ALP contribution to the Strong CP problem

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and
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arXiv:2403.12133

Asymmetry
Essential Asymmetries of Nature

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26th Conference "From the Planck Scale to the Electroweak Scale"

Axion-like particles (ALPs)

Axions and ALPs are:

- pseudo-Goldstone bosons of some new $U(1)$

- well motivated NP candidates

- targeted by an extensive experimental program

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$\Longrightarrow$ light particle $m_a \ll f_a$

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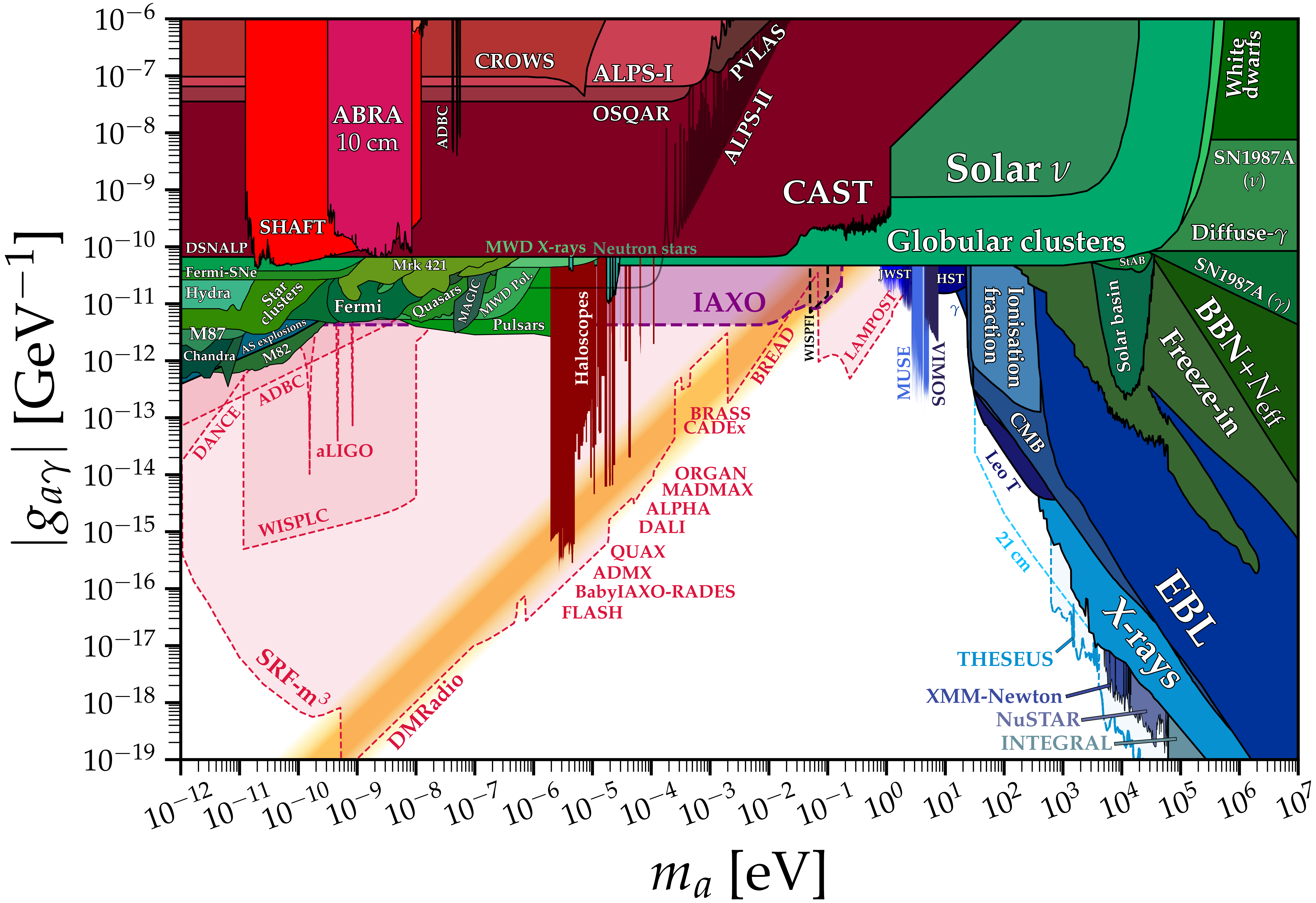
	Axion	**ALPs**
Strong CP problem	✓	✗
Dark Matter	✓	✓
Cosmic Inflation	✓	✓
Baryogenesis	✓	✓

arXiv:2403.12133

[cajohare.github.io/AxionLimits]



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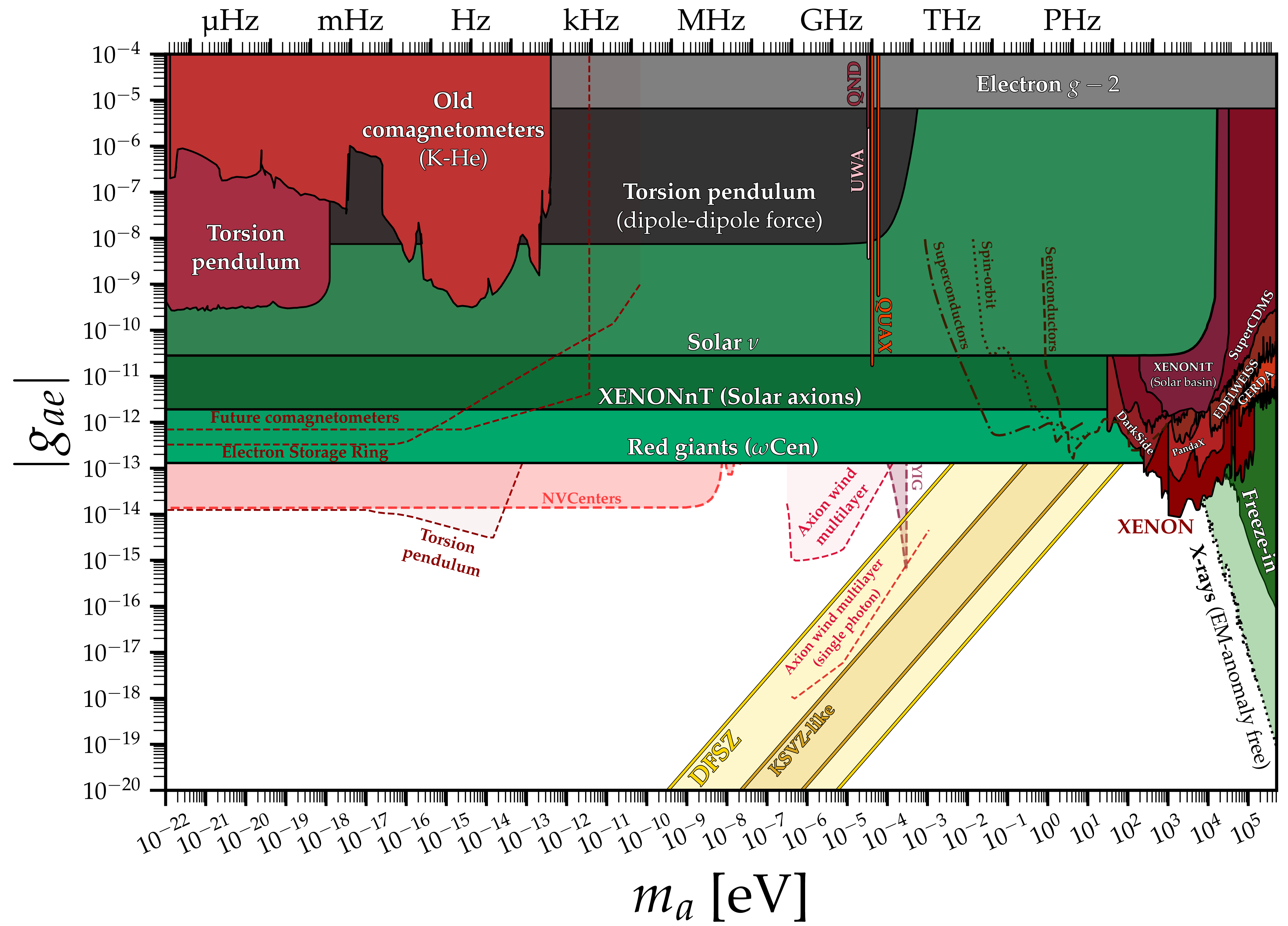

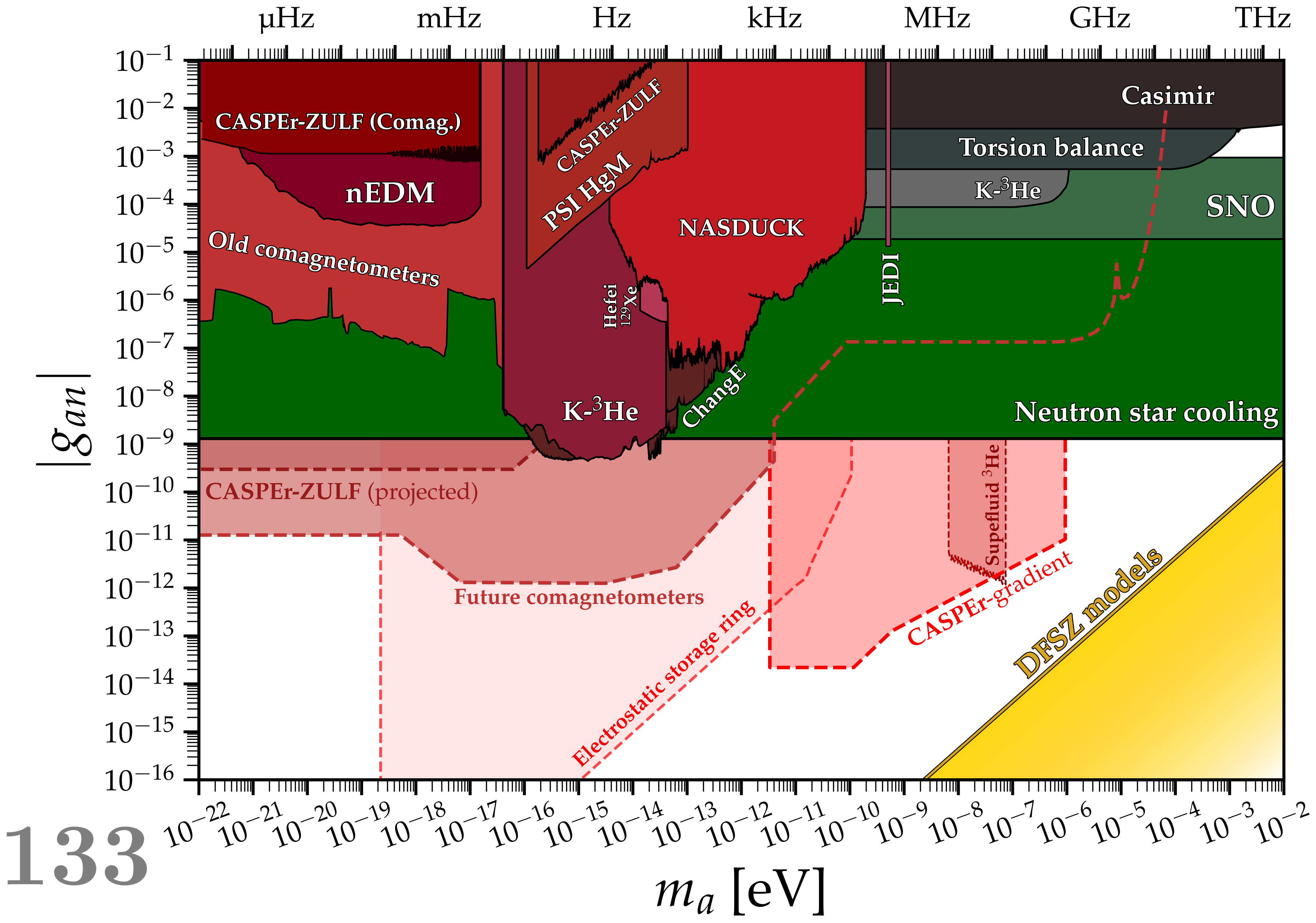

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The ALP Effective Field Theory

