Searching for exotic spin-dependent interactions with single electron spin quantum sensors

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Exploring new physics beyond standard model by NV centers

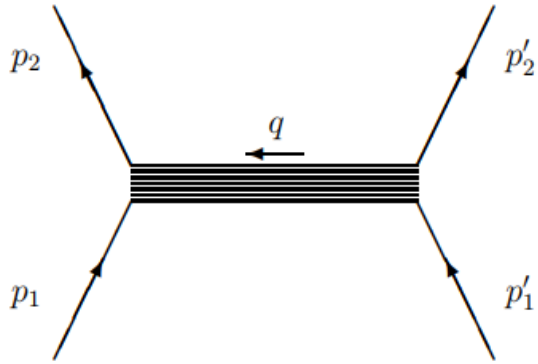
- Searching for new particles beyond the standard model is crucial for understanding several fundamental conundrums such as
  - Dark matter
  - Dark energy
  - Hierarchy problem
  - …

Space Sci. Rev. 98, 329 (2001)

Top 20 unsolved fundamental problems in physics

2.1. Supersymmetry and Vacuum Fields
2.2. The Electromagnetic Zero-Point Field
2.3. The Cosmological Constant Problem
2.4. The Hierarchy Problem
2.5. Grand Unification
2.6. Quantum Gravity
2.7. Neutrinos
2.8. The Identity of Dark Matter
2.9. The Microwave Background Horizon Problem
2.10. Particle Properties and Causality
2.11. Fundamental Constants
2.12. Was There a Big Bang?
2.13. The Topology of Space
2.14. The Dimensionality of the World
2.15. Mach's Principle
2.16. Negative Mass
2.17. The Origin of Galaxies and Other Structure
2.18. The Origin of the Spins of Galaxies
2.19. The Angular Momentum/Mass Relation
2.20. Life and the Fermi-Hart Paradox

Spin-dependent macroscopic forces from new particle exchange



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$$
\begin{aligned}
\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) \ , \qquad (3.6) \\
\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\} \\
&\quad\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) \ . \qquad (3.8)
\end{aligned}
$$

B. Dobrescu and I. Mocioiu, J. High Energy Phys. 11, 005(2006).

Searches for exotic spin-dependent interactions with NV centers

- spin-mass interaction

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

Xing Rong et al., Nature Communications, 9:739 (2018)

- exotic dipole-dipole interaction

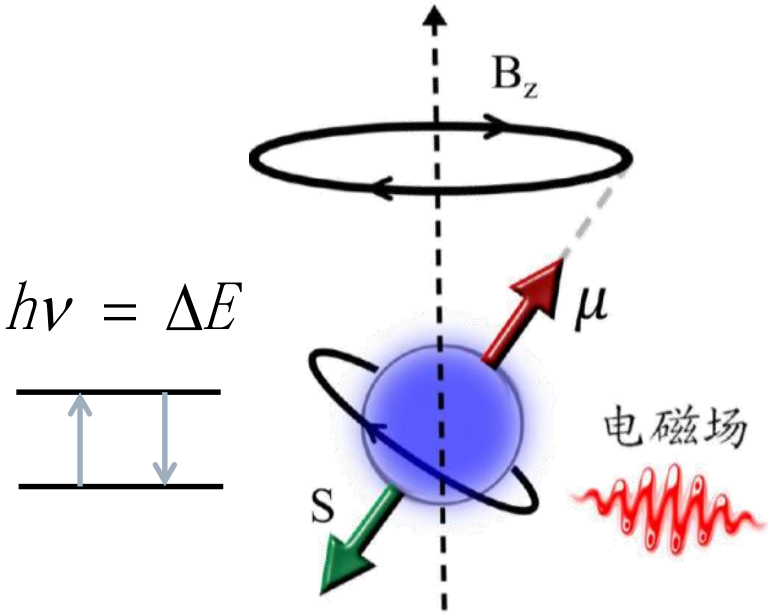
$$\mathcal{V}_2 = \frac{1}{r}\,\vec{\sigma}\cdot\vec{\sigma}\,'\,y(r)\ ,$$

