Dark Matter and Axion Quality from the Axion-Higgs Portal

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Outline

1. The model
2. Constraints from collider physics
3. Dark Matter
4. Strong CP problem & axion quality

The Model

Axion Couplings

The Axion-Higgs Portal

A simple UV Completion

Axion Couplings

$a \xrightarrow{X} a + f_a \alpha$

- Axion = Goldstone boson of a spontaneously broken global symmetry X

	Higgs Boson	Fermions	Gauge bosons	Higgs Boson (again)
coupling	$\frac{\partial_\mu a}{f_a} H^\dagger i \overleftrightarrow{D}^\mu H$	$\frac{\partial_\mu a}{f_a} \bar{f} \gamma^\mu \gamma_5 f$	$\frac{\alpha_G}{8\pi} \left(\frac{a}{f_a} + \theta_G \right) G \tilde{G}$	$\frac{(\partial_\mu a)^2}{f_a^2} H^\dagger H$
UV explanation	Higgs Boson charged under X	Fermion charged under X	Chiral Anomaly of X with the Gauge Group G	Generic mixing Heavy Scalar/Higgs

The Axion-Higgs Portal

Derivative suppression

Z_2 symmetry $a \to -a$

$$\mathscr{L} \supset -\frac{c_a}{f_a}\frac{1}{v}(\partial_\mu a)^2 H^\dagger H$$

Only 2 parameters $\left(\frac{c_a}{f_a}, m_a\right)$

A Simple UV Completion

$$\mathscr{L} = \mathscr{L}_{\rm SM} + (\partial_\mu S)^\dagger(\partial^\mu S) + \mu_S^2 S^\dagger S - \lambda_S (S^\dagger S)^2 + g(S^\dagger S)H^\dagger H$$

A Simple UV Completion

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1. SSB $S = \frac{f_a + s}{\sqrt{2}} e^{ia/f_a}$ $\Rightarrow$ $$\mathscr{L} \supset \frac{1}{2f_a^2}(f_a+s)^2(\partial_\mu a)^2 - \frac{m_s^2}{2}s^2 - \frac{m_h^2}{2}h^2 - g v_s v_h s h$$

2. Mass diagonalization $\begin{pmatrix} s \\ h \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \tilde{s} \\ \tilde{h} \end{pmatrix}$ with $\tan 2\theta = \frac{2 g v_s v_h}{m_s^2 - m_h^2}$

   SM Higgs Boson

3. Integrate out $\tilde{s}$ $\Rightarrow$ $\mathscr{L} \supset \frac{1}{2f_a^2}(f_a + \sin\theta \tilde{h})^2(\partial_\mu a)^2 \supset -\frac{\sin\theta}{f_a}\tilde{h}(\partial_\mu a)^2 \subset -\frac{\sin\theta}{f_a}\frac{1}{v}\tilde{H}^\dagger\tilde{H}(\partial_\mu a)^2$

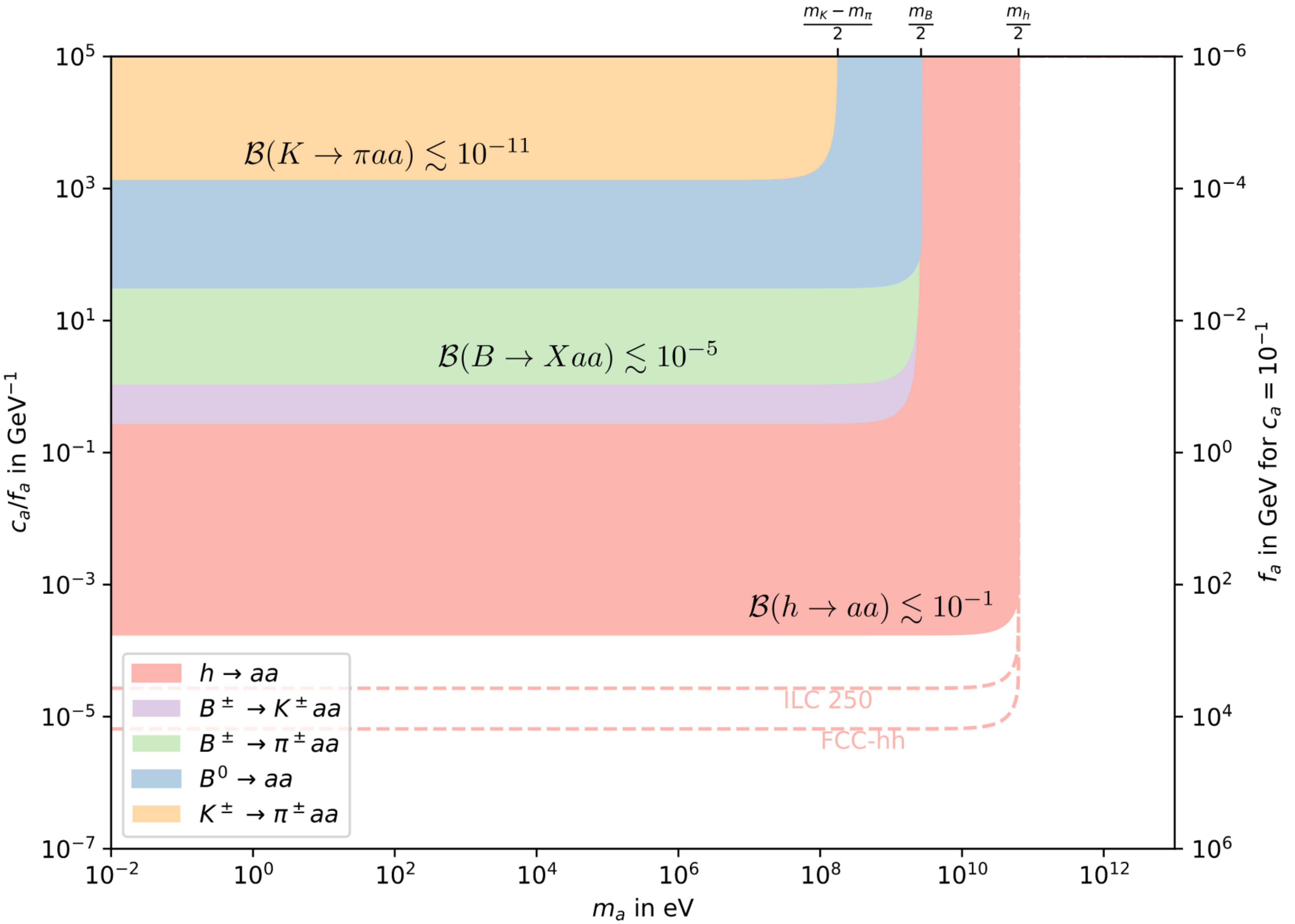
$\Rightarrow c_a = \sin\theta \lesssim 0.3$ is a small parameter

