UV/IR Flavour Connection in Axion Models

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HIDDeν

Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Outline

1. Motivation
    1.1. **Strong-CP Problem** and axion solution
    1.2. **Flavour violation** in the **axion**
2. Flavour violation in DFSZ models
    2.1. **IR:** Flavour violation in the **axion**
    2.2. **UV:** Flavour violation in the **Higgs**
    2.3. **UV/IR** Connection
3. **Example** in the quark sector

1. Motivation: The Strong-CP Problem

$$\mathcal{L} = \sum_q \bar{q}\left(i\not{D} - m_q e^{i\theta_q}\right) q - \frac{1}{4} G^a_{\mu\nu} G^{a\,\mu\nu} + \frac{g_s^2}{32\,\pi^2} \theta\, G^a_{\mu\nu} \widetilde{G}^{a\,\mu\nu}$$

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θ is not invariant $\quad q \to e^{i\alpha\gamma_5} q \longrightarrow \begin{cases} \theta \to \theta - 2\alpha \\ \theta_q \to \theta_q + 2\alpha \end{cases}$

The physical quantity is then

$$\bar{\theta} = \theta + \sum_q \theta_q \overset{\text{SM}}{=} \theta + \arg\det Y_u Y_d$$

see Di Luzio *et al.* 2003.01100

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A neutron Electric Dipole Moment (**nEDM**) is generated

$$\mathcal{L} = -d_n \frac{i}{2}\bar{n}\sigma_{\mu\nu}\gamma_5 n F^{\mu\nu} \to H = d_n \vec{S}\cdot\vec{E}$$

$$d_n = 2.4(1.0)\cdot 10^{-16}\bar{\theta}\, e\,\text{cm}$$

Pospelov, Ritz. hep-ph/9908508

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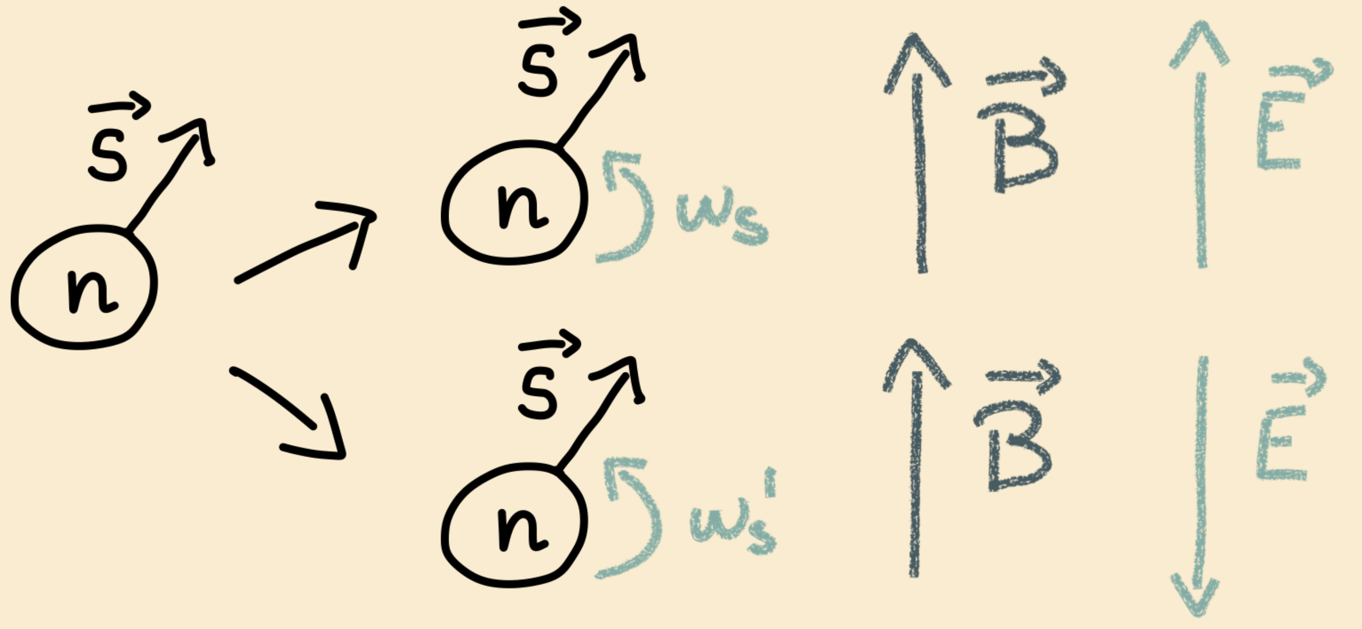

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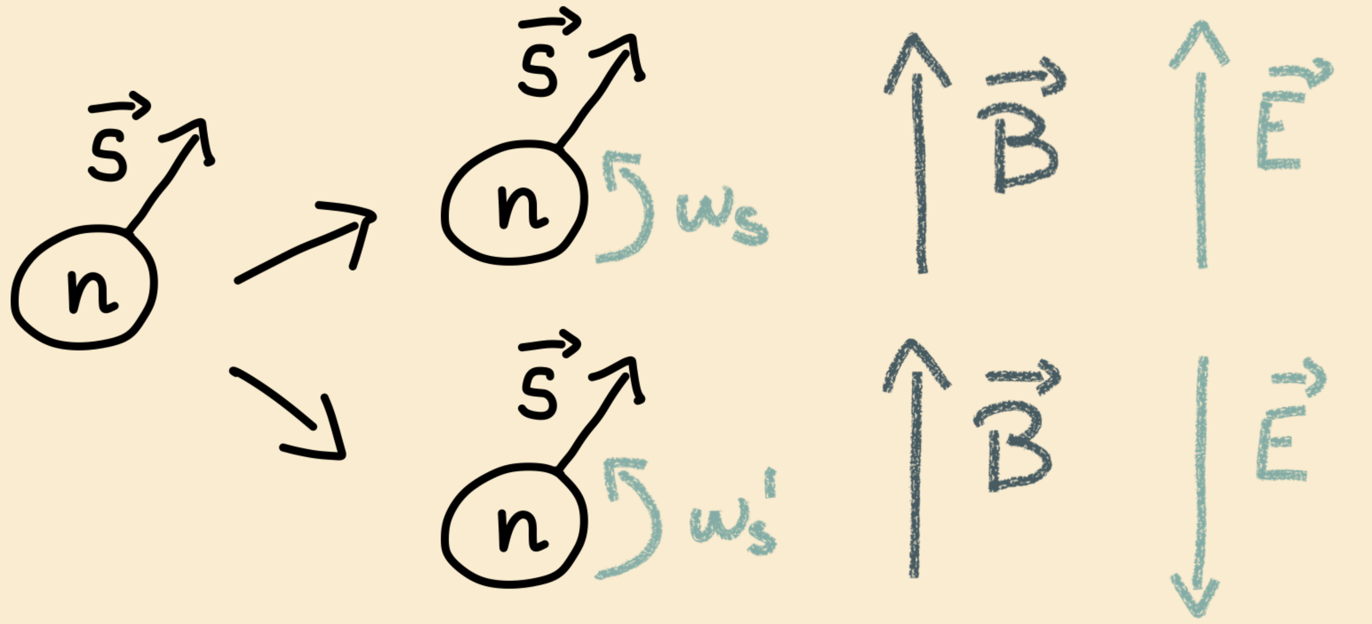

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$$\boxed{\bar{\theta} \lesssim 10^{-10}}$$

Abel *et al.* 2001.11966

see Di Luzio *et al.* 2003.01100

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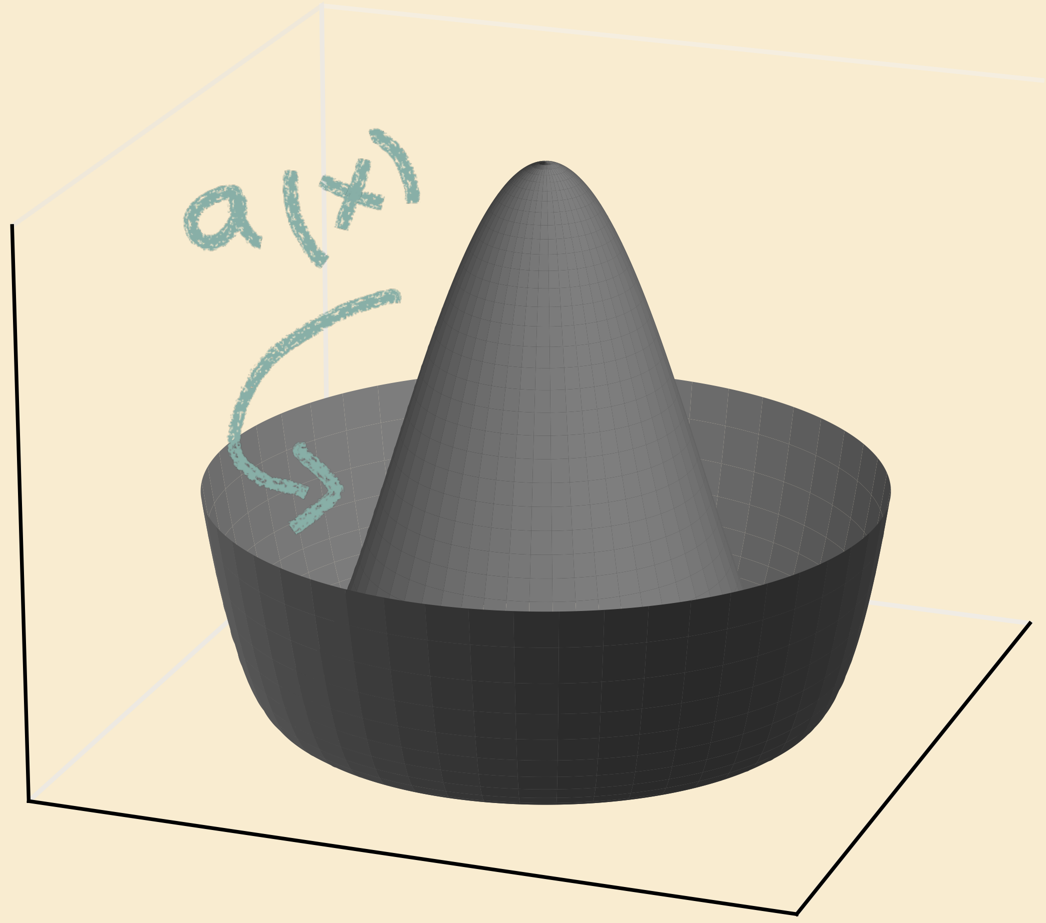
Peccei and Quinn proved that under a $U(1)$ global symmetry **anomalous** under **QCD**, which breaks spontaneously, the minimum of the theory is found where $a(x) = \bar{\theta}$

Peccei Quinn PRL. 38 (1977) 1440 , PRD. 16 (1977) 1791



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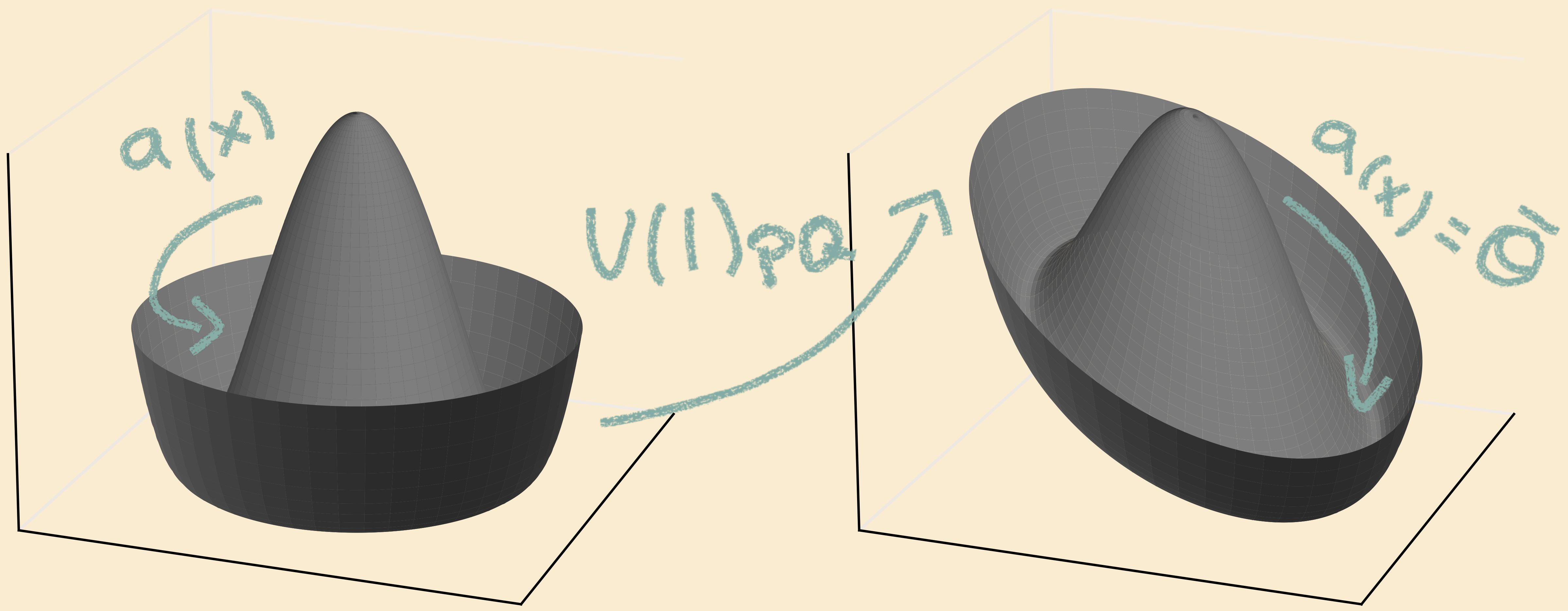

