How viable is a 10MeV QCD axion?

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arXiv: 2405.13425 with S. Girmohanta, Y. Nakai, & J. Xu

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1. Introduction

The strong CP problem can be solved by Peccei-Quinn (PQ) mechanism.

Peccei and Quinn (1977)

However, this is only the case that $U(1)_{\mathrm{PQ}}$ is exact.

Quality problem of $U(1)_{\mathrm{PQ}}$

- Comosite axion models e.g. Kim (1985), Choi and Kim (1985), Randall (1992)
- Warped extra dimension models e.g. Dienes, Dudas, Gherghetta (2000), Choi (2004)
- Gauge symmetry to protect $U(1)_{\mathrm{PQ}}$ e.g. Cheng and Kaplan (2001), Harigaya, Ibe, Schmitz, Yanagida (2013)
- Superconformal axion model Nakai and Suzuki (2021), **Nakagawa**, Nakai, Yamada, Zhang (2024), **Nakagawa**, Nakai, Xu, Zhang (appear soon)
- Heavy axion e.g. Rubakov (1997), Berezhiani, Gianfagna, Giannottoi (2001)

1. Introduction

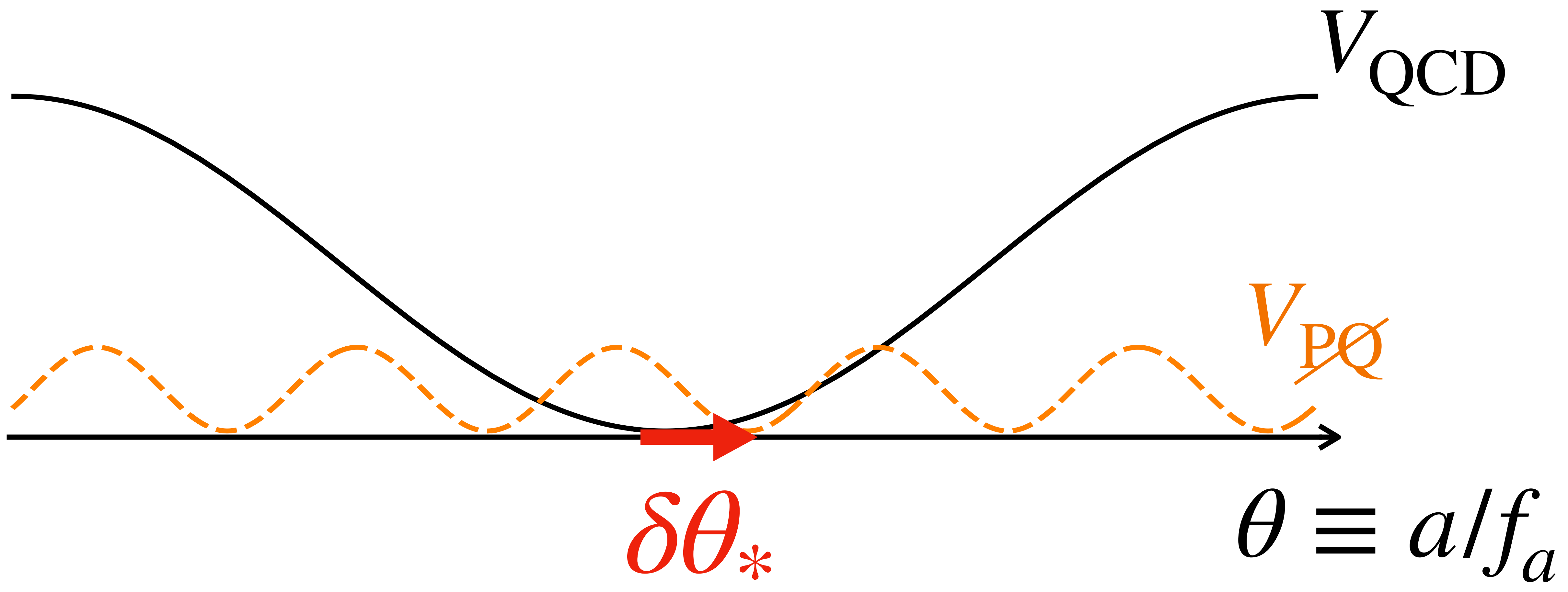
For example, explicit PQ breaking operator under Z_N

$$\mathcal{L} = c\frac{\Phi^N}{M_{\rm Pl}^{N-4}} + \text{h.c.} \quad \rightarrow \quad V_{\cancel{PQ}} = \kappa\frac{f_a^N}{M_{\rm Pl}^{N-4}}\cos\left(N\frac{a}{f_a}+\delta\right)$$

$$\delta\theta_* \sim \frac{f_a^{N-2}}{M_{\rm Pl}^{N-4}m_a^2} \propto m_a^{-N}$$

$$\sim 10^{-14}\left(\frac{m_a}{10\text{MeV}}\right)^{-5} \quad (N=5)$$

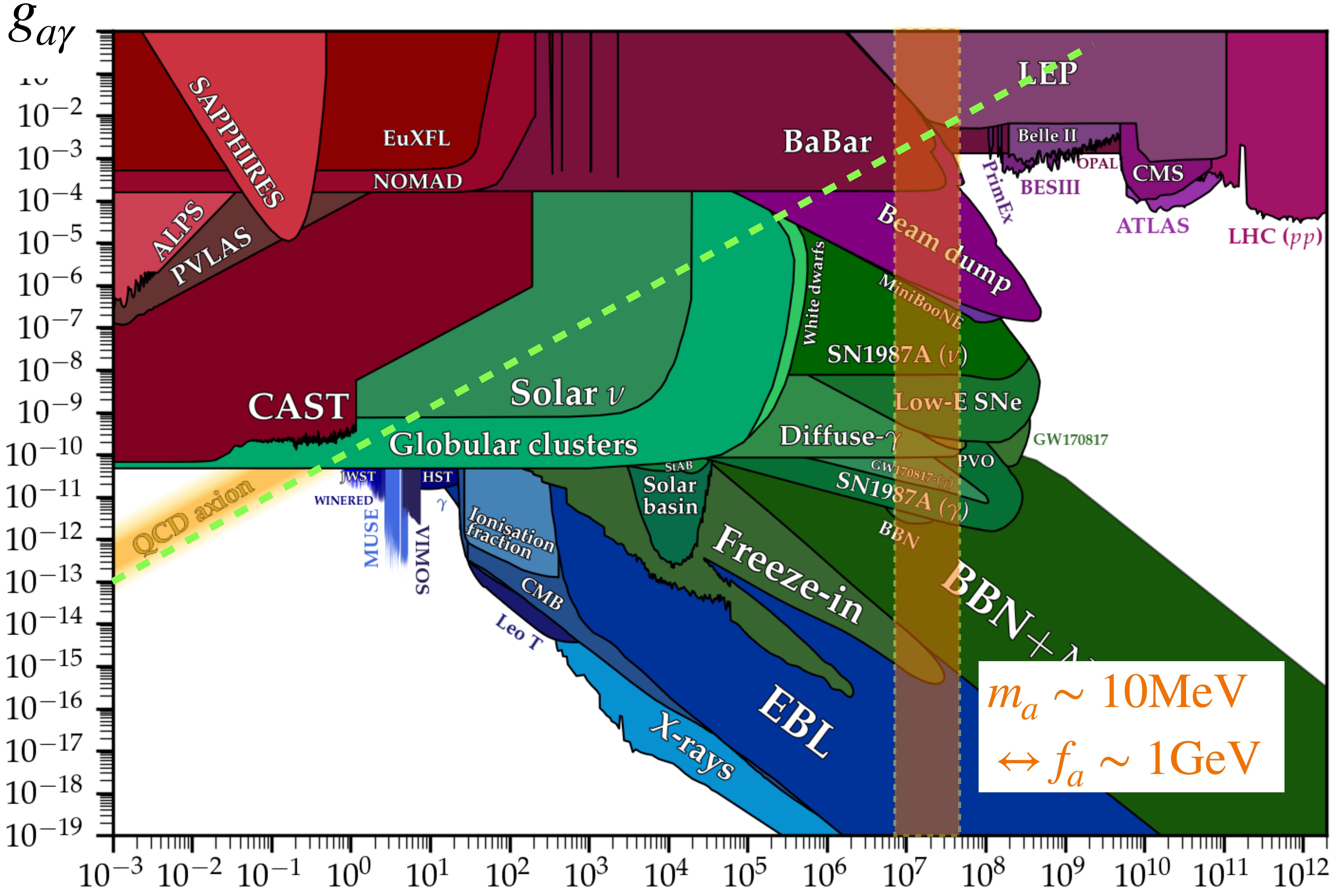
$$\ll 10^{-10}$$



It may be solved (though depending on particle contents and charges).

