Spin-Independent Searches for Axions via Second-Order Interactions

Sheakha Aldaihan

King Saud University

Talk @ 54th SLAC Summer Institute (SSI 2026)
, SLAC
August 10-14, 2026

Axions

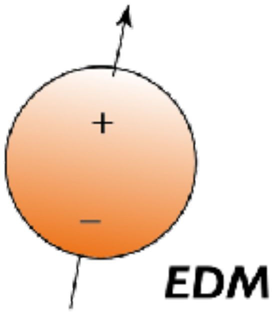
- Pseudoscalar light particle, Spin-0, wide range of masses.

- Introduced to solve the strong CP-problem: $L \supset \frac{g_s^2}{32\pi^2}\bar{\theta}\; G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a$

The neutron electric dipole moment

$$d_N \sim \frac{e}{m_N}\left(\frac{m_q}{m_N}\right)\left|\bar{\theta}\right| \sim 10^{-16}\left|\bar{\theta}\right| \text{ e-cm}$$

Current bound on nEDM: $\bar{\theta} \leq 10^{-10}$



Solution:
Turn $\bar{\theta}$ into a dynamical field
An axion

PRL. 38, 1440 (1977)

Axions

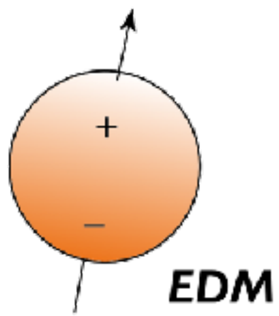
- Pseudoscalar light particle, Spin-0, wide range of masses.

- Introduced to solve the strong CP-problem: $L \supset \frac{g_s^2}{32\pi^2} \bar{\theta} \; G^a_{\mu\nu} \tilde{G}_a^{\mu\nu}$

The neutron electric dipole moment

$$d_N \sim \frac{e}{m_N}\left(\frac{m_q}{m_N}\right)\left|\bar{\theta}\right| \sim 10^{-16}\left|\bar{\theta}\right| \text{ e-cm}$$

Current bound on nEDM: $\bar{\theta} \leq 10^{-10}$

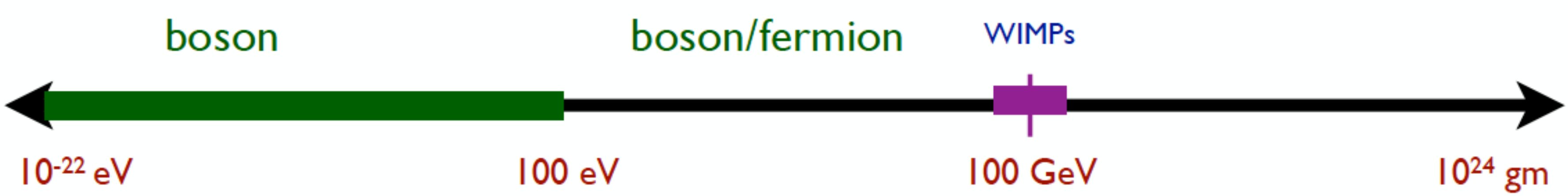


Solution:

PRL. 38, 1440 (1977) Turn $\bar{\theta}$ into a dynamical field

An axion

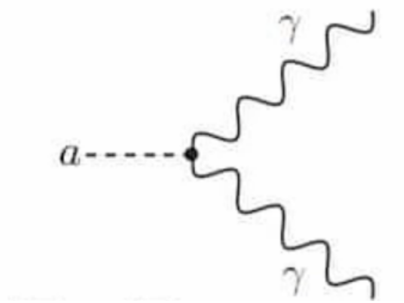
- Weakly-interacting bosons are consistent with dark matter abundance in the keV - 10^{-22} eV mass range



Ways Axions couple to matter

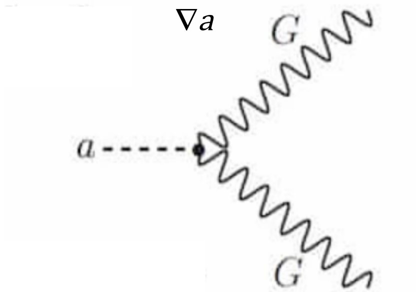
Coupling to photons

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



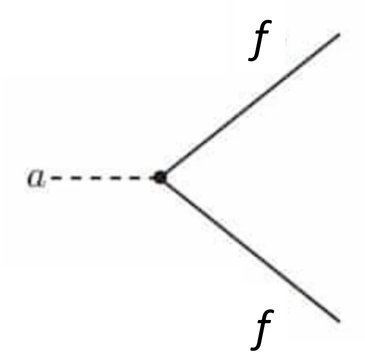
Coupling to gluons

$$L \supset \frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}$$



Coupling to fermions

$$L \supset \frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

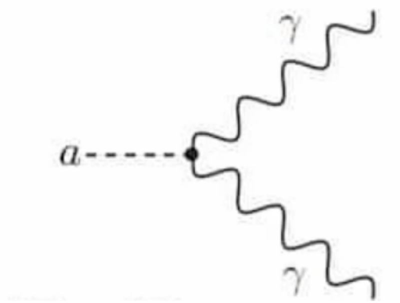


PRX QUANTUM 4, 020101 (2023)

