ALP contribution to the Strong CP problem

Instituto de Física Teórica UAM-CSIC

Universidad Autónoma de Madrid

Víctor Enguita

Work in collaboration with

Belén Gavela,
Benjamín Grinstein
and
Pablo Quílez

arXiv:2403.12133

AsYmmetry Essential Asymmetries of Nature

Funded by the Horizon 2020 Framework Programme of the European Union

SUSY 2024 Theory meets Experiment

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-like particles (ALPs)

Axions and ALPs are:

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

  $\Longrightarrow$ shift symmetry $a \to a + \text{const.}$

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

- **well motivated NP candidates**

- **targeted by an extensive experimental program**

arXiv:2403.12133

Axion-like particles (ALPs)

Axions and ALPs are:

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

  $\Longrightarrow$ shift symmetry $a \to a + \text{const.}$

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

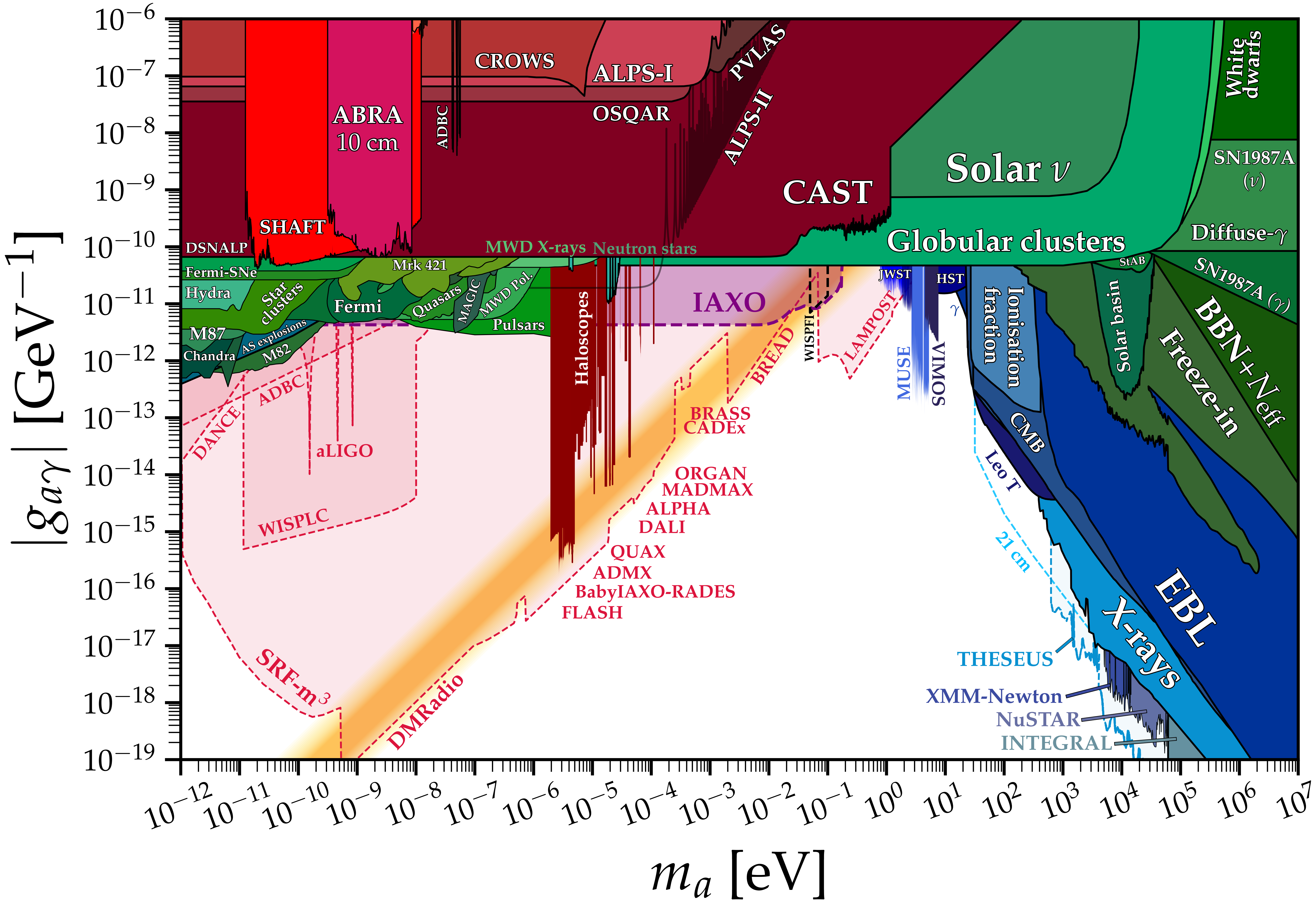
- **well motivated NP candidates**

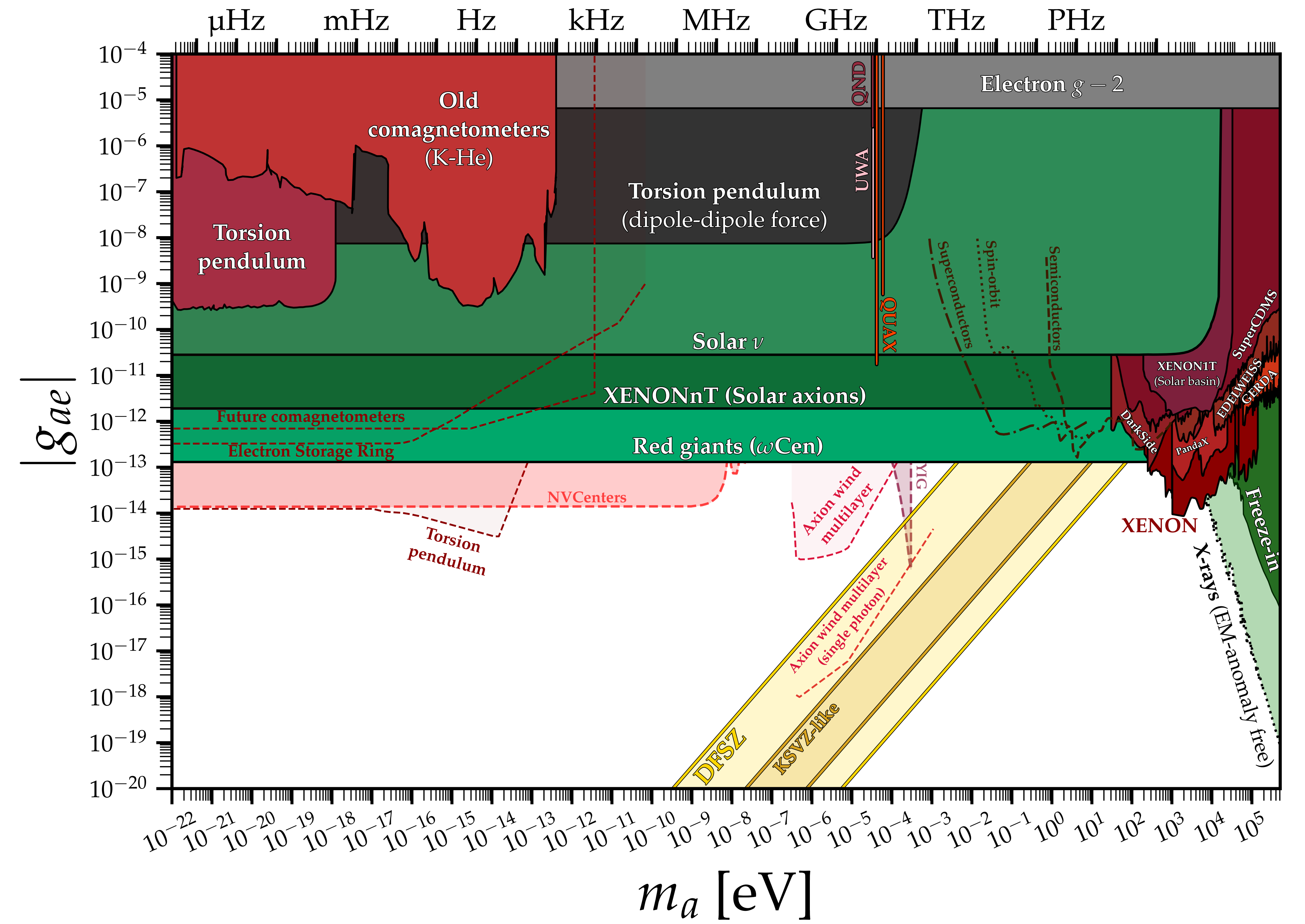
- **targeted by an extensive experimental program**

