Flavor Probes of Axion-Like Particles

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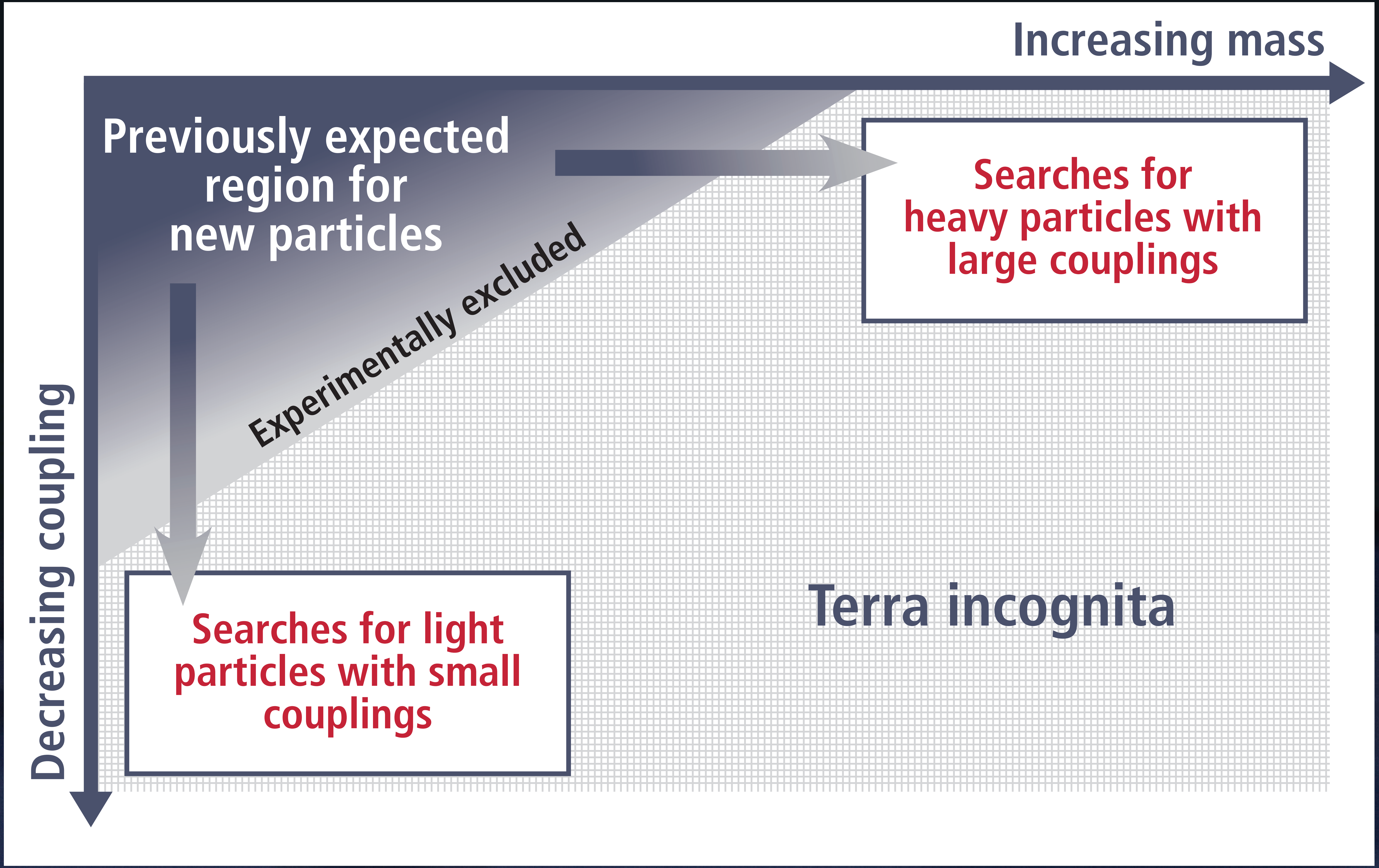
M. Bauer, MN, A. Thamm: 1704.08207 (PRL), 1708.00443 (JHEP)
M. Bauer, MN, S. Renner, M. Schnubel, A. Thamm: 2012.12272 (JHEP), 2102.13112 (PRL), 2110.10698 (JHEP)
C. Cornella, A. Galda, MN, D. Wyler: 2308.16903

20th Rencontres du Vietnam, ICISE, Quy Nhon, 7-12 January 2024 — BSM in Particle Physics and Cosmology: 50 Years Later

Limits of the Standard Model



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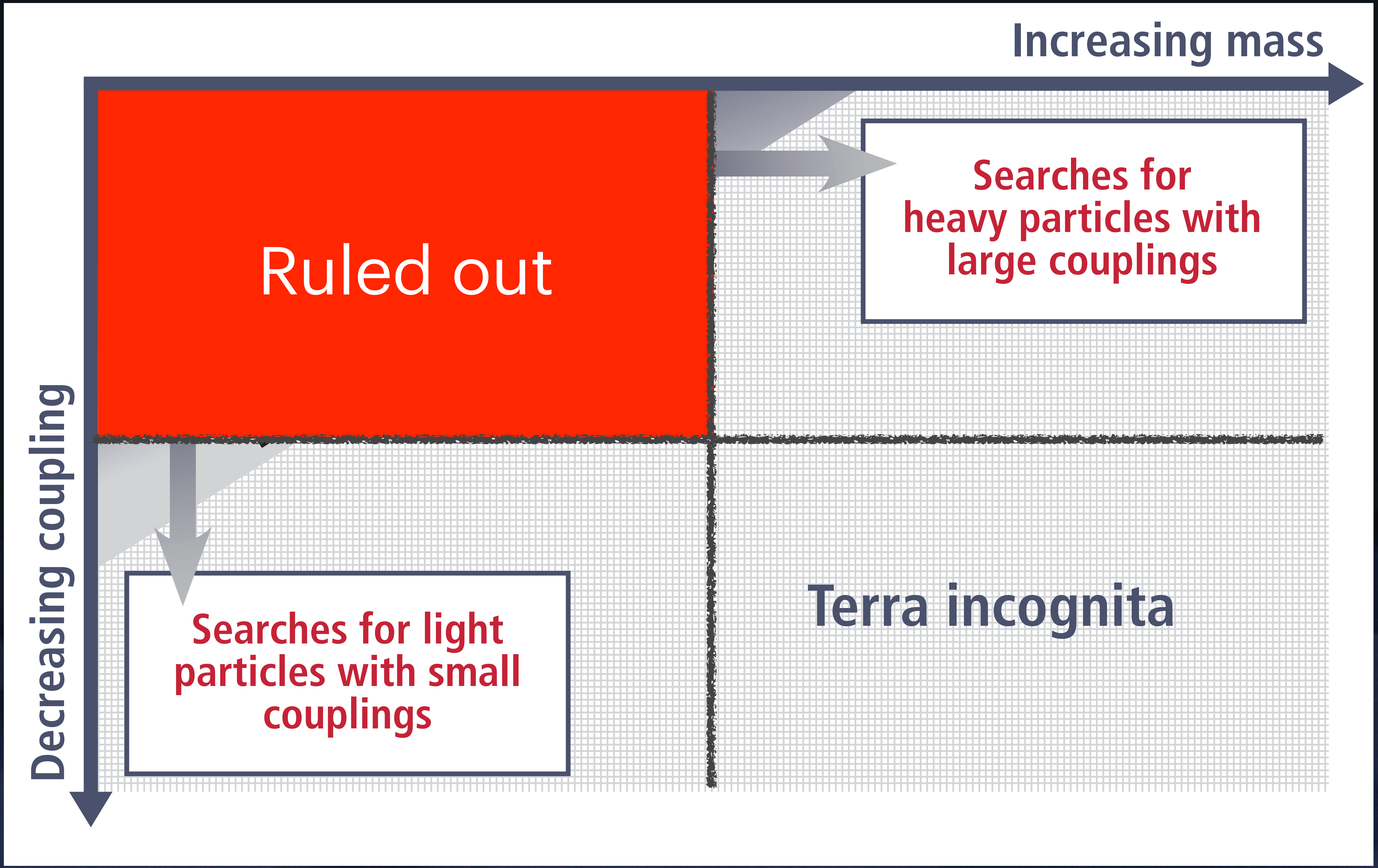

Increasing mass

Decreasing coupling

Ruled out

Searches for heavy particles with large couplings

Searches for light particles with small couplings

Terra incognita

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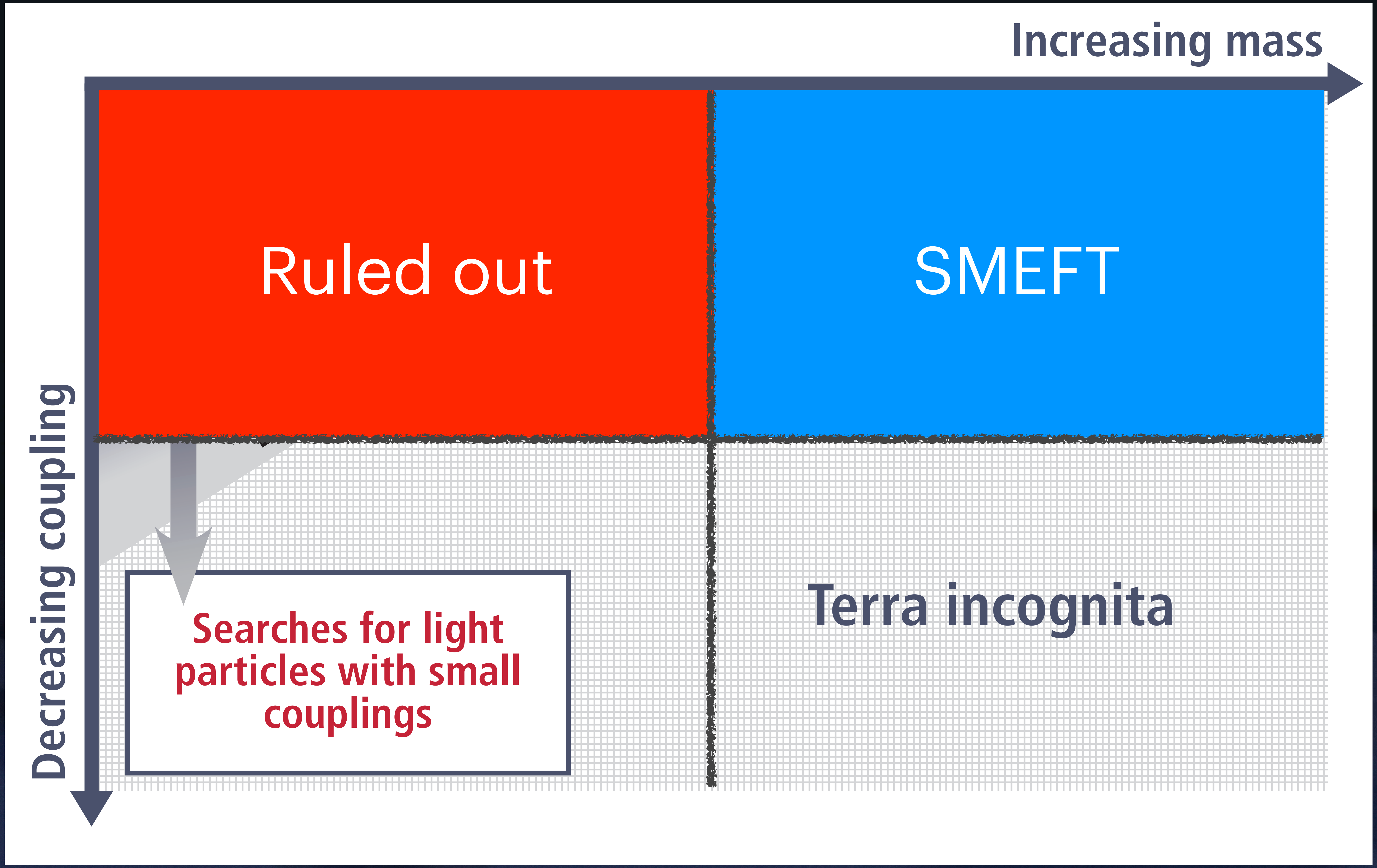
Limits of the Standard Model



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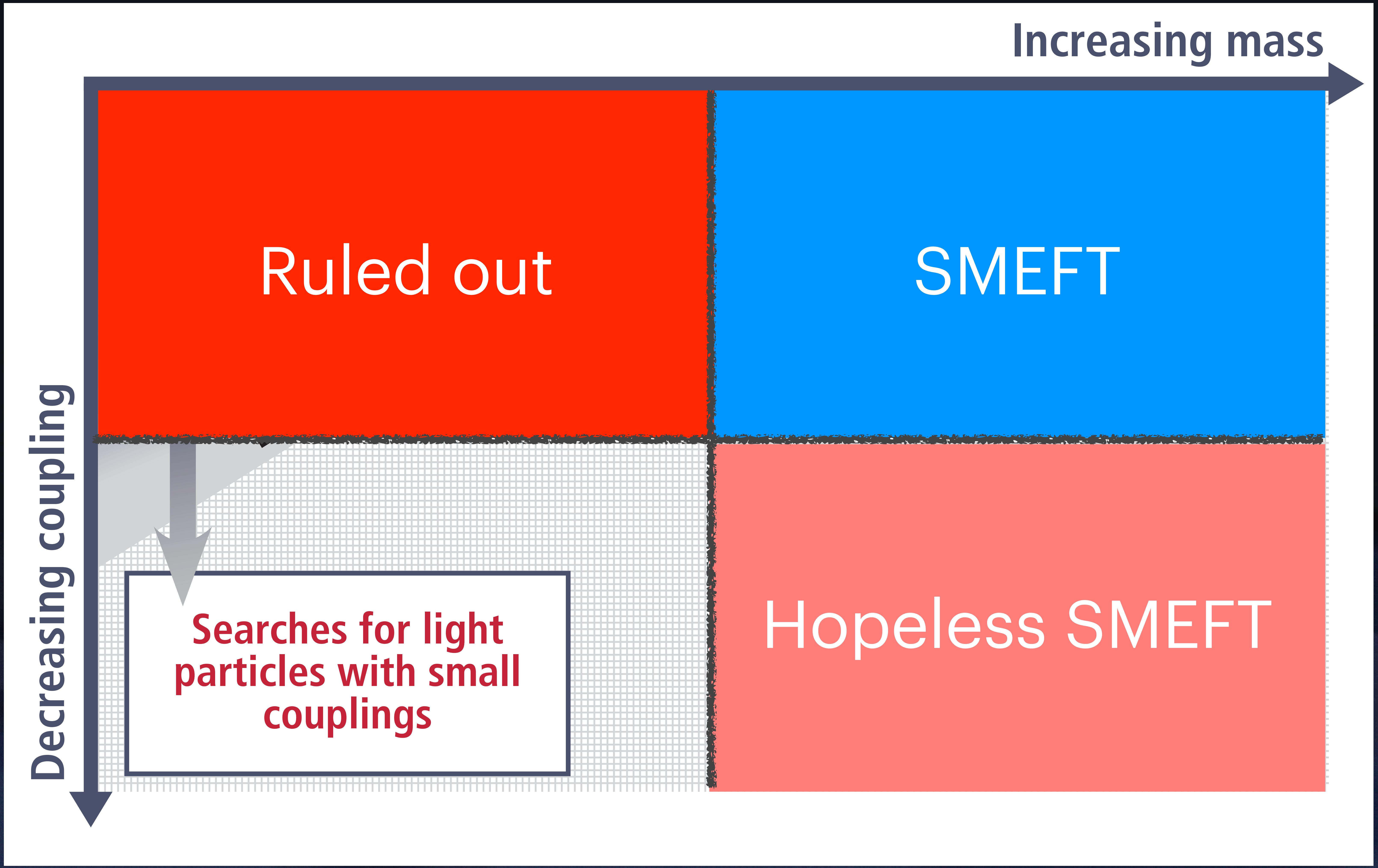

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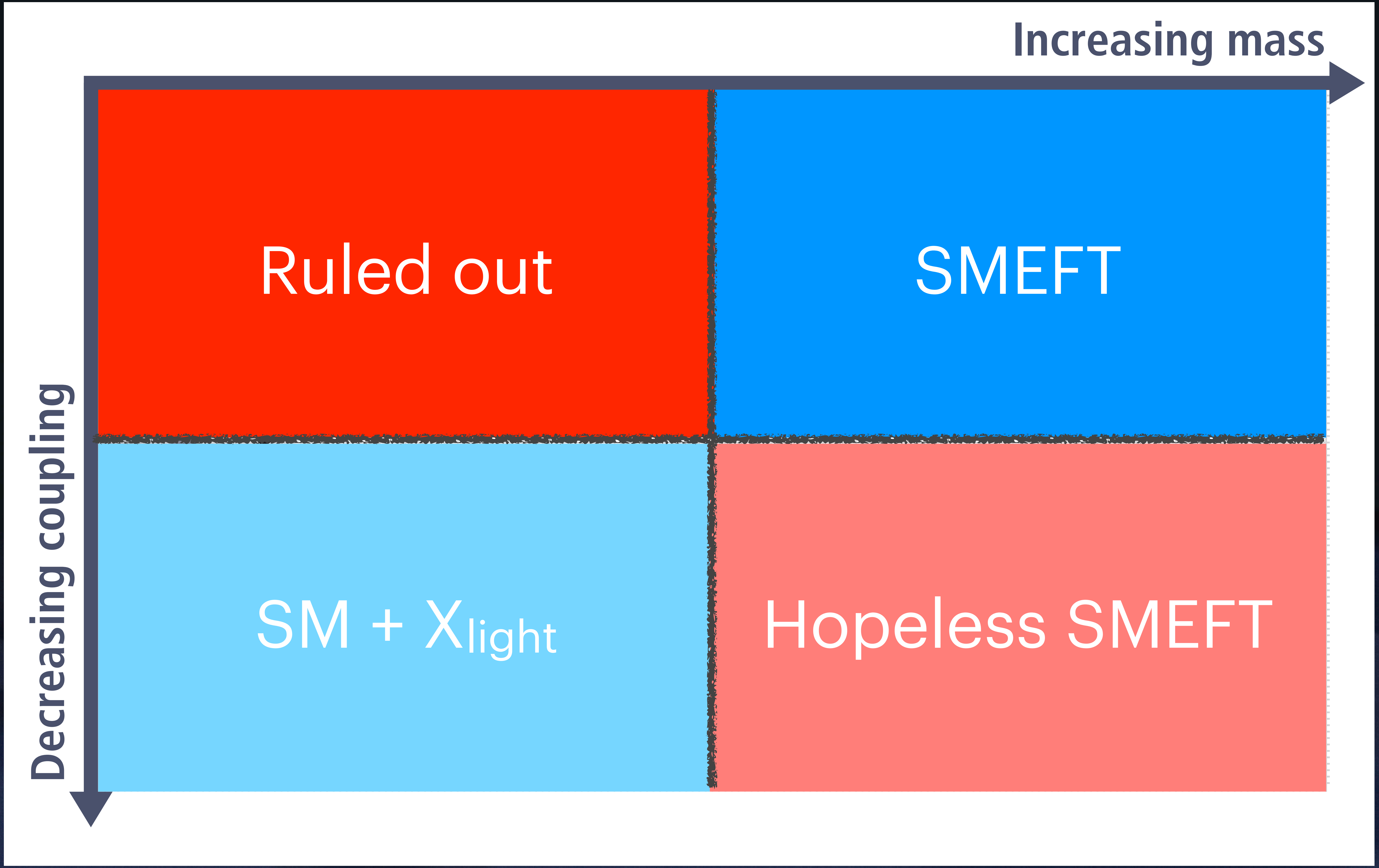

