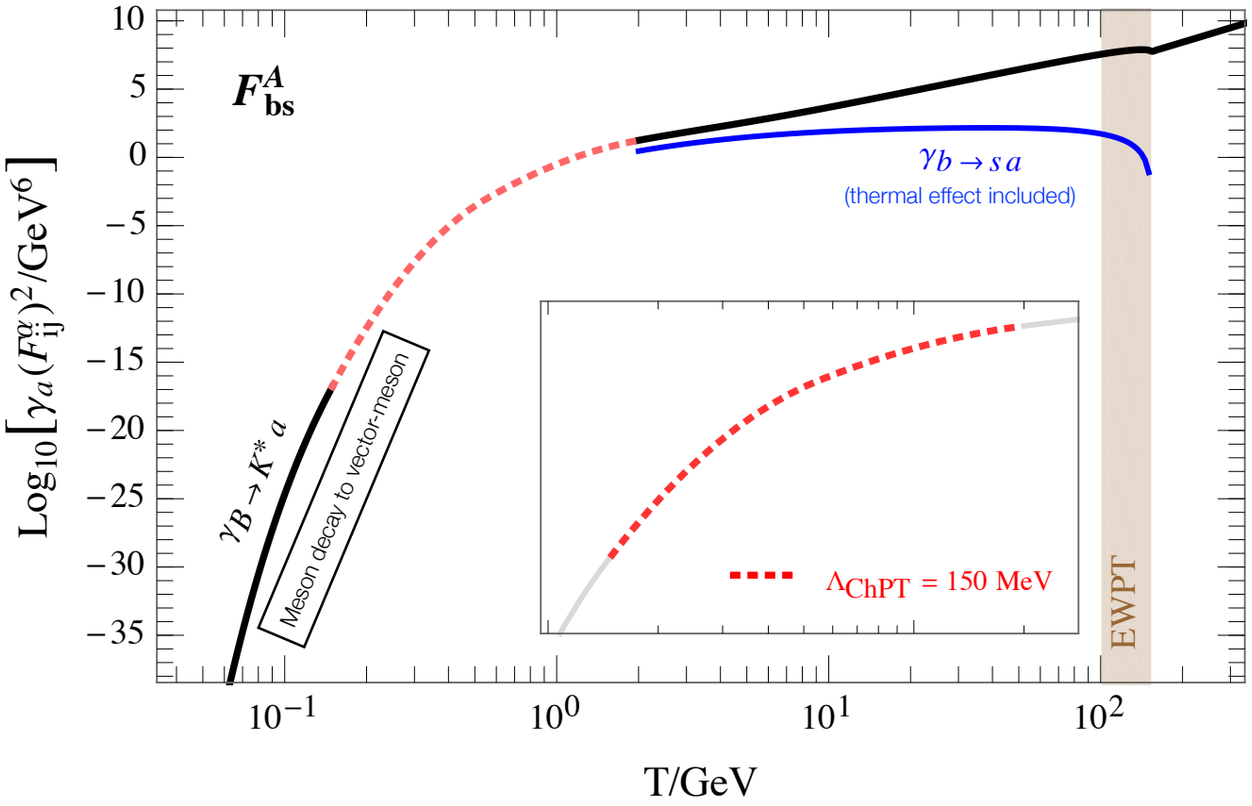
- $\dfrac{\partial_\mu a}{F_{bd}^{\mathrm{V}}}\,\bar{d}\gamma^\mu b$

