中国科学技术大学
University of Science and Technology of China

The 2026 International Conference on Instrumentation for Colliding Beam Physics (INSTR 2026) Hefei, China, October 12 to 16, 2026

Spin-Based Magnetometry for Probing New Physics Beyond the Standard Model

Xinhua Peng

Univ. of Sci. & Tech. of China (USTC)

Laboratory of Spin Magnetic Resonance

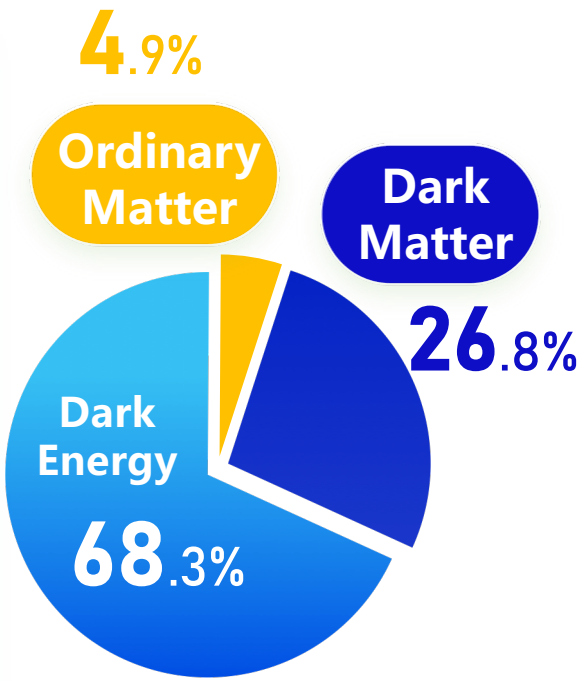
Oct. 15, 2026

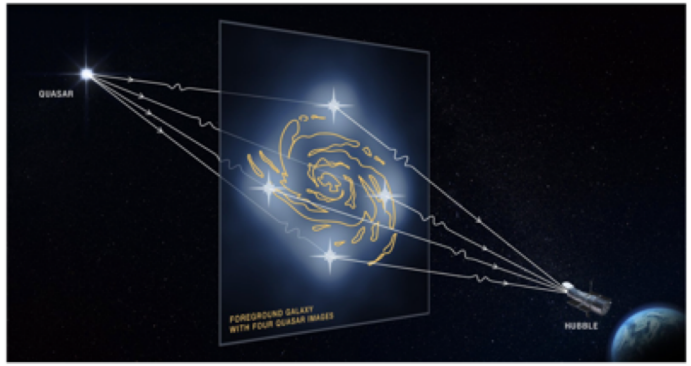
Outline

1. Background: Dark matter and spin-based magnetometry
2. Our spin amplification technique and SAPHIRE project
3. Recent achievements on Dark matter detection
4. Summary and outlook

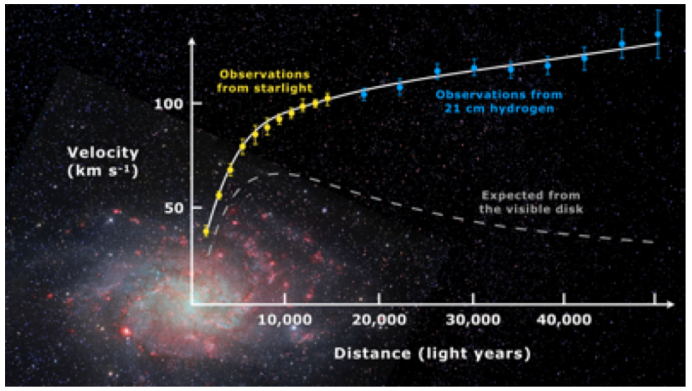
What is the Universe Made of?







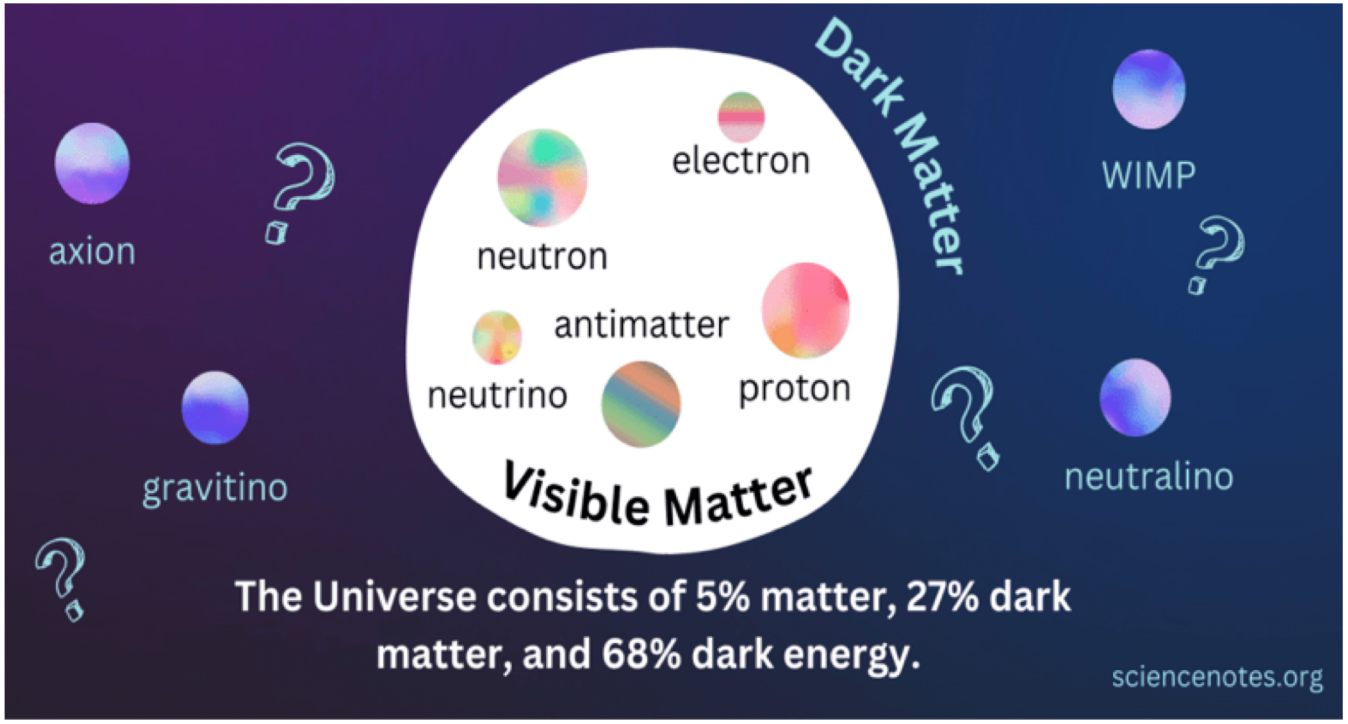
Gravitational lensing



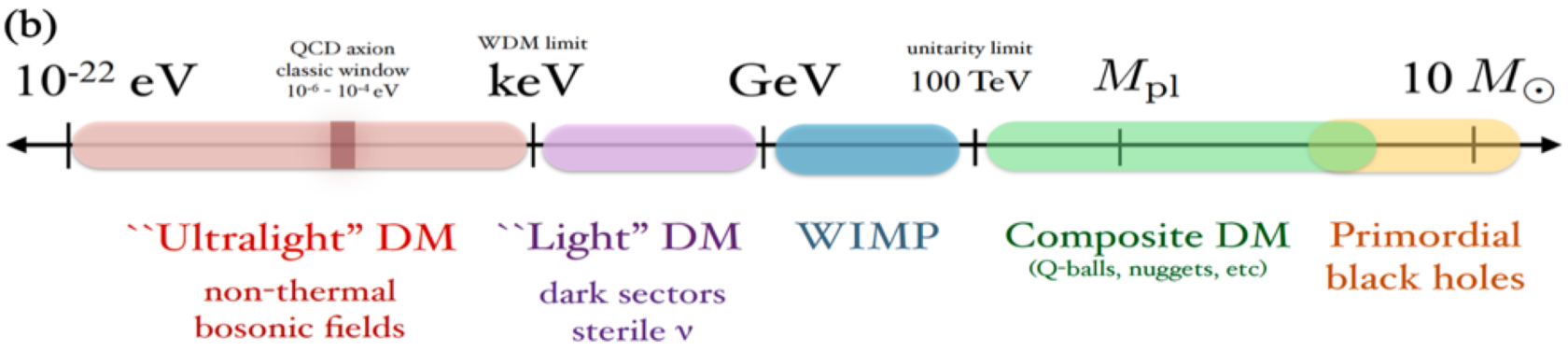
Rotation curves of galaxies

What is Dark Matter?

Dark matter is **a hypothesized form of matter** that does not interact with light or other forms of electromagnetic radiation, but exerts gravitational effects on visible matter, light, and the structure of the universe.



What is Dark Matter?



Wide energy range

Extremely weak Signal

A hypothetical element particle to solve the strong CP problem in QCD



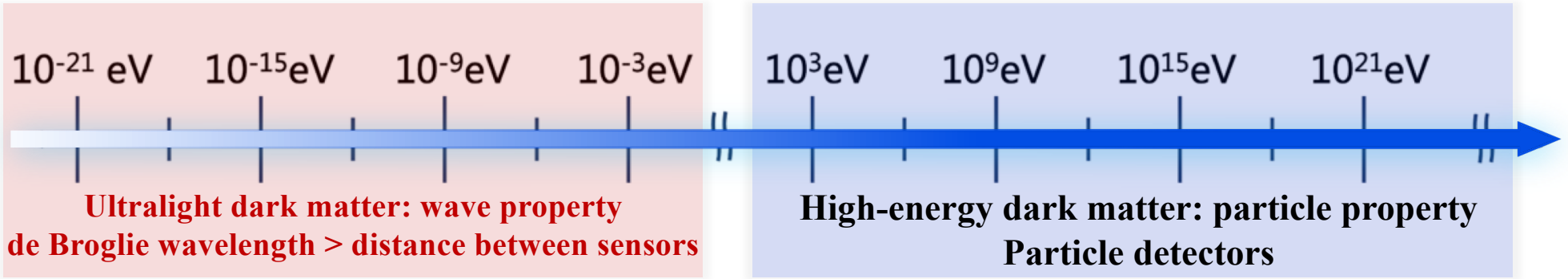


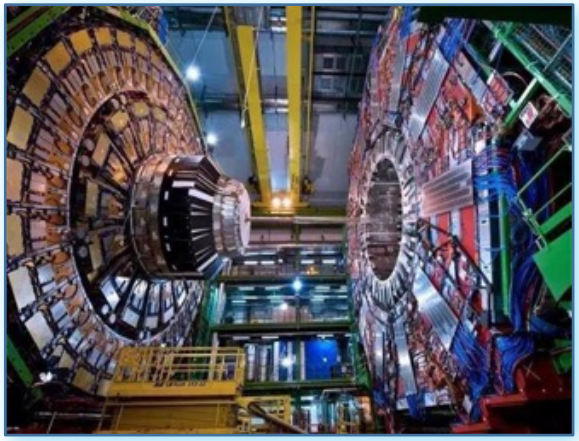
Steven Weinberg



Frank Wilczek

Dark matter searches

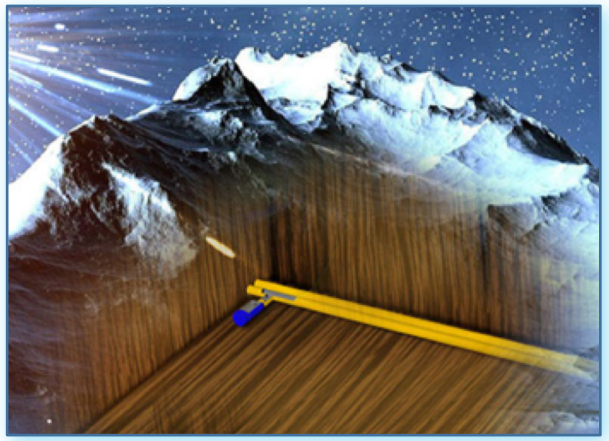




Large Colliders
(LHC, BESIII, etc.)



