Catching the axion via new CP-violating forces

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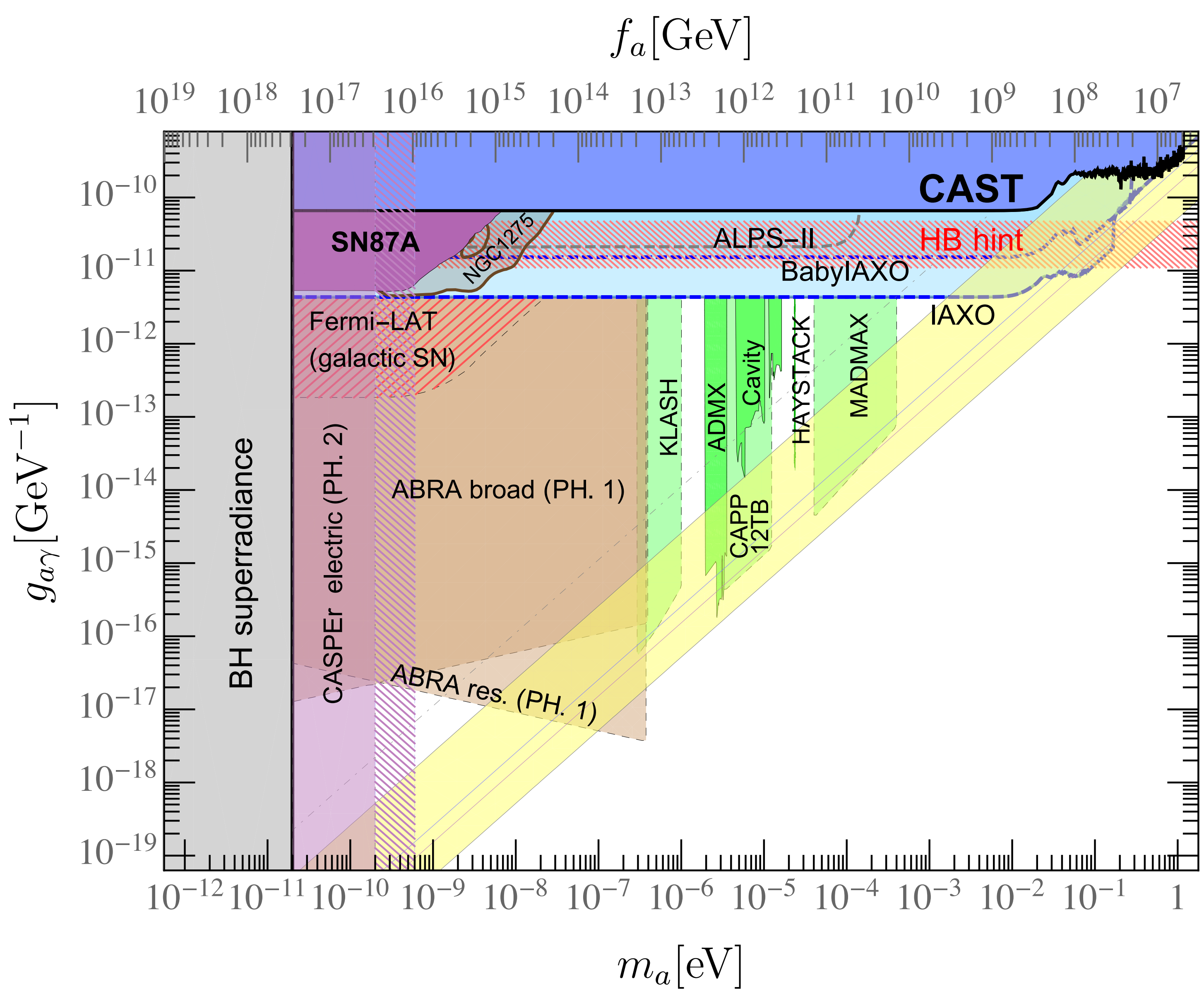
Luca Di Luzio

Università degli Studi di Padova

Dipartimento di Fisica e Astronomia "Galileo Galilei"

