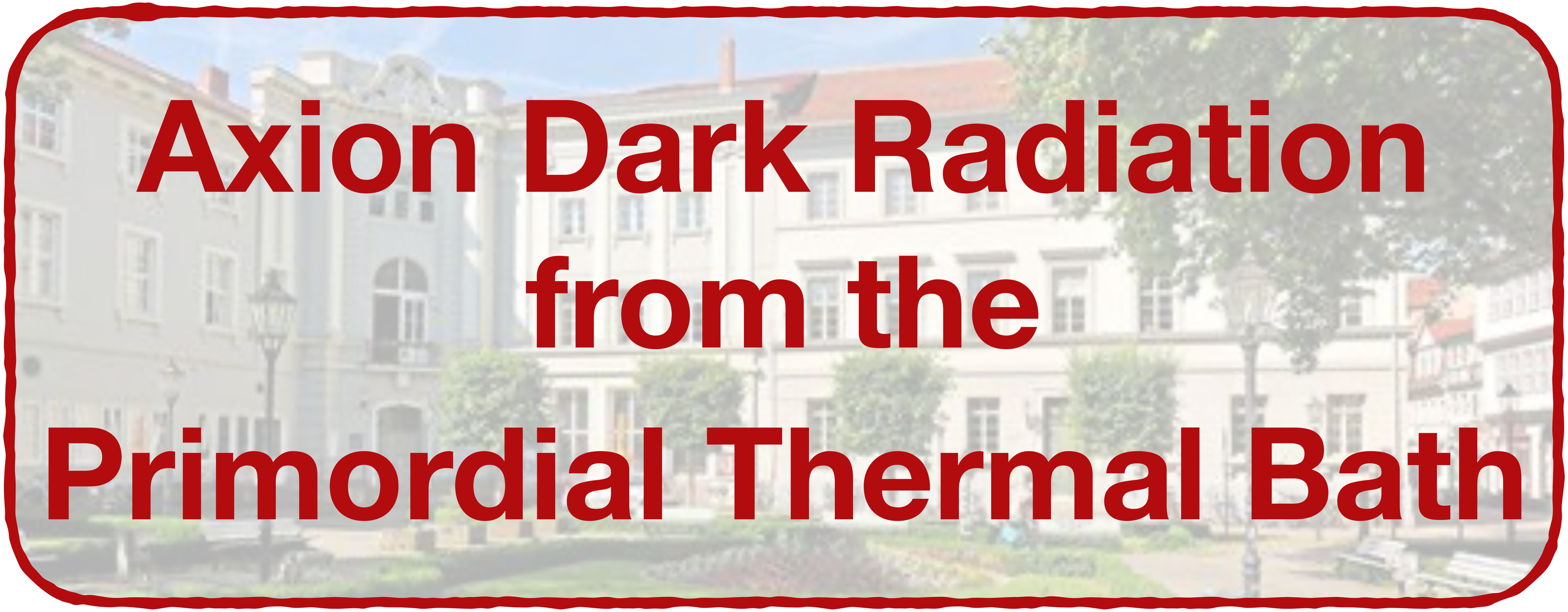

Axion Dark Radiation from the Primordial Thermal Bath

Francesco D'Eramo

UNIVERSITÀ DEGLI STUDI DI PADOVA

INFN PADOVA

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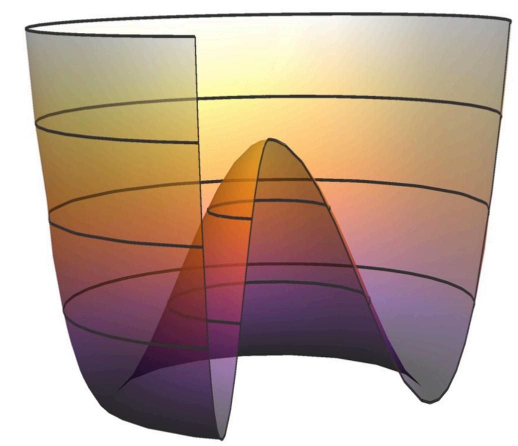
Invisibles 23 Workshop, University of Göttingen — 29 August 2023

