

**The 29th International Conference on Atomic Physics (ICAP2026)**

June 14 to June 19, 2026, Wuhan, China

# **Quantum spin dynamics and its cutting-edge applications in quantum technologies**

Fundamental Mechanisms, Experimental Platforms and Frontier Developments

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Univ. of Sci. & Tech. of China (USTC)  
Laboratory of Spin Magnetic Resonance

**June 18 (11:35 – 12:00), 2026**

# Outline

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**1**

**Background: Spin & NMR & QIP**

**2**

**Experimental platforms**

**3**

**Cutting-edge applications in quantum technologies**

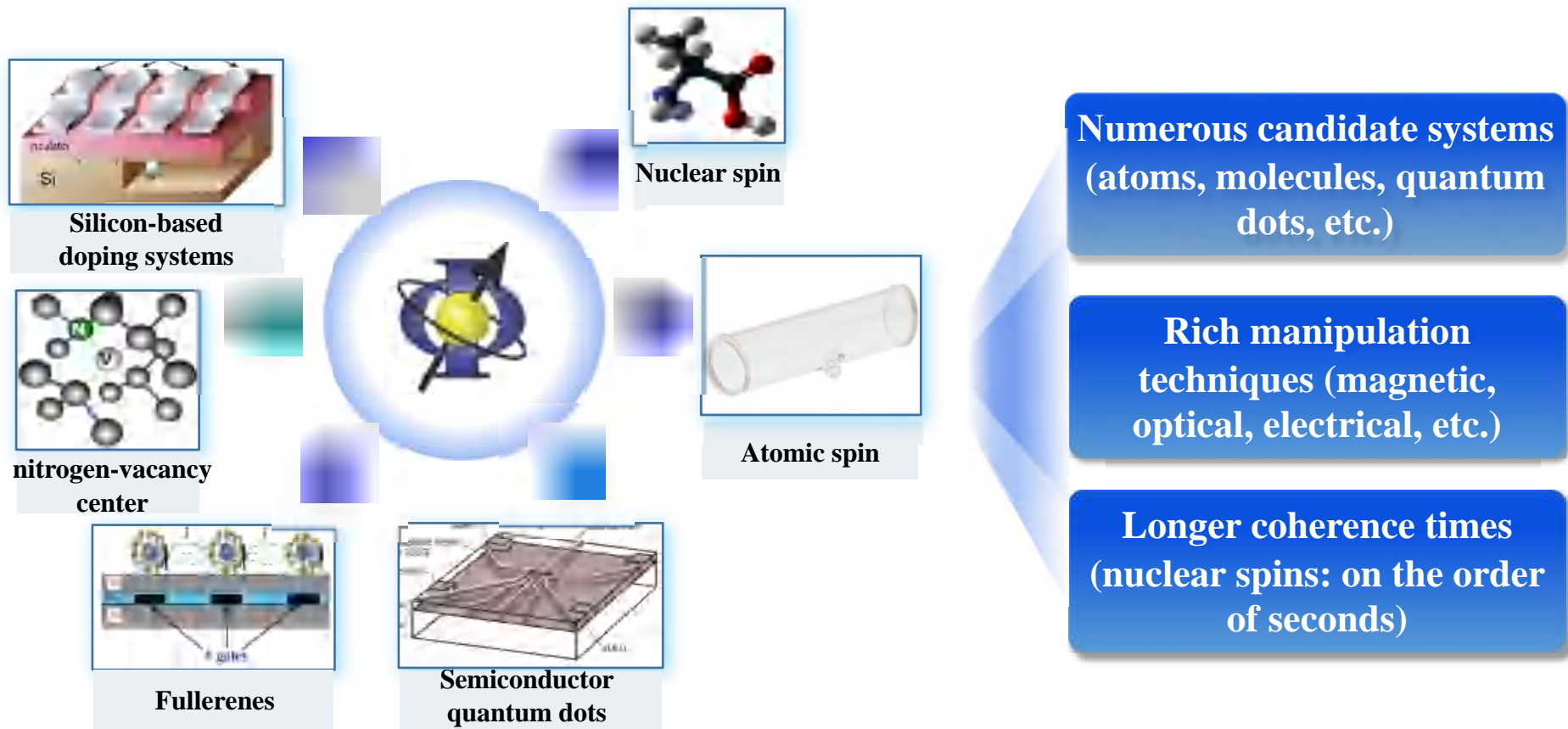
**4**

**Summary & Outlook**

# Spin

## An important physical carrier of quantum information

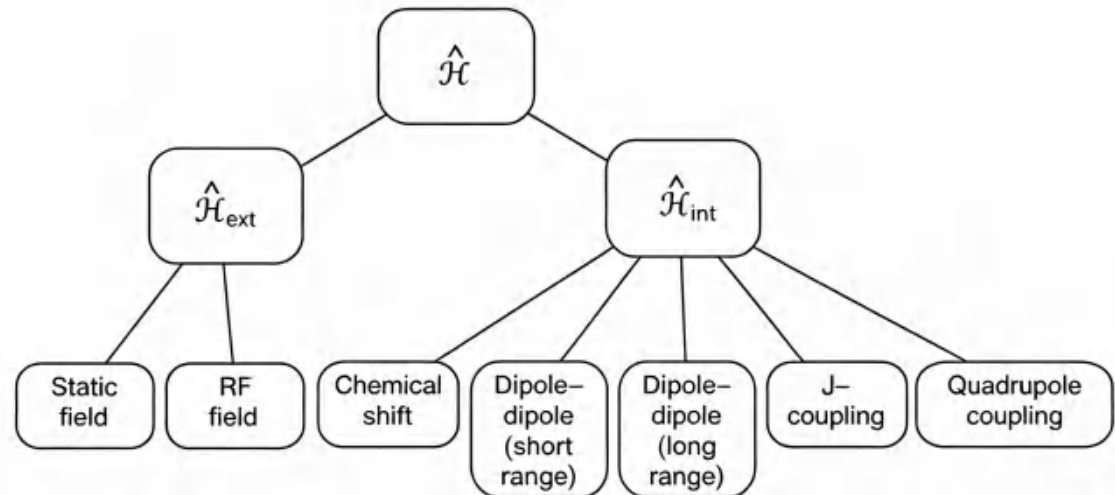
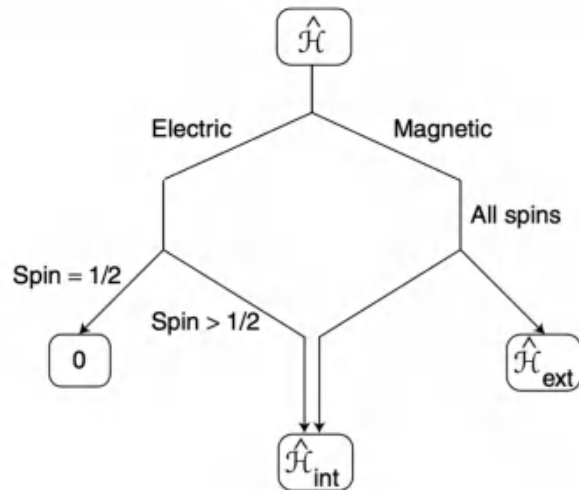
Spin is one of the most robust, easily manipulated quantum degrees of freedom.



# Rich quantum nuclear spin dynamics

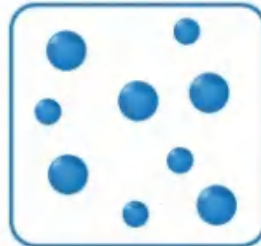


- The time evolution
- Coherent manipulation
- Incoherent relaxation & decoherence
- Internal spin interactions (electrons, nuclei, atoms, defects etc)
- External fields (magnetic, optical, electronic)



# Nuclear spins in gases, liquids and solids

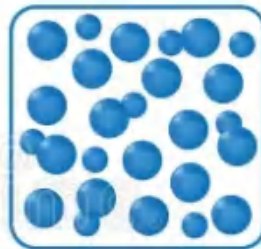
Gas



Simple spin dynamics  
Little intramolecular and intermolecular spin interactions  
 $T_1 \approx T_2$

**Bloch Equation**

Liquid



Relative simple spin dynamics  
Intramolecular spin interactions  
 $T_1$  and  $T_2$  are still comparable

**Spin-spin interactions**

Solid



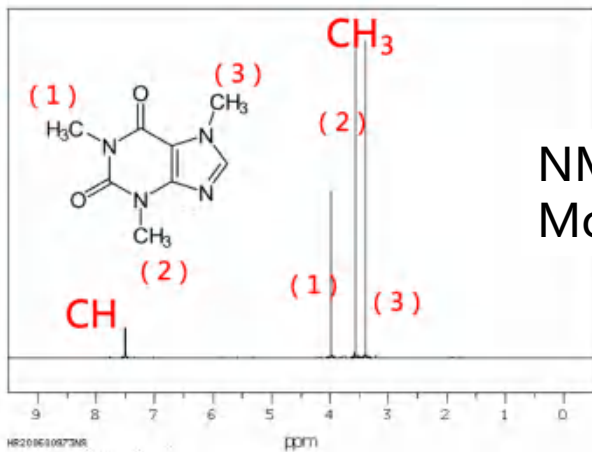
Complex spin dynamics  
Strong intramolecular and intermolecular spin interactions  
 $T_1 \gg T_2$

**Quantum Liouville Equation**  
**Lindblad Master Equation**

# Nuclear Magnetic Resonance ( NMR )

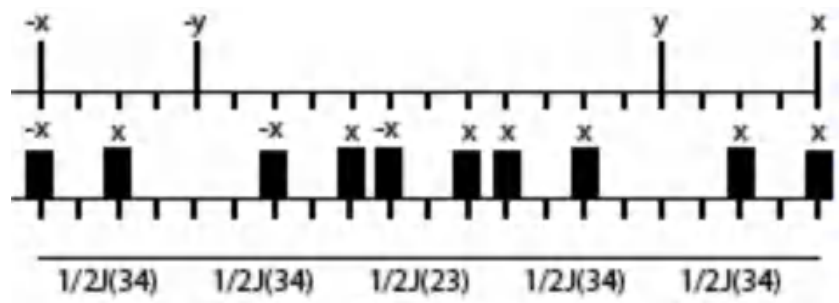
## Direct probes of nuclear spins

Nuclear spins are the engines of NMR.



NMR Spectroscopy :  
Molecule Fingerprint

Pulse sequence: Controlling quantum spin dynamics



# Mainstream Experimental Platforms (in our group)

## Gas ODMR



Ensemble weak-coupled spins  
**Spin-photon** interface  
**High** nuclear spin polarization

Spin dynamics  
Quantum sensing

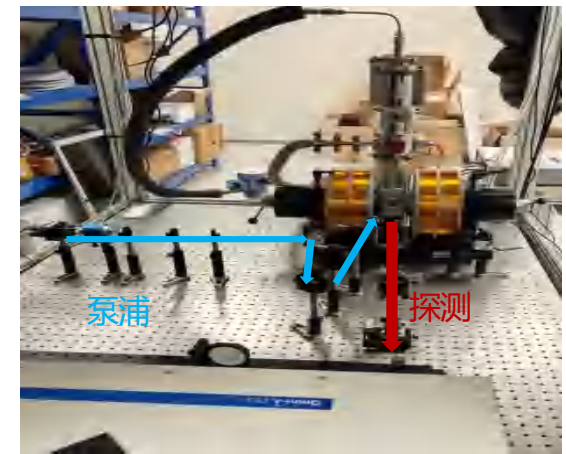
## Liquid & solid NMR



Ensemble **coupled** spins  
Low nuclear spin polarization  
Mature pulse control

Multi-Spin dynamics  
Quantum control/simulation

## Semiconductor ODMR



Low-temperature  
Ensemble/single **coupled** spins  
**Long** nuclear spin lifetime  
**Spin-photon** interface  
**High** nuclear spin polarization

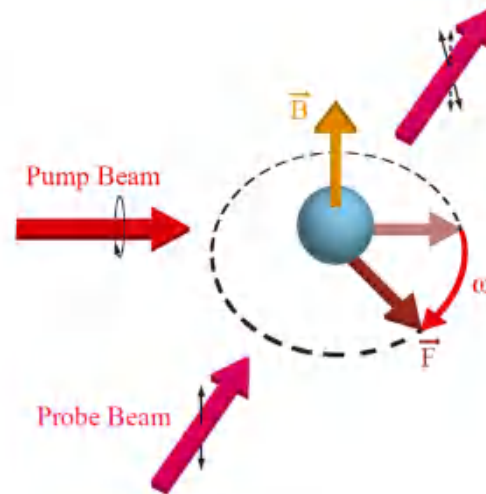
Multi-Spin dynamics  
Quantum simulation/metrology

# Application 1 – Quantum Sensing

## Ultra-Sensitive Magnetic Sensing & Imaging

### Atomic optical magnetometers

Alkali-metal (Rb, K)