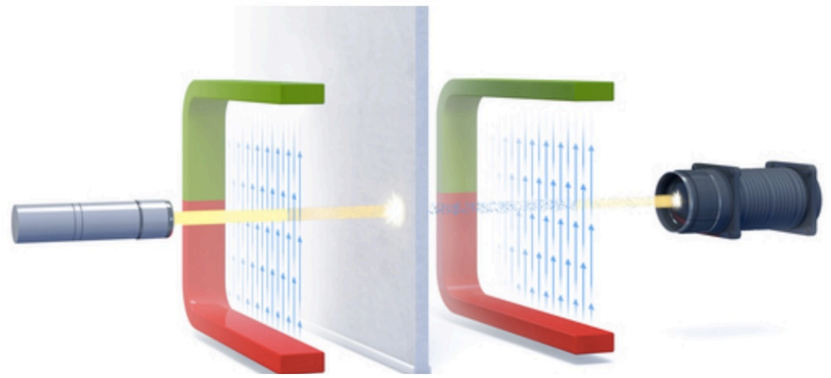
INFN Padova

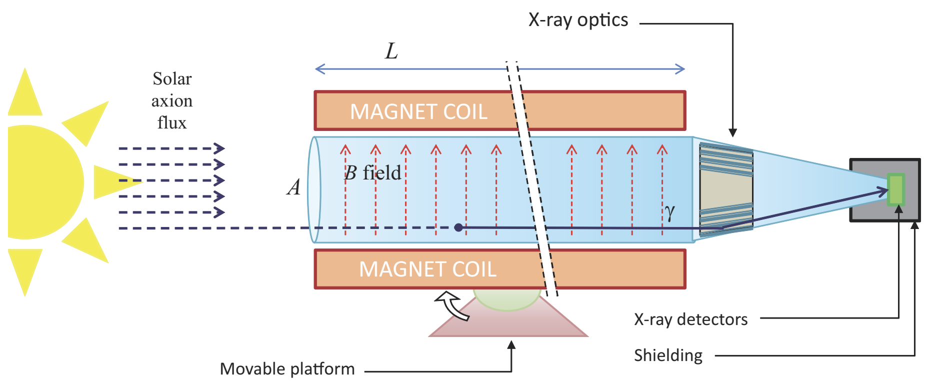
In 10 years from now ?

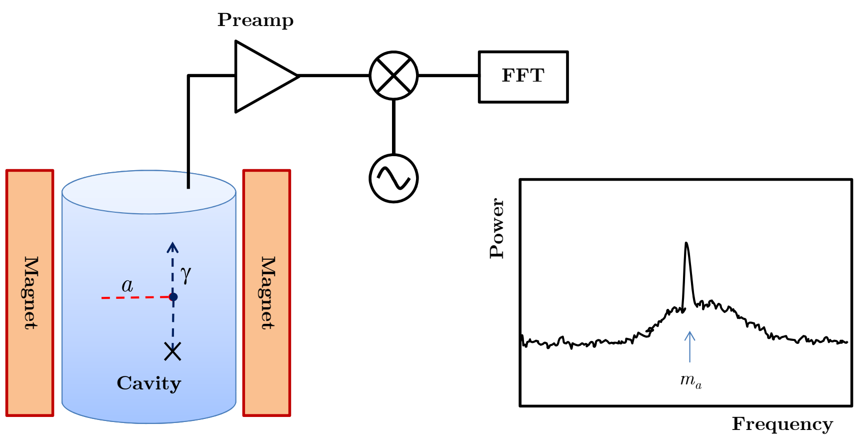


[LDL, Giannotti, Nardi, Visinelli 2003.01100 (Physics Reports)]

