Axions in the Early Universe

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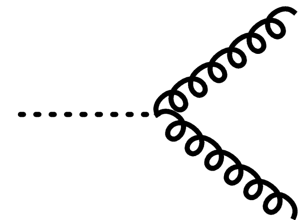
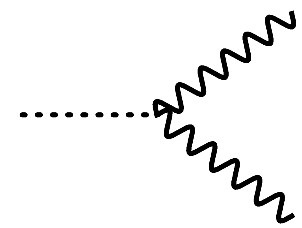
Baden-Baden — 10 November 2022

The QCD Axion

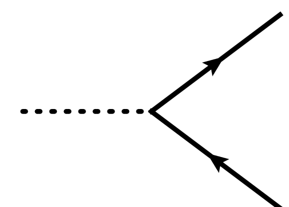
- Coupling to gluons and (not mandatory) to electroweak gauge bosons
- Derivative couplings to fermions



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



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



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

The QCD axion is <u>elusive</u>!

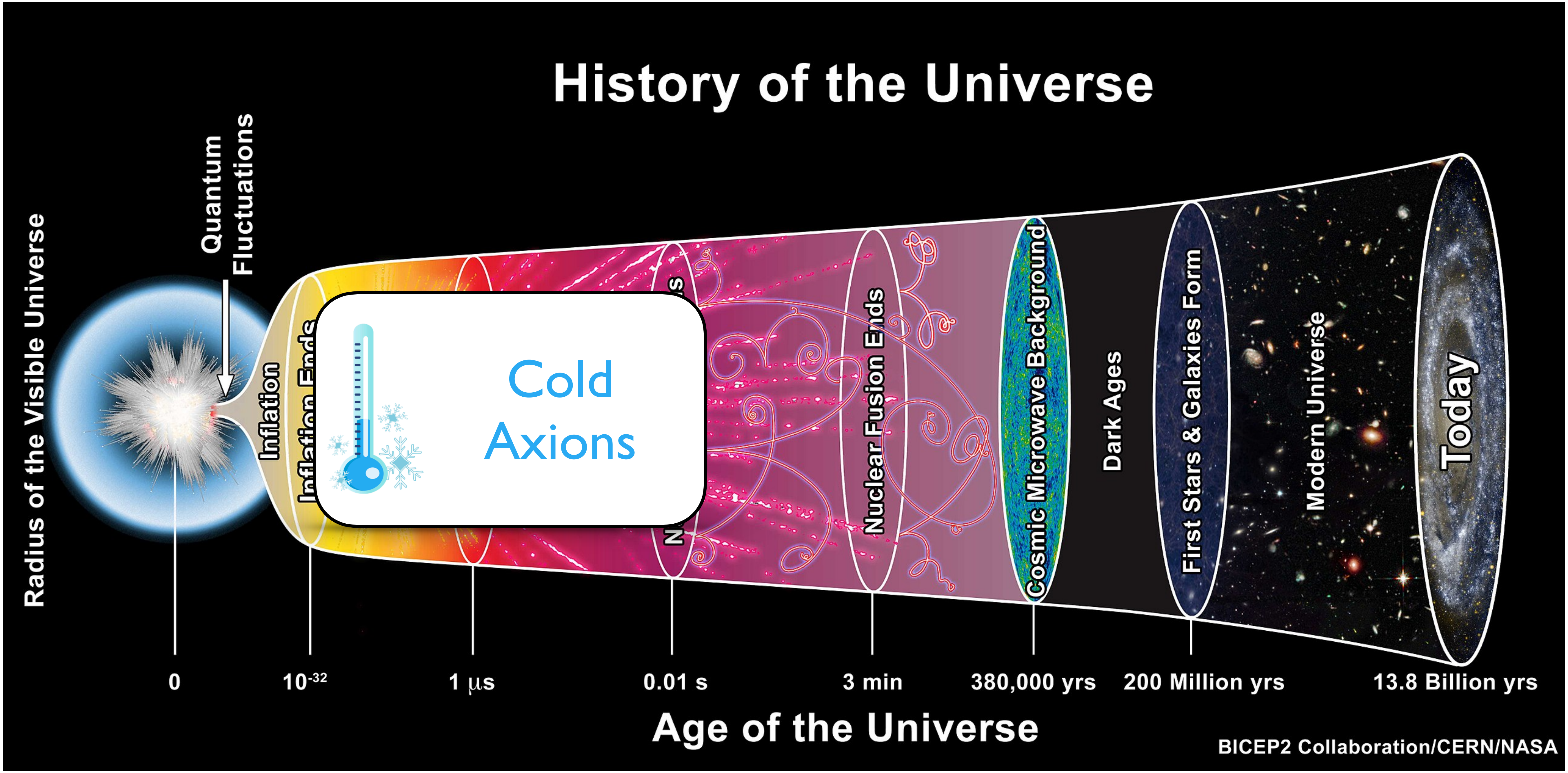
Axion (zero-temperature) mass from non-perturbative potential

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

The QCD axion is <u>very light</u>!

Georgi, Kaplan, Randall, PLB169 (1986)
Grilli di Cortona, Hardy, Vega, Villadoro, JHEP 1601 (2016)

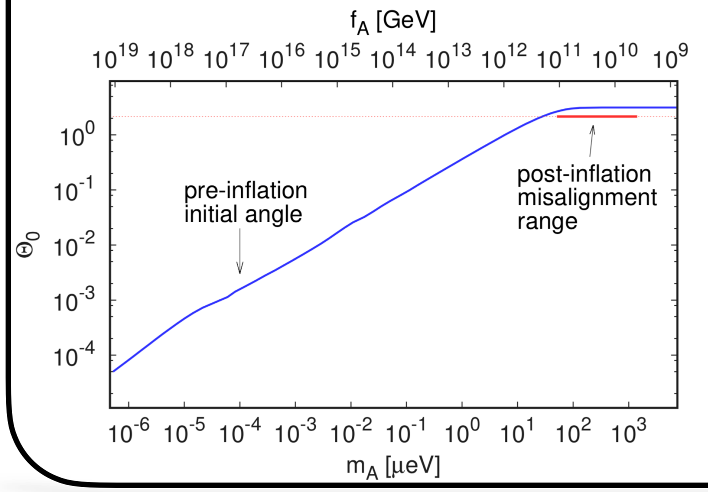
Axions in the Early Universe



QCD Axion Cold Dark Matter

Pre-Inflation

Axion cold dark matter from misalignment (initial field value?)



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

Post-Inflation

Axion cold dark matter from strings

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

Gorghetto, Hardy, Villadoro
JHEP 07 (2018) and SciPost Phys.10 (2021)