SERF magnetometers: The most sensitive magnetic field measurement devices ( $0.16 \text{ fT/Hz}^{1/2}$ )

### Bloch equation (Rb,K)

$$\frac{d\mathbf{P}}{dt} = \frac{1}{q} [\gamma_e \mathbf{B} \times \mathbf{P} + R_{\text{OP}}(\hat{z} - \mathbf{P}) - R_{\text{rel}}\mathbf{P}]$$

$$\beta = \gamma_e \mathbf{B} / (R_{\text{OP}} + R_{\text{rel}}), \quad P_0 = R_{\text{OP}} / (R_{\text{OP}} + R_{\text{rel}})$$

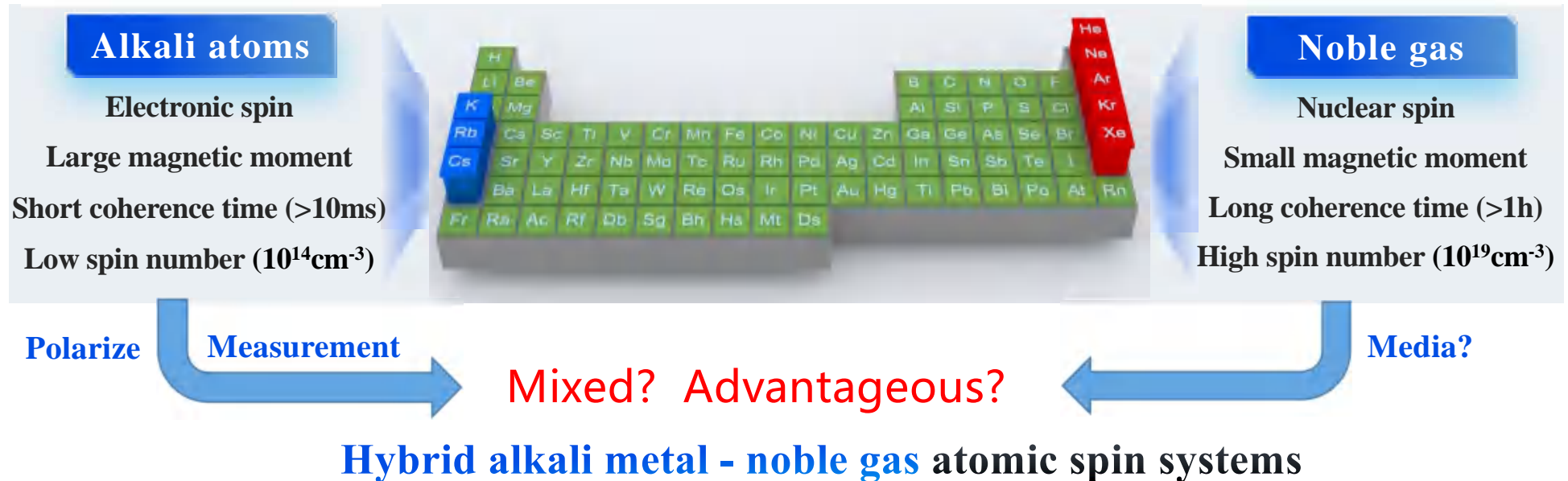
For weak magnetic fields

Steady solution:

$$|\beta| \ll 1 \quad \gamma_e B_x, \gamma_e B_y \ll R_{\text{OP}} + R_{\text{rel}}$$

$$P_x \approx P_0 \frac{(R_{\text{OP}} + R_{\text{rel}}) \gamma_e B_y}{(\gamma_e B_z)^2 + (R_{\text{OP}} + R_{\text{rel}})^2}$$

# Hybrid 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.

# Spin dynamics in hybrid Alkali-metal & Noble-gas ensemble

The coupled Bloch equations

Electronic spins  
( $^{87}\text{Rb}$ )

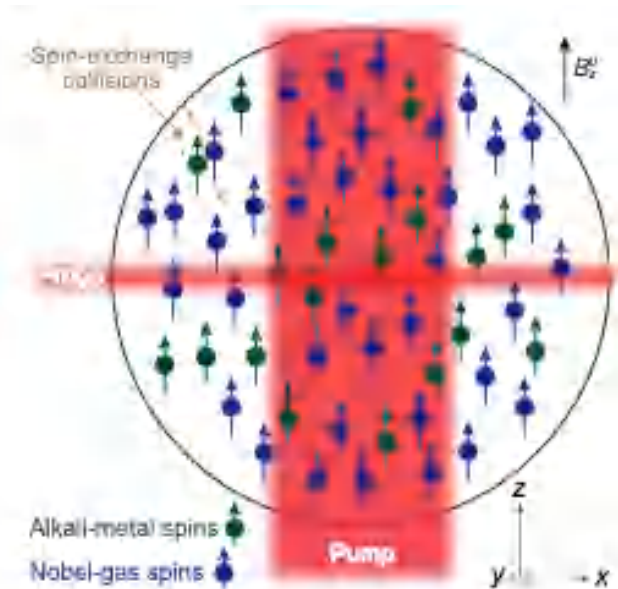
$$\frac{\partial \mathbf{P}^e}{\partial t} = \frac{\gamma_e}{Q} (\underbrace{B_z^0 \hat{z}}_{\text{Bias field}} + \underbrace{\beta M_0^n \mathbf{P}^n}_{\text{Effective fields}}) \times \mathbf{P}^e + \frac{P_0^e \hat{z} - \mathbf{P}^e}{T_e Q},$$

Bias field    Effective fields

Nuclear spins  
( $^{129}\text{Xe}$ )

$$\frac{\partial \mathbf{P}^n}{\partial t} = \gamma_n (\underbrace{B_z^0 \hat{z}}_{\text{Bias field}} + \underbrace{B_{ac} \hat{y}}_{\text{to be measured}} + \underbrace{\beta M_0^e \mathbf{P}^e}_{\text{Effective fields}}) \times \mathbf{P}^n + \frac{P_0^n \hat{z} - \mathbf{P}^n}{\{T_{2n}, T_{2n}, T_{1n}\}},$$

to be measured



Steady solution:

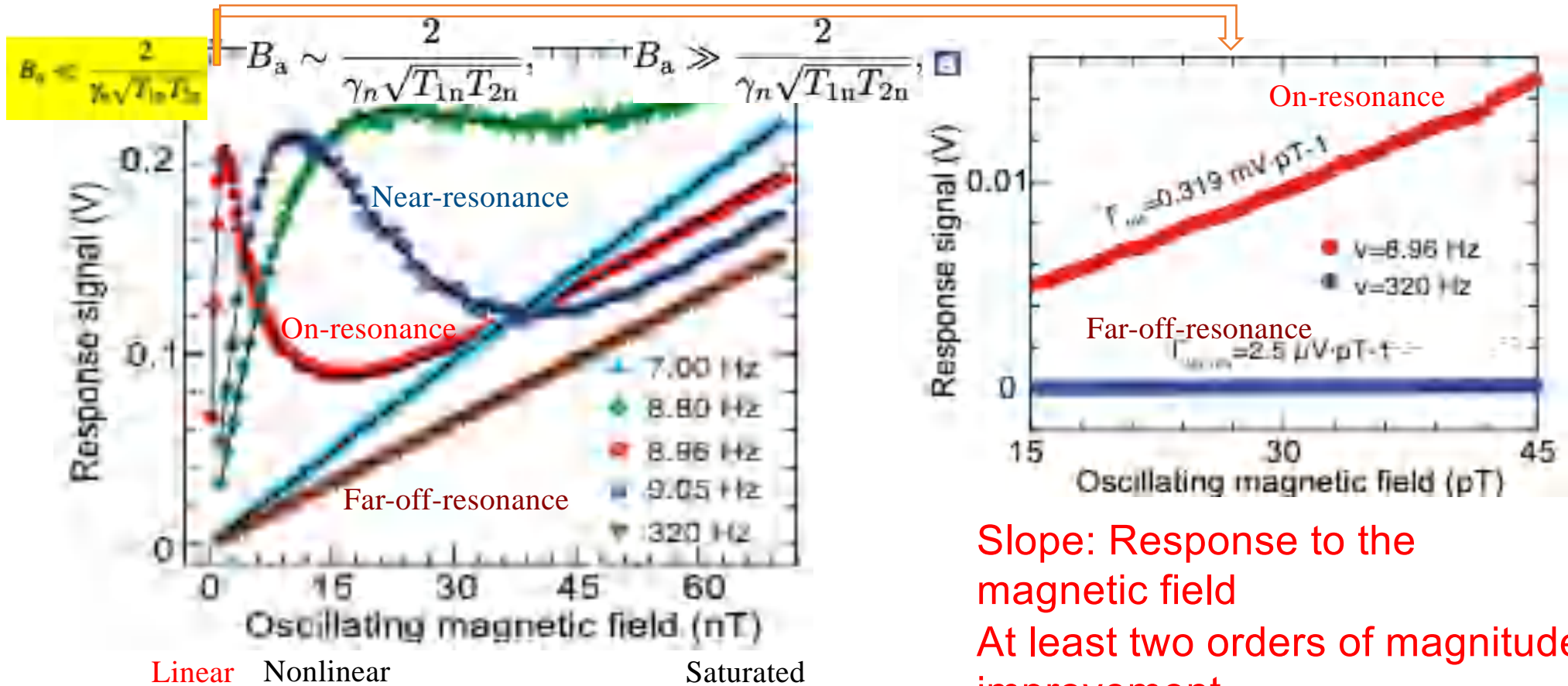
$$\mathbf{B}_{\text{eff}} = \frac{1}{2} \lambda M^n P_0^n \gamma_n T_{2n} B_{ac} \frac{\cos(2\pi \nu t) + 2\pi(\nu - \nu_0) T_{2n} \sin(2\pi \nu t)}{1 + (\gamma_n B_{ac}^y / 2)^2 T_{1n} T_{2n} + [2\pi(\nu - \nu_0)]^2 T_{2n}^2} \mathbf{x}$$

Field amplification

Power saturation

Resonance response

# Spin dynamics in hybrid Alkali-metal & Noble-gas ensemble

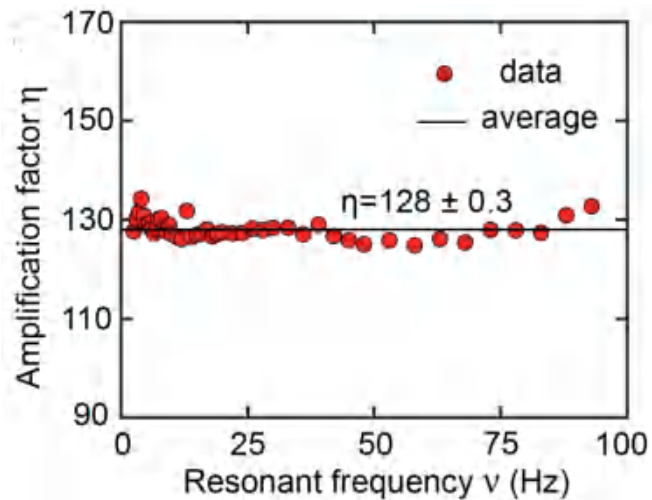
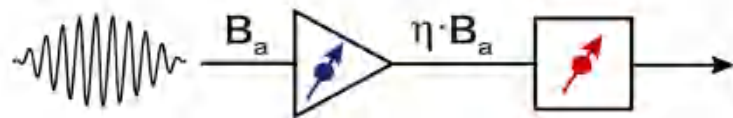


Slope: Response to the magnetic field  
 At least two orders of magnitude improvement

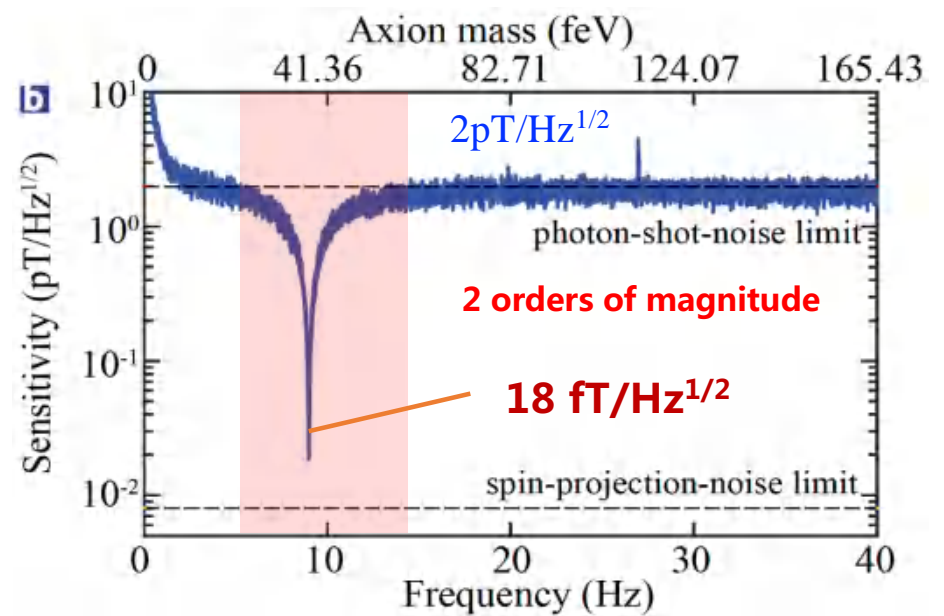
# Quantum sensing with spin-based amplifier: First demonstration