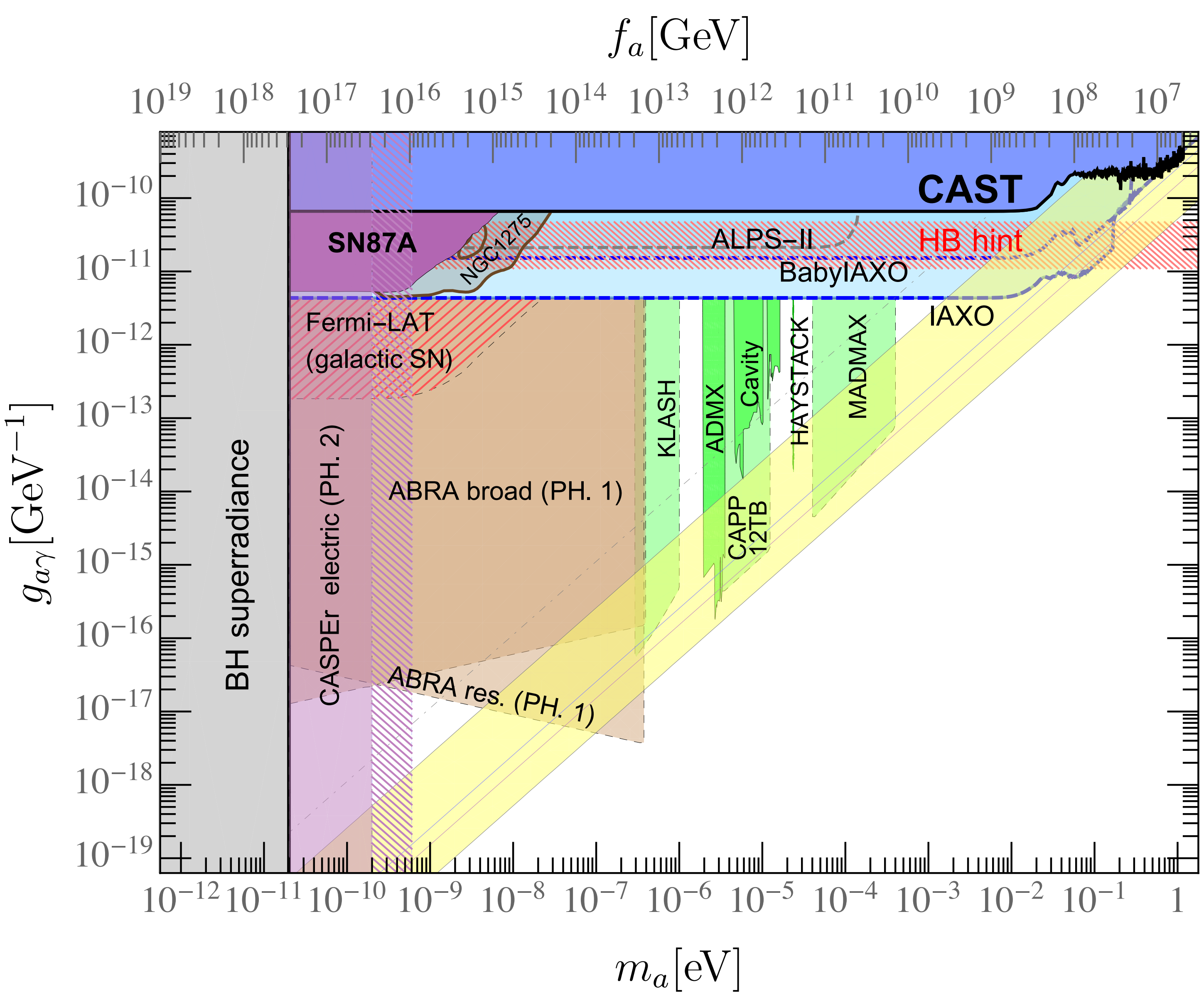
✤ An experimental opportunity







In 10 years from now ?



✤ An experimental opportunity

★ Time <u>now</u> to rethink the axion

1. QCD axion & CP

2. Axion-mediated forces

3. *Scalar* axion-nucleon coupling (connection to CPV sources)

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

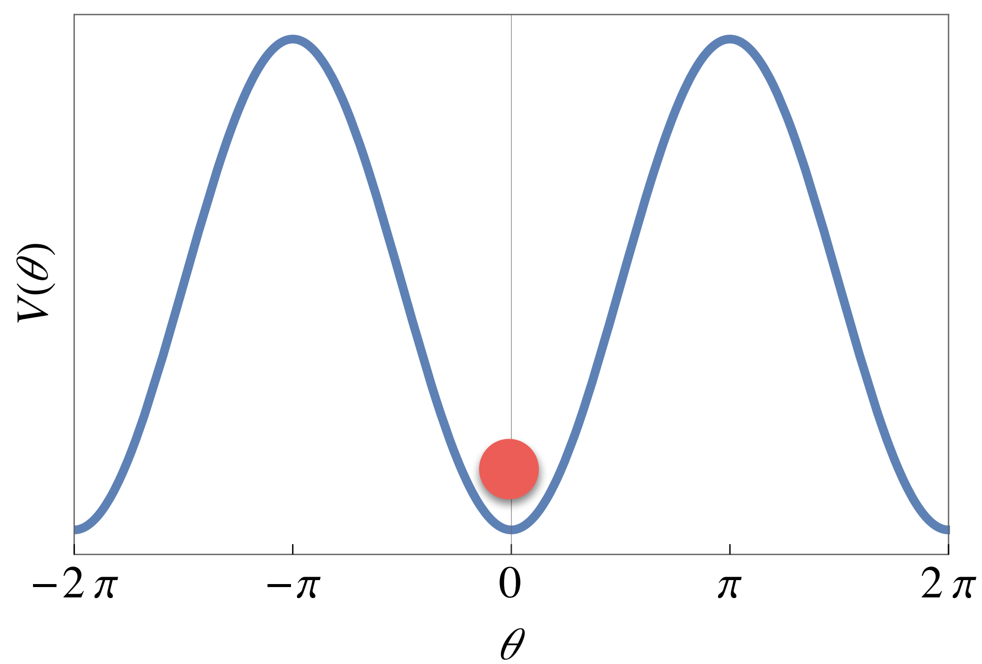
[Bertolini, LDL, Nesti 2006.12508 (Physical Review Letters)]

QCD axion

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

$$\delta\mathcal{L}_{\rm QCD} = \theta \frac{\alpha_s}{8\pi} G\tilde{G} \qquad |\theta| \lesssim 10^{-10}$$ (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> $\frac{a}{f_a}\frac{\alpha_s}{8\pi}G\tilde{G}$ $\longrightarrow$ $E(0) \leq E(\langle a \rangle)$ [Vafa-Witten, PRL 53 (1984)]

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

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

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- Does the axion really relax to zero ?

