中国工程物理研究院
CHINA ACADEMY OF ENGINEERING PHYSICS

Searching for Axions and Axion-Like Particles via Spin-Dependent Interactions

H.Yan

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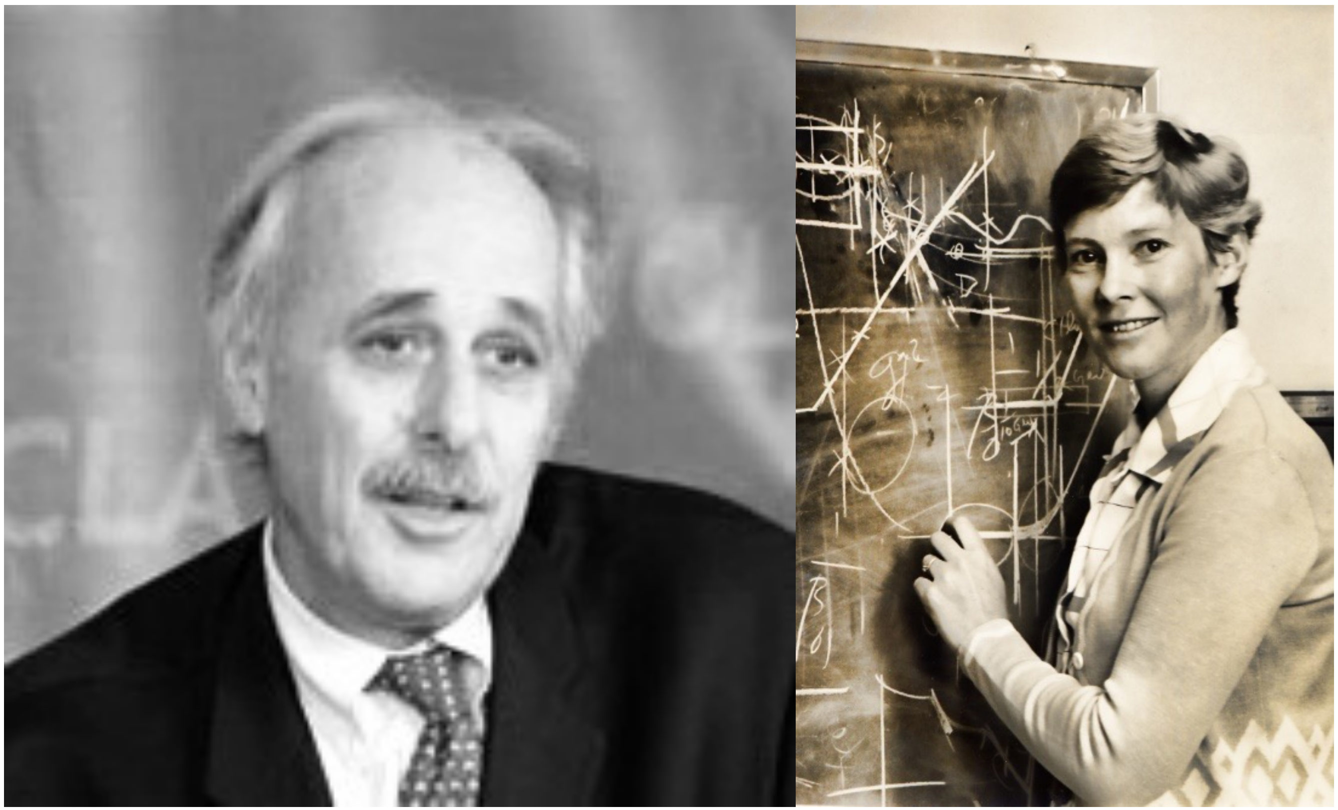
Outline

- Background
- Magnetometer array study
- Constraints at Astrophysical distances

PQ Mechanism：Proposed by Peccei and Quinn In 1977

A new global symmetry is introduced and spontaneously broken：

$$\mathfrak{L} = -\tfrac{1}{4} F_{\mu\nu}{}^{a} F^{\mu\nu a} + i\,\bar{\psi} D_{\mu}\gamma^{\mu}\psi + \bar{\psi}\left[G\varphi\tfrac{1}{2}(1+\gamma_5) + G^{*}\varphi^{*}\tfrac{1}{2}(1-\gamma_5)\right]\psi - |\partial_{\mu}\varphi|^2 - \mu^2|\varphi|^2 - h|\varphi|^4; \quad \mu^2 < 0.$$



R.Peccei与H.Quinn

W&W: noticing axion generation simultaneously

), Number 4 PHYSICAL REVIEW LETTERS 23 January 1978

A New Light Boson?

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

It is pointed out that a global U(1) symmetry, that has been introduced in order to preserve the parity and time-reversal invariance of strong interactions despite the effects of instantons, would lead to a neutral pseudoscalar boson, the "axion," with mass roughly of order 100 keV to 1 MeV. Experimental implications are discussed.

umber 5 PHYSICAL REVIEW LETTERS 30 January 1978

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

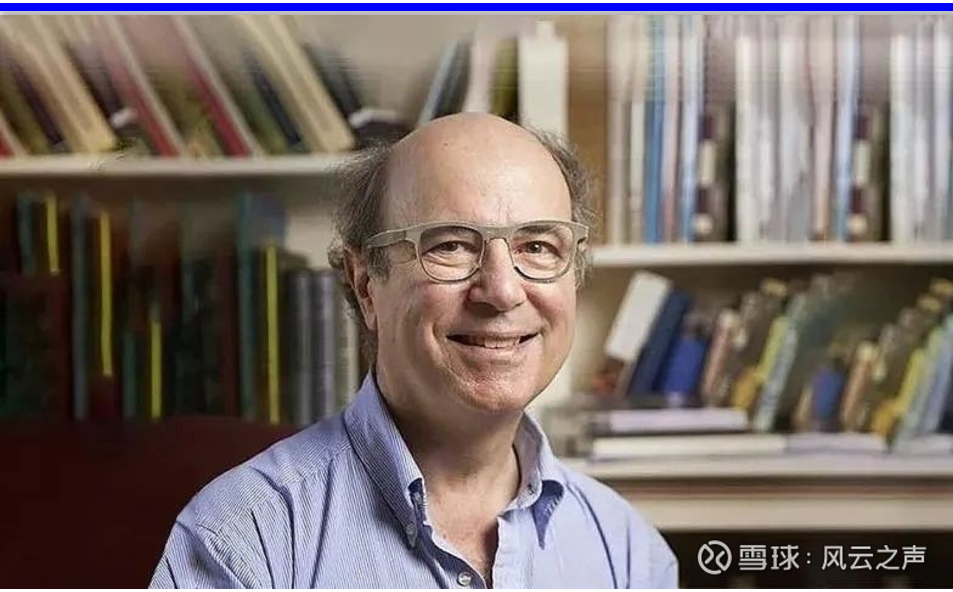
F. Wilczek[a]
:olumbia University, New York, New York 10027, and The Institute for Advanced Studies, Princeton, New Jersey 08540[b]
(Received 29 November 1977)

The requirement that *P* and *T* be approximately conserved in the color gauge theory of strong interactions without arbitrary adjustment of parameters is analyzed. Several possibilities are identified, including one which would give a remarkable new kind of very light, long-lived pseudoscalar boson.

S.Weinberg与F.Wilczek

F. Wilczek：More than Just the Namer of Axion

Spin



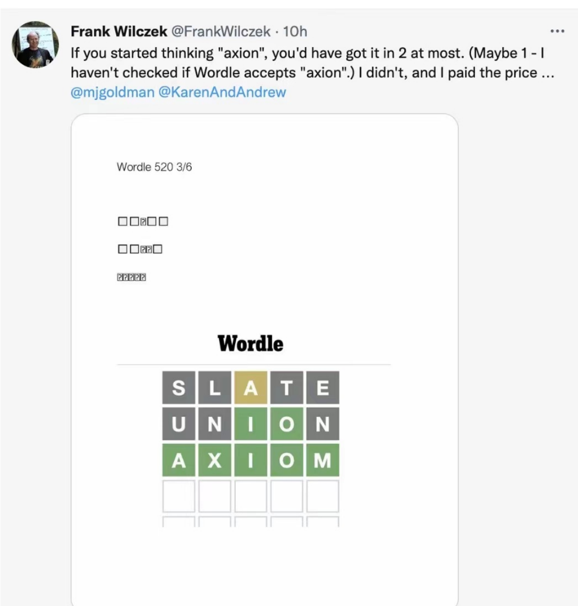
Accounting for a Wrinkle in Time

In most cases, physics follows the same rules whether things run forward or backward—but not quite always

ILLUSTRATION: TOMASZ WALENTA

By Frank Wilczek

Nov. 17, 2022 at 3:27 pm ET



Axions are predicted to be hard to detect, but research physicists around the world are designing and building instruments that could be up to the job. If so, the ultimate explanation for exceptions to T would be different from Feynman's joke and more in line with one of Einstein's:

"Subtle is the Lord, but malicious He is not!"

