Thermal Axions: Production Mechanisms and Cosmological Signals

Francesco D'Eramo

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UNIVERSITÀ DEGLI STUDI DI PADOVA

INFN Istituto Nazionale di Fisica Nucleare Sezione di Padova

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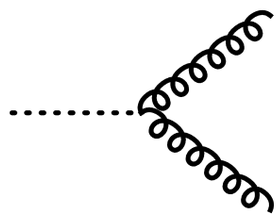
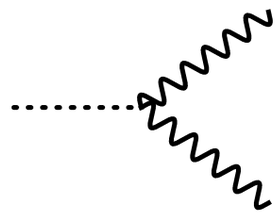
Washington University in St. Louis — 6 June 2022

The QCD Axion

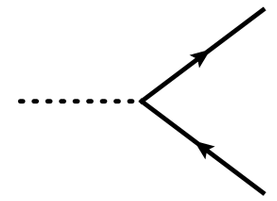
- Coupling to gluons and (not mandatory) to electroweak gauge bosons
- Derivative couplings to fermions



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



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



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

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

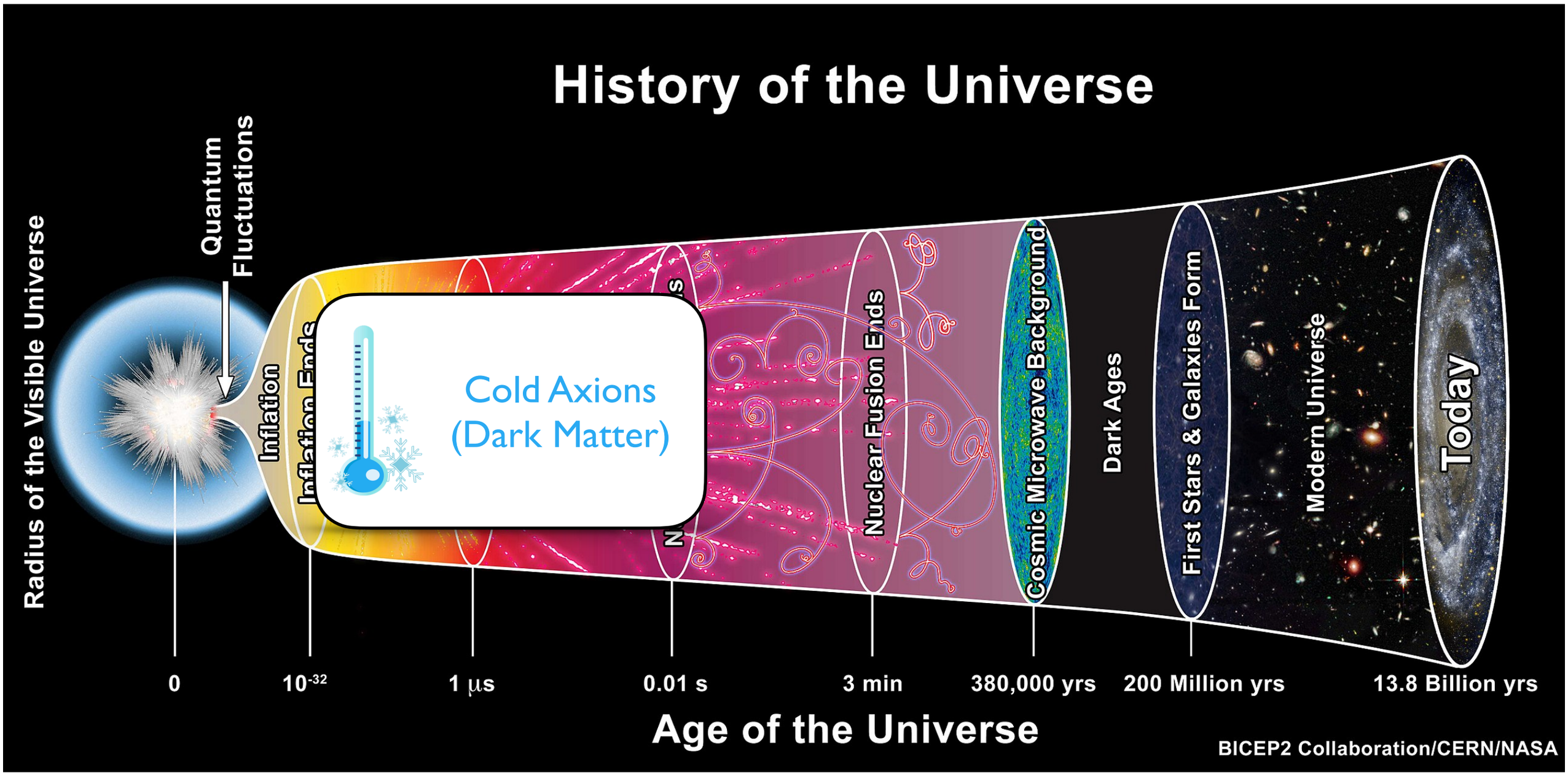
Axion (zero-temperature) mass from non-perturbative potential

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

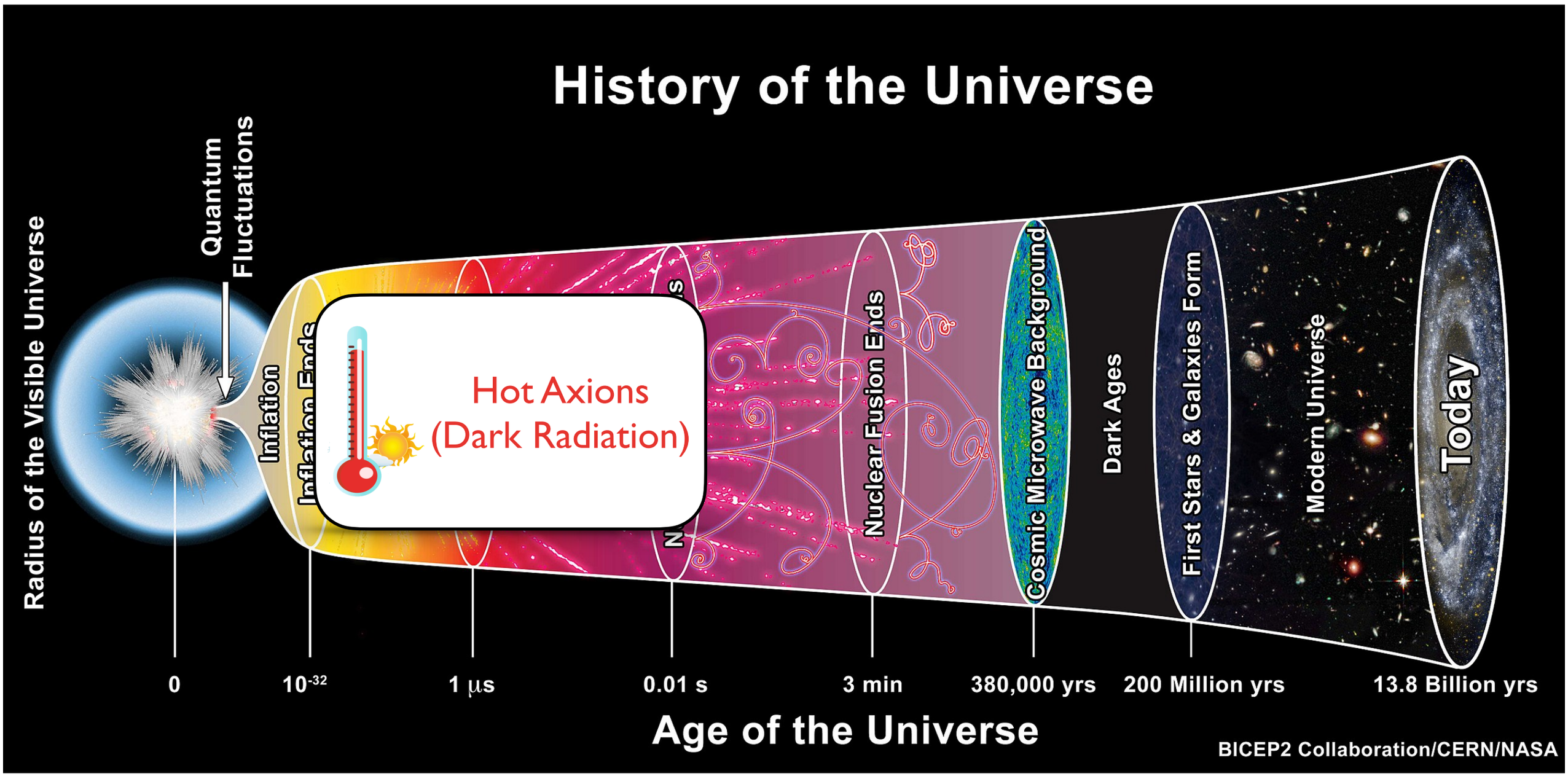
The QCD axion is <u>very light</u>!

