

# QCD Axion-mediated Dark Matter

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UC SANTA CRUZ

# Motivation

Neutron EDM is tightly constrained  $\rightarrow$  QCD CP-violating  $\theta$  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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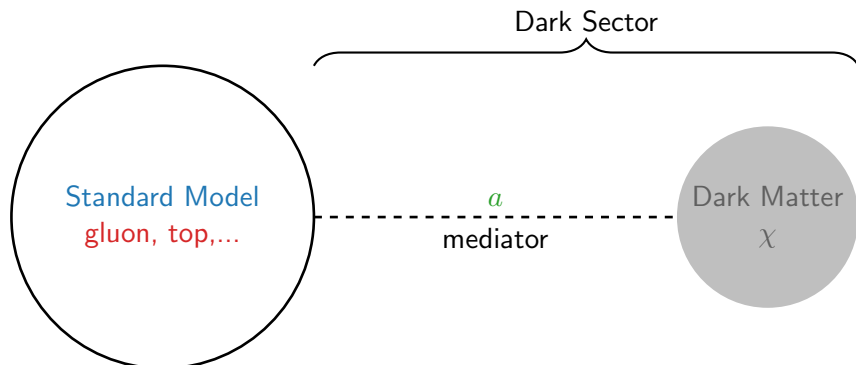
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**Option 2:** QCD axion can be the mediator between DM and SM for smaller  $10^9$  GeV  $\lesssim f_a \lesssim 10^{11}$  GeV.

# 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

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

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

$c_\chi$  : axion-DM coupling.

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

$c_\gamma$  : axion-photon coupling.

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

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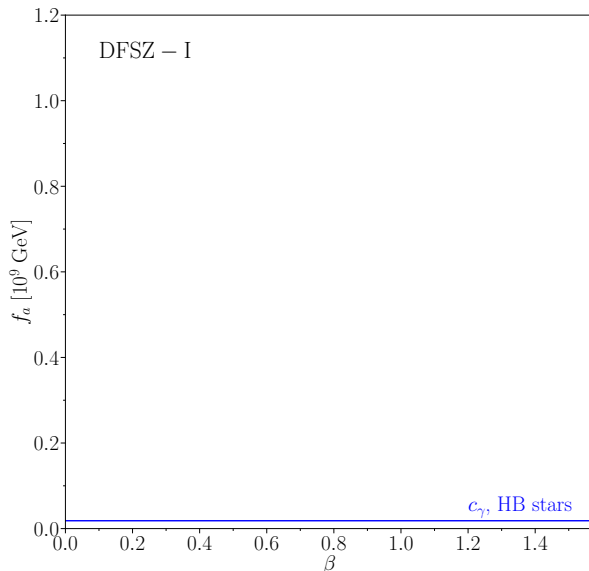
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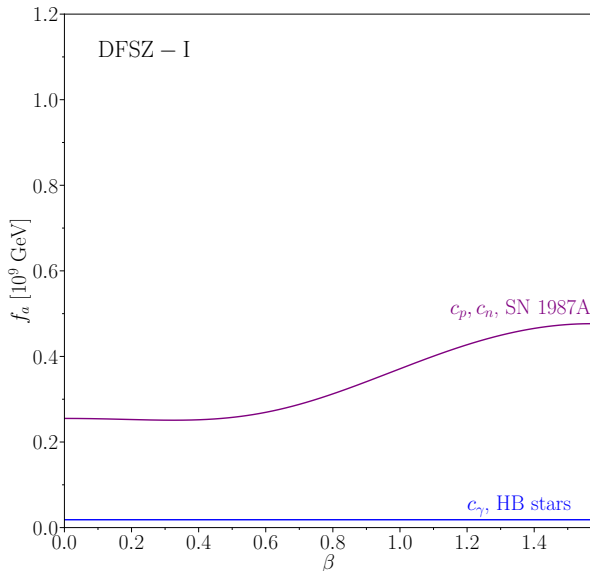
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Axions  $\rightarrow$  additional cooling of stars  $\rightarrow$  constrain axion couplings.