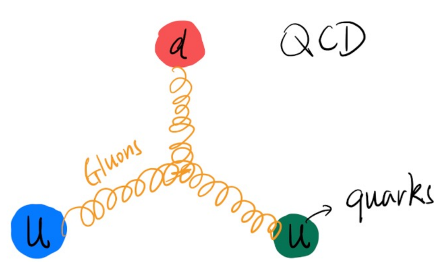
Just a few hours ago:

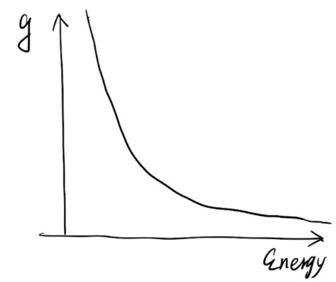
Lecture description from Wilczek

The first lecture or two will be devoted to the confinement problem of QCD, leading including new ideas about flux tubes and their junctions (“treeons”), channeling flux, and a new approach to hadronic matter that these insights suggest.

The next 5-6 lectures will revolve around time reversal symmetry (T). This will lead us through the foundational work that establishes the “strong T problem” as a shortcoming of the standard model of fundamental physics. Topics include Kramers’ theorem, anomalies, instantons, and the deep structure of the standard model itself. Then I will discuss axion physics: how addressing the strong T problem leads us to introduce axions, their properties, their potential to make the “dark matter” of the universe, and the ongoing quest to detect the cosmic axion background experimentally. I will discuss in some detail the ALPHA project, which is one such effort, that brings in new ideas for resonator design, metamaterials, and quantum sensing. Then I will discuss how T violation manifests itself in laboratory experiments, both as a fundamental phenomenon and as an emergent characteristic of several interesting, technologically significant materials. Finally, in this series, I will discuss the established and potential role of T violation in biology, also touching on biological P violation as a interesting role model.

Finally, if time permits, I will discuss metastability in matter and cosmology; specifically, indicators of eventual decay that can be seen well before that happens (or not). This leads in several interesting directions …





Axions: mediating macroscopic interactions

PHYSICAL REVIEW D VOLUME 30, NUMBER 1 1 JULY 1984

New macroscopic forces?

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

The forces mediated by spin-0 bosons are described, along with the existing experimental limits. The mass and couplings of the invisible axion are derived, followed by suggestions for experiments to detect axions via the macroscopic forces they mediate. In particular, novel tests of the *T*-violating axion monopole-dipole forces are proposed.

$$\mathcal{L}_\phi = \bar{\psi}(g_s + i g_p \gamma_5)\psi\phi \longrightarrow V_{SP}(r) = \frac{\hbar^2 g_S g_P}{8\pi m_e}\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right)\exp(-r/\lambda)\vec{\sigma}\cdot\hat{r}$$

1.The most elegant and promising solution to the strong CP problem in QCD;

2.Very hard to detect, couple to the ordinary matter very weakly—candidate for cold dark matter;

$$m_A{}^2 = \frac{-v}{F^2}\left[\frac{m_u m_d m_s}{m_u m_d + m_d m_s + m_s m_u}\right] \qquad H_{\text{int}} = a\frac{m_e}{F}\bar{e}\, i\gamma_5 e\ .$$

3.Axion and ALPs can mediate macroscopic interactions thus can be probed through the bosonic field they generate;

4. Spin dependent interactions can be propagated—polarized spins are needed.

Axion Like Particles: generalization

Spin

Spin 1 boson coupled Lagrangian: $\mathcal{L}_X = \bar{\psi}(g_V\gamma^\mu + g_A\gamma^\mu\gamma_5)\psi X_\mu$

$$V_{VA}(r) = \frac{\hbar g_V g_A}{2\pi}\frac{\exp(-r/\lambda)}{r}\vec{\sigma}\cdot\vec{v}$$

$$V_{AA}(r) = \frac{\hbar^2 g_A^2}{16\pi mc}(\frac{1}{\lambda r} + \frac{1}{r^2})\exp(-r/\lambda)\vec{\sigma}\cdot(\vec{v}\times\hat{r})$$

1.**Dobrescu et al: the propagator of the new interaction could be spin-1 particle;**

2.Fayet noticed that spontaneous breaking of supersymmetry theory could generate spin 1 particle with light mass and weak coupling.

B. Dobrescu and I. Mocioiu, J. High Energy Phys. 11, 005(2006).
P.Fayet, Phys. Lett., 95B(2), 285, (1980).

Axions & ALPs:

The intersection of the most important problems in modern physics and astronomy

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Axions in string theory

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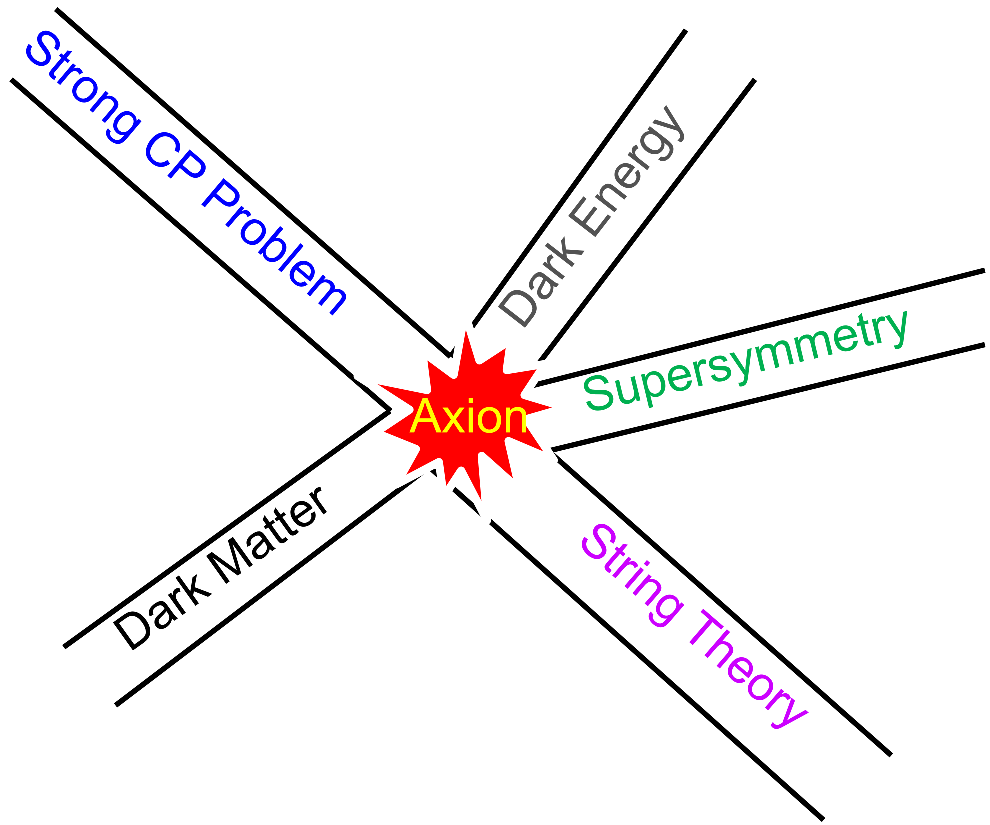
Abstract: In the context of string theory, axions appear to provide the most plausible solution of the strong CP problem. However, as has been known for a long time, in many string-based models, the axion coupling parameter F_a is several orders of magnitude higher than the standard cosmological bounds. We re-examine this problem in a variety of models, showing that F_a is close to the GUT scale or above in many models that have GUT-like phenomenology, as well as some that do not. On the other hand, in some models with Standard Model gauge fields supported on vanishing cycles, it is possible for F_a to be well below the GUT scale.

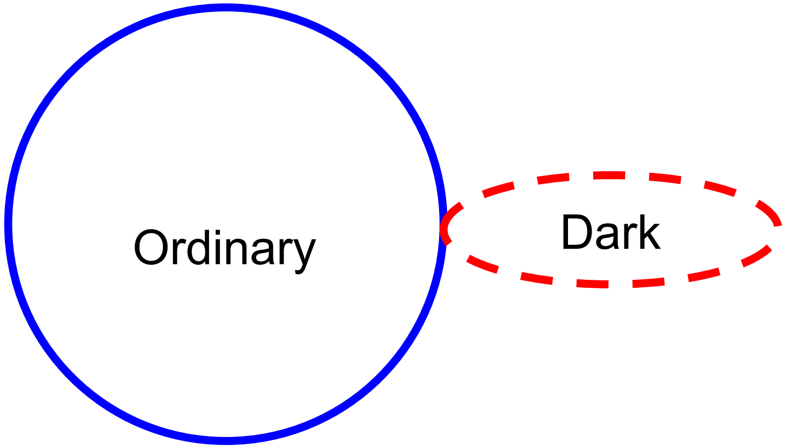
Keywords: Superstring Vacua, QCD.

