IR - UV interplay in axion flavour violation

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Università degli Studi di Padova

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Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Motivation

- Many reasons for a Flavour-Violating (FV) axion:
  - Phenomenology: $K \to \pi\, a$ $\mu \to e\, a$ [Wilczeck '82]
  - Astrophobic scenario: $m_a \lesssim 0.2$ eV [Di Luzio, Mescia, Nardi, Panci, Ziegler '16] [Badziak, Harigaya '23] [Takahashi, Yin '23]
  - Flavour Connections:
    - Froggatt-Nielsen axion: Flaxion/Axiflavon [Ema, Hamaguchi, Moroi, Nakayama '16] [Calibbi, Goertz, Redigolo, Ziegler, Zupan '16]
    - Quality Problem and Flavour [Darmé, Nardi, Smarra '22]

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If an axion is observed in a FV golden channel, e.g. $K \to \pi\, a$ would it possible to obtain any information about the UV modes?

related work by [Badziak, di Cortona, Tabet, Ziegler '21]

DFSZ-like Axion

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In the IR

$U(1)_{\text{PQ}} : \chi_f$ diagonal matrices in flavour space

$$\mathcal{L}_{IR} = \frac{\partial_\mu a}{f_a}\left(\bar{d}_L \gamma^\mu V_{d_L}^\dagger \chi_q V_{d_L} d_L + \bar{d}_R \gamma^\mu V_{d_R}^\dagger \chi_{d_R} V_{d_R} d_R\right)$$

$$C_d^{R,L} = \frac{1}{2N} V_{d_{R,L}}^\dagger \chi_{d_{R,L}} V_{d_{R,L}}$$

Condition for FV: $\chi_f \neq \chi_f \mathbb{1}$

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In the UV (completion)

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

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

$$\epsilon_{ij}^d \equiv (V^\dagger_{d_L} Y_2^d V_{d_R})_{ij}$$

Condition for FV: $M_d \not\propto Y^d_{1(2)}$

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DFSZ-like Axion

n)

$U(1)_{\mathrm{PQ}}:$ … $\tilde{H}_2)d_R$

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Co … 2)

DFSZ-like Axion

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$$M_d = \frac{v}{\sqrt{2}} c_\beta Y_1^d + \frac{v}{\sqrt{2}} s_\beta Y_2^d \;\Big|\; -\chi_q Y_{1,2}^d + Y_{1,2}^d \chi_d - \chi_{1,2} Y_{1,2}^d = 0$$

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$$\epsilon^d = V_{d_L}^\dagger Y_2^d V_{d_R} = \frac{\sqrt{2}}{v s_\beta} \left(-V_{d_L}^\dagger \chi_q V_{d_L} \hat{M}_d + \hat{M}_d V_{d_R}^\dagger \chi_d V_{d_R} - \chi_1 \hat{M}_d \right)$$

Flavour Connection

- In the particular set-up where the charges are 2 + 1 and in the alignment limit, one can easily relate flavour observables

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

For all the details soon on the arXiv!
[di Luzio, Guerrera, XPD, Rigolin '23]

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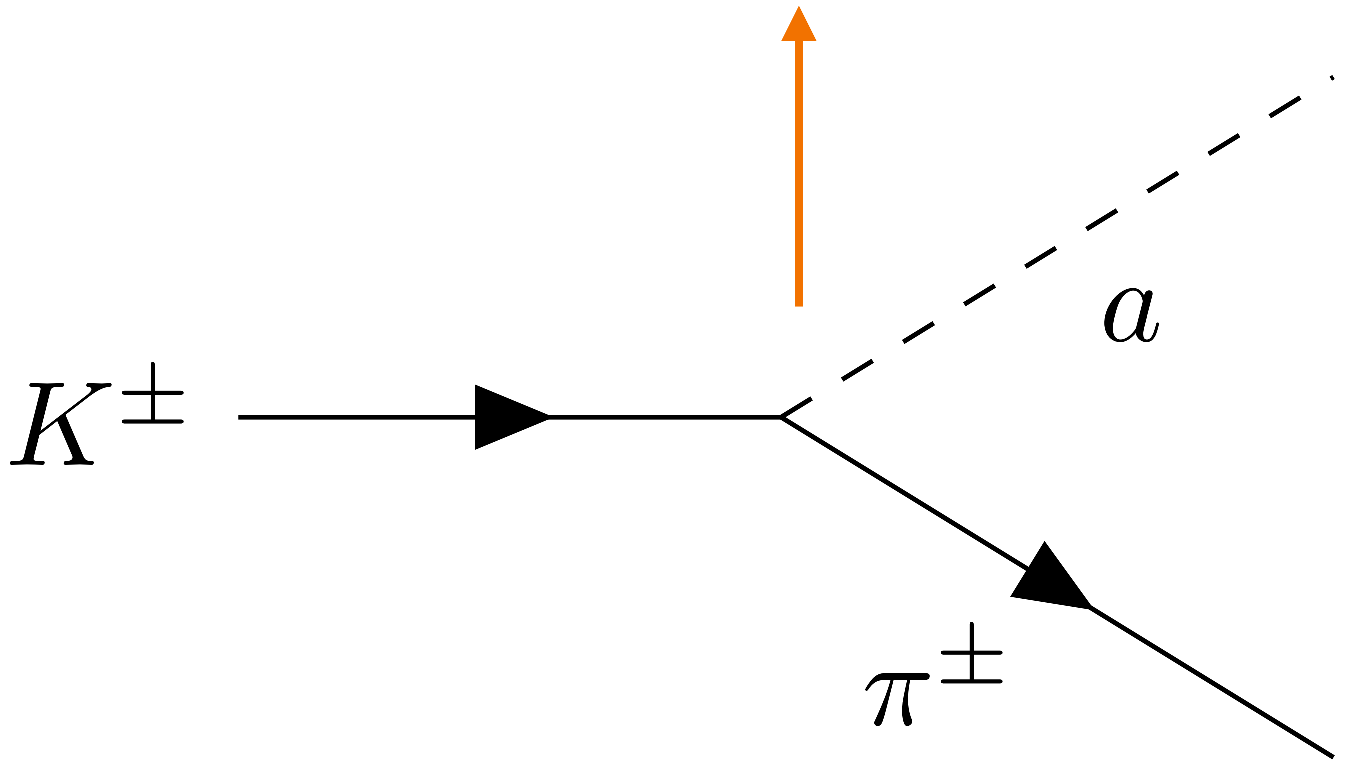

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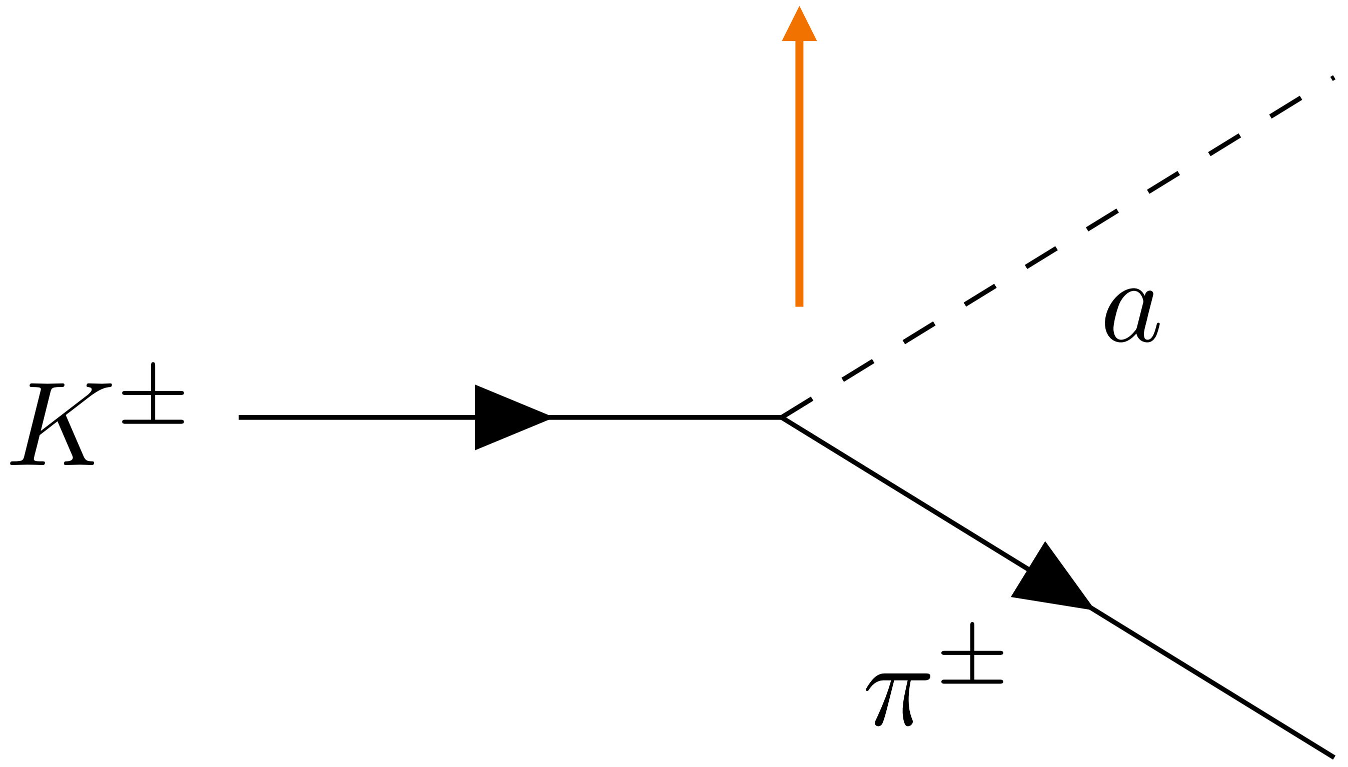