## Quantum amplification of a magnetic field

Magnetic field Xe amplifier Rb detector



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



Femtotesla-level sensitivity!  
18fT/Hz<sup>1/2</sup>

M. Jiang et al., *Nature Physics* **17**, 1402 (2021)

# 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<sup>1,2,3,7</sup>, Haowen Su<sup>1,2,3,7</sup>, Antoine Garcon<sup>4,5</sup>, Xinhua Peng<sup>1,2,3</sup>   and Dmitry Budker<sup>4,5,6</sup> 

Hybrid spins:

Alkali metal  
(K, Rb, Cs)

Noble gas  
(<sup>3</sup>He, <sup>129</sup>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:**  $\sim 128$  ( Latest : **5400** ), **Sensitivity:**  $18 \text{ fT/Hz}^{1/2}$  ( Latest : **0.8 fT/Hz}^{1/2}** )

# Improvement: Noble-gas magnetic amplification

Amp. Fact

128



First realization  
2021

500



Floquet Amp.  
2022

1000



Cooperative spins  
2022

5400



Dark spins  
2024



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

Min Jiang<sup>1,2,3,7</sup>, Haowen Su<sup>1,2,3,7</sup>, Antoine Garcon<sup>4,5</sup>, Xinhua Peng<sup>1,2,3,8</sup> and Dmitry Budker<sup>4,5,6</sup>

## PHYSICAL REVIEW LETTERS

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Editor's Suggestion

Access by University of Science

### Floquet Spin Amplification

Min Jiang, Yushu Qin, Xin Wang, Yuanhong Wang, Haowen Su, Xinhua Peng, and Dmitry Budker  
Phys. Rev. Lett. **128**, 233201 – Published 9 June 2022

## Science Advances

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### Floquet maser

Min Jiang<sup>1,2,3</sup>, Haowen Su<sup>1,2,3</sup>, Ze Wu<sup>1,2,3</sup>, Xinhua Peng<sup>1,2,3,\*</sup> and Dmitry Budker<sup>4,5,6</sup>

## PNAS

RESEARCH ARTICLE | PHYSICS

### Observation of magnetic amplification using dark spins

Min Jiang<sup>1,2,3</sup>, Ying Huang<sup>4,5,6,7</sup>, Chang Guo<sup>8,9</sup>, Haowen Su<sup>1,2,3</sup>, Yuanhong Wang<sup>10</sup>, Xinhua Peng<sup>1,2,3,\*</sup>, and Dmitry Budker<sup>11,12</sup>

Edited by Joshua Combes, University of Colorado, Boulder, CO, received September 9, 2023; accepted February 10, 2024, by Editorial Board Member Bernard F. Schury

# Improvement: sub-fT magnetic detection sensitivity

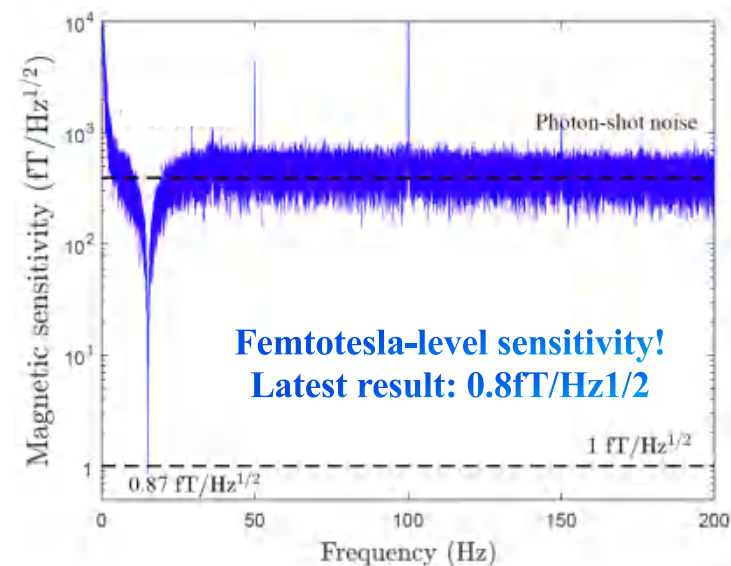
## System improvement

**$^{87}\text{Rb}$ - $^{129}\text{Xe}$**

- Large spin-destruction cross section
- Short noble gas coherence time (~10 s)
- Small noble gas gyromagnetic ratio (0.0118 T/Hz)

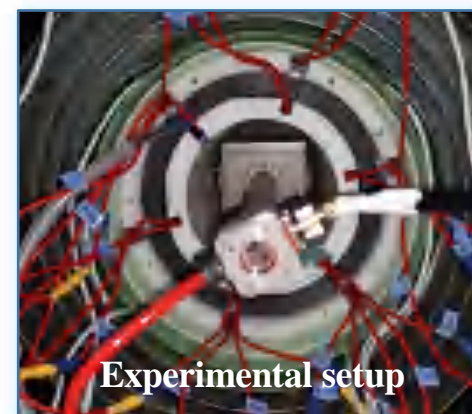
**$^{39}\text{K}$ - $^3\text{He}$**

- smaller spin-destruction cross section (five orders)
- Longer noble gas coherence time (~1000 s)
- Larger noble gas gyromagnetic ratio (0.0324 T/Hz)



## Key experimental technologies

- High-quality hybrid atomic vapor cell with long coherence time
- Active and passive ultra-low magnetic noise shielding system
- Ultra-low noise high-power vacuum heating system



Guo et al., Phys. Rev. A **113**, 032411 (2026)

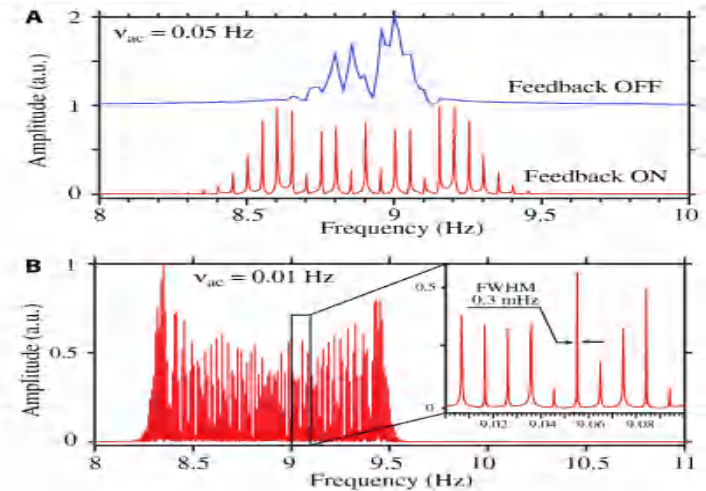
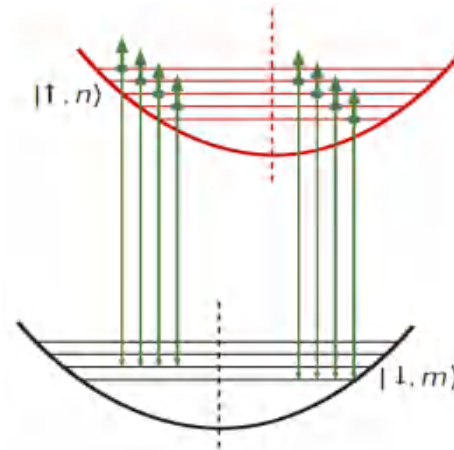
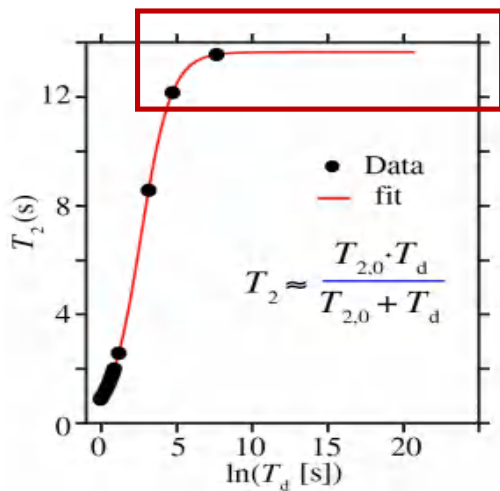
# Nonlinear spin gas: Floquet maser

SCIENCE ADVANCES | RESEARCH ARTICLE

PHYSICS

## Floquet maser

Min Jiang<sup>1,2,3</sup>, Haowen Su<sup>1,2,3</sup>, Ze Wu<sup>1,2,3</sup>, Xinhua Peng<sup>1,2,3\*</sup>, Dmitry Budker<sup>4,5,6</sup>



Masing regime  
(**Feedback**)



Floquet spins  
(**Periodic driving**)

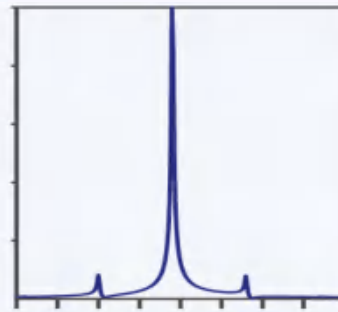
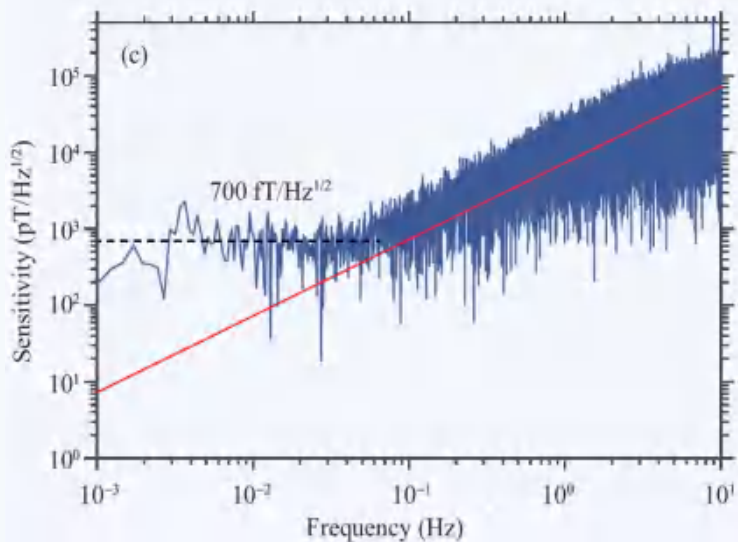


Freq. comb ~130 lines  
(sub-mHz linewidth)

# Floquet spin maser

## Spin magnetometers based on the Floquet system

Sci. Adv. 7, eabe0719 (2021)



Floquet sidebands

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

$$\delta B \propto \nu_{ac}$$

The **best** magnetic sensitivity in the **ultra-low frequency range** !

Commentary on Science Perspective

... the generation of new genes has been on some duplication followed by the diversification of these duplicates into distinct genes (7). However, many gene duplications remain structurally similar to their parents. Coste *et al.* demonstrate that transposon domains capture in a systematic mechanism by which entirely new capabilities can be introduced in genes that were absent in the host parent, such as DNA-binding capacity. This is not specific to host-transposon interaction. Gene fusion and exon shuffling among host genes can similarly create new combinations of already-existing capabilities. In contrast to this class of new gene formation mechanisms, in which the innovation consists of rearranging functional domains in new contexts, the phenomenon of de novo gene birth from a noncoding sequence generates completely new domains and genes. Although once thought rare, well-characterized cases of de novo genes have now been reported in numerous taxa (8). New genes and domains can also arise through extreme

PHYSICS

### A masing ladder

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

By Ren-Bao Liu<sup>1,2</sup>

**M**asers, the strongest and highest-frequency (HF) counterparts of lasers, have many applications in metrology, communications, and spectroscopy. Jiang *et al.* (1) demonstrate a new type of maser in which its radiation is amplified by stimulated emission from transitions between periodically modulated quantum states, called Floquet states (2), unlike a conventional maser which uses transitions between states

Professor Liu Renbao (recipient of the Lamb Prize) commented, "A novel microwave oscillator... It is expected to play a crucial role in the search for ultra-light dark matter particles..."

