nEDM limits on ALP couplings to fermions

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Asymmetry
Essential Asymmetries of Nature

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Work in collaboration with
Belén Gavela, Benjamín Grinstein and Pablo Quílez

arXiv:2403.12133

Rencontres de Moriond since 1966

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

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

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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 $U(1)_{\textbf{Axial}}$

$\Longrightarrow$ **Physical combination is**

$$\bar{\theta} = \theta + \operatorname{Arg}\det\left(\boldsymbol{M}_u \boldsymbol{M}_d\right)$$

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CP-violation in flavor-nondiagonal entries

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

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Will source CP-violating observables e.g. EDMs

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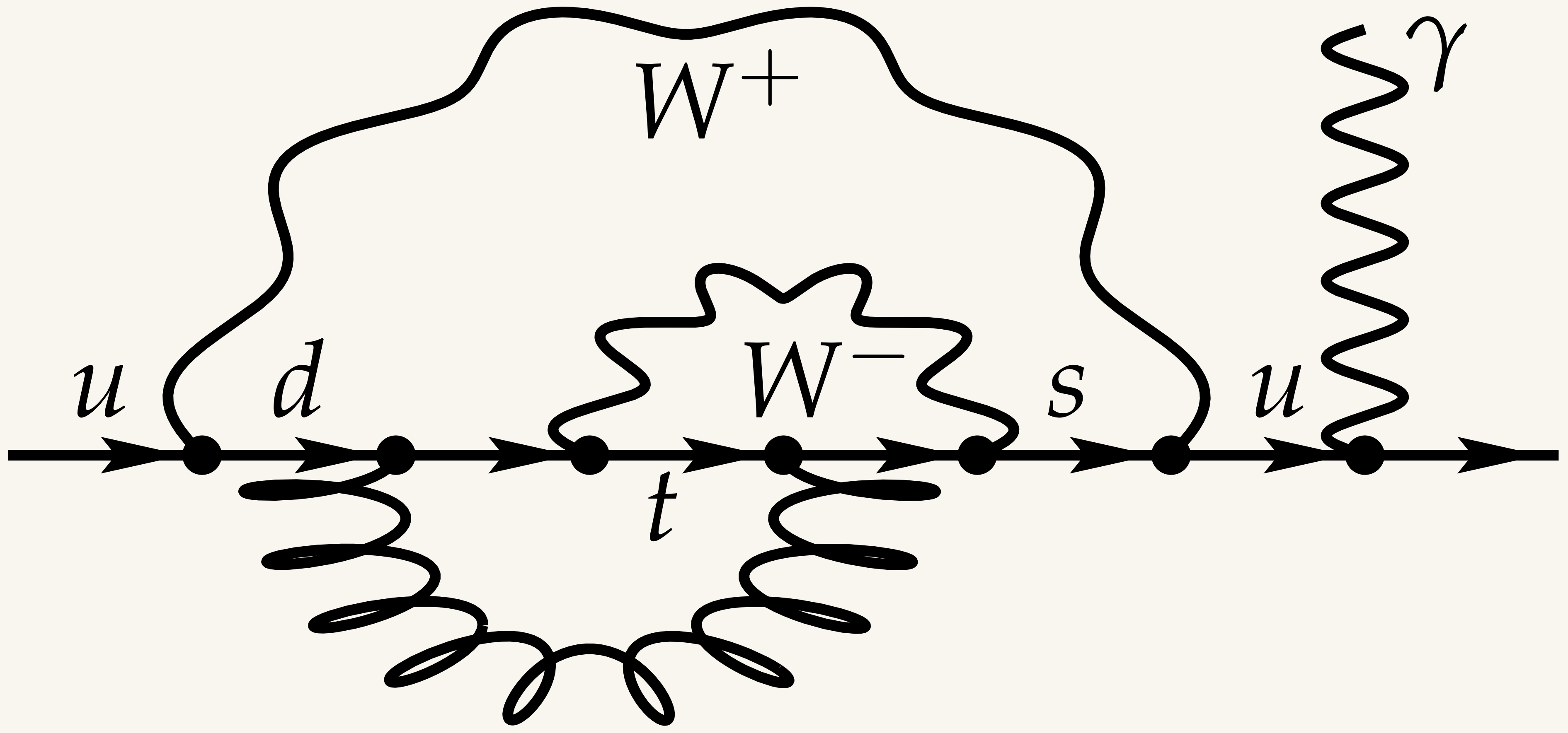
The neutron EDM

SM prediction 3-loop suppressed!!