Ways Axions couple to matter

Coupling to photons

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

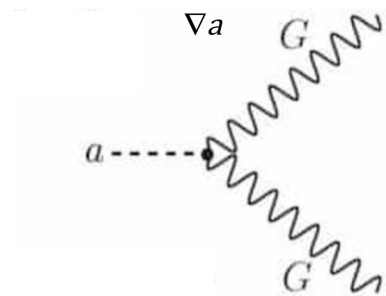


$$H_\gamma \supset g_{a\gamma\gamma}\, a\, \mathbf{E} \cdot \mathbf{B}$$

Axion interacting with electromagnetic fields

Coupling to gluons

$$L \supset \frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

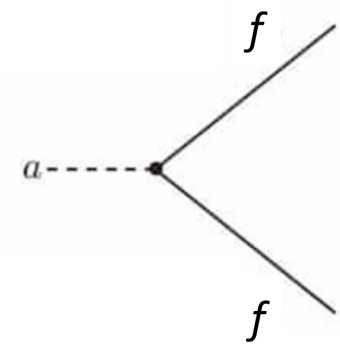


$$H_d \supset g_d\, a\, \boldsymbol{\sigma} \cdot \mathbf{E}$$

The nucleon spin σ couples to E an effective electric field

Coupling to fermions

$$L \supset \frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$



$$H_N \supset g_{aff}\, \boldsymbol{\nabla} a \cdot \boldsymbol{\sigma}_f$$

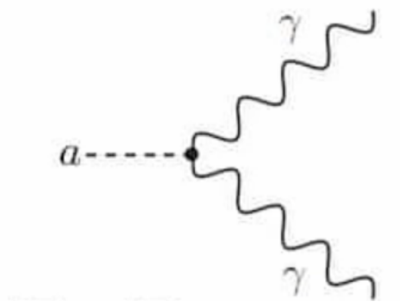
Fermion spin σ interacts with an effective magnetic field ∇a

PRX QUANTUM 4, 020101 (2023)

Ways Axions couple to matter

Coupling to photons

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

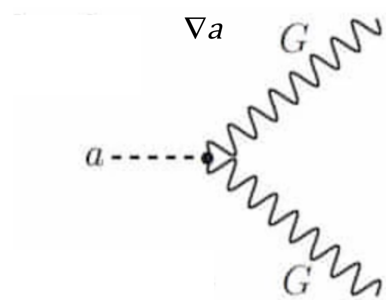


$$H_\gamma \supset g_{a\gamma\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}$$

Axion interacting with electromagnetic fields

Coupling to gluons

$$L \supset \frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

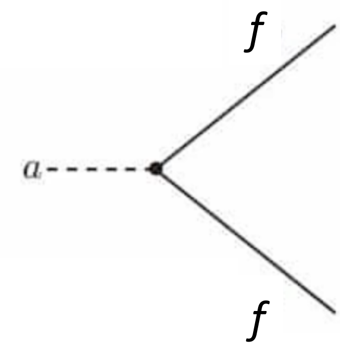


$$H_d \supset g_d\, a\, \boldsymbol{\sigma}\cdot\mathbf{E}$$

The nucleon spin σ couples to E an effective electric field

Coupling to fermions

$$L \supset \frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$



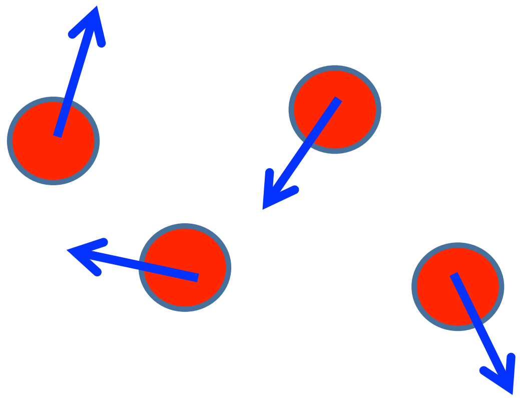
$$H_N \supset g_{aff}\, \boldsymbol{\nabla} a \cdot \boldsymbol{\sigma}_f$$

Fermion spin σ interacts with an effective magnetic field ∇a

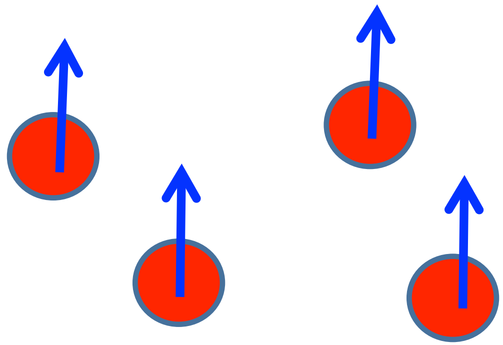
PRX QUANTUM 4, 020101 (2023)

leading to spin-dependent observables.