Phenomenology

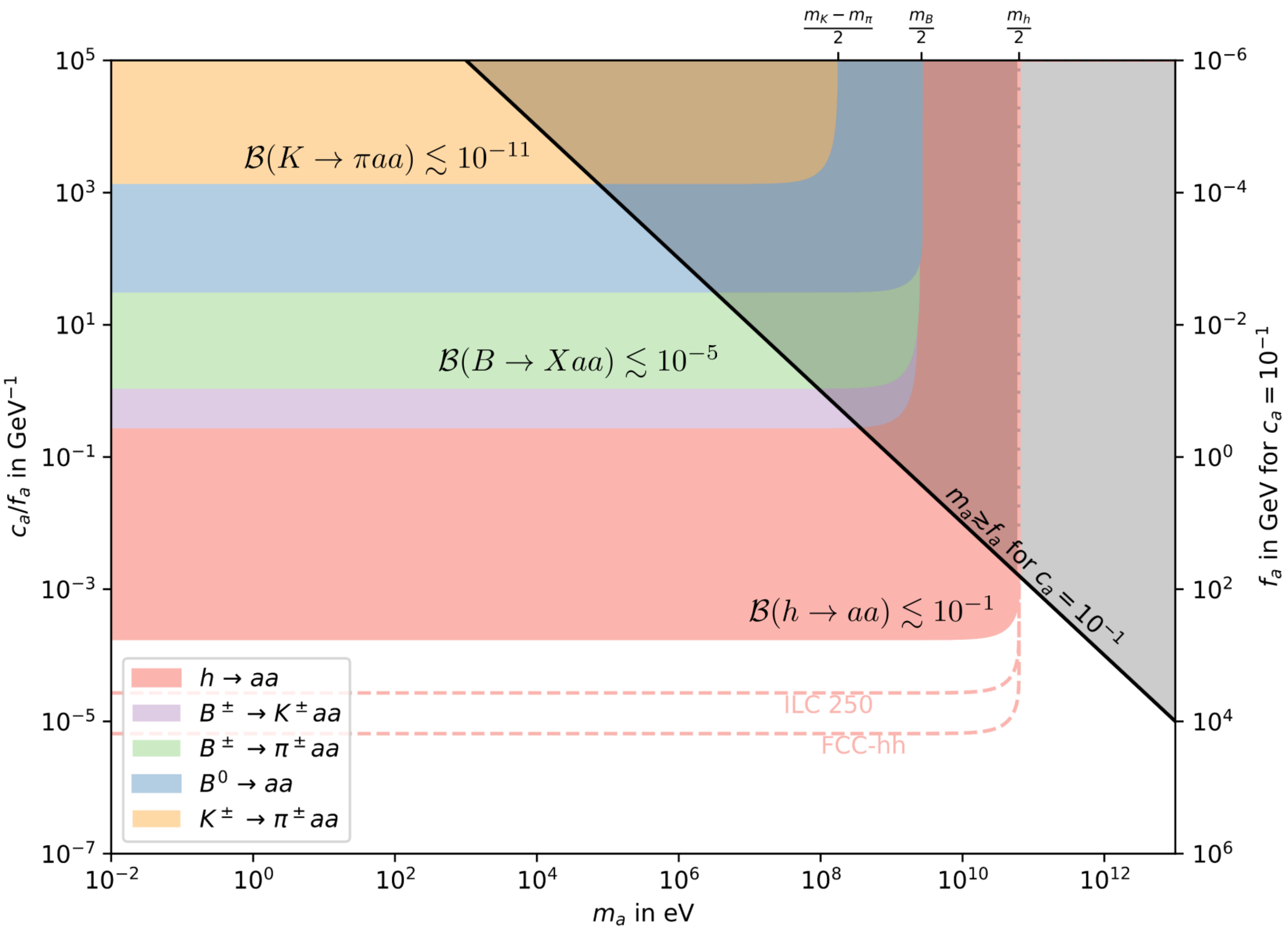
Collider Constraints

Dark Matter

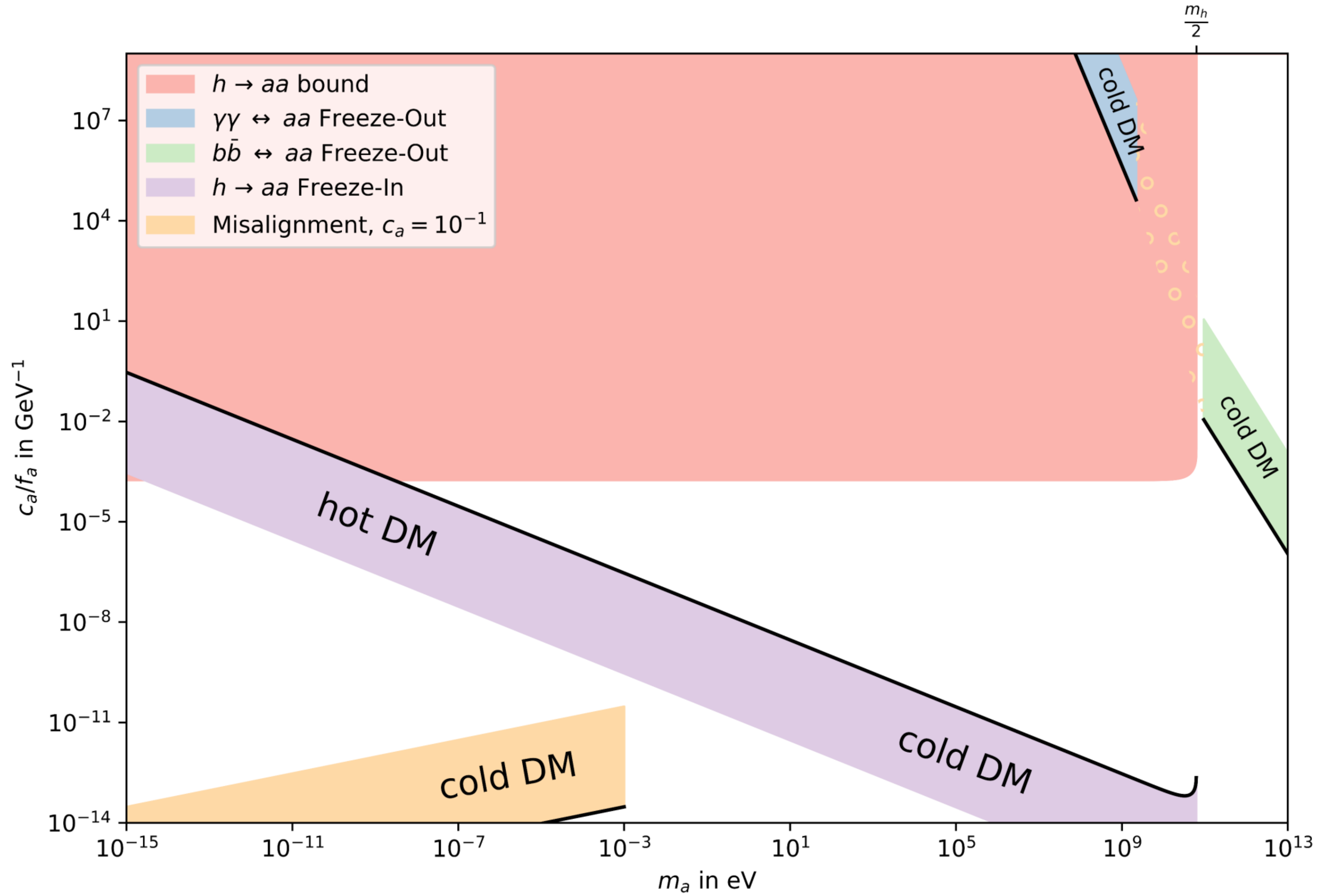
Constraints from Collider Experiments



Constraints from Collider Experiments



Dark Matter



$h \to aa$ bound
$\gamma\gamma \leftrightarrow aa$ Freeze-Out
$b\bar{b} \leftrightarrow aa$ Freeze-Out
$h \to aa$ Freeze-In
Misalignment, $c_a = 10^{-1}$
hot DM
cold DM
cold DM
cold DM
cold DM
$\frac{m_h}{2}$
c_a/f_a in GeV^{-1}
m_a in eV
10^{7}
10^{4}
10^{1}
10^{-2}
10^{-5}
10^{-8}
10^{-11}
10^{-14}
10^{-15}
10^{-11}
10^{-7}
10^{-3}
10^{1}
10^{5}
10^{9}
10^{13}

