Axion Dark Radiation from the Primordial Thermal Bath

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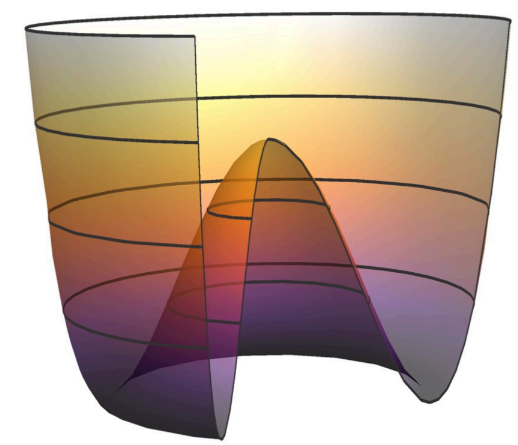
The QCD Axion

New global $U(1)_{PQ}$ symmetry

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

Pseudo Nambu-Goldstone boson in the low-energy spectrum ("QCD axion") with ("anomalous") coupling to gluons



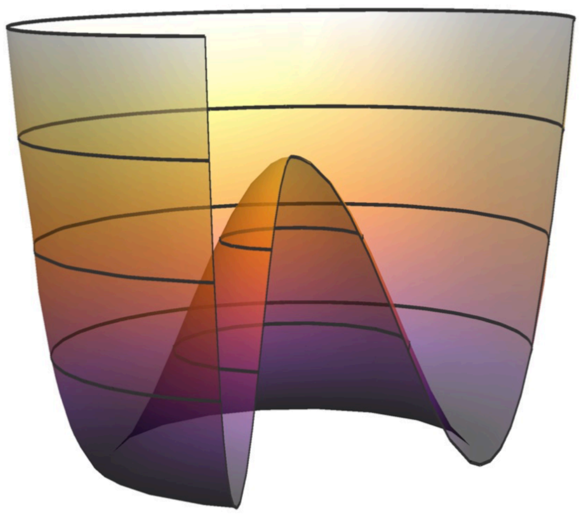
$$\frac{a}{f_a}\frac{\alpha_s}{8\pi}G^{\mu\nu}\tilde{G}_{\mu\nu}$$

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

Peccei, Quinn, Phys.Rev.Lett. 38 (1977) and Phys.Rev.D 16 (1977)
Wilczek, Phys.Rev.Lett. 40 (1978)
Weinberg, Phys. Rev. Lett. 40 (1978)

Axion-Like-Particles (ALPs)

Ubiquitous in motivated
extension of the Standard Model



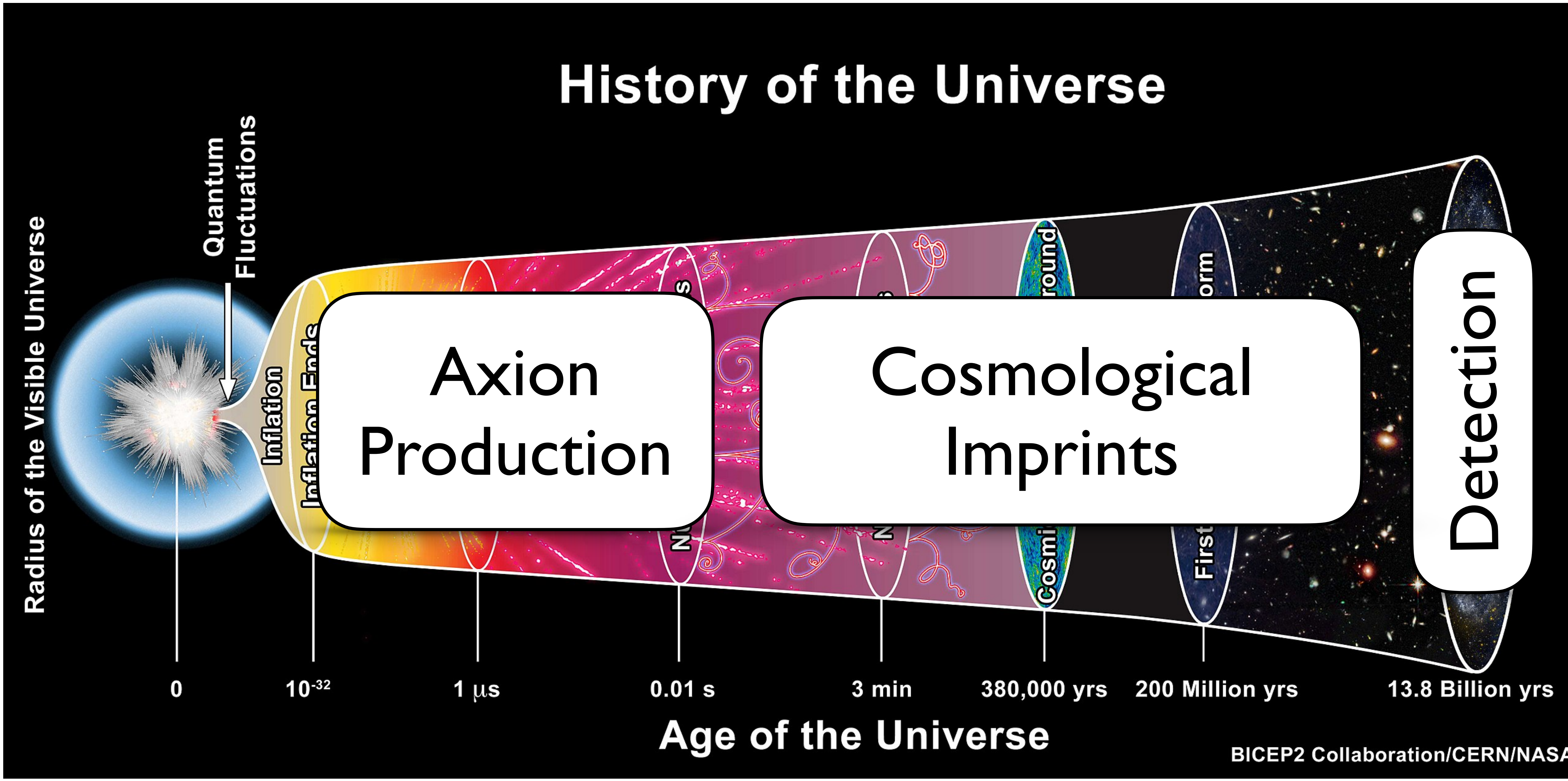
- Pseudo-Nambu-Goldstone-bosons in field theory
- Axions in string theory

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

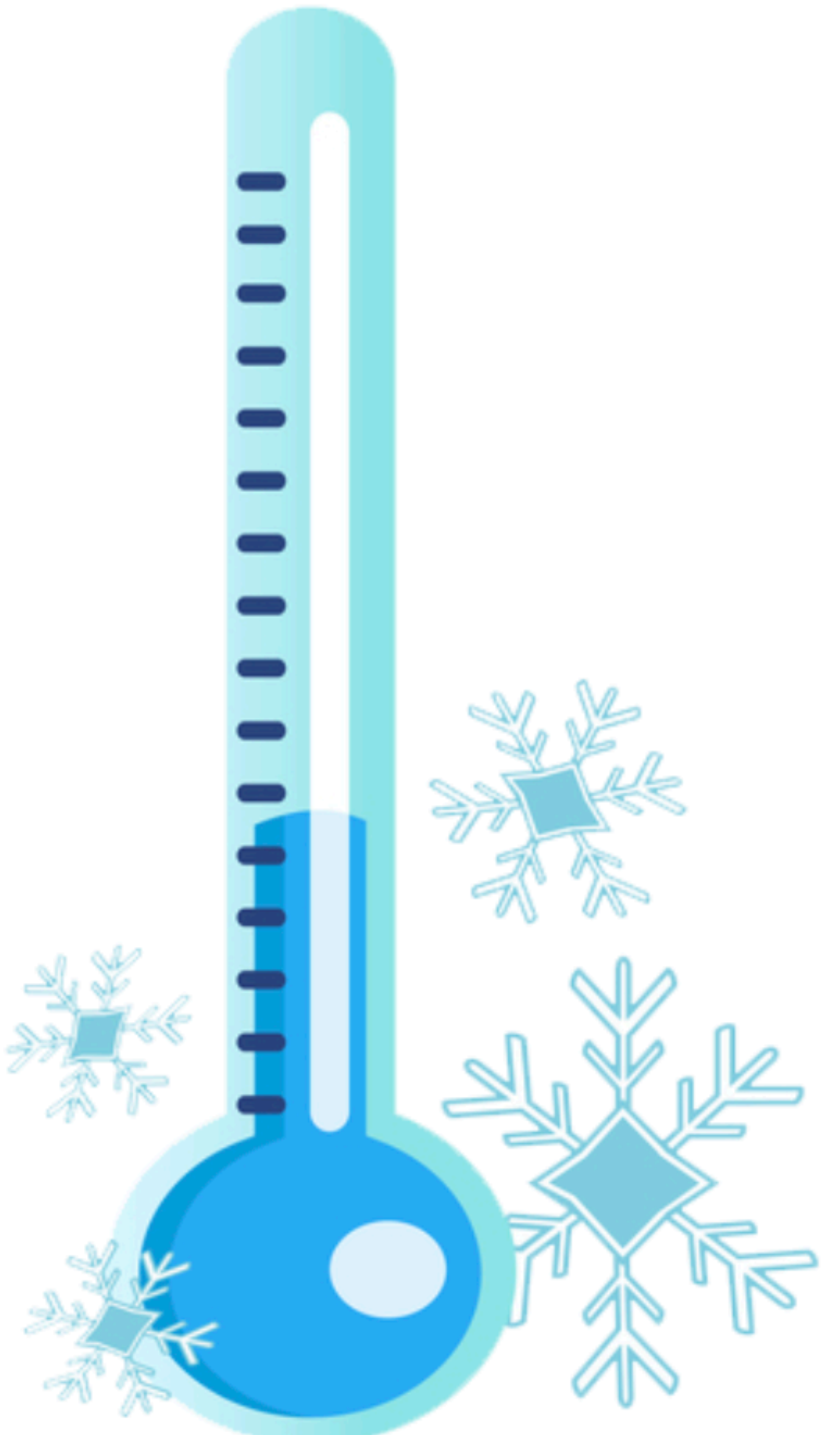
$$m_a \simeq \frac{\Lambda^2}{f_a}$$

Results in this talk mostly about the QCD axion, easily generalized (especially when the mass does not play any role)