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

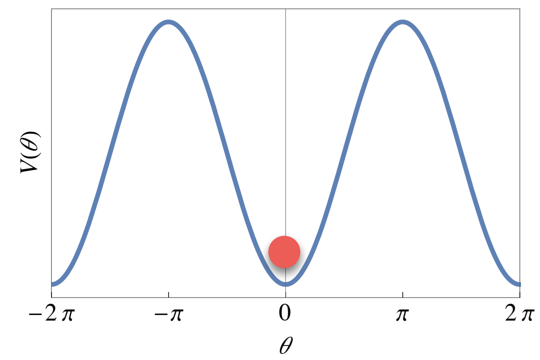
does not apply to the SM !

QCD axion & CP

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

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

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



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

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

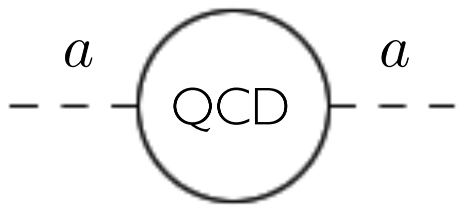
the CKM sources an odd piece for the potential, responsible for an axion VEV

Estimating θ_{eff} in the SM

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

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

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

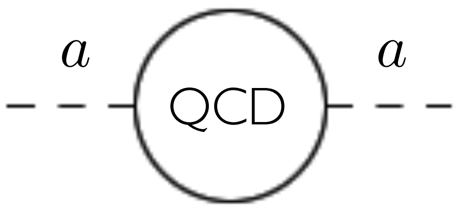


Estimating $\theta_{\rm eff}$ in the SM

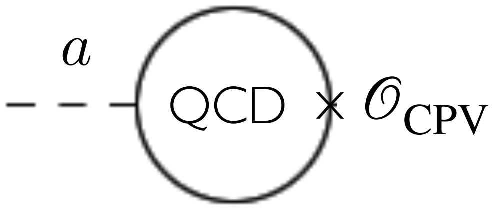
- Axion potential in the presence of $\mathcal{O}_{\rm CPV}$

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

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



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



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

Estimating θ_{eff} in the SM

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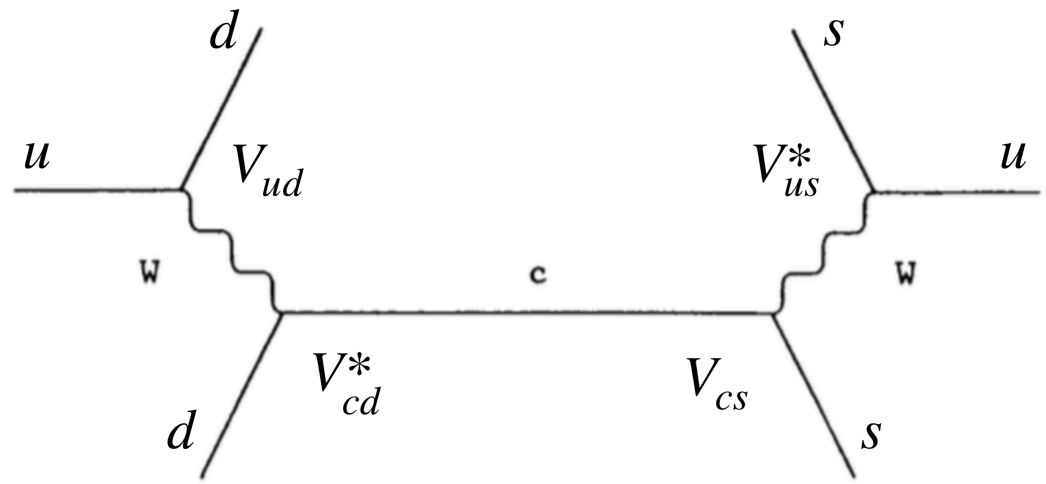
$$V(a) \simeq \frac{1}{2} K \left(\frac{a}{f_a}\right)^2 + K' \left(\frac{a}{f_a}\right)$$

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

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

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



[Georgi Randall, NPB276 (1986)]

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

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 ?

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

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

needs huge improvements both from exp. and theory

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

is there another way to test the axion ground state ?

Axion-mediated forces

- θ_{eff} sources a <u>scalar</u> axion-nucleon coupling

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

[Moody, Wilczek PRD30 (1984)]

