Dark Radiation from Heavy QCD Axions

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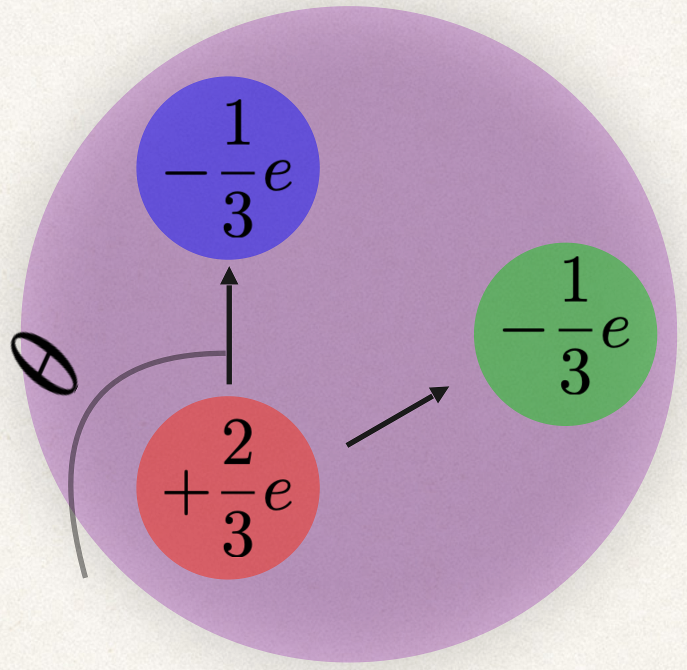
Strong CP Problem

- Why is neutron electric dipole moment so small?

- Classically:



Hook 2018

(small θ limit)

$$\vec{d}_n = \sum q\vec{r}_i \qquad \theta \times 1\,\mathrm{fm}\cdot e \qquad \leq 10^{-12}\,\mathrm{fm}\cdot e$$

Expectation — Reality

Why θ so small is the Strong CP Problem

- Quantum mechanically: $\mathcal{L}_{CP} = \frac{\theta}{32\pi^2} G\tilde{G}$

Standard QCD Axion

- One of most popular solutions: promote θ to a field

$$\mathcal{L}_{CP} = \frac{\theta}{32\pi^2} G\tilde{G} \quad \to \left(\theta + \frac{a}{f_a}\right) \frac{1}{32\pi^2} G\tilde{G}$$

(Now $d_n \propto \theta + a/f_a$)

- Below $\Lambda_{\rm QCD} \sim 150\,{\rm MeV}$, axion acquires a potential from strong dynamics

$$V \approx -\Lambda_{\rm QCD}^4 \cos(\theta + a/f_a)$$

$$\frac{\partial V}{\partial a} = 0 \longrightarrow \langle d_n \rangle = 0$$

$$m_a^2 \equiv -\left.\frac{\partial^2 V}{\partial a^2}\right|_{\langle a \rangle} \simeq \frac{\Lambda_{\rm QCD}^4}{f_a^2} \simeq \left(0.6\,{\rm eV}\frac{10^7 {\rm GeV}}{f_a}\right)^2$$

Axion Quality Problem

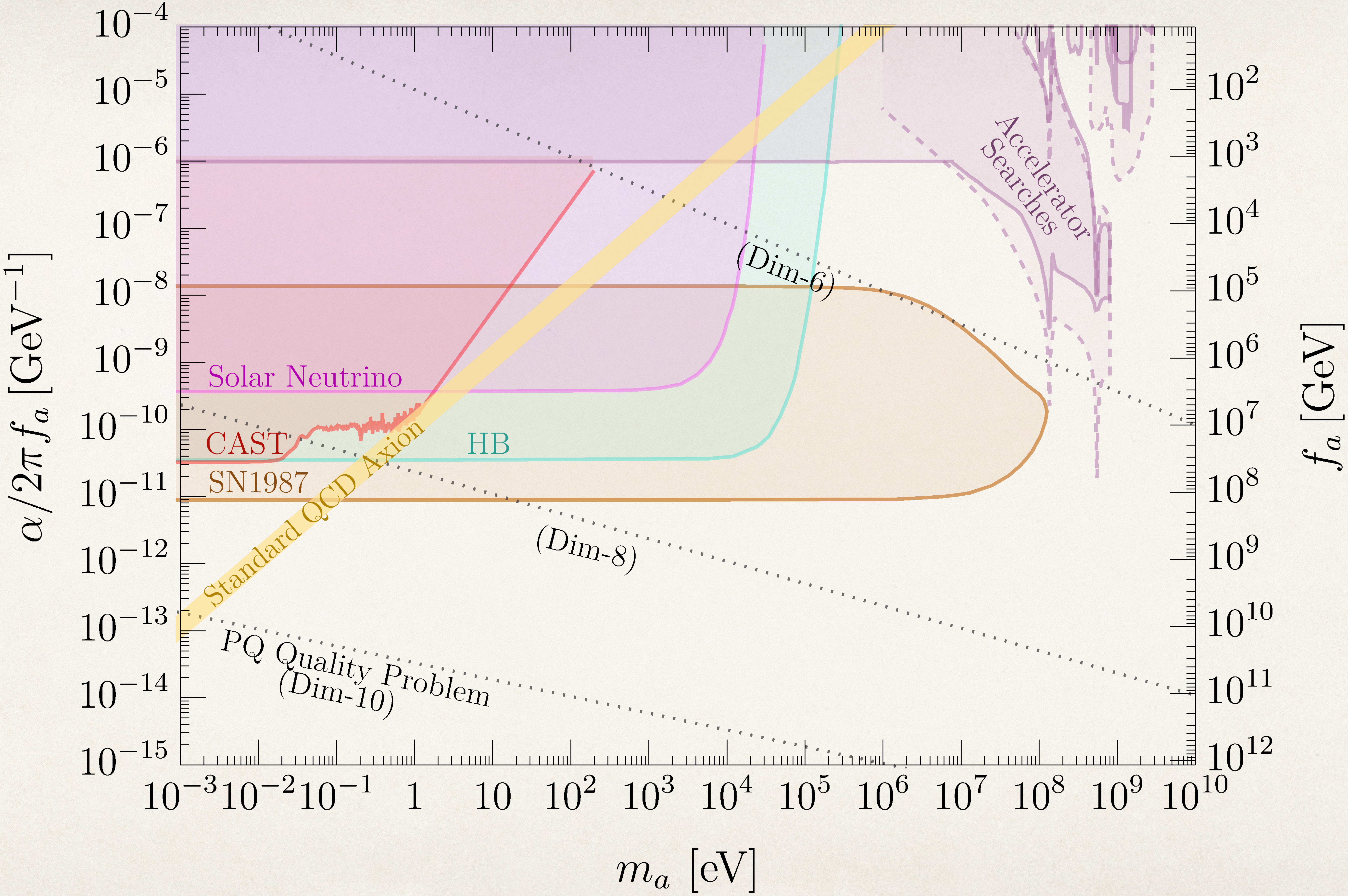
- $U(1)_{\rm PQ}$ symmetry not gauged $\longrightarrow$ expected to be broken by higher-dim operators