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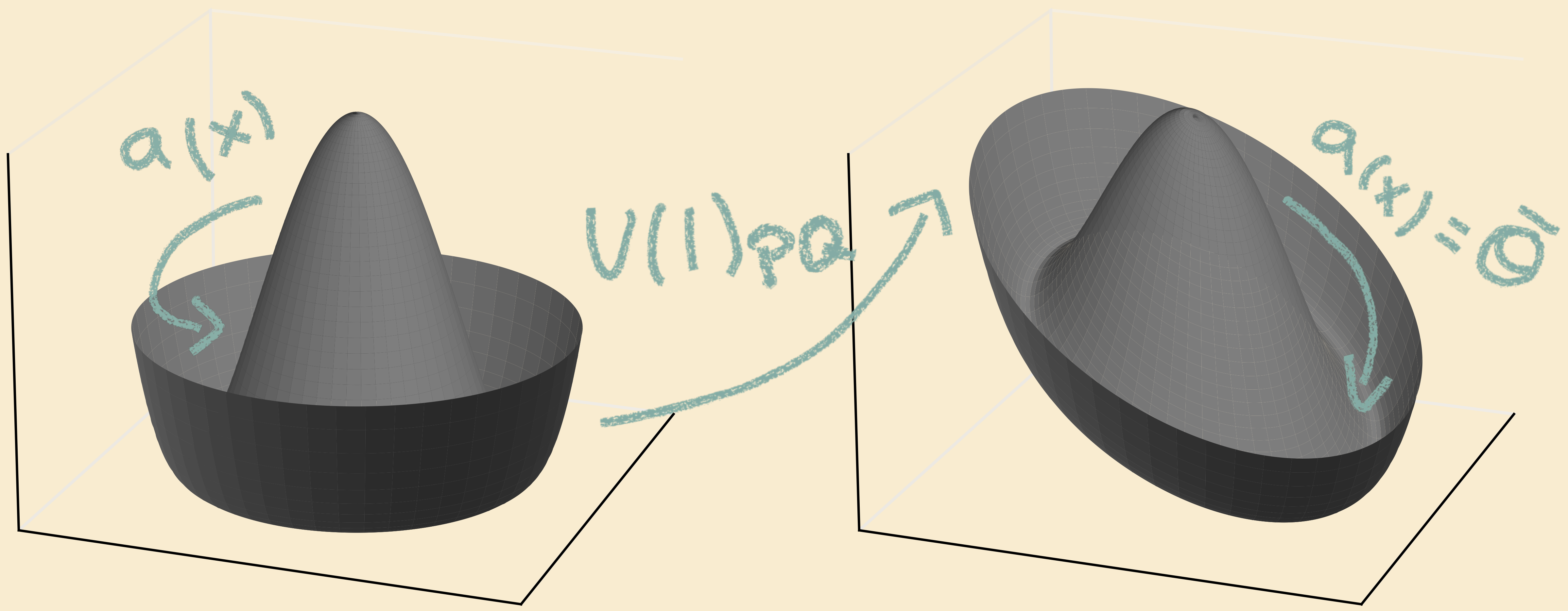

The presence of a **pseudo-Nambu Goldstone Boson (pNGB)** was found by Weinberg and Wilczek

Weinberg PRL. 40 (1978) 223
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Currently the PQ solution to the Strong-CP Problem is understood as:

$$U(1)_{\rm PQ} \to \mathcal{L}_{an.} = \frac{g_s^2}{32\pi^2}\left(\frac{a}{f_a} + \theta\right) G^a_{\mu\nu}\widetilde{G}^{a\,\mu\nu}$$

pNGB: the axion

f_a : axion decay constant

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Shift symmetry characteristic of pNGB $a \to a - f_a\,\theta$

Vafa-Witten theorem:
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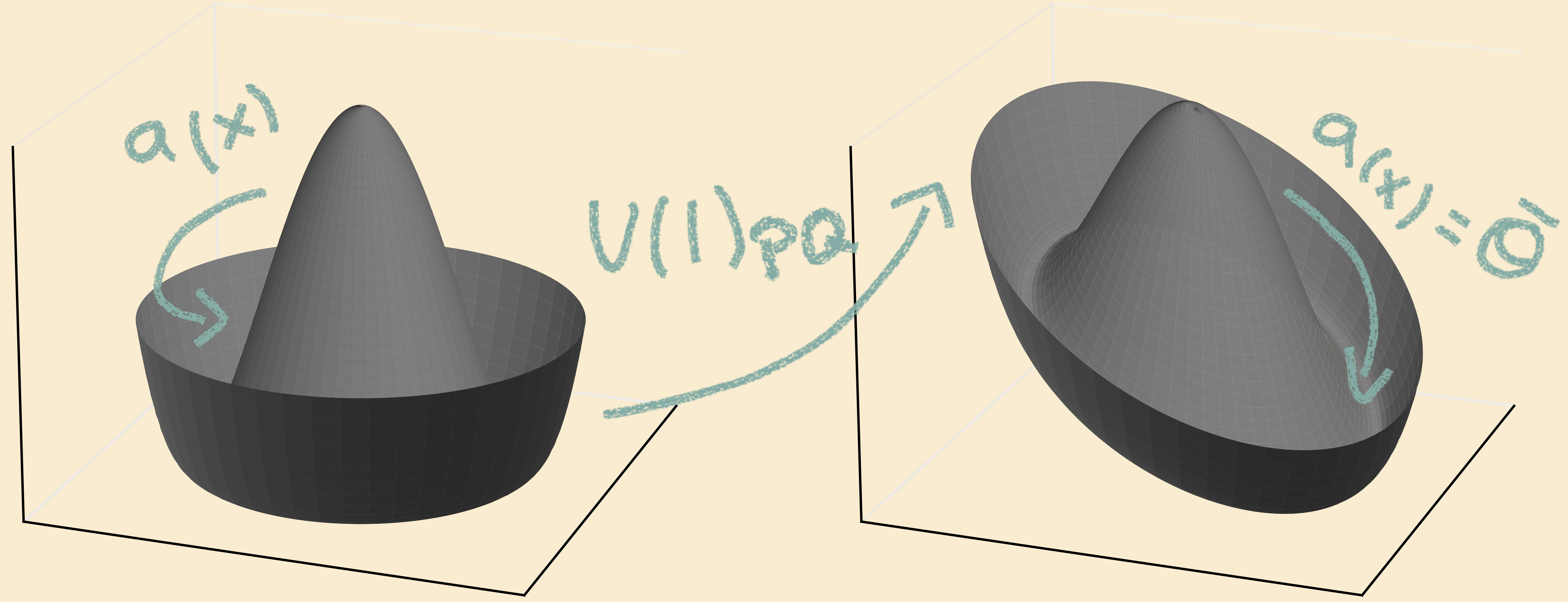

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$$m_a = \frac{\sqrt{m_u m_d}}{(m_u + m_d)}\frac{m_\pi f_\pi}{f_a} \simeq 5.7\mu\mathrm{eV}\left(\frac{10^{12}\,\mathrm{GeV}}{f_a}\right)$$

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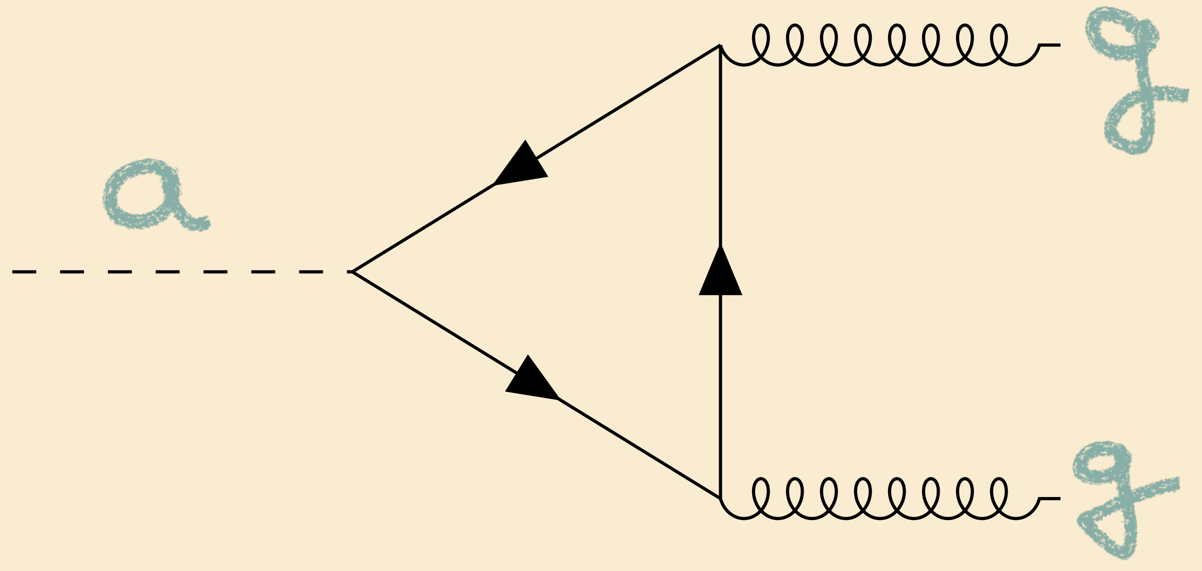
How to make a global symmetry **anomalous** under **QCD**?

New fields are **needed** to generate a $U(1)_{\rm PQ}$



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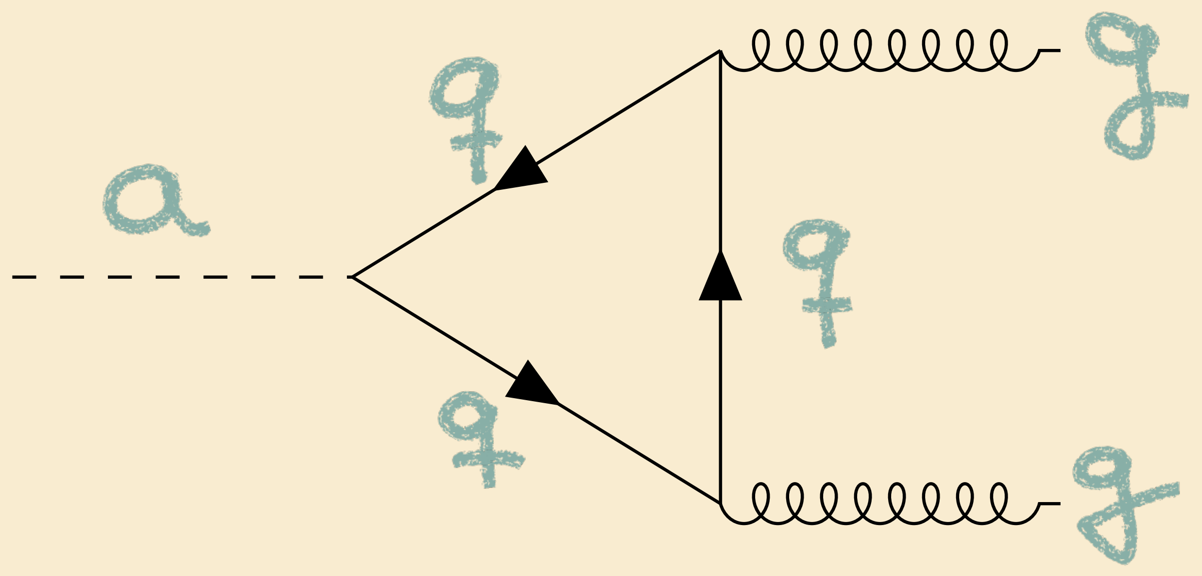

PQ-WW: 2HDM

$$\mathcal{L}_{\mathrm{WW}} = \bar{q}_L u_R \tilde{H}_u + \bar{q}_L d_R H_d$$

$$m_a \simeq 23\,\mathrm{keV}\frac{2N_f}{\sin 2\beta}$$

$$\tan\beta = \frac{v_d}{v_u}$$

Couplings proportional to $f_a \sim v$
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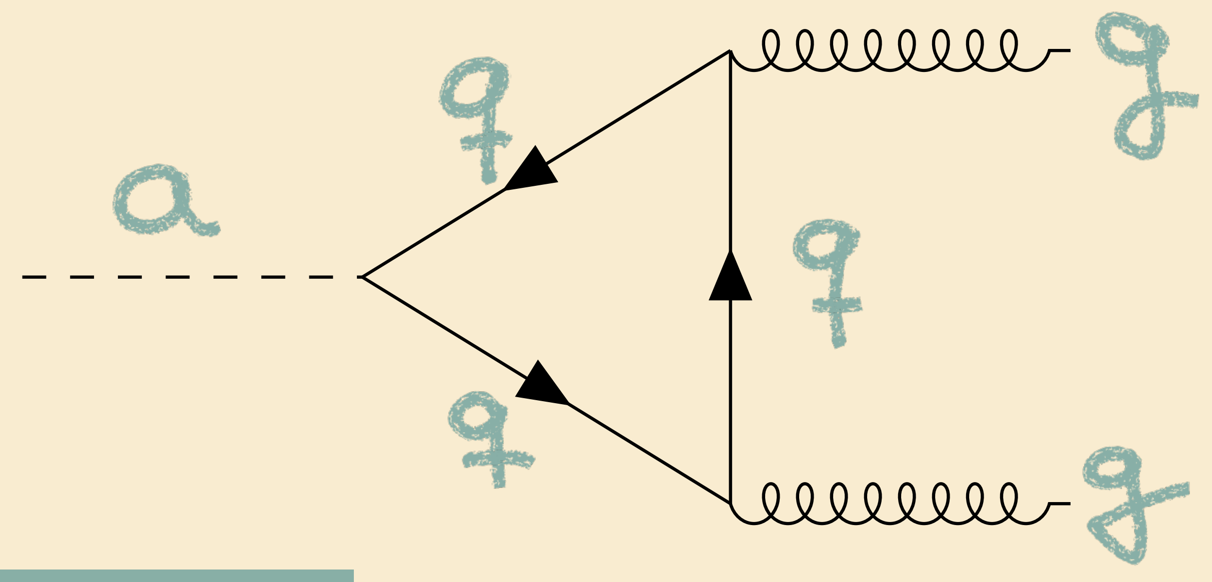