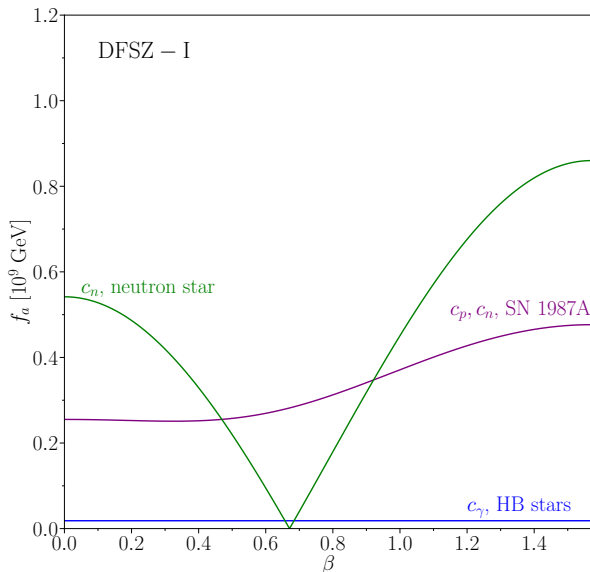
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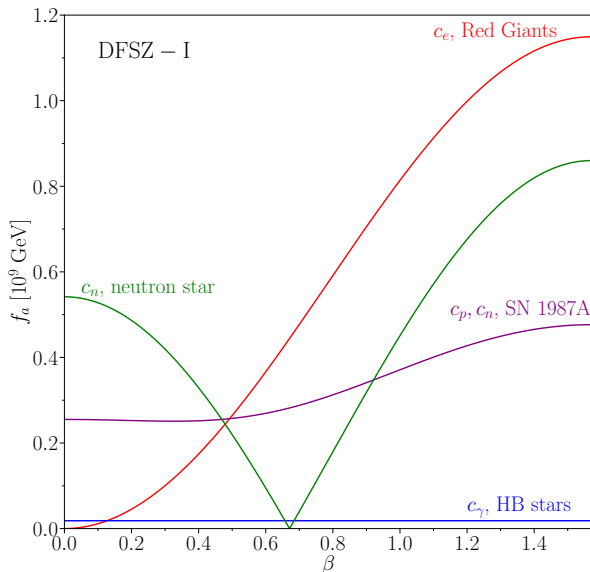
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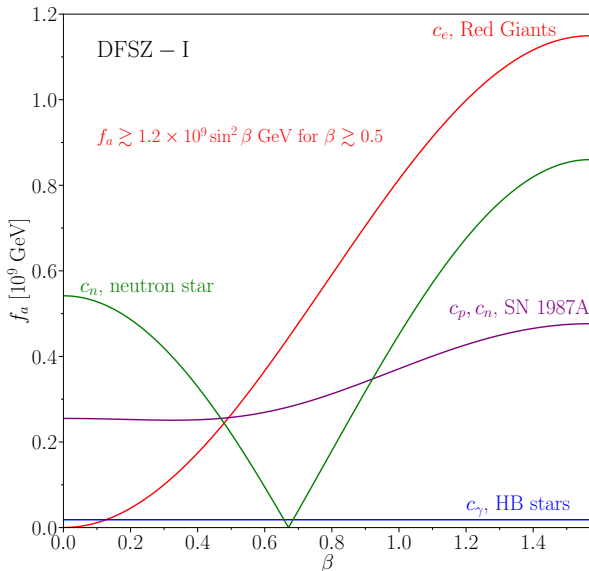
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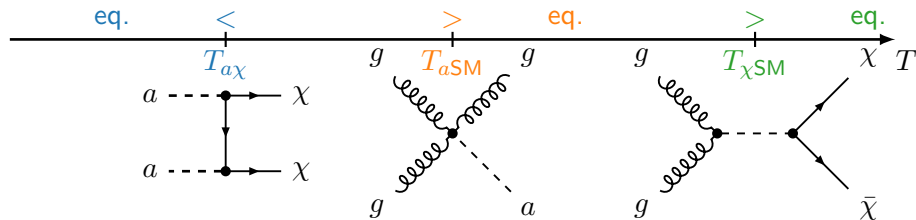