- For PQ breaking field $\phi = (f_a + s)e^{ia/f_a}$

$$V_{\not{\rm PQ}} = \lambda_n \frac{\phi^n}{M_{\rm Pl}^{n-4}} \longrightarrow$$ Shifts minimum of axion potential

$$m_a \gtrsim {\rm MeV} \left(\frac{f_a}{10^5\,{\rm GeV}}\right)^2 \left(\frac{f_a}{M_{\rm Pl}}\right)^{\frac{n-6}{2}} \lambda_n$$

(For axion to still solve Strong CP Problem)



10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
$\alpha/2\pi f_a\,[\mathrm{GeV}^{-1}]$
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
$f_a\,[\mathrm{GeV}]$
10^{-3} 10^{-2} 10^{-1} 1 10 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8} 10^{9} 10^{10}
m_a [eV]
Solar Neutrino
CAST
HB
SN1987
Standard QCD Axion
Accelerator Searches
(Dim-6)
(Dim-8)
PQ Quality Problem
(Dim-10)

Origin of Heavy QCD Axions

- Heavy QCD axions can arise from:
  - SU(3) or embeddings of SU(3) becoming confined at high energies
    Dimopolous 1979, Tye 1981, Holdom & Peskin 1982, Holdom 1985, Flynn and Randall 1987, Agrawal and Howe 2018
  - 5D instantons (see Tony Gherghetta's talk from Tuesday)
    Gherghetta et al 2020
  - Mirror QCD theories
    Rubakov 1997, Berezhiani 2001