# Next opportunity: Strong coupling regime

## Amplification mechanism with interacting atomic gases

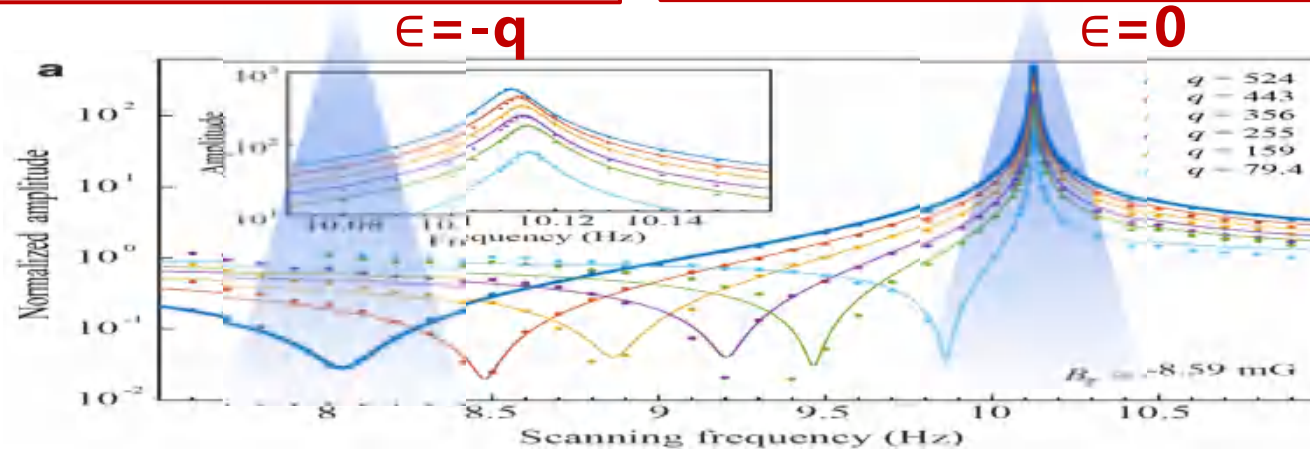
Min Jiang<sup>a,b,c,1</sup>, Yushu Qin<sup>a,b,c,1</sup>, Yuanhong Wang<sup>a,b,c</sup>, Ying Huang<sup>a,b,c</sup>, Xinhua Peng<sup>a,b,c,2</sup>, and Dmitry Budker<sup>d,e,f,g</sup>

$$\partial_t \begin{pmatrix} \hat{a} \\ \hat{b} \end{pmatrix} = i \begin{pmatrix} \omega_a + i\Gamma_a & -J \\ -J & \omega_b + i\Gamma_b \end{pmatrix} \begin{pmatrix} \hat{a} \\ \hat{b} \end{pmatrix} + \begin{pmatrix} h_a \\ h_b \end{pmatrix} \rightarrow F(\epsilon) = \mathcal{A}(\epsilon) \frac{(q + \epsilon)^2}{1 + \epsilon^2} + \mathcal{B}(\epsilon)$$

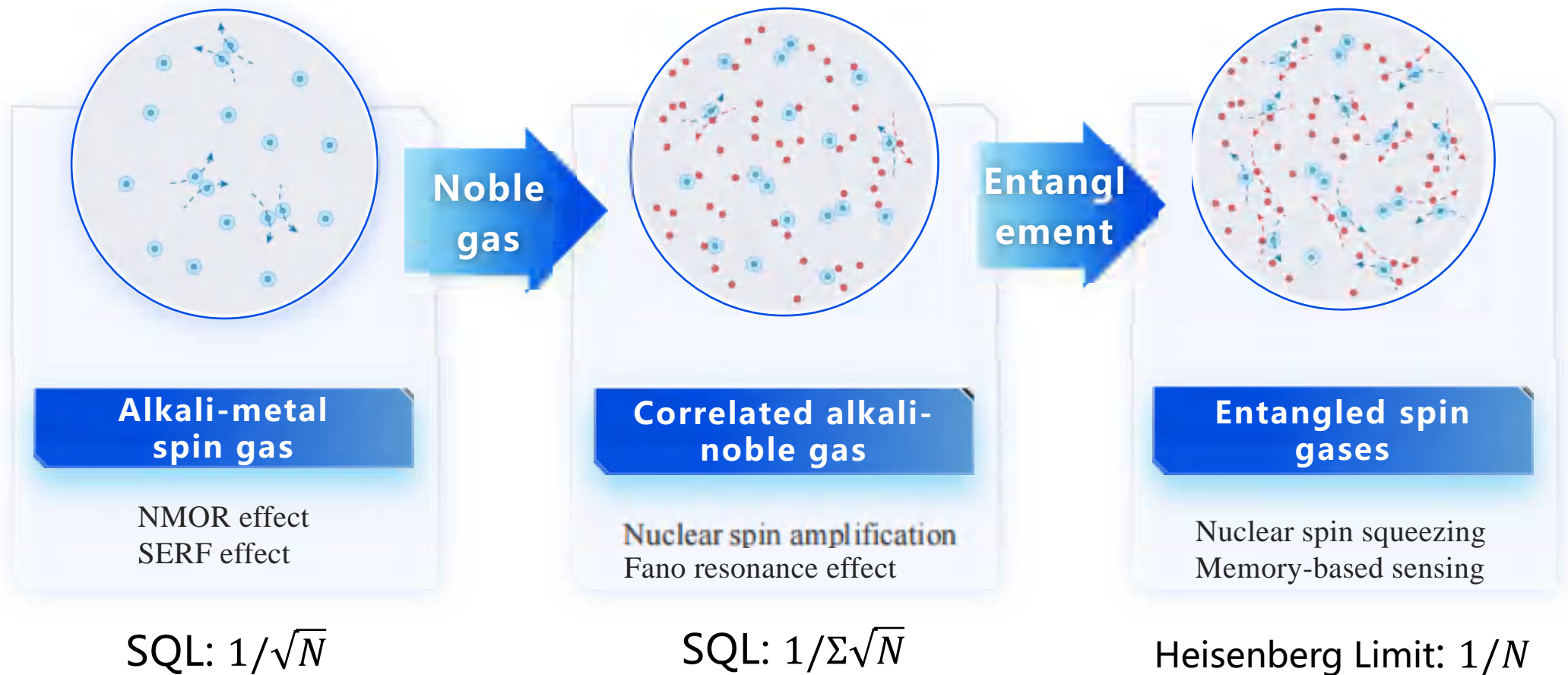
Interference destructive:  
**Quantum de-amplification**

Interference enhancement:  
**Quantum amplification**

**Fano response:  
External magnetic  
field interacts  
with interacting  
spin gases**



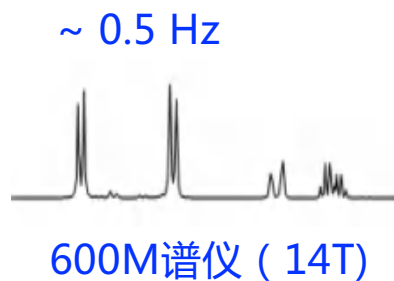
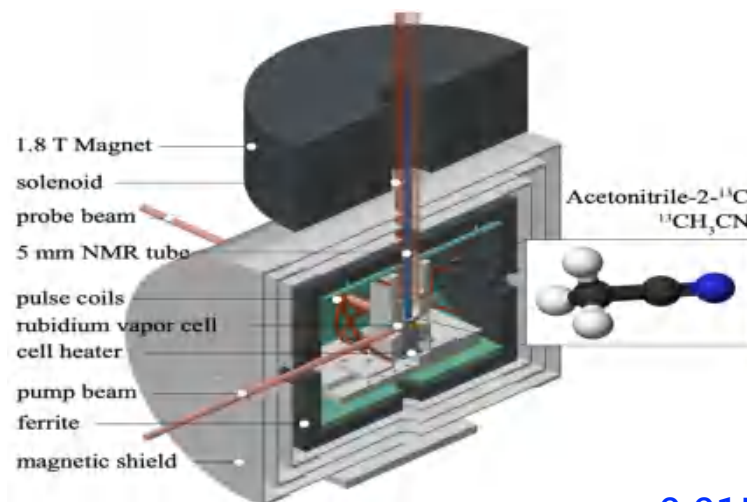
# Opportunity: Interaction, Correlation, and Entanglement



# Application 2 – Zero- & Low-field NMR (ZULF)

## Molecule fingerprinting

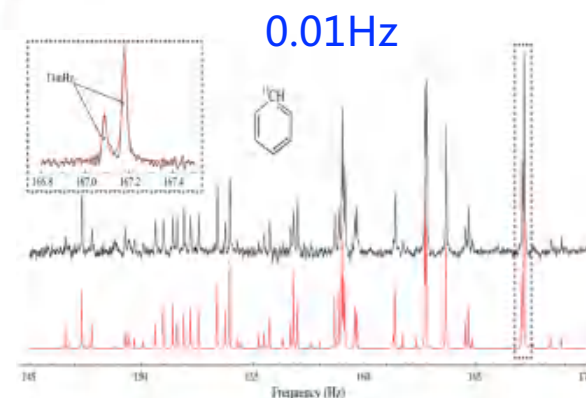
*Sci. Adv. 4, eaar6327 (2018)*



**No supermagnet** : small, portable, cheap

**High resolution** : linewidth ~ 0.01 mHz

**Safety** : e.g., for people with pacemaker

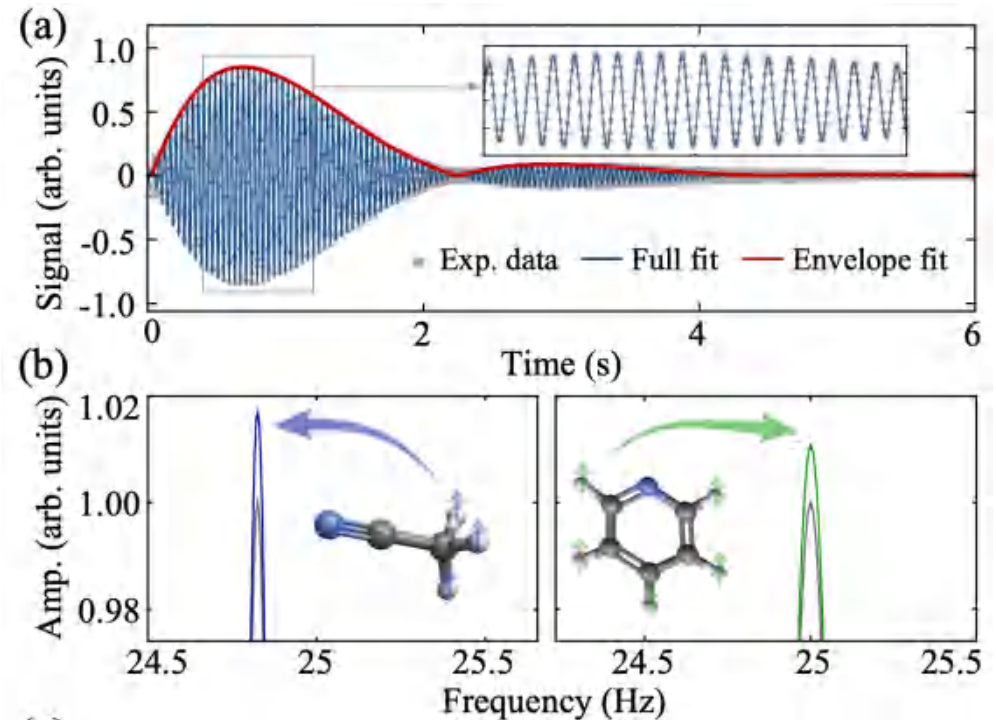
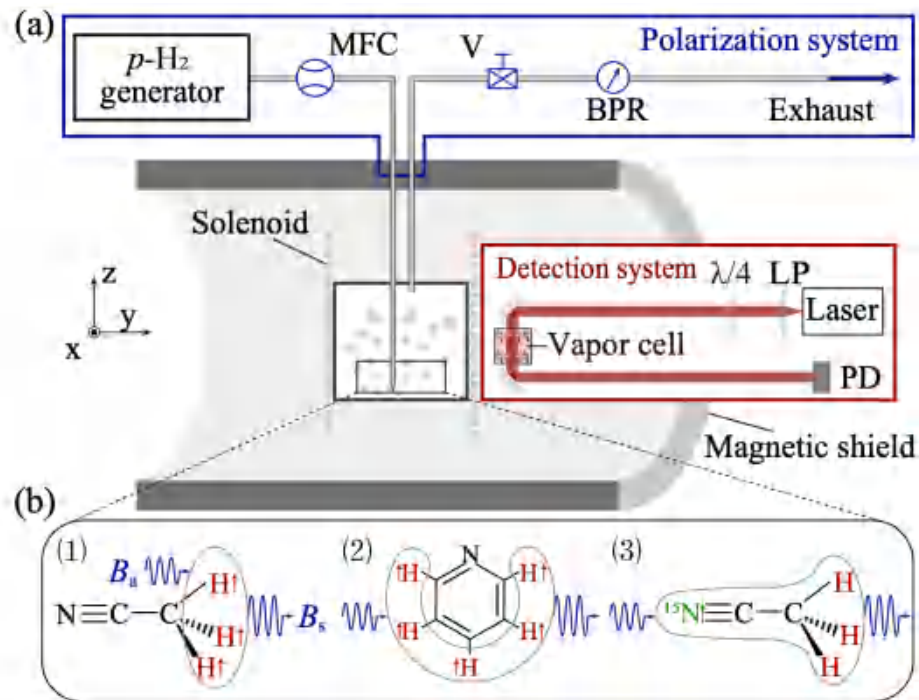


