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Thermal axions in the early universe

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Phys.Rev.Lett. 128 (2022) 15, 152001 [arXiv:2108.04259]
JHEP 10 (2021) 224, JHEP 10 (2021) 224 [arXiv:2108.05371]
Phys.Rev.D 105 (2022) 7, 075002 [arXiv:2111.12108]
Phys.Rev.D 105 (2022) 7, 075002 [arXiv:2205.07849]

Outline

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

02 Hot axion relic and its implications

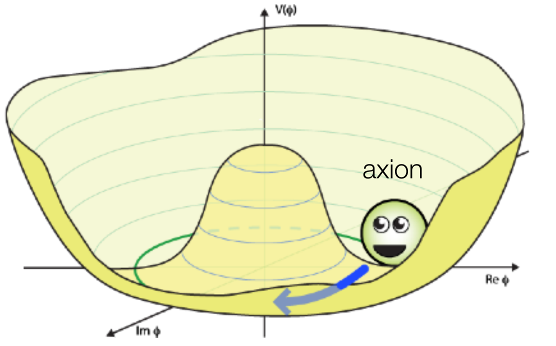
KSVZ axion scenario
- Heavy PQ fermion threshold
- QCD threshold

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

Flavor violating?

03 Conclusion

Axion



$\lesssim 10^{-10}$

- Solution for the strong CP problem $\bar{\theta}_s G_{\mu\nu}\tilde{G}^{\mu\nu}$
- Global Peccei-Quinn symmetry - Pseudo Nambu-Goldstone boson after spontaneous breaking at f_a
- Mass and coupling $\propto f_a^{-1}$ (axion-like particle if mass is independent of f_a)
- Dark matter candidate

Cold ❄

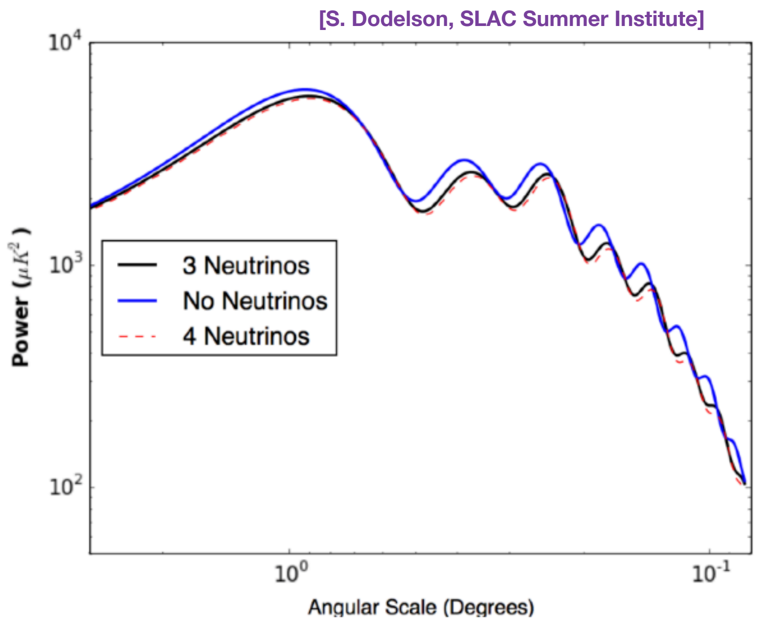
- Wave dark matter (e.g., θ_i or $\dot{\theta}_i$)
  - ✓ $\Omega_a/\Omega_{\rm DM} \simeq 1$ for $f_a \sim 10^{12}\,{\rm GeV}$ & $\theta_i \simeq 1$

Hot ♨

- Cosmic axion background
  - ***thermal production***
  - decay of heavy DM or topological defect
  - etc

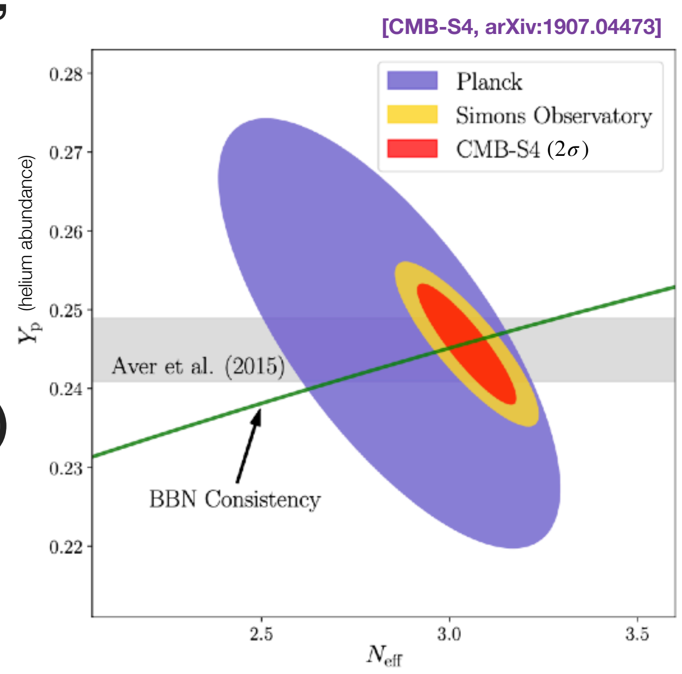
Axion dark radiation?

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



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

✤ BBN primordial light element abundances



- Current bound from *Planck* $N_{\rm eff} = 2.99 \pm 0.17$ ☞ $\Delta N_{\rm eff} < 0.3$
- Future sensitivity from *CMB-S4* $\Delta N_{\rm eff} = 0.03\ (0.06)$ for $1\sigma\ (2\sigma)$

Boltzmann equation

- Quantitative tool to track the abundance

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

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

RD era $\begin{cases} n\leq 4 & \cdots \texttt{ IR} \\ n>4 & \cdots \texttt{ UV} \end{cases}$

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

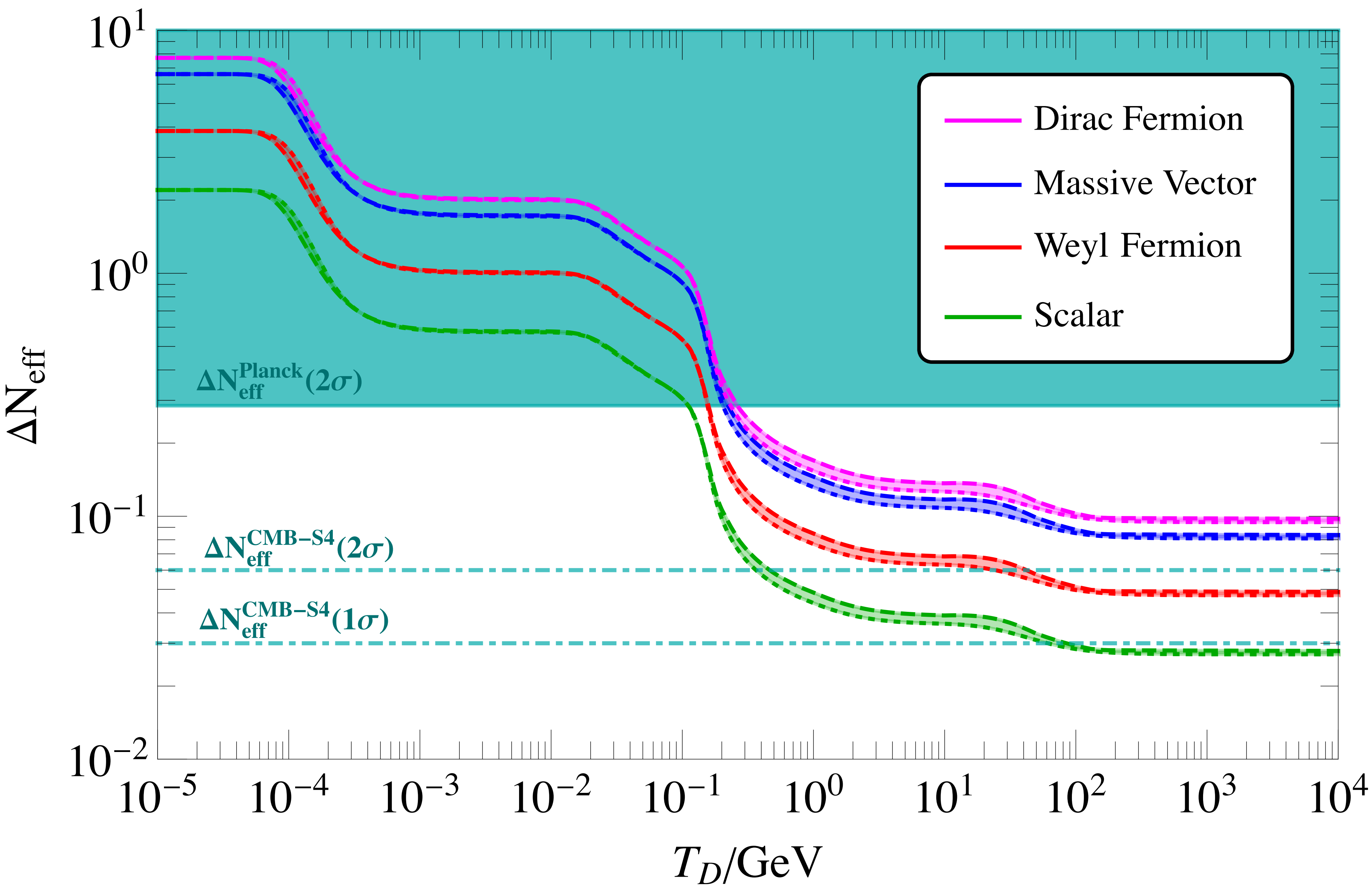
$$\longrightarrow \frac{dY_a}{d\log x}=\left(1-\frac{1}{3}\frac{d\log g_{*s}}{d\log x}\right)\frac{\gamma_a}{sH}\left(1-\frac{Y_a}{Y_a^{\rm eq}}\right)$$

$\gamma(T_d)/n_a(T_d)\sim H(T_d)$

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

$\simeq 13.7\,g_{*s}^{-4/3}(T_d)$

ΔN_{eff} VS T_D



Axion interactions

[H. Gerogi et al, 86]

- Linearly realized

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

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

- Non-Linearly realized

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

$\Rightarrow$ PQ current

- Axion shift symmetry $a \to a + \mathrm{const}$
- PQ current $\Rightarrow$ relevant to matching

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

field redefinition relying on div. of PQ currents $\partial_\mu j^\mu_{\mathrm{PQ}}$

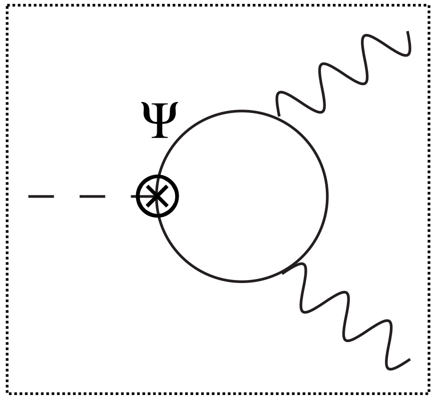
KSVZ axion scenario

- Ingredients: heavy colored PQ fermion (Ψ) & PQ singlet scalar ($\varphi \to f_a e^{ia/f_a}/\sqrt{2}$)