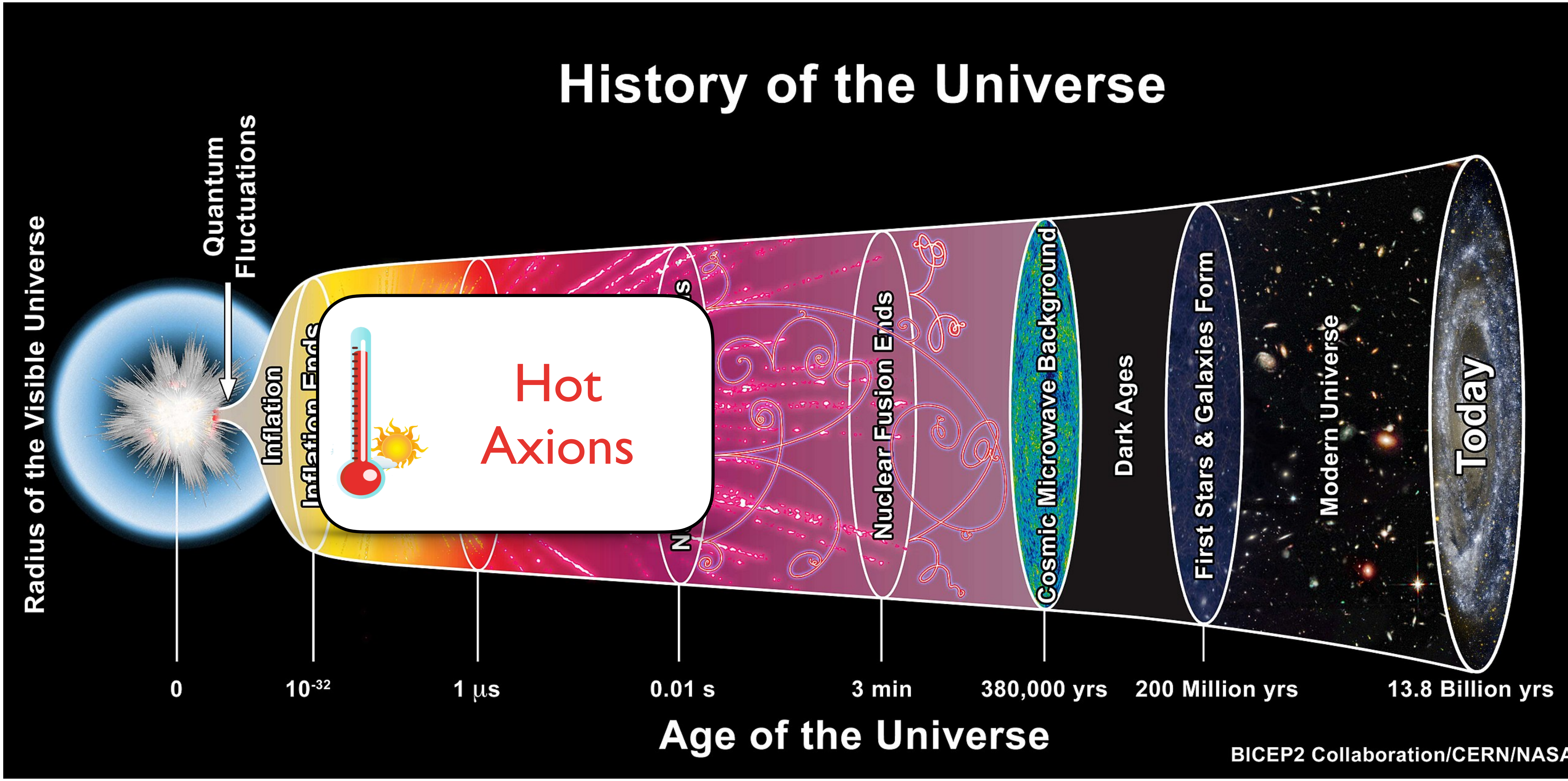
Buschmann, Foster, Safdi
PRL124 (2020) and Nature Commun. 13 (2022)

Range for f_a (<u>with caveats</u>):

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

- Larger f_a: dilute dark matter abundance or fine-tune initial field value
- Lower f_a: axion sub-dominant dark matter component

Axions in the Early Universe



<u>In this talk:</u> Hot axions in the early universe

How they are produced and their imprint in cosmological observables

Thermal Production

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

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

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

Additional radiation at:

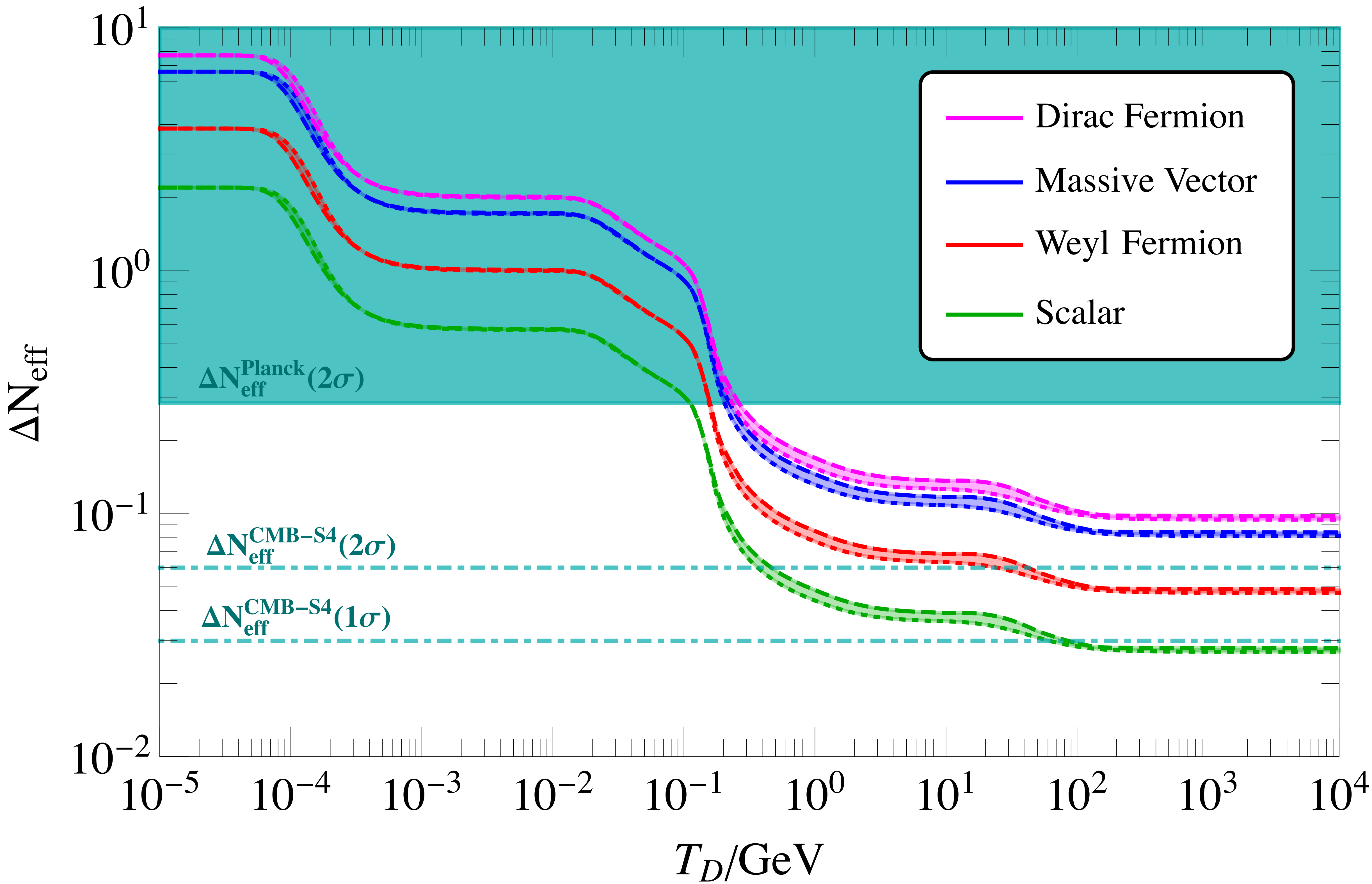
- BBN ($m_a \lesssim$ MeV)
- Recombination ($m_a \lesssim 0.3$ eV)

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

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

Turner, Phys.Rev Lett. 59 (1987)
Brust, Kaplan, Walters, JHEP 12 (2013)
Baumann, Green, Wallisch, Phys. Rev. Lett. 117 (2016)

Dark Radiation in the CMB

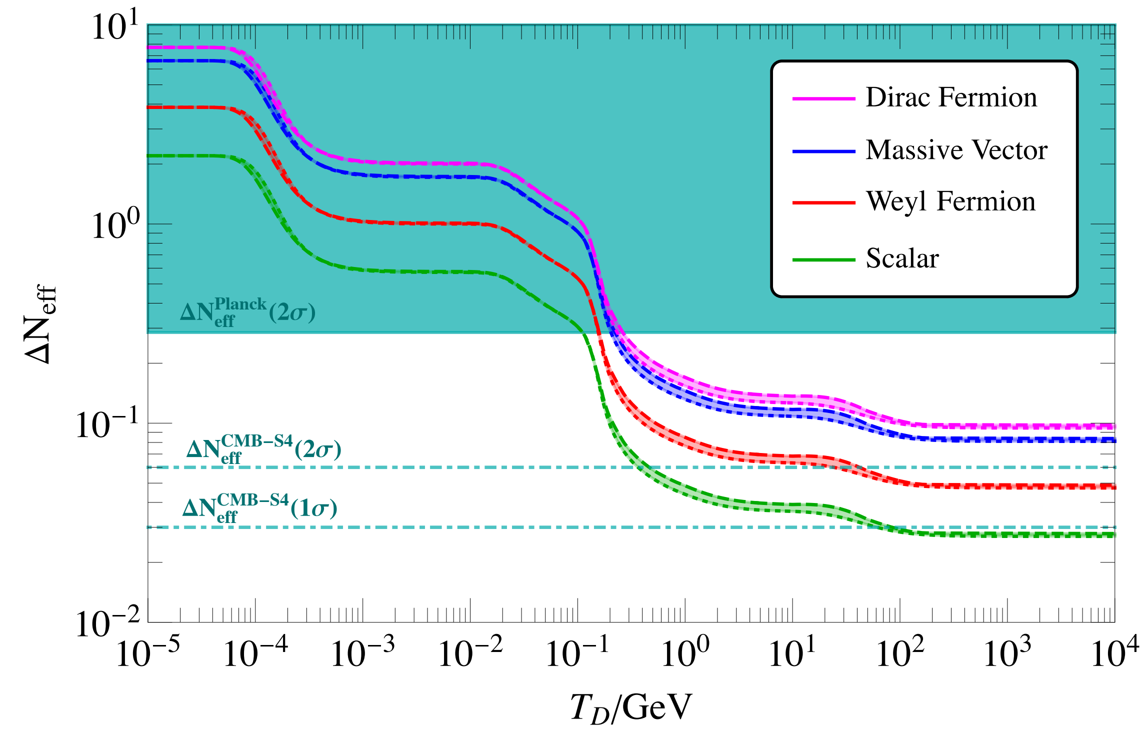


FD, Hajkarim, Yun, JHEP 10 (2021)