Axions in the Early Universe

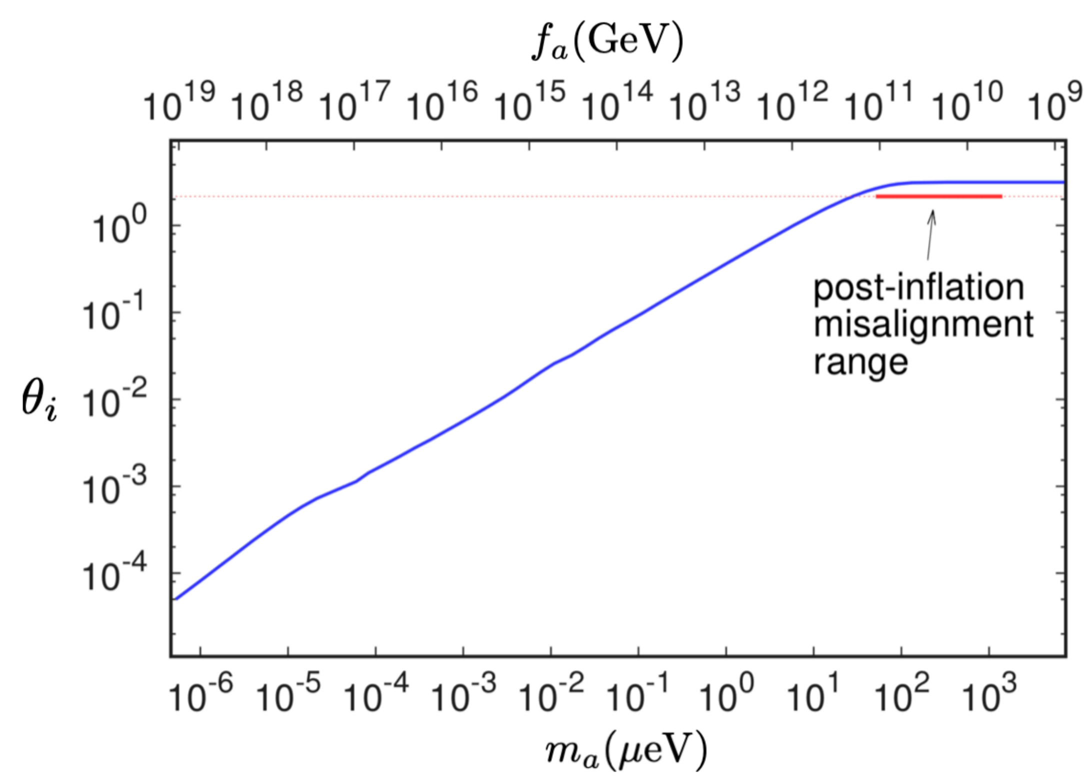


Cold Axions — Dark Matter



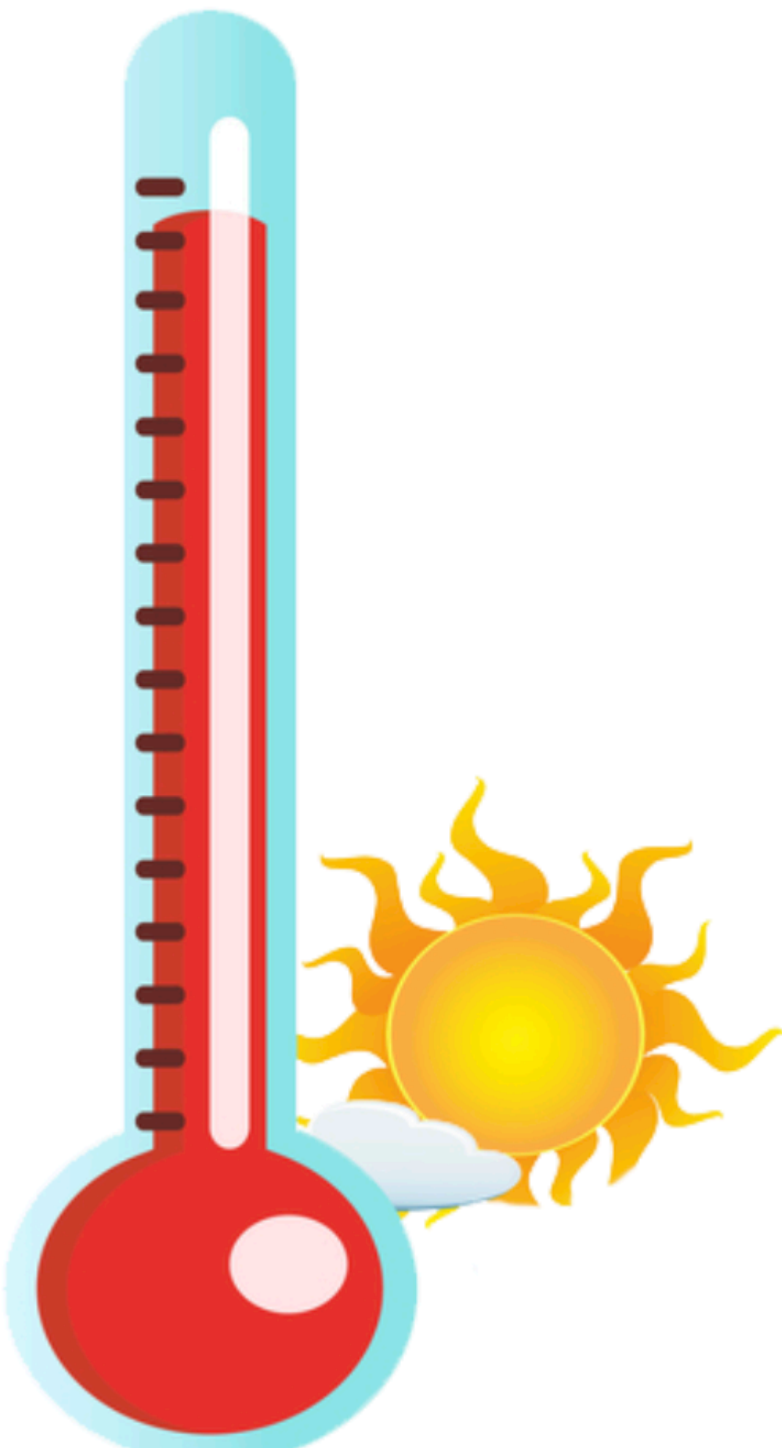
Range for f_a (with caveats)

$$10^9\ \mathrm{GeV} \lesssim f_a \lesssim 10^{11}\ \mathrm{GeV}$$



Borsanyi et al., Phys.Lett.B 752 (2016) and Nature 539 (2016)

Hot Axions — Dark Radiation



Axions produced with kinetic energy much larger than their mass (i.e. "hot")

Additional radiation at:

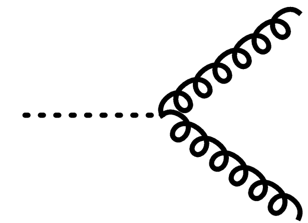
- BBN ($m_a \lesssim$ MeV)
- CMB formation ($m_a \lesssim 0.3$ eV)

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

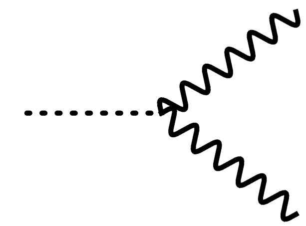
$$\Delta N_{\rm eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_a}{\rho_\gamma}$$

Thermal Axions

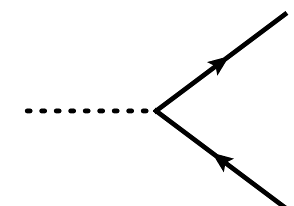
Scatterings and/or decays involving primordial thermal bath particles (axion energy ≫ m_a, i.e. "hot")



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



$$c_{\gamma\gamma}\frac{\alpha_{\rm em}}{8\pi}\frac{a}{f_a}F^{\mu\nu}\widetilde{F}_{\mu\nu}$$



$$c_{\psi}\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$$

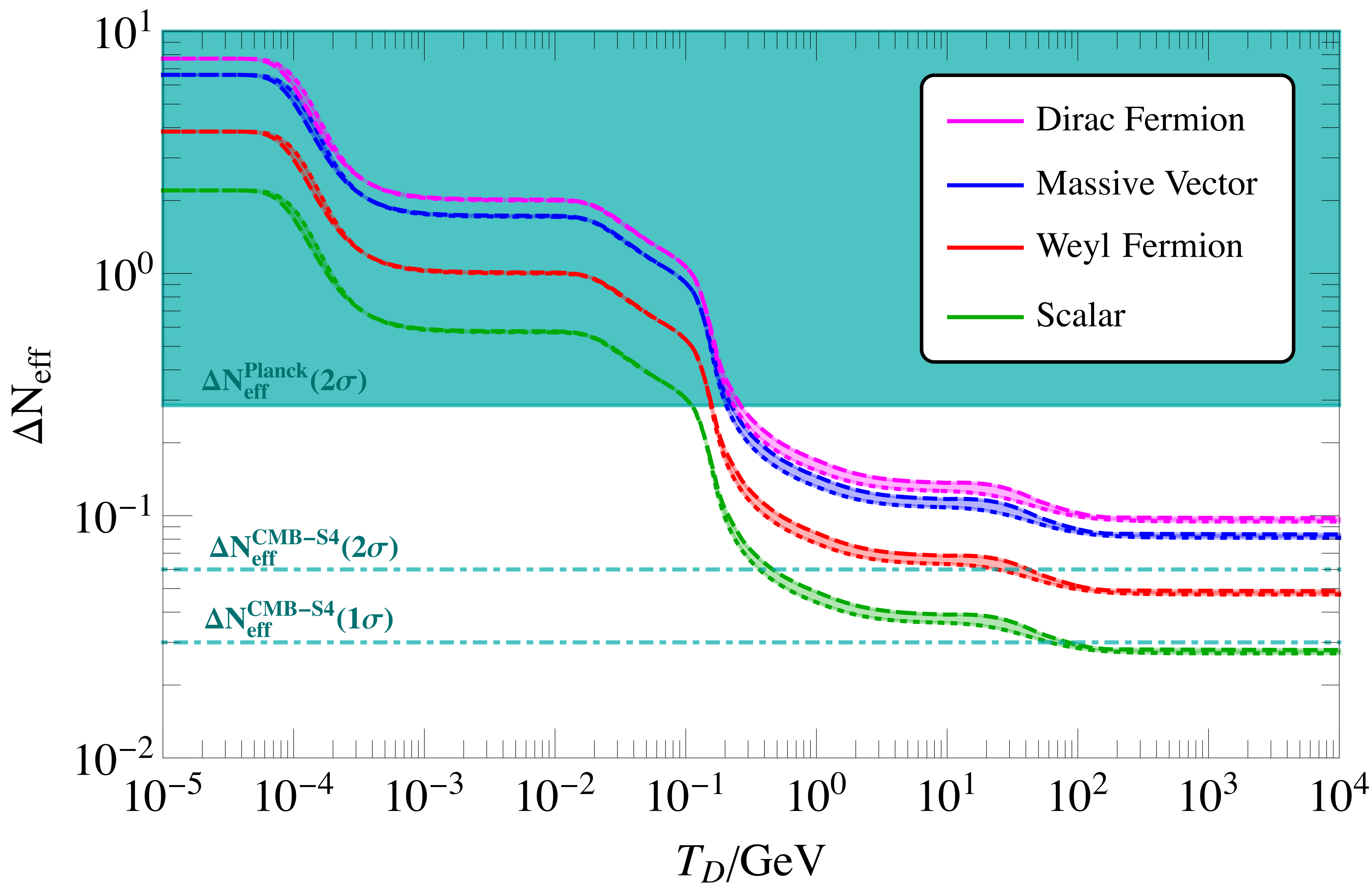
<u>Unavoidable</u>
Production Source!

<u>GOALS</u>:

- Compute how many axions are produced in the early universe
- Quantify the resulting effect on cosmological observables

$$\boxed{\frac{dn_a}{dt}+3Hn_a=\gamma_a}$$

Bounds and Prospects



FD, Hajkarim, Yun, JHEP 10 (2021)

Scenarios for Thermal Axions

Single Coupling Switched On

Axion coupled to a given Standard Model field

Ferreira, Notari, Phys.Rev.Lett. 120 (2018)
FD et al, JCAP 11 (2018)
Arias-Aragón et al., JCAP 11 (2020) and JCAP 03 (2021)
Green at al., JCAP 02 (2022)
FD et al., Phys.Rev.Lett. 128 (2022)

UV Completions

FD, Hajkarim, Yun, JHEP 10 (2021)

- **KSVZ Axion:** Standard Model fields are PQ-neutral and color anomaly from heavy colored and PQ-charged fermion Ψ

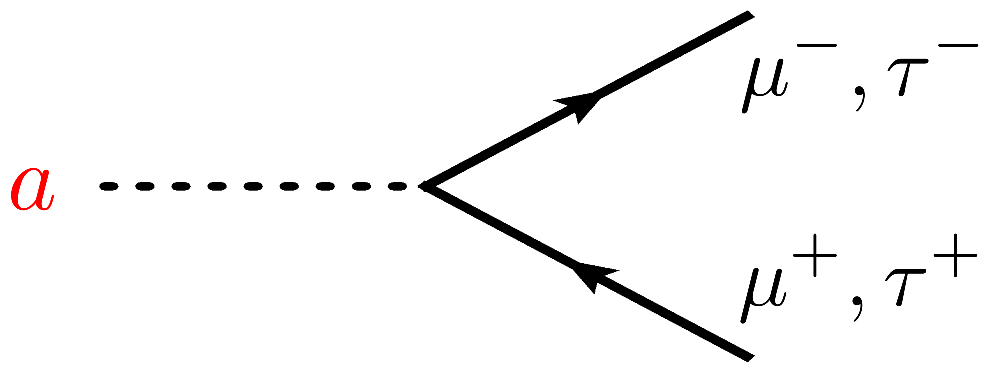
Kim, PRL 43 (1979)
Shifman, Vainshtein, Zakharov, NPB 166 (1980)

- **DFSZ Axion:** Standard Model fields charged (two Higgs doublets) and color anomaly from quarks