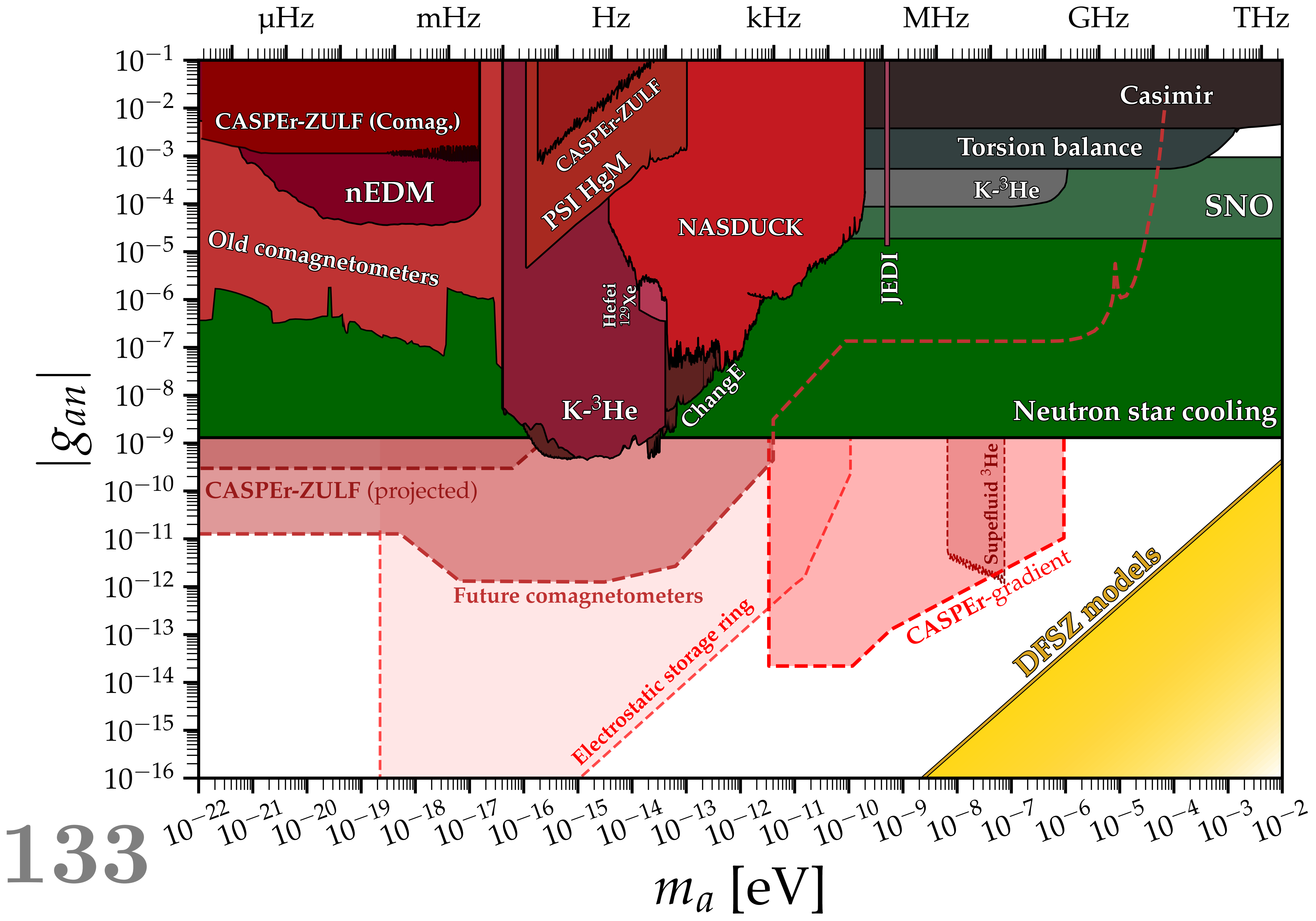
	Axion	**ALPs**
Strong CP problem	✓	✗
Dark Matter	✓	✓
Cosmic Inflation	✓	✓
Baryogenesis	✓	✓

arXiv:2403.12133

[cajohare.github.io/AxionLimits]







- **targeted by an extensive experimental program**

arXiv:2403.12133

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*]

arXiv:2403.12133

The ALP Effective Field Theory

ALP couplings to up- and down-type quarks:

$$\mathcal{L}_a \supset \left(\bar{u}_L \boldsymbol{M}_u u_R + \bar{d}_L \boldsymbol{M}_d d_R + \text{h.c.}\right) + \theta \frac{\alpha_s}{8\pi} G_{\mu\nu}\widetilde{G}^{\mu\nu}$$

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

$\Longrightarrow$ **Physical combination is**

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

arXiv:2403.12133

ALP couplings to fermions

ALP couplings to up- and down-type quarks:

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

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

arXiv:2403.12133

ALP couplings to fermions

ALP couplings to up- and down-type quarks:

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

CP-violation in flavor-nondiagonal entries

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

arXiv:2403.12133

ALP couplings to fermions

ALP couplings to up- and down-type quarks:

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

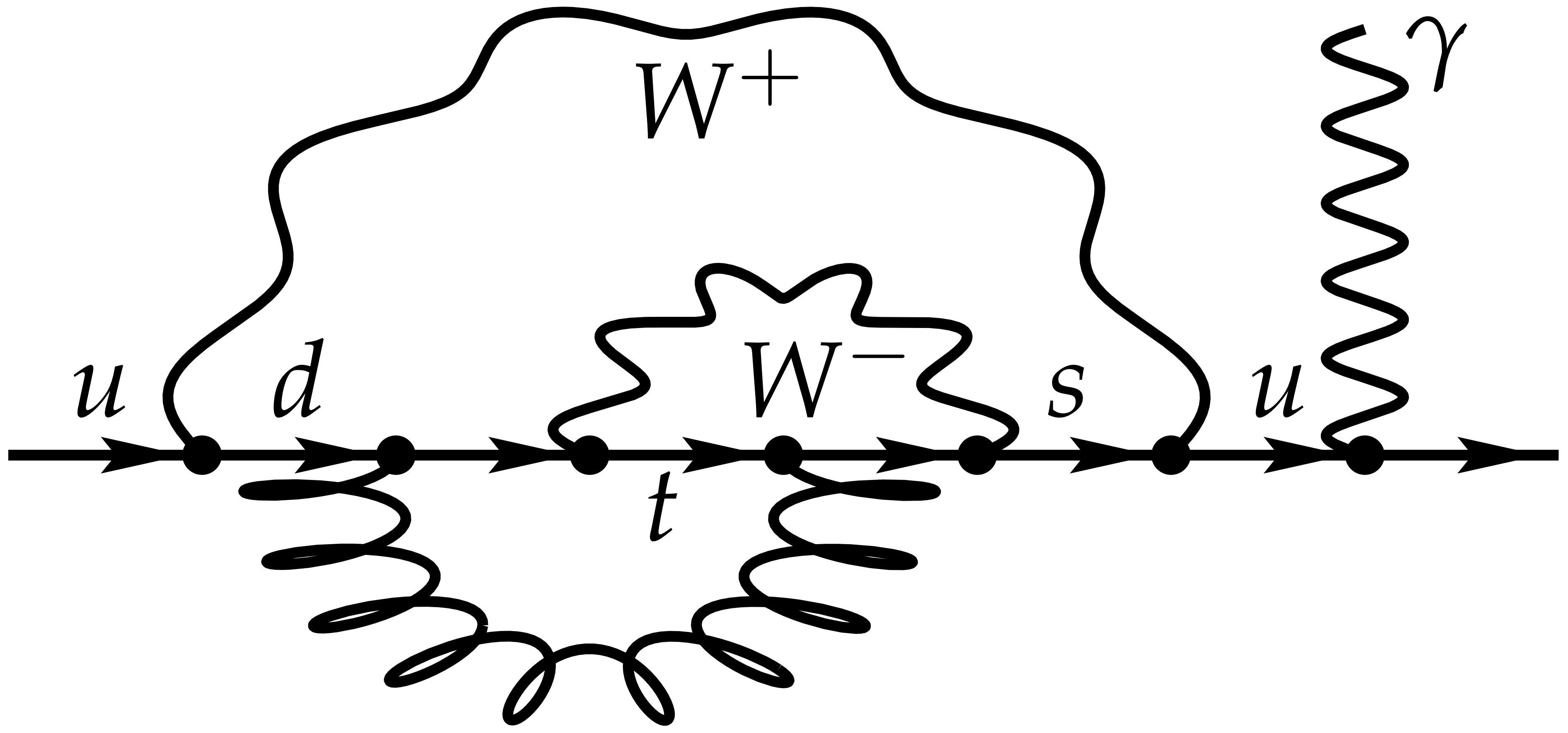
CP-violation in flavor-nondiagonal entries

Will source CP-violating observables e.g. EDMs

arXiv:2403.12133

The neutron EDM

SM prediction extremely suppressed!!!

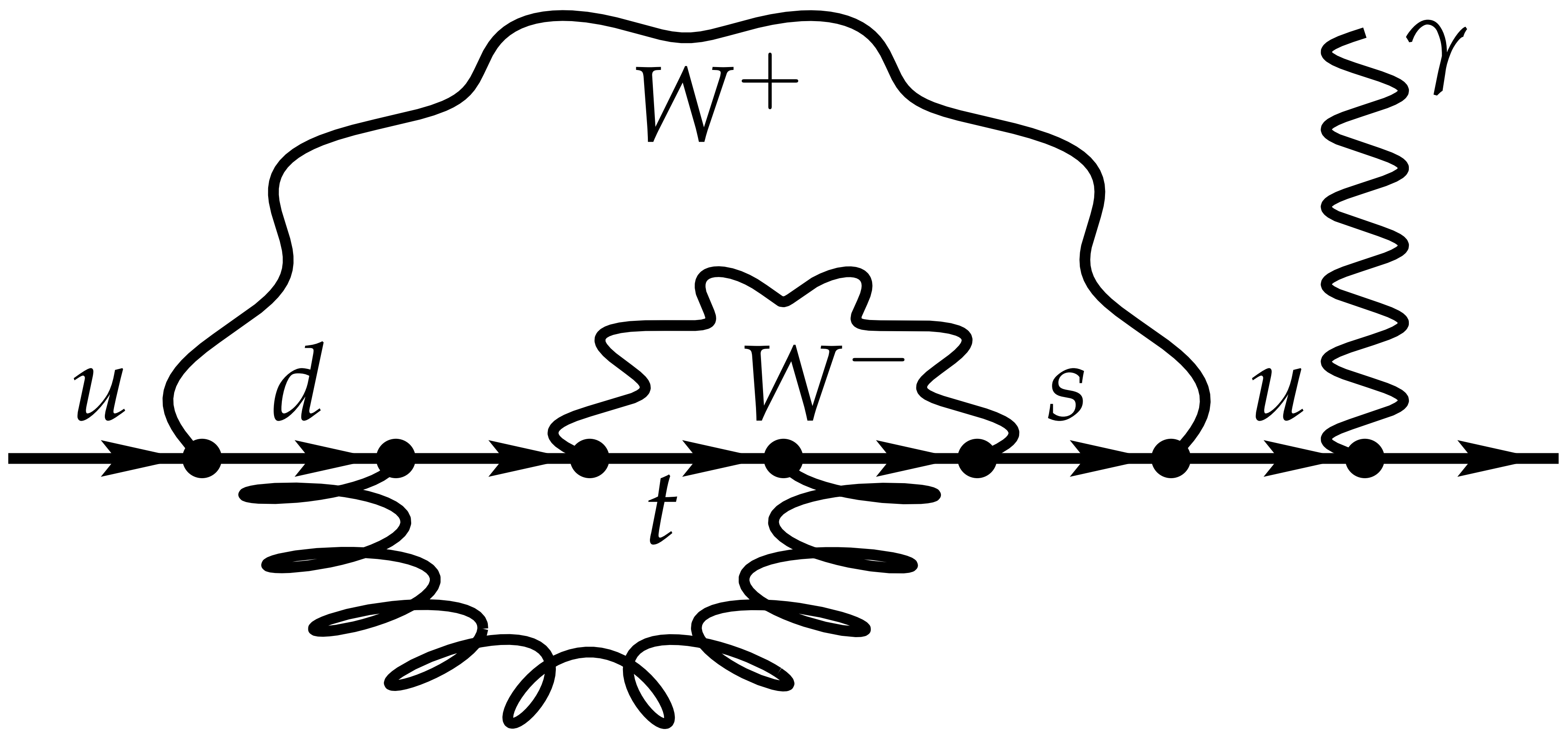


nEDM extremely well constrained: $d_n^{\text{exp}} \lesssim 2.6 \times 10^{-26}$ [$e{\cdot}$cm]

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

The neutron EDM

SM prediction extremely suppressed!!!



