量子计算与高能核物理交叉前沿讲习班 @华南师范大学，广州
2022年11月13日至28日

Quantum Sensing and searches for new particles

—— Sapphire: Spin Amplifier for Particle PHysIcs REsearches

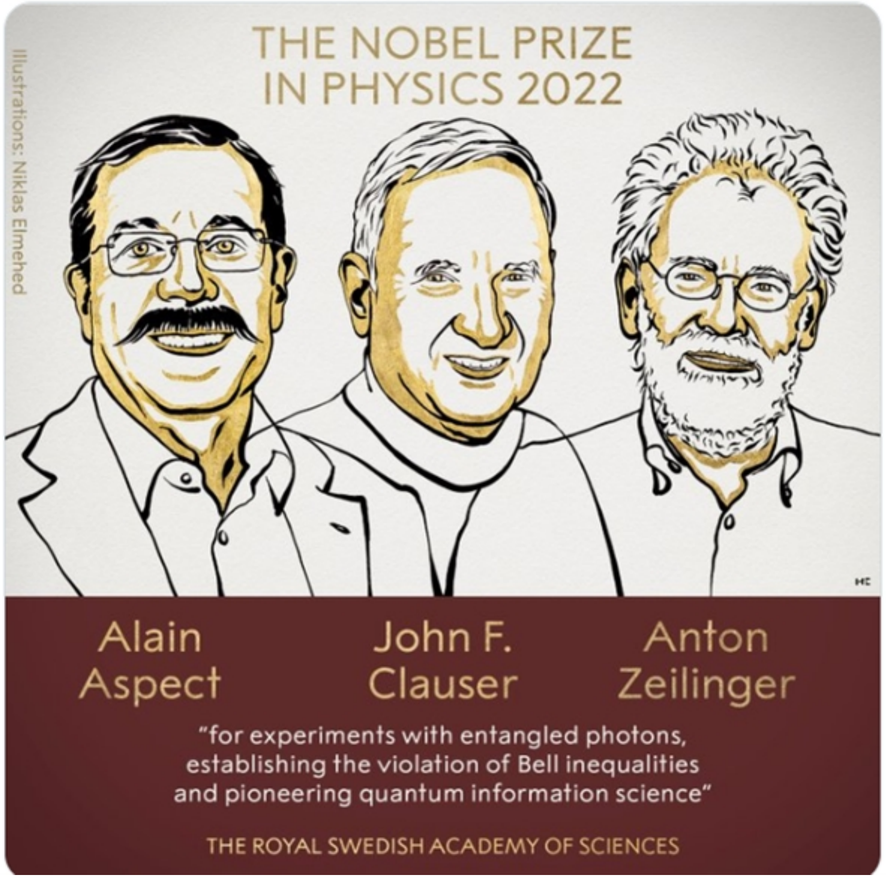
Xinhua Peng

Nov. 22, 2022

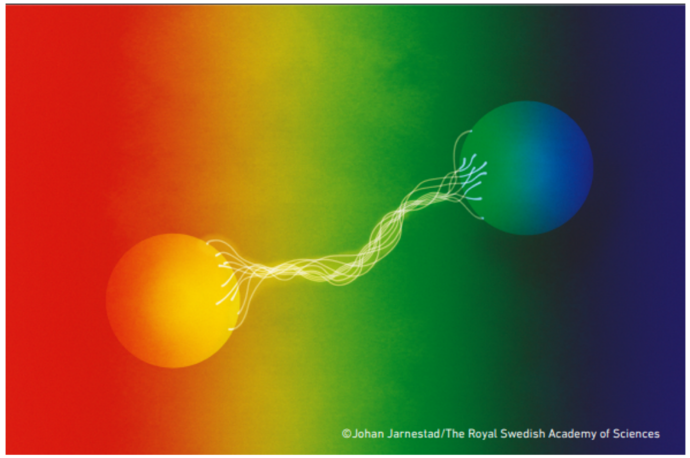
Univ. of Sci. & Tech of China (USTC)

CAS Key Laboratory of Microscale Magnetic Resonance

Nobel Prize in Physics 2022

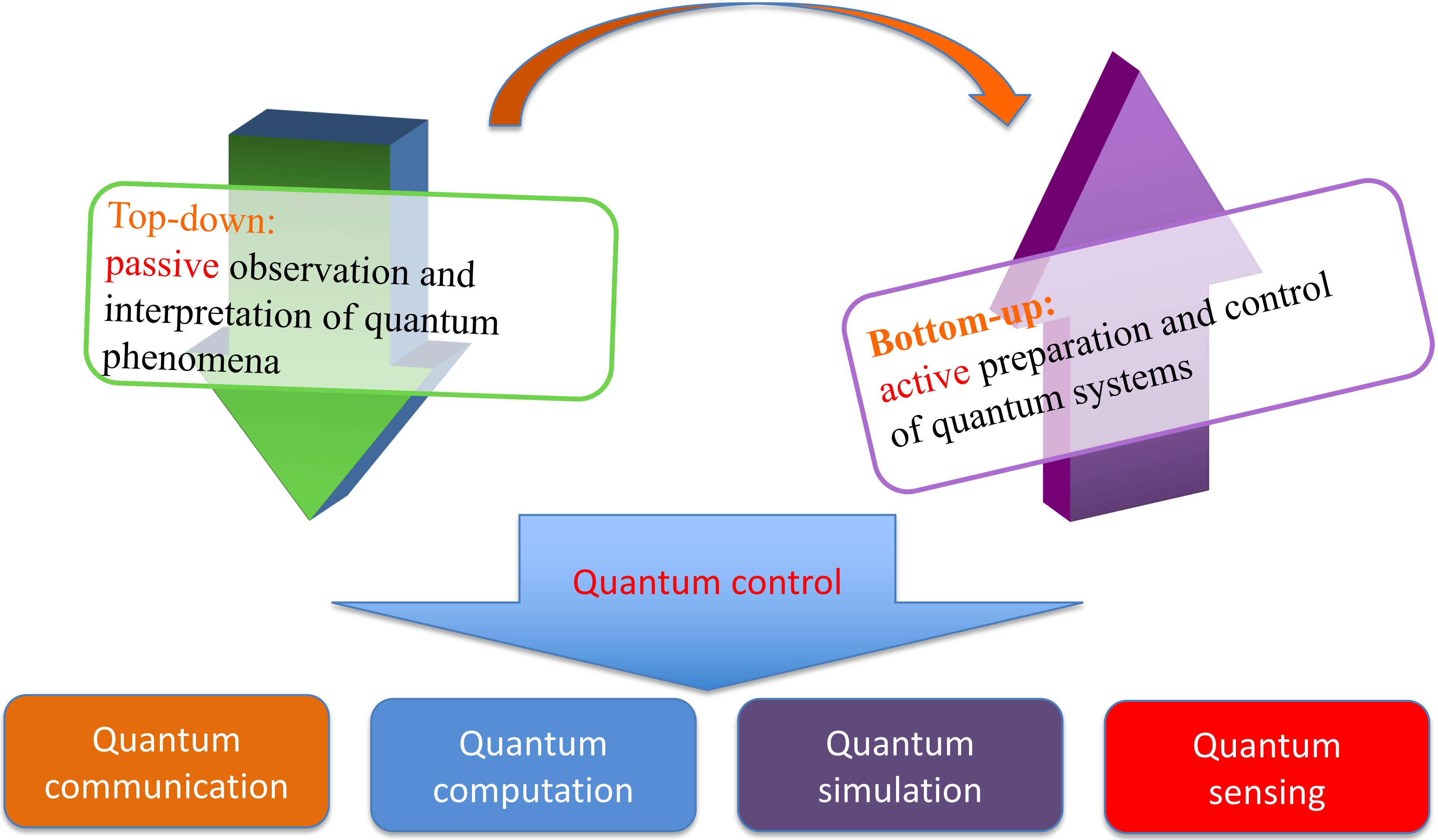


"for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science"



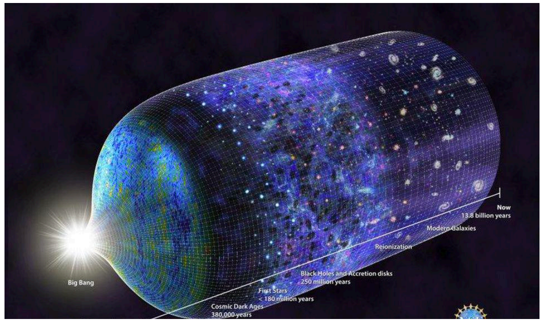
Alain Aspect, John Clauser and Anton Zeilinger have each conducted groundbreaking experiments using entangled quantum states, where two particles behave like a single unit even when they are separated. Their results have cleared the way for new technology based upon quantum information.

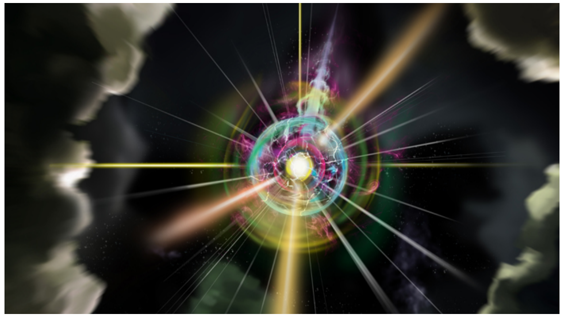
The second quantum revolution

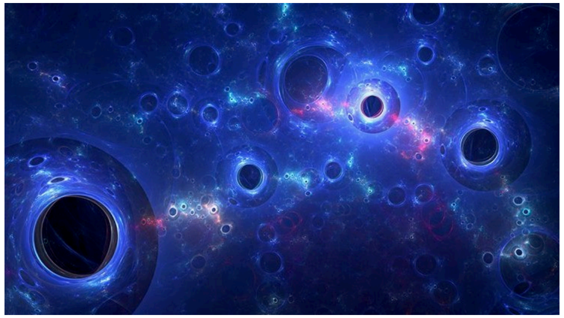


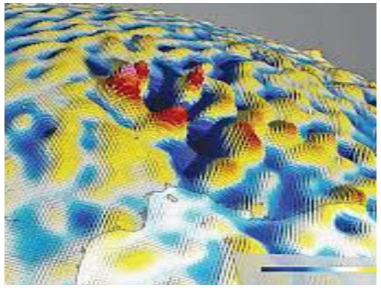
Break the limits of classical technologies

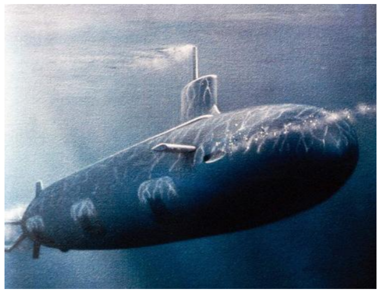
Quantum precision measurement


Dark energy


Monopoles


Dark matter


Navigation


Defence security

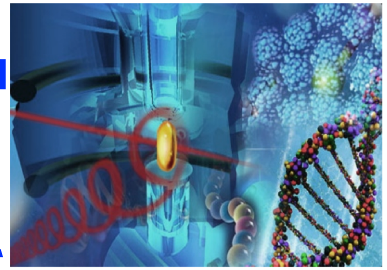
To meet the major national strategic needs

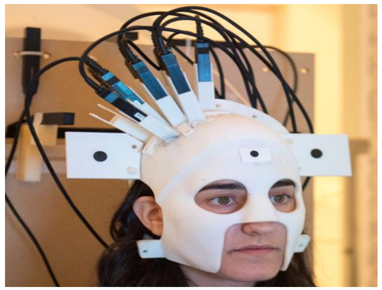
Facing the world's frontier of science and technology

Weak magnetic field measurement

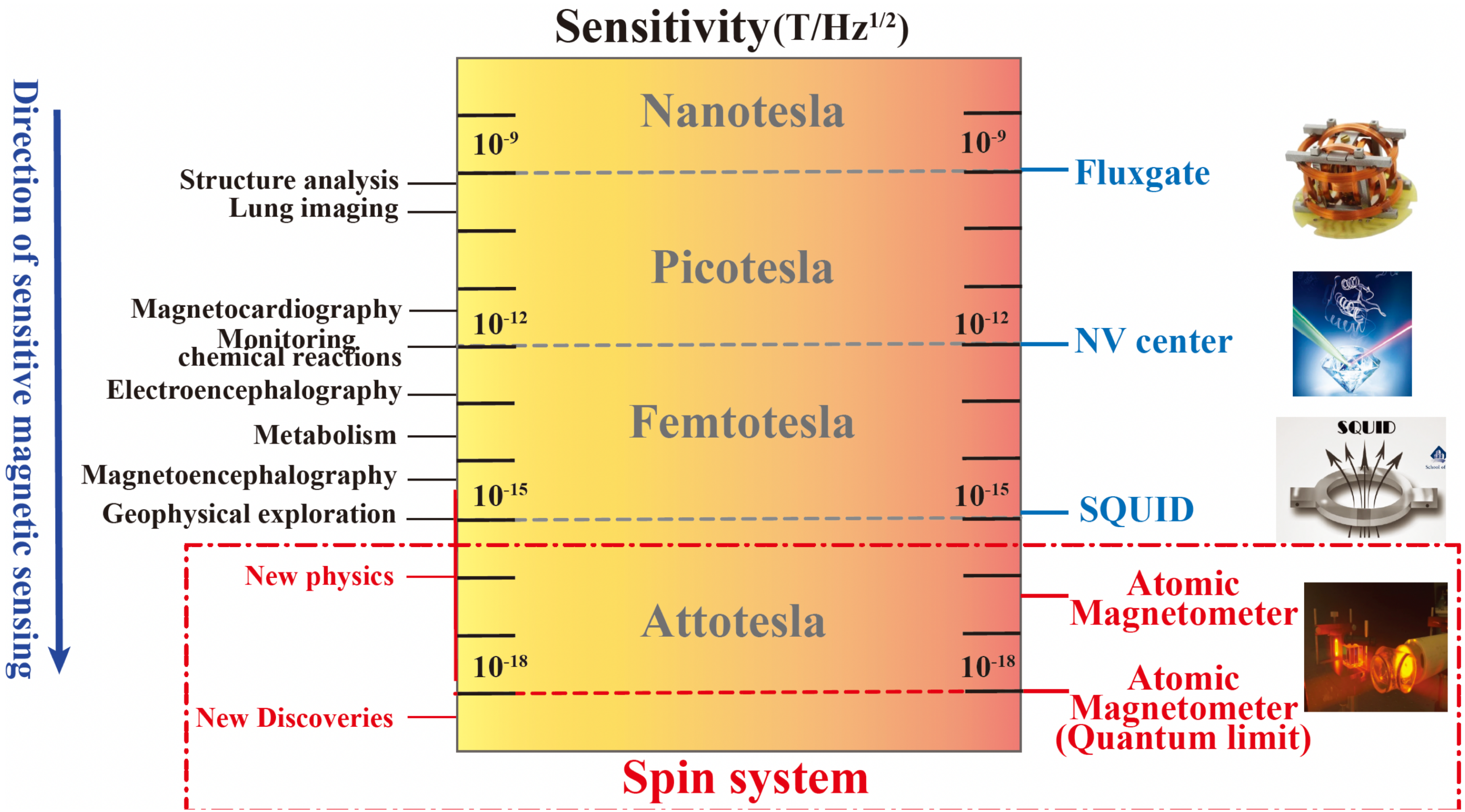
Quantum precision measurement

To meet people's life and health needs


MRI

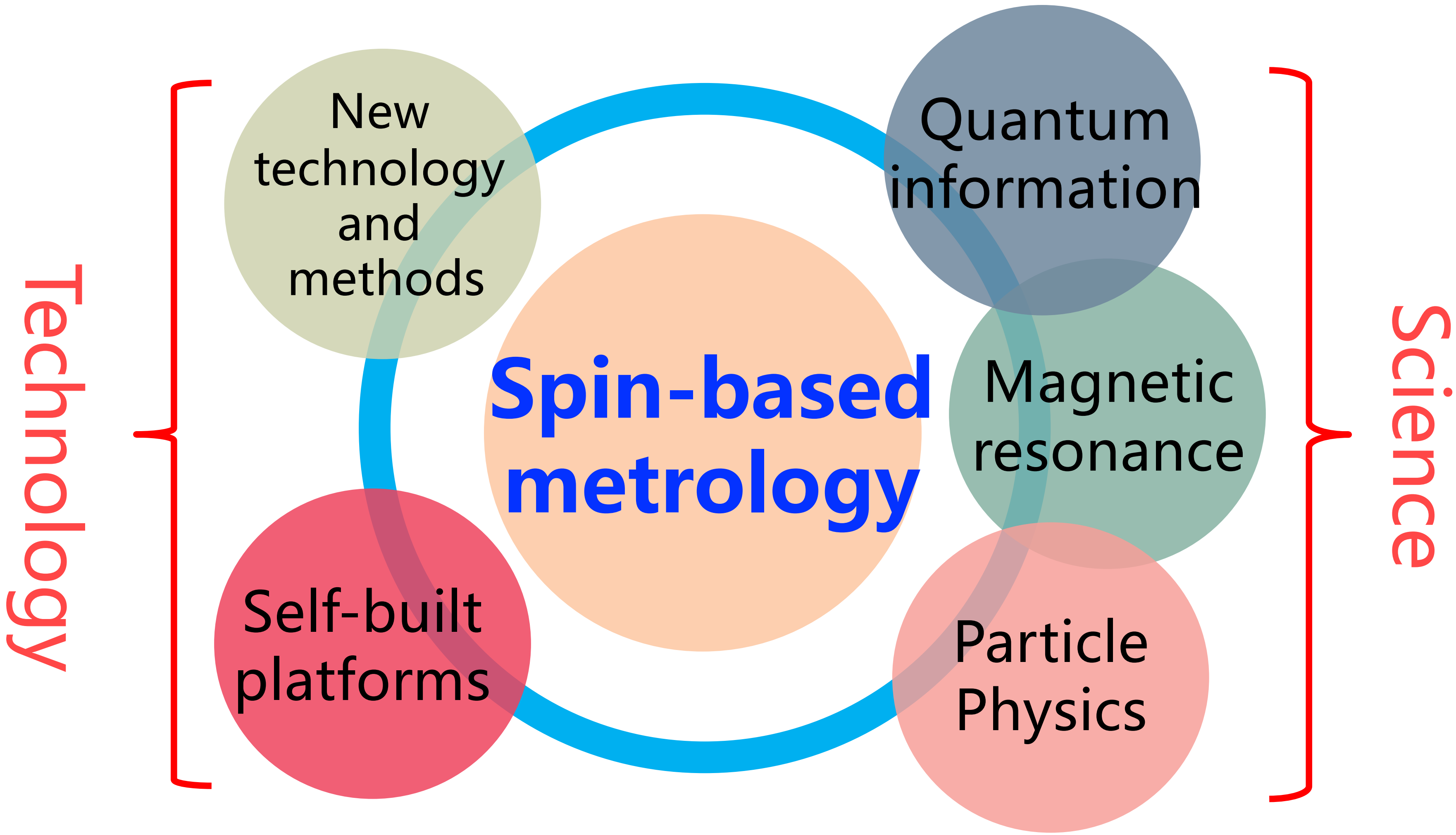

MEG/MCG

Magnetic phenomena and their strength



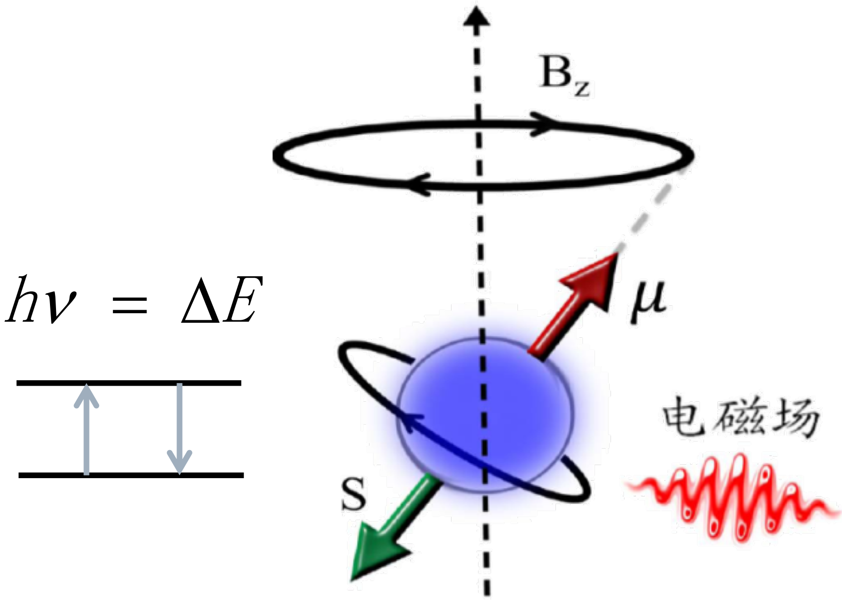
Quantum sensors make new discovery possible！

Our research



Spin-based quantum precision measurement

Principle： **The nucleus or electron spins** placed in an external magnetic field, can absorb and release the electromagnetic radiation of the corresponding frequency, then the magnetic resonance phenomenon occurs.