# Next opportunity: Hyperpolarized molecules

PHYSICAL REVIEW LETTERS **136**, 133201 (2026)

## Hyperpolarized Molecular Nuclear Spins Achieve Magnetic Amplification

Shengbang Zhou,<sup>1,3</sup> Qing Li,<sup>1,3</sup> Yi Ren,<sup>1</sup> Jingyan Xu<sup>4,5,6</sup>, Raphael Kircher<sup>4,5,6</sup>, Danila A. Barskiy<sup>4,5,6,7</sup>,  
Dmitry Budker<sup>4,5,6,8</sup>, Min Jiang,<sup>1,\*</sup> and Xinhua Peng<sup>1,2,3,†</sup>



# Zero- & Ultra-low NMR

## Our review paper on 《Fundamental Research》



Contents lists available at [ScienceDirect](#)

Fundamental Research

journal homepage: <http://www.keaipublishing.com/en/journals/fundamental-research/>

Review

### Zero- to ultralow-field nuclear magnetic resonance and its applications

Min Jiang<sup>a,b,c</sup>, Ji Bian<sup>a,b,c</sup>, Qing Li<sup>a,b,c</sup>, Ze Wu<sup>a,b,c</sup>, Haowen Su<sup>a,b,c</sup>, Minxiang Xu<sup>a,b,c</sup>,  
Yuanhong Wang<sup>a,b,c</sup>, Xin Wang<sup>a,b,c</sup>, Xinhua Peng<sup>a,b,c,\*</sup>

<sup>a</sup> Hefei National Laboratory for Physical Sciences at the Microscale and Department of Modern Physics, University of Science and Technology of China, Hefei 230026, China

<sup>b</sup> CAS Key Laboratory of Microscale Magnetic Resonance, University of Science and Technology of China, Hefei 230026, China

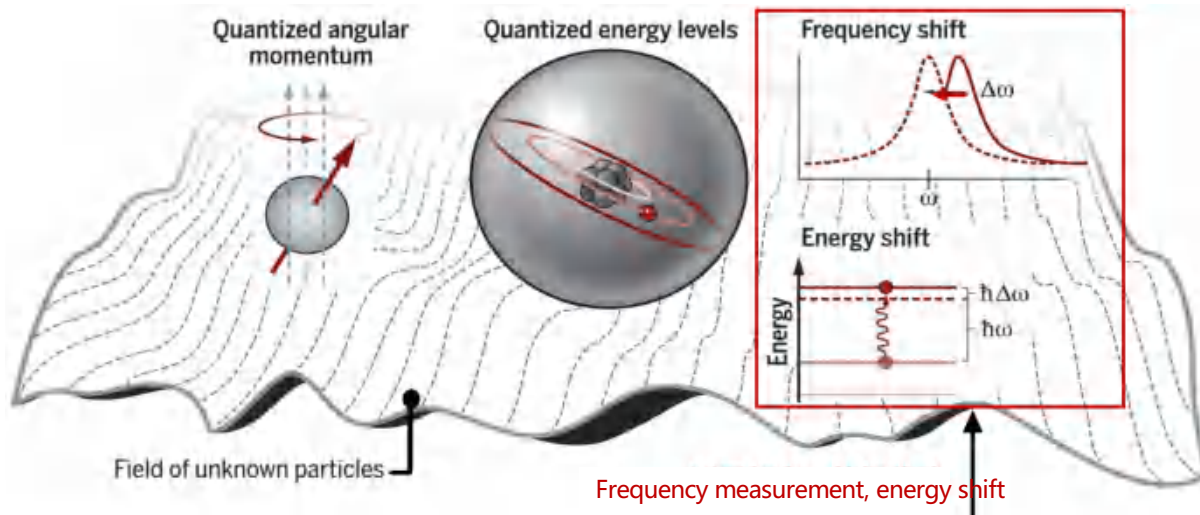
<sup>c</sup> Synergetic Innovation Center of Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei 230026, China



**Jiang, et al., Fundamental Research 1, 68 (2021)**

# Application 3 – Fundamental physics & particle physics

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



“pseudo-magnetic” field:

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

Amplitude:  
Coupling strength

Oscillation frequency:  
Compton frequency

Axion (dark matter)

**Hamiltonian =**

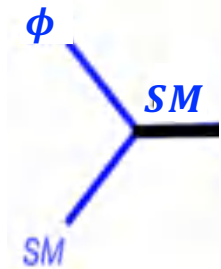
$$+ \sqrt{\frac{e_0}{m_0}} g_{agg} \int a \mathbf{E} \cdot \mathbf{B} dV \quad \text{Axion-photon}$$

$$+ g_{aff} \hbar c \nabla a \cdot \hat{S} \quad \text{Axion-spin}$$

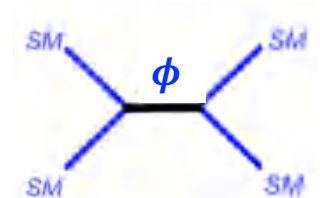
$$+ \sqrt{e_0 (\hbar c)^3} g_{EDM} a \hat{S} \cdot \mathbf{E} \quad \text{Axion-gluon}$$

# SAPPHIRE project

## Spin Amplifier for Particle PHysics Research



Can I Afford a Blue Sapphire?

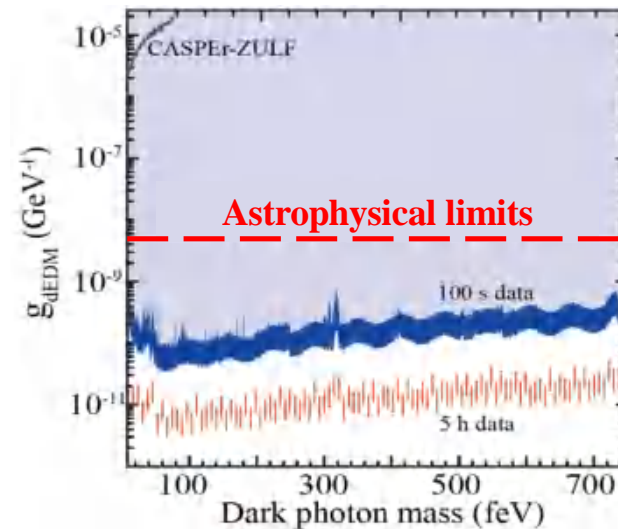
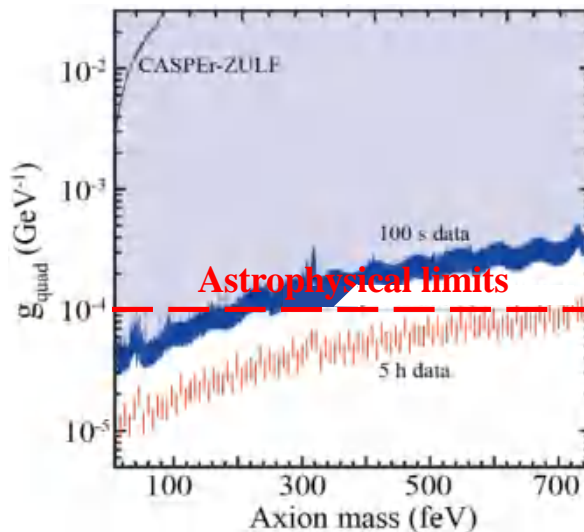
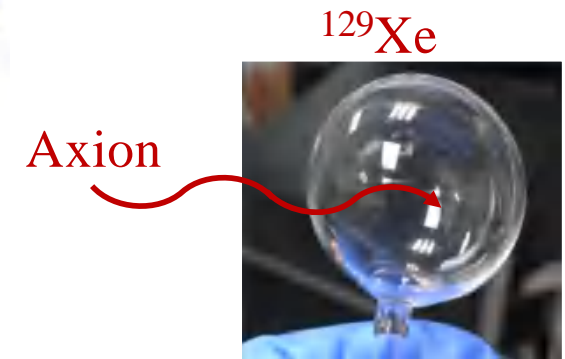


Wang, Y., Huang, Y., Guo, C., Jiang, M., ... & Budker, D., Sci. Adv.9, eade0353 (2023)

# Axion dark matter searches: Beyond astrophysical limit

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

Min Jiang<sup>1,2,3,7</sup>, Haowen Su<sup>1,2,3,7</sup>, Antoine Garcon<sup>4,5</sup>, Xinhua Peng<sup>1,2,3</sup> and Dmitry Budker<sup>4,5,6</sup>

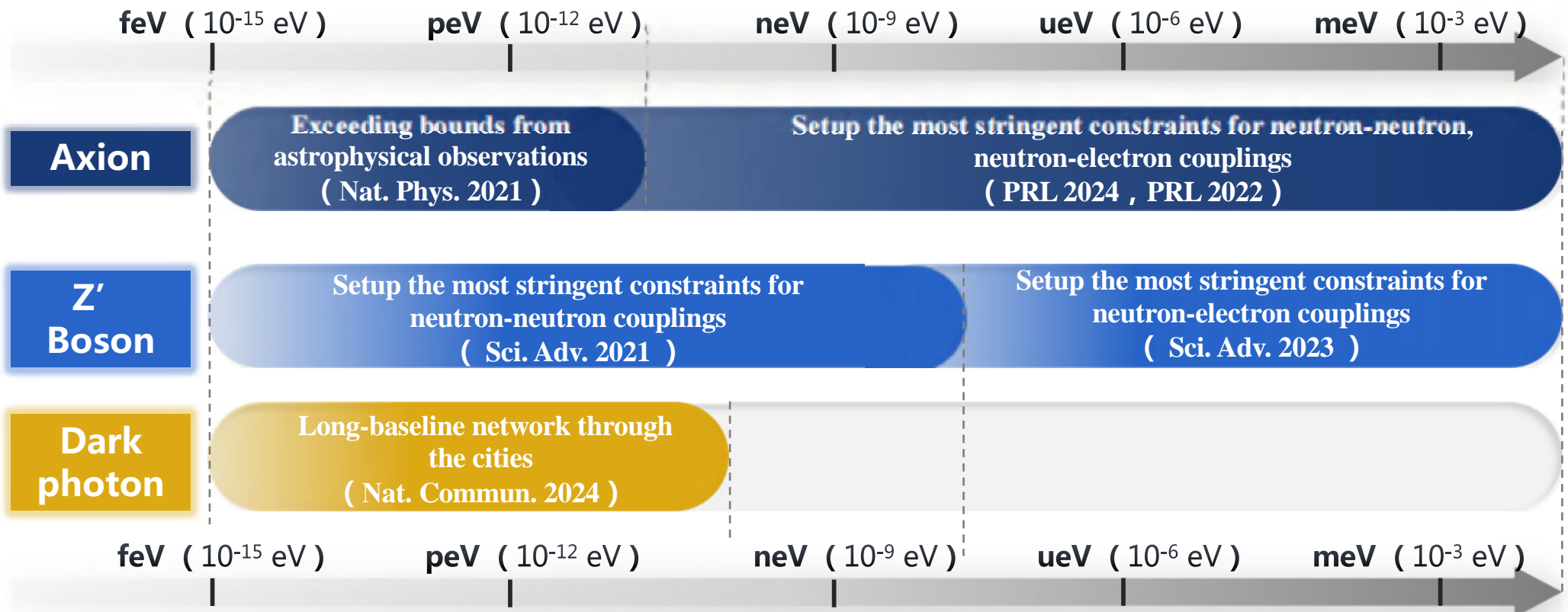


Spin-amplification: 128  
Sensitivity:  $18 \text{ fT/Hz}^{1/2}$   
**5 hours average: 130aT**  
Axion-nucleon interaction:  
 $\leq 10^{-9} \text{ GeV}^{-1} \text{ (feV-peV)}$

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

# Application 3: Searching ultralight dark matter

□ Searching for different low energy regions for axions, Z' bosons and dark photons, providing the latest new constraints



