Prominent Enhancement of Axion Thermalization Rate from axion-kaon Interaction

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Introduction

The thermal axion scenario, constrained by ΔN_{eff}, provides an important and independent bound on axion coupling. In $T < T_c$, the hadronic contribution to axion thermalization rate has long been estimated by only taking $a\pi \leftrightarrow \pi\pi$ reaction into account, while the other channels, such as $aK \leftrightarrow \pi K$, $aN \leftrightarrow \pi N$, etc., are neglected because of Boltzmann suppression.

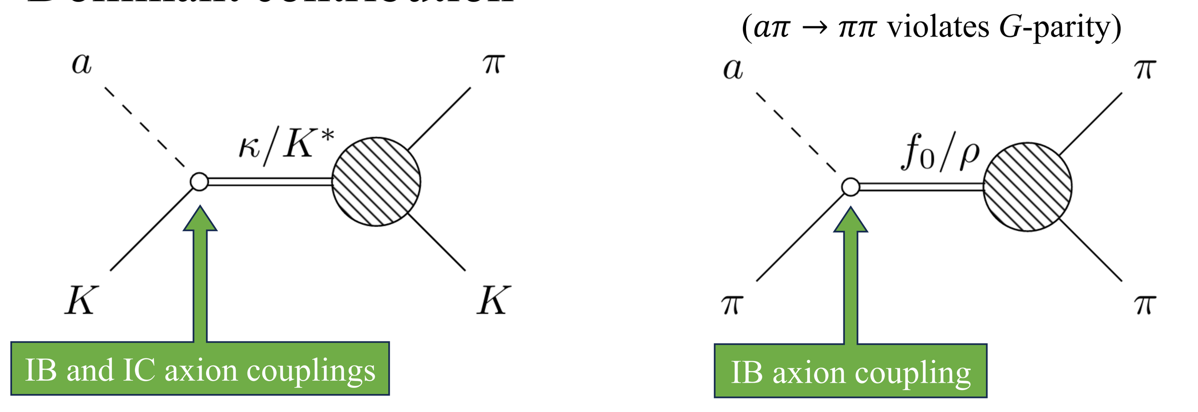
$$\Gamma_a(T) \propto \int d\widetilde{\Gamma}|\mathcal{M}|^2 \left[\prod_i f_i(E_i)\right]\left[\prod_j 1 \pm f_j(E_j)\right]$$

This approximation ignores the dynamical enhancement due to the nonperturbative hadronic interactions in the reaction amplitudes. We reexamine this assumption, focusing on $aK \leftrightarrow \pi K$ (vs. $a\pi \leftrightarrow \pi\pi$).

➢ Channels

$$\begin{bmatrix} aK^+ \to \pi^+K^0, \pi^0K^+ \\ aK^- \to \pi^-\bar{K}^0, \pi^0K^- \\ aK^0 \to \pi^0K^0, \pi^-K^+ \\ a\bar{K}^0 \to \pi^0\bar{K}^0, \pi^+K^- \end{bmatrix} \text{ vs. } \begin{bmatrix} a\pi^0 \to \pi^+\pi^-, \pi^0\pi^0 \\ a\pi^\pm \to \pi^\pm\pi^0 \end{bmatrix}$$

➢ Dominant contribution



IB=isospin-breaking, IC=isospin-conserving

Framework

KSVZ axion: $\mathcal{L}_{\text{axion}} = \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{f_a}\frac{\alpha_s}{8\pi}G\tilde{G}$

Equivalent representation by $q = (u,d,s)^T \to \exp\left(i\frac{a}{2f_a}Q_a\gamma_5\right)q$

$Q_a = \frac{M^{-1}}{\langle M^{-1}\rangle}$, $M = \text{diag}(m_u,\ m_d,\ m_s)$, $\langle\cdots\rangle$ denotes flavor trace.

$$\mathcal{L}_{\text{axion-int}} = -\frac{\partial_\mu a}{2f_a}\sum_{i=3,8} C_i\bar{q}\gamma^\mu\gamma_5\frac{\lambda_i}{2}q - iC_S\frac{a}{B_0 f_a}\bar{q}\gamma_5 q$$
$$+[\text{singlet current contribution (ignored)}]$$

$C_3 \simeq 0.341,\quad C_8 \simeq 0.550,\quad C_S \simeq 0.216\, m_\pi^2$

SU(3) ChPT with axion couplings:

$$\mathcal{L}_{eff}^{(2)} = \frac{F_\pi^2}{4}\langle\partial_\mu U\partial^\mu U^\dagger + \chi(a)U^\dagger + U\chi^\dagger(a)\rangle - \frac{\partial_\mu a}{2f_a}\sum_{i=3,8} C_i J_{A,i}^\mu$$

$U = \exp\left(\frac{i\sum_{i=1}^{8}\lambda_i\phi_i}{F_\pi}\right)$, ϕ_i are SU(3) octet pNGBs.