Lamor precession

$$\omega = \gamma B$$

Outline

- Dark Matter and Axion： What is it and Why now?
- Quantum sensors： How to see it?
  - Noble-gas spin systems: intrinsic systems vs. Floquet systems
  - Noble-gas spin amplification effect
  - Noble-gas spin Masing effect
- Dark matter searches with spin-based-amplifier magnetometers
  - Axion dark matter
  - Exotic interactions mediated by new particles (the fifth force)

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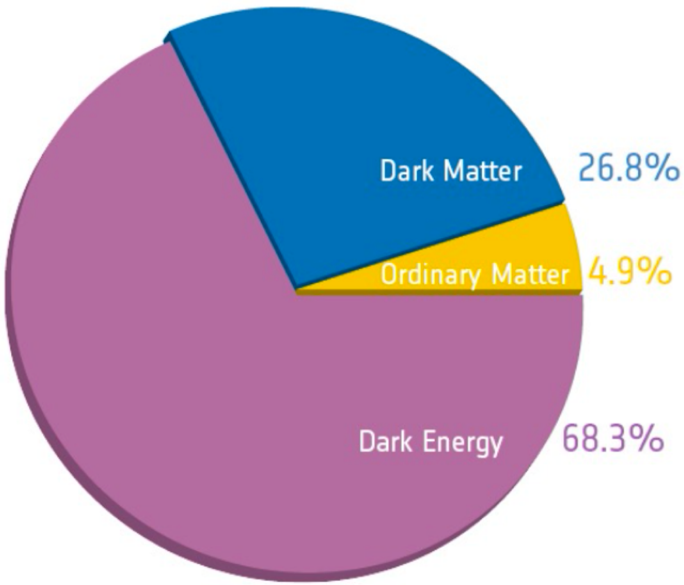
Dark matter

What is the nature of dark matter?



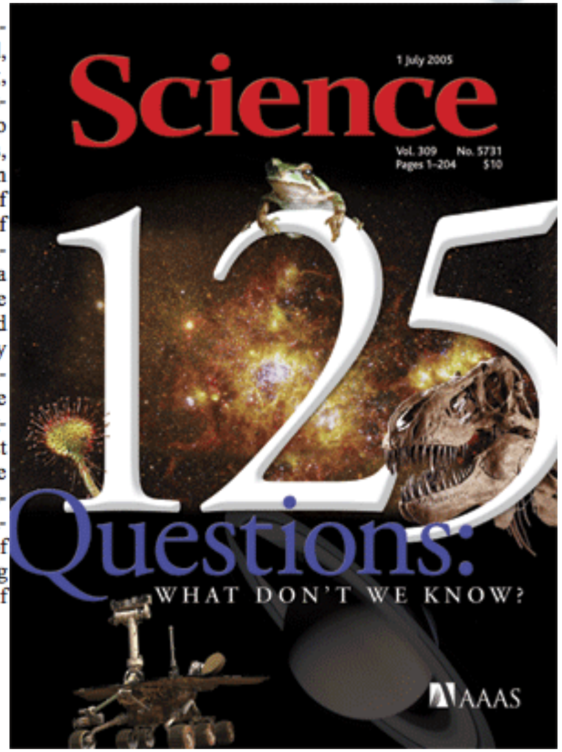
→What kind of microscopic particles are made of?
→How do particles interact?

Special Section

WHAT DON'T WE KNOW?

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



Axions and axion-like particles

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.

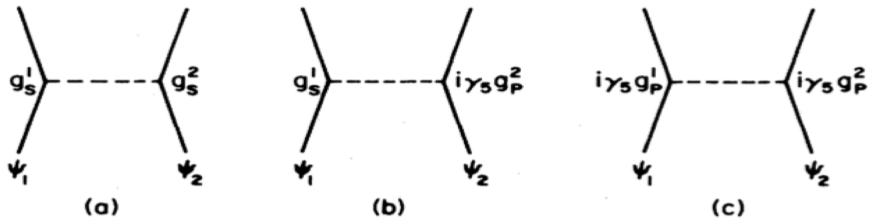
Frank Wilczek

PHYSICAL REVIEW D VOLUME 30, NUMBER 1 1 JULY 1984

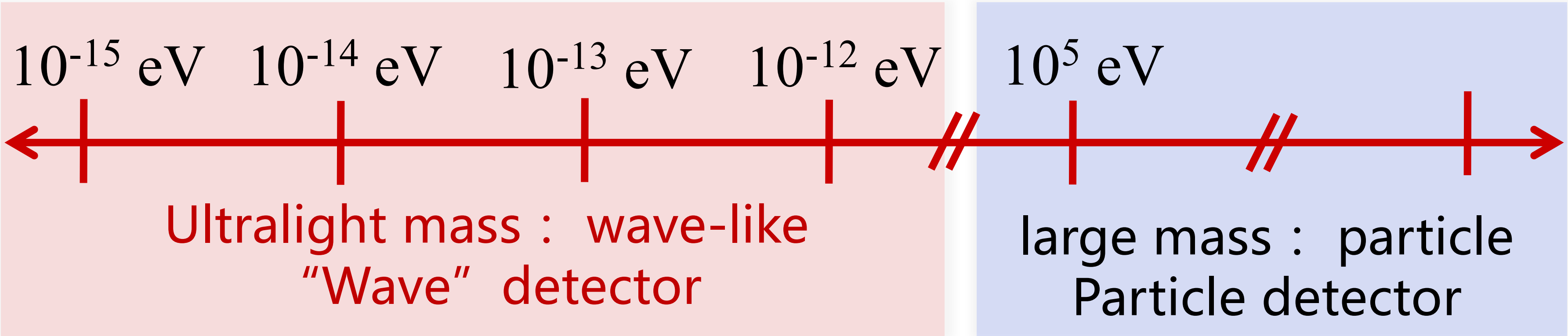
New macroscopic forces?

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.

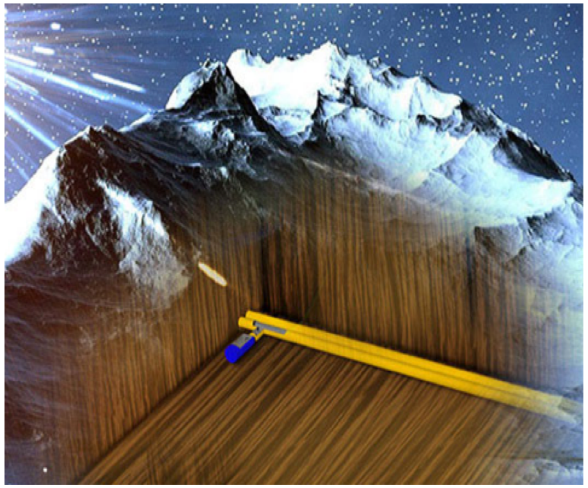


How to see it?



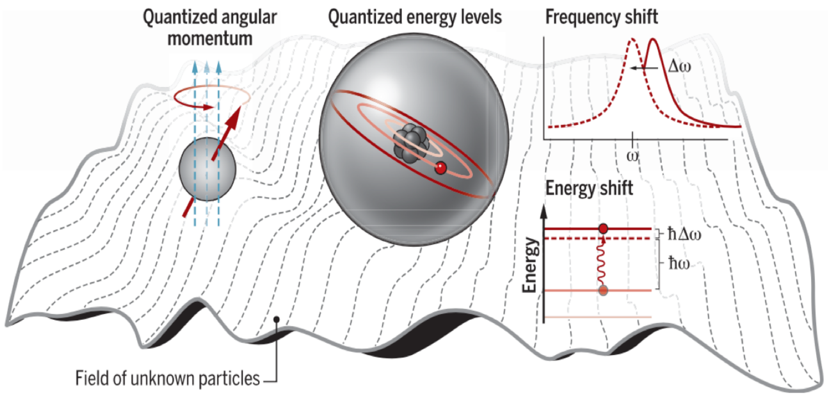
Collider exp.
(LHC、BESIII)

Space exp.
(DAMPE、AMS)



Underground exp.
(PandaX、CDEX)

Quantum sensors: sensitive low-energy tools



Dark matter is very weakly coupled to **atomic molecular systems**, causing small energy shifts

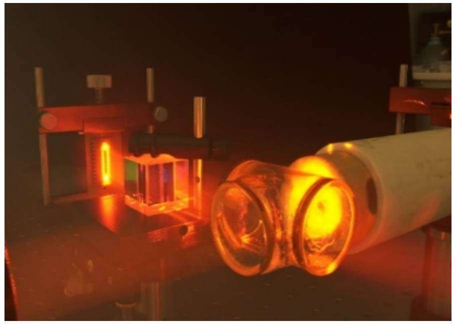
Science 357，990 （2017）

Rev. Mod. Phys. 90,025008 (2018)

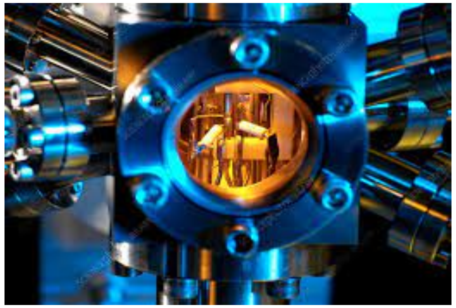
- Sensitive ：quantum-noise limits
- Tabletop ：small size and cheap
- Networks ：low false-alarm rate

Beyond the astrophysical limits！

Quantum sensors



Magnetic field: Magnetometers (or spin sensor)



Time standard: Optical clocks

Gravity: Interferometry

Outline

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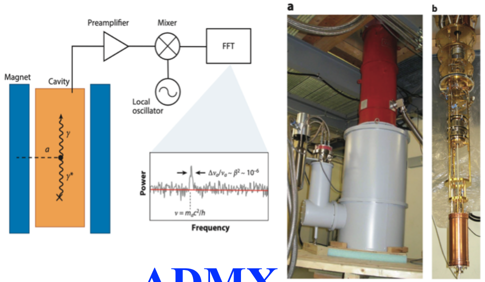
How to see it?

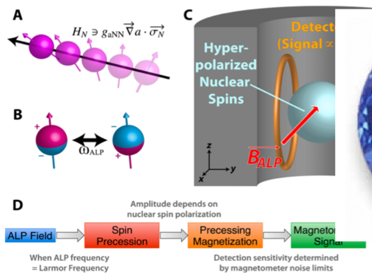
The nonrelativistic Hamiltonian

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

Couplings	axion-photon	axion-fermion	axion-gluon
Effects	axions is converted to real photons	axions generate pseudomagnetic field on spins	axions generate oscillating EDM

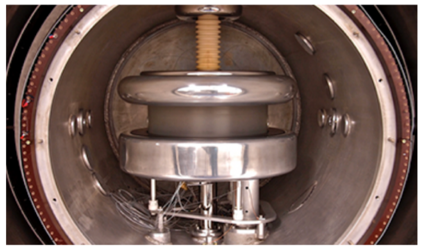


ADMX



CASPEr

Sapphire



nEDM

Quantum spin metrology

$$\omega = \gamma B$$

- Alkali-metal atoms K，Rb，Cs
- Hyperpolarized noble gas ^{3}He，^{129}Xe

Precision limit： $\delta\omega = \frac{1}{P\gamma\sqrt{NT_2 t}}$

- Polarization: P
- Number of spins: N
- Spin relaxation: T_2

Why we choose alkali metal atoms/noble gas？

- Alkali metal atoms: Well-developed pump and probe techniques
- Noble gas: Long coherence time (>10 s)
- Spin exchange interactions via collisions (Allow information transfer between them)

Coherence time (T_2^*)

^{3}He: I=1/2, T2 >1 h, abundance: 0.01%

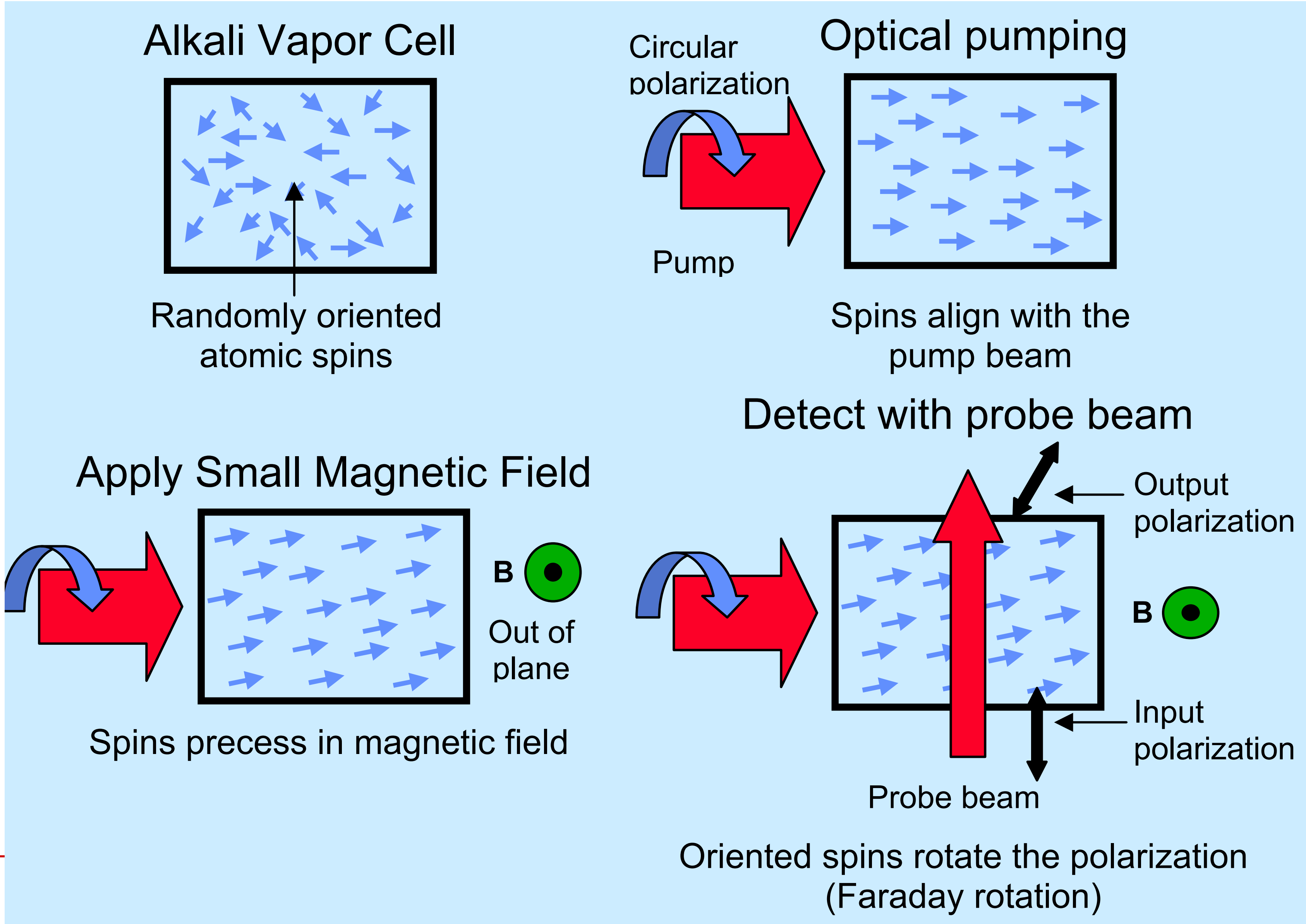
^{129}Xe: I=1/2, T2~20 s, abundance: 26.4%