ALP couplings to up- and down-type quarks:

$$\mathcal{L}_a \supset \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2$$
$$+ \left(\bar{u}_L \boldsymbol{M}_u u_R + \bar{d}_L \boldsymbol{M}_d d_R + \text{h.c.}\right) + \theta \frac{\alpha_s}{8\pi} G_{\mu\nu} \widetilde{G}^{\mu\nu}$$
$$+ \frac{\partial_\mu a}{f_a} \left(\bar{Q}_L \gamma^\mu \boldsymbol{C}_Q Q_L + \bar{u}_R \gamma^\mu \boldsymbol{C}_{u_R} u_R + \bar{d}_R \gamma^\mu \boldsymbol{C}_{d_R} d_R\right)$$

[Georgi, Kaplan, Randall, *Phys. Lett. B 169 (1986) 73-78*]

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related by anomalous $U(1)_{\textbf{Axial}}$ symmetry

$\Longrightarrow$ **Physical combination is**

$$\bar{\theta} = \theta + \text{Arg}\,\det(\boldsymbol{M}_u \boldsymbol{M}_d)$$

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ALP couplings to fermions

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CP-violation in flavor-nondiagonal entries

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CP-violation in flavor-nondiagonal entries

Will source CP-violating observables e.g. EDMs

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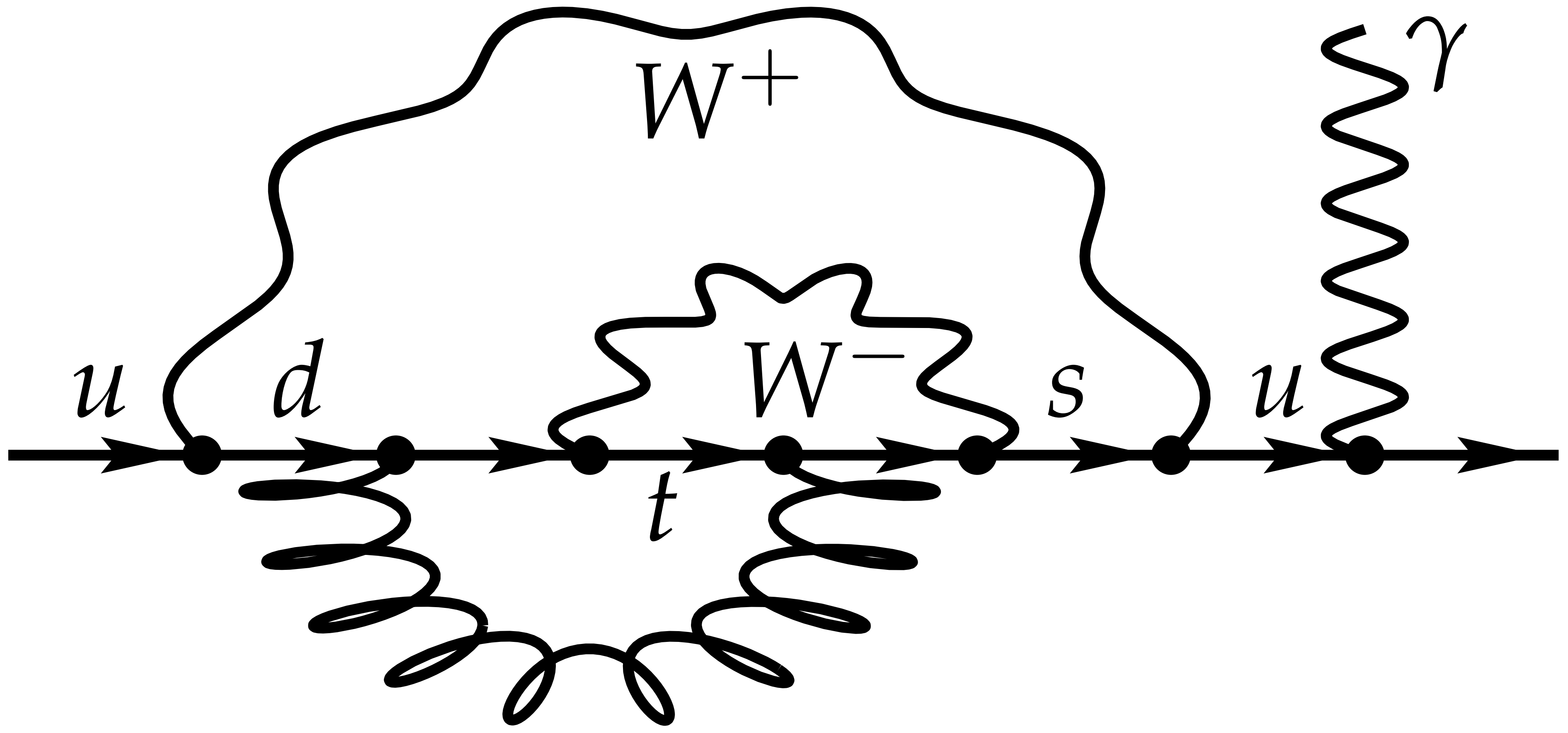
The neutron EDM

SM prediction extremely suppressed!!!



nEDM extremely well constrained: $d_n^{\exp} \lesssim 2.6 \times 10^{-26}$ $[e \cdot \mathrm{cm}]$

[Abel et al., 2001.11966] [Pendlebury *et al.*, 2001.11966]

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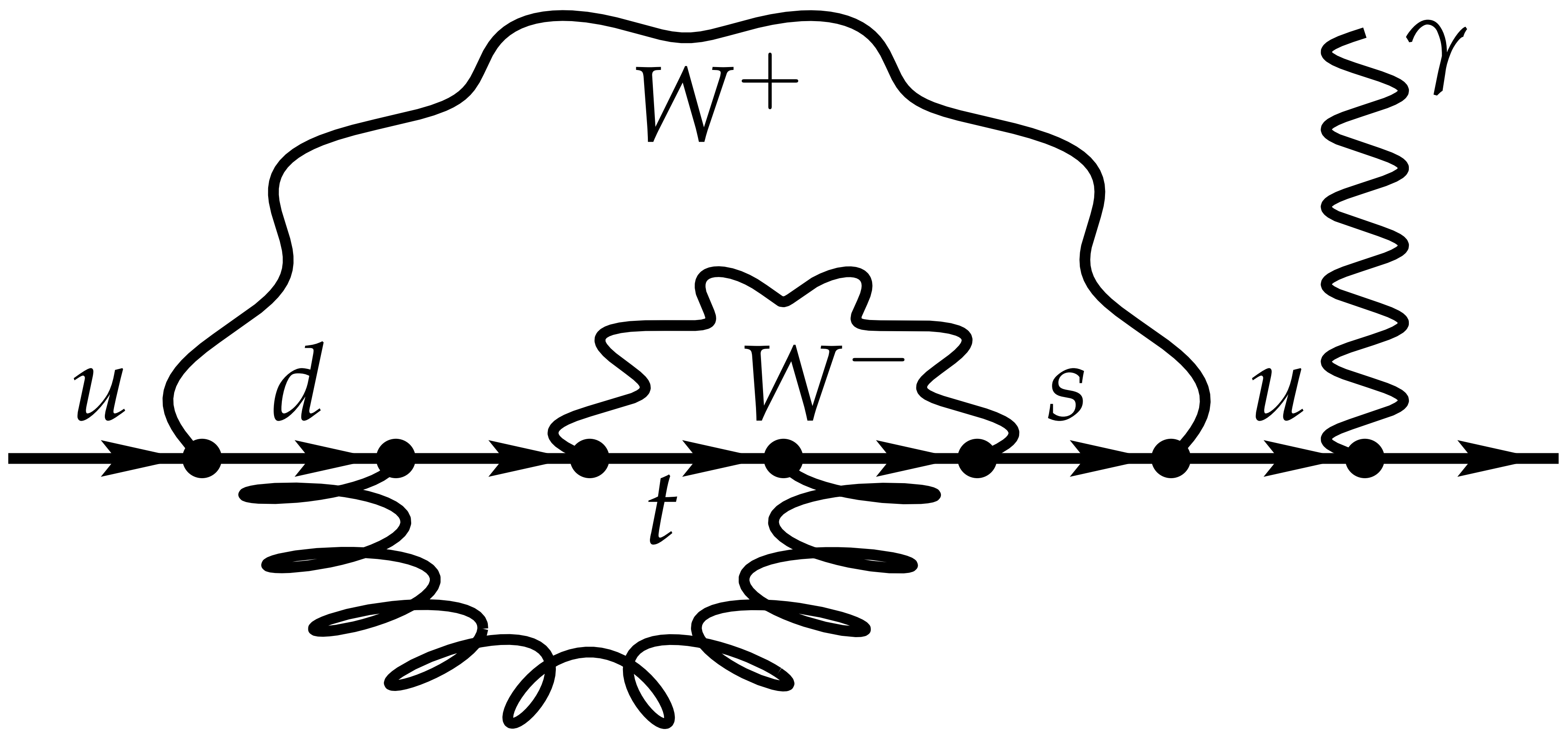

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How can C_Q, C_{u_R}, C_{d_R} contribute?

nEDM sourced by

- Quark EDMs and CEDMs
- **The $\bar{\theta}$ parameter**

ALP contributions appear at 1-loop

[Baluni, *Phys. Rev. D 19, 2227*] **arXiv:2403.12133**

Radiative corrections to $\bar{\theta}$

How does $\bar{\theta}$ change under radiative corrections?

$$\bar{\theta} = \theta + \mathrm{Arg}\,\det(\boldsymbol{M}_u \boldsymbol{M}_d)$$

[Ellis, Gaillard, Nucl.Phys.B 150 (1979) 141-162]

