# Flavor Violating Axions in the Early Universe

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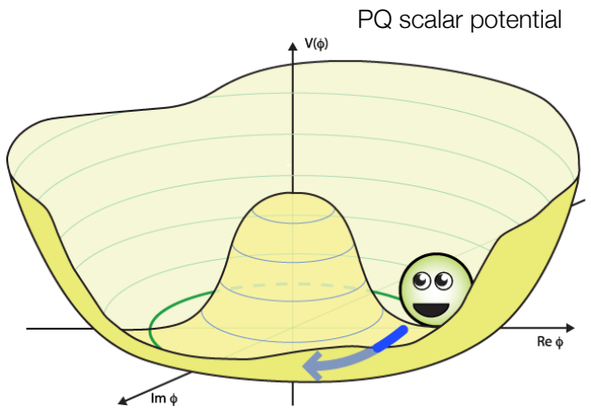
# Outline

# Axion

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




www.quantumdiaries.org

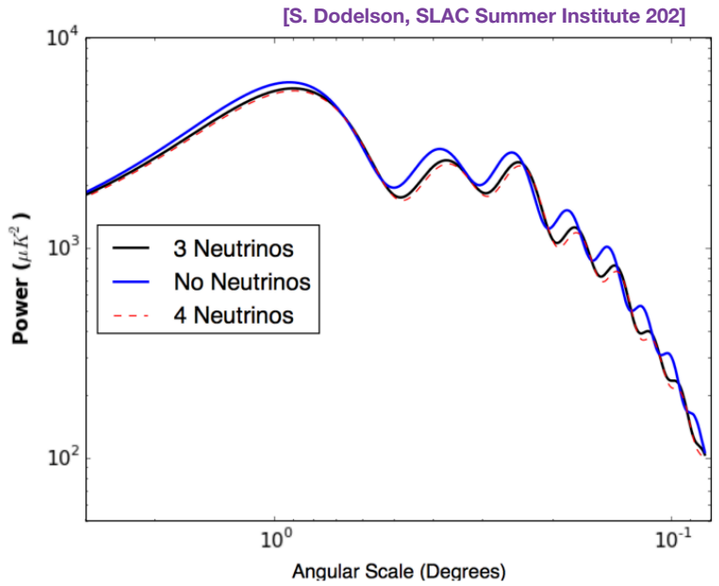
- Global Peccei-Quinn symmetry - Pseudo Nambu-Goldstone boson after spontaneous breaking at $\sim f_a$

- Mass and coupling proportional to $f_a^{-1}$; if only coupling, Axion-like particle (ALP)

# Axionic dark radiation?

- Parametrized by $\Delta N_{\rm eff} \equiv N_{\rm eff} - N_{\rm eff}^{\rm SM}$

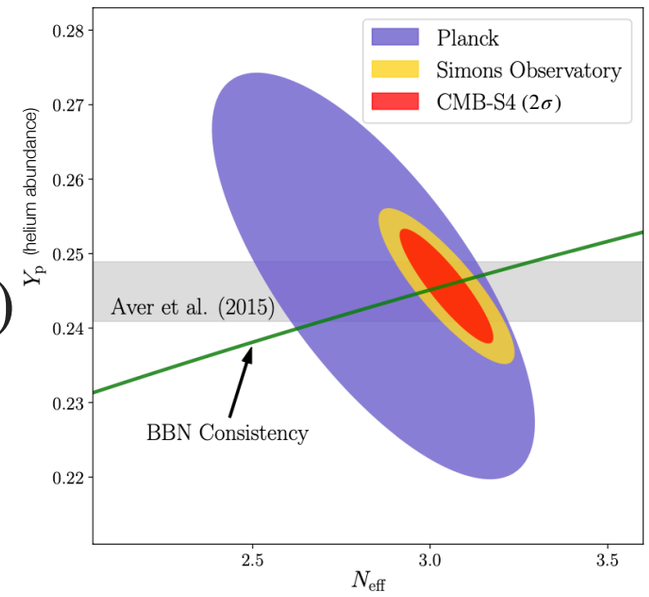
[S. Dodelson, SLAC Summer Institute 202]




- 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 $\Delta N_{\rm eff} = 0.03\ \left(0.06\right)$ for $1\sigma\ (2\sigma)$

[CMB-S4, arXiv:1907.04473]



# Boltzmann equation

- Quantitative tool to track the abundance

d=4 axion production rate

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

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

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

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

# Axion interactions

[H. Gerogi et al, 86]

- Lagrangian with the non-linearly realized PQ symmetry (i.e, $a \to a + \text{const}$)

$$\mathscr{L}_a \supset \frac{\partial_\mu a}{2f_a} \sum_{f_i f_j} \bar{f}_i \gamma^\mu \left( c^V_{f_i f_j} + c^A_{f_i f_j} \gamma^5 \right) f_j$$

$\Rightarrow$ PQ current

- Field redefinition by axionic rotation ☞ linear realized PQ symmetric (*non-der.*) basis

**relying on div. of PQ currents** $\partial_\mu j^\mu_{\rm PQ}$

- In general, flavor dependent & violating structure

$$F^\alpha_{f_i f_j} \equiv \frac{2f_a}{c^\alpha_{f_i f_j}} \qquad \{\alpha = V, A\} \qquad \{i \neq j\}$$

