Thermal Axions: Production Mechanisms and Cosmological Signals

Francesco D’Eramo

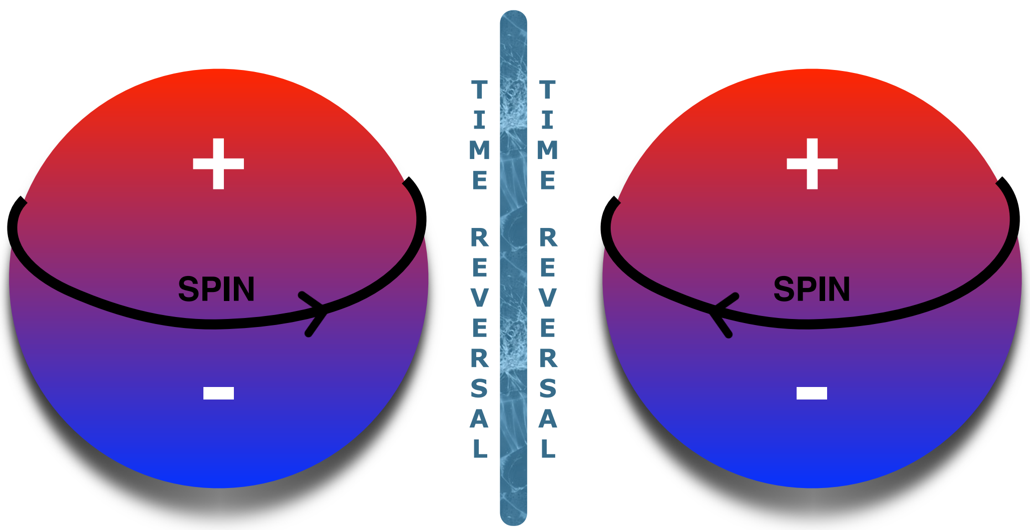
1222·2022 800 ANNI

Università degli Studi di Padova

INFN Istituto Nazionale di Fisica Nucleare Sezione di Padova

IJS-FMF high-energy physics seminar — Ljubljana, 2 June 2022

The Strong CP Problem



No detection of time reversal invariance violation by strong interactions

VS

Why is the θ parameter of the QCD Lagrangian so small?

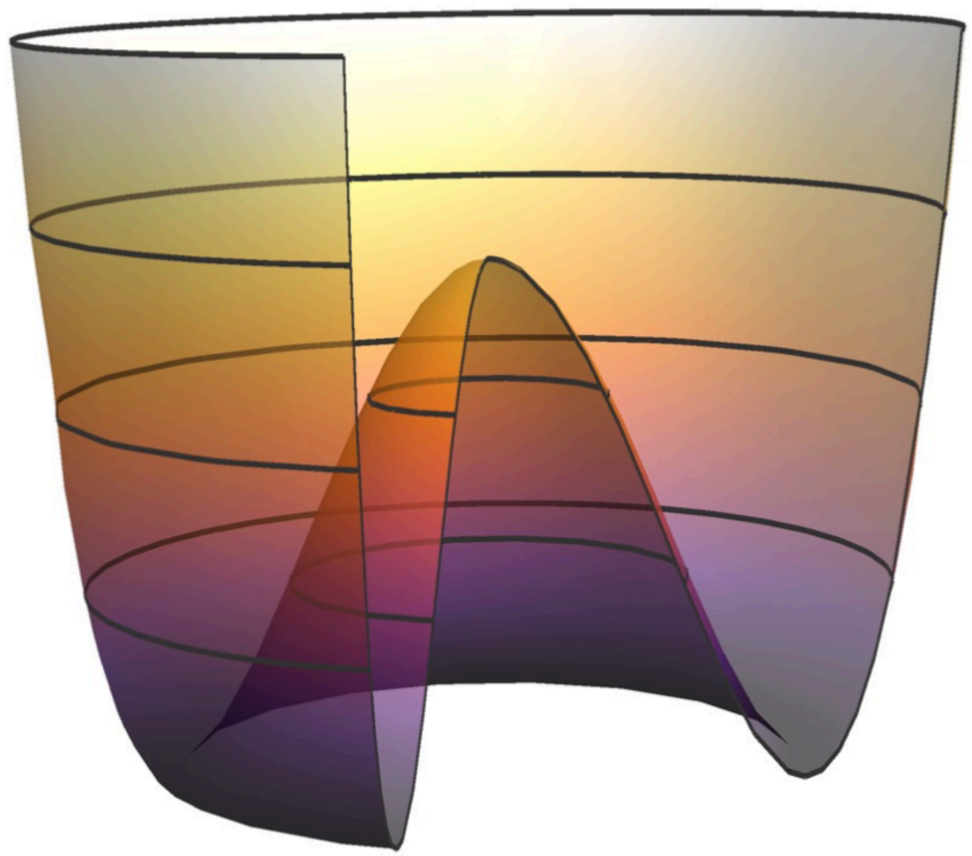
$$|\theta| \lesssim 10^{-10}$$

The Peccei-Quinn Mechanism

Dynamical solution to the strong CP problem

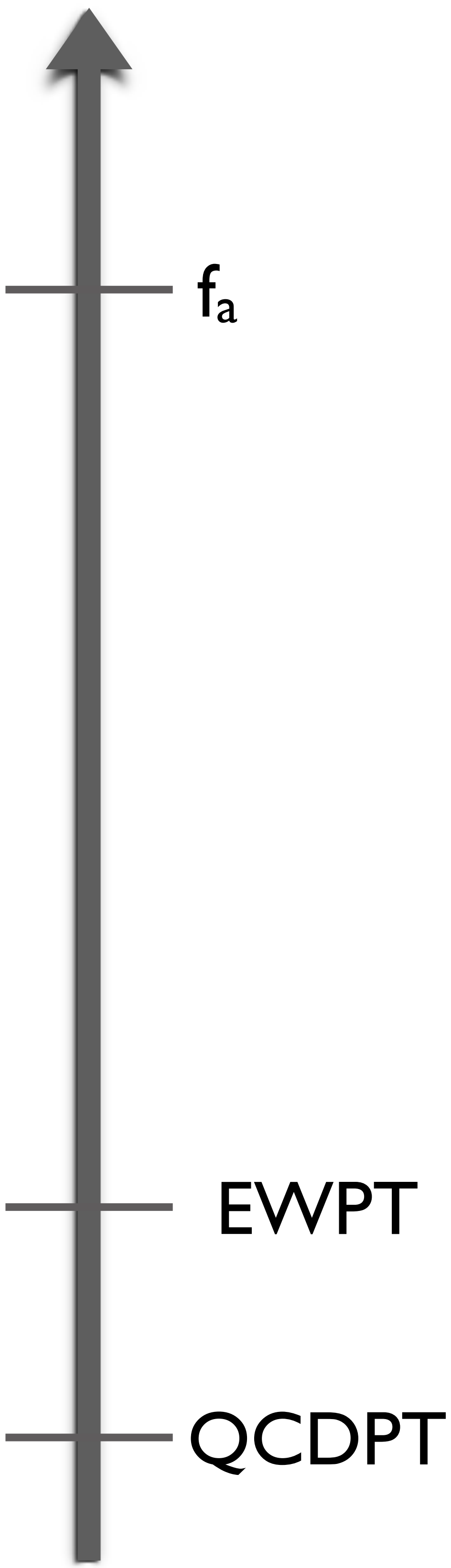
New global $U(1)_{PQ}$ symmetry

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



Peccei, Quinn, Phys.Rev.Lett. 38 (1977) and Phys.Rev.D 16 (1977)

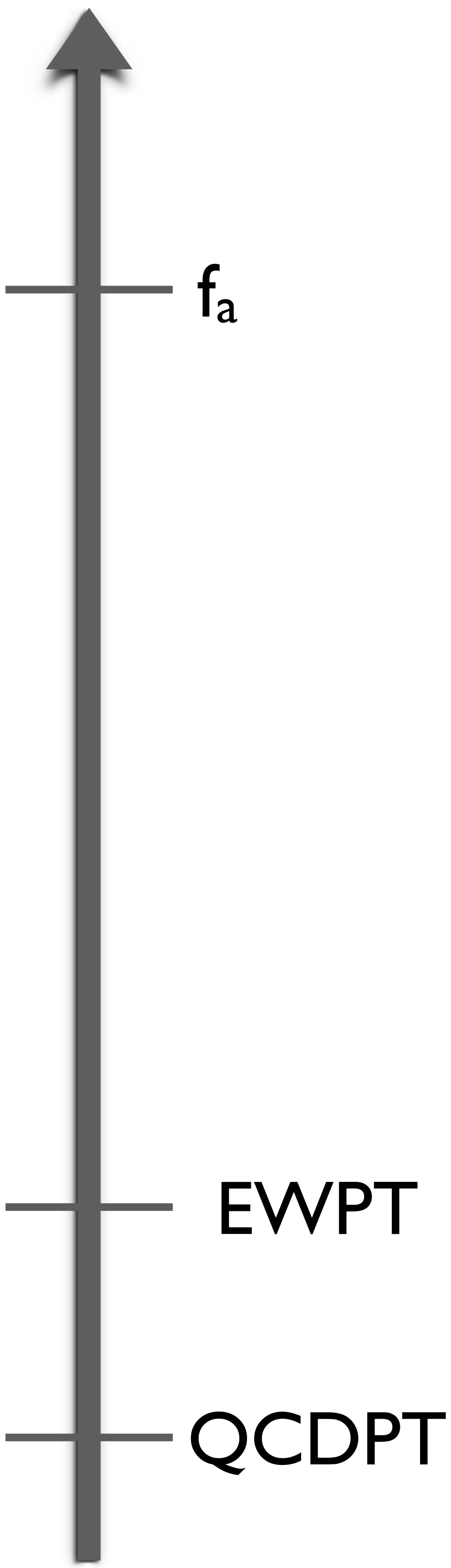
The Peccei-Quinn Mechanism



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

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

The Peccei-Quinn Mechanism



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

CP-conserving minimum!

Strong CP Problem Solved!

$$V(a) \simeq \frac{1}{2}m_a^2 a^2$$

The QCD Axion

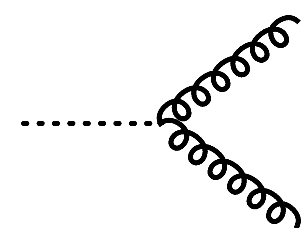
Axion (zero-temperature) mass from non-perturbative potential

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

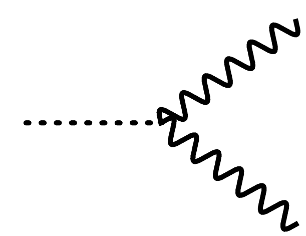
The QCD axion is very light!

- Anomalous coupling to gluons and (not mandatory) to EW gauge bosons
- Derivative couplings to fermions

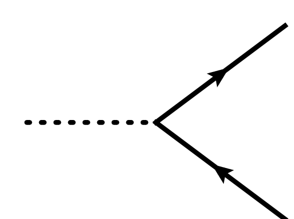
The QCD axion is very elusive!



$$\frac{g_s^2}{32\pi^2}\frac{a}{f} G^{\mu\nu}\tilde{G}_{\mu\nu}$$



$$c_{\gamma\gamma}\frac{e^2}{32\pi^2}\frac{a}{f} F^{\mu\nu}\tilde{F}_{\mu\nu}$$



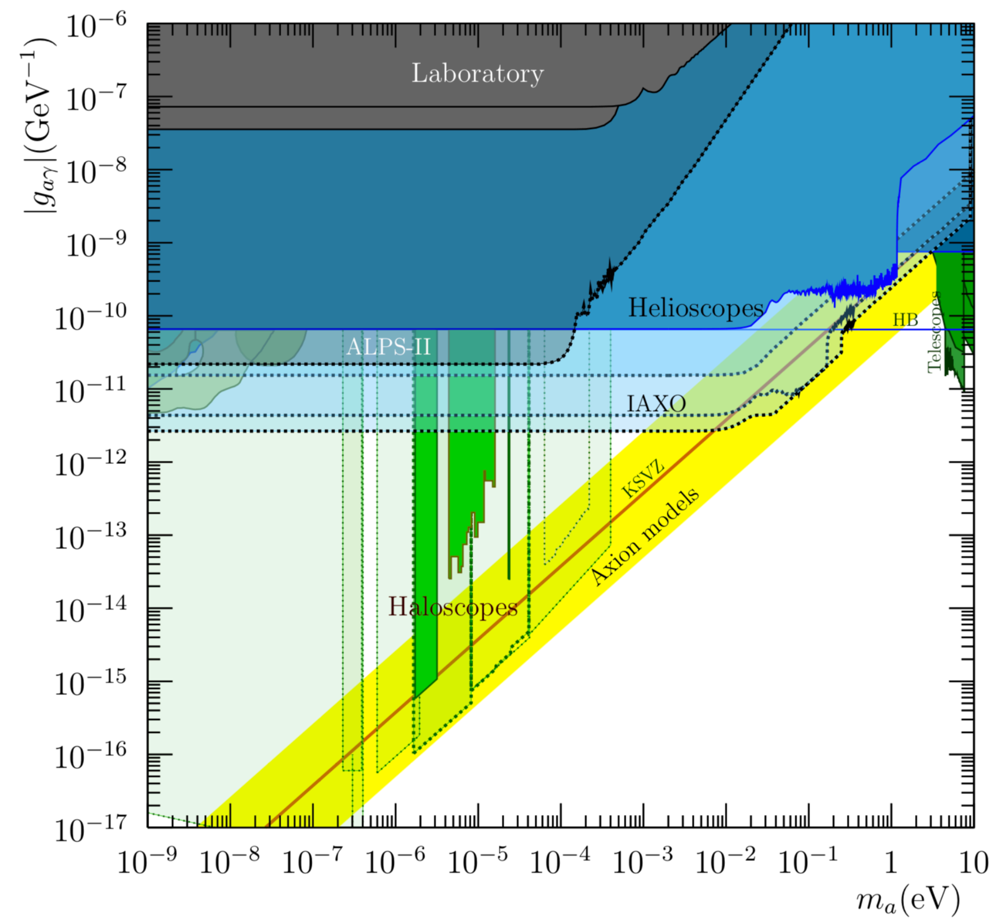
$$c_f \frac{\partial_\mu a}{f}\bar{f}\gamma^\mu\gamma^5 f$$

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

Axion Signals

Very light and weakly coupled:

- detection challenging
- prominent role in the early universe

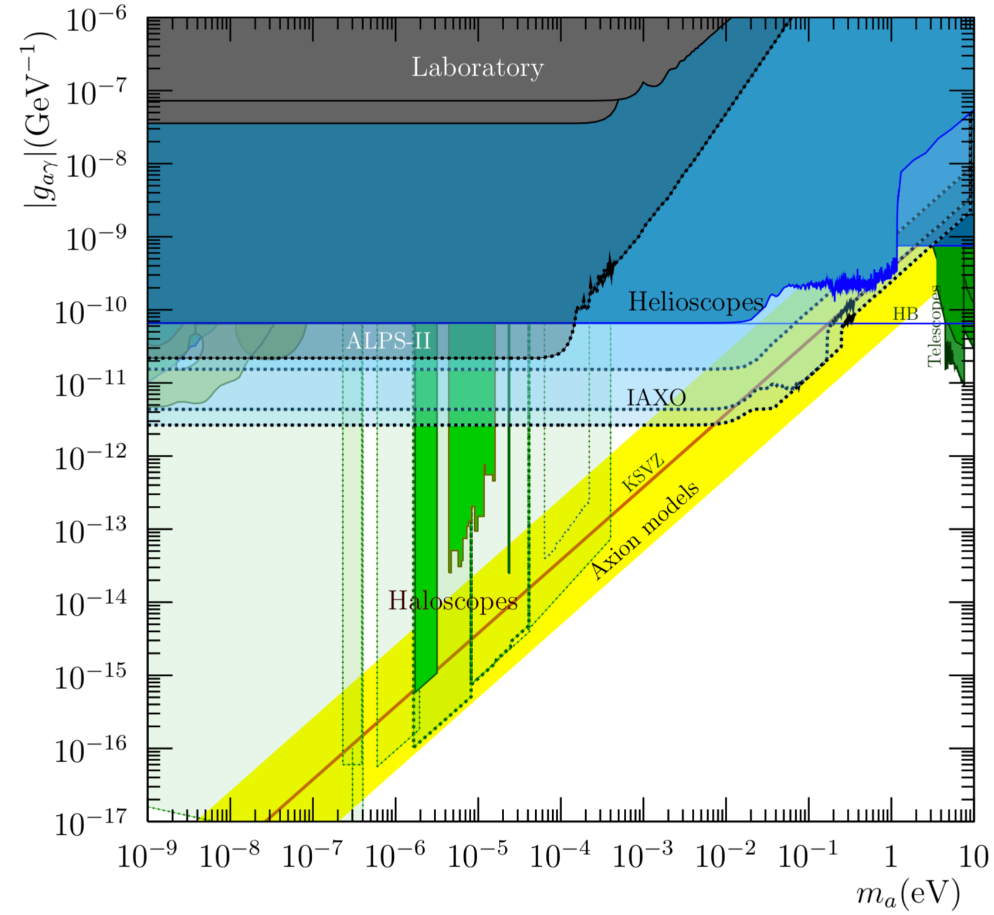


Irastorza and Redondo, Prog.Part.Nucl.Phys. 102 (2018)

Axion Signals

Very light and weakly coupled:

- detection challenging
- prominent role in the early universe

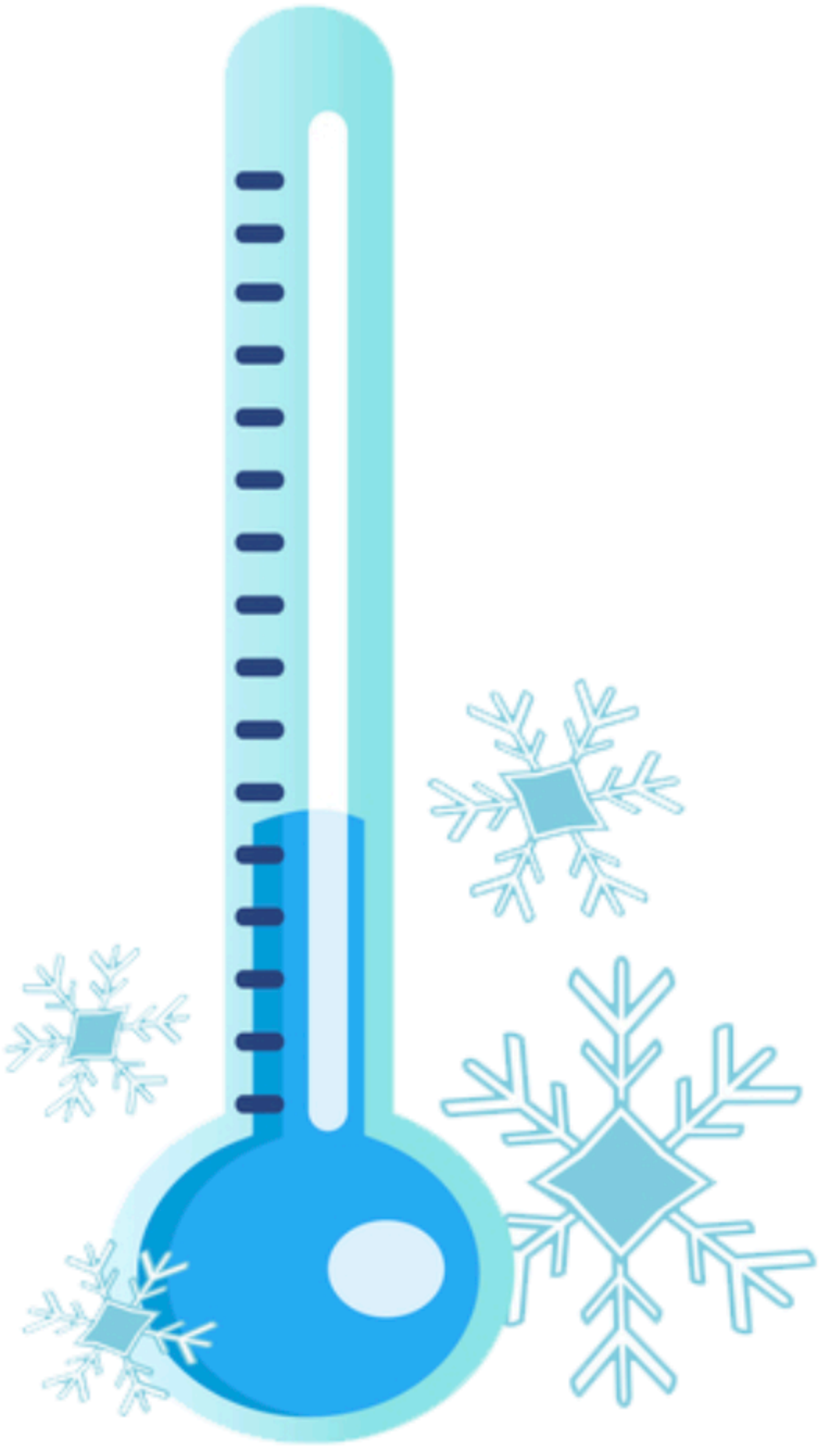


Irastorza and Redondo, Prog.Part.Nucl.Phys. 102 (2018)

In this talk:

Thermal (hot) axions in the early universe

How they are produced and their imprint in cosmological observables



Cold Axions

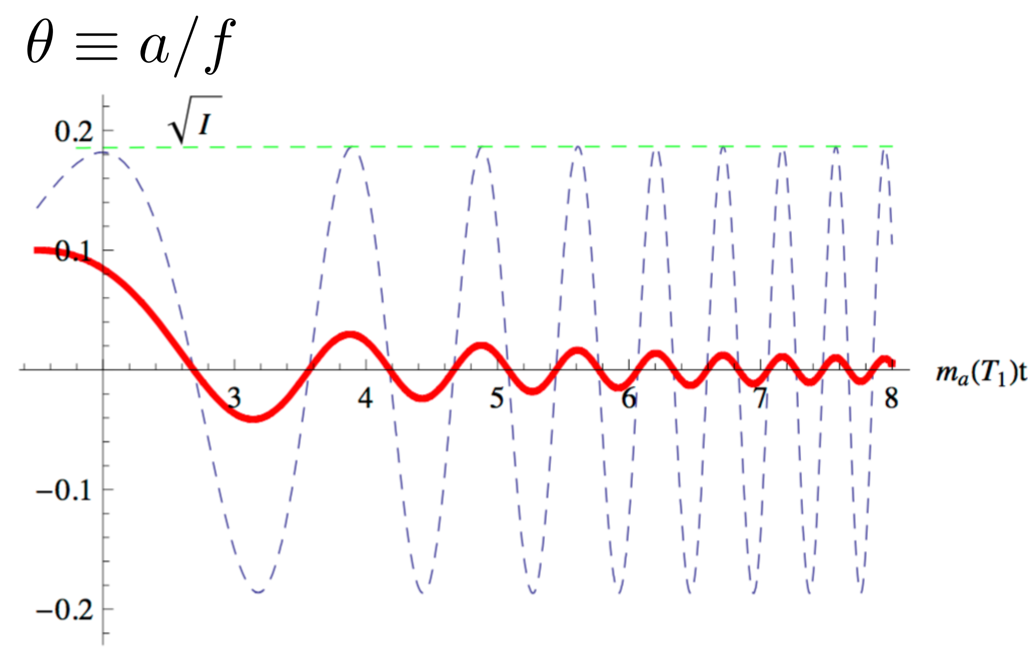
(Dark Matter)

Axion Dark Matter

Dark matter relic density gives us a hint about what f could be

$$\Omega_a h^2 \simeq 0.1\, \theta_i^2 \left(\frac{f}{10^{11}\,\mathrm{GeV}} \right)^{1.18}$$

Initial field value? It depends…



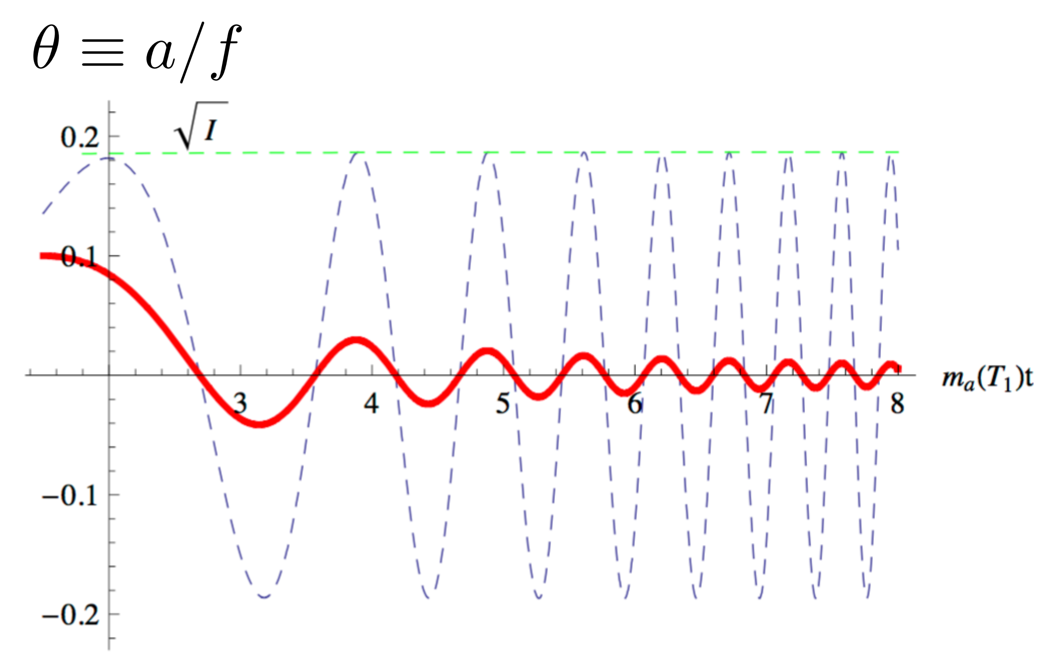
Bae, Huh, Kim, JCAP 0809 (2008)

Axion Dark Matter

Dark matter relic density gives us a hint about what f could be

$$\Omega_a h^2 \simeq 0.1\,\theta_i^2 \left(\frac{f}{10^{11}\,\mathrm{GeV}}\right)^{1.18}$$

Initial field value? It depends…



Bae, Huh, Kim, JCAP 0809 (2008)

Was PQ broken during inflation?

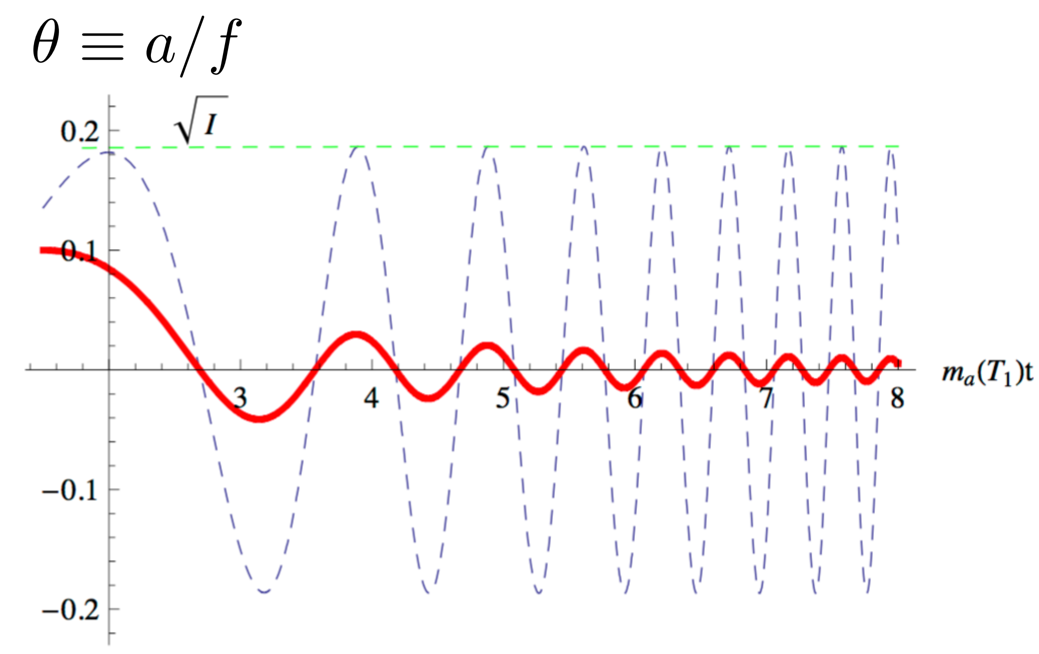
If yes, was it restored afterward?