Spin-Based Searches Require Spin-Ensemble Engineering



Directions of spins in normal matter are random adding up to zero



Need to introduce **a magnetic field** to get a non-zero net spin → polarization

Experimental difficulties associated with polarization:

- Difficult to maintain polarization of members of the ensemble
- Magnetic-field shielding/control
- Spin-projection noise
- Both internal and external magnetic fields produce large systematic effects in delicate experiments.
- ....

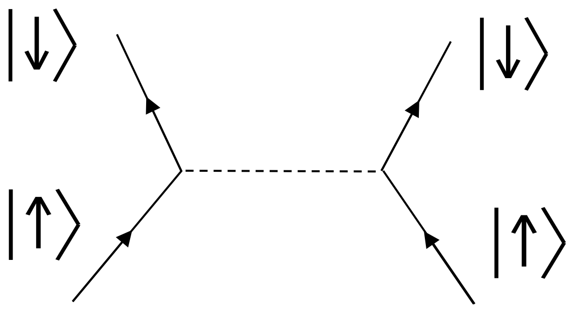
PRX QUANTUM 4, 020101 (2023)

Axion-Fermion Coupling

Example: $H_N \supset g_{aff} \, \boldsymbol{\nabla} a \cdot \boldsymbol{\sigma}_f$

Axion-Fermion Coupling

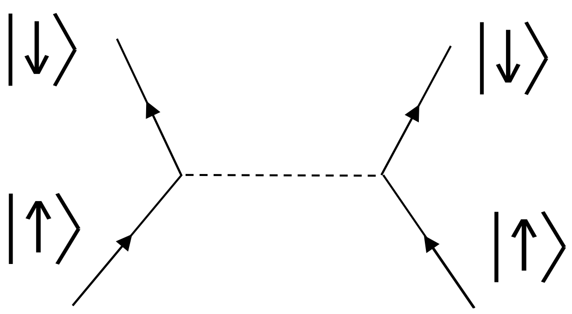
$$H_N \supset g_{aff}\ \boldsymbol{\nabla} a \cdot \boldsymbol{\sigma}_f$$



