UV/IR flavour connection in axion models

Invisibles23 Workshop

Xavier Ponce Díaz

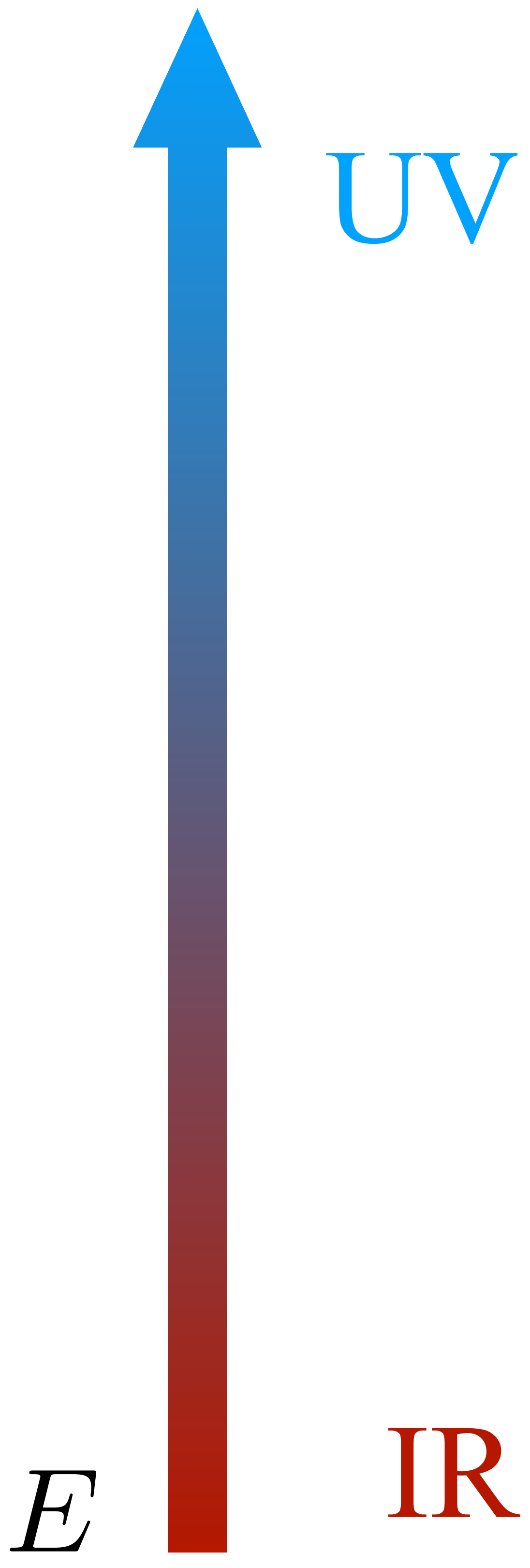
based on: JHEP 06 (2023) 046, arXiv:2304.04643
with Luca Di Luzio, Alfredo Guerrera, Stefano Rigolin

Università degli Studi di Padova

INFN

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

What is this talk about?



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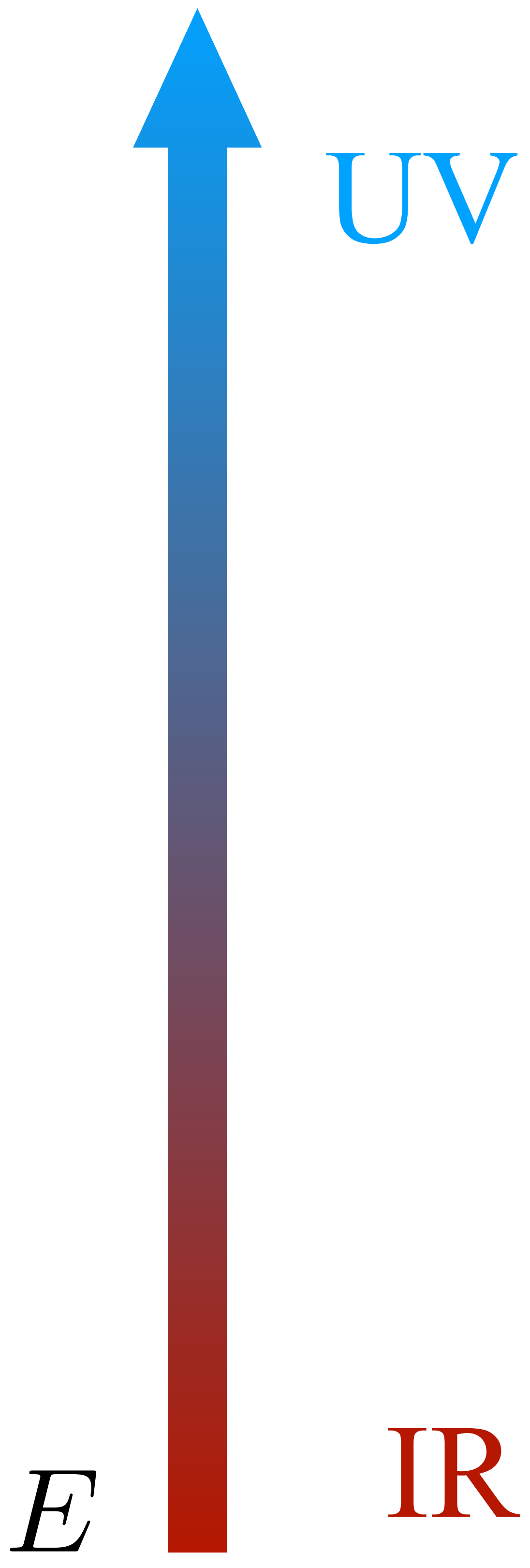

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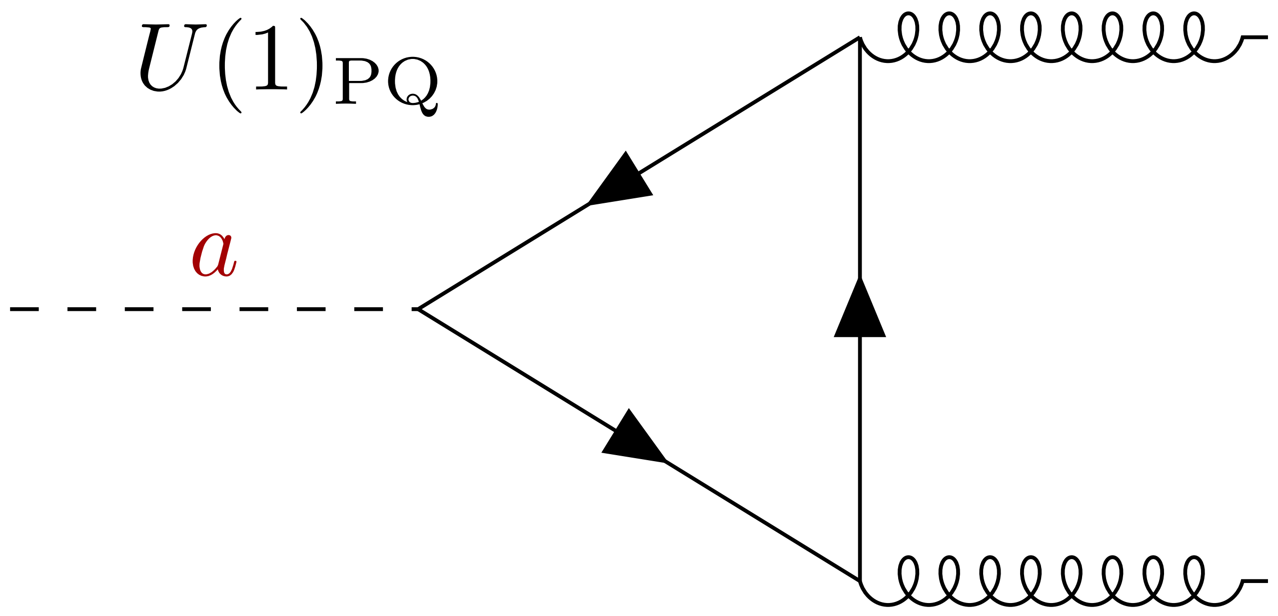
$U(1)_{\mathrm{PQ}}$



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PQ-WW: 2HDM — $f_a \sim v$ ✗ Ruled out!

KSVZ: Singlet + New Heavy Quarks

DFSZ: Singlet + 2HDM + SM fermions

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E

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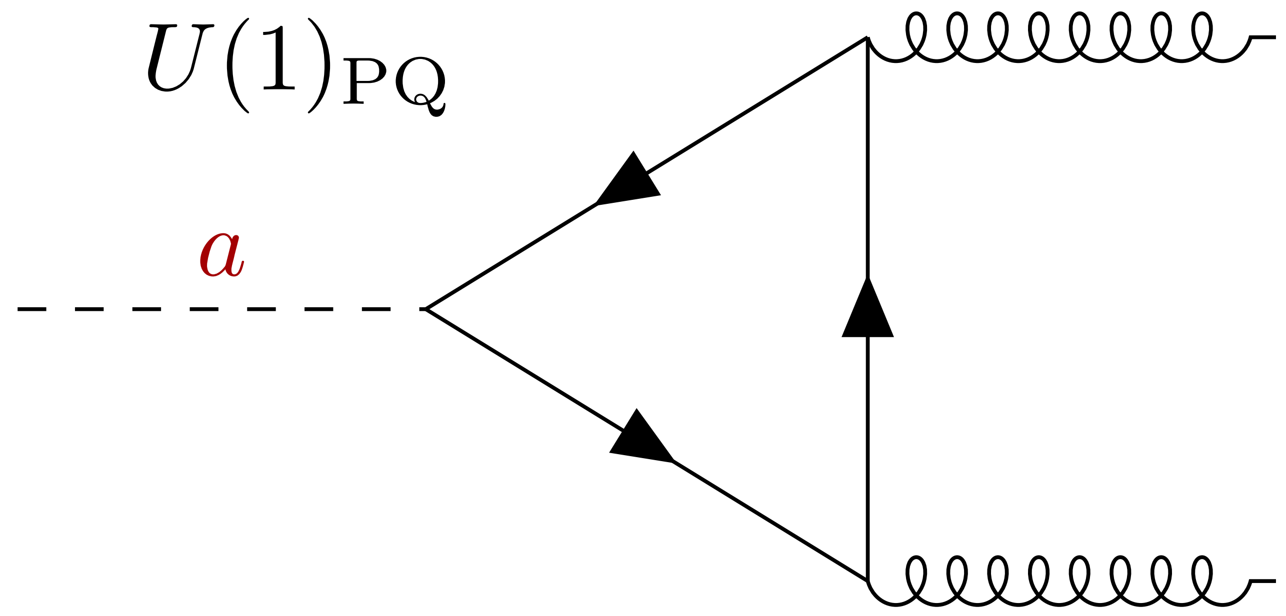

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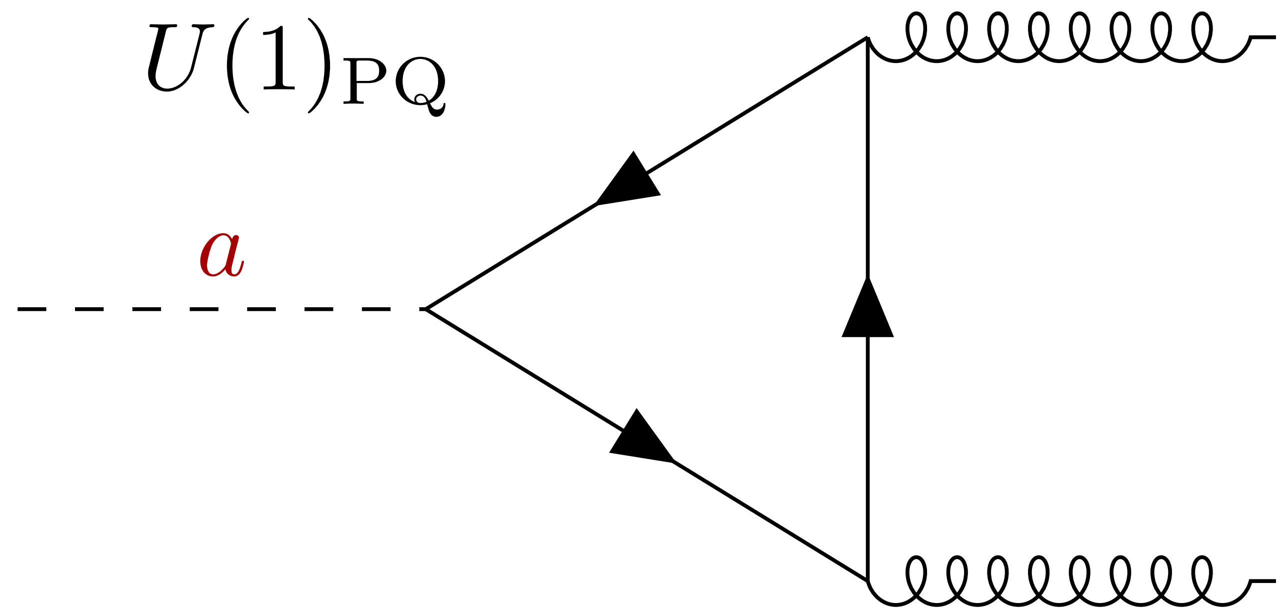

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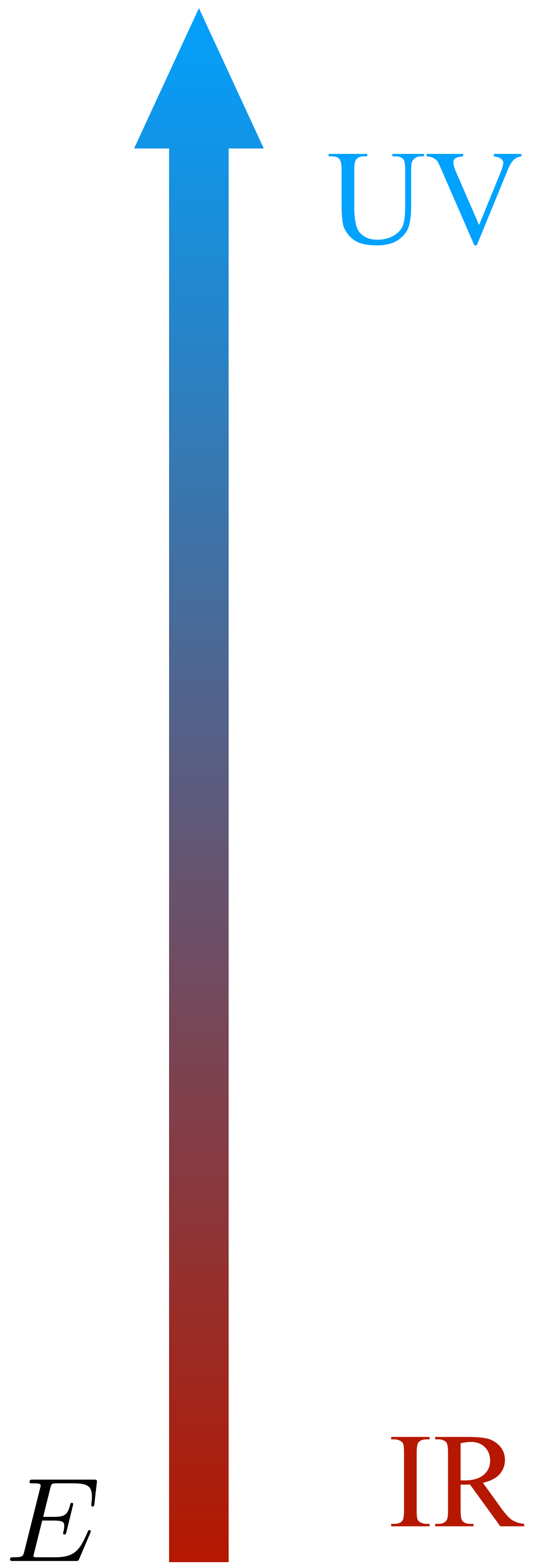

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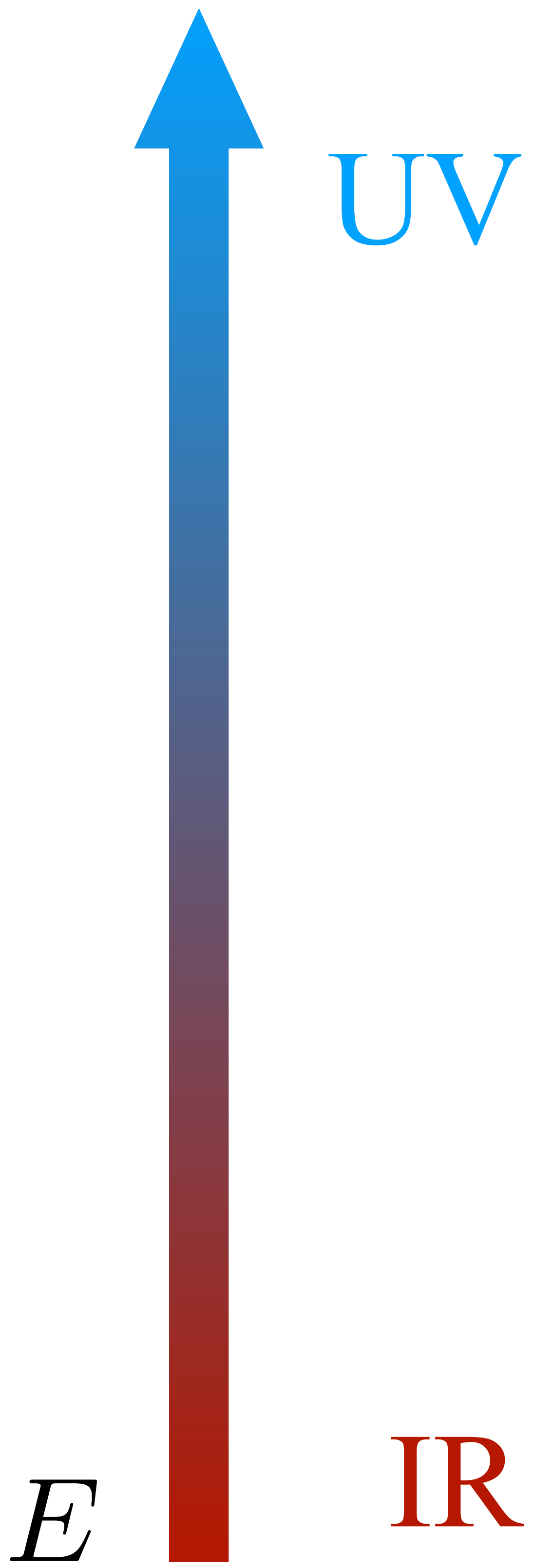

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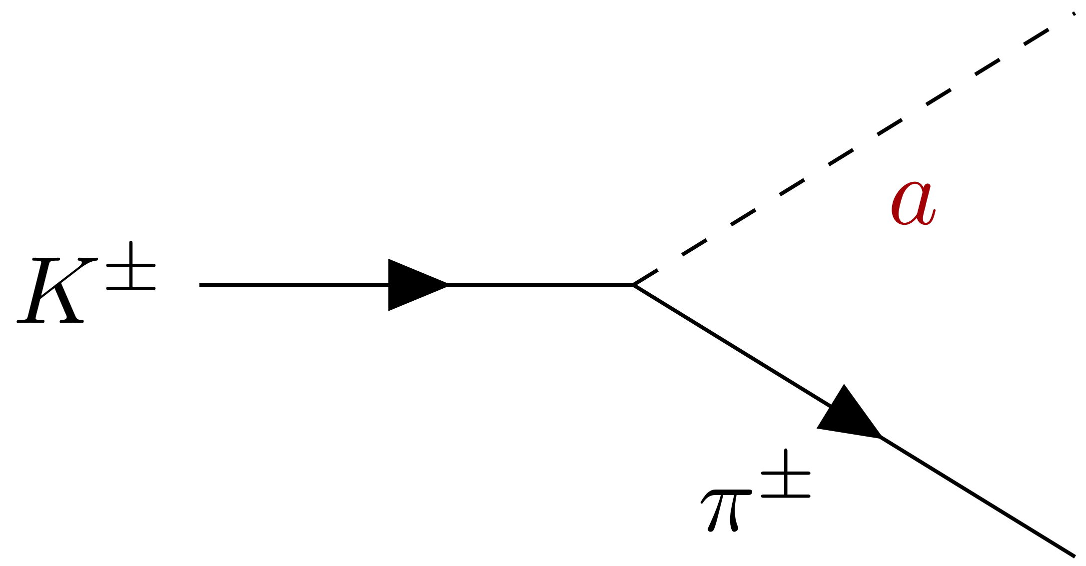

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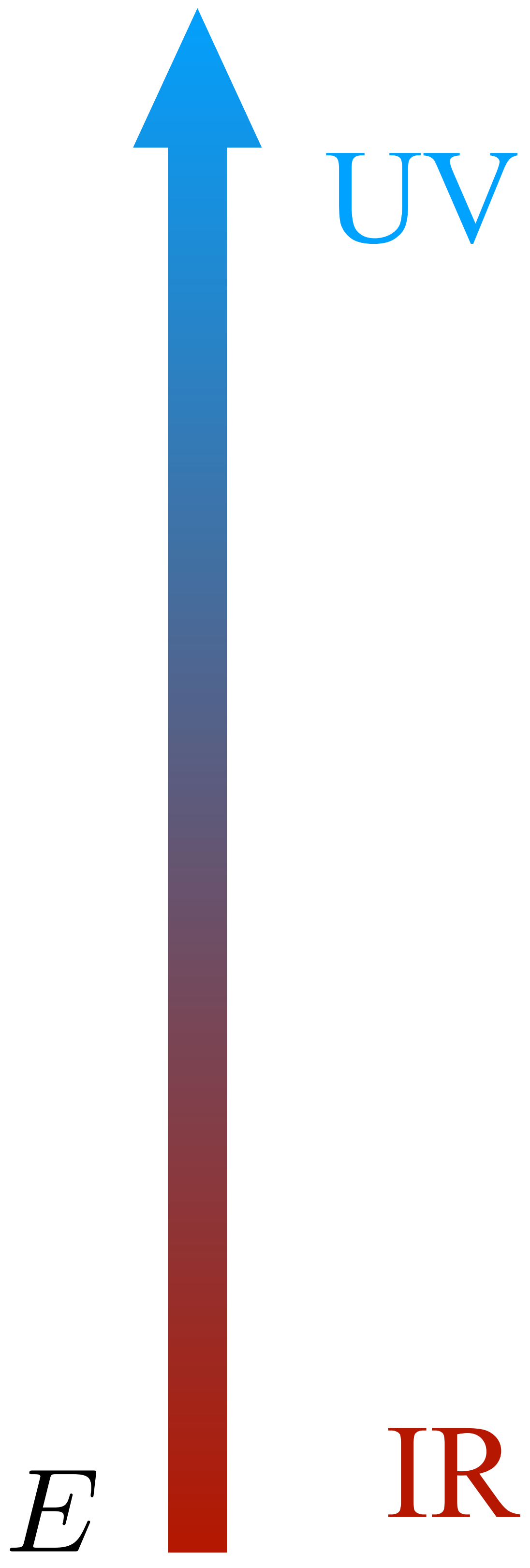