Space experiments
(DAMPE, AMS, etc.)



Underground experiments
(PandaX, CDEX, etc.)

New physics searches via atoms and molecules

REVIEWS OF MODERN PHYSICS, VOLUME 90, APRIL–JUNE 2018

Search for new physics with atoms and molecules

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REVIEWS OF MODERN PHYSICS, VOLUME 97, APRIL–JUNE 2025

Spin-dependent exotic interactions

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https://doi.org/10.1088/1361-6633/ad99e6

Review

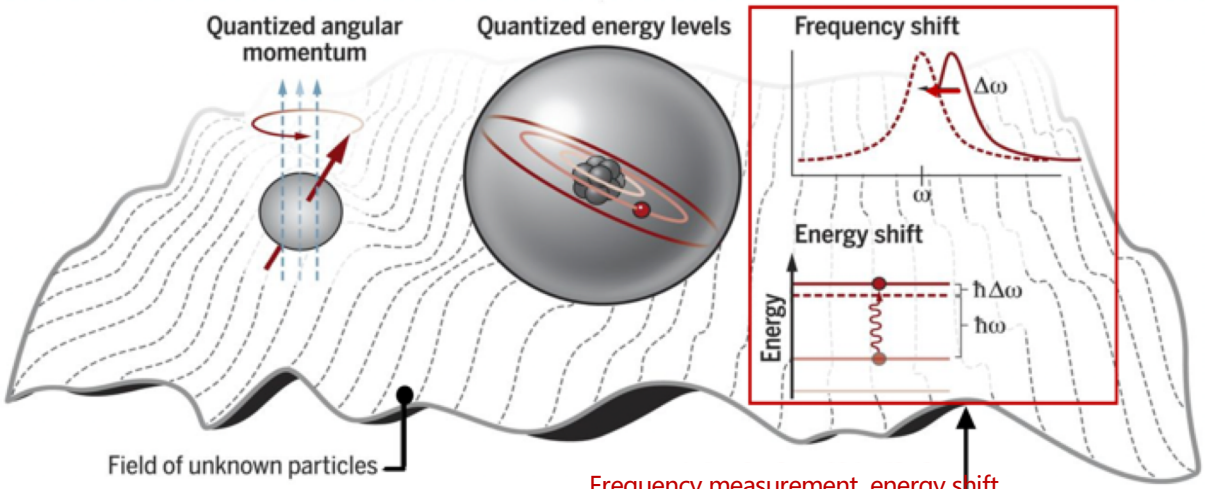
Searches for exotic spin-dependent interactions with spin sensors

Min Jiang[1,2,6], Haowen Su[1,2,6], Yifan Chen[3,6], Man Jiao[4,5], Ying Huang[1,2], Yuanhong Wang[1,2], Xing Rong[1,2], Xinhua Peng[1,2,*] and Jiangfeng Du[1,2,4]

Introduction to the Progress of Spin Sensors in exotic spin-dependent interactions detection

New physics searches via atoms and molecules

Exotic interactions (e.g., axion-spin coupling) induce spin energy shift



"pseudo-magnetic" field:

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

Amplitude: Coupling strength

Oscillation frequency: Compton frequency

Axion

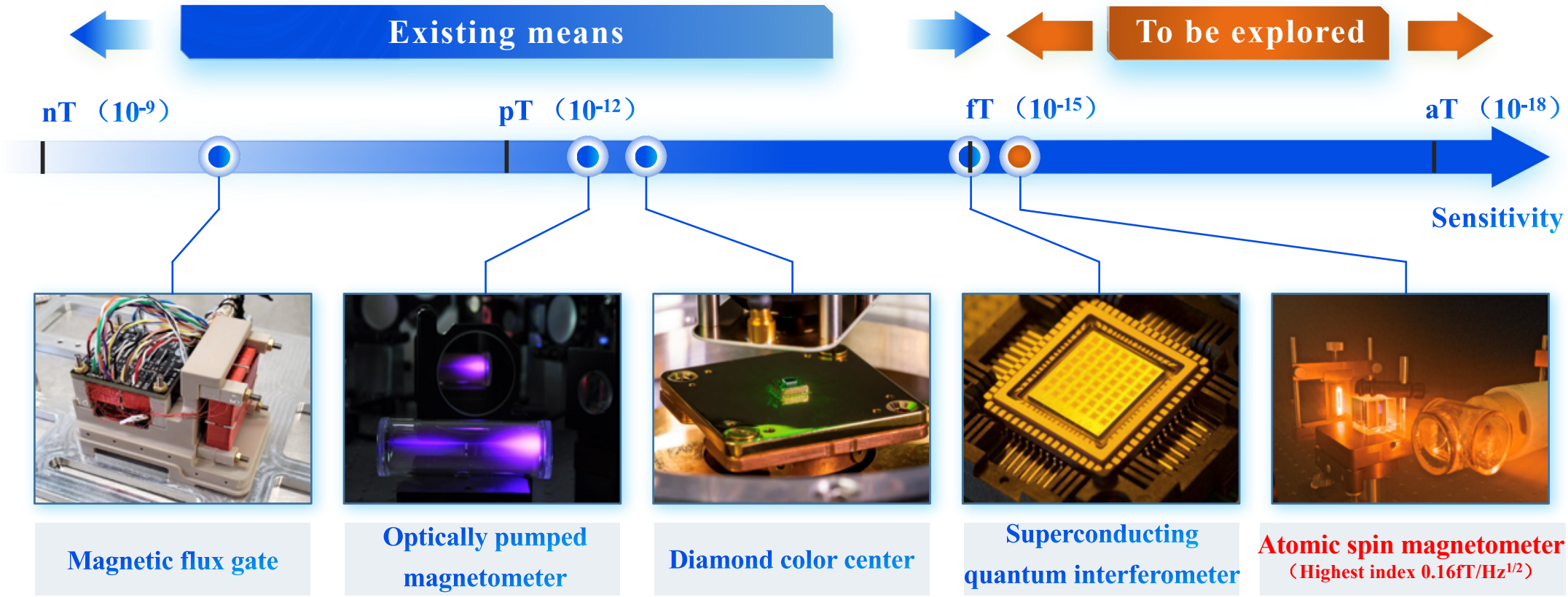
Hamiltonian =

$$+\sqrt{\frac{\varepsilon_0}{\mu_0}}\, g_{a\gamma\gamma} \int a\mathbf{E}\cdot\mathbf{B}dV$$ **Axion-photon**

$$+ g_{\mathrm{aff}} \hbar c \nabla a \cdot \hat{\mathbf{S}}$$ **Axion-spin**

$$+\sqrt{\varepsilon_0 (\hbar c)^3}\, g_{\mathrm{EDM}}\, a\hat{\mathbf{S}}\cdot\mathbf{E}$$ **Axion-gluon**

Magnetometer -- Measuring ultra-weak magnetic field



From classical to quantum

Sensitivity: Measuring the ability of the instrument

Key problem: How to improve the practical sensitivity?

Classical noise
(Technical noise)

Quantum noise
(Uncertainty principle)

Fundamental limit

SQL : $\propto 1/\sqrt{N}$
HL : $\propto 1/N$

Noise

Overcome

Fundamental Sensitivity

$$\delta B = \frac{\delta M}{|\partial M/\partial B|}$$

Enhance

Response

Physical systems

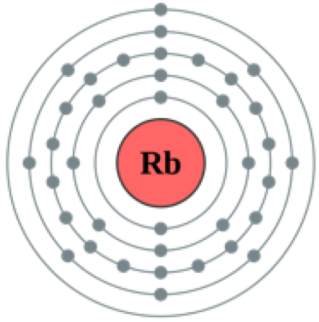
Encoding principle

Measurement strategy

Atomic spin Magnetometer

Alkali-metal Atoms

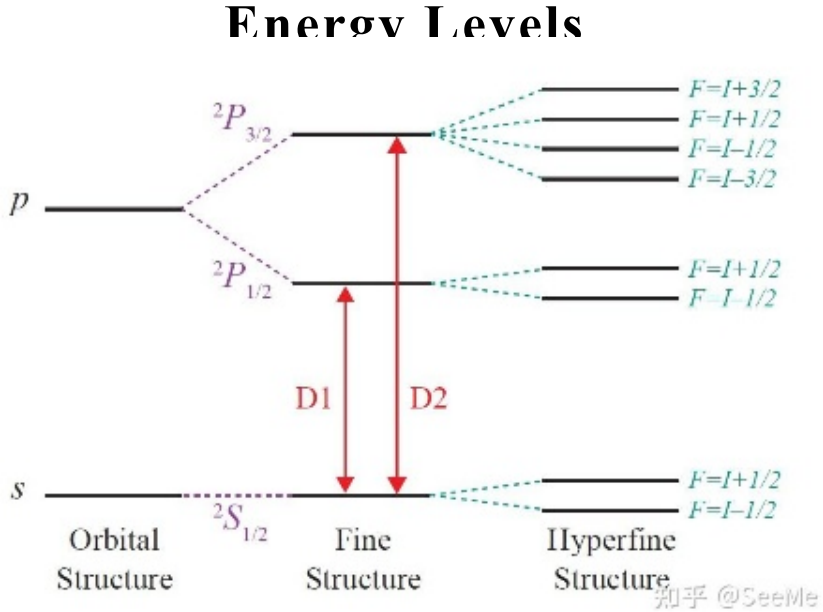
^{87}Rb



Spin

e: 1/2

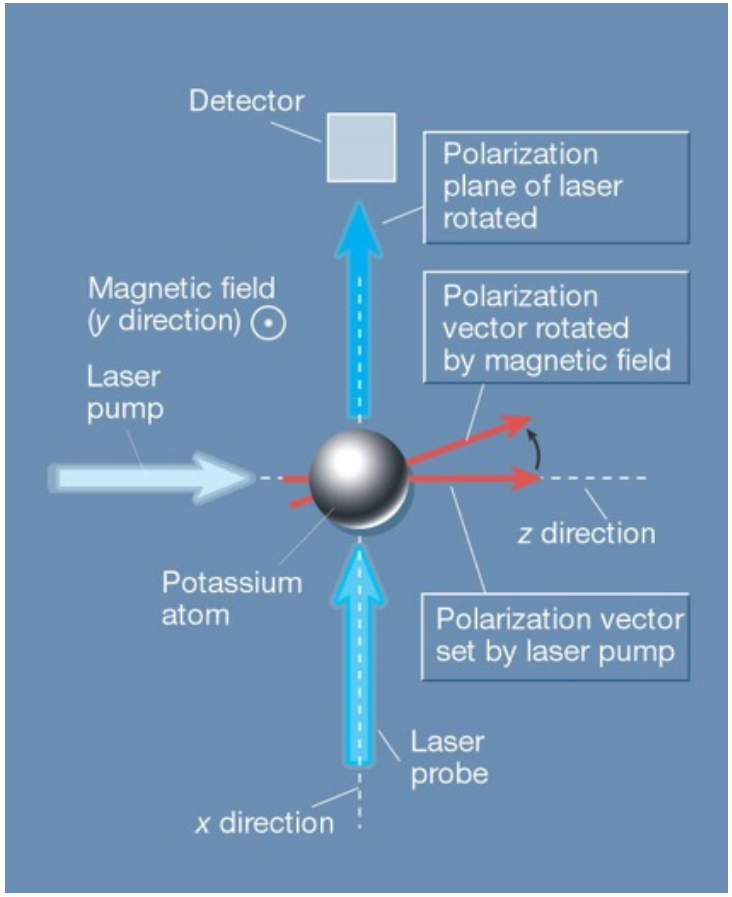
n: 3/2



- Single Valence Electron (relatively simple and well-understood)
- Strong Magnetic Dipole Moments (unpaired electron)
- Optical Accessibility (efficient optical pumping)
- Vapor Cell with High number density at Room Temperatures (practical implementation)
- Long Coherence Times (higher sensitivity and precision)