Strong CP Problem & Axion Quality

strong CP problem: $\theta_c \lesssim 10^{-10}$

Axion Potential

Axion Quality Problem

The Case of the Axion-Higgs Portal

$\underbrace{\qquad\qquad\qquad\qquad}_{\text{QCD axion}}$

QCD Axion Potential

- QCD Axion potential:

$$V_S = \overbrace{-\mu^2 S^\dagger S + \lambda (S^\dagger S)^2}^{\text{SSB}} + \overbrace{V_{\text{QCD}}}^{V_a}$$

non-perturbative
QCD effects

$\langle \theta_{\text{eff}} \rangle = 0$

$$V_{\text{QCD}} \simeq -\Lambda^4_{\text{QCD}} \cos\left(\underbrace{\frac{a}{f_a} + \theta_c}_{=\theta_{\text{eff}}}\right)$$

from $\mathscr{L} \supset \frac{\alpha_c}{8\pi}\left(\frac{a}{f_a} + \theta_c\right) G\tilde{G}$

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- Expect every global symmetry to be explicitly broken at high energy scales

QCD Axion Potential

- QCD Axion potential:

$$V_S = \overbrace{-\mu^2 S^\dagger S + \lambda (S^\dagger S)^2}^{\text{SSB}} + \overbrace{V_{\text{QCD}} + V_{U(1)}}^{V_a}$$

$S = \frac{f_a}{\sqrt{2}} e^{ia/f_a}$

non-perturbative QCD effects

explicit U(1) breaking

$\langle \theta_{\text{eff}} \rangle = 0$

$\langle \theta_{\text{eff}} \rangle = n\theta_c \sim 1$

$$V_{\text{QCD}} \simeq -\Lambda_{\text{QCD}}^4 \cos\Big(\underbrace{\frac{a}{f_a} + \theta_c}_{=\theta_{\text{eff}}}\Big)$$

$$V_{U(1)} = -\sum_n \frac{c_n}{\Lambda_{U(1)}^{n-4}} S^n + \text{h.c.} \simeq -\sum_n c_n \frac{f_a^n}{\Lambda_{U(1)}^{n-4}} \cos\left(n\frac{a}{f_a}\right)$$

from $\mathscr{L} \supset \frac{\alpha_c}{8\pi}\left(\frac{a}{f_a} + \theta_c\right) G\tilde{G}$

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$\langle \theta_{\text{eff}} \rangle = n\theta_c \sim 1$

$$V_{U(1)} = -\sum_n \frac{c_n}{\Lambda^{n-4}_{U(1)}} S^n + \text{h.c.} \simeq -\sum_n c_n \frac{f_a^n}{\Lambda^{n-4}_{U(1)}} \cos\left(n\frac{a}{f_a}\right)$$

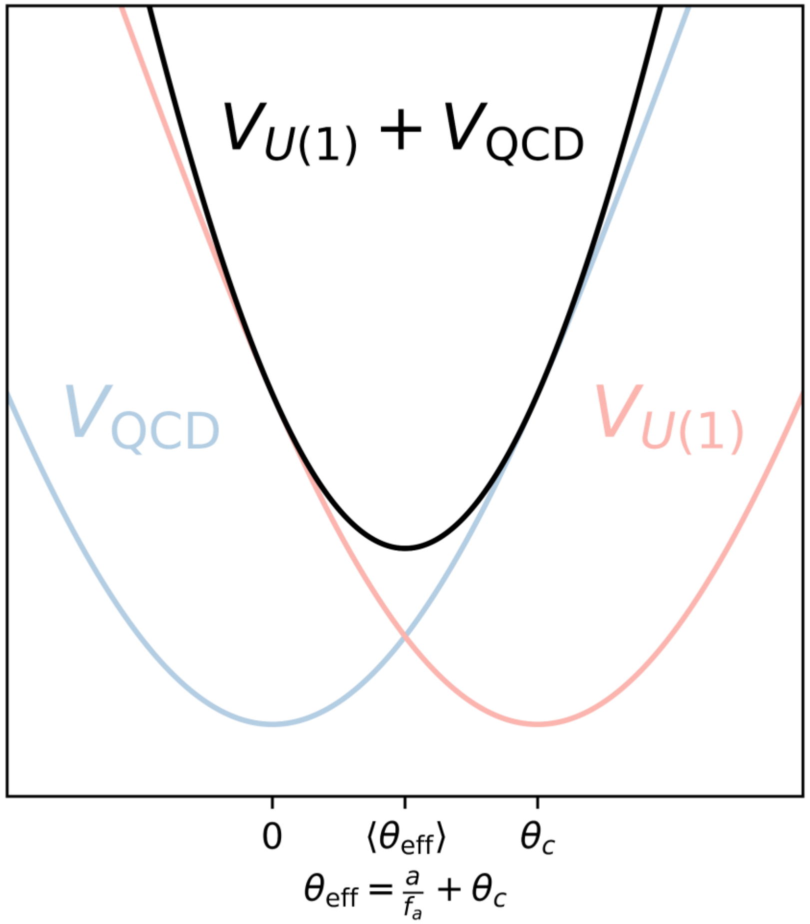
$$= n \text{ odd} - c_2 \Lambda^2_{U(1)} S^2 - c_4 \Lambda^0_{U(1)} S^4 - \frac{c_6}{\Lambda^2_{U(1)}} S^6 + \cdots + \text{h.c.}$$

$c_n \ll 1$ $\quad c_2 \lll 1$ $\quad c_4 \lll 1$ $\quad c_6 \sim 1$ $\quad c_n \sim 1$

