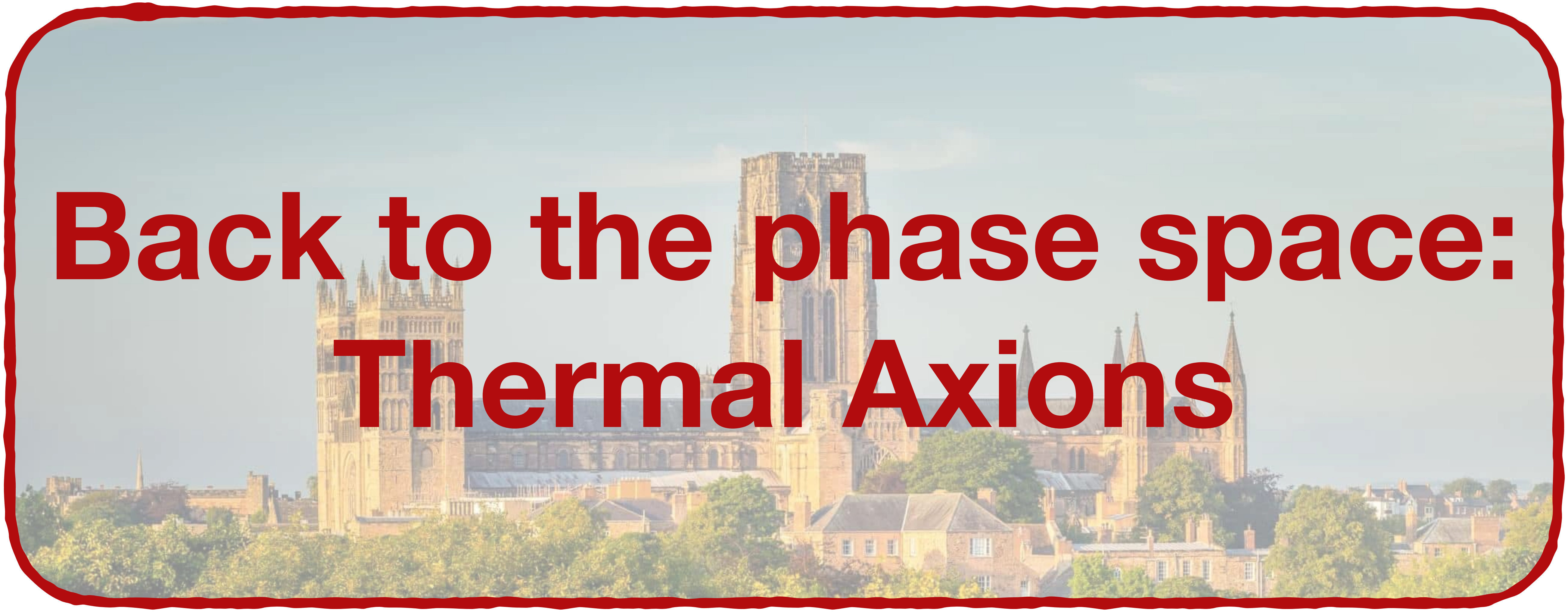


Back to the phase space: Thermal Axions

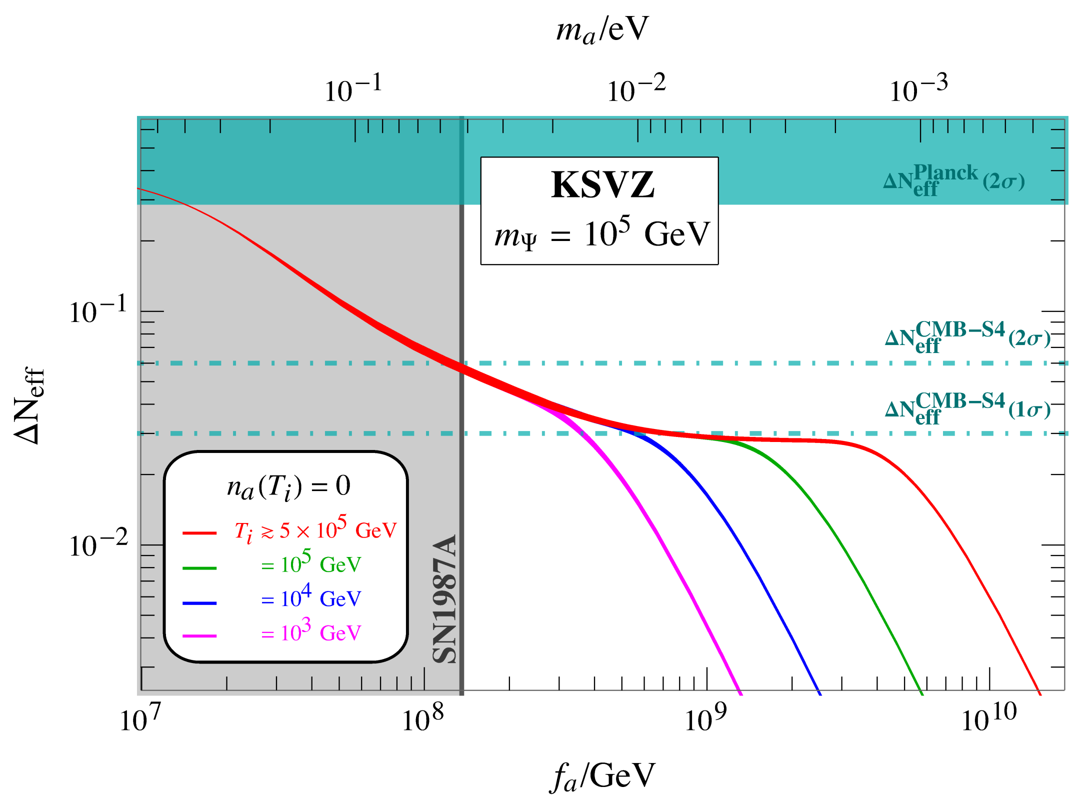
Francesco D'Eramo

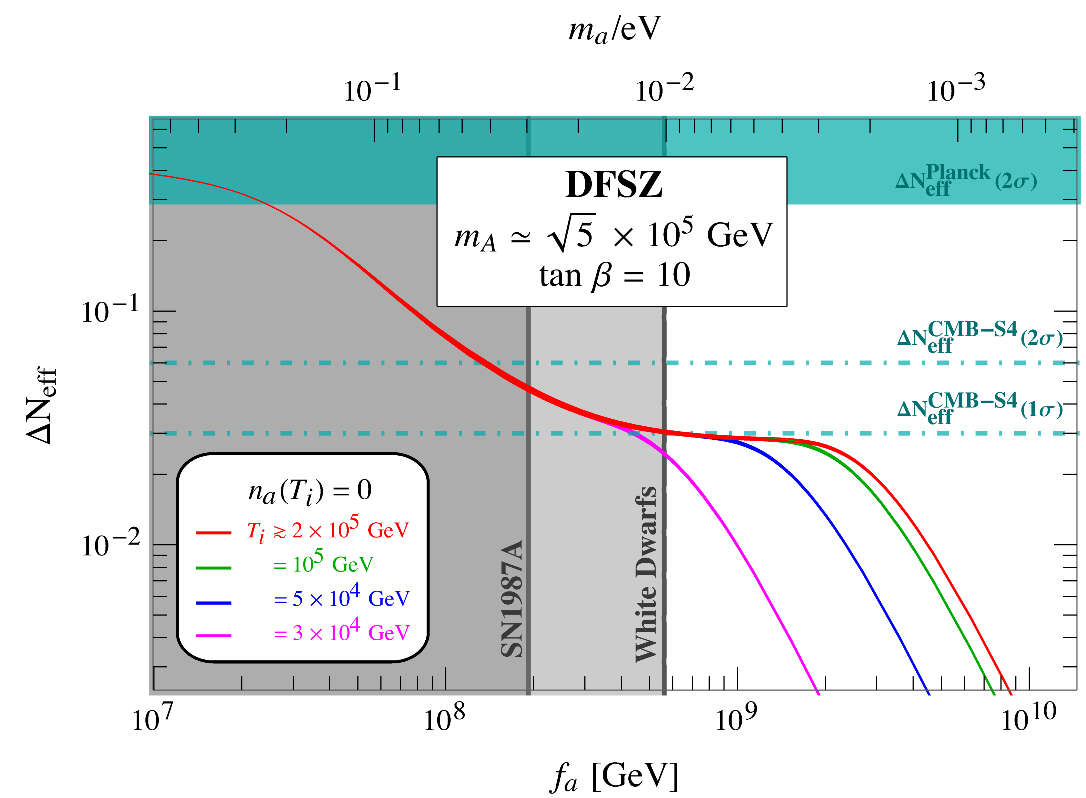
Università degli Studi di Padova

INFN Padova

Dark Matter Beyond the Weak Scale II — Durham University, 27 March 2024

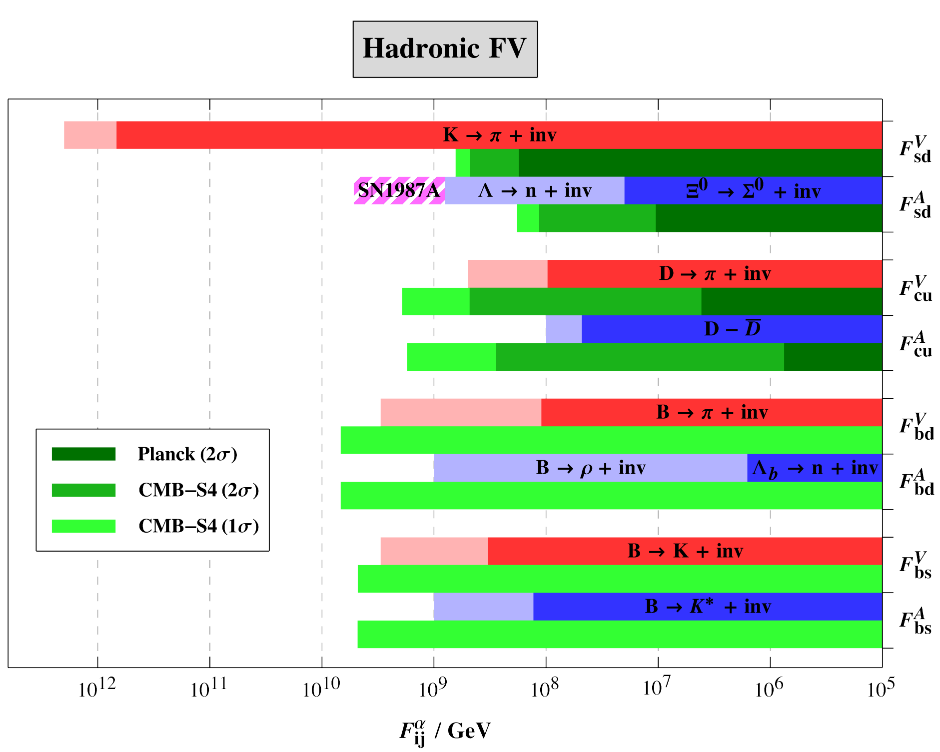
The way back I: ΔN_{eff}

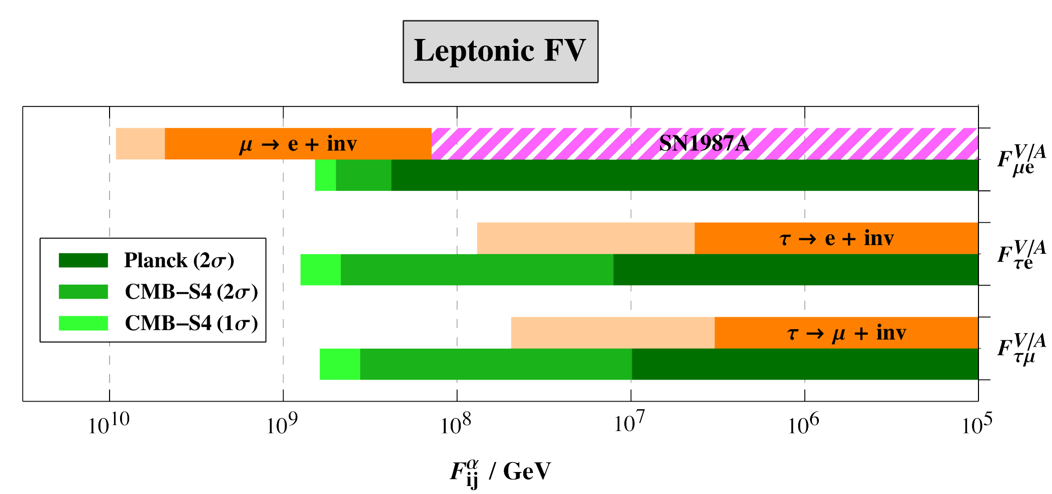




FD, Hajkarim, Yun, **Phys.Rev.Lett. 128 (2022)**

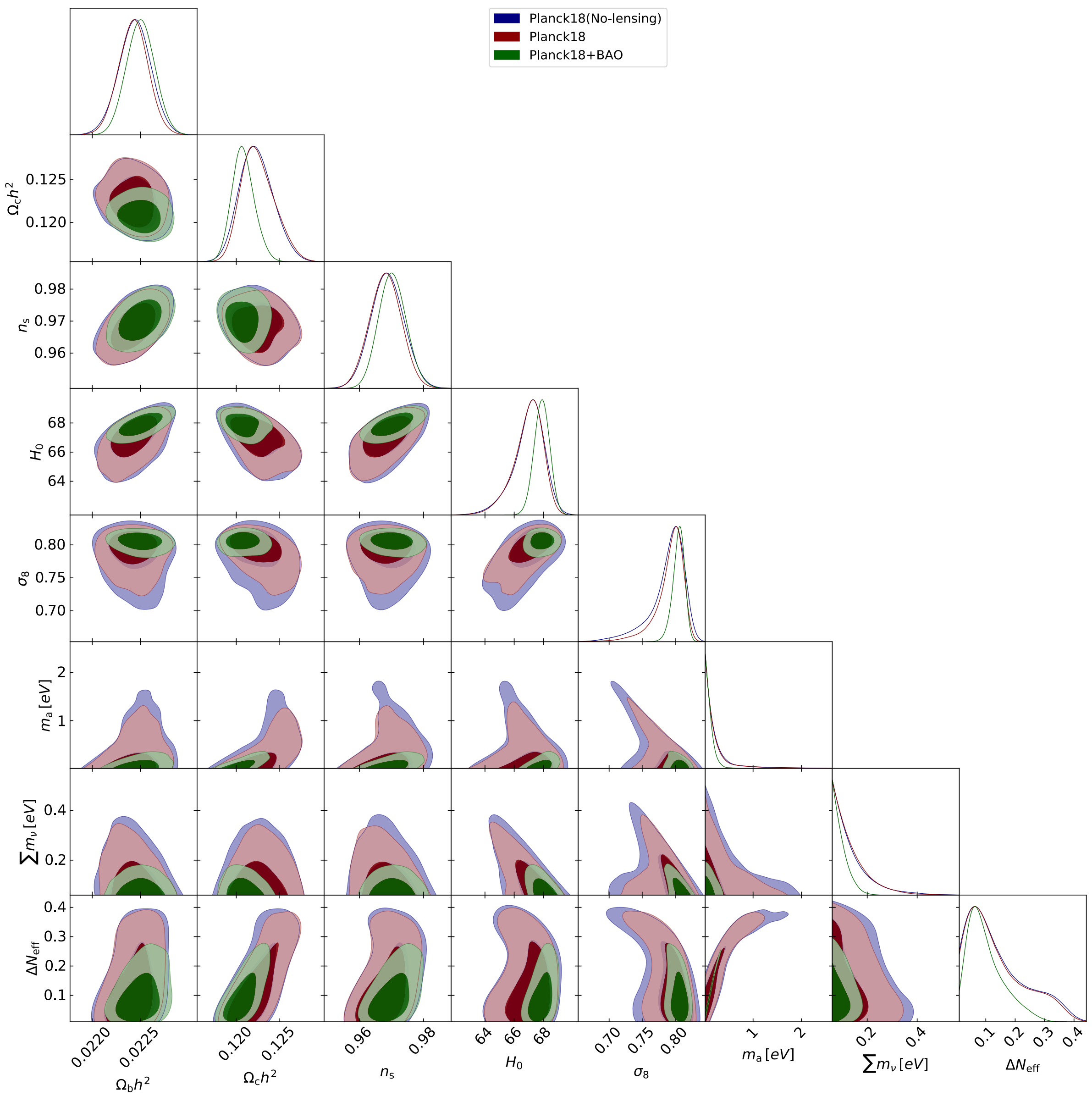
FD, Hajkarim, Yun, J**HEP 10 (2021)**





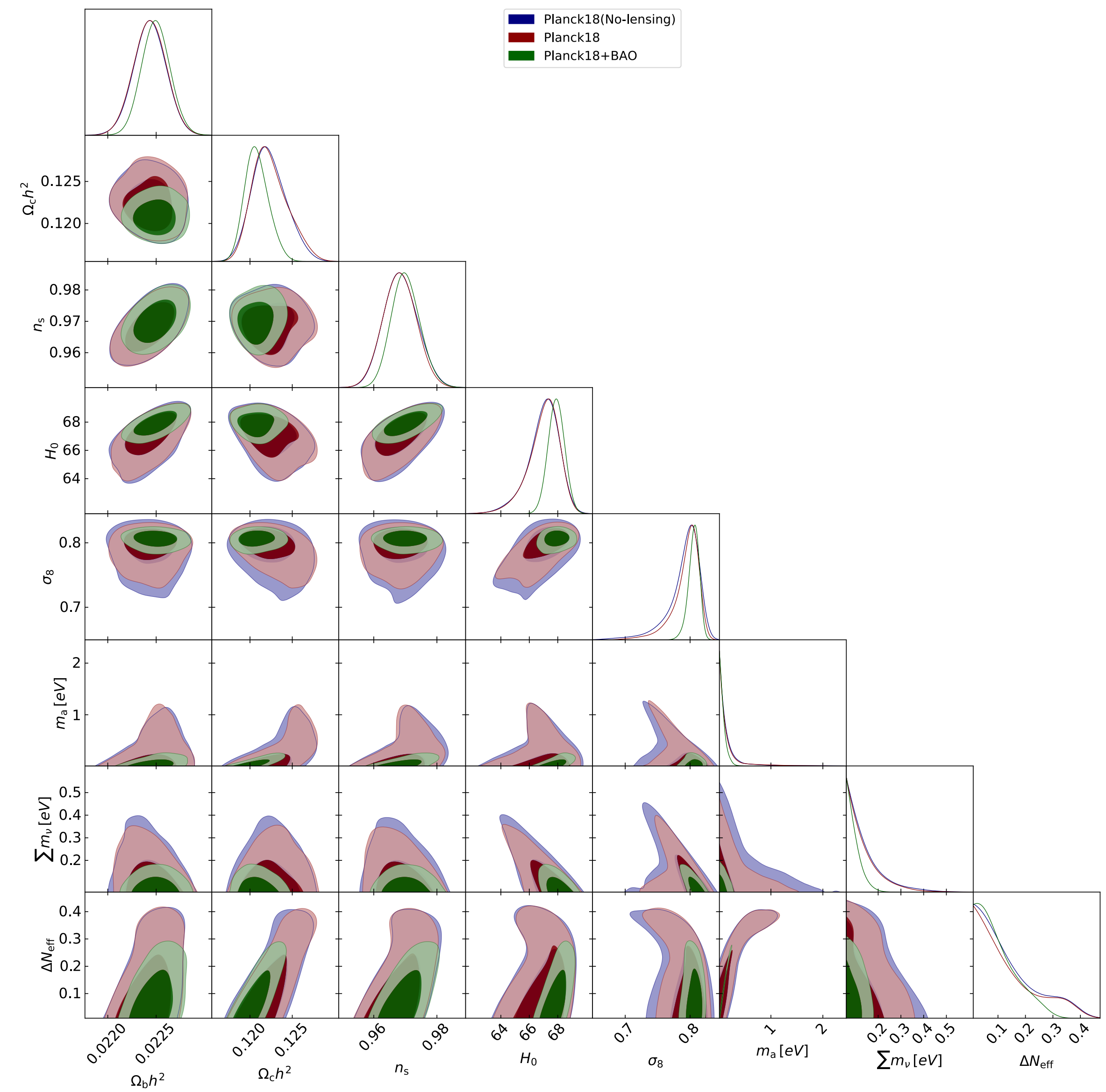
FD, Yun, **Phys.Rev.D 105 (2022)**

The way back II: Mass Bound



KSVZ

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

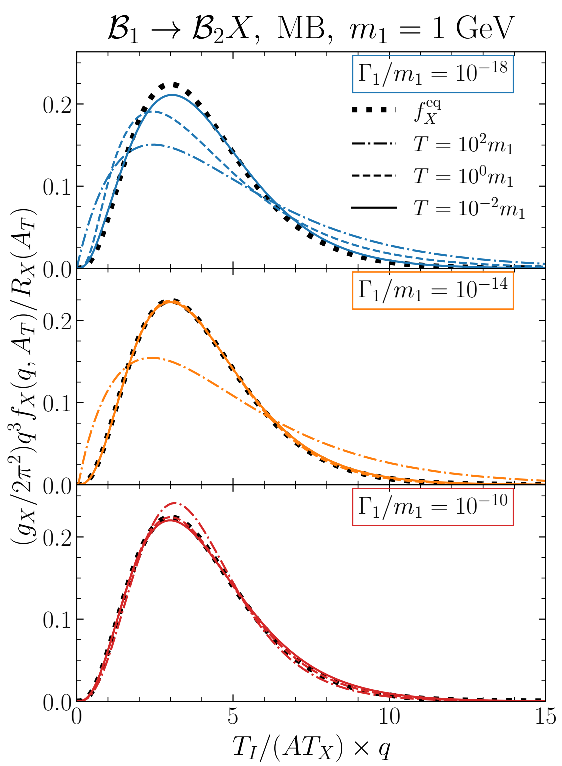


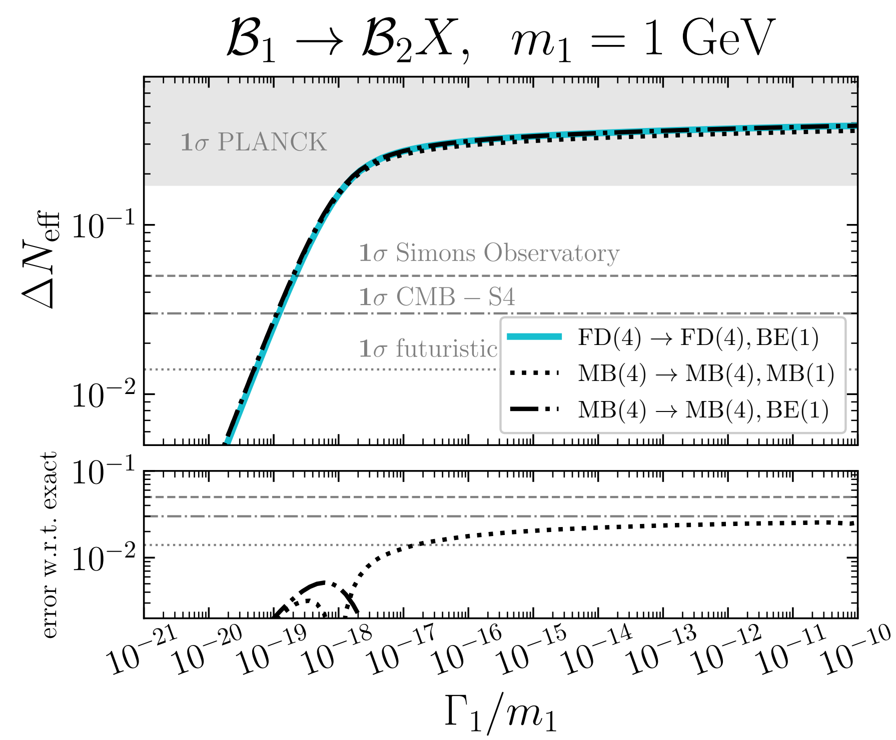
DFSZ

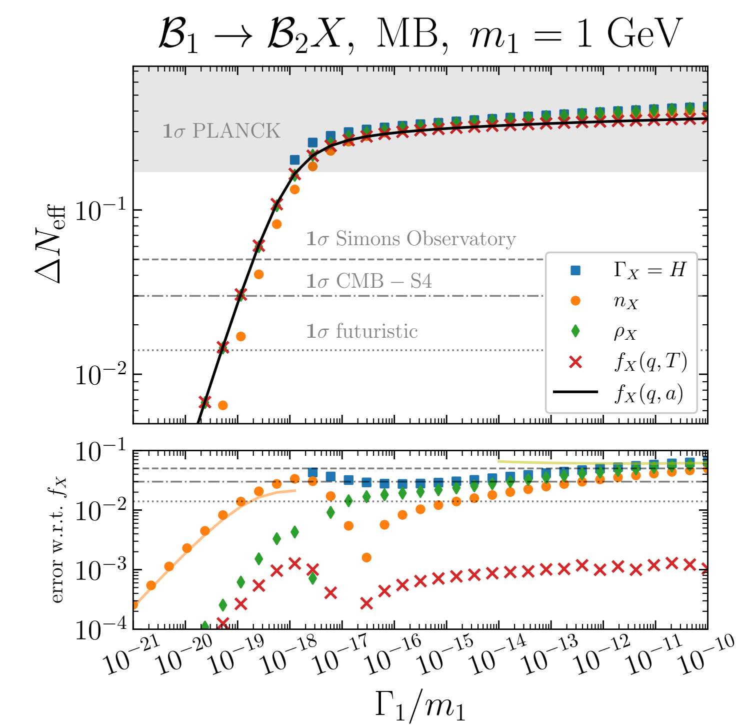
$$m_a \leq 0.209(0.293)\,\mathrm{eV}$$

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

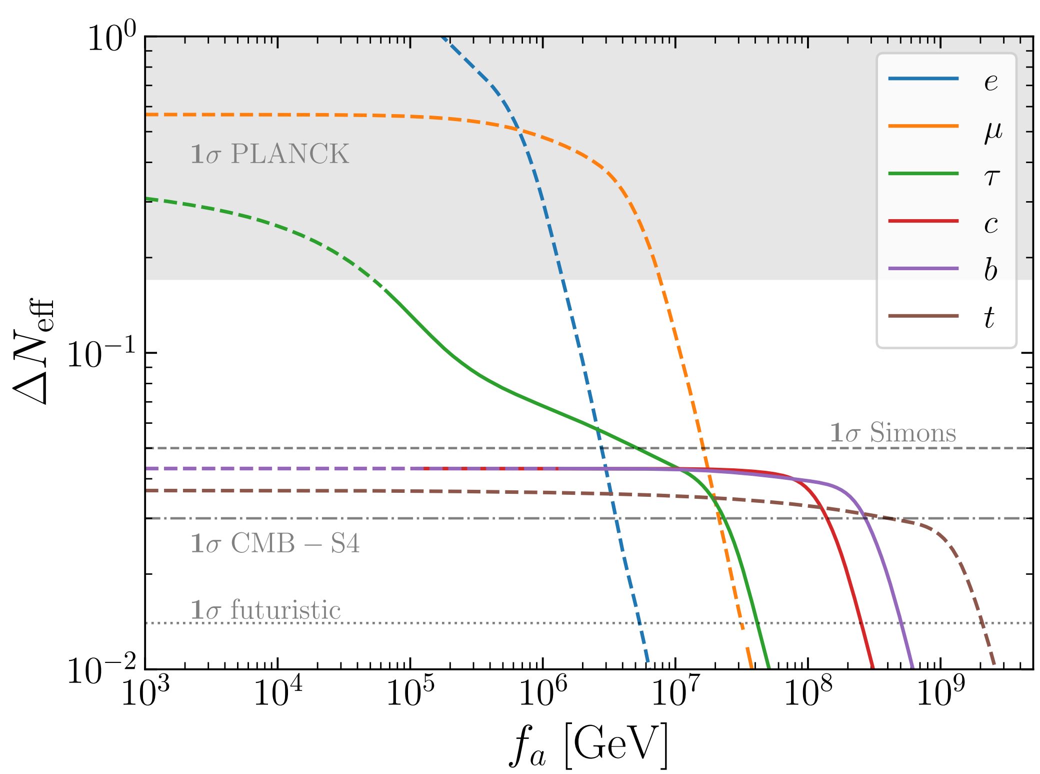