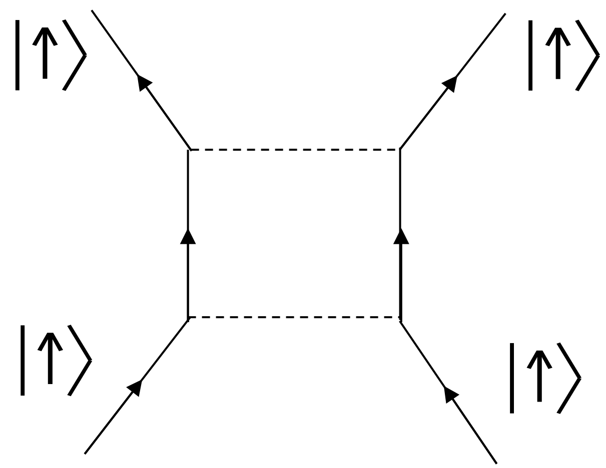
Long-range *spin-dependent* interaction

Axion-Fermion Coupling

$$H_N \supset g_{aff}\, \nabla a \cdot \boldsymbol{\sigma}_f$$



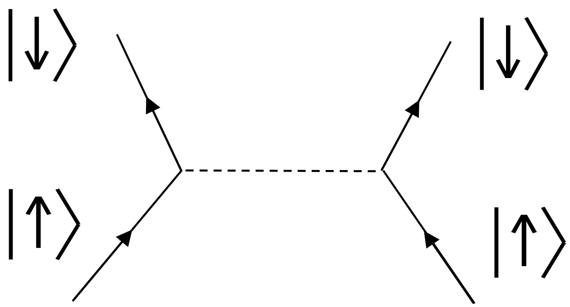
Long-range *spin-dependent* interaction



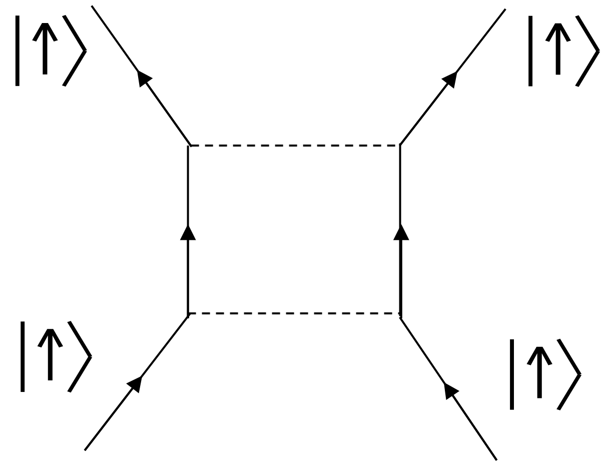
Spin-*independent* interaction

Axion-Fermion Coupling

$$H_N \supset g_{aff}\, \nabla a \cdot \boldsymbol{\sigma}_f$$



Long-range *spin-dependent* interaction

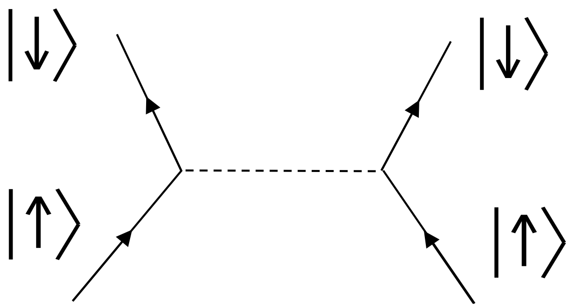


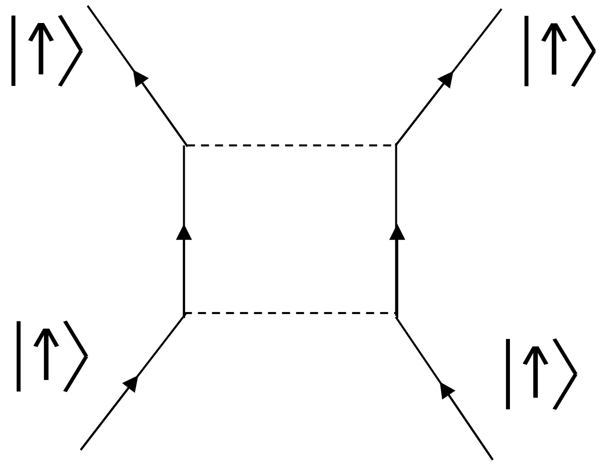
Spin-*independent* interaction

Removing the requirement for polarization enables the use of large-mass ensembles, whose responses can add coherently, resulting in enhanced sensitivity.

Axion-Fermion Coupling

$$H_N \supset g_{aff}\, \boldsymbol{\nabla} a \cdot \boldsymbol{\sigma}_f$$





Long-range *spin-dependent* interaction

$$V_a \sim \frac{1}{f_a^2 r^3}$$

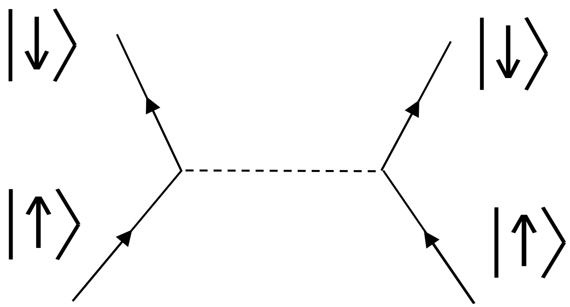
Spin-*independent* interaction

$$V_{2a}^{vac} \sim \frac{1}{f_a^4 r^5}$$

Removing the requirement for polarization enables the use of large-mass ensembles, whose responses can add coherently, resulting in enhanced sensitivity.