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

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

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?

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

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

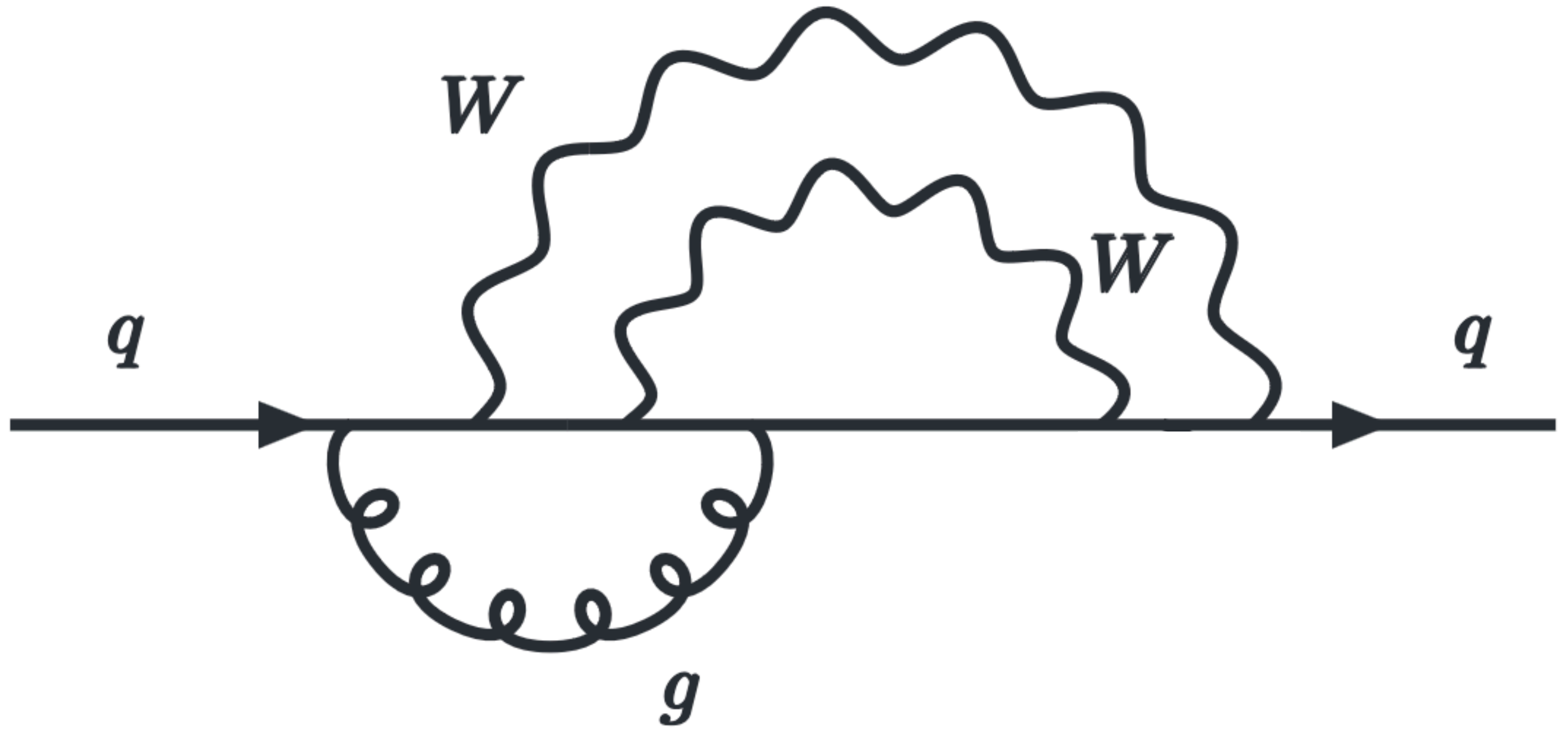
Radiative corrections to $\bar{\theta}$

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

$$\bar{\theta} = \theta + \boxed{\mathrm{Arg}\,\det(M_u M_d)}$$

SM $\longrightarrow$ three-loop

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



arXiv:2403.12133

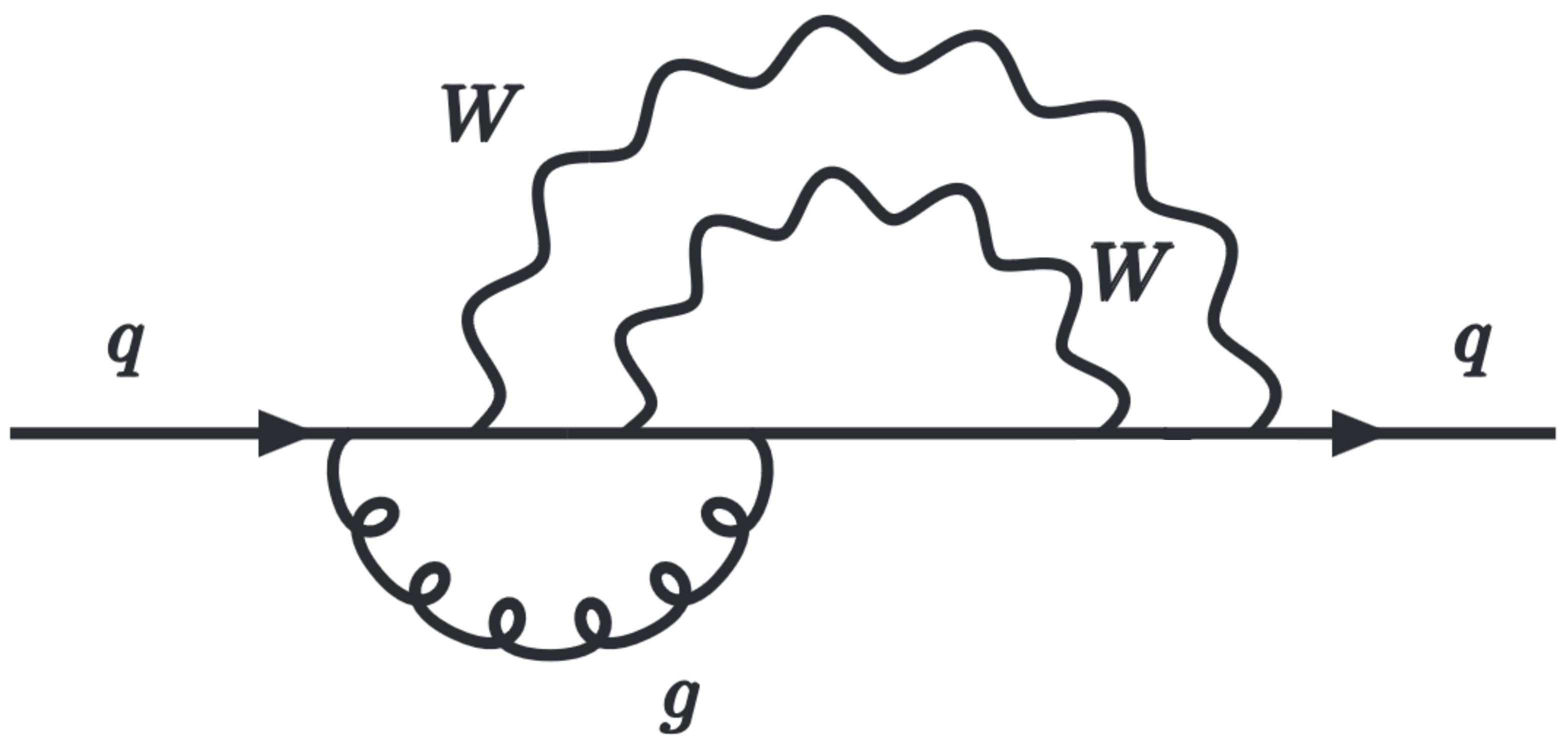
Radiative corrections to $\bar{\theta}$

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

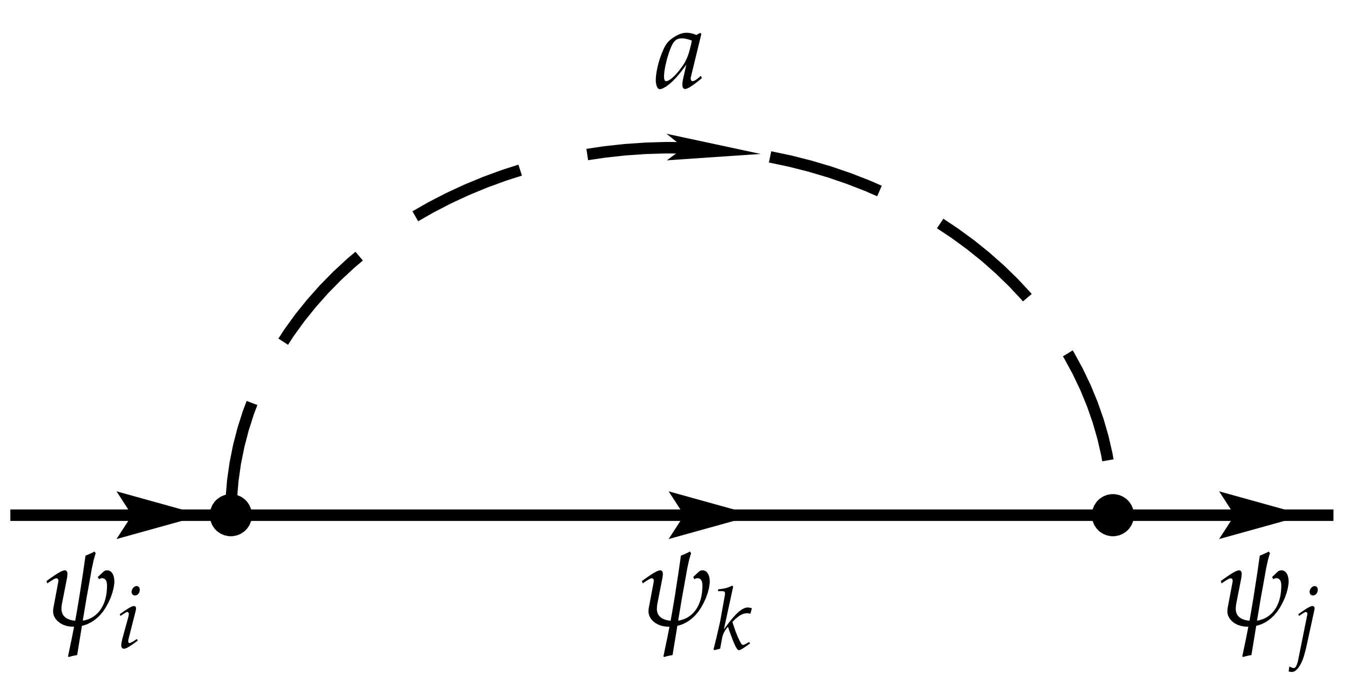
$$\bar{\theta} = \theta + \text{Arg}\det(M_u M_d)$$