The way back III: Phase Space







FD, Hajkarim, Lenoci, **JCAP 03 (2024)**



Updated predictions
via a rigorous phase space analysis

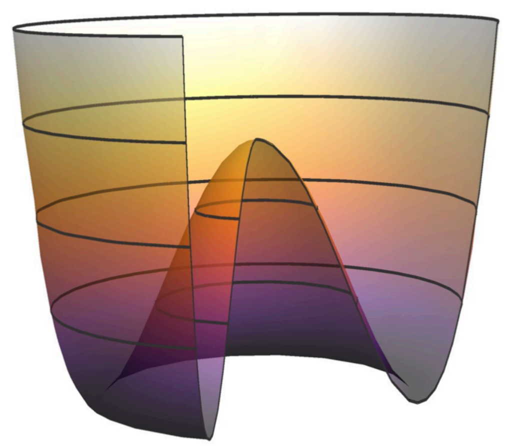
FD, Lenoci, **in preparation**

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



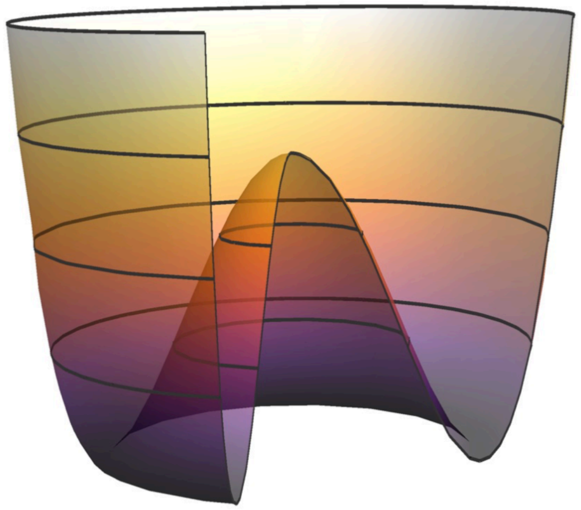
$$\frac{a}{f_a}\frac{\alpha_s}{8\pi}G^{\mu\nu}\tilde{G}_{\mu\nu}$$

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

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



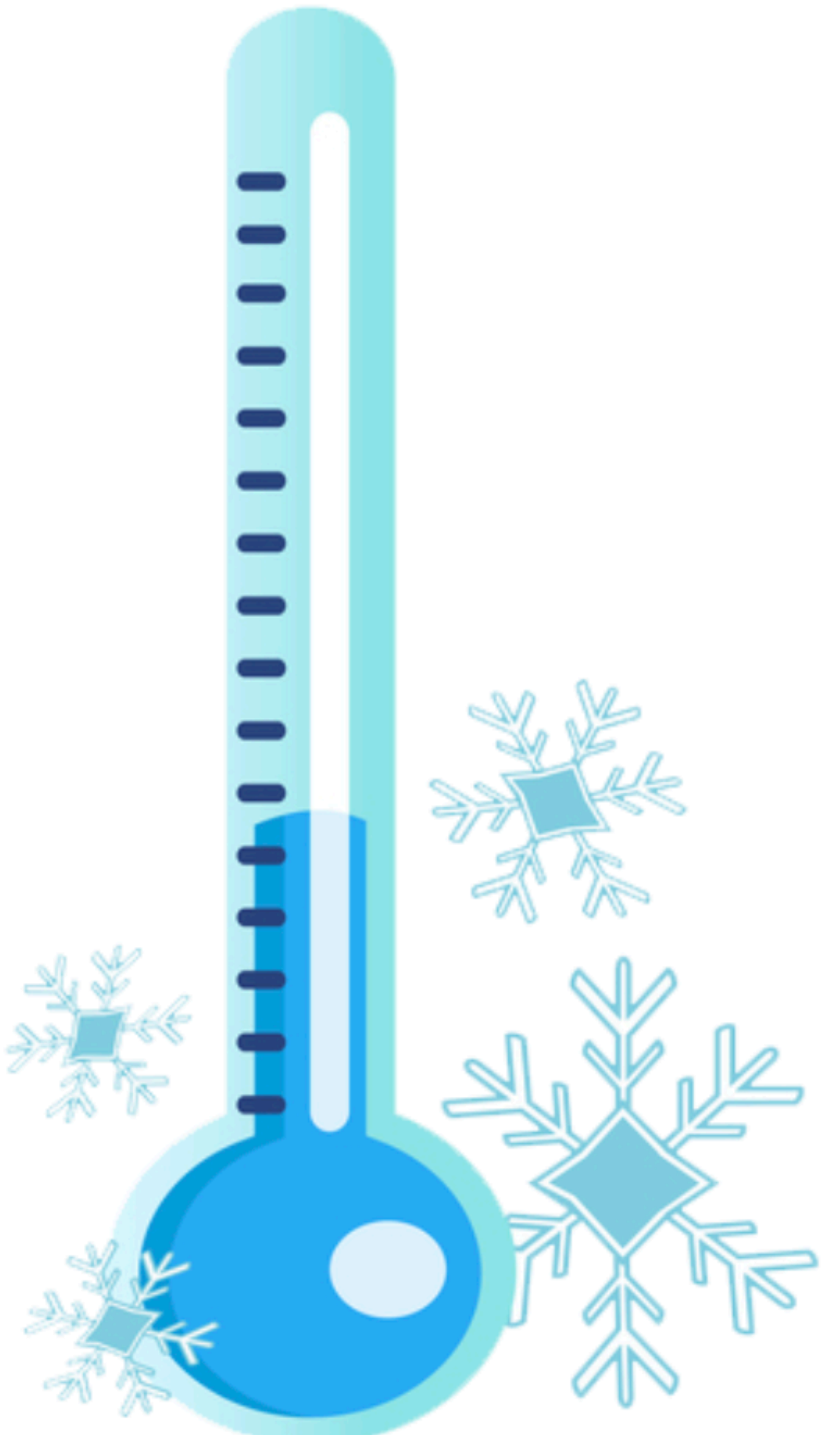
- Pseudo-Nambu-Goldstone-bosons in field theory
- Axions in string theory

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

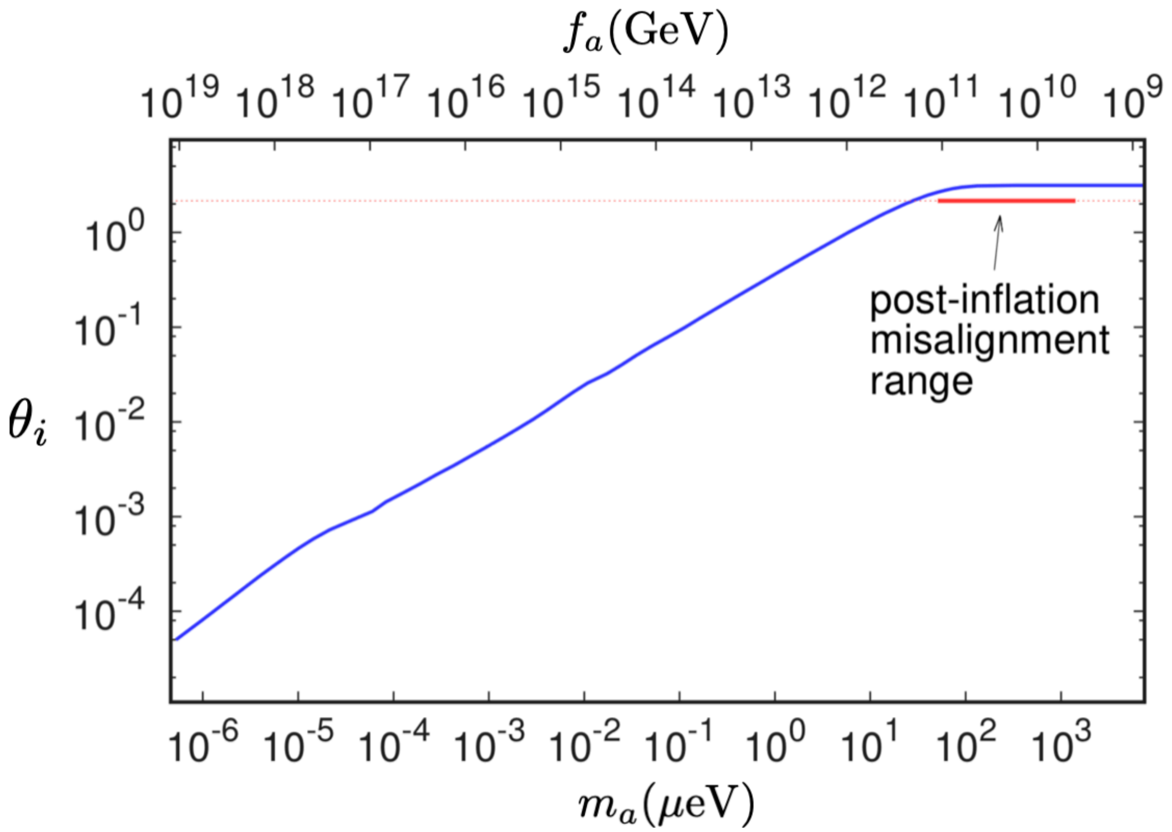
$$m_a \simeq \frac{\Lambda^2}{f_a}$$

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

Cold Axions — Dark Matter



Predicting f_a (with caveats)



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

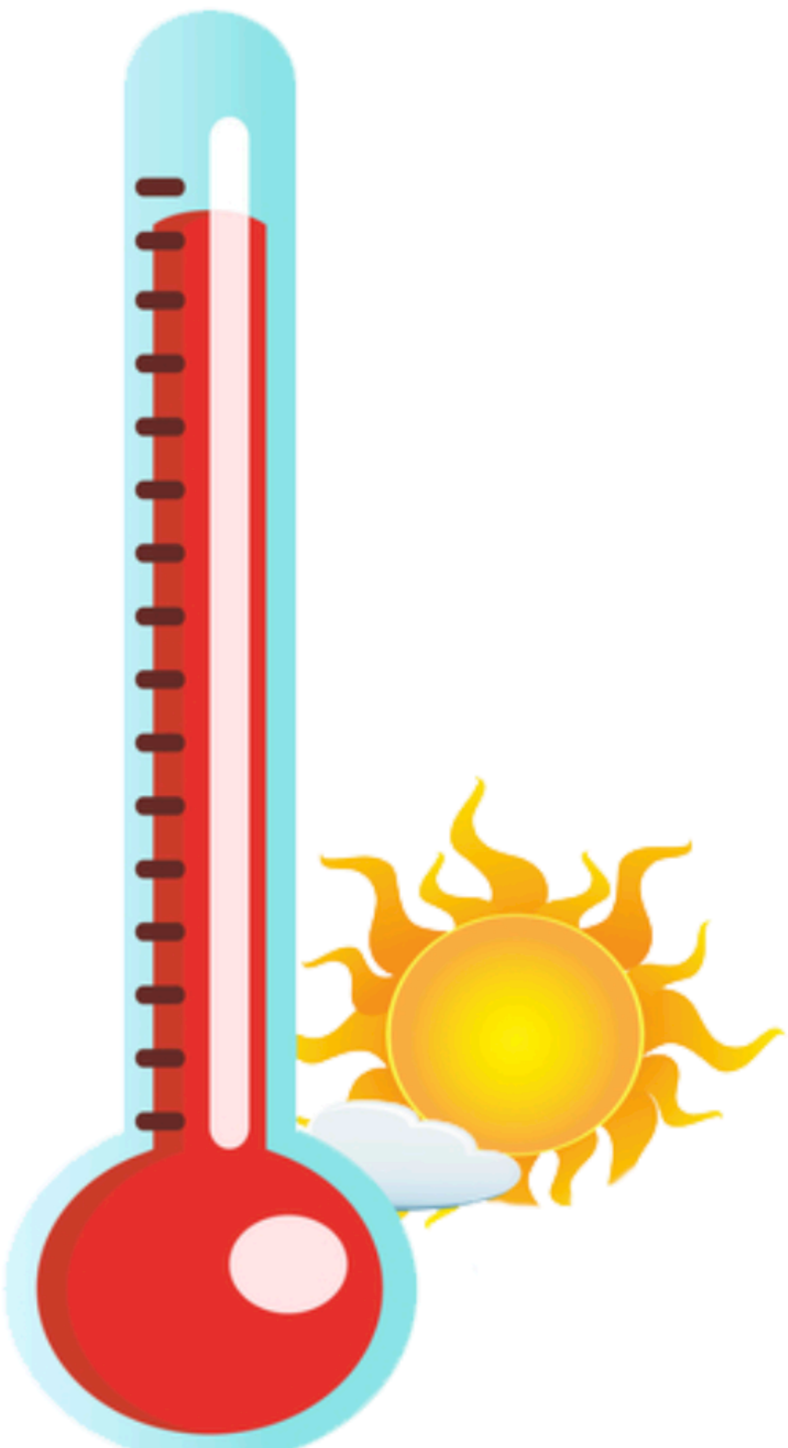
Axion string contribution?