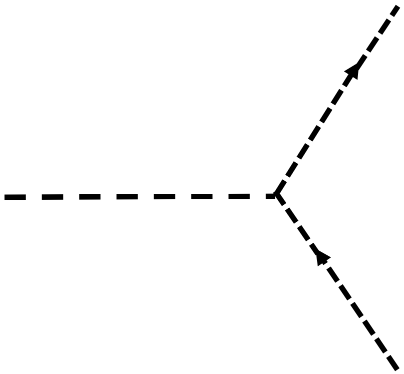
JHEP06(2006)051

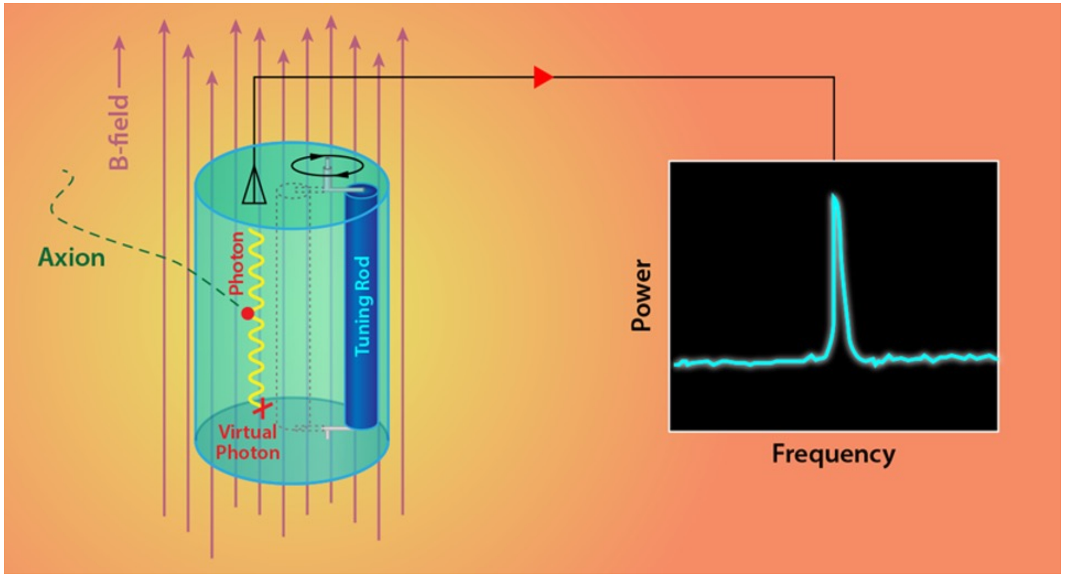


A detective board:

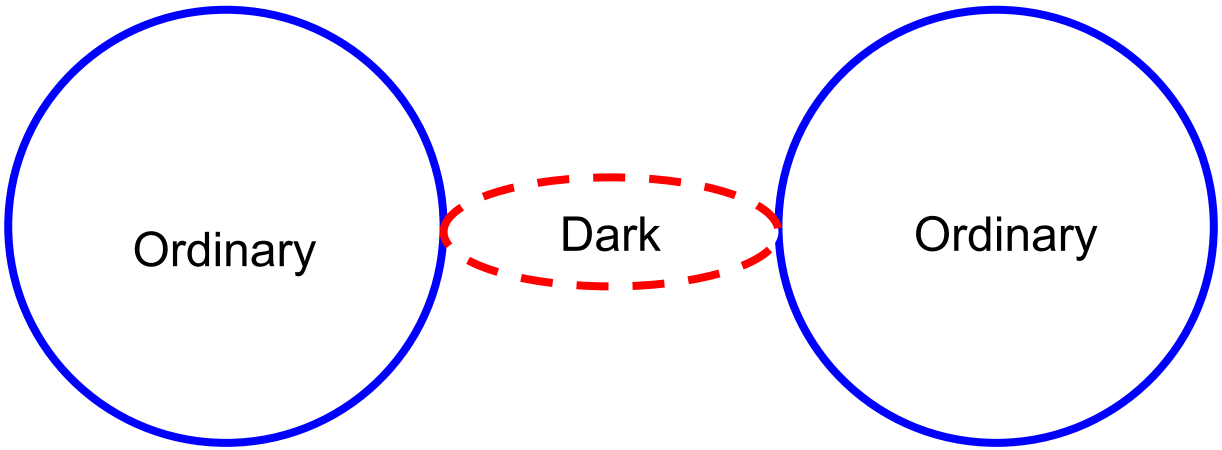
To detect, you have to interact:

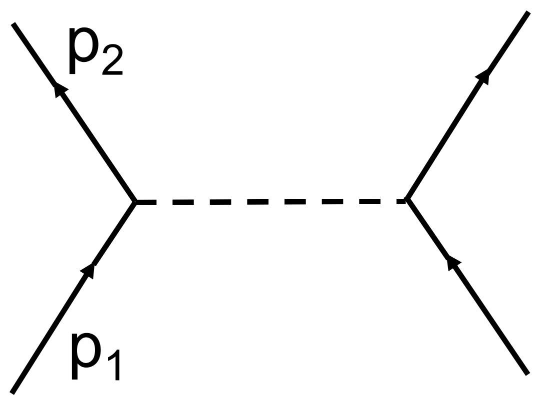






To detect, you have to interact:





Three scalars to be measured：

$$\mathcal{L}_\phi = \bar{\psi}(g_s + i g_p \gamma_5)\psi\phi \rightarrow V_{SP}(r) = \frac{\hbar^2 g_S g_P}{8\pi m_e}\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right)\exp(-r/\lambda)\vec{\sigma}\cdot\hat{r}$$

$$V_{VA}(r) = \frac{\hbar g_V g_A}{2\pi}\frac{\exp(-r/\lambda)}{r}\vec{\sigma}\cdot\vec{v}$$

$$\mathcal{L}_X = \bar{\psi}(g_V\gamma^\mu + g_A\gamma^\mu\gamma_5)\psi X_\mu \rightarrow$$

$$V_{AA}(r) = \frac{\hbar^2 g_A^2}{16\pi m c}\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right)\exp(-r/\lambda)\vec{\sigma}\cdot(\vec{v}\times\hat{r})$$

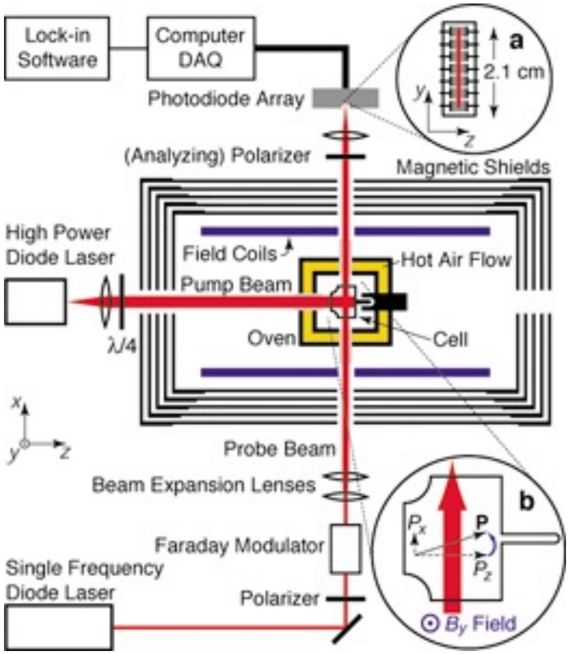
1. **σ·r** pseudo-Scalar, breaks P and T

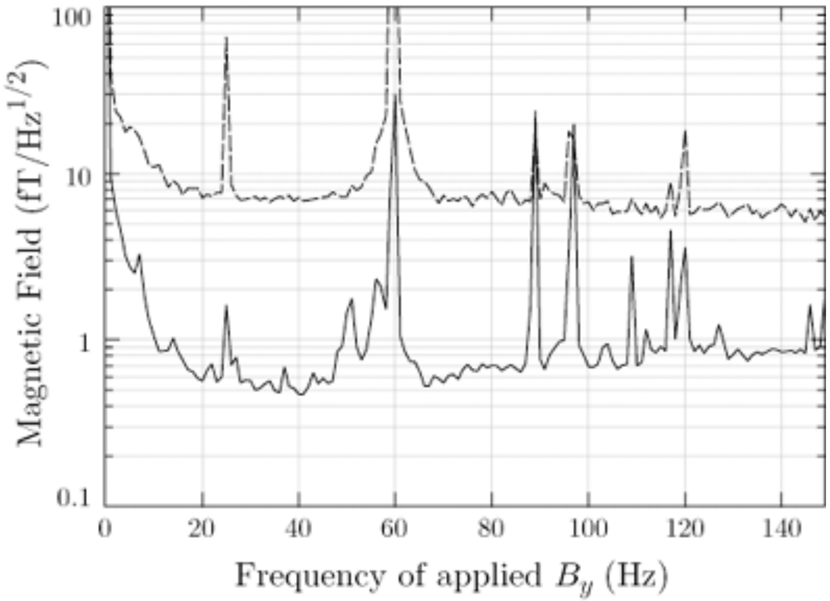
2. **σ·v** pseudo-Scalar, breaks P and C