$\chi(a) = 2B_0 M e^{-i\frac{a}{f_a}Q_a}$.

Unitarization recipe accounting for the hadron resonances in both $a\pi \to \pi\pi$ and $aK \to \pi K$:

➢ Meson-meson scattering:

$$T_{IJ}^{uni} = T_{IJ}^{(2)} \cdot \left[T_{IJ}^{(2)} - T_{IJ}^{(4,\text{LECs})} - T_{IJ}^{(2)} \cdot \mathcal{G} \cdot T_{IJ}^{(2)}\right]^{-1} \cdot T_{IJ}^{(2)}$$

➢ Axion reaction:

$$\vec{M}_{IJ}^{uni} = T_{IJ}^{(2)} \cdot \left[T_{IJ}^{(2)} - T_{IJ}^{(4,\text{LECs})} - T_{IJ}^{(2)} \cdot \mathcal{G} \cdot T_{IJ}^{(2)}\right]^{-1} \cdot \vec{M}_{IJ}^{(2)}$$

- $\mathcal{G} = \text{diag}(G_1, G_2, \cdots)$ is the diagonal matrix of two-point one-loop functions (DR+$\overline{\text{MS}}$ with subtraction constant).
- IB effects are neglected in the meson-meson scattering.

➢ Additional coupled states in the coupled channel formalism:

$a\pi^0 \to \pi^+\pi^-, \pi^0\pi^0$

$$\begin{cases} (\pi\pi)_{IJ=00}: \Leftarrow (K\bar{K})_{IJ=00} \\ (\pi\pi)_{IJ=20}: \text{ elastic } \pi\pi \end{cases}$$

$a\pi^+ \to \pi^+\pi^0$:

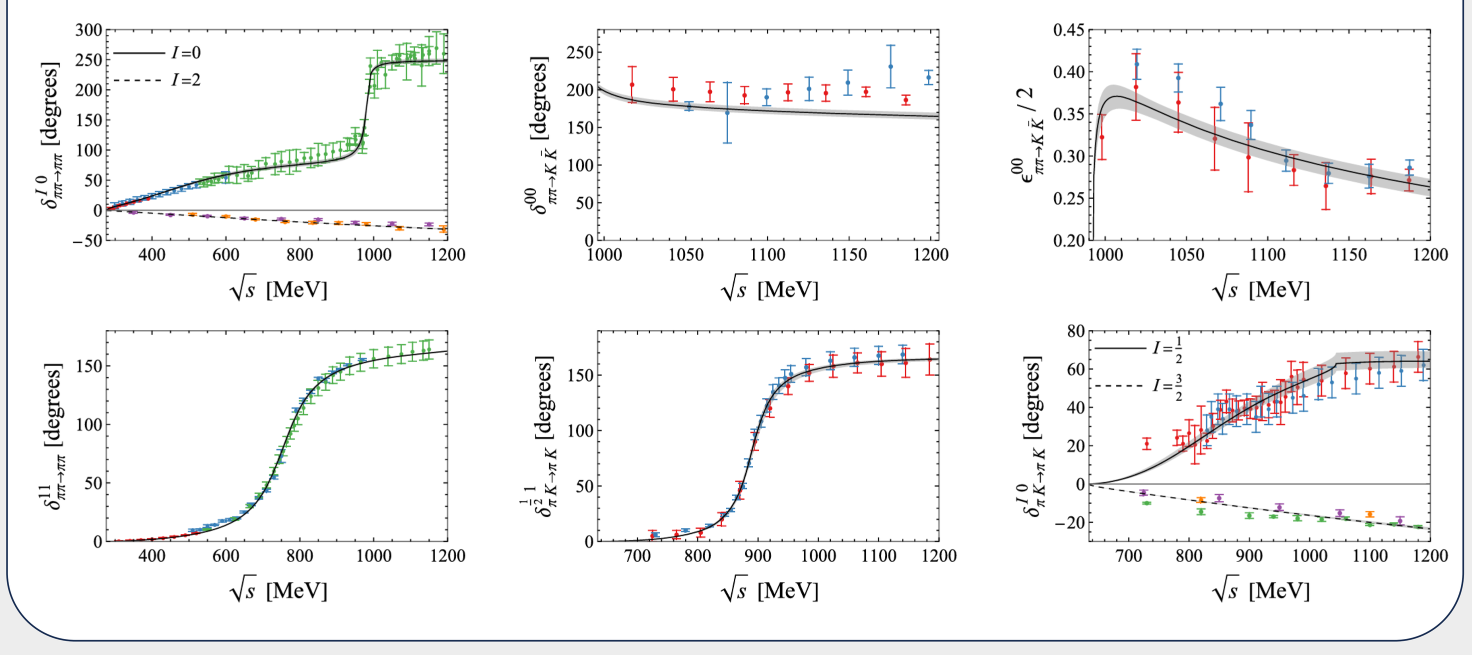
$$\begin{cases} (\pi\pi)_{IJ=11}: \Leftarrow (K\bar{K})_{IJ=11} \\ (\pi\pi)_{IJ=20}: \text{ elastic } \pi\pi \end{cases}$$