Severe constraints

Not allowed for conventional model



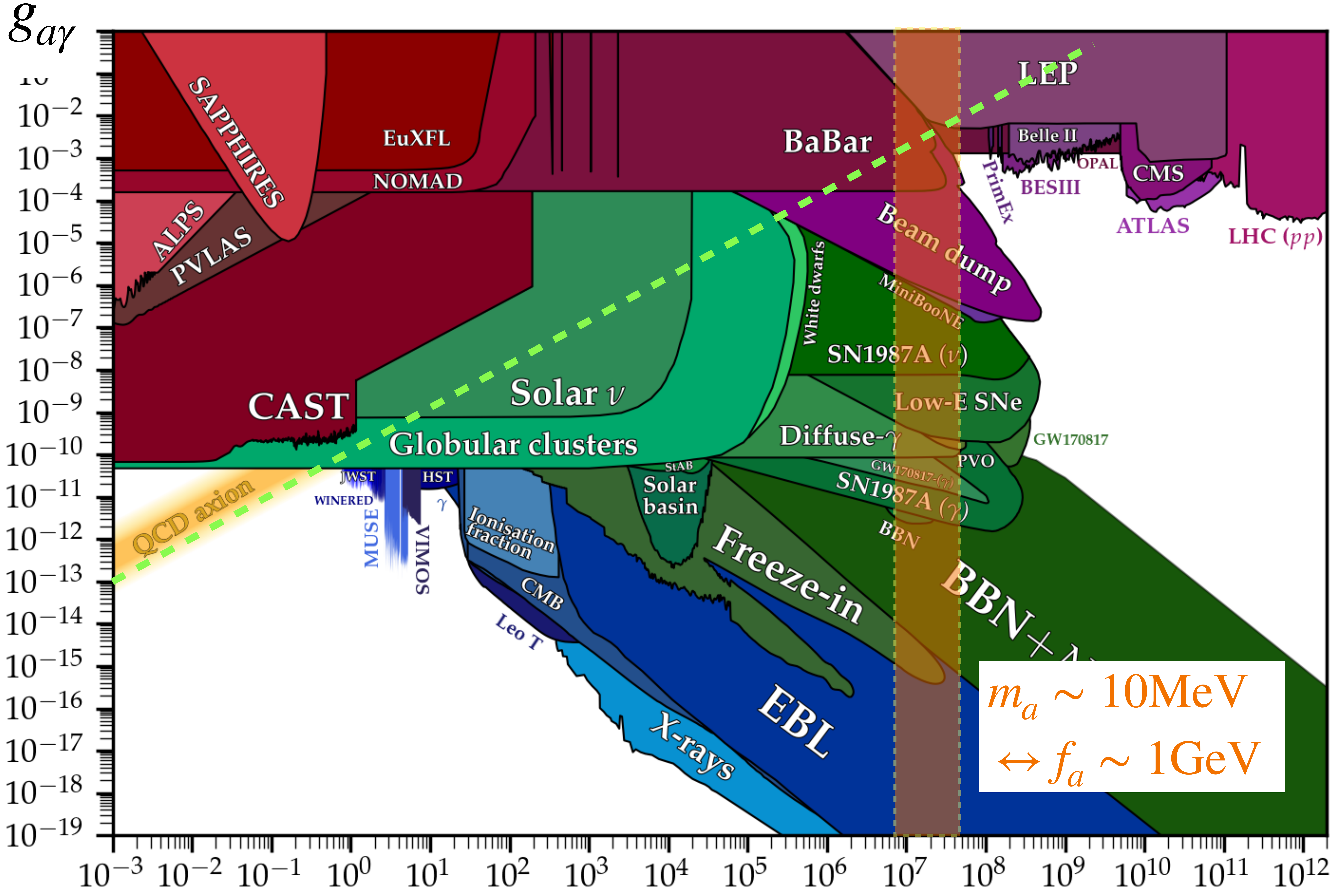
$m_a \sim 10\mathrm{MeV}$
$\leftrightarrow f_a \sim 1\mathrm{GeV}$

From AxionLimits

m_a [eV]

Severe constraints

Not allowed for conventional model

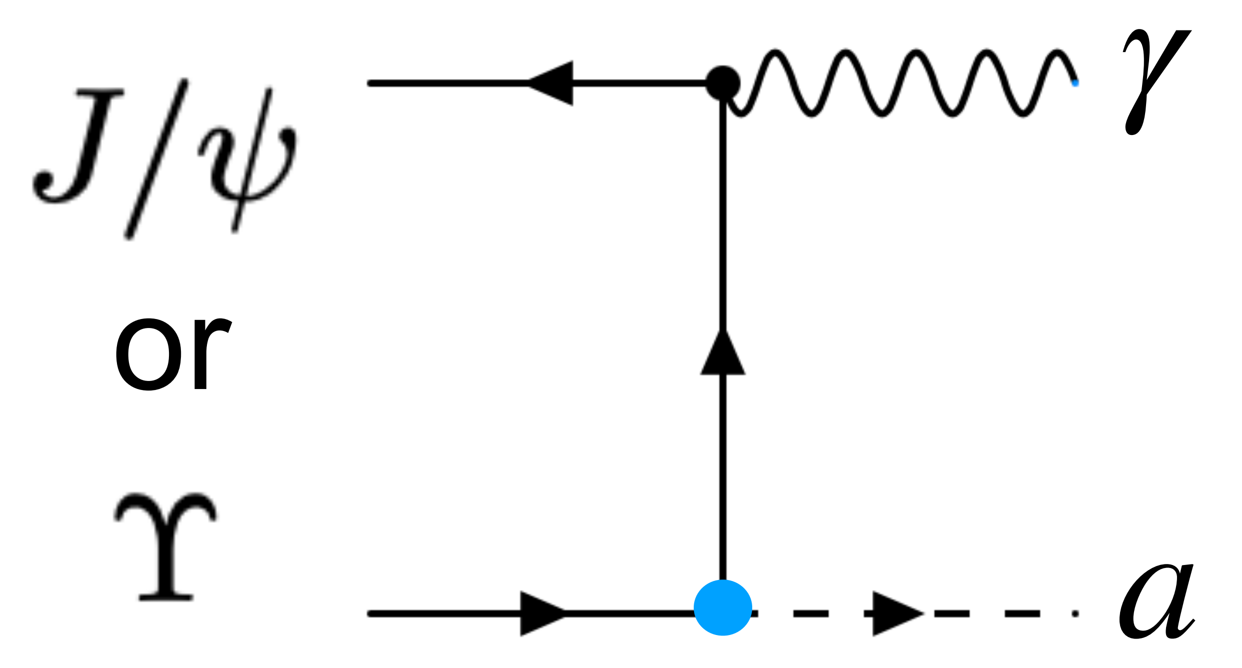


$m_a \sim 10\text{MeV}$
$\leftrightarrow f_a \sim 1\text{GeV}$

From AxionLimits

m_a [eV]

More stringently with coupling to c, b



$O(m_{b,c}/f_a) \sim 0.1 - 1$

1. Introduction

We focus on O(10)MeV QCD axion proposed by D. Alves & N. Weiner. Alves and Weiner (2018), Liu, McGinnis, Wagner, Wang (2021), Alves (2021)

How to evade experimental constraints

1. Coupling to exclusively first-generation fermions, u, d, e

J/ψ, Υ decay can be suppressed.

Beam dump bound is ignored for $\tau_{a\to ee} \lesssim 10^{-13}\mathrm{sec}$.

e.g. Blumlein, et al. (1991)

2. Pion-phobia ($|\theta_{a\pi}| \ll 1$) Krauss & Nash (1988)

Induced pion decay must be suppressed. $\pi^+ \to e^+\nu_e(a \to e^+e^-)$

$|\theta_{a\pi}| \lesssim (0.5 - 0.7) \times 10^{-4}$ SINDRUM collaboration (1986)

What we did

We study this O(10)MeV axion from the following two viewpoints:

(i) PQ quality and cosmology

Domain wall problem $\because\ f_a \sim 1\mathrm{GeV}$

→ Low-scale inflation

(ii) Phenomenology

- Electron electric dipole moment (EDM)
- B decay induced from gluon loop

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1. Introduction
2. Model of O(10)MeV axion
3. Quality and cosmology
4. Electron EDM
5. $B \to Ka$ induced from gluon loop

2. Model of O(10)MeV axion

The following model is considered.