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Zhitnitsky SJNP 31 (1980) 260
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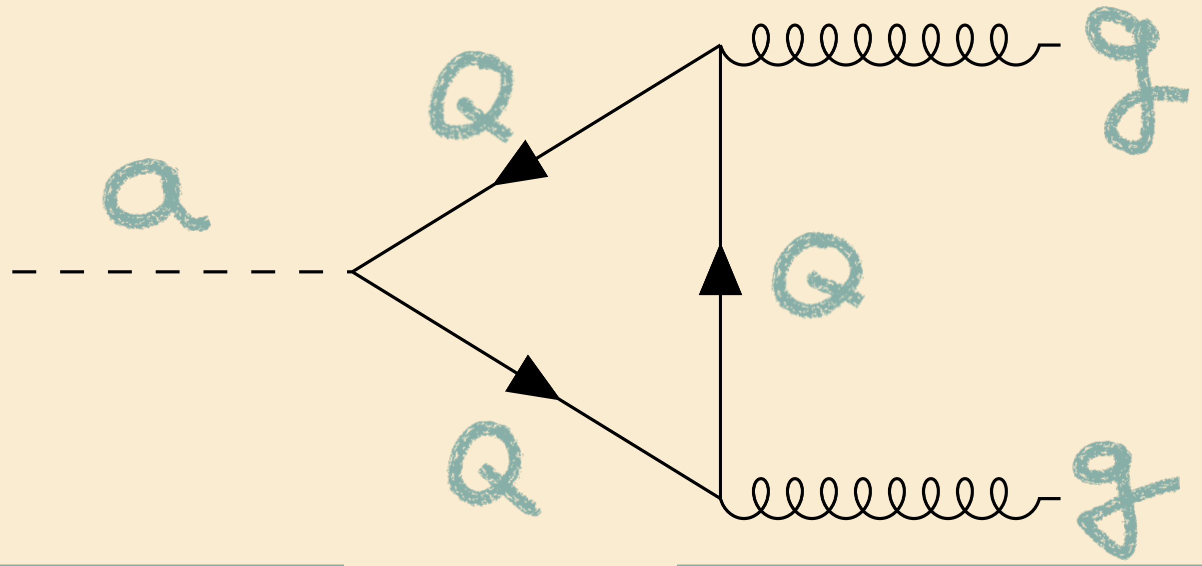

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KSVZ: Singlet + New Heavy Quarks

$$\mathcal{L}_{\mathrm{KSVZ}} = \bar{\mathcal{Q}}_L \mathcal{Q}_R \phi$$

The anomalous coefficients depend on the **representation** of the heavy quarks.

The couplings to **fermions** are **model dependent**

Kim PRL 43 (1979) 103
Shifman *et al.* NPB 166 (1980) 493.

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From where does the **flavour violation** arise?

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Condition for flavour violation: $[\mathcal{X}_f,\, V_f] \neq 0$ $\Longrightarrow$ **Necessary** condition: $\boxed{\mathcal{X}_f \not\propto \mathbf{1}_3}$

For flavour violation, we require **non-universal** PQ-charges

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Axiflavon/Flaxion

Ema, *et al.* 1612.05492 ,
Calibbi *et al.* 1612.08040

The Froggatt-Nielsen mechanism to explain the **flavour puzzle** contains a **pNGB** that may solve the Strong-CP problem

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$$\lambda = \frac{\langle\phi\rangle}{\Lambda} \simeq 0.2$$

$$Y^d_{\text{eff.}} \sim \begin{pmatrix} \lambda^7 & \lambda^6 & \lambda^6 \\ \lambda^6 & \lambda^5 & \lambda^5 \\ \lambda^4 & \lambda^3 & \lambda^3 \end{pmatrix}$$

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see also Arias-Aragón, Merlo 1709.07039,
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Non-universal charges, now in **4x4** flavour space. **Mixing with** the **heavy quark** induces axion flavour violation for lower generations (also in other sectors, e.g. Higgs).

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To obtain non-universal charges we may couple **different generations** to different **Higgs**.

$$H_1^\dagger H_2 \phi \;\to\; \mathcal{X}_1 = s_\beta^2,\; \mathcal{X}_2 = -c_\beta^2$$

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We will focus on this type of model in **this talk**.

see for instance, Björkeroth *et al.* 1811.09637,
Di Luzio, Guerrera, XPD, Rigolin 2304.04643
Cox *et al.* 2310.16348 …

Outline

1. Motivation
    1.1. Strong-CP Problem and axion solution
    1.2. Flavour violation in the axion
2. Flavour violation in DFSZ models
    2.1. **IR:** Flavour violation in the **axion**
    2.2. **UV:** Flavour violation in the **Higgs**
    2.3. **UV/IR** Connection
3. **Example** in the quark sector

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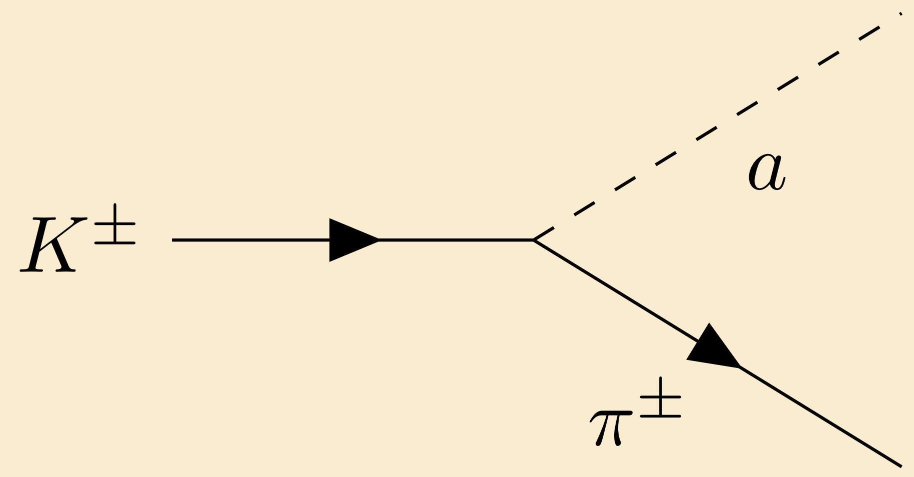
IR:



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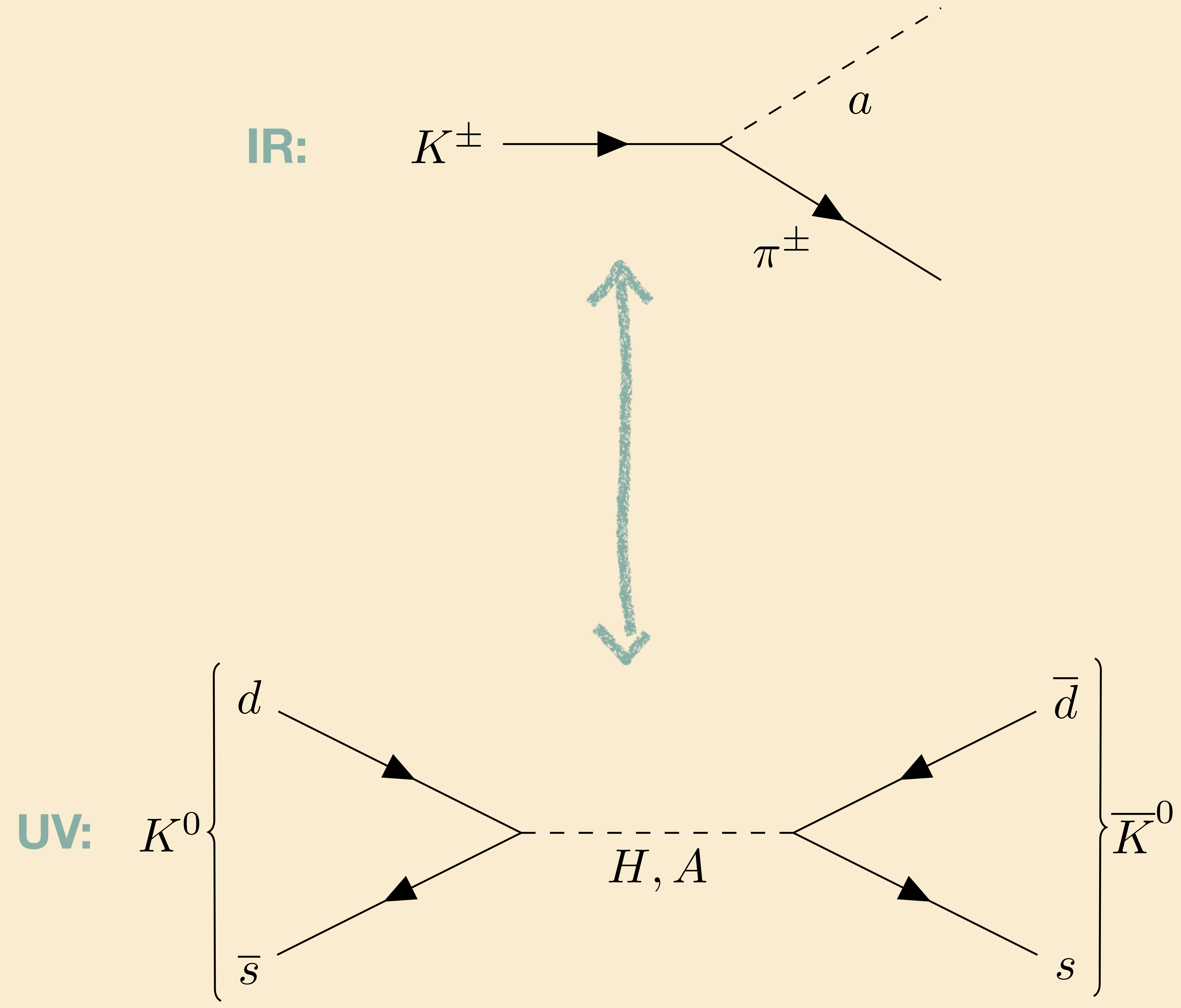

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$$\mathcal{L}_a \supset \sum_{f=u,d,e} \frac{\partial_\mu a}{f_a} \bar{f}_i \gamma^\mu \left((C_f^L)_{ij} P_L + (C_f^R)_{ij} P_R \right) f_j \, ,$$

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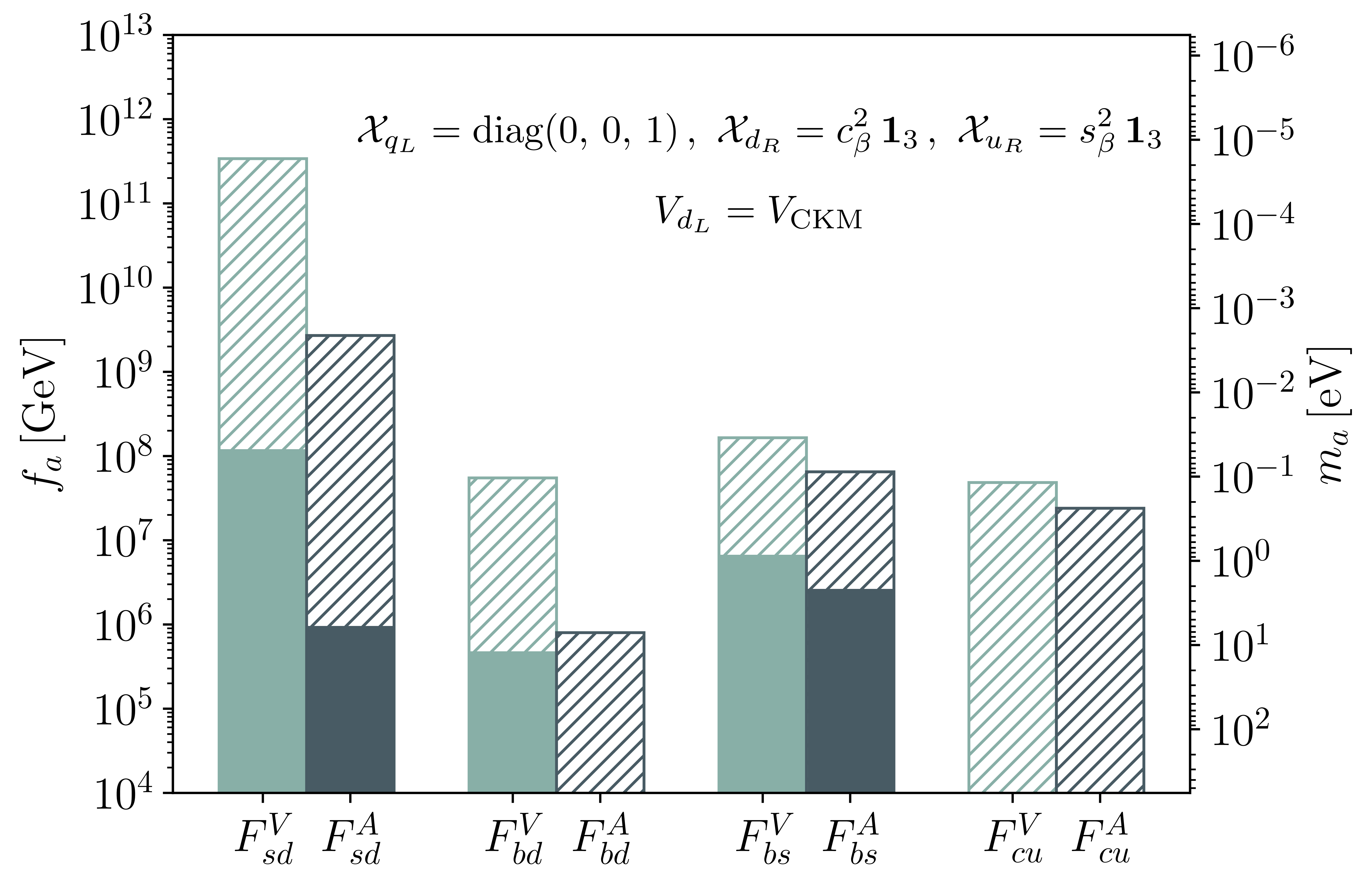
Bounds very 'assumption'-dependent:

- **Unknown** fermion-**mixing matrices**
- Accidental **protection** due to **charges**



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$$\mathcal{L}_Y^{\text{PQ-2HDM}} = \bar{q}_L(Y_1^d H_1 + Y_2^d H_2^d)d_R + \ldots$$

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Example:

$$\mathcal{X}_{q_L} = \text{diag}(0,\, 0,\, 1), \quad \mathcal{X}_{d_R} = \text{diag}(c_\beta^2,\, c_\beta^2,\, c_\beta^2)$$

New **heavy** degrees of freedom: $H,\ A,\ H^+$

SM Higgs: h

$$Y_1^d = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ y_{31}^d & y_{32}^d & y_{33}^d \end{pmatrix}, \quad Y_2^d = \begin{pmatrix} y_{11}^d & y_{12}^d & y_{13}^d \\ y_{21}^d & y_{22}^d & y_{23}^d \\ 0 & 0 & 0 \end{pmatrix} .$$

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What is the relation between the flavour violation in the Higgs and the axion?

