CP-violating axions

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Luca Di Luzio

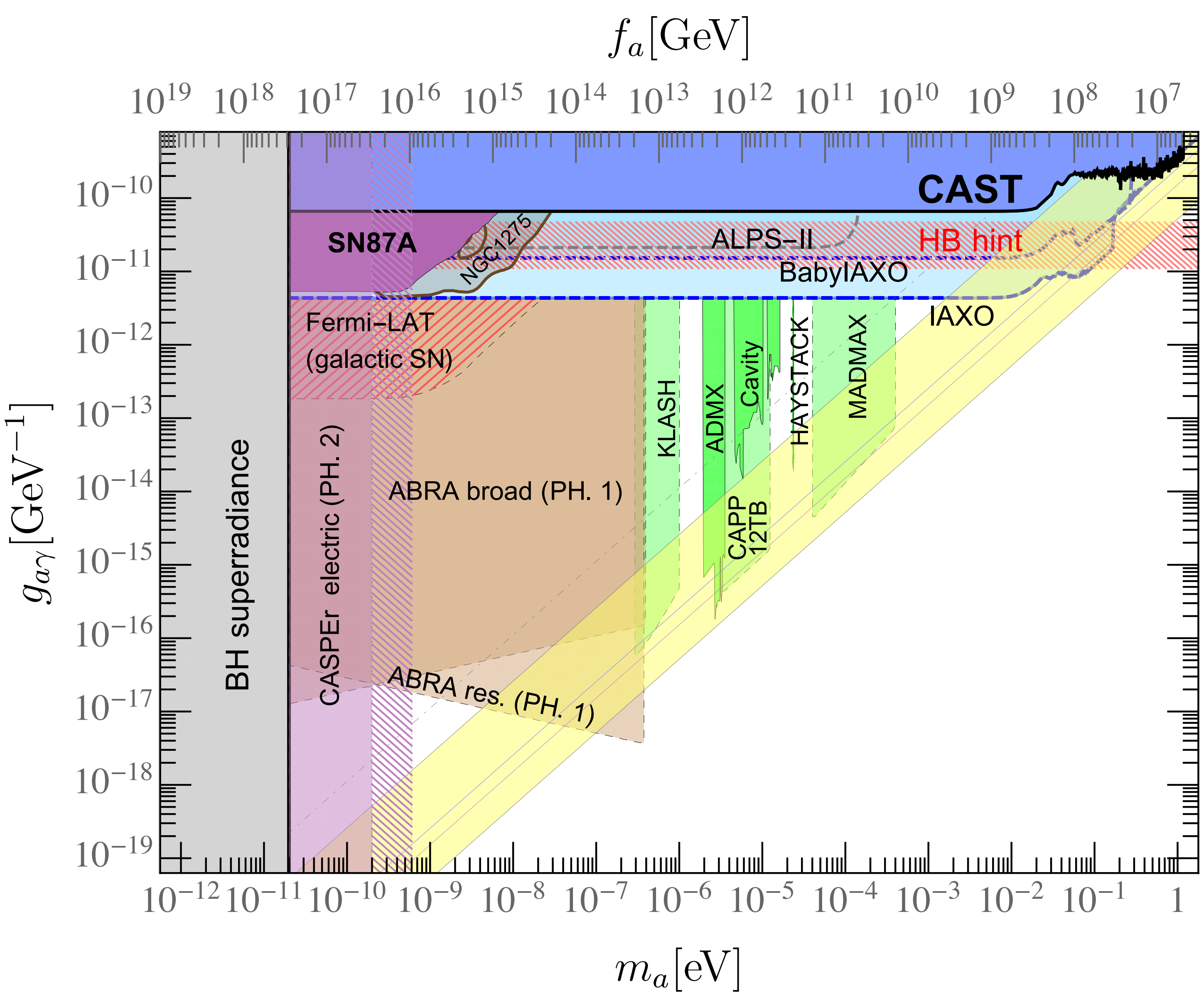
1222·2022 800 ANNI

Università degli Studi di Padova

Dipartimento di Fisica e Astronomia "Galileo Galilei"

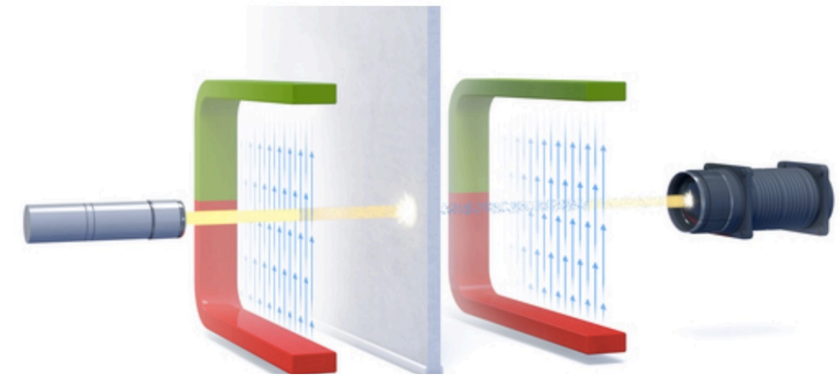
INFN Padova

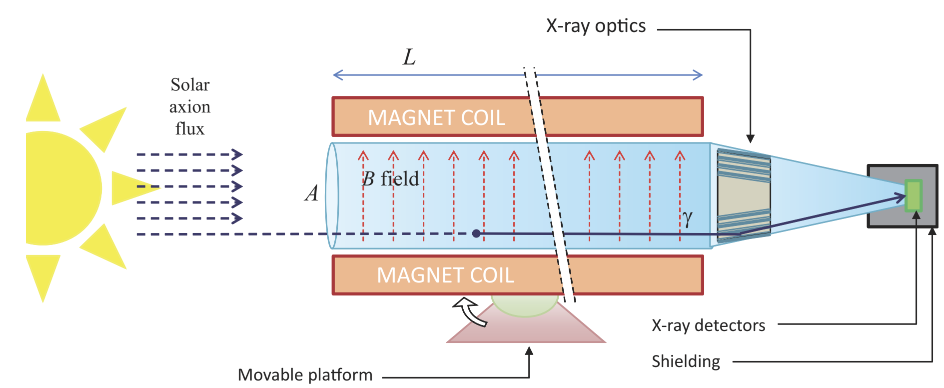
In 10 years from now ?

