QCD Axion-mediated Dark Matter

arXiv:2306.03145 (JHEP 2023)

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UC SANTA CRUZ

Motivation

Neutron EDM is tightly constrained $\rightarrow$ QCD CP-violating θ term $-\theta \frac{\alpha_s}{8\pi} G\tilde{G}$ is small (or zero) $\bar{\theta} \lesssim 10^{-10}$ (strong CP problem).

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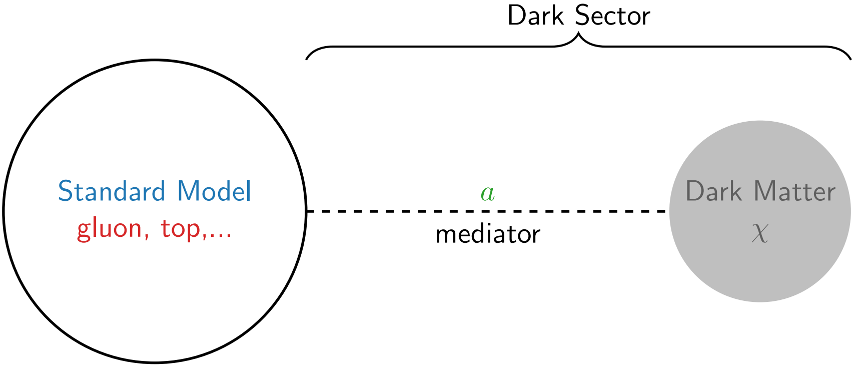
Option 2: QCD axion can be the mediator between DM and SM for smaller 10^9 GeV $\lesssim f_a \lesssim 10^{11}$ GeV.

Minimal Setup



Other studies : 2209.03932 Bharucha et al. (JHEP 2022)
2306.03128 Fitzpatrick et al. (PRD 2023)
2207.02221 Coffey et al. (PRD 2022)

Model

$$\mathcal{L} \supset \frac{c_\chi}{2f_a}\partial_\mu a\bar{\chi}\gamma^\mu\gamma^5\chi + \frac{c_{\psi_i}}{2f_a}\partial_\mu a\bar{\psi}_i\gamma^\mu\gamma^5\psi_i + \frac{c_\gamma}{4f_a}aF_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{\alpha_s}{8\pi}\frac{a}{f_a}G^A_{\mu\nu}\tilde{G}^{A\mu\nu}$$

ψ_i = SM leptons (e) and up/down-type quarks (u/d).

c_χ : axion-DM coupling.

$c_{\psi_i} = c_e, c_u, c_d$ (axion-matter couplings).

c_γ : axion-photon coupling.

$g_{a\chi} \equiv \frac{c_\chi m_\chi}{f_a}$, m_χ and f_a $\rightarrow$ parameters of the model.

DFSZ : SM matter-axion couplings depend on an angle β.
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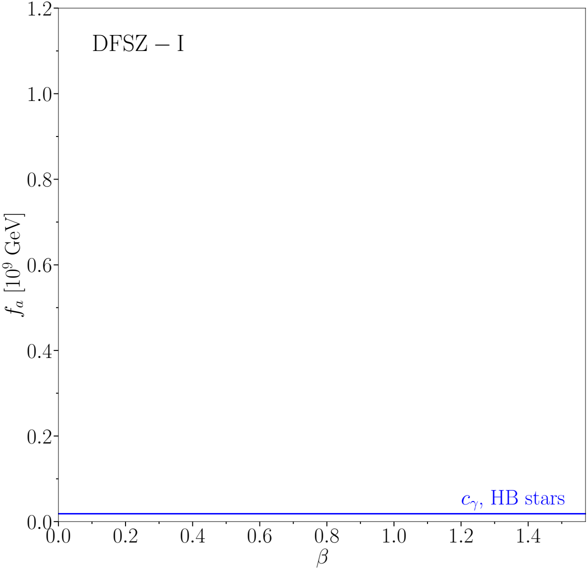
Axions → additional cooling of stars → constrain axion couplings.