Alves and Weiner (2018), Liu, McGinnis, Wagner, Wang (2021)

	H	H_u	H_d	H_e	Φ_u	Φ_d	Φ_e
$SU(2)_L$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$U(1)_Y$	$1/2$	$-1/2$	$1/2$	$1/2$	0	0	0
$U(1)_{\rm PQ}$	0	$-Q_u$	$-Q_d$	$-Q_e$	$-Q_u$	$-Q_d$	$-Q_e$

Q_u, Q_d, Q_e

for u_R, d_R, e_R

No lower bound on $|\theta_{a\pi}|$

$$\boxed{\frac{Q_u}{Q_d} = 2} \Rightarrow \theta_{a\pi} \sim \frac{4Q_d}{3}\left(\frac{1}{2} - \frac{m_u}{m_d}\right)\frac{f_\pi}{f_a} \sim \frac{(1.3 \underline{\pm 3.5}) \times 10^{-3}}{f_a/\mathrm{GeV}}$$

$\because \theta_{a\pi} \propto Q_u/Q_d - m_d/m_u$

where $m_u/m_d = 0.474 \pm 0.029,\ Q_d = 1$

2. Model of O(10)MeV axion

Fixing the charges as follows: $Q_u = 2, \quad Q_d = 1, \quad Q_e = \frac{1}{n}$ $\quad n = 2{,}3$

Yukawa terms

$$\mathcal{L}^{Y}_{\mathrm{PQ}} = -\sum_{i=1,2,3} \left(\bar{Q}^i Y_u^{i1} H_u \underline{u_R^1} + \bar{Q}^i Y_d^{i1} H_d \underline{d_R^1} + \bar{L}^i Y_e^{i1} H_e \underline{e_R^1}\right) + \mathrm{h.c.}$$

$$\mathcal{L}^{Y}_{\mathrm{SM}} = -\sum_{i=1,2,3}\sum_{j=2,3} \left(\bar{Q}^i Y_u^{ij} \tilde{H} u_R^j + \bar{Q}^i Y_d^{ij} H d_R^j + \bar{L}^i Y_e^{ij} H e_R^j\right) + \mathrm{h.c.}$$

Potential terms

$$V_{\mathrm{PQ}} = \left(A_1 H H_u \Phi_u^* + A_2 H H_d^\dagger \Phi_d + A_3 H_e H^\dagger \Phi_e^* + A_4 \Phi_u^* \Phi_d^2 + A_5 \Phi_d^* \Phi_e^n\right) + \mathrm{h.c.}$$

$$V_{\mathrm{dia}} = \sum_{\Psi} -\mu_\Psi \Psi^\dagger \Psi + \lambda_\Psi (\Psi^\dagger \Psi)^2$$

$\Psi = H, H_u, H_d, H_e, \Phi_u, \Phi_d, \Phi_e$

2. Model of O(10)MeV axion

EW and PQ are spontaneously broken by VEV of Higgses,

$$\langle H\rangle = v_{\mathrm{EW}} \quad \langle H_f\rangle = v_f \quad \langle \Phi_f\rangle = v_{\Phi_f} \qquad f = u, d, e$$

The axion is a linear combination of pseudo-scalars.

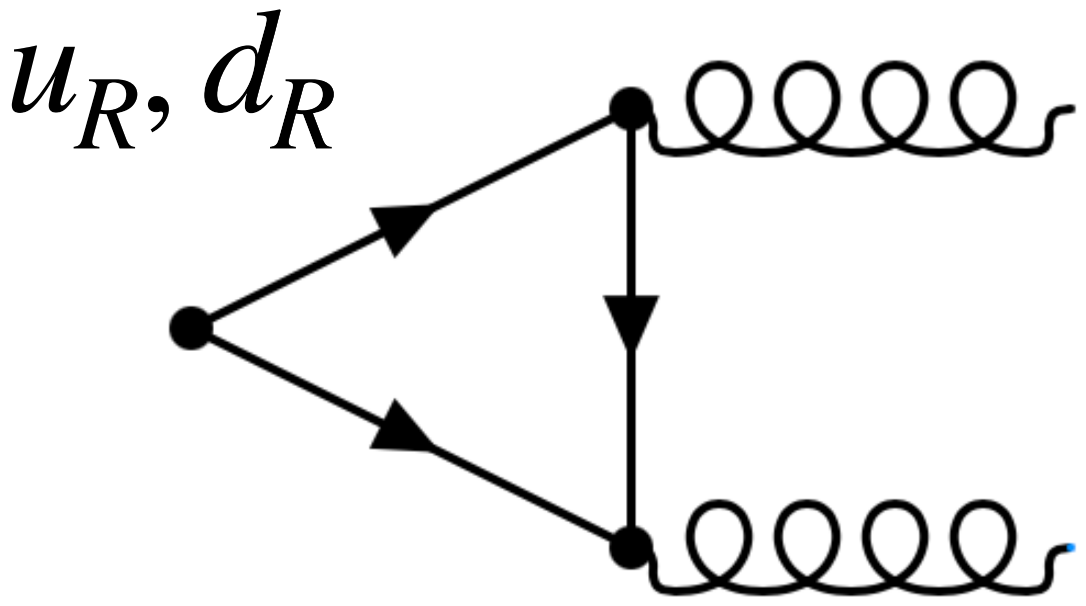
All other modes are heavy enough by taking the parameters as follows:

$$\boxed{\begin{aligned} &A_4 \gg A_{k(=1,2,3)} \simeq 20\ \mathrm{GeV}, \\ &v_{f(=u,d,e)} \simeq 20\ \mathrm{MeV}, \quad v_{\Phi_{f(=u,d,e)}} \simeq 1\ \mathrm{GeV}. \end{aligned}}$$

$$v_a \equiv \sqrt{\textstyle\sum_f Q_f^2 (v_f^2 + v_{\Phi_f}^2)}$$

$$\longrightarrow v_a \sim 1\mathrm{GeV}$$

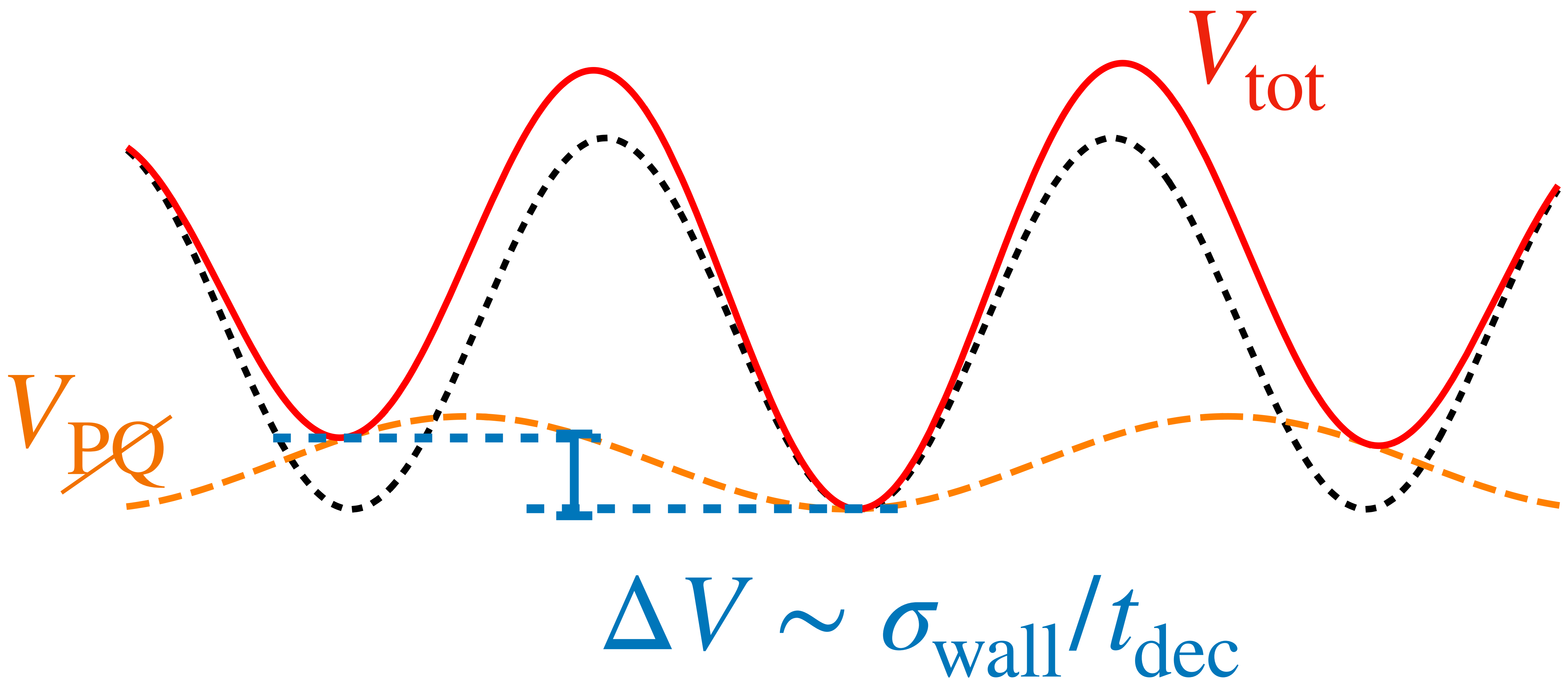
3. Quality & cosmology



$$N_{\mathrm{DW}} = Q_u + Q_d = 3$$

→ Stable domain wall (DW) network

PQ breaking operators can break the DW.



