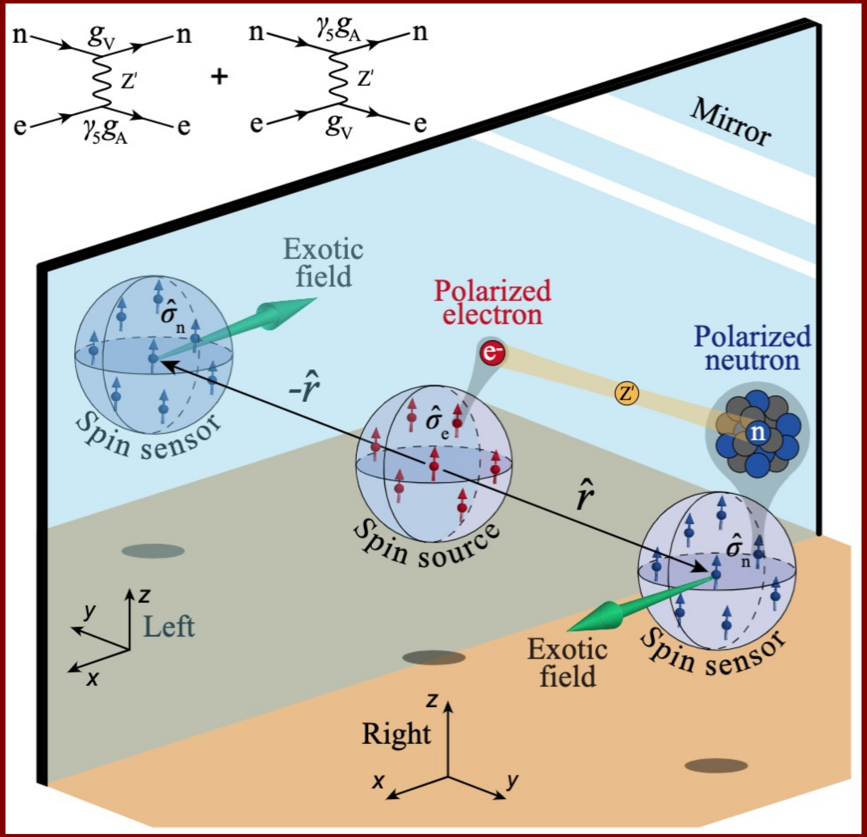
In search for ultralight (pseudo)scalars and other Dark Matter wannabes



Dmitry Budker

Helmholtz Institute, Johannes Gutenberg University, Mainz & UC Berkeley

COST Colloquium: June 21st, 2023

Prologue:
A story of an open question:
Is parity conserved by gravitation?

ONE THING LEADS TO ANOTHER

- Is parity conserved by gravitation ?
- How to check? ➔ centrifuge (EEP)

$$\vec{\sigma}\cdot\left(\vec{\Omega}\times\vec{r}\right)=\vec{\sigma}\cdot\vec{v}=\vec{\sigma}\cdot\vec{p}/m$$

- Can we test gravity via APV ?
- Probably not…
- … but can look for exotic cosmic fields

Phys. Rev. Lett. 113; Phys. Rev. D 90 (2014)

Limits on $\mathcal{P}$-odd interactions of cosmic fields with electrons, protons and neutrons

B. M. Roberts,[1,*] Y. V. Stadnik,[1,†] V. A. Dzuba,[1] V. V. Flambaum,[1,2] N. Leefer,[3] and D. Budker[3,4,5]

[1]*School of Physics, University of New South Wales, Sydney 2052, Australia*
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[3]*Helmholtz Institute Mainz, Johannes Gutenberg University, 55099 Mainz, Germany*
[4]*Department of Physics, University of California at Berkeley, Berkeley, CA 94720-7300, USA*
[5]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

(Dated: April 15, 2014)

We propose methods for extracting limits on the strength of $\mathcal{P}$-odd interactions of pseudoscalar and pseudovector cosmic fields with electrons, protons and neutrons. Candidates for such fields are dark matter (including axions) and dark energy, as well as several more exotic sources described by standard-model extensions. Calculations of parity nonconserving amplitudes and atomic electric dipole moments induced by these fields are performed for Li, Na, K, Rb, Cs, Ba^+, Tl, Dy, Fr, and Ra^+. From these calculations and existing measurements in Dy and Cs, we constrain the parity-violating interaction of a static pseudovector cosmic field at 2.1×10^{-19} GeV for the electron, and 3.1×10^{-8} GeV for the proton.

TABLE II. Limits on the dimensionless constants b_0^e and b_0^p quantifying the interaction strength of a PV cosmic field with electrons and protons, respectively.

PNC quantity		Limits $\lvert b_0^e \rvert$	Limits $\lvert b_0^p \rvert$
Cs	$E_{\rm PNC}(6s\text{-}7s)$	21×10^4	5.1×10^{13}
Tl	$E_{\rm PNC}(6p_{1/2}\text{-}6p_{3/2})$	95×10^4	1.4×10^{14}
Dy	$\langle A \lvert \hat{h} \rvert B \rangle$	340	

From nuclear anapoles

The Element of Success
66
162.50
2562
1.1
1409
Dy
8.55
3
Customize it!

Quantum technologies and the elephants

Marianna S Safronova[5,1] and Dmitry Budker[2,3,4]

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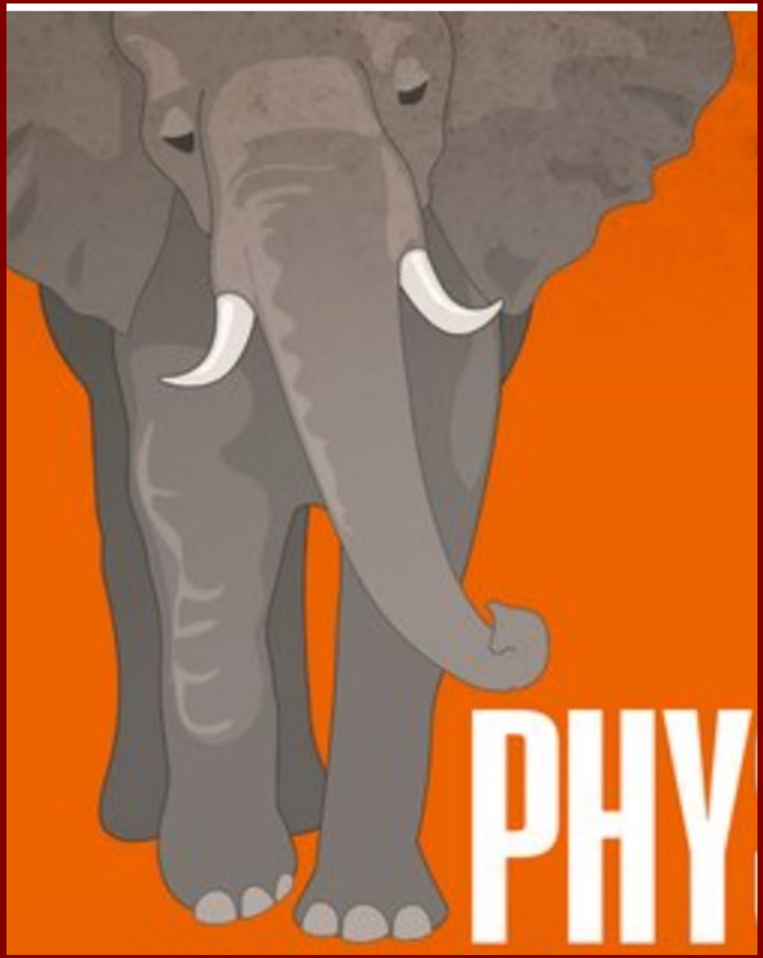
Quantum Science and Technology, Volume 6, Number 4

Quantum sensors for new-physics discoveries
November 2022

Dark matter: an elephant in the room



Cover image from D. Budker and A. O. Sushkov, **Physics on Your Feet**; Second Edition, 280 pp, OUP 2021

What can it be ?