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

- Triangle diagram with Ψ-loop leads to

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

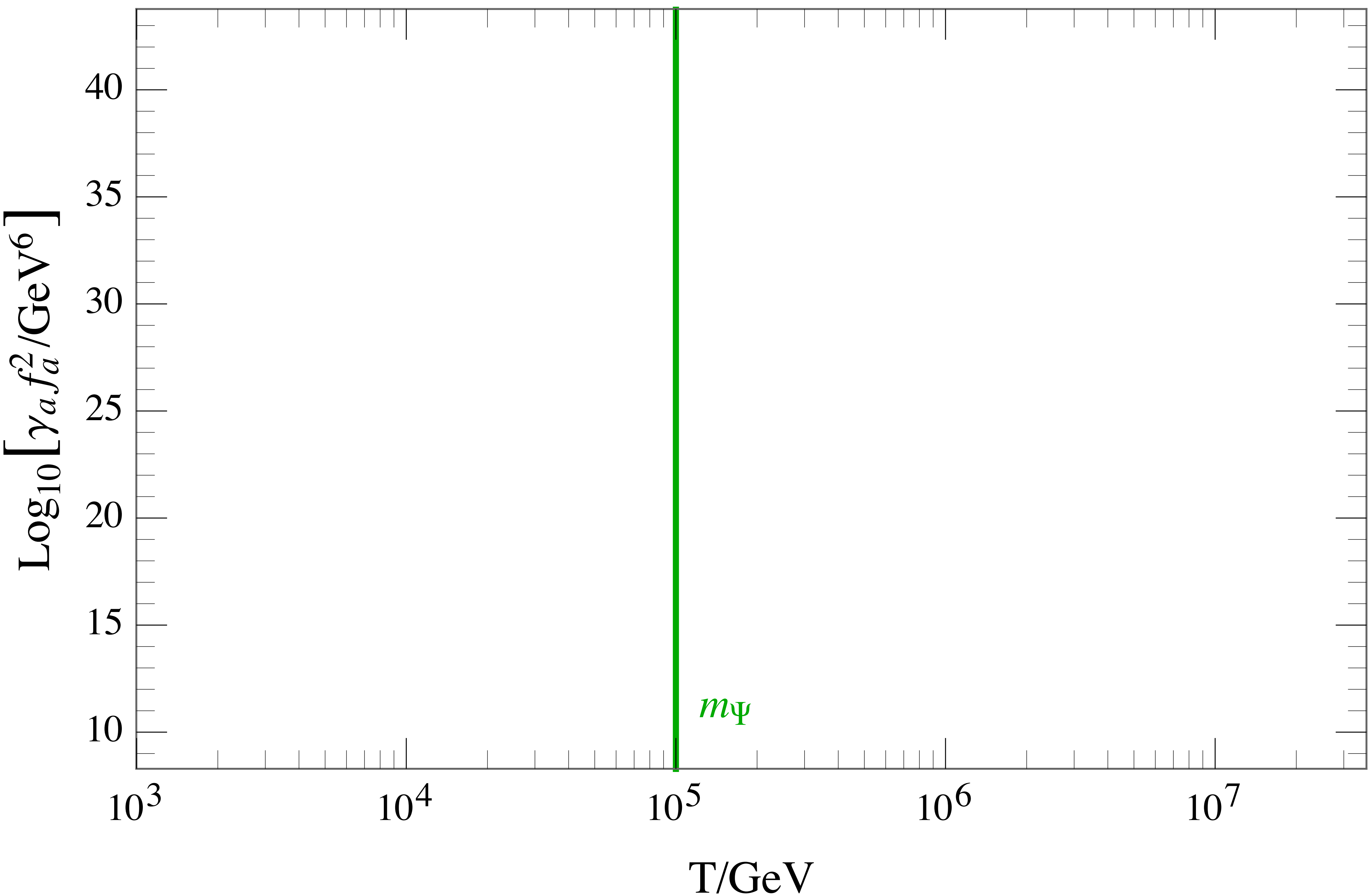


- Two thresholds

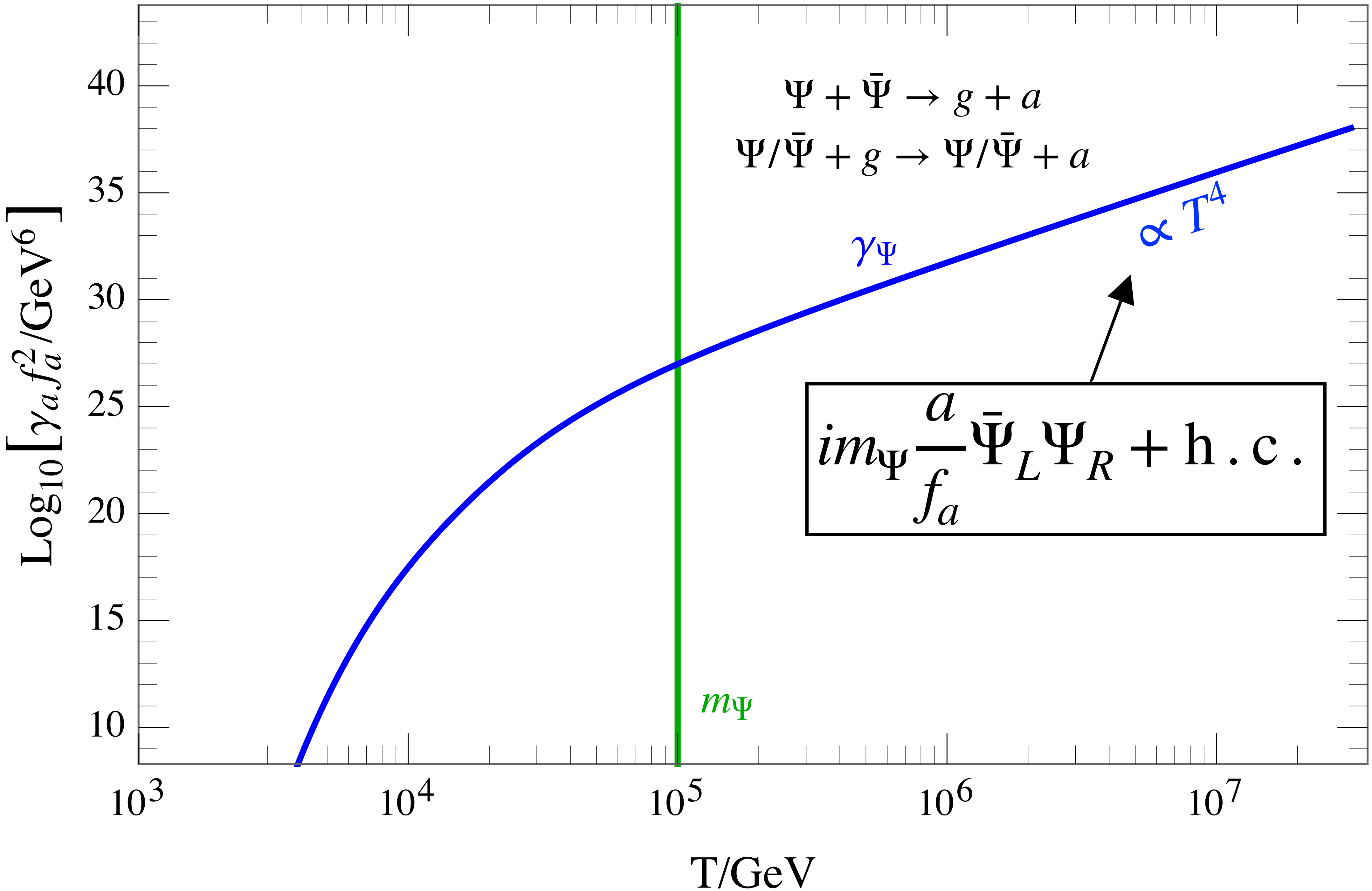
  @ *mass of* $\Psi \equiv m_\Psi$

  @ *QCD confinement* $\Lambda_{\rm QCD}$

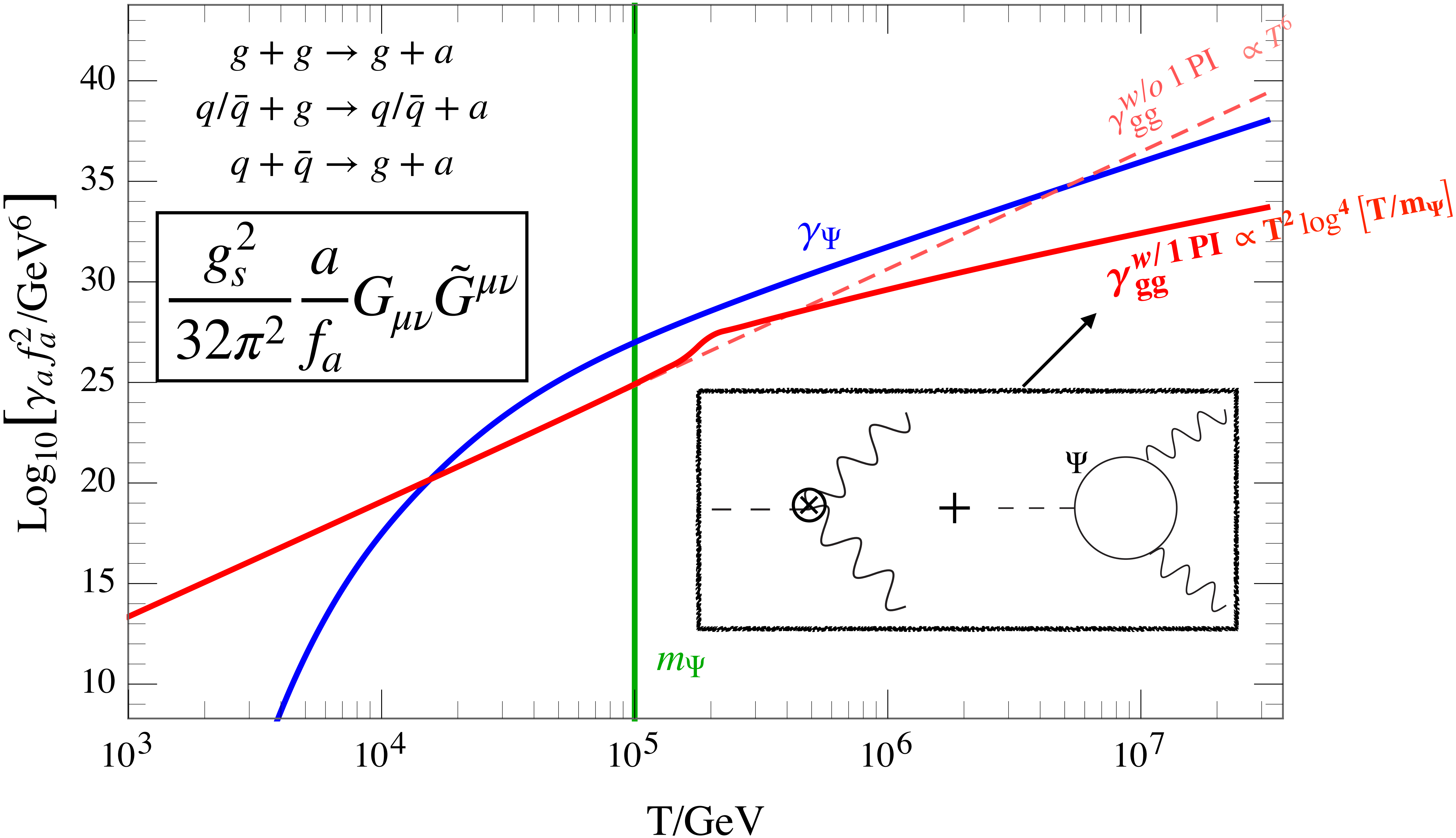
Heavy PQ fermion threshold



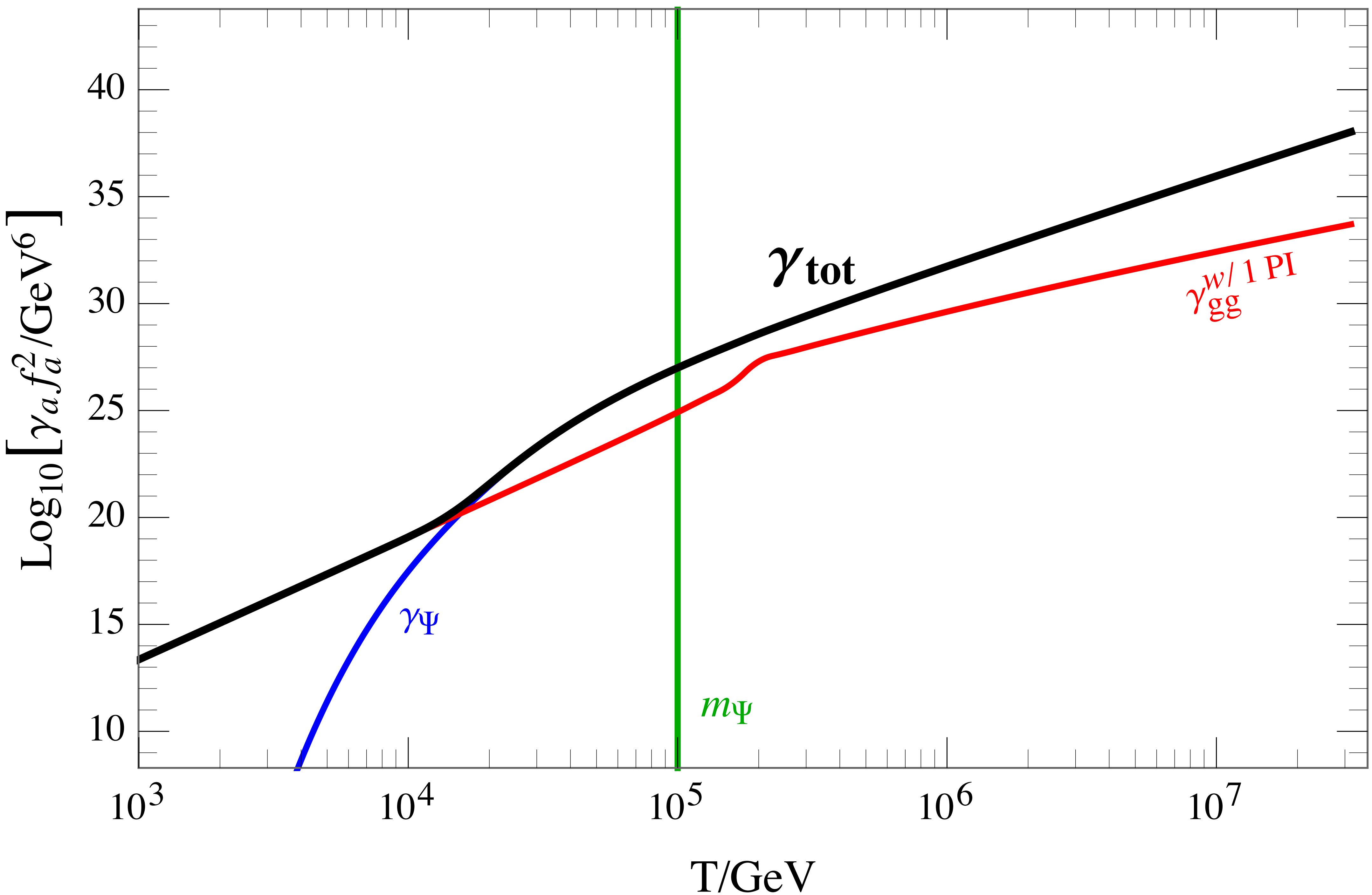
Heavy PQ fermion threshold



Heavy PQ fermion threshold

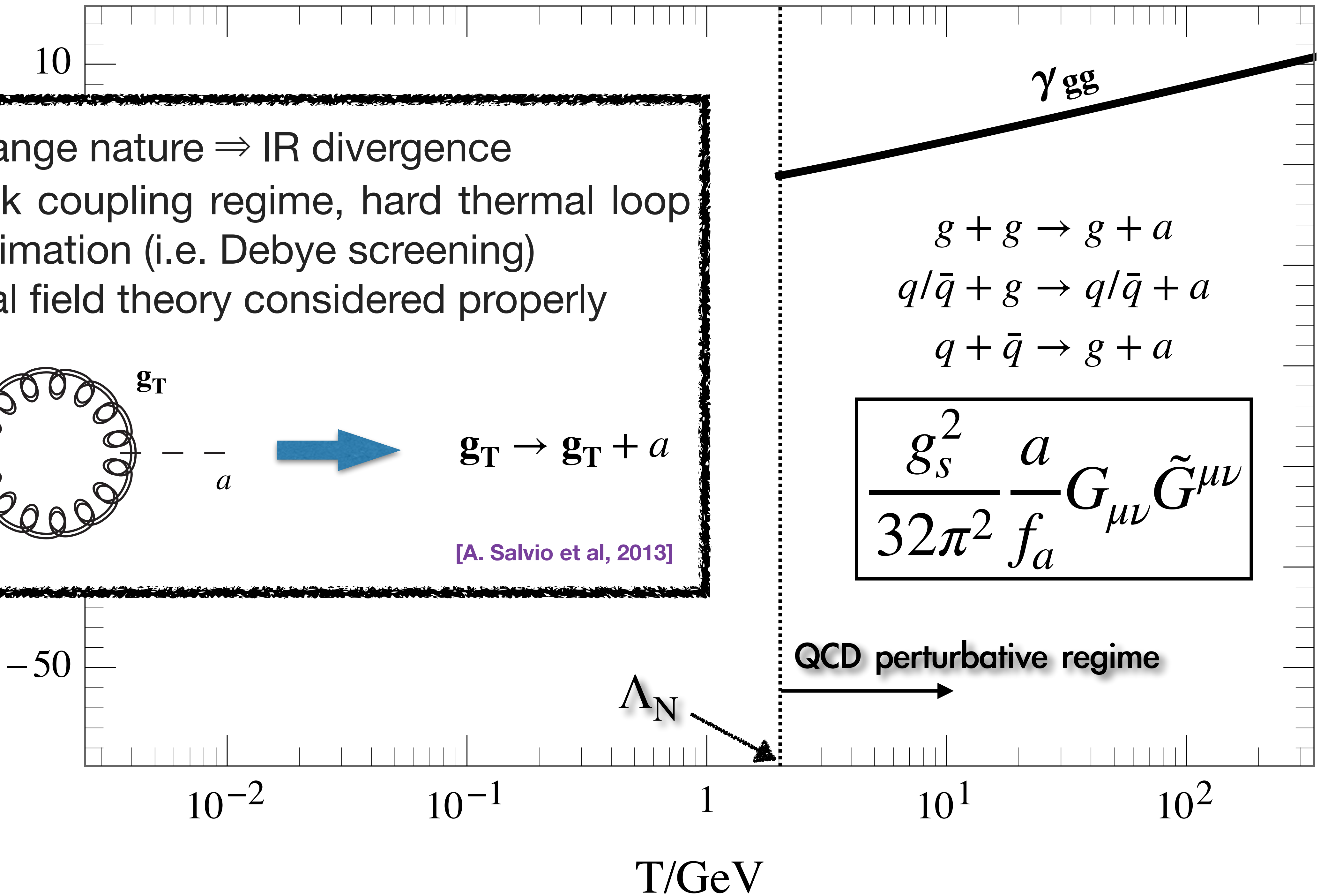


Heavy PQ fermion threshold

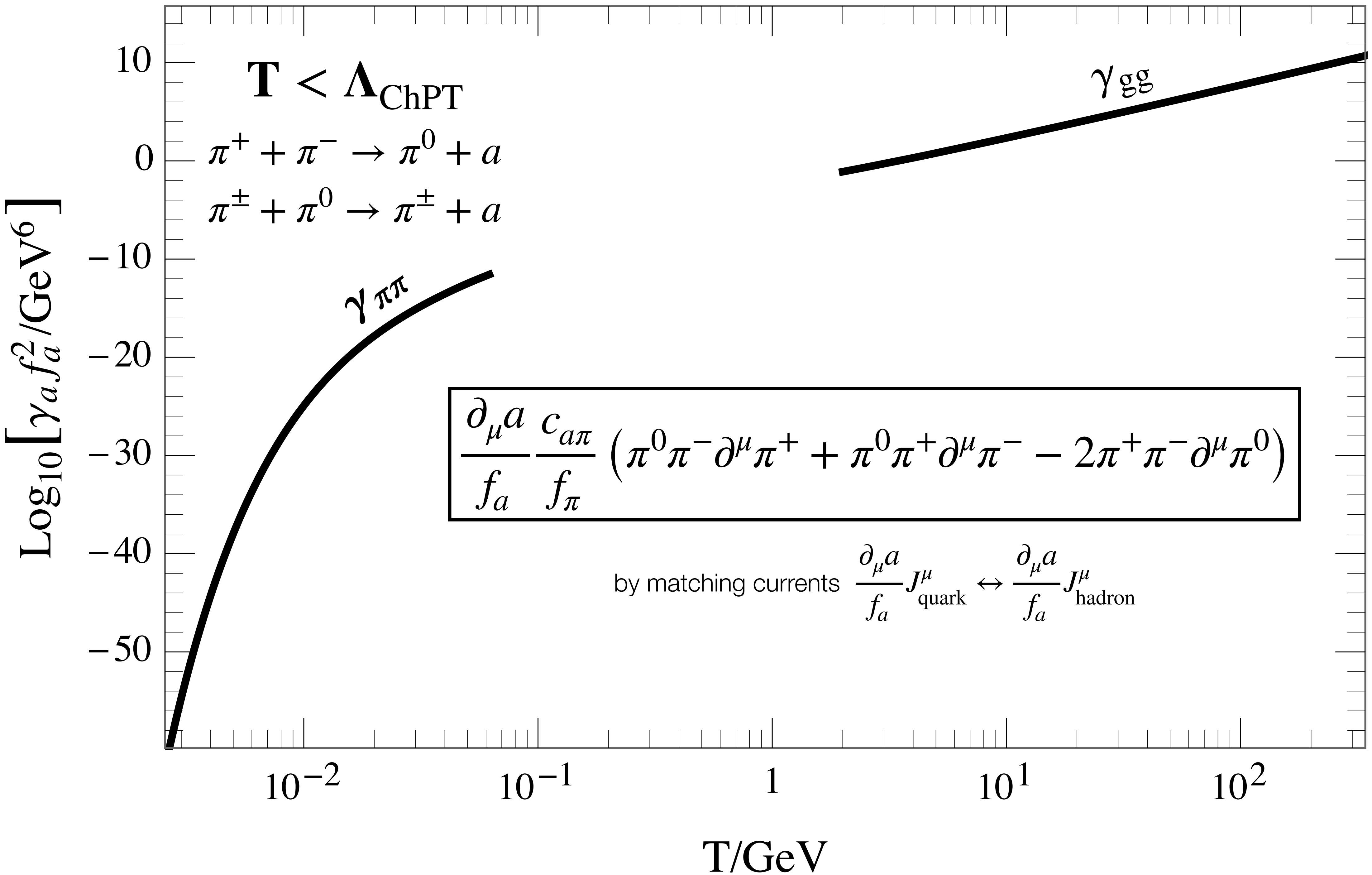


QCD threshold

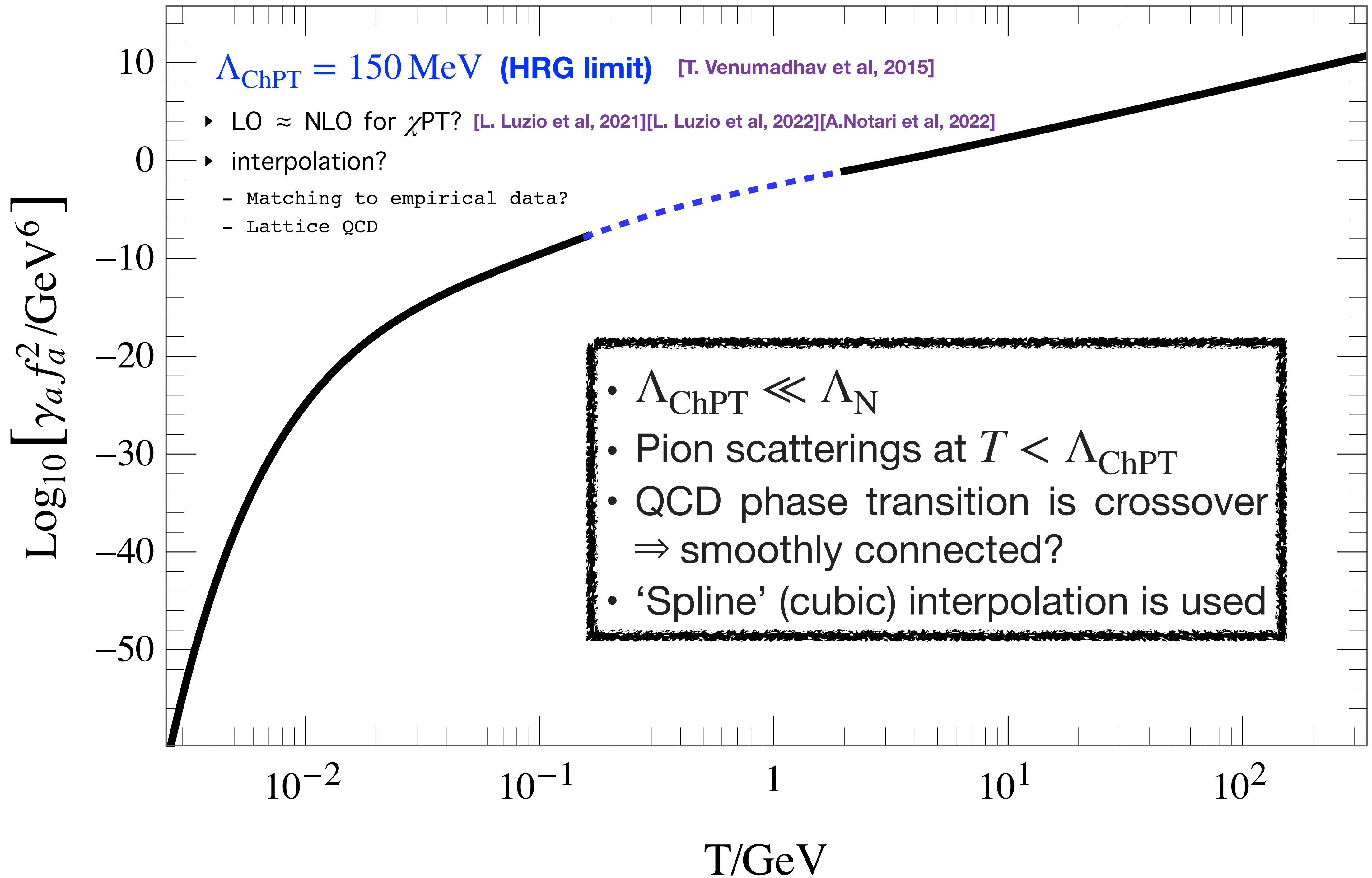
- Long range nature ⇒ IR divergence
- At weak coupling regime, hard thermal loop approximation (i.e. Debye screening)
- Thermal field theory considered properly