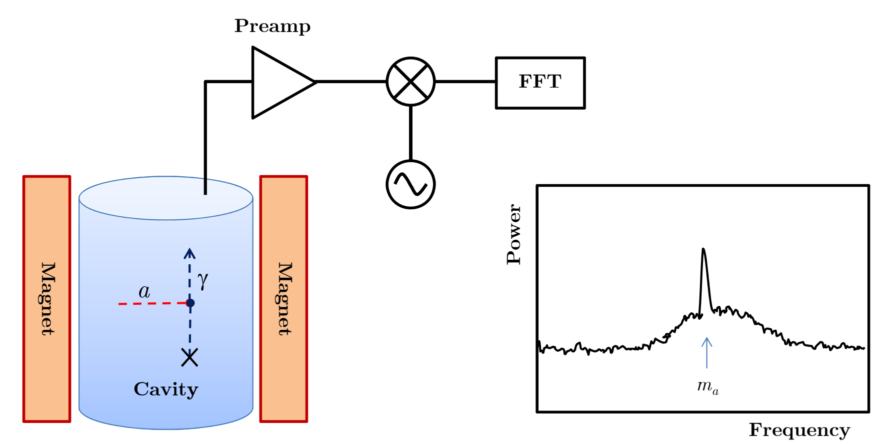


[LDL, Giannotti, Nardi, Visinelli 2003.01100 (Physics Reports)]

✤ An experimental opportunity







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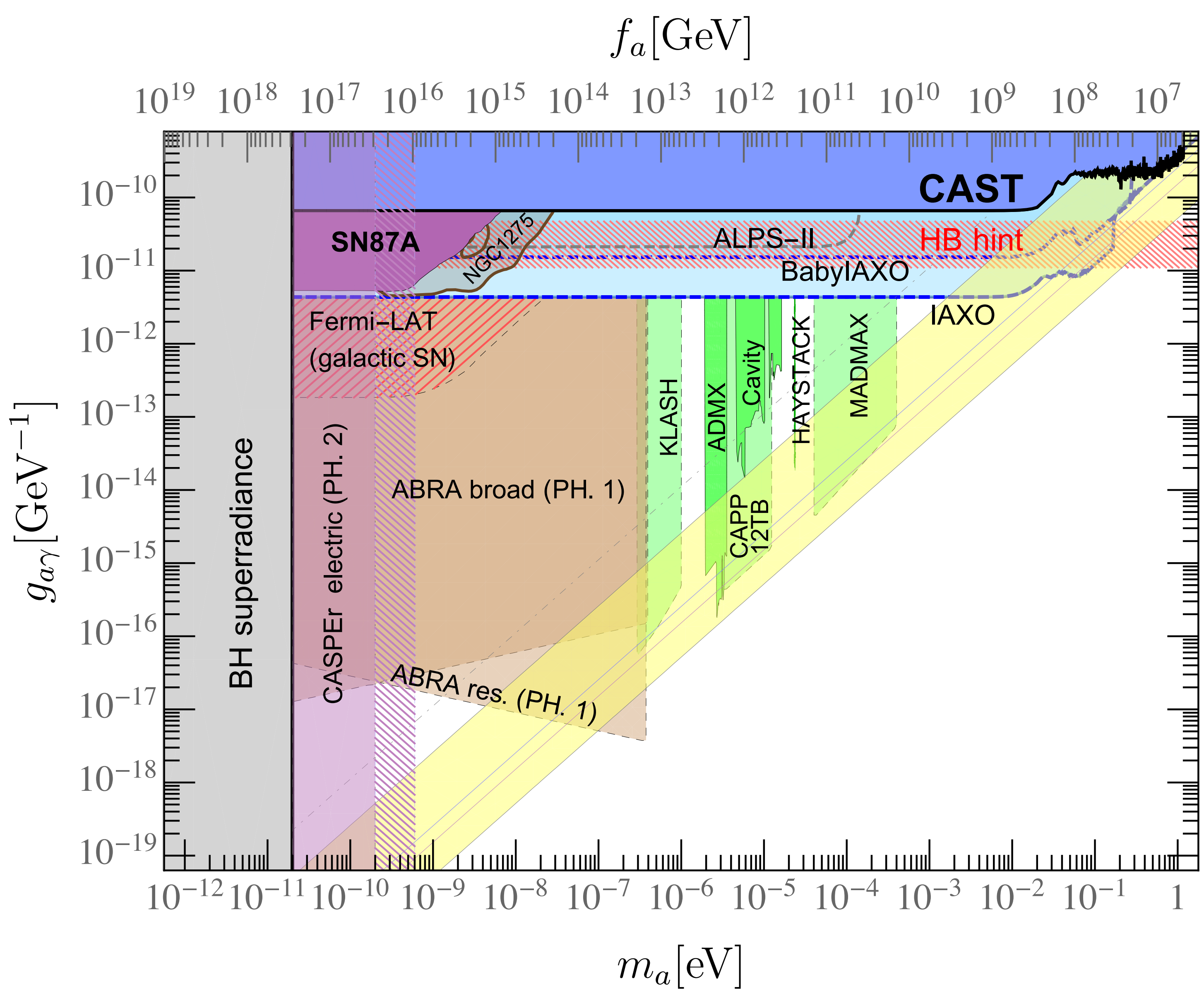


[LDL, Giannotti, Nardi, Visinelli 2003.01100 (Physics Reports)]

[Bertolini, LDL, Nesti 2006.12508 (Physical Review Letters)]