2. UV/IR Connection

On the one hand, **flavour violation** is **determined** in the **IR** by the **charges** of the axion

$$C_d^{R,L} = V_{d_{R,L}}^\dagger \mathcal{X}_{d_{R,L}} V_{d_{R,L}}$$

On the other hand, in the **UV** completion, **flavour violation** is **dependent** on the **Yukawa** structure

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$$M_d = \frac{v}{\sqrt{2}} c_\beta Y_1^d + \frac{v}{\sqrt{2}} s_\beta Y_2^d$$

$$Y_1^d = \frac{\sqrt{2}}{v c_\beta} \left(\mathcal{X}_q M_d - M_d \mathcal{X}_d + \mathcal{X}_2 M_d \right) ,$$
$$Y_2^d = \frac{\sqrt{2}}{v s_\beta} \left(-\mathcal{X}_q M_d + M_d \mathcal{X}_d - \mathcal{X}_1 M_d \right) .$$

All flavour violation of the Higgs sector is also encoded in the charges!

$$\epsilon^d = \frac{\sqrt{2}}{v s_\beta} \left(-C_d^L \hat{M}_d + \hat{M}_d C_d^R - \cancel{\frac{\mathcal{X}_1}{2N}} \hat{M}_d \right) ,$$

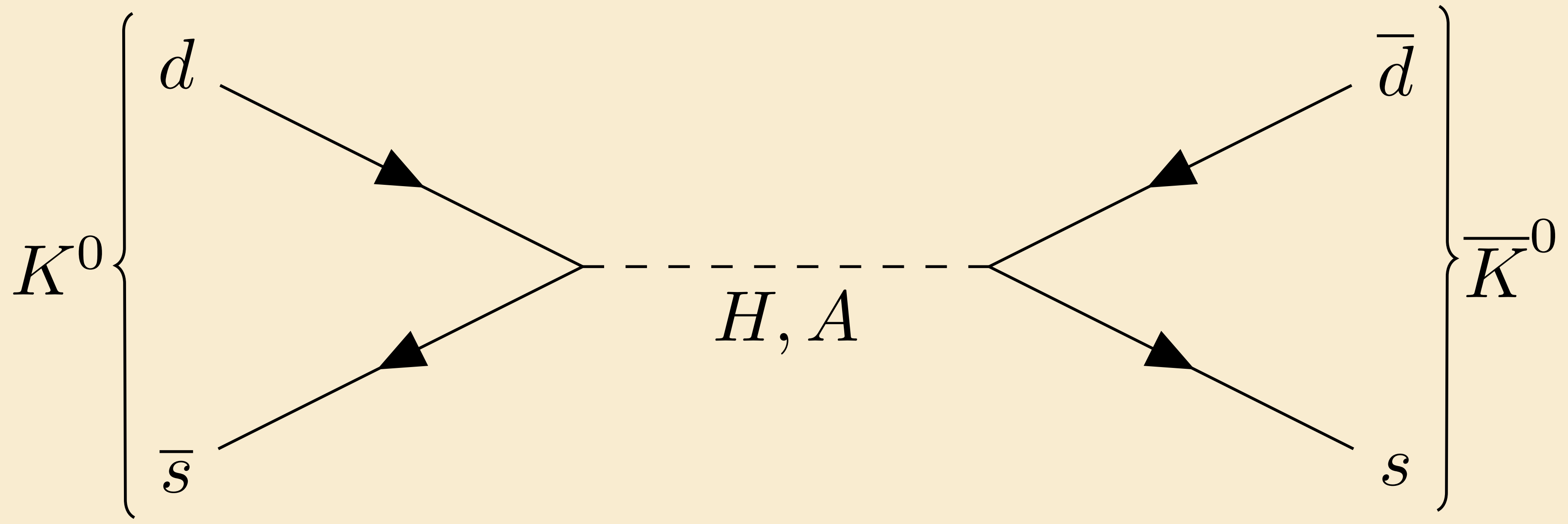
diagonal

Di Luzio, Guerrera, XPD, Rigolin 2304.04643

Outline

1. Motivation
    1.1. **Strong-CP Problem** and axion solution
    1.2. **Flavour violation** in the **axion**
2. Flavour violation in DFSZ models
    2.1. **IR:** Flavour violation in the **axion**
    2.2. **UV:** Flavour violation in the **Higgs**
    2.3. **UV/IR** Connection
3. **Example** in the quark sector

3. Examples: Quark sector



$$\frac{2|M_{12}^{\mathrm{NP}}|}{3.5\cdot 10^{-15}\,\mathrm{GeV}} \sim \left(\frac{4\,\mathrm{TeV}}{s_{2\beta}\,m_H}\right)^2 \left|\frac{\epsilon_{12}^d \epsilon_{21}^{d\,*}}{y_s^2\,\lambda^2}\right| ,$$

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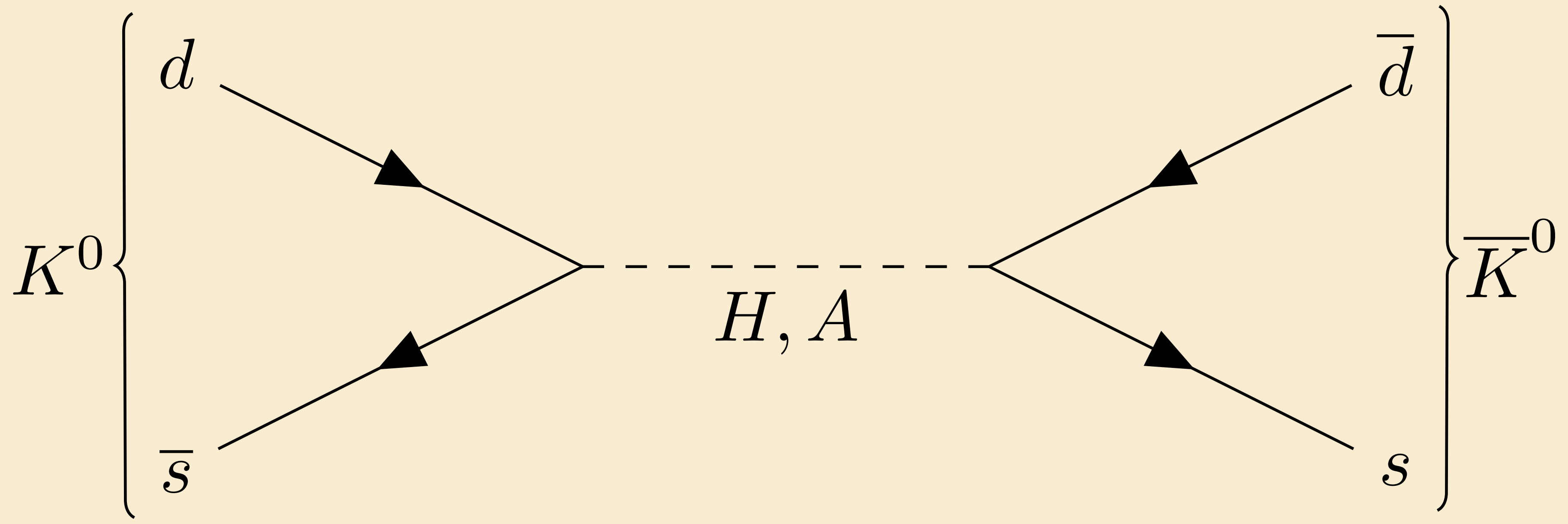

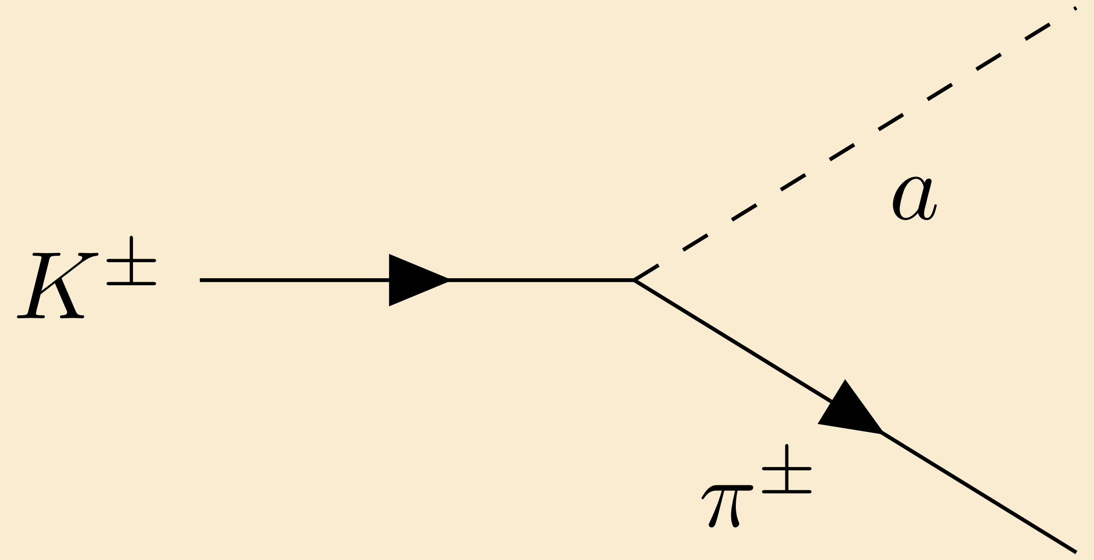

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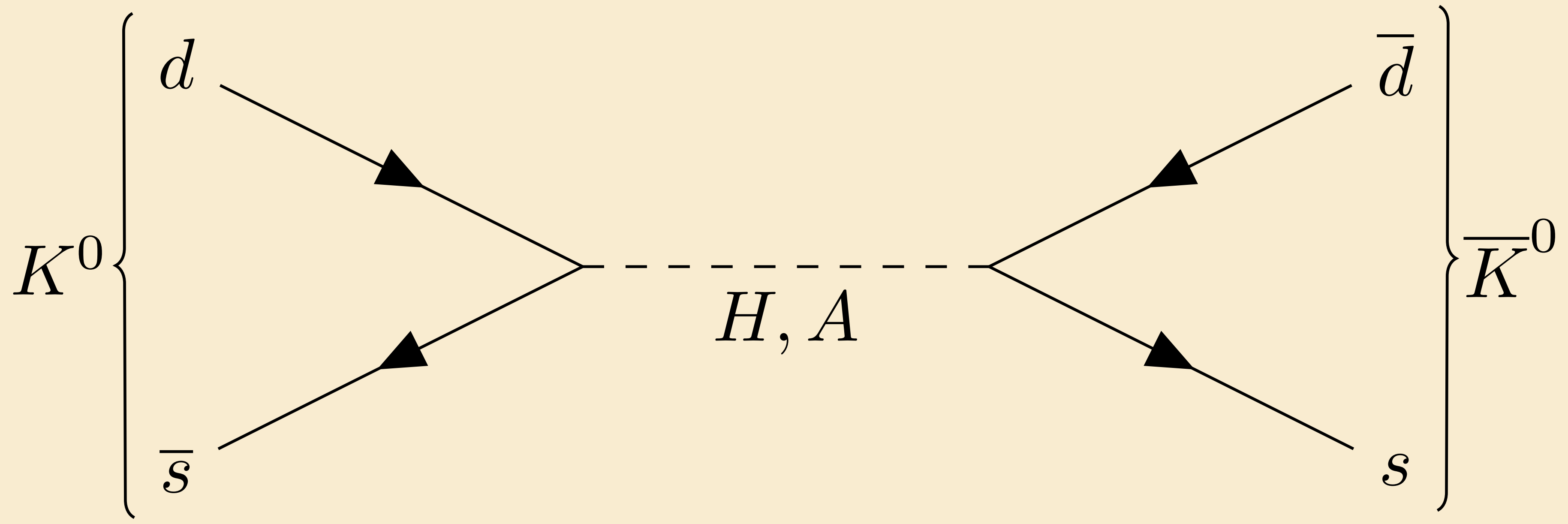