Predicting ΔN_{eff}

Axions may never thermalize

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



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

GOAL: compute the right-hand side that accounts for processes changing the number of axions

Scenarios for Hot Axions

Single Coupling Switched On

Axion production controlled by its interaction with 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)

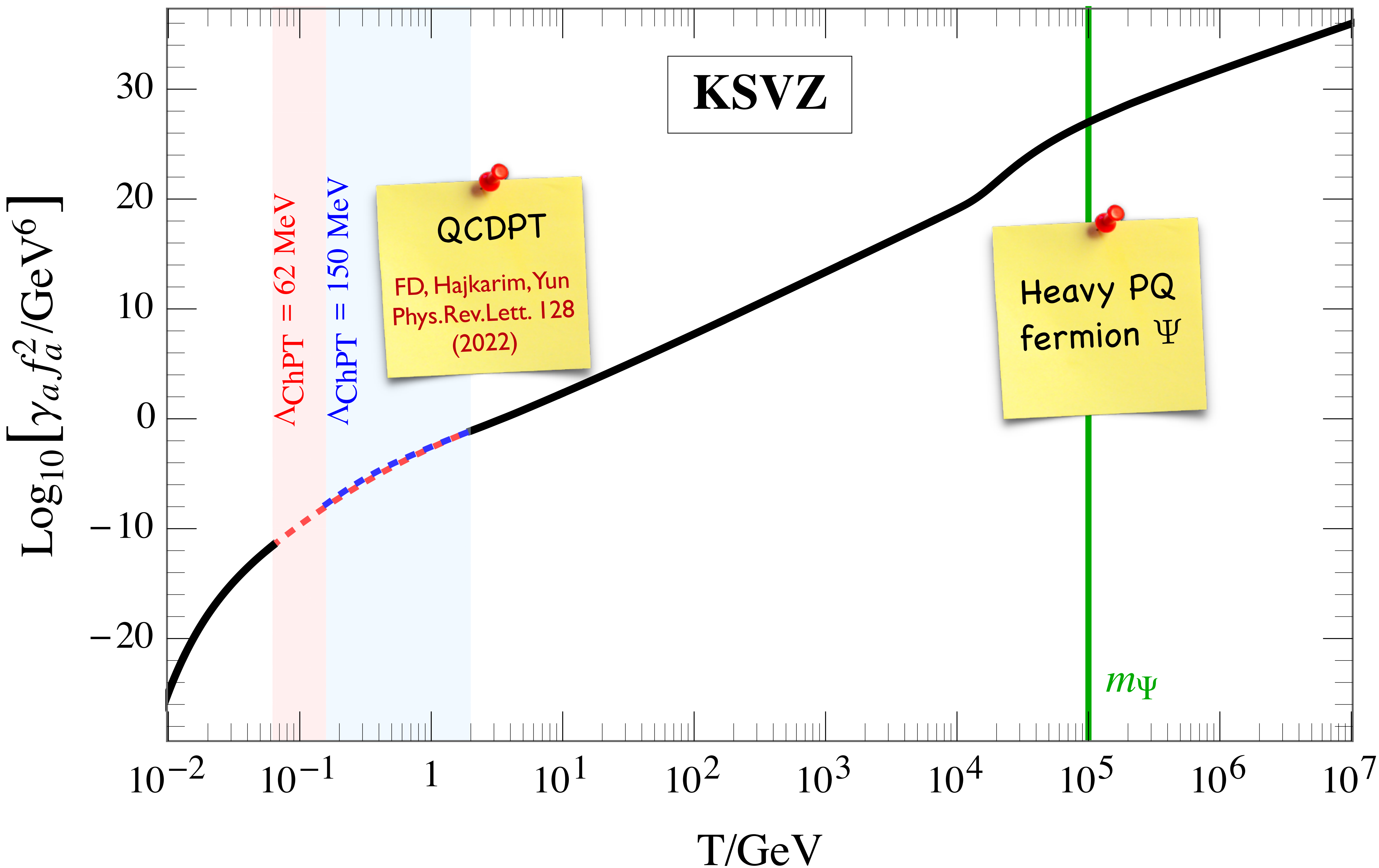
- **KSVZ Axion:** Standard Model fields are PQ-neutral and color anomaly from heavy colored and PQ-charged fermion Ψ

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

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

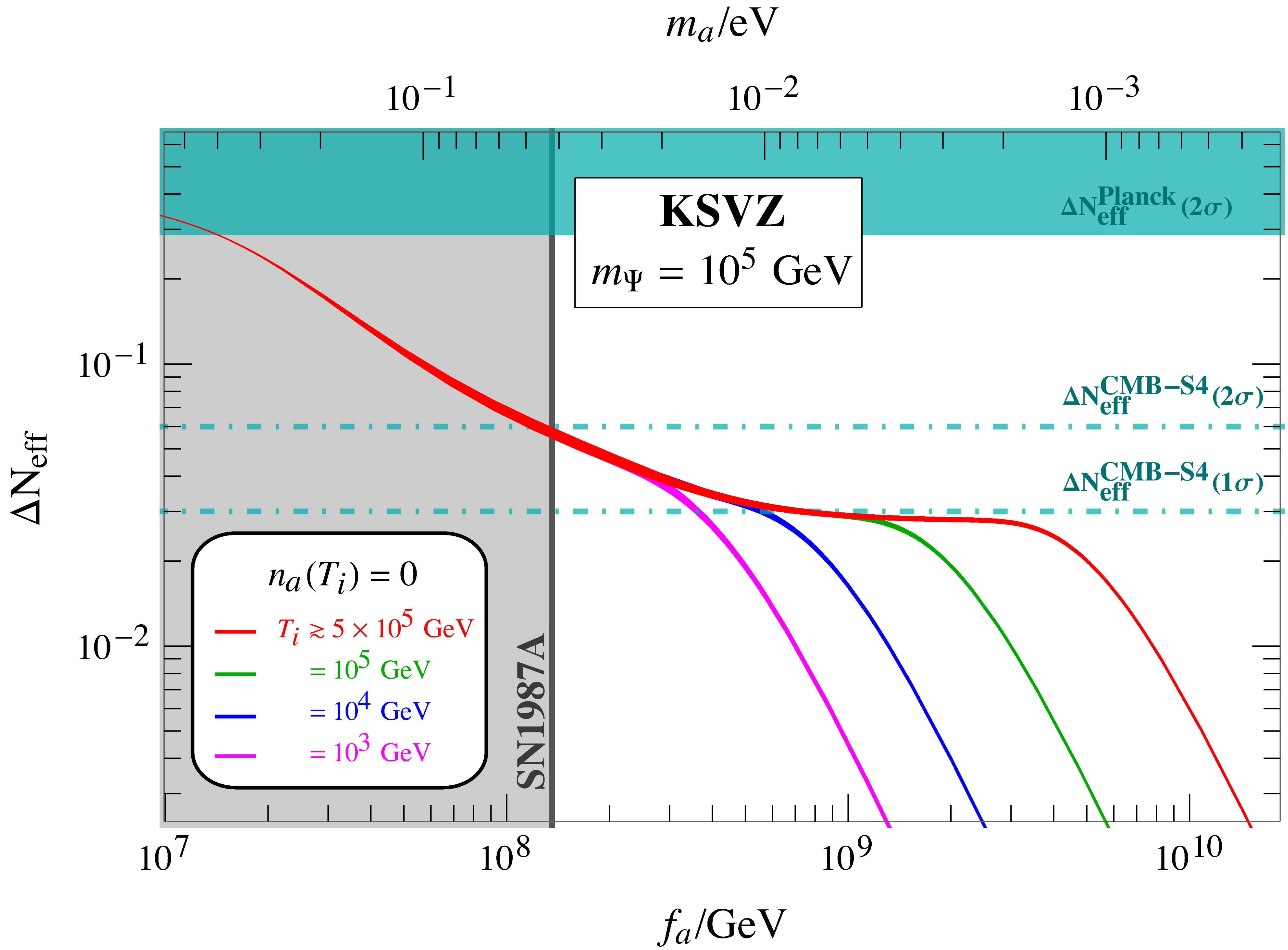
Zhitnitsky, SJNP 31 (1980)
Dine, Fischler, Srednicki, PLB 104 (1981)

