ALPs coupling to fermions: CP-even and CP-odd

Planck 2024

Lisbon, 3-7 2024

Belén Gavela
Univ. Autónoma de Madrid and IFT

H2020

Why CP-violation ?

Why CP-violation ?

Why 3 generations of quarks and leptons,

with mixing and CP-violation….

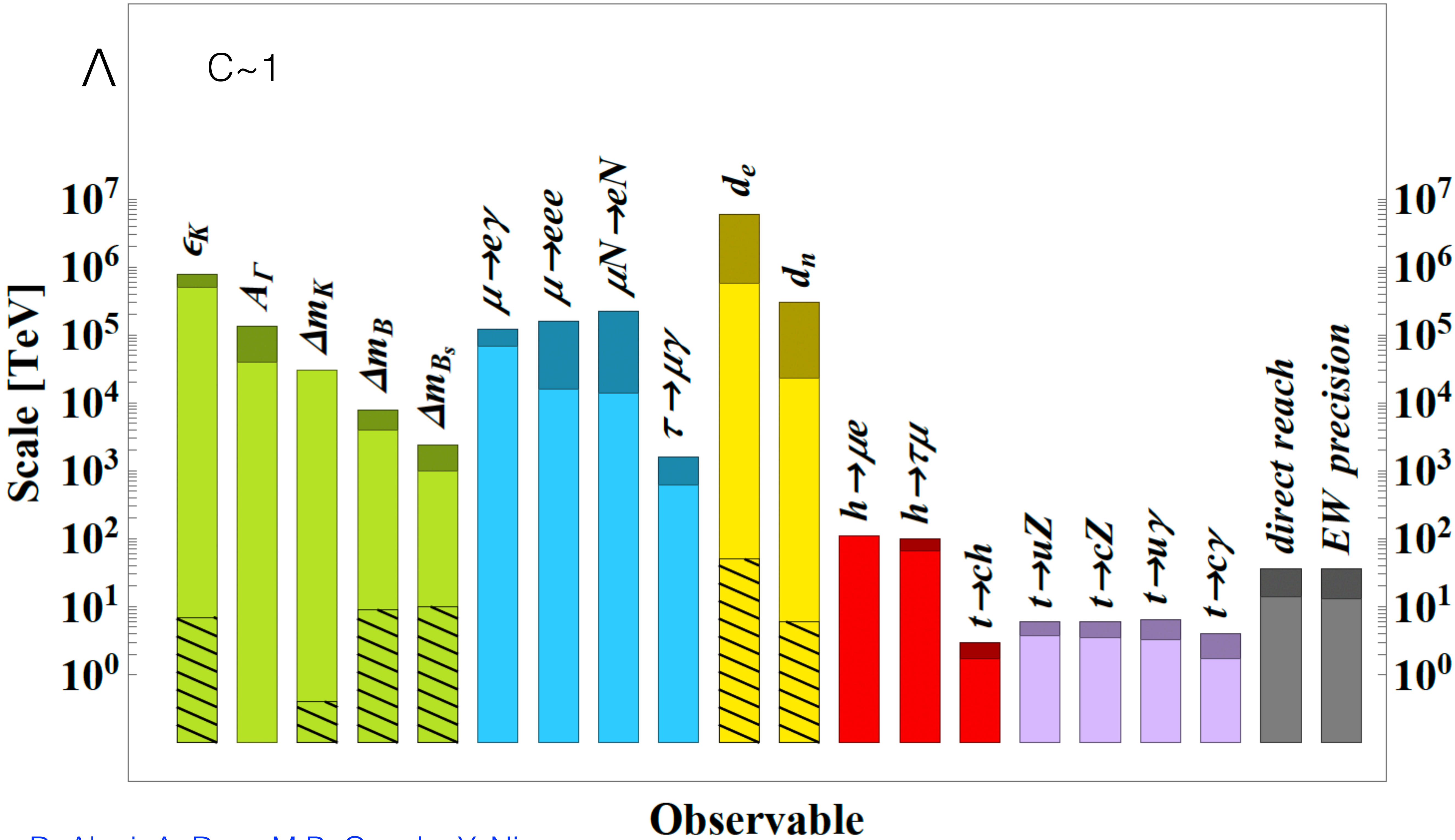
for ``nothing”?

Why CP-violation ?

CP-violation is a fantastic window to BSM

$$\boxed{\frac{C_6^a}{\Lambda^2}\mathscr{O}_a^{(6)}}$$

Flavour physics



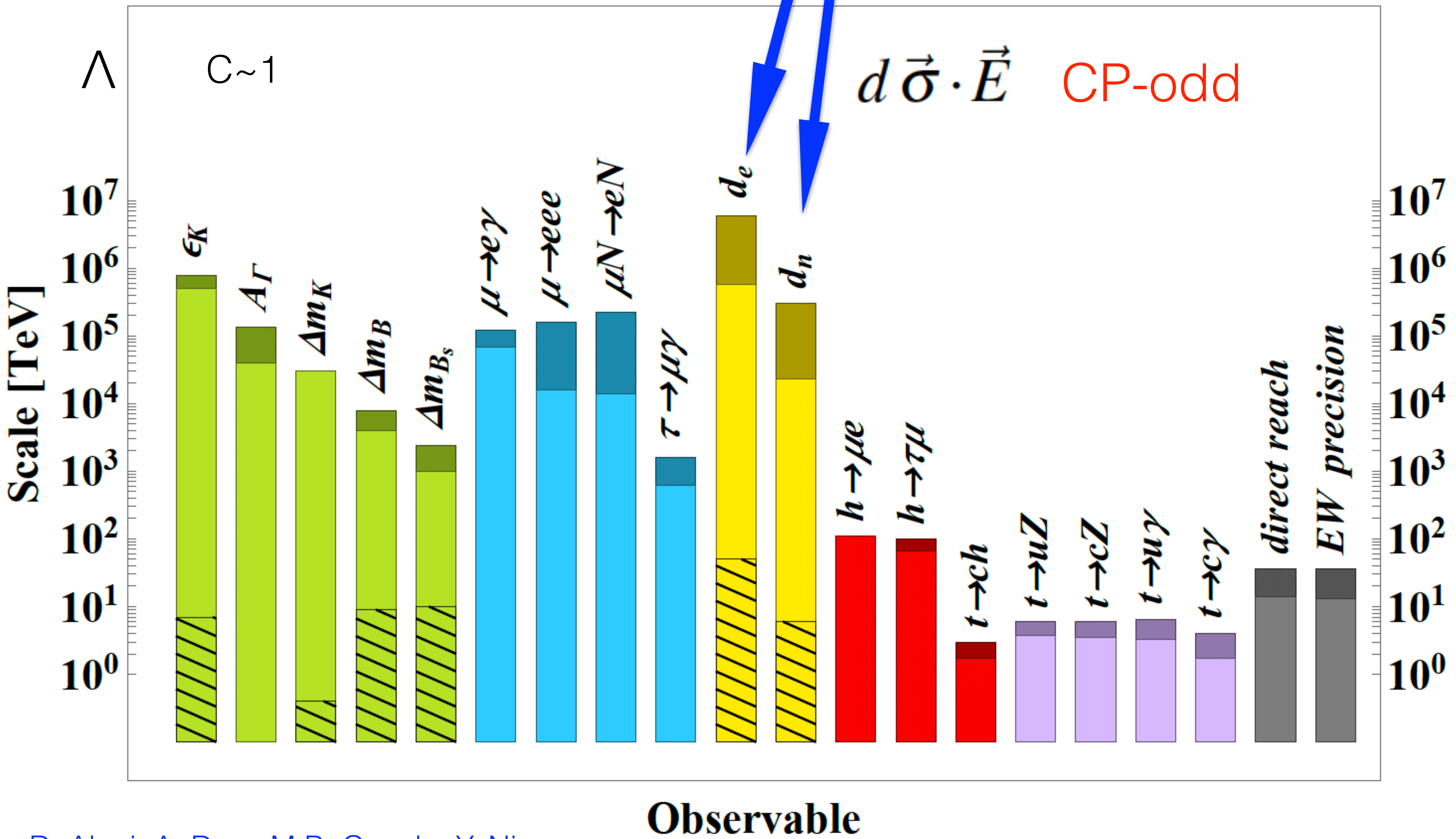
D. Aloni, A. Dery, M.B. Gavela, Y. Nir

European Strategy for Particle Physics 2020

$$\boxed{\frac{C_6^a}{\Lambda^2}\mathcal{O}_a^{(6)}}$$

Electric dipole moments

$d\,\vec{\sigma}\cdot\vec{E}$ CP-odd



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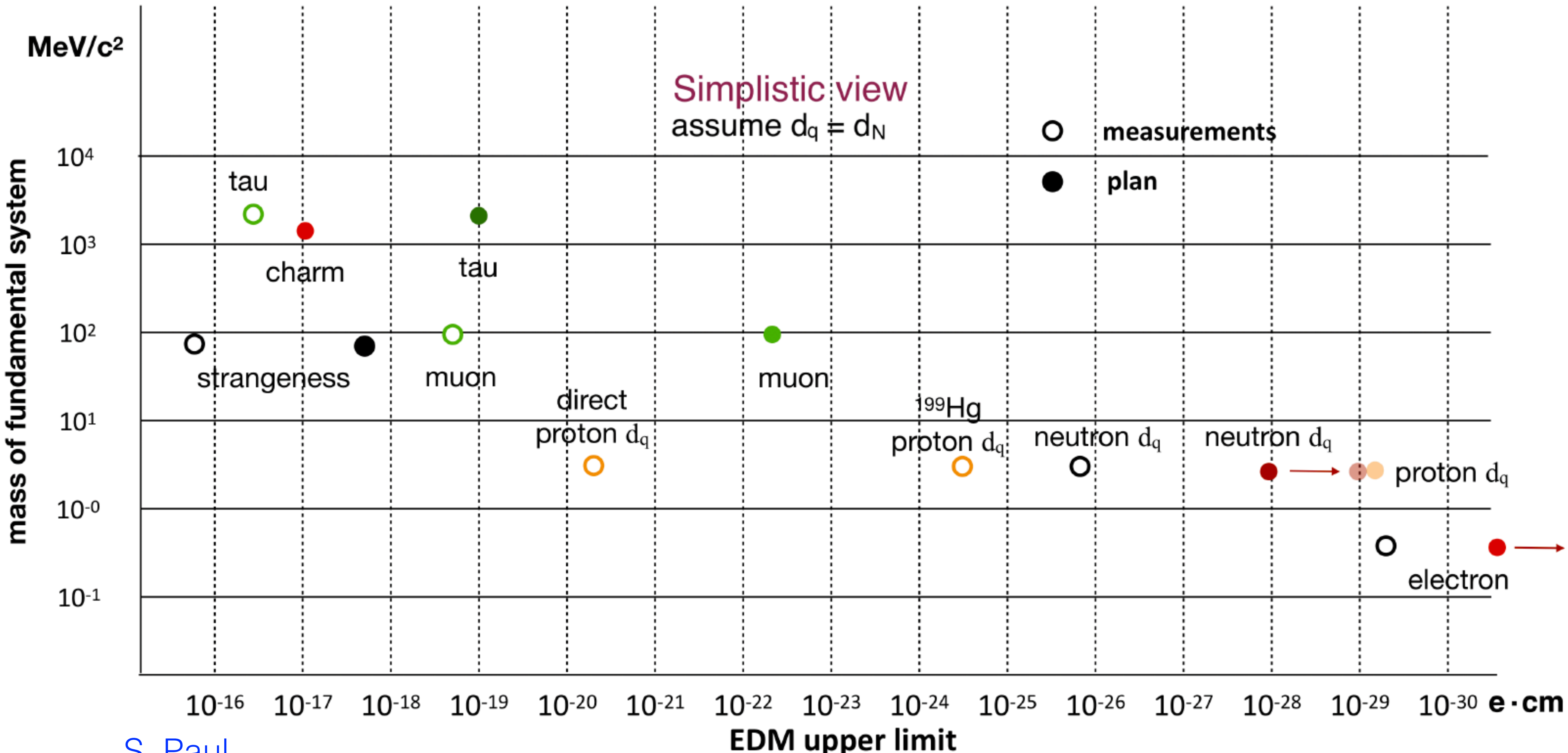
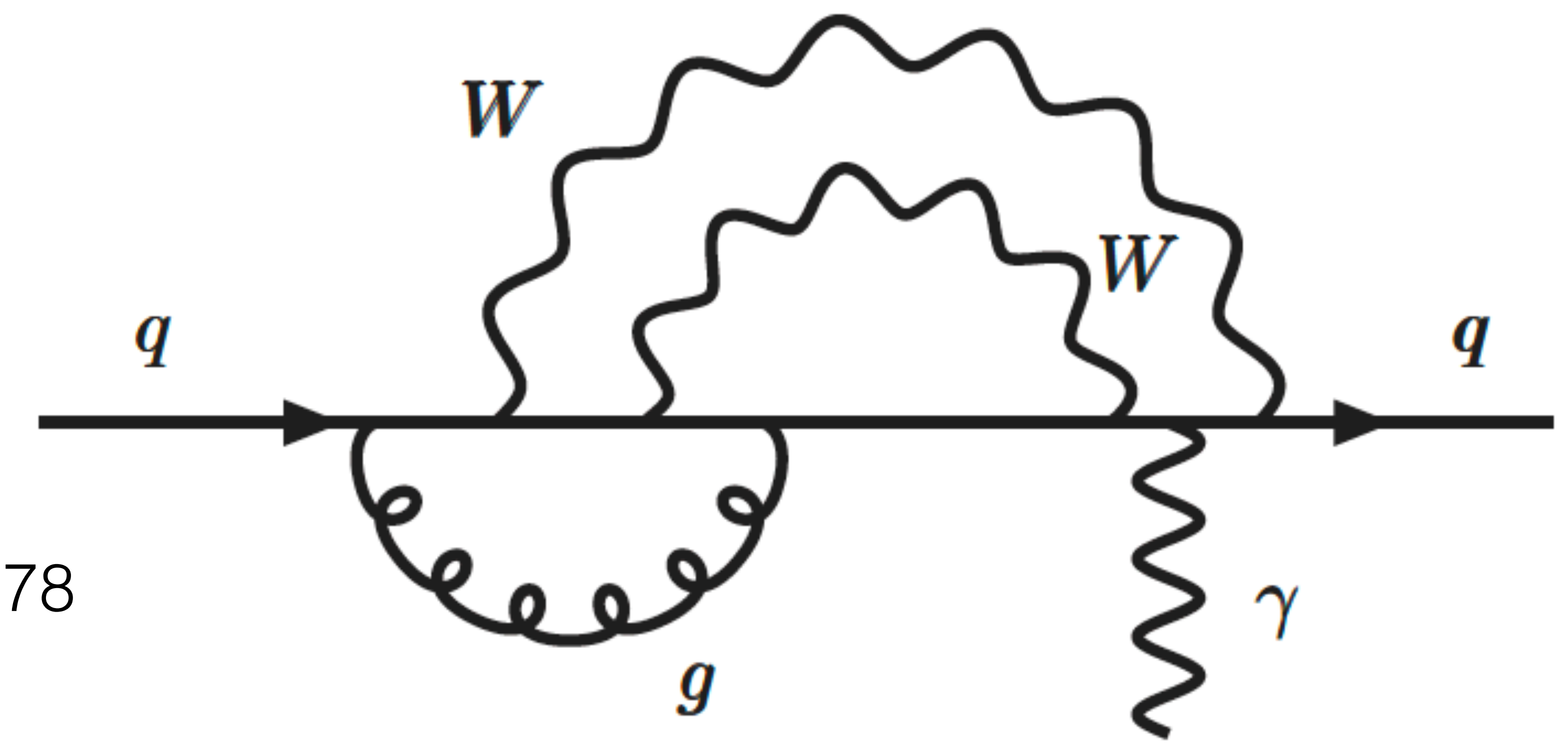
Electric dipole moments $d\,\vec{\sigma}\cdot\vec{E}$



S. Paul

Fig. 5.3: Summary of current EDM limits (empty circles) and short/mid-term planned sensitivities (full circles) for light quarks, strange and charm quarks, electron, muon and tau [257].

In the SM the quark EDM is 3-loop suppressed

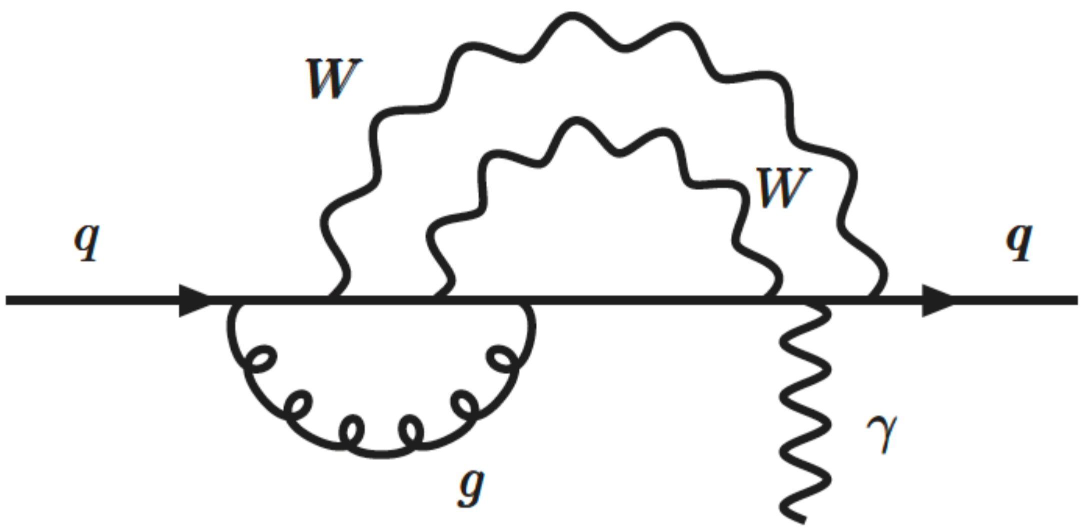


Shabalin 78

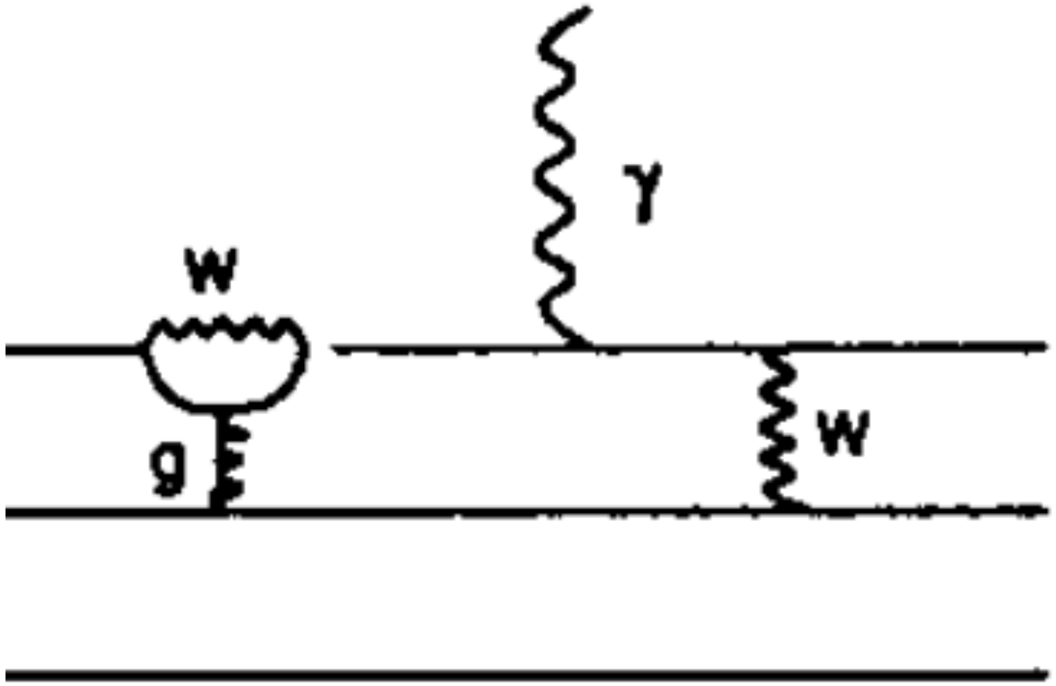
SM quark EDMs $d_n \sim 10^{-34}$ e·cm

Experiment: $d_n < 3.6 \times 10^{-26}$ e·cm at 95% CL

In the SM the neutron EDM is very suppressed



``penguin dominated''



(80's: Gavela at al.,
Khriplovich+Zhitnitsky)

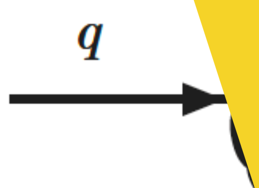
SM predicts d_n ~ 10^{-30} - 10^{-32} e·cm

Experiment: $d_n < 3.6 \times 10^{-26}$ e·cm at 95% CL

In the SM the neutron EDM is very suppressed

ominated''

BSM window: In general BSM electric dipole moments appear at one loop



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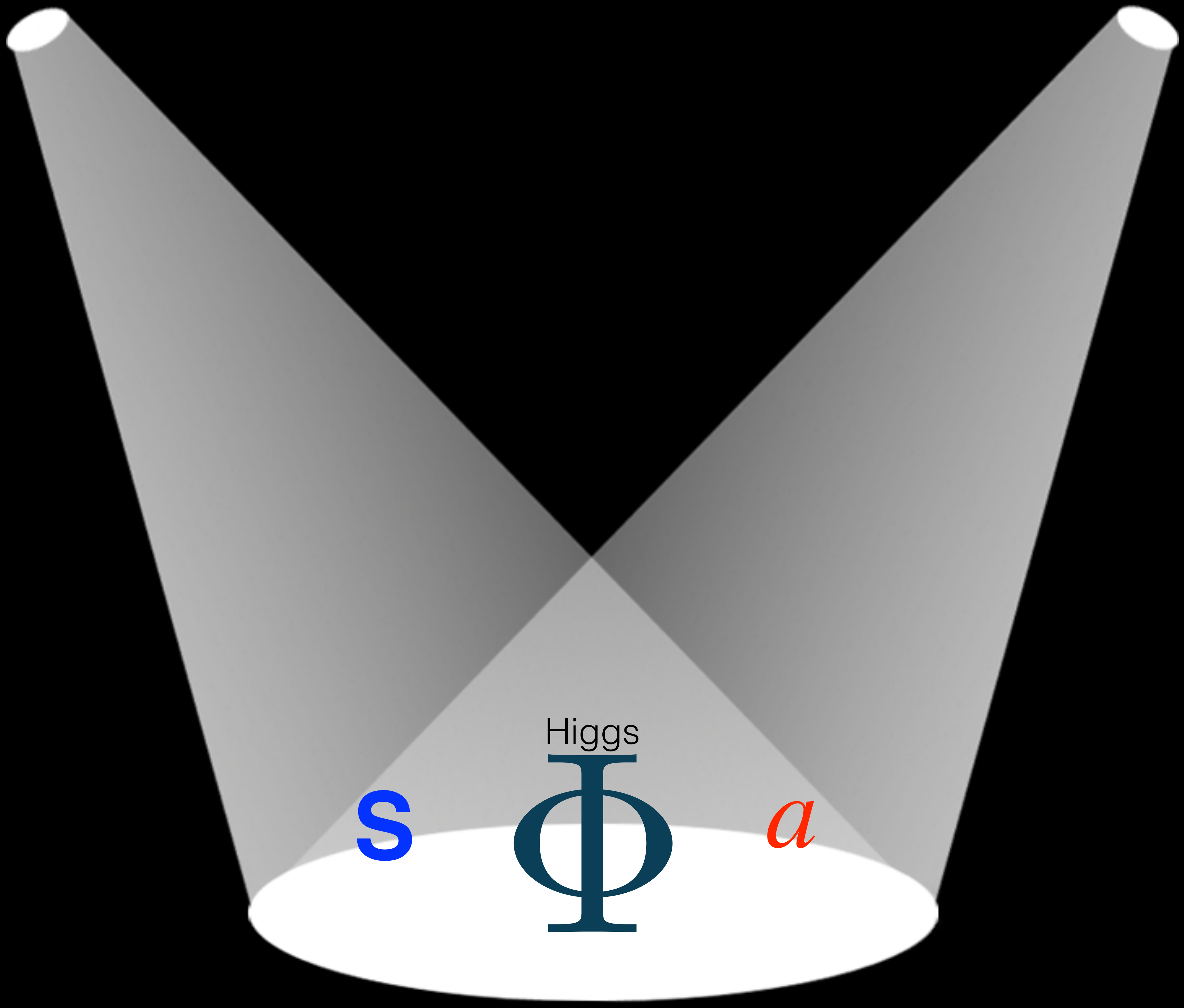
Why ALPs ?