- Expect every global symmetry to be explicitly broken at high energy scales

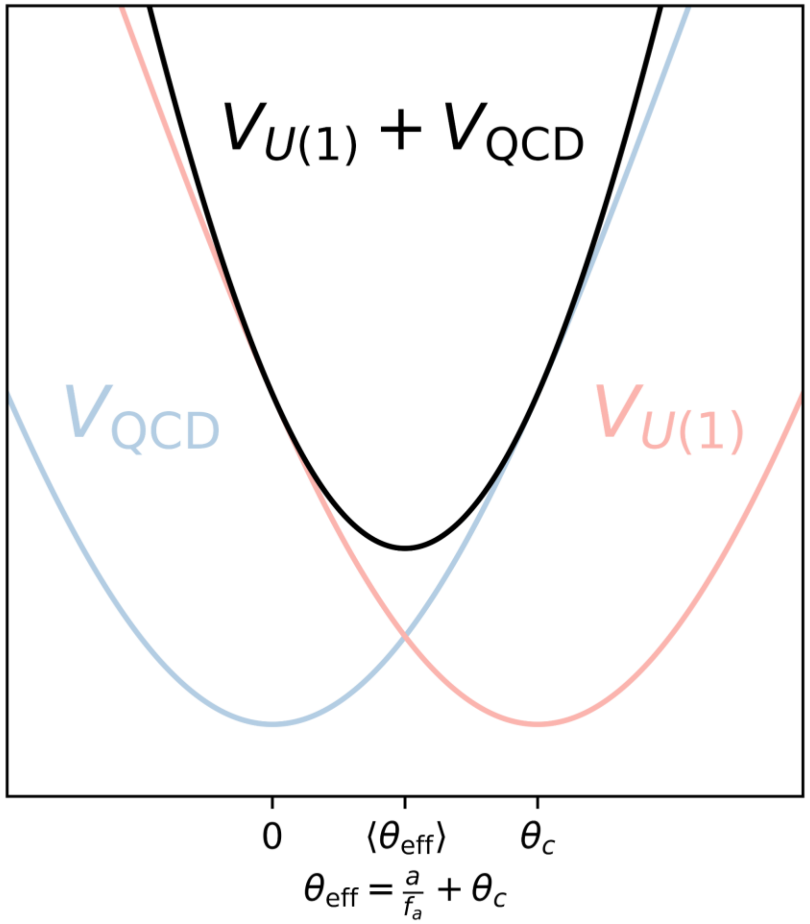
QCD Axion Quality Problem

$$V_a = \underbrace{-\Lambda_{\rm QCD}^4 \cos\theta_{\rm eff}}_{V_{\rm QCD}} \underbrace{- c_n \frac{f_a^n}{\Lambda_{U(1)}^{n-4}} \cos\Big(n(\theta_{\rm eff} - \theta_c)\Big)}_{V_{U(1)}}$$



QCD Axion Quality Problem

$$V_a = \underbrace{-\Lambda^4_{\mathrm{QCD}} \cos\theta_{\mathrm{eff}}}_{V_{\mathrm{QCD}}} \underbrace{- c_n \frac{f_a^n}{\Lambda^{n-4}_{U(1)}} \cos\left(n(\theta_{\mathrm{eff}} - \theta_c)\right)}_{V_{U(1)}}$$



- Minimize V_a to find $\langle\theta_{\mathrm{eff}}\rangle$

$$0 \stackrel{!}{=} \frac{\partial V_a}{\partial \theta_{\mathrm{eff}}} \simeq \Lambda^4_{\mathrm{QCD}} \sin\theta_{\mathrm{eff}} + c_n \frac{f_a^n}{\Lambda^{n-4}_{U(1)}} n \sin\left(n(\theta_{\mathrm{eff}} - \theta_c)\right)$$

$$\stackrel{\theta_{\mathrm{eff}} \ll 1}{\simeq} \Lambda^4_{\mathrm{QCD}} \theta_{\mathrm{eff}} - c_n \frac{f_a^n}{\Lambda^{n-4}_{U(1)}} n \sin n\theta_c$$

$$\boxed{\langle\theta_{\mathrm{eff}}\rangle \simeq c_n \left(\frac{f_a}{\Lambda_{\mathrm{QCD}}}\right)^4 \left(\frac{f_a}{\Lambda_{U(1)}}\right)^{n-4} n \sin n\theta_c}$$

- Experimentally: $\langle\theta_{\mathrm{eff}}\rangle \lesssim 10^{-10}$, $f_a \gtrsim 10^{10}\mathrm{GeV}$

$\Lambda_{U(1)} \sim m_P$

$n \sin n\theta_c \sim 1$

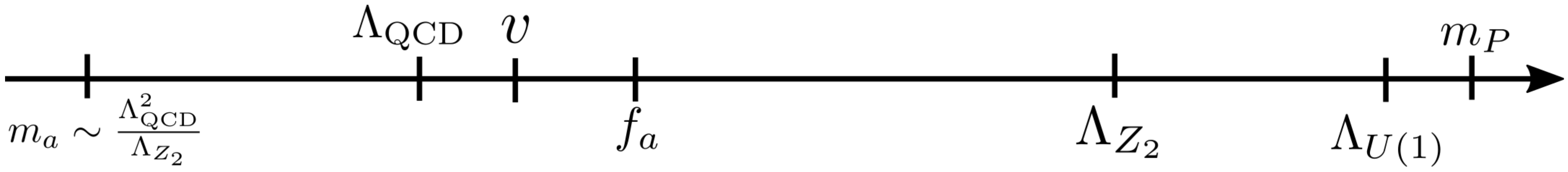
Leading n	6	8	10	12
$c_n \lesssim$	10^{-38}	10^{-22}	10^{-6}	10^{10}

QCD axion quality problem

The Case of the Axion-Higgs Portal

- All possible QCD axion couplings generated by explicit Z_2 breaking at scale $\Lambda_{Z_2} \gtrsim 10^{10}\mathrm{GeV}$

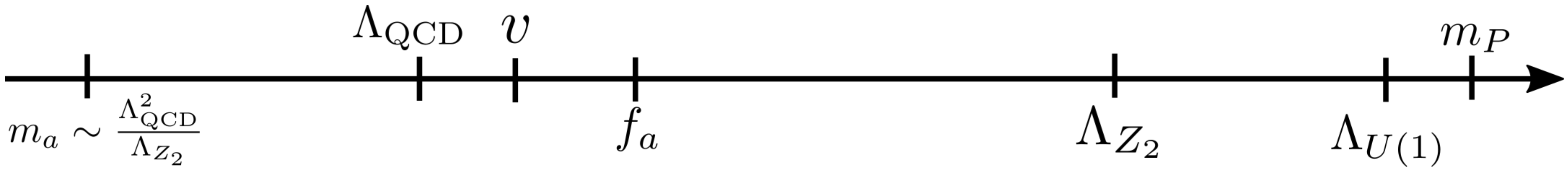
$$\mathscr{L} \supset \frac{\alpha_c}{8\pi}\left(\frac{a}{\Lambda_{Z_2}} + \theta_c\right)G\tilde{G} + C_\gamma \frac{\alpha_Q}{8\pi}\frac{a}{\Lambda_{Z_2}}F\tilde{F} + \frac{\partial_\mu a}{\Lambda_{Z_2}}\bar{f}C_f\gamma^\mu\gamma_5 f$$



The Case of the Axion-Higgs Portal

- All possible QCD axion couplings generated by explicit Z_2 breaking at scale $\Lambda_{Z_2} \gtrsim 10^{10}\mathrm{GeV}$

$$\mathscr{L} \supset \frac{\alpha_c}{8\pi}\left(\frac{a}{\Lambda_{Z_2}} + \theta_c\right) G\tilde{G} + C_\gamma \frac{\alpha_Q}{8\pi}\frac{a}{\Lambda_{Z_2}} F\tilde{F} + \frac{\partial_\mu a}{\Lambda_{Z_2}} \bar{f} C_f \gamma^\mu \gamma_5 f$$