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

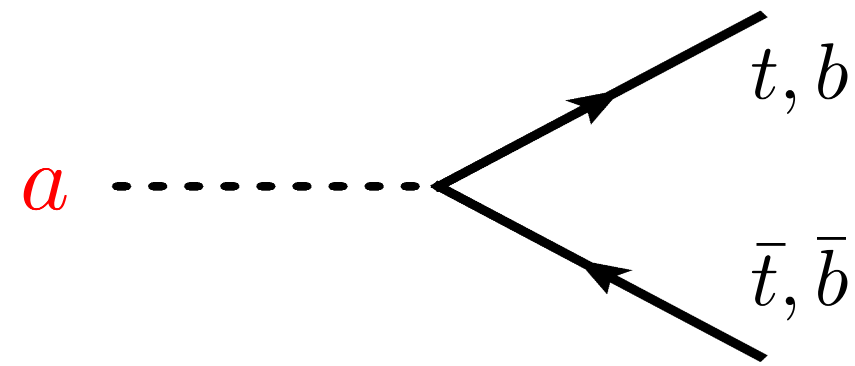
Single Coupling Switched On

Leptons



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

3rd Gen. Quarks



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

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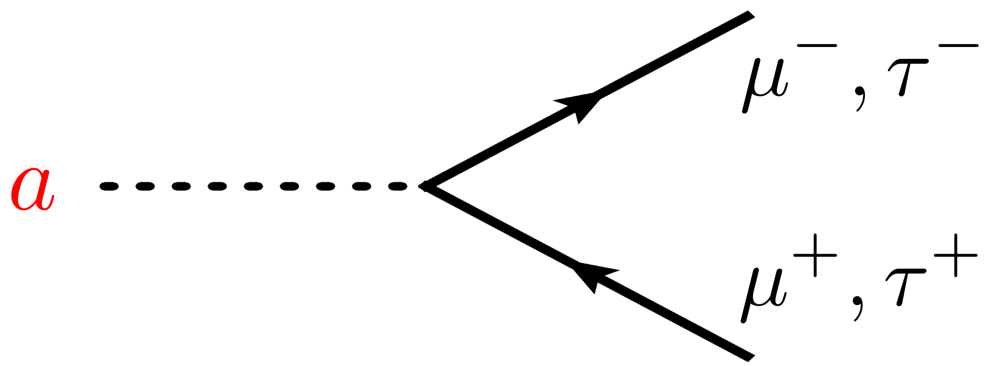

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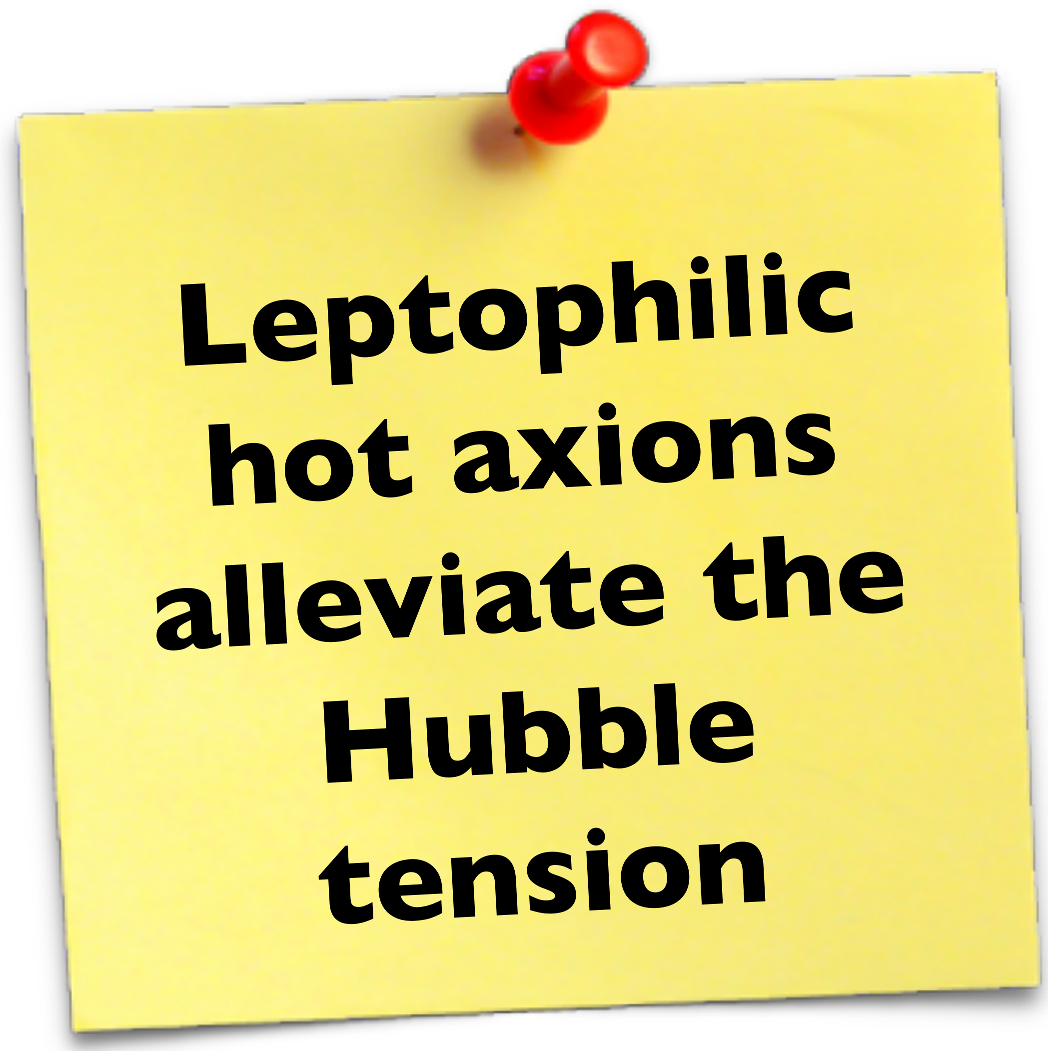

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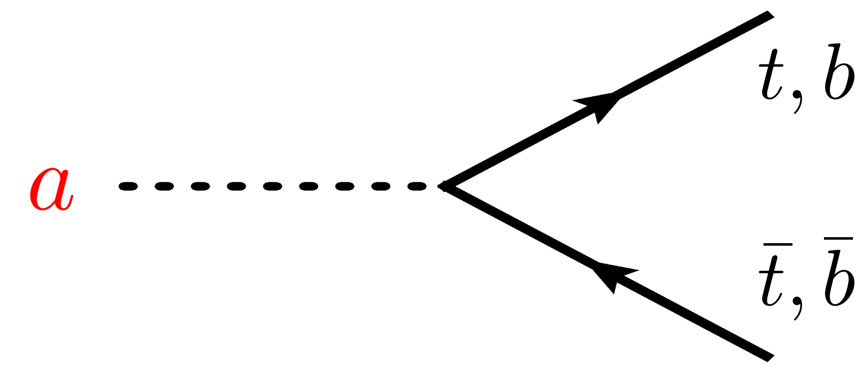

Arias-Aragon, FD, Ferreira, Merlo, Notari, JCAP 03 (2021)

Smooth rate across EWPT, within reach of CMB-S4 surveys

Irreducible Part for the QCD Axion

Strong CP Problem

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

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Above

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

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

Masso, Rota, Zsembinszki, PRD66 (2002)
Graf, Steffen, PRD 83 (2011)
Salvio, Strumia, Xue, JCAP 01 (2014)

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Masso, Rota, Zsembinszki, PRD66 (2002)
Graf, Steffen, PRD 83 (2011)
Salvio, Strumia, Xue, JCAP 01 (2014)

Below

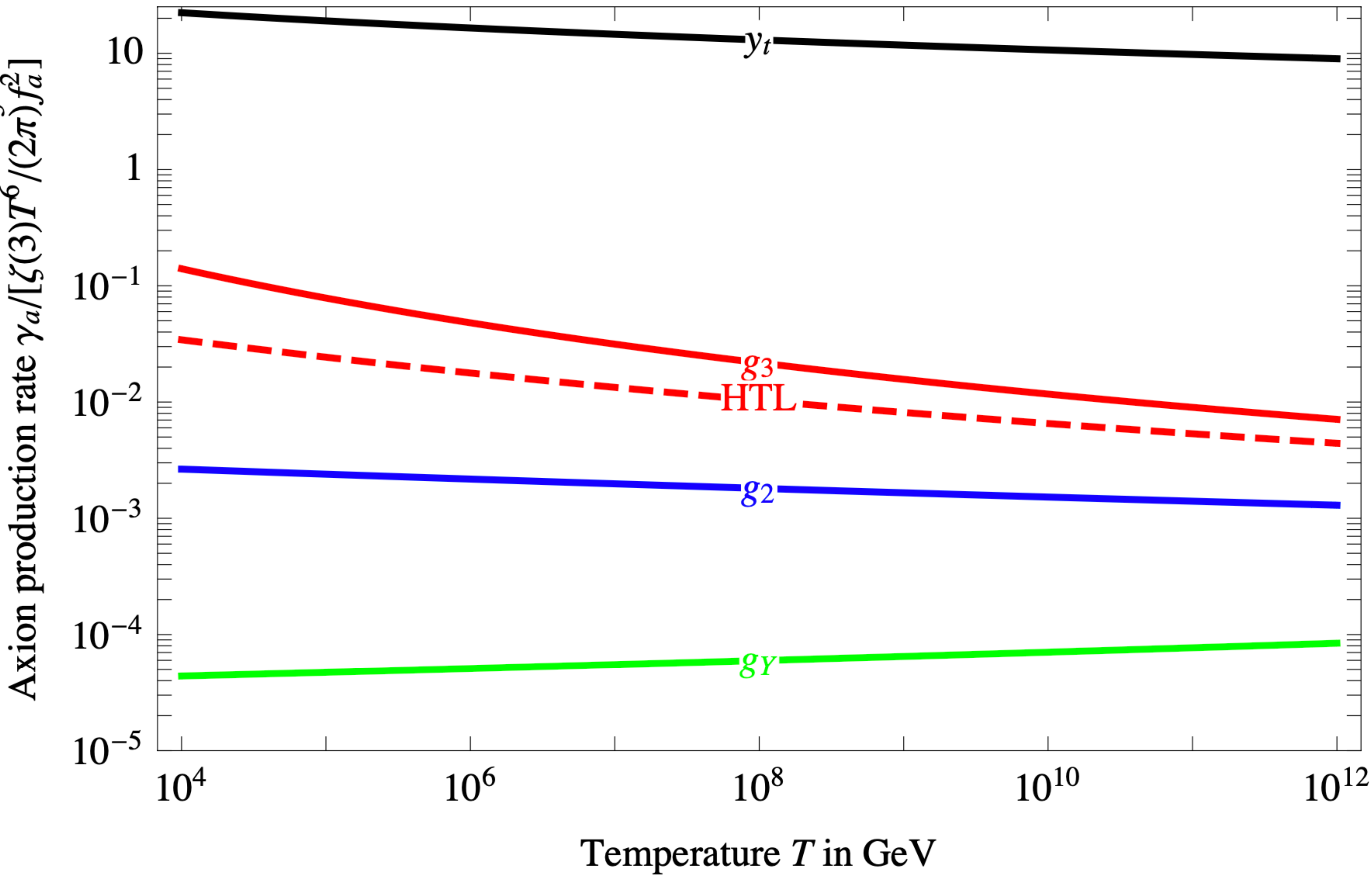
Pion scattering

$$\pi\pi \to \pi a$$

Chang, Choi, Phys.Lett.B 316 (1993)

Recent studies:
Di Luzio, Martinelli, Piazza, Phys.Rev.Lett. 126 (2021)
Notari, Rompineve, Villadoro, Phys.Rev.Lett. 131 (2023)
Di Luzio, Camalich, Martinelli, Piazza, arXiv:2211.05073

Thermal Gluon Scattering



Salvio, Strumia, Xue, JCAP 01 (2014)
See also: Rychkov, Strumia, Phys.Rev.D 75 (2007)

