

# The Flavor of QCD Axion Dark Matter

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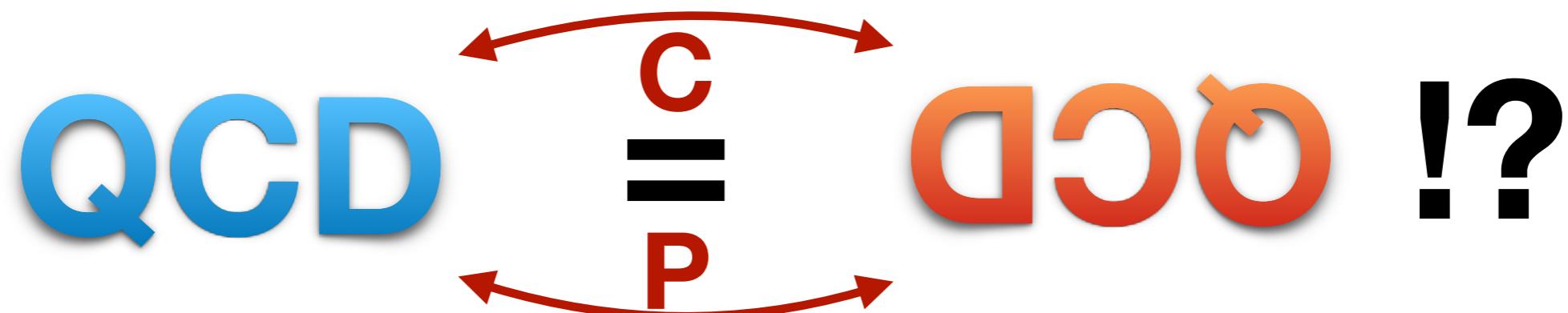
based on [2305.00018] with Tianzhuo Xiao & Jim Cline



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# QCD axion dark matter

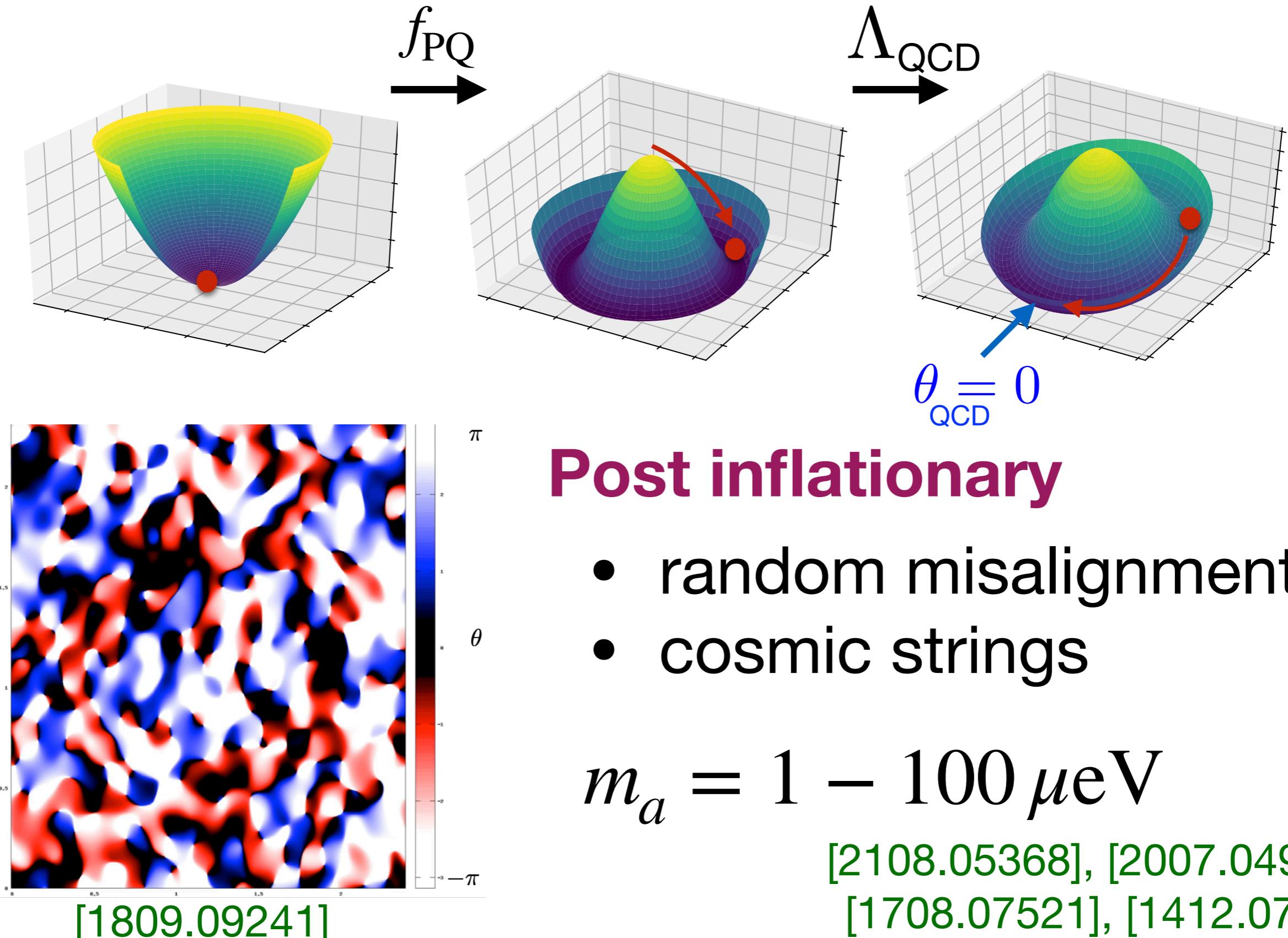
Focus on QCD axions that solve the strong CP problem



Two main classes of models:

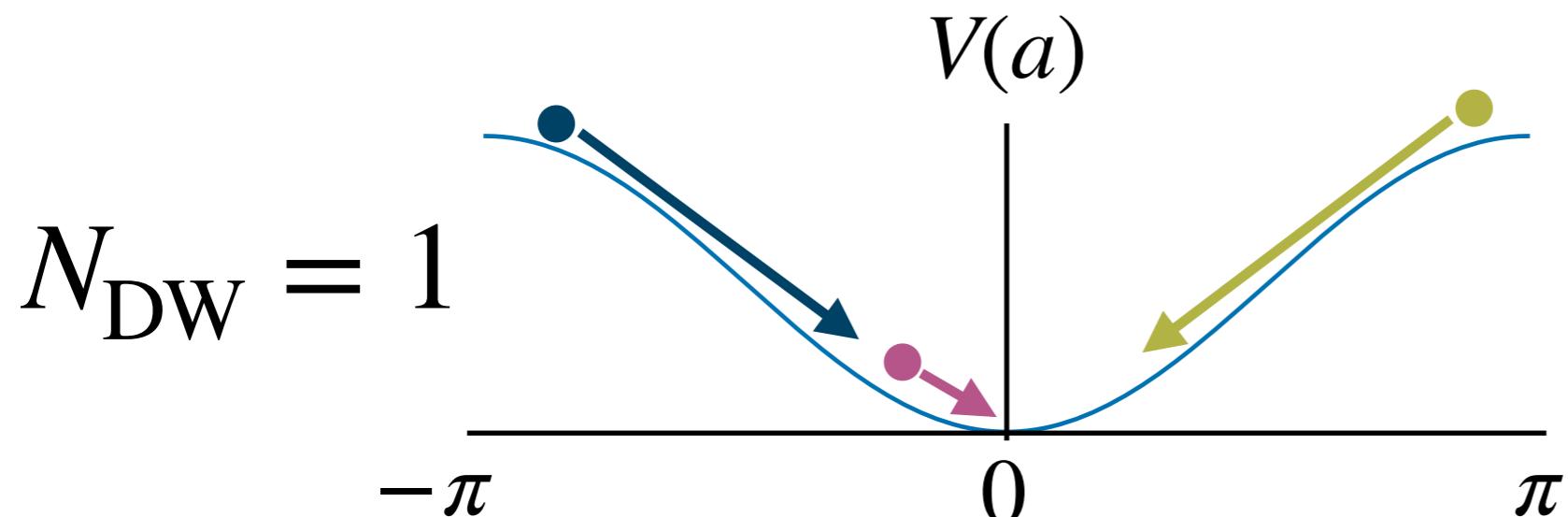
PQ charge	DFSZ	KSVZ
SM quarks	✓	✗
Heavy quarks	✗	✓

# Misalignment mechanism

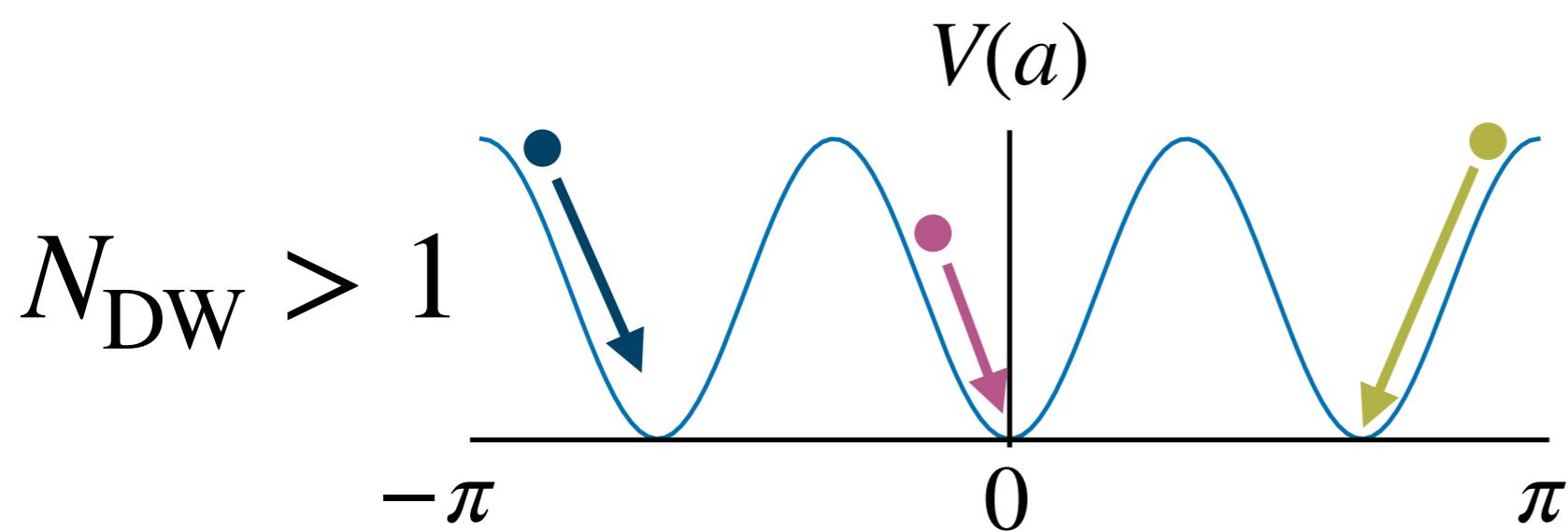


# Domain wall number

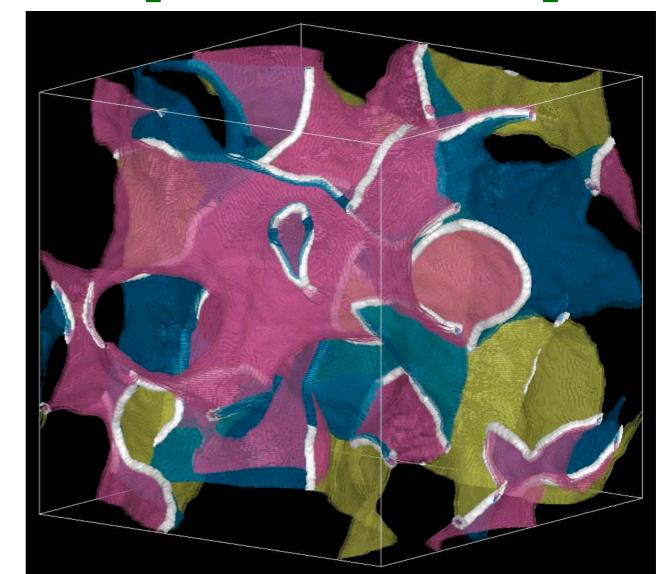
In general,  $V_a \simeq \Lambda_{\text{QCD}}^4 \left[ 1 - \cos \left( N_{\text{DW}} \frac{a}{f_{\text{PQ}}} \right) \right]$



No stable DW



[1207.3166]



Catastrophic

# Strongly interacting relics

$Q$  produced in the early universe through freeze-out



They form stable hadrons



Their abundance is extremely constrained

$$\frac{n_Q}{n_b} < 10^{-20}$$

Perl et al (2009)

Solution: they must decay into SM quarks

$$\tau_Q < 10^{-2} \text{ s} \quad [1610.07593]$$

# Viable models

QCD axion dark matter models must satisfy:

1.  $N_{\text{DW}} = 1$
2. Q couple to SM q through operator of  $d \leq 5$
3.  $f_a = 5 \times 10^9 - 3 \times 10^{11} \text{ GeV}$

Only **two** possibilities:

- KSVZ-I:  $Q \sim (3, 1, -1/3)$
- KSVZ-II:  $Q \sim (3, 1, 2/3)$

# Heavy quark couplings

KSVZ-I:

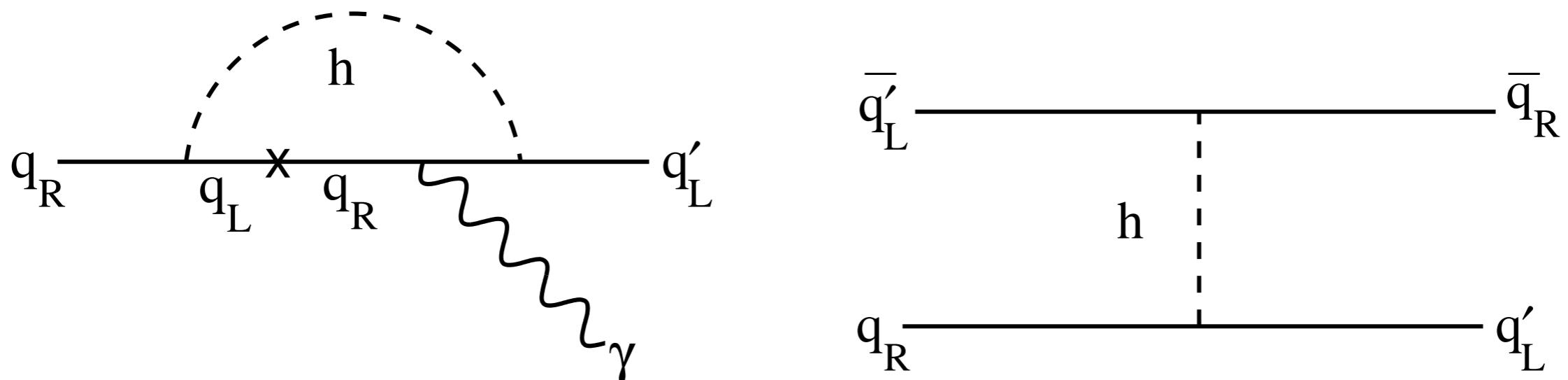
$$\begin{aligned}\mathcal{O}_4^M &= M_d \bar{Q}_L d_R, & \text{for } (\chi_L, \chi_R) &= (0, -1), \\ \mathcal{O}_4^H &= y_{1,d} H \bar{d}_L Q_R, & \text{for } (\chi_L, \chi_R) &= (1, 0), \\ \mathcal{O}_4^\Phi &= y_{2,d} \Phi \bar{Q}_L d_R, & \text{for } (\chi_L, \chi_R) &= (1, 0), \\ \mathcal{O}_4^{\Phi^\dagger} &= y_{3,d} \Phi^\dagger \bar{Q}_L d_R, & \text{for } (\chi_L, \chi_R) &= (-1, -2).\end{aligned}$$

Mass mixing between heavy & SM quarks



# Flavor-violating Higgs couplings

SM quark masses not aligned with Higgs couplings

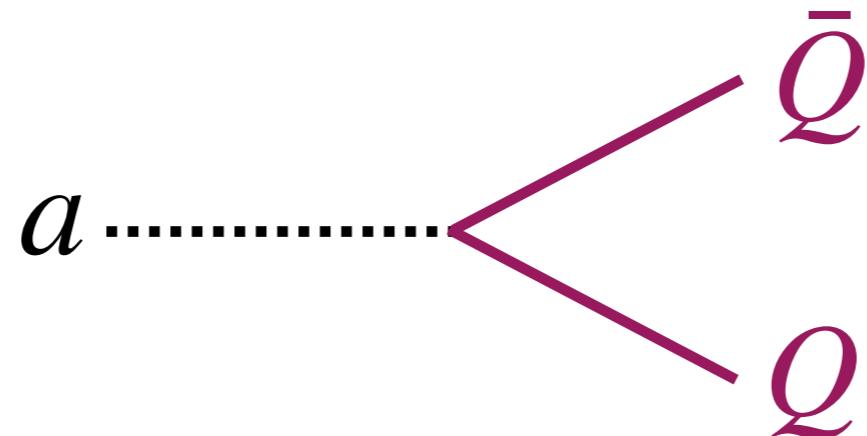


Mixings have to be  $\theta_{Qq} \lesssim 0.1 - 0.01$

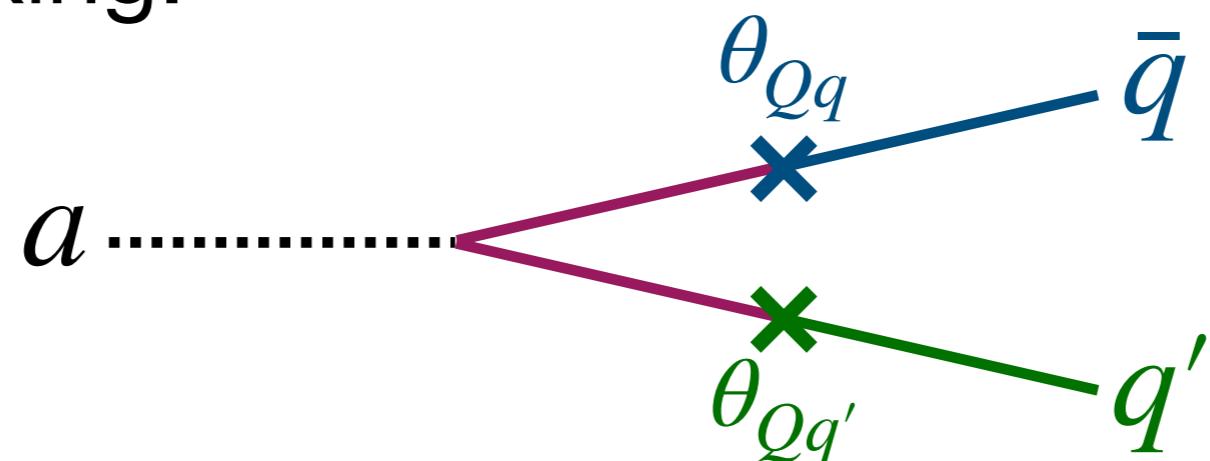


# Axion-quark couplings

Before mass mixing:



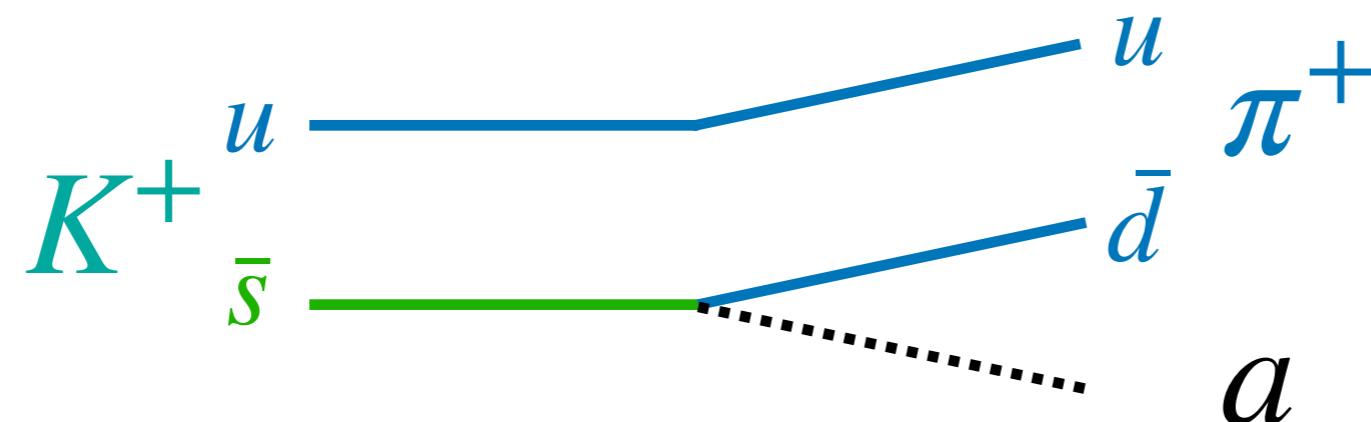
After mass mixing:



Large flavor-violating coupling to quarks

# Flavor-violating axion couplings

Induce rare decays and other processes



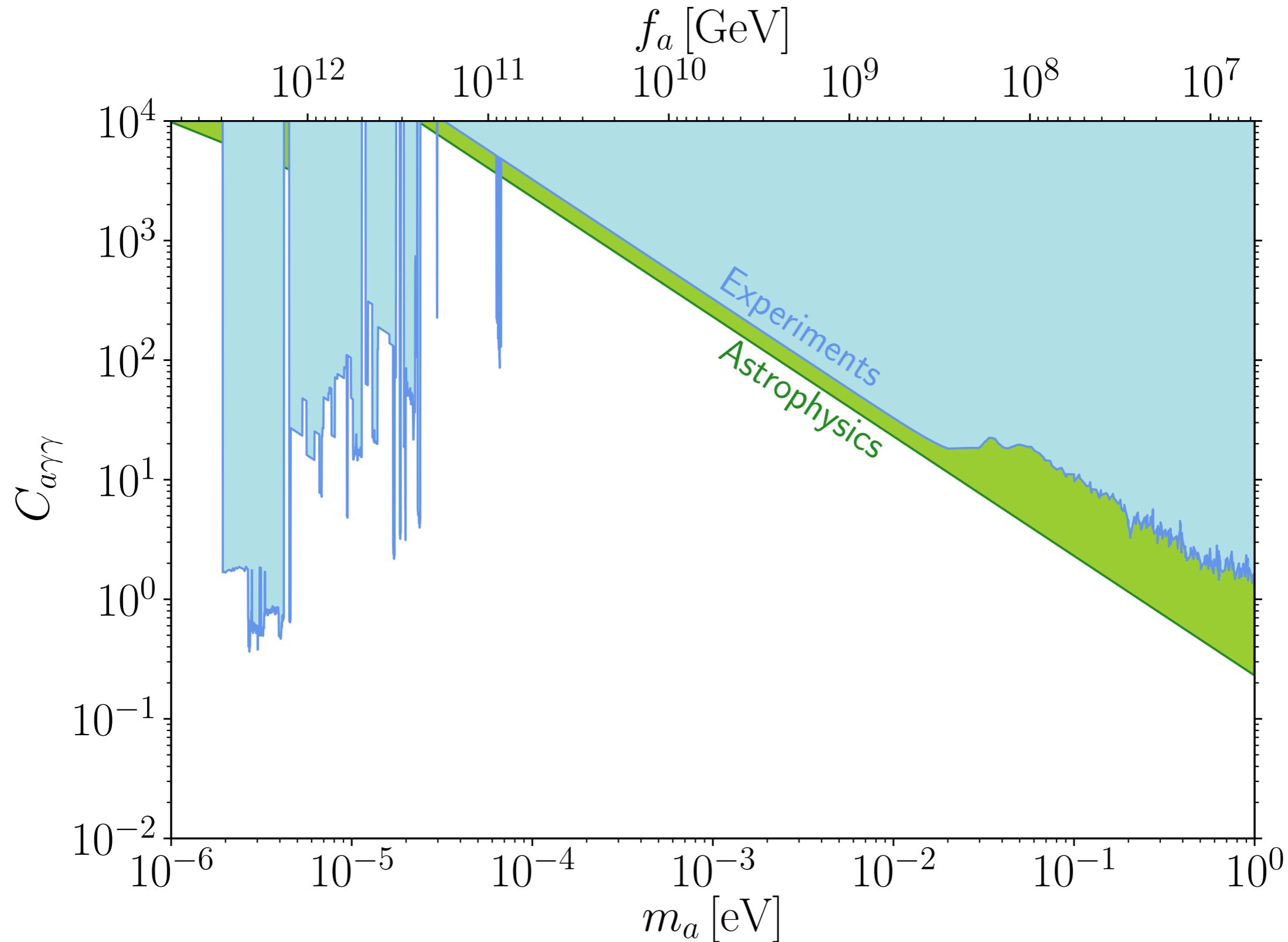
E949, NA62, KOTO:  $\text{BR}(K^+ \rightarrow \pi^+ a) < 7.3 \times 10^{-11}$   
[0709.1000], [2011.11329]