$aK^+ \to \pi^+K^0, \pi^0K^+$

$$\begin{cases} (\pi K)_{IJ=\frac{1}{2}0,\frac{1}{2}1}: \Leftarrow (\eta K)_{IJ=\frac{1}{2}0,\frac{1}{2}1} \\ (\pi K)_{IJ=\frac{3}{2}0}: \text{ elastic } \pi K \\ (\pi K)_{IJ=\frac{3}{2}1}: \text{ rather weak, neglected} \end{cases}$$

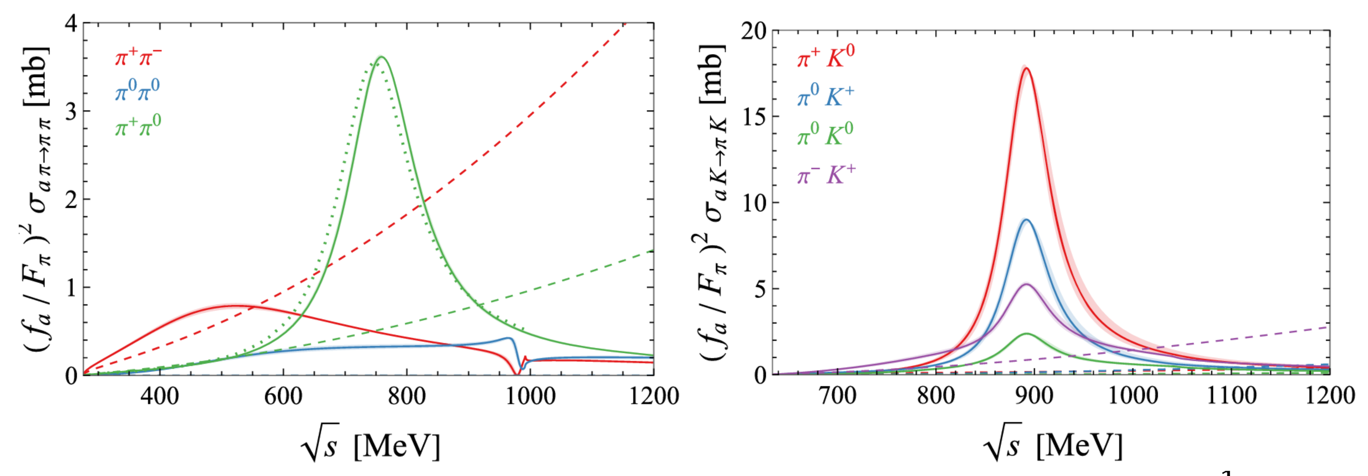
(similar for aK^0 channels)

➢ Fix the meson-meson FSIs using the scattering data up to $\sqrt{s} = 1.2$ GeV.