Xing Rong et al., arXiv:1804.07026 (2018)

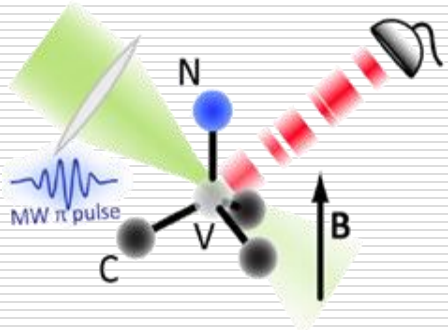
Spin Magnetic Resonance

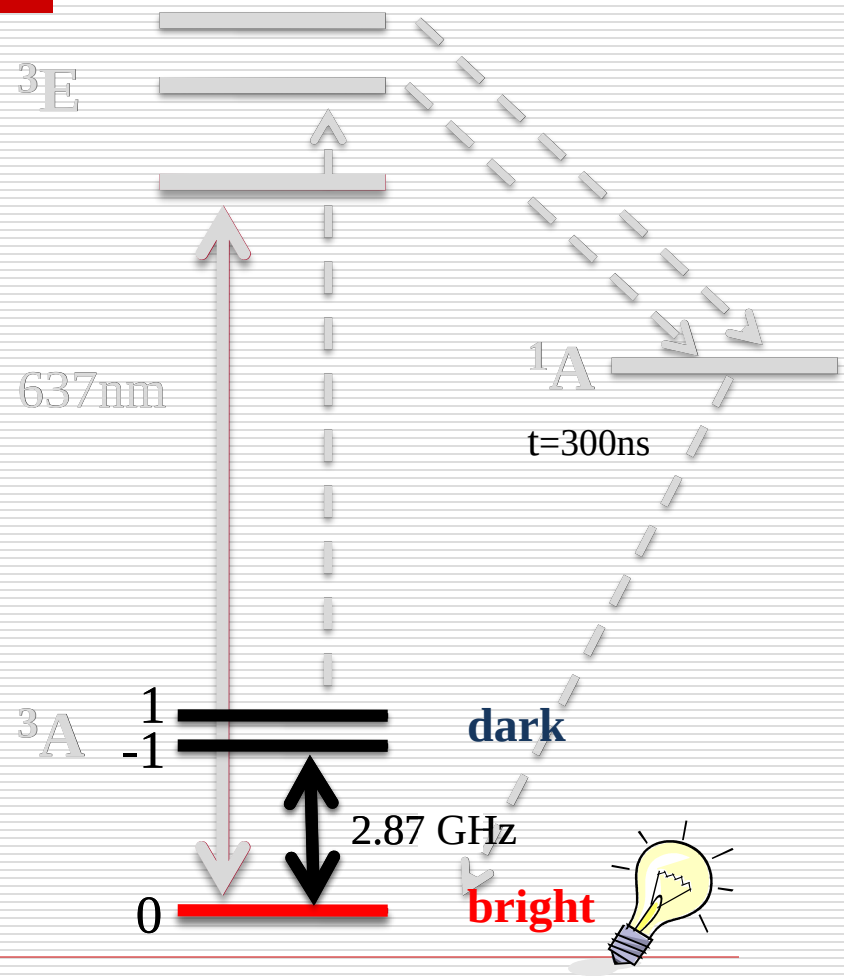
Principle: The spins which locate in a magnetic field can absorb and re-emit electromagnetic radiation with a specific resonance frequency.

The MR technology is capable of obtaining information of subjects composition and structure in an accurate, rapid and non-destructive way.