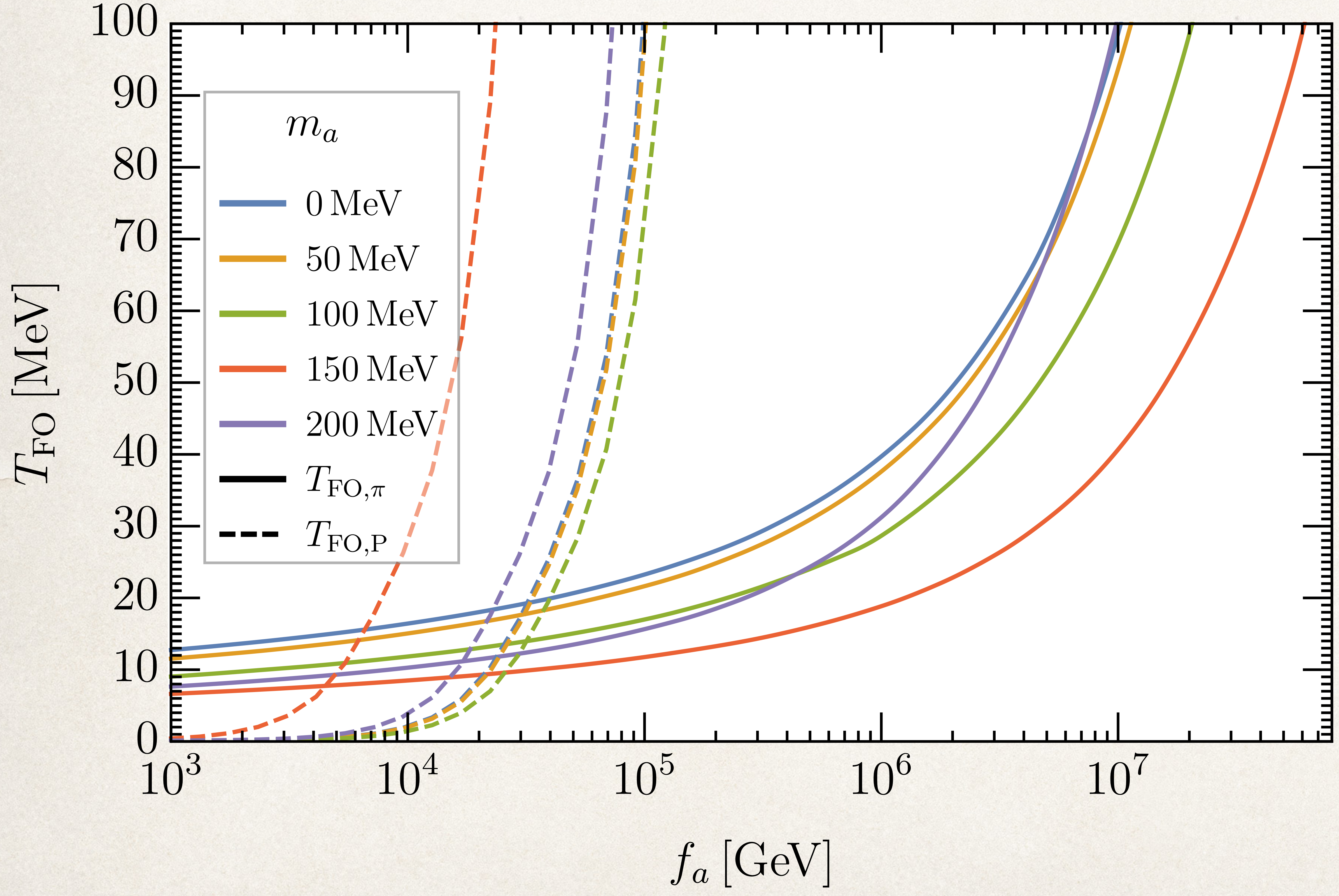
Cosmological Signals of Heavy QCD Axion

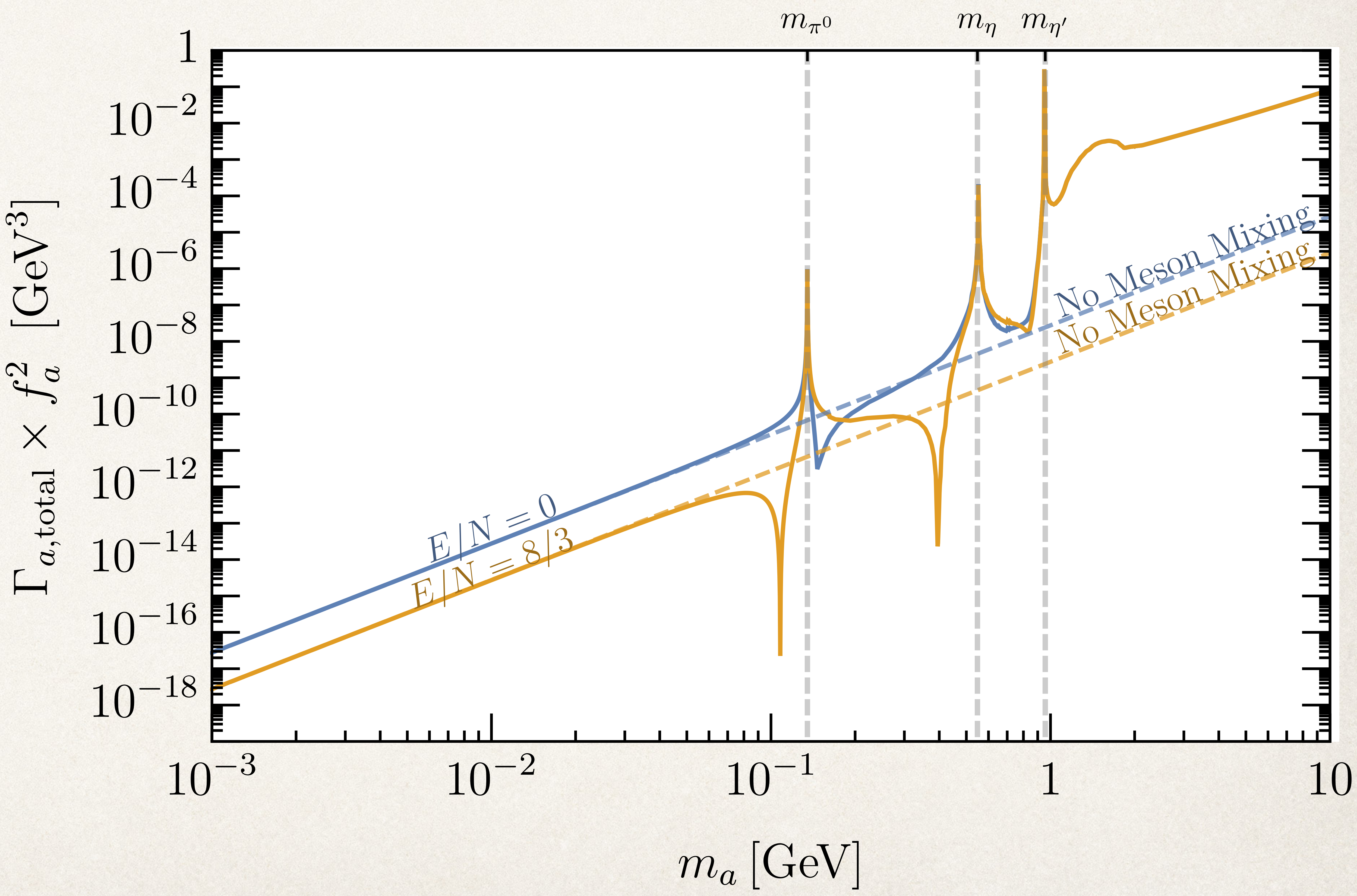
- For much of this parameter space, axion can decay around or after neutrino decoupling
- Axion decays heat up photons relative to neutrinos → *negative* $\Delta N_{\rm eff}$ $(N_{\rm eff} < 3.044)$ $\quad (N_{\rm eff} \propto \frac{\rho_\nu}{\rho_\gamma})$
- Accurate calculation requires momentum-space Boltzmann equation $f(\mathbf{p})$ because of:
  - Danger of some fraction of axions decaying late (high momentum, time dilation)
  - Precision CMB measurements