ΔV is inconsistent with $\delta\theta_*$ for usual QCD axion.

Quality-DW tension

Ringwald & Saikawa (2016)

3. Quality & cosmology

The most dangerous PQ breaking operators are given by

$$\mathcal{L}_{\cancel{\mathrm{PQ}}} = \sum_{f=u,d,e} \left(g_1 \frac{(HH^\dagger)^2 \Phi_f}{M_{\mathrm{Pl}}} + g_2 \frac{HH^\dagger \Phi_f^3}{M_{\mathrm{Pl}}} + g_3 \frac{\Phi_f^5}{M_{\mathrm{Pl}}} + \cdots \right) + \mathrm{h.c.}$$

$$\boxed{\begin{aligned} & A_4 \gg A_{k(=1,2,3)} \simeq 20~\mathrm{GeV}, \\ & v_{f(=u,d,e)} \simeq 20~\mathrm{MeV}, \quad v_{\Phi_{f(=u,d,e)}} \simeq 1~\mathrm{GeV}. \end{aligned}}$$

$$\langle H \rangle = v_{\mathrm{EW}}$$

3. Quality & cosmology

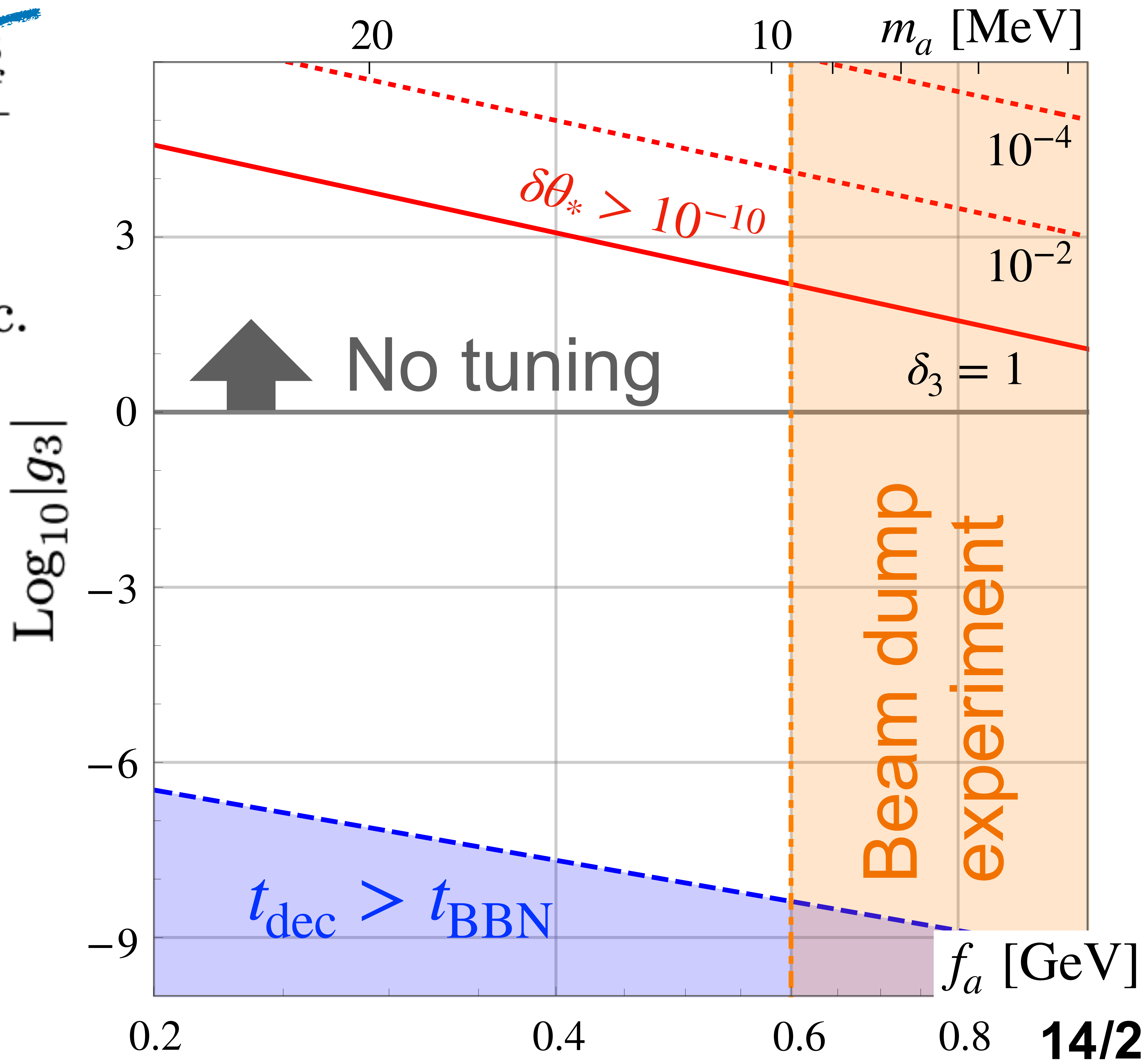
Fixing $n = 2$

$$\mathcal{L}_{\cancel{\rm PQ}} = \sum_{f=u,d,e}\left(\cancel{g_1\frac{(HH^\dagger)^2\Phi_f}{M_{\rm Pl}} + g_2\frac{HH^\dagger\Phi_f^3}{M_{\rm Pl}}}\right.$$

$$\left. + \, g_3\frac{\Phi_f^5}{M_{\rm Pl}} + \cdots\right) + \text{h.c.}$$

$$\to V \propto \cos\left(\alpha\frac{a}{f_a} + \delta_i\right)$$

- $U(1)_{\rm PQ}$ is high-quality.
- Quality-DW tension can be also solved.

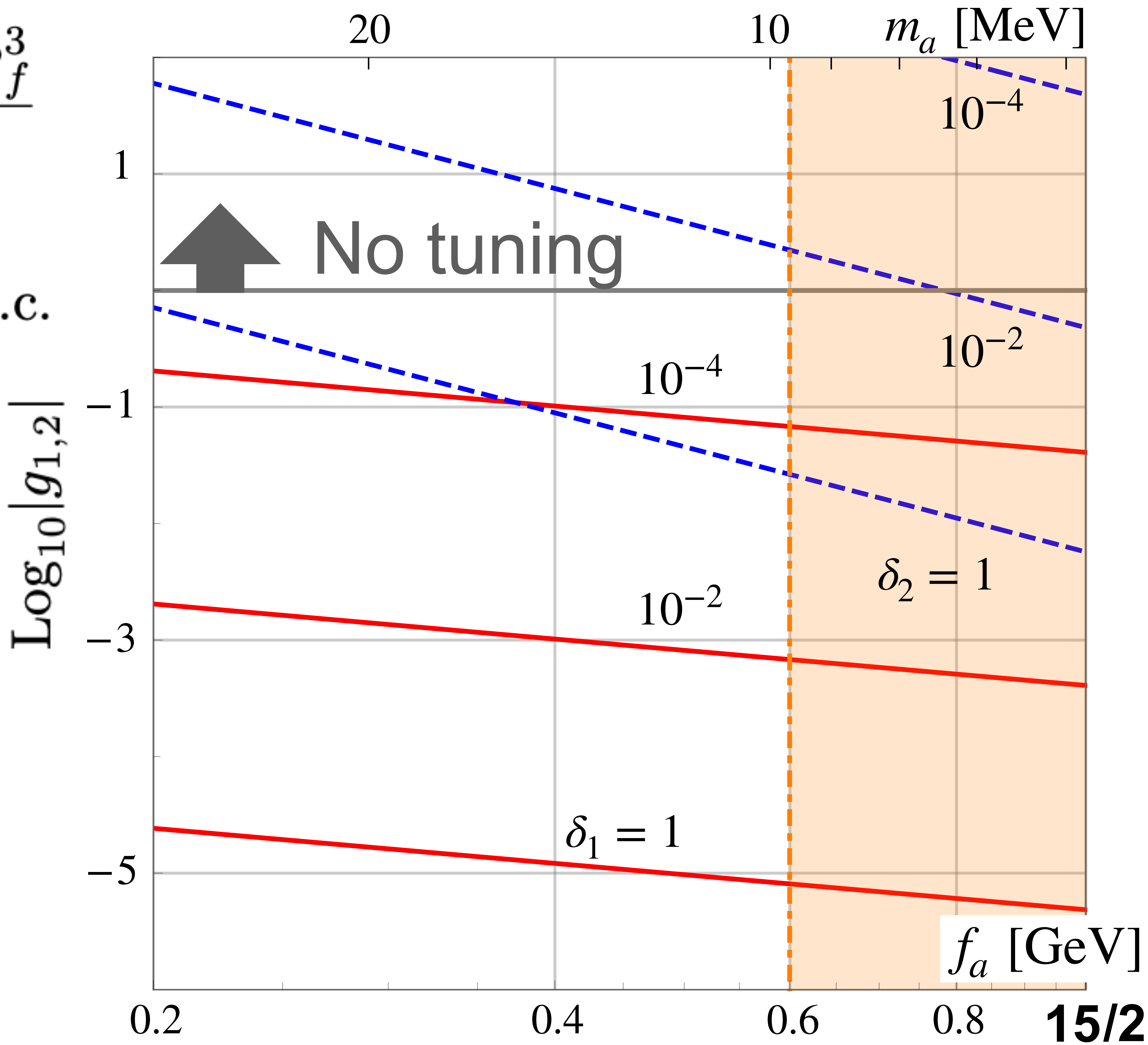


3. Quality & cosmology

Fixing $n = 2$

$$\mathcal{L}_{\cancel{\mathrm{PQ}}} = \sum_{f=u,d,e}\left(g_1\frac{(HH^\dagger)^2\Phi_f}{M_{\mathrm{Pl}}} + g_2\frac{HH^\dagger\Phi_f^3}{M_{\mathrm{Pl}}} + g_3\,\frac{\Phi_f^5}{M_{\mathrm{Pl}}} + \cdots\right) + \mathrm{h.c.}$$