NV的基本性质





- NV具有三能级的基态结构，再结合邻近的耦合自旋，有多种量子比特的编码选择；
- 特殊的光学性质使NV单自旋能用光学方法定位、初始化和读出；
- 室温可以达到5毫秒量级的超长相干时间，量子操作次数可达百万量级。

$$H = \hat{S} \cdot \overleftrightarrow{D} \cdot \hat{S} \rightarrow DS_z^2 + E(S_x^2 - S_y^2)$$

NV体系室温下优越的性质 + 量子控制技术

应用前景？

$$H = D \cdot S_z^2 + E \cdot (S_x^2 - S_y^2) - \gamma_e \mathbf{B} \cdot \mathbf{S} + \mathbf{S} \cdot \sum_i \mathbf{A}_i \cdot \mathbf{I}_i$$

探测温度

Nano Lett. 13, 2738 (2013)
Nature 500, 54-58 (2013)

探测电场

Nat. Phys. 7, 459 (2011)

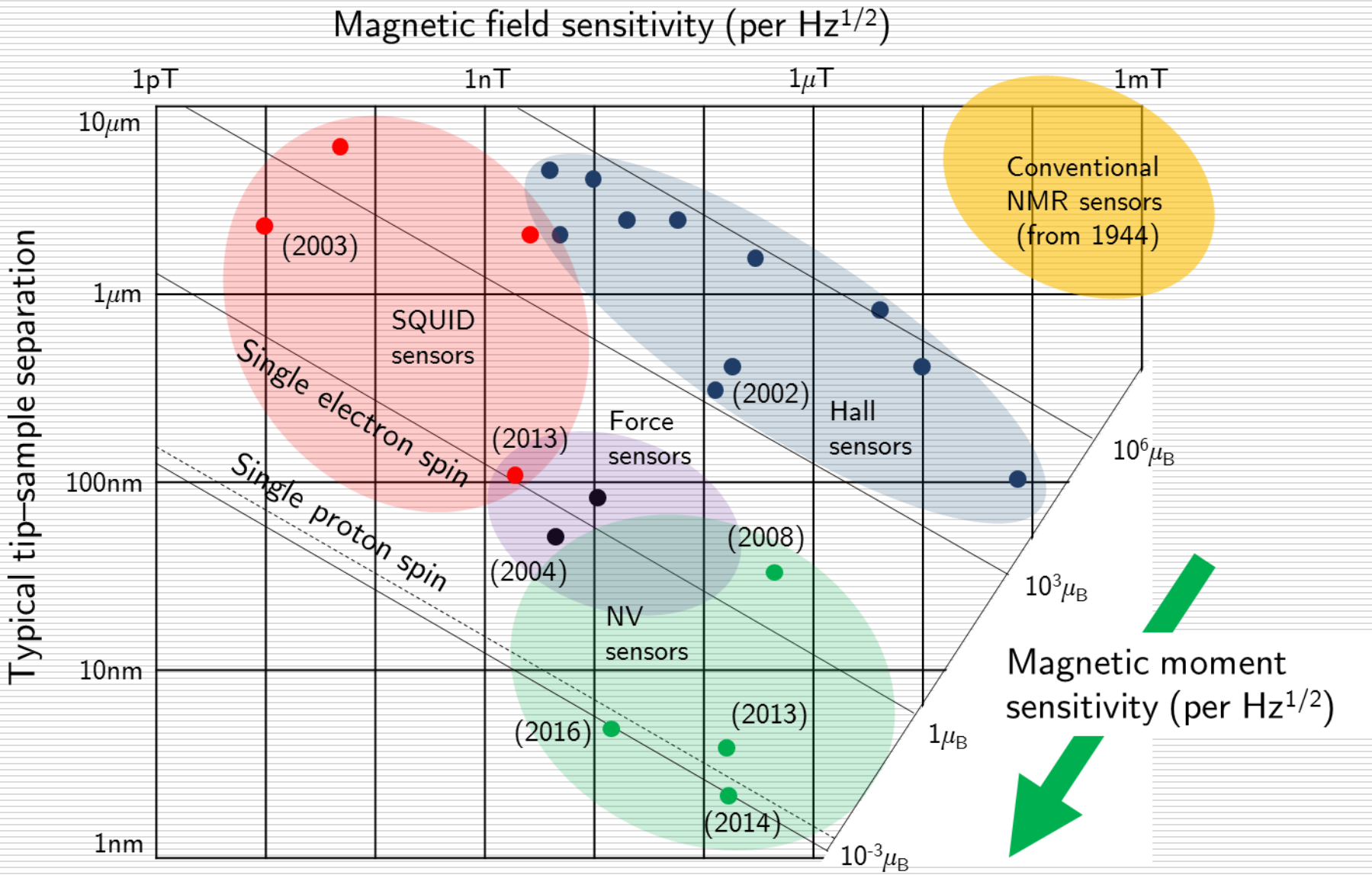
探测磁场

见下页磁探测进展图示