Georgi, Kaplan, Randall, PLB169 (1986)
Grilli di Cortona, Hardy, Vega, Villadoro, JHEP1601 (2016)

Axions in the Early Universe



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:

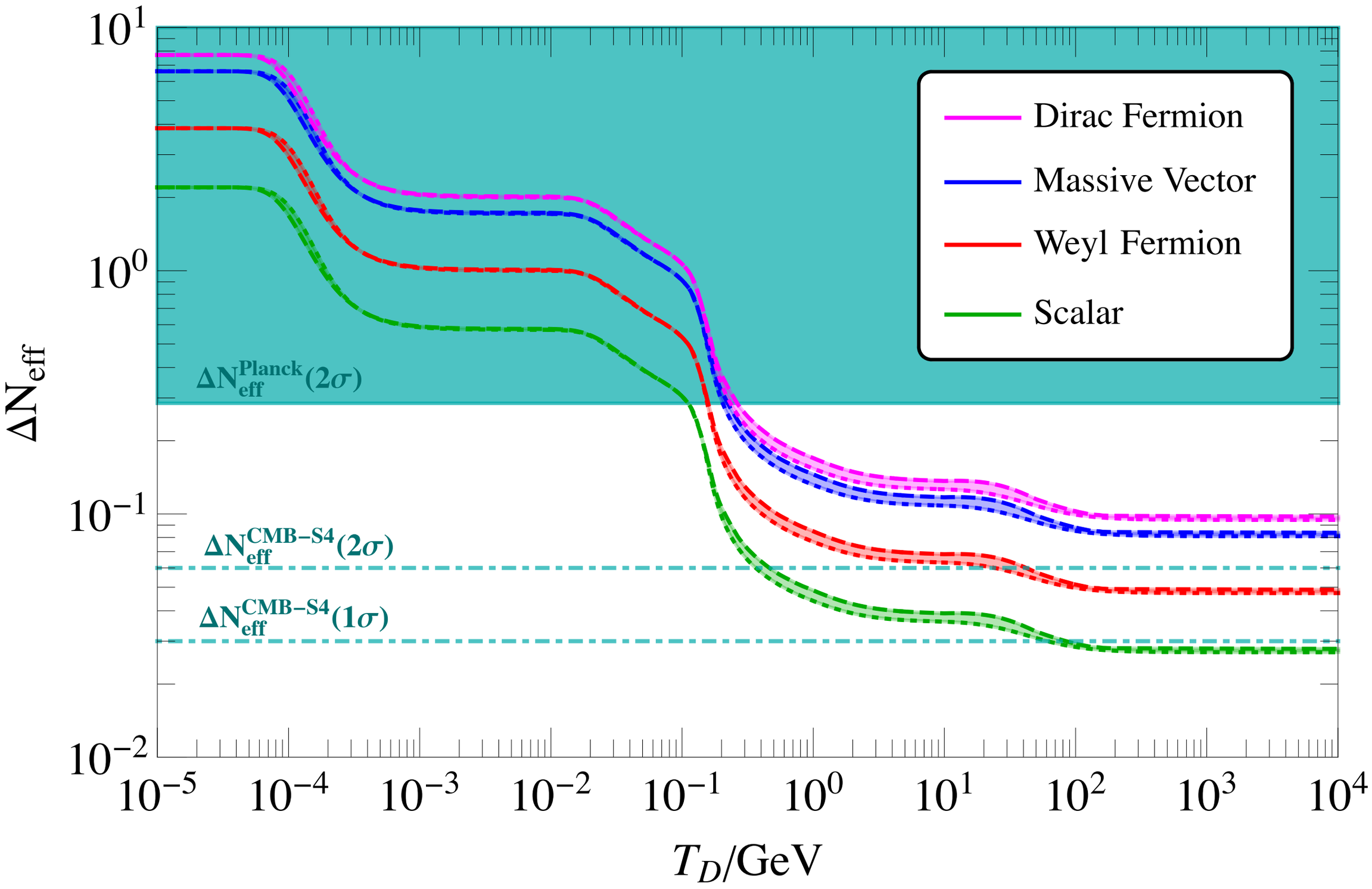
- BBN ($m_a \lesssim$ MeV)
- Recombination ($m_a \lesssim$ 0.3 eV)

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

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

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

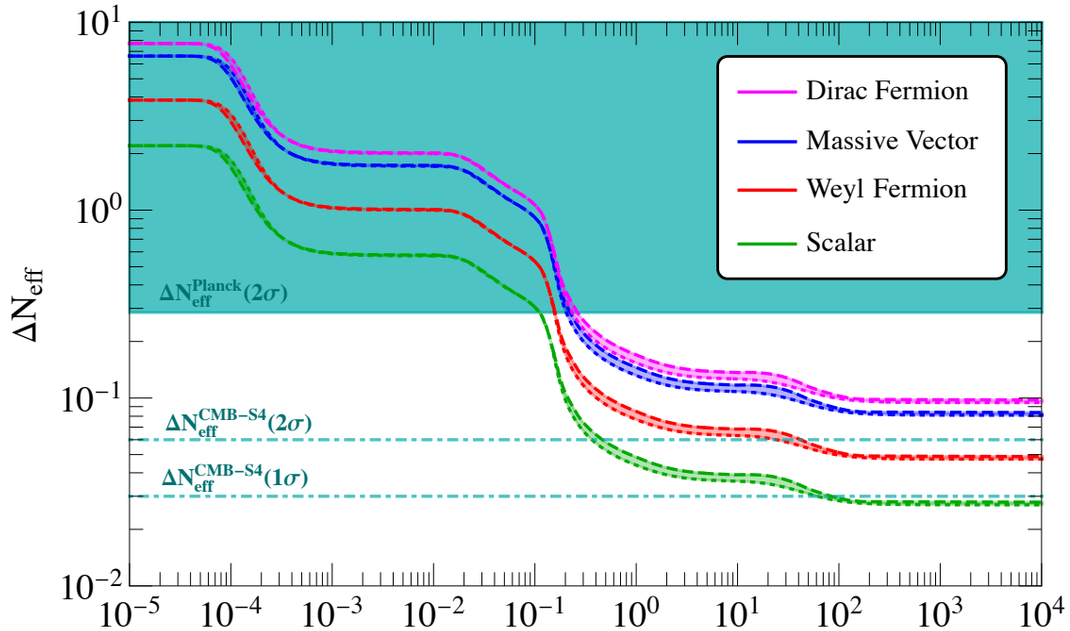


FD, Hajkarim, Yun, JHEP 10 (2021)

Predicting ΔN_{eff}

Axions may never thermalize

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



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

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

FD, Hajkarim, Yun, JHEP 10 (2021)

Explicit UV Completions

KSVZ Axion

Standard Model fields are PQ-neutral

Color anomaly: heavy colored and PQ-charged fermion Ψ

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

DFSZ Axion

Standard Model fields charged (2 Higgs doublets)

Color anomaly: quarks

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

FD, Hajkarim, Yun, JHEP 10 (2021)

Explicit UV Completions

KSVZ Axion

Standard Model fiel are PQ-neutral

Color anomaly: arged fermion Ψ

Kim, PRL 43 (1979)
nshtein, Zakharov, NPB 166 (1980)

Large coupling to leptons alleviate the Hubble tension

FD, Ferreira, Notari, Bernal, JCAP 11 (2018)

