Axion-Like Particles @ Colliders

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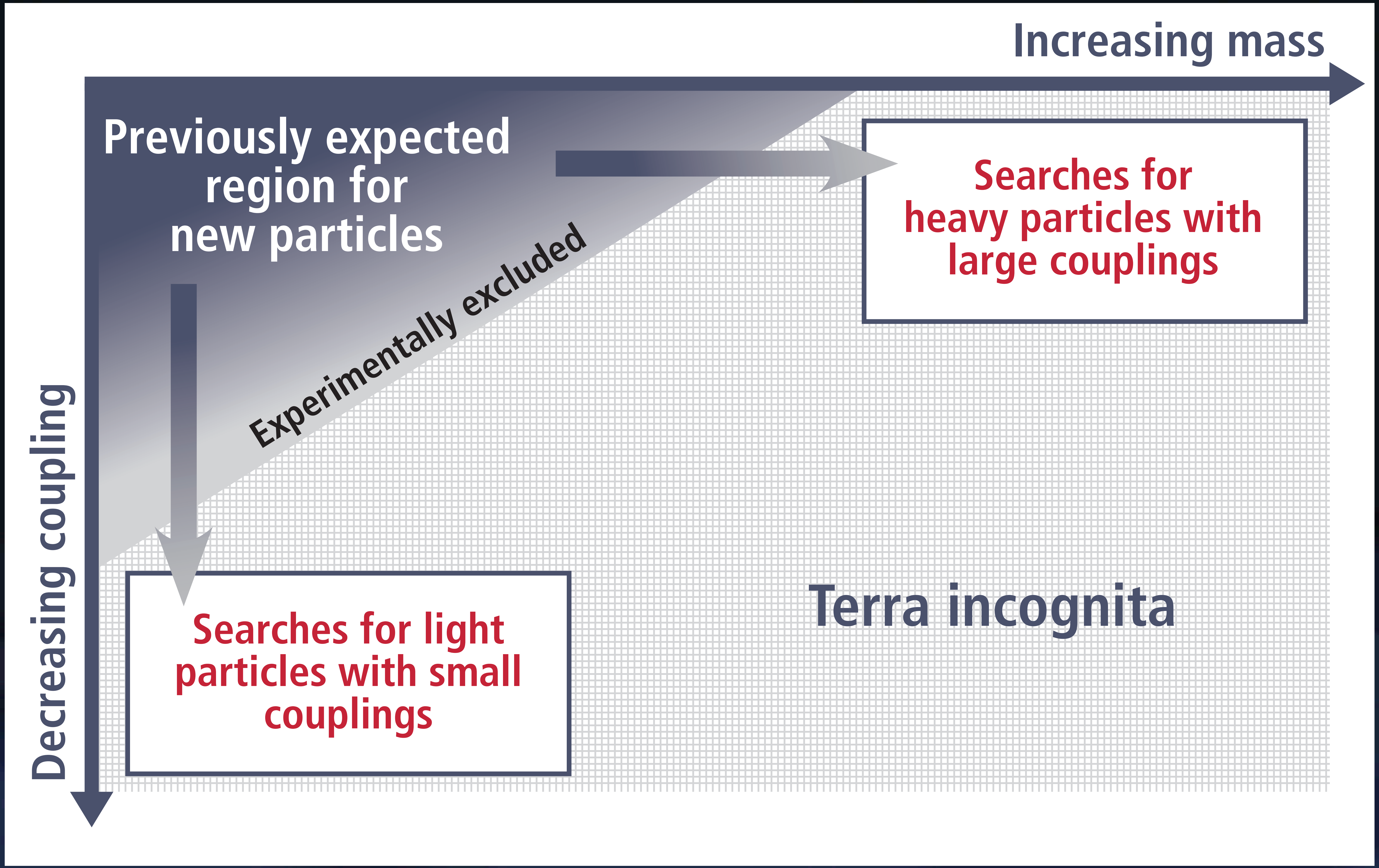
M. Bauer, MN, A. Thamm: 1704.08207 (PRL), 1708.00443 (JHEP)
M. Bauer, MN, S. Renner, M. Schnubel, A. Thamm: 2012.12272 (JHEP), 2102.13112 (PRL), 2110.10698 (JHEP)
C. Cornella, A. Galda, MN, D. Wyler: 2308.16903

Les Rencontres de Physique de la Vallée d'Aoste — La Thuile, Italy, 3—9 March 2024

Limits of the Standard Model



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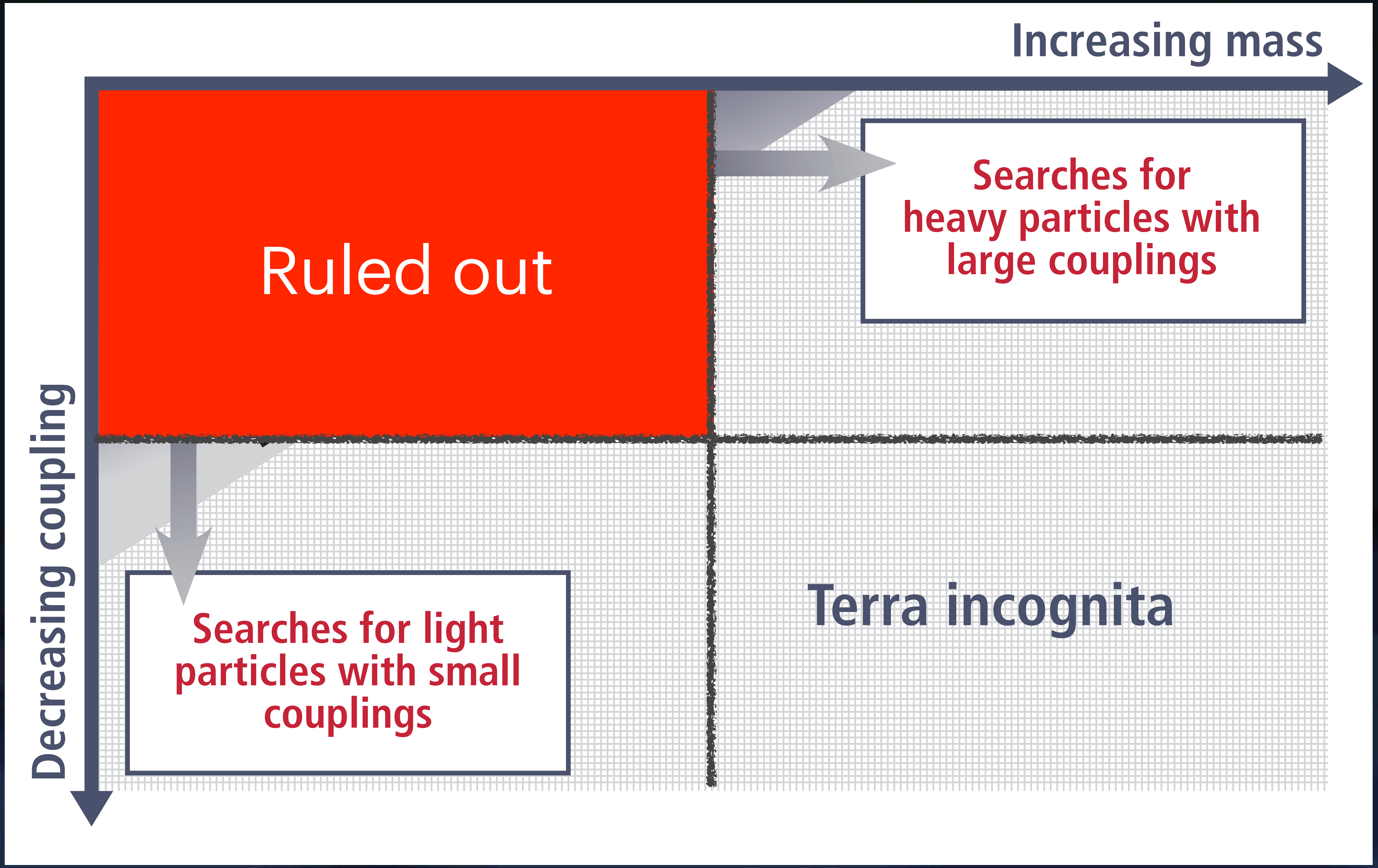

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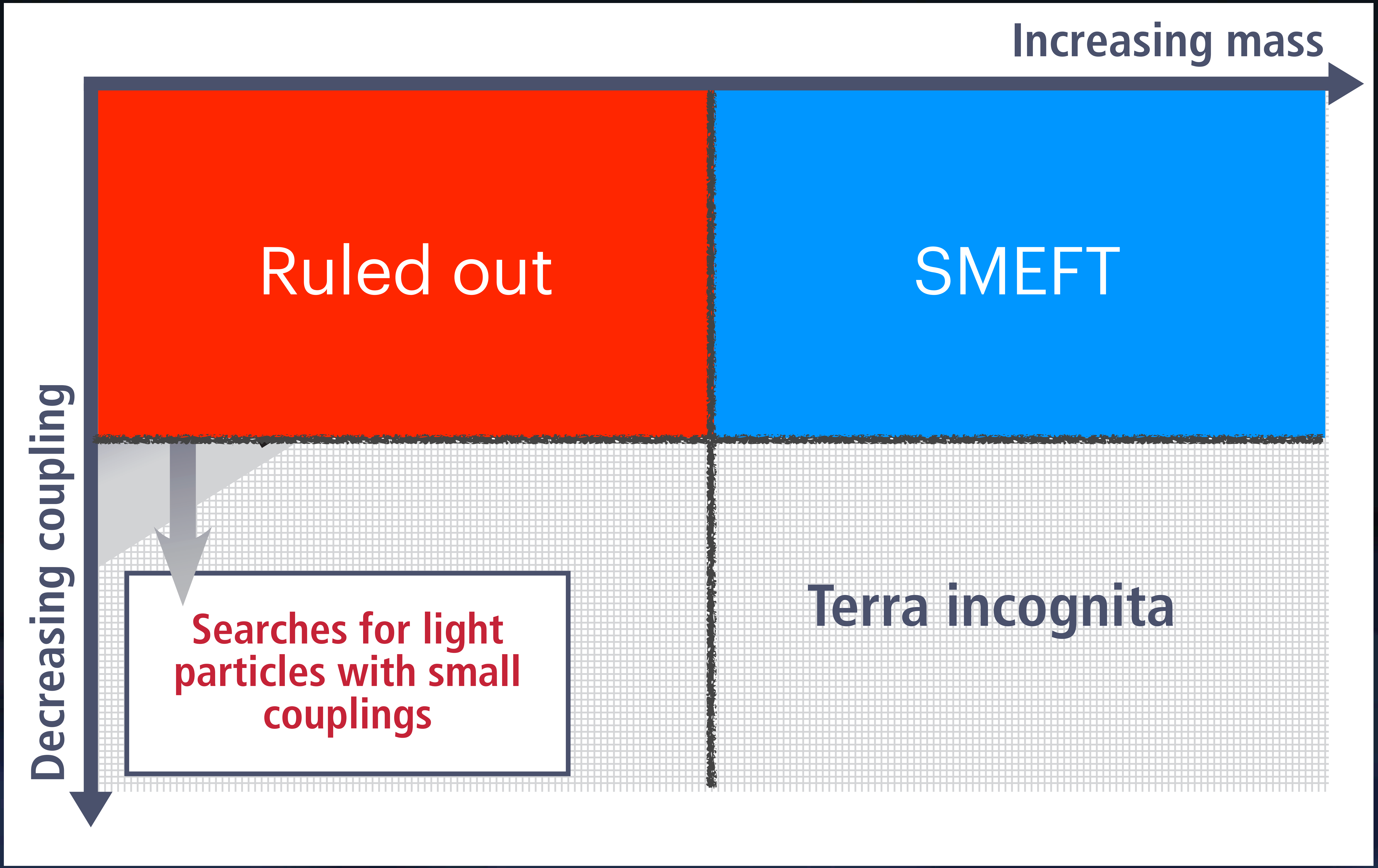

Increasing mass

Decreasing coupling

Ruled out

SMEFT

Searches for light particles with small couplings

Terra incognita

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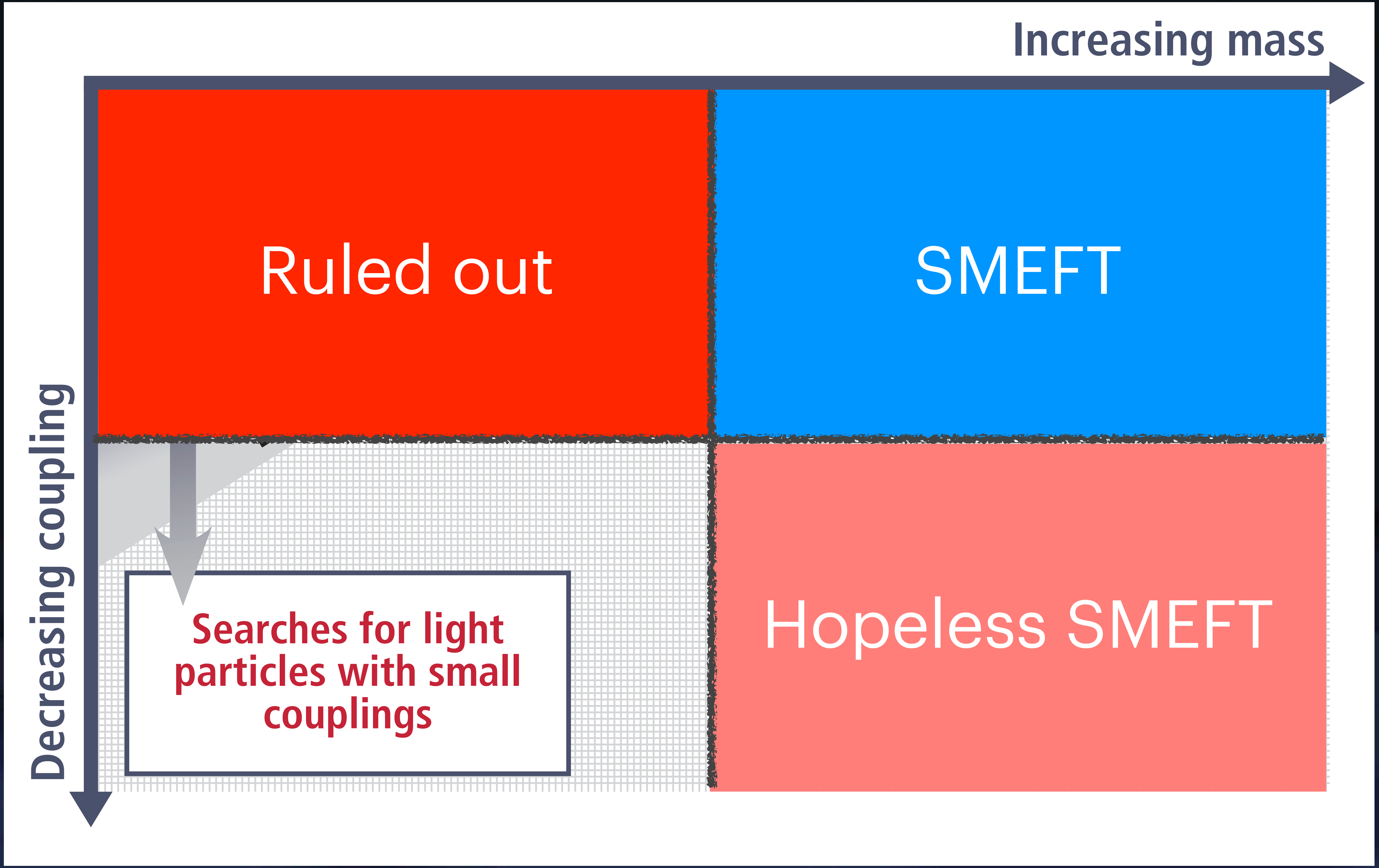
Limits of the Standard Model