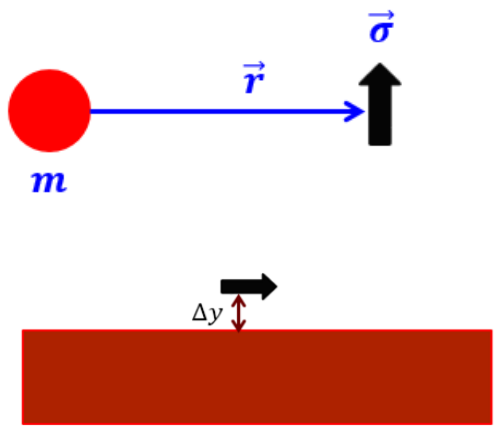
自旋耦合

Science 316, 1312 (2007)
Nat. Phys. 9, 29 (2012)
PRL 109, 137602 (2012)
.....

NV sensor

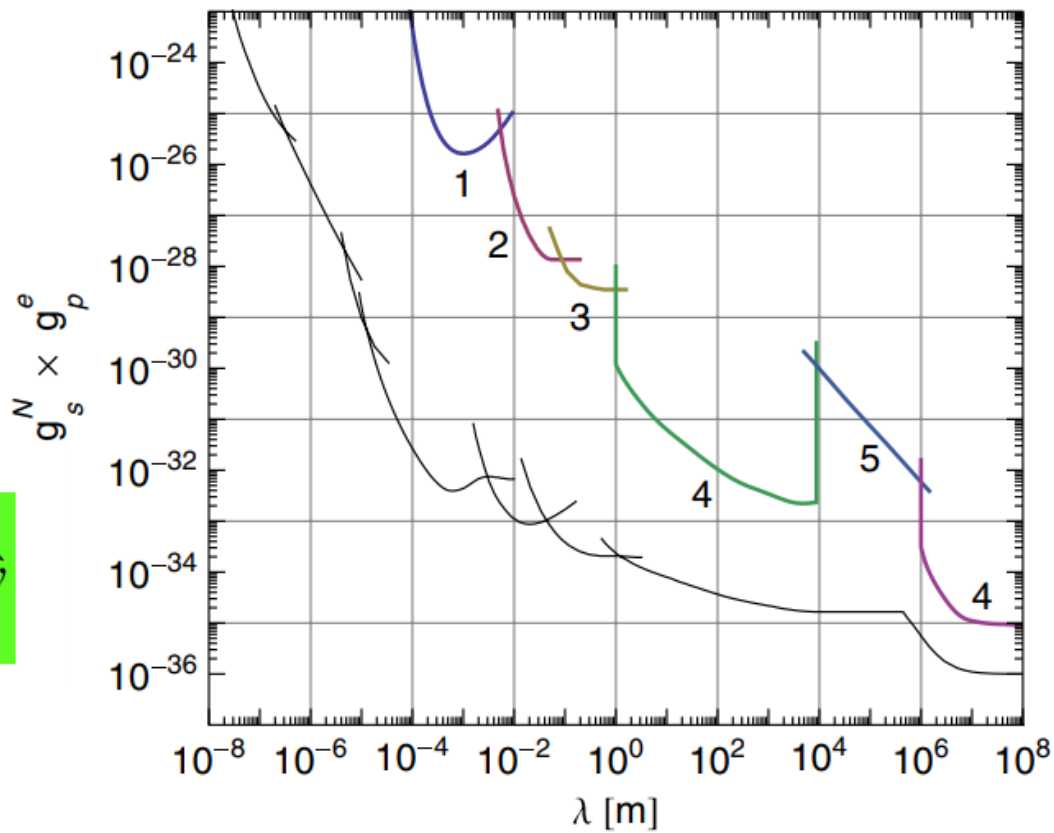

Magnetic field sensitivity (per Hz$^{1/2}$)
1pT
1nT
1μT
1mT
10μm
1μm
100nm
10nm
1nm
Typical tip–sample separation
(2003)
SQUID sensors
Single electron spin
Single proton spin
(2013)
(2004)
Force sensors
(2002)
Hall sensors
Conventional NMR sensors (from 1944)
(2008)
NV sensors
(2016)
(2013)
(2014)
$10^6\mu_B$
$10^3\mu_B$
$1\mu_B$
$10^{-3}\mu_B$
Magnetic moment sensitivity (per Hz$^{1/2}$)

