Constraints on ALPs-Lepton coupling via $\Delta N_{\rm eff}^{\rm BBN}$

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Divya Sachdeva

Indian Institute of Science Education
and Research, Pune

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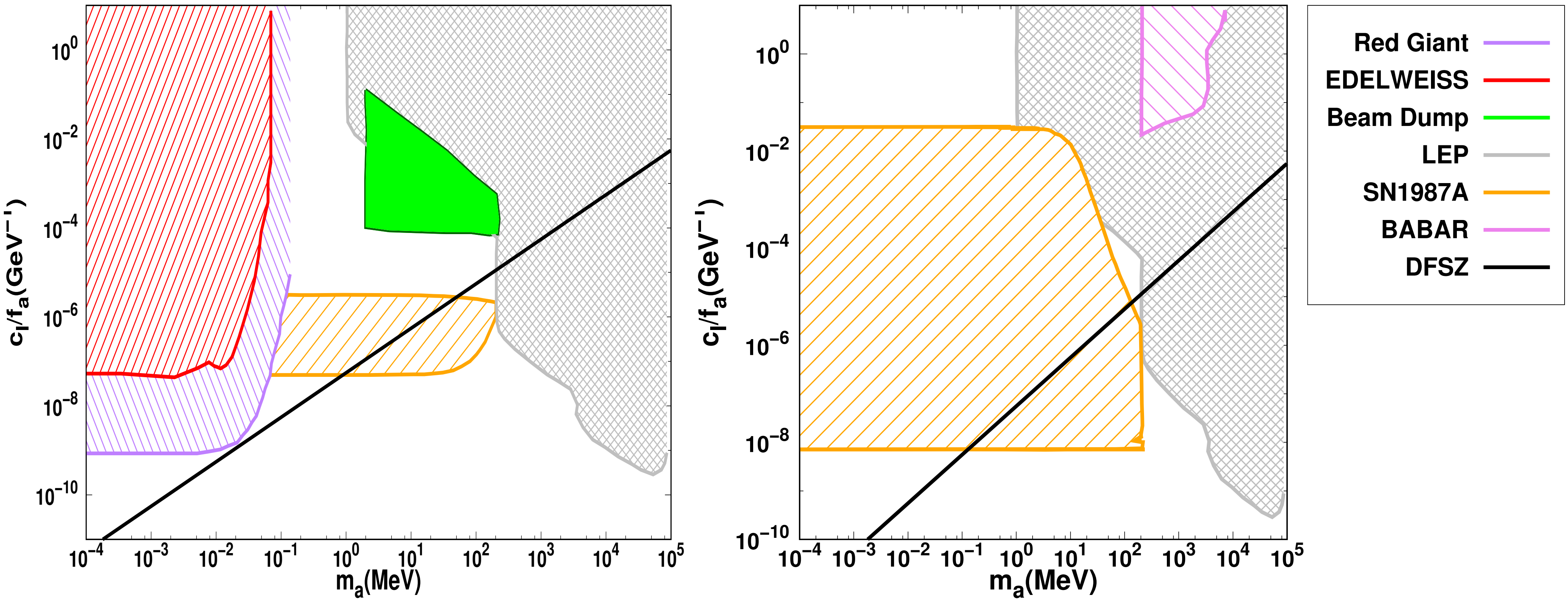
Bounds and Searches via lepton coupling



- Collider bound assumes $g_{a\gamma\gamma} \sim 10^{-3}$.
- EDELWEISS, LUX, PandaX II, XENON1T bounds are stronger for axion as CDM XENON Collaboration [2006.09721]
- CAST constrain $g_{a\gamma\gamma} c_e/f_a < 10^{-19}\,\mathrm{GeV}^{-2}$ for $m_a \lesssim 0.7\mathrm{eV}$ K. Barth et al., 2013

Bounds depicted in the figure are taken from Raffelt et al, Burst et al [1303.5379], Bauer et al. [1708.00443], Calibbi et al. [2006.04795], Croon et al. [2006.13942] etc.