Rocio del Rey

Strong motivation for singlet (pseudo)scalars from fundamental SM problems

The nature of DM is unknown

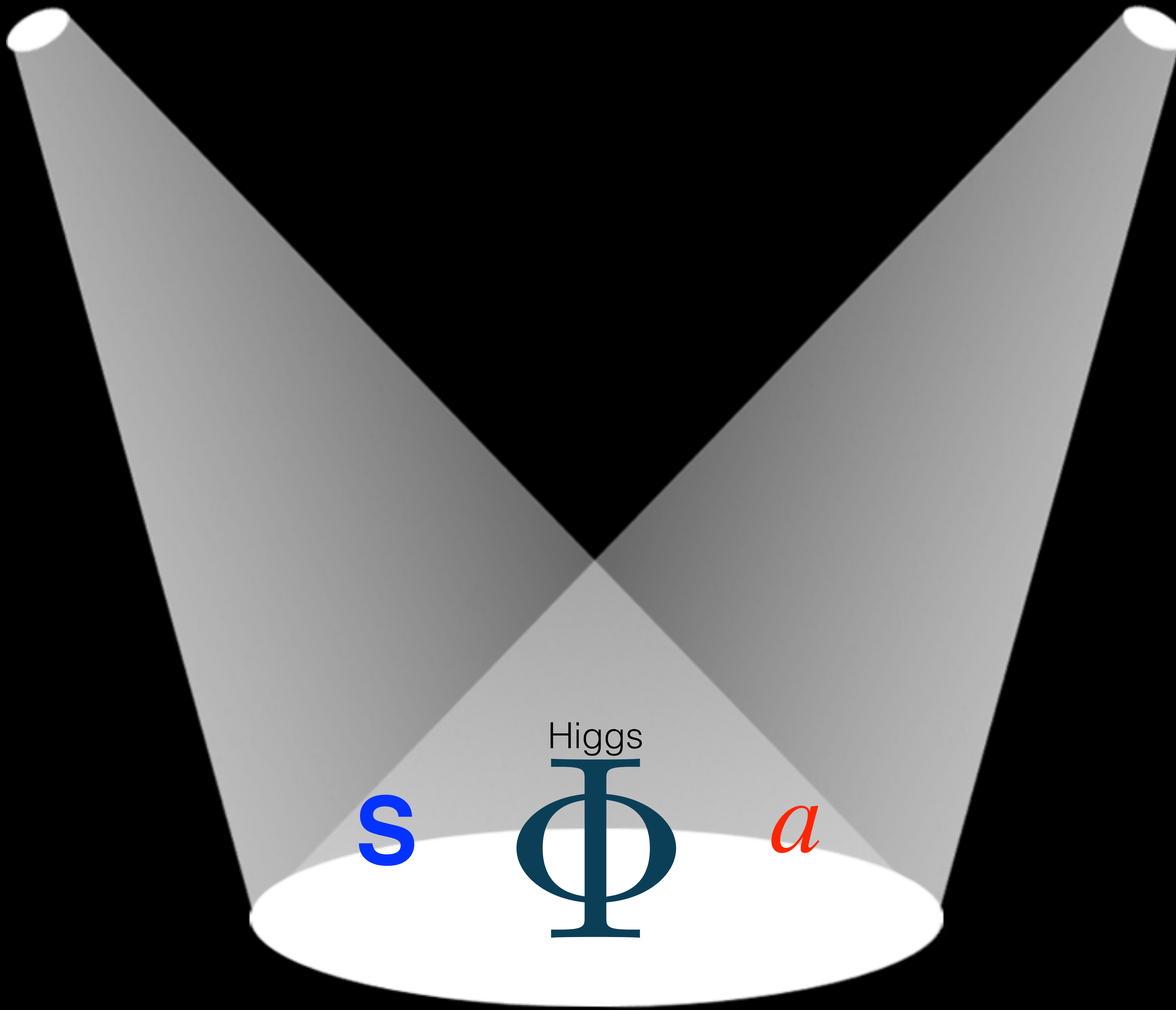
It may be a (SM singlet) scalar S

the "Higgs portal"

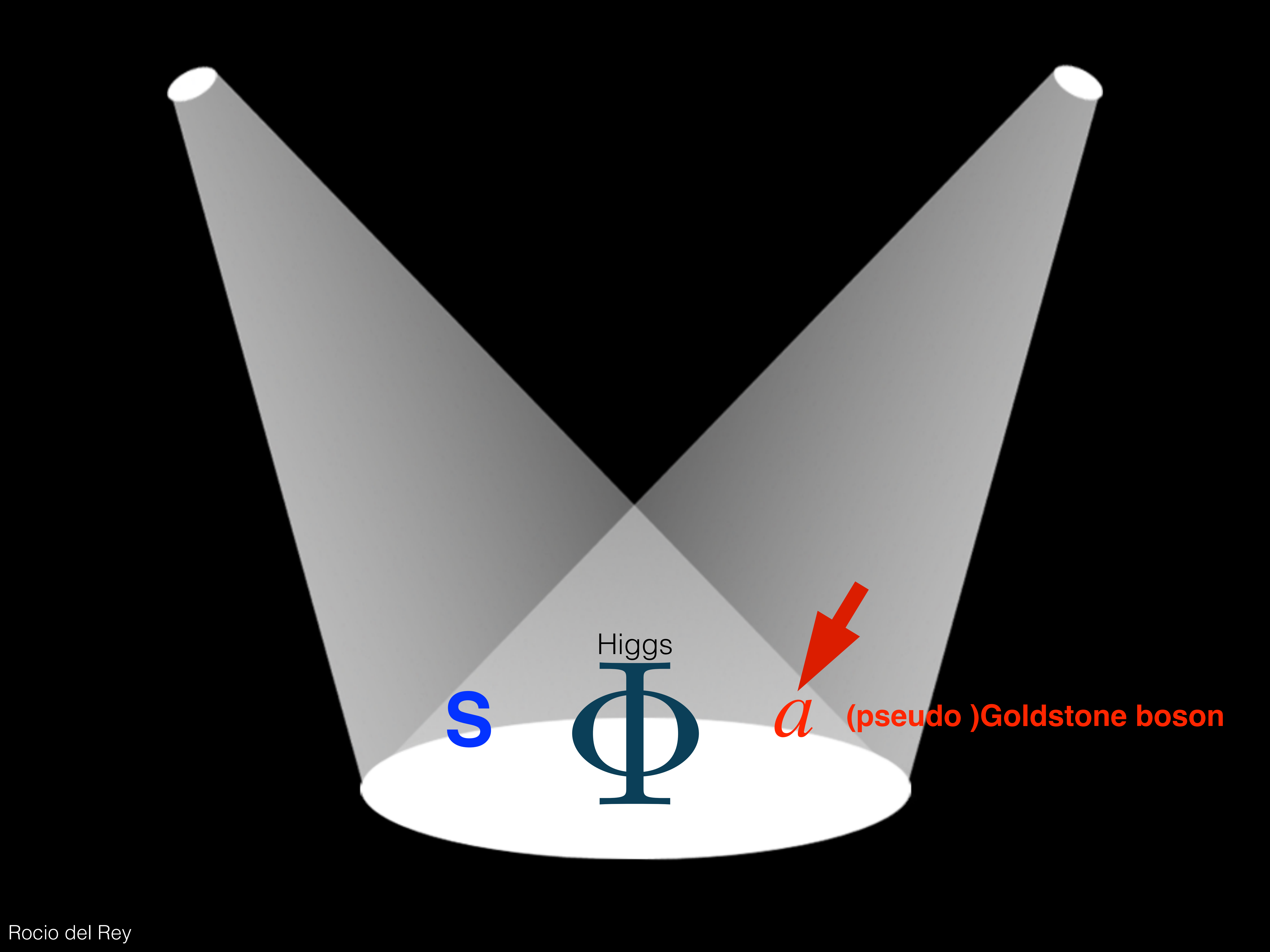
$$\delta\mathcal{L} = \Phi^{+}\Phi S^{2}$$

S has polynomial couplings

Silveira+Zee; Veltman+Yndurain; Patt+Wilczek…



Rocio del Rey


Higgs
S
Φ
a
(pseudo)Goldstone boson
Rocio del Rey

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Why is the QCD **θ** parameter so small?

$$\mathcal{L}_{QCD} \supset \theta\, G_{\mu\nu}\tilde{G}^{\mu\nu}$$

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→ the axion a

It is a pGB: ~ derivative couplings

$\sim \partial_\mu a$

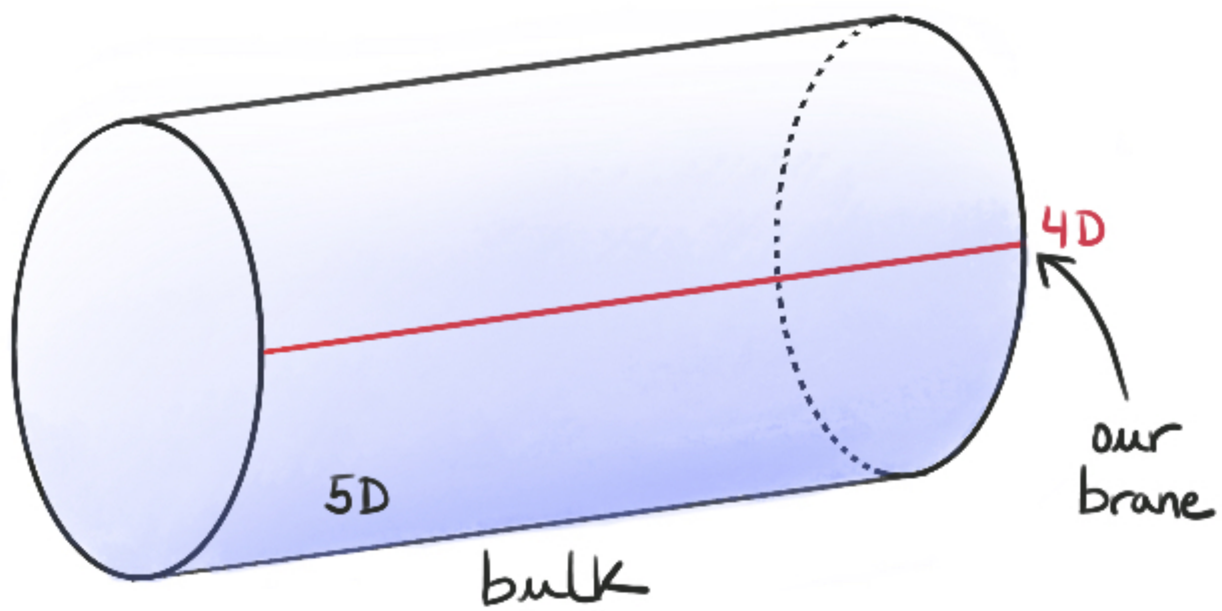
Also excellent DM candidate

Peccei+Quinn; Wilczek…

(Pseudo)Goldstone Bosons appear in many BSM theories

* e.g. Extra-dim Kaluza-Klein: 5d gauge field compactified to 4d

The Wilson line around the circle is a GB, which behaves as an axion in 4d



* Majorons, for dynamical neutrino masses

* From string models

* The Higgs itself may be a pGB ! (“composite Higgs” models)

* Axions a that solve the strong CP problem, and ALPs (axion-like particles)

……

Because they are (pseudo)Goldstone bosons,

Axions and ALPs a

are the tell-tale of hidden

symmetries

awaiting discovery

Think of the pions…

and of the massive W and Z…

ALPs (axion-like-particles)

An ALP (axion-like particle) is a generic scalar field a

with derivative couplings to SM particles

and free scale f_a:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{\partial_\mu a}{f_a} \times {\rm SM}^\mu$$

general effective couplings

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$$\{m_a, f_a\}$$

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$X^{\mu\nu} = F^{\mu\nu}, G^{\mu\nu}, Z^{\mu\nu}, W^{\mu\nu} \ldots$

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$$\left\{ m_a , \frac{c_i}{f_a} \right\}$$

ALP-Linear effective Lagrangian at NLO

II
SM EFT

Complete basis (bosons+fermions):

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) + \sum_i^{\text{total}} c_i \mathbf{O}_i^{d=5} - \frac{1}{2} m_a^2 a^2$$

$$\mathbf{O}_{\tilde{B}} = -B_{\mu\nu}\tilde{B}^{\mu\nu}\frac{a}{f_a} \qquad \mathbf{O}_{\tilde{G}} = -G^a_{\mu\nu}\tilde{G}^{a\mu\nu}\frac{a}{f_a}$$

$$\mathbf{O}_{\tilde{W}} = -W^a_{\mu\nu}\tilde{W}^{a\mu\nu}\frac{a}{f_a} \qquad \frac{\partial_\mu a}{f_a}\sum_{\substack{\psi=Q_L,Q_R,\\ L_L,L_R}} \bar{\psi}\gamma_\mu X_\psi \psi$$

where X_ψ is a general 3x3 matrix in flavour space

Georgi + Kaplan + Randall 1986
Choi + Kang + Kim, 1986
Salvio + Strumia + Shue, 2013

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||
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Difference between and ALP and a true axion:

an ALP does not intend to solve the strong CP problem

otherwise, the phenomenology is alike (even for DM)

Georgi + Kaplan + Randall 1986
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For an ALP:

$$\{ m_a \, , \, f_a \}$$

are independent parameters

Georgi + Kaplan + Randall 1986
Choi + Kang + Kim, 1986
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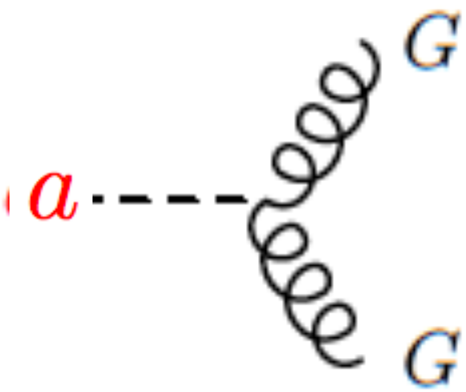
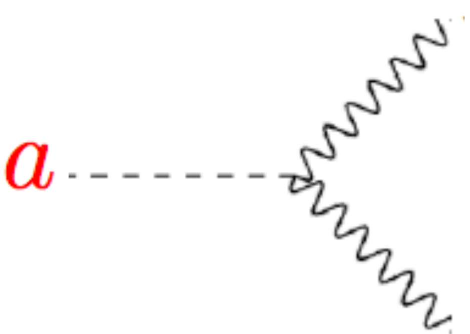
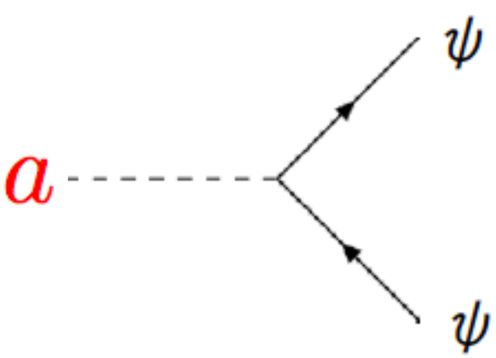


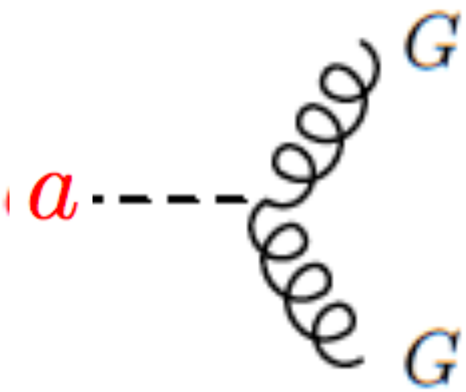
$$a\, G_{\mu\nu}\tilde{G}^{\mu\nu}$$



$$a\, F_{\mu\nu}\tilde{F}^{\mu\nu}\,,\quad a\, F^{\mu\nu}\tilde{Z}_{\mu\nu}\,,\quad a\, Z^{\mu\nu}\tilde{Z}_{\mu\nu}\,,\quad a\, W^{\mu\nu}\tilde{W}_{\mu\nu}$$



$$\partial_\mu a\, \bar{\psi}\gamma_\mu\psi$$



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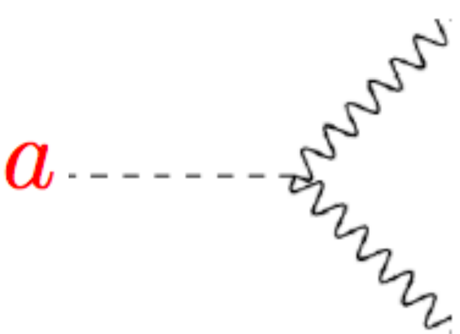

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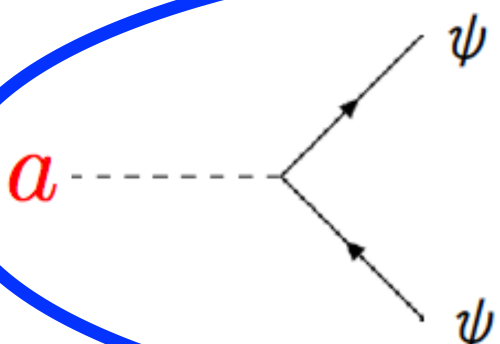
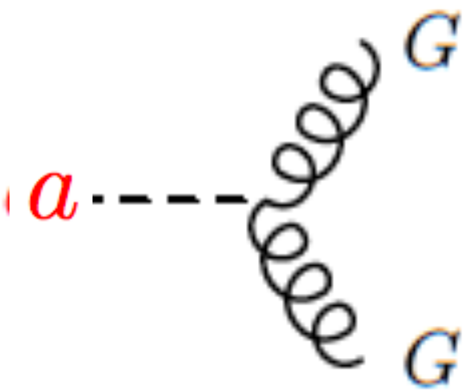


$$\partial_\mu a\,\bar{\psi}\gamma_\mu\psi$$

neutron, proton, top,
electron, muon…



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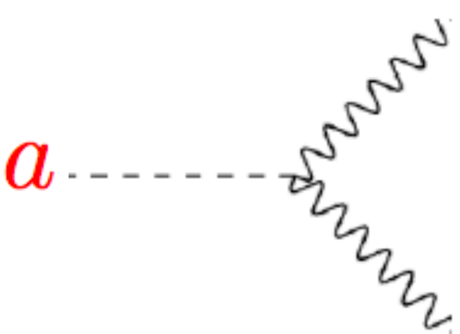

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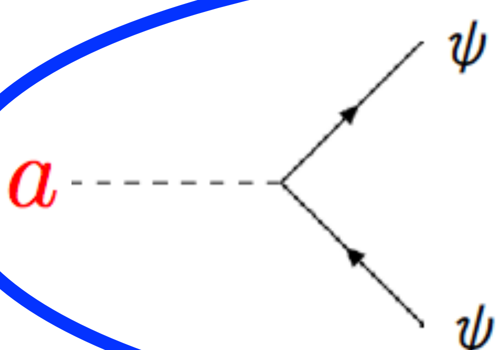

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neutron, proton, top,
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neutrinos ?

Bonilla, B.G, Machado [arXiv:2309.15910]

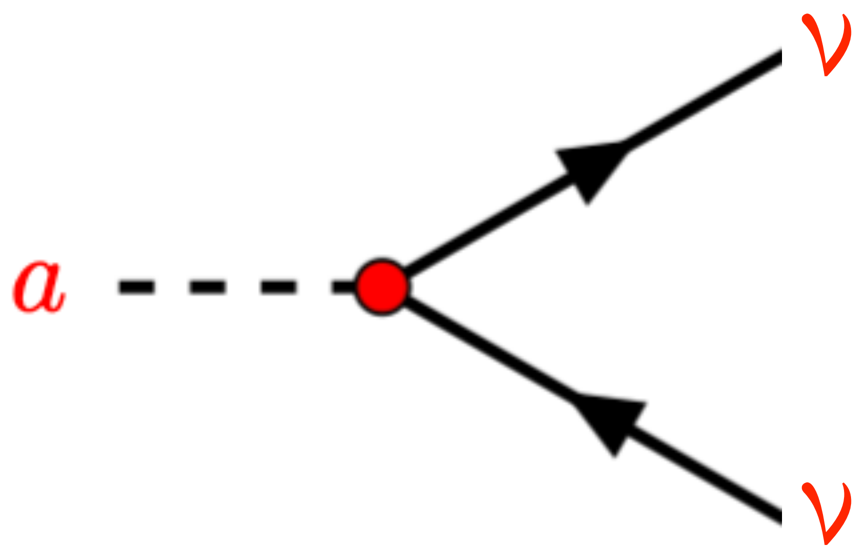
a-neutrino couplings

Neutrinos are excellent messengers onto the dark sectors of the universe

What about a-neutrino couplings ?

Bonilla, Gavela, Machado [arXiv:2309.15910] Phys.Rev.D 109 (2024)

Bounds on ALP-neutrino couplings



????

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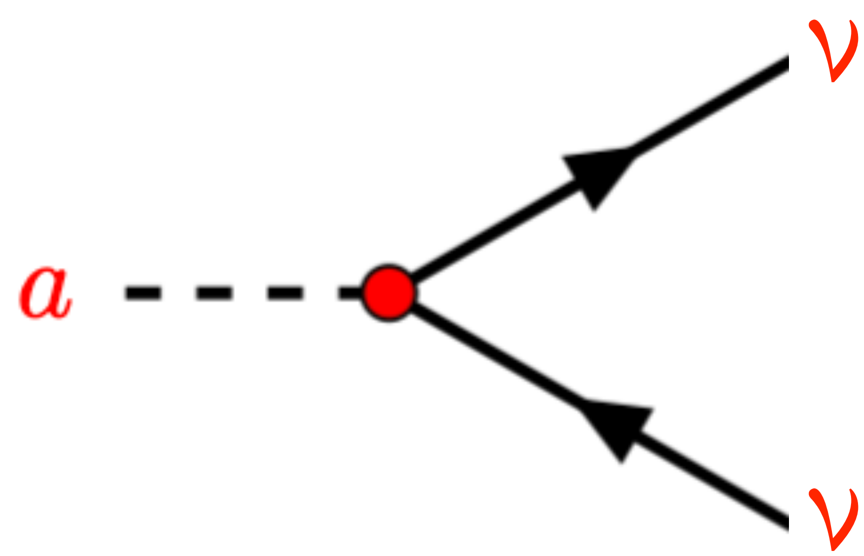

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EOM

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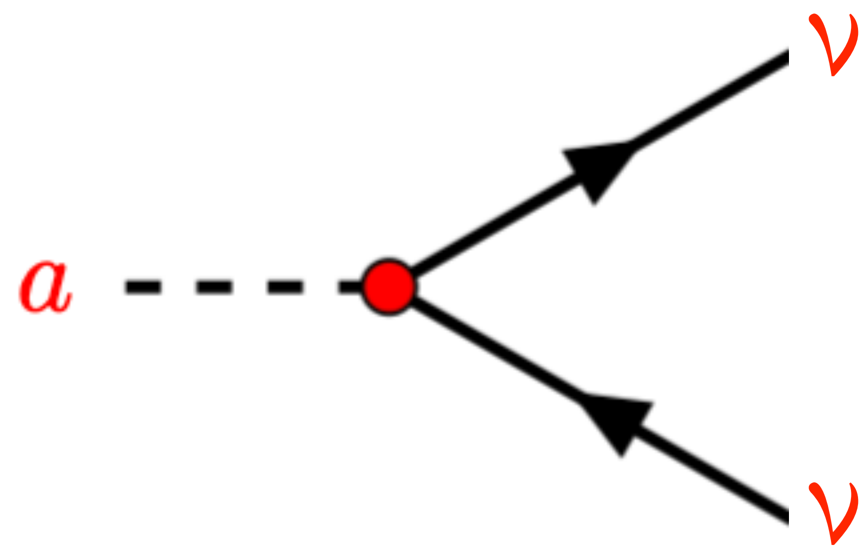

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Bonilla, Gavela, Machado [arXiv:2309.15910] Phys.Rev.D 109 (2024)