Klaer and Moore, JCAP 10 and JCAP 11 (2017)

Gorghetto, Hardy, Villadoro
JHEP 07 (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)

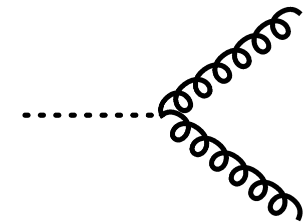
$$\rho_{\rm rad} = \left[1 + \frac{7}{8}\left(\frac{T_\nu}{T_\gamma}\right)^4 N_{\rm eff}\right]\rho_\gamma$$

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

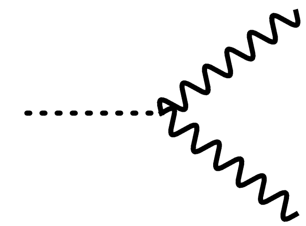
Thermal Axions

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

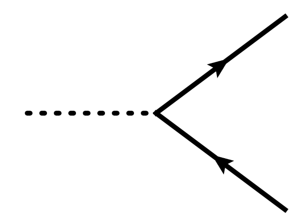
<u>Unavoidable</u>
Production Source!



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



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



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

Thermal Axions

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

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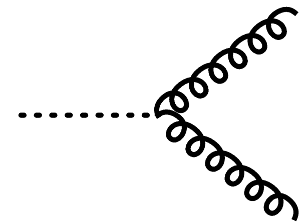

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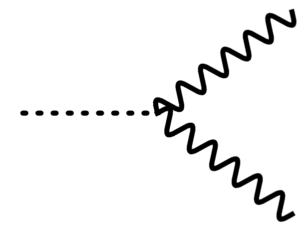

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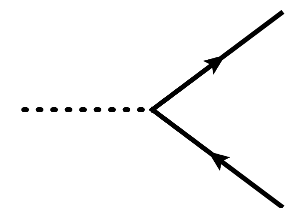


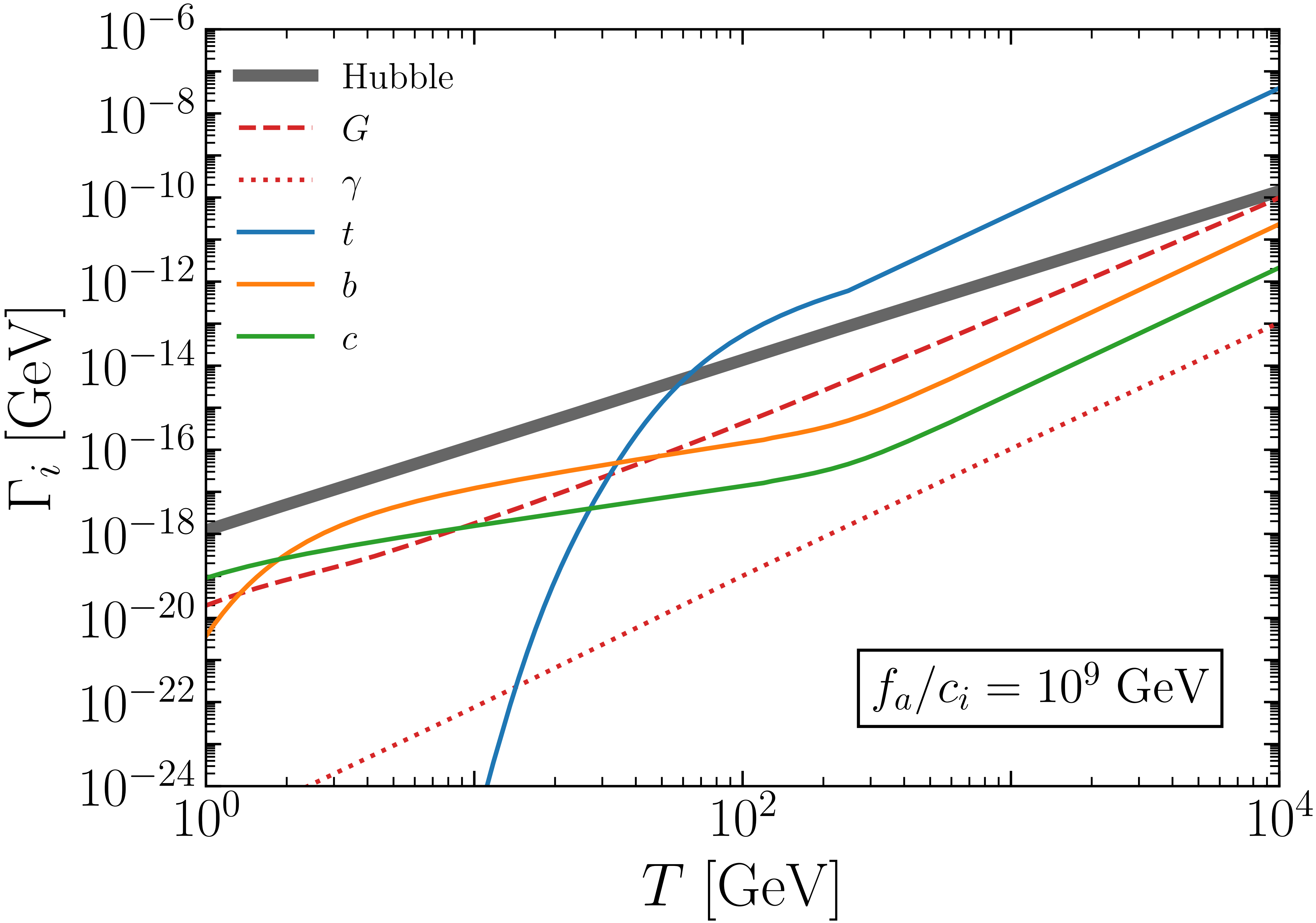
$$c_\psi\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$$

ROUGH ESTIMATE (instantaneous decoupling)

- Assume they thermalize at early times
- Estimate the decoupling temperature, $\Gamma(T_D) = H(T_D)$, and the resulting $\Delta N_{\rm eff}$

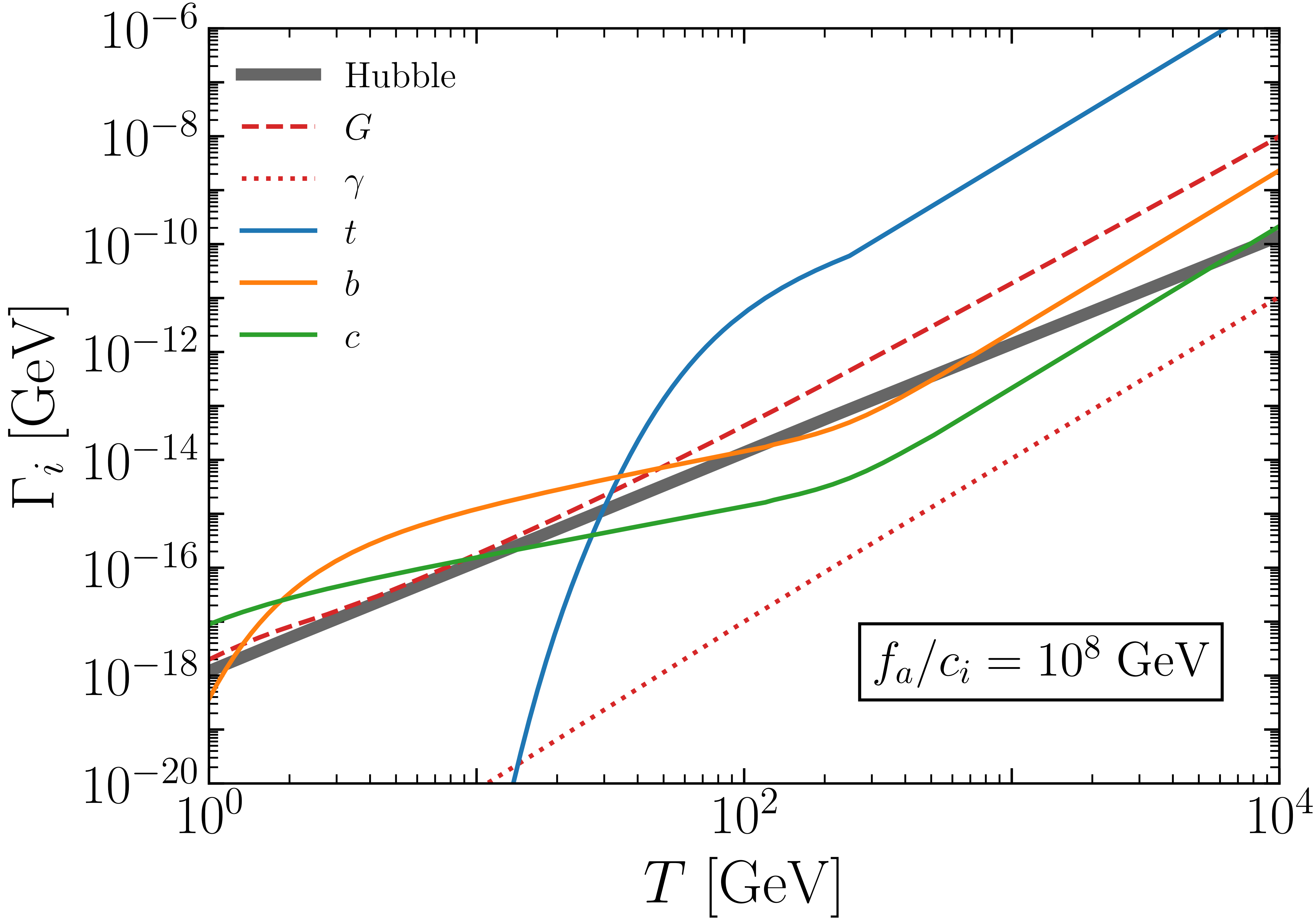
$$\Delta N_{\rm eff} \simeq 0.027\left(\frac{106.75}{g_{*s}(T_D)}\right)^{4/3}$$

Do they thermalize? And when?



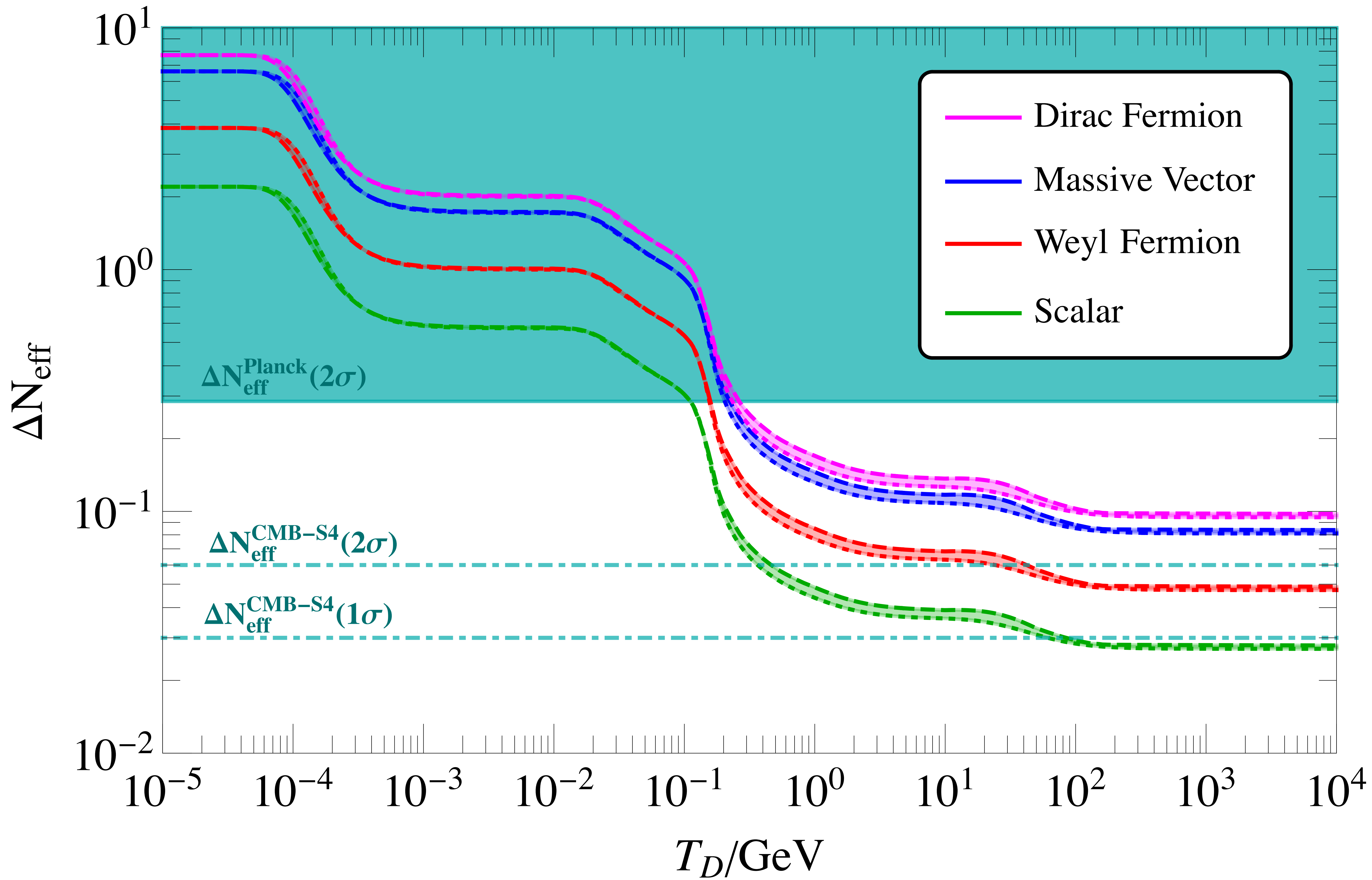
FD, Lenoci, **in preparation**

Do they thermalize? And when?



FD, Lenoci, **in preparation**

Bounds and Prospects

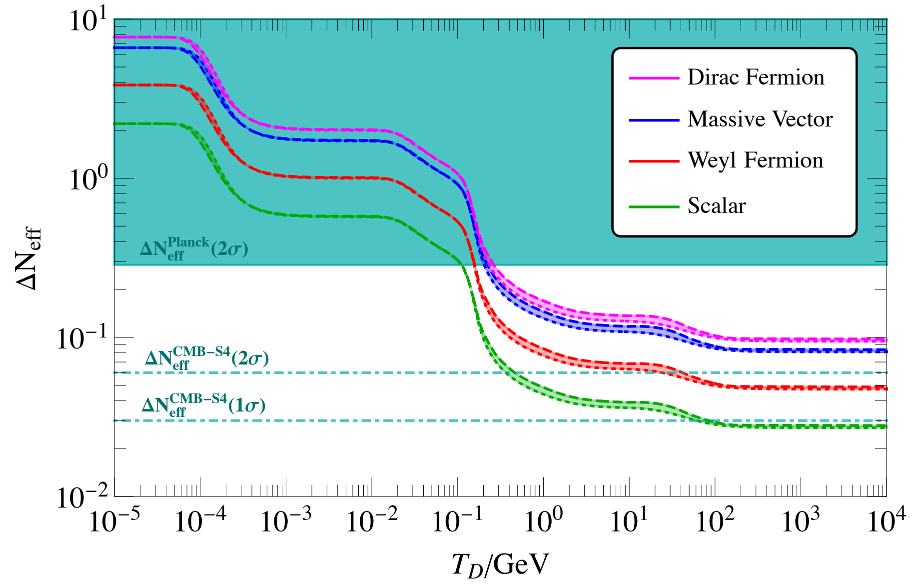


FD, Hajkarim, Yun, **JHEP 10 (2021)**

Predicting ΔN_{eff}

Axions may never thermalize

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



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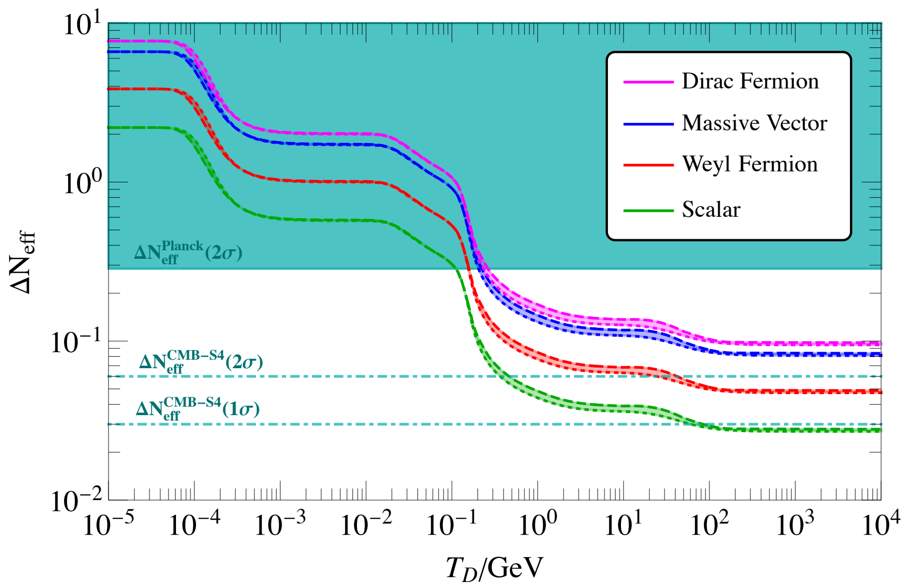

An improved methodology

- Track the number density of axions
- Convert the asymptotic result to ΔN$_{eff}$ via the equilibrium distribution