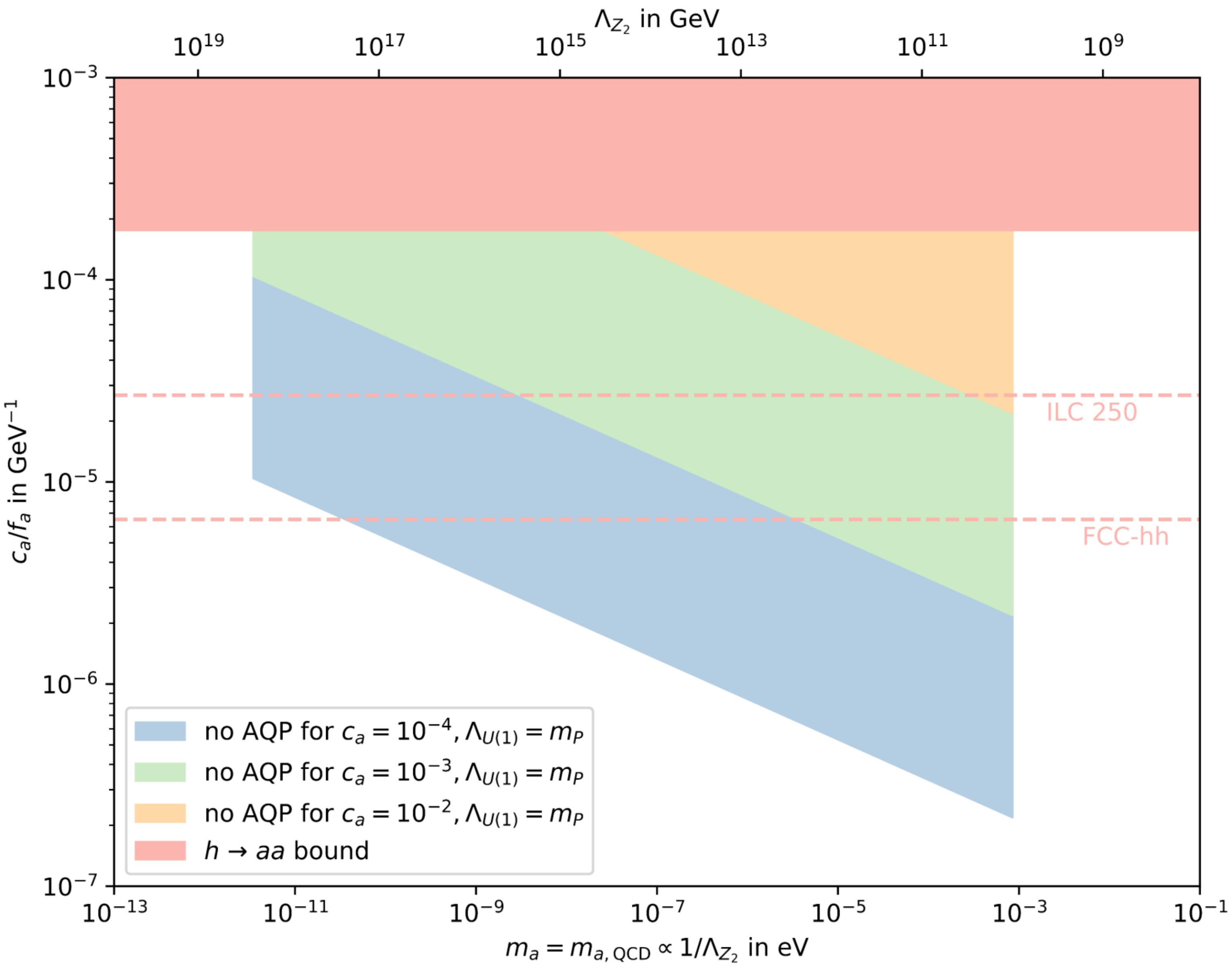
- Same calculation as before leads to

$$\langle\theta_{\mathrm{eff}}\rangle \simeq c_n \frac{\Lambda_{Z_2}}{f_a}\left(\frac{f_a}{\Lambda_{\mathrm{QCD}}}\right)^4 \left(\frac{f_a}{\Lambda_{U(1)}}\right)^{n-4} n \sin n\theta_c$$

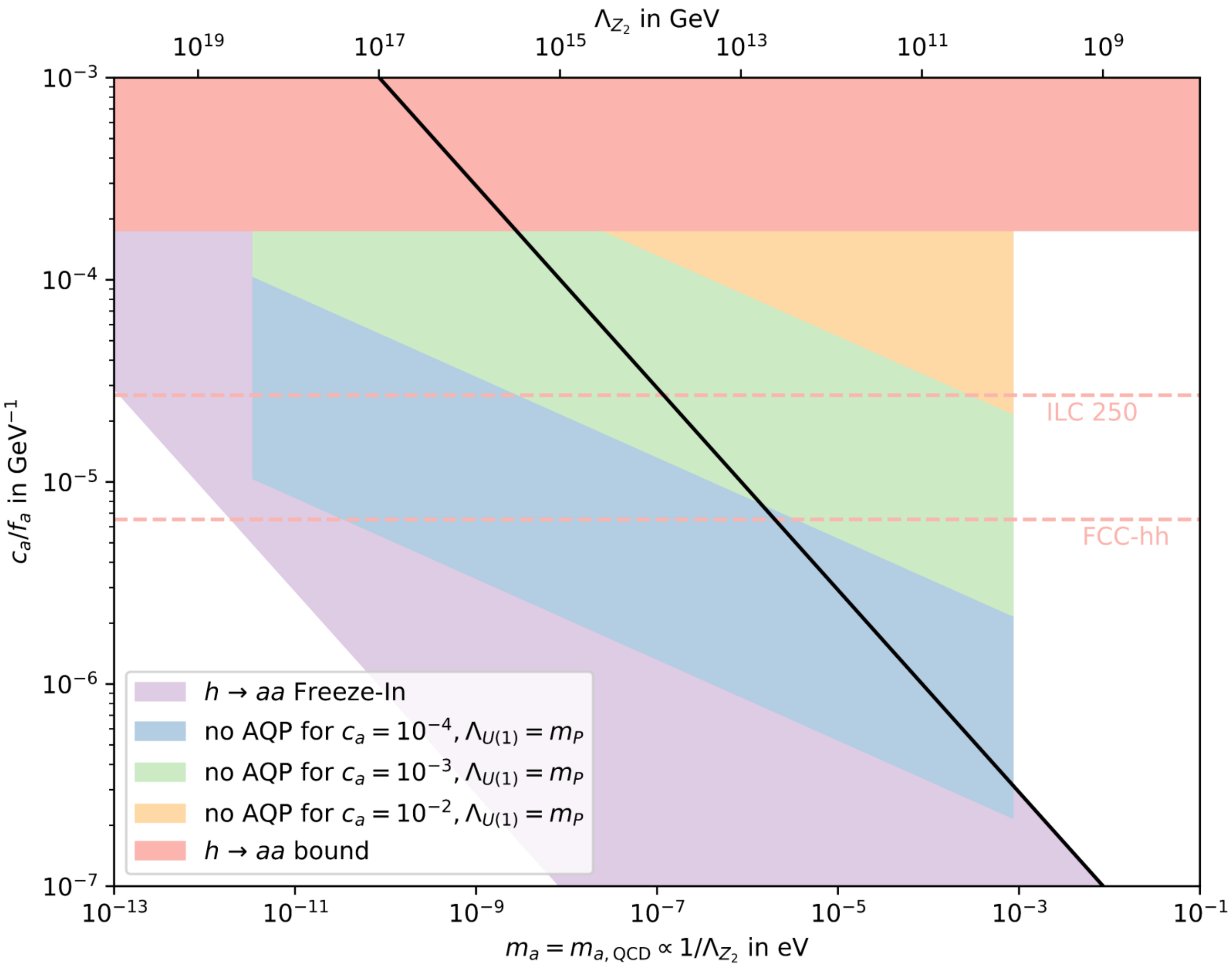
For $f_a \sim 10^2\mathrm{GeV}, \Lambda_{Z_2} \sim 10^{10}\mathrm{GeV}$:

Leading n	6	8	10	12
$c_n \lesssim$	10^2	10^{34}	10^{66}	10^{98}

No axion quality problem



Λ_{Z_2} in GeV
10^{19}
10^{17}
10^{15}
10^{13}
10^{11}
10^{9}
c_a/f_a in GeV^{-1}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
ILC 250
FCC-hh
no AQP for $c_a = 10^{-4}, \Lambda_{U(1)} = m_P$
no AQP for $c_a = 10^{-3}, \Lambda_{U(1)} = m_P$
no AQP for $c_a = 10^{-2}, \Lambda_{U(1)} = m_P$
$h \to aa$ bound
10^{-13}
10^{-11}
10^{-9}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
$m_a = m_{a,\mathrm{QCD}} \propto 1/\Lambda_{Z_2}$ in eV



Λ_{Z_2} in GeV
10^{19}
10^{17}
10^{15}
10^{13}
10^{11}
10^{9}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
c_a/f_a in GeV^{-1}
ILC 250
FCC-hh
$h \to aa$ Freeze-In
no AQP for $c_a = 10^{-4}, \Lambda_{U(1)} = m_P$
no AQP for $c_a = 10^{-3}, \Lambda_{U(1)} = m_P$
no AQP for $c_a = 10^{-2}, \Lambda_{U(1)} = m_P$
$h \to aa$ bound
10^{-13}
10^{-11}
10^{-9}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
$m_a = m_{a,\,\mathrm{QCD}} \propto 1/\Lambda_{Z_2}$ in eV

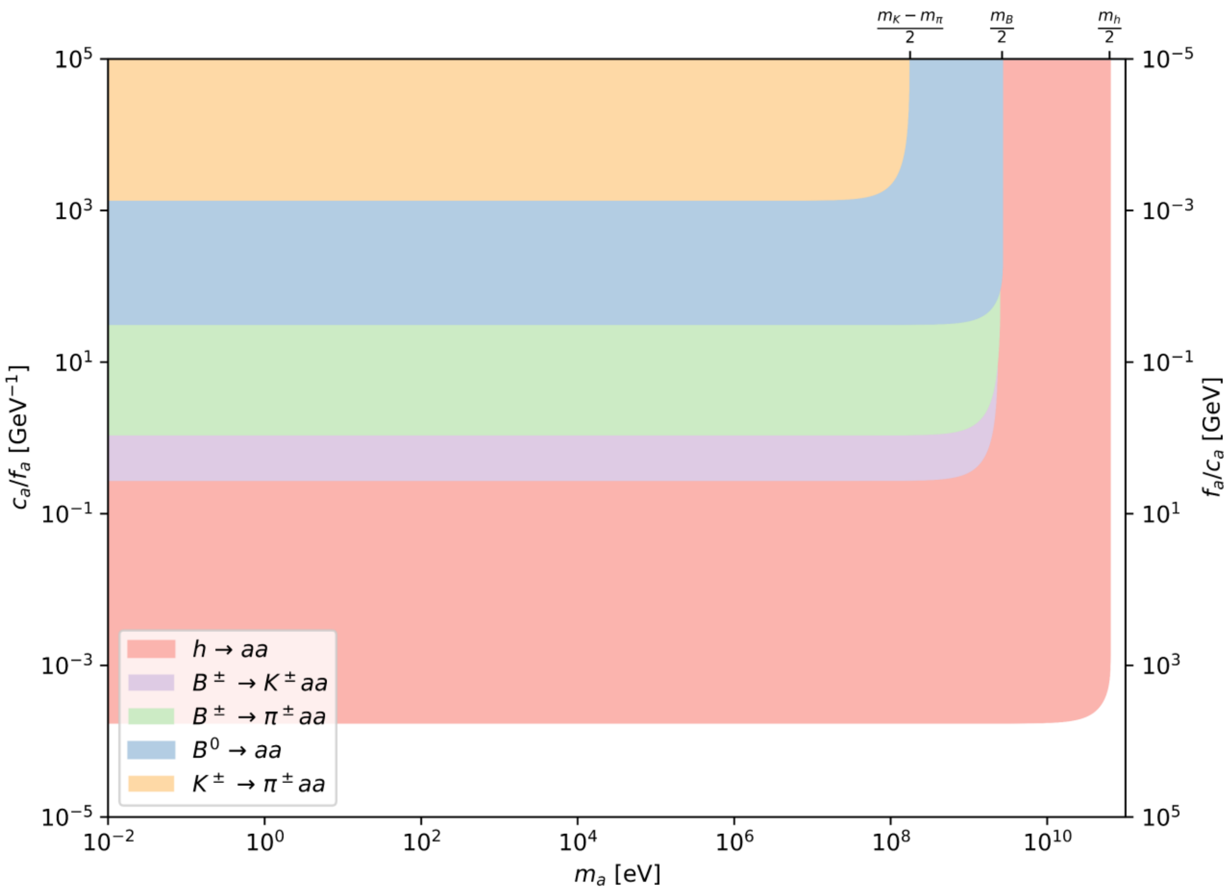
Summary

- Axion-Higgs portal: Axion couplings only from mixing of heavy scalar with SM Higgs boson
- Avoid usual constraints on f_a through derivative suppression and Z_2 symmetry
- Can produce Dark Matter through Freeze-In or vacuum misalignment
- Solve strong CP problem through explicit Z_2 breaking, axion quality problem avoided by scale separation $f_a \ll \Lambda_{Z_2}, \Lambda_{U(1)}$