# 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]**

⋮

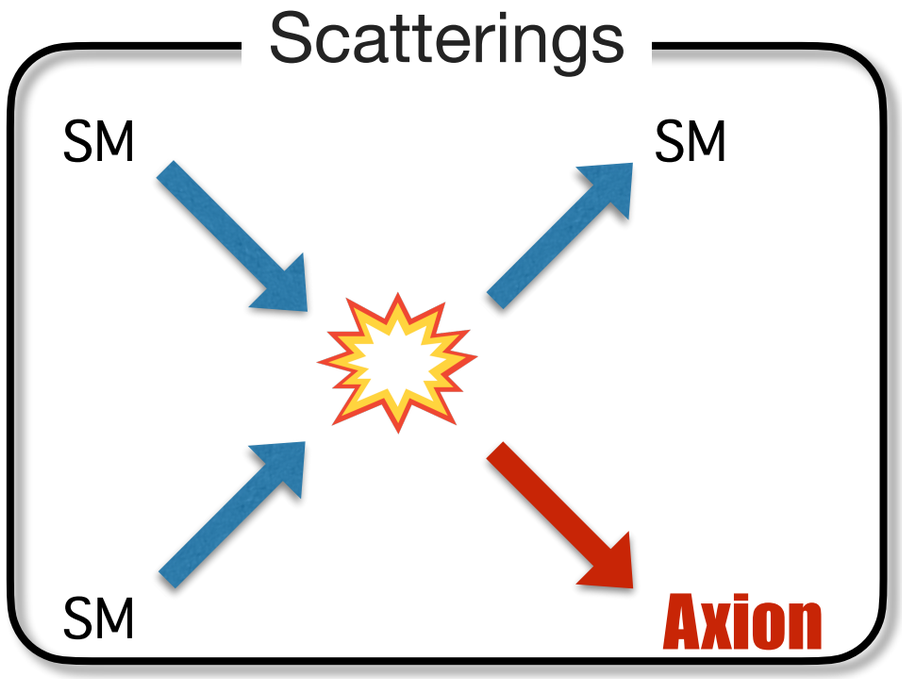
✦ Radiatively induced

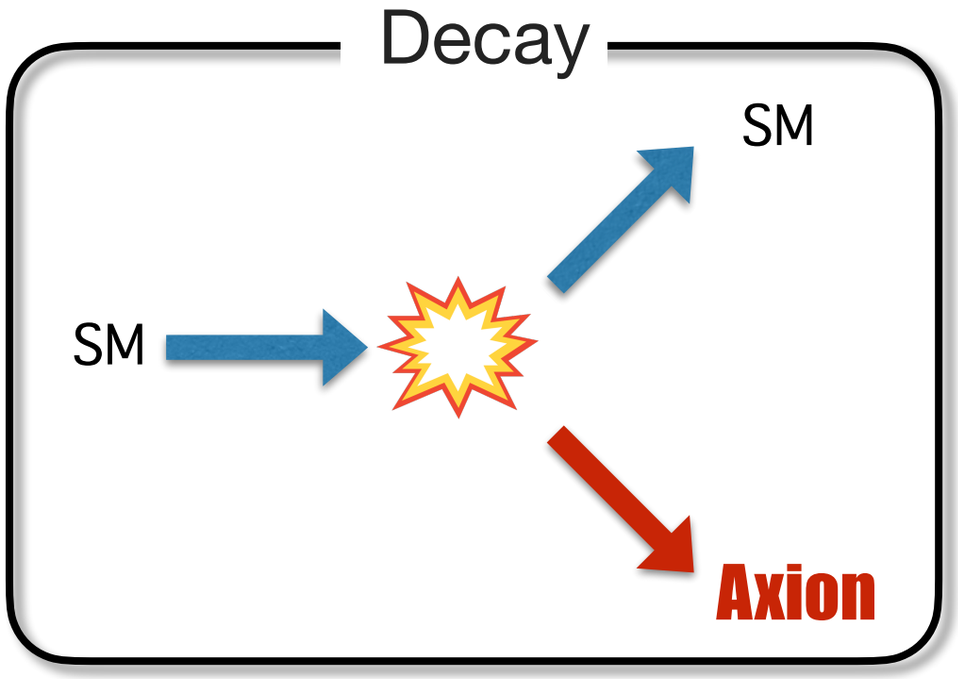