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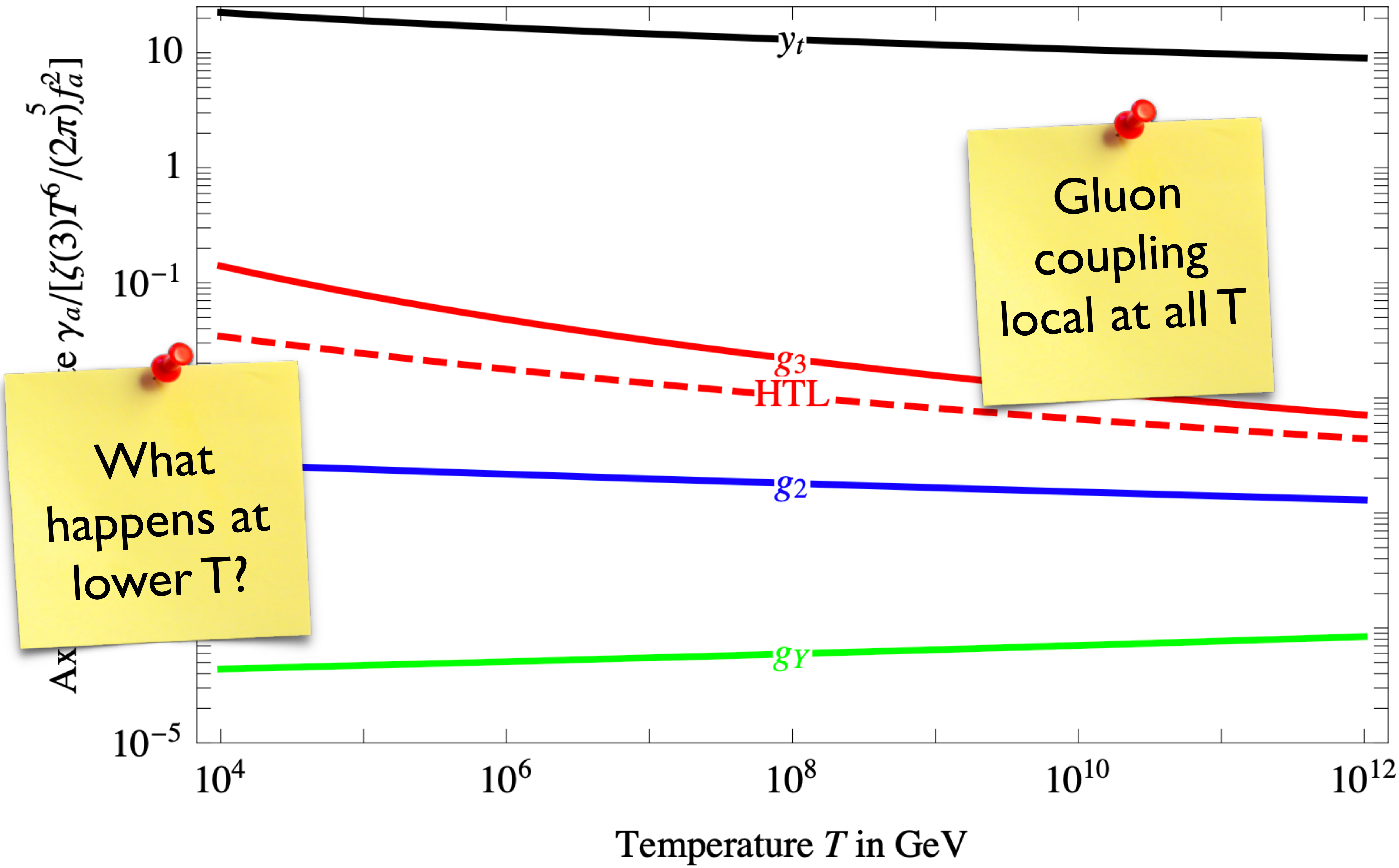

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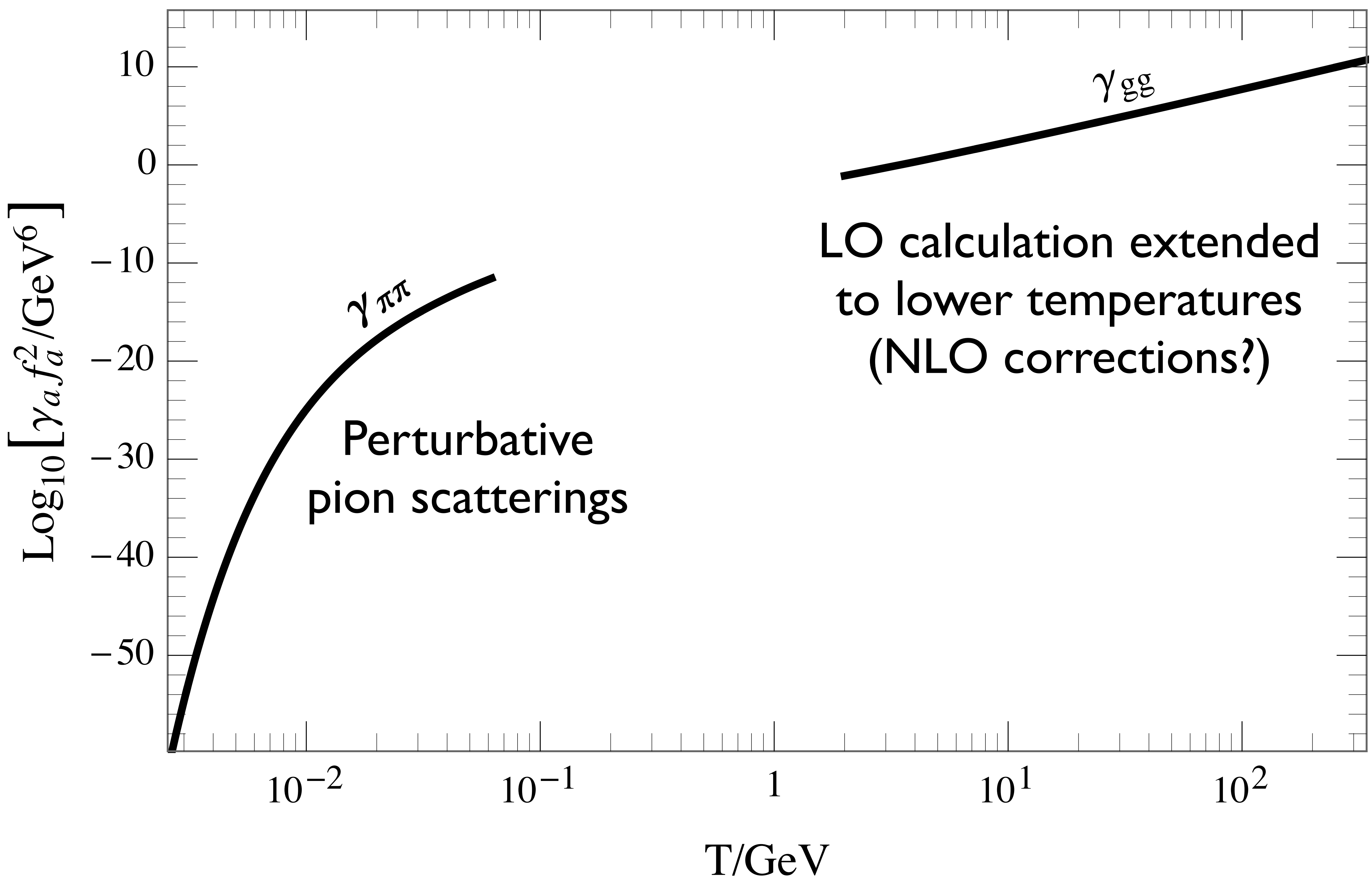
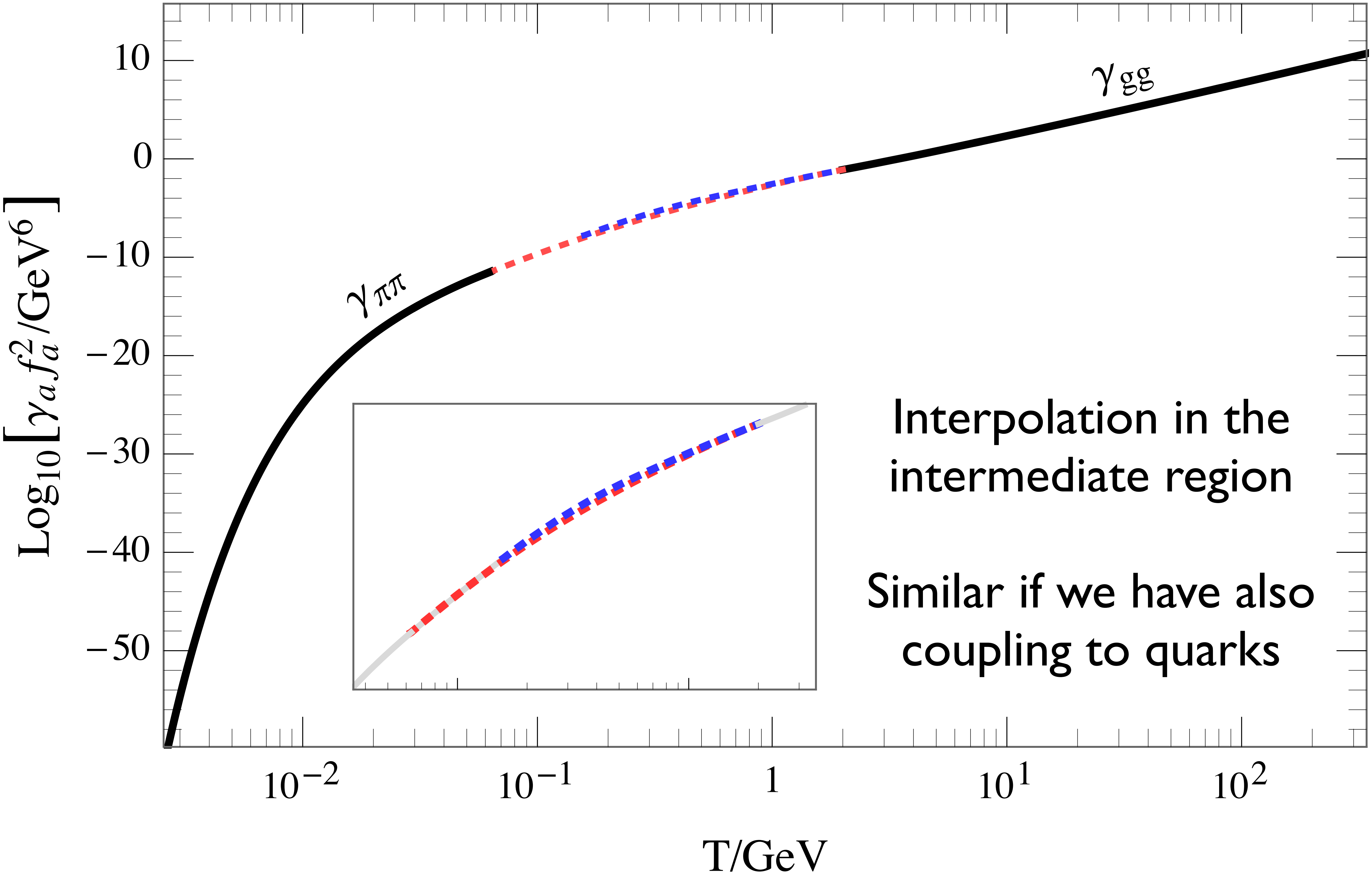
Approaching the QCDPT



FD, Hajkarim, Yun, Phys.Rev.Lett. 128 (2022)

Approaching the QCDPT

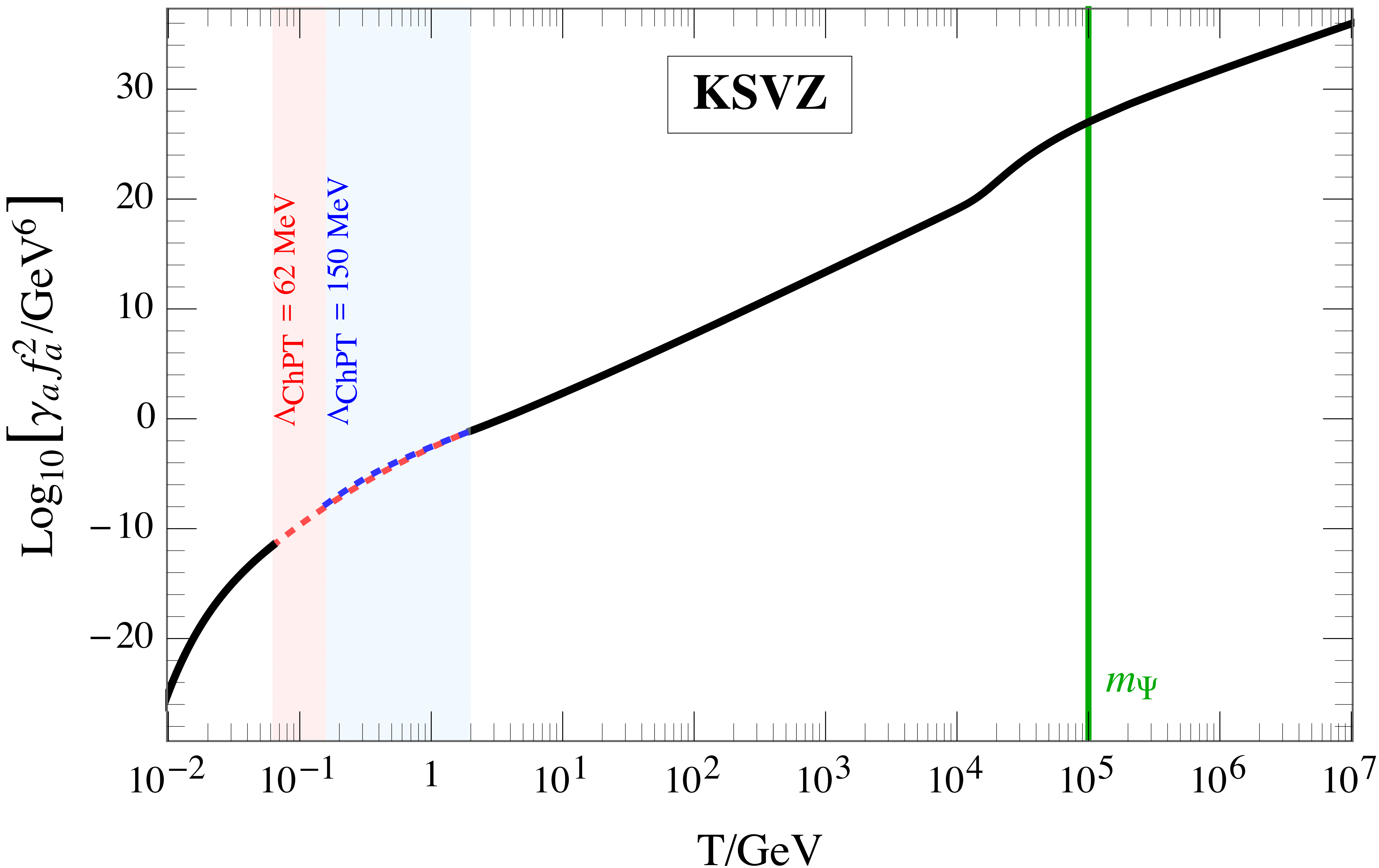


Interpolation in the intermediate region

Similar if we have also coupling to quarks

FD, Hajkarim, Yun, Phys.Rev.Lett. 128 (2022)

