Hot and Cold Axions

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Strong CP Problem

CP violation in Quantum Chromodynamics

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

Observable consequence:
neutron electric
dipole moment

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

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

Experimental Bound

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

Pendlebury et al.. PRD92 (2016)

Strong CP Problem

Why so small?

Experimental Bound

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Pendlebury et al.. PRD92 (2016)

The PQ Mechanism

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

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

Peccei, Quinn, PRL38 (1977) and PRD16 (1977)

Dynamical solution to the strong CP problem

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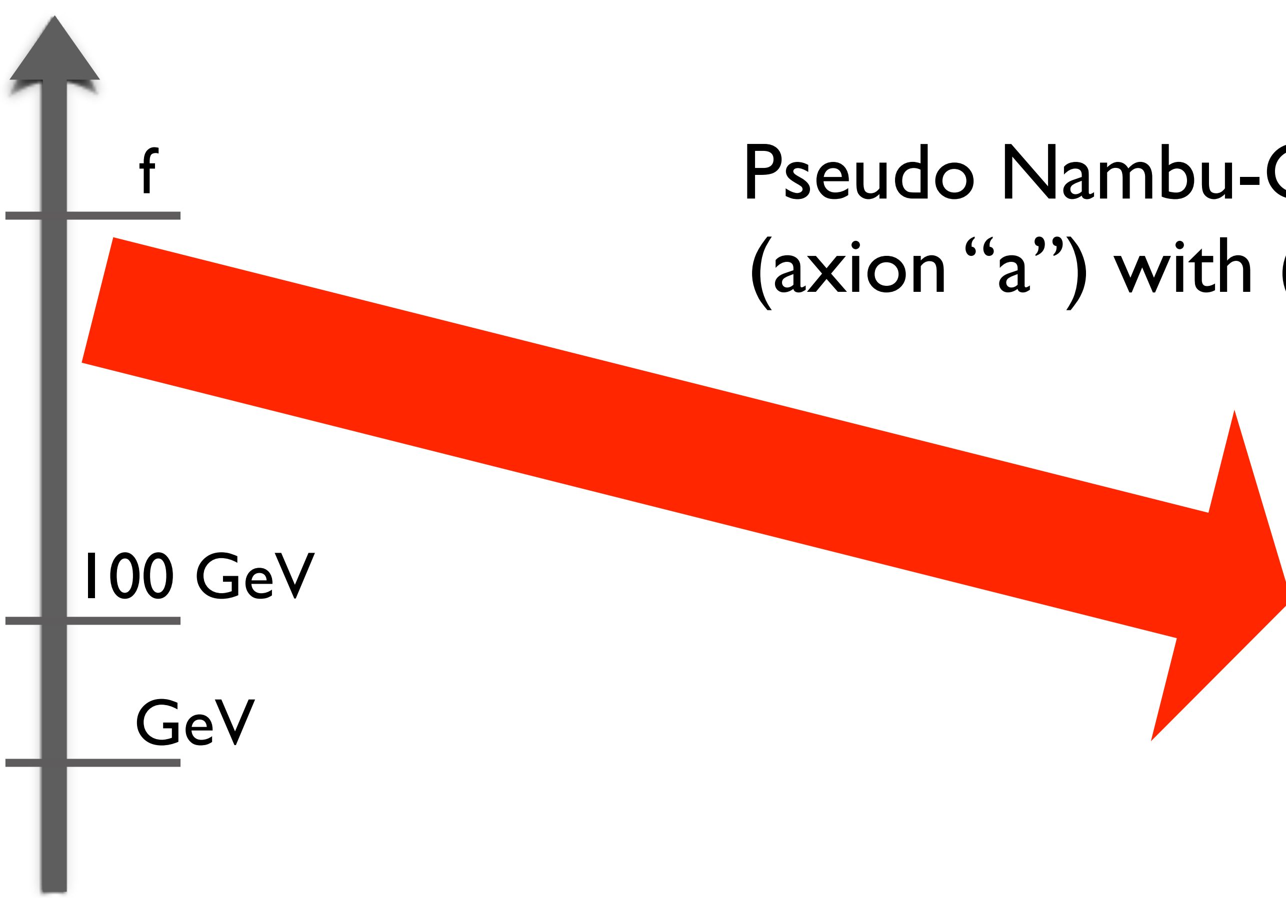

Pseudo Nambu-Goldstone boson in the spectrum (axion “a”) with (“anomalous”) coupling to gluons

$$\mathcal{L}_{\rm QCD} \supset \frac{a}{f} \frac{g_s^2}{32\pi^2} G^{\mu\nu} \tilde{G}_{\mu\nu}$$

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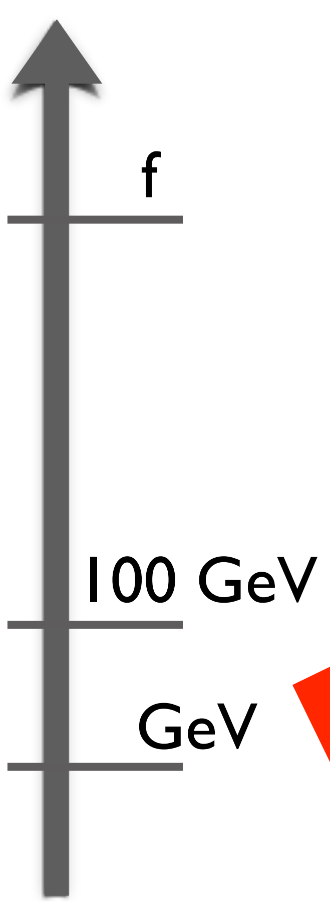

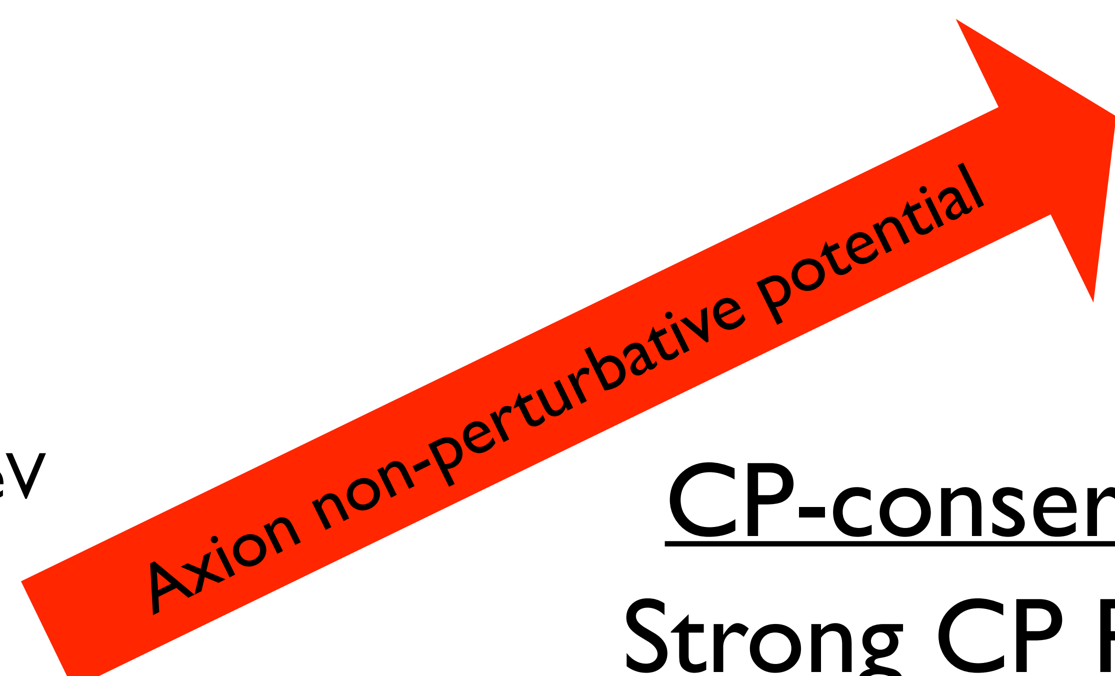

$$V(a) \simeq \frac{1}{2} m_a^2 a^2$$

CP-conserving minimum!

Strong CP Problem Solved!

The QCD Axion

Axion (zero-temperature) mass from non-perturbative potential ($f \geq 10^8$ GeV)

The QCD axion is very light!

