自旋量子精密测量及其应用

彭新华

中国科学技术大学近代物理系

2025年12月4日

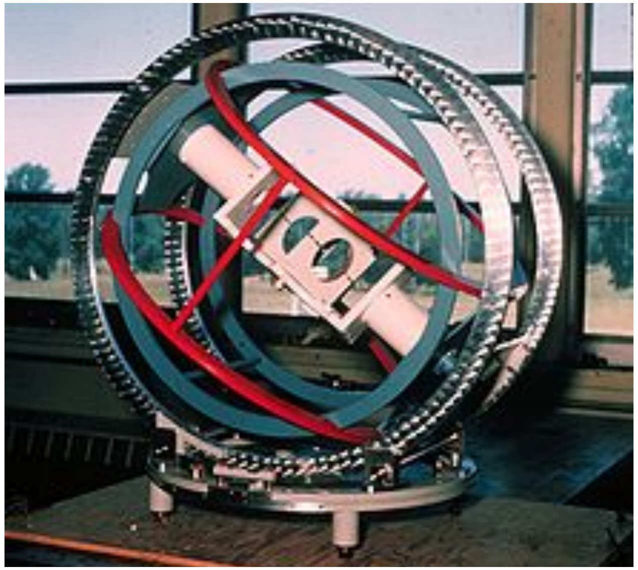
(1) 为什么需要测量极弱磁场？

(2) 如何测量极弱磁场？

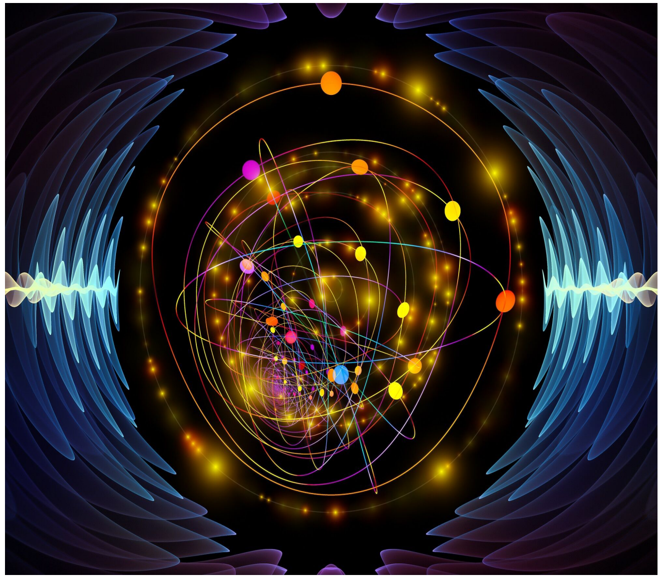
(3) 有什么前沿科学应用？

超灵敏弱磁探测迎来飞特斯拉时代

传统技术



量子技术



弱磁探测达到超高灵敏度水平——fT时代

1fT=10^{-15}T 相当于地磁场的**1000亿分之一**！

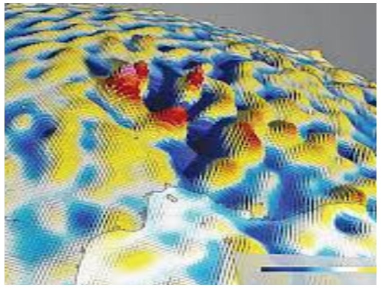
极弱磁场科学与技术

提升极弱磁场的测量精度，将推动相关科学发展

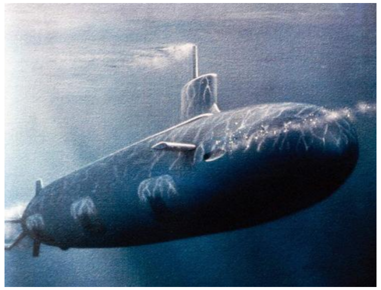
极弱磁场测量

面向国家重大战略需求

自主导航

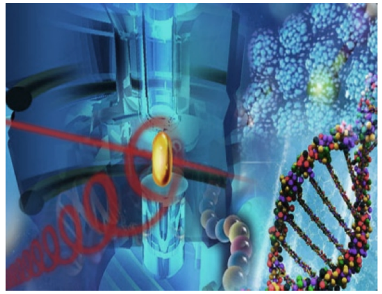


磁异常探测

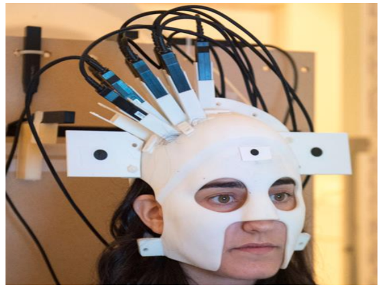


面向人民生命健康需求

医学成像



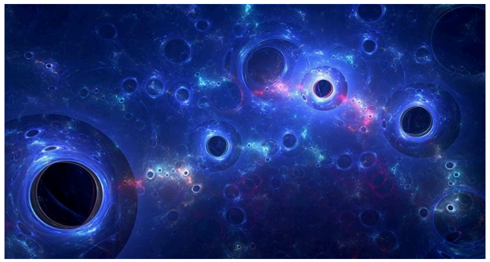
心脑疾病诊断



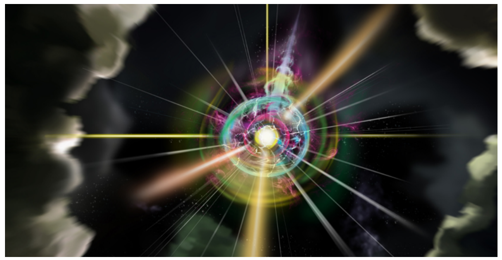
面向世界科技前沿

暗能量

磁单极子



暗物质



Applications: Sensing of known/unknown spin interactions

Quantum sensing → Spin interactions → Scientific Applications

$$H = H_{spin} + H_{spin-spin} + H_{chiral} + H_{PNC} + H_{DM} + H_{new\ force}$$

H_{spin}	$H_{spin-spin}$	H_{chiral}	H_{PNC}	H_{DM}	$H_{new\ force}$
Zeeman interaction	Nuclear spin-spin coupling	Chiral molecules	Parity breaking	Dark Matter	Exotic interactions
≳1000fT	1-100fT	0.5fT	0.1fT	≪0.01fT (Unknown)	

研究背景

宇宙由何构成？

宇宙由何构成？

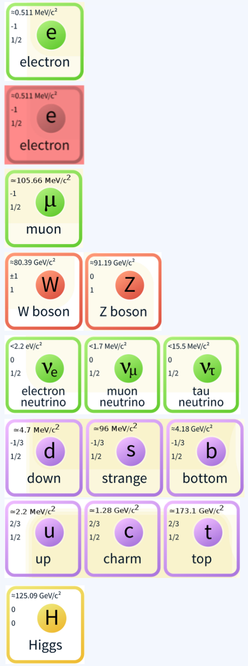

WHAT DON'T WE KNOW?

Special Section

What Is the Universe Made Of

Every once in a while, cosmologists are dragged, kicking and screaming, into a universe much more unsettling than they had any reason to expect. In the 1500s and 1600s, Copernicus, Kepler, and Newton showed that Earth is just one of many planets orbiting one of many stars, destroying the comfortable Medieval notion of a closed and tiny cosmos. In the 1920s, Edwin Hubble showed that our universe is constantly expanding and evolving, a finding that eventually shattered the idea that the universe is unchanging and eternal. And in the past few decades, cosmologists have discovered that the ordinary matter that makes up stars and galaxies and people is less than 5% of everything there is. Grappling with this new understanding of

粒子物理标准模型（SM）



18次

电子 1906 汤姆孙

正电子 1932 安德逊

介子 1949 汤川秀树

W/Z 玻色子 1984 卡罗鲁比亚等

中微子 1988, 1995, 2002, 2015

夸克 2004 格罗斯等人

希格斯玻色子 2013 希格斯等人

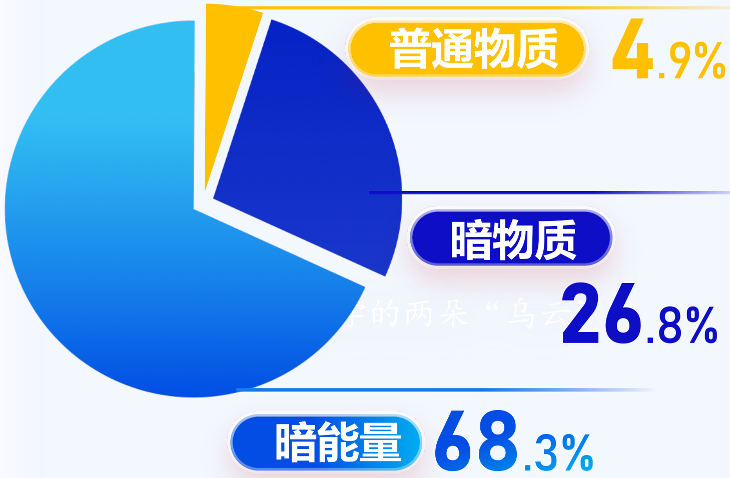
理解物质世界微观结构及其相互作用的关键理论

二十世纪物理学最成功的理论之一

研究背景

标准模型面临最严峻的挑战

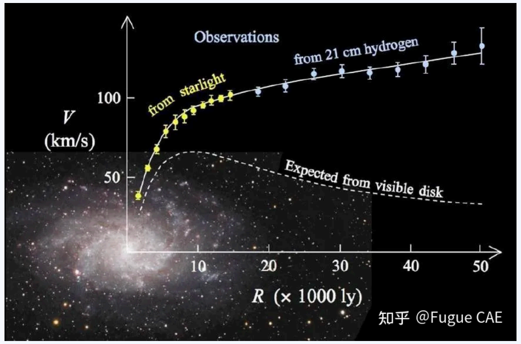
宇宙构成



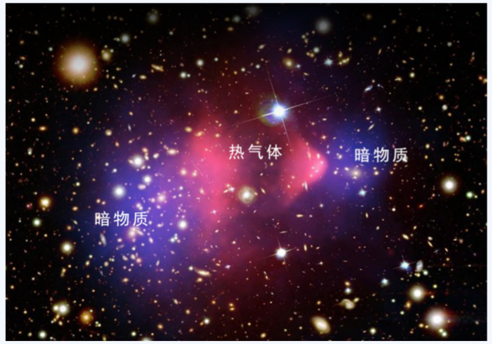
暗物质和暗能量：二十一世纪物理学的两朵“乌云”

暗物质存在的证据（天文观测）

星系旋转曲线



子弹星系团



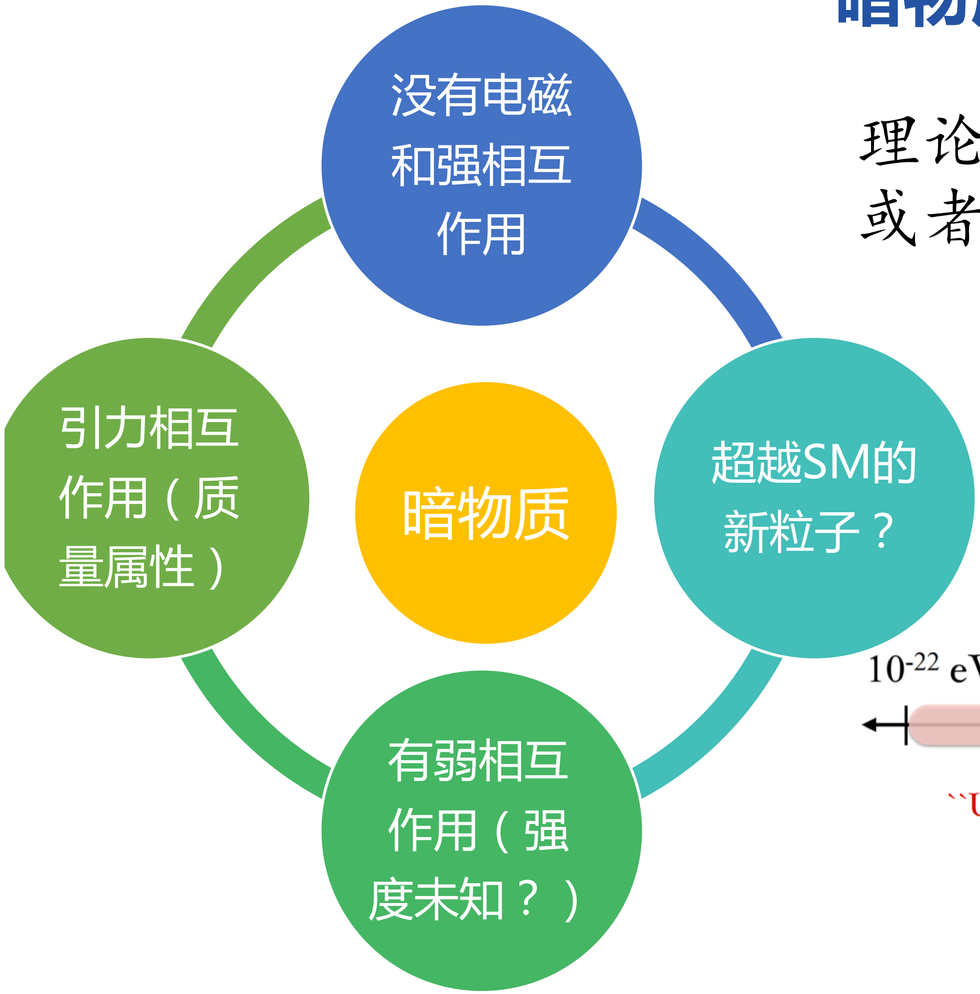
标准模型（SM）只能解释宇宙中5%的物质

对95%的物质一无所知

研究背景

暗物质到底是什么？

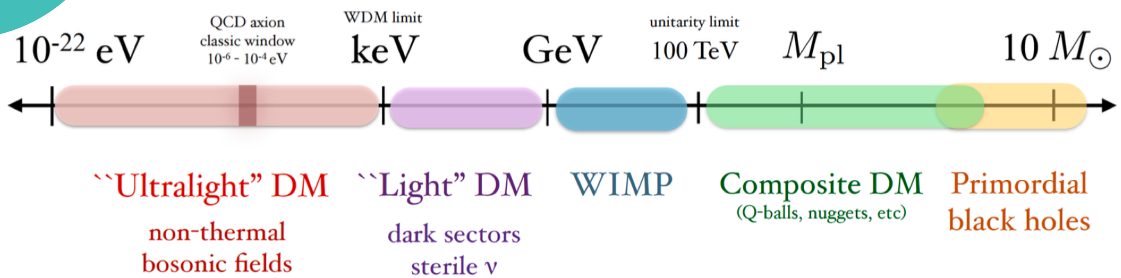
暗物质到底是什么？物理学家还不知道



理论学家提出了暗物质可能是由一种或者多种超越标准模型的新粒子组成。

热门的暗物质候选粒子：
WIPMs、轴子等

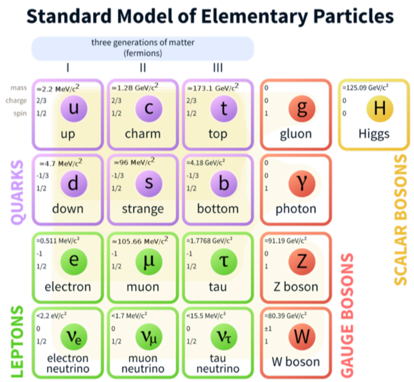
90 个数量级



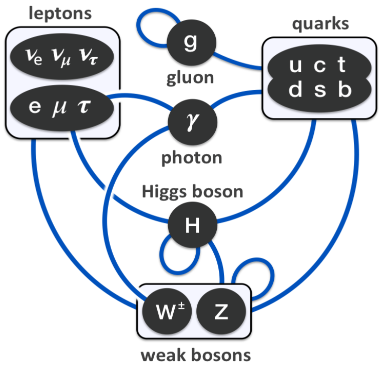
✓ **能区范围广**　✓ **信号极其微弱**

Beyond the standard model

Particles



Interactions



Unexplained problems

Dark matter and energy

Strong CP problem

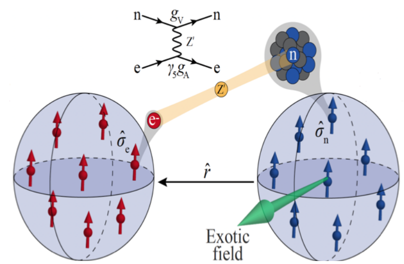
Neutrino oscillations

Proton radius problem

......