KSVZ Axion — Production Rate



FD, Hajkarim, Yun, JHEP 10 (2021)

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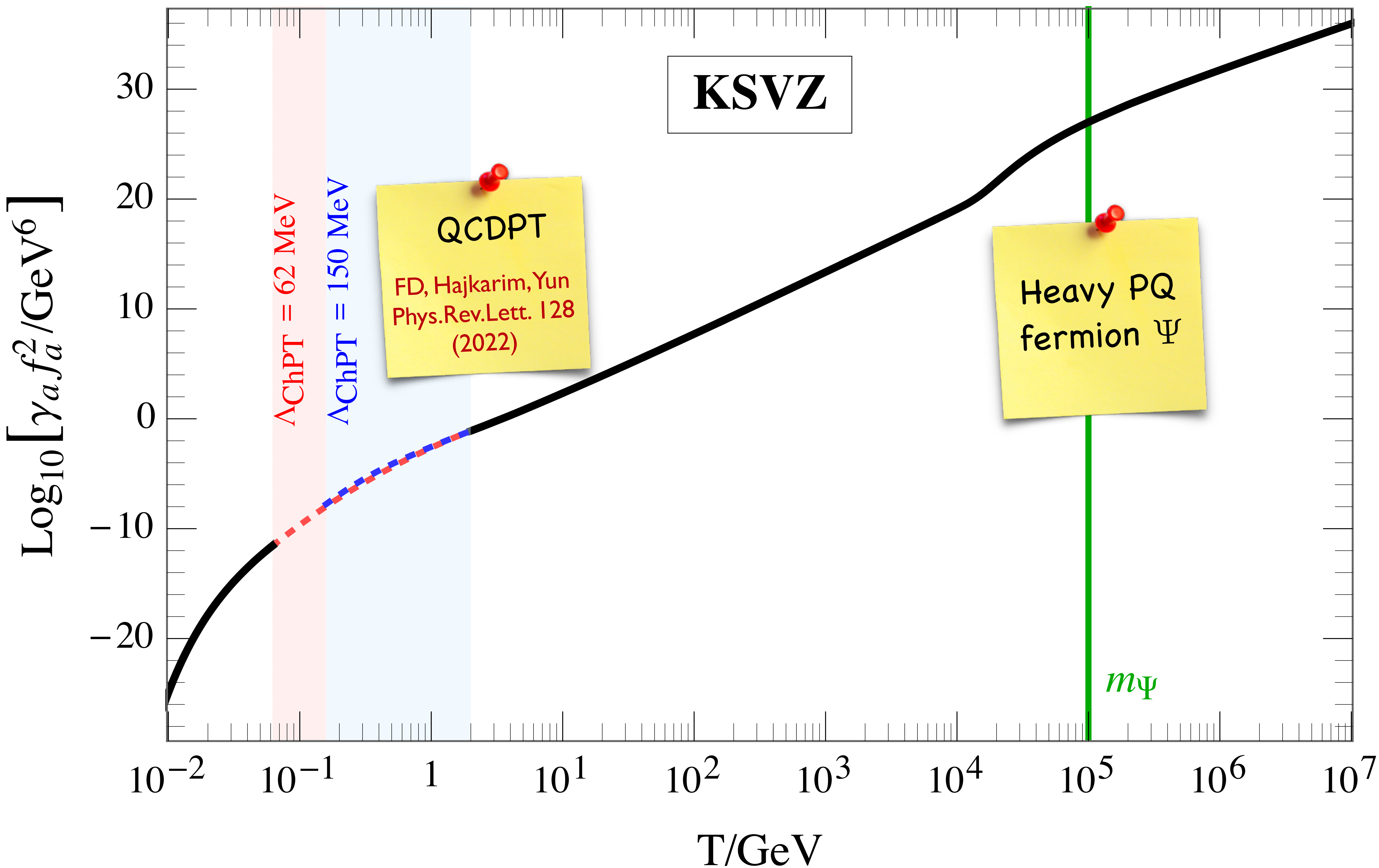
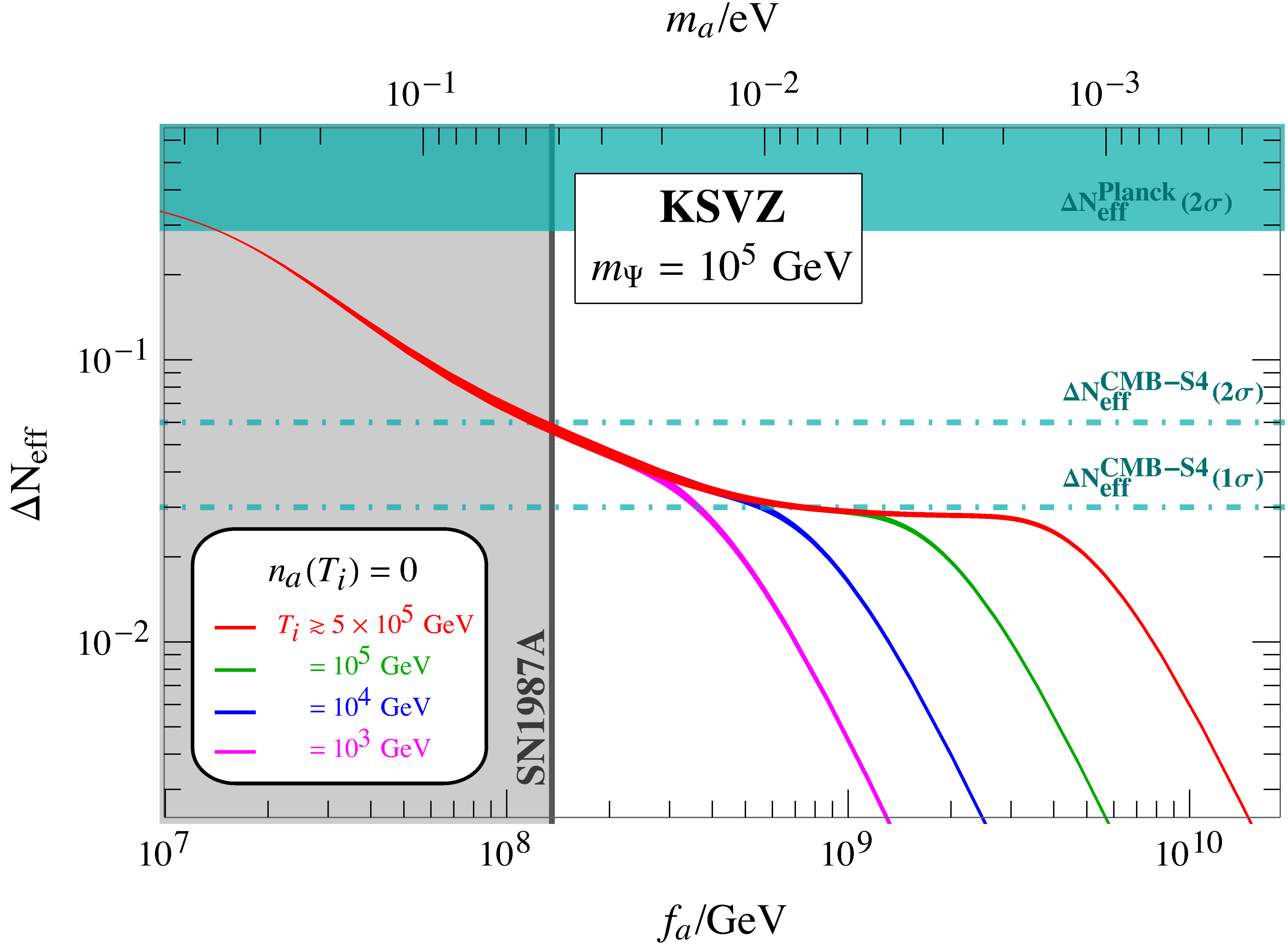


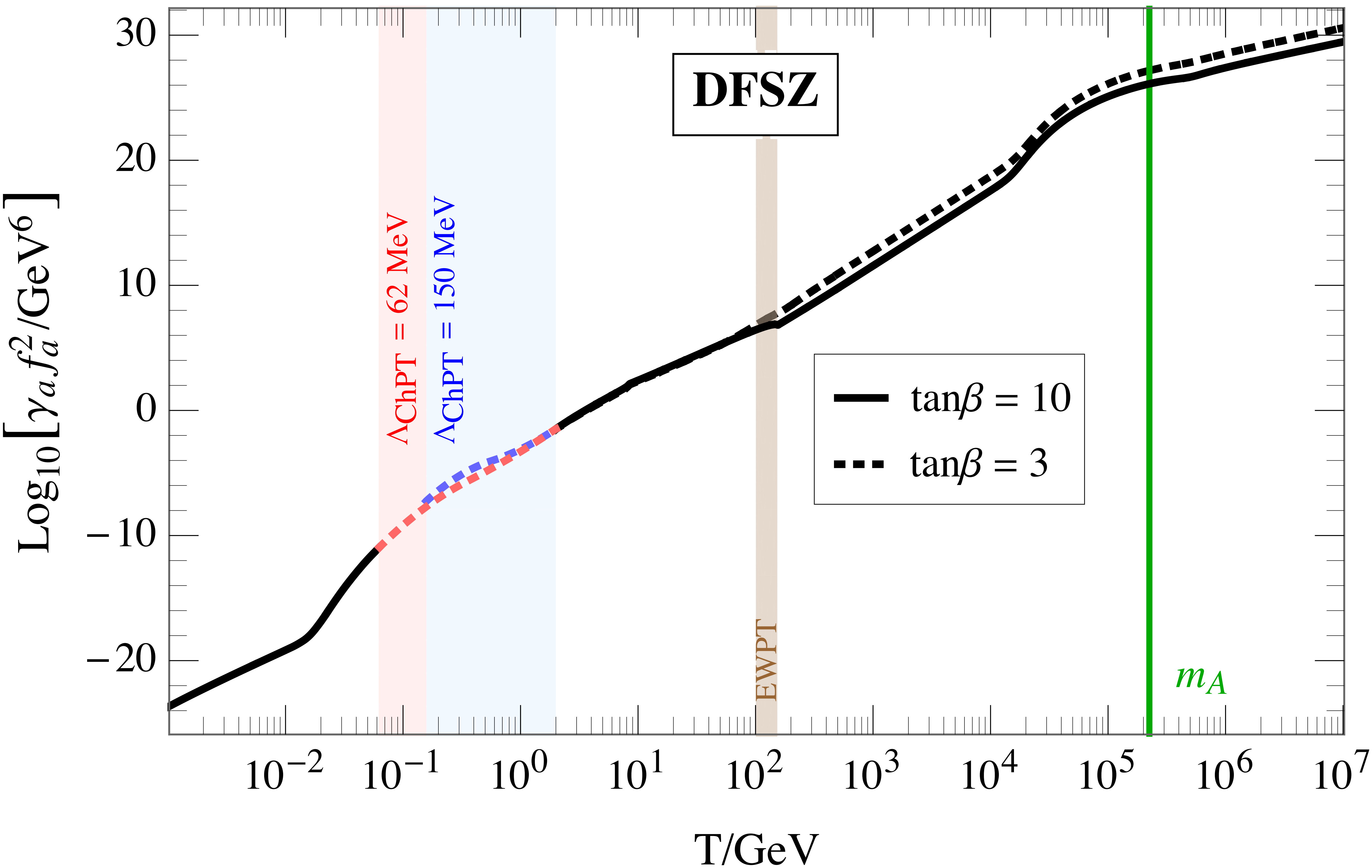
FD, Hajkarim, Yun, JHEP 10 (2021)