^{21}Ne: I=3/2, abundance: 21%

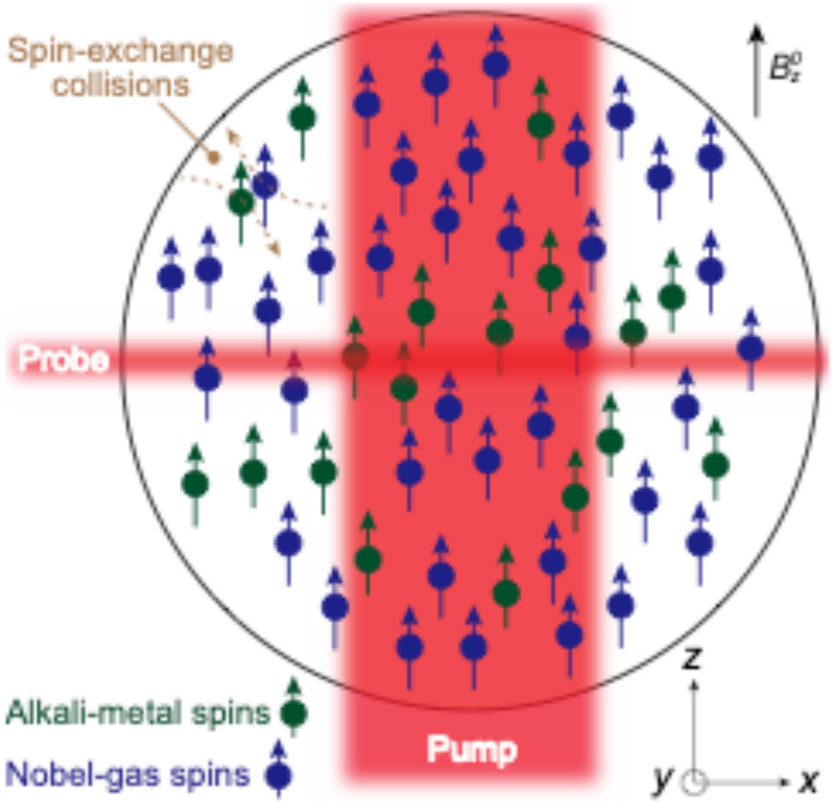
^{83}Kr: I=9/2, abundance: 83%

^{131}Xe: I=3/2, T2~5 s, abundance: 21.2%

Atomic magnetometer



Spin dynamics



$$\beta M_0^e \mathbf{P}^e \ll \beta M_0^n \mathbf{P}^n$$

Coupled Bloch equations

$$\frac{\partial \mathbf{P}^e}{\partial t} = \frac{\gamma_e}{Q}(B_z^0 \hat{z} + \mathbf{B}_a + \beta M_0^n \mathbf{P}^n) \times \mathbf{P}^e + \frac{P_0^e \hat{z} - \mathbf{P}^e}{T_e Q},$$

$$\frac{\partial \mathbf{P}^n}{\partial t} = \gamma_n (B_z^0 \hat{z} + \mathbf{B}_a) \times \mathbf{P}^n + \frac{P_0^n \hat{z} - \mathbf{P}^n}{\{T_{2n}, T_{2n}, T_{1n}\}}.$$

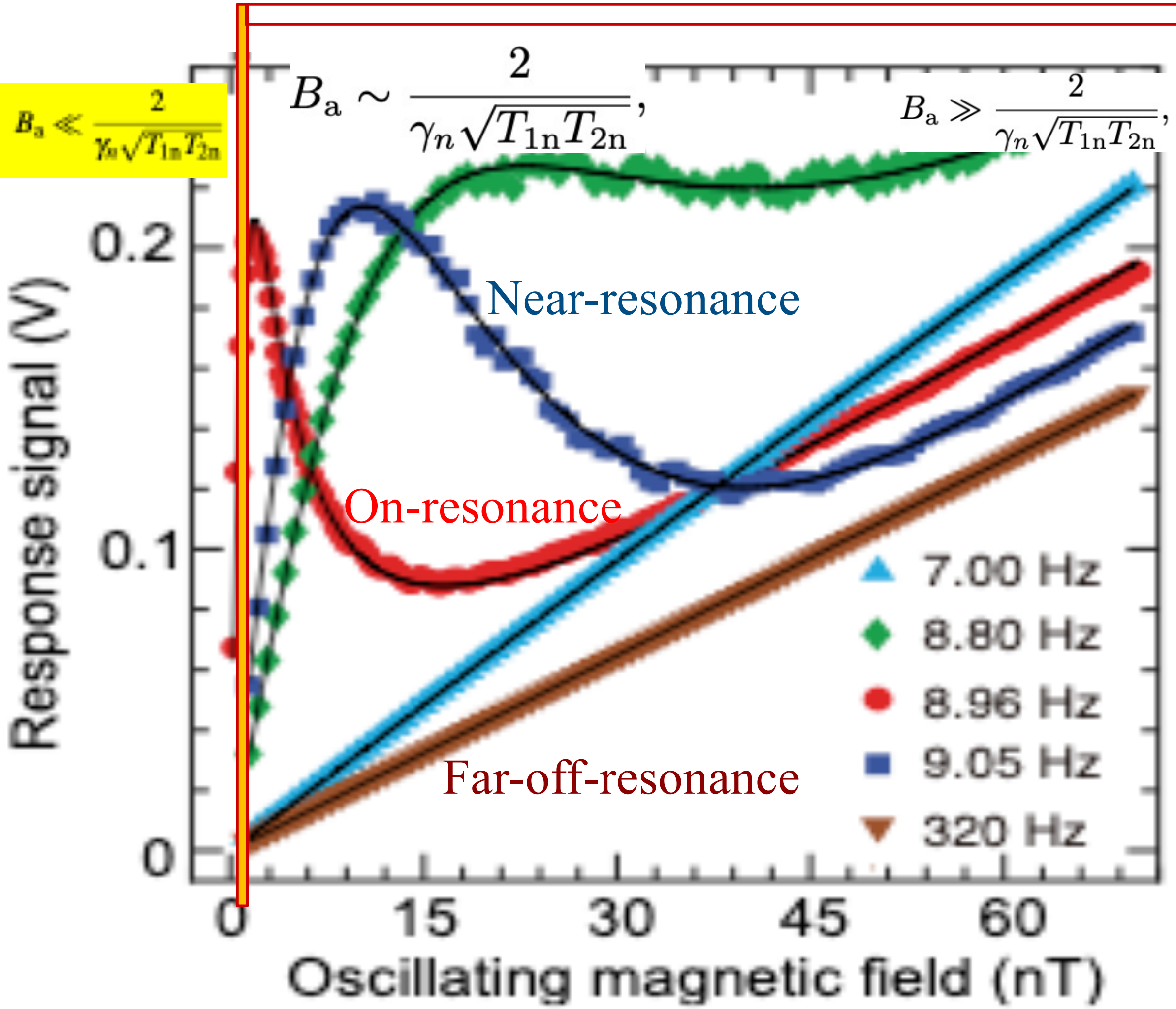
Polarized noble-gas nuclear spins generate an effective field experienced by alkali-metal atoms due to the Fermi-contact interactions

$$\mathbf{B}_{\text{eff}}^n = \beta M_0^n \mathbf{P}^n$$

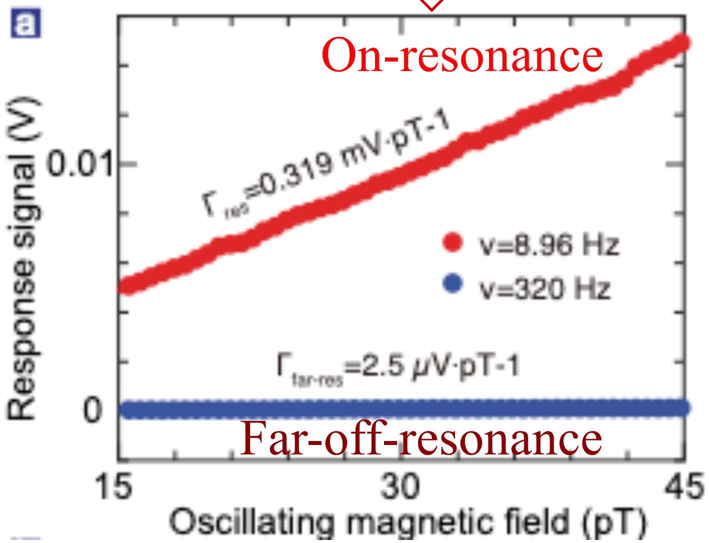
Fermi-contact factor $\kappa_0 \sim 540$ (Rb+Xe)

$$\beta = 8\pi\kappa_0/3$$

Spin dynamics



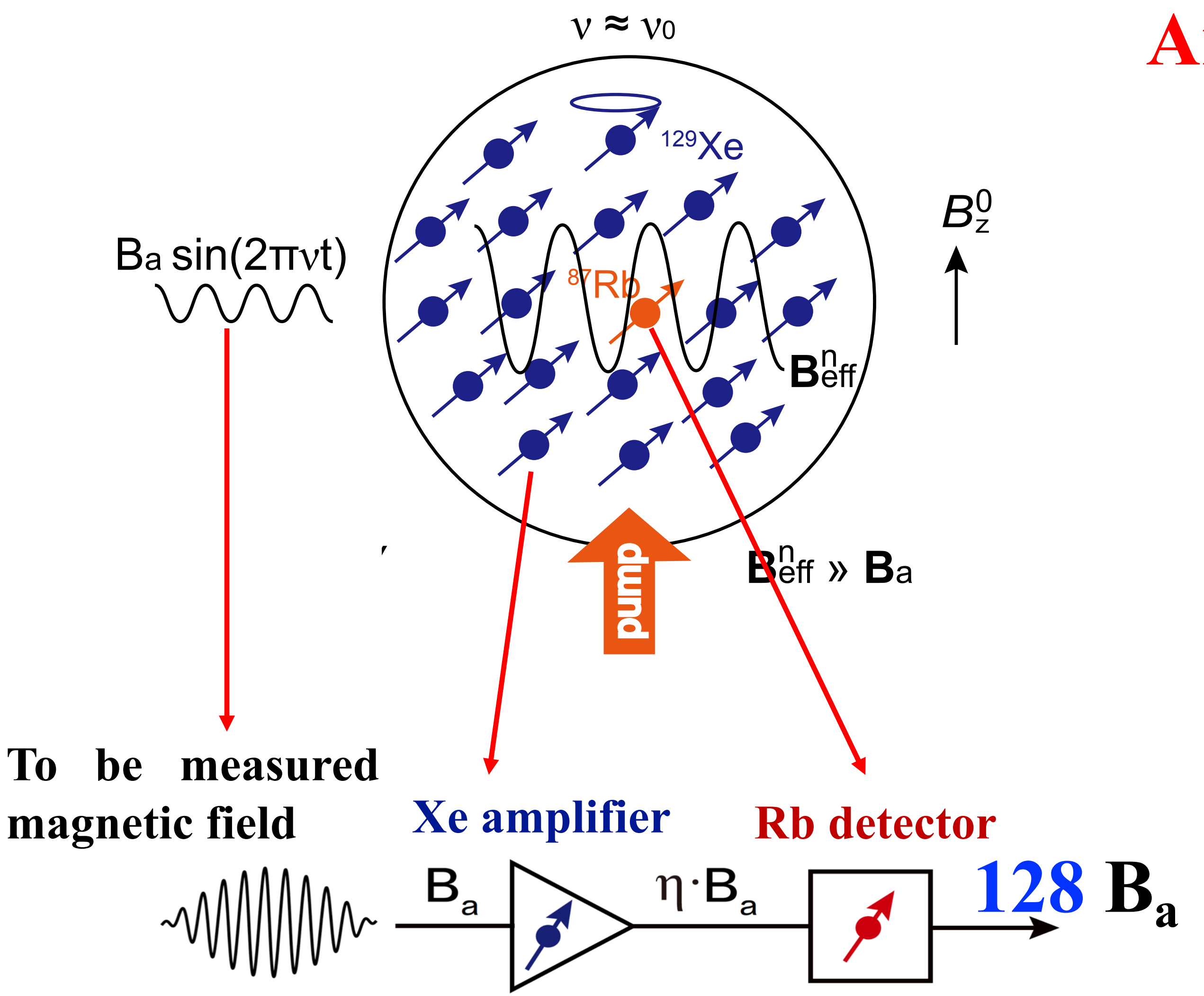
Linear Nonlinear Saturated



Slope: Response to the magnetic field

At least two orders of magnitude improvement

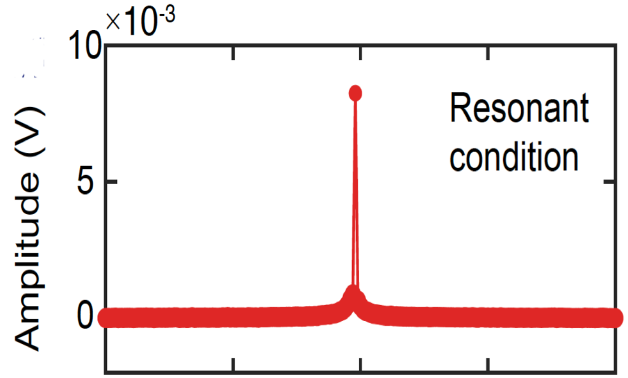
Amplification-assisted magnetometer



Amplification factor:

$$\eta = \frac{1}{2}\beta M_0^n P_0^n \gamma_n T_{2n} \gg 1$$

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



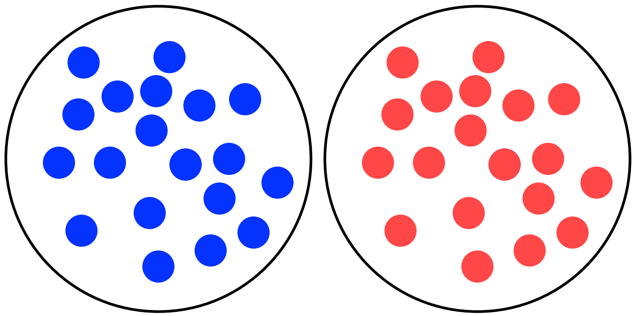
Jiang et al., Nature Physics (2021). DOI: 10.1038/s41567-021-01392-z

Spin amplifier: Amplification of magnetic field

Magnetic interaction

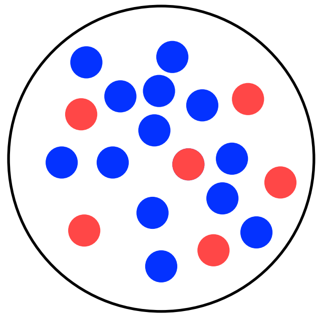
$$\mathbf{B}(\mathbf{r}) = \overbrace{\frac{\mu_0}{4\pi}\frac{3\hat{r}(\hat{r}\cdot\mathbf{m})-\mathbf{m}}{r^3}}^{\text{“remote”}} + \overbrace{\frac{2\mu_0\mathbf{m}}{3}}^{\text{“contact”}}\delta(\mathbf{r}),$$

External readout (dipole field)



Nuclear spins   Alkali-metal spins

Fermi contact readout



Noble-gas + alkali-metal overlapping spins

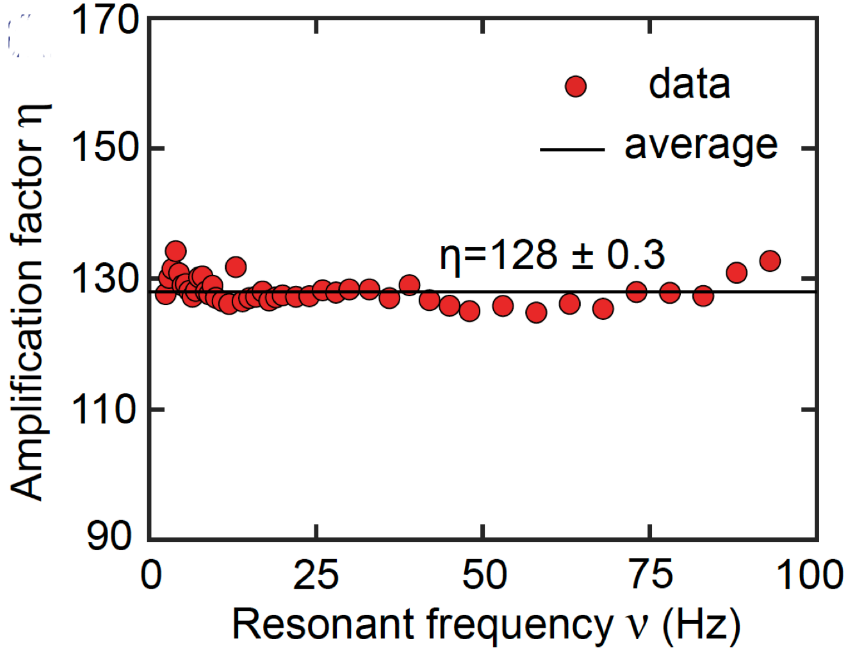
➔ Large Fermi-contact enhancement (~600 for Rb-Xe)

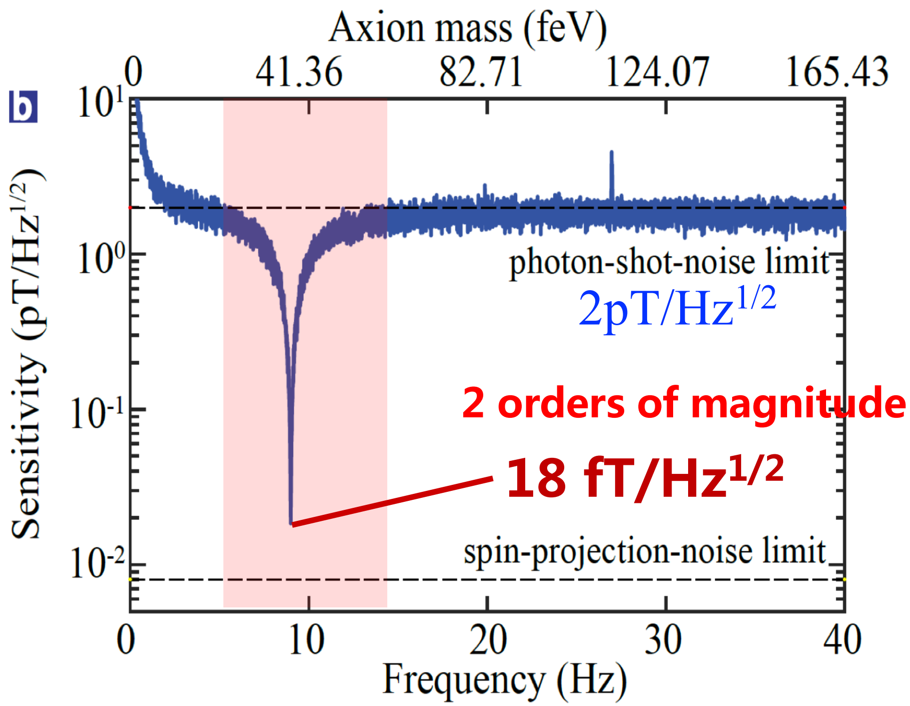
➔ Without spin polarization loss

➔ Continous measurement

Jiang et al., Nature Physics **17**, pages 1402–1407 (2021)

Ultrasensitive magnetic field sensing





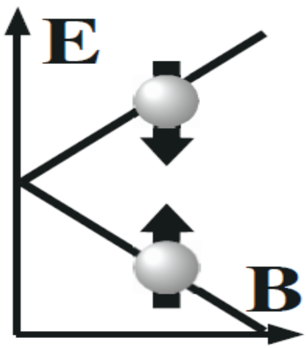
Magnetic field is amplified by a factor of more than 100!