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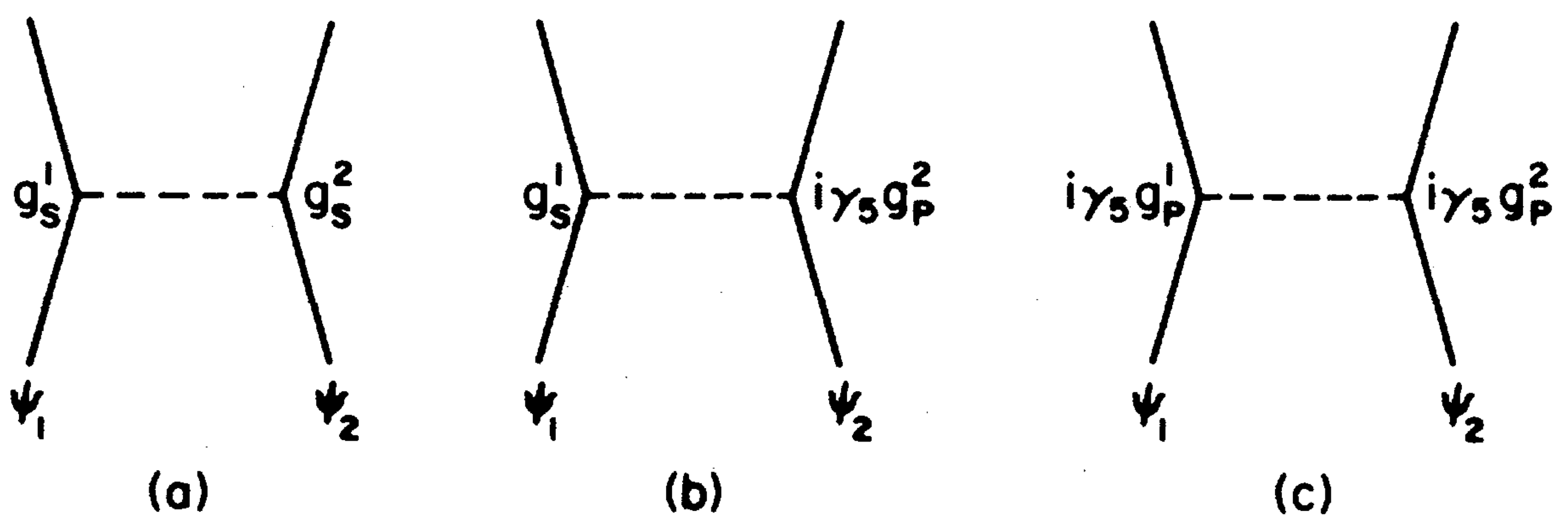
- New macroscopic forces from non-relativistic potentials* [Moody, Wilczek PRD30 (1984)]



monopole-monopole | monopole-dipole | dipole-dipole

**does not rely on the hypothesis that the axion is DM*

Axion-mediated forces

- $\theta_{\rm eff}$ sources a <u>scalar</u> axion-nucleon coupling

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

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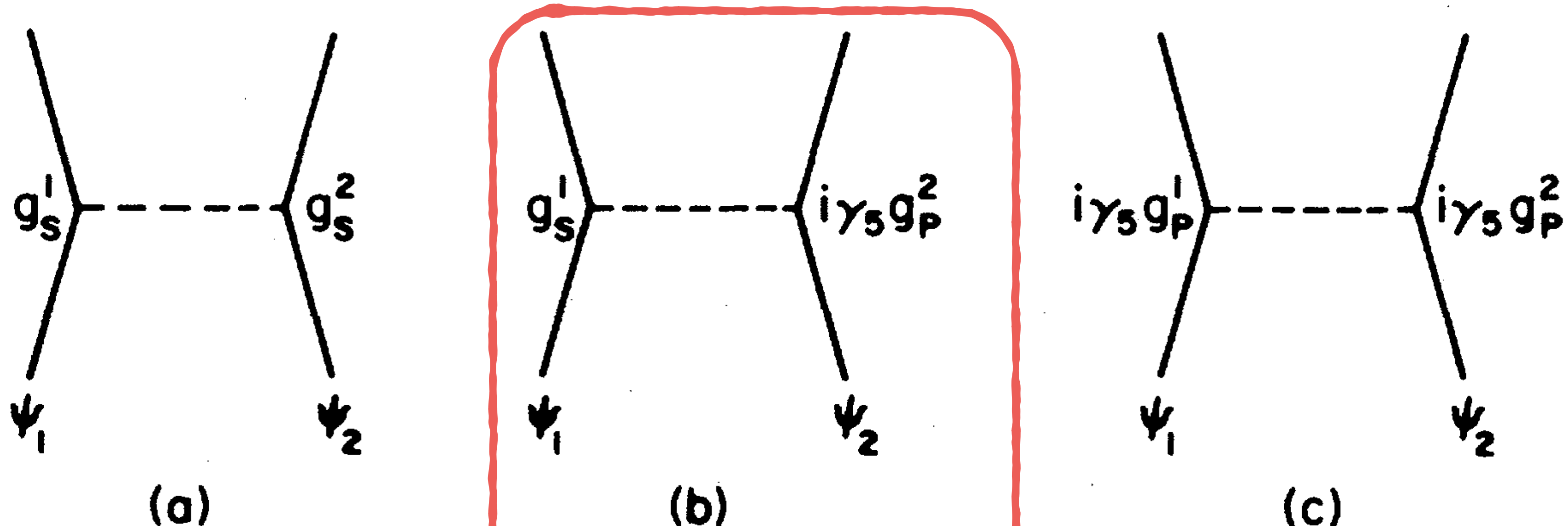