KSVZ Axion — ΔN_{eff}



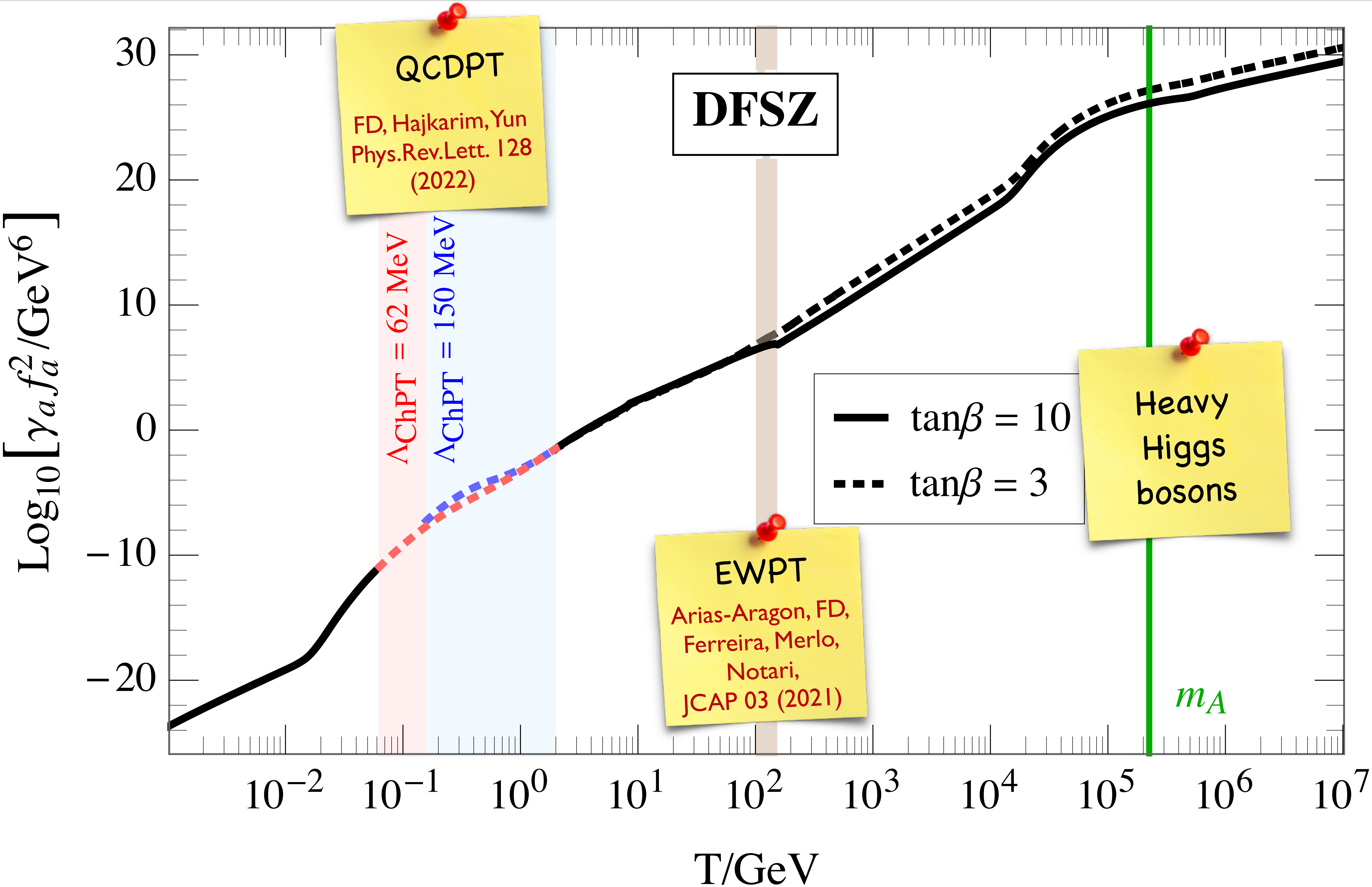
FD, Hajkarim, Yun, JHEP 10 (2021)

DFSZ Axion — Production Rate



FD, Hajkarim, Yun, JHEP 10 (2021)

DFSZ Axion — Production Rate



FD, Hajkarim, Yun, JHEP 10 (2021)

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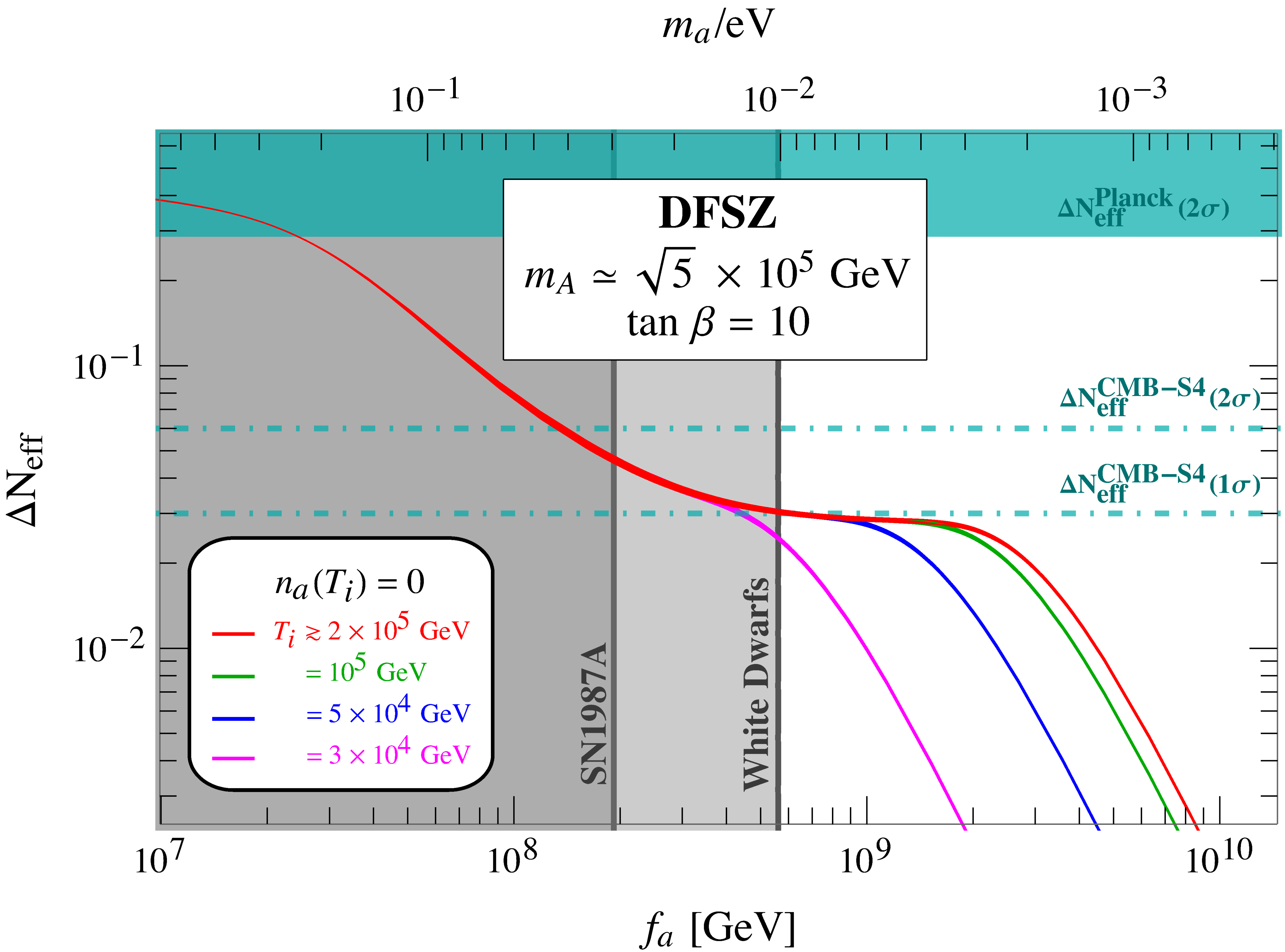
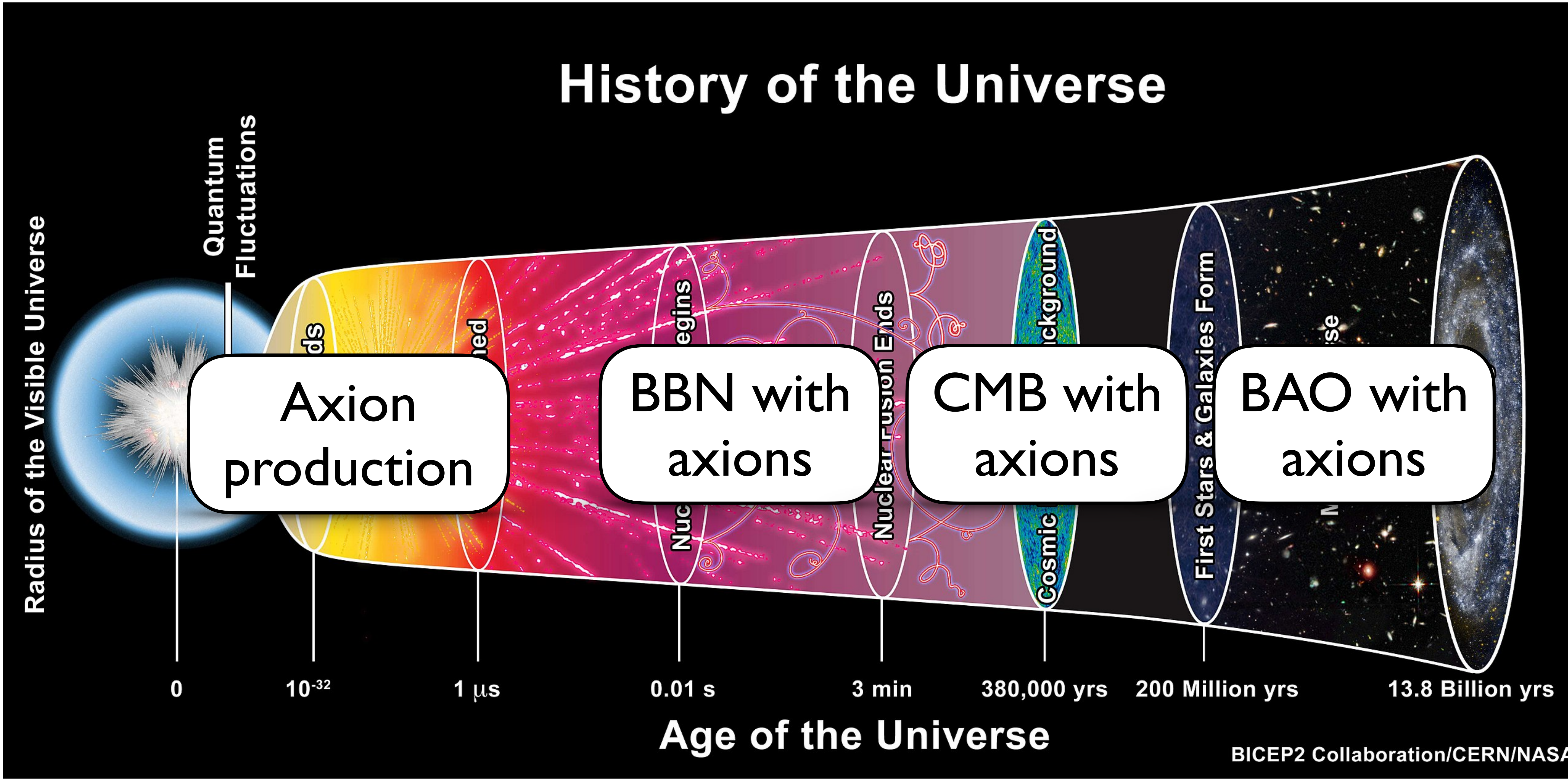