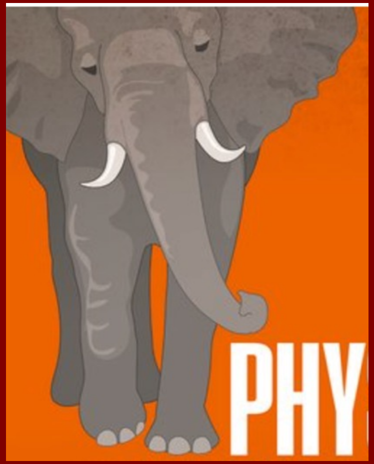
- Ultralight bosonic particles
  - Axions (pseudoscalar)
  - ALPs (pseudoscalar)
  - Dilatons (scalar)
  - Vector particles

Relaxions (mixed)

- Antiquark Nuggets (AQN)

- Millicharged particles
- Not even particles

- A gross misunderstanding of gravity (MOND, …) ???
- Proca MHD (finite photon mass) ☹?
- Black holes, dark planets, interstellar gas, … ☹?
- WIMPS ☺



Elephant Safari

Direct DM searches

Indirect DM searches

- Spectroscopy
- NMR
- Antimatter
- EDMs
- Astrophysics
- Accelerator based searches

Indirect searches via fifth forces (examples)

The latest catalog of EXOTIC potentials

PHYSICAL REVIEW A **99**, 022113 (2019)

Revisiting spin-dependent forces mediated by new bosons: Potentials in the coordinate-space representation for macroscopic- and atomic-scale experiments

Pavel Fadeev,[1] Yevgeny V. Stadnik,[1] Filip Ficek,[2] Mikhail G. Kozlov,[3,4] Victor V. Flambaum,[1,5] and Dmitry Budker[1,6,7]

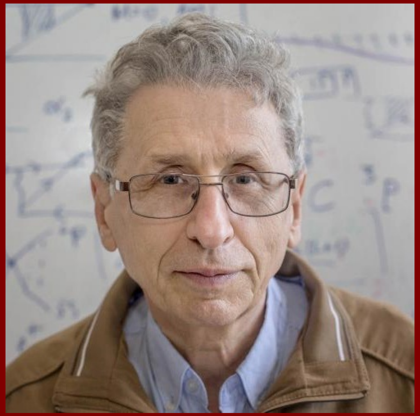
PHYSICAL REVIEW A **105**, 022812 (2022)

Pseudovector and pseudoscalar spin-dependent interactions in atoms

Pavel Fadeev,[1,*] Filip Ficek,[2] Mikhail G. Kozlov,[3,4] Dmitry Budker,[1,5] and Victor V. Flambaum[1,6]

Previous catalogs:

- J. E. Moody and F. Wilczek, Phys. Rev. D 30, 130 (1984)
- B. A. Dobrescu and I. Mocioiu, J. High Energy Phys. 11 (2006)



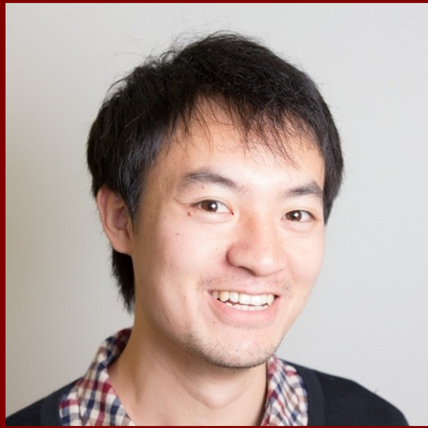
SAPPHIRE: Search for exotic parity-violation interactions with quantum spin amplifiers

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

[1)] *CAS Key Laboratory of Microscale Magnetic Resonance and School of Physical Sciences, University of Science and Technology of China, Hefei, Anhui 230026, China*

arXiv:2205.07222

Science Advances **9**, eade0353 (2023



Dr. Min Jiang, USTC

Dr. Wei Ji, HI Mainz

$$V_{11} = -f_{11}\left[(\hat{\sigma}_n \times \hat{\sigma}_e)\cdot\hat{r}\right]\left(\frac{1}{\lambda r}+\frac{1}{r^2}\right)\frac{e^{-r/\lambda}}{4\pi m_e}$$

P-odd, T-even

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Yuanhong Wang,[1,2,a)] Ying Huang,[1,2,a)] Chang Guo,[1,2] Min Jiang,[1,2,b)] Xiang Kang,[1,2] Haowen Su,[1,2]
Yushu Qin,[1,2] Wei Ji,[3,4] Dongdong Hu,[5] Xinhua Peng,[1,2,c)] and Dmitry Budker[3,4,6]
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arXiv:2205.07222

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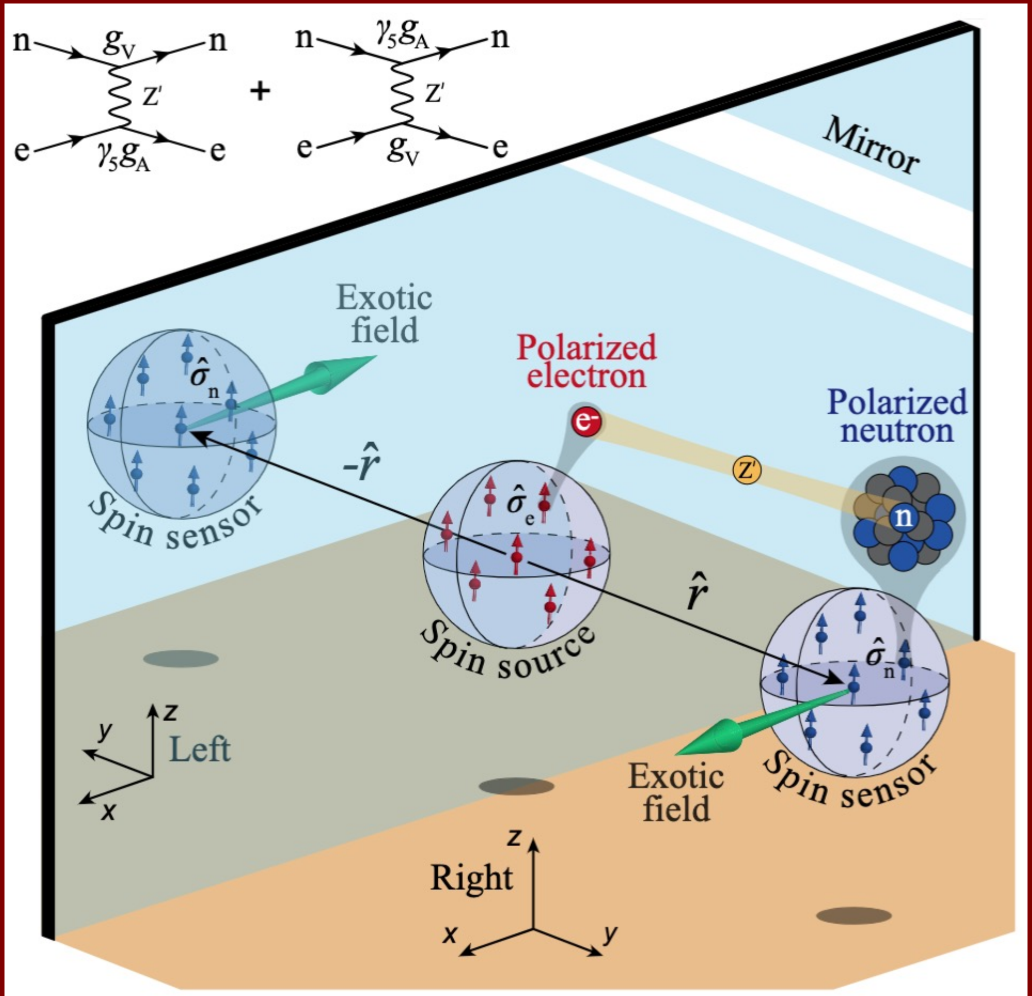