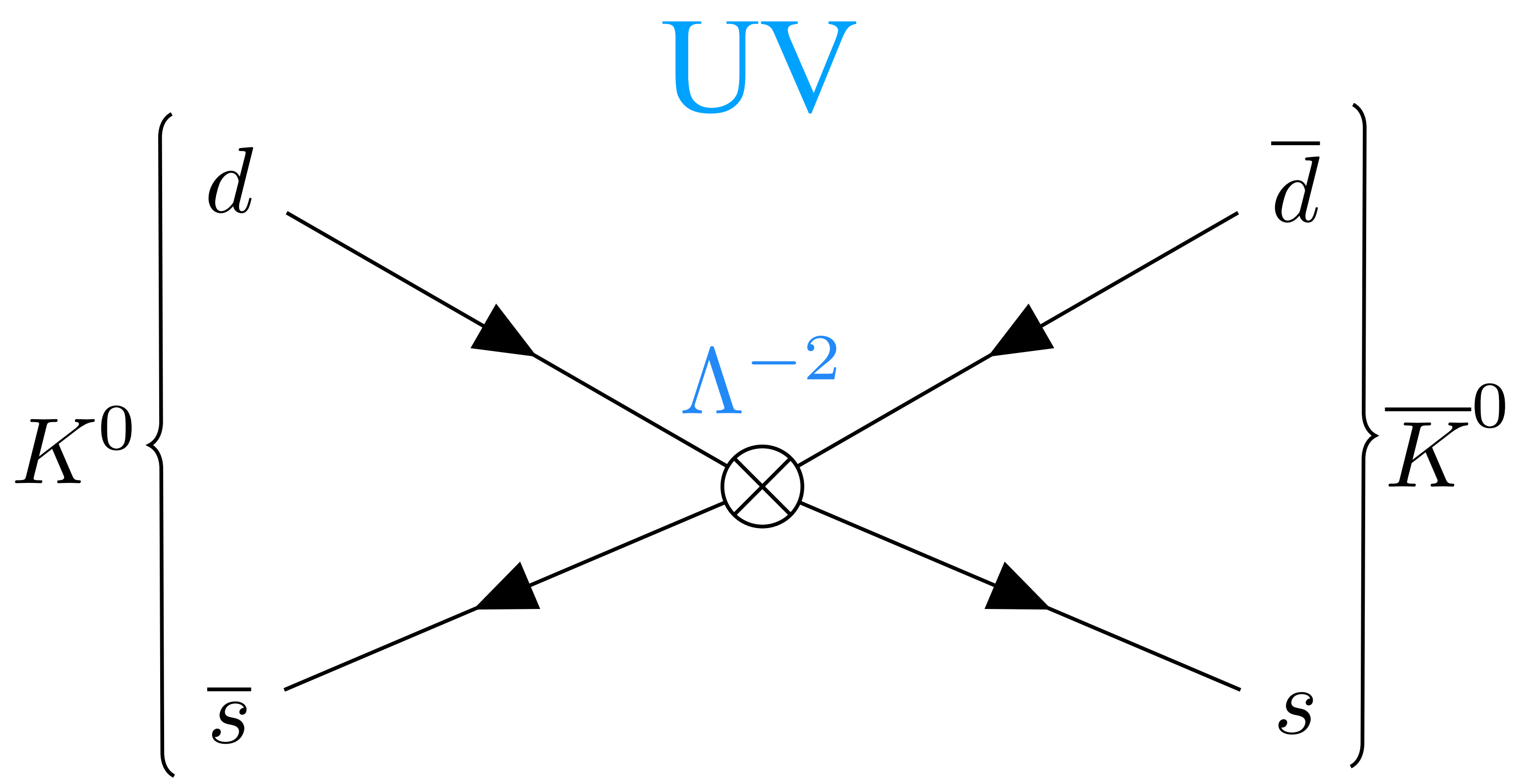

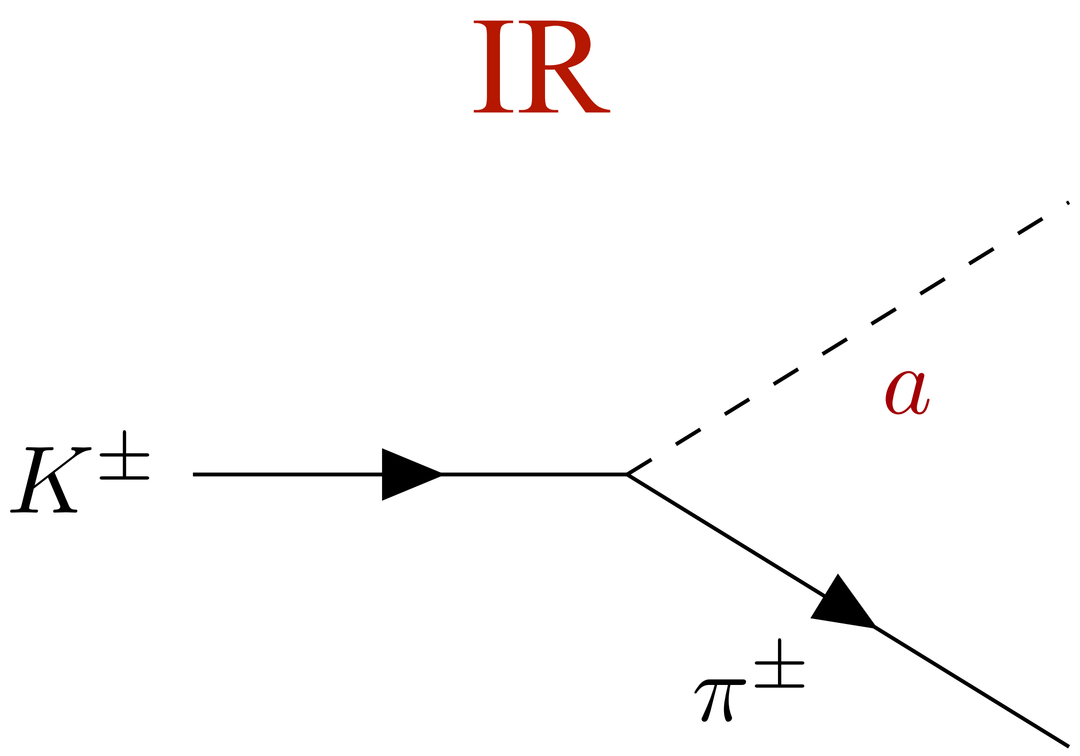

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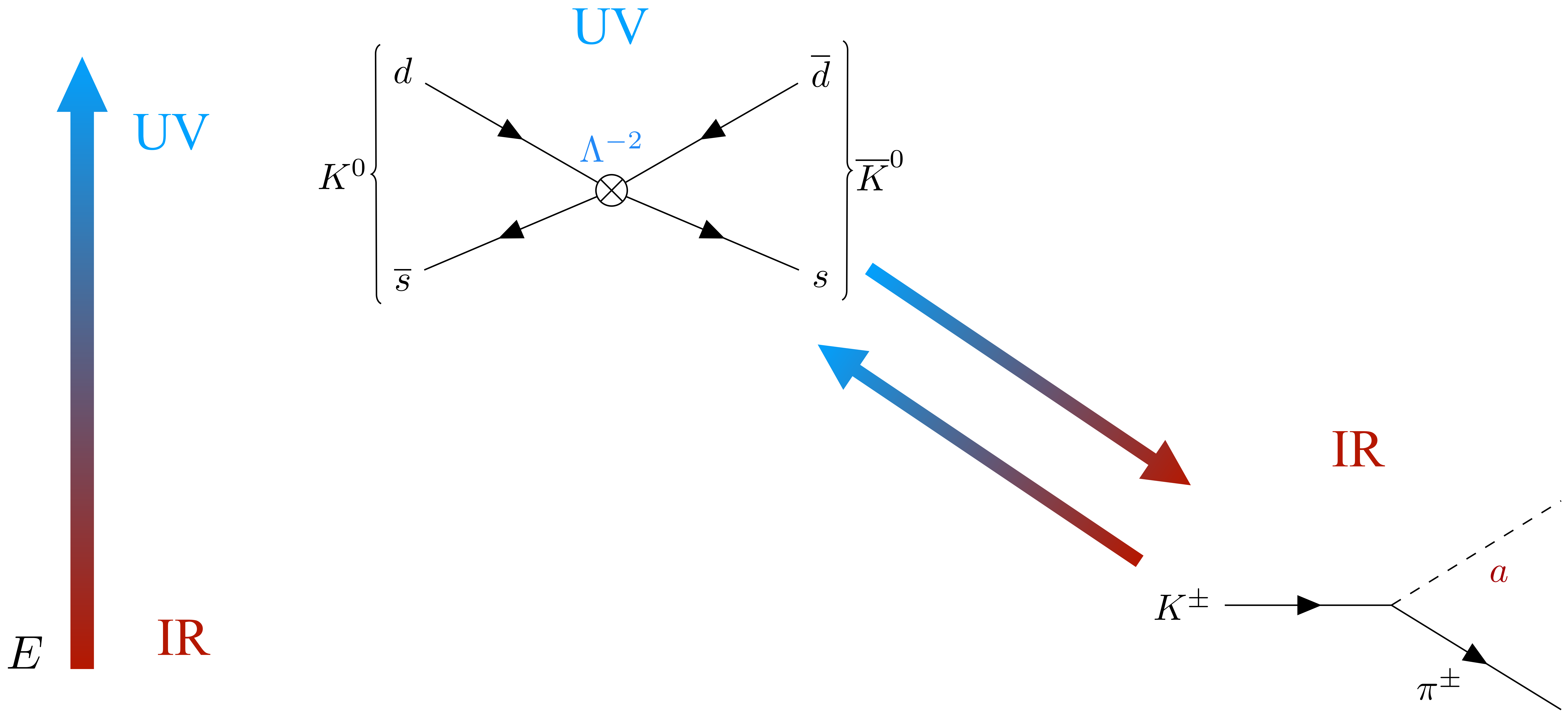

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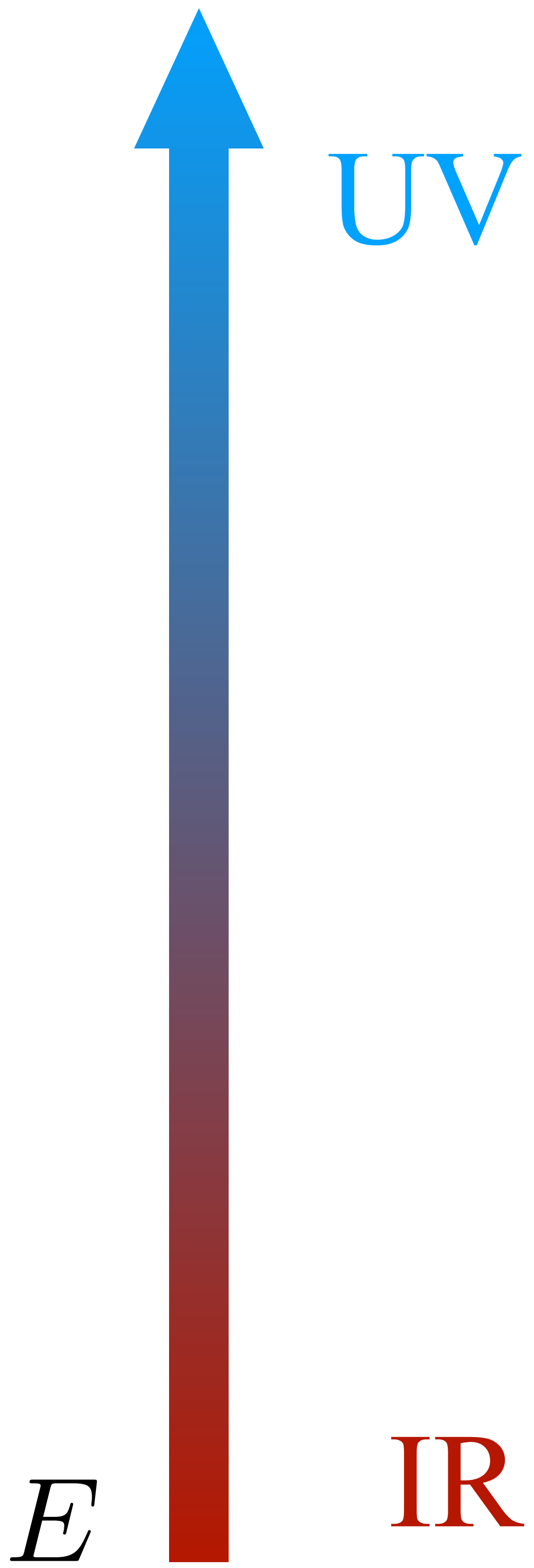
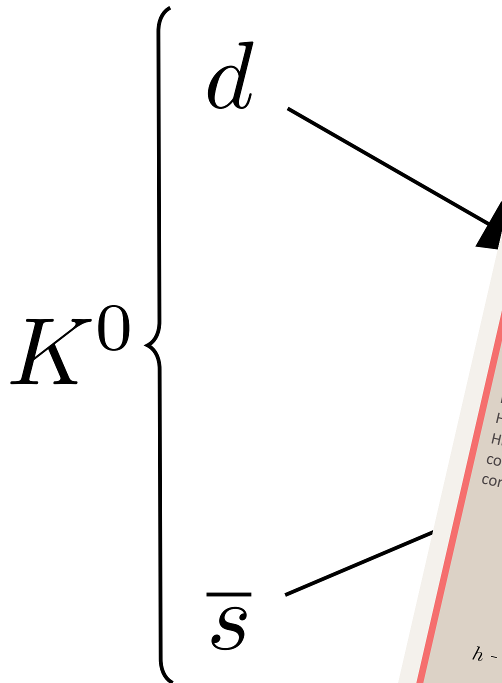
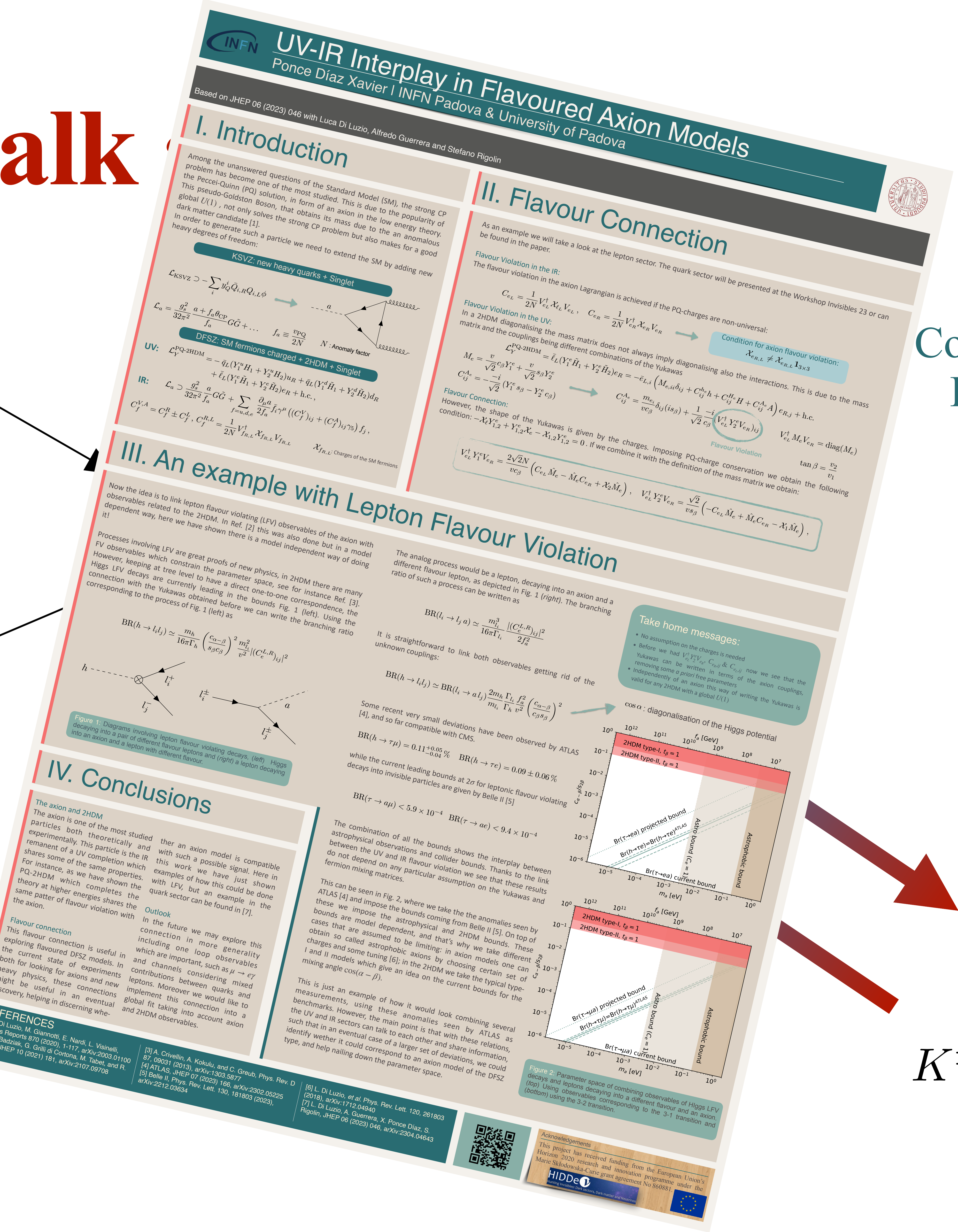
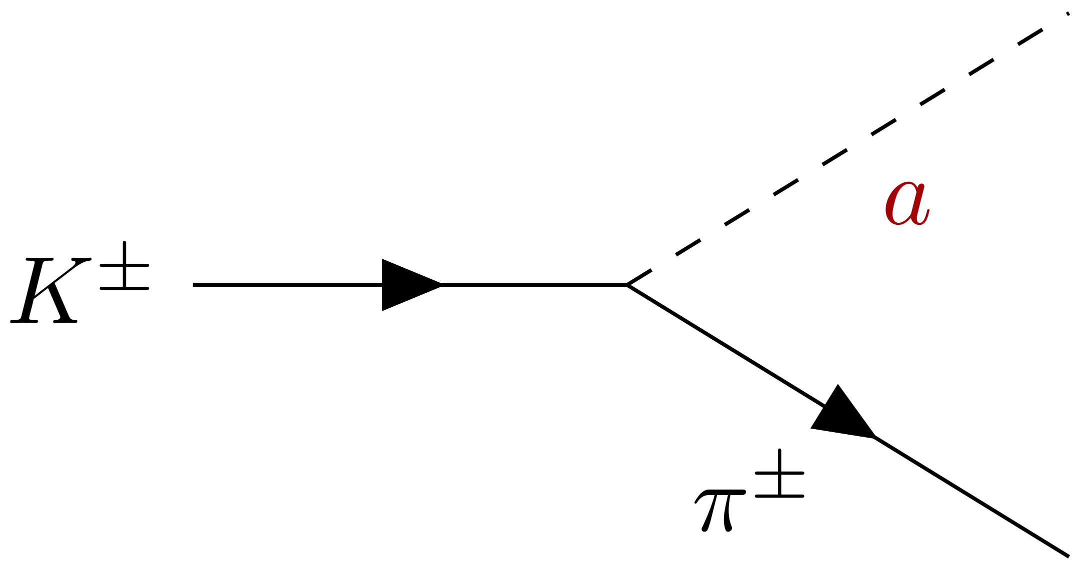




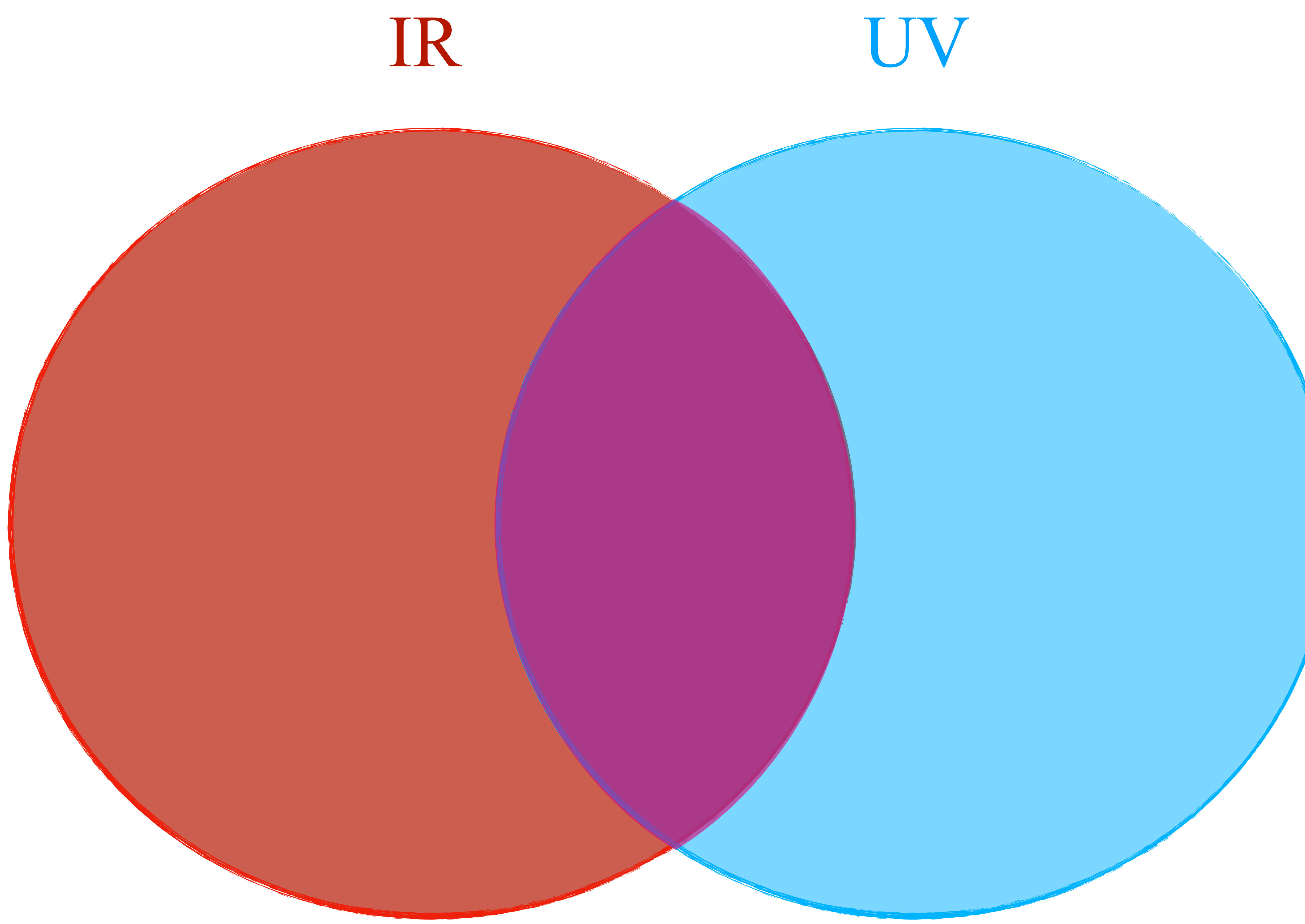


Come to the poster to see the Lepton Flavour violation part!