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

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

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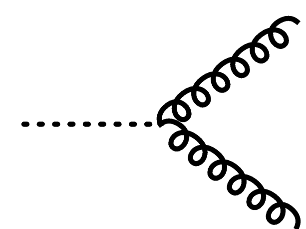
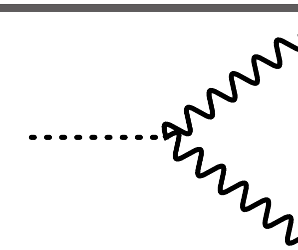
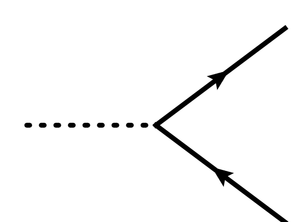


$$\frac{g_s^2}{32\pi^2} \frac{a}{f} G^{\mu\nu} \tilde{G}_{\mu\nu}$$

The QCD axion is extremely weakly coupled to Standard Model particles



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



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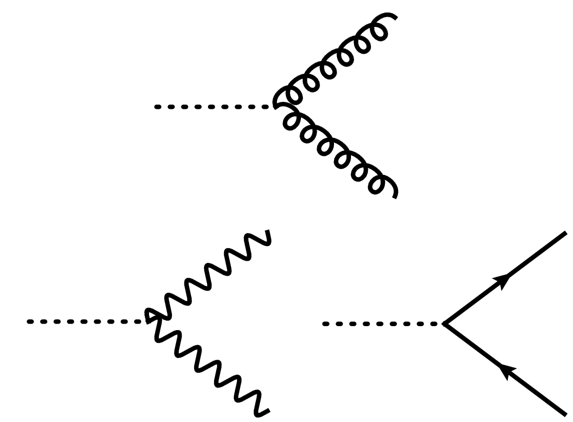
Very light and extremely weakly coupled



Axion detection challenging, but several novel ideas

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

Potential prominent role in cosmology

Wilczek, Phys.Rev.Lett.40 (1978)
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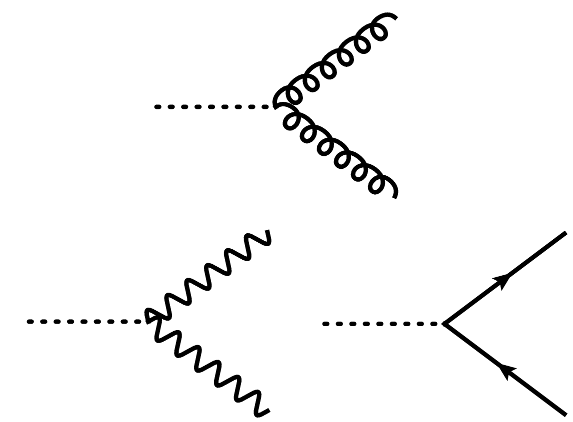

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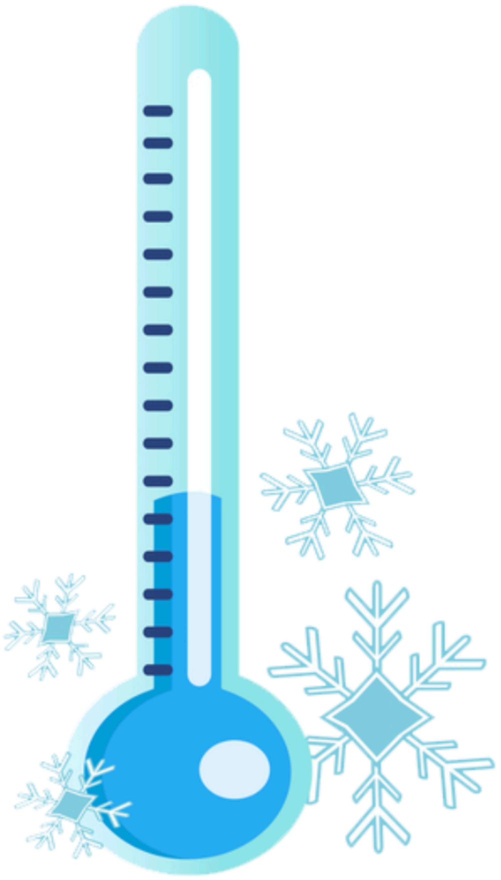
In this talk:

Cosmological production of axions in the early universe



Cold Axions

(Dark Matter)

Cold Dark Matter

Axion condensate evolution in the early universe

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

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

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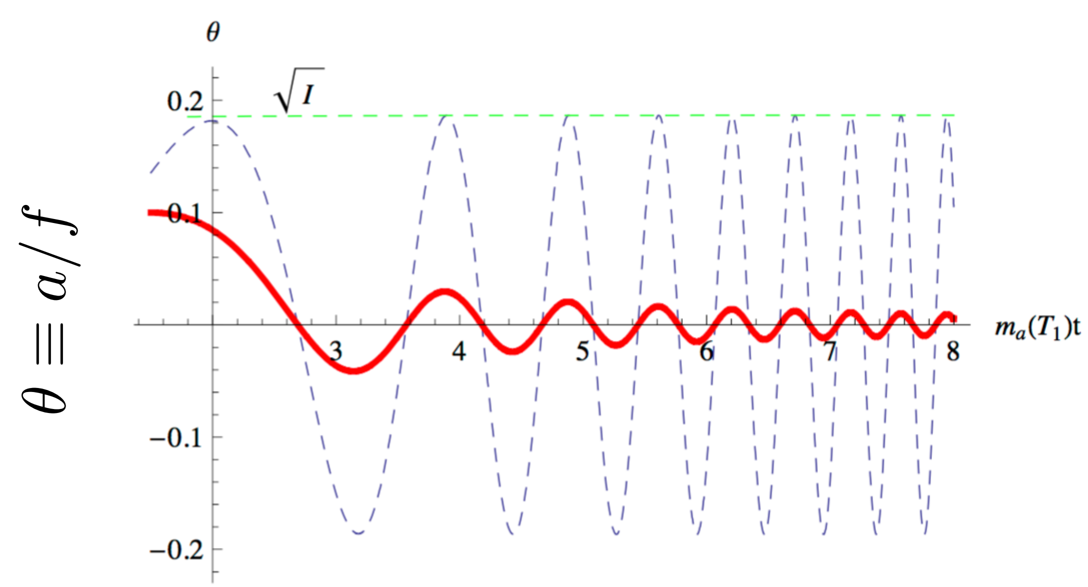
$$\Omega_a h^2 \simeq 0.1\,\theta_i^2 \left(\frac{f}{10^{11}\,\mathrm{GeV}}\right)^{1.18}$$



Bae, Huh, Kim, JCAP 0809 (2008)

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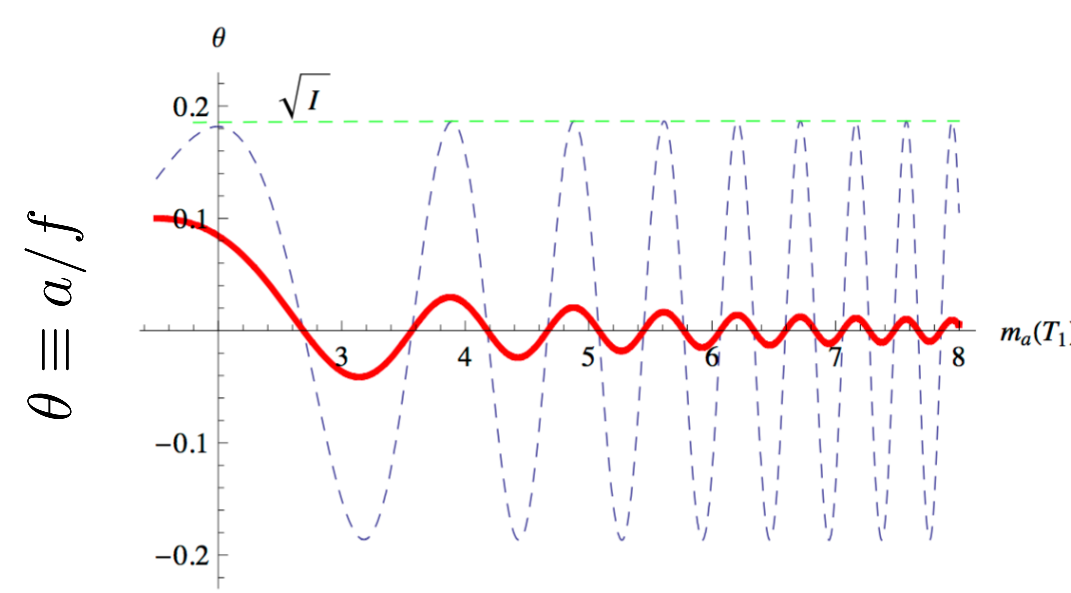
What is the initial axion field value?
It depends…