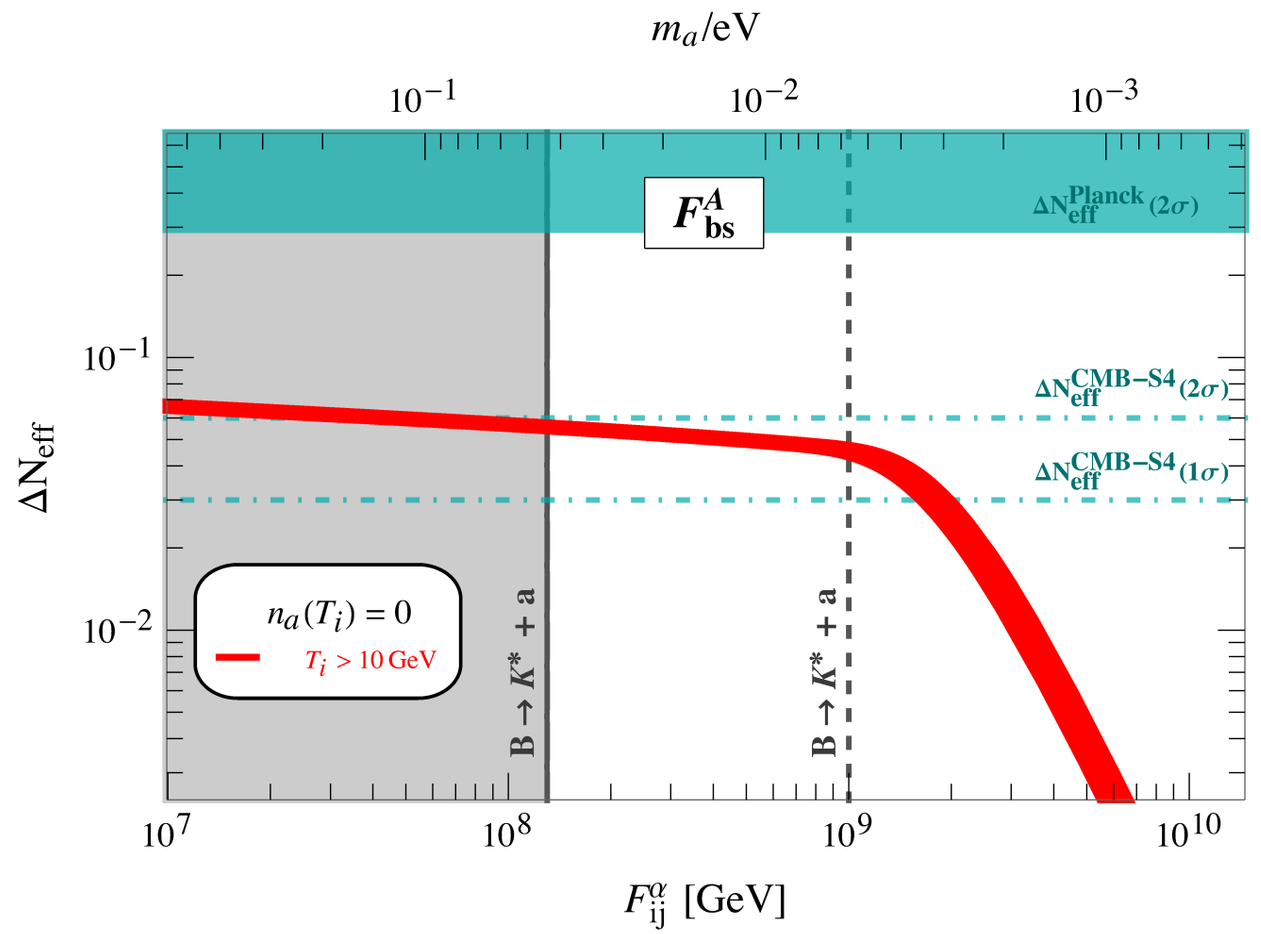




b-s axial current

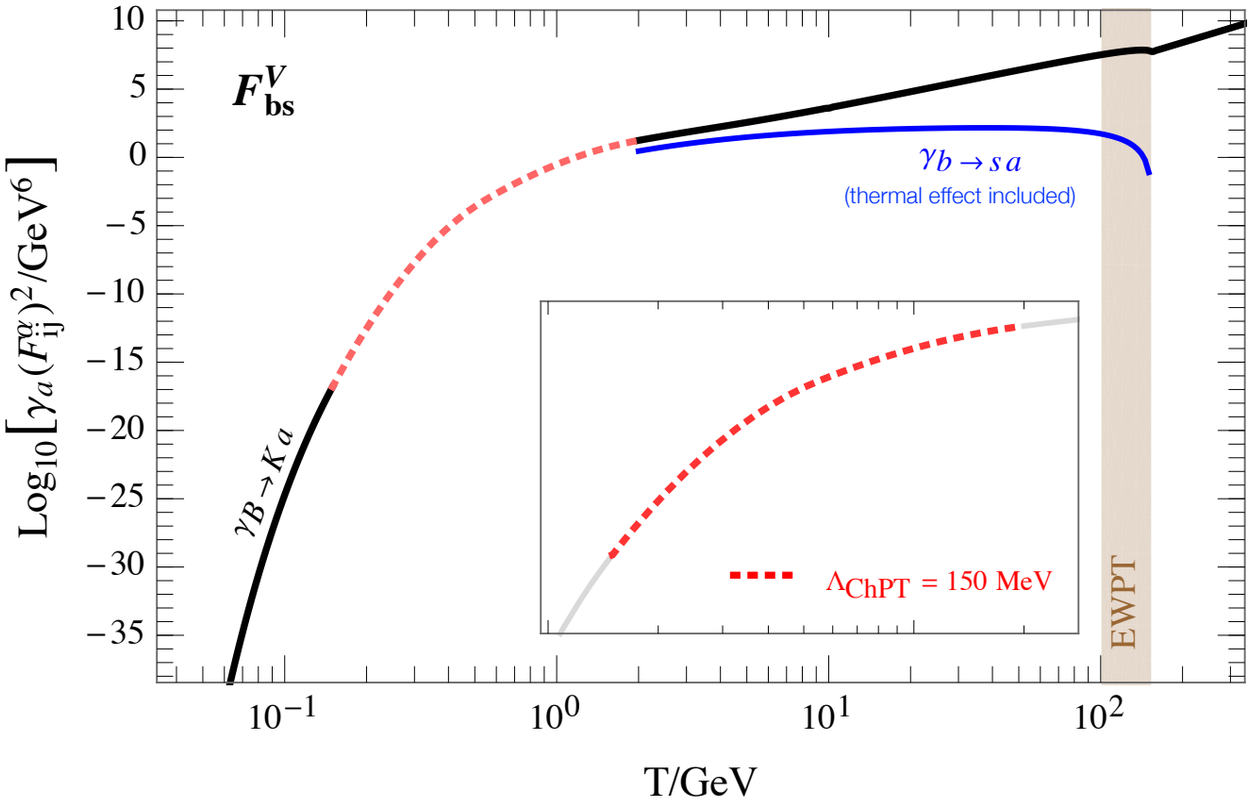
- $\frac{\partial_\mu a}{F_{bd}^{\mathrm{A}}}\,\bar{d}\gamma^\mu\gamma^5 b$