SM $\longrightarrow$ three-loop

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



ALP EFT $\longrightarrow$ one-loop

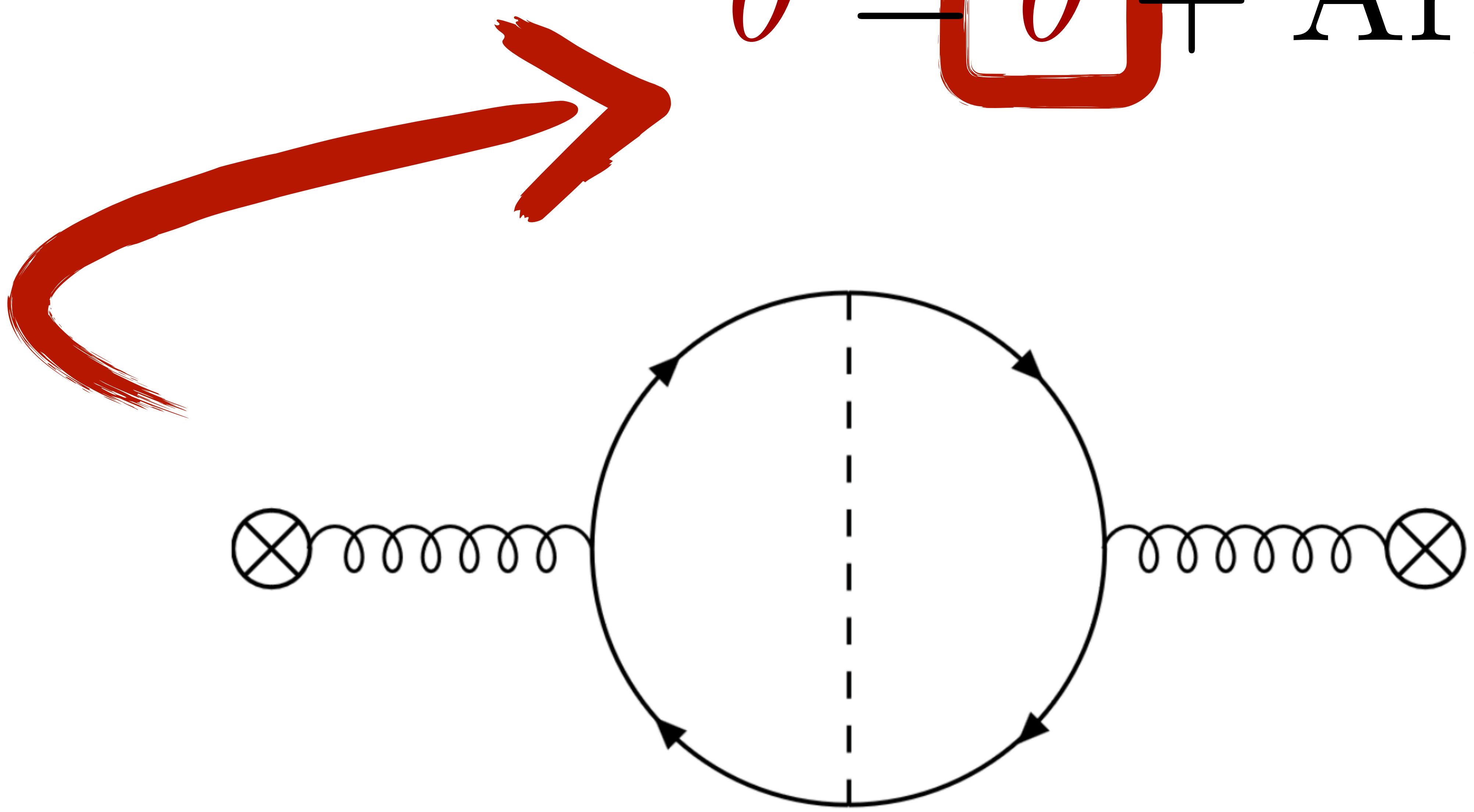


arXiv:2403.12133

Radiative corrections to $\bar{\theta}$

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

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



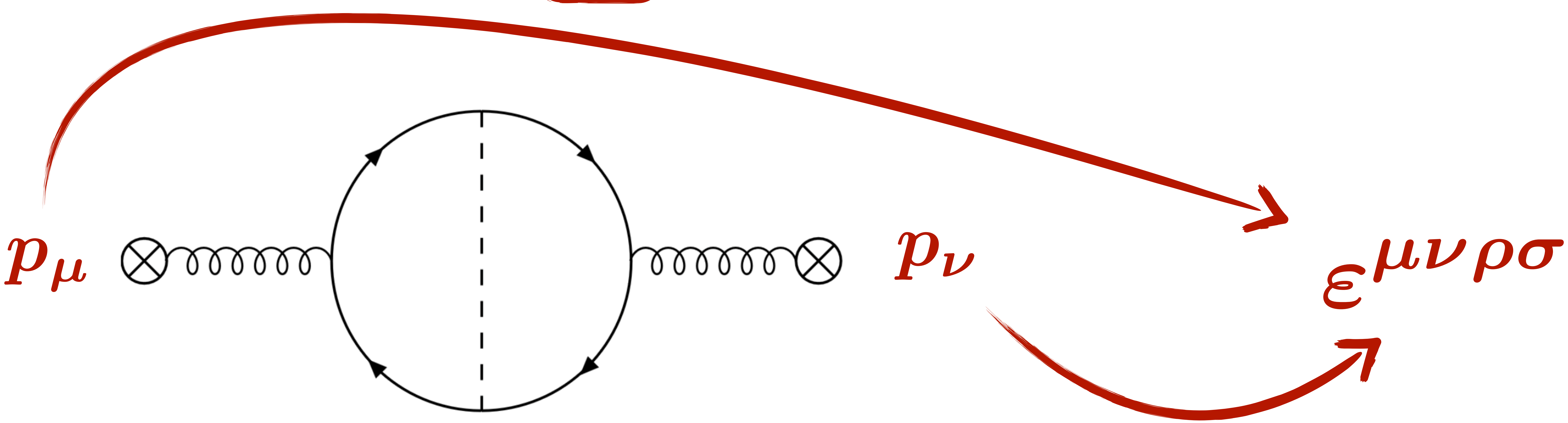
[Banno et al., 2311.07817]

arXiv:2403.12133

Radiative corrections to $\bar{\theta}$

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

$$\bar{\theta} = \theta + \operatorname{Arg}\det(M_u M_d)$$



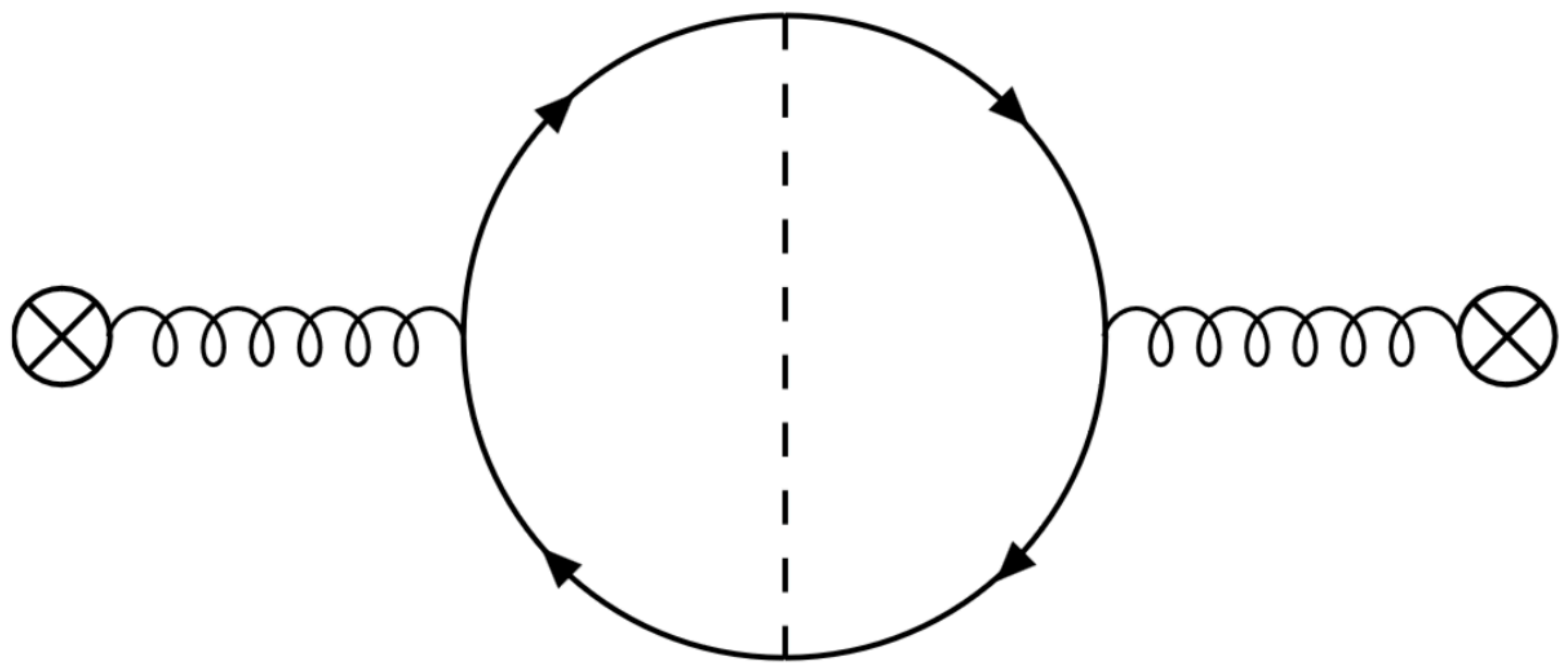
[Banno et al., 2311.07817]