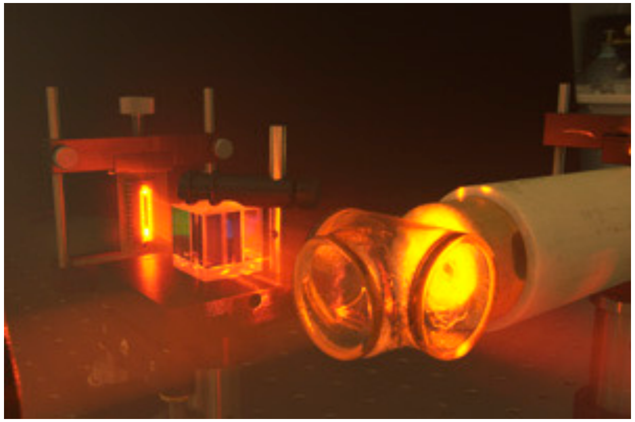
3. **σ·(v×r)** scalar

SERF Magnetometers:

based on polarized alkaline metal and have ultra high sensitivity

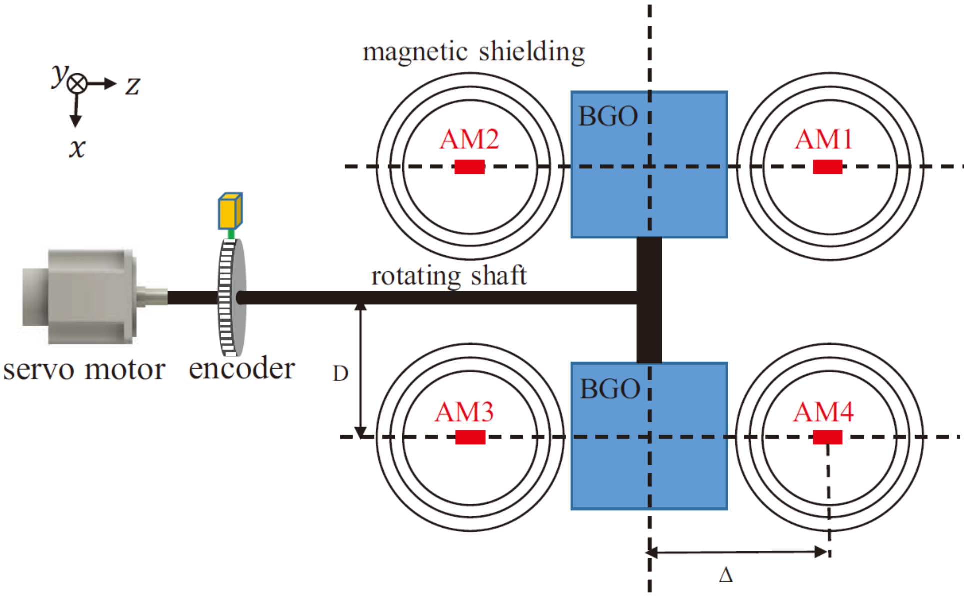


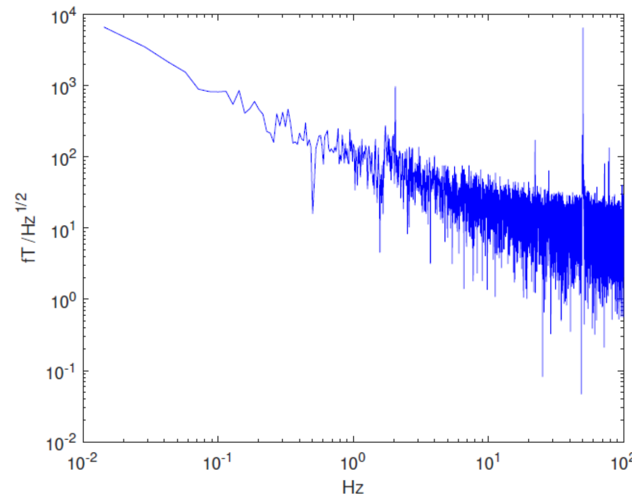




I. K. Kominis, T. W. Kornack, J. C. Allred & M. V. Romalis, "A subfemtotesla multichannel atomic magnetometer." *Nature* **422**, 596 (2003).

The proposed experiment scheme:





The typical noise power density of a Rb magnetometer

High speed rotating mass sources + magnetometer array

1.Modulation frequency~20Hz， 40 times noise reduction；

2.Magnetometer array， increases statistics and cancels common-mode noise

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

$$\begin{aligned} B'_{P_z} &= \frac{1}{4}(B_{1z} - B_{2z} + B_{3z} - B_{4z}) \\ &= B'_{P_z} + \sqrt{{B_{bg}}^2 + {B_{bg}}^2 + {B_{bg}}^2 + {B_{bg}}^2} \\ &= B'_{P_z} + \frac{1}{2}B_{bg} \end{aligned}$$

$$\begin{aligned} B_{1z} &= B'_{SP_z} + B_{com} + B_{bg} \\ B_{2z} &= -B'_{SP_z} + B_{com} + B_{bg} \\ B_{3z} &= -B'_{SP_z} + B_{com} + B_{bg} \\ B_{4z} &= B'_{SP_z} + B_{com} + B_{bg} \end{aligned}$$

K. Y. Wu, S. Y. Chen, J. Gong, M. Peng, and H. Yan， Phys. Rev. D **105**, 055020（2022）

Data processing method：

$$\vec{B'}_{VA}(\vec{r}) = \frac{g_V g_A}{\pi\gamma_e}\int d^3\vec{r}'\frac{\exp\left(-|\vec{r}-\vec{r}'|/\lambda\right)}{|\vec{r}-\vec{r}'|}\vec{v}$$

$$\vec{B'}_{AA}(\vec{r}) = \frac{\hbar g_A^2}{8\pi m_e c\gamma_e}\int d^3\vec{r}'\left(\frac{1}{\lambda|\vec{r}-\vec{r}'|}+\frac{1}{|\vec{r}-\vec{r}'|^2}\right)\times \exp\left(-|\vec{r}-\vec{r}'|/\lambda\right)\left(\vec{v}\times\frac{\vec{r}-\vec{r}'}{|\vec{r}-\vec{r}'|}\right)$$

$$g_V g_A = g_A^2 = 1$$

$$B'(t) = c_0 + \sum_{n=1}^{\infty} c_n \cos(n\omega_0 t + \phi)$$

$$c_n = \frac{2}{NT}\int_0^{NT}\cos\left(n\omega_0 t + \phi\right)B'(t)dt$$

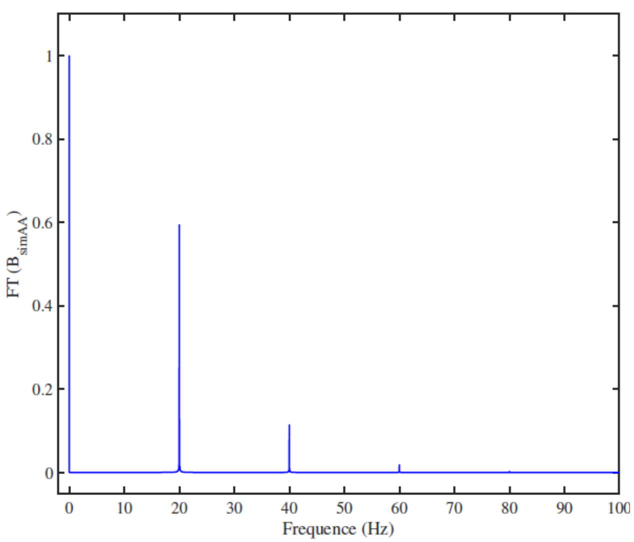
$$B_{\exp}(t) = \alpha c_0 + \alpha\sum_{n=1}^{\infty} c_n\cos(n\omega_0 t + \phi) + n(t)$$