IR



Flavour-violating axion



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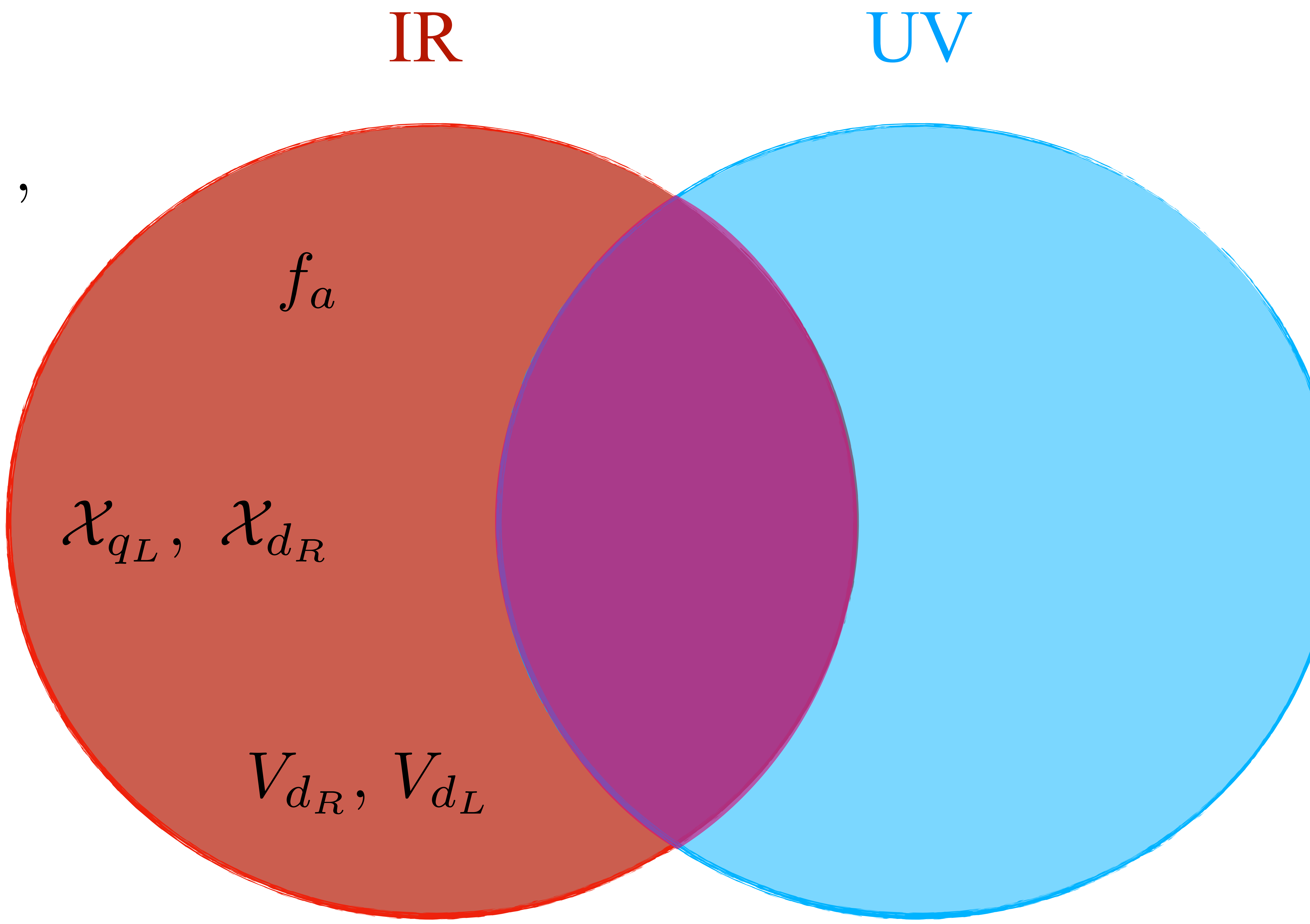
In the IR:

$$\mathcal{L}_a \supset \frac{\partial_\mu a}{f_a} \bar{d}_i \gamma^\mu \left((C_{d_L})_{ij} \gamma^\mu P_L + (C_{d_R})_{ij} \gamma^\mu P_R \right) d_j \,,$$

$$C_{d_L} = \frac{1}{2N} V_{d_L}^\dagger \mathcal{X}_{q_L} V_{d_L} \,, \quad C_{d_R} = \frac{1}{2N} V_{d_R}^\dagger \mathcal{X}_{d_R} V_{d_R}$$



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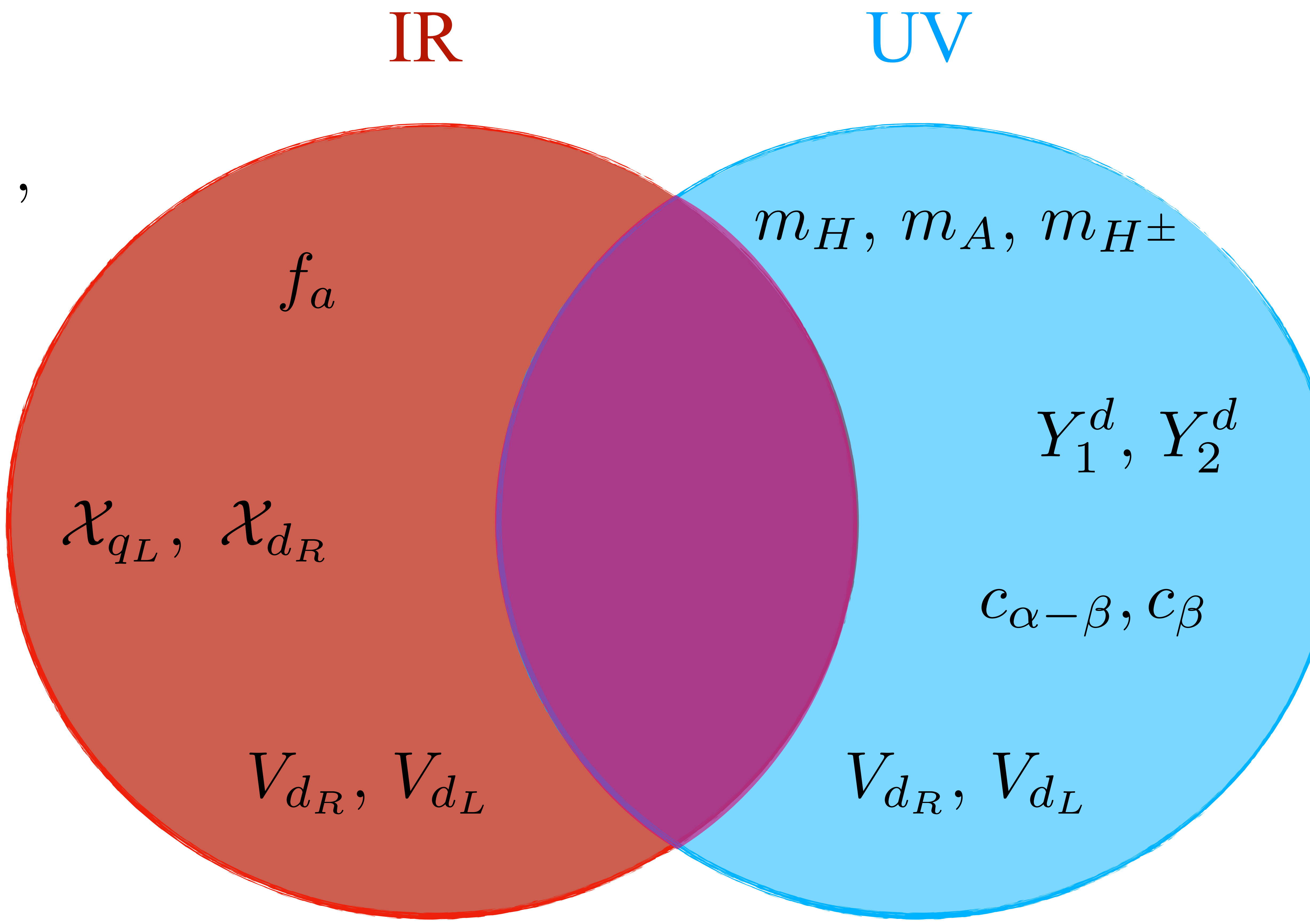
In the UV:

$$\mathcal{L}_Y^{\text{PQ-2HDM}} = \bar{q}_L (Y_1^d \tilde{H}_1 + Y_2^d \tilde{H}_2^d) d_R + \ldots$$

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

$$C_{ij}^{X_d} \sim (V_{d_L}^\dagger Y_2^e V_{d_R})_{ij} \equiv \epsilon_{ij}^d$$



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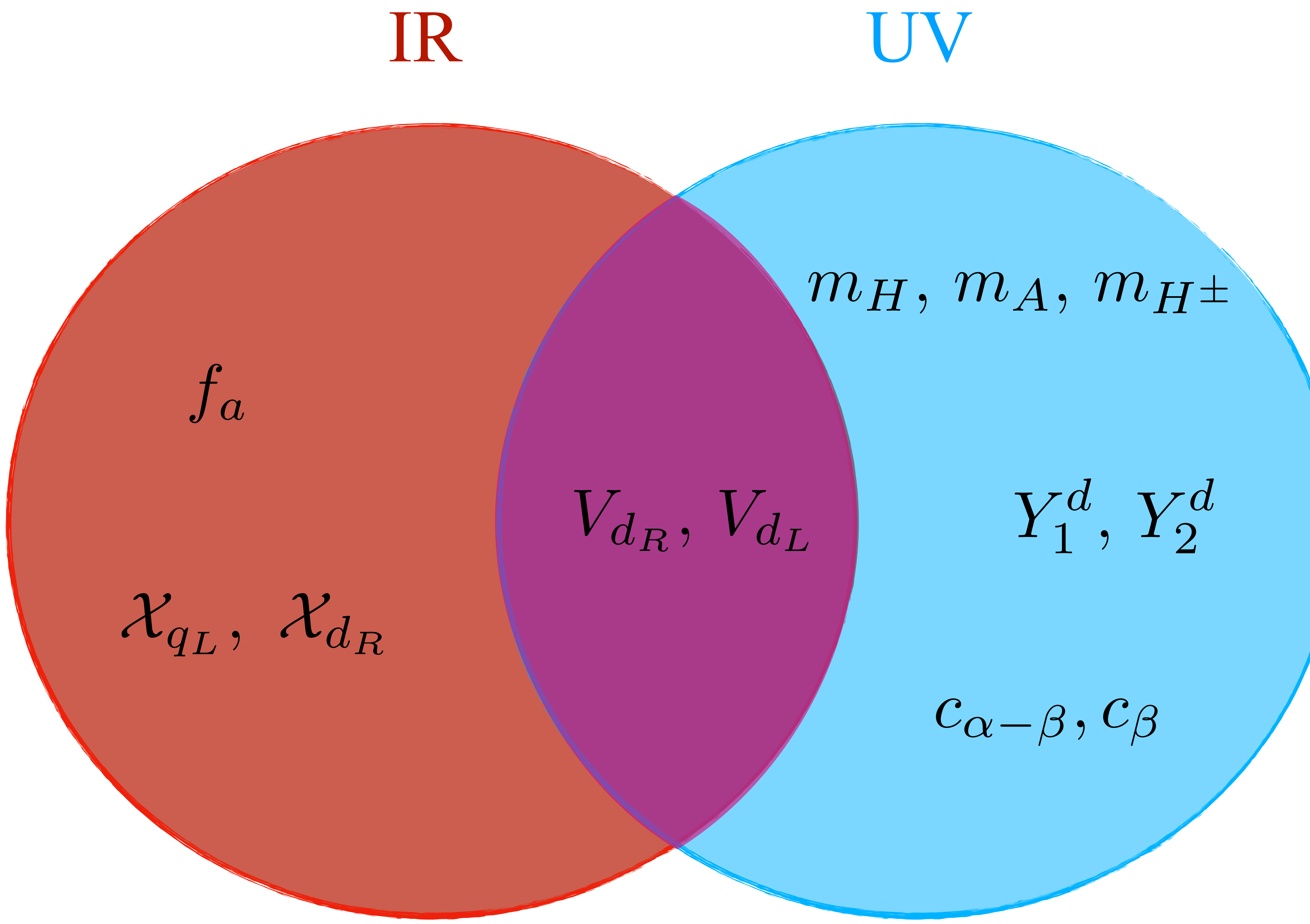

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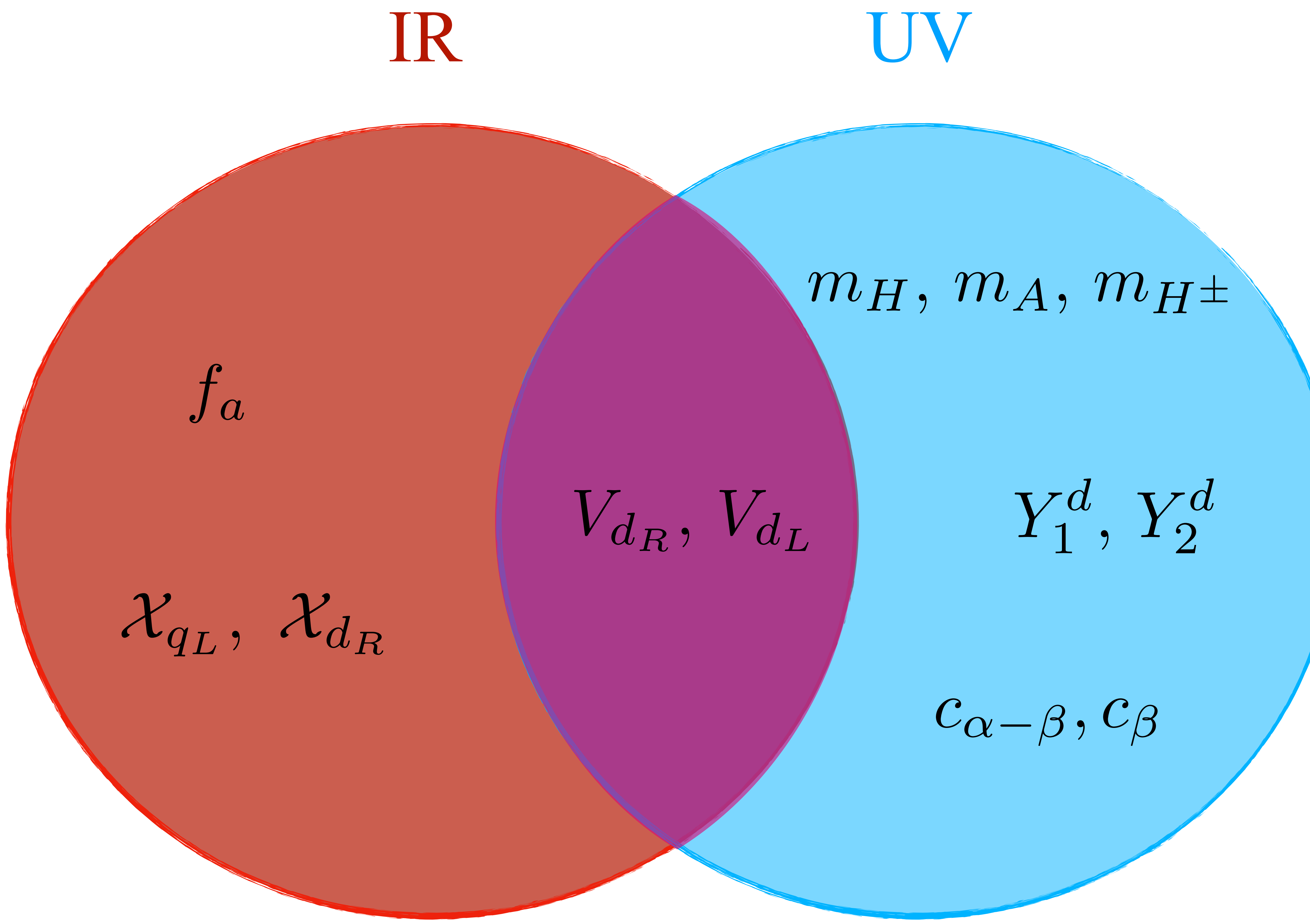

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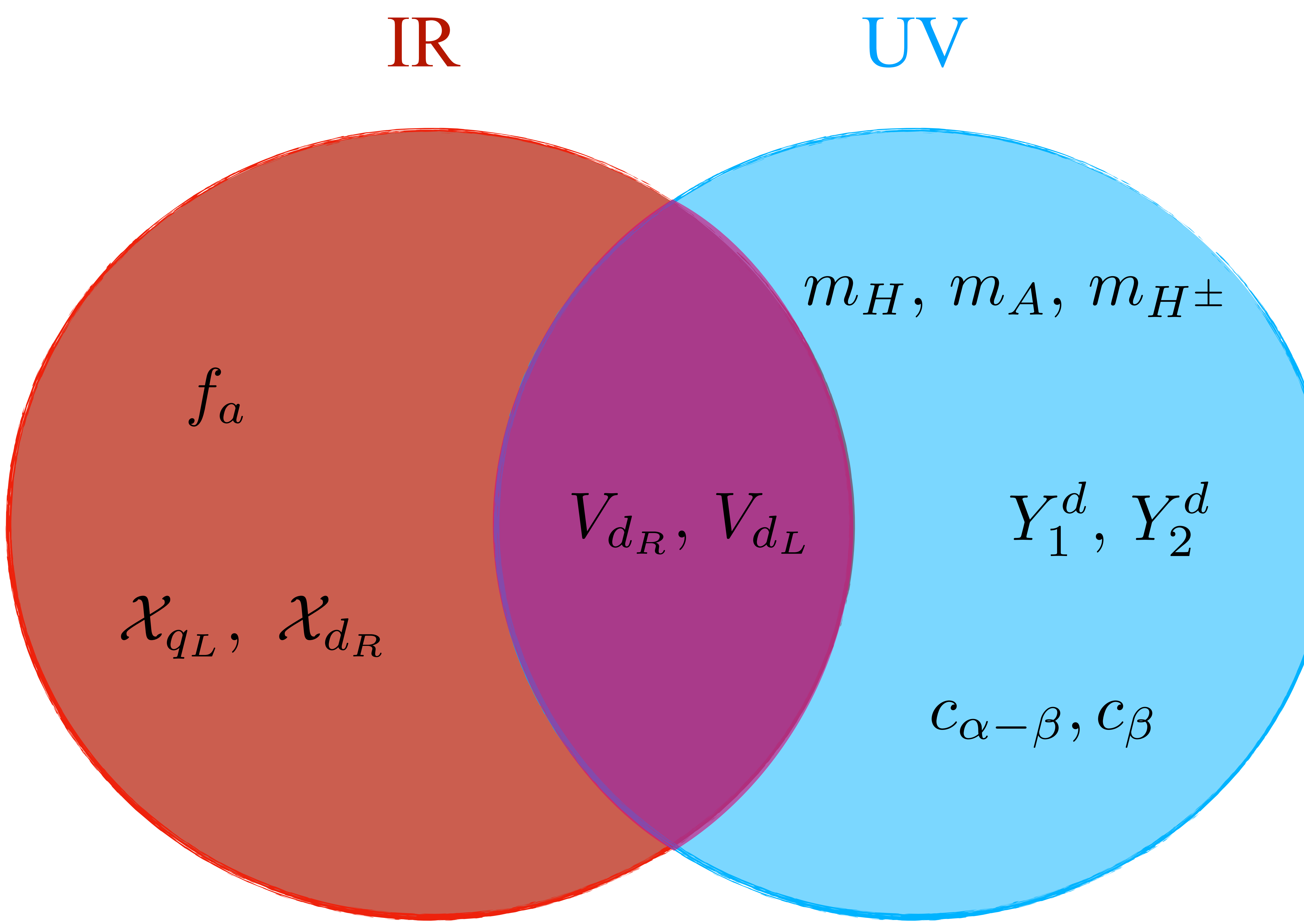

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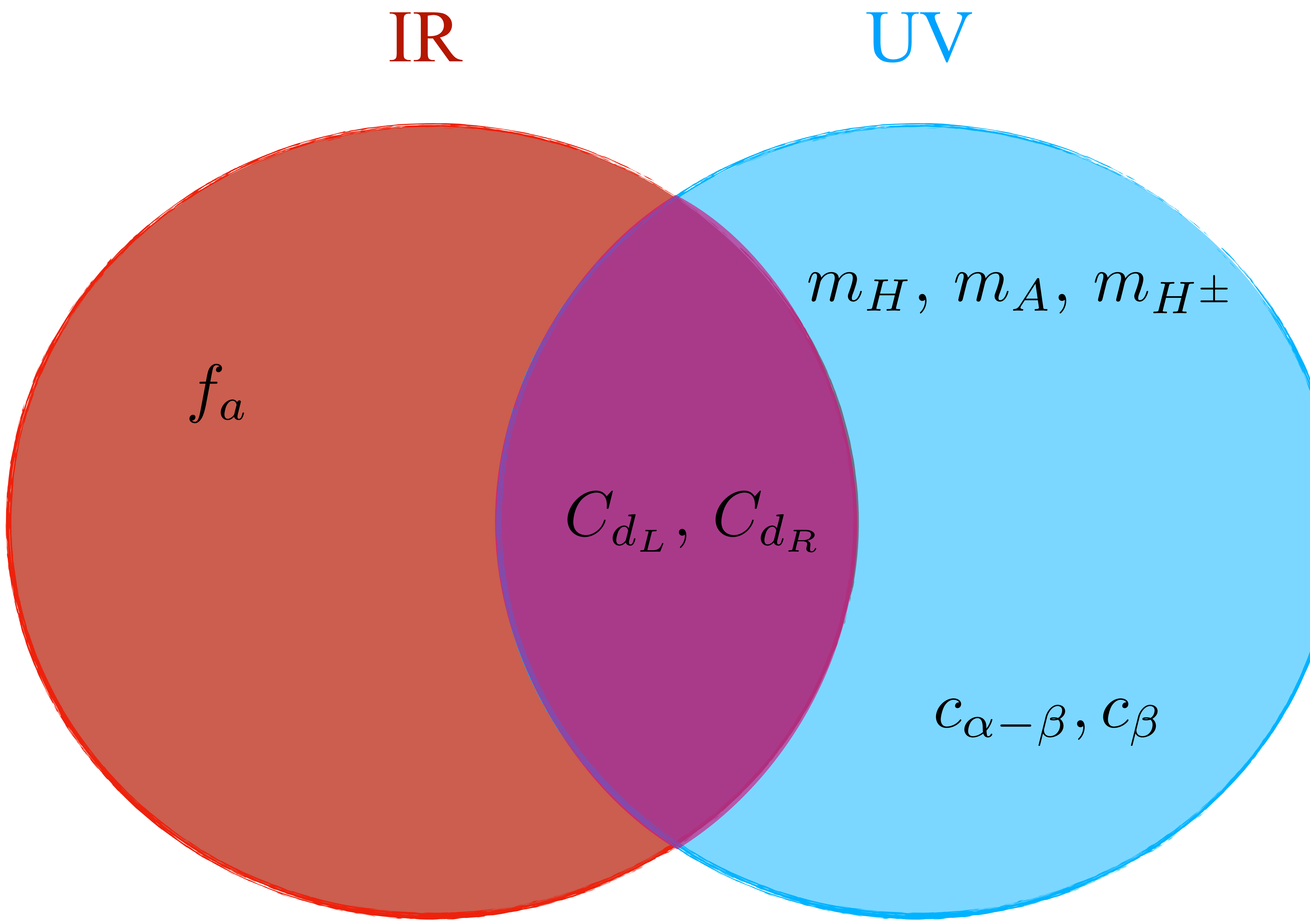
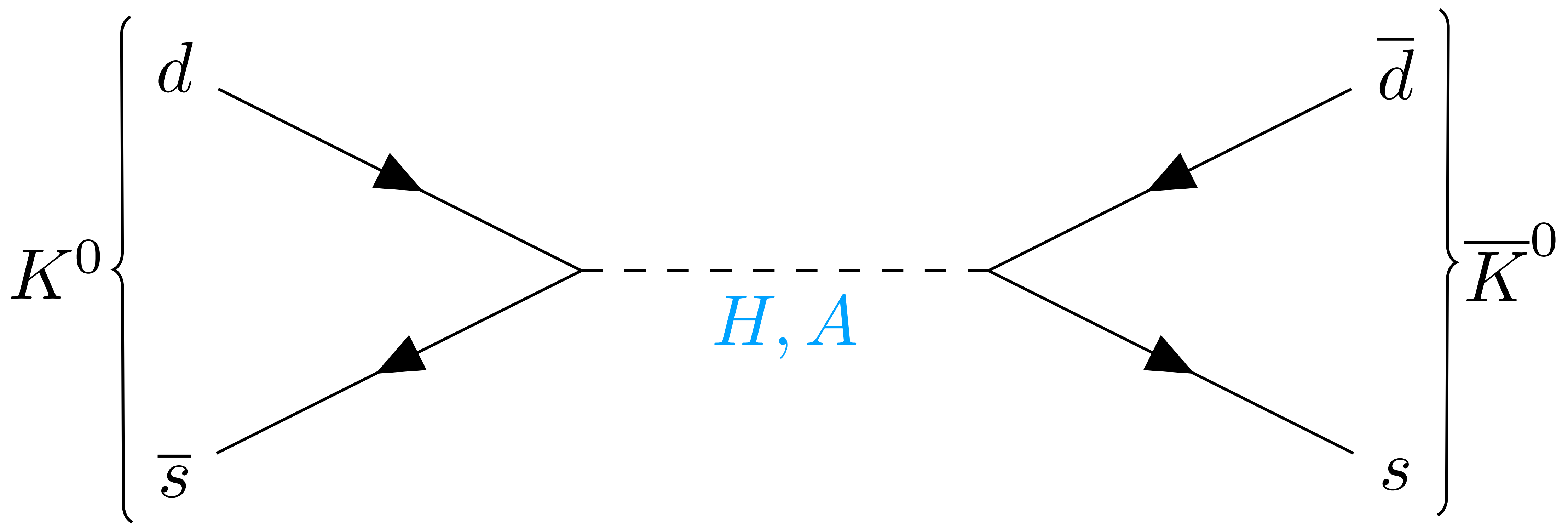