Probe QCD axions with

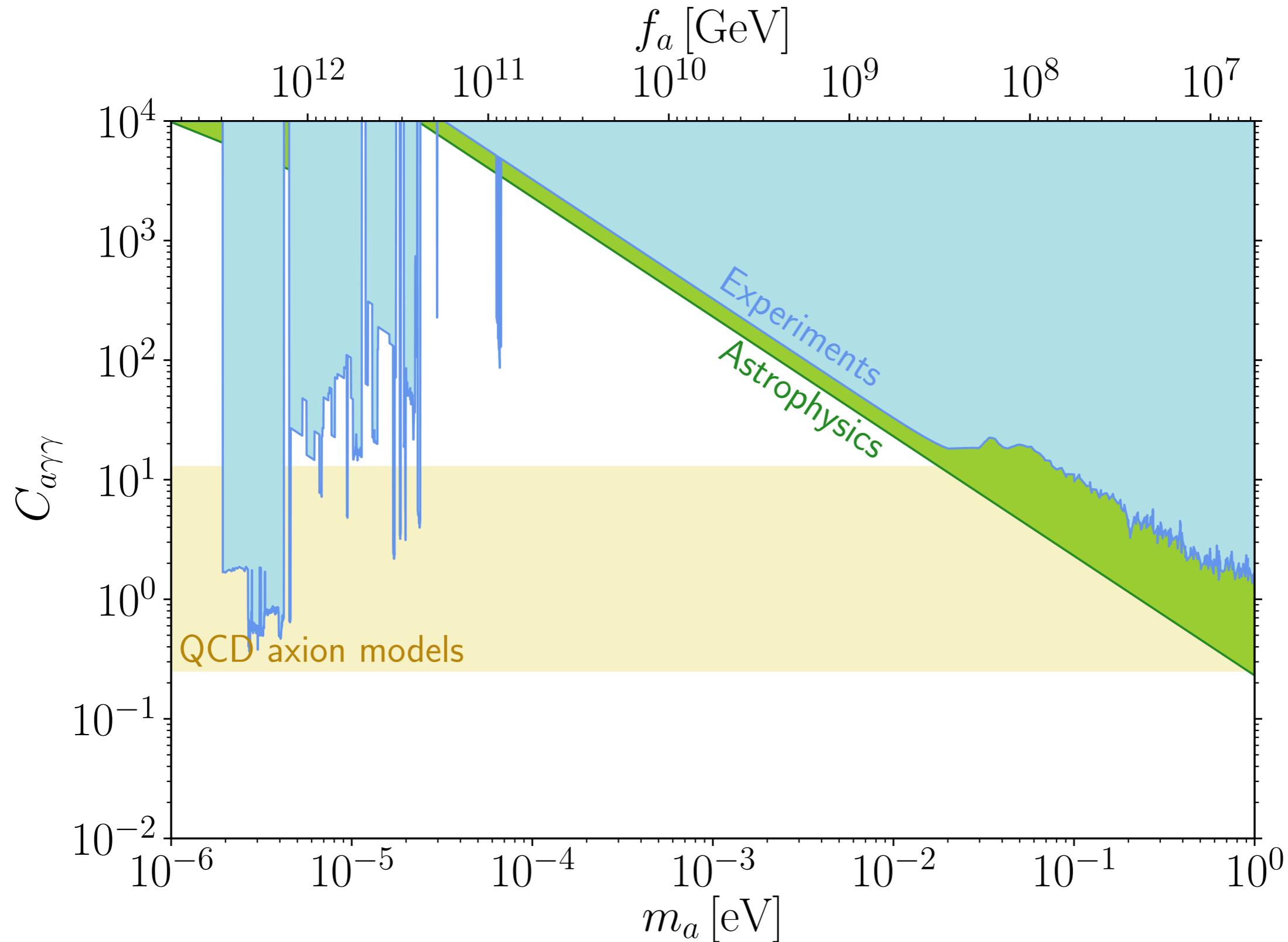
$$f_a \sim 10^{10} - 10^{11} \text{ GeV}$$