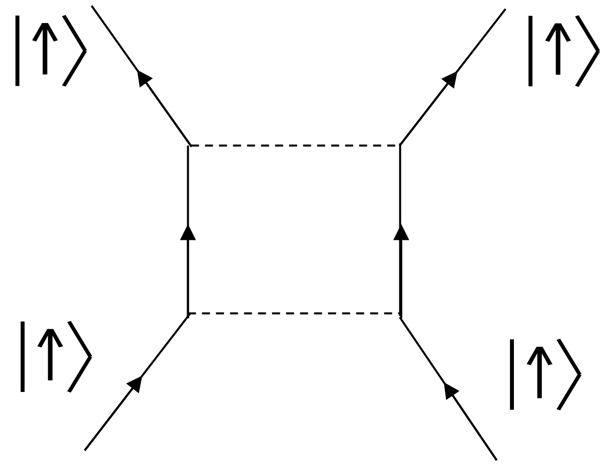
Axion-Fermion Coupling

$$H_N \supset g_{aff} \, \boldsymbol{\nabla} a \cdot \boldsymbol{\sigma}_f$$



Long-range *spin-dependent* interaction

$$V_a \sim \frac{1}{f_a^2 r^3}$$

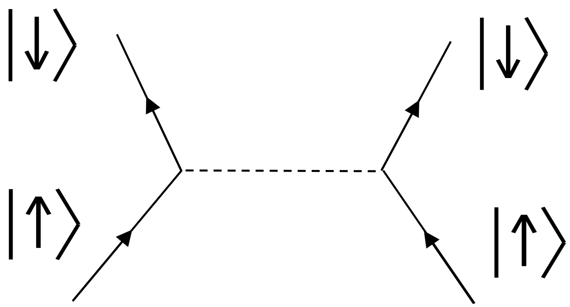


Spin-*independent* interaction

$$V_{2a}^{vac} \sim \frac{1}{f_a^4 r^5}$$ **Vacuum**

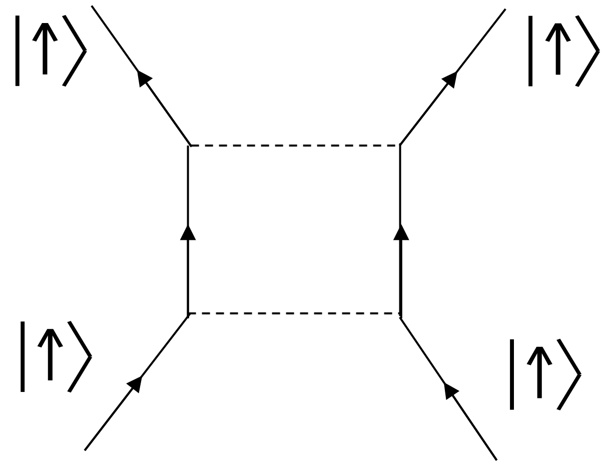
Spin-Based Searches Require Spin-Ensemble Engineering

Example: $H_N \supset g_{aff} \, \boldsymbol{\nabla} a \cdot \boldsymbol{\sigma}_f$



Long-range *spin-dependent* interaction

$$V_a \sim \frac{1}{f_a^2 r^3}$$



Spin-*independent* interaction

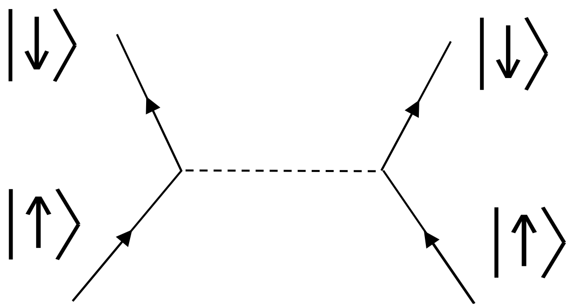
$$V_{2a}^{vac} \sim \frac{1}{f_a^4 r^5}$$ **Vacuum**

$$V_{2a}^{shift} \sim \frac{1}{f_a^4 r^3}$$ **Shift symmetry breaking**

M. Bauer and G.Rostagni. *"Fifth Forces from QCD Axions Scale Differently"*. PRL, 132(10):101802, (2024).
M. Bauer, F. Chadha-Day, A. Eberhart. "Discovering the Axiverse via Fifth Forces". arXiv:2606.06606 (2026)
Y. Grossman, B. Yu, and S. Zhou. *"Axion forces in axion backgrounds"*. JHEP, 01:145, (2026).
Y.Cheng and S.Ge. "Background-enhanced axion force by axion dark matter". PRD 113, L111701 (2026).

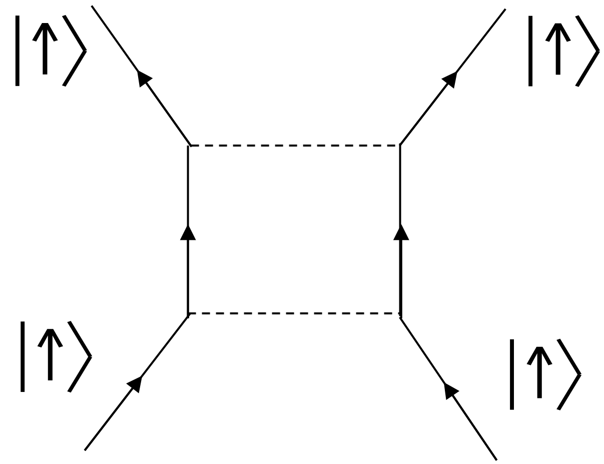
Spin-Based Searches Require Spin-Ensemble Engineering