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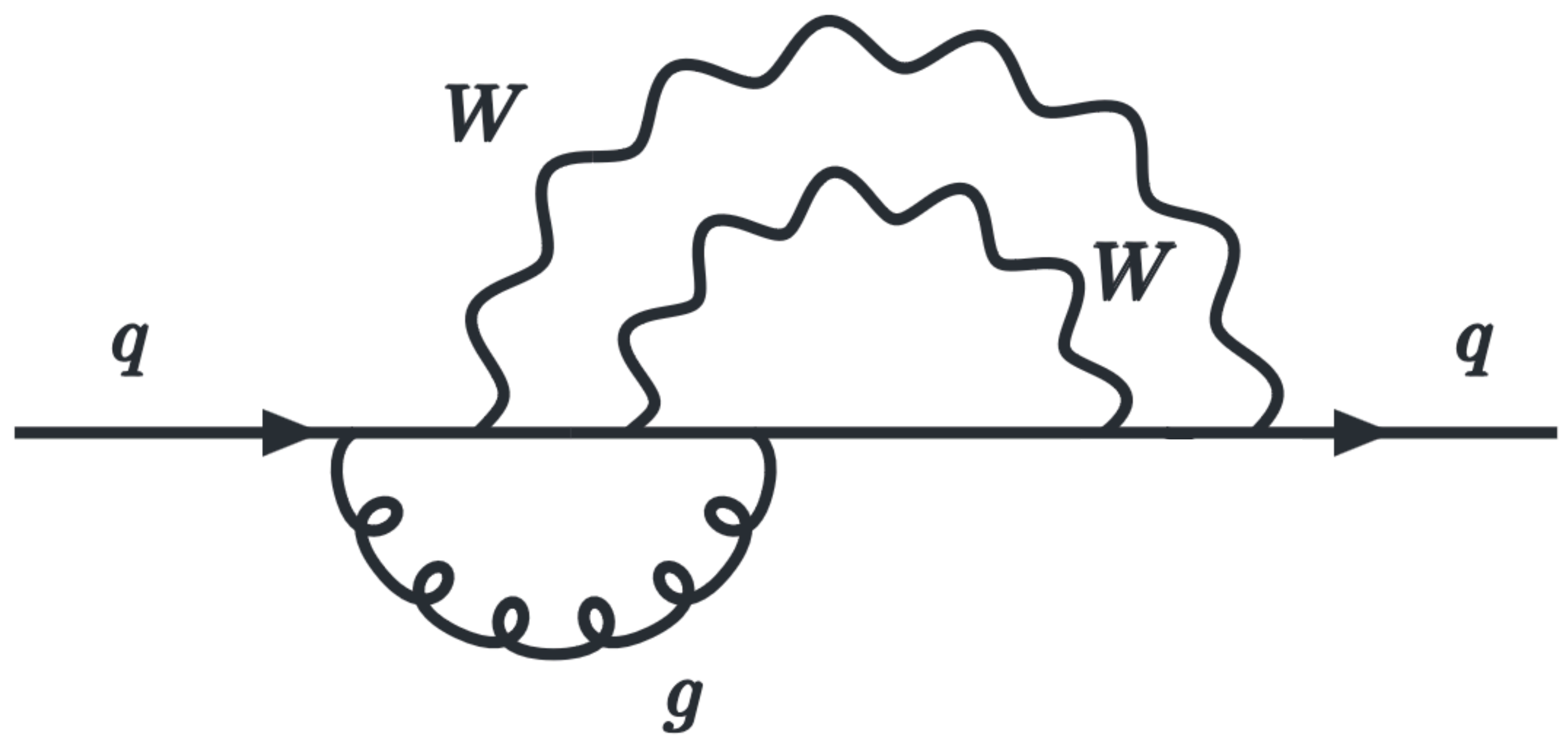

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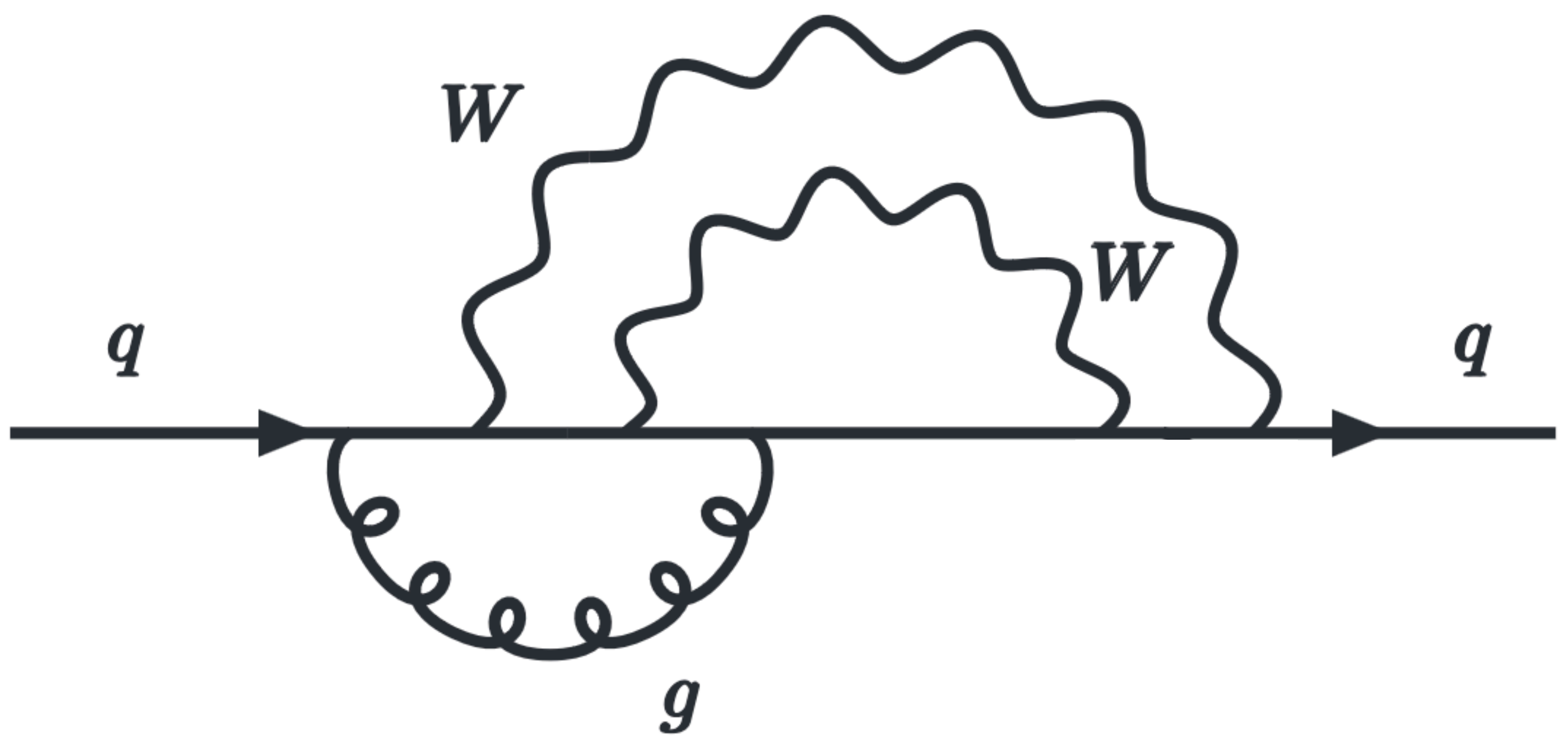
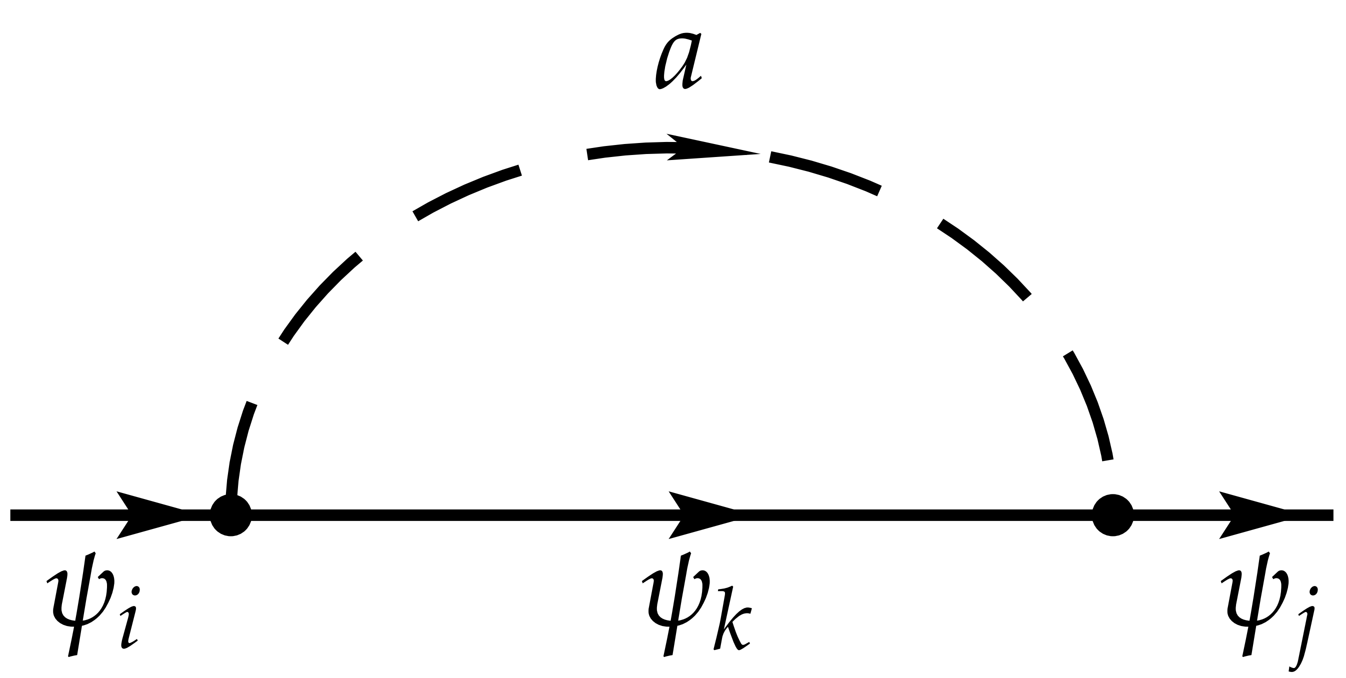