Femtotesla-level sensitivity!

$1fT = 10^{-15}T$

Jiang et al., Nature Physics **17**, pages 1402–1407 (2021)

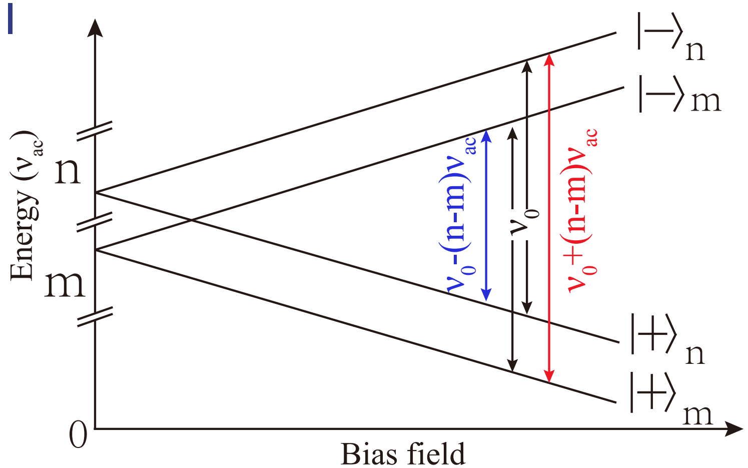
Periodically driven (Floquet) spin systems



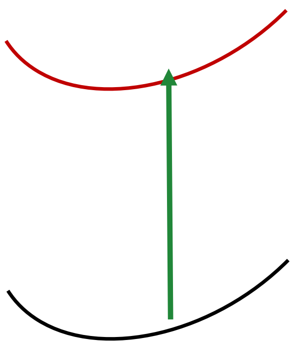
Two-level spin system

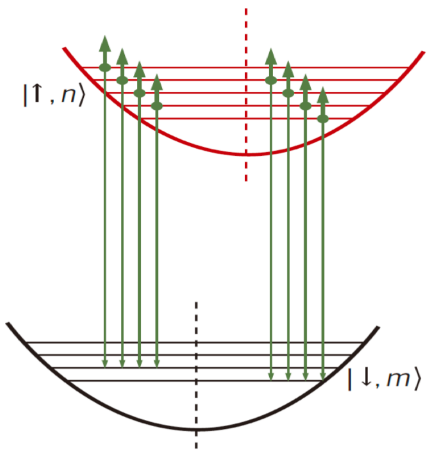
Extended to a series of Floquet states

Floquet levels/Floquet states



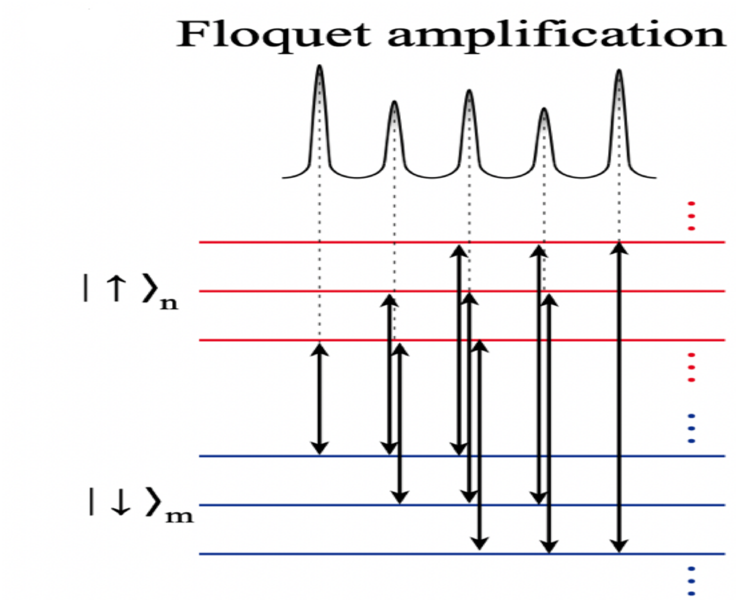
One transition

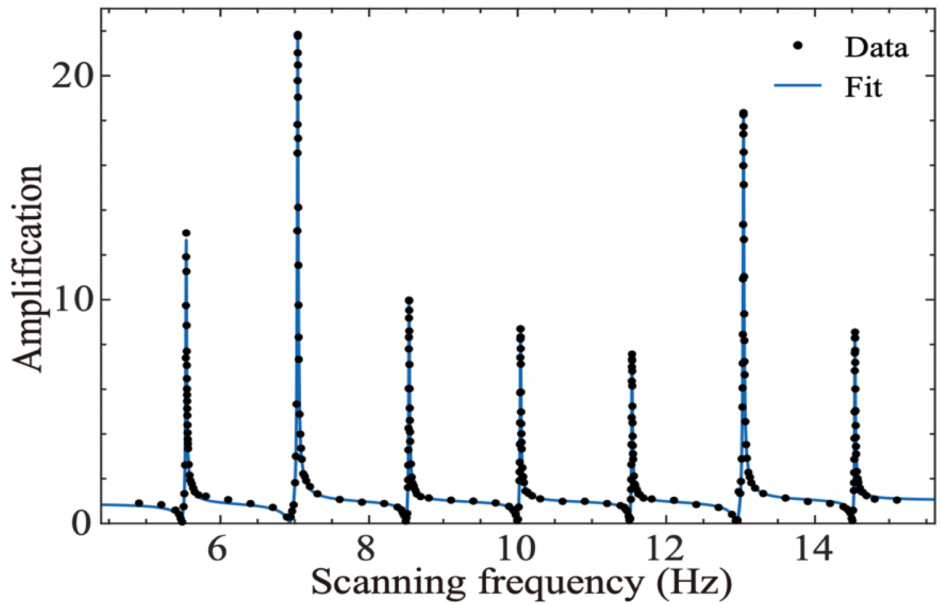




Many Floquet transitions

Floquet spin amplification





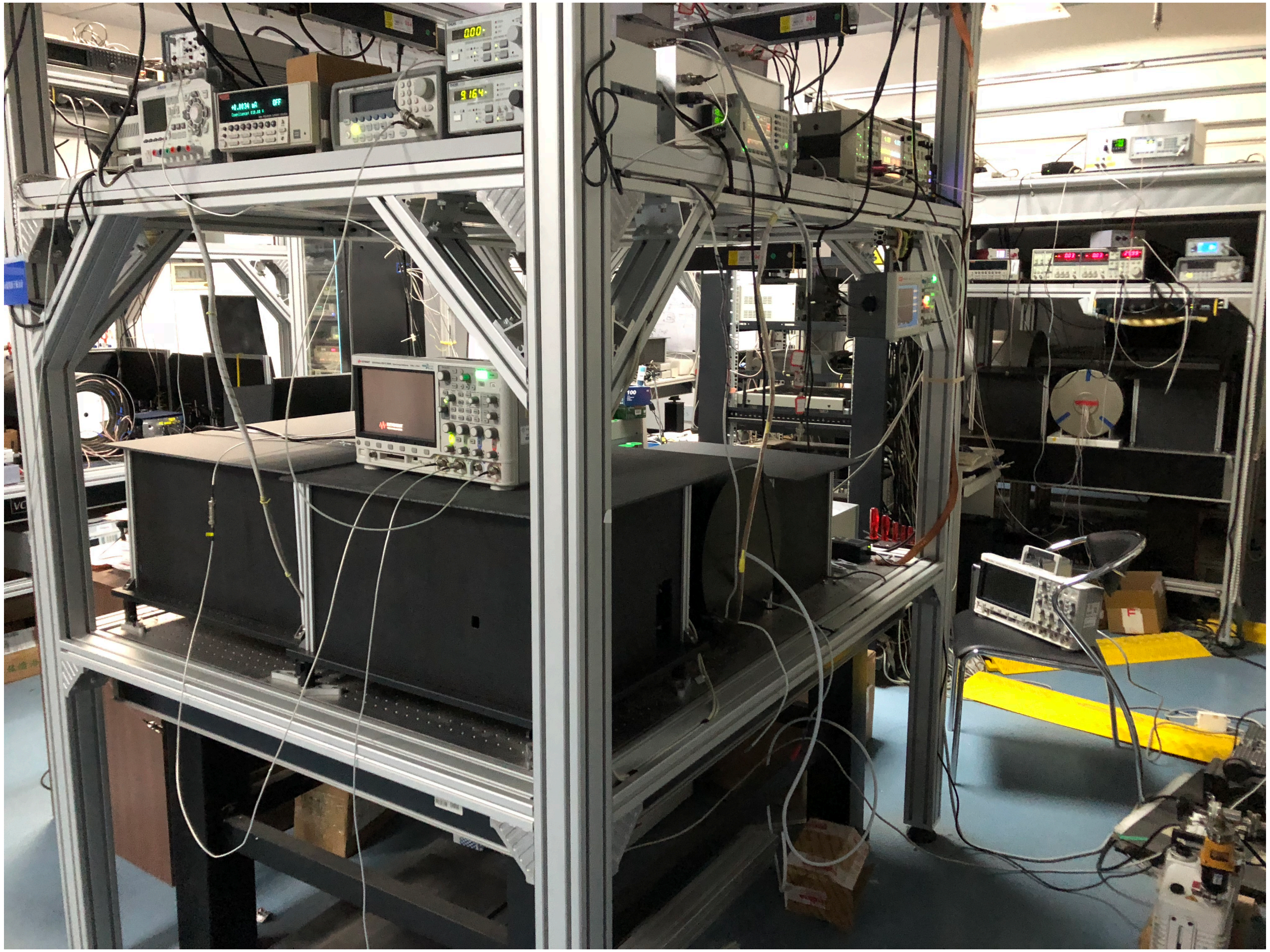
Amplification factor:

$$\eta_{k,0}(u) = \frac{4\pi}{3}\kappa_0 M^n P_0^n \gamma_n T_{2n} J_k^2(u)$$

10 times improvement in the detection range, fT/Hz$^{1/2}$ detect sensitivity

Jiang et al., PRL 128, 233201 (2022) Editors' suggestion

飞特斯拉（fT）级别的自旋传感装置



Noble-gas masing effect

Spin amplification combines with a “cavity-like” feedback

Spin amplifier

Radiation Damping

$T_{\mathrm{d}}/T_{2\mathrm{n}} \ll 1$

feedback

Spin Maser

A feedback mechanism

Coherent spin oscillations “Atomic clocks”

Spin amplification combines with a feedback

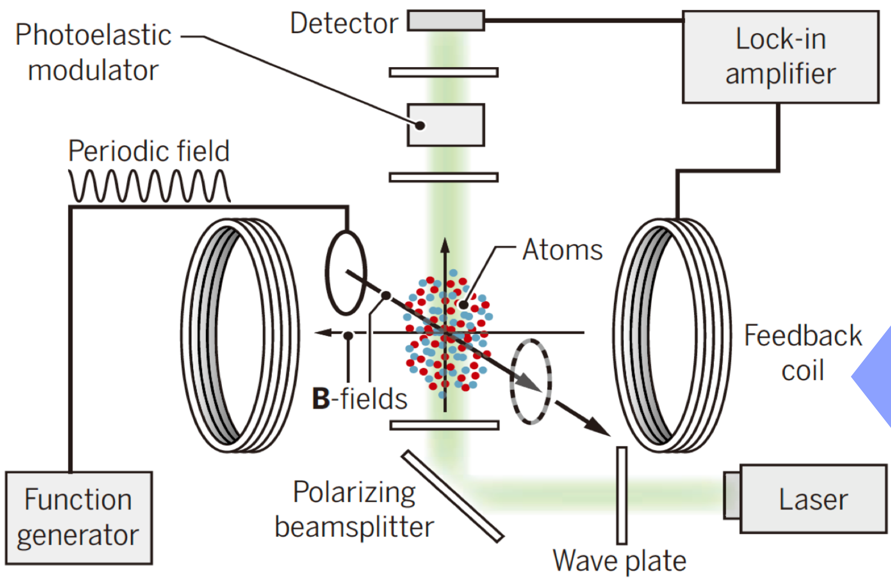
Nobel Prize: Maser and atomic clock

C. Townes

G.Basov

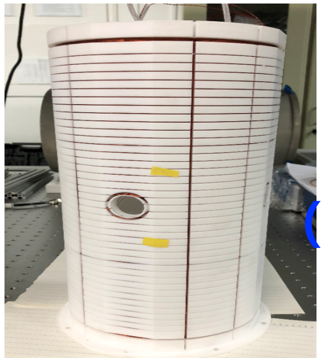
M. Prokhorov

N. F. Ramsey



Optical frequency
(Optical cavity)

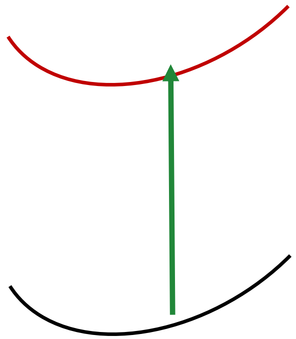
Microwave frequency
(Cavity)



Radio frequency
(feedback Coils)

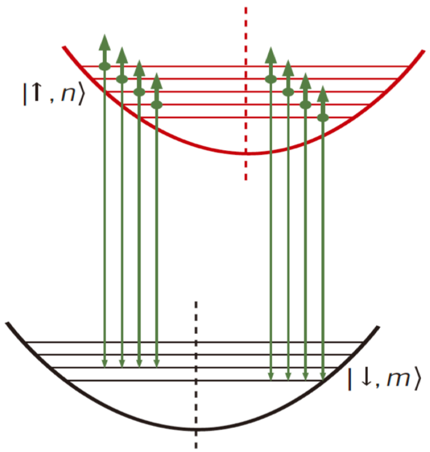
Periodically driven (Floquet) spin maser

Two-level spin system

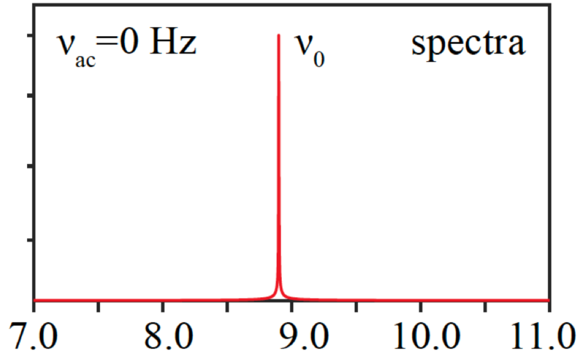


Pseudo-magnetic field from particles

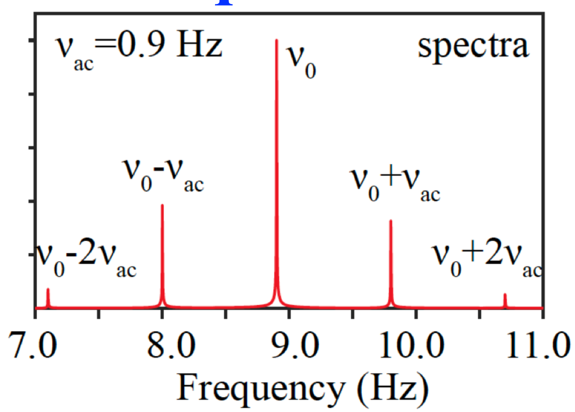
Extended to a series of Floquet states



traditional maser

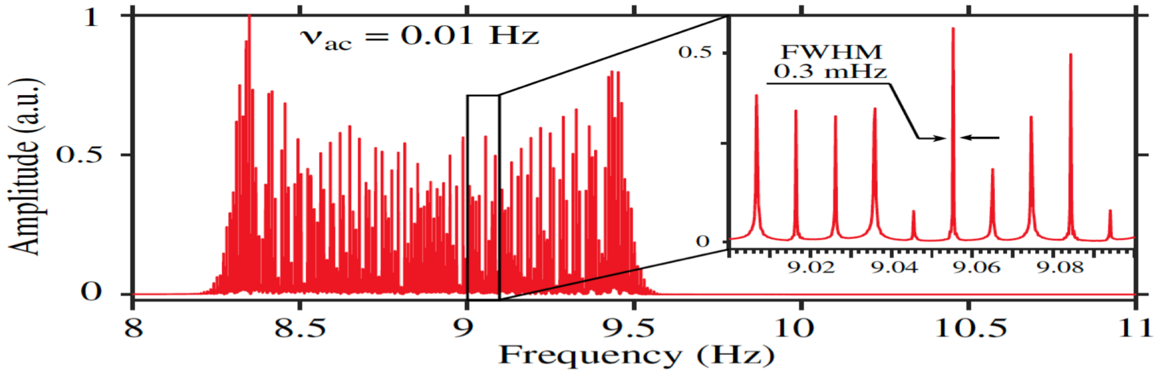


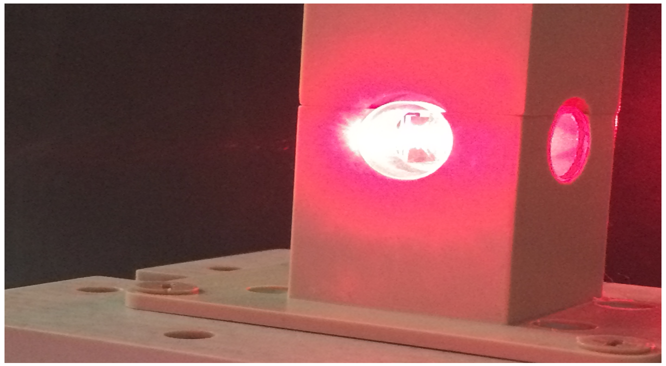
Floquet maser



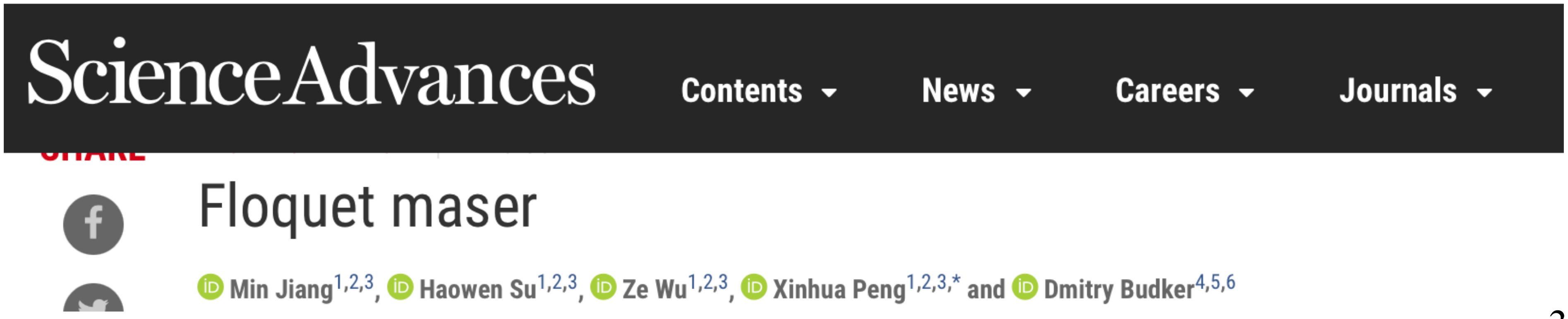
Jiang *et al.* Floquet maser, **Science Advances** 7， eabe0719（2021）