Atomic Magnetometer

D.Budker. ***: A new spin on magnetometry,*** *Nature (News&Views)* **422**, 574 (2003)



A “pump-precession-probe” scheme

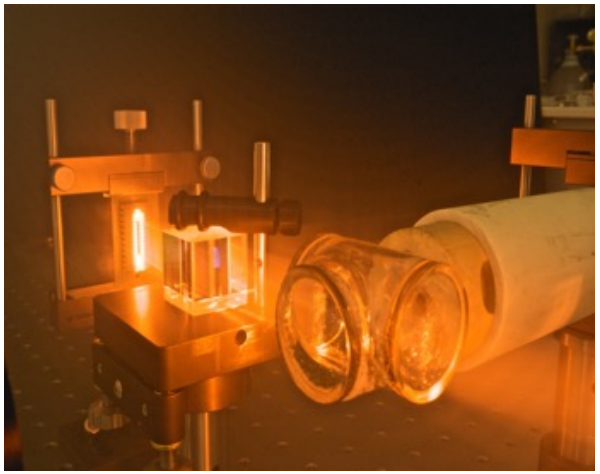
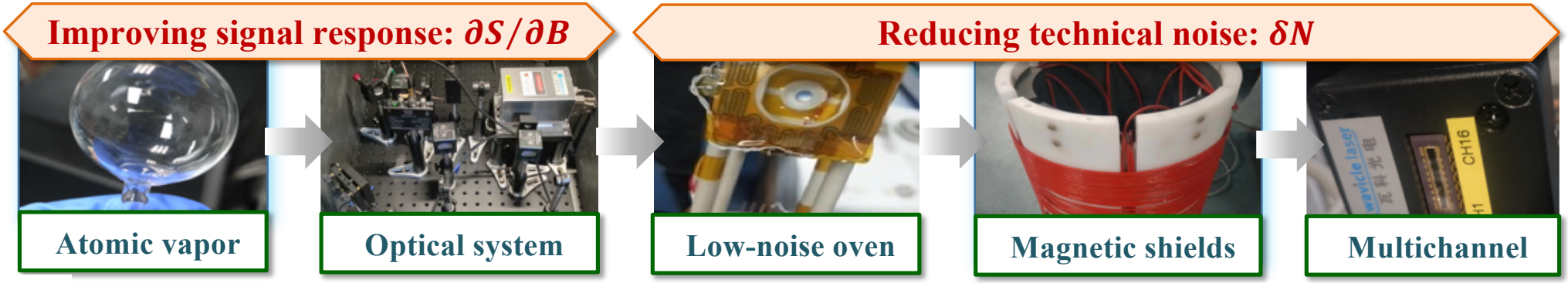


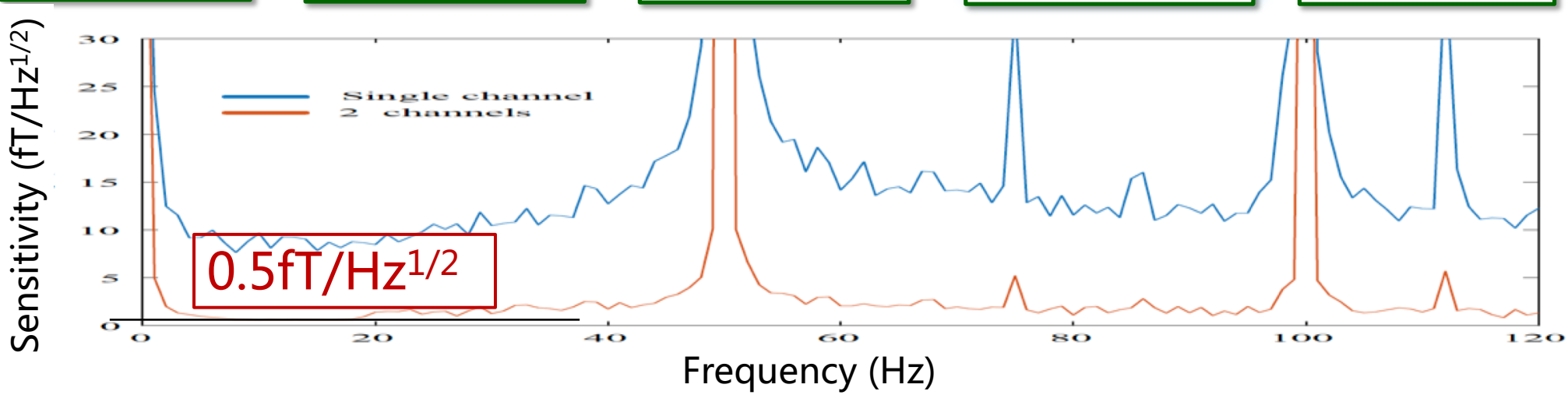
Figure from M. Romalis group

Atomic magnetometers are based on atomic vapors and optical pump/probe techniques, and have the best magnetic-field sensitivity（ 0.16fT/$Hz^{1/2}$）

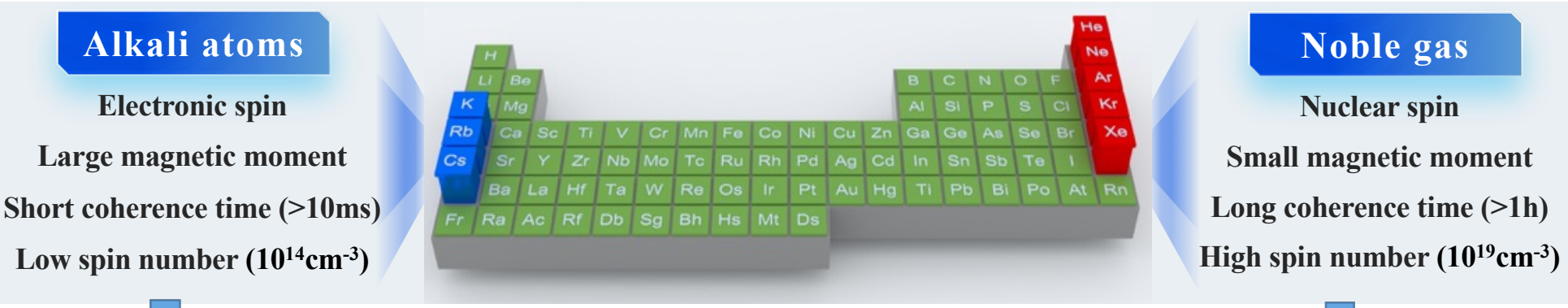
Alkali-metal (Rb, K) magnetometers in USTC

Sub-femtotesla sensitivity has been realized via improving signal response ($\partial S/\partial B$) and reducing technical noise (δS)





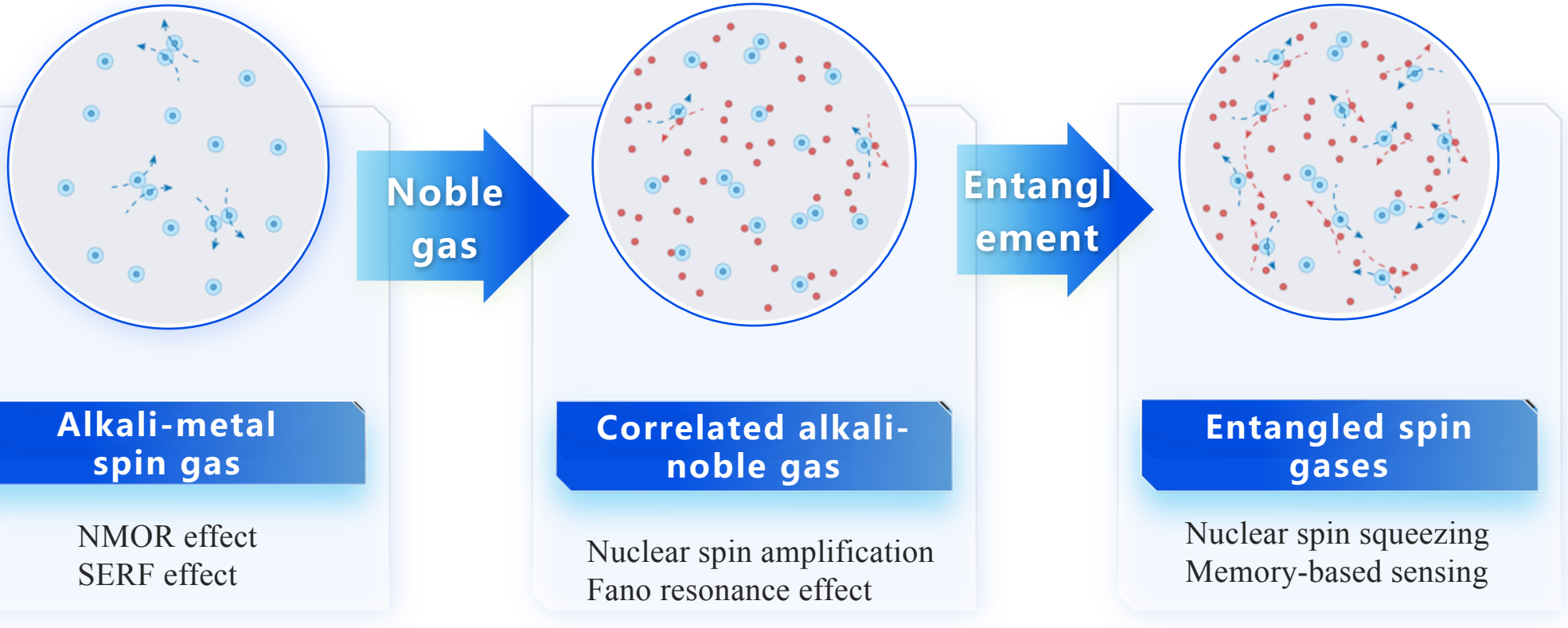
Hybrid spin systems



Hybrid alkali metal - noble gas atomic spin systems

- Light induces transitions between different electronic states
- No direct transfer to nuclear spins from photon
- The coupling between electronic and nuclear angular momentum is usually strong enough to provide an efficient transfer mechanism.

