Robust cosmological constraints on axion-like particles

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$\alpha_{\gamma\gamma}$ HB stars

$\alpha_{\gamma\gamma}$ SN1987a

$\alpha_{\gamma\gamma}$ SN1987a ($\phi \rightarrow \gamma\gamma$)

DFSZ

beam dump

$g_{\phi\gamma}$ [1/GeV]

$m_{\phi}$ [MeV]
Introduction

- \[ \mathcal{L}_{\text{ALP}} = \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m_\phi^2 \phi^2 - \frac{g_{\phi \gamma}}{4} \phi F_{\mu \nu} \tilde{F}^{\mu \nu} \]
- Translates to lifetime \( \tau_\phi = \frac{64 \pi}{m_\phi^3 g_{\phi \gamma}^2} \)
- Impact early Universe cosmology if \( 1 \text{ keV} \lesssim m_\phi \lesssim 1 \text{ GeV}, \tau_\phi \ll \text{age of the Universe} \)
- Description via Boltzmann equation
- Simple picture:
  - (Thermal) production via Primakoff process
  - (ALP becoming non-relativistic)
  - Decay into photons
- Constraints complementary to other astrophysical and collider physics probes, in particular also to projected sensitivities of Belle II and SHiP
Impact of ALPs on BBN and the CMB

- In the context of axion-like particles (ALPs) big bang nucleosynthesis (BBN) sensitive to modifications of
  - Hubble rate
  - Time-temperature relation
  - $\nu$-decoupling temperature
  - Baryon-to-photon ratio $\eta$
    - Input value from cosmic microwave background (CMB) observations, best-fit value sensitive to effective number of $\nu$s, i.e. $N_{\text{eff}}$
- CMB sensitive to $N_{\text{eff}}$
Impact of ALPs on BBN and the CMB

Constraints in the vanilla case
Robustness of constraints

Effect of additional radiation $\Delta N_{\text{eff}}$ and $\nu$ chemical potential $\xi_{\nu_e}$
Robustness of constraints

Complementarity to projections of Belle II and SHiP

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Robustness of constraints

Effect of reheating temperature $T_R$

$T_R = 10^9$ MeV

$T_R = 10^6$ MeV

$T_R = 10^3$ MeV

$T_R = 10^1$ MeV

$\frac{\tau}{s}$ vs $m_\phi$ [MeV]
Summary

• BBN and CMB can put constraints on ALPs with masses in keV – GeV range
• Complementary to other astrophysical and particle physics probes, in particular also to projected sensitivities of Belle II and SHiP
• Constraints can be weakened by e.g.
  • additional radiation
  • neutrino chemical potential
  • low reheating temperature
• Still, very relevant and robust cosmological constraints remain
Thank you
Backup Slides
Production and decay in the early Universe

- Description via $\frac{\partial f_\phi}{\partial t} - Hp \frac{\partial f_\phi}{\partial p} = C \times \left( f^\text{eq}_\phi - f_\phi \right)$

- Contributions to collision term $C = C_q + C_\gamma$ from
  - Primakoff process $C_q$, in equilibrium for $T > T_{f_0}$
  - (inverse) decay $C_\gamma$, in equilibrium for $T < T_{re}$

- Physics depends on the order of
  - Primakoff freeze-out
  - ALP becoming non-relativistic
  - (re-)equilibration via (inverse) decay
Production and decay in the early Universe

\[ T_{\phi} = 1 \text{ MeV} \]
\[ T_{\phi} = 10 \text{ MeV} \]
\[ T_{\phi} = 1 \text{ GeV} \]
\[ T_{\phi} = 1 \text{ TeV} \]
\[ T_{\phi} = 1 \text{ PeV} \]
\[ T_{\phi} = 1 \text{ EeV} \]

\[ T_{\text{re}} = 0 \]
\[ T_{\text{re}} = 1 \text{ MeV} \]
\[ T_{\text{re}} = 10 \text{ MeV} \]

\[ \Omega_X(t) \ll \Omega_0 \]

\[ \rho_X(t) / \rho_0 \times R(t)^4 \]

\[ m = 10^{-2} \text{ MeV} \]
\[ \tau_\phi = 10^4 \text{ s} \]

\[ \rightarrow \text{ BBN} \rightarrow \]

Robustness of constraints

- Effect of a low reheating temperature $T_R$:
  - In principle $10 \, \text{MeV} \lesssim T_R \lesssim 10^{16} \, \text{GeV}$
  - If $T_R \lesssim T_{fo}$ one only has 'freeze-in' contribution to $\phi$ abundance, no equilibrium in early Universe

- Effect of additional radiation, parametrized as $\Delta N_{\text{eff}}$:
  - Decay of ALPs after $\nu$-decoupling reduces $N_{\text{eff}}$, this can be compensated for

- Effect of non-vanishing neutrino chemical potential $\xi_{\nu_e} = \mu_{\nu_e} / T_\nu$:
  - Gives contribution to $\Delta N_{\text{eff}}$, which we vary independently
  - Influences neutron-to-proton conversion via weak interaction
    $\Rightarrow$ neutron-to-proton ratio in equilibrium $n_n / n_p \propto \exp(-\xi_{\nu_e})$
    $\Rightarrow$ smaller values for $^4\text{He}$ and D abundances for smaller neutron densities
More general coupling structures

- In general constraints expected to be similar if $\tau_\phi$ is interpreted as total lifetime
- Depending on region in parameter space constraints might get weaker or stronger, e.g. if:
  - freeze-out happens at smaller temperature if $\phi$ becomes non-rel. before decay $\Rightarrow$ weaker constraint
  - additional final states, hadro-dissociation possible $\Rightarrow$ possibly stronger constraints