Exploring Exotic Spin-Dependent Interactions Beyond the Standard Model

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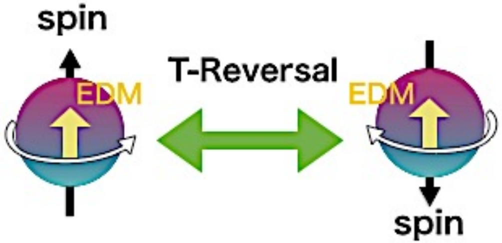
Outline

- Motivation and Theoretical Background
- Experimental Investigations
- Summary

Spin-dependent interactions mediated by axions

CP-violation in Strong Interaction

$$\mathcal{L}_{QCD}^{\mathrm{CP-odd}} = \theta \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

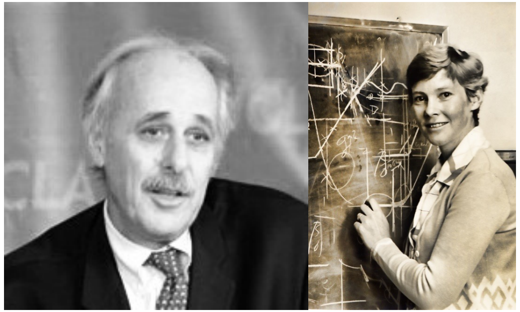


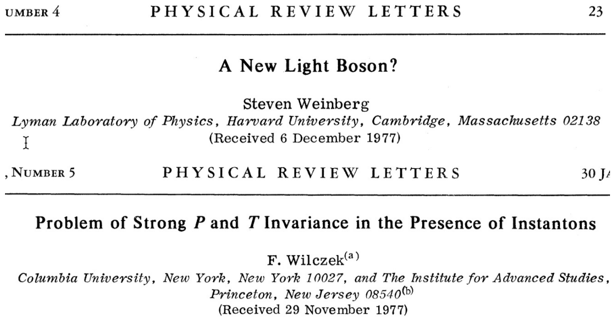
$\theta < 10^{-10}$, limited by the neutron EDM.

Peccei-Quinn (PQ) Symmetry

The θ-term is dynamically resolved with additional pseudoscalar particles and chiral U(1) symmetry, $U_{PQ}(1)$.

R. Peccei and H. Quinn, Phys. Rev. Lett. 38, 1440 (1977);
R. Peccei and H. Quinn, Phys. Rev. D 16, 1791 (1977).





UMBER 4 PHYSICAL REVIEW LETTERS 23

A New Light Boson?

Steven Weinberg
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 6 December 1977)

, NUMBER 5 PHYSICAL REVIEW LETTERS 30 J

Problem of Strong *P* and *T* Invariance in the Presence of Instantons

F. Wilczek[a]
Columbia University, New York, New York 10027, and The Institute for Advanced Studies, Princeton, New Jersey 08540[b]
(Received 29 November 1977)

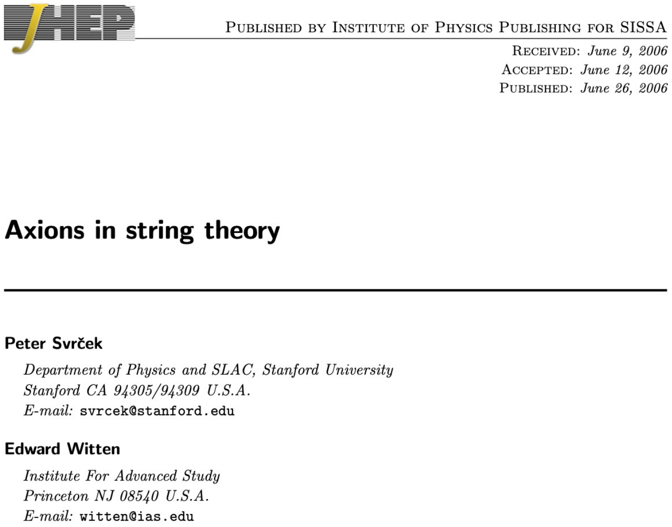
Wilczek and Weinberg identify axions, very light, neutral pseudoscalar particles, arising from this mechanism.

F. Wilczek, Phys. Rev. Lett. 40, 279 (1978);
S. Weinberg, Phys. Rev. Lett. 40, 223 (1978).

Axions: Bridging Modern Physics and Astronomy

NINGBO UNIVERSITY

Axions and axion-like particles (ALPs) also appear in many theories.



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Axions in string theory

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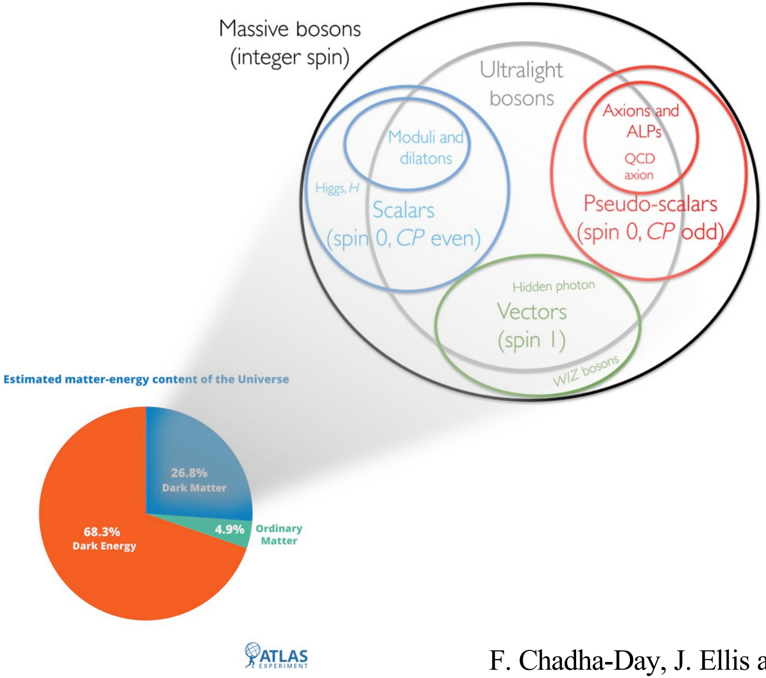
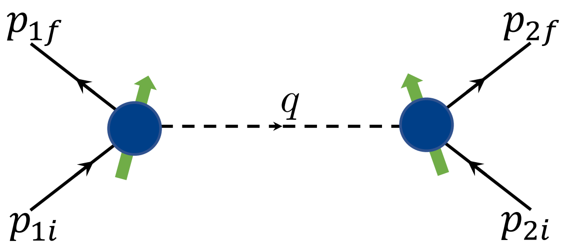
Plausible Dark Matter Candidate



F. Chadha-Day, J. Ellis and D. Marsh, Sci. Adv. 8, eabj3618 (2022).

Spin-dependent interactions mediated by axions

Being extremely light, axions may mediate macroscopic forces ($\lambda \sim \hbar / m_a c$) among ordinary matter.