✤ An experimental opportunity

★ Time now to rethink the axion

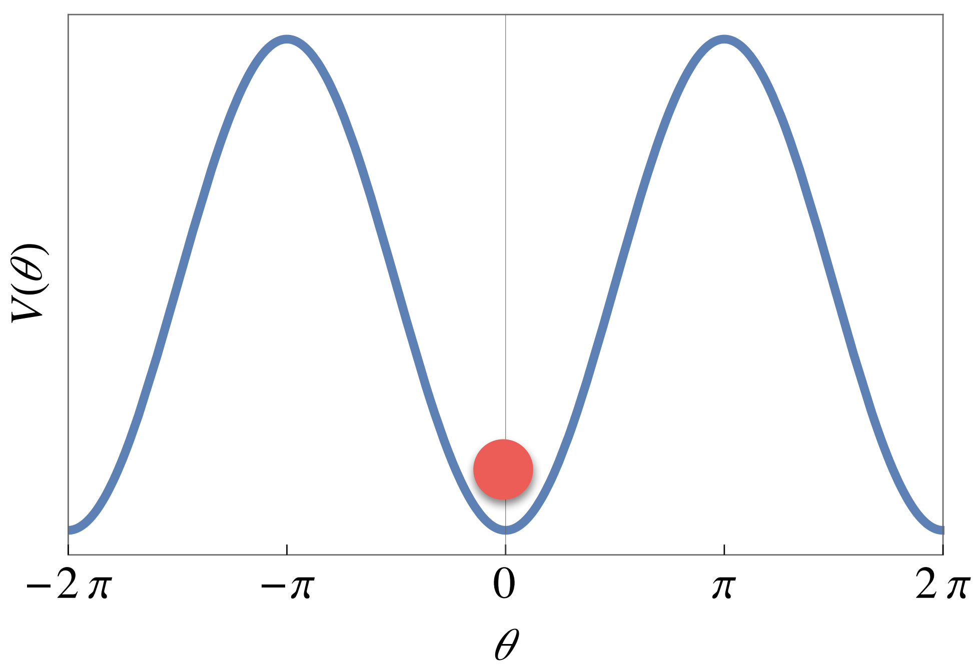
1. QCD axion & CP
2. Axion-mediated forces
3. *Scalar* axion-nucleon coupling (connection to CPV sources)

QCD axion

- Originally introduced to *wash-out* CP violation from strong interactions

$$\delta\mathcal{L}_{\rm QCD} = \theta \frac{\alpha_s}{8\pi} G\tilde{G} \qquad |\theta| \lesssim 10^{-10} \qquad \text{(strong CP problem)}$$

→ *promote* $\boldsymbol{\theta}$ *to a dynamical field, which relaxes to zero via QCD dynamics*



[Peccei, Quinn '77, Weinberg '78, Wilczek '78]

$$\theta \to \frac{a}{f_a} \qquad \textit{with} \qquad \langle a \rangle = 0$$

QCD axion [a closer look]

- Assume a spin-0 boson with a pseudo-shift symmetry $a \to a + \alpha\, f_a$

<u>broken only by</u> $\frac{a}{f_a}\frac{\alpha_s}{8\pi} G\tilde{G}$ → $E(0) \leq E(\langle a \rangle)$ [Vafa-Witten, PRL 53 (1984)]

$$\theta_{\rm eff} = \frac{\langle a \rangle}{f_a}$$

$$\begin{aligned} e^{-V_4 E(\theta_{\rm eff})} &= \int \mathcal{D}\varphi\, e^{-S_0 + i\theta_{\rm eff} \int G\tilde{G}} \\ &= \left| \int \mathcal{D}\varphi\, e^{-S_0 + i\theta_{\rm eff} \int G\tilde{G}} \right| \\ &\leq \int \mathcal{D}\varphi\, \left| e^{-S_0 + i\theta_{\rm eff} \int G\tilde{G}} \right| = e^{-V_4 E(0)} \end{aligned}$$

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- Does the axion really relax to zero ?

$\mathcal{D}\varphi \equiv dA^a_\mu \det(\not{D} + M)$ → *path-integral measure positive definite only for a vector-like theory (e.g. QCD)*

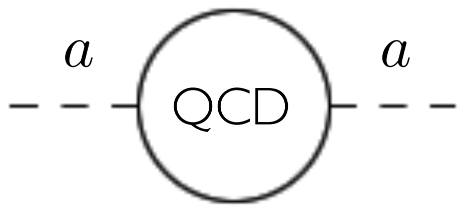
does not apply to the SM !

Estimating $\theta_{\rm eff}$ in the SM

- Axion potential in the presence of $\mathcal{O}_{\rm CPV}$

$$V(a) \simeq \frac{1}{2} K \left(\frac{a}{f_a} \right)^2$$

$$K = \left\langle G\tilde{G}, G\tilde{G} \right\rangle \sim \Lambda_\chi^4$$



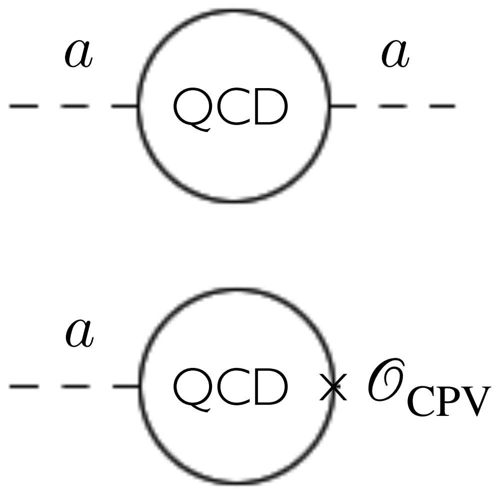
Estimating θ_{eff} in the SM

- Axion potential in the presence of $\mathcal{O}_{\text{CPV}}$

$$V(a) \simeq \frac{1}{2} K \left(\frac{a}{f_a}\right)^2 + K' \left(\frac{a}{f_a}\right)$$

$$K = \left\langle G\tilde{G}, G\tilde{G} \right\rangle \sim \Lambda_\chi^4$$

$$K' = \left\langle G\tilde{G}, \mathcal{O}_{\text{CPV}} \right\rangle$$



$$\longrightarrow \quad \theta_{\text{eff}} \equiv \frac{\langle a \rangle}{f_a} \simeq -\frac{K'}{K}$$