$$\rightarrow V \propto \cos\left(\alpha\frac{a}{f_a} + \delta_i\right)$$



- Quality-DW tension can be still solved.
- Some suppression is required for high quality.

4. Electron EDM

The model includes the seven-Higgs model.

→ too large electron EDM?

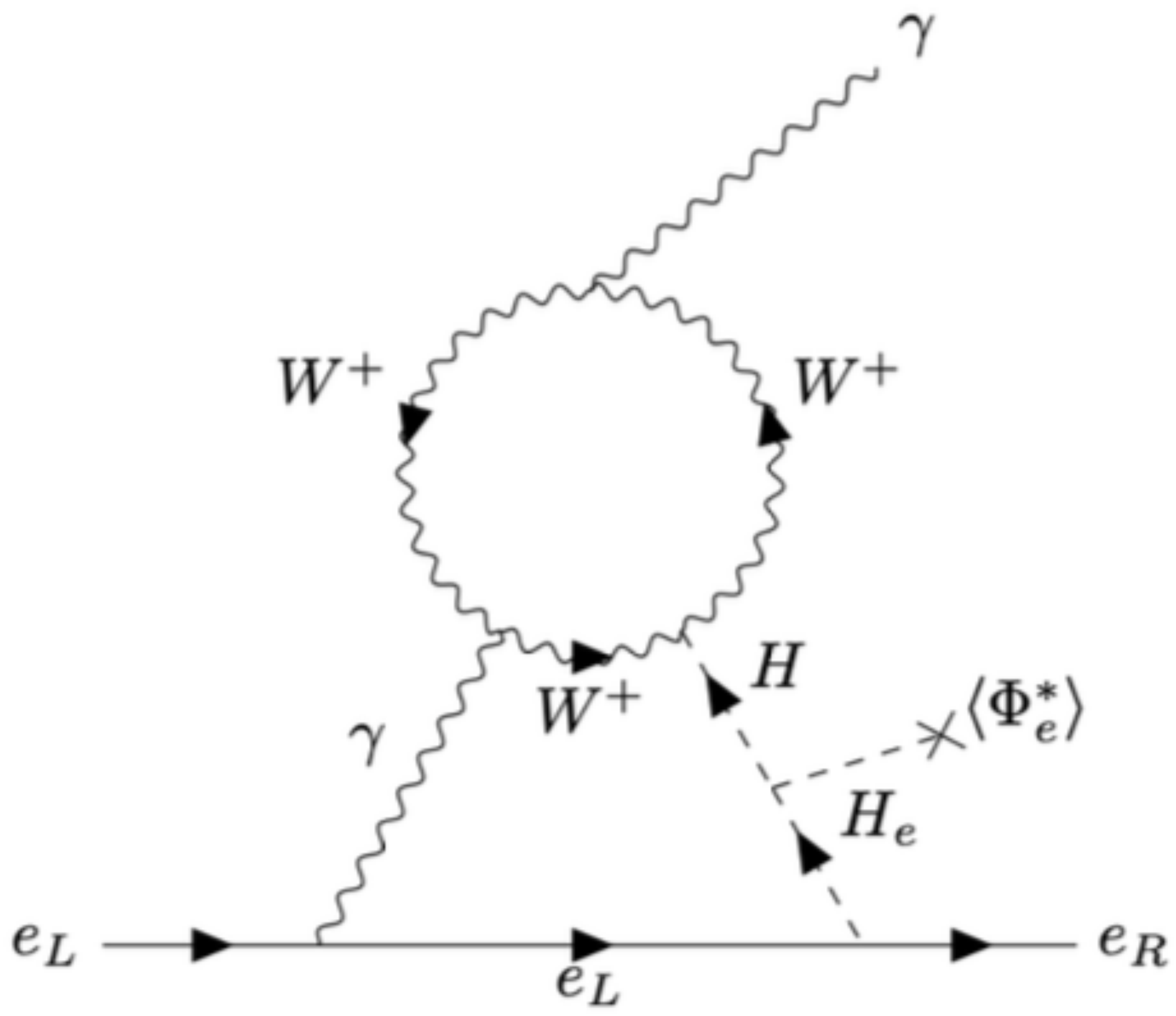
Extra PQ symmetric terms is as follows:

So many!

$$\begin{aligned} V^{(n=2)}_{\text{scalar}} &= A_1 H H_u \Phi_u^* + A_2 H H_d^\dagger \Phi_d + A_3 H_e H^\dagger \Phi_e^* + A_4 \Phi_u^* \Phi_d^2 + A_5 \Phi_d^* \Phi_e^2 + A_6 H_d H_e^\dagger \Phi_e^* \\ &+ B_1 H H_u \Phi_d^{*2} + B_2 H H_d^\dagger \Phi_u \Phi_d^* + B_3 H H_d^\dagger \Phi_e^2 + B_4 H^\dagger H_e \Phi_d^* \Phi_e + B_5 H_u H_e \Phi_u^* \Phi_e^* + B_6 H_u H_d \Phi_u^* \Phi_d^* \\ &+ B_7 H_d^\dagger H_e \Phi_d \Phi_e^* + B_8 \Phi_u \Phi_d^* \Phi_e^{*2} + B_9 H_e^2 H^\dagger H_d^\dagger + \text{h.c.}\,, \end{aligned}$$

$$\begin{aligned} V^{(n=3)}_{\text{scalar}} &= A_1 H H_u \Phi_u^* + A_2 H H_d^\dagger \Phi_d + A_3 H_e H^\dagger \Phi_e^* + A_4 \Phi_u^* \Phi_d^2 + A_5' \Phi_d^* \Phi_e^3 + B_1 H H_u \Phi_d^{*2} \\ &+ B_2 H H_d^\dagger \Phi_u \Phi_d^* + B_5 H_u H_e \Phi_u^* \Phi_e^* + B_6 H_u H_d \Phi_u^* \Phi_d^* + B_7 H_d^\dagger H_e \Phi_d \Phi_e^* + B_{10} H_d H_e^\dagger \Phi_e^{*2} + \text{h.c.} \end{aligned}$$

4. Electron EDM



Barr-Zee type diagram

Barr & Zee (1990)

$$\frac{d_e}{e} \sim \frac{\alpha_e \zeta}{(4\pi)^3}\sqrt{2} G_F m_e \left(3f\left(\frac{m_W^2}{m_H^2}\right) + 5g\left(\frac{m_W^2}{m_H^2}\right)\right)$$

$$\times \left|\frac{A_3 v_{\Phi_e}^*}{2\sqrt{2}M^2}\right| \left(\sin^2\beta \tan\beta\right) ,$$

Nakai & Reece (2017)

$$d_e^{(\mathrm{exp})} \leq 4.1 \times 10^{-30} e\mathrm{cm}$$ Roussy, et al. (2023)