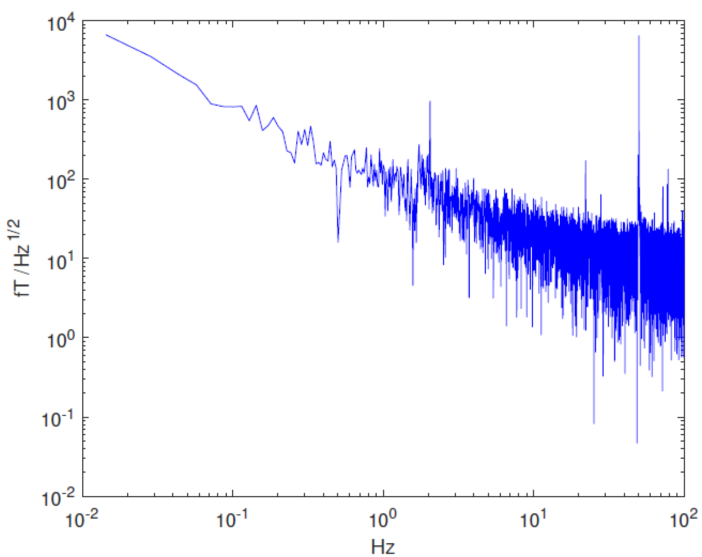
$\alpha = g_V g_A$ for the VA interaction

$\alpha = g_A^2$ for the AA interaction

$$\alpha|_n = \frac{2\int_0^{NT}\cos\left(n\omega_0 t + \phi\right)B_{exp}(t)dt}{c_n NT}$$

$$\delta\bar{\alpha}|_{noise} \sim \sqrt{S_N(nf_0)}\sqrt{\frac{2}{NT}}\frac{1}{\sqrt{\sum_{n=1}^{4} c_n^2}}$$



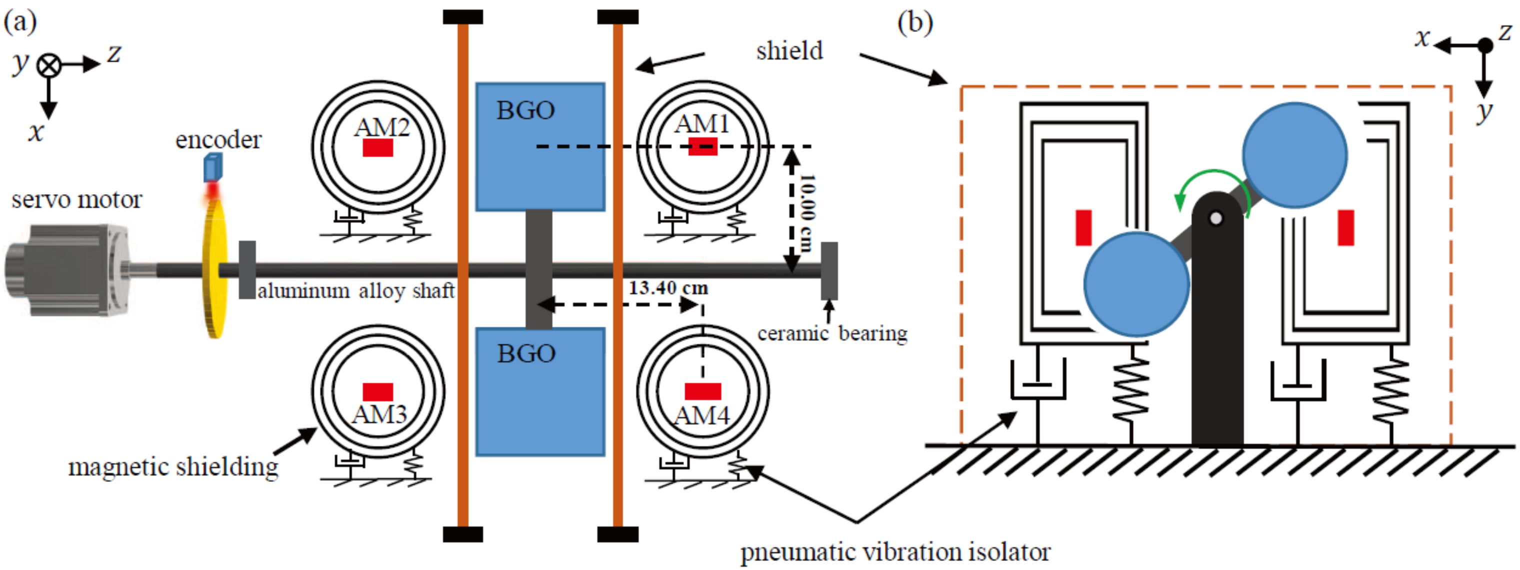


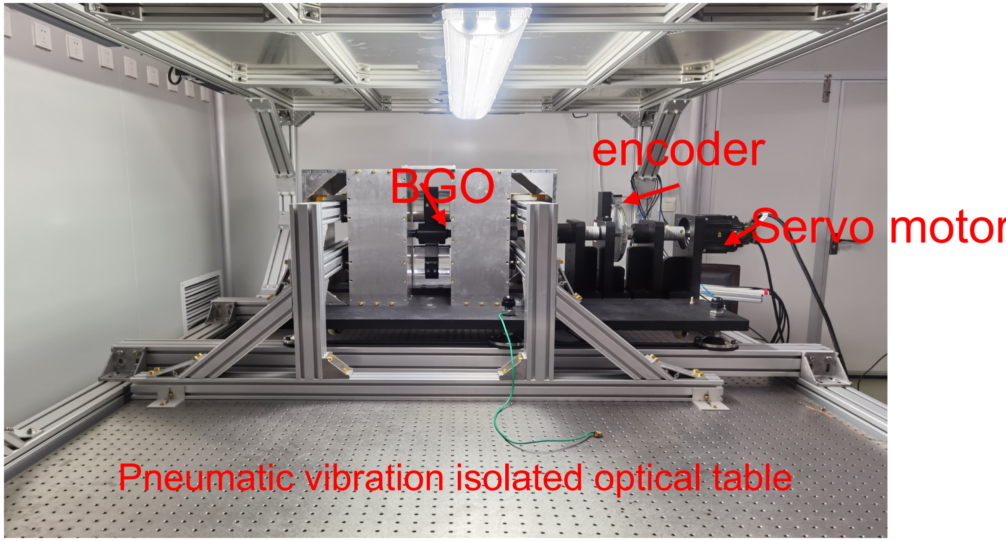
$$\bar{\alpha} = \frac{\sum_{n=1}^{4} c_n^2\alpha|_n}{\sum_{n=1}^{4} c_n^2}$$