Estimating $\theta_{\rm eff}$ in the SM

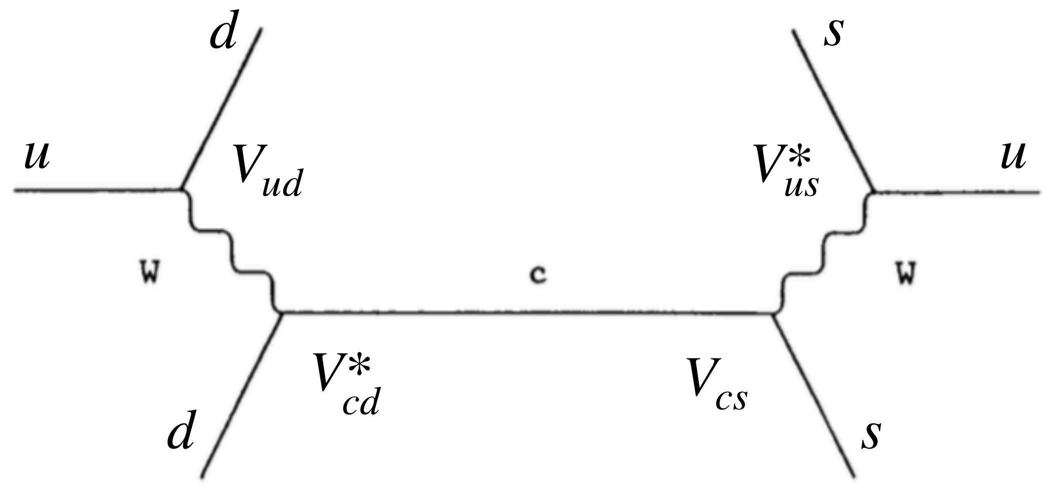
- Axion potential in the presence of $\mathcal{O}_{\rm CPV}$

$$V(a) \simeq \frac{1}{2} K \left(\frac{a}{f_a}\right)^2 + K' \left(\frac{a}{f_a}\right)$$

$$K = \left\langle G\tilde{G}, G\tilde{G} \right\rangle \sim \Lambda_\chi^4$$

$$K' = \left\langle G\tilde{G}, \mathcal{O}_{\rm CPV} \right\rangle \sim \frac{G_F^2}{m_c^2} J_{\rm CKM} \Lambda_\chi^{10}$$

$$J_{\rm CKM} = {\rm Im}\, V_{ud} V_{cd}^* V_{cs} V_{us}^* \simeq 3 \times 10^{-5}$$



[Georgi Randall, NPB276 (1986)]

$$\longrightarrow \quad \theta_{\rm eff} \equiv \frac{\langle a \rangle}{f_a} \simeq -\frac{K'}{K} \sim G_F^2 \Lambda_\chi^4 J_{\rm CKM} \sim 10^{-18}$$

Estimating θ_{eff} in the SM

- Two observations:

1. The Peccei-Quinn mechanism works <u>accidentally</u> in the SM
2. A <u>no-lose theorem</u> for the SM axion ?

$$d_n^{\text{axion}} \sim \underbrace{10^{-16}\theta_{\text{eff}}}_{10^{-34}} \, e\,\text{cm} \qquad d_n^{\text{SM}} \simeq 10^{-32} \; e\,\text{cm} \qquad |d_n^{\text{exp}}| \lesssim 10^{-26} \; e\,\text{cm}$$

[For SM prediction see Pospelov Ritz hep-ph/0504231 + refs. therein]

needs huge improvements both from exp. and theory

→ $$\theta_{\text{eff}} \equiv \frac{\langle a \rangle}{f_a} \simeq -\frac{K'}{K} \sim G_F^2 \Lambda_\chi^4 J_{\text{CKM}} \sim \boxed{10^{-18}}$$

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is there another way to test the axion ground state ?

Axion-mediated forces

- θ_{eff} sources a scalar axion-nucleon coupling

$$\mathcal{L} \supset g^S_{aN} a \overline{N} N + g^P_{af} a \overline{f} i\gamma_5 f$$

$$\frac{\Lambda_\chi}{2} \frac{a^2}{f_a^2} \overline{N} N \xrightarrow{\langle a \rangle \neq 0} g^S_{aN} a \overline{N} N$$

$$g^S_{aN} \sim \frac{\Lambda_\chi}{f_a} \theta_{\text{eff}} \qquad g^P_{af} \sim \frac{m_f}{f_a}$$

[Moody, Wilczek PRD30 (1984)]

