Novel cosmological bounds on thermally-produced axion-like particles

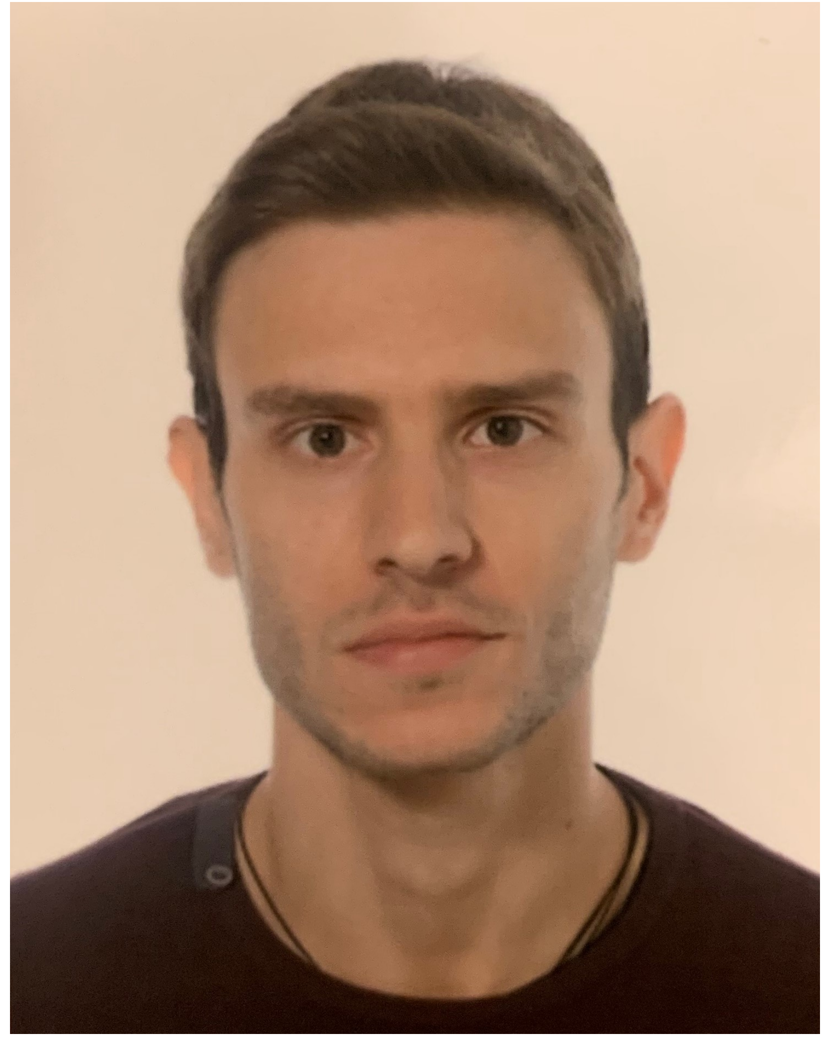
Based on L. Caloni, MG, M. Lattanzi and L. Visinelli, JCAP 2022

Martina Gerbino (INFN Ferrara), PADUA workshop, 14 Sep 2022

Outline

1. Phenomenology of thermally produced axion-like particles (axions)
2. The chiral axion Lagrangian
3. Cosmological analysis
4. Summary and outlook

Work led by Luca Caloni (U Ferrara)



Cosmological phenomenology

Thermally produced axions via coupling with gluons and photons in the early Universe

Freeze-out condition $H(T_d) \simeq \Gamma(T_d)$

Decoupling temperature Td sets axion abundance

$$\frac{\langle p_{a,\mathrm{rec}} \rangle}{m_a} \approx 2.7 \, \frac{T_{a,\mathrm{rec}}}{m_a} = 2.7 \, \frac{T_{\mathrm{CMB}}}{m_a} \left(\frac{g_{*s}(T_{\mathrm{CMB}})}{g_{*s}(T_d)} \right)^{1/3}$$

Small masses ma

Large masses ma

Contribution to radiation density

$$\Delta N_{\mathrm{eff}} \equiv \frac{\rho_a^{\mathrm{mless}}}{\rho_\nu^{\mathrm{mless}}} \propto \frac{g_a}{g_\gamma} \left(\frac{T_a}{T_\gamma} \right)^4 \simeq 0.027 \left(\frac{g_{*s}(T_d)}{106.75} \right)^{-4/3}$$

$$\Delta N_{\mathrm{eff}}^{\mathrm{CMB}} \equiv \frac{\rho_a(m_a)}{\rho^{\mathrm{mless}}} \propto m_a g_{*s}(T_d)^{1/3}$$

