New tests of ALP-fermion interactions

INVISIBLES24

Bologna July 1 - 5 2024

Belén Gavela
Univ. Autónoma de Madrid and IFT

H2020

New tests of ALP-fermion interactions

CP-violation

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Why CP-violation ?

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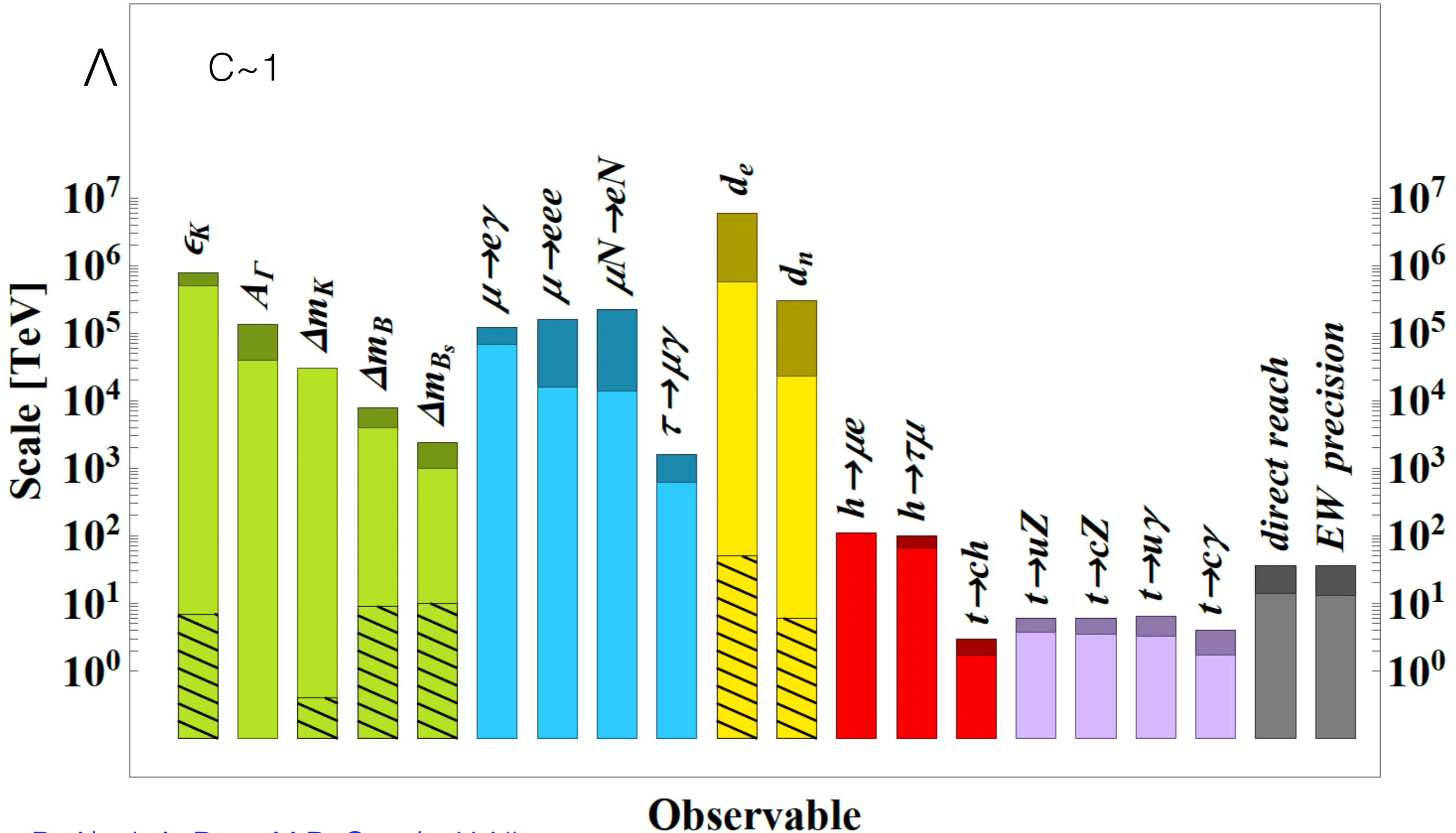**Why 3 generations of quarks and leptons,**

with mixing and CP-violation….

for ``nothing''?

Why CP-violation ?
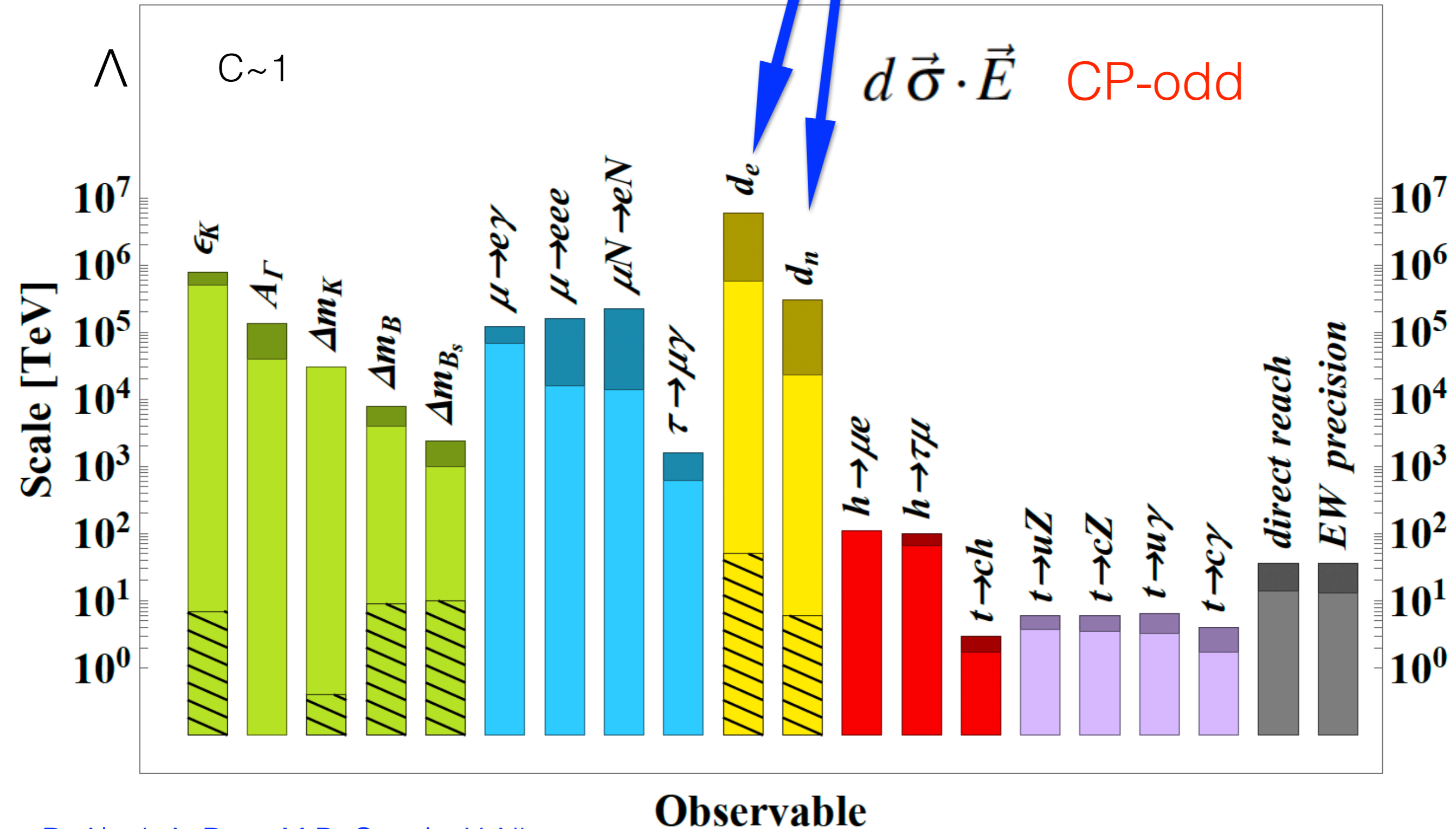
CP-violation is a fantastic window to BSM

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
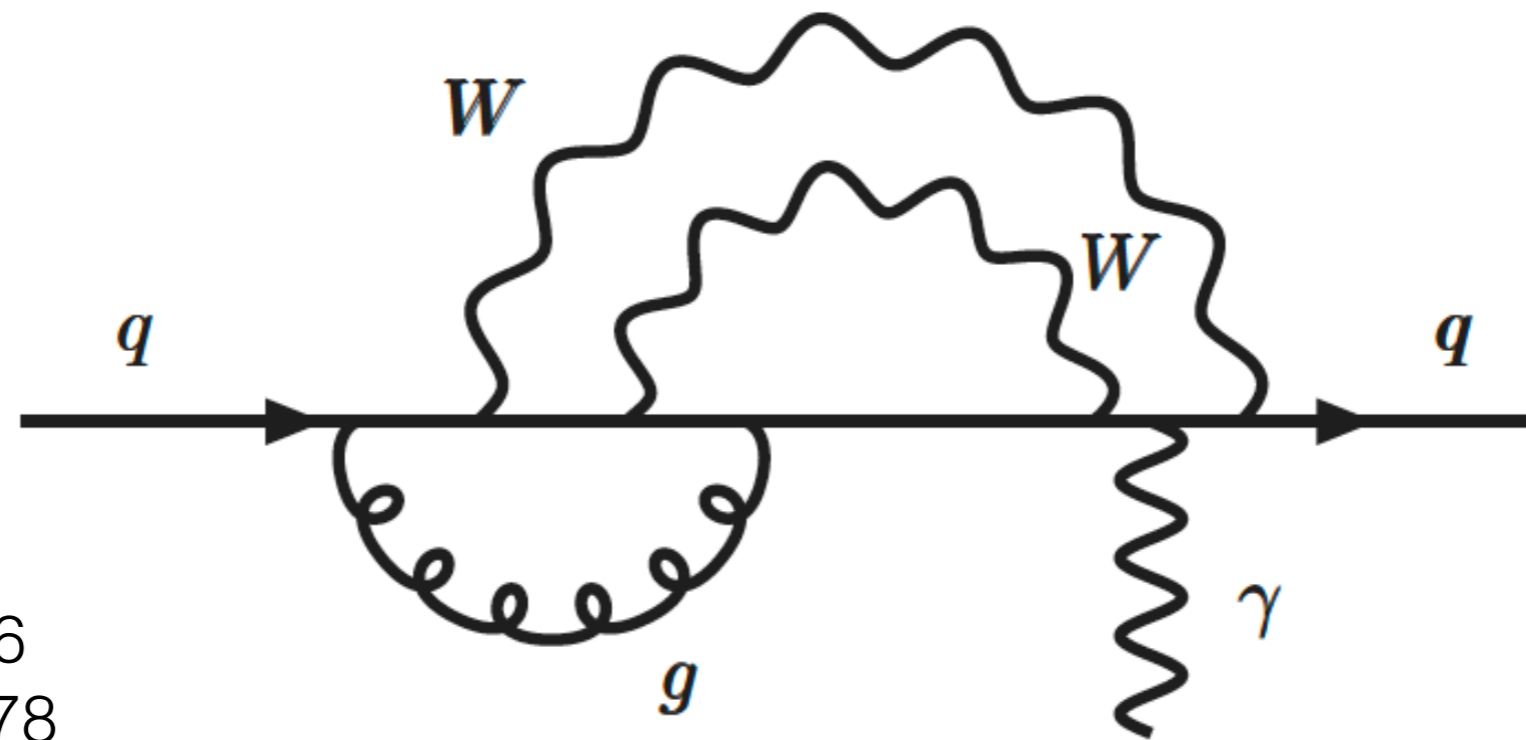
Maiani 76
Shabalin 78

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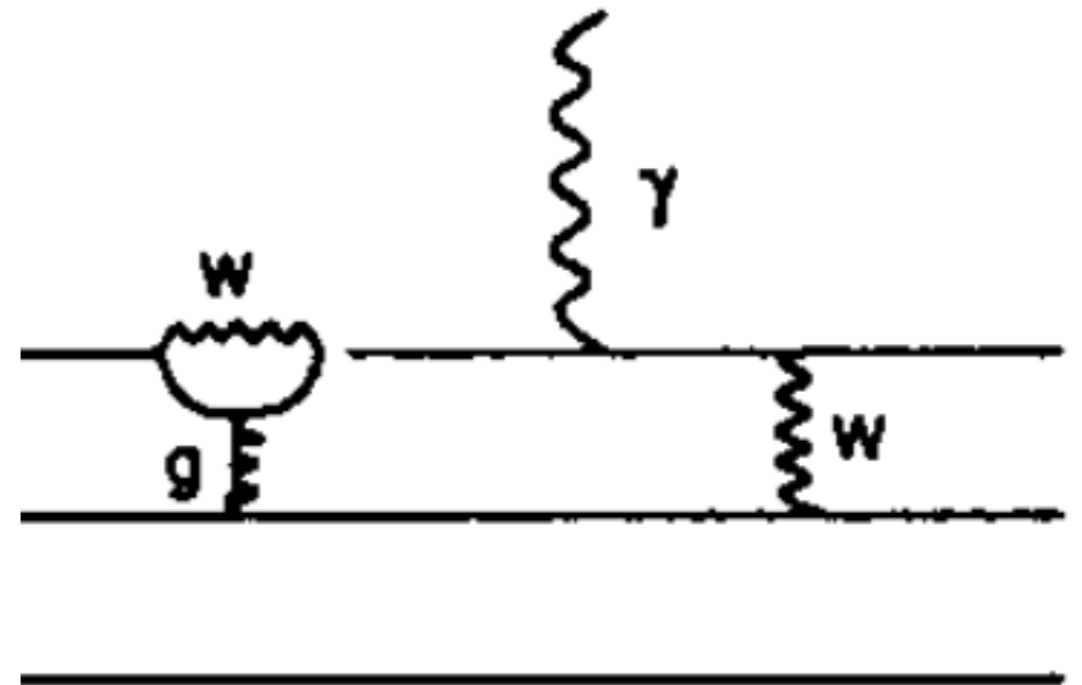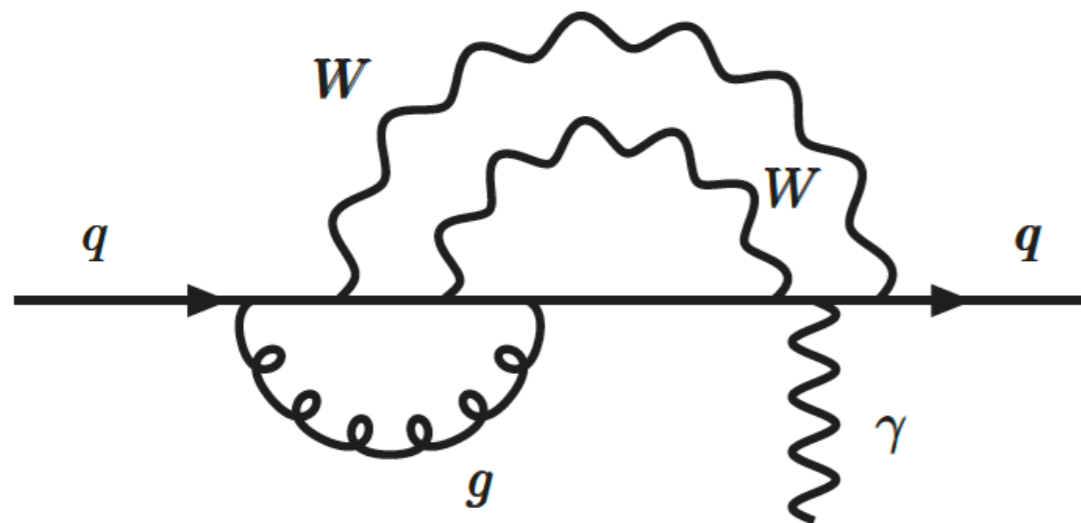
(80's: Gavela at al.,
Khriplovich+Zhitnitsky)

SM predicts $d_n \sim 10^{-30} - 10^{-32}$ e·cm

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

In the SM they are 3-loop suppressed

BSM window: In general electric dipole moments at one loop

ξ^{γ}

SM predicts $d_n \sim 10^{-30} - 10^{-32}$ e·cm

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

Why ALPs

or general Scalars ?

Higgs

s Φ a

S Φ a (pseudo)Goldstone boson

Higgs

Rocio del Rey
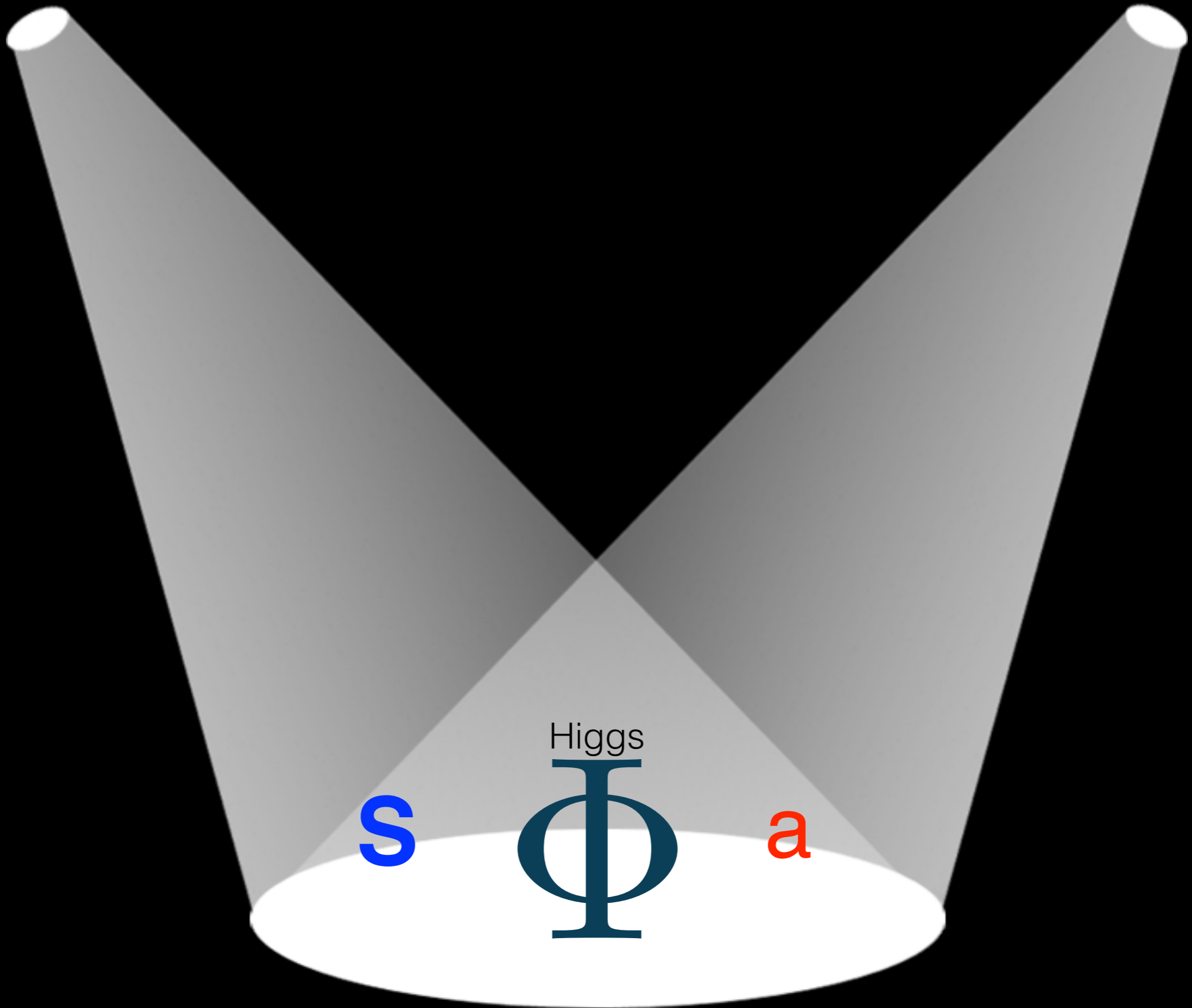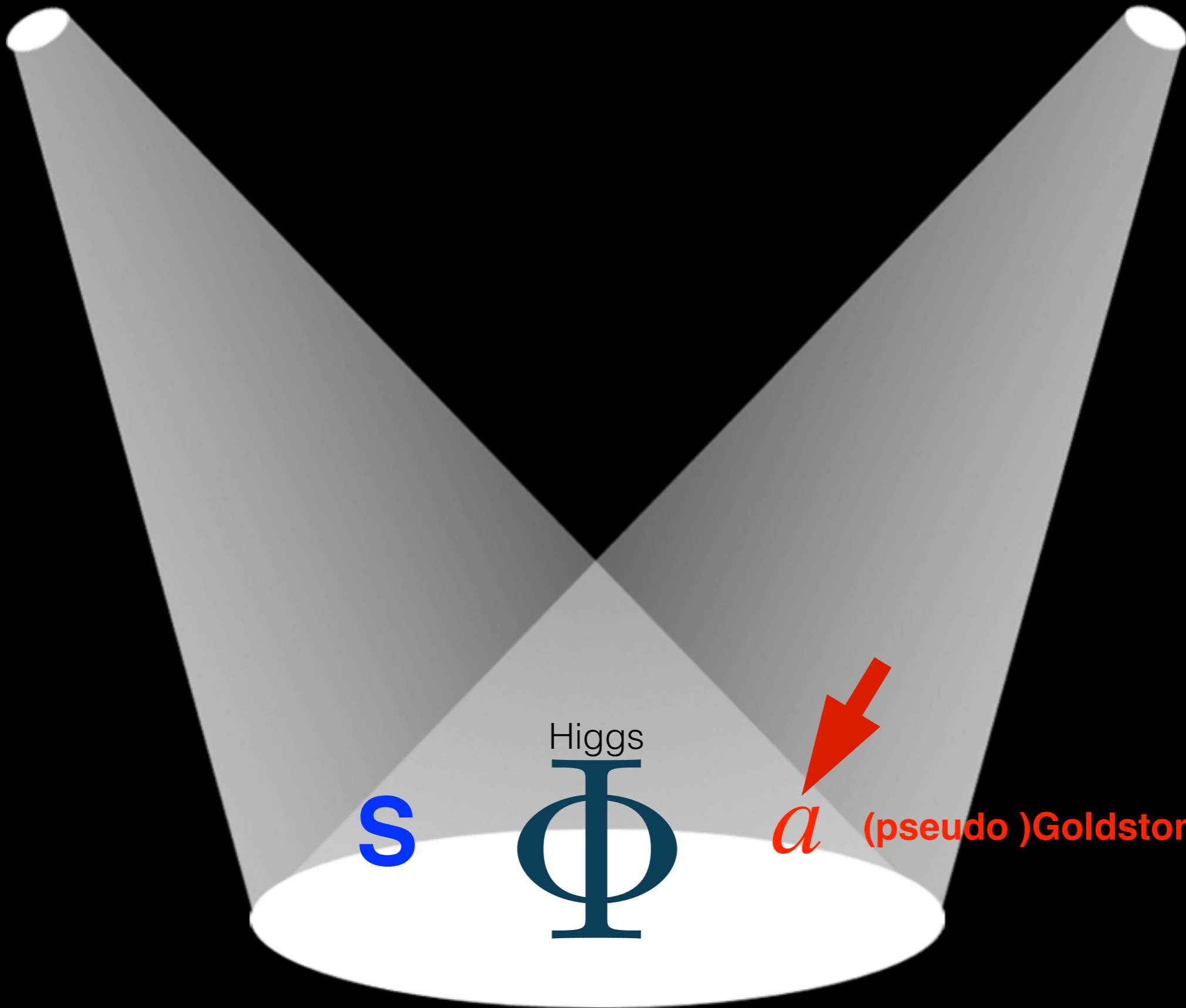
Because they are (pseudo)Goldstone bosons,

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:

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

general effective couplings

$$\{m_a, f_a\}$$

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

with derivative couplings to SM particles

and free scale f_a:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{\partial_\mu a}{f_a} \times \text{SM}^\mu + c_i \frac{a}{f_a} X_{\mu\nu} X^{\widetilde{\mu\nu}} + \ldots\ldots$$

general effective couplings

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

$$\{m_a, f_a\}$$

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general effective couplings

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

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

$$\underset{\underset{\text{SM EFT}}{\parallel}}{}$$

Complete basis (bosons+fermions):

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

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

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

where X_ψ is a general 3x3 matrix in flavour space

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

II
SM EFT

Complete basis (bosons+fermions):

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

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Georgi + Kaplan + Randall 1986
Choi + Kang + Kim, 1986
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$$\left\{ m_a, \frac{c_i}{f_a} \right\}$$

ALP-Linear effective Lagrangian at NLO

Complete basis (bosons+fermions):

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

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
Choi + Kang + Kim, 1986
Salvio + Strumia + Shue, 2013

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

$$\underset{\text{SM EFT}}{\overset{\text{II}}{}}$$

Complete basis (bosons+fermions):

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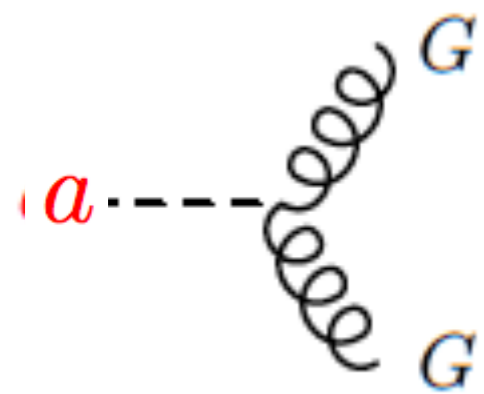
For an ALP:

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

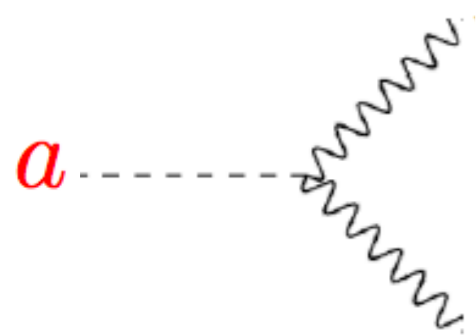**are independent parameters**

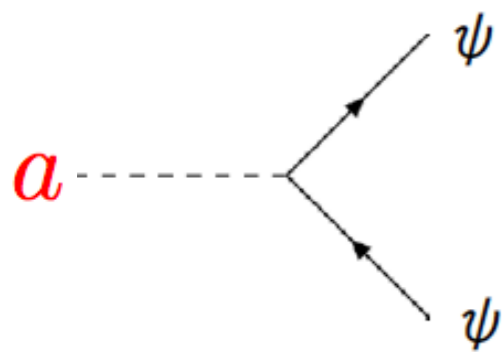Georgi + Kaplan + Randall 1986
Choi + Kang + Kim, 1986
Salvio + Strumia + Shue, 2013

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

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

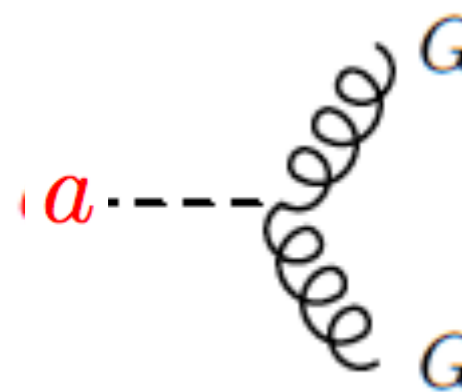$$\partial_{\mu}a\,\bar{\psi}\gamma_{\mu}\psi$$

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

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

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

neutron, proton, top, electron, muon...
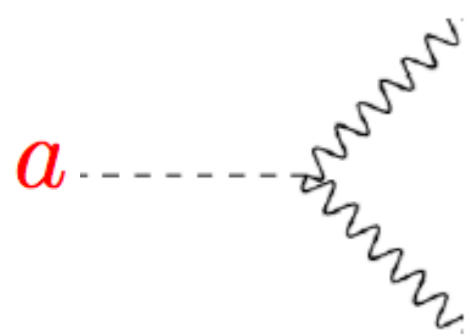
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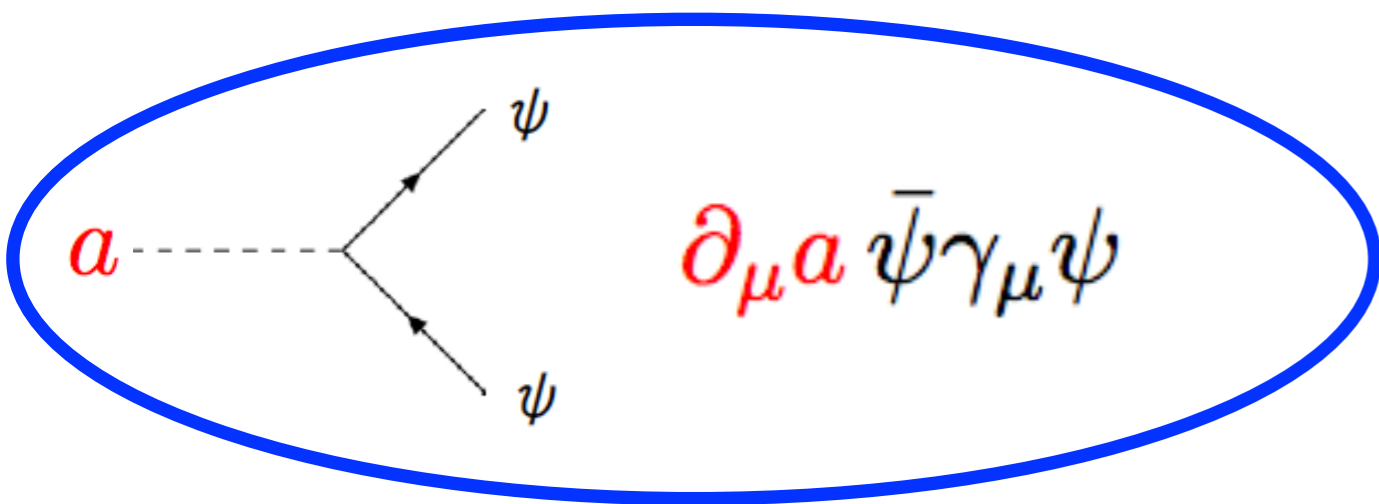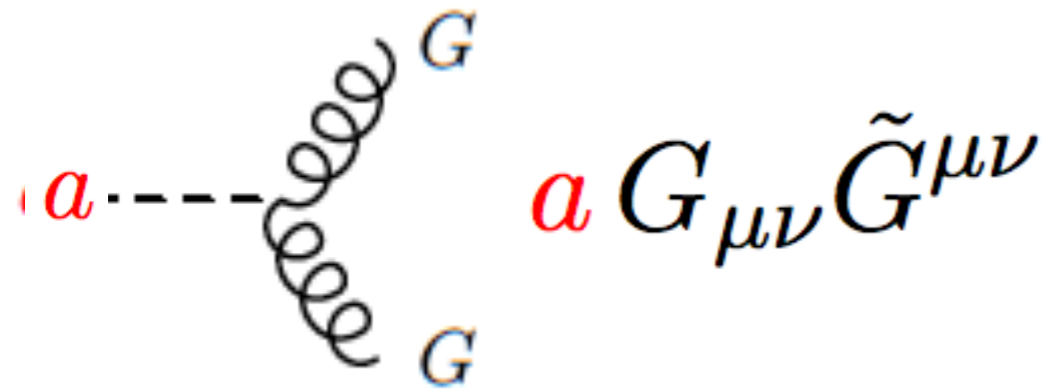
$$\partial_{\mu}a\,\bar{\psi}\gamma_{\mu}\psi$$
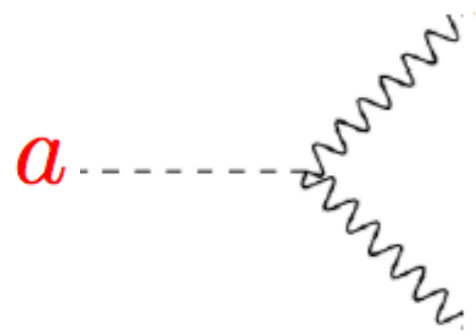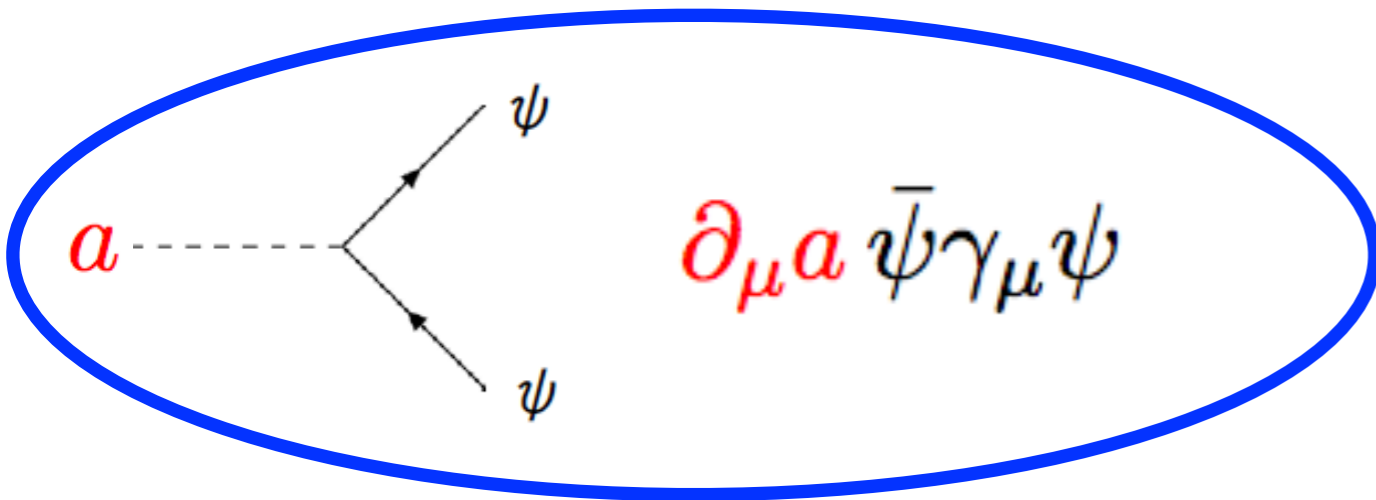
neutron, proton, top,
electron, muon...

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)

NEW

Bounds on ALP-neutrino couplings
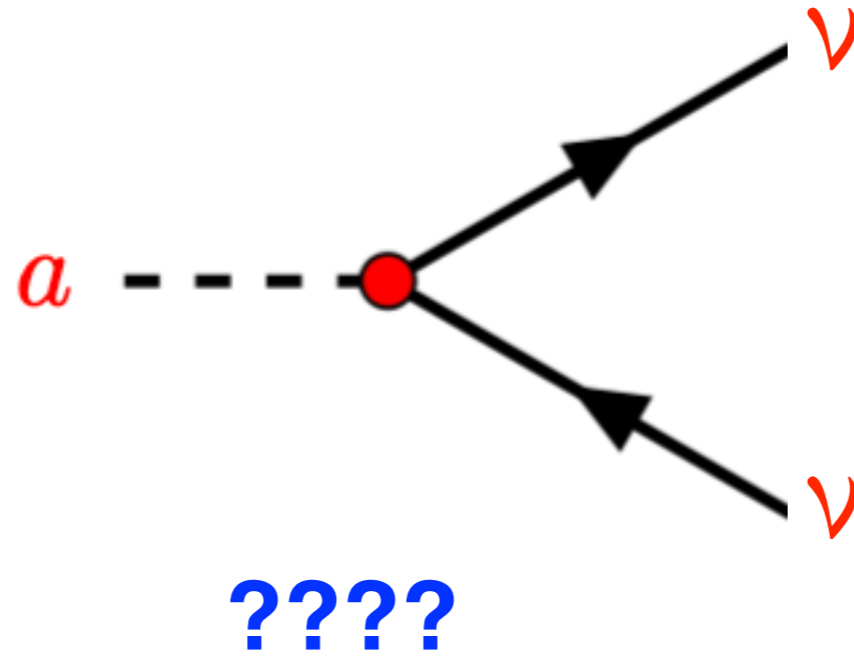
$$\mathcal{L}^{\nu}_{\partial a} = \frac{\partial_{\mu} a}{f_a} \bar{\nu}_L \gamma^{\mu} \mathbf{c}_L \nu_L$$

Bounds on ALP-neutrino couplings

$$\mathcal{L}_{\partial a}^{\nu} = \frac{\partial_\mu a}{f_a} \bar{\nu}_L \gamma^\mu \mathbf{c}_L \nu_L = \left(i \frac{a}{f_a} \bar{\nu}_L \mathbf{M}_\nu \mathbf{c}_L \nu_R + \text{h.c.} \right)$$

Bounds on ALP-neutrino couplings

????

EOM

$$\mathcal{L}^{\nu}_{\partial a} = \frac{\partial_\mu a}{f_a} \bar{\nu}_L \gamma^\mu \mathbf{c}_L \nu_L = \left(i\frac{a}{f_a} \bar{\nu}_L \mathbf{M}_\nu \mathbf{c}_L \nu_R + \text{h.c.} \right)$$

$$- \text{Tr}\left[\mathbf{c}_L\right] \frac{a}{f_a} \left[\frac{g'^2}{64\pi^2} B_{\mu\nu} \tilde{B}^{\mu\nu} + \frac{g^2}{64\pi^2} W_{\mu\nu} \tilde{W}^{\mu\nu} \right]$$
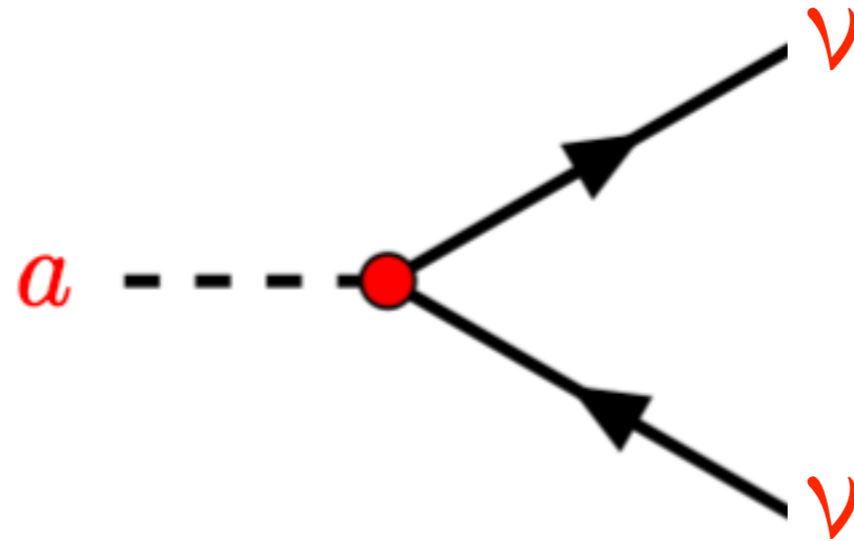
Bonilla, Gavela, Machado [arXiv:2309.15910] Phys.Rev.D 109 (2024)

Bounds on ALP-neutrino couplings

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Bonilla, Gavela, Machado [arXiv:2309.15910] Phys.Rev.D 109 (2024)
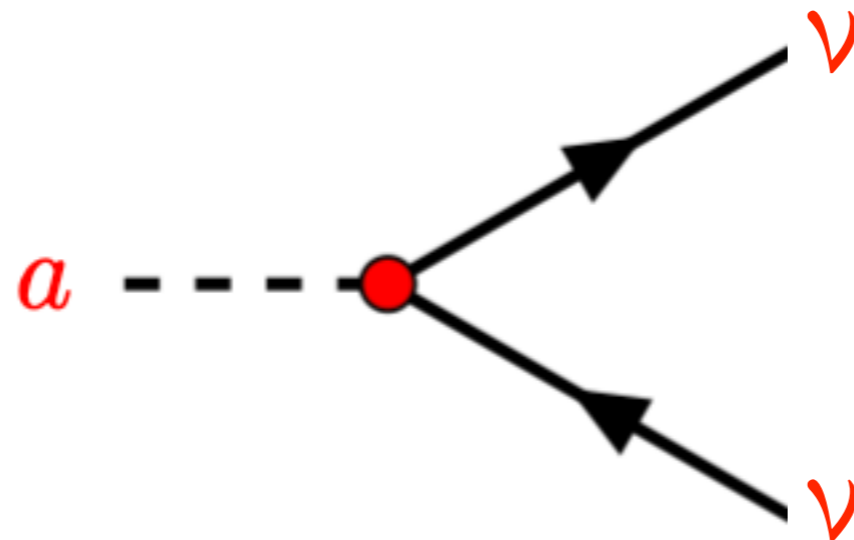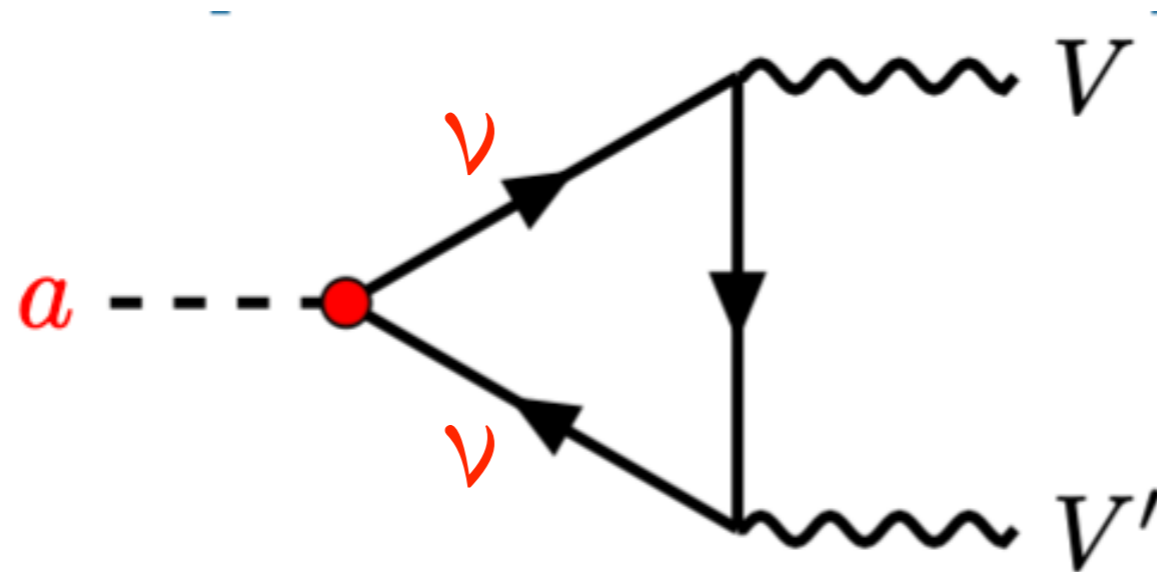
Bounds on ALP-neutrino couplings

????

EOM

$$\mathcal{L}_{\partial a}^{\nu} = \frac{\partial_\mu a}{f_a} \bar{\nu}_L \gamma^\mu \mathbf{c}_L \nu_L = \left(i \frac{a}{f_a} \bar{\nu}_L \mathbf{M}_\nu \mathbf{c}_L \nu_R + \text{h.c.} \right)$$

$$- \text{Tr} \left[\mathbf{c}_L \right] \frac{a}{f_a} \left[\frac{g'^2}{64\pi^2} B_{\mu\nu} \tilde{B}^{\mu\nu} + \frac{g^2}{64\pi^2} W_{\mu\nu} \tilde{W}^{\mu\nu} \right]$$

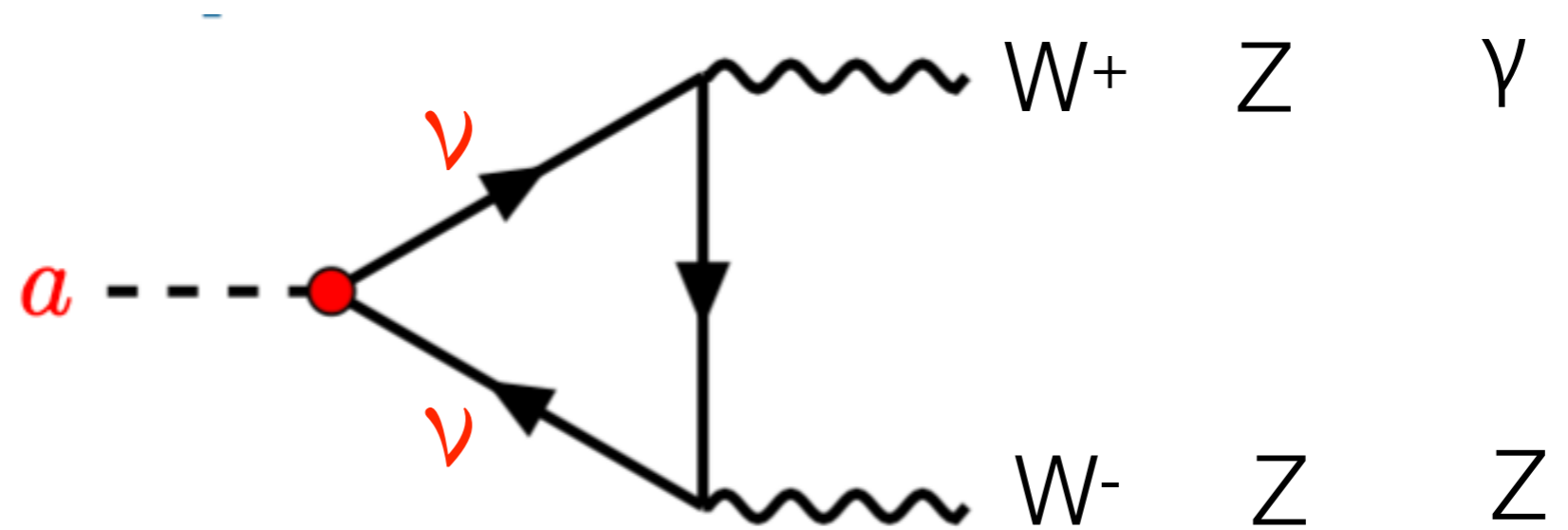Bonilla, Gavela, Machado [arXiv:2309.15910] Phys.Rev.D 109 (2024)

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

connected by gauge invariance

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

CLASSICAL EOM

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

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

$$\frac{\partial_\mu a}{f_a} \bar{\nu}_L \gamma^\mu c_L \nu_L = \left(i \frac{a}{f_a} \bar{\nu}_L \mathbf{M}_\nu c_L \nu_R + \text{h.c.} \right)$$

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

↓

Bounds ALP-neutrino

CLASSICAL EOM　　　　**ONE-LOOP EFFECT**

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

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

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

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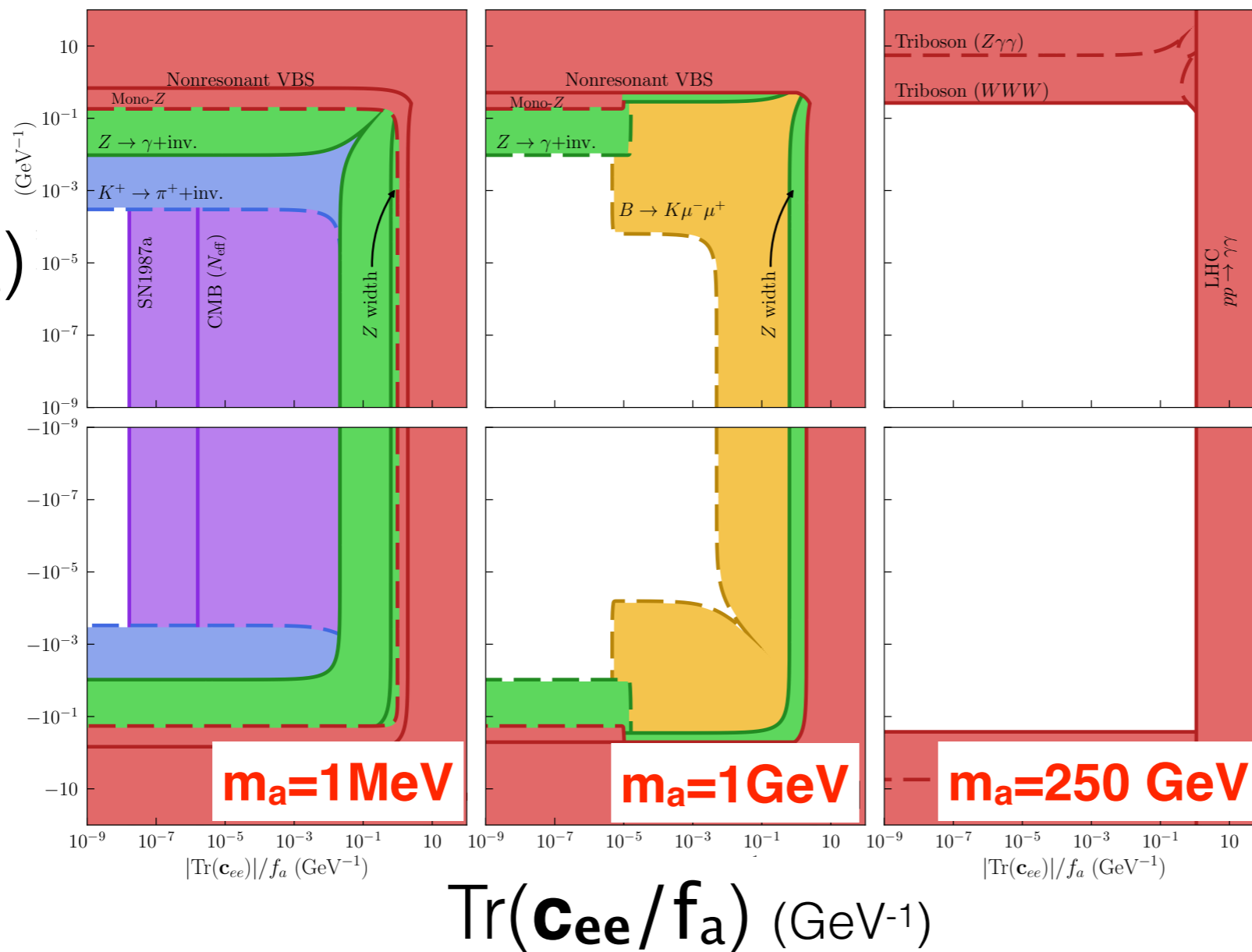
M. Chala *et al*, Eur. Phys. J. C 81 (2021), no. 2 181
M. Bauer *et al*, JHEP 04 (2021) 063
J. Bonilla *et al*, JHEP 11 (2021) 168

one-loop anomalous current

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

Bounds on ALP-neutrino coupling

Lots of space to explore by LHC and future colliders
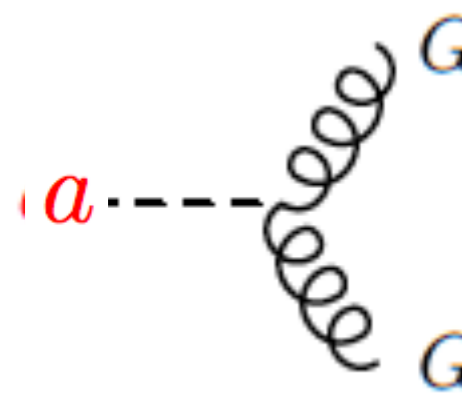
ALPs (axion-like-particles)

CP-violation

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

CP-violation

$m_a > 1$ GeV

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

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

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

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

The ALP EFT

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

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

The ALP EFT

$$\mathcal{L}_a \supset \frac{\partial_\mu a}{f_a} \underbrace{\left(\bar{Q}_L \gamma^\mu \boldsymbol{C}_Q Q_L + \bar{u}_R \gamma^\mu \boldsymbol{C}_{u_R} u_R + \bar{d}_R \gamma^\mu \boldsymbol{C}_{d_R} d_R \right)}_{\text{CP-violation in flavor-nondiagonal entries}}$$
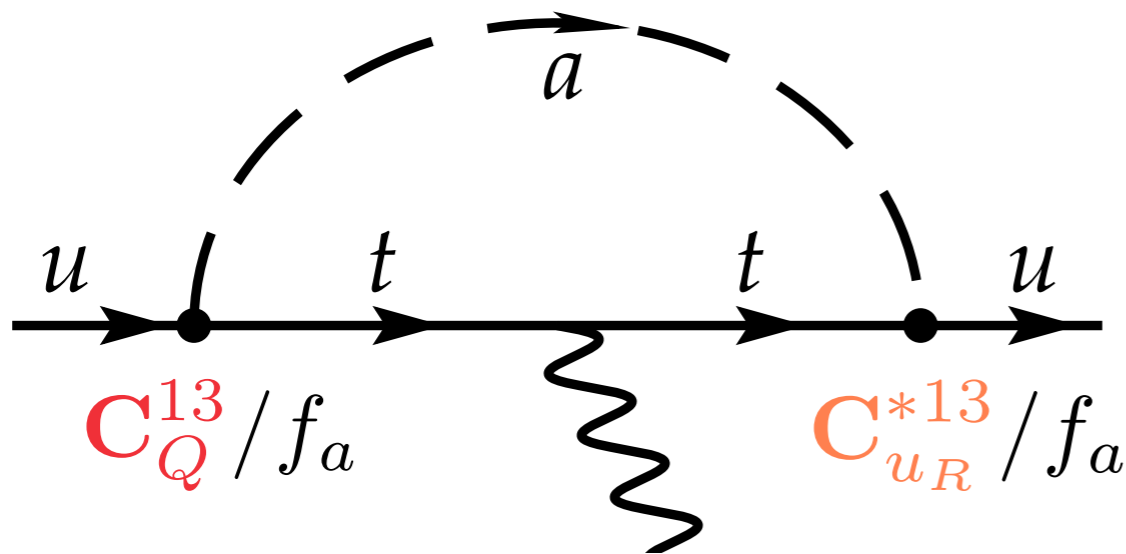
It will source CP-violation observables, e.g. EDMs… at one loop!