Axion Dark Matter

Dark matter relic density gives us a hint about what f could be

$$\Omega_a h^2 \simeq 0.1\, \theta_i^2 \left(\frac{f}{10^{11}\,\mathrm{GeV}} \right)^{1.18}$$

Initial field value? It depends…



Bae, Huh, Kim, JCAP 0809 (2008)

Pre-Inflation

Single initial field value

Relic density depends on f and θ_i

Misalignment only

Post-Inflation

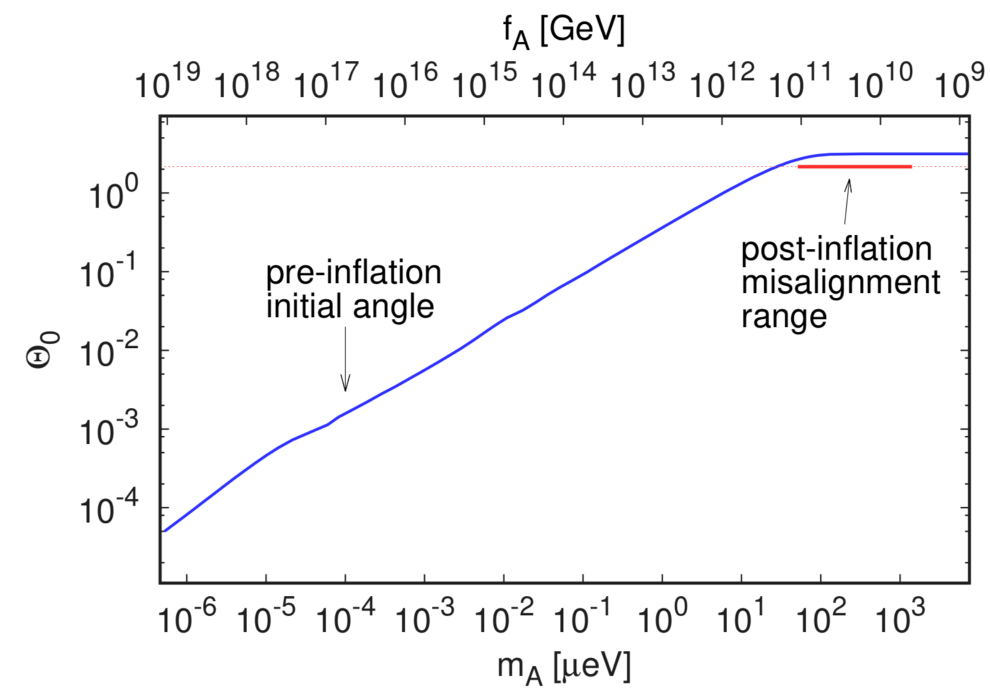
Average over initial field value

Relic density depends on f only

Misalignment + Topological defects

Axion Dark Matter

- PRE: initial field value unknown leads to a relation between θ and f (i.e. m_a)
- POST: uncertain topological defects contribution leads to a range for f (i.e. m_a)

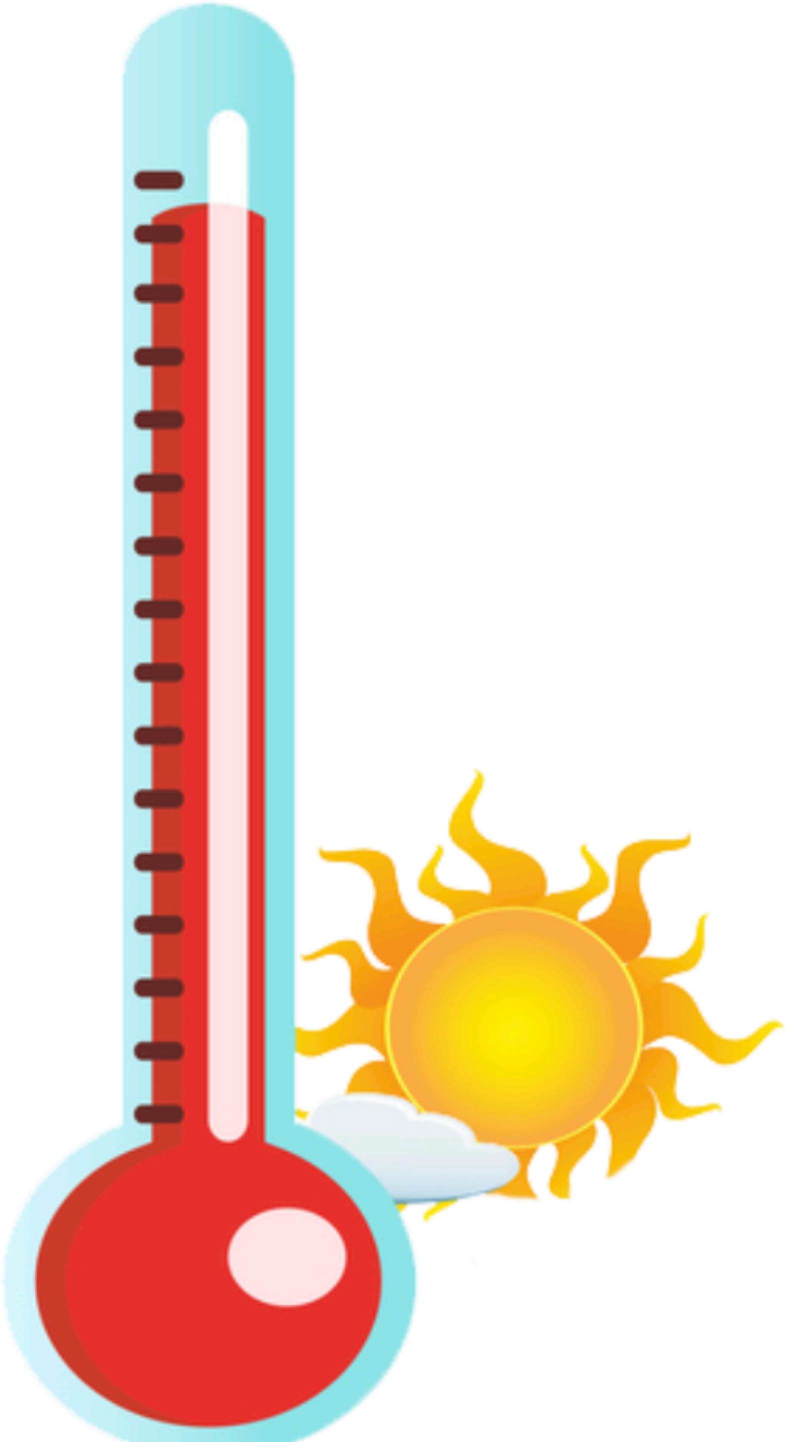


Borsanyi et al., Nature 539 (2016)

Motivated range for f (<u>with caveats</u>):

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

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



Hot Axions

(Dark Radiation)

Thermal Axions

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

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

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

Thermal Axions

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

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

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

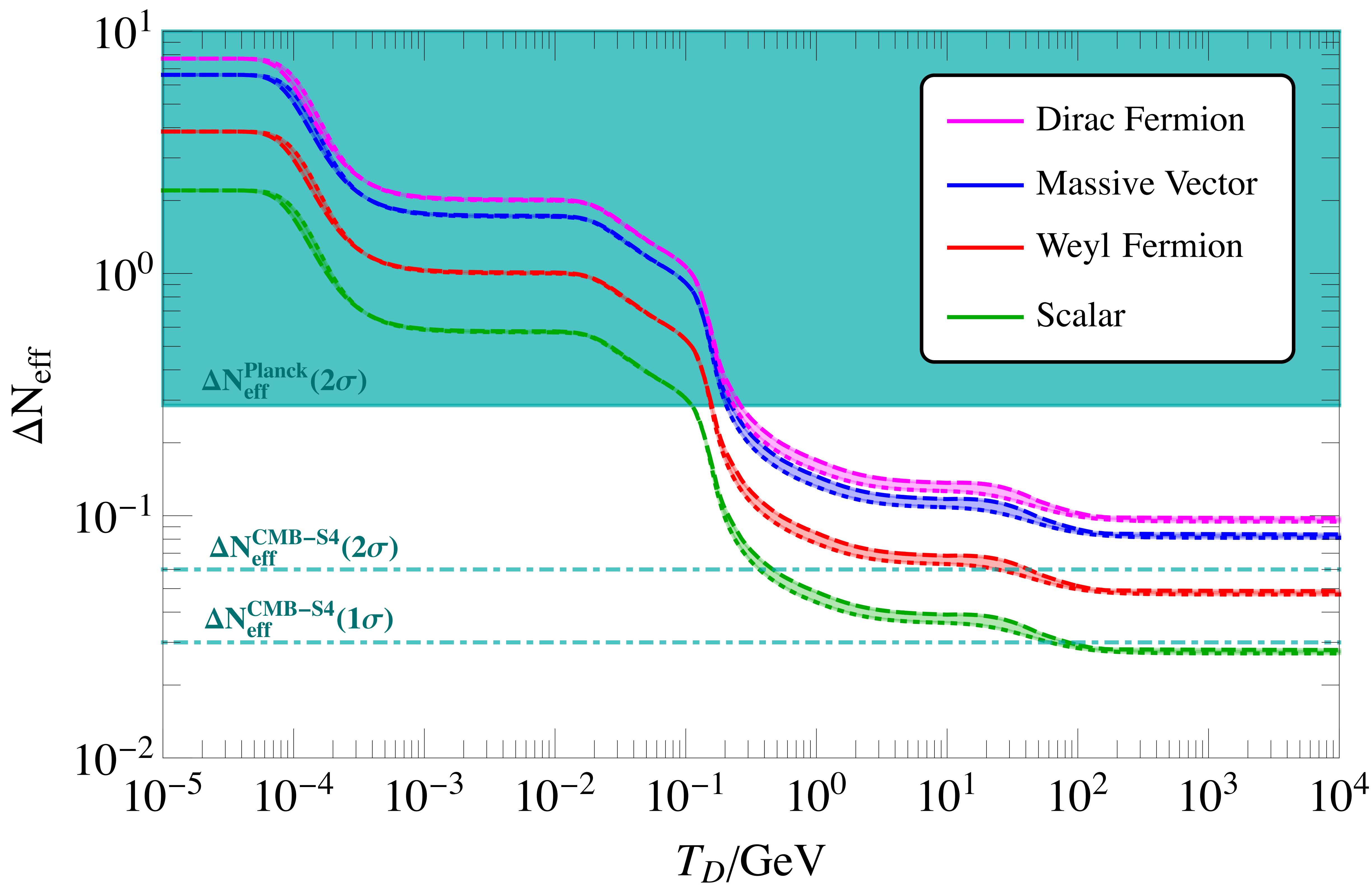
Additional radiation at:

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

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

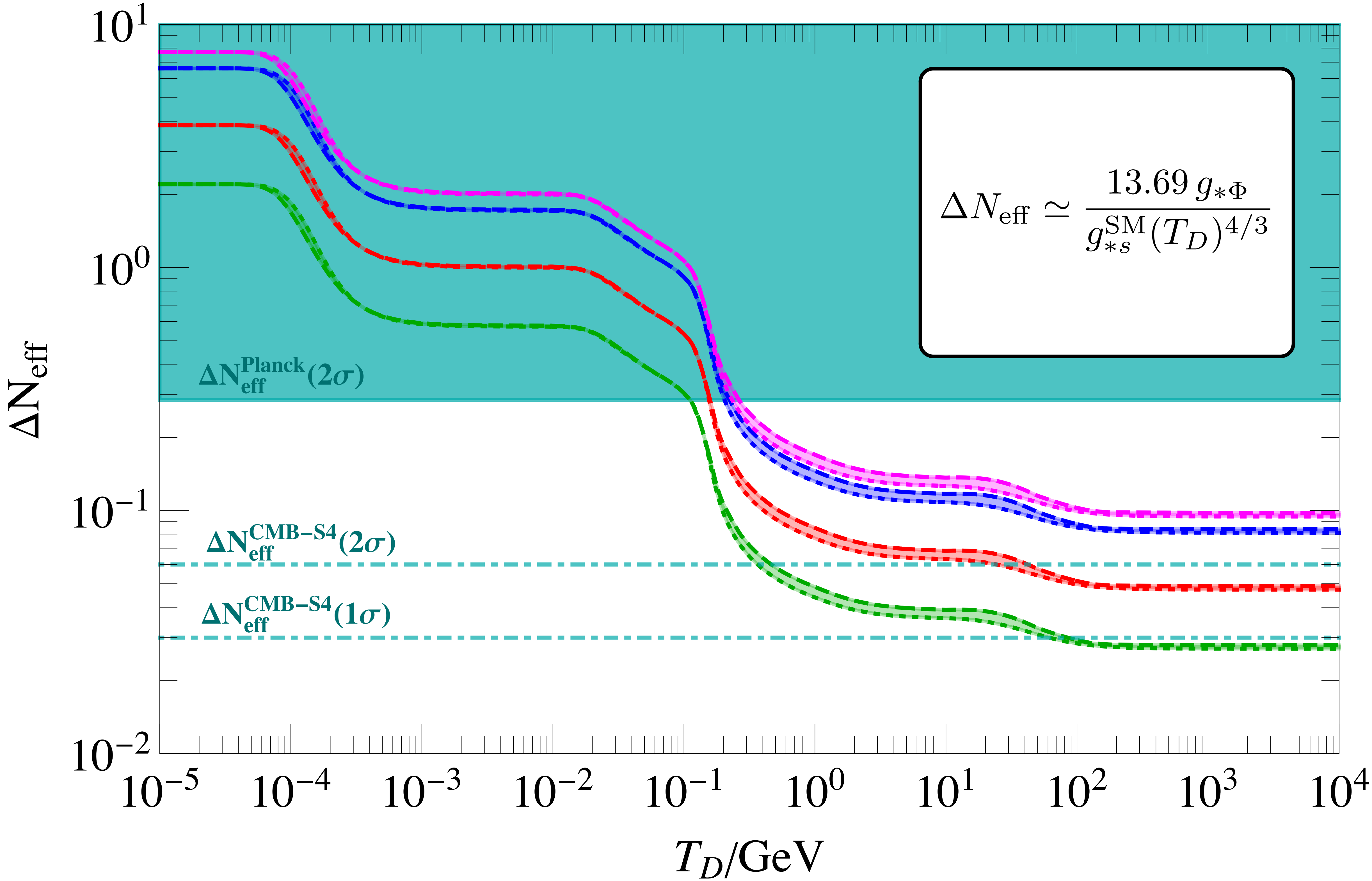
$$\Delta N_{\rm eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_a}{\rho_\gamma}$$

Dark Radiation in the CMB



FD, Hajkarim, Yun, JHEP 10 (2021)

Dark Radiation in the CMB

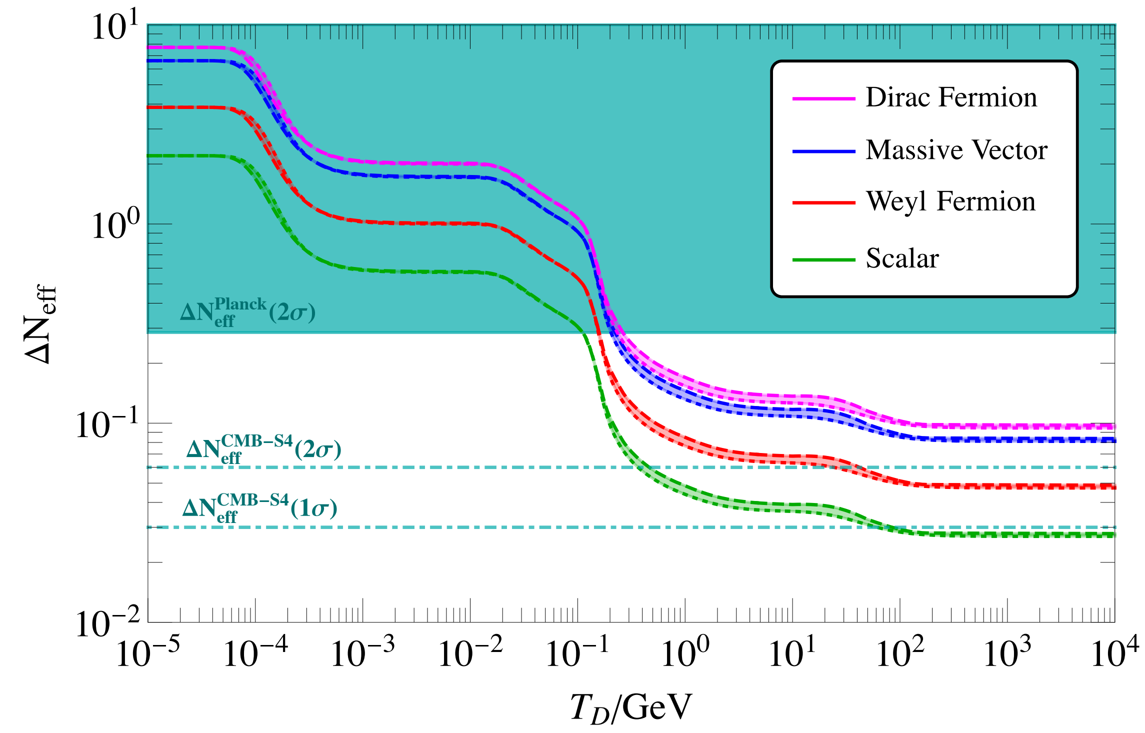


FD, Hajkarim, Yun, JHEP 10 (2021)

Predicting ΔN_{eff}

Axions may never thermalize

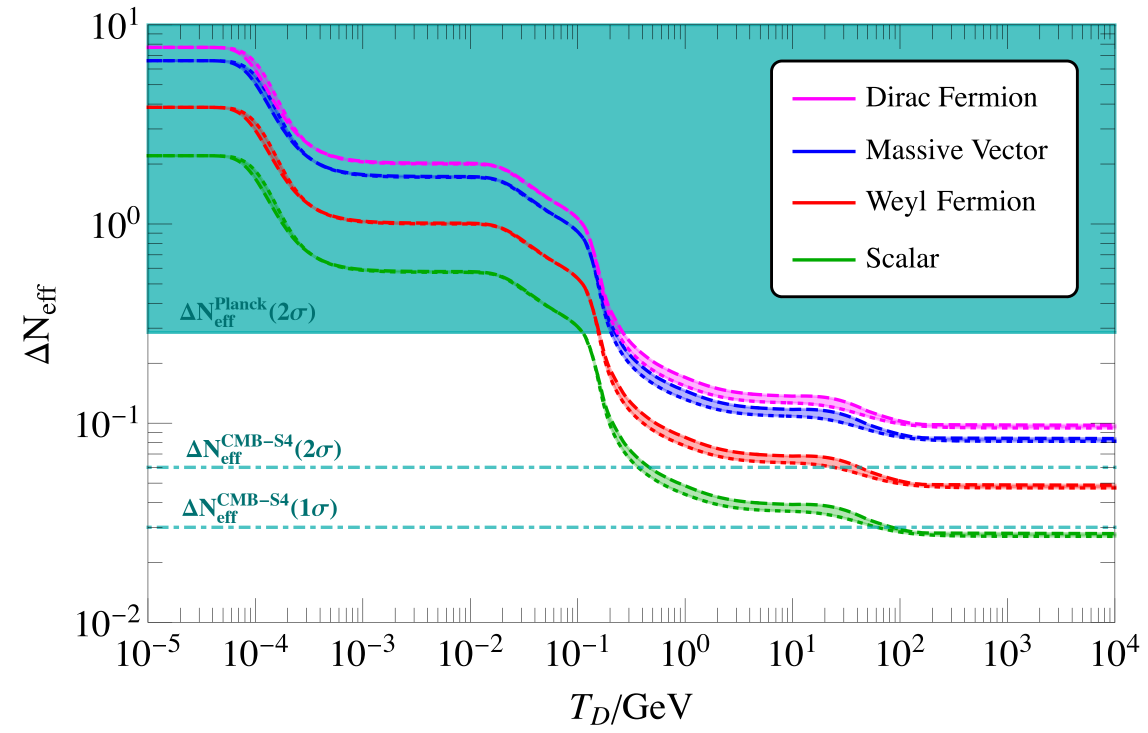
If they do, decoupling detail relevant
(effect larger the experimental error)



Predicting ΔN_{eff}

Axions may never thermalize

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



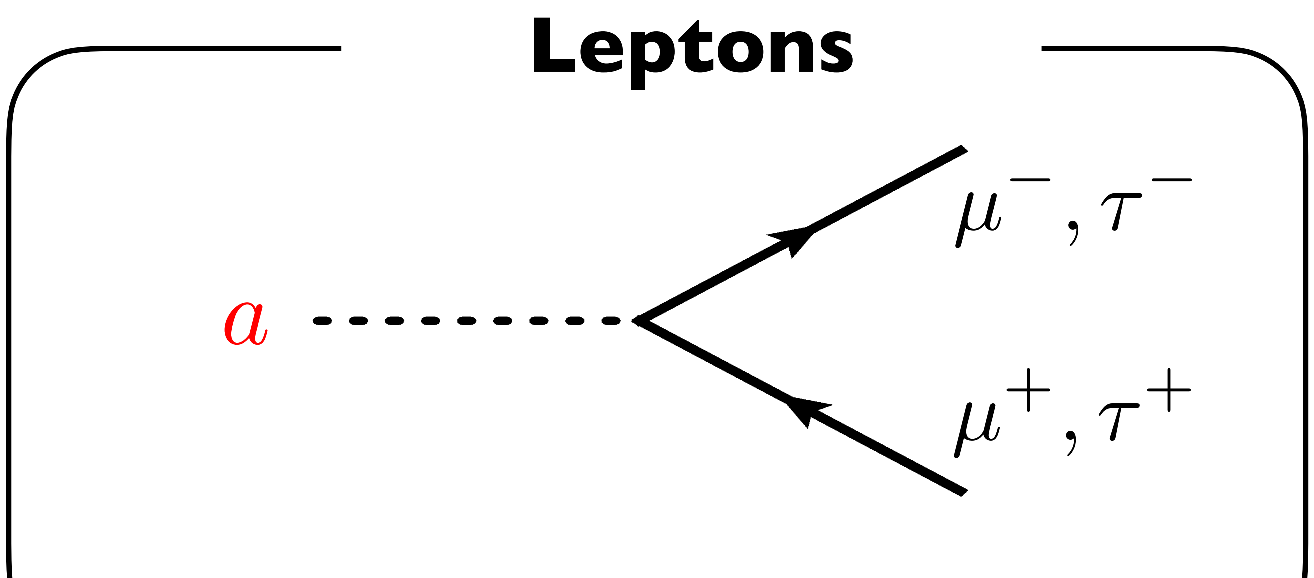
$$\frac{dn_a}{dt} + 3Hn_a = \sum_\alpha \gamma_\alpha$$

Right-hand side: processes changing number of axions

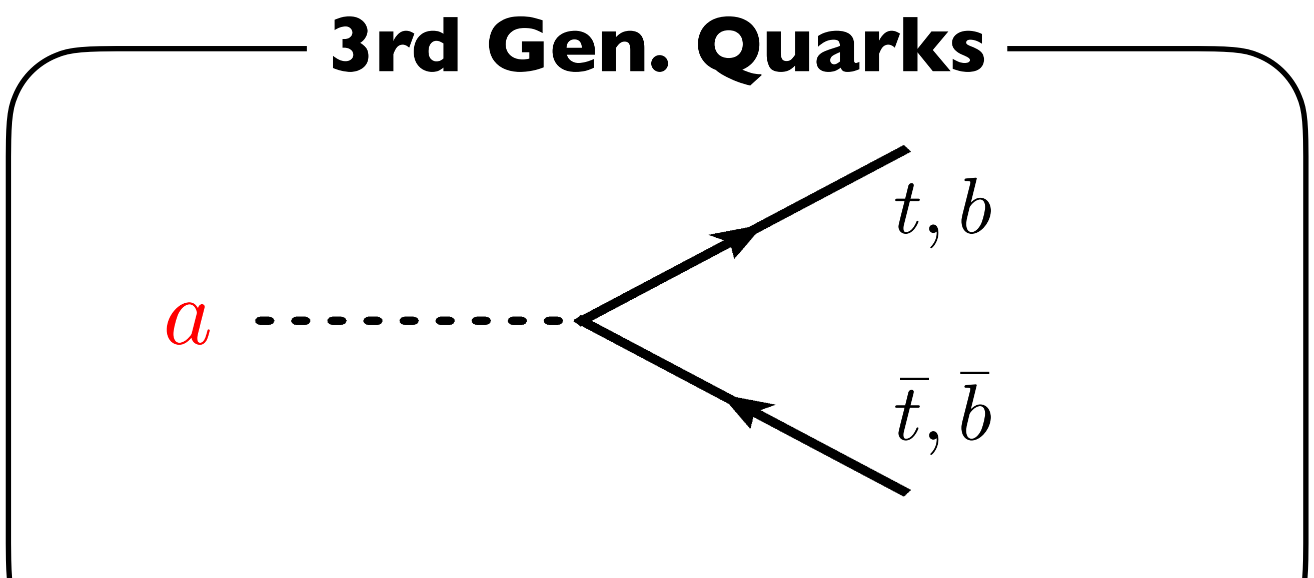
$$\Delta N_{\rm eff} = \frac{4}{7}\left(\frac{11}{4}\right)^{4/3} \left[\frac{2\pi^4 g_{*s}^{\rm CMB}}{45\zeta(3)} Y_a\right]^{4/3} \simeq 74.85\, Y_a^{4/3}$$

$$Y_a \equiv \frac{n_a}{s}$$

Production Mechanisms



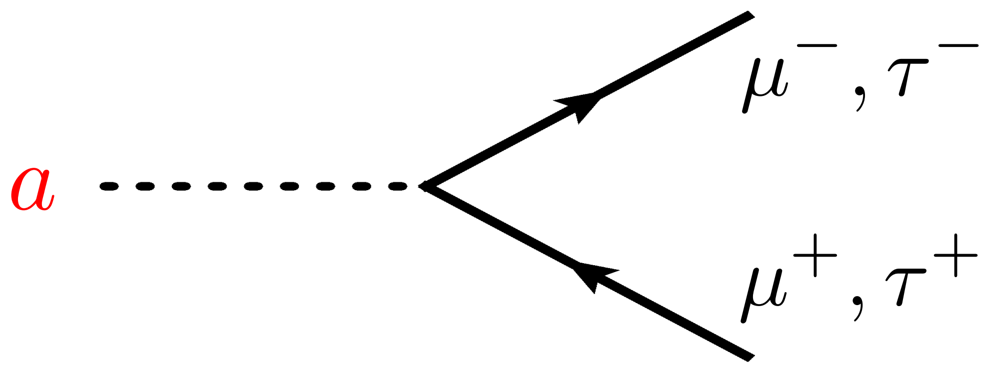
FD, Ferreira, Notari, Bernal, JCAP 1811 (2018)