New particles

New interactions



Standard model still meets challenges

Dark matter candidates (partial)

Table 1. Properties of various dark matter candidates.

Type	Particle spin	Approximate mass scale
Axion	0	μeV–meV
Inert Higgs doublet	0	50 GeV
Sterile neutrino	1/2	keV
Neutralino	1/2	10 GeV–10 TeV
Kaluza–Klein (KK) UED	1	TeV

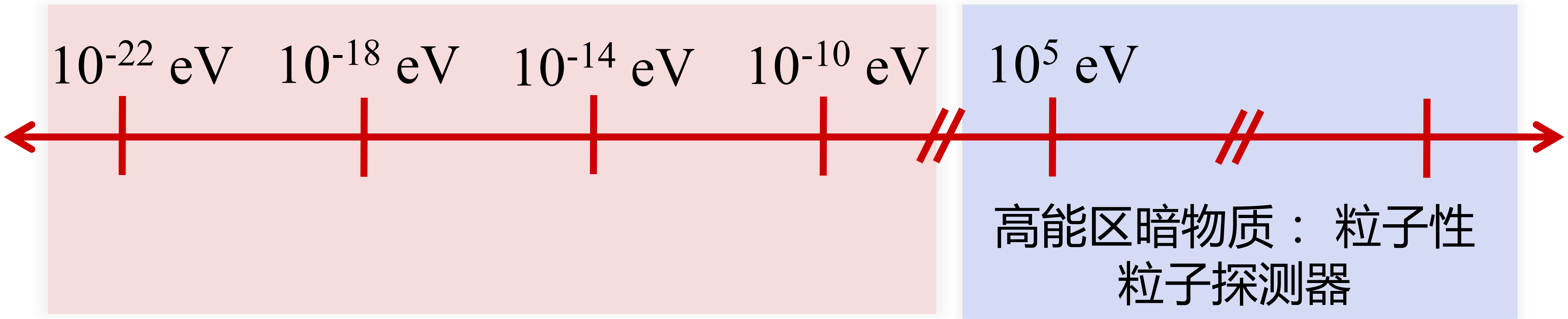
New Journal of Physics **11** (2009) 105006

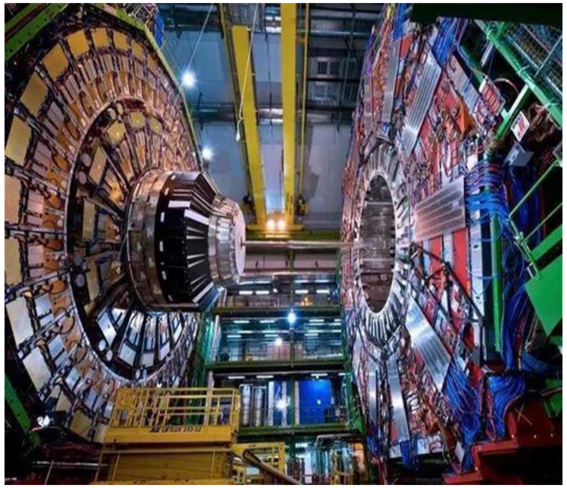
Axions are closely related with fundamental questions:

Cosmological matter-antimatter asymmetry   Strong CP problem

研究背景

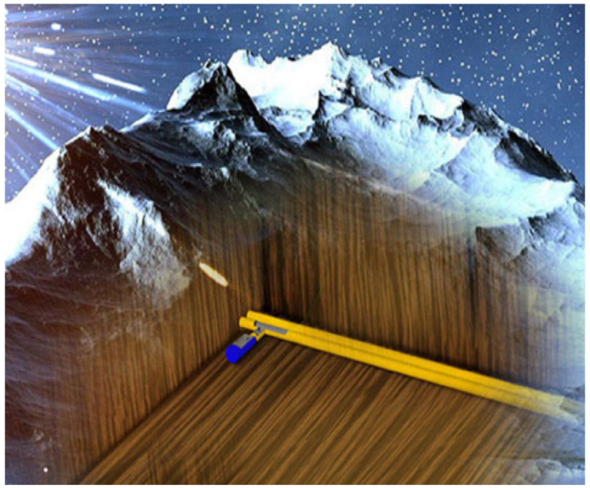
寻找暗物质 — 实验探测途径





大型对撞机实验
(LHC、BESIII等)

深空实验
(DAMPE、AMS等)

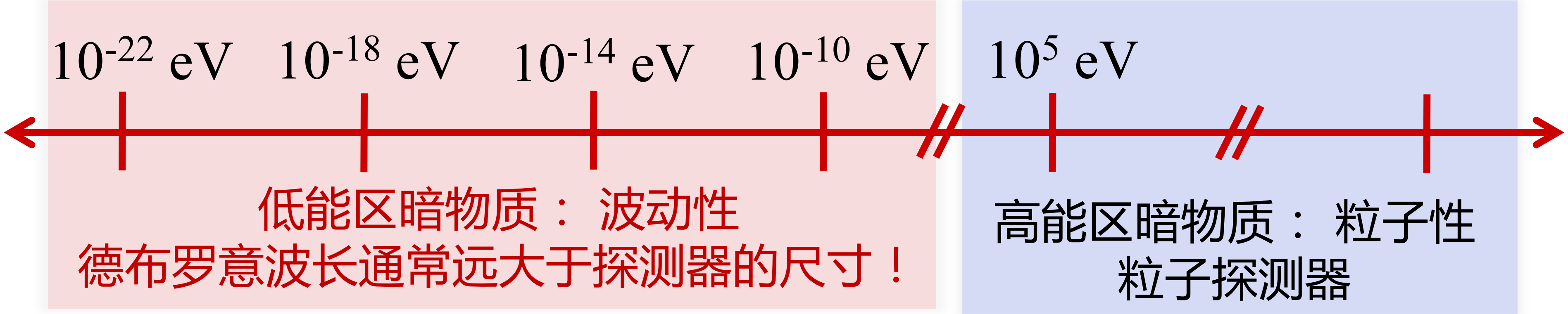


地下实验
(PandaX、CDEX等)

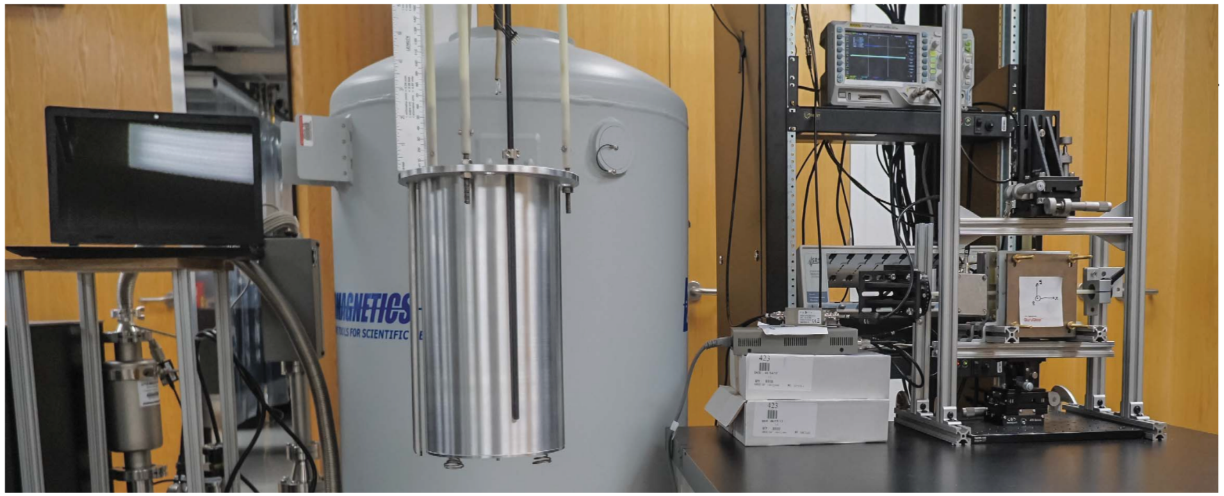
目前仍未找到直接证据！

寻找暗物质

“桌面式”量子精密测量



新机遇——量子精密测量



- ✓ **高灵敏**
- ✓ **集成化**
- ✓ **阵列式**

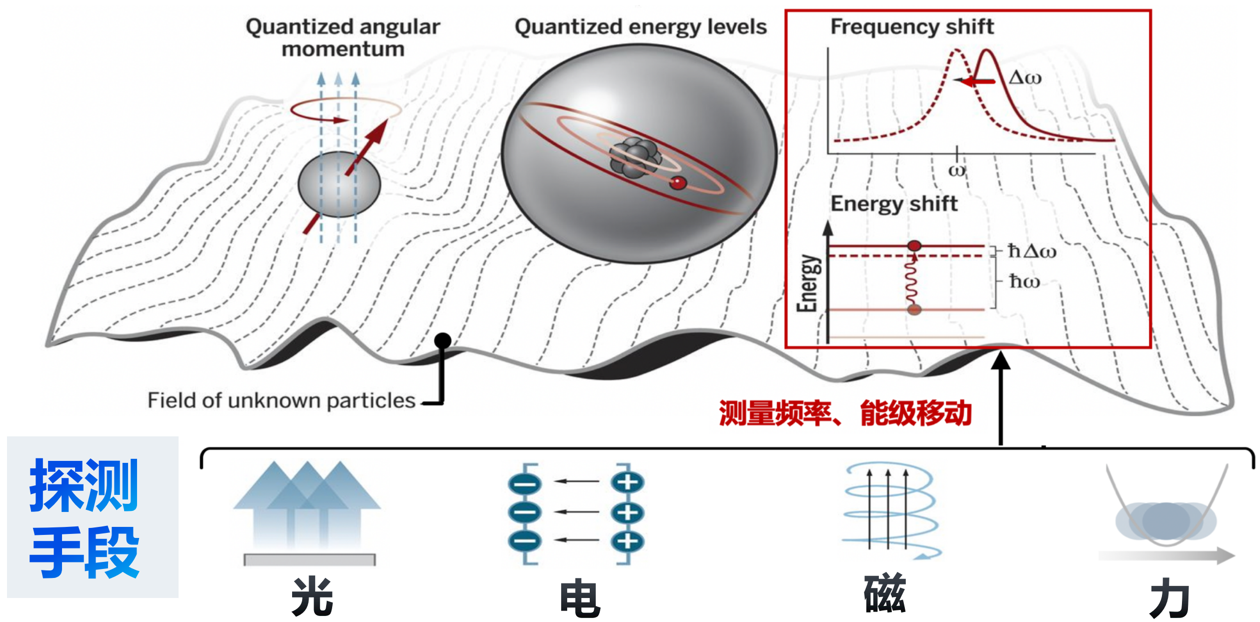
为超轻质量暗物质搜寻提供全新的研究手段，带来新的机遇！

DeMille et al., Science 357, 990 (2017)　　Safronova et al., Rev. Mod. Phys. 90, (2018)

How to see it ?

- 随着量子精密测量的飞速发展，可以利用自旋、原子分子等量子体系开展超高精度的实验测量，为超轻暗物质探索提供了全新的途径

测量原理：暗物质导致自旋频率、能级移动



How to see it?: axions interact with SM particles

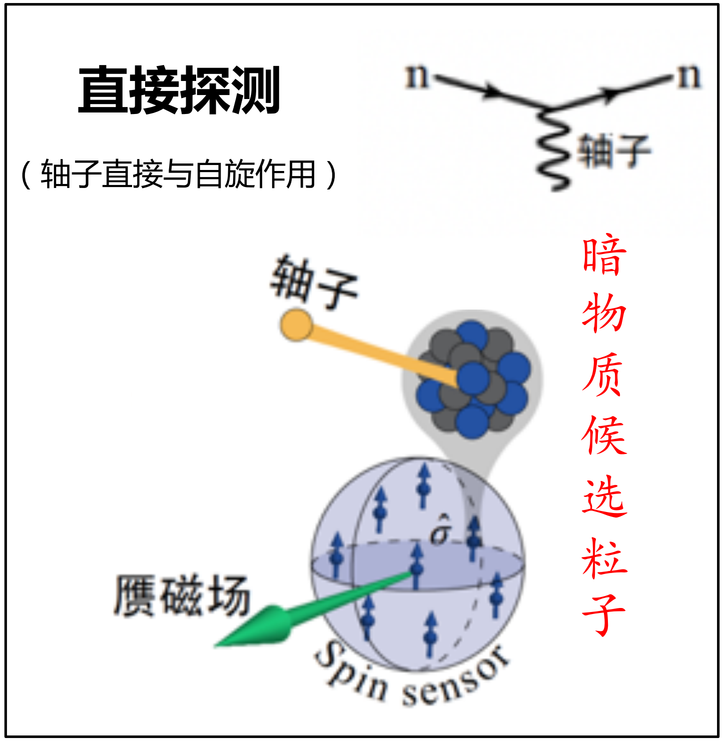
The nonrelativistic Hamiltonian

Dark matter field: $a(t) = a_0 \cos(\omega' t)$

$$\mathcal{H} = \sqrt{\frac{\varepsilon_0}{\mu_0}}\, g_{a\gamma\gamma} \int a\mathbf{E}\cdot\mathbf{B}\, dV + g_{aff}\,\hbar c\, \nabla a \cdot \hat{\mathbf{S}} + \sqrt{\varepsilon_0 (\hbar c)^3}\, g_{EDM}\, a\hat{\mathbf{S}}\cdot\mathbf{E}$$

Couplings	axion-photon	axion-fermion	axion-gluon
Effects	axions is converted to real photons	axions generate pseudomagnetic field on spins	axions generate oscillating EDM
Experiments	Cavity resonators in strong magnetic fields ADMX， IAXO	**Magnetometry** GNOME， ARIADNE **SAPPHIRE**	NMR spectroscopy Storage ring EDM methods CASPEr