Increasing mass

Decreasing coupling

Ruled out

SMEFT

SM + X_{light}

Hopeless SMEFT

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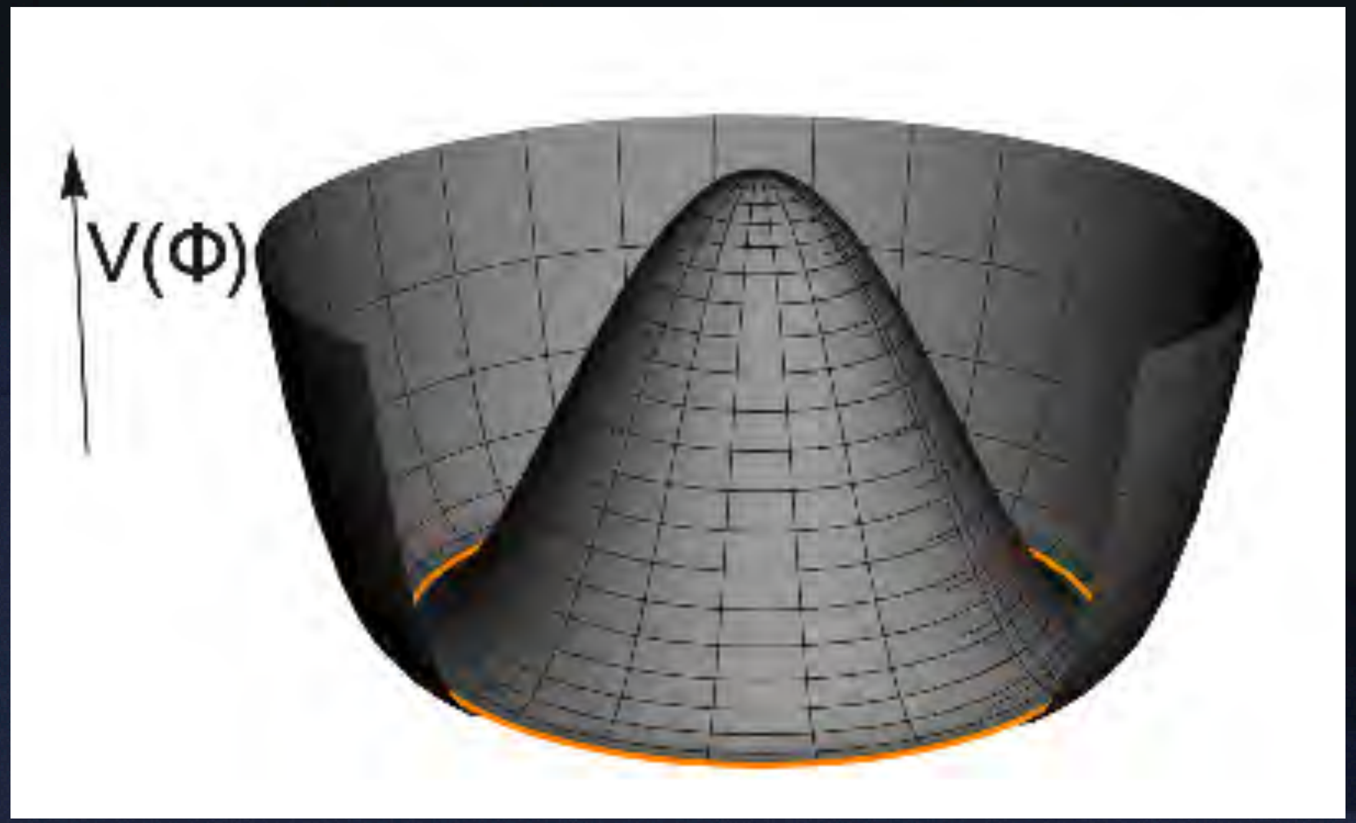
Axions and axion-like particles (ALPs)

Well motivated theoretically:

- Peccei—Quinn solution to strong CP problem: new scalar field $\boldsymbol{\Phi} = |\,\Phi\,|\, e^{ia/f_a}$ charged under a new symmetry U(1)$_{\text{PQ}}$ coupled to chiral fermions [Peccei, Quinn 1977; Weinberg 1978; Wilczek 1978]



- Spontaneous symmetry breaking yields a VEV for $\boldsymbol{\Phi}$
- Performing a chiral transformation on the fermion fields, one finds:

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

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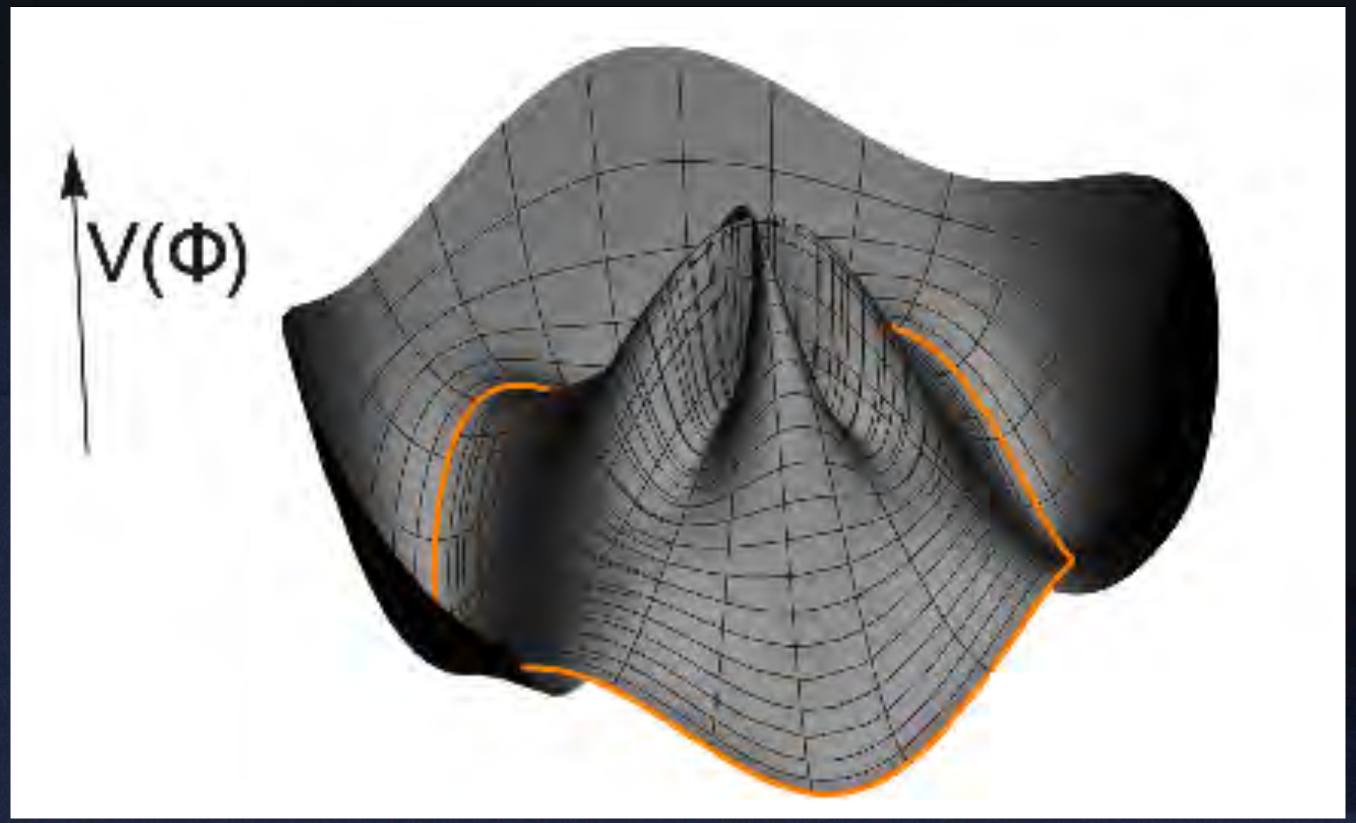


- Performing a chiral transformation on the fermion fields, one finds:

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

- QCD instantons break the continuous shift symmetry $a \to a +$ const to a discrete subgroup, generating a potential and a mass for the axion and enforcing $\theta_{\rm eff} = 0$ mod 2π

Axions and axion-like particles (ALPs)

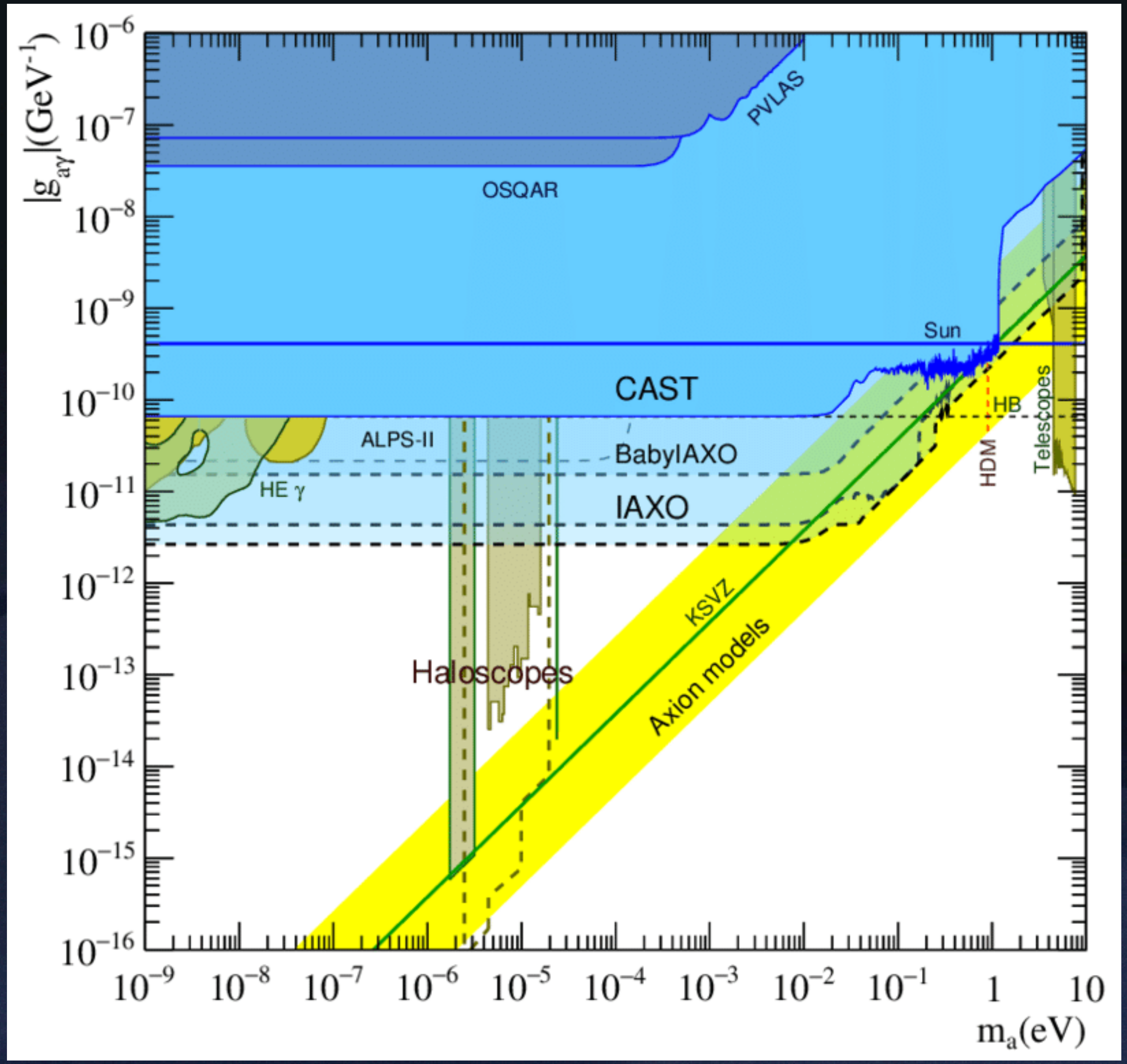
Well motivated theoretically:

- 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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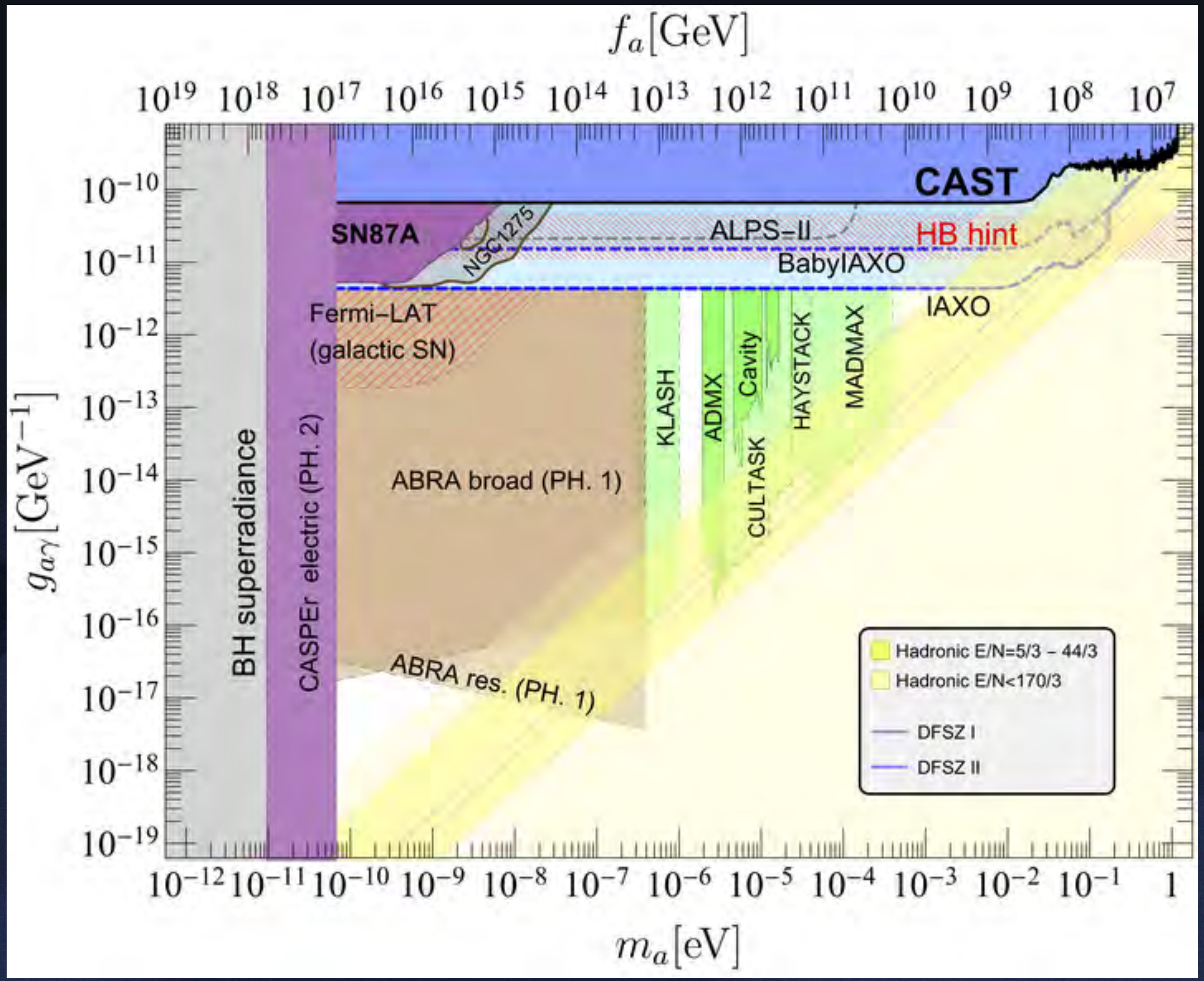

[Di Luzio, Gianotti, Nardi, Visinelli 2022]

Axions and axion-like particles (ALPs)

Well motivated theoretically:

- There are ways to relax the strict relation between the axion mass and photon coupling, so that the mass becomes a free parameter, while the strong CP problem can still be solved

  [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

- Particle-physics experiments can play an important role in constraining these couplings

  [Bauer, MN, Thamm 2017; ...]