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

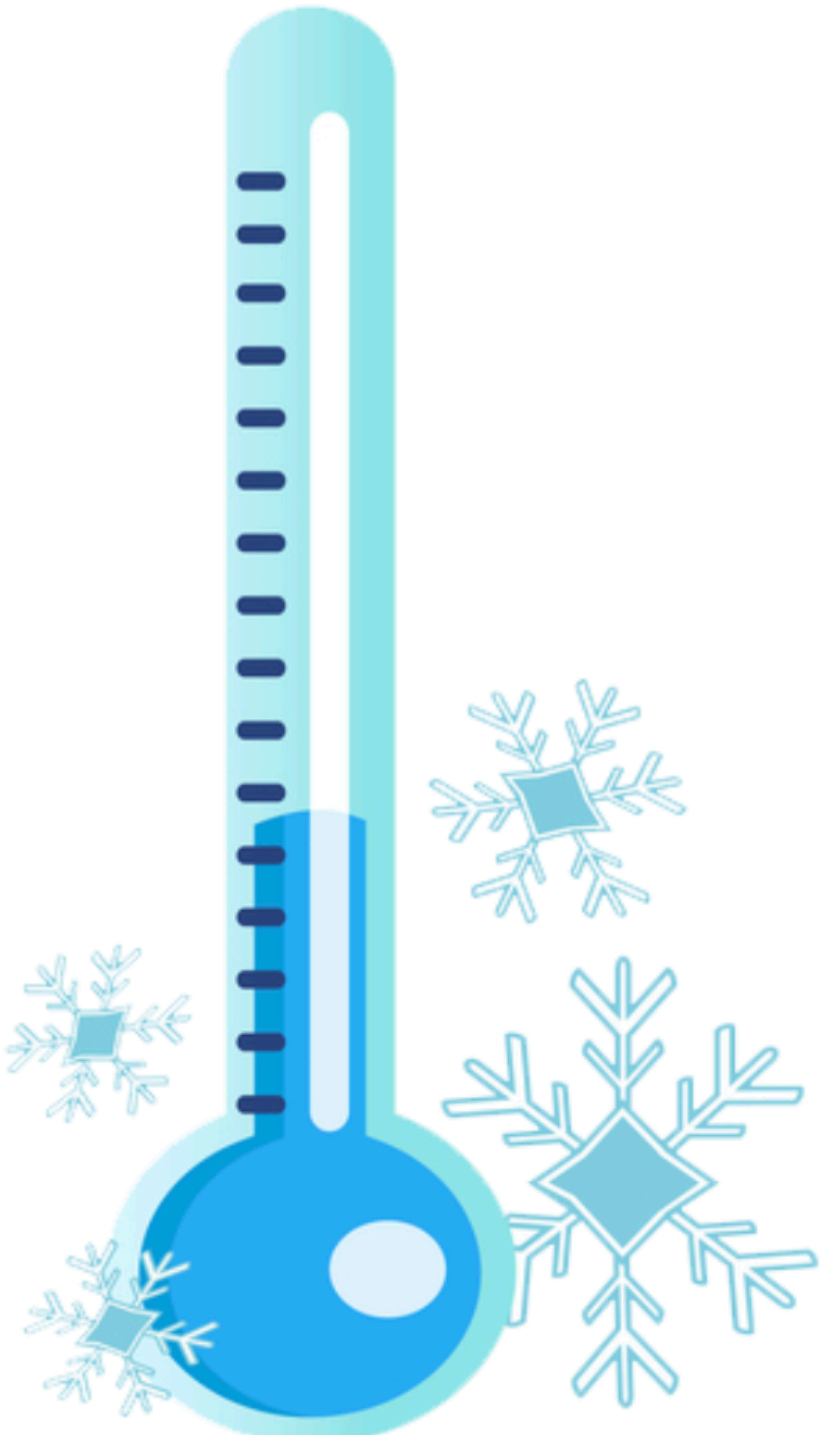


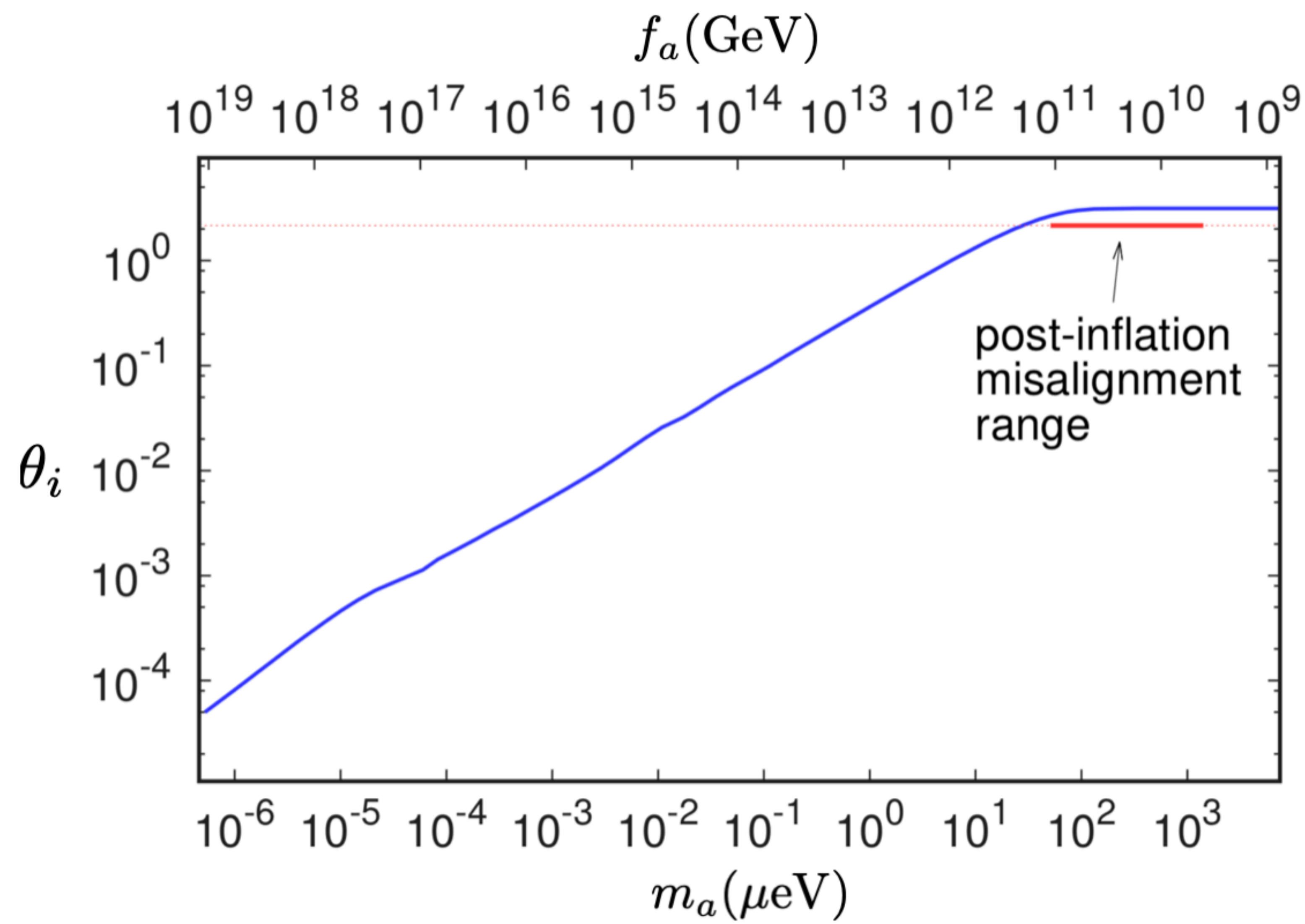
$$\frac{a}{f_a}\frac{\alpha_s}{8\pi}G^{\mu\nu}\tilde{G}_{\mu\nu}$$

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

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)

Cold Axions — Dark Matter





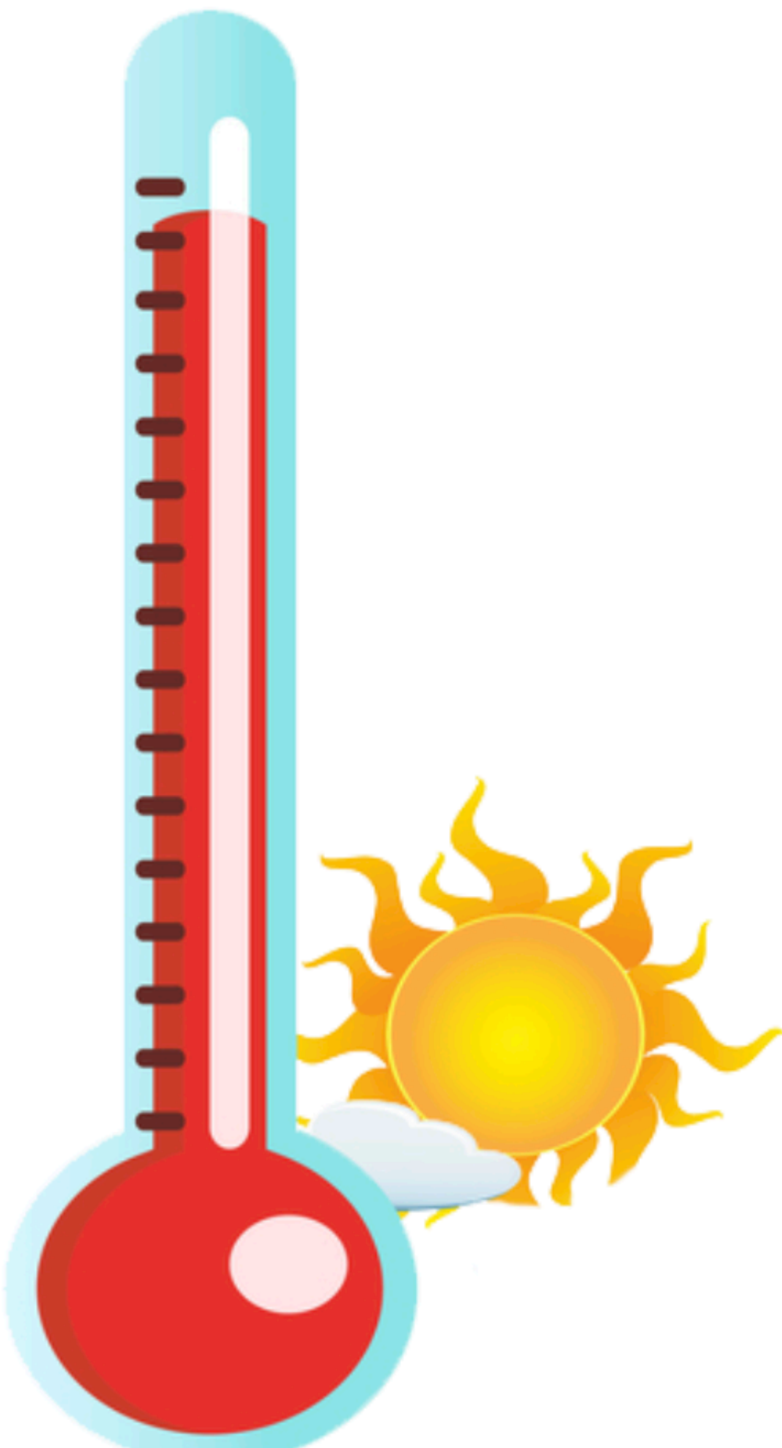
Borsanyi et al., Phys.Lett.B 752 (2016) and Nature 539 (2016)

Recent work on post-inflationary axion dark matter:

Gorghetto, Hardy, Villadoro
JHEP07 (2018) and SciPost Phys.10 (2021)

Buschmann, Foster, Safdi
PRL124 (2020) and Nature Commun. 13 (2022)

Hot Axions — Dark Radiation



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

Additional radiation at:

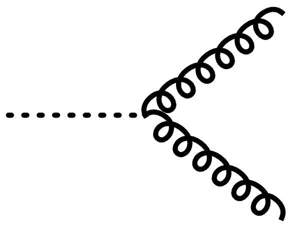
- BBN ($m_a \lesssim$ MeV)
- CMB formation ($m_a \lesssim 0.3$ eV)

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

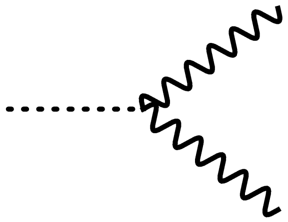
$$\Delta N_{\rm eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_a}{\rho_\gamma}$$

Thermal Axions

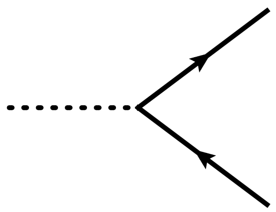
Scatterings and/or decays involving primordial thermal bath particles (axion energy ≫ m_a, i.e. "hot")



