Cosmological Imprints of Hot Axions

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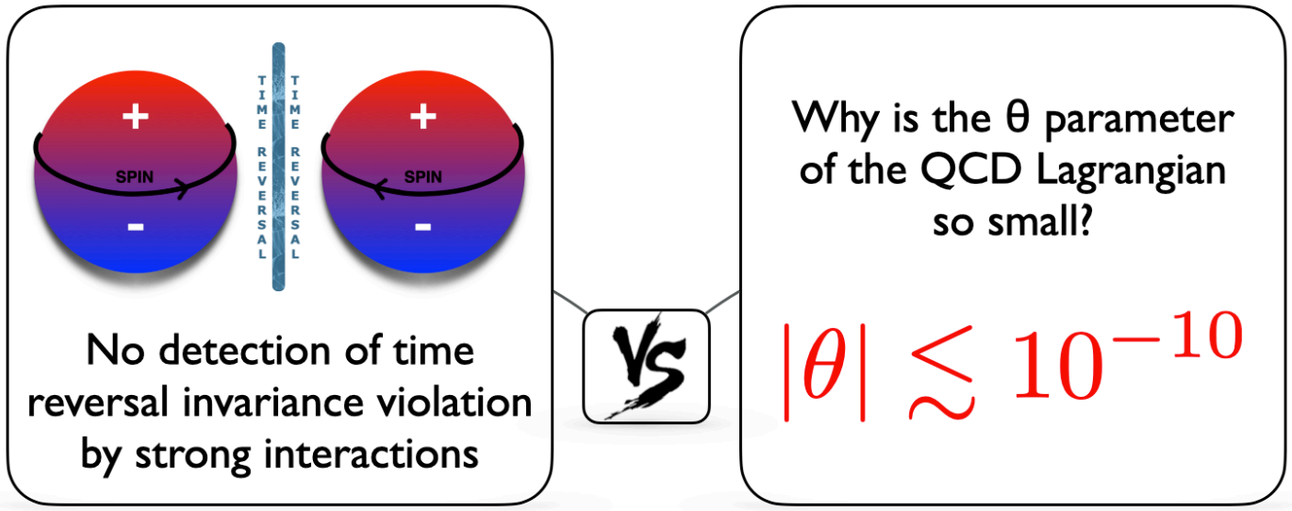
The Strong CP Problem

Strong CP Problem:
Serious Puzzle in Fundamental Physics

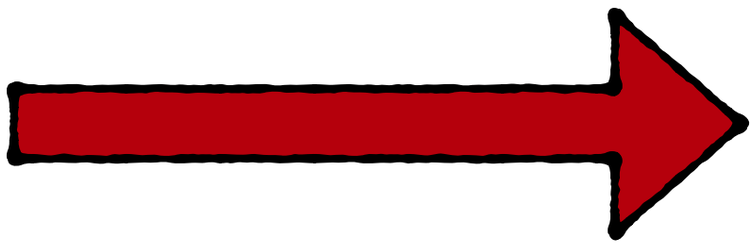


Peccei-Quinn Mechanism: New Global $U(1)_{PQ}$

- spontaneously broken at the scale f_a (with $f_a \gg$ weak scale)
- anomalous under strong interactions

Peccei, Quinn, PRL 38 (1977) and PRD 16 (1977)

The QCD Axion

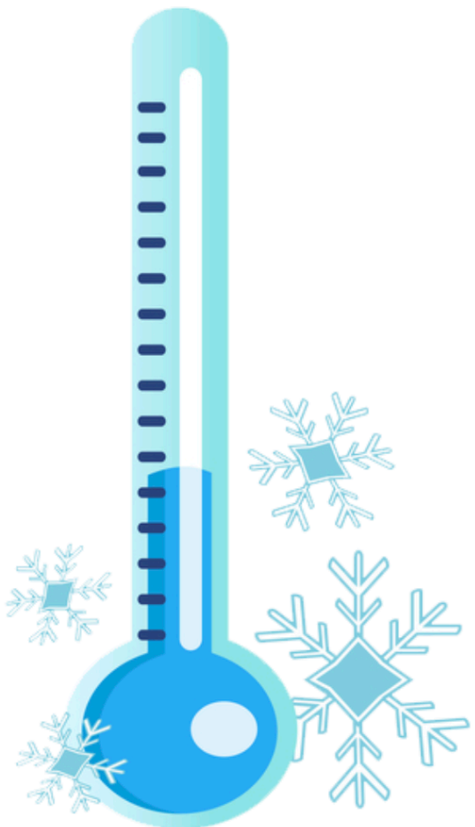


$$\frac{a}{f_a}\frac{\alpha_s}{8\pi}G^{\mu\nu}\tilde{G}_{\mu\nu}$$

CP-conserving minimum!
Strong CP Problem Solved!

$$V(a) \simeq \frac{1}{2}m_a^2 a^2$$

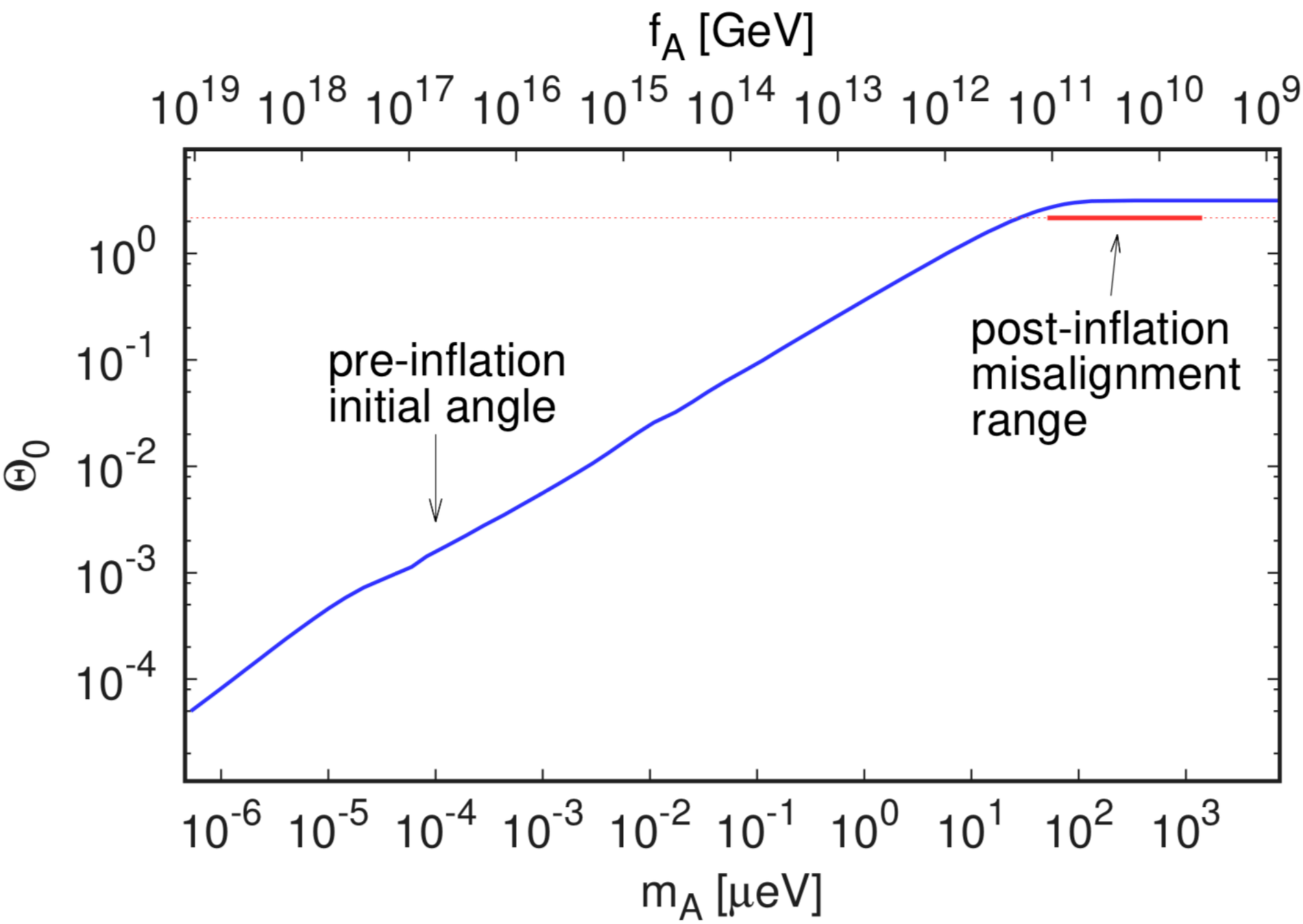
$$m_a \simeq 5.7\left(\frac{10^{12}\,\mathrm{GeV}}{f_a}\right)\,\mu\mathrm{eV}$$