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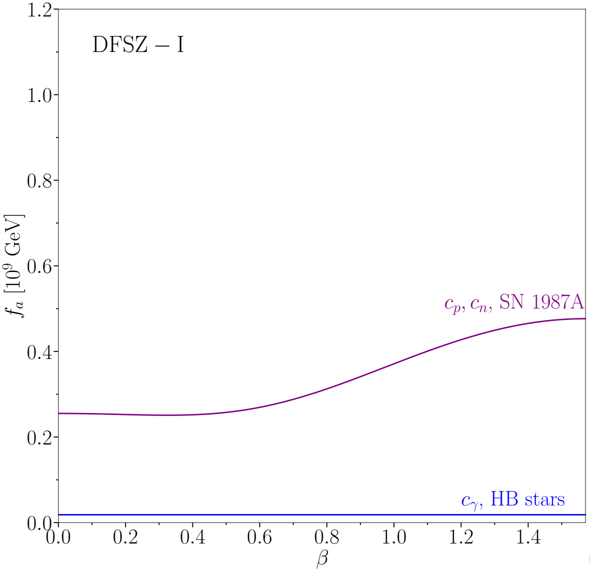

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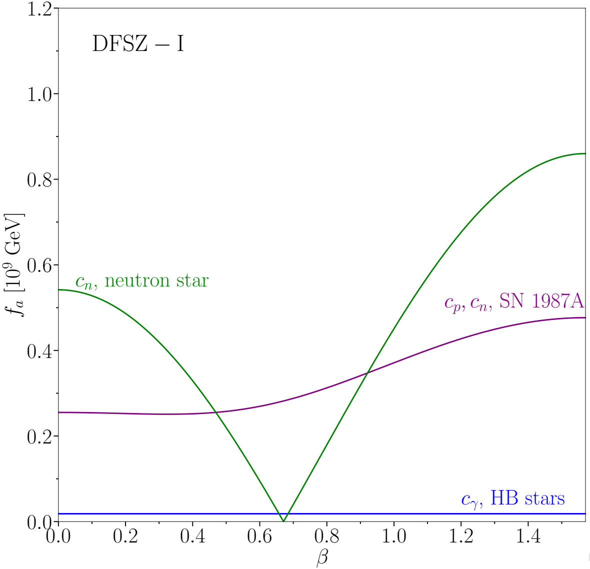

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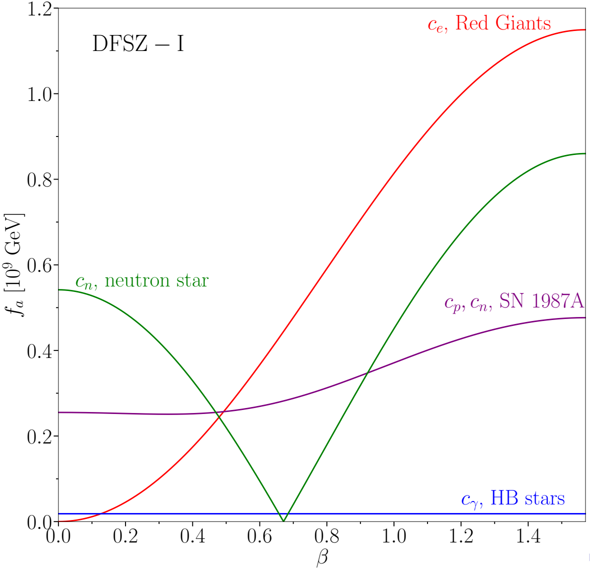