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

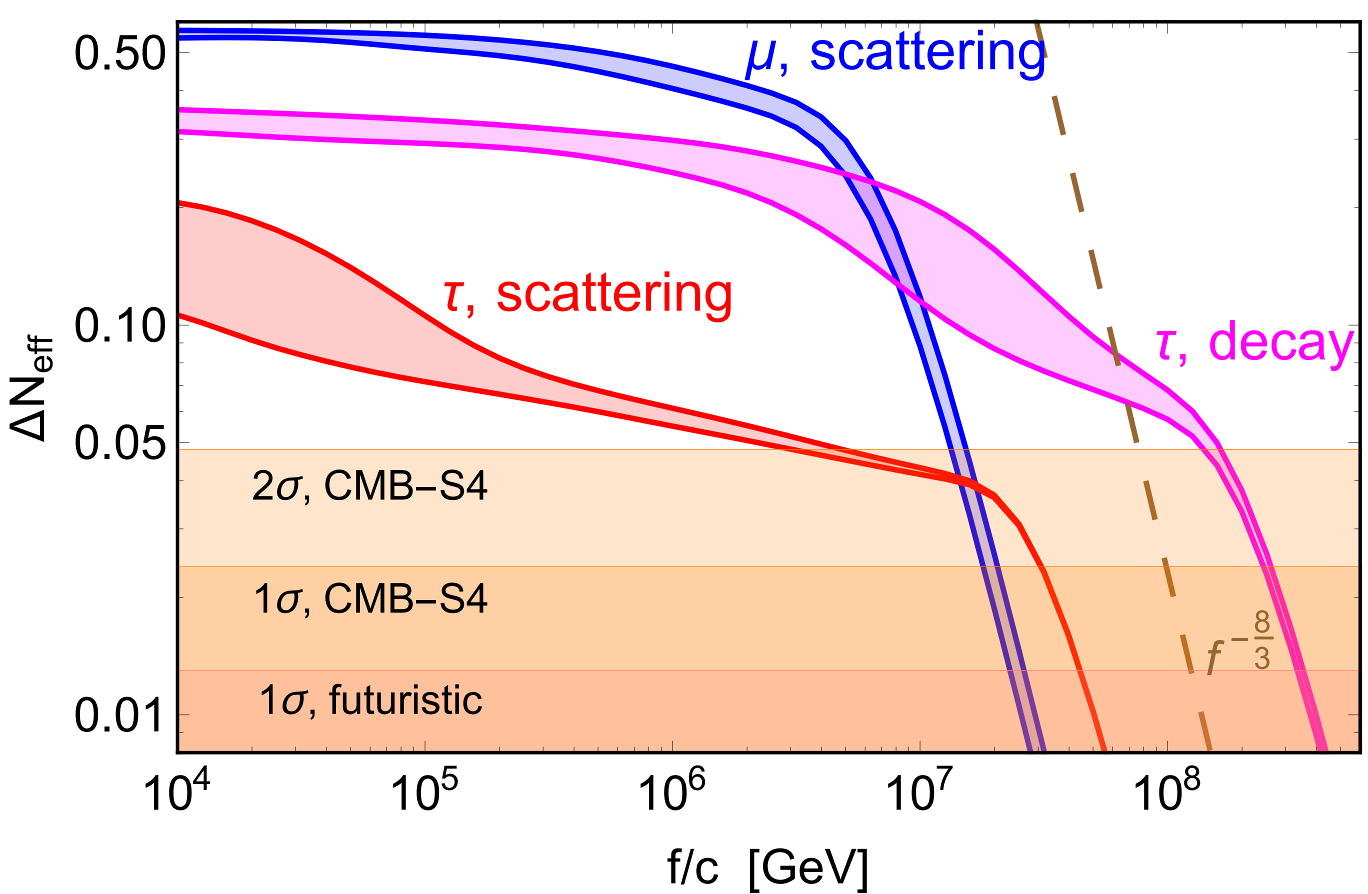
Production Mechanisms

Leptons



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

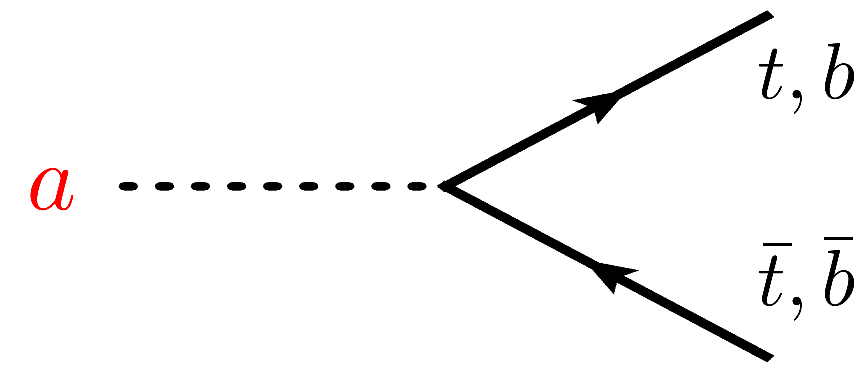
They can alleviate the Hubble tension



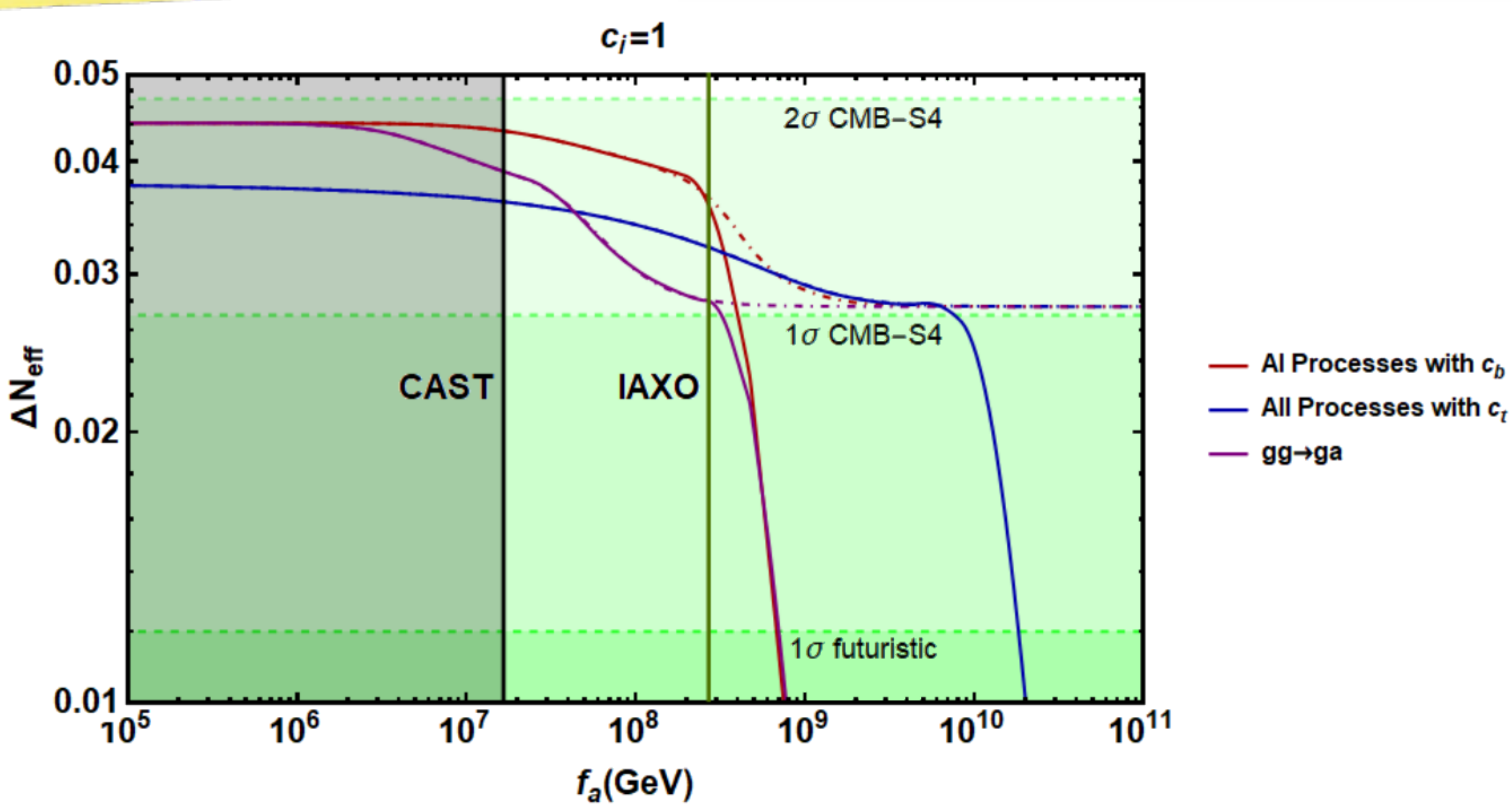
Production Mechanisms

Within the reach of CMB-S4 surveys

3rd Gen. Quarks

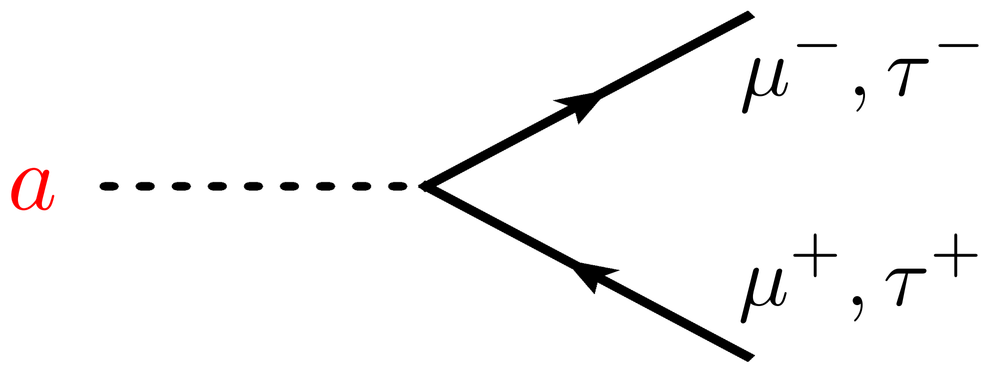


Arias-Aragon, FD, Ferreira, Merlo, Notari, JCAP 03 (2021)



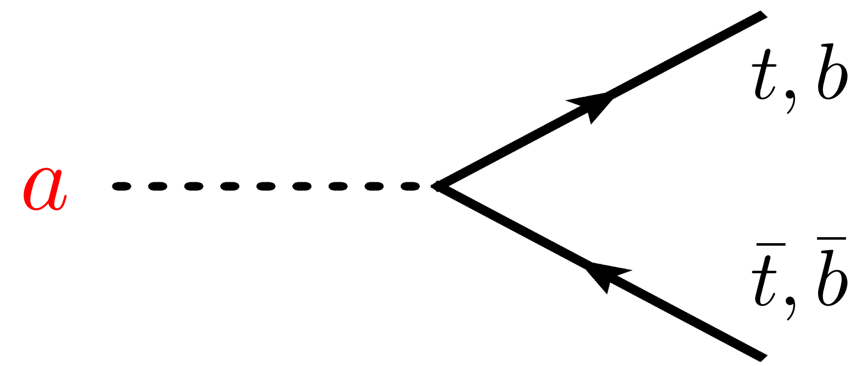
Production Mechanisms

Leptons



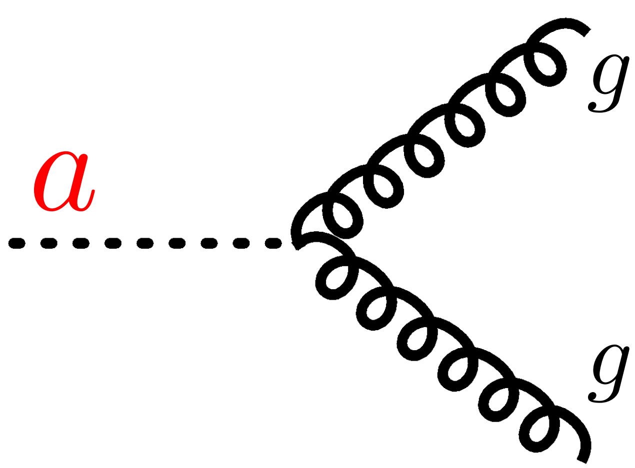
FD, Ferreira, Notari, Bernal, JCAP 1811 (2018)

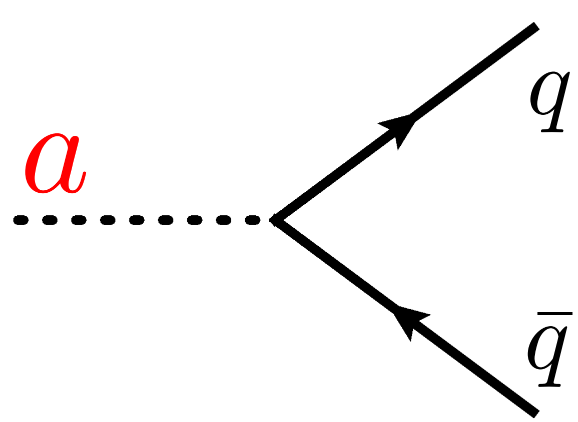
3rd Gen. Quarks



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

1st and 2nd Gen. Quarks and Gluons

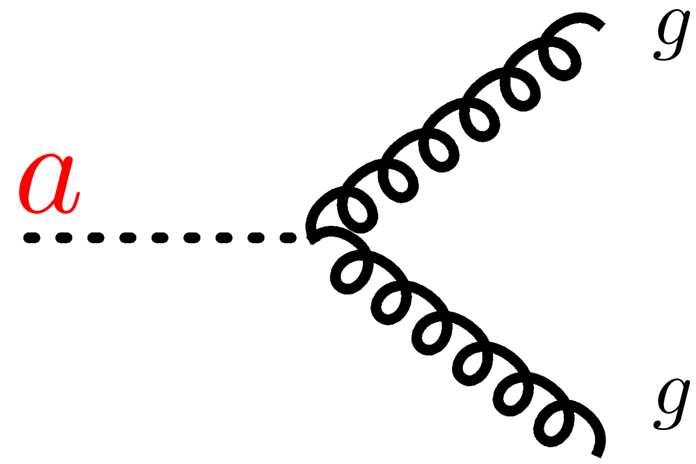




QCD phase transition cannot be ignored

FD, Hajkarim, Yun, Phys.Rev.Lett. 128 (2022)
FD, Hajkarim, Yun, JHEP 10 (2021)

Gluon coupling



FD, Hajkarim, Yun, Phys.Rev.Lett. 128 (2022) 15

Model Independent Contribution

Strong CP Problem

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

Model Independent Contribution

Strong CP Problem

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

Above QCDPT

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

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)

Model Independent Contribution

Strong CP Problem

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

Above QCDPT

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

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 QCDPT

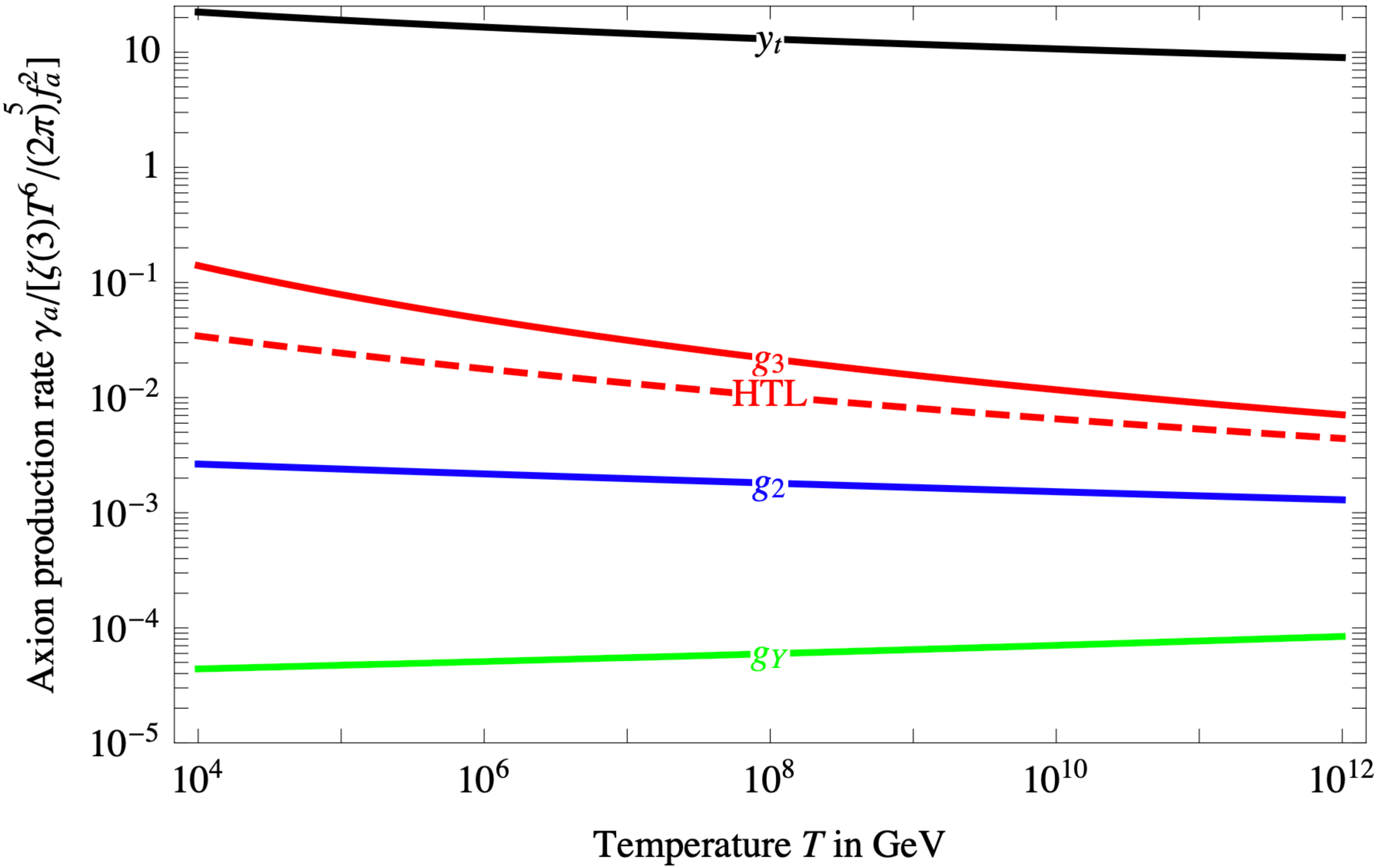
$$\pi\pi \to \pi a$$

Thermalization via pion scattering requires rather small values of f_a

Perturbative control only for T < 62 MeV

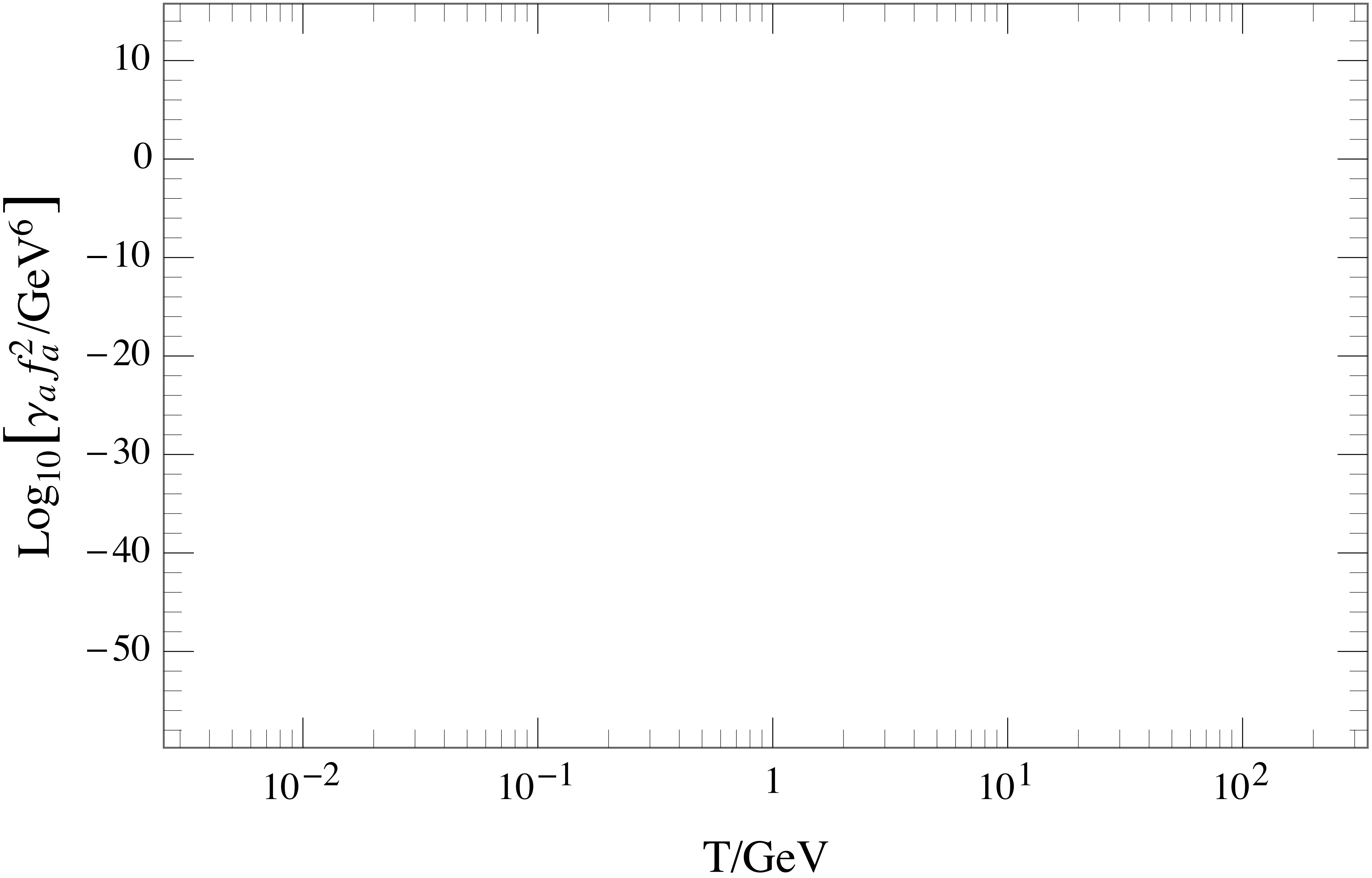
Phys.Lett.B 316 (1993)
Di Luzio, Martinelli, Piazza, Phys.Rev.Lett. 126 (2021)

Thermal Gluon Scattering



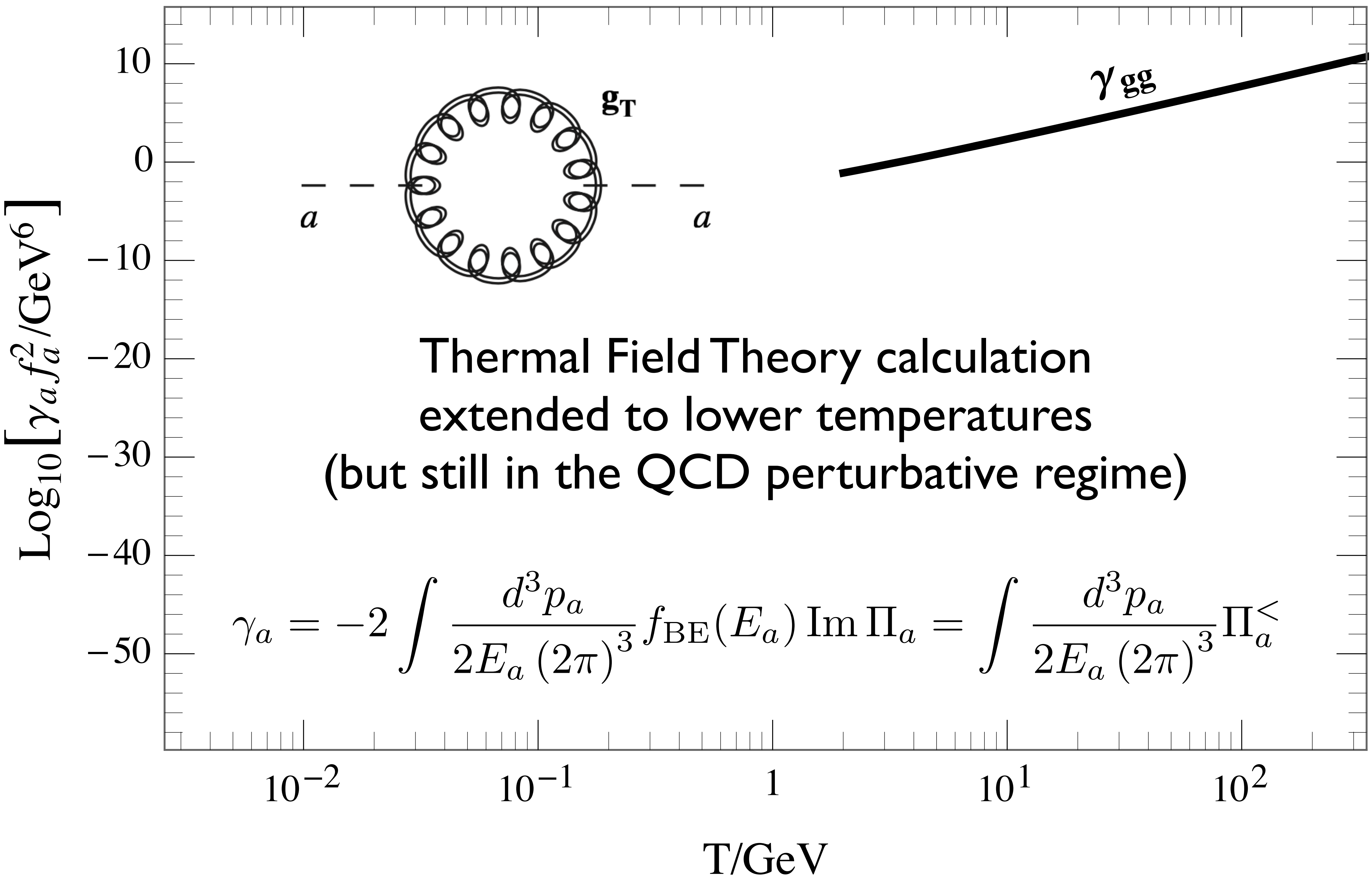
Salvio, Strumia, Xue, JCAP 01 (2014)

Rate Across the QCDPT



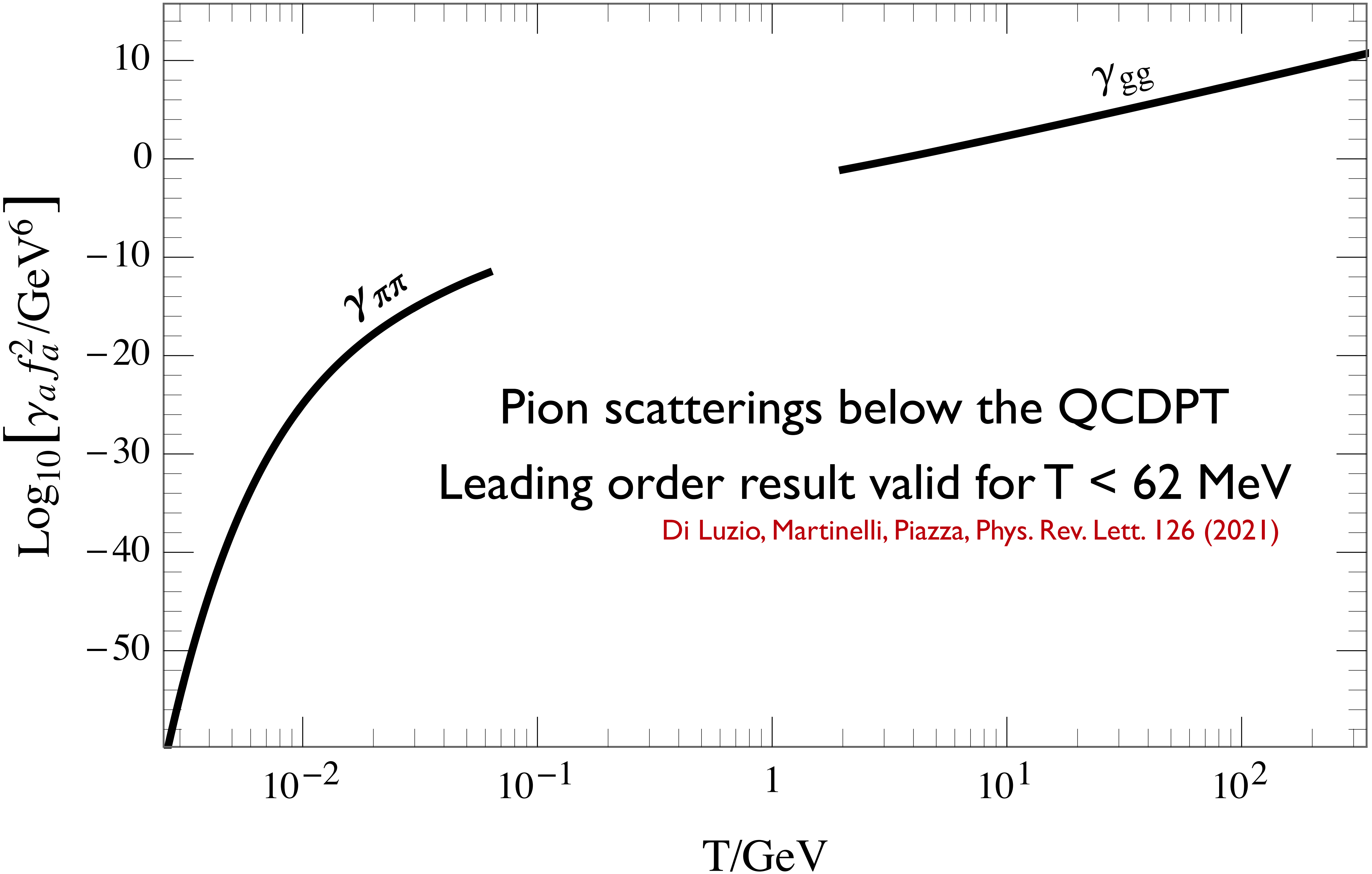
FD, Hajkarim, Yun, Phys.Rev.Lett. 128 (2022)

Rate Across the QCDPT



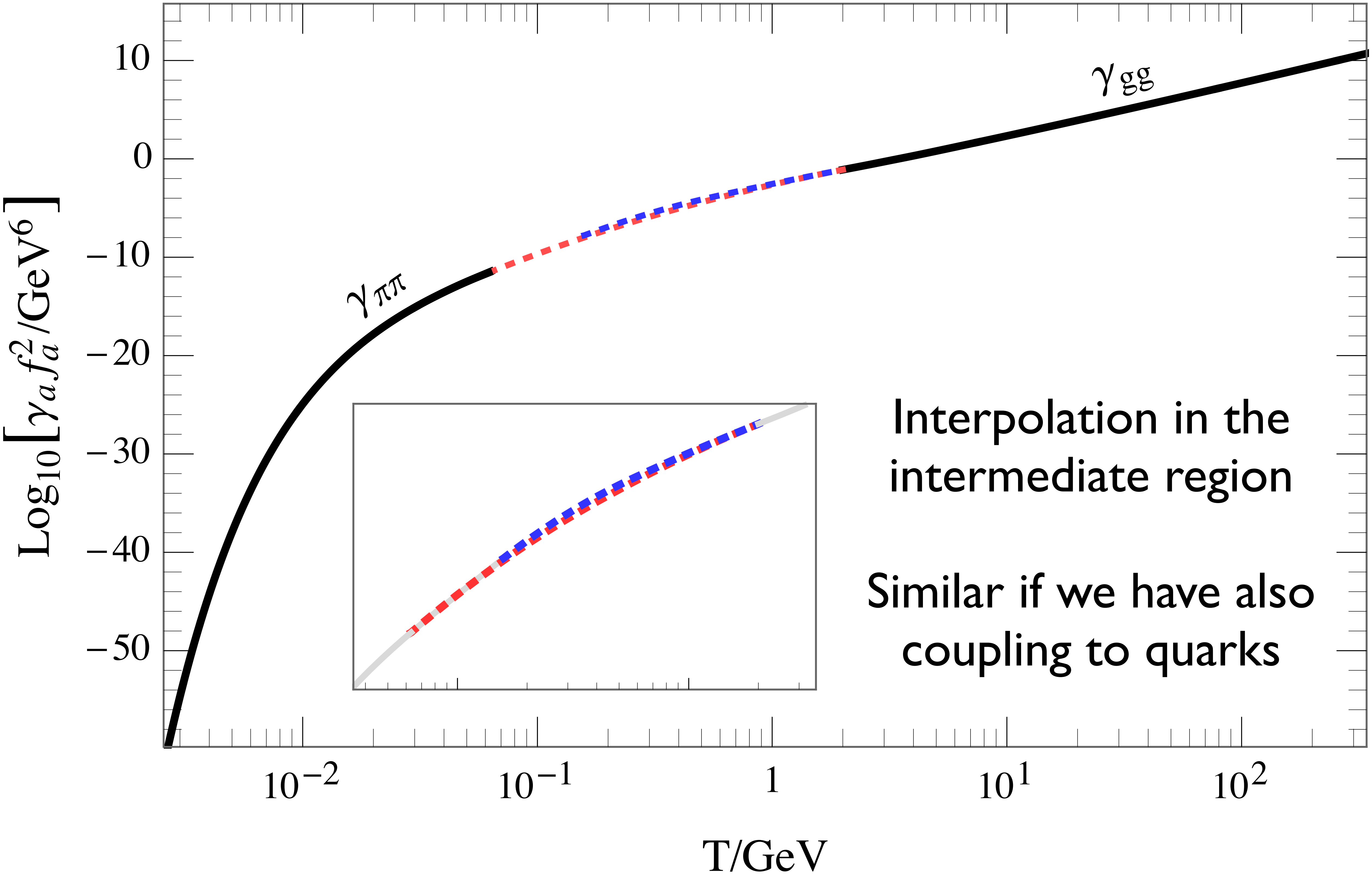
FD, Hajkarim, Yun, Phys.Rev.Lett. 128 (2022)

Rate Across the QCDPT



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

Rate Across the QCDPT



Interpolation in the intermediate region

Similar if we have also coupling to quarks

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

UV Completions

FD, Hajkarim, Yun, JHEP 10 (2021)