Two fermions interacting via exchanging axion.

V D VOLUME 30, NUMBER 1

New macroscopic forces?

J. E. Moody* and Frank Wilczek
Institute for Theoretical Physics, University of California, Santa Barbara, California 93106
(Received 17 January 1984)

Phys. Rev. D 30, 130 (1984).

Interaction Lagrangian

$$\mathcal{L}_{\mathrm{SP}} = \bar{\psi}\phi(g_S + g_P i\gamma_5)\psi$$

- Monopole-dipole type

$$V_{\mathrm{SP}} = -g_S^1 g_P^2 \vec{\sigma}_2 \cdot \hat{r}\left(\frac{1}{r^2} + \frac{1}{\lambda r}\right)\frac{e^{-r/\lambda}}{8\pi m_2}$$

Interacting range: $\lambda = \dfrac{h}{mc}$

Spin-dependent interactions are ubiquitous

Light Z' boson exchange

$$\mathcal{L}_{\mathrm{VA}} = X_\mu \bar{\psi}\gamma^\mu (g_V + \gamma_5 g_A)\psi$$

P. Fayet, Phys. Lett., 95B(2), 285, (1980).

Interactions depend on the spin (σ), velocity (v), and separation (r) between two fermions.

- Monopole-dipole type

$$V_{\mathrm{VA}} = \underbrace{g_V^1 g_A^2}_{f_{12+13}} \underbrace{\vec{\sigma}_2 \cdot \vec{v}\frac{e^{-r/\lambda}}{4\pi r}}_{V_{12+13}}$$

$$V_{\mathrm{AA}} = \underbrace{-g_A^1 g_A^2 \frac{m_2^2}{4m_1(m_1+m_2)}}_{f_{4+5}} \underbrace{\vec{\sigma}_2 \cdot (\vec{v}\times\nabla)\frac{e^{-r/\lambda}}{4\pi m_2 r}}_{V_{4+5}}$$

Other types of spin-dependent interactions

Axion-wind

$$\mathcal{L} = g_{a\bar{\psi}\psi}\partial_\mu\phi\bar{\psi}_N\gamma^\mu\gamma_5\psi_N - \frac{i}{2}g_{EDM}\phi\bar{\psi}_N\sigma^{\mu\nu}\gamma_5\psi_N F^{\mu\nu}$$

Peter W. Graham and Surjeet Rajendran,
Phys. Rev. D 88, 035023 (2013).

As a dark-matter candidate, the light axion behaves as an oscillating field that couples to spin.

$$V = -g_{\phi\bar{\psi}\psi}\boxed{\nabla\phi\cdot\vec{\sigma}} - g_{\mathrm{EDM}}\boxed{\phi\vec{E}\cdot\vec{\sigma}}$$

magnetic-dipole coupling electric-dipole coupling

Lorentz and CPT-violating field

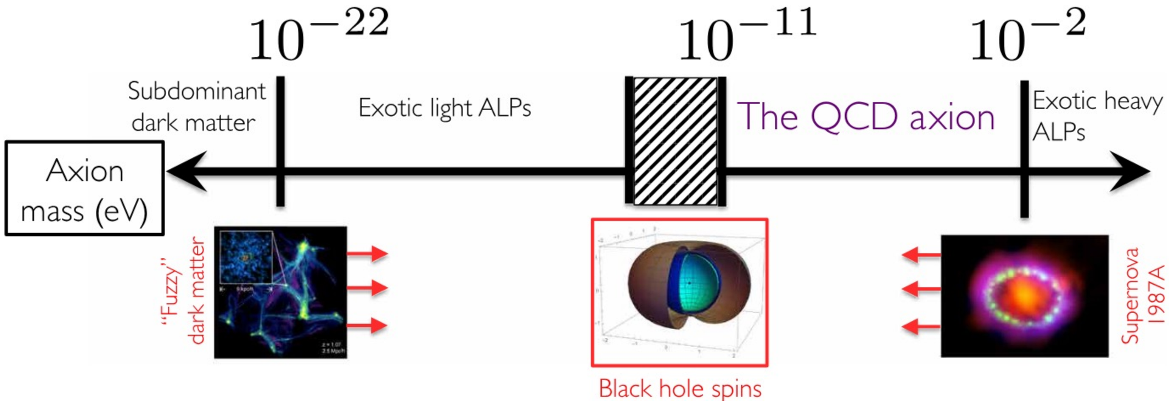
$$\mathcal{L} = -b_\mu\bar{\psi}\gamma^5\gamma^\mu\psi + \frac{1}{2}ig_{\mu\nu\lambda}\bar{\psi}\sigma^{\mu\nu}\gamma^5\partial^\lambda\psi - \frac{1}{2}H_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi + id_{\mu\nu}\bar{\psi}\gamma^5\gamma^\mu\partial^\nu\psi$$

V. Kostelecky and Charles D. Lane, Phys. Rev. D 60, 116010 (1999).

The spin-dependent interactions arise from the Lorentz-violating extension of the standard model.