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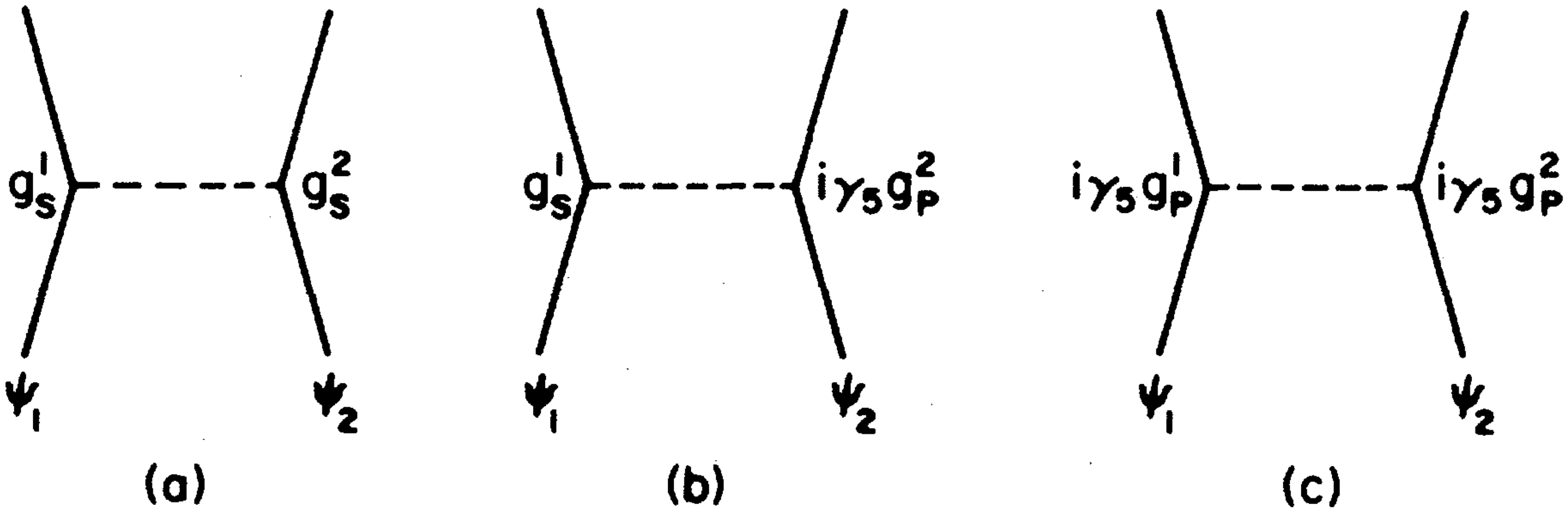
- New macroscopic forces from non-relativistic potentials* [Moody, Wilczek PRD30 (1984)]



monopole-monopole monopole-dipole dipole-dipole

does not rely on the hypothesis that the axion is DM

Axion-mediated forces

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$$\mathcal{L} \supset g^S_{aN} a \overline{N} N + g^P_{af} a \overline{f} i\gamma_5 f \qquad \frac{\Lambda_\chi}{2}\frac{a^2}{f_a^2}\overline{N}N \xrightarrow{\langle a \rangle \neq 0} g^S_{aN} a \overline{N} N \qquad g^S_{aN} \sim \frac{\Lambda_\chi}{f_a}\theta_{\text{eff}} \qquad g^P_{af} \sim \frac{m_f}{f_a}$$

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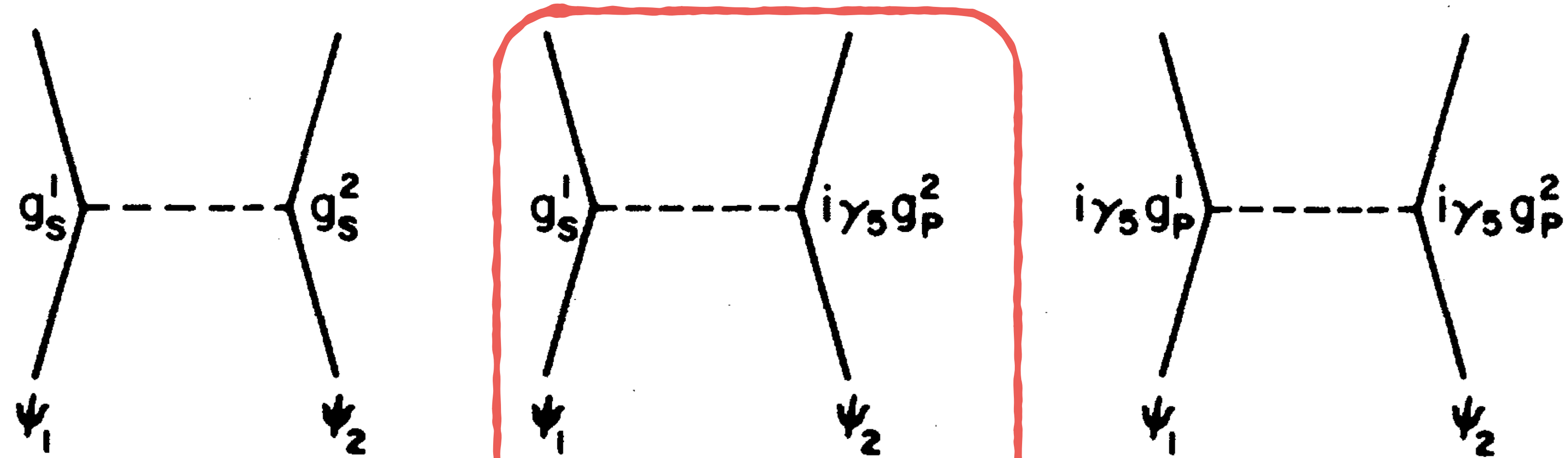