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

$$\Delta N_{\rm eff} \simeq 74.85\, Y_a^{4/3}$$

Predicting ΔN_{eff}

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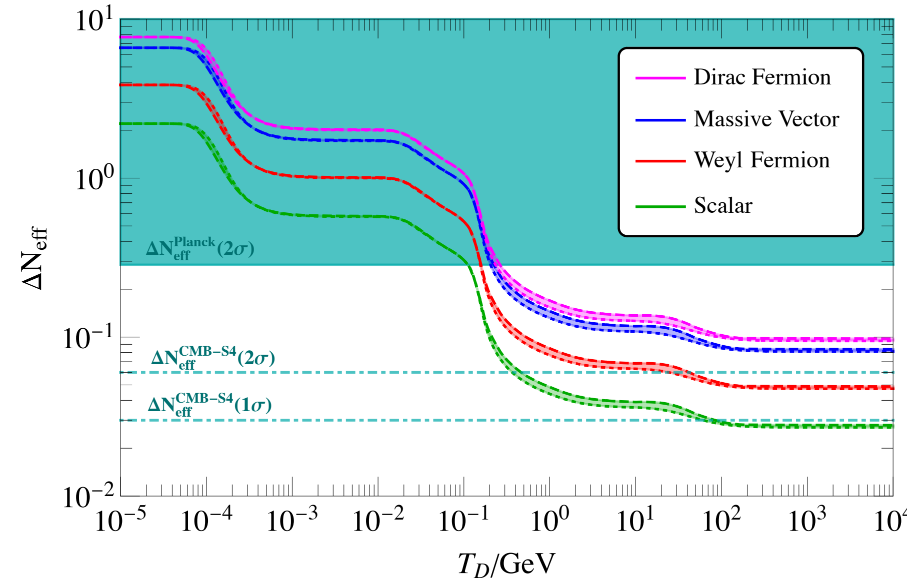

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$$\frac{dn_a}{dt} + 3Hn_a = \sum_\alpha \gamma_\alpha$$

$$\Delta N_{\rm eff} \simeq 74.85 \, Y_a^{4/3}$$

Equilibrium thermodynamics, Spectral distortions neglected, Maxwell-Boltzmann statistics (i.e., no quantum effects), Static thermal bath (i.e., no energy exchanged)

Irreducible Part for the QCD Axion

Strong CP Problem

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

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)

Below

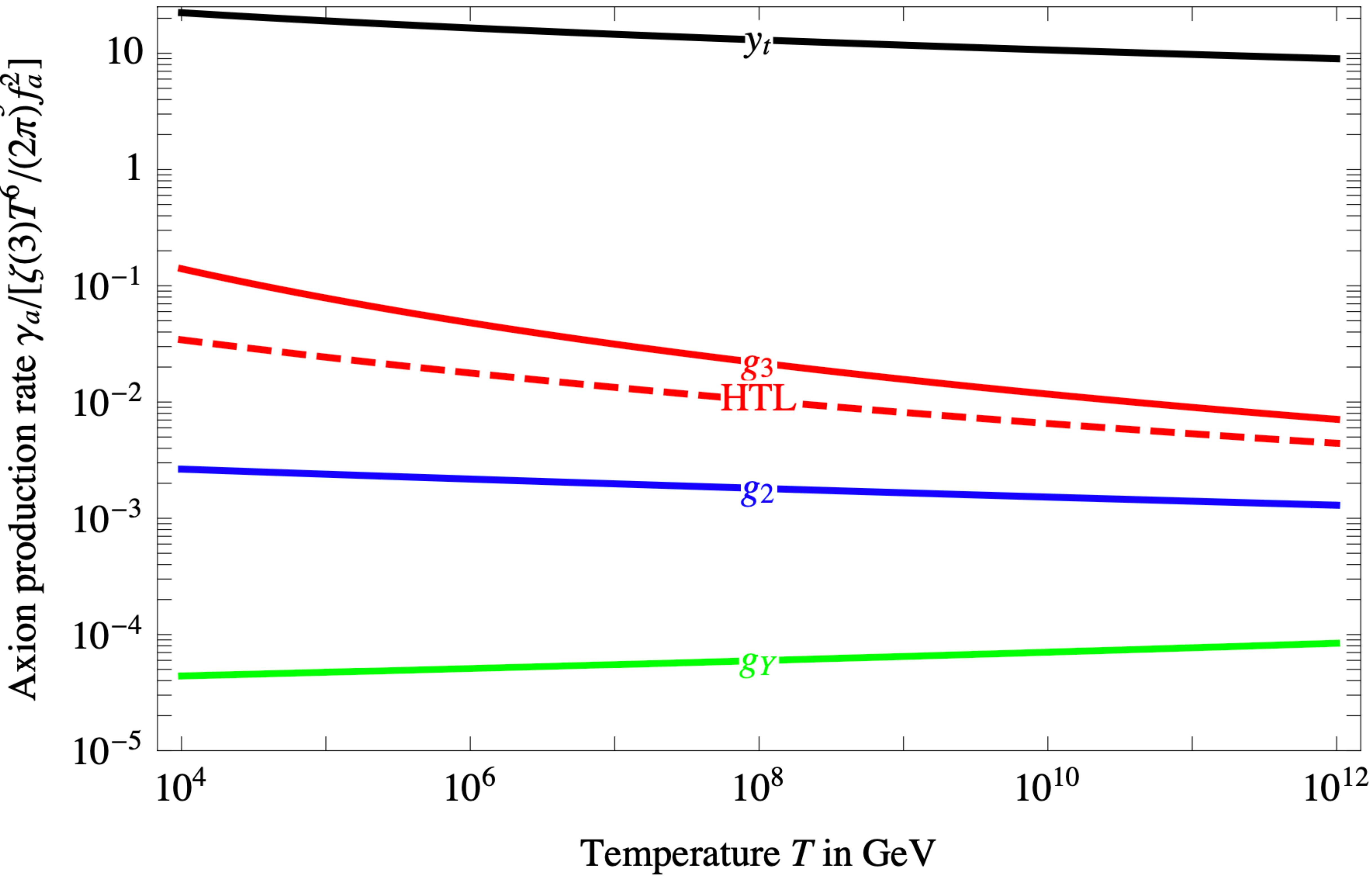
Pion scattering

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

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

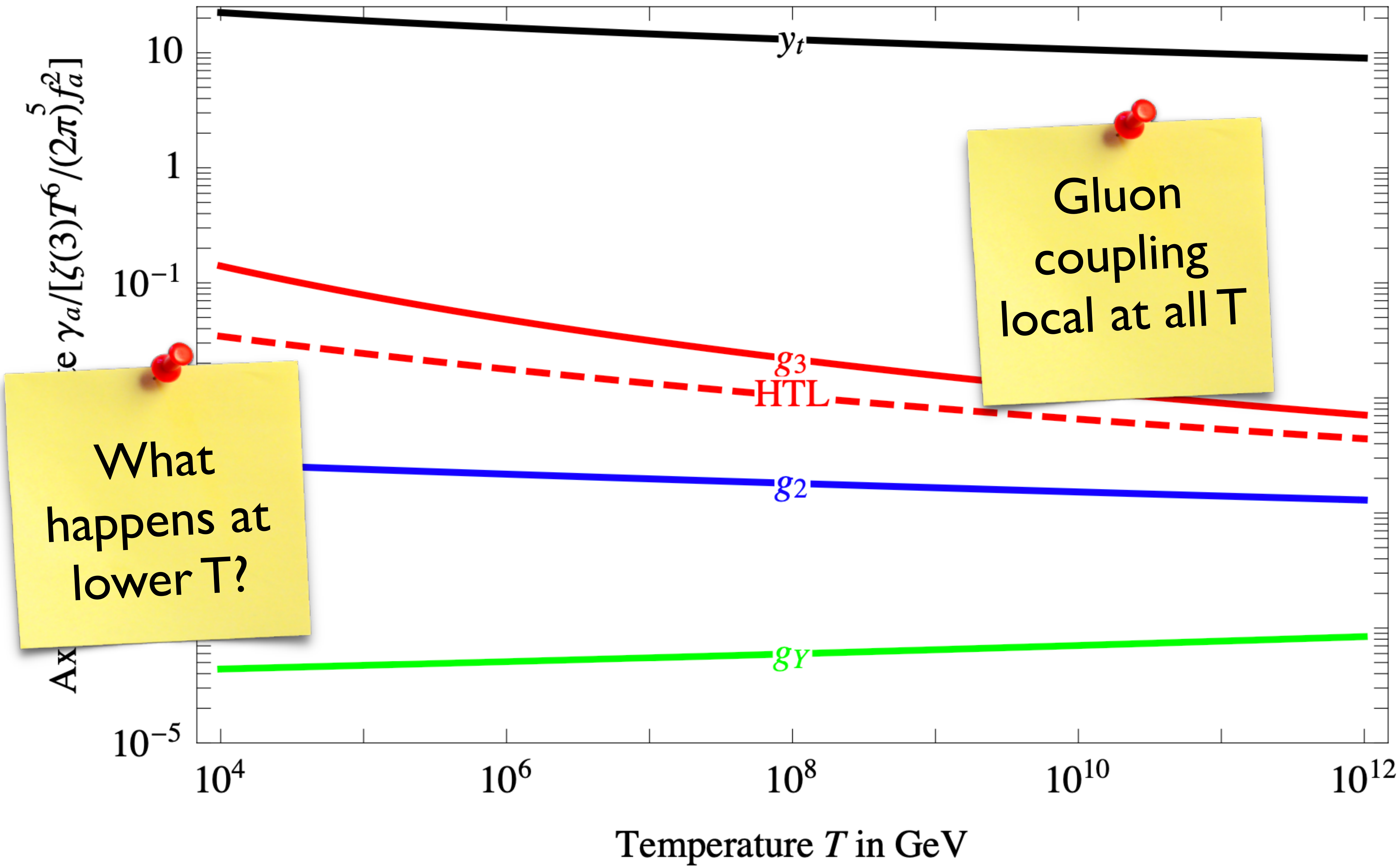
Recent studies:
Di Luzio, Martinelli, Piazza, Phys.Rev.Lett. 126 (2021)
Notari, Rompineve, Villadoro, Phys.Rev.Lett. 131 (2023)
Di Luzio, Camalich, Martinelli, Piazza, Phys.Rev.D 108 (2023)

Thermal Gluon Scattering



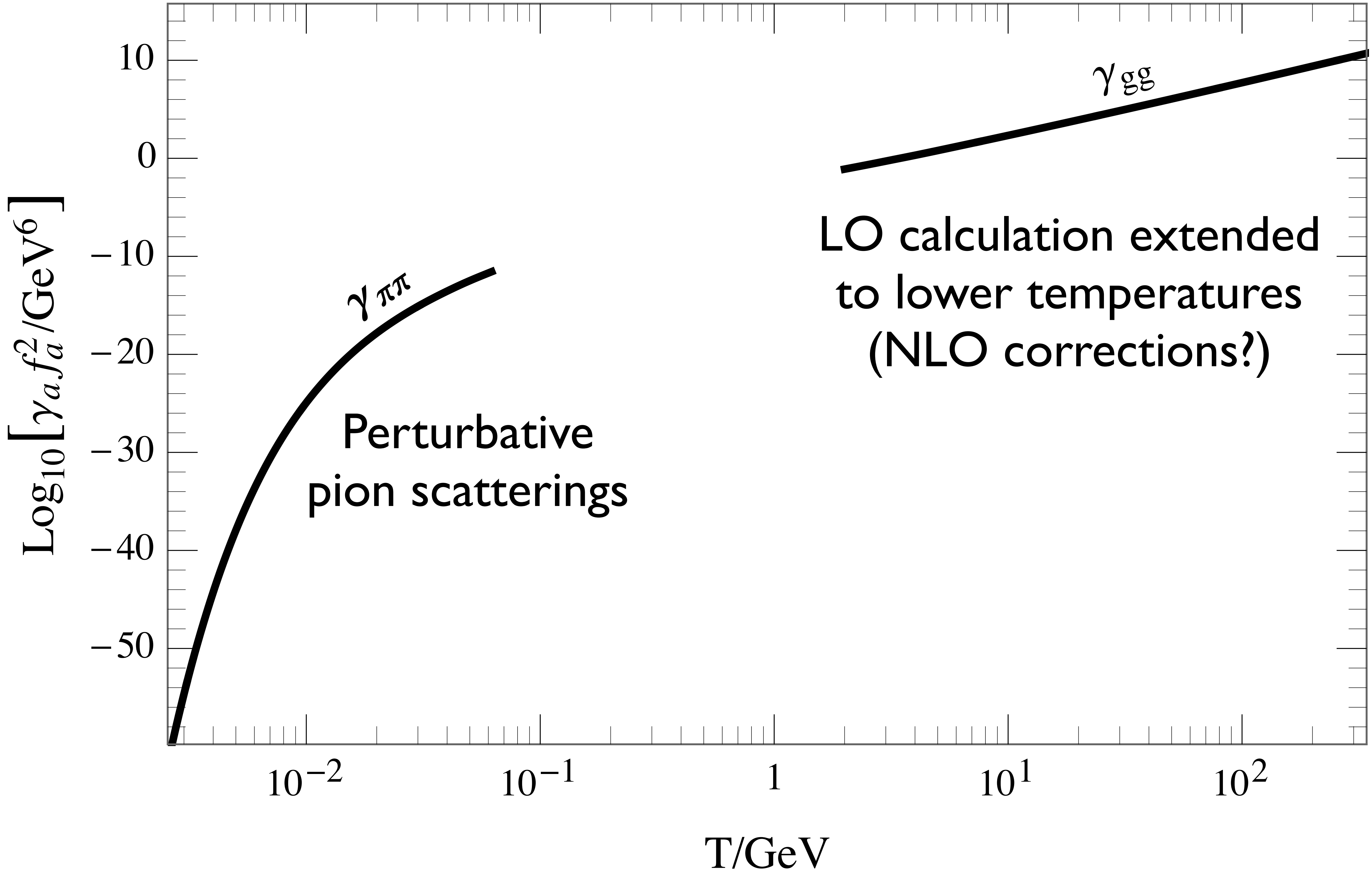
Salvio, Strumia, Xue, JCAP 01 (2014)
See also: Rychkov, Strumia, Phys.Rev.D 75 (2007)

Thermal Gluon Scattering



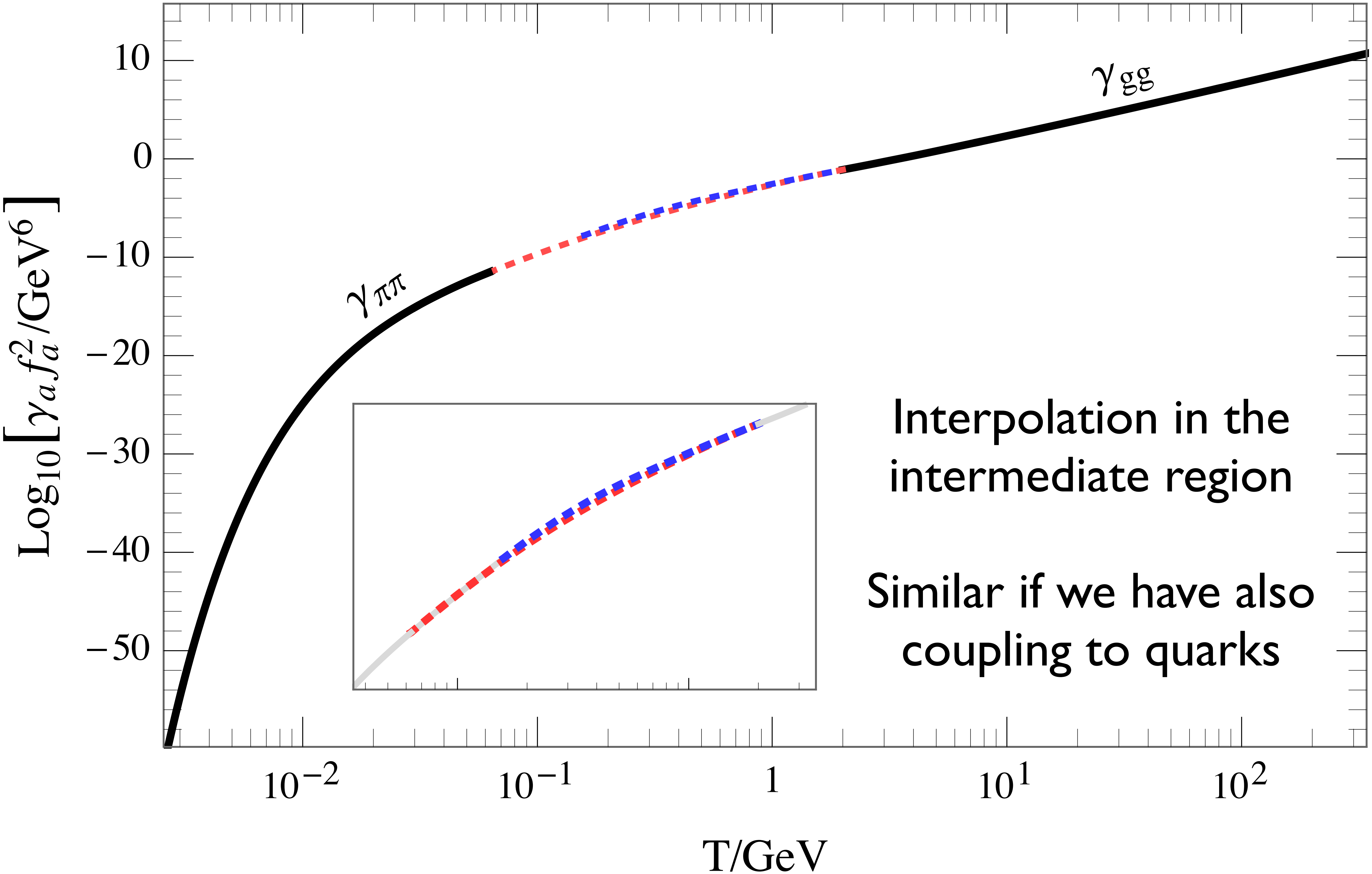
Salvio, Strumia, Xue, JCAP 01 (2014)
See also: Rychkov, Strumia, Phys.Rev.D 75 (2007)