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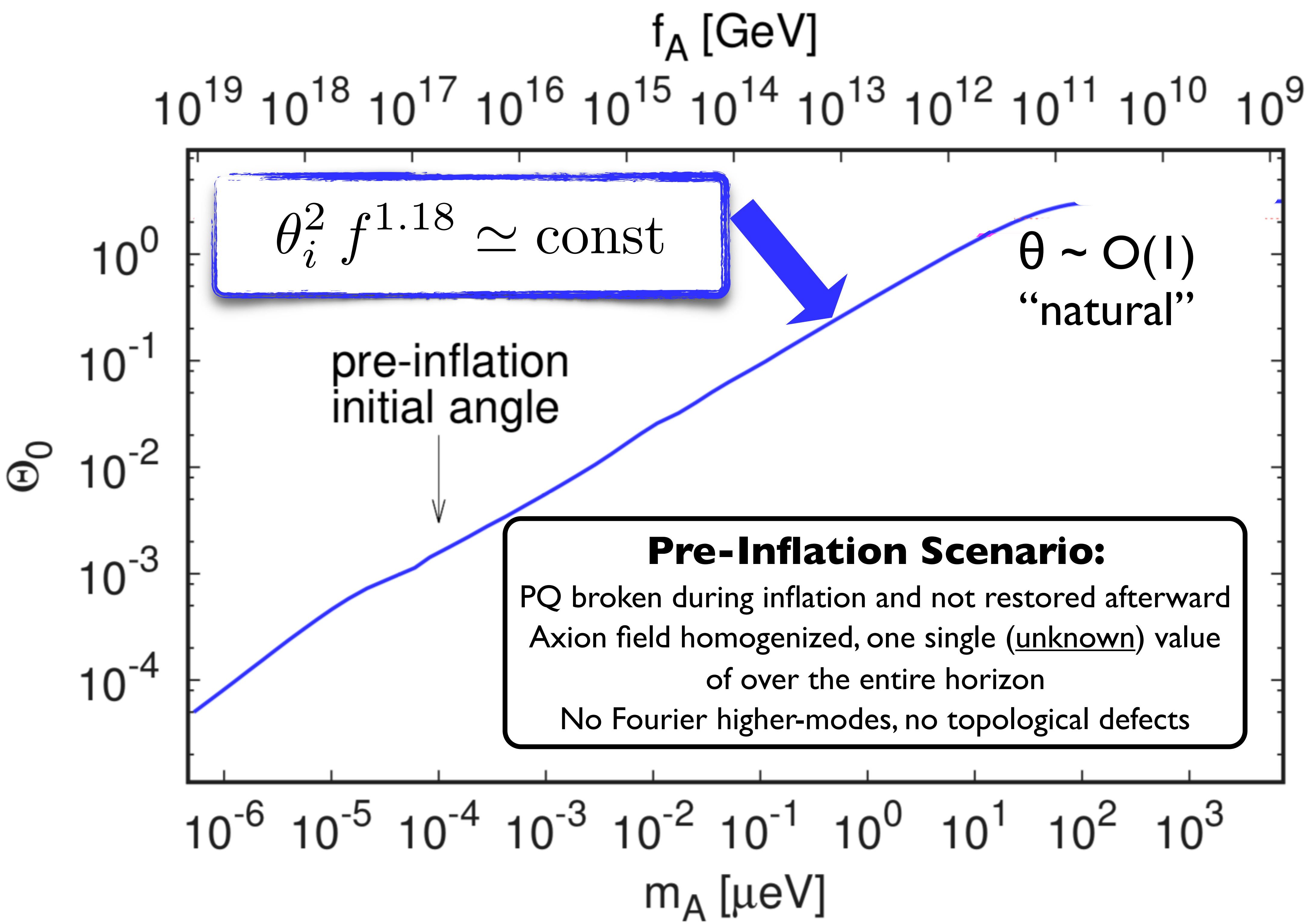
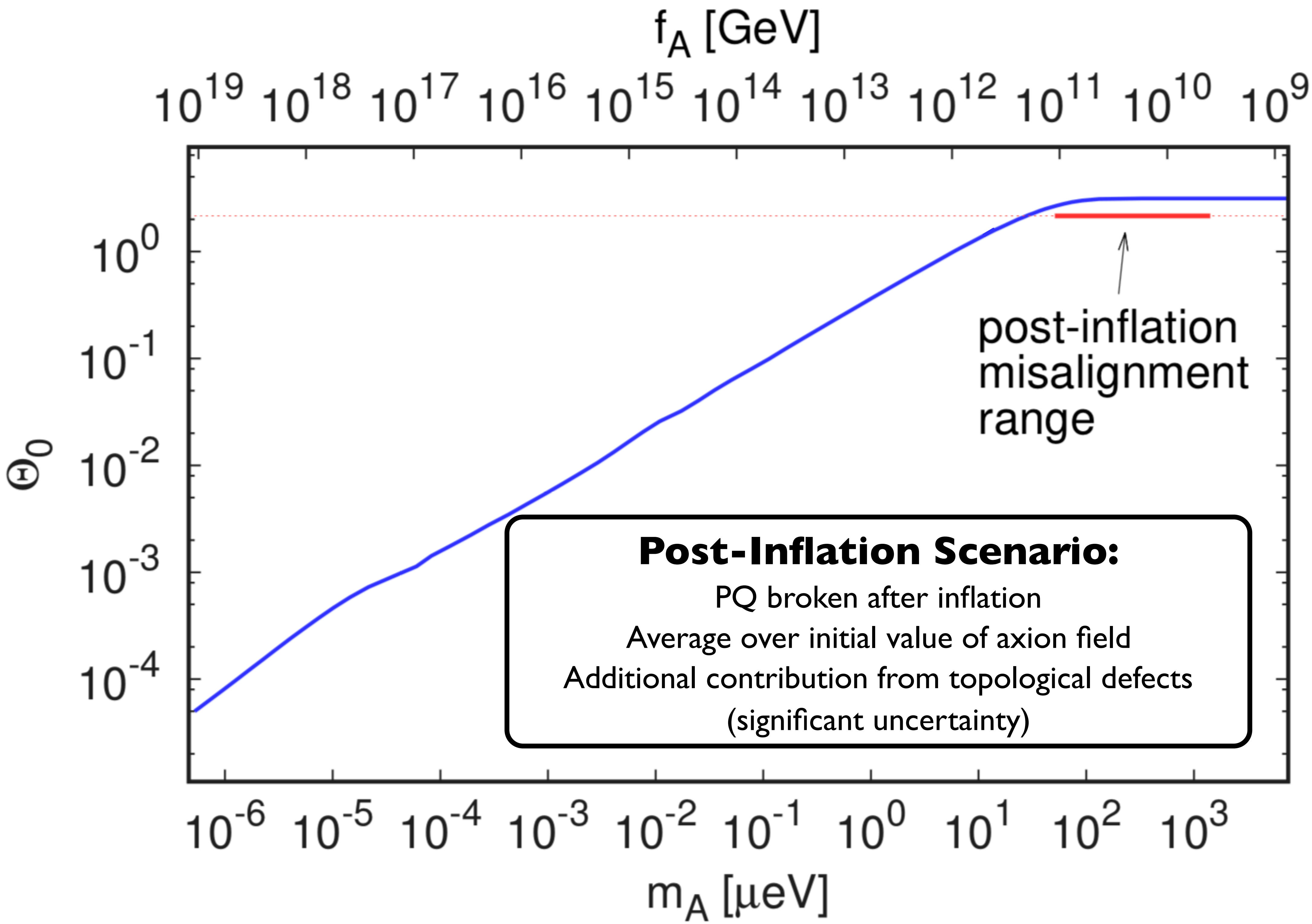
Pre vs Post Inflation



Borsanyi et al., Nature 539 (2016)

Pre vs Post Inflation



Post-Inflation Scenario:

PQ broken after inflation

Average over initial value of axion field

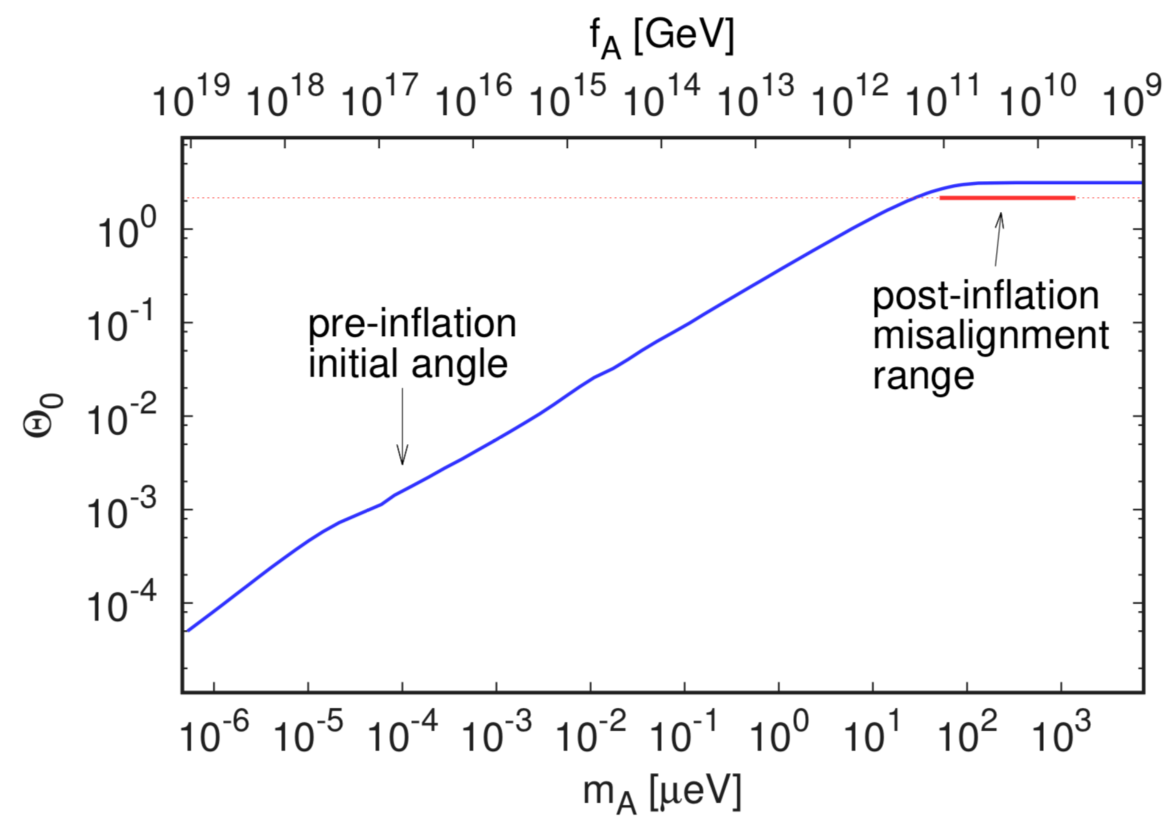
Additional contribution from topological defects