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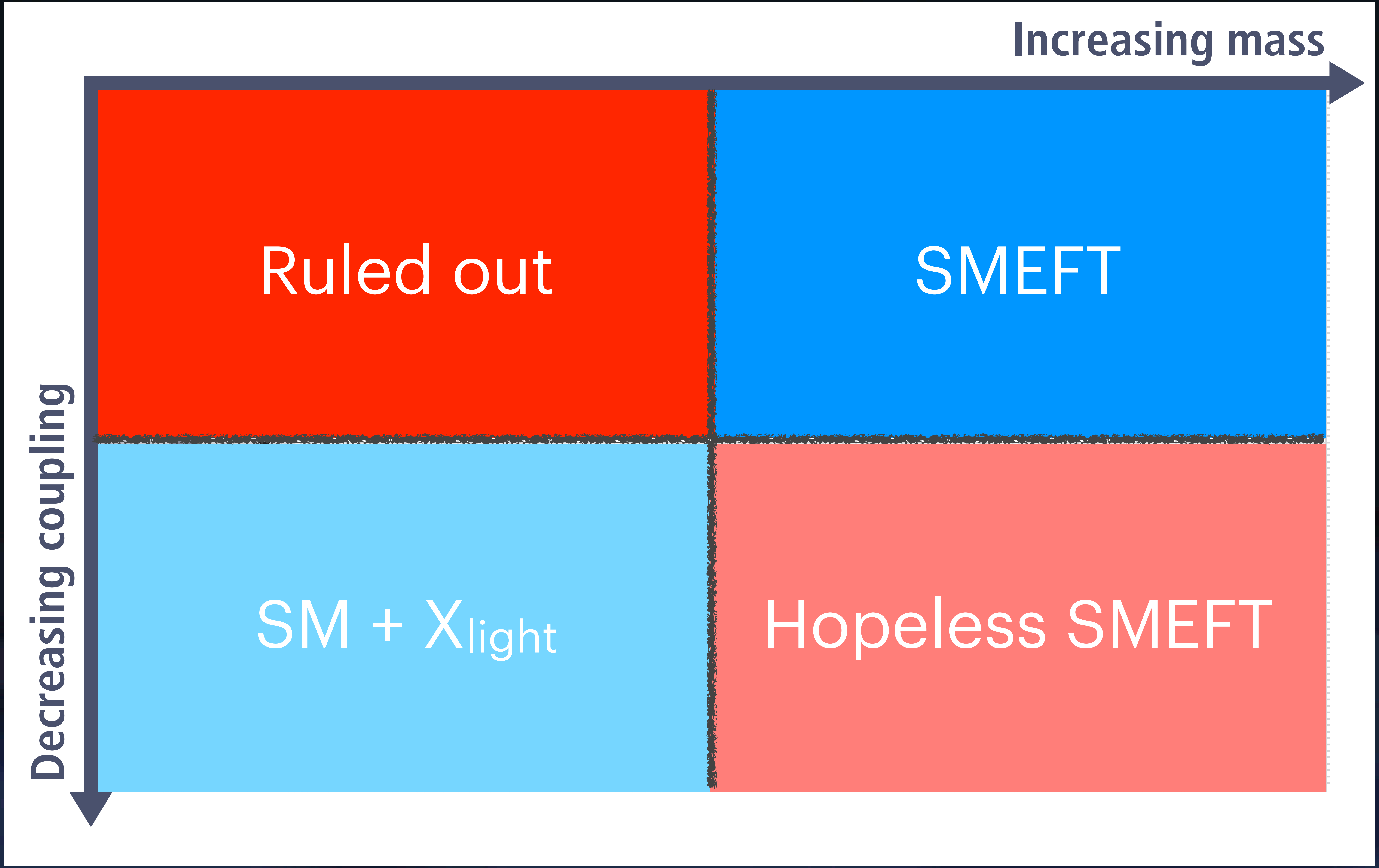

Increasing mass

Decreasing coupling

Ruled out

SMEFT

SM + X_{light}

Hopeless SMEFT

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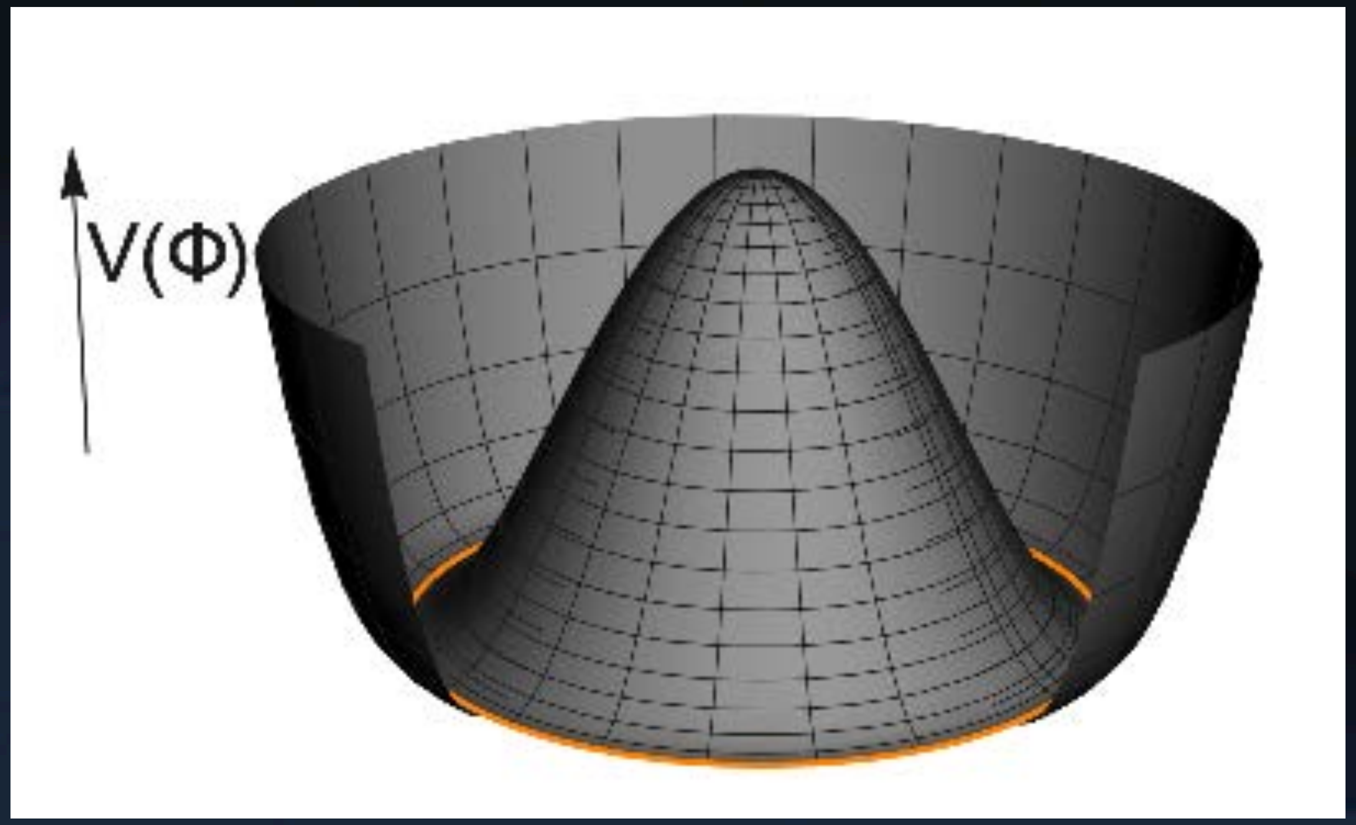
Axions and axion-like particles (ALPs)

Well motivated theoretically:

- Peccei—Quinn solution to strong CP problem: new scalar field $\mathbf{\Phi} = |\mathbf{\Phi}|\, e^{ia/f_a}$ coupled to chiral fermions, charged under a symmetry U(1)$_{\text{PQ}}$ [Peccei, Quinn 1977; Weinberg 1978; Wilczek 1978]
- Spontaneous symmetry breaking yields a VEV for $\mathbf{\Phi}$
- Performing a chiral transformation on the fermion fields, one finds:

$$\mathcal{L}_{\text{QCD}} \to \left(\theta + \frac{a}{f_a}\right) \frac{\alpha_s}{8\pi}\, G^a_{\mu\nu} \widetilde{G}^{\mu\nu,a} + \dots$$



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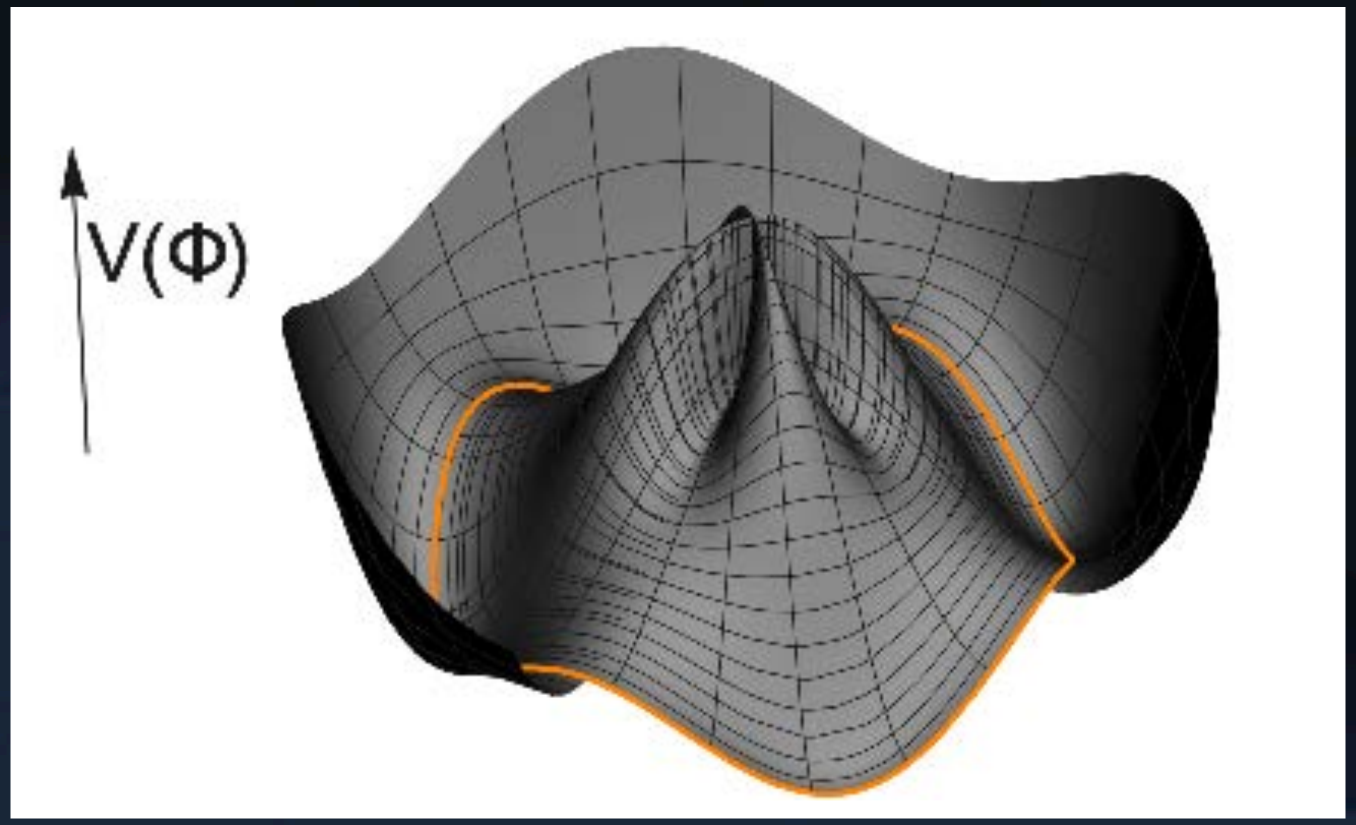

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- QCD instantons generate a potential for the axion and enforce $\theta_{\text{eff}} = 0$ mod 2π

Axions and axion-like particles (ALPs)

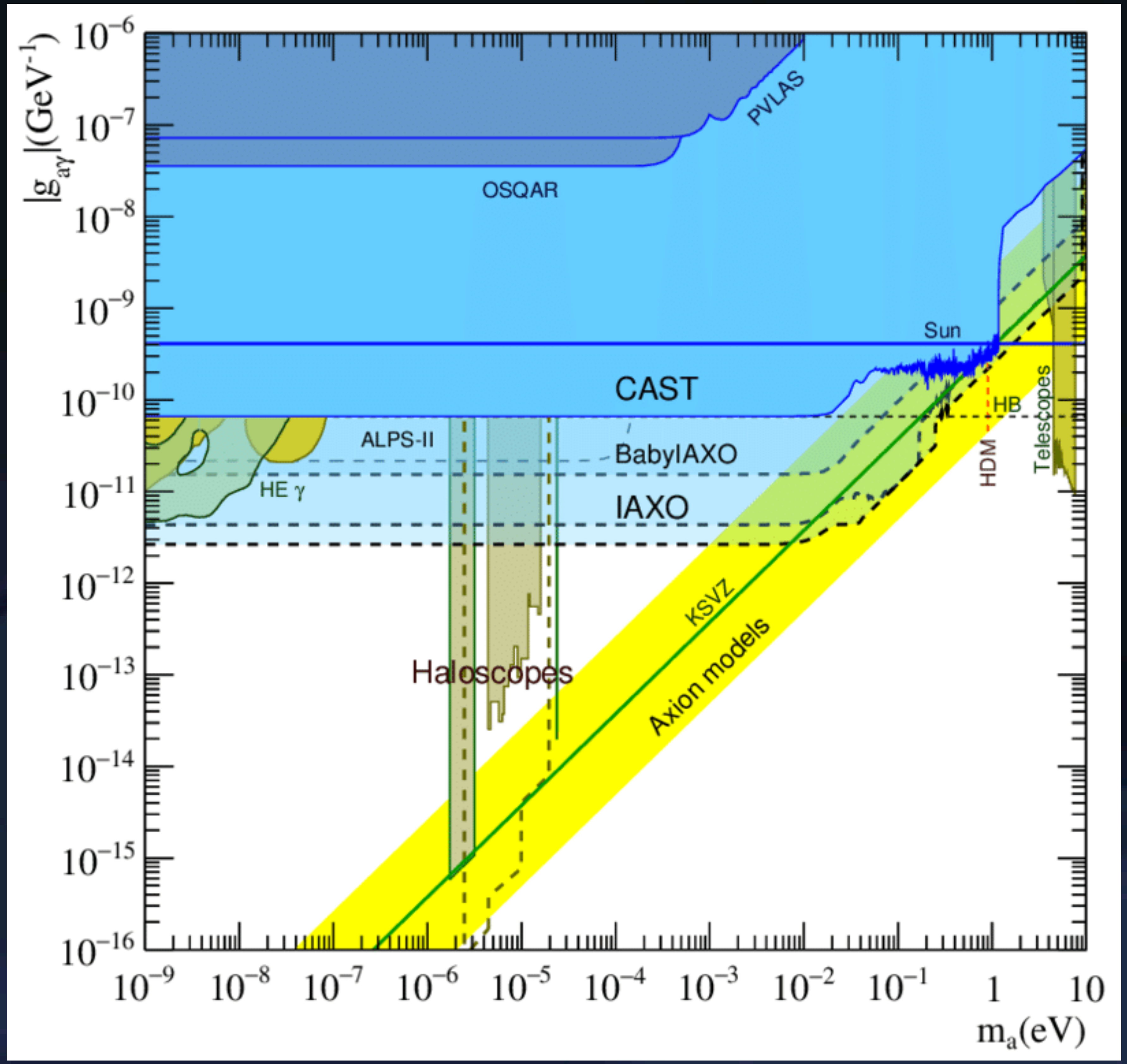
Well motivated theoretically:

- Axion mass is inversely proportional to f_a and can be very light if f_a is sufficiently large:

$$m_a^2 f_a^2 = \frac{m_\pi^2 f_\pi^2}{2} \, \frac{m_u m_d}{(m_u + m_d)^2}$$

- Axion coupling to photons is also inversely proportional to f_a with a model-dependent coefficient

[Kim 1979; Shifman, Vainshtein, Zakharov 1980 (KSVZ)]
[Dine, Fishler, Srednicki 1981; Zhitnitsky 1980 (DFSZ)]



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Axions and axion-like particles (ALPs)

Well motivated theoretically:

- There are ways to relax the strict relation between the axion mass and photon coupling
  [for recent ideas, see e.g.: Elahi, Elor, Kivel, Laux, Najjari, Yu 2023; Gavela, Quílez, Ramos 2023]
- More generally, axion-like particles (ALPs) can arise as pseudo Nambu—Golstone bosons of a spontaneously broken global U(1) symmetry in a large class of BSM models
- For heavier ALPs, couplings to SM particles other than the photon play an important role and can be probed in particle-physics experiments
  [Bauer, MN, Thamm 2017; ...]

Effective Lagrangian for a light ALP

- Most general effective Lagrangian for a pseudoscalar boson ***a*** coupled to the SM via classically shift-invariant interactions (broken softly by a mass term): [Georgi, Kaplan, Randall 1986]

couplings to chiral fermions   coupling to Higgs doublet

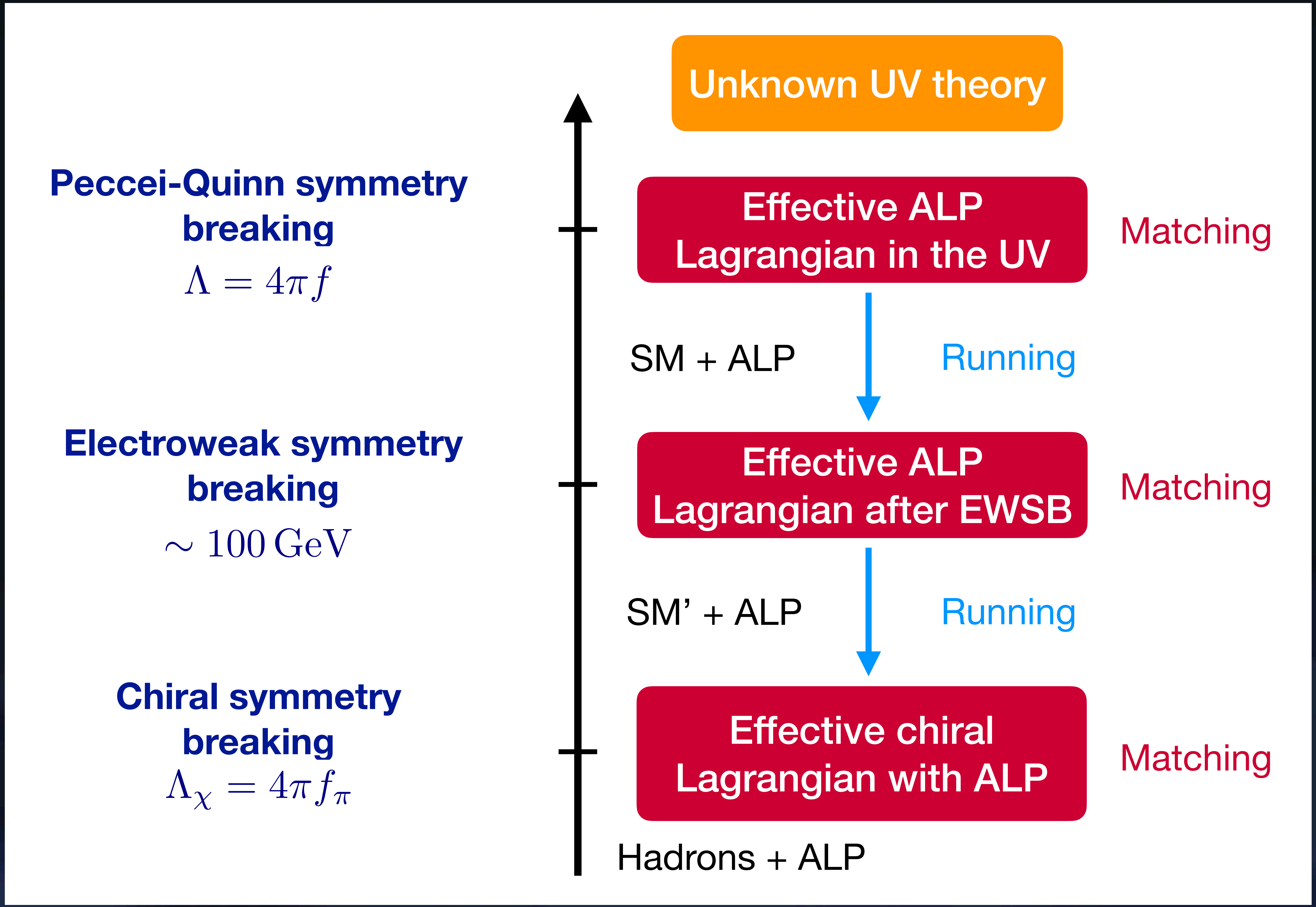
$$\mathcal{L}_{\rm eff}^{D\le 5} = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}\,a^2 + \frac{\partial^\mu a}{f}\sum_F \bar\psi_F c_F \gamma_\mu \psi_F + c_\phi\,\frac{\partial^\mu a}{f}\,(\phi^\dagger i \overleftrightarrow{\boldsymbol{D}}_\mu \phi)$$

coupling to gluons   coupling to SU(2)$_L$ bosons   coupling to hypercharge boson

$$+\, c_{GG}\,\frac{\alpha_s}{4\pi}\,\frac{a}{f}\,G_{\mu\nu}^a\,\tilde G^{\mu\nu,a} + c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W_{\mu\nu}^A\,\tilde W^{\mu\nu,A} + c_{BB}\,\frac{\alpha_1}{4\pi}\,\frac{a}{f}\,B_{\mu\nu}\,\tilde B^{\mu\nu}$$

- All interactions are suppressed by inverse powers of f, with $f/|2c_{GG}| = f_a$
- 5 out of the 49 real couplings in this Lagrangian are redundant
- Will always work with physical combinations $\tilde c_{VV}, c_{qq}^a$ of coupling parameters

RG evolution from the UV to lower scales



Unknown UV theory

Peccei-Quinn symmetry breaking
$\Lambda = 4\pi f$

Effective ALP Lagrangian in the UV

Matching

SM + ALP

Running

Electroweak symmetry breaking
$\sim 100\,\mathrm{GeV}$

Effective ALP Lagrangian after EWSB

Matching

SM’ + ALP

Running

Chiral symmetry breaking
$\Lambda_\chi = 4\pi f_\pi$

Effective chiral Lagrangian with ALP

Matching

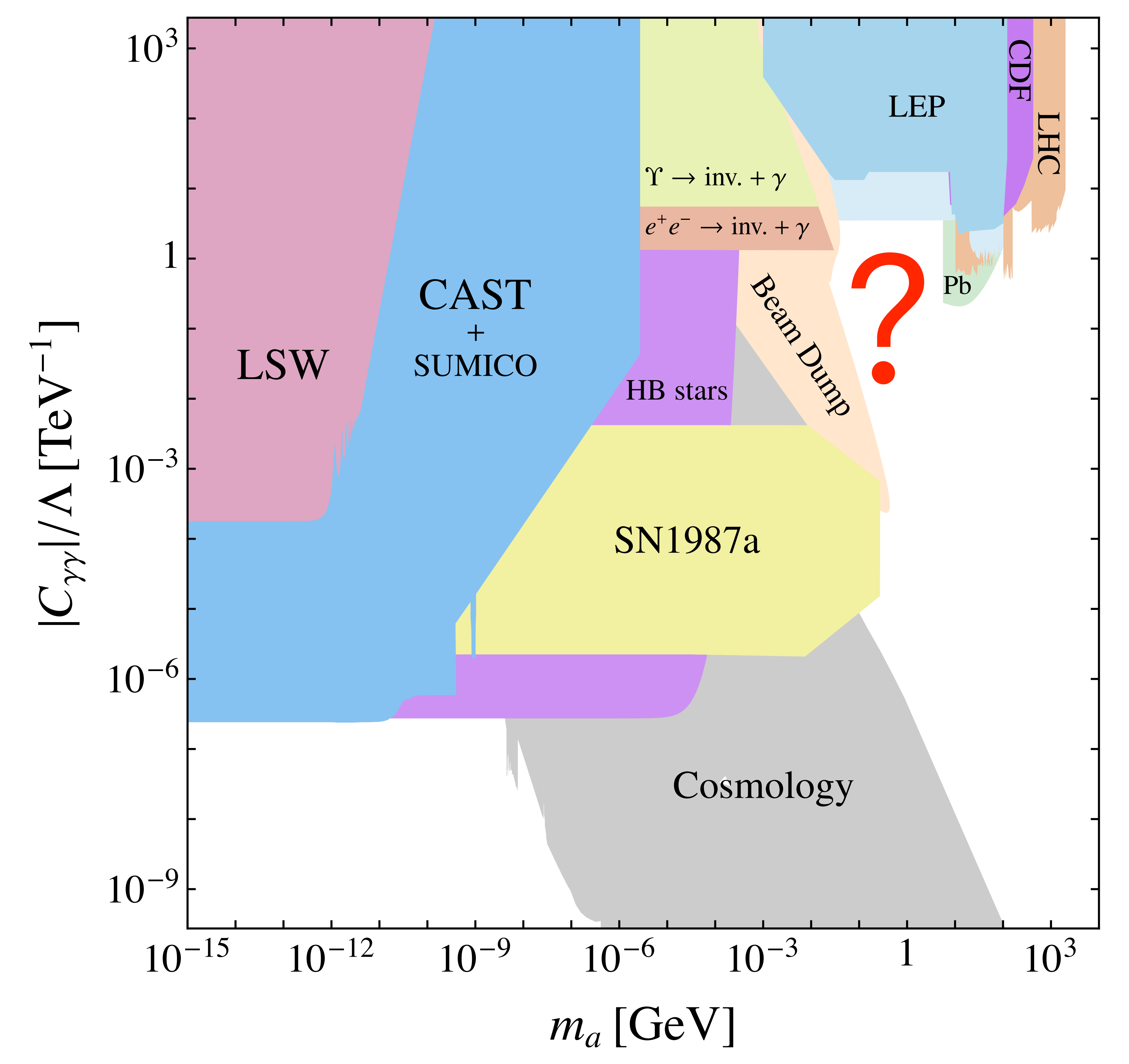
Hadrons + ALP

[Bauer, MN, Renner, Schnubel, Thamm 2020; Chala, Guedes, Ramos, Santiago 2020]

High-energy probes of ALP couplings

ALP production in Higgs-boson decays

Interesting search channel $h \to aa \to 4\gamma$



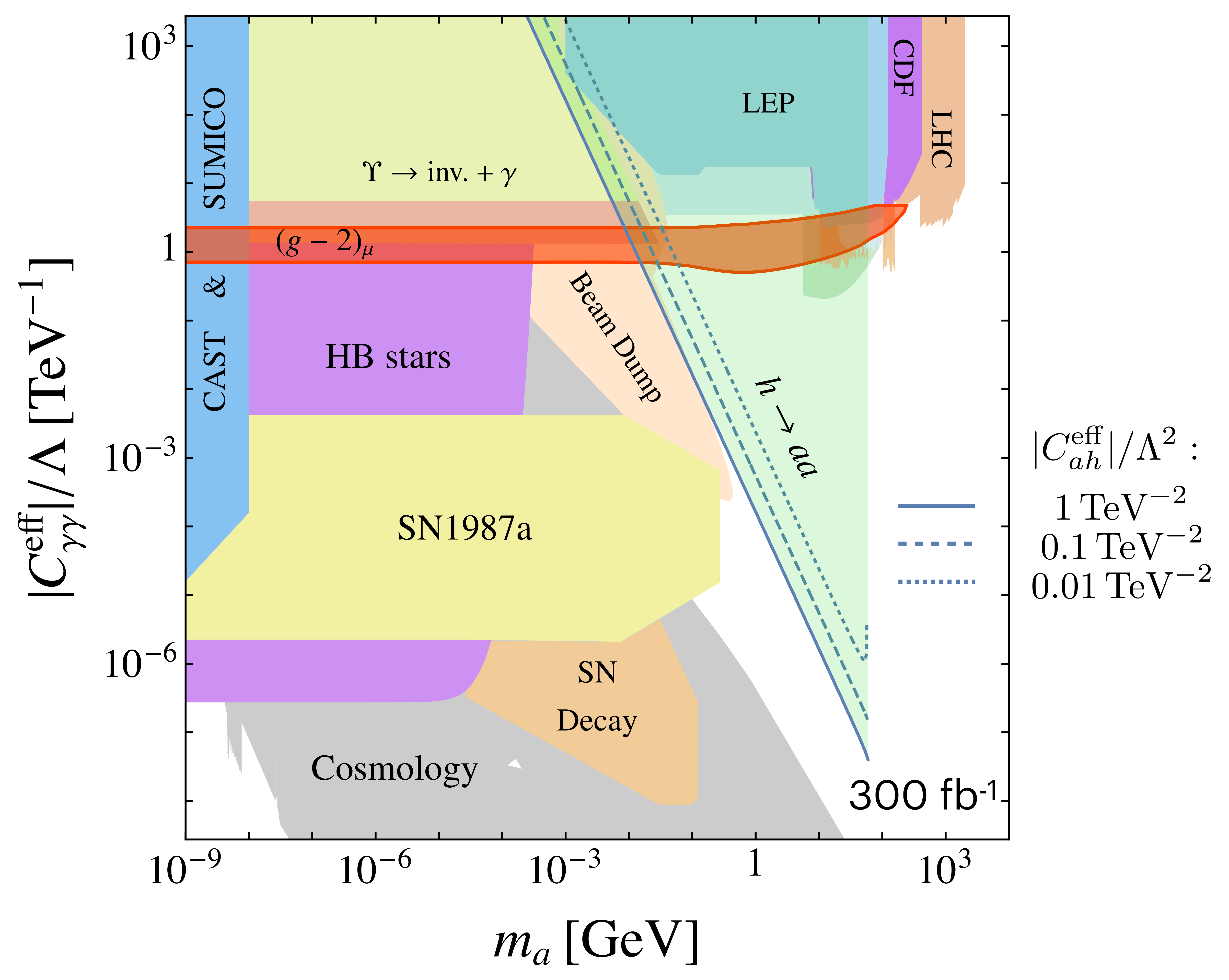
[Bauer, MN, Thamm 2017]