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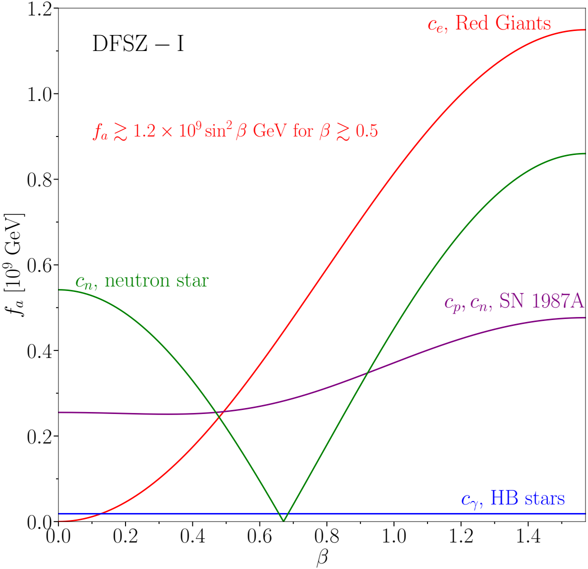
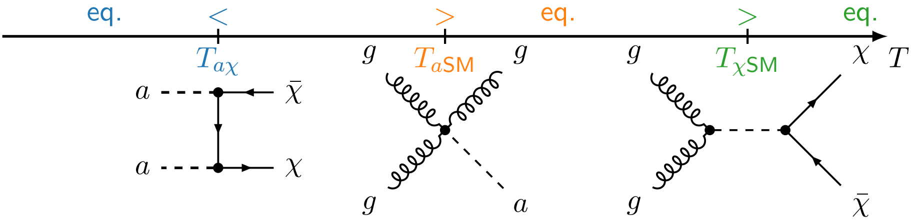


Thermalization I

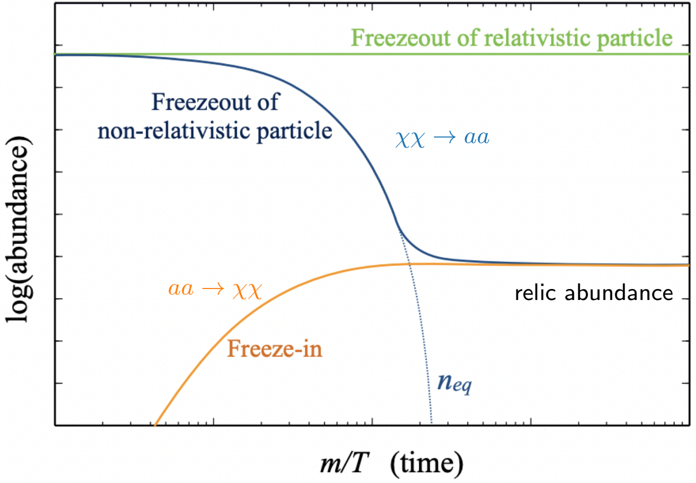


three possible hierarchies: $T_{a\chi} \ll T_{a\mathrm{SM}} \ll T_{\chi\mathrm{SM}}$ (as shown), $T_{a\mathrm{SM}} \ll T_{a\chi} \ll T_{\chi\mathrm{SM}}$, and $T_{a\mathrm{SM}} \ll T_{\chi\mathrm{SM}} \ll T_{a\chi}$ depending on the size of $g_{a\chi}$ and f_a.

$+$ reheat temperature T_{RH} $\rightarrow$ cosmological history $\rightarrow$ dominant production mechanism.