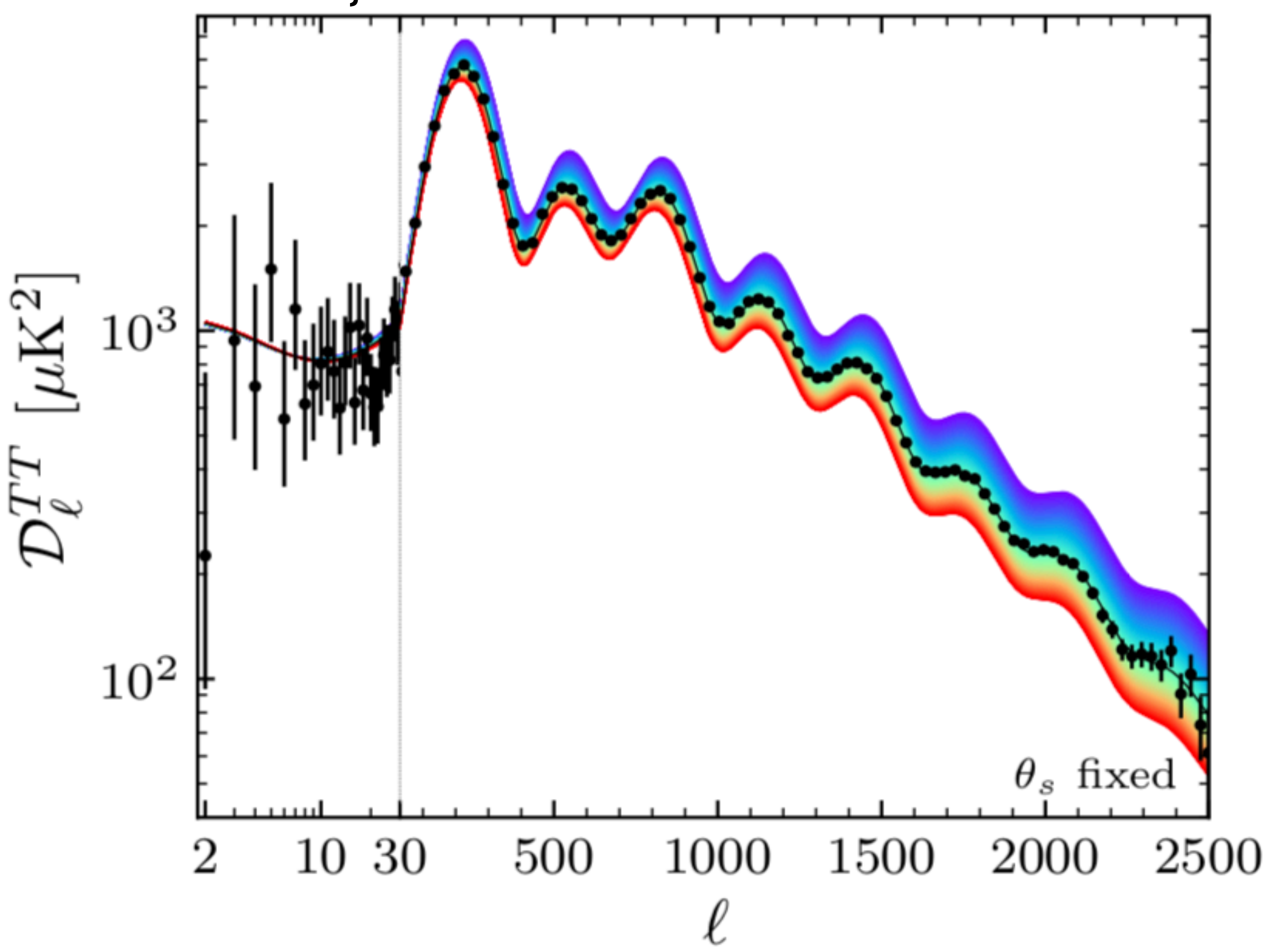
Contribution to matter density

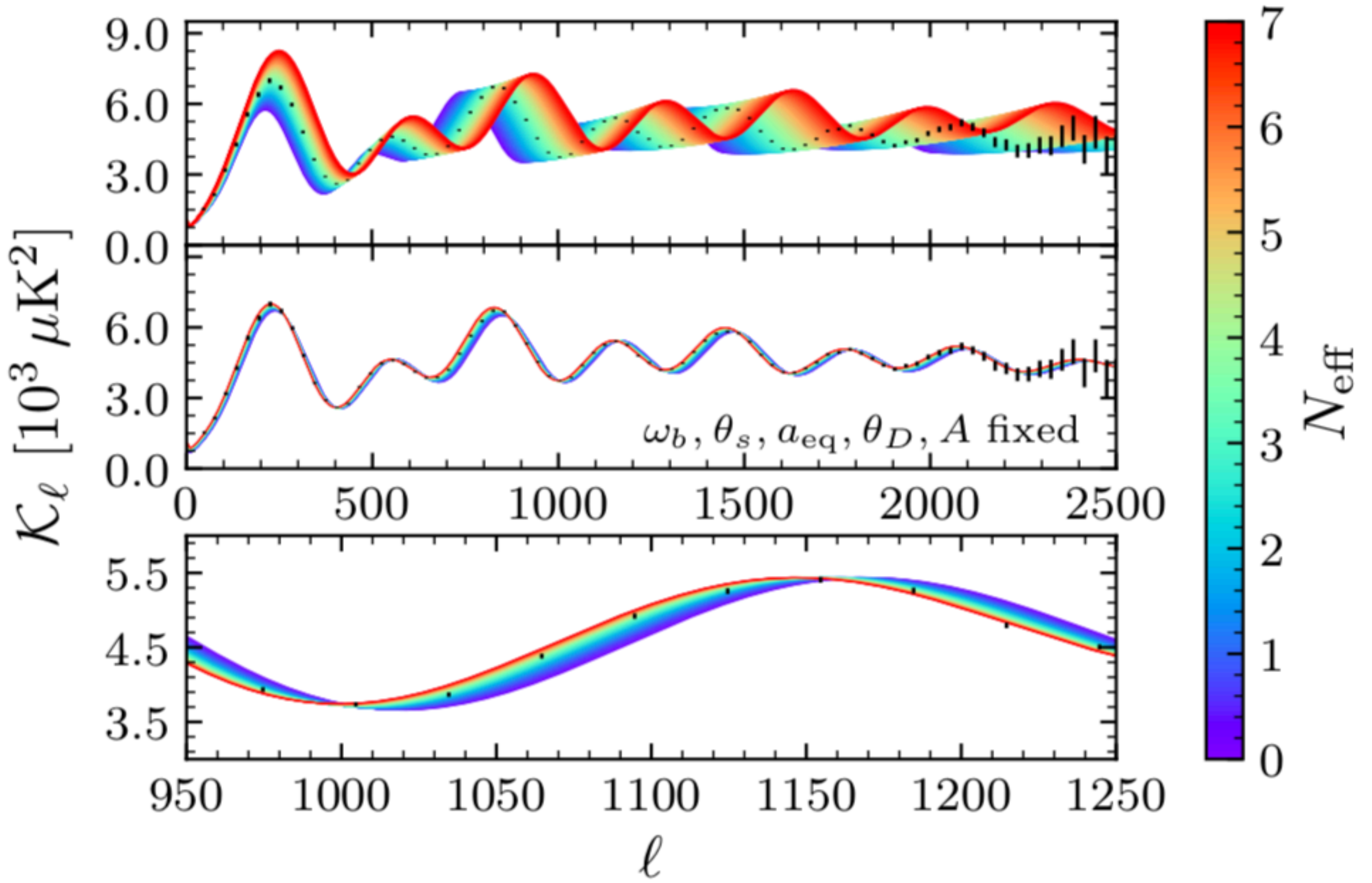
$$\omega_a \simeq m_a n_a \simeq \left(\frac{m_a}{130\,\mathrm{eV}} \right) \left(\frac{g_{*,s}(T_d)}{10} \right)^{-1} = 0.011 \left(\frac{m_a}{\mathrm{eV}} \right) \Delta N_{\mathrm{eff}}^{3/4}$$

Model completely defined by two parameters: ma and Td; or any two between DNeff, DNeff_CMB, omega_a