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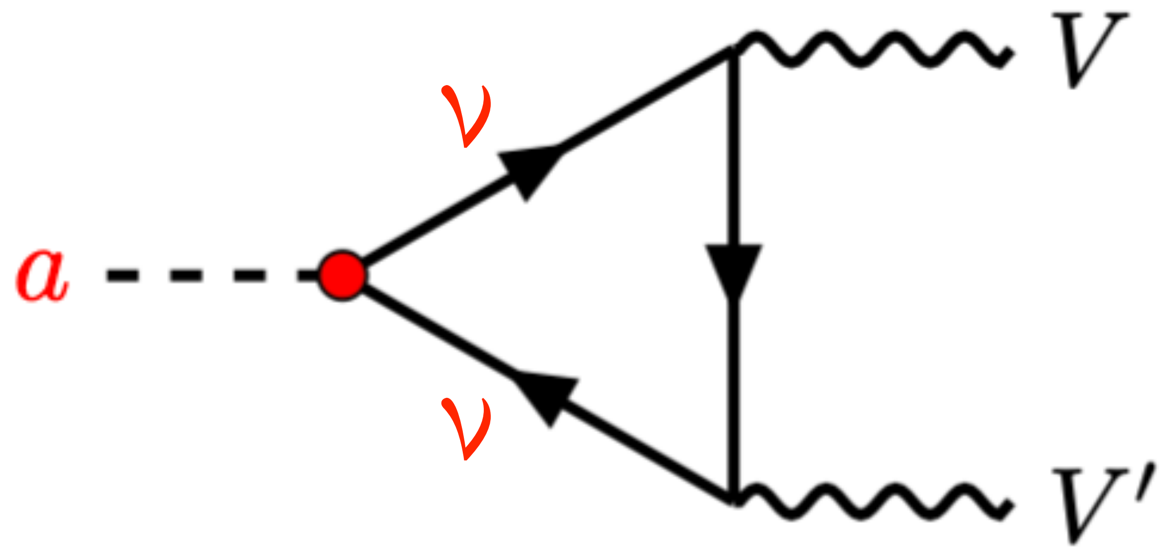

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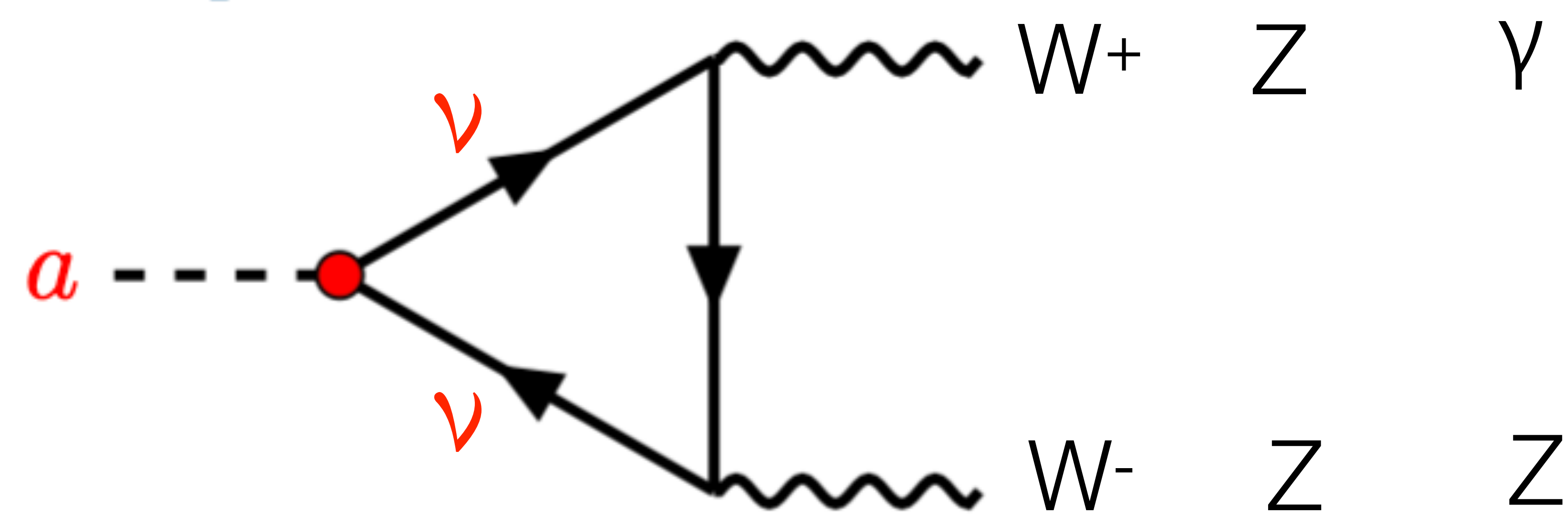

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Bonilla, Gavela, Machado [arXiv:2309.15910] Phys.Rev.D 109 (2024)

$$L_L \equiv \begin{pmatrix} e_L \\ \nu_L \end{pmatrix}$$

connected by gauge invariance

$$\boxed{\mathscr{L}_{ALP} \supset \frac{\partial_\mu a}{f_a} \overline{L}_L \gamma^\mu c_L L_L + \frac{\partial_\mu a}{f_a} \bar{e}_R \gamma^\mu c_E e_R}$$

CLASSICAL EOM

$$\frac{\partial_\mu a}{f_a} \bar{e}_R \gamma^\mu c_E e_R = -\left(i \frac{a}{f_a} \bar{e}_L \mathbf{M}_E c_E e_R + \text{h.c.} \right)$$

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Mass-suppressed

M. Chala *et al*, Eur. Phys. J. C 81 (2021), no. 2 181
M. Bauer *et al*, JHEP 04 (2021) 063
J. Bonilla *et al*, JHEP 11 (2021) 168

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Bounds ALP-gauge bosons

$\Downarrow$

Bounds ALP-neutrino

CLASSICAL EOM **ONE-LOOP EFFECT**

$$\frac{\partial_\mu a}{f_a} \bar{e}_R \gamma^\mu c_E e_R = -\left(i \frac{a}{f_a} \bar{e}_L \mathbf{M}_E c_E e_R + \text{h.c.}\right) + \text{Tr}\left[c_E\right] \frac{a}{f_a} \frac{g'^2}{16\pi^2} B_{\mu\nu} \tilde{B}^{\mu\nu}$$

$$\frac{\partial_\mu a}{f_a} \bar{e}_L \gamma^\mu c_L e_L = \left(i \frac{a}{f_a} \bar{e}_L \mathbf{M}_E c_L e_R + \text{h.c.}\right) - \text{Tr}\left[c_L\right] \frac{a}{f_a} \left[\frac{g'^2}{64\pi^2} B_{\mu\nu} \tilde{B}^{\mu\nu} + \frac{g^2}{64\pi^2} W_{\mu\nu} \tilde{W}^{\mu\nu}\right]$$

$$\frac{\partial_\mu a}{f_a} \bar{\nu}_L \gamma^\mu c_L \nu_L = \left(i \frac{a}{f_a} \bar{\nu}_L \mathbf{M}_\nu c_L \nu_R + \text{h.c.}\right) - \text{Tr}\left[c_L\right] \frac{a}{f_a} \left[\frac{g'^2}{64\pi^2} B_{\mu\nu} \tilde{B}^{\mu\nu} + \frac{g^2}{64\pi^2} W_{\mu\nu} \tilde{W}^{\mu\nu}\right]$$

Mass-suppressed Mass-independent

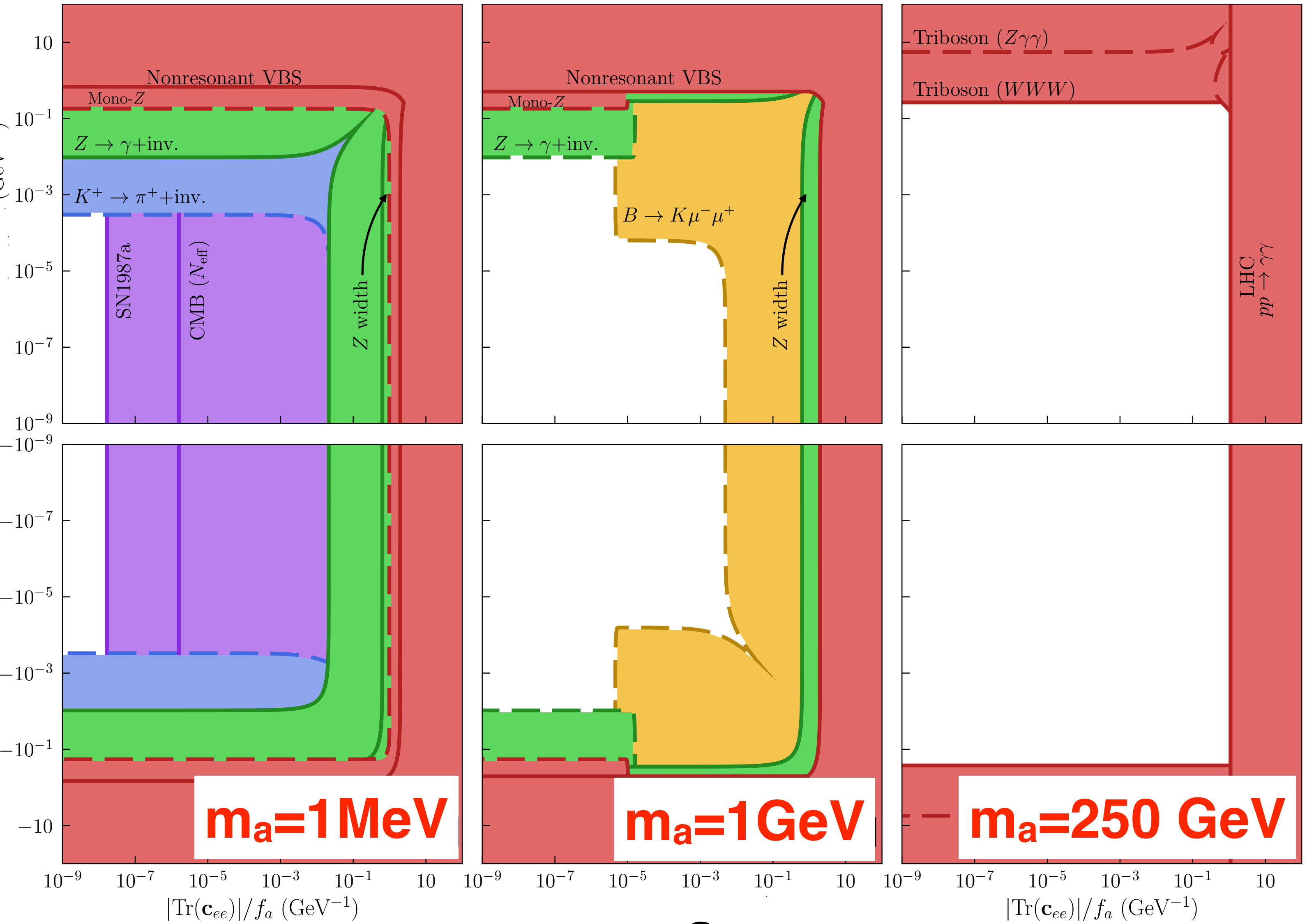
M. Chal *et al*, Eur. Phys. J. C 81 (2021), no. 2 181
M. Bauer *et al*, JHEP 04 (2021) 063
J. Bonilla *et al*, JHEP 11 (2021) 168

one-loop anomalous current

Tr($\mathbf{c}_{\nu\nu}/f_a$) vs. Tr($\mathbf{c}_{ee}/f_a$)

Bounds on ALP-neutrino coupling

Tr($\mathbf{c}_{\nu\nu}/f_a$)



Tr($\mathbf{c}_{ee}/f_a$) (GeV^{-1})

Lots of space to explore by LHC and future colliders

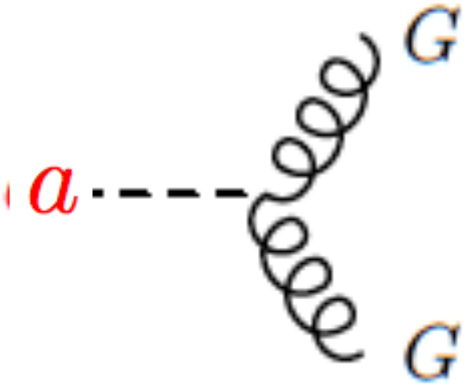
Bonilla, Gavela, Machado [arXiv:2309.15910] Phys.Rev.D 109 (2024)

ALPs (axion-like-particles)

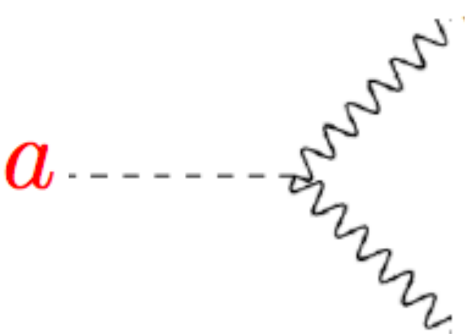
CP-violation

$m_a > 1$ GeV

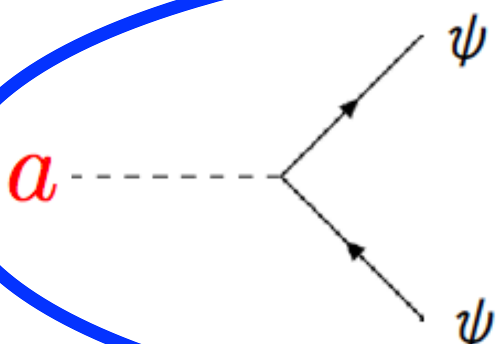
V. Enguita, M.B. Gavela, B. Grinstein, P. Quilez, arXiv: 2403.13133



$$a\, G_{\mu\nu}\tilde{G}^{\mu\nu}$$



$$a\, F_{\mu\nu}\tilde{F}^{\mu\nu}\,,\; a\, F^{\mu\nu}\tilde{Z}_{\mu\nu}\,,\; a\, Z^{\mu\nu}\tilde{Z}_{\mu\nu}\,,\; a\, W^{\mu\nu}\tilde{W}_{\mu\nu}$$



$$\partial_\mu a\, \bar{\psi}\gamma_\mu\psi$$

The ALP EFT

$$\mathcal{L}_a \supset \frac{\partial_\mu a}{f_a} \underbrace{(\bar{Q}_L \gamma^\mu \boldsymbol{C}_Q Q_L + \bar{u}_R \gamma^\mu \boldsymbol{C}_{u_R} u_R + \bar{d}_R \gamma^\mu \boldsymbol{C}_{d_R} d_R)}_{\textbf{CP-violation in flavor-nondiagonal entries}}$$

It will source CP-violation observables, e.g. EDMs… at one loop!

The ALP EFT

$$\mathcal{L}_a \supset \frac{\partial_\mu a}{f_a} \underbrace{\left(\bar{Q}_L \gamma^\mu \boldsymbol{C}_Q Q_L + \bar{u}_R \gamma^\mu \boldsymbol{C}_{u_R} u_R + \bar{d}_R \gamma^\mu \boldsymbol{C}_{d_R} d_R\right)}_{\textbf{CP-violation in flavor-nondiagonal entries}}$$

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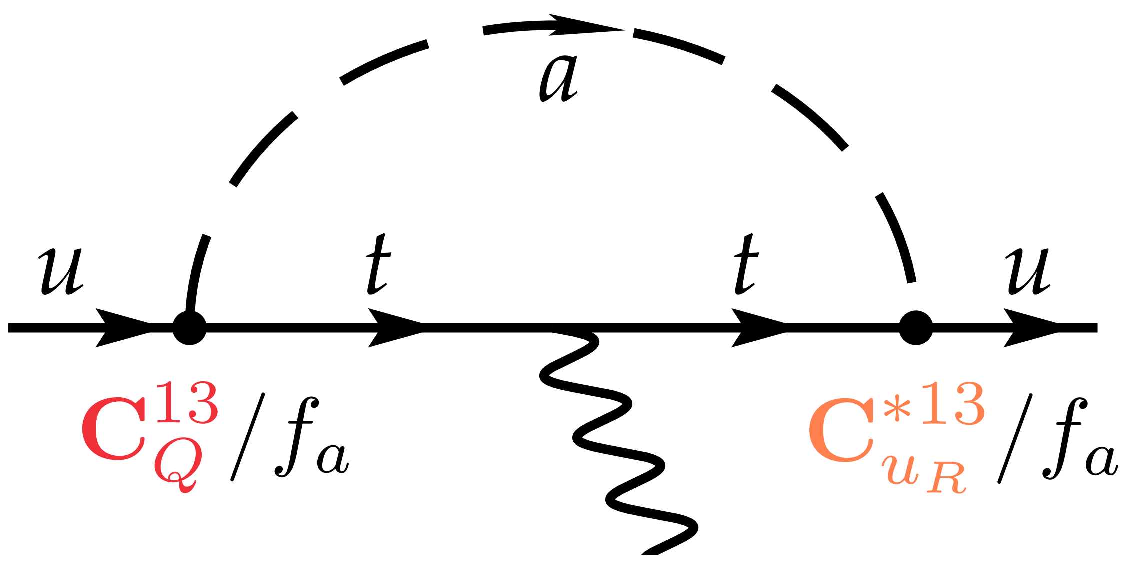
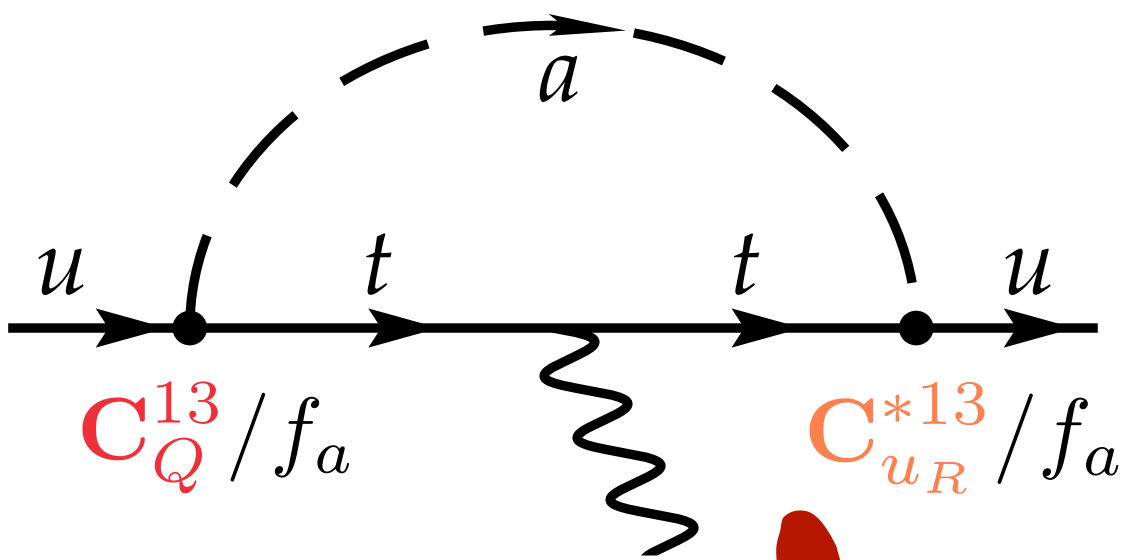


[Di Luzio et al., 2010.13760]

The ALP EFT

$$\mathcal{L}_a \supset \frac{\partial_\mu a}{f_a} \underbrace{(\bar{Q}_L \gamma^\mu \boldsymbol{C}_Q Q_L + \bar{u}_R \gamma^\mu \boldsymbol{C}_{u_R} u_R + \bar{d}_R \gamma^\mu \boldsymbol{C}_{d_R} d_R)}_{\textbf{CP-violation in flavor-nondiagonal entries}}$$

It will source CP-violation observables, e.g. EDMs… at one loop!



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

[Di Luzio et al., 2010.13760]

The ALP EFT

$$\mathcal{L}_a \supset \quad \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2$$

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

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

The ALP EFT

$$\mathcal{L}_a \supset \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2$$

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

Related by the $U_A(1)$ anomaly

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

nEDM data imply $\bar{\theta} < \sim 10^{-10}$

The ALP EFT

$$\mathcal{L}_a \supset \quad \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2$$

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

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

The ALP EFT

$$\mathcal{L}_a \supset \quad \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2$$

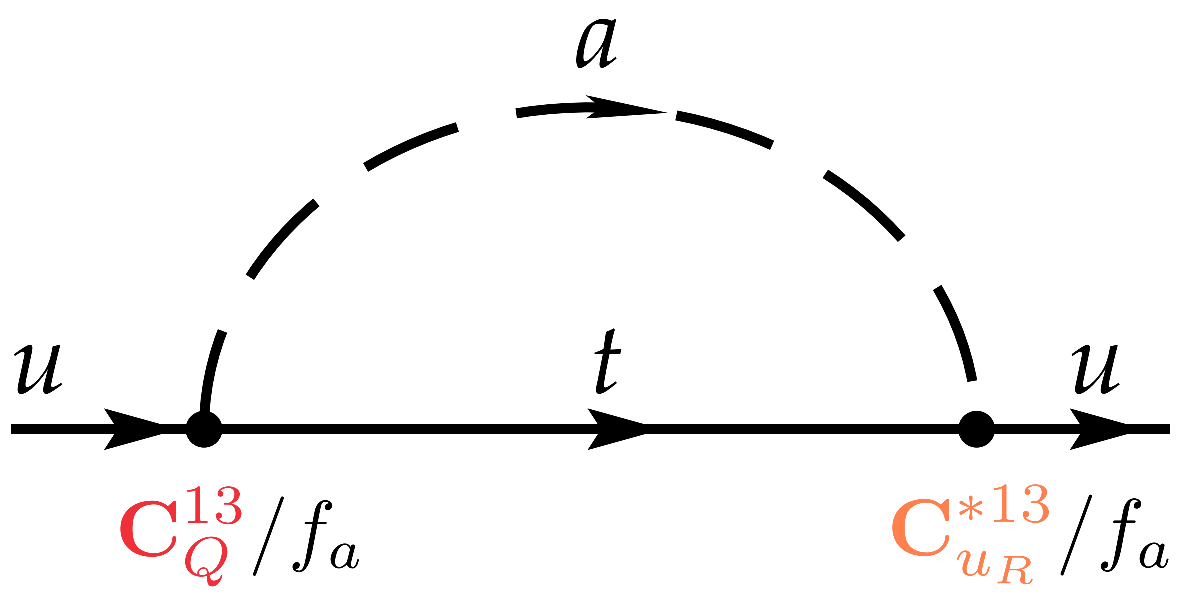
$$+\left(\bar{u}_L \boldsymbol{M}_u u_R + \bar{d}_L \boldsymbol{M}_d d_R + \text{h.c.}\right) + \theta\, \frac{\alpha_s}{8\pi} G_{\mu\nu}\widetilde{G}^{\mu\nu}$$

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

ALPs contribute at one-loop to the quark mass terms,
i.e. ALPs contribute to $\bar{\theta}$

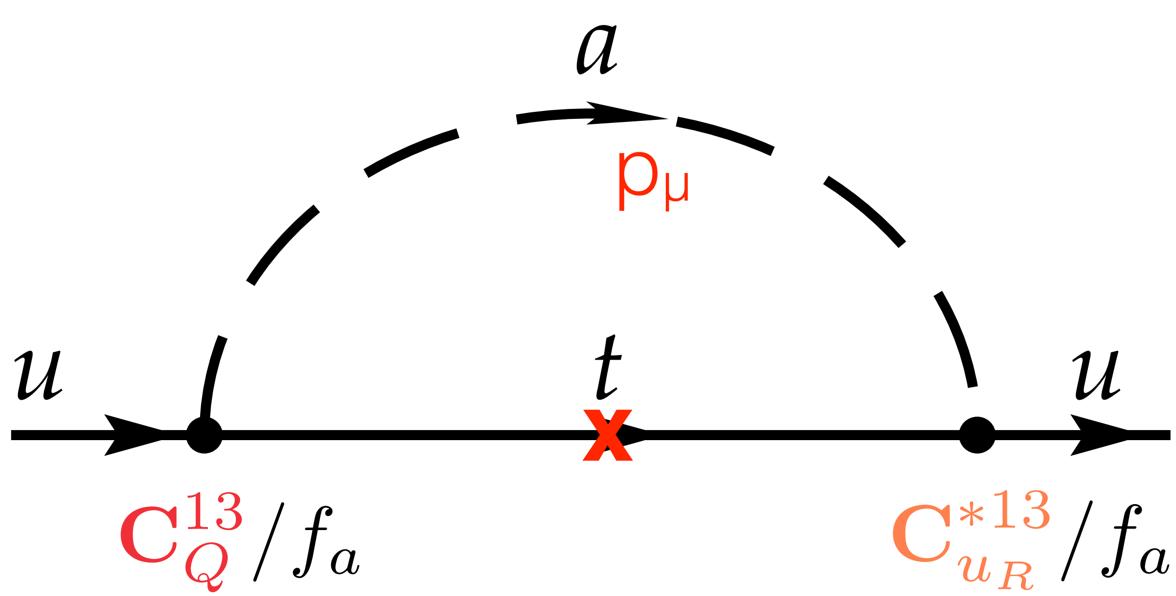
physical $\bar{\theta} = \theta + \operatorname{Arg}\det(\boldsymbol{M}_u \boldsymbol{M}_d)$