(significant uncertainty)

Borsanyi et al., Nature 539 (2016)

Axion CDM Summary

- PRE: initial field value unknown, just a relation between θ and f (i.e. m_a)
- POST: theoretical uncertainty on topological defects contribution gives a range for f (i.e. m_a)



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

Correct dark matter abundance for POST, and PRE if there is a O(1) initial misalignment angle

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

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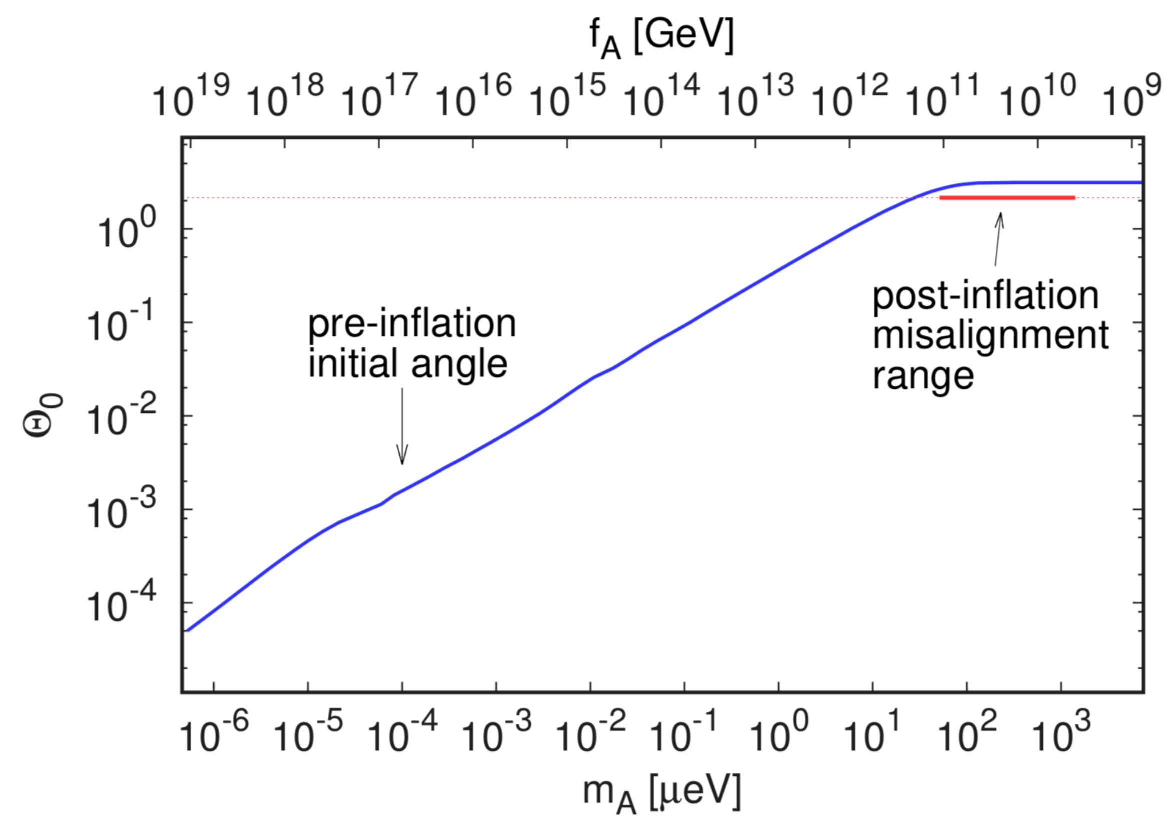

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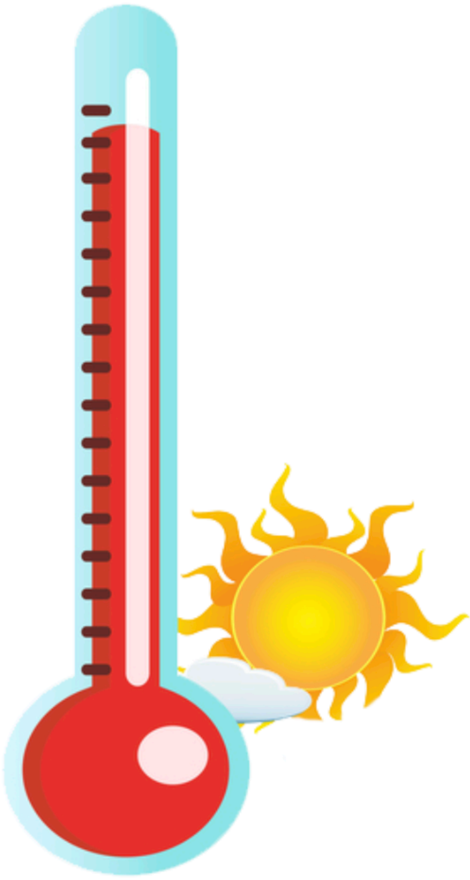
What about hot axions in this range?



Hot Axions

(Dark Radiation)

Axion Dark Radiation

Axions produced by 2→2 processes involving particles in the primordial thermal bath (final energy much higher than m_a, i.e. "hot")

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

They are still around today!
How do we unveil their presence?

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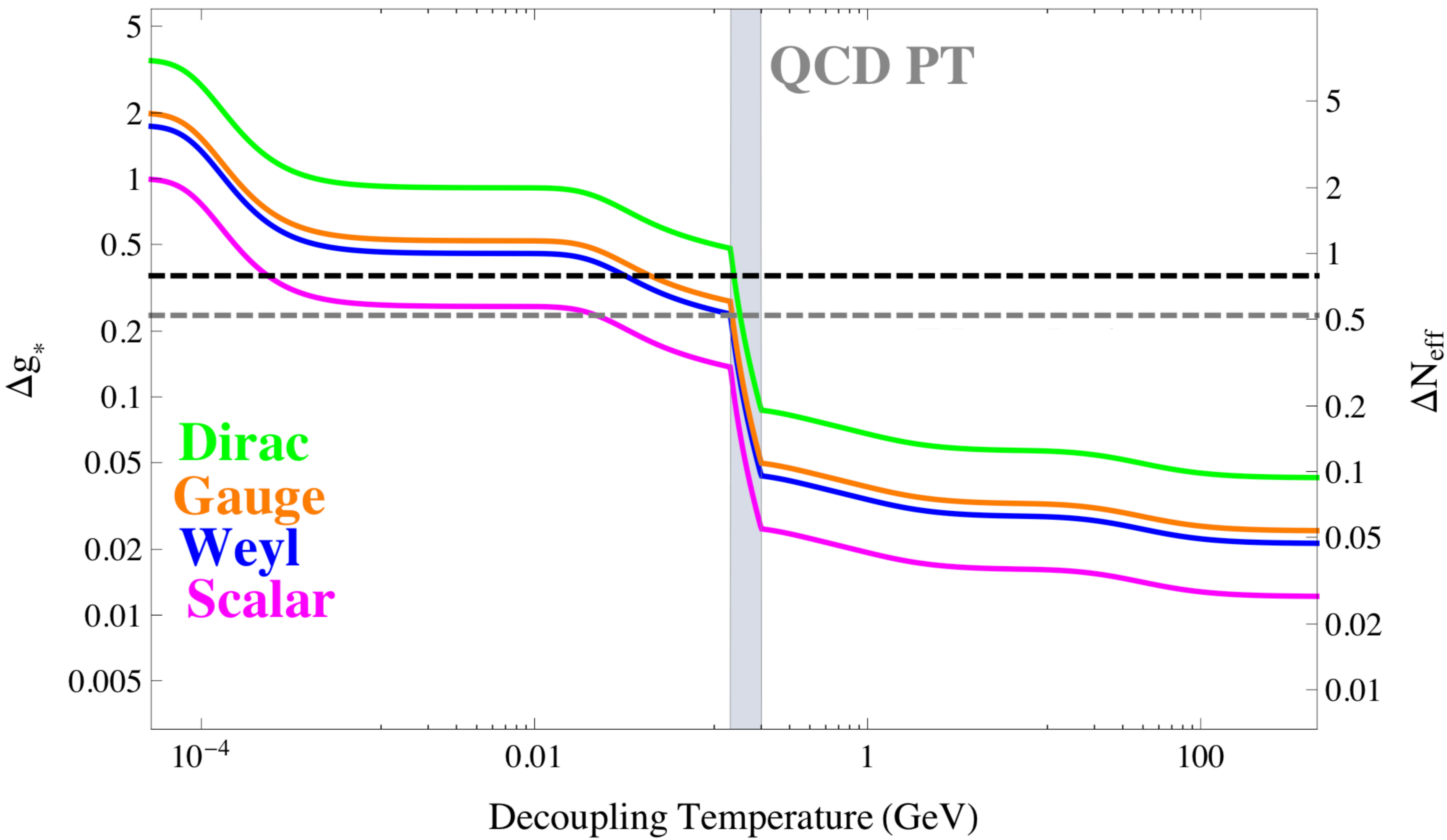
"Hot axions" can be inferred by studying the CMB, manifesting as additional neutrino species