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

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

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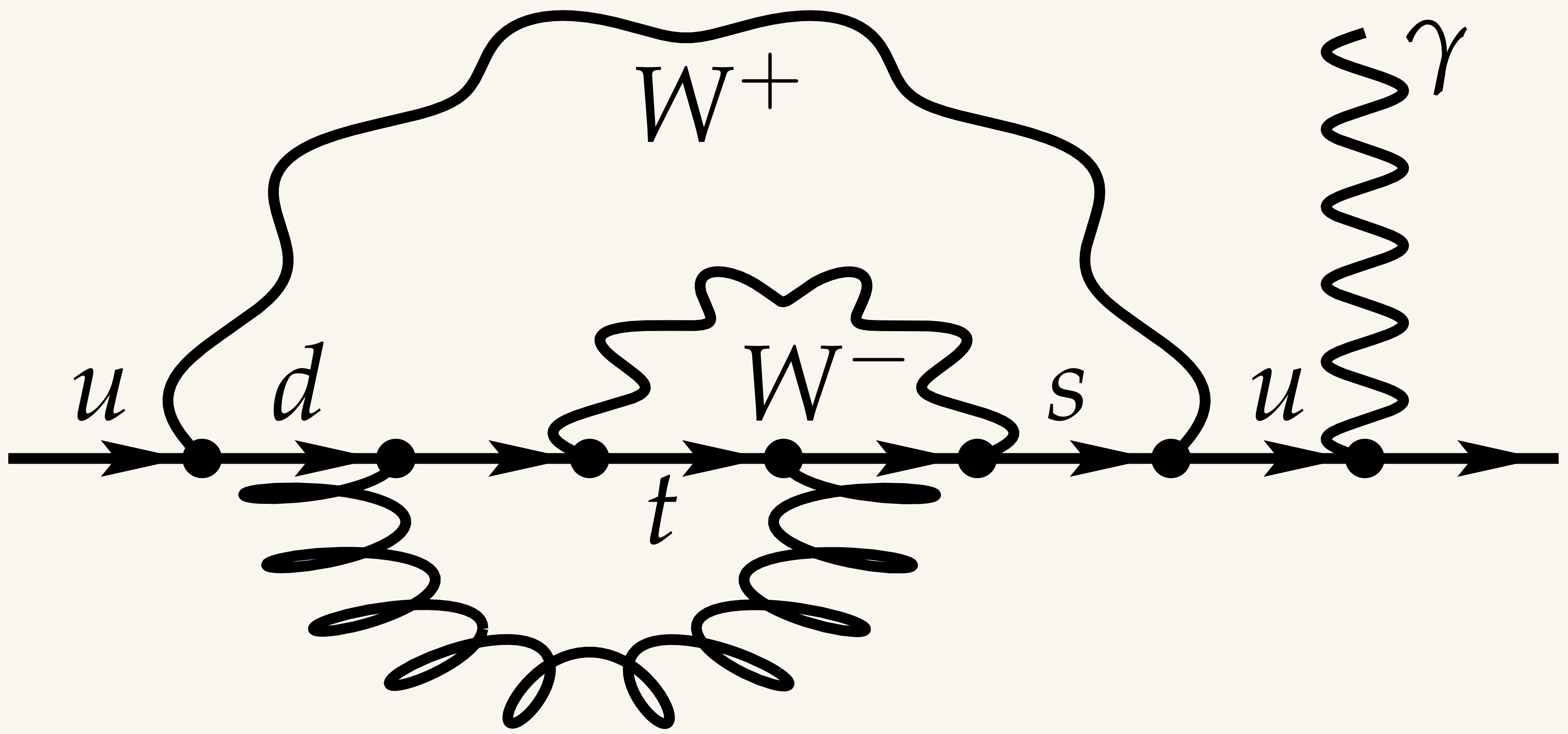

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How can C_Q, C_{u_R}, C_{d_R} contribute?