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# Thermalization I



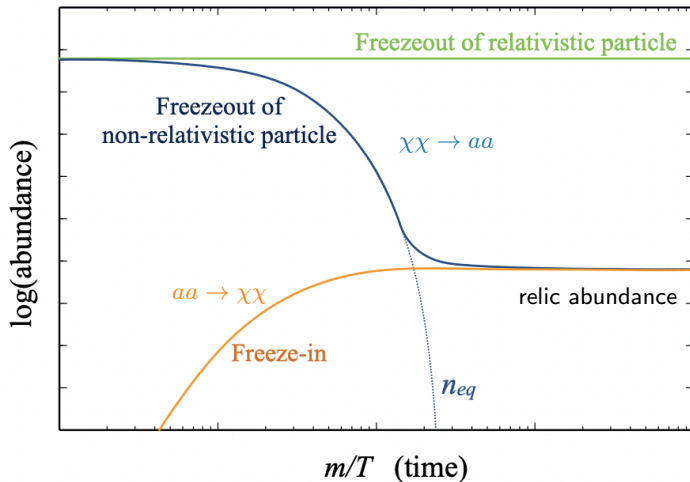
three possible hierarchies:  $T_{a\chi} \ll T_{aSM} \ll T_{\chi SM}$  (as shown),  
 $T_{aSM} \ll T_{a\chi} \ll T_{\chi SM}$ , and  $T_{aSM} \ll T_{\chi SM} \ll T_{a\chi}$  depending on the size of  
 $g_{a\chi}$  and  $f_a$ .

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



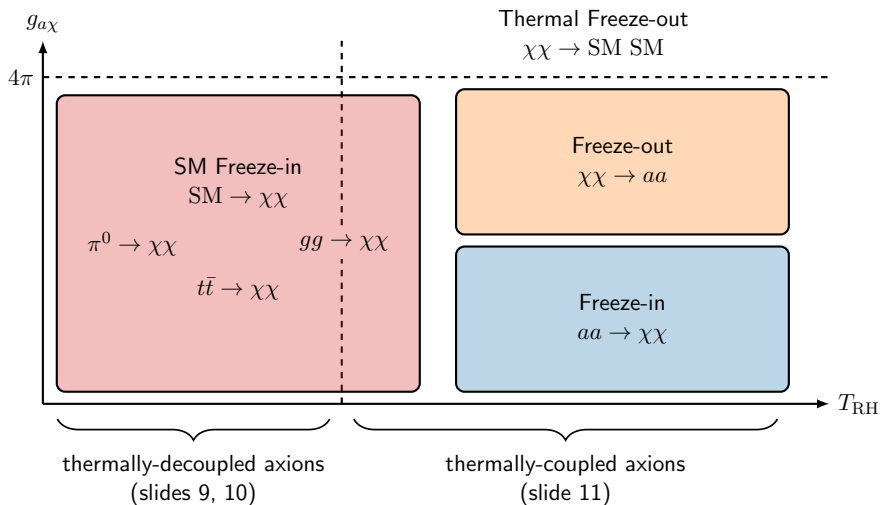
# Pedestrian's guide to DM production

T. Lin arXiv 1904.07915



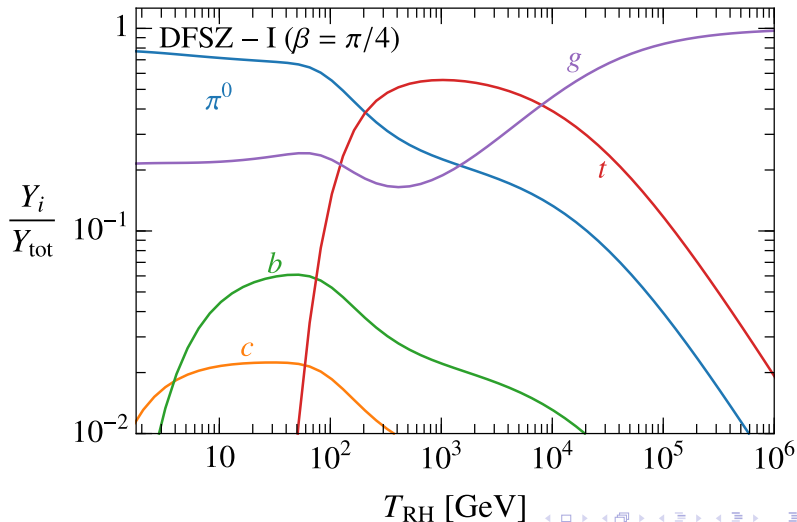
# A Bird's Eye view

arXiv:2306.03145 (Dror, Gori and Munbodh)



# Thermally decoupled axions I

$T_{RH} < T_{aSM}$ . Freeze-in :  $\pi^0 \rightarrow \chi\chi$ ,  $gg \rightarrow \chi\chi$ ,  $t\bar{t} \rightarrow \chi\chi \dots$