monopole-monopole | monopole-dipole | dipole-dipole

double $\theta_{\rm eff}$ suppression

ARIADNE, QUAX-gpgs, …
NMR enhancement

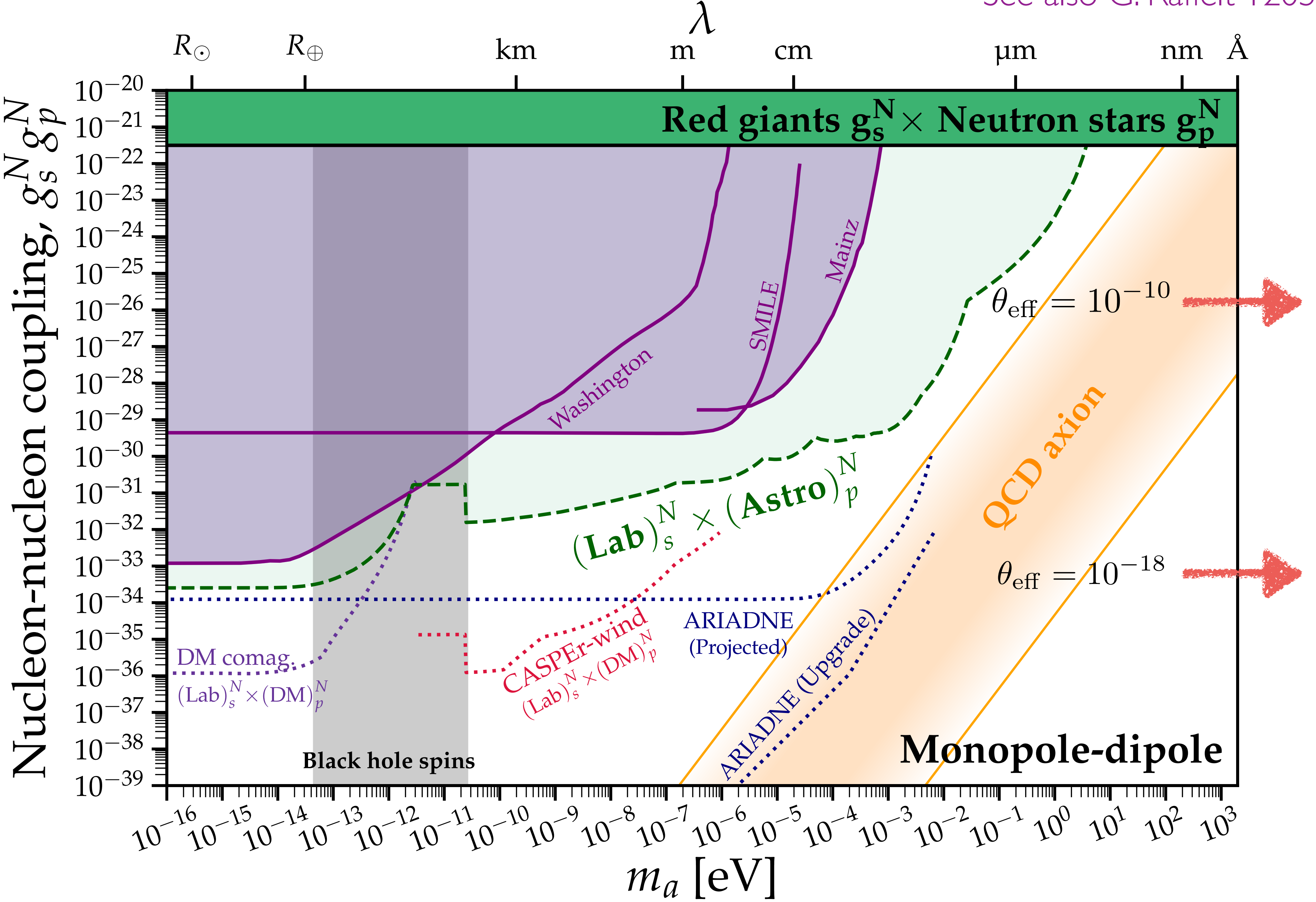
spin suppression + bkgd from ordinary magnetic forces

Monopole-dipole

- ARIADNE will probe into the QCD axion region (depending on θ_{eff})

[See talk by A. Geraci on Tuesday]

[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 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]

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

meson tadpoles

iso-spin breaking

MW missed a factor 1/2

A new master formula

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

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

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meson tadpoles

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An application: Left-Right

- Low-scale (PQ)Left-Right with P-parity [Bertolini, LDL, Nesti 2006.12508]

4-quark op. from W_R *exchange*

$$\mathcal{O}_1^{ud} = (\overline{u}u)(\overline{d}i\gamma_5 d) \xrightarrow{\textit{chiral representation}} c_3(U^\dagger_{11}U_{22} - U_{11}U^\dagger_{22})$$