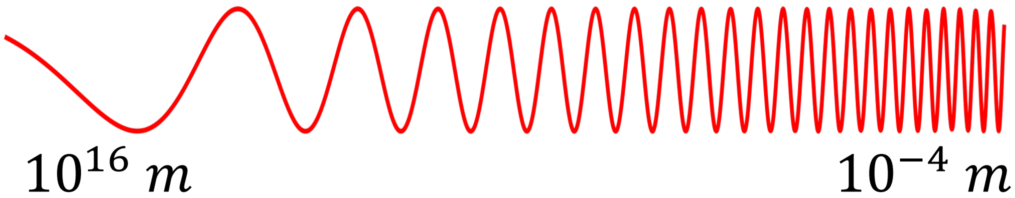
$$V_{\mathrm{LV}} = -(\vec{b} - m\vec{d} + m\vec{g} - \vec{H})\cdot\vec{\sigma}$$

The Possible Axion Mass Range



Compton wavelength

$$\lambda = \frac{h}{mc}$$



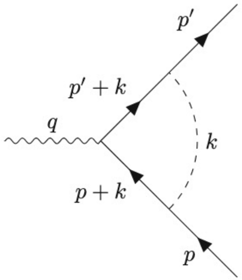
F. Chadha-Day, J. Ellis and D. Marsh, Sci. Adv. 8, eabj3618 (2022).

A variety of experiments are needed to explore the entire parameter space.

Detection at atomic scales: Muon g-2

The electromagnetic vertex correction contributed by new interactions.

$$\bar{u}(p')\Gamma_\mu u(p) = \bar{u}(p')(\gamma_\mu + \gamma_\mu F_1(q^2) + i\frac{\sigma_{\mu\nu}q_\nu}{2m}F_2(q^2) + \frac{\gamma_5\sigma_{\mu\nu}q_\nu}{2m}F_2(q^2))u(p)$$



EDM:

$$d_\mu = -\frac{e}{8\pi^2 m_\mu}\int_0^1 d_x \frac{(1-x)^2}{(1-x)^2 + x(m_\phi/\mu_m u)^2}$$

H. Yan, Eur. Phys. J. C (2019) 79:971.

Muon g-2:

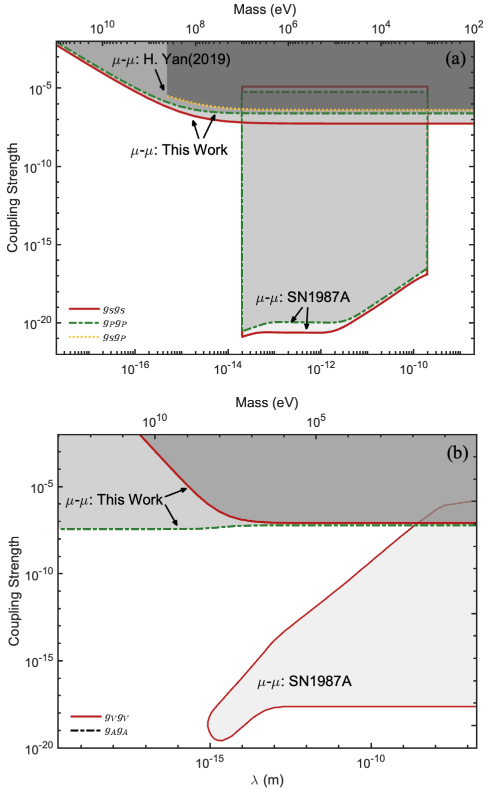
$$\delta a_\mu = \frac{1}{8\pi^2}\int_0^1 \left[g_S^2\frac{(1-x)^2(1+x)}{(1-x)^2 + x(m_\phi/m_\mu)^2} - g_P^2\frac{(1-x)^3}{(1-x)^2 + x(m_\phi/m_\mu)^2}\right]dx$$
$$+ \frac{m_\mu^2}{4\pi^2 m_X^2}\int_0^1 \left[g_V^2\frac{x^2(1-x)}{1-x+x^2(m_\mu/m_X)^2} - g_A^2\frac{x(1-x)(4-x)+2x^3(m_\mu/m_X)^2}{1-x+x^2(m_\mu/m_X)^2}\right]dx$$

Latest result on muon g-2:

$$\Delta a_\mu = a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (38 \pm 63) \times 10^{-11}$$

R. Aliberti, arXiv.2505.21476.

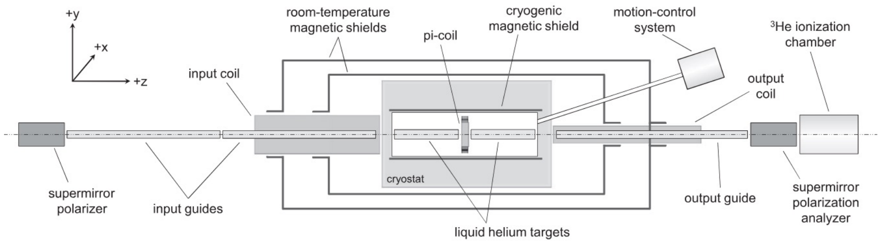
Constraints on the coupling strengths of scalar and vector particles to muon.



L. Y. Wu and H. Yan, arXiv:2508.00504.

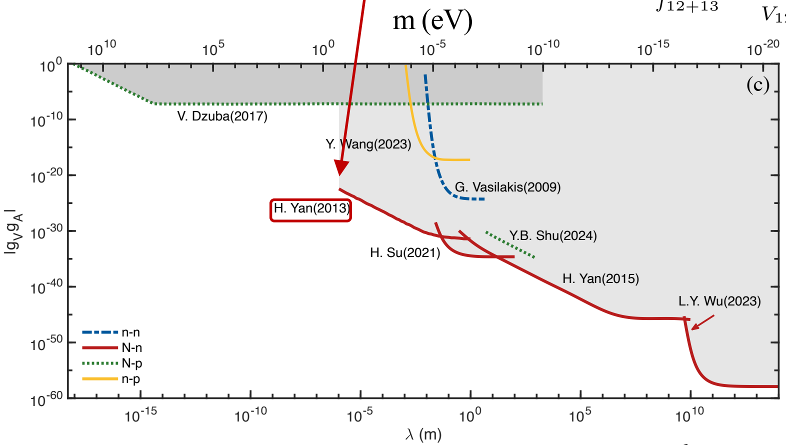
Detection at mesoscopic scales (mm-um): spin rotation

$$\frac{d\phi}{dL} = 1.7 \pm 9.1(\mathrm{stat}) \pm 1.4\mathrm{syst}) \times 10^{-7}\ \mathrm{rad/m}$$