$\to M \gtrsim 8\mathrm{TeV}$ for $\zeta \sim 1$

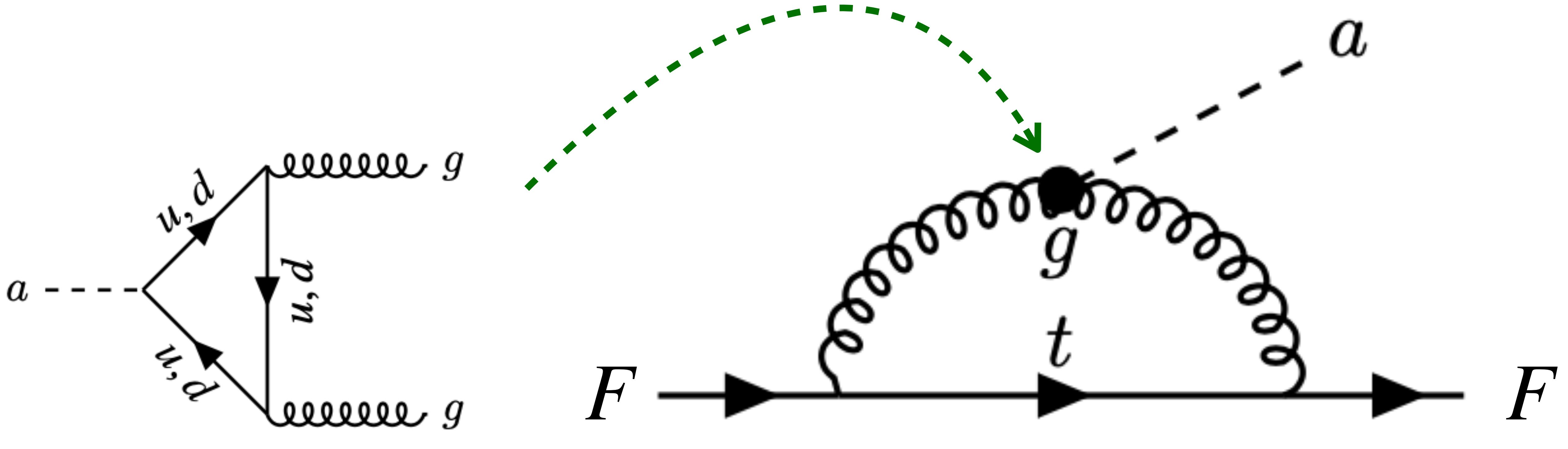
Typical scale of $M \sim O(100)\mathrm{GeV}$

Fine tuning is necessarily required.

5. $B \to Ka$ induced from gluon loop

We have no interaction with 2nd & 3rd generation fermions at the tree-level. (c, s, t, b)

However, gluon loops induce such couplings.

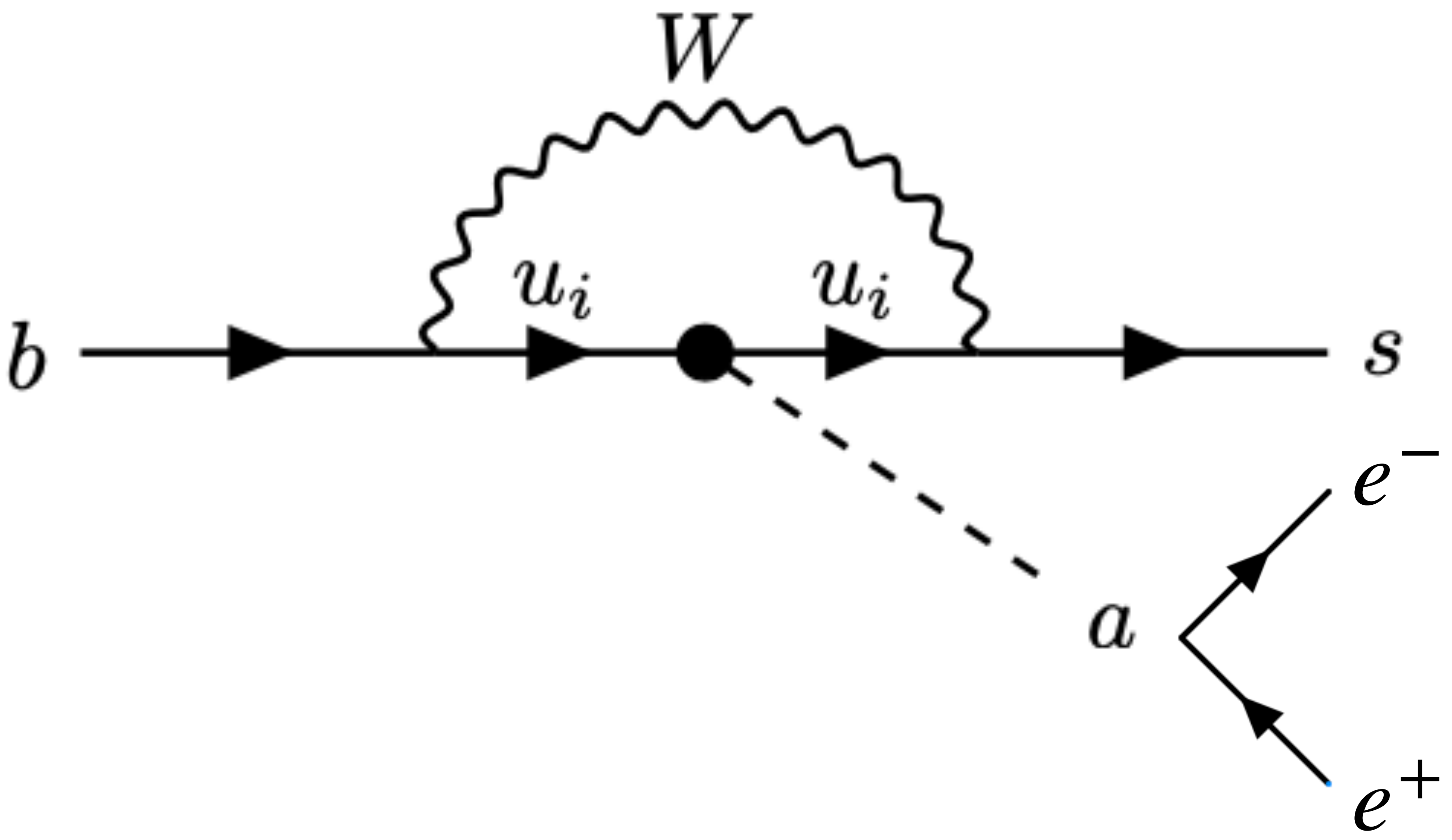


$F = c, s, t, b$

$$\mathcal{L}_{aFF} = Q^{\rm PQ}_{F,\rm eff}\frac{m_F}{v_a} a\bar{F} i\gamma_5 F$$

$$Q^{\rm PQ}_{F,\rm eff} \simeq \frac{4}{3}\left(\frac{\alpha_s}{4\pi}\right)^2$$

5. $B \to Ka$ induced from gluon loop



$$\mathcal{L}_{bsa} = -i g_{bsa} \bar{s}_L b_R a + \text{h.c.}$$

$$g_{bsa} = \frac{G_F m_W^2}{4\sqrt{2}\pi^2} \frac{m_b}{v_a} \sum_{u_i=u,c,t} Q^{\text{PQ}}_{u_i,\text{eff}} \frac{m_{u_i}^2}{m_W^2} V^*_{u_i s} V_{u_i b} \ln\left(\frac{\Lambda_{\text{UV}}^2}{m_{u_i}^2}\right)$$

Batell, Pospelov, & Ritz (2011)

$$\frac{\mathcal{B}^{\text{BSM}}(B^0 \to K^{*0} a(\to e^+ e^-))}{\mathcal{B}^{\text{SM}}(B^0 \to K^{*0} e^+ e^-)} \simeq 10^3 \ln\left(\frac{\Lambda_{\text{UV}}}{m_t}\right)^2$$ for $m_a = 10\text{MeV}$.

The LHCb result has excluded the range of $m_a \gtrsim 30\text{MeV}$.

Aaij, et al. [LHCb] (2013)