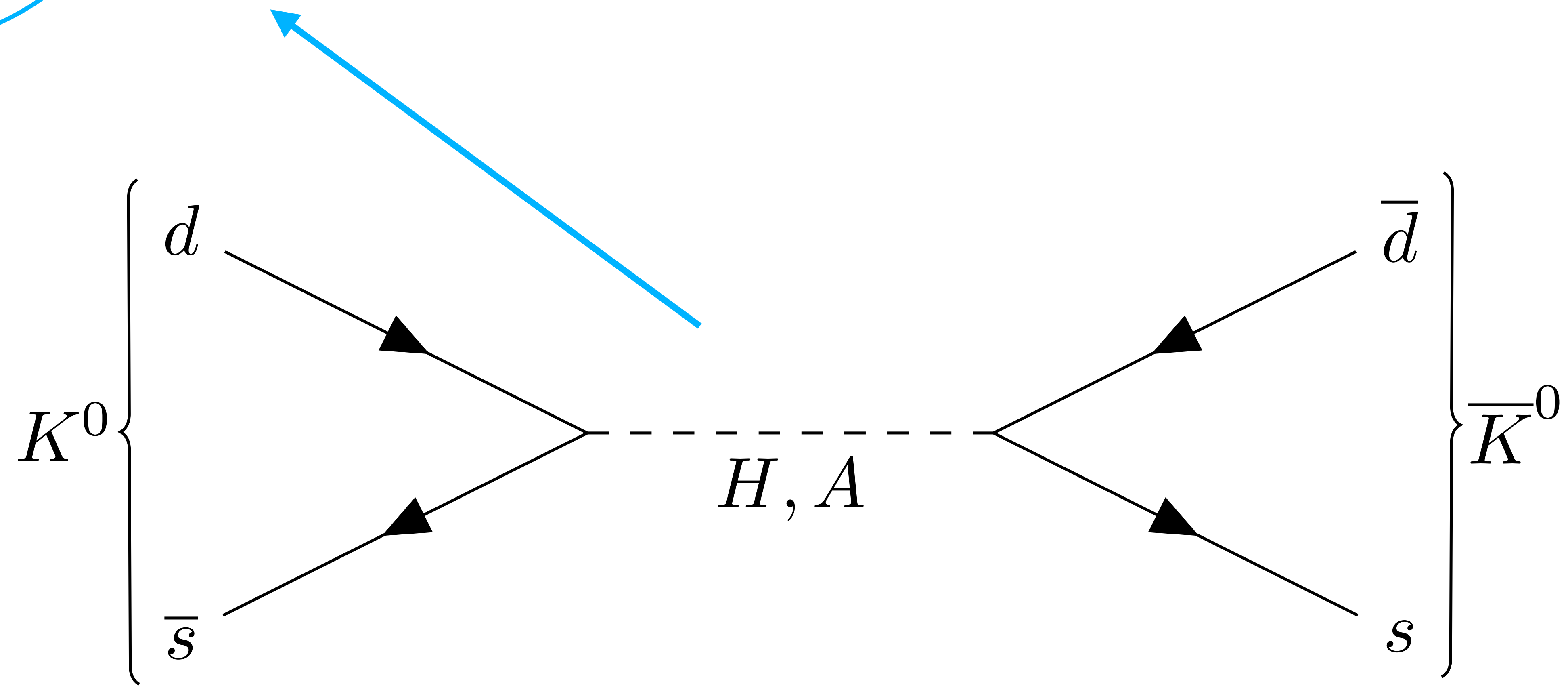

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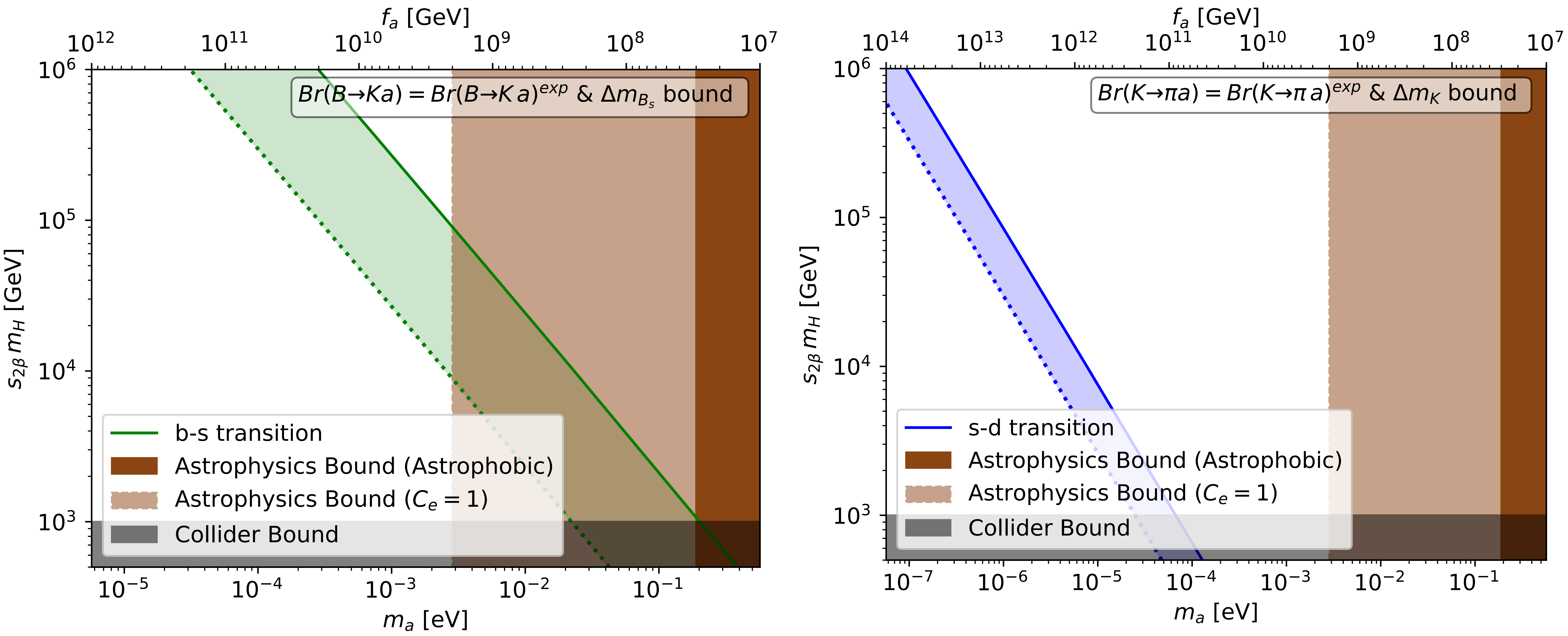

bounds from [Camalich, Pospelov, Vuong, Ziegler, Zupan '20]