# Correlation sensing via multiple-sensor network

## Single sensor

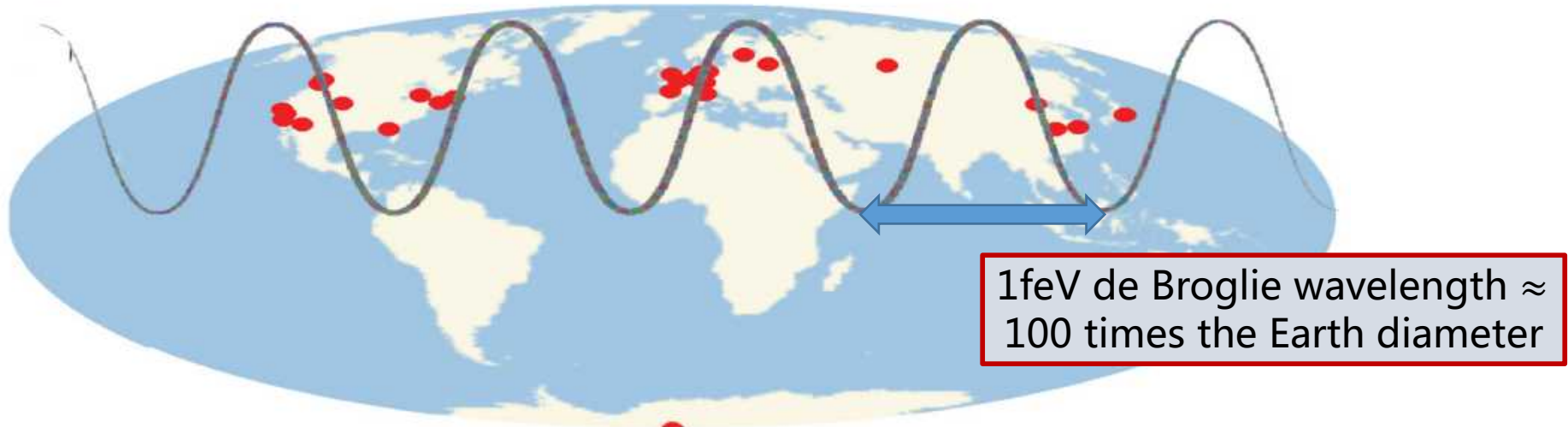
Localized noise is hard to suppress  
Detection deadzone  
Can't tell the orientation of DMs



## 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<sup>1,2,3,12</sup>, Taizhou Hong<sup>1,2,3,12</sup>, Dongdong Hu<sup>3,4,12</sup>, Yifan Chen<sup>5</sup>,  
Fengwei Yang<sup>6</sup>, Tao Hu<sup>7</sup>, Xiaodong Yang<sup>7</sup>, Jing Shu<sup>8,9,10</sup>, Yue Zhao<sup>6</sup>,  
Xinhua Peng<sup>1,2,3</sup> & Jiangfeng Du<sup>1,2,3,11</sup>



Collaboration with Yue Zhao, Jing Shu, Yifan Chen

# Correlation sensing via multiple-sensor network

Article

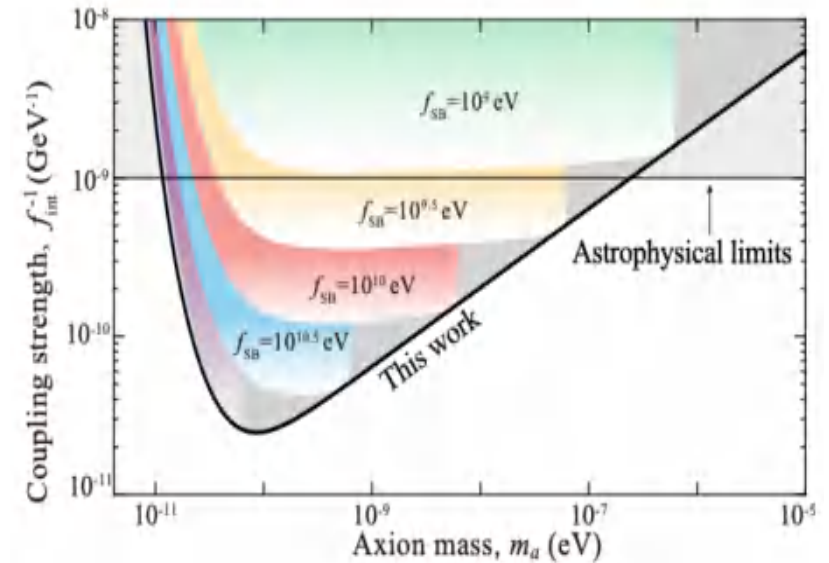
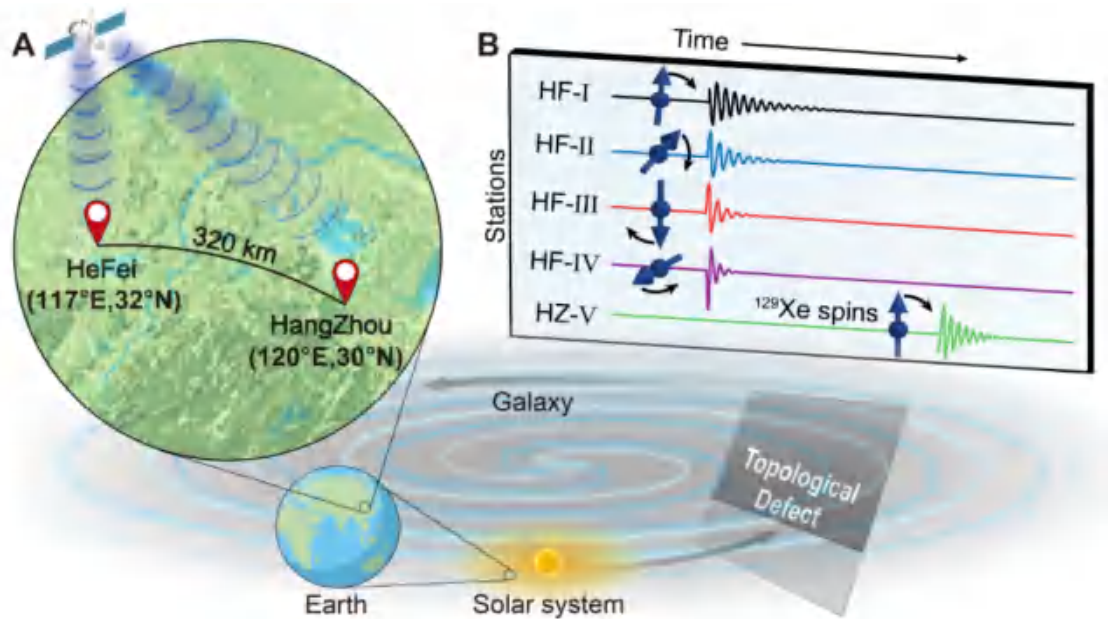
## Constraints on axion dark matter by distributed intercity quantum sensors

*Nature* 650, 314 (2026)

<https://doi.org/10.1038/s41586-025-10034-w>

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

Received: 15 April 2025



Collaboration with Szymon Pustelny

# The first nuclear-spin quantum sensor network



# Space-based new physics searches “昆仑计划”



“**昆仑**”源自中国古代《山海经》，是神仙居住的神山，象征着**神秘莫测的力量（—暗物质）**。昆仑山在中国传统文化中被视为**连接天地的桥梁（—>天地一体化）**。

PERSPECTIVE

National Science Review

12: rwaf389, 2025

<https://doi.org/10.1093/nsr/rwaf389>

Advance access publication 22 September 2025

PHYSICS

## Quantum sensors in space: unveiling the invisible universe

Yuanhong Wang<sup>1,2,†</sup>, Xingming Huang<sup>1,2,†</sup>, Min Jiang<sup>1,2,\*</sup>, Qing Lin<sup>3,4</sup>, Wenqiang Zheng<sup>5</sup>, Yuan Sun<sup>6,5</sup>, Liang Liu<sup>6,5</sup>, Xinhua Peng<sup>1,2,\*</sup>, Zhengguo Zhao<sup>3,4</sup> and Jiangfeng Du<sup>2,8</sup>

PHYSICAL REVIEW D 112, 095015 (2025)

## Hunting for exotic bosons with flying quantum sensors in space

Xingming Huang<sup>6,7</sup>, Yuanhong Wang,<sup>1,†</sup> Xiang Kang,<sup>1</sup> Jiayi Li<sup>1,2</sup>, Haowen Su,<sup>1</sup> Zehao Wang<sup>1</sup>, Qing Lin<sup>3,4</sup>, Wenqiang Zheng,<sup>5</sup> Yuan Sun,<sup>6</sup> Liang Liu,<sup>6</sup> Min Jiang,<sup>1,7,1</sup> Xinhua Peng<sup>1,2,3,4</sup>, Zhengguo Zhao,<sup>3,4</sup> and Jiangfeng Du<sup>2,8</sup>

# Application 4 – Quantum many-body physics/quantum simulations

QSD is the core research tool for exploring frontier fundamental quantum many-body problems



Goal : Quantum advantage in quantum simulation

Few → Many, equilibrium → non-equilibrium

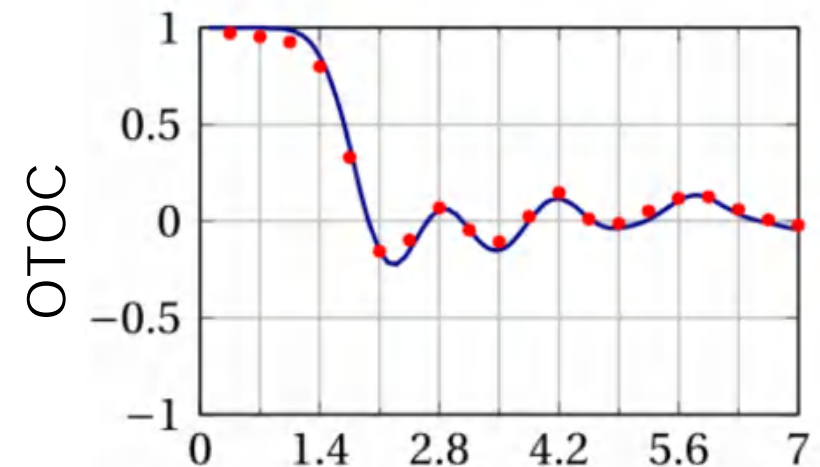
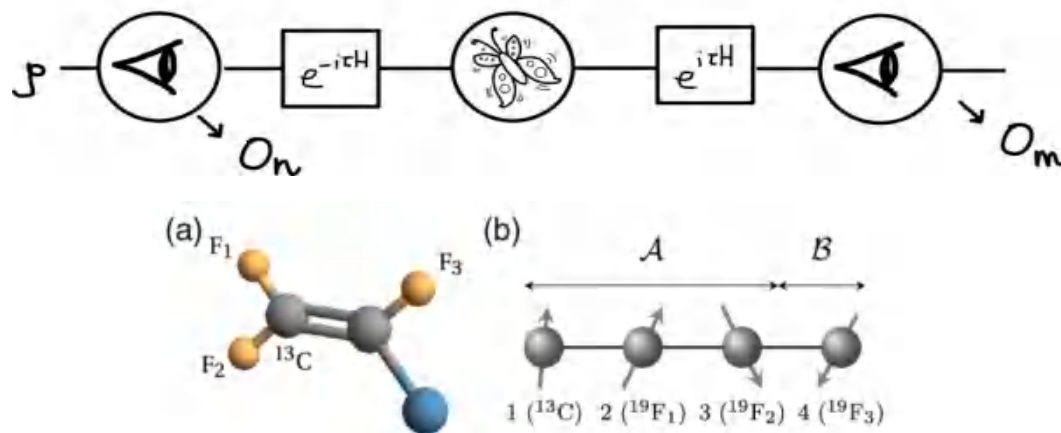
# First Experimental Measurements of OTOC

Selected for a **Viewpoint in Physics**  
PHYSICAL REVIEW X **7**, 031011 (2017)

Citation > 500

## Measuring Out-of-Time-Order Correlators on a Nuclear Magnetic Resonance Quantum Simulator

Jun Li,<sup>1</sup> Ruihua Fan,<sup>2,3</sup> Hengyan Wang,<sup>3</sup> Bingtian Ye,<sup>3</sup> Bei Zeng,<sup>4,5,2,\*</sup> Hui Zhai,<sup>2,6,†</sup> Xinhua Peng,<sup>7,8,9,‡</sup> and Jiangfeng Du<sup>7,8</sup>