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

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

Hot Axions and CMB



Brust, Kaplan, Walters, JHEP 1312 (2013)

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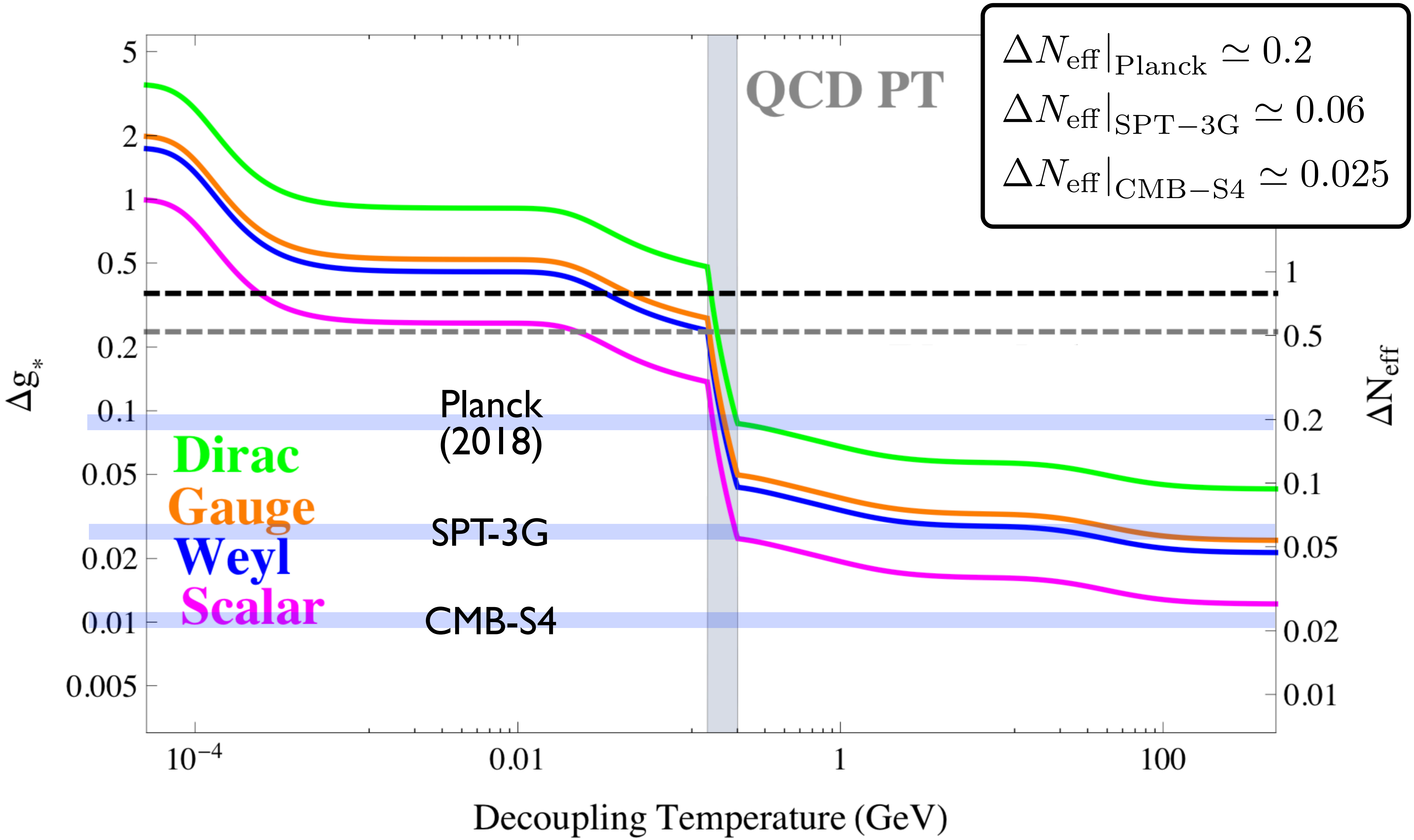

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Rate vs Temperature

$$g\,g \;\to\; g\,a$$
$$f\,h \;\to\; f\,a$$
(and others)

$$\Gamma_{\mathrm{UV}} \propto \frac{T^3}{f^2}$$

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Efficient at high temperatures
(UV production)

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

$$\Gamma_{\mathrm{IR}} \propto m_f^2 \frac{T}{f^2}$$

Efficient at low temperatures
(IR production)

This has to be compared with the expansion rate H(T)

$$Y_a(T) \equiv \frac{n_a(T)}{s(T)} \simeq \Gamma(T)/H(T) \simeq M_{\mathrm{Pl}}\Gamma(T)/T^2$$

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ΔNeff barely within reach of future CMB survyes

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Potentially large contribution to ΔNeff

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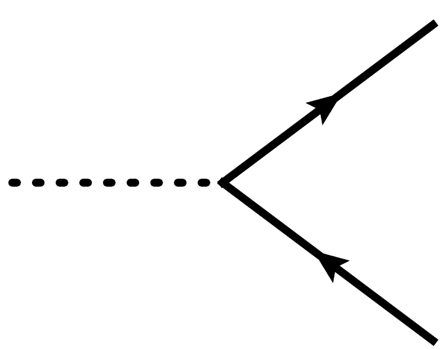


$$c_f \frac{\partial_\mu a}{f} \bar{f} \gamma^\mu \gamma^5 f$$

Axion coupling to fermions mediate processes leading to detectable ΔNeff

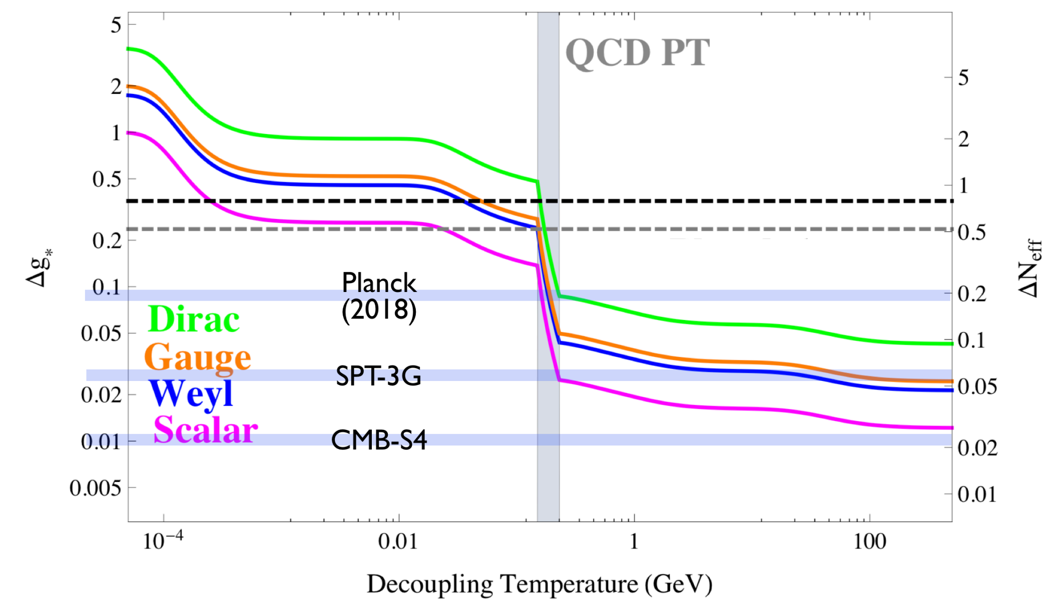
Baumann, Green, Wallisch, Phys.Rev.Lett. 117 (2016)

A Note on Precision

Importance of a precise calculation:

Axions may never thermalize

If they thermalize, decoupling details relevant (i.e. effect larger the experimental error)