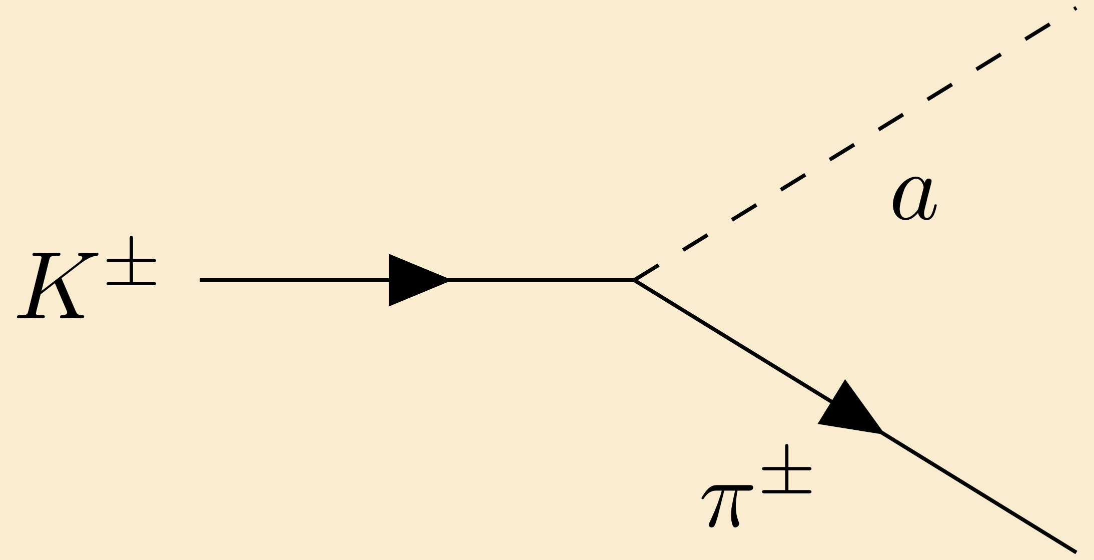

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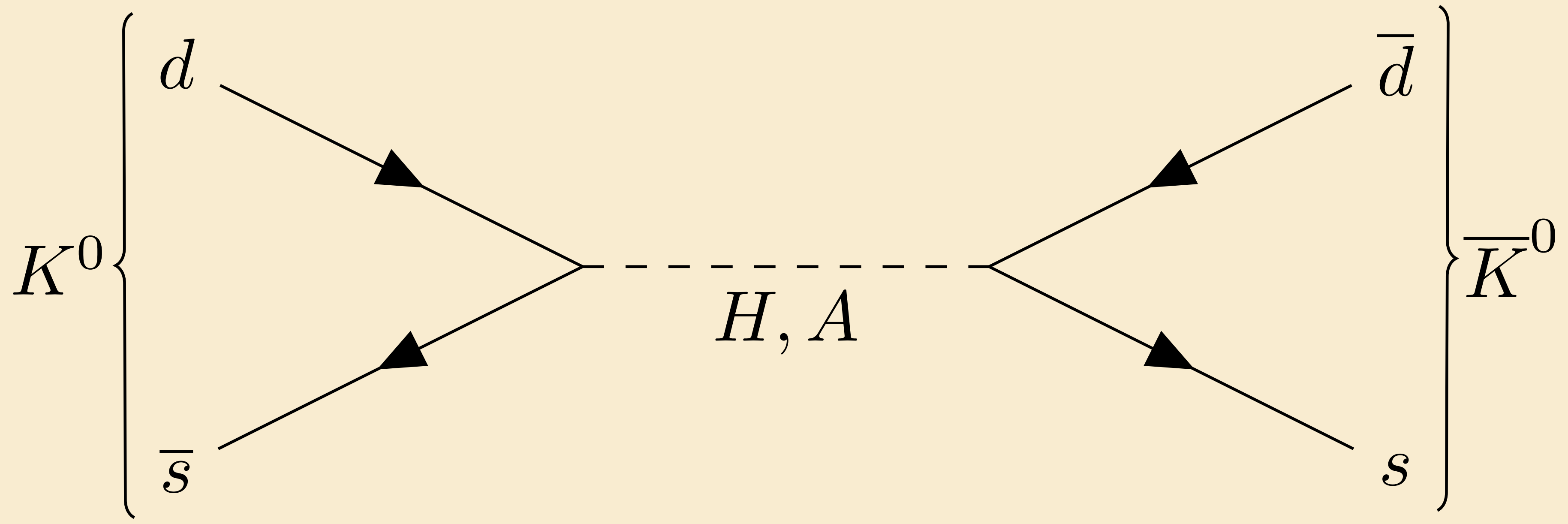

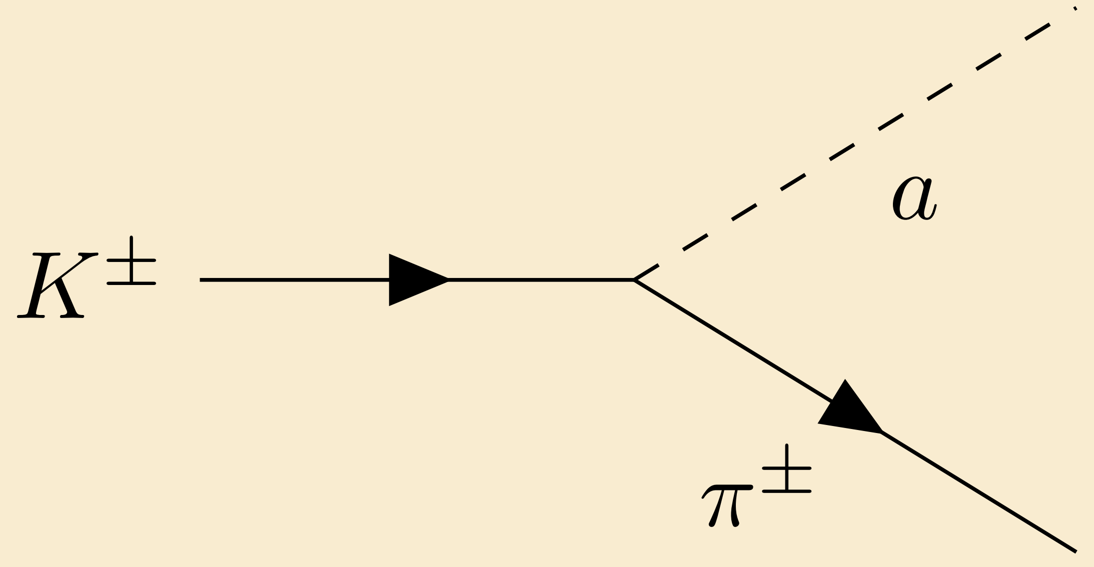

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Simplifications:

- only flavour violation in LH-quarks or RH-quarks
- Alignment limit: $c_{\alpha-\beta} = 0 \quad m_A \simeq m_H$

$$\left(\frac{f_a}{10^{11}\,\mathrm{GeV}}\right)^2 \left(\frac{1\,\mathrm{TeV}}{s_{2\beta}\,m_H}\right)^2 \left(\frac{\mathrm{Br}(K\to\pi a)}{7.3\cdot 10^{-11}}\right) = \frac{2\,|M_{12}^{\mathrm{NP}}|}{3.5\cdot 10^{-15}\,\mathrm{GeV}}$$

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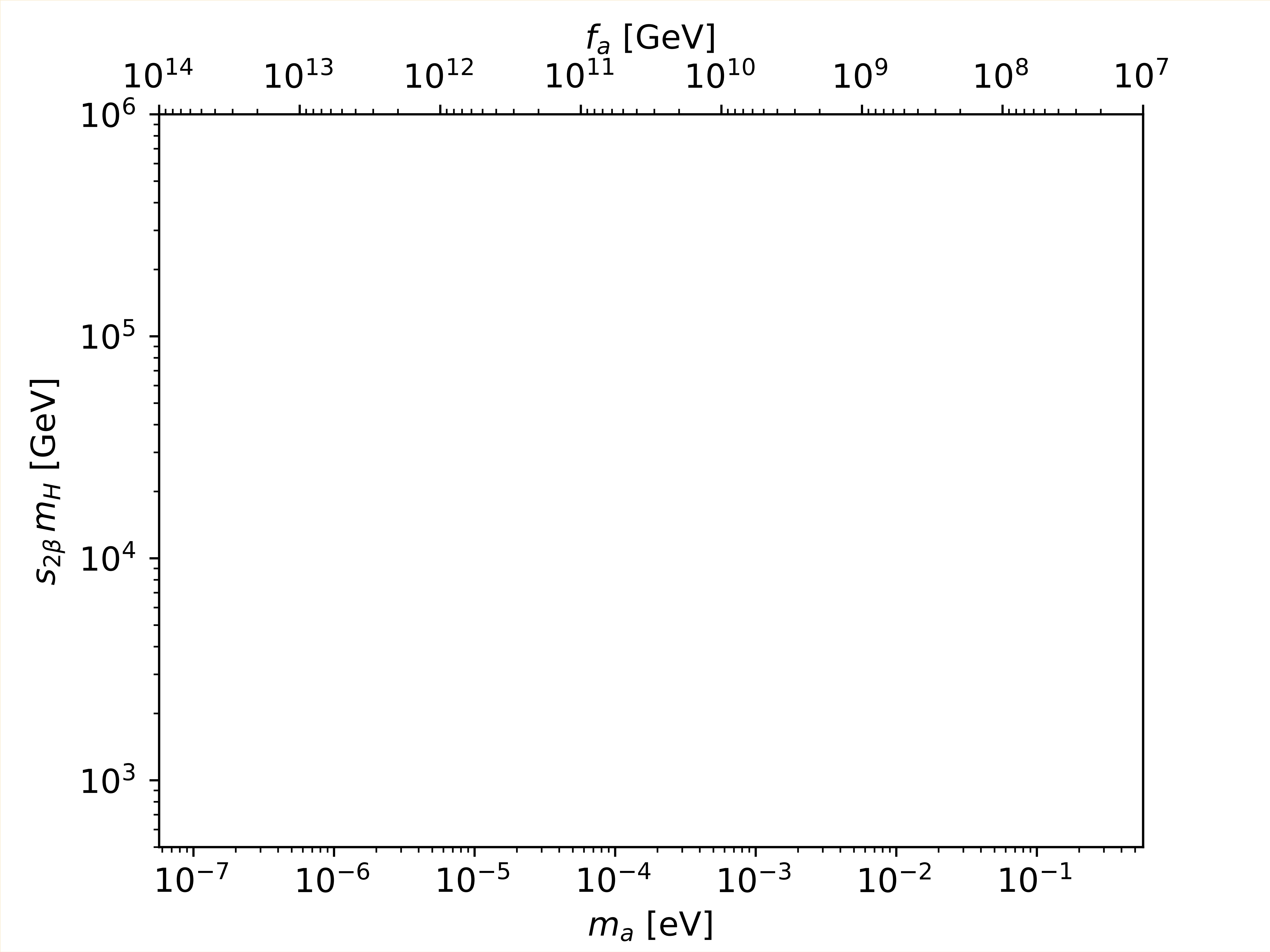

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Flavour violation in the $s \to d$ transition

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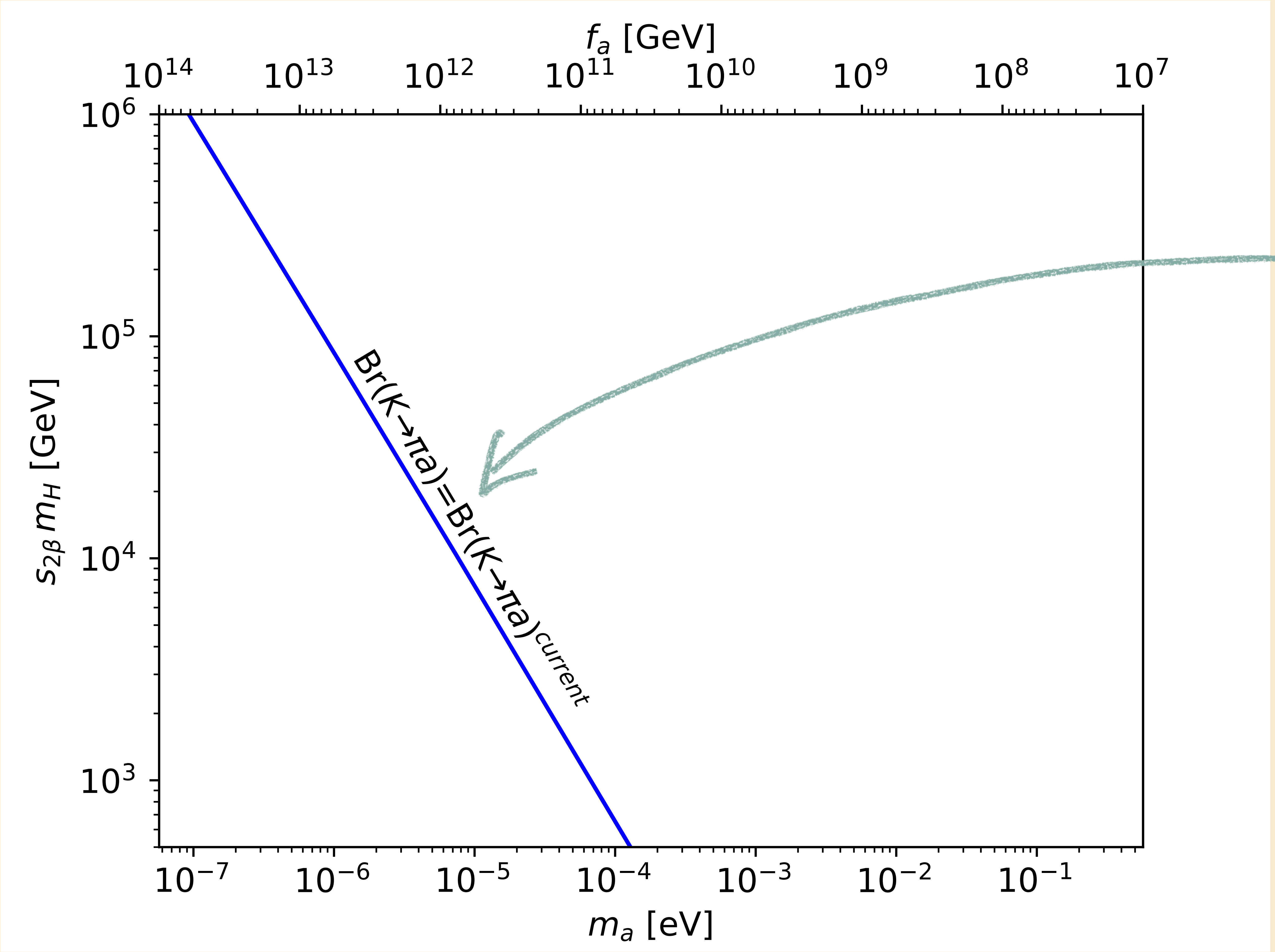