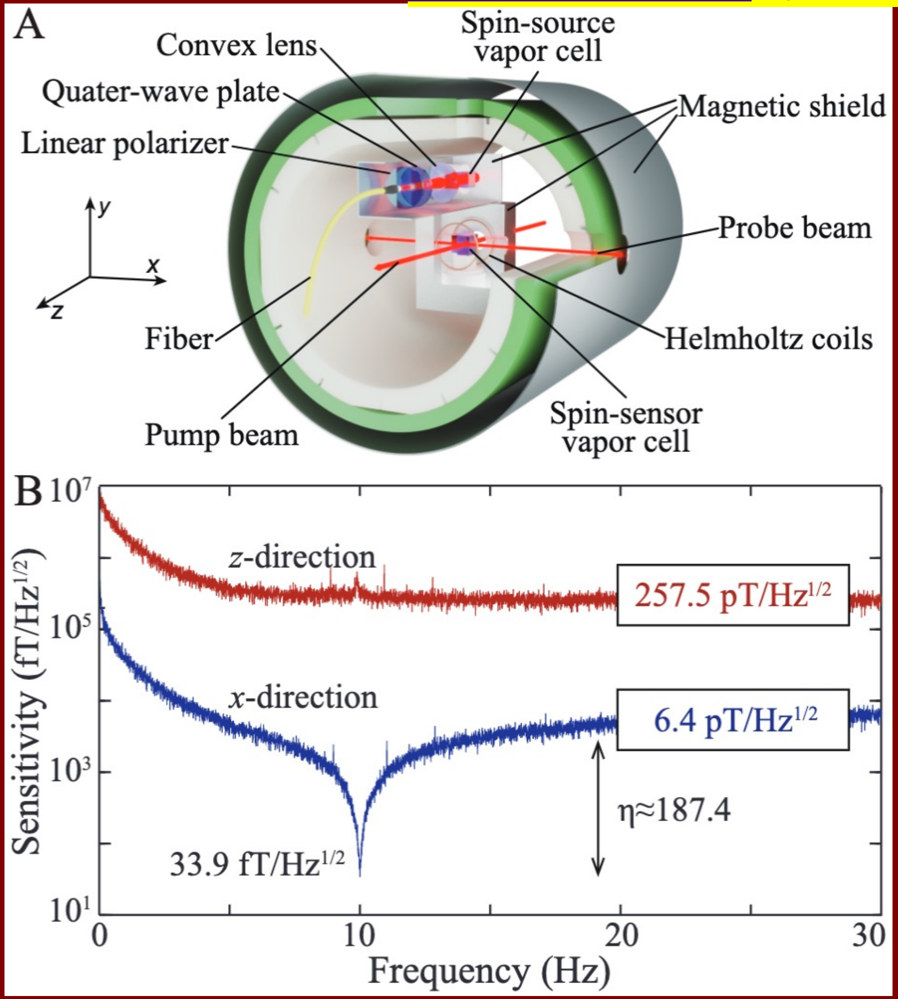

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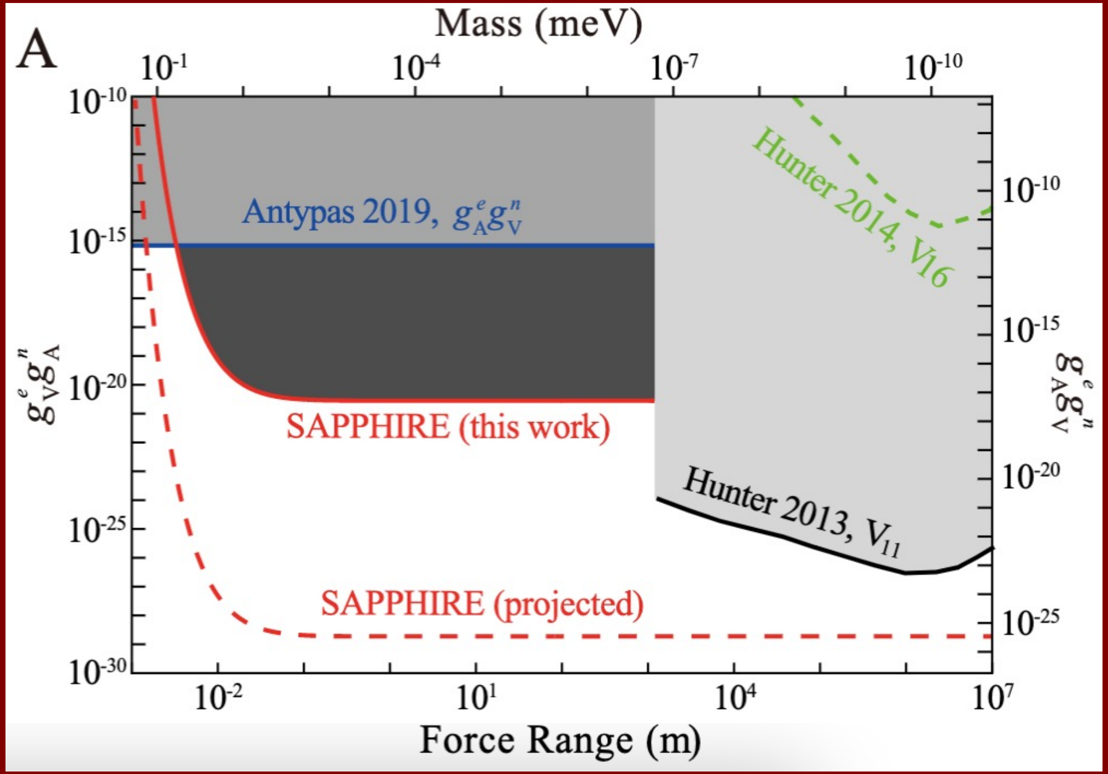
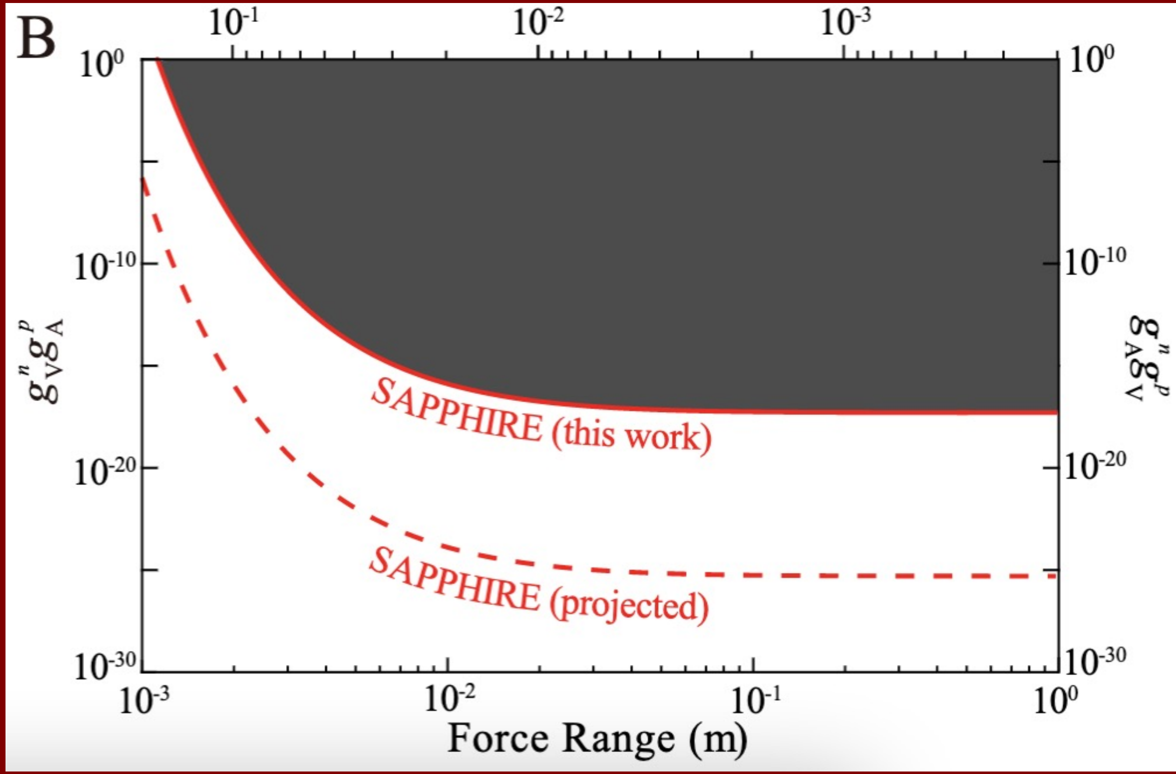
arXiv:2205.07222
Science Advances **9**, eade0353 (2023)