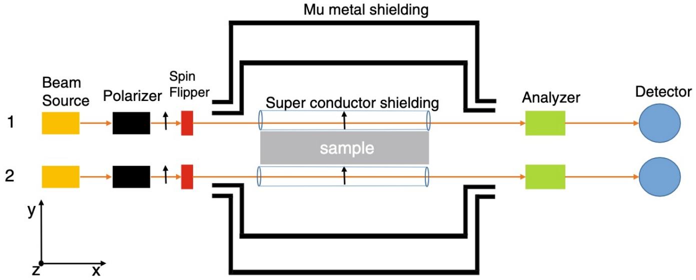
H. Yan and W. M. Snow, Phys. Rev. Lett. 110, 082003 (2013).

Parity-odd: $V_{\mathrm{VA}} = \underbrace{g_V^1 g_A^2}_{f_{12+13}} \underbrace{\vec{\sigma}_2 \cdot \vec{v} \frac{e^{-r/\lambda}}{4\pi r}}_{V_{12+13}}$



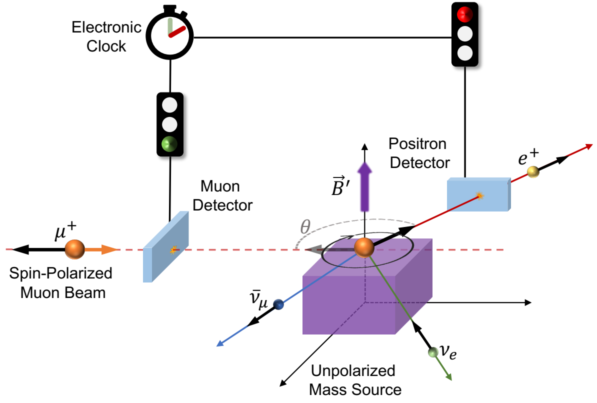
The most stringent constraint to date at $10^{-6} < \lambda < 10^{-2}\ m$.

^{3}He beam with high beam intensity ($\sim 10^{14}\ atoms/s$)



^{3}He spin rotation

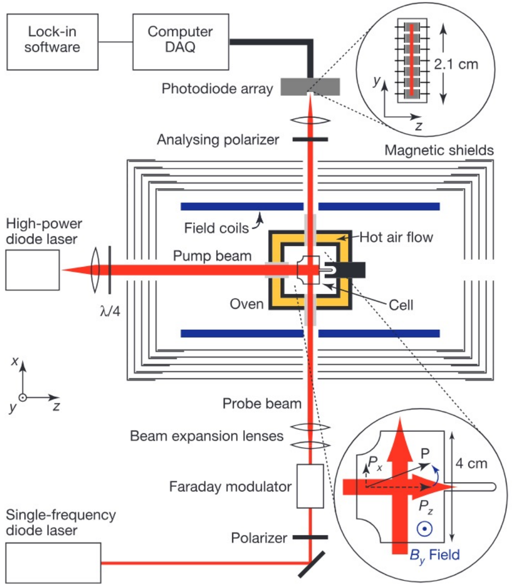
H. Yan and et al., Eur. Phys. J. C (2014) 74:3088.

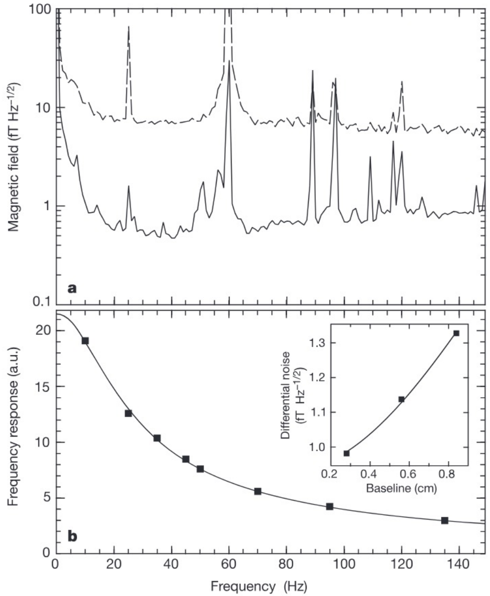


Muon spin rotation based on μSR technique

Detection at laboratory scales: atomic magnetometers

The spin-polarized alkali vapor magnetometers working in SERF region show ultra-high sensitivity ($\sim f\mathrm{T}/\sqrt{Hz}$).





I. Kominis, T. Kornack, J. Allred and M. Romalis, Nature **422**, 596 (2003).

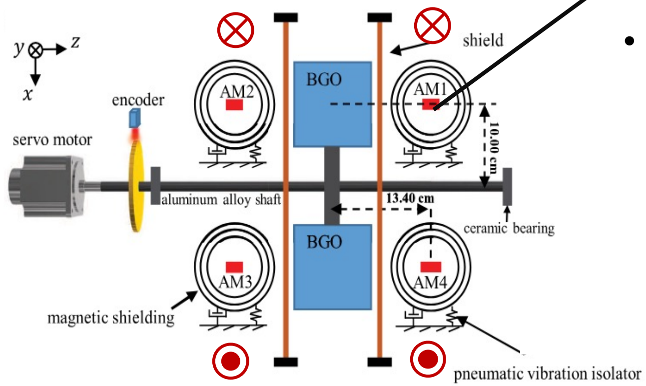
Commercial available alkali magnetometer by QuSpin Inc.