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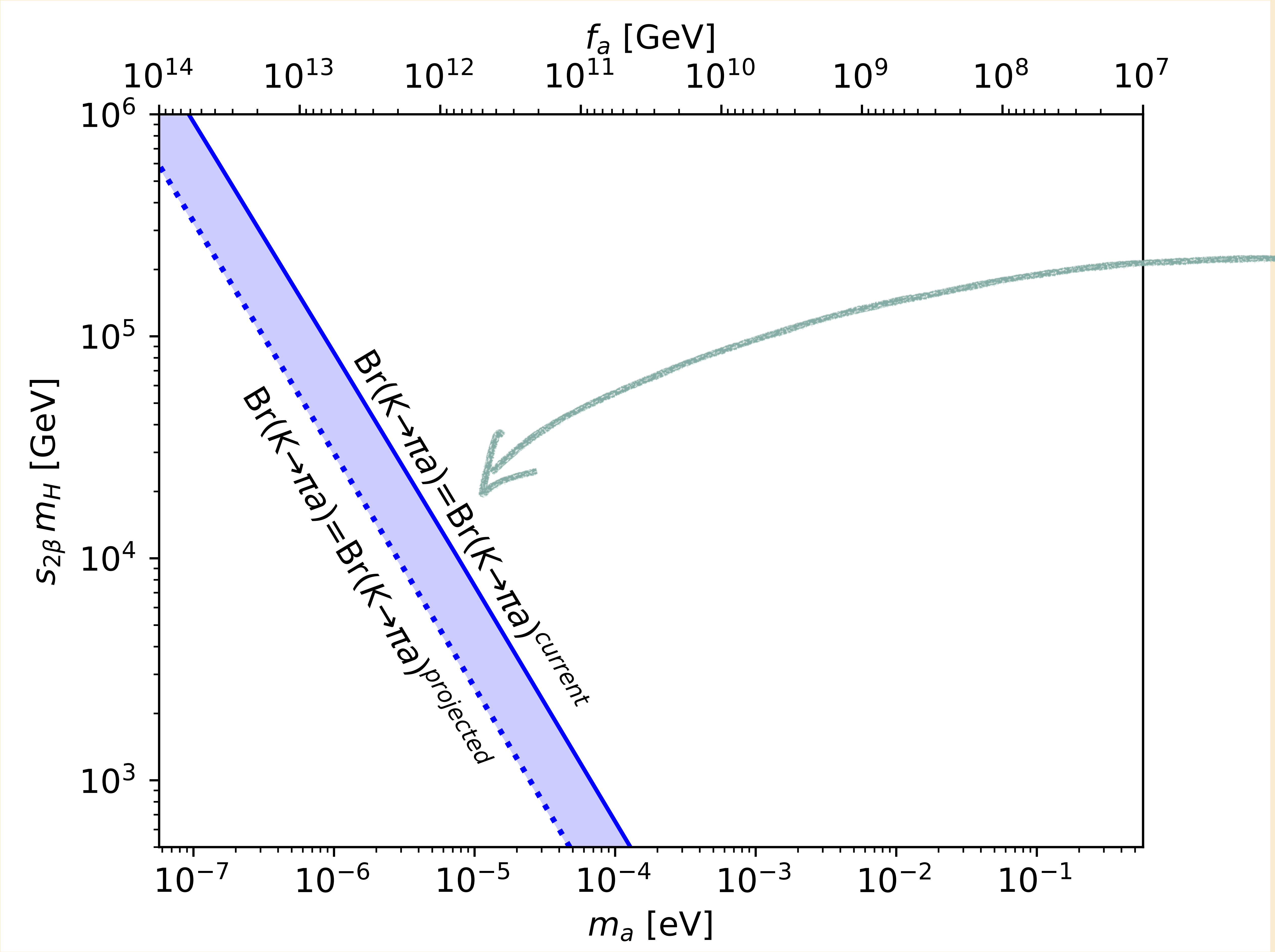

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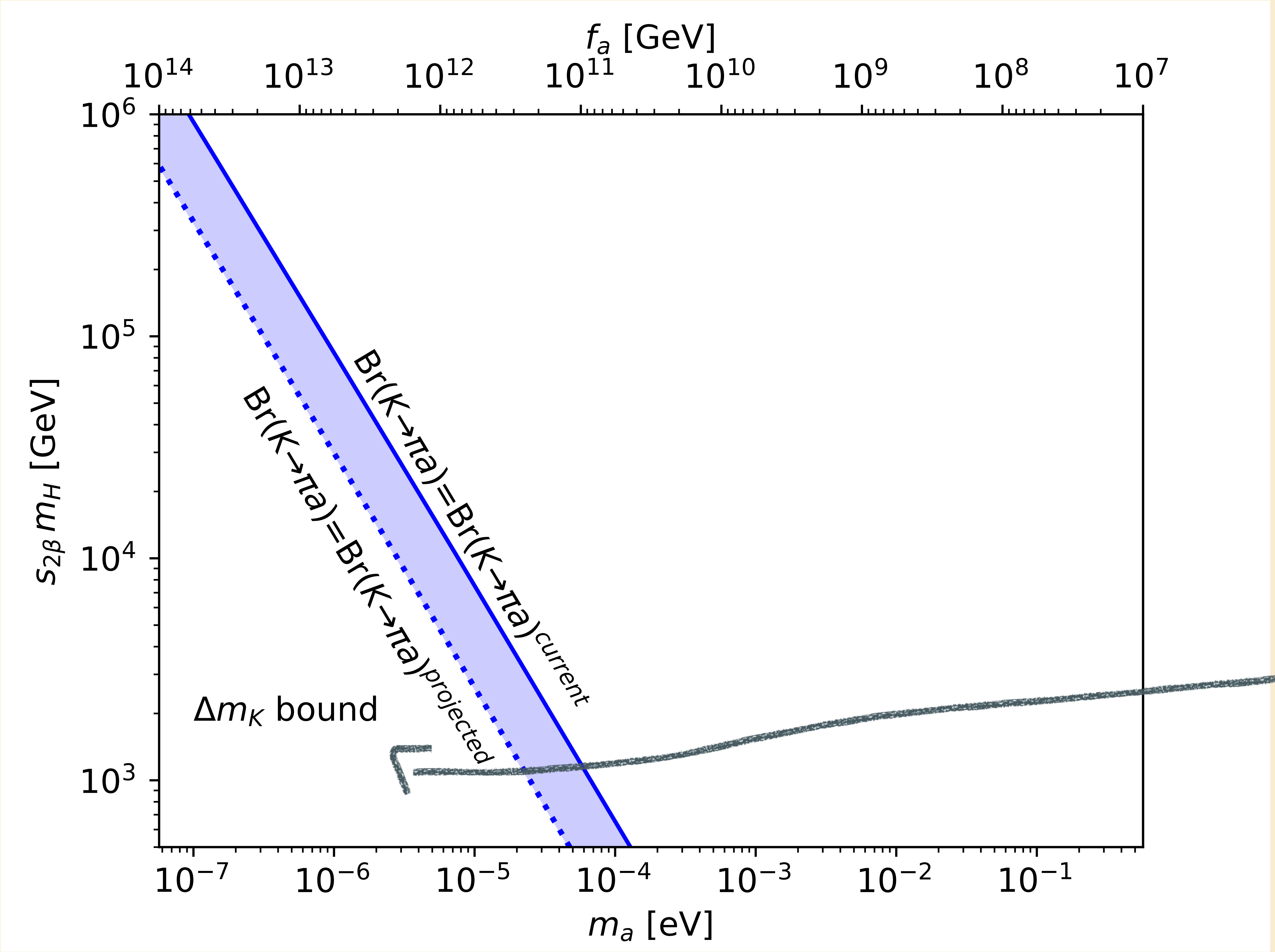

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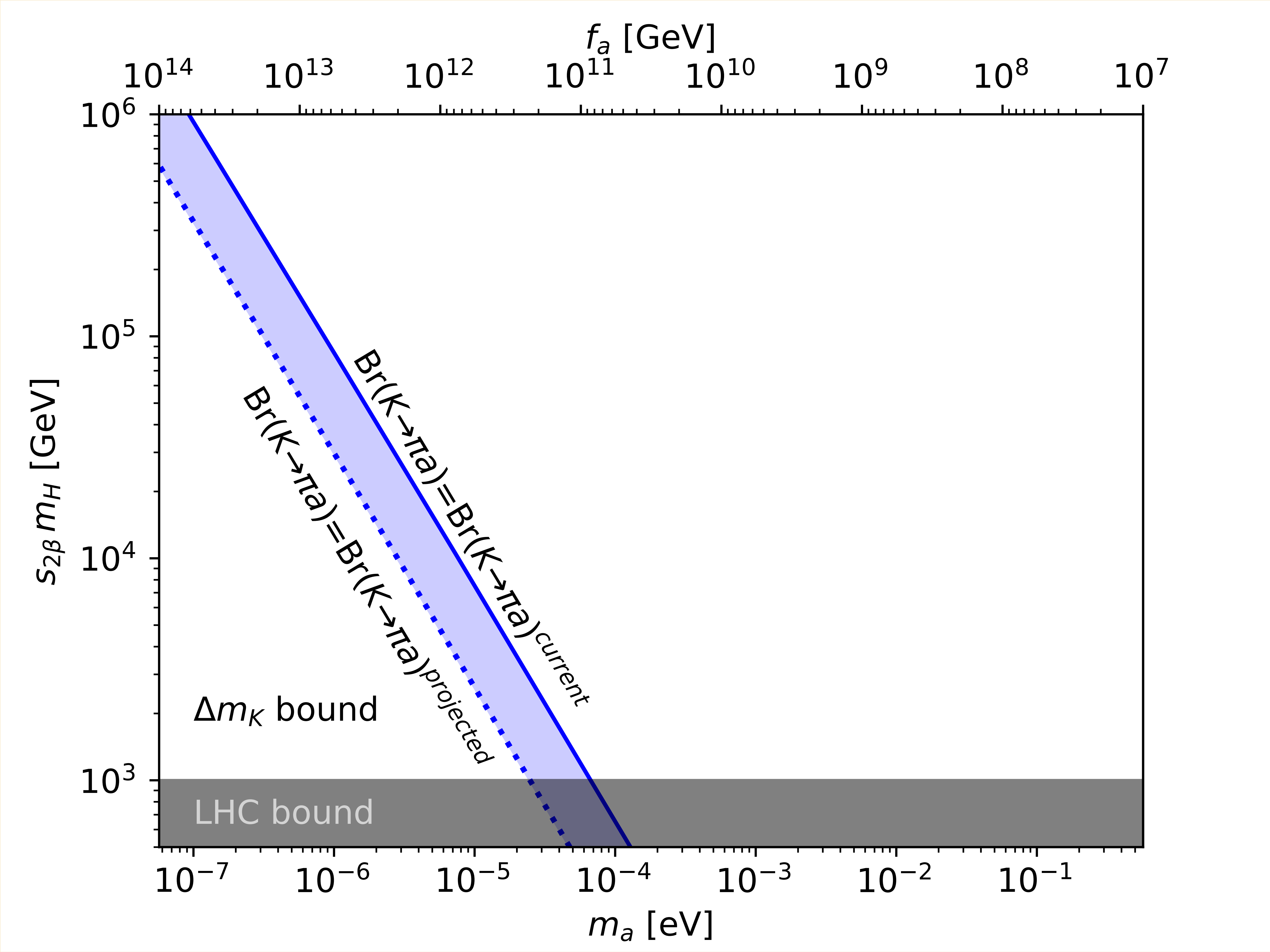