Electron-neutron couplings



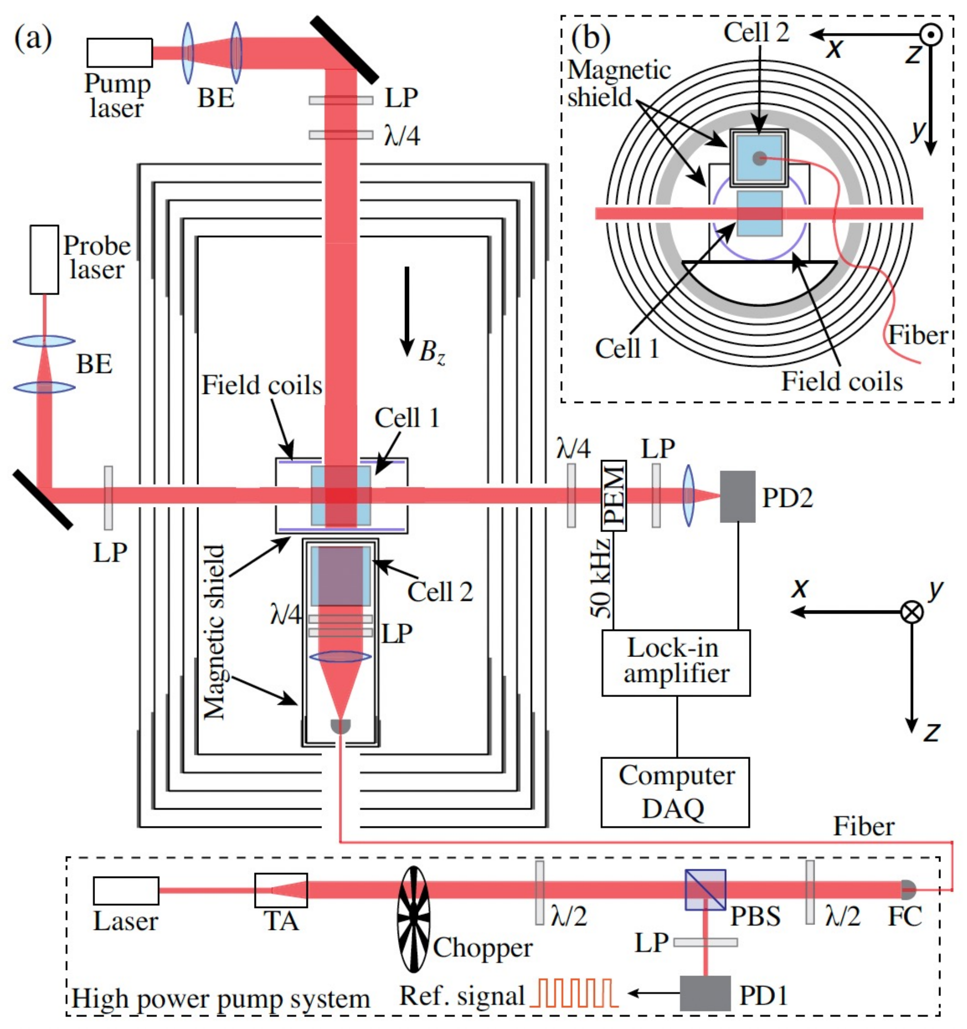
Proton-neutron couplings

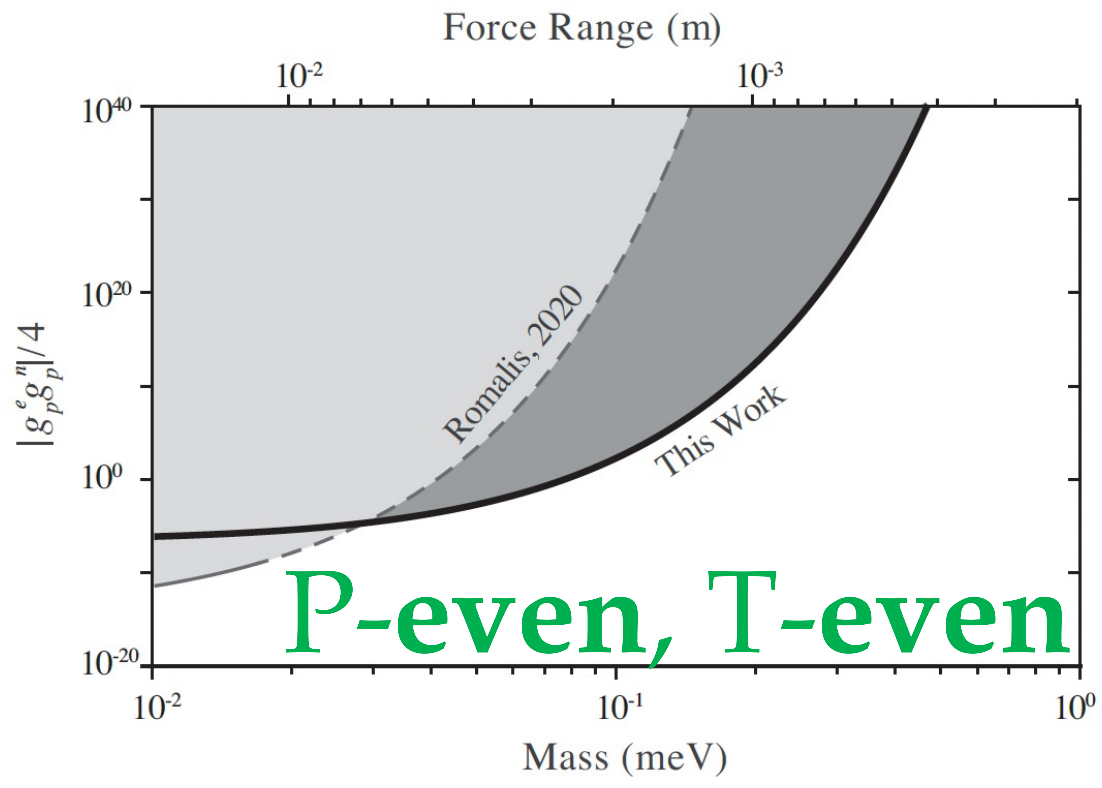
In another geometry---also sensitive to parity-conserving fifth forces

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]





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

…and
velocity-dependent monopole-dipole coupling

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

Sci. Adv. **7**, eabi9535 (2021)

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]