Axion production in the early Universe

ALPs in early Universe can be generated by the following processes

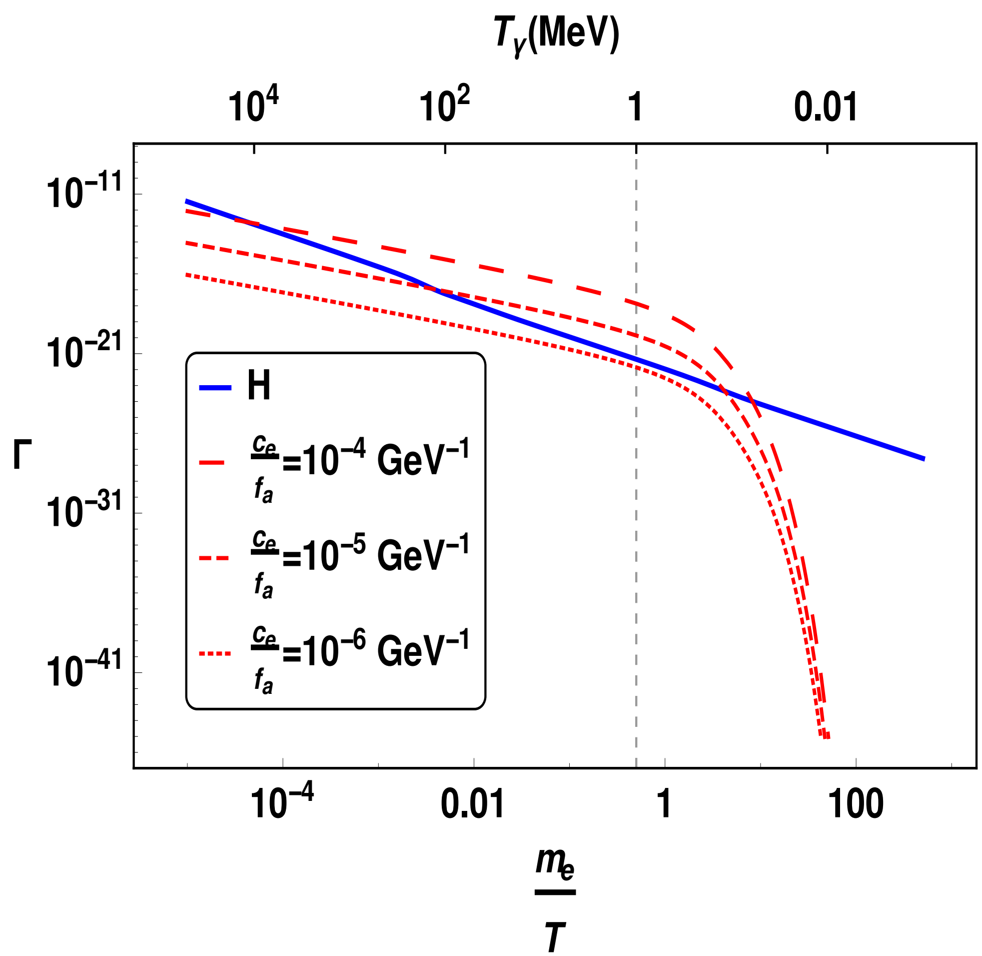
$$l^{\pm}\,\gamma \to l^{\pm}\,a$$
$$l^{-}\,l^{+} \to \gamma\,a.$$

Based on dimensional analysis,

$$\langle \sigma v \rangle \sim \begin{cases} \dfrac{c_l^2\, m_l^2}{f_a^2\, T^2}\,; & T \gg m_{l,a}\,, \\ \dfrac{c_l^2\, m_l^2}{f_a^2\, \mathrm{F}(m_a^2, m_l^2)}\,; & T \ll m_l\,. \end{cases}$$

and thus

$$\frac{\Gamma}{H} \sim \begin{cases} \dfrac{n_{l,\gamma}\langle \sigma v\rangle\, M_{\rm pl}}{T^2} \propto \dfrac{1}{T}\,; & T \gg m_{l,a}\,, \\ \dfrac{n_{\gamma}\langle \sigma v\rangle\, M_{\rm pl}}{T^2} \propto T\,; & T \ll m_l\,. \end{cases}$$



Relativistic degrees of freedom and $\Delta N_{\rm eff}$

- The non-negligible yield the energy density of BSM particles, during the BBN, increase the Hubble parameter.
- A larger Hubble parameter $\Longrightarrow$ modification to the neutron-to-proton ratio, which in turn changes the abundance of Helium-4 and Deuterium.
- This effect is captured by a quantity called $\Delta\, N_{\rm eff}^{\rm BBN}$ defined as

$$\Delta\, N_{\rm eff}^{\rm BBN} = \frac{8}{7}\frac{\rho_{\rm BSM}}{\rho_\gamma}$$