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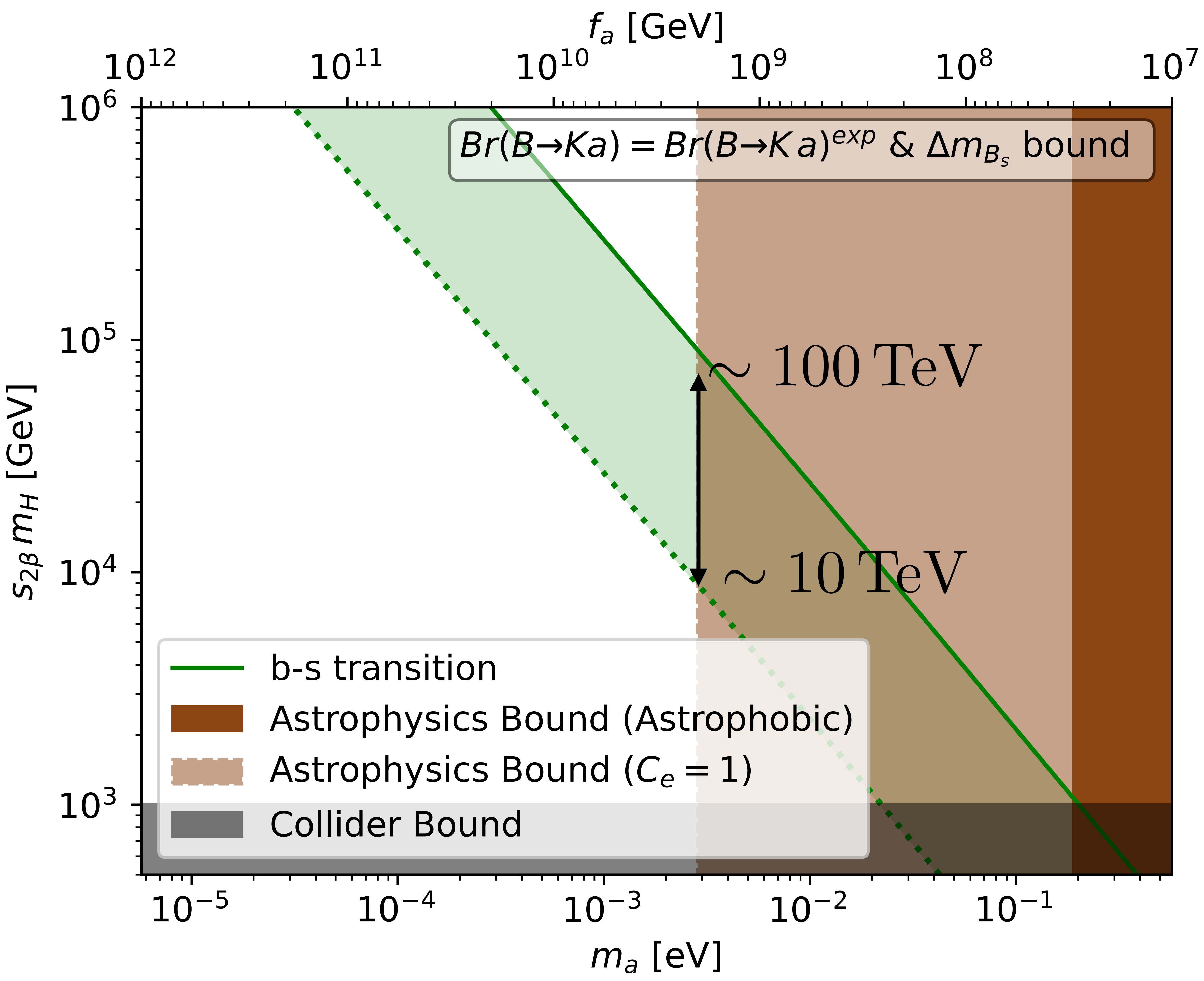

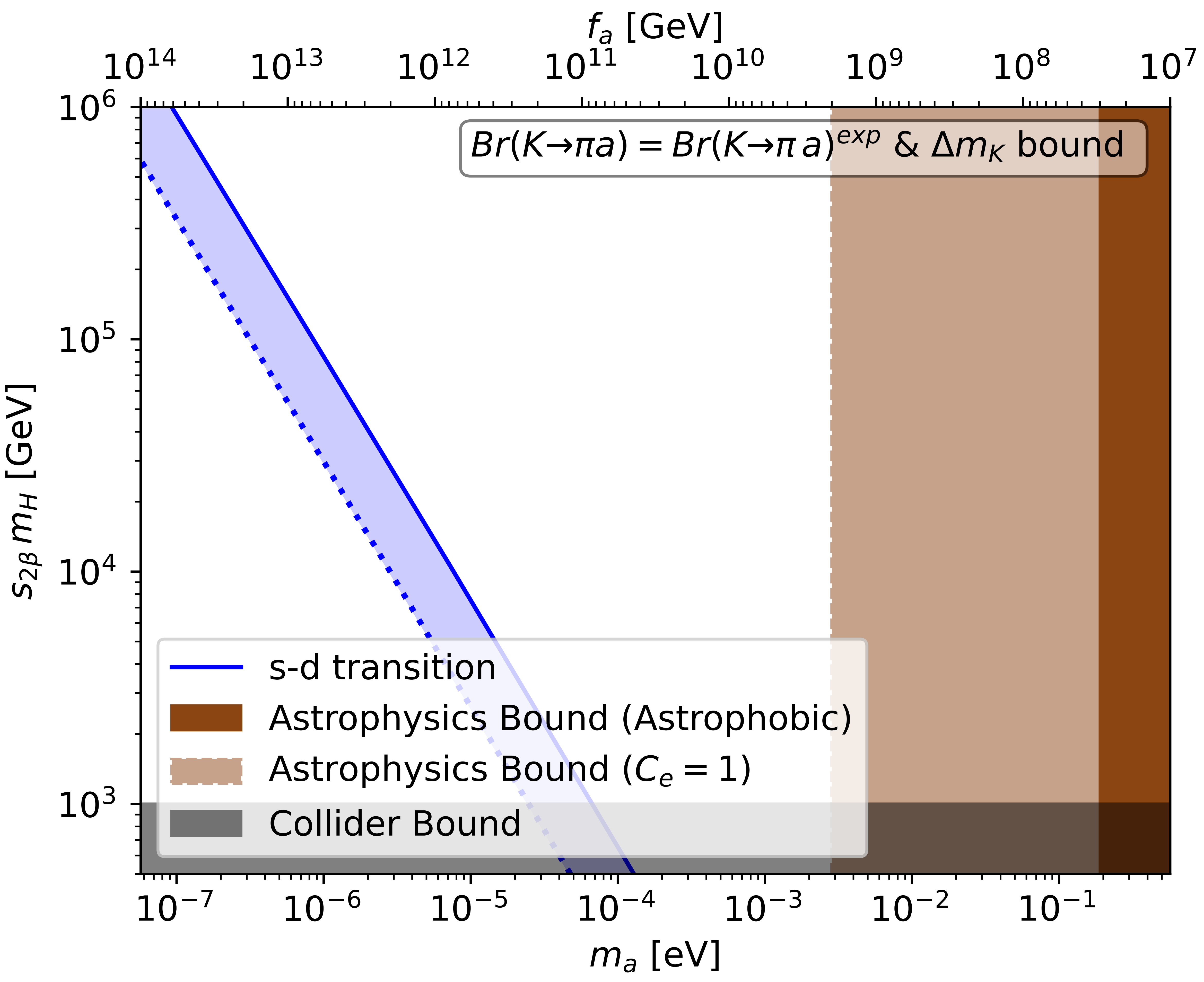

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Conclusions

- We have shown a model independent way of parameterising the flavour violation between the IR and UV.
- This allows you to relate UV-IR observables with their scales: $(\Delta m,\ \mathrm{Br}) \to (m_H,\ f_a)$
- If we find a FV axion, we could say if it is possible to observe the UV modes at LHC.
- More in the paper:
    - Analysis of 2HDM meson mixing with and without alignment limit,
    - Lepton Flavour Violation,
    - Model-dependent bounds.

Thanks for your attention!

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Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

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The Scalar Sector

$$V(H_1, H_2, \phi) = \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 + \frac{\lambda_1}{2}|H_1|^4 + \frac{\lambda_2}{2}|H_2|^4 + \lambda_3|H_1|^2|H_2|^2$$
$$+\lambda_4(H_1^\dagger H_2)(H_2^\dagger H_1) + \frac{\lambda_1^\phi}{2}|\phi|^2|H_1|^2 + \frac{\lambda_2^\phi}{2}|\phi|^2|H_2|^2 + \lambda_3^\phi\left(|\phi|^2 - \frac{v_\phi^2}{2}\right)^2$$
$$-\left(\mu_\phi H_2^\dagger H_1 \phi + \text{h.c.}\right)$$

Common problem to invisible axion models.

Possible solution: use "ultra-weak" couplings $\lambda_{1,2}^\phi \sim v^2/v_\phi^2\,, \quad \mu_\phi \sim v^2/v_\phi$
which allows to separate the scales in a "technically natural way" [Foot, Kobakhidze, McDonald, Volkas '13]