Cosmological phenomenology

2203.07377, credit: B. Wallisch



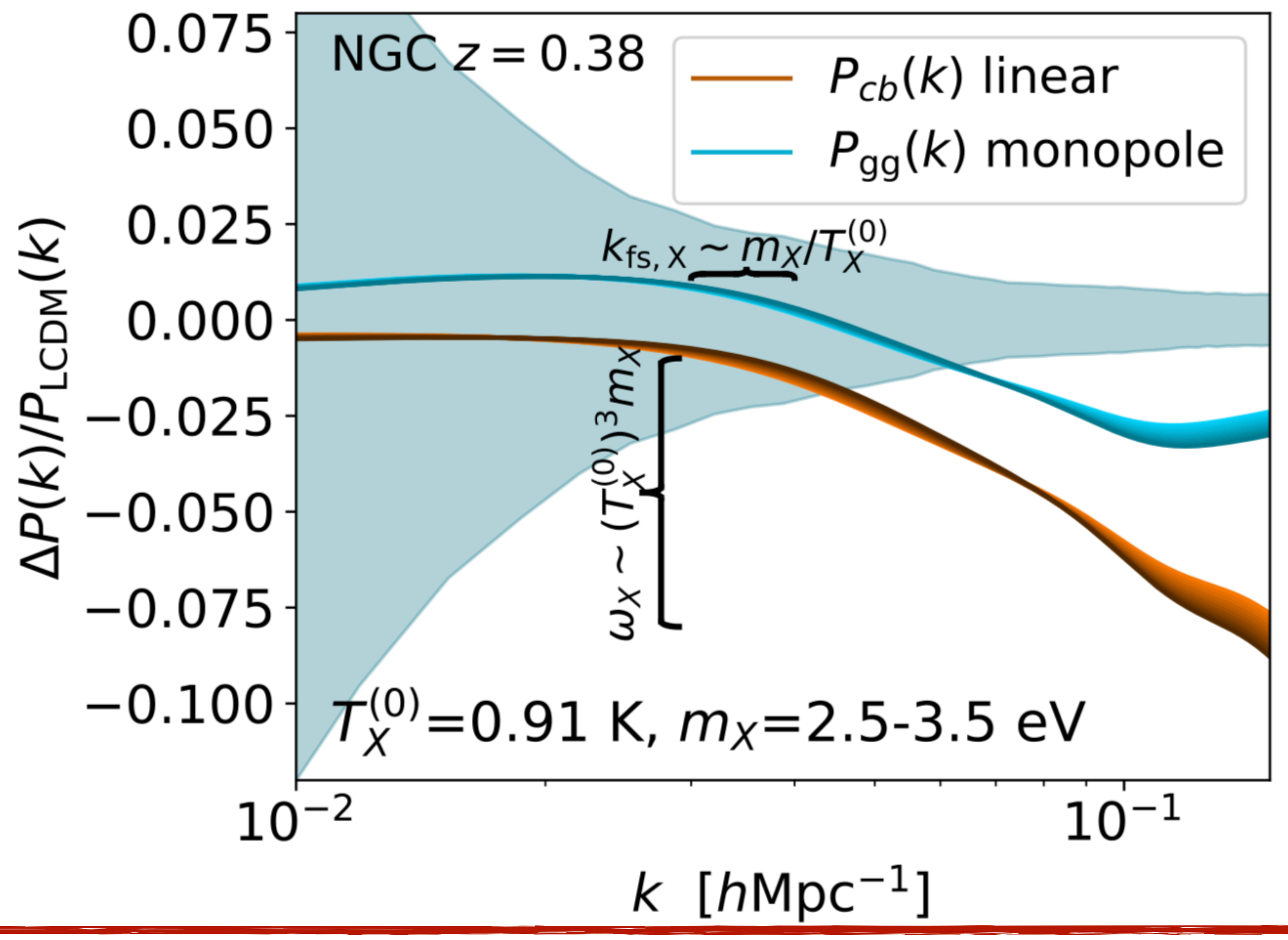


Damping tail suppression:
theta_d~sqrt(H(Neff))

Shift of acoustic peak position:
phi~Neff

Amplitude from abundance: omega_a ~ma/g*s(Td)