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



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



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

<u>Unavoidable</u>

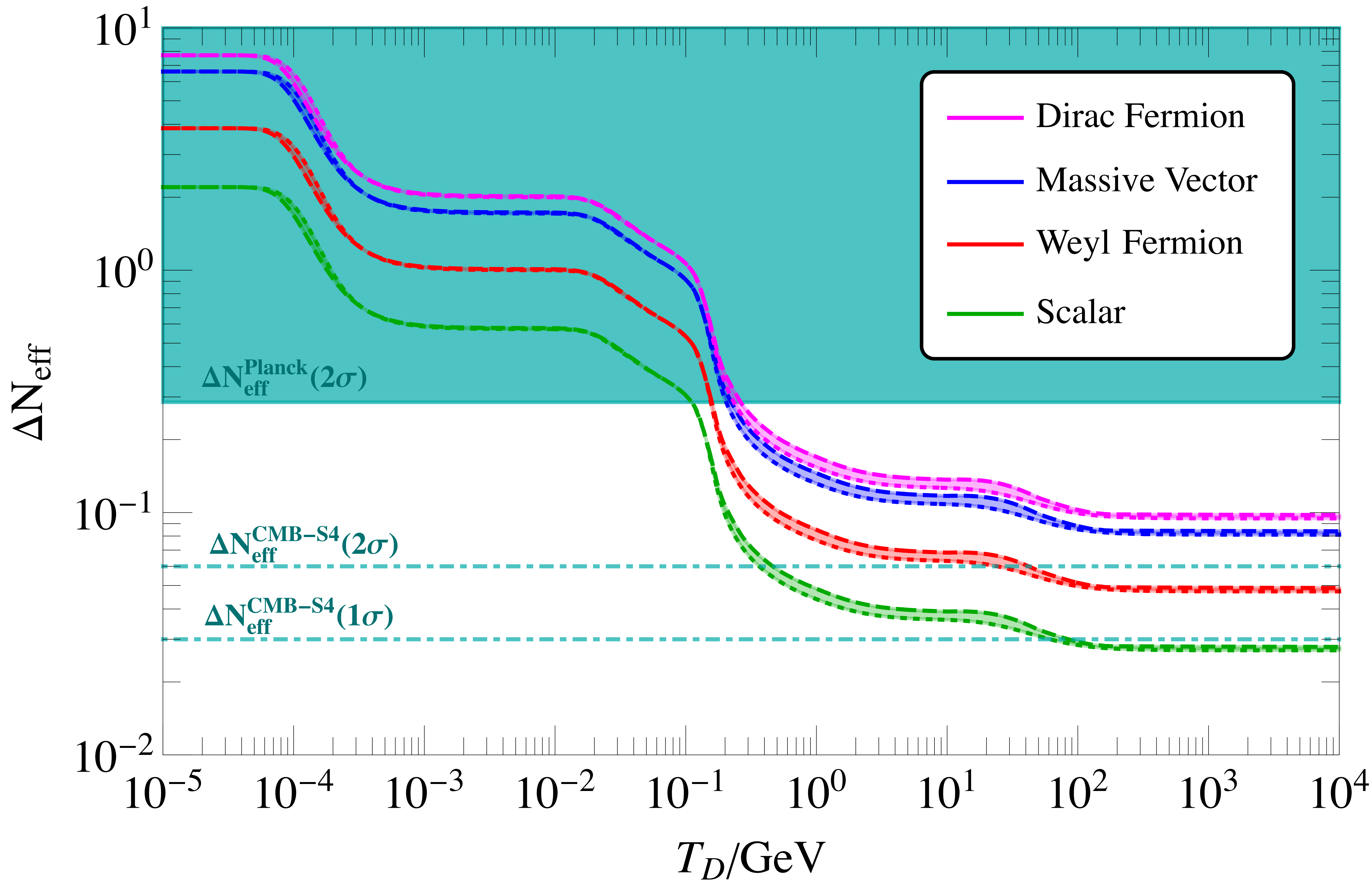
Production Source!

<u>GOALS</u>:

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

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

Bounds and Prospects



FD, Hajkarim, Yun, JHEP 10 (2021)

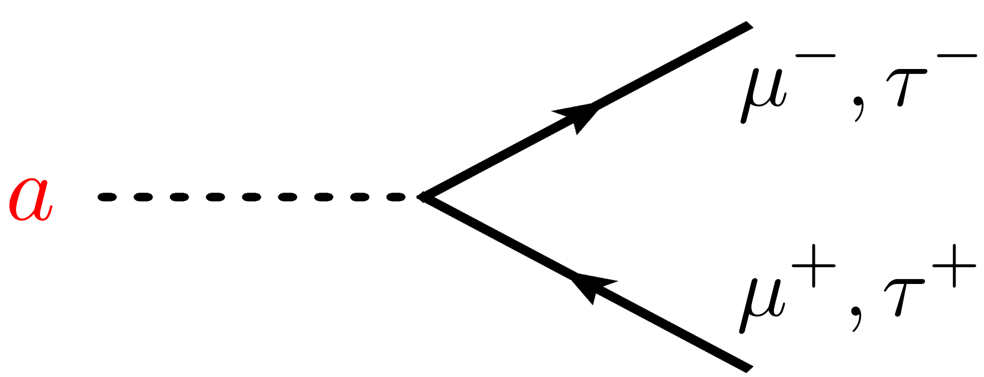
Single Coupling Switched On

Simplified Scenario

Axion coupled to a single Standard Model field

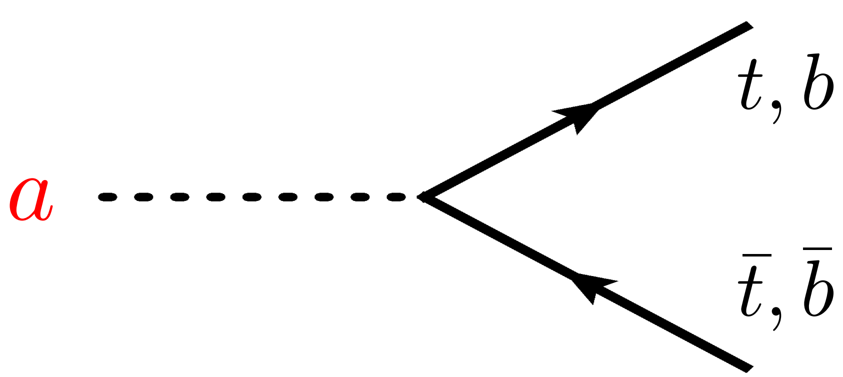
Ferreira, Notari, Phys.Rev.Lett. 120 (2018)
FD et al, JCAP 11 (2018)
Arias-Aragón et al., JCAP 11 (2020) and JCAP 03 (2021)
Green at al., JCAP 02 (2022)
FD et al., Phys.Rev.Lett. 128 (2022)