Constraints on spin-mass interaction



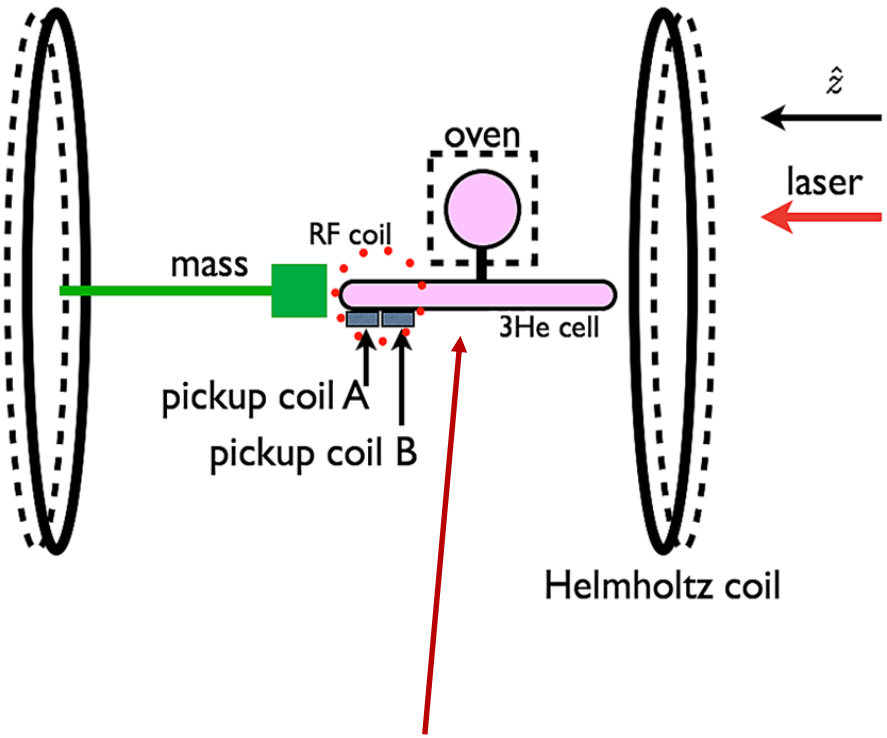
$$\vec{B}_{eff} = \frac{1}{\gamma}\frac{\hbar g_s g_p}{2m}\rho\lambda e^{-\frac{\Delta y}{\lambda}}(1-e^{-\frac{d}{\lambda}})\hat{y}$$

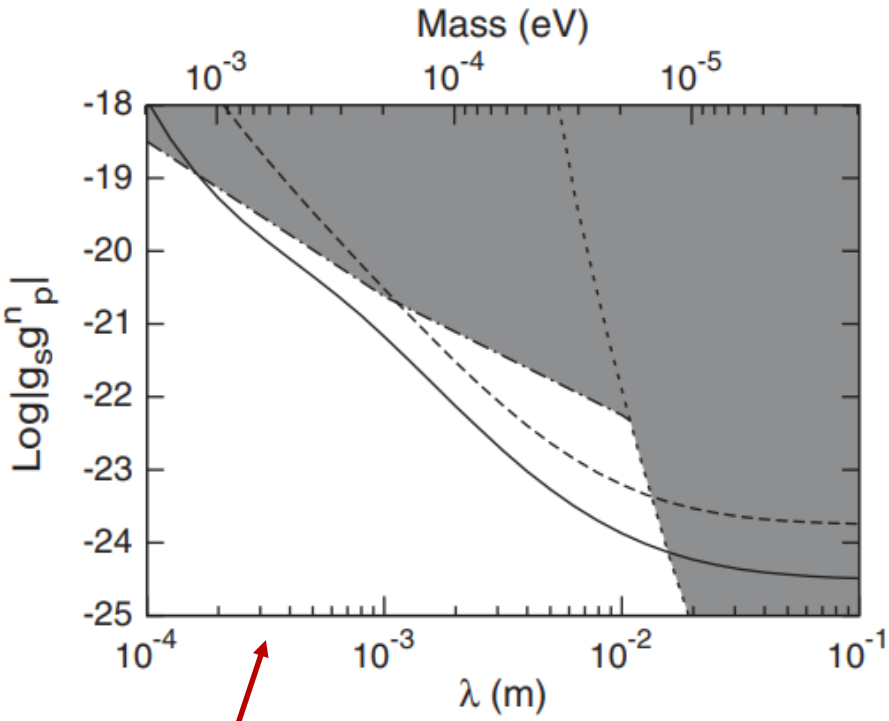
PRD 86, 015001 (2012)