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

ALP contributions appear at 1-loop

[Baluni, *Phys. Rev. D 19, 2227*]

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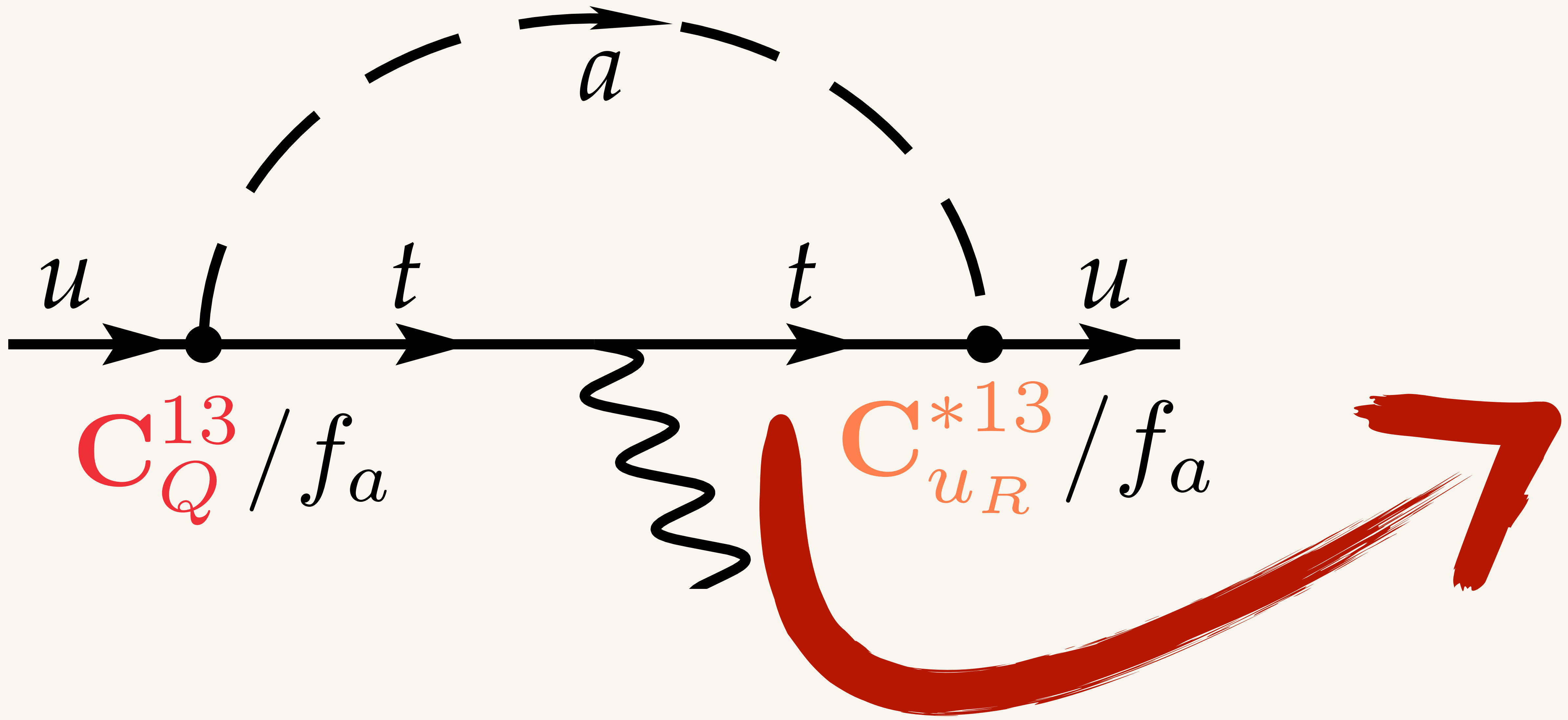
ALP contributions to the nEDM



$$\frac{d_u}{e} \sim \frac{Q_u}{32\pi^2} m_t \frac{\mathrm{Im}(\mathbf{C}_Q^{13}\mathbf{C}_{u_R}^{*13})}{f_a^2}$$

Corrections to the quark EDMs and CEDMs

[Di Luzio et al., 2010.13760]