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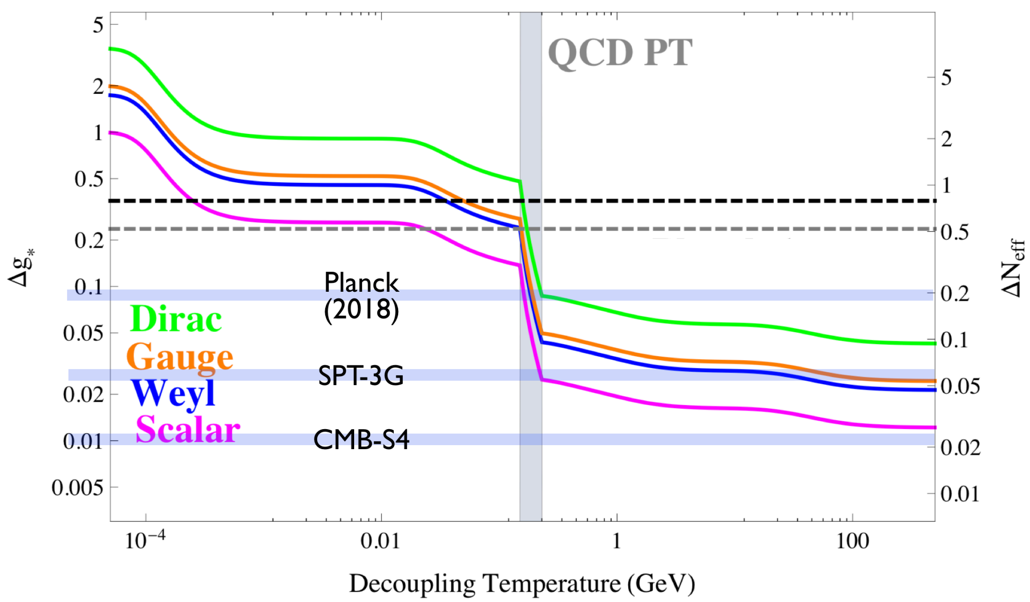
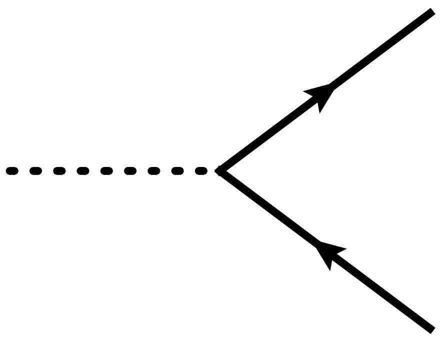


Tracking the axion number density

$$\frac{dn_a}{dt} + 3Hn_a = \sum_\alpha \mathcal{C}_\alpha$$

Collision operators accounting for all processes (scattering and decays) changing the axion number density

Coupling to fermions



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

Compute axion production mediated by coupling to Standard Model fermions

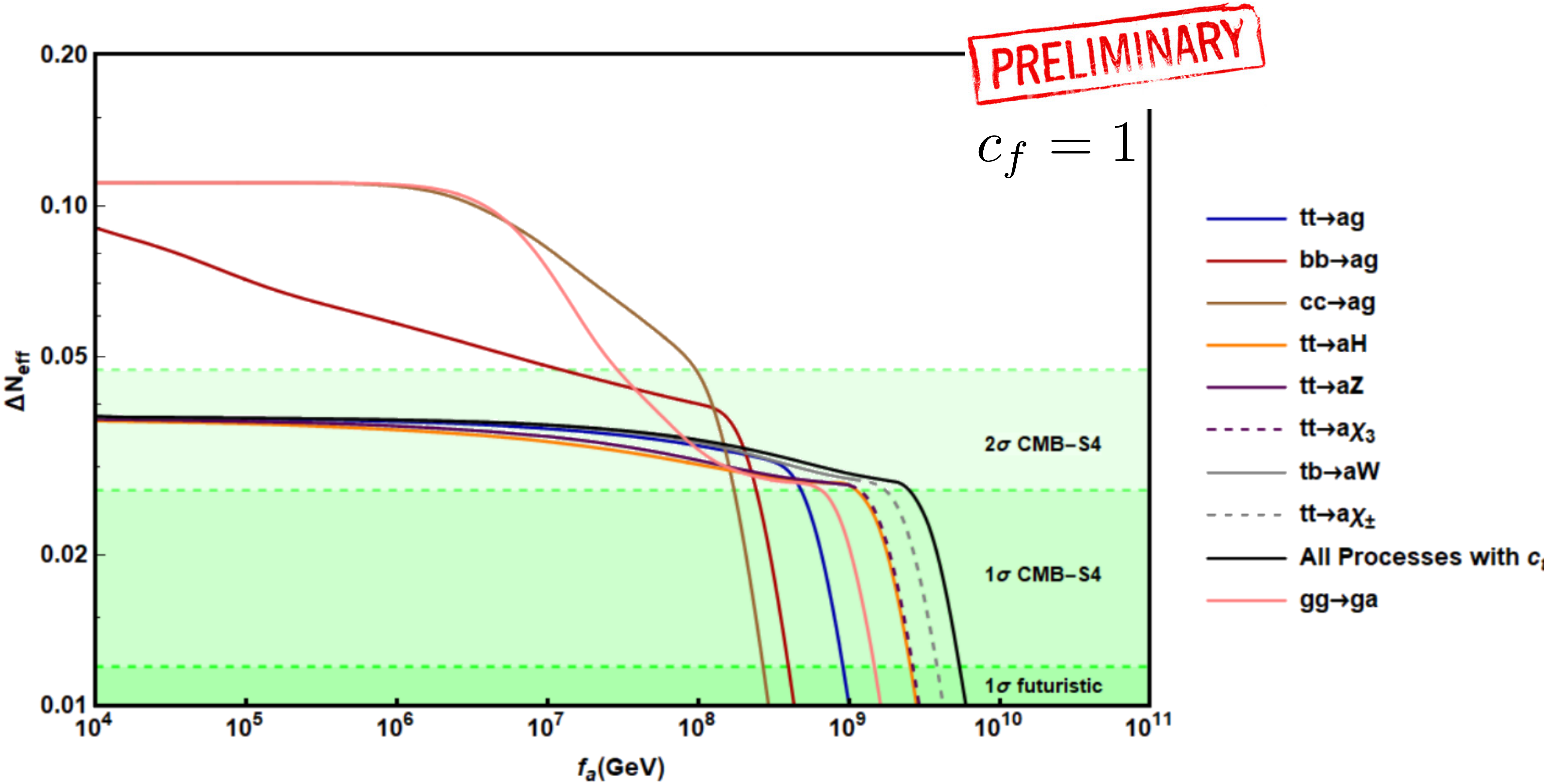
Compton-like processes contribute to rates

Ferreira, Notari, Phys.Rev.Lett. 120 (2018)

- Include all possible processes with all electroweak states
- ElectroWeak Phase Transition and temperature dependent Higgs vev
- Thermal masses
- Axion from decays (for off-diagonal couplings)

Aragon, FD, Ferreira, Merlo, Notari, in preparation

Results: Scattering



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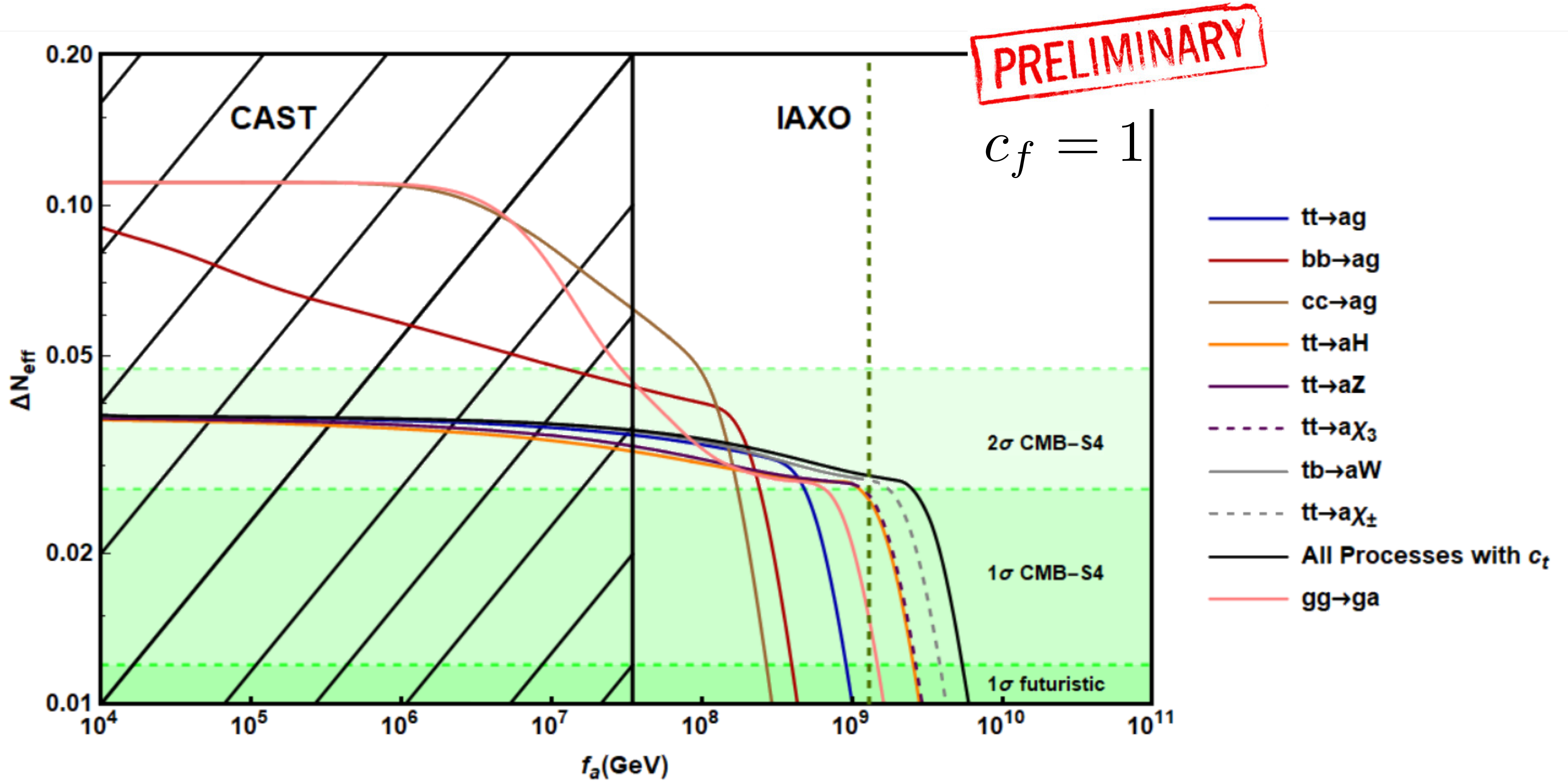