ALP EFT $\longrightarrow$ one-loop



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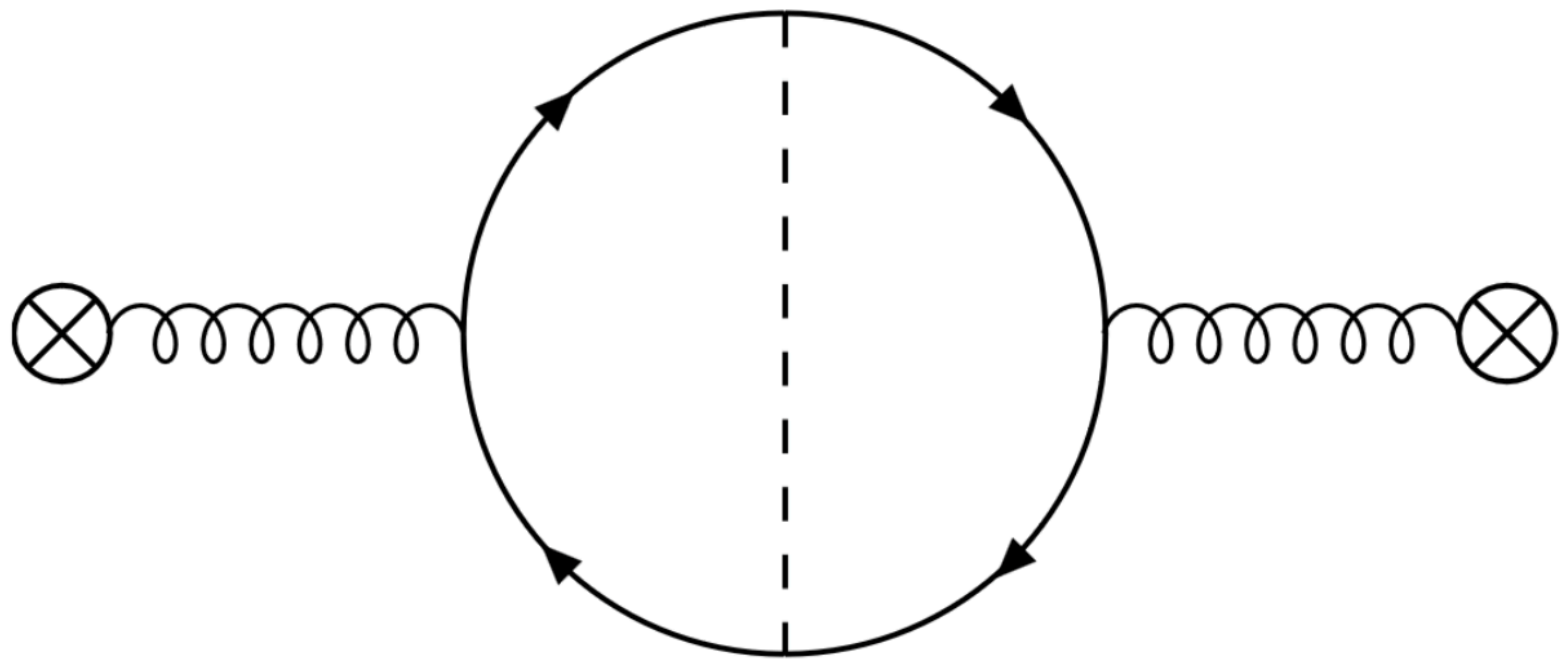

[Banno et al., 2311.07817]

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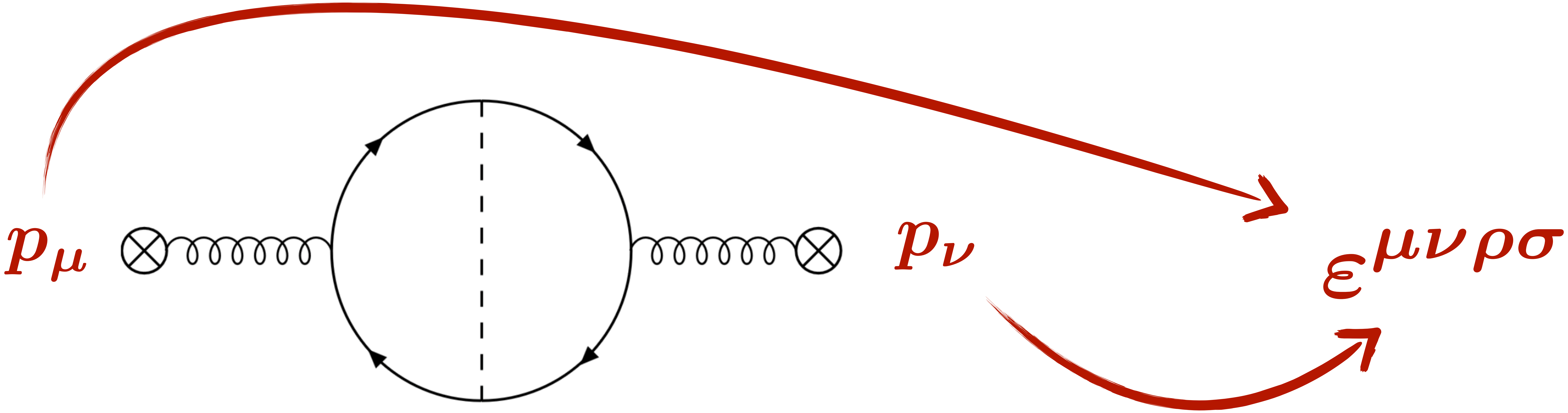

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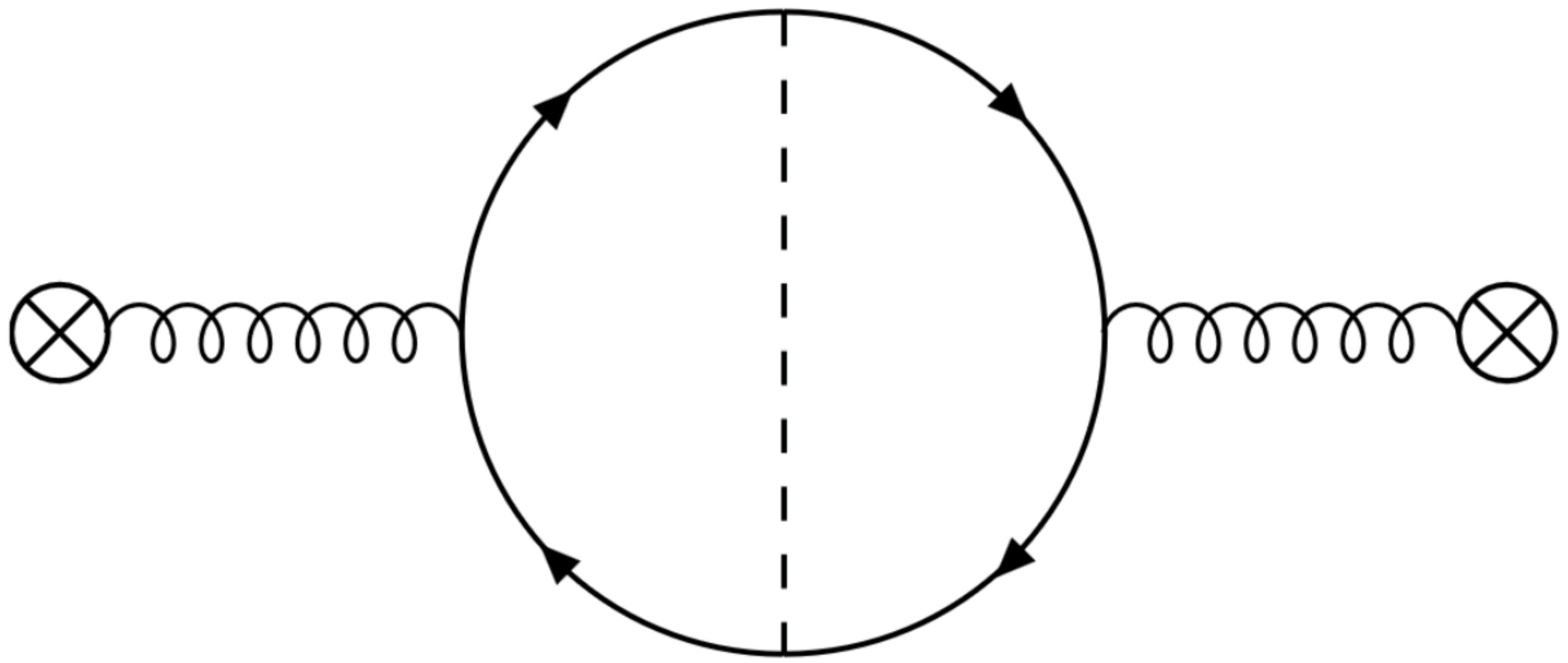

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BUT

New contributions highly subdominant

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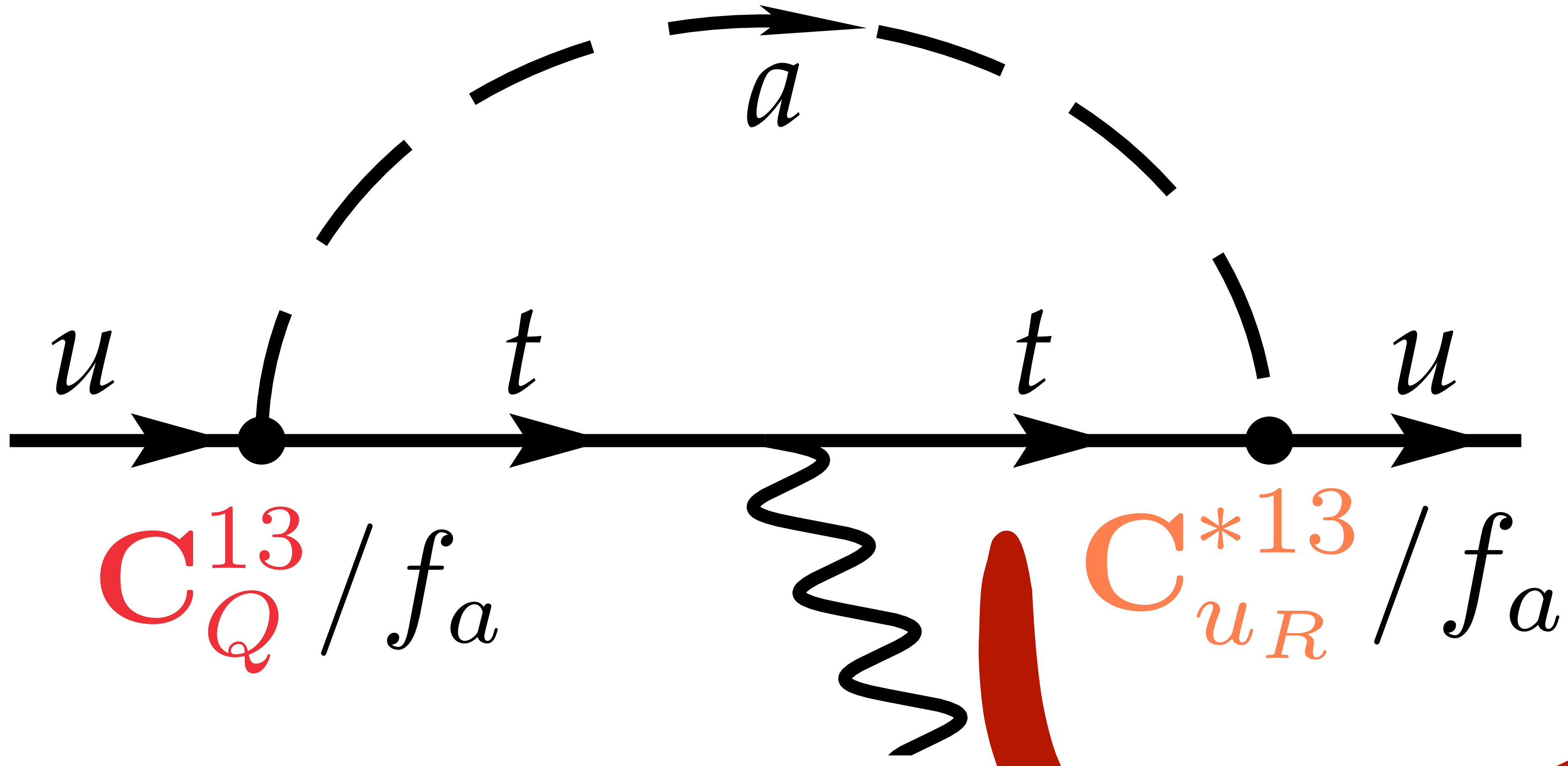
ALP contributions to the nEDM

nEDM sourced by
- Quark EDMs and CEDMs
- **The $\bar{\theta}$ parameter**



$$\frac{d_u}{e} \sim \frac{Q_u}{32\pi^2} m_t \frac{\mathrm{Im}(C_Q^{13} C_{u_R}^{*13})}{f_a^2}$$