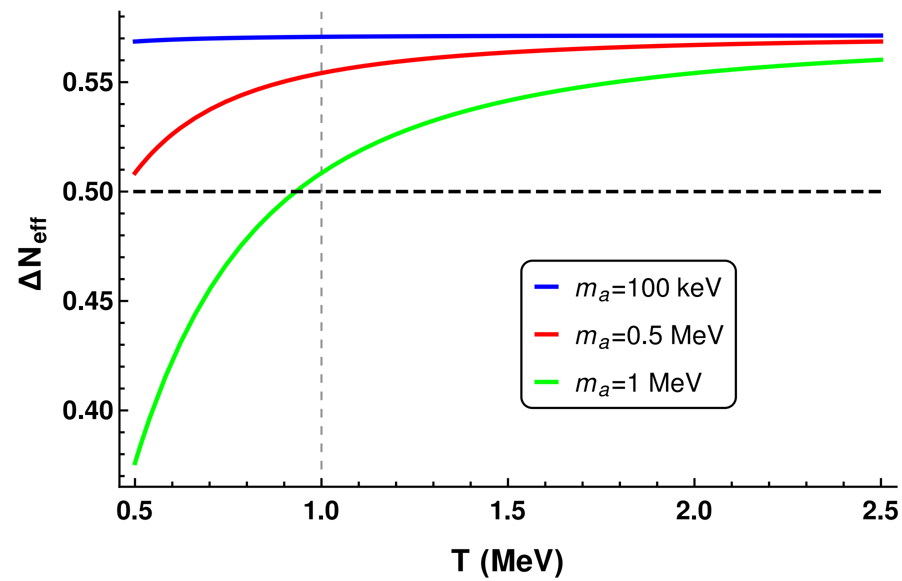
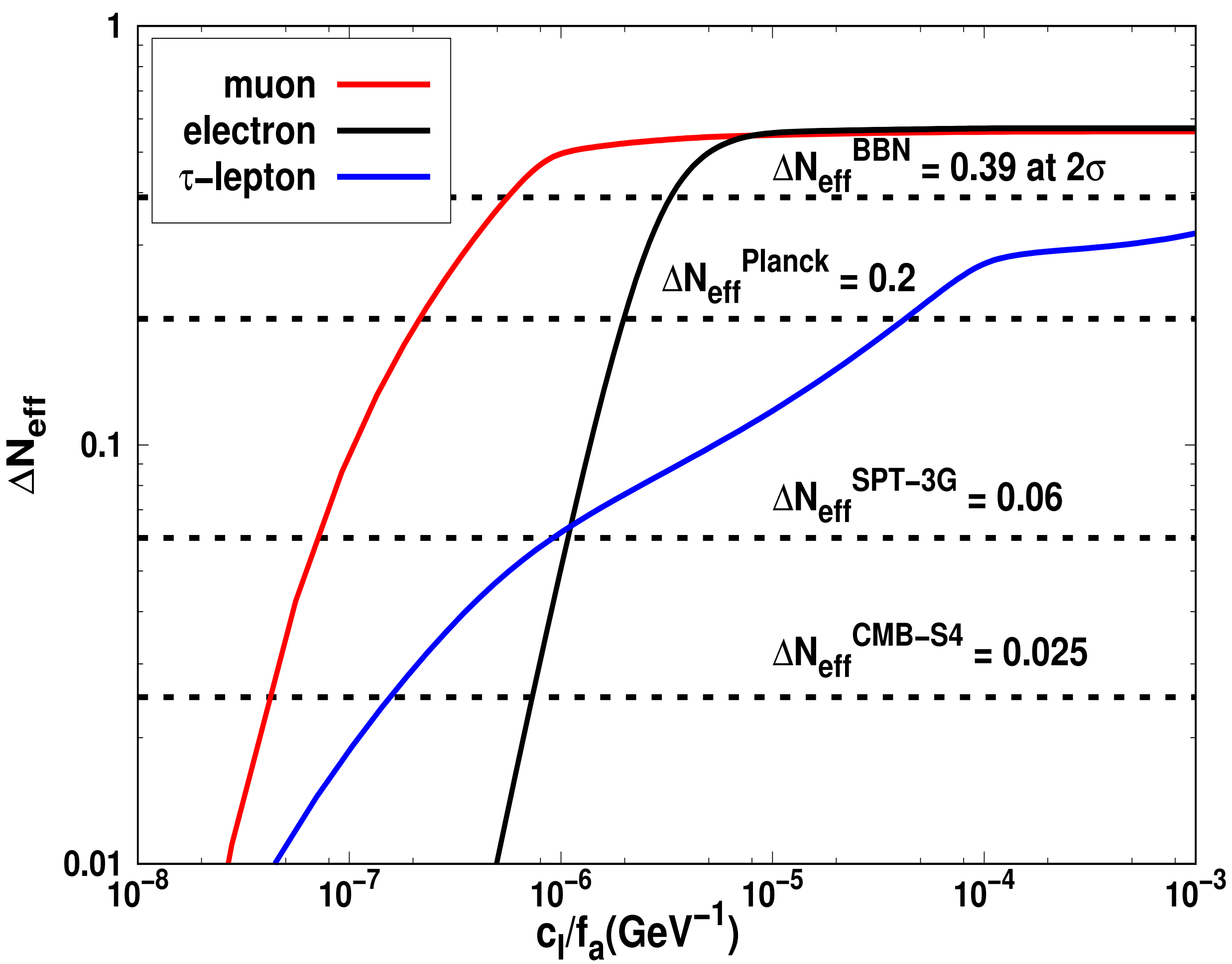


Figure: *$\Delta N_{\rm eff}$ as function of T assuming that the ALPs are in thermal equilibrium.*

ALPs out of equilibrium can also contribute to the total energy budget of Universe.