Leptons



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

3rd Gen. Quarks



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

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

Studied for T > 10^4 GeV

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

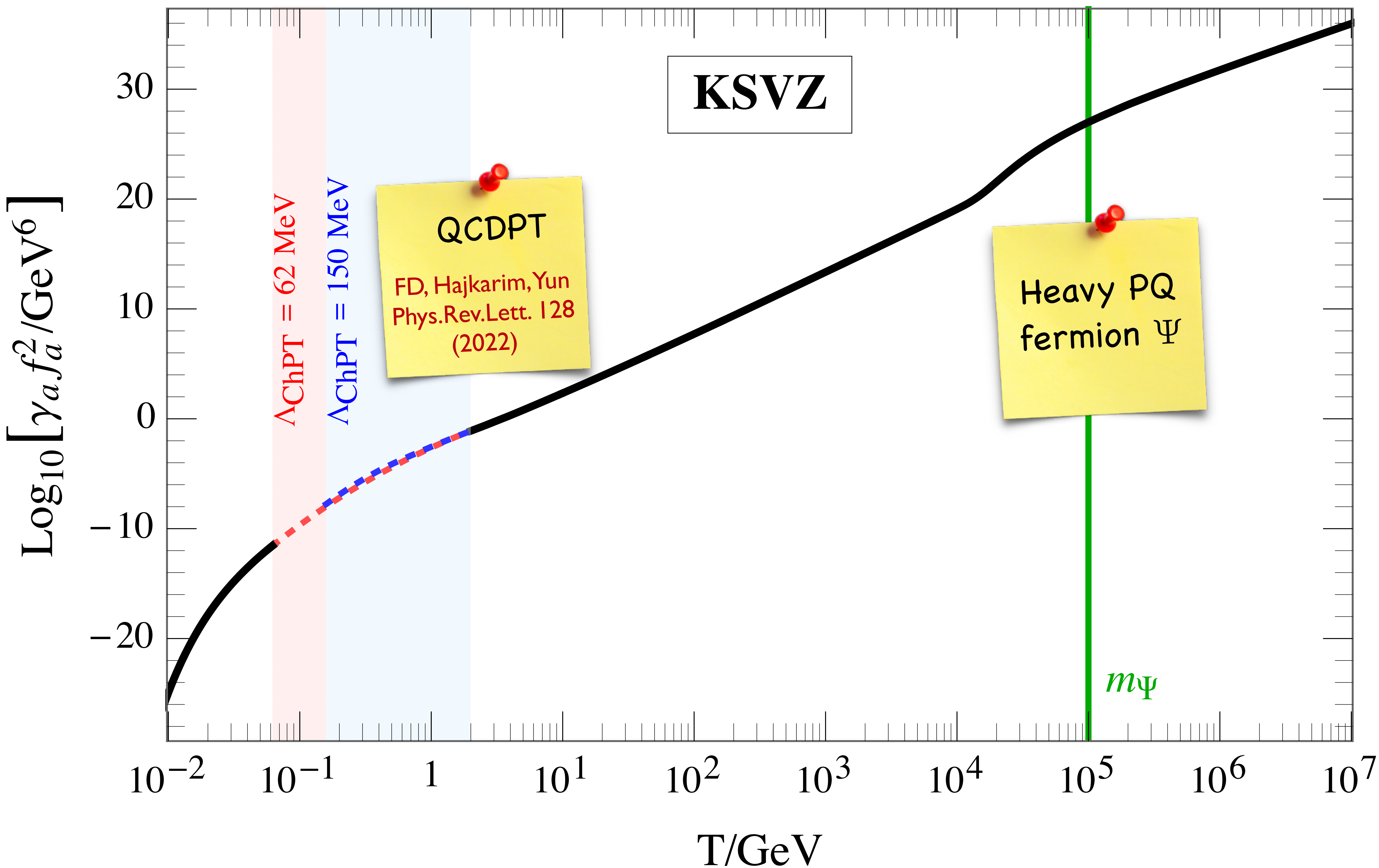
Pion scattering

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

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

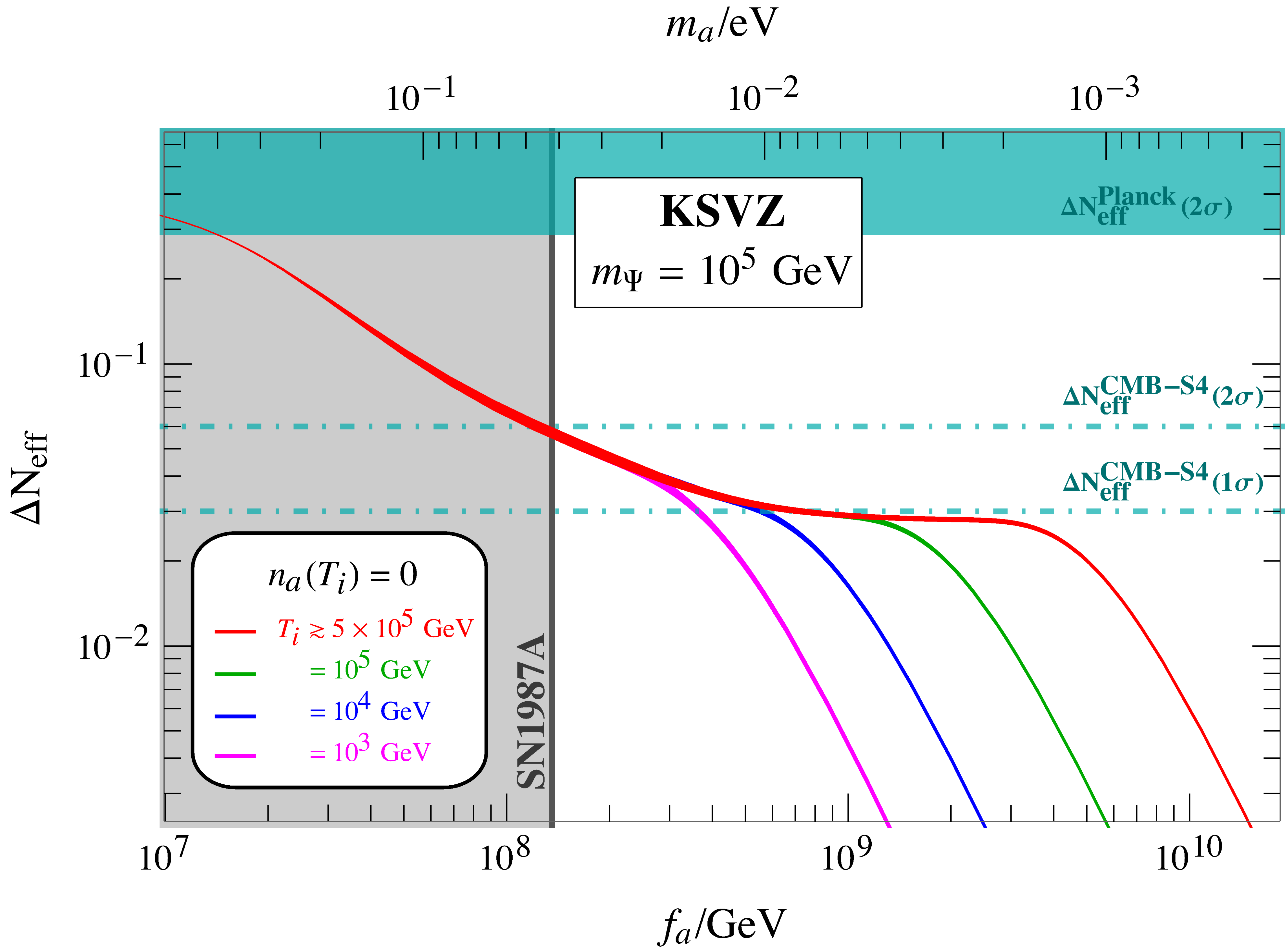
Recent studies:
Di Luzio, Martinelli, Piazza, Phys.Rev.Lett. 126 (2021)
Notari, Rompineve, Villadoro, Phys.Rev.Lett. 131 (2023)
Di Luzio, Camalich, Martinelli, Phys. Rev. D 108 (2023)

KSVZ Axion — Production Rate



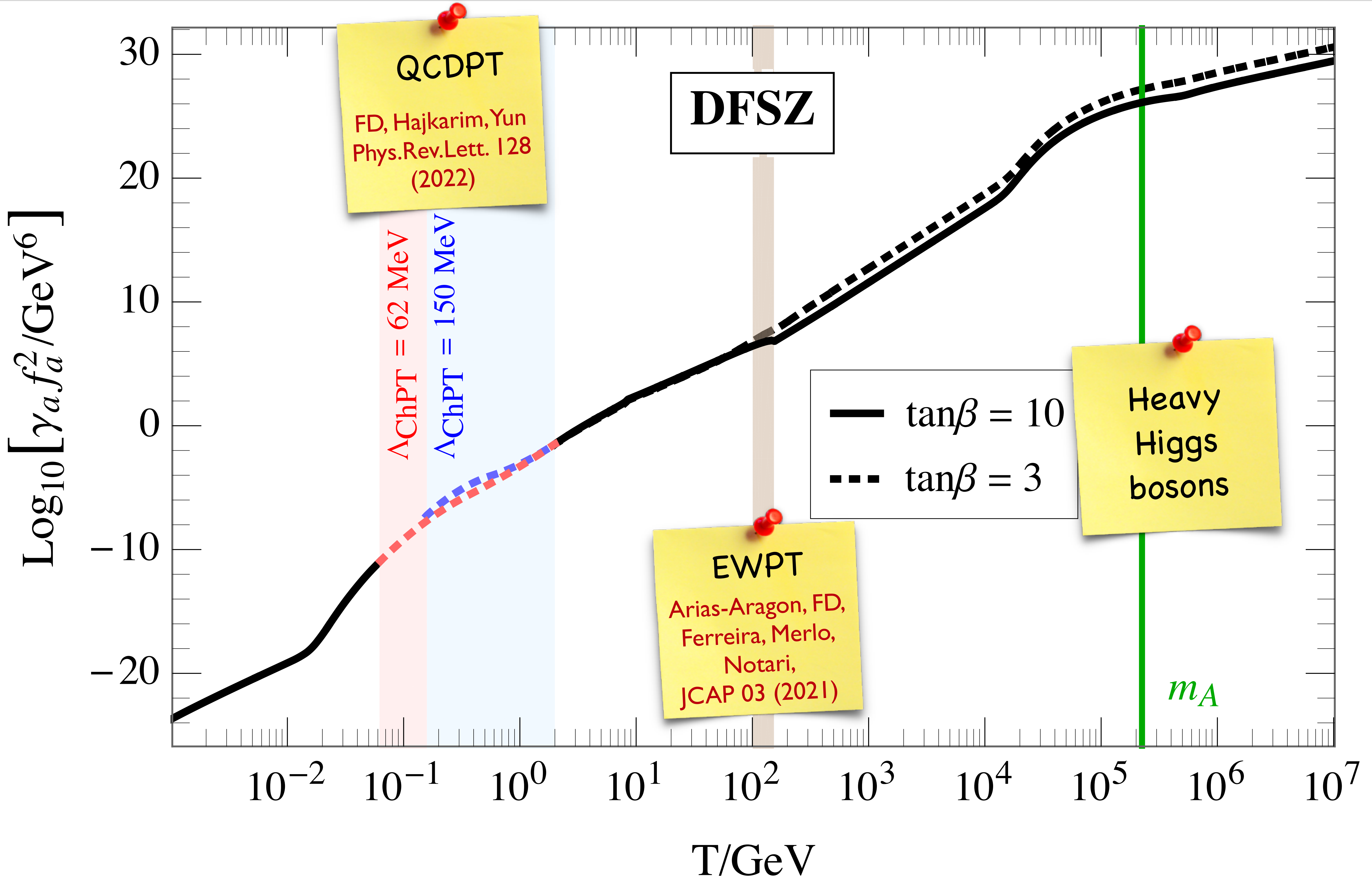
FD, Hajkarim, Yun, JHEP 10 (2021)