KSVZ Axion — Theory

Energy

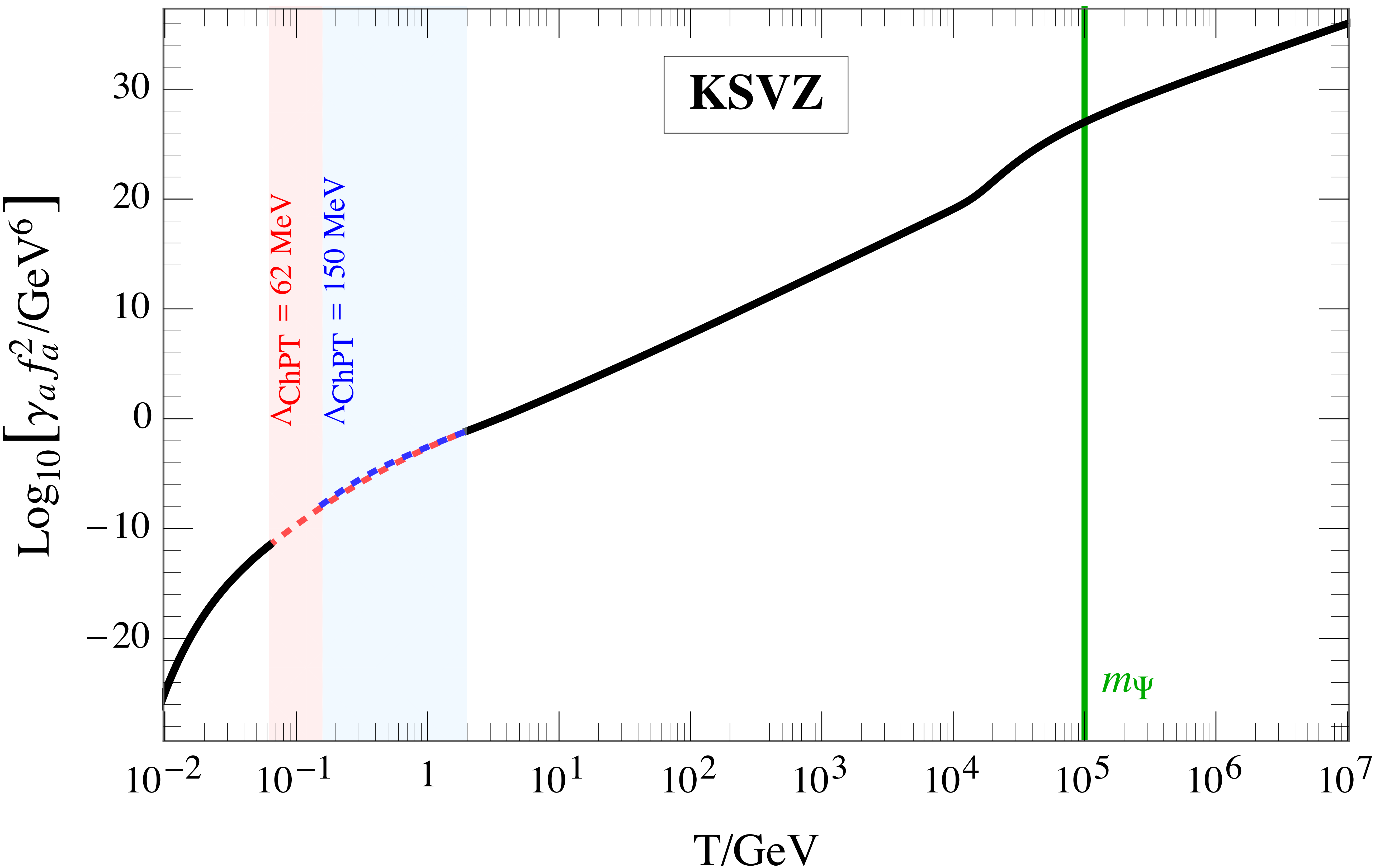
$$(\partial^\mu \varphi)^\dagger \partial_\mu \varphi + \bar{\Psi} i \not{D} \Psi - \lambda_\varphi \left(|\varphi|^2 - v_\varphi^2/2 \right)^2 - \left(y_\Psi \, \varphi^\dagger \bar{\Psi}_L \Psi_R + \text{h.c.} \right)$$

$$\frac{1}{2} \partial^\mu a \partial_\mu a + \bar{\Psi} i \not{D} \Psi - \left[m_\Psi e^{-ia/v_\varphi} \bar{\Psi}_L \Psi_R + \text{h.c.} \right]$$

$$\frac{1}{2} \partial^\mu a \partial_\mu a + \frac{\alpha_s}{8\pi} \frac{a}{v_\varphi} G^A_{\mu\nu} \widetilde{G}^{A\mu\nu}$$

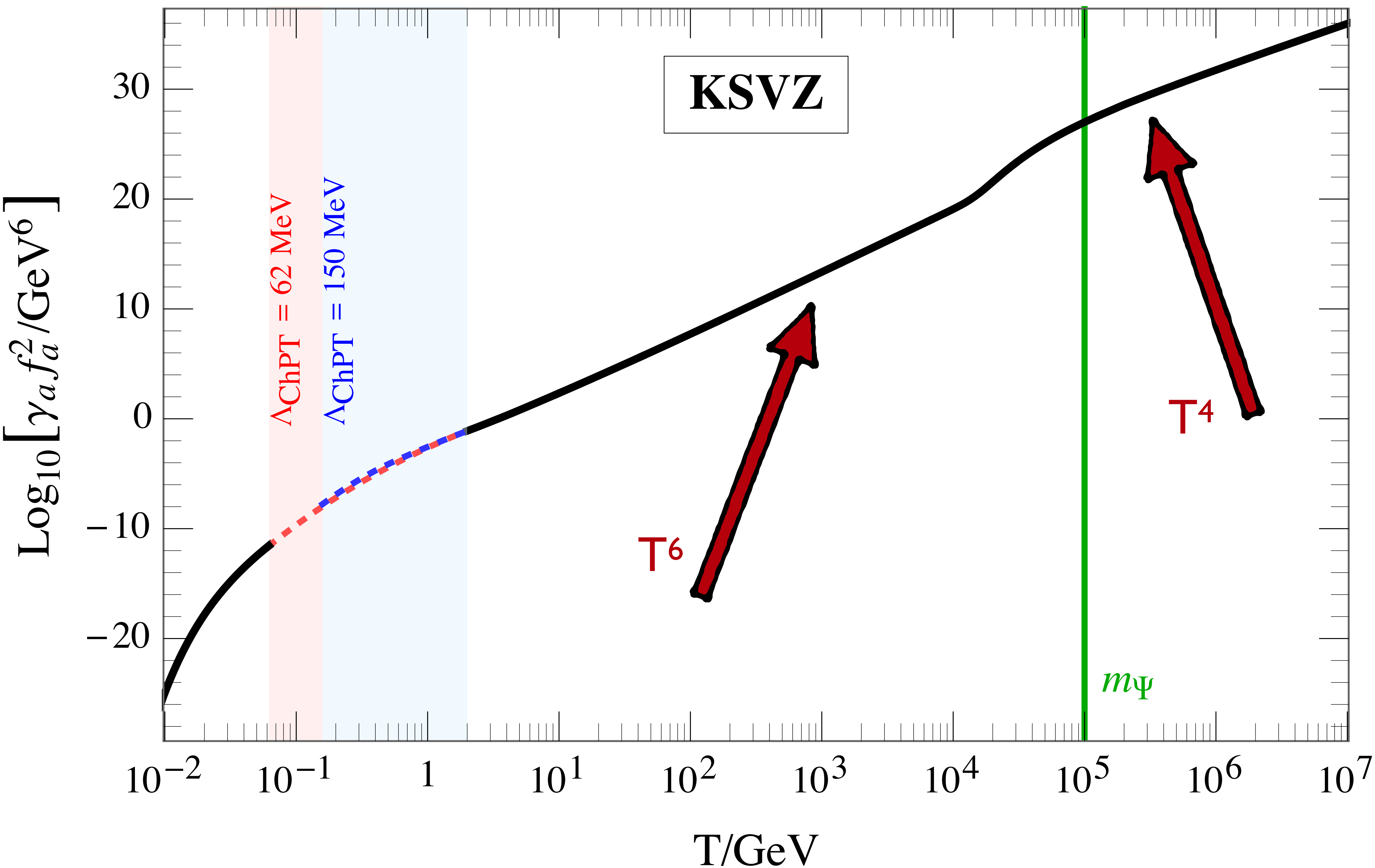
Kim, PRL 43 (1979)
Shifman, Vainshtein, Zakharov, NPB 166 (1980)

KSVZ Axion — Production Rate



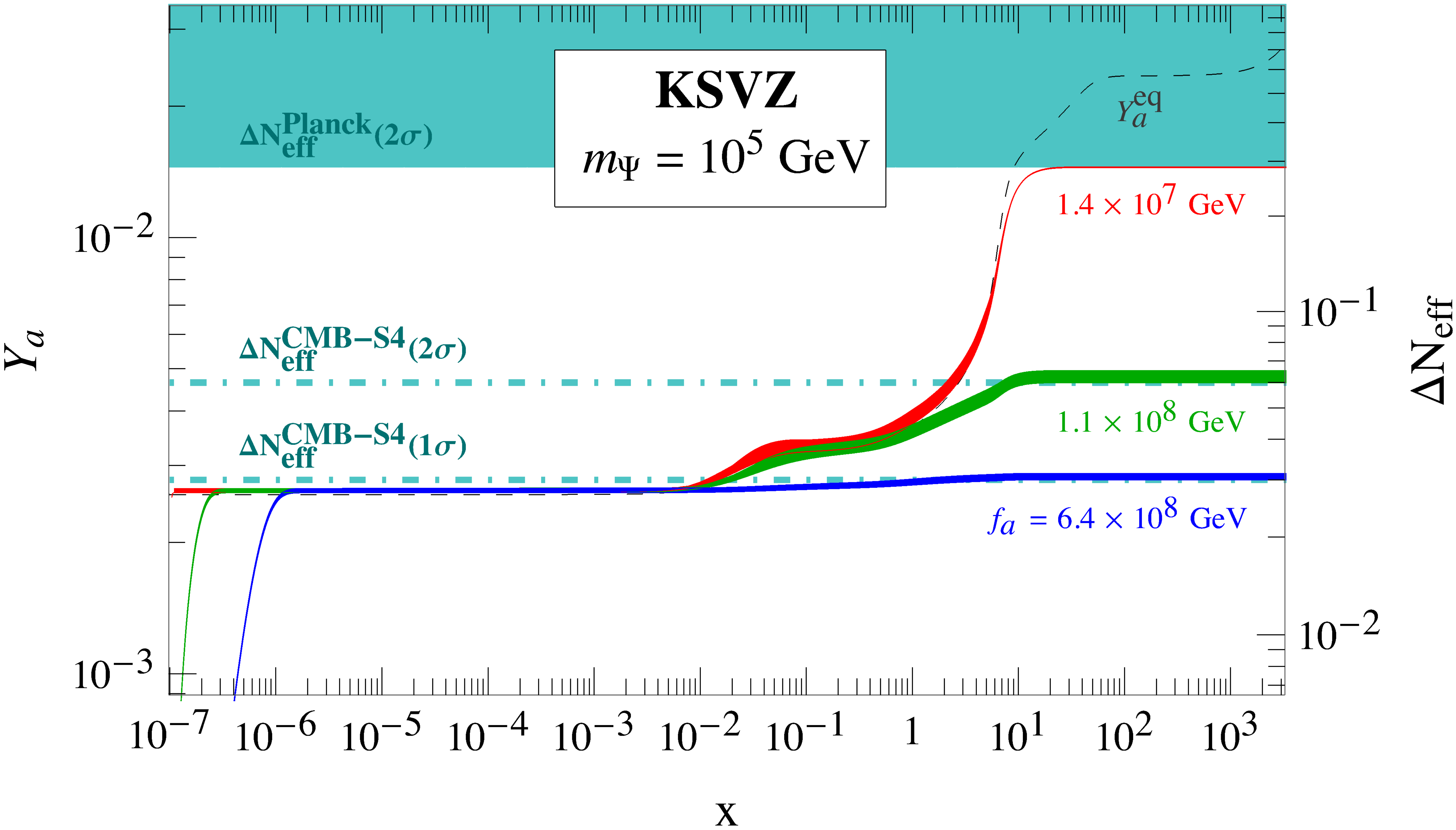
FD, Hajkarim, Yun, JHEP 10 (2021)

KSVZ Axion — Production Rate



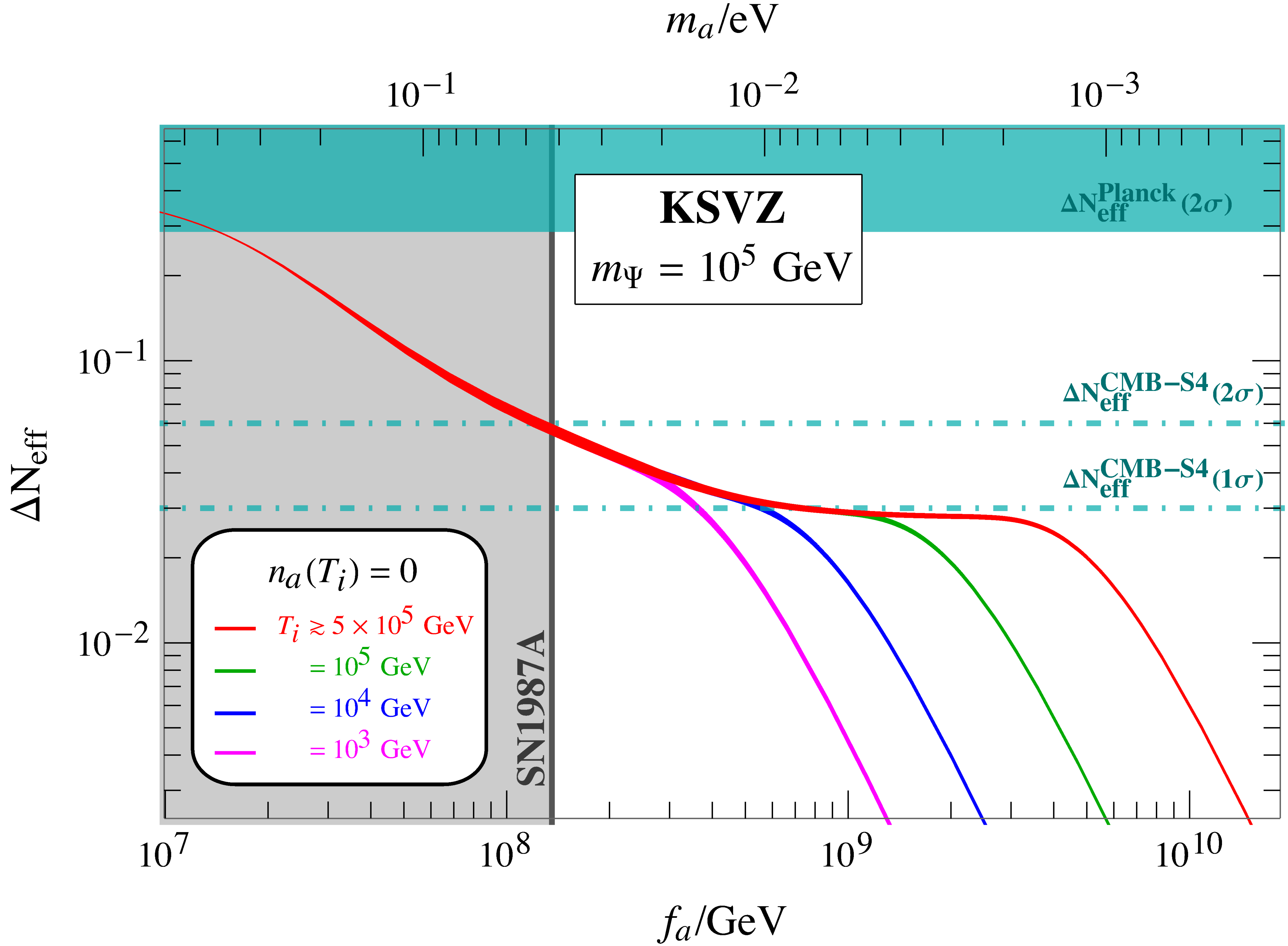
FD, Hajkarim, Yun, JHEP 10 (2021)

KSVZ Axion — Y_a vs x



FD, Hajkarim, Yun, JHEP 10 (2021)

KSVZ Axion — ΔN_{eff}



FD, Hajkarim, Yun, JHEP 10 (2021)

DFSZ Axion — Theory

Energy

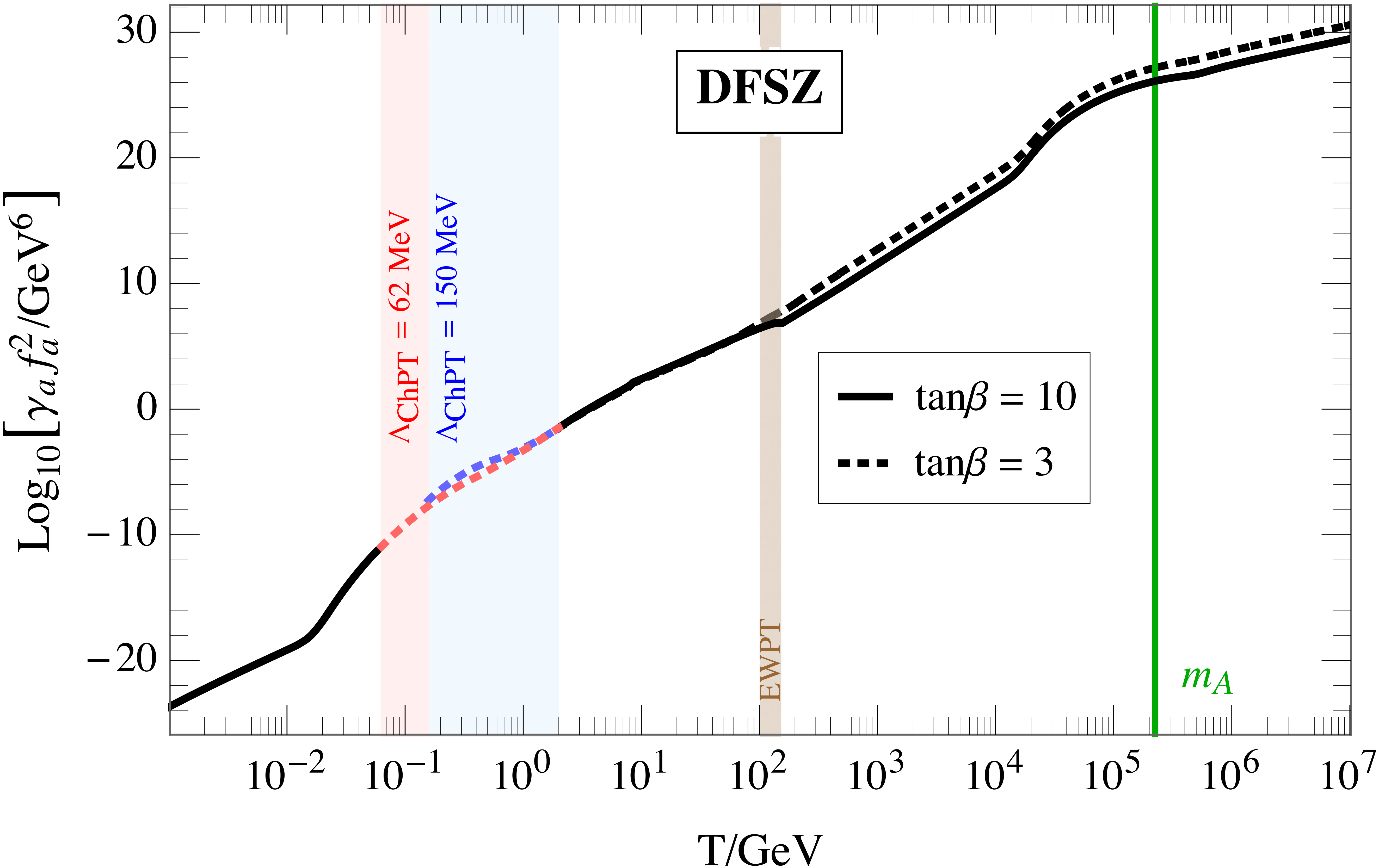
$$B\left(\frac{\varphi^\dagger}{v_\varphi/\sqrt{2}}\right)^r H_u^T i\sigma^2 H_d + \text{h.c.}$$

$$\frac{1}{2}\partial^\mu a \partial_\mu a - B\left[e^{-i\frac{N_{\text{DW}}}{3}\frac{a}{v_\varphi}} H_u^T i\sigma^2 H_d + \text{h.c.}\right]$$

$$\frac{1}{2}\partial^\mu a \partial_\mu a - \frac{\partial_\mu a}{v_\varphi}\left[\sum_f q_f \bar{f}\gamma^\mu f + \sum_\alpha q_{H_\alpha} H_\alpha^\dagger i \overleftrightarrow{D}^\mu H_\alpha\right]$$
$$+\frac{a}{v_\varphi}\left[N_{\text{DW}}\frac{g_s^2}{32\pi^2}G_{\mu\nu}^A \widetilde{G}^{A\mu\nu} + c_W \frac{g^2}{32\pi^2} W_{\mu\nu}^I \widetilde{W}^{I\mu\nu} + c_Y \frac{g'^2}{32\pi^2} B_{\mu\nu}\widetilde{B}^{\mu\nu}\right]$$

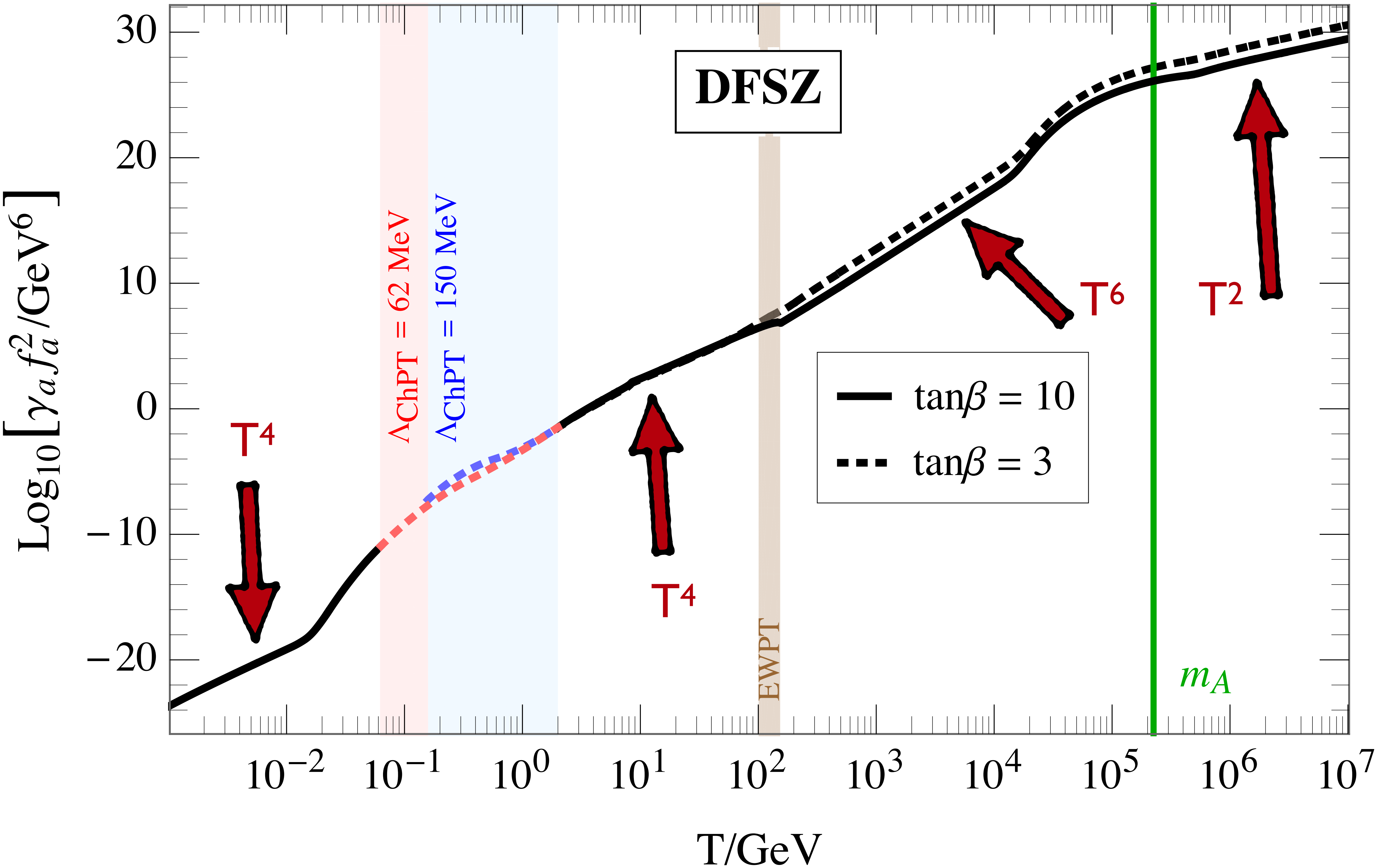
Zhitnitsky, SJNP 31 (1980)
Dine, Fischler, Srednicki, PLB 104 (1981)

DFSZ Axion — Production Rate



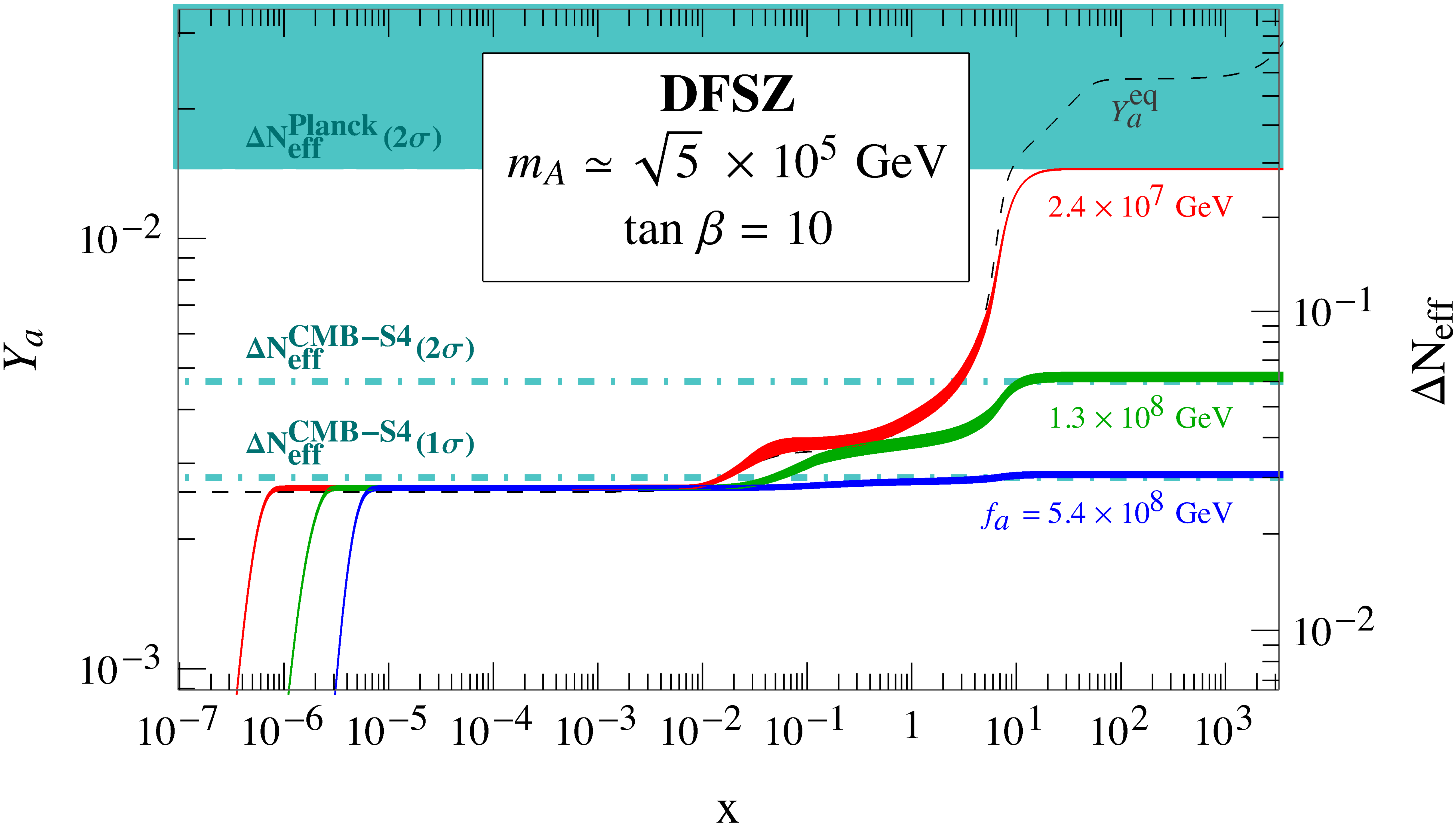
FD, Hajkarim, Yun, JHEP 10 (2021)