Suppression from free-streaming scale: kfs~ma g*s(Td)^1/3

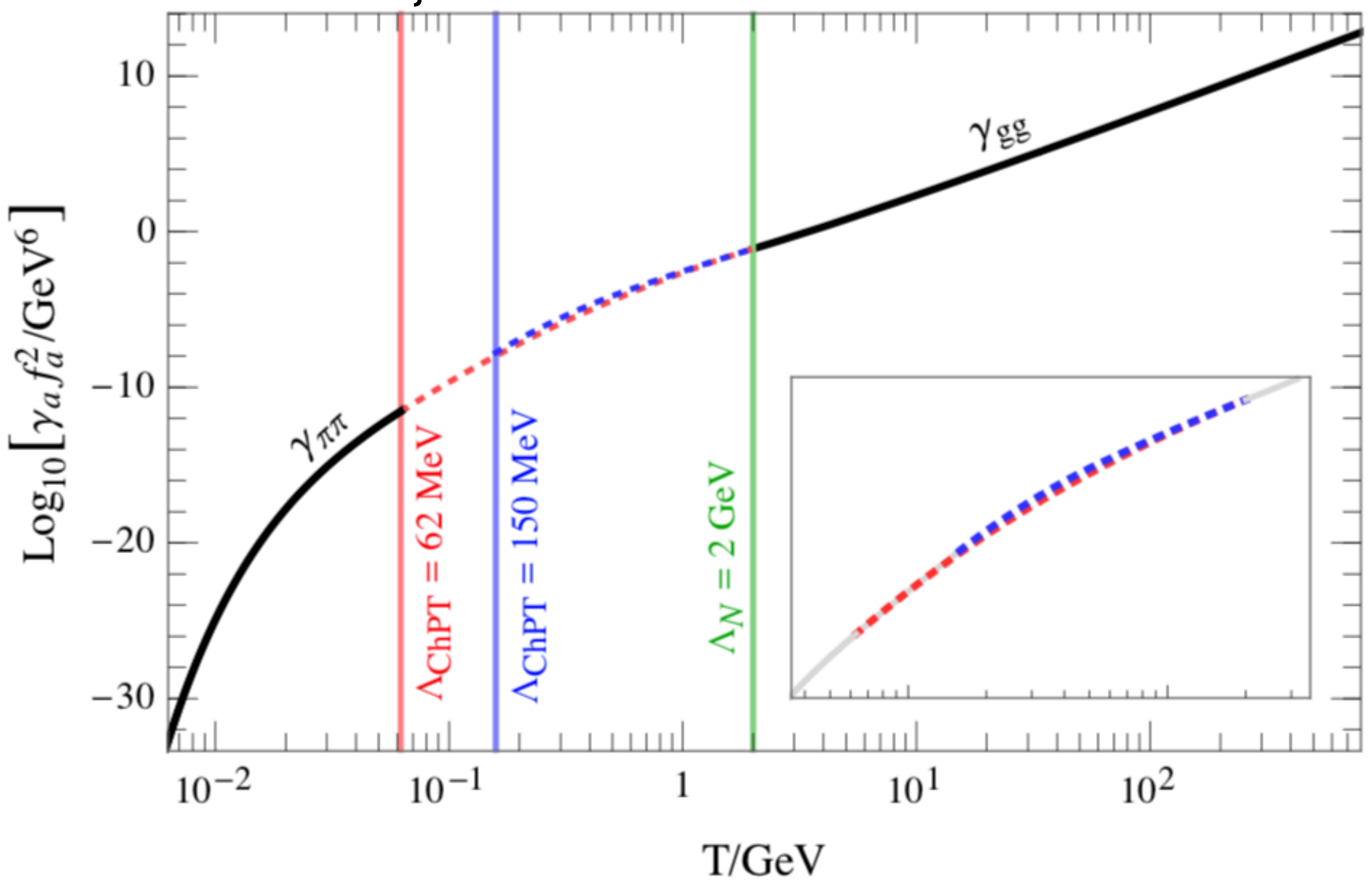


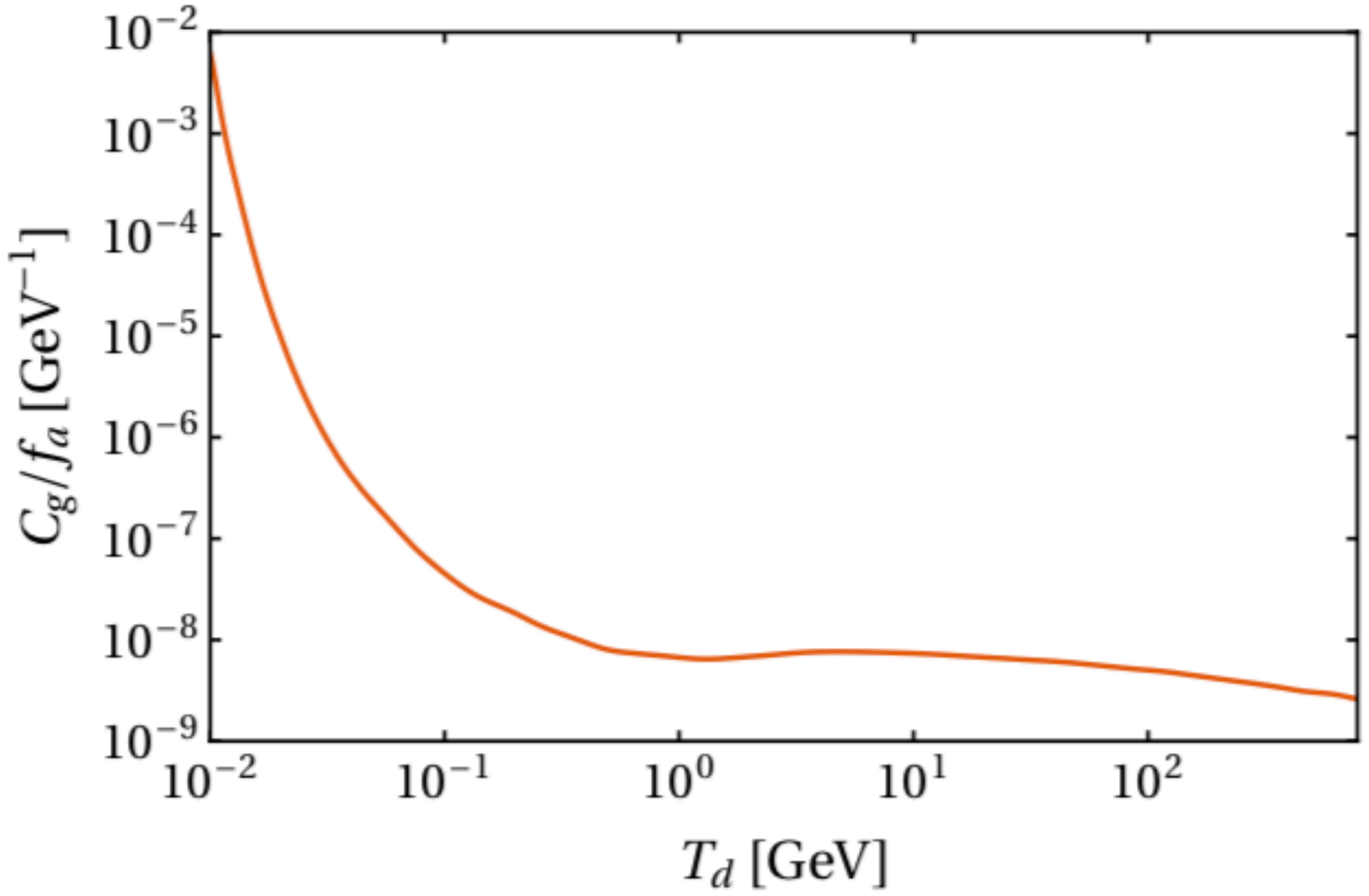
Xu,Munoz,Dvorkin,2022

Axion-gluon coupling

$$\mathcal{L}_{\rm eff} \supset \frac{1}{2}(\partial^\mu a)(\partial_\mu a) - \frac{1}{2}m_0^2 a^2 + \mathcal{L}_{ag} + \mathcal{L}_{a\gamma}\,, \quad \mathcal{L}_{ag} = \frac{\alpha_s}{8\pi}\frac{C_g}{f_a}\, a G^i_{\mu\nu}\tilde{G}^{\mu\nu,i} \;\Rightarrow\; \gamma_g = \frac{\zeta(3)}{4\pi^5}\,\alpha_s^2\, T^6 \left(\frac{C_g}{f_a}\right)^2 F_g(T)$$

D'Eramo+, PRL2022





Comparison with lab:
Irreducible electric dipole moment of neutron
(assumption: from axion-gluon coupling,
axion-fermion coupling suppressed)

$$d_n = g_d a_0 \cos(m_a t); \quad g_d = \frac{C_{an\gamma}}{m_n}\frac{C_g}{f_a}$$

Effective axion mass

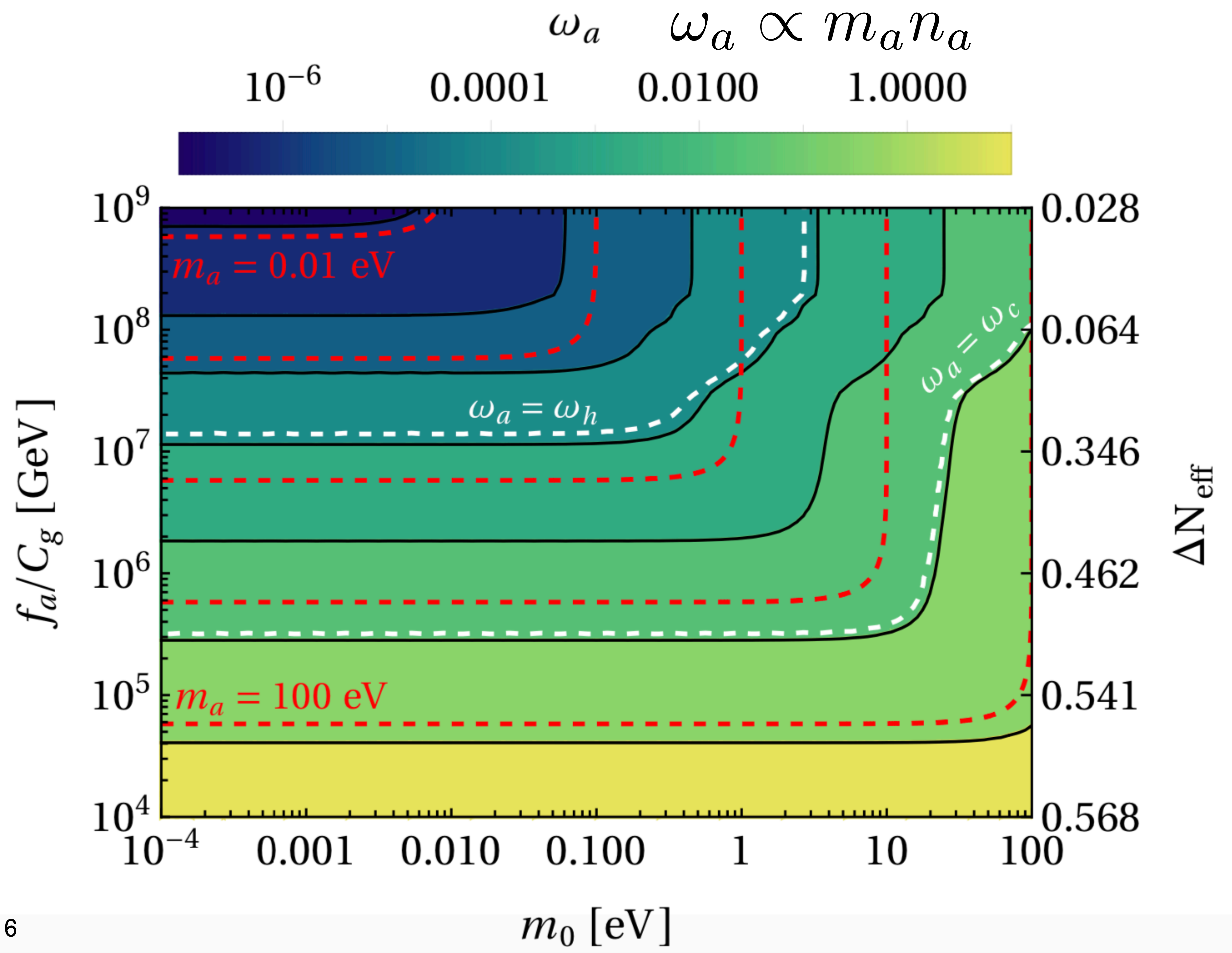
After rotation of the quark fields and explicit mass breaking:

Effective axion mass

$$m_a^2 = m_0^2 + \left(\frac{C_g}{f_a}\right)^2 F_\pi^2 m_\pi^2 \frac{z}{(1+z)^2} \approx m_0^2 + \left(5.8\,\mu\text{eV}\,\frac{10^{12}\,\text{GeV}}{f_a/C_g}\right)^2$$

If dominant, ma decoupled from fa

At fixed fa/Cg, contribution to axion abundance:
- dominated by number density (Td) for small m0
- mostly due to ma for large m0



Axion-photon coupling

$$\mathcal{L}_{\rm eff} \supset \frac{1}{2}(\partial^\mu a)(\partial_\mu a) - \frac{1}{2}m_0^2 a^2 + \mathcal{L}_{ag} + \mathcal{L}_{a\gamma}\,, \quad \mathcal{L}_{a\gamma} = \frac{1}{4} g^0_{a\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