Approaching the QCDPT



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

Approaching the QCDPT

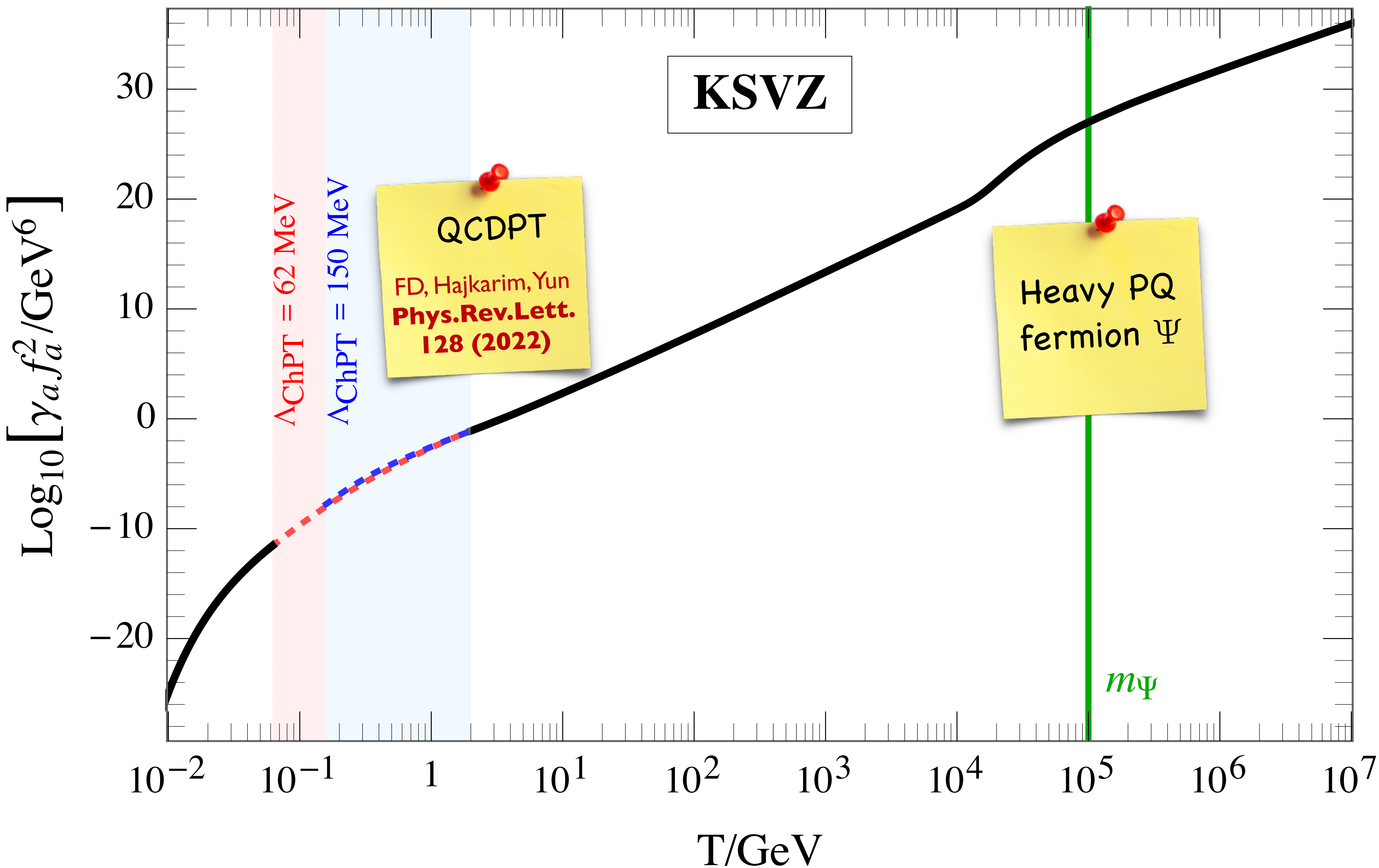


Interpolation in the intermediate region

Similar if we have also coupling to quarks

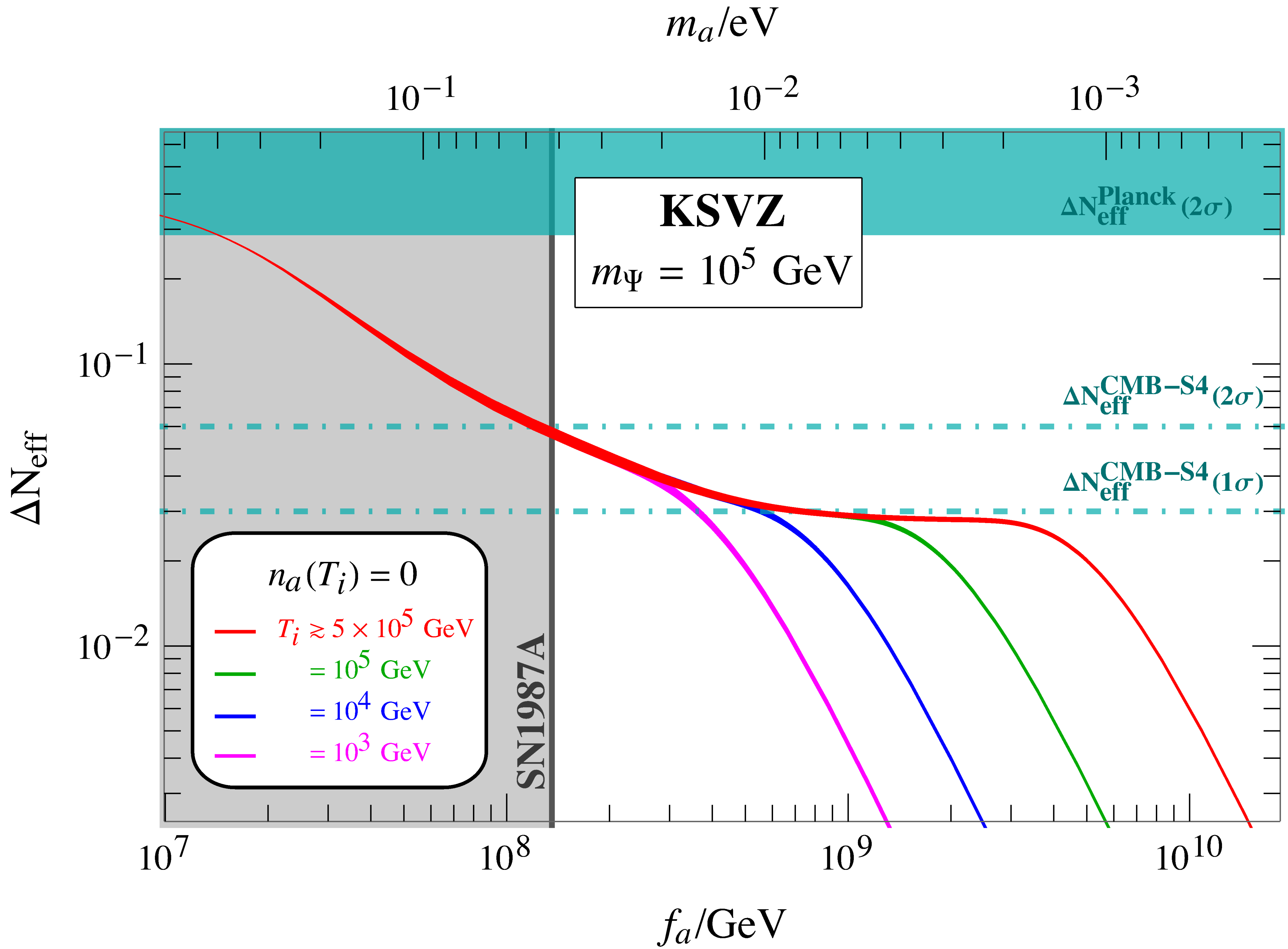
FD, Hajkarim, Yun, **Phys.Rev.Lett. 128 (2022)**