well into the DM range

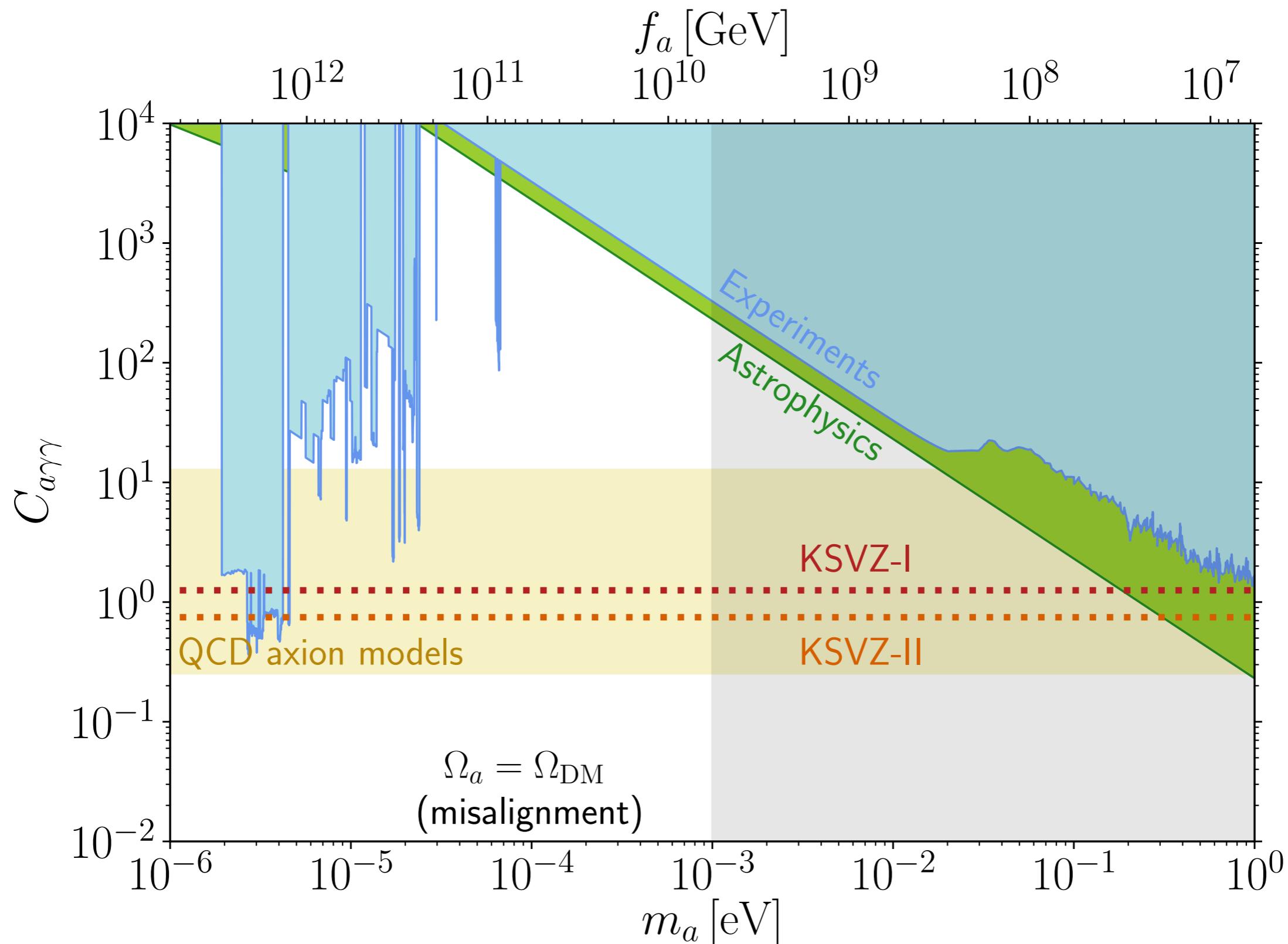
# QCD axion parameter space



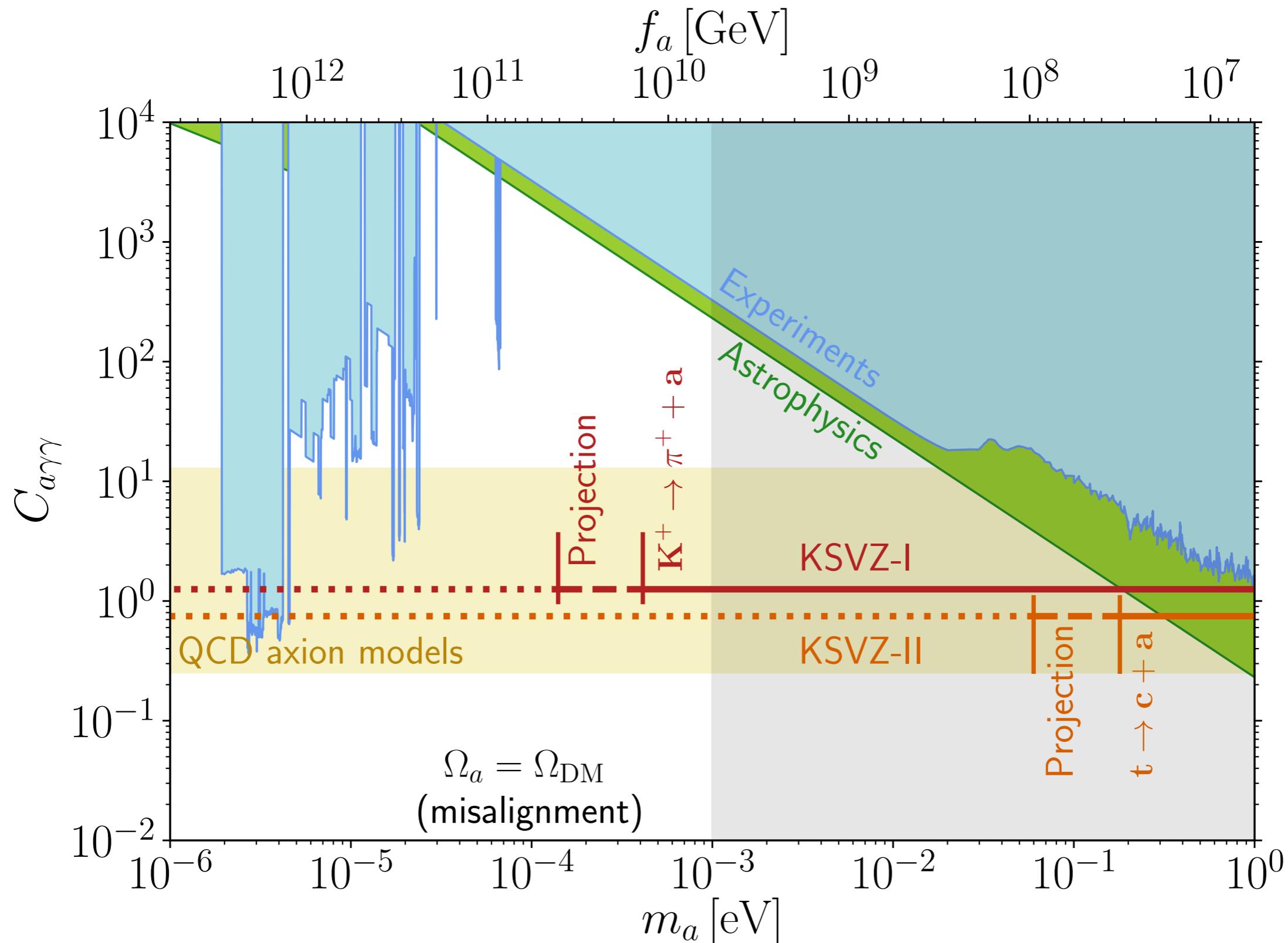
# QCD axion parameter space



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# QCD axion parameter space



# Conclusions

- Viable QCD axion DM: KSVZ-I and KSVZ-II
- Flavor-violating axion-quark couplings
- **Discover QCD axion DM through  $K \rightarrow \pi + a$**

# Conclusions

- Viable QCD axion DM: KSVZ-I and KSVZ-II
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**Thanks!**

# Backup

# Heavy quark couplings

KSVZ-I:

$$\mathcal{O}_4^M = M_d \bar{Q}_L d_R, \quad \text{for } (\chi_L, \chi_R) = (0, -1),$$

$$\mathcal{O}_4^H = y_{1,d} H \bar{d}_L Q_R, \quad \text{for } (\chi_L, \chi_R) = (1, 0),$$

$$\boxed{\mathcal{O}_4^\Phi = y_{2,d} \Phi \bar{Q}_L d_R, \quad \text{for } (\chi_L, \chi_R) = (1, 0)},$$

$$\mathcal{O}_4^{\Phi^\dagger} = y_{3,d} \Phi^\dagger \bar{Q}_L d_R, \quad \text{for } (\chi_L, \chi_R) = (-1, -2).$$

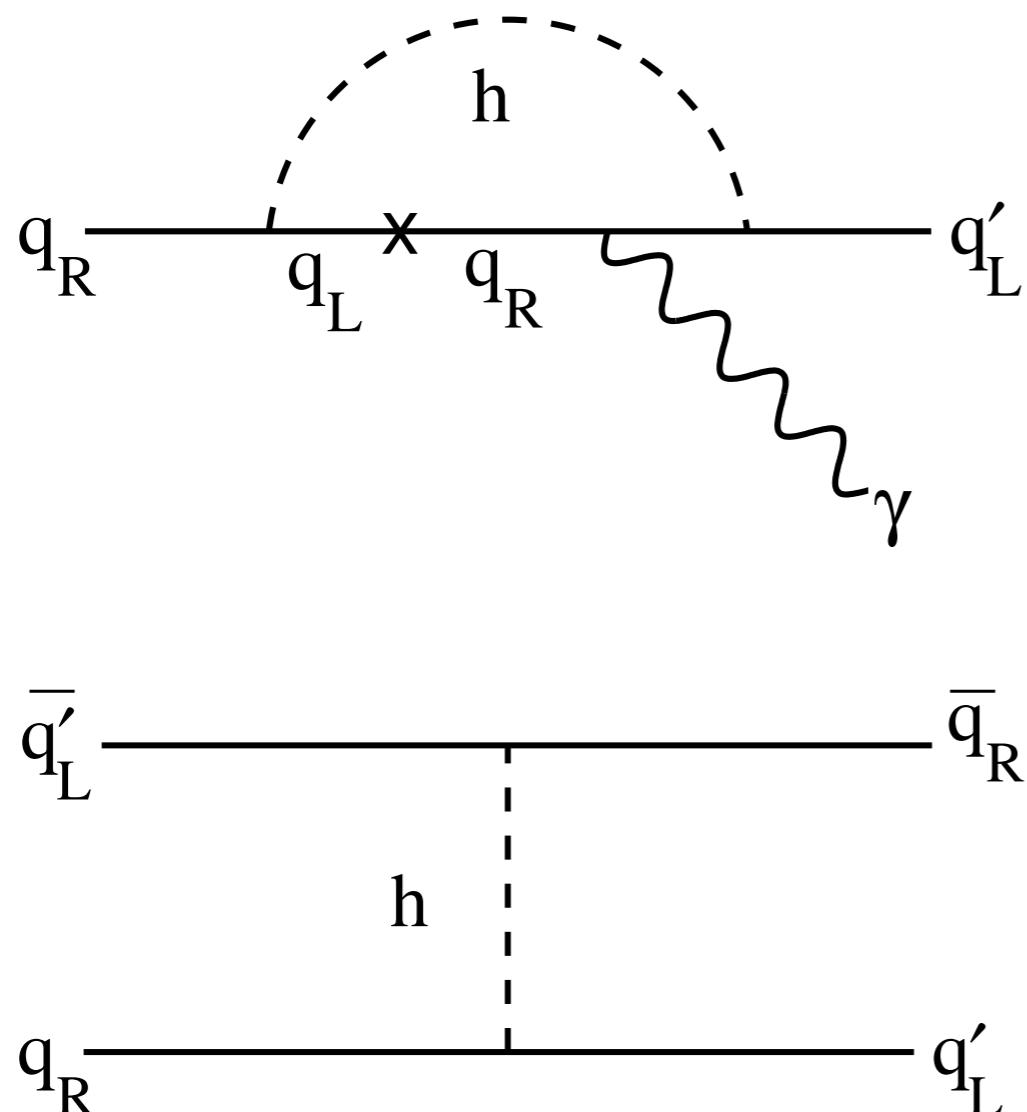
Quark mass matrix:

$$(\bar{d}_L \ \bar{s}_L \ \bar{b}_L \ \bar{Q}_L) \begin{pmatrix} m_d & 0 & 0 & 0 \\ 0 & m_s & 0 & 0 \\ 0 & 0 & m_b & 0 \\ y_{2,d} f_a & y_{2,s} f_a & y_{2,b} f_a & m_Q \end{pmatrix} \begin{pmatrix} d_R \\ s_R \\ b_R \\ Q_R \end{pmatrix}$$

Mass mixing between heavy & SM quarks

# Flavor-violating Higgs couplings

SM quark masses not aligned with Higgs couplings



$(C_a^R)_{qq'}$	
$\text{Re } C_K (sd)$	$4.1 \times 10^{-2}$
$\text{Im } C_K (sd)$	$2.1 \times 10^{-3}$
$ C_{B_d}  (bd)$	$5.5 \times 10^{-3}$
$ C_{B_s}  (bs)$	$1.8 \times 10^{-2}$
$\text{Im } C_D (cu)$	$1.4 \times 10^{-3}$
$t \rightarrow h j (tu)$	$9.5 \times 10^{-2}$
$t \rightarrow h j (tc)$	$9.1 \times 10^{-2}$

Limit the size of the flavor-violating axion couplings

# Axion-quark couplings

Before mass mixing:

$$\mathcal{L} \supset -\frac{1}{2f_a} \partial_\mu a (\chi_L \bar{Q}_L \gamma^\mu Q_L + \chi_R \bar{Q}_R \gamma^\mu Q_R)$$

After mass mixing:

$$\begin{aligned} \mathcal{L} \supset & -\frac{1}{2f_a} \partial_\mu a \left[ \chi_L (\bar{q}_L \bar{Q}_L) \boxed{C_a^L} \gamma^\mu \begin{pmatrix} q_L \\ Q_L \end{pmatrix} \right. \\ & \left. + \chi_R (\bar{q}_R \bar{Q}_R) \boxed{C_a^R} \gamma^\mu \begin{pmatrix} q_R \\ Q_R \end{pmatrix} \right] \end{aligned}$$