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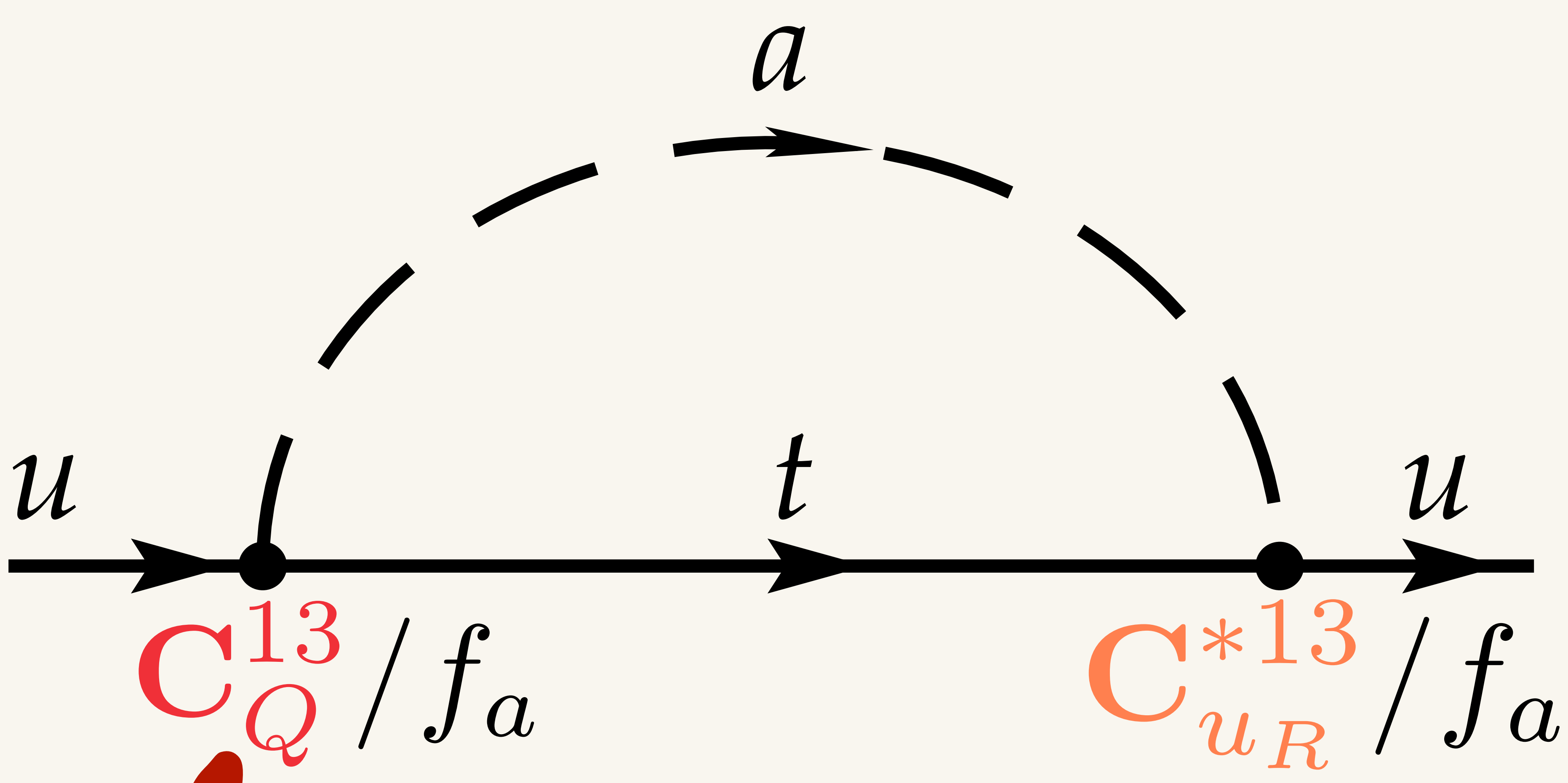
ALP contributions to the nEDM