DFSZ Axio

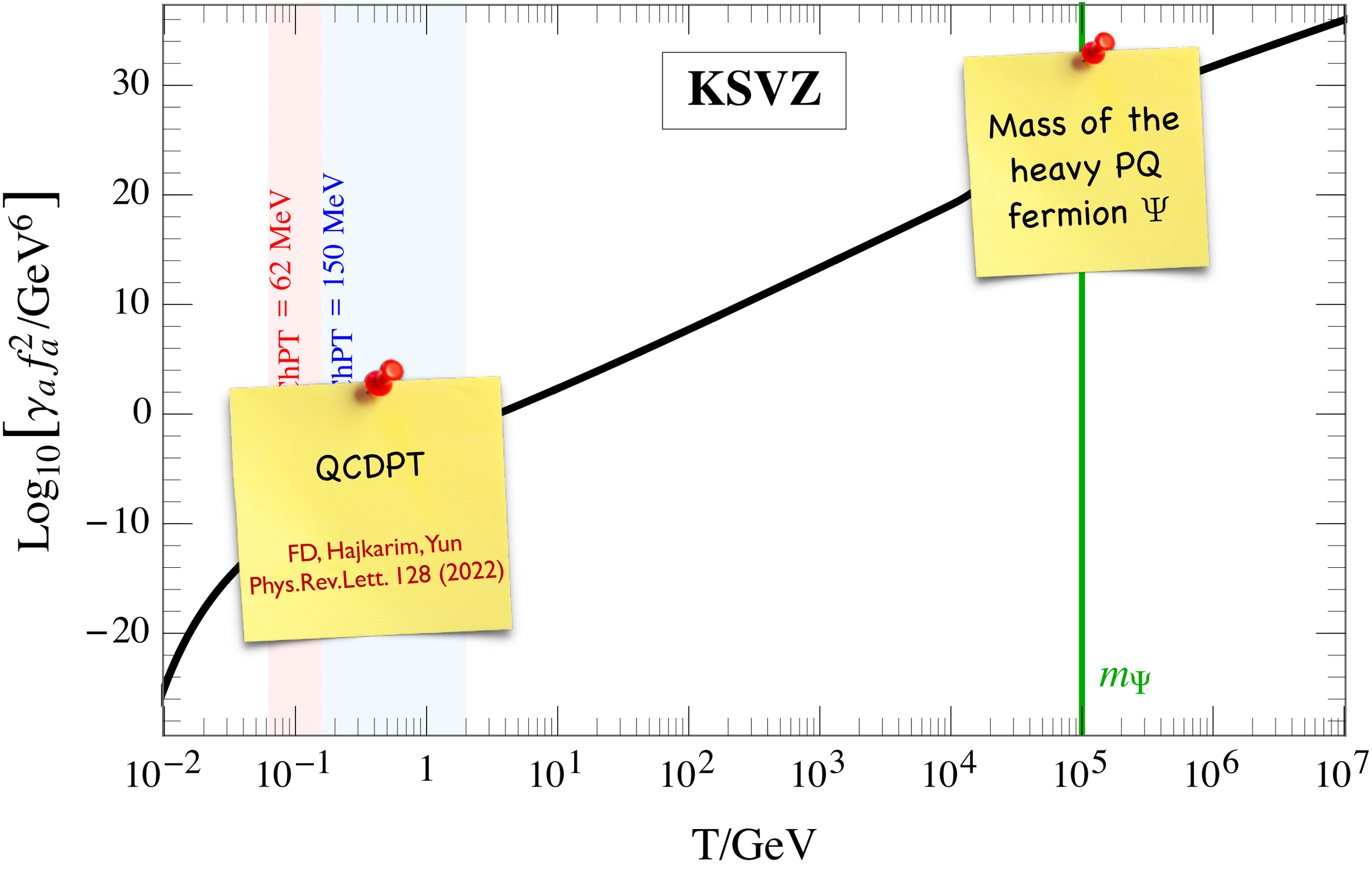
Standard M s doublets)

Color anomaly: quarks

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

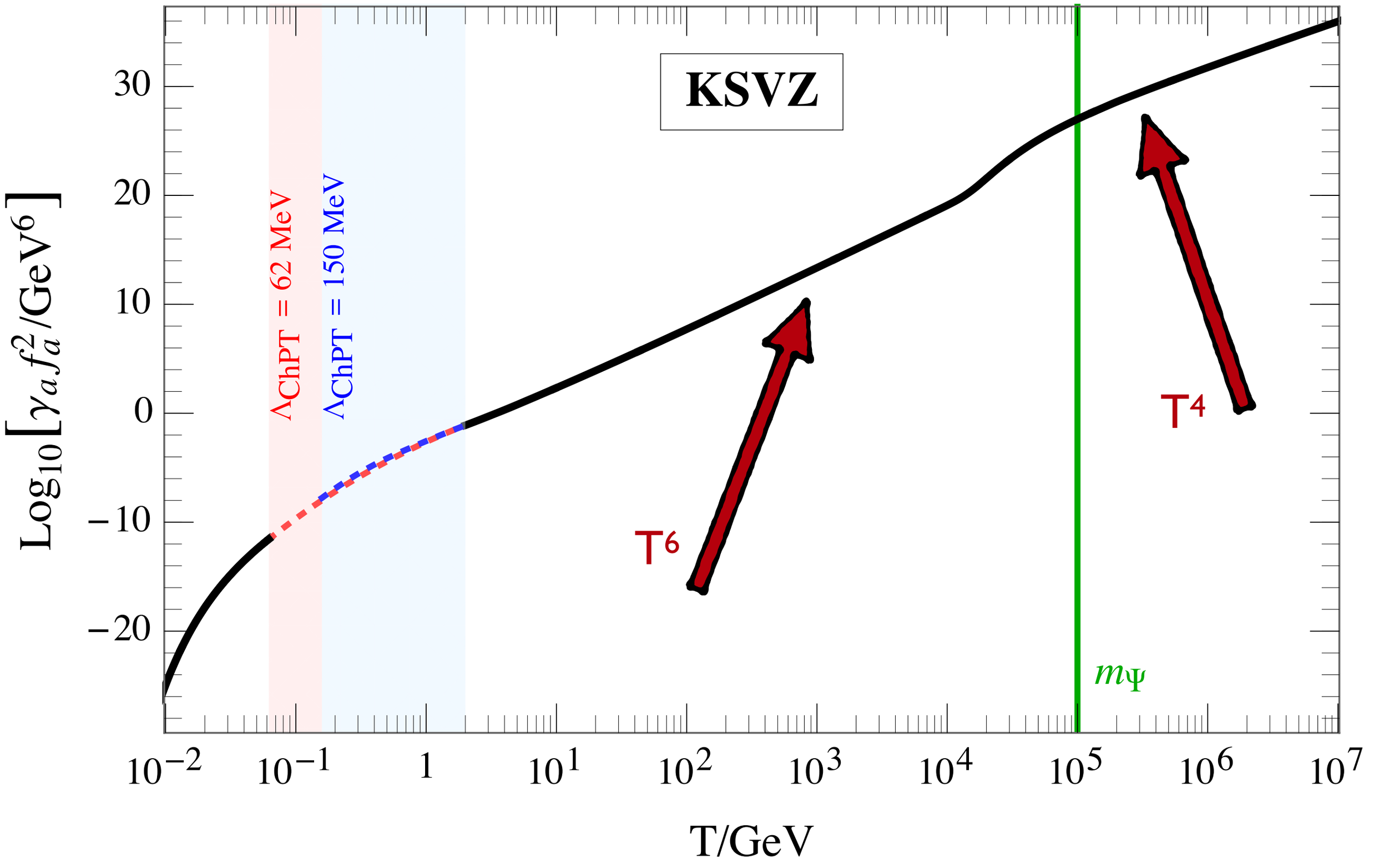
FD, Hajkarim, Yun, JHEP 10 (2021)

KSVZ Axion — Production Rate



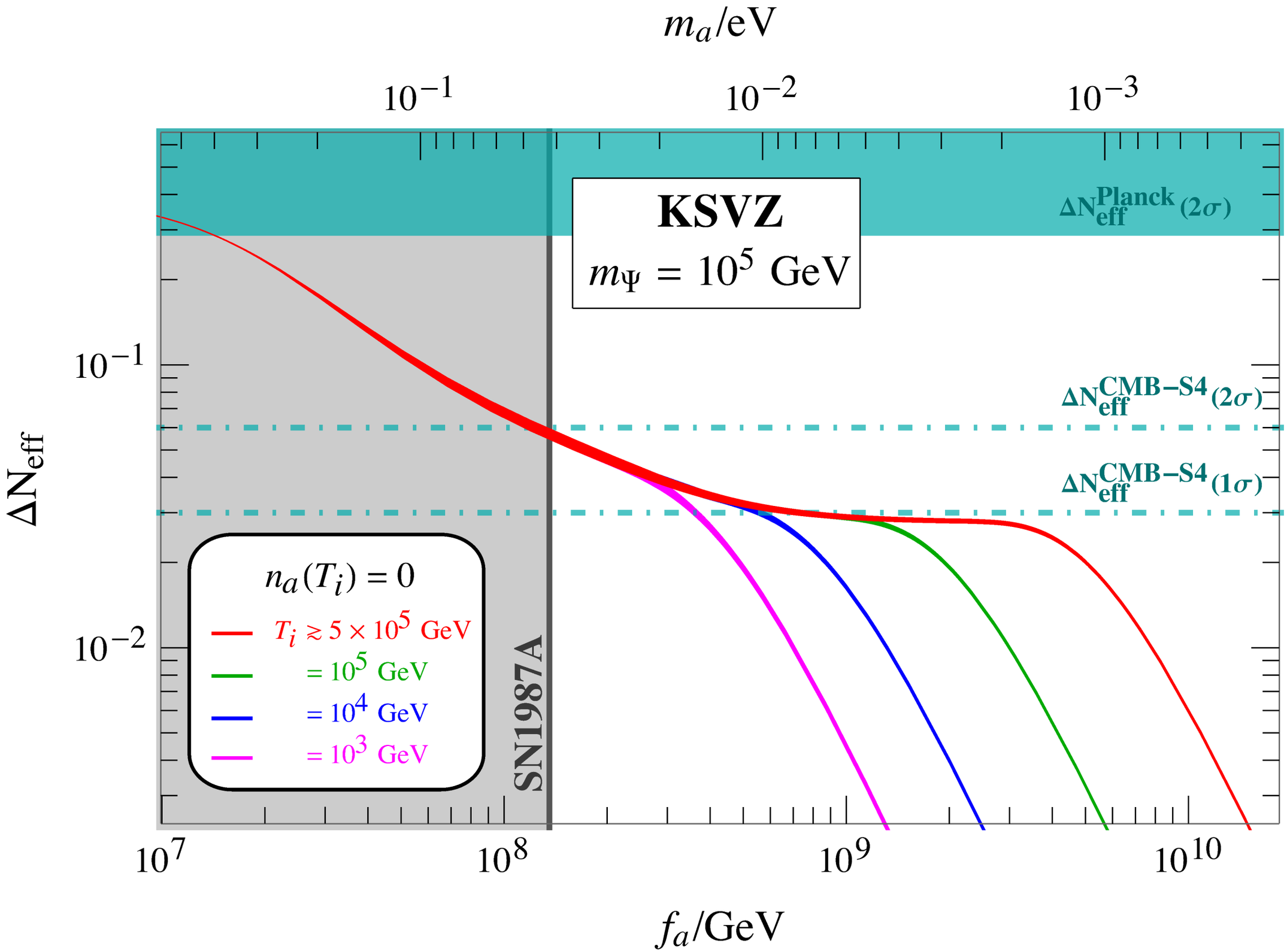
FD, Hajkarim, Yun, JHEP 10 (2021)