Important Effects for Heavy QCD Axions

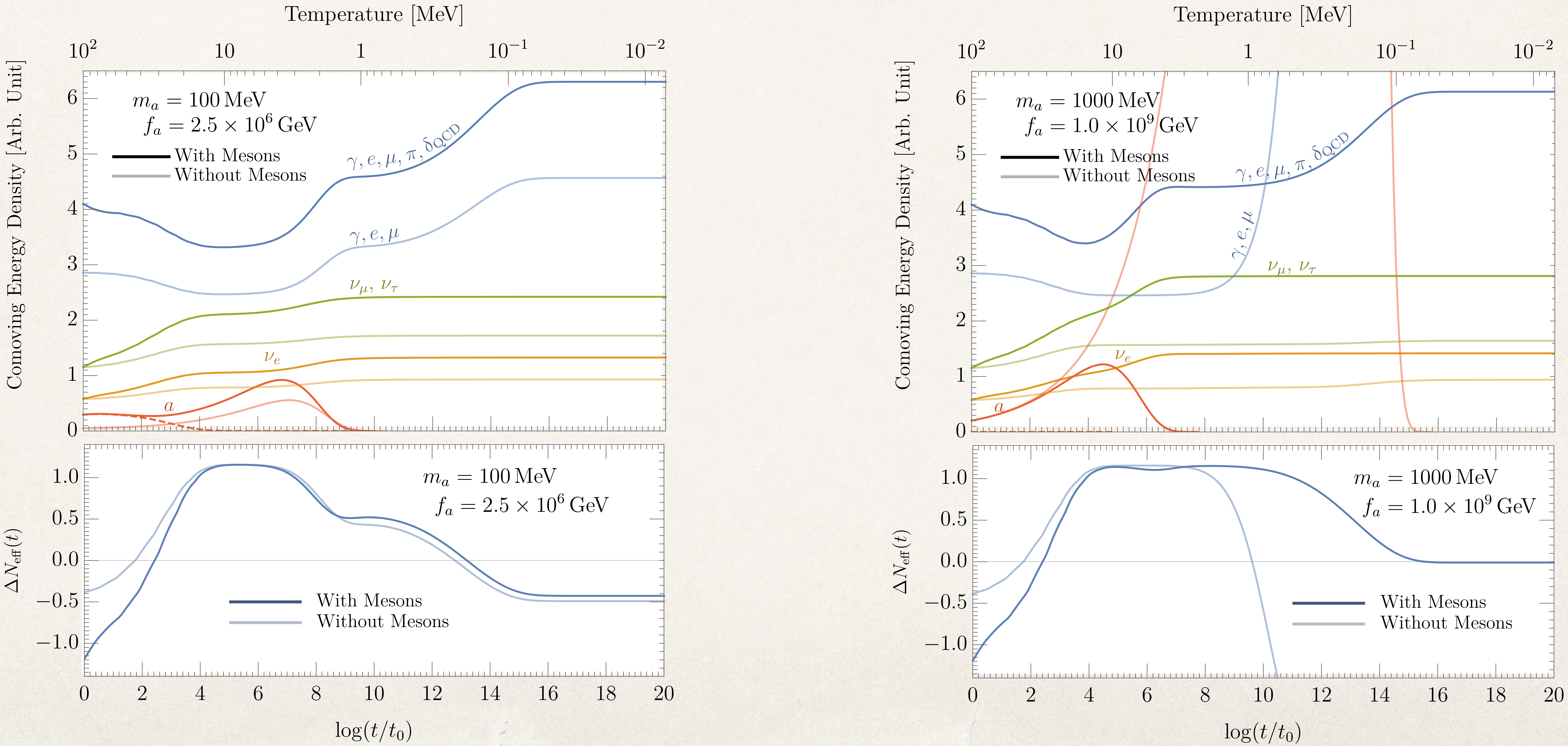
- Previous work calculated N_{eff} for heavy Axion Like Particles (ALPs), *not* QCD axions
  Cadamuro & Redondo 2012, Millea et al 2015, Depta et al 2020
- We must incorporate the following key effects:
  - Axion-pion scattering
  - Axion-meson mixing in photon coupling
    Aloni et al 2019
  - Proper axion lifetime (QCD decay channels)
    Aloni et al 2019
  - Enhanced frozen-out abundance from gluons
    Salvio et al 2013, D'Eramo et al 2021
  - QCD contributions to the background energy density
    Saikawa and Shirai 2018