Backup

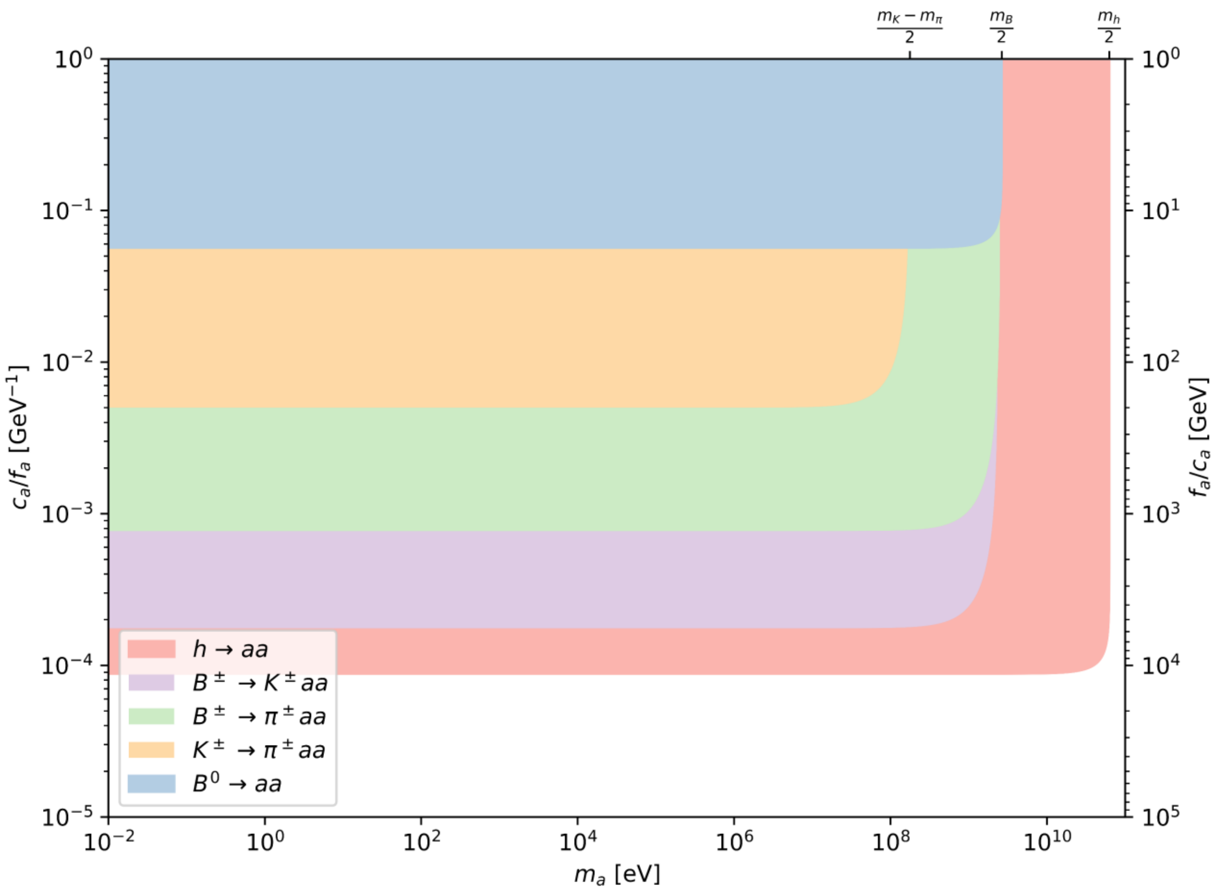
Axion-Higgs Portal

$$\mathscr{L} \supset \frac{c_a}{f_a v}(\partial_\mu a)^2 H^\dagger H$$



Higgs Portal

$$\mathscr{L} \supset \frac{c_a}{f_a v}(m_h a)^2 H^\dagger H$$



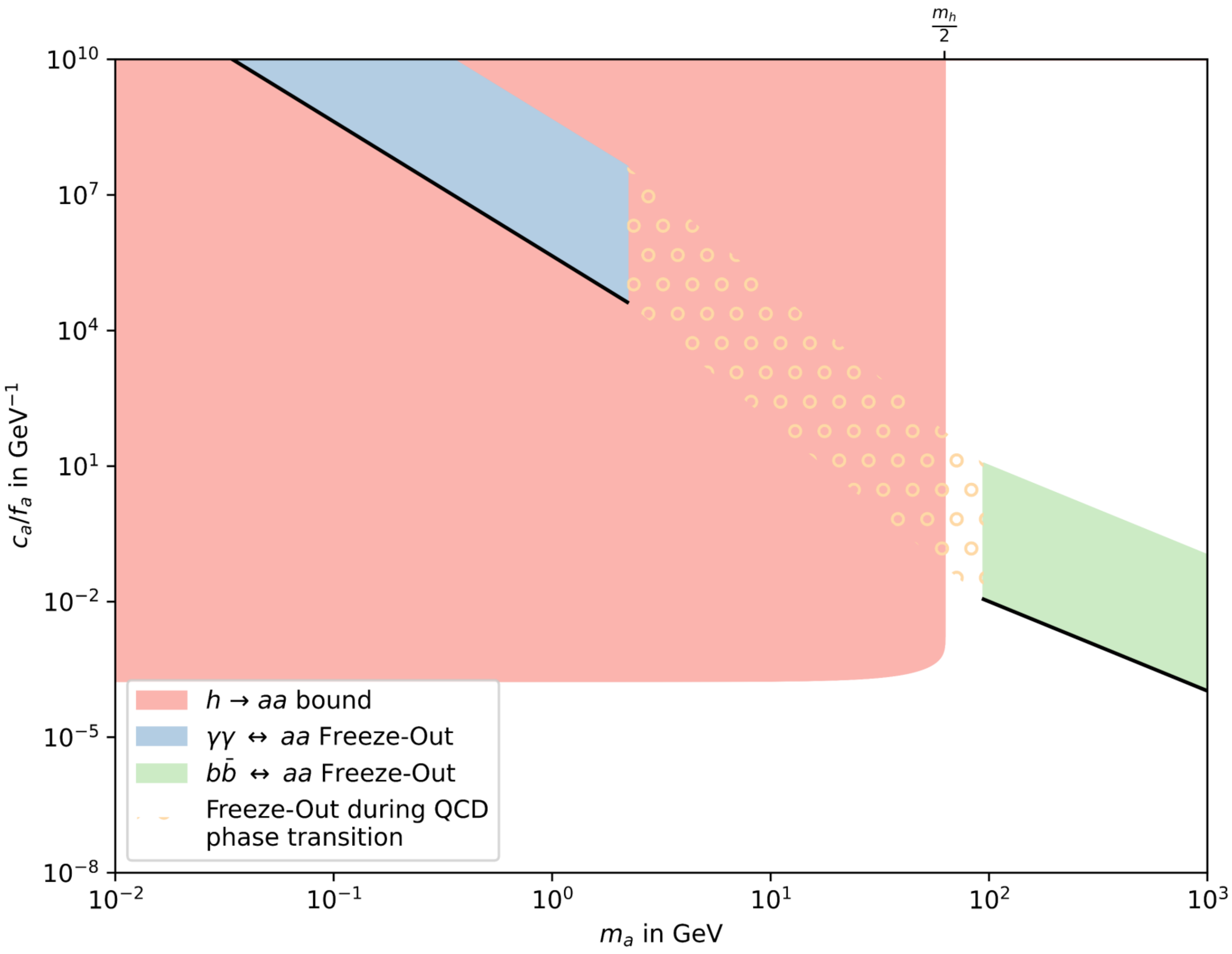
Axion-Higgs Portal Couplings

$$
\begin{aligned}
\mathscr{L} \supset & -\frac{c_a}{f_a} h (\partial_\mu a)^2 \\
\supset & -\frac{c_a}{f_a} \frac{g_L m_W}{m_h^2} (\partial_\mu a)^2 W_\mu^a W_a^\mu \\
& + \sum_f \frac{c_a}{f_a} \frac{m_f}{v m_h^2} (\partial_\mu a)^2 \bar{f} f + \text{h.c.} \\
& - \frac{c_a}{f_a} \frac{1}{v m_h^2} (\partial_\mu a)^2 \left(c_\gamma F_{\mu\nu} F^{\mu\nu} + c_g G_{\mu\nu} G^{\mu\nu} \right)
\end{aligned}
$$

