Constraints on ALPs-Lepton coupling via $\Delta\mathrm{N}_{\mathrm{eff}}^{\mathrm{BBN}}$

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A Lightening review: Axions/ALPs

Strong CP problem

The CP violating part of the SM after EWSB is

$$\mathcal{L} = -m_q e^{i\theta_m} \bar{q} q (+\text{h.c.}) - \frac{\alpha_s \theta_{\text{QCD}}}{8\pi} G_{a\mu\nu} \tilde{G}^{a\mu\nu}.$$

The CP violating phase from the Yukawa term can be related to $G_{a\mu\nu} \tilde{G}^{a\mu\nu}$ term as,

$$\theta = \theta_{\text{QCD}} + N_f \theta_m.$$

The observational consequence $\rightarrow$ electric dipole moment of neutron which is constrained to very small value $|d_n| < 10^{-26} e.cm$

The smallness of this parameter is intriguing as it gets contribution from completely unrelated phases - strong CP problem.

Axions

- Solution to the strong-CP problem = promote θ to dynamical field

$$\mathcal{L}_{\rm axion} = \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{g^2}{32\pi^2}\frac{a(x)}{f_a} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

- Field is driven to zero under spontaneous breaking of a new global U(1) symmetry (Peccei-Quinn symmetry)
- **Axions** - the pseudo-Nambu goldstone bosons of spontaneously broken global symmetry
- Symmetry is broken explicitly at $\Lambda_{\rm QCD}$ due to non perturbative QCD effects - **small axion mass** following a relation

$$m_a = 6\mu\,{\rm eV}\left(\frac{10^{12}{\rm GeV}}{f_a}\right)$$

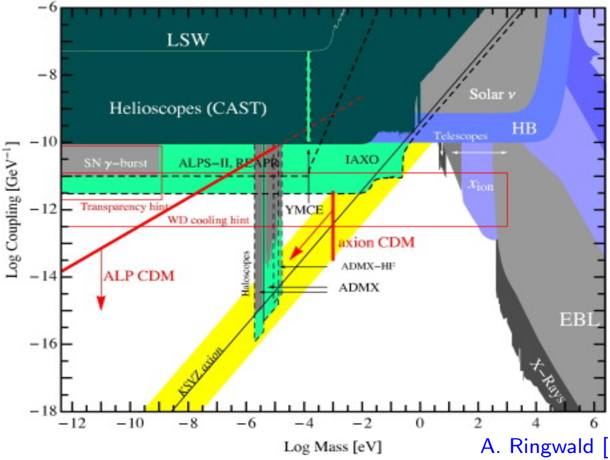
Axion like particles(ALPs) .. & properties

- Generalization of axions to any pseudoscalar (spin 0) associated with a spontaneously broken $U(1)$ - but **may not** solve the strong CP problem example: majorons.
- Their mass and coupling to photons, in general, are not related.

The Lagrangian density describing the interactions of axions or ALPs to SM particles is

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 + \frac{g_{a\gamma\gamma}}{4f_a} a F_{\mu\nu}\tilde{F}^{\mu\nu} + c_\psi \frac{\partial_\mu a}{2f_a}\bar{\psi}\gamma^\mu\gamma_5\psi.$$

Bounds and Searches via photon coupling



A. Ringwald [1210.5081]

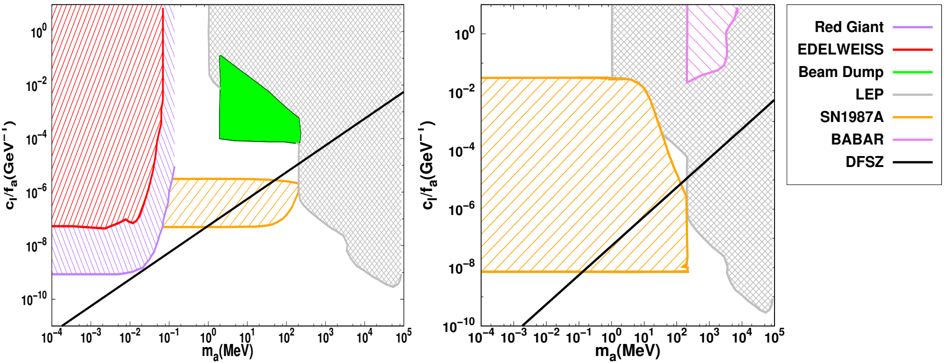
The recent NA64 experiment study limits $m_a \lesssim 55\,\mathrm{MeV}$ with $2\times10^{-4} \lesssim g_{a\gamma\gamma} \lesssim 5\times10^{-2}$ NA64 collaboration [2005.02710]