Differences Between Heavy QCD Axions and Heavy ALPs

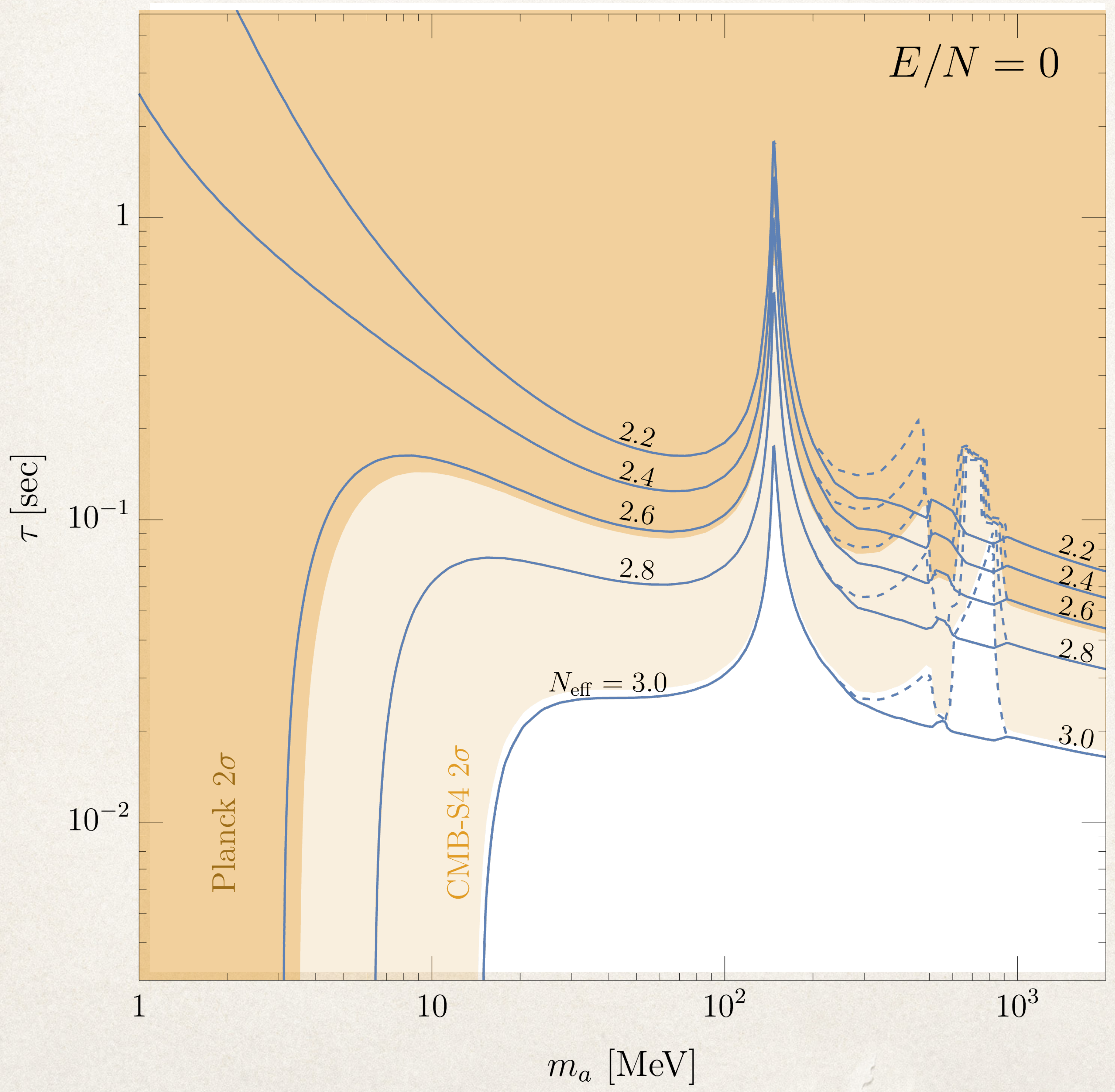


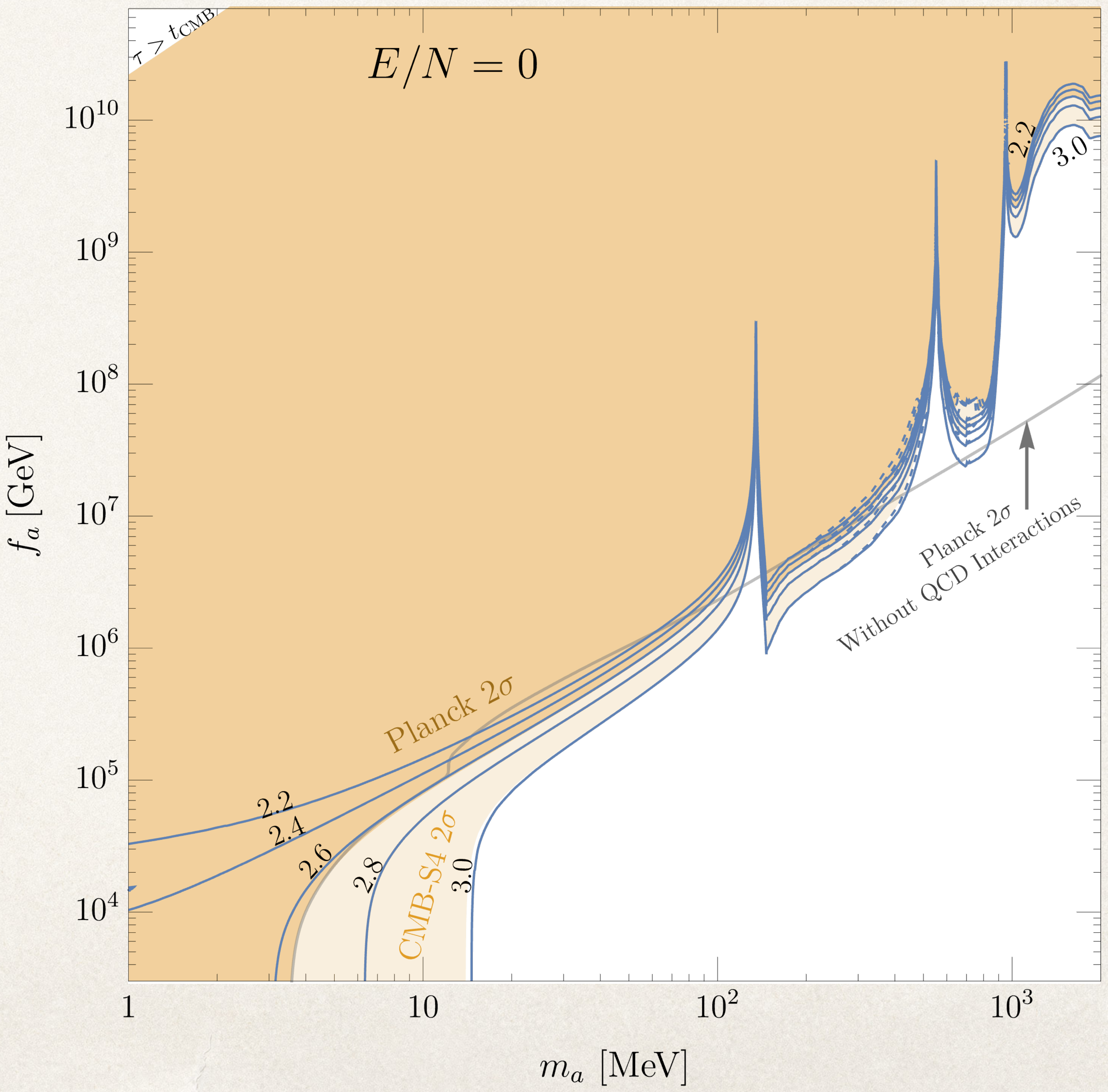


Cosmological History of Heavy QCD Axion



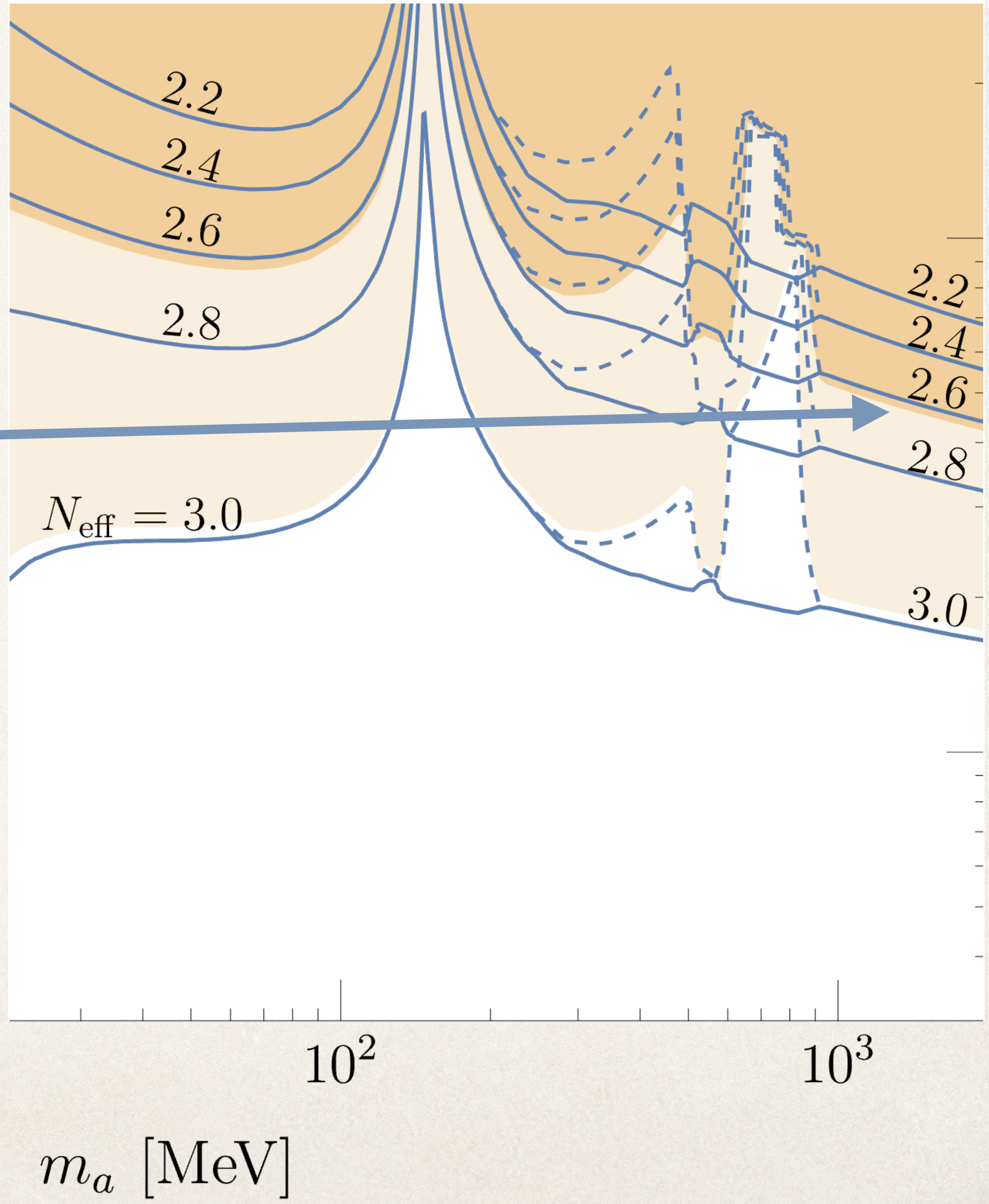
N_{eff} Results: Boltzmann Calculation



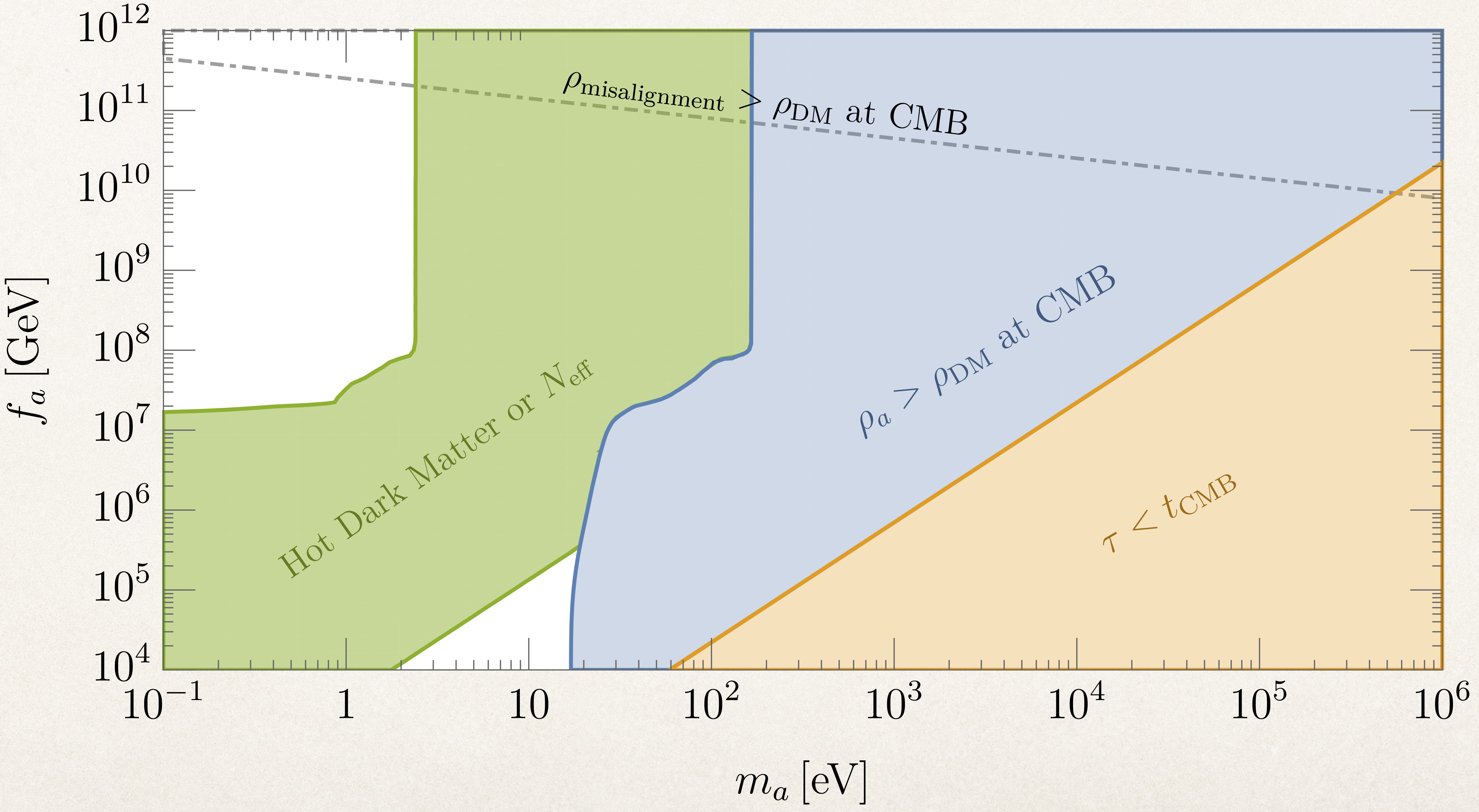


High m_a region

- For $m_a > 2\,\mathrm{GeV}$, axion decays dominantly to gluons
- Note slight decrease in slope in $m_a - \tau$ plane
- For fixed, τ, axion energy density at decay increases with increasing mass
- Axion must lie on further tail of exponential suppression