arXiv:2403.12133

Radiative corrections to $\bar{\theta}$

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

$$\bar{\theta} = \theta + \mathrm{Arg}\,\det(M_u M_d)$$



BUT

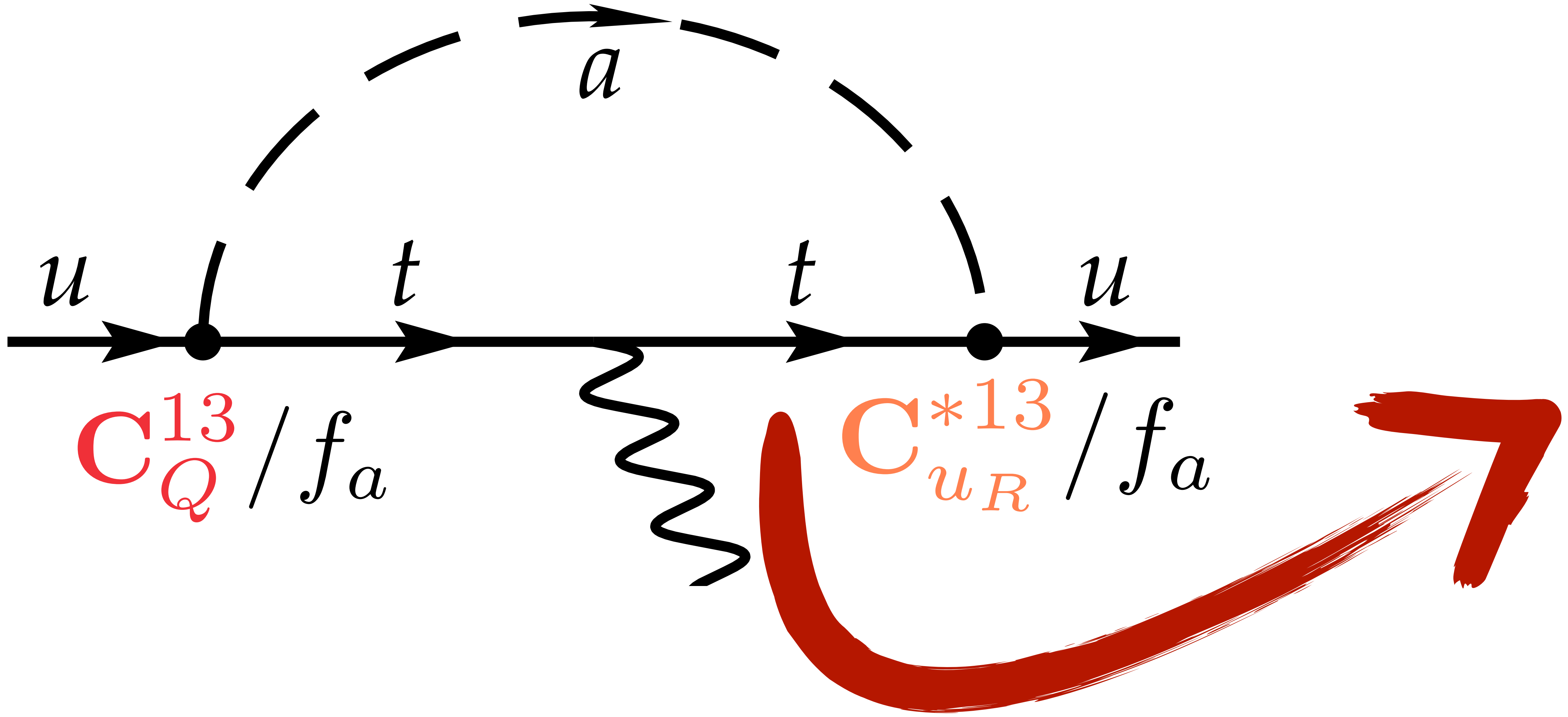
New contributions highly subdominant

[Banno et al., 2311.07817]

arXiv:2403.12133

ALP contributions to the nEDM

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



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

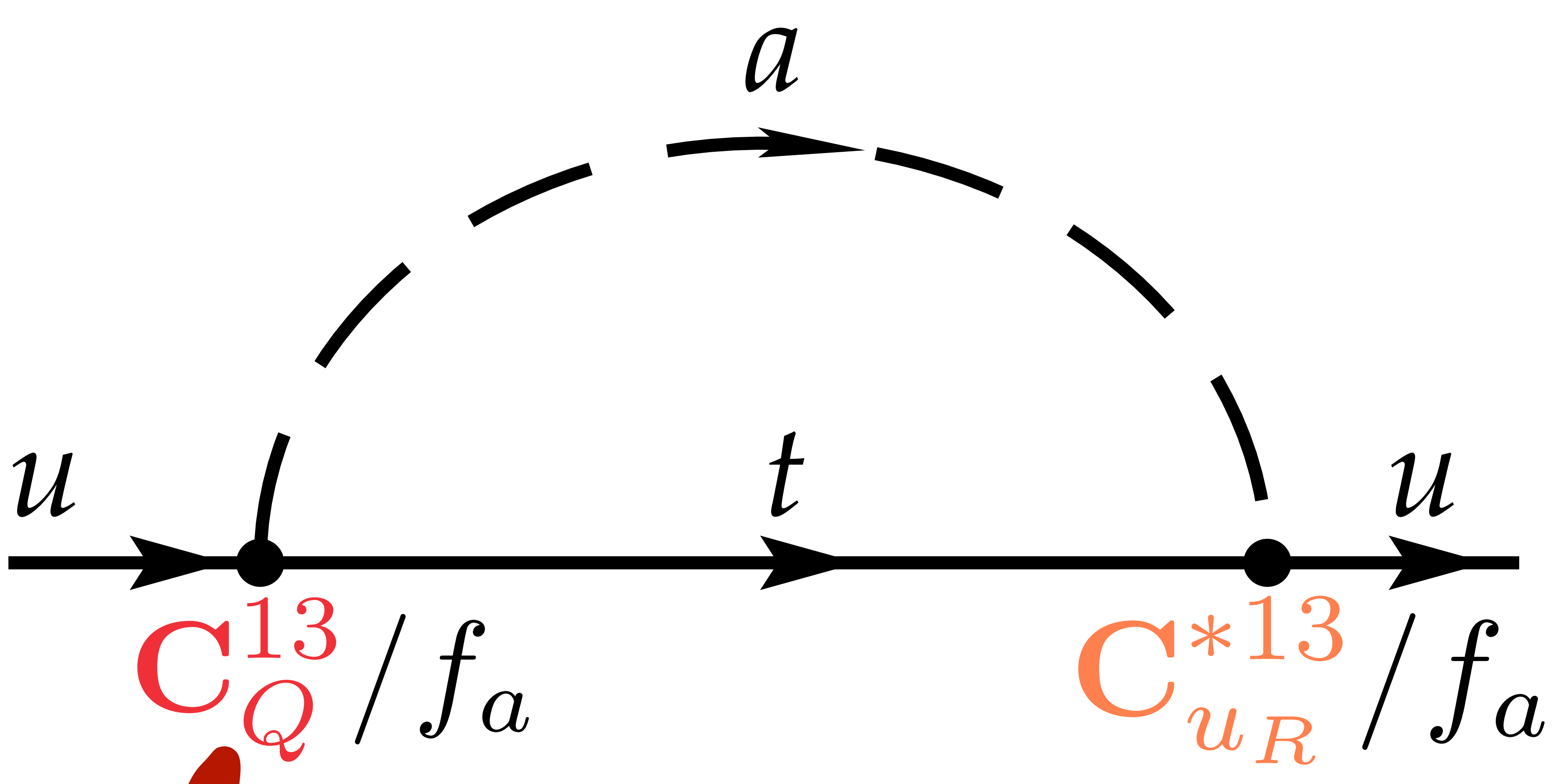
Corrections to the quark EDMs and CEDMs

[Di Luzio et al., 2010.13760]

arXiv:2403.12133

ALP contributions to the nEDM

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



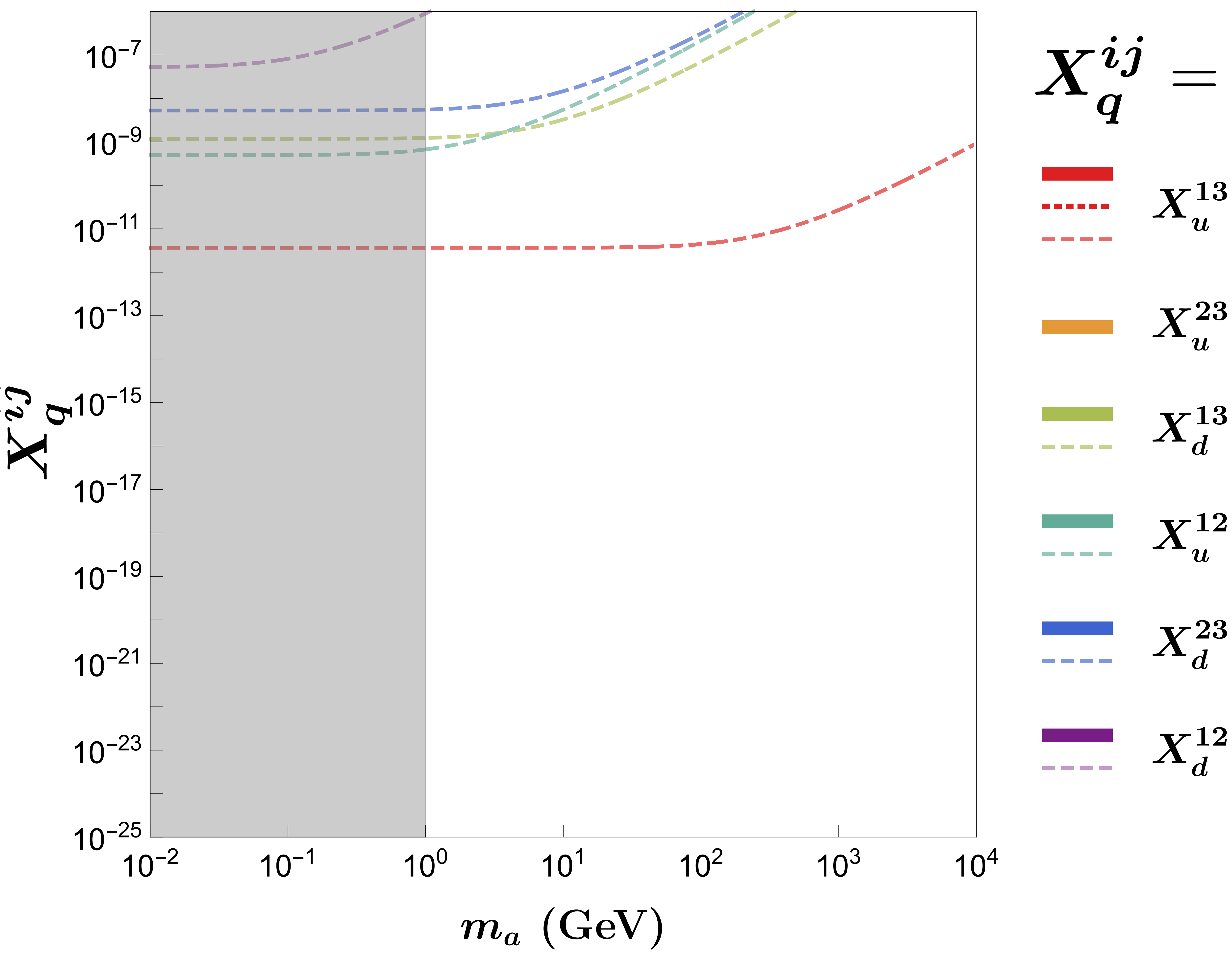
$$\Delta\bar{\theta}_{\text{ALP}} \sim \frac{1}{16\pi^2}\left(\frac{m_t^3}{m_u}\right)\frac{\text{Im}(C_Q^{13}\,C_{u_R}^{*13})}{f_a^2}$$