**[K. Choi, S. Im, C. Park, SY, 2017]**

**[M. Chala, 2020]**

**[K. Choi et al, 2021]**

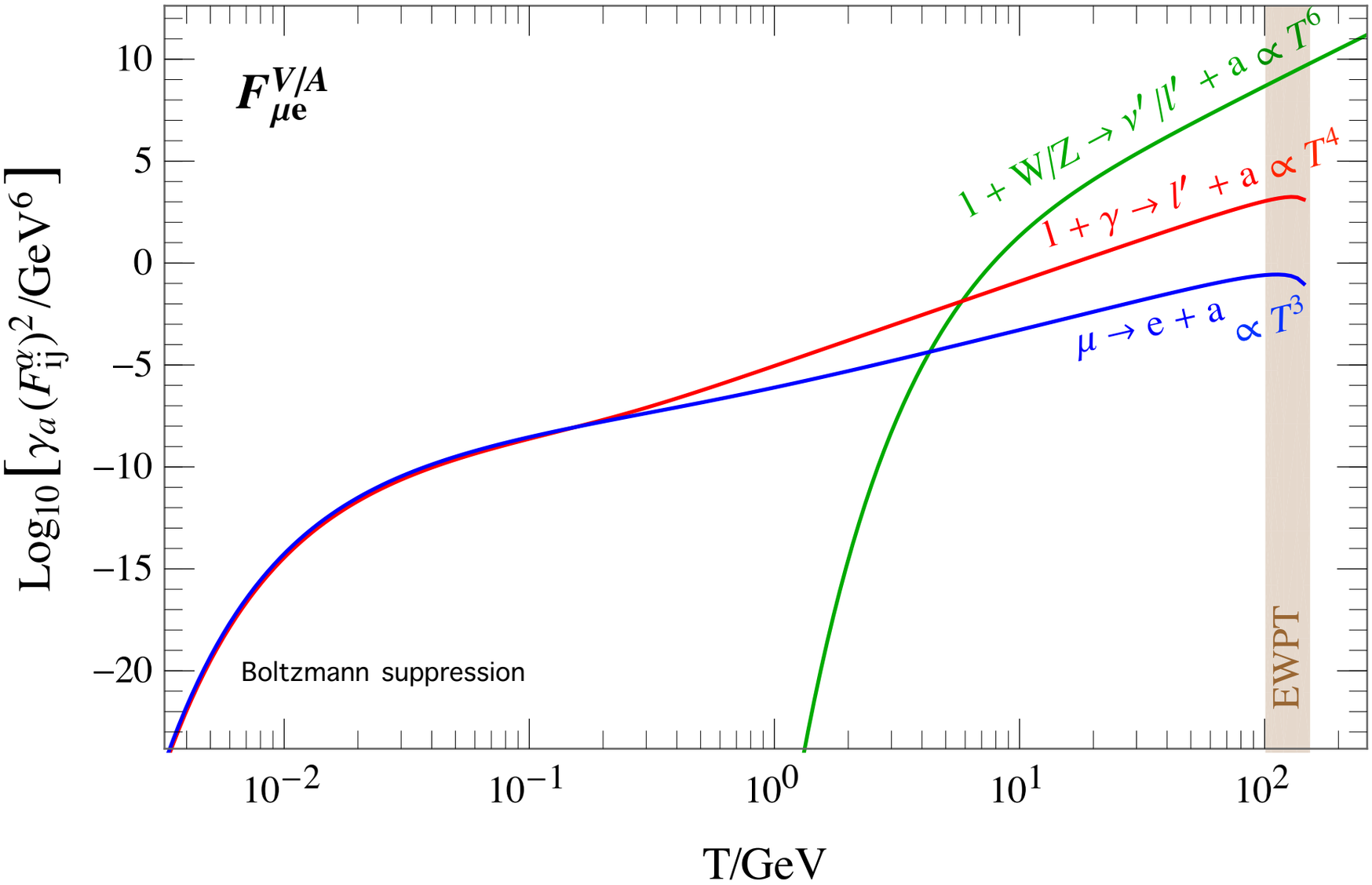
⋮



[F. D'Eramo, SY, 2021]