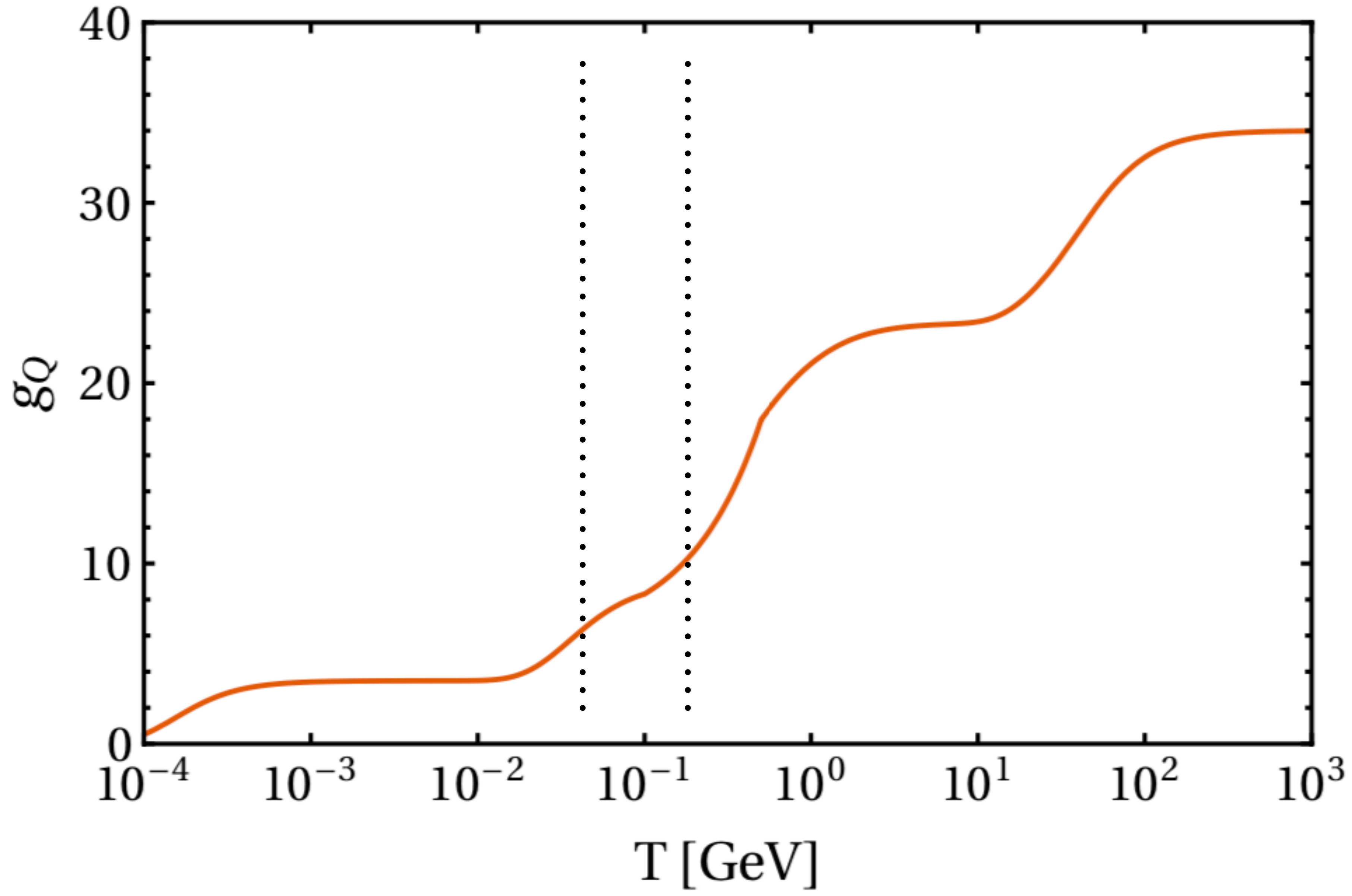
After rotation of the quark fields and explicit mass breaking:

$$g_{a\gamma} = g^0_{a\gamma} - \frac{\alpha_{\rm EM}}{3\pi}\frac{C_g}{f_a}\frac{4+z}{1+z} \approx g^0_{a\gamma} - 2.3\times 10^{-15}\,{\rm GeV}^{-1}\left(\frac{10^{12}\,{\rm GeV}}{f_a/C_g}\right)$$

Effective axion-photon coupling

Primakoff effect as leading production mechanism

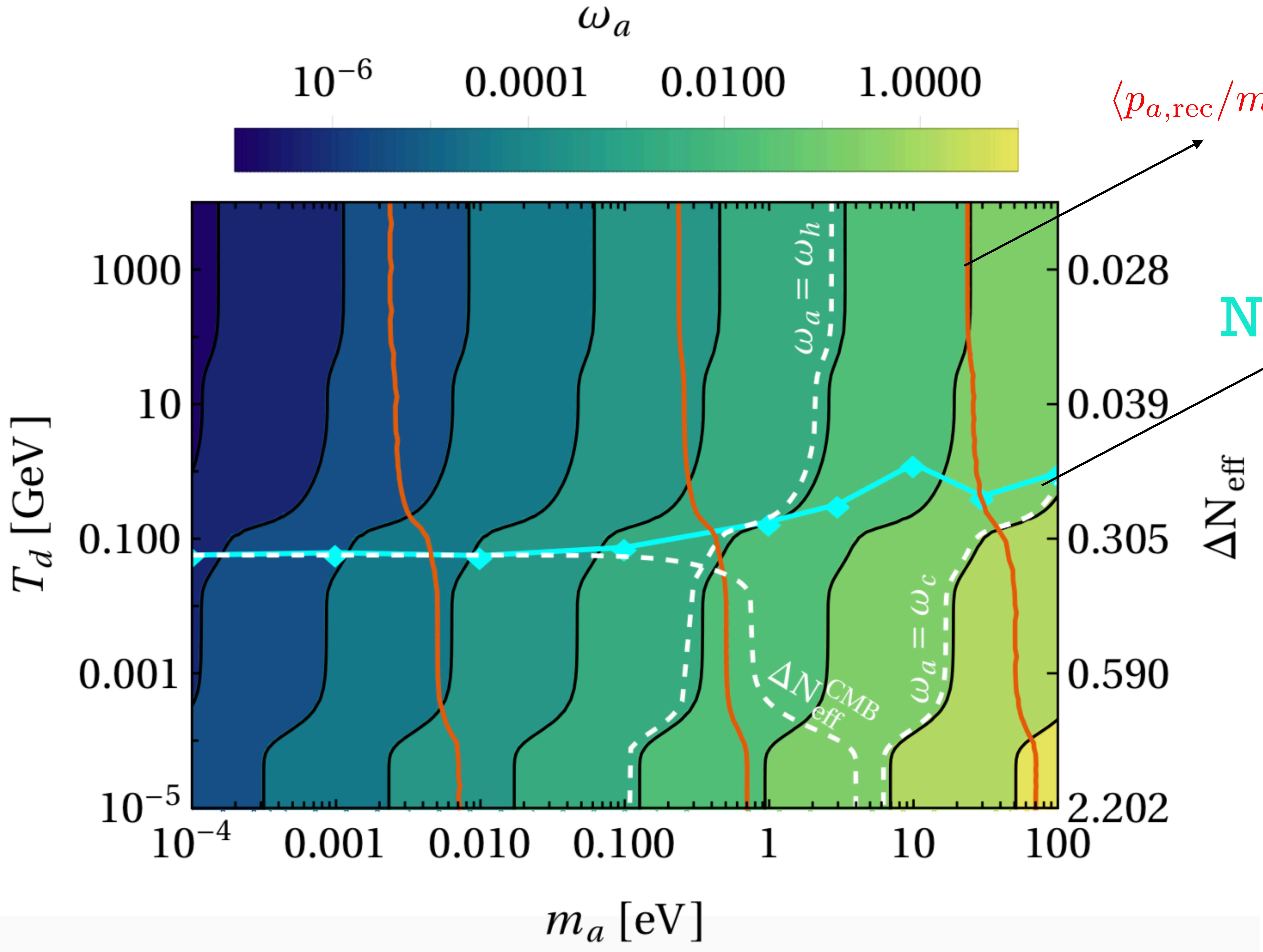
$$\Gamma_{Q\gamma\to Qa} \simeq \frac{\alpha_{\rm EM}\pi^2 g^2_{a\gamma}}{36\zeta(3)}\left[\ln\left(\frac{T^2}{m_\gamma^2}\right) + 0.8194\right] n_Q$$



Condition on cosmological stability of axions imposed

$$\frac{\Gamma_{a\to\gamma\gamma}}{H_0} \simeq 3.48\times 10^{-2}\left(\frac{g_{a\gamma}}{10^{-7}\,{\rm GeV}^{-1}}\right)^2\left(\frac{m_a}{\rm eV}\right)^3 \ll 1$$

Summary of cosmological results



$\langle p_{a,\mathrm{rec}}/m_a \rangle = [10^2,\, 1,\, 10^{-2}]$

Novel bounds!