Detection at laboratory scales: atomic magnetometers

$$V_{\mathrm{VA}} = \underbrace{g_V^1 g_A^2}_{f_{12+13}} \underbrace{\vec{\sigma}_2 \cdot \vec{v} \frac{e^{-r/\lambda}}{4\pi r}}_{V_{12+13}} \longrightarrow$$

Effective magnetic field: $\vec{B}_{\mathrm{eff}} = \frac{1}{\gamma} g_V^1 g_A^2 \vec{v} \frac{e^{-r/\lambda}}{2\pi r}$

Exotic field direction



K. Y. Wu and et al., Phys. Rev. Lett. 129, 051802 (2022).

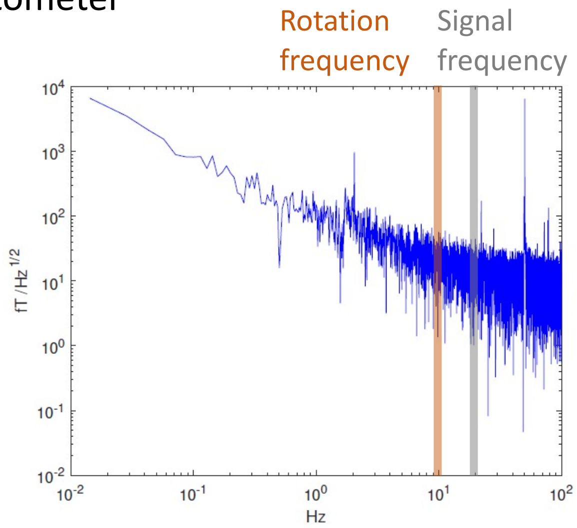
Commercial available SERF magnetometer

- Size: centimeter-scale
- Sensitivity: 20 $f\mathrm{T}/\sqrt{Hz}$

$$\vec{B}_{\mathrm{sig}} = \frac{1}{4}(\vec{B}_1 + \vec{B}_2 - \vec{B}_3 - \vec{B}_4)$$

Noise is suppressed by 50 percent

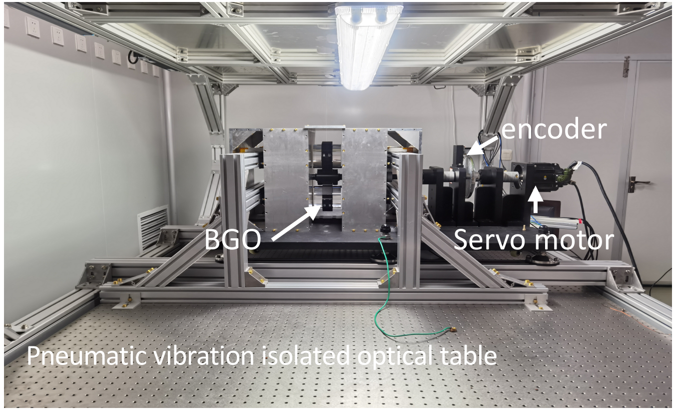
$$\delta B_{\mathrm{sig}} = \frac{1}{2}\delta B_1$$



The typical noise power density of the magnetometer.

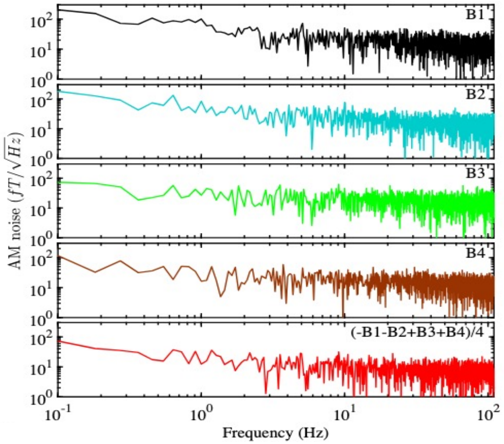
1. Modulation the mass source at $\sim$20 Hz where noise is reduced;
2. Using Magnetometer array to cancel common-mode noise.

Detection at laboratory scales: atomic magnetometers

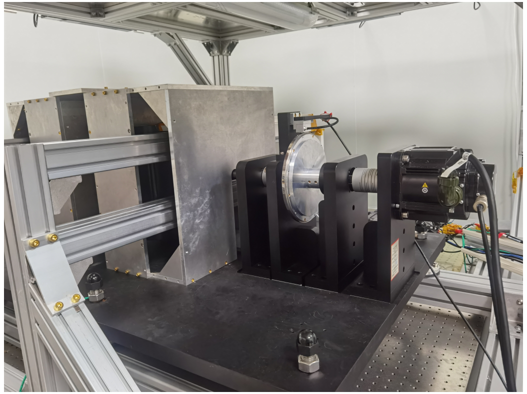


Common noise is suppressed with commercial SERF magnetometers in array.

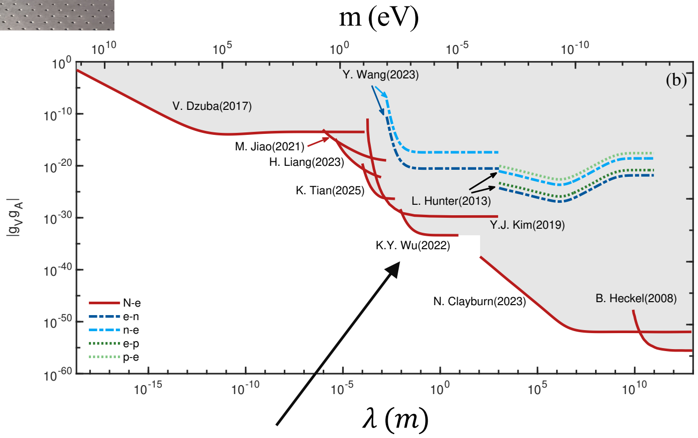
$$B_{\text{exp}} = \frac{1}{4}(-B_1 - B_2 + B_3 + B_4)$$



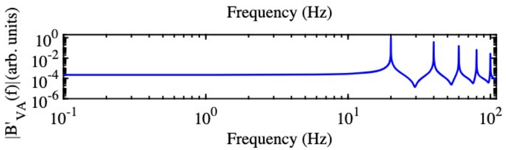
Noise PSD



Experimental Setup



The constraint on VA coupling after 130 h data integration.