NEW

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

arXiv:2403.12133

nEDM limits on ALP-fermion couplings



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

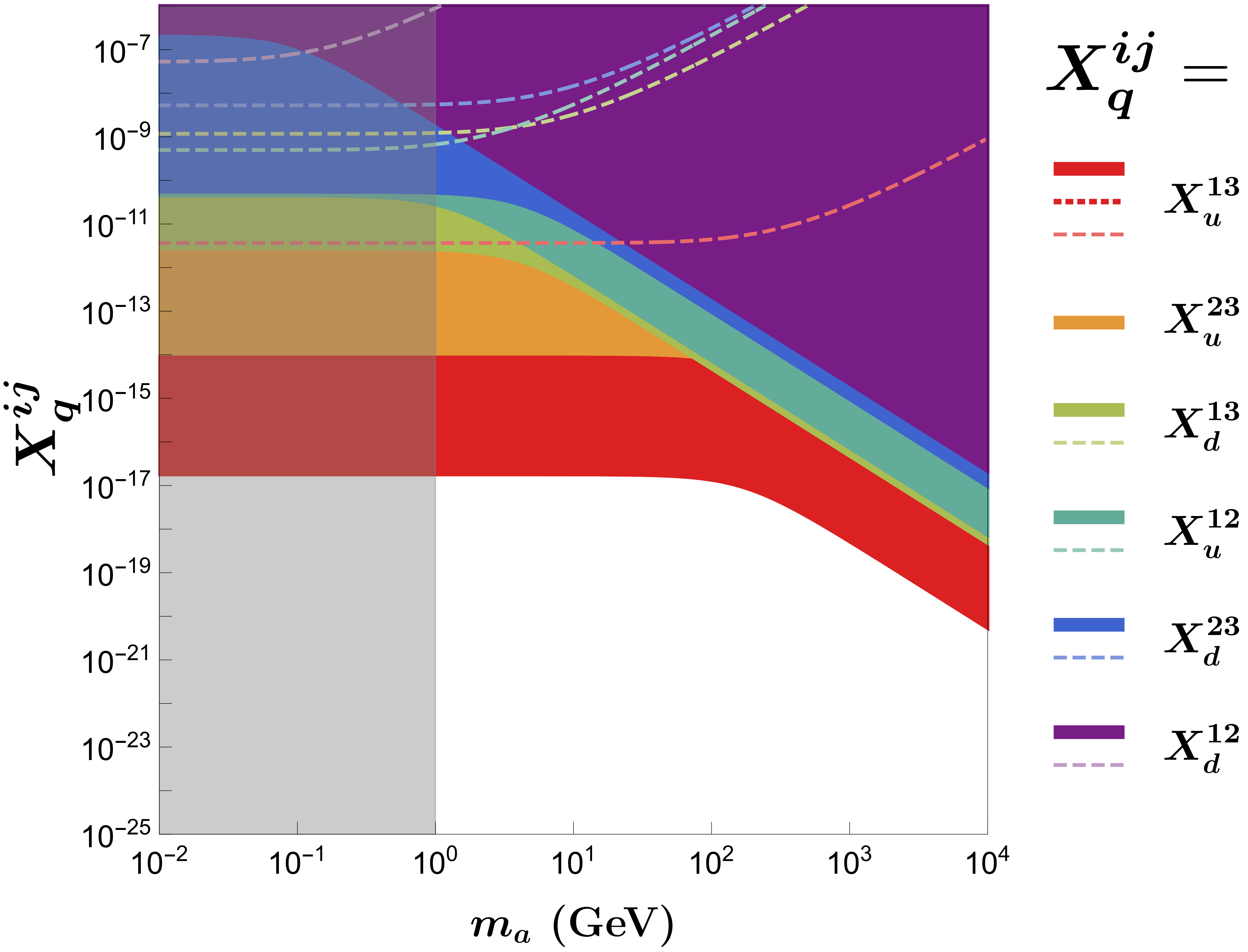
Dotted lines:

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

OLD

arXiv:2403.12133

nEDM limits on ALP-fermion couplings



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

Dotted lines:

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

OLD

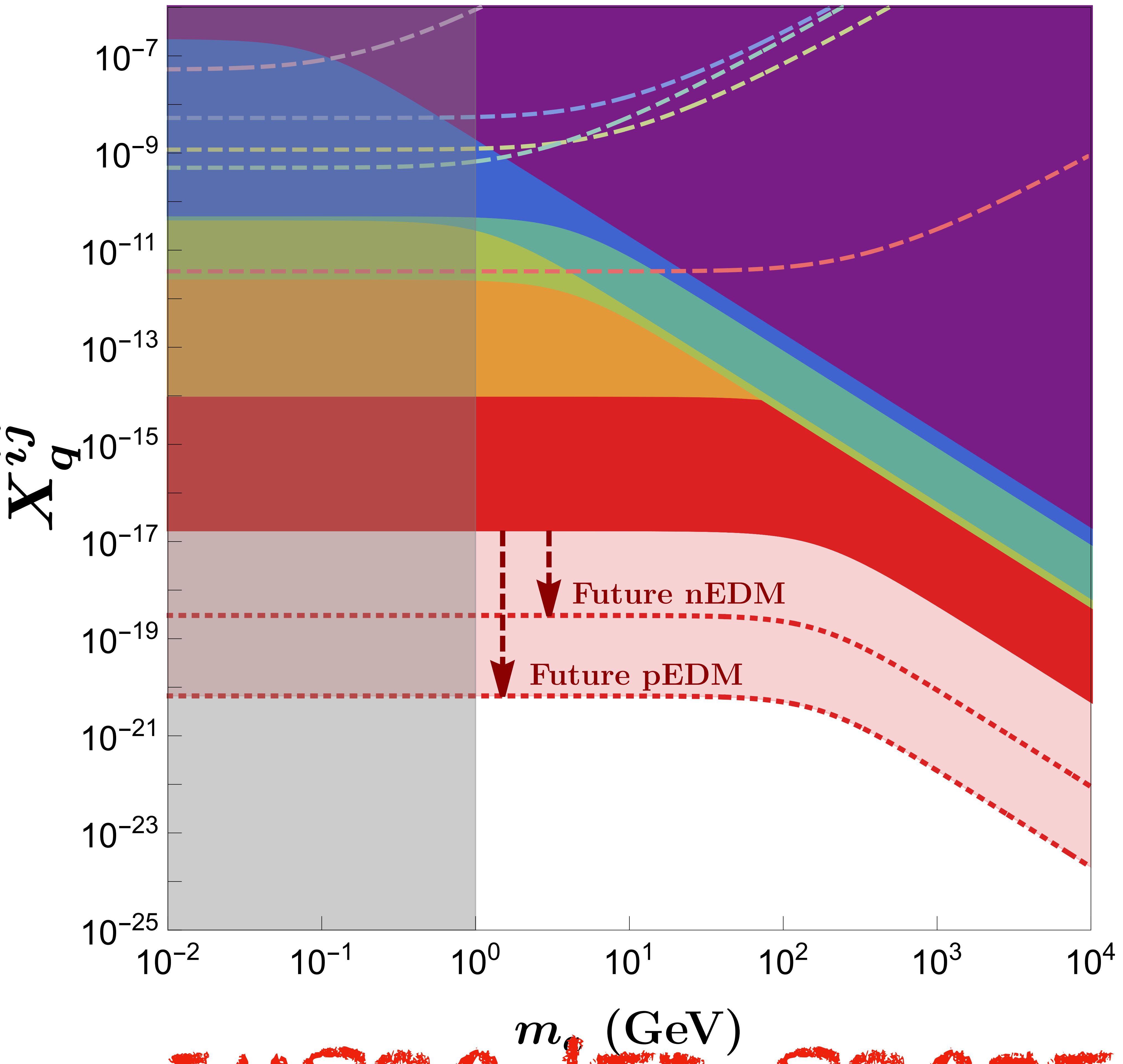
Solid regions:

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

NEW

arXiv:2403.12133

nEDM limits on ALP-fermion couplings



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

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

Dotted lines:

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

OLD

Solid regions:

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

NEW

IMPROVED PROJECTED REACH!

arXiv:2403.12133

General scalar theory

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

$\Longrightarrow$ more parametric freedom

- **The effective Lagrangian is**

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

arXiv:2403.12133

General scalar theory

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

$\Longrightarrow$ more parametric freedom

- **The effective Lagrangian is**

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

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

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

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

arXiv:2403.12133

General scalar theory

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

$\Longrightarrow$ more parametric freedom

Needed to restore shift-symmetry!!