Flavour Connection

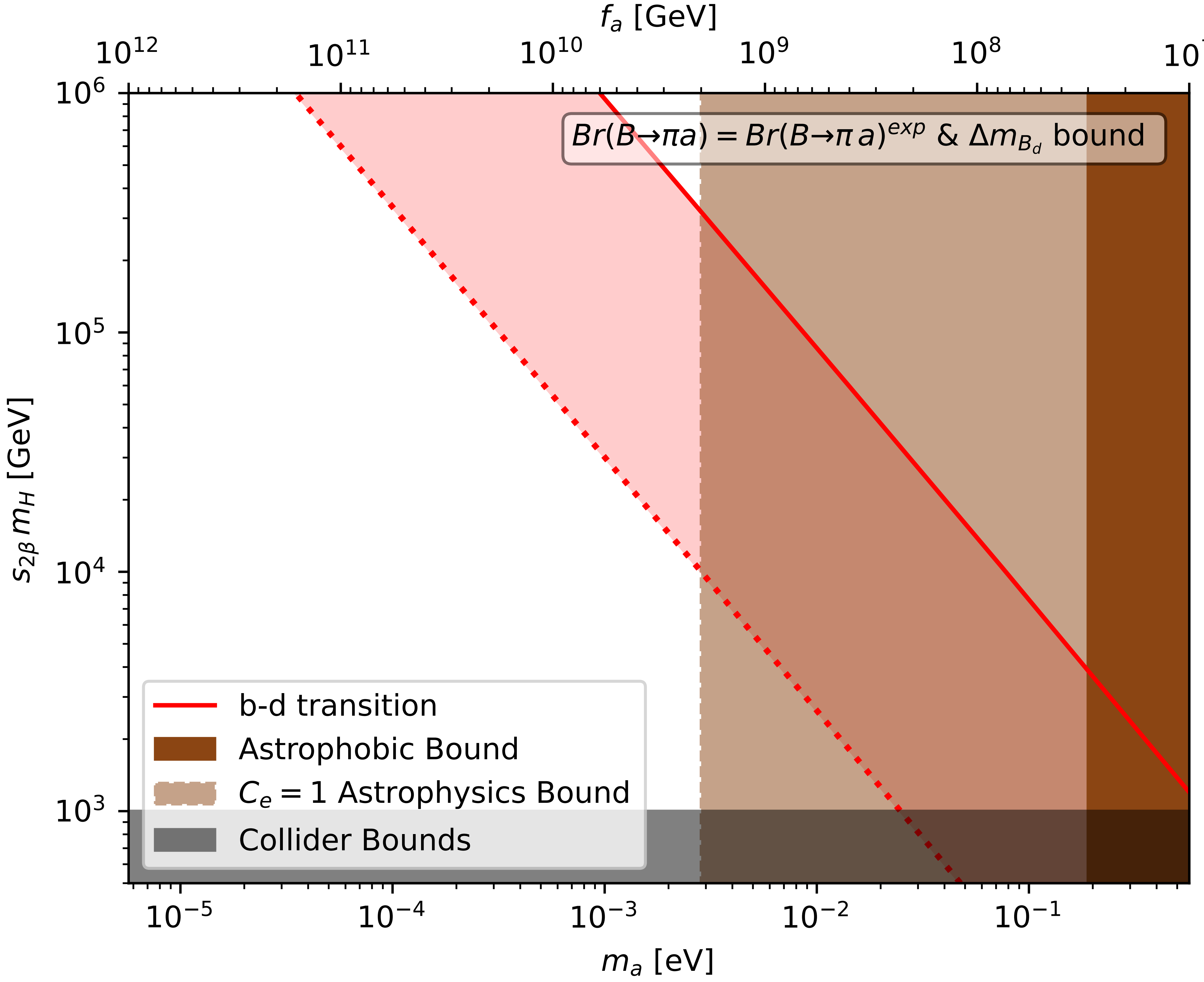
$$\left(\frac{f_a}{10^8\,\mathrm{GeV}}\right)^2\left(\frac{1\,\mathrm{TeV}}{s_{2\beta}\,m_H}\right)^2\left(\frac{\mathrm{Br}(K\to\pi a)}{7.3\cdot 10^{-11}}\right)10^{-6}=\frac{2\,|M_{12}^{\mathrm{NP}}|}{3.5\cdot 10^{-15}\,\mathrm{GeV}}\,,$$

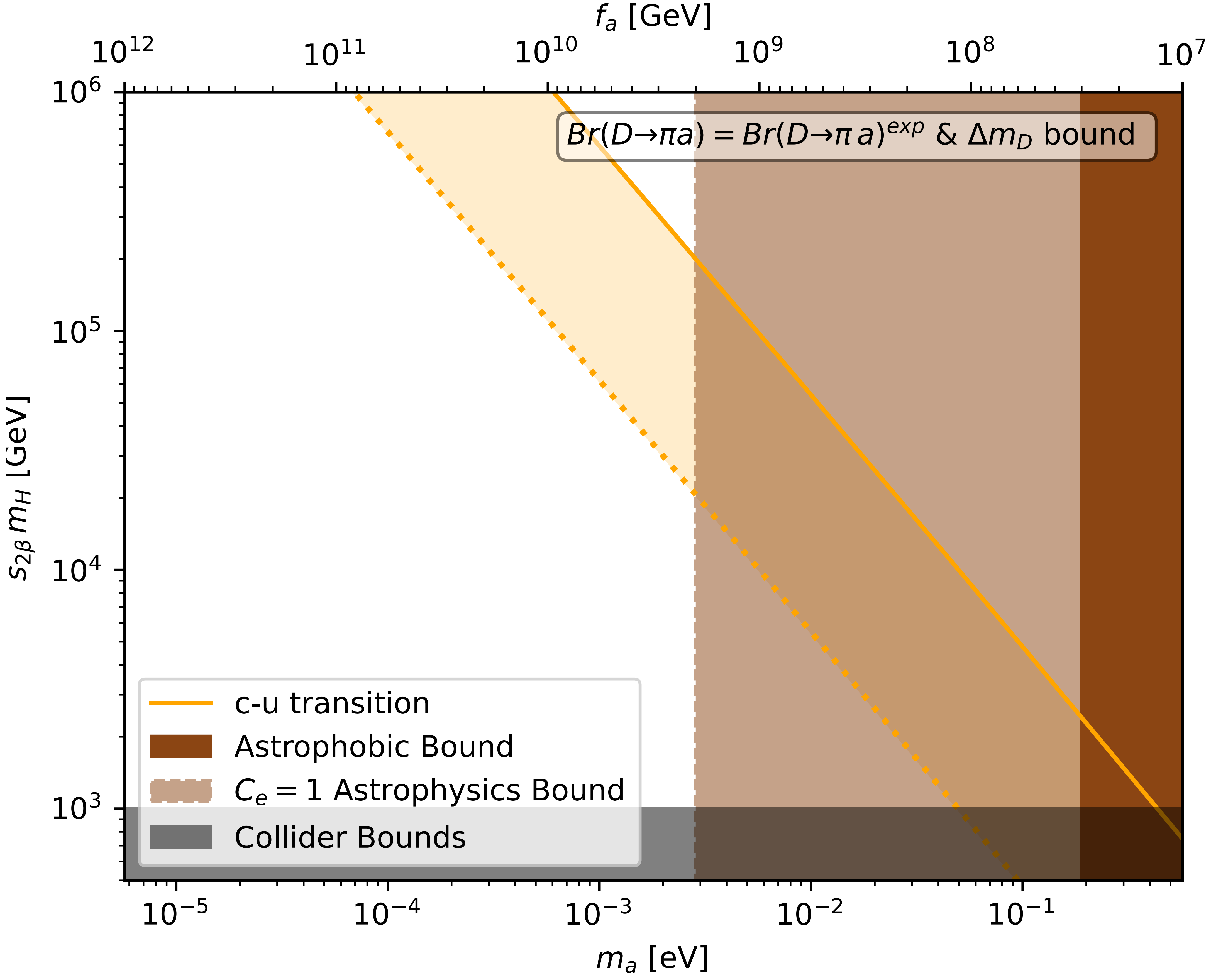
$$\left(\frac{f_a}{10^8\,\mathrm{GeV}}\right)^2\left(\frac{1\,\mathrm{TeV}}{s_{2\beta}\,m_H}\right)^2\left(\frac{\mathrm{Br}(B\to\pi a)}{2.3\cdot 10^{-5}}\right)12.8=\frac{2\,|M_{12}^{\mathrm{NP}}|}{3.3\cdot 10^{-13}\,\mathrm{GeV}}\,,$$

$$\left(\frac{f_a}{10^8\,\mathrm{GeV}}\right)^2\left(\frac{1\,\mathrm{TeV}}{s_{2\beta}\,m_H}\right)^2\left(\frac{\mathrm{Br}(B\to K a)}{7.1\cdot 10^{-6}}\right)1.3=\frac{2\,|M_{12}^{\mathrm{NP}}|}{1.2\cdot 10^{-11}\,\mathrm{GeV}}\,,$$

$$\left(\frac{f_a}{10^8\,\mathrm{GeV}}\right)^2\left(\frac{1\,\mathrm{TeV}}{s_{2\beta}\,m_H}\right)^2\left(\frac{\mathrm{Br}(D\to\pi a)}{8\cdot 10^{-6}}\right)72.5=\frac{2\,|M_{12}^{\mathrm{NP}}|}{6.7\cdot 10^{-15}\,\mathrm{GeV}}\,.$$