Cosmological analysis

LCDM model augmented with axion mass and contribution to Neff

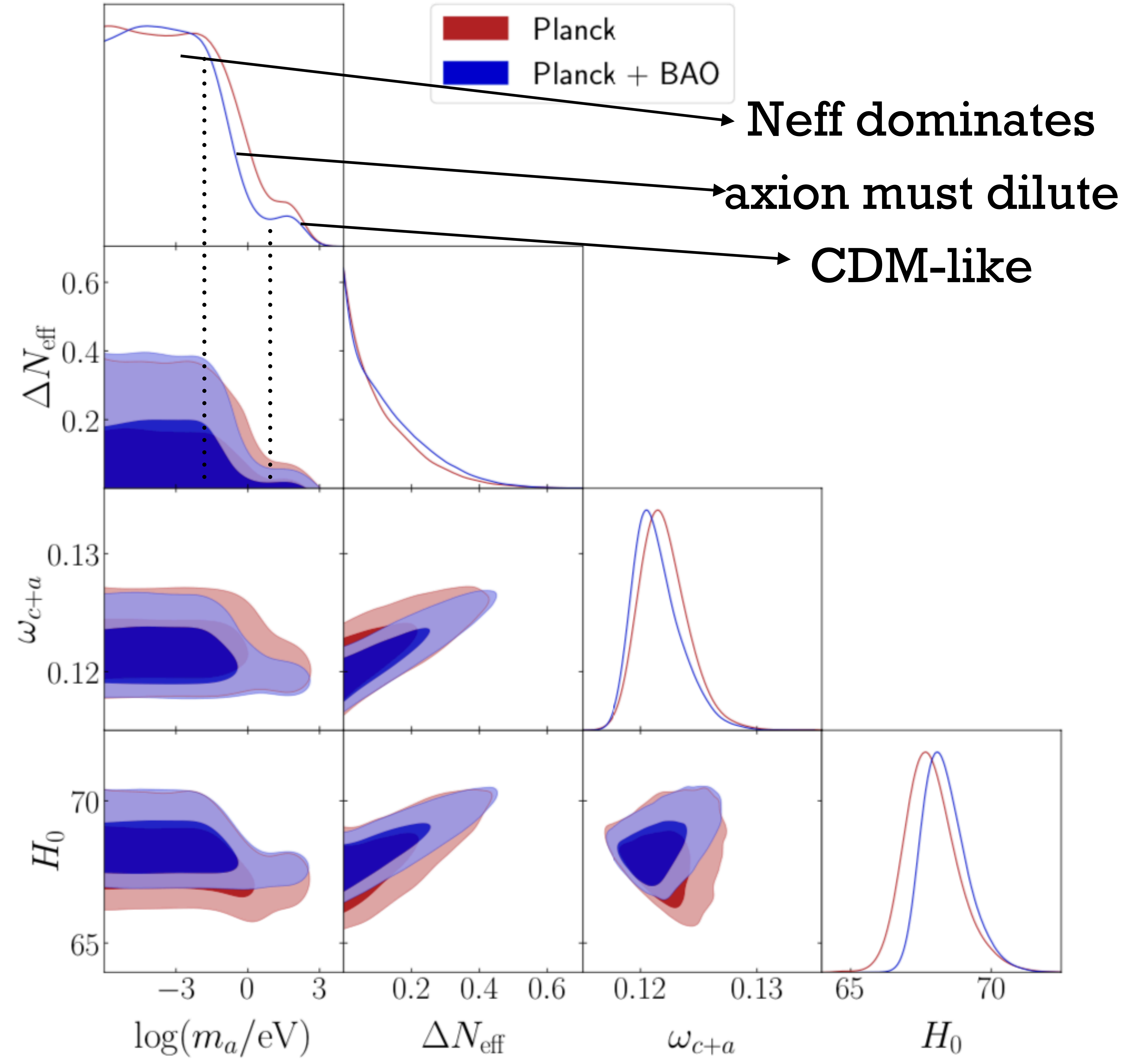
$$\Theta_{\Delta N_{\rm eff}+m_a} = \{\omega_b,\, \theta_s,\, \tau,\, \ln(10^{10}A_s),\, n_s,\, \omega_{c+a},\, m_a,\, \Delta N_{\rm eff}\}$$

Data: CMB: Planck TTTEEE+lensing (+ ACT TTTEEE)
LSS: BAO measurements from BOSS, 6dF, SDSS

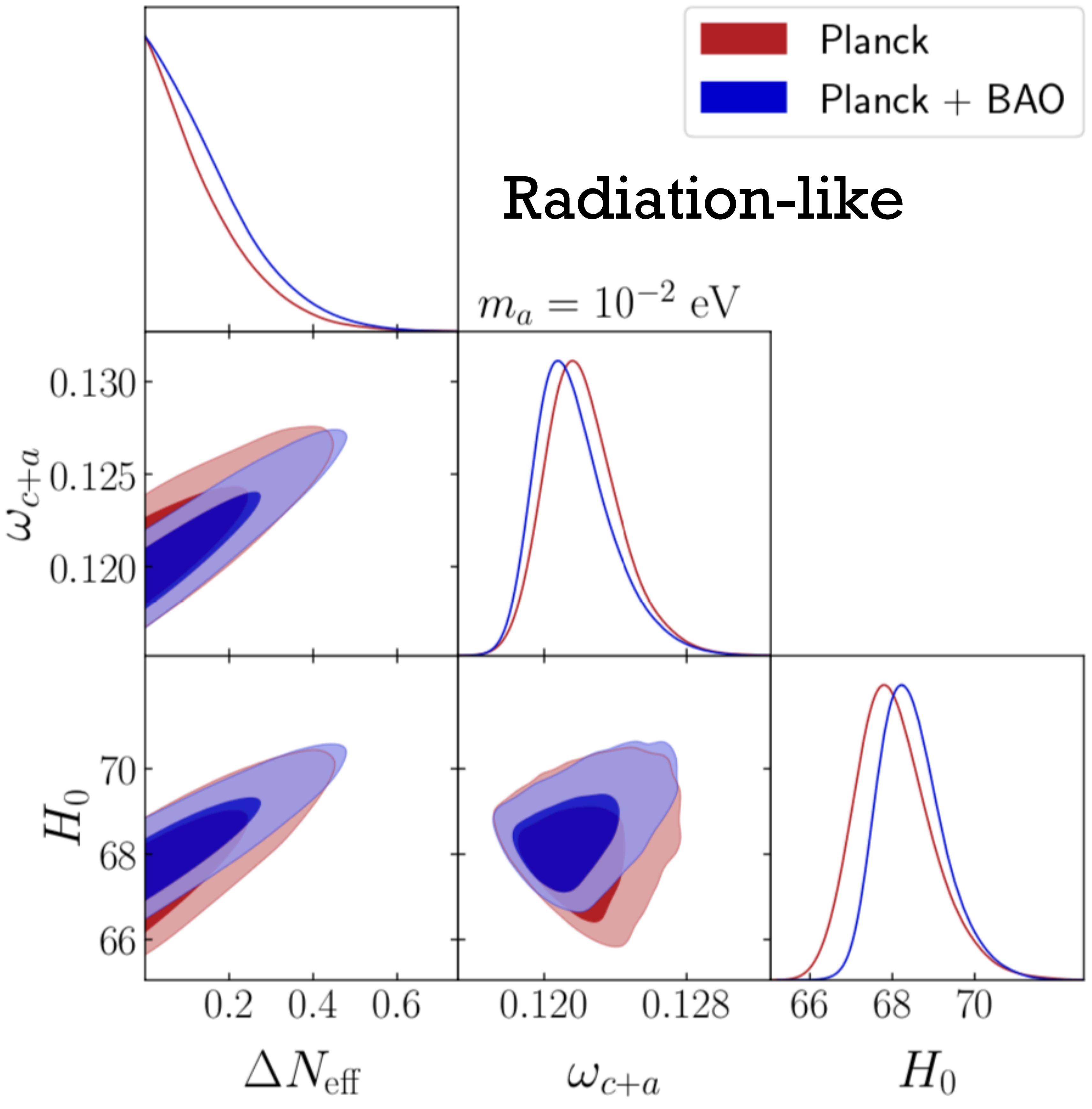
Bounds on Neff converted to bounds on axion couplings