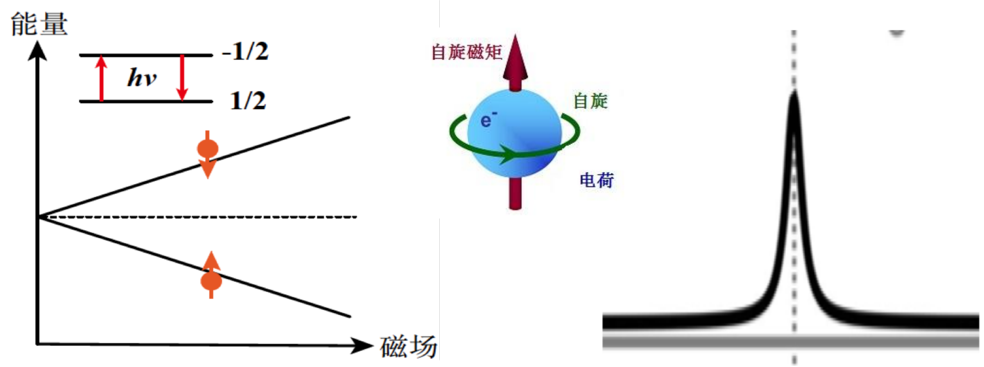
基于自旋量子精密测量的轴子探测



Energy shift $V = g_{\mathrm{aff}} \hbar c \nabla a \cdot \hat{\mathbf{S}}$

轴子和核自旋相互作用引起能量移动，等效于在核自旋上产生一个赝磁场

$-\boldsymbol{\mu}_{\mathrm{Xe}} \cdot \mathbf{B}_j^{\mathrm{exo}} = V_j$ Measure $\mathbf{B}_j^{\mathrm{exo}}$



"pseudo-magnetic" field:

$$\vec{B}_{\mathrm{ALP}} \propto g_{\mathrm{aNN}} \cos(m_{\mathrm{ALP}} t)\vec{v}$$

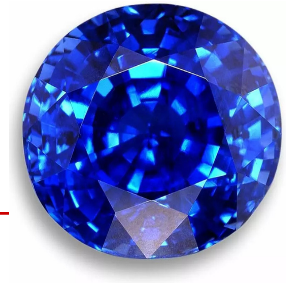
低能区 m_{ALP} ➡ 低频磁传感器

更小相互作用 g_{aNN} ➡ 高灵敏磁传感器

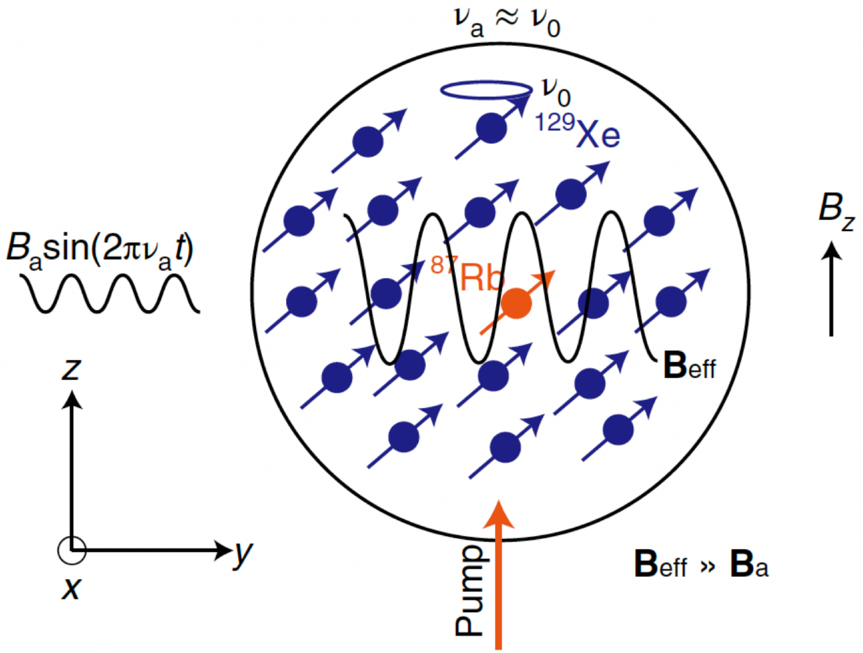
Sapphire project（“蓝宝石”计划）

Spin Amplifier for Particle PHysIcs Research

“Sapphire” （蓝宝石）研究计划



Spin Amplifier for Particle PHysIcs Research



暗物质搜寻放大原理

$$\vec{B}_{\mathrm{ALP}} \propto g_{\mathrm{aNN}} \cos(m_{\mathrm{ALP}} t)\vec{v}$$

更小相互作用g_{aNN} ➡ 更灵敏的传感器

灵敏度：10fT/Hz$^{1/2}$，
5h-测量精度：0.1fT

低能区m_{ALP} ➡ 低频传感器

频率可测范围：2-180Hz，
轴子质量：8feV-750peV

暗物质观测：突破超新星观测界限

nature physics

ARTICLES

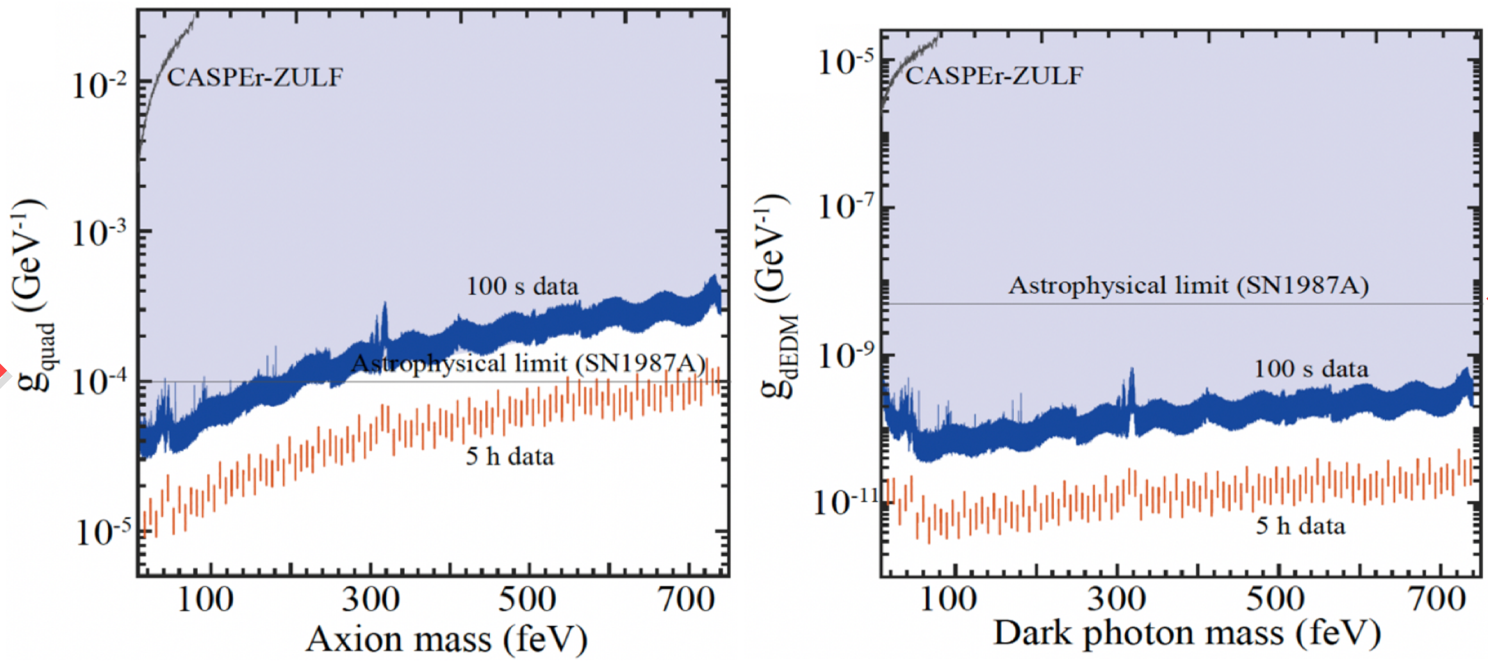
https://doi.org/10.1038/s41567-021-01392-z

Check for updates

Search for axion-like dark matter with spin-based amplifiers

Min Jiang[1,2,3,7], Haowen Su[1,2,3,7], Antoine Garcon[4,5], Xinhua Peng[1,2,3] ✉ and Dmitry Budker[4,5,6]

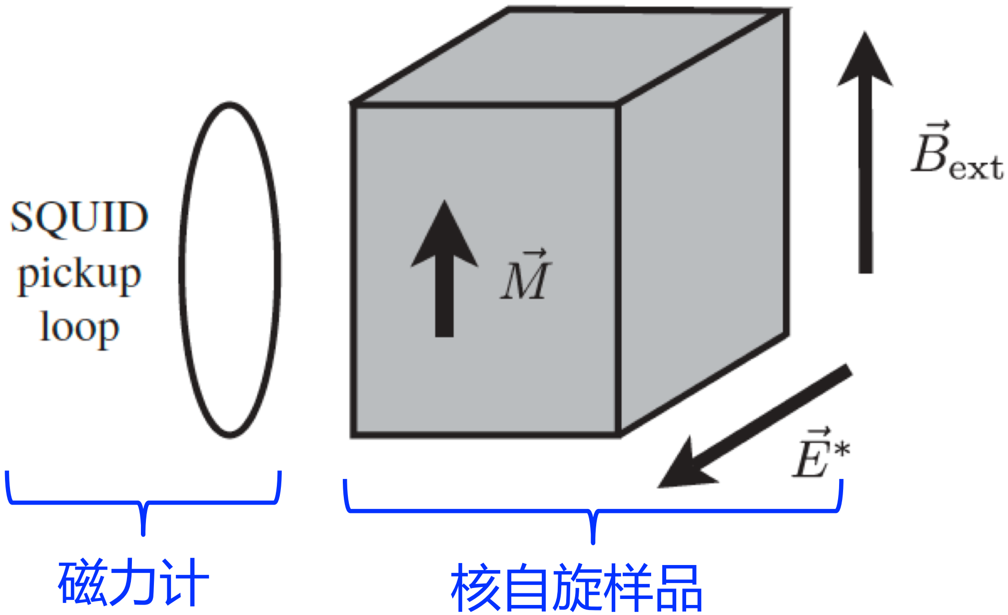
超新星界限



超新星界限

CASPEr： **C**osmic **A**xion **S**pin **P**rocession **E**xpe**r**iment

CASPEr方案：磁力计外部测量轴子引起的核自旋信号



标准量子极限：

$$\delta B = \frac{1}{P\gamma\sqrt{N T_2 t}}$$

极化度P低≈10^{-6}

相干时间T_2短≈10s

CASPEr项目要突破超新星观测界限，需要**10^{11}年**

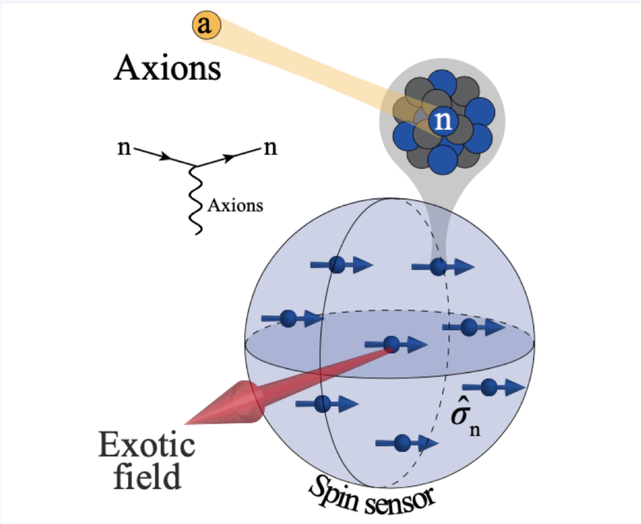
Budker et al., Phys. Rev. X, 4:021030, (2014)

Garcon et al., Sci. Adv. **5**, eaax4539 (2019)

How to see dark matter?

Direct detection

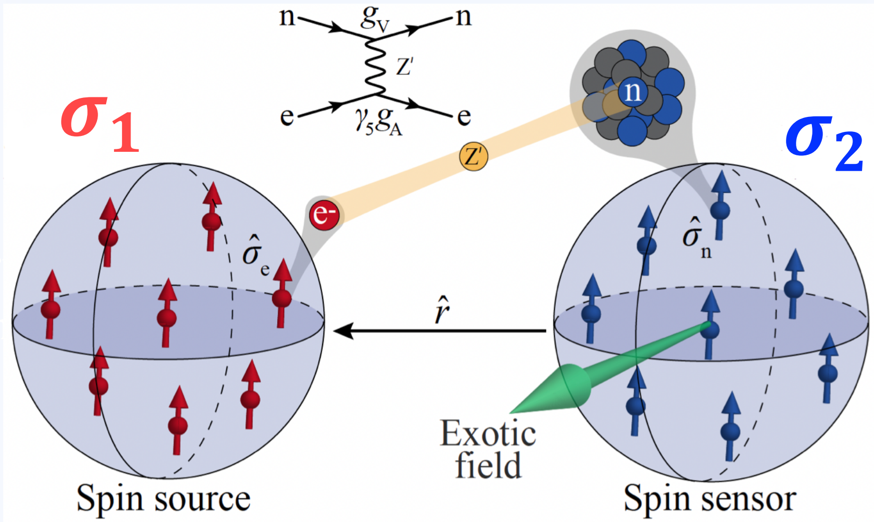
Dark matter candidates



Energy shift $V = g_{\mathrm{aff}} \hbar c \nabla a \cdot \hat{\mathbf{S}}$

Indirect detection

Exotic interactions (the 5th forth)



Energy shift $V \propto f_X(\boldsymbol{\sigma_1} \cdot \boldsymbol{\sigma_2})$

$V \propto f_X(\boldsymbol{\sigma_1} \cdot r)(\boldsymbol{\sigma_2} \cdot r)$ ……

$$-\boldsymbol{\mu}_{\mathrm{Xe}} \cdot \mathbf{B}_j^{\mathrm{exo}} = V_j$$

Measure $\mathbf{B}_j^{\mathrm{exo}}$

寻找新相互作用：轴子及其诱导的新相互作用

Steven Weinberg

VOLUME 40, 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.