Flavour Connection





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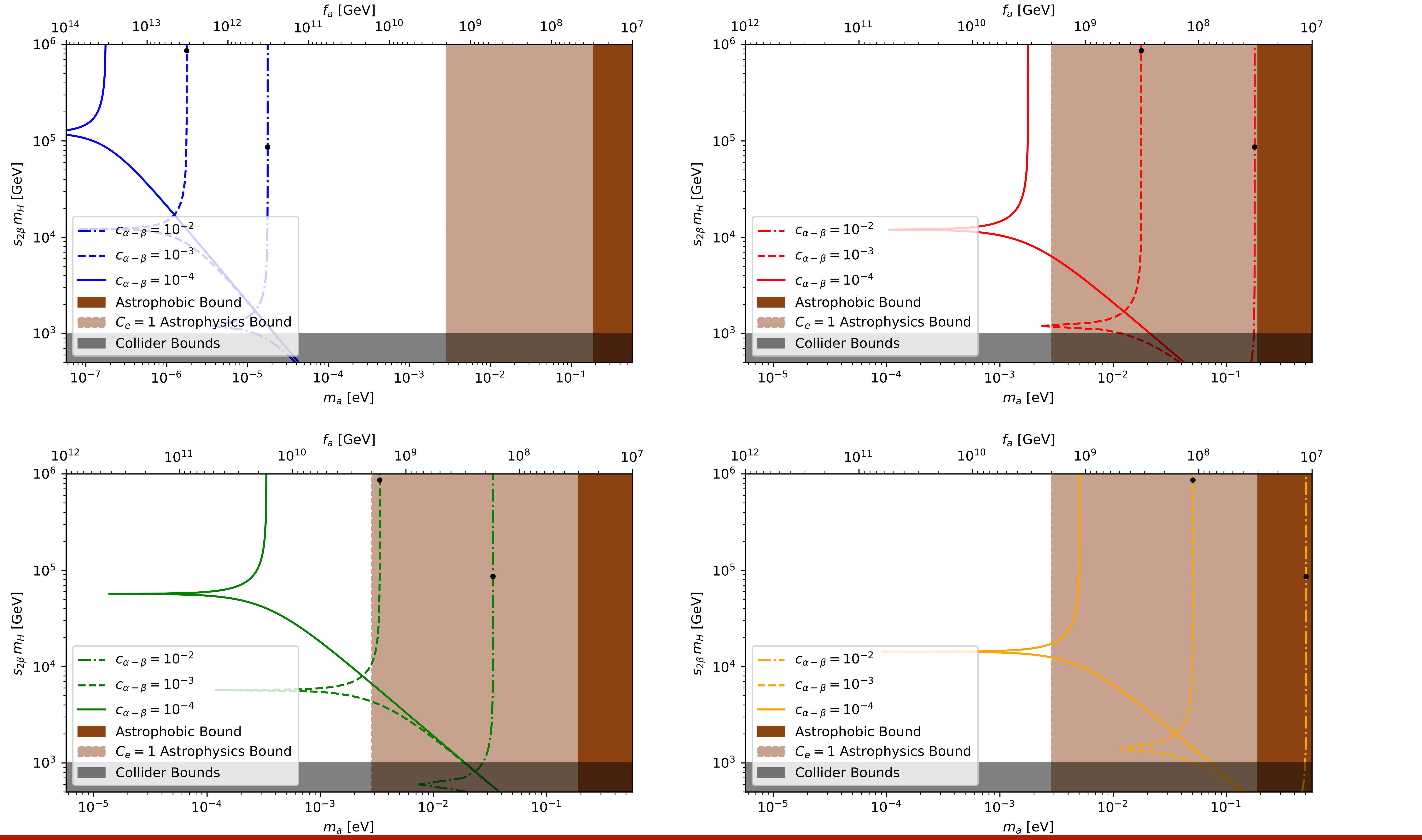
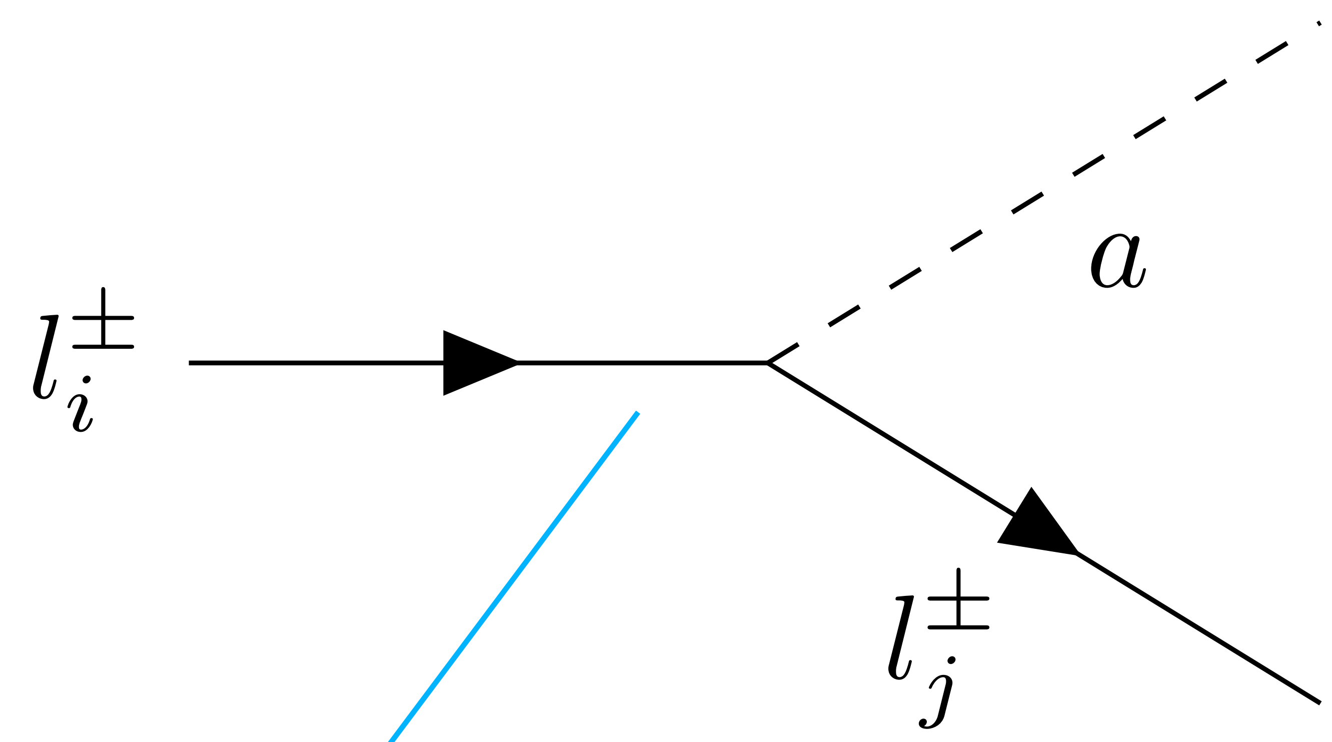
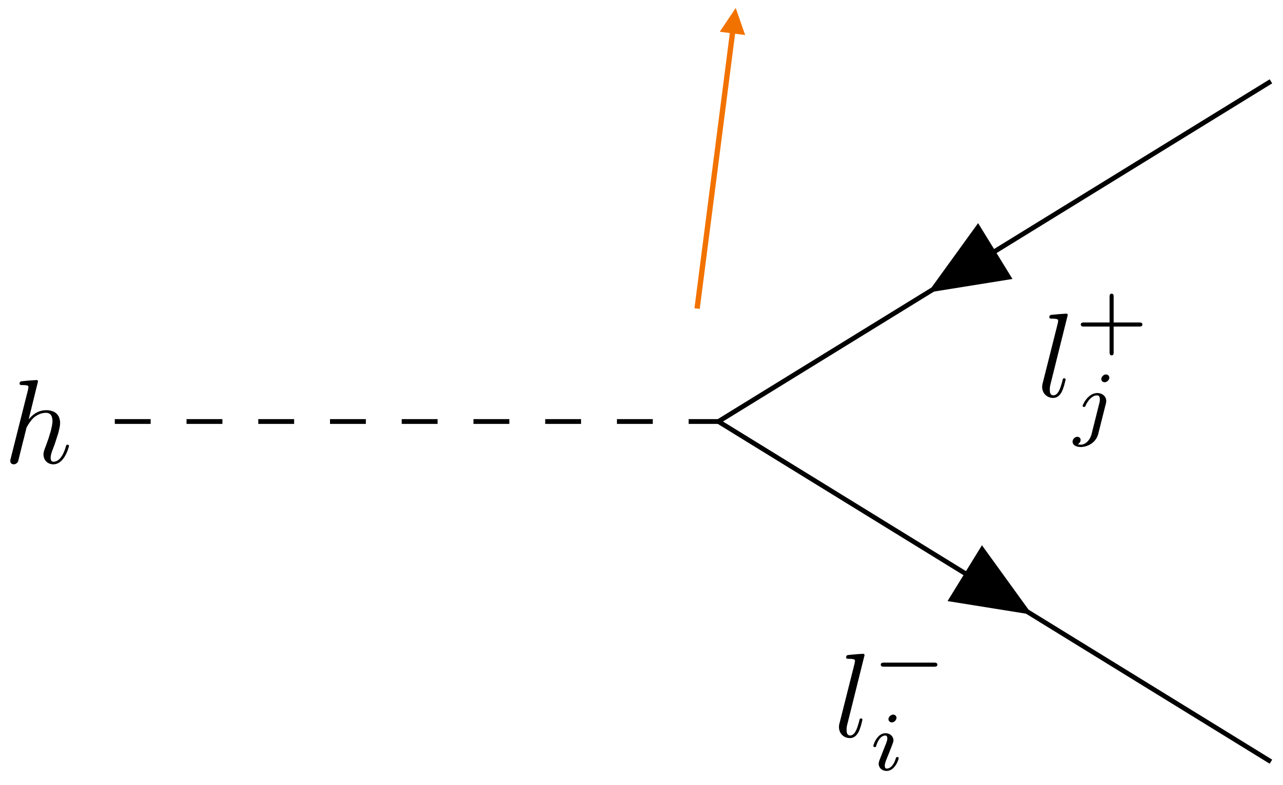