KSVZ Axion — ΔN_{eff}



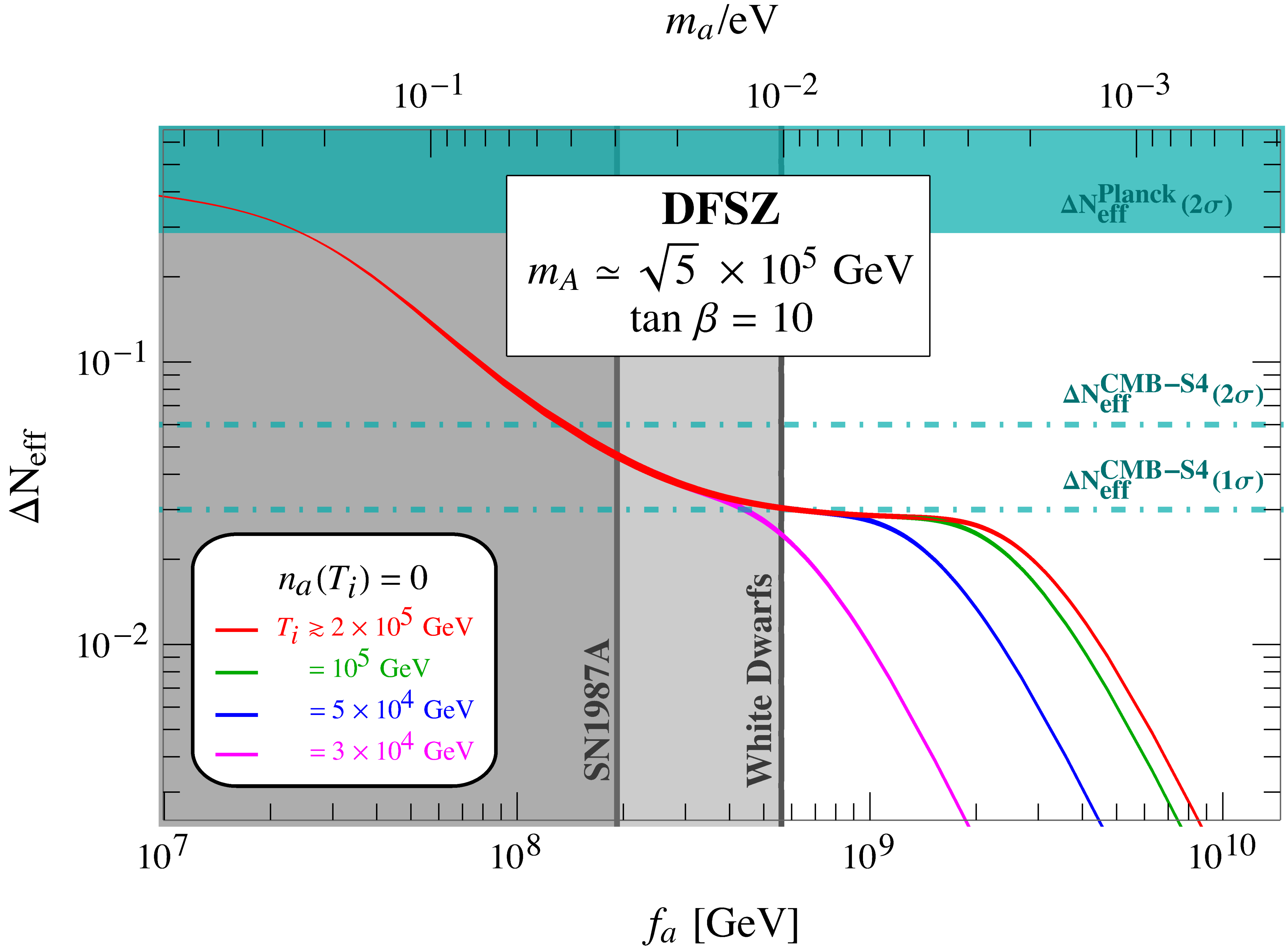
FD, Hajkarim, Yun, JHEP 10 (2021)

DFSZ Axion — Production Rate



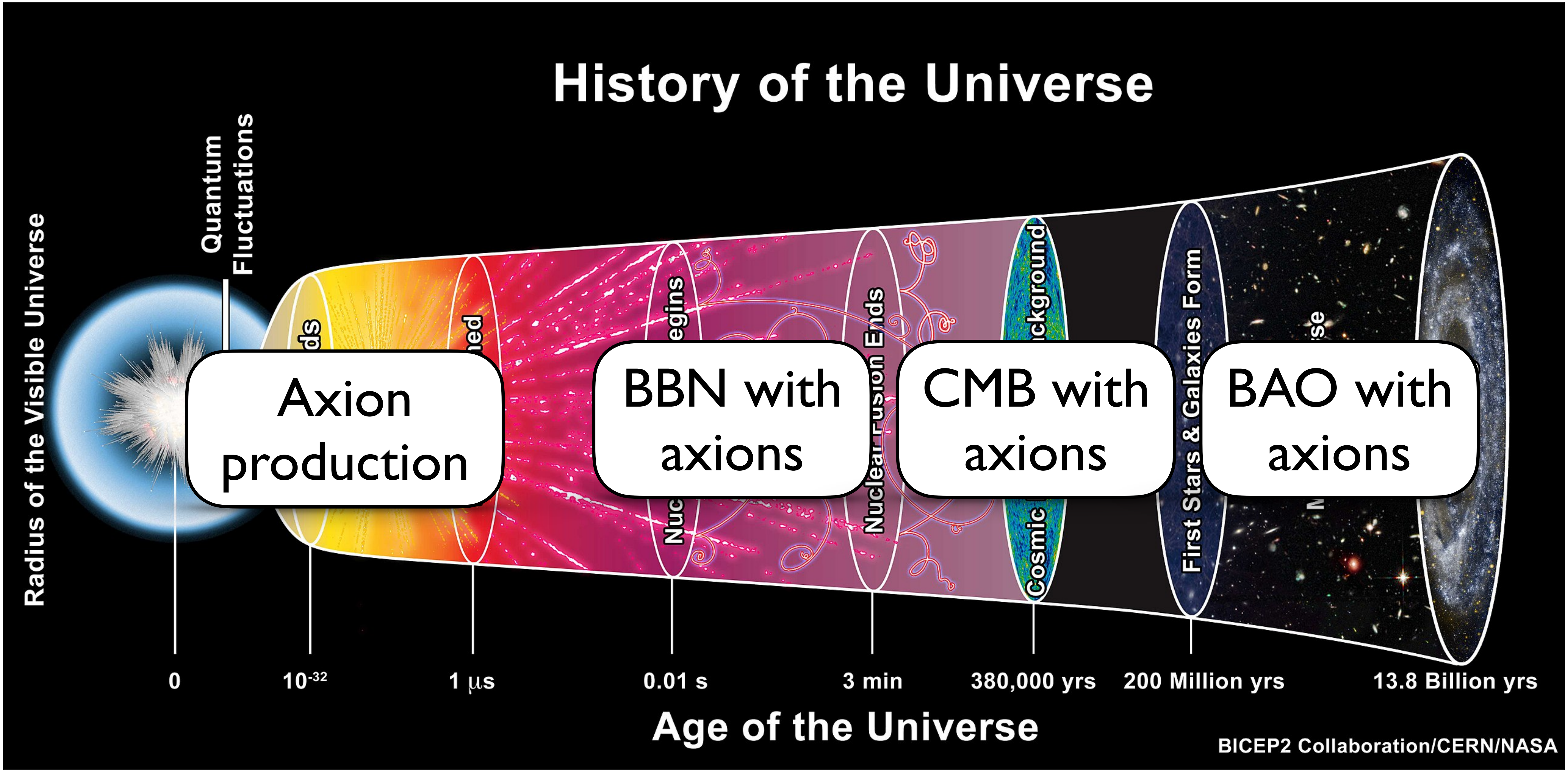
FD, Hajkarim, Yun, JHEP 10 (2021)