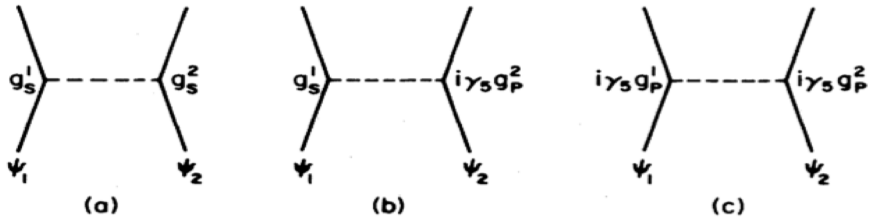
Frank Wilczek

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)

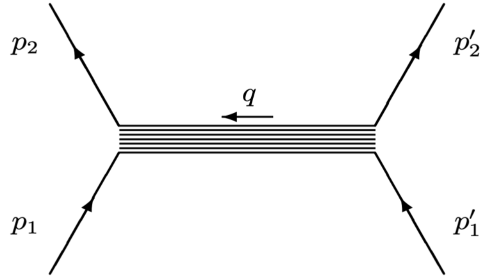
The forces mediated by spin-0 bosons are described, along with the existing experimental limits. The mass and couplings of the invisible axion are derived, followed by suggestions for experiments to detect axions via the macroscopic forces they mediate. In particular, novel tests of the *T*-violating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



Exotic interactions beyond the standard model

B. A. Dobrescu

I. Mocioiu



Extend axion to new mediator bosons and lead to 16 interactions

$$\mathcal{V}_1 = \frac{1}{r}\, y(r) \;,$$

$$\mathcal{V}_2 = \frac{1}{r}\, \vec{\sigma}\cdot\vec{\sigma}'\, y(r) \;,$$

$$\mathcal{V}_3 = \frac{1}{m^2 r^3}\left[\vec{\sigma}\cdot\vec{\sigma}'\left(1 - r\frac{d}{dr}\right) - 3\left(\vec{\sigma}\cdot\hat{\vec{r}}\right)\left(\vec{\sigma}'\cdot\hat{\vec{r}}\right)\left(1 - r\frac{d}{dr} + \frac{1}{3}r^2\frac{d^2}{dr^2}\right)\right] y(r)$$

$$\mathcal{V}_{4,5} = -\frac{1}{2m\, r^2}\left(\vec{\sigma}\pm\vec{\sigma}'\right)\cdot\left(\vec{v}\times\hat{\vec{r}}\right)\left(1 - r\frac{d}{dr}\right) y(r) \;,$$

$$\mathcal{V}_{6,7} = -\frac{1}{2m\, r^2}\left[\left(\vec{\sigma}\cdot\vec{v}\right)\left(\vec{\sigma}'\cdot\hat{\vec{r}}\right) \pm \left(\vec{\sigma}\cdot\hat{\vec{r}}\right)\left(\vec{\sigma}'\cdot\vec{v}\right)\right]\left(1 - r\frac{d}{dr}\right) y(r) \;,$$

$$\mathcal{V}_8 = \frac{1}{r}\left(\vec{\sigma}\cdot\vec{v}\right)\left(\vec{\sigma}'\cdot\vec{v}\right) y(r) \;,$$

$$\mathcal{V}_{9,10} = -\frac{1}{2m\, r^2}\left(\vec{\sigma}\pm\vec{\sigma}'\right)\cdot\hat{\vec{r}}\left(1 - r\frac{d}{dr}\right) y(r) \;,$$

$$\mathcal{V}_{11} = -\frac{1}{m\, r^2}\left(\vec{\sigma}\times\vec{\sigma}'\right)\cdot\hat{\vec{r}}\left(1 - r\frac{d}{dr}\right) y(r) \;,$$

$$\mathcal{V}_{12,13} = \frac{1}{2r}\left(\vec{\sigma}\pm\vec{\sigma}'\right)\cdot\vec{v}\, y(r) \;,$$

$$\mathcal{V}_{14} = \frac{1}{r}\left(\vec{\sigma}\times\vec{\sigma}'\right)\cdot\vec{v}\, y(r) \;,$$

$$\mathcal{V}_{15} = -\frac{3}{2m^2 r^3}\left\{\left[\vec{\sigma}\cdot\left(\vec{v}\times\hat{\vec{r}}\right)\right]\left(\vec{\sigma}'\cdot\hat{\vec{r}}\right) + \left(\vec{\sigma}\cdot\hat{\vec{r}}\right)\left[\vec{\sigma}'\cdot\left(\vec{v}\times\hat{\vec{r}}\right)\right]\right\} \times \left(1 - r\frac{d}{dr} + \frac{1}{3}r^2\frac{d^2}{dr^2}\right) y(r) \;,$$

$$\mathcal{V}_{16} = -\frac{1}{2m\, r^2}\left\{\left[\vec{\sigma}\cdot\left(\vec{v}\times\hat{\vec{r}}\right)\right]\left(\vec{\sigma}'\cdot\vec{v}\right) + \left(\vec{\sigma}\cdot\vec{v}\right)\left[\vec{\sigma}'\cdot\left(\vec{v}\times\hat{\vec{r}}\right)\right]\right\}\left(1 - r\frac{d}{dr}\right) y(r)$$

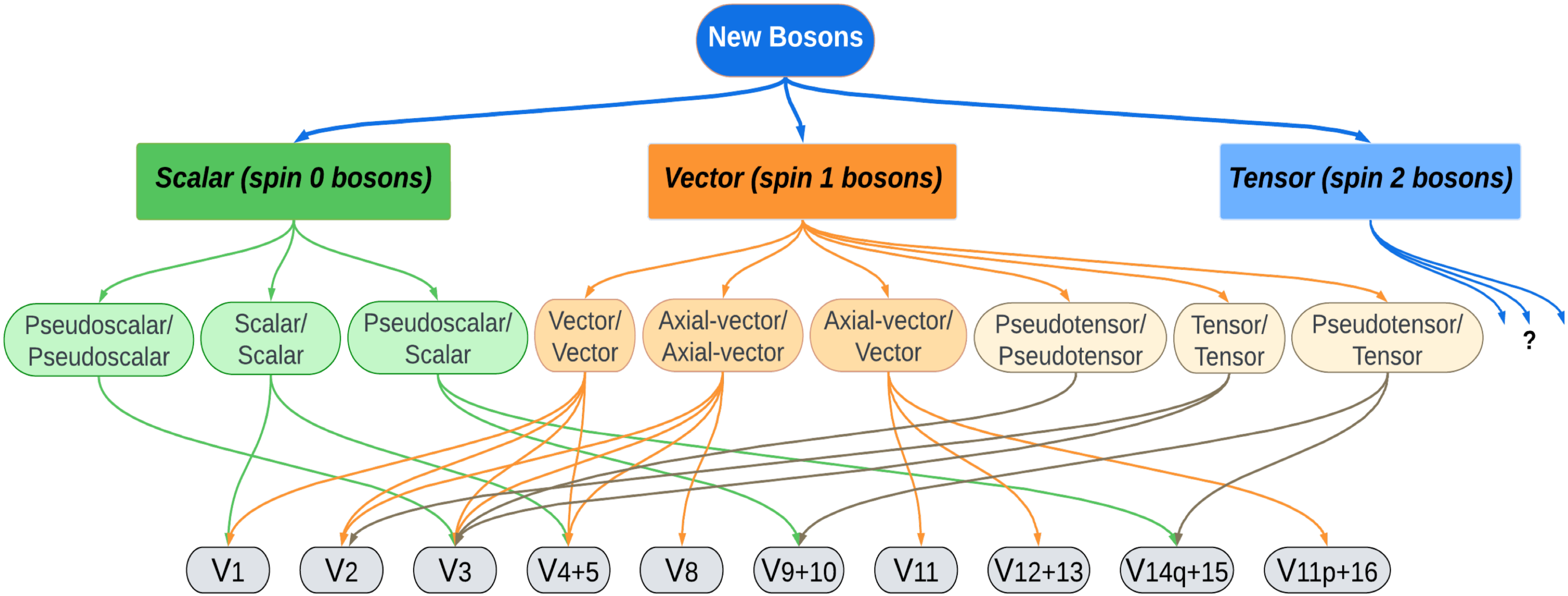
B. Dobrescu, I. Mocioiu, JEHP 11, 005 (2006)

Spin-dependent exotic interactions

Lei Cong[*,†], Wei Ji[*,‡], Pavel Fadeev, Filip Ficek, Min Jiang, Victor V. Flambaum, Haosen Guan, Derek F. Jackson Kimball, Mikhail G. Kozlov *et al.*

Show more

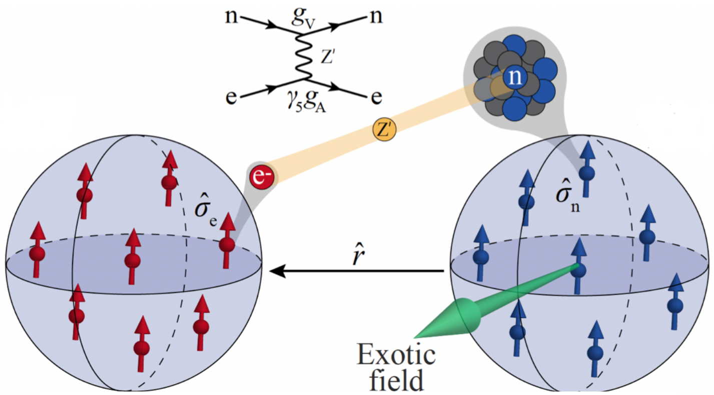
Rev. Mod. Phys. **97**, 025005 – **Published 24 June, 2025**



How to see it

Electron、
Proton、
Neutron、
nucleon

“Spin source” “Spin sensor”



σ_1 σ_2

Noble-gas spin amplifier

xeon-129: ~70% neutron

Energy shift → Exotic (pseudo-magnetic) field

$$-\boldsymbol{\mu}_{Xe} \cdot \mathbf{B}_j^{exo} = V_j$$

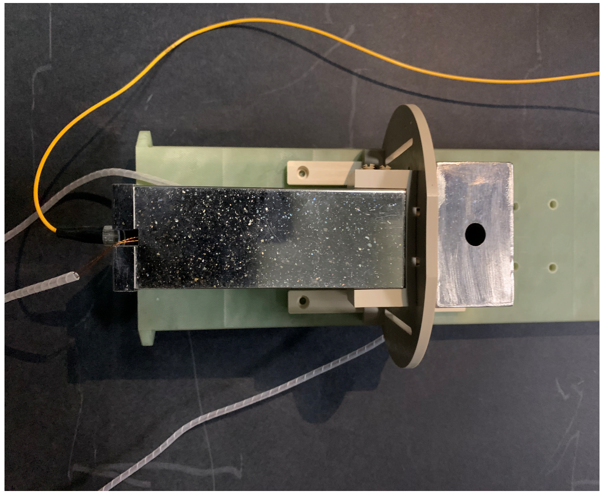
$$\mathbf{B}_{12+13}^{exo} = -f_{12+13} \frac{\hbar}{8\pi |\boldsymbol{\mu}_{Xe}|} \iiint \rho(\hat{r})(\boldsymbol{v})\left(\frac{1}{r}\right) e^{-r/\lambda} d\boldsymbol{r}$$

Coupling to be measured

More sensitive detector → Smaller coupling f

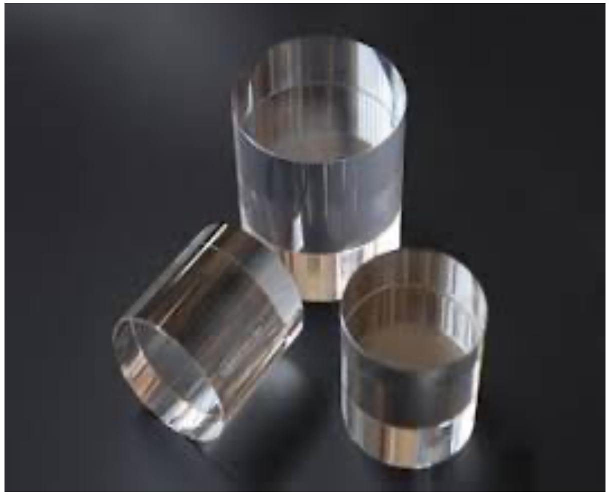
Various spin sources

I: electron/proton (Rb) vapor
high polarization
Short force range (small size)



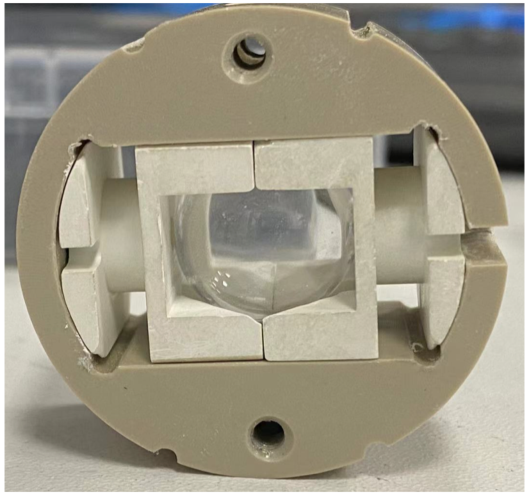
Electron/proton-neutron interaction

II: BGO crystal
high nucleon density
Non-magnetic effect



Nucleon-neutron interaction

III: Noble-gas vapor
high polarization
Short force range



Neutron-neutron interaction

Develop spin sources for different exotic interaction searches

Searched exotic interactions in our study

$$\mathcal{V}_1 = \frac{1}{r} y(r) ,$$

$$\mathcal{V}_2 = \frac{1}{r} \vec{\sigma} \cdot \vec{\sigma}' y(r) ,$$

$$\mathcal{V}_3 = \frac{1}{m^2 r^3} \left[\vec{\sigma} \cdot \vec{\sigma}' \left(1 - r\frac{d}{dr} \right) - 3 \left(\vec{\sigma} \cdot \hat{\vec{r}} \right) \left(\vec{\sigma}' \cdot \hat{\vec{r}} \right) \left(1 - r\frac{d}{dr} + \frac{1}{3} r^2 \frac{d^2}{dr^2} \right) \right] y(r)$$

$$\mathcal{V}_{4,5} = -\frac{1}{2m r^2} (\vec{\sigma} \pm \vec{\sigma}') \cdot \left(\vec{v} \times \hat{\vec{r}} \right) \left(1 - r\frac{d}{dr} \right) y(r) ,$$

$$\mathcal{V}_{6,7} = -\frac{1}{2m r^2} \left[(\vec{\sigma} \cdot \vec{v}) \left(\vec{\sigma}' \cdot \hat{\vec{r}} \right) \pm \left(\vec{\sigma} \cdot \hat{\vec{r}} \right) (\vec{\sigma}' \cdot \vec{v}) \right] \left(1 - r\frac{d}{dr} \right) y(r) ,$$

$$\mathcal{V}_8 = \frac{1}{r} (\vec{\sigma} \cdot \vec{v}) (\vec{\sigma}' \cdot \vec{v}) \, y(r) ,$$

$$\mathcal{V}_{9,10} = -\frac{1}{2m r^2} (\vec{\sigma} \pm \vec{\sigma}') \cdot \hat{\vec{r}} \left(1 - r\frac{d}{dr} \right) y(r) ,$$

$$\mathcal{V}_{11} = -\frac{1}{m r^2} (\vec{\sigma} \times \vec{\sigma}') \cdot \hat{\vec{r}} \left(1 - r\frac{d}{dr} \right) y(r) ,$$

$$\mathcal{V}_{12,13} = \frac{1}{2r} (\vec{\sigma} \pm \vec{\sigma}') \cdot \vec{v} \, y(r) ,$$

$$\mathcal{V}_{14} = \frac{1}{r} (\vec{\sigma} \times \vec{\sigma}') \cdot \vec{v} \, y(r) ,$$

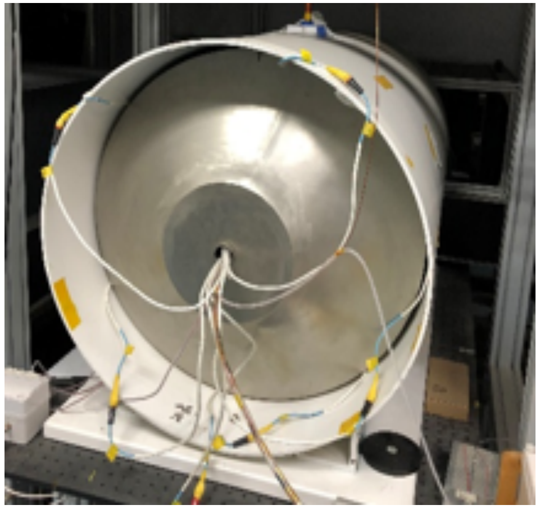
$$\mathcal{V}_{15} = -\frac{3}{2m^2 r^3} \left\{ \left[\vec{\sigma} \cdot \left(\vec{v} \times \hat{\vec{r}} \right) \right] \left(\vec{\sigma}' \cdot \hat{\vec{r}} \right) + \left(\vec{\sigma} \cdot \hat{\vec{r}} \right) \left[\vec{\sigma}' \cdot \left(\vec{v} \times \hat{\vec{r}} \right) \right] \right\} \times \left(1 - r\frac{d}{dr} + \frac{1}{3} r^2 \frac{d^2}{dr^2} \right) y(r) ,$$

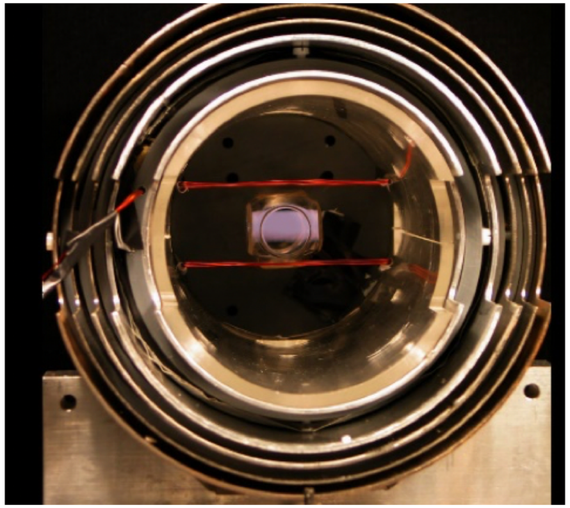
$$\mathcal{V}_{16} = -\frac{1}{2m r^2} \left\{ \left[\vec{\sigma} \cdot \left(\vec{v} \times \hat{\vec{r}} \right) \right] (\vec{\sigma}' \cdot \vec{v}) + (\vec{\sigma} \cdot \vec{v}) \left[\vec{\sigma}' \cdot \left(\vec{v} \times \hat{\vec{r}} \right) \right] \right\} \left(1 - r\frac{d}{dr} \right) y(r)$$

V3 exp.	V11 exp.	V4,5 and V12,13 exp.
polarized electron/proton (rubidium vapor)	polarized electron/proton (rubidium vapor)	Unpolarized nucleon (BGO crystal)
force mediator: axion	force mediator: Z' bosons	

How to shield the spurious ordinary field?