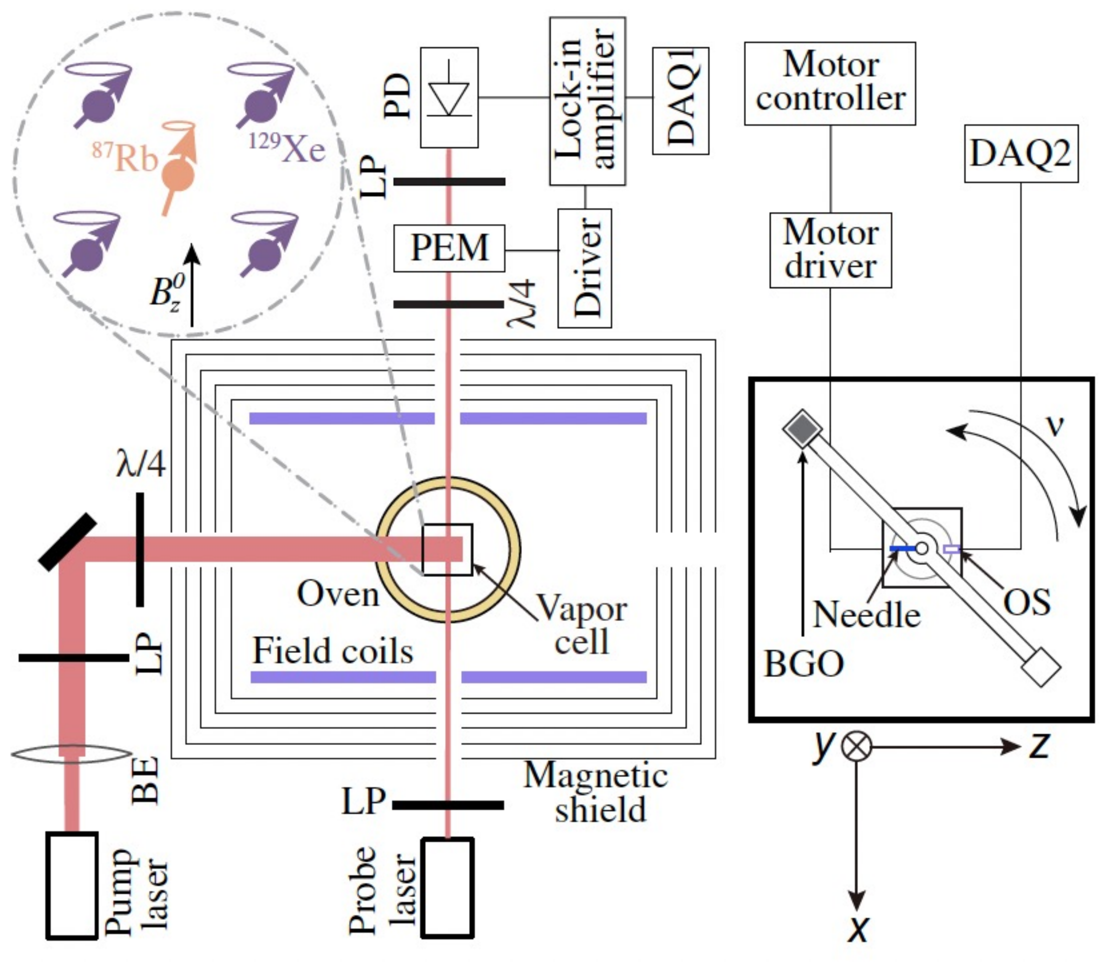


Fig. 1. Experimental setup. The ^{87}Rb magnetometer uses a 0.5-cm^3 cubic cell consisting of 5 torr isotopically enriched ^{129}Xe, 250 torr N_2 as buffer gas, and a droplet of ^{87}Rb. The vapor cell is placed inside a five-layer cylindrical μ-metal shield to reduce the ambient magnetic field. A bias field $B_z^0\hat{z}$ is applied along *z* to tune the ^{129}Xe Larmor frequency to $\nu_0 \approx 4.995$ Hz. The ^{87}Rb spins are polarized by optical pumping with 795-nm D1 light. ^{87}Rb-^{129}Xe spin-exchange collisions polarize ^{129}Xe spins to ~30% (*40*, *47*). The *x* component of ^{87}Rb spins is measured via optical rotation of a linearly polarized probe beam (*54*–*57*), which is blue-detuned 110 GHz to ^{87}Rb D2 transition at 780 nm. The right inset shows the configuration of a bismuth germanate insulator [$Bi_4Ge_3O_{12}$ (BGO)] mass and a motor. A single BGO mass at the end of an aluminum rod rotates with frequency $\nu_0 \approx 4.995$ Hz to generate the spin- and velocity-dependent interactions. BE, beam expander; LP, linear polarizer; λ/4, quarter–wave plate; PD, photodiode; PEM, photoelastic modulator; DAQ, data acquisition; OS, optoelectronic switch.

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

P-even, T-even

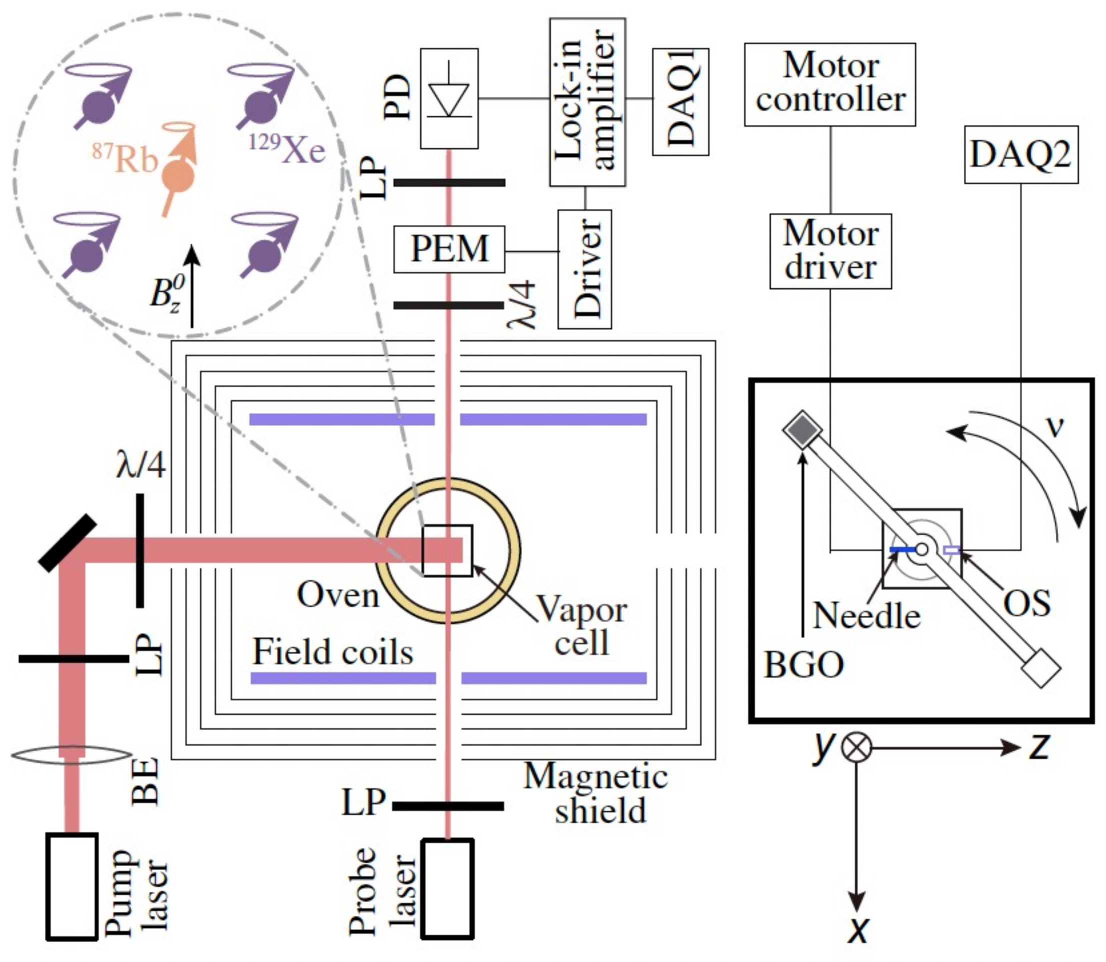
$$V_{12+13} = f_{12+13}\frac{\hbar}{8\pi}(\hat{\sigma}\cdot\boldsymbol{v})\left(\frac{1}{r}\right)e^{-r/\lambda}$$

P-odd, T-even

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

Sci. Adv. **7**, eabi9535 (2021)

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]