Flavour Connection: LFV



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



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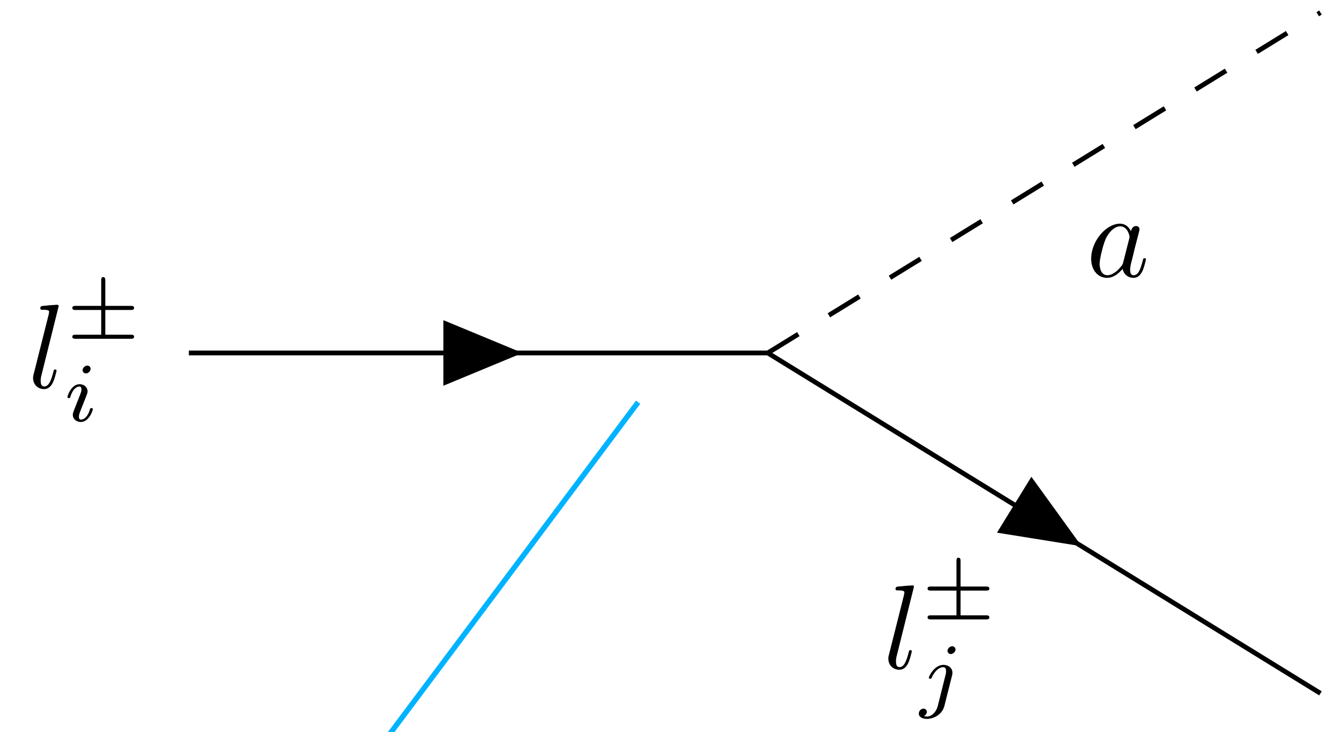

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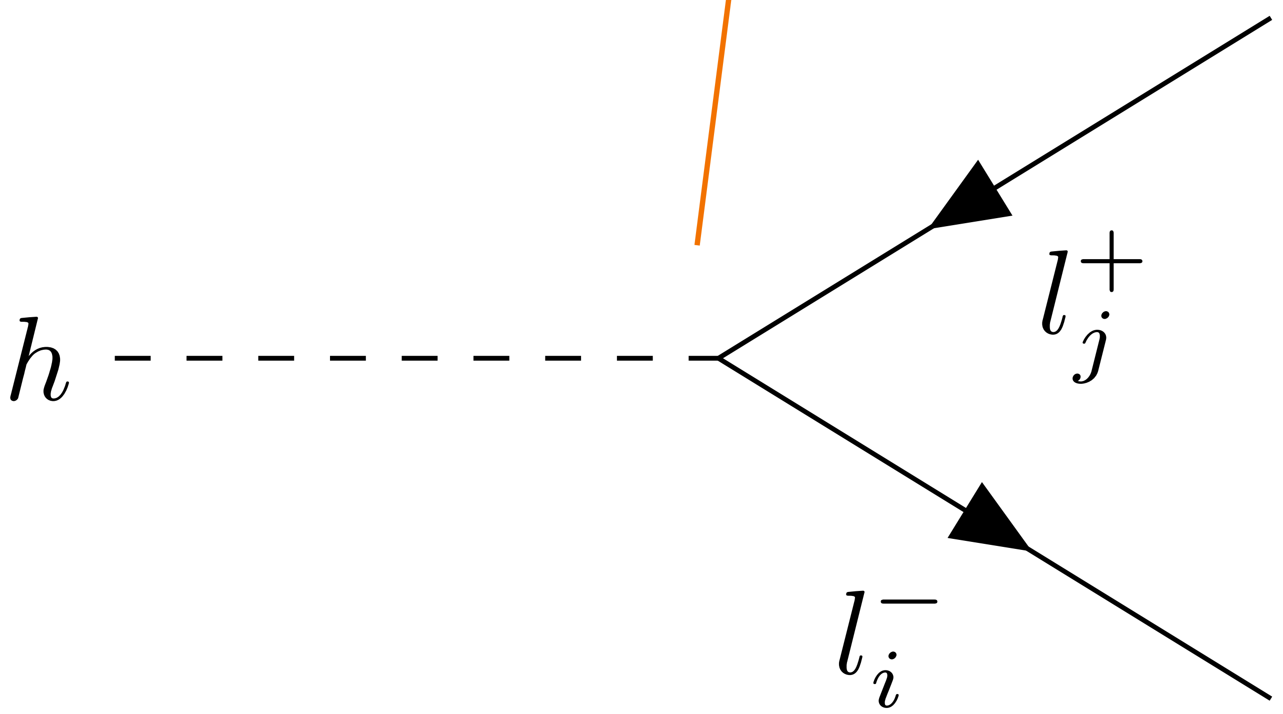


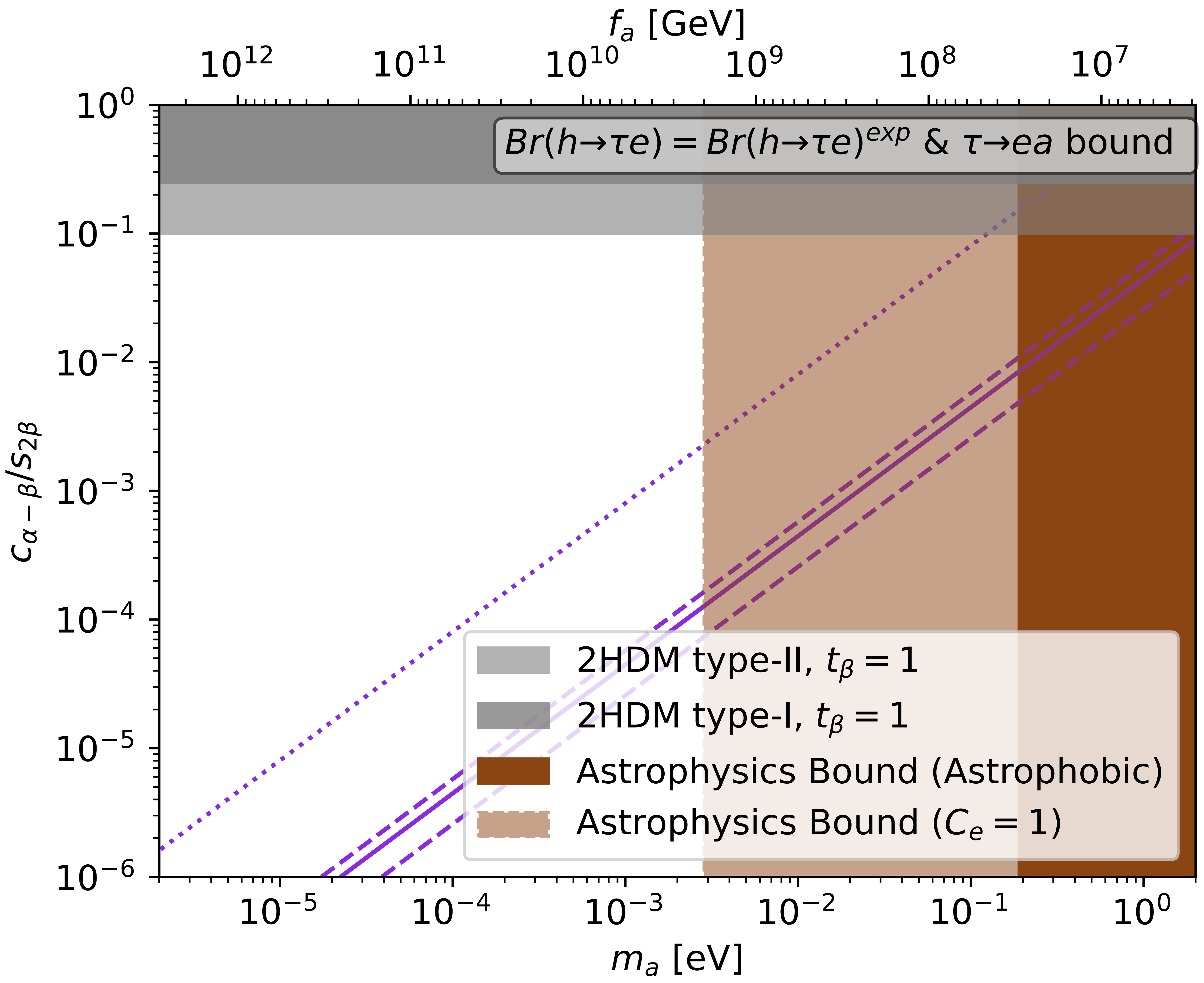
Where we can fix to the deviations:

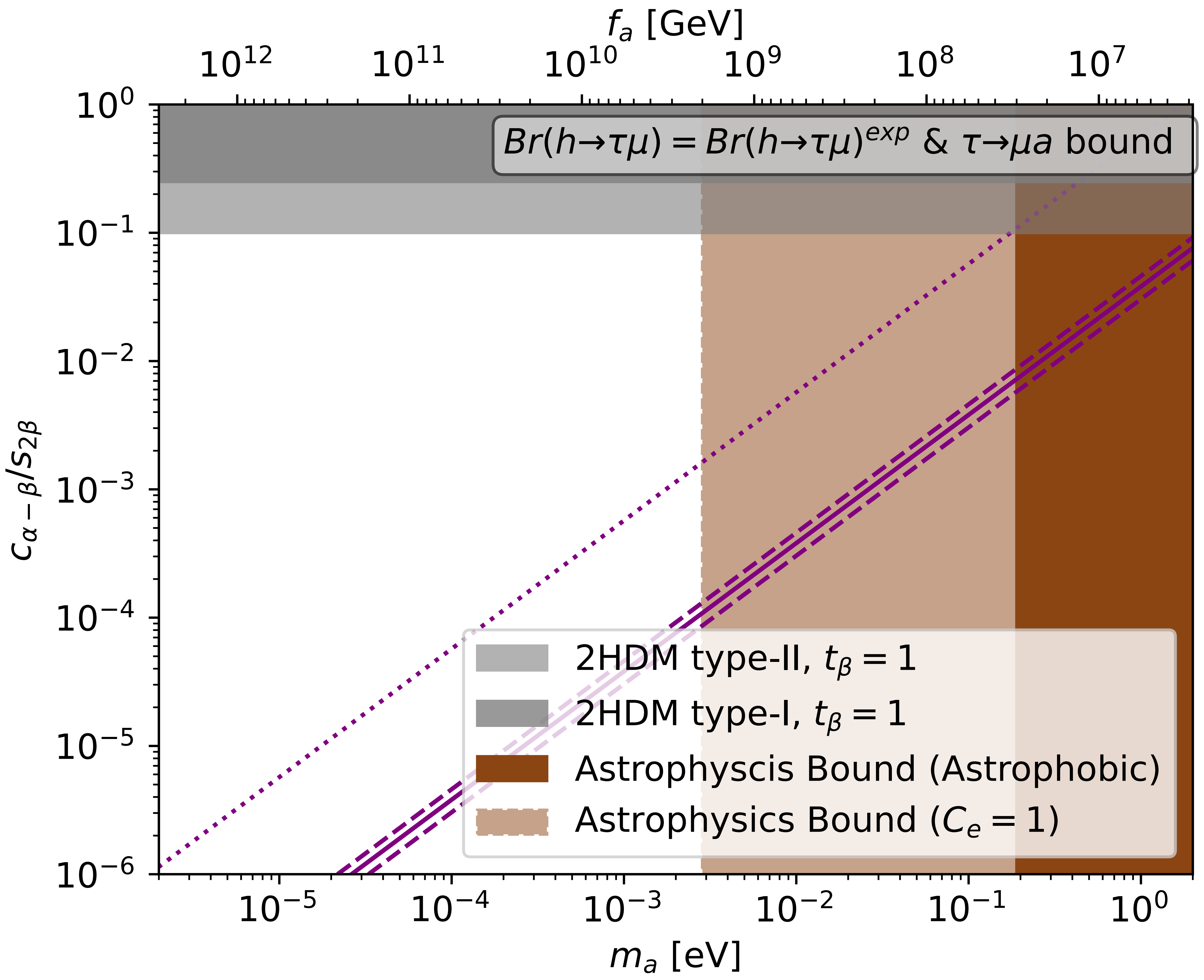
$$\mathrm{BR}(h \to \tau e) = 0.09 \pm 0.06\,\%$$

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

[ATLAS '23]

Flavour Connection: LFV





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Specific Models

M1 Model

$$\mathcal{X}_q = \mathrm{diag}\,(0,0,1)\,, \quad \mathcal{X}_u = \mathrm{diag}\,(s_\beta^2, s_\beta^2, s_\beta^2)\,,$$
$$\mathcal{X}_d = \mathrm{diag}\,(c_\beta^2, c_\beta^2, c_\beta^2)\,, \mathcal{X}_l = -\mathcal{X}_q\,,$$
$$\mathcal{X}_e = -\mathcal{X}_u\,.$$

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

M4 Model

$$\mathcal{X}_q = \mathrm{diag}\,(0,0,0)\,, \qquad \mathcal{X}_u = \mathrm{diag}\,(s_\beta^2,\ s_\beta^2,\ s_\beta^2)\,,$$
$$\mathcal{X}_d = \mathrm{diag}\,(c_\beta^2,\ -s_\beta^2,\ -s_\beta^2)\,, \mathcal{X}_\ell = -\mathrm{diag}\,(0,1,1)\,,$$
$$\mathcal{X}_e = -\mathcal{X}_u\,,$$

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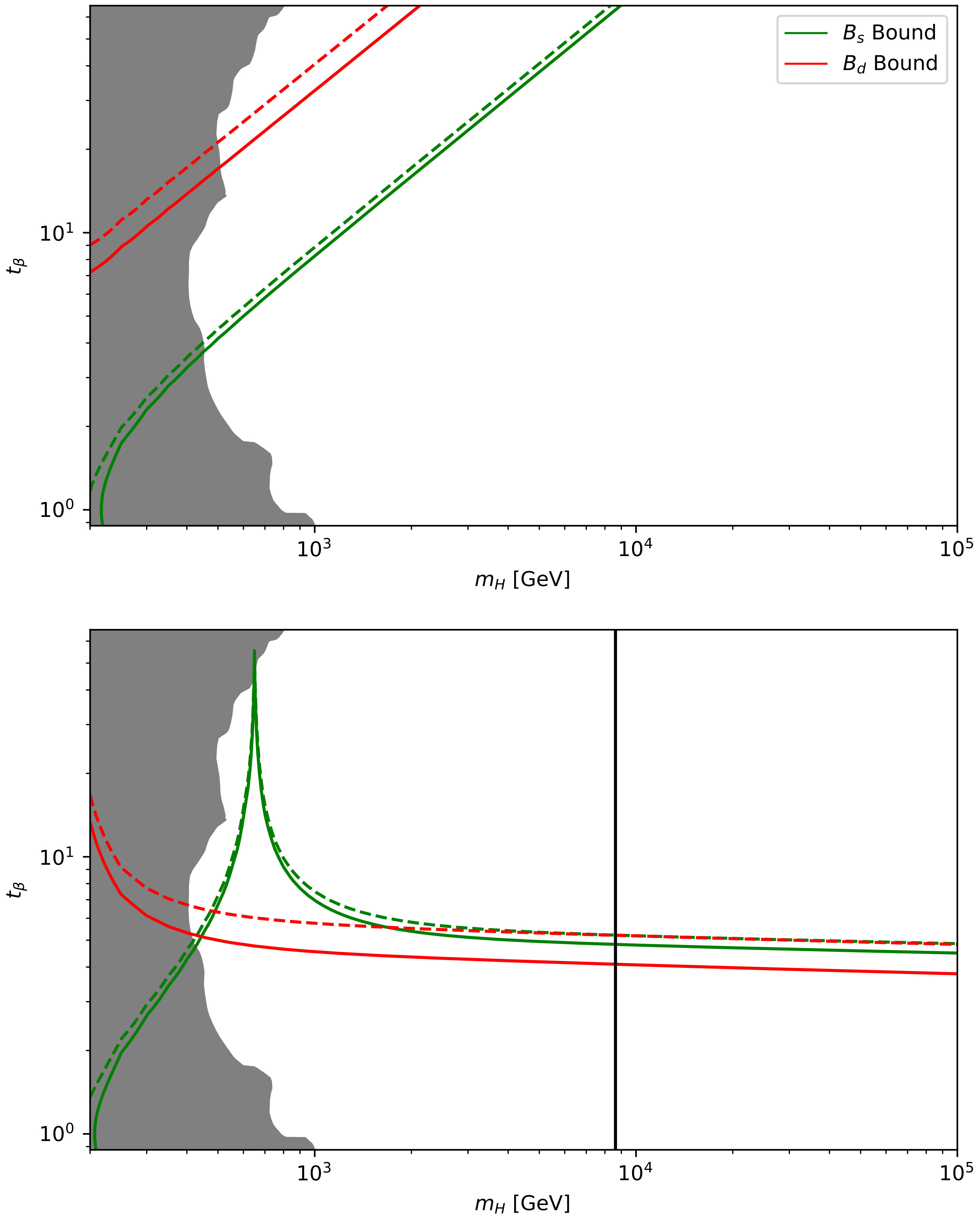