Limitation： The size of the sensor!

Limitation of the sensor (an example)



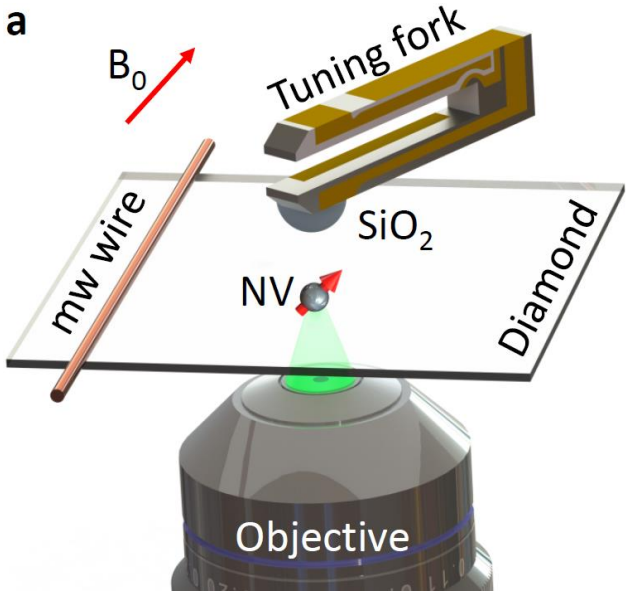


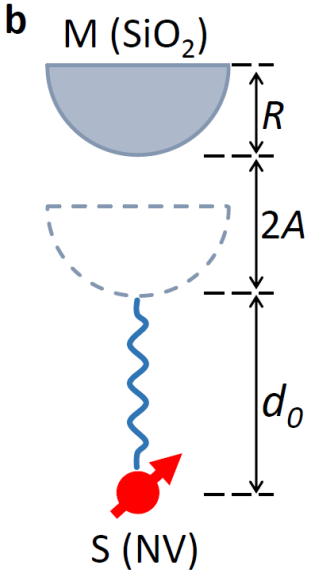
The thickness of the cell (the sensor) is 250 μm. It is very challenging to make it much thinner.

The investigated force range is above ~100 μm

PHYSICAL REVIEW D 87, 011105(R) (2013)