Opportunity: Interaction, Correlation, and Entanglement



Noble-gas magnetic amplification: First demonstration

nature physics

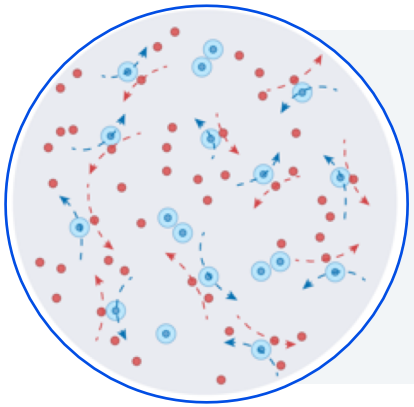
ARTICLES

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]



Hybrid spins:

Alkali metal
(K, Rb, Cs)
Noble gas
(^{3}He, ^{129}Xe)

Magnetic amplification

$$\Sigma = \lambda \Upsilon M P T_2$$

Amp. factor — Fermi-contact enhancement

Magnetic sensitivity

$$\delta B_b = \delta B_a / \Sigma$$

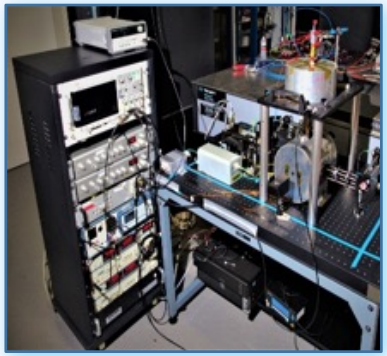
Final sensitivity — Alkali-metal sensitivity

Amplification: ~128 (Latest : **5400**) , **Sensitivity:** 18 fT/Hz$^{1/2}$ (Latest : **0.8fT/Hz$^{1/2}$**)

Our progress on quantum sensors

Improving sensitivity

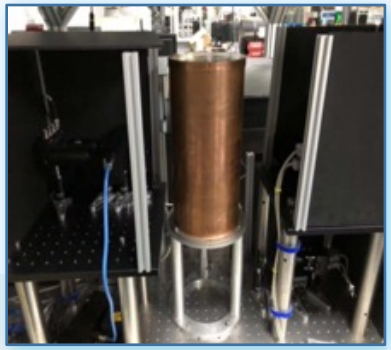
Alkali metal (Rb)



2016

150 fT/Hz$^{1/2}$

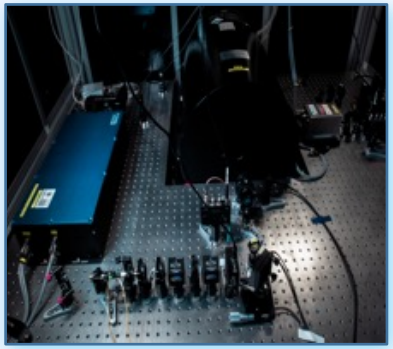
Alkali metal (Rb)



2018

30 fT/Hz$^{1/2}$

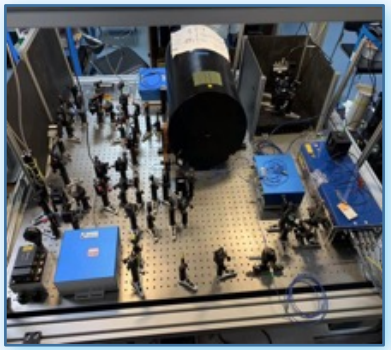
Hybrid system (Rb, 129Xe)



2021

18 fT/Hz$^{1/2}$

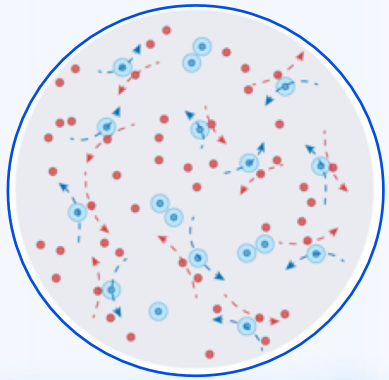
Hybrid system (K, 3He)



2023

0.8 fT/Hz$^{1/2}$

Quantum correlation /entanglement

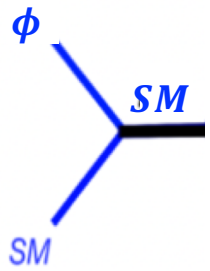


Future

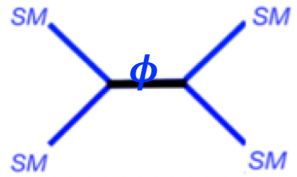
0.01 fT/Hz$^{1/2}$

SAPPHIRE project

Spin Amplifier for Particle PHysIcs Research







Wang, Y., Huang, Y., Guo, C., Jiang, M., ... & Budker, D., Sci. Adv.9, eade0353 (2023)

Axion dark matter searches: Beyond astrophysical limit

nature physics

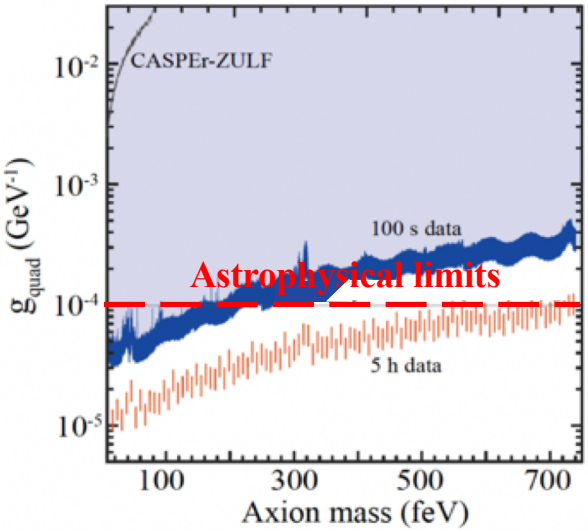
ARTICLES

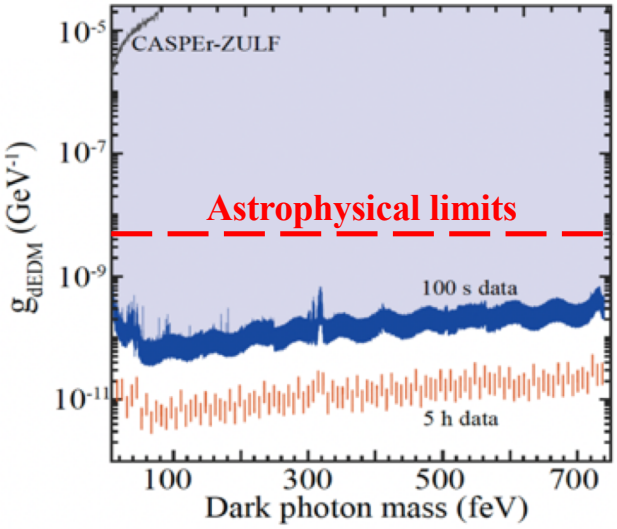
https://doi.org/10.1038/s41567-021-01392-z

Check for updates

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

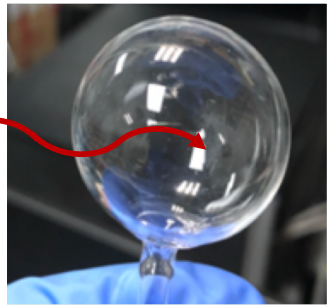
Min Jiang[1,2,3,7], Haowen Su[1,2,3,7], Antoine Garcon[4,5], Xinhua Peng[1,2,3] ✉ and Dmitry Budker[4,5,6]





^{129}Xe

Axion

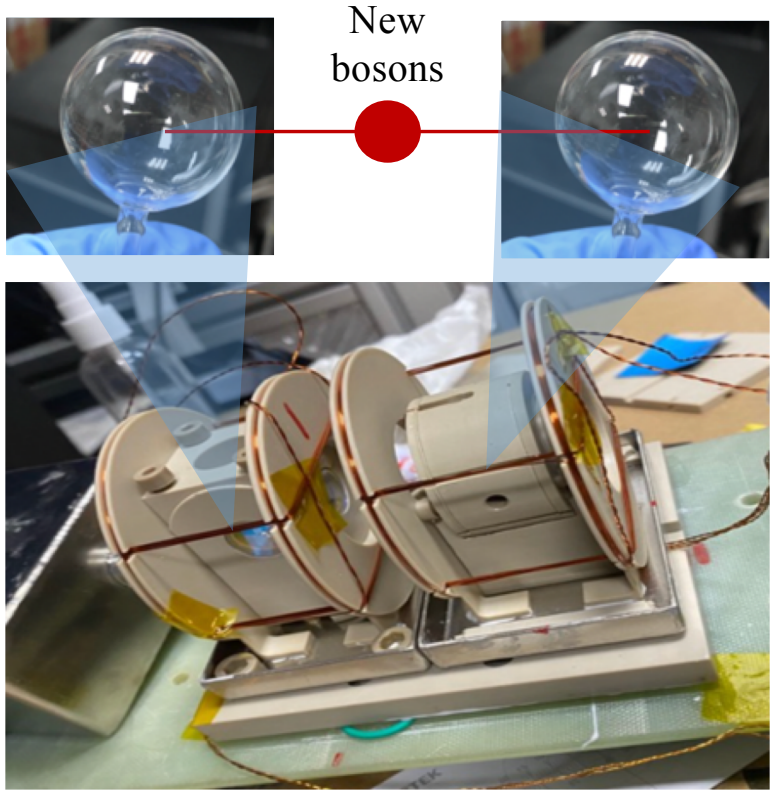


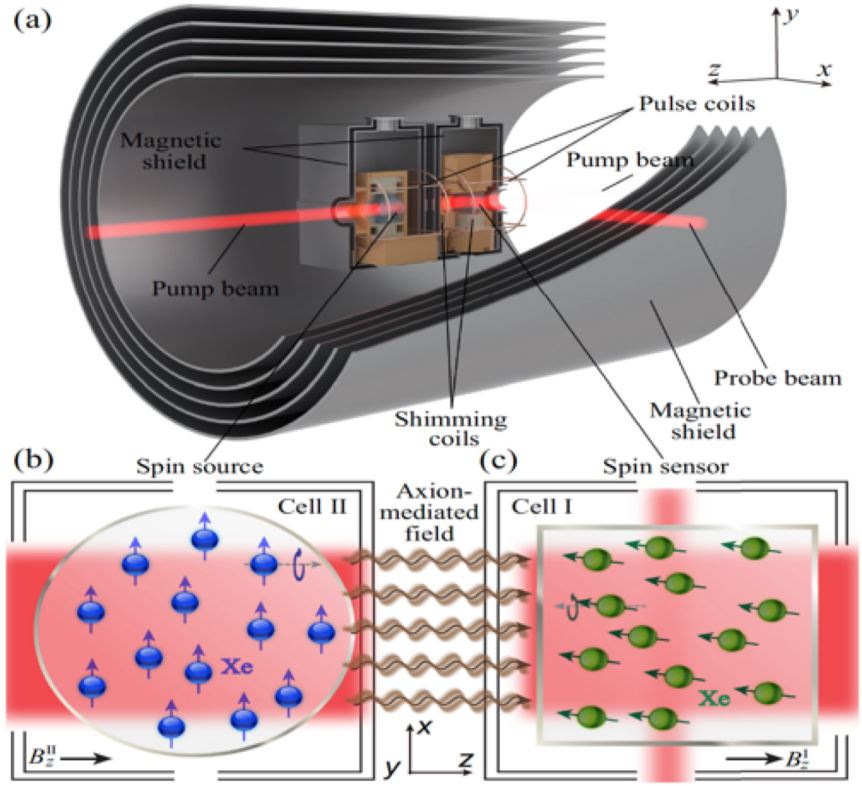
Spin-amplification: 128
Sensitivity: 18fT/Hz$^{1/2}$
5 hours average: 130aT
Axion-nucleon interaction: $\leq 10^{-9}$GeV^{-1} (feV-peV)