# Leptonic flavor violation



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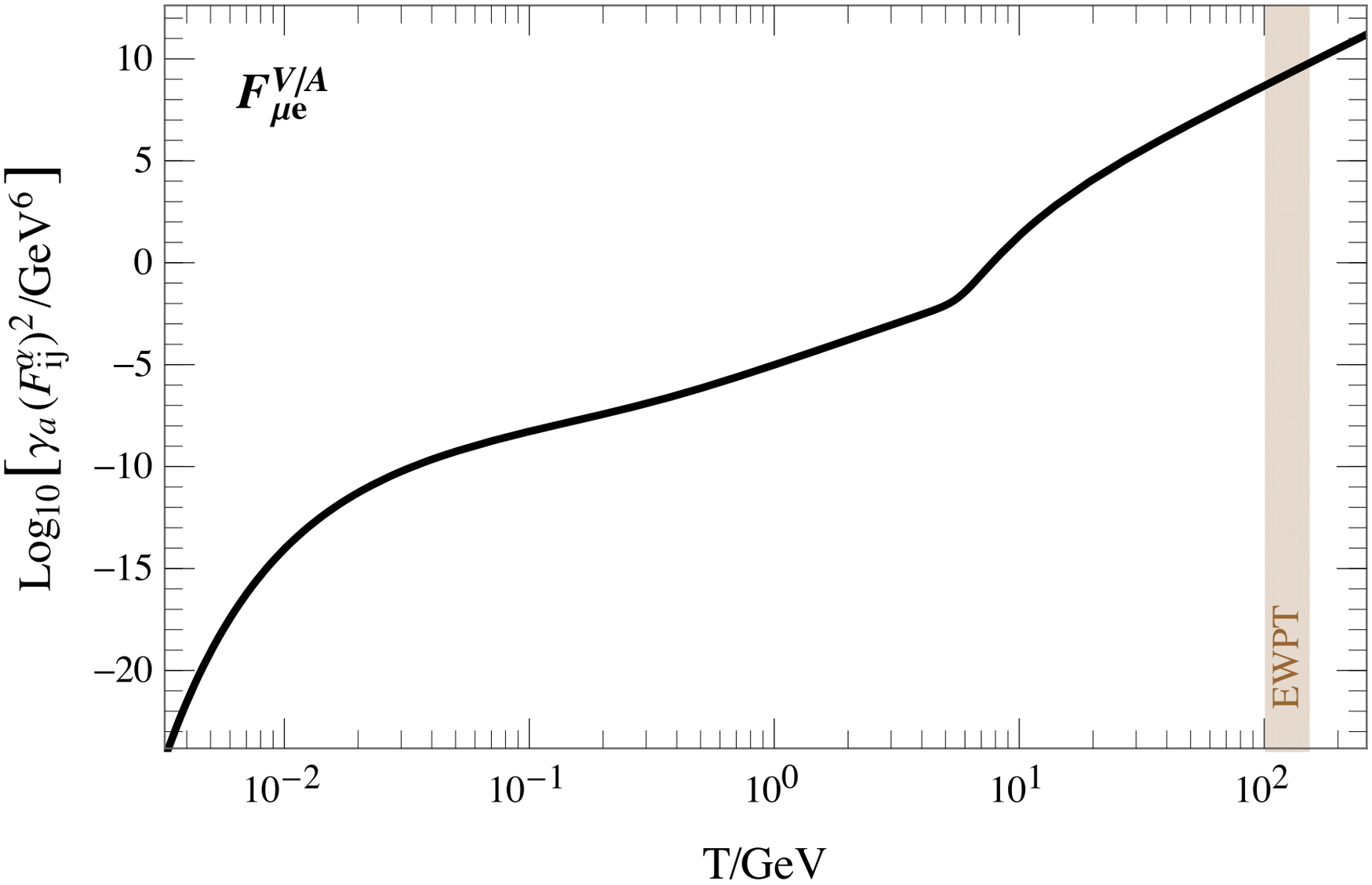

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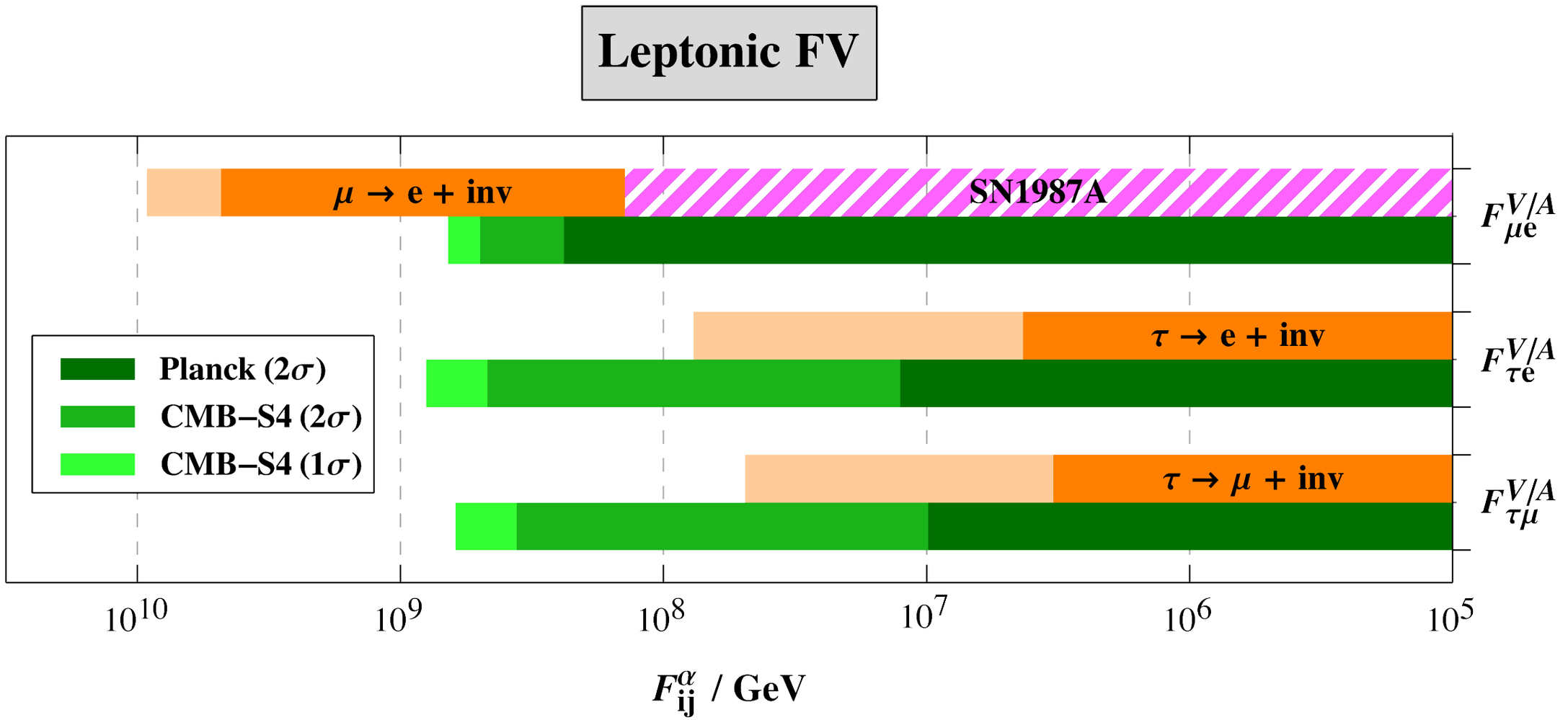