Summary

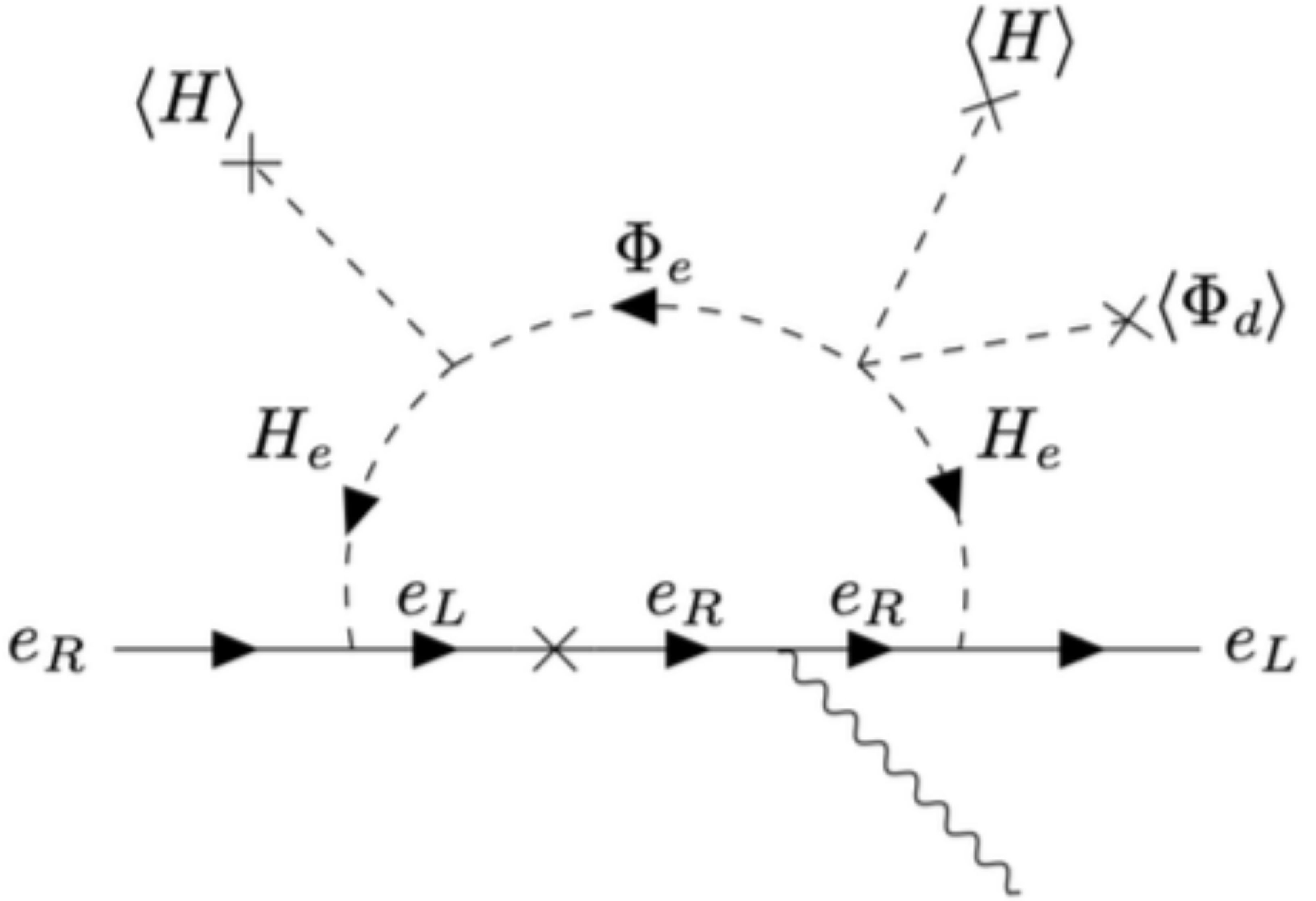
The model is not excluded, but we found new bounds.

	Constraints	Summary comments
Quality/cosmology	$\lvert g_{1,2}\rvert \lesssim 10^{-5}$	Quality-DW tension can be solved, but we still need fine tuning for PQ breaking.
eEDM	$\lvert\zeta\rvert \lesssim 10^{-8}$	The bound on mass of light scalar modes requires the tuning of CP violating phases.
B→K decay	$m_a \lesssim 30\mathrm{MeV}$	LHCb and Belle II can probe the lighter mass range, which may determine the fate of this 10MeV model.

Thanks a lot!

Back Up

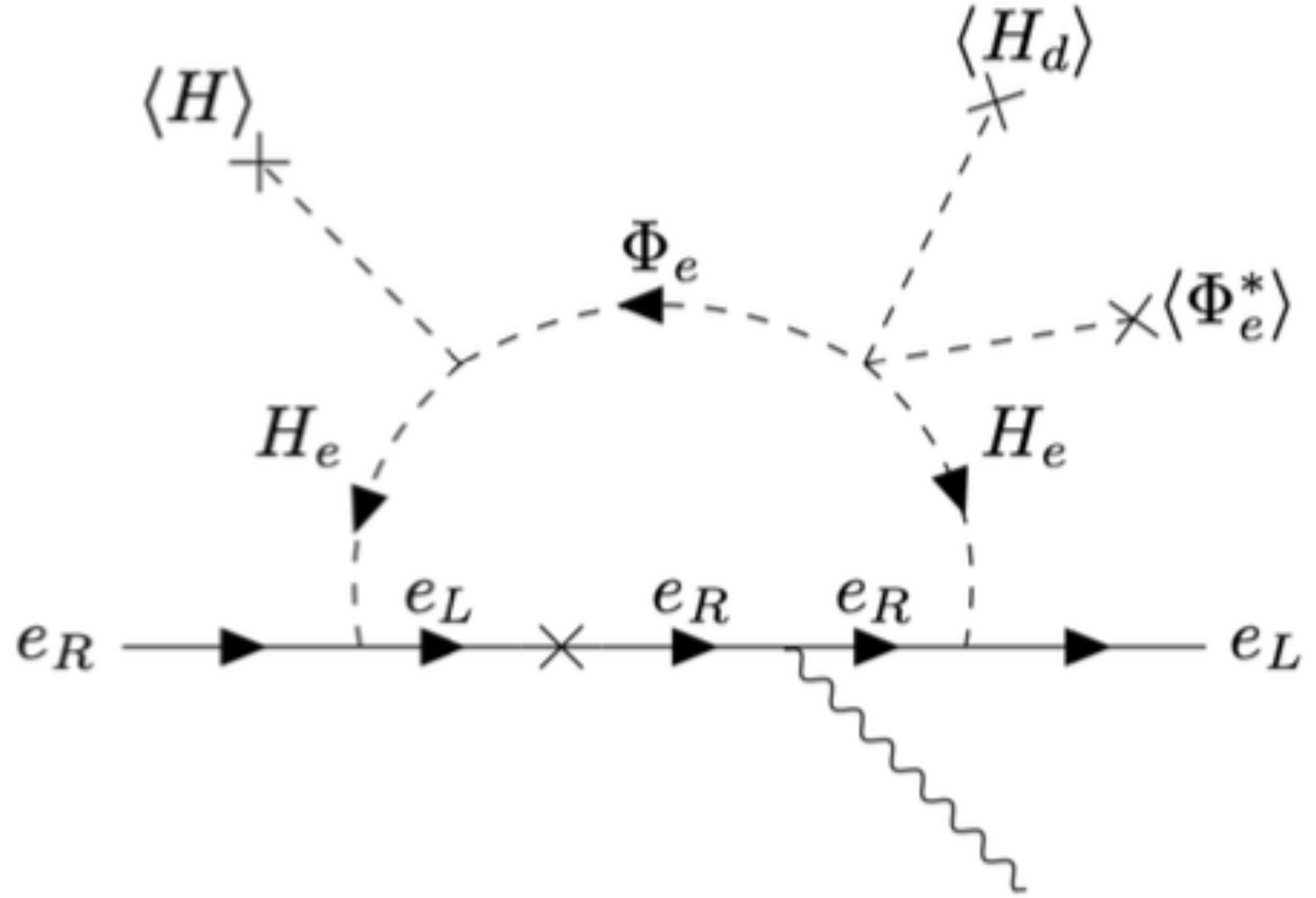
One loop contribution



For $n = 2$,

$$\frac{d_e}{e} \sim \frac{\theta}{16\pi^2}|A_3^* B_4^* v^2 v_{\Phi_d}|\frac{m_e}{M^6} \rightarrow M \gtrsim 500\mathrm{GeV}$$

Marginally consistent



For $n = 3$,

$$\frac{d_e}{e} \sim \frac{\delta}{16\pi^2}|A_3^* B_{10} v v_d v_{\Phi_e}^*|\frac{m_e}{M^6}, \rightarrow M \gtrsim 100\mathrm{GeV}$$

Tuning is required, because one pseudoscalar is O(1)GeV.

Leading order chiral PT

Alves & Weiner (2018)

$$\mathcal{L}_{\chi}^{(0)} = \frac{f_\pi^2}{4}\,\mathrm{Tr}\left[2BM_q(a)\,U + \mathrm{h.c.}\right] - \frac{1}{2}M_0^2\eta_0^2$$

$$M_q(a) \equiv \begin{pmatrix} m_u\, e^{iQ_u a/f_a} & & \\ & m_d\, e^{iQ_d\, a/f_a} & \\ & & m_s \end{pmatrix}$$

$U:\ \ SU(3)_{\mathrm{chiral}}$ nonet

Note: The second order perturbation and UV correction may contribute.