DFSZ Axion — Production Rate



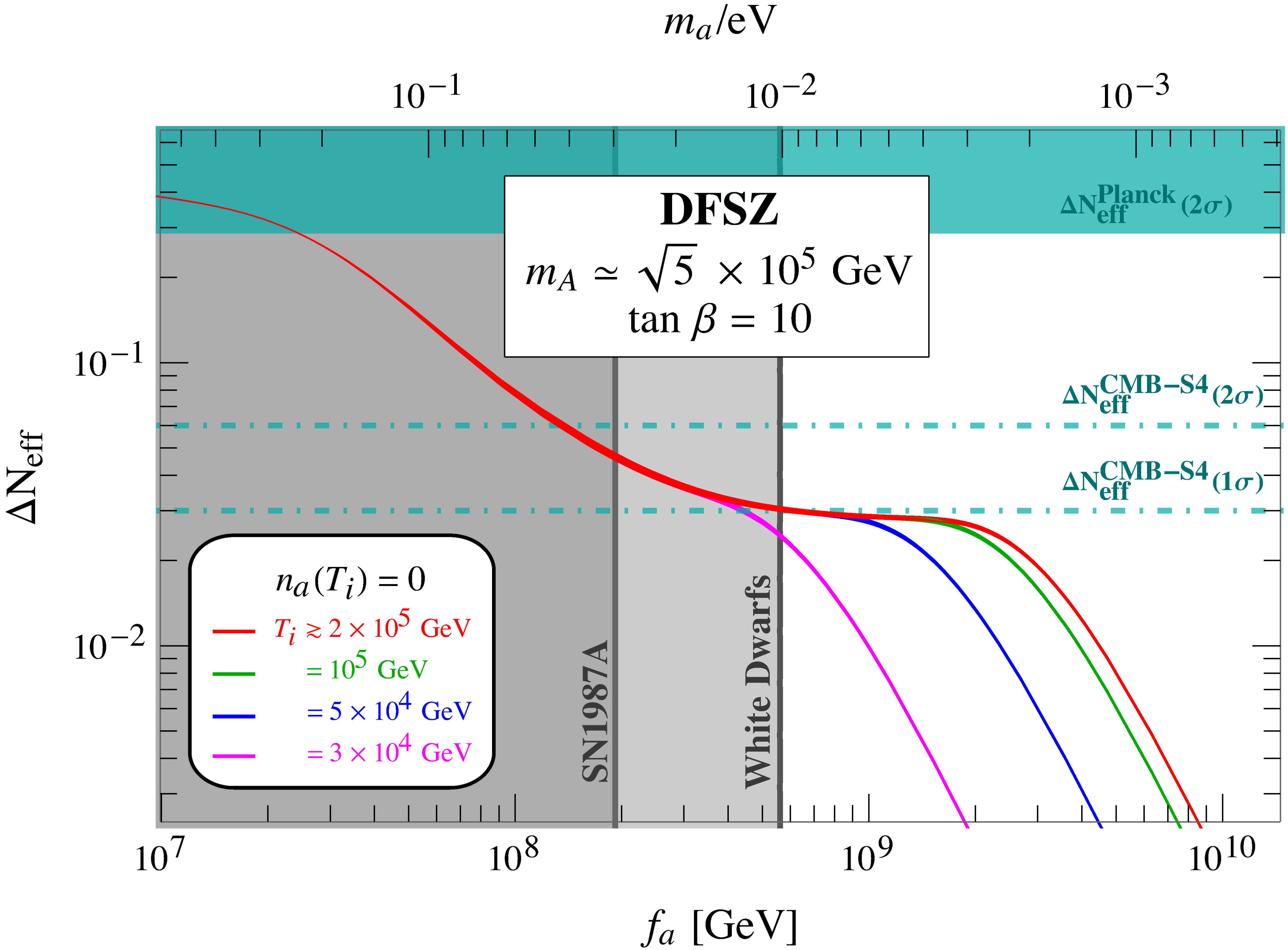
FD, Hajkarim, Yun, JHEP 10 (2021)

DFSZ Axion — Y_a vs x



FD, Hajkarim, Yun, JHEP 10 (2021)

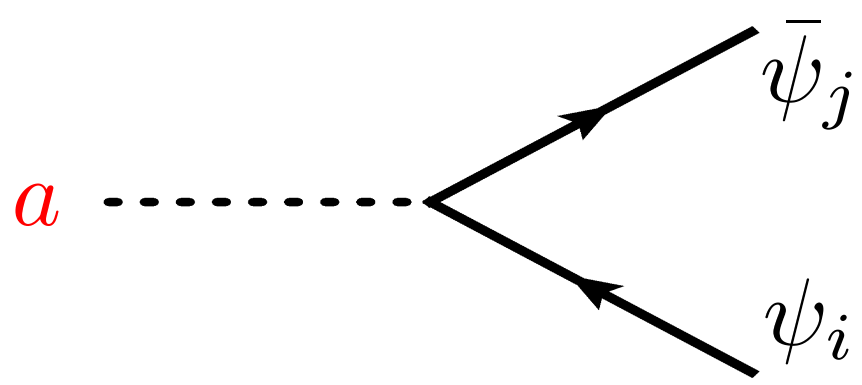
DFSZ Axion — ΔN_{eff}



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

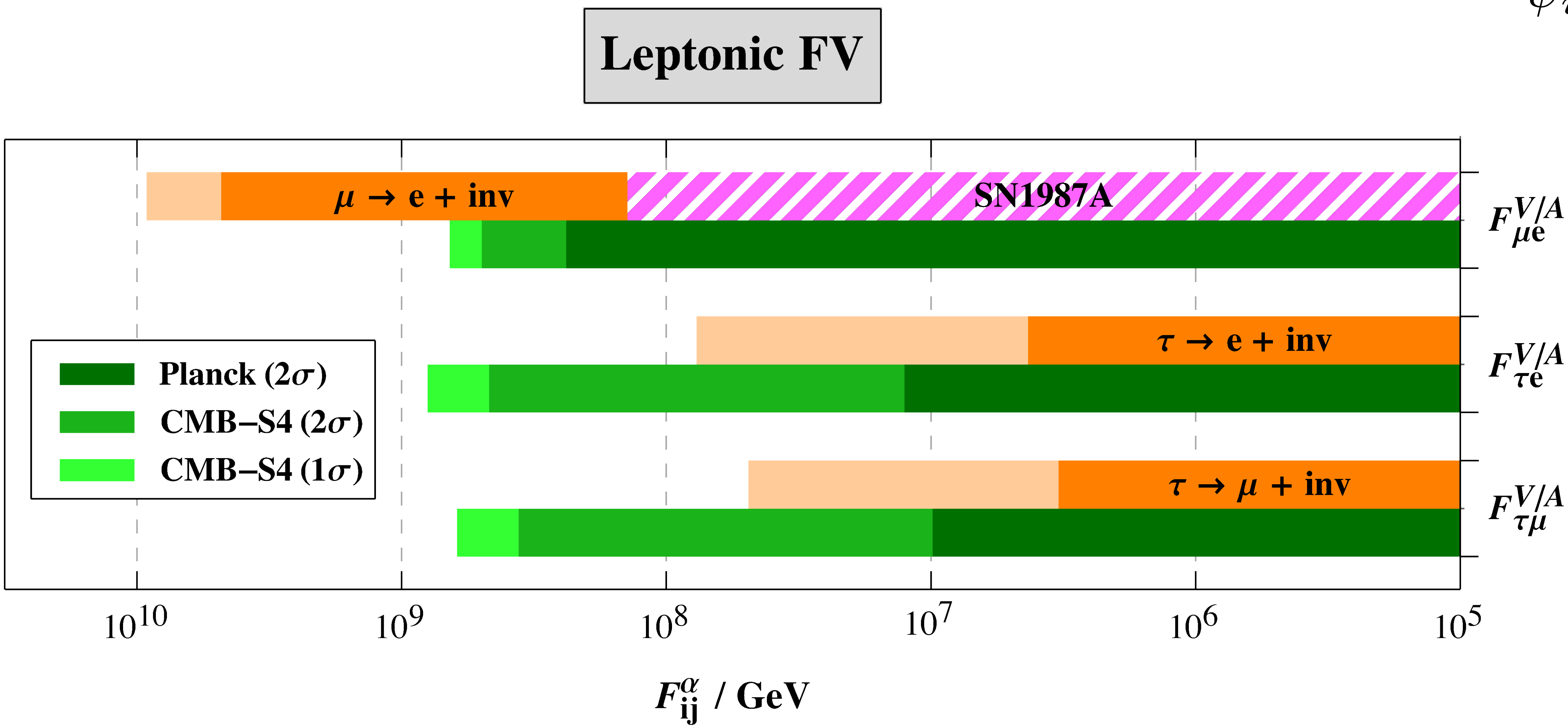
What about their role in the early universe?

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

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

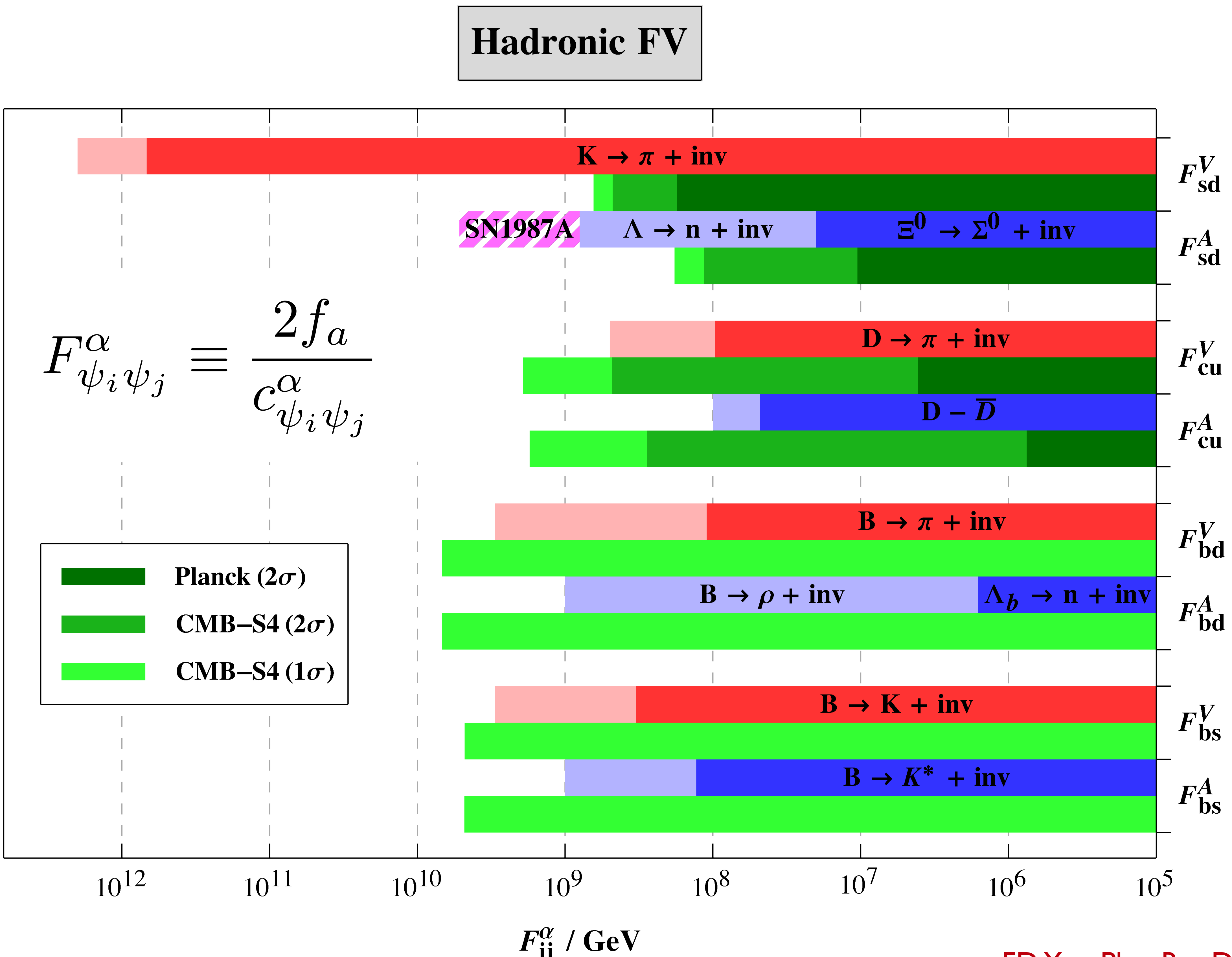
Flavor Violating Axions

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



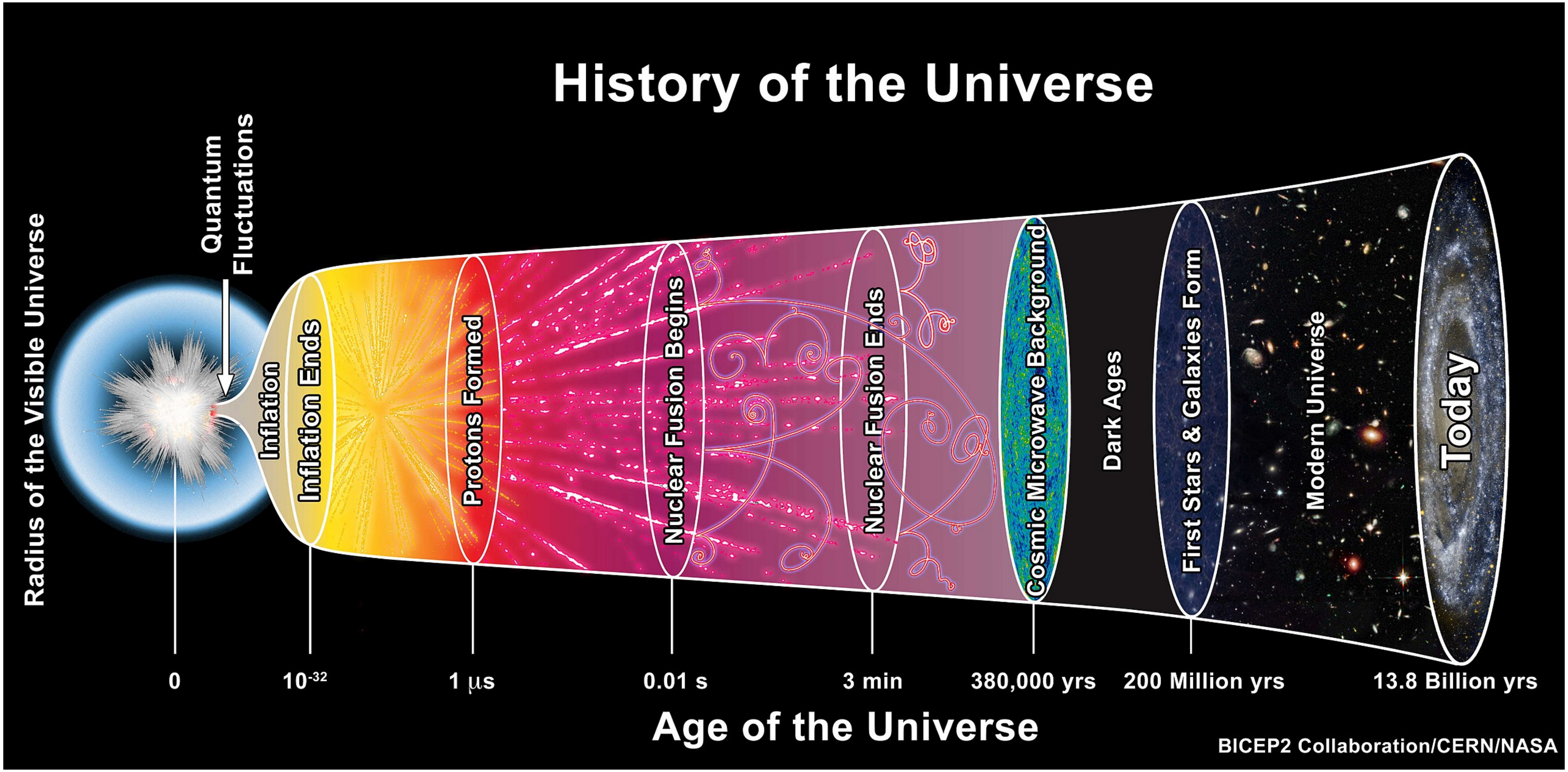
FD, Yun, Phys.Rev.D 105 (2022)

Flavor Violating Axions



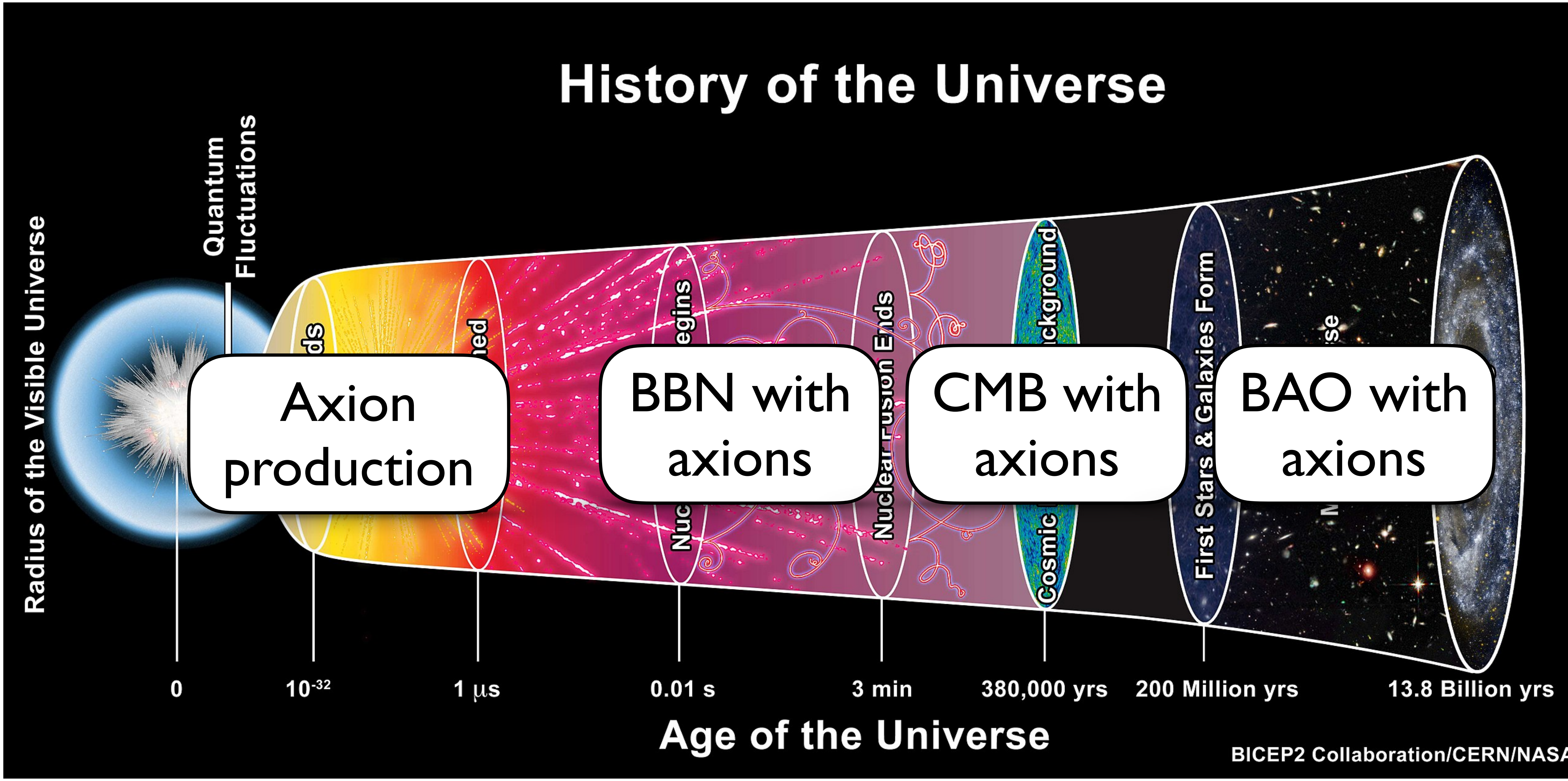
FD, Yun, Phys.Rev.D 105 (2022)

Global Cosmological Analysis



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

Global Cosmological Analysis



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

KSVZ Axion Mass Bound

KSVZ Axion Model

Parameter	Planck 2018 (TT TE EE)	Planck 2018 + lensing	Planck 2018 +lensing+BAO
$\Omega_b h^2$	0.02244 ± 0.00017	0.02243 ± 0.00015	0.02250 ± 0.00015
$\Omega_c h^2$	$0.1224^{+0.0018}_{-0.0021}$	$0.1225^{+0.0016}_{-0.0022}$	$0.1208^{+0.0012}_{-0.0014}$
$100\,\theta_{MC}$	$1.04060^{+0.00038}_{-0.00034}$	1.04058 ± 0.00036	1.04081 ± 0.00032
τ	0.0557 ± 0.0079	0.0564 ± 0.0076	$0.0581^{+0.0070}_{-0.0080}$
$\log(10^{10} A_S)$	3.053 ± 0.017	$3.055^{+0.015}_{-0.016}$	$3.055^{+0.014}_{-0.016}$
n_s	0.9687 ± 0.0051	0.9681 ± 0.0049	0.9703 ± 0.0043
m_a [eV]	$< 1.04\ (< 1.86)$	$< 0.888\ (< 1.67)$	$< 0.282\ (< 0.420)$
f_a [10^7 GeV]	$> 0.55\,(> 0.31)$	$> 0.64\,(> 0.34)$	$> 2.02\,(> 1.35)$
$\sum m_\nu$ [eV]	$< 0.297\ (< 0.422)$	$< 0.278\ (< 0.381)$	$< 0.156\ (< 0.192)$
$\Delta N_{\rm eff}$	$< 0.349\ (< 0.378)$	$< 0.340\ (< 0.373)$	$< 0.226\ (< 0.275)$
Y_P	$0.24746^{+0.00077}_{-0.0017}$	$0.24741^{+0.00074}_{-0.0016}$	$0.24693^{+0.00048}_{-0.00097}$
$10^5 \cdot (D/H)$	$2.556^{+0.033}_{-0.042}$	$2.558^{+0.029}_{-0.040}$	2.531 ± 0.028
H_0 [Km/s/Mpc]	$67.0^{+1.2}_{-0.77}$	$66.9^{+1.2}_{-0.73}$	67.90 ± 0.53
σ_8	$0.790^{+0.029}_{-0.012}$	$0.793^{+0.023}_{-0.011}$	$0.8052^{+0.0099}_{-0.0075}$

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

KSVZ Axion Mass Bound

KSVZ Axion Model

Parameter	Planck 2018 (TT TE EE)	Planck 2018 + lensing	Planck 2018 +lensing+BAO
$\Omega_b h^2$	0.02244 ± 0.00017	0.02243 ± 0.00015	0.02250 ± 0.00015
$\Omega_c h^2$	$0.1224^{+0.0018}_{-0.0021}$	$0.1225^{+0.0016}_{-0.0022}$	$0.1208^{+0.0012}_{-0.0014}$
$100\,\theta_{MC}$	$1.04060^{+0.00038}_{-0.00034}$	1.04058 ± 0.00036	1.04081 ± 0.00032
τ	0.0557 ± 0.0079	0.0564 ± 0.0076	$0.0581^{+0.0070}_{-0.0080}$
$\log(10^{10} A_S)$	3.053 ± 0.017	$3.055^{+0.015}_{-0.016}$	$3.055^{+0.014}_{-0.016}$
n_s	0.9687 ± 0.0051	0.9681 ± 0.0049	0.9703 ± 0.0043
m_a [eV]	$< 1.04\ (< 1.86)$	$< 0.888\ (< 1.67$[illegible]	$< 0.282\ (< 0.420)$
f_a [10^7 GeV]	$> 0.55\ (> 0.31)$	$> 0.64\ (> 0.34)$	$> 2.02\ (> 1.35)$
$\sum m_\nu$ [eV]	$< 0.297\ (< 0.422)$	$< 0.278\ (< 0.381)$	$< 0.156\ (< 0.192)$
$\Delta N_{\rm eff}$	$< 0.349\ (< 0.378)$	$< 0.340\ (< 0.373)$	$< 0.226\ (< 0.275)$
Y_P	$0.24746^{+0.00077}_{-0.0017}$	$0.24741^{+0.00074}_{-0.0016}$	$0.24693^{+0.00048}_{-0.00097}$
$10^5 \cdot (D/H)$	$2.556^{+0.033}_{-0.042}$	$2.558^{+0.029}_{-0.040}$	2.531 ± 0.028
H_0 [Km/s/Mpc]	$67.0^{+1.2}_{-0.77}$	$66.9^{+1.2}_{-0.73}$	67.90 ± 0.53
σ_8	$0.790^{+0.029}_{-0.012}$	$0.793^{+0.023}_{-0.011}$	$0.8052^{+0.0099}_{-0.0075}$

95% and 99% CL

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

DFSZ Axion Mass Bound

DSFZ Axion Model ($\tan\beta = 3$)

Parameter	Planck 2018 (TT TE EE)	Planck 2018 + lensing	Planck 2018 +lensing+BAO
$\Omega_b h^2$	0.02243 ± 0.00017	0.02244 ± 0.00017	0.02250 ± 0.00015
$\Omega_c h^2$	$0.1223^{+0.0018}_{-0.0023}$	$0.1224^{+0.0017}_{-0.0024}$	$0.1208^{+0.0012}_{-0.0016}$
$100\,\theta_{\rm MC}$	$1.04061^{+0.00039}_{-0.00035}$	$1.04061^{+0.00040}_{-0.00035}$	1.04081 ± 0.00031
τ	0.0554 ± 0.0080	$0.0566^{+0.0071}_{-0.0081}$	$0.0576^{+0.0069}_{-0.0077}$
$\log(10^{10} A_S)$	3.052 ± 0.017	$3.055^{+0.015}_{-0.017}$	3.054 ± 0.015
n_s	0.9685 ± 0.0053	0.9682 ± 0.0052	$0.9702^{+0.0042}_{-0.0048}$
m_a [eV]	$< 0.710\,(< 1.81)$	$< 0.697\,(< 1.42)$	$< 0.209\,(< 0.293)$
f_a [10^7 GeV]	$> 0.80\,(> 0.31)$	$> 0.82\,(> 0.40)$	$> 2.72\,(> 1.94)$
$\sum m_\nu$ [eV]	$< 0.312\,(< 0.426)$	$< 0.288\,(< 0.390)$	$< 0.157\,(< 0.193)$
$\Delta N_{\rm eff}$	$< 0.358\,(< 0.401)$	$< 0.360\,(< 0.392)$	$< 0.243\,(< 0.290)$
Y_P	$0.24732^{+0.00077}_{-0.0018}$	$0.24731^{+0.00077}_{-0.0018}$	$0.24689^{+0.00061}_{-0.0012}$
$10^5 \cdot (D/H)$	$2.554^{+0.032}_{-0.041}$	$2.554^{+0.032}_{-0.042}$	2.531 ± 0.028
H_0 [Km/s/Mpc]	$67.0^{+1.2}_{-0.82}$	$67.0^{+1.2}_{-0.79}$	67.90 ± 0.58
σ_8	$0.792^{+0.027}_{-0.012}$	$0.794^{+0.022}_{-0.010}$	$0.8059^{+0.0093}_{-0.0071}$

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

DFSZ Axion Mass Bound

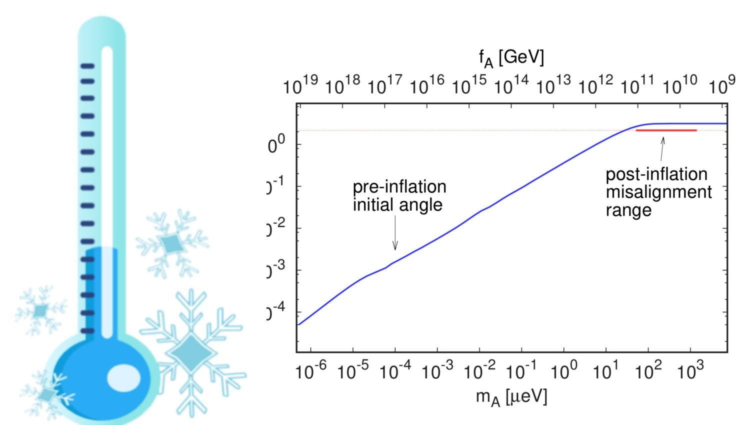
DSFZ Axion Model ($\tan\beta = 3$)

Parameter	Planck 2018 (TT TE EE)	Planck 2018 + lensing	Planck 2018 +lensing+BAO
$\Omega_b h^2$	0.02243 ± 0.00017	0.02244 ± 0.00017	0.02250 ± 0.00015
$\Omega_c h^2$	$0.1223^{+0.0018}_{-0.0023}$	$0.1224^{+0.0017}_{-0.0024}$	$0.1208^{+0.0012}_{-0.0016}$
$100\,\theta_{MC}$	$1.04061^{+0.00039}_{-0.00035}$	$1.04061^{+0.00040}_{-0.00035}$	1.04081 ± 0.00031
τ	0.0554 ± 0.0080	$0.0566^{+0.0071}_{-0.0081}$	$0.0576^{+0.0069}_{-0.0077}$
$\log(10^{10} A_S)$	3.052 ± 0.017	$3.055^{+0.015}_{-0.017}$	3.054 ± 0.015
n_s	0.9685 ± 0.0053	0.9682 ± 0.0052	$0.9702^{+0.0042}_{-0.0048}$
m_a [eV]	$< 0.710\,(< 1.81)$	$< 0.697\,(< 1.42)$	$< 0.209\,(< 0.293)$
f_a [10^7 GeV]	$> 0.80\,(> 0.31)$	$> 0.82\,(> 0.40)$	$> 2.72\,(> 1.94)$
$\sum m_\nu$ [eV]	$< 0.312\,(< 0.426)$	$< 0.288\,(< 0.390)$	$< 0.157\,(< 0.193)$
$\Delta N_{\rm eff}$	$< 0.358\,(< 0.401)$	$< 0.360\,(< 0.392)$	$< 0.243\,(< 0.290)$
Y_P	$0.24732^{+0.00077}_{-0.0018}$	$0.24731^{+0.00077}_{-0.0018}$	$0.24689^{+0.00061}_{-0.0012}$
$10^5 \cdot (D/H)$	$2.554^{+0.032}_{-0.041}$	$2.554^{+0.032}_{-0.042}$	2.531 ± 0.028
H_0 [Km/s/Mpc]	$67.0^{+1.2}_{-0.82}$	$67.0^{+1.2}_{-0.79}$	67.90 ± 0.58
σ_8	$0.792^{+0.027}_{-0.012}$	$0.794^{+0.022}_{-0.010}$	$0.8059^{+0.0093}_{-0.0071}$