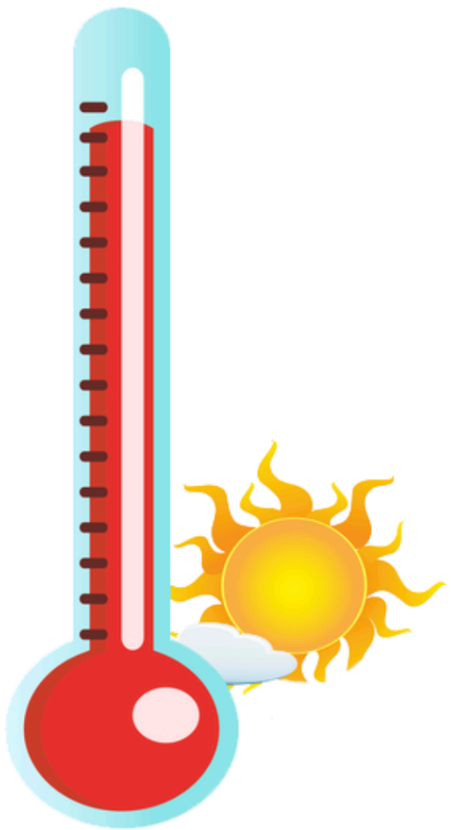
Cold Axions

(Dark Matter)

Cold Axions: Dark Matter



Borsanyi et al., Nature 539 (2016) — 1606.07494



Hot Axions

(Dark Radiation)

Hot Axions: Dark Radiation

Scatterings and/or decays involving particles belonging to the primordial thermal bath

(axion energy much higher than m_a, i.e. "hot")

$$B_1\, B_2 \;\rightarrow\; B_3\, a$$

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They manifest themselves as additional radiation in the CMB anisotropy spectrum

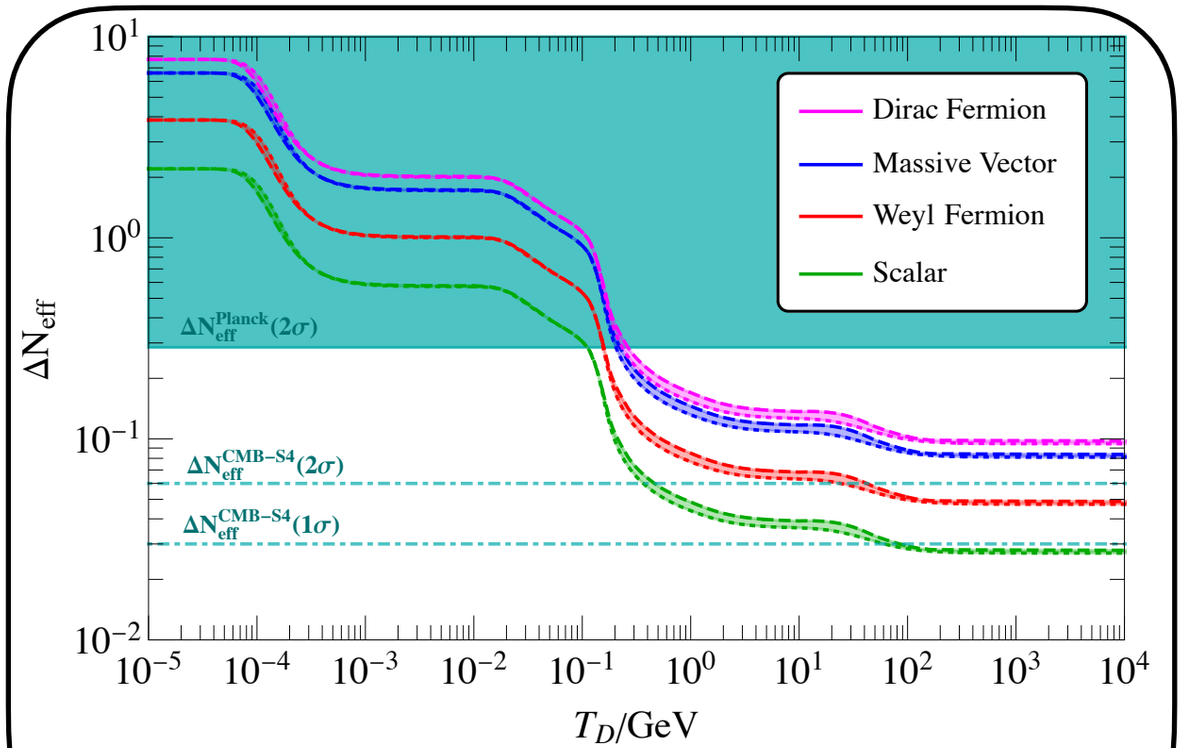
$$\rho_{\rm rad} = \left[1 + \frac{7}{8}\left(\frac{T_\nu}{T_\gamma}\right)^4 N_{\rm eff}\right]\rho_\gamma$$

$$\Delta N_{\rm eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_a}{\rho_\gamma}$$

ΔN_{eff}: Reliable Predictions

Axions may never thermalize

If they do, decoupling detail relevant (effect larger the experimental error)



FD, Hajkarim, Yun, JHEP 10 (2021) 224 — 2108.05371

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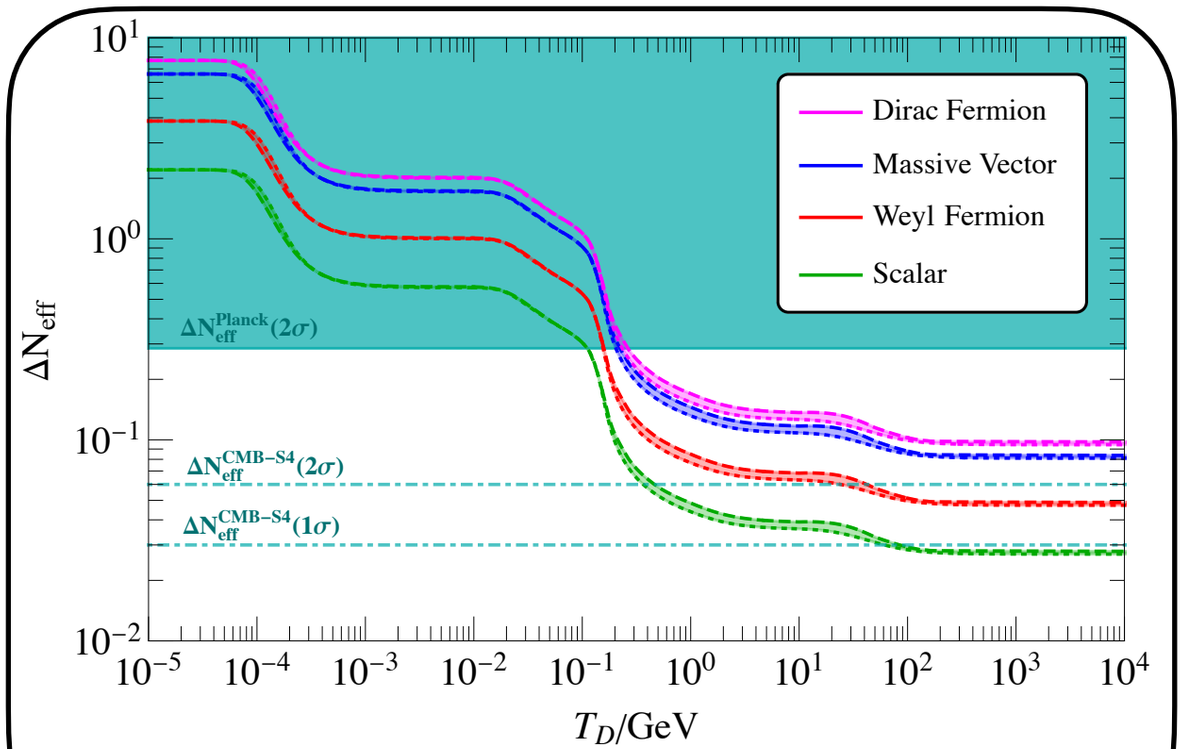


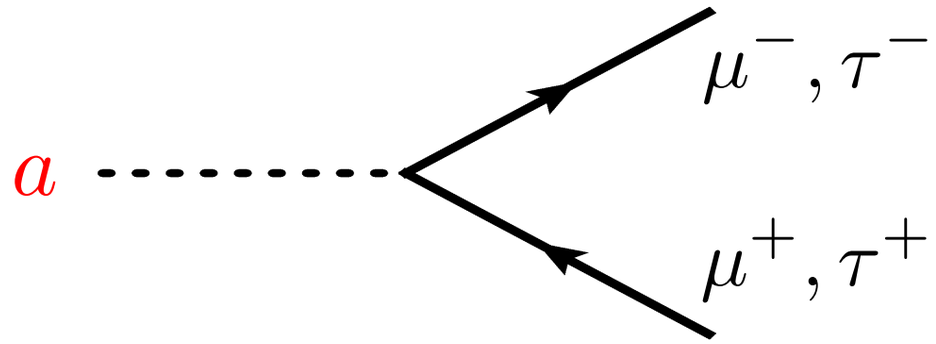
FD, Hajkarim, Yun, JHEP 10 (2021) 224 — 2108.05371

$$\frac{dn_a}{dt} + 3Hn_a = \sum_\alpha \gamma_\alpha$$

$$\mathcal{L}_{\rm int} = c_X \frac{a}{f_a} \frac{\alpha_X}{8\pi} X^{\mu\nu} \tilde{X}_{\mu\nu} + c_\psi \frac{\partial_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$$