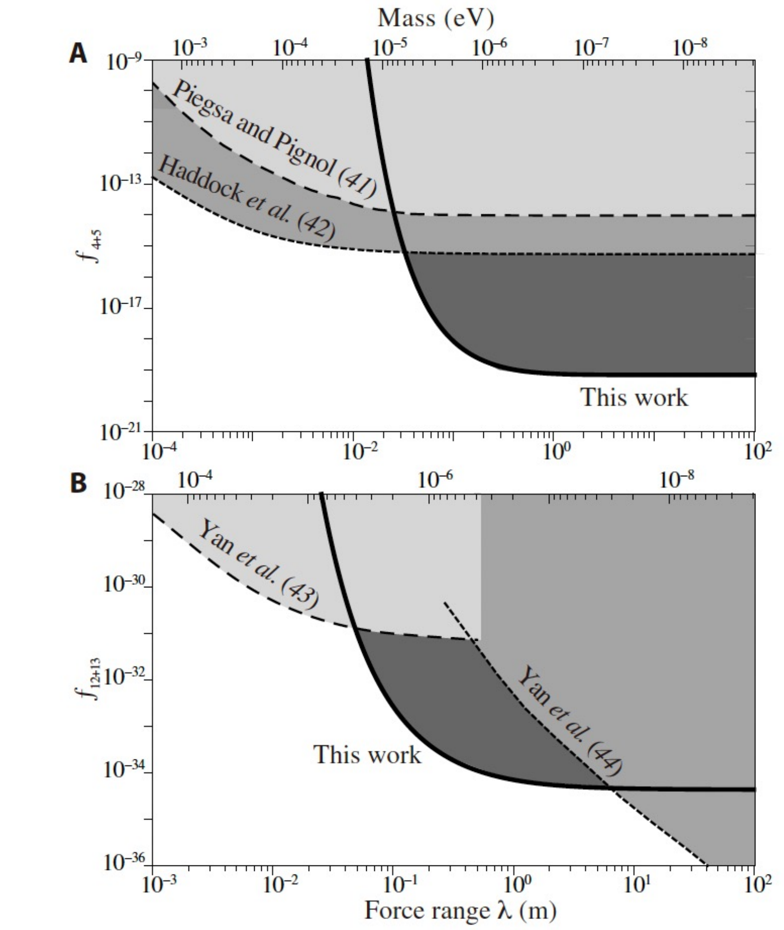


Fig. 4. Constraints (95% C.L.) on f_{4+5} and f_{12+13}. % In (**A**), the dashed lines represent bounds of f_{4+5} from (*41*, *42*). Our work (solid line) sets the most stringent constraints on f_{4+5} for the force range from 0.04 to 100 m. In (**B**), the dashed lines are from (*43*, *44*). The solid line is the constraint of f_{12+13} established by our work, which set the most stringent constraints in the force range from 0.05 to 6 m.

More fun with spin amplifiers

PHYSICAL REVIEW LETTERS **128**, 233201 (2022)

Editors' Suggestion

Floquet Spin Amplification

Min Jiang,[1,2] Yushu Qin,[1,2] Xin Wang,[1,2] Yuanhong Wang,[1,2] Haowen Su,[1,2]
Xinhua Peng,[1,2,*] and Dmitry Budker[3,4,5]

Direct searches for pseudoscalars (example)

How to search for halo Axions (ALPs) ?

Axion (ALP) Interactions

Gravity

+

Gauge Fields

axion field amplitude

symmetry breaking scale

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

Most Searches,
DM radio

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

nEDM, HfF^+,…
CASPEr-E

Fermions

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

GNOME, QUAX, nEDM, comag,…
CASPEr-grad

Nonrelativistic forms

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

coupling to gluons

→ creates oscillating nucleon electric dipole moment (EDM)
this is why axions were invented

→ spin $\boldsymbol{\sigma}$ to axion coupling:

$$H_e \propto a \boldsymbol{\sigma} \cdot \boldsymbol{E}^*$$

CASPEr-electric

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

coupling to fermions

→ via axion field gradient

→ spin $\boldsymbol{\sigma}$ to axion gradient coupling:

$$H_g \propto \boldsymbol{\sigma} \cdot \boldsymbol{\nabla} a$$

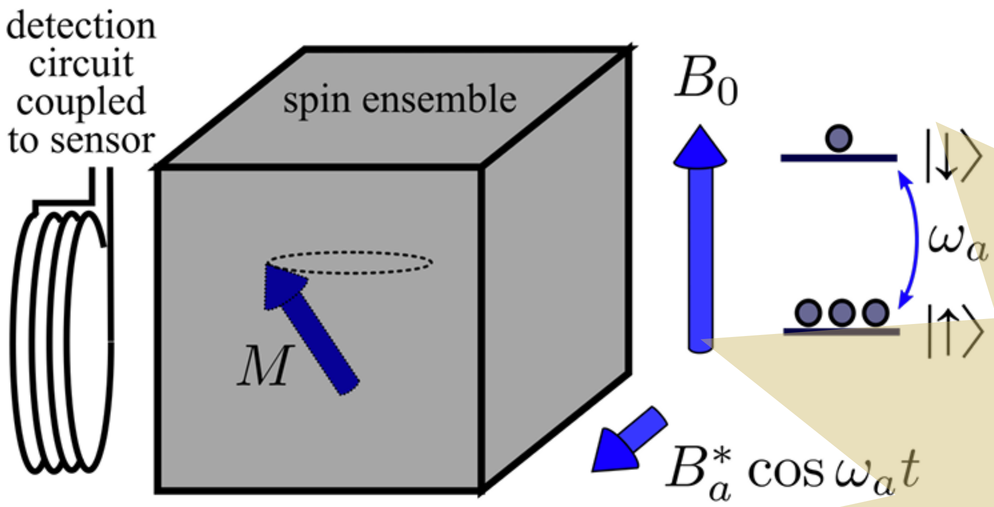
CASPEr-gradient

CASPEr (Cosmic Axion Spin Precession Experiments) searches for experimental signatures of these couplings

P-odd, T-odd

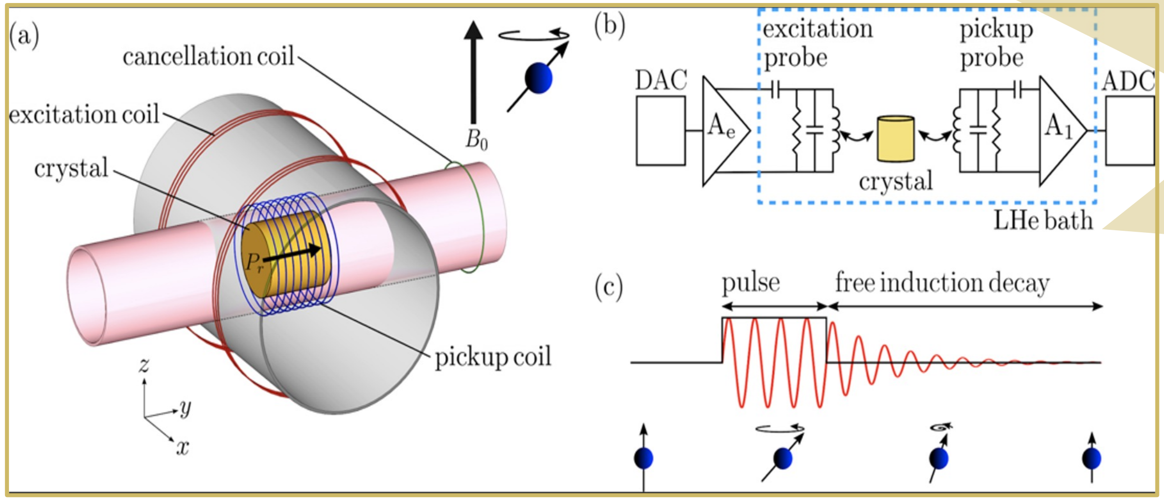
P-even, T-even

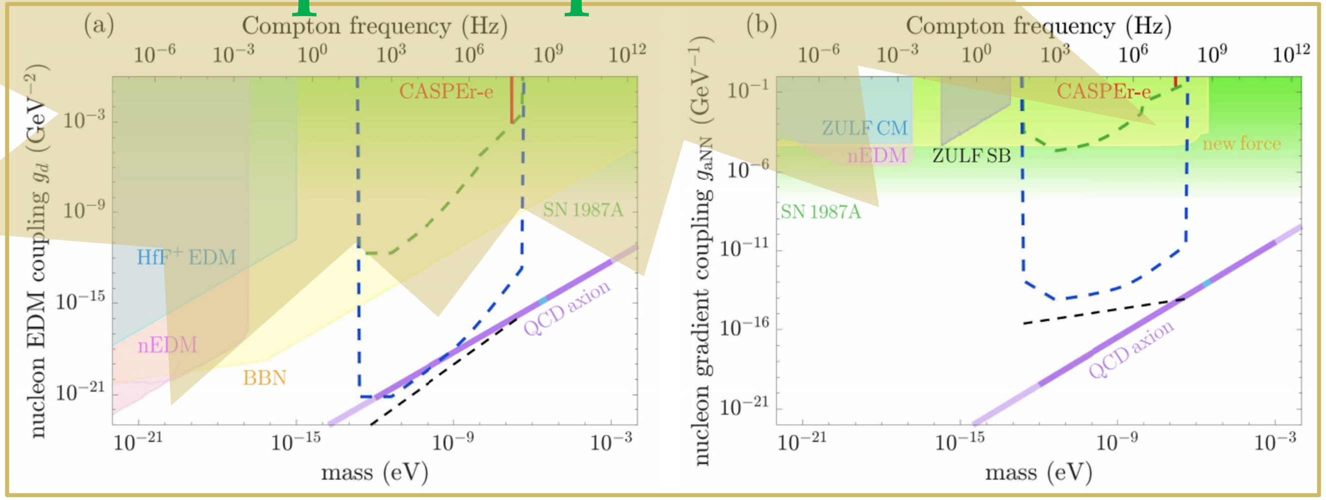
CASPEr: cosmic axion spin-precession experiments; first physics results: 2019-21