Establish the most stringent limits on axion-nucleon coupling **beyond astrophysical limits**

Exotic spin-dependent forces

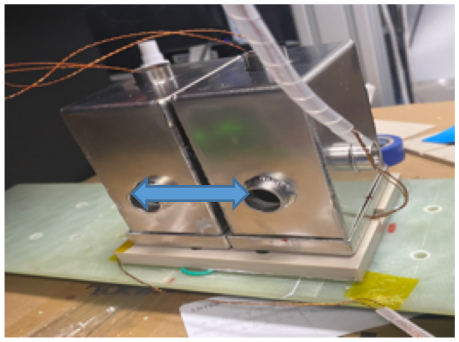
New bosons (e.g. axions) act as force mediator and then induce exotic spin interactions between two spin ensembles (here we use atomic gas)





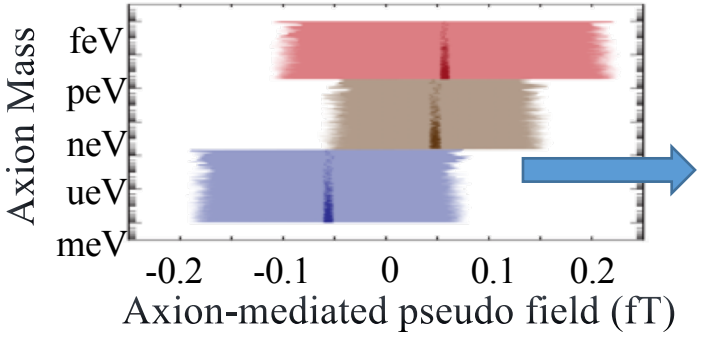
Axion-mediated spin-dependent forces

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

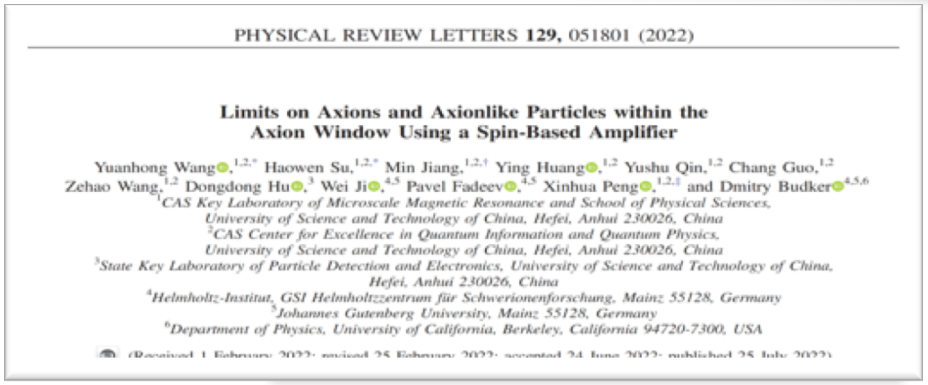


Search setup
(Spin amplifier+shield)

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]

[1]*CAS Key Laboratory of Microscale Magnetic Resonance and School of Physical Sciences, University of Science and Technology of China, Hefei, Anhui 230026, China*
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[3]*State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, Anhui 230026, China*
[4]*Helmholtz-Institut, GSI Helmholtzzentrum für Schwerionenforschung, Mainz 55128, Germany*
[5]*Johannes Gutenberg University, Mainz 55128, Germany*
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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]

[1]*CAS Key Laboratory of Microscale Magnetic Resonance and School of Physical Sciences, University of Science and Technology of China, Hefei, Anhui 230026, China*
[2]*CAS Center for Excellence in Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei, Anhui 230026, China*
[3]*Helmholtz-Institut, GSI Helmholtzzentrum für Schwerionenforschung, Mainz 55128, Germany*
[4]*Johannes Gutenberg University, Mainz 55128, Germany*
[5]*Department of Physics, University of California, Berkeley, California 94720-7300, USA*

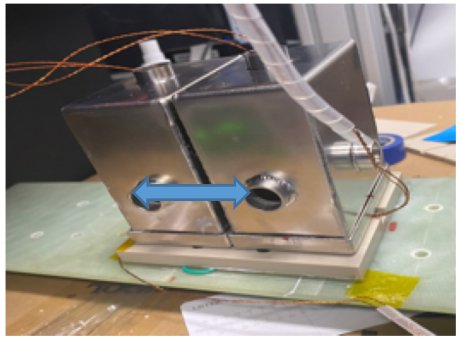
(Received 13 November 2023; revised 6 June 2024; accepted 12 August 2024; published 4 November 2024)

Wang…Jiang* *et al.*, *Phys. Rev. Lett.* 129, 051801 (2022)

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

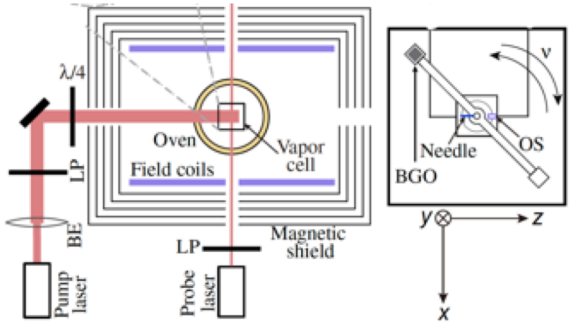
Z’ boson-mediated spin-dependent forces

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

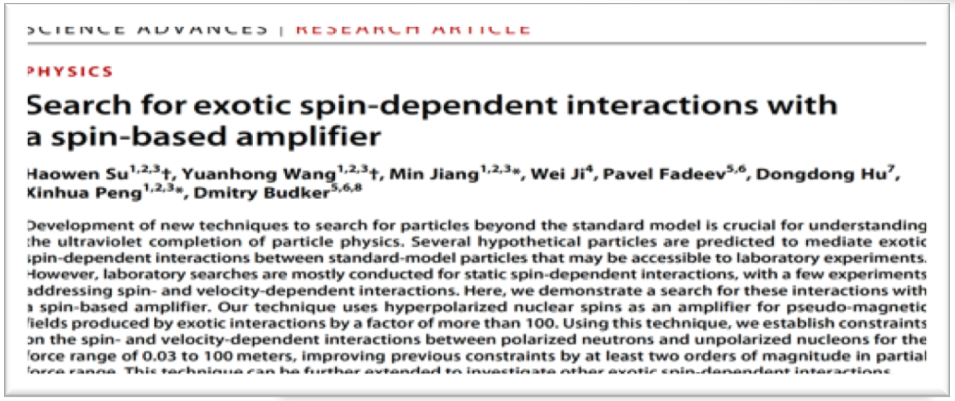


Search setup
(Spin amplifier+shield)

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



Modulating spin-dependent force



SCIENCE ADVANCES | RESEARCH ARTICLE

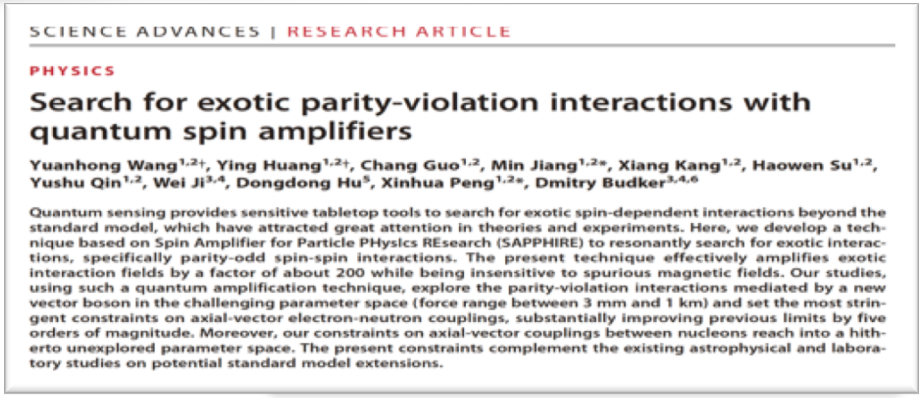
PHYSICS

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 partial force range. This technique can be further extended to investigate other exotic spin-dependent interactions

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



SCIENCE ADVANCES | RESEARCH ARTICLE

PHYSICS

Search for exotic parity-violation interactions with quantum spin amplifiers

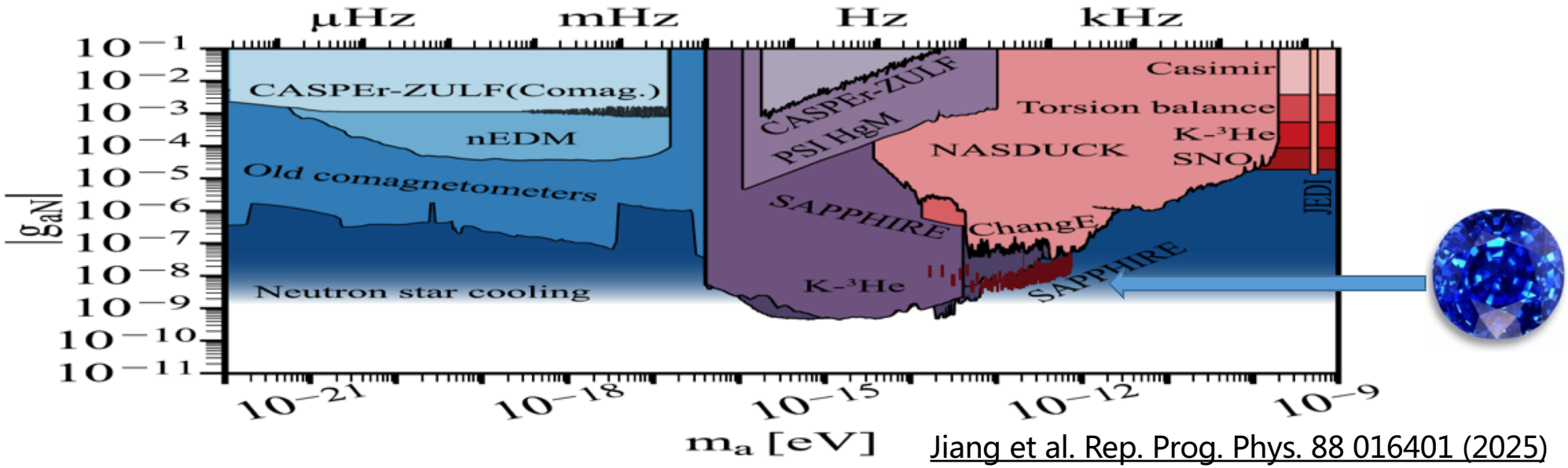
Yuanhong Wang[1,2†], Ying Huang[1,2†], Chang Guo[1,2], Min Jiang[1,2*], Xiang Kang[1,2], Haowen Su[1,2], Yushu Qin[1,2], Wei Ji[3,4], Dongdong Hu[5], Xinhua Peng[1,2*], Dmitry Budker[3,4,6]

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.