KSVZ Axion — Production Rate



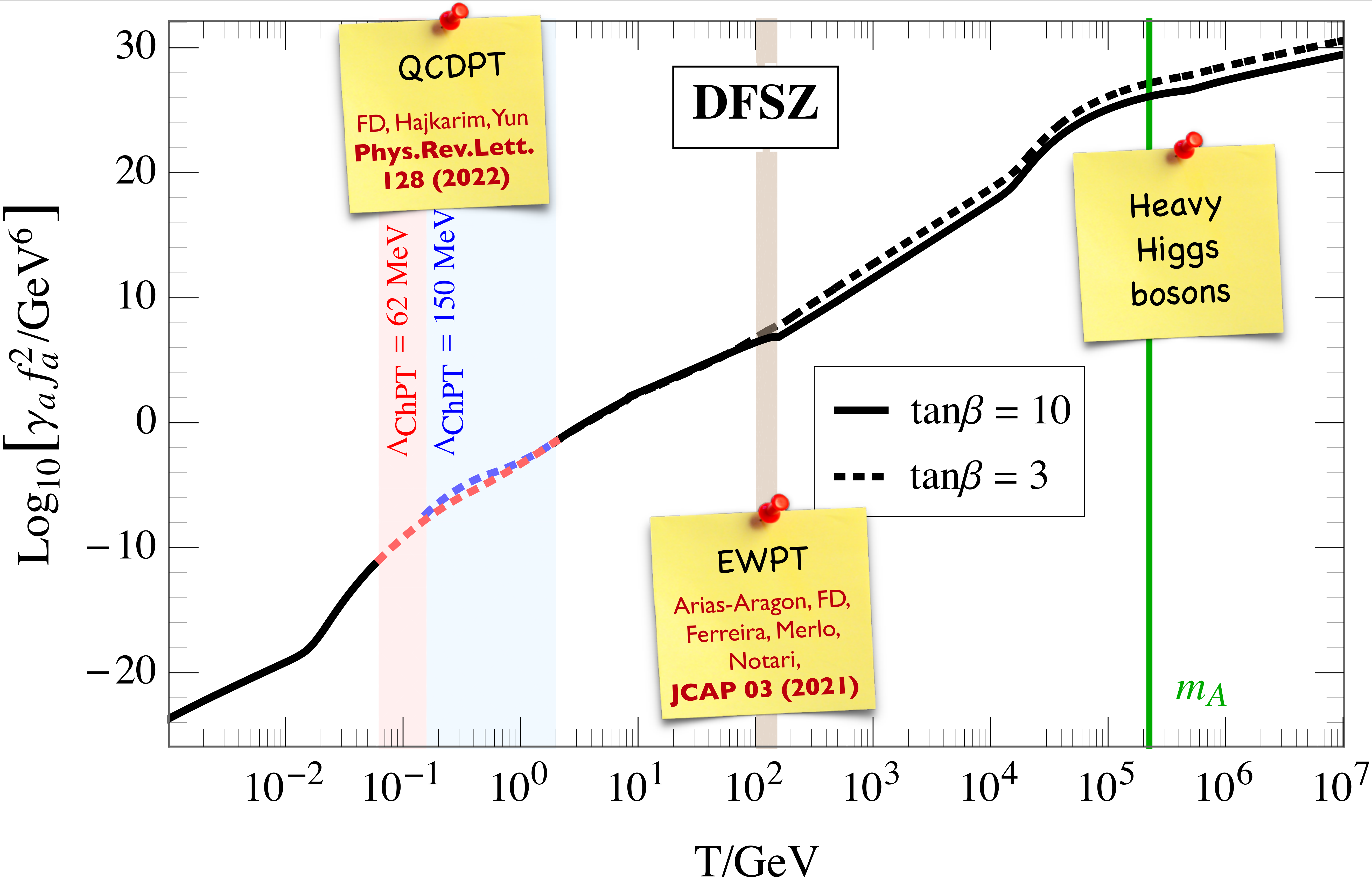
FD, Hajkarim, Yun, **JHEP 10 (2021)**

KSVZ Axion — ΔN_{eff}



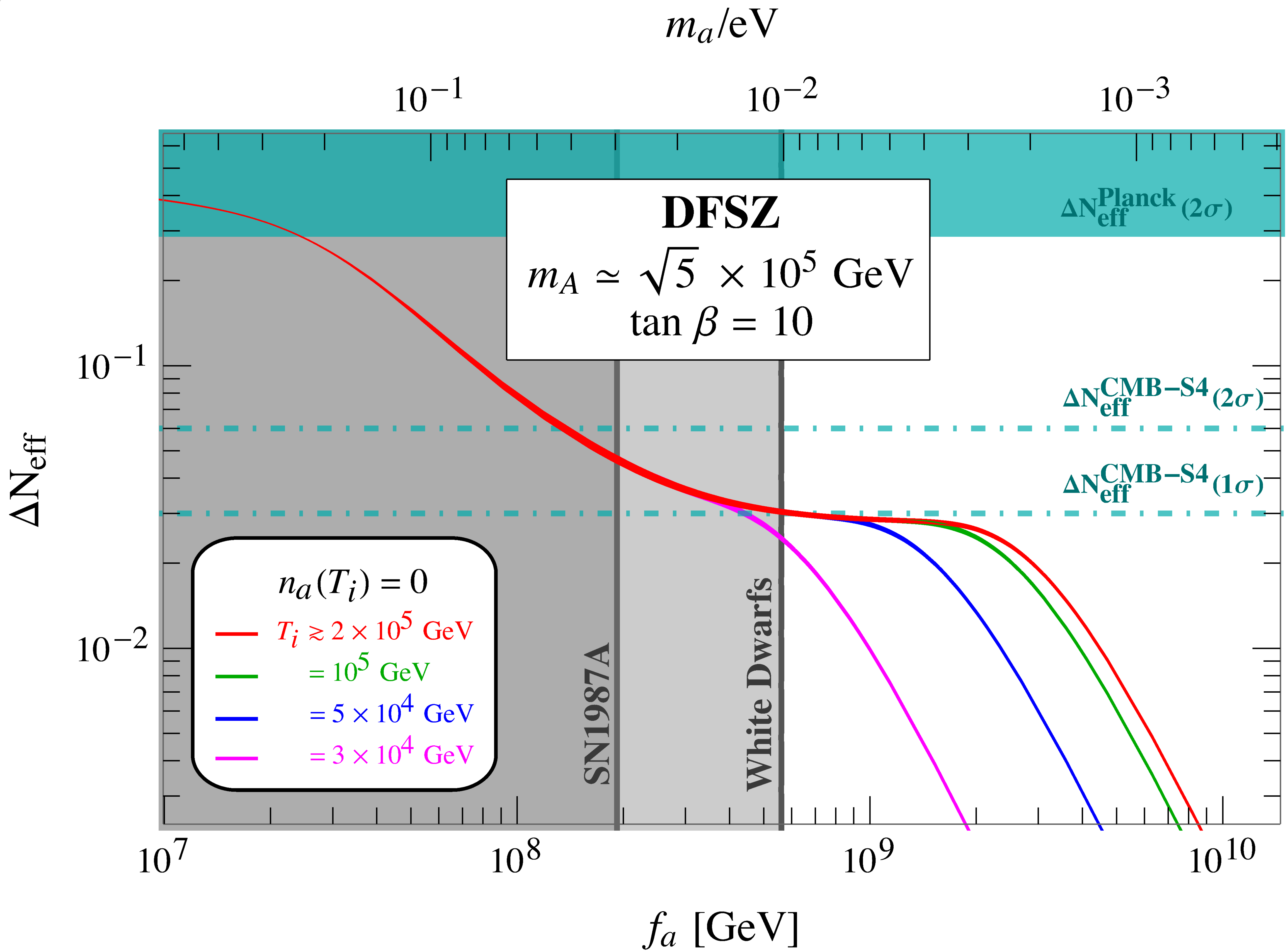
FD, Hajkarim, Yun, **JHEP 10 (2021)**

DFSZ Axion — Production Rate



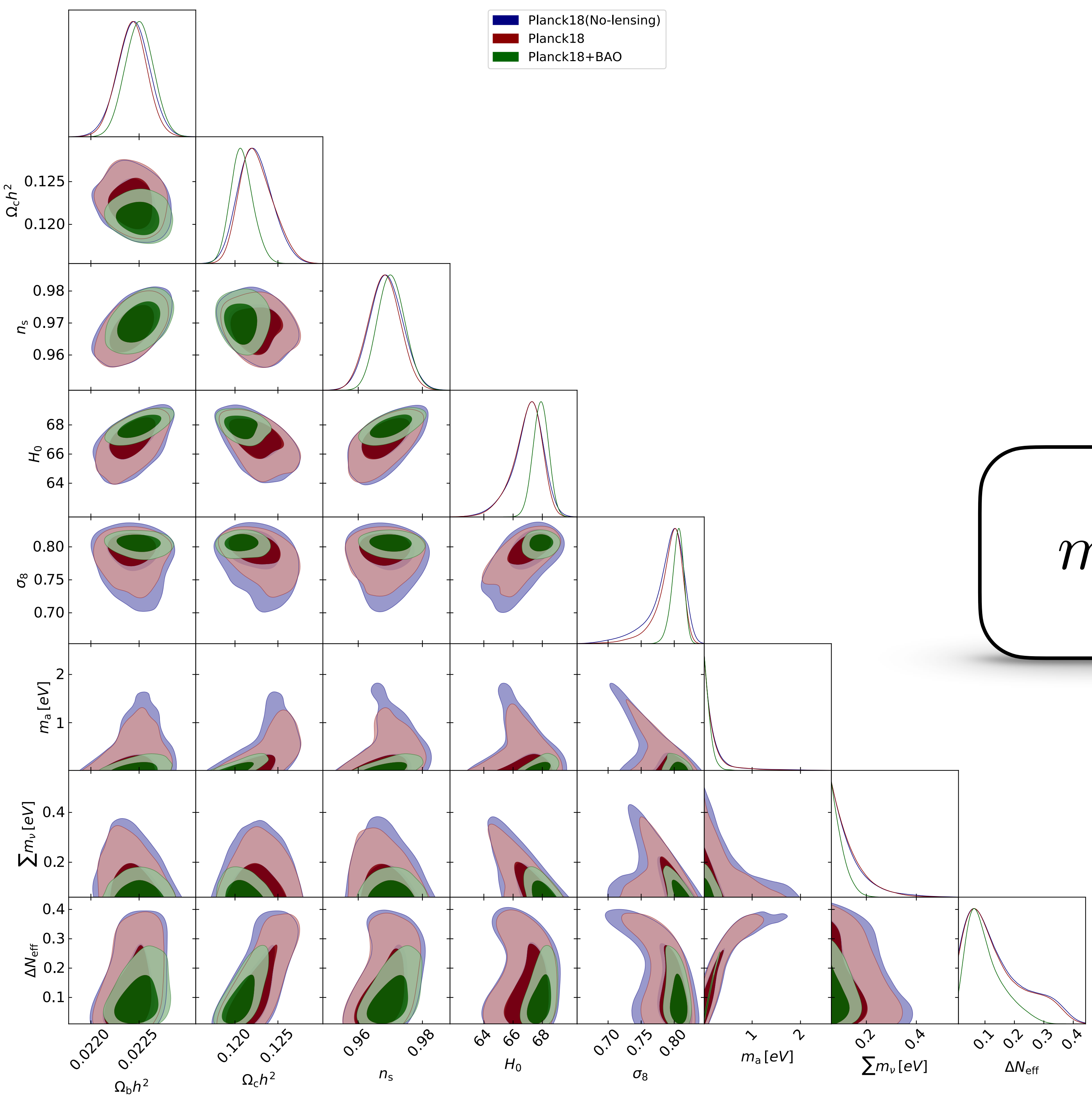
FD, Hajkarim, Yun, **JHEP 10 (2021)**

DFSZ Axion — ΔN_{eff}



FD, Hajkarim, Yun, **JHEP 10 (2021)**

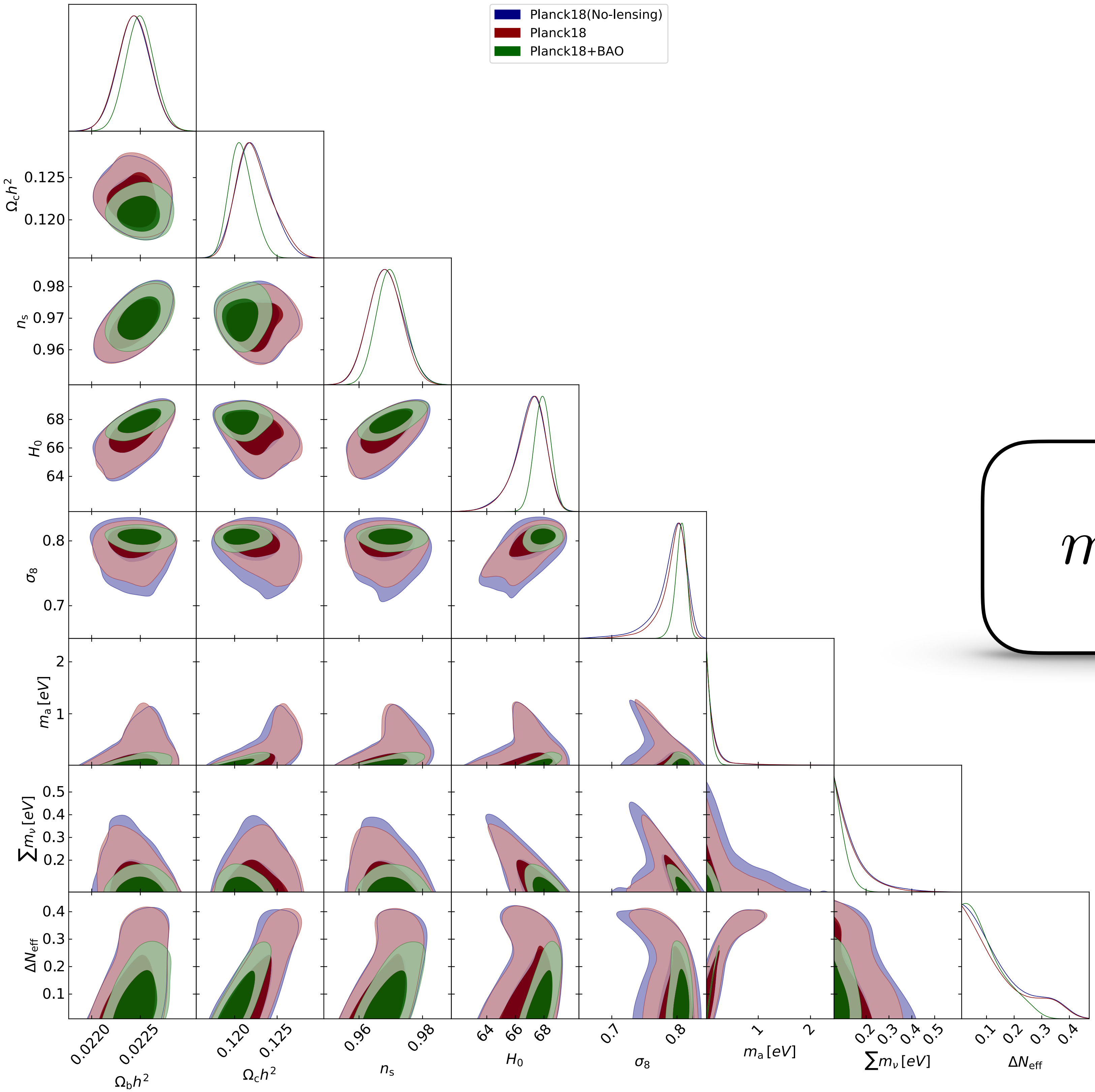
KSVZ Axion Mass Bound



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

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

DFSZ Axion Mass Bound

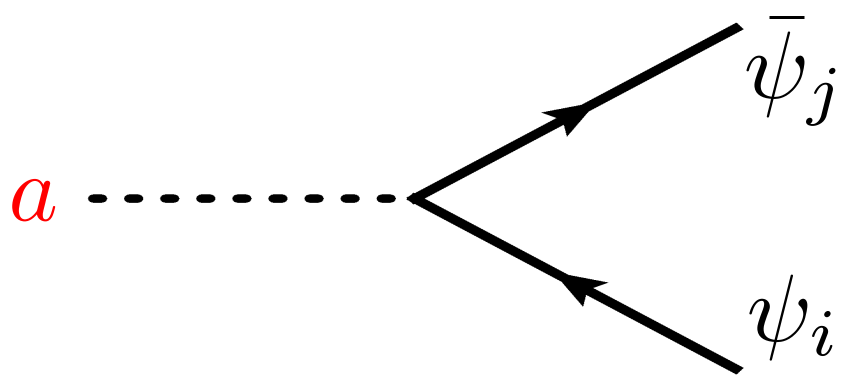


$$m_a \leq 0.209(0.293)\,\mathrm{eV}$$

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

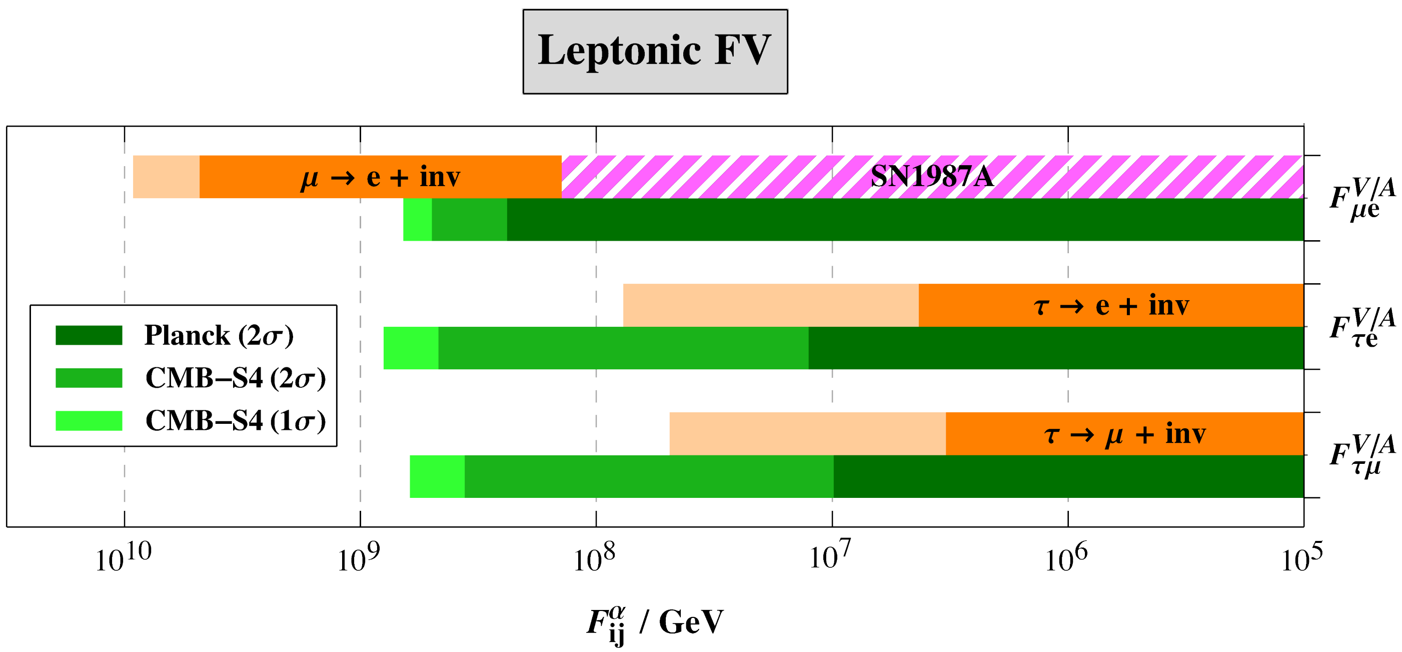
Camalich et al., Phys.Rev.D 102 (2020)
Calibbi et al., JHEP 09 (2021)

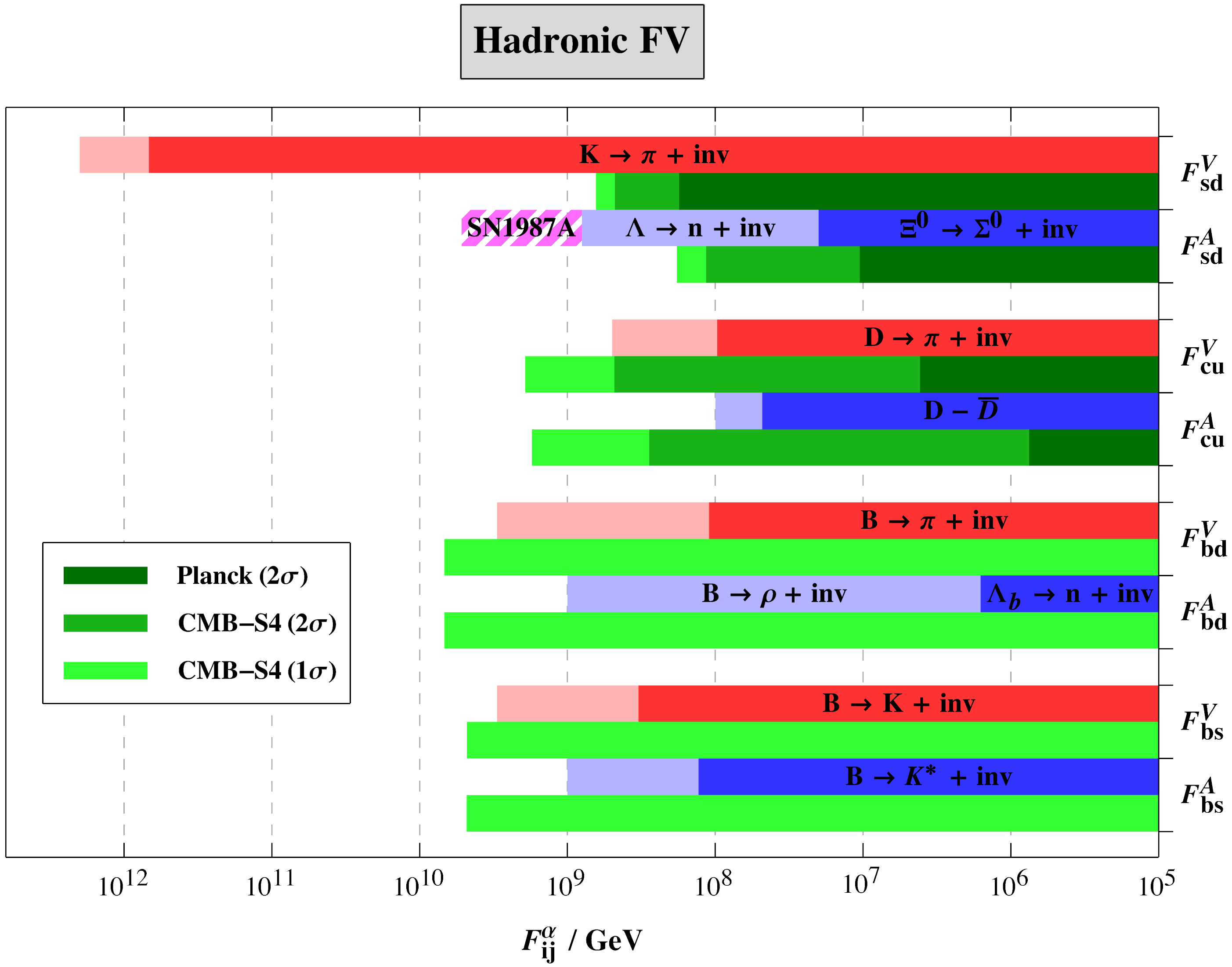
What about their role in the early universe?

They mediate hot axion production!

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

A Minor Variation: FV Axions

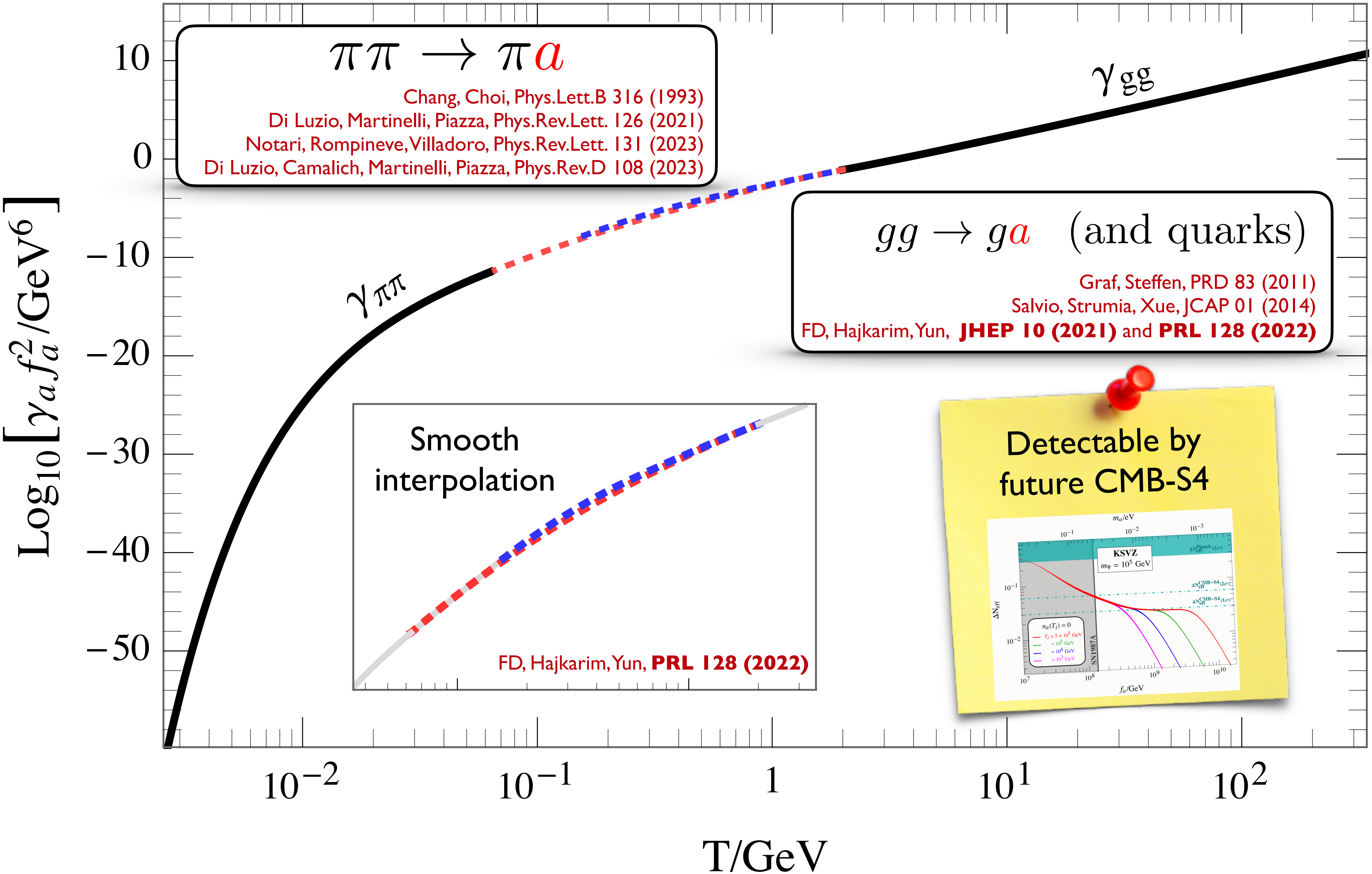




$$F^{\alpha}_{\psi_i\psi_j} \equiv \frac{2 f_a}{c^{\alpha}_{\psi_i\psi_j}}$$

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?

Back to the Phase-Space

Model-independent analysis:
generic thermal bath production of a single dark radiation particle X

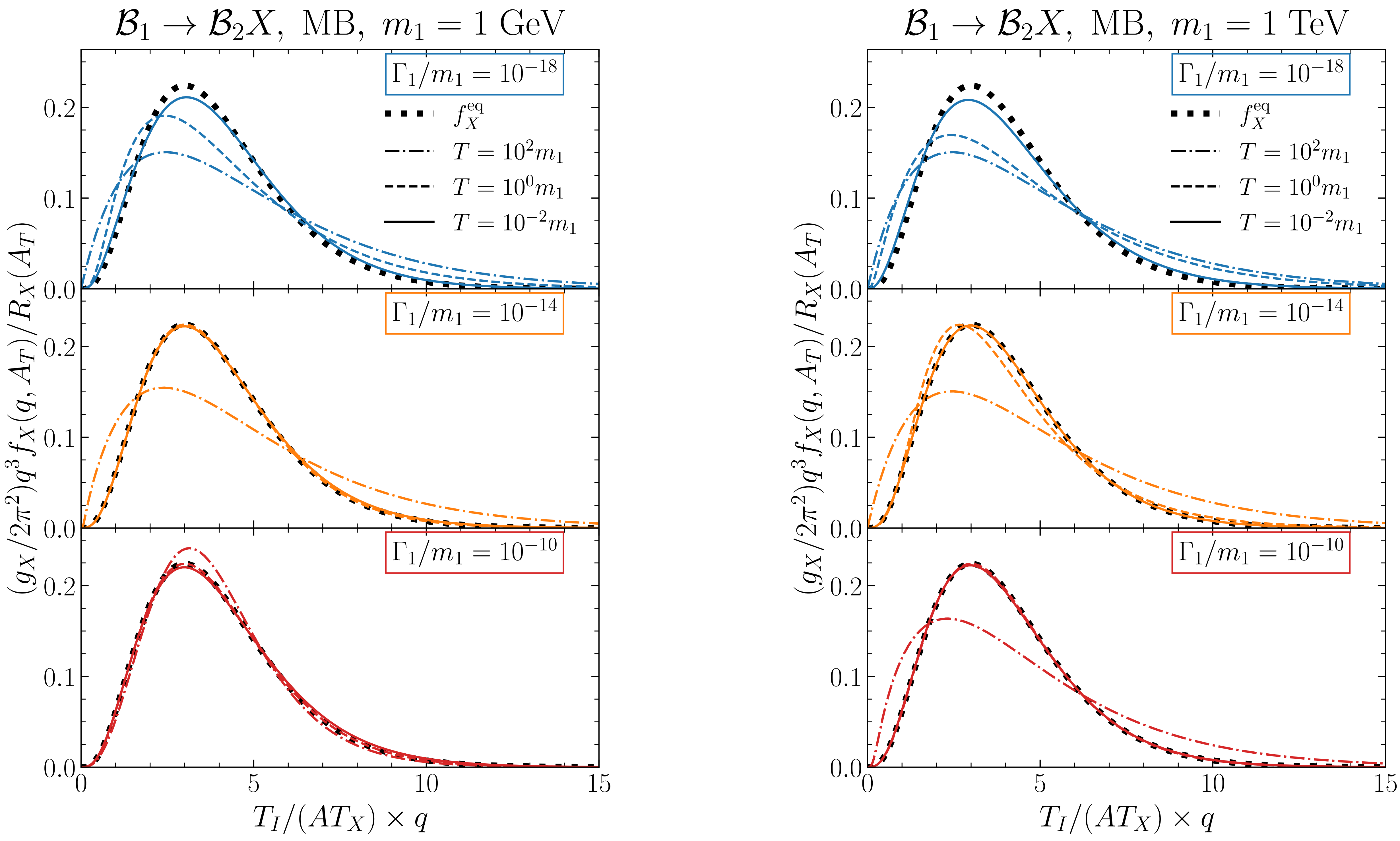
$$\mathcal{B}_1 \dots \mathcal{B}_n \; \rightarrow \; \mathcal{B}_{n+1} \dots \mathcal{B}_m \, X$$

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

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

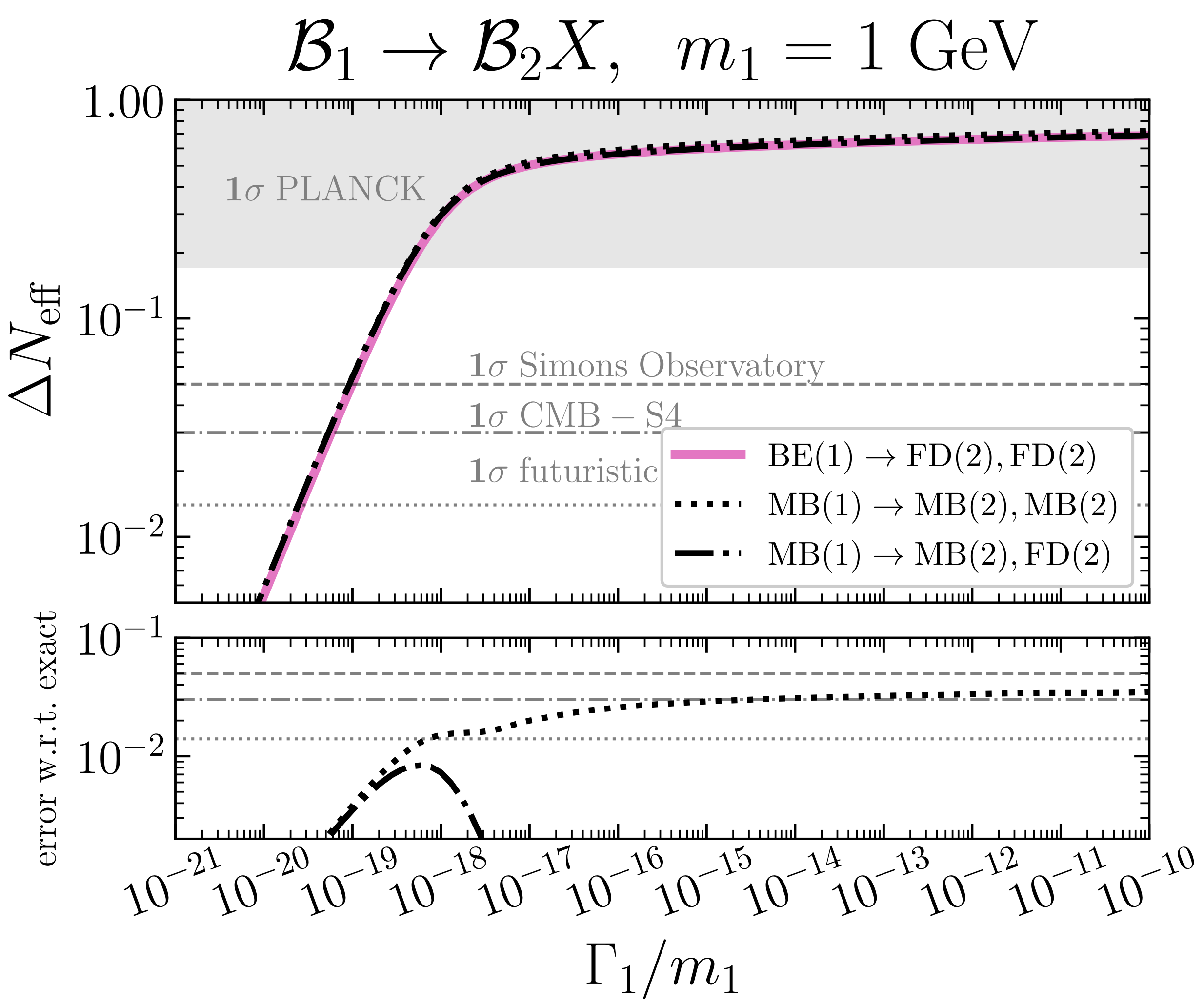
FD, Hajkarim, Lenoci, **JCAP 03 (2024)**