Quark flavour connection



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

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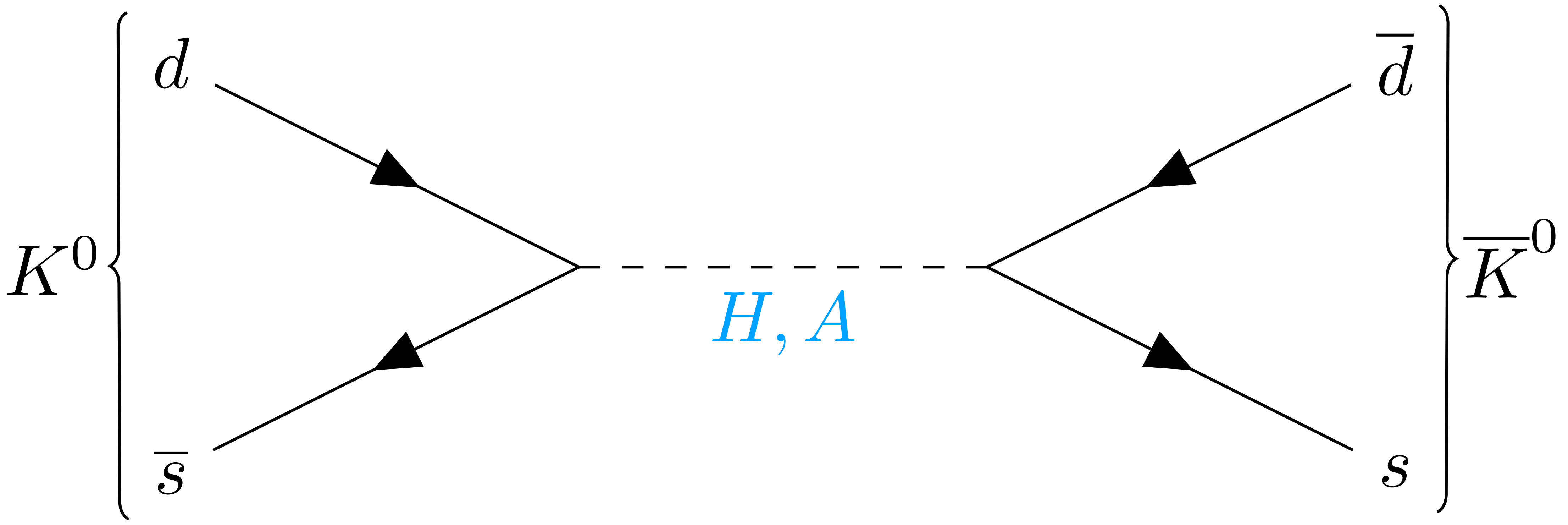

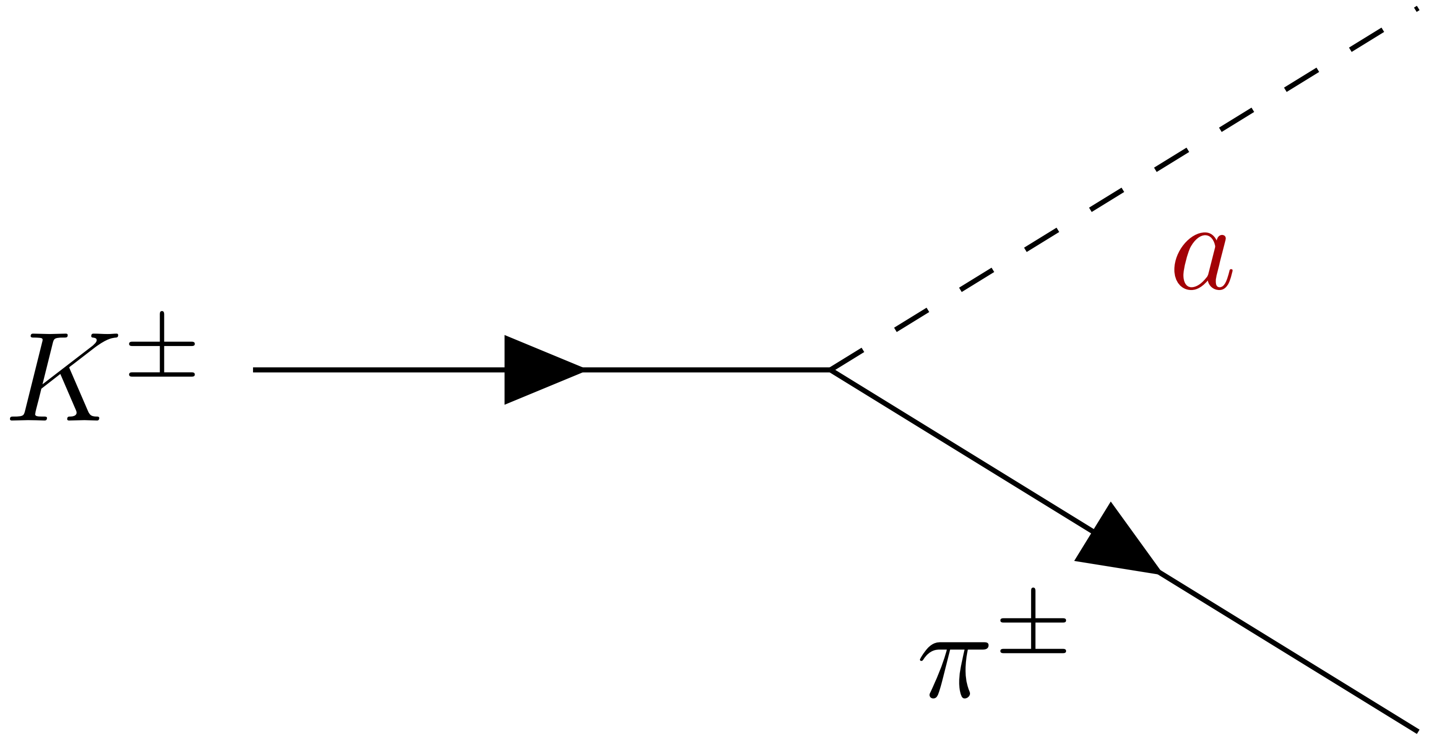

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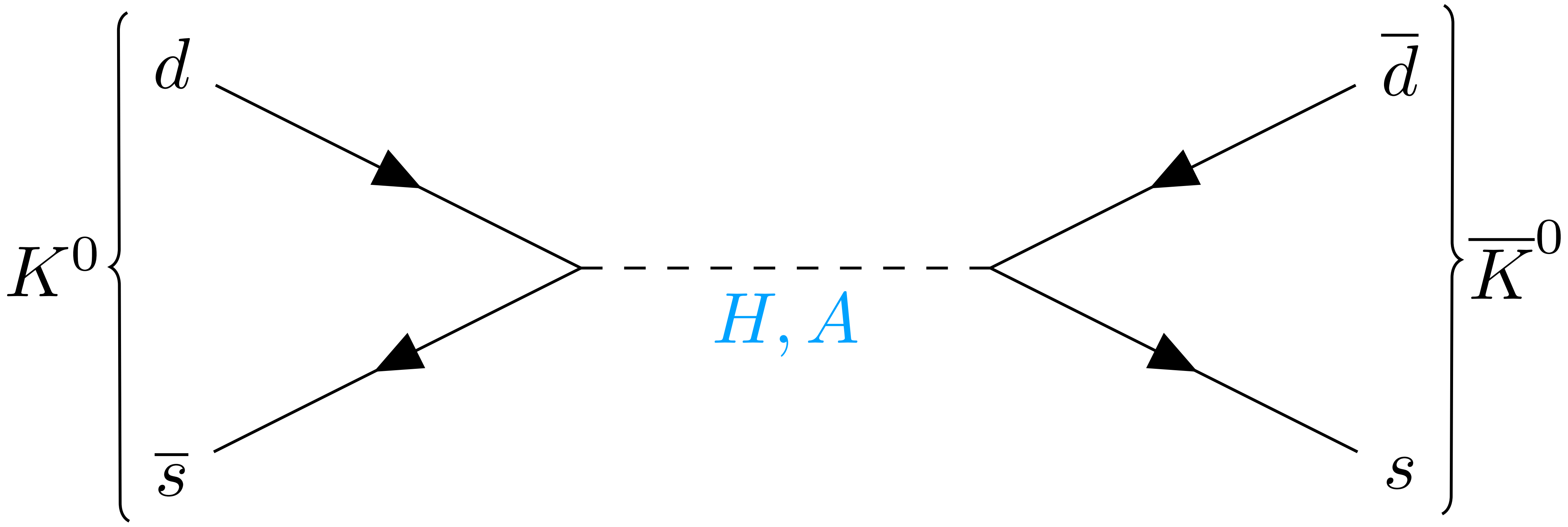

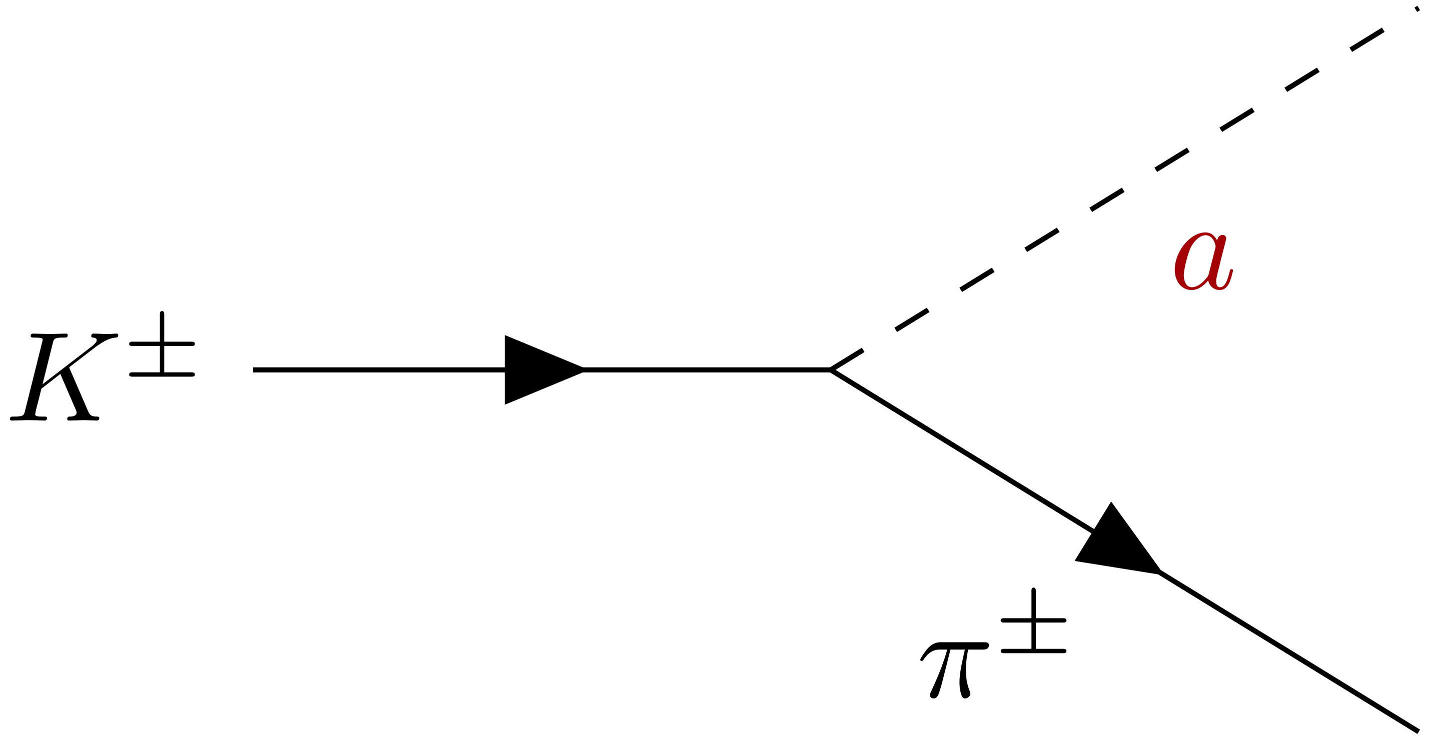

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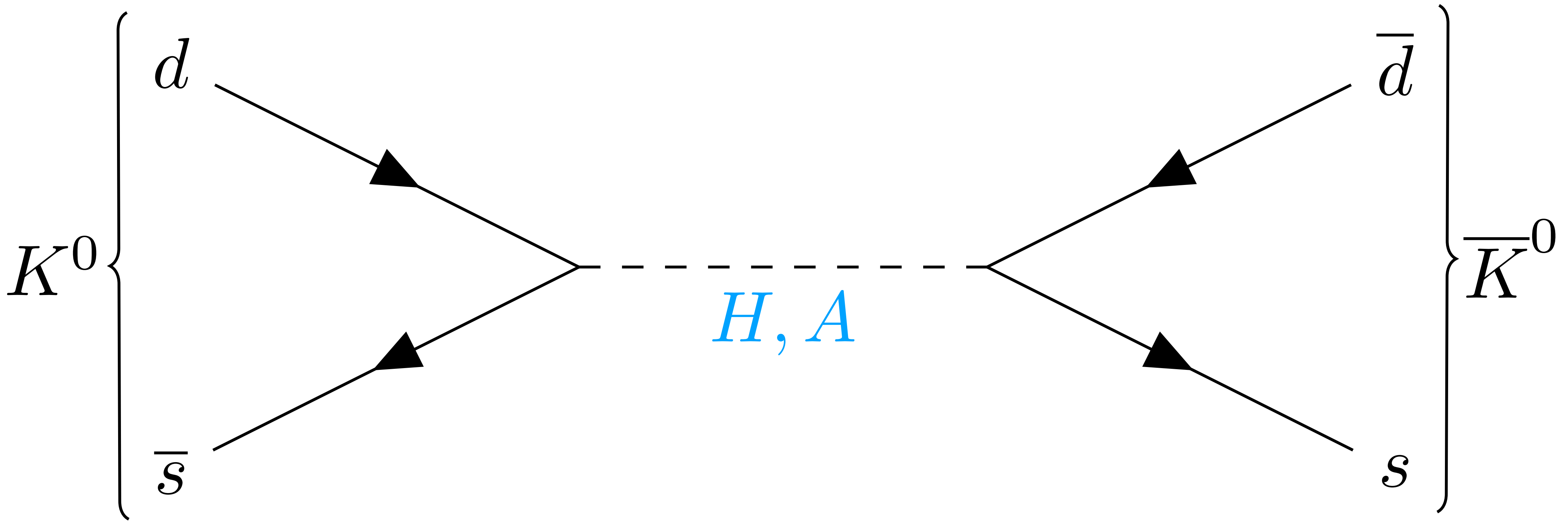

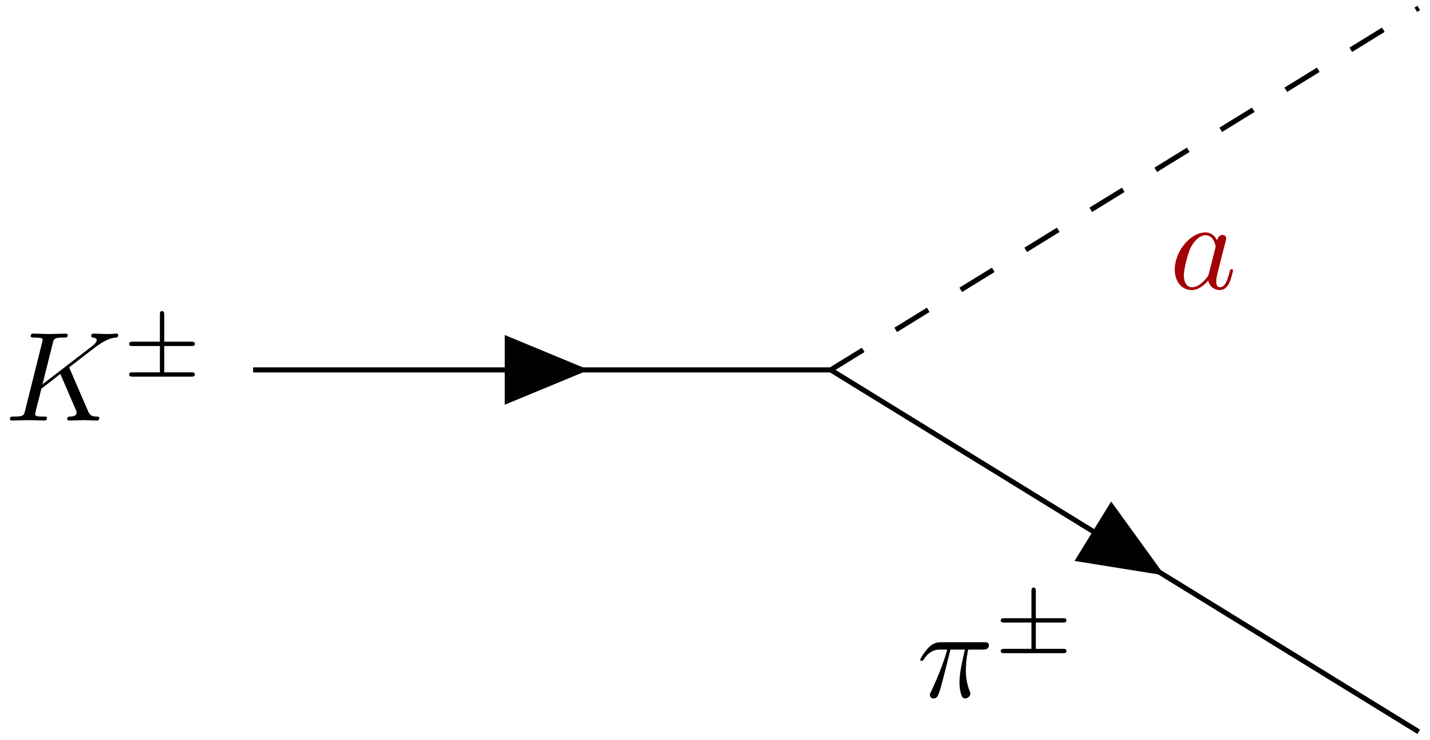

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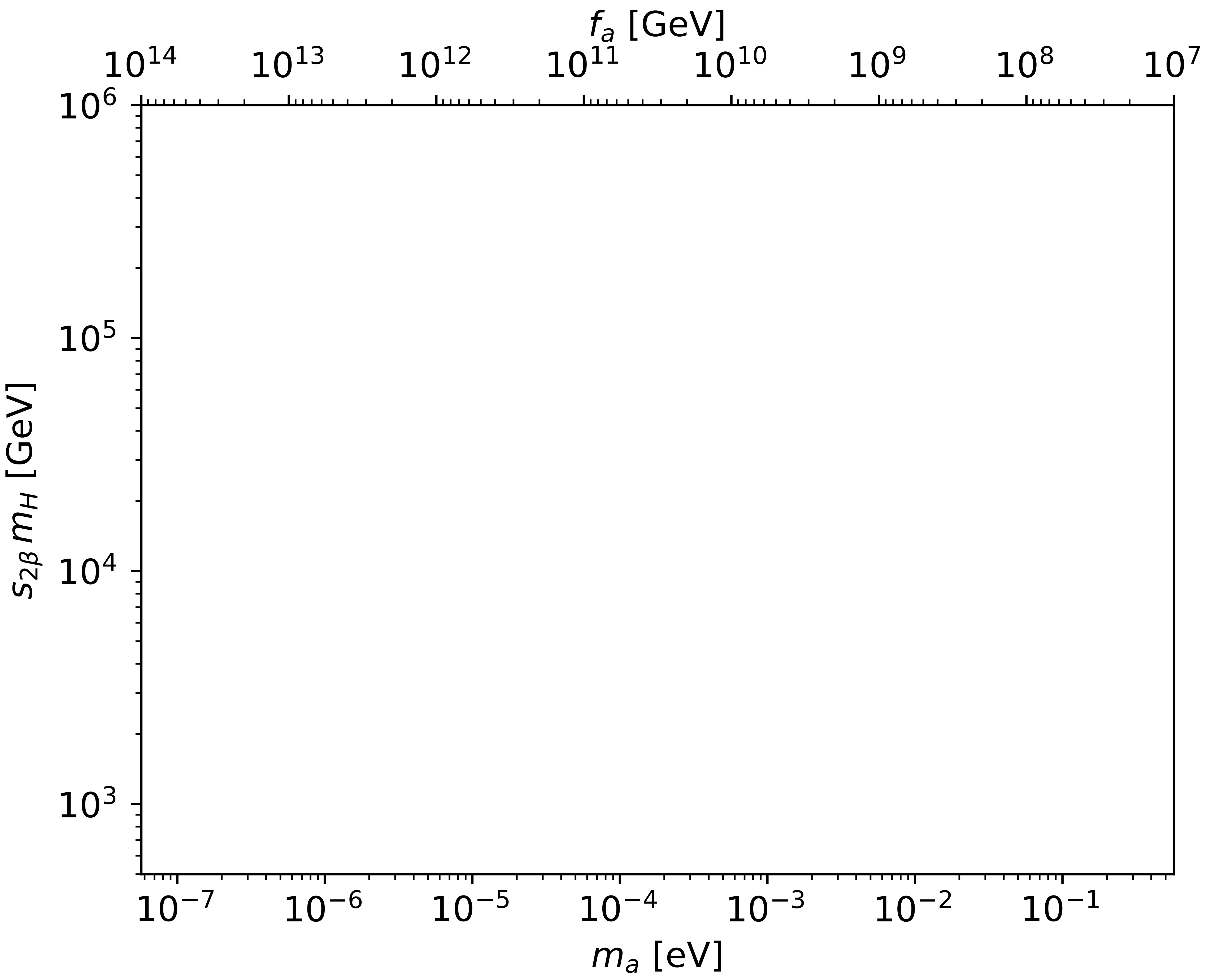