ALP contribution to $\bar{\theta}$



V. Enguita, M.B. Gavela, B. Grinstein, P. Quilez, arXiv: 2403.13133

ALP contribution to $\bar{\theta}$

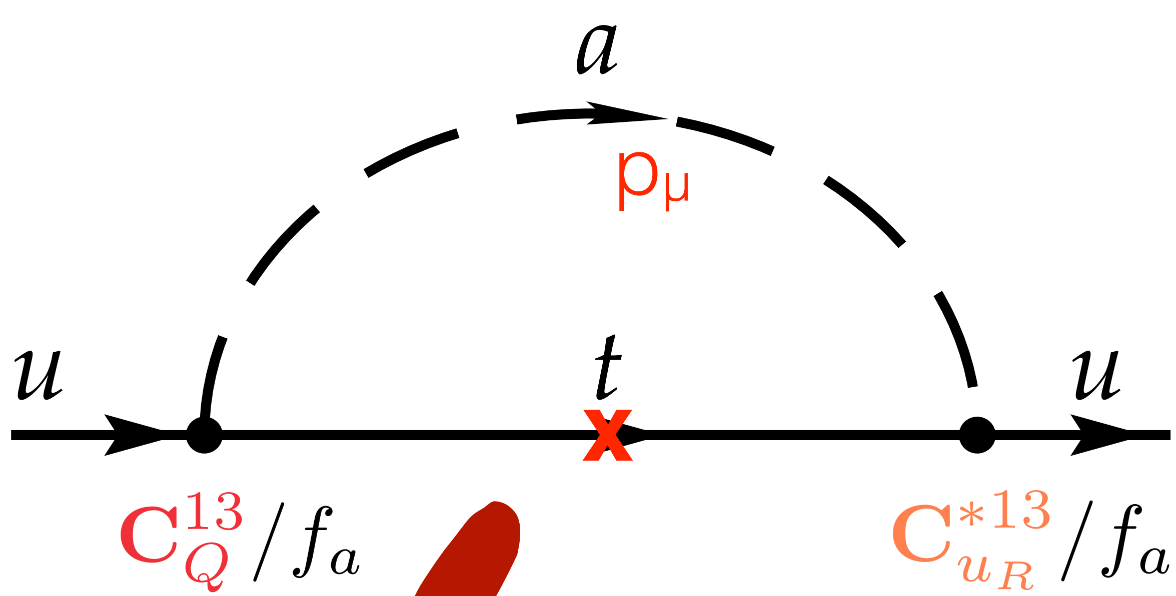


* Factor m_t for chirality flip

* Factor p_μ^2 from vertices

V. Enguita, M.B. Gavela, B. Grinstein, P. Quilez, arXiv: 2403.13133

ALP contribution to $\bar{\theta}$



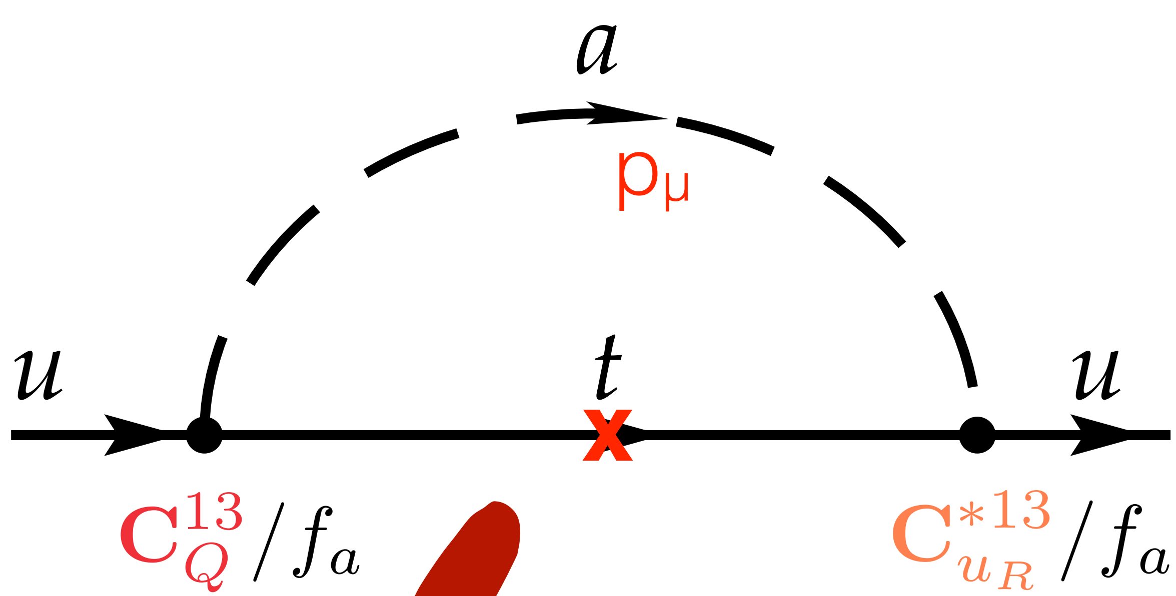
* Factor m_t for chirality flip

* Factor $p_\mu{}^2$ from vertices

$$\Delta\bar{\theta}_{\rm ALP} \simeq \frac{m_t\,\max(m_a^2, m_t^2)}{16\pi^2 f_a^2 m_u}\,\mathrm{Im}(C_Q^{13} C_{u_R}^{*13})$$

V. Enguita, M.B. Gavela, B. Grinstein, P. Quilez, arXiv: 2403.13133

ALP contribution to $\bar{\theta}$



* Factor m_t for chirality flip
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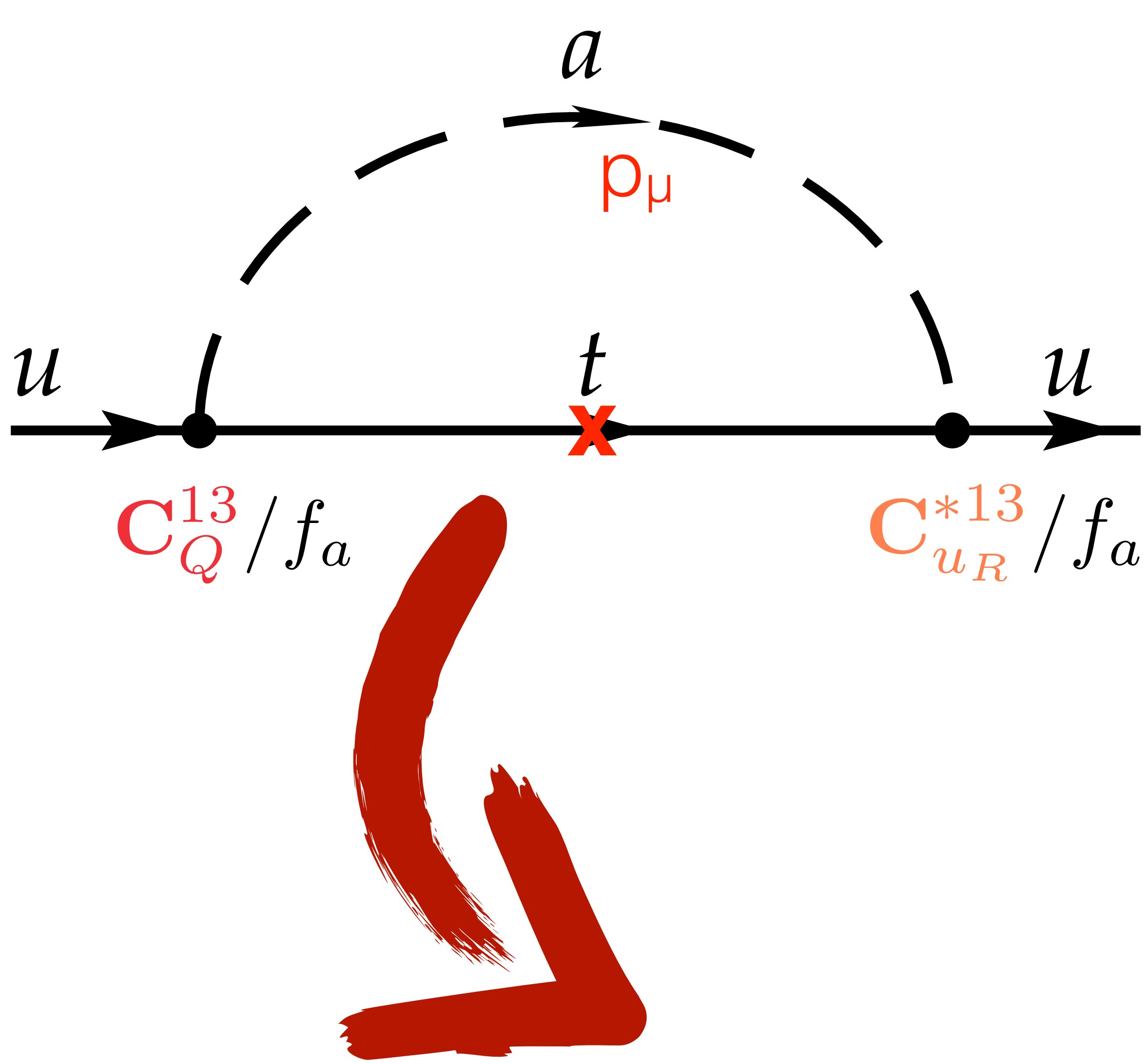
$$\Delta\bar{\theta}_{\mathrm{ALP}} \simeq \frac{m_t \max(m_a^2, m_t^2)}{16\pi^2 f_a^2 m_u} \mathrm{Im}(C_Q^{13} C_{u_R}^{*13})$$

V. Enguita, M.B. Gavela, B. Grinstein, P. Quilez, arXiv: 2403.13133

ALP contribution to $\bar{\theta}$



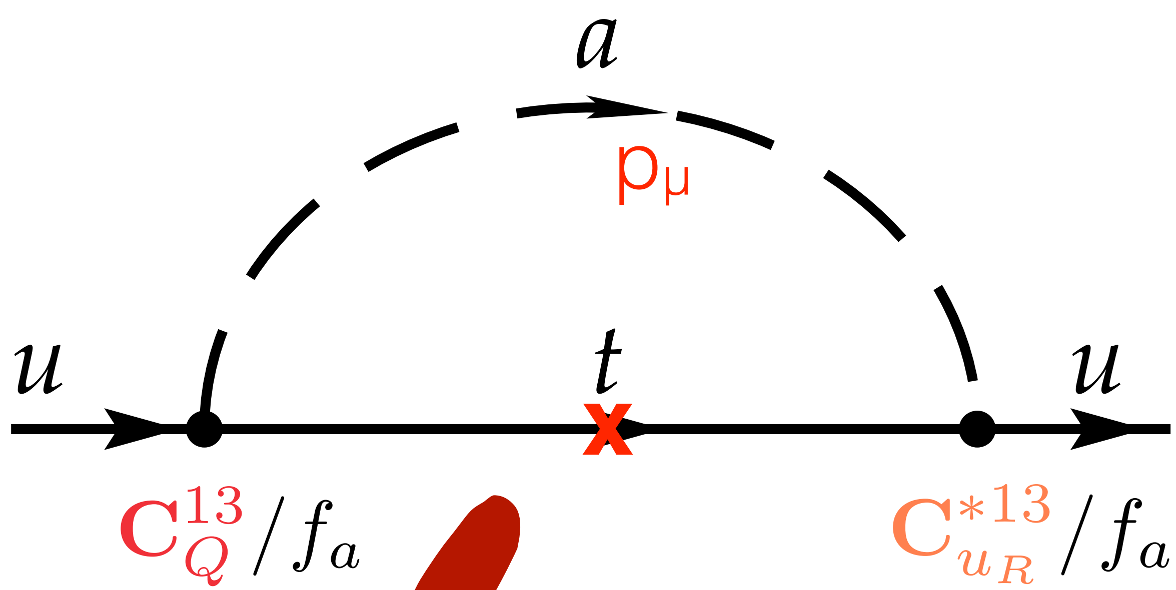
* Factor m_t for chirality flip

* Factor p_μ^2 from vertices

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

V. Enguita, M.B. Gavela, B. Grinstein, P. Quilez, arXiv: 2403.13133

ALP contribution to $\bar{\theta}$



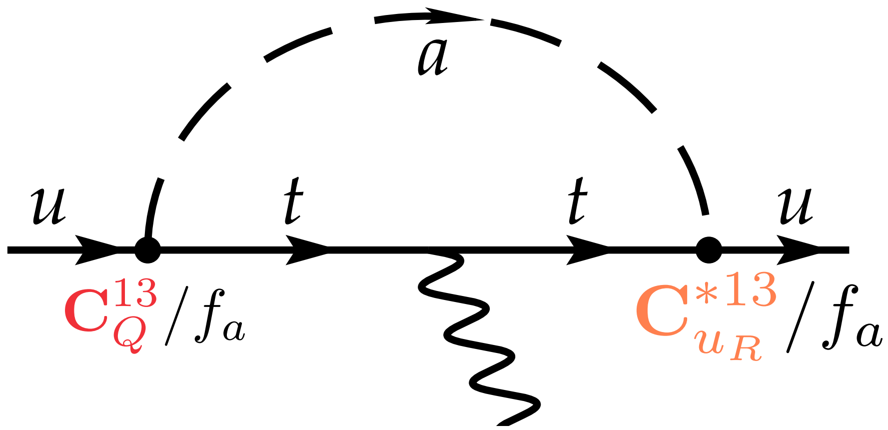
* Factor m_t for chirality flip

* Factor p_μ^2 from vertices

$m_a < m_t$:

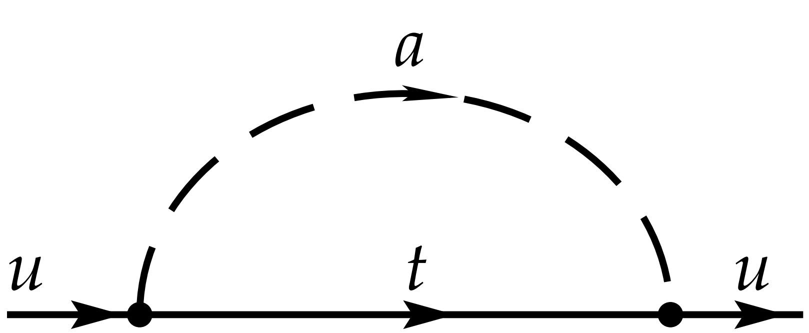
$$\left.\frac{d_n}{e}\right|_{\bar{\theta}} \sim \frac{\mathcal{O}(10^{-3}\ \mathrm{GeV}^{-1})}{16\pi^2} \times \left(\frac{m_t^3}{m_u}\right) \frac{\mathrm{Im}(C_Q^{13}\, C_{u_R}^{*13})}{f_a^2}$$

nEDM limits on ALP-fermion couplings



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

OLD



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

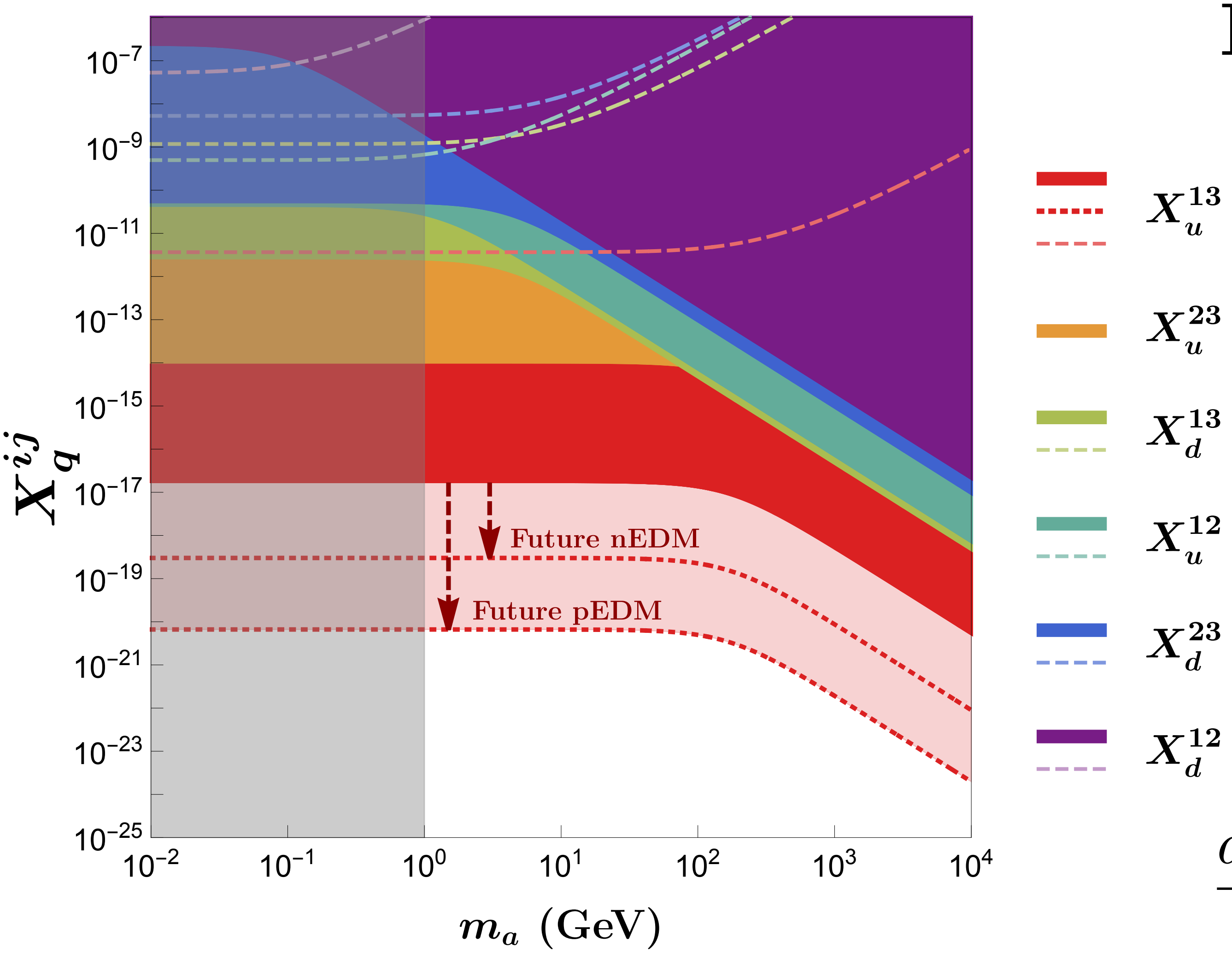
Bounds many orders of magnitude stronger

NEW

V. Enguita, M.B. Gavela, B. Grinstein, P. Quilez, arXiv: 2403.13133

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:

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

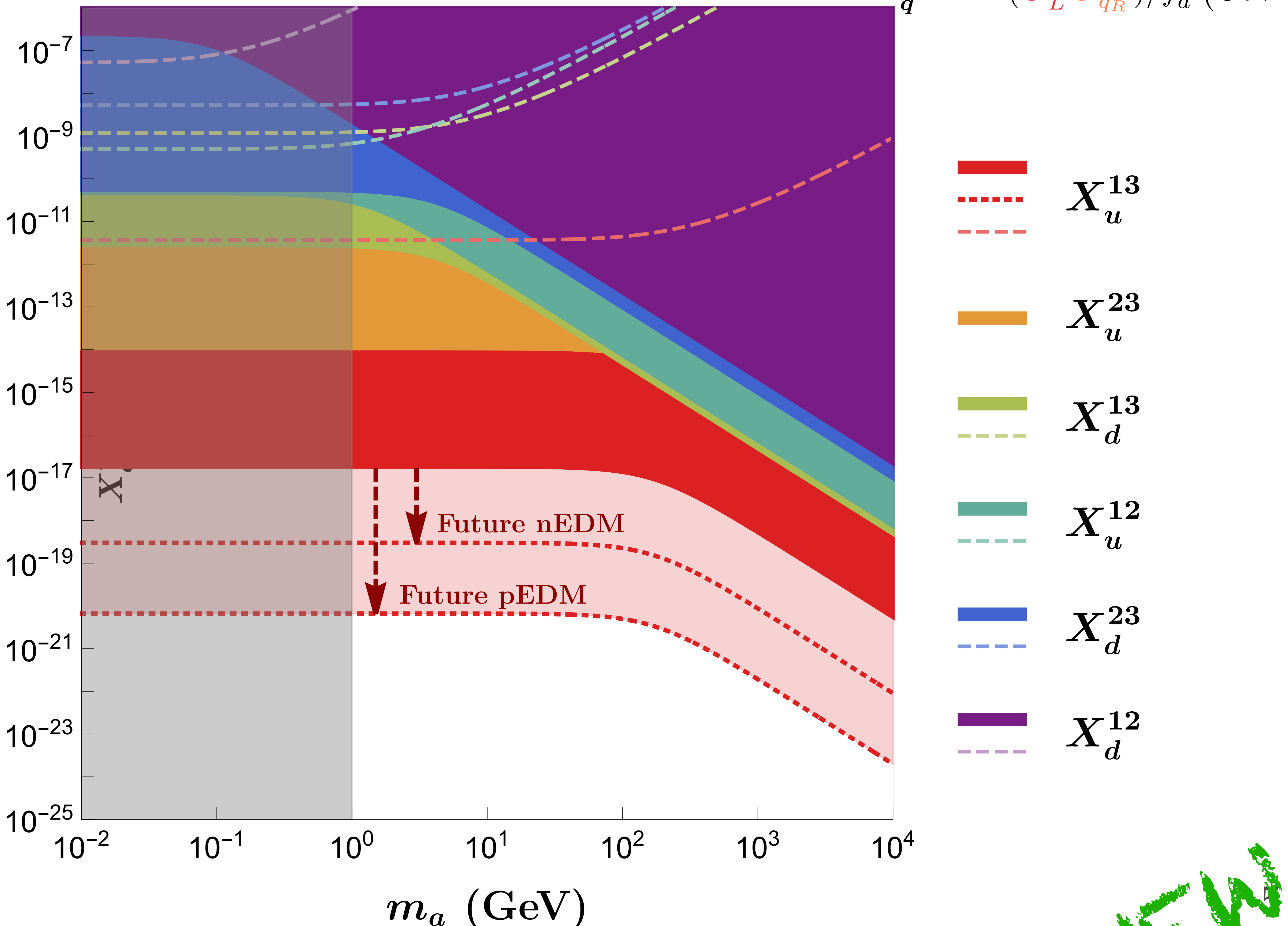
Solid regions:

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

Bounds many orders of magnitude stronger

V. Enguita, M.B. Gavela, B. Grinstein, P. Quilez, arXiv: 2403.13133

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

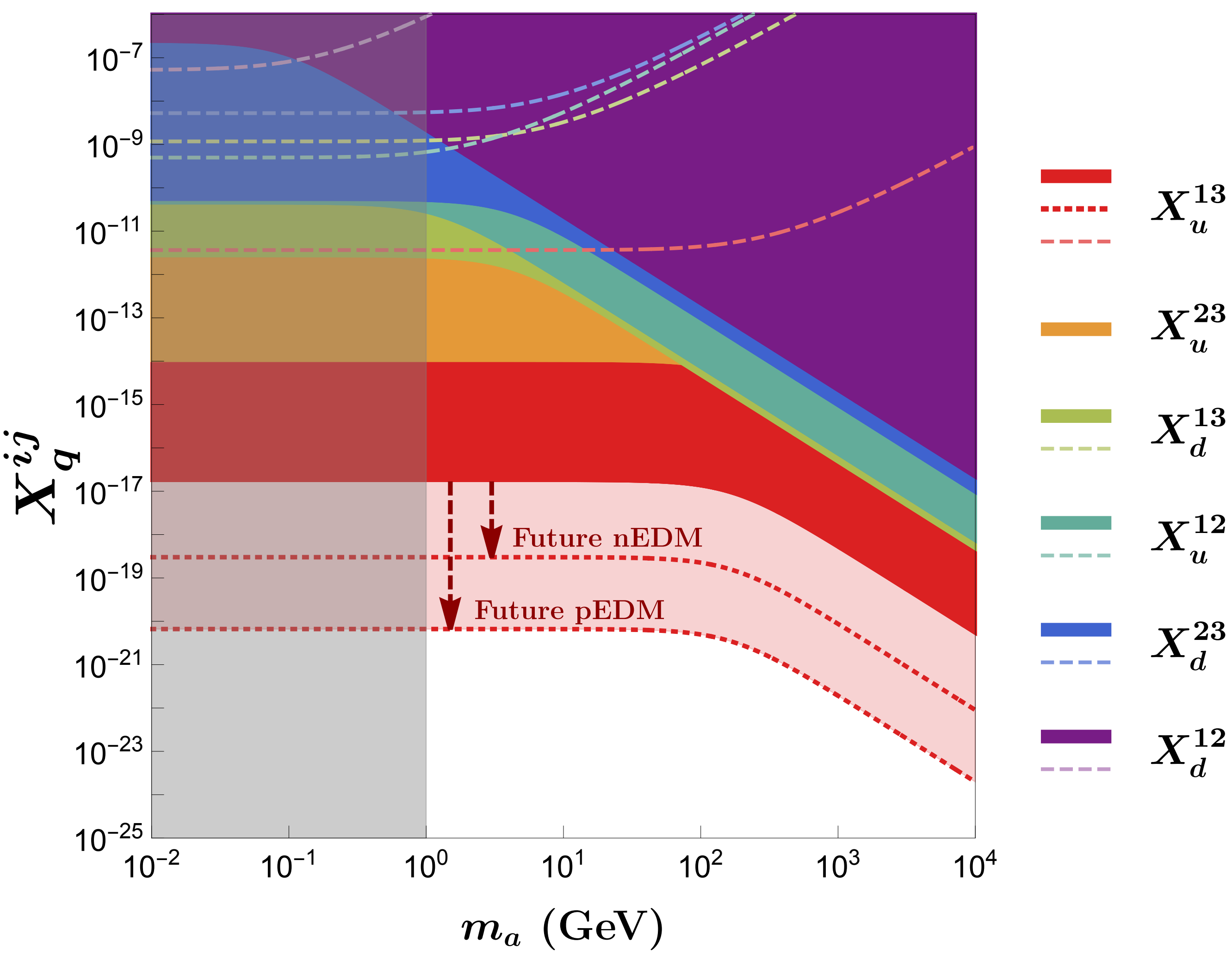


Bounds many orders of magnitude stronger

V. Enguita, M.B. Gavela, B. Grinstein, P. Quilez, arXiv: 2403.13133

nEDM limits on ALP-fermion couplings

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



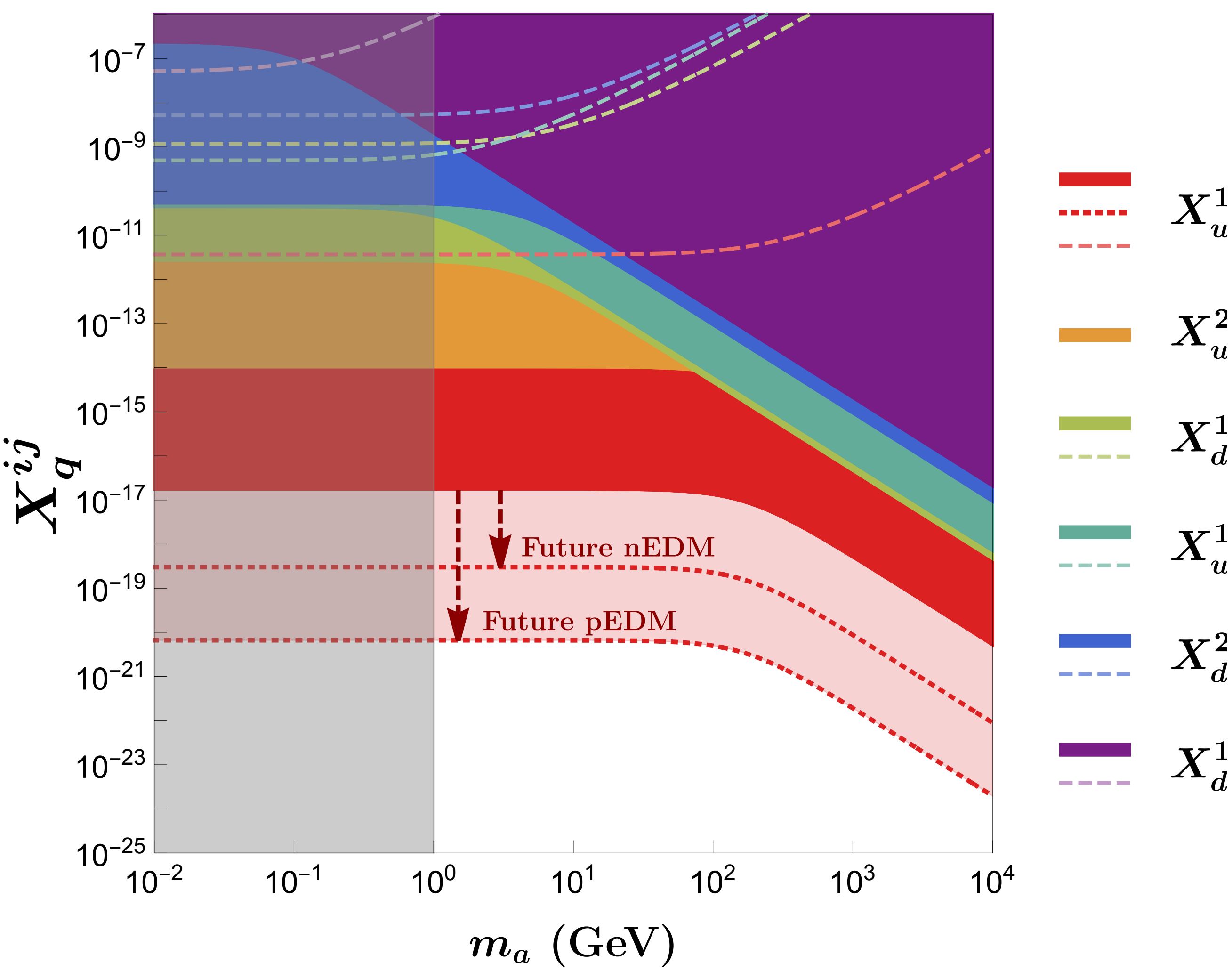
Combination	$\bar{\theta}$-bounds (GeV^{-2})	qEDM & cEDM (GeV^{-2})
$\lvert \mathrm{Im}[C_Q^{13} C_{u_R}^{*13}]/f_a^2 \rvert$	1.8×10^{-17}	3.7×10^{-12}
$\lvert \mathrm{Im}[C_Q^{23} C_{u_R}^{*23}]/f_a^2 \rvert$	1.1×10^{-14}	8.3×10^{-8}
$\lvert \mathrm{Im}[C_Q^{13} C_{d_R}^{*13}]/f_a^2 \rvert$	1.1×10^{-12}	1.9×10^{-9}
$\lvert \mathrm{Im}[C_Q^{12} C_{u_R}^{*12}]/f_a^2 \rvert$	2.7×10^{-12}	2.3×10^{-9}
$\lvert \mathrm{Im}[C_Q^{23} C_{d_R}^{*23}]/f_a^2 \rvert$	2.3×10^{-11}	8.7×10^{-9}
$\lvert \mathrm{Im}[C_Q^{12} C_{d_R}^{*12}]/f_a^2 \rvert$	8.6×10^{-11}	1.2×10^{-5}

m_a = 5 GeV

V. Enguita, M.B. Gavela, B. Grinstein, P. Quilez, arXiv: 2403.13133

nEDM limits on ALP-fermion couplings

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



As a function of m_a

$\mathrm{Im}[C_Q^{13} C_{u_R}^{*13}]/f_a^2$	$<$	$\left(\frac{m_t^2}{m_a^2+m_t^2}\right)$	2×10^{-17}
$\mathrm{Im}[C_Q^{23} C_{u_R}^{*23}]/f_a^2$	$<$	$\left(\frac{m_t^2}{m_a^2+m_t^2}\right)$	1×10^{-14}
$\mathrm{Im}[C_Q^{13} C_{d_R}^{*13}]/f_a^2$	$<$	$\left(\frac{m_b^2}{m_a^2+m_b^2}\right)$	3×10^{-12}
$\mathrm{Im}[C_Q^{12} C_{u_R}^{*12}]/f_a^2$	$<$	$\left(\frac{m_c^2}{m_a^2+m_c^2}\right)$	5×10^{-11}
$\mathrm{Im}[C_Q^{23} C_{d_R}^{*23}]/f_a^2$	$<$	$\left(\frac{m_b^2}{m_a^2+m_b^2}\right)$	6×10^{-11}
$\mathrm{Im}[C_Q^{12} C_{d_R}^{*12}]/f_a^2$	$<$	$\left(\frac{m_s^2}{m_a^2+m_s^2}\right)$	3×10^{-7}

Bounds on $\mathrm{Im}[C_Q^{ij} C_{q_R}^{*ij}]/f_a^2$ in GeV^{-2} obtained from the $\bar{\theta}$ correction.

V. Enguita, M.B. Gavela, B. Grinstein, P. Quilez, arXiv: 2403.13133

We checked our results in the ``chirality-flip'' basis

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

Chiral rot.:
$$\begin{cases} u_L \longrightarrow e^{i\frac{a}{f_a}\boldsymbol{C}_Q} u_L\,, & d_L \longrightarrow e^{i\frac{a}{f_a}\boldsymbol{C}_Q} d_L\,, \\ u_R \longrightarrow e^{i\frac{a}{f_a}\boldsymbol{C}_{u_R}} u_R\,, & d_R \longrightarrow e^{i\frac{a}{f_a}\boldsymbol{C}_{d_R}} d_R \end{cases}$$

We checked our results in the ``chirality-flip" basis

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

Chiral rot.: $$\begin{cases} u_L \longrightarrow e^{i\frac{a}{f_a}\boldsymbol{C}_Q} u_L\,, & d_L \longrightarrow e^{i\frac{a}{f_a}\boldsymbol{C}_Q} d_L\,, \\ u_R \longrightarrow e^{i\frac{a}{f_a}\boldsymbol{C}_{u_R}} u_R\,, & d_R \longrightarrow e^{i\frac{a}{f_a}\boldsymbol{C}_{d_R}} d_R \end{cases}$$

$$\boxed{\begin{aligned} \mathcal{L} \supset\ & \bar{u}_L\, v\, \left[i\frac{a}{f_a}\boldsymbol{K}_u + \frac{a^2}{f_a^2}\boldsymbol{F}_u\right] u_R \\ & + \bar{d}_L\, v\, \left[i\frac{a}{f_a}\boldsymbol{K}_d + \frac{a^2}{f_a^2}\boldsymbol{F}_d\right] d_R + \text{h.c.} + \ldots \end{aligned}}$$

V. Enguita, M.B. Gavela, B. Grinstein, P. Quilez, arXiv: 2403.13133

We checked our results in the ``chirality-flip'' basis

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

Chiral rot.: $$\begin{cases} u_L \longrightarrow e^{i\frac{a}{f_a}\boldsymbol{C}_Q} u_L\,, & d_L \longrightarrow e^{i\frac{a}{f_a}\boldsymbol{C}_Q} d_L\,, \\ u_R \longrightarrow e^{i\frac{a}{f_a}\boldsymbol{C}_{u_R}} u_R\,, & d_R \longrightarrow e^{i\frac{a}{f_a}\boldsymbol{C}_{d_R}} d_R \end{cases}$$

$$\boxed{\begin{aligned}\mathcal{L} \supset\ & \bar{u}_L\, v \left[i\frac{a}{f_a}\boldsymbol{K}_u + \frac{a^2}{f_a^2}\boldsymbol{F}_u\right] u_R \\ & + \bar{d}_L\, v \left[i\frac{a}{f_a}\boldsymbol{K}_d + \frac{a^2}{f_a^2}\boldsymbol{F}_d\right] d_R + \text{h.c.} + \ldots\end{aligned}}$$

where $$\boxed{\begin{aligned} v\,\boldsymbol{K}_q &\equiv \boldsymbol{C}_Q\boldsymbol{M}_q - \boldsymbol{M}_q\boldsymbol{C}_{q_R}\,, \\ 2\,v\,\boldsymbol{F}_q &\equiv 2\boldsymbol{C}_Q\boldsymbol{M}_q\boldsymbol{C}_{q_R} - \boldsymbol{C}_Q^2\boldsymbol{M}_q - \boldsymbol{M}_q\boldsymbol{C}_{q_R}^2\end{aligned}}$$

We checked our results in the ``chirality-flip'' basis

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

Chiral rot.:

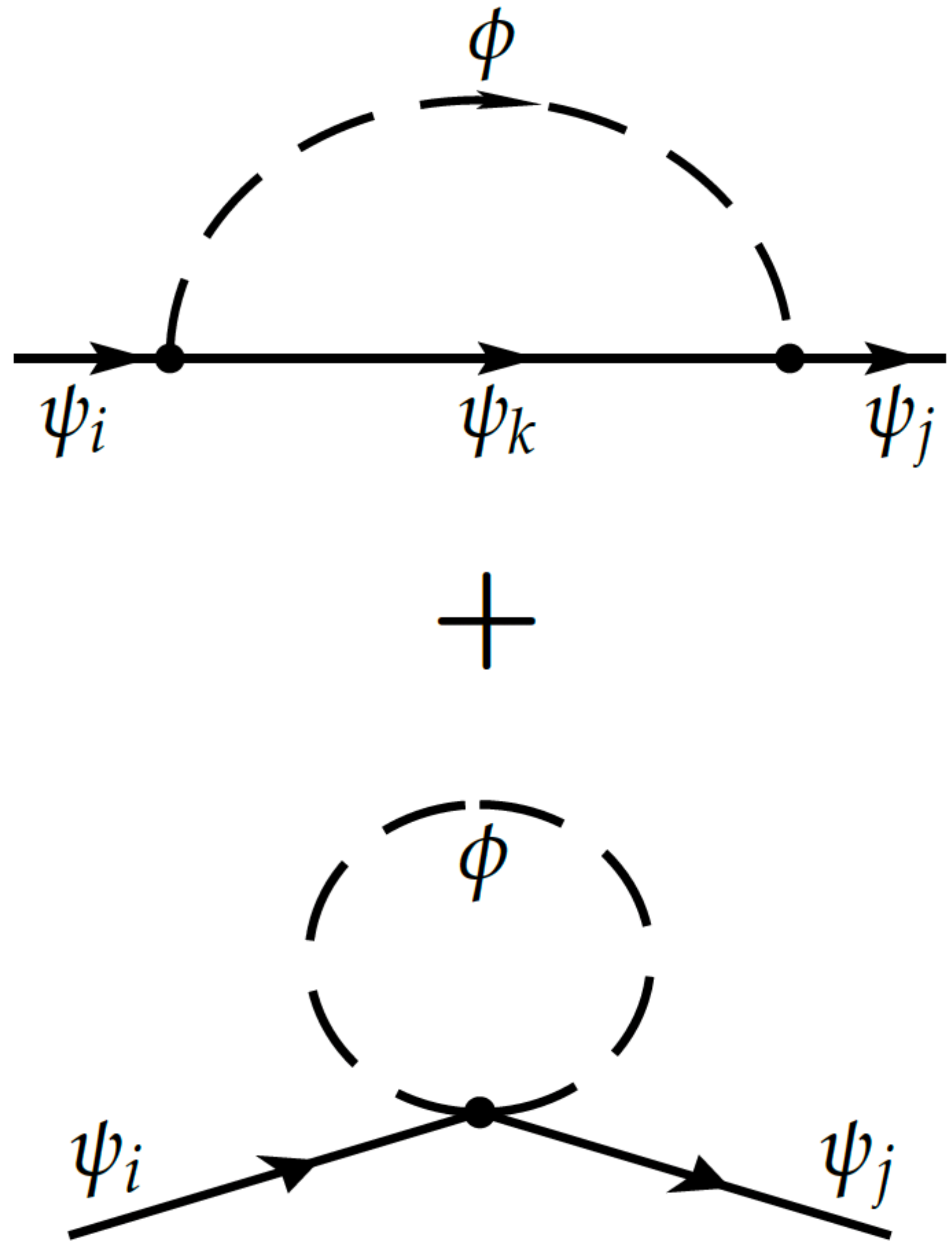
$$\begin{cases} u_L \longrightarrow e^{i\frac{a}{f_a}\boldsymbol{C}_Q} u_L\,, & d_L \longrightarrow e^{i\frac{a}{f_a}\boldsymbol{C}_Q} d_L\,, \\ u_R \longrightarrow e^{i\frac{a}{f_a}\boldsymbol{C}_{u_R}} u_R\,, & d_R \longrightarrow e^{i\frac{a}{f_a}\boldsymbol{C}_{d_R}} d_R \end{cases}$$

$$\begin{aligned} \mathcal{L} \supset\, & \bar{u}_L\, v \left[i\frac{a}{f_a}\boldsymbol{K}_u + \frac{a^2}{f_a^2}\boldsymbol{F}_u \right] u_R \\ & + \bar{d}_L\, v \left[i\frac{a}{f_a}\boldsymbol{K}_d + \frac{a^2}{f_a^2}\boldsymbol{F}_d \right] d_R + \text{h.c.} + \ldots \end{aligned}$$

where

$$\begin{aligned} v\,\boldsymbol{K}_q &\equiv \boldsymbol{C}_Q \boldsymbol{M}_q - \boldsymbol{M}_q \boldsymbol{C}_{q_R}\,, \\ 2\,v\,\boldsymbol{F}_q &\equiv 2\boldsymbol{C}_Q \boldsymbol{M}_q \boldsymbol{C}_{q_R} - \boldsymbol{C}_Q^2 \boldsymbol{M}_q - \boldsymbol{M}_q \boldsymbol{C}_{q_R}^2 \end{aligned}$$

There are two diagrams in the ``chirality-flip” basis:



V. Enguita, M.B. Gavela, B. Grinstein, P. Quilez, arXiv: 2403.13133

General Scalar

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_S$$

CP-violation

V. Enguita, M.B. Gavela, B. Grinstein, P. Quilez, arXiv: 2403.13133

General Scalar

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{S}$$

CP-violation

$\bar{\theta}$ -> bounds also improved by orders of magnitude

see talk by Victor Enguita tomorrow afternoon

V. Enguita, M.B. Gavela, B. Grinstein, P. Quilez, arXiv: 2403.13133

What happens if there is a PQ symmetry (in addition) ?

either for ALPs or generic scalars

With a PQ symmetry present:

$\bar{\theta}$ disappears but a residual $\bar{\theta}$ induced remains:

Vafa-Witten theorem does not apply with extra explicit CP sources and

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

we have updated the bounds in this case

M. Pospelov, arXiv: hep-ph/9707431, Phys. Re. D 58 (1998) 097703

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:

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

M. Pospelov, A. Ritz, hep-ph/0504321, 073015

J. Hisano et al., arXiv:1205.2212

Without a PQ mechanism:

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

chromo-electric EDMs

In the presence of a PQ mechanism:

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

chromo-electric EDMs

sum rules Hisano et al.

Without a PQ mechanism:

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

Lattice
+ sum rules

In the presence of a PQ mechanism:

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

ALPs

Combination	With PQ (GeV^{-2})	Without PQ (GeV^{-2})
$\mathrm{Im}(\boldsymbol{C}_L^{13}\boldsymbol{C}_{u_R}^{13})/f_a^2$	3.7×10^{-12}	3.7×10^{-12}
$\mathrm{Im}(\boldsymbol{C}_L^{13}\boldsymbol{C}_{d_R}^{13})/f_a^2$	1.9×10^{-9}	3.2×10^{-9}
$\mathrm{Im}(\boldsymbol{C}_L^{12}\boldsymbol{C}_{u_R}^{12})/f_a^2$	2.3×10^{-9}	2.4×10^{-9}
$\mathrm{Im}(\boldsymbol{C}_L^{23}\boldsymbol{C}_{d_R}^{23})/f_a^2$	8.7×10^{-9}	1.2×10^{-7}
$\mathrm{Im}(\boldsymbol{C}_L^{12}\boldsymbol{C}_{d_R}^{12})/f_a^2$	1.2×10^{-5}	1.9×10^{-6}

TABLE IV: *ALP case.* Comparison of bounds w/o the presence of a PQ symmetry. All bounds are in units of GeV^{-2}, and $m_a = 5$ GeV has been assumed for illustration.

V. Enguita, M.B. Gavela, B. Grinstein, P. Quilez, arXiv: 2403.13133

CONCLUSIONS

*** ALP couplings to fermions induce one-loop corrections to $\bar{\theta}$ —> to the nEDM**

*** We have improved the bounds on CP-odd ALP-fermion couplings by ~ 4 orders of magnitude**

*** The same kind of improvement applies to generic singlet scalars**

* Novel bounds on ALP-neutrino couplings

Backup

$$\boldsymbol{M}_{u,d}^{1\,\text{loop}} = \boldsymbol{M}_{u,d} + \Delta\boldsymbol{M}_{u,d}$$

$$\begin{aligned}
\Delta\bar{\theta}_{\text{ALP}}(\mu) &= \sum_{q=u,d} \arg\left[\det\left(\boldsymbol{M}_q\left(1 + \boldsymbol{M}_q^{-1}\Delta\boldsymbol{M}_q\right)\right)\right] \\
&\simeq \sum_{q=u,d} \operatorname{Im}\operatorname{Tr}\left(\boldsymbol{M}_q^{-1}\Delta\boldsymbol{M}_q\right)
\end{aligned}$$

$$\Delta\bar{\theta}_{\text{ALP}}(\mu) \simeq \frac{1}{f_a^2} \sum_{q=u,d} \operatorname{Im}\operatorname{Tr}\left[\boldsymbol{M}_q^{-1}\mathbf{C}_Q\boldsymbol{L}\mathbf{C}_{q_R}\right]$$

$$\boldsymbol{L} \equiv \operatorname{diag}(L_1, L_2, L_3)$$

$$\begin{aligned}
L_k = \frac{m_{q_k}}{16\pi^2}\Bigg[&\left(m_a^2 + m_{q_k}^2\right)\left(1 + \log\frac{\mu^2}{m_a^2}\right) \\
&+ \frac{m_{q_k}^4}{m_{q_k}^2 - m_a^2}\log\frac{m_a^2}{m_{q_k}^2}\Bigg]
\end{aligned}$$

V. Enguita, M.B. Gavela, B. Grinstein, P. Quilez, arXiv: 2403.13133

$$\frac{d\bar{\theta}}{d\mu} = \sum_{q=u,d} \mathrm{Im} \frac{d}{d\mu} \ln \det \boldsymbol{\mathcal{M}}_q = \sum_{q=u,d} \mathrm{Im} \frac{d}{d\mu} \mathrm{Tr} \ln \boldsymbol{\mathcal{M}}_q$$

$$= \sum_{q=u,d} \mathrm{Im}\,\mathrm{Tr} \left(\boldsymbol{\mathcal{M}}_q^{-1} \frac{d}{d\mu} \boldsymbol{\mathcal{M}}_q \right) \quad ($$

$$\mu \frac{d\bar{\theta}}{d\mu} \simeq \frac{1}{f_a^2} \sum_{q=u,d} \mathrm{Im}\,\mathrm{Tr} \left[\boldsymbol{M}_q^{-1} \mathbf{C}_Q \boldsymbol{\mathcal{L}} \mathbf{C}_{q_R} \right]$$

$$\mathcal{L}_k = \frac{m_{q_k}}{8\pi^2} \left(m_a^2 + m_{q_k}^2 \right)$$

Neglecting threshold corrections

For an ALP:

$$\bar{\theta}\left(\mu_{\mathrm{IR}}\right) \simeq \bar{\theta}_0 +$$

$$\sum_{u_i=\{u,c,t\}} \frac{m_{u_k}\left(m_a^2+\widehat{m}_{u_k}^2\right)}{16\pi^2 f_a^2 m_{u_i}} \operatorname{Im}\left(\boldsymbol{C}_Q^{ik}\boldsymbol{C}_{u_R}^{*ik}\right) \log\frac{f_a^2}{\max\left(m_a^2, m_{u_k}^2\right)}$$