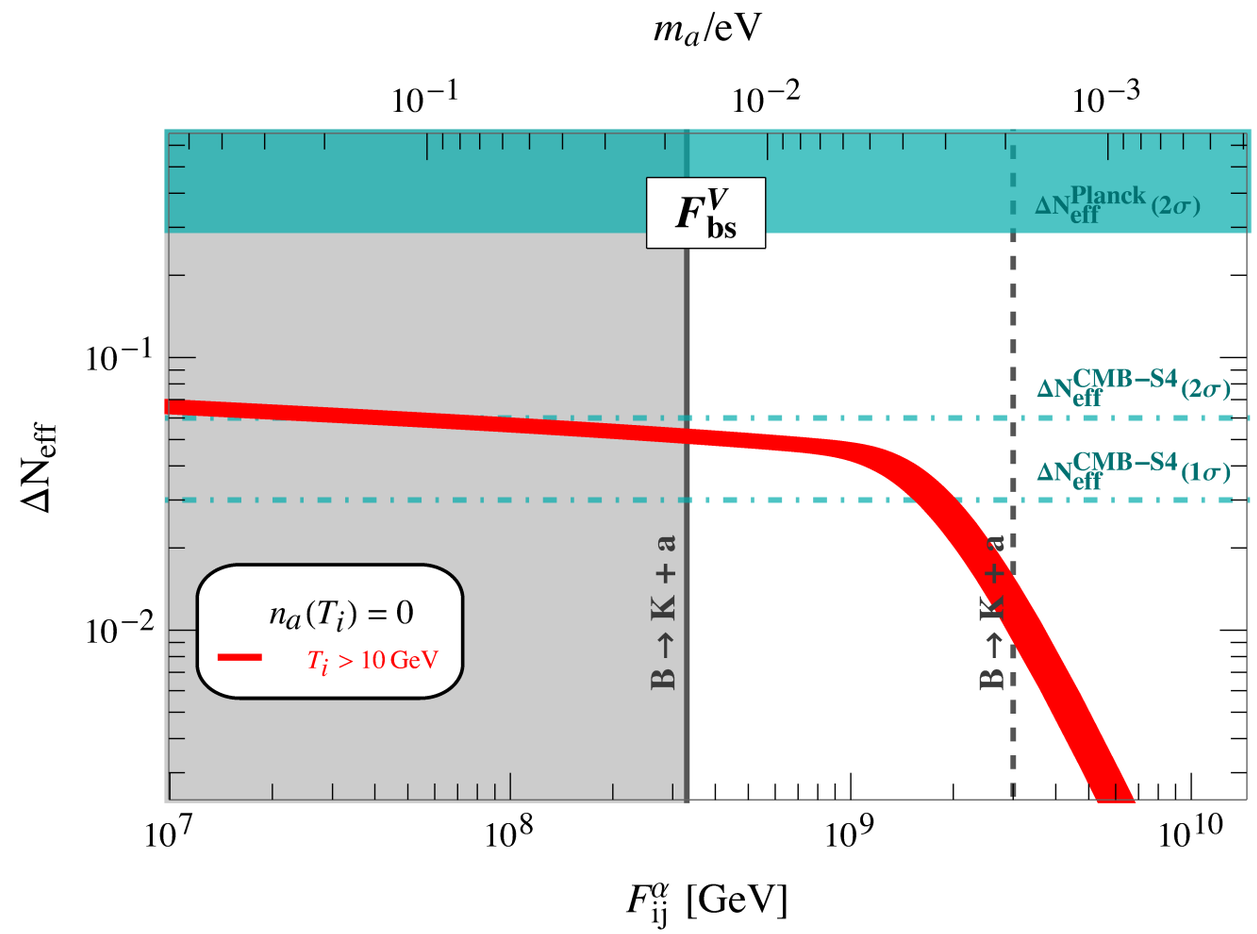




b-s vector current

- $\frac{\partial_\mu a}{F_{bd}^{\mathrm{V}}}\,\bar{d}\gamma^\mu b$

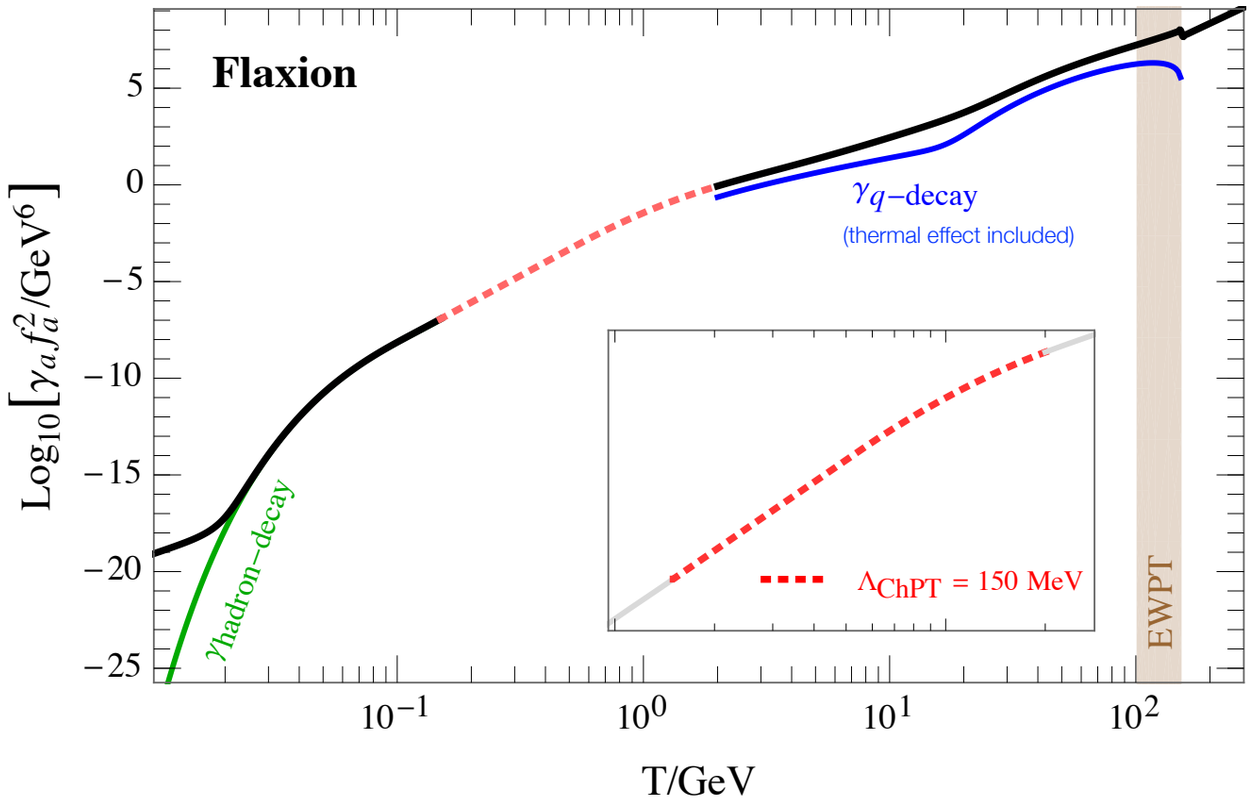