KSVZ Axion — Production Rate



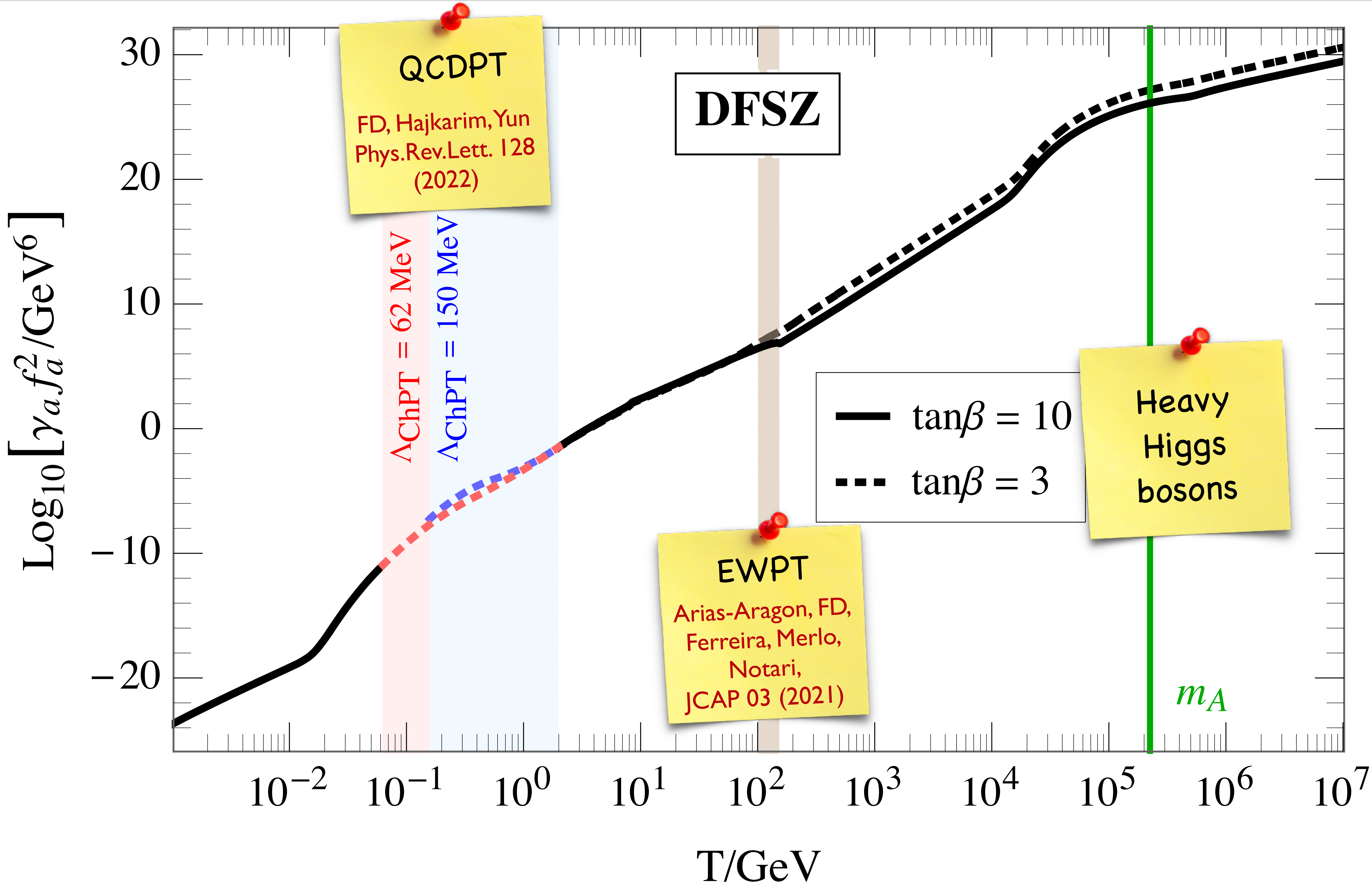
FD, Hajkarim, Yun, JHEP 10 (2021)

KSVZ Axion — ΔN_{eff}



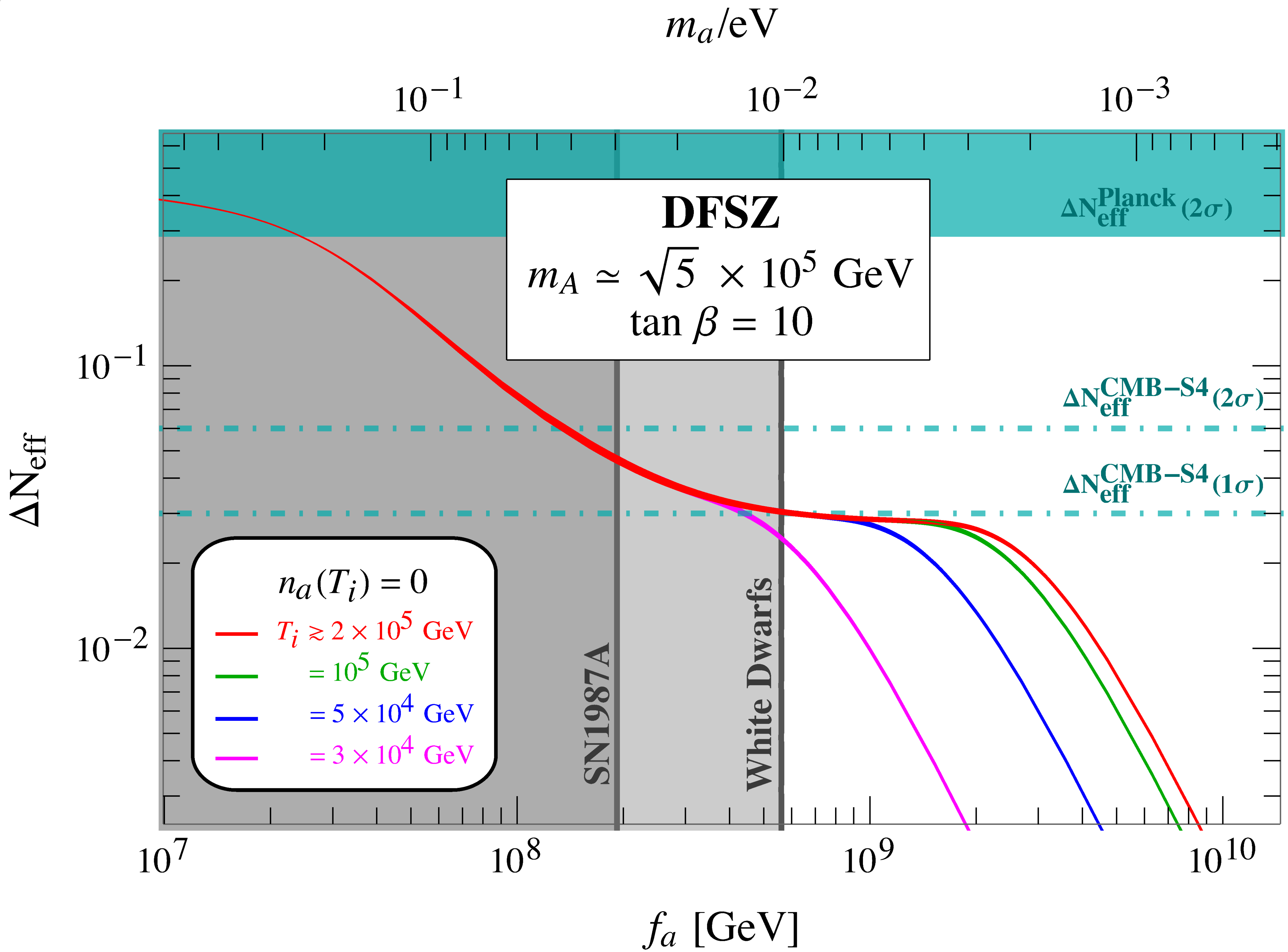
FD, Hajkarim, Yun, JHEP 10 (2021)