DFSZ Axion — ΔN_{eff}



FD, Hajkarim, Yun, JHEP 10 (2021)

QCD Axion Mass Bound



KSVZ

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

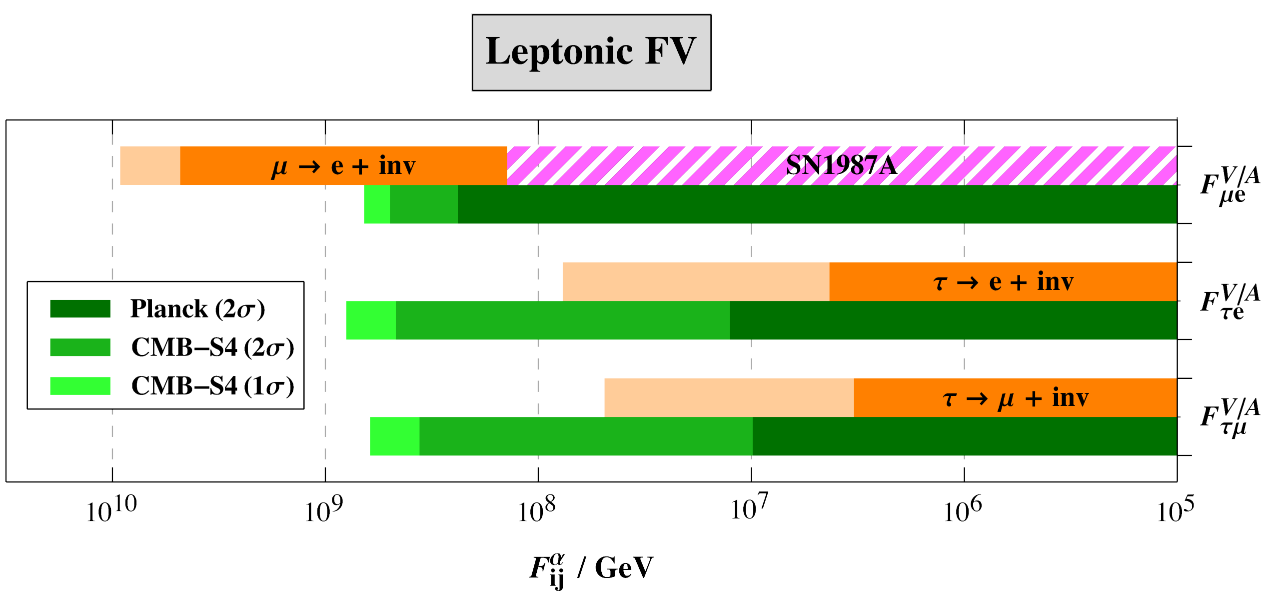
DFSZ

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

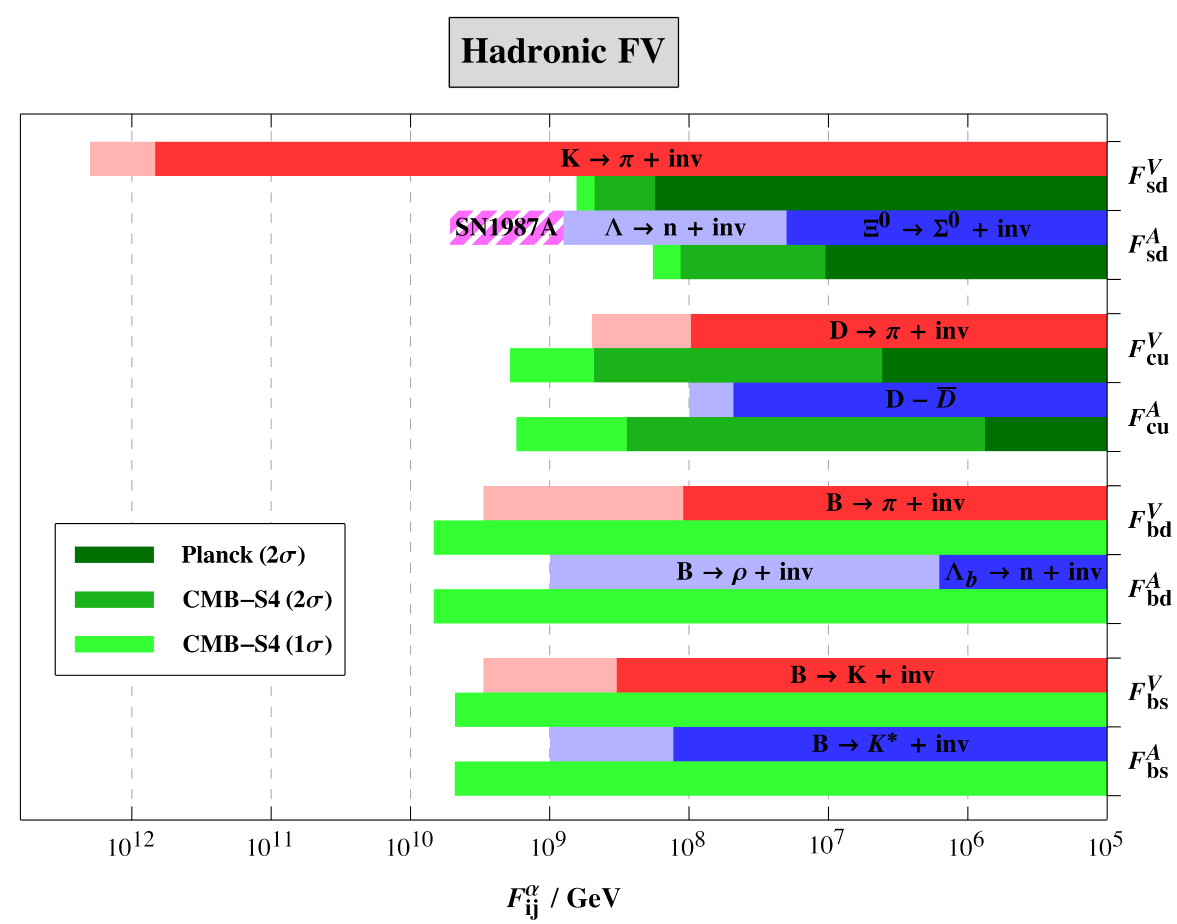
FD, Di Valentino, Giarè, Hajkarim, Melchiorri, Mena, Renzi, Yun, JCAP 09 (2022)