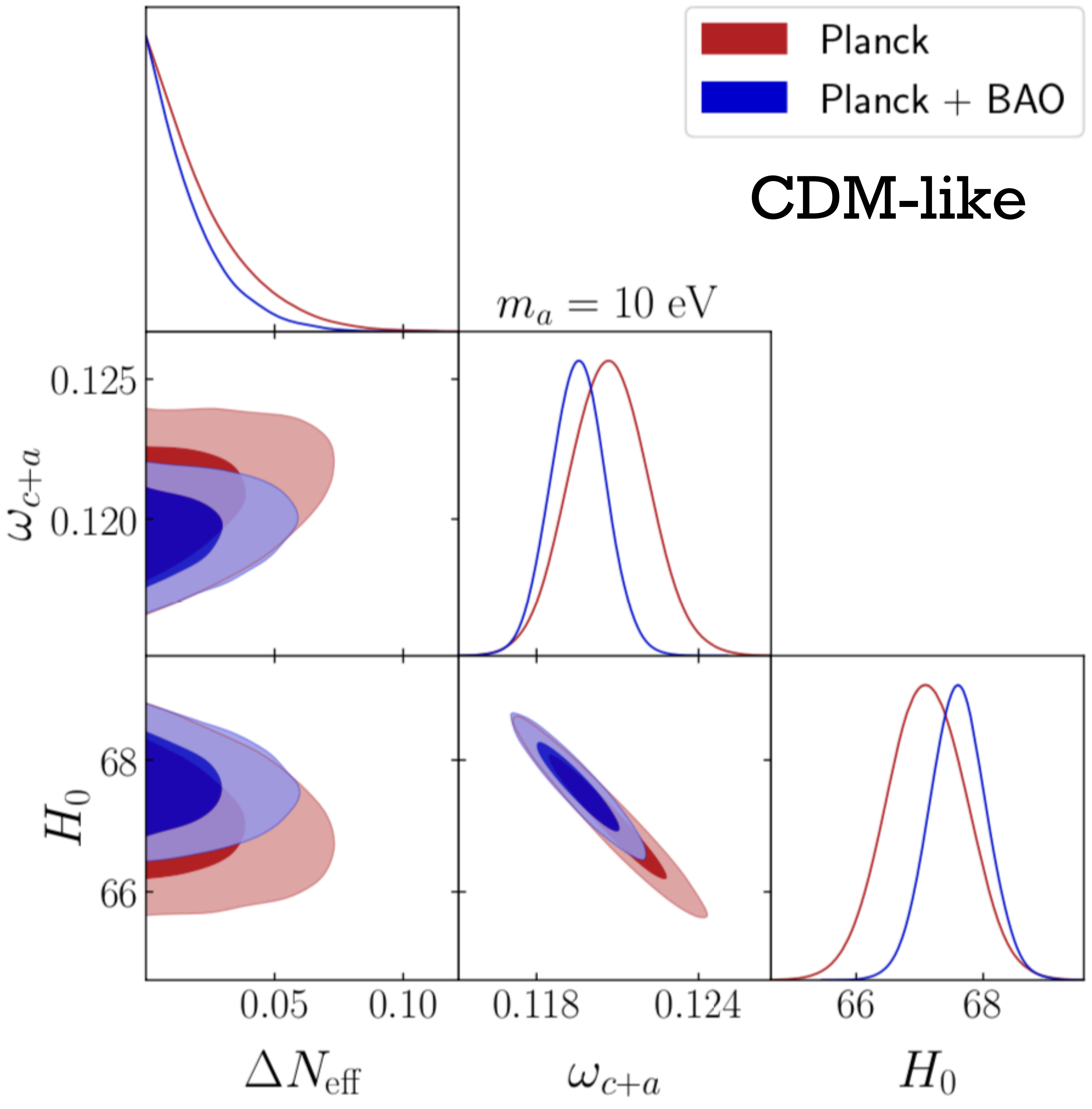
$$g_{a\gamma} < \begin{cases} 2.84 \times 10^{-8}\,\mathrm{GeV}^{-1} & \textit{Planck}\ 2018 \\ 3.16 \times 10^{-8}\,\mathrm{GeV}^{-1} & \textit{Planck}\ 2018 + \mathrm{BAO} \end{cases}$$

$$\frac{C_g}{f_a} < \begin{cases} 6.98 \times 10^{-8}\,\mathrm{GeV}^{-1} \\ 1.06 \times 10^{-7}\,\mathrm{GeV}^{-1} \end{cases} \quad \text{or} \quad g_d < \begin{cases} 2.47 \times 10^{-10}\,\mathrm{GeV}^{-2} & \textit{Planck}\ 2018 \\ 3.77 \times 10^{-10}\,\mathrm{GeV}^{-2} & \textit{Planck}\ 2018 + \mathrm{BAO} \end{cases}$$