Example: $H_N \supset g_{aff} \, \nabla a \cdot \sigma_f$



Long-range *spin-dependent* interaction

$$V_a \sim \frac{1}{f_a^2 r^3}$$



Spin-*independent* interaction

$$V_{2a}^{vac} \sim \frac{1}{f_a^4 r^5}$$ **Vacuum**

$$V_{2a}^{shift} \sim \frac{1}{f_a^4 r^3}$$ **Shift symmetry breaking**

$$V_{2a}^{bkg} \sim \frac{1}{f_a^4 r}$$ **Axion backgrounds**

M. Bauer and G.Rostagni. *“Fifth Forces from QCD Axions Scale Differently”*. PRL, 132(10):101802, (2024).

M. Bauer, F. Chadha-Day, A. Eberhart. “Discovering the Axiverse via Fifth Forces”. arXiv:2606.06606 (2026)

Y. Grossman, B. Yu, and S. Zhou. *“Axion forces in axion backgrounds”*. JHEP, 01:145, (2026).

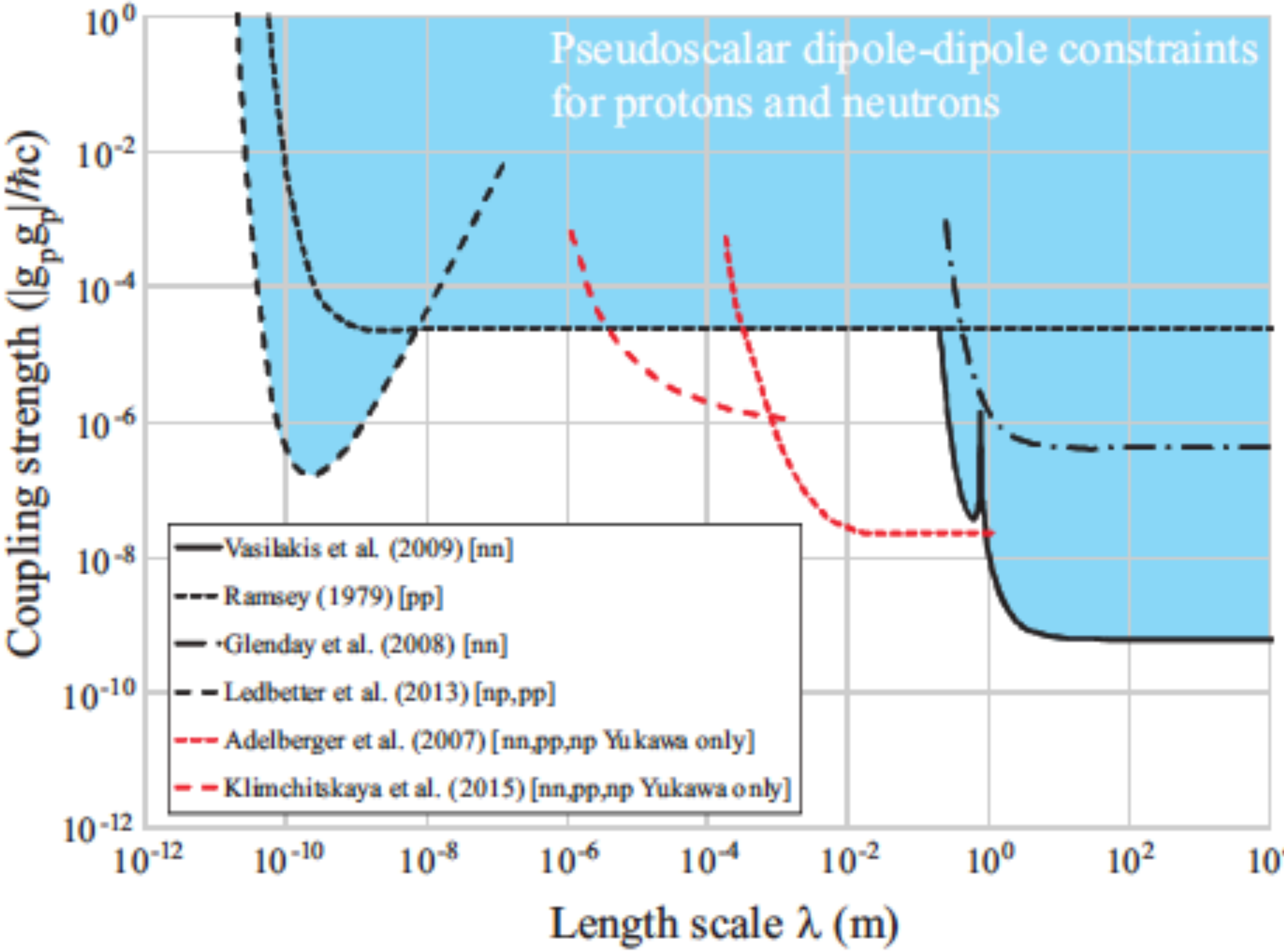
Y.Cheng and S.Ge. “Background-enhanced axion force by axion dark matter”. PRD 113, L111701 (2026).