Effective Lagrangian for a light ALP

- Assume that the scale of global symmetry breaking $\Lambda = 4\pi f$ is above the weak scale, and that the ALP is the only new particle at scales relevant to experiments

- Consider the most general effective Lagrangian for a pseudoscalar boson a coupled to the SM via classically shift-invariant interactions, broken softly by amass term: [Georgi, Kaplan, Randall 1986]

$$\mathcal{L}_{\text{eff}}^{D\le 5} = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}\,a^2 + \overset{\text{couplings to chiral fermions}}{\frac{\partial^\mu a}{f}\sum_F \bar\psi_F c_F \gamma_\mu \psi_F} + \overset{\text{coupling to Higgs doublet}}{c_\phi\,\frac{\partial^\mu a}{f}\,(\phi^\dagger i \overleftrightarrow{\boldsymbol{D}}_\mu \phi)}$$

$$+ \overset{\text{coupling to gluons}}{c_{GG}\,\frac{\alpha_s}{4\pi}\,\frac{a}{f}\,G_{\mu\nu}^a\,\tilde G^{\mu\nu,a}} + \overset{\text{coupling to SU(2)}_\text{L}\text{ bosons}}{c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W_{\mu\nu}^A\,\tilde W^{\mu\nu,A}} + \overset{\text{coupling to hypercharge boson}}{c_{BB}\,\frac{\alpha_1}{4\pi}\,\frac{a}{f}\,B_{\mu\nu}\,\tilde B^{\mu\nu}}$$

- Importantly, all interactions are suppressed by inverse powers of f, with $f/|2c_{GG}| = f_a$

Effective Lagrangian for a light ALP

- Effective Lagrangian:

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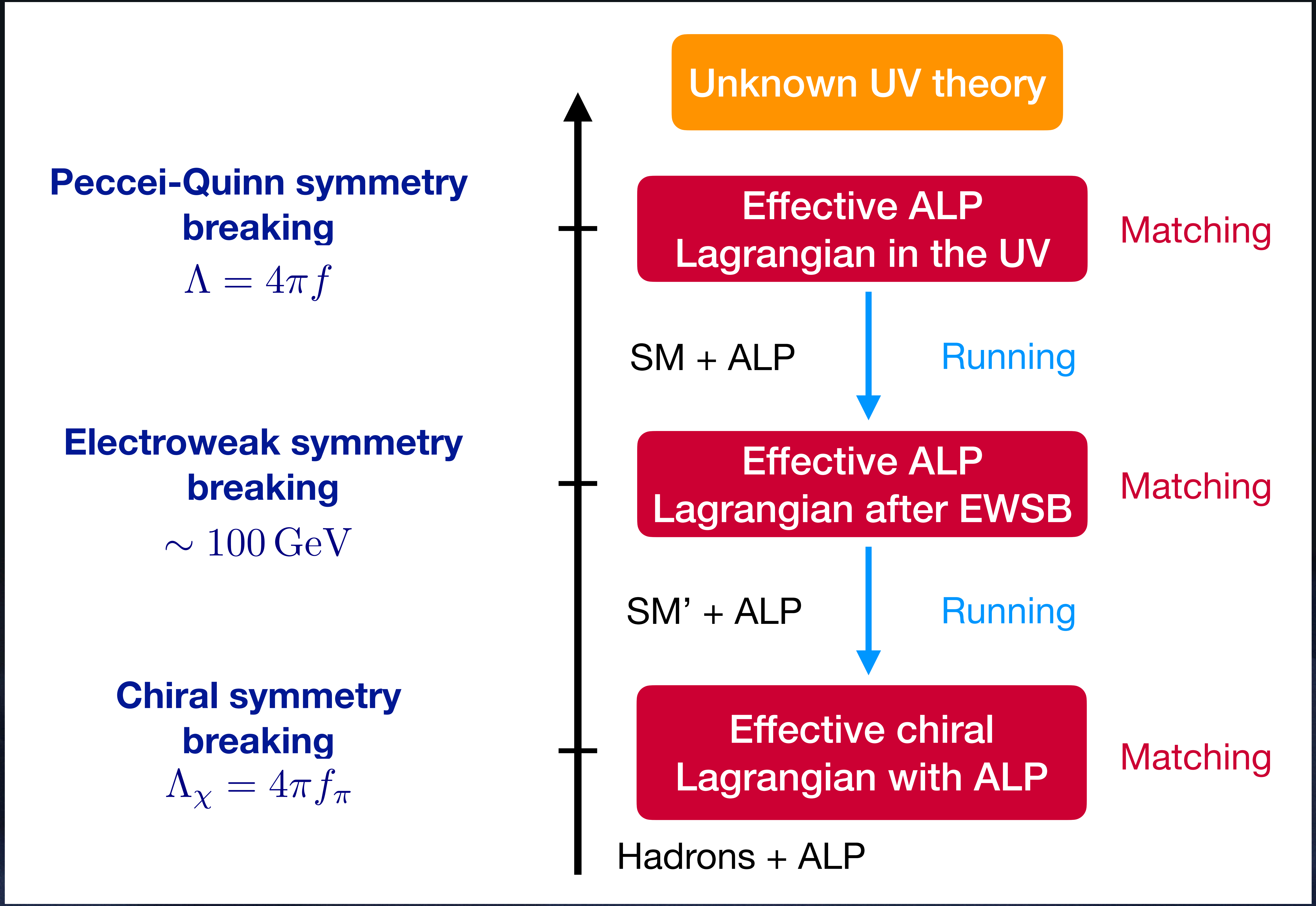
$$+\, c_{GG}\,\frac{\alpha_s}{4\pi}\,\frac{a}{f}\,G_{\mu\nu}^a\,\tilde G^{\mu\nu,a} + c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W_{\mu\nu}^A\,\tilde W^{\mu\nu,A} + c_{BB}\,\frac{\alpha_1}{4\pi}\,\frac{a}{f}\,B_{\mu\nu}\,\tilde B^{\mu\nu}$$

- Using the five global U(1) of the SM Lagrangian (*Y*, *B*, L_i) one can show that 5 out of the 49 real coupling parameters in this Lagrangian are redundant [Georgi, Kaplan, Randall 1986]

- One can use this freedom to eliminate the coupling to the Higgs boson as well as **one** of the two couplings c_{WW} or c_{BB}; however the sum $c_{\gamma\gamma} = c_{WW} + c_{BB}$ is invariant

- We will always work with physical combinations ($\tilde c_i$) 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
$\Lambda_\chi = 4\pi f_\pi$

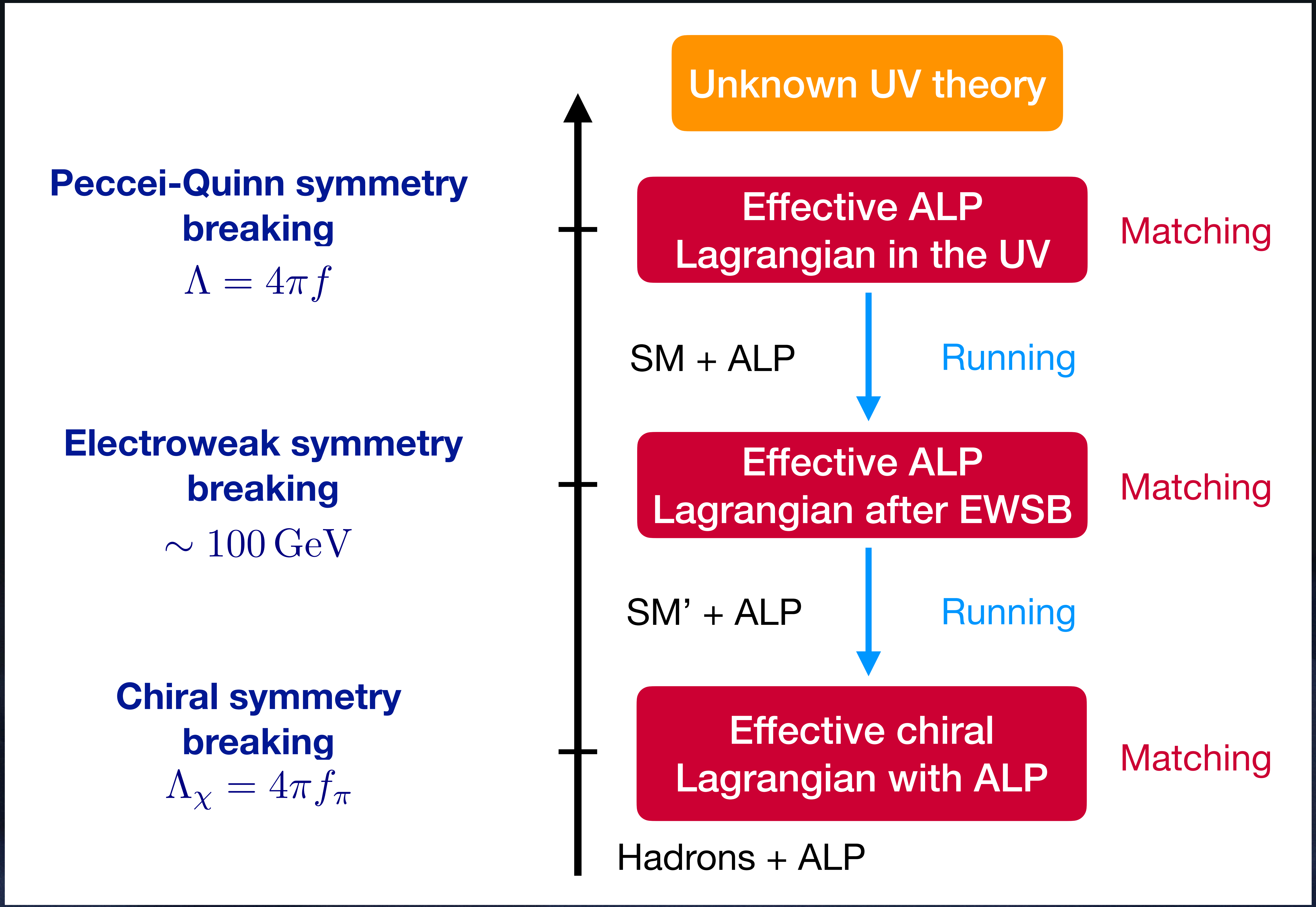
Effective chiral Lagrangian with ALP

Matching

Hadrons + ALP

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

RG evolution from the UV to lower scales



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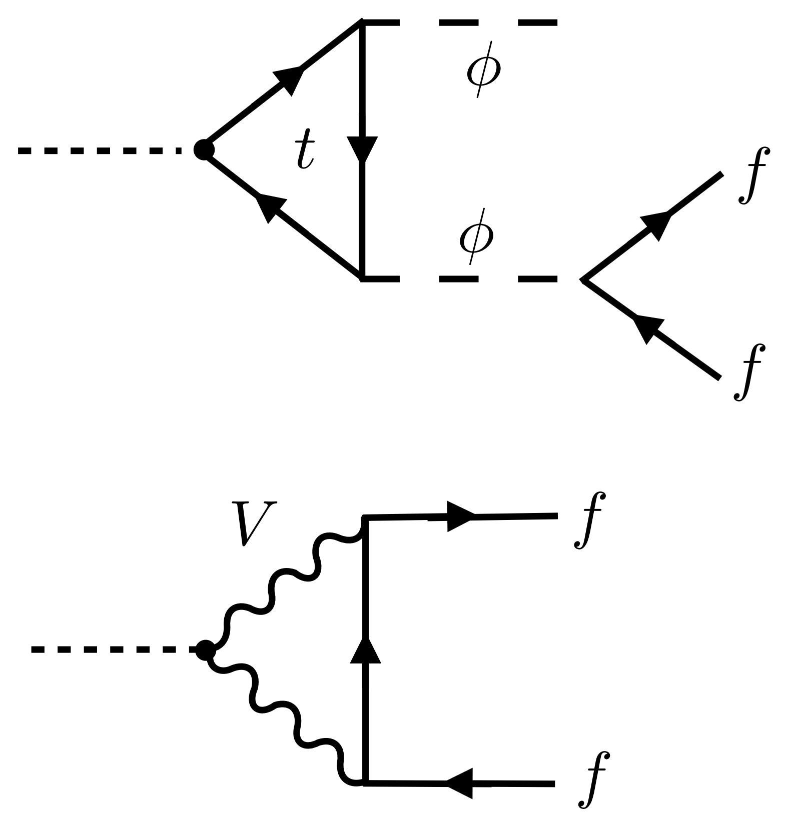


[Bauer, MN, Renner, Schnubel, Thamm 2020; Chala, Guedes, Ramos, Santiago 2020]

RG evolution from the UV to lower scales

ALP-fermion couplings at the weak scale, for $\Lambda = 4\pi f$ and $f = 1$ TeV:

$$c_{uu,cc}(m_t) \simeq c_{uu,cc}(\Lambda) - 0.116\, c_{tt}(\Lambda) - \Big[6.35\, \tilde{c}_{GG}(\Lambda) + 0.19\, \tilde{c}_{WW}(\Lambda) + 0.02\, \tilde{c}_{BB}(\Lambda)\Big] \cdot 10^{-3}$$

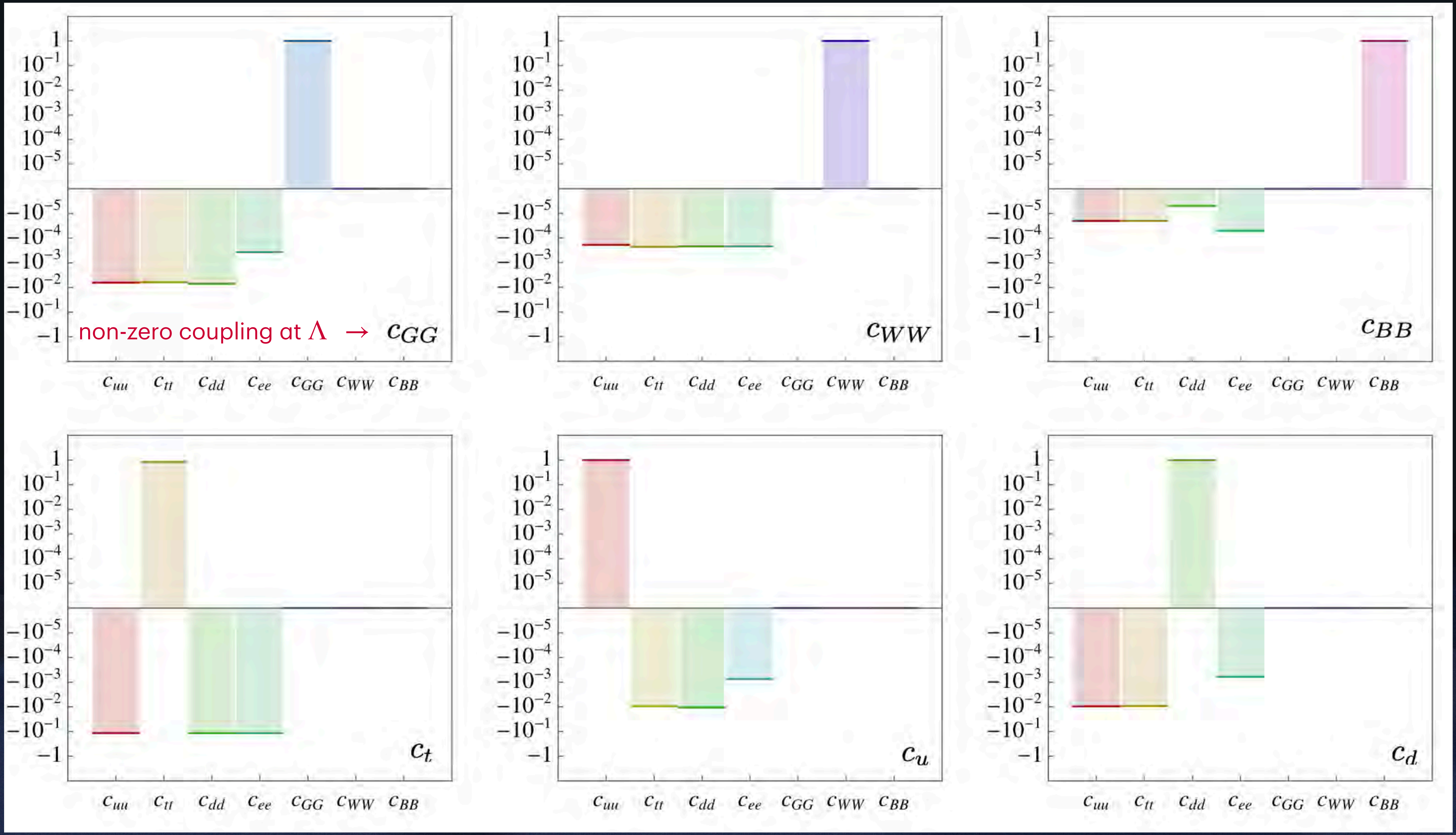
$$c_{dd,ss}(m_t) \simeq c_{dd,ss}(\Lambda) + 0.116\, c_{tt}(\Lambda) - \Big[7.08\, \tilde{c}_{GG}(\Lambda) + 0.22\, \tilde{c}_{WW}(\Lambda) + 0.005\, \tilde{c}_{BB}(\Lambda)\Big] \cdot 10^{-3}$$

$$c_{bb}(m_t) \simeq c_{bb}(\Lambda) + 0.097\, c_{tt}(\Lambda) - \Big[7.02\, \tilde{c}_{GG}(\Lambda) + 0.19\, \tilde{c}_{WW}(\Lambda) + 0.005\, \tilde{c}_{BB}(\Lambda)\Big] \cdot 10^{-3}$$

$$c_{e_ie_i}(m_t) \simeq c_{e_ie_i}(\Lambda) + 0.116\, c_{tt}(\Lambda) - \Big[0.37\, \tilde{c}_{GG}(\Lambda) + 0.22\, \tilde{c}_{WW}(\Lambda) + 0.05\, \tilde{c}_{BB}(\Lambda)\Big] \cdot 10^{-3}$$