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

Ultralight axion dark matter searches

Noble gas becomes important systems to perform dark matter searches



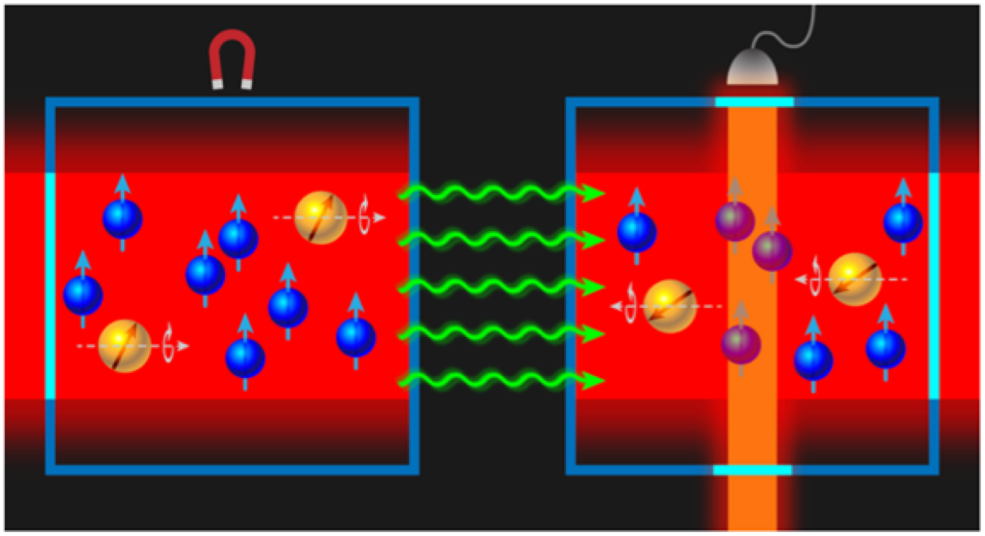
Jiang et al. Rep. Prog. Phys. 88 016401 (2025)

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

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

Correlation sensing via multiple-sensor network

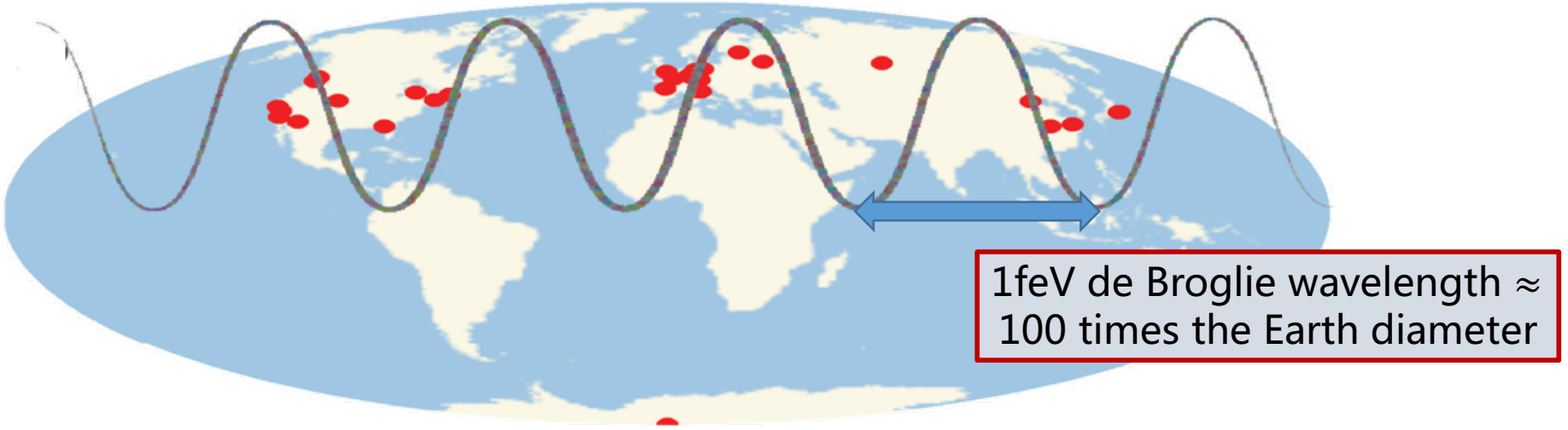
Single sensor

Localized noise is hard to suppress
Detection deadzone
Can't tell the orientation of DMs

N-sensor network

Suppress the false alarm rate $\propto p^N$
Enhance sensitivity $\propto 1/\sqrt{N}$
Omni-directional detection
Network contains DM orientation inf.

Ultralight dark matter with long de Broglie wavelength enables the network detection



Dark photon network searches （AMAILS）

nature communications

New limits on dark photon dark matter

Article

https://doi.org/10.1038/s41467-024-47566-0

Long-baseline quantum sensor network as dark matter haloscope

Received: 13 September 2023

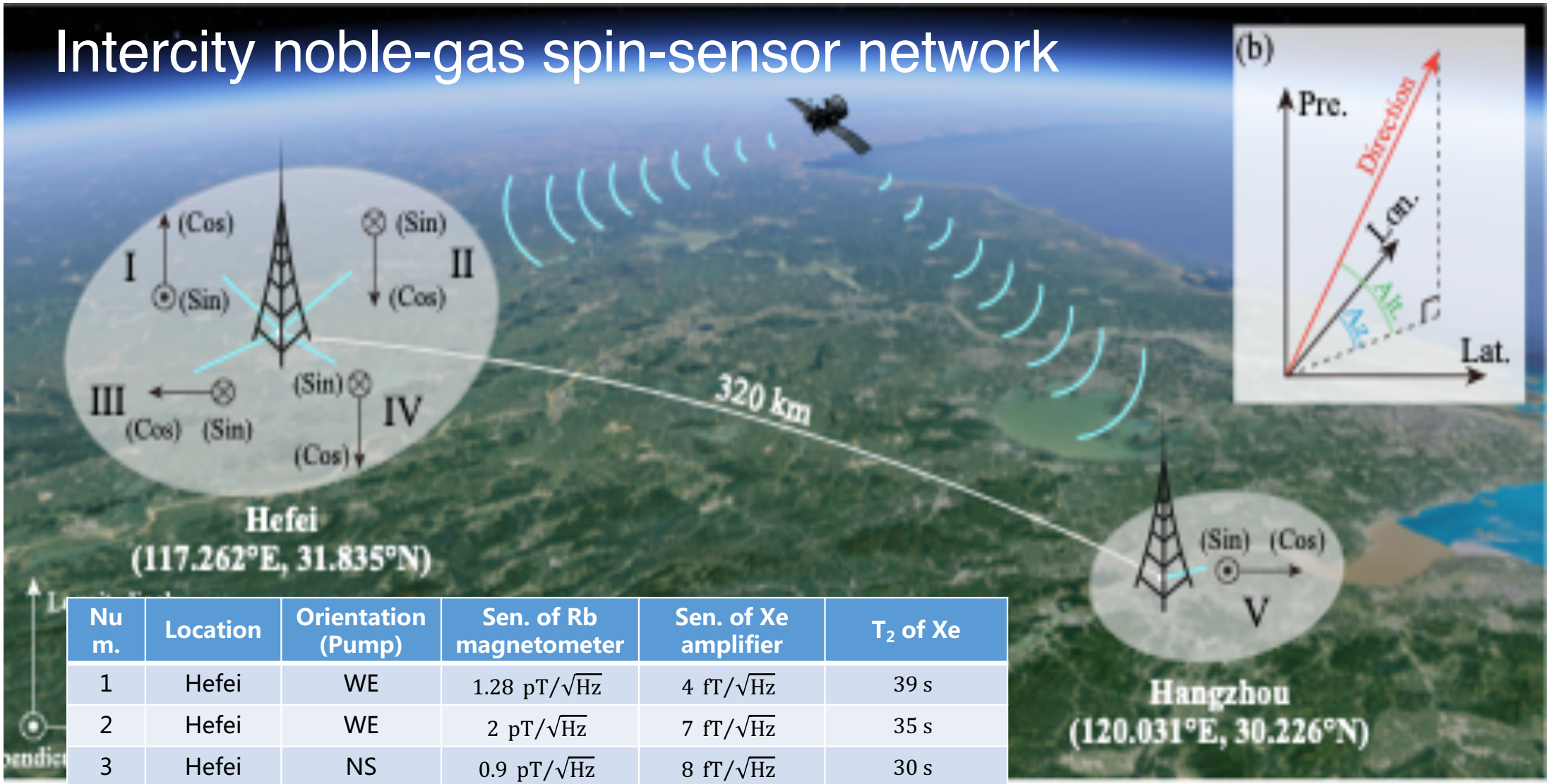
Accepted: 4 April 2024

Min Jiang[1,2,3,12], Taizhou Hong[1,2,3,12], Dongdong Hu[3,4,12], Yifan Chen[5], Fengwei Yang[6], Tao Hu[7], Xiaodong Yang[7], Jing Shu[8,9,10] ✉, Yue Zhao[6] ✉, Xinhua Peng[1,2,3] ✉ & Jiangfeng Du[1,2,3,11]



Collaboration with Yue Zhao, Jing Shu, Yifan Chen

Intercity noble-gas spin-sensor network



Num.	Location	Orientation (Pump)	Sen. of Rb magnetometer	Sen. of Xe amplifier	T_2 of Xe
1	Hefei	WE	1.28 $\mathrm{pT}/\sqrt{\mathrm{Hz}}$	4 $\mathrm{fT}/\sqrt{\mathrm{Hz}}$	39 s
2	Hefei	WE	2 $\mathrm{pT}/\sqrt{\mathrm{Hz}}$	7 $\mathrm{fT}/\sqrt{\mathrm{Hz}}$	35 s
3	Hefei	NS	0.9 $\mathrm{pT}/\sqrt{\mathrm{Hz}}$	8 $\mathrm{fT}/\sqrt{\mathrm{Hz}}$	30 s
4	Hefei	WE	3 $\mathrm{pT}/\sqrt{\mathrm{Hz}}$	10 $\mathrm{fT}/\sqrt{\mathrm{Hz}}$	42 s
5	Hangzhou	NS	1.9 $\mathrm{pT}/\sqrt{\mathrm{Hz}}$	14 $\mathrm{fT}/\sqrt{\mathrm{Hz}}$	15 s

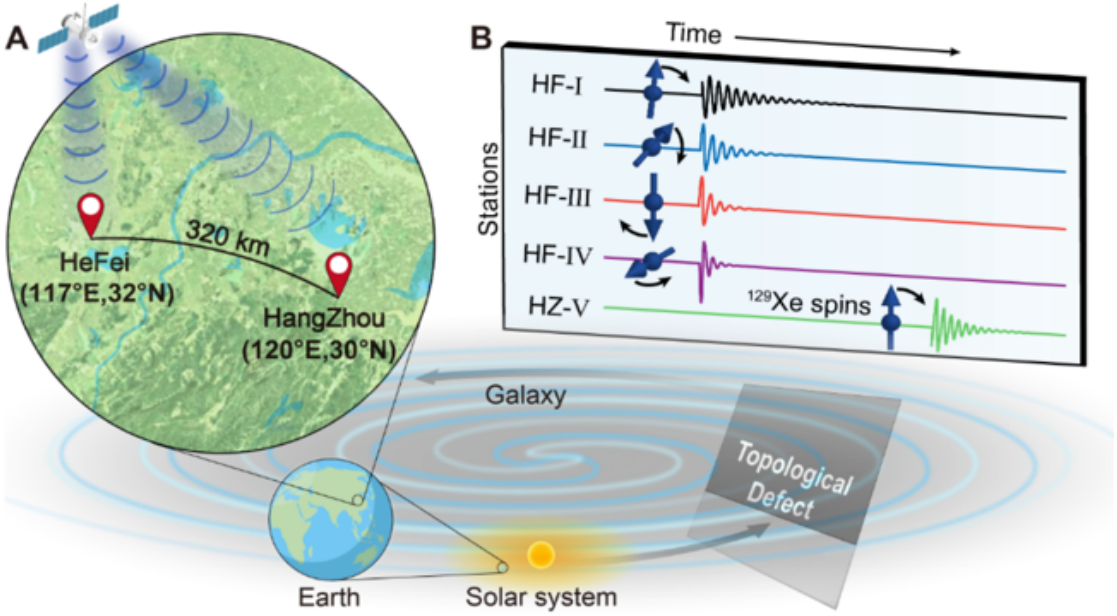
Correlation sensing via multiple-sensor network