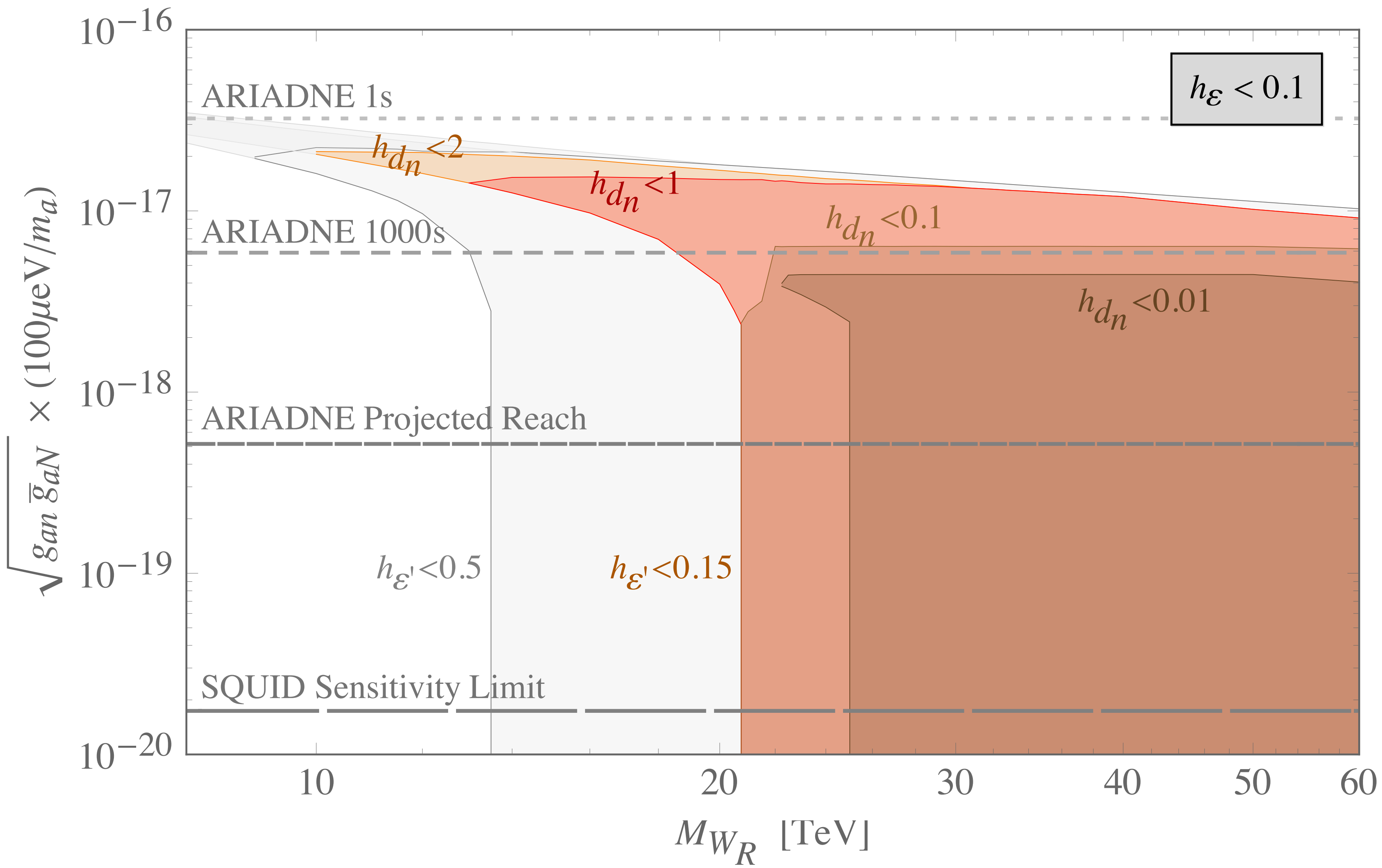
$$U = \exp\left[\frac{2i}{\sqrt{6}F_0}\eta_0 I + \frac{2i}{F_\pi}\Pi\right]$$

$$\boxed{\begin{aligned}
\frac{\langle \pi^0 \rangle}{F_\pi} &\simeq \frac{G_F}{\sqrt{2}}\,\mathcal{C}_1^{[ud]}\,\frac{c_3}{B_0 F_\pi^2}\,\frac{m_u + m_d + 4m_s}{m_u m_d + m_d m_s + m_s m_u} \\
\frac{\langle \eta_8 \rangle}{F_\pi} &\simeq \frac{G_F}{\sqrt{2}}\,\mathcal{C}_1^{[ud]}\,\frac{\sqrt{3}c_3}{B_0 F_\pi^2}\,\frac{m_d - m_u}{m_u m_d + m_d m_s + m_s m_u} \\
\theta_{\text{eff}} &\simeq \frac{G_F}{\sqrt{2}}\,\mathcal{C}_1^{[ud]}\,\frac{2c_3}{B_0 F_\pi^2}\,\frac{m_d - m_u}{m_u m_d}
\end{aligned}}$$

An application: Left-Right

- Low-scale (PQ)Left-Right with P-parity [Bertolini, LDL, Nesti 2006.12508]

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



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

Conclusions

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

Fundamental origin of CP violation
Baryogenesis ?