Mono, tri-photon searches at LEP, CDF and LHC puts bound on $m_a \sim 1 - 10^6\mathrm{MeV}$ with $g_{a\gamma\gamma} \lesssim 10^{-3}$

Jaeckel, Jankowiak, Spannowsky [1212.3620,1509.00476]

ALPs-Lepton coupling

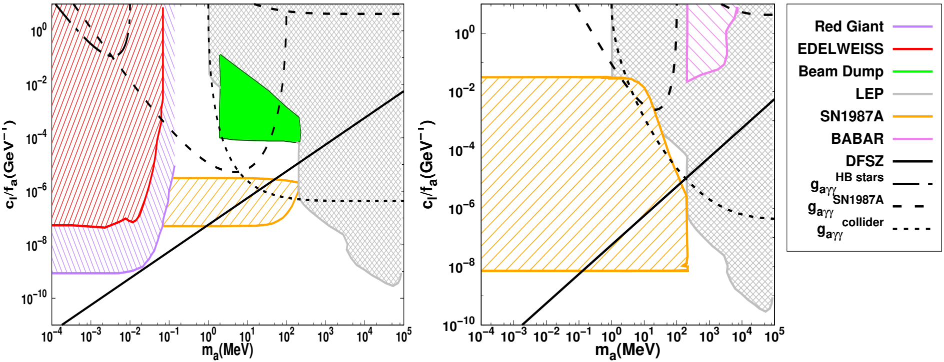
Bounds and Searches via lepton coupling



- 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.

Induced ALPs-photon coupling



ALPs-Lepton coupling can generate the axion photon coupling at one loop:

$$g_{a\gamma\gamma}^{\text{loop}} = \frac{\alpha_{\text{em}}}{4\pi}\,\frac{c_l}{f_a}\,4\,f\left(\frac{m_a^2}{m_l^2}\right) \quad \text{where,} \qquad f\left(\frac{m_a^2}{m_l^2}\right) \sim \begin{cases} -\dfrac{m_a^2}{12\,m_l^2}\,; & m_l \gg m_a\,, \\ 1\,; & m_a \gg m_l\,. \end{cases}$$

ALPs-Lepton coupling and BBN

Axion production in the early Universe

ALPs in early Universe can be generated by the following processes

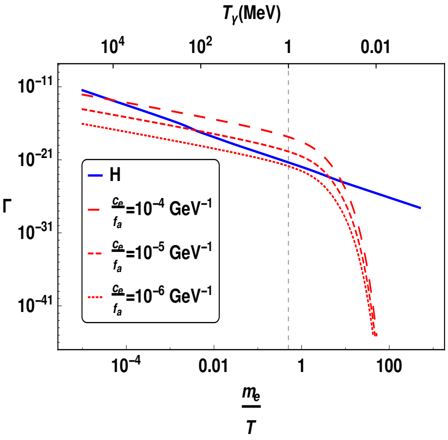
$$l^{\pm}\,\gamma \to l^{\pm}\,a$$
$$l^{-}\,l^{+} \to \gamma\,a.$$

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

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

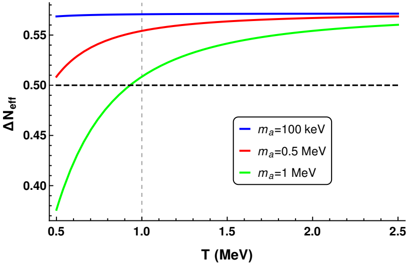


Figure: $\Delta N_{\rm eff}$ *as function of* T *assuming that the ALPs are in thermal equilibrium.*

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

How to calculate ρ_a?