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Flavour violation in the $s \to d$ transition

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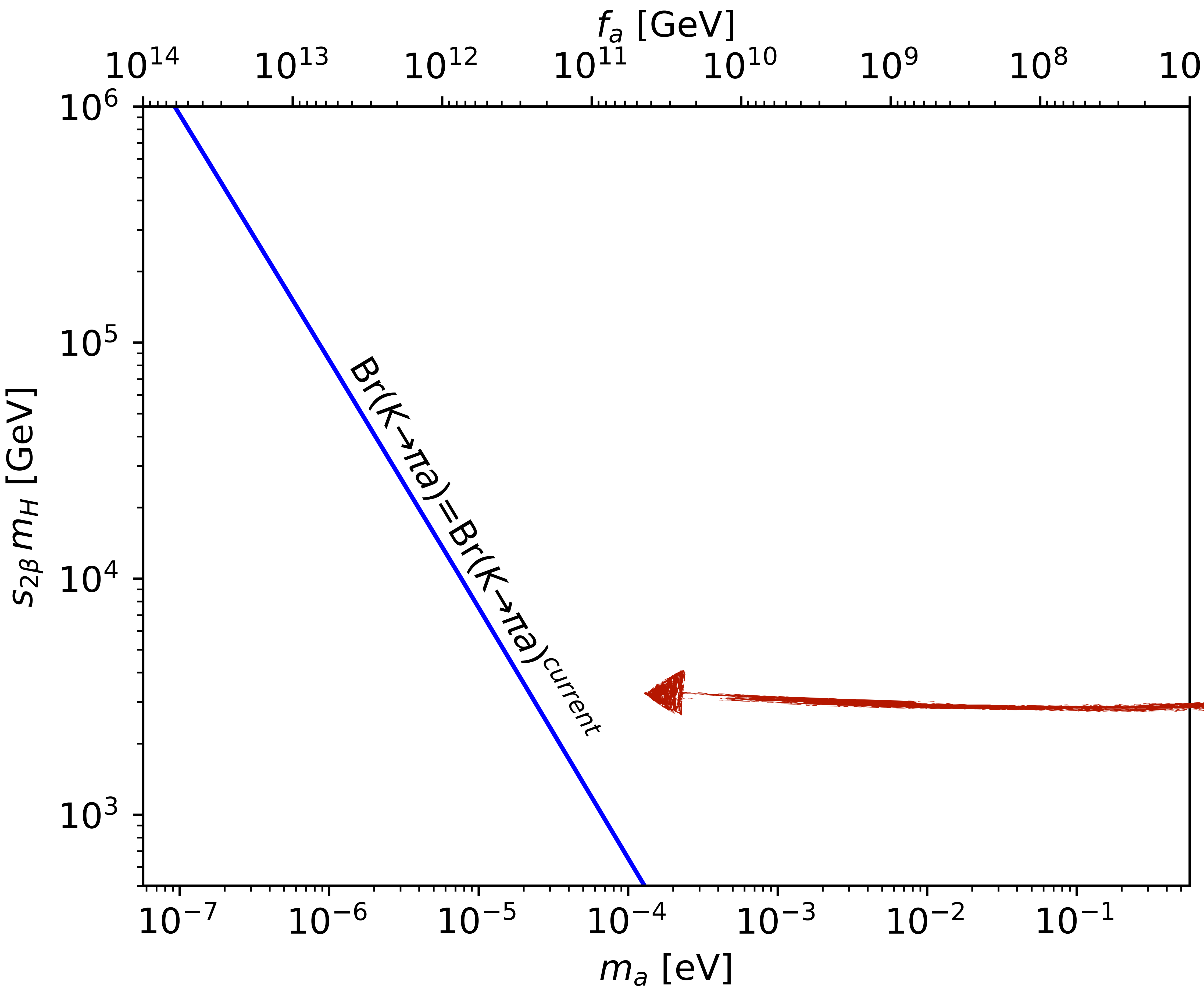

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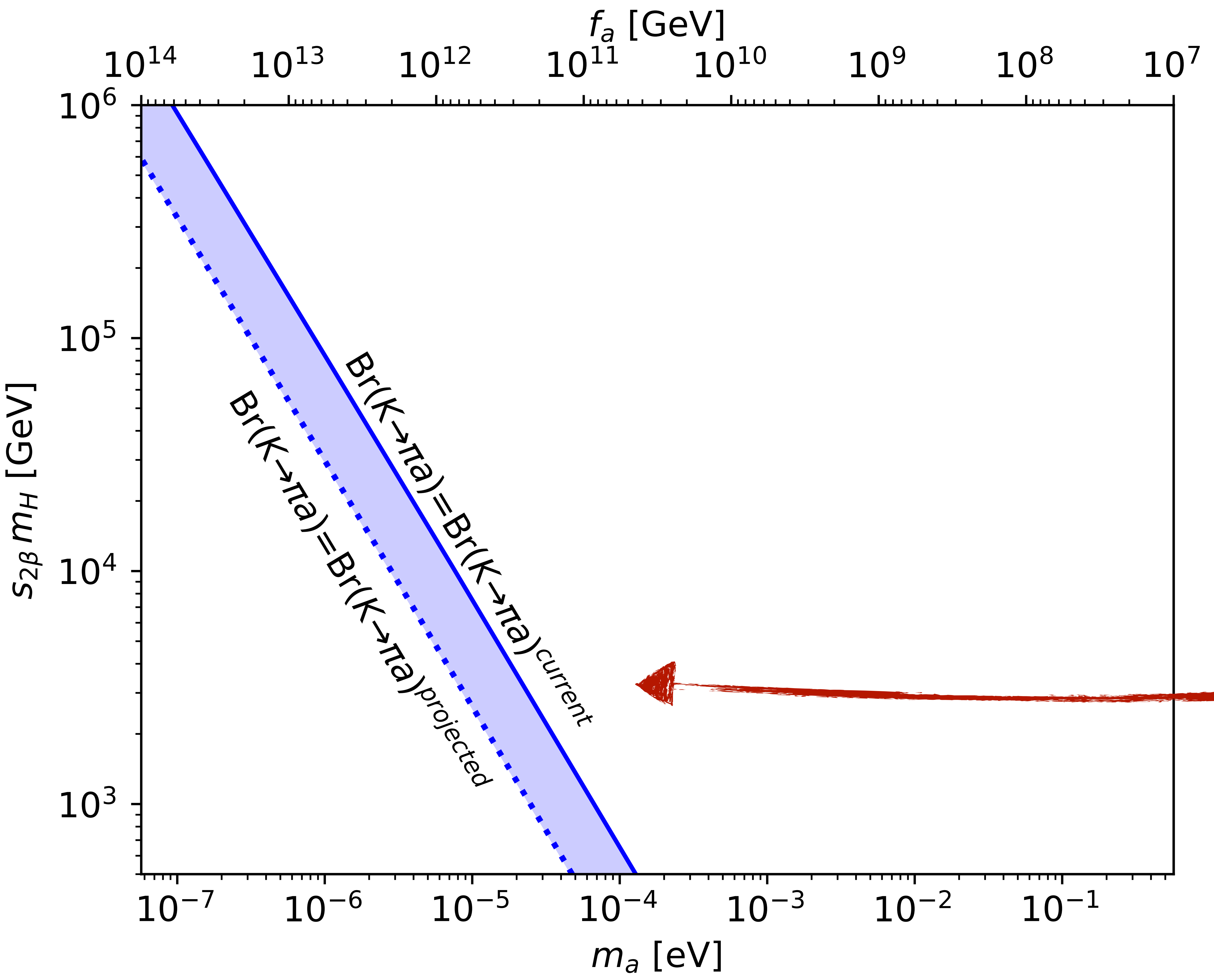

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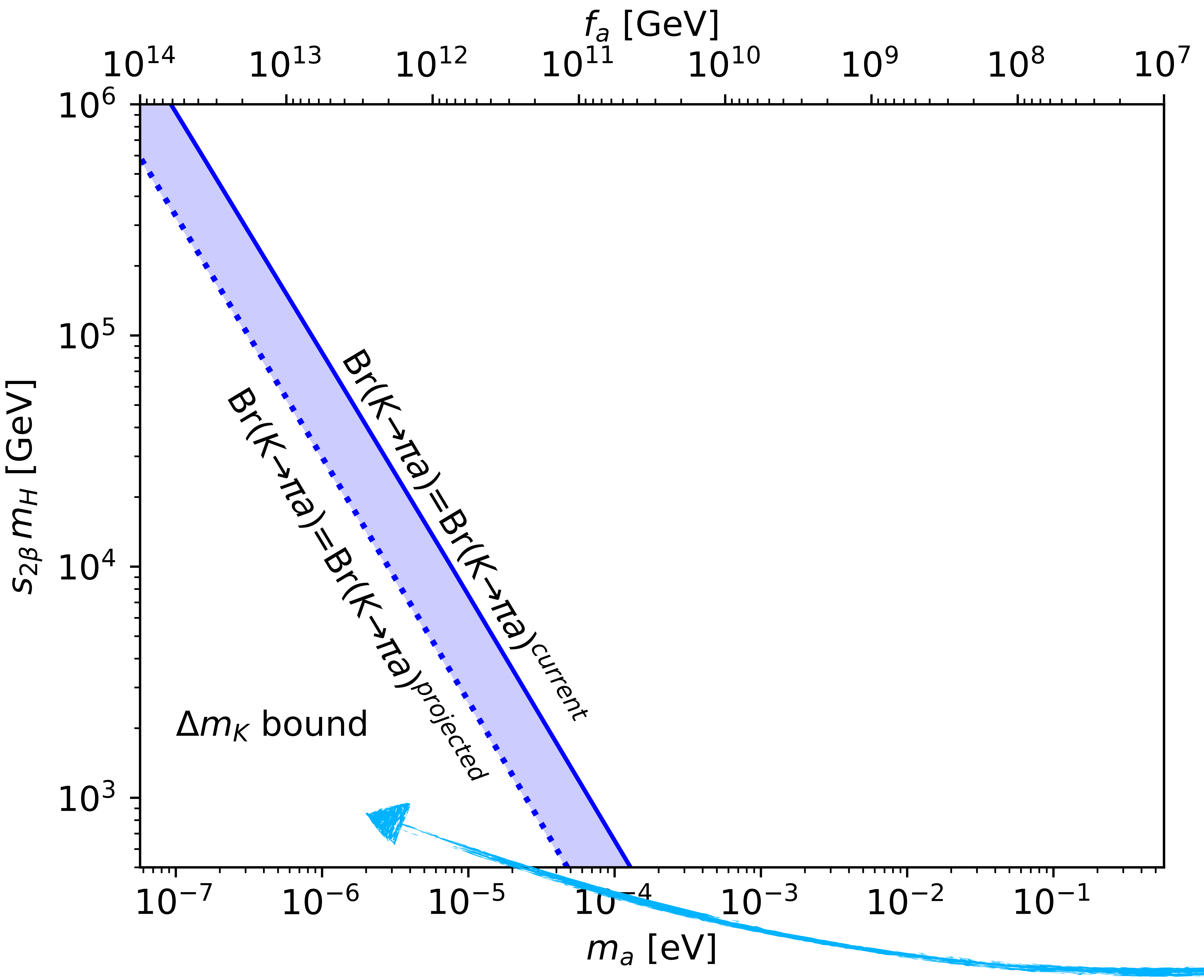

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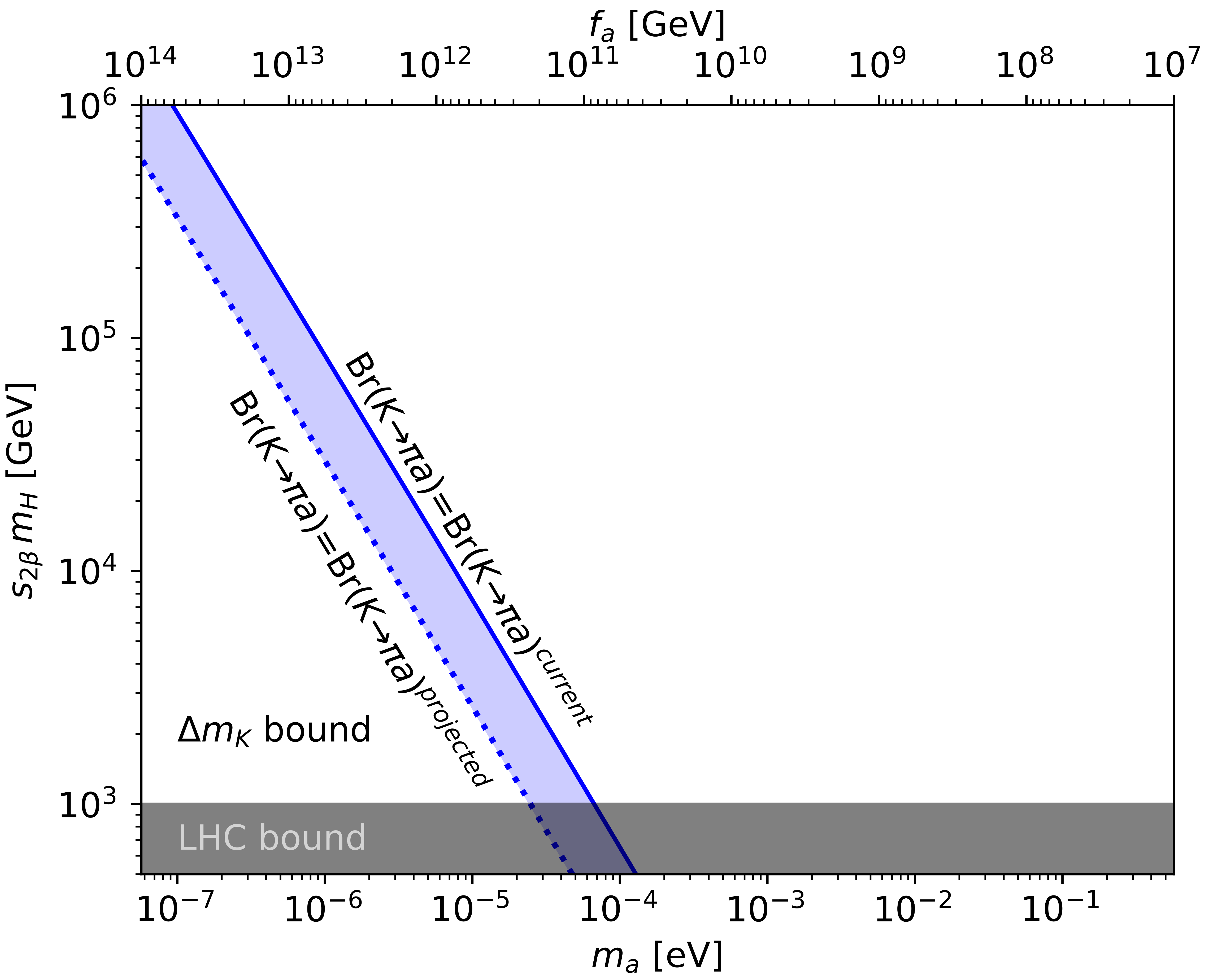

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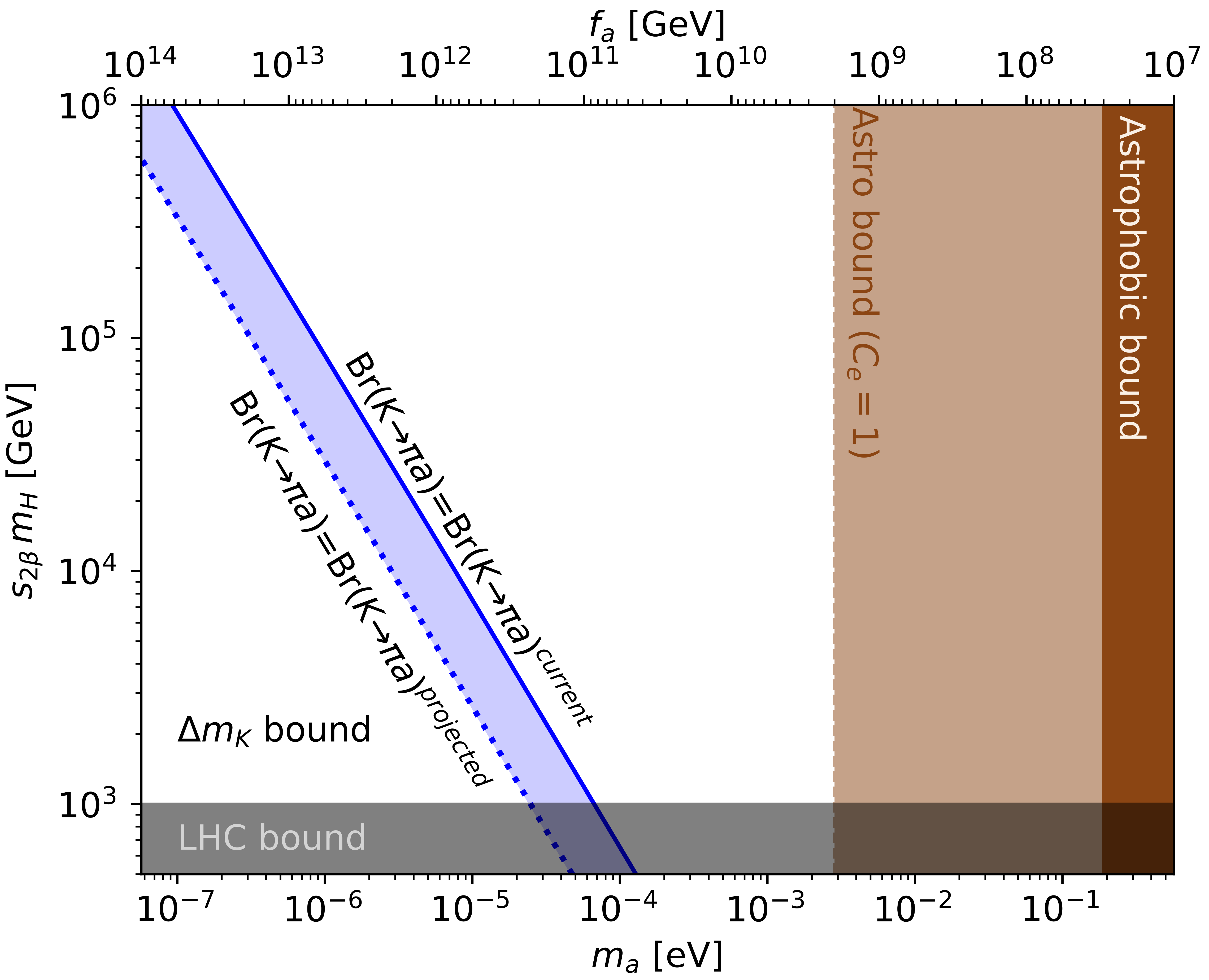

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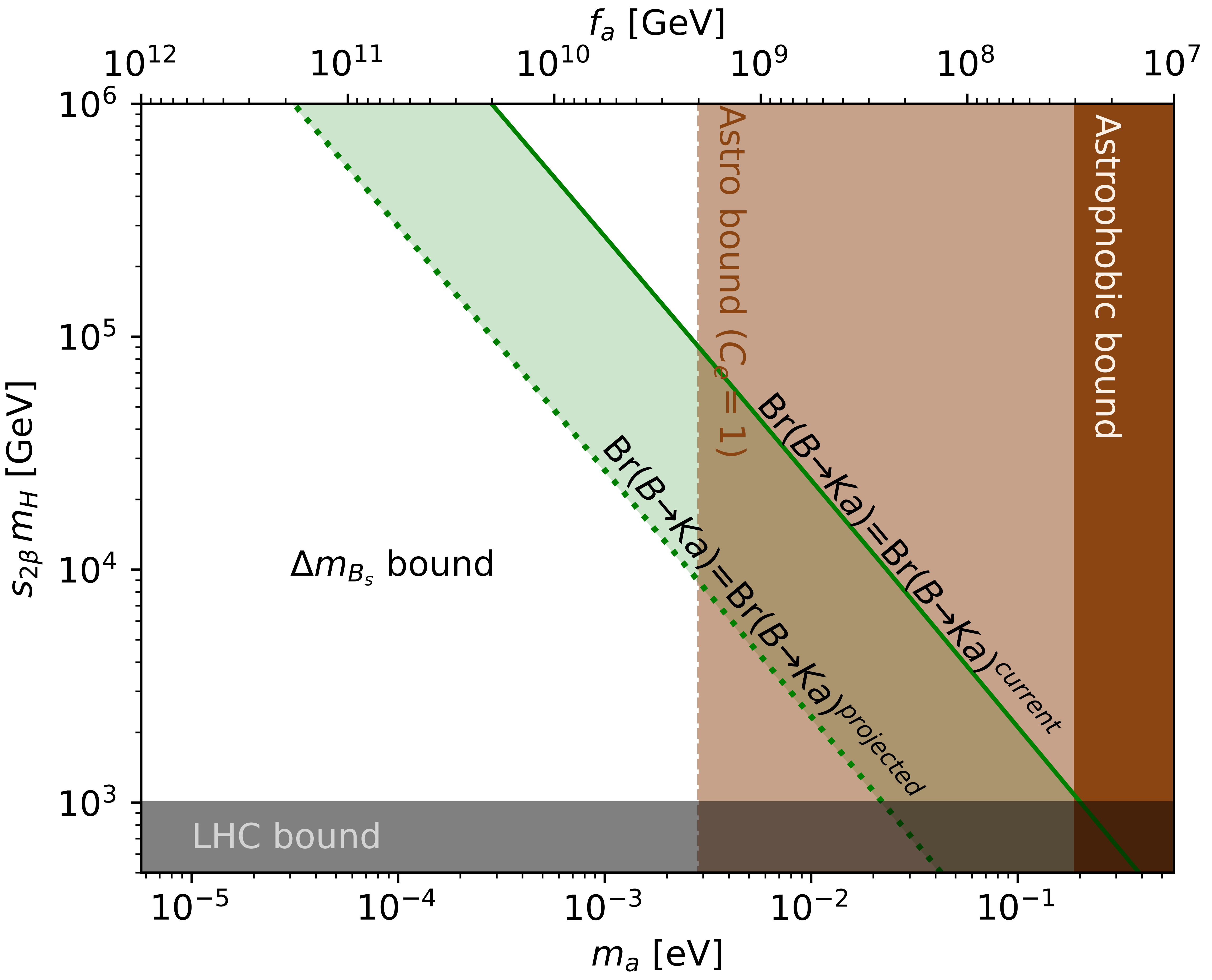