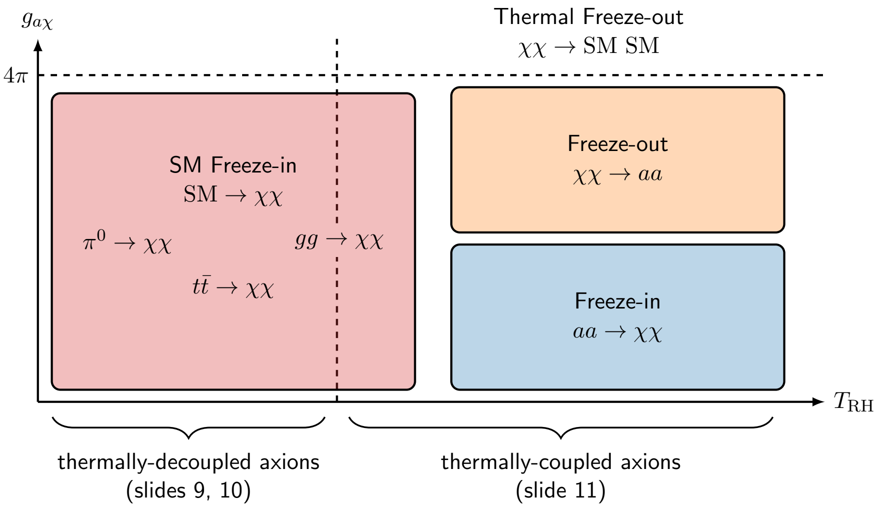
Pedestrian's guide to DM production

T. Lin arXiv 1904.07915



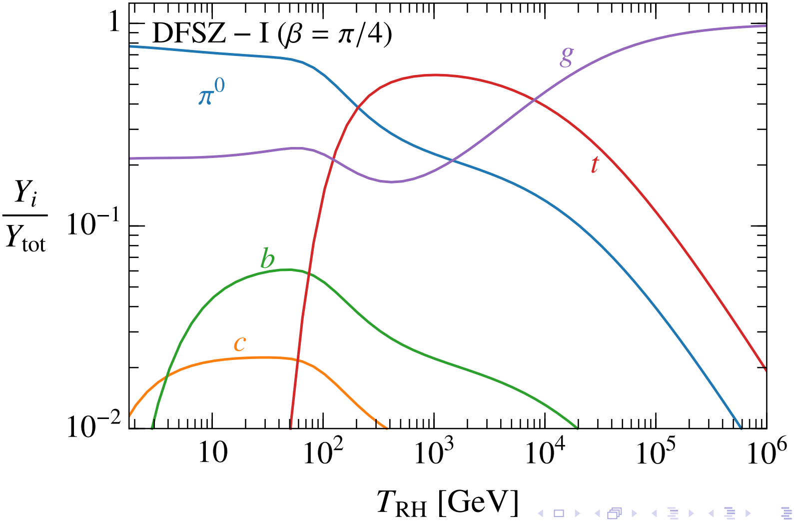
A Bird's Eye view

arXiv:2306.03145 (Dror, Gori and Munbodh)



Thermally decoupled axions I

$T_{\mathrm{RH}} < T_{a\mathrm{SM}}$. Freeze-in : $\pi^0 \to \chi\chi$, $gg \to \chi\chi$, $t\bar{t} \to \chi\chi \ldots$