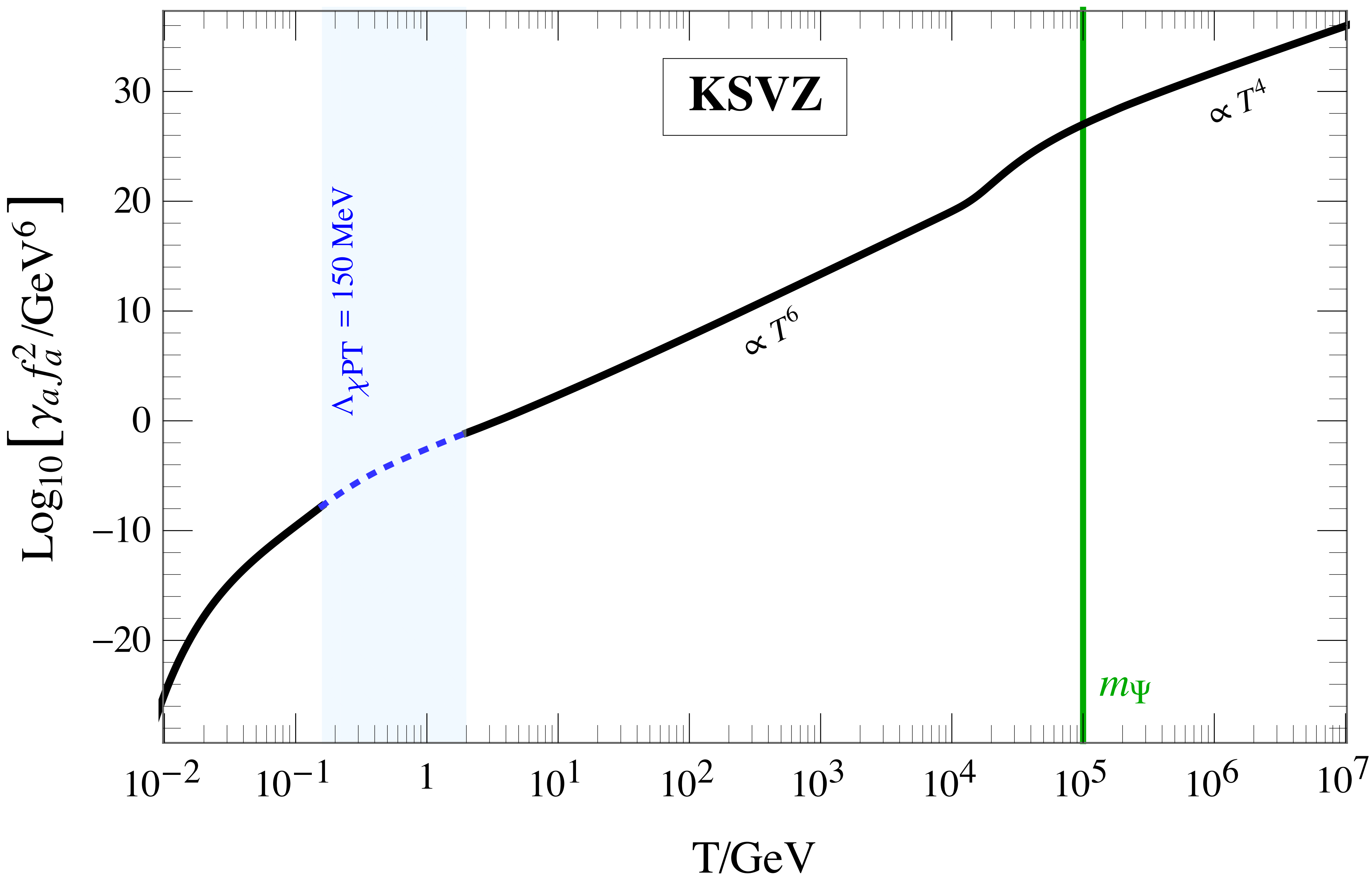
QCD threshold



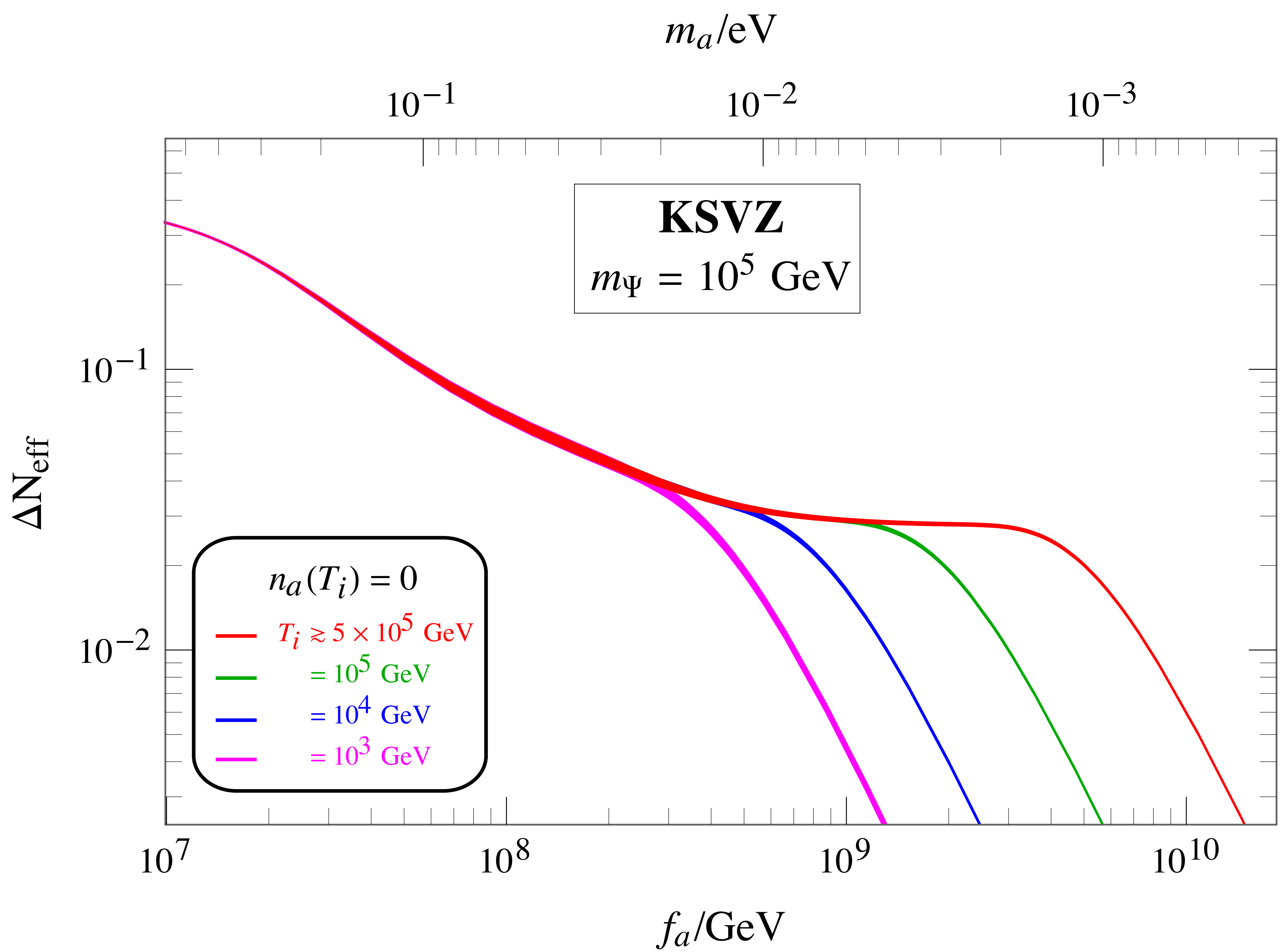
QCD threshold



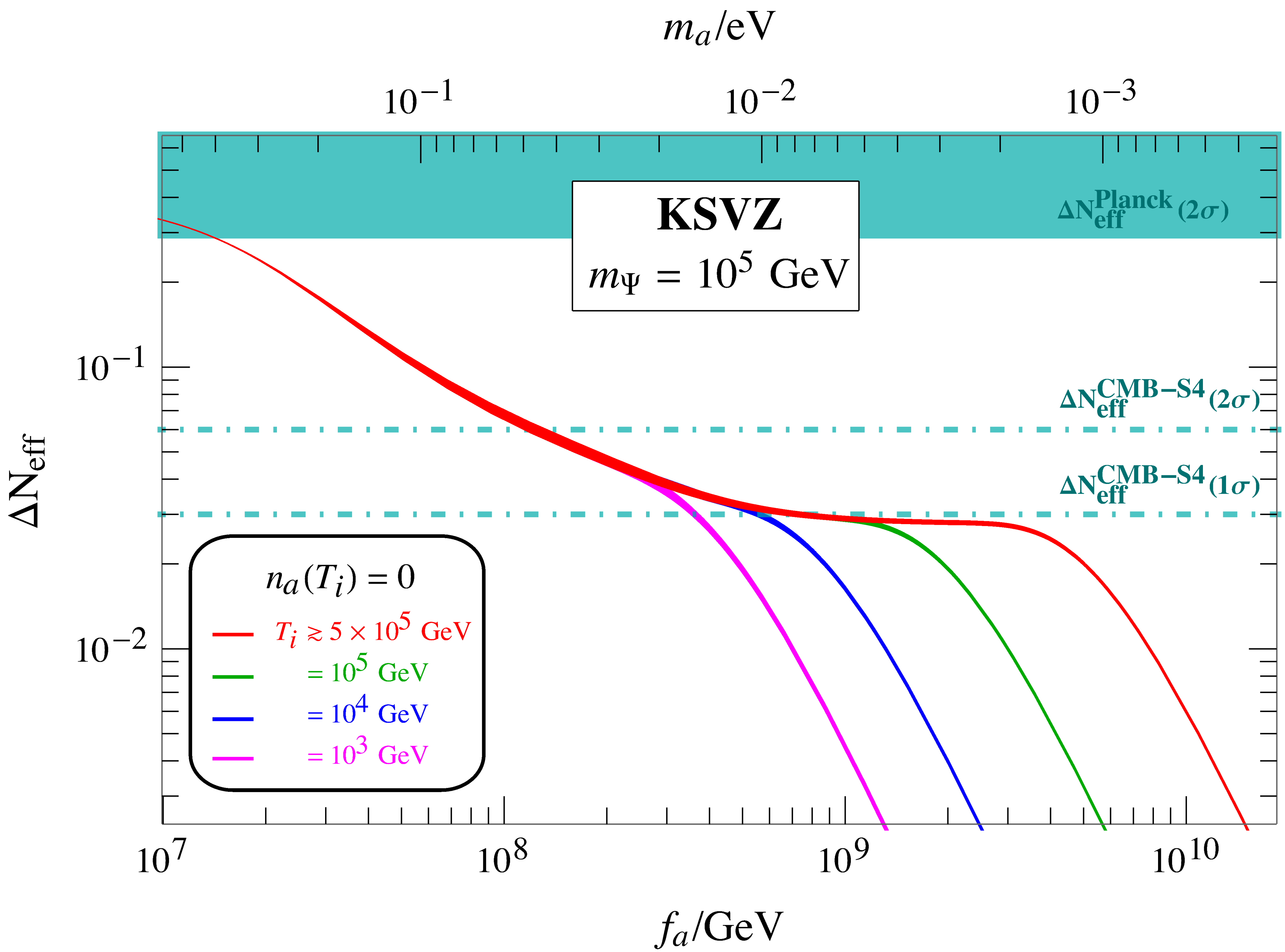
KSVZ axion production rate



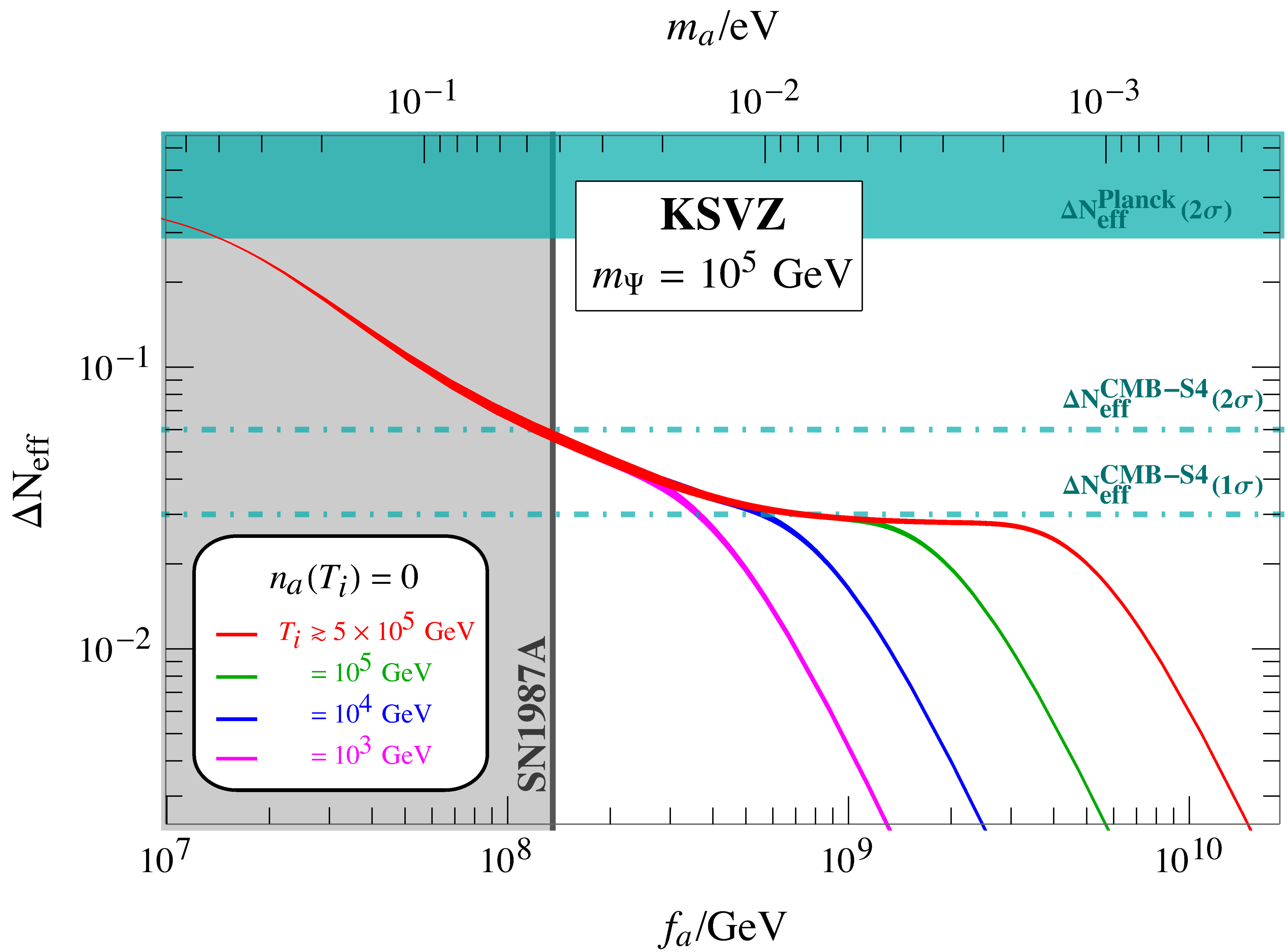
Hot KSVZ axion relic



Hot KSVZ axion relic



Hot KSVZ axion relic



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

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

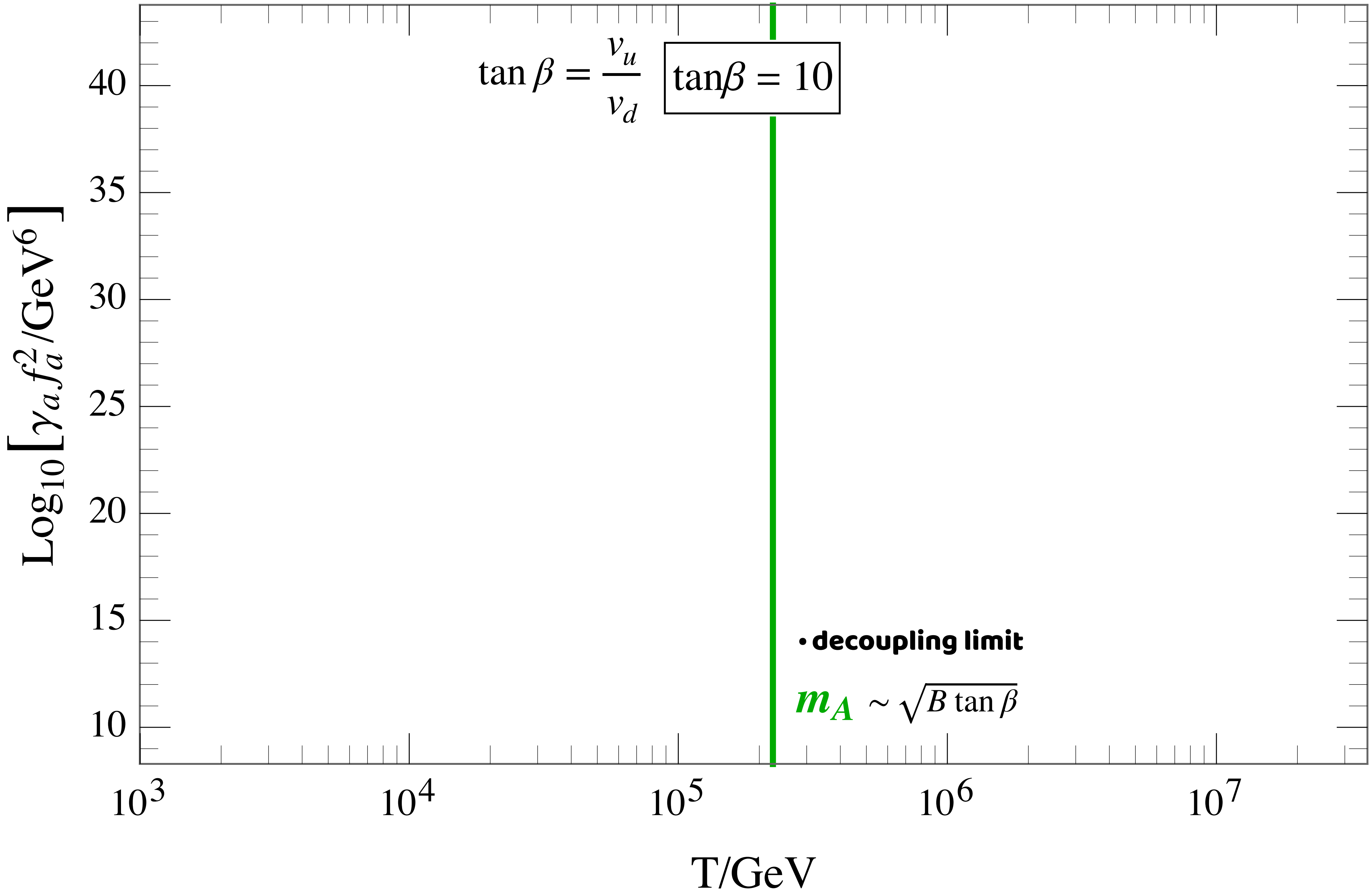
- Two + one thresholds

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

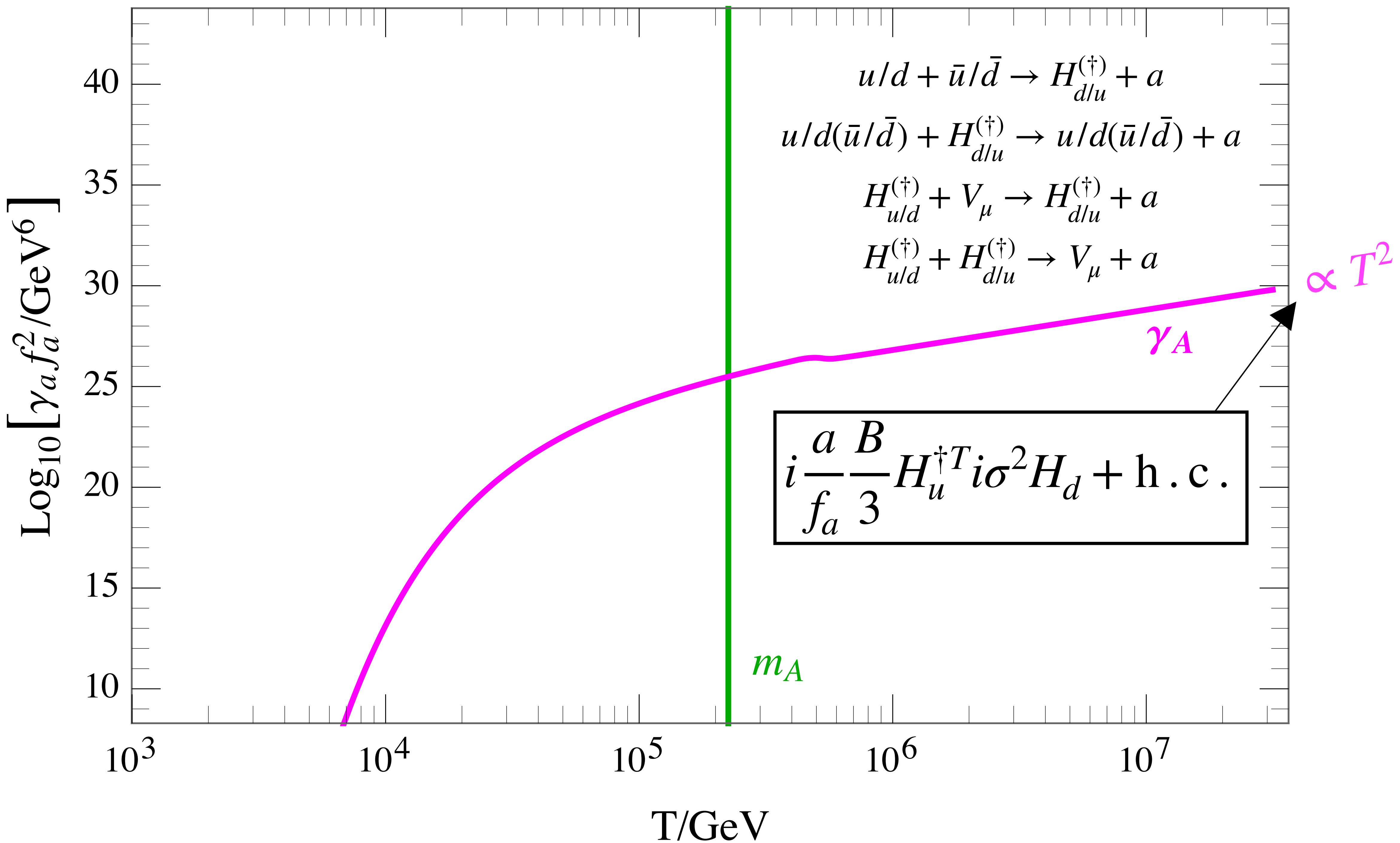
@ electroweak phase transition

@ QCD confinement