# First Experimental Measurements of OTOC

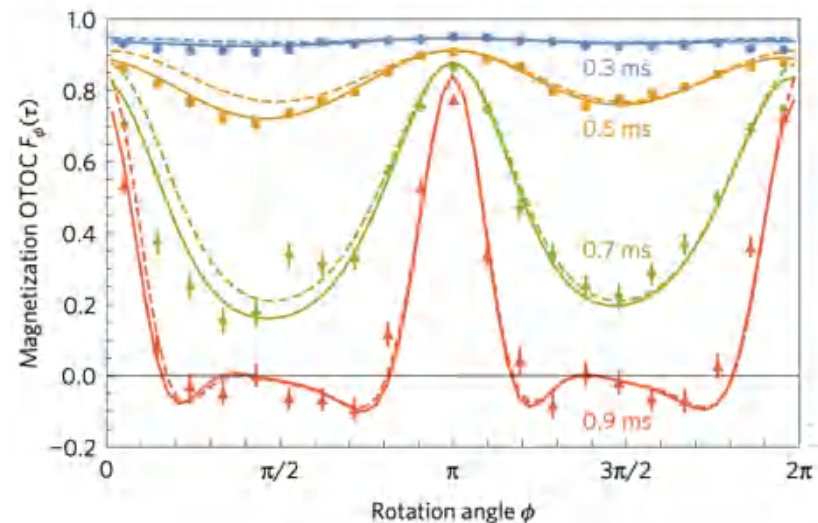
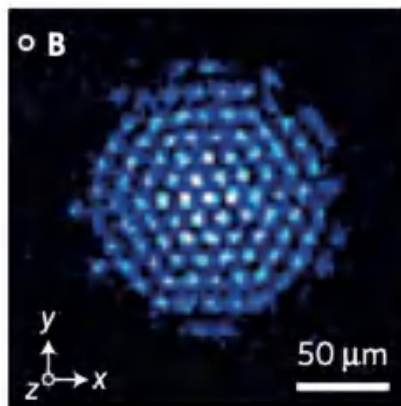
nature  
physics

ARTICLES

PUBLISHED ONLINE: 22 MAY 2017 | DOI: 10.1038/NPHYS4119

## Measuring out-of-time-order correlations and multiple quantum spectra in a trapped-ion quantum magnet

Martin Gärttner<sup>1†</sup>, Justin G. Bohnet<sup>2†</sup>, Arghavan Safavi-Naini<sup>1</sup>, Michael L. Wall<sup>1</sup>, John J. Bollinger<sup>2</sup>  
and Ana Maria Rey<sup>1\*</sup>



# Following-up Experiments on OTOC

## Emergent Prethermalization Signatures in Out-of-Time Ordered Correlations

Ken Xuan Wei,<sup>1</sup> Paj Peng (彭湃),<sup>2</sup> Oles Shtanko,<sup>1</sup> Iman Marvian,<sup>3</sup> Seth Lloyd,<sup>4</sup>  
Chandrasekhar Ramanathan,<sup>5</sup> and Paola Cappellaro<sup>6,\*</sup>

Solid NMR Experiment by MIT group, PRL 2019

LETTER

<https://doi.org/10.1028/A1586-019-0952-6>

## Verified quantum information scrambling

K. A. Landsman<sup>1\*</sup>, C. Figgatt<sup>1,2</sup>, T. Schuster<sup>2</sup>, N. M. Linke<sup>1</sup>, B. Yoshida<sup>3</sup>, N. Y. Yao<sup>1,2</sup> & C. Monroe<sup>1,2</sup>

Trap Ion Experiment by Maryland group, Nature, 2019

REPORT QUANTUM SIMULATION

f x 9

## Information scrambling in quantum circuits

Superconducting Experiment by Google Group, Science 2021

QUANTUM SENSING

## Improving metrology with quantum scrambling

Zeyang Li (李泽阳)<sup>1</sup>, Simone Colombo<sup>1</sup>, Chi Shu<sup>1,2</sup>, Gustavo Velez<sup>1,3</sup>, Saúl Pilatowsky-Cameo<sup>4</sup>,  
Roman Schmied<sup>2</sup>, Soonwon Choi<sup>4</sup>, Mikhail Lukin<sup>2</sup>, Edwin Pedrozo-Peñafiel<sup>1</sup>, Vladan Vuletić<sup>1,2</sup>

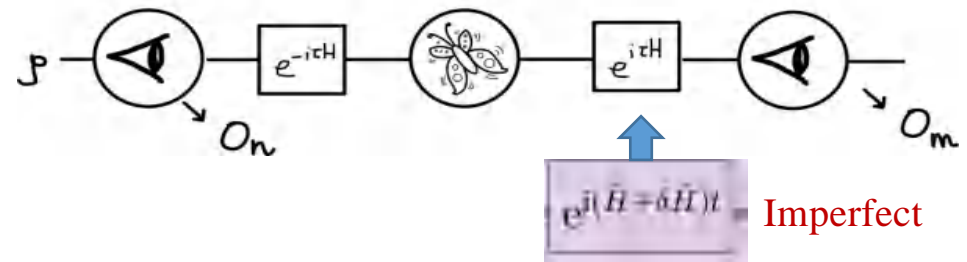
Cold Atom Experiment by MIT Group, Science 2023

$$\text{Tr}[[\hat{W}(0), \hat{V}(t)]^2] \sim e^{\lambda t}$$

↑  
Lyapunov exponent

None of these experiments sees well-defined exponential behavior of OTOC and is able to extract the Lyapunov exponent.

Why?



# First experimental measurements of OTOC

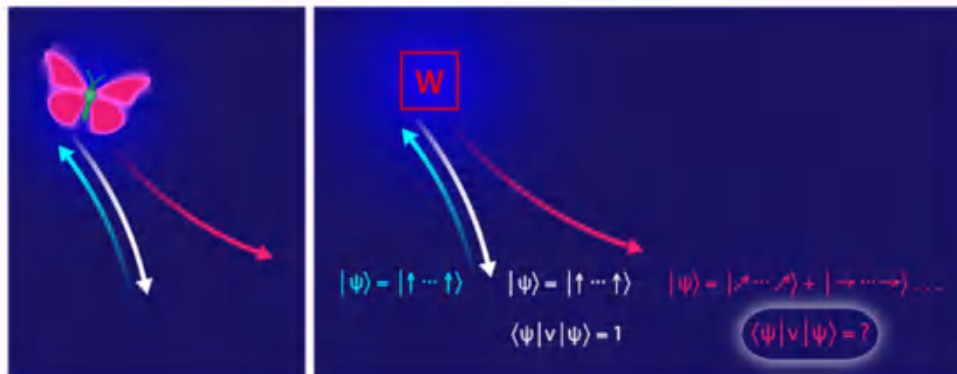
Physics

VIEWPOINT

## Seeing Scrambled Spins

by Brian Swingle\* and Norman Y. Yao†

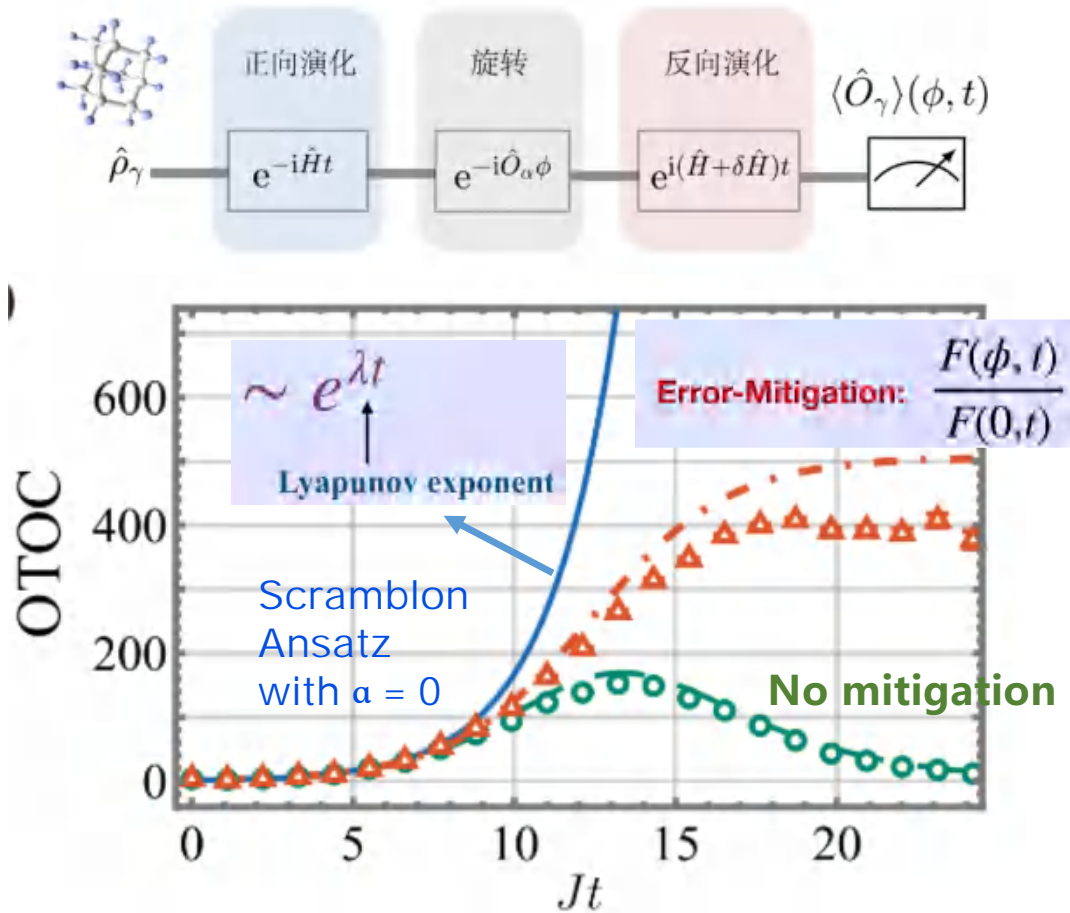
information. Two groups, one in China [5] and one in the US [6], have taken a step towards tracking this scrambling of information in systems of quantum spins.



While neither experiment reaches the limit of true many-body chaos, both raise crucial questions. Can one distinguish information that is scrambled from that which is simply lost because of environmental noise and spin decoherence? Can one correct for small errors that result from imperfectly evolving a system backward in time? Using the rich data set from their ion experiment, Gärtner *et al.* were able to explore and model various sources of such imperfection such as magnetic-field noise.

Quantum thermalization is a rapidly developing field. In fact, two new scrambling experiments appeared just recently [11, 12]. The near future promises experiments of increasing complexity—both larger system sizes and more chaotic Hamiltonians. Building on the work by Li *et al.* and Gärtner *et al.*, it seems likely that experiments will soon forge beyond what computers can simulate, revealing the dynamics of information scrambling in previously inaccessible regimes.

# A first experiment to extract Lyapunov exponent in a many-body system



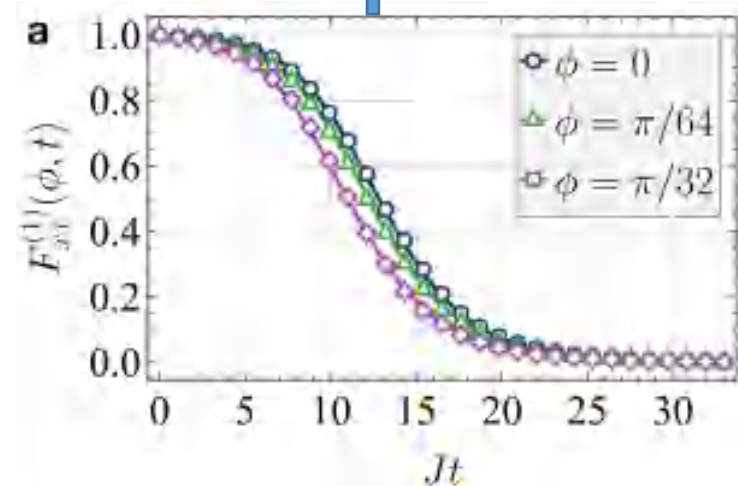
## Scramblon Theory for OTOC

Yingfei Gu, A. Kitaev and Pengfei Zhang, JHEP 2022

Scramblon Ansatz for OTOC with Imperfections

$$F_{\alpha\gamma}(\phi, t) = \frac{1}{(1 + ae^{\kappa t} + b\phi^2 e^{\kappa t})^{2\Delta}}$$

$\{a, b, \kappa, \Delta\}$  Verification



# Span a decade of close theoretical and experimental collaboration



The image shows a screenshot of a Physical Review Letters article page. At the top, the journal name "Physical Review Letters" is displayed in white on a dark background. Below it is a navigation bar with links: "Highlights", "Recent", "Accepted", "Collections", "Authors", "Referees", "Press", "About", and "Edit". The article title is "Error-Resilient Reversal of Quantum Chaotic Dynamics Enabled by Scramblons". The authors listed are Yu-Chen Li, Tian-Gang Zhou, Shengyu Zhang, Ze Wu, Liqiang Zhao, Haochuan Yin, Xiaoxue An, Hui Zhai, and Pengfei Zhang. The article is published in Phys. Rev. Lett. 136, 060403 on February 9, 2026. The DOI is https://doi.org/10.1103/cg3f-rggs.