[Di Luzio et al., 2010.13760]

The ALP EFT

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

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

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

[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

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

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

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

Related by the U$_A$(1) anomaly

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

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

The ALP EFT

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

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

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

The ALP EFT

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

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

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

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

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

ALP contribution to $\bar{\theta}$

V. Enguita, M.B. Gavela, B. Grinstein, P. Quilez, arXiv: 2403.13133
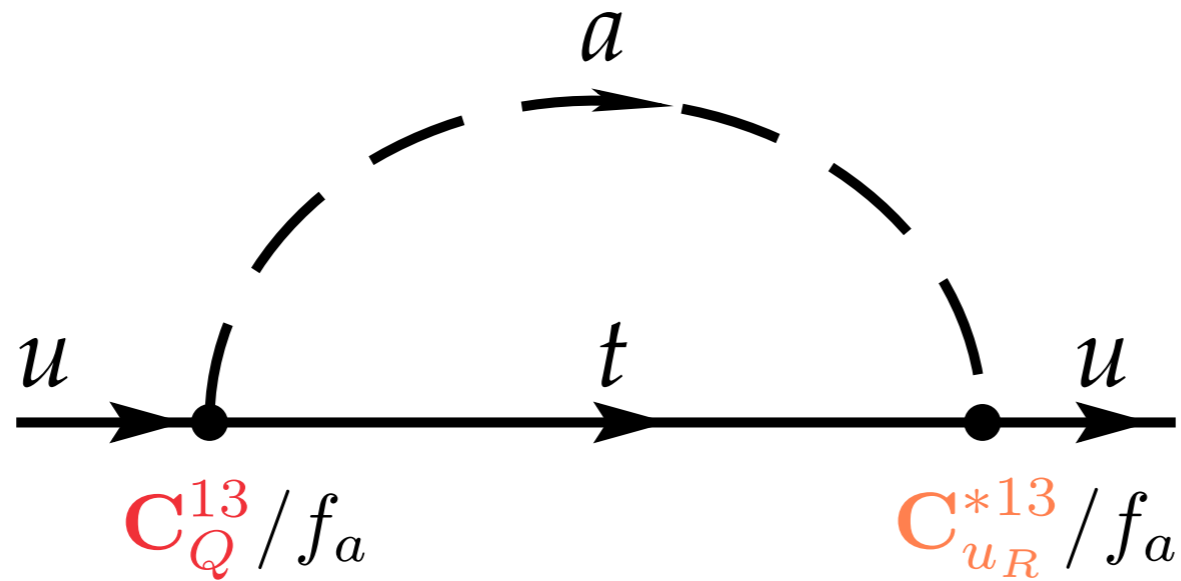
ALP contribution to $\bar{\theta}$
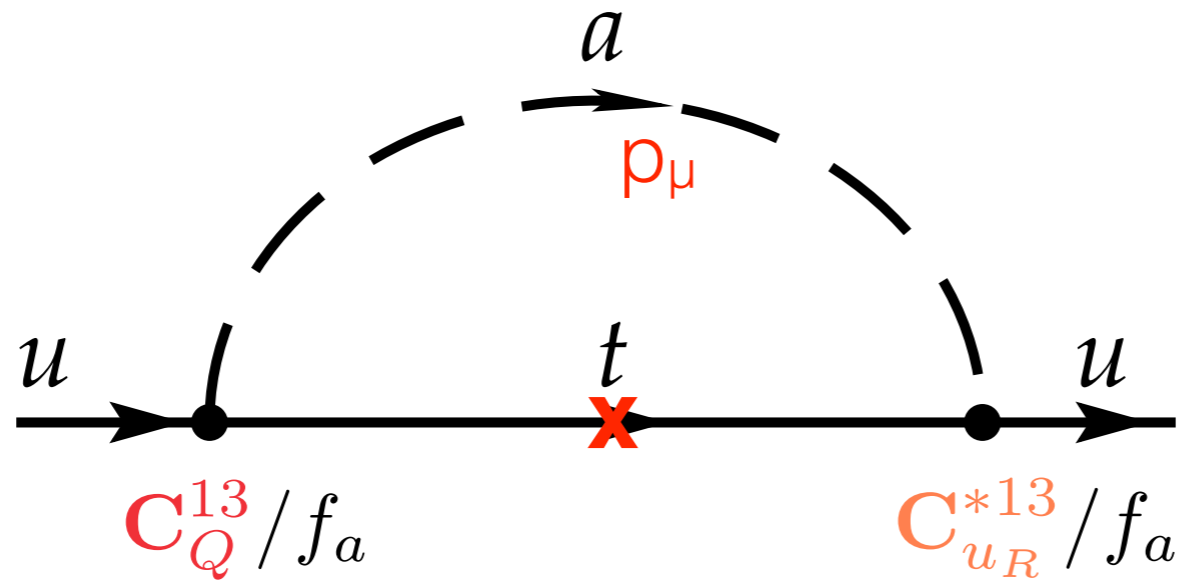
* Factor m_t for chirality flip

* Factor p_μ^2 from vertices

ALP contribution to $\bar{\theta}$

* Factor m_t for chirality flip

* Factor p_μ^2 from vertices

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

Neglecting threshold corrections

For an ALP:

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

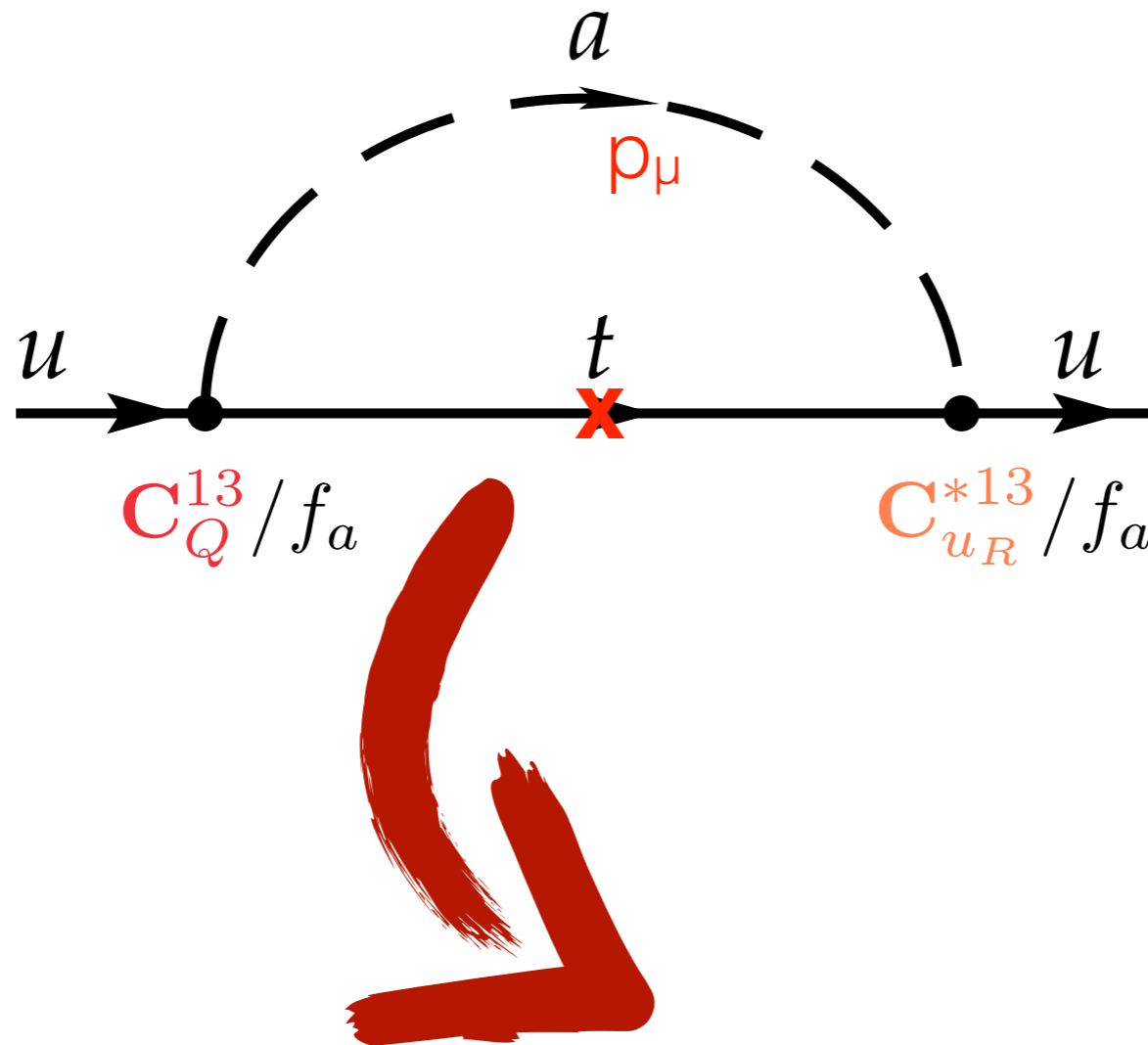$$\sum_{u_i=\{u,c,t\}} \frac{m_{u_k}\left(m_a^2 + \widehat{m}_{u_k}^2\right)}{16\pi^2 f_a^2 m_{u_i}} \,\mathrm{Im}\left(\boldsymbol{C}_Q^{ik} \boldsymbol{C}_{u_R}^{*ik}\right) \log \frac{f_a^2}{\max\left(m_a^2, m_{u_k}^2\right)}$$

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

ALP contribution to $\bar{\theta}$

* Factor m_t for chirality flip

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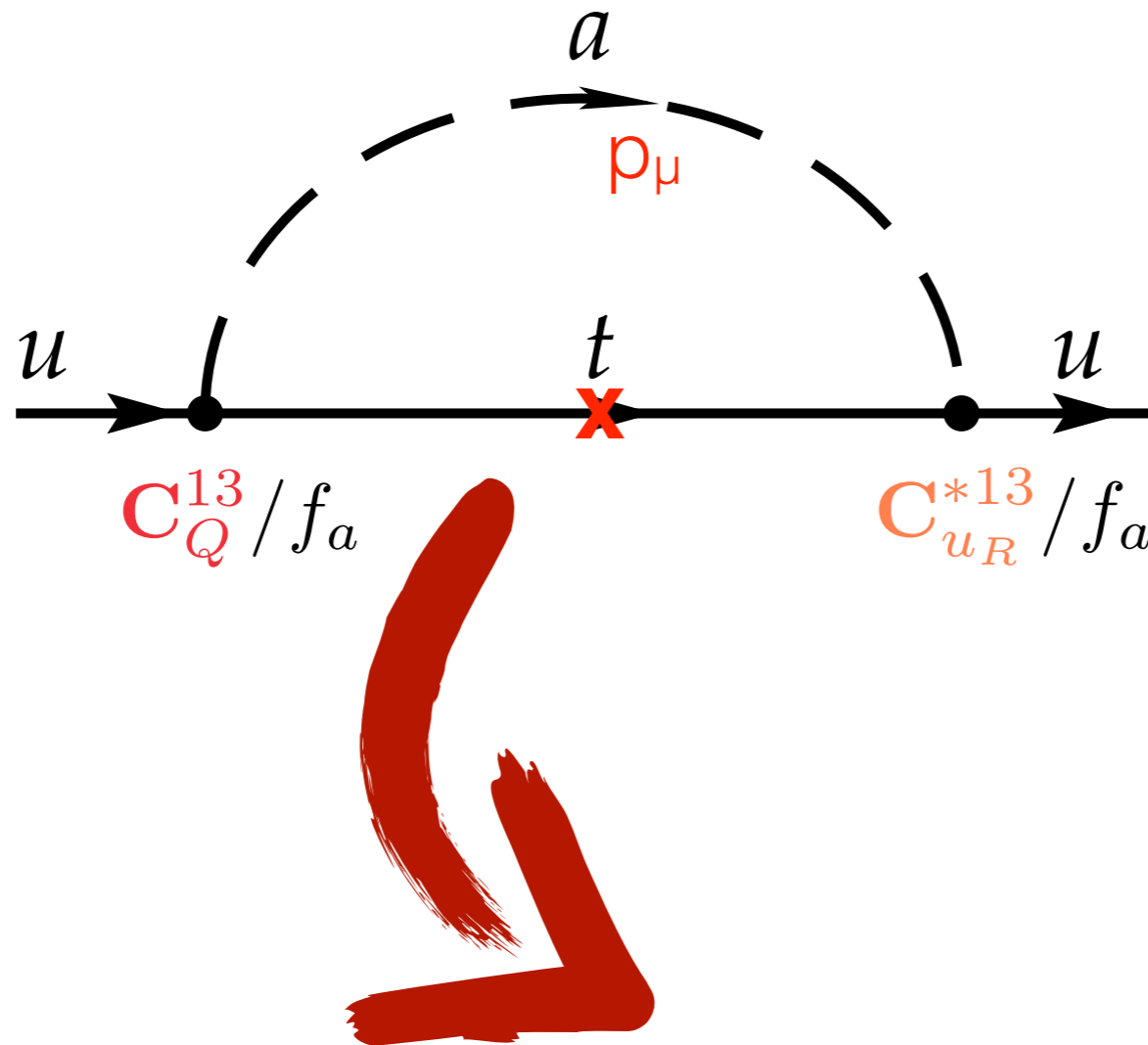
$$\Delta\bar{\theta}_{\mathrm{ALP}} \simeq \frac{m_t \max(m_a^2, m_t^2)}{16\pi^2 f_a^2 m_u} \mathrm{Im}(C_Q^{13} C_{u_R}^{*13})$$

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

$m_a < m_t$:

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

ALP contribution to $\bar{\theta}$
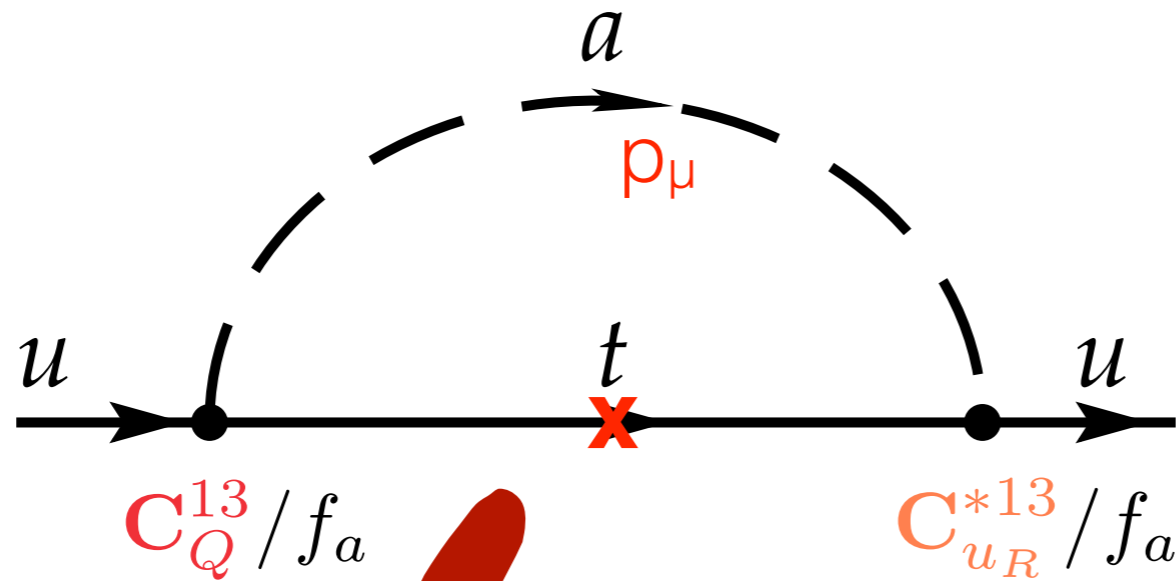
* Factor m_t for chirality flip

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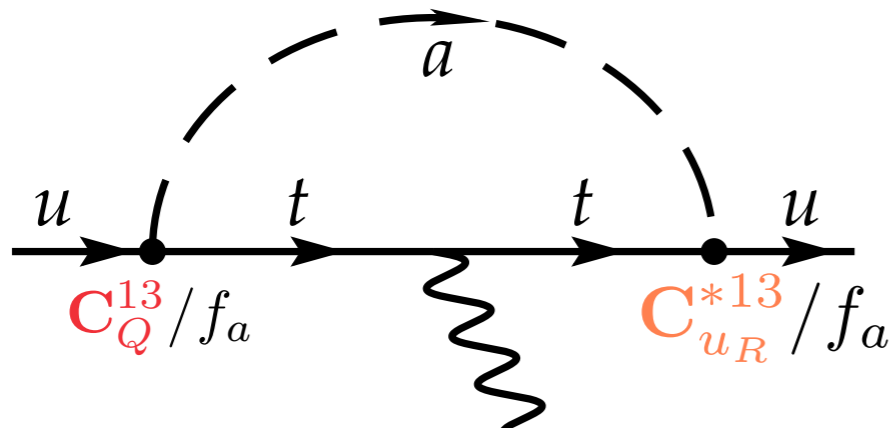
$$\frac{d_n}{e}\bigg|_{d_q,\tilde{d}_q} \sim \mathcal{O}(1) \times \frac{Q_u}{32\pi^2} m_t \frac{\mathrm{Im}(C_Q^{13} C_{u_R}^{*13})}{f_a^2}$$

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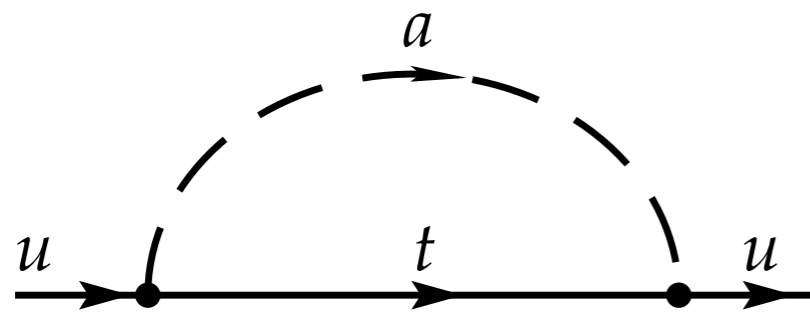
$$\frac{d_n}{e}\bigg|_{\bar{\theta}} \sim \frac{\mathcal{O}(10^{-3}\ \mathrm{GeV}^{-1})}{16\pi^2} \times \left(\frac{m_t^3}{m_u}\right) \frac{\mathrm{Im}(C_Q^{13} C_{u_R}^{*13})}{f_a^2}$$

Bounds many orders of magnitude stronger
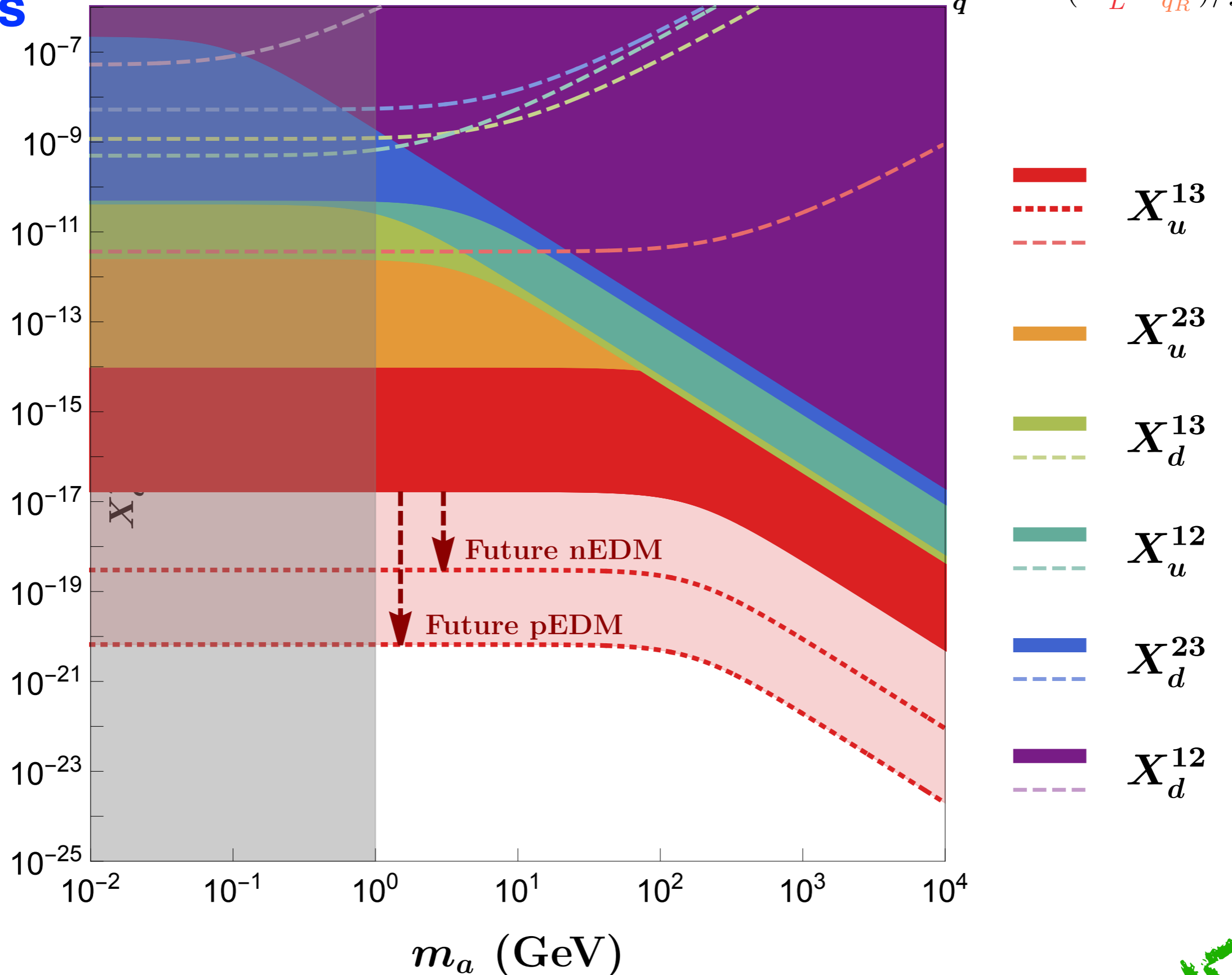
NEW