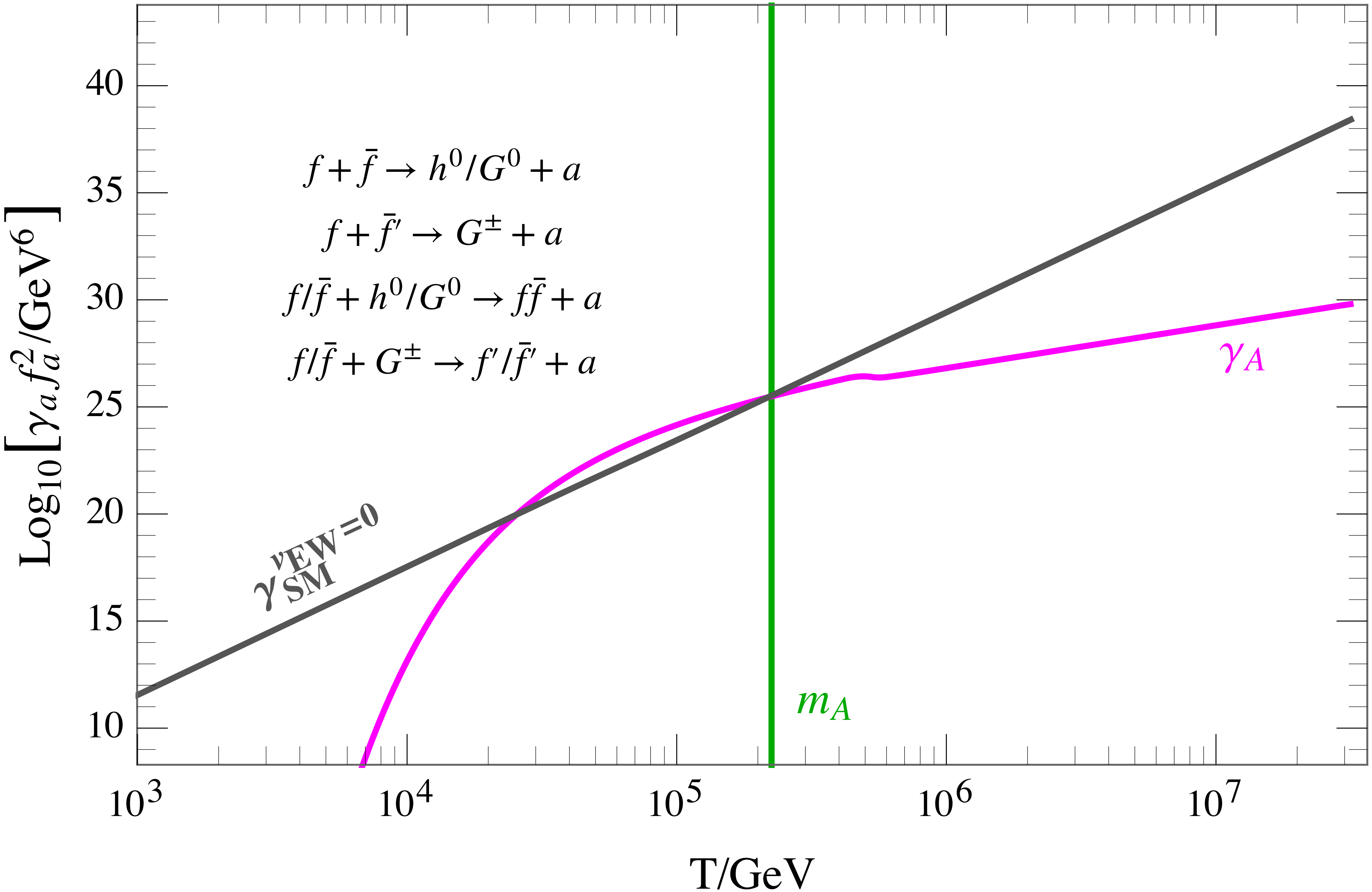
Heavy Higgs boson threshold



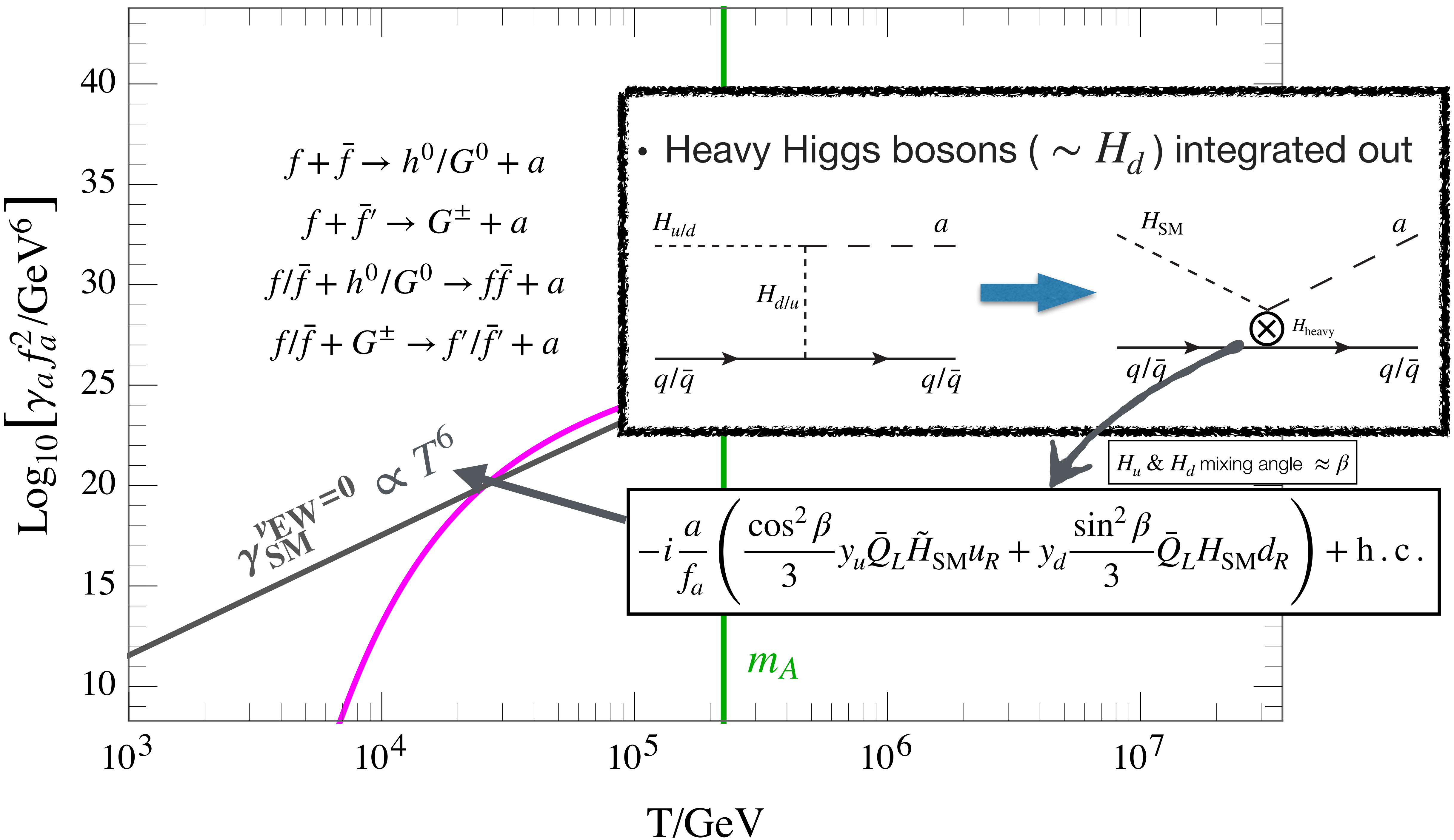
Heavy Higgs boson threshold



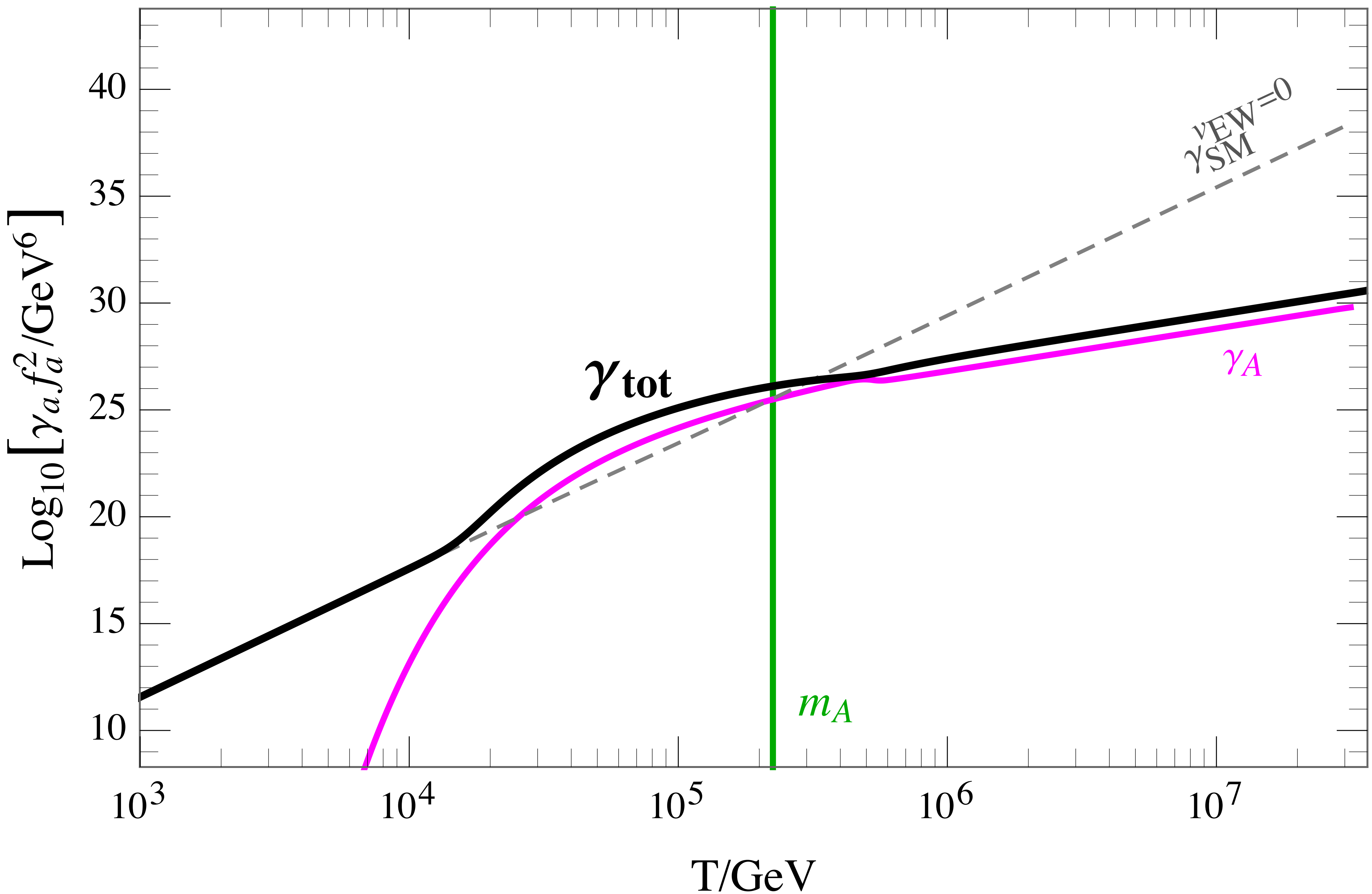
Heavy Higgs boson threshold



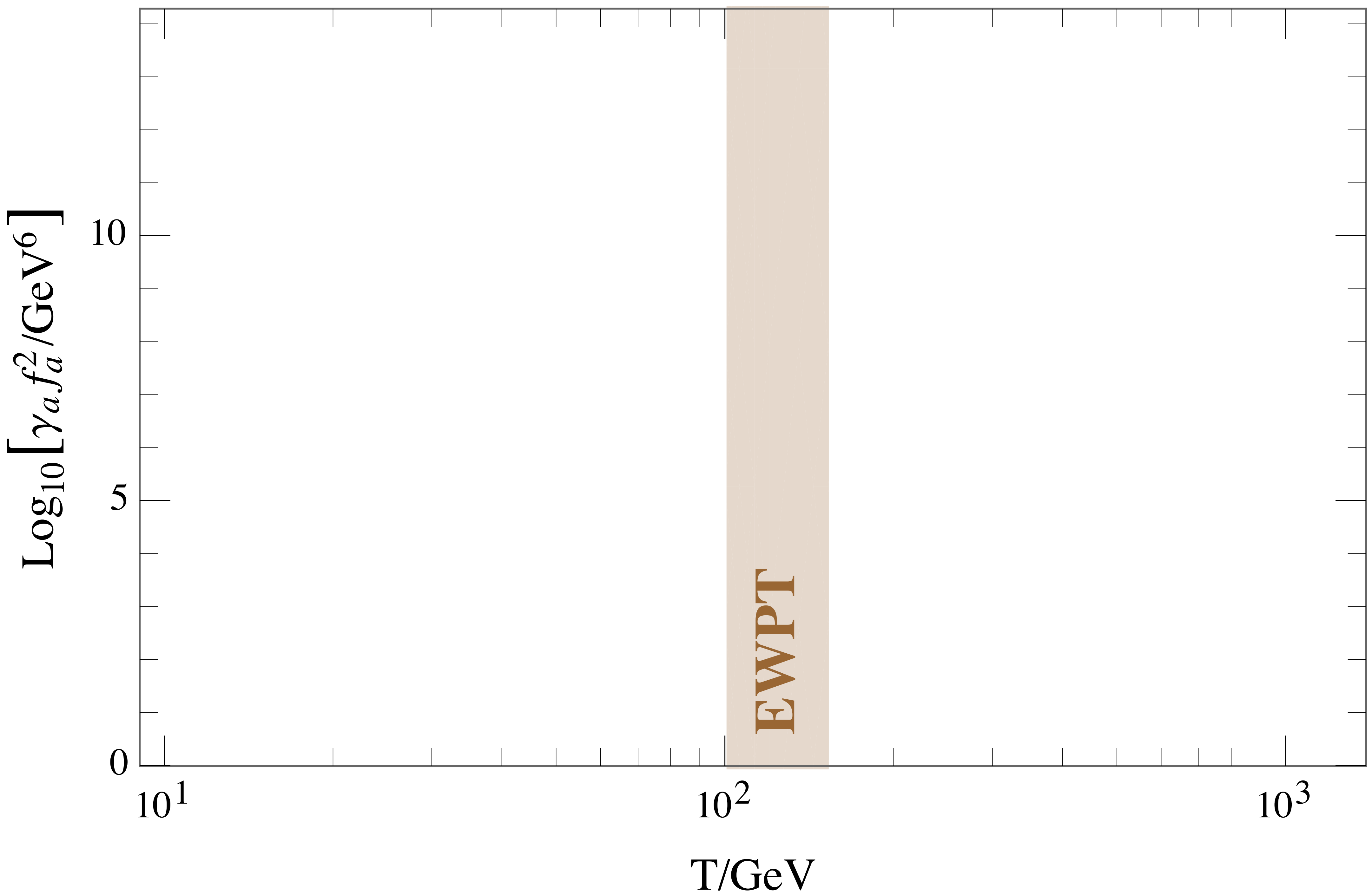
Heavy Higgs boson threshold



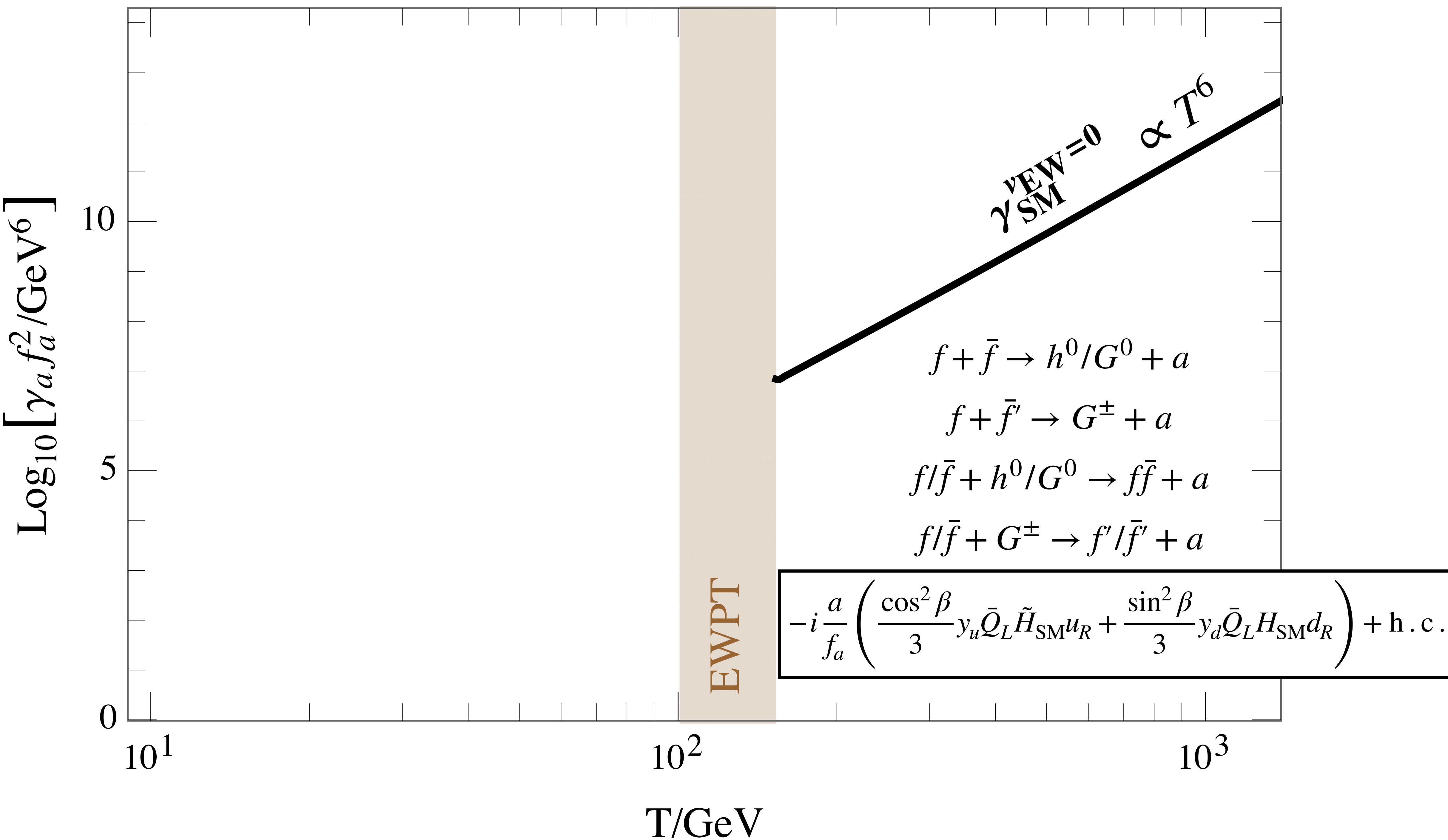
Heavy Higgs boson threshold



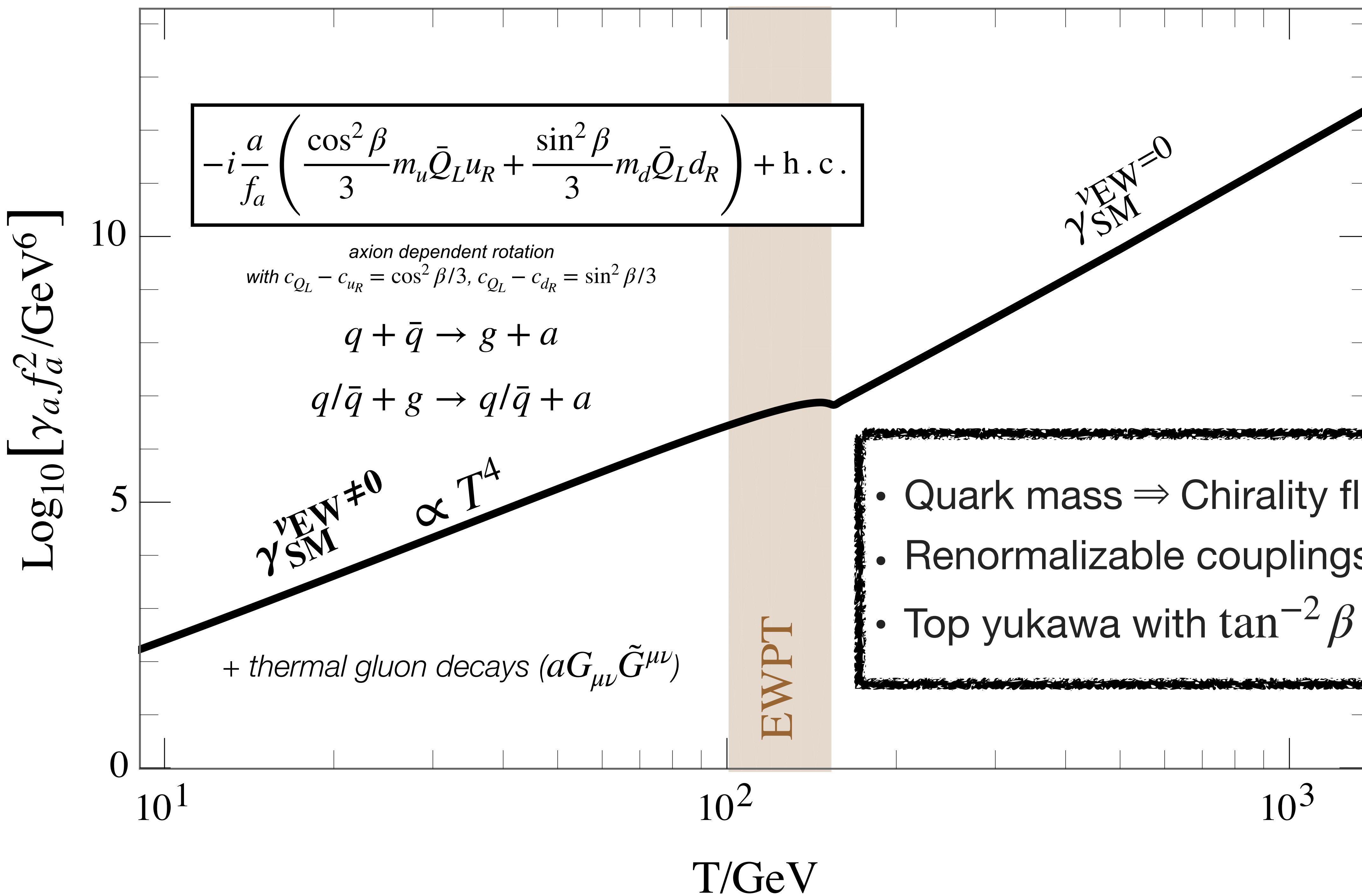
Electroweak threshold



Electroweak threshold

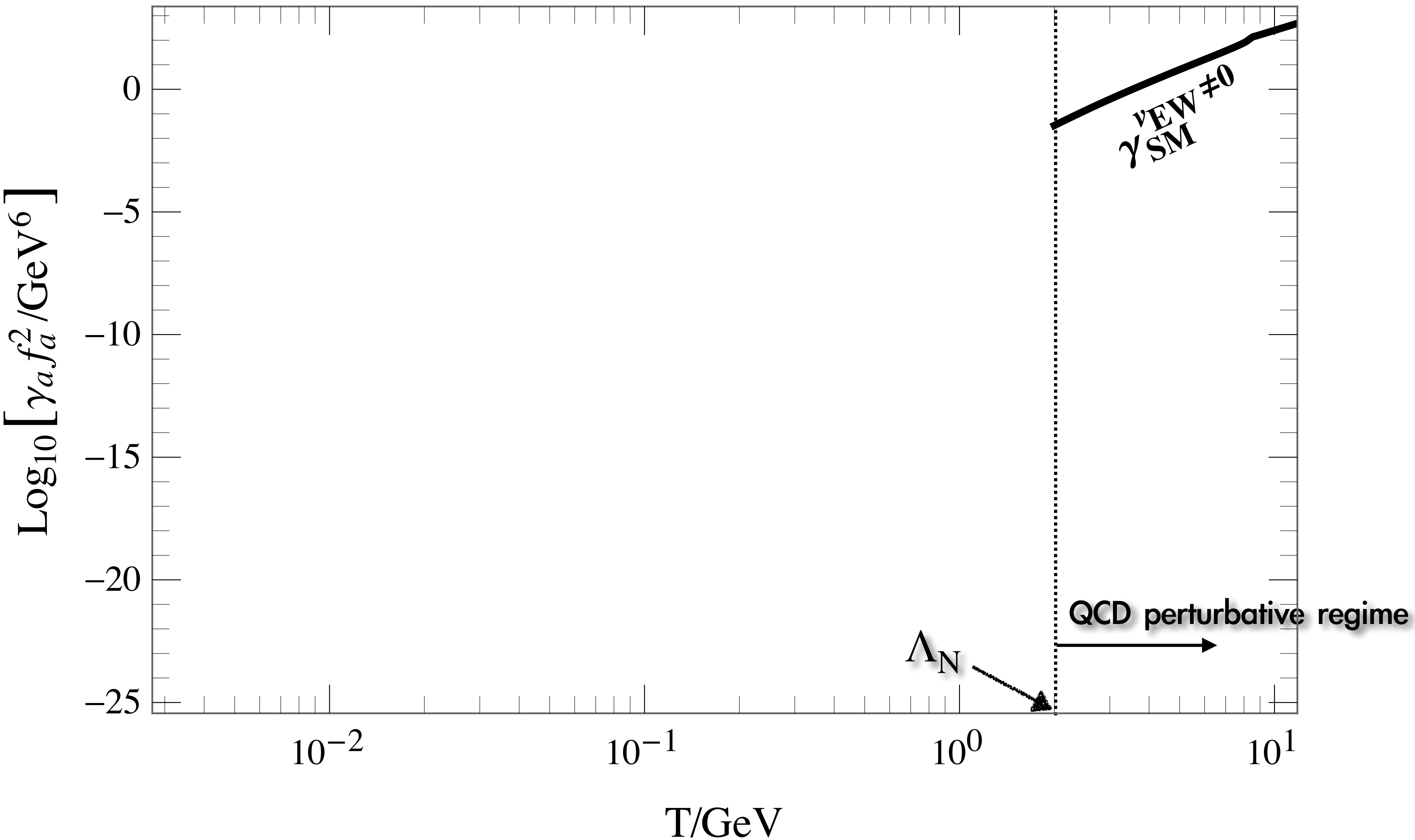


Electroweak threshold

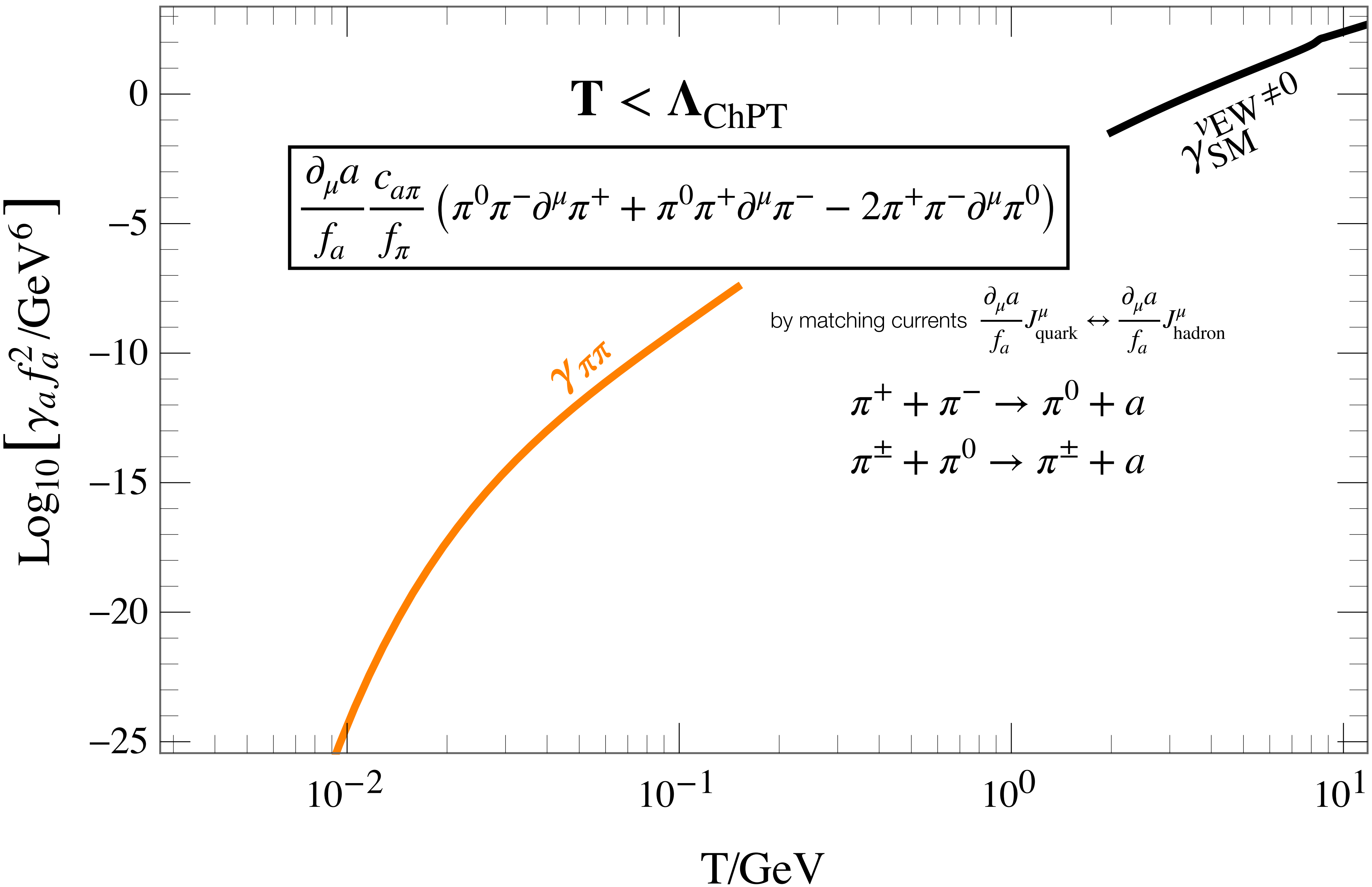


- Quark mass ⇒ Chirality flip
- Renormalizable couplings m_q/f_a
- Top yukawa with $\tan^{-2}\beta$