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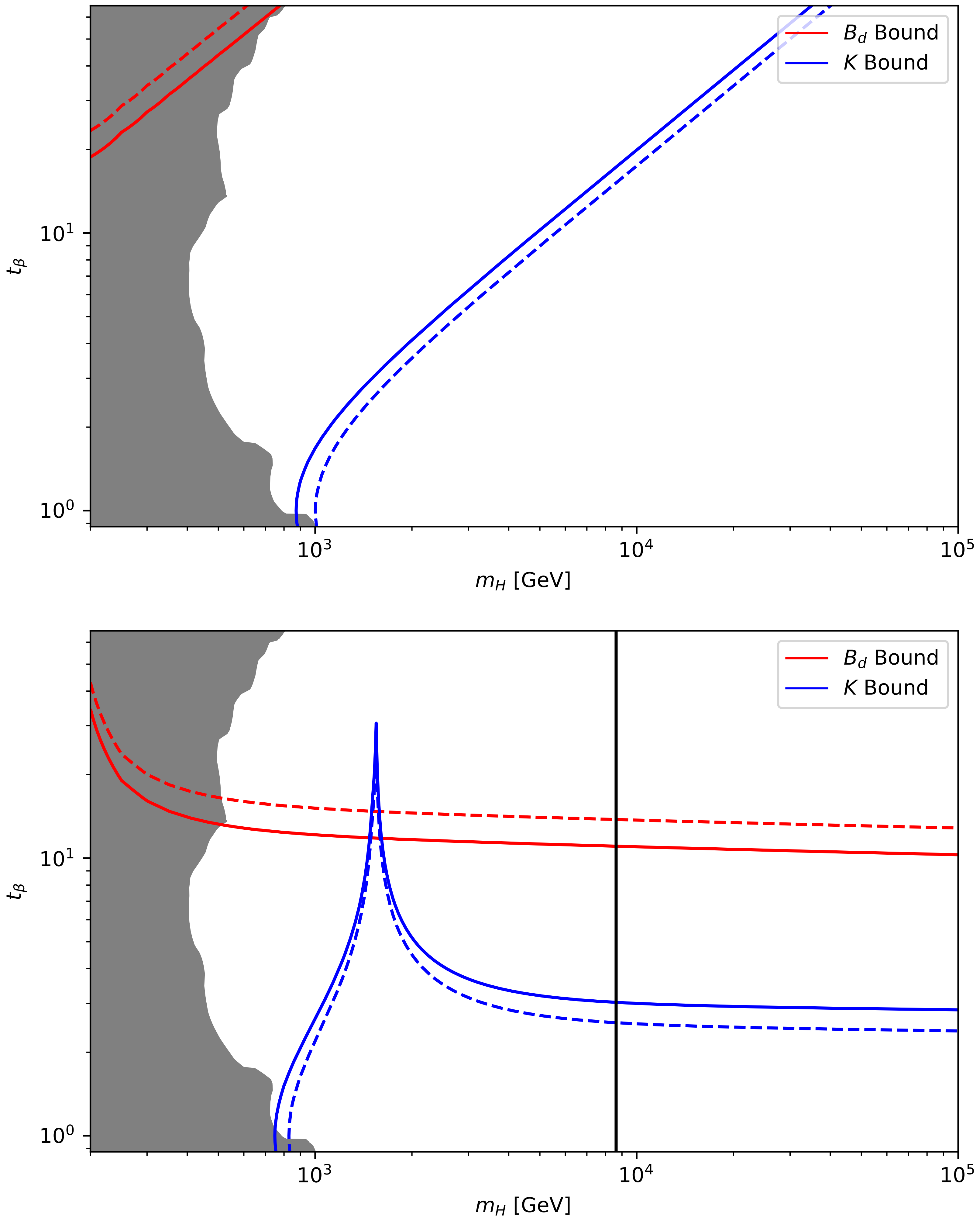

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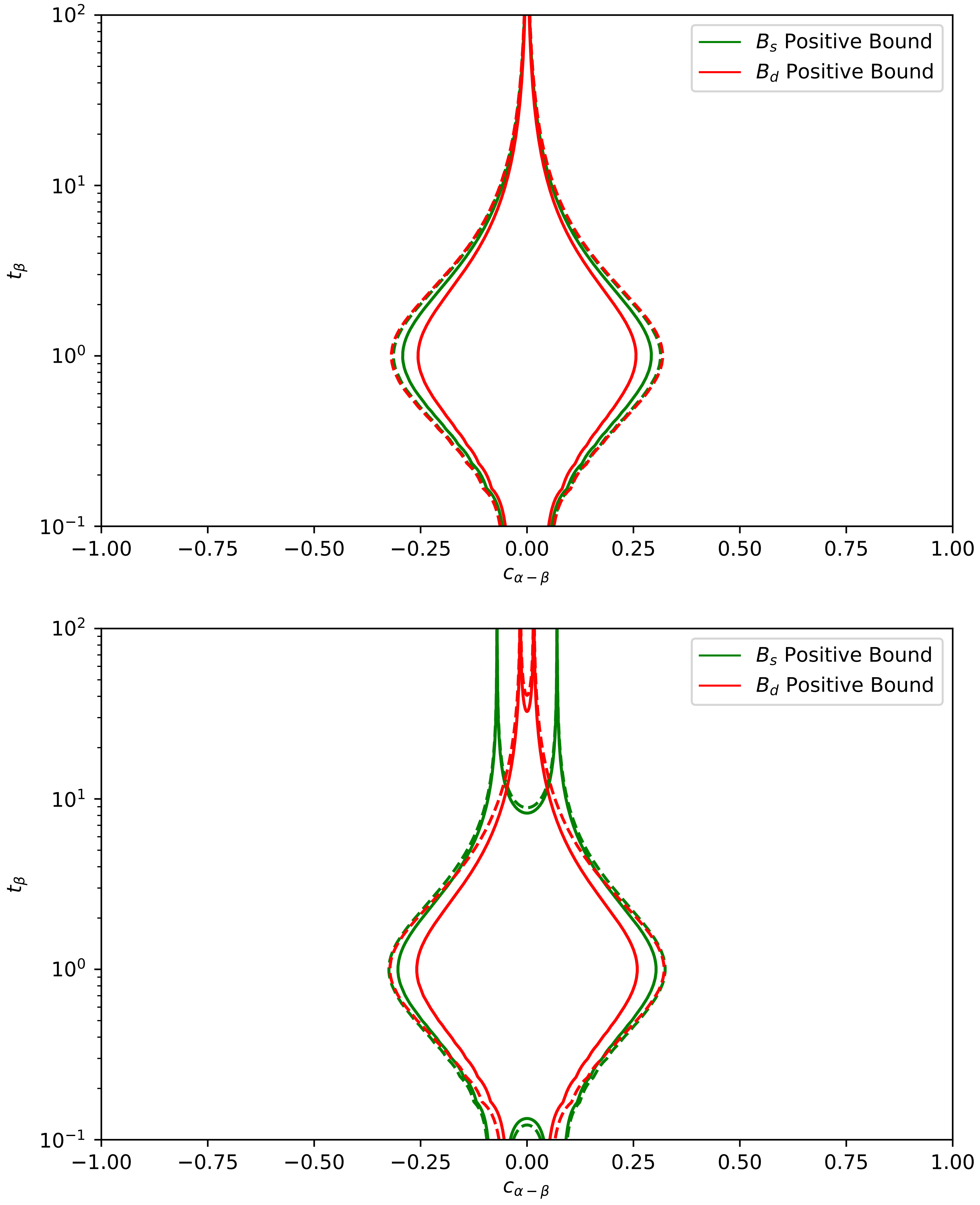

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