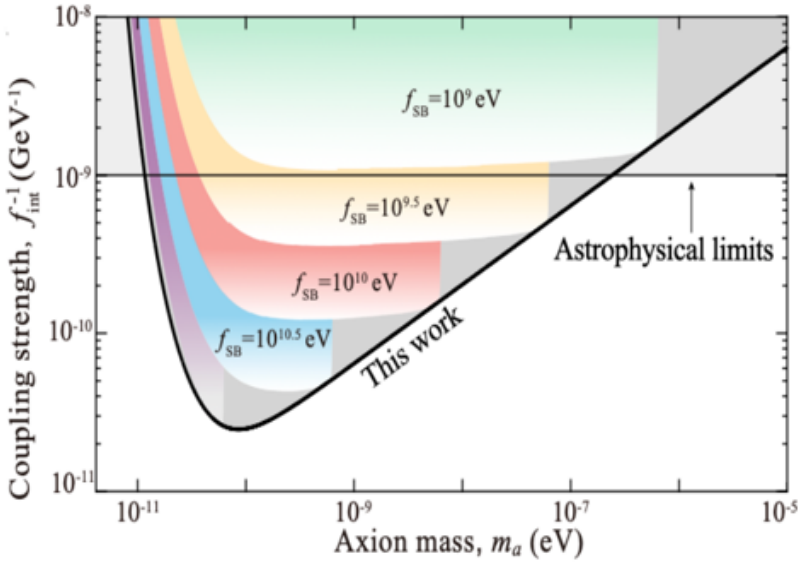
Article

Constraints on axion dark matter by distributed intercity quantum sensors

https://doi.org/10.1038/s41586-025-10034-w
Received: 15 April 2025

Yuanhong Wang[1], Ying Huang[1], Xiang Kang[1], Dangui Chang[2], Jiaxuan Xu[1], Yifan Chen[3,4], Szymon Pustelny[5], Wenqiang Zheng[2], Min Jiang[1]✉, Xinhua Peng[1,6,7]✉ & Jiangfeng Du[6,8]



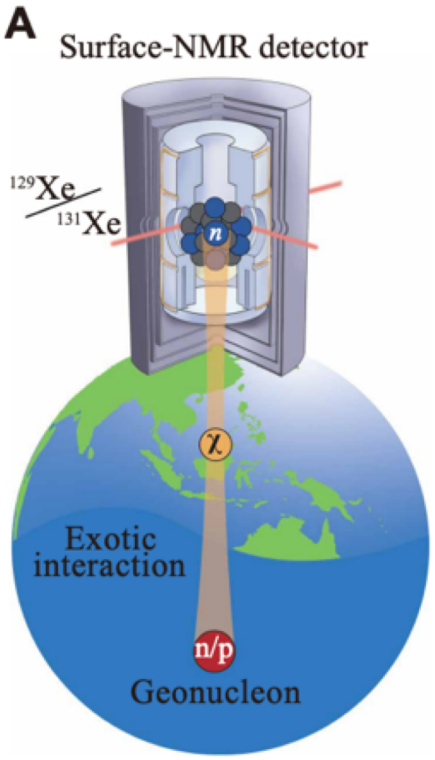


Nature 650, 314 (2026)

The first nuclear-spin quantum senor network

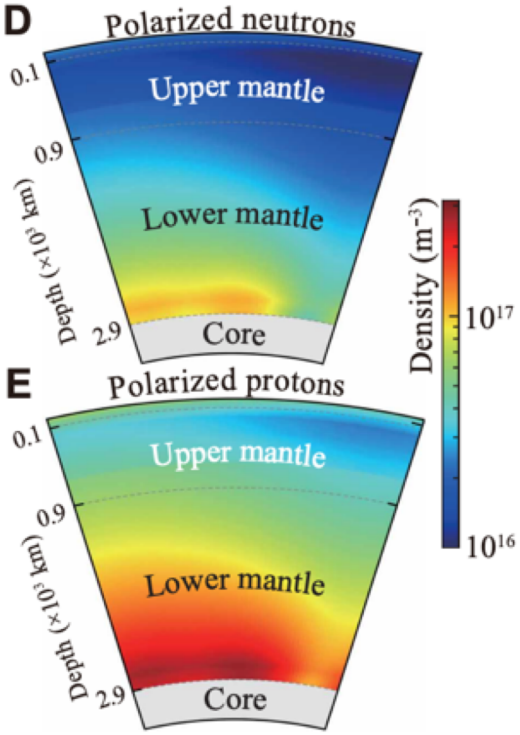


Earth as a source (nuclear spins)



Nuclear shell model
Schmidt model
FLP semiempirical model

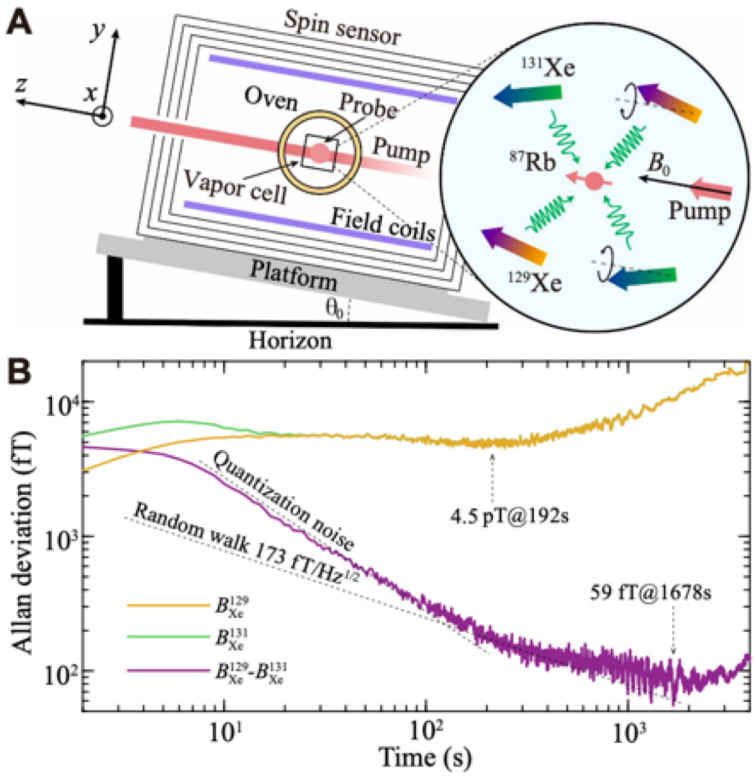
~ 2.2×10^{37}



~ 5.3×10^{37}

> 10^{16} times than Lab

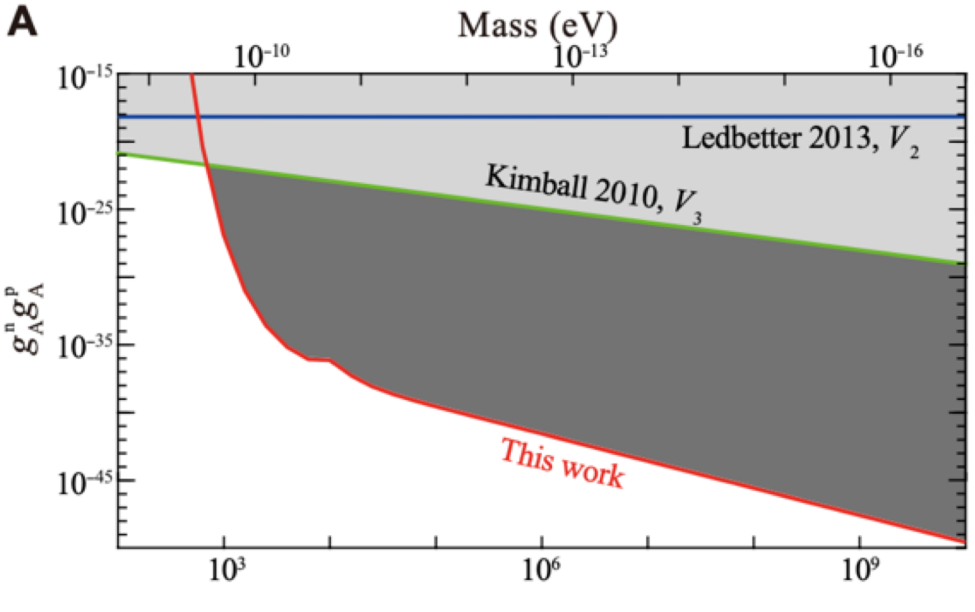
Surface- NMR detector



Constraints on spin- spin- interaction coupling constants

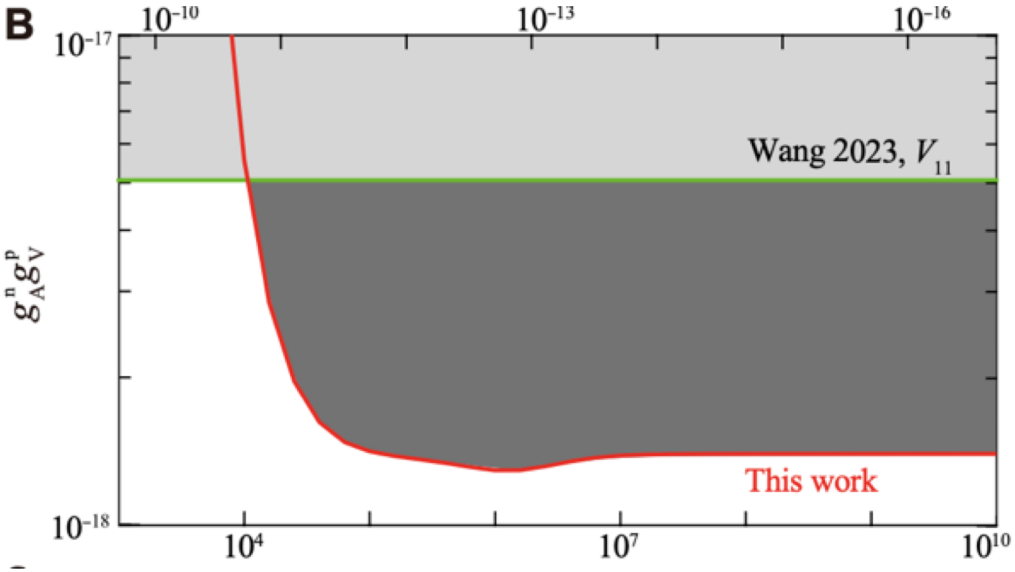
Z′ boson–mediated proton- neutron coupling