Periodically driven (Floquet) spin maser



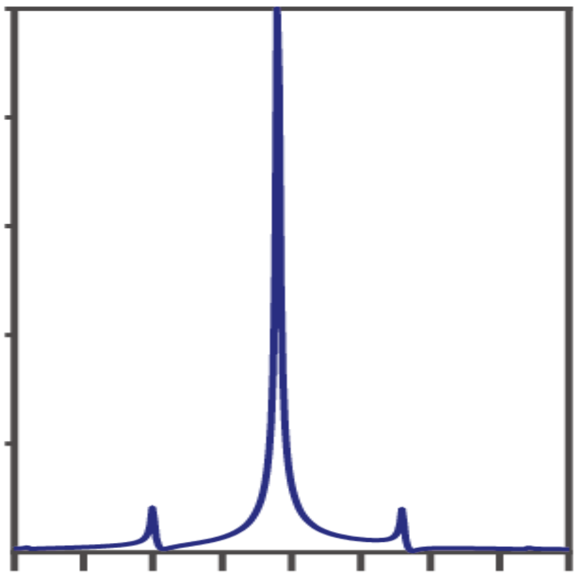


频率梳~130
条跃迁线

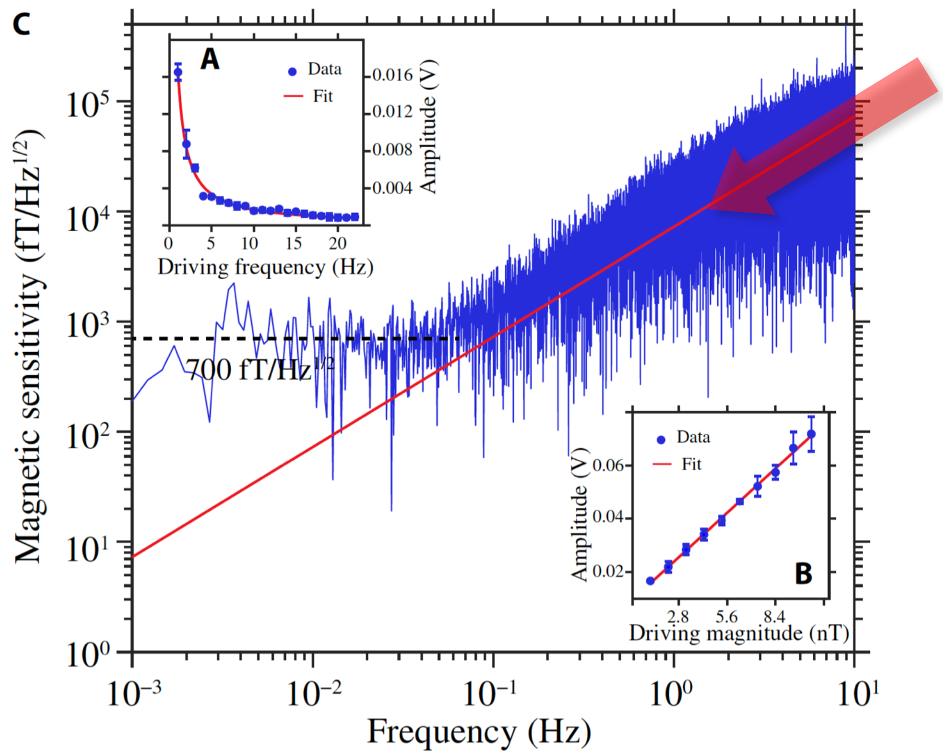


Floquet-maser-based sensing

1-1000mHz： axion-mass 10^{-17}eV-10^{-14}eV



$$S_1 \propto J_1\left(\frac{\gamma B_{ac}}{\upsilon_{ac}}\right) \approx \frac{\gamma}{2\upsilon_{ac}} B_{ac}$$



Best sensor for 1-100mHz！

Jiang *et al.* **Science Advances** 7，eabe0719（2021）

Science Advances Contents News Careers Journals

SHARE

Floquet maser

Min Jiang[1,2,3], Haowen Su[1,2,3], Ze Wu[1,2,3], Xinhua Peng[1,2,3,*] and Dmitry Budker[4,5,6]

Science

A masing ladder

A maser that amplifies emission of periodically modulated quantum states has uses in metrology

PHYS.ORG

Extending maser techniques to Floquet systems

techniques to Floquet systems. In their paper published in the journal *Science Advances*, the group describes their approach to creating a new type of maser by amplifying radio frequencies in Floquet systems. Ren-Bao Liu, with the Chinese

physicsworld RESEARCH UPDATE

New Floquet maser is very good at detecting low frequency magnetic fields

《Science》 Perspectives reports：

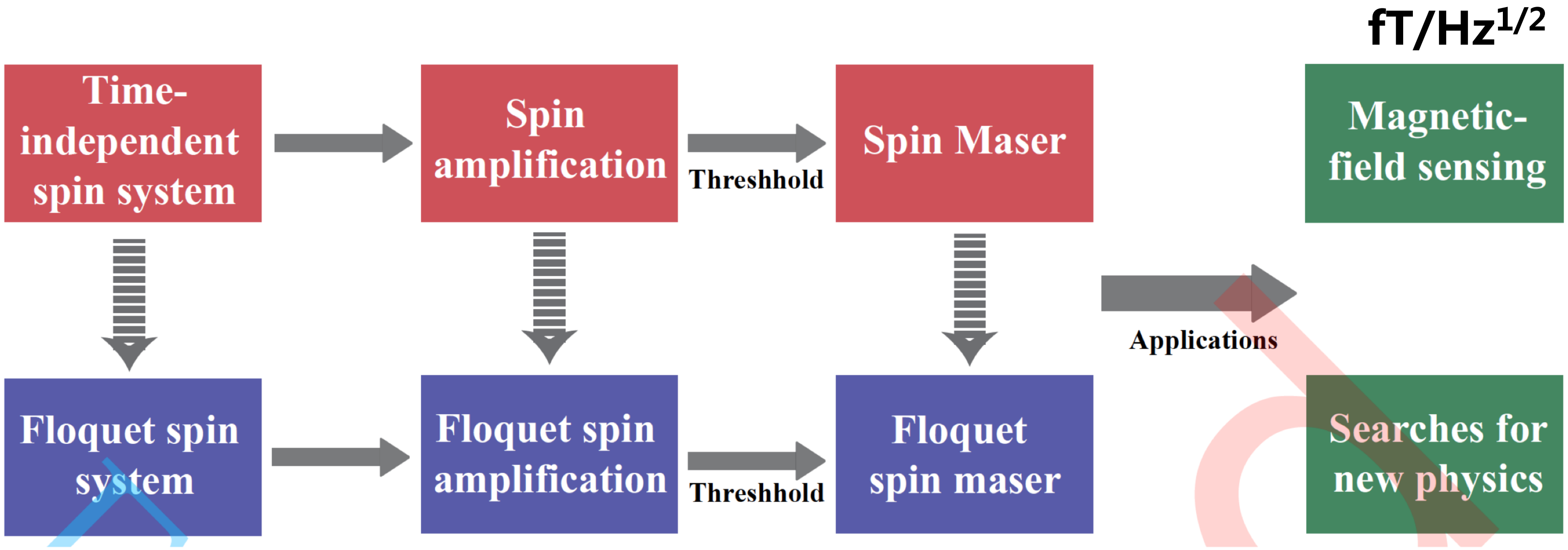
"… demonstrate a new type of maser… Conceivable applications of this work include precision clocks and detection of ultralight dark matter particles such as axions"

Spin amplification

SCIENCE CHINA
Information Sciences

Review of noble-gas spin amplification via the spin-exchange collisions

Haowen Su[1,2], Min Jiang[1,2] and Xinhua Peng[1,2]



Outline

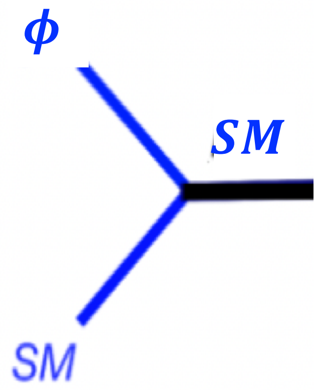
- Dark Matter and Axion： What is it and Why now?
- Quantum sensors： How to see it?
  - Noble-gas spin systems: intrinsic systems vs. Floquet systems
  - Noble-gas spin amplification effect
  - Noble-gas spin Masing effect
- Dark matter searches with spin-based-amplifier magnetometers
  - Axion dark matter
  - Exotic interactions mediated by new particles (the fifth force)

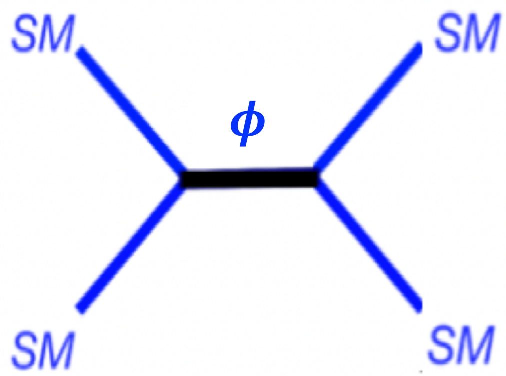
"Sapphire" project

Spin Amplifier for Particle PHysIcs Research

Sapphire project（“蓝宝石”计划）

Spin Amplifier for Particle PHysIcs Research





直接探测：
暗物质候选粒子
轴子、暗光子

“蓝宝石”计划：
自旋放大、fT灵敏度、
阵列探测、桌面式

间接探测：
新奇相互作用
新粒子作为传播子

Direct detection for ALP

Goal: to detect an oscillating nuclear-spin-dependent energy shift caused by the weak coupling between Spin and Axion

"pseudo-magnetic" field:

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

Resonance frequency probes the mass m_{ALP}

Amplitude B_{ALP} probes the coupling value of g_{aNN}

More sensitive detector → Smaller coupling g_{aNN}

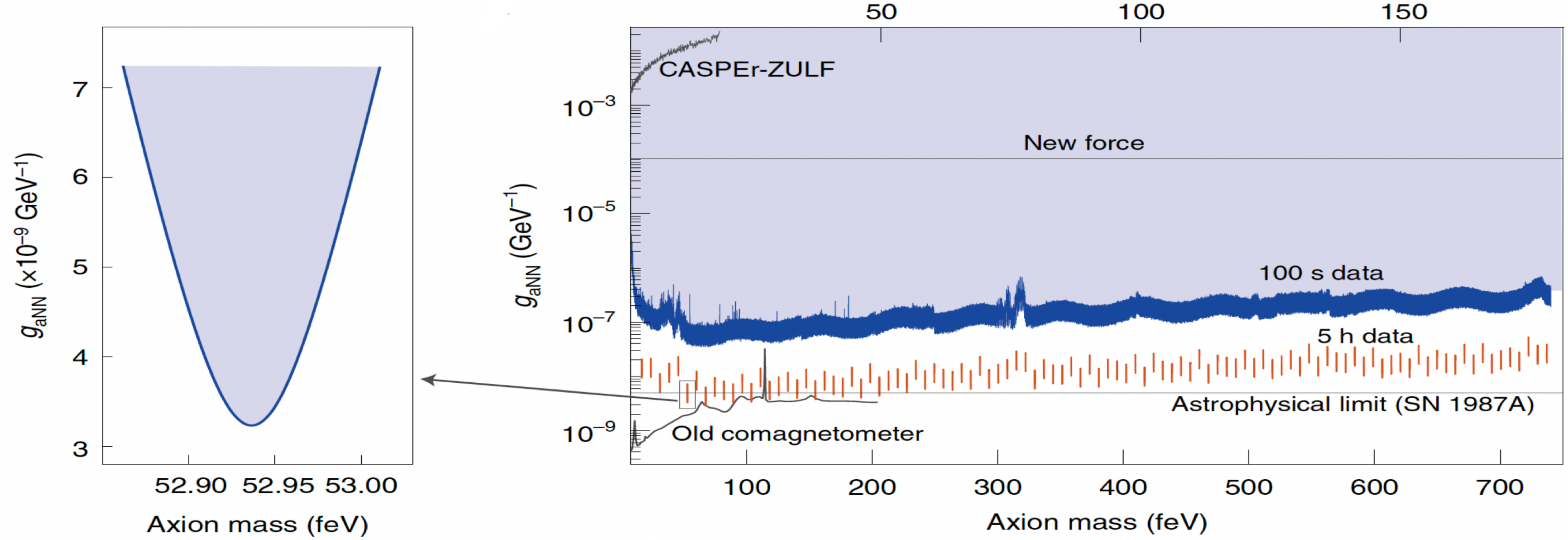
Lower-frequency detector → Lighter mass m_{ALP}

Beyond the astrophysical limits

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

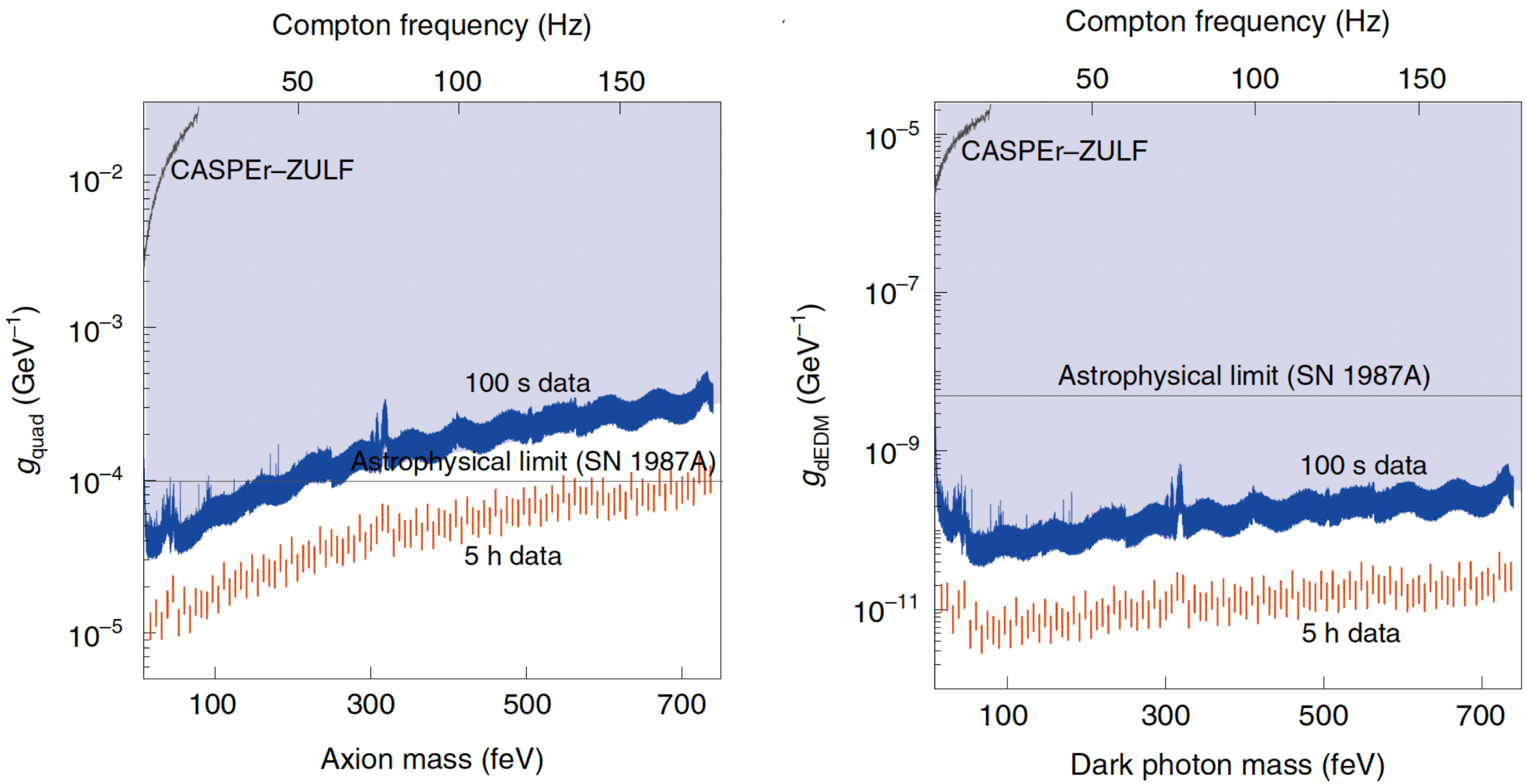
Min Jiang[1,2,3,7], Haowen Su[1,2,3,7], Antoine Garcon[4,5], Xinhua Peng[1,2,3] and Dmitry Budker[4,5,6]



New constraints on axion-neutron coupling

Jiang et al., Nature Physics **17**, pages 1402–1407 (2021)

Beyond the astrophysical limits



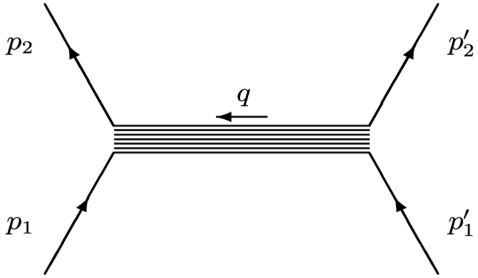
At least five orders of magnitude improvement, beyond the astrophysical limits

Jiang et al., Nature Physics **17**, pages 1402–1407 (2021)