Corrections to the quark EDMs and CEDMs

[Di Luzio et al., 2010.13760]

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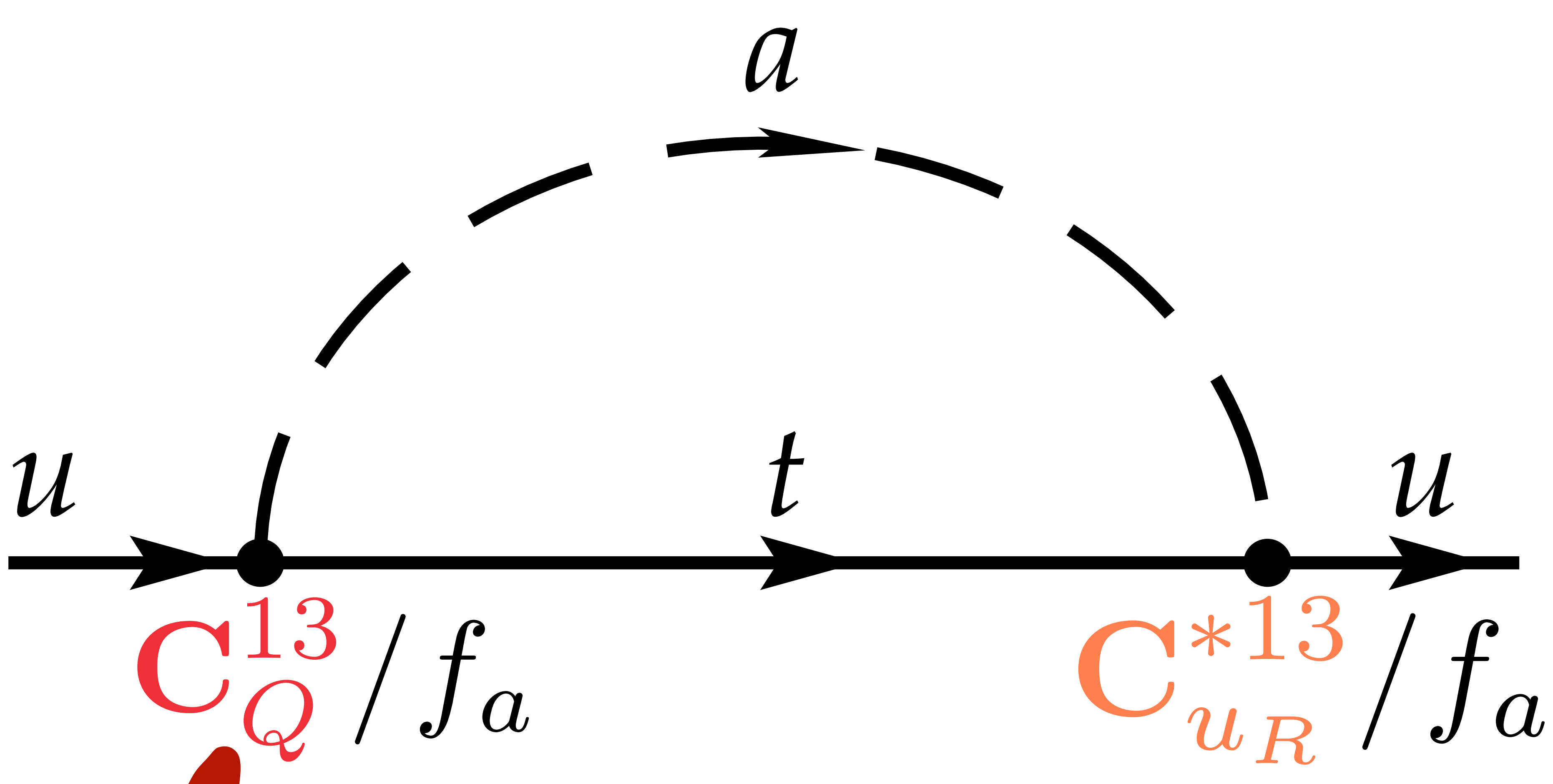

$$\Delta\bar{\theta}_{\mathrm{ALP}} \sim \frac{1}{16\pi^2}\left(\frac{m_t^3}{m_u}\right)\frac{\mathrm{Im}(C_Q^{13}\, C_{u_R}^{*13})}{f_a^2}$$

NEW

Corrections to $\bar{\theta} = \theta + \mathbf{Arg}\,\mathbf{det}(\,M_u M_d)$

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ALP contributions to the nEDM

$$\mu \frac{d\bar{\theta}}{d\mu} \simeq \sum_{q=u,d} \text{Im Tr}\left(\boldsymbol{M}_q^{-1} \mu \frac{d}{d\mu} \Delta \boldsymbol{M}_q \right)$$

Run down from $\boldsymbol{\Lambda_{\text{UV}} = f_a \longrightarrow \mu_{\text{IR}} = \Lambda_{\text{QCD}}}$

$$\bar{\theta}\left(\mu_{\text{IR}}\right) \simeq \bar{\theta}_0 + \sum_{u_i=\{u,c,t\}} \frac{m_{u_k}\left(m_a^2 + \widehat{m}_{u_k}^2\right)}{16\pi^2 f_a^2 m_{u_i}} \text{Im}\left(C_Q^{ik} C_{u_R}^{*ik} \right) \log \frac{f_a^2}{\max\left(m_a^2, m_{u_k}^2\right)}$$

$$+ \sum_{d_i=\{d,s,b\}} \frac{m_{d_k}\left(m_a^2 + \widehat{m}_{d_k}^2\right)}{16\pi^2 f_a^2 m_{d_i}} \text{Im}\left(C_Q^{ik} C_{d_R}^{*ik} \right) \log \frac{f_a^2}{\max\left(m_a^2, m_{d_k}^2\right)}$$

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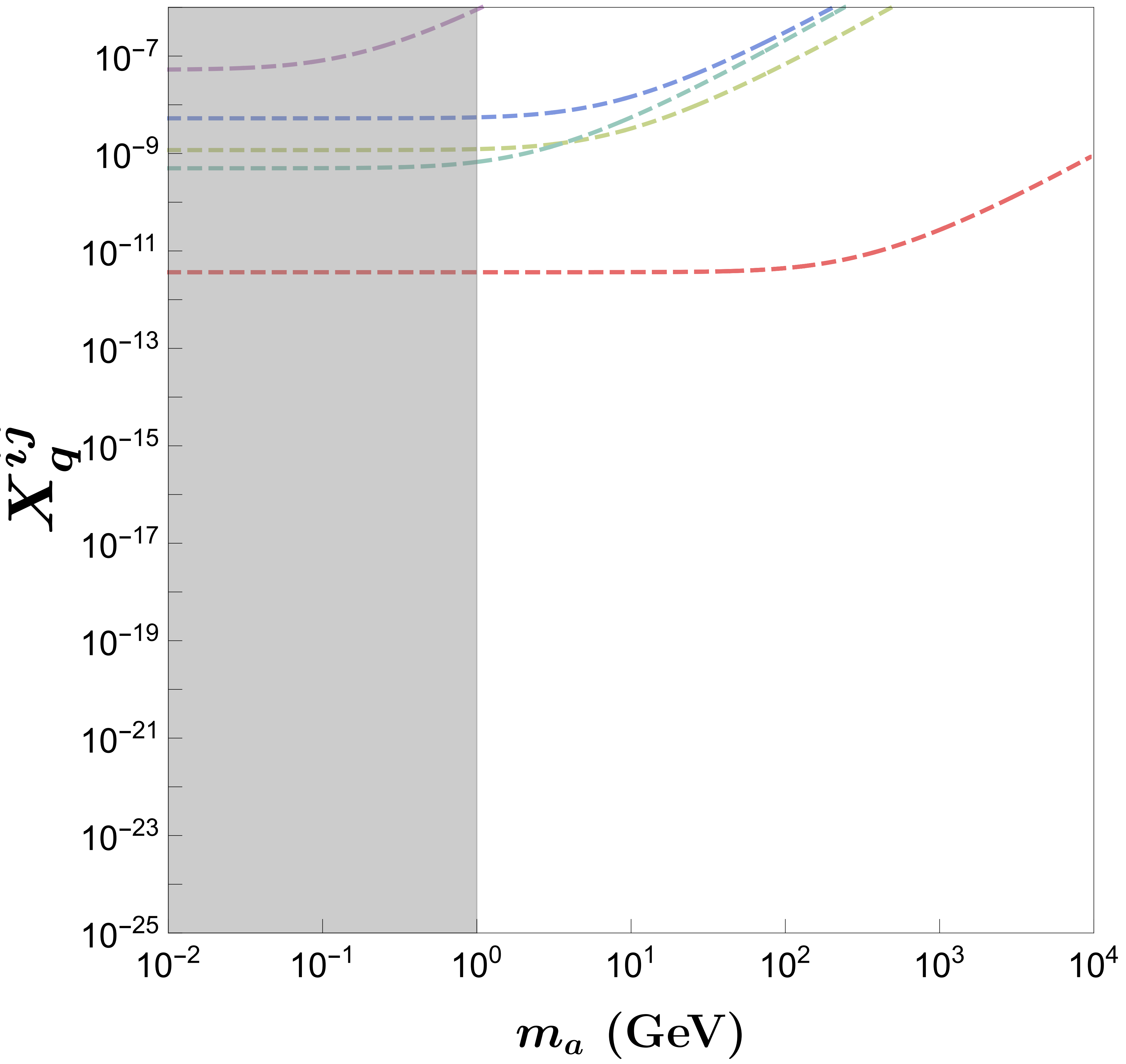
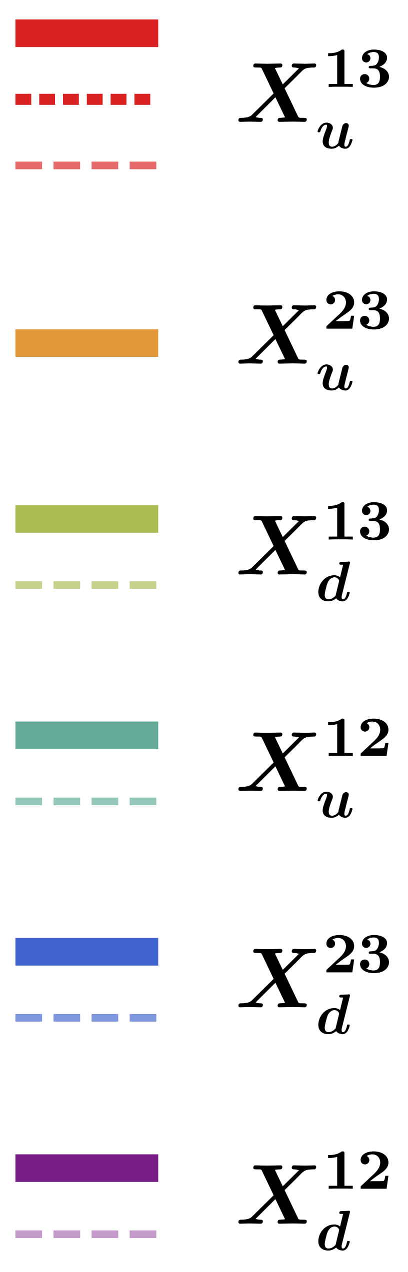
nEDM limits on ALP-fermion couplings



$$X_q^{ij} = \mathrm{Im}(C_L^{ij} C_{q_R}^{*ij})/f_a^2 \ (\mathrm{GeV}^{-2})$$



Dotted lines:

$$\left.\frac{d_n}{e}\right|_{d_q,\tilde{d}_q} \sim \mathcal{O}(1) \times \frac{Q_u}{32\pi^2} m_t \frac{\mathrm{Im}(\mathrm{C}_Q^{13}\mathrm{C}_{u_R}^{*13})}{f_a^2}$$