DFSZ Axion — Production Rate



FD, Hajkarim, Yun, JHEP 10 (2021)

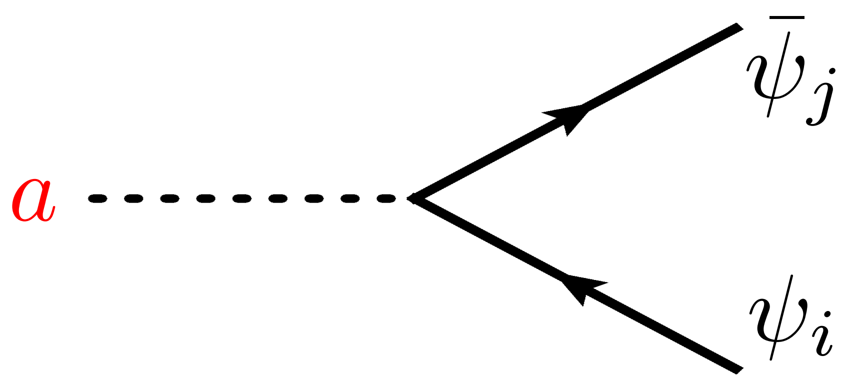
DFSZ Axion — ΔN_{eff}



FD, Hajkarim, Yun, JHEP 10 (2021)

Flavor Violating 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

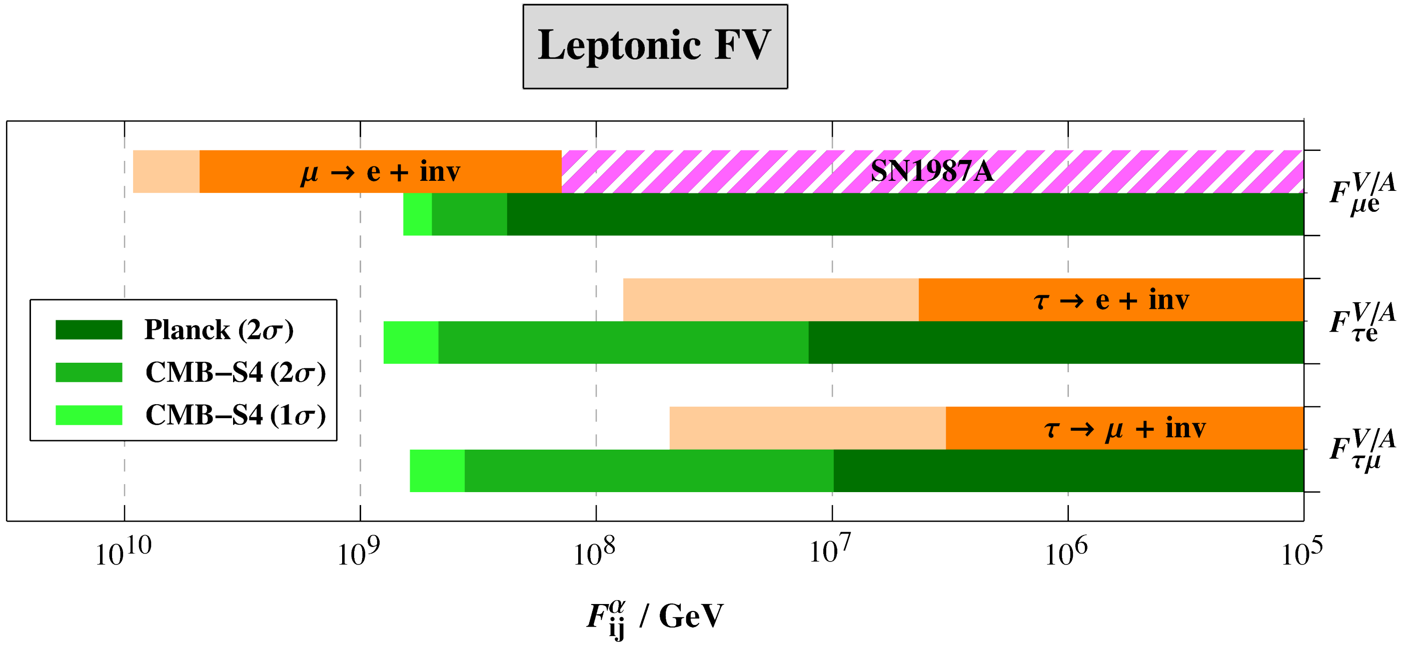
Camalich et al., Phys.Rev.D 102 (2020)
Calibbi et al., JHEP 09 (2021)

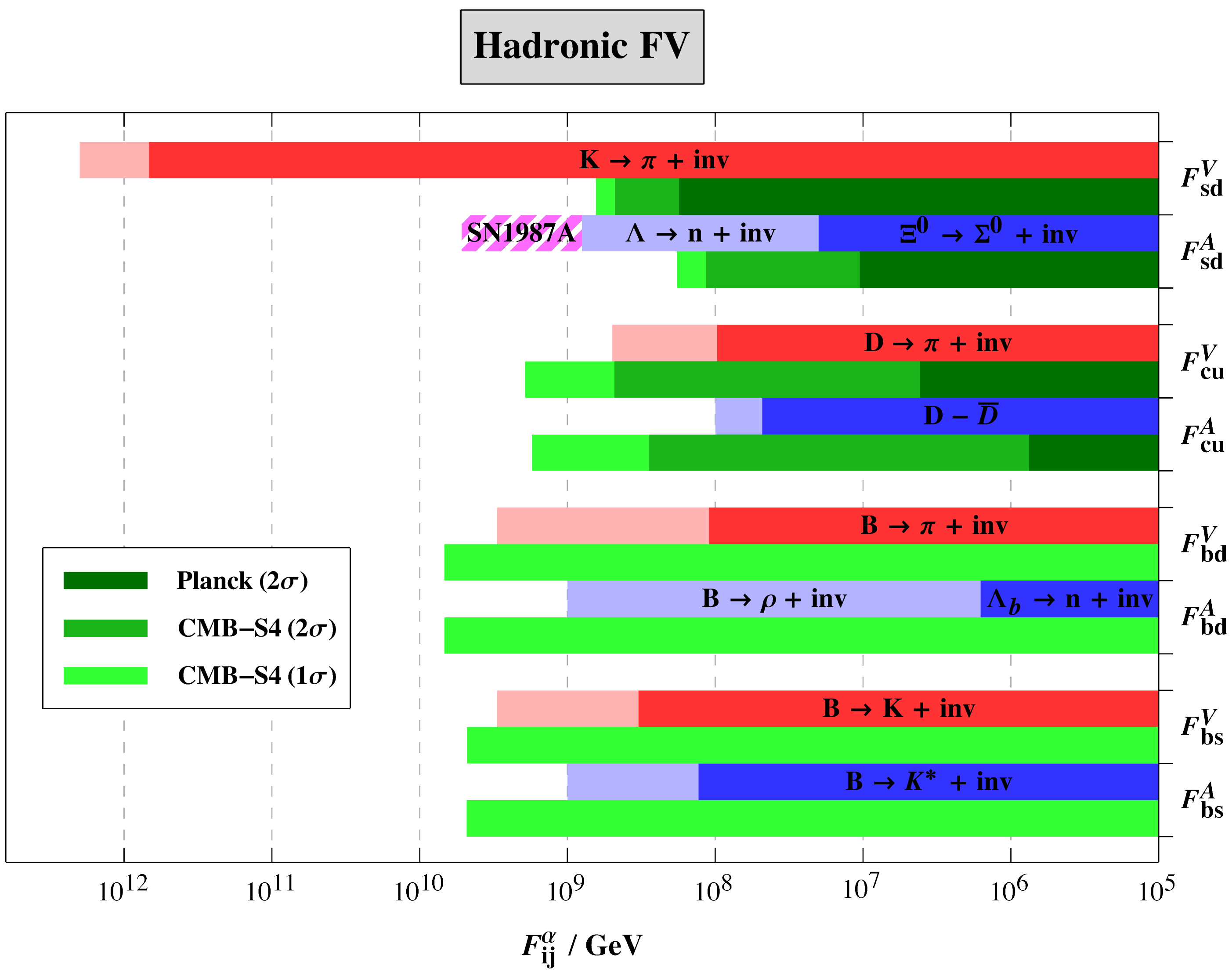
What about their role in the early universe?