Exotic interactions beyond the standard model

B. A. Dobrescu

I. Mocioiu



Extend axion to new mediator bosons and lead to 16 interactions

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

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

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

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

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

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

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

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

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

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

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

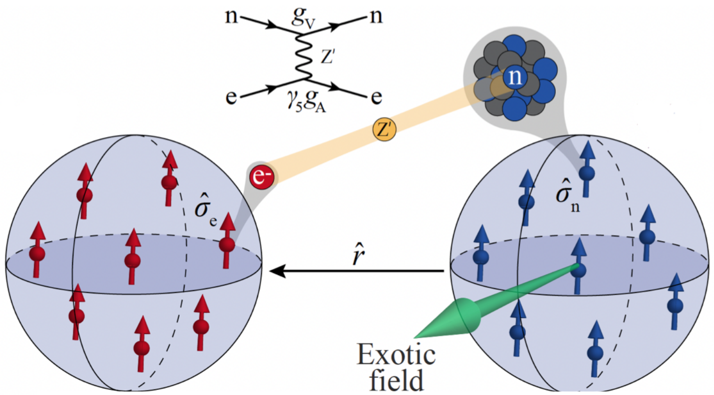
$$\mathcal{V}_{16} = -\frac{1}{2m\,r^2}\left\{\left[\vec{\sigma}\cdot\left(\vec{v}\times\hat{\vec{r}}\right)\right]\left(\vec{\sigma}'\cdot\vec{v}\right) + \left(\vec{\sigma}\cdot\vec{v}\right)\left[\vec{\sigma}'\cdot\left(\vec{v}\times\hat{\vec{r}}\right)\right]\right\}\left(1 - r\frac{d}{dr}\right)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

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

How to see it？

"Spin source" "Spin sensor"

Electron、
Proton、
Neutron、
nucleon



Noble-gas
spin amplifier

xeon-129:
~70% neutron

Energy shift → Exotic (pseudo-magnetic) field

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

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

Coupling to be measured

More sensitive detector → Smaller coupling f

Searched exotic interactions in our study

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

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

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

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

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

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

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

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

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

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

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

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

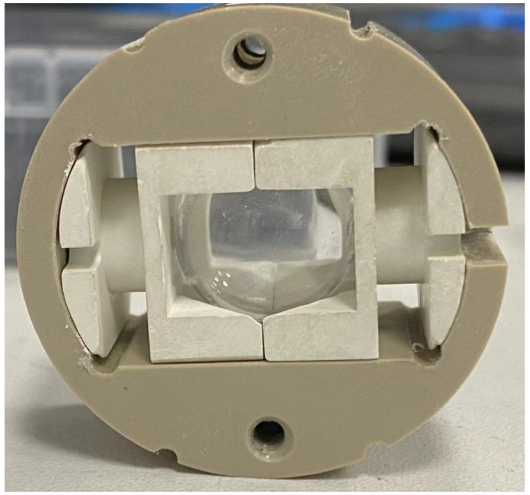
V3 exp.	V11 exp.	V4,5 and V12,13 exp.
polarized electron/proton (rubidium vapor)	polarized electron/proton (rubidium vapor)	Unpolarized nucleon (BGO crystal)

force mediator: axion

force mediator: Z' bosons

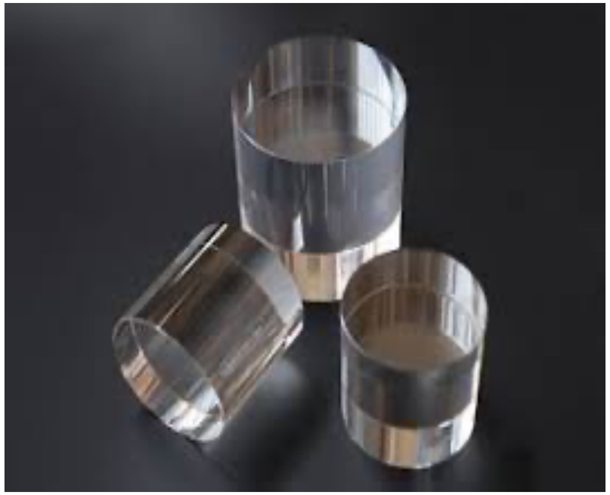
Various spin sources

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



Electron/proton-neutron coupling

II: BGO crystal
high nucleon density
Non-magnetic effect



Nucleon-neutron coupling

Develop spin sources for different exotic interaction searches

Resonant detection with spin amplifiers

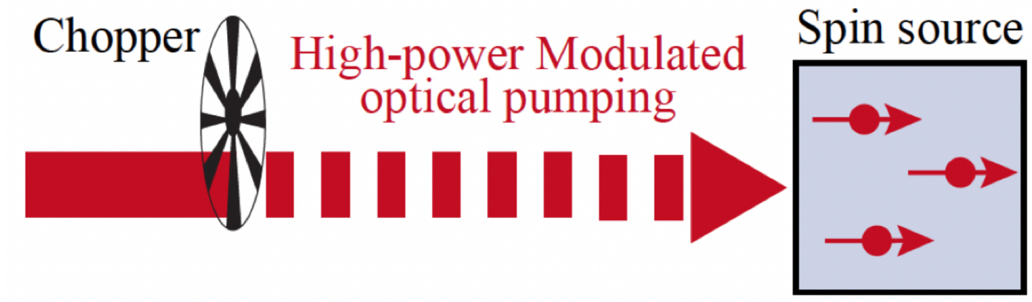
Static exotic field

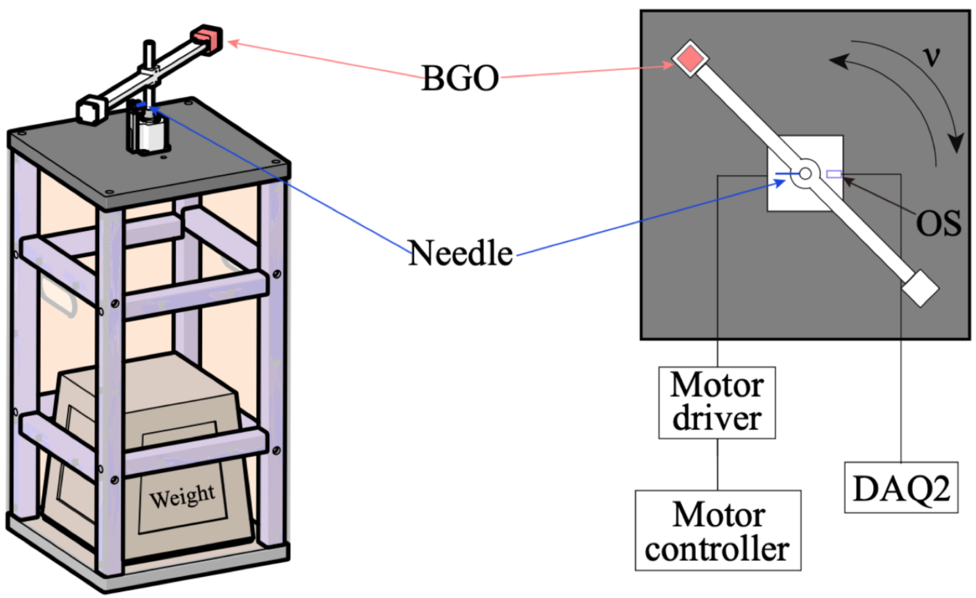
Modulating spin polarization

Modulating the distance between spin source and sensor

Oscillatory field

Resonantly searches

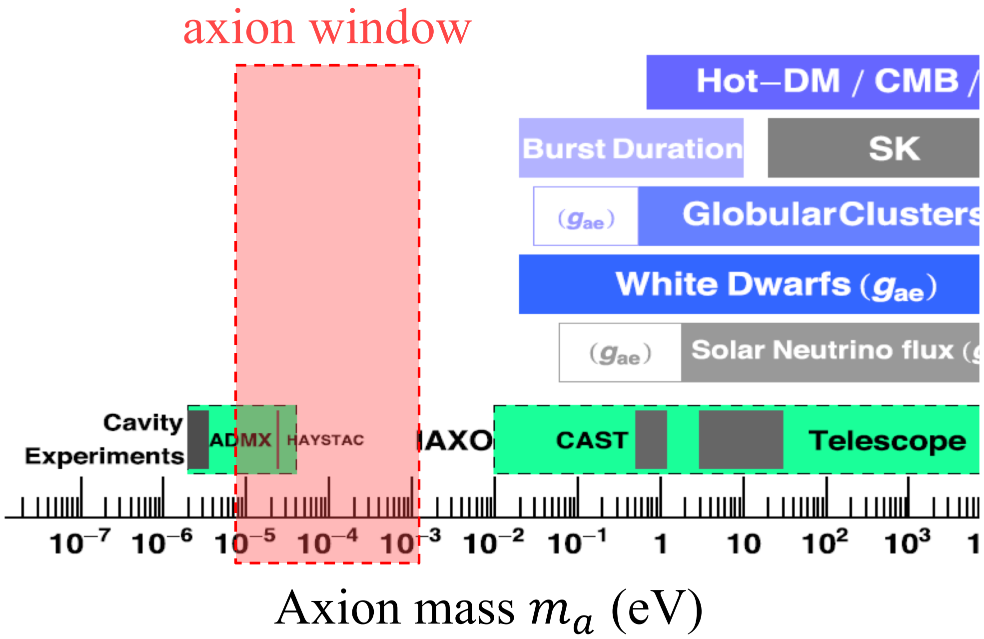




Searches for an axion-mediated interaction

Axion-mediated dipole-dipole interaction

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



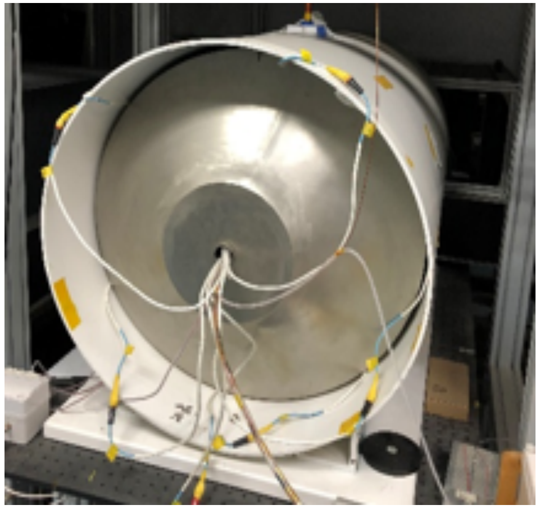
High-temperature QCD
SMASH model
Axion string networks

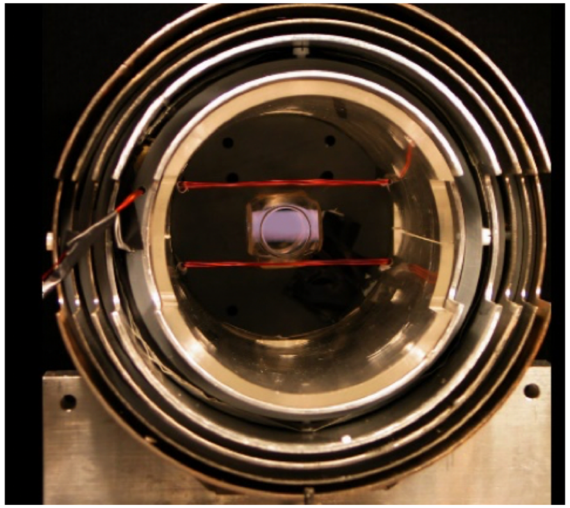
Axion window
$\left(\begin{array}{c}10\ \mu\text{eV} \sim 1\ \text{meV}, \\ \lesssim 2\text{cm force range}\end{array}\right)$

Spurious dipole field: Search remains challenging in the axion window

How to shield the spurious ordinary field?

High-permeability materials: μ-metal





Meter scale — Decimeter scale — Centimeter scale

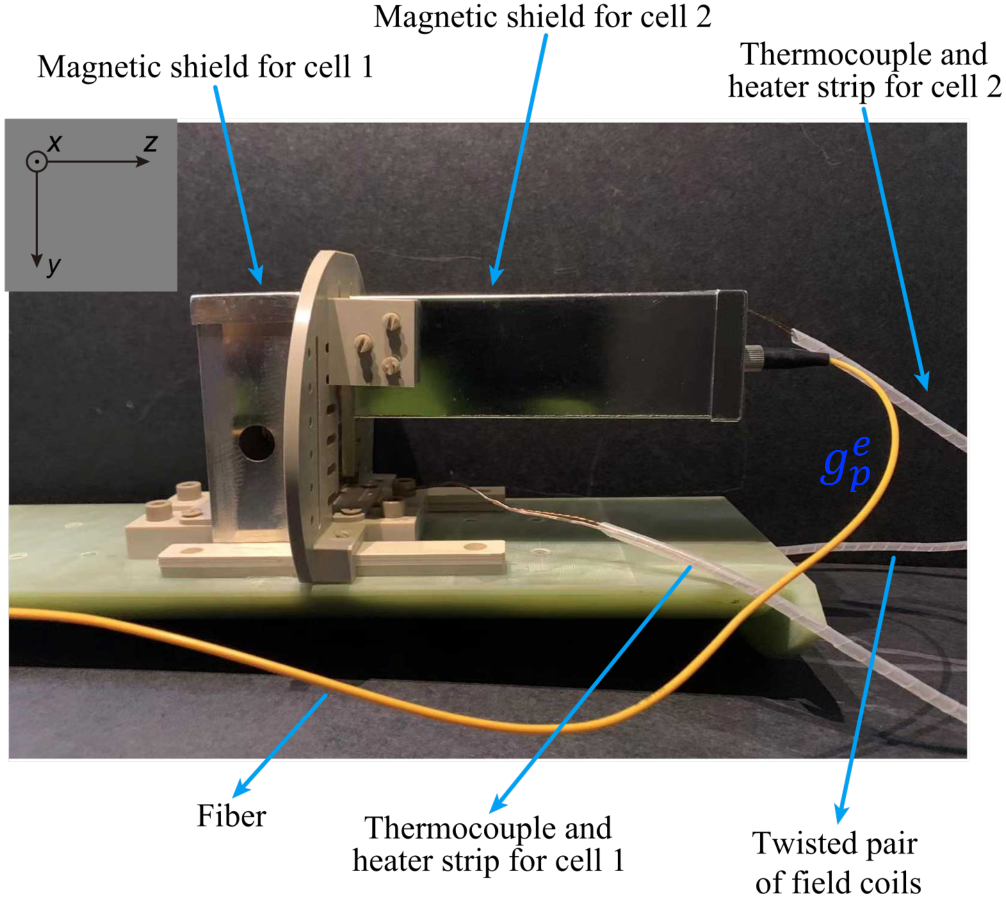
Axion window

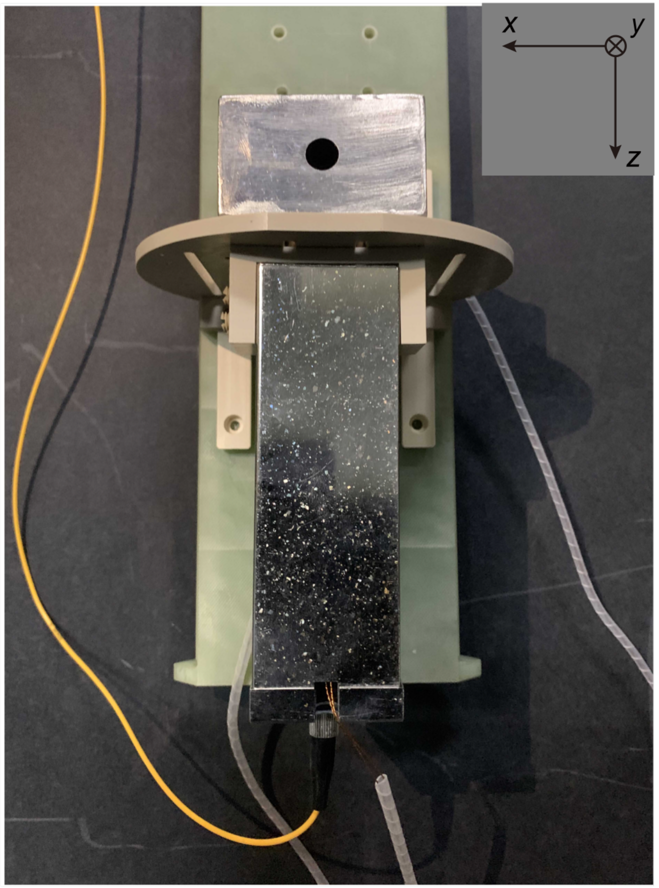
Mass range $\longrightarrow$ Force range

(10 μeV ~ 1 meV) $\longrightarrow$ (0.2 mm ~ 20mm)

Y. Wang, H. Su, **M. Jiang**†, X. Peng† *et al*., PRL 129, 051801 (2022)

How to shield the spurious ordinary field?