- **The effective Lagrangian is**

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

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

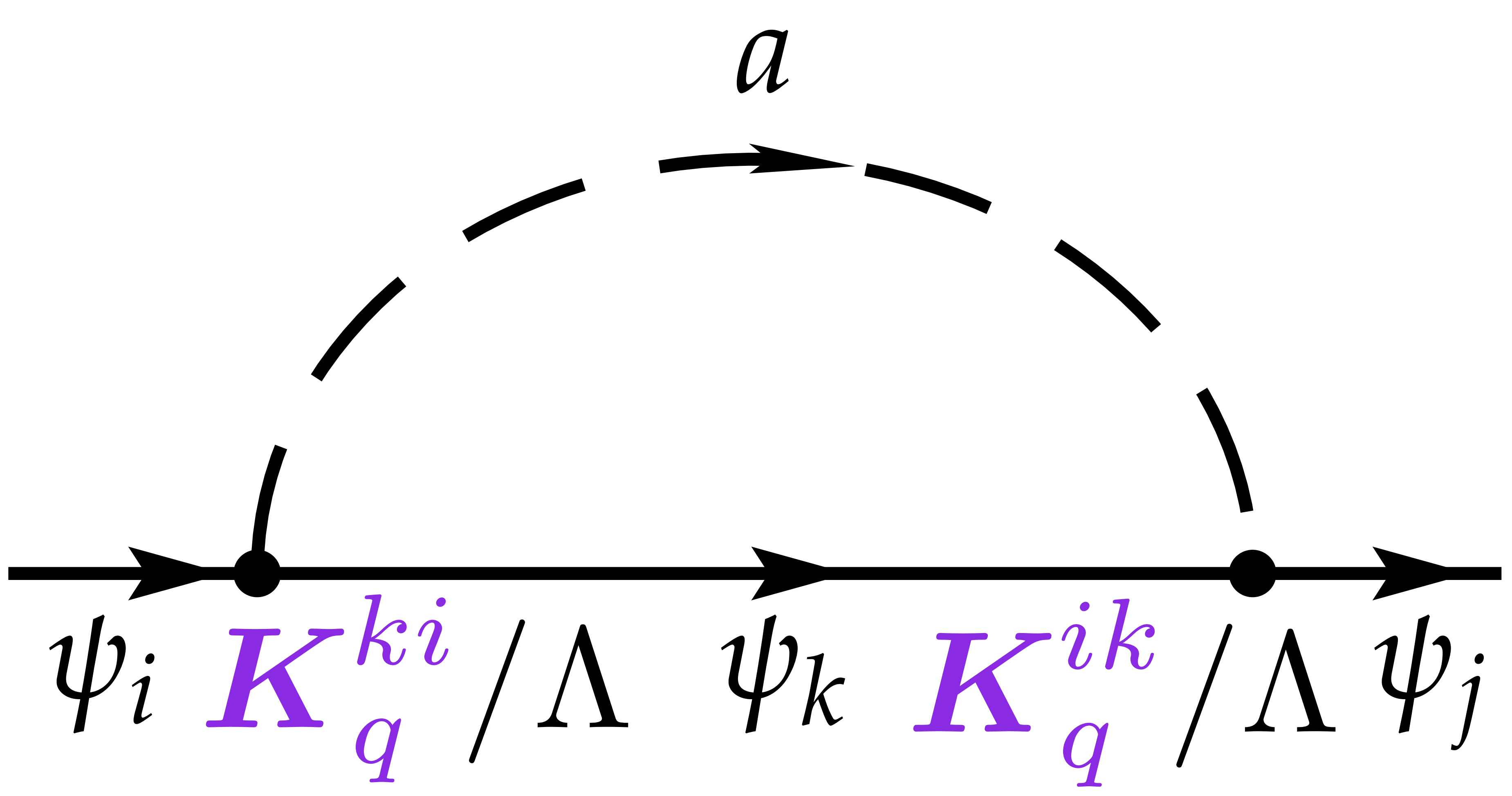
$$v \boldsymbol{K}_q \equiv \boldsymbol{C}_Q \boldsymbol{M}_q - \boldsymbol{M}_q \boldsymbol{C}_{q_R}$$

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

arXiv:2403.12133

ϕ contribution to the nEDM

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



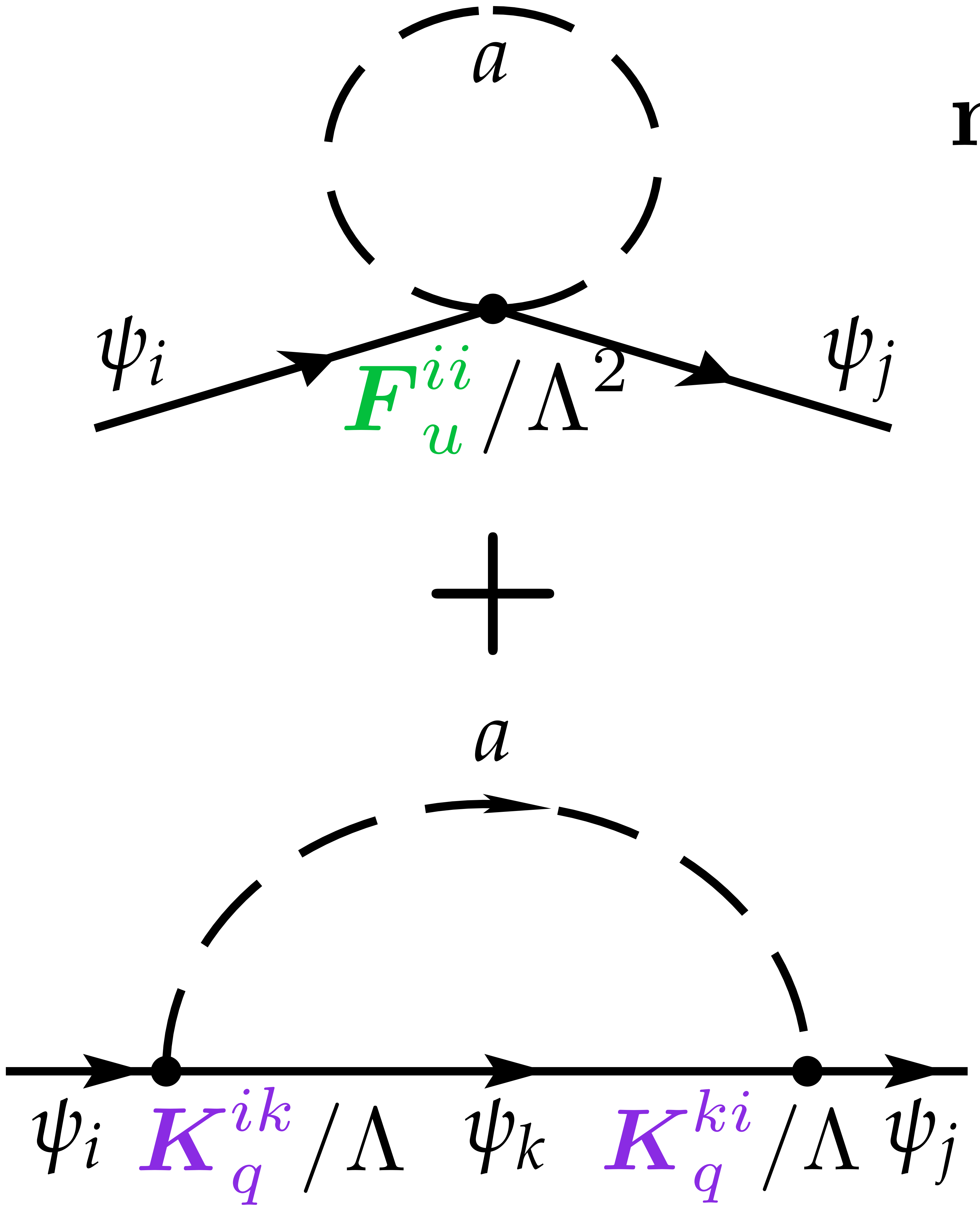
$$\left.\frac{d_n}{e}\right|_{d_q,\tilde{d}_q} \sim \frac{Q_u}{32\pi^2}\frac{v^2}{\Lambda^2}\frac{1}{m_t}\,\mathrm{Im}\left[\mathbf{K}_u^{13}\mathbf{K}_u^{31}\right]$$

Corrections to the quark EDMs and CEDMs

[Di Luzio et al., 2010.13760]

arXiv:2403.12133

ϕ contribution to the nEDM



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

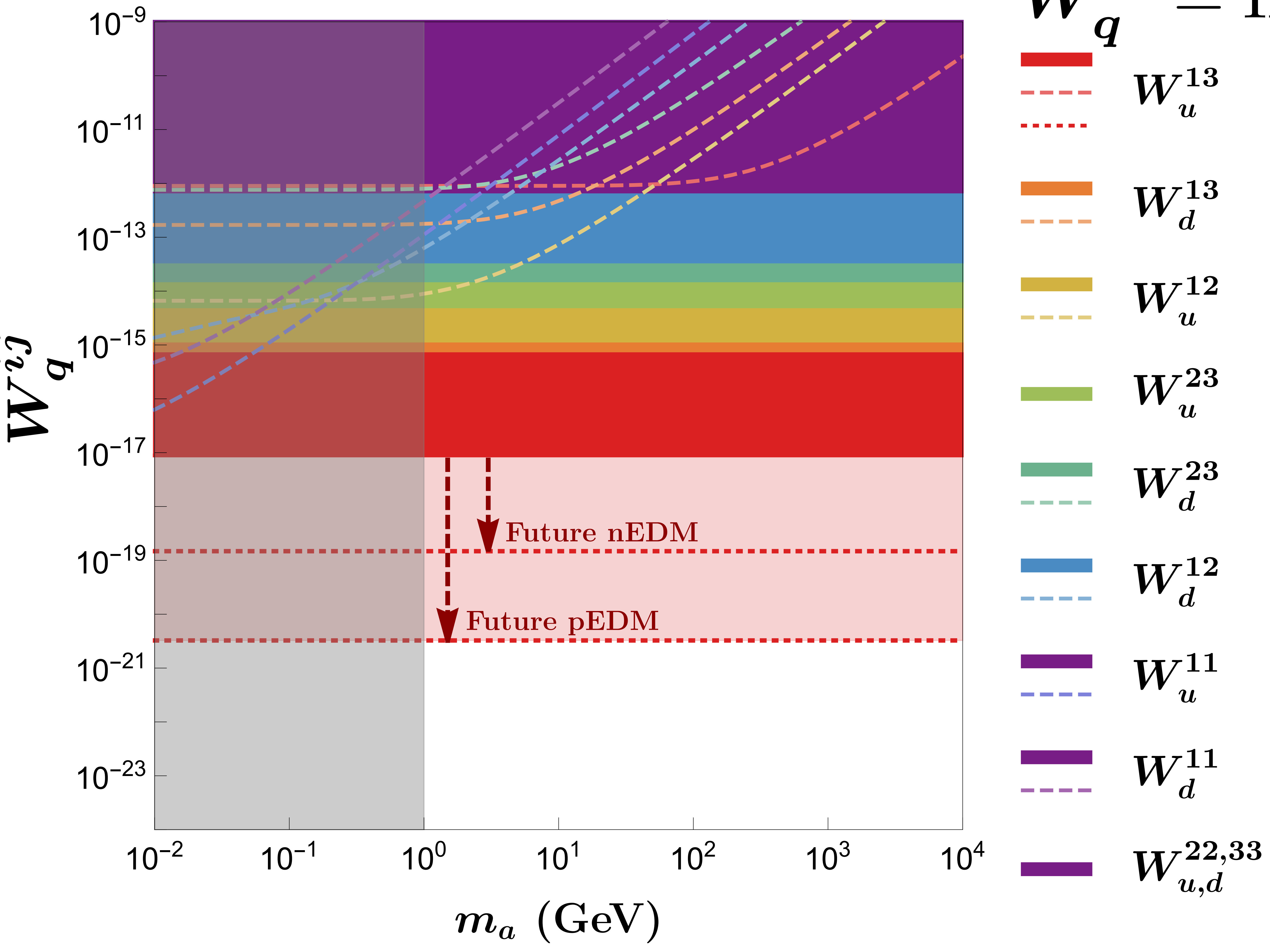
Corrections to $\bar{\theta} = \theta + \mathbf{Arg\,det}(M_u M_d)$