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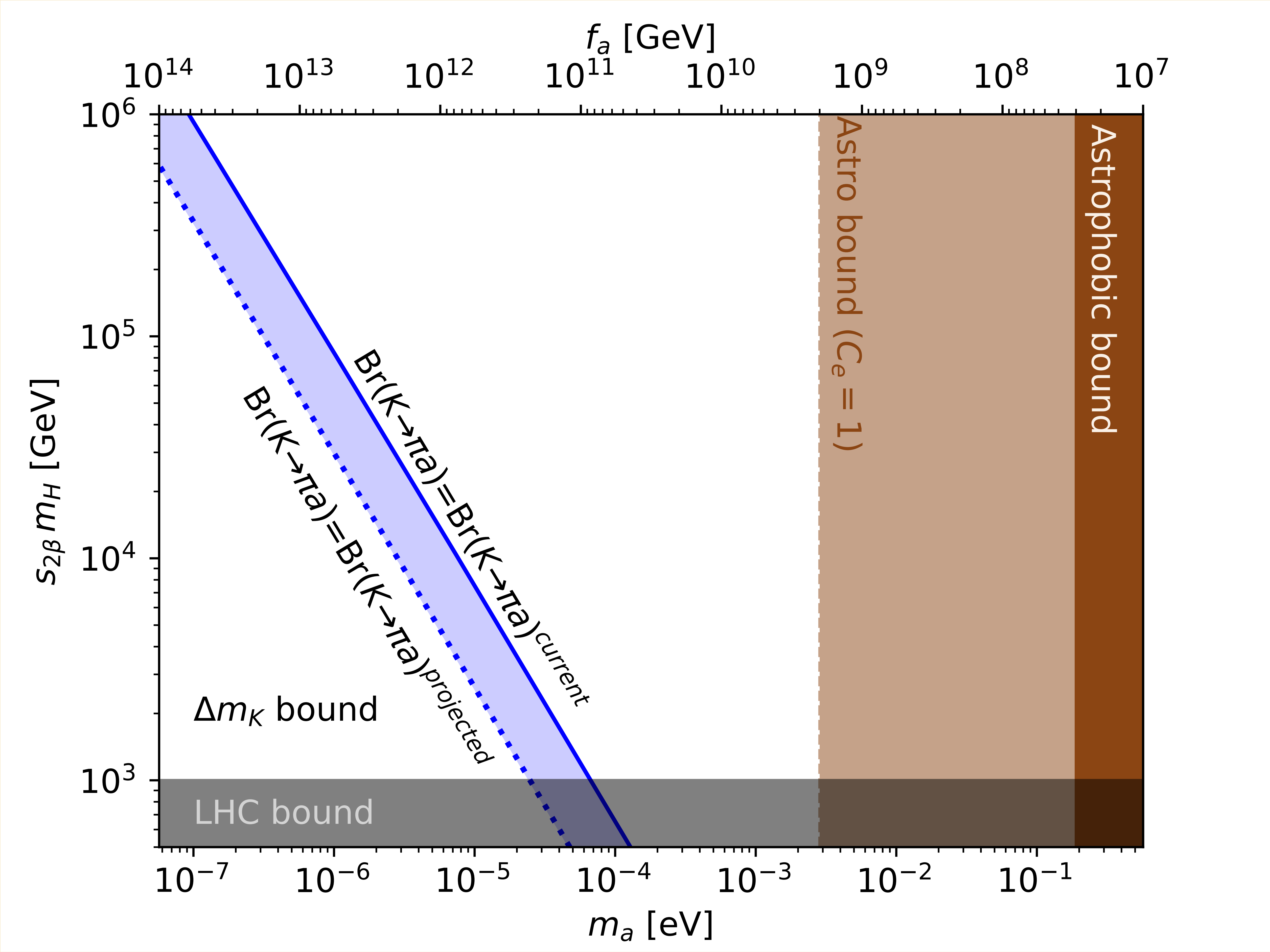

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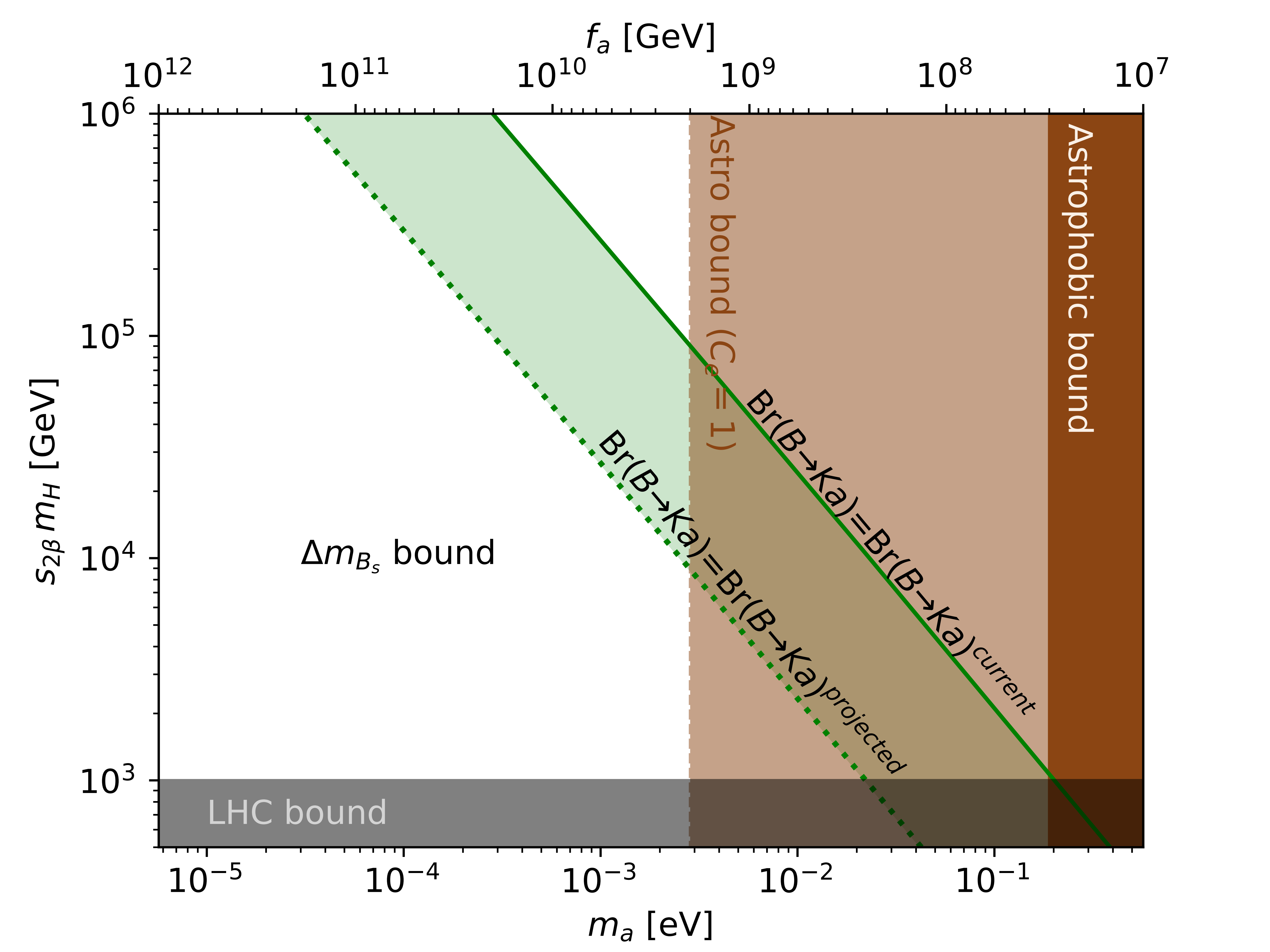
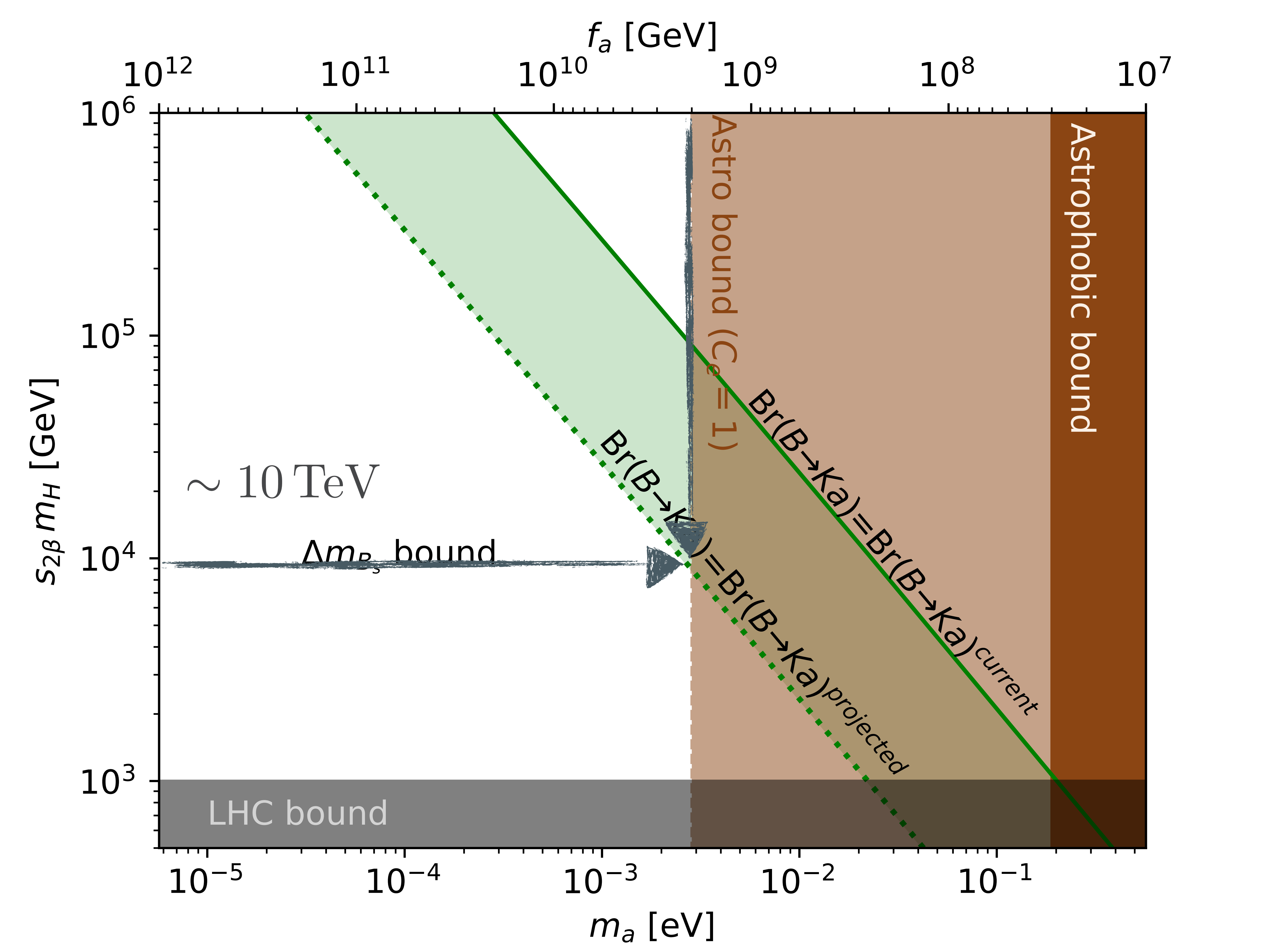


$$\left(\frac{f_a}{8.8\cdot 10^7\,\mathrm{GeV}}\right)^2 \left(\frac{1\,\mathrm{TeV}}{s_{2\beta}\, m_H}\right)^2 \left(\frac{\mathrm{Br}(B\to Ka)}{7.1\cdot 10^{-6}}\right) = \frac{2\,|M_{12}^{\mathrm{NP}}|}{1.2\cdot 10^{-11}\,\mathrm{GeV}}$$

Flavour violation in the $b \to s$ transition

3. Examples: Quark sector



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Conclusions

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Conclusions

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- **LHC + astrophysical bounds** combine in an interesting **interplay**, e.g. astrophysics giving lower bounds on the mass of the heavy scalars.

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- Easily expandable to other observables $h \to \tau\,\mu(e)\,,\ \tau \to a\,\mu(e)\ \ldots$

Conclusions

- **Flavour** violation in the **UV completion** is in **1-to-1 correspondence** with the flavour violation of the **axion**.
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Thanks for your attention!

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BACKUP

Scalar Potential: Alignment Limit

$$V(\Phi_1,\,\Phi_2) = M_{11}^2\,\Phi_1^\dagger\Phi_1 + M_{22}^2\,\Phi_2^\dagger\Phi_2 - \left(M_{12}\Phi_1^\dagger\Phi_2 + \text{h.c.}\right) + \frac{\Lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\Lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \Lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \Lambda$$

$$+\left\{\frac{1}{2}\Lambda_5(\Phi_1^\dagger\Phi_2)^2 + \left[\Lambda_6(\Phi_1^\dagger\Phi_1) + \Lambda_7(\Phi_2^\dagger\Phi_2)\right]\Phi_1^\dagger\Phi_2 + \text{h.c.}\right\},$$

$$H_1 = \begin{pmatrix} G^+ \\ -\frac{1}{\sqrt{2}}(v + c_{\alpha-\beta}H - s_{\alpha-\beta}h - iG^0) \end{pmatrix}, \quad H_2 = \begin{pmatrix} H^+ \\ -\frac{1}{\sqrt{2}}(c_{\alpha-\beta}h + s_{\alpha-\beta}H - iA) \end{pmatrix}$$

$$\begin{pmatrix} m_H^2 & 0 \\ 0 & m_h^2 \end{pmatrix} = \begin{pmatrix} c_{\alpha-\beta} & s_{\alpha-\beta} \\ -s_{\alpha-\beta} & c_{\alpha-\beta} \end{pmatrix} \begin{pmatrix} \Lambda_1 v^2 & \Lambda_6 v^2 \\ \Lambda_6 v^2 & m_A^2 + \Lambda_5 v^2 \end{pmatrix} \begin{pmatrix} c_{\alpha-\beta} & -s_{\alpha-\beta} \\ s_{\alpha-\beta} & c_{\alpha-\beta} \end{pmatrix},$$

Alignment limit:

$$\Phi_1 = \begin{pmatrix} G^+ \\ -\frac{1}{\sqrt{2}}(v - h - iG^0) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} H^+ \\ -\frac{1}{\sqrt{2}}(H - iA) \end{pmatrix}$$

$$c_{\alpha-\beta} = 0 \qquad c_{\alpha-\beta}^2 = \frac{\Lambda_6^2 v^4}{(m_H^2 - m_h^2)(m_H^2 - \Lambda_1 v^2)}$$

Two ways of achieving alignment:

Decoupling:

$$m_H^2 \simeq m_A^2 \gg v^2$$

$$m_h^2 \simeq \Lambda_1 \frac{v^2}{2}$$

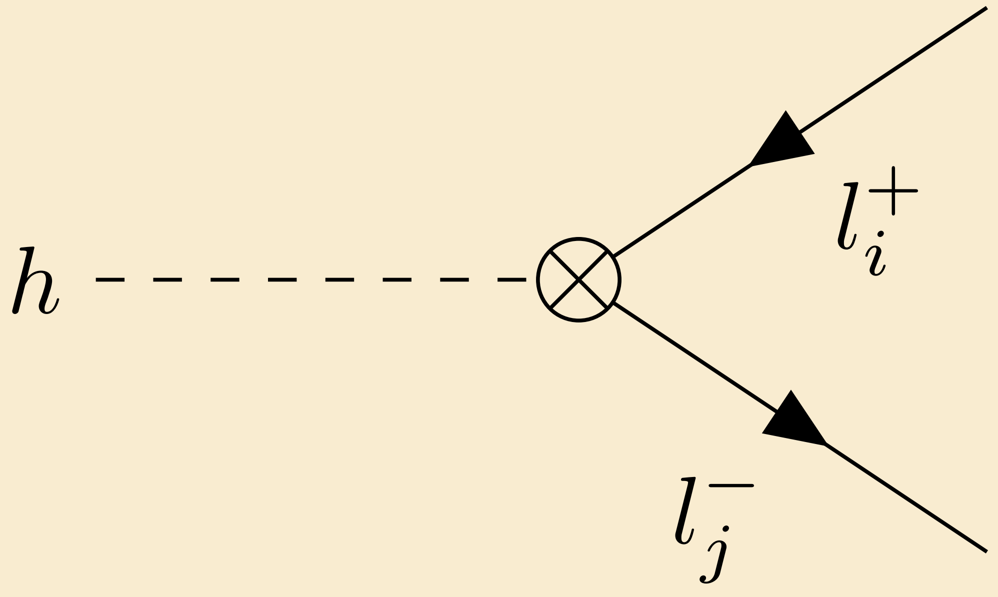
Non-decoupling: $\Lambda_6 \to 0$

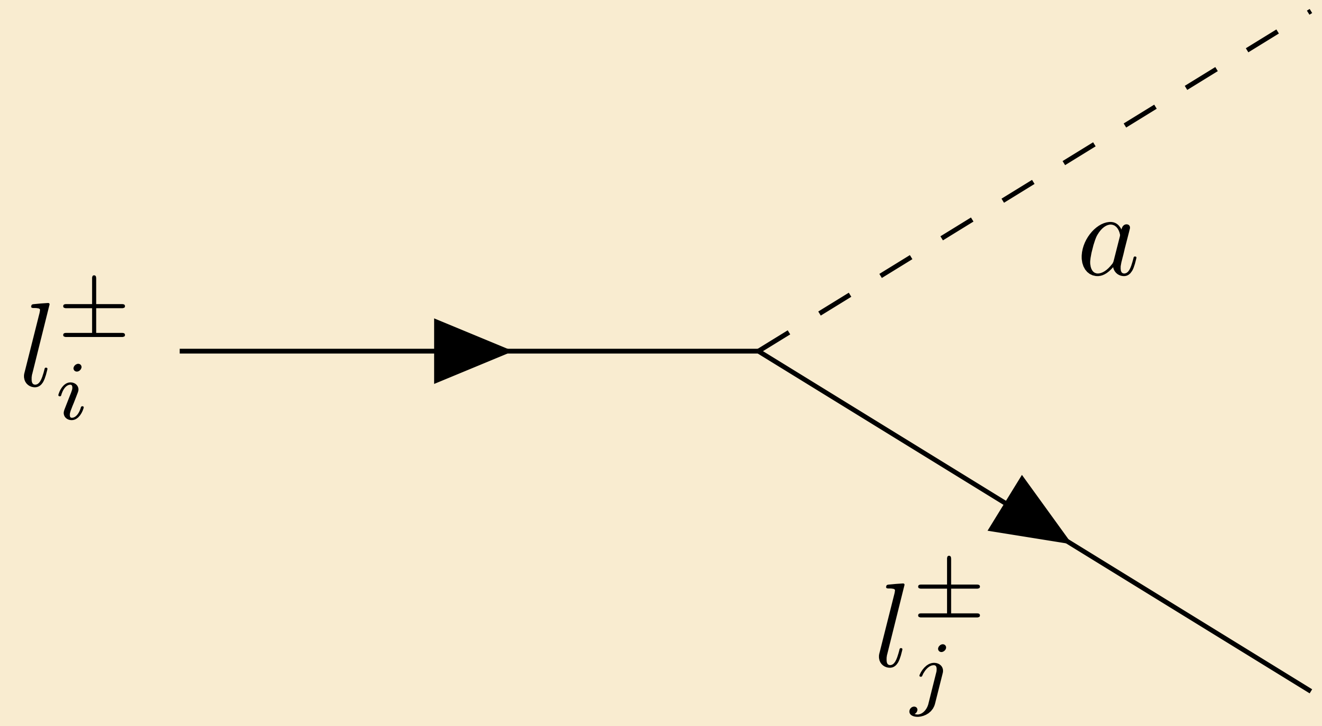
$$m_A^2 + \Lambda_5 v^2 \simeq m_h^2$$

$$m_H^2 \simeq \Lambda_1 \frac{v^2}{2}$$

The new scalars can be at the EW scale

Lepton Flavour Violation Example





$$\mathrm{BR}(h \to l_i l_j) \simeq \frac{m_h}{16\pi\Gamma_h}\left(\frac{c_{\alpha-\beta}}{s_\beta c_\beta}\right)^2 \frac{m_{l_i}^2}{v^2}|(C_e^{L,R})_{ij}|^2\,,$$

$$\mathrm{BR}(l_i \to l_j\, a) \simeq \frac{m_{l_i}^3}{16\pi\Gamma_{l_i}}\frac{|(C_e^{L,R})_{ij}|^2}{2f_a^2}$$

$$\mathrm{BR}(h \to l_i l_j) \simeq \mathrm{BR}(l_i \to a\, l_j)\frac{2m_h}{m_{l_i}}\frac{\Gamma_{l_i}}{\Gamma_h}\frac{f_a^2}{v^2}\left(\frac{c_{\alpha-\beta}}{c_\beta s_\beta}\right)^2$$

Some mild deviations at ATLAS

$$\mathrm{BR}(h \to \tau e) = 0.09 \pm 0.06\,\%$$

ATLAS 2302.05225

$$\mathrm{BR}(h \to \tau\mu) = 0.11^{+0.05}_{-0.04}\,\%$$

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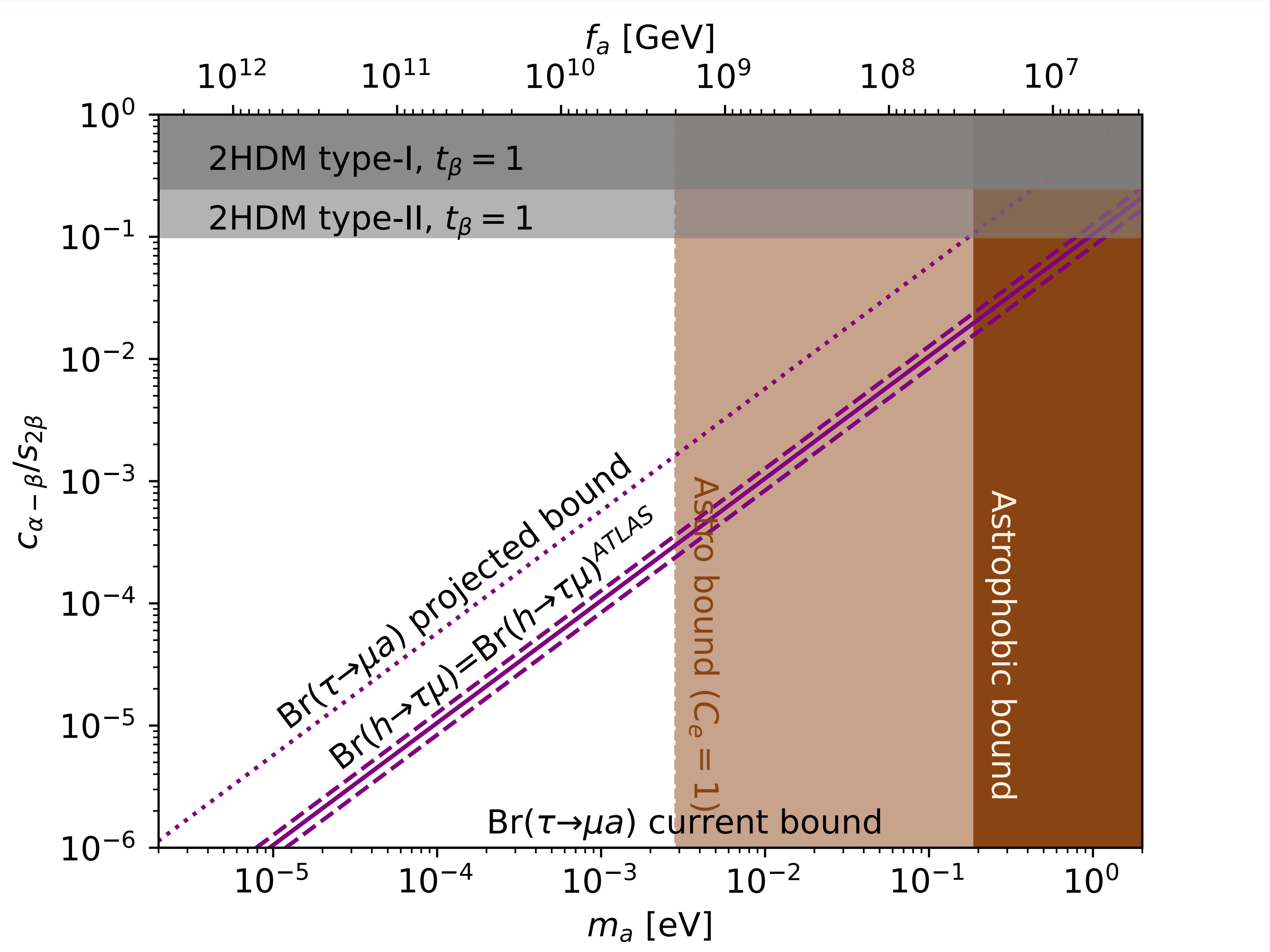

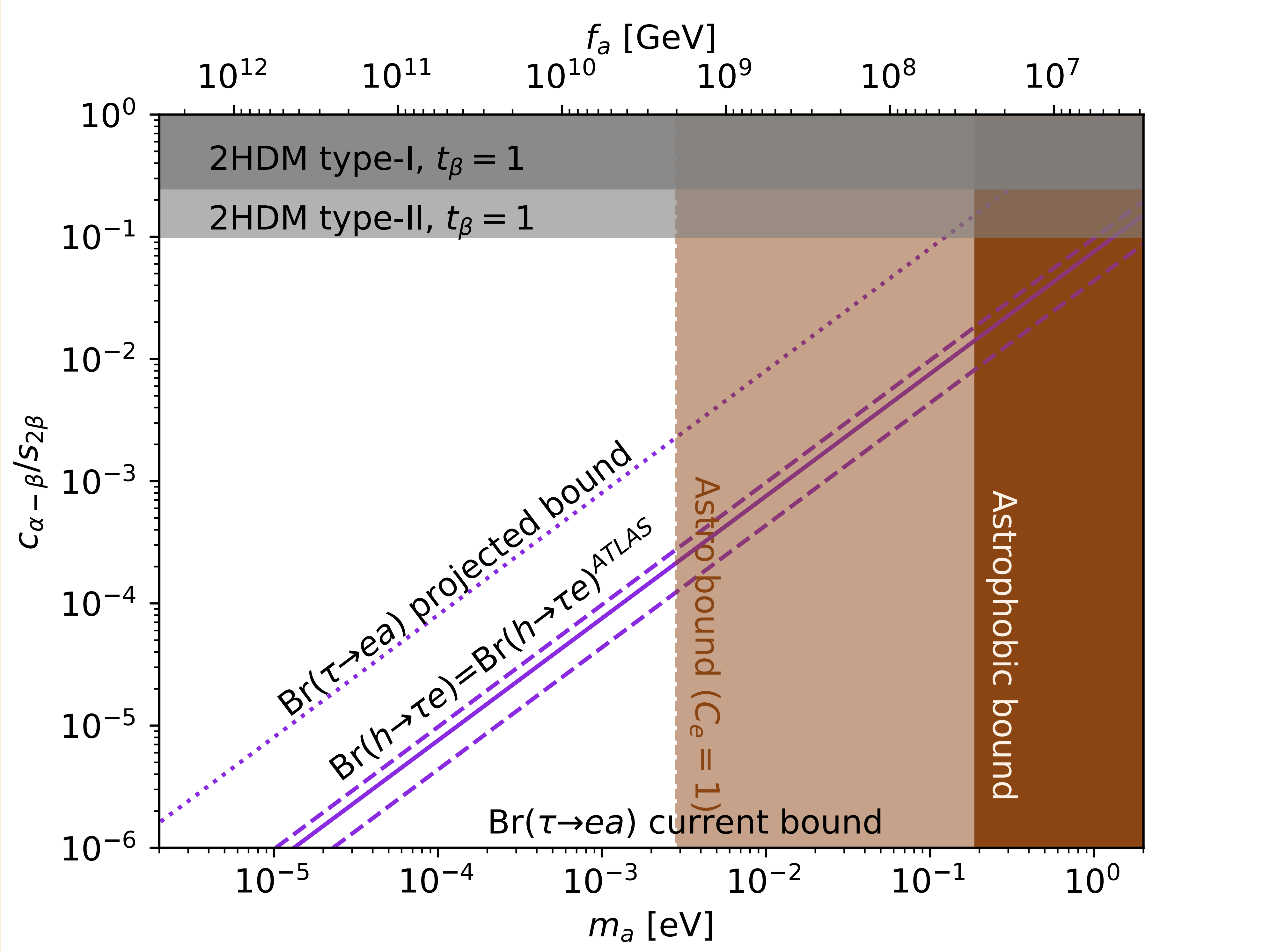

$$\mathrm{BR}(h \to l_i l_j) \simeq \mathrm{BR}(l_i \to a\, l_j) \frac{2m_h}{m_{l_i}} \frac{\Gamma_{l_i}}{\Gamma_h} \frac{f_a^2}{v^2} \left(\frac{c_{\alpha-\beta}}{c_\beta s_\beta}\right)^2$$