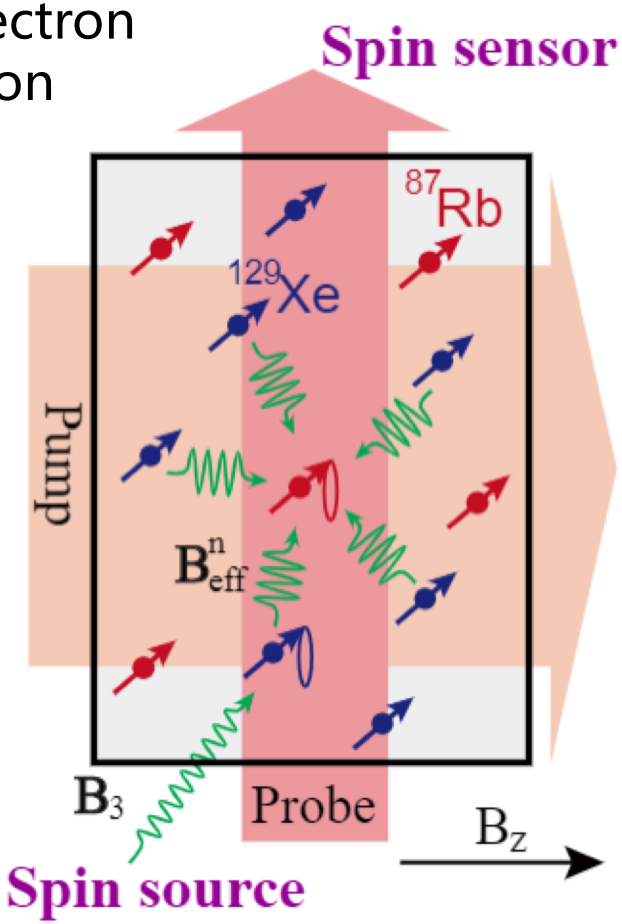


Spurious dipole field is suppressed at least ~10^4

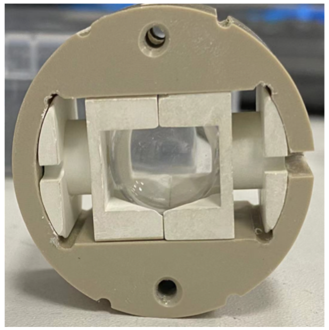
Y. Wang, H. Su, **M. Jiang**†, X. Peng† *et al.*, PRL 129, 051801 (2022)

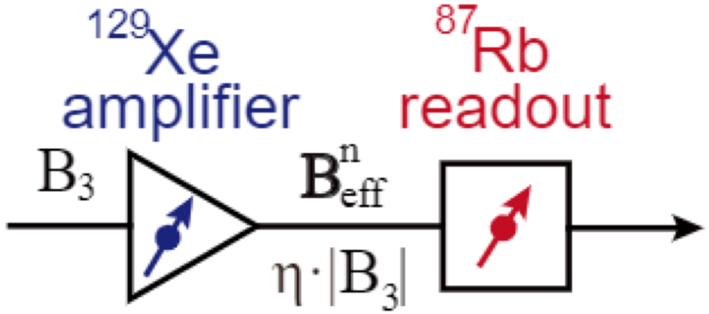
Search for an axion-mediated interaction

Neutron-electron interaction



Polarized electron





Resonantly search for the exotic interaction between electron and neutron

Y. Wang, H. Su, **M. Jiang**†, X. Peng† *et al.*, PRL 129, 051801 (2022)

Search for an axion-mediated interaction

PHYSICAL REVIEW LETTERS

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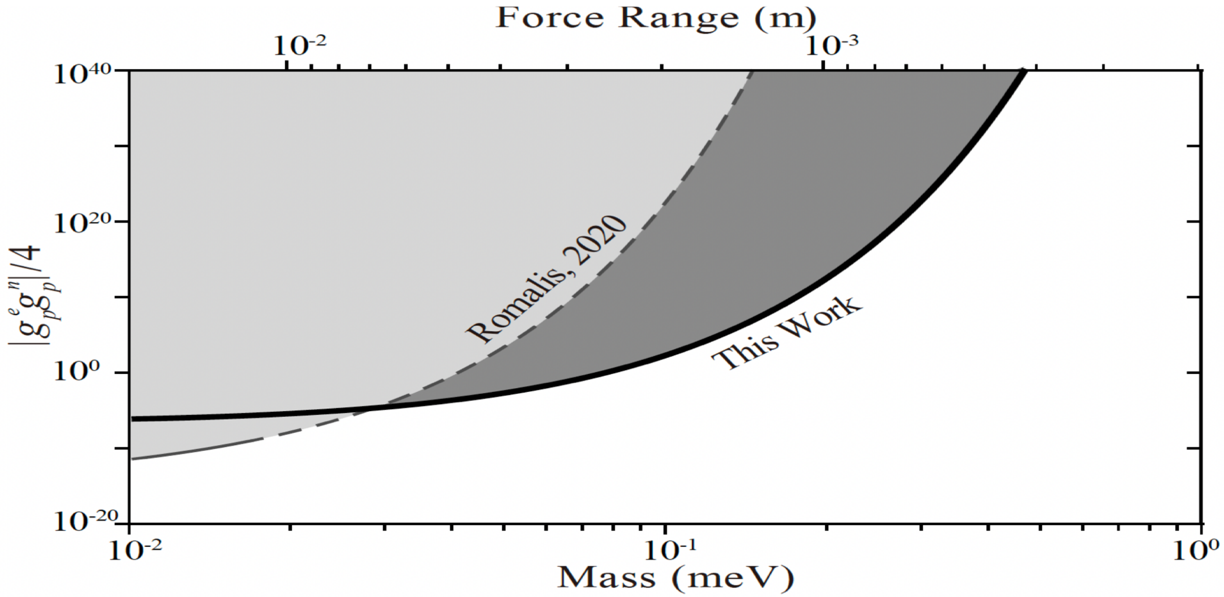
Limits on Axions and Axionlike Particles within the Axion Window Using a Spin-Based Amplifier

Yuanhong Wang, Haowen Su, Min Jiang, Ying Huang, Yushu Qin, Chang Guo, Zehao Wang, Dongdong Hu, Wei Ji, Pavel Fadeev, Xinhua Peng, and Dmitry Budker

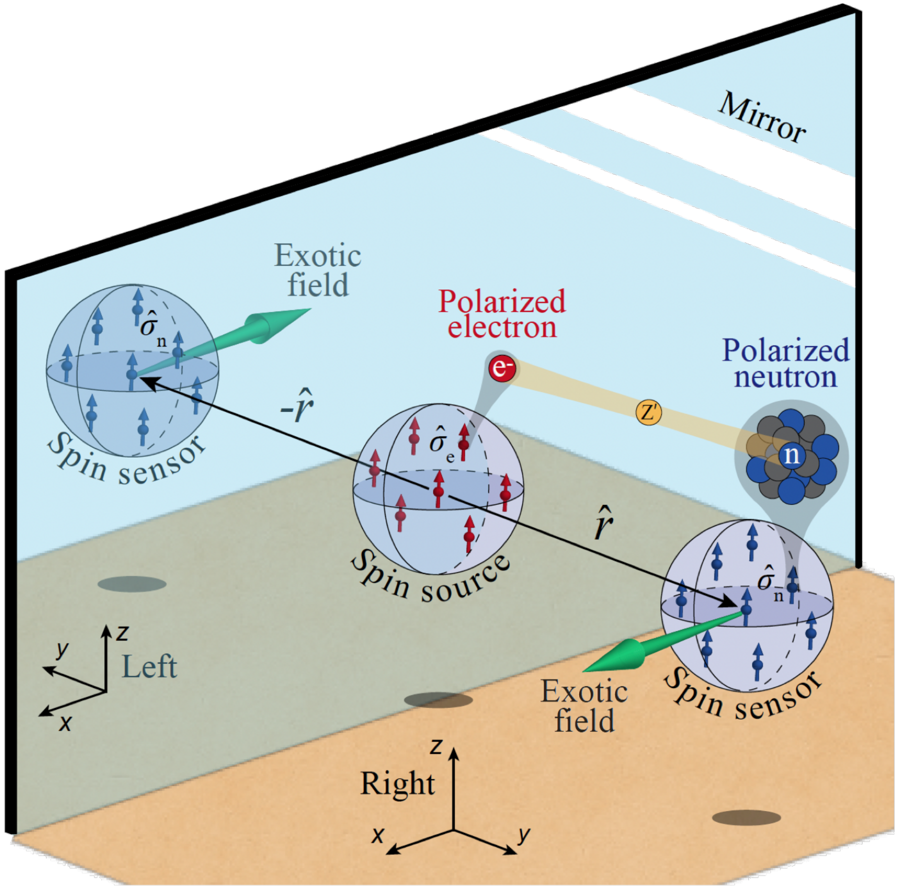
Phys. Rev. Lett. **129**, 051801 – Published 25 July 2022

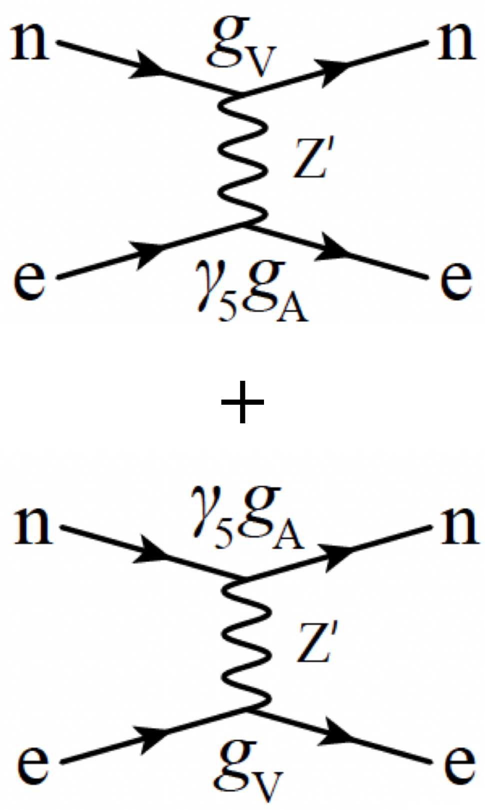


The most stringent constraints on $g_p^e g_p^n$ within the axion window

Y. Wang, H. Su, **M. Jiang**†, X. Peng† *et al.*, PRL 129, 051801 (2022)

Search for exotic parity-violation interactions

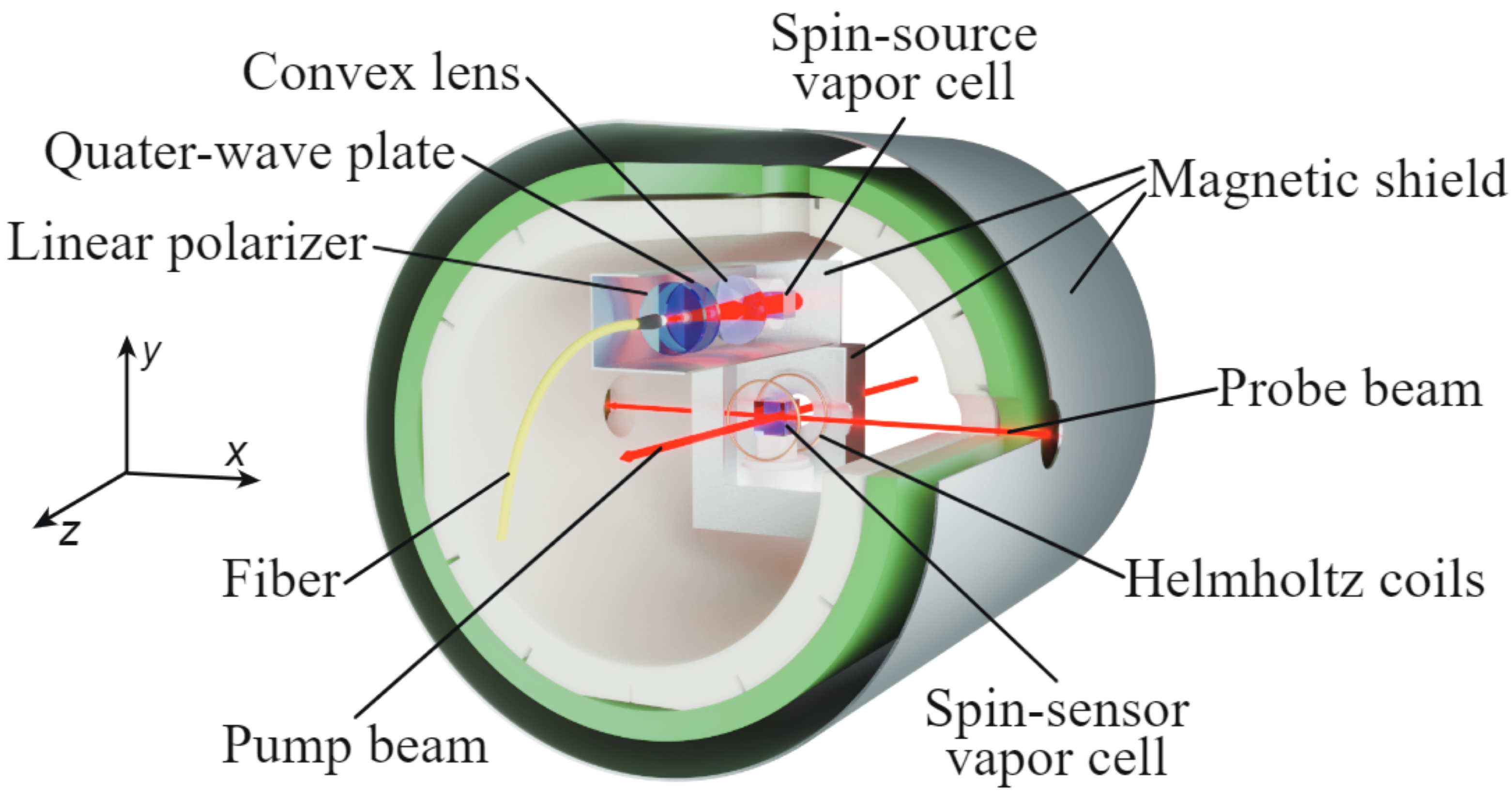




Parity-odd spin-spin interaction mediated by Z′ boson

arXiv:2205.07222 (2022); under review in Science Advances

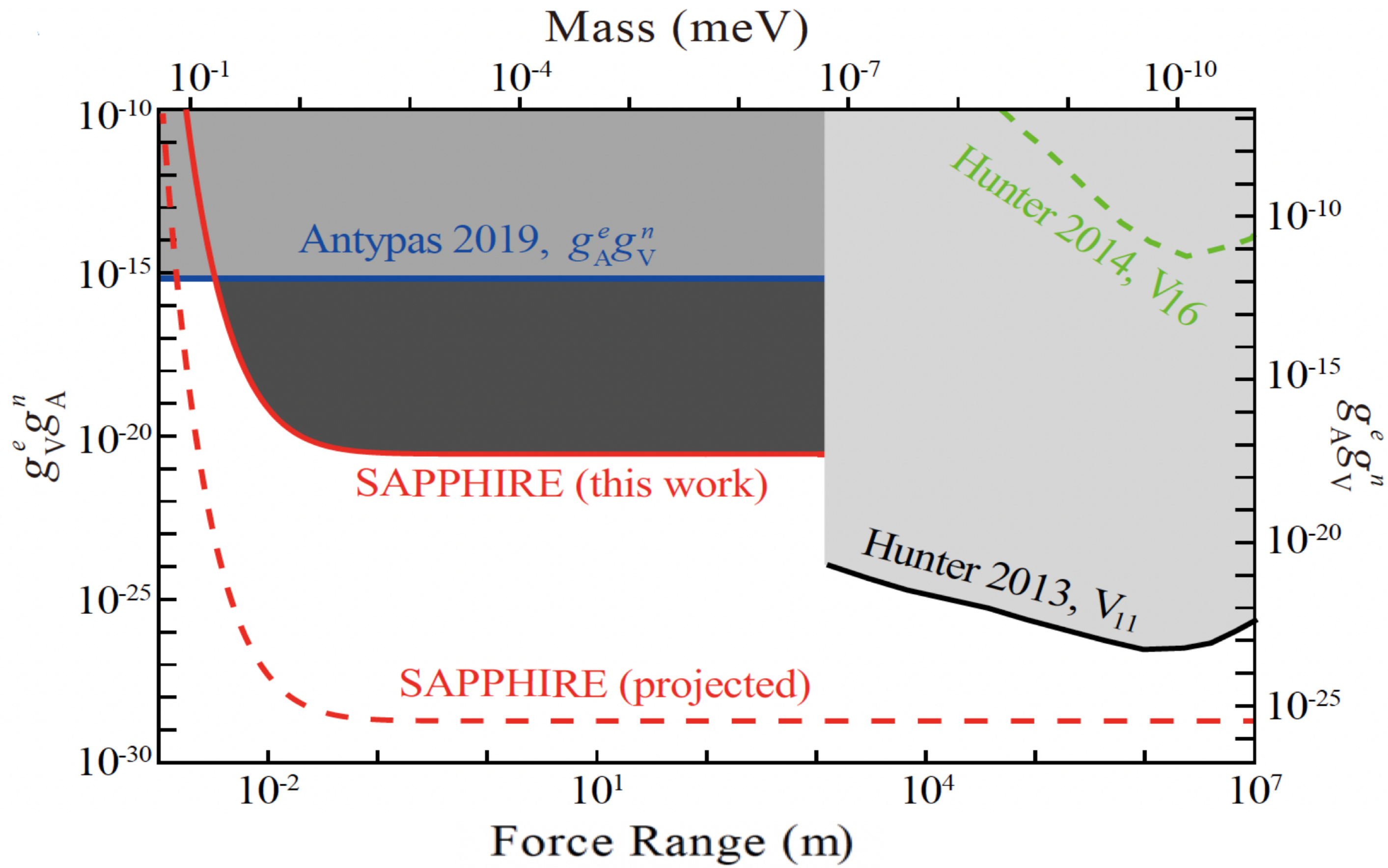
Search for exotic parity-violation interactions



Experimental setup

arXiv:2205.07222 (2022); under review in Science Advances

Constraints on electron-neutron coupling

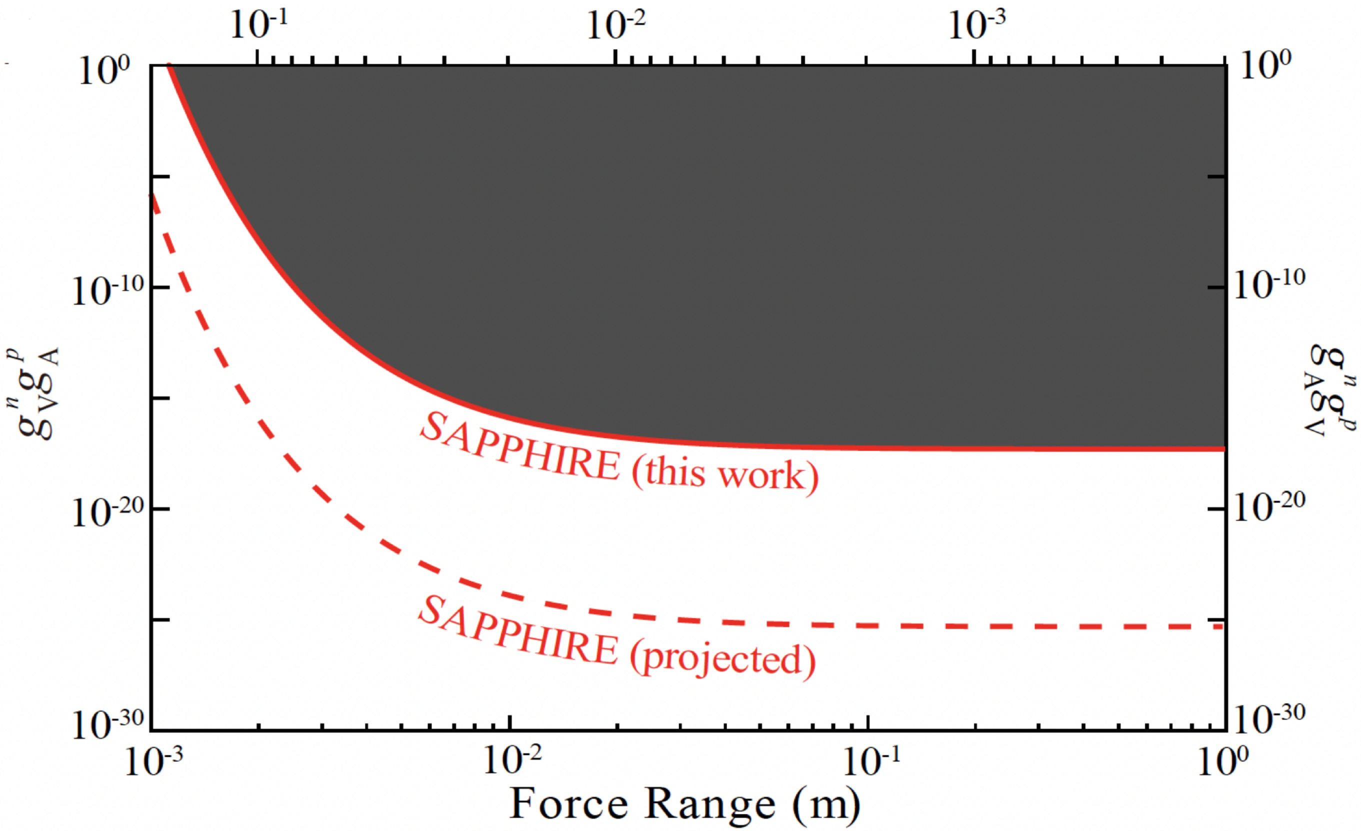


$$f_{11}^{en} = \frac{1}{2} g_V^e g_A^n + \frac{m_e}{2m_n} g_A^e g_V^n ,$$

A five-order-of-magnitude improvement

arXiv:2205.07222 (2022); under review in Science Advances

Constraints on proton-neutron coupling



$$f_{11}^{np} = \frac{m_e}{2m_p} g_A^n g_V^p + \frac{m_e}{2m_n} g_V^n g_A^p .$$

p – valence protons within the Rb nuclei in the source

n – valence neutrons within the Xe nuclei in the sensor

arXiv:2205.07222 (2022); under review in Science Advances

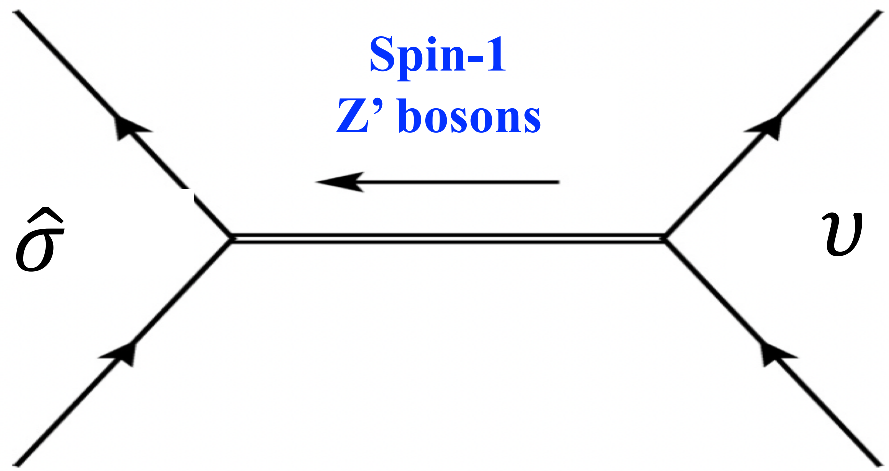
Search for exotic spin-dependent interactions