They mediate hot axion production via decays and scatterings

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

Flavor Violating Axions

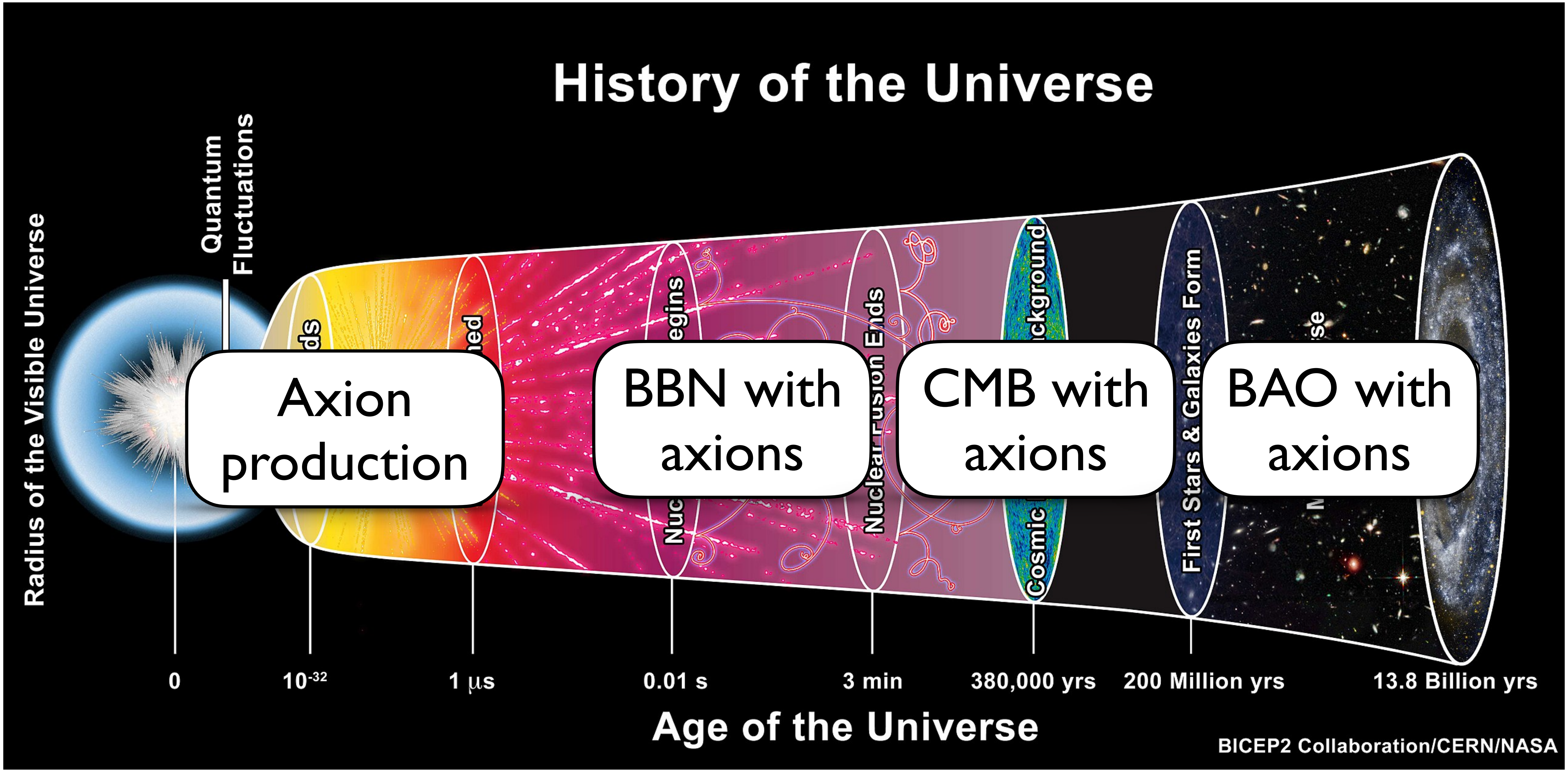




$$F^{\alpha}_{\psi_i\psi_j} \equiv \frac{2 f_a}{c^{\alpha}_{\psi_i\psi_j}}$$

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

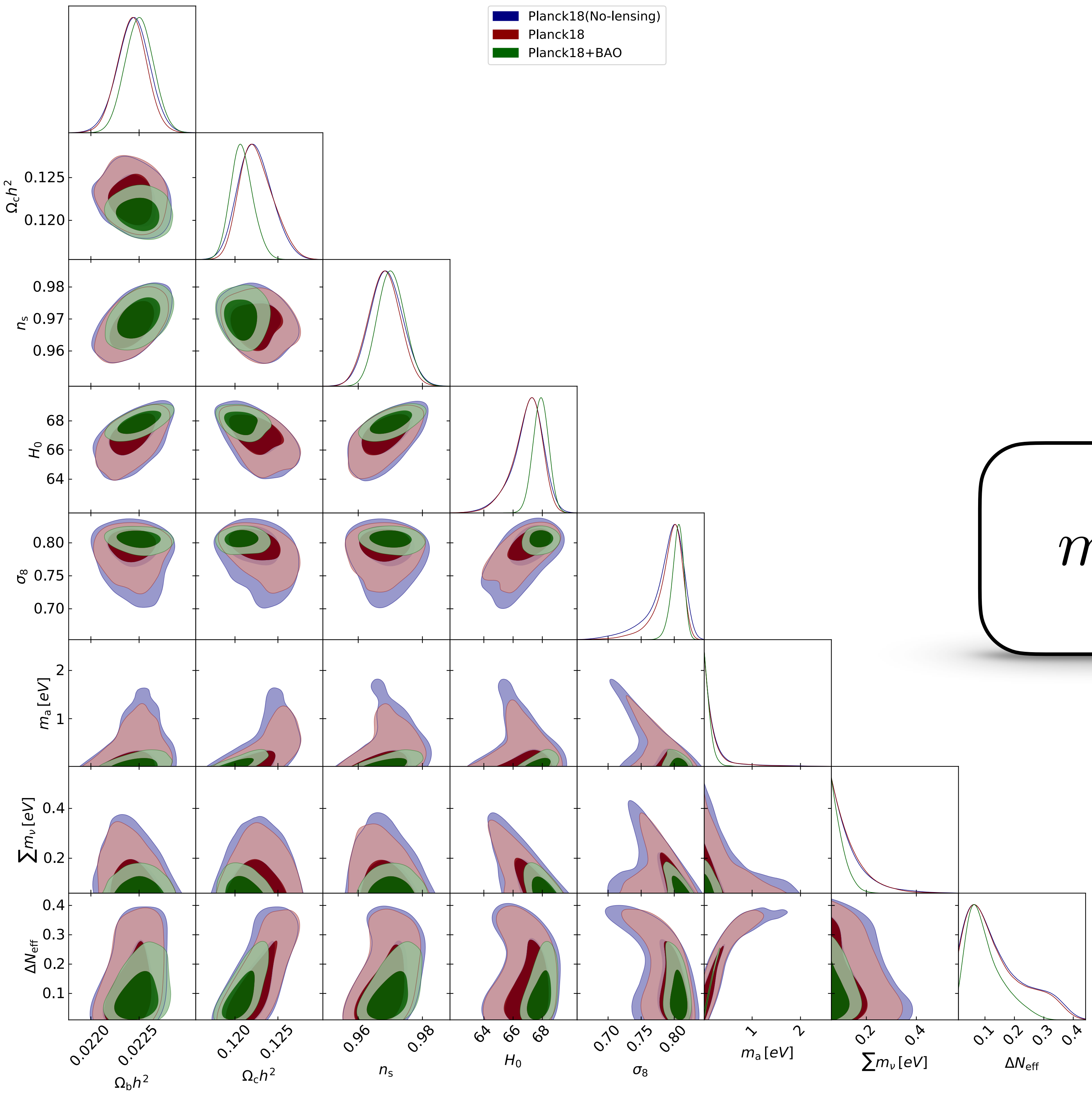
QCD Axion Mass Bound



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

Gluon and Photon Couplings only: see also Caloni, Gerbino, Lattanzi, Visinelli, JCAP 09 (2022)
Pion Couplings only: see also Notari, Rompineve, Villadoro, arXiv:2211.03799