High-permeability materials: μ-metal





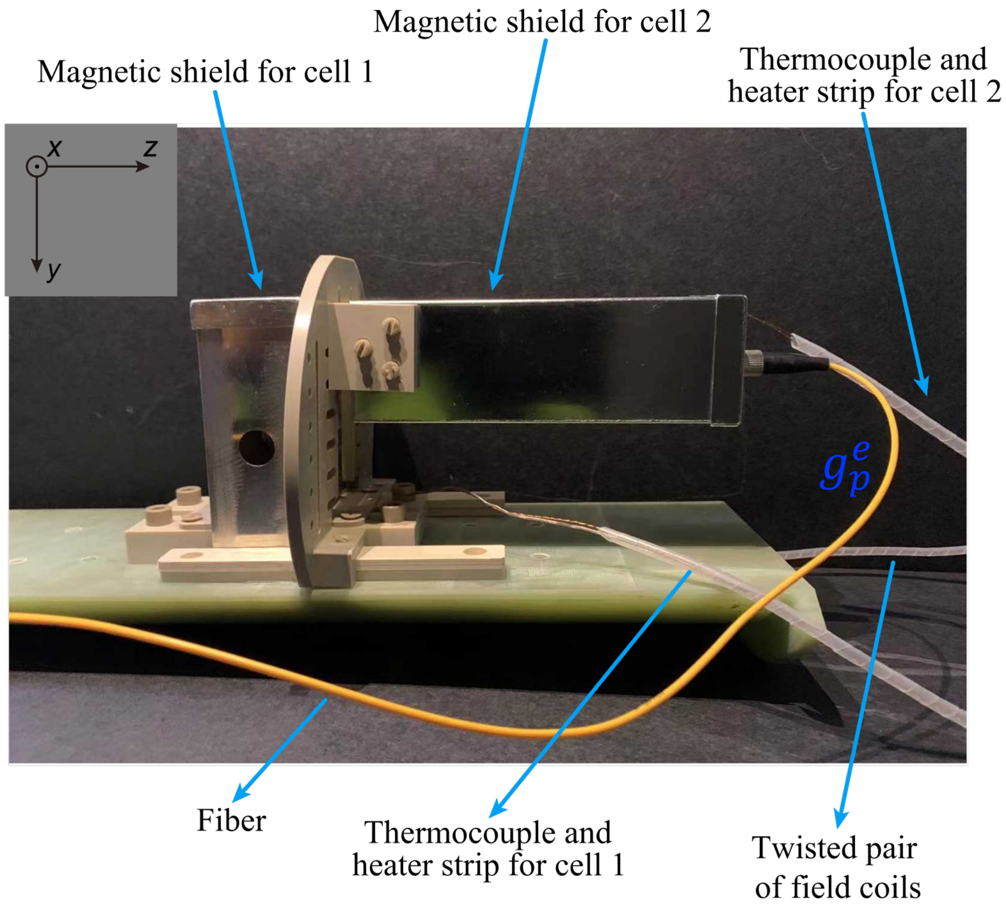
Meter scale — Decimeter scale — Centimeter scale

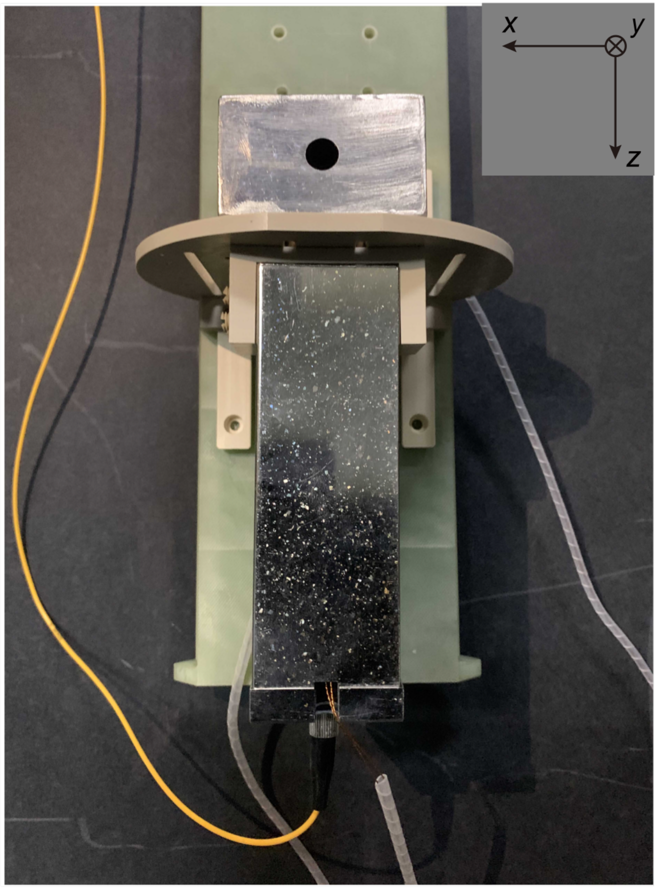
Axion window

Mass range $\longrightarrow$ Force range

$(10\ \mu\text{eV} \sim 1\ \text{meV}) \longrightarrow (0.2\ \text{mm} \sim 20\text{mm})$

How to shield the spurious ordinary field?



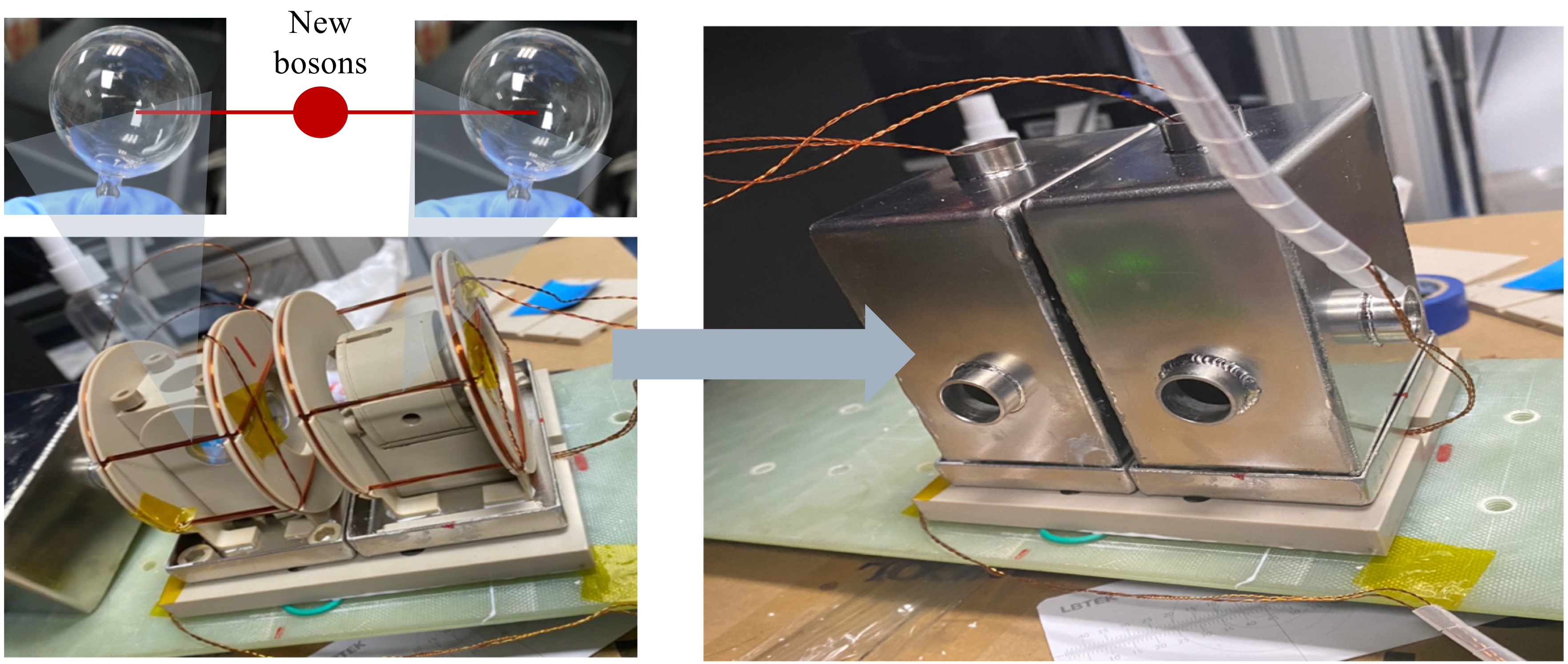


Spurious dipole field is suppressed at least ~10^4

PRL 129, 051801 (2022)

New boson mediated fifth force searches

New bosons (e.g. axions) act as force mediator and then induce exotic spin interactions between two spin ensembles (here we use atomic gas)



Resonant detection with spin amplifiers

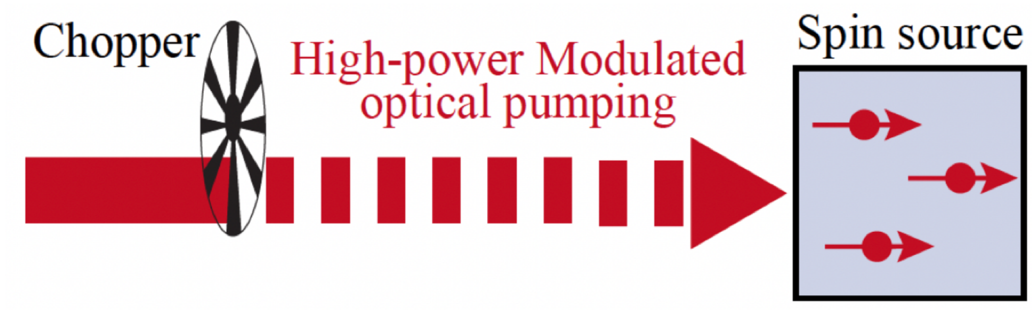
Static exotic field

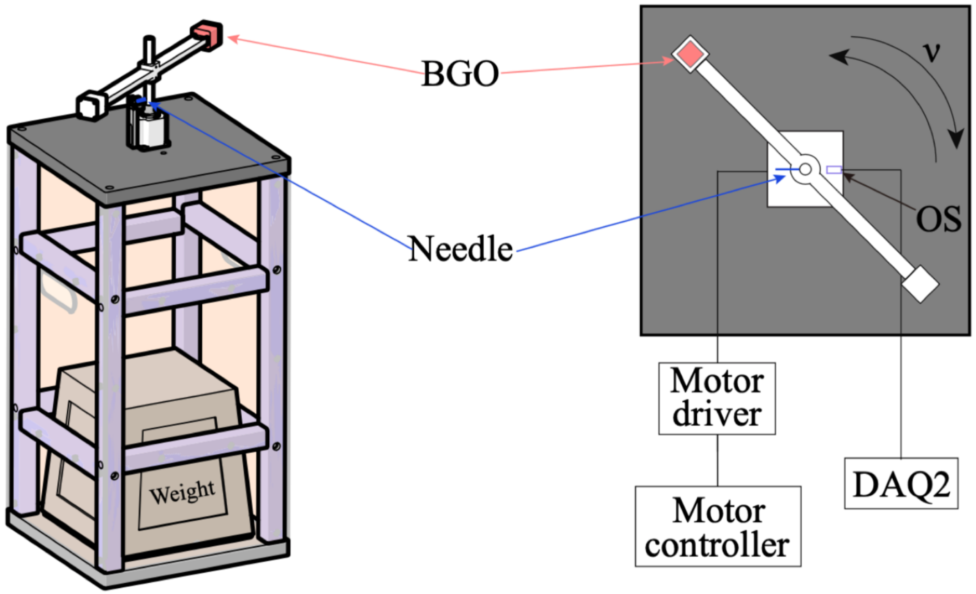
Modulating spin polarization

Modulating the distance between spin source and sensor

Oscillatory field

Resonantly searches

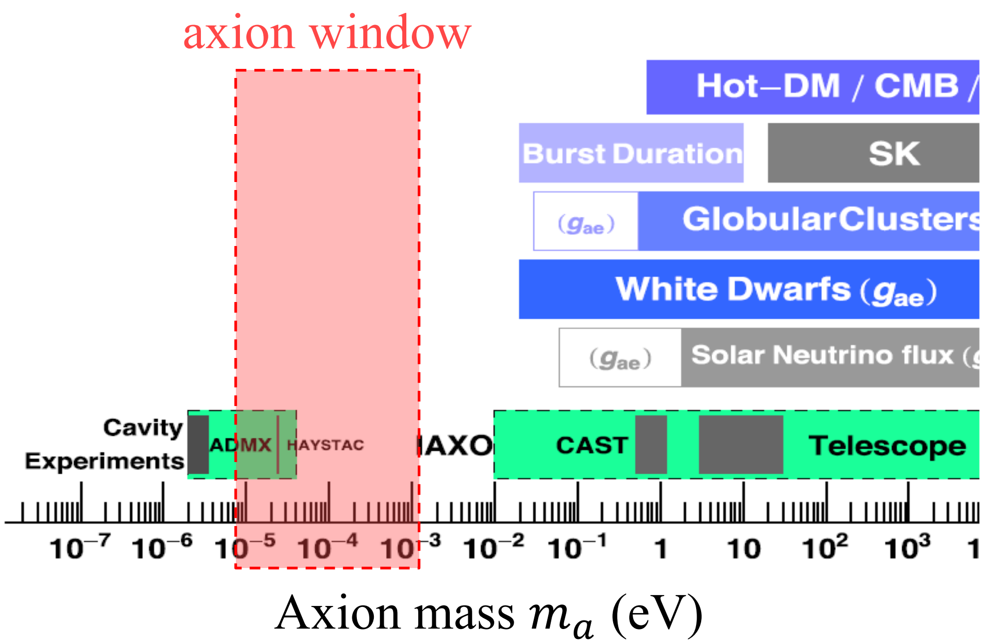




Searches for an axion-mediated interaction

Axion-mediated dipole-dipole interaction

$$V_{pp} = -\frac{g_p^1 g_p^2}{4}\left[(\hat{\boldsymbol{\sigma}}_1 \cdot \hat{\boldsymbol{\sigma}}_2)\left(\frac{m_a}{r^2}+\frac{1}{r^3}\right) - (\hat{\boldsymbol{\sigma}}_1 \cdot \hat{r})(\hat{\boldsymbol{\sigma}}_2 \cdot \hat{r})\left(\frac{m_a^2}{r}+\frac{3m_a}{r^2}+\frac{3}{r^3}\right)\right]\frac{e^{-m_a r}}{4\pi m_1 m_2}$$