OLD

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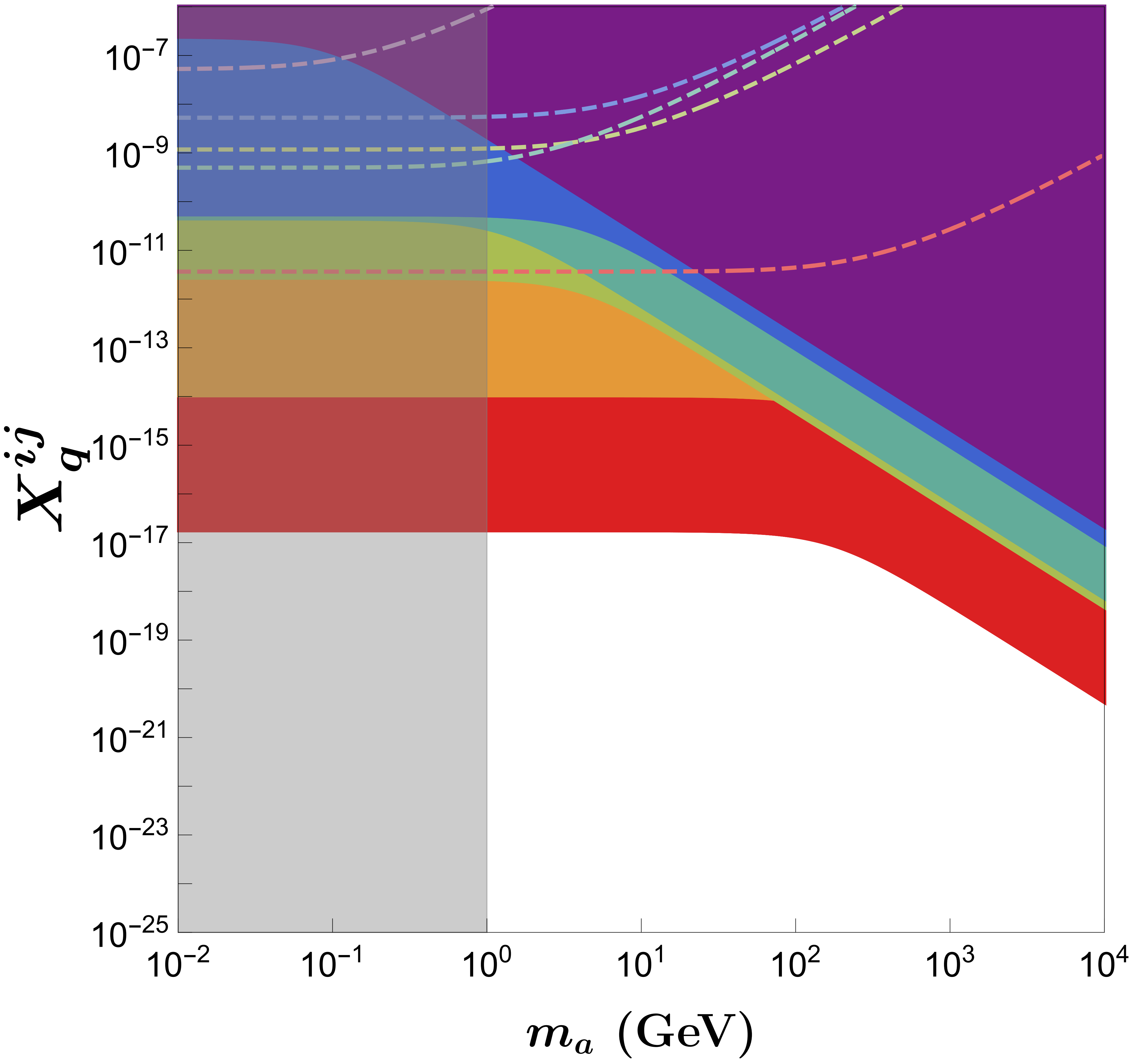

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OLD

Solid regions:

$$\frac{d_n}{e}\Big|_{\bar{\theta}} \sim \frac{\mathcal{O}(10^{-3}\ \mathrm{GeV}^{-1})}{16\pi^2} \times \left(\frac{m_t^3}{m_u}\right) \frac{\mathrm{Im}(C_Q^{13} C_{u_R}^{*13})}{f_a^2}$$

NEW

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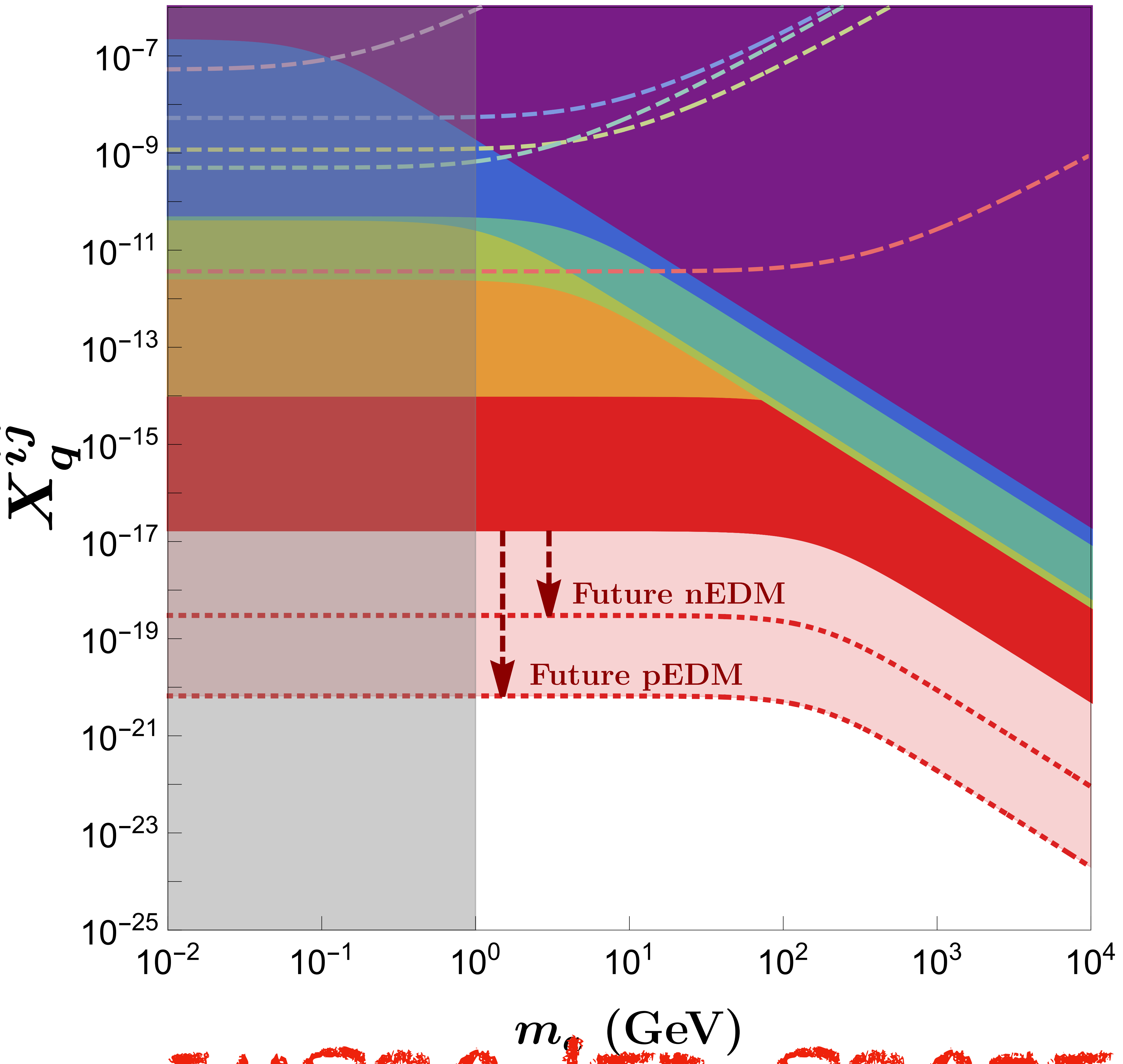

$$\boldsymbol{X_q^{ij}} = \mathrm{Im}(C_L^{ij} C_{q_R}^{*ij})/f_a^2 \; (\mathrm{GeV}^{-2})$$

- X_u^{13}
- X_u^{23}
- X_d^{13}
- X_u^{12}
- X_d^{23}
- X_d^{12}

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NEW

IMPROVED PROJECTED REACH!

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General scalar theory

- **A scalar which may not be a pseudo-Goldstone**

$\Longrightarrow$ more parametric freedom

- **The effective Lagrangian is**

$$\mathcal{L} \supset \bar{u}_L v \left[i\boldsymbol{K}_u \frac{\phi}{\Lambda} + \boldsymbol{F}_u \frac{\phi^2}{\Lambda^2} \right] u_R + \bar{d}_L v \left[i \frac{\phi}{\Lambda} \boldsymbol{K}_d + \frac{\phi^2}{\Lambda^2} \boldsymbol{F}_d \right] d_R + \text{ h.c.}$$

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- **The shift-symmetry is restored when**

$$v\boldsymbol{K}_q \equiv \boldsymbol{C}_Q \boldsymbol{M}_q - \boldsymbol{M}_q \boldsymbol{C}_{q_R}$$

$$2v\boldsymbol{F}_q \equiv 2\boldsymbol{C}_Q \boldsymbol{M}_q \boldsymbol{C}_{q_R} - \boldsymbol{C}_Q^2 \boldsymbol{M}_q - \boldsymbol{M}_q \boldsymbol{C}_{q_R}^2$$

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Needed to restore shift-symmetry!!