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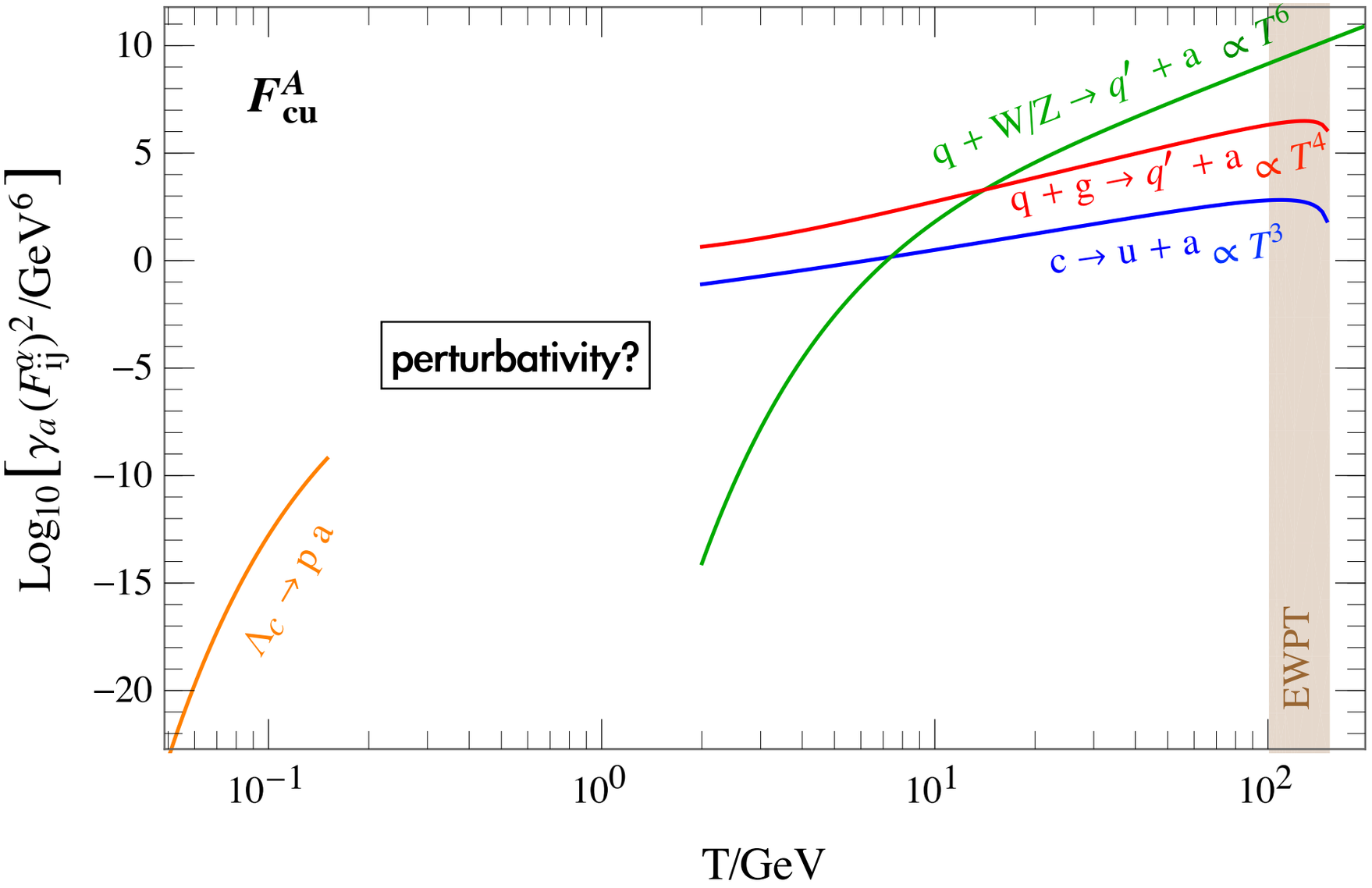