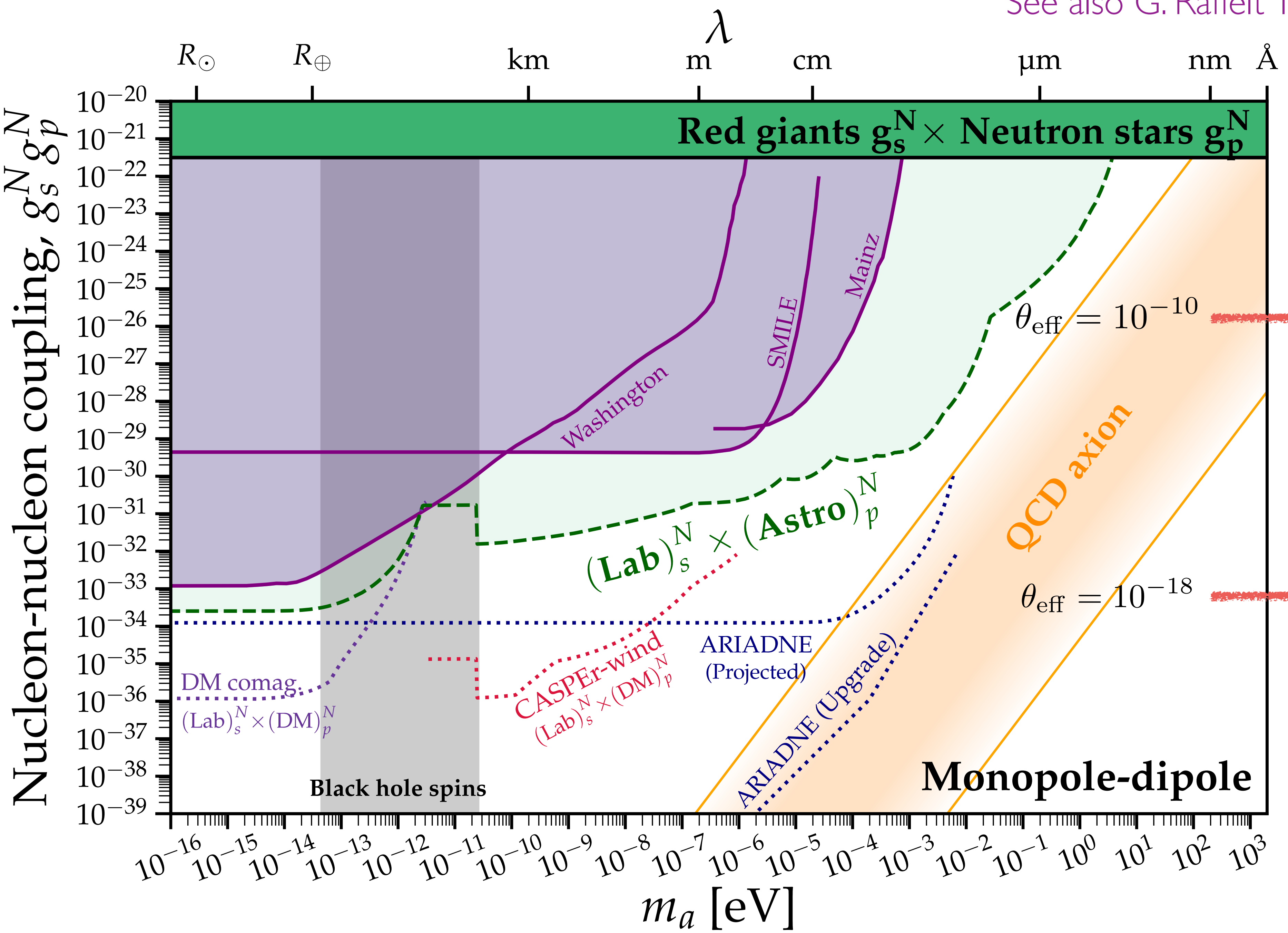
(a) (b) (c)

monopole-monopole	monopole-dipole	dipole-dipole
double θ_{eff} suppression	ARIADNE, QUAX-gpgs, … NMR enhancement	*spin suppression + bkgd from ordinary magnetic forces*

Monopole-dipole

- ARIADNE will probe into the QCD axion region (depending on $\theta_{\rm eff}$)

[O'Hare, Vitagliano 2010.03889,
See also G. Raffelt 1205.1776]



BSM
(optimistic)

SM
(pessimistic)

Axion-nucleon *scalar* coupling

- Moody-Wilczek formula

[Moody, Wilczek PRD30 (1984)]

$$g^S_{aN} = \frac{\theta_{\rm eff}}{f_a} \frac{m_u m_d}{m_u + m_d} \langle N | \overline{u} u + \overline{d} d | N \rangle \simeq \theta_{\rm eff} \left(\frac{17 \text{ MeV}}{f_a} \right)$$

- See also:

[Barbieri, Romanino, Strumia hep-ph/9605368 → Naive dimensional analysis
Pospelov hep-ph/9707431 → Meson tadpoles
Bigazzi, Cotrone, Jarvinen, Kiritsis 1906.12132 → isospin breaking]

- Two relevant questions:

1. How to connect $\boldsymbol{g^S_{aN}}$ *to UV sources of CP violation ?*

2. How to properly impose the nEDM bound ?

A new master formula

- Moody-Wilczek formula [Moody, Wilczek PRD30 (1984)]

$$g^S_{aN} = \frac{\theta_{\rm eff}}{f_a}\frac{m_u m_d}{m_u+m_d}\langle N|\overline{u}u+\overline{d}d|N\rangle \simeq \theta_{\rm eff}\left(\frac{17\ \text{MeV}}{f_a}\right)$$

- From LO bary-meson chiral Lagrangian [Bertolini, LDL, Nesti 2006.12508 PRL126 (2021)]

$$g^S_{an,\,p} \simeq \frac{4B_0\, m_u m_d}{f_a(m_u+m_d)}\left[\pm(b_D+b_F)\frac{\langle\pi^0\rangle}{F_\pi}+\frac{b_D-3b_F}{\sqrt{3}}\frac{\langle\eta_8\rangle}{F_\pi}-\sqrt{\frac{2}{3}}(3b_0+2b_D)\frac{\langle\eta_0\rangle}{F_\pi}-\left(b_0+(b_D+b_F)\frac{m_{u,d}}{m_d+m_u}\right)\theta_{\rm eff}\right]$$

meson tadpoles

iso-spin breaking

MW missed a factor 1/2

A new master formula

- Moody-Wilczek formula [Moody, Wilczek PRD30 (1984)]

$$g^S_{aN} = \frac{1}{2}\frac{\theta_{\rm eff}}{f_a}\frac{m_u m_d}{m_u + m_d}\langle N|\overline{u}u + \overline{d}d|N\rangle \simeq \frac{1}{2}\theta_{\rm eff}\left(\frac{17\ \text{MeV}}{f_a}\right)$$

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meson tadpoles

iso-spin breaking

MW missed a factor 1/2

An application: Left-Right

- Low-scale (PQ)Left-Right with P-parity

[Bertolini, LDL, Nesti 2006.12508 PRL126 (2021)]