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

RG evolution from the UV to lower scales

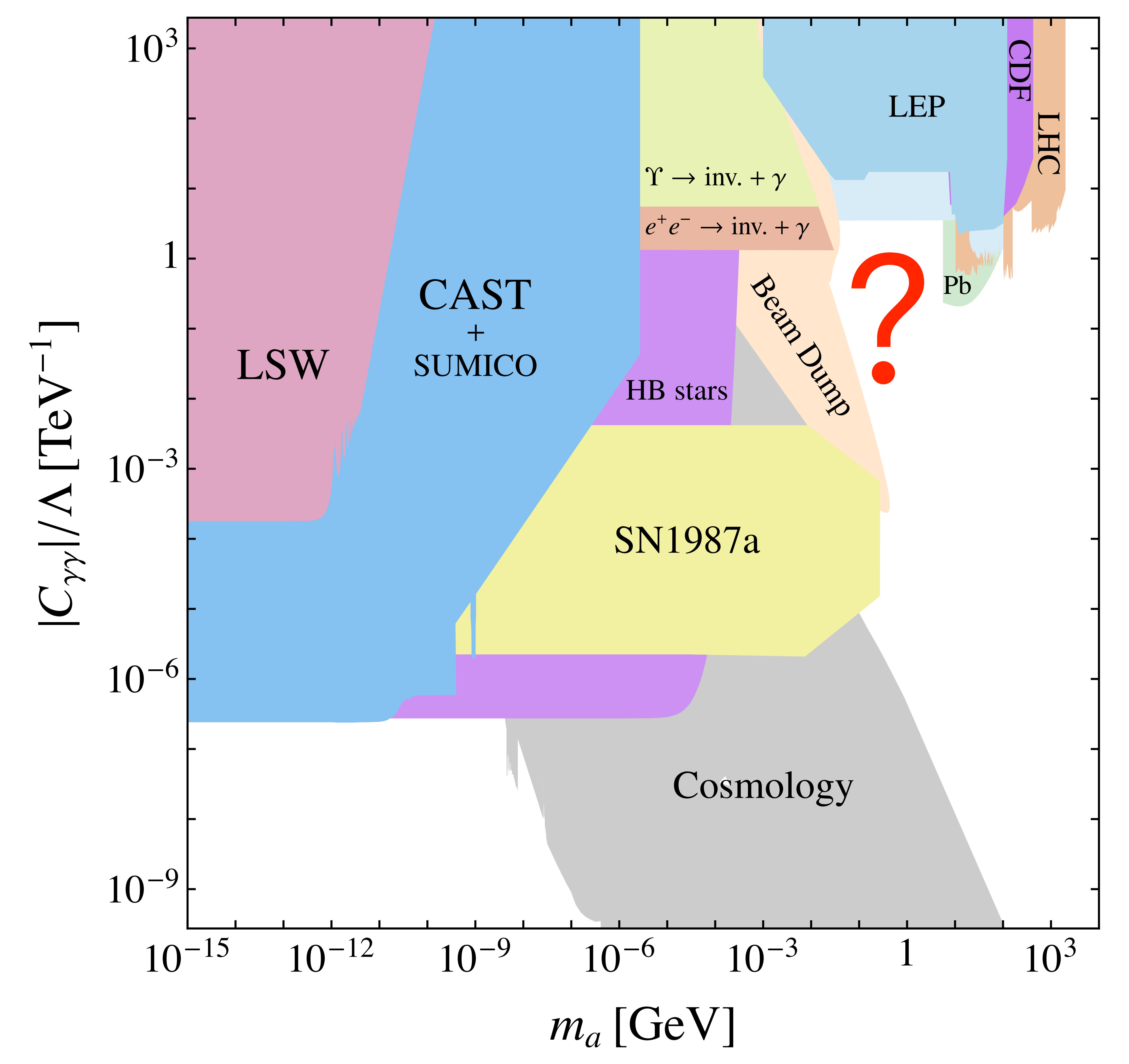


non-zero coupling at Λ → c_{GG}

ALP production in Higgs-boson decays

An interesting search channel is $h \to aa \to 4\gamma$

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



[Bauer, MN, Thamm 2017]

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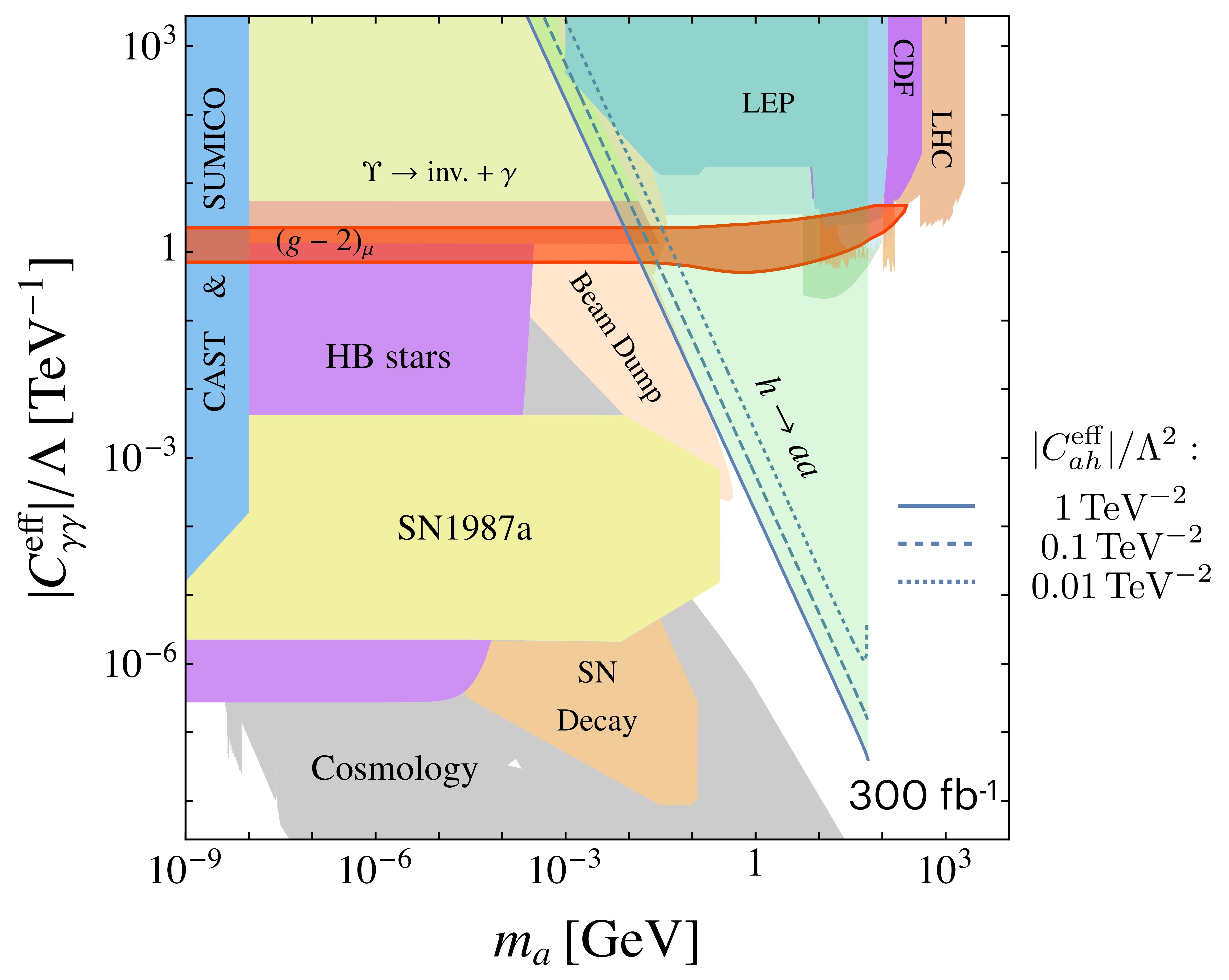

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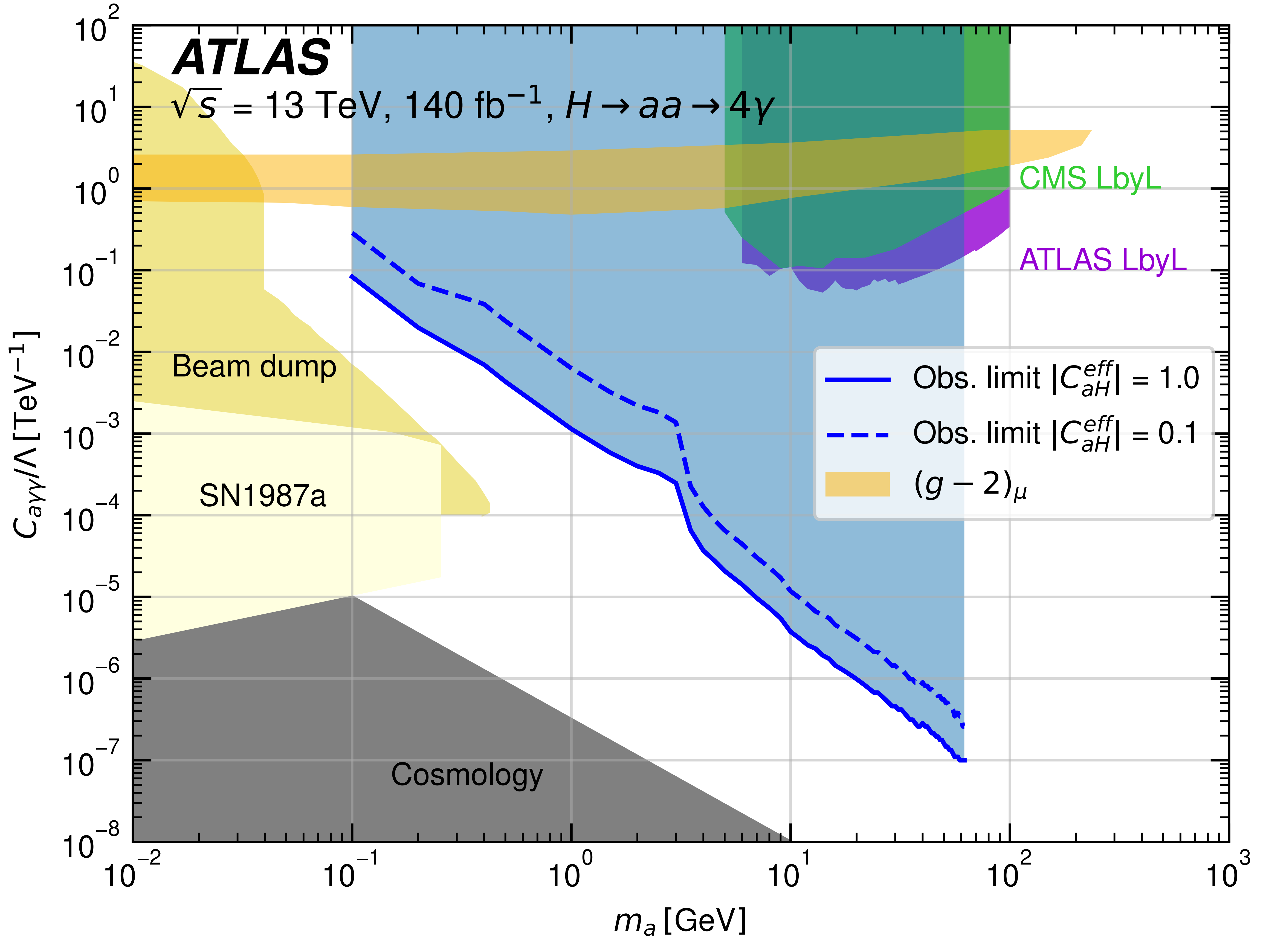
- Bounds are independent of the $h \to \gamma\gamma$ branching ratio as long as this is larger than 0.006, 0.049, and 0.49 for a Higgs coupling of 1, 0.1, and 0.01 TeV^{-2}
- Analysis by ATLAS confirms our estimates

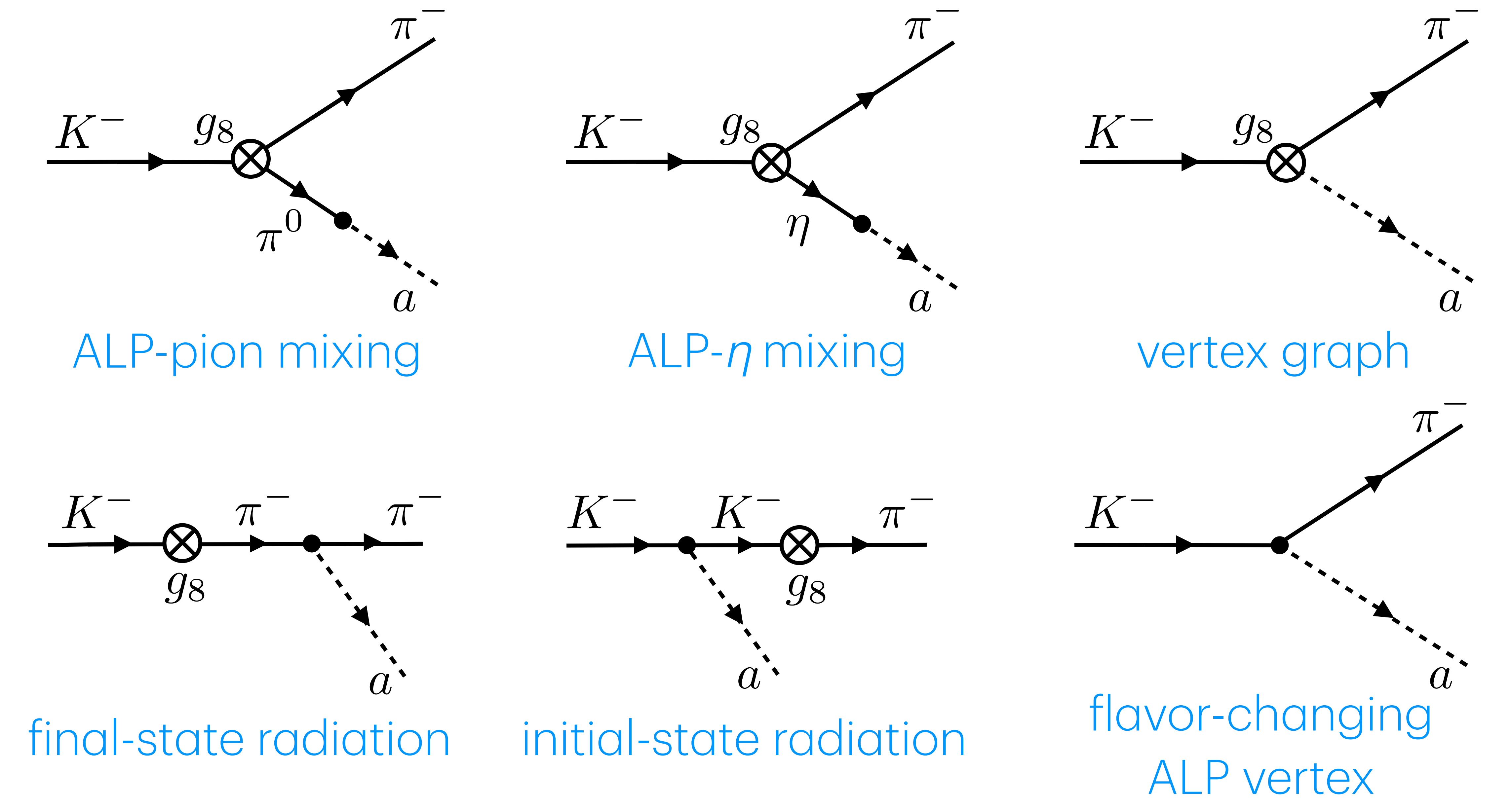


[ATLAS collaboration, arXiv:2312.03306]

ALP production in rare kaon decays

Most interesting search channel is $K^- \to \pi^- a$

- Model-independent analysis using chiral perturbation theory
- Find that previous calculations used an incorrect implementation of chiral currents
- Branching ratio gets enhanced by factor 37 when the correct implementation is used
- Obtain strong constraints on flavor-violating and flavor-conserving ALP couplings



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

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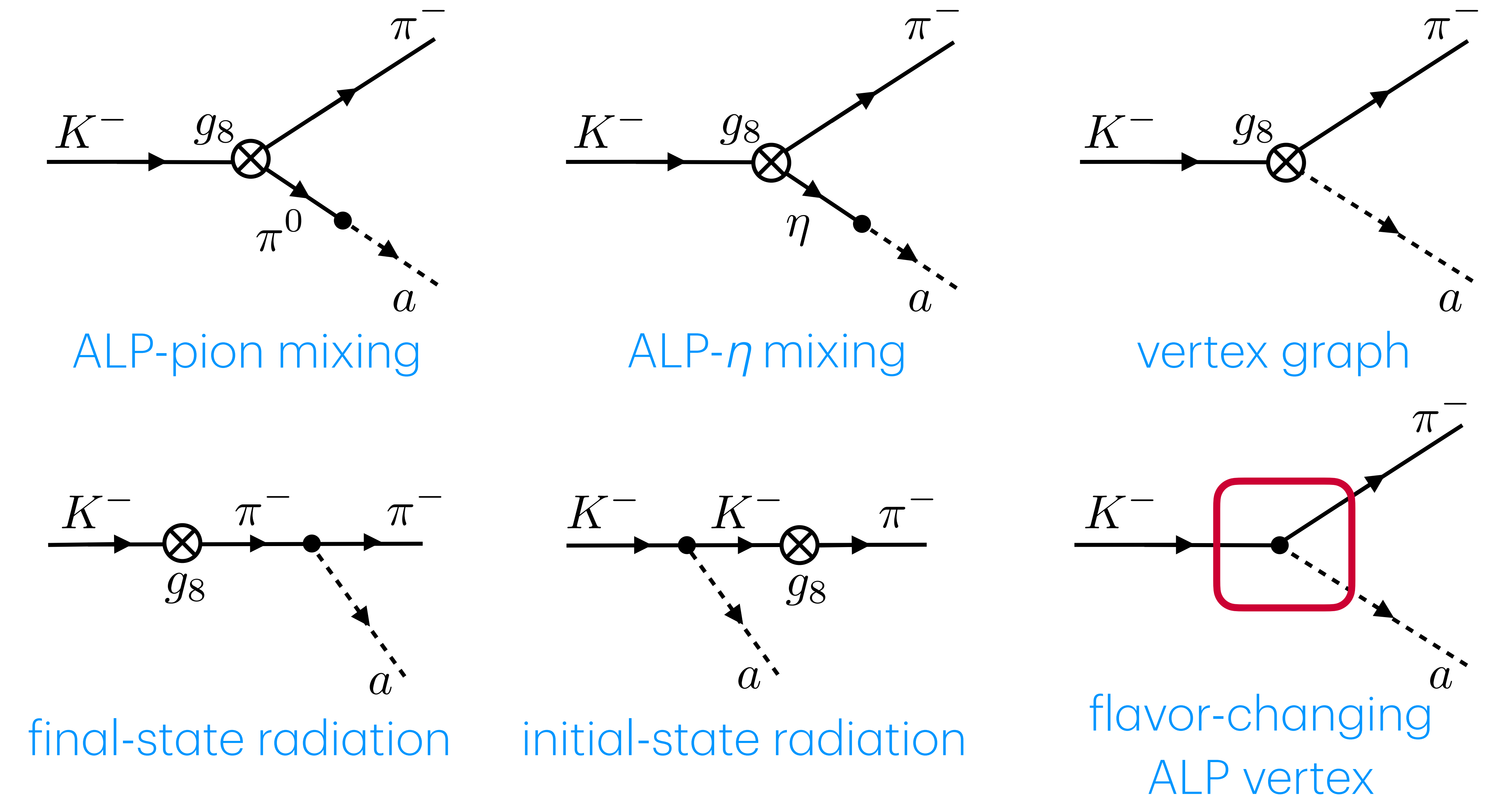