Axion-meson mixing

$$\theta_{a\pi}^{(0)} = -\frac{1}{(1+\epsilon_{\eta\eta'})}\left(\frac{(Q_u m_u - Q_d m_d)}{(m_u+m_d)} + \epsilon_{\eta\eta'}\frac{(Q_u - Q_d)}{2}\right)\frac{f_\pi}{f_a}$$

$$\theta_{a\eta_0}^{(0)} = -\sqrt{6}\,(Q_u+Q_d)^{-1}\,\frac{f_a}{f_\pi}\,\frac{m_a^2}{M_0^2}$$

$$\theta_{a\eta_8}^{(0)} = -\sqrt{\frac{3}{2}}\,\frac{\epsilon_{\eta\eta'}}{(1+\epsilon_{\eta\eta'})}\,(Q_u+Q_d)\,\frac{f_\pi}{f_a}$$

Charged Kaon decay

$K^+ \to \pi^+ a$ is unreliable for judging the model. Alves & Weiner (2018)

1. The conventional bound was not estimated properly.
2. The uncertainty from chiral PT for branching ratio

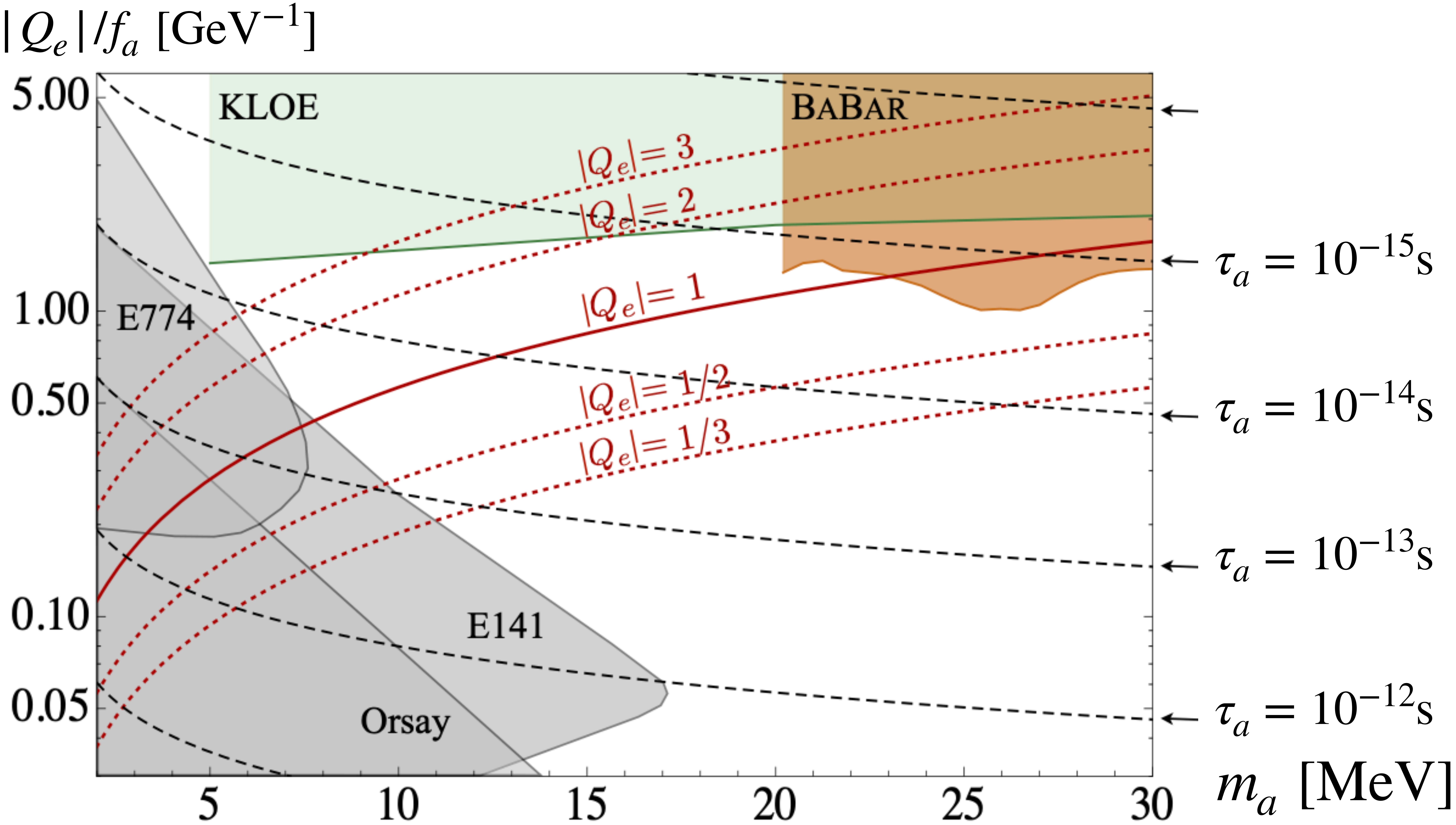
$$\mathcal{M}(K^+ \to \pi^+ a)\big|_{a-\eta_{8,0}\ \mathrm{mixing}} = \theta_{a\eta_8}\, \mathcal{M}(K^+ \to \pi^+ \eta_8) + \theta_{a\eta_0}\, \mathcal{M}(K^+ \to \pi^+ \eta_0),$$

As long as pion-phobia, pion mixing doesn't give a large contribution.

$\mathrm{Br}(K^+ \to \pi^+ a)$ Depending on chiral PT order

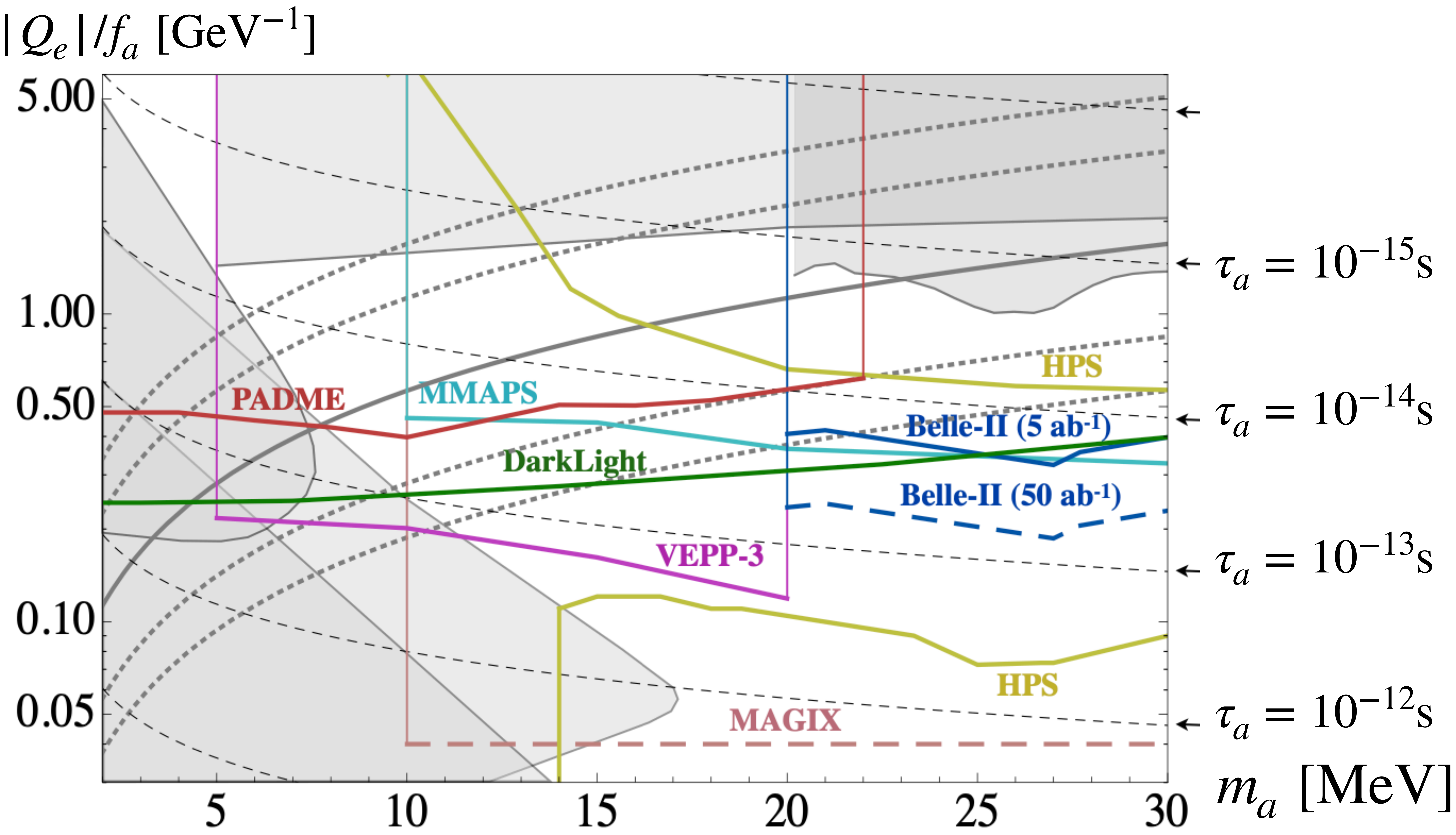
3. The uncertainty from chiral PT for eta-axion mixing

Beam dump & ee collision



Alves & Weiner (2018)

Future prospects for DP bounds



Alves & Weiner (2018)

$(g-2)_e$

$$g_{ae} = \frac{Q_e m_e}{f_a} \simeq \frac{Q_e}{Q_d} \frac{m_e}{\text{GeV}}$$

$$\boxed{\frac{Q_e}{Q_d} = 0.28 - 2.}$$

$$\rightarrow n = \frac{1}{2}, 1, 2, 3$$