Boston and Mainz

CASPEr is a
spin amplifier



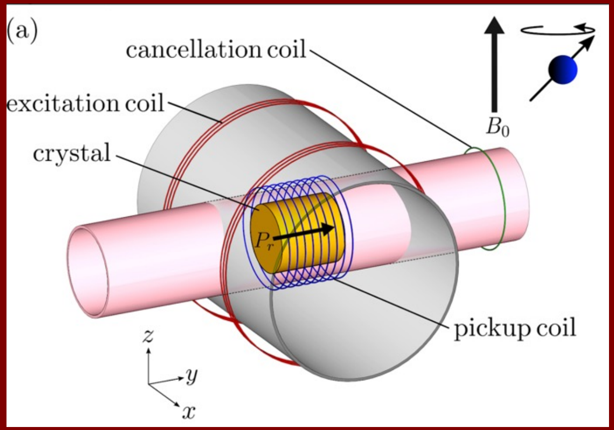


D. Aybas et al PhysRevLett.126.141802 (2021)

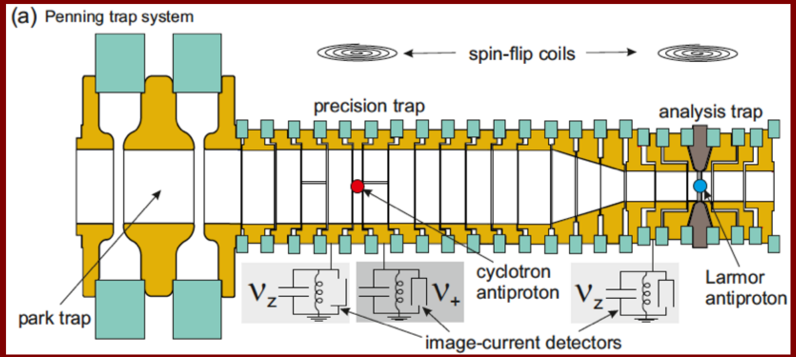
A lot is going on in UBDM searches…

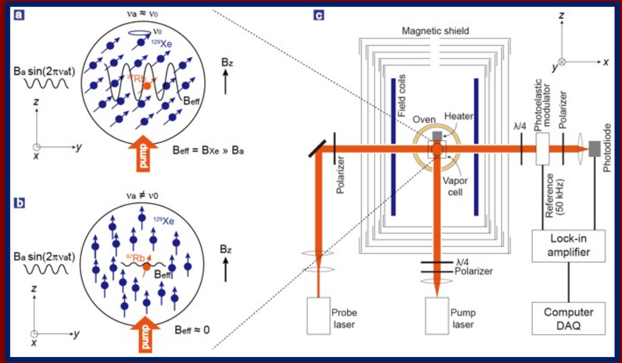
Searching for Ultralight Bosonic (and other) DM

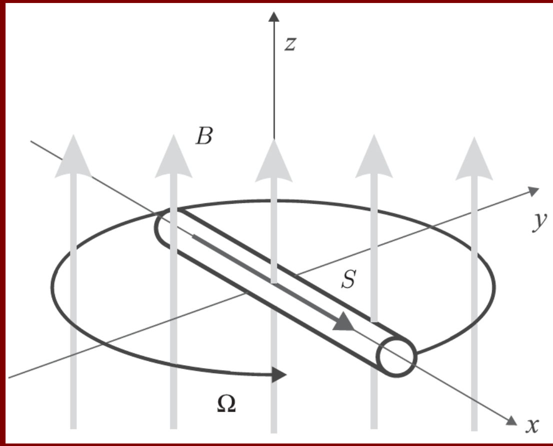
- NMR (CASPEr)
- Spin-based sensors for DM: masers, spin amplifiers
- Spin-based sensors for fifth-force searches (single NV, cells)
- GNOME, clock networks, hybrid networks
- Gravimeters
- Atomic spectroscopy
- Antimatter
- Levitated magnets

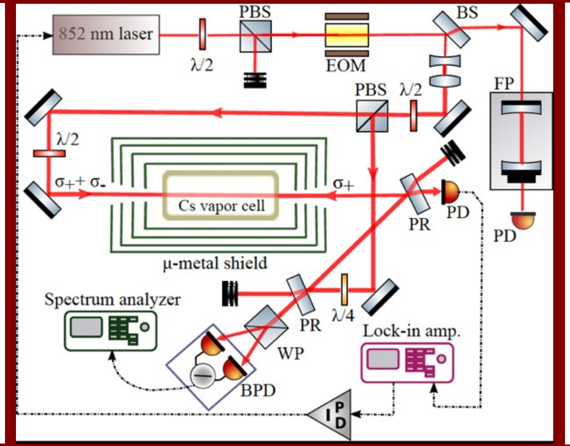


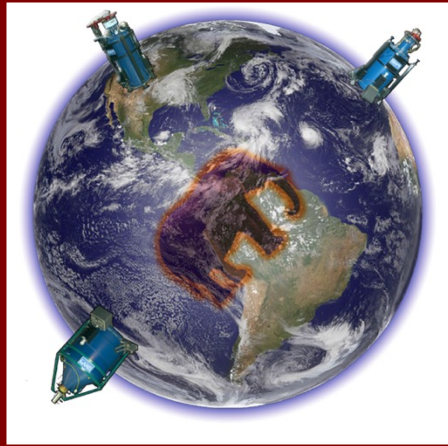
Nataniel Figueroa Liegh

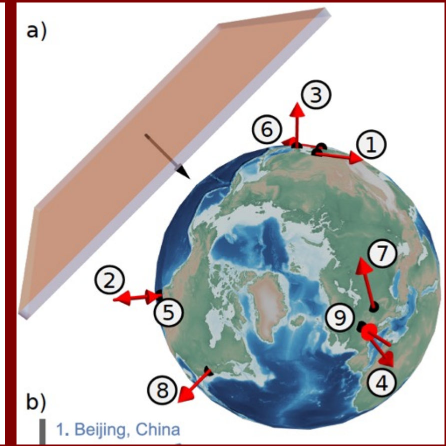


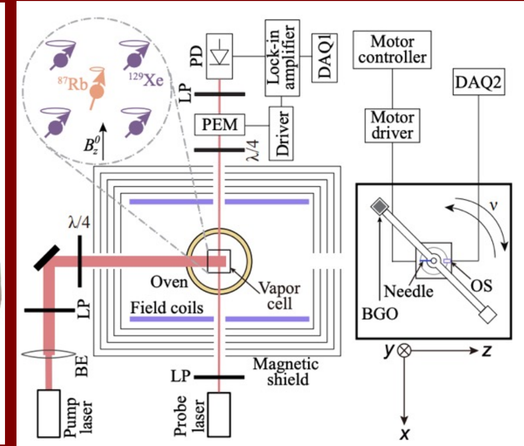








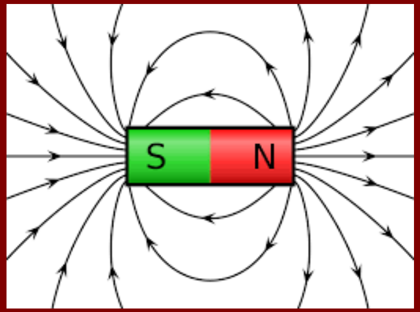




Hot off the press:

•Abhishek Banerjee et al, Oscillating nuclear charge radii as sensors for ultralight dark matter, arXiv:2301.10784 (2023)

•I.M. Bloch et al , Scalar dark matter induced oscillation of permanent-magnet field, Phys. Rev. D **107**, 075033, arXiv:2301.08514 (2023)



•Xue Zhang et al, Search for ultralight dark matter with spectroscopy of radio-frequency atomic transitions, Phys. Rev. Lett. (accepted) arXiv:2212.04413 (2022)

•Kai Wei et al , Ultrasensitive atomic comagnetometer with enhanced nuclear spin coherence, Phys. Rev. Lett. **130**, 063201 (2023), arXiv:2210.09027