A Minor Variation: FV Axions

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

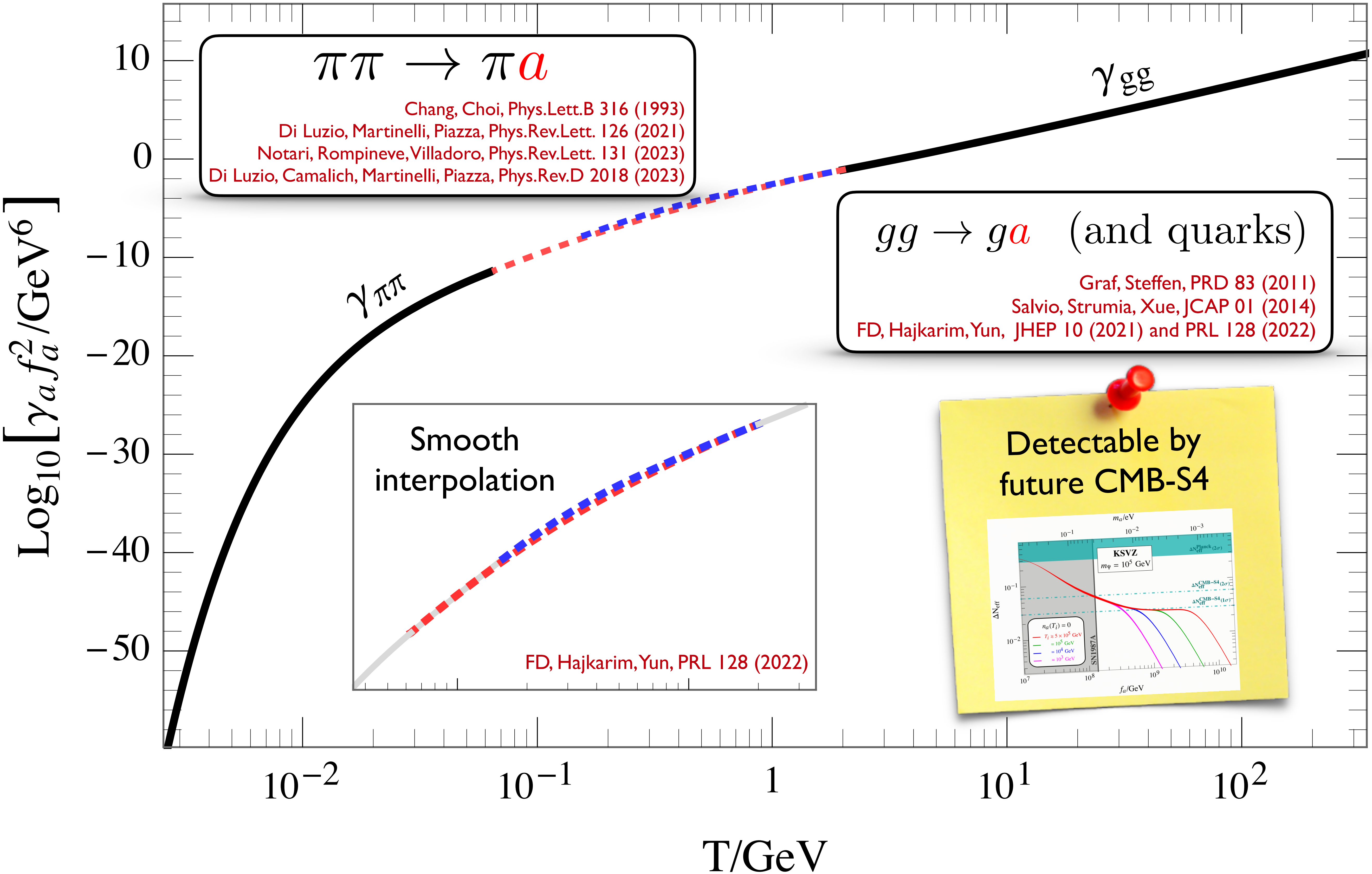


$$F^\alpha_{\psi_i \psi_j} \equiv \frac{2 f_a}{c^\alpha_{\psi_i \psi_j}}$$



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

Where Do We Stand?



What's Next?

Axion production rate

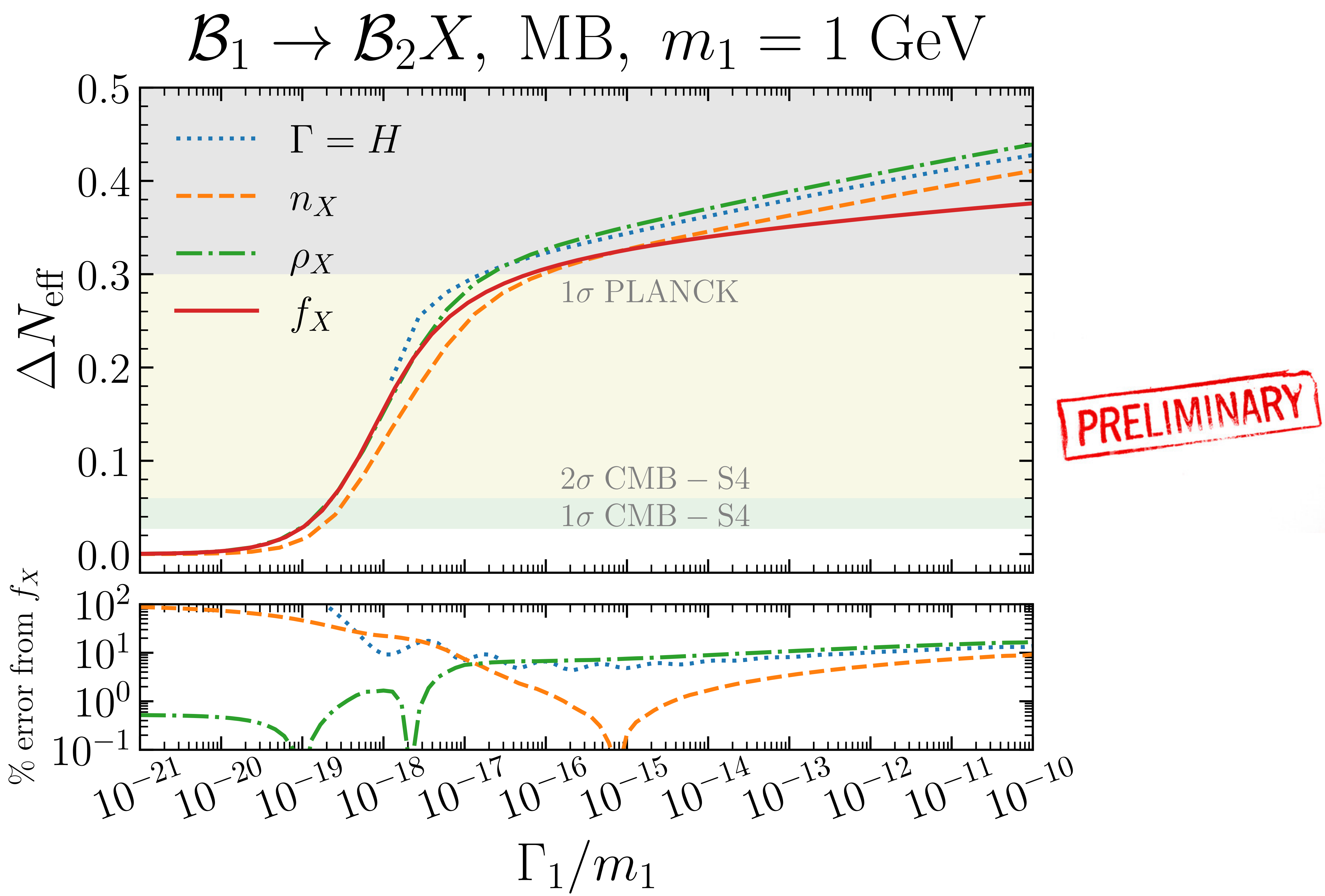
across the confinement scale still unknown

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

Thermal bath Particle Physics

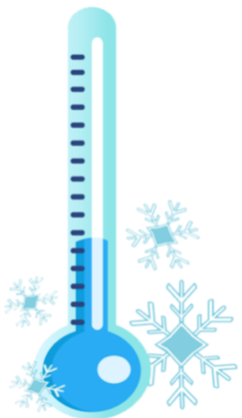
1. Cross sections with other hadrons?
2. Thermal bath description between 150 MeV and fews GeV?
3. Boltzmann equation evolution and cosmological observables?