Spin-Independent Precision Experiments

Experiments	$\delta V\,/\,V_{\text{grav}}$	$\langle r \rangle$
MICROSCOPE	3.8×10^{-15}	~ 7100km
Washington2007	1.8×10^{-13}	~ 6400km
Washington1999	3.0×10^{-9}	~ 0.3m
Irvine1985	7×10^{-5}	$2 - 5$cm
HUST2012	10^{-3}	~ 2mm
Eöt-Wash2006	2×10^{-3}	~ 0.5mm
HUST2020	3×10^{-3}	~ 0.3mm
Washington2020	~ 1	52μm
Future levitated optomechanics	$\sim 10^4$	1μm
IUPUI2014	2.7×10^7	560nm

V_{grav} is the Newtonian potential
δV is the contribution from long-range forces other than gravity.
The third column lists the typical length scale of the corresponding experiment.

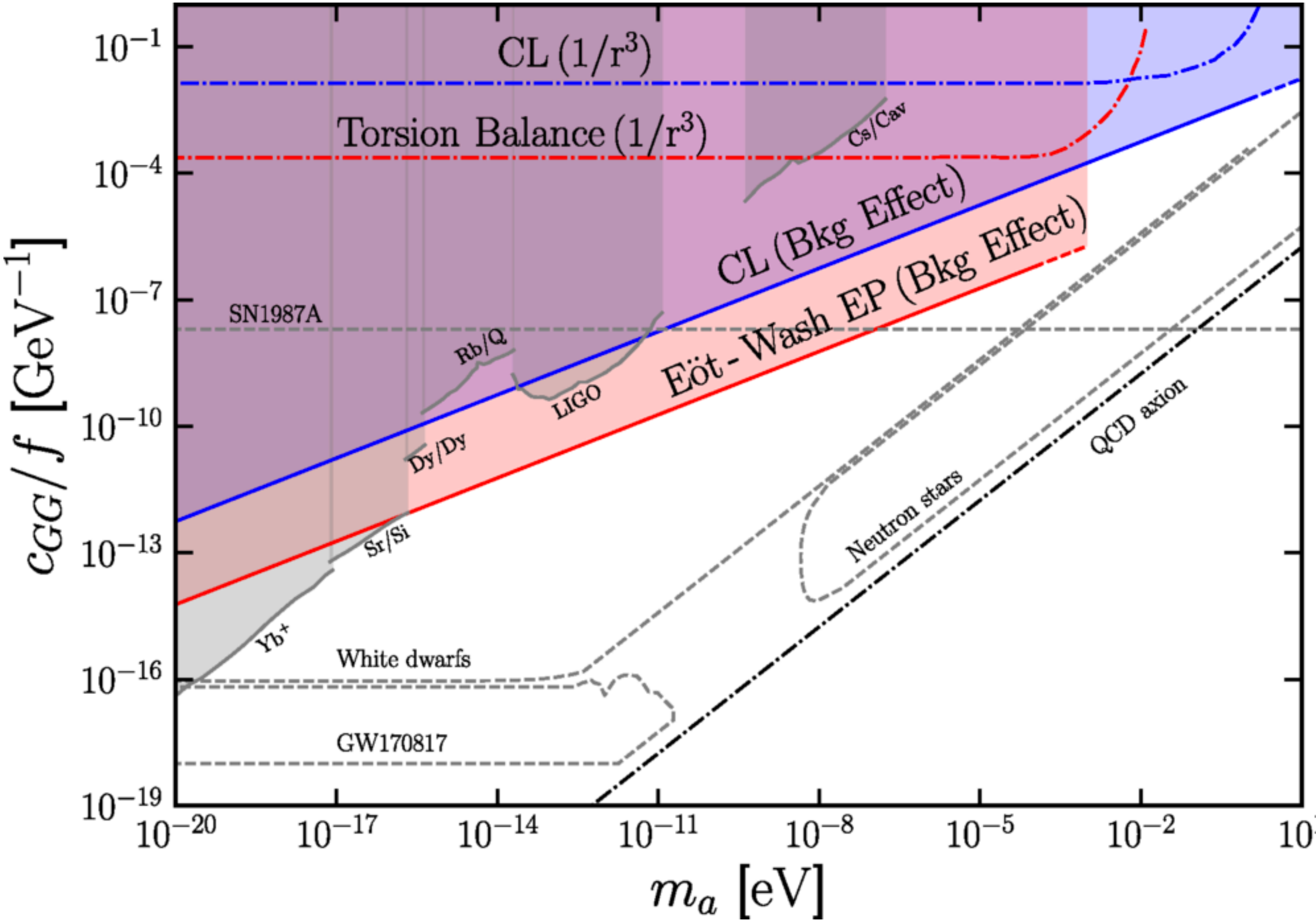
Constraints on the Axion Pseudoscalar Coupling