# Thermally decoupled axions II

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

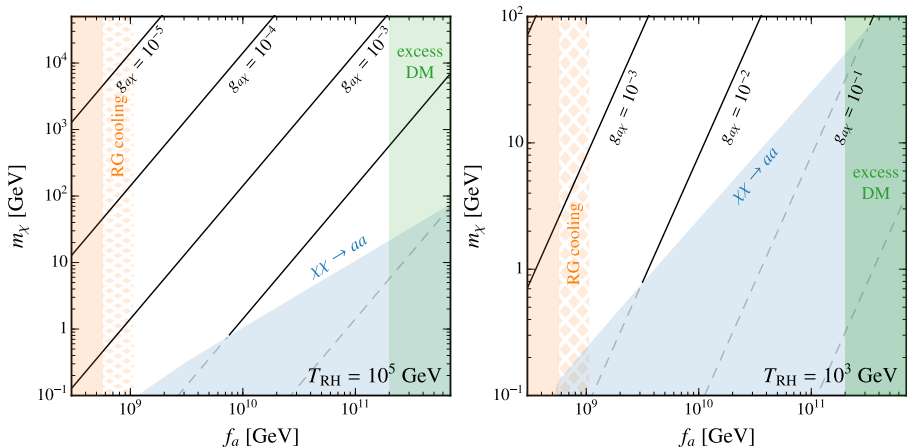
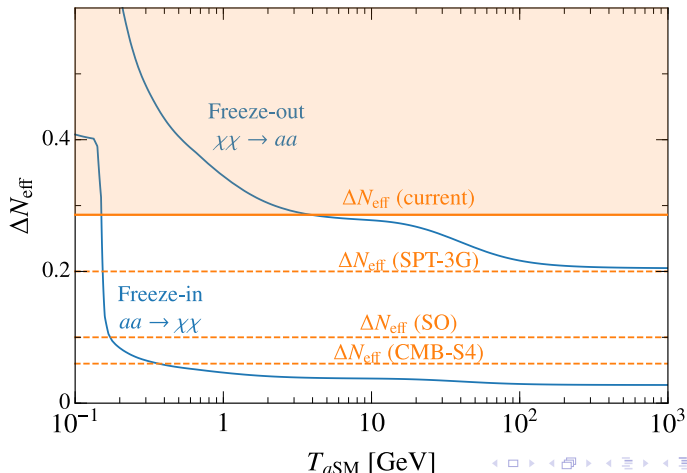


Figure: LEFT :  $gg \rightarrow \chi\chi$  , RIGHT:  $gg \rightarrow \chi\chi, t\bar{t} \rightarrow \chi\chi$

# Thermally coupled axions I

$$T_{\text{RH}} > T_{a\text{SM}}$$

Dark Sector decouples from SM at  $T_{a\text{SM}} \rightarrow$  Dark radiation  $\rightarrow$  change from SM prediction  $N_{\text{eff}} = 3.044$ .



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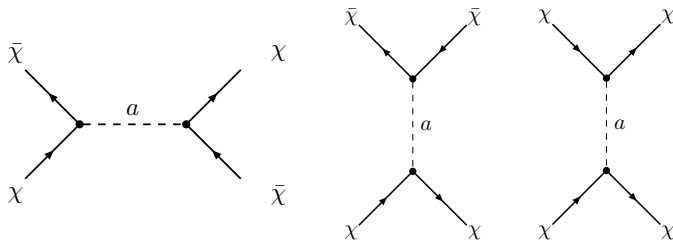
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- interplay of  $\chi\chi \rightarrow aa$  with SM  $\rightarrow \chi\chi$  (blue region on slide 10).
- Out-of-equilibrium collisions of the axions  $aa \rightarrow \chi\chi$  frozen-in from SM  $\rightarrow$  SM  $a$  (Sequential Freeze-in).

# Backup Slide I : Experimental Constraints II (SIDM)



Self-interacting DM

Transfer

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

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

## Backup slide II : Thermally coupled axions I

Freeze-out (secluded)  $\chi\bar{\chi} \rightarrow aa$ .

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  $aa \rightarrow \bar{\chi}\chi$ .

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  $m_\chi/f_a$  for weak-scale  $m_\chi$ .