- Set up the Boltzmann equation

$$\frac{\partial f_i(|\vec{p}|,t)}{\partial t} - H|\vec{p}|\frac{\partial f_i(|\vec{p}|,t)}{\partial|\vec{p}|} = C[f_i(|\vec{p}|,t)$$

  for distribution functions, f_i with $i =$ axion, neutrinos and electrons.

- Use Friedmann equations

$$H^2 = \frac{8\pi G\,\rho^{\mathrm{tot.}}}{3} \qquad \frac{d\rho}{dt} = -3\mathrm{H}(\rho + \mathrm{P})$$

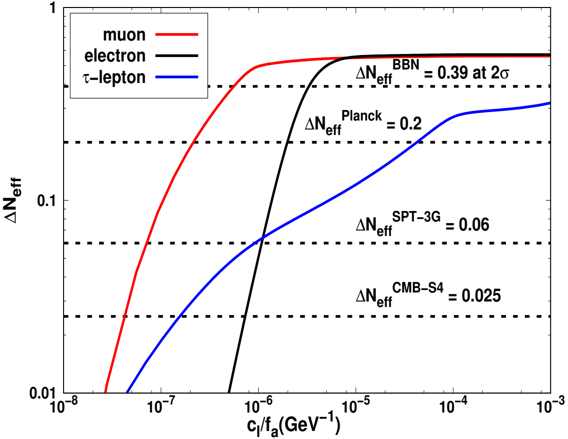
  to calculate the evolution of temperature of the plasma.

- **Initial abundance of axions is taken zero**.
- The energy density is calculated as

$$\rho_i = \frac{g}{2\pi^2}\int_0^\infty dp\,p^2\,E\,f_i$$

- To solve these first-order partial differential equations, the characteristics curves method is adopted.

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

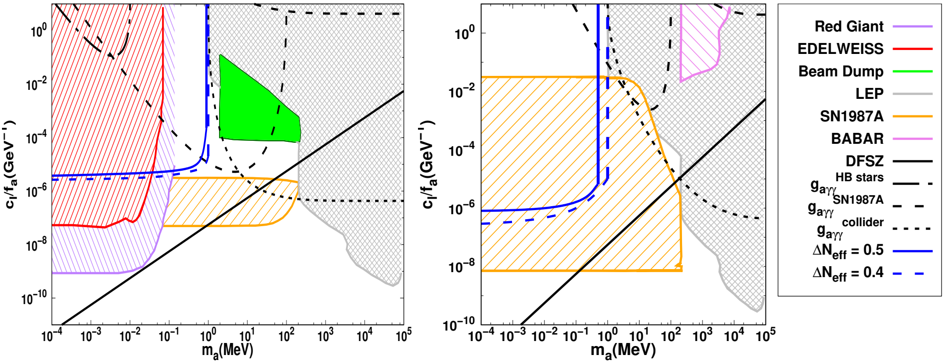


For relativistic axions during CMB decoupling, Planck 2018 results limits

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

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

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



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

  Fields, Olive, Yeh, Young [1912.01132]

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

Summary

- **In the presence of non-zero c_l/f_a, the ALPs can be produced in the early universe and contribute to $\Delta \mathrm{N}_{\mathrm{eff}}$.**
- **The full Boltzmann equations are solved for ALPs that are not in equilibrium with the thermal plasma and $\Delta \mathrm{N}_{\mathrm{eff}}^{\mathrm{BBN}}$ is calculated.**
- **Bounds obtained are the most stringent one for the ALP-electron interaction strength for $20\mathrm{keV} \leq m_a \leq 1\mathrm{MeV}$.**
- **Analysis improves limit for the ALP-muon interaction strength for $m_a < 1\mathrm{MeV}$ and $c_\mu/f_a \leq 10^{-2}\mathrm{GeV}^{-1}$.**