axial- vector/axial- vector coupling



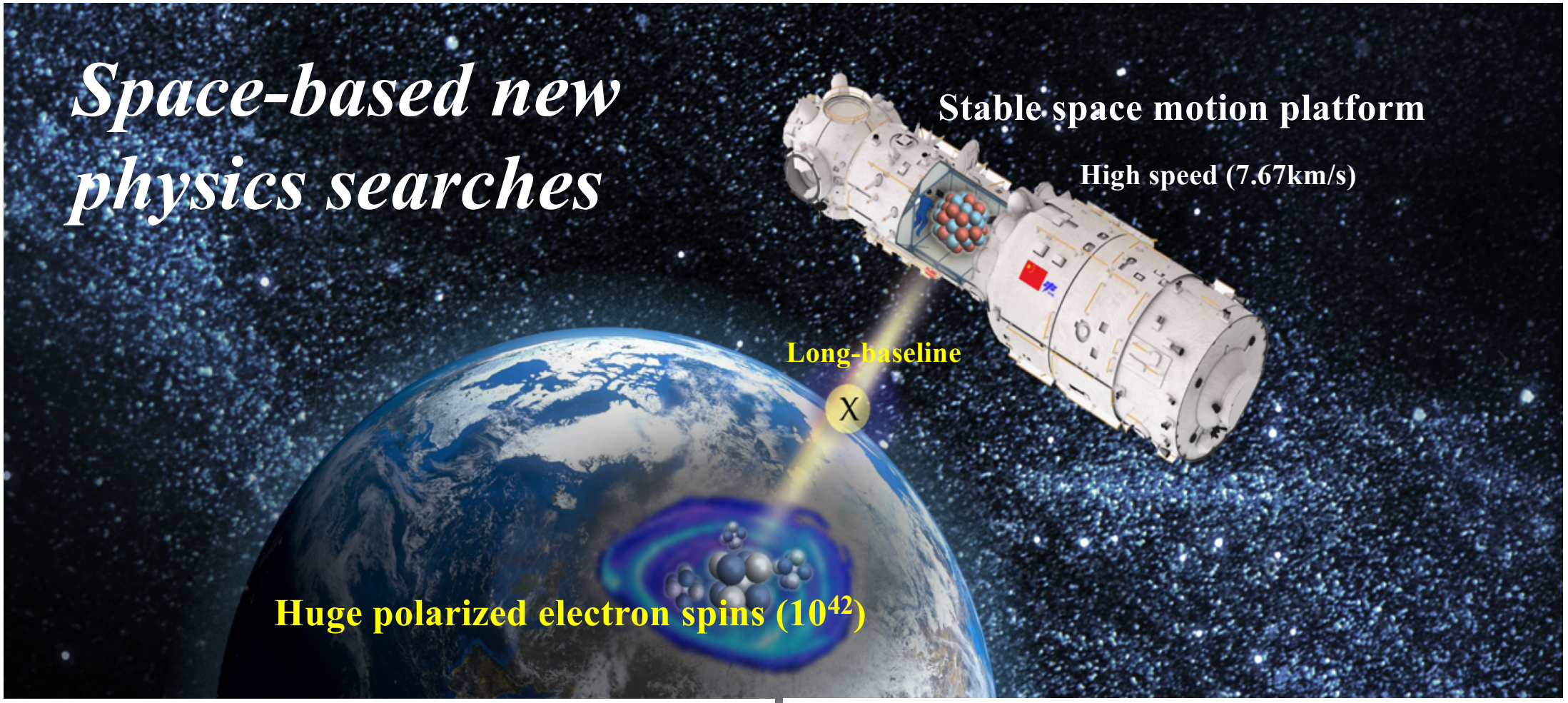
Ledbetter 2013: Phys. Rev. Lett. 110, 040402 (2013)
Kimball 2010: Phys. Rev. A 82, 062714 (2010).

axial- vector/vector coupling



Wang 2023: Sci. Adv. 9, eade0353 (2023).

This work: Wang et al., Sci. Adv. 12, eaeg0974 (2026)



PERSPECTIVE

National Science Review
12: nwaf389, 2025
https://doi.org/10.1093/nsr/nwaf389
Advance access publication 22 September 2025

PHYSICS

Quantum sensors in space: unveiling the invisible universe

Yuanhong Wang[1,2,†], Xingming Huang[1,2,†], Min Jiang[1,2,*], Qing Lin[3,4], Wenqiang Zheng[4], Yuan Sun[5], Liang Liu[5], Xinhua Peng[1,2,*], Zhengguo Zhao[3,4] and Jiangfeng Du[2]

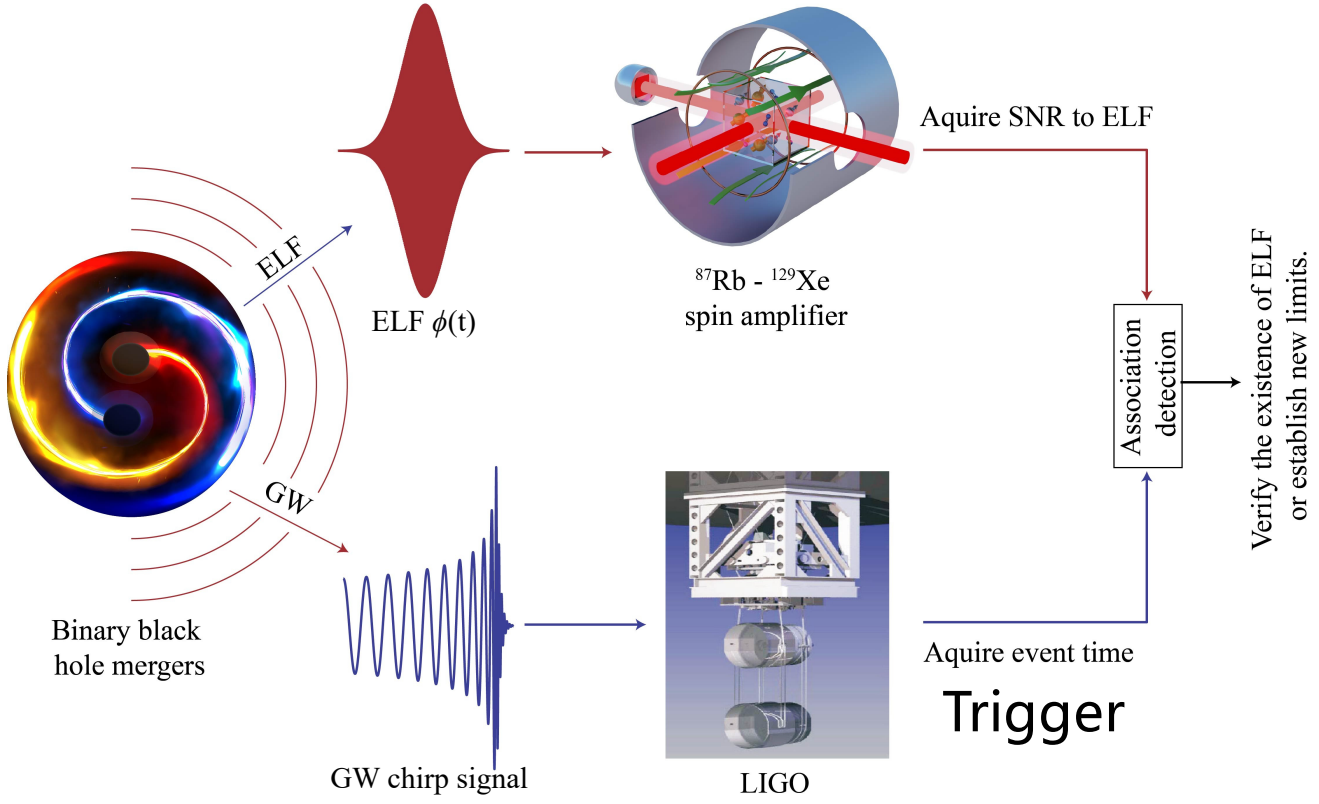
PHYSICAL REVIEW D **112,** 095015 (2025)

Hunting for exotic bosons with flying quantum sensors in space

Xingming Huang,[1,*] Yuanhong Wang,[1,*] Xiang Kang,[1] Jiaxi Li,[1,2] Haowen Su,[1] Zehao Wang,[1] Qing Lin,[3,4] Wenqiang Zheng,[5] Yuan Sun,[6] Liang Liu,[6] Min Jiang,[1,7,†] Xinhua Peng,[1,2,7,‡] Zhengguo Zhao,[3,4] and Jiangfeng Du[2,8]

Multi-messenger astrophysical research

Multi-messenger astrophysical research for exotic low-mass field (ELF) signals with the spin-sensor network



A correlation analysis between the signals detected by the spin sensor and those observed by LIGO allows us to verify the presence of an ELF signals or to set new constraints.

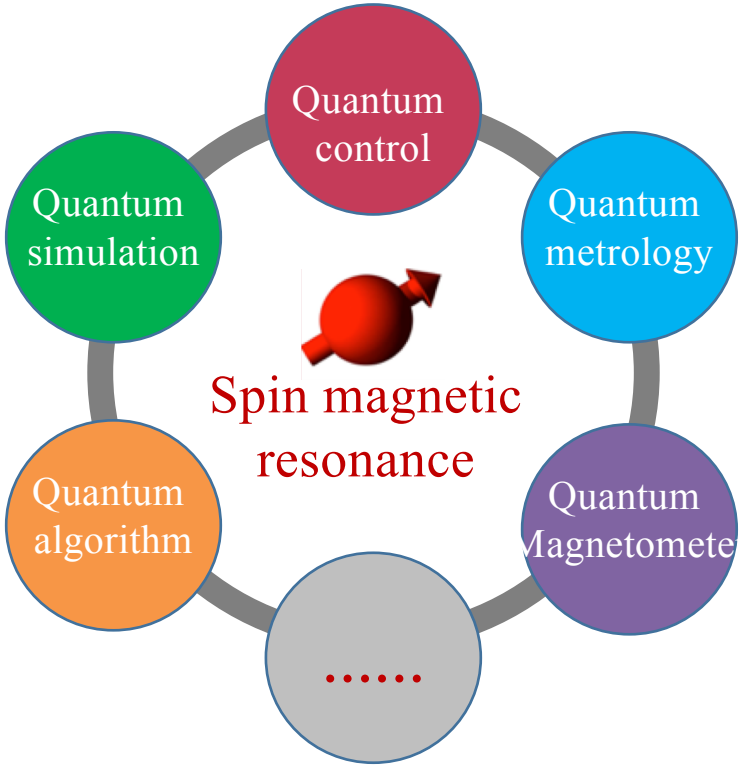
Thanks to ……

Prof. Jiangfeng Du

Collaborators:
Prof. Dmitry Budker
Prof. Zhengguo Zhao
Prof. Yue Zhao
Prof. Jing Shu
Prof. Yifan Chen
Dr. Xiao Xue
……

Funding:
USTC, CAS, NNSFC……

Thank you for your attention !

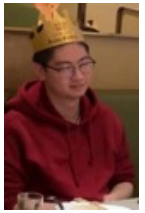


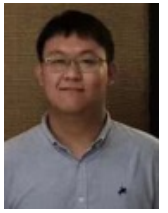
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Yushu Qing
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M. Jiang


H. Su


Y. Wang