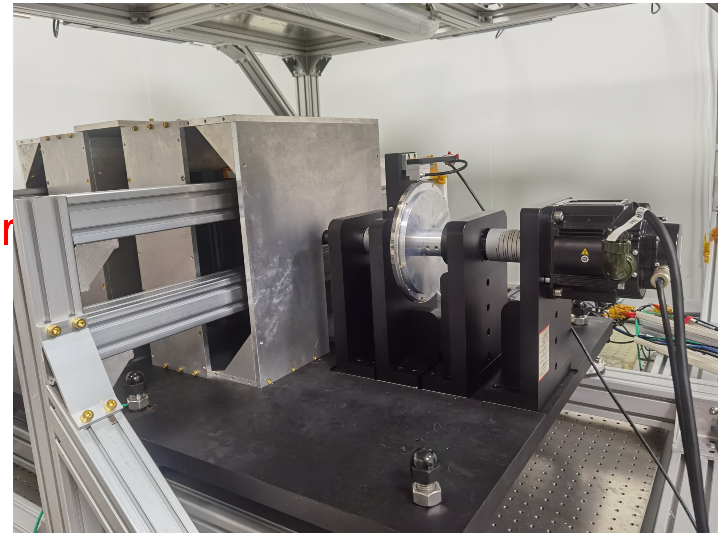
30 days~10aT(10^{-17}T) precision

Phys. Rev. D **105**, 055020（2022）

The experiment setup：

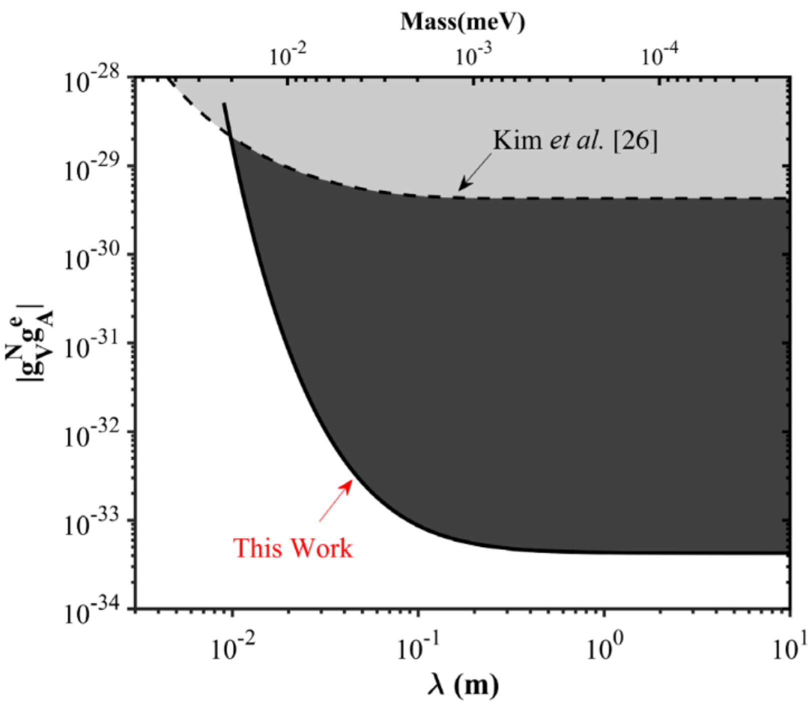


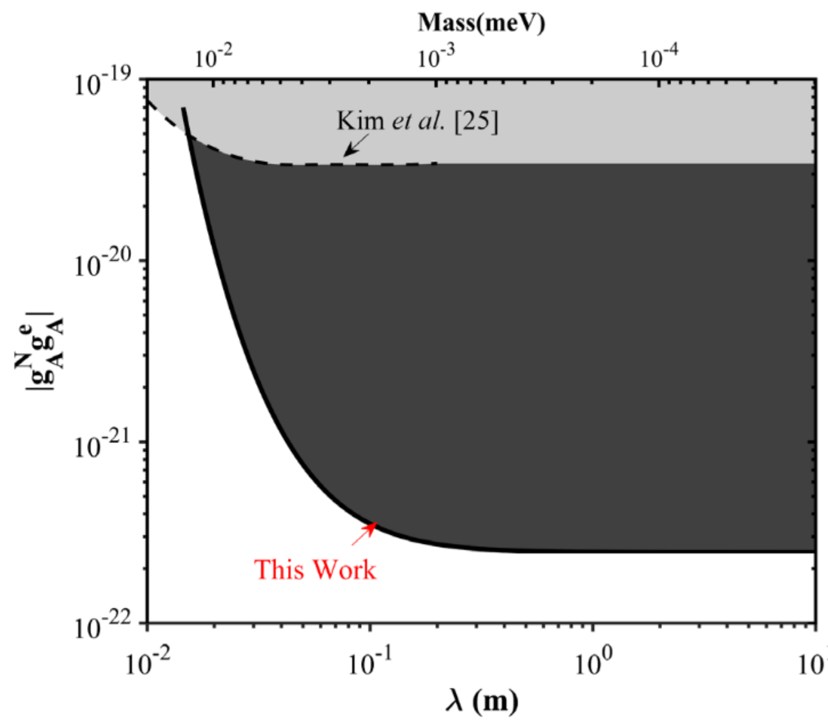




K. Y. Wu, S. Y. Chen, G. A. Sun, S. M. Peng, M. Peng, and H. Yan, Phys. Rev. Lett. **129** 051802 (2022)

Main results:



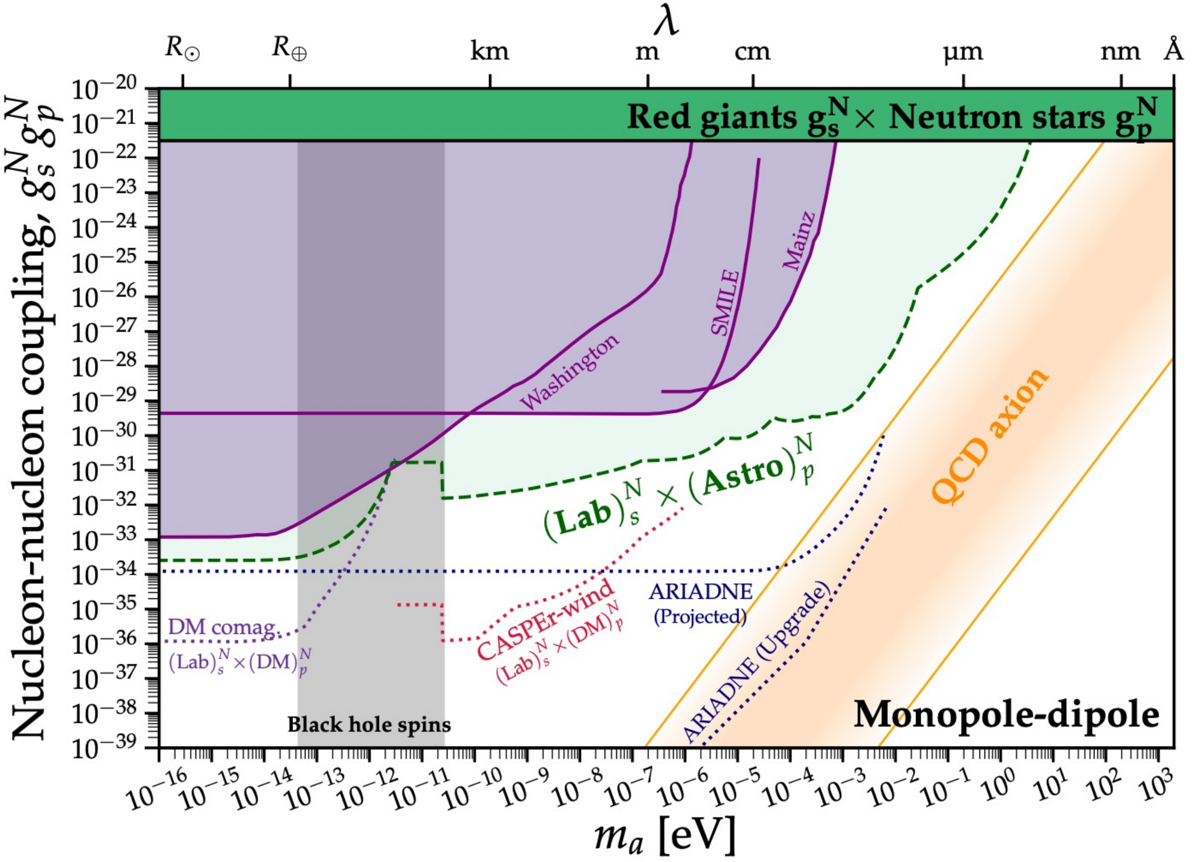


$$g_V^N g_A^e = 0.07 \pm 2.06(\text{stat}) \pm 0.07(\text{syst}) \times 10^{-34},$$

$$g_A^N g_A^e = -0.06 \pm 2.36(\text{stat}) \pm 0.08(\text{syst}) \times 10^{-22}.$$

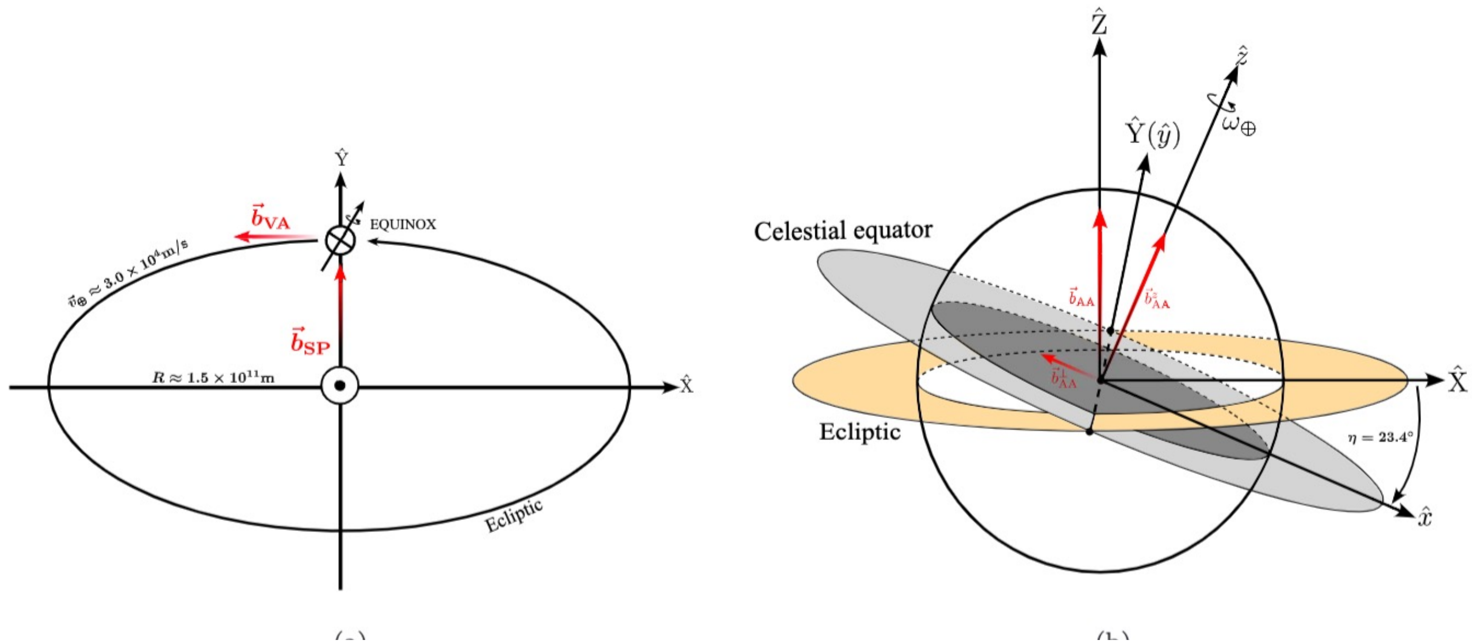
K. Y. Wu, S. Y. Chen, G. A. Sun, S. M. Peng, M. Peng, and H. Yan, Phys. Rev. Lett. **129** 051802 (2022)