KSVZ Axion — Production Rate



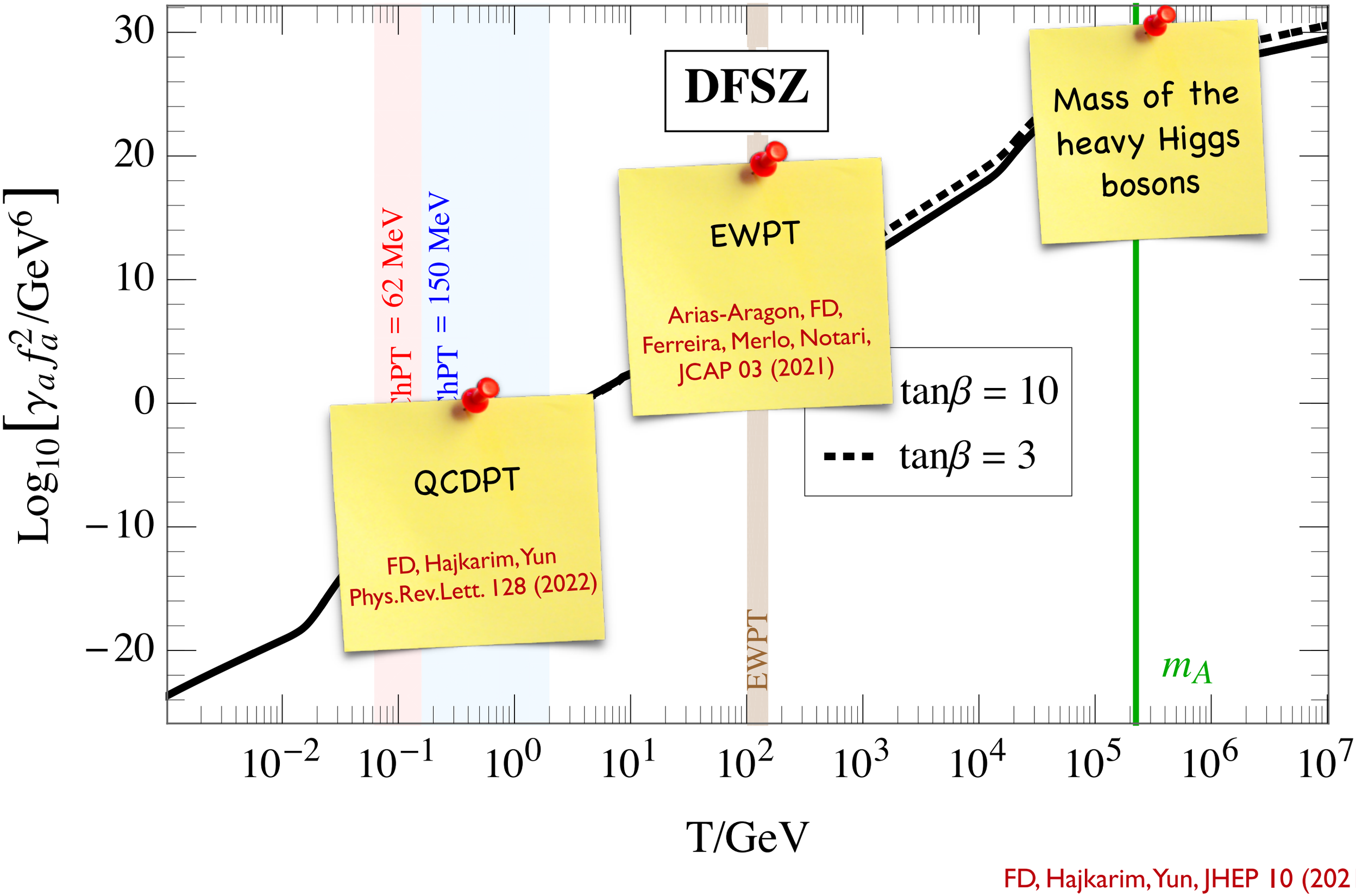
FD, Hajkarim, Yun, JHEP 10 (2021)

KSVZ Axion — ΔN_{eff}



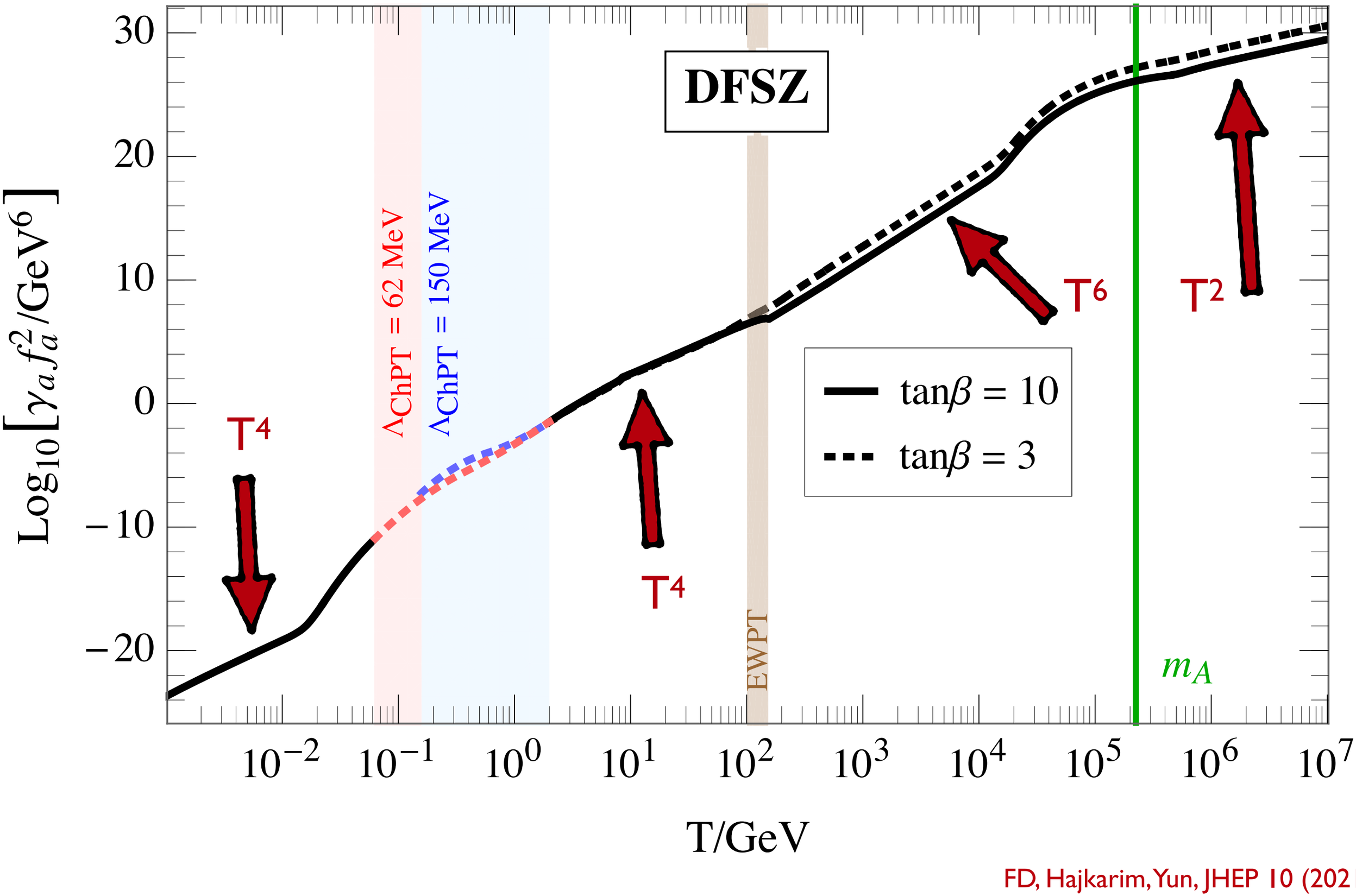
FD, Hajkarim, Yun, JHEP 10 (2021)