FD, Hajkarim, Yun, JHEP 10 (2021)

QCD Axion Mass Bound



KSVZ

$$m_a \leq 0.282(0.420)\,\mathrm{eV}$$

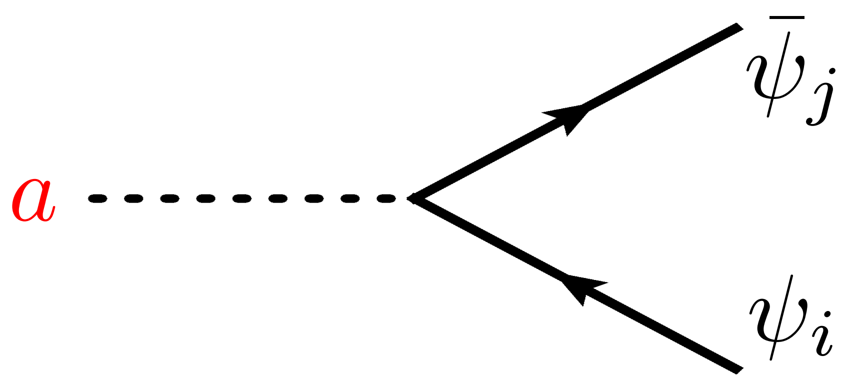
DFSZ

$$m_a \leq 0.209(0.293)\,\mathrm{eV}$$

FD, Di Valentino, Giarè, Hajkarim, Melchiorri, Mena, Renzi, Yun, JCAP 09 (2022)

A Minor Variation: FV Axions

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



Target of several terrestrial experiments

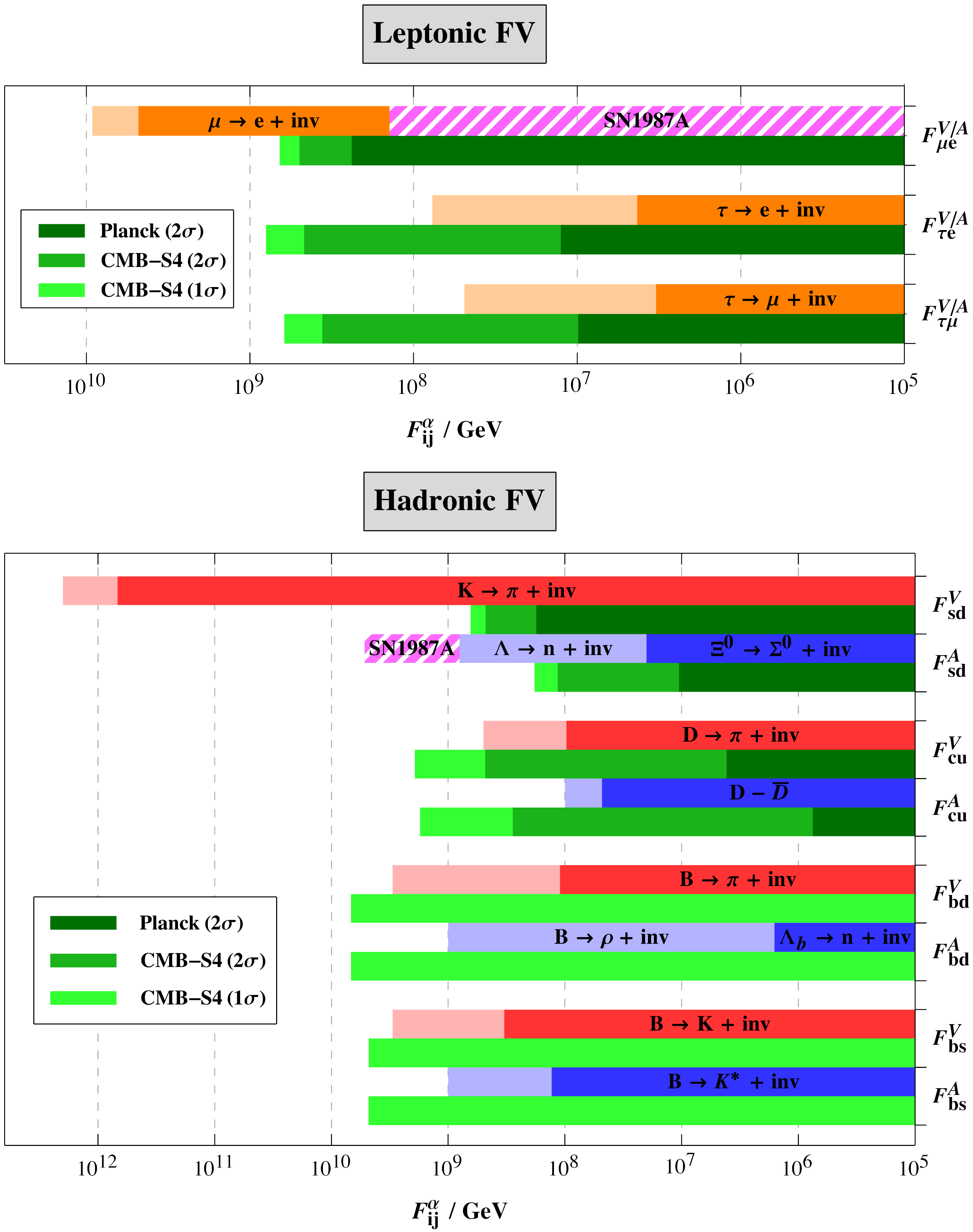
Camalich et al., Phys.Rev.D 102 (2020)
Calibbi et al., JHEP 09 (2021)

What about their role in the early universe?

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

FD, Yun, Phys.Rev.D 105 (2022)

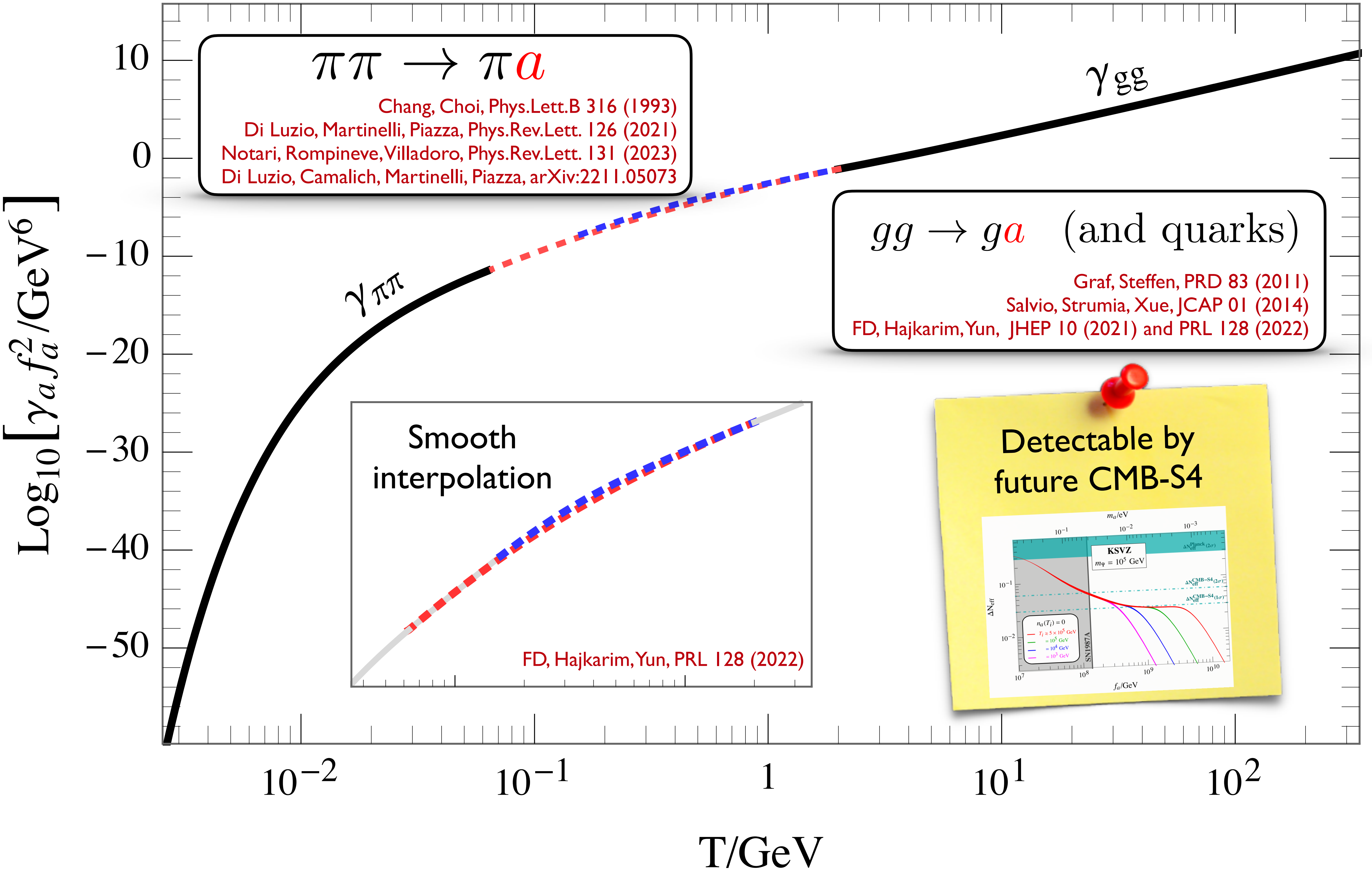
A Minor Variation: FV Axions



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

FD, Yun, Phys.Rev.D 105 (2022)

Where Do We Stand?



What's Next?

Axion production rate

across the confinement scale still unknown

$$\gamma_a = n_i n_j \times \langle \sigma_{ij \to ja} v_{\rm rel} \rangle$$

Thermal bath Particle Physics

1. Cross sections with other hadrons?
2. Thermal bath description between 150 MeV and fews GeV?
3. Boltzmann equation evolution and cosmological observables?

Phase-Space Analysis — Theory

Model-independent analysis:

generic thermal bath production of a single dark radiation particle X

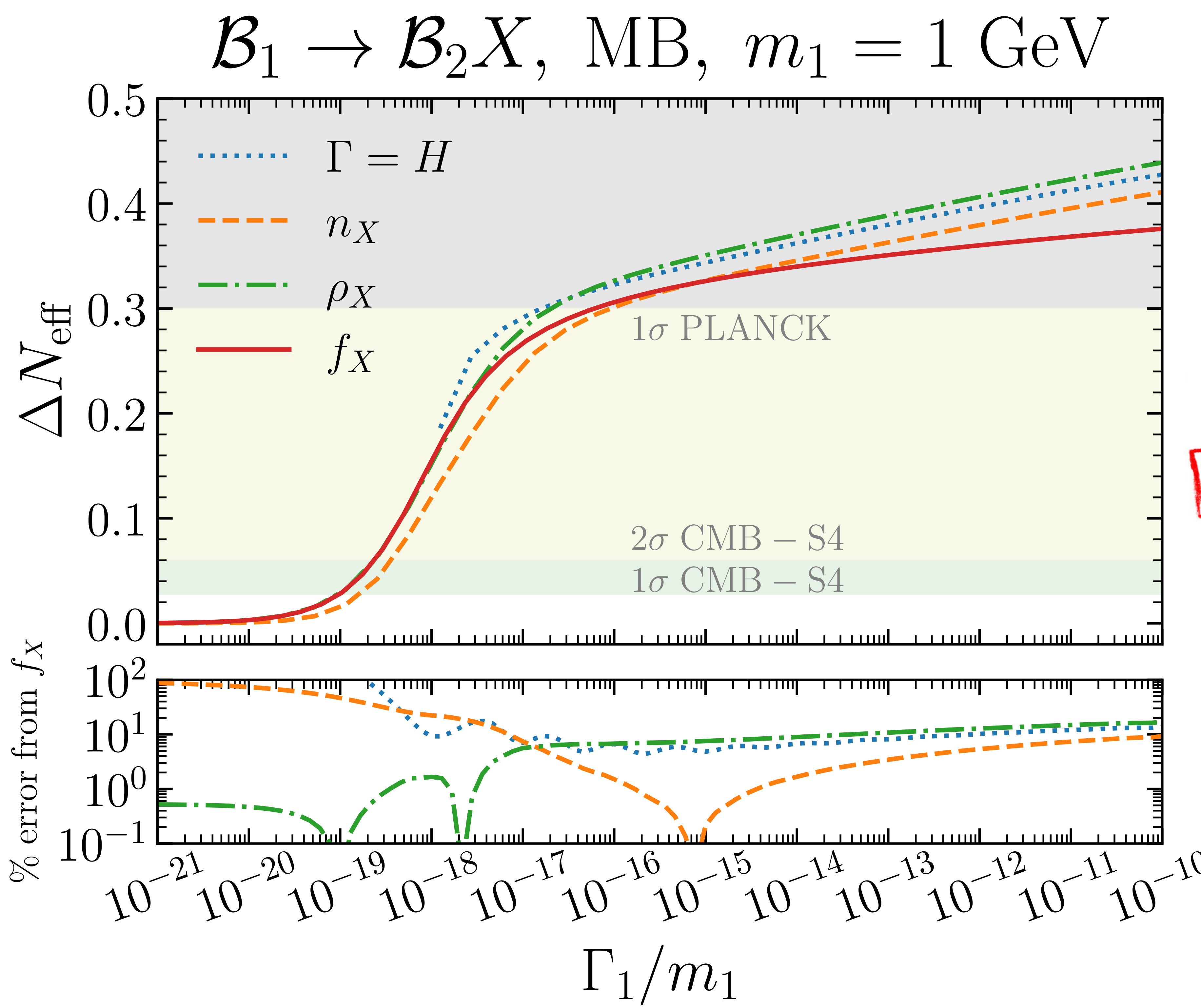
$$\mathcal{B}_1 \ldots \mathcal{B}_n \to \mathcal{B}_{n+1} \ldots \mathcal{B}_m \, X$$

$$\boxed{\frac{df_X(k,t)}{dt} = \left(1 - \frac{f_X(k,t)}{f_X^{\mathrm{eq}}(k,t)}\right) \mathcal{C}_{n\to mX}(k,t)}$$