ALP production in Higgs-boson decays

Interesting search channel $h \to aa \to 4\gamma$

- Resulting bounds on the ALP—photon coupling (ALP decay) depend on the ALP coupling $(\partial_\mu a)^2\,\phi^\dagger\phi$ to Higgs bosons (ALP production)

- Potential to cover the parameter space in which an ALP could explain $(g\text{-}2)_\mu$



[Bauer, MN, Thamm 2017]

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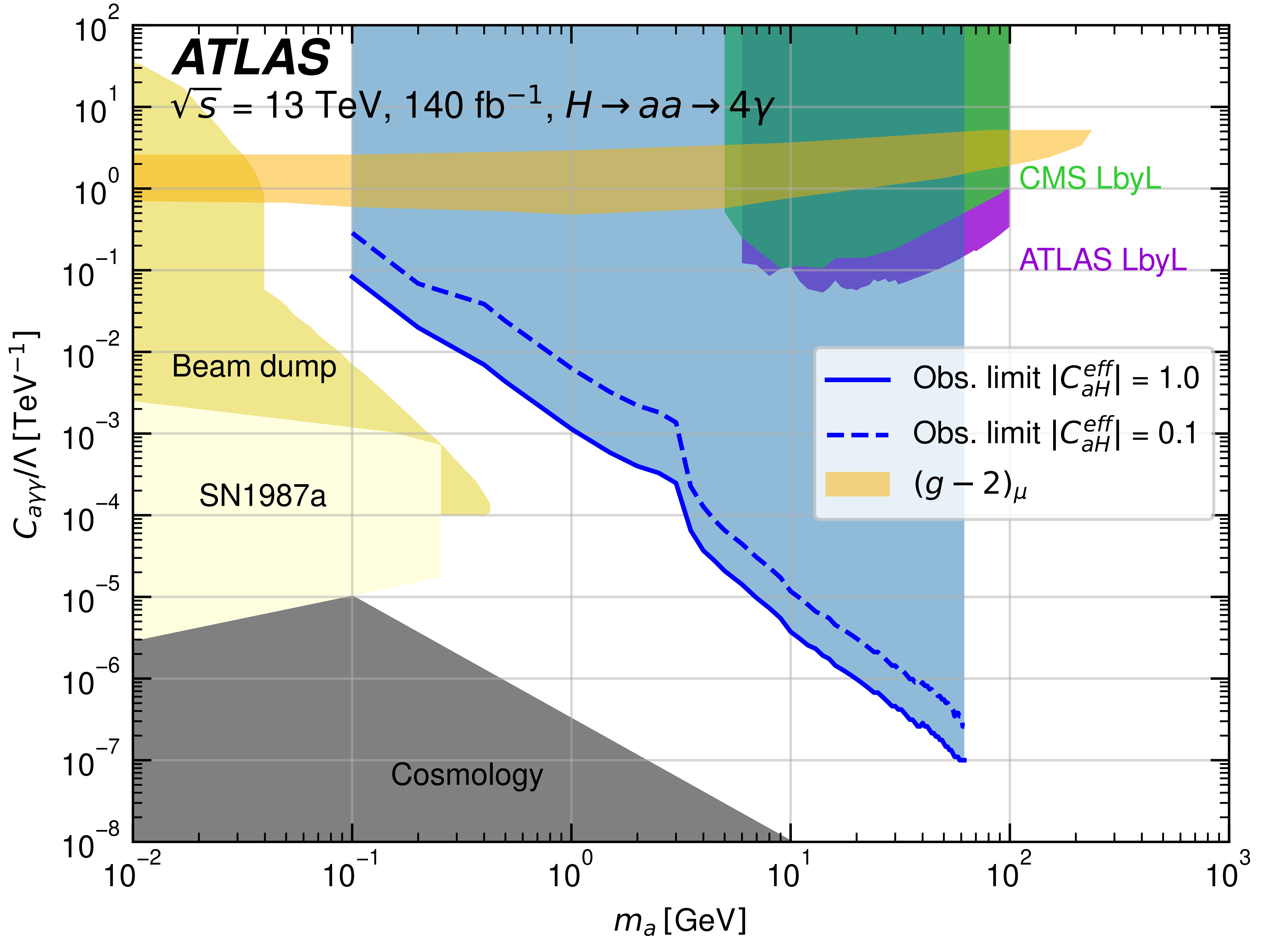
- Potential to cover the parameter space in which an ALP could explain $(g\text{-}2)_\mu$
- Recent ATLAS analysis confirms our estimates



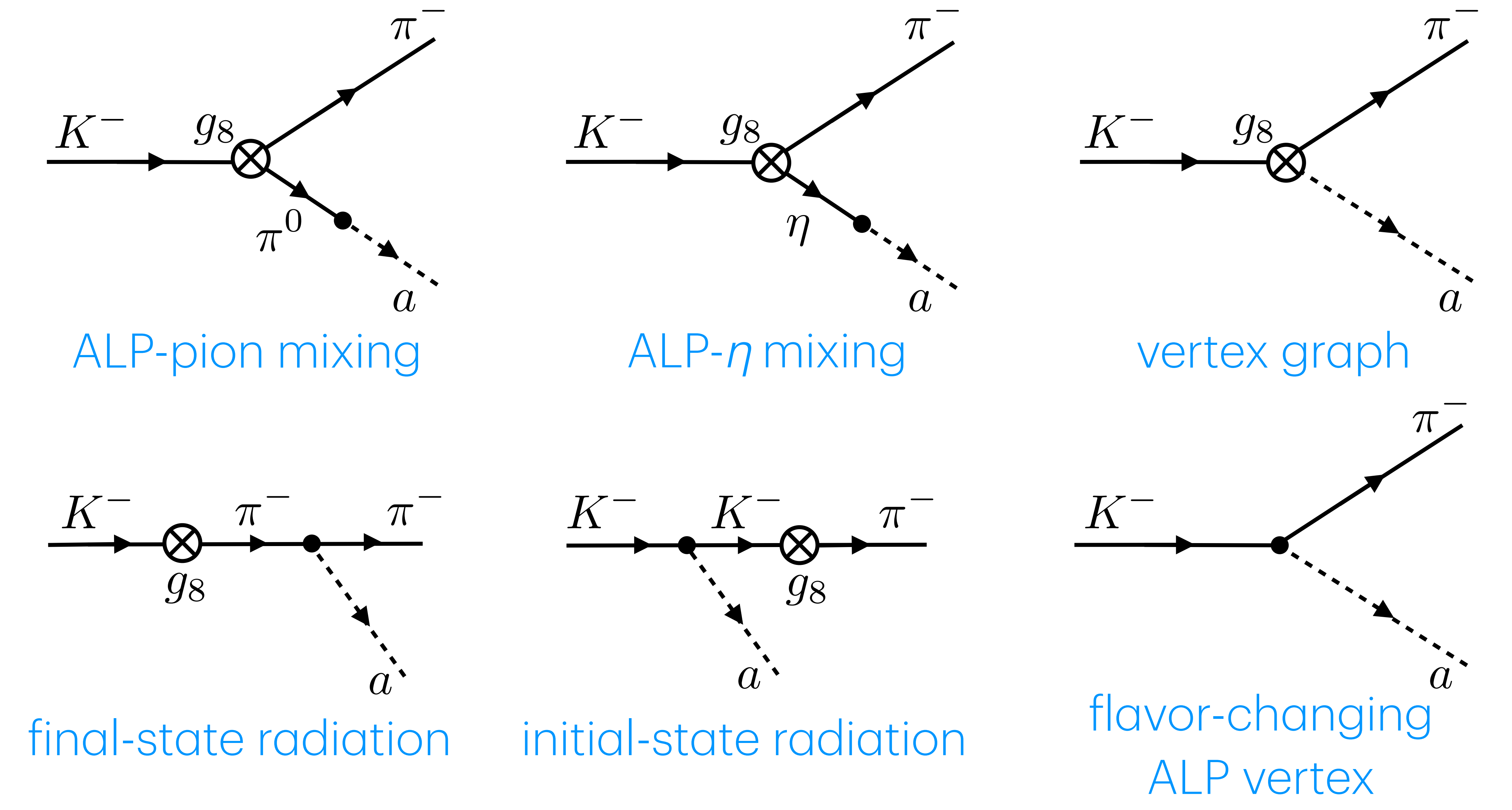
[ATLAS collaboration, arXiv:2312.03306]

Flavor probes of ALP couplings

ALP production in rare kaon decays

Interesting search channel $K^- \to \pi^- a$

- Model-independent analysis using chiral perturbation theory
- Previous calculations used an incorrect implementation of the chiral currents; as a result, the BR gets enhanced by factor 37
- Strong constraints on flavor-violating and flavor-conserving ALP couplings



ALP-pion mixing

ALP-η mixing

vertex graph

final-state radiation

initial-state radiation

flavor-changing ALP vertex

[Bauer, MN, Renner, Schnubel, Thamm 2021]

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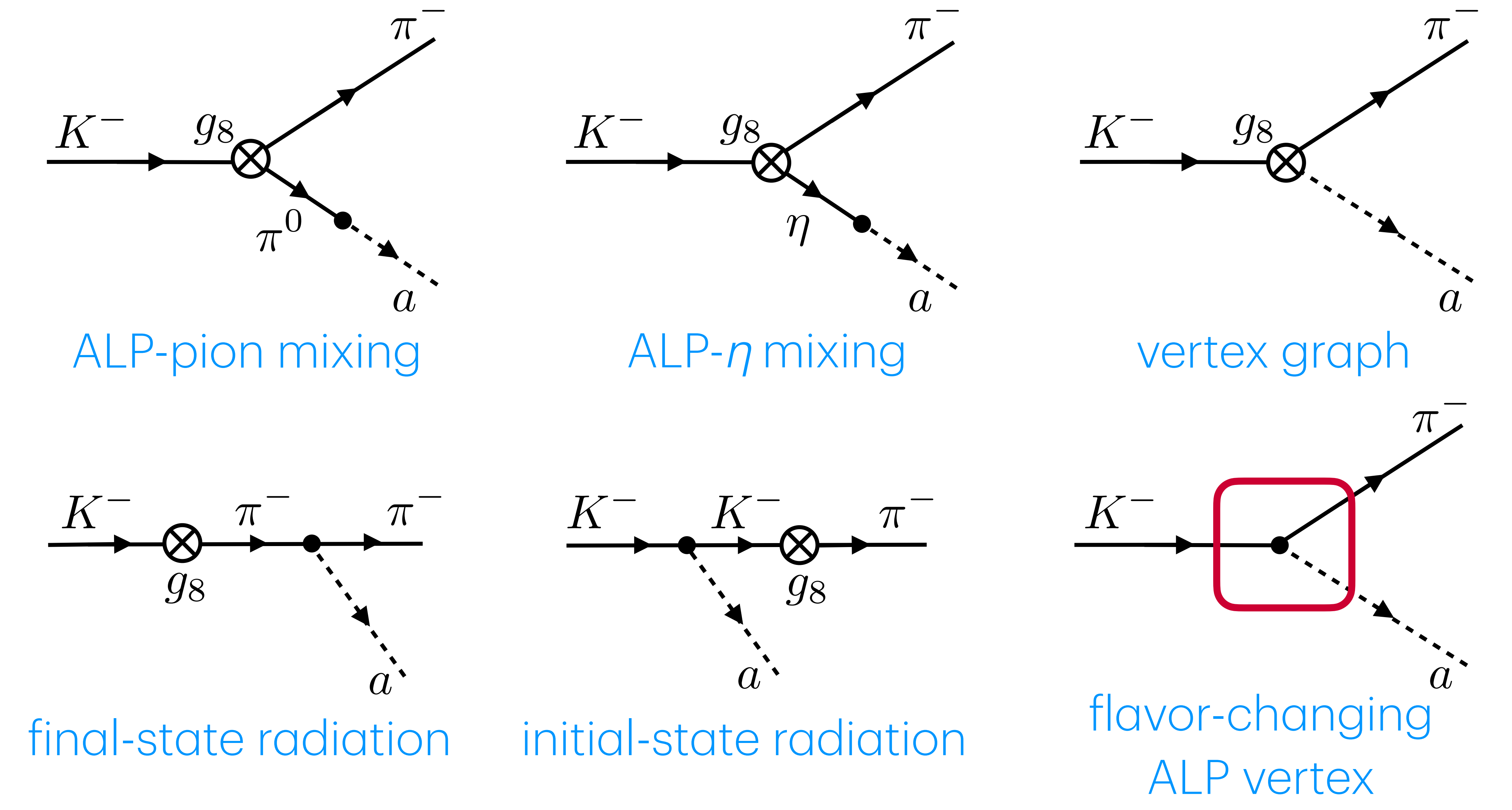
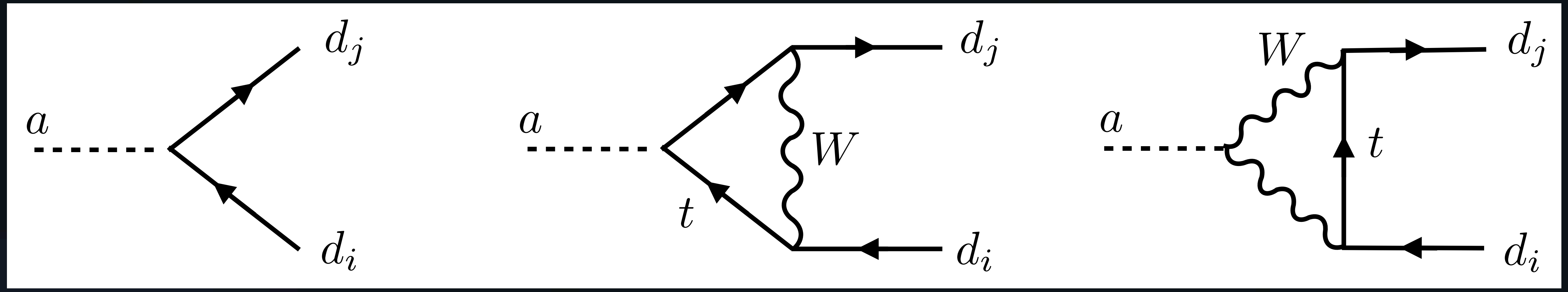


[Bauer, MN, Renner, Schnubel, Thamm 2021]

ALP production in rare kaon decays

Interesting search channel $K^- \to \pi^- a$

- ALP flavor violation can arise from the UV theory and/or from the SM
- Assuming **flavor universality** in the UV and $f = 1$ TeV yields in the mass basis:



[Bauer, MN, Renner, Schnubel, Thamm 2021]

$$[k_{U,E}(m_t)]_{ij} = [k_{u,d,e}(m_t)]_{ij} = 0$$

$$[k_D(m_t)]_{ij} \simeq 0.019\, V_{ti}^* V_{tj} \left[c_{tt}(\Lambda) - 0.0032\, \tilde{c}_{GG}(\Lambda) - 0.0057\, \tilde{c}_{WW}(\Lambda) \right]$$

flavor change through SM loops containing *W*-bosons

ALP production in rare kaon decays

[Cornella, Galda, MN 2023]

Important subtlety: a new SU(3) octet operator arises in the LO weak chiral Lagrangian

$$\mathcal{L}_{\rm QCD}^{(p^2)} = \frac{F^2}{8}\langle (D_\mu\Sigma)\,(D^\mu\Sigma^\dagger) + \chi\Sigma^\dagger + \Sigma\chi^\dagger\rangle + \frac{F^2}{8}\,H_0\,(D_\mu\theta)(D^\mu\theta)$$

$$\mathcal{L}_{\rm weak}^{(p^2)} = \frac{F^4}{4}\Big[G_8\langle\lambda_6 L_\mu L^\mu\rangle + G_8^\theta\,\underline{(D_\mu\theta)\langle\lambda_6 L^\mu\rangle}\Big] + \text{h.c.}$$

$$L_\mu = \Sigma\, i\left(D_\mu\Sigma^\dagger\right)$$

$$D_\mu\theta = -2\tilde{c}_{GG}(\partial_\mu a)/f$$

$$\Sigma(x) = e^{-\frac{i}{2}\theta(x)\,\kappa_q}\,\Sigma_0(x)\,e^{-\frac{i}{2}\theta(x)\,\kappa_q}$$

ALP production in rare kaon decays

[Cornella, Galda, MN 2023]

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Whereas $\boldsymbol{G_8}$ is known from $\boldsymbol{K \to \pi\pi}$ decays, $\boldsymbol{G_8^\theta}$ is still unknown

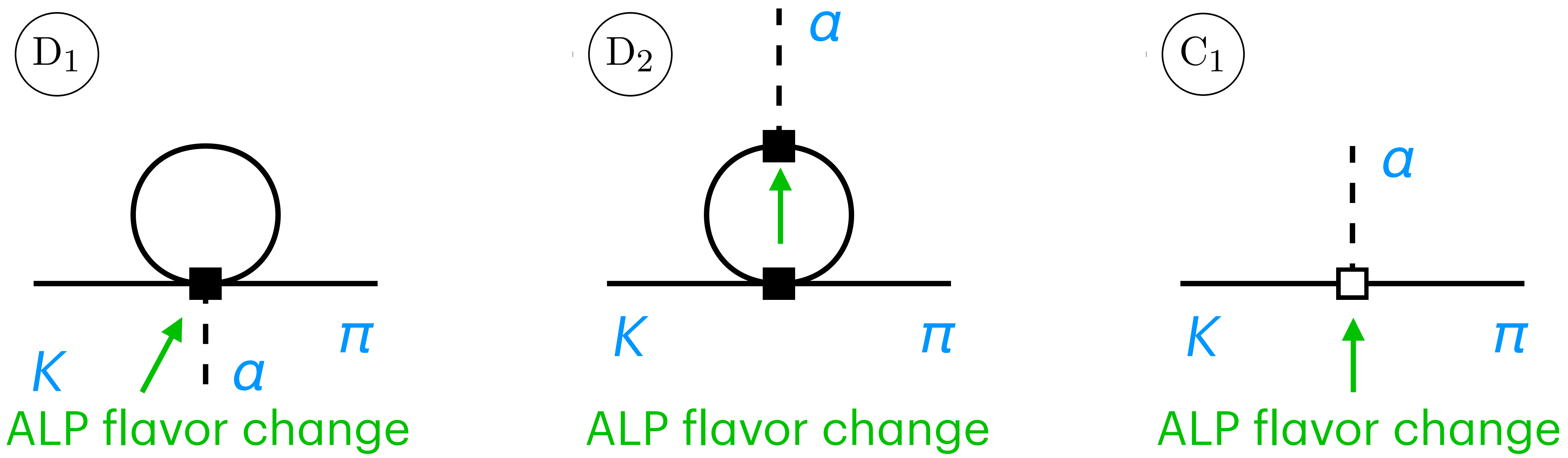
- will vary it later within reasonable limits

ALP production in rare kaon decays

Interesting search channel $K^- \to \pi^- a$

- At NLO in chiral perturbation theory the calculation is far more involved
- NLO QCD and weak chiral Lagrangians need to be supplemented by 3 resp. 9 operators involving $D_\mu \theta$
- Sensitivity to several poorly known low-energy constants

Diagrams involving flavor-changing ALP couplings:



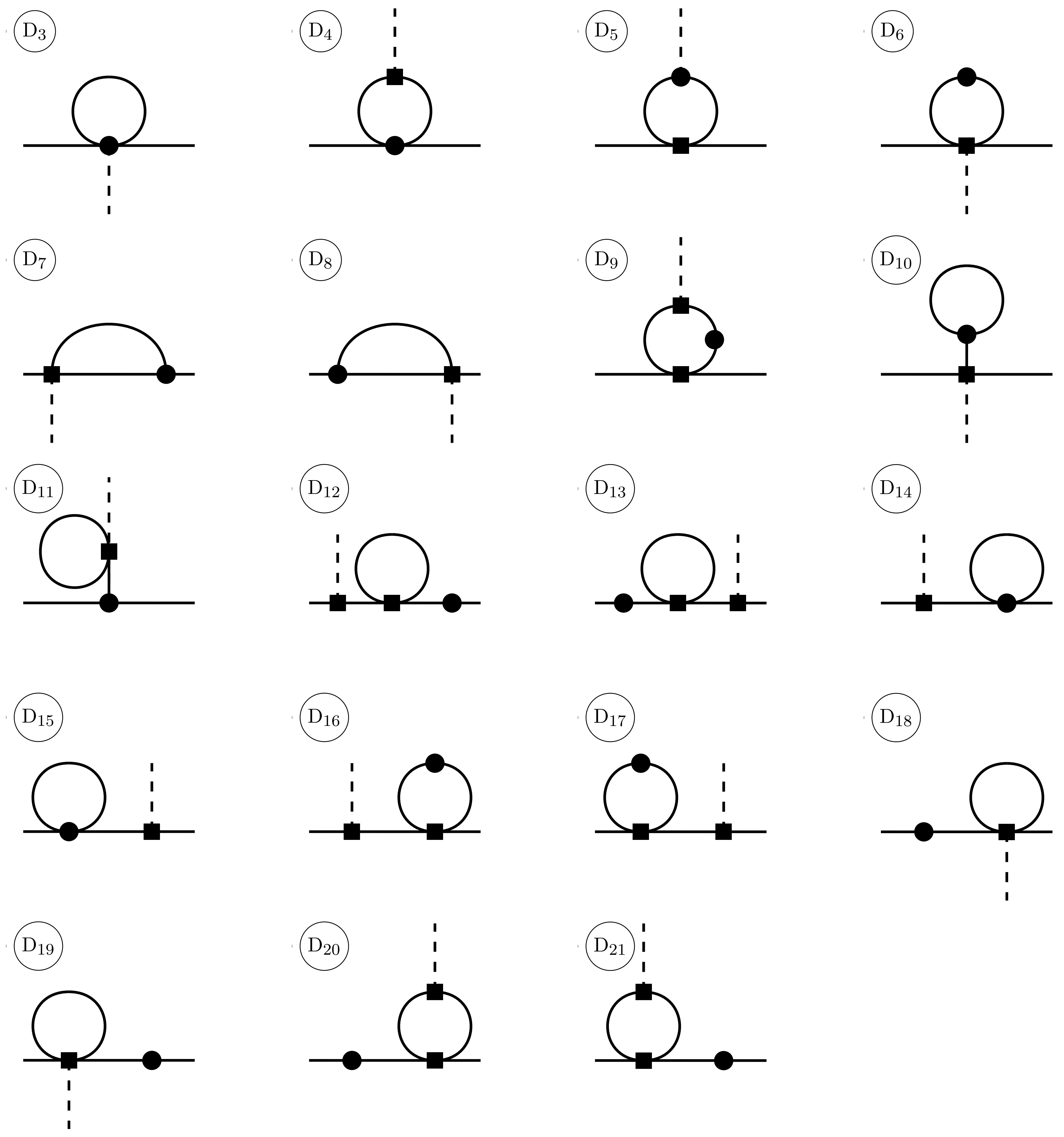
■ QCD chiral Lagrangian (LO)

□ QCD chiral Lagrangian (NLO)

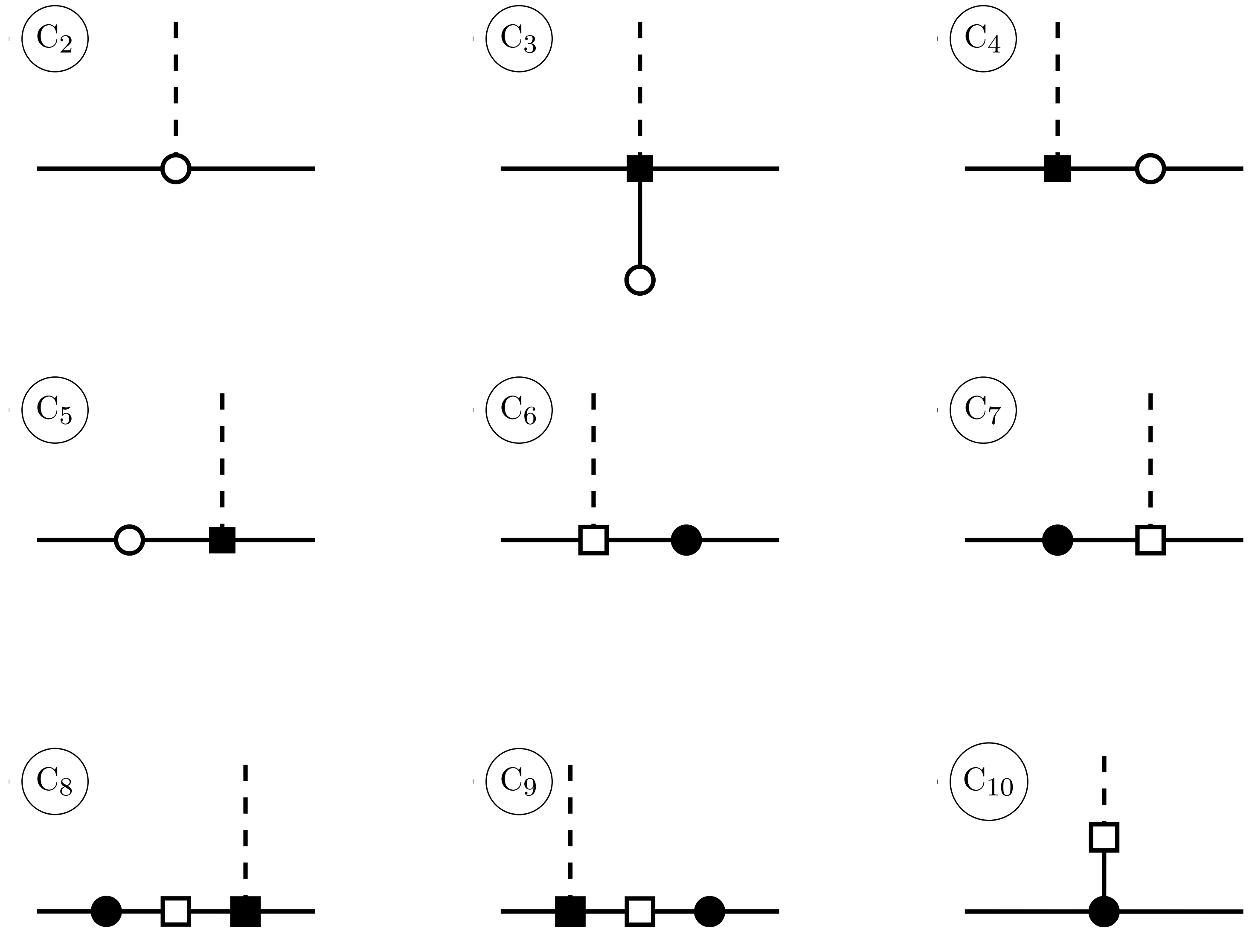
[Cornella, Galda, MN 2023]

$$i\mathcal{A}^{\mathrm{FV}}_{\mathrm{LO+NLO}} = -(m_K^2 - m_\pi^2)\,\frac{[k_d + k_D]_{12}}{2f}\,F_0^{K\to\pi}(q^2 = m_a^2)\,; \qquad F_0^{K\to\pi}(0) = (1_{\,\mathrm{LO}} - 0.023_{\,\mathrm{NLO}})$$

ALP production in rare kaon decays



Diagrams with flavor-conserving ALP couplings:



- ■ QCD chiral Lagrangian (LO)
- □ QCD chiral Lagrangian (NLO)
- ● weak chiral Lagrangian (LO)
- ○ weak chiral Lagrangian (NLO)

[Cornella, Galda, MN 2023]

ALP production in rare kaon decays

Contributions proportional to G_8 (for $m_a = 0$):

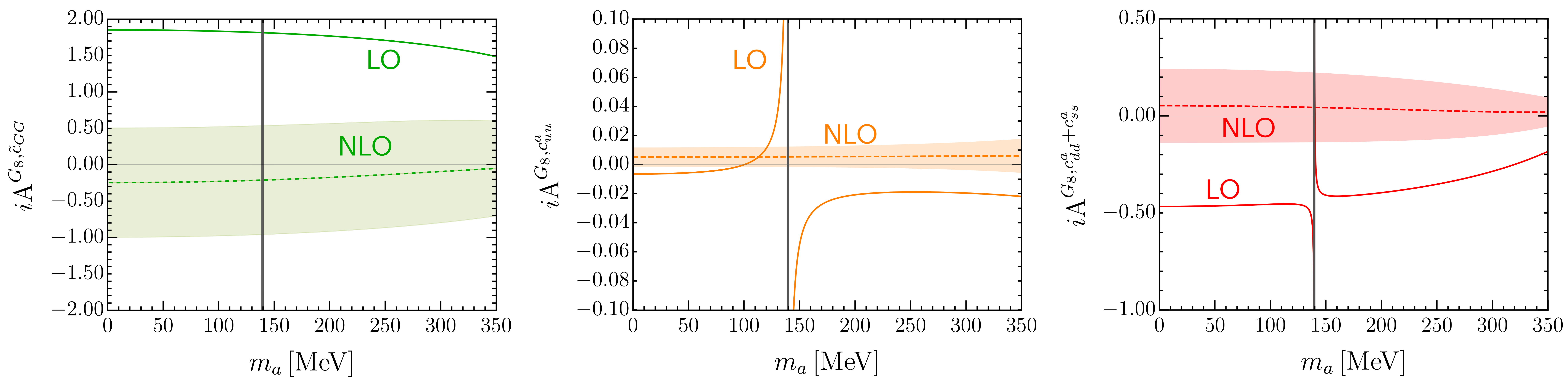
$$i\mathcal{A}_{\text{LO}}^{G_8} = \frac{G_8 F_\pi^2\, m_K^2}{2f} \left[1.88\,\tilde{c}_{GG} - 0.02\, c_{uu}^a - 0.48\,(c_{dd}^a + c_{ss}^a) \right]$$

$$\begin{aligned} i\mathcal{A}_{\text{NLO}}^{G_8} = \frac{G_8 F_\pi^2\, m_K^2}{2f} \Big[& (-0.25 \pm 0.43 \pm 0.61)\,\tilde{c}_{GG} + (5.21 \pm 1.03 \pm 6.52) \cdot 10^{-3}\, c_{uu}^a \\ & + (0.06 \pm 0.11 \pm 0.16)\,(c_{dd}^a + c_{ss}^a) \Big] \end{aligned}$$