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

arXiv:2403.12133

nEDM on scalar-fermion couplings

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



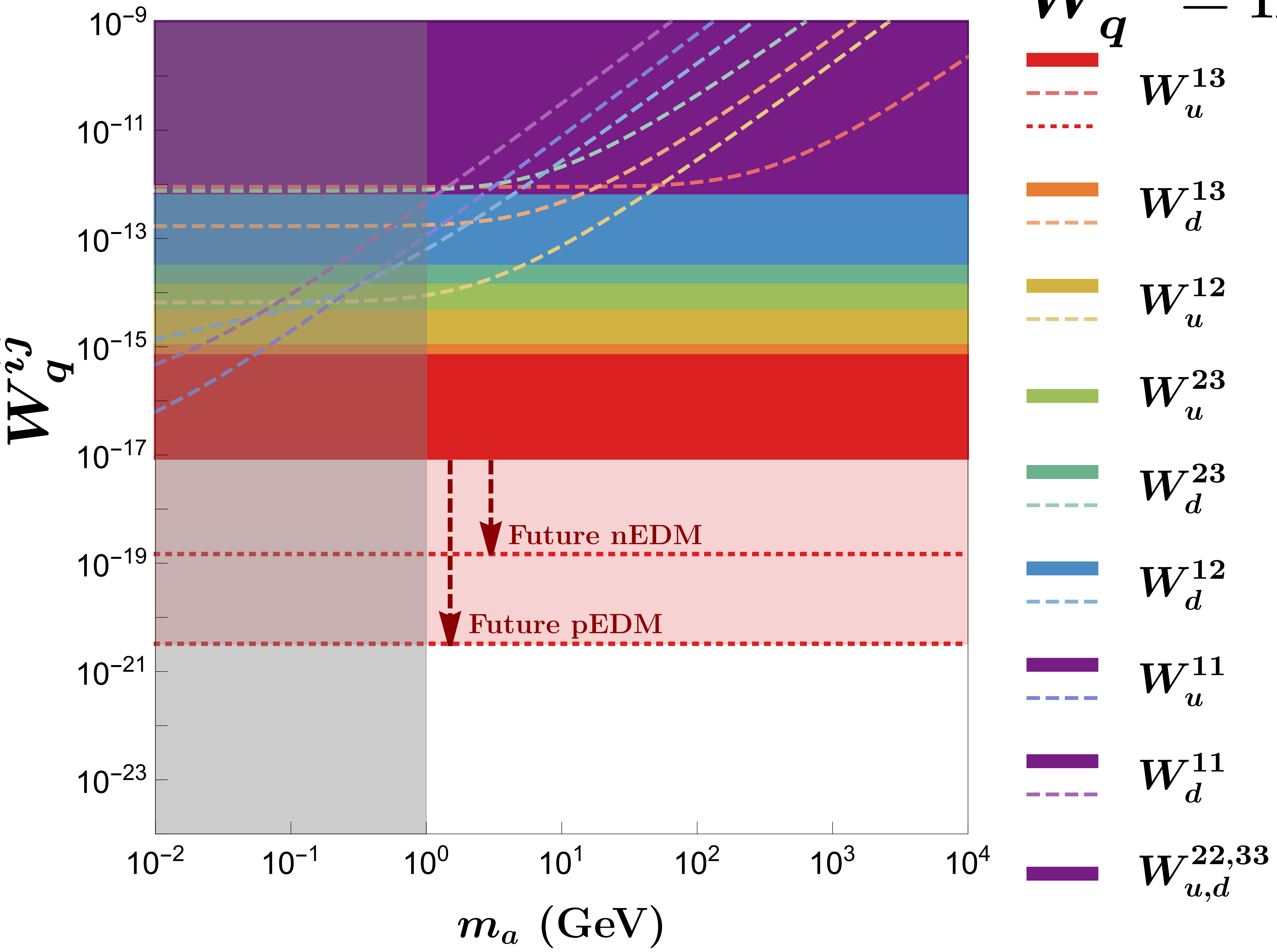
Dotted lines:

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

OLD

arXiv:2403.12133

nEDM on scalar-fermion couplings



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

Dotted lines:

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

OLD

Solid regions:

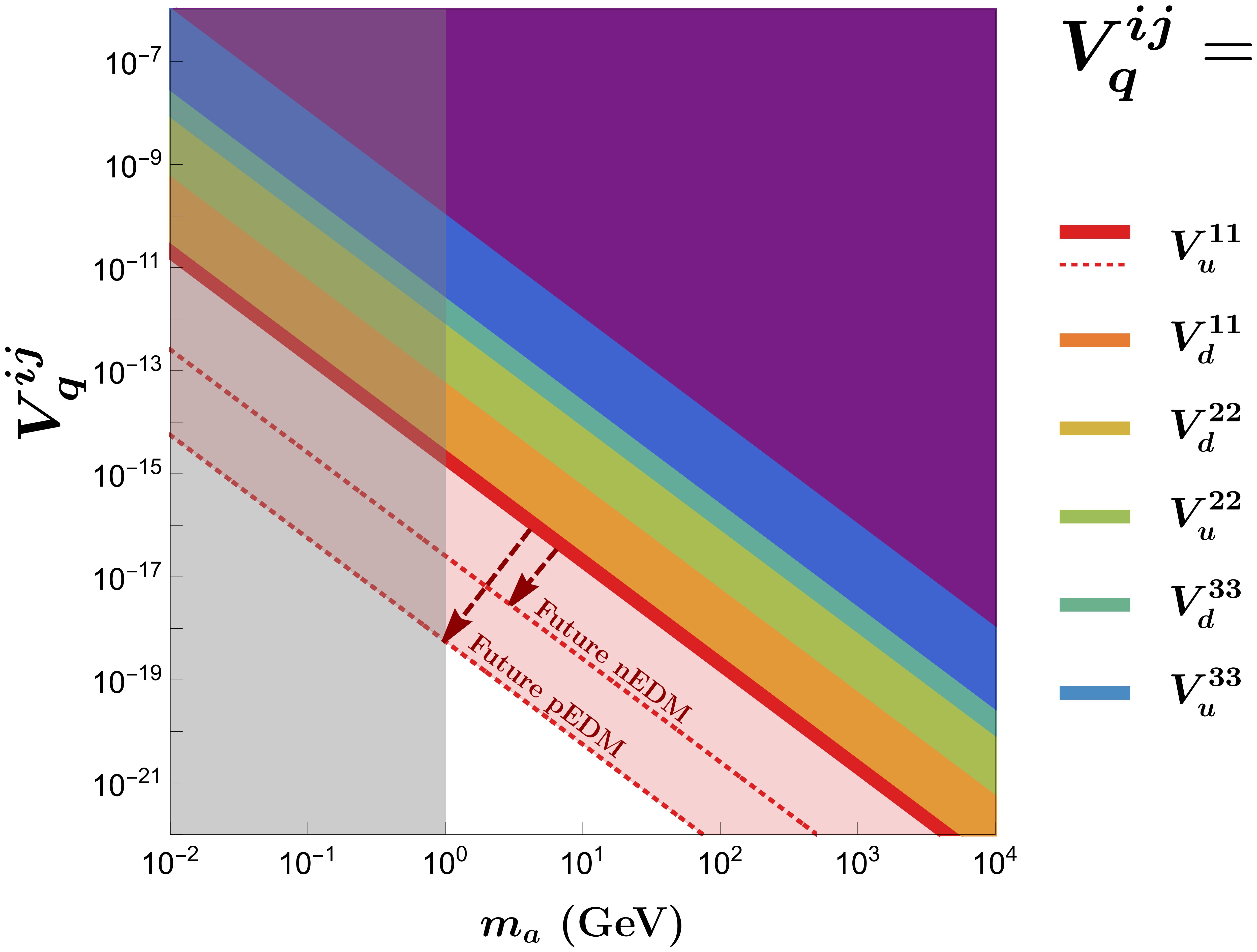
$$\left.\frac{d_n}{e}\right|_{\bar{\theta}} \sim \frac{v^2}{16\pi^2}\,\mathcal{O}(10^{-3}\ \mathrm{GeV}^{-1}) \times \times \left(\frac{m_t}{m_u}\right)\frac{\mathrm{Im}(K_u^{13}\,K_u^{13})}{f_a^2}$$

NEW

arXiv:2403.12133

nEDM on scalar-fermion couplings

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



Solid regions:

$$\left.\frac{d_n}{e}\right|_{\bar\theta} \sim \frac{v}{16\pi^2}\,\mathcal{O}(10^{-3}\ \mathrm{GeV}^{-1})\times$$
$$\times\left(\frac{m_a^2}{m_{u,d}}\right)\frac{\mathrm{Im}(F^{ii}_{u,d})}{f_a^2}$$

NEW

arXiv:2403.12133

$\bar{\theta}$ 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]

arXiv:2403.12133

$\bar{\theta}$ 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]

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

arXiv:2403.12133

$\bar{\theta}$ 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

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

e.g.

Nelson-Bar mechanism

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 ~4 orders of magnitude
- The same kind of improvement applies for a general scalar

MORE IN OUR PAPER

arXiv:2403.12133

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:

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

arXiv:2403.12133