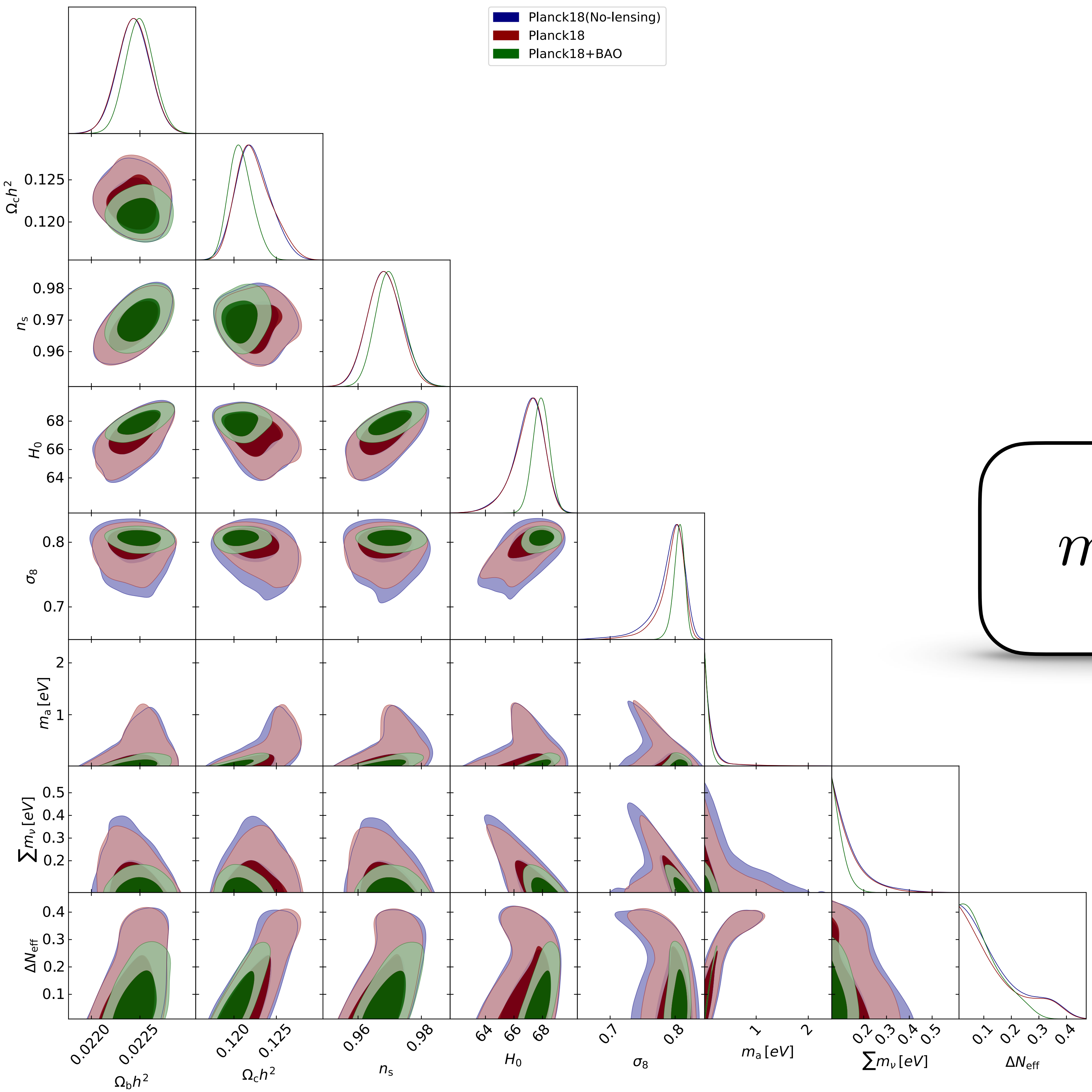
KSVZ Axion Mass Bound



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

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

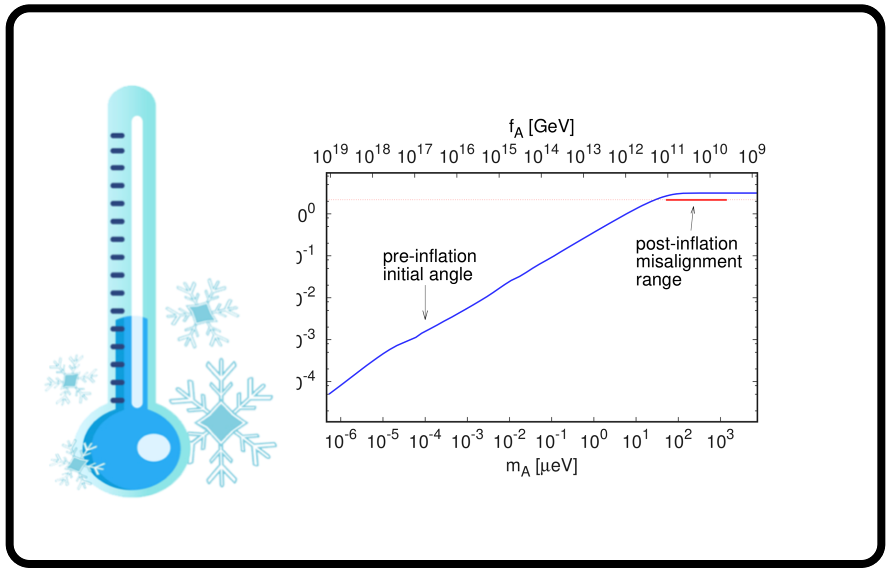
DFSZ Axion Mass Bound



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

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

Outlook



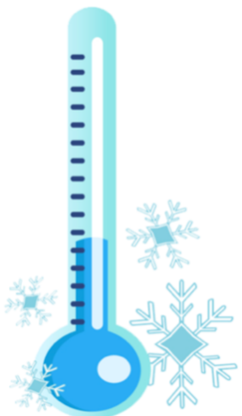
<u>Peccei-Quinn Mechanism and the QCD Axion</u>