$\Lambda_{\rm CPV}$

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

$\Lambda_{\rm QCD}$

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

$\longrightarrow$ g^S_{aN} *new macroscopic forces*

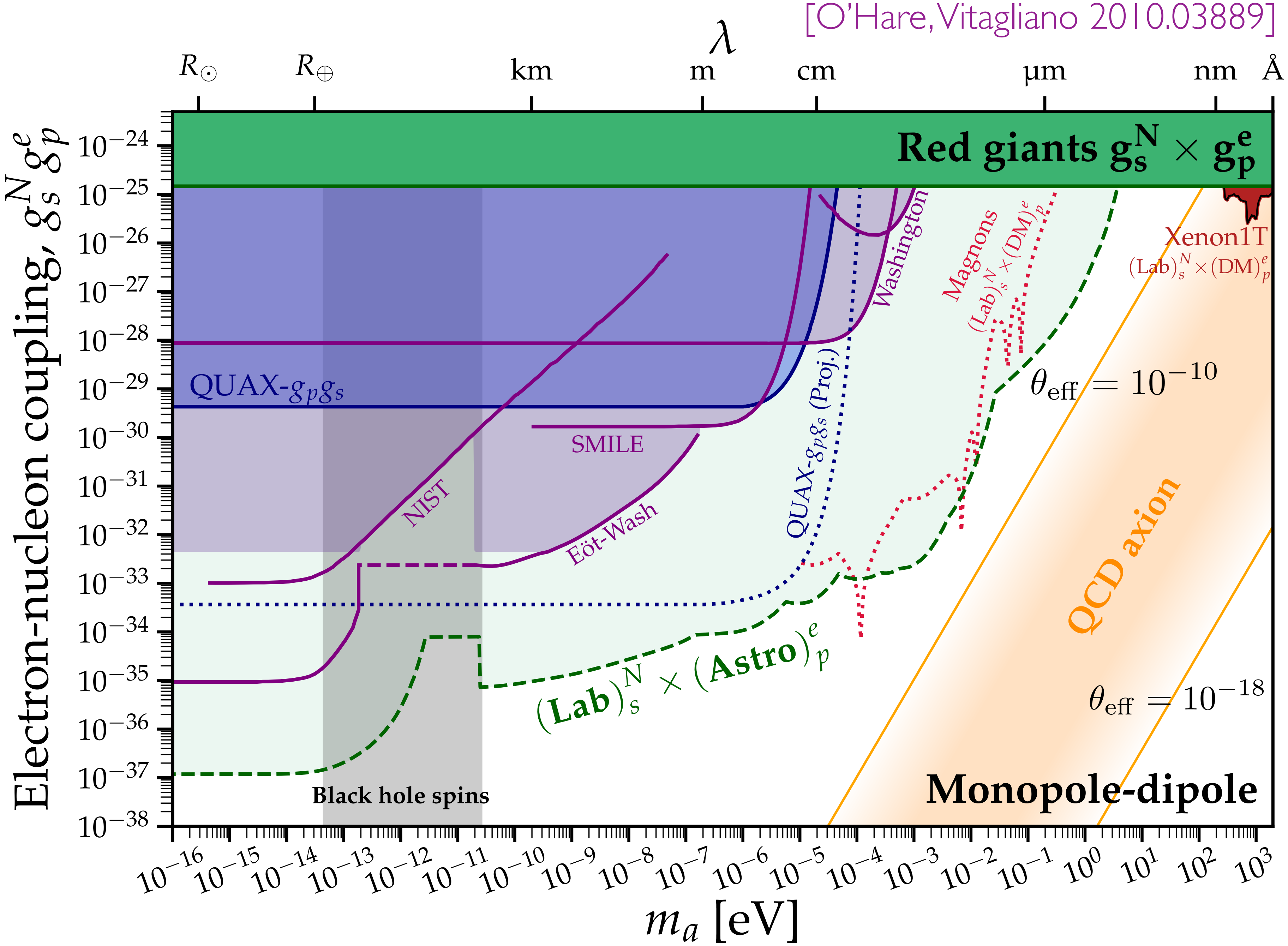
strong CP problem or strong CP opportunity ?

Backup slides

Axion-mediated forces

- Monopole-dipole (QUAX-gpgs)

[O'Hare, Vitagliano 2010.03889]



Axion-mediated forces

- Monopole-Monopole

[O'Hare, Vitagliano 2010.03889]