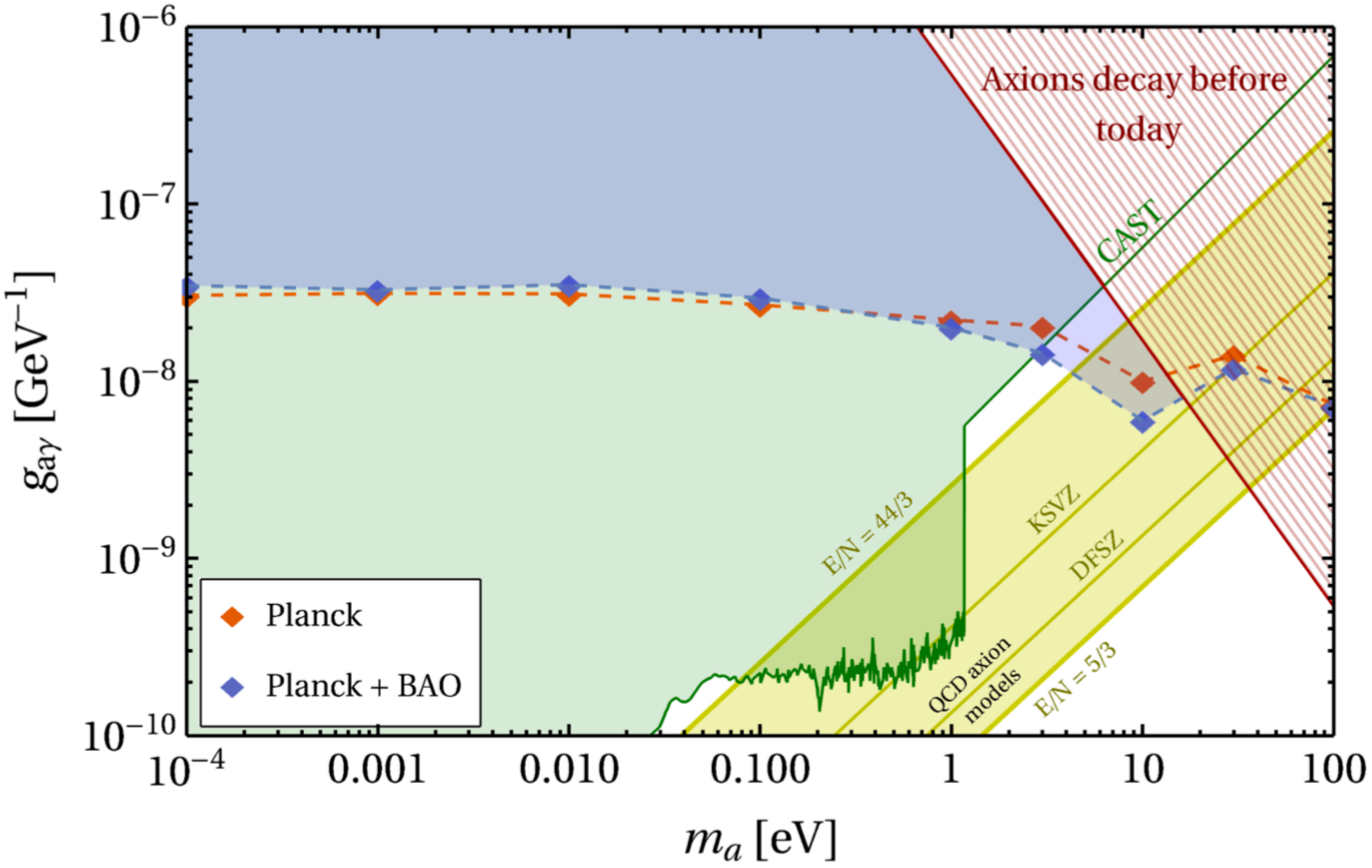
Cosmological analysis





Two different regimes in mass leads to two different cosmological scenarios (theoretical motivation)
Features in the data+phenomenology explain red-blue behaviour

Bounds on axion-photon coupling



Current cosmology:

Broader than CAST below eV

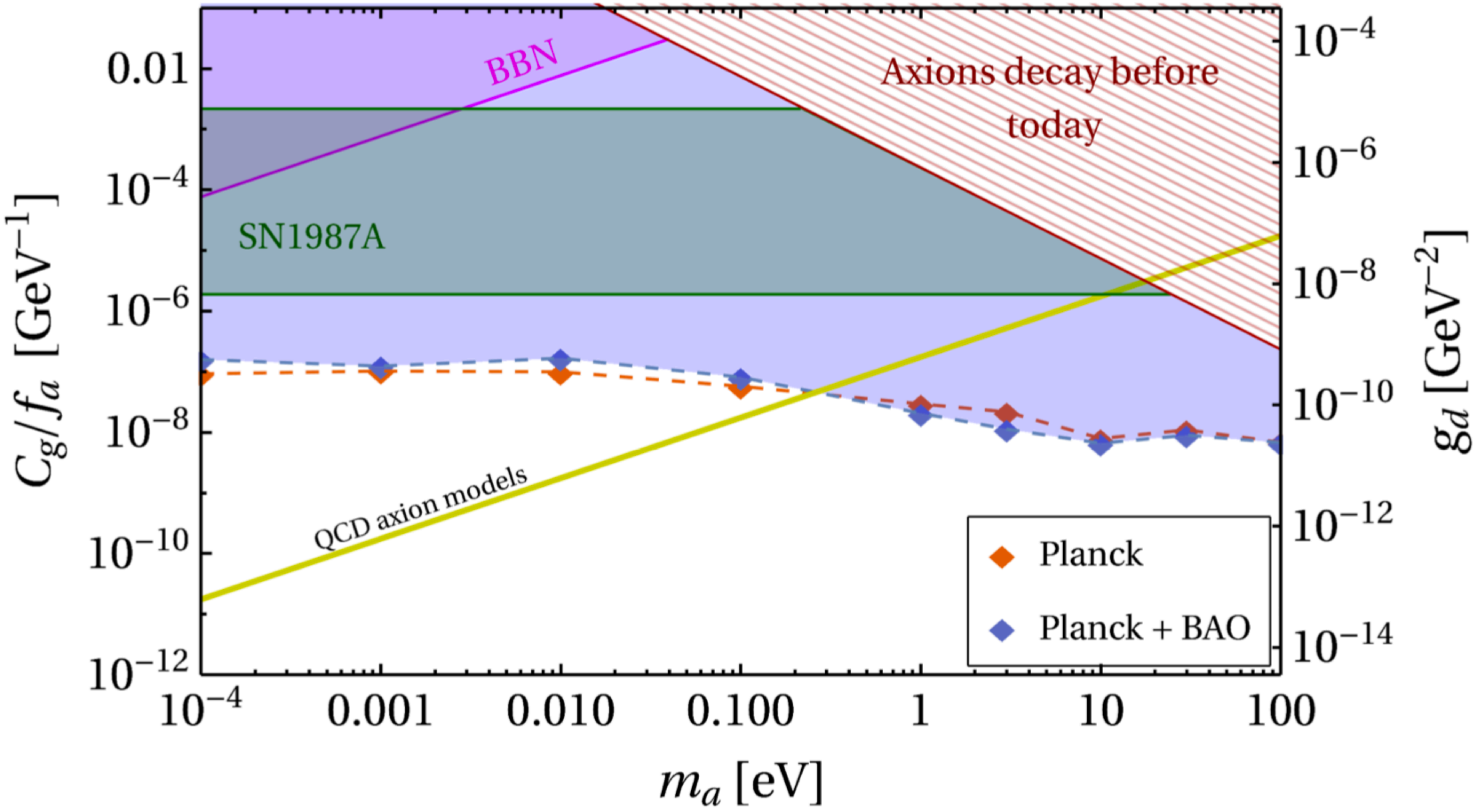
Excludes
a still-viable region
in the ~10eV mass range
where axions are stable

Above ~20eV, must account
for radiative decay

+ACT: 1.6x stronger bounds
in the low-mass regime

For light axions:
From stellar evolution:
2x stronger bounds
From globular clusters:
3x stronger bounds

Bounds on axion-gluon coupling



Current cosmology:

Directly constrains Cg/fa

Much tighter
than any other bounds
in the mass range considered

+ACT: ~6x stronger bounds
in the low-mass regime

KSVZ QCD axion: fa>2 10^7 GeV
-> ma < 0.3 eV

Note:

BBN bounds assume
axion=100% DM

SN1987A constrains gd
translated in a model-dependent way
to Cg/fa

Summary and outlook

Novel bounds on axion-gluon and axion-photon couplings responsible for thermal population of axions:

- most updated results for the production rate in case of axion-gluon coupling
- effective axion mass and axion-photon coupling from chiral representation
- CAMB with extra species with BE distribution function

Cosmological bounds on Neff translated into bounds on axion couplings:

- stronger than CAST bounds for ma>3eV
- 10x stronger than SN1987A bounds on gd over the full range of masses
- implications for KSVZ QCD axions: (roughly) fa>2 GeV -> ma<0.3 eV

Inclusion of small CMB angular scales (ACT) significantly improves the bounds by better constraining Neff -> promising prospects with new data releases from ACT and SPT

Even more promising prospects with future CMB surveys (SO, CMB-S4)
Caveat: correct treatment of the non-linear evolution of matter perturbations in LCDM+axions