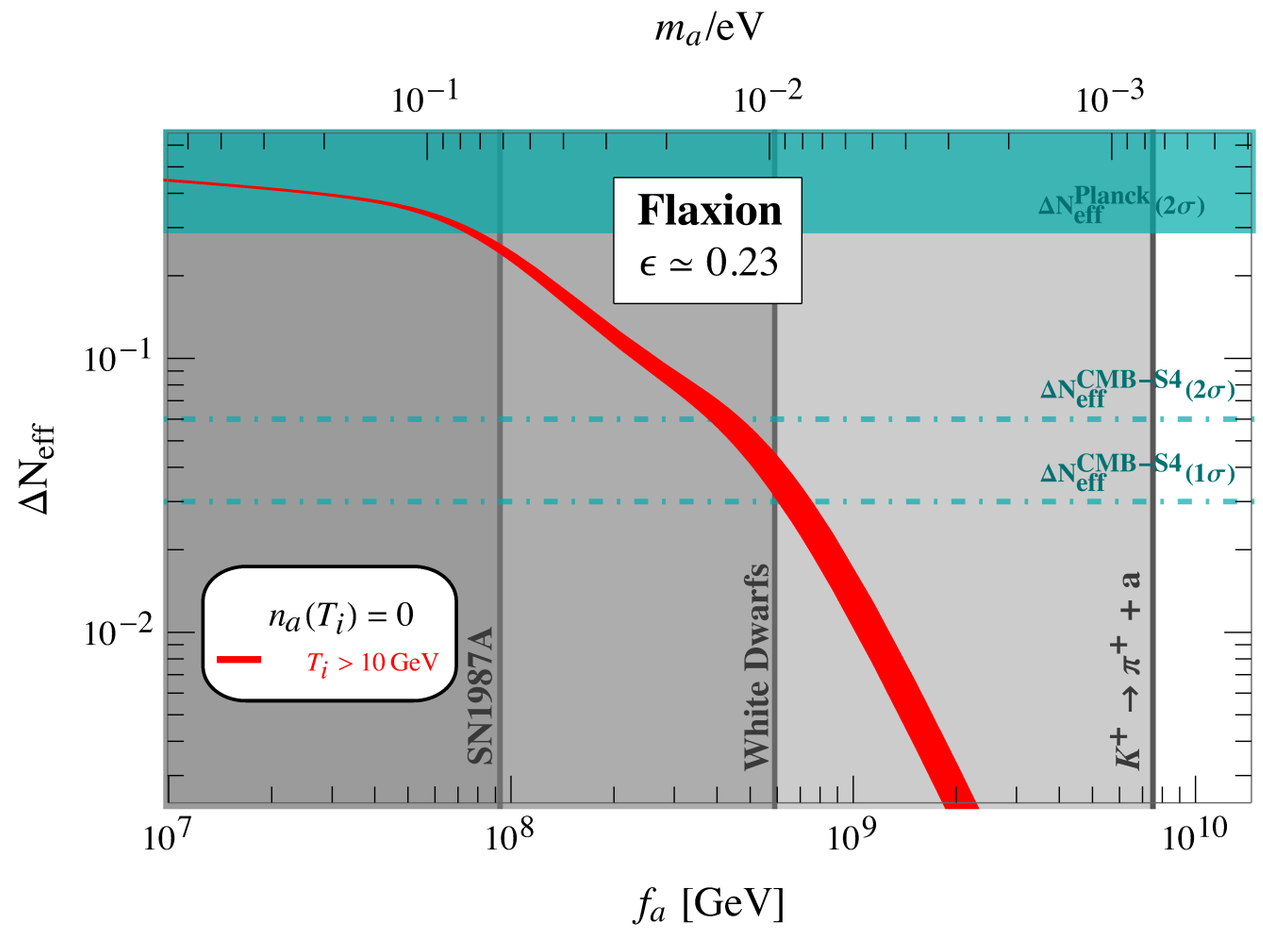


[Y. Ema et al, 2016]

Flaxion

- Froggatt-Nielson mechanism such as $-y_{ij}^{q}\left(\frac{\phi}{M}\right)^{n_{ij}^{q}}\bar{Q}_i H^{(*)} q_j$





[F. D'Eramo, SY, in progress]