- Modest NLO corrections with sizable uncertainties

ALP production in rare kaon decays

Contributions proportional to G_8:

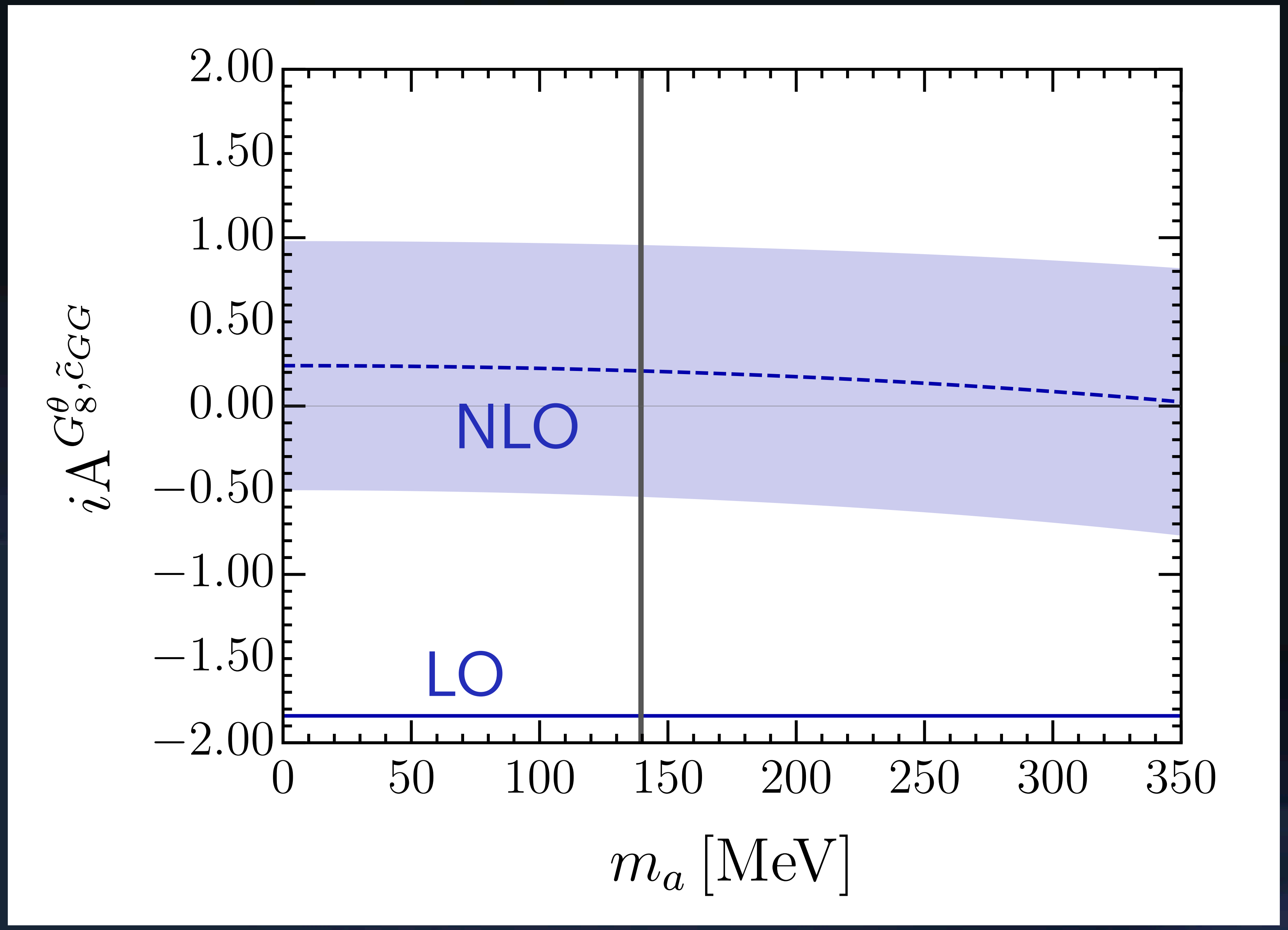


- Weak dependence on ALP mass, except for $m_a \approx m_{\pi^0}$

ALP production in rare kaon decays

Contribution proportional to G_8^θ:

$$i\mathcal{A}^{G_8^\theta}_{\mathrm{LO+NLO}} = \frac{G_8^\theta\, F_\pi^2\, m_K^2}{2f} \times \Big[-1.84_{\mathrm{LO}} + (0.25 \pm 0.43 \pm 0.60)_{\mathrm{NLO}} \Big]\, \tilde{c}_{GG}$$



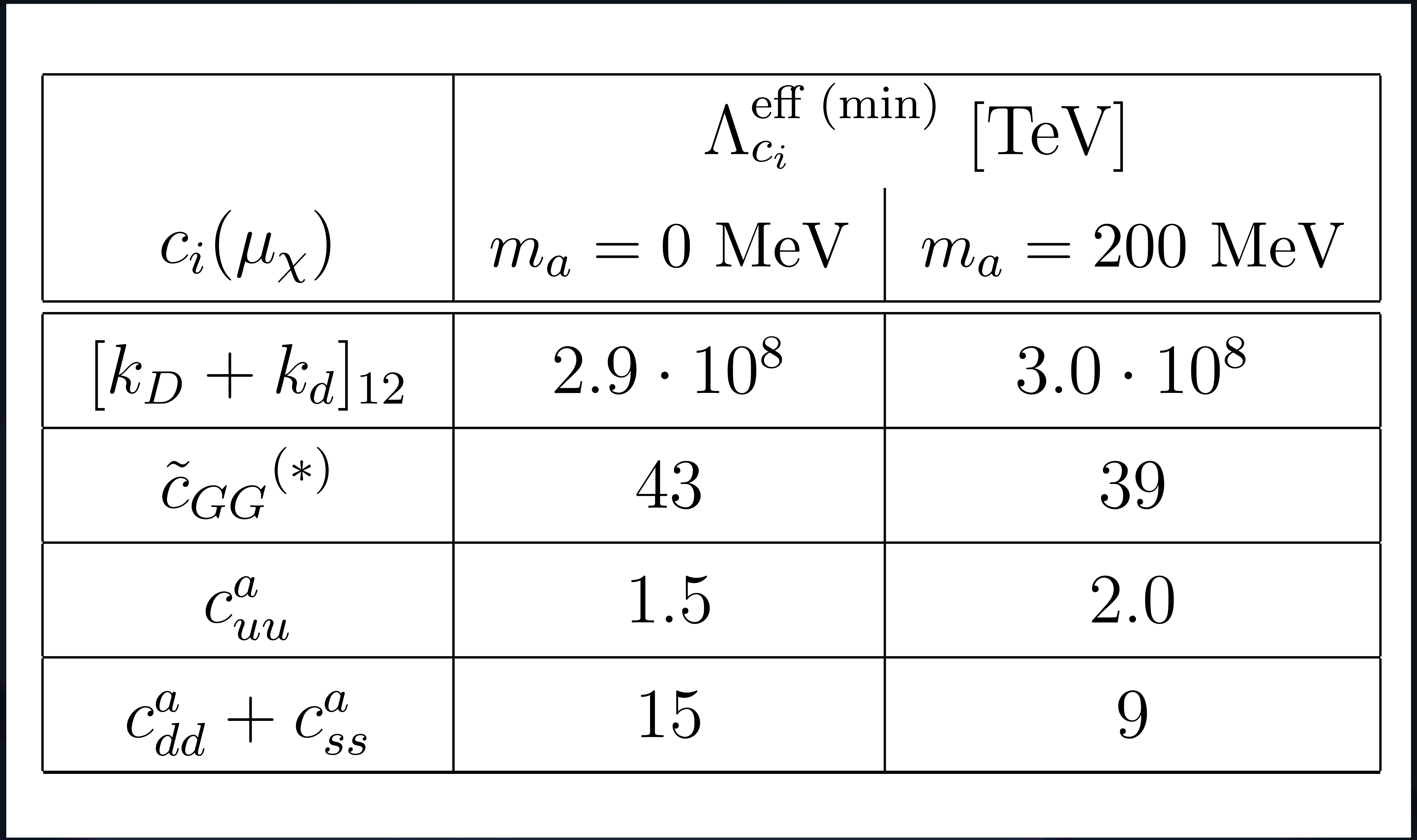
- Only a single physical ALP coupling enters, but the low-energy coupling G_8^θ is unknown
- Modest NLO corrections with sizable uncertainties

Bounds on ALP couplings

Interesting search channel $K^- \to \pi^- a$

- NA62 experimental limits on $K^- \to \pi^- X$ imply bounds on ALP couplings (one at a time), which we express in the form of parameters $\Lambda^{\text{eff}}_{c_i} = f/|c_i|$ [NA62: 2103.15389]
- New-physics scales probed range from few to tens of TeV

(*) assuming $G^{\theta}_8 = 0$



	$\Lambda^{\text{eff (min)}}_{c_i}$ [TeV]	
$c_i(\mu_\chi)$	$m_a = 0$ MeV	$m_a = 200$ MeV
$[k_D + k_d]_{12}$	$2.9 \cdot 10^8$	$3.0 \cdot 10^8$
$\tilde{c}_{GG}{}^{(*)}$	43	39
c^a_{uu}	1.5	2.0
$c^a_{dd} + c^a_{ss}$	15	9

[Cornella, Galda, MN 2023]

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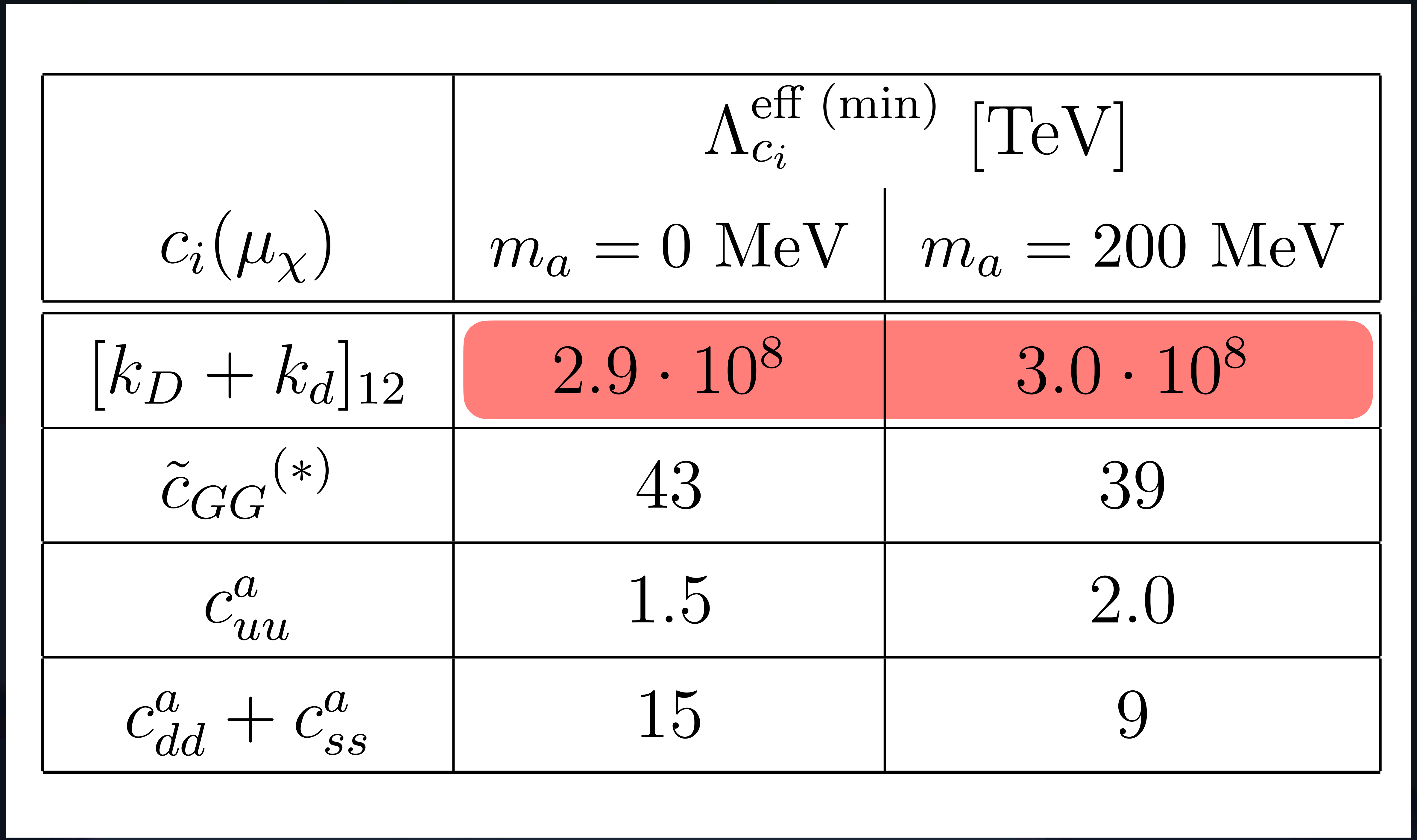
- New-physics scales probed range from few to tens of TeV
- Very strong bounds on flavor-changing ALP couplings call for a **flavor symmetry**, else:

$$f_a \sim f > 30 \cdot 10^{10}\ \text{GeV}$$



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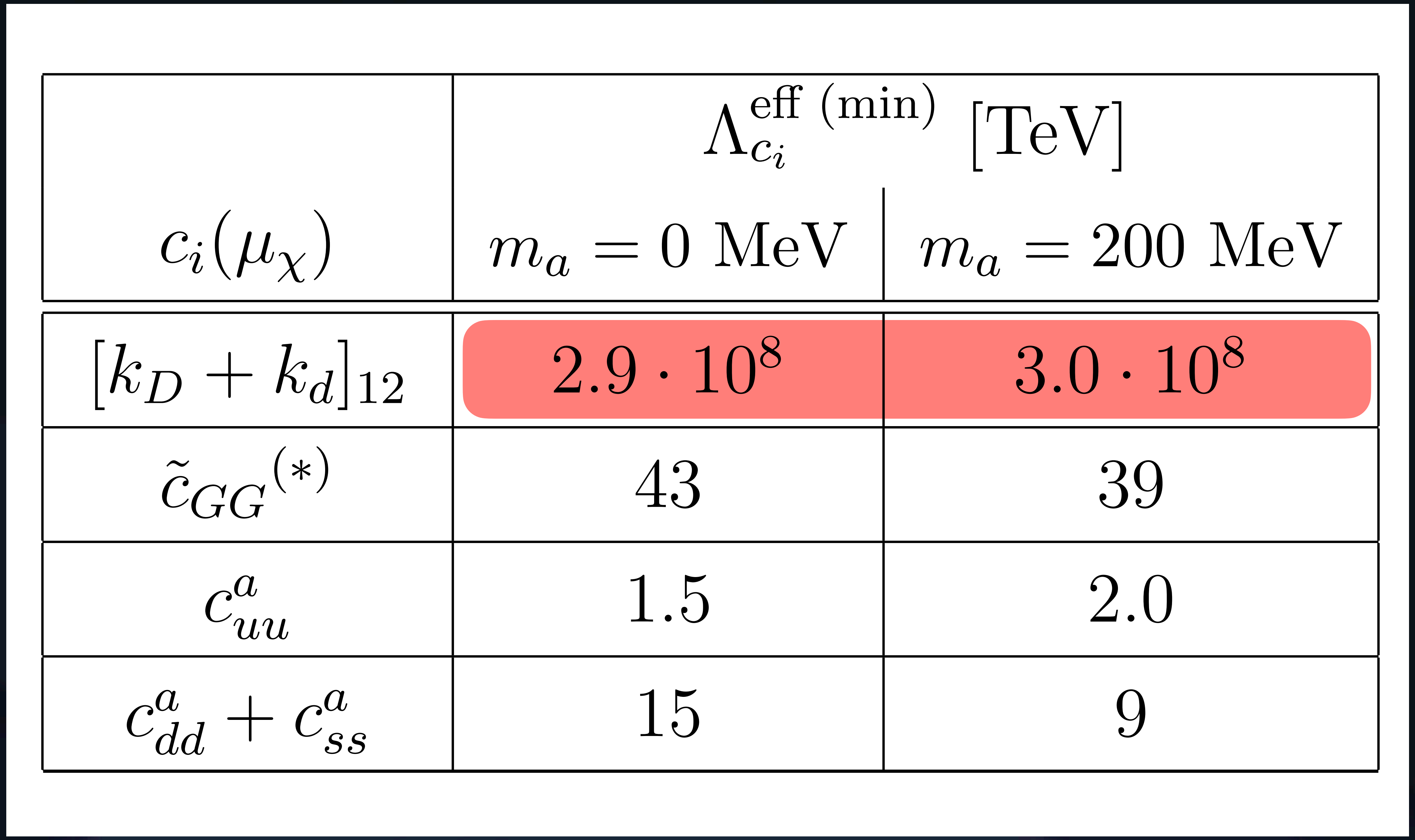

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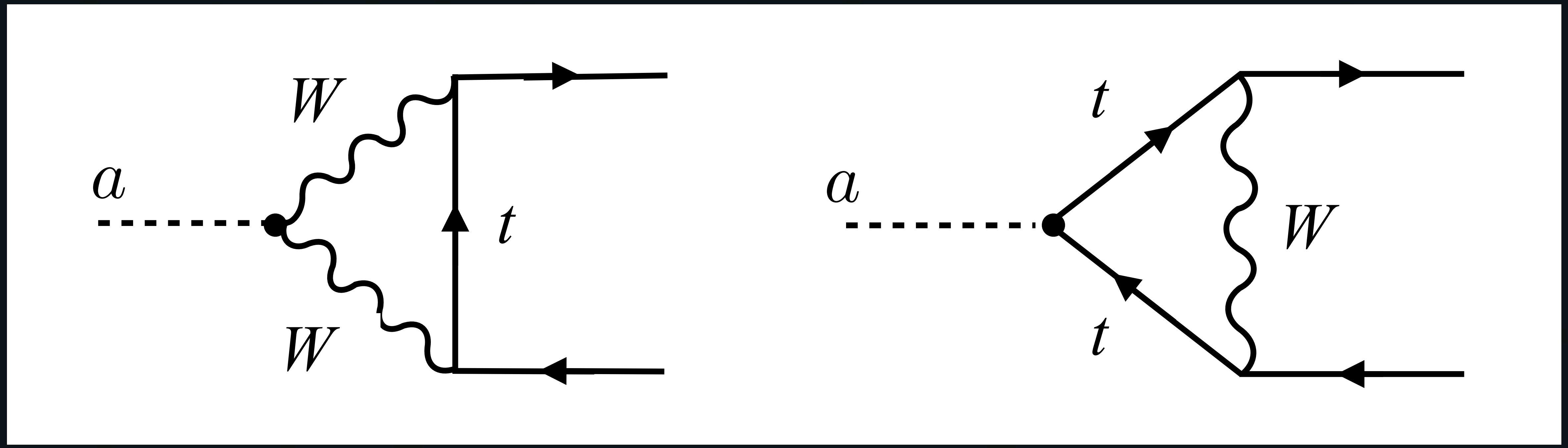
Cosmological upper bound:

$$f_a \lesssim 10^{10}\ \text{GeV} \quad \text{(KSVZ)}$$
$$2 \cdot 10^{9}\ \text{GeV} \quad \text{(DFSZ)}$$

[Gorghetto, Hardy, Villadoro 2021]

Bounds on ALP couplings

- Large flavor-changing ALP couplings can be avoided by assuming a **flavor-universal ALP** at the UV scale $\Lambda = 4\pi f$
- Still, at low energies flavor-changing couplings are generated by RG effects



[Cornella, Galda, MN 2023]

$$[k_d(\mu_\chi) + k_D(\mu_\chi)]_{12}^{\text{univ}} \simeq 10^{-5}\, V_{td}^* V_{ts} \left[1.9 \cdot 10^3\, \tilde{c}_u(\Lambda) - 6.1\, \tilde{c}_{GG}(\Lambda) - 2.8 \tilde{c}_{WW}(\Lambda) - 0.02\, \tilde{c}_{BB}(\Lambda) \right]$$

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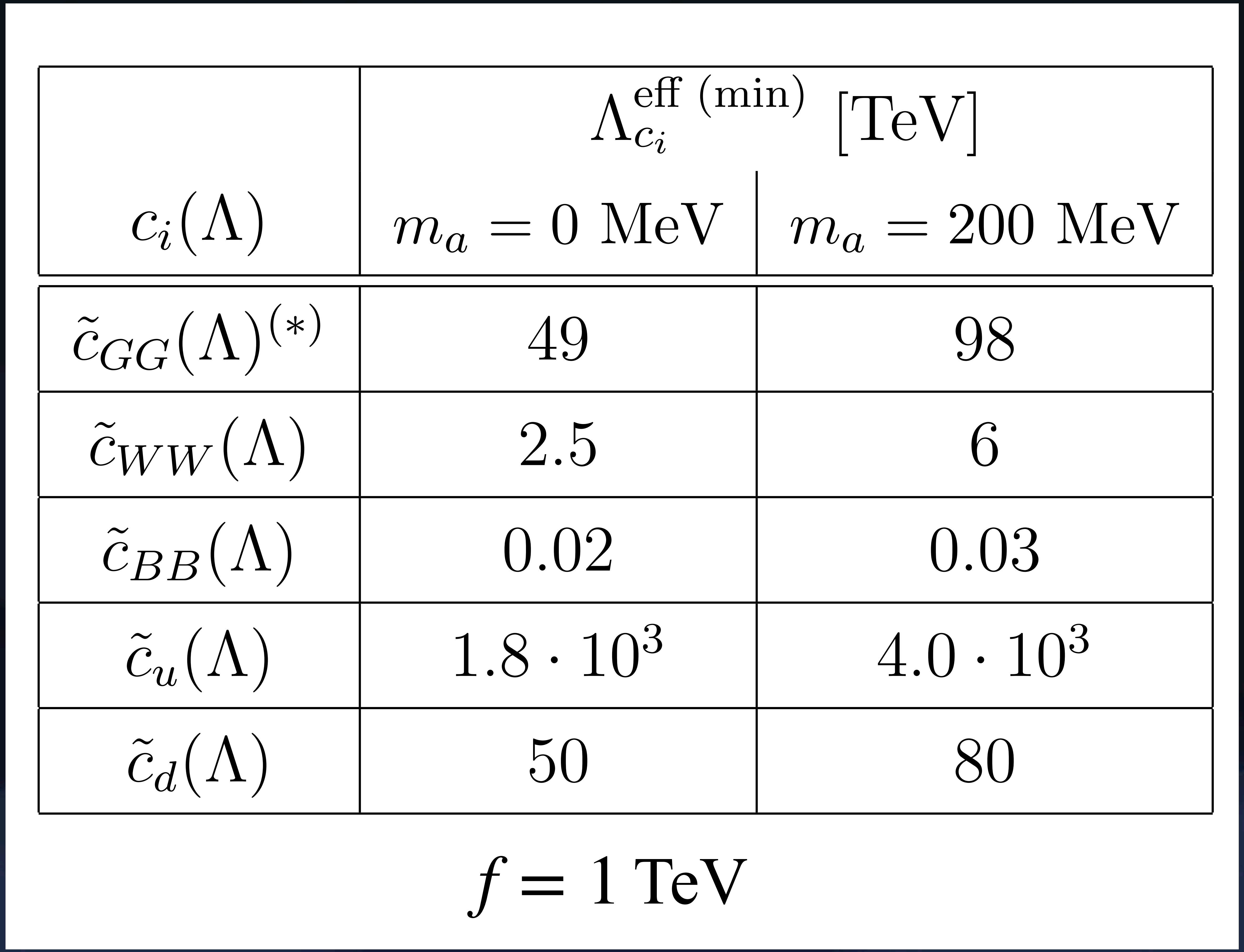

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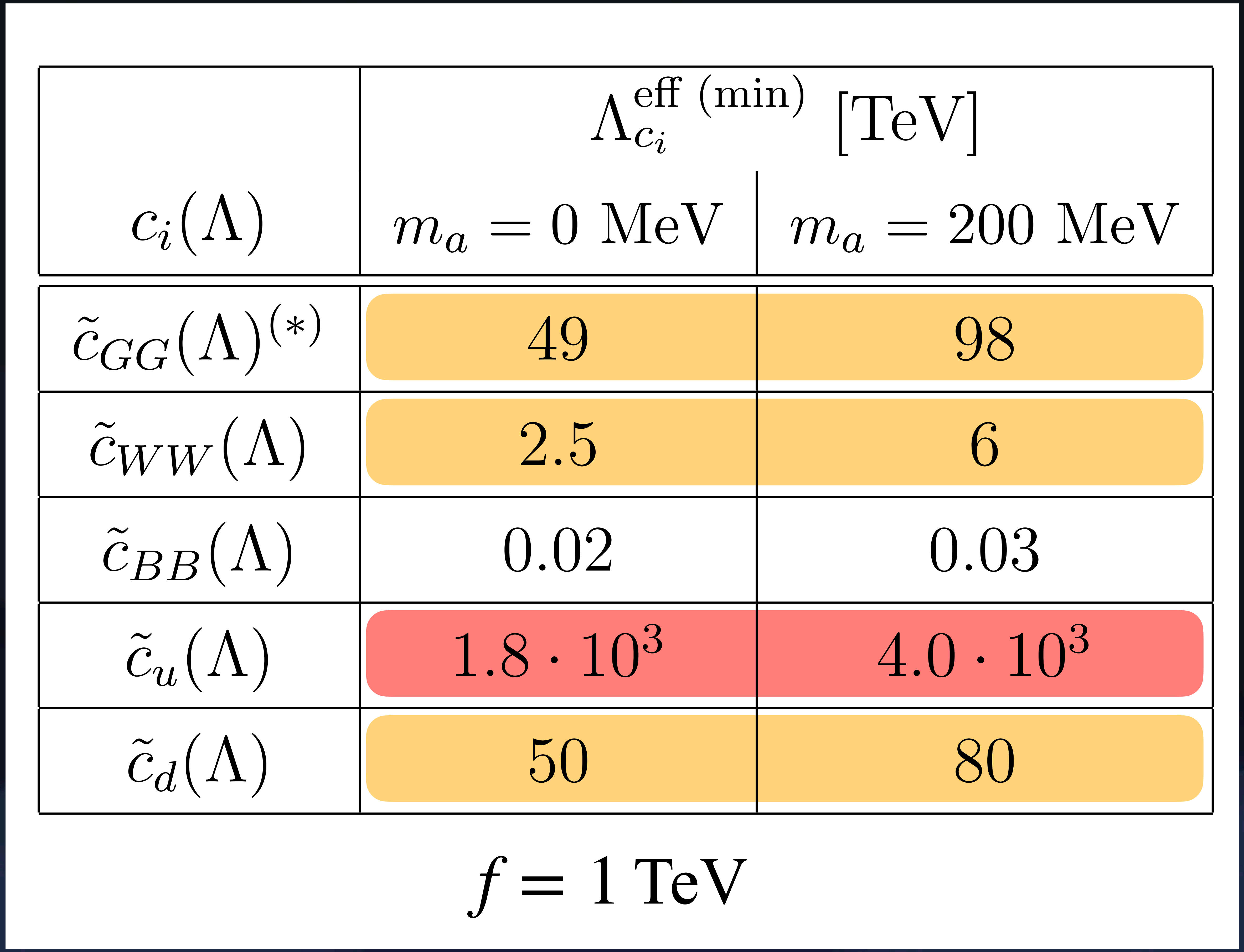
$\tilde{c}_{GG}(\Lambda)^{(*)}$	49	98
$\tilde{c}_{WW}(\Lambda)$	2.5	6
$\tilde{c}_{BB}(\Lambda)$	0.02	0.03
$\tilde{c}_{u}(\Lambda)$	$1.8 \cdot 10^3$	$4.0 \cdot 10^3$
$\tilde{c}_{d}(\Lambda)$	50	80

$f = 1$ TeV

[Cornella, Galda, MN 2023]

Bounds on ALP couplings

- Large flavor-changing ALP couplings can be avoided by assuming a **flavor-universal ALP** at the UV scale $\Lambda = 4\pi f$
- Still, at low energies flavor-changing couplings are generated by RG effects
- Obtained strong bounds on the ALP couplings to gluons, *W*-bosons and quarks are the **best particle-physics bounds** in the mass range below 340 MeV