95% and 99% CL

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

Outlook



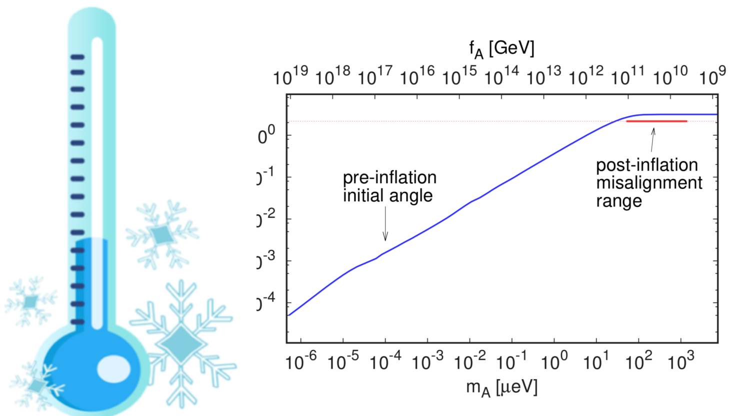
Peccei-Quinn Mechanism and QCD Axion

Motivated and testable scenario

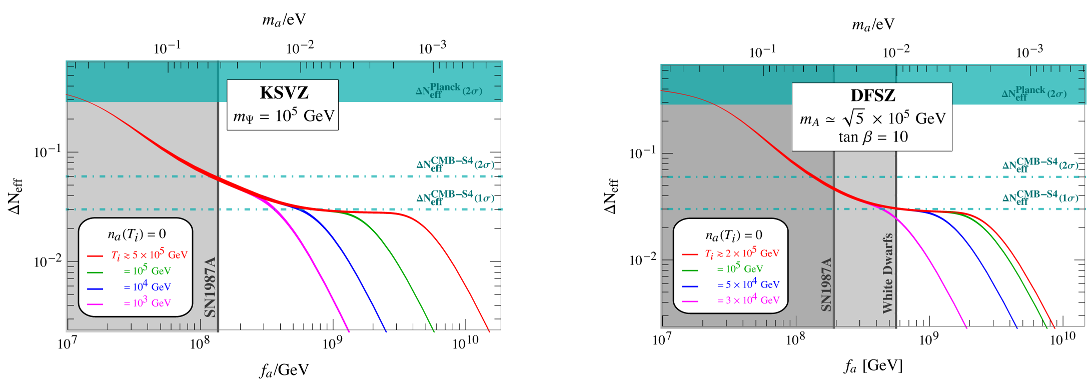
for physics beyond the standard model

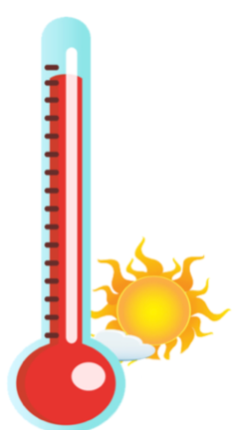
rich of cosmological consequences

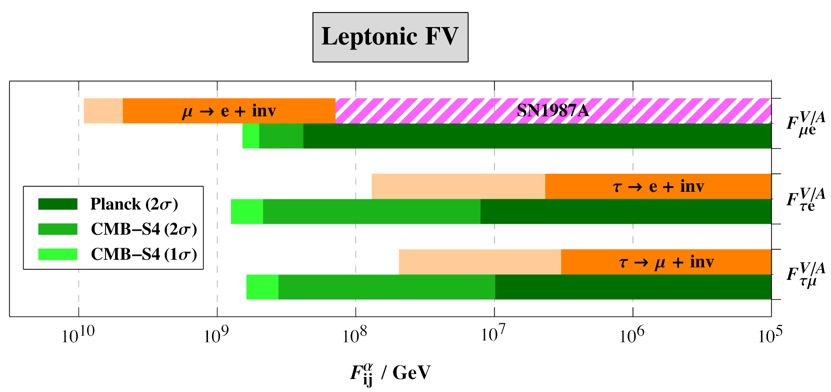
Outlook

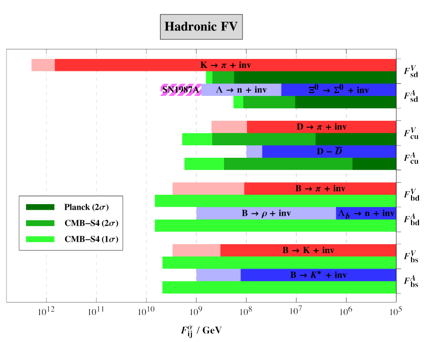


&









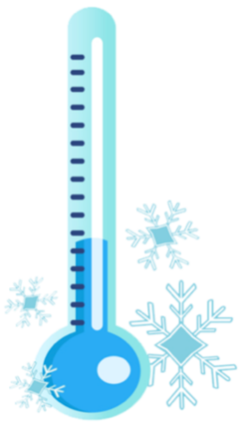
KSVZ Axion Model

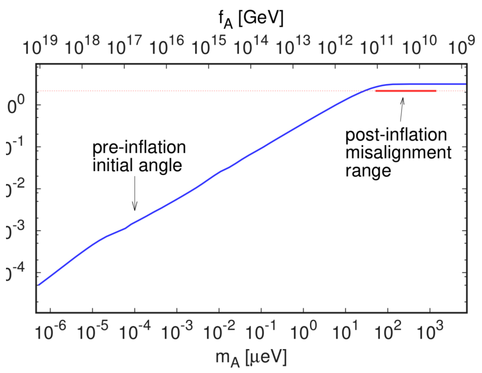
Parameter	Planck 2018 (TT TE EE)	Planck 2018 + lensing	Planck 2018 +lensing+BAO
$\Omega_b h^2$	0.02244 ± 0.00017	0.02243 ± 0.00015	0.02250 ± 0.00015
$\Omega_c h^2$	$0.1224^{+0.0018}_{-0.0021}$	$0.1225^{+0.0016}_{-0.0022}$	$0.1208^{+0.0012}_{-0.0014}$
$100\,\theta_{MC}$	$1.04060^{+0.00038}_{-0.00034}$	1.04058 ± 0.00036	1.04081 ± 0.00032
τ	0.0557 ± 0.0079	0.0564 ± 0.0076	$0.0581^{+0.0070}_{-0.0080}$
$\log(10^{10} A_S)$	3.053 ± 0.017	$3.055^{+0.015}_{-0.016}$	$3.055^{+0.014}_{-0.016}$
n_s	0.9687 ± 0.0051	0.9681 ± 0.0049	0.9703 ± 0.0043
m_a [eV]	< 1.04 (< 1.86)	< 0.888 (< 1.67)	< 0.282 (< 0.420)
f_a [10^7 GeV]	> 0.55 (> 0.31)	> 0.64 (> 0.34)	> 2.02 (> 1.35)
$\sum m_\nu$ [eV]	< 0.297 (< 0.422)	< 0.278 (< 0.381)	< 0.156 (< 0.192)
ΔN_{eff}	< 0.349 (< 0.378)	< 0.340 (< 0.373)	< 0.226 (< 0.275)
Y_P	$0.24746^{+0.00077}_{-0.0017}$	$0.24741^{+0.00074}_{-0.0016}$	$0.24693^{+0.00048}_{-0.00097}$
$10^5 \cdot (D/H)$	$2.556^{+0.033}_{-0.042}$	$2.558^{+0.029}_{-0.040}$	2.531 ± 0.028
H_0 [Km/s/Mpc]	$67.0^{+1.2}_{-0.77}$	$66.9^{+1.2}_{-0.73}$	67.90 ± 0.53
σ_8	$0.790^{+0.029}_{-0.012}$	$0.793^{+0.023}_{-0.011}$	$0.8052^{+0.0099}_{-0.0075}$

Thermally Produced Axions

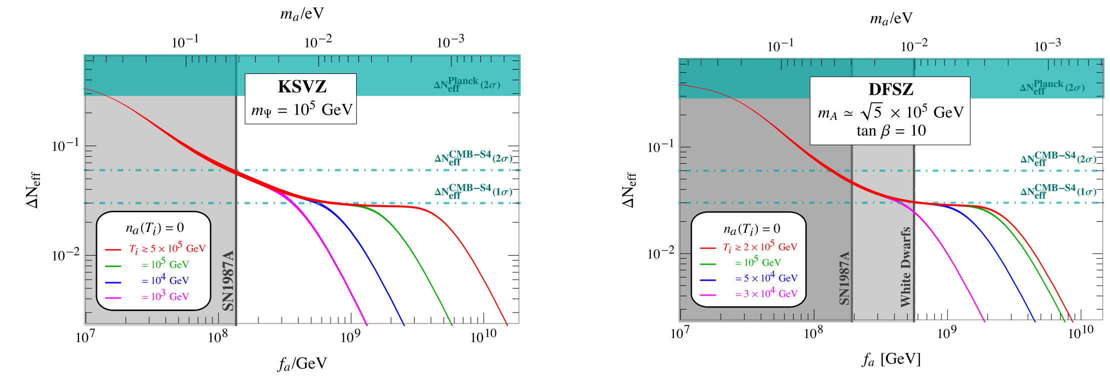
Complementary to other probes of the PQ mechanism

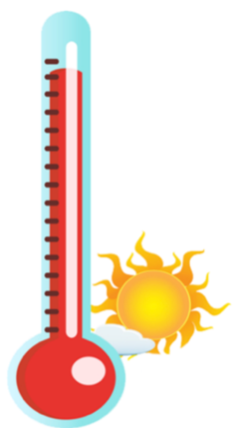
Outlook

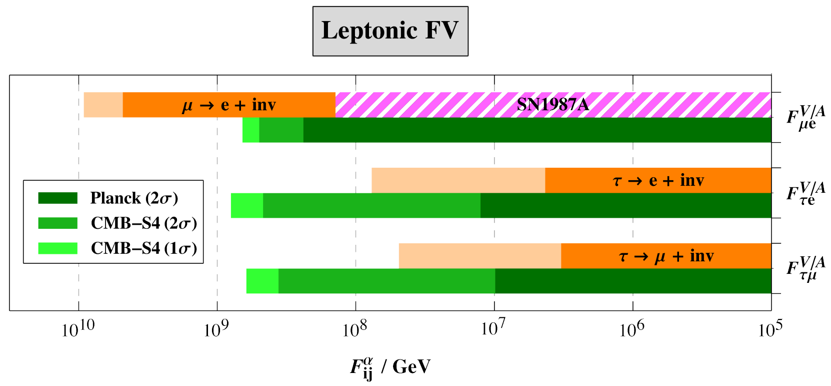


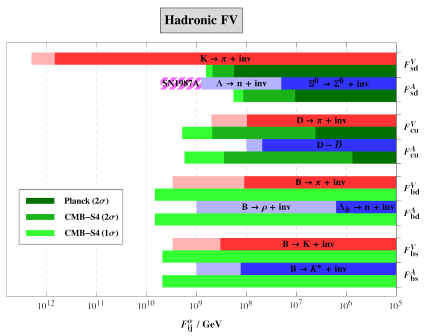


&









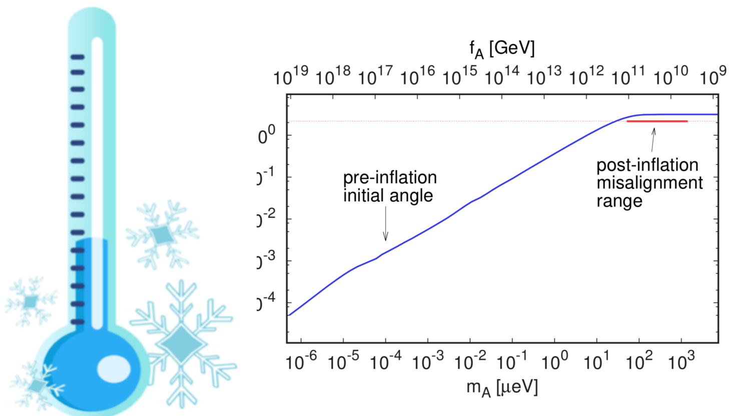
KSVZ Axion Model

Parameter	Planck 2018 (TT TE EE)	Planck 2018 + lensing	Planck 2018 +lensing+BAO
$\Omega_b h^2$	0.02244 ± 0.00017	0.02243 ± 0.00015	0.02250 ± 0.00015
$\Omega_c h^2$	$0.1224^{+0.0018}_{-0.0021}$	$0.1225^{+0.0016}_{-0.0022}$	$0.1208^{+0.0012}_{-0.0014}$
$100\,\theta_{MC}$	$1.04060^{+0.00038}_{-0.00034}$	1.04058 ± 0.00036	1.04081 ± 0.00032
τ	0.0557 ± 0.0079	0.0564 ± 0.0076	$0.0581^{+0.0070}_{-0.0080}$
$\log(10^{10} A_S)$	3.053 ± 0.017	$3.055^{+0.015}_{-0.016}$	$3.055^{+0.014}_{-0.016}$
n_s	0.9687 ± 0.0051	0.9681 ± 0.0049	0.9703 ± 0.0043
m_a [eV]	< 1.04 (< 1.86)	< 0.888 (< 1.67)	< 0.282 (< 0.420)
f_a [10^7 GeV]	> 0.55 (> 0.31)	> 0.64 (> 0.34)	> 2.02 (> 1.35)
$\sum m_\nu$ [eV]	< 0.297 (< 0.422)	< 0.278 (< 0.381)	< 0.156 (< 0.192)
$\Delta N_{\rm eff}$	< 0.349 (< 0.378)	< 0.340 (< 0.373)	< 0.226 (< 0.275)
Y_P	$0.24746^{+0.00077}_{-0.0017}$	$0.24741^{+0.00074}_{-0.0016}$	$0.24693^{+0.00048}_{-0.00097}$
$10^5 \cdot (D/H)$	$2.556^{+0.033}_{-0.042}$	$2.558^{+0.029}_{-0.040}$	2.531 ± 0.028
H_0 [Km/s/Mpc]	$67.0^{+1.2}_{-0.77}$	$66.9^{+1.2}_{-0.73}$	67.90 ± 0.53
σ_8	$0.790^{+0.029}_{-0.012}$	$0.793^{+0.023}_{-0.011}$	$0.8052^{+0.0099}_{-0.0075}$

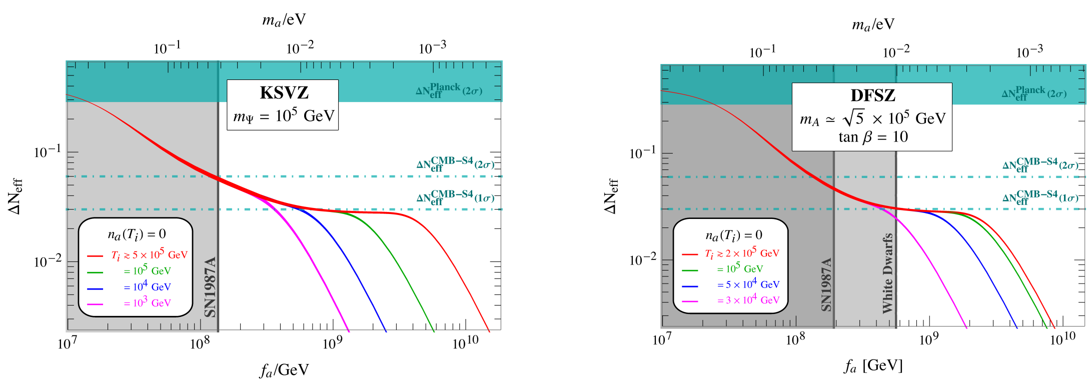
Future Work

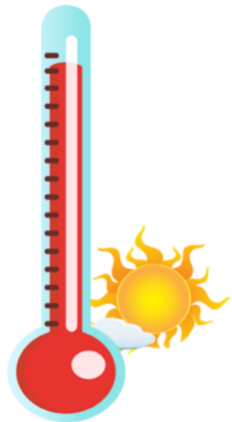
Other UV completions (e.g. for flavor violation), modified cosmological histories, beyond the QCD axion…

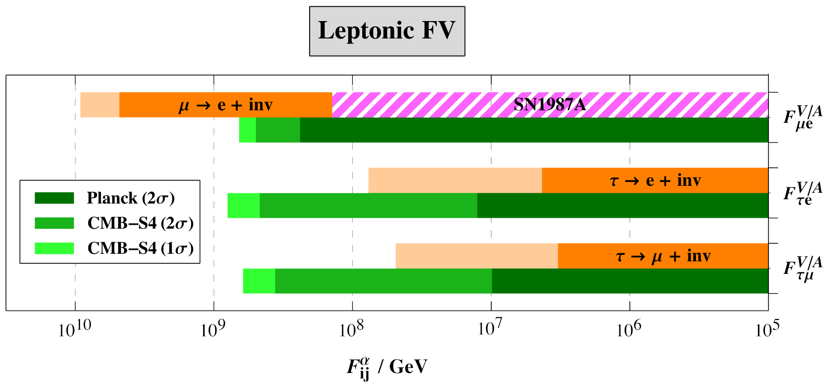
Outlook

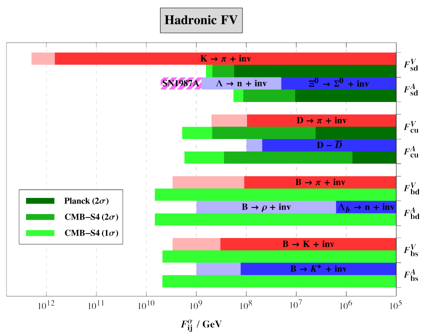


&









KSVZ Axion Model

Parameter	Planck 2018 (TT TE EE)	Planck 2018 + lensing	Planck 2018 +lensing+BAO
$\Omega_b h^2$	0.02244 ± 0.00017	0.02243 ± 0.00015	0.02250 ± 0.00015
$\Omega_c h^2$	$0.1224^{+0.0018}_{-0.0021}$	$0.1225^{+0.0016}_{-0.0022}$	$0.1208^{+0.0012}_{-0.0014}$
$100\,\theta_{MC}$	$1.04060^{+0.00038}_{-0.00034}$	1.04058 ± 0.00036	1.04081 ± 0.00032
τ	0.0557 ± 0.0079	0.0564 ± 0.0076	$0.0581^{+0.0070}_{-0.0080}$
$\log(10^{10} A_S)$	3.053 ± 0.017	$3.055^{+0.015}_{-0.016}$	$3.055^{+0.014}_{-0.016}$
n_s	0.9687 ± 0.0051	0.9681 ± 0.0049	0.9703 ± 0.0043
m_a [eV]	$< 1.04\ (< 1.86)$	$< 0.888\ (< 1.67)$	$< 0.282\ (< 0.420)$
f_a [10^7 GeV]	$> 0.55\ (> 0.31)$	$> 0.64\ (> 0.34)$	$> 2.02\ (> 1.35)$
$\sum m_\nu$ [eV]	$< 0.297\ (< 0.422)$	$< 0.278\ (< 0.381)$	$< 0.156\ (< 0.192)$
$\Delta N_{\rm eff}$	$< 0.349\ (< 0.378)$	$< 0.340\ (< 0.373)$	$< 0.226\ (< 0.275)$
Y_P	$0.24746^{+0.00077}_{-0.0017}$	$0.24741^{+0.00074}_{-0.0016}$	$0.24693^{+0.00048}_{-0.00097}$
$10^5 \cdot (D/H)$	$2.556^{+0.033}_{-0.042}$	$2.558^{+0.029}_{-0.040}$	2.531 ± 0.028
H_0 [Km/s/Mpc]	$67.0^{+1.2}_{-0.77}$	$66.9^{+1.2}_{-0.73}$	67.90 ± 0.53
σ_8	$0.790^{+0.029}_{-0.012}$	$0.793^{+0.023}_{-0.011}$	$0.8052^{+0.0099}_{-0.0075}$

HVALA VAM!

BACKUP SLIDES

The Strong CP Problem

CP violation in Quantum Chromodynamics

$$\mathcal{L}_{\mathrm{QCD}} \supset -\theta \frac{g_s^2}{32\pi^2} G^{\mu\nu}\tilde{G}_{\mu\nu} - \sum_q \bar{q}\, m_q e^{-i\theta_q \gamma_5} q$$

Observable consequence:
neutron electric dipole moment

$$d_n \simeq 2.4 \times 10^{-16}\, \bar{\theta}\, e\,\mathrm{cm} \qquad \bar{\theta} \equiv \theta - \sum_q \theta_q$$

Crewther, Di Vecchia, Veneziano, Witten, PLB88 (1979) and PLB91 (1980)

Experimental Bound

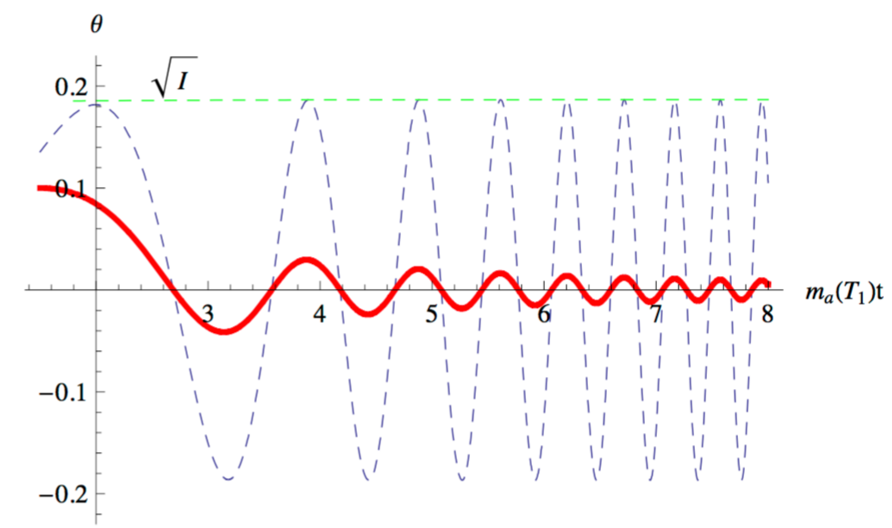
$$|\bar{\theta}| \lesssim 10^{-10}$$

Pendlebury et al.. PRD92 (2016)

The QCD Axion

Peccei-Quinn (PQ) solution:
θ promoted to a field (axion)

Axion field value is
dynamically relaxed to zero



An appealing dark matter candidate

Theoretical top-down motivation

Recent experimental effort,
new ideas for axion detection

Axion Cold Dark Matter

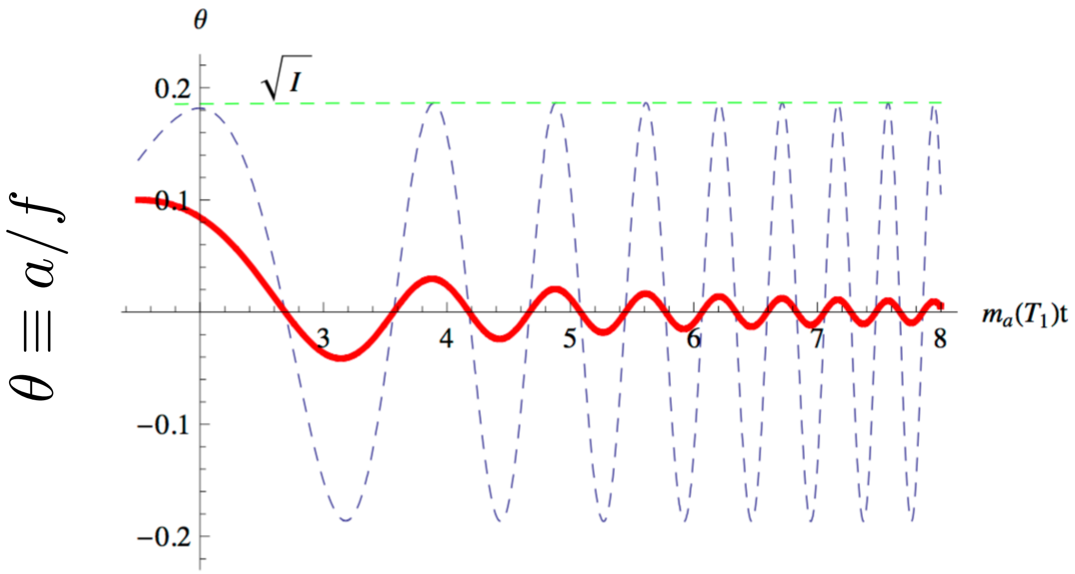
Axion condensate evolution in the early universe

$$\frac{d^2a}{dt^2} + 3H\frac{da}{dt} + m_a(T)^2 a = 0$$

- 3H(T) > m_a(T): axion field stuck by "Hubble "friction
- 3H(T) < m_a(T): axion field oscillates, energy density stored in oscillations evolves as non-relativistic matter

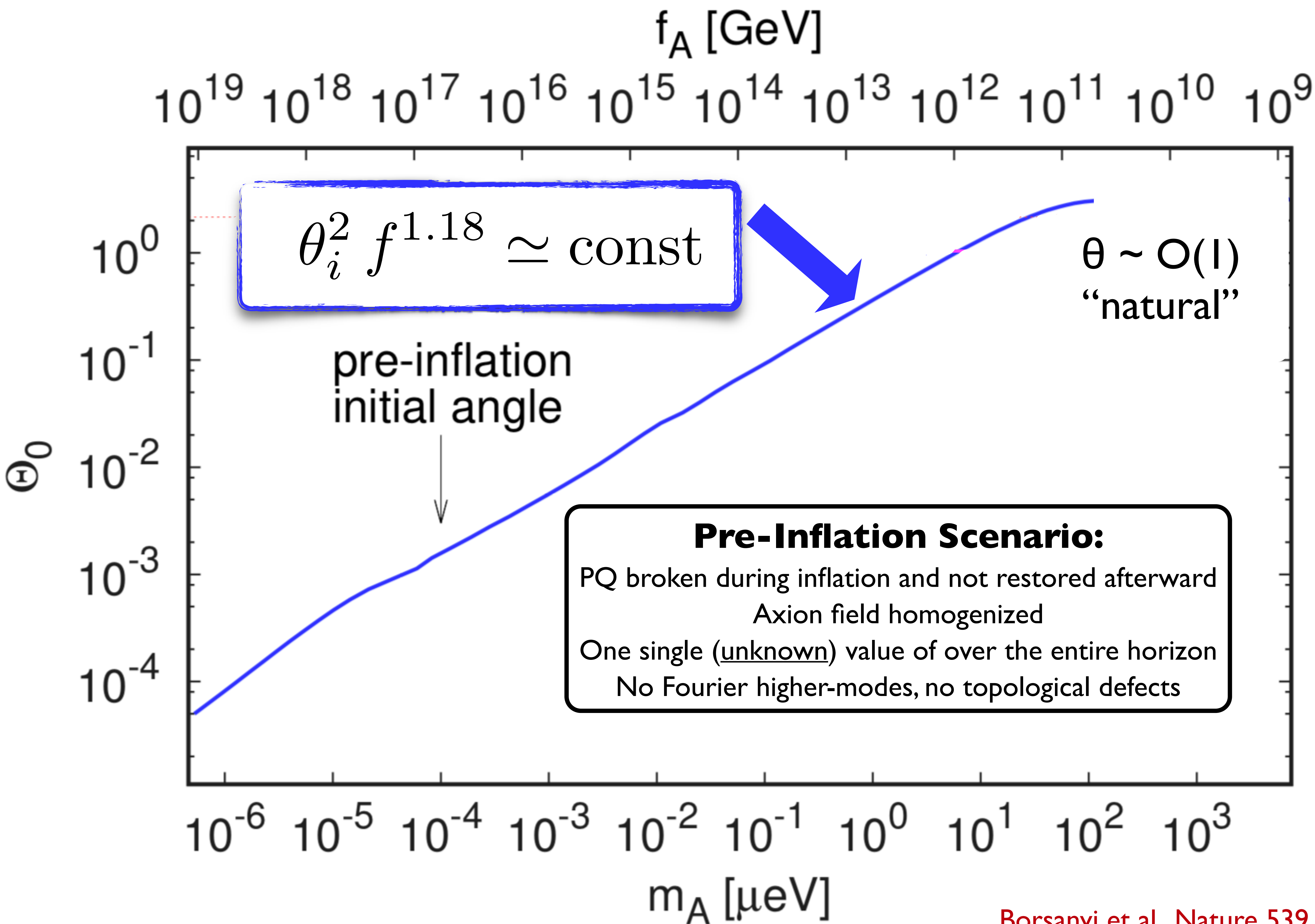
$$\Omega_a h^2 \simeq 0.1\,\theta_i^2 \left(\frac{f}{10^{11}\,\mathrm{GeV}}\right)^{1.18}$$

What is the initial axion field value?
It depends…



Bae, Huh, Kim, JCAP 0809 (2008)

Pre-Inflation Scenario



Pre-Inflation Scenario:

PQ broken during inflation and not restored afterward

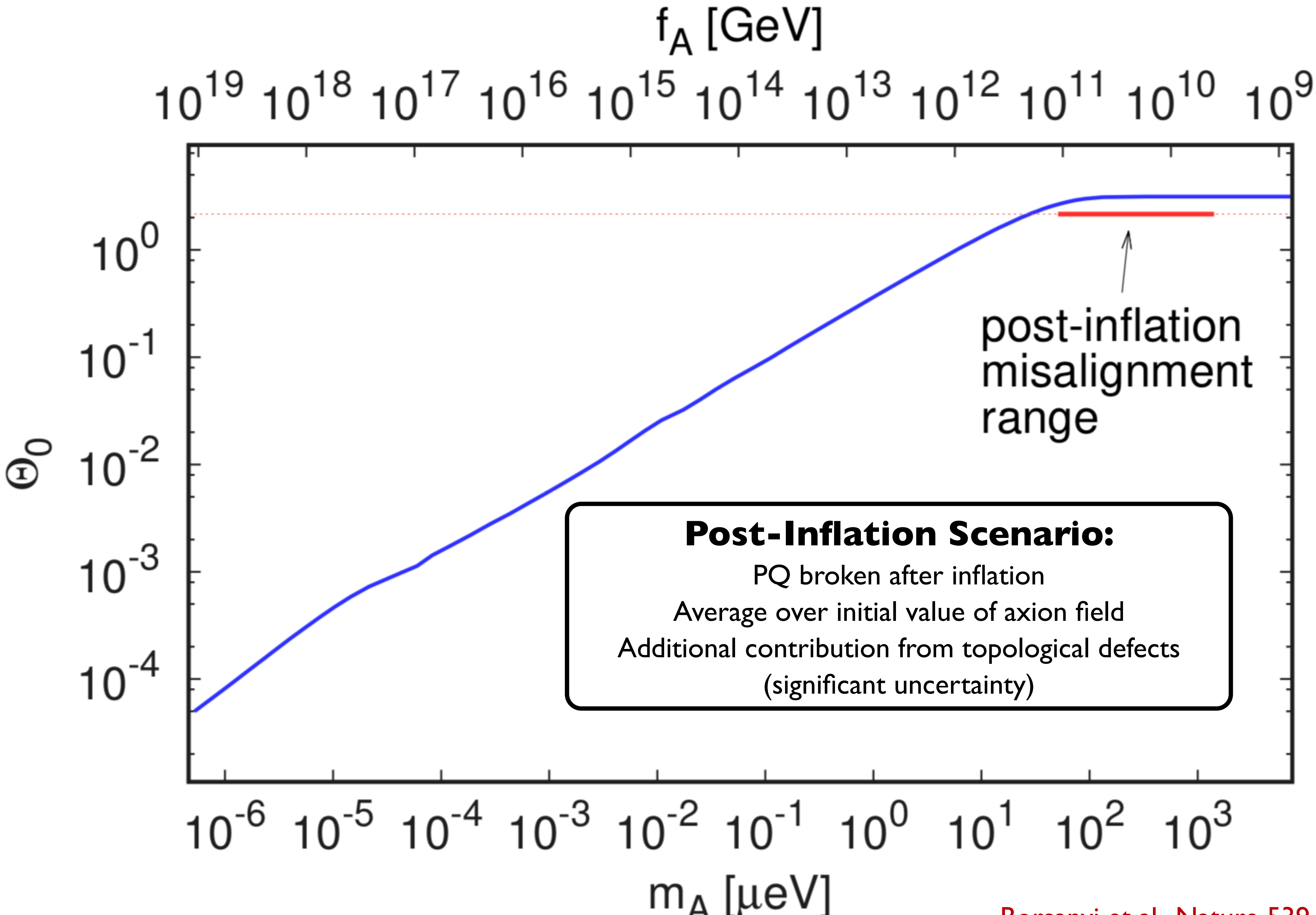
Axion field homogenized

One single (unknown) value of over the entire horizon

No Fourier higher-modes, no topological defects

Borsanyi et al., Nature 539 (2016)

Post-Inflation Scenario



Post-Inflation Scenario:

PQ broken after inflation

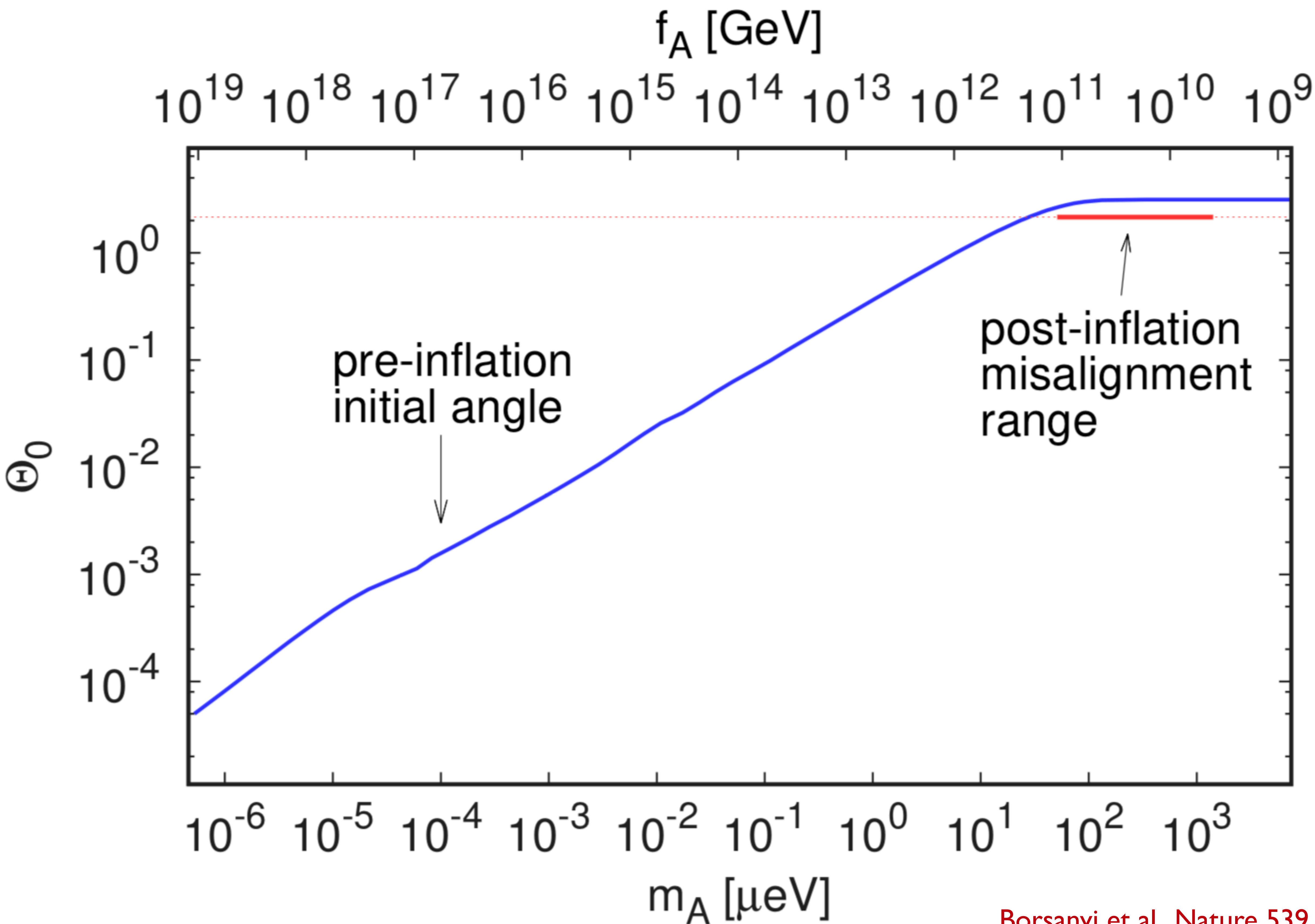
Average over initial value of axion field

Additional contribution from topological defects

(significant uncertainty)

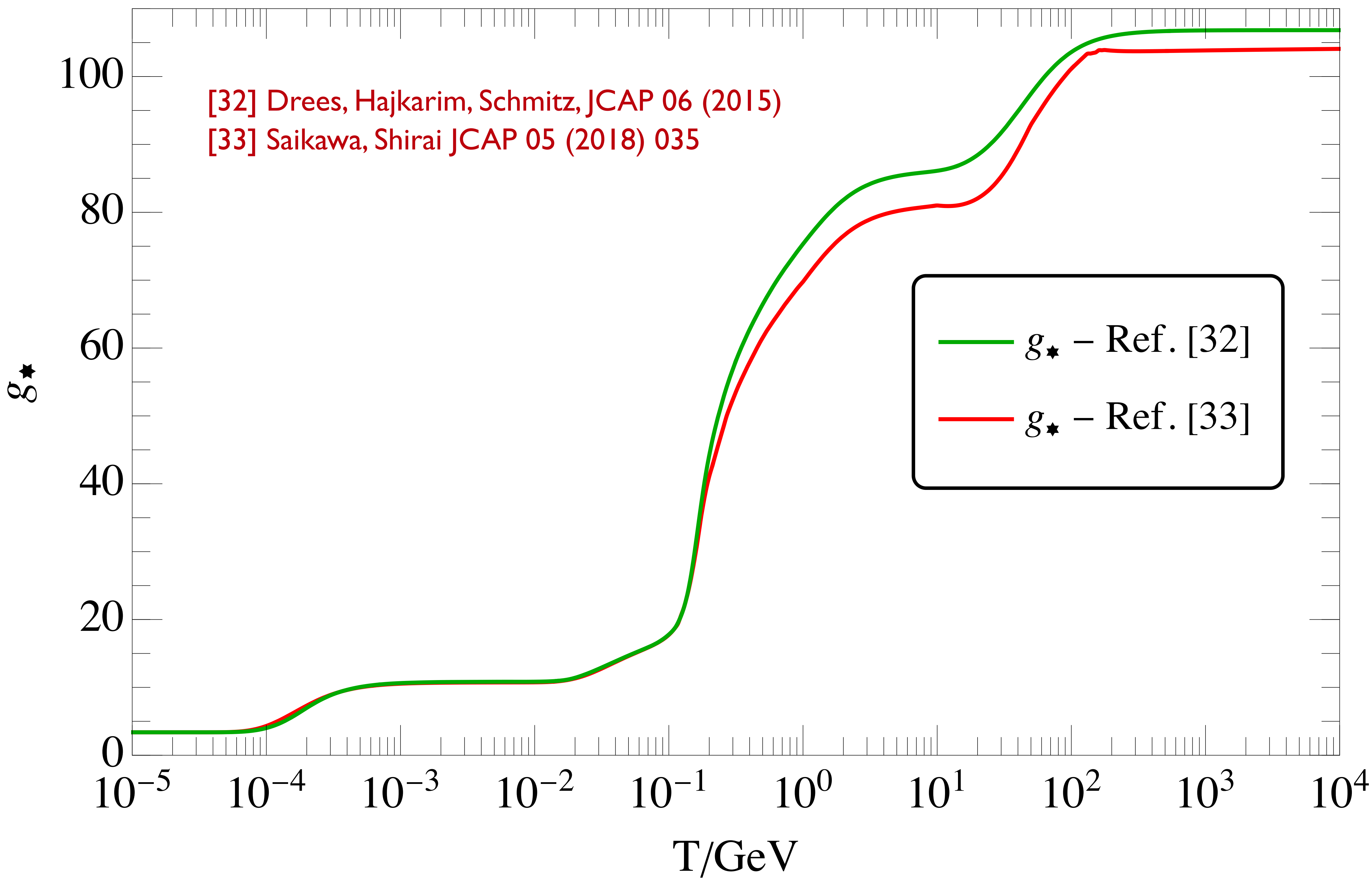
Borsanyi et al., Nature 539 (2016)

Axion Cold Dark Matter



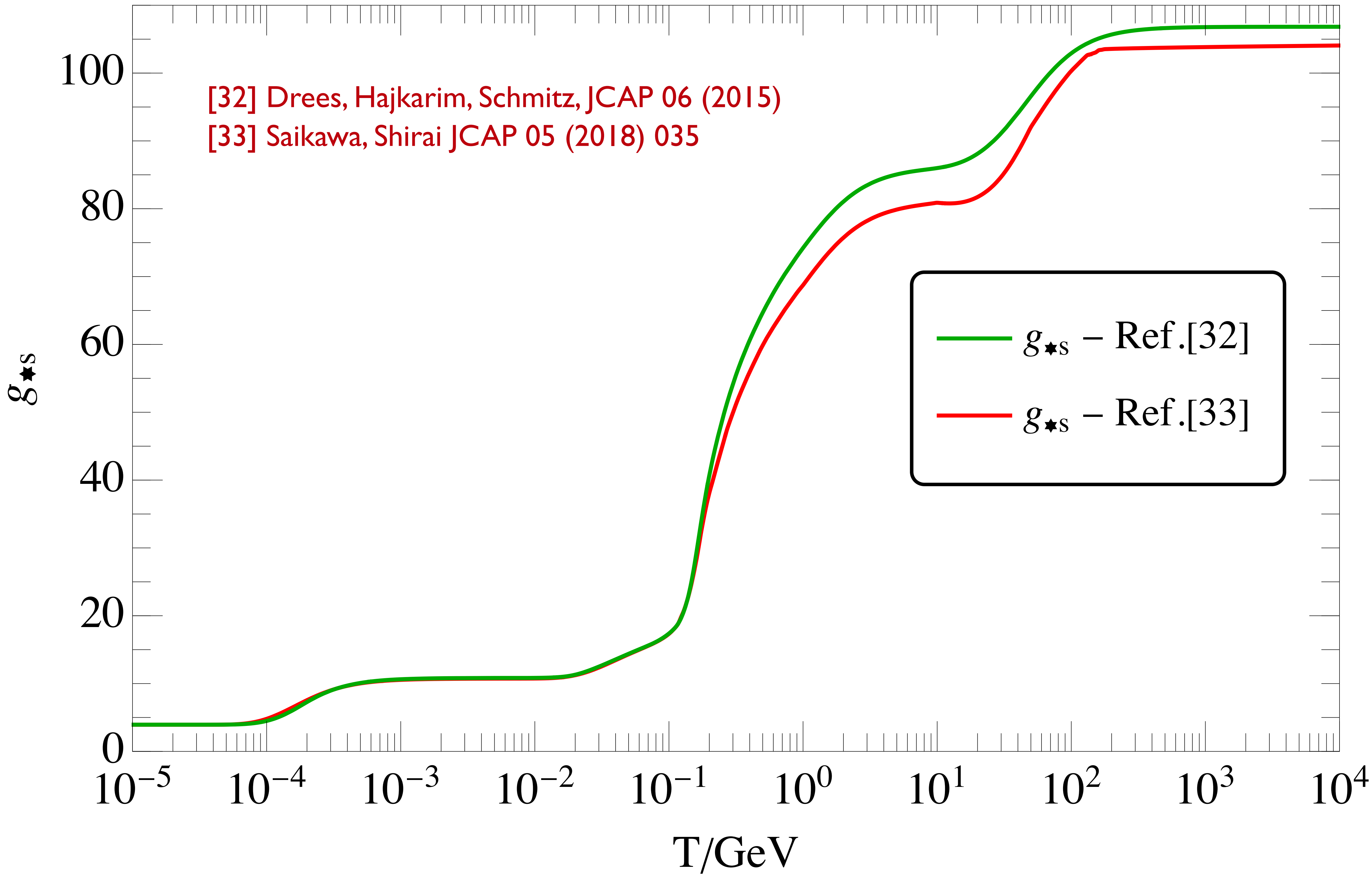
Borsanyi et al., Nature 539 (2016)

Thermal Bath I - Energy



FD, Hajkarim, Yun, JHEP 10 (2021) 224

Thermal Bath II - Entropy



FD, Hajkarim, Yun, JHEP 10 (2021) 224

Collision Rates

$g\, g \rightarrow g\, a$
(and others)

$$\Gamma_{\text{gauge}} \propto \alpha_s^3 \frac{T^3}{f^2}$$

$f\, h \rightarrow f\, a$

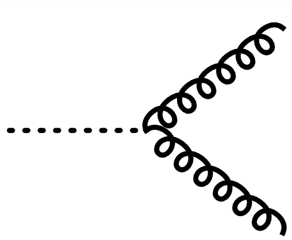
$$\Gamma_{\text{fermion}}^{\text{UV}} \propto y_f^2 \frac{T^3}{f^2}$$

$f\, g \rightarrow f\, a$

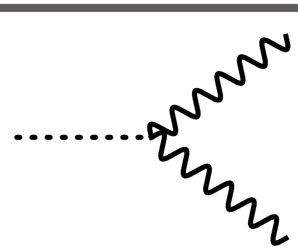
$$\Gamma_{\text{fermion}}^{\text{IR}} \propto \alpha_s m_f^2 \frac{T}{f^2}$$

ΔN_{eff} barely within reach of future CMB survyes

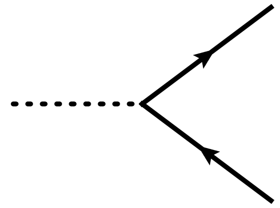
Potentially large contribution to ΔN_{eff}



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

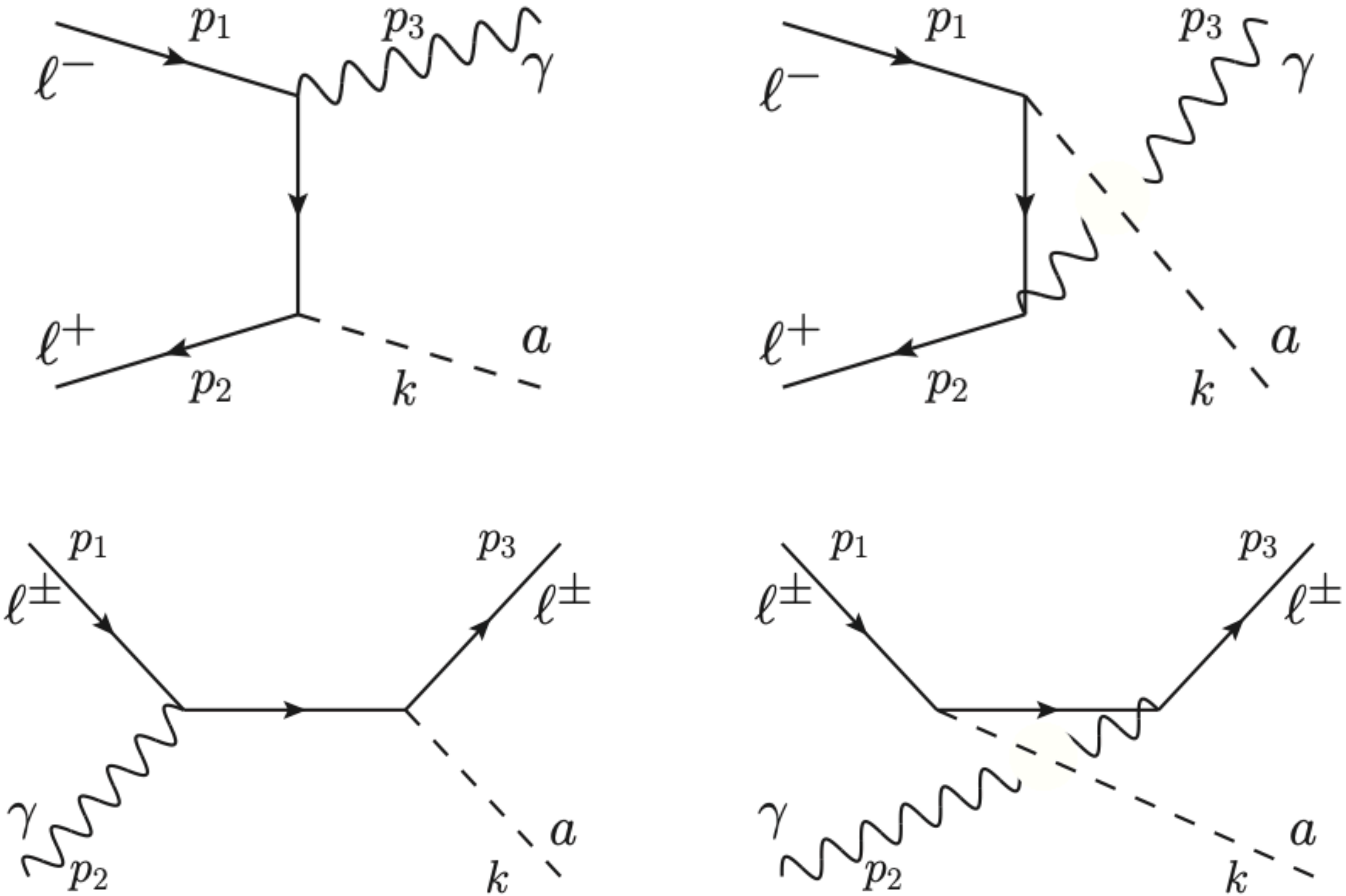


$$c_{a\gamma\gamma} \frac{a}{f_a} \frac{\alpha_{\text{em}}}{8\pi} F^{\mu\nu} \tilde{F}_{\mu\nu}$$



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

Production via Fermions



Production Rates — Leptons

Production vs Expansion Rates:

$$Y_a(T) \simeq \frac{\Gamma(T)}{H(T)} \simeq \frac{\Gamma(T) M_{\rm Pl}}{T^2}$$

Above EWPT

$$L_L e_R \to H a$$

(and others)

$$\Gamma_{\rm UV} \propto y_l^2 \frac{T^3}{f_a^2}$$

Below EWPT

$$l^+ l^- \to \gamma a$$

(and others)

$$\Gamma_{\rm IR} \propto \alpha_{\rm em}\, m_l^2 \frac{T}{f_a^2}$$

Production Rates — Leptons

Production vs Expansion Rates:

$$Y_a(T) \simeq \frac{\Gamma(T)}{H(T)} \simeq \frac{\Gamma(T) M_{\rm Pl}}{T^2}$$

Above EWPT

$$L_L e_R \to H a$$

(and others)

Efficient at high temperatures (UV production)

Below EWPT

$$l^+ l^- \to \gamma a$$

(and others)

Efficient at low temperatures (IR production)

Production Rates — Leptons

Production vs Expansion Rates:

$$Y_a(T) \simeq \frac{\Gamma(T)}{H(T)} \simeq \frac{\Gamma(T) M_{\rm Pl}}{T^2}$$

Above EWPT

$$L_L e_R \to H a$$

(and others)

ΔN_{eff} barely within reach of future CMB survyes

Below EWPT

$$l^+ l^- \to \gamma a$$

(and others)

Potentially large contribution to ΔN_{eff}

Production Rates — Leptons

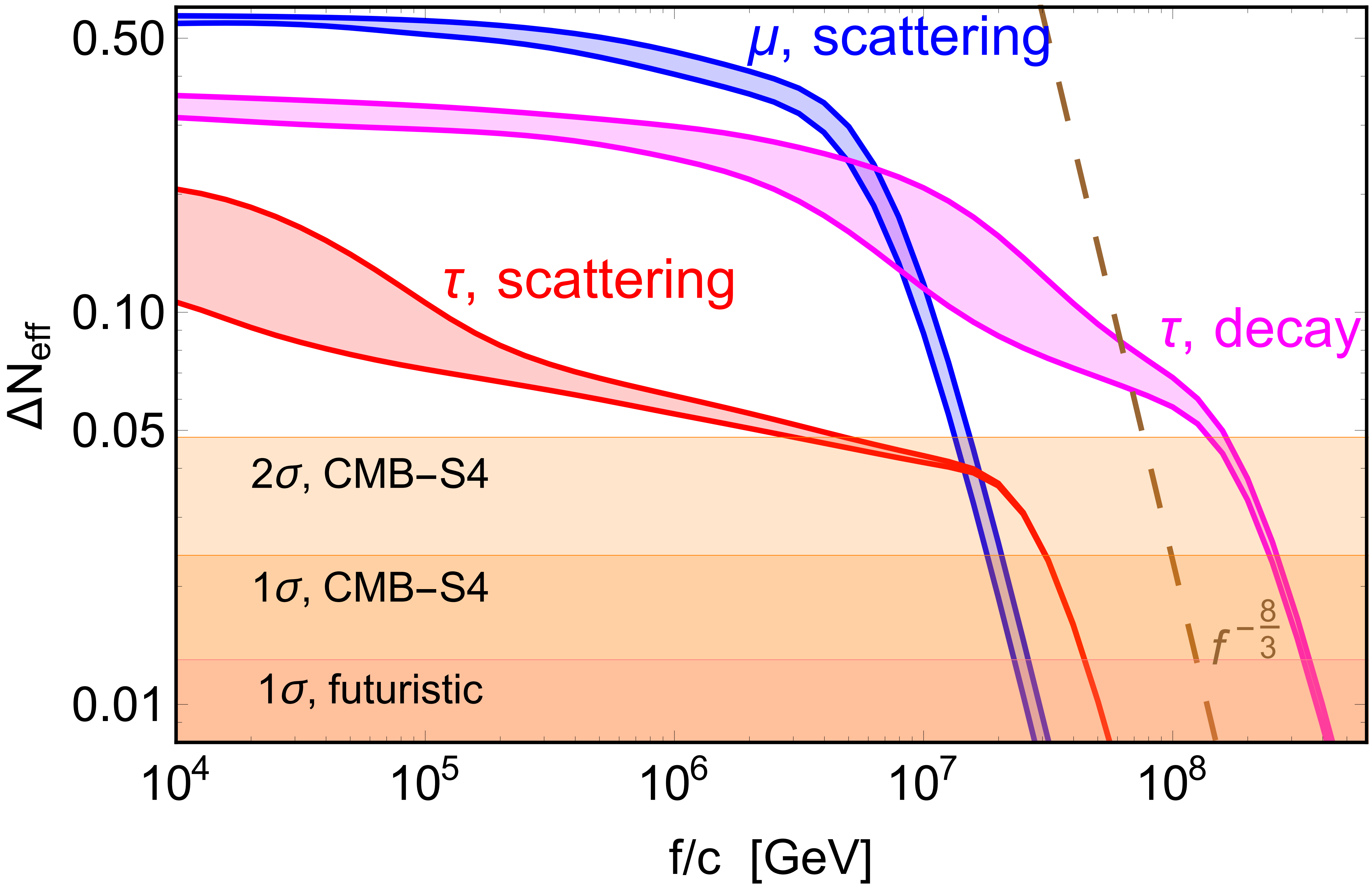
$$Y_a(T) \simeq \frac{\Gamma(T)}{H(T)} \simeq \frac{\Gamma(T) M_{\rm Pl}}{T^2}$$

$$\Gamma_{\rm UV} \propto y_l^2 \frac{T^3}{f_a^2}$$

$$\Gamma_{\rm IR} \propto \alpha_{\rm em}\, m_l^2 \frac{T}{f_a^2}$$

- Production rate enhanced for heavy leptons
- IR domination makes largest achievable $\Delta N_{\rm eff}$ originating from light leptons

ΔN$_{eff}$ from Leptophilic Axions



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

Hot Axions and H_0 Tension

Mismatch between early and late universe measurements

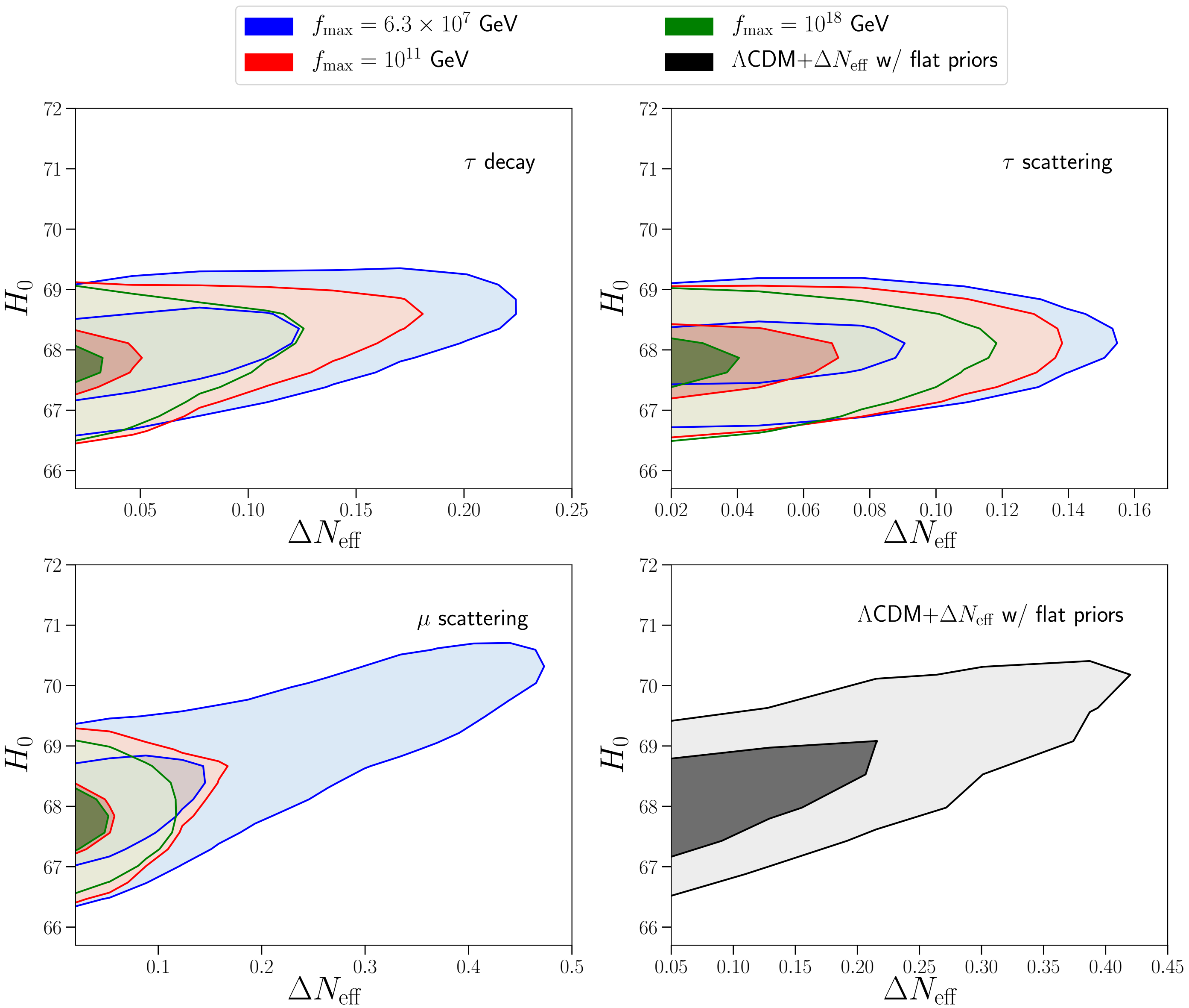
Planck 2018 results —1807.06209
A. G. Riess et al., Astrophys.J. 861 (2018)

ΔN_{eff} can be the origin

Bernal, Verde, Riess, JCAP 1610 (2016)

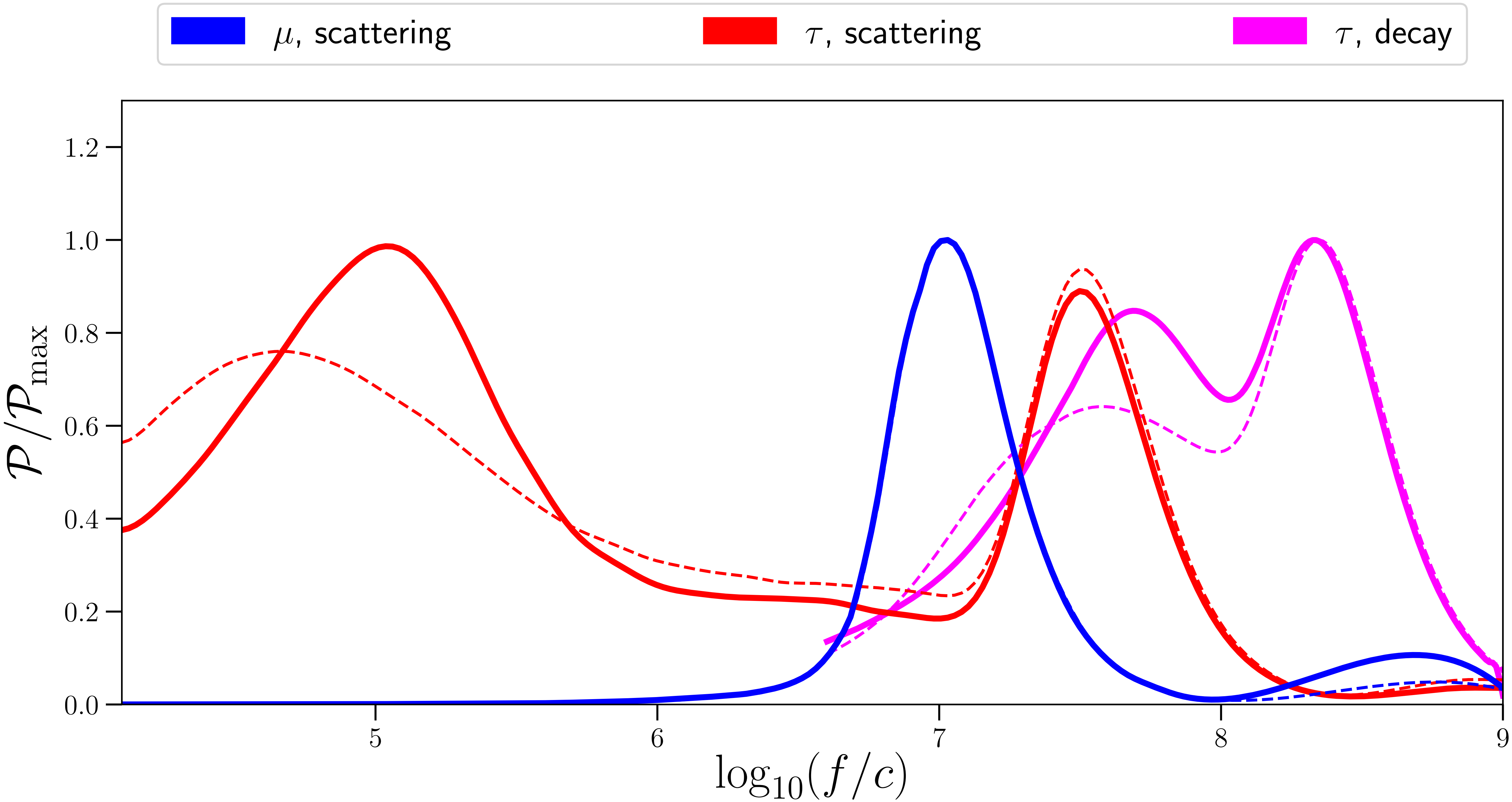
Could it be from axions?