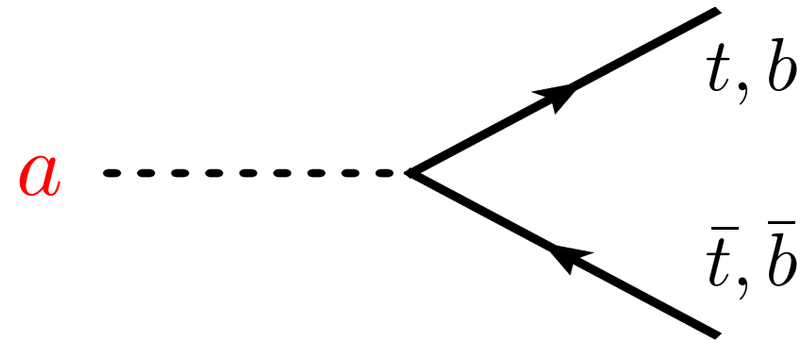
Production Mechanisms

Leptons



FD, Ferreira, Notari, Bernal
JCAP 1811 (2018) — 1808.07430

3rd Gen. Quarks



Arias-Aragon, FD, Ferreira, Merlo, Notari
JCAP 03 (2021) — 2012.04736

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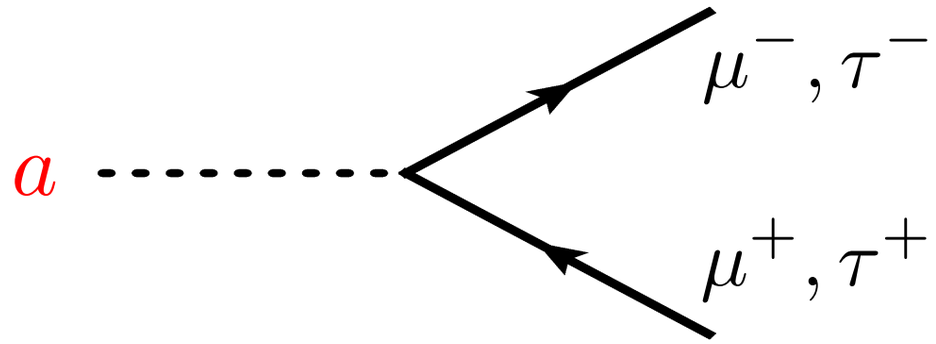
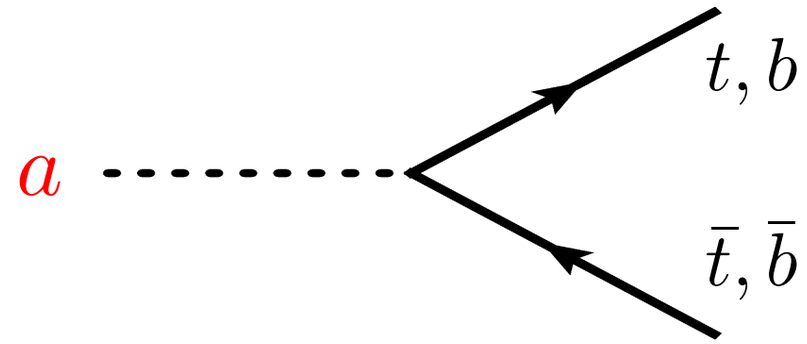


FD, Ferreira, Notari, Bernal
JCAP 1811 (2018) [1808.07430]

They can alleviate the Hubble tension

3rd Gen. Quarks



Arias-Aragon, FD, Ferreira, Merlo, Notari
JCAP 03 (202[illegible] 2012.04726]

Within the reach of CMB-S4 surveys

Production Mechanisms

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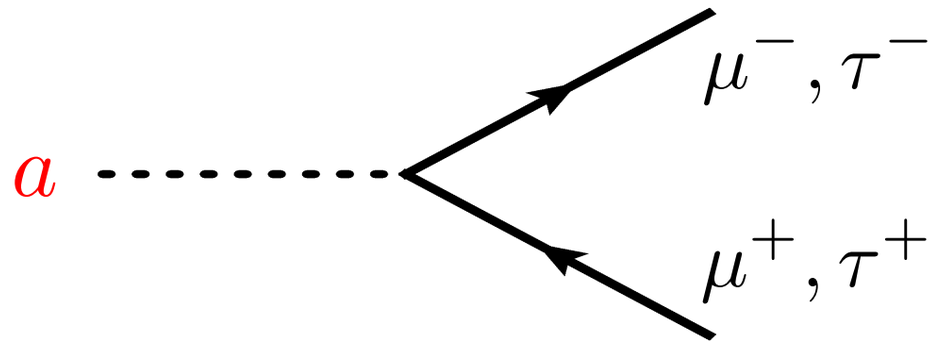

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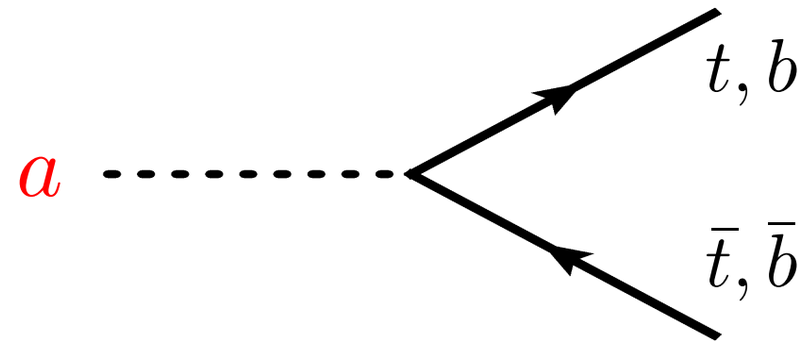

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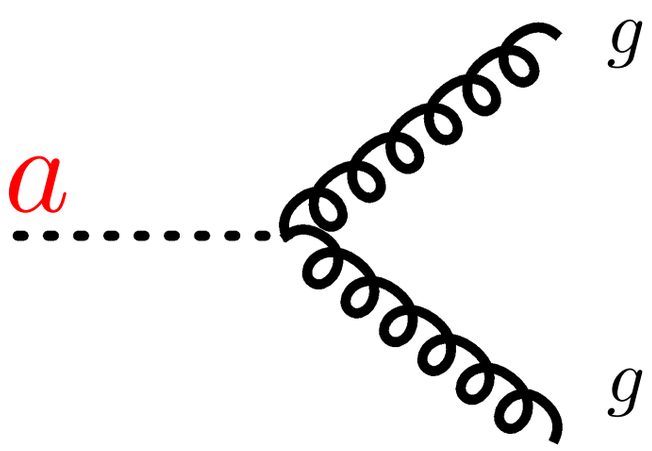
1st and 2nd Gen. Quarks and Gluons



QCD phase transition cannot be ignored

FD, Hajkarim, Yun — 2108.04259
FD, Hajkarim, Yun, JHEP 10 (2021) 224 — 2108.05371

Model Independent Contribution

Strong CP Problem

$$\frac{a}{f_a}\frac{\alpha_s}{8\pi}G^{\mu\nu}\tilde{G}_{\mu\nu}$$

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Above QCDPT

$$gg \to g\mathcal{a}$$
$$\bar{q}q \to g\mathcal{a}$$
$$q/\bar{q}\; g \to q/\bar{q}\; \mathcal{a}$$

Long-range of gluon-mediated interactions give rise to unpleasant IR behavior

Masso, Rota, Zsembinszki, PRD66 (2002) — 0203221
Graf, Steffen, PRD 83 (2011) — 1008.4528
Salvio, Strumia, Xue, JCAP 01 — 1310.6982