Monte Carlo Simulation

KY Wu, SY Chen, GA Sun, SM Peng, M Peng, H Yan
Physical Review Letters 129 (5), 051802

Detection at Earth Range: ^{3}He Relaxation

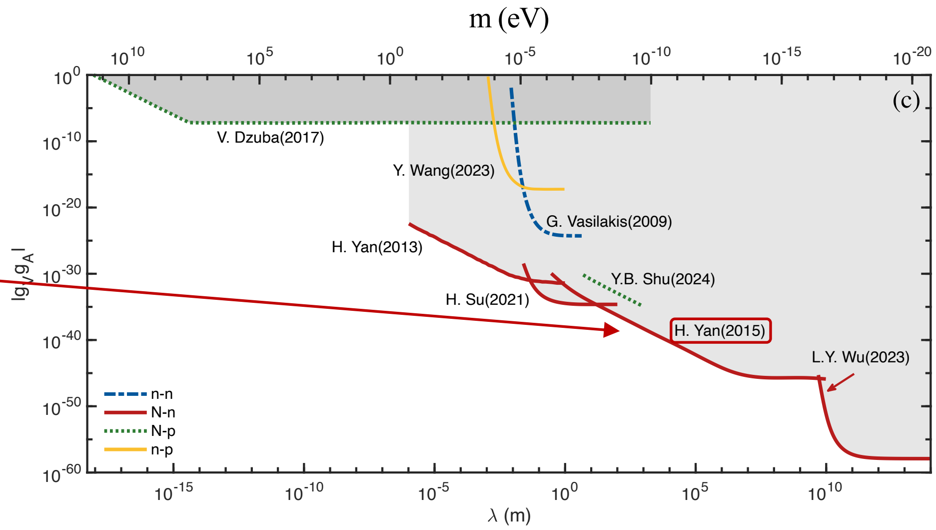
$$V_{\mathrm{VA}} = \underbrace{g_V^1 g_A^2}_{f_{12+13}} \underbrace{\vec{\sigma}_2 \cdot \vec{v}\frac{e^{-r/\lambda}}{4\pi r}}_{V_{12+13}}$$

Relaxation of ^{3}He caused by fluctuated exotic field:

$$1/T_2 \propto \int_{-\infty}^{\infty} < B'(0)B'(\tau) > e^{-i\omega_0\tau} d\tau$$

Taking advantage of

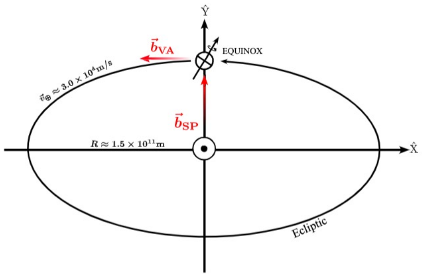
- Long ^{3}He relaxation time $T_2 \sim 60$ h
- Large unpolarized nucleon in the Earth 10^{51}



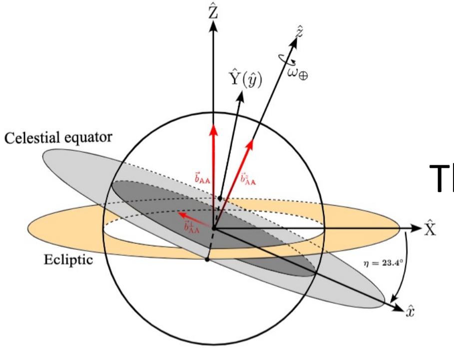
H Yan, GA Sun, SM Peng, Y Zhang, C Fu, H Guo, BQ Liu, Phys. Rev. Lett., 115, 182001 (2015).

Detection at astronomical distances

$$V_{\mathrm{SP}} = \underbrace{\frac{g_S^1 g_P^2}{2}}_{f_{9+10}} \underbrace{\vec{\sigma}_2 \cdot \nabla \frac{e^{-r/\lambda}}{4\pi m_2 r}}_{V_{9+10}} \qquad V_{\mathrm{VA}} = \underbrace{g_V^1 g_A^2}_{f_{12+13}} \underbrace{\vec{\sigma}_2 \cdot \vec{v} \frac{e^{-r/\lambda}}{4\pi r}}_{V_{12+13}}$$



(a)



(b)

The spin-dependent interactions in Sun-centered and Earth-based frames.

The unpolarized nucleon in the Sun as source

$$\boldsymbol{B}'_{\mathrm{SP}} = \frac{\hbar g_S^N g_P^n N_{\odot}}{4\pi m_n \gamma_n}(\frac{1}{\lambda R} + \frac{1}{R^2})\exp(-R/\lambda)[\cos(\Omega_{\oplus} t)\hat{X} + \sin(\Omega_{\oplus} t)\hat{Y}]$$

$$\boldsymbol{B}'_{\mathrm{VA}} = \frac{g_V^N g_A^n N_{\odot}}{\pi \gamma_n} \frac{\exp(-R/\lambda)}{R}[-\Omega_{\oplus} R \sin(\Omega_{\oplus} t)\hat{X} + \Omega_{\oplus} R \cos(\Omega_{\oplus} t)\hat{Y}]$$

The Earth's rotation as a modulation to the exotic signal

$$\boldsymbol{b}_{\mathrm{SP}\perp} = \frac{\hbar g_S^N g_P^n N_{\odot}}{4\pi m_n \gamma_n}(\frac{1}{\lambda R} + \frac{1}{R^2}) \exp(-R/\lambda) [\sin(\omega_{\oplus} t)\hat{x} + \cos(\omega_{\oplus} t)\hat{y}]$$

$$\boldsymbol{b}_{\mathrm{VA}\perp} = -\frac{g_V^N g_A^n N_{\odot}}{\pi \gamma_n} \frac{\exp(-R/\lambda)}{R} v_{\oplus} \cos\eta [-\cos(\omega_{\oplus} t)\hat{x} + \sin(\omega_{\oplus} t)\hat{y}]$$

Detection at astronomical distances

Search for sidereal modulation on the spin precession in ^{3}He-^{129}Xe comagnetometer caused by the exotic interaction.

$$\omega_1 = \gamma_3 B_0 + b\cos(\omega_\oplus t)$$
$$\omega_2 = \gamma_{129} B_0 + b\cos(\omega_\oplus t)$$
$$b\cos(\omega_\oplus t) = \frac{\gamma_{129}\omega_1 - \gamma_3\omega_2}{\gamma_{129} - \gamma_3}$$