Astrophysical limits： hard to exceed



C. A. J. O'Hare and E. Vitagliano, Phys. Rev. D 102, 115026 (2020).

Using the Sun as a source:



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

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

$$\boldsymbol{B}'_{\mathrm{AA}} = -\frac{\hbar g_A^N g_A^n N_\odot}{8\pi m_n c \gamma_n}\left(\frac{1}{\lambda R} + \frac{1}{R^2}\right)\exp(-R/\lambda)\Omega_\oplus R\hat{Z},$$

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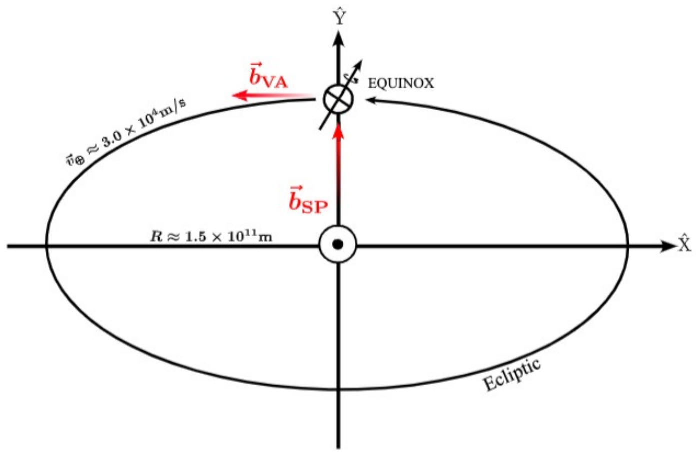
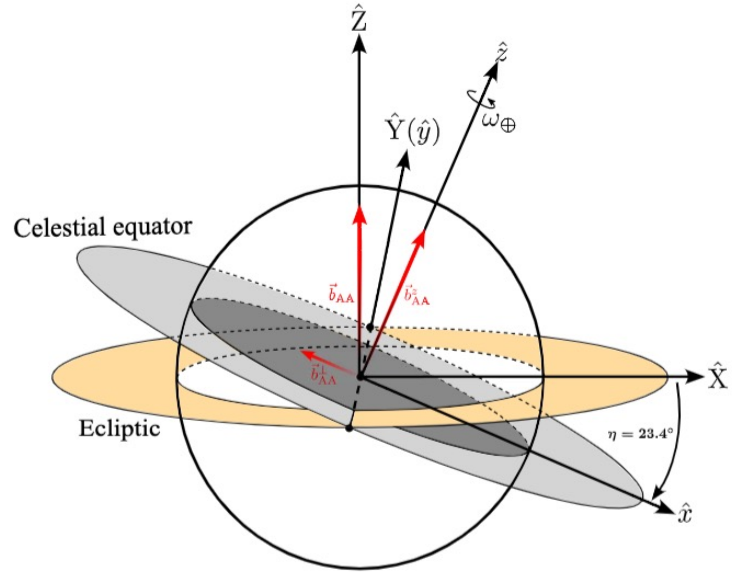
Earth's rotation as a modulation:



(a)



(b)

$$\boldsymbol{b}_{\rm SP} = \frac{\hbar g_S^N g_P^n N_\odot}{4\pi m_n \gamma_n}\left(\frac{1}{\lambda R}+\frac{1}{R^2}\right)\exp(-R/\lambda)\begin{bmatrix} \cos\eta\cos(\Omega_\oplus t)\cos\omega_\oplus t + \sin(\Omega_\oplus t)\sin\omega_\oplus t \\ -\cos\eta\cos(\Omega_\oplus t)\sin\omega_\oplus t + \sin(\Omega_\oplus t)\cos\omega_\oplus t \\ \sin\eta\cos(\Omega_\oplus t) \end{bmatrix},$$

$$\boldsymbol{b}_{\rm VA} = \frac{g_V^N g_A^n N_\odot}{\pi\gamma_n}\frac{\exp(-R/\lambda)}{R}v_\oplus\begin{bmatrix} -\cos\eta\cos\omega_\oplus t\sin(\Omega_\oplus t) + \sin\omega_\oplus t\cos(\Omega_\oplus t) \\ \cos\eta\sin\omega_\oplus t\sin(\Omega_\oplus t) + \cos\omega_\oplus t\cos(\Omega_\oplus t) \\ -\sin\eta\sin(\Omega_\oplus t) \end{bmatrix},$$

$$\boldsymbol{b}_{\rm AA} = \frac{\hbar g_A^N g_A^n N_\odot}{8\pi m_n c\gamma_n}\left(\frac{1}{\lambda R}+\frac{1}{R^2}\right)\exp(-R/\lambda)v_\oplus\begin{bmatrix} \sin\eta\cos\omega_\oplus t \\ -\sin\eta\sin\omega_\oplus t \\ -\cos\eta \end{bmatrix},$$

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Effective field perpendicular to the Earth's rotation axis:

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

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

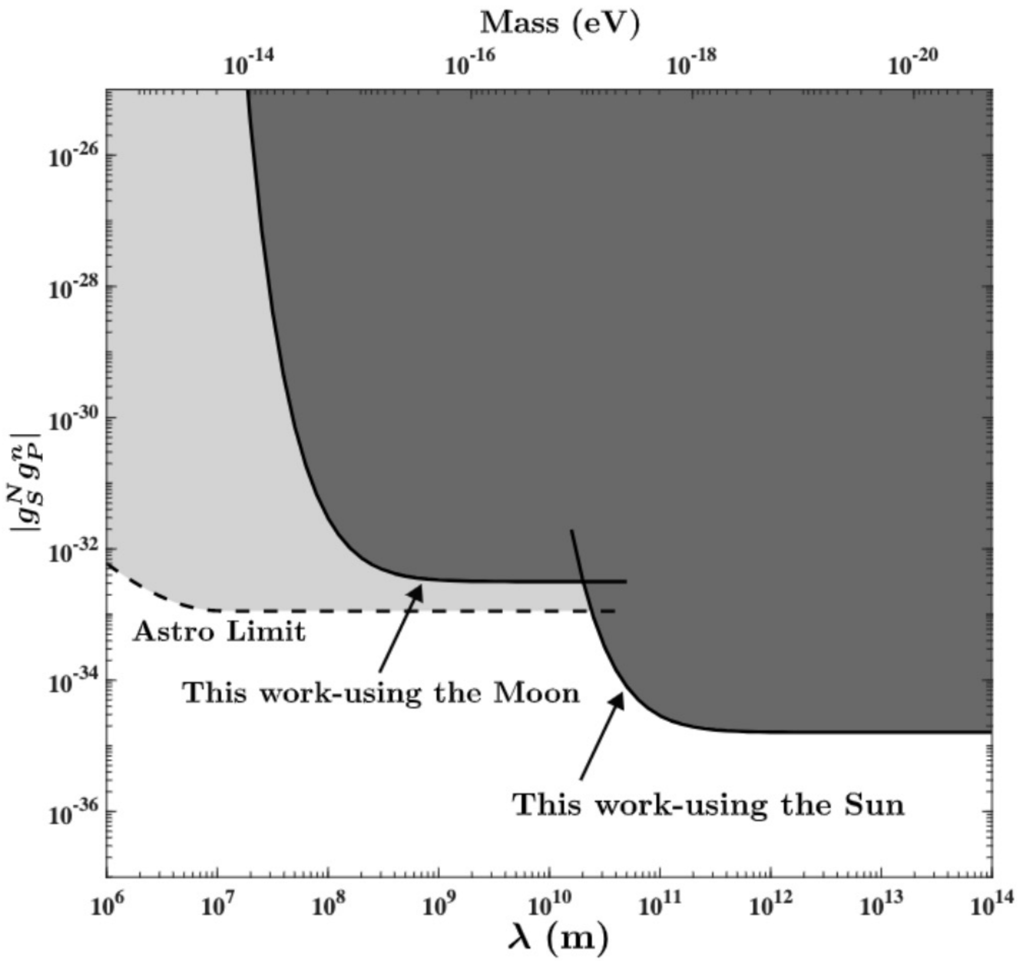
$$\boldsymbol{b}_{\mathrm{AA}\perp} = \frac{\hbar g_A^N g_A^n N_\odot}{8\pi m_n c \gamma_n}\left(\frac{1}{\lambda R} + \frac{1}{R^2}\right)\exp(-R/\lambda) v_\oplus \sin\eta$$
$$[\cos(\omega_\oplus t)\hat{x} - \sin(\omega_\oplus t)\hat{y}].$$