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Flavour violation in the $b \to s$ transition

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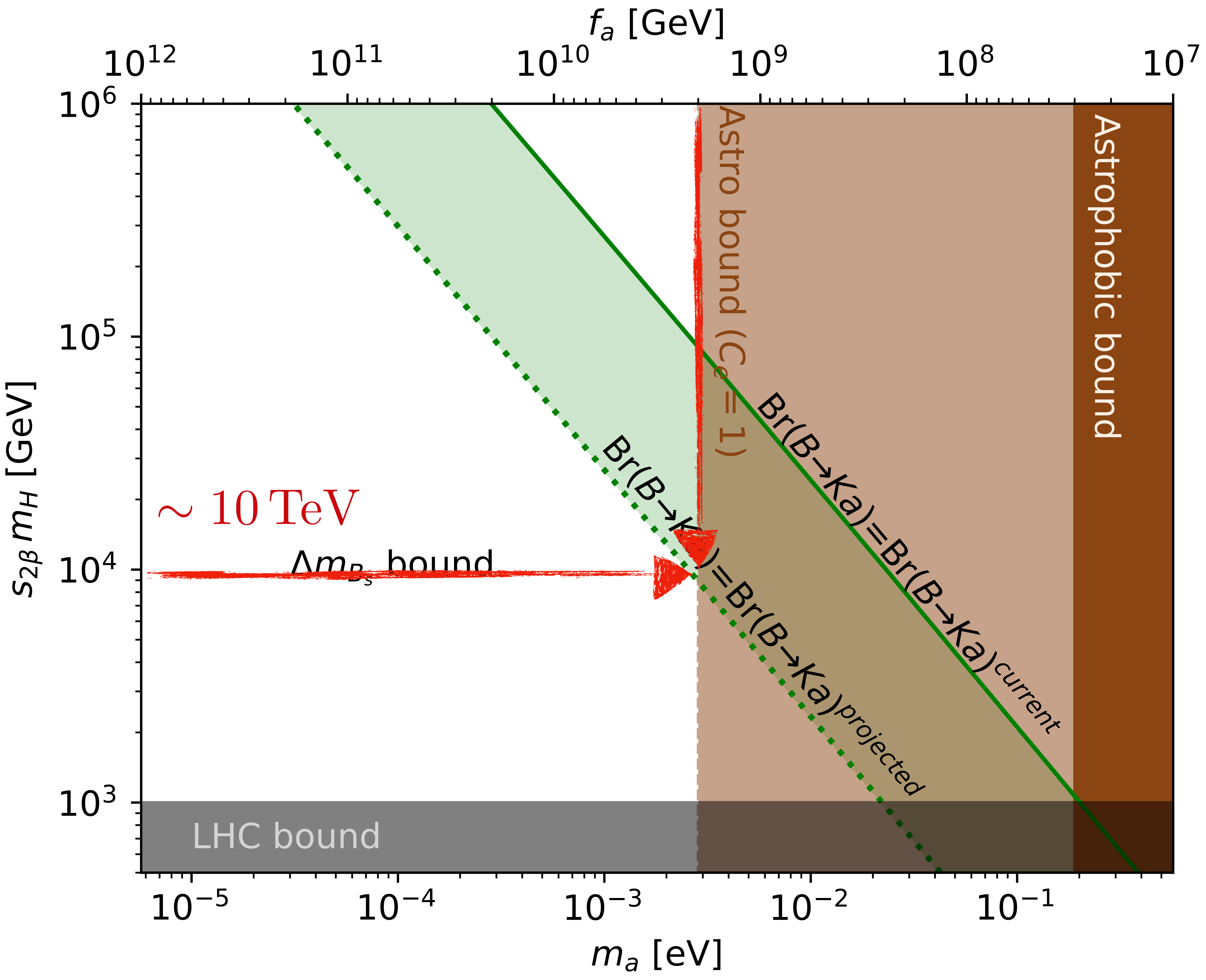

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Flavour violation in the $b \to s$ transition

Take-home message

- Model independent 1-to-1 correspondence of FV observables between the UV and IR
- No assumption on the Yukawas or charges is needed
- Information on one sector is relevant to the other!

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Thanks for your attention!

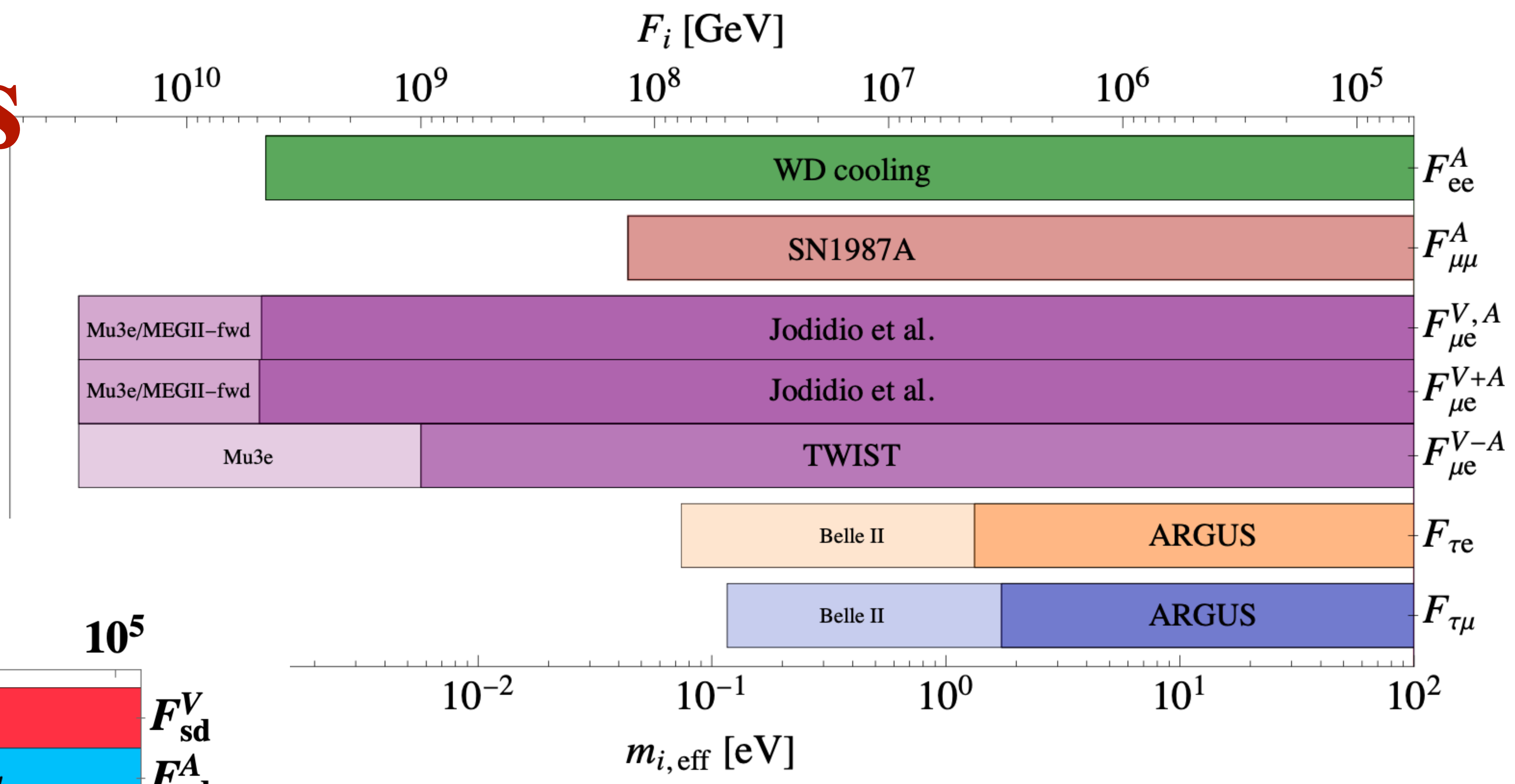
Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 860881.

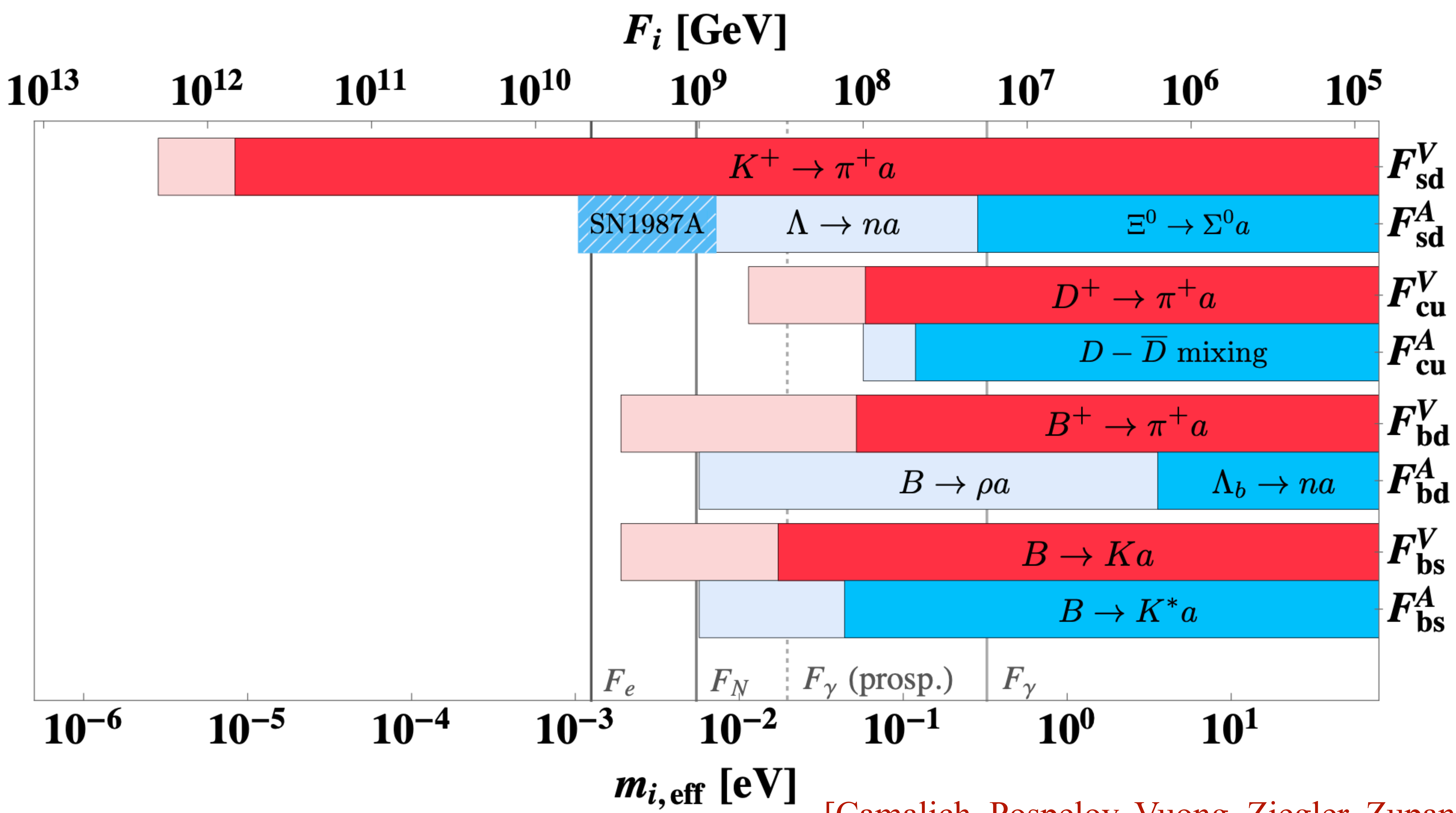
HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Backup

Flavoured axion bounds



[Calibbi, Redigolo, Ziegler, Zupan 2006.04795]



[Camalich, Pospelov, Vuong, Ziegler, Zupan 2002.04623]

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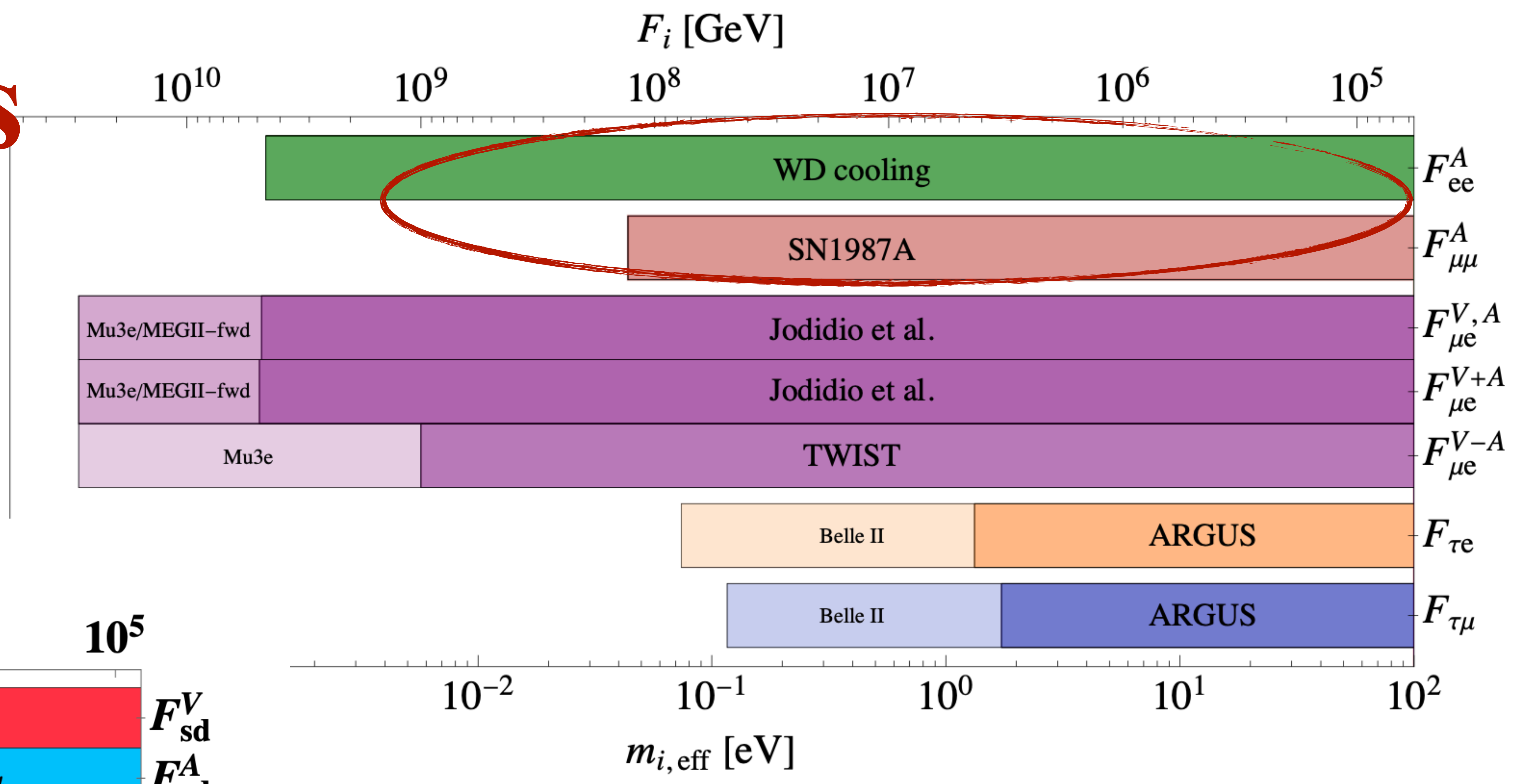

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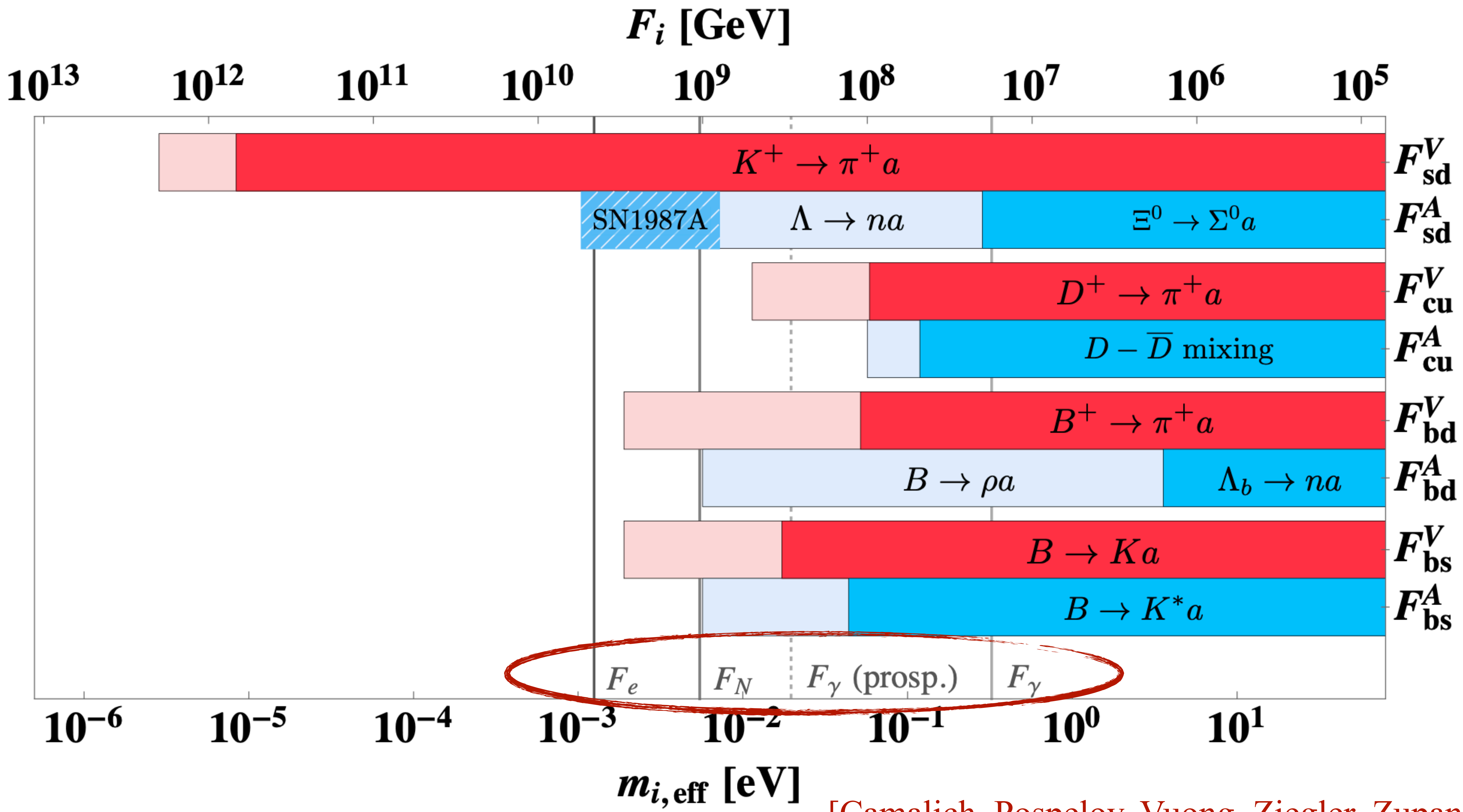

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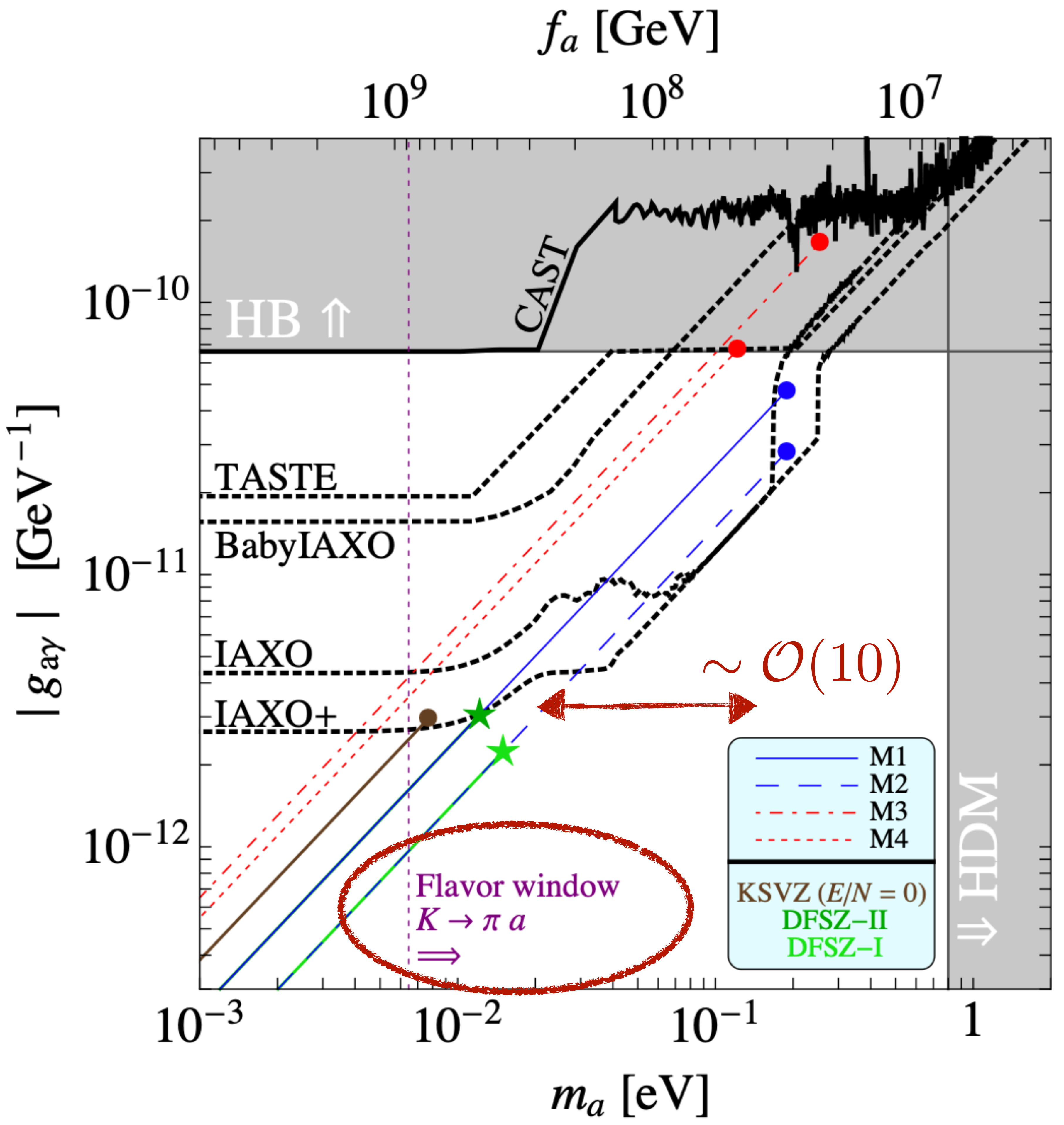
Astrophobic Models

Astrophobic models

→ Astrophobia: nucleophobia + electrophobia

- Can saturate the best fit: cooling anomalies + astrophysical bounds*
- Improved sensitivity for IAXO
- Flavour violation is a consequence!