Constrain spin-mass interaction with μm scale





advantages

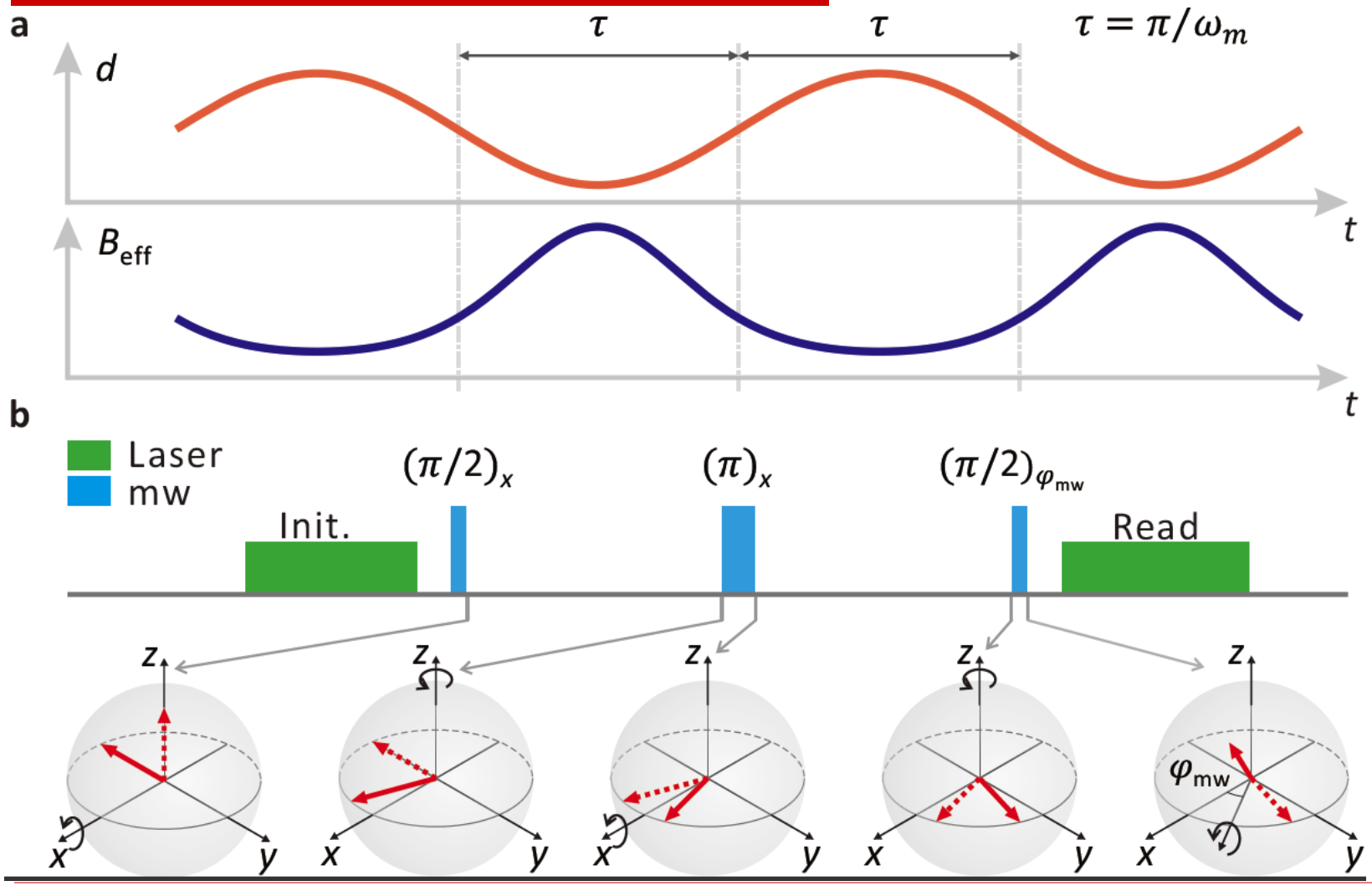
- ✓ Atomic scale
- ✓ Near surface

→ Shorter force range

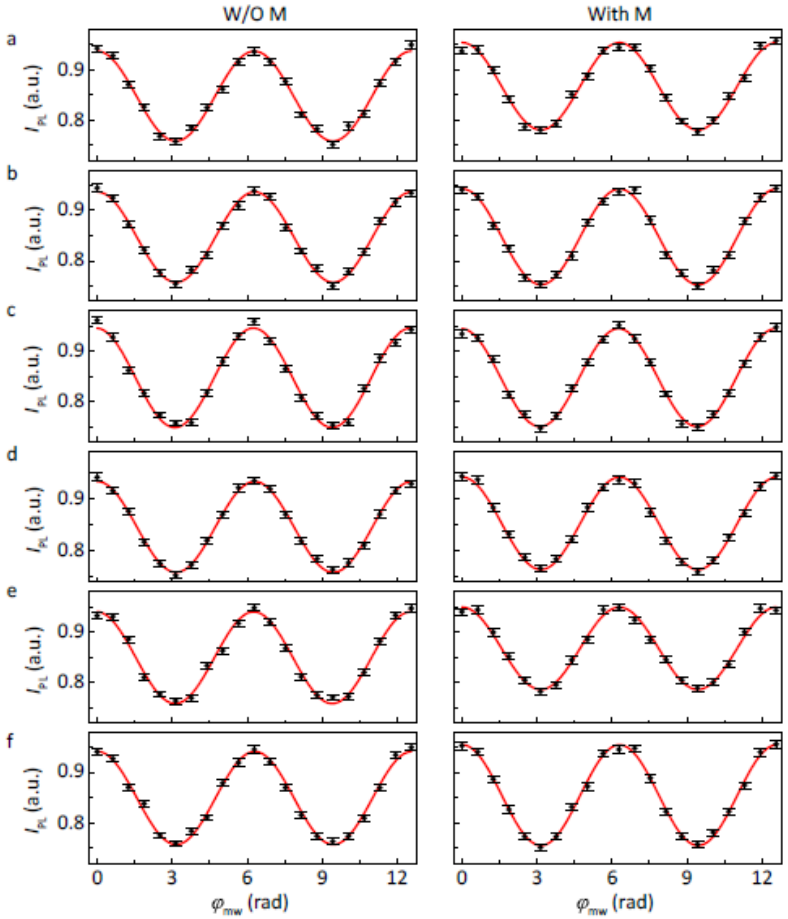