Thermally decoupled axions II

$T_{\mathsf{RH}} < T_{a\mathsf{SM}}$

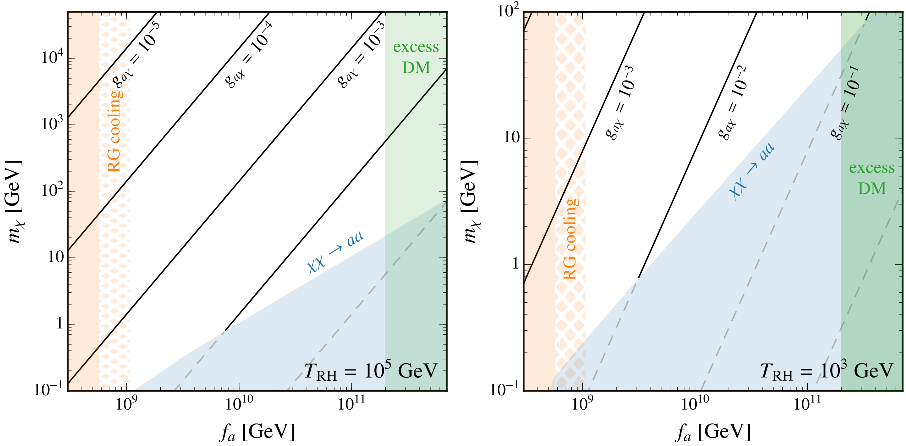
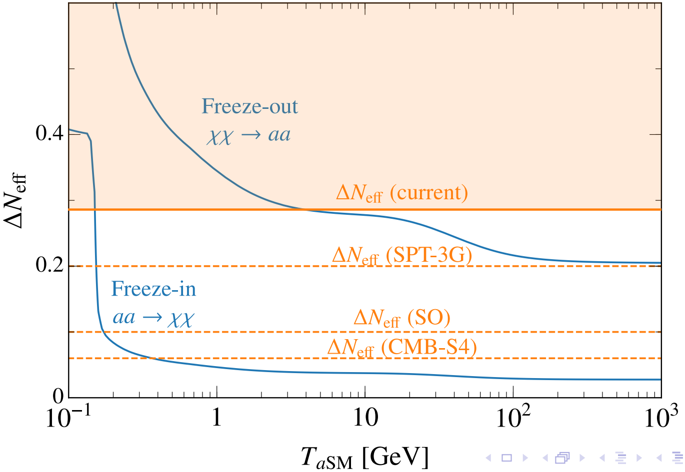


Figure: LEFT : $gg \to \chi\chi$, RIGHT: $gg \to \chi\chi$, $tt \to \chi\chi$

Thermally coupled axions I

$T_{\rm RH} > T_{a\rm SM}$
Dark Sector decouples from SM at $T_{a\rm SM}$ → Dark radiation → change from SM prediction $N_{\rm eff} = 3.044$.



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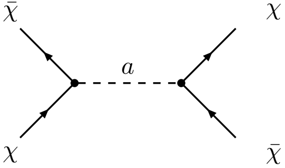
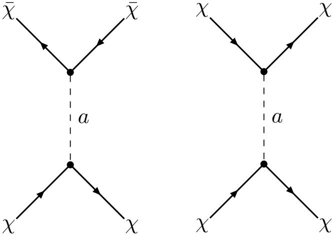
Future studies of out-of-equilibrium dynamics :

- interplay of $\chi\chi \rightarrow aa$ with SM $\rightarrow \chi\chi$ (blue region on slide 10).
- Out-of-equilibrium collisions of the axions $aa \rightarrow \chi\chi$ frozen-in from SM $\rightarrow$ SM a (Sequential Freeze-in).

Backup Slide I : Experimental Constraints II (SIDM)





Self-interacting DM

Transfer

$$\sigma_T = \int d\Omega \, \frac{d\sigma_{\mathsf{SIDM}}}{d\Omega} (1 - \cos\theta) \lesssim 1 \frac{\mathsf{cm}^2}{\mathsf{g}} \, ,$$

$$\Rightarrow g_{a\chi} \lesssim 0.21 \left(\frac{m_\chi}{1 \ \mathsf{MeV}} \right)^{\frac{3}{4}} \, .$$

Freeze-out (secluded) $\chi\bar{\chi} \to aa$.
Hierarchy : $T_{\text{RH}} \gtrsim T_{\chi\text{SM}}$ or $T_{a\chi} \gtrsim T_{\text{RH}} \gtrsim T_{a\text{SM}}$.
For $m_\chi \sim 10$ GeV, $g_{a\chi} \sim 0.1$.

Freeze-in $aa \to \bar{\chi}\chi$.
Hierarchy : $T_{a\text{SM}} \lesssim T_{\text{RH}} \lesssim T_{\chi\text{SM}}$ and $T_{\text{RH}} \gtrsim T_{a\chi}$
$g_{a\chi}$ can be in its natural regime m_χ/f_a for weak-scale m_χ.