[Di Luzio, Mescia, Nardi, Panci, Ziegler 1712.04940]
[Björkeroth, Di Luzio, Mescia, Nardi, Panci, Ziegler 1907.06575]
[Di Luzio, Mescia, Nardi, Okawa 2205.15326]

* [Di Luzio, Fedele, Giannotti, Mescia, Nardi 2109.10368]

Astrophobic axions

- Astrophobic scenario: nucleophobia + electrophobia [Di Luzio, Mescia, Nardi, Panci, Ziegler 1712.04940]

Implementing nucleophobia:

Non-universal charges required

$$N_2 = N_3 = 0$$

$$N_2 = -N_3$$

$$C_p + C_n \simeq 0.50(5)(C_u + C_d - 1) \longrightarrow C_u + C_d = \frac{\mathcal{X}_{u_R} + \mathcal{X}_{d_R} - 2\mathcal{X}_{q_L}}{2N} = \frac{N_1}{N} = 1$$

$$C_p - C_n \simeq 1.273(2)(C_u - C_d - \frac{1}{3}) \longrightarrow \frac{\mathcal{X}_{u_R} - \mathcal{X}_{d_R}}{N} = \frac{1}{3}$$

Implementing electrophobia:

- Tuning: large mixing angles in the leptonic sector can cancel the electron coupling.
- 3HDM: see [Björkeroth, Di Luzio, Mescia, Nardi, Panci, Ziegler 1907.06575]

The Scalar Sector

$$V\left(H_1, H_2, \phi\right) = \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 + \frac{\lambda_1}{2}|H_1|^4 + \frac{\lambda_2}{2}|H_2|^4 + \lambda_3|H_1|^2|H_2|^2$$

$$+\lambda_4(H_1^\dagger H_2)(H_2^\dagger H_1) + \frac{\lambda_1^\phi}{2}|\phi|^2|H_1|^2 + \frac{\lambda_2^\phi}{2}|\phi|^2|H_2|^2 + \lambda_3^\phi\left(|\phi|^2 - \frac{v_\phi^2}{2}\right)^2$$

$$-\left(\mu_\phi H_2^\dagger H_1 \phi + \text{h.c.}\right)$$

Common problem to invisible axion models.

Possible solution: use "ultra-weak" couplings which allows to separate the scales in a "technically natural way"

$$\lambda_{1,2}^\phi \sim v^2/v_\phi^2\,, \quad \mu_\phi \sim v^2/v_\phi$$

[Volkas, Davies, Joshi PLB 215 1988]

[Foot, Kobakhidze, McDonald, Volkas 1310.0223]

The Scalar Sector

$$V(\Phi_1,\,\Phi_2) = M_{11}^2\,\Phi_1^\dagger\Phi_1 + M_{22}^2\,\Phi_2^\dagger\Phi_2 - \left(M_{12}\Phi_1^\dagger\Phi_2 + \text{h.c.}\right)$$
$$+\frac{\Lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\Lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \Lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \Lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$
$$+\left\{\frac{1}{2}\Lambda_5(\Phi_1^\dagger\Phi_2)^2 + \left[\Lambda_6(\Phi_1^\dagger\Phi_1) + \Lambda_7(\Phi_2^\dagger\Phi_2)\right]\Phi_1^\dagger\Phi_2 + \text{h.c.}\right\},$$

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

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

The Scalar Sector: Higgs alignment

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

SM-like Higgs properties

$$c^2_{\alpha-\beta} = \frac{\Lambda_6^2 v^4}{(m_H^2 - m_h^2)(m_H^2 - \Lambda_1 v^2)}$$

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Decoupling:

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

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non-decoupling: $\Lambda_6 \to 0$

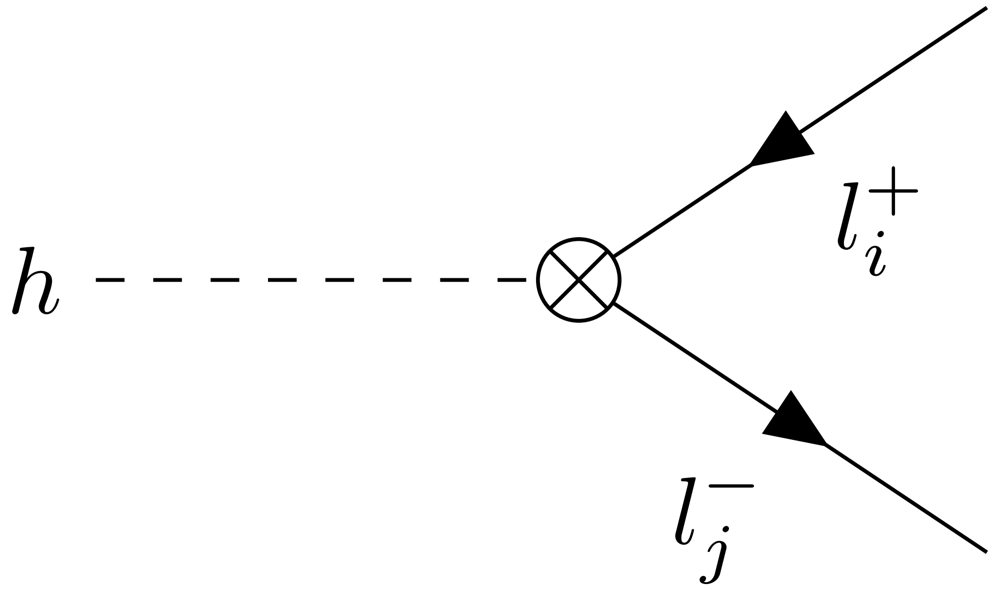
$$m_A^2 + \Lambda_5 v^2 \simeq m_H^2$$

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

The new scalars can be at the EW scale

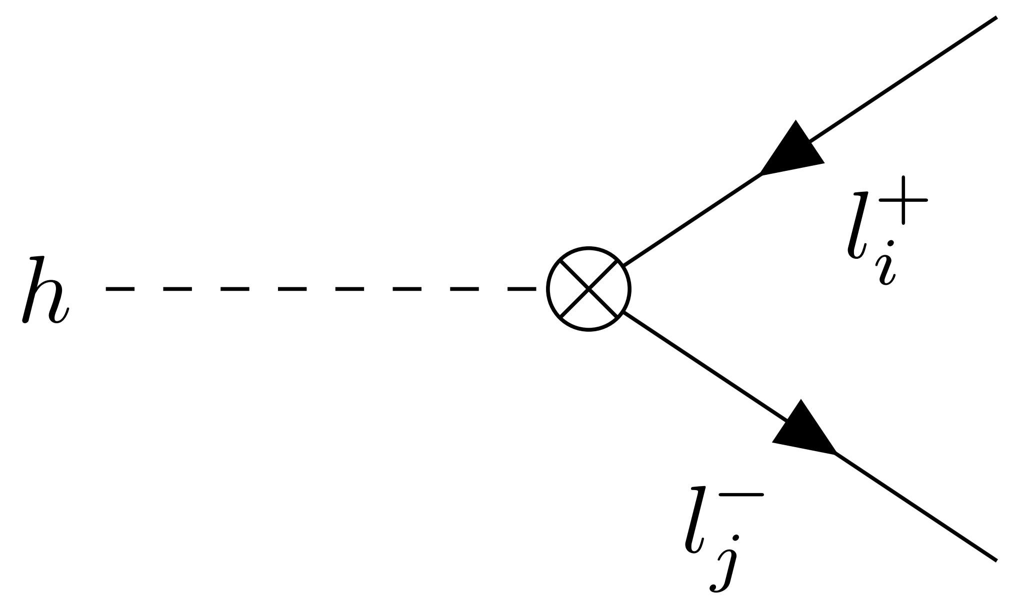
Lepton flavour connection

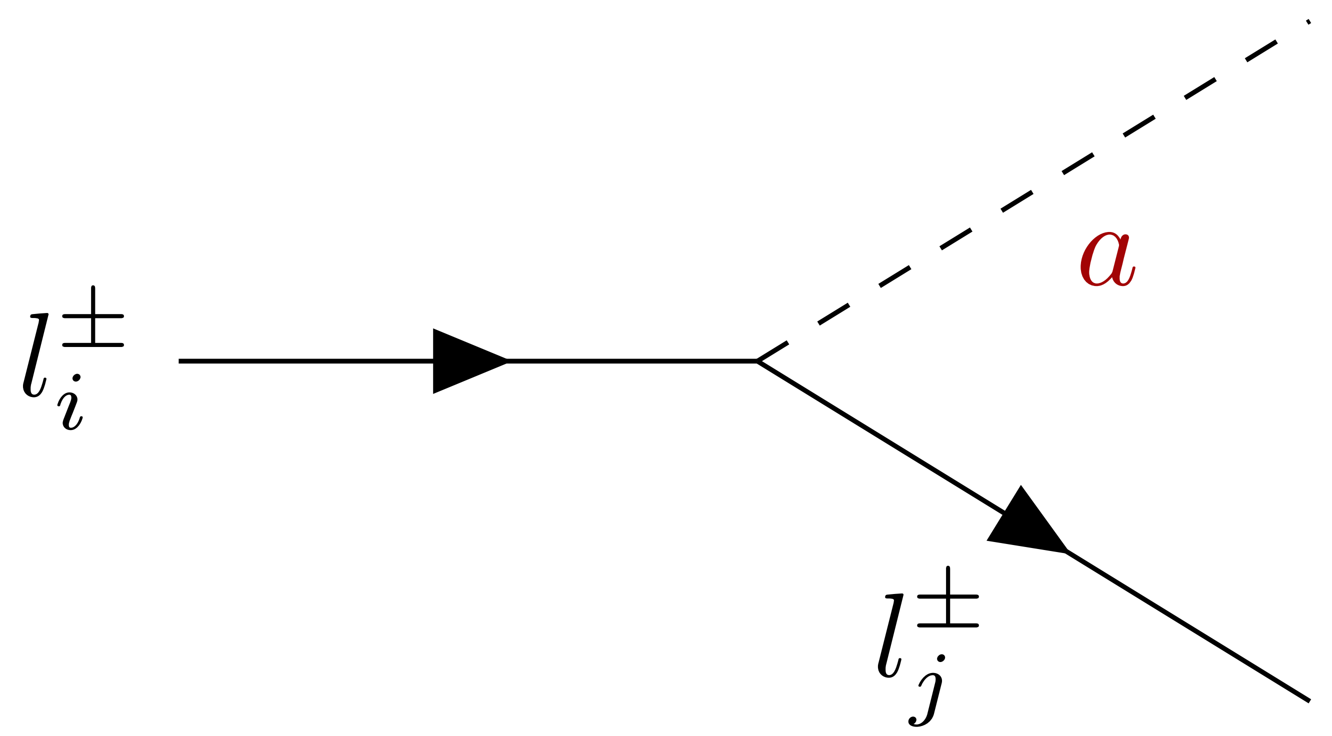
Lepton flavour connection



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

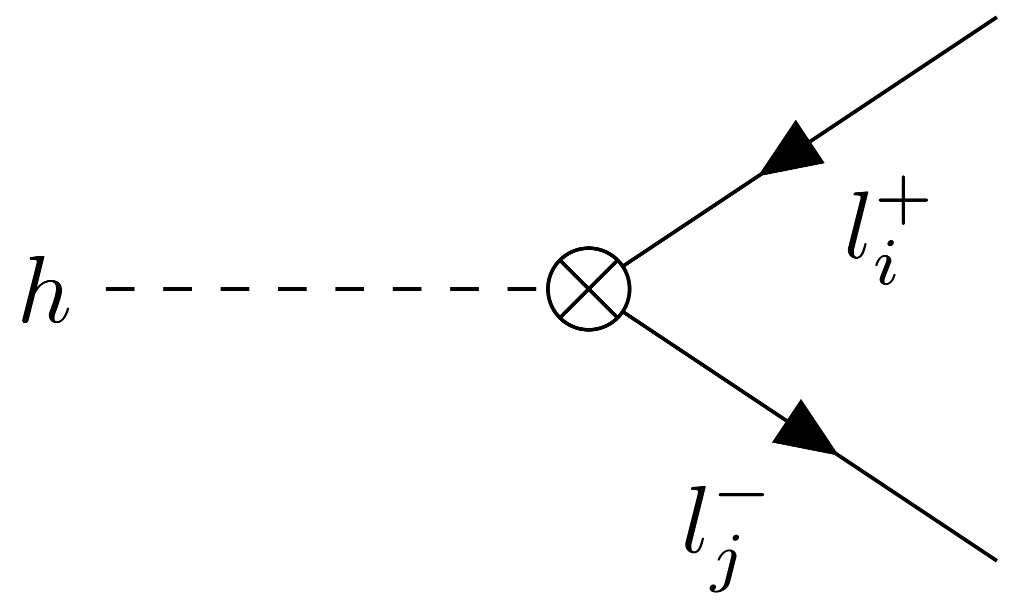
Lepton flavour connection

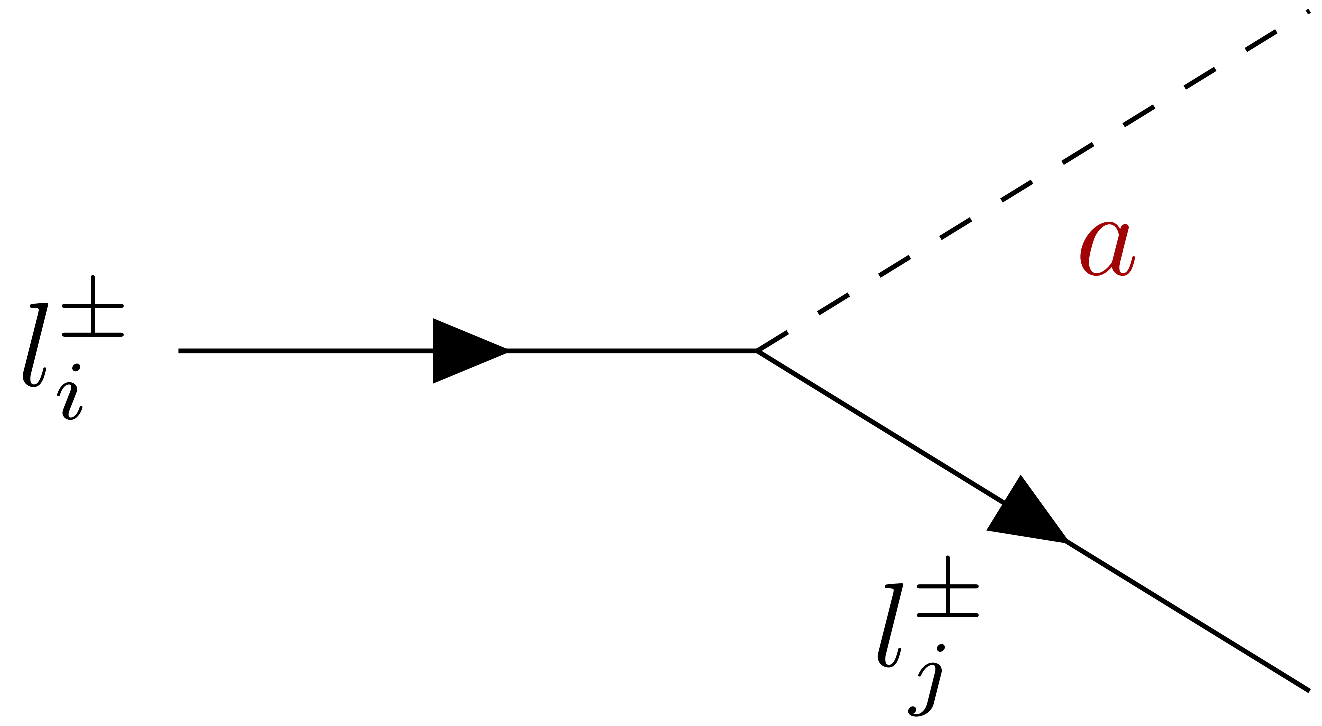




$$\mathrm{BR}(h \to l_i l_j) \simeq \frac{m_h}{16\pi\Gamma_h}\left(\frac{c_{\alpha-\beta}}{s_\beta c_\beta}\right)^2 \frac{m_{l_i}^2}{v^2}|(C_e^{L,R})_{ij}|^2 \,, \qquad \mathrm{BR}(l_i \to l_j\, a) \simeq \frac{m_{l_i}^3}{16\pi\Gamma_{l_i}} \frac{|(C_e^{L,R})_{ij}|^2}{2f_a^2}$$

Lepton flavour connection

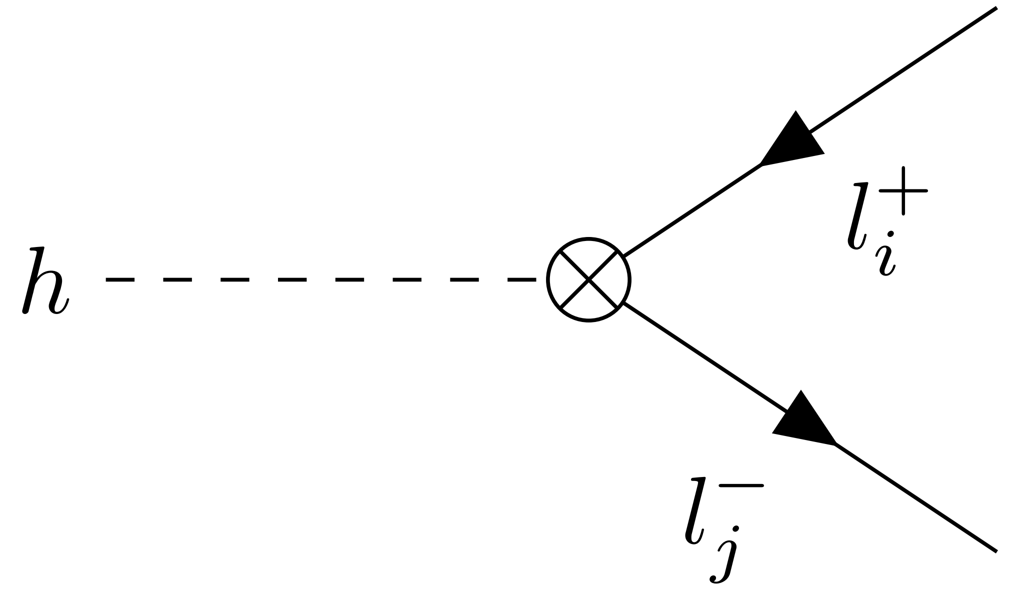


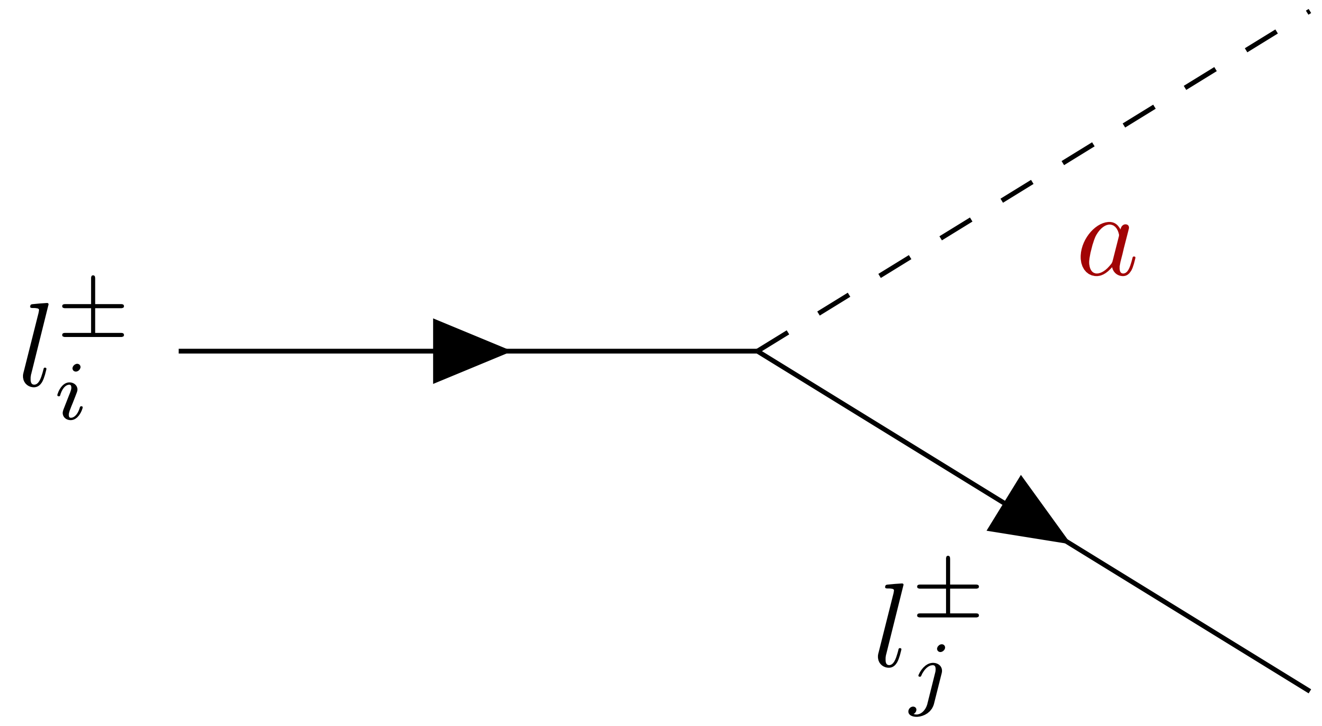


$$\mathrm{BR}(h \to l_i l_j) \simeq \frac{m_h}{16\pi\Gamma_h}\left(\frac{c_{\alpha-\beta}}{s_\beta c_\beta}\right)^2 \frac{m_{l_i}^2}{v^2}|(C_e^{L,R})_{ij}|^2\,, \qquad \mathrm{BR}(l_i \to l_j\, a) \simeq \frac{m_{l_i}^3}{16\pi\Gamma_{l_i}}\frac{|(C_e^{L,R})_{ij}|^2}{2f_a^2}$$