Results

➢ **Cross sections of axion reaction processes**

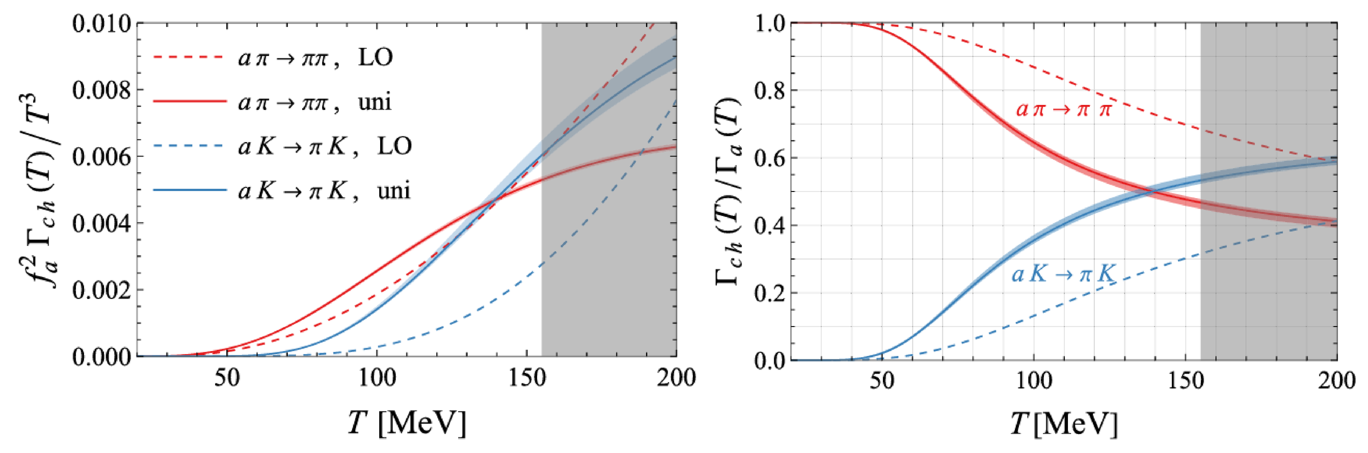


➢ In aK^+ channels, C_3 and C_8 contributions interfere: constructively in $IJ = \frac{1}{2}1$ sector; destructively in $IJ = \frac{1}{2}0$ sector.

➢ In aK^0 channels, C_3 and C_8 contributions interfere: constructively in $IJ = \frac{1}{2}0$ sector; destructively in $IJ = \frac{1}{2}1$ sector.

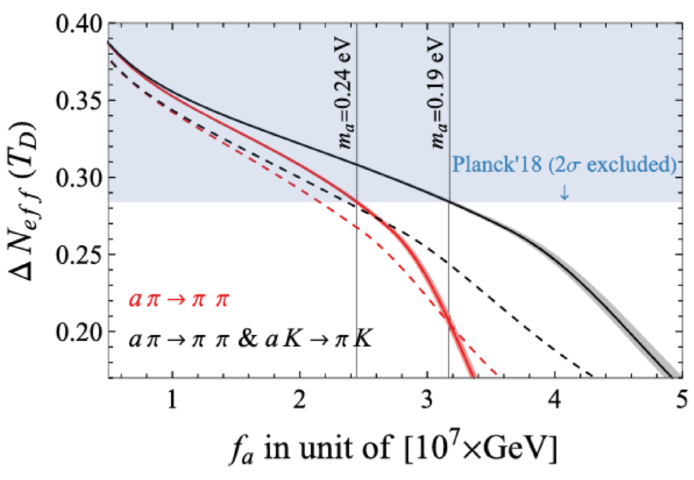
The $aK^+ \to \pi^+K^0$ process exhibits a particularly large cross section — about four times greater than that of $a\pi^+ \to \pi^+\pi^0$, challenging the assumption that $a\pi \to \pi\pi$ process is the dominant hadronic axion thermalization channel below T_c.

➢ **Axion thermalization rate:** $aK \leftrightarrow \pi K$ vs. $a\pi \leftrightarrow \pi\pi$



The $aK \leftrightarrow \pi K$ channel begins to account for more than 40% of the total rate at temperatures above 110 MeV, and surpasses the $a\pi \leftrightarrow \pi\pi$ contribution around 130 MeV. The Kaon channels should be considered despite Boltzmann suppression!

➢ **Bounds on f_a** in the KSVZ axion model



The cosmological bound on f_a in the KSVZ axion model is tightened by approximately 30% after $aK \leftrightarrow \pi K$ channel is included.

Summary

➢ The assumption that $a\pi \leftrightarrow \pi\pi$ dominates the hadronic axion thermalization rate below T_c, which has long been adopted in the literature, is not valid.

➢ We calculated the $aK \longrightarrow \pi K$ scattering amplitudes using a coupled-channel unitarization framework that incorporates the relevant resonance dynamics.

➢ The axion thermalization rate from the $aK \leftrightarrow \pi K$ channel becomes comparable to, and eventually exceeds, that from the $a\pi \leftrightarrow \pi\pi$ channel for the temperatures above 110 MeV. The $aK \leftrightarrow \pi K$ channel is therefore non-negligible below the QCD crossover. Including its contribution tightens the HDM bounds on axions by up to 30%.

references

This poster is based on: J. B. Wang, Z. H. Guo and H. Q. Zhou, Phys. Rev. D 112, no.3, L031701 (2025), doi:10.1103/xsvj-g811.

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