4-quark op. from W_R *exchange*

chiral representation

$$\mathcal{O}_1^{ud} = (\overline{u}u)(\overline{d}i\gamma_5 d) \longrightarrow c_3(U_{11}^\dagger U_{22} - U_{11}U_{22}^\dagger)$$

$$U = \exp\left[\frac{2i}{\sqrt{6}F_0}\eta_0 I + \frac{2i}{F_\pi}\Pi\right]$$

$$\frac{\langle \pi^0 \rangle}{F_\pi} \simeq \frac{G_F}{\sqrt{2}} \mathcal{C}_1^{[ud]} \frac{c_3}{B_0 F_\pi^2} \frac{m_u + m_d + 4m_s}{m_u m_d + m_d m_s + m_s m_u}$$

$$\frac{\langle \eta_8 \rangle}{F_\pi} \simeq \frac{G_F}{\sqrt{2}} \mathcal{C}_1^{[ud]} \frac{\sqrt{3}c_3}{B_0 F_\pi^2} \frac{m_d - m_u}{m_u m_d + m_d m_s + m_s m_u}$$

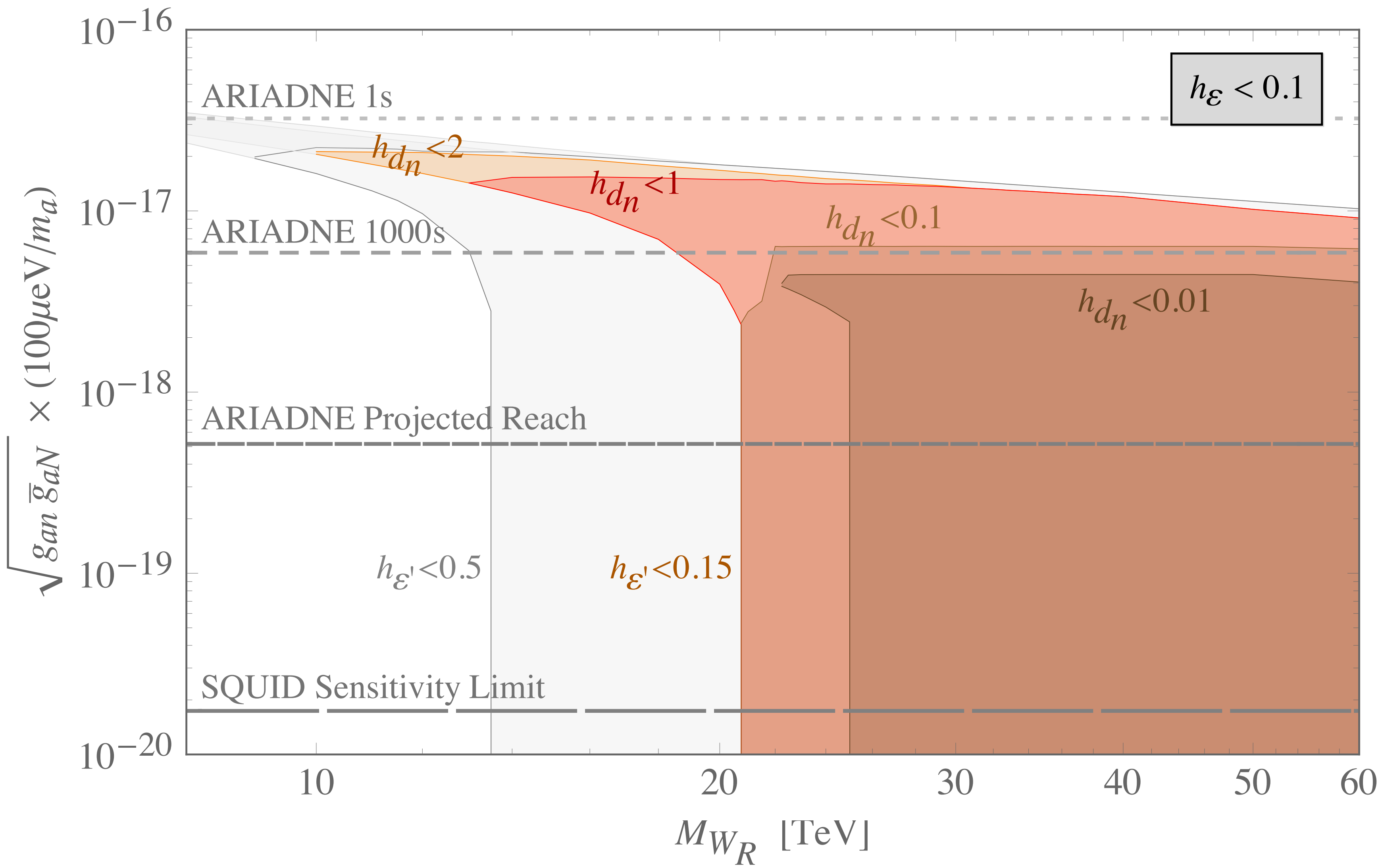
$$\theta_{\rm eff} \simeq \frac{G_F}{\sqrt{2}} \mathcal{C}_1^{[ud]} \frac{2c_3}{B_0 F_\pi^2} \frac{m_d - m_u}{m_u m_d}$$

An application: Left-Right

- Low-scale (PQ)Left-Right with P-parity

[Bertolini, LDL, Nesti 2006.12508 PRL126 (2021)]

4 CPV observables $(\varepsilon,\ \varepsilon',\ d_n,\ \bar{g}_{aN})$ *function of a single phase* $\boldsymbol{\alpha}$ $\langle\Phi\rangle = \text{diag}\{v_1, e^{i\alpha}v_2\}$



$$h_{\mathcal{O}} \equiv \frac{\mathcal{O}^{\text{th}}}{\mathcal{O}^{\text{exp}}}$$

Conclusions

- Rethinking the axion as a portal to UV sources of CP-violation

Fundamental origin of CP violation
Baryogenesis ?

$\Lambda_{\rm CPV}$

$\mathcal{O}_{\rm CPV}$

$\Lambda_{\rm QCD}$

$\left\langle G\tilde{G}, \mathcal{O}_{\rm CPV} \right\rangle \neq 0$ → $\theta_{\rm eff} \equiv \frac{\langle a \rangle}{f_a}$ *nEDM (bound)*

→ g^S_{aN} *new macroscopic forces*

strong CP problem or strong CP opportunity ?