High-temperature QCD
SMASH model
Axion string networks

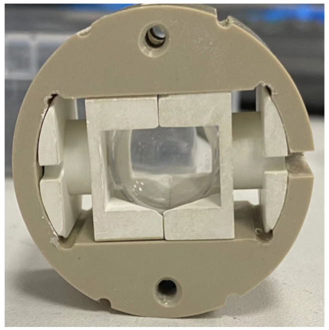
Axion window
($10\ \mu$eV ~ 1 meV, $\lesssim$ 2cm force range)

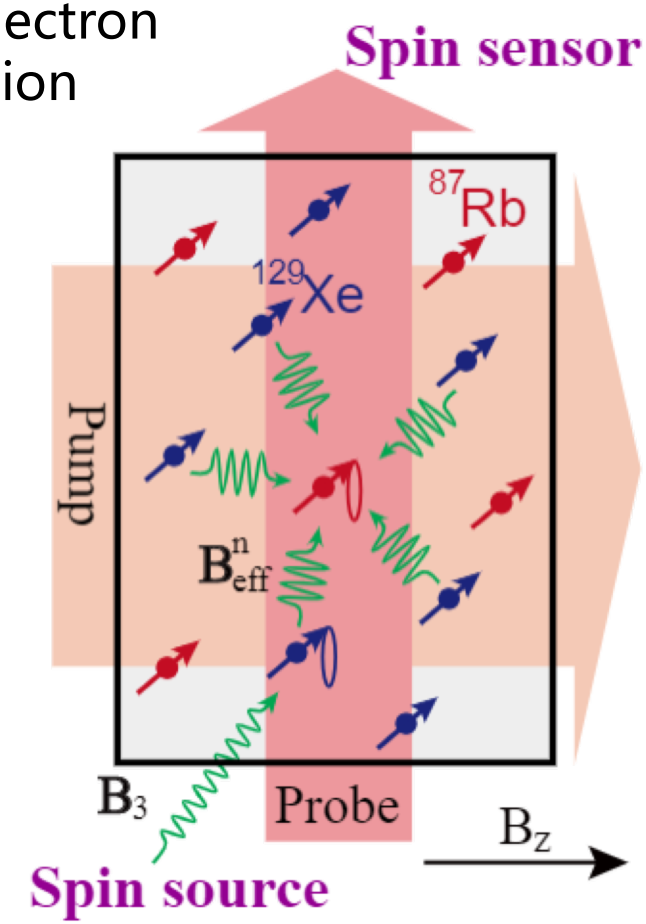
Spurious dipole field: Search remains challenging in the axion window

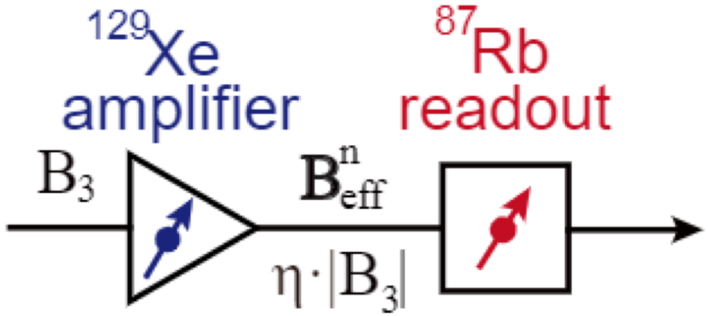
Search for an axion-mediated interaction

Neutron-electron interaction

Polarized electron





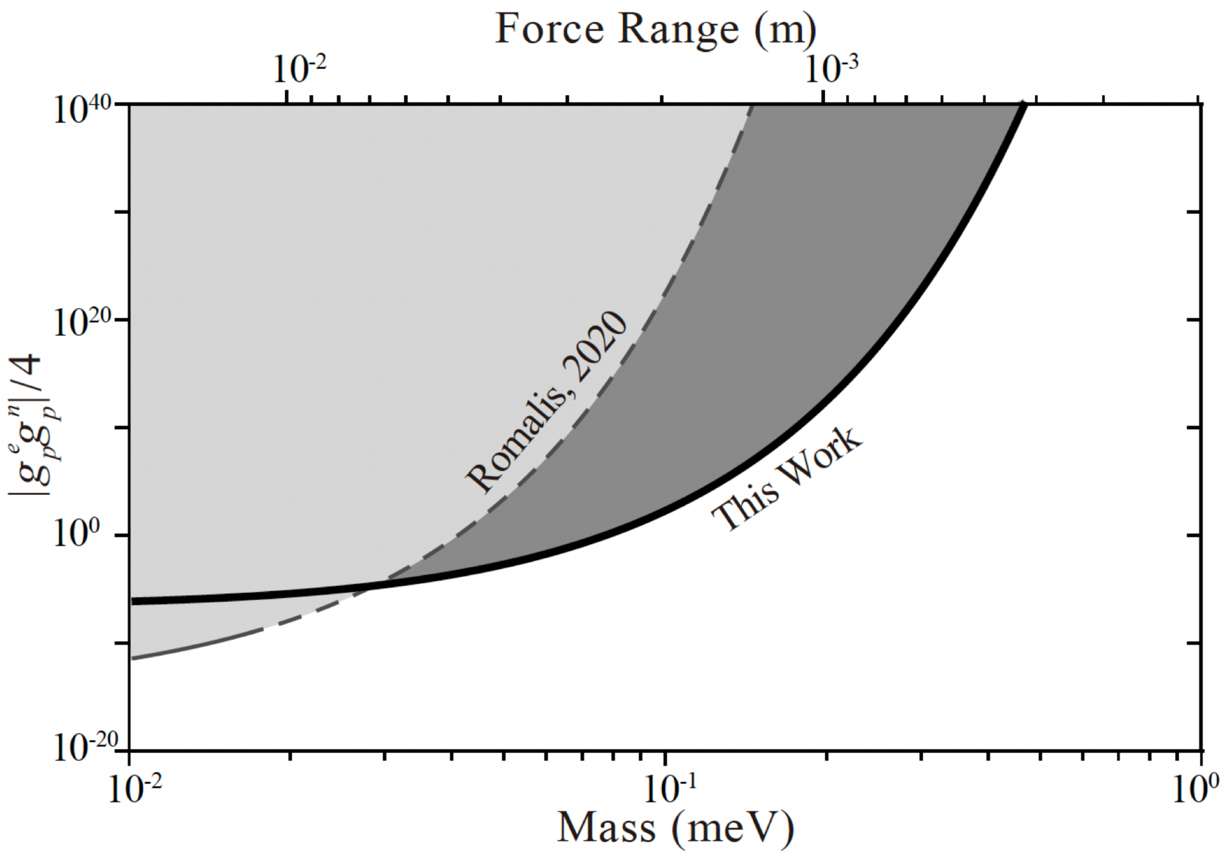


Resonantly search for the exotic interaction between electron and neutron

$$V_{pp} = -\frac{g_p^1 g_p^2}{4}\left[(\hat{\boldsymbol{\sigma}}_1 \cdot \hat{\boldsymbol{\sigma}}_2)\left(\frac{m_a}{r^2} + \frac{1}{r^3}\right) - (\hat{\boldsymbol{\sigma}}_1 \cdot \hat{r})(\hat{\boldsymbol{\sigma}}_2 \cdot \hat{r})\left(\frac{m_a^2}{r} + \frac{3m_a}{r^2} + \frac{3}{r^3}\right)\right]\frac{e^{-m_a r}}{4\pi m_1 m_2},$$

PRL 129, 051801 (2022)

Search for an axion-mediated interaction

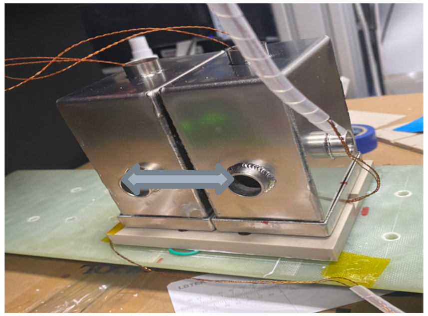


The most stringent constraints on $g_p^e g_p^n$ within the axion window

PRL 129, 051801 (2022)

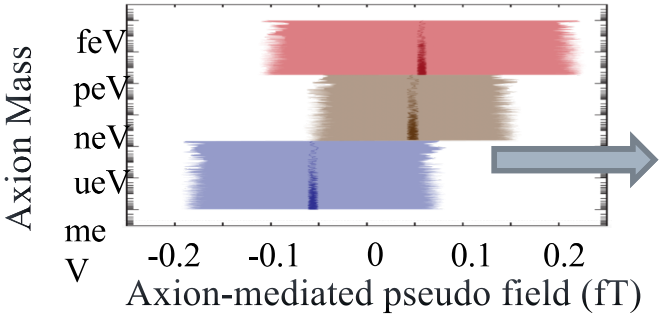
Axion-mediated spin-dependent forces

Two types of experiments are performed to search for axion-mediated electron-neutron and neutron-neutron interactions

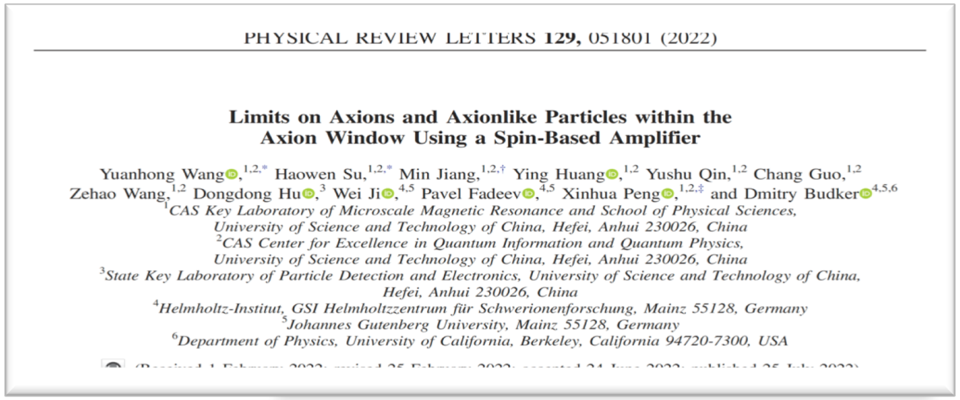


Search setup
(Spin amplifier+shield)

Exp#1: Rb cell-Xe cell
Exp#2: Xe cell-Xe cell



Pseudomagnetic fields are limited below 0.1 fT


PHYSICAL REVIEW LETTERS **129,** 051801 (2022)

Limits on Axions and Axionlike Particles within the Axion Window Using a Spin-Based Amplifier

Yuanhong Wang,[1,2,*] Haowen Su,[1,2,*] Min Jiang,[1,2,†] Ying Huang,[1,2] Yushu Qin,[1,2] Chang Guo,[1,2] Zehao Wang,[1,2] Dongdong Hu,[3] Wei Ji,[4,5] Pavel Fadeev,[4,5] Xinhua Peng,[1,2,‡] and Dmitry Budker[4,5,6]
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PHYSICAL REVIEW LETTERS **133,** 191801 (2024)

Editors' Suggestion   Featured in Physics

New Constraints on Axion-Mediated Spin Interactions Using Magnetic Amplification

Haowen Su,[1,2] Min Jiang,[1,2,*] Yuanhong Wang,[1,2] Ying Huang,[1,2] Xiang Kang,[1,2] Wei Ji,[3,4] Xinhua Peng,[1,2,†] and Dmitry Budker[3,4,5]
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Wang…Jiang* *et al.*, *Phys. Rev. Lett.* 129, 051801 (2022)

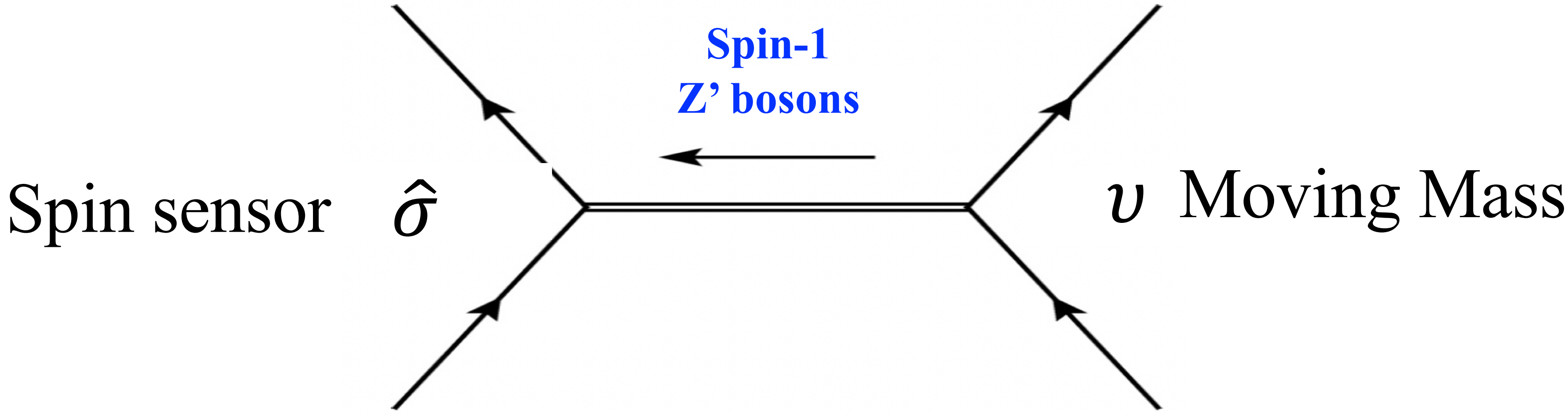
Su…Jiang* *et al.*, *Phys. Rev. Lett.* 133, 191801 (2024)

Search for exotic spin-dependent interactions

$$V_{4+5} = -f_{4+5}\frac{\hbar^2}{8\pi mc}[\hat{\sigma}\cdot(\boldsymbol{v}\times\hat{r})]\left(\frac{1}{\lambda r}+\frac{1}{r^2}\right)e^{-r/\lambda},$$

$$V_{12+13} = f_{12+13}\frac{\hbar}{8\pi}(\hat{\sigma}\cdot\boldsymbol{v})\left(\frac{1}{r}\right)e^{-r/\lambda},$$

Velocity dependence

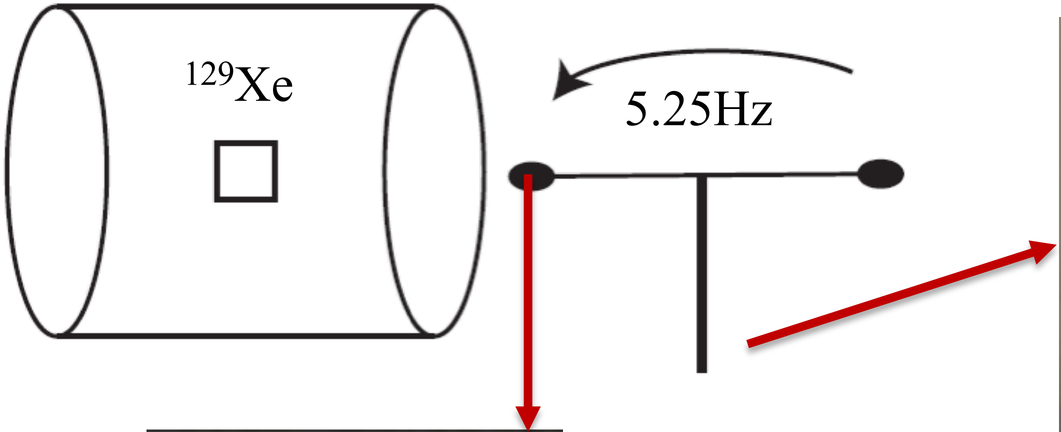


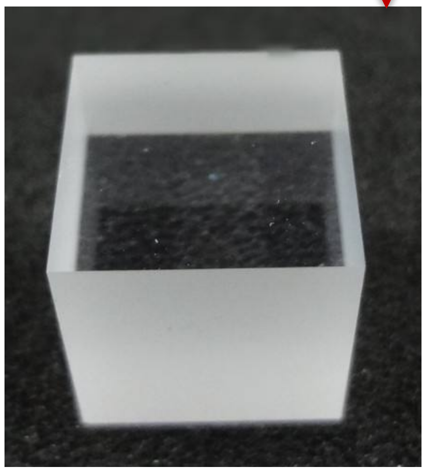
H. Su*, Y. Wang*, **M. Jiang†**, **X. Peng†** *et al*. Science Advances 7, eabi9535 (2021).