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

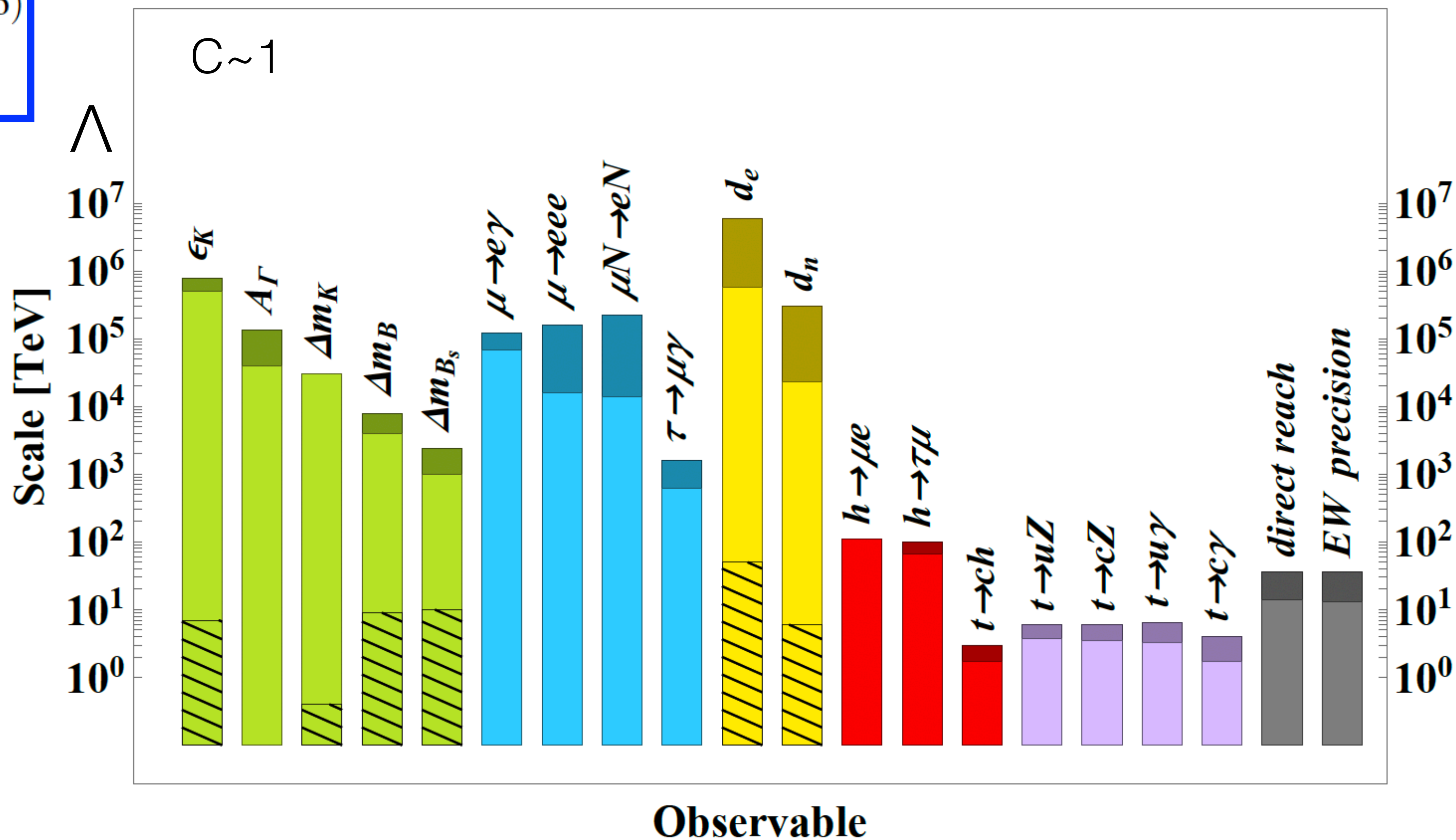
Neglecting threshold corrections

For a generic scalar:

$$\bar{\theta}\left(\mu_{IR}\right) \simeq \bar{\theta}_0 + \frac{v^2}{16\pi^2\Lambda^2} \times \left(\sum_{i,k} \left[\frac{m_{u_k}\,\mathrm{Im}\left(\boldsymbol{K}_u^{ik}\boldsymbol{K}_u^{ki}\right)}{m_{u_i}} - \frac{m_\phi^2\,\mathrm{Im}\left(\boldsymbol{F}_u^{ik}\right)}{m_{u_i}} \right] \log\frac{\Lambda^2}{\mathtt{max}(m_\phi^2, m_{u_k}^2)} + \sum_{i,k} \left[\frac{m_{d_k}\,\mathrm{Im}\left(\boldsymbol{K}_d^{ik}\boldsymbol{K}_d^{ki}\right)}{m_{d_i}} - \frac{m_\phi^2\,\mathrm{Im}\left(\boldsymbol{F}_d^{ik}\right)}{m_{d_i}} \right] \log\frac{\Lambda^2}{\mathtt{max}(m_\phi^2, m_{d_k}^2)} \right)$$

$$\frac{C_6^a}{\Lambda^2}\mathcal{O}_a^{(6)}$$

European Strategy for Particle Physics 2020



D. Aloni, A. Dery, M.B. Gavela, Y. Nir

Fig. 5.1: Reach in new physics scale of present and future facilities, from generic dimension six operators. Colour coding of observables is: green for mesons, blue for leptons, yellow for EDMs, red for Higgs flavoured couplings and purple for the top quark. The grey columns illustrate the reach of direct flavour-blind searches and EW precision measurements. The operator coefficients are taken to be either ~ 1 (plain coloured columns) or suppressed by MFV factors (hatch filled surfaces). Light (dark) colours correspond to present data (mid-term prospects, including HL-LHC, Belle II, MEG II, Mu3e, Mu2e, COMET, ACME, PIK and SNS).

e.g. Casper electric

$\{m_a, 1/f_a\}$: direct **a - gluon coupling**

$$\mathcal{L} \supset \frac{a}{f_a}\frac{\alpha_s}{8\pi} G\tilde{G}$$

$$\delta\mathcal{L} \equiv -\frac{i}{2}\frac{0.011\,e}{m_n}\frac{a}{f_a}\bar{n}\sigma_{\mu\nu}\gamma_5 n F^{\mu\nu}$$

$$\equiv g_{a\gamma n}$$

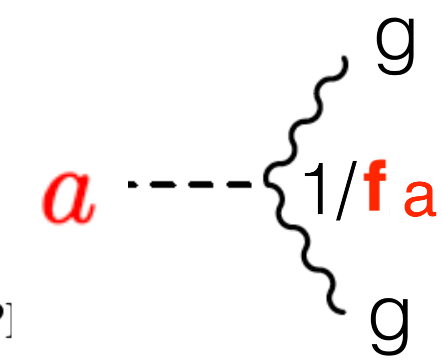
$$m_a^2 f_a^2 \simeq m_\pi^2 f_\pi^2 \frac{m_u\, m_d}{(m_u + m_d)^2}$$

Coupling to the nEDM

Axion mass

Intensely looked for experimentally...

direct a-**gluon coupling**



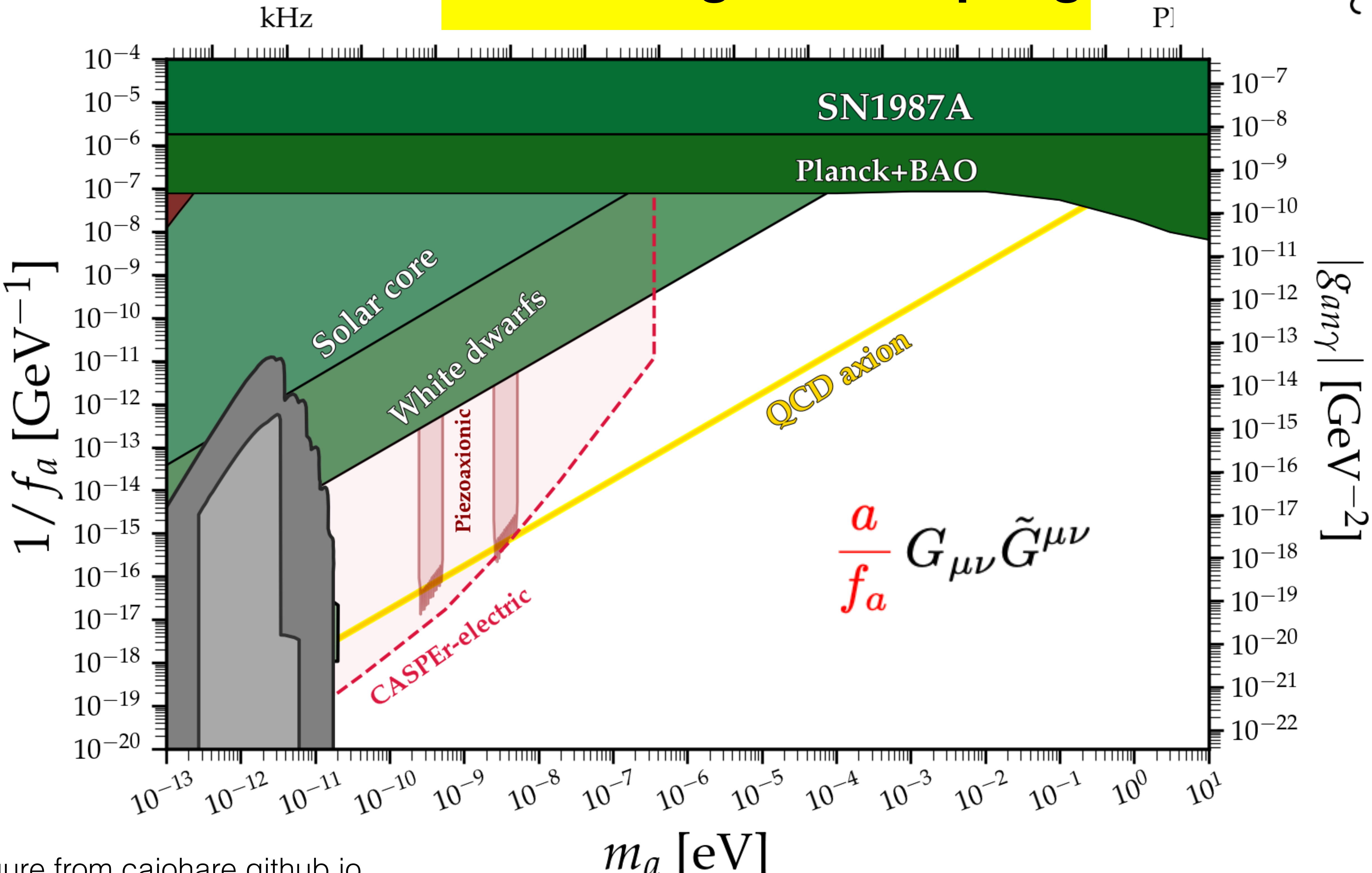
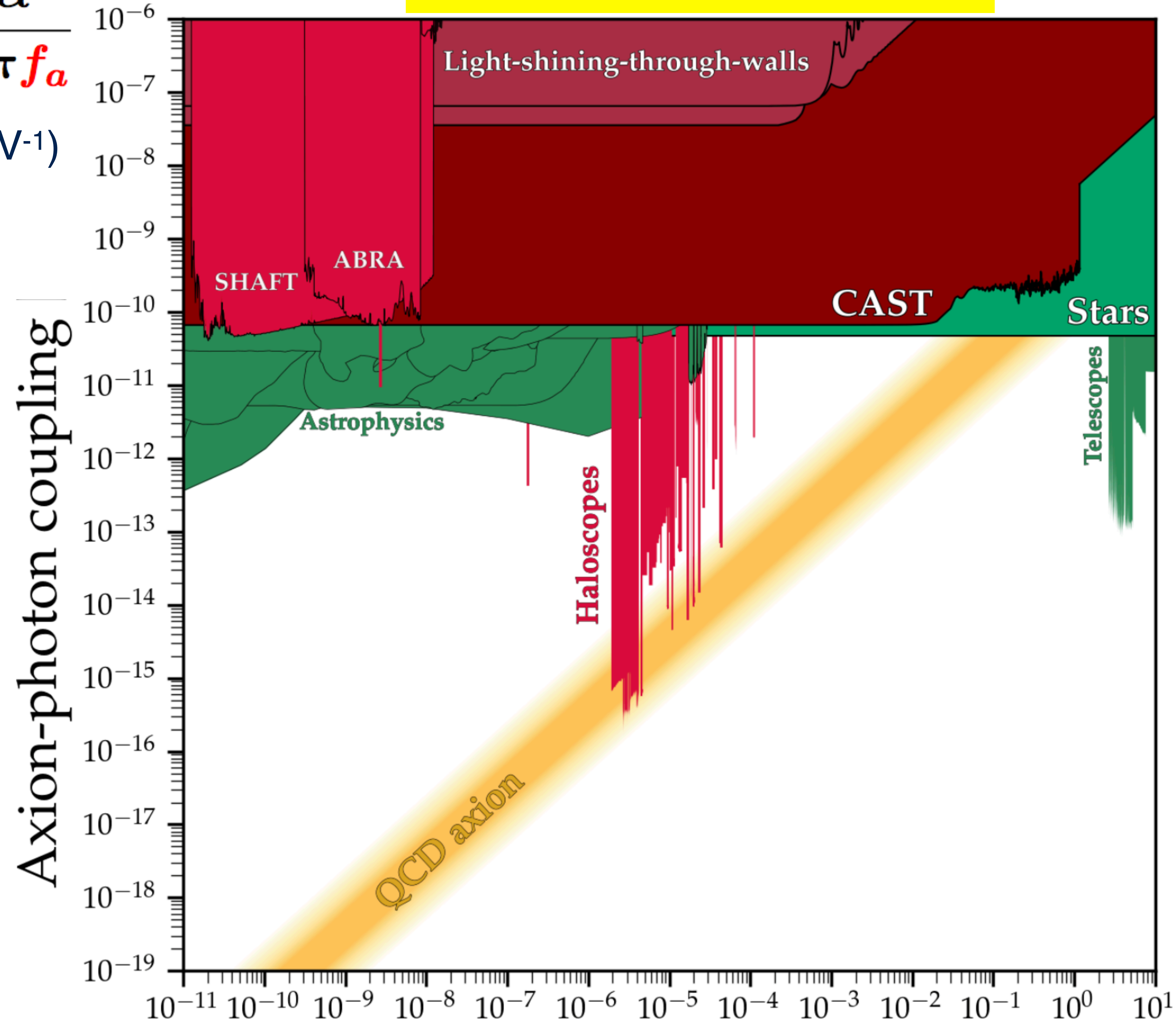


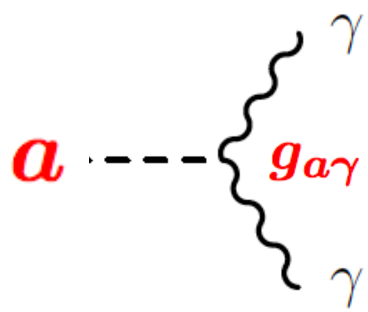
figure from cajohare.github.io

a-photon coupling

$$g_{a\gamma} \sim \mathbf{C}\,\frac{\alpha}{8\pi f_a}$$

(GeV^{-1})



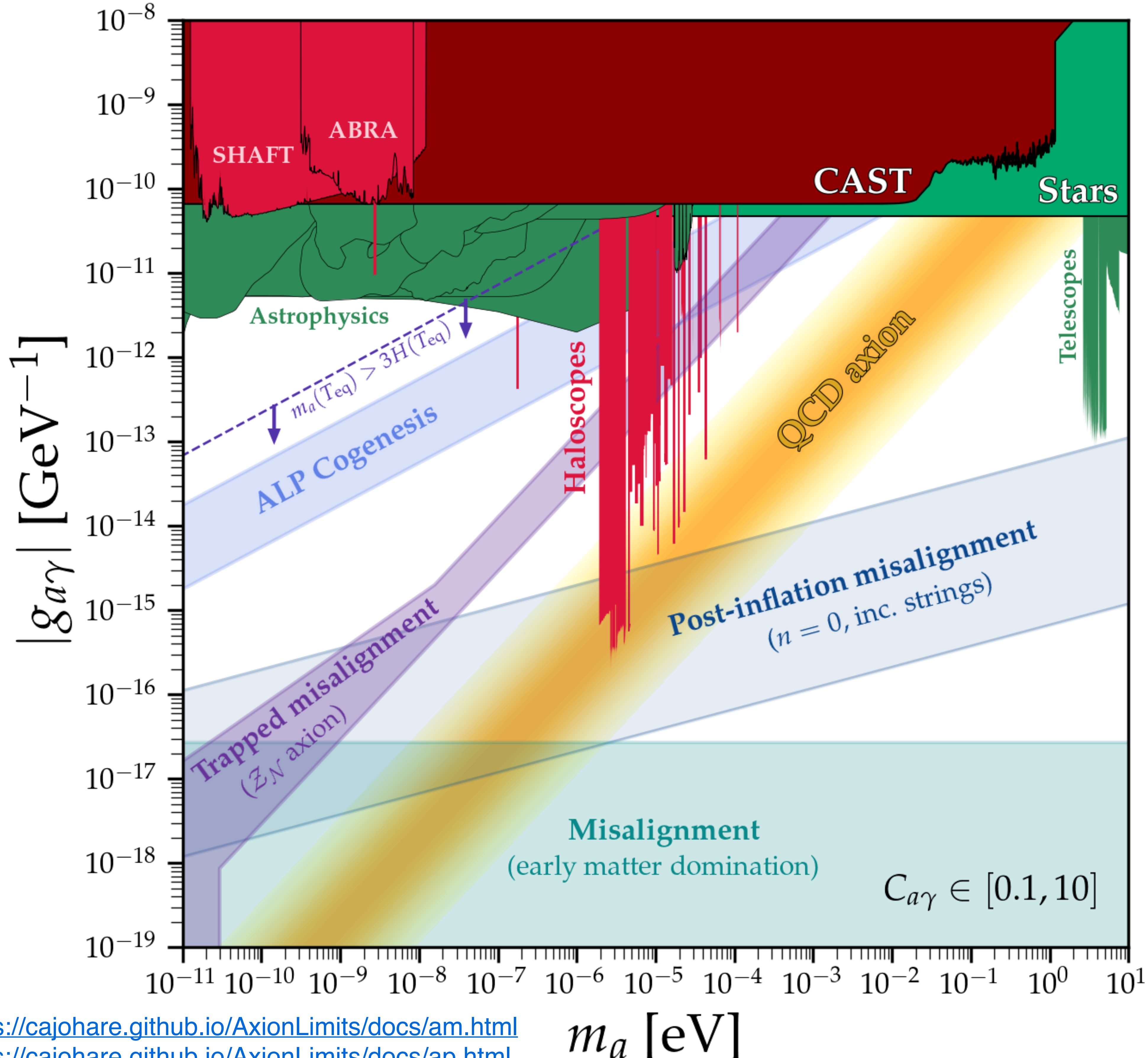


$$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$\mathbf{m_a}$ (eV)

figure from cajohare.github.io

Axions and ALPs can explain Dark Matter



a **- photon**

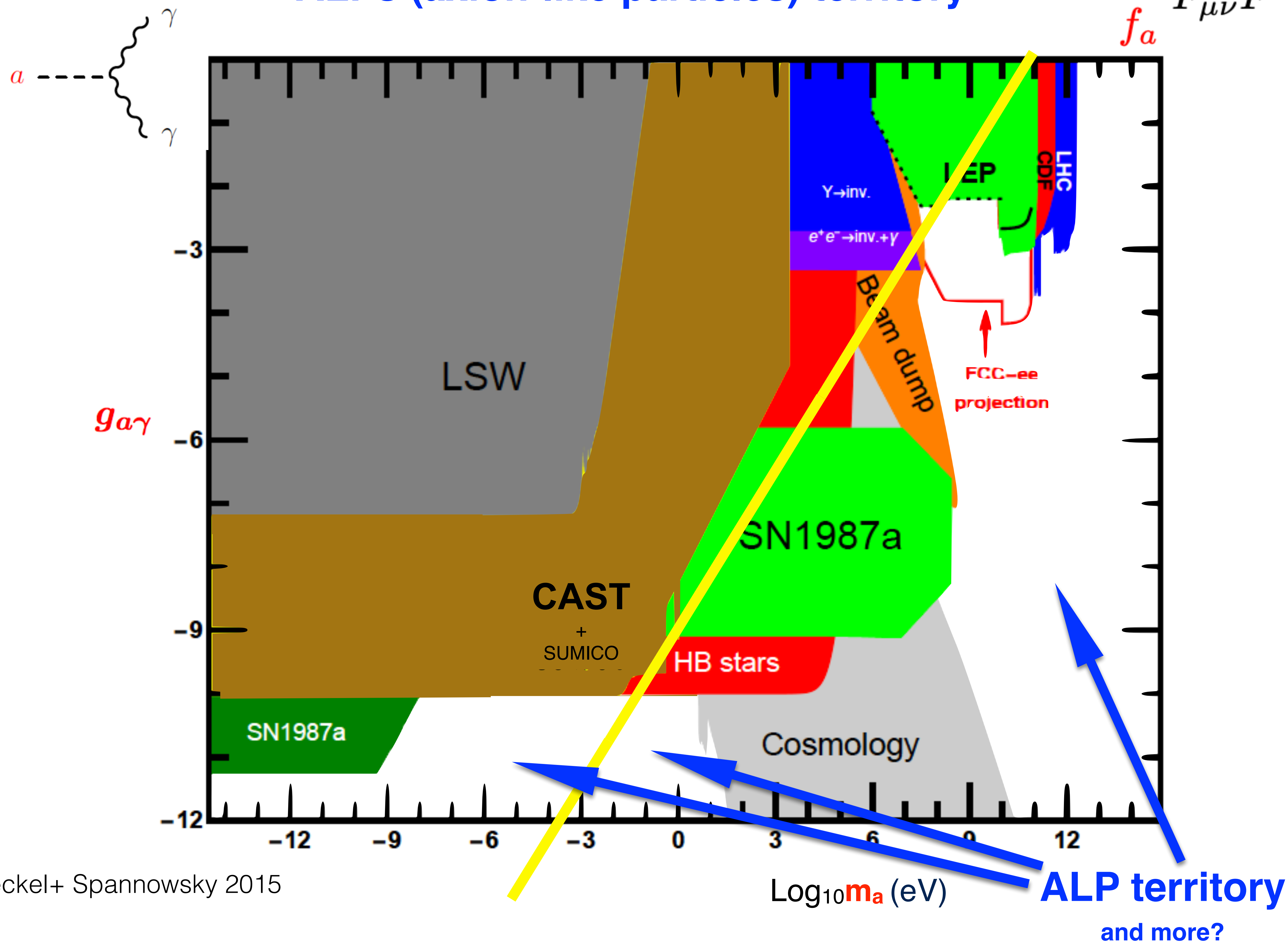
coupling

within the blueish bands axions/ALPs would account for all the DM

https://cajohare.github.io/AxionLimits/docs/am.html
https://cajohare.github.io/AxionLimits/docs/ap.html