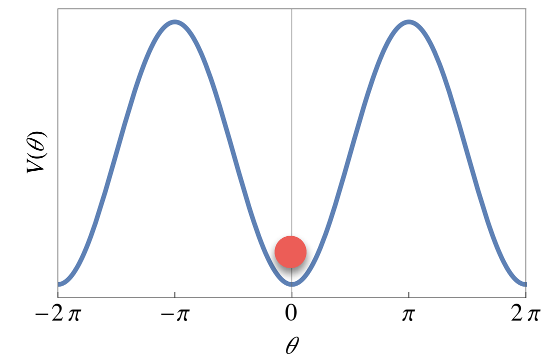
Backup slides

QCD axion & CP

- In absence of UV sources of CP violation (e.g. in QCD)

$$e^{-V_4 E(\theta_{\rm eff})} = \int \mathcal{D}\varphi \, e^{-S_0(\varphi)+i\theta_{\rm eff}\int G\tilde{G}}$$
$$\overset{\varphi \xrightarrow{\rm CP} \varphi'}{=} \int \mathcal{D}\varphi' \, e^{-S_0(\varphi')+i\theta_{\rm eff}\int G'\tilde{G}'}$$
$$= \int \mathcal{D}\varphi \, e^{-S_0(\varphi)-i\theta_{\rm eff}\int G\tilde{G}} = e^{-V_4 E(-\theta_{\rm eff})}$$

$\longrightarrow$ $E(\theta_{\rm eff}) = E(-\theta_{\rm eff})$



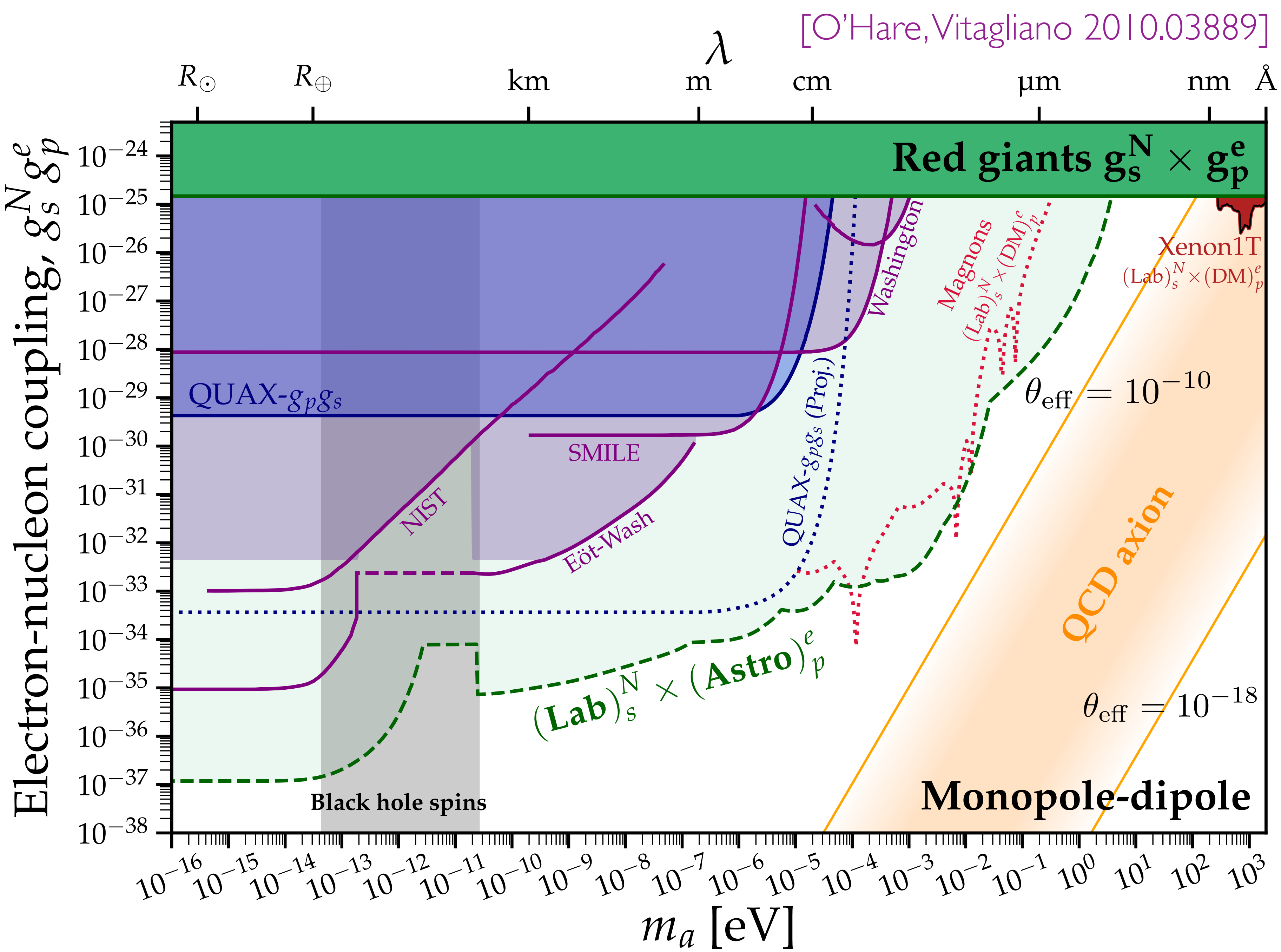
- However CP is violated in the SM by the CKM phase

$S_0(\varphi') \neq S_0(\varphi)$ $\longrightarrow$ $E(\theta_{\rm eff}) \neq E(-\theta_{\rm eff})$

the CKM sources an odd piece for the potential, responsible for an axion VEV

Axion-mediated forces

- Monopole-dipole (electron)



Axion-mediated forces

- Monopole-Monopole

[O'Hare, Vitagliano 2010.03889]