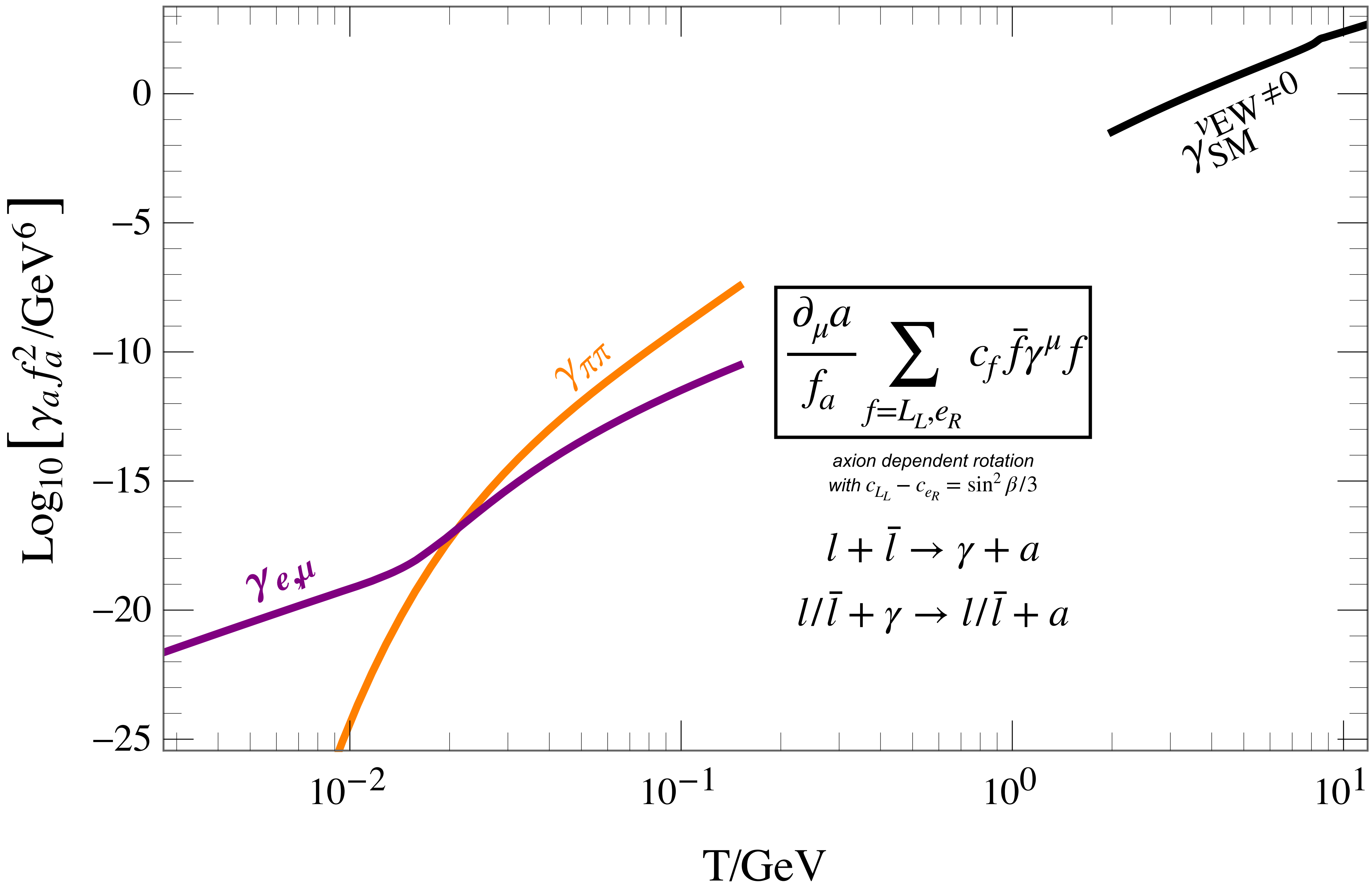
QCD threshold



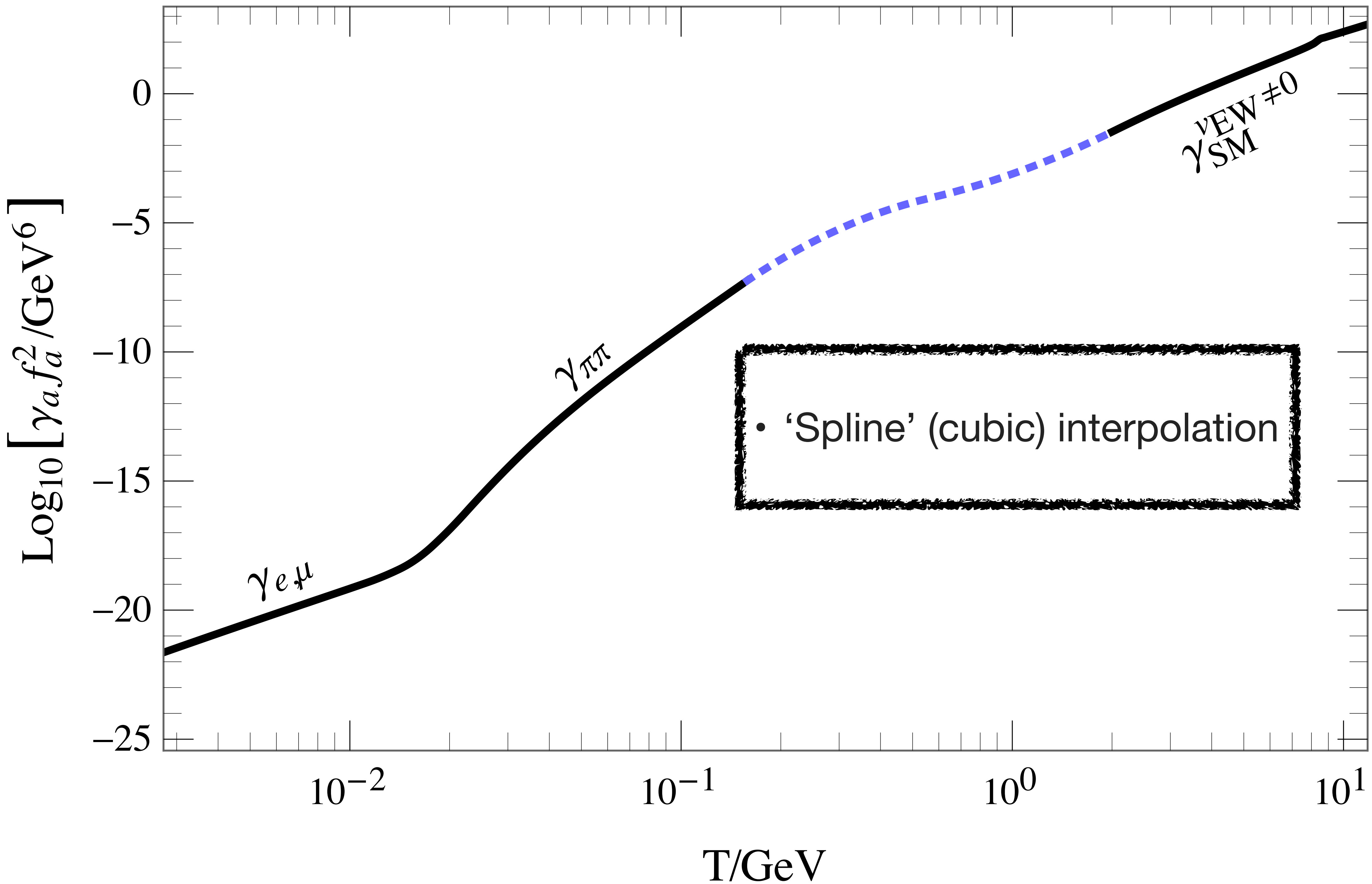
QCD threshold



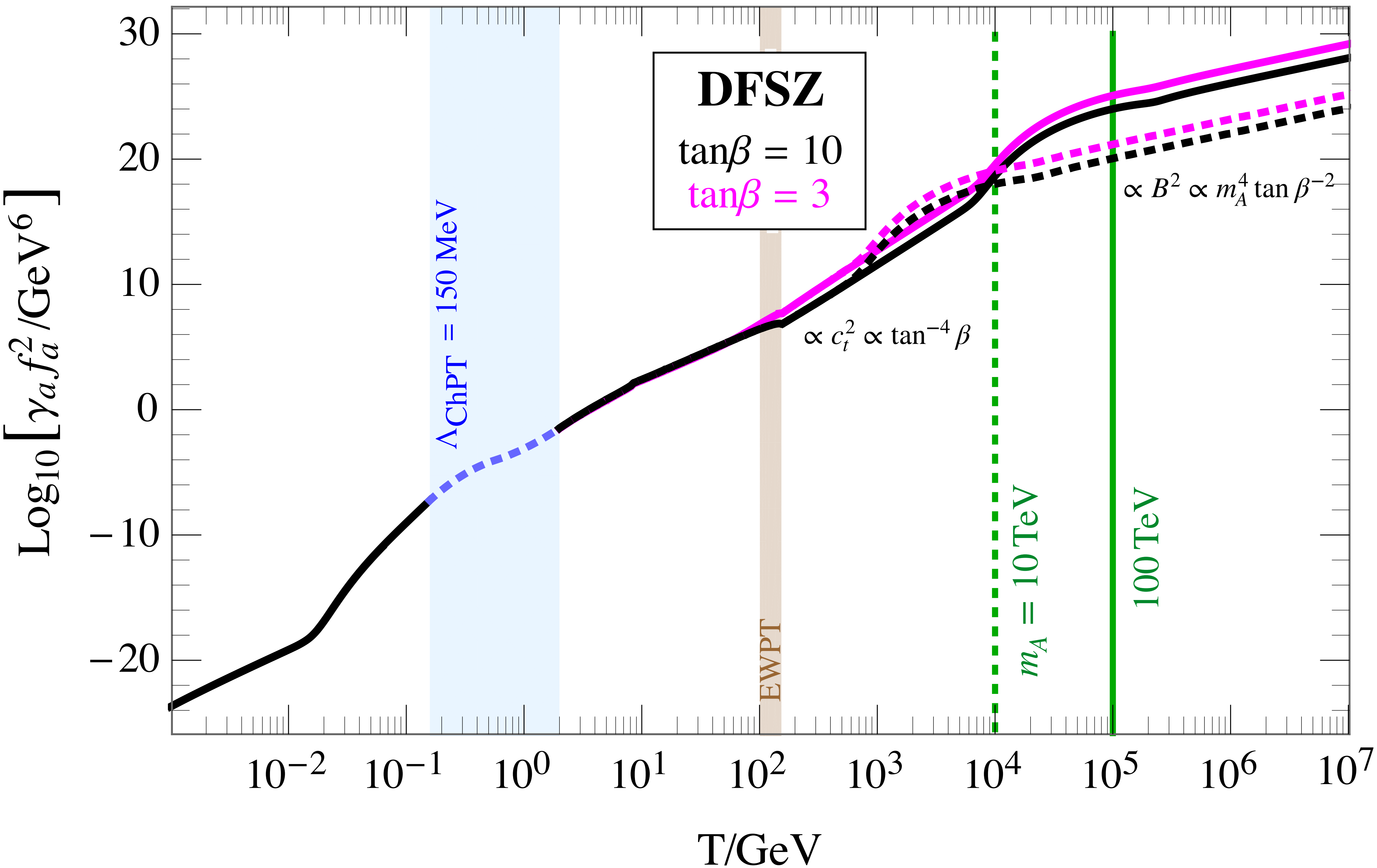
QCD threshold



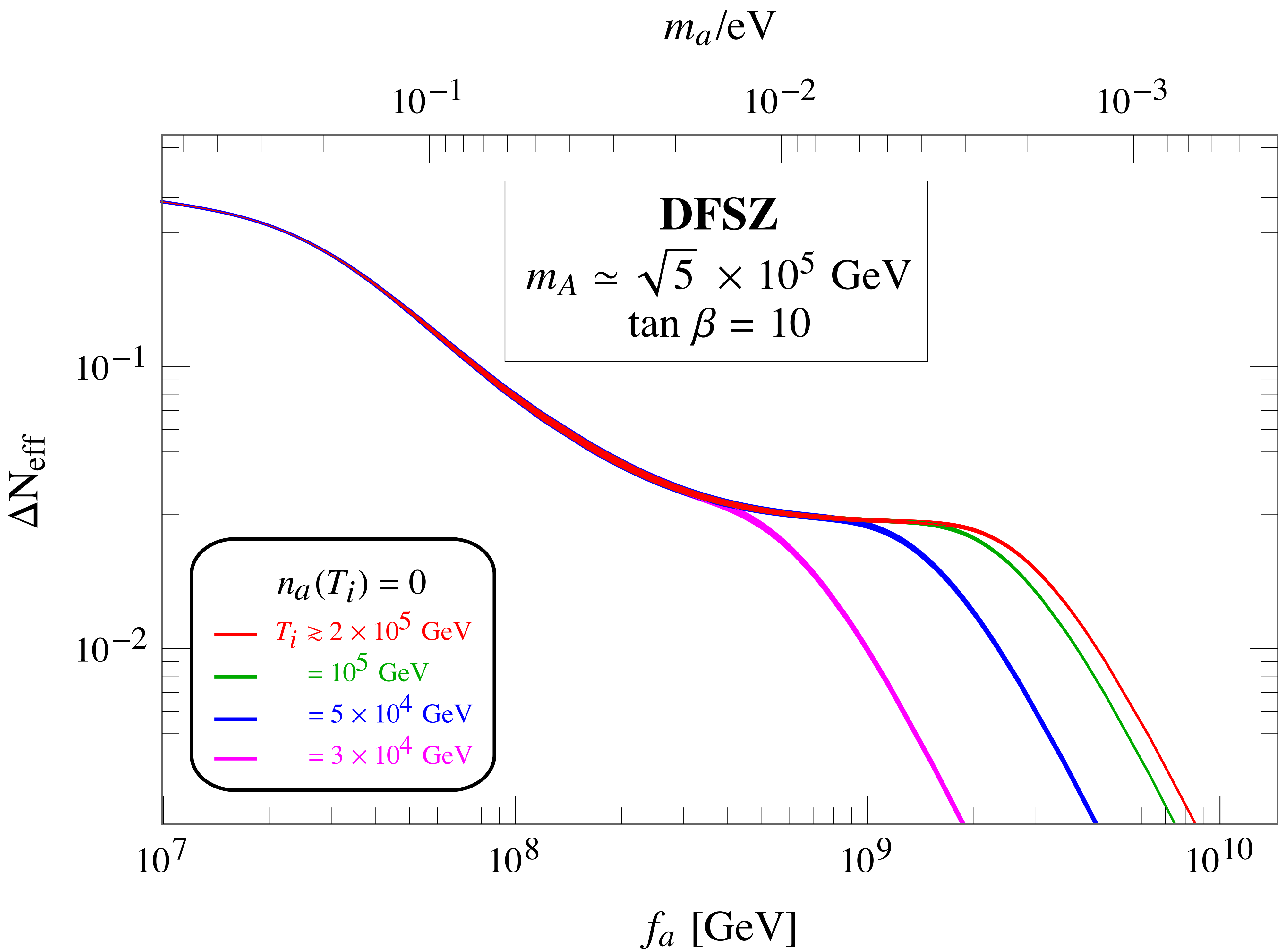
QCD threshold



DFSZ axion production rate



Hot DFSZ axion relic



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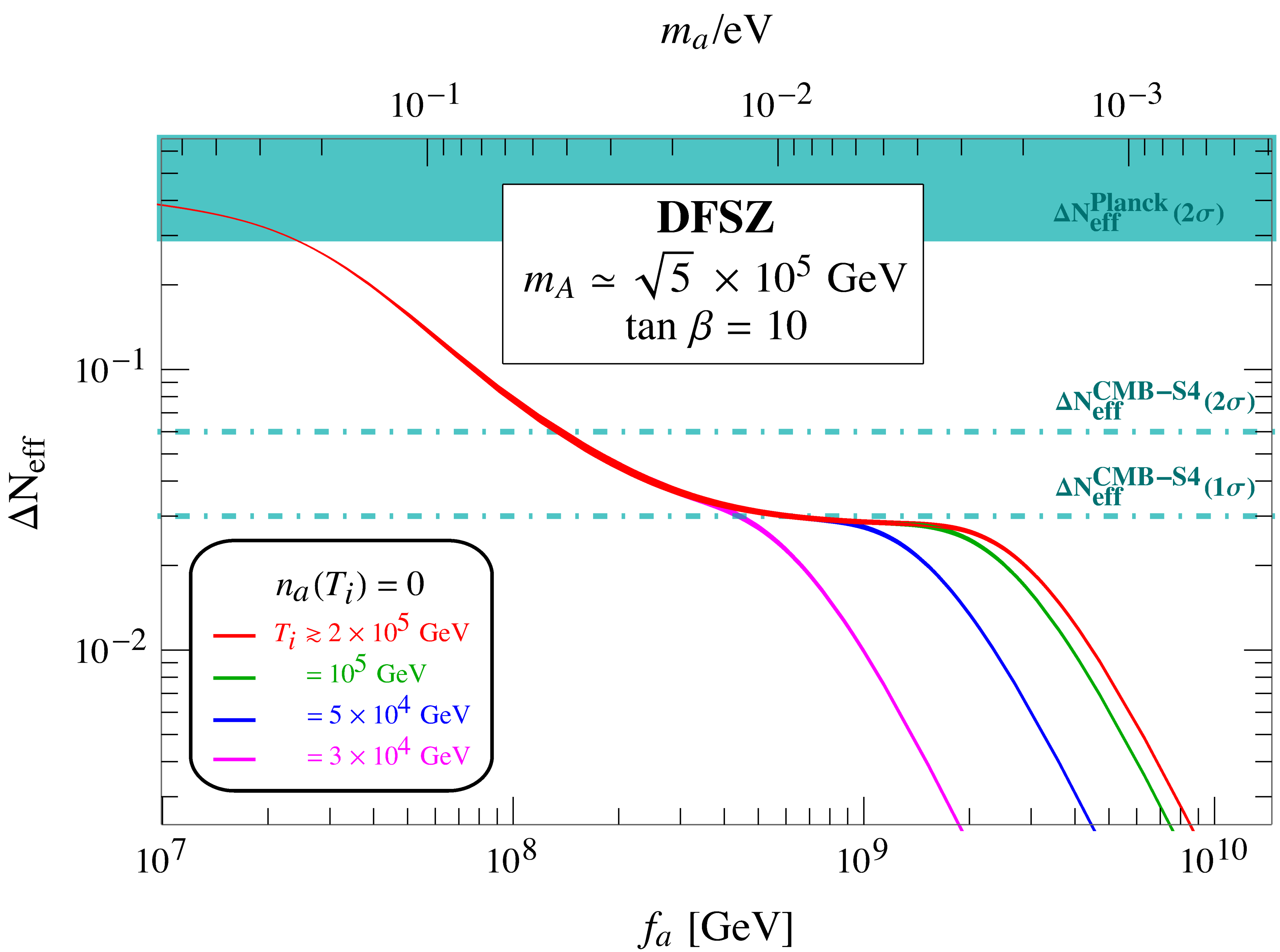
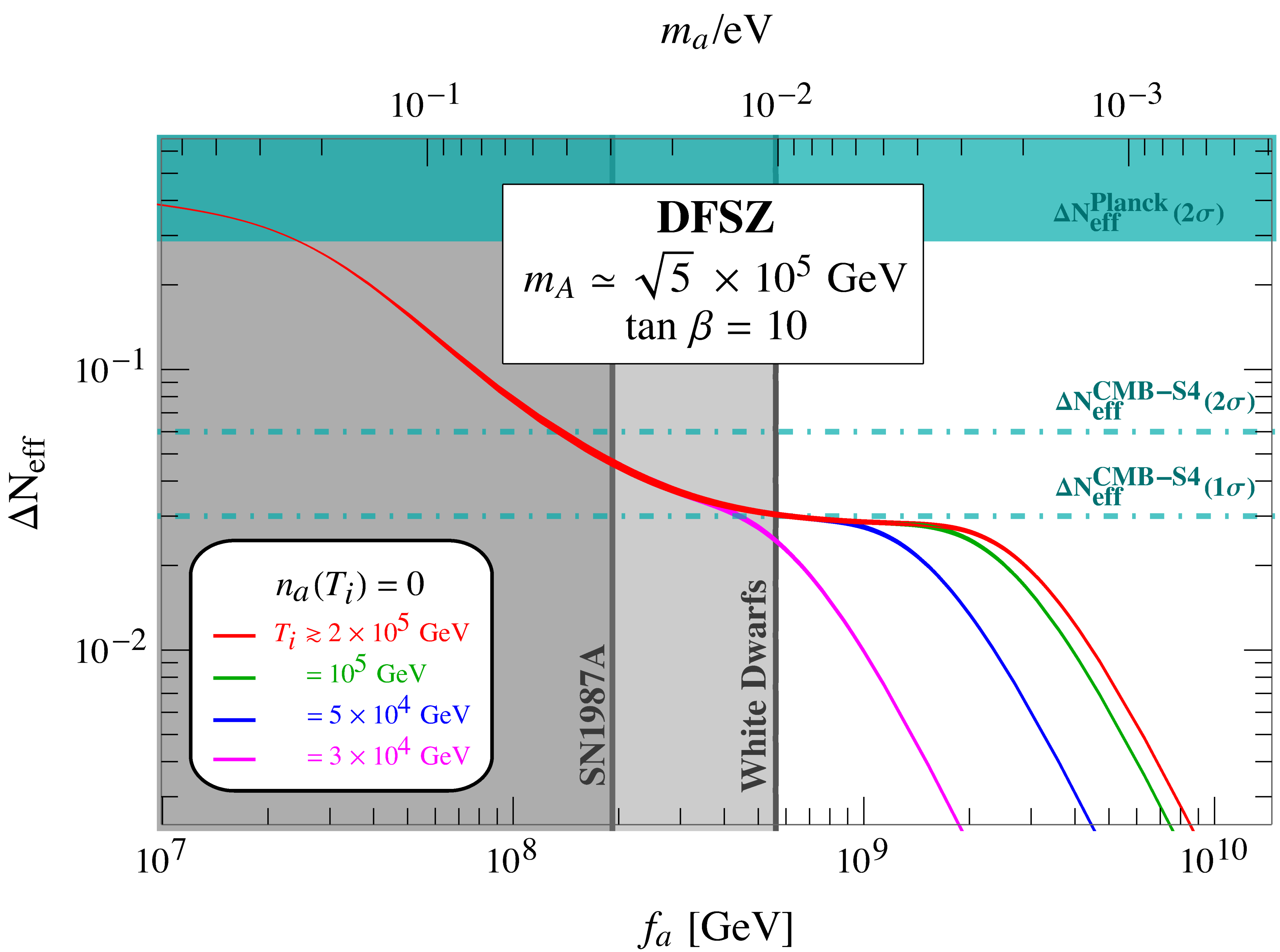


Hot DFSZ axion relic



$\{\alpha = V, A\}$

$\{i \neq j\}$

Flavor-violating couplings $F^{\alpha}_{f_i \neq f_j}$

✦ Explicit charge assignments

e.g., through the Froggatt-Nielsen mechanism

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

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

⋮

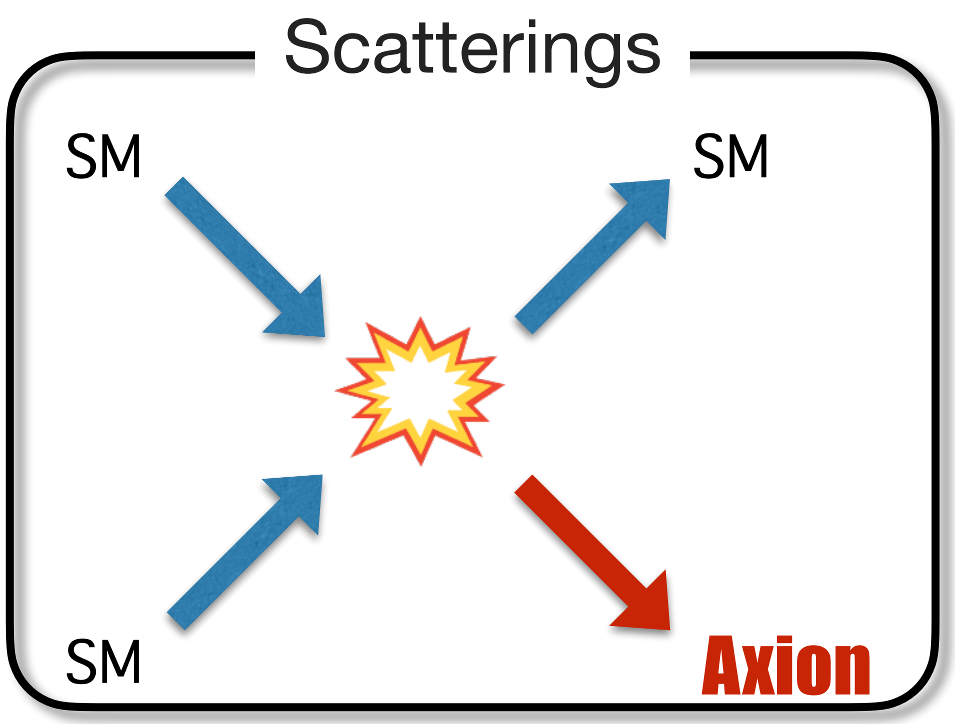
✦ Radiatively induced

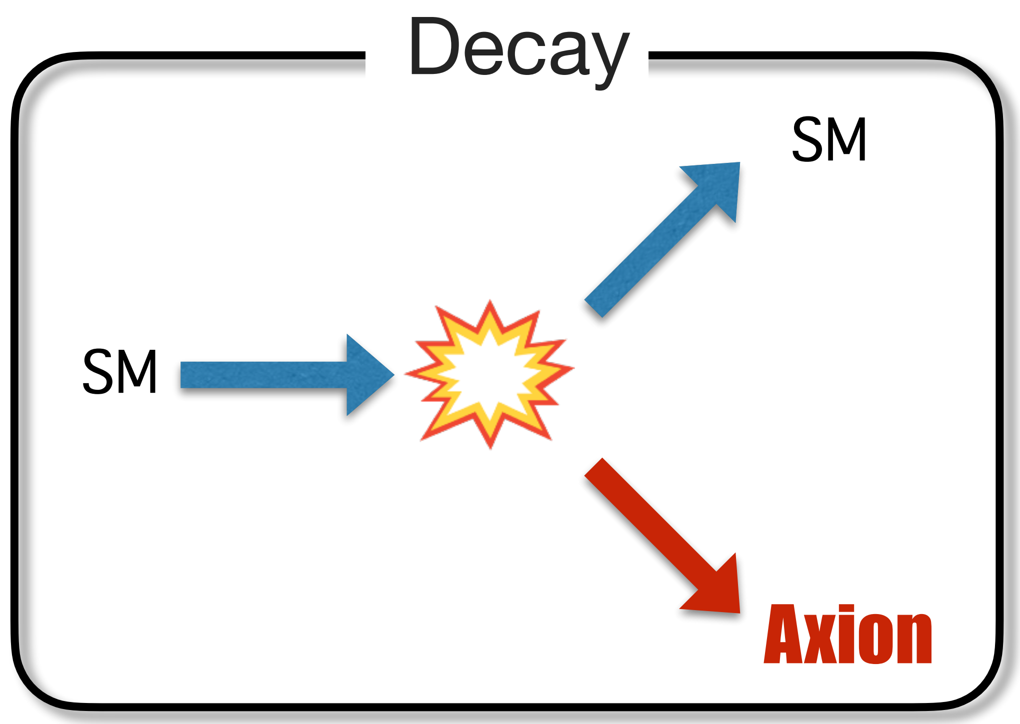
[K. Choi, S. Im, C. Park, SY, 2017]

[M. Chala, 2020]