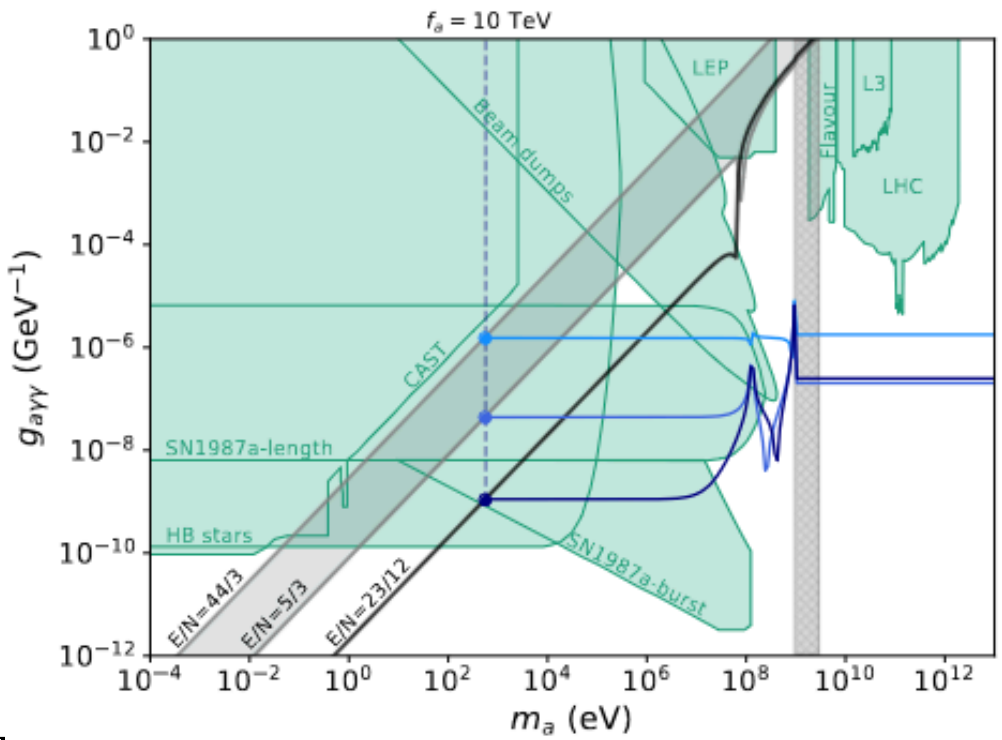
ALPs (axion-like particles) territory

$$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

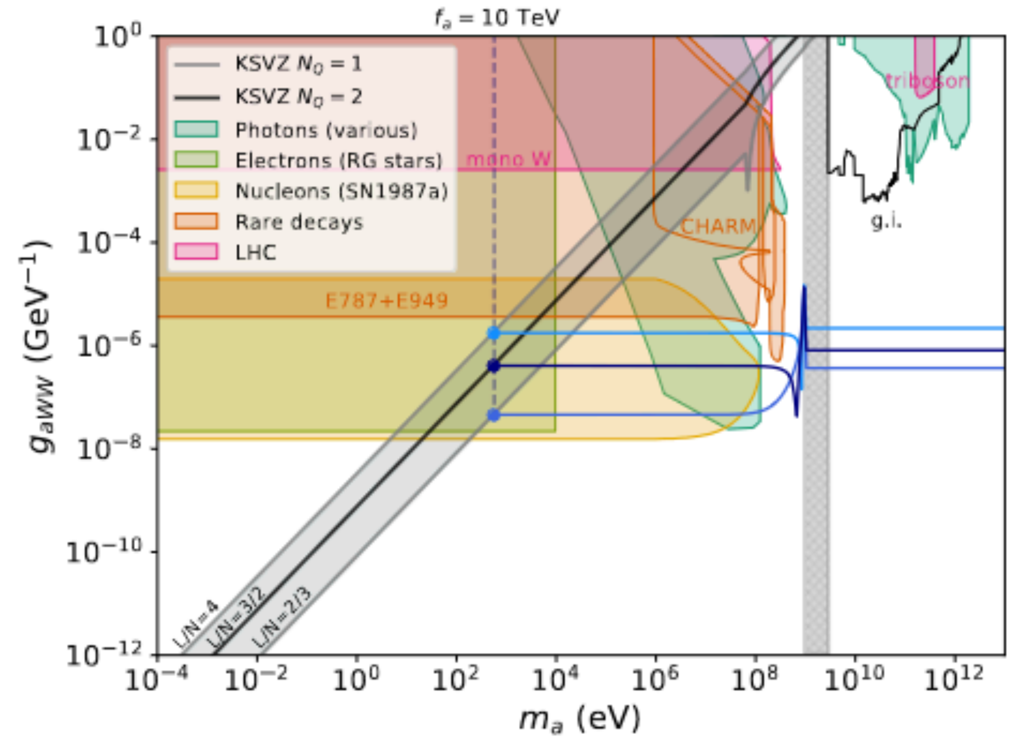


Jaeckel+ Spannowsky 2015

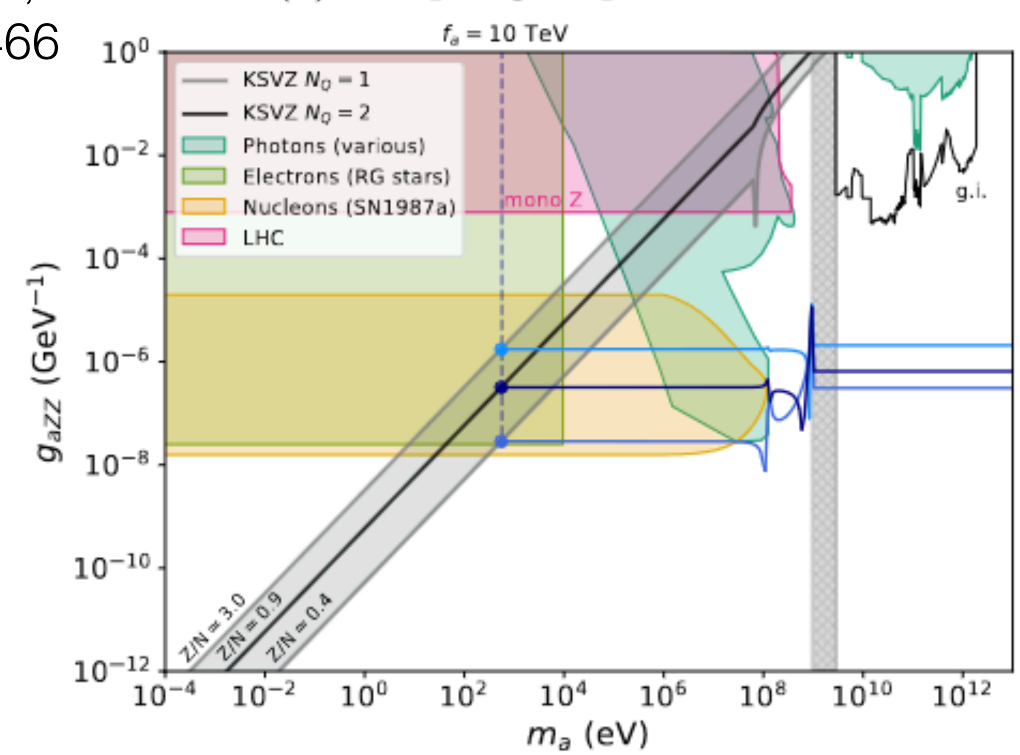
Alonso-Alvarez, Gavela, Quilez, arXiv:1811.05466



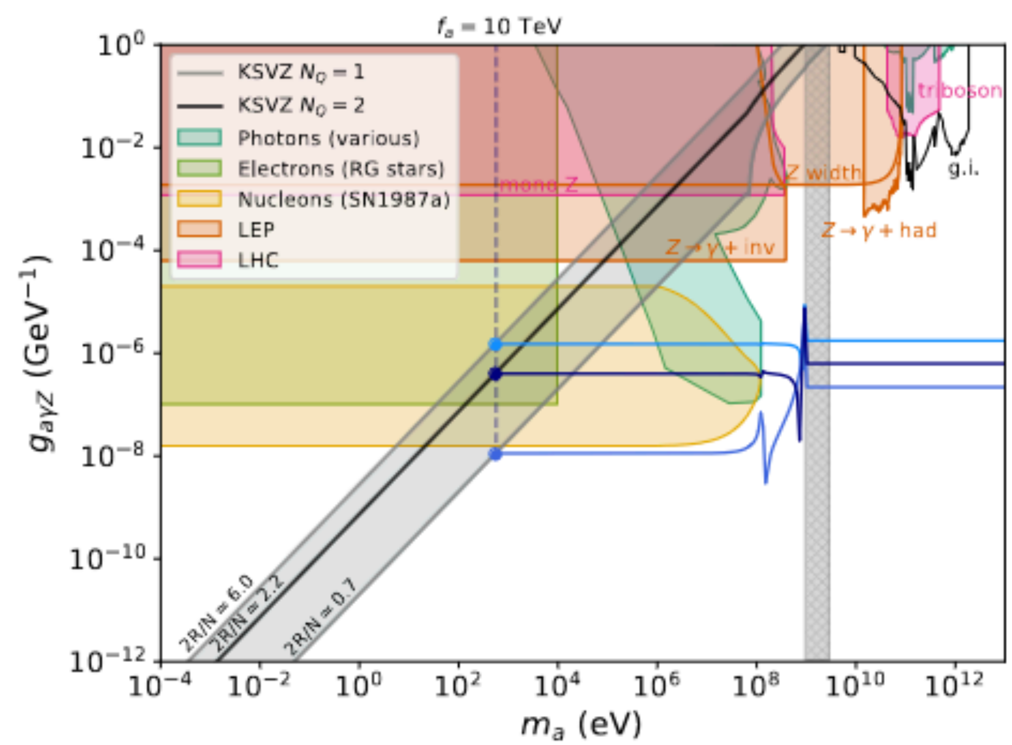
(a) Coupling to photons.



(b) Coupling to W bosons.



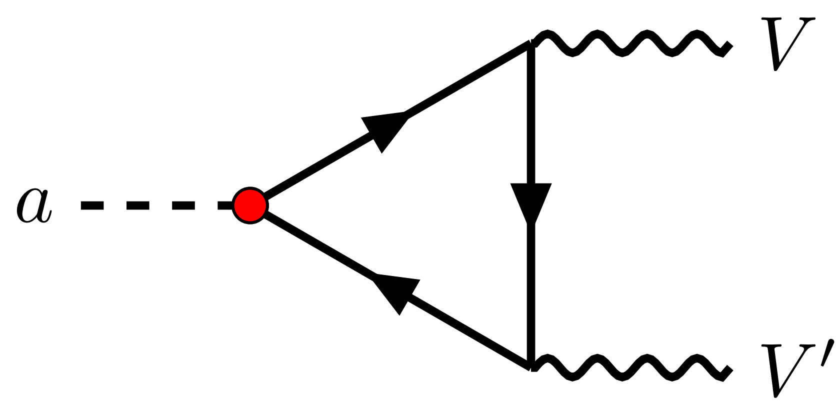
(c) Coupling to Z bosons.



(d) Coupling to a photon and a Z boson.

Figure 4: Coupling to EW gauge bosons. A two-operator framework is used: each panel assumes the existence of the corresponding electroweak coupling plus the axion-gluon coupling. The

One-loop induced couplings



$$g_{a\gamma\gamma}^{\rm loop} = -\frac{\alpha_{\rm em}}{\pi f_a}\left[\underbrace{\mathrm{Tr}\{(\mathbf{c}_{ee})\}}_{\text{ANOMALOUS}} + 2\sum_\ell \underbrace{(\mathbf{c}_{ee})_{\ell\ell} m_\ell^2 \mathcal{C}_0\left(0,0,m_a^2,m_\ell,m_\ell,m_\ell\right)}_{\text{MASS-DEPENDENT}}\right]$$

$$g_{aZZ}^{\rm loop} = -\frac{\alpha_{\rm em}}{2c_w^2 s_w^2 \pi f_a}\left[(1-2s_w^2)\,\mathrm{Tr}(\mathbf{c}_{\nu\nu}) + 2s_w^4\,\mathrm{Tr}(\mathbf{c}_{ee}) + \mathcal{O}\left(\frac{m_\ell^2}{M_Z^2}\right)\right]$$

$$g_{a\gamma Z}^{\rm loop} = \frac{\alpha_{\rm em}}{c_w s_w \pi f_a}\left[\mathrm{Tr}\{(\mathbf{c}_{\nu\nu})\} - 2s_w^2\,\mathrm{Tr}\{(\mathbf{c}_{ee})\} + \mathcal{O}\left(\frac{m_\ell^2}{M_Z^2}\right)\right]$$

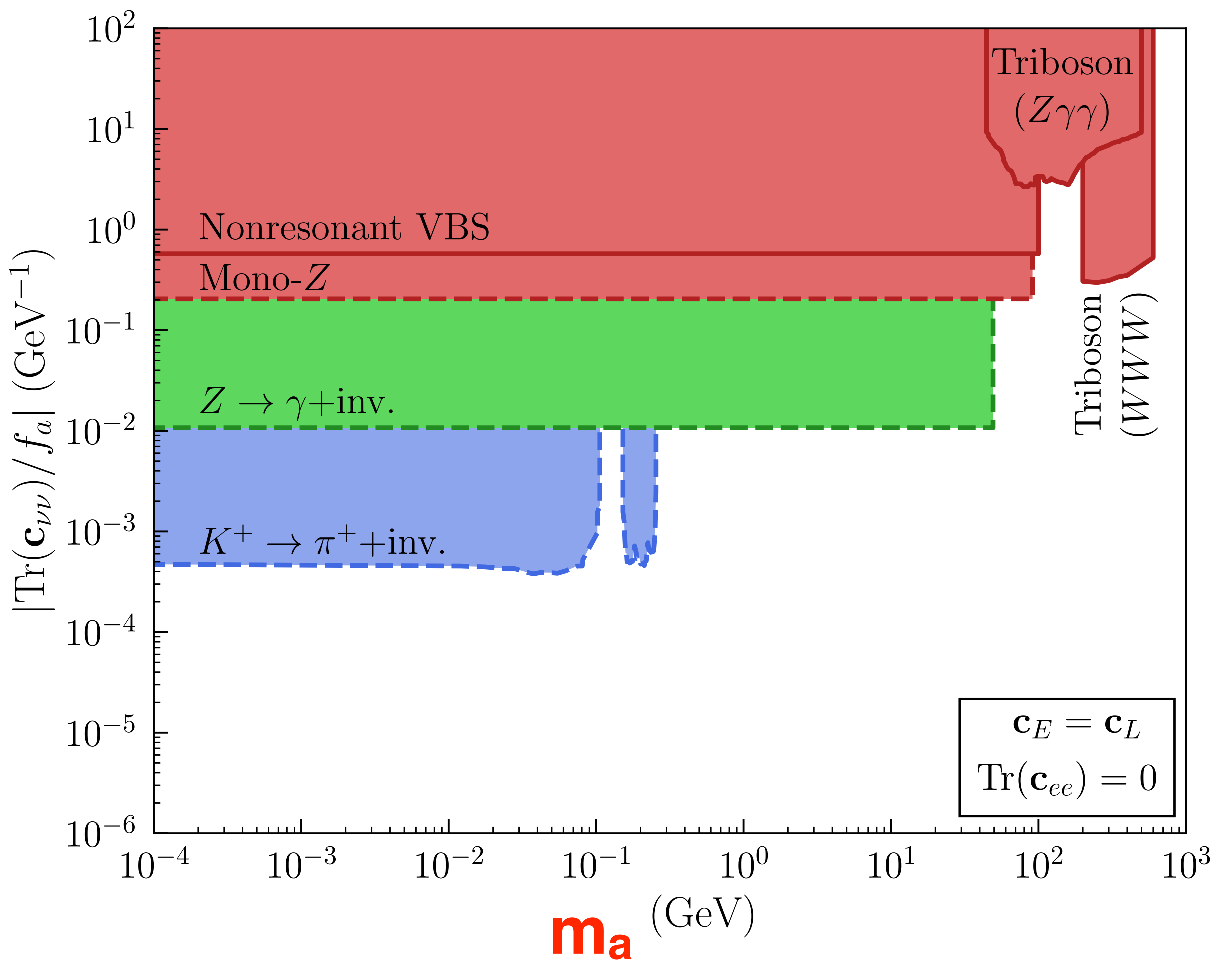
$$g_{aWW}^{\rm loop} = -\frac{\alpha_{\rm em}}{2s_w^2 \pi f_a}\left[\mathrm{Tr}(\mathbf{c}_{\nu\nu}) + \mathcal{O}\left(\frac{m_\ell^2}{M_W^2}\right)\right]$$

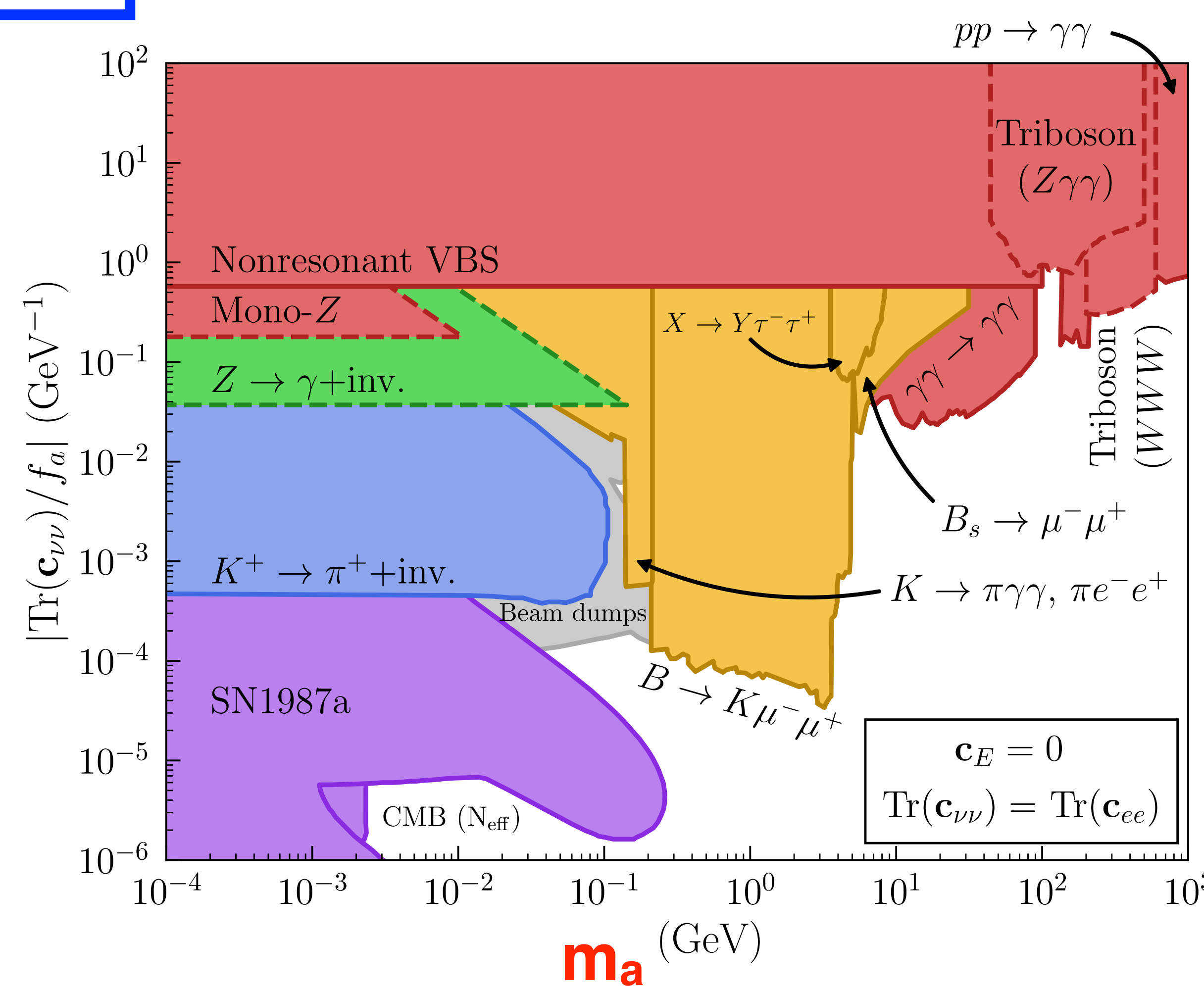
Package X, arXiv:1612.00009
FeynCalc, arXiv:2001.04407

In collaboration with J. Bonilla and J. Machado [2309.15910]

Bounds on ALP-neutrino coupling

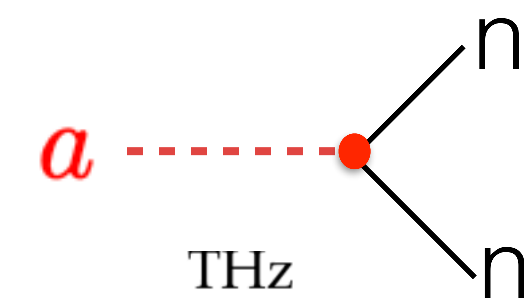
$\mathrm{Tr}(\mathbf{c}_{\nu\nu}/f_a)$





In collaboration with J. Bonilla and J. Machado [arXiv:2309.15910]