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

Lepton flavour connection





Some mild deviations at ATLAS

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

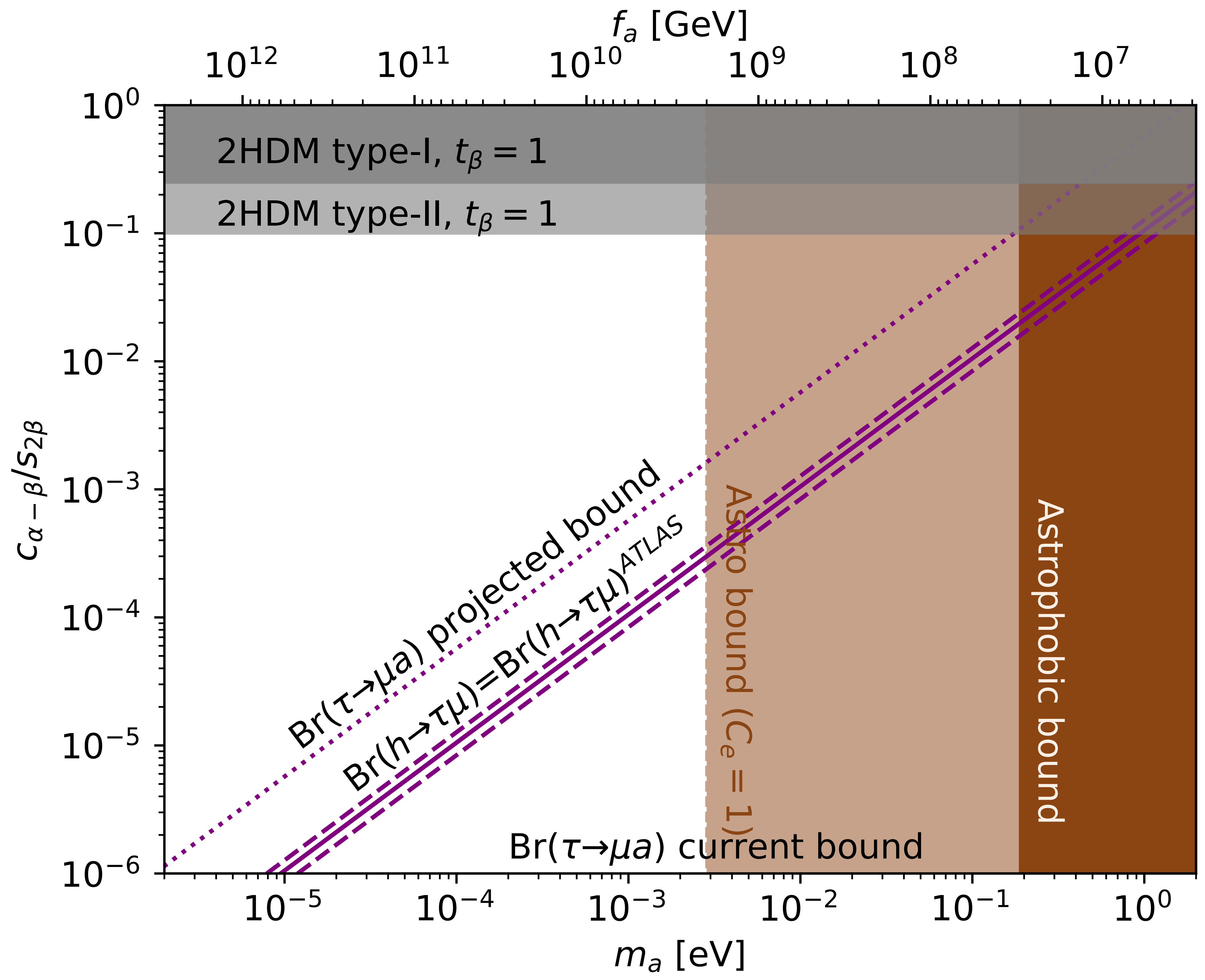
$$\mathrm{BR}(h \to \tau \mu) = 0.11^{+0.05}_{-0.04}\,\%$$

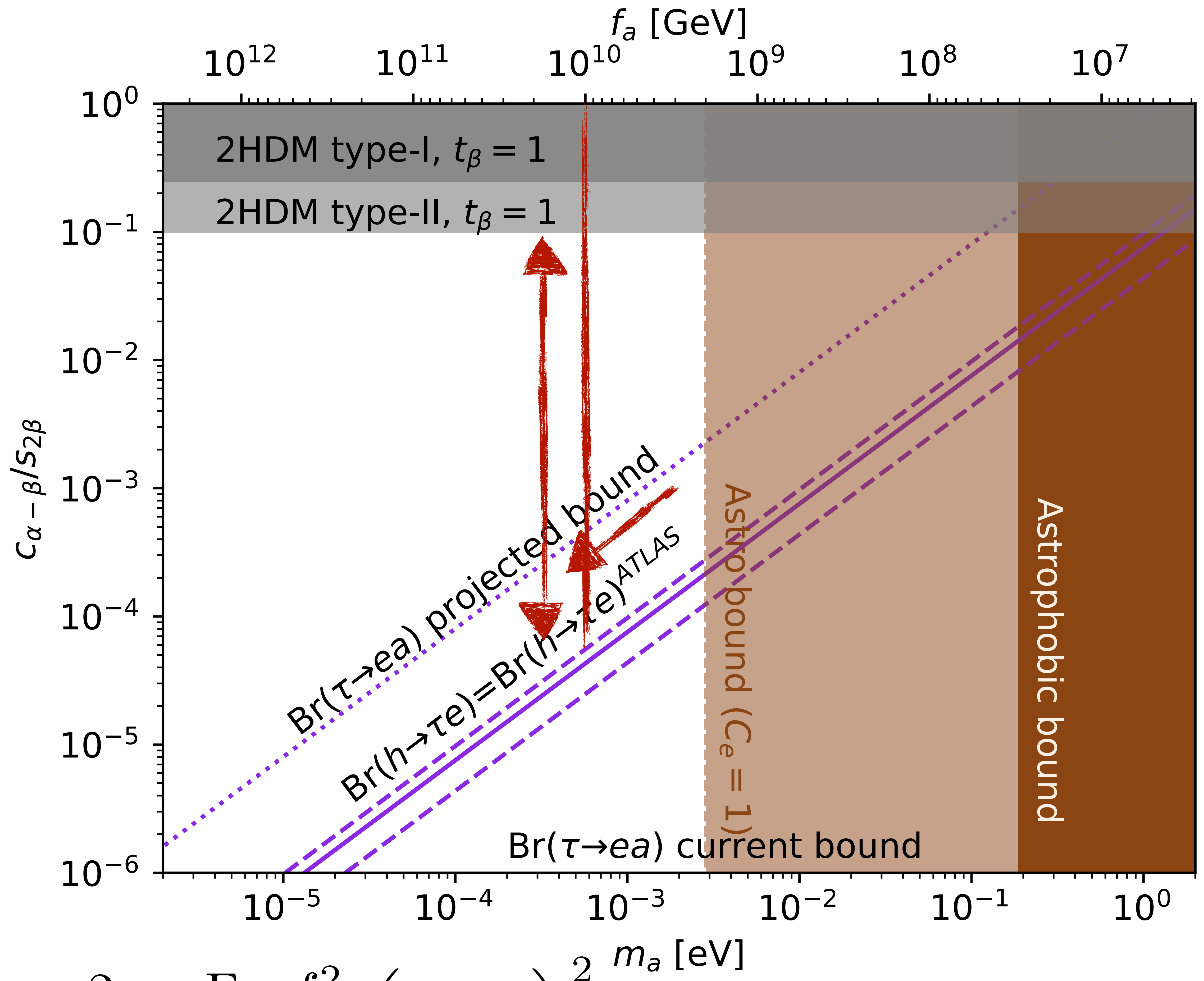
[ATLAS 2302.05225]

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

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

Lepton flavour connection





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

Yukawa textures

Astrophobic M1 model:

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

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

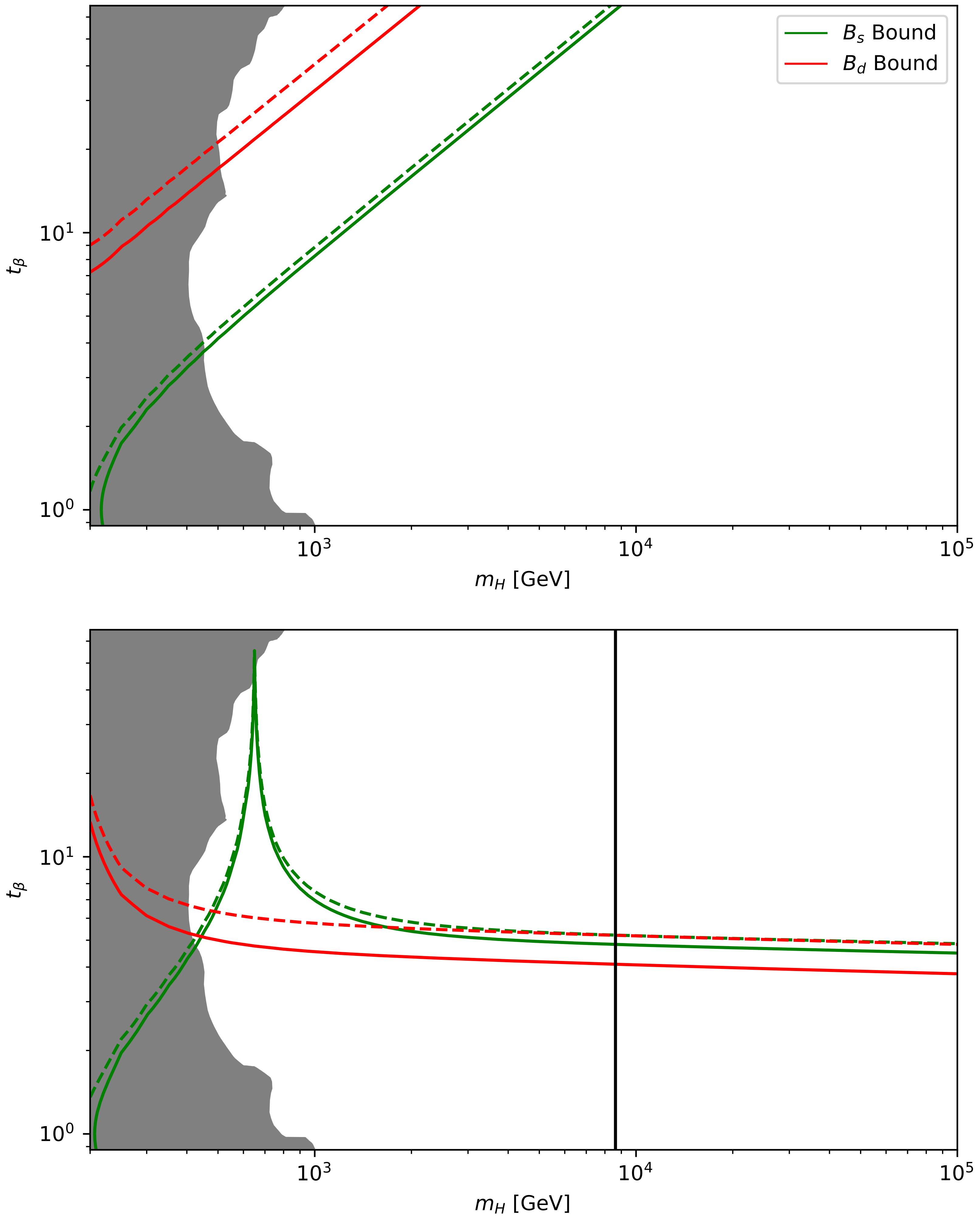
Astrophobic M4 model:

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

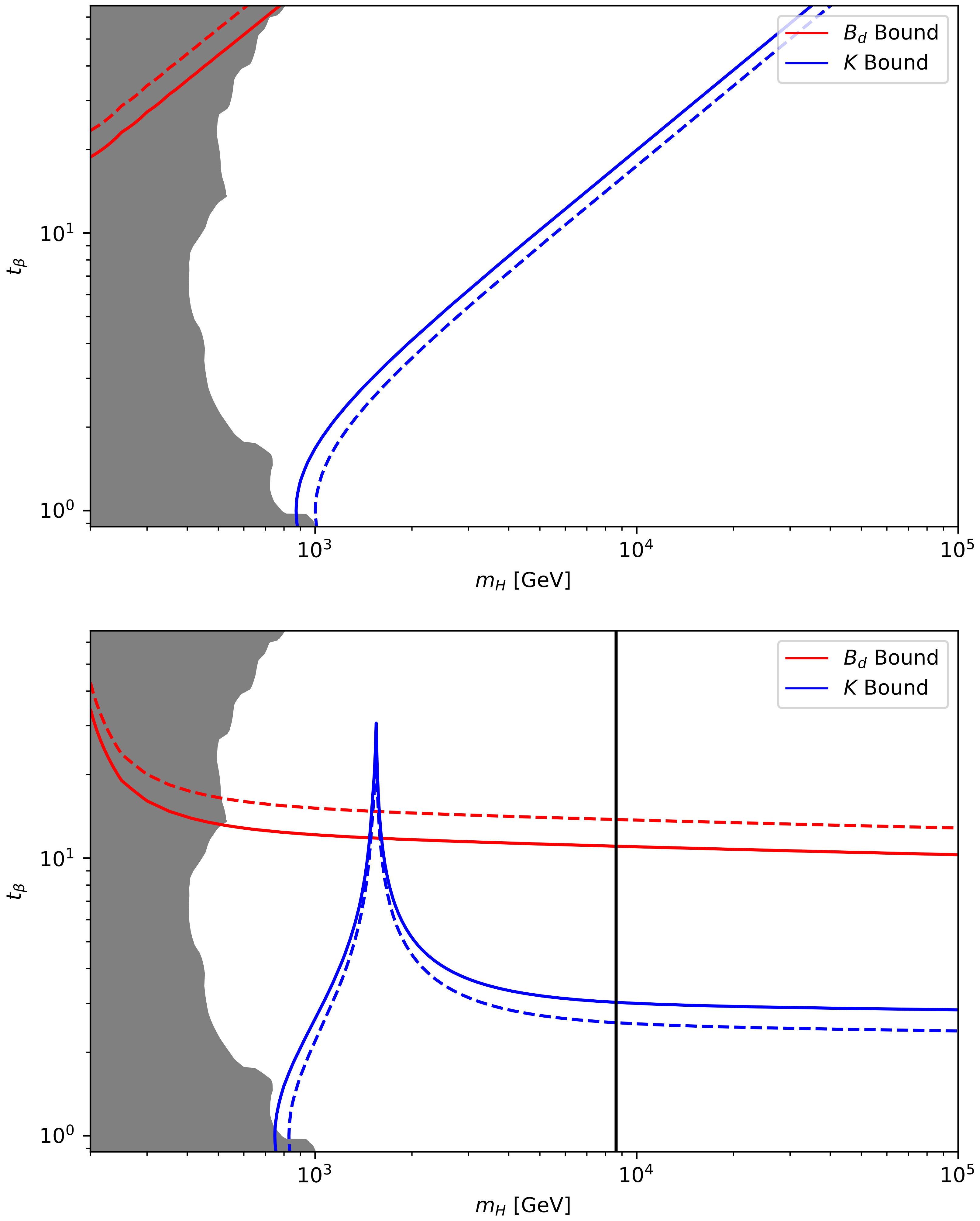
$$Y_1^u = \begin{pmatrix} y_{11}^u & y_{12}^u & y_{13}^u \\ y_{21}^u & y_{22}^u & y_{23}^u \\ y_{31}^u & y_{32}^u & y_{33}^u \end{pmatrix}, \quad Y_2^u = 0,$$
$$Y_1^d = \begin{pmatrix} 0 & y_{12}^d & y_{13}^d \\ 0 & y_{22}^d & y_{23}^d \\ 0 & y_{32}^d & y_{33}^d \end{pmatrix}, \quad Y_2^d = \begin{pmatrix}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

Specific Models

M4 Model



M1 Model

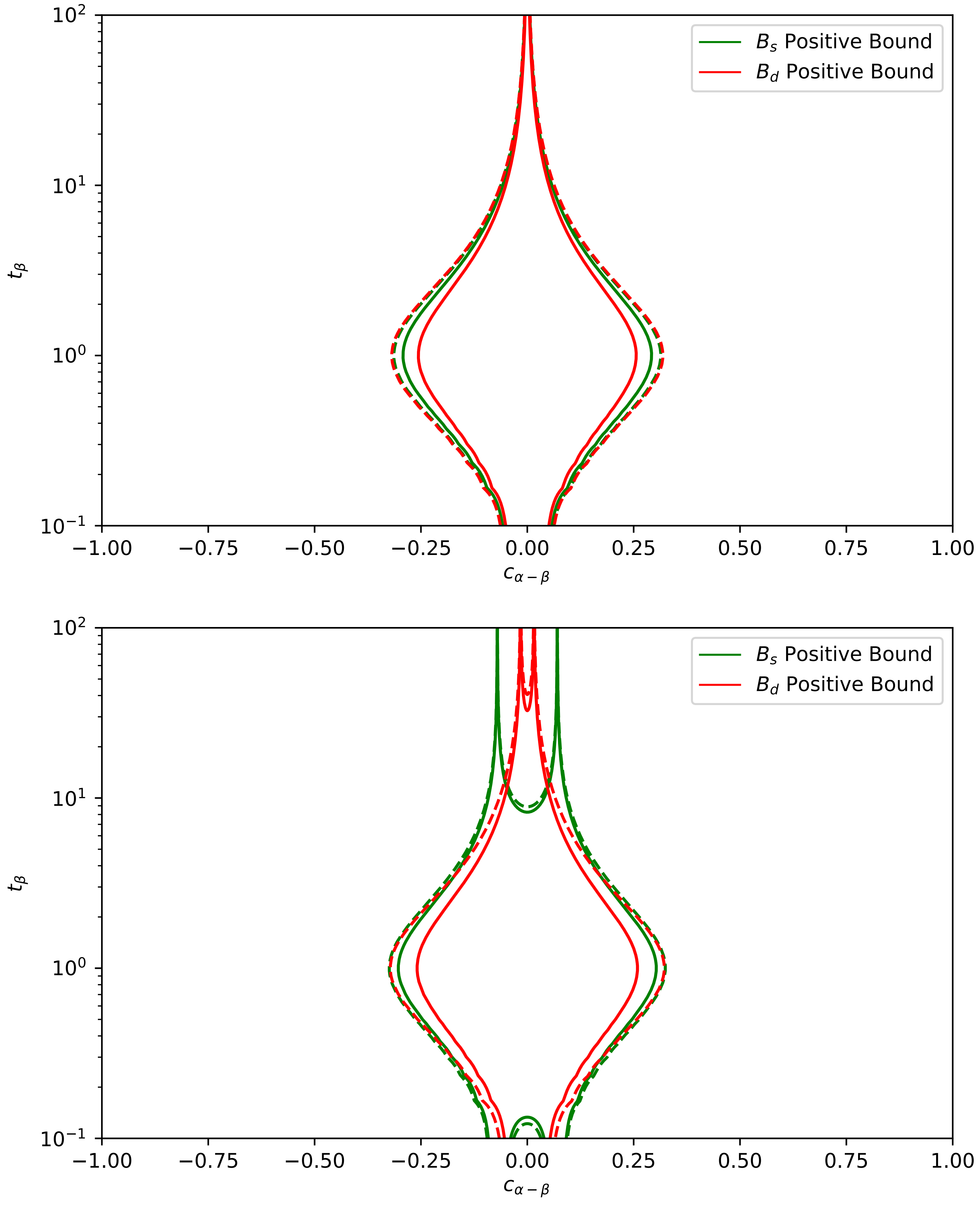


Assumption

$$V_{d_L,d_R} = V_{\text{CKM}}$$

Specific Models

M4 Model



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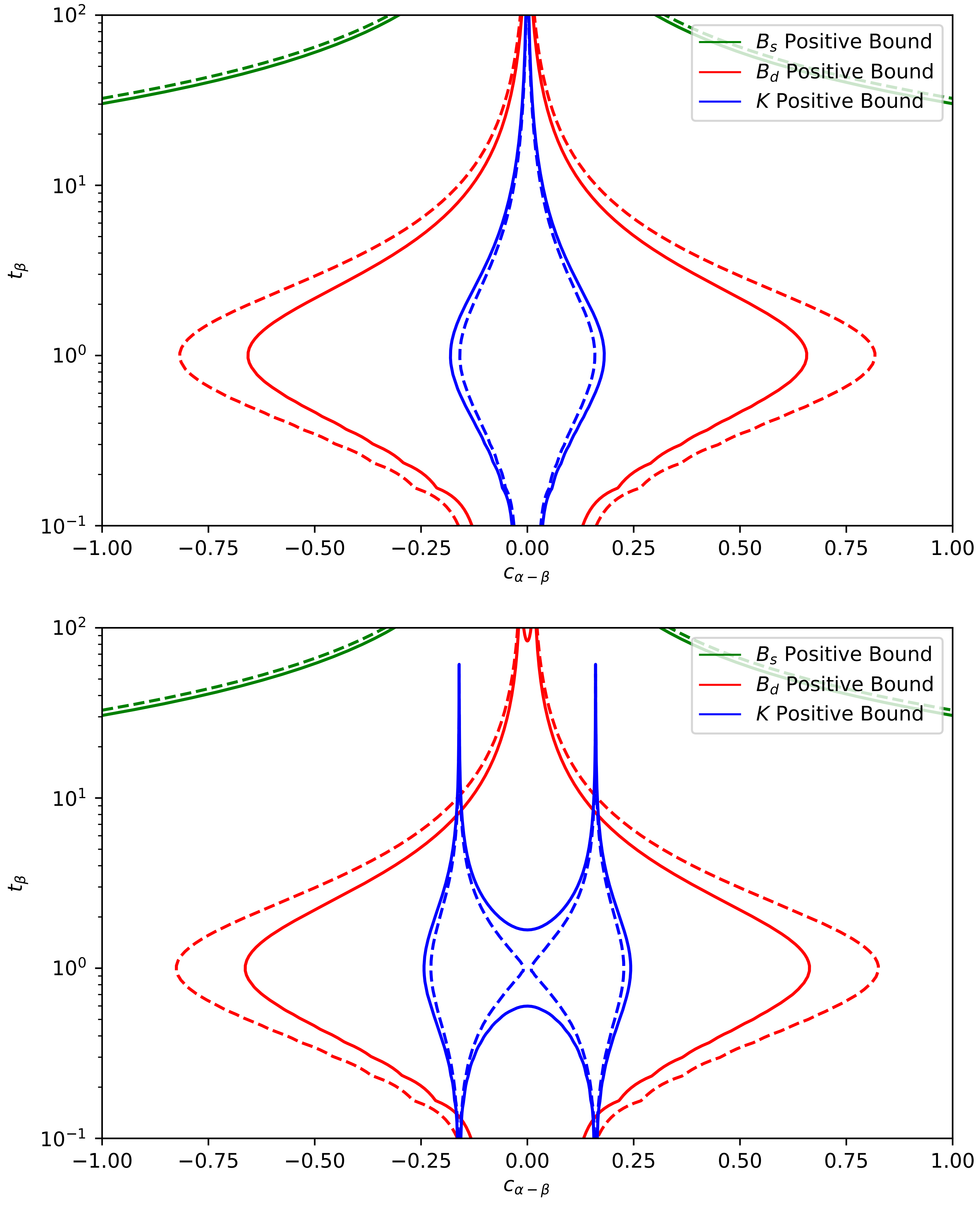

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