DFSZ Axion — Production Rate



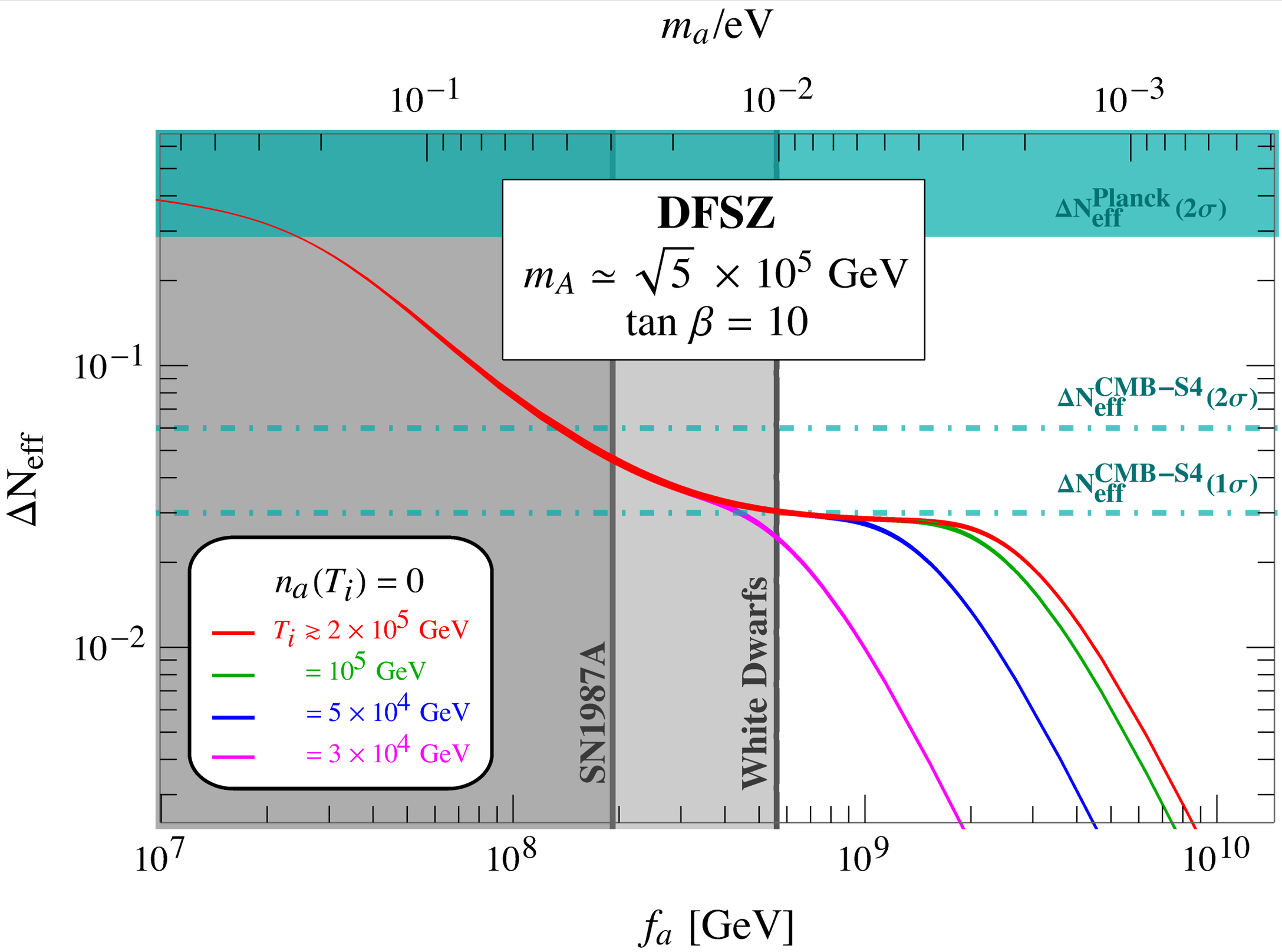
FD, Hajkarim, Yun, JHEP 10 (2021)

DFSZ Axion — Production Rate



FD, Hajkarim, Yun, JHEP 10 (2021)

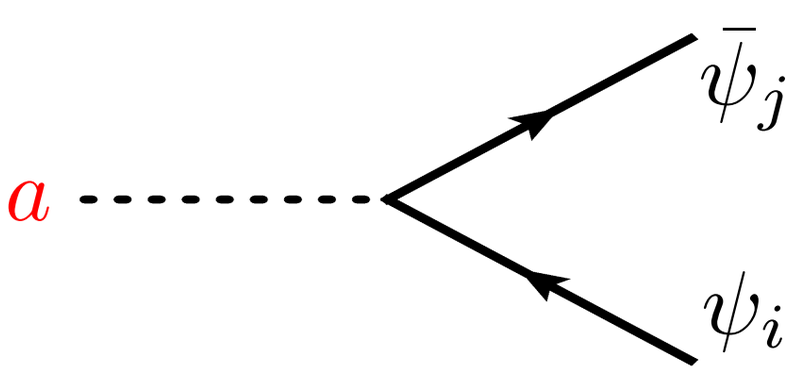
DFSZ Axion — ΔN_{eff}



FD, Hajkarim, Yun, JHEP 10 (2021)

Flavor Violating Axions

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



Target of several terrestrial experiments

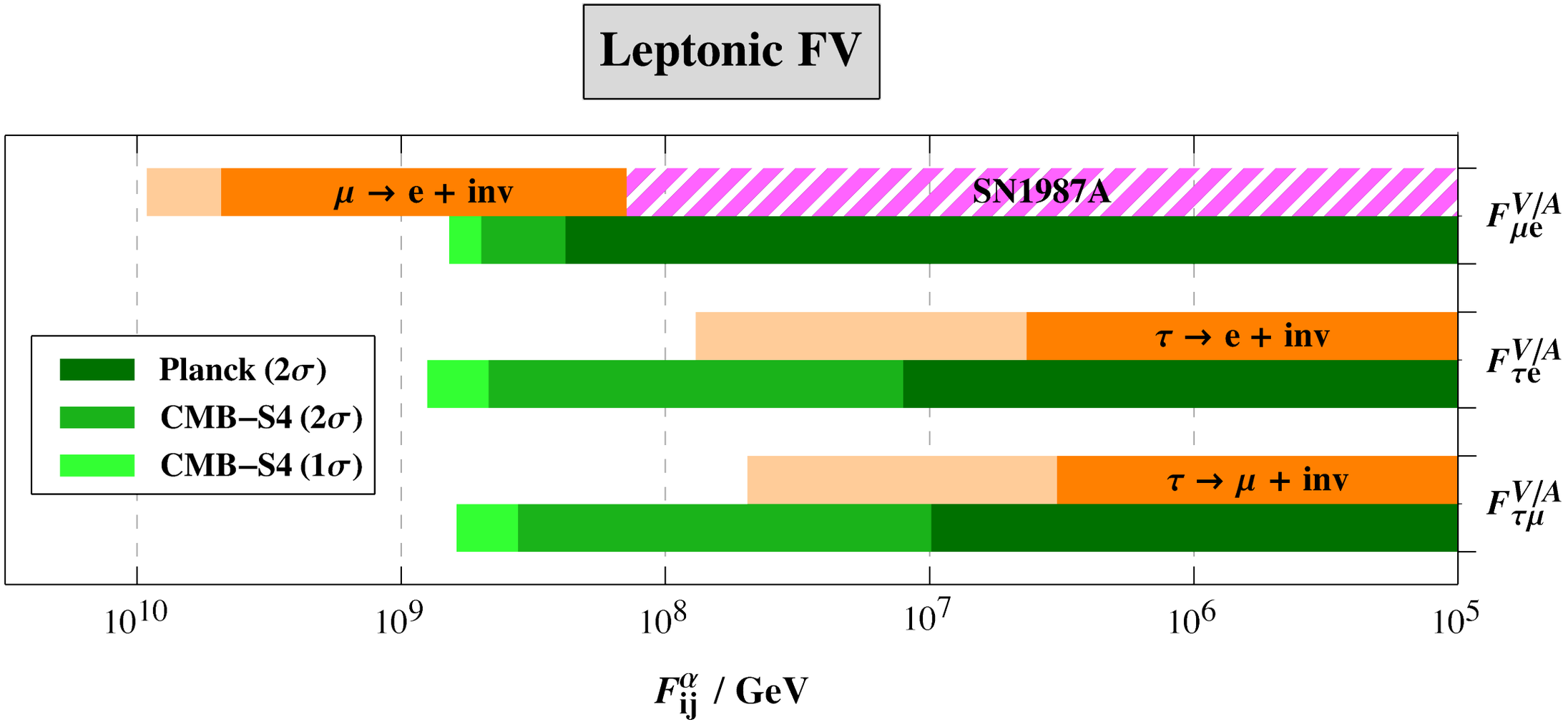
Camalich et al., Phys.Rev.D 102 (2020)
Calibbi et al., JHEP 09 (2021) 173

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)