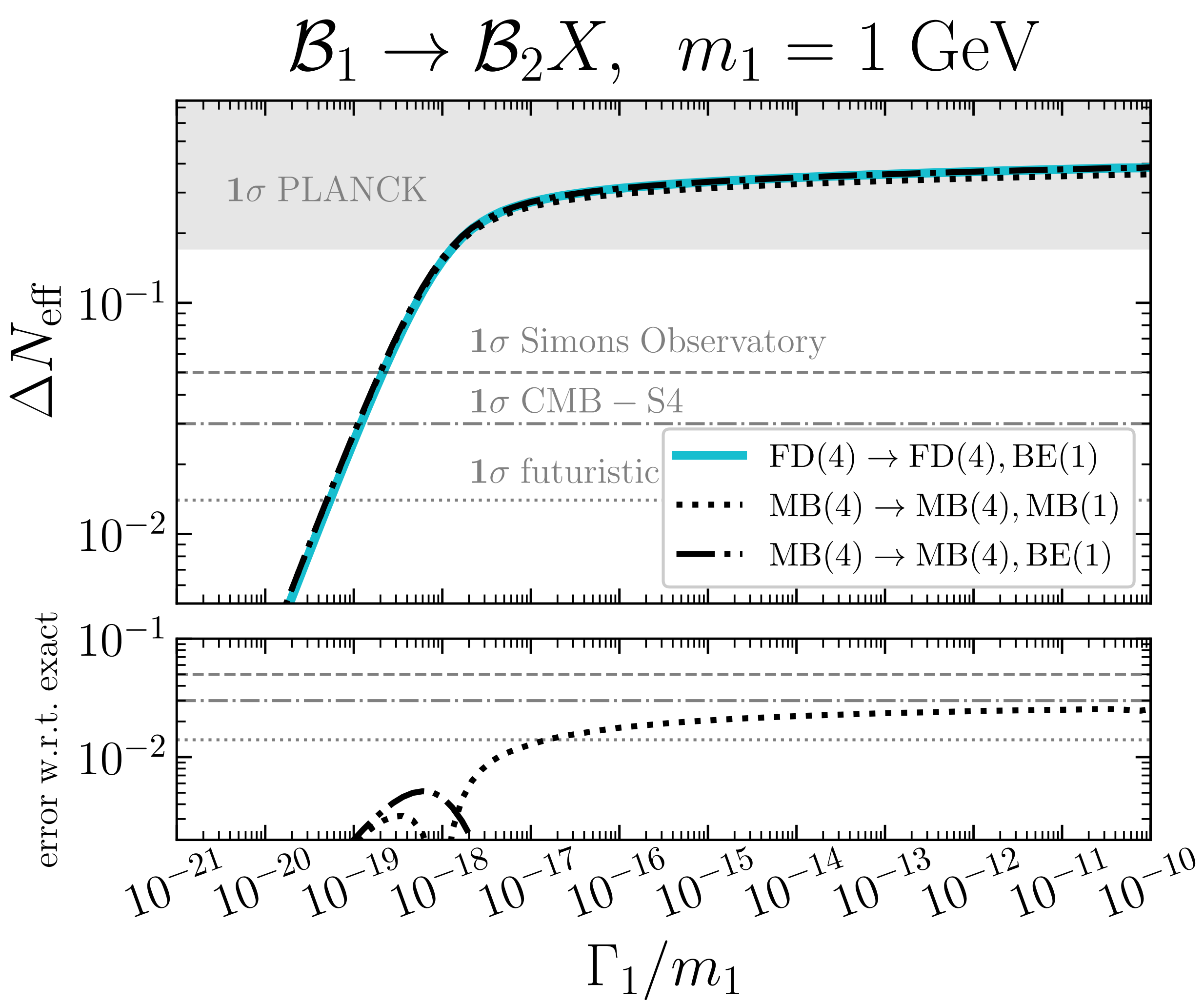
Phase Space Distributions



FD, Hajkarim, Lenoci, **JCAP 03 (2024)**

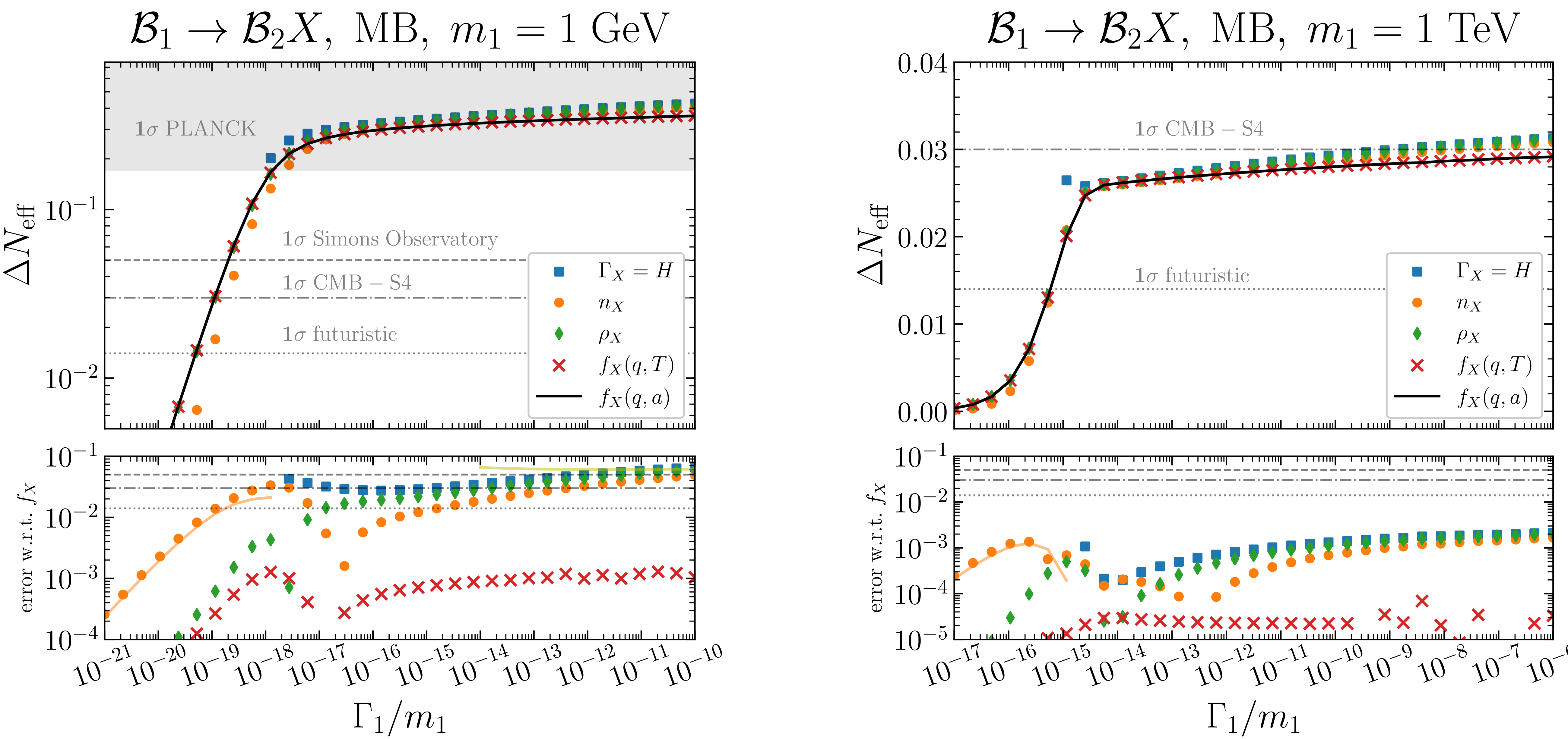
Quantum Statistical Effects





FD, Hajkarim, Lenoci, **JCAP 03 (2024)**

Error in predicting $\Delta N_{\rm eff}$

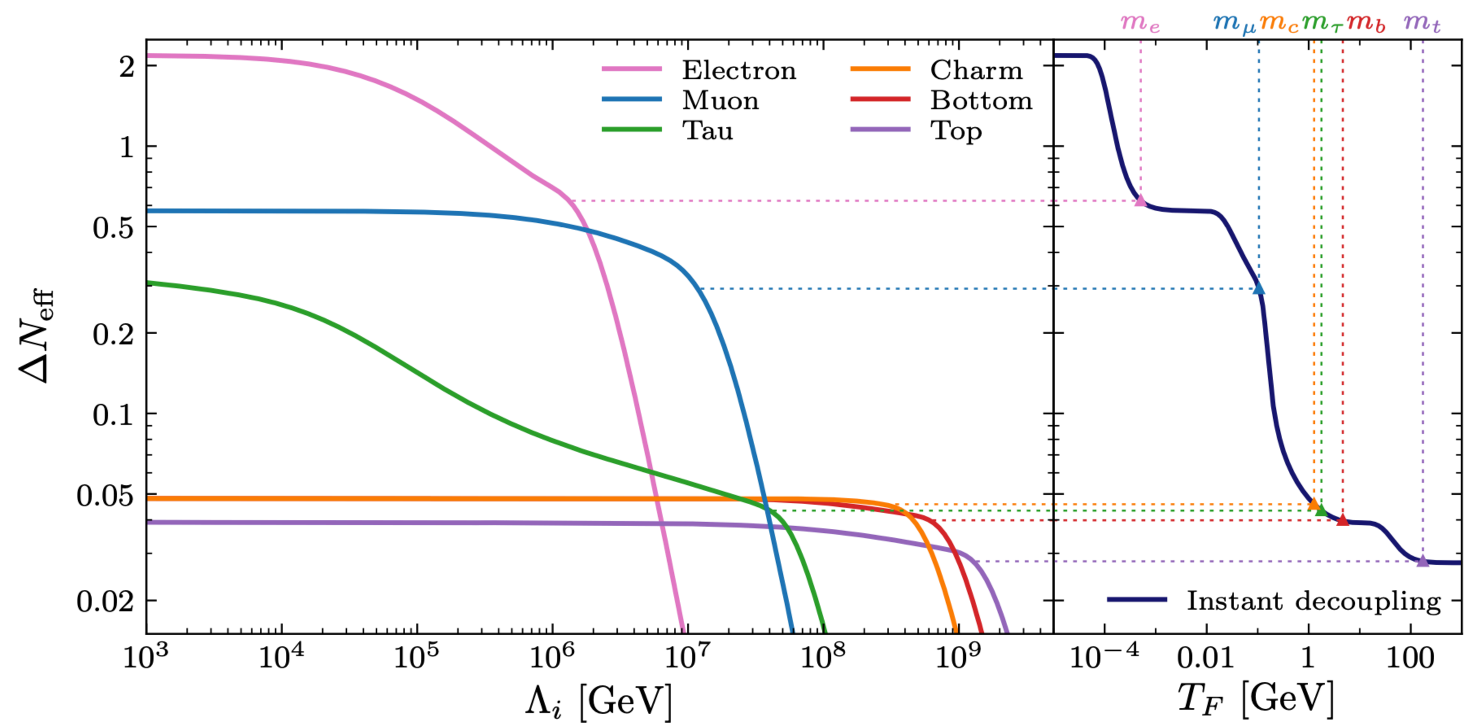


FD, Hajkarim, Lenoci, **JCAP 03 (2024)**

Axion-Fermion Interactions

$$\mathcal{L}_{\rm int} = \frac{\partial_\mu a}{2 f_a} \sum_\psi c_\psi \overline{\psi} \gamma^\mu \gamma_5 \psi$$

Baumann et al, Phys.Rev.Lett. 117 (2016)
Ferreira, Notari, Phys.Rev.Lett. 120 (2018)
FD et al, **JCAP 11 (2018)**
Arias-Aragón et al., **JCAP 11 (2020)**
and **JCAP 03 (2021)**



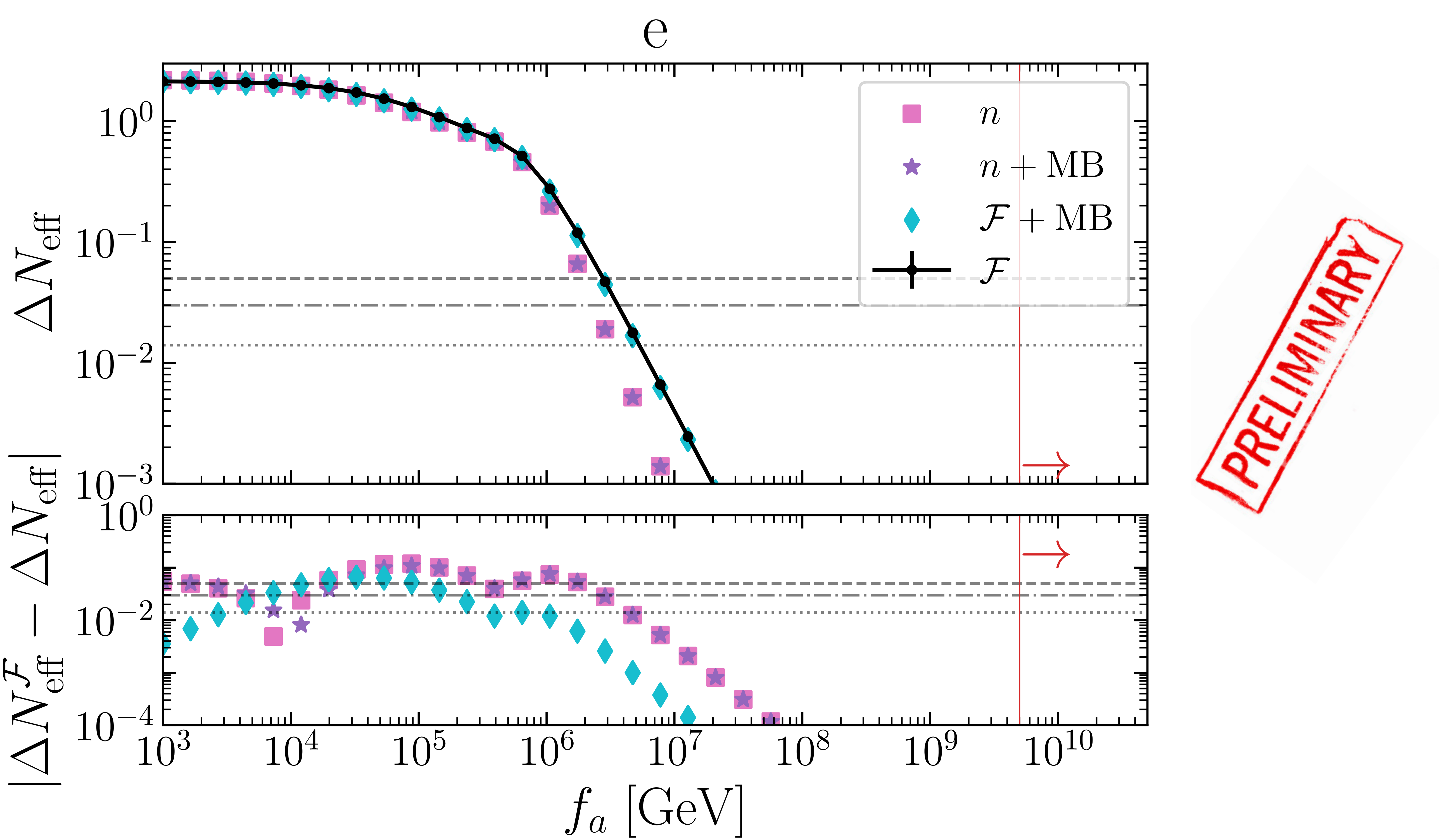
Green at al., JCAP 02 (2022)

<u>Related work:</u>

KSVZ axion mass bound in the phase space (<u>pion scattering only</u>)

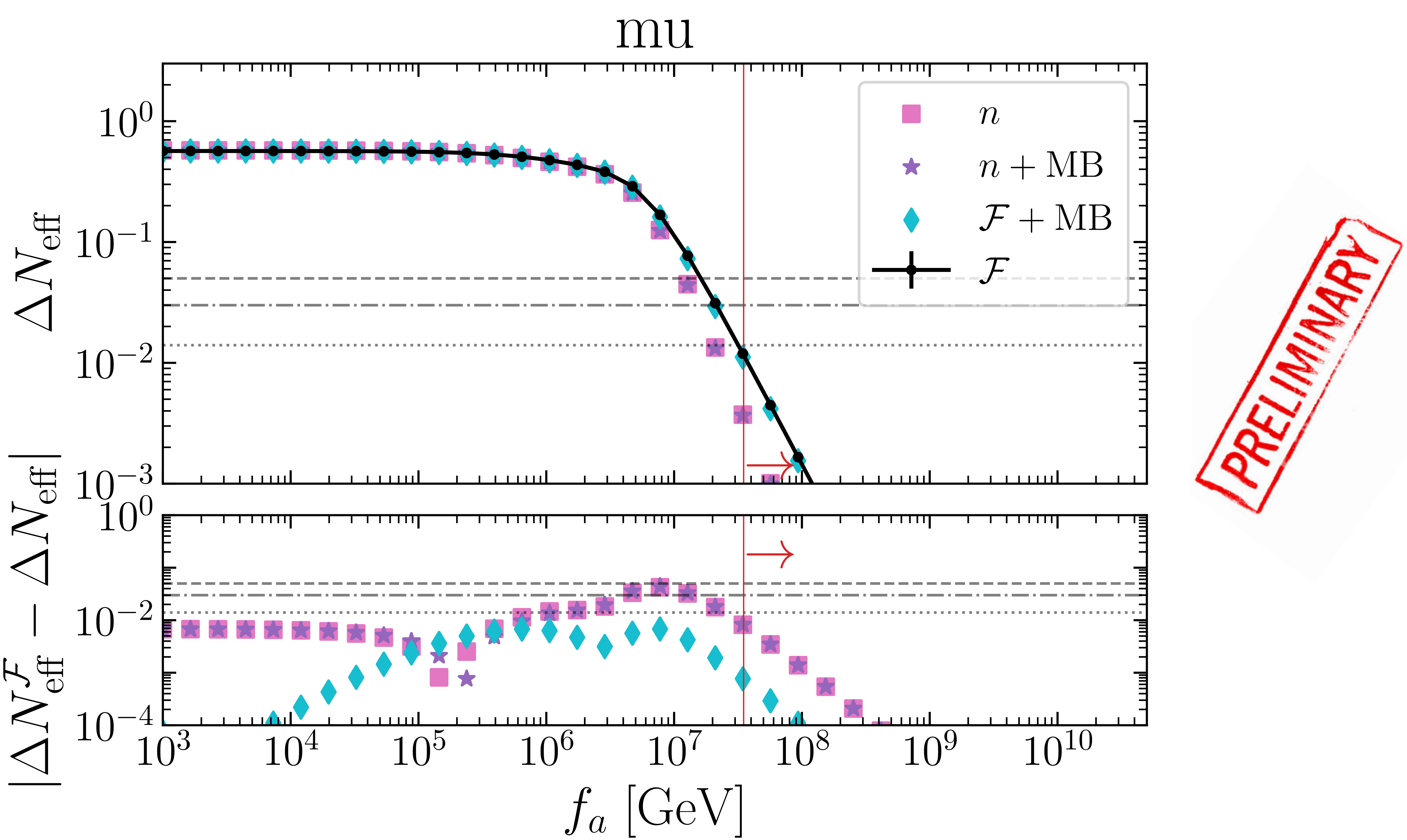
Notari, Rompineve, Villadoro, Phys.Rev.Lett. 131 (2023)
Bianchini, Grilli di Cortona, Valli, 2310.08169 [hep-ph]