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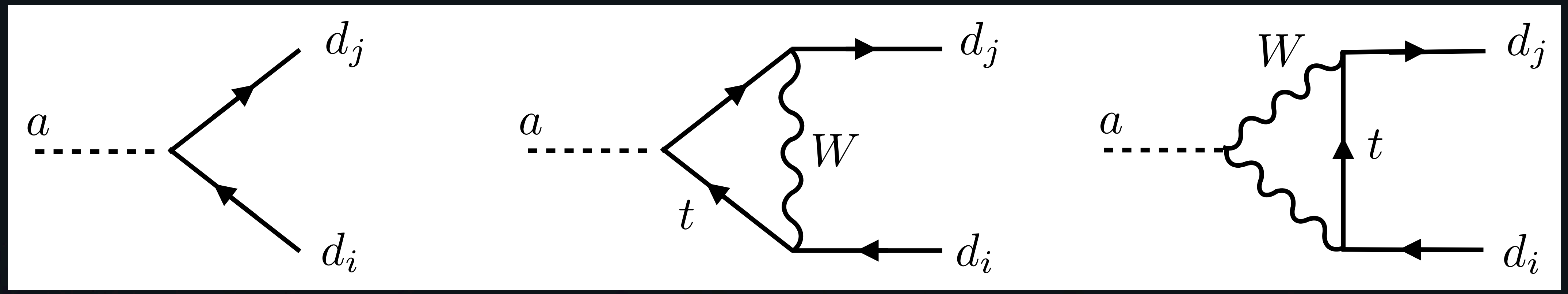


[Bauer, MN, Renner, Schnubel, Thamm 2021]

- ALP flavor violation can arise from the UV theory or from the SM
- Assuming MFV and $f = 1$ TeV yields for the ALP—fermion couplings in the mass basis:

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

$$[k_D(m_t)]_{ij} \simeq \overset{\text{possible UV flavor change}}{[k_D(\Lambda)]_{ij}} + 0.019\, V_{ti}^* V_{tj} \overset{\text{flavor change through SM loops containing } W\text{-bosons}}{\left[c_{tt}(\Lambda) - 0.0032\, \tilde{c}_{GG}(\Lambda) - 0.0057\, \tilde{c}_{WW}(\Lambda) \right]}$$

vanishes for a flavor-universal ALP

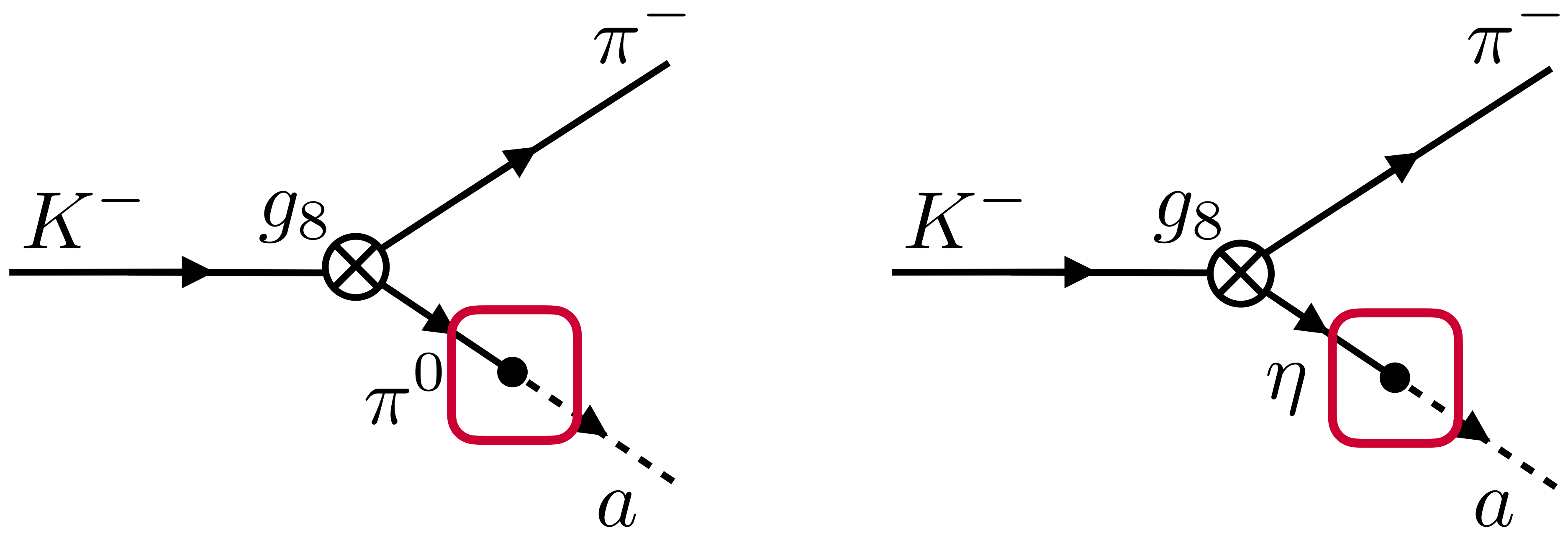
ALP production in rare kaon decays

Most interesting search channel is $K^- \to \pi^- a$

- Importantly, one should not estimate the amplitude based on $K^- \to \pi^- \pi^0$ and the ALP—pion mixing angle:

$$\underset{\substack{\uparrow \\ \Delta\text{I=1/2 transition}}}{\mathcal{A}_{K^-\to\pi^- a}} \neq \theta_{\pi a}\, \underset{\substack{\uparrow \\ \Delta\text{I=3/2 transition}}}{\mathcal{A}_{K^-\to\pi^-\pi^0}}$$

- Such mixing angles are unphysical, and other diagrams must also be included!



ALP-pion mixing

ALP-η mixing

$$\pi^0 = \pi^0_{\text{phys}} + \theta_{\pi a}\, a_{\text{phys}}$$

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

ALP production in rare kaon decays

Important subtlety: two new SU(3) octet operators arise in the LO (p^2) weak chiral Lagrangian, in addition to $g_8 \langle \lambda_6 (D_\mu \Sigma)(D^\mu \Sigma^\dagger) \rangle$, namely: [Cornella, Galda, MN 2023]

- operator $g_8^\theta (D_\mu \theta) \langle \lambda_6 i \Sigma (D^\mu \Sigma^\dagger) \rangle$ involving the covariant derivative $D_\mu \theta = -2\tilde{c}_{GG} (\partial_\mu a)/f$, where $2\tilde{c}_{GG} \equiv 2c_{GG} + c_{uu}^a + c_{dd}^a + c_{ss}^a$
- "weak mass term" $g_8' \langle \lambda_6 (\chi \Sigma^\dagger + \Sigma \chi^\dagger) \rangle$, which is unobservable without the ALP

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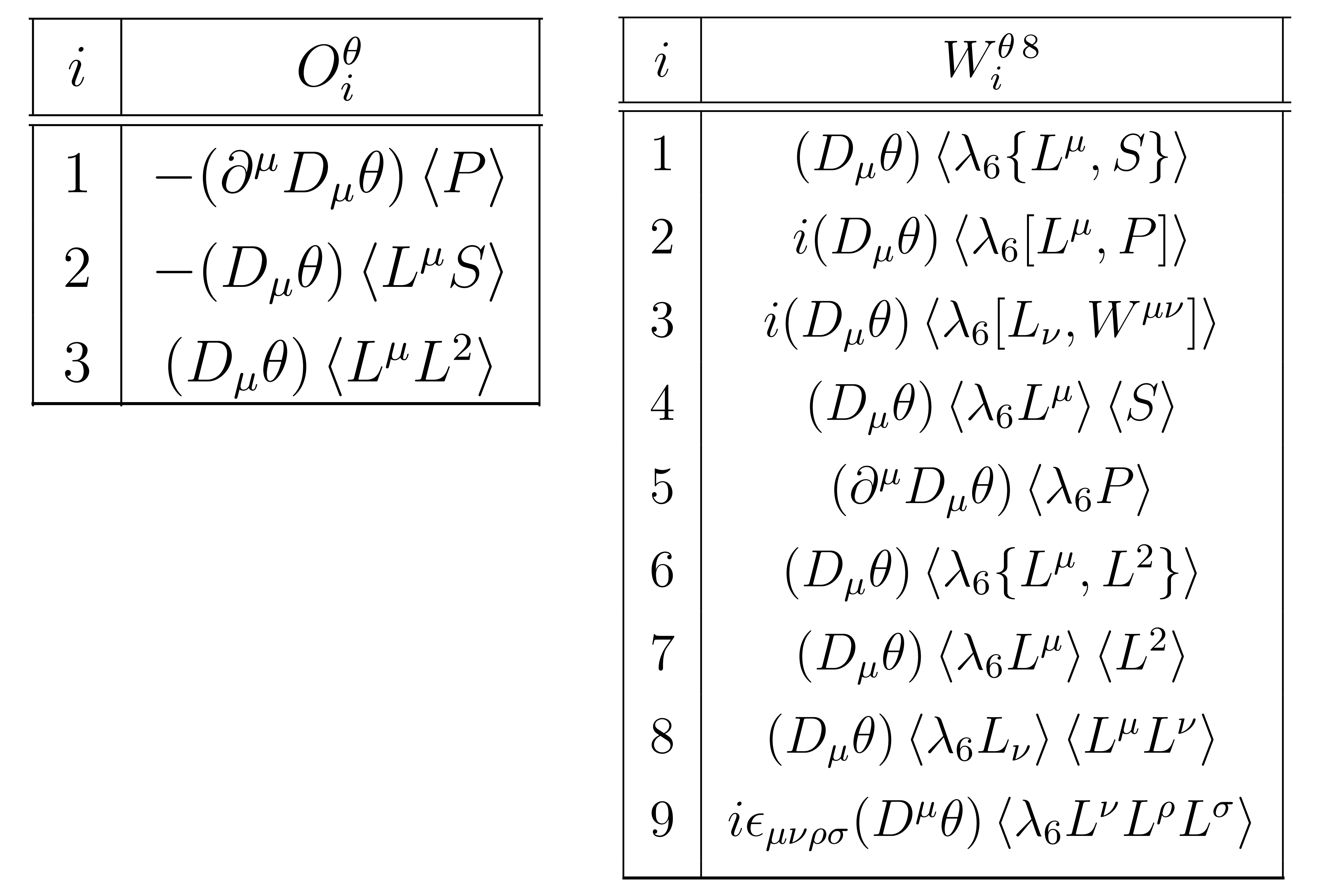
Whereas $g_8 = 3.61 \pm 0.28$ is known from $K \to \pi\pi$ decay, the couplings g_8^θ and g_8' are at present completely unknown

- however, contributions promotional to g_8' vanish for the case of MFV (or flavor universality) in the UV, which we assume from now on

ALP production in rare kaon decays

Most interesting search channel is $K^- \to \pi^- a$

- At NLO in chiral perturbation theory the calculation is far more involved
- NLO (p^4) QCD and weak chiral Lagrangians need to be supplemented by 3 resp. 9 operators involving $D_\mu \theta$
- Sensitivity to several unknown (or poorly known) low-energy constants



i	O_i^θ
1	$-(\partial^\mu D_\mu\theta)\,\langle P\rangle$
2	$-(D_\mu\theta)\,\langle L^\mu S\rangle$
3	$(D_\mu\theta)\,\langle L^\mu L^2\rangle$

i	$W_i^{\theta\,8}$
1	$(D_\mu\theta)\,\langle\lambda_6\{L^\mu, S\}\rangle$
2	$i(D_\mu\theta)\,\langle\lambda_6[L^\mu, P]\rangle$
3	$i(D_\mu\theta)\,\langle\lambda_6[L_\nu, W^{\mu\nu}]\rangle$
4	$(D_\mu\theta)\,\langle\lambda_6 L^\mu\rangle\,\langle S\rangle$
5	$(\partial^\mu D_\mu\theta)\,\langle\lambda_6 P\rangle$
6	$(D_\mu\theta)\,\langle\lambda_6\{L^\mu, L^2\}\rangle$
7	$(D_\mu\theta)\,\langle\lambda_6 L^\mu\rangle\,\langle L^2\rangle$
8	$(D_\mu\theta)\,\langle\lambda_6 L_\nu\rangle\,\langle L^\mu L^\nu\rangle$
9	$i\epsilon_{\mu\nu\rho\sigma}(D^\mu\theta)\,\langle\lambda_6 L^\nu L^\rho L^\sigma\rangle$

[Cornella, Galda, MN 2023]

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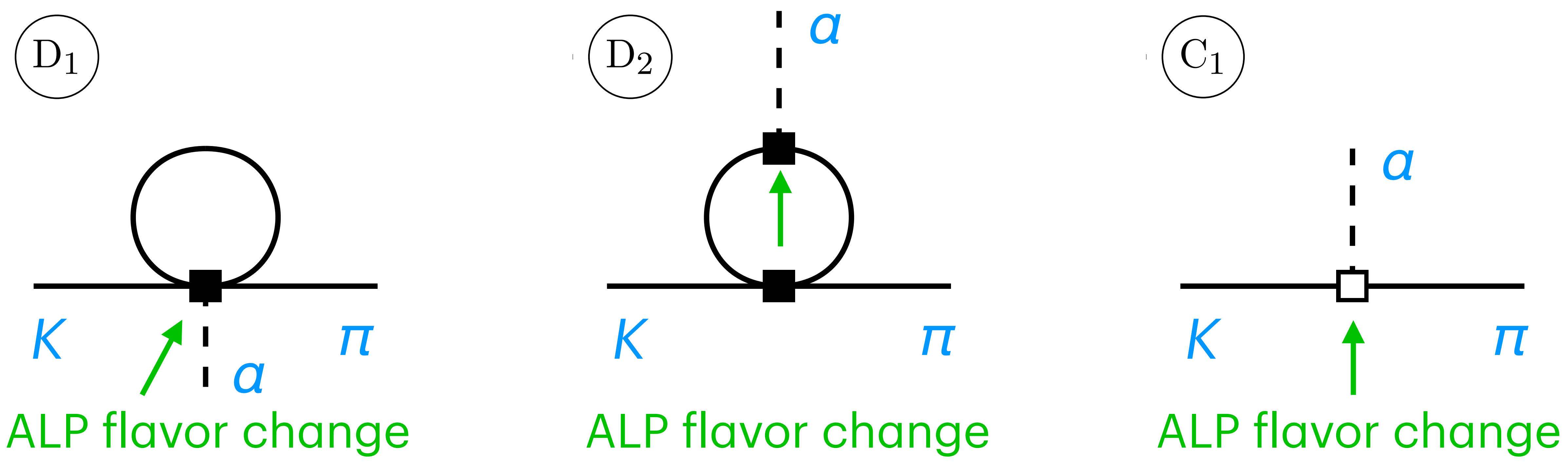
Diagrams involving flavor-changing ALP couplings:



■ QCD chiral Lagrangian (LO)

□ QCD chiral Lagrangian (NLO)

[Cornella, Galda, MN 2023]