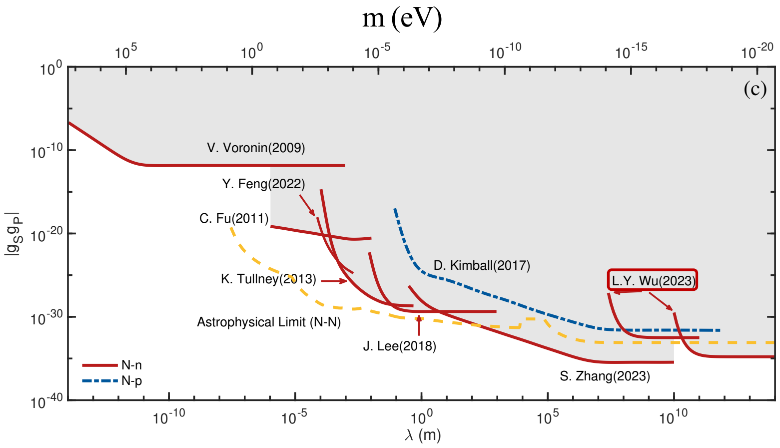
Based on the Lorentz-violation test experiment using ^{3}He-^{129}Xe comagnetometer.

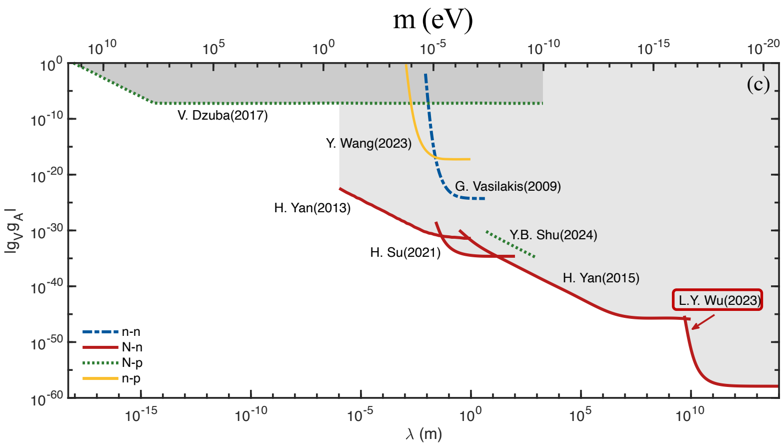
F. Allmendinger and et al., Phys. Rev. Lett. 112(11):110801, (2014).

Upper limit on the exotic magnetic field sourced by the Sun:

$$|B_{\text{eff}}| \leq 0.023\ fT\ (95\% - \text{CL})$$

L. Y. Wu, KY Zhang, M Peng, J Gong, H Yan., Phys. Rev. Lett. 131, 091002 (2023).





Constraining the axion wind

The axion with large occupation acting like a “classical field” around the Earth.

Wave vector $k = m_a v$

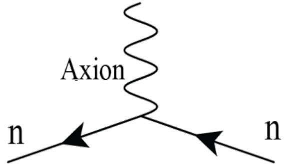
Random phase

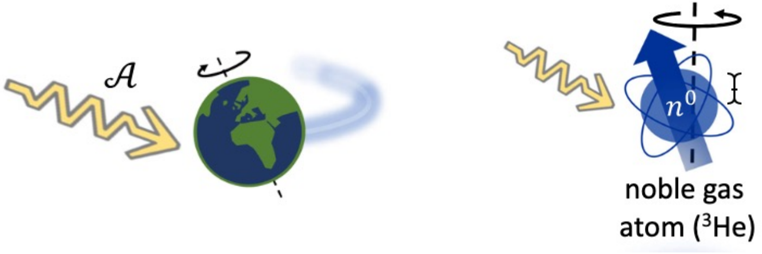
$$a(t) = a_0 \cos(\omega t - \vec{k} \cdot \vec{r} + \phi)$$

Amplitude decided by local DM density $\rho = 0.4\ \mathrm{GeV/cm^3}$.

Compton frequency $\omega = m_a c^2/\hbar$

axion-fermion coupling





I. Bloch and et al., Nature Communications | (2023)14:5784

Modulation on Larmor frequency:

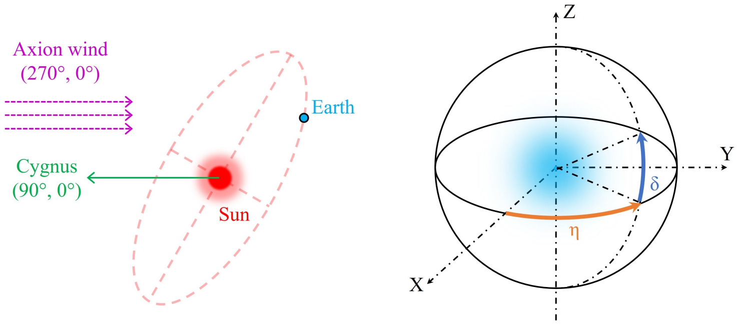
$$\nu(t) = \nu_0 + \delta\nu \cos(\omega_a t + \phi)$$

Constraining the axion wind

For ultralow frequencies axion field:

$$V = 2g_{\mathrm{aNN}}\sqrt{2\hbar^3 c\rho_a}\sin(2\pi\nu_a t+\phi)\vec{v}_a\cdot\vec{I}_N$$
$$\approx \underline{2g_{\mathrm{aNN}}\sqrt{2\hbar^3 c\rho_a}\sin(\phi)\vec{v}_a}\cdot\vec{I}_N$$