Axion-Fermion Interactions



FD, Lenoci, **in preparation**

Axion-Fermion Interactions



FD, Lenoci, **in preparation**

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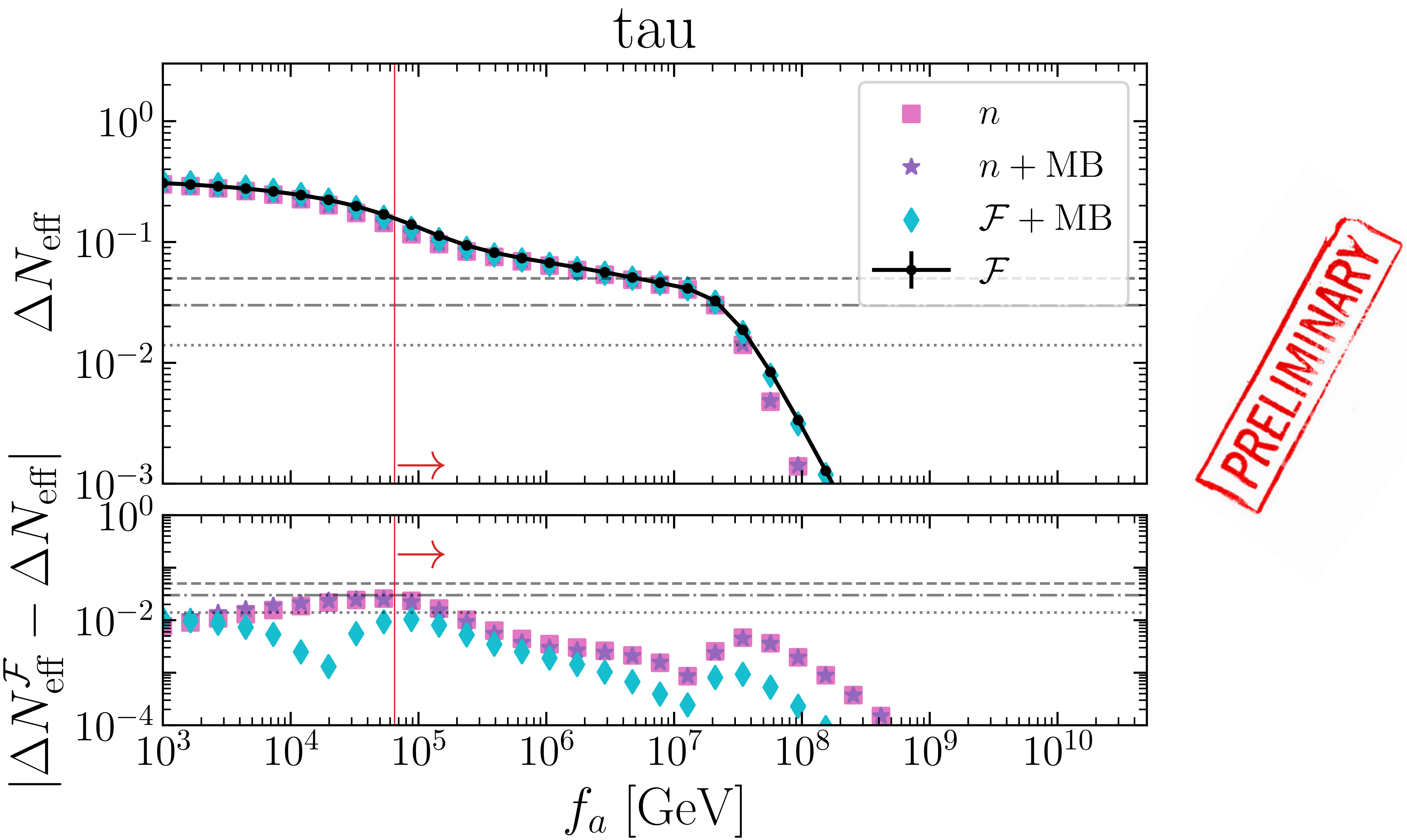
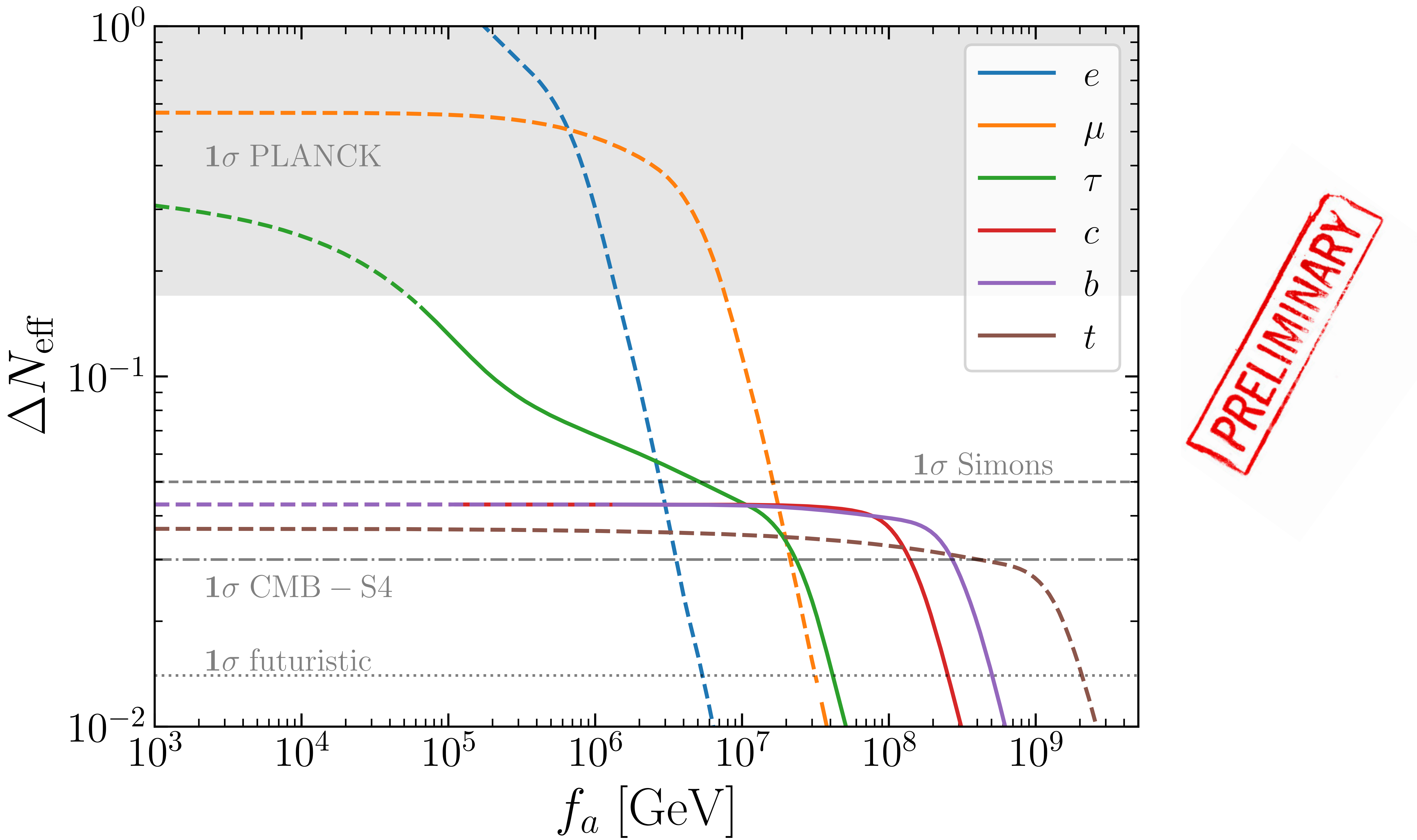


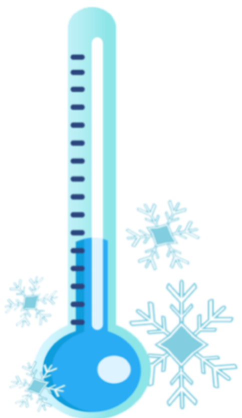
FD, Lenoci, **in preparation**

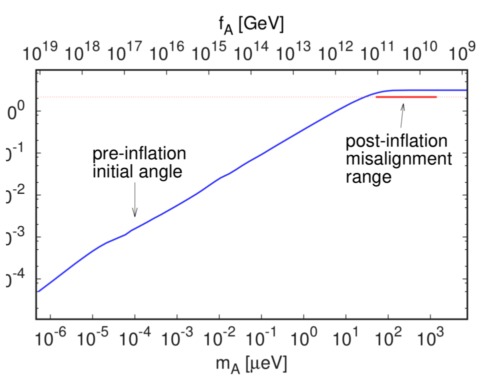
Axion-Fermion Interactions



FD, Lenoci, **in preparation**

Outlook





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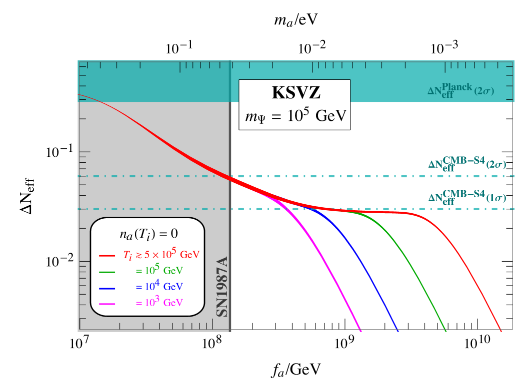
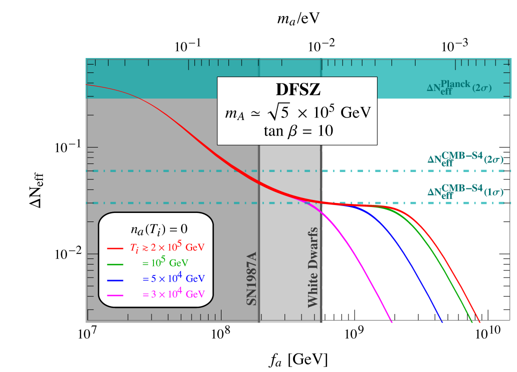
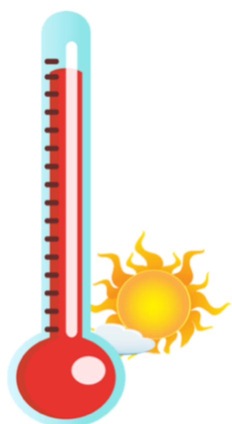
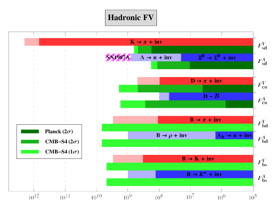
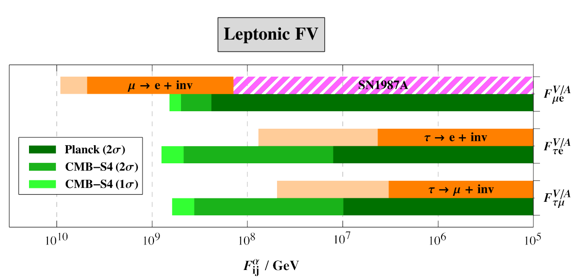
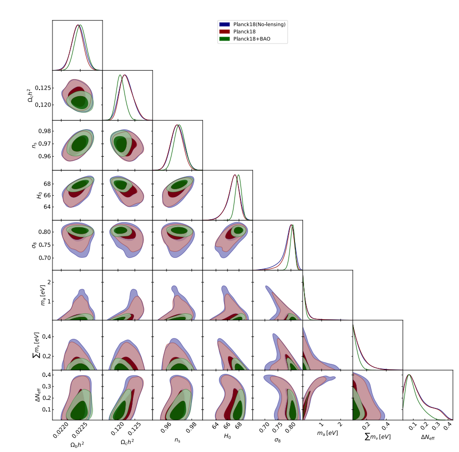


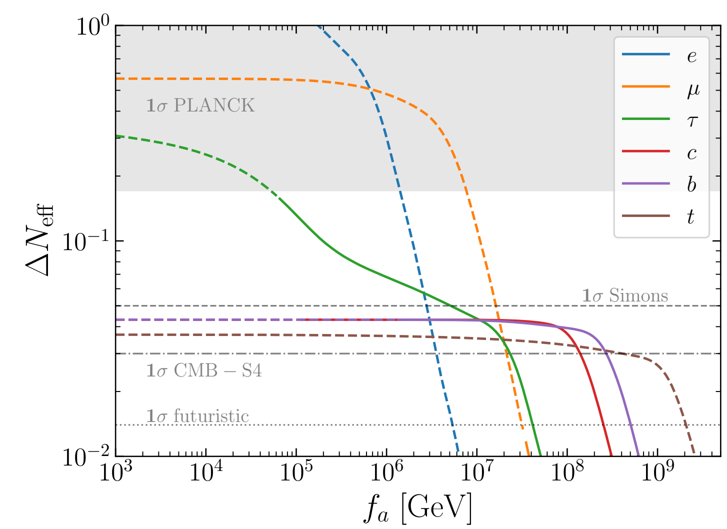








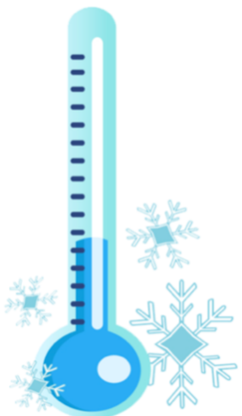


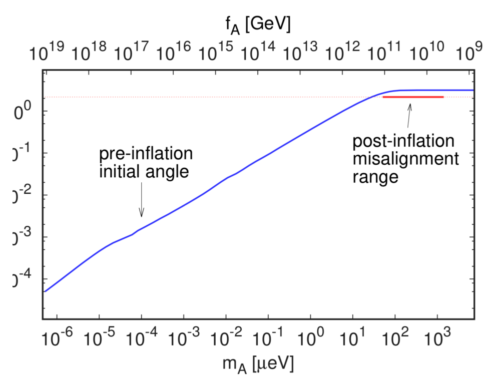


Thermal Axions

Complementary to other probes of the PQ mechanism

Outlook





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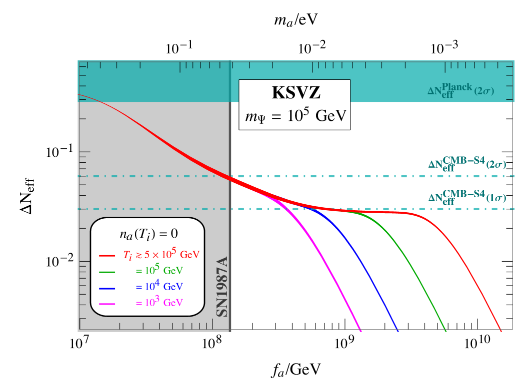

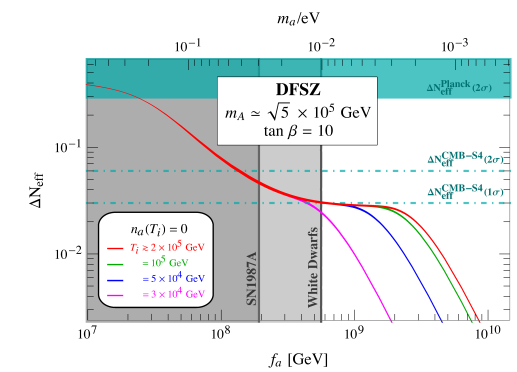

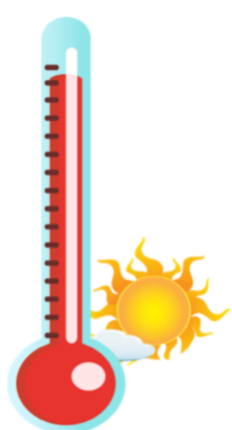

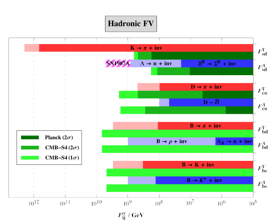

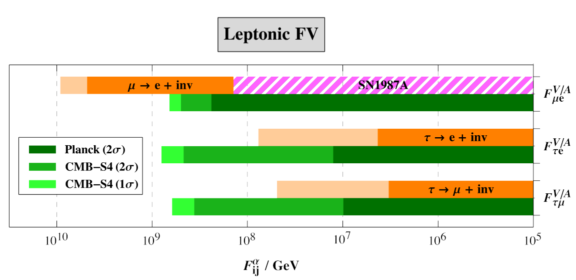

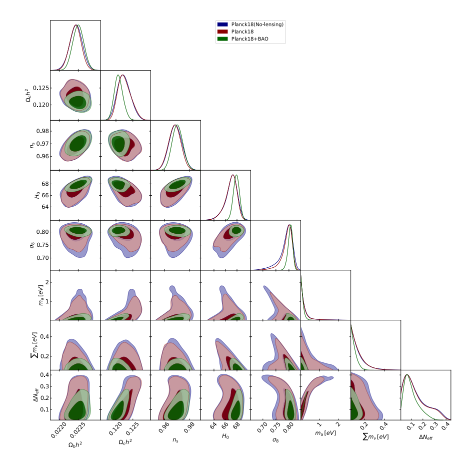

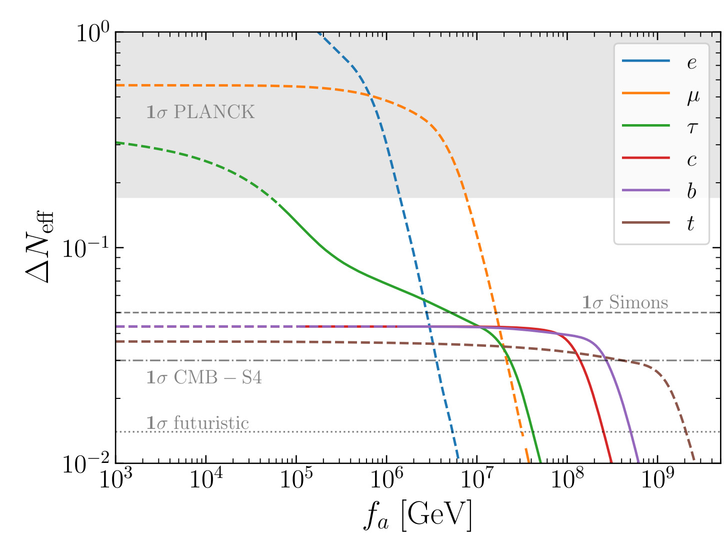

THANK YOU!