a-neutron coupling



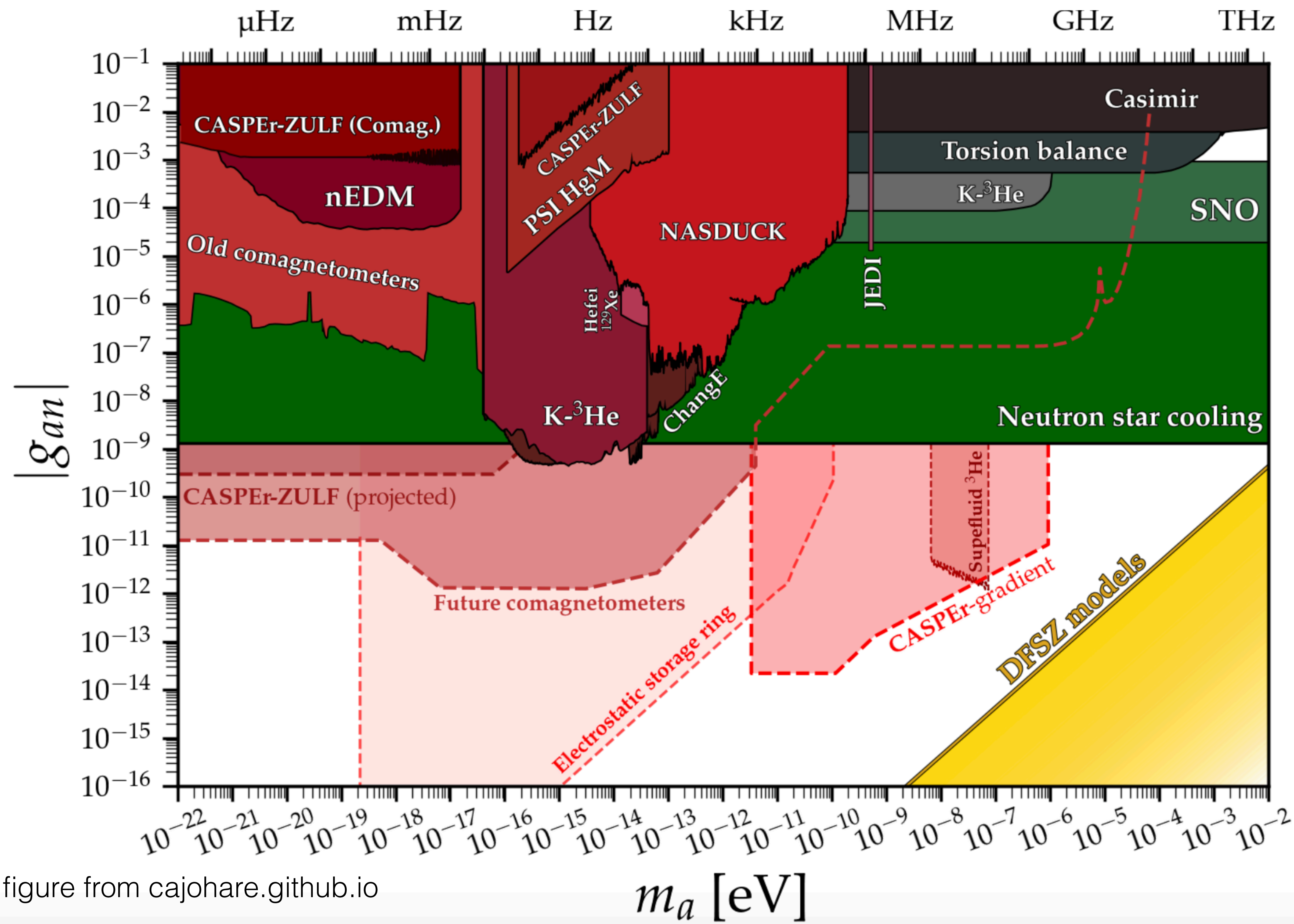


figure from cajohare.github.io

a-proton coupling

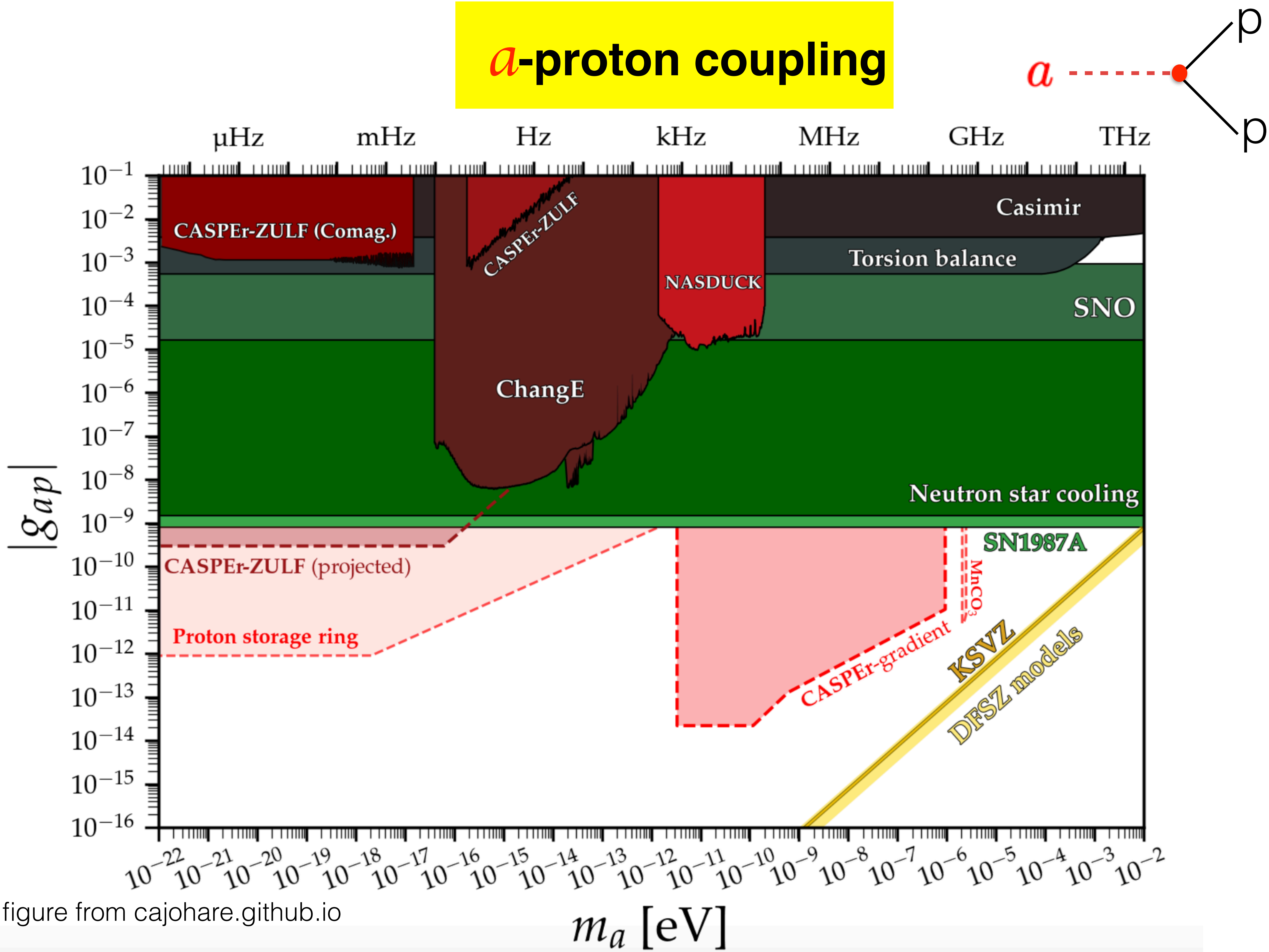


figure from cajohare.github.io

a-top coupling

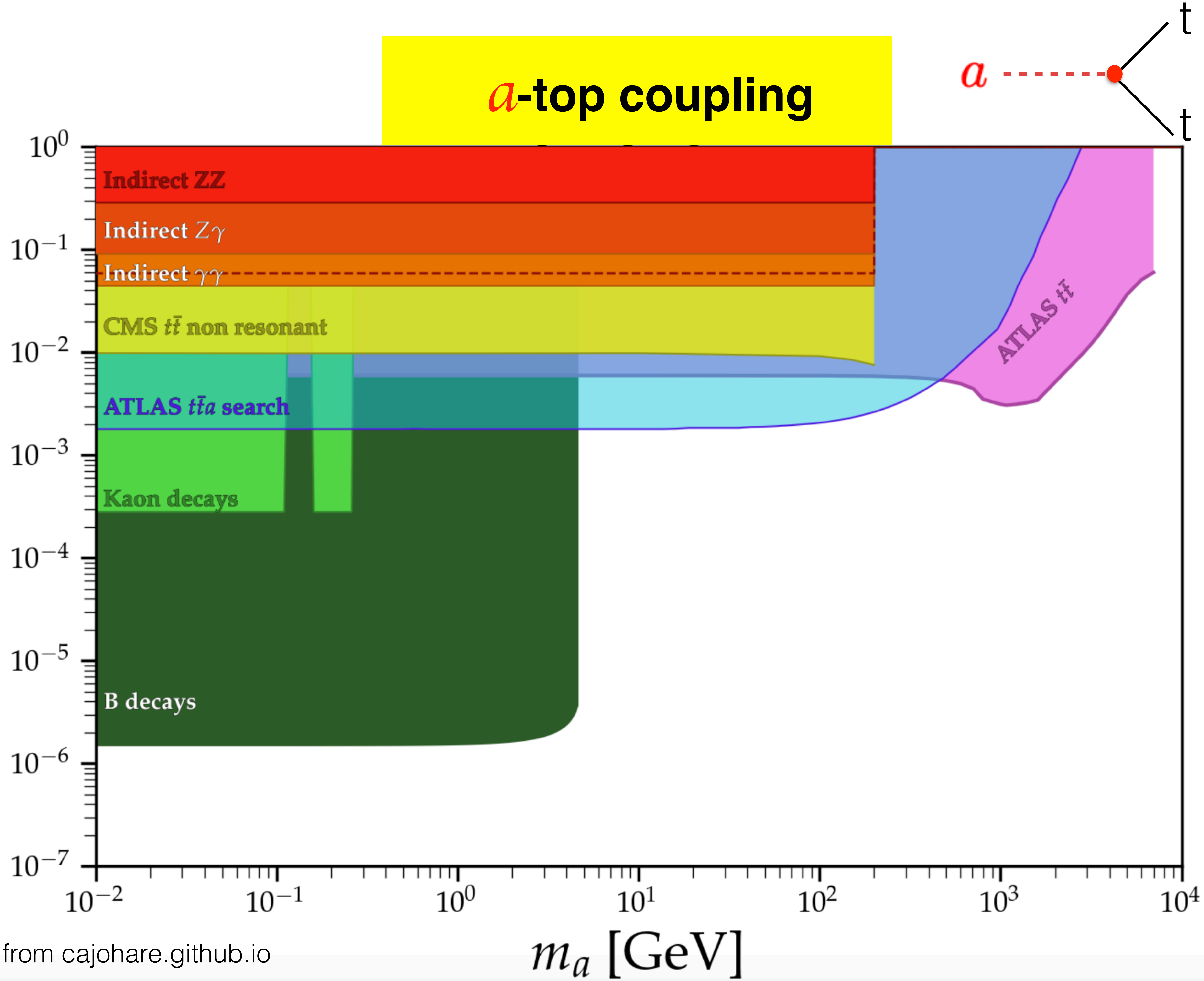
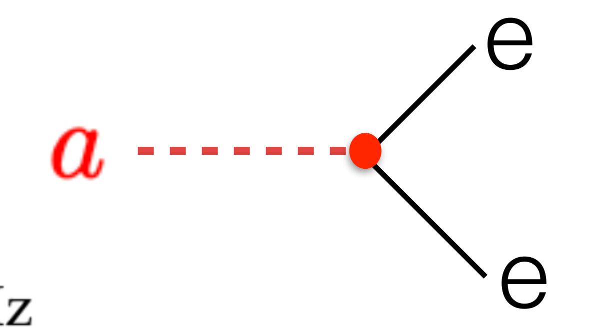


figure from cajohare.github.io

a-electron coupling



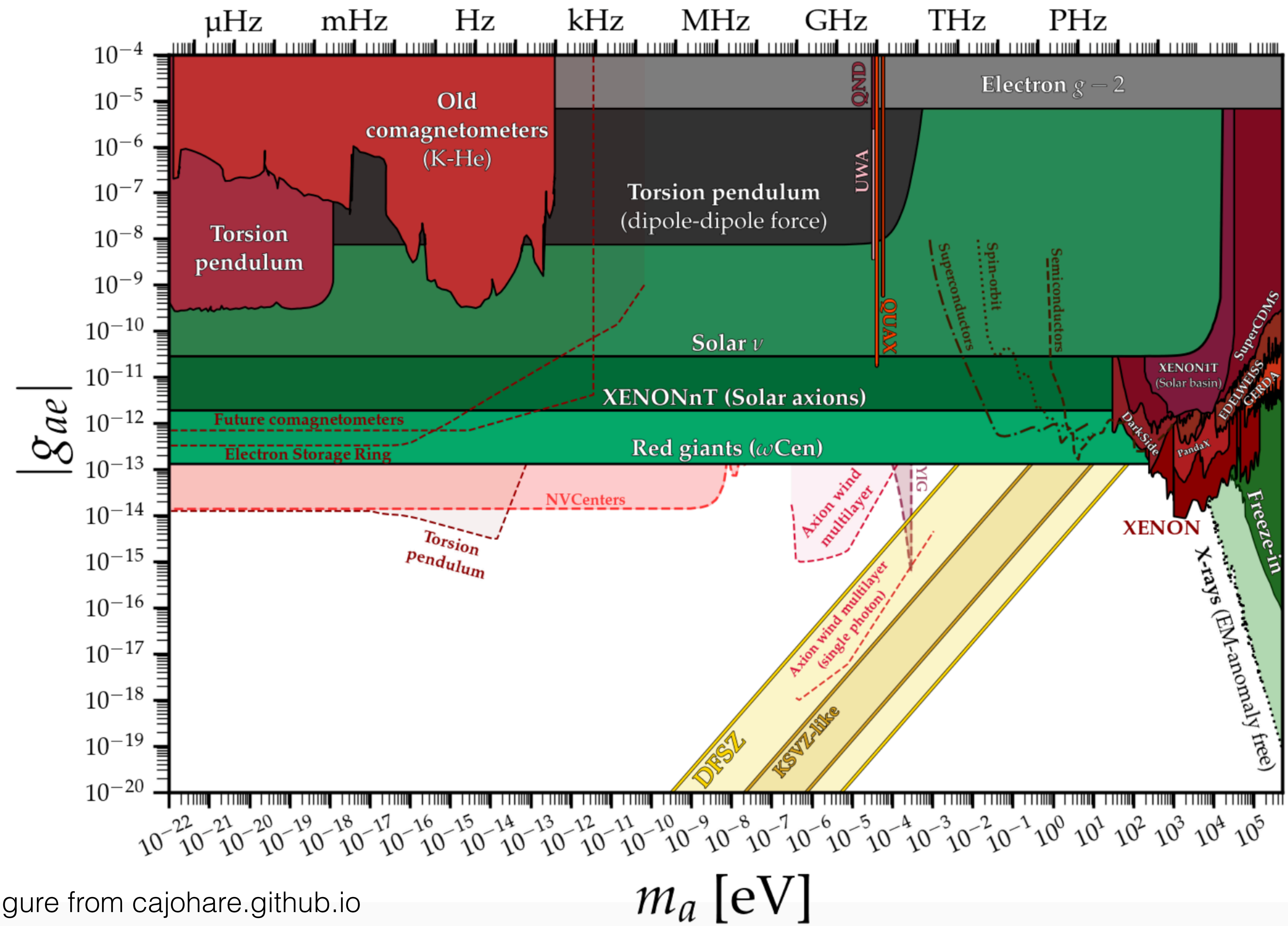


figure from cajohare.github.io

Generic scalar

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

K and **F** arbitrary: more parameters than for ALPs

e.g. CP-violation in flavour-diagonal couplings

V. Enguita, M.B. Gavela, B. Grinstein, P. Quilez, arXiv: 2403.13133

Generic scalar

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

K and **F** arbitrary: more parameters than for ALPs

e.g. CP-violation in flavour-diagonal couplings

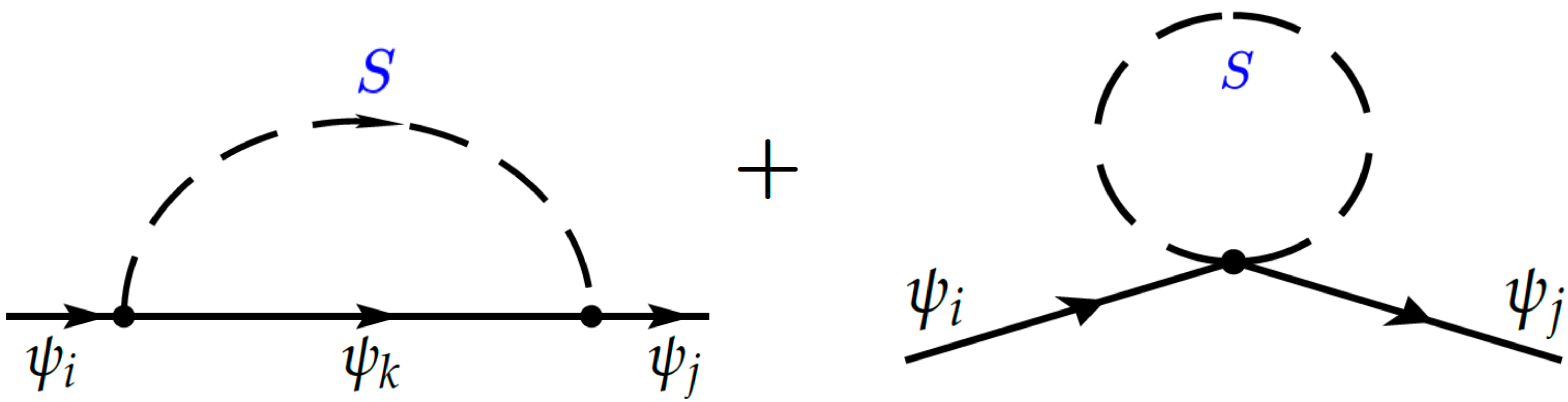
V. Enguita, M.B. Gavela, B. Grinstein, P. Quilez, arXiv: 2403.13133

Generic scalar

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

K and **F** arbitrary: more parameters than for ALPs

Contribution to $\bar{\theta}$ from:



bounds also improved by orders of magnitude

Generic scalar

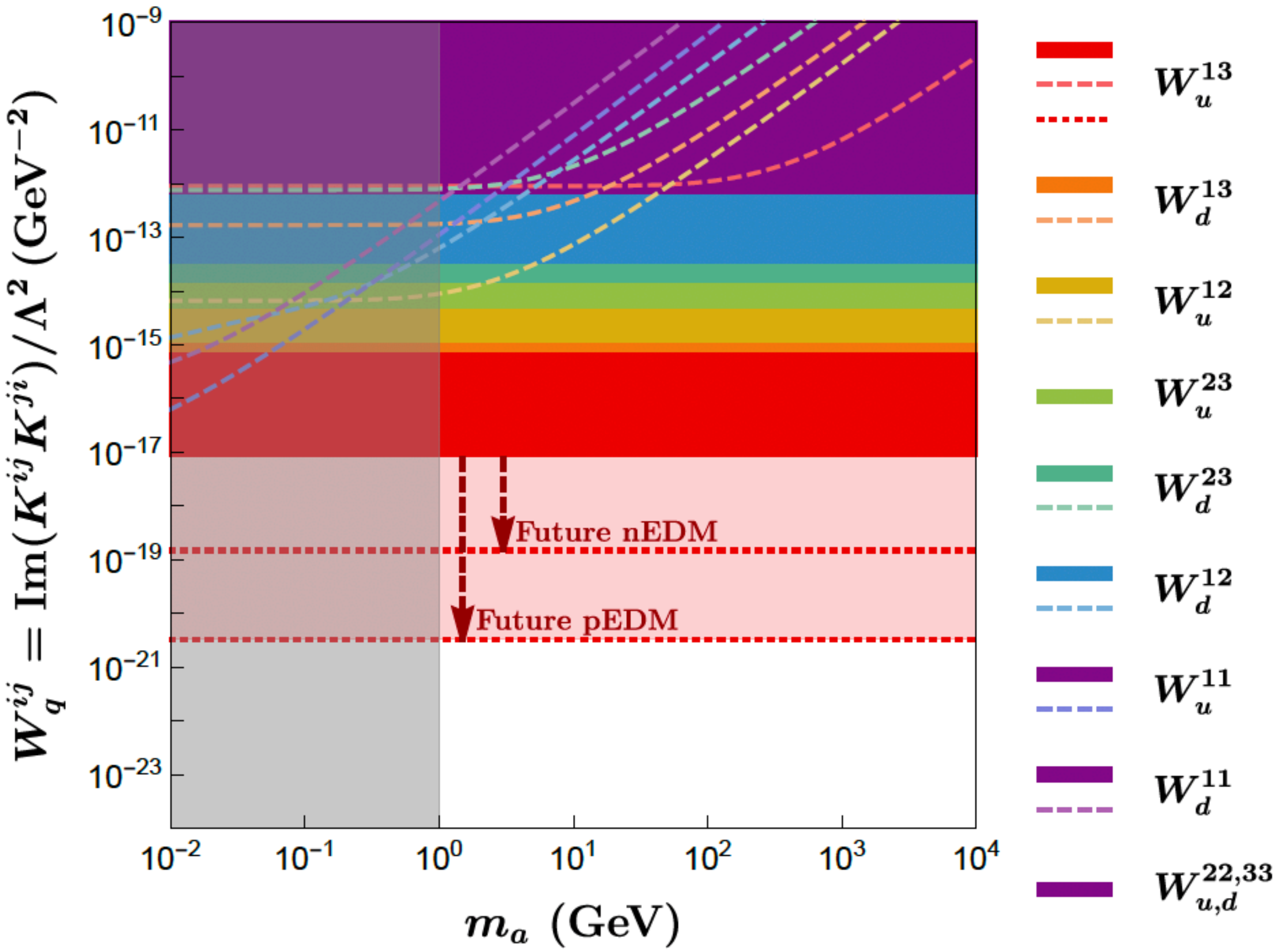


FIG. 5: *General scalar.* Upper bounds on $W_q^{ij} \equiv \mathrm{Im}(\boldsymbol{K}_q^{ij}\boldsymbol{K}_q^{ji})/\Lambda^2$ stemming from the contributions of $\bar{\theta}$ (solid regions) and from the sum of qEDMs and cEDMs (dashed lines) to the nEDM. The red dotted line shows the projected bounds on W_u^{13} from future nEDM and pEDM experiments [44, 45]. The grey shaded area is as described in Fig. 2.

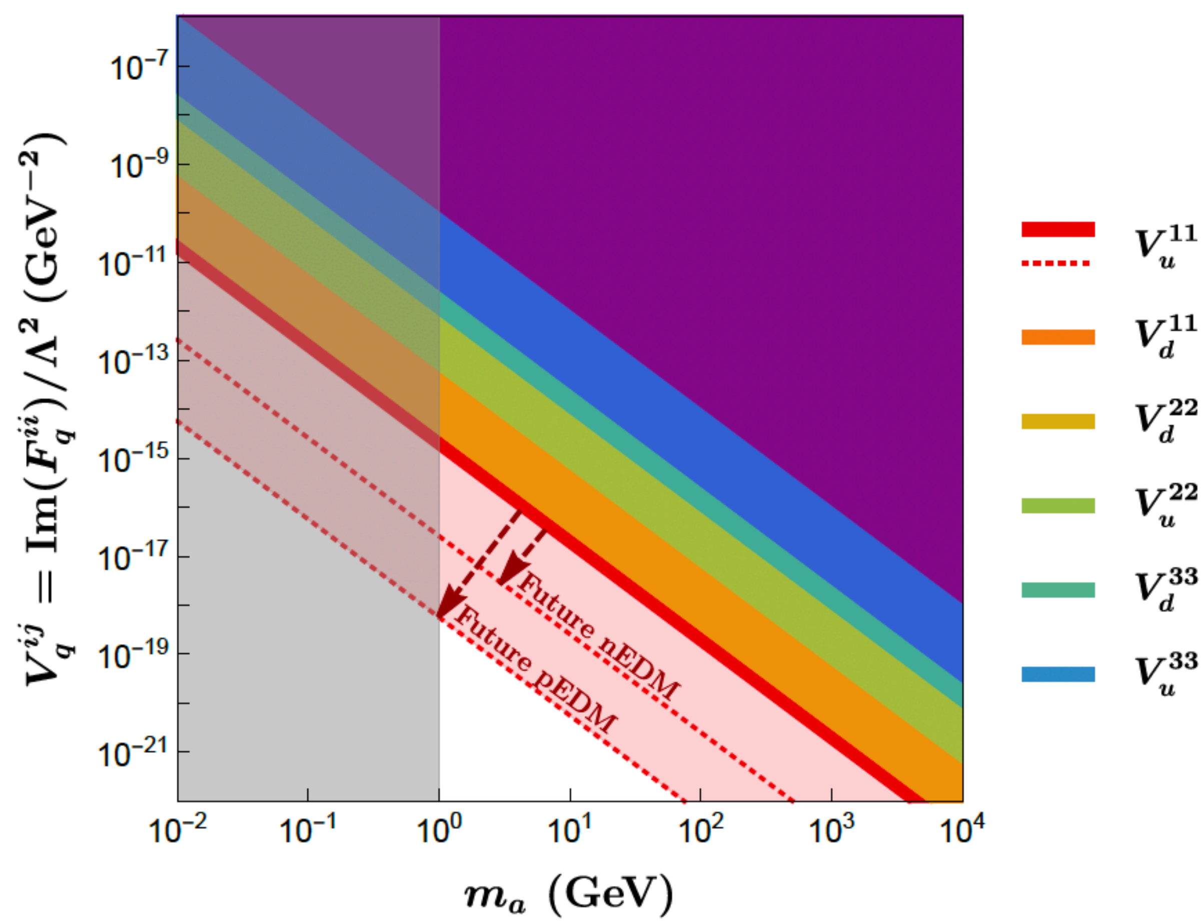


FIG. 6: *General scalar.* Upper bounds on $V_q^{ij} \equiv \mathrm{Im}\left(F_q^{ij}\right)/\Lambda^2$ stemming from the contributions of $\bar{\theta}$ (solid regions) to the nEDM. The red dotted line shows the projected bounds on V_u^{11} from future nEDM and pEDM experiments [44, 45]. The grey shaded area is as described in previous plots.

V. Enguita, M.B. Gavela, B. Grinstein, P. Quilez, arXiv: 2403.13133

Generic scalar

Combination	With PQ (GeV^{-2})	Without PQ (GeV^{-2})
$\mathrm{Im}(\boldsymbol{K}_u^{13}\boldsymbol{K}_u^{31})/\Lambda^2$	9.0×10^{-7}	9.2×10^{-7}
$\mathrm{Im}(\boldsymbol{K}_d^{13}\boldsymbol{K}_d^{31})/\Lambda^2$	2.8×10^{-7}	4.6×10^{-8}
$\mathrm{Im}(\boldsymbol{K}_u^{12}\boldsymbol{K}_u^{21})/\Lambda^2$	3.1×10^{-8}	3.1×10^{-8}
$\mathrm{Im}(\boldsymbol{K}_d^{23}\boldsymbol{K}_d^{23})/\Lambda^2$	1.3×10^{-6}	1.8×10^{-5}
$\mathrm{Im}(\boldsymbol{K}_d^{12}\boldsymbol{K}_d^{21})/\Lambda^2$	8.2×10^{-7}	1.4×10^{-7}
$\mathrm{Im}(\boldsymbol{K}_d^{22}\boldsymbol{K}_d^{22})/\Lambda^2$	3.8×10^{-6}	5.3×10^{-5}
$\mathrm{Im}(\boldsymbol{K}_u^{11}\boldsymbol{K}_u^{11})/\Lambda^2$	2.2×10^{-6}	2.2×10^{-6}
$\mathrm{Im}(\boldsymbol{K}_d^{11}\boldsymbol{K}_d^{11})/\Lambda^2$	8.7×10^{-6}	1.4×10^{-6}

V. Enguita, M.B. Gavela, B. Grinstein, P. Quilez, arXiv: 2403.13133

TABLE V: *General scalar.* Comparison of bounds w/o the presence of a PQ symmetry. All bounds are in units of GeV^{-2}, and for $m_\phi = 5$ GeV.

* Other contributions to $\bar{\theta}$?

General scalar, toy model, Fock-Schwinger gauge

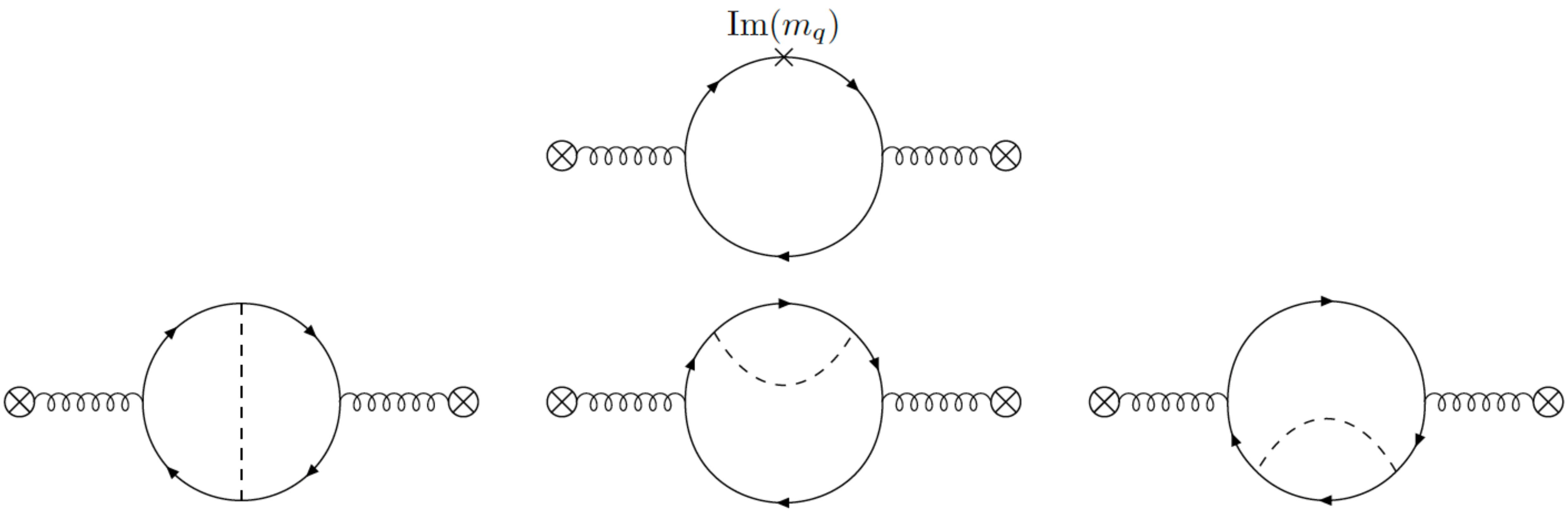


Figure 2: The one-loop and two-loop babble diagrams which contribute to the radiative corrections to the QCD θ parameter. The one-loop diagram gives a simple result $\delta\theta|_{1\mathrm{L}} = -\mathrm{Im}(m_q)/\mathrm{Re}(m_q)$. For the two-loop diagrams, the first one generates $I_{(2;2)}$ loop function in Eq. (3.4), while the others $2\bar{I}_{(3;1)}$ in total.

Banno, Hisano, Kitahara, Osatura, 2311.07817