$$(C_a^L)_{dd'} \simeq \frac{m_d m_{d'} y_{2,d}^* y_{2,d'} f_a^2}{m_Q^4}$$

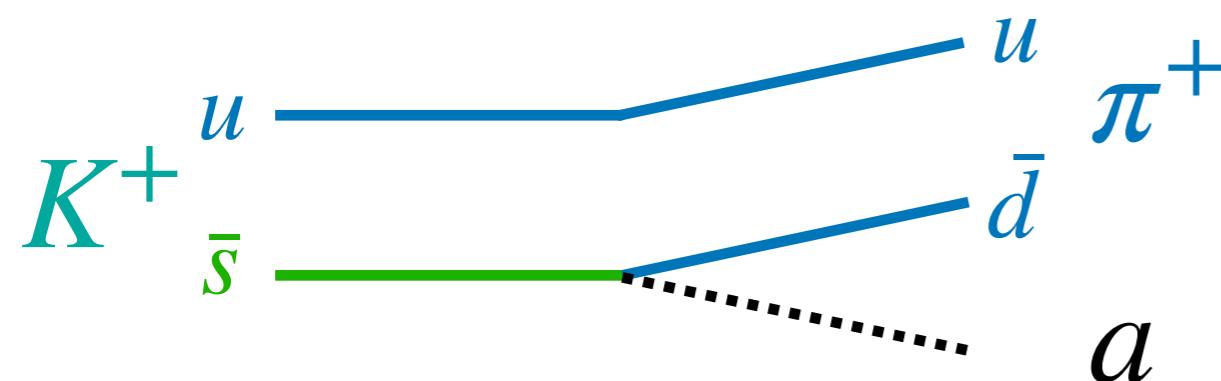
**Small**

$$(C_a^R)_{dd'} \simeq \frac{y_{2,d}^* y_{2,d'} f_a^2}{m_Q^2}$$

**Large**

# Flavor-violating axion couplings

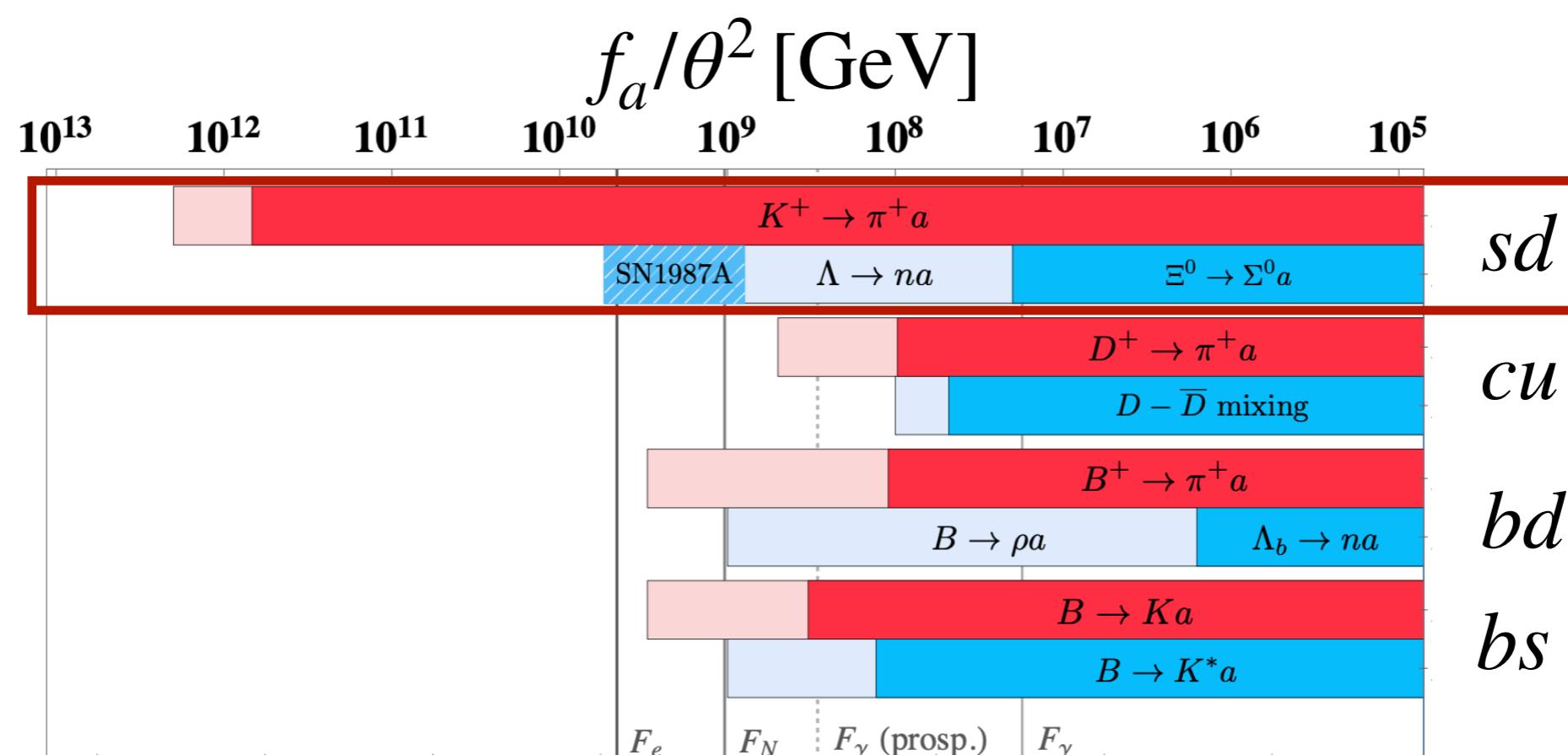
Induce rare decays and other processes



E949, NA62:

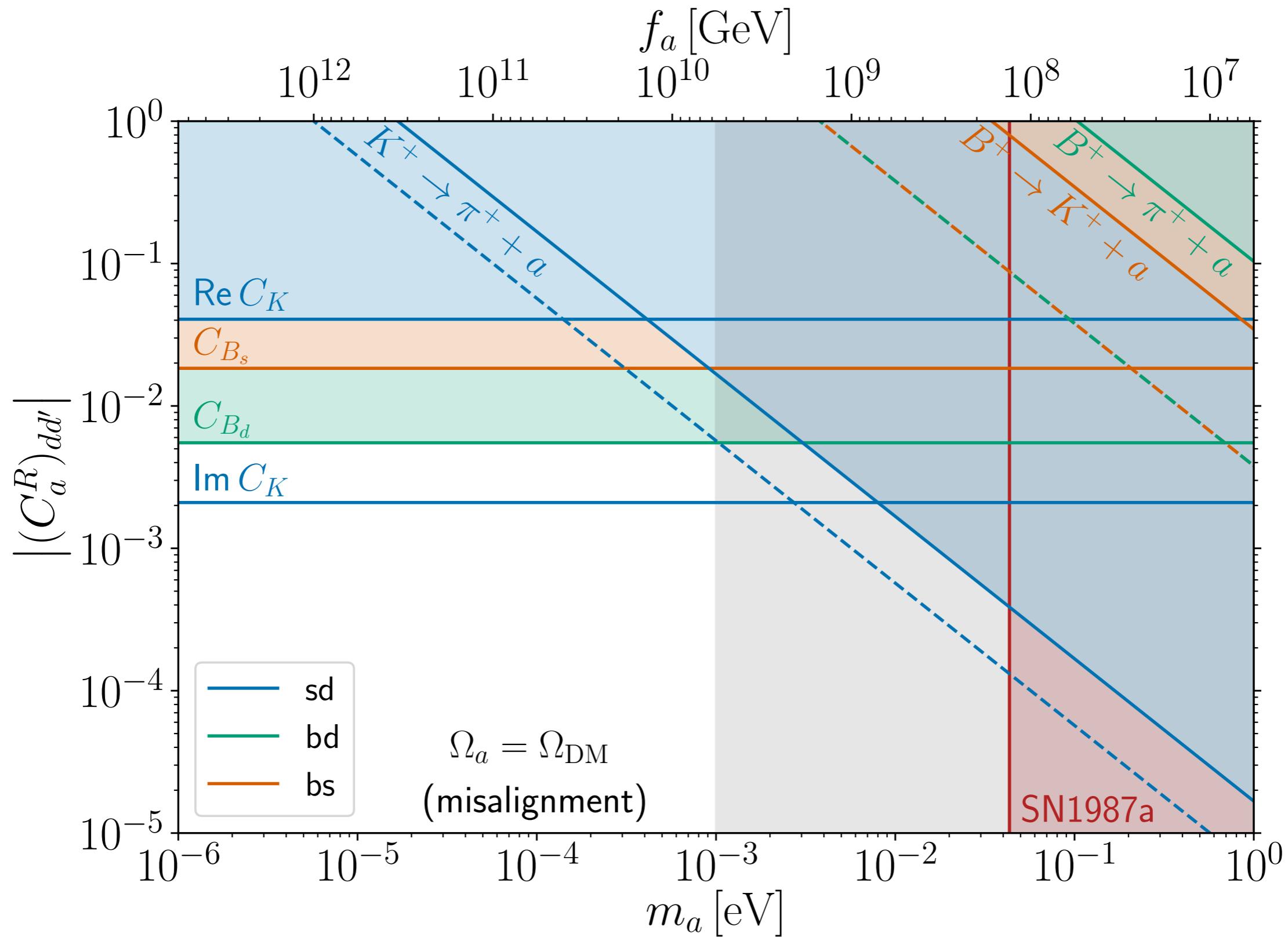
$\text{BR}(K^+ \rightarrow \pi^+ a) < 7.3 \times 10^{-11}$

[0709.1000], [2011.11329]



[2002.04623]

# KSVZ-II: down-type quarks



# KSVZ-II: up-type quarks