Search setup

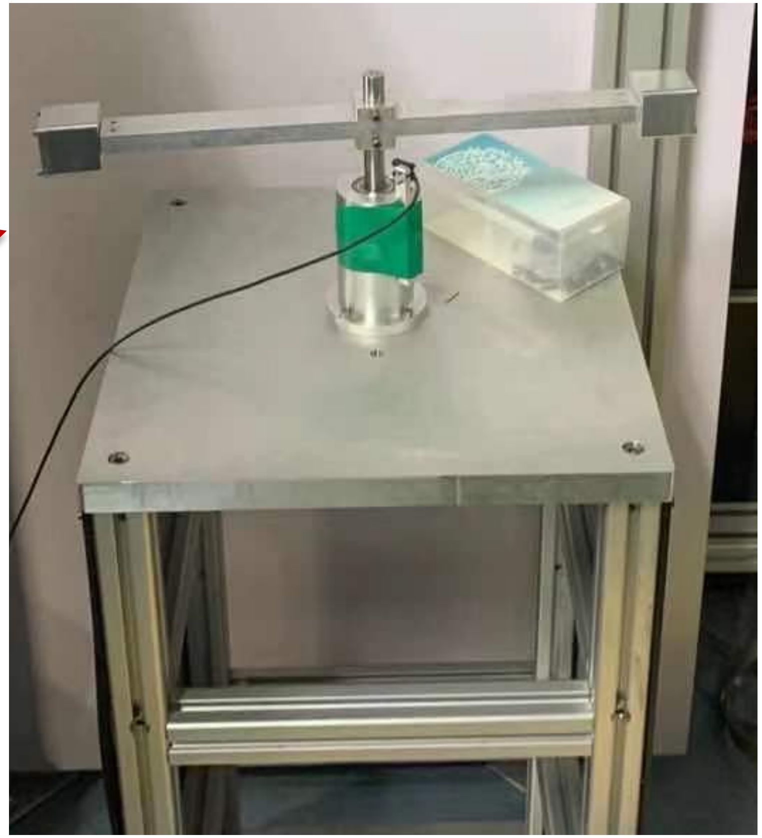
Spin-mass coupling

Rotator



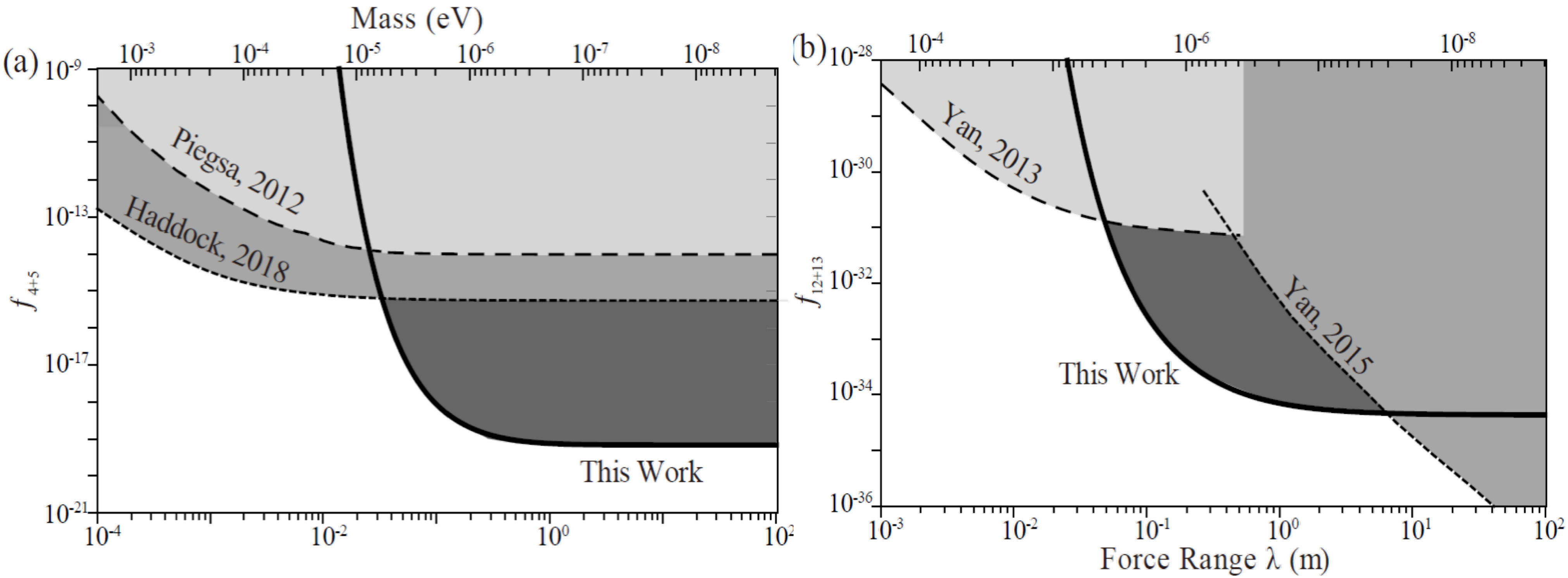


BGO



H. Su*,Y. Wang*, **M. Jiang†**, **X. Peng†** *et al*. Science Advances 7, eabi9535 (2021).

Constraints on spin-dependent interactions



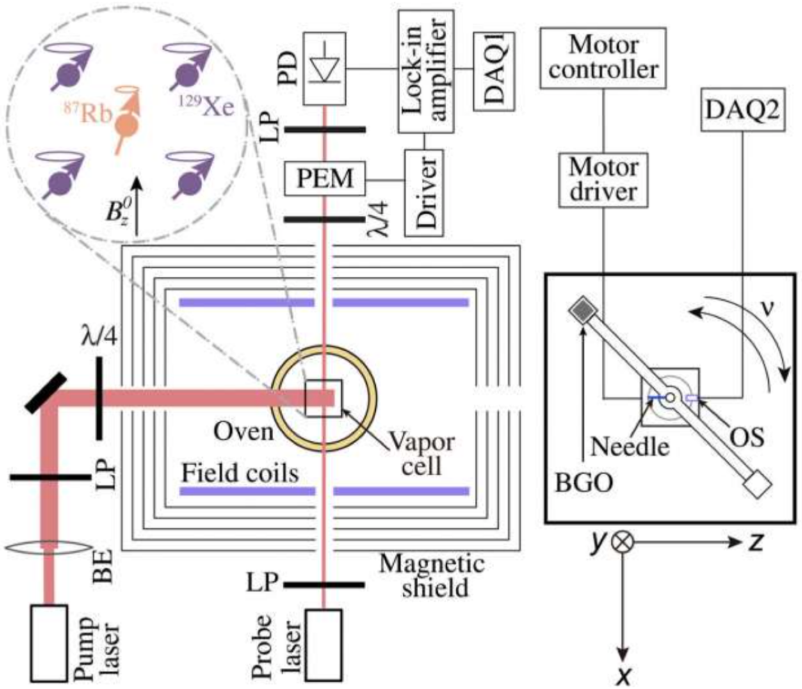
At least 2 orders of magnitude improvement on constraints on Z’ boson

H. Su*,Y. Wang*, **M. Jiang†**, **X. Peng†** *et al*. Science Advances 7, eabi9535 (2021).

DECEMBER 6, 2021

Ultra-high precision search for exotic interactions

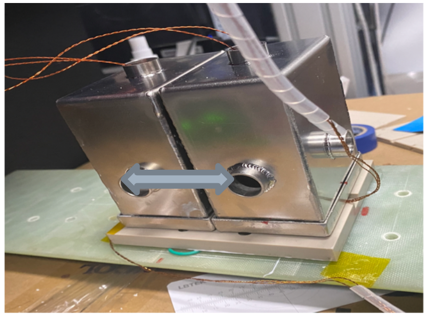
by Liu Jia, Chinese Academy of Sciences



In a study published in *Science Advances*, the research team led by Prof. Peng Xinhua from University of Science and Technology of China of the Chinese Academy of Sciences, collaborating with Prof. Dmitry Budker from Helmholtz Institution, realized ultra-high precision search of exotic spin- and velocity-dependent interactions beyond the standard model, and amplified the magnetic field signal of exotic interactions at least two
technique to the investigation of exotic velocity-
'eloped quantum spin-based amplifier.

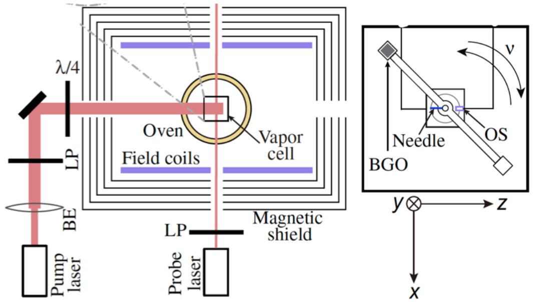
Z’ boson-mediated spin-dependent forces

Two types of experiments are performed to search for Z’ boson-mediated neutron-nucleon and neutron-electron interactions

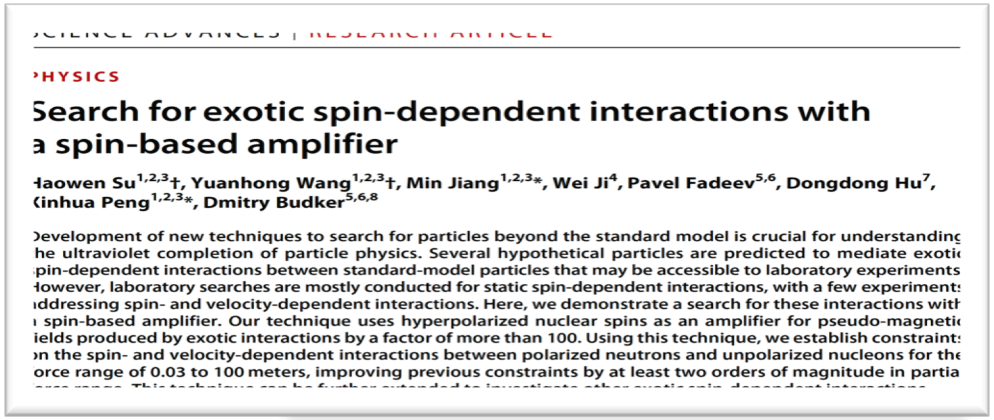


Search setup
(Spin amplifier+shield)

Exp#1: Xe cell-BGO crystal
Exp#2: Xe cell-Rb cell



Modulating spin-dependent force



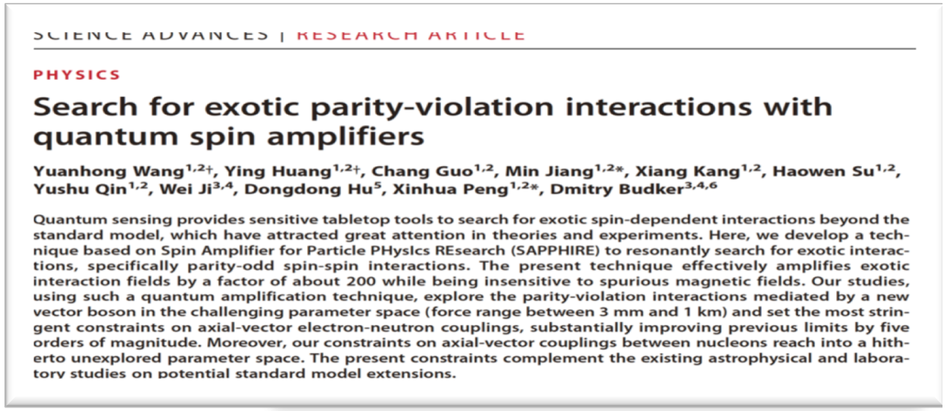
SCIENCE ADVANCES | RESEARCH ARTICLE

PHYSICS

Search for exotic spin-dependent interactions with a spin-based amplifier

Haowen Su[1,2,3]†, Yuanhong Wang[1,2,3]†, Min Jiang[1,2,3]*, Wei Ji[4], Pavel Fadeev[5,6], Dongdong Hu[7], Xinhua Peng[1,2,3]*, Dmitry Budker[5,6,8]

Development of new techniques to search for particles beyond the standard model is crucial for understanding the ultraviolet completion of particle physics. Several hypothetical particles are predicted to mediate exotic spin-dependent interactions between standard-model particles that may be accessible to laboratory experiments. However, laboratory searches are mostly conducted for static spin-dependent interactions, with a few experiments addressing spin- and velocity-dependent interactions. Here, we demonstrate a search for these interactions with a spin-based amplifier. Our technique uses hyperpolarized nuclear spins as an amplifier for pseudo-magnetic fields produced by exotic interactions by a factor of more than 100. Using this technique, we establish constraints on the spin- and velocity-dependent interactions between polarized neutrons and unpolarized nucleons for the force range of 0.03 to 100 meters, improving previous constraints by at least two orders of magnitude in partia



SCIENCE ADVANCES | RESEARCH ARTICLE

PHYSICS

Search for exotic parity-violation interactions with quantum spin amplifiers

Yuanhong Wang[1,2]†, Ying Huang[1,2]†, Chang Guo[1,2], Min Jiang[1,2]*, Xiang Kang[1,2], Haowen Su[1,2], Yushu Qin[1,2], Wei Ji[3,4], Dongdong Hu[5], Xinhua Peng[1,2]*, Dmitry Budker[3,4,6]

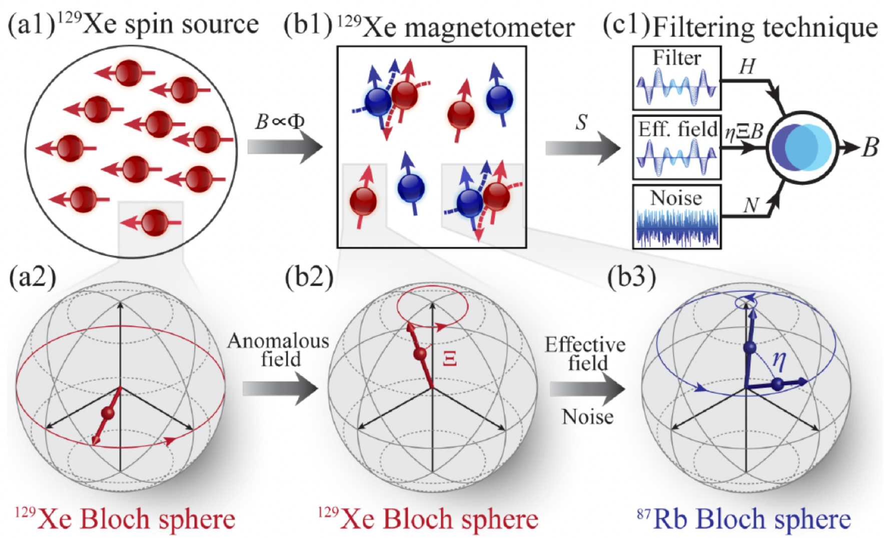
Quantum sensing provides sensitive tabletop tools to search for exotic spin-dependent interactions beyond the standard model, which have attracted great attention in theories and experiments. Here, we develop a technique based on Spin Amplifier for Particle PHysIcs REsearch (SAPPHIRE) to resonantly search for exotic interactions, specifically parity-odd spin-spin interactions. The present technique effectively amplifies exotic interaction fields by a factor of about 200 while being insensitive to spurious magnetic fields. Our studies, using such a quantum amplification technique, explore the parity-violation interactions mediated by a new vector boson in the challenging parameter space (force range between 3 mm and 1 km) and set the most stringent constraints on axial-vector electron-neutron couplings, substantially improving previous limits by five orders of magnitude. Moreover, our constraints on axial-vector couplings between nucleons reach into a hitherto unexplored parameter space. The present constraints complement the existing astrophysical and laboratory studies on potential standard model extensions.