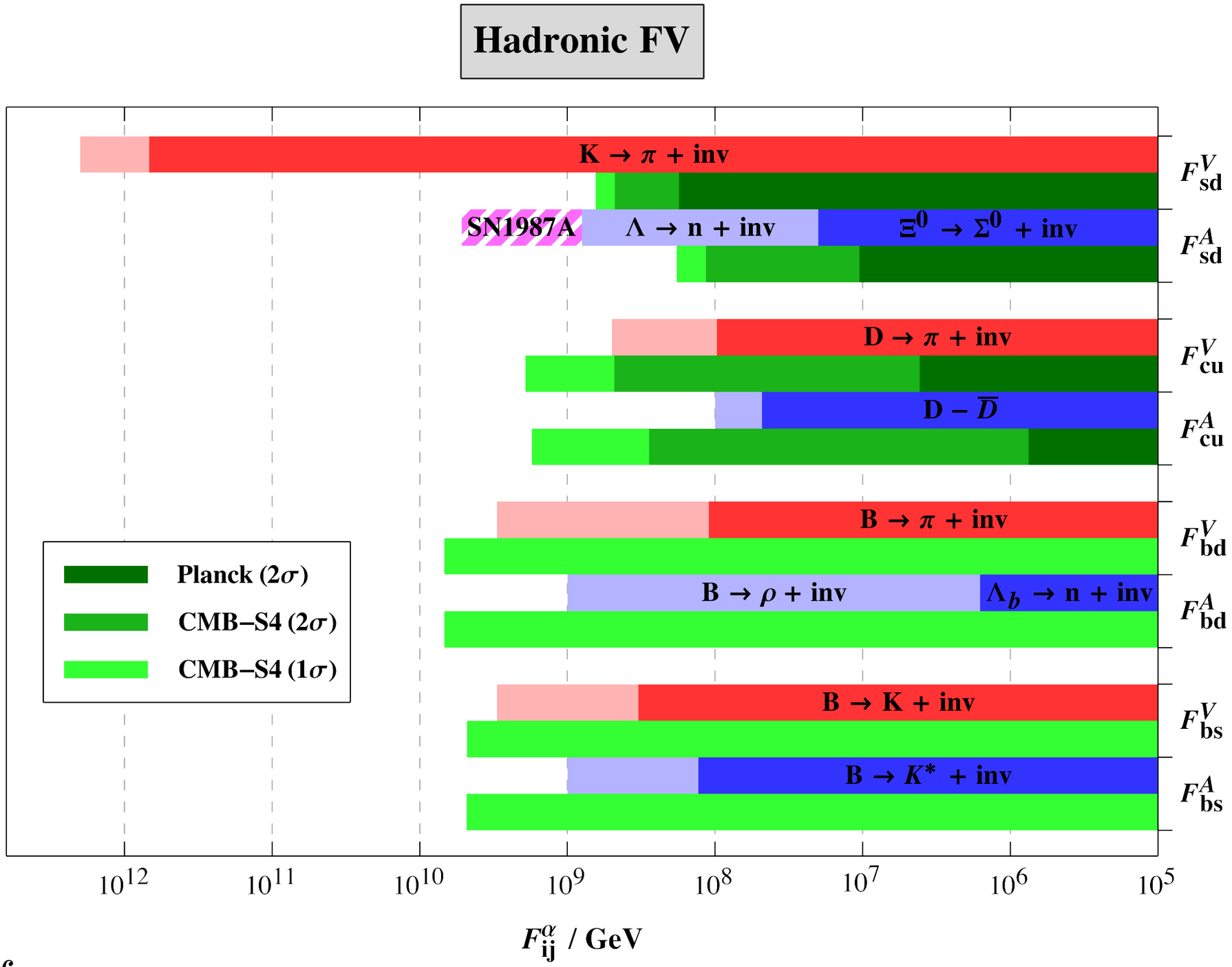
Flavor Violating Axions



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

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

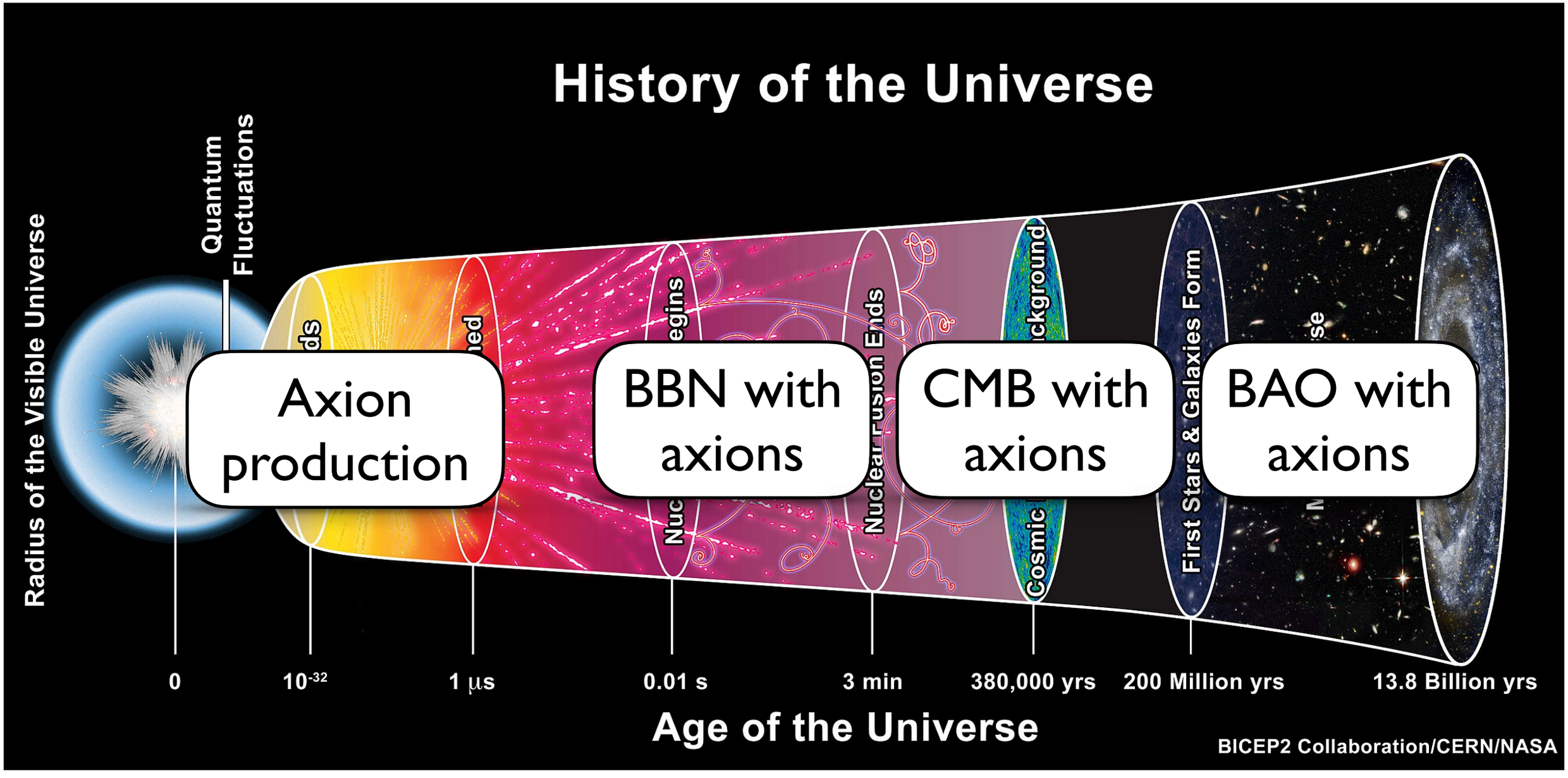
Flavor Violating Axions



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

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

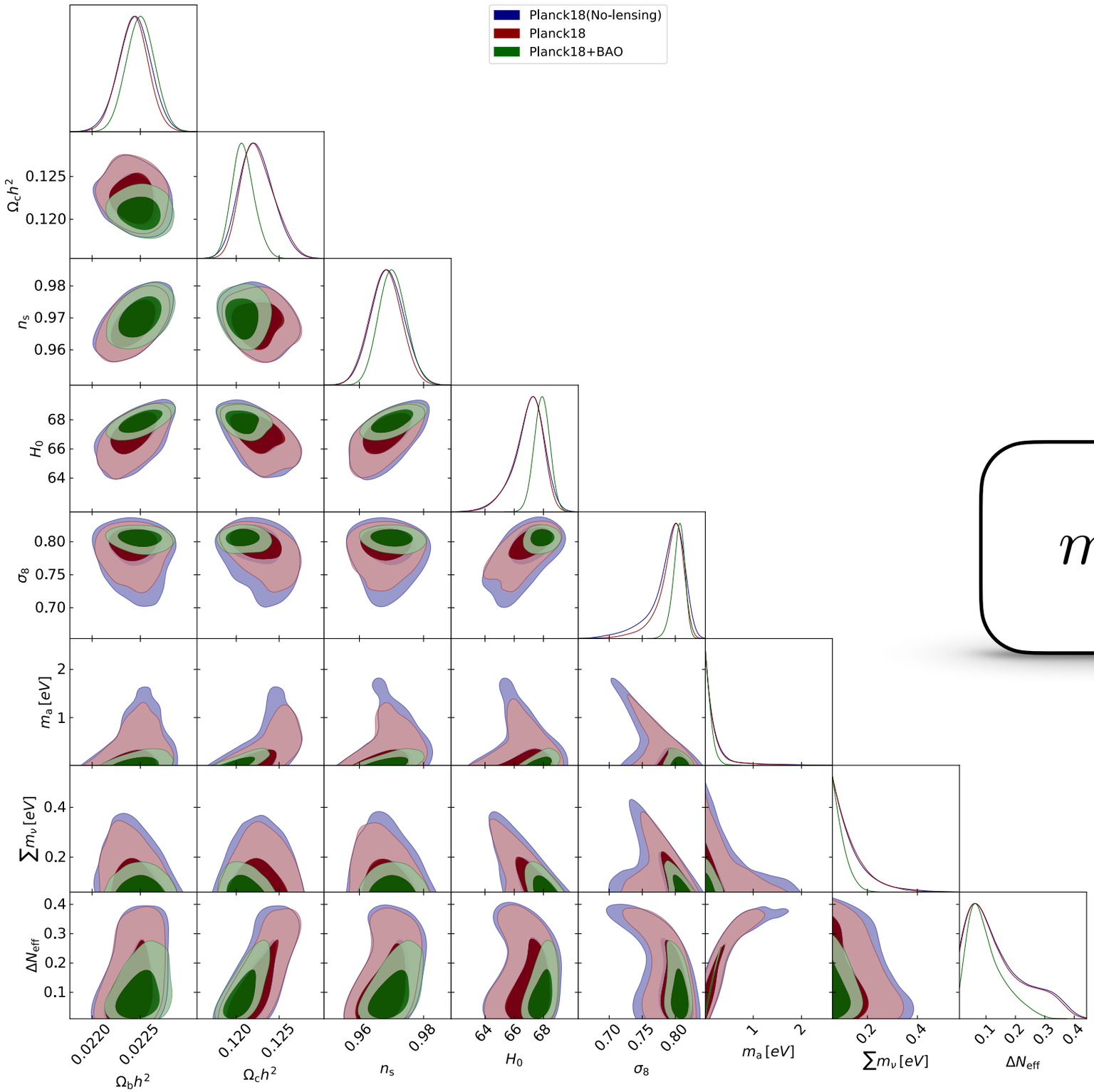
Global Cosmological Analysis



FD, Di Valentino, Giarè, Hajkarim, Melchiorri, Mena, Renzi, Yun, arXiv:2205.07849