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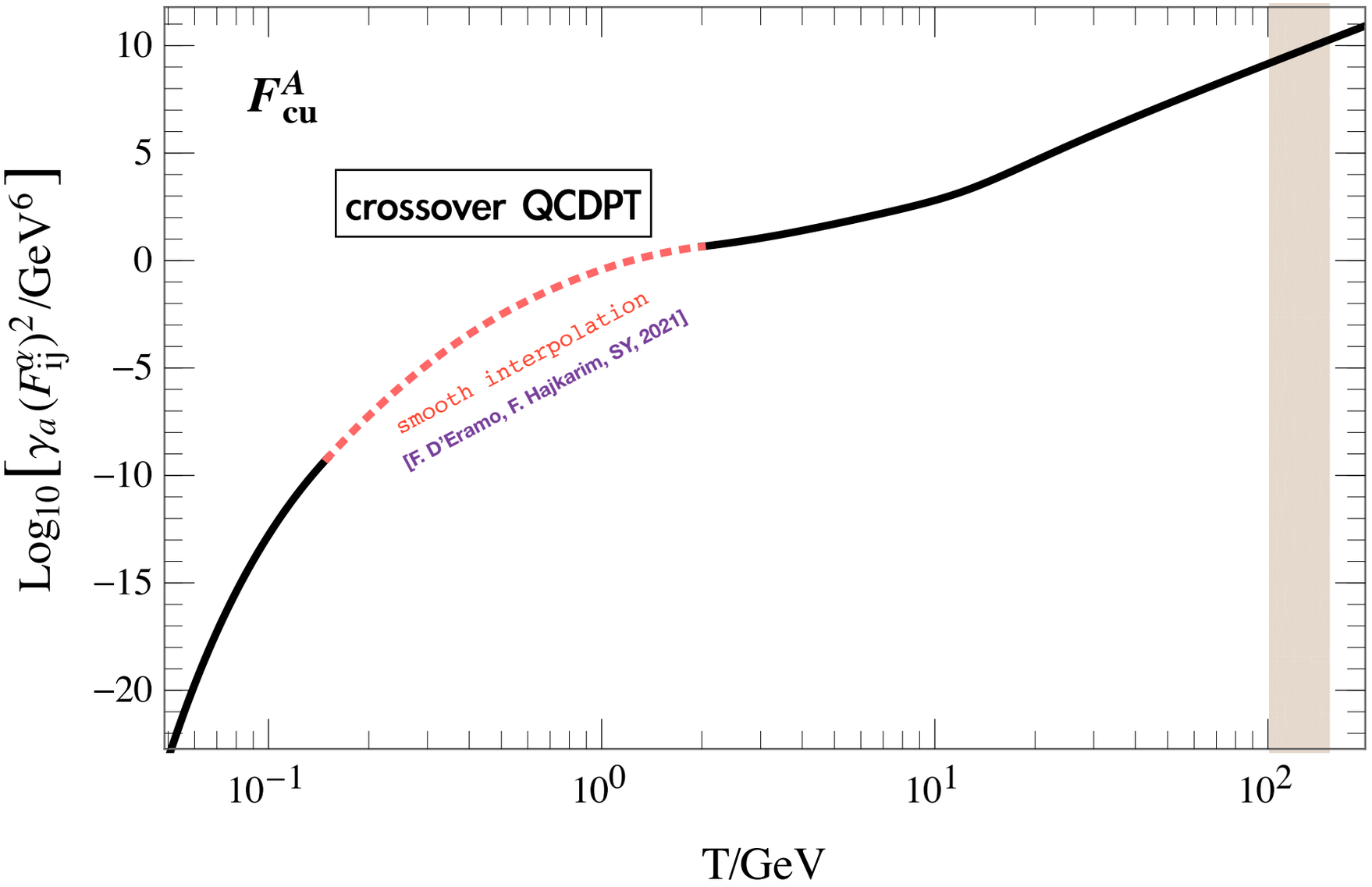