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

nEDM limits on ALP-fermion couplings

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

Dotted lines:

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

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

Solid regions:

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

OLD

Bounds many orders of magnitude stronger NEW
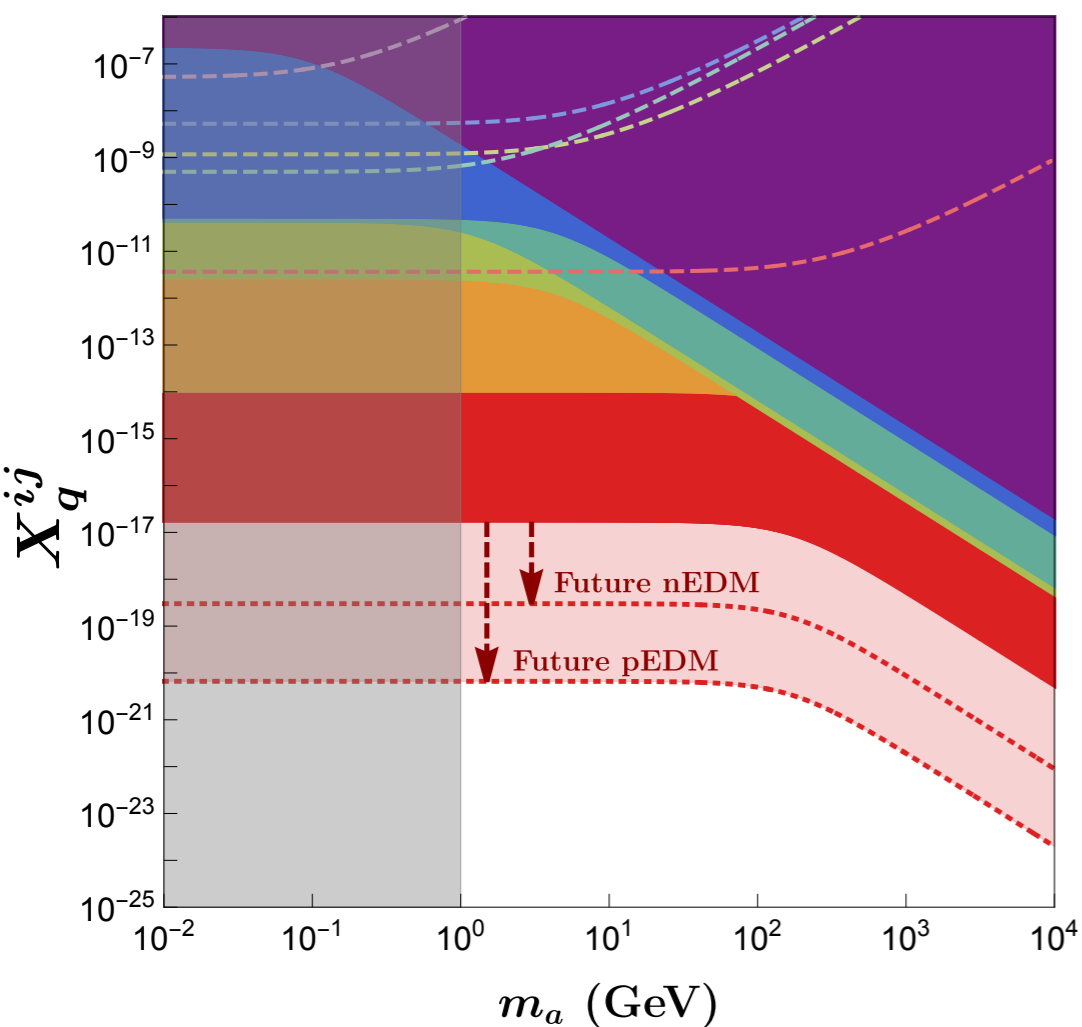
V. Enguita, M.B. Gavela, B. Grinstein, P. Quilez, arXiv: 2403.13133

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

ALPs

Future nEDM

Future pEDM

X_u^{13}

X_u^{23}

X_d^{13}

X_u^{12}

X_d^{23}

X_d^{12}

m_a (GeV)

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

$$X_q^{ij} = \mathrm{Im}(C_L^{ij} C_{q_R}^{*ij})/f_a^2 \; (\mathrm{GeV}^{-2})$$
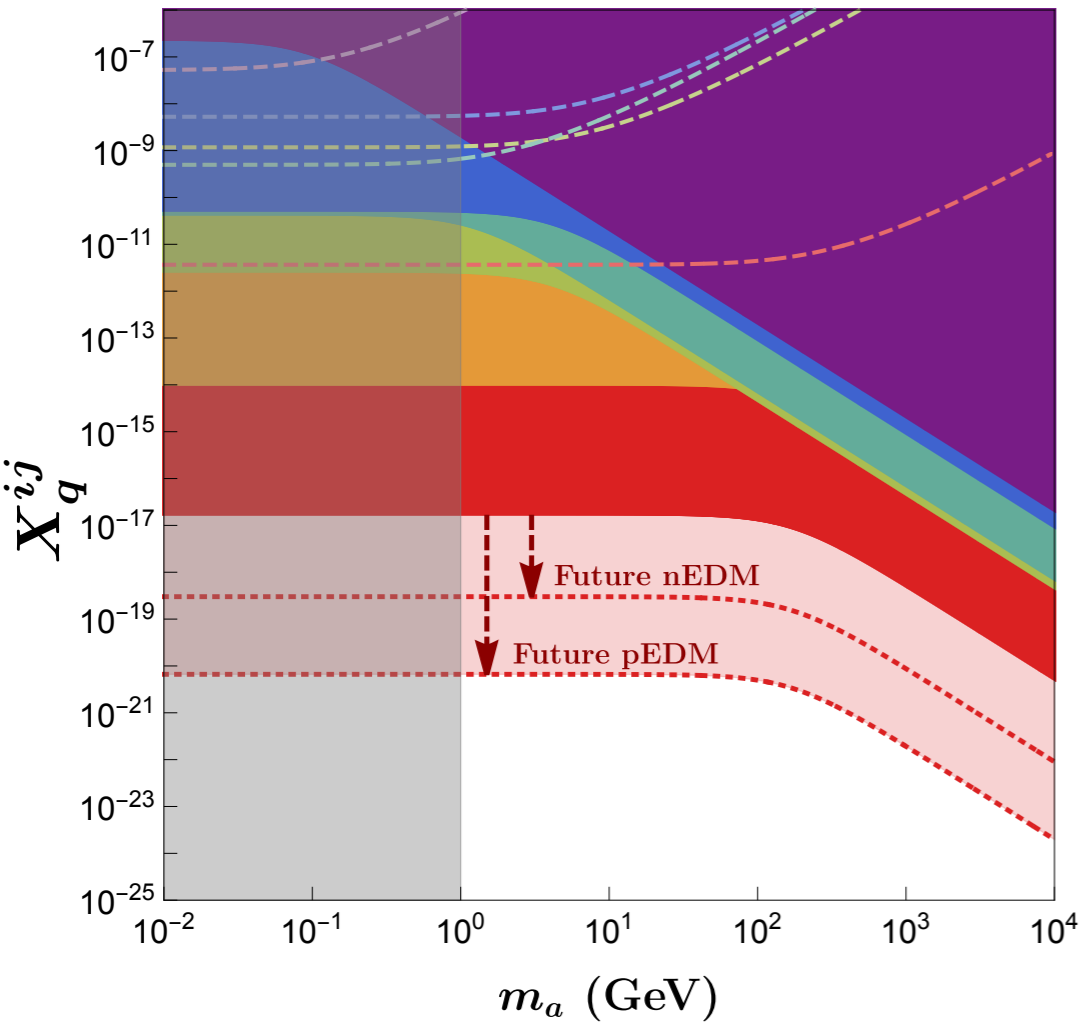
Combination		$\bar{\theta}$-bounds (GeV^{-2})	qEDM & cEDM (GeV^{-2})
X_u^{13}	$\mathrm{Im}[C_Q^{13} C_{u_R}^{*13}]/f_a^2$	1.8×10^{-17}	3.7×10^{-12}
X_u^{23}	$\mathrm{Im}[C_Q^{23} C_{u_R}^{*23}]/f_a^2$	1.1×10^{-14}	$-$
X_d^{13}	$\mathrm{Im}[C_Q^{13} C_{d_R}^{*13}]/f_a^2$	1.1×10^{-12}	1.9×10^{-9}
X_u^{12}	$\mathrm{Im}[C_Q^{12} C_{u_R}^{*12}]/f_a^2$	2.7×10^{-12}	2.3×10^{-9}
X_d^{23}	$\mathrm{Im}[C_Q^{23} C_{d_R}^{*23}]/f_a^2$	2.3×10^{-11}	8.7×10^{-9}
X_d^{12}	$\mathrm{Im}[C_Q^{12} C_{d_R}^{*12}]/f_a^2$	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

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

As a function of m_a
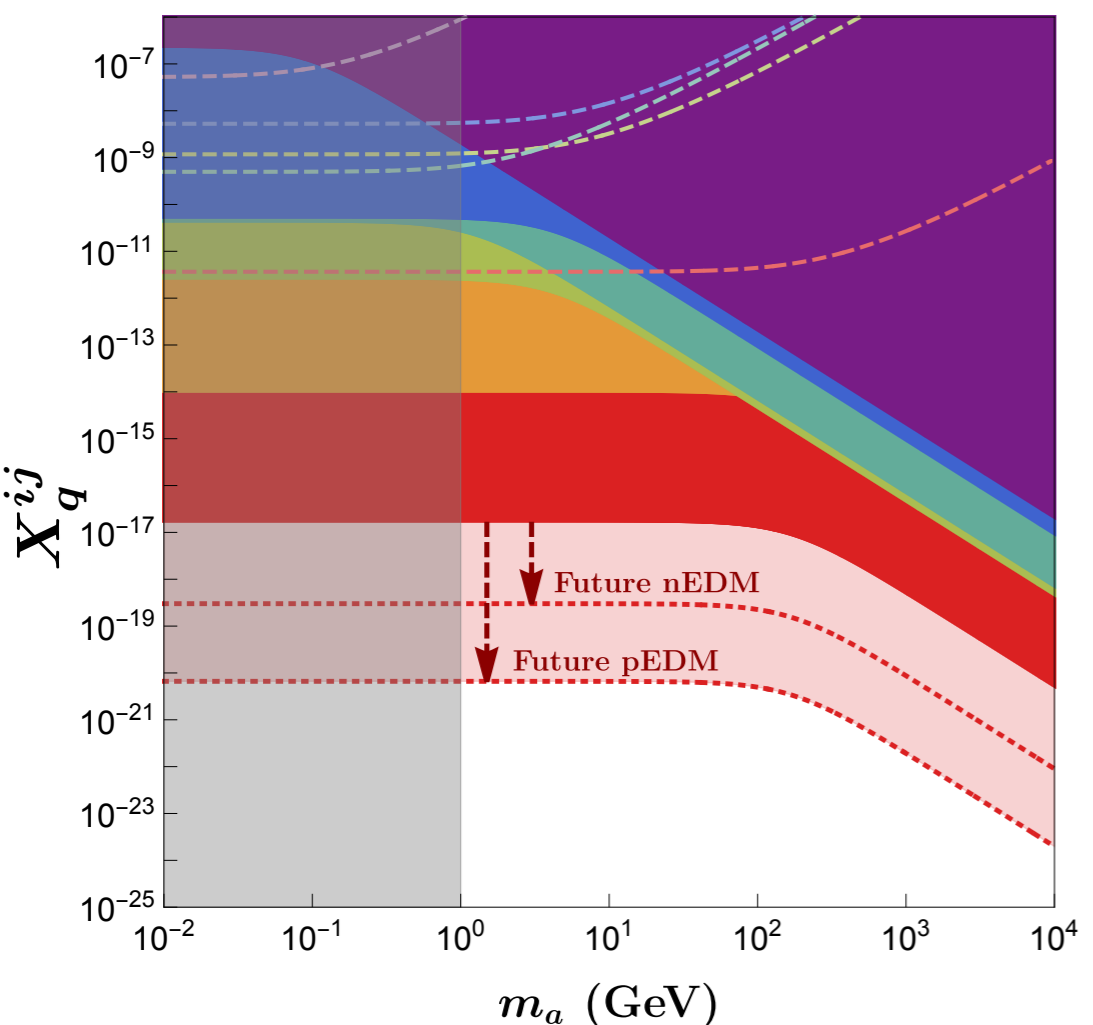
▬ (red, solid)	X_u^1	$\text{Im}[C_Q^{13} C_{u_R}^{*13}]/f_a^2 < \left(\dfrac{m_t^2}{m_a^2+m_t^2}\right) 2 \times 10^{-17}$
▬ (orange)	X_u^2	$\text{Im}[C_Q^{23} C_{u_R}^{*23}]/f_a^2 < \left(\dfrac{m_t^2}{m_a^2+m_t^2}\right) 1 \times 10^{-14}$
▬ (green)	X_d^1	$\text{Im}[C_Q^{13} C_{d_R}^{*13}]/f_a^2 < \left(\dfrac{m_b^2}{m_a^2+m_b^2}\right) 3 \times 10^{-12}$
▬ (teal)	X_u^1	$\text{Im}[C_Q^{12} C_{u_R}^{*12}]/f_a^2 < \left(\dfrac{m_c^2}{m_a^2+m_c^2}\right) 5 \times 10^{-11}$
▬ (blue)	X_d^2	$\text{Im}[C_Q^{23} C_{d_R}^{*23}]/f_a^2 < \left(\dfrac{m_b^2}{m_a^2+m_b^2}\right) 6 \times 10^{-11}$
▬ (purple)	X_d^1	$\text{Im}[C_Q^{12} C_{d_R}^{*12}]/f_a^2 < \left(\dfrac{m_s^2}{m_a^2+m_s^2}\right) 3 \times 10^{-7}$

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

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.:
$$\begin{cases} u_L \longrightarrow e^{i\frac{a}{f_a}\boldsymbol{C}_Q} u_L \,, & d_L \longrightarrow e^{i\frac{a}{f_a}\boldsymbol{C}_Q} d_L \,, \\[2mm] u_R \longrightarrow e^{i\frac{a}{f_a}\boldsymbol{C}_{u_R}} u_R \,, & d_R \longrightarrow e^{i\frac{a}{f_a}\boldsymbol{C}_{d_R}} d_R \end{cases}$$

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

$$\mathcal{L} \supset \bar{u}_L \, v \left[i\frac{a}{f_a} \boldsymbol{K}_u + \frac{a^2}{f_a^2} \boldsymbol{F}_u \right] u_R$$

$$+ \bar{d}_L \, v \left[i\frac{a}{f_a} \boldsymbol{K}_d + \frac{a^2}{f_a^2} \boldsymbol{F}_d \right] d_R + \text{h.c.} + \ldots$$

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

$$\mathcal{L} \supset \bar{u}_L \, v \left[i\frac{a}{f_a} \boldsymbol{K}_u + \frac{a^2}{f_a^2} \boldsymbol{F}_u \right] u_R$$

$$+ \, \bar{d}_L \, v \left[i\frac{a}{f_a} \boldsymbol{K}_d + \frac{a^2}{f_a^2} \boldsymbol{F}_d \right] d_R + \text{h.c.} + \dots$$

where
$$v\,\boldsymbol{K}_q \equiv C_Q M_q - M_q C_{q_R}\,,$$
$$2\,v\,\boldsymbol{F}_q \equiv 2C_Q M_q C_{q_R} - C_Q^2 M_q - M_q C_{q_R}^2$$

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

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

where
$$v \, \boldsymbol{K}_q \equiv C_Q M_q - M_q C_{q_R}\,,$$
$$2 \, v \, \boldsymbol{F}_q \equiv 2 C_Q M_q C_{q_R} - C_Q^2 M_q - M_q C_{q_R}^2$$

There are two diagrams in the ``chirality-flip'' basis:
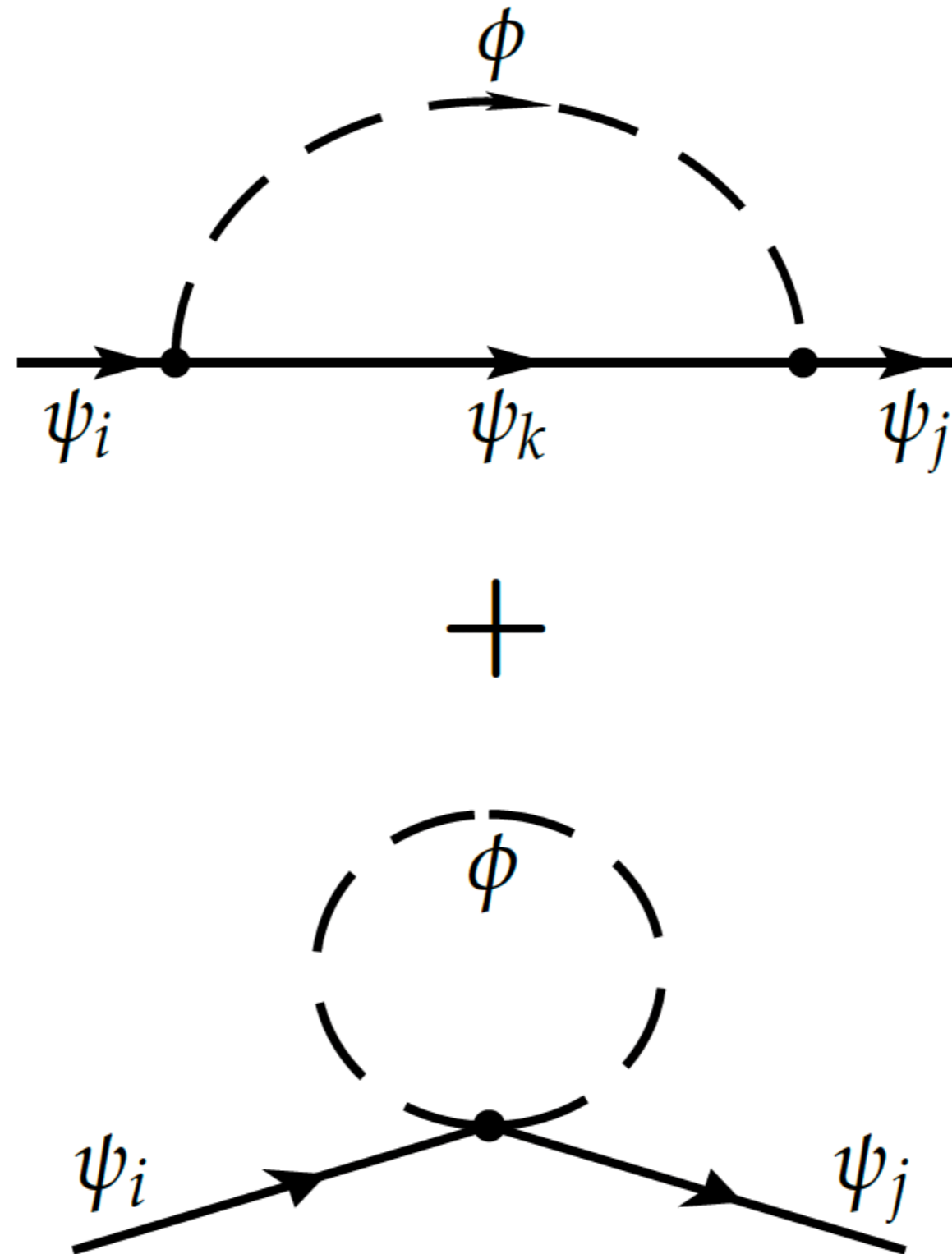
General Scalar

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

CP-violation

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

Generic scalar

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

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

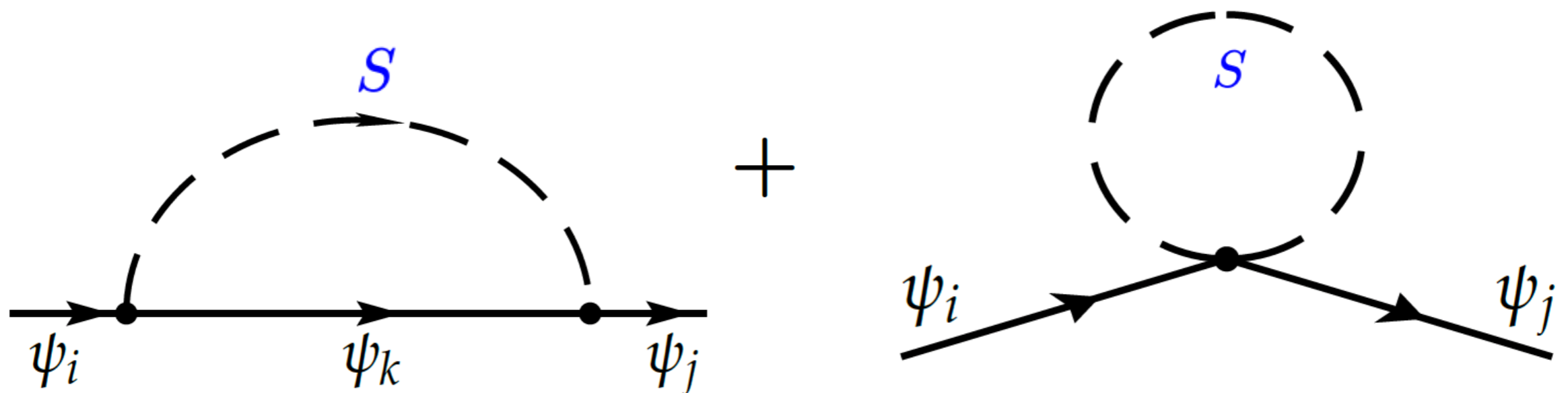**K** and **F** arbitrary: more parameters than for ALPs

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

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:

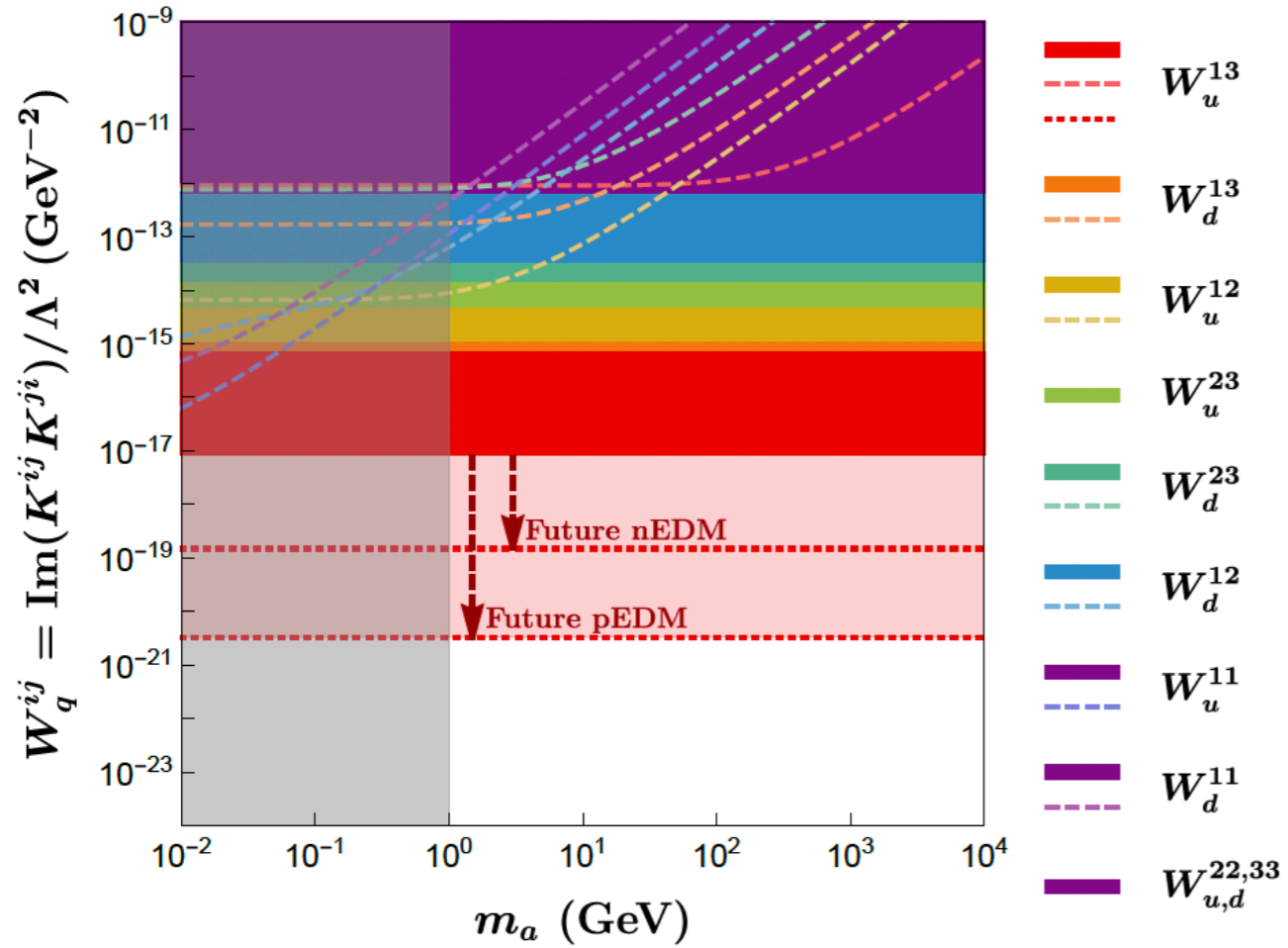**bounds also improved by orders of magnitude**