(for gluon and photon coupling see also Caloni, Gerbino, Lattanzi, Visinelli, arXiv:2205.01637)

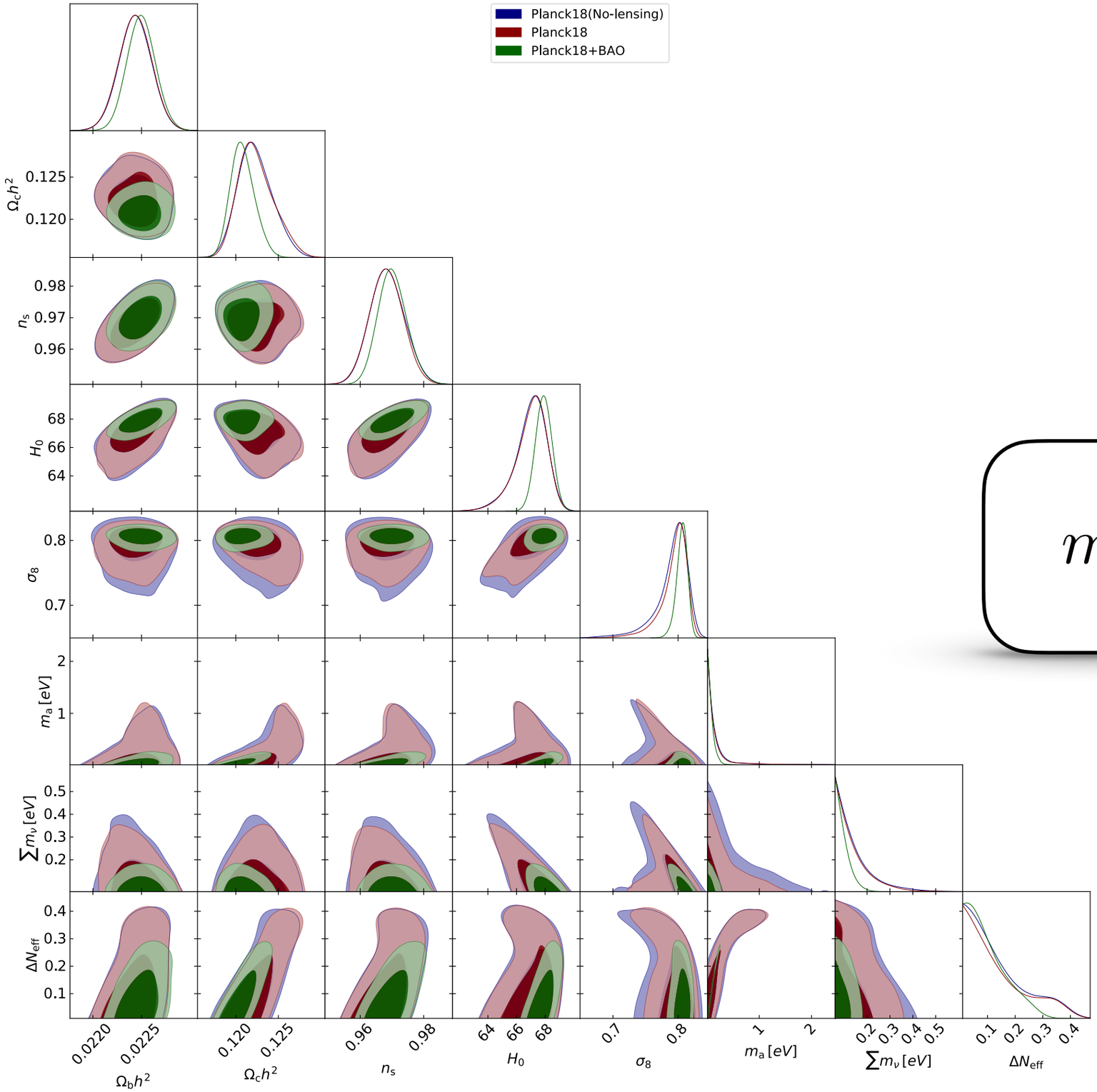
KSVZ Axion Mass Bound



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

FD, Di Valentino, Giarè, Hajkarim, Melchiorri, Mena, Renzi, Yun, arXiv:2205.07849

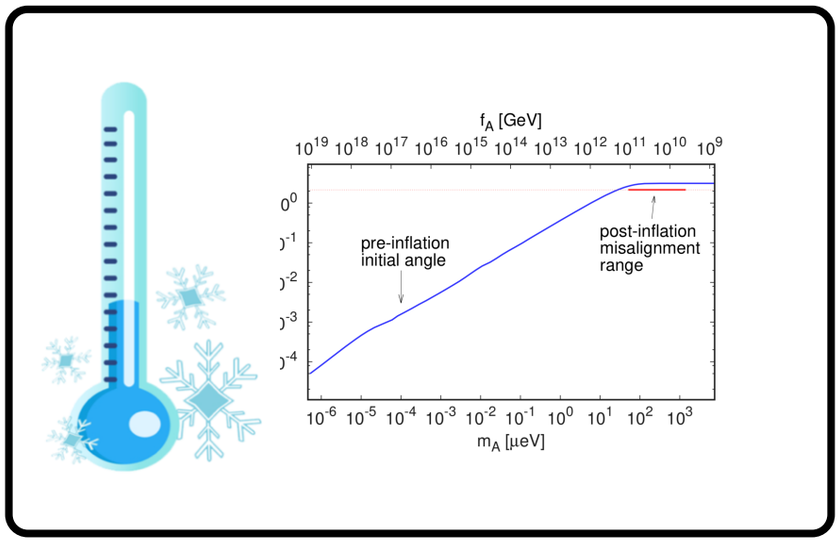
DFSZ Axion Mass Bound



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

FD, Di Valentino, Giarè, Hajkarim, Melchiorri, Mena, Renzi, Yun, arXiv:2205.07849