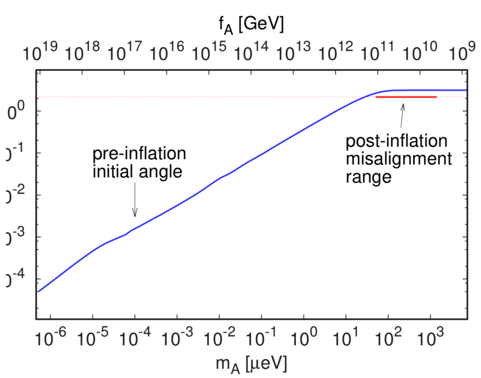
Phase-Space Analysis



FD, Lenoci, Hajkarim — in preparation

Outlook





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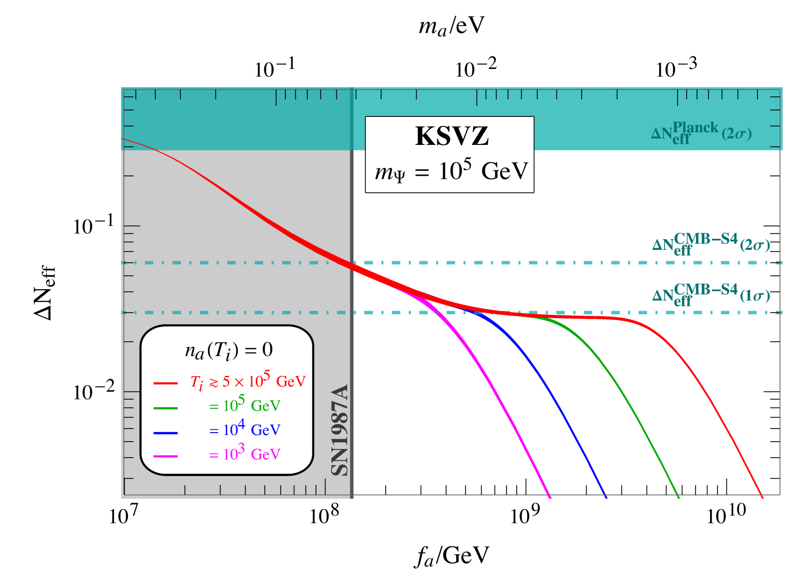
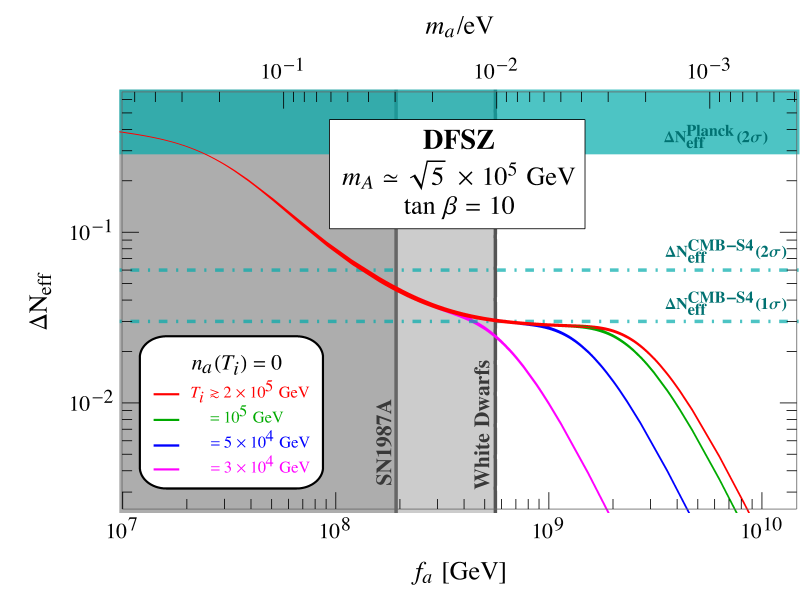
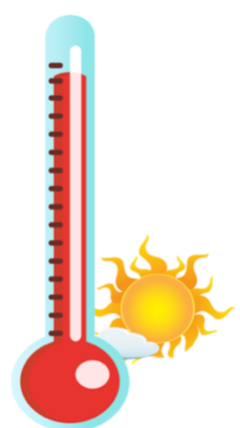
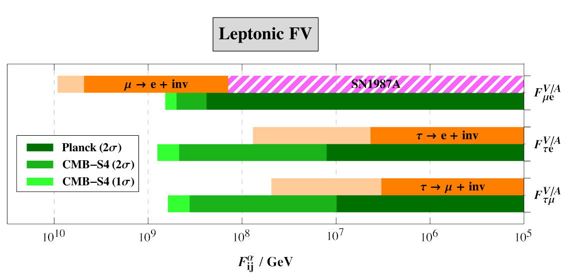
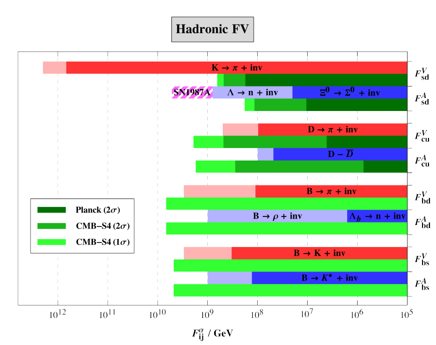






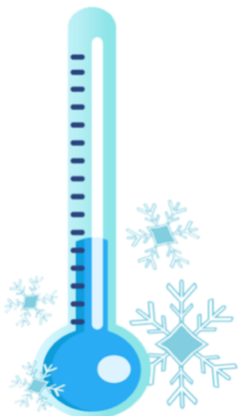


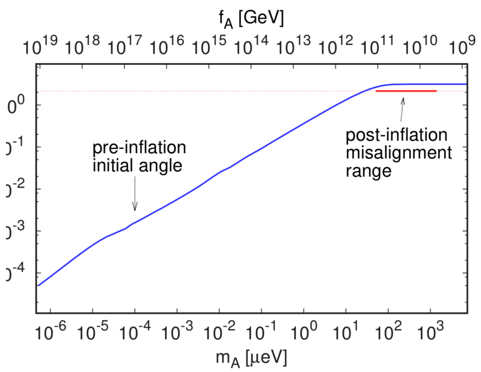


Thermal Axions

Complementary to other probes of the PQ mechanism

Outlook





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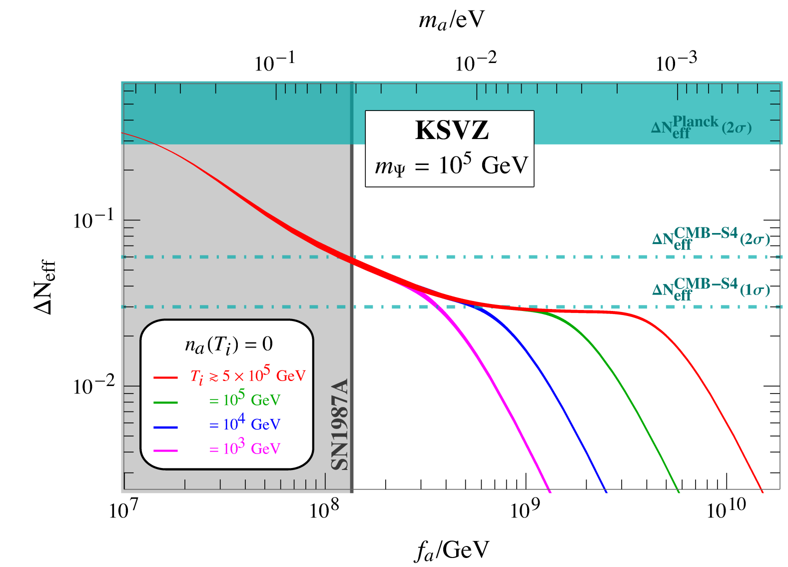

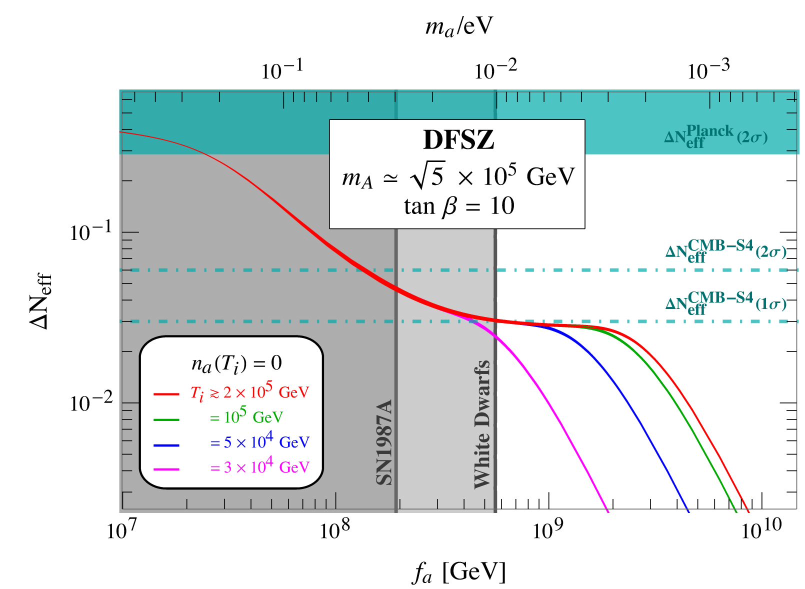

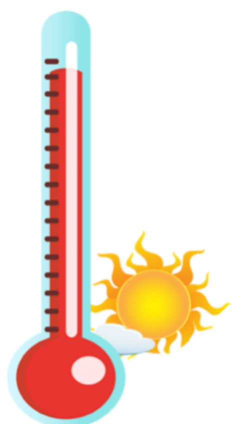

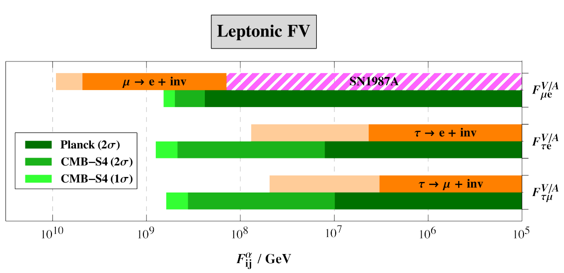

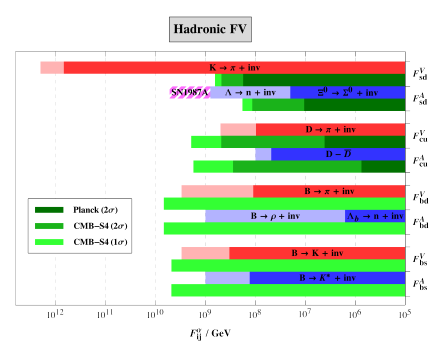

THANKS!