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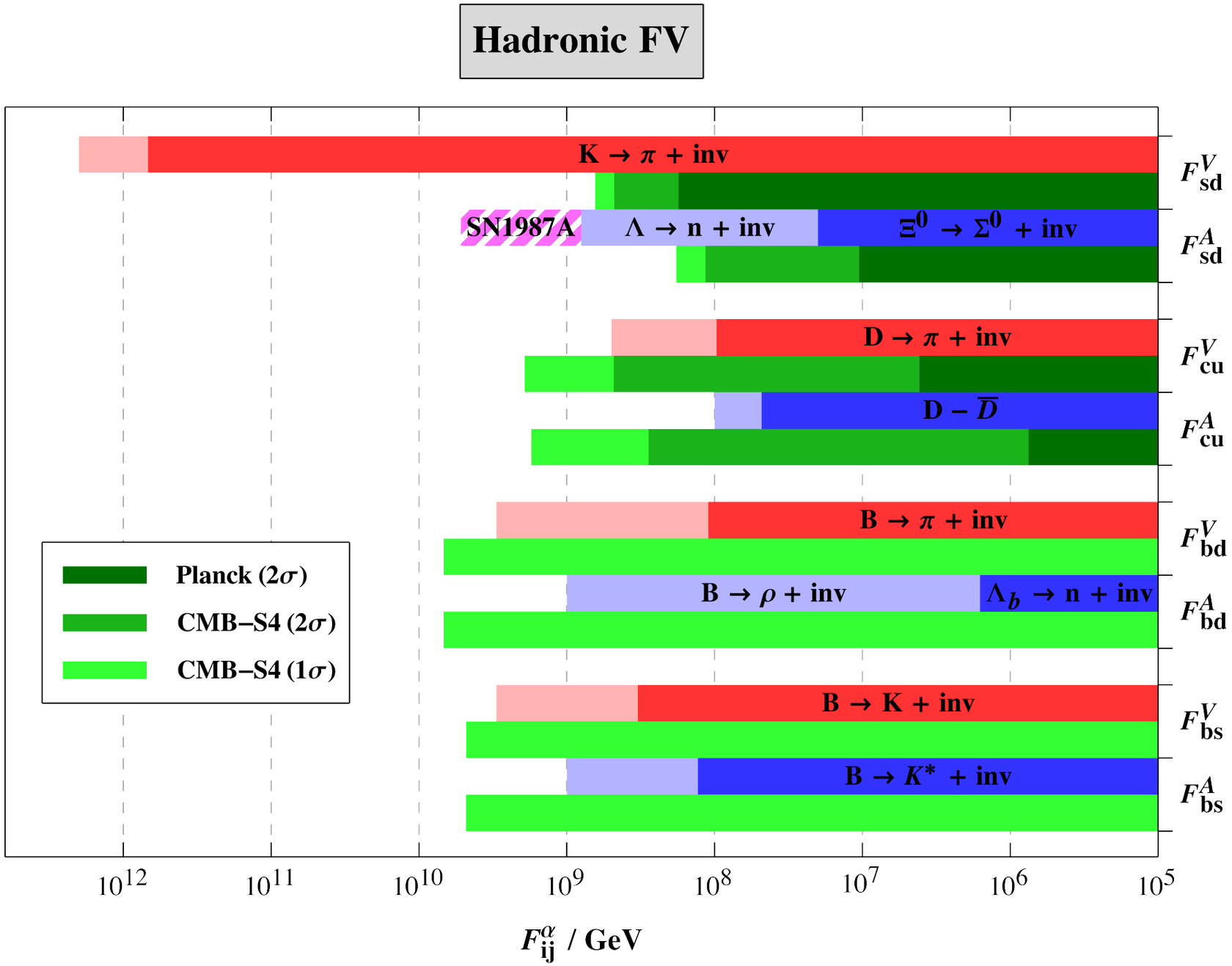