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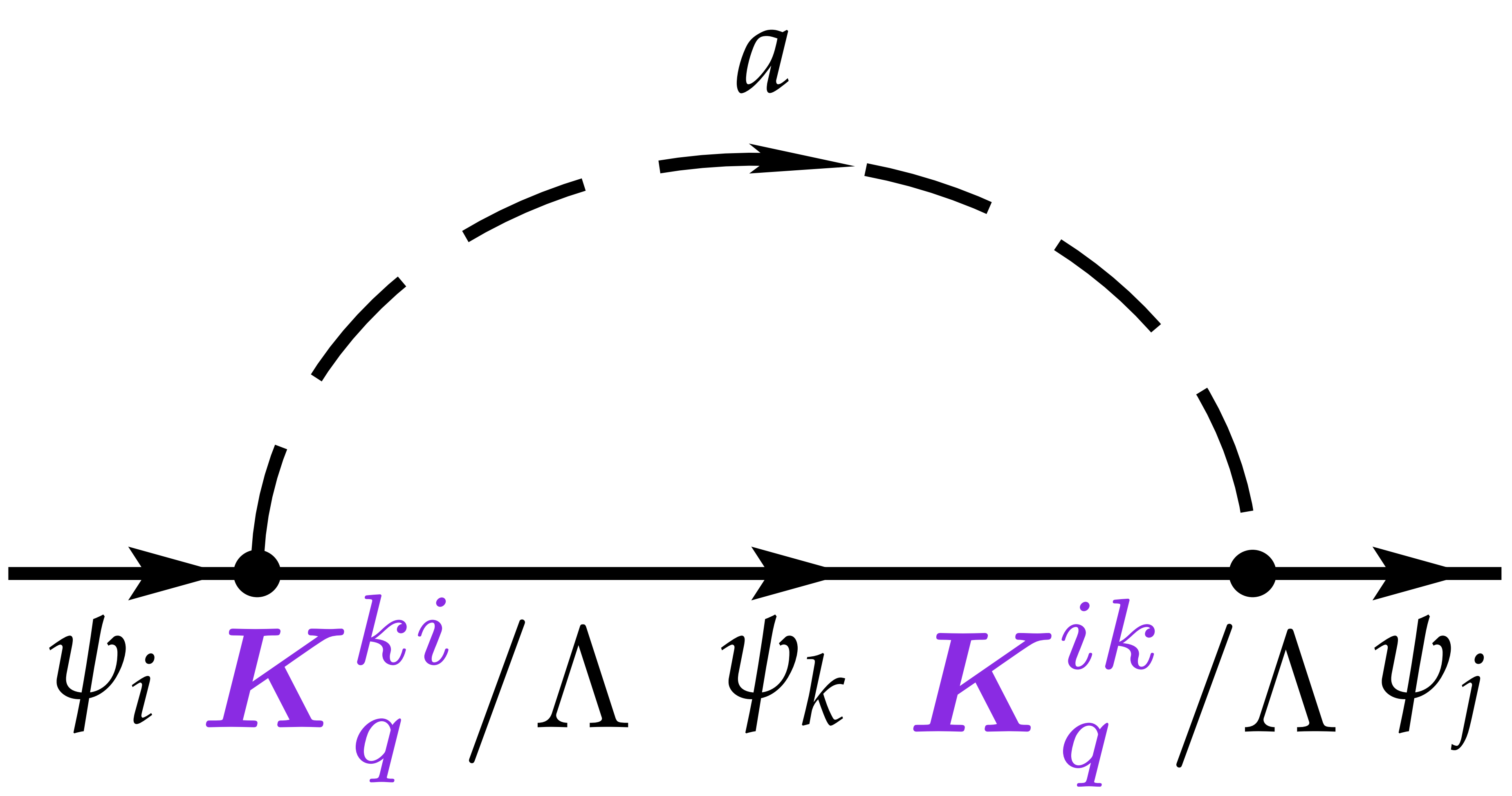
ϕ contribution to the nEDM

nEDM sourced by
- Quark EDMs and CEDMs
- **The $\bar{\theta}$ parameter**



$$\left.\frac{d_n}{e}\right|_{d_q,\tilde{d}_q} \sim \frac{Q_u}{32\pi^2}\frac{v^2}{\Lambda^2}\frac{1}{m_t}\,\mathrm{Im}\left[\mathbf{K}_u^{13}\mathbf{K}_u^{31}\right]$$

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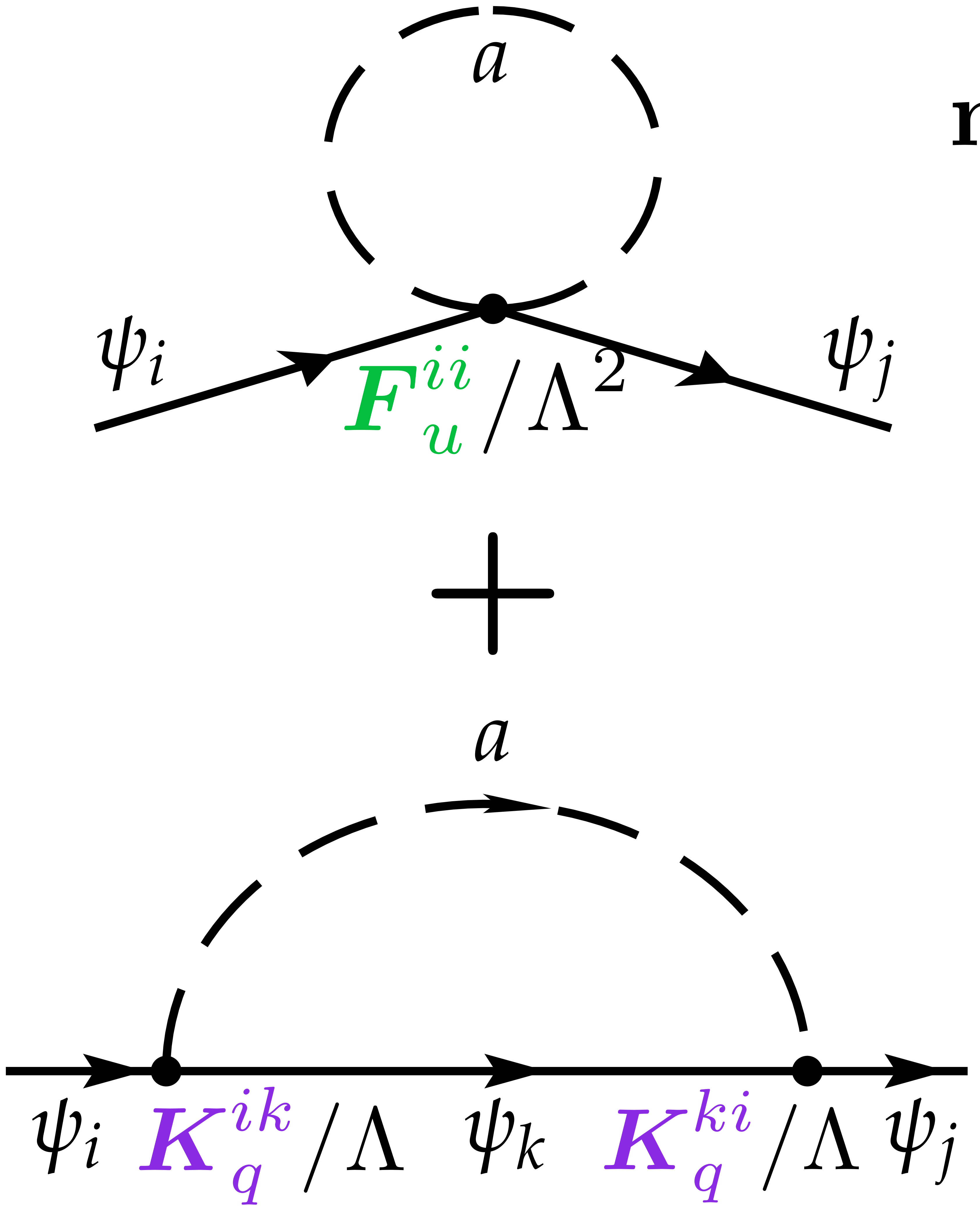

nEDM sourced by
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- **The $\bar{\theta}$ parameter**

Corrections to $\bar{\theta} = \theta + \mathbf{Arg\,det}(M_u M_d)$

$$\Delta\bar{\theta}_{\text{scalar}} \sim \frac{v}{16\pi^2}\left[\frac{v\, m_t}{m_u}\frac{\text{Im}\left(K_u^{13}K_u^{31}\right)}{\Lambda^2} - \frac{m_\phi^2}{m_u}\frac{\text{Im}(F_u^{ii})}{\Lambda^2}\right]$$

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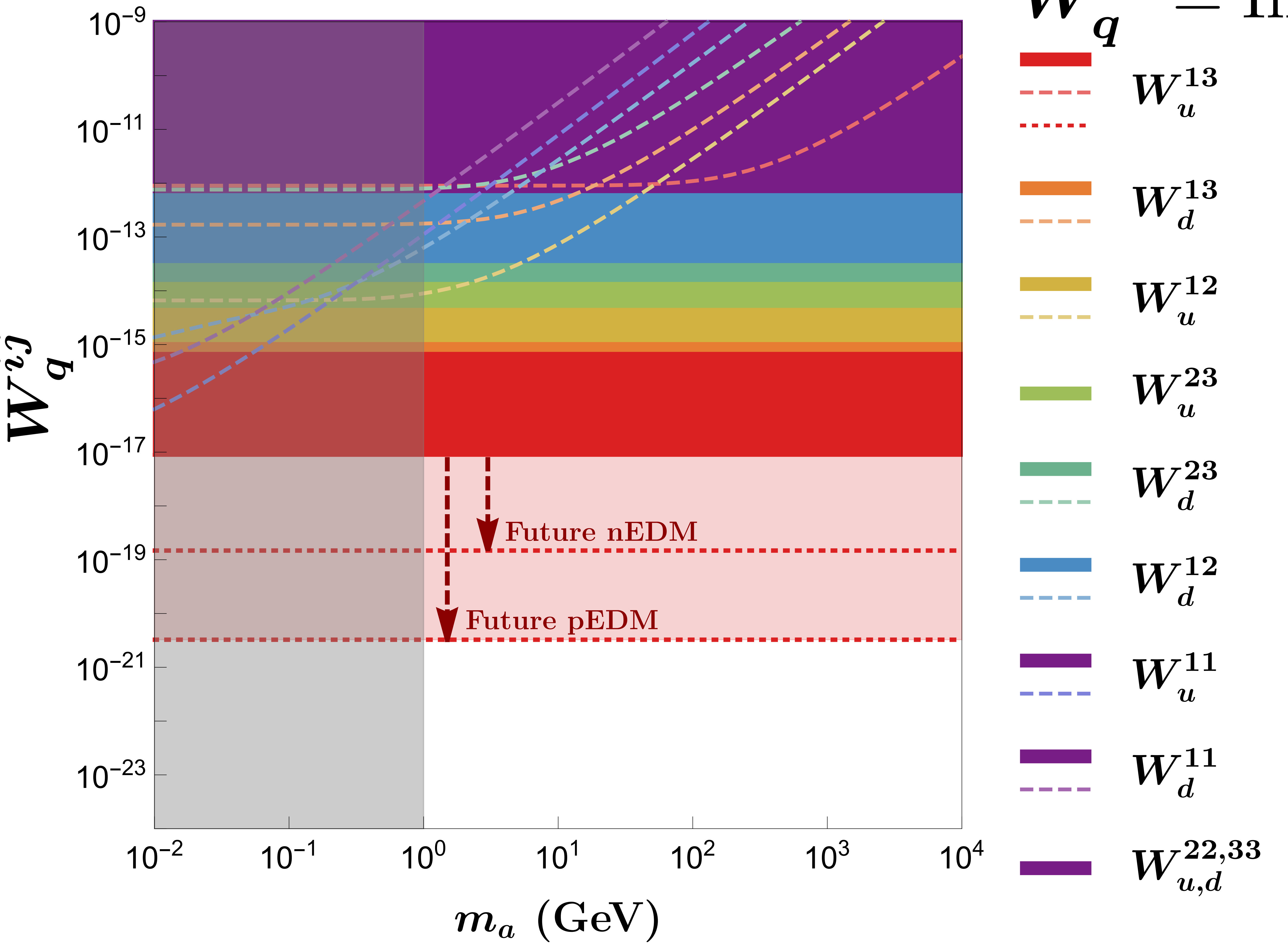
nEDM on scalar-fermion couplings



$$\boldsymbol{W_q^{ij}} = \mathrm{Im}\left(\boldsymbol{K_q^{ij}}\boldsymbol{K_q^{ji}}\right)/\Lambda^2$$