1. Keep track of phase-space and compute the energy density
2. Quantum statistical effects take into account
3. Energy exchanged with the thermal bath accounted for

FD, Lenoci, Hajkarim — in preparation

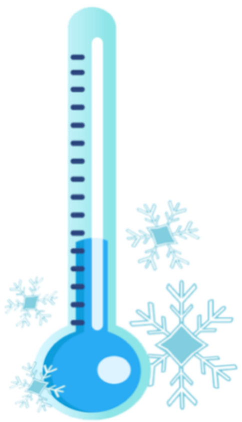
Phase-Space Analysis — Results

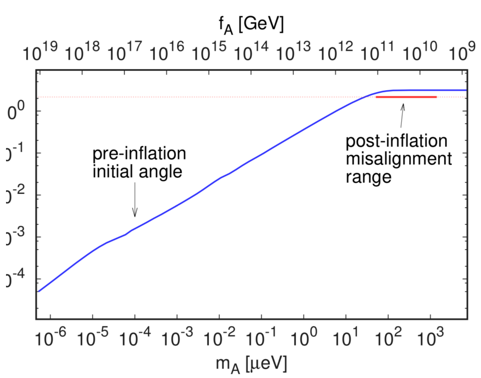


PRELIMINARY

FD, Lenoci, Hajkarim — in preparation

Outlook





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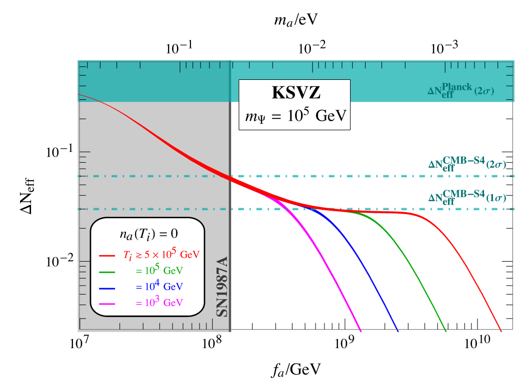
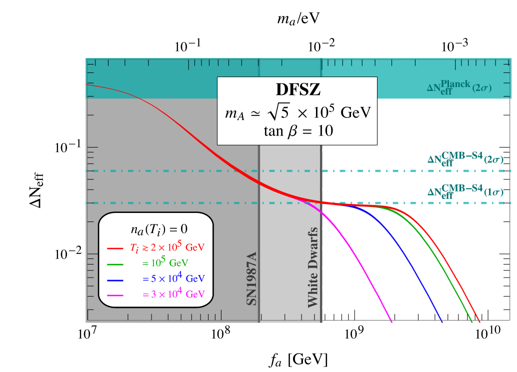
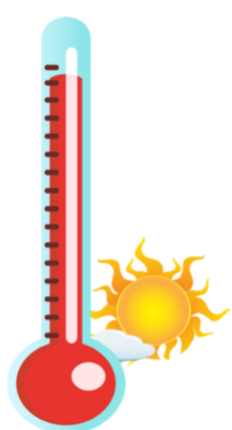
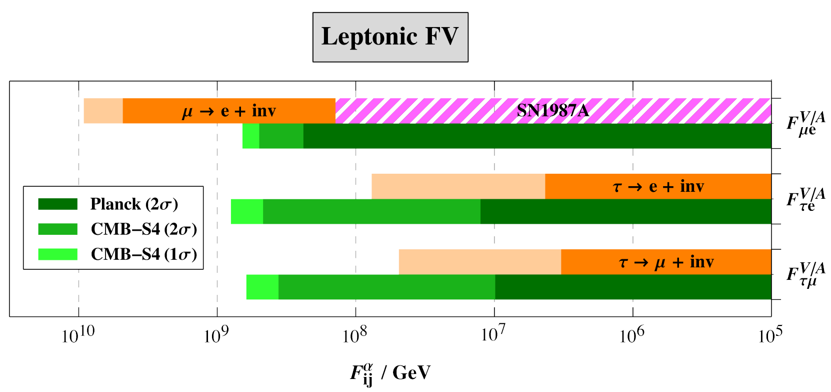
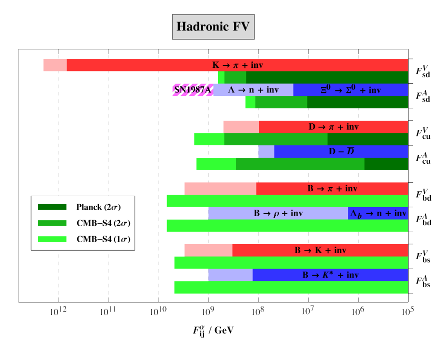
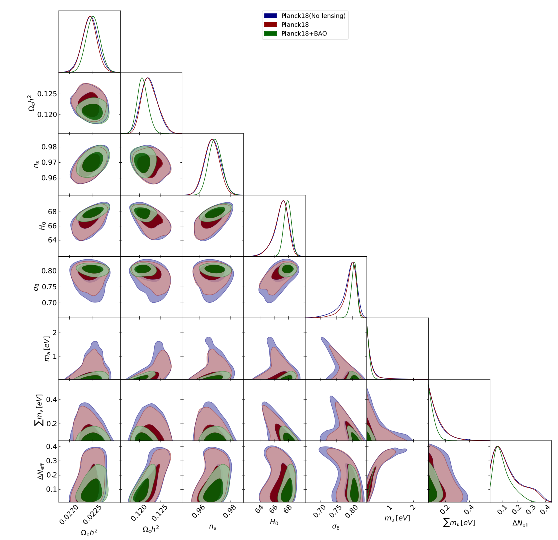








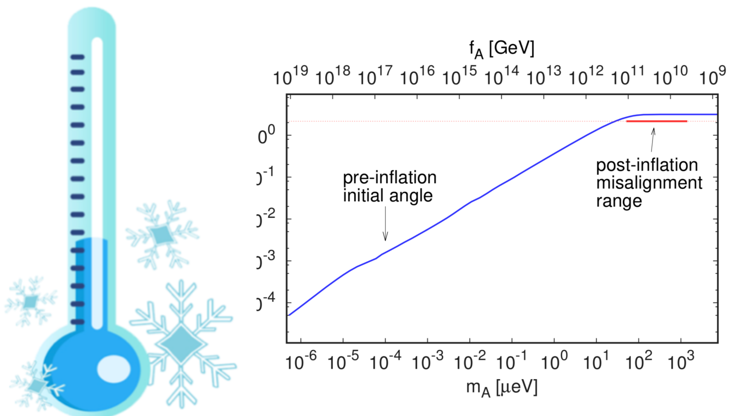




<u>Thermal Axions</u>

Complementary to other probes of the PQ mechanism

Outlook



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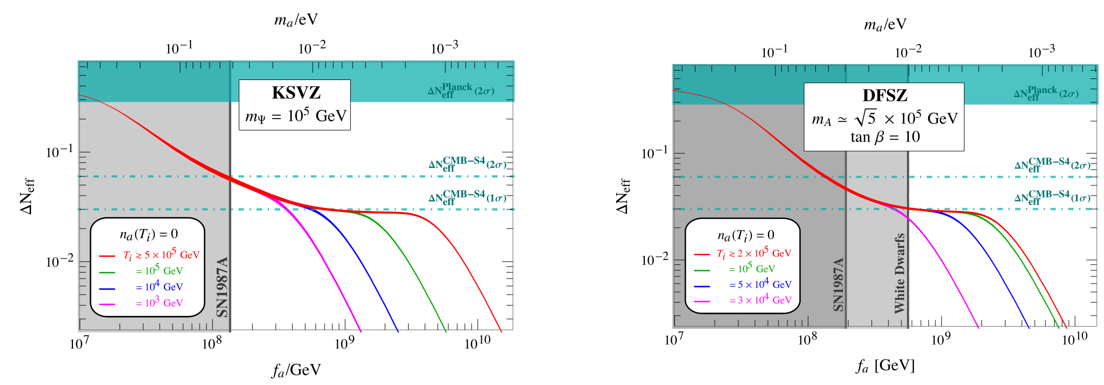

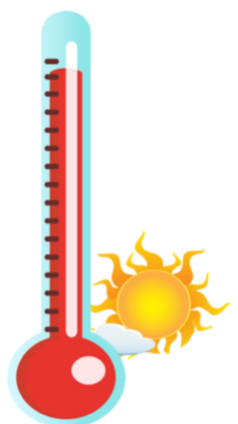

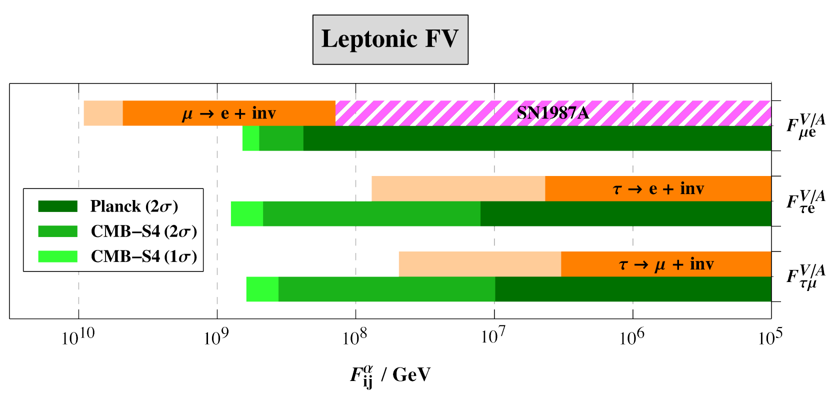

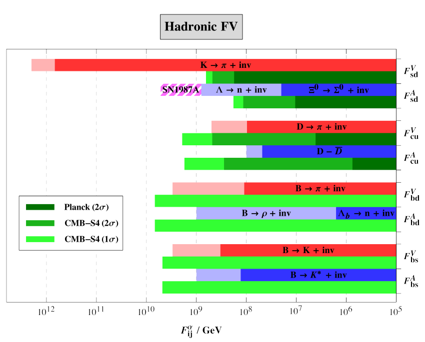

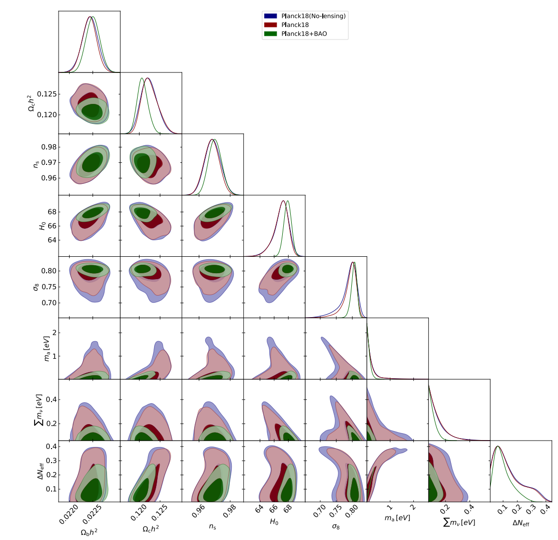

谢谢大家