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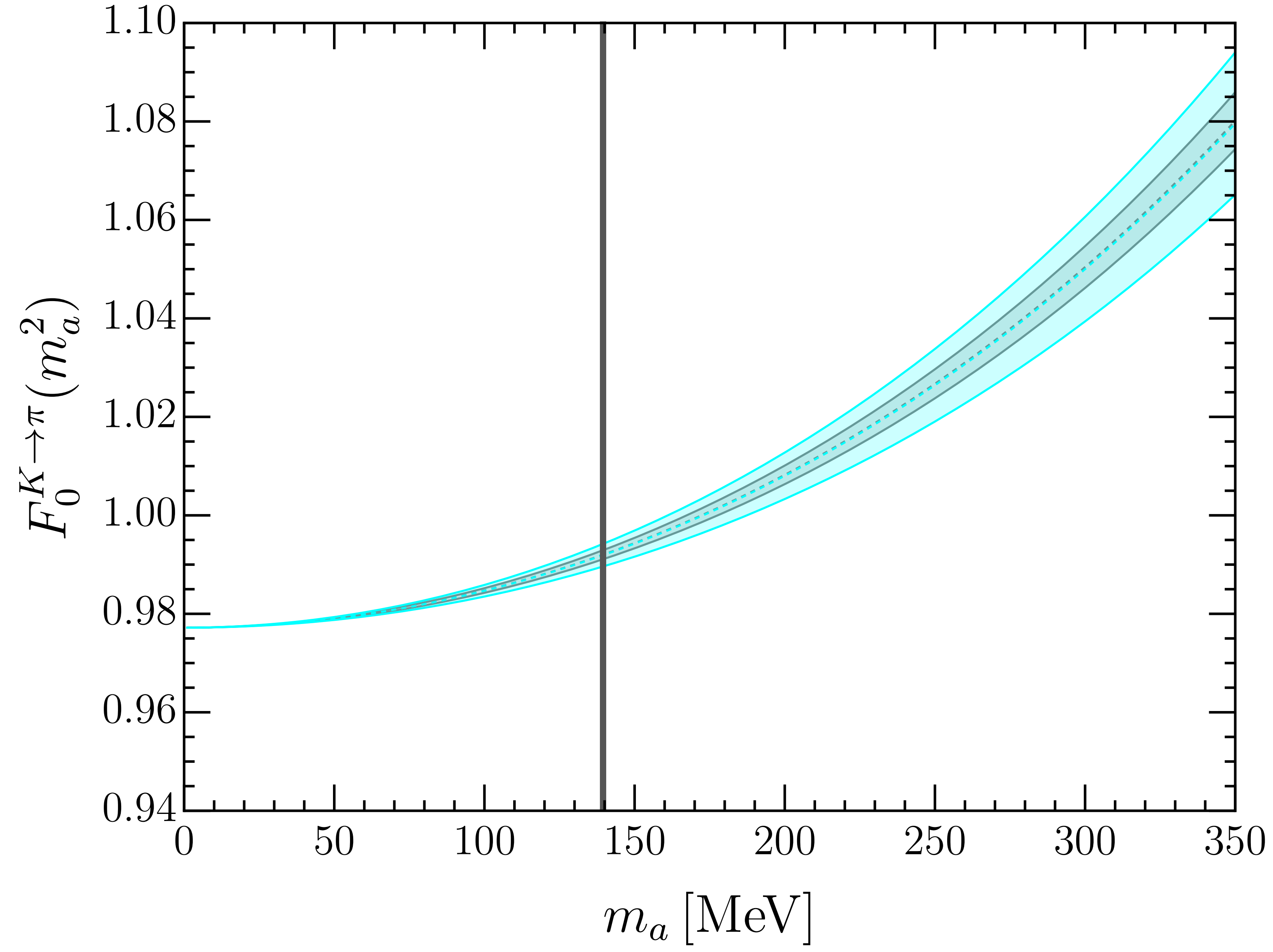
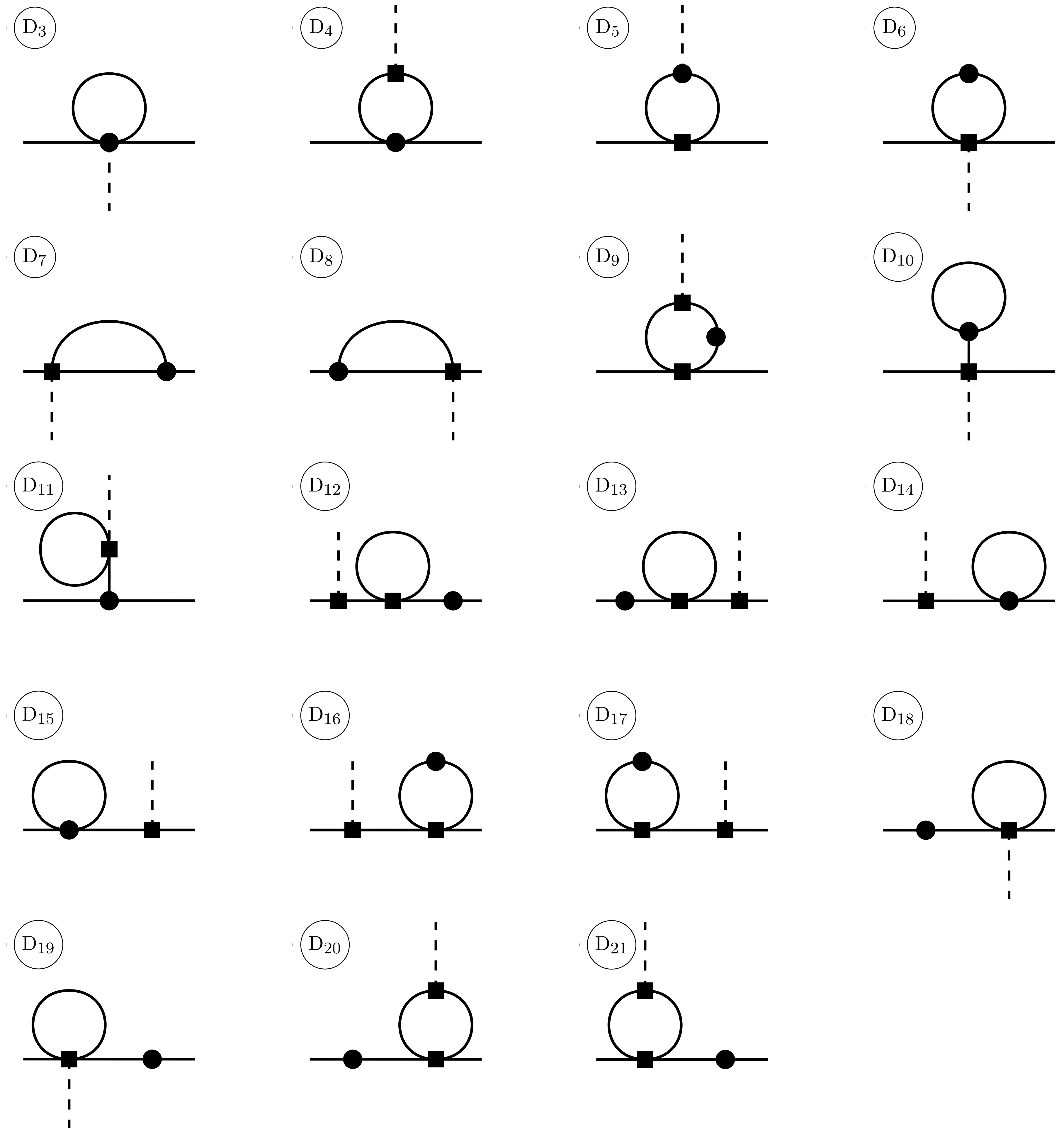


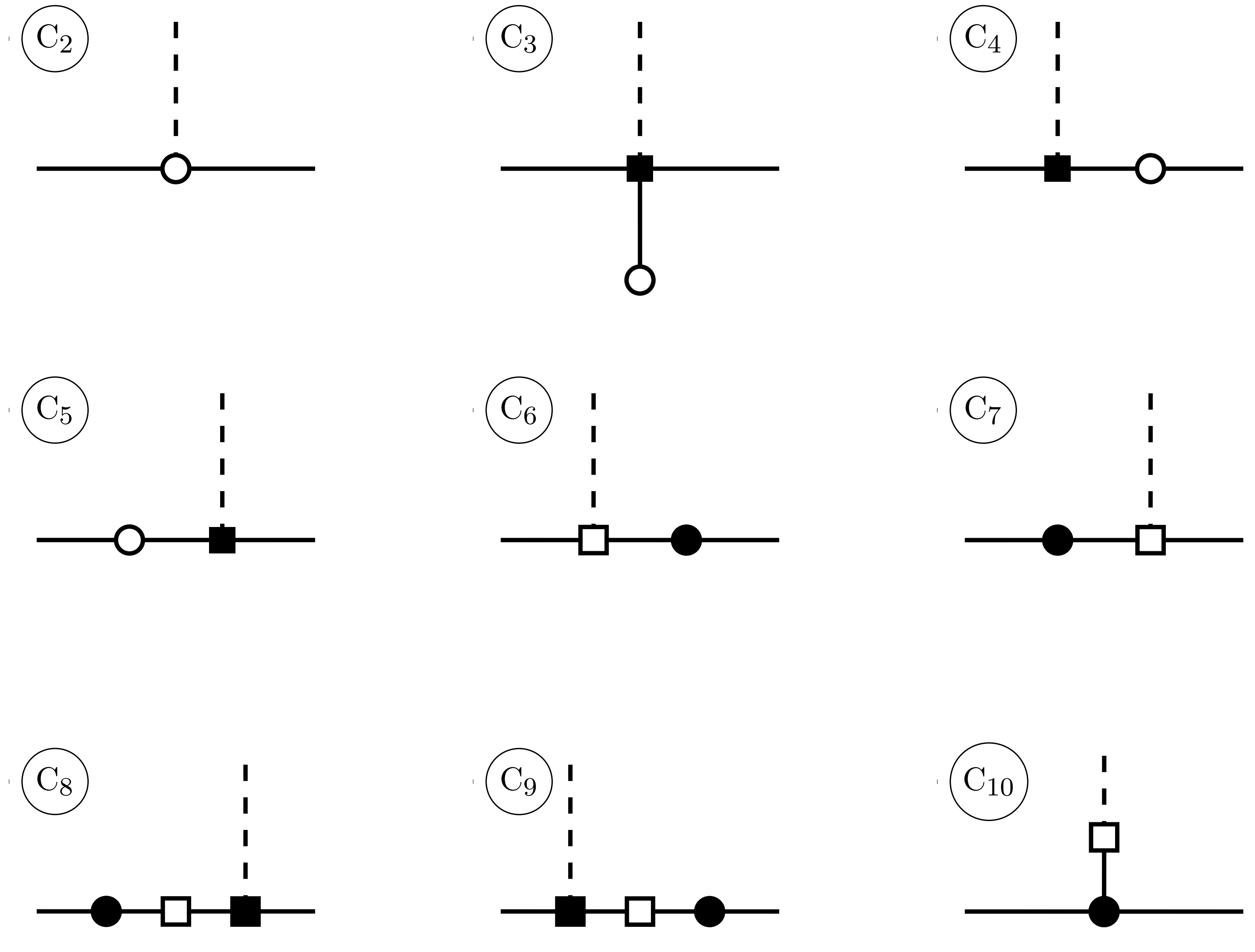
[Cornella, Galda, MN 2023]

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

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

$$G_i = -\frac{G_F}{\sqrt{2}}\, V_{ud}^* V_{us} \left(\boxed{g_i} - \underbrace{\frac{V_{td}^* V_{ts}}{V_{ud}^* V_{us}}}_{\sim 10^{-3}} g_i^t \right)$$

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

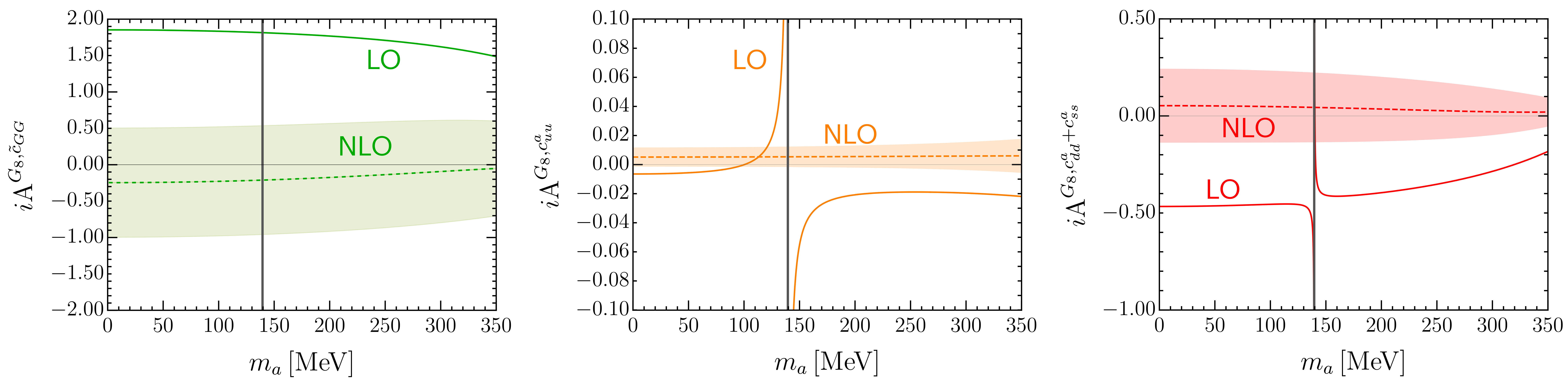
$$i\mathcal{A}_{\rm LO}^{G_8} = \frac{G_8 F_\pi^2\, m_K^2}{2f} \Big[1.88\, \tilde{c}_{GG} - 0.02\, c_{uu}^a - 0.48\, (c_{dd}^a + c_{ss}^a) + 0.54\, (\cancel{c_{dd}^v - c_{ss}^v}) \Big]$$

$$\begin{aligned} i\mathcal{A}_{\rm NLO}^{G_8} = \frac{G_8 F_\pi^2\, m_K^2}{2f} \Big[& (-0.25 \pm 0.43 \pm 0.61)\, \tilde{c}_{GG} + (5.21 \pm 1.03 \pm 6.52) \cdot 10^{-3}\, c_{uu}^a \\ & + (0.06 \pm 0.11 \pm 0.16)\, (c_{dd}^a + c_{ss}^a) - (0.27 \pm 0.10 \pm 0)\, (\cancel{c_{dd}^a - c_{ss}^a}) \\ & + (0.24 \pm 0.23 \pm 0.18)\, (\cancel{c_{dd}^v - c_{ss}^v}) \Big] \end{aligned}$$

- Modest NLO corrections with sizable uncertainties
- Crossed-out terms vanish for the case of MFV or a flavor-universal ALP in the UV

ALP production in rare kaon decays

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



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

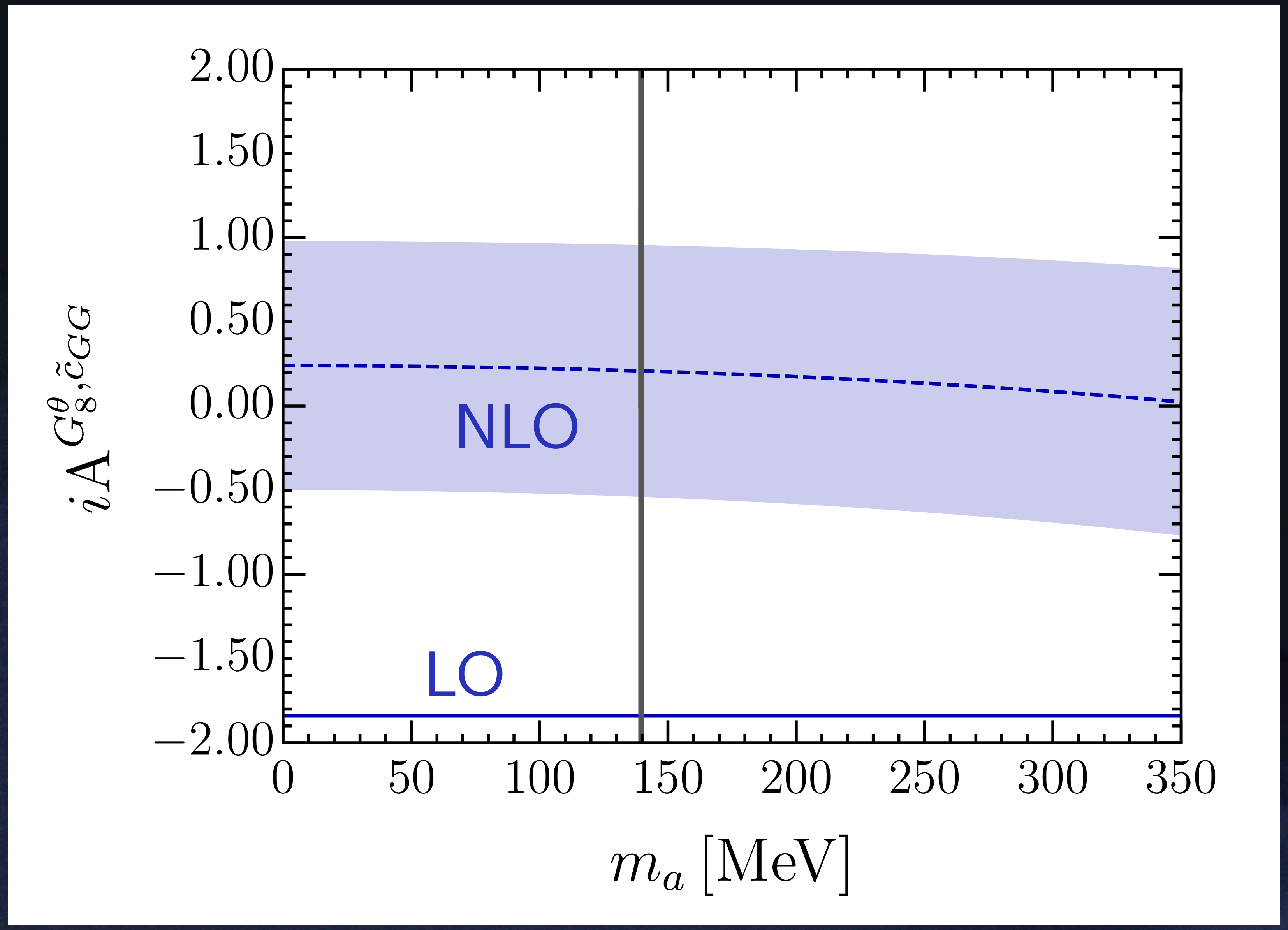
ALP production in rare kaon decays

$$G_i = -\frac{G_F}{\sqrt{2}} V_{ud}^* V_{us} \left(\boxed{g_i} - \underbrace{\frac{V_{td}^* V_{ts}}{V_{ud}^* V_{us}}}_{\sim 10^{-3}} g_i^t \right)$$

Contribution proportional to G_8^θ (for $m_a = 0$):

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

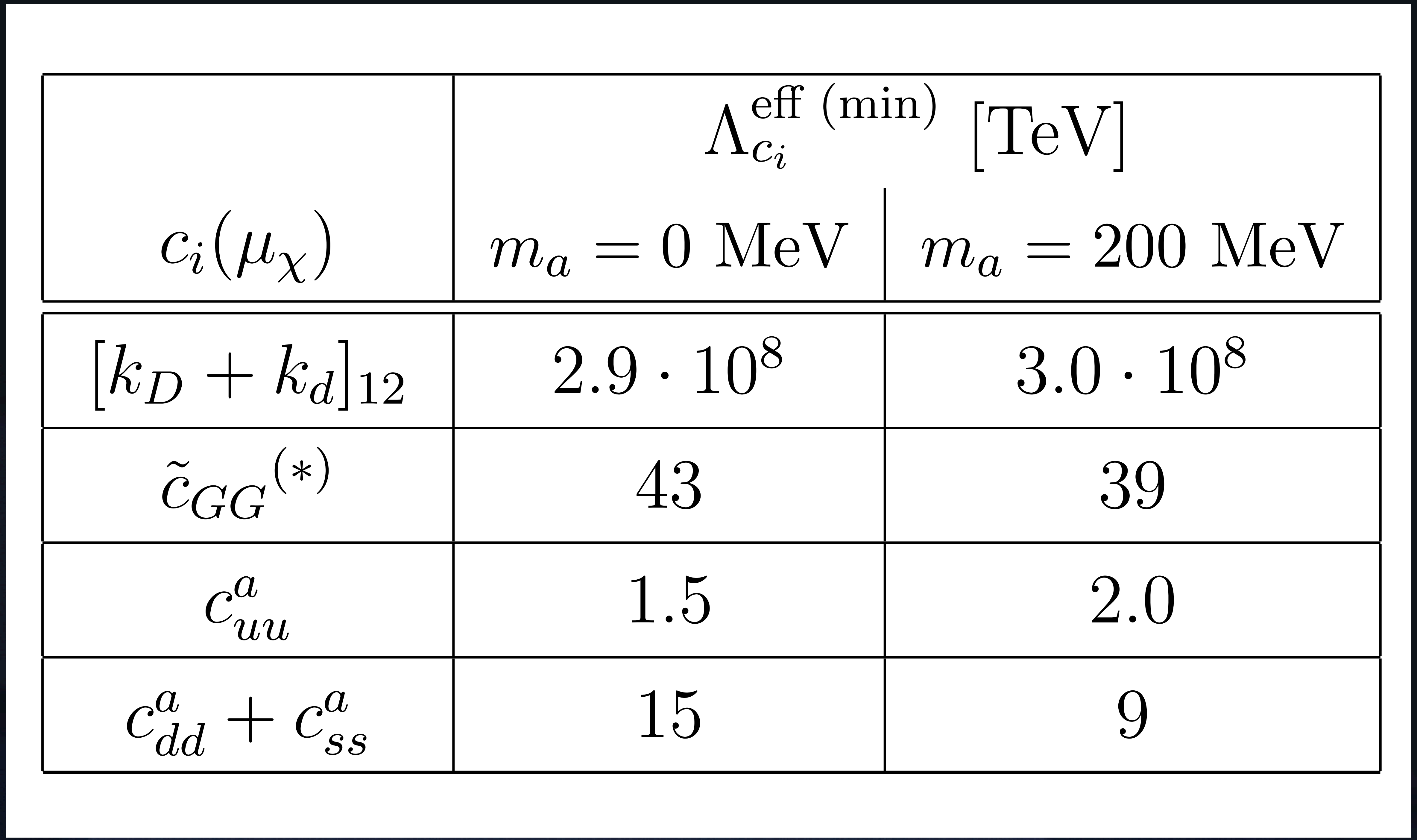
- Only a single physical ALP coupling enters, but the low-energy coupling g_8^θ is unknown
- Modest NLO corrections with sizable uncertainties