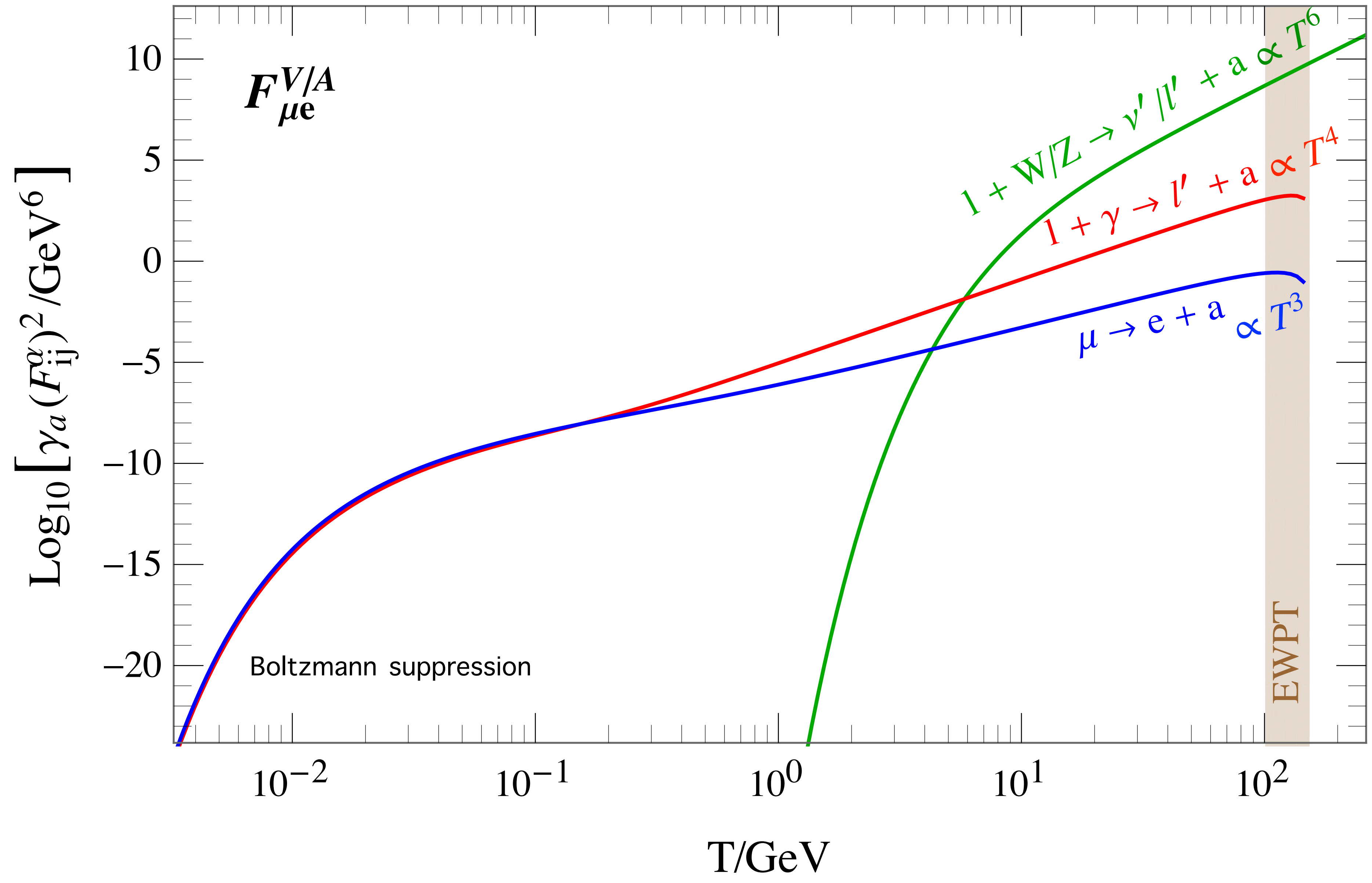
[K. Choi et al, 2021]

⋮





Leptonic flavor violation



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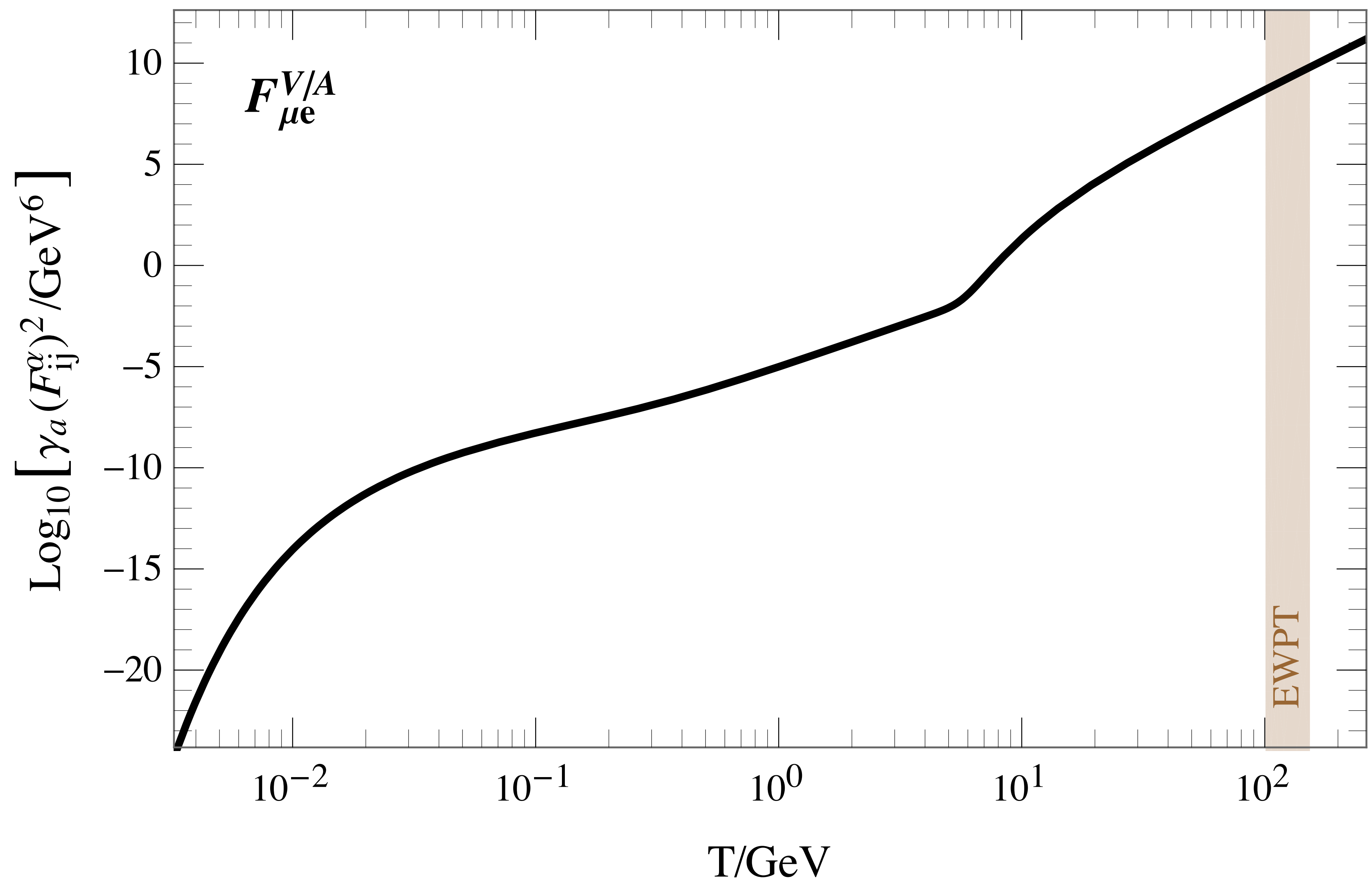
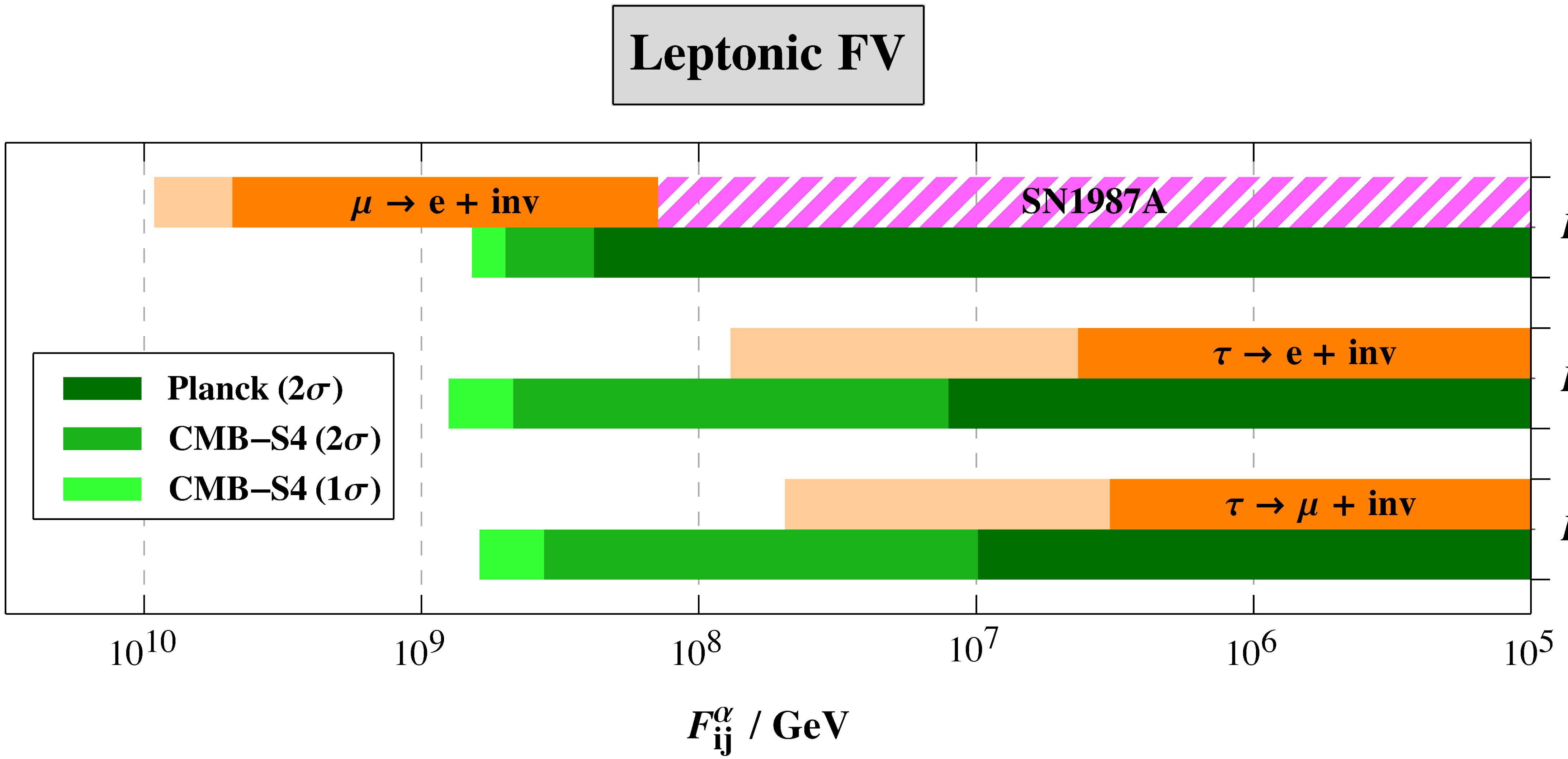
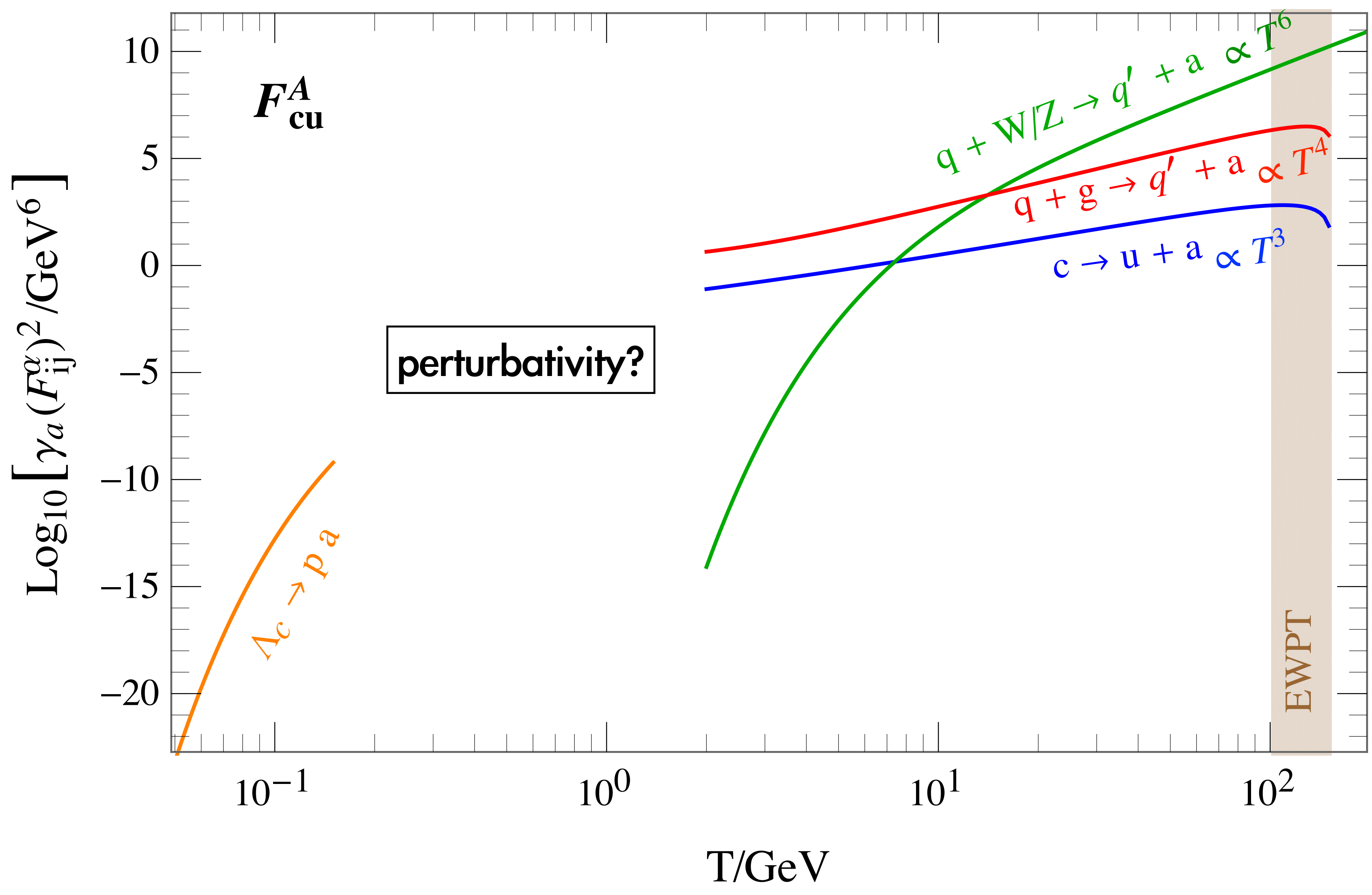


[F. D'Eramo, SY, 2021]

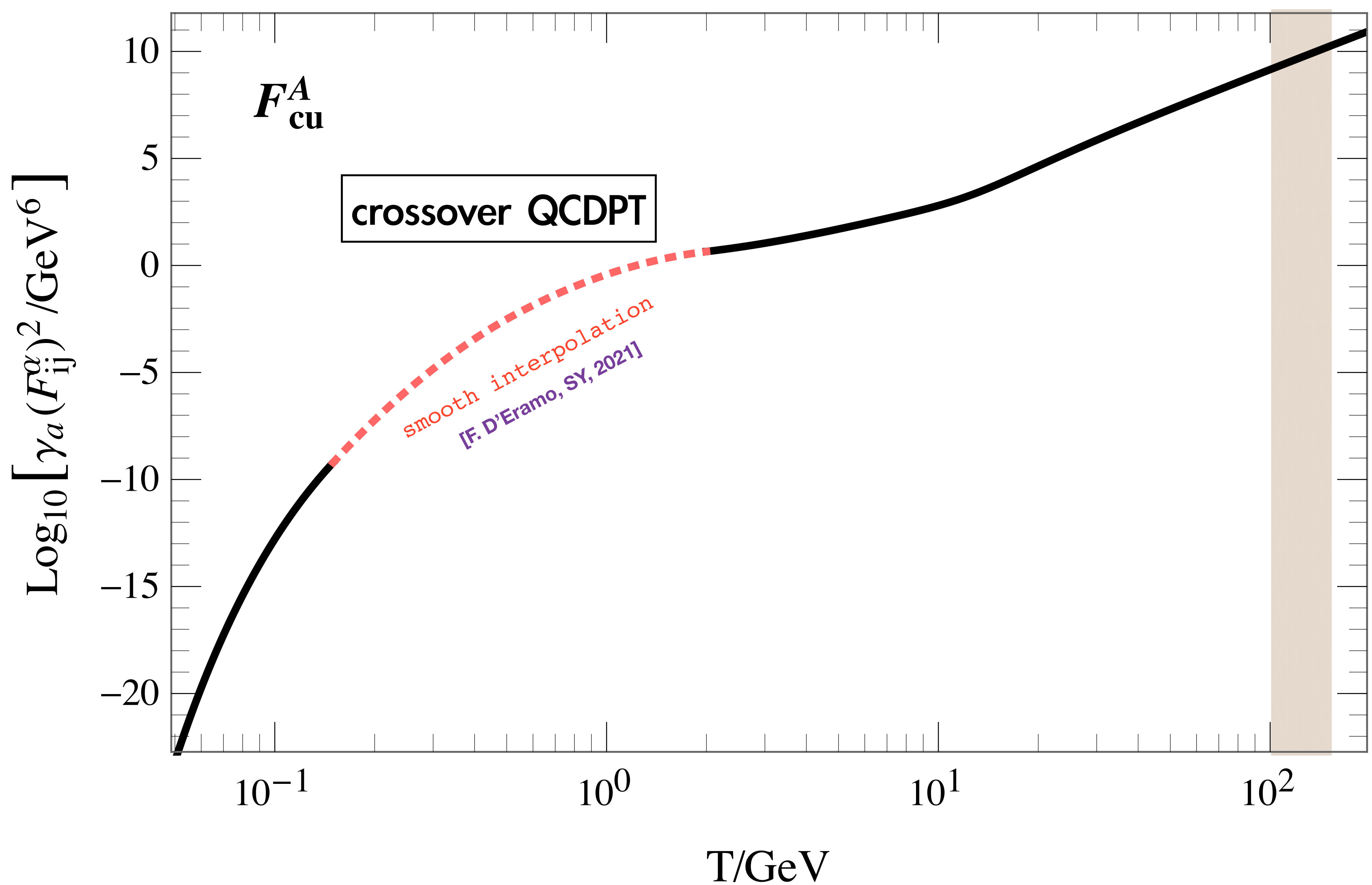
Leptonic flavor violation



Hadronic flavor violation

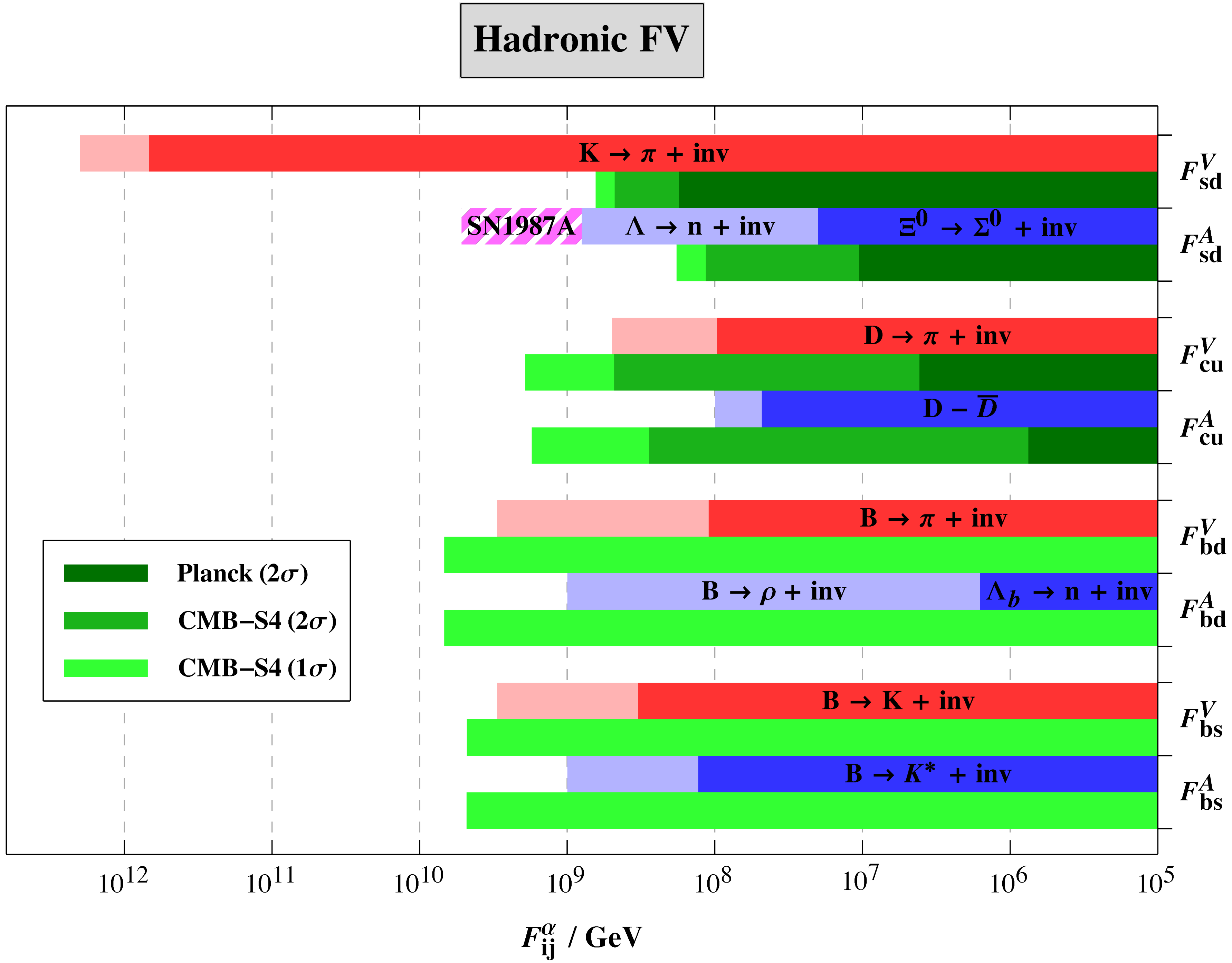


Hadronic flavor violation



[F. D'Eramo, SY, 2021]