Two papers recommended by Physical Review

From pioneering OTOC measurements to the first extraction of quantum chaos effects



Yingfei Gu  
Kitaev  
Pengfei Zhang  
Scramblon theory

Physics

## Seeing the Quantum Butterfly Effect

A combined experimental and theoretical study reveals the emergence of quantum chaos in a complex system, suggesting that it can be described with a universal theoretical framework.

By Xiao-Liang Qi

# First experimental measurements of OTOC

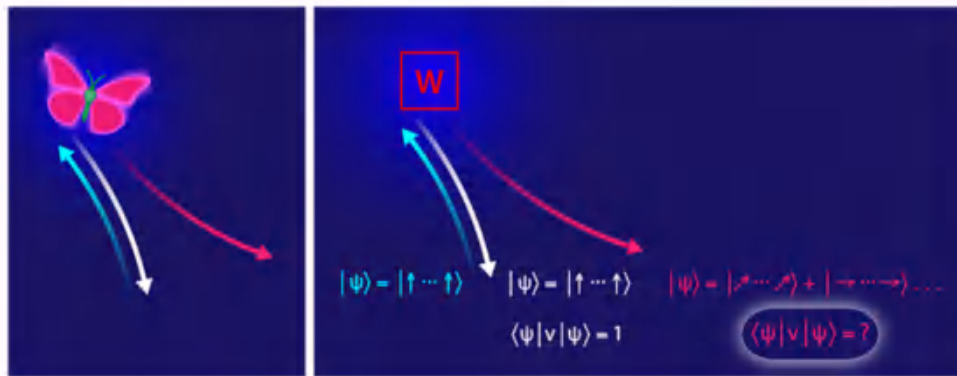
Physics

VIEWPOINT

## Seeing Scrambled Spins

by Brian Swingle\* and Norman Y. Yao†

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Quantum thermalization is a rapidly developing field. In fact, two new scrambling experiments appeared just recently [11, 12]. The near future promises experiments of increasing complexity—both larger system sizes and more chaotic Hamiltonians. Building on the work by Li *et al.* and Gärttner *et al.*, it seems likely that experiments will soon forge beyond what computers can simulate, revealing the dynamics of information scrambling in previously inaccessible regimes.

# Universality of non-equilibrium dynamics in complex spin systems

nature physics

All complex systems are driven by extremely simple logic.

Article

<https://doi.org/10.1038/s41567-024-024-024-024>

## Emergent universal quench dynamics in randomly interacting spin models

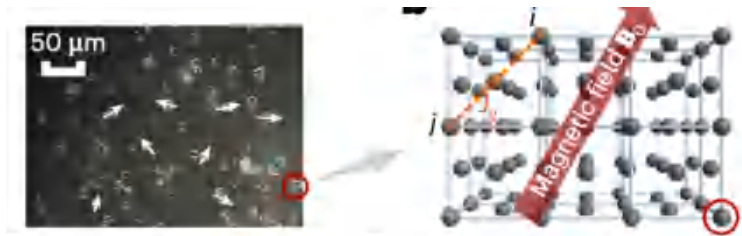


Received: 16 November 2023

Accepted: 12 September 2024

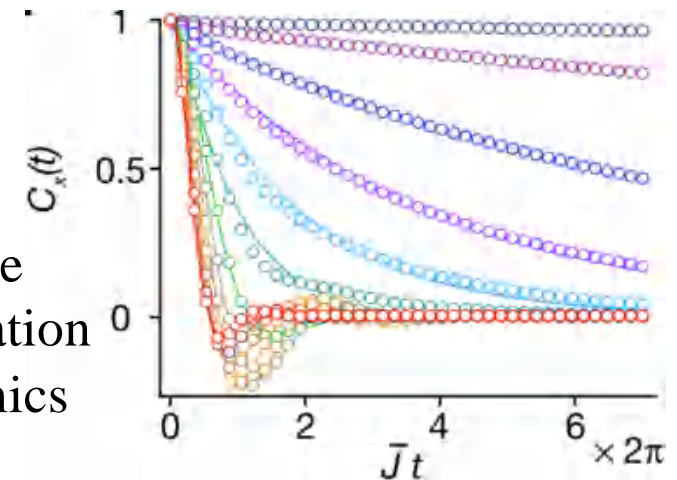
Published online: 14 October 2024

Yuchen Li<sup>1,2,13</sup>, Tian-Gang Zhou<sup>3,13</sup>, Ze Wu<sup>1,2,4,13</sup>, Pai Peng<sup>5</sup>, Shengyu Zhang<sup>1,2,4,6</sup>, Riqiang Fu<sup>7</sup>, Ren Zhang<sup>6,8</sup>, Wei Zheng<sup>4,6,9</sup>, Pengfei Zhang<sup>10,11</sup>, Hui Zhai<sup>3,6</sup>, Xinhua Peng<sup>1,2,4,6</sup> & Jiangfeng Du<sup>1,2,4,6,12</sup>



$\sim 10^{22}$  spins ( $\sim 10^3$  correlated spins)  
(classically intact)

A universal behavior for the spin depolarization quench dynamics



$$\mathbf{y}(t) = A \cos(\boldsymbol{\Omega} t + \boldsymbol{\Phi}) \exp(-\boldsymbol{\Lambda} t)$$

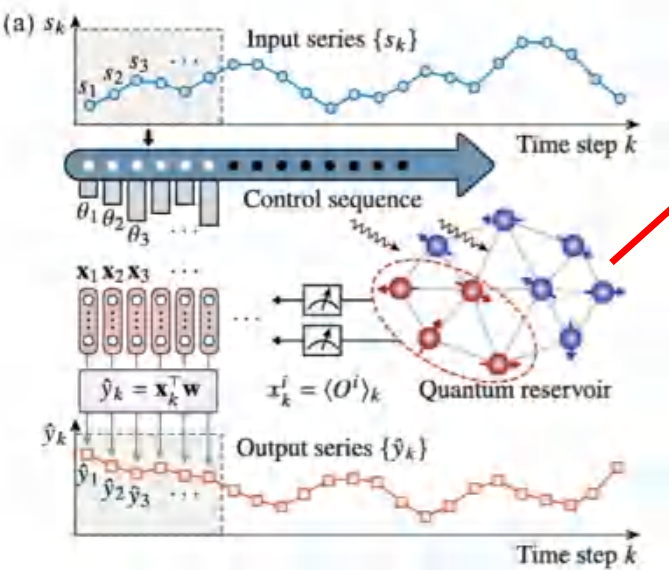
# Application 5 -- Correlated spin dynamics for AI QC

High-Accuracy Temporal Prediction via Experimental Quantum Reservoir Computing in Correlated Spins

PRL 136, 120602 (2026)

Yanjun Hou<sup>1,\*</sup>, Juncheng Hua<sup>1,2,\*</sup>, Ze Wu<sup>1,3</sup>, Wei Xia<sup>3</sup>, Yuquan Chen<sup>1</sup>, Xiaopeng Li<sup>4,5,6,7,†</sup>, Zhaokai Li<sup>1,2,7,‡</sup>, Xinhua Peng<sup>1,2,7,§</sup> and Jiangfeng Du<sup>8,||</sup>

**A first experimental demonstration of quantum machine learning outperforming large-scale classical models on real-world tasks.**



9 spin system

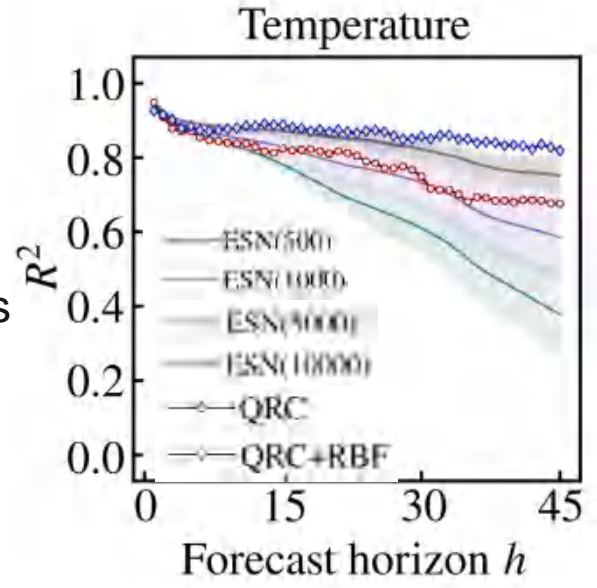
Intrinsic spin dynamics  
Exponentially large Hilbert space & Complex correlations

Unitary and nonunitary

$$\rho_k = e^{\tau \mathcal{L}_H} \circ \mathcal{U}_{s_k} [\rho_{k-1}]$$

Larger spin systems

A daily climate dataset from Delhi



# Summary

---

- Quantum spin dynamics studies the coherent evolution, relaxation and collective behavior of quantum spins, and is the foundation of modern quantum technologies.
- Diverse experimental platforms (NMR, QDs, NV centers, magnonics) support versatile spin manipulation and research.
- Cutting-edge applications cover quantum sensing, computing, spintronics, fundamental physics and interdisciplines, with great development potential.
- Decoherence and scalability remain major obstacles. Future work will focus on coherence protection, multi-spin precise control and device practicalization.

# Thanks to .....



Prof. Jiangfeng Du

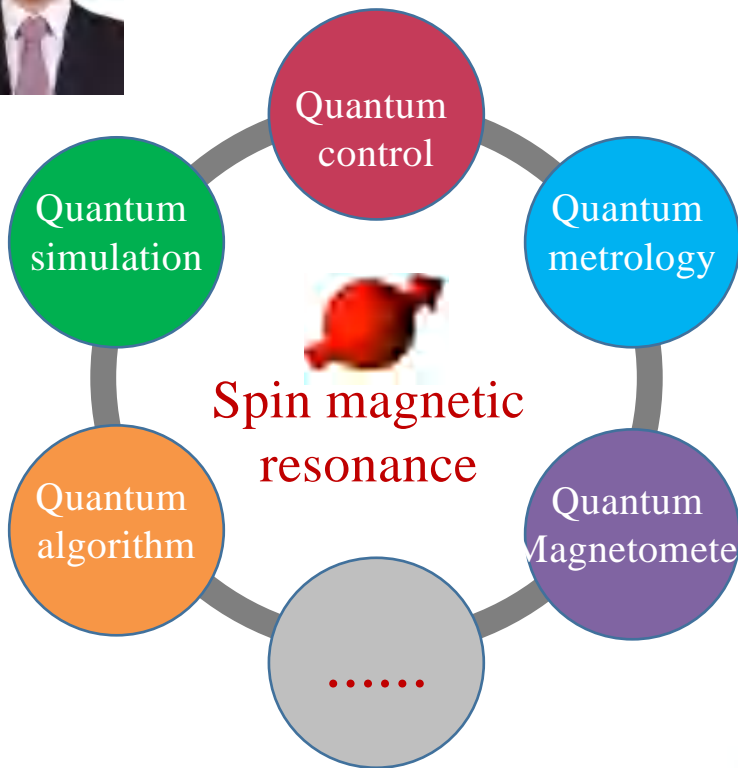
Collaborators:

- Prof. Dieter Suter
- Prof. Dmitry Budker
- Prof. Renbao Liu
- Prof. Hui Zhai
- Prof. Pengfei Zhang
- Prof. Bei Zeng
- Prof. Haidong Yuan

.....

Funding:

USTC, CAS, NNSFC.....



Group members:

- Prof. Min Jiang
- Ze Wu (Postdoc.)
- Haowen Su (Postdoc.)
- Yuanhong Wang (Postdoc.)
- Yuchen Li (Postdoc.)
- Qing Li
- Shiming Song
- Minxiang Xu
- Yushu Qing
- Xingming Huang

.....



# Outlook

## Traditional NMR (liquid/solids)



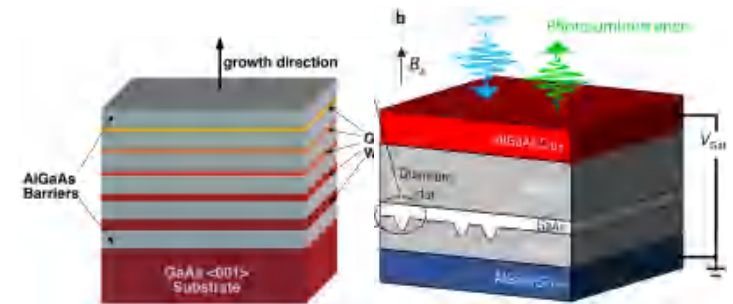
Low polarization  
High temperature  
Spin-spin interactions  
Quantum control  
Quantum simulation

## Hyperpolarized gas



High polarization  
High temperature  
Weak Spin-spin interactions  
Quantum metrology

## Hyperpolarized solids



High polarization  
Low temperature  
Spin-spin interactions  
Quantum simulation  
Quantum metrology