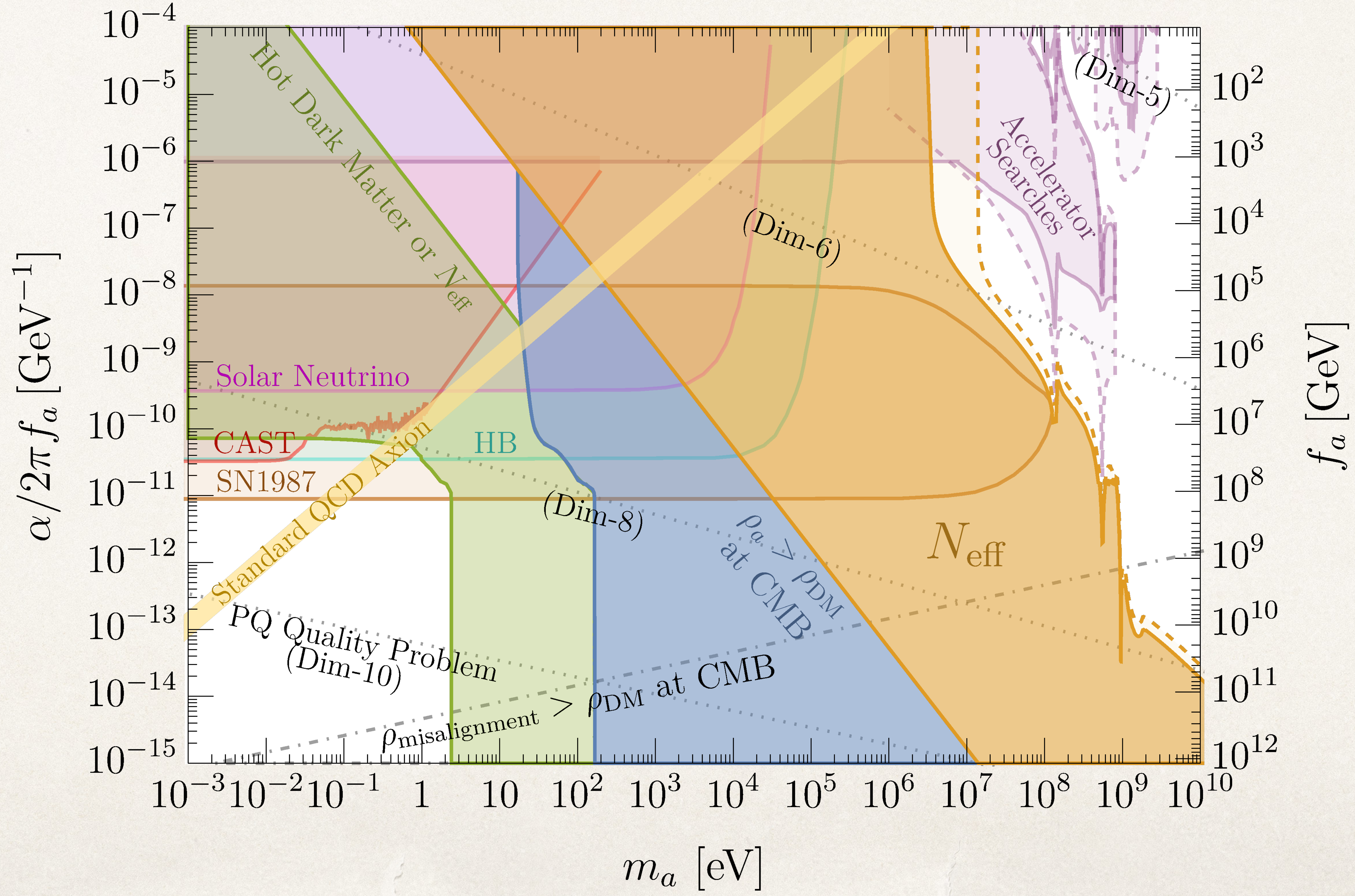


Low m_a region: Hot Dark Matter and $N_{\rm eff}$



Hot dark matter bounds
Reinterpreted from
Xu et al 2021

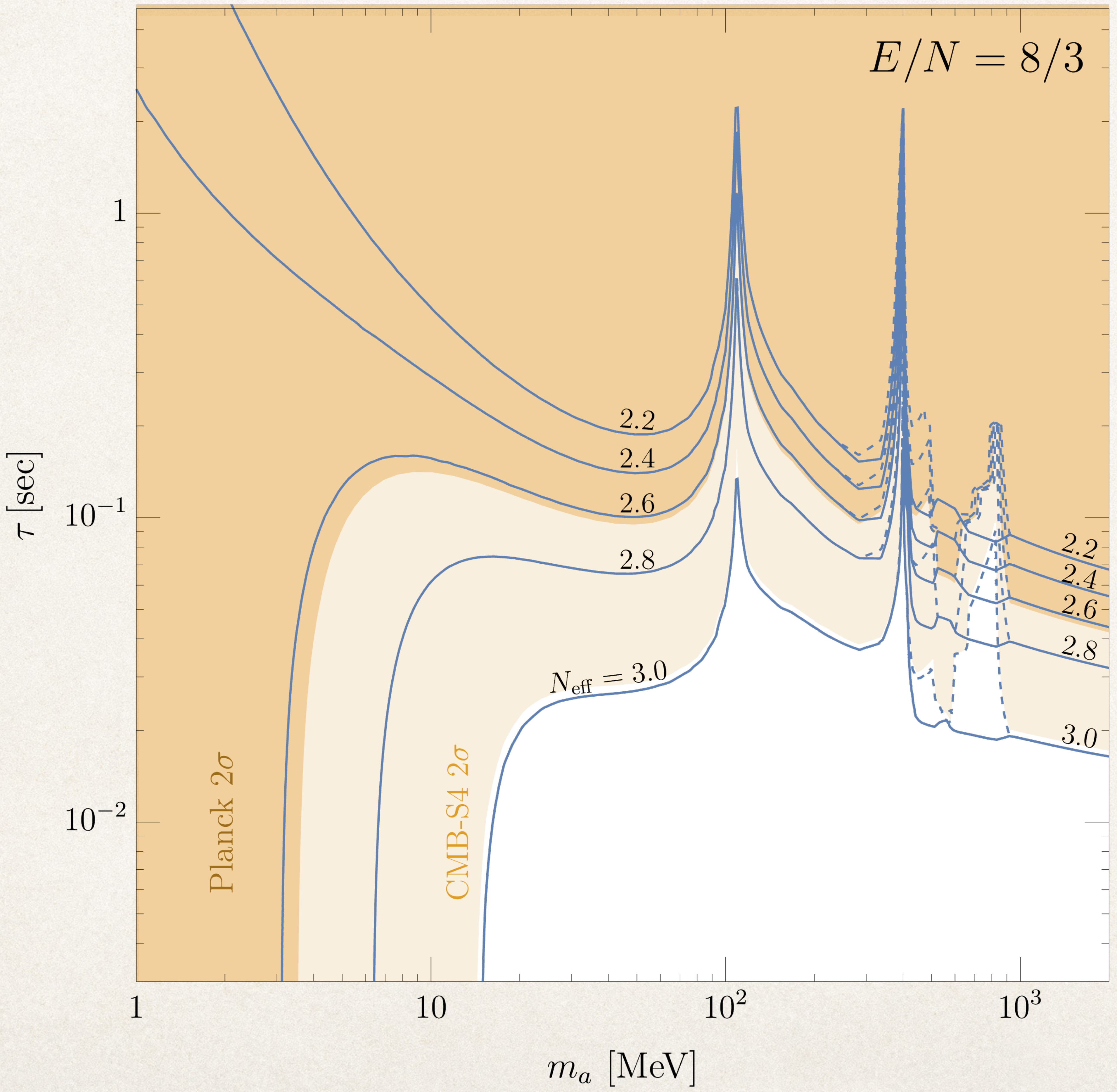
Summary



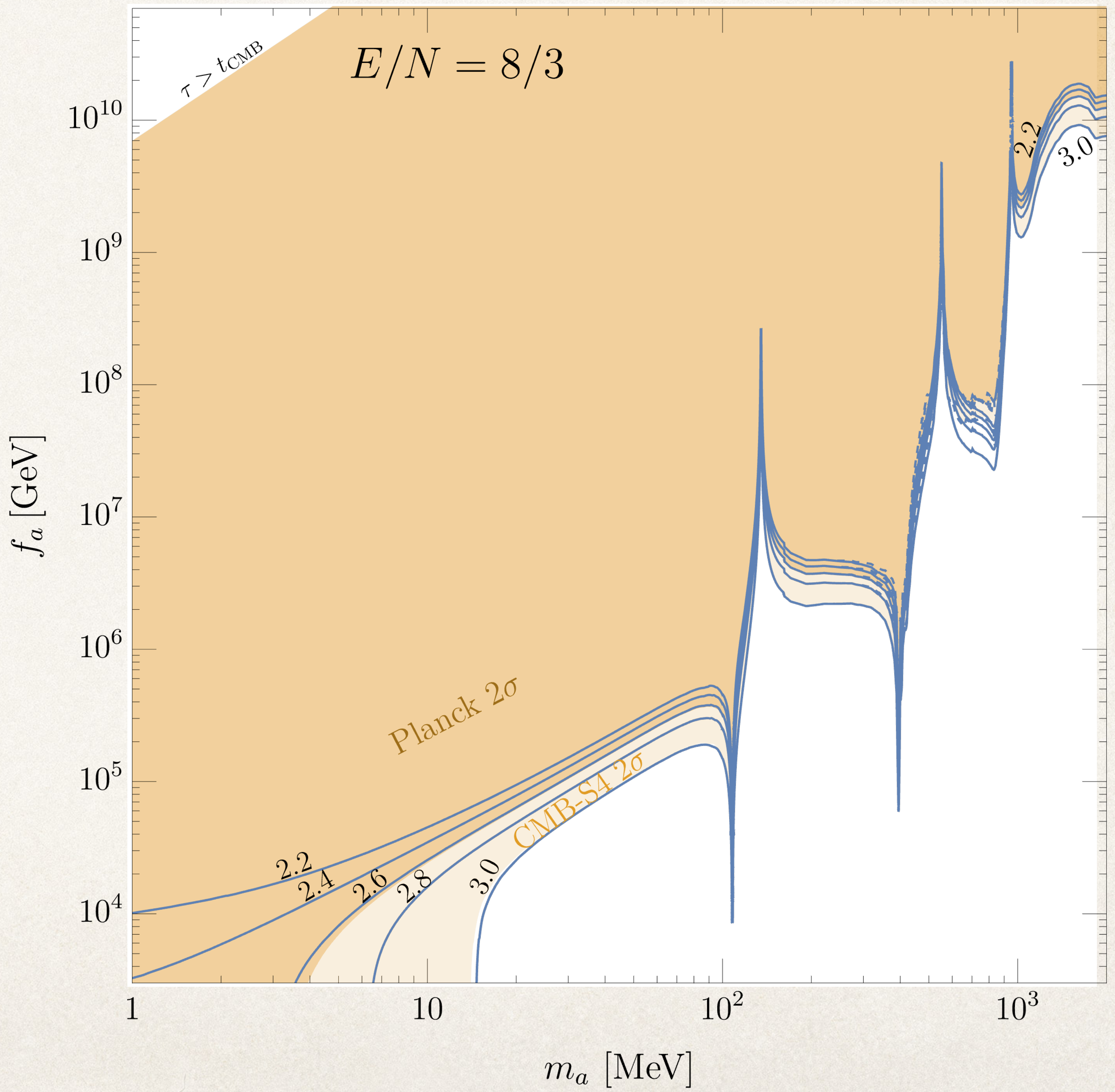
Hot Dark Matter or $N_{\rm eff}$
(Dim-5)
Accelerator Searches
(Dim-6)
Solar Neutrino
CAST
HB
SN1987
Standard QCD Axion
(Dim-8)
$\rho_a > \rho_{\rm DM}$ at CMB
$N_{\rm eff}$
PQ Quality Problem (Dim-10)
$\rho_{\rm misalignment} > \rho_{\rm DM}$ at CMB
$\alpha/2\pi f_a\ [\mathrm{GeV}^{-1}]$
f_a [GeV]
m_a [eV]

Thank you!

E/N = 8/3



$E/N = 8/3$
2.2
2.4
2.6
2.8
$N_{\rm eff} = 3.0$
3.0
Planck 2σ
CMB-S4 2σ
1
10^{-1}
10^{-2}
τ [sec]
1
10
10^2
10^3
m_a [MeV]



$\tau > t_{\rm CMB}$
$E/N = 8/3$
2.2
3.0
Planck 2σ
CMB-S4 2σ
2.2
2.4
2.6
2.8
3.0
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
f_a [GeV]
1
10
10^2
10^3
m_a [MeV]

Incorporation of Mirror Photon