Bounds from coupling to photons (assuming order one couplings)
Region relevant to cosmology within reach of future axion terrestrial searches!

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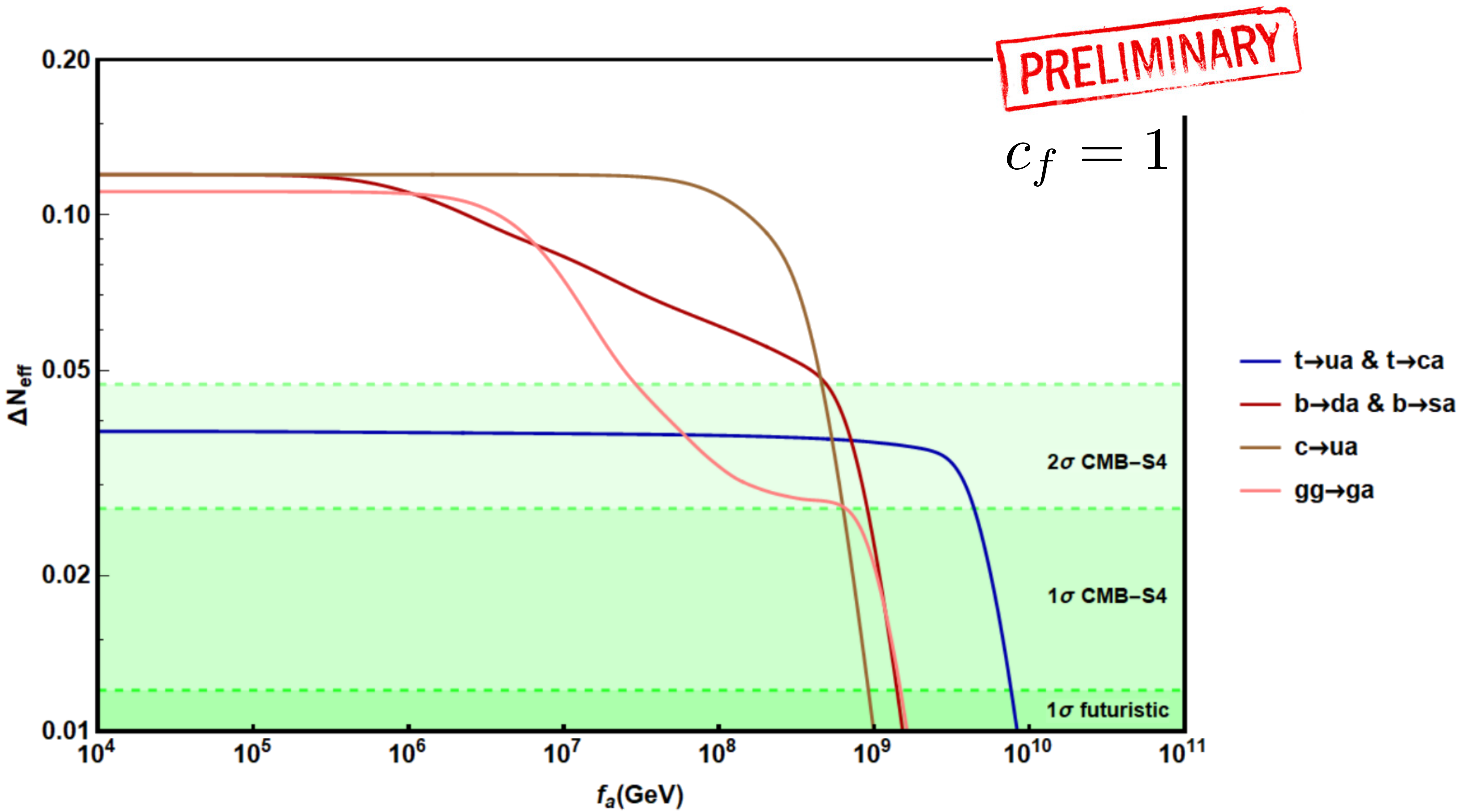

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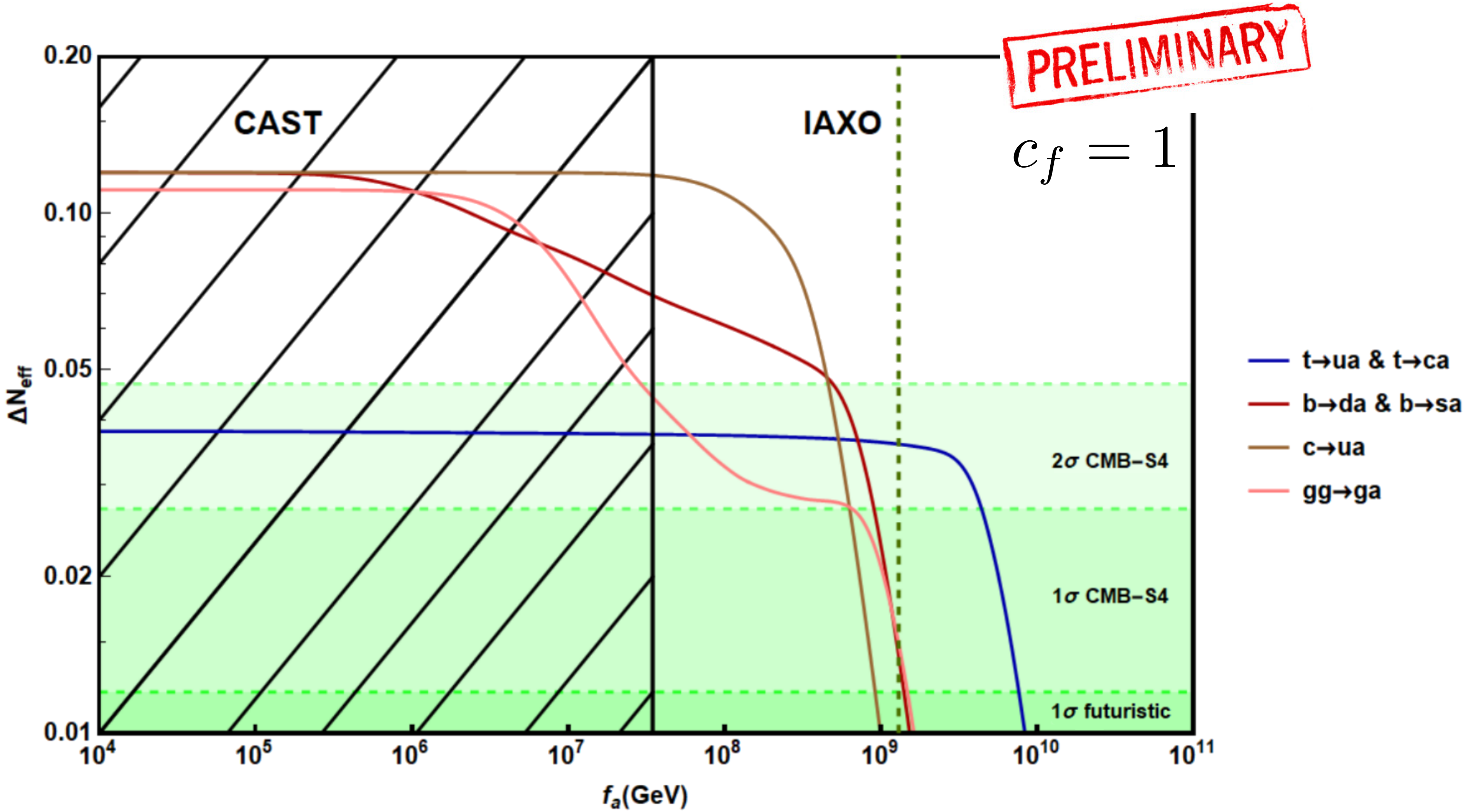