Effective magnetic field with random amplitude



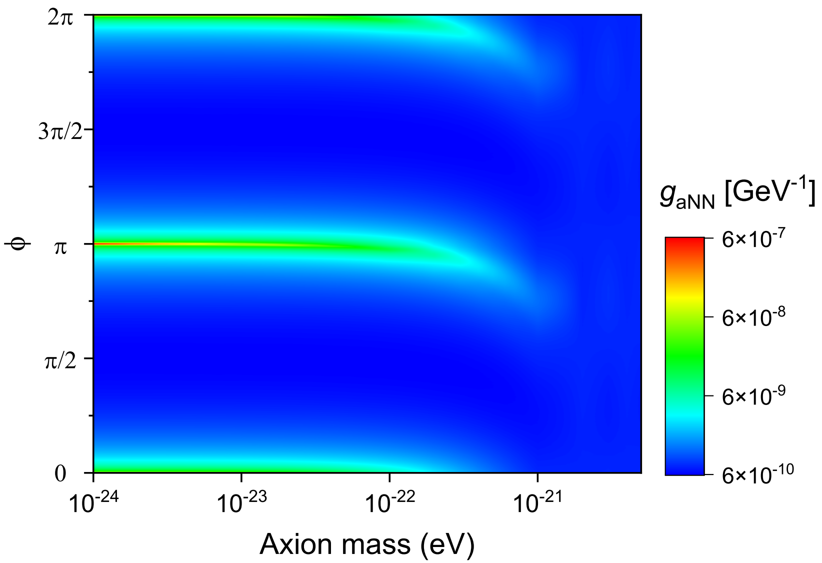
(a) Galactic coordinates (b) Celestial coordinates

Axion wind in the galactic and and celestial coordinates.

K. Y. Zhang, L. Y. Wu and H. Yan. Phys. Rev. Lett. (Accepted 29 August, 2025)

The Lorentz-violation test experiment with ^{3}He-^{129}Xe comagnetometer is always sensitive to axion wind coupling.

F. Allmendinger and et al., Phys. Rev. Lett. 112(11):110801, (2014).

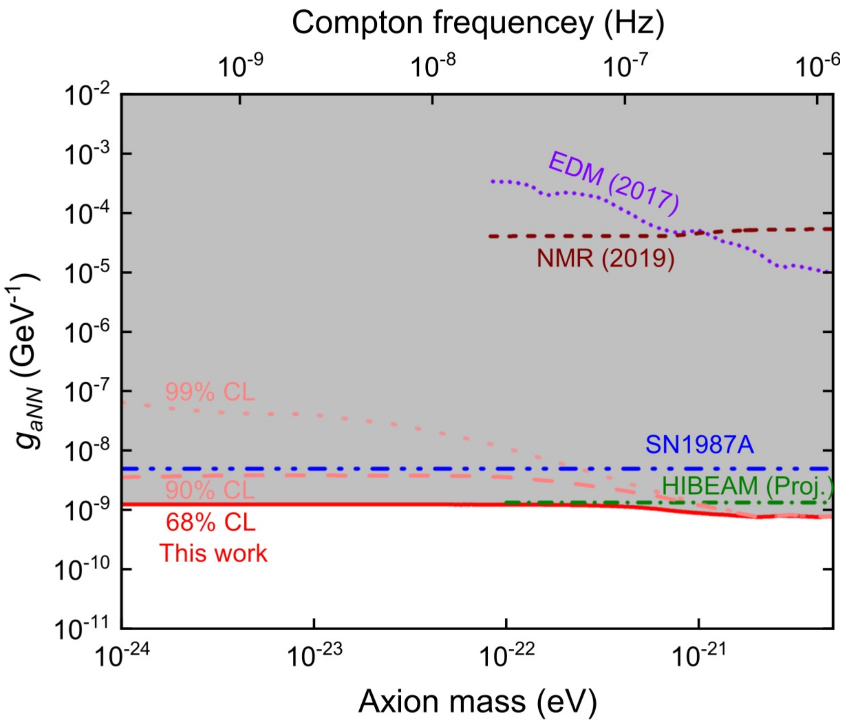


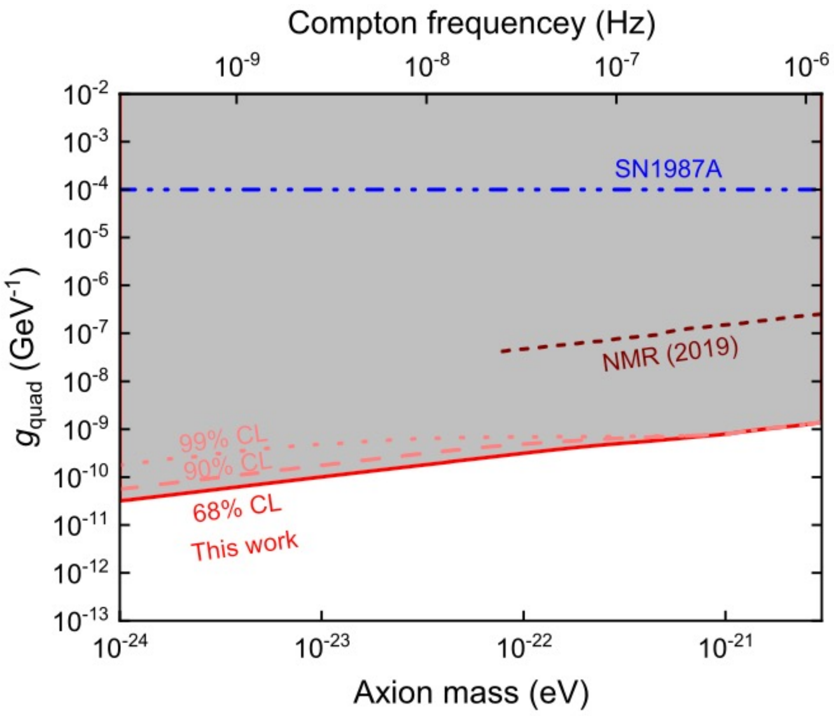
Influence of the random phase ϕ on the coupling strength g_{aNN} is significant at low mass.

Constraining the axion wind

New limits on g_{aNN} over the axion mass region $10^{-24} < m_a < 5\times 10^{-21}$ eV.

$$V = 2g_{\rm quad}^2\hbar^2c^2\frac{\rho_a}{2\pi\nu_a}\sin(4\pi\nu_a t+\phi)\boldsymbol{v}_a\cdot\boldsymbol{I}_N$$





Summary

- The spin-dependent interactions are common features of the new physics;
- Spin-based sensors are sensitive to detect such interactions;
- The parameter space ($\lambda{\sim}g_i g_j$) of the interactions should be explored using different strategies.

Thank you for your attention.