- ✓ Precise quantum control → Good sensitivity
- ✓ NV + AFM → Cancel unwanted signals

Xing Rong et al., Nature Communications, 9:739 (2018)

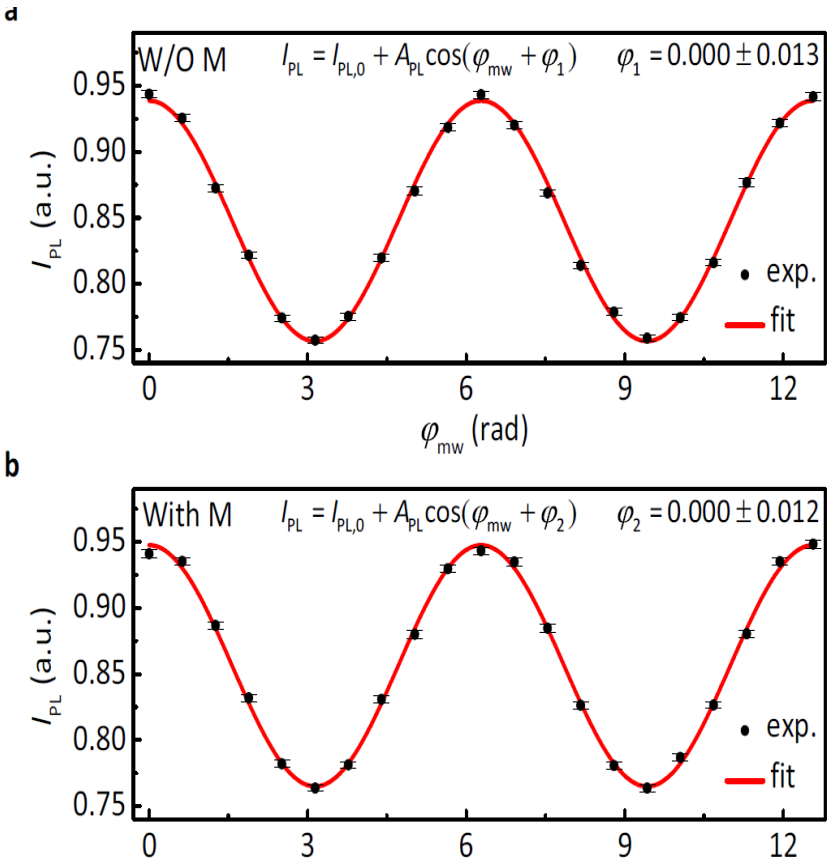
Experimental sequence



Experimental result