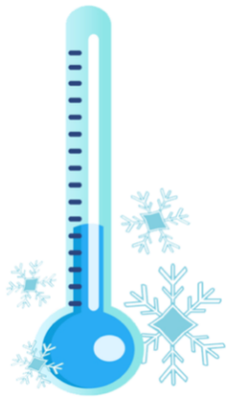
Outlook

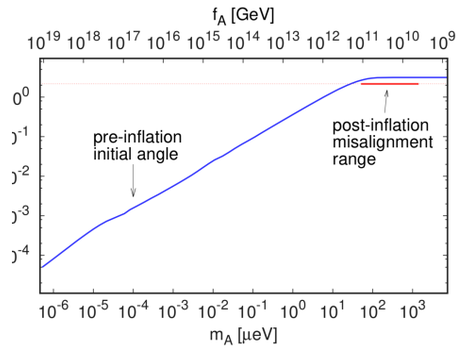


Peccei-Quinn Mechanism and the QCD Axion

Motivated and testable scenario
for physics beyond the standard model
rich of cosmological consequences

Outlook





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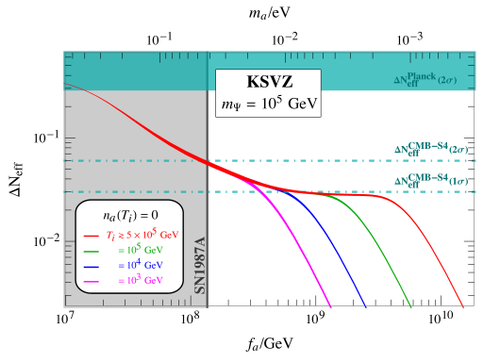
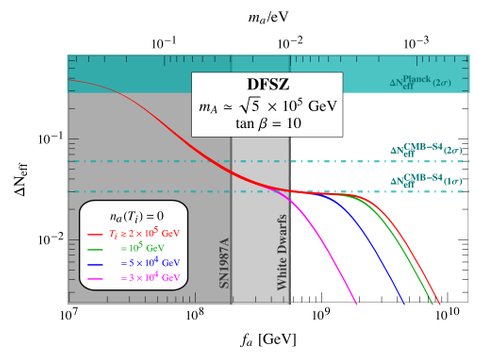
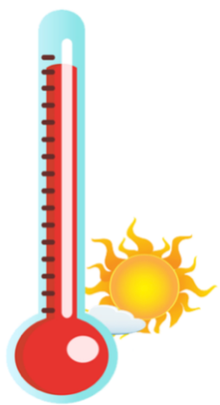
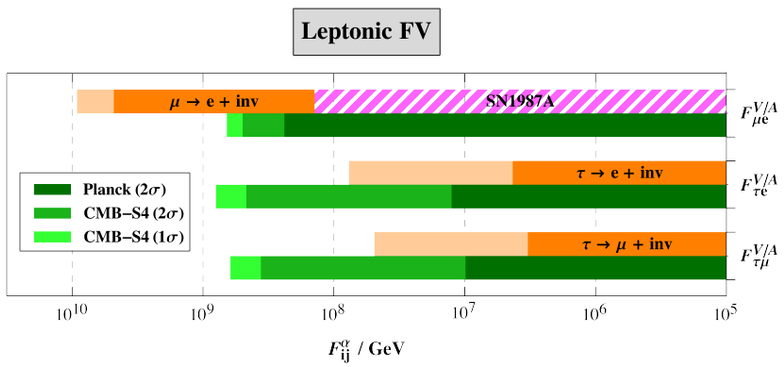
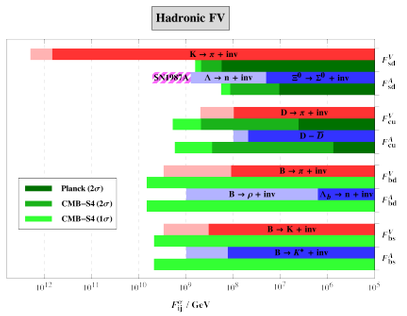
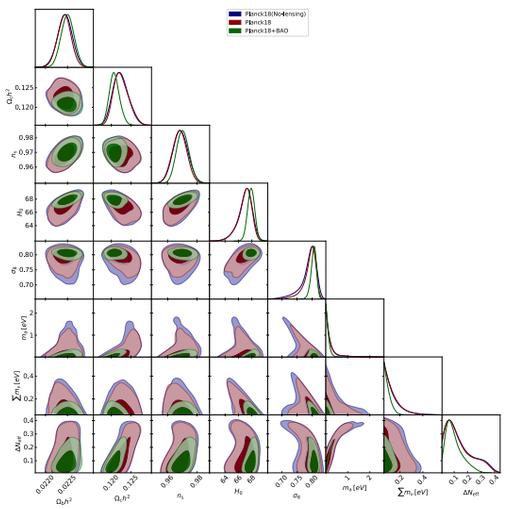








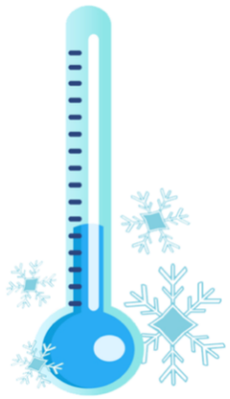


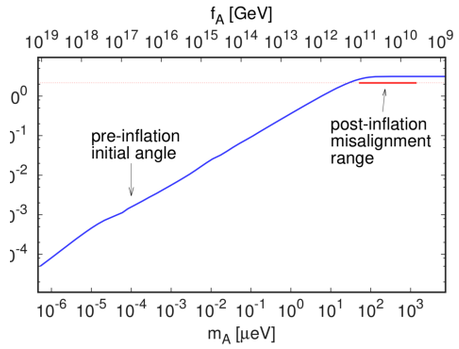


Thermal Axions

Complementary to other probes of the PQ mechanism

Outlook





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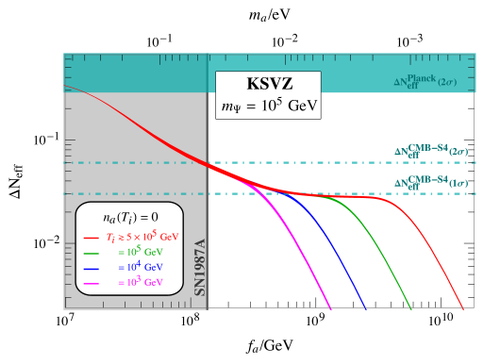

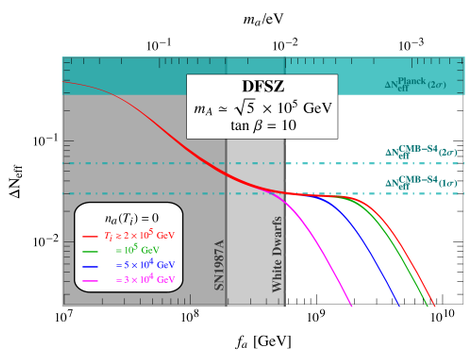

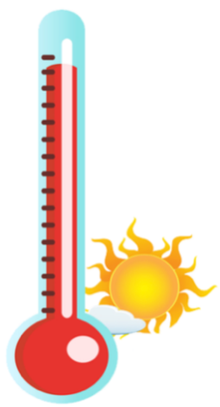

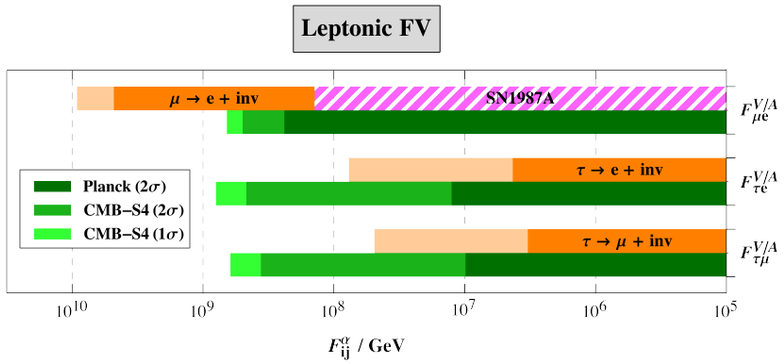

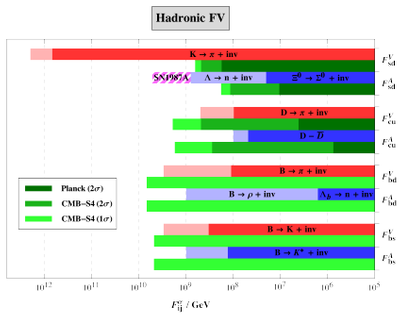

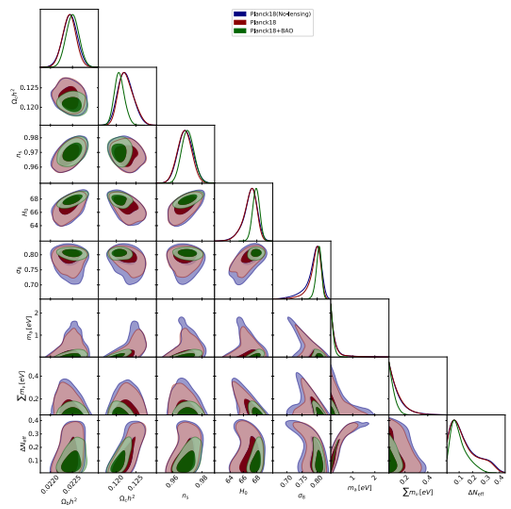

THANK YOU!