Hadronic flavor violation

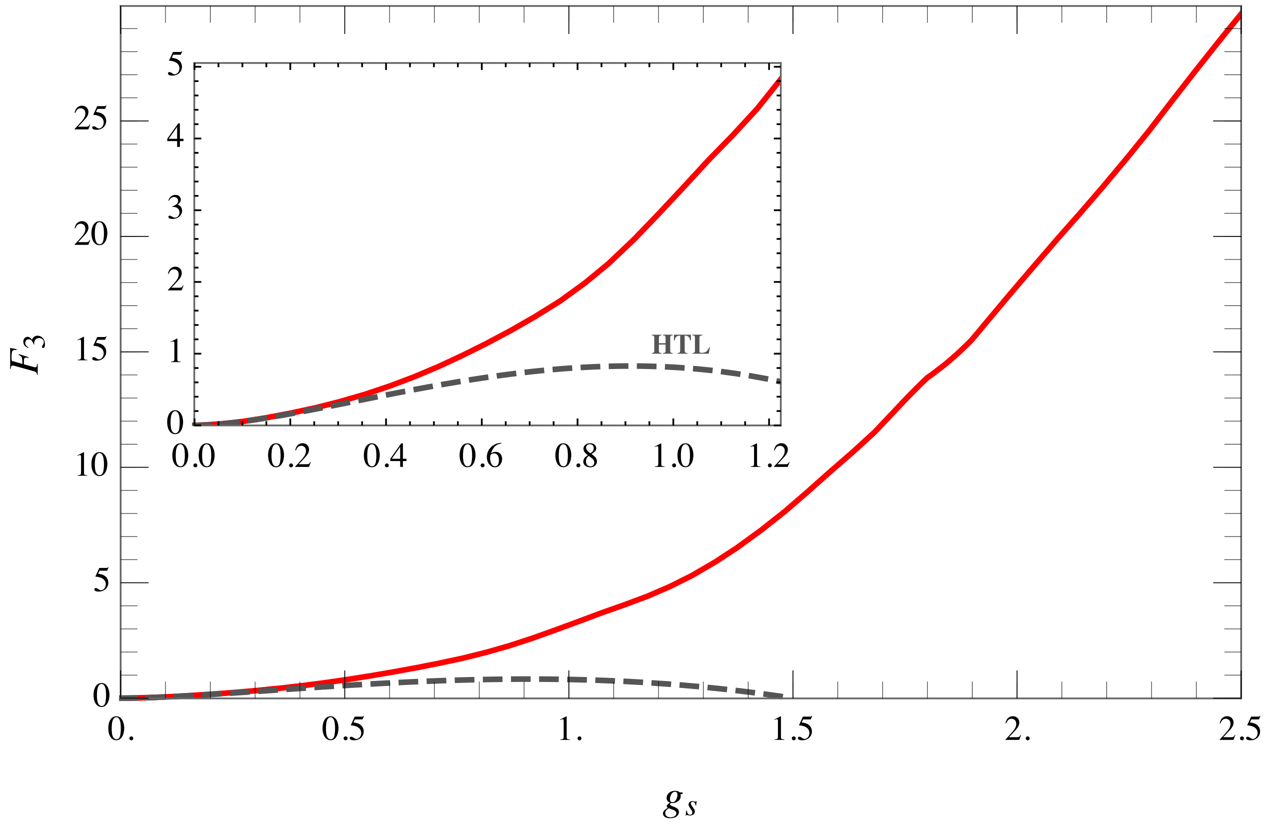


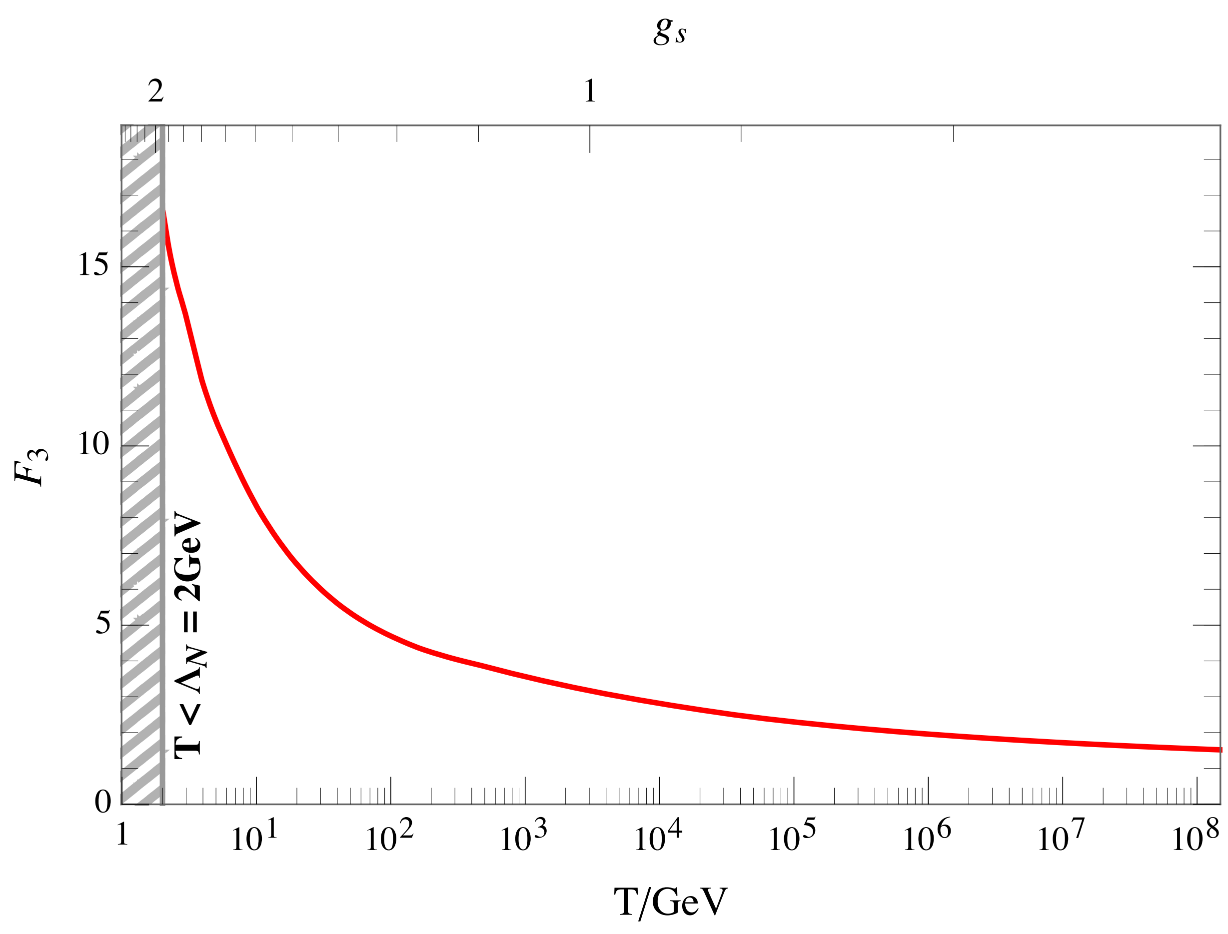
Conclusion

- We calculate the axion production rate in the full range for the typical QCD axion scenario: KSVZ & DFSZ & Flavor violating (for ALP)
- 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

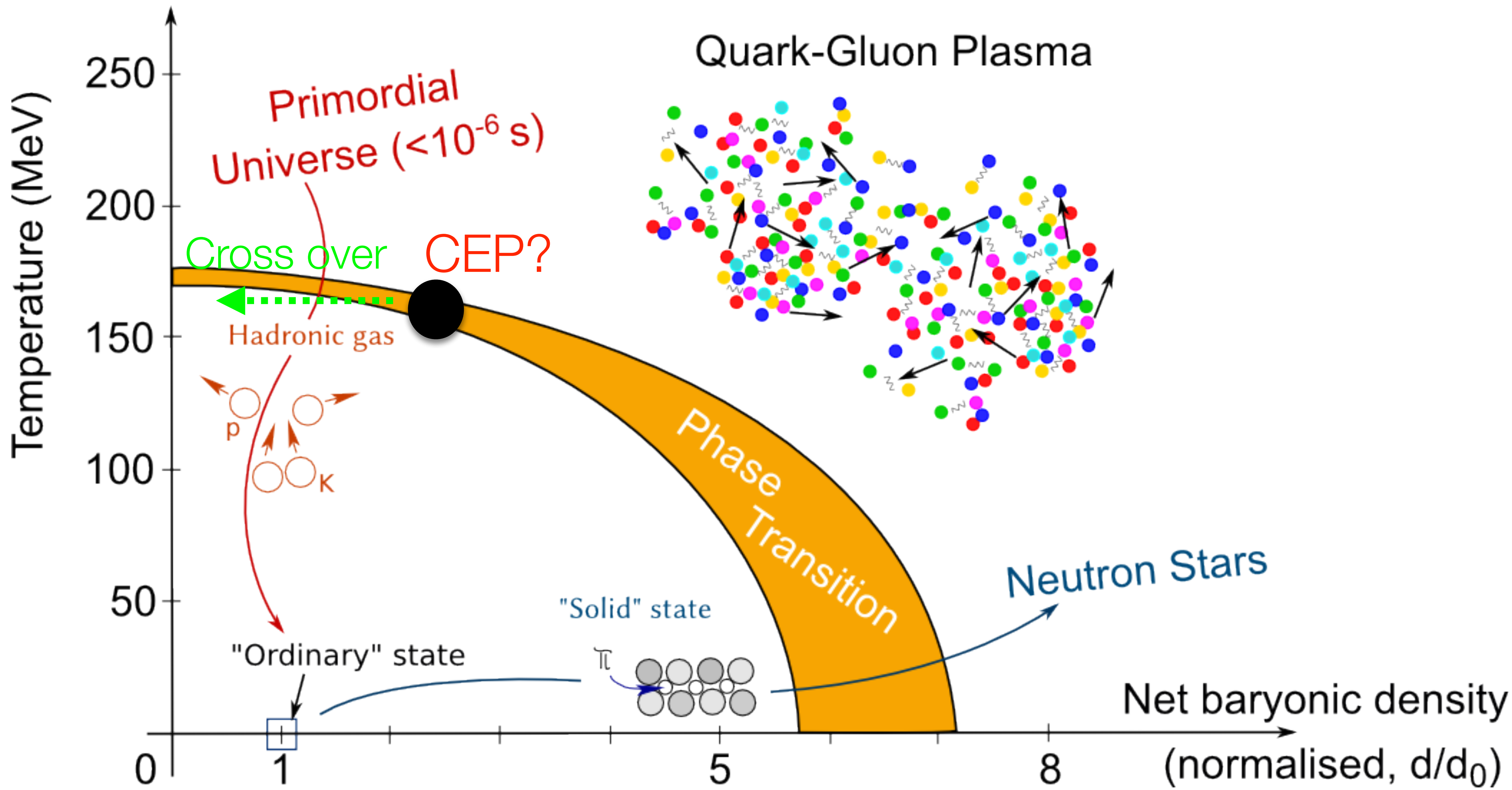
Control function for gluon scatterings



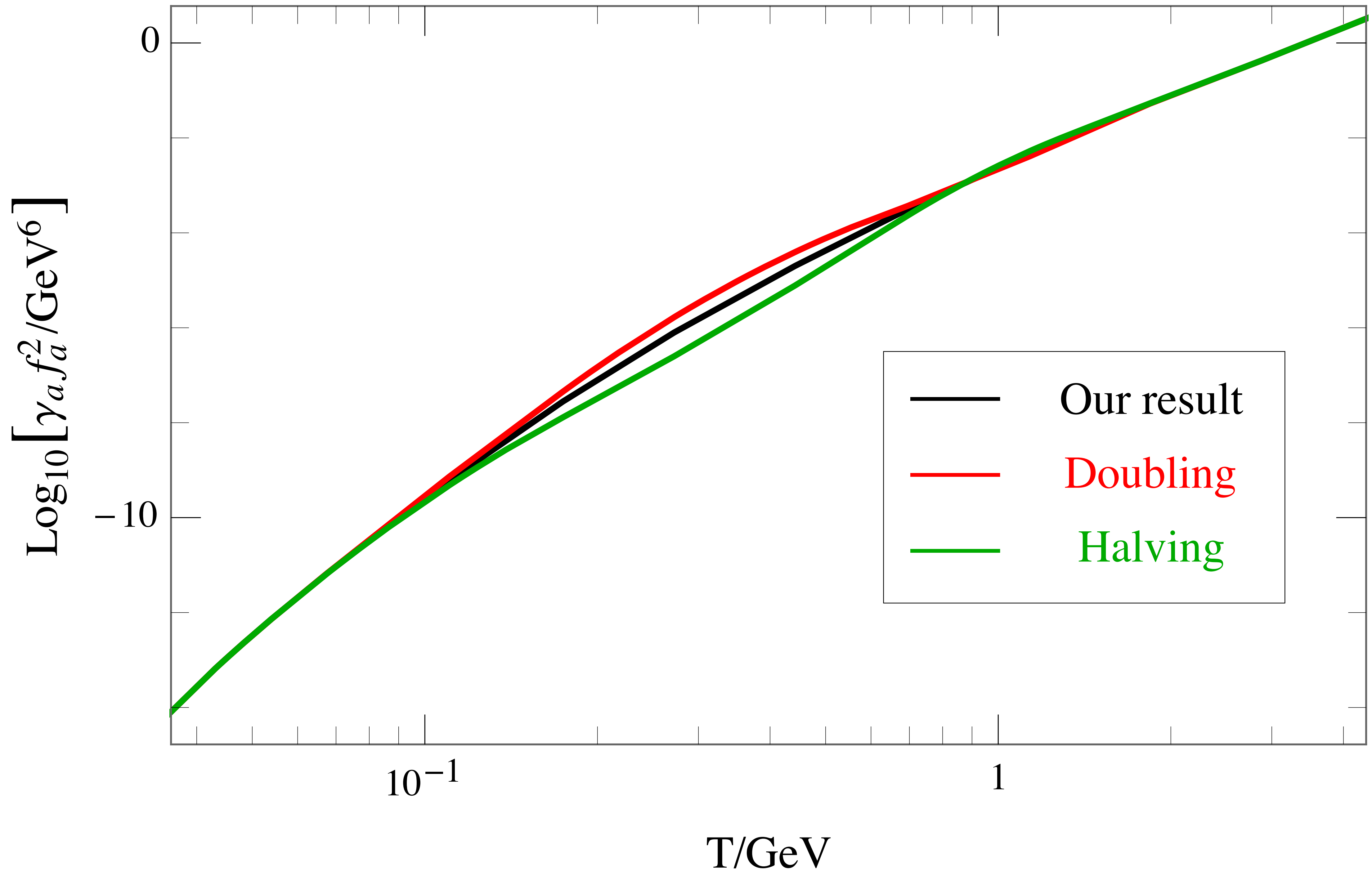


QCD phase diagram

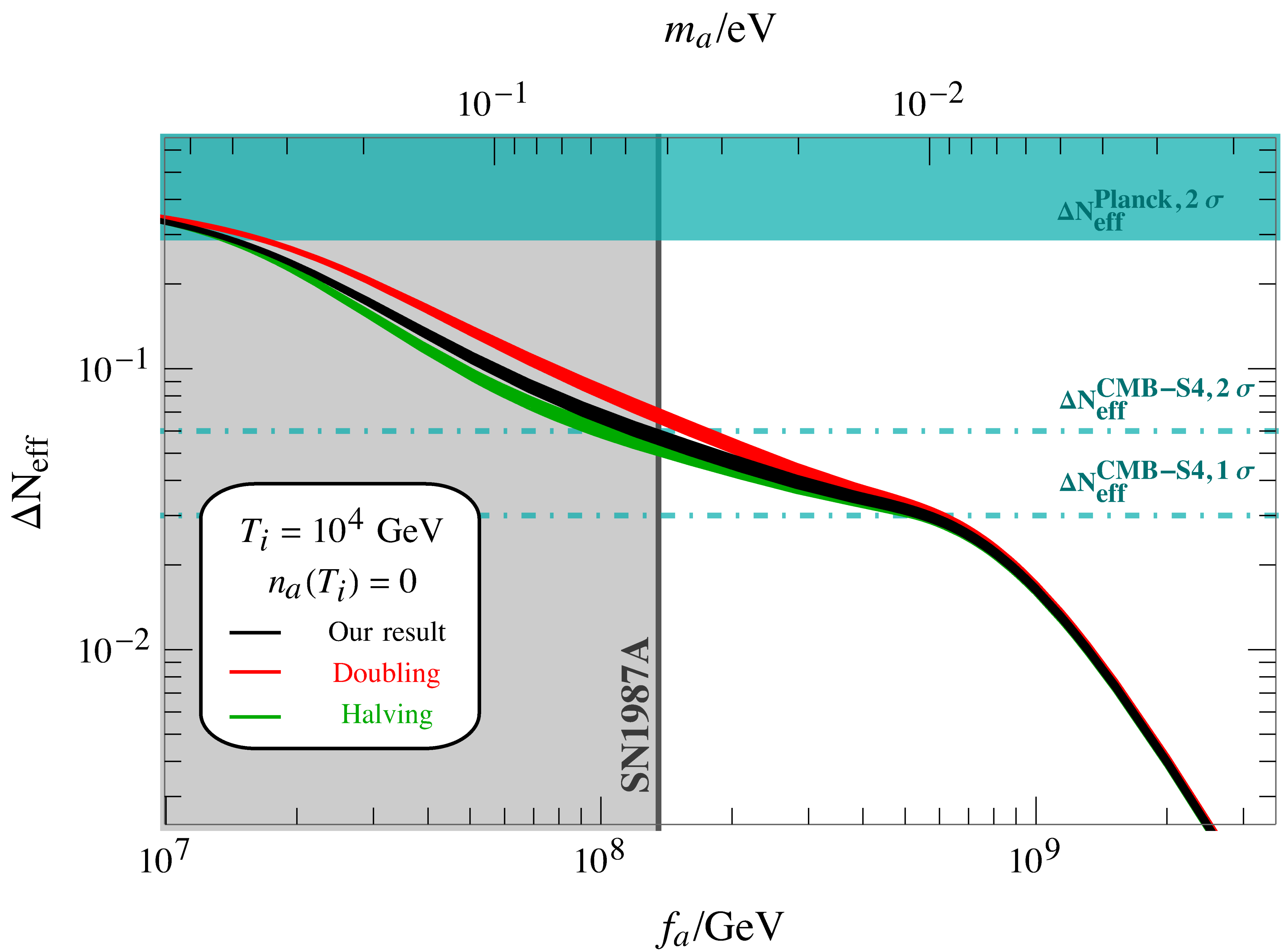
[A. Maire, 2015]



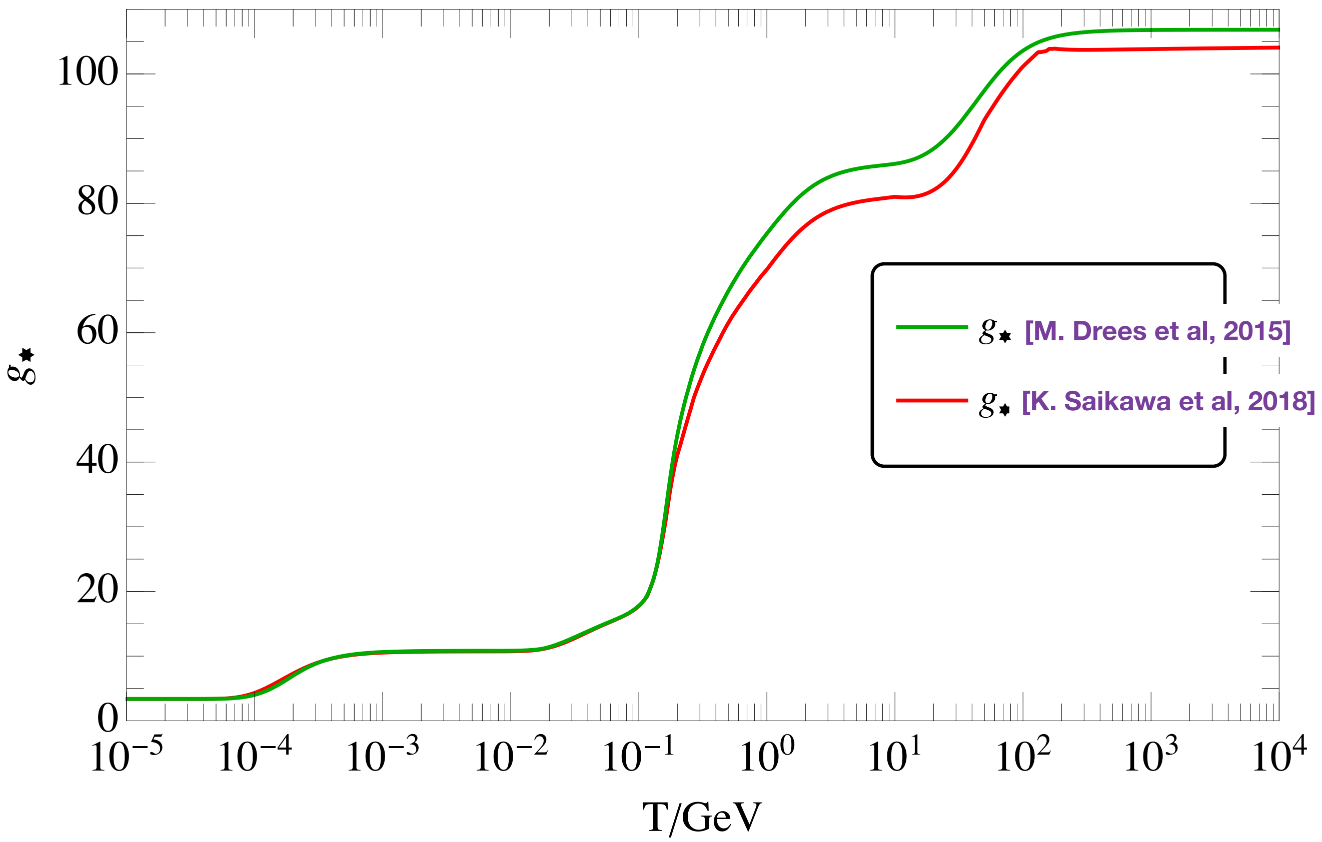
Issue on interpolation?

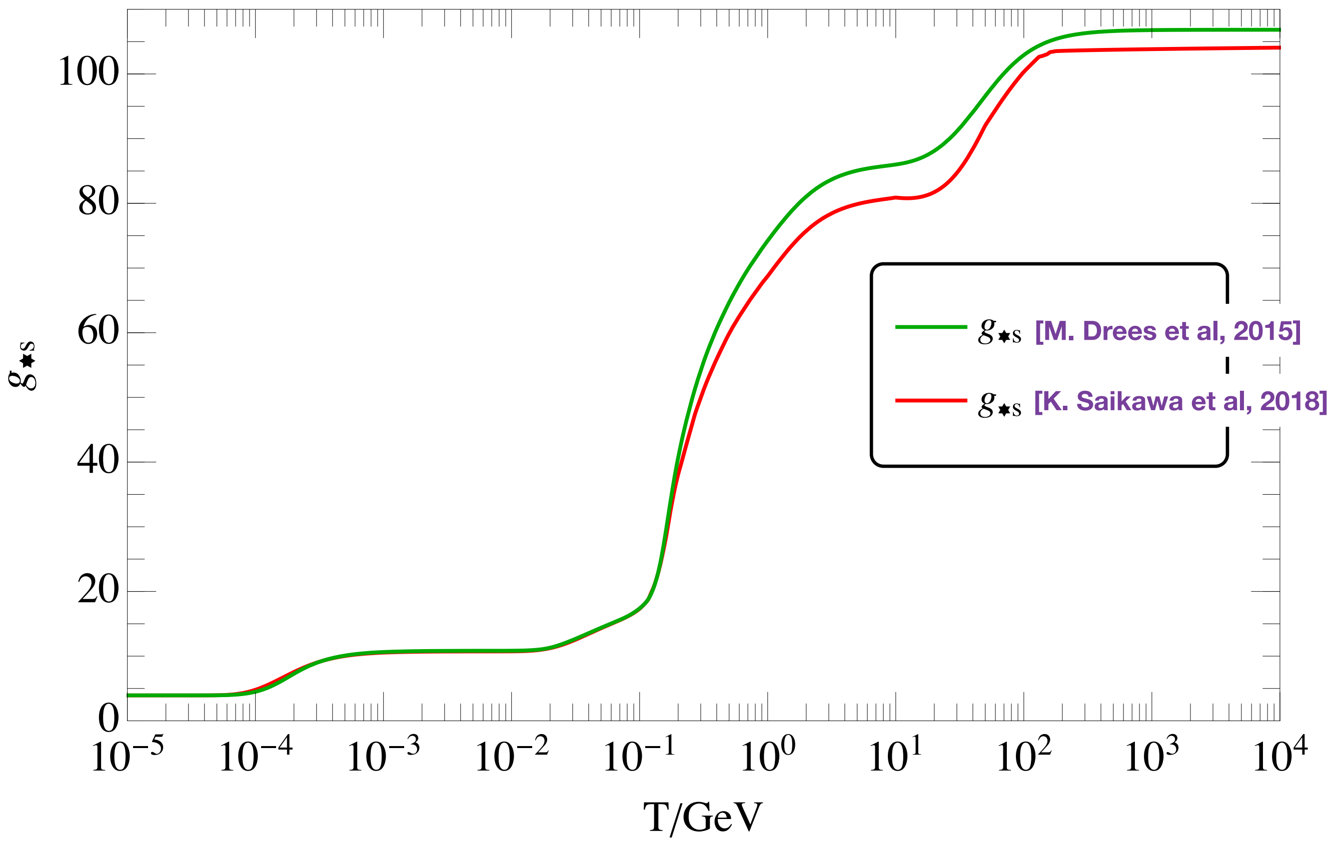


Issue on interpolation?