Blue → limits from spin-based experiments Red → spin-independent measurements

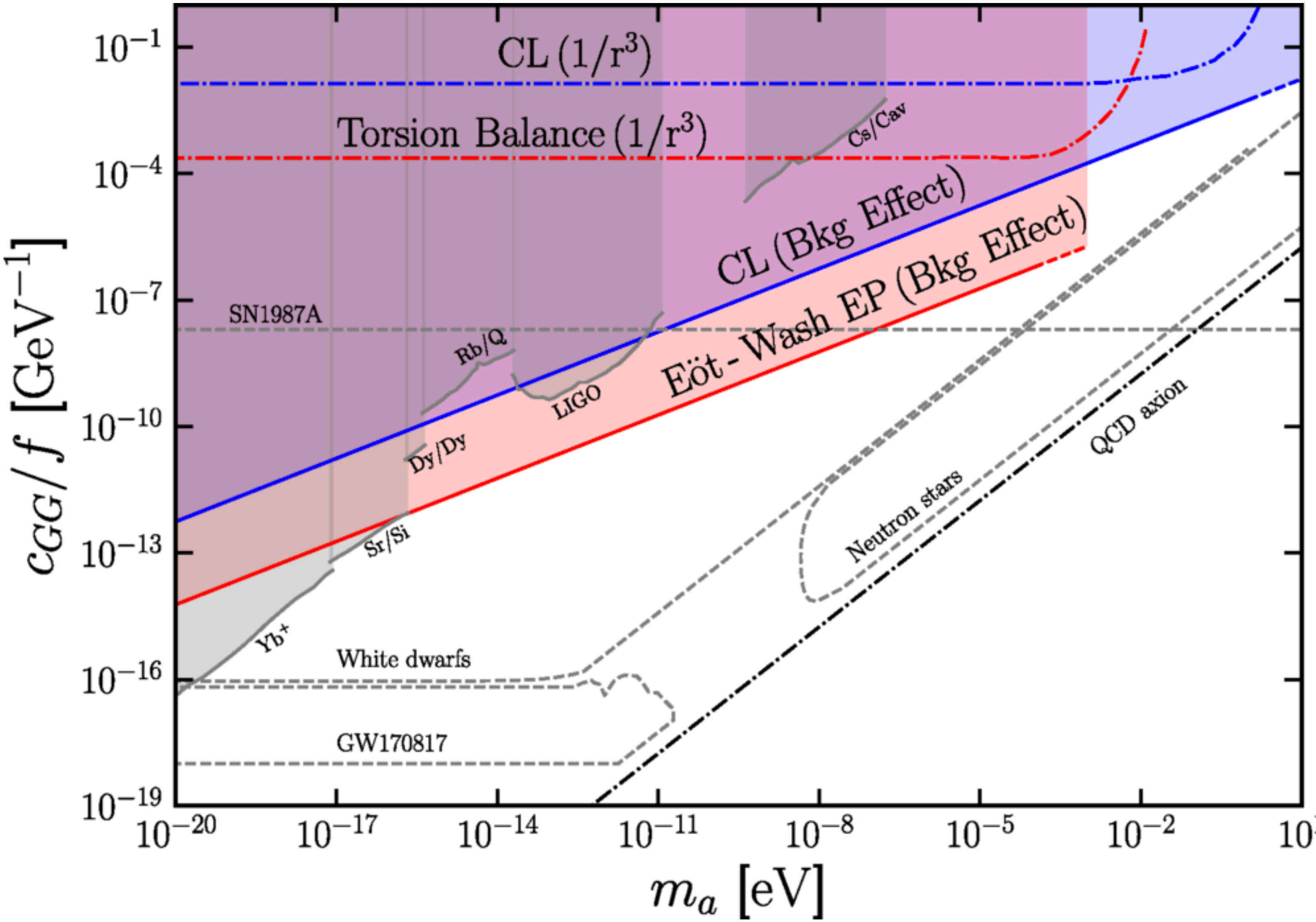
Reviews of Modern Physics, 90, 025008 (2018).

Constraints on the Axion's Parameters from Spin-Independent Measurements



PRD 113, L111701 (2026)

Constraints on the Axion's Parameters from Spin-Independent Measurements



A proof that sensitive experimental searches for spin-independent interactions can also yield interesting limits on spin-dependent interactions at certain distance scales.

Conclusion:

- ❖ Axion searches have traditionally focused on leading-order spin-dependent interactions, motivating highly sensitive polarized-spin experiments.

- ❖ Spin-based sensors offer tremendous sensitivity, but their ultimate performance depends on polarization, coherence, magnetic-field control, and spin-projection noise.

- ❖ Two-axion interactions provide a variety of spin-independent observables.

- ❖ Together with spin-independent precision measurements—and ultimately spin-independent quantum sensors—they provide a complementary route to axion searches that deserves further exploration.