Tension alleviated but… interacting only with heavy leptons and large couplings



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

Posterior Distribution (flat ΔN_{eff})



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

Hubble Tension

Model	Coupling	Prior $(f/c)_{\max}$ [GeV]	H_0 [km s^{-1} Mpc^{-1}]	$\mathcal{T}$ ($N\sigma$)
ΛCDM+$\Delta N_{\rm eff}$	μ scattering	3×10^7	$68.0^{+0.8}_{-0.7}(^{+2.3}_{-1.1})$	3.06 (2.75*)
		10^{11}	$67.8^{+0.6}_{-0.5}(^{+1.4}_{-1.1})$	3.36
		10^{18}	$67.7^{+0.5}_{-0.4}(^{+1.2}_{-1.0})$	3.38
	τ decay	6.3×10^7 GeV	$68.1^{+0.6}_{-0.5}(^{+1.2}_{-1.0})$	3.18
		10^{11}	$67.8^{+0.6}_{-0.5}(^{+1.2}_{-0.9})$	3.35
		10^{18}	$67.7^{+0.5}_{-0.4}(^{+1.1}_{-0.9})$	3.39
	τ scattering	5×10^8	$68.0^{+0.5}_{-0.5}(^{+1.0}_{-1.0})$	3.25
		10^{11}	$67.8^{+0.5}_{-0.5}(^{+1.1}_{-1.0})$	3.33
		10^{18}	$67.7^{+0.5}_{-0.5}(^{+1.1}_{-0.9})$	3.39
	No coupling	-	$68.3^{+0.8}_{-0.7}(^{+1.8}_{-1.2})$	2.93
ΛCDM+$N_{\rm eff}$	No coupling	-	$67.4^{+1.1}_{-1.2}(^{+2.3}_{-2.3})$	3.08
ΛCDM	No coupling	-	$67.7^{+0.5}_{-0.4}(^{+0.9}_{-0.9})$	3.46

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

Production Rates — Heavy Quarks

Production vs Expansion Rates:

$$Y_a(T) \simeq \frac{\Gamma(T)}{H(T)} \simeq \frac{\Gamma(T) M_{\rm Pl}}{T^2}$$

Above EWPT

$$Q_L q_R \to H a$$

(and others)

$$\Gamma_{\rm UV} \propto y_q^2 \frac{T^3}{f_a^2}$$

Below EWPT

$$q\bar{q} \to g a$$

(and others)

$$\Gamma_{\rm IR} \propto \alpha_s m_q^2 \frac{T}{f_a^2}$$

Production Rates — Heavy Quarks

$$Y_a(T) \simeq \frac{\Gamma(T)}{H(T)} \simeq \frac{\Gamma(T) M_{\rm Pl}}{T^2}$$

$$\Gamma_{\rm UV} \propto y_q^2 \frac{T^3}{f_a^2}$$

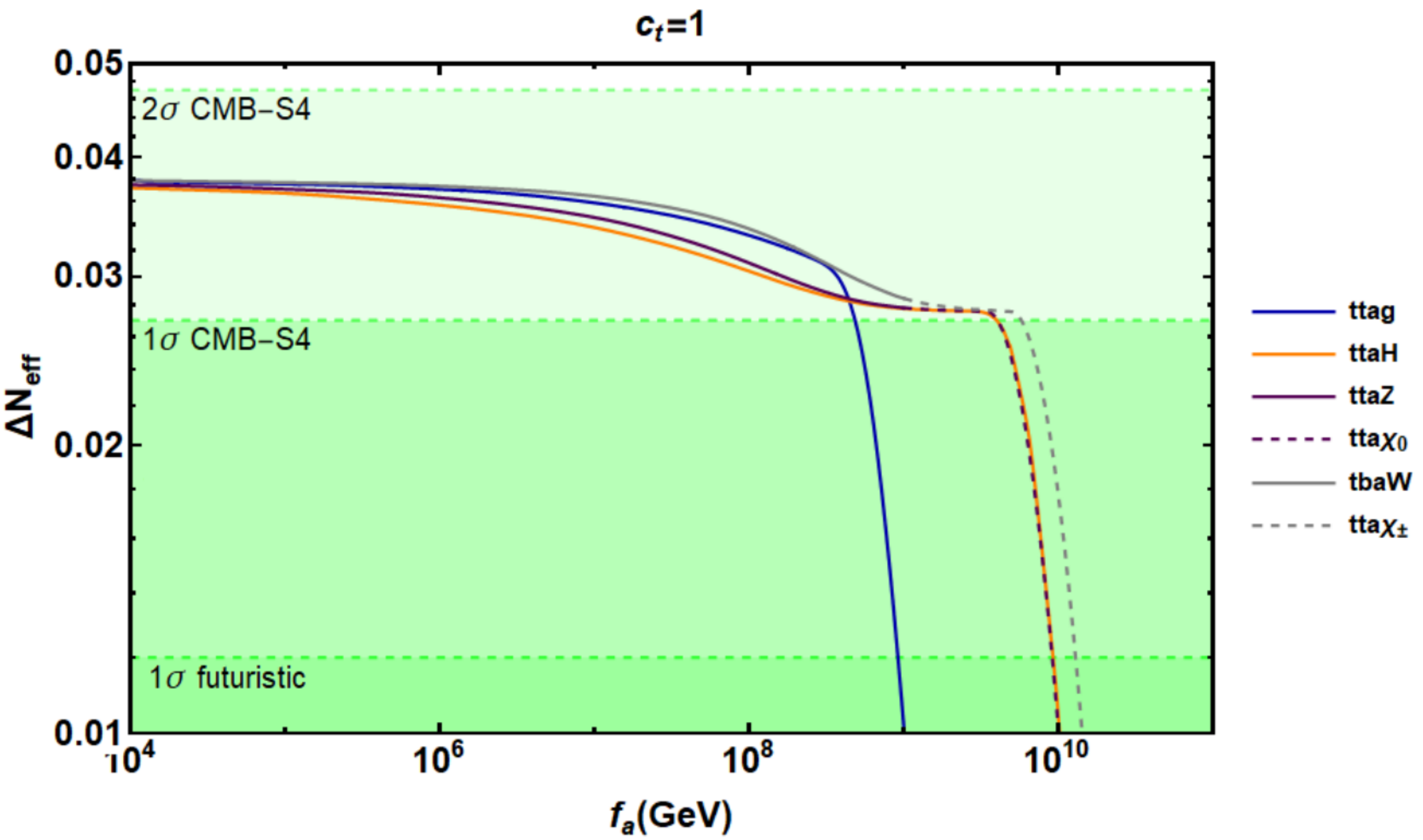
$$\Gamma_{\rm IR} \propto \alpha_s m_q^2 \frac{T}{f_a^2}$$

- Strong interactions enhance the rate
- Top quark requires a careful evaluation of EWPT
  (well-studied above and below the EWPT)

Salvio, Strumia, Xue, JCAP 1401 (2014)
Ferreira, Notari, Phys.Rev.Lett. 120 (2018)

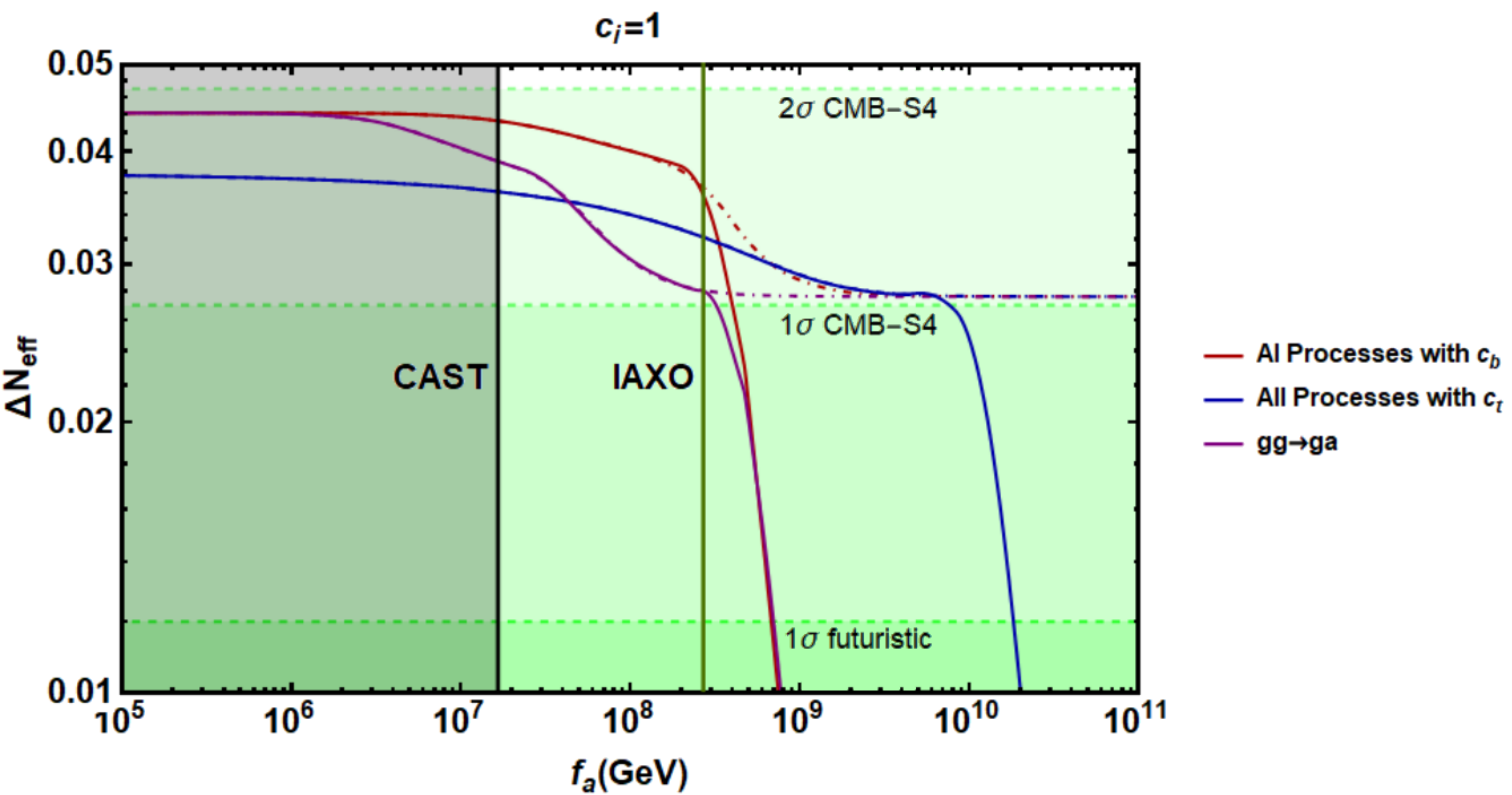
- Perturbative analysis only for b and t (confinement)

Top scatterings across the EWPT



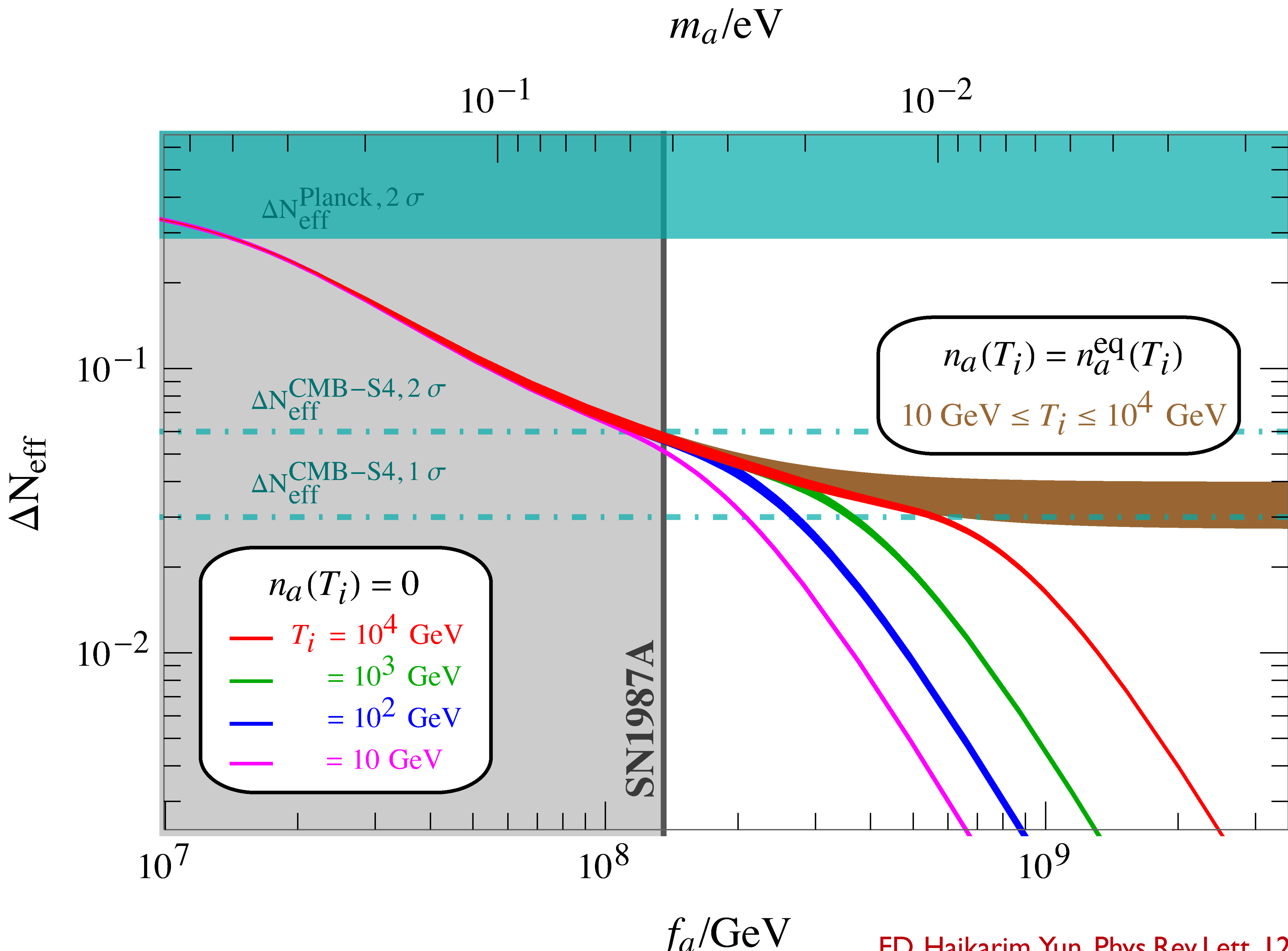
Arias-Aragon, FD, Ferreira, Merlo, Notari, JCAP 03 (2021)

ΔN_{eff} from Heavy Quarks



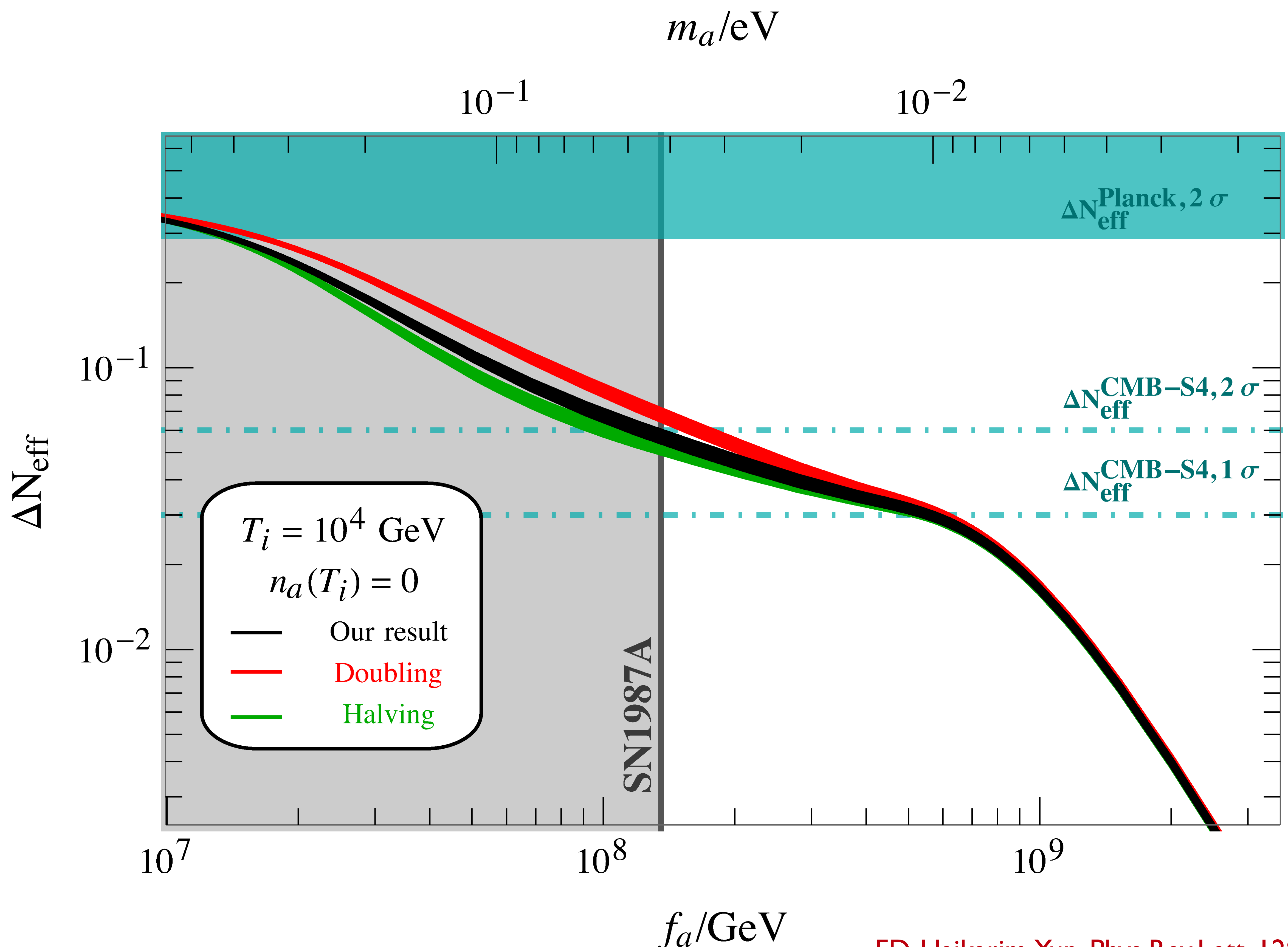
Arias-Aragon, FD, Ferreira, Merlo, Notari, JCAP 03 (2021)

ΔN_{eff} around the QCDPT



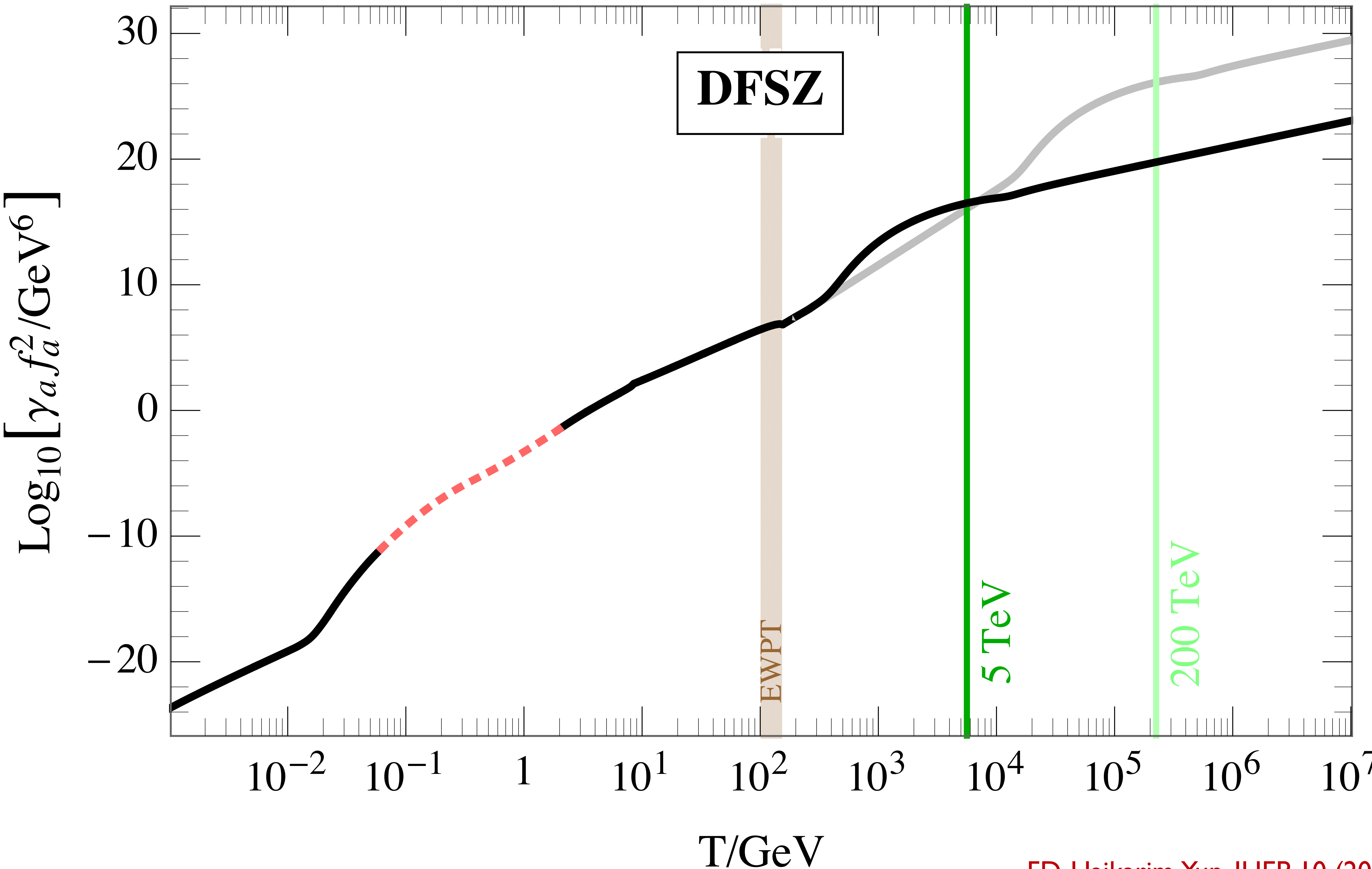
FD, Hajkarim, Yun, Phys.Rev.Lett. 128 (2022)

More on the Interpolation



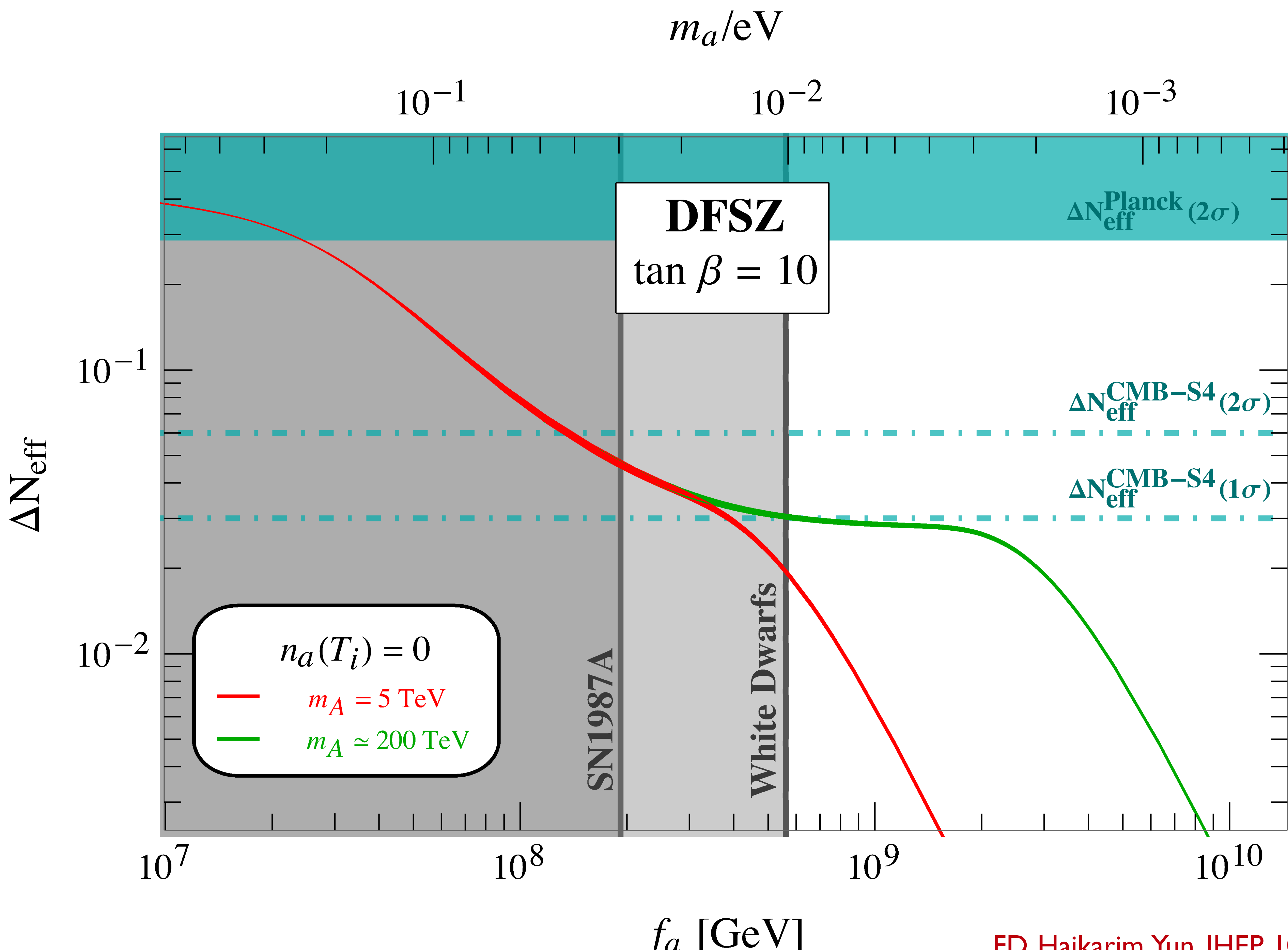
FD, Hajkarim, Yun, Phys.Rev.Lett. 128 (2022)

DFSZ with TeV Heavy Higgses



FD, Hajkarim, Yun, JHEP 10 (2021)

DFSZ with TeV Heavy Higgses



FD, Hajkarim, Yun, JHEP 10 (2021)