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.
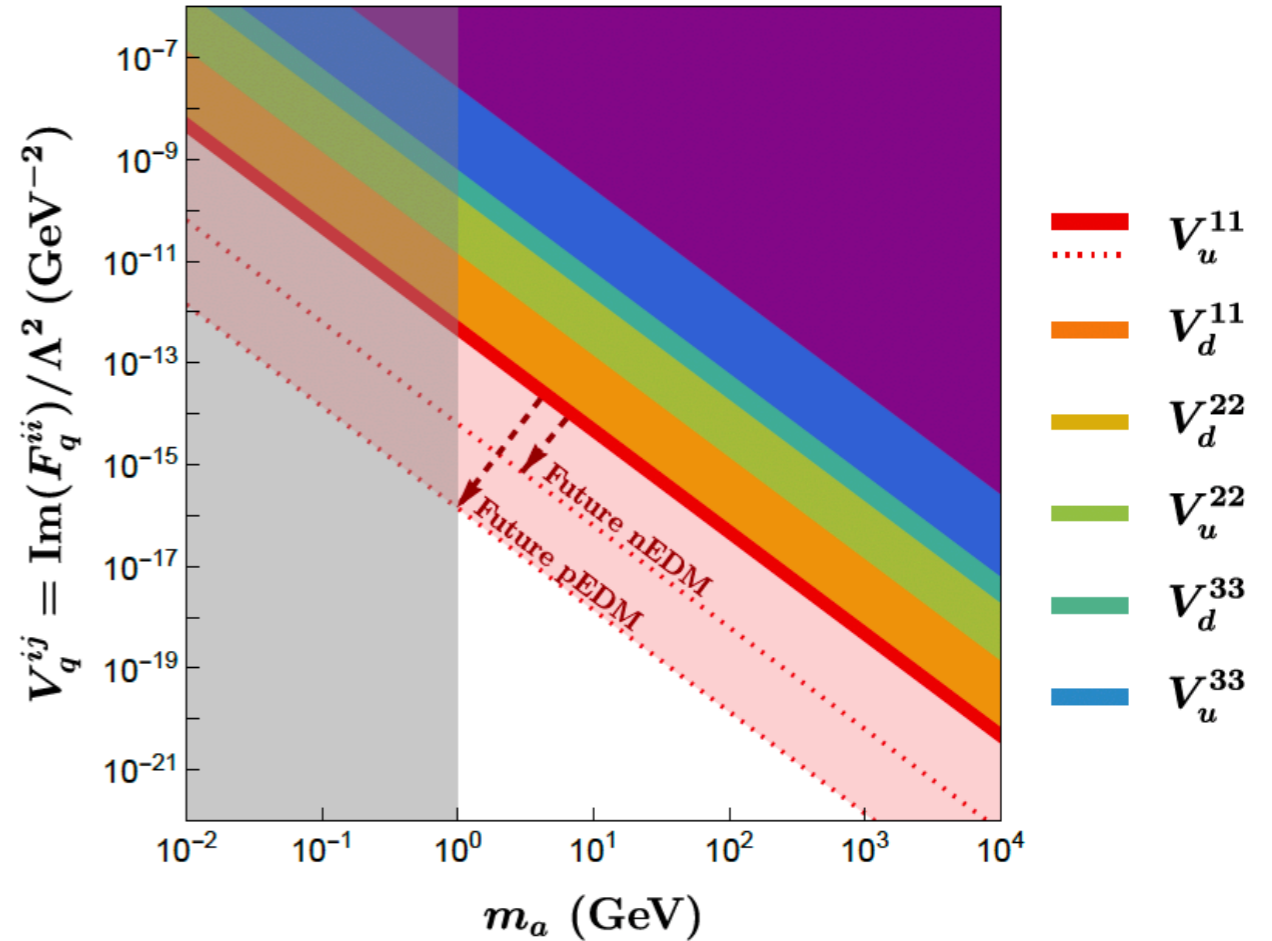
FIG. 6: *General scalar.* Upper bounds on $V_q^{ij} \equiv \left|\mathrm{Im}\left(F_q^{ij}\right)/\Lambda^2\right|$ stemming from the contributions of $\bar{\theta}$ (solid regions) to the nEDM. The red dotted line shows the projected bounds on V_u^{11} from future nEDM and pEDM experiments [47, 48]. The grey shaded area is as described in previous plots.

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

Without a PQ mechanism:

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

In the presence of a PQ mechanism:

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

Without a PQ mechanism:

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

chromo-electric EDMs

In the presence of a PQ mechanism:

$$d_n^{\mathrm{PQ}} = -0.204(11)d_u + 0.784(28)d_d - 0.0028(17)d_s$$
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chromo-electric EDMs

Without a PQ mechanism:

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

Lattice
+ sum rules

In the presence of a PQ mechanism:

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

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.

Generic scalar

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

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

$$M_{u,d}^{1\,\text{loop}} = M_{u,d} + \Delta M_{u,d}$$

$$\Delta\bar{\theta}_{\text{ALP}}(\mu) = \sum_{q=u,d} \arg\left[\det\left(M_q\left(1 + M_q^{-1}\Delta M_q\right)\right)\right]$$

$$\simeq \sum_{q=u,d} \text{Im}\,\text{Tr}\left(M_q^{-1}\Delta M_q\right)$$

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

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

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

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

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

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

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

$$M_{u,d}^{1\,\text{loop}} = M_{u,d} + \Delta M_{u,d}$$

$$\Delta\bar{\theta}_{\text{ALP}}(\mu) = \sum_{q=u,d} \arg\left[\det\left(M_q\left(1 + M_q^{-1}\Delta M_q\right)\right)\right]$$

$$\simeq \sum_{q=u,d} \text{Im}\,\text{Tr}\left(M_q^{-1}\Delta M_q\right)$$

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

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

Neglecting threshold corrections
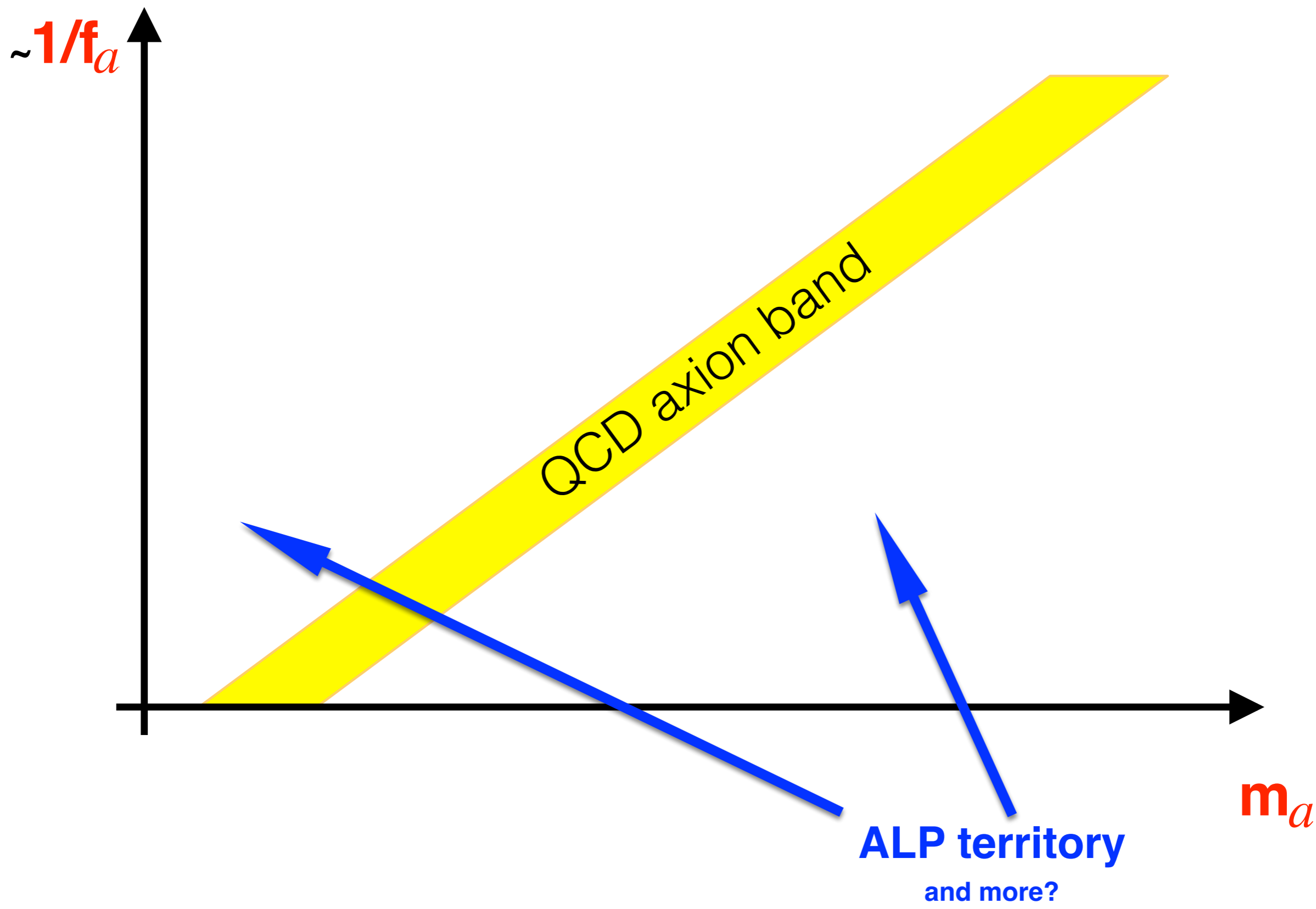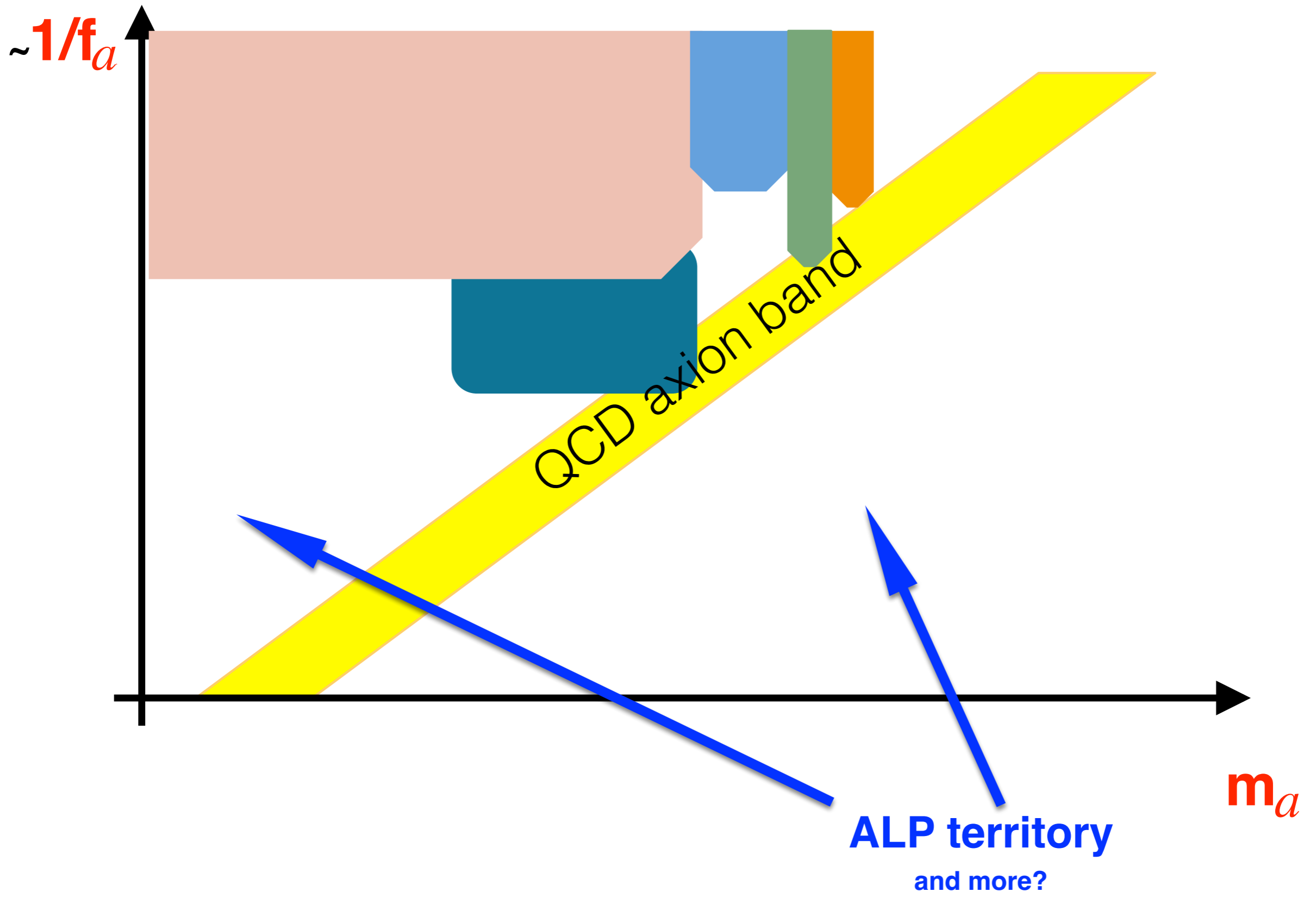
For an ALP:

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

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

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

Neglecting threshold corrections

For a generic scalar:

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

$$\left. + \sum_{i,k} \left[\frac{m_{d_k} \operatorname{Im}\left(\boldsymbol{K}_d^{ik} \boldsymbol{K}_d^{ki}\right)}{m_{d_i}} - \frac{m_\phi^2 \operatorname{Im}\left(\boldsymbol{F}_d^{ik}\right)}{m_{d_i}} \right] \log \frac{\Lambda^2}{\max(m_\phi^2, m_{d_k}^2)} \right)$$

~1/f_a

QCD axion band

ALP territory
and more?

m_a

Intensely looked for experimentally…

g

a ----{ $1/f_a$

g

direct a**-gluon coupling**

figure from cajohare.github.io

Axis labels: $1/f_a$ [GeV^{-1}], m_a [eV], $|g_{a\gamma\gamma}|$ [GeV^{-2}]

SN1987A, Planck+BAO, Solar core, White dwarfs, Piezoaxionic, QCD axion, CASPEr-electric

$$\frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$$
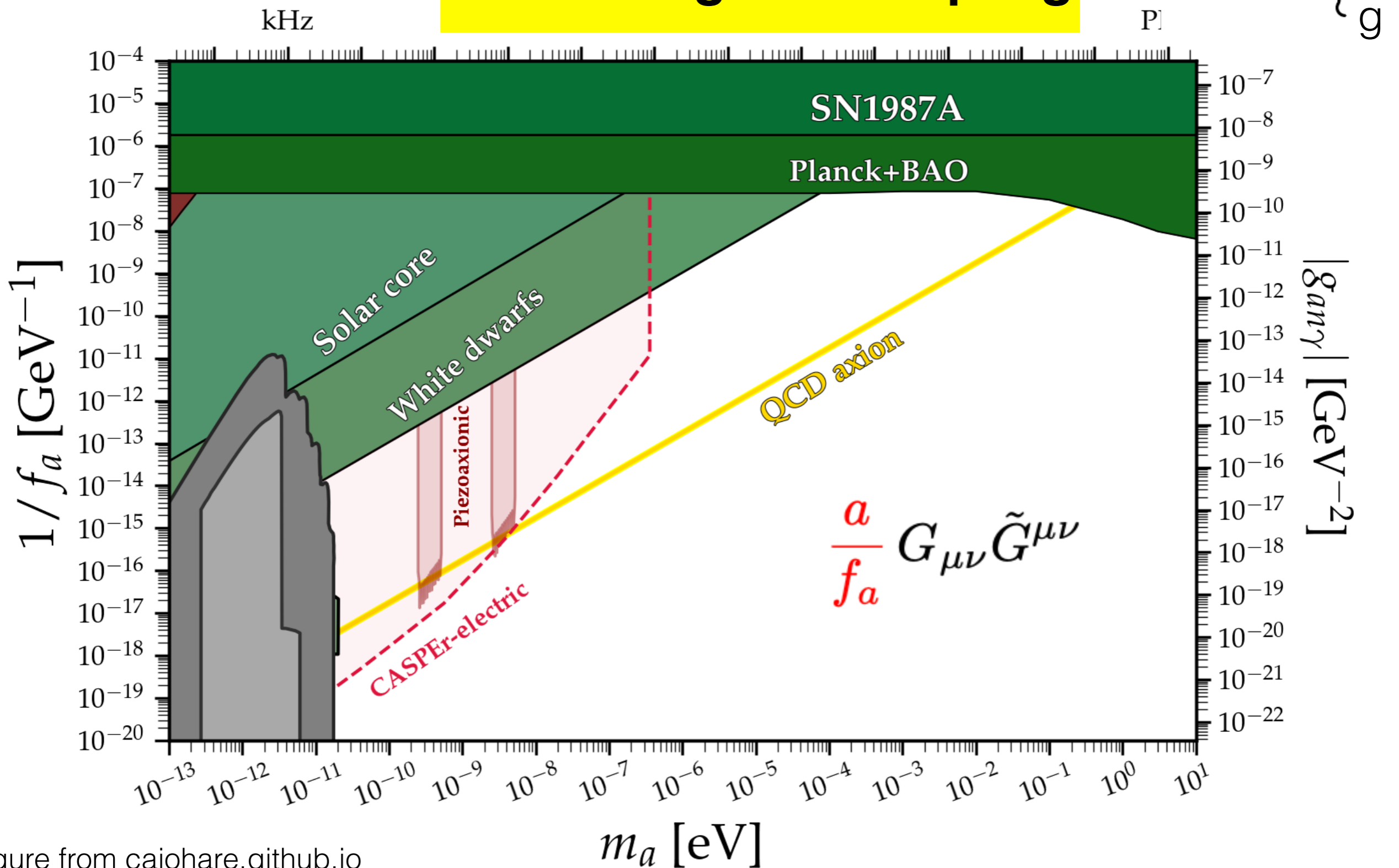
a-photon coupling

$$g_{a\gamma} \sim c \frac{\alpha}{8\pi f_a}$$

(GeV^{-1})
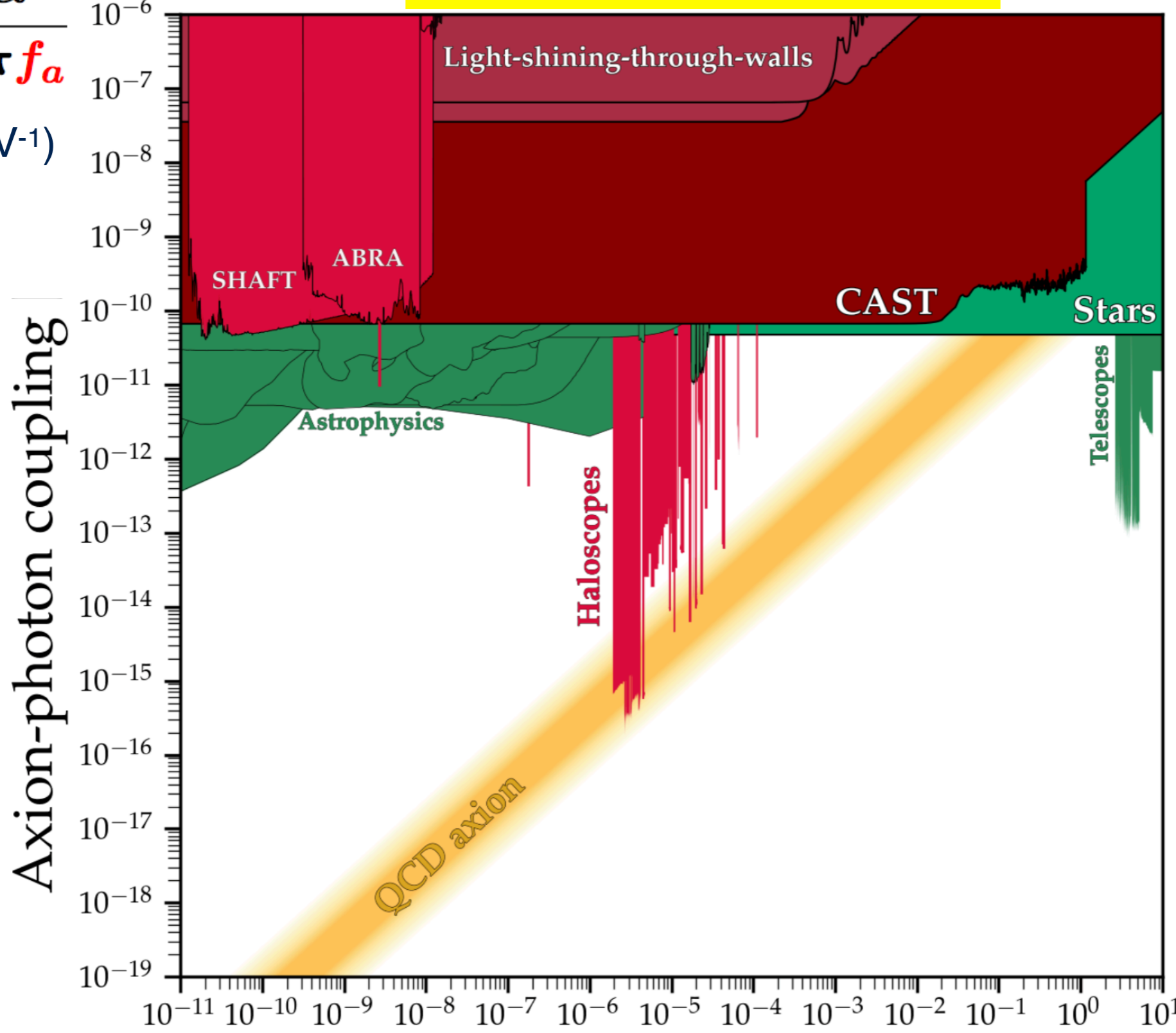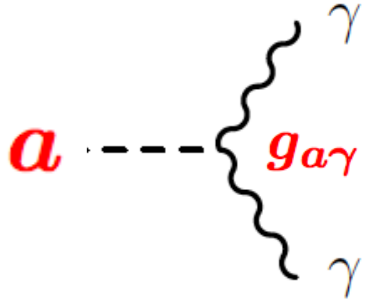
$$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

figure from cajohare.github.io

m$_a$ (eV)

Axions and ALPs can explain Dark Matter
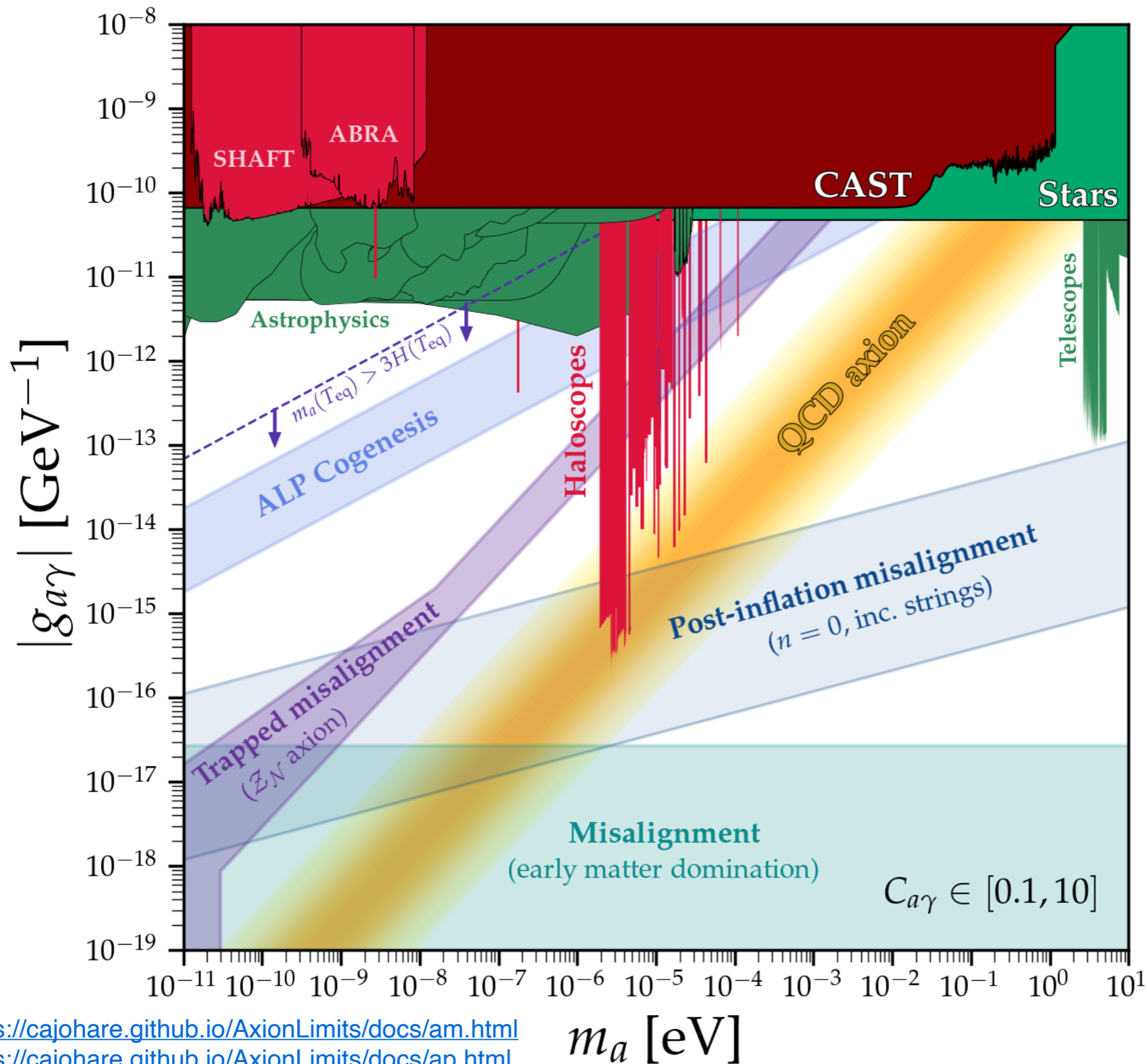
a - photon
coupling