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The H_0 Tension

Mismatch between early and late universe measurements of the Hubble constant H_0

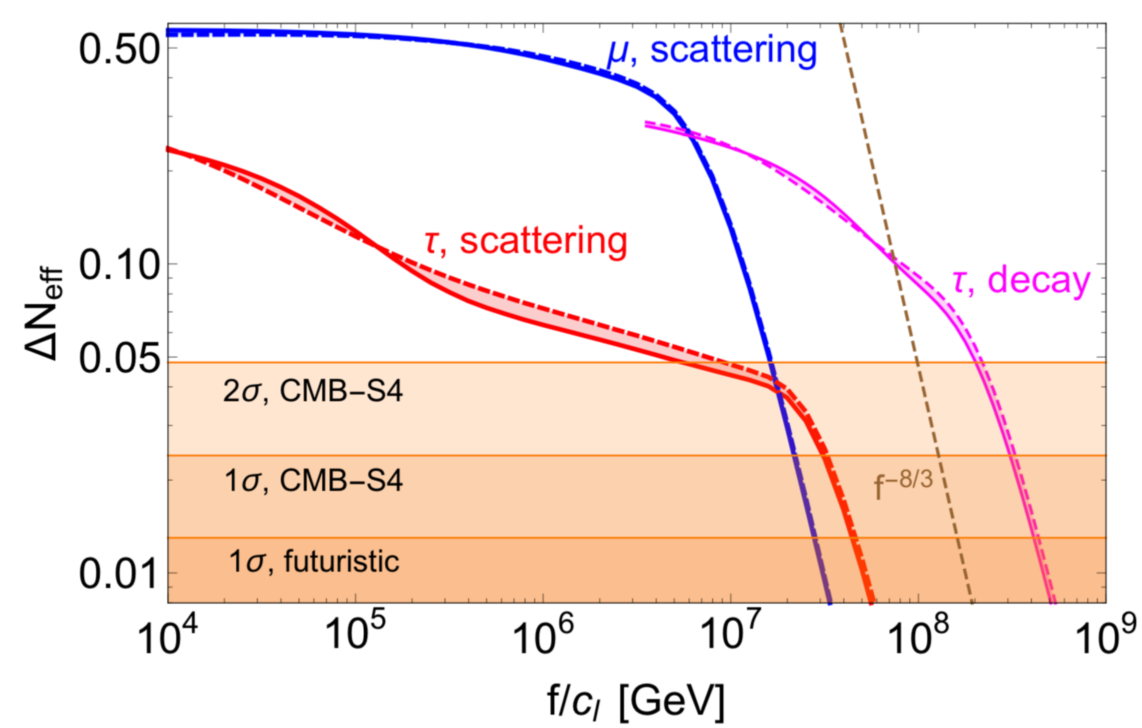
Planck Collaboration, Planck 2018 results.,arXiv:1807.06209]
A. G. Riess et al., Astrophys.J. 861 (2018)

A substantial (~ 0.2) contribution to ΔN_{eff} can be the origin

Bernal, Verde, Riess, JCAP 1610 (2016)

Could it be from axions? Yes!

But… axion interacting with heavier lepton flavors and large couplings

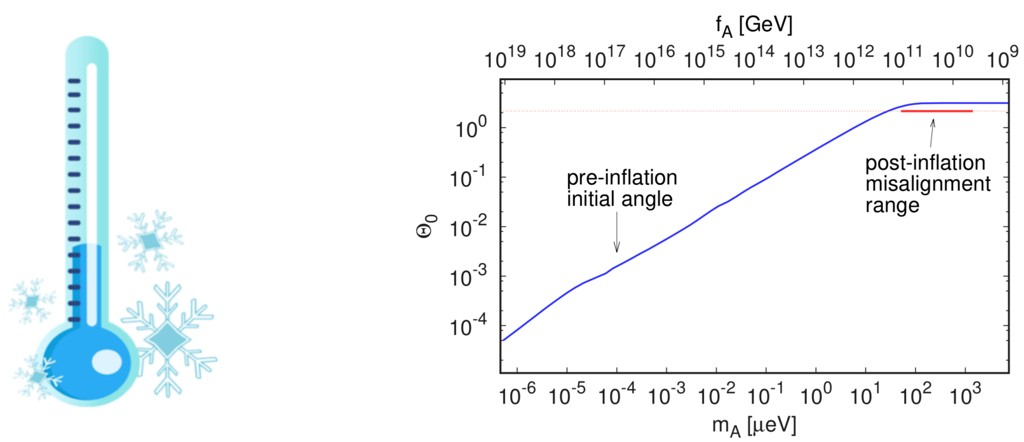


FD, Ferreira, Notari, Bernal, JCAP 1811 (2018)

Outlook

QCD axion: motivated hypothetical particle with substantial cosmological consequences

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



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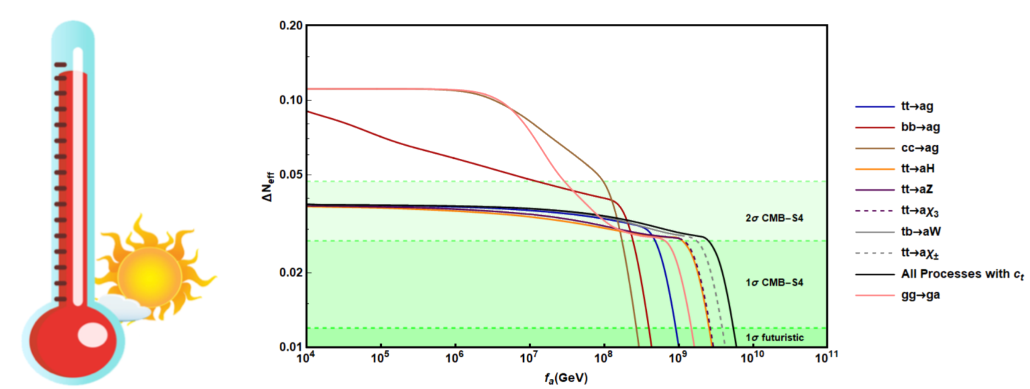

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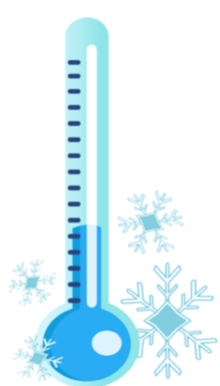

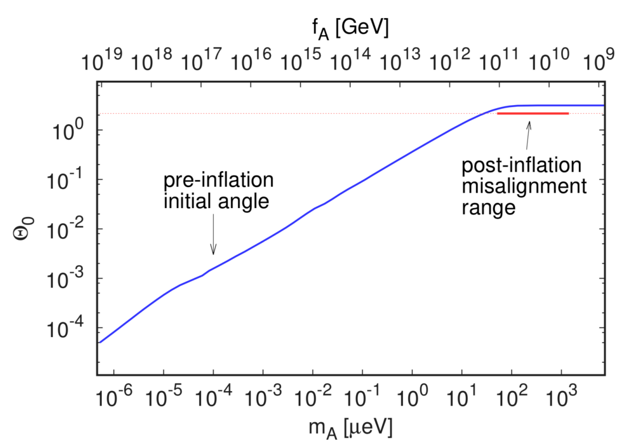

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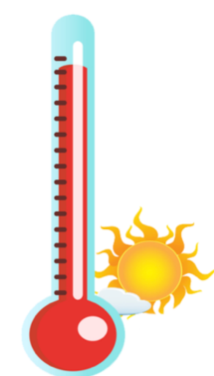

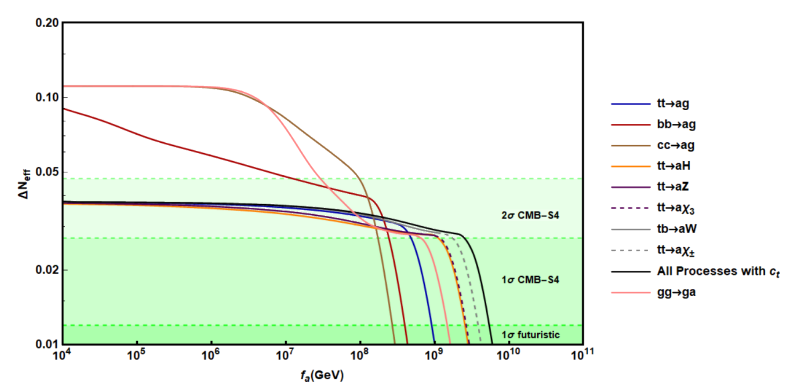

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