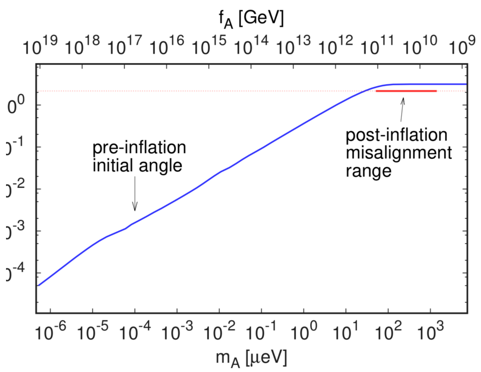
Motivated and testable scenario

for physics beyond the standard model

rich of cosmological consequences

Outlook





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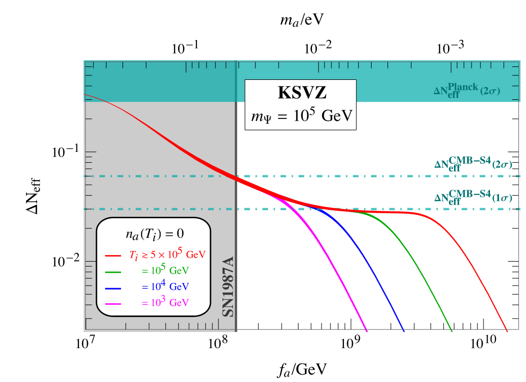
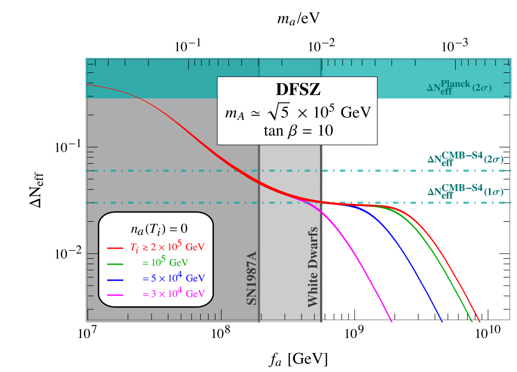
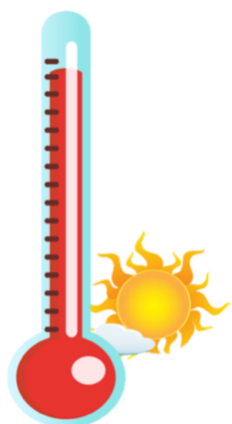
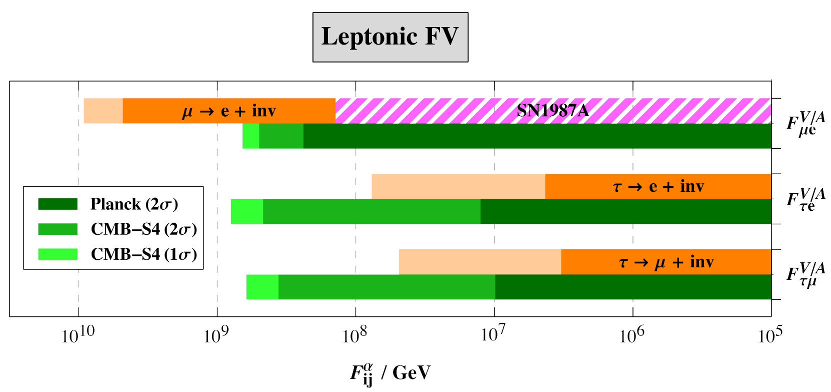
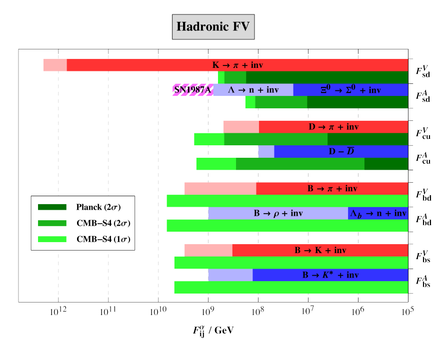
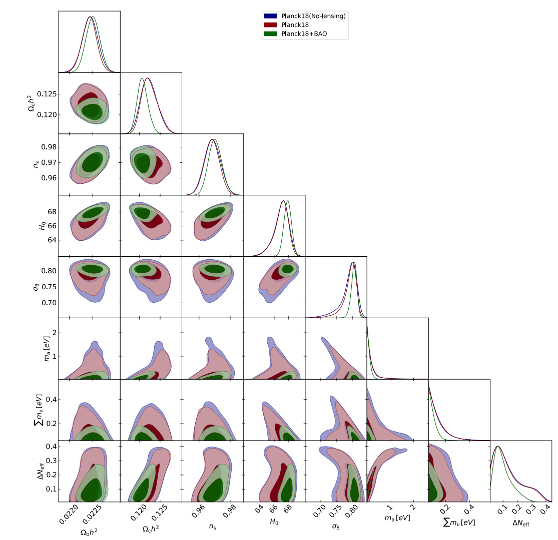








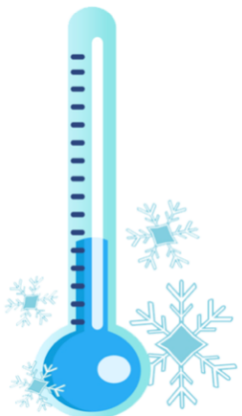


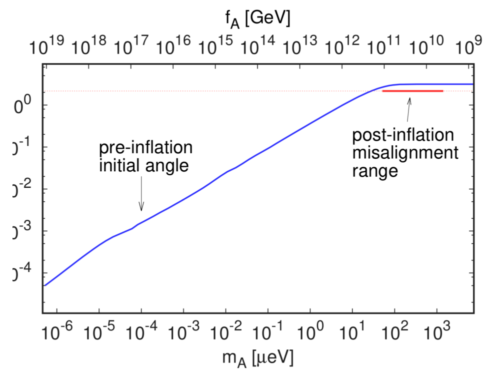


<u>Thermal Axions</u>

Complementary to other probes of the PQ mechanism

Outlook





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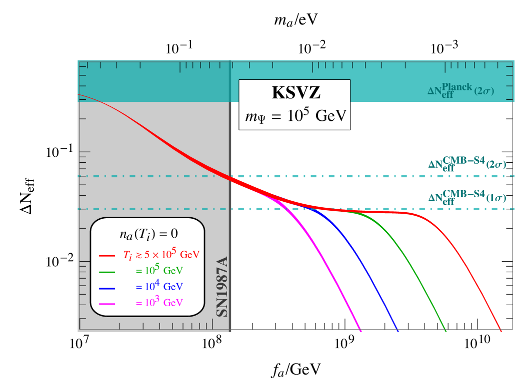

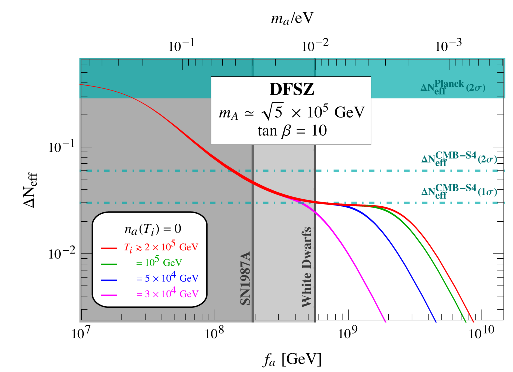

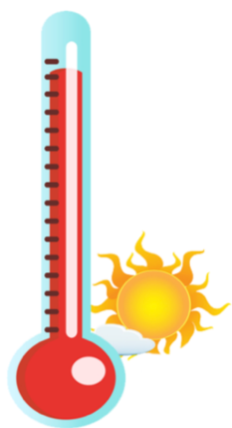

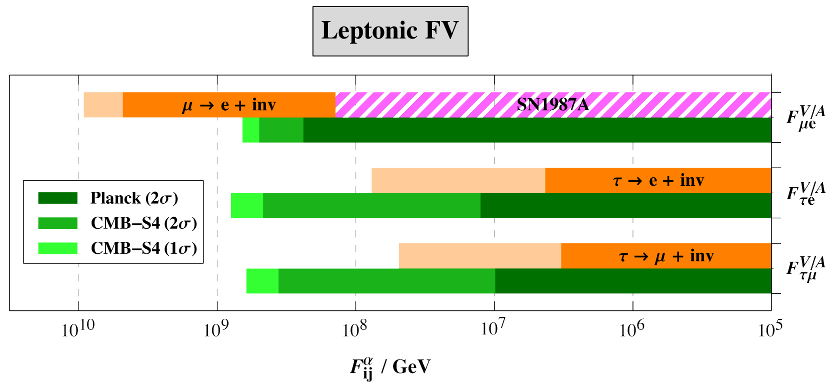

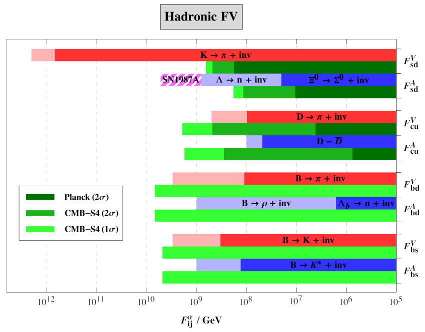

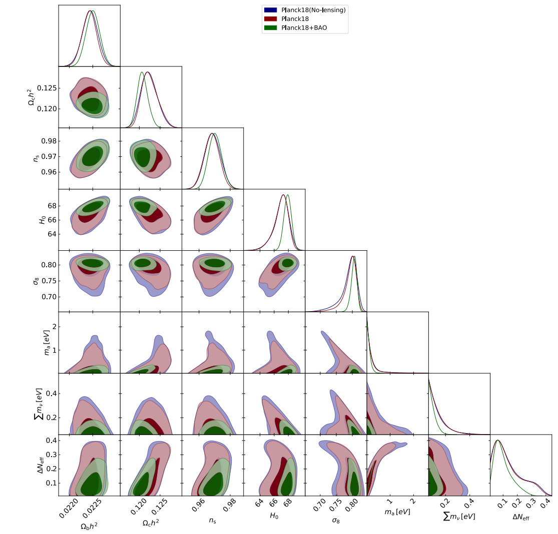

THANK YOU!