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

NEW

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

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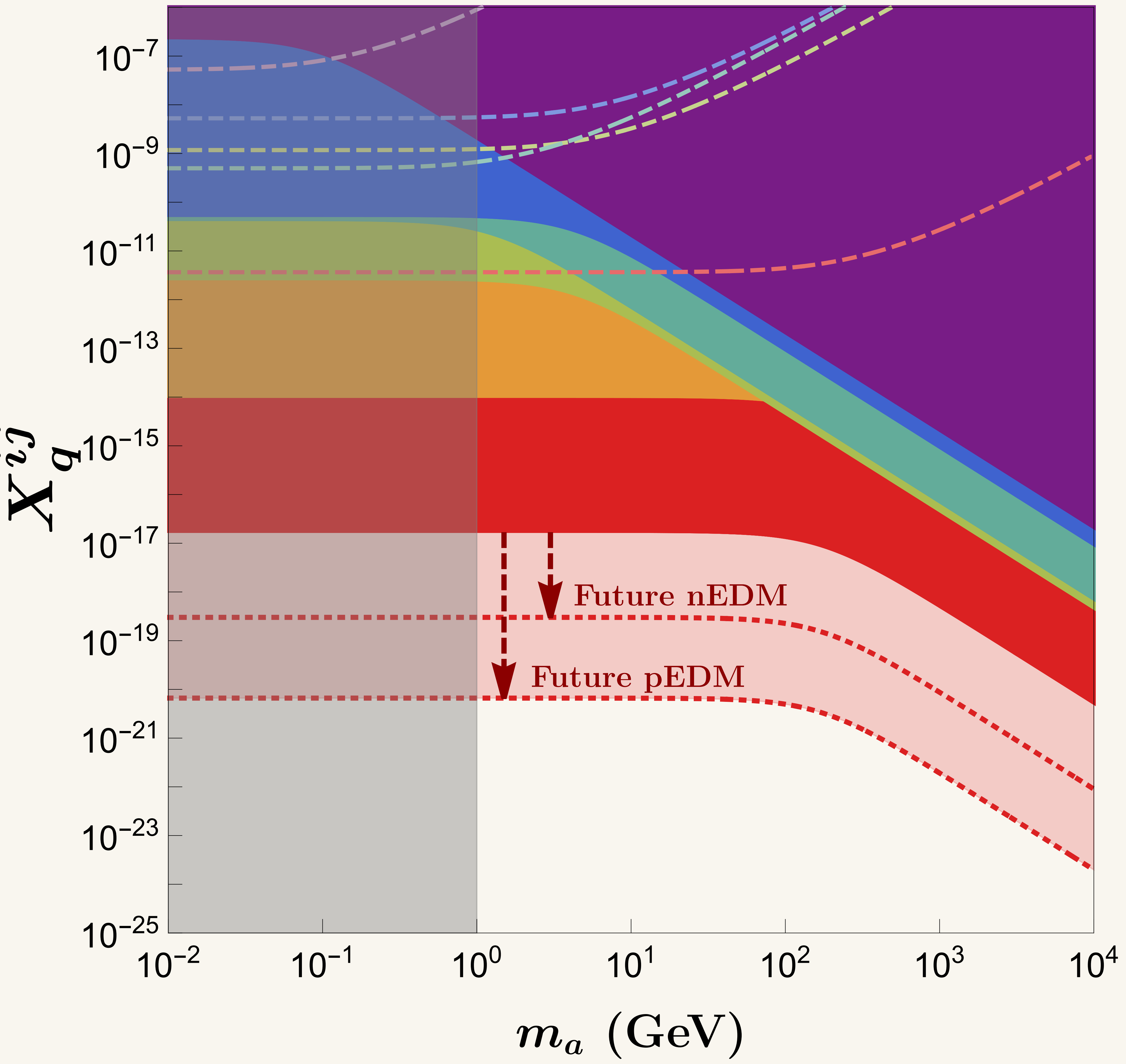
nEDM limits on ALP-fermion couplings



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

Dotted lines:

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

Solid regions:

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

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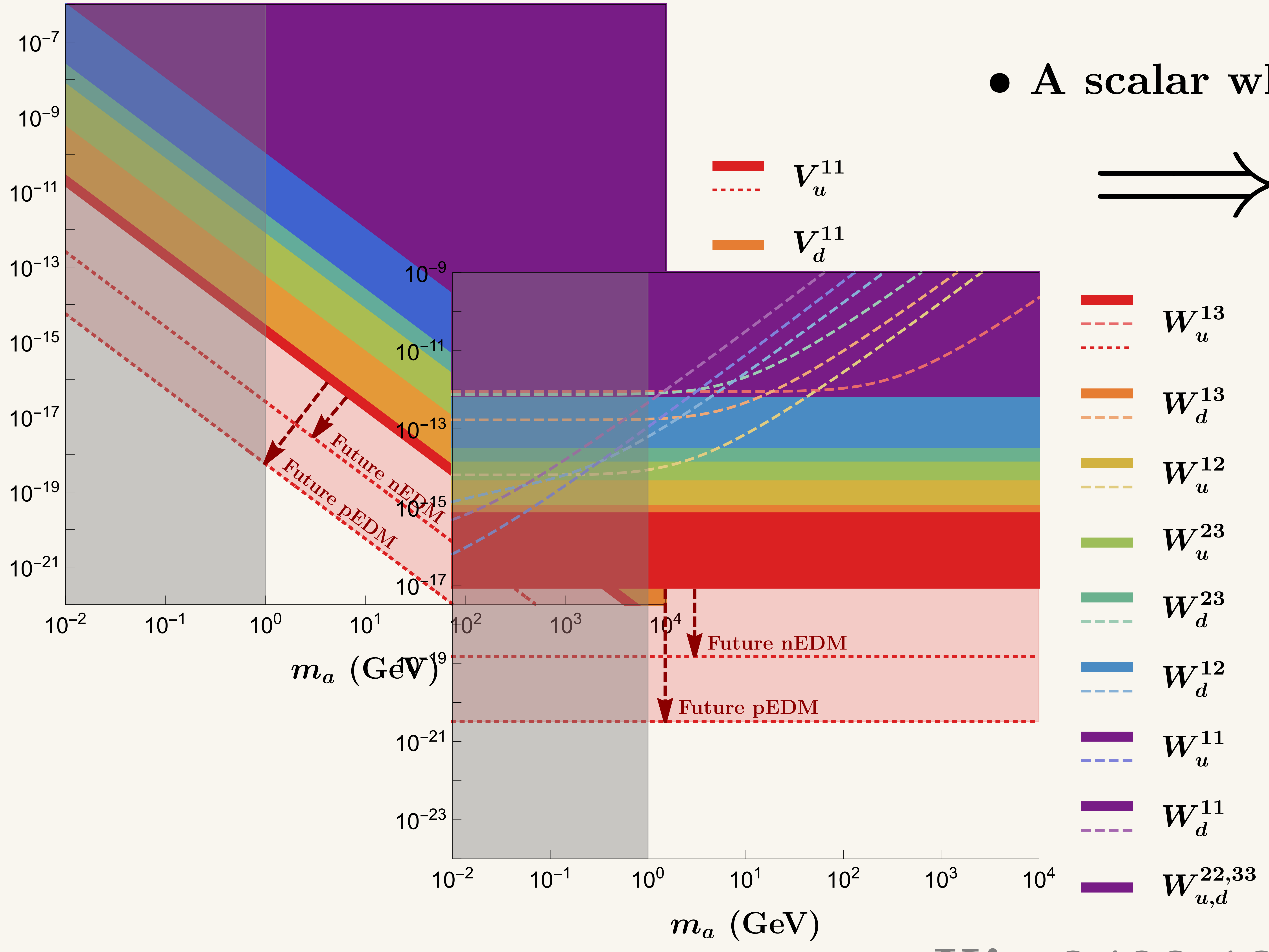
General scalar theory



- A scalar which may not be a pseudo-Goldstone

$\Longrightarrow$ More parametric freedom

We also

- Improved existing bounds
- Established new bounds

MORE IN OUR PAPER

arXiv:2403.12133

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

Interactions of the quarks with an ALP:

$$\mathcal{L}_a \supset \frac{\partial_\mu a}{f_a}\left(\bar{Q}_L \gamma^\mu \boldsymbol{C}_Q Q_L + \bar{u}_R \gamma^\mu \boldsymbol{C}_{u_R} u_R + \bar{d}_R \gamma^\mu \boldsymbol{C}_{d_R} d_R\right)$$

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

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

Interactions of the quarks with a general scalar:

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

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Backup

Without a PQ mechanism:

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

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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Backup

$$\bar{\theta}\left(\mu_{\mathrm{IR}}\right) \simeq \bar{\theta}_0 + \sum_{u_i=\{u,c,t\}} \frac{m_{u_k}\left(m_a^2+\widehat{m}_{u_k}^2\right)}{16\pi^2 f_a^2 m_{u_i}} \operatorname{Im}\left(\boldsymbol{C}_Q^{ik}\boldsymbol{C}_{u_R}^{*ik}\right) \log\frac{f_a^2}{\max\left(m_a^2, m_{u_k}^2\right)} + \sum_{d_i=\{d,s,b\}} \frac{m_{d_k}\left(m_a^2+\widehat{m}_{d_k}^2\right)}{16\pi^2 f_a^2 m_{d_i}} \operatorname{Im}\left(\boldsymbol{C}_Q^{ik}\boldsymbol{C}_{d_R}^{*ik}\right) \log\frac{f_a^2}{\max\left(m_a^2, m_{d_k}^2\right)}$$

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