Dotted lines:

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OLD

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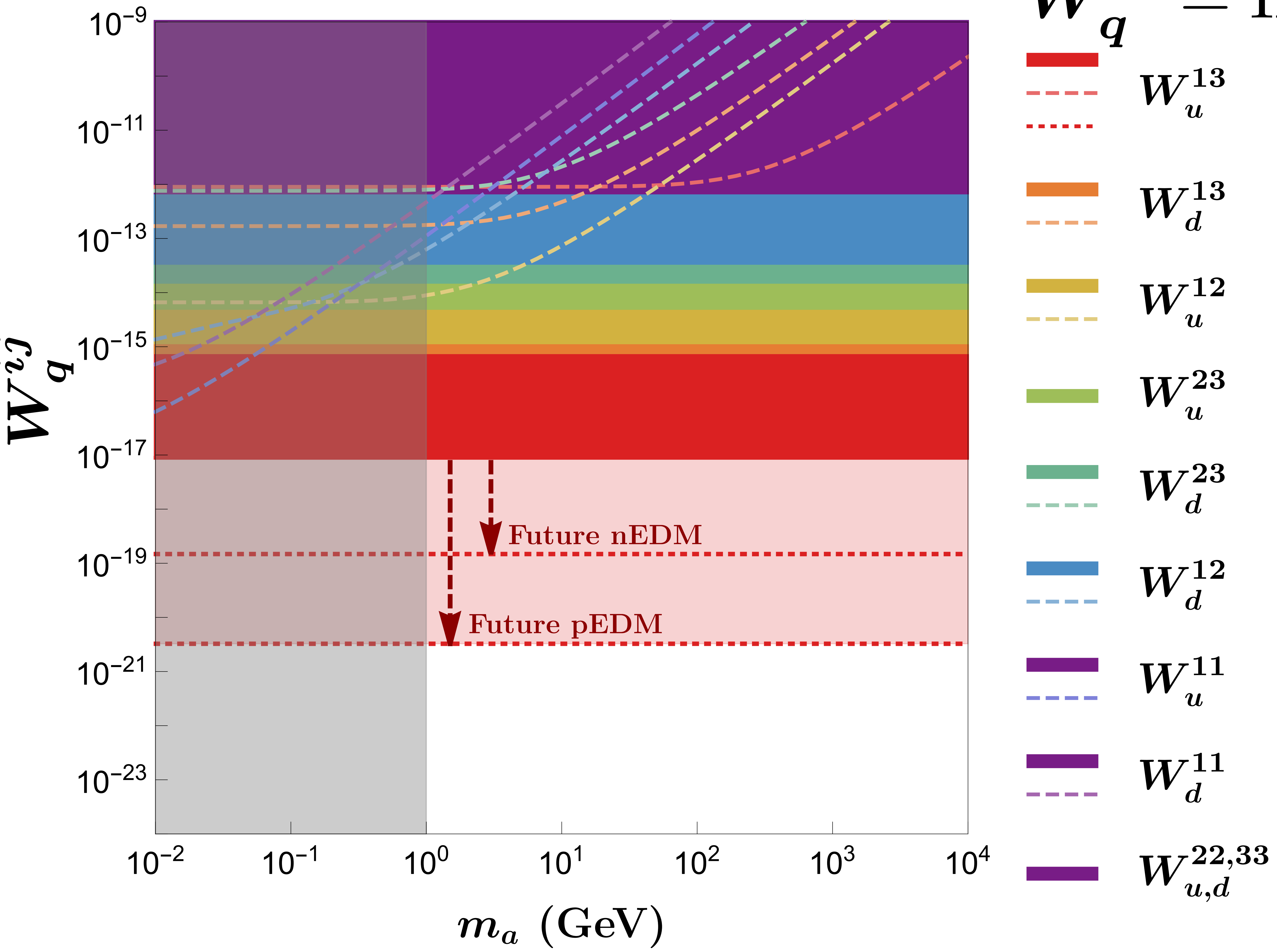

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OLD

Solid regions:

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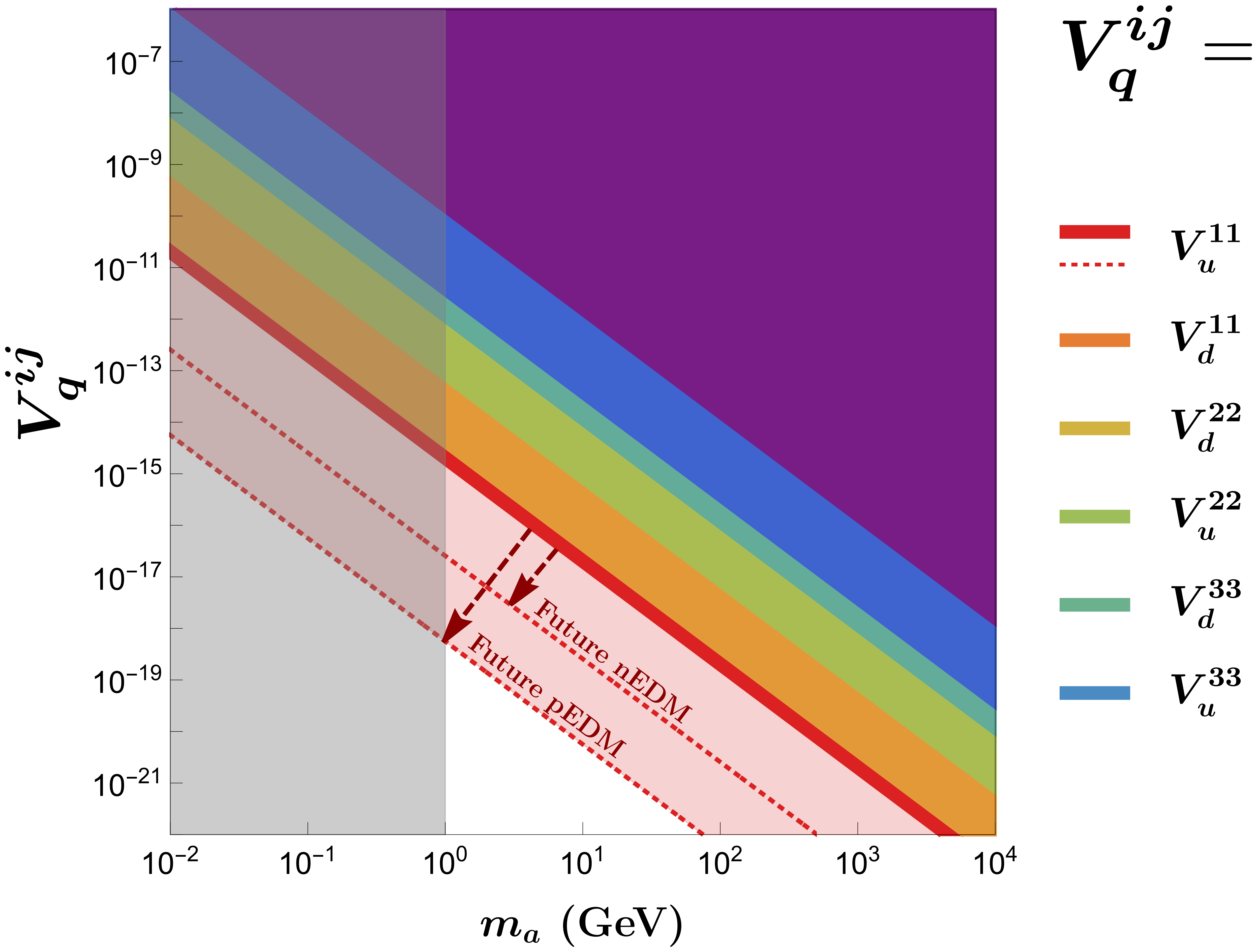

$$V_q^{ij} = \mathrm{Im}\left(F_q^{ii}\right)/\Lambda^2$$

Solid regions:

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NEW

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$\bar{\theta}$ and the Strong CP problem

Several mechanisms to explain smallness of $\bar{\theta}$

$\bar{\theta} = 0$ at IR

e.g.

Peccei-Quinn mechanism

[Peccei, Quinn, Phys.Rev.Lett. 38, 1440]

$\bar{\theta} = 0$ at UV

e.g.

Nelson-Bar mechanism

[Nelson, Phys.Lett. B 136, 5–6]
[Barr, Phys.Rev.Lett. 53, 329]

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[Peccei, Quinn, Phys.Rev.Lett. 38, 1440]

$$\bar{\theta}_{\text{ind}} = -\frac{m_0^2}{2} \sum_{q=u,d,s} \frac{\tilde{d}_q}{m_q}$$

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$\bar{\theta}$ and the Strong CP problem

Several mechanisms to explain smallness of $\bar{\theta}$

$$\Lambda_{\text{UV}} \longrightarrow \mu_{\text{IR}}$$

$\Delta\bar{\theta}$ generated at the IR

$$\bar{\theta} = 0 \text{ at UV}$$

e.g.

Nelson-Bar mechanism

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Conclusions

- ALP couplings to fermion induce parametrically enhanced corrections to the nEDM at one loop

- We have improved the bounds on CP-odd ALP-fermion couplings by $\sim$4 orders of magnitude

- The same kind of improvement applies for a general scalar

MORE IN OUR PAPER

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Backup

Without a PQ mechanism:

$$d_n = 0.6(3) \times 10^{-16}\bar{\theta}[e \cdot \mathrm{cm}]$$
$$- 0.204(11)d_u + 0.784(28)d_d - 0.0028(17)d_s$$
$$- 0.32(15) \text{ e } \tilde{d}_u + 0.32(15) \text{ e } \tilde{d}_d - 0.014(7)e\tilde{d}_s.$$

In the presence of a PQ mechanism:

$$d_n^{\mathrm{PQ}} = -0.204(11)d_u + 0.784(28)d_d - 0.0028(17)d_s$$
$$- 0.31(15)e\tilde{d}_u + 0.62(31)e\tilde{d}_d$$

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