Lorentz violation experiment: F. Allmendinger et al, PRL 112(11),110801, (2014).

$$|\boldsymbol{b}_\perp| < 0.023\ \mathrm{fT}\quad(95\%\ \mathrm{C.L.}).$$

L.Y.Wu,K.Y.Zhang, M.Peng, J.Gong H.Yan, PRL,131,091002,(2023)

SP type interaction—exceed the astrophysical limit: σ·r



Exceeds the astrophysical limit by ~70 times

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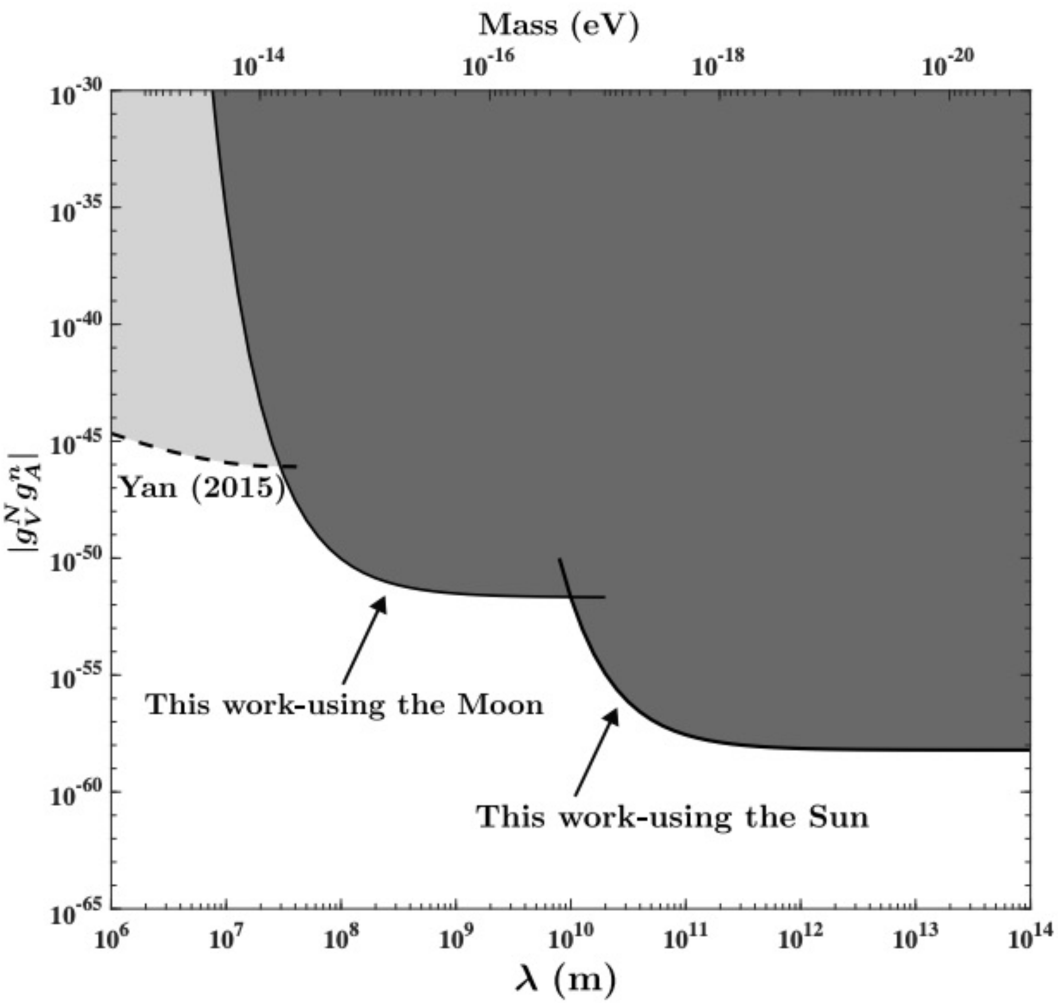
VA type interaction: limits improved by many orders σ·v



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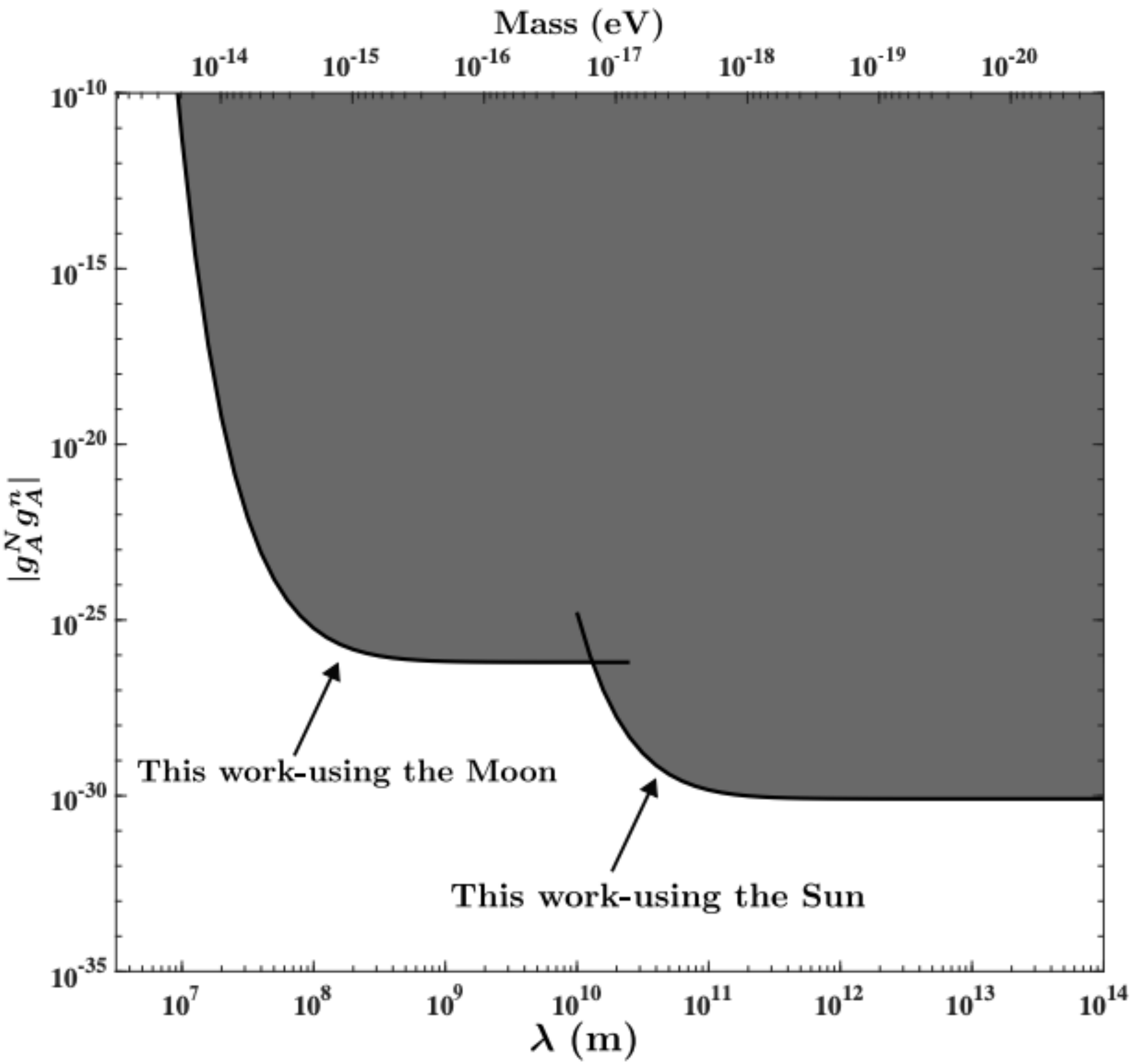
AA Type interaction：established constraints at astronomical distances

σ·(v×r)



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Conclusion & Discussion:

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Many of these interactions could potentially be spin-dependent.

请批评指正！

谢谢