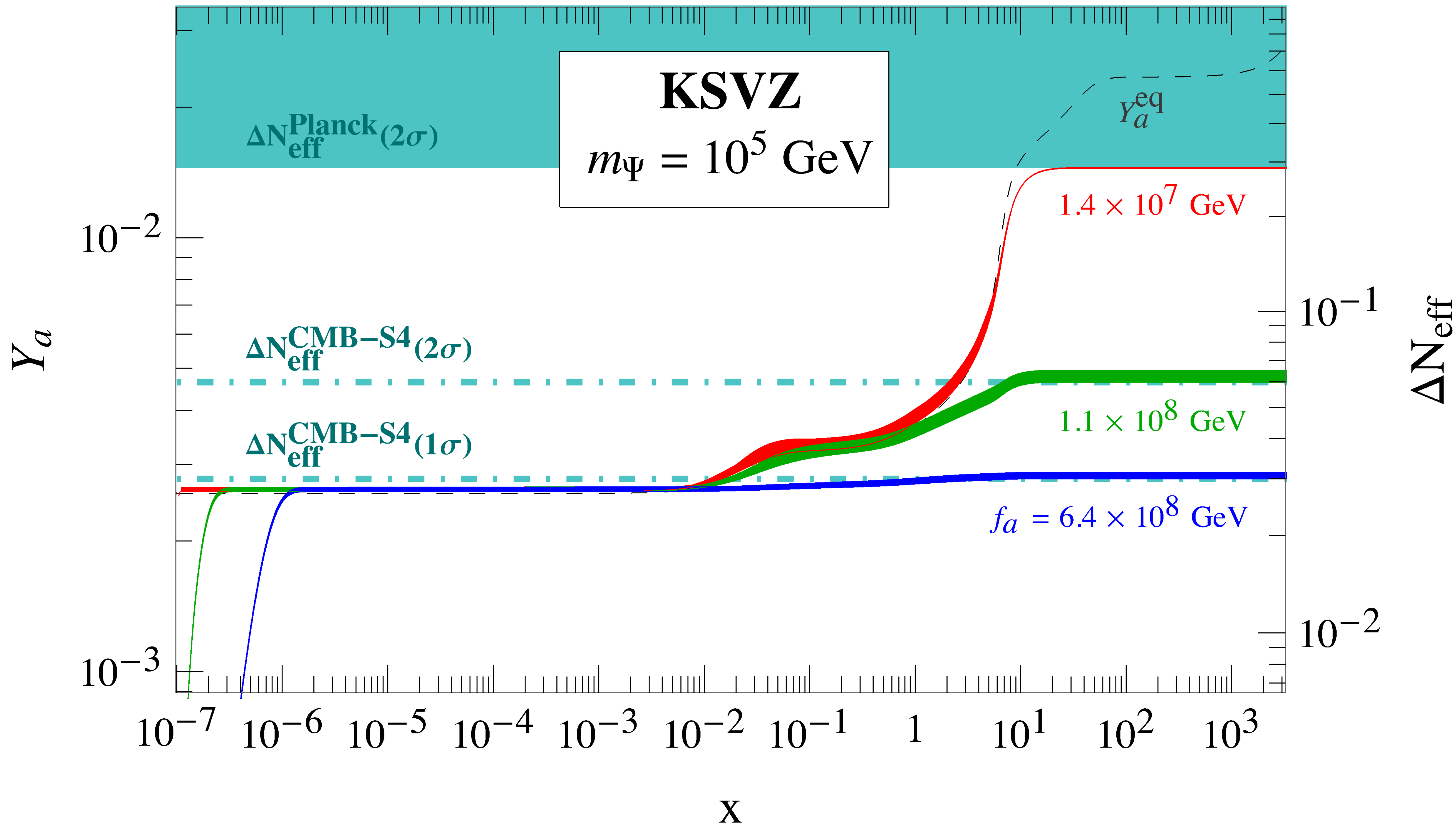


Cosmological profile

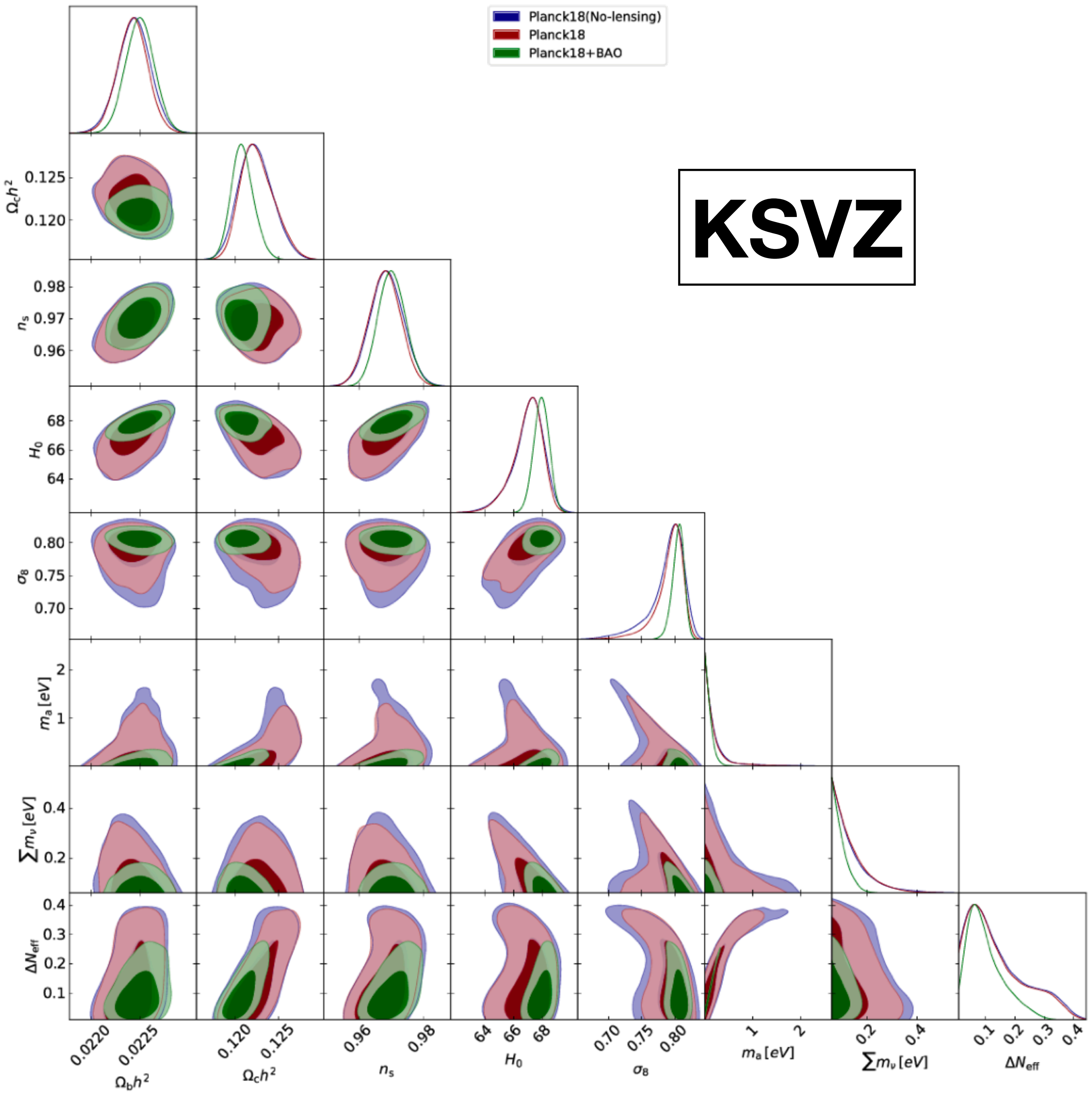




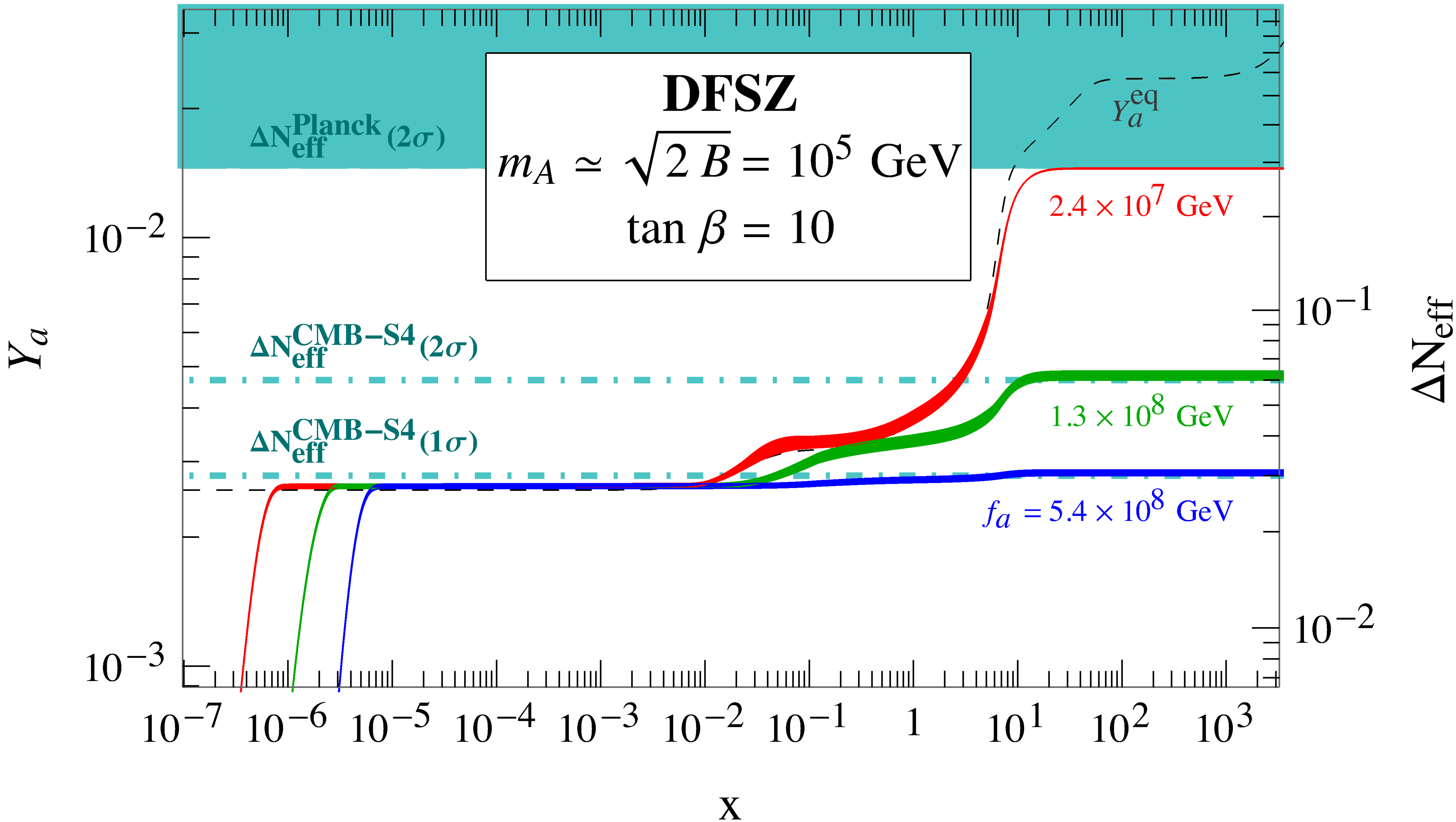
Evolution of KSVZ axion relic density



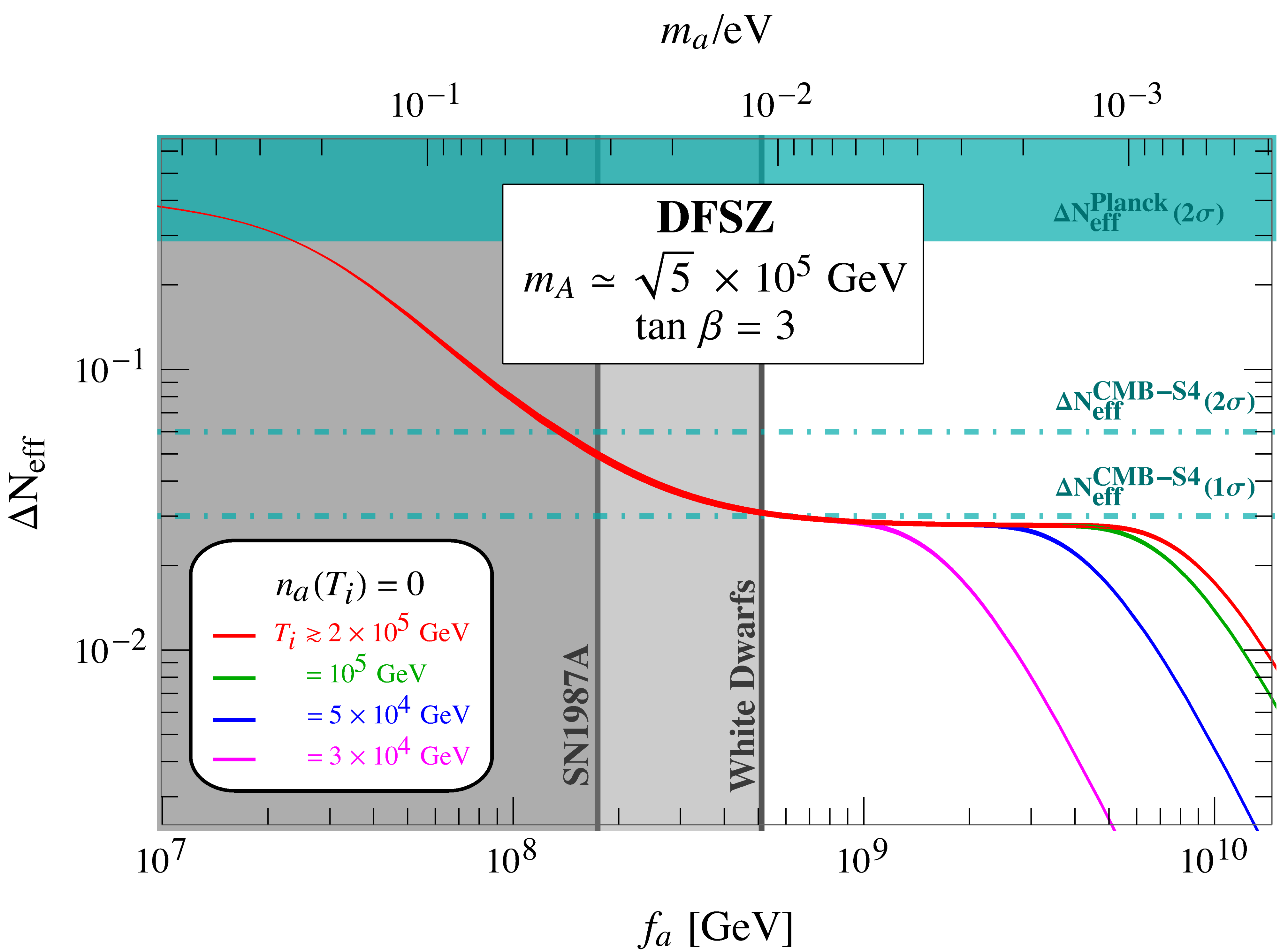
Numerical analysis



Evolution of DFSZ axion relic density



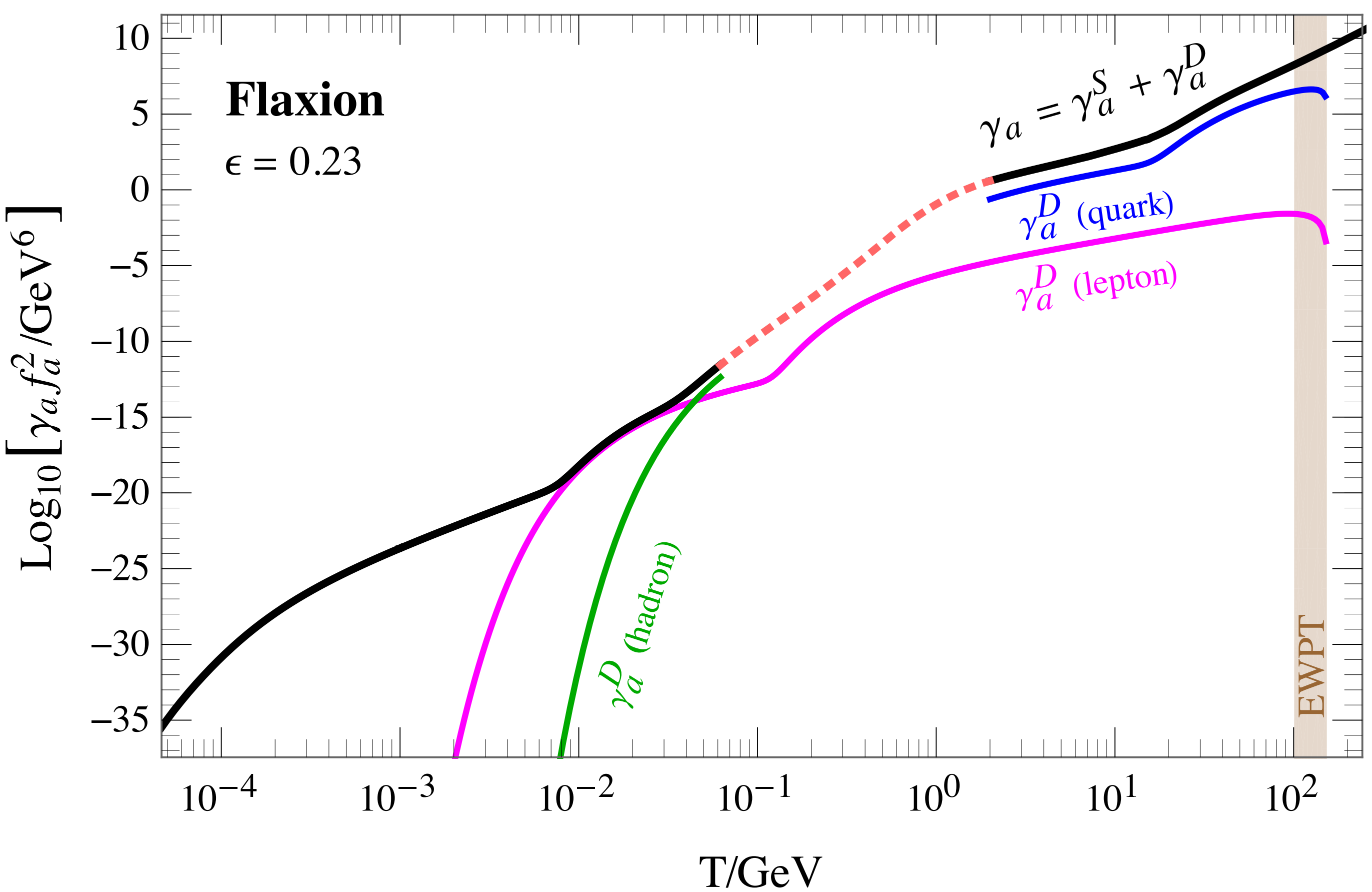
Hot DFSZ axion relic for $\tan\beta = 3$

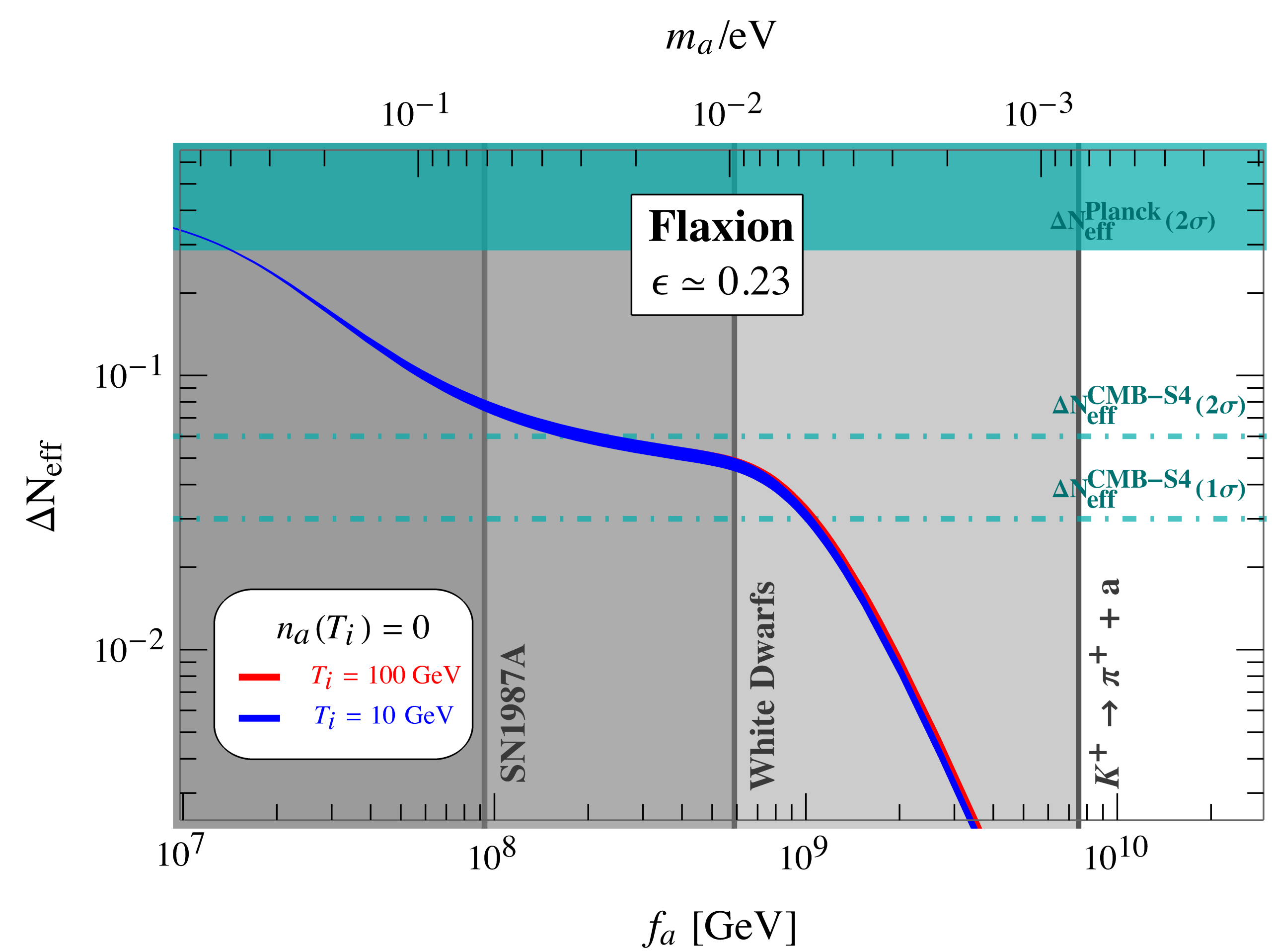


[Y. Ema et al, 2016]

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 preparation]