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

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

$g_{a\gamma}$

Log$_{10}$m$_a$ (eV)

Jaeckel+ Spannowsky 2015
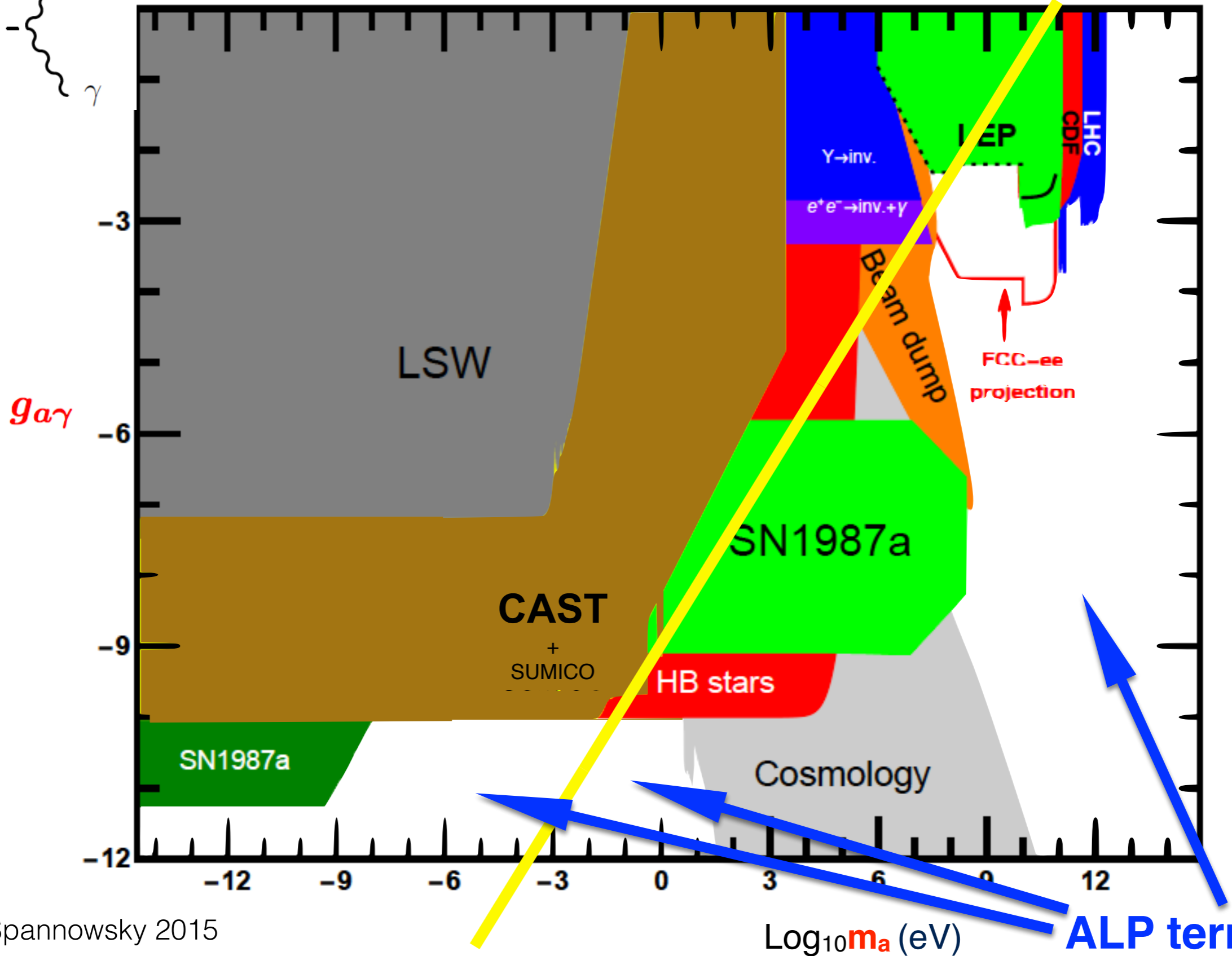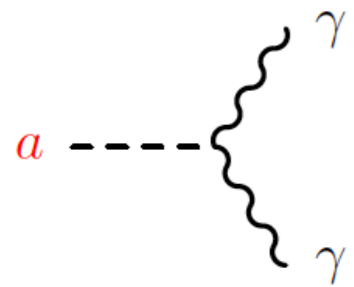
ALP territory

and more?

Other new ways to probe ALPs at LHC (Fdez. de Troconiz, Gavela, No, Sanz, 2019)

Non - resonant diboson searches
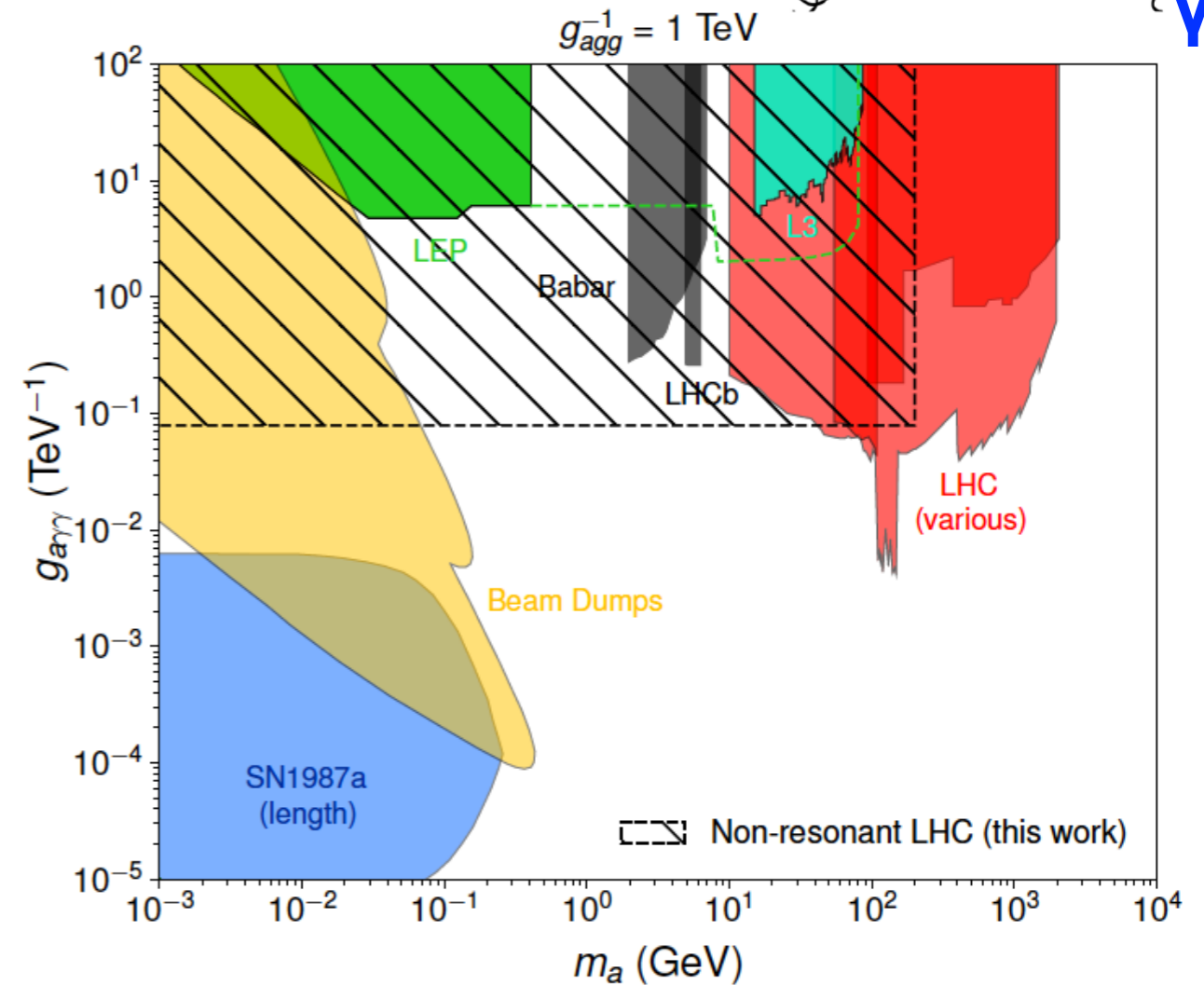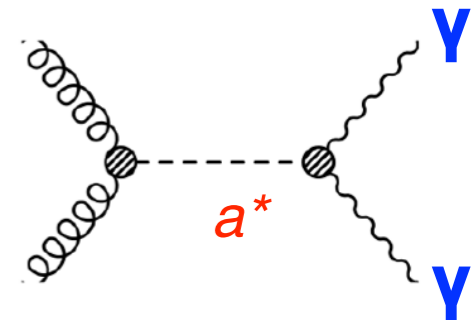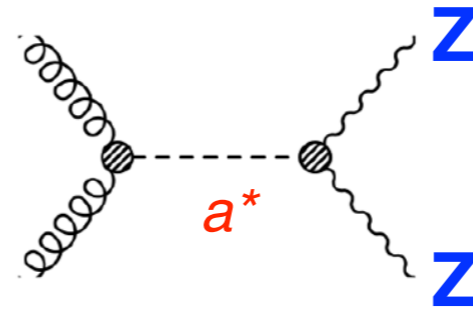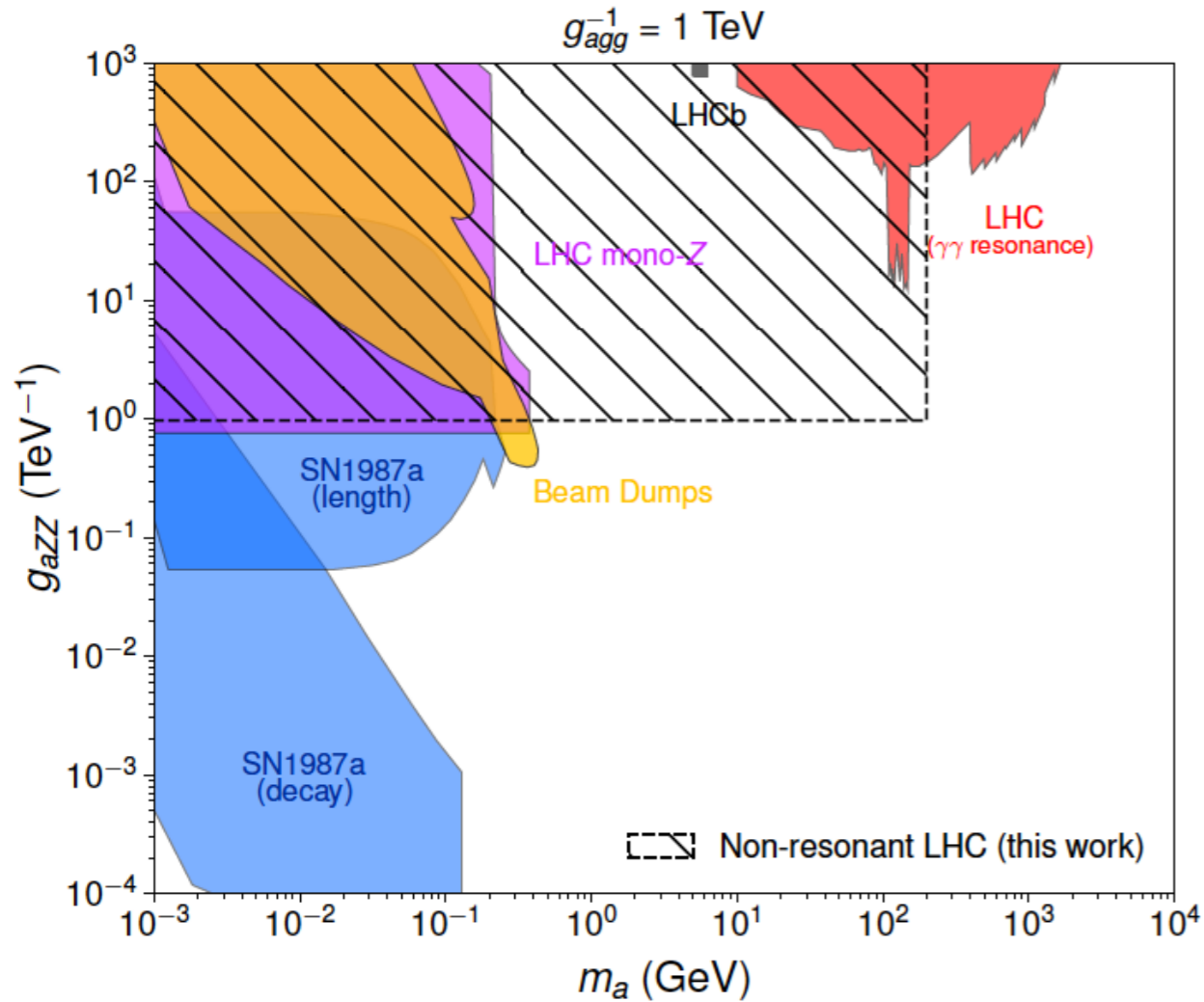
We also looked at two jets:
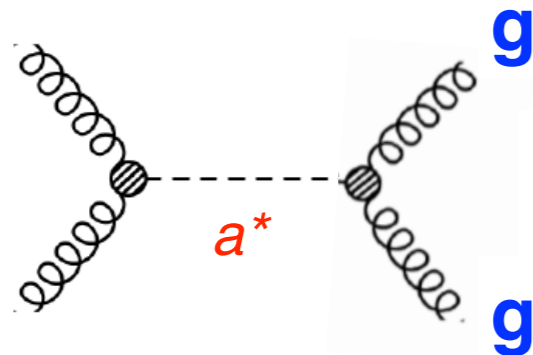
$$f_a/c_{\tilde{G}} > 2.5 \text{ TeV}$$

2022: **ALP-mediated EW VBS (vector-boson fusion)**

- **Vector Boson Scattering**
  $\rightarrow$ production of a diboson pair + 2 face-to-face jets with high invariant mass
  $\rightarrow$ explore **ALP EW couplings** with reduced dependence on the gluon coupling

- EW ALP-mediated processes $q_1 q_2 \rightarrow q_1' q_2' V_1 V_2$

VBS s-channel

VBS t-channel
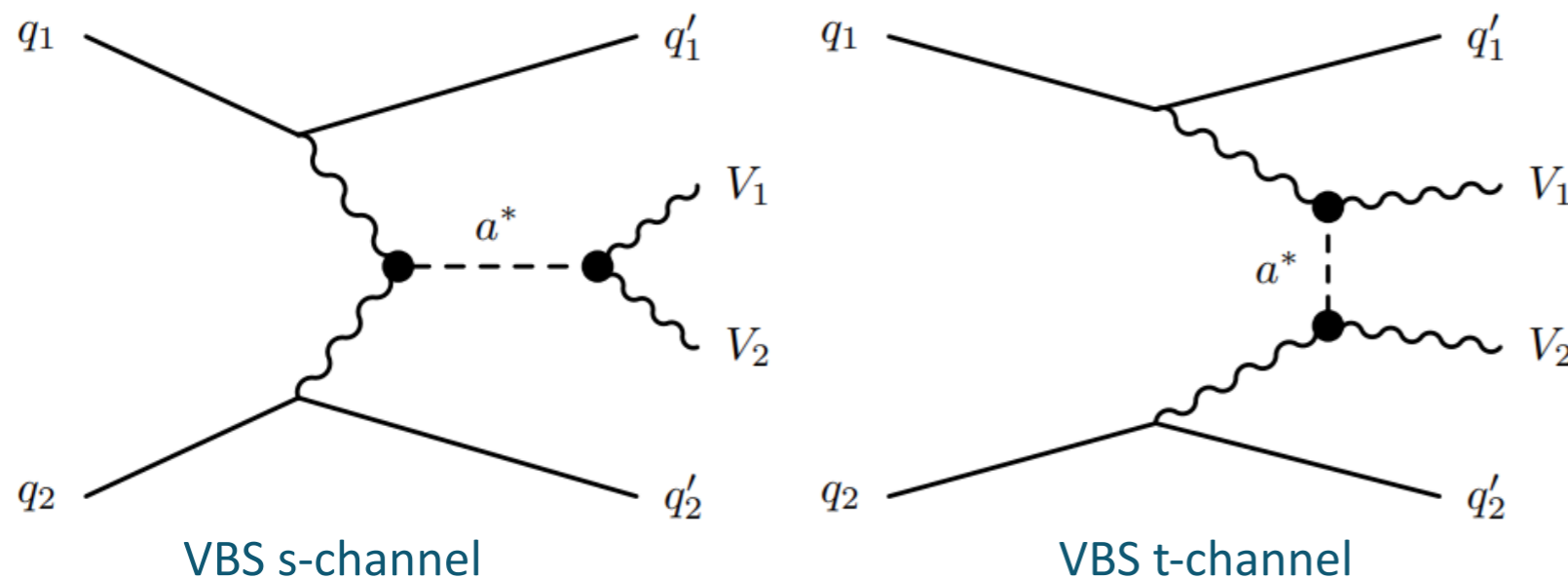
Reinterpretation of Run 2 CMS analysis:
$V_1 V_2 = ZZ, Z\gamma, W^{\pm}\gamma, W^{\pm}Z, W^{\pm}W^{\pm}$

CMS-SMP-20-001, CMS-SMP-20-016,
CMS-SMP-19-008, CMS-SMP-19-012

RESULTS

$-2\,\Delta\text{LLR} = 3.84$
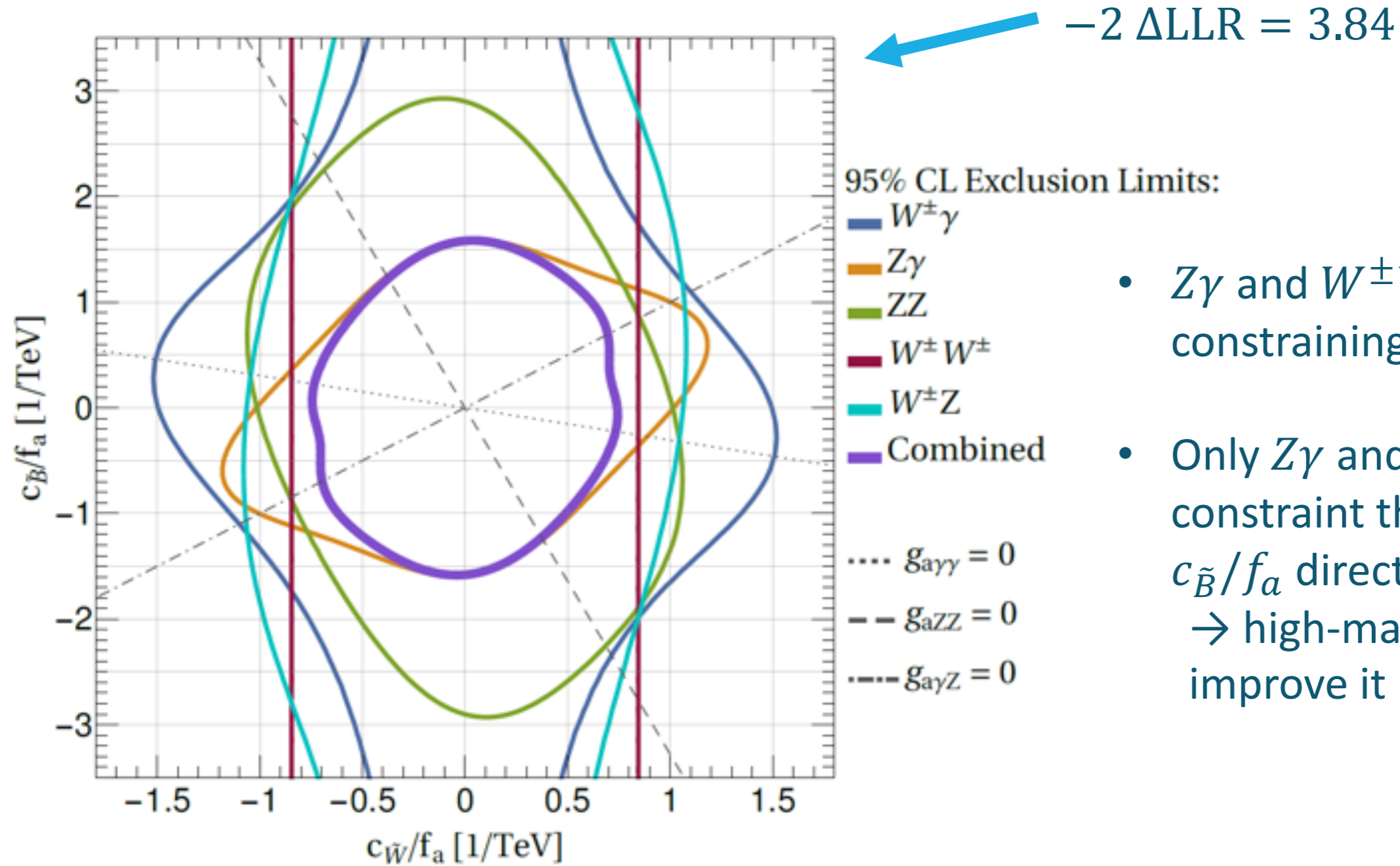
- $Z\gamma$ and $W^{\pm}W^{\pm}$ are the most constraining channels

- Only $Z\gamma$ and ZZ can constraint the plane in the $c_{\tilde{B}}/f_a$ direction.
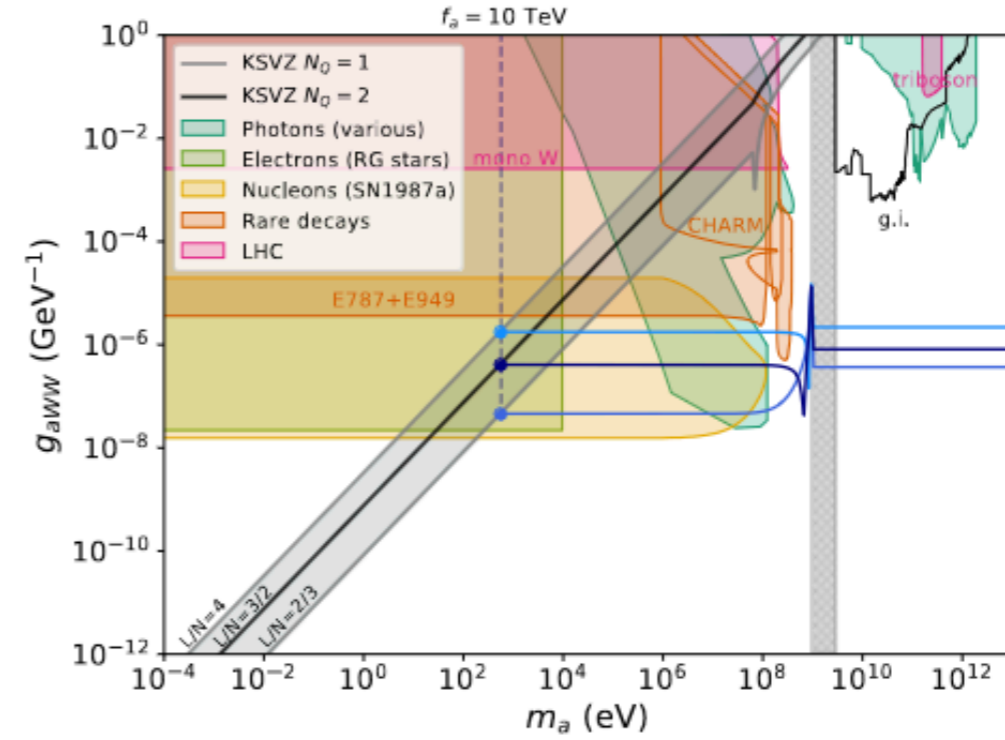 → high-mass $\gamma\gamma$ channel can improve it