$\Delta N_{\rm eff}$ vs c_l/f_a

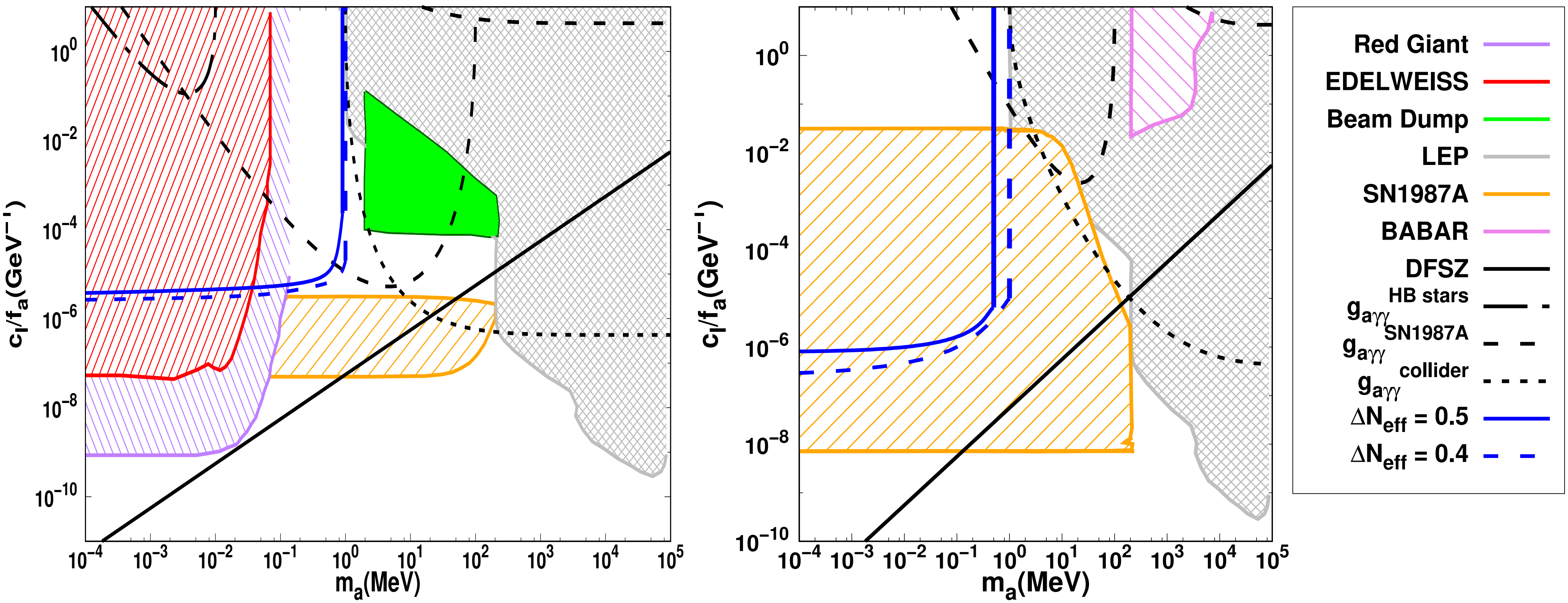


For relativistic axions during CMB decoupling, Planck 2018 results limits

$$(c_e/f_a, c_\mu/f_a, c_\tau/f_a) \sim (10^{-6}, 10^{-7}, 10^{-6})$$

confirms the result in Brust, Kaplan, Walters [1303.5379]

$\Delta N_{\rm eff}^{\rm BBN}$ tells us ....



- **Latest measurement and analysis of Helium and Deuterium abundance constrain $N_{\rm eff}^{\rm BBN} = 2.878 \pm 0.278$ at 68.3% CL**

  Fields, Olive, Yeh, Young [1912.01132]

- $\Longrightarrow$ $\Delta N_{\rm eff}^{\rm BBN} < 0.39$ **at** 2σ **using** $N_{\rm eff}^{\rm SM} = 3.046$
- **The stronger constraint on $\Delta N_{\rm eff}$ obtained from the CMB is applicable only for $m_a \gtrsim \mathrm{eV}$.**