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

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

Velocity dependence

Spin sensor $\hat{\sigma}$



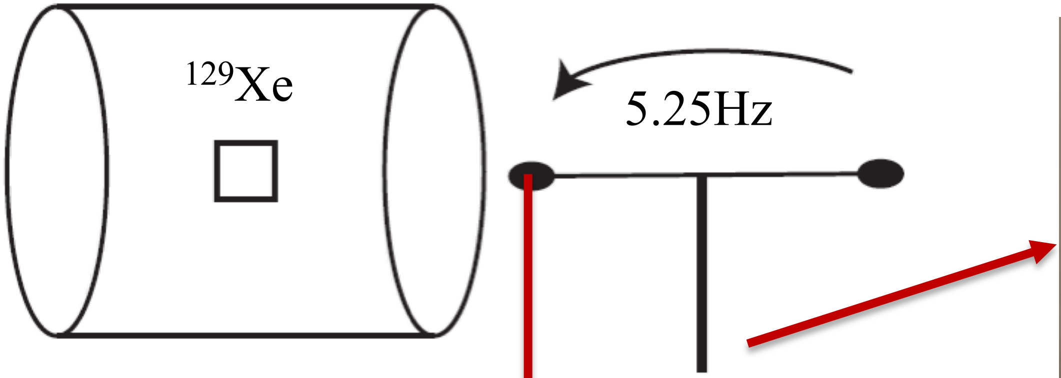
υ Moving Mass

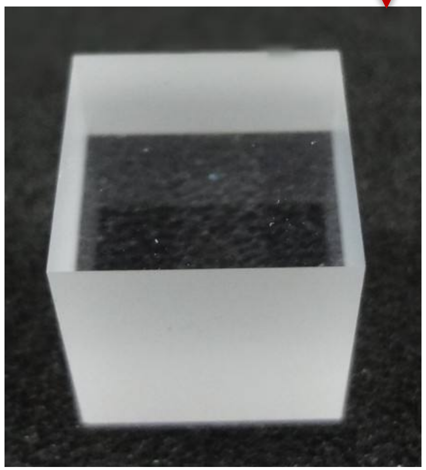
H. Su, Y. Wang, **M. Jiang†**, **X. Peng†** *et al*. Science Advances 7, eabi9535 (2021).

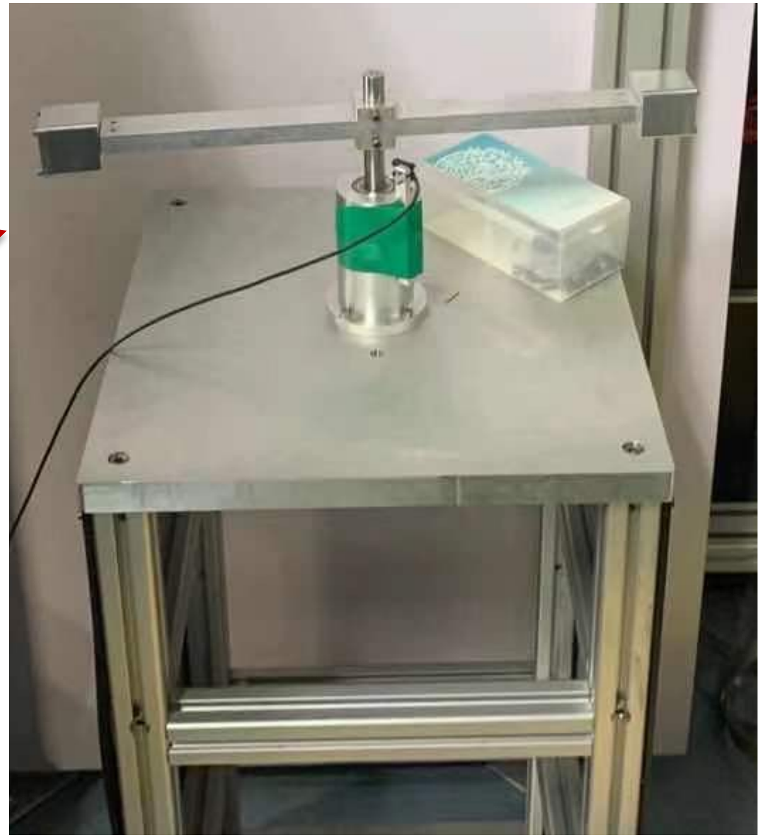
Search setup

Spin-mass coupling

Rotator



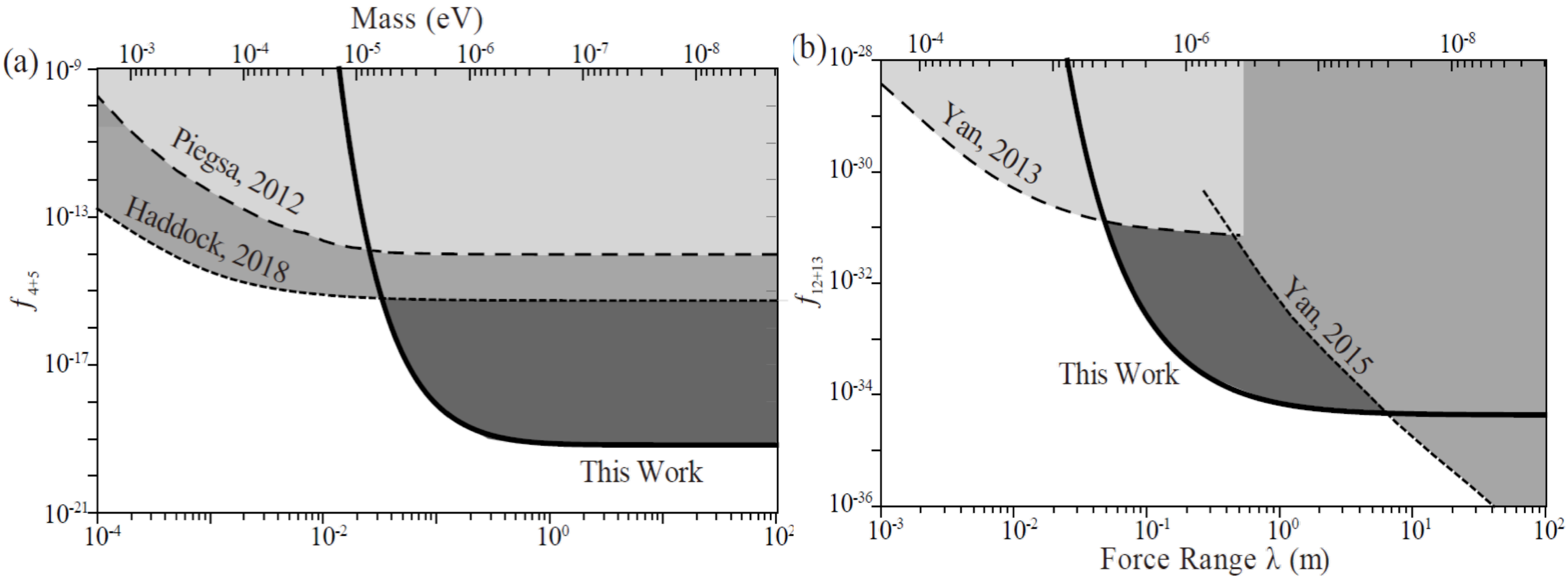




BGO

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

Constraints on spin-dependent interactions



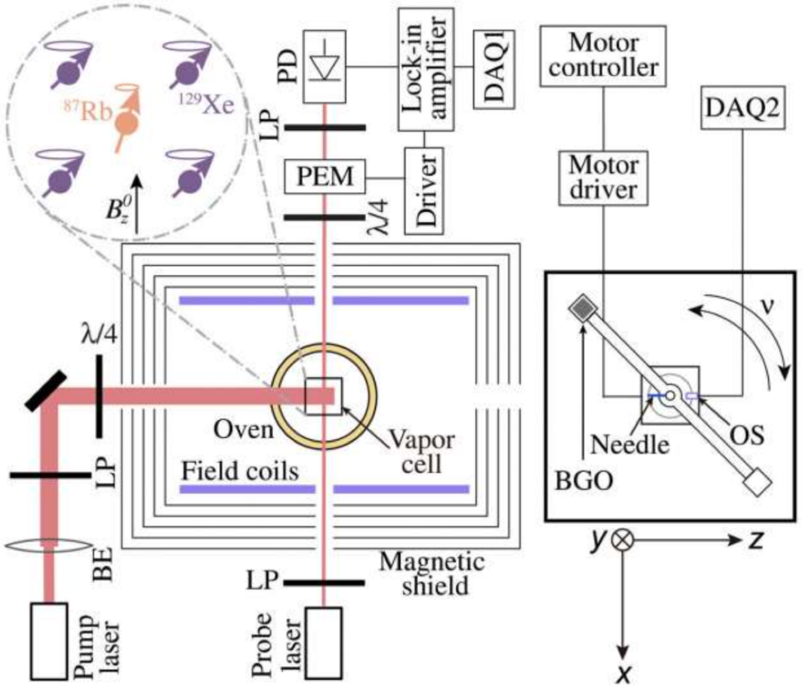
At least 2 orders of magnitude improvement on constraints on Z′ boson

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



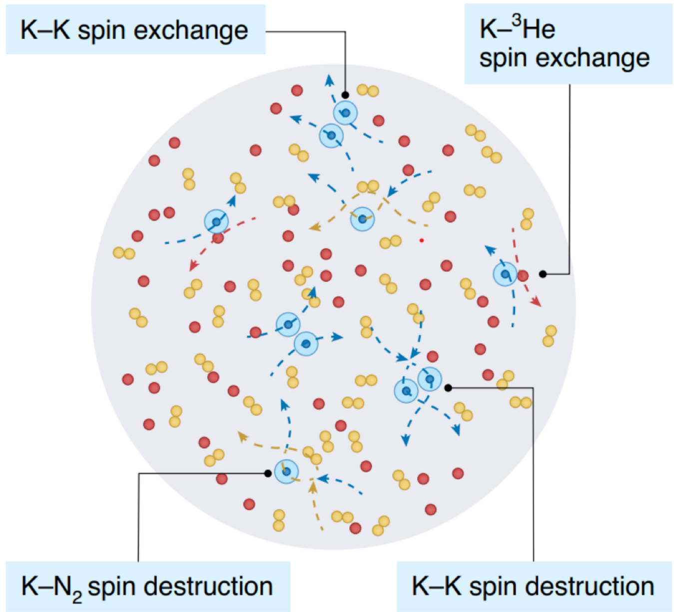
In a study published in *Science Advances*, the research team led by Prof. Peng Xinhua from University of Science and Technology of China of the Chinese Academy of Sciences, collaborating with Prof. Dmitry Budker from Helmholtz Institution, realized ultra-high precision search of exotic spin- and velocity-dependent 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.

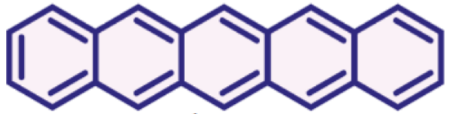
SAPPHIRE projected sensitivity

^{3}He-K spin amplifier

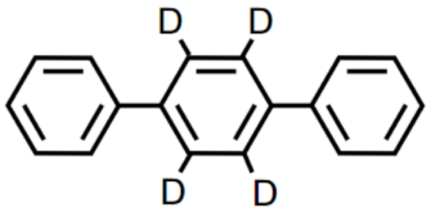


4 orders of magnitude improvement

Solid-state spin source



pentacene



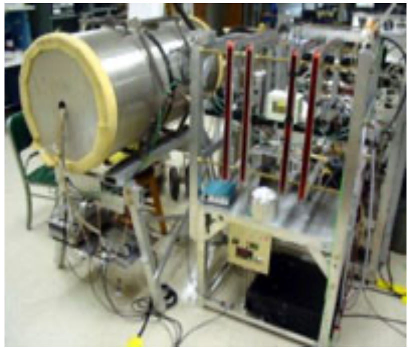
p-terphenyl
-2',3',5',6'-d_4

10^{14} cm^{-3} → 10^{18} cm^{-3}

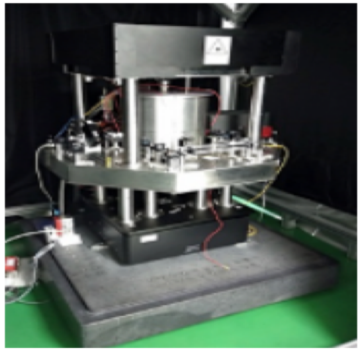
8 orders of magnitude improvements are ongoing !

正在开展: **aT级别**弱磁测量新方法和技术

国际公开报道最高指标

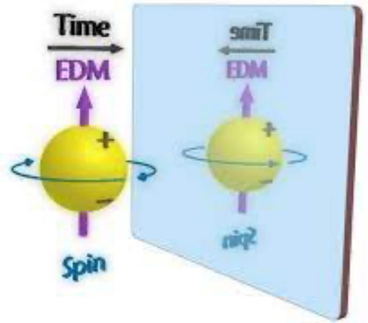


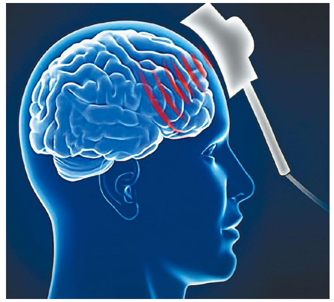
普林斯顿160aT/Hz$^{1/2}$



北航680aT/Hz$^{1/2}$

亟需突破





aT测量技术：开启科学新大门

核心挑战：弱磁探测响应机理，厘清经典/量子噪声机制及抑制技术

新方法

基于原子自旋新效应：
自旋量子放大
自旋协同效应
多体量子相变等

新技术

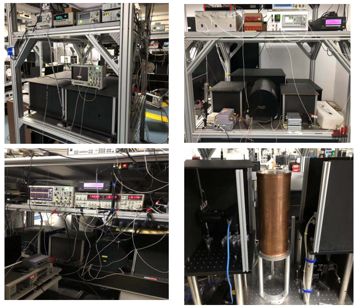
发展超低噪声器件及噪声抑制技术：
高性能原子气室设计和加工
（高气压、长寿命、低漏率）
超导屏蔽技术、超稳激光等

正在开展："蓝宝石"计划及暗物质**测量网络**

✓ 研究趋势：从单个传感器到阵列式；从单一类型到多种类型

提高灵敏度 $\propto 1/\sqrt{N}$　　显著降低报警率$\propto p^N$　　结构信息

"**蓝宝石**"计划发展规划



USTC： 1台
2019-2020年

USTC：4台
2021年

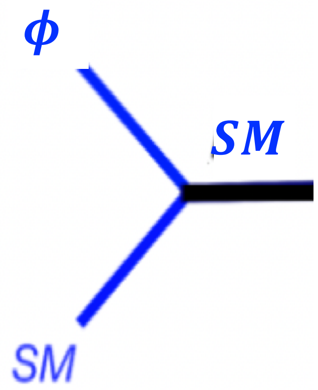
4个城市：5台
2022年

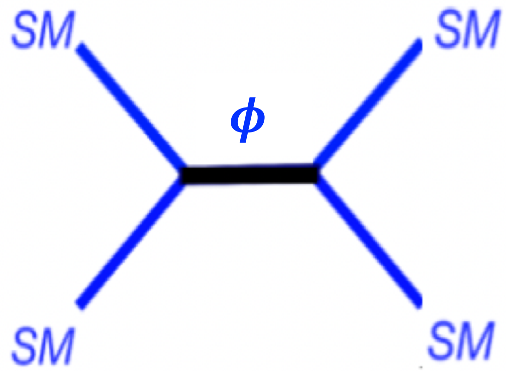
空间站、月球与深空
2022-

建成5台探测器阵列（合肥，杭州，苏州，哈尔滨）
已完成2个月数据采集和分析，即将公布结果！

基金委原创探索项目（2021-2024）

Summary





Search for axions, axion-like particles, dark photon

Develop sensitive spin amplifier for particle physics (SAPPHIRE)

Exotic fifth force between SM particles

Thanks to ……

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Dr. Yue Zhao
Dr. Xiao Xue
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Dmitry Budker

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Yushu Qing
…….

Min Jiang

Thank you for your attention!