J. Bonilla, I. Brivio, J. Machado-Rodríguez and J. F. de Trocóniz [2202.0345]

Comparison with existing bounds
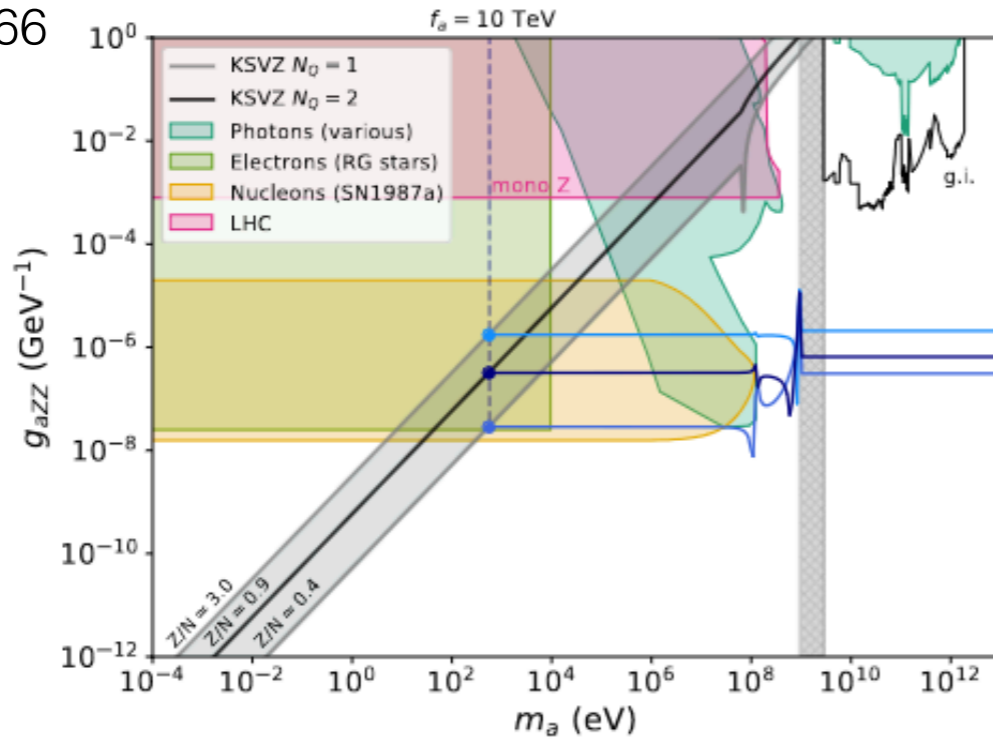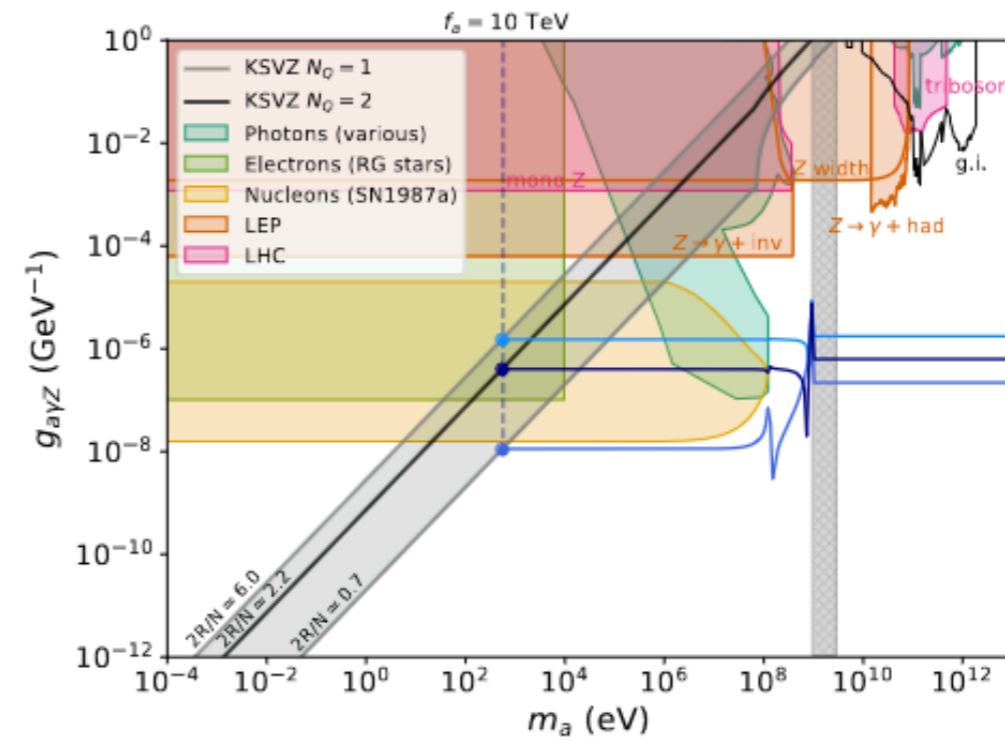
J. Bonilla, I. Brivio, J. Machado-Rodríguez and J. F. de Trocóniz [2202.0345]

Alonso-Alvarez, Gavela, Quilez, arXiv:1811.05466
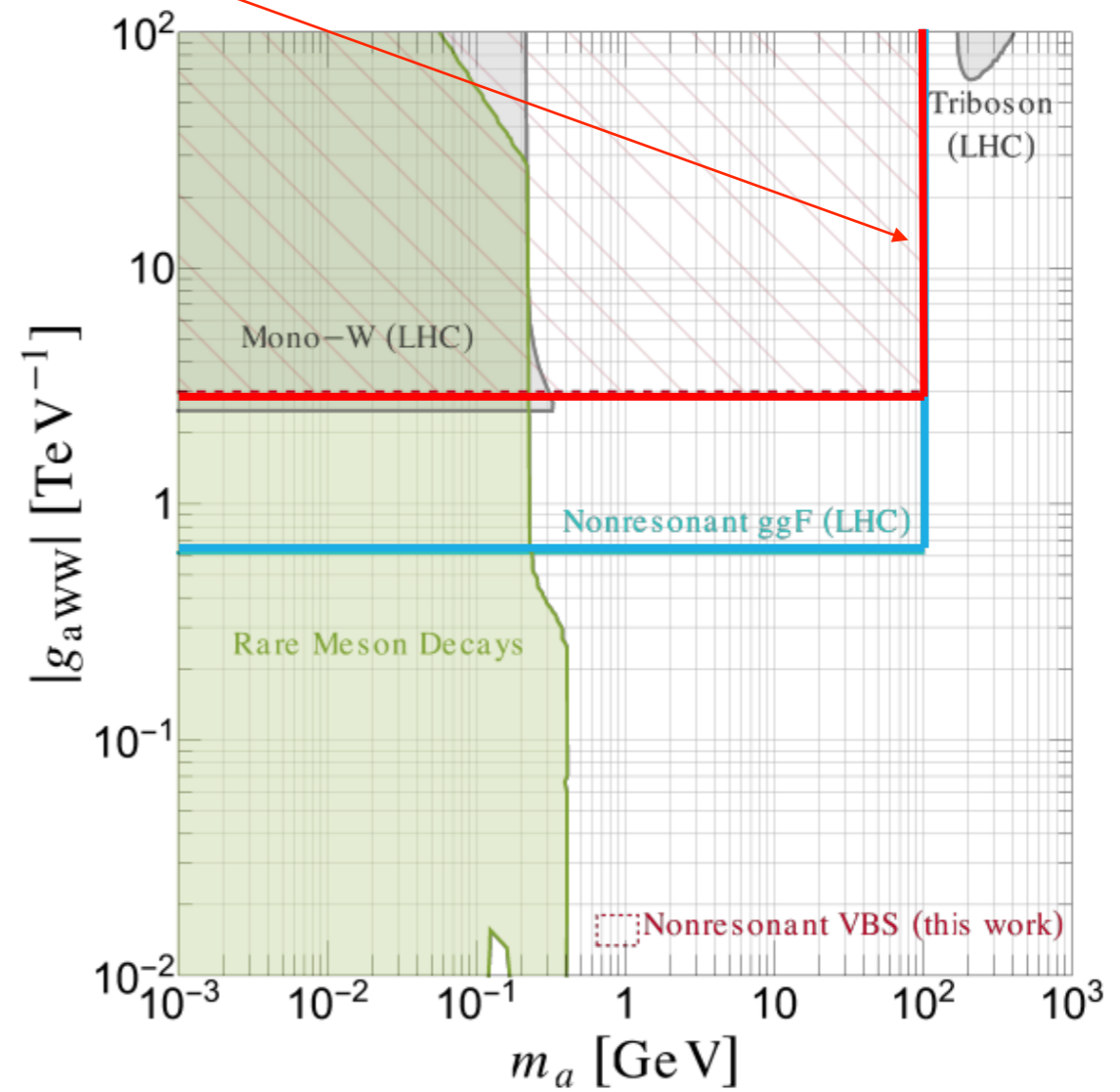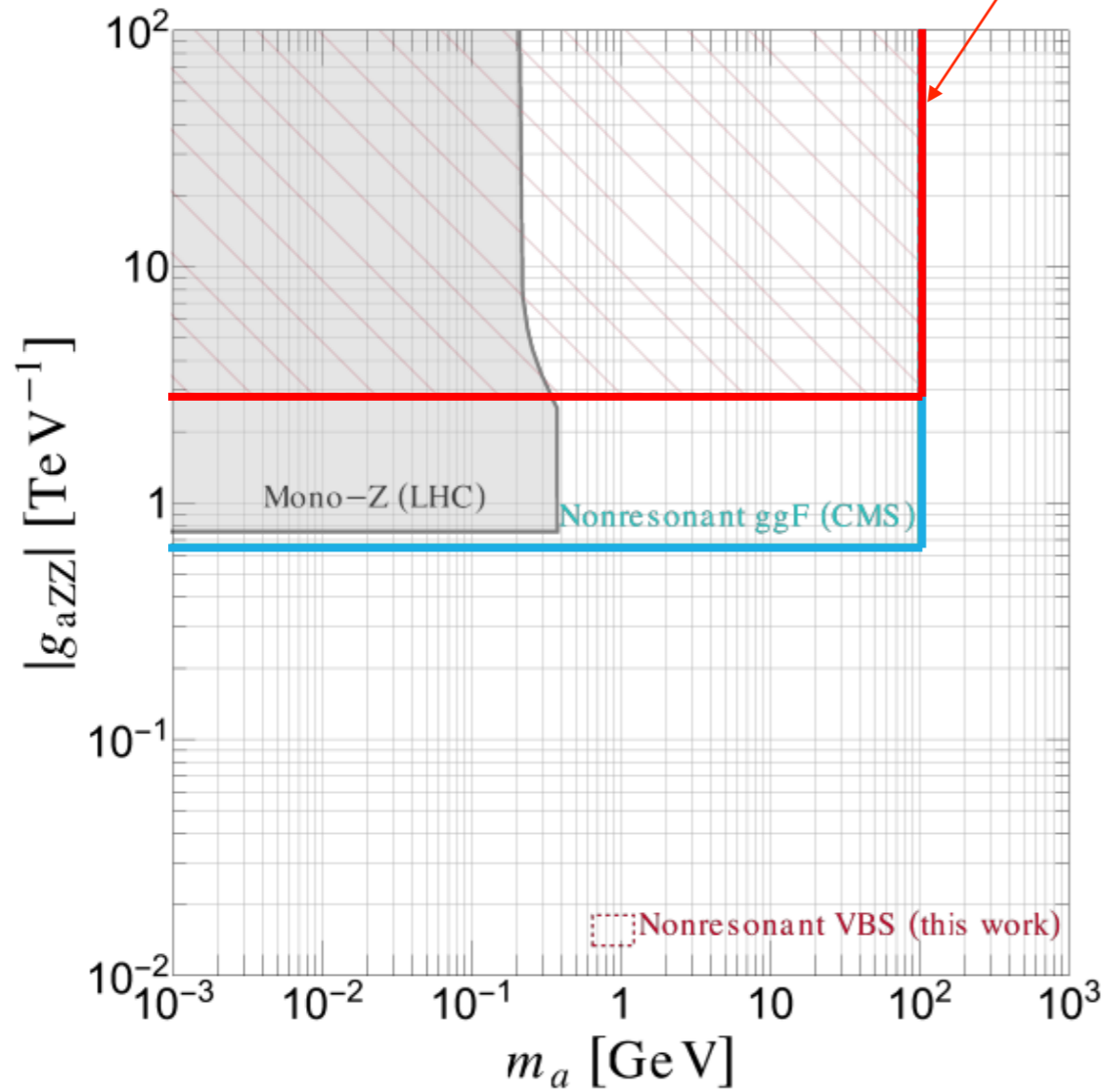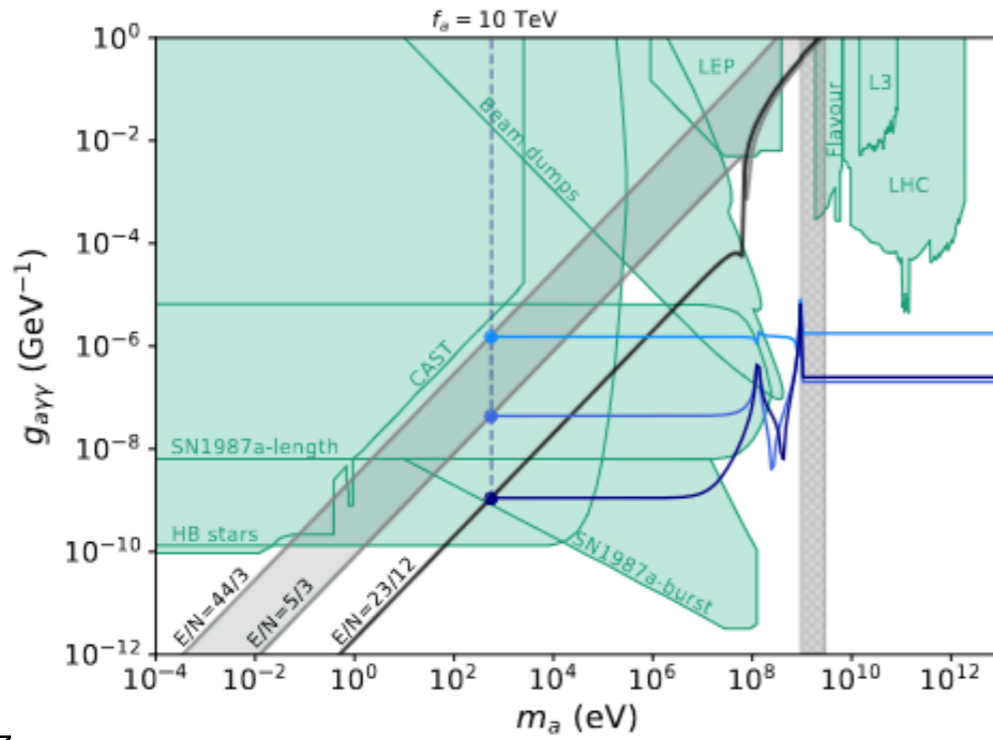
(a) Coupling to photons.

(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

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

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

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

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

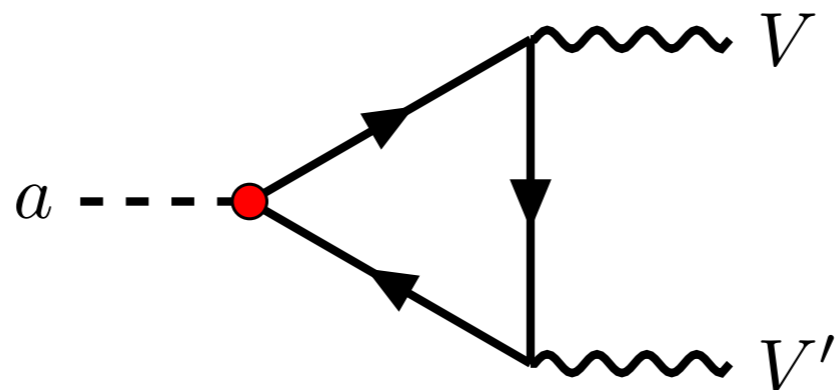$$m_a^2 f_a^2 \simeq m_\pi^2 f_\pi^2 \frac{m_u\, m_d}{(m_u + m_d)^2}$$

Coupling to the nEDM

Axion mass
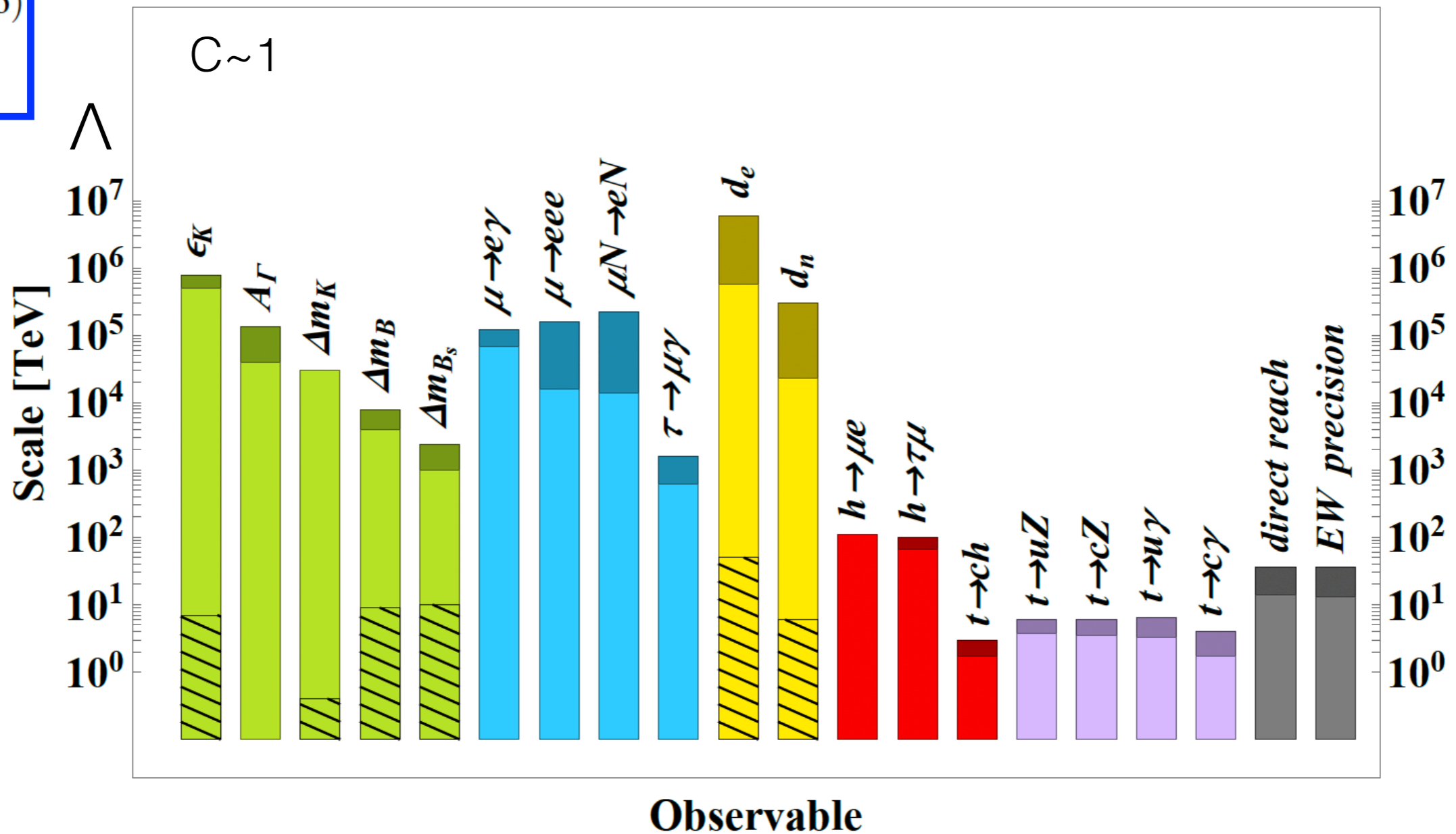
Fig. 5.1: Reach in new physics scale of present and future facilities, from generic dimension six operators. Colour coding of observables is: green for mesons, blue for leptons, yellow for EDMs, red for Higgs flavoured couplings and purple for the top quark. The grey columns illustrate the reach of direct 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).

One-loop induced couplings

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

ANOMALOUS　MASS-DEPENDENT

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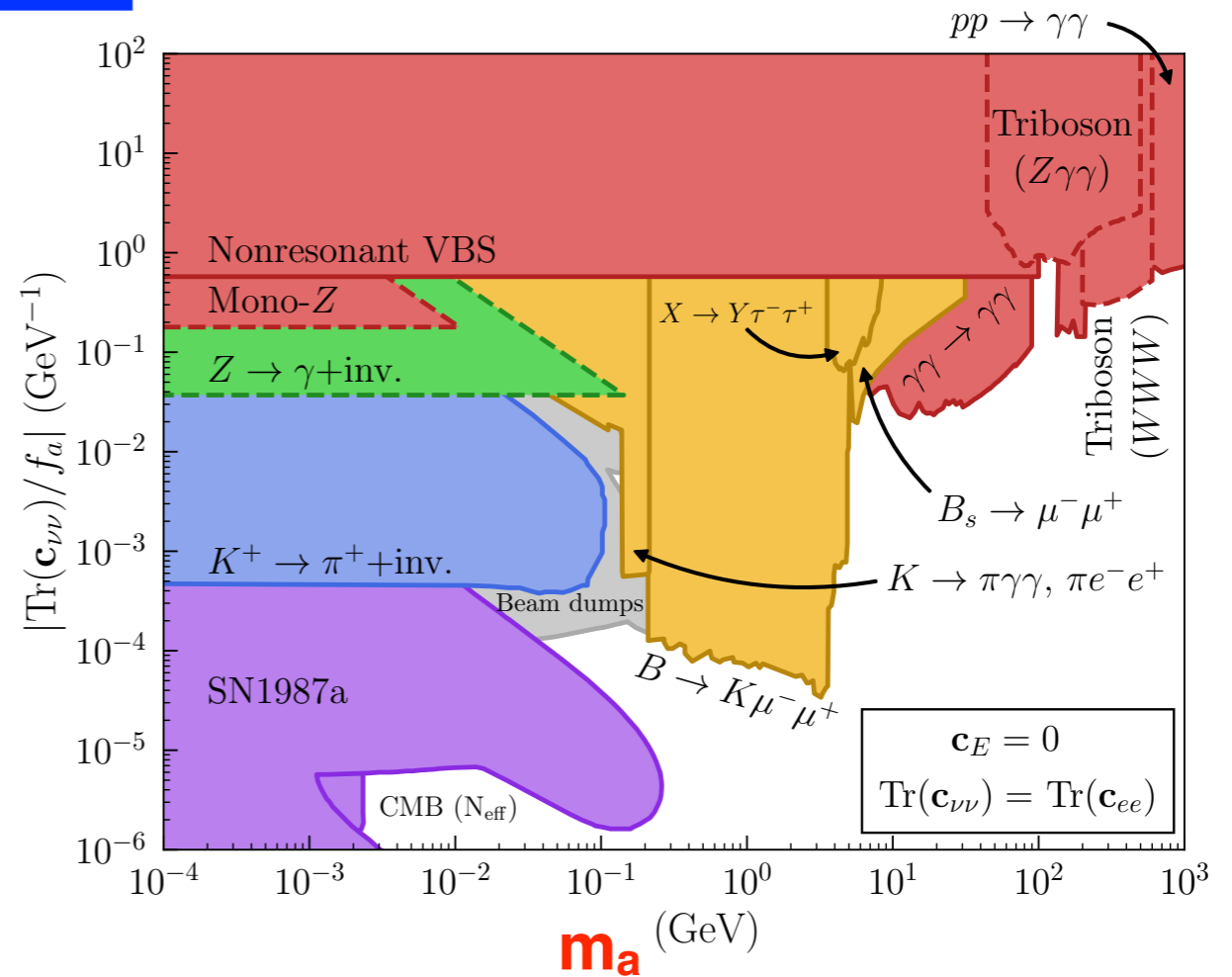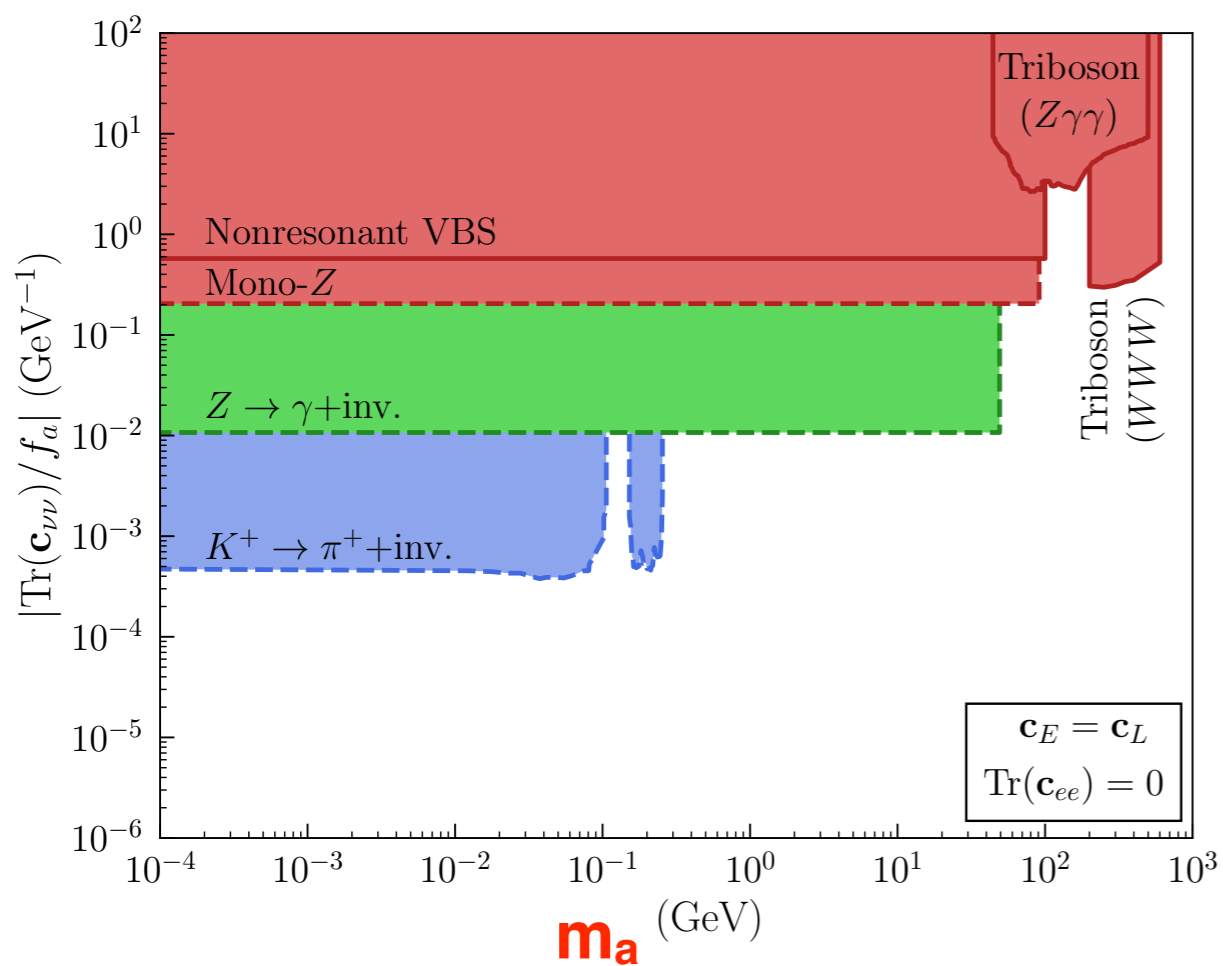
$$g_{a\gamma Z}^{\text{loop}} = \frac{\alpha_{\text{em}}}{c_w s_w \pi f_a} \left[\text{Tr}\{(\mathbf{c}_{\nu\nu})\} - 2s_w^2 \text{Tr}\{(\mathbf{c}_{ee})\} + \mathcal{O}\left(\frac{m_\ell^2}{M_Z^2}\right) \right]$$