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$f = 1$ TeV

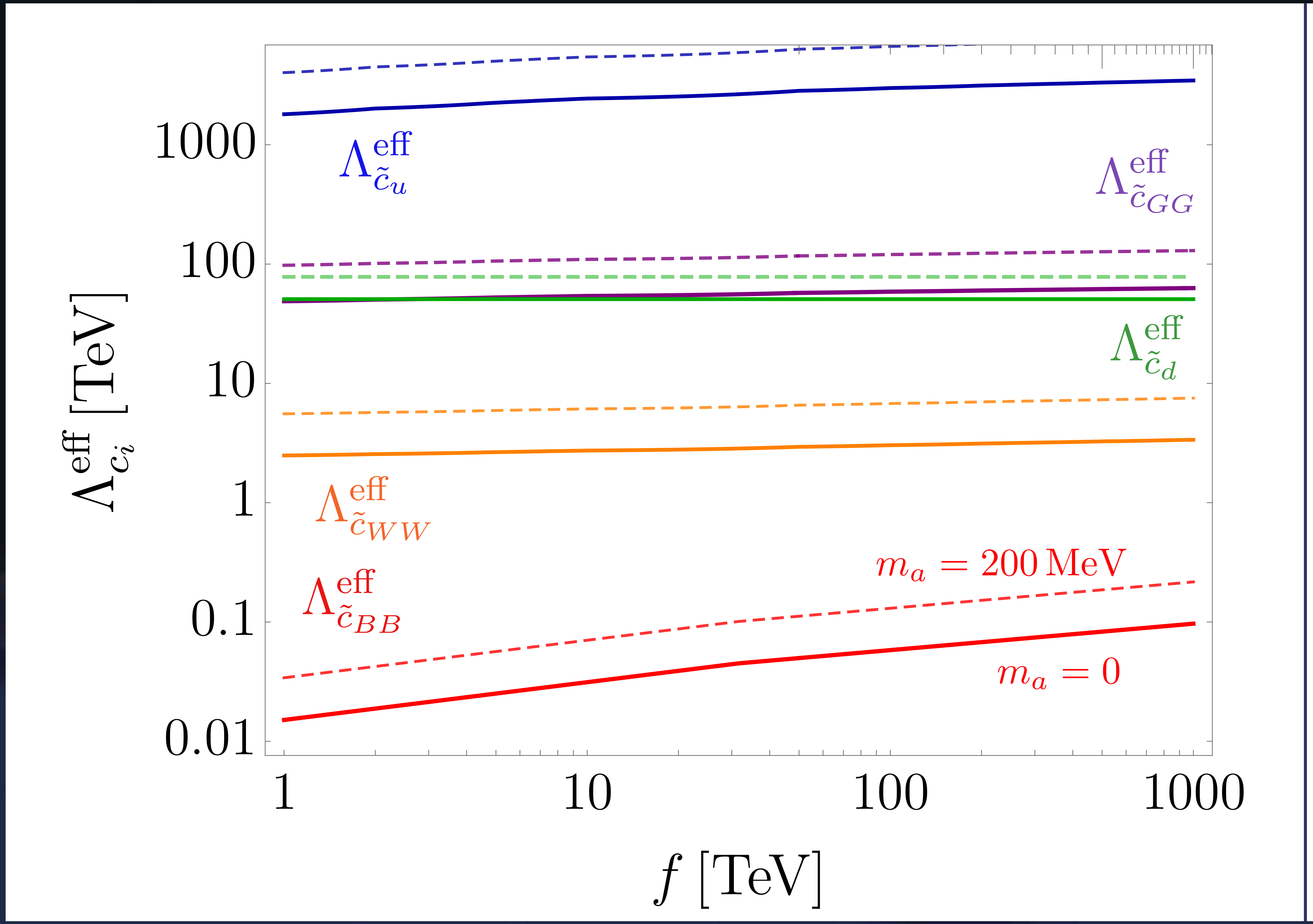
[Cornella, Galda, MN 2023]

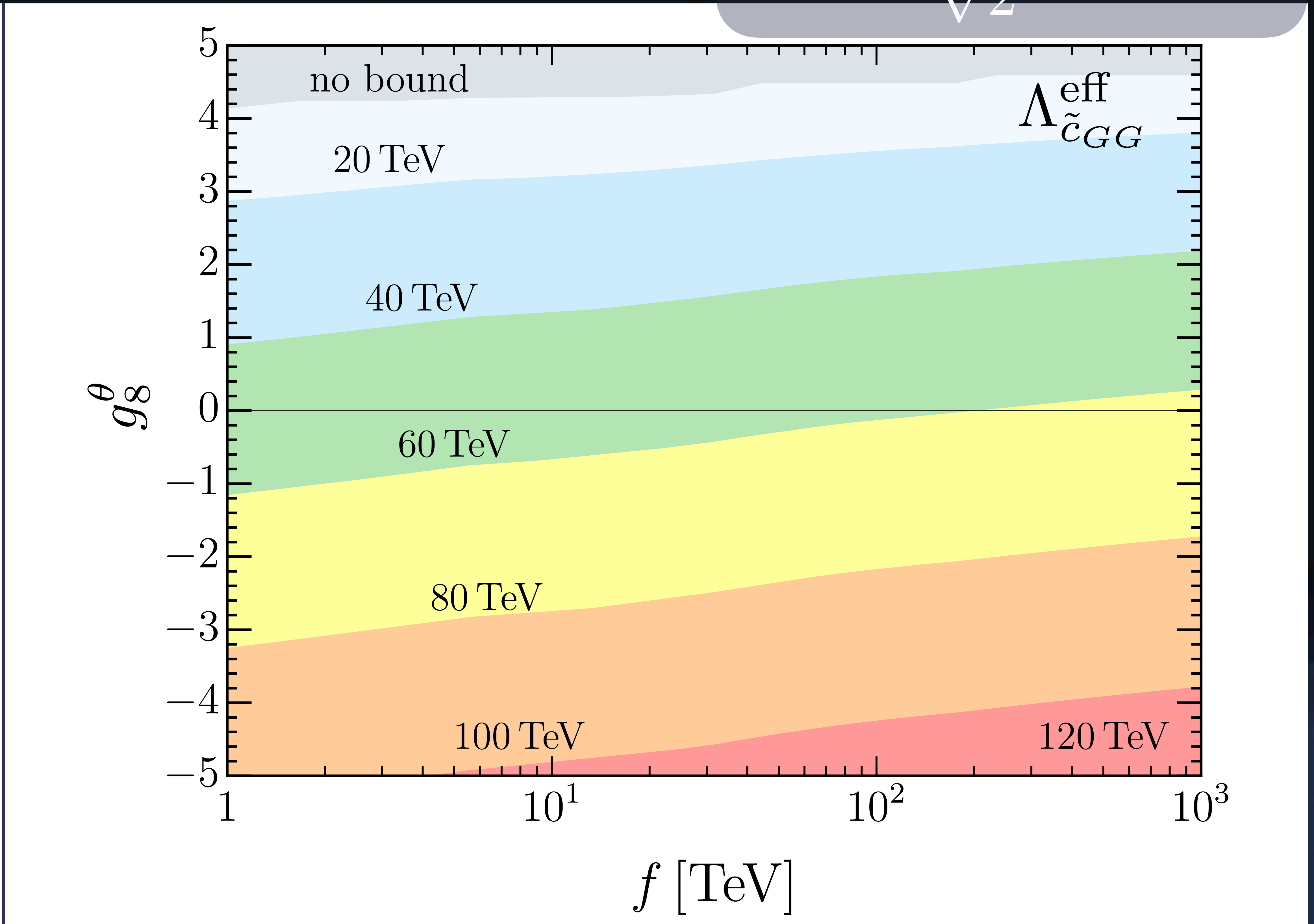
Bounds on ALP couplings

Logarithmic dependence of the effective new-physics scales on f:

Dependence of $\Lambda^{\text{eff}}_{\tilde{c}_{GG}}$ on the low-energy constant G_8^θ:

$$G_8^\theta = -\frac{G_F}{\sqrt{2}} V_{ud}^* V_{us} \boxed{g_8^\theta}$$

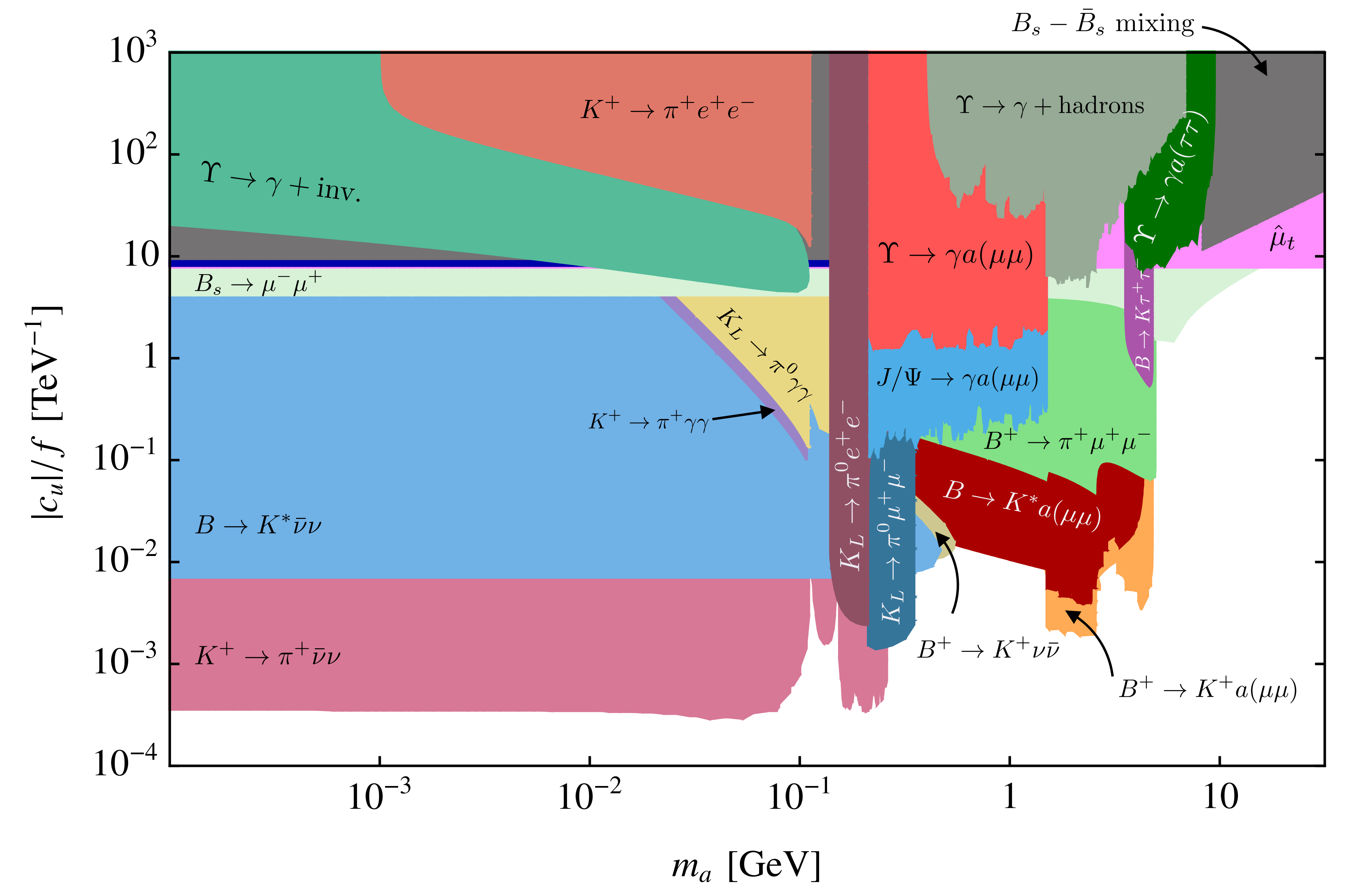




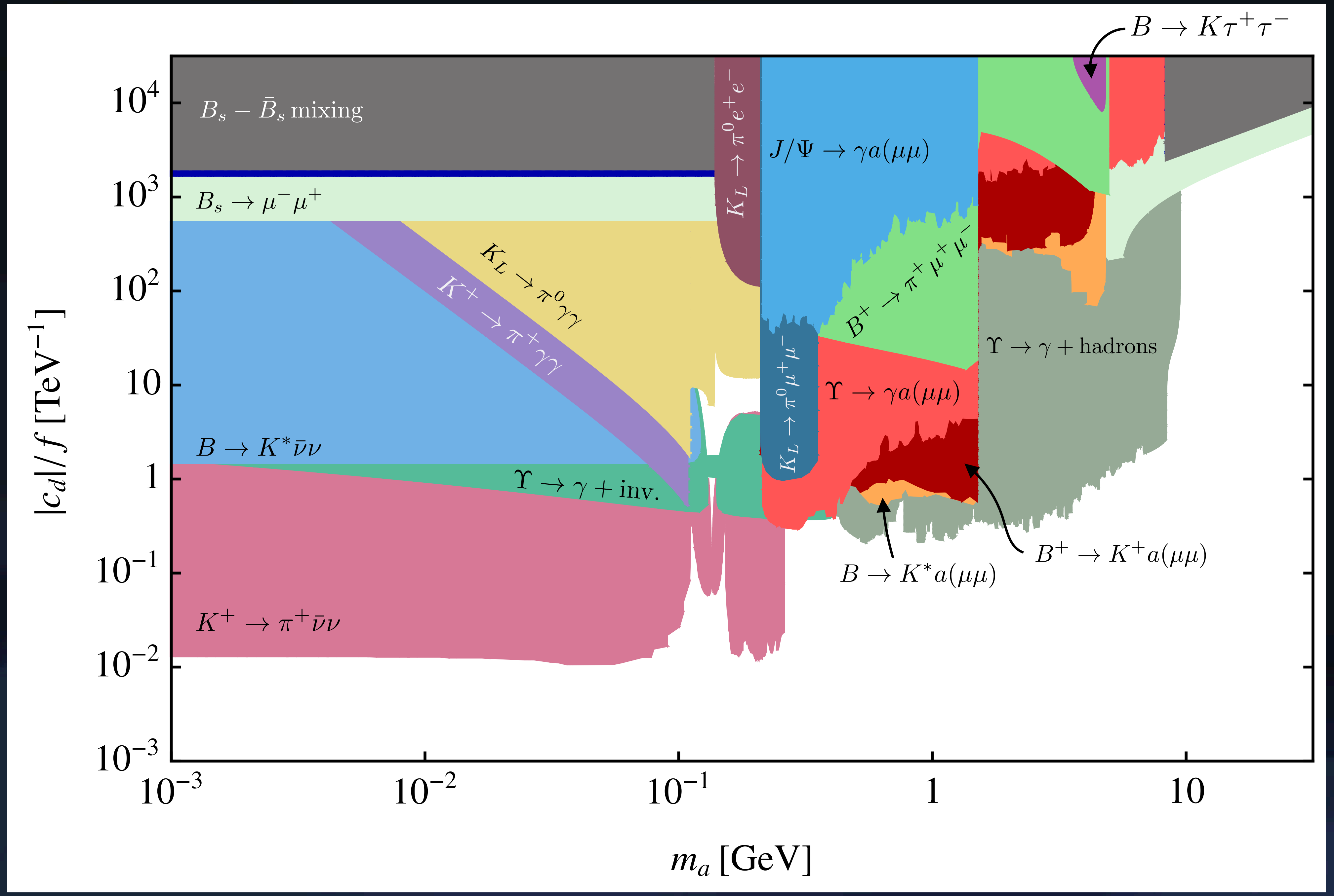
[Cornella, Galda, MN 2023]

Other flavor bounds (examples)

ALP—u_R coupling in the UV:



ALP—d_R coupling in the UV:



[Bauer, MN, Renner, Schnubel, Thamm 2021]

Conclusions

- Axions and axion-like particles belong to a class of well-motivated light BSM particles with weak couplings to the Standard Model
- They are interesting targets for searches in high-energy physics, using collider, flavor, and precision probes
- Examples from Higgs physics ($h \to aa \to 4\gamma$) and rare meson decays ($K^- \to \pi^- a$) have been discussed in detail, with the latter process providing the strongest particle-physics bounds (for $m_a < 340$ MeV) on almost all ALP couplings to the SM

Thank you!