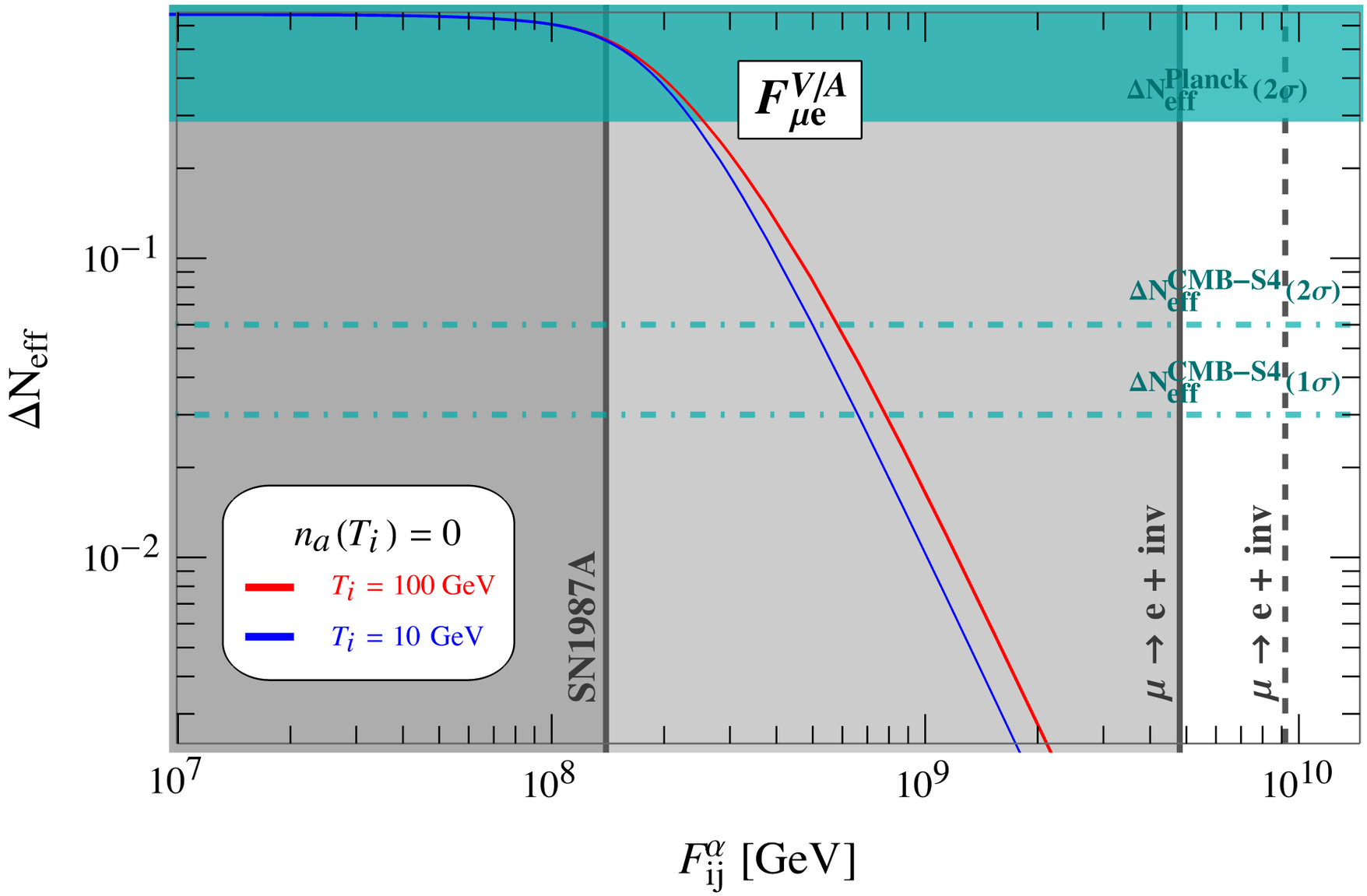
# Conclusion

- Flavor violating axion production rate in the full temperature range
- In comparison with terrestrial experiments, future CMB surveys would give comparable or even better sensitivities to probe flavor violating axion couplings
- Possibility to detect flavor violating axion signal for $F^{\alpha}_{f_i f_j} \sim \mathcal{O}(10^{9\text{-}10})\,\mathrm{GeV}$

# Back up

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

# Leptonic flavor violation



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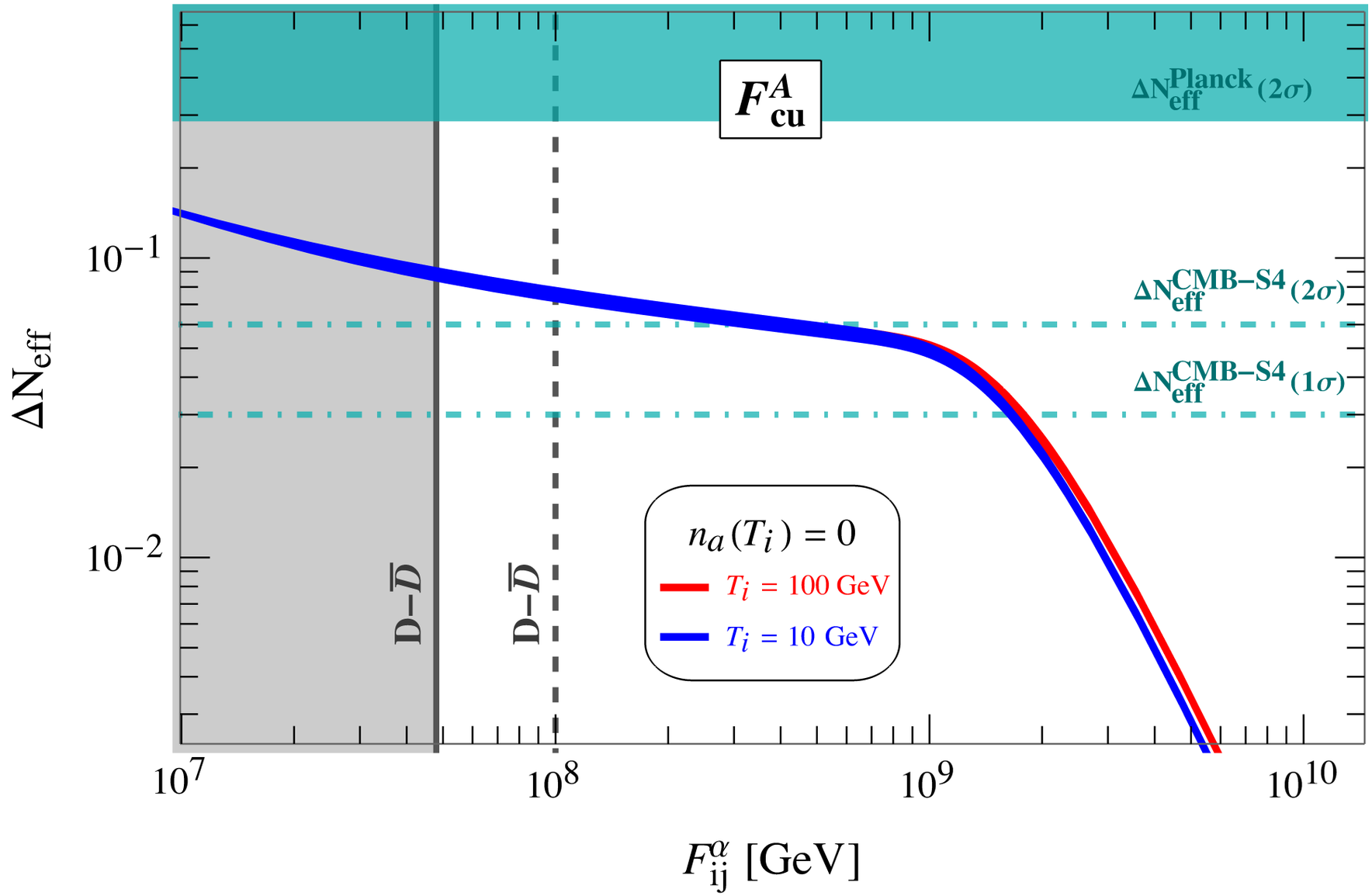

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# Flaxion