Hot off the press:

- Kai Wei, Zitong Xu, Yuxuan He, Xiaolin Ma, Xing Heng, Xiaofei Huang, Wei Quan, Wei Ji, Jia Liu, Xiaoping Wang, Jiancheng Fang, and Dmitry Budker, Dark matter search with a strongly-coupled hybrid spin system, arXiv:2306.08039 (2023)

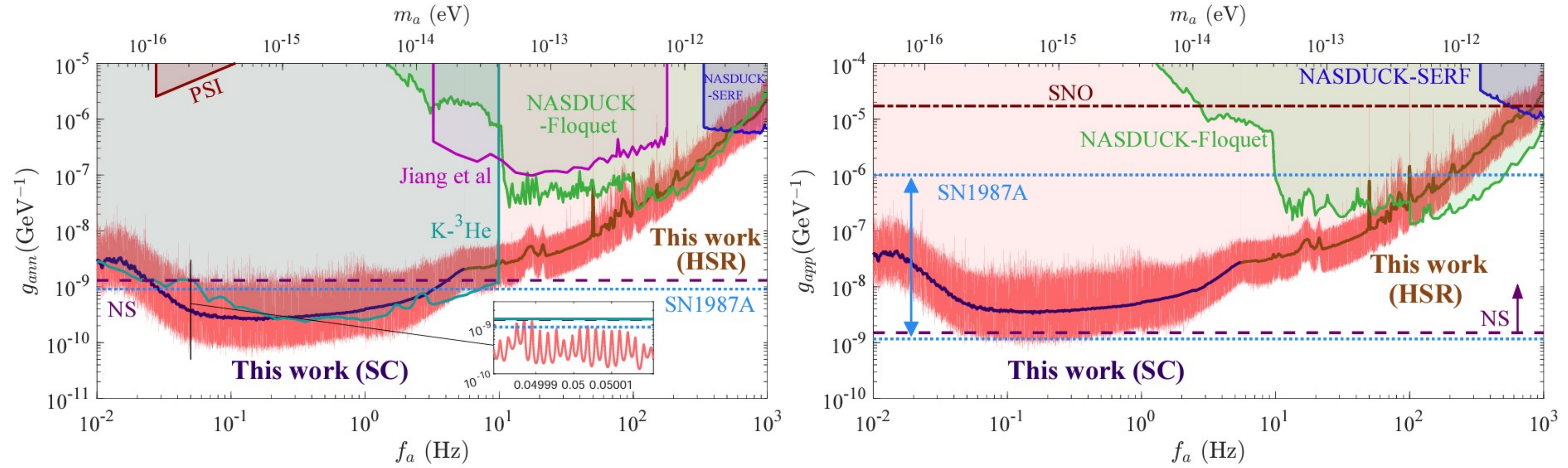


FIG. 4. The 95% C.L. upper limits (red lines) for axion-neutron coupling g_{ann} and axion-proton coupling g_{app} from measurements in both the self-compensating (SC) and hybrid spin-resonance (HSR) regimes. The full data of the limits cannot be shown in the figure, but are tabulated in [31]. To guide the readers' eye, for each f_a, the couplings g_{ann} and g_{app} are averaged in a bin from $0.99f_a$ to $1.01f_a$. We plot the average as the dark blue line in the [0.01, 10] Hz range for the SC data and as the brown line (HSR) for [3, 1000] Hz for HSR data. We also show other terrestrial limits from Jiang et al. [19], K-^{3}He comagnetometer [18], NASDUCK-Floquet [32], NASDUCK-SERF [16], CASPEr-ZULF [14] and PSI [33]. The astrophysical limits from neutron star (NS) cooling [21], supernova SN1987A [20] and solar axion at SNO [34] are shown as horizontal lines respectively.

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]

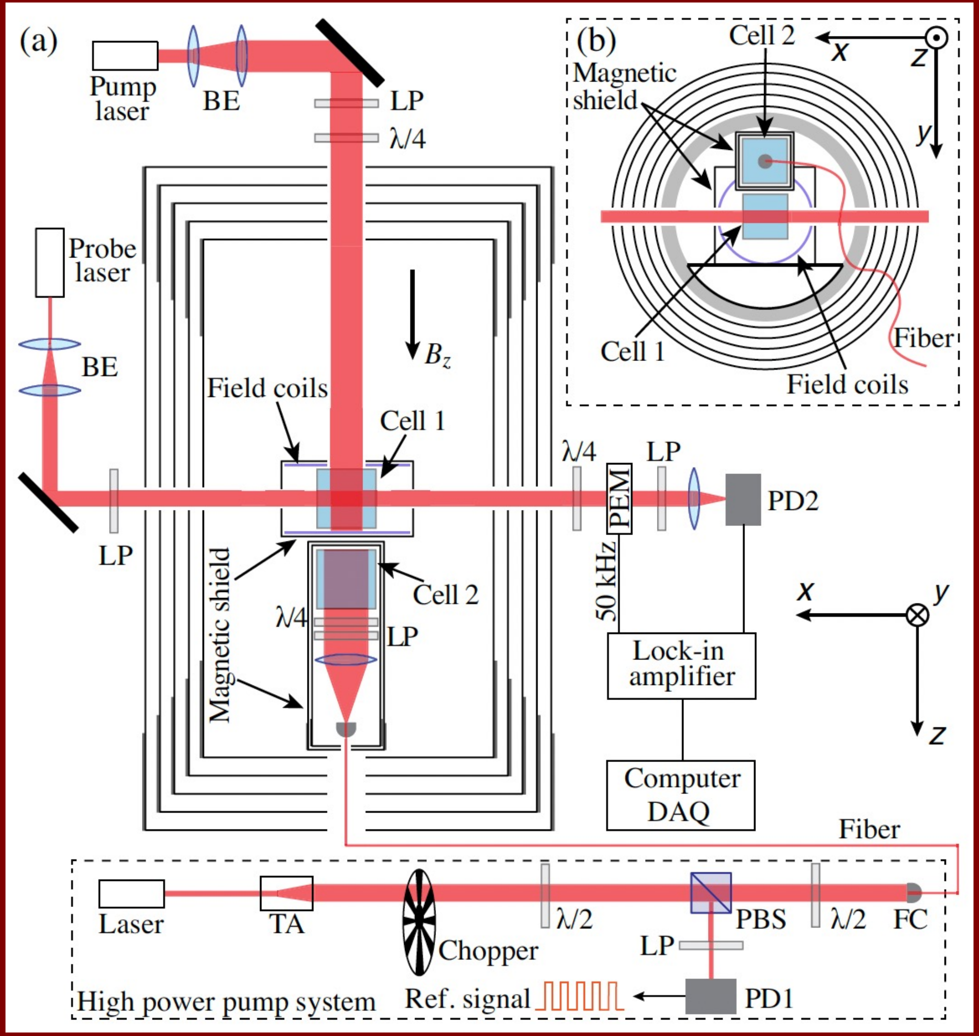


FIG. 1. The experimental setup consists of a spin-based amplifier and a spin source. (a) Experimental schematic in the xz plane. The spin source (cell 2) is shielded by a small-size two-layer magnetic shield. The spin sensor (cell 1) is shielded by a small-size one-layer magnetic shield. Both the source and the sensor are enclosed in five-layer magnetic shield. The cell 1 [60,61,65] containing 5 torr of isotopically enriched ^{129}Xe, 250 torr N_2, and a droplet of ^{87}Rb is heated to 165 °C. The ^{87}Rb spins are polarized with a circularly polarized beam of 795 nm D1 light. ^{129}Xe spins are polarized to ~30% in spin-exchange collisions with polarized ^{87}Rb spins [10,66]. The x component of ^{87}Rb spins is measured via optical rotation of a linearly polarized probe beam, which is detuned to higher frequencies by 110 GHz from the D2 resonance. (b) Experimental schematic in the xy plane. BE, beam expander; LP, linear polarizer; $\lambda/4$, quarter-wave plate; $\lambda/2$, half-wave plate; PD, photodiode; TA, tapered amplifier; PBS, polarizing beam splitter; FC, fiber coupler; PEM, photoelastic modulator; DAQ, data acquisition.

CASPEr-gradient-low-field Mainz