Integrate out higgs boson

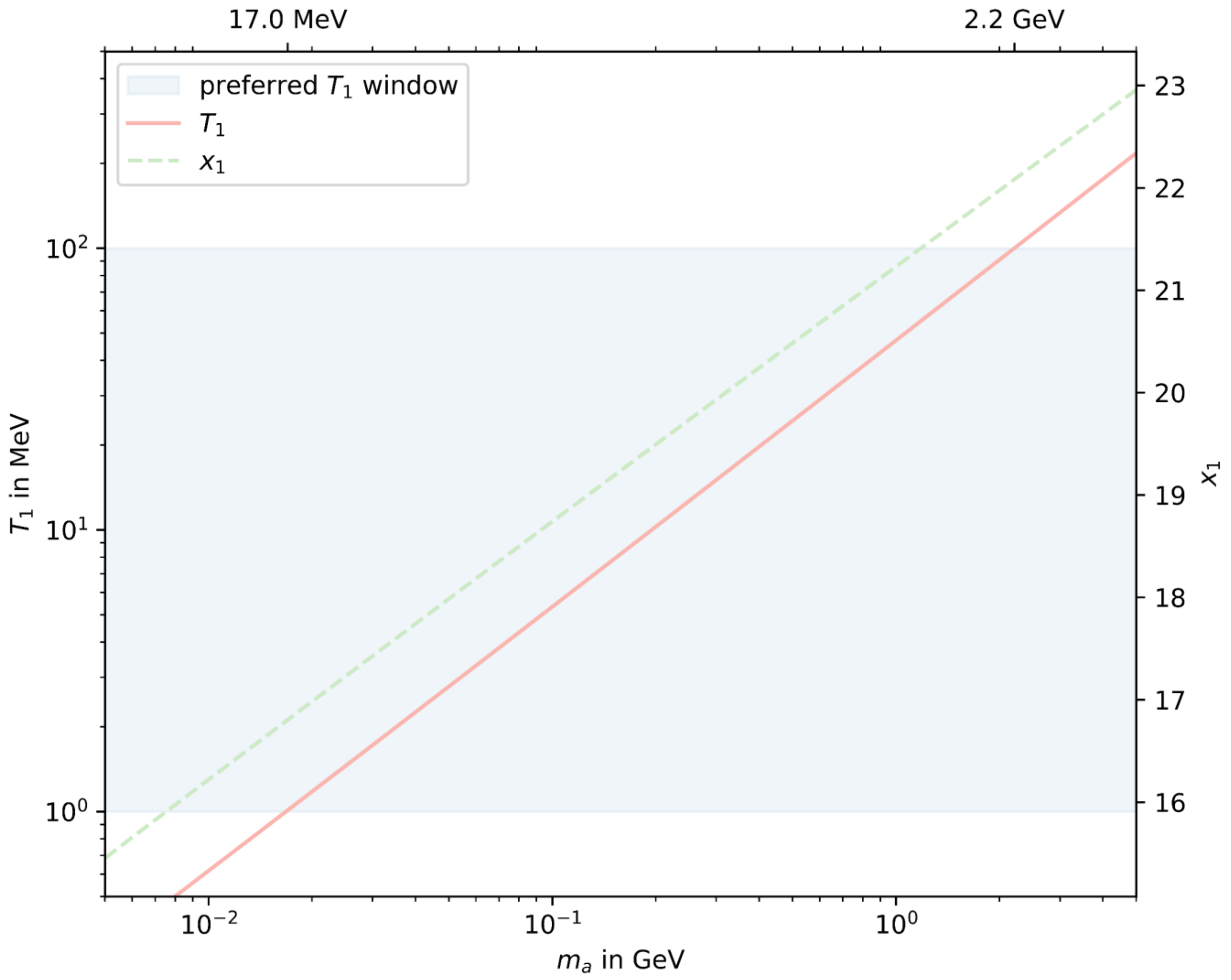
Wilson coefficients for triangle diagrams

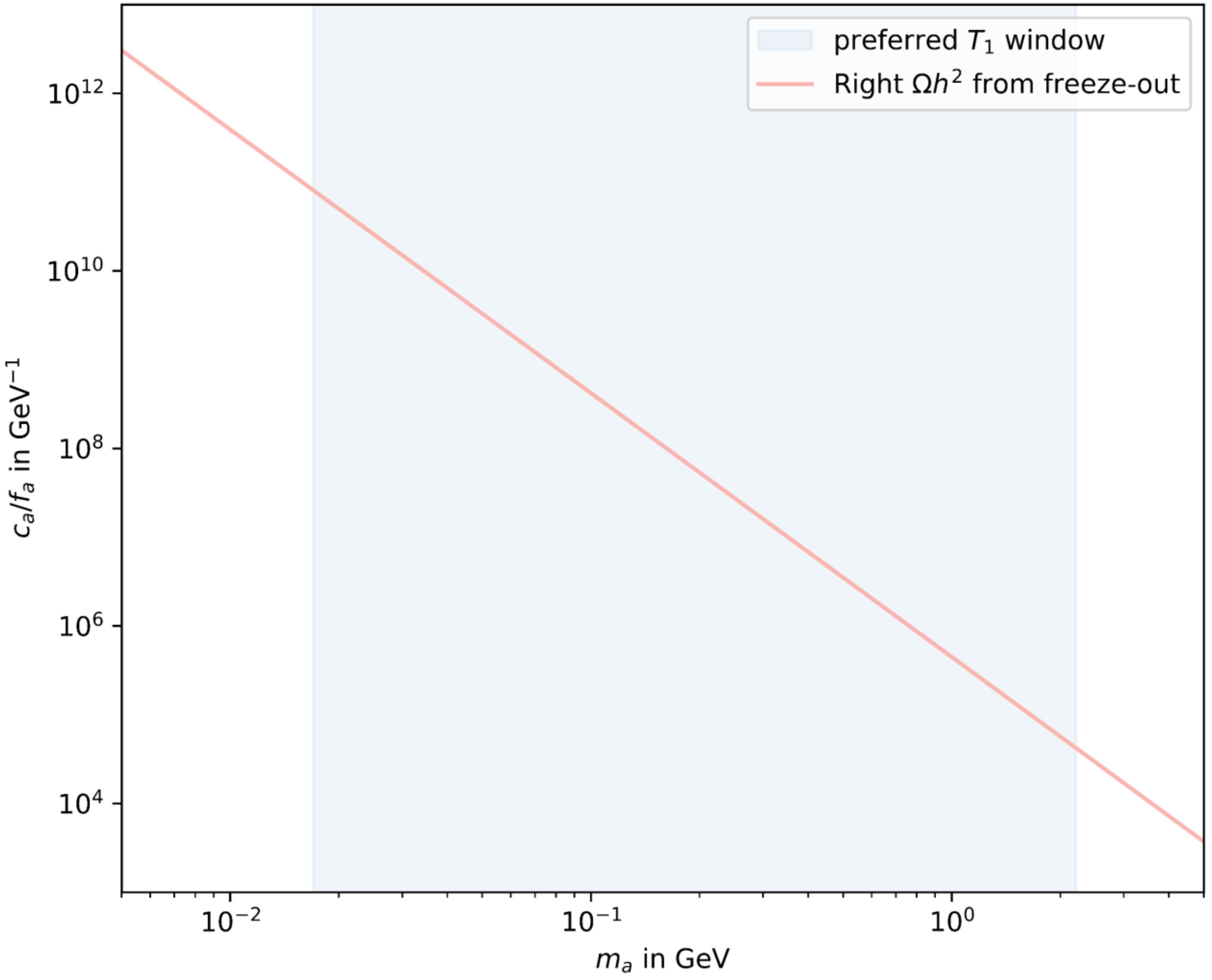
Freeze-Out



$\frac{m_h}{2}$
10^{10}
10^{7}
10^{4}
10^{1}
10^{-2}
10^{-5}
10^{-8}
c_a/f_a in GeV^{-1}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
m_a in GeV
$h \to aa$ bound
$\gamma\gamma \leftrightarrow aa$ Freeze-Out
$b\bar{b} \leftrightarrow aa$ Freeze-Out
Freeze-Out during QCD phase transition

Freeze-Out $aa \leftrightarrow \gamma\gamma$





FREEZE-OUT $aa \leftrightarrow \bar{b}b$