Su…Jiang* *et al.*, *Sci. Adv.* 7, eabi9535 (2021)

Wang…Jiang* *et al.*, *Sci. Adv.* 9, eade0353 (2023)

New limits on spin-spin interactions

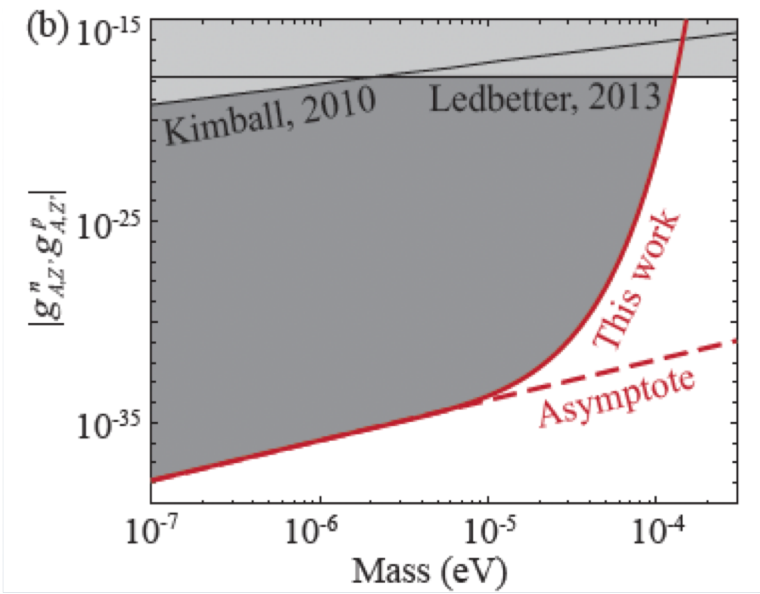
By integrating quantum sensing with NMR and optimal filtering, the limit on certain spin interactions has improved by several orders



Spin modulation

NMR

Optimal filtering

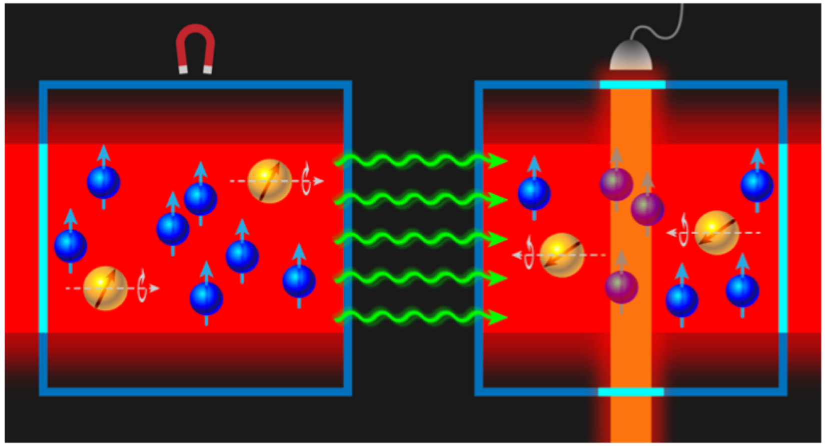


Phys. Rev. Lett. 134, 223201 (2025)

Searching for Axions in Polarized Gas

By exploiting polarized-gas collisions, researchers have conducted a sensitive search for exotic spin-dependent interactions, placing new constraints on a dark matter candidate called the axion.

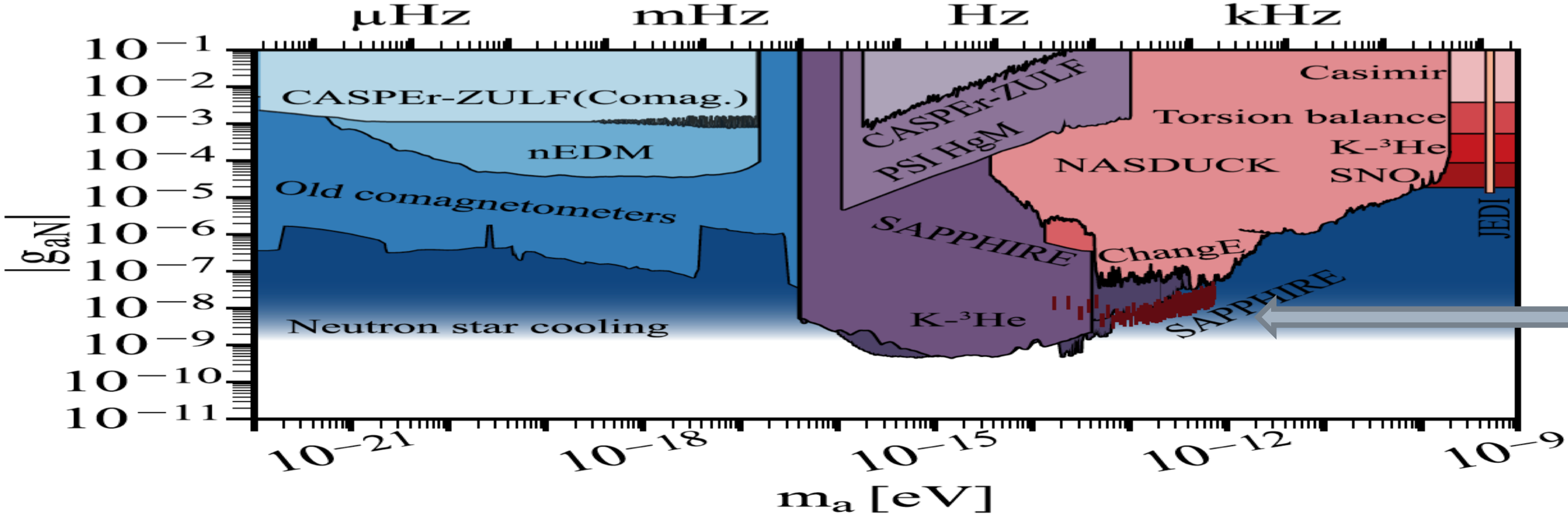
By **W. Michael Snow**



The standard model of fundamental particles and interactions has now been in place for about a half-century. It has successfully passed experimental test after experimental test at particle accelerators. However, many of the model's features are poorly understood, and it is now clear that standard-model particles only compose about 5% of the observed energy density of the Universe. This situation

Ultralight axion dark matter searches

Noble gas becomes important systems to perform dark matter searches

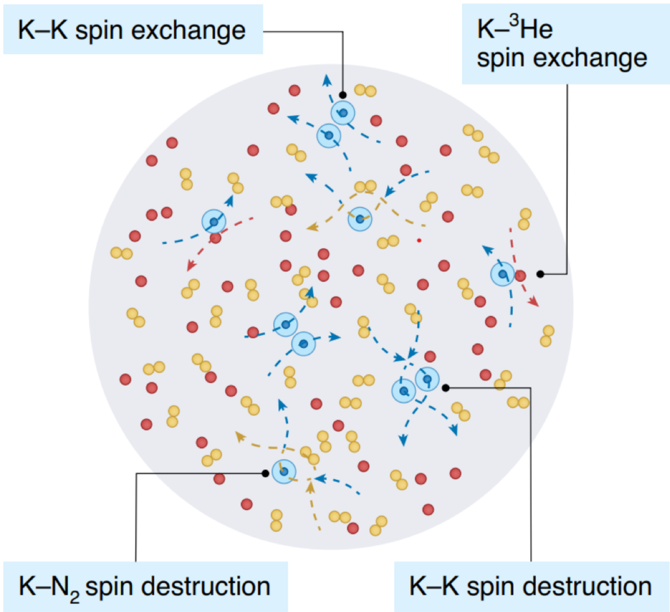


Noble-gas Experiments	Sapphire (Our work)	NASDUCK (Weizmann Institute)	K-^{3}He Comag. (Princeton)	ChangE (Beihang)
Noble gas	Rb-^{129}Xe	Rb-^{129}Xe	K-^{3}He	Rb-^{21}Ne
Published	Nat. Phys. 2021	Sci. Adv. 2022	PRX 2023	Comm. Phys. 2025

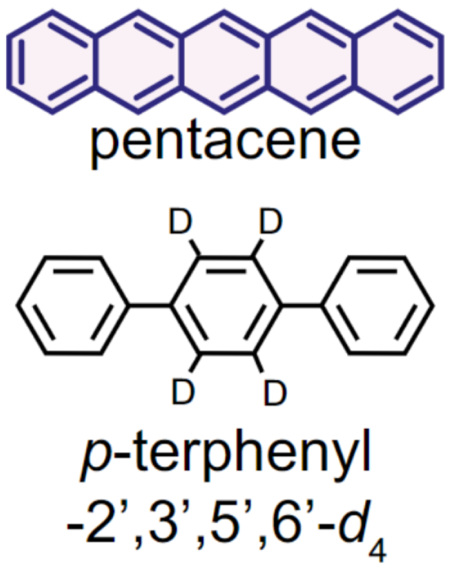
Jiang et al. Rep. Prog. Phys. 88 016401 (2025)

SAPPHIRE projected sensitivity

^{3}He-K spin amplifier



Solid-state spin source



4 orders of magnitude improvement

10^{14} cm^{-3} → 10^{18} cm^{-3}

8 orders of magnitude improvements are possible

被国内外多个研究组使用

NASDUCK暗物质探测(以色列)

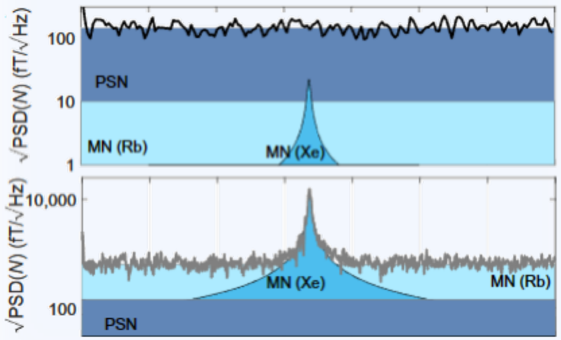
SCIENCE ADVANCES | RESEARCH ARTICLE

PHYSICS

New constraints on axion-like dark matter using a Floquet quantum detector

Itay M. Bloch[1,2]†, Gil Ronen[2,3]†, Roy Shaham[2,4], Ori Katz[3], Tomer Volansky[1], Or Katz[4]*‡

Dark matter is one of the greatest mysteries in physics. It interacts via gravity and composes most of our universe, but its elementary composition is unknown. We search for nongravitational interactions of axion-like dark matter with atomic spins using a precision quantum detector. The detector is composed of spin-polarized xenon gas that can coherently interact with a background dark matter field as it traverses through the galactic dark matter halo. Conducting a 5-month-long search, we report on the first results of the Noble and Alkali Spin Detectors for Ultra-light Coherent darK matter (NASDUCK) collaboration. We limit ALP-neutron interactions in the mass range of 4×10^{-15} to 4×10^{-12} eV/c^2 and improve upon previous terrestrial bounds by up to 1000-fold for masses above 4×10^{-13} eV/c^2. We also set bounds on pseudoscalar dark matter models with quadratic coupling.



利用Floquet自旋放大器暗物质探测
Science Advances (2022)

Advanced-GNOME网络(德国)

REVIEW

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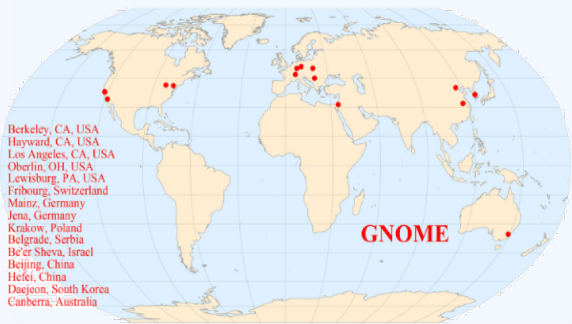
What Can a GNOME Do? Search Targets for the Global Network of Optical Magnetometers for Exotic Physics Searches

Samer Afach, Deniz Aybas Tumturk, Hendrik Bekker, Ben C. Buchler, Dmitry Budker, Kaleb Cervantes, Andrei Derevianko, Joshua Eby, Nataniel L. Figueroa, Ron Folman, Daniel Gavilán-Martín, Menachem Givon, Zoran D. Grujić, Hong Guo, Paul Hamilton, Morgan P. Hedges, Derek F. Jackson Kimball, Sami Khamis, Dongok Kim, Emmanuel Klinger, Abaz Kryemadhi, Xiyu Liu, Grzegorz Łukasiewicz, Hector Masia-Roig, Mikhail Padniuk, Christopher A. Palm, Sun Yool Park, Heather R. Pearson, Xiang Peng, Maxim Pospelov, Szymon Pustelny, Yossi Rosenzweig, Ophir M. Ruimi, Theo Scholtes,*



Advanced-GNOME网络引入自旋放大器
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ChangE-NMR计划(北航)

Constraining Ultralight Dark Matter through an Accelerated Resonant Search

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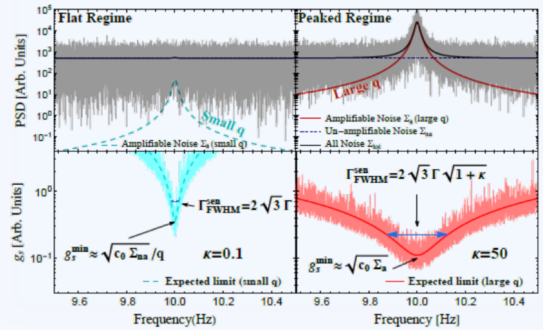

北航ChangE-NMR计划采用自旋放大器对暗物质进行探测，
arXiv:2309.16600v1 (2023年9月)