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

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]

In "true axion" models (= which solve the strong CP problem):

$$m_a \, f_a = \text{cte.}$$
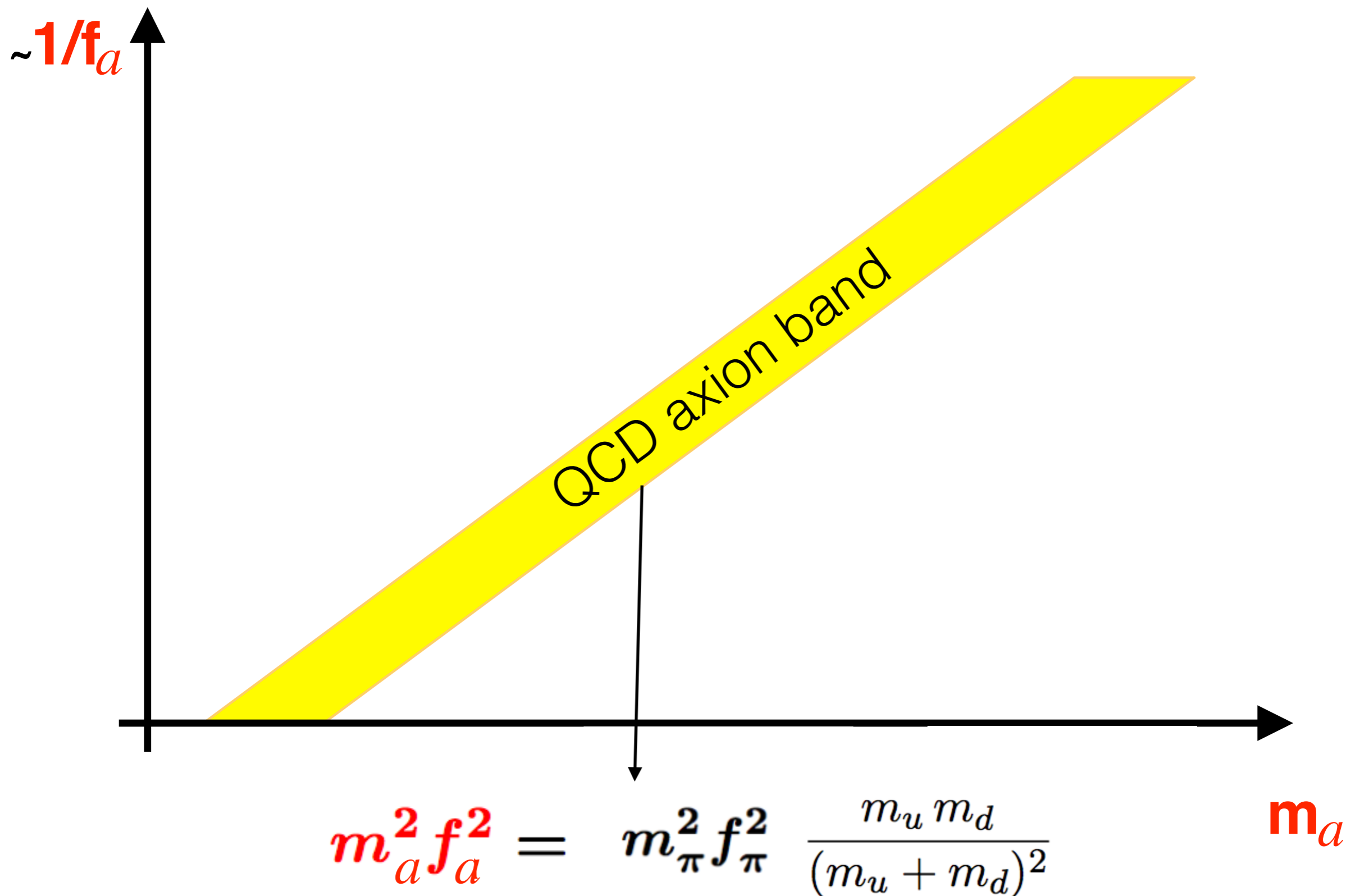
~$1/f_a$

QCD axion band

m_a

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

QCD axion band

ALP territory

and more?

$\sim 1/f_a$

m_a

~1/f_a

Difference between and ALP and a true axion:

an ALP does not intend to solve the strong CP problem

otherwise, the phenomenology is alike

m_a

ALP territory

and more?

Difference between the ALP and a true axion:

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

are independent parameters for ALPs

ALP territory

and more?

$\sim 1/f_a$
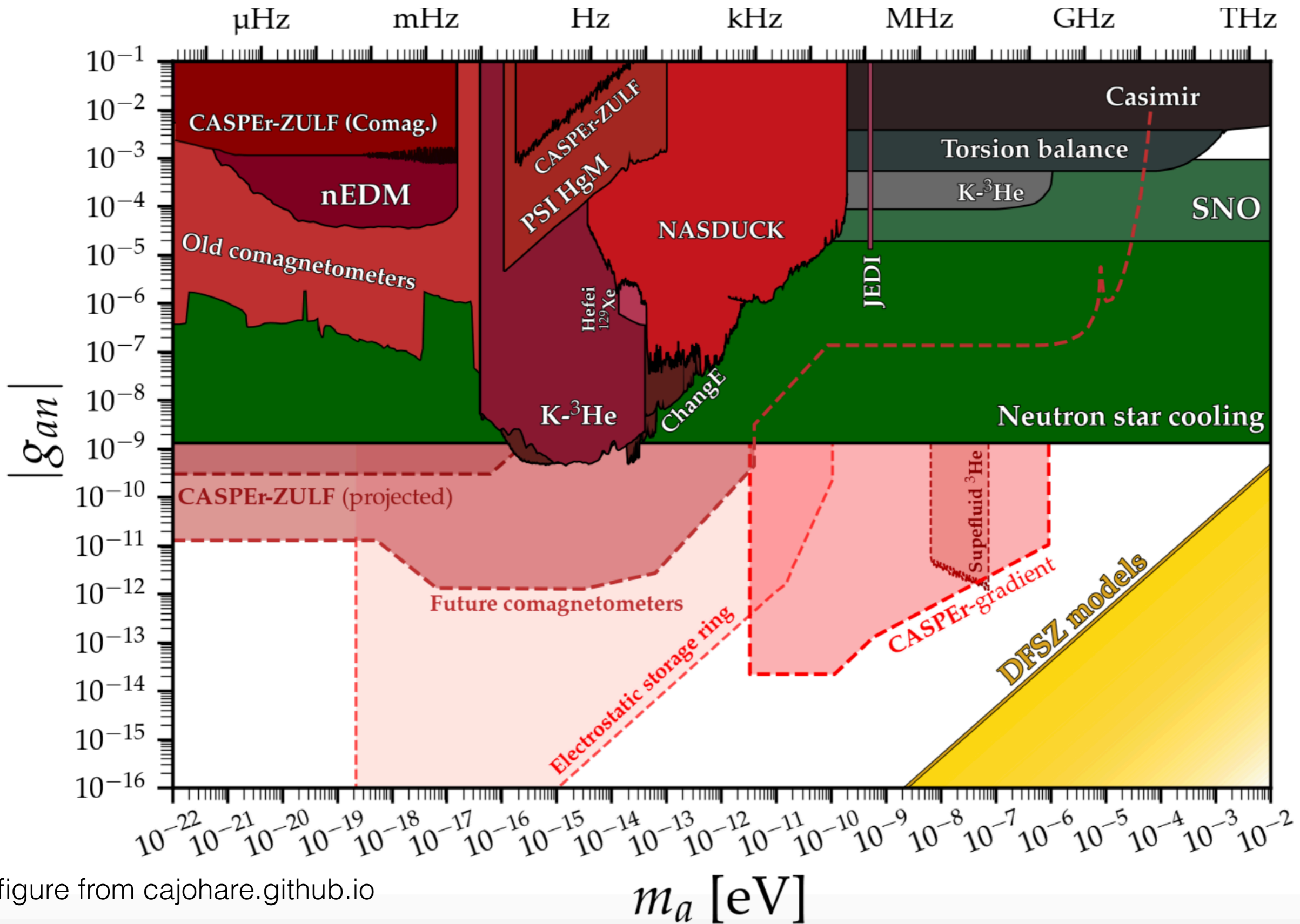
m_a

figure from cajohare.github.io

figure from cajohare.github.io
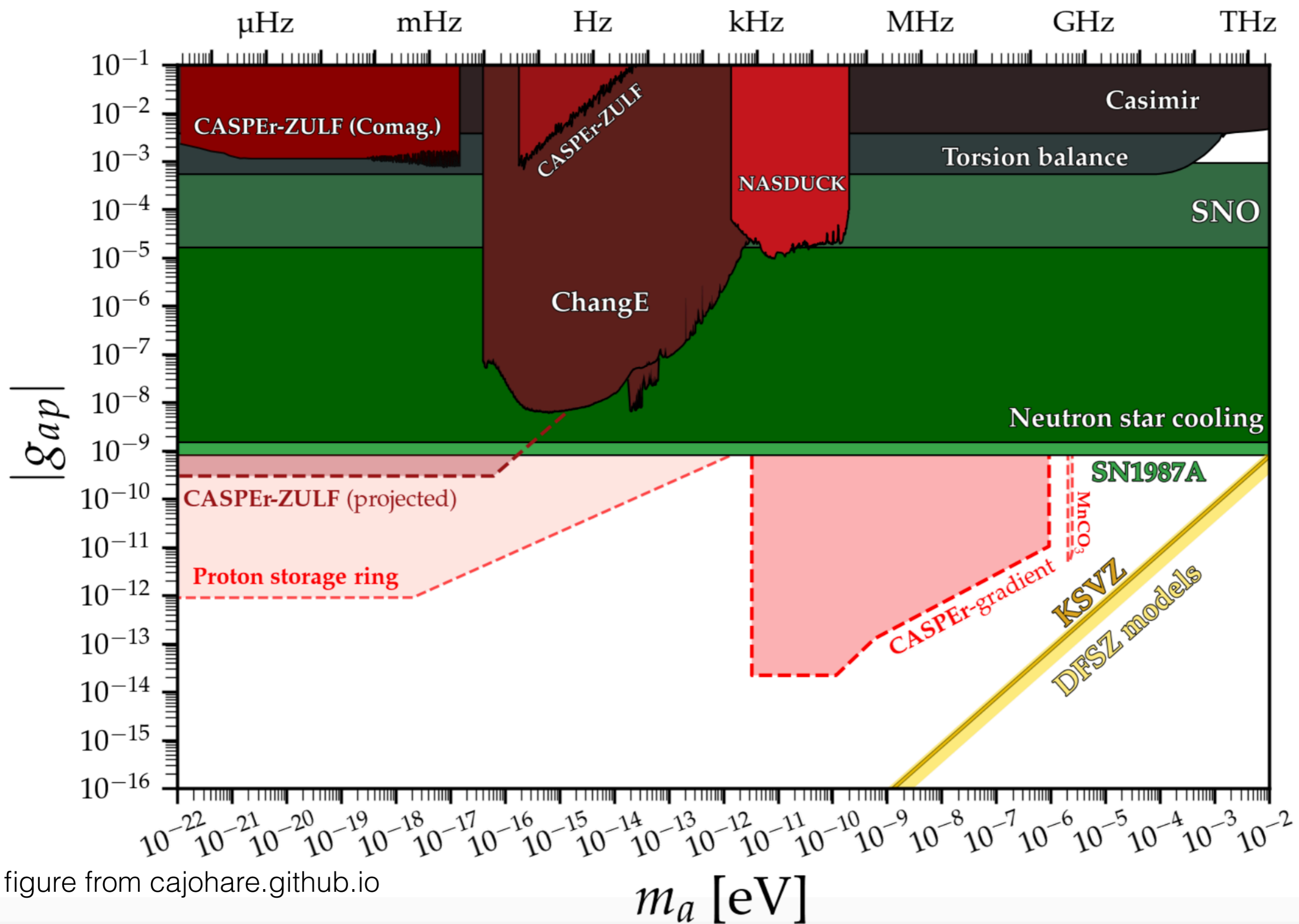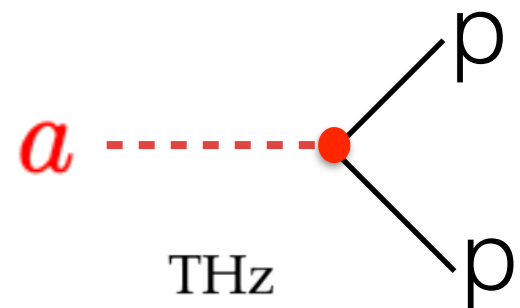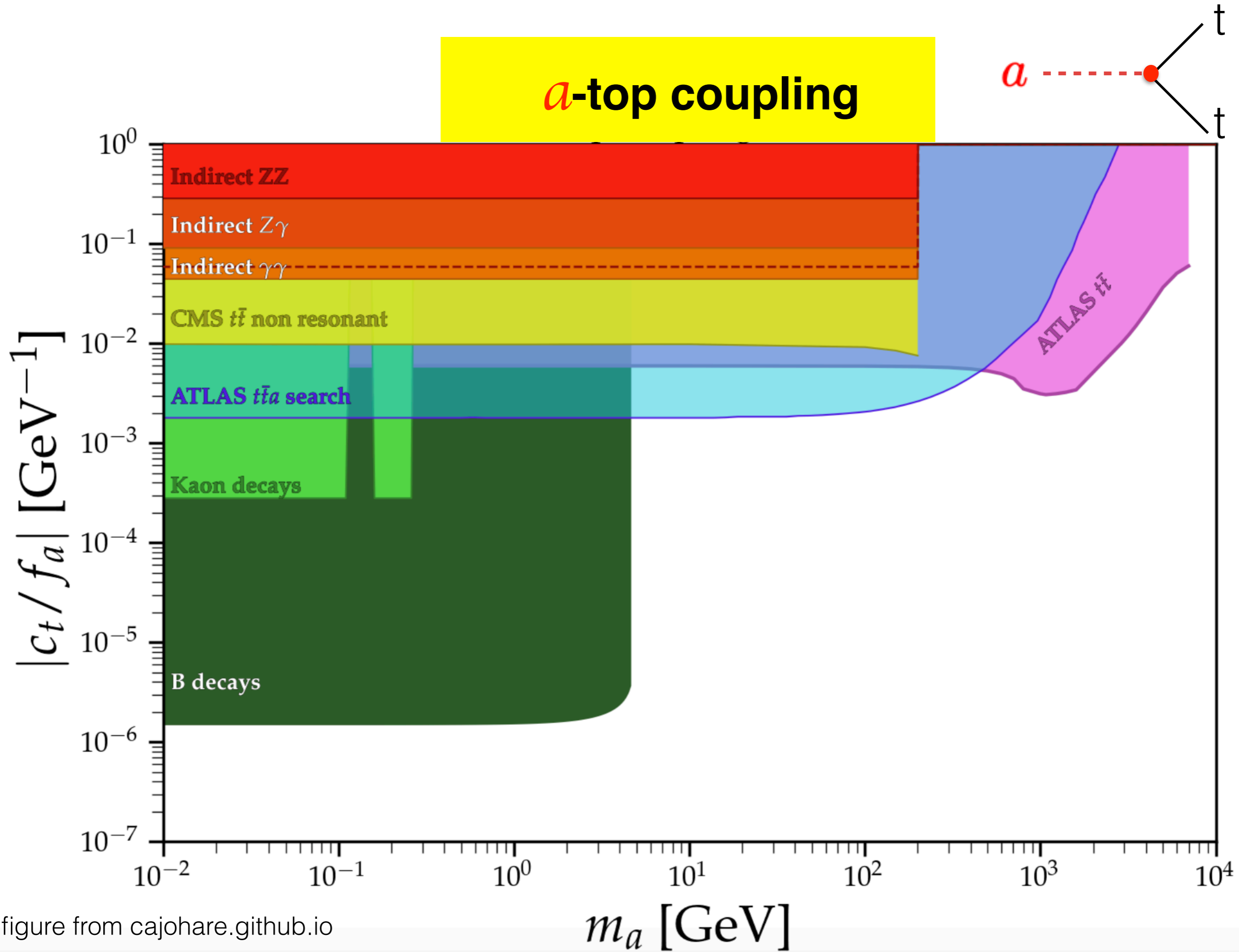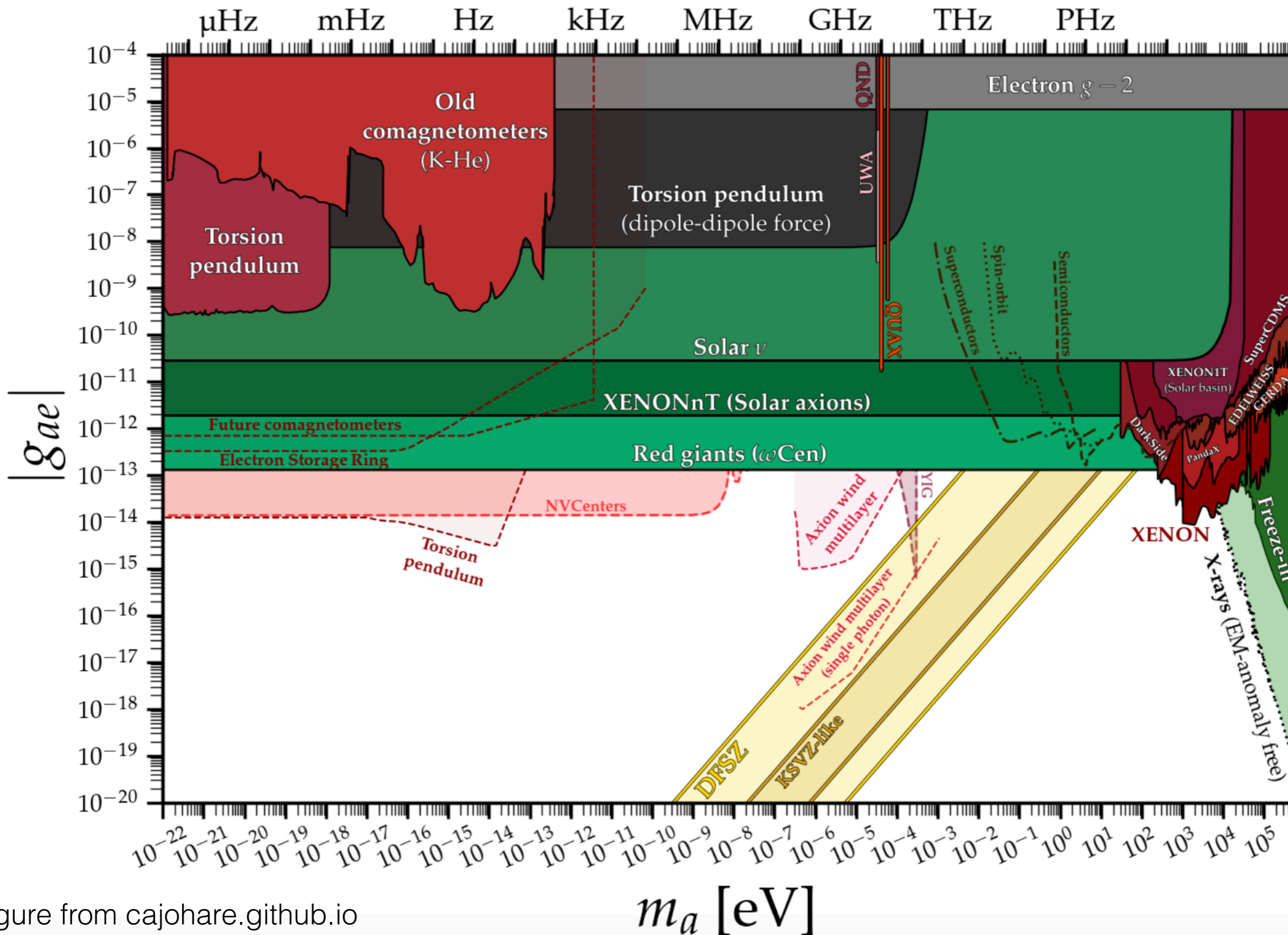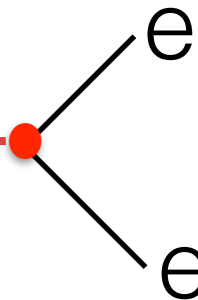
figure from cajohare.github.io

figure from cajohare.github.io

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…

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The strong CP problem

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

$$\mathcal{L}_{QCD} \supset \mathbf{\theta}\ G_{\mu\nu}\widetilde{G}^{\mu\nu}$$

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A dynamical U(1)$_A$ solution

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Peccei+Quinn; Wilczek…

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The strong CP problem

Why is the QCD θ parameter so small?

$$\mathcal{L}_{QCD} \supset \frac{a}{f_a} G_{\mu\nu}\widetilde{G}^{\mu\nu}$$

A dynamical $U(1)_A$ solution

$\rightarrow$ the axion a

Peccei+Quinn; Wilczek...

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

The nature of DM is unknown

The strong CP problem

Why is the QCD $\boldsymbol{\theta}$ parameter so small?

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It may be a (SM singlet) scalar S
the "Higgs portal"

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

A dynamical $U(1)_A$ solution

$\rightarrow$ the axion a

It is a pGB: ~ derivative couplings

$$\sim \partial_\mu a$$

S has polynomial couplings

Also excellent DM candidate

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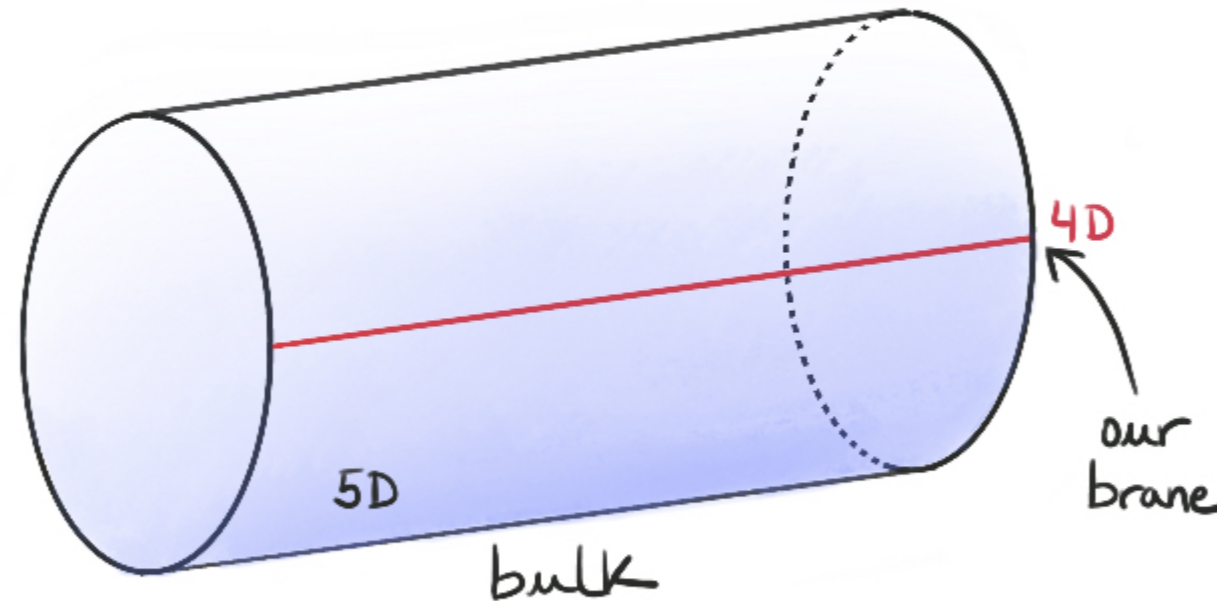
Peccei+Quinn; Wilczek…

(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)

......