Bounds on ALP couplings

Most interesting search channel is $K^- \to \pi^- a$

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



	$\Lambda_{c_i}^{\text{eff (min)}}$ [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_{uu}^a	1.5	2.0
$c_{dd}^a + c_{ss}^a$	15	9

[Cornella, Galda, MN 2023]

(*) assuming $g_8^\theta = 0$

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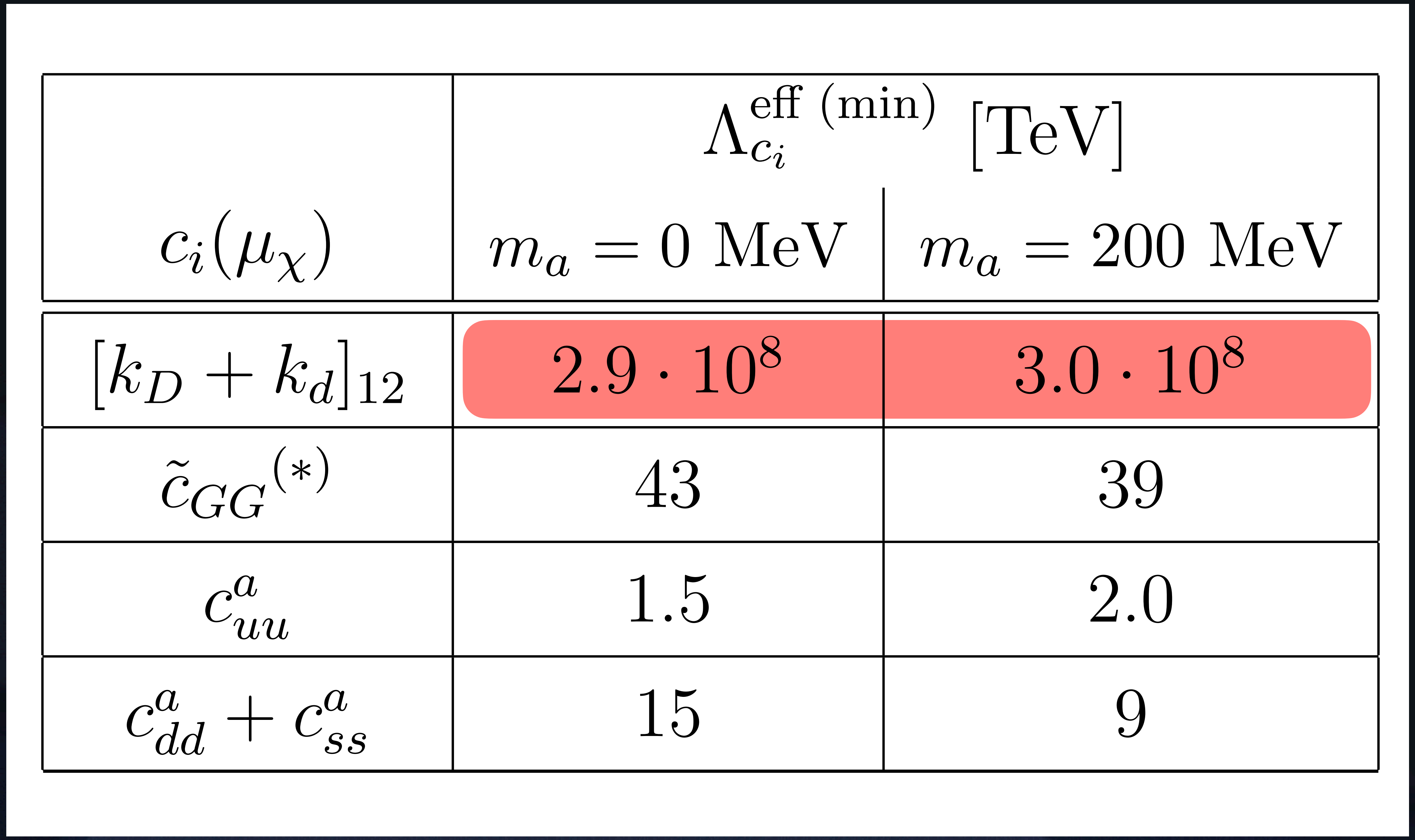
- New-physics scales probed range from few to tens of TeV
- Very strong bounds on flavor-changing ALP couplings call for a flavor symmetry!



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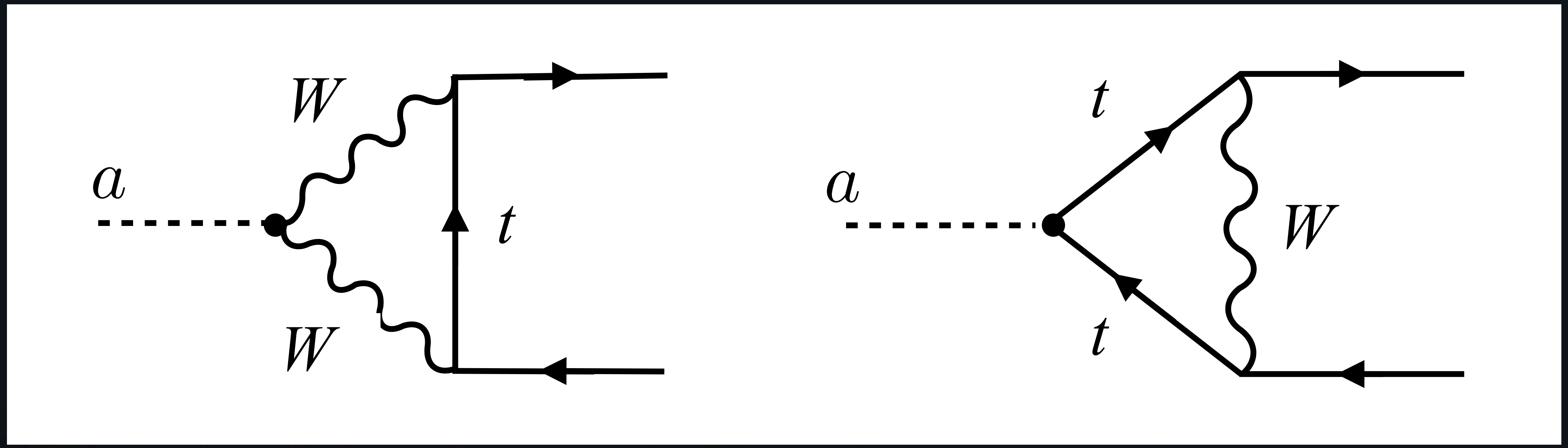
[Cornella, Galda, MN 2023]

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



[Cornella, Galda, MN 2023]

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

$$[c_{uu}^a(\mu_\chi)]^{\text{univ}} \simeq 0.90\, \tilde{c}_u(\Lambda) + 0.008\, \tilde{c}_d(\Lambda) - 0.042\, \tilde{c}_{GG}(\Lambda) - 10^{-4}\left[2.1\, \tilde{c}_{WW}(\Lambda) + 0.34\, \tilde{c}_{BB}(\Lambda)\right]$$

$$[c_{dd,ss}^a(\mu_\chi)]^{\text{univ}} \simeq 0.13\, \tilde{c}_u(\Lambda) + 1.00\, \tilde{c}_d(\Lambda) - 0.042\, \tilde{c}_{GG}(\Lambda) - 10^{-4}\left[2.3\, \tilde{c}_{WW}(\Lambda) + 0.10\, \tilde{c}_{BB}(\Lambda)\right]$$

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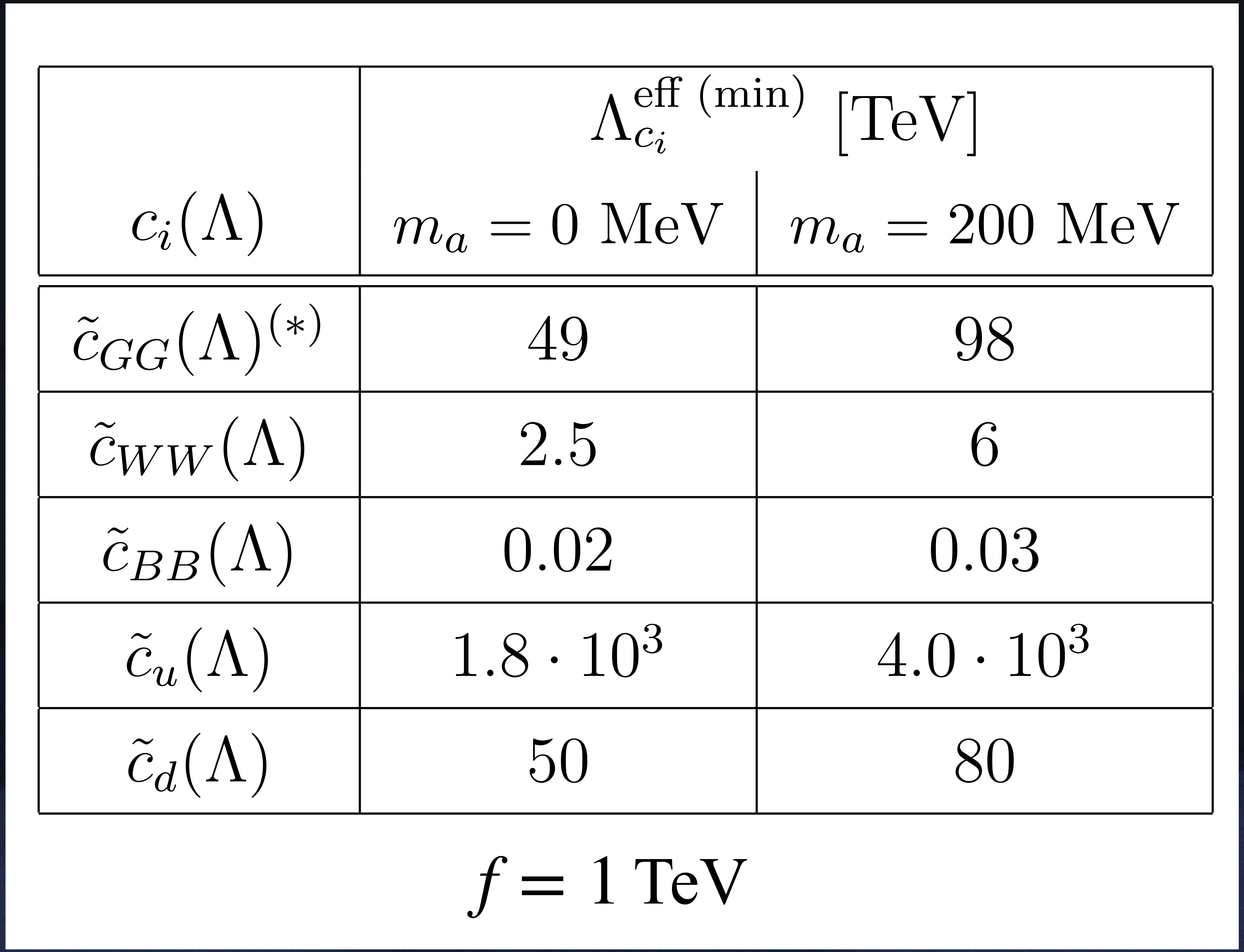
(*) assuming $g_8^\theta = 0$



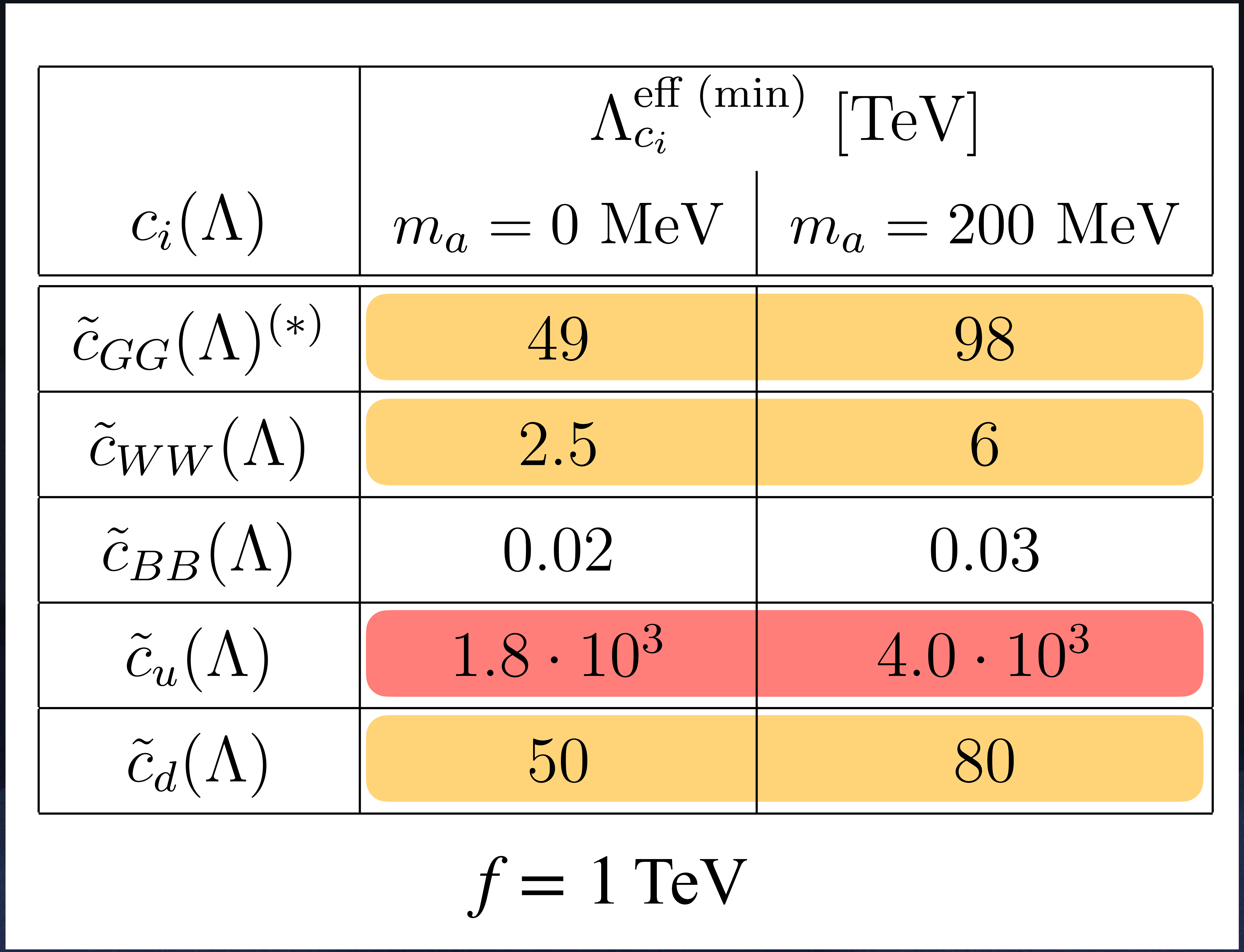
$c_i(\Lambda)$	$\Lambda_{c_i}^{\text{eff (min)}}$ [TeV]	
	$m_a = 0$ MeV	$m_a = 200$ MeV
$\tilde{c}_{GG}(\Lambda)^{(*)}$	49	98
$\tilde{c}_{WW}(\Lambda)$	2.5	6
$\tilde{c}_{BB}(\Lambda)$	0.02	0.03
$\tilde{c}_u(\Lambda)$	$1.8 \cdot 10^3$	$4.0 \cdot 10^3$
$\tilde{c}_d(\Lambda)$	50	80

$f = 1$ 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
- One obtains very strong bounds on the ALP couplings to gluons, *W*-bosons and quarks, which are the best particle-physics bounds on these couplings in the mass range below 340 MeV