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Below QCDPT

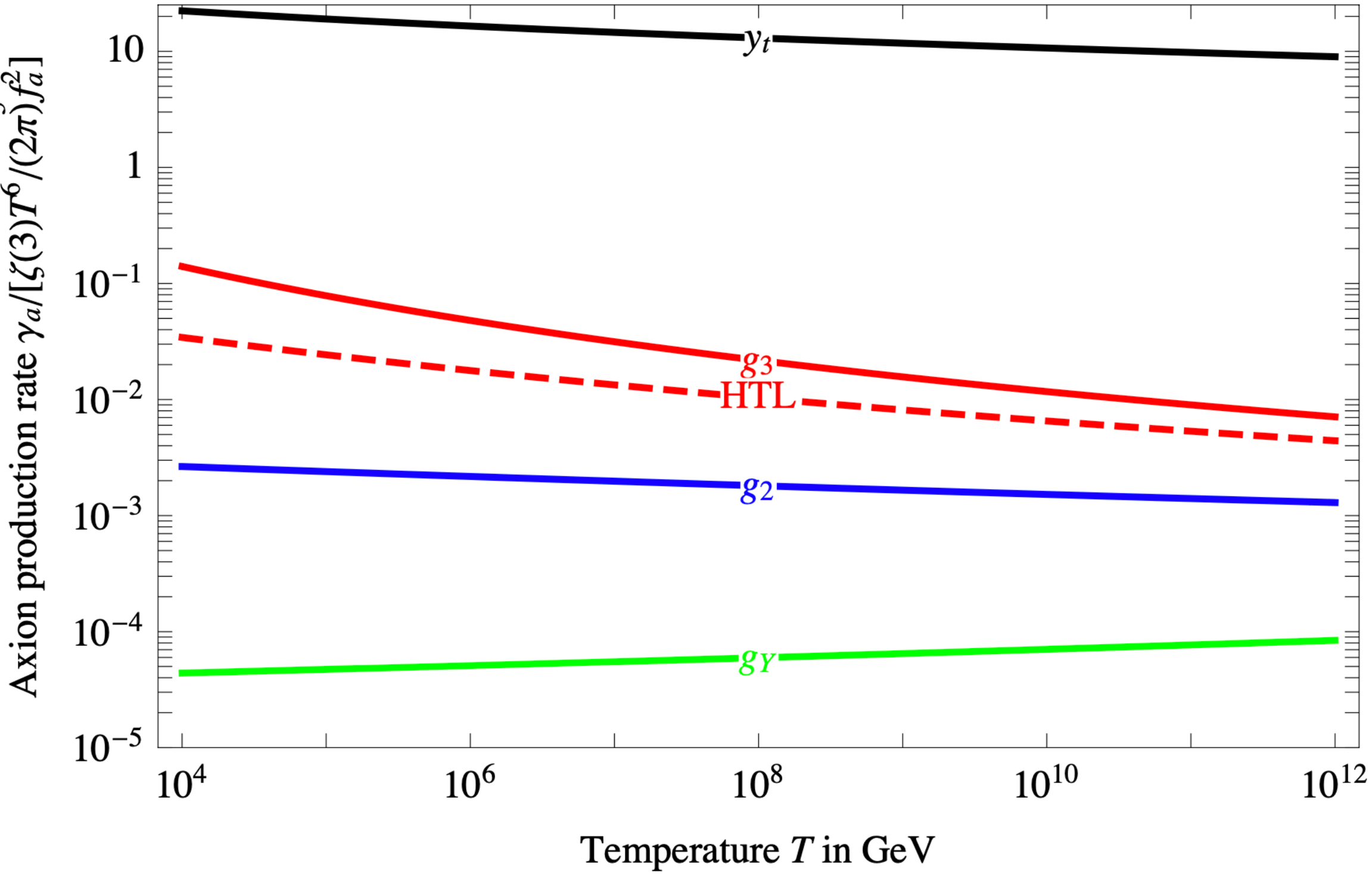
$$\pi\pi \to \pi\mathcal{a}$$

Thermalization via pion scattering requires rather small values of f_a

Perturbative control only for T < 62 MeV

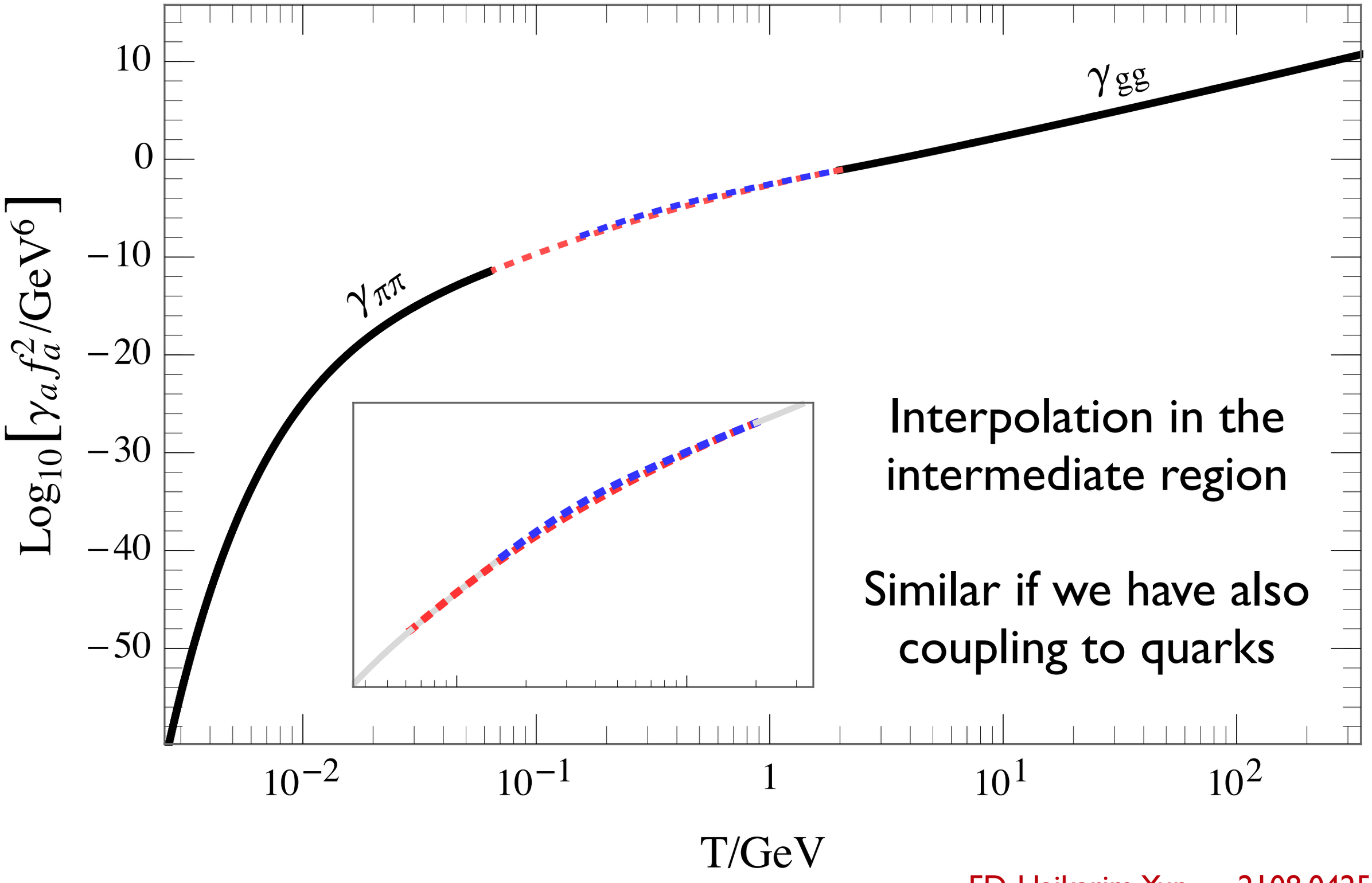
Chang, Choi, PLB 316 (1993) — 9306216
Di Luzio, Martinelli, Piazza, PRL 126 (2021) — 2101.10330

Thermal Gluon Scattering



Salvio, Strumia, Xue, JCAP 01 — 1310.6982 [hep-ph]

Rate Across the QCDPT



FD, Hajkarim, Yun — 2108.04259

KSVZ Axion — Theory

Energy

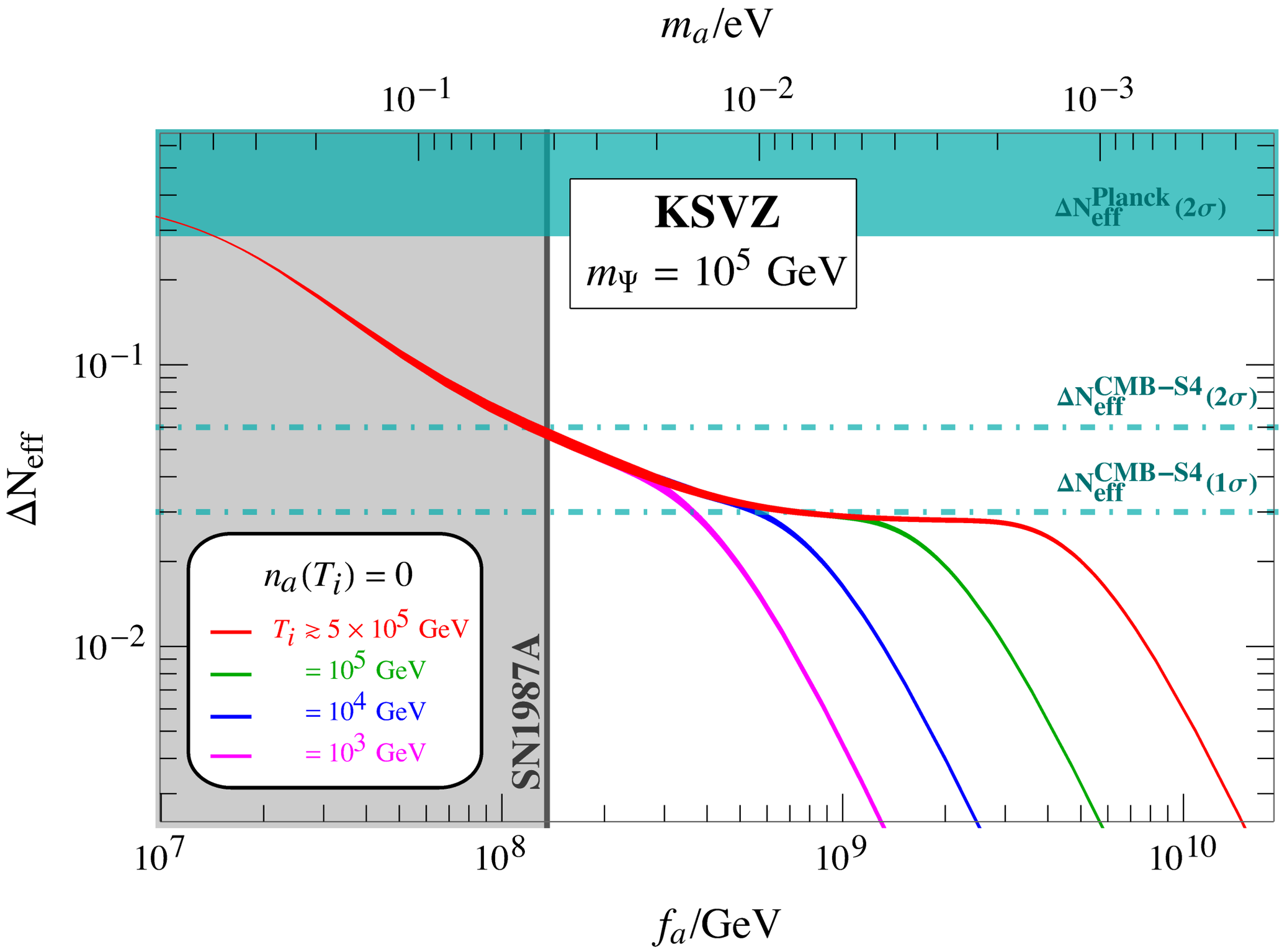
$$(\partial^\mu \varphi)^\dagger \, \partial_\mu \varphi + \bar{\Psi} i \not{\partial} \Psi - \lambda_\varphi \left(|\varphi|^2 - v_\varphi^2/2 \right)^2 - \left(y_\Psi \, \varphi^\dagger \bar{\Psi}_L \Psi_R + \text{h.c.} \right)$$

$$\frac{1}{2} \partial^\mu a \partial_\mu a + \bar{\Psi} i \not{D} \Psi - \left[m_\Psi e^{-ia/v_\varphi} \bar{\Psi}_L \Psi_R + \text{h.c.} \right]$$

$$\frac{1}{2} \partial^\mu a \partial_\mu a + \frac{\alpha_s}{8\pi} \frac{a}{v_\varphi} G^A_{\mu\nu} \widetilde{G}^{A\mu\nu}$$

Kim, PRL 43 (1979)
Shifman, Vainshtein, Zakharov, NPB 166 (1980)

KSVZ Axion — ΔN_{eff}



FD, Hajkarim, Yun, JHEP 10 (2021) 224 — 2108.05371

DFSZ Axion — Theory

Energy

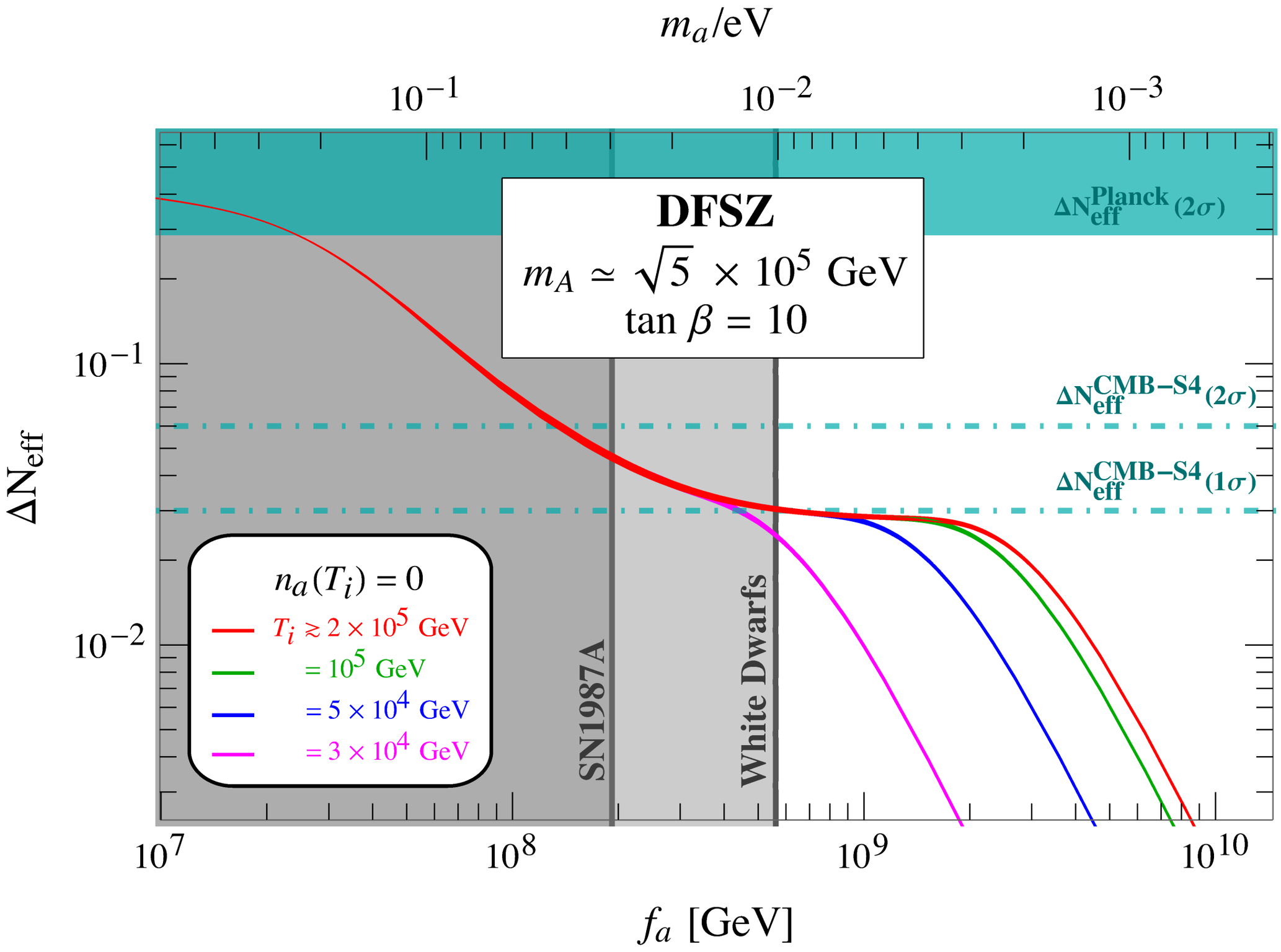
$$B\left(\frac{\varphi^\dagger}{v_\varphi/\sqrt{2}}\right)^r H_u^T i\sigma^2 H_d + \text{h.c.}$$

$$\frac{1}{2}\partial^\mu a \partial_\mu a - B\left[e^{-i\frac{N_{\text{DW}}}{3}\frac{a}{v_\varphi}} H_u^T i\sigma^2 H_d + \text{h.c.}\right]$$

$$\frac{1}{2}\partial^\mu a \partial_\mu a - \frac{\partial_\mu a}{v_\varphi}\left[\sum_f q_f \bar{f}\gamma^\mu f + \sum_\alpha q_{H_\alpha} H_\alpha^\dagger i\overleftrightarrow{D}^\mu H_\alpha\right]$$
$$+\frac{a}{v_\varphi}\left[N_{\text{DW}}\frac{g_s^2}{32\pi^2}G^A_{\mu\nu}\widetilde{G}^{A\mu\nu} + c_W\frac{g^2}{32\pi^2}W^I_{\mu\nu}\widetilde{W}^{I\mu\nu} + c_Y\frac{g'^2}{32\pi^2}B_{\mu\nu}\widetilde{B}^{\mu\nu}\right]$$

Zhitnitsky, SJNP 31 (1980)
Dine, Fischler, Srednicki, PLB 104 (1981)

DFSZ Axion — ΔN_{eff}



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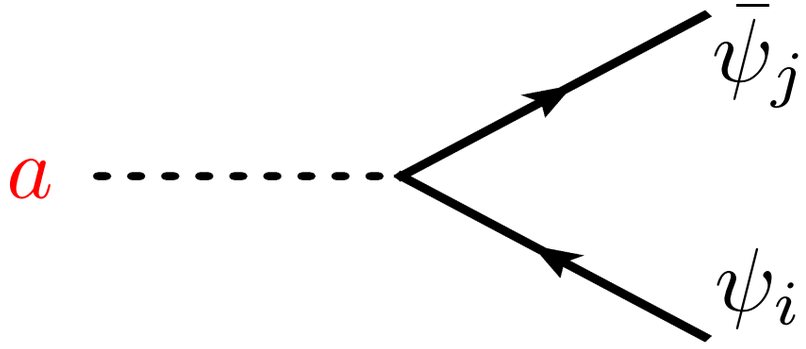
Flavor Violating Axions

$$\mathcal{L}_{\rm FV}^{(a)} = \frac{\partial_\mu a}{2f_a} \sum_{\psi_i \neq \psi_j} \bar{\psi}_i \gamma^\mu \left(c^V_{\psi_i \psi_j} + c^A_{\psi_i \psi_j} \gamma^5 \right) \psi_j$$



Target of several terrestrial experiments

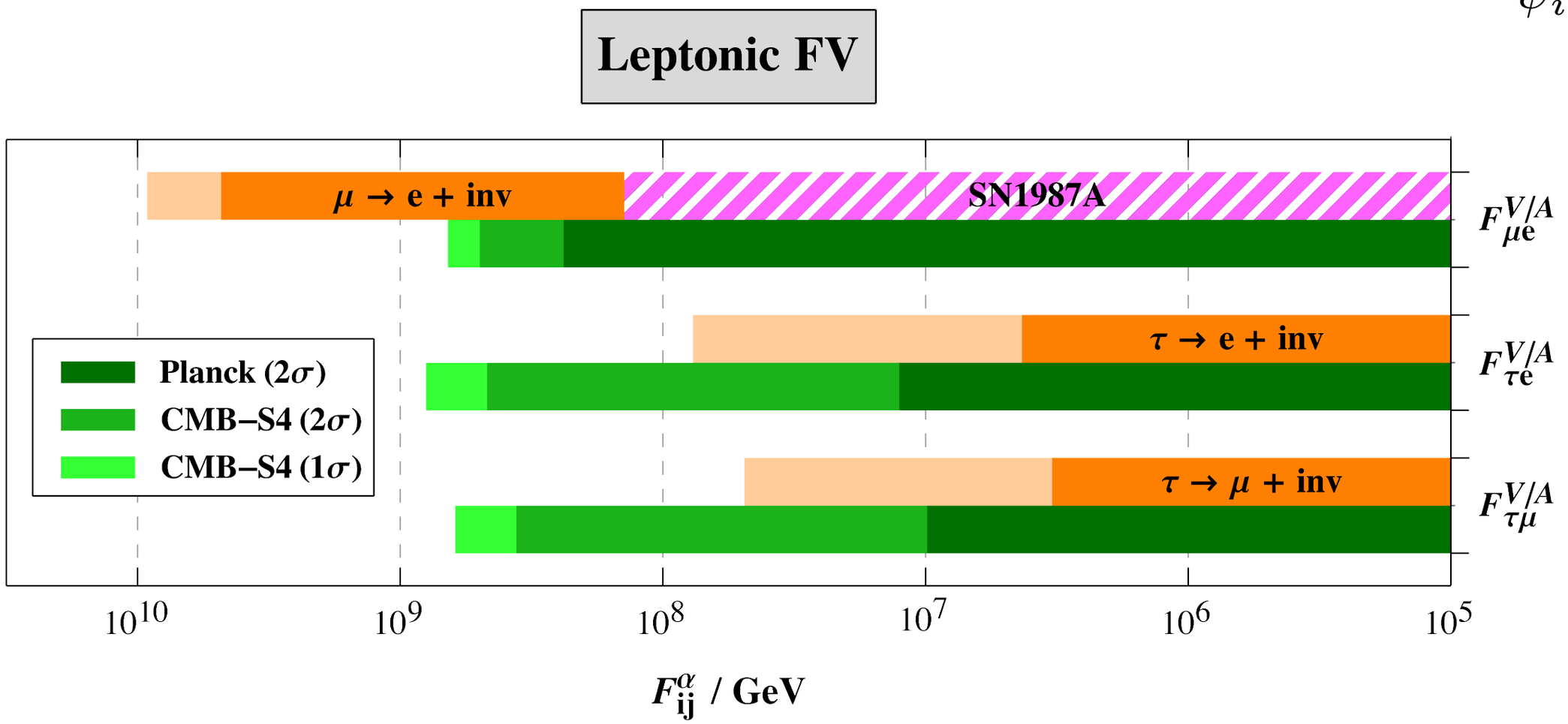
What about their role in the early universe?

They mediate hot axion production via <u>decays</u> and <u>scatterings</u>

FD, Yun — 2111.12108

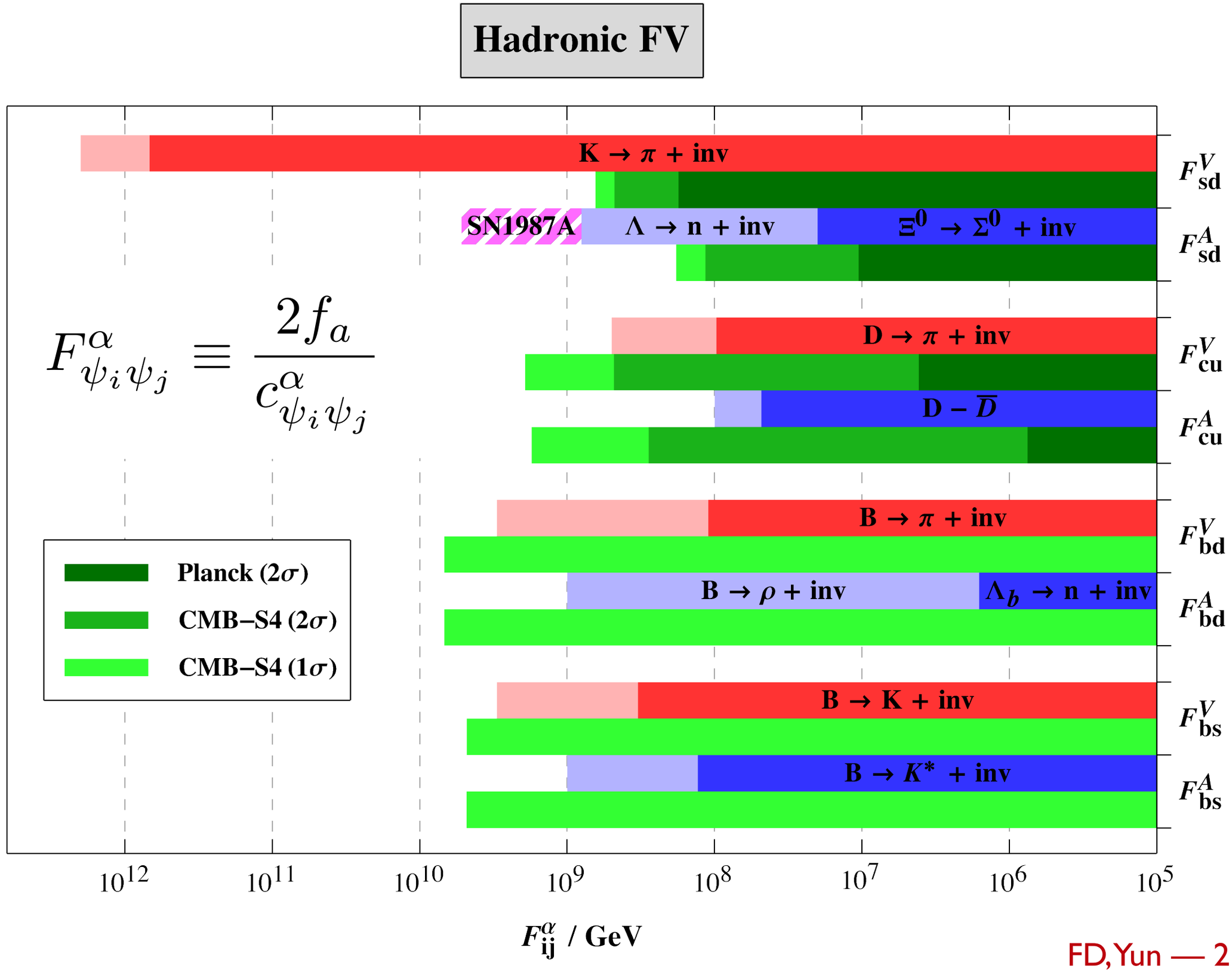
Flavor Violating Axions

$$F^{\alpha}_{\psi_i\psi_j} \equiv \frac{2f_a}{c^{\alpha}_{\psi_i\psi_j}}$$



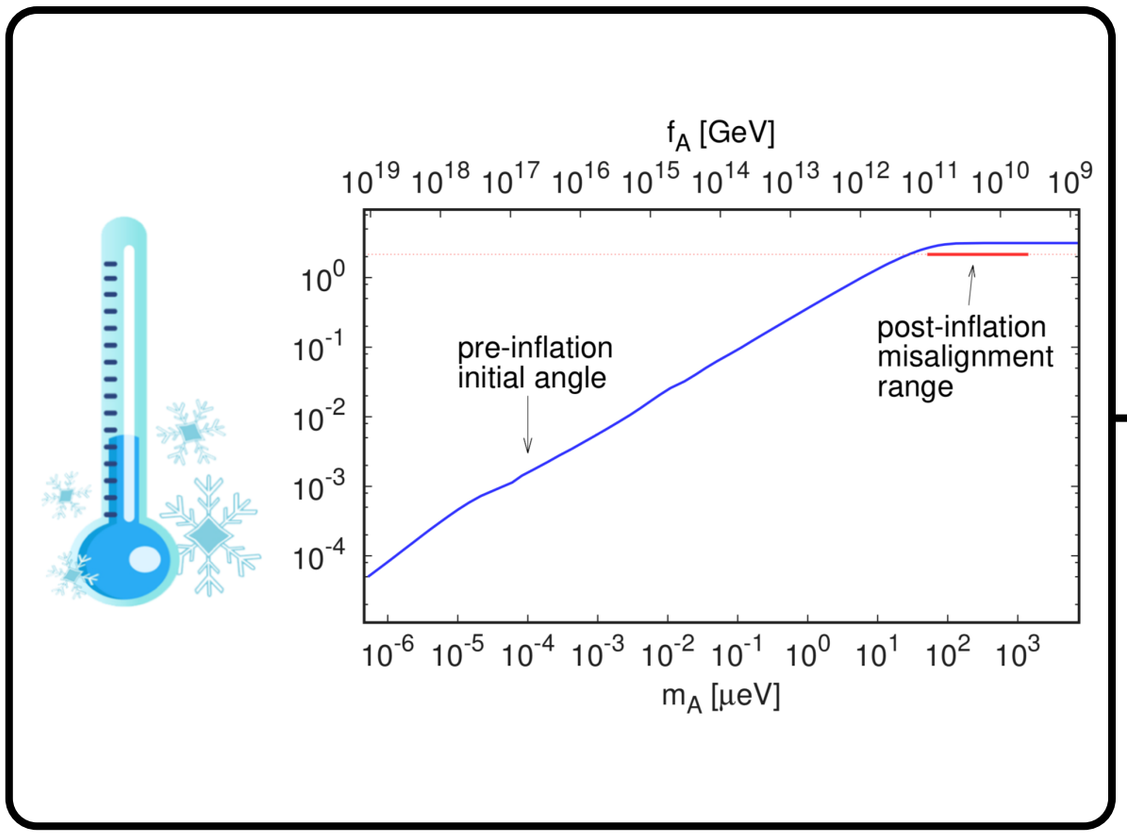
FD, Yun — 2111.12108

Flavor Violating Axions



FD, Yun — 2111.12108

Outlook



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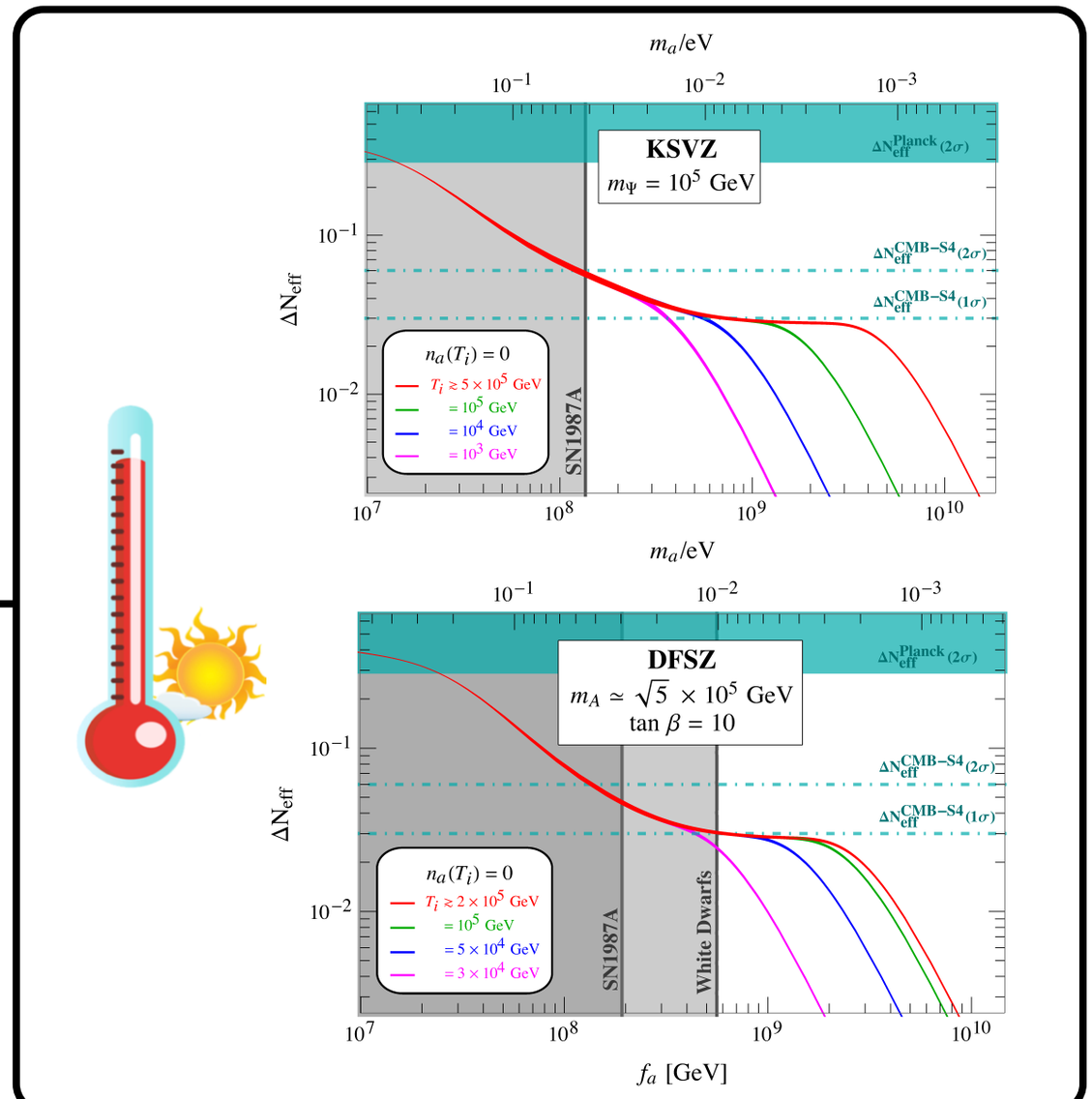
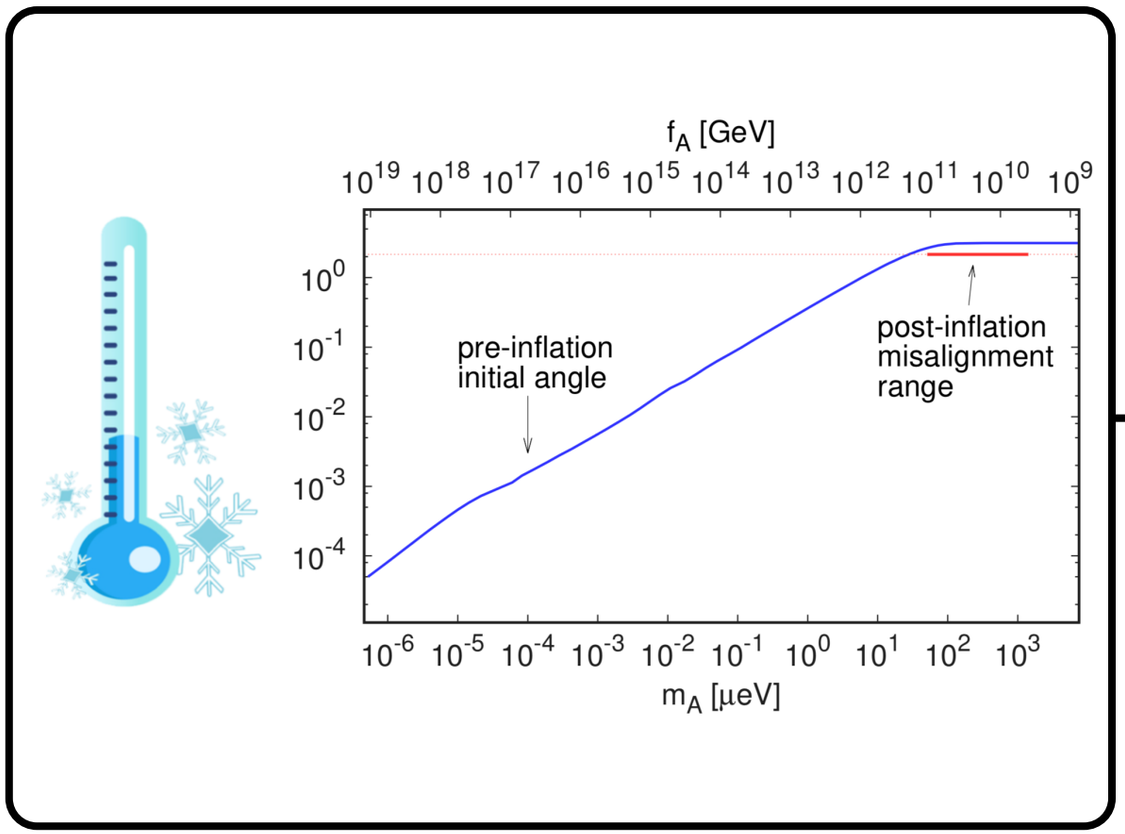


Hot Axions

Complementary to other probes of the
PQ mechanism and flavor violation

Outlook



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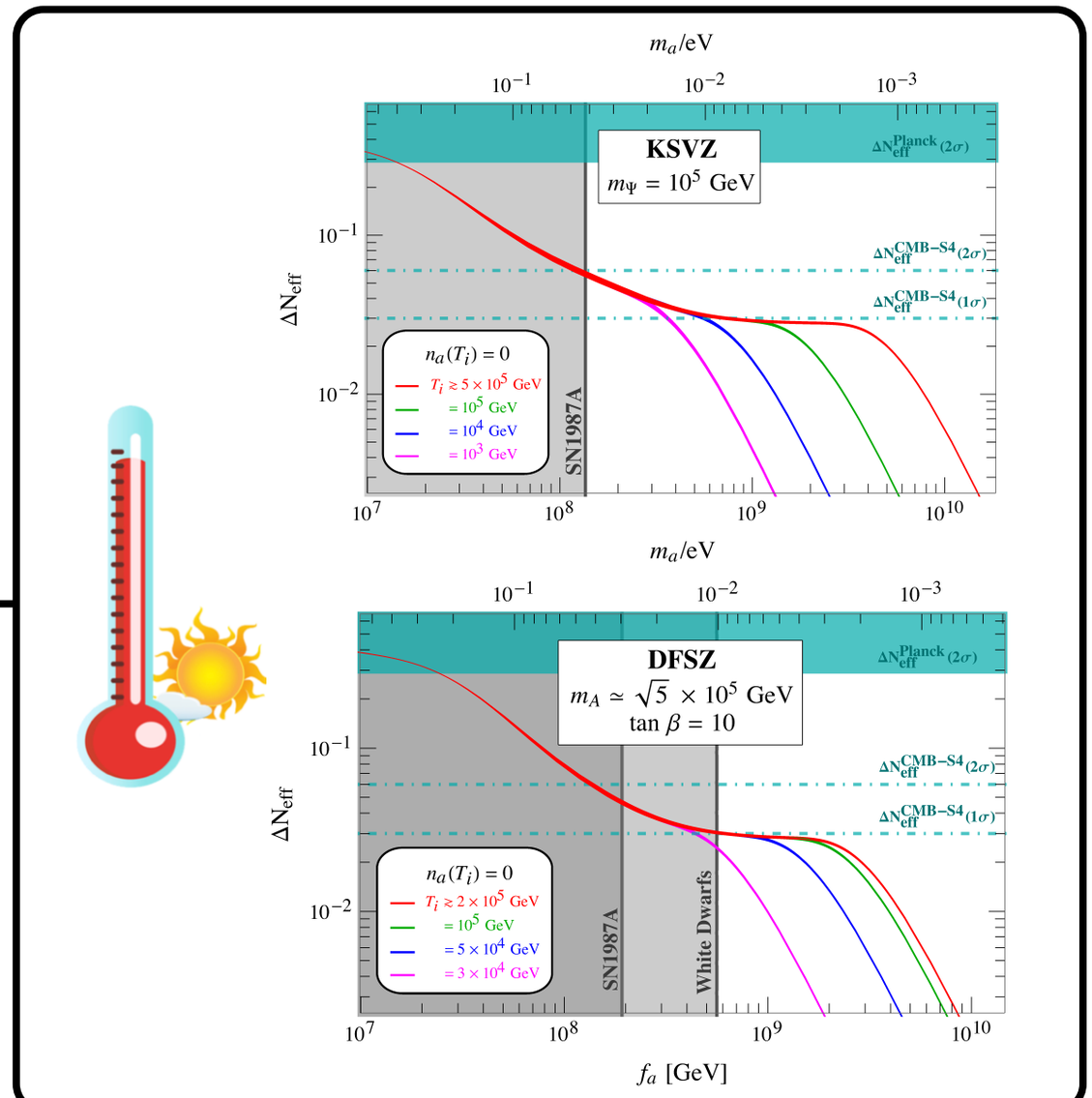
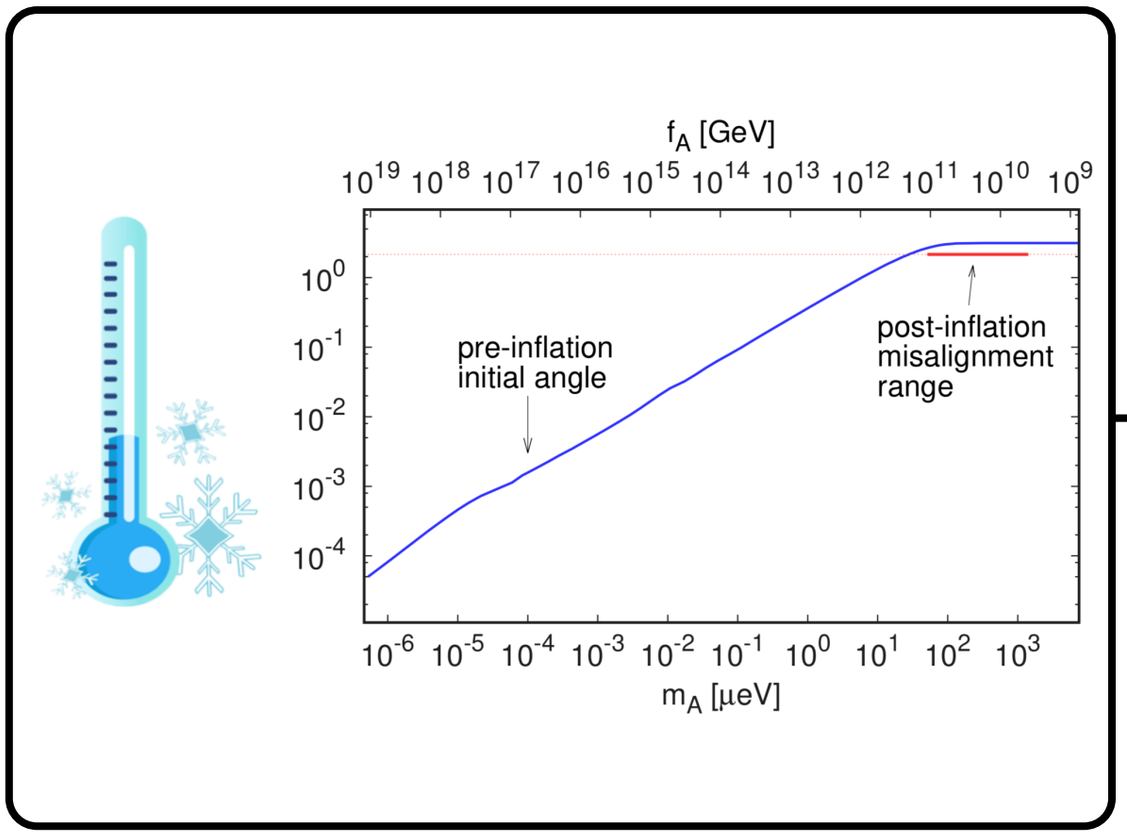


Future Work

Other UV completions (e.g. for flavor violation),
modified cosmological histories, beyond the QCD axion…

Outlook



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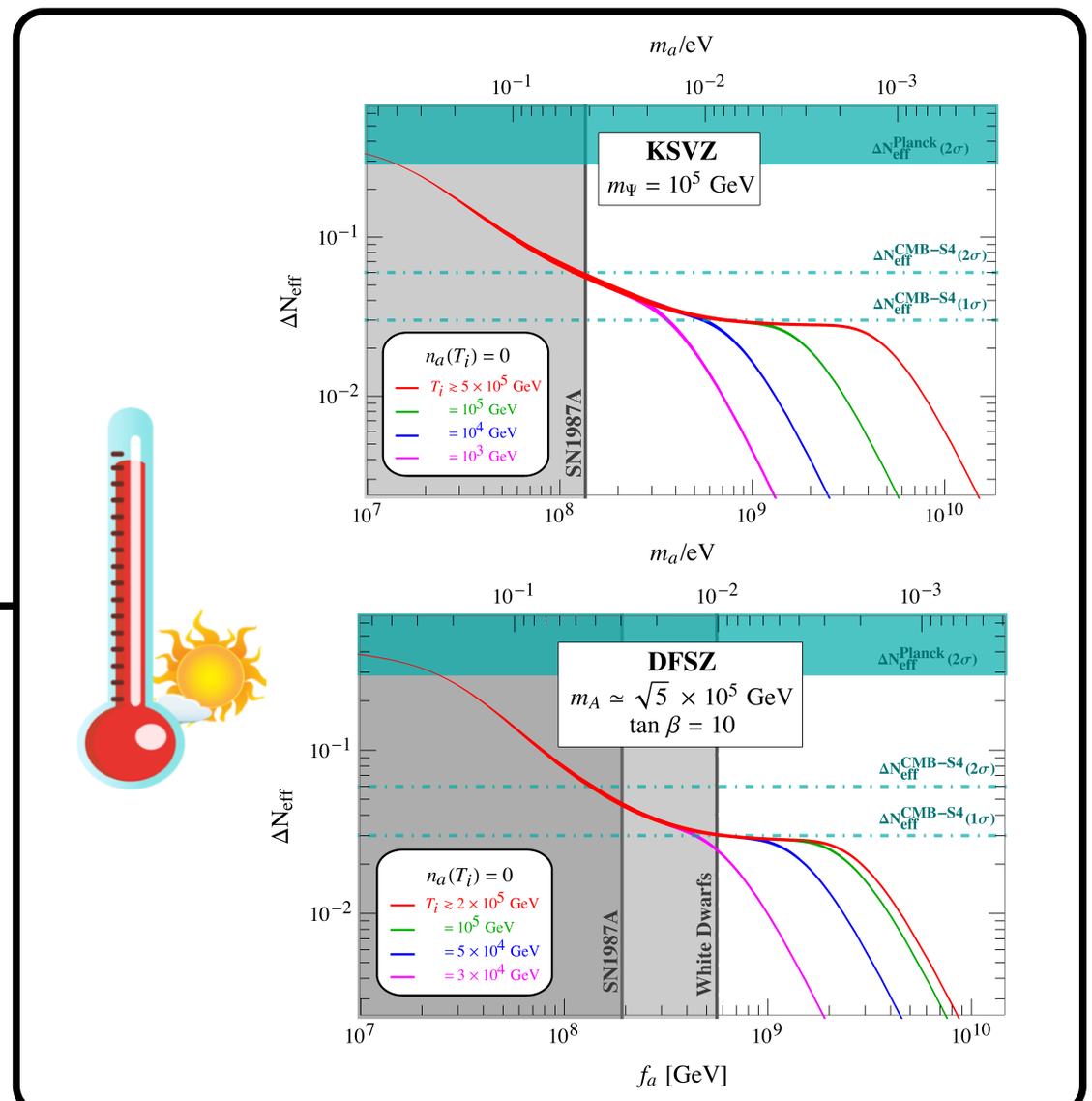

THANK YOU!