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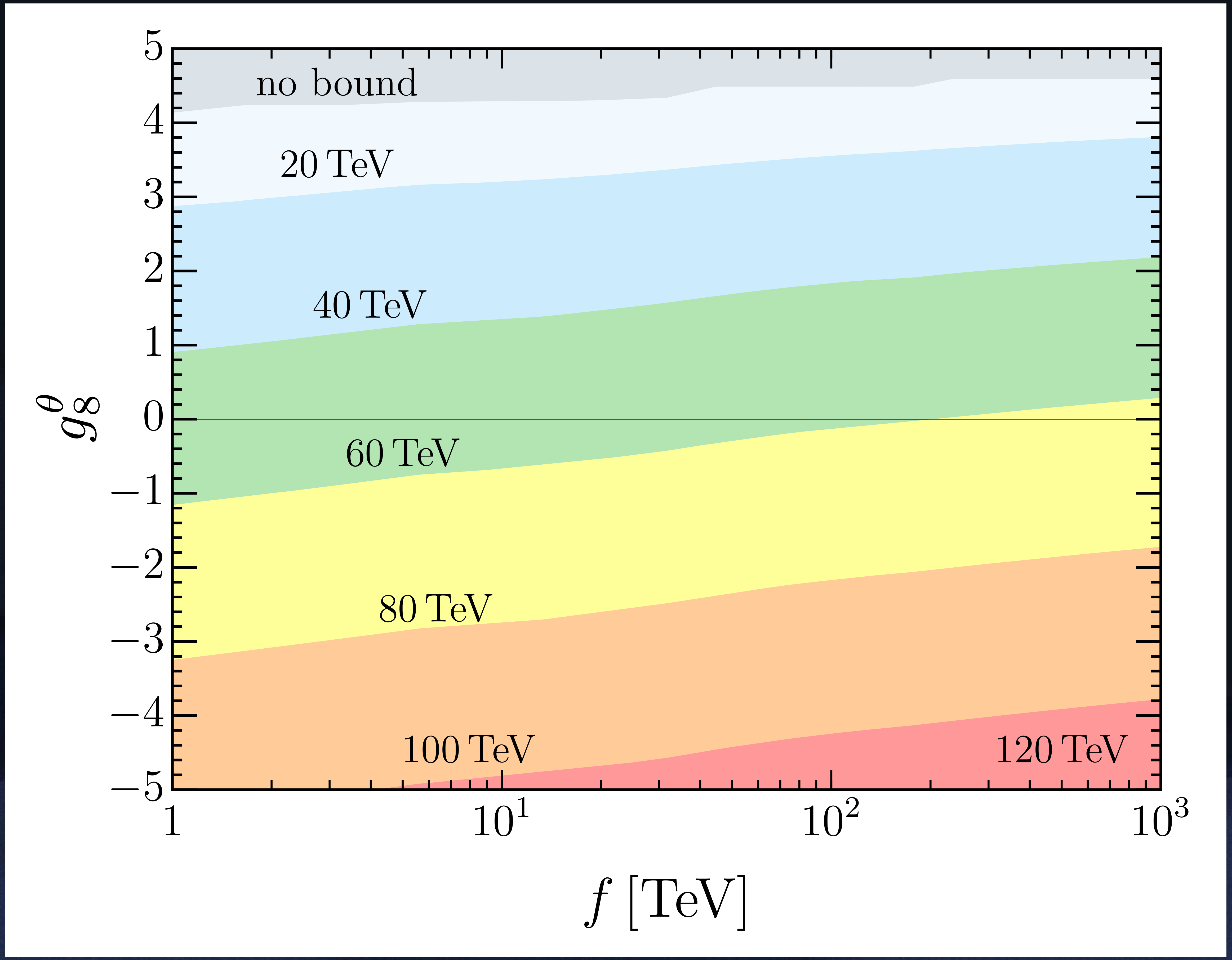
[Cornella, Galda, MN 2023]

Bounds on ALP couplings

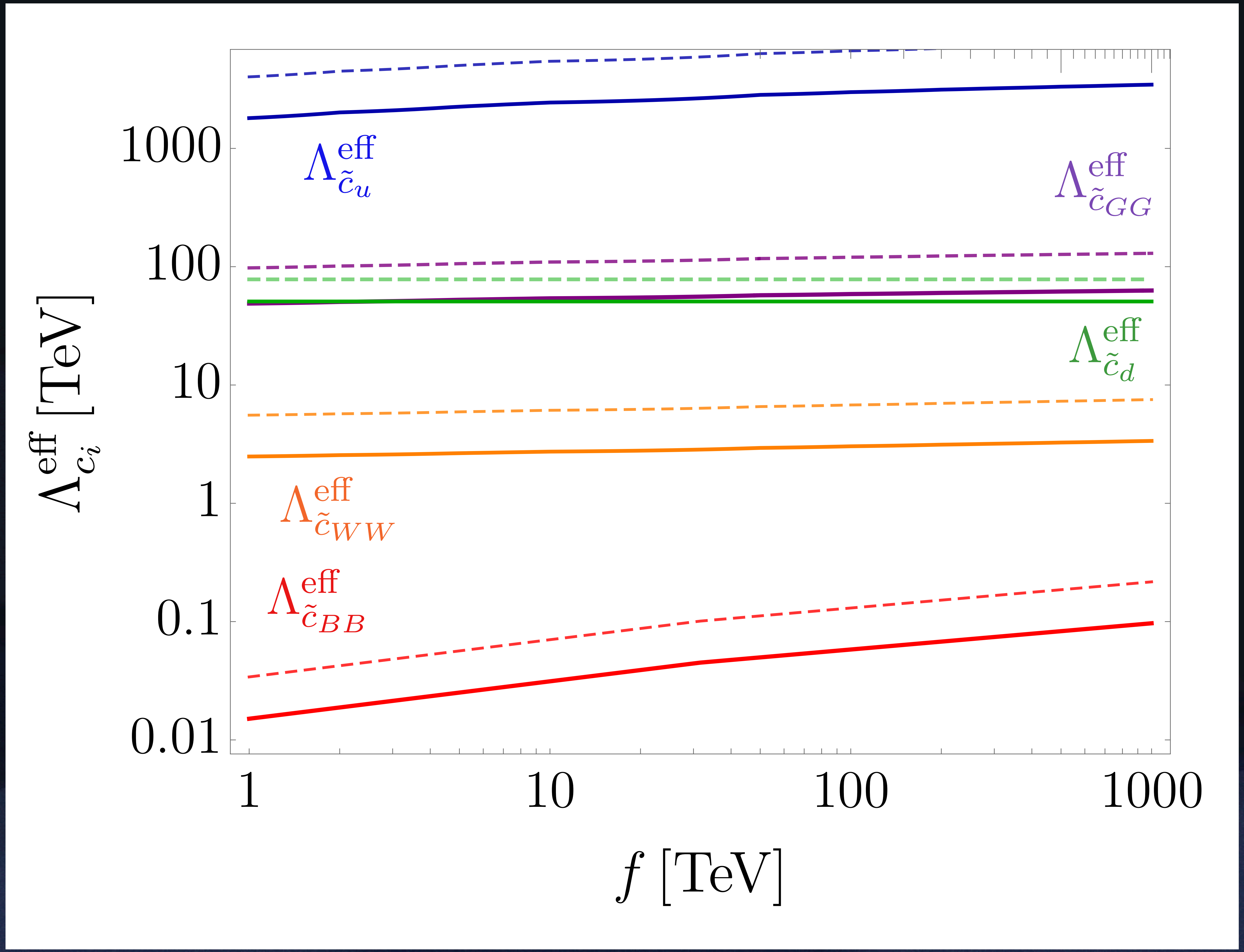
- Large flavor-changing ALP couplings can be avoided by assuming a flavor-universal ALP at the UV scale $\Lambda = 4\pi f$
- Still, at low energies flavor-changing couplings are generated by RG effects
- Bound on $\tilde{c}_{GG}(\Lambda)$ depends on the unknown low-energy constant g_8^θ



[Cornella, Galda, MN 2023]

Bounds on ALP couplings

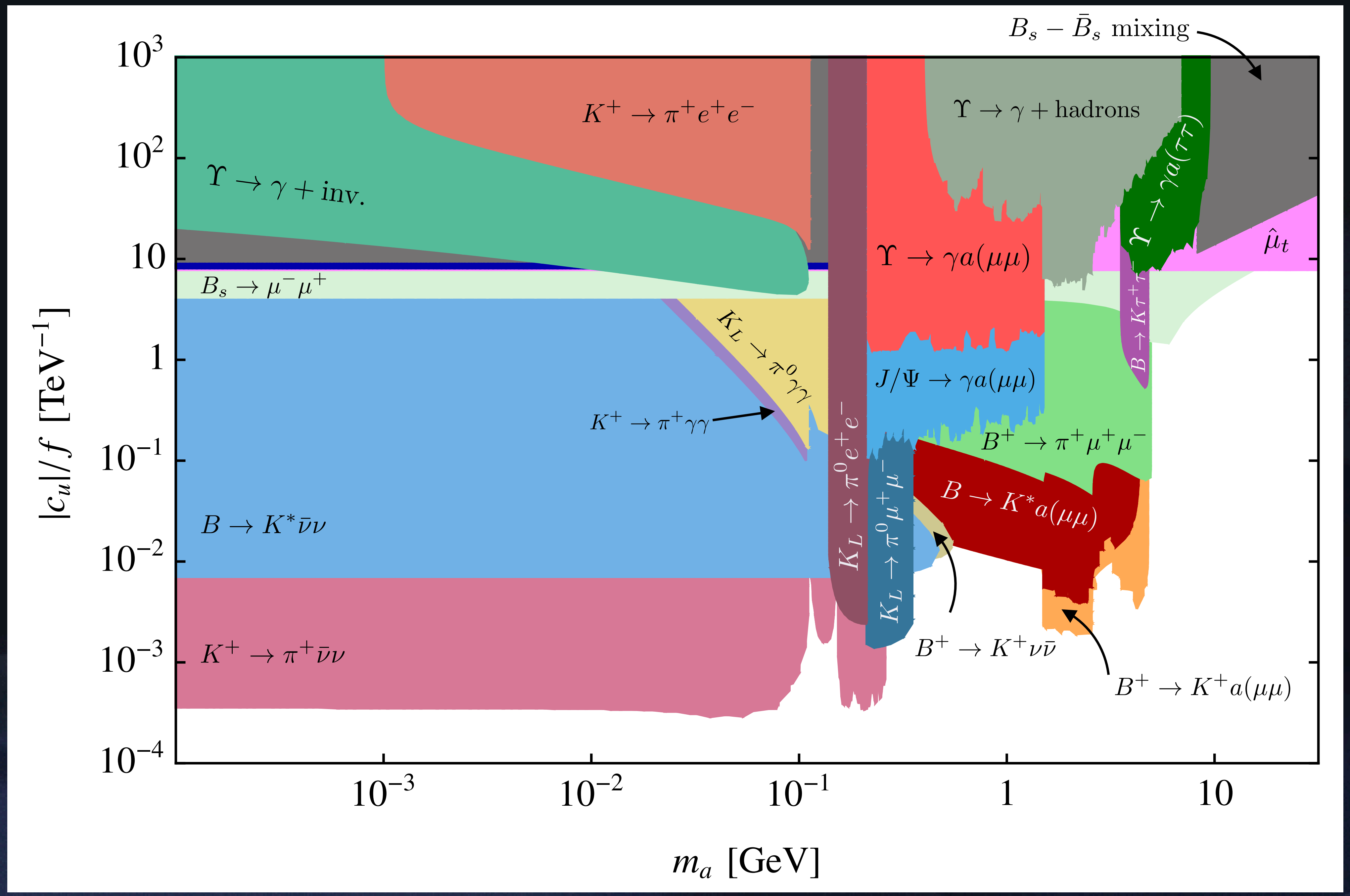
- Large flavor-changing ALP couplings can be avoided by assuming a flavor-universal ALP at the UV scale $\Lambda = 4\pi f$
- Still, at low energies flavor-changing couplings are generated by RG effects
- Bounds get stronger (logarithmically) as one raises the value of f



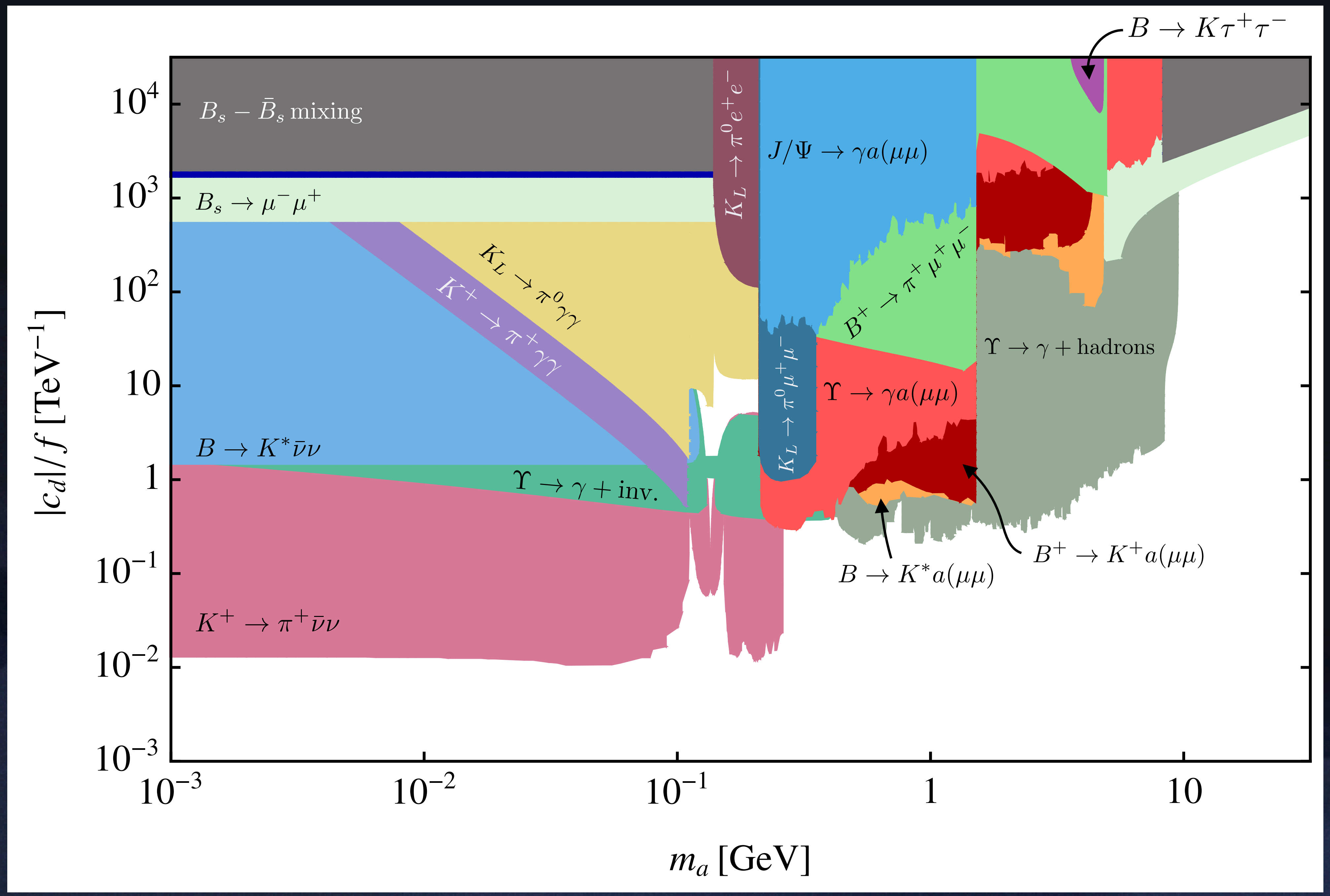
[Cornella, Galda, MN 2023]

Other flavor bounds (examples)

ALP—u_R coupling in the UV:



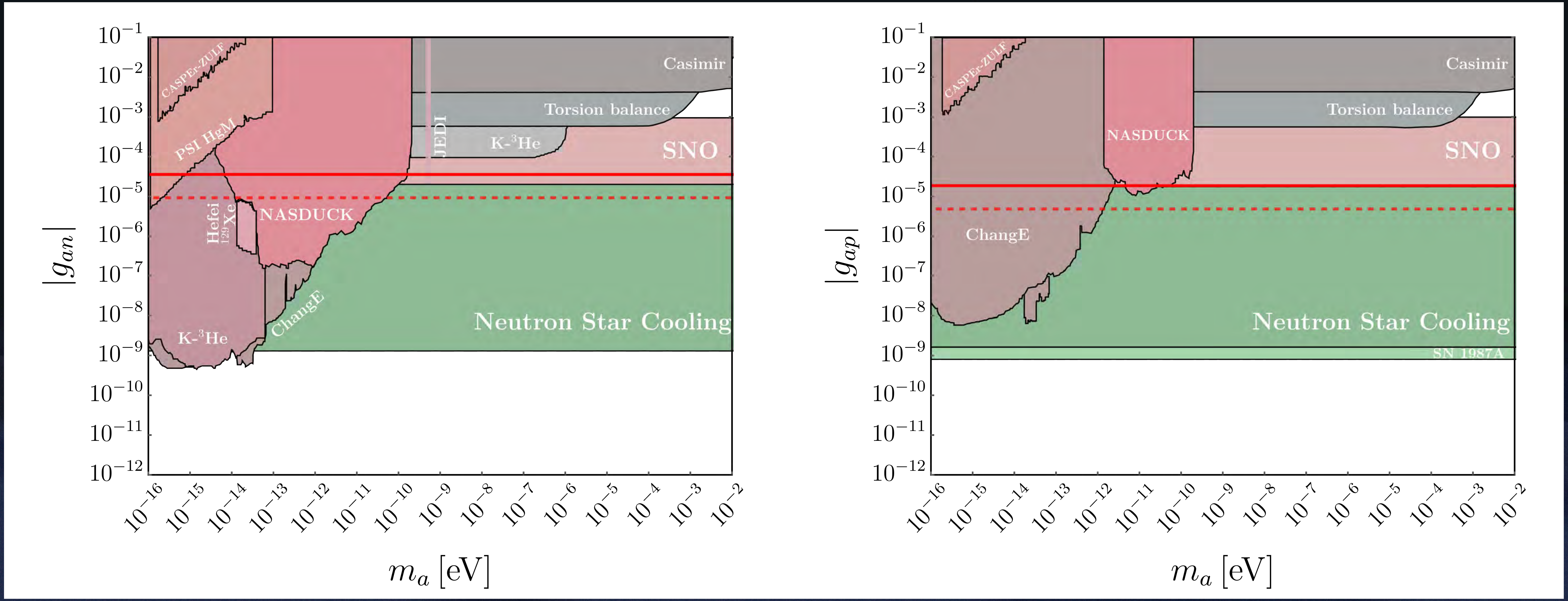
ALP—d_R coupling in the UV:



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

Bounds on ALP couplings

These bounds also apply to very light ALPs and to the QCD axion, and they imply competitive bounds, e.g., on the axion couplings to nucleons: [Cornella, Galda, MN 2023]



Conclusions

- Axions and axion-like particles belong to a class of well-motivated light BSM particles with weak couplings to the Standard Model (interactions via higher-dimensional operators)

- They are an interesting target 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; the latter provide the strongest particle-physics bounds on almost all ALP couplings to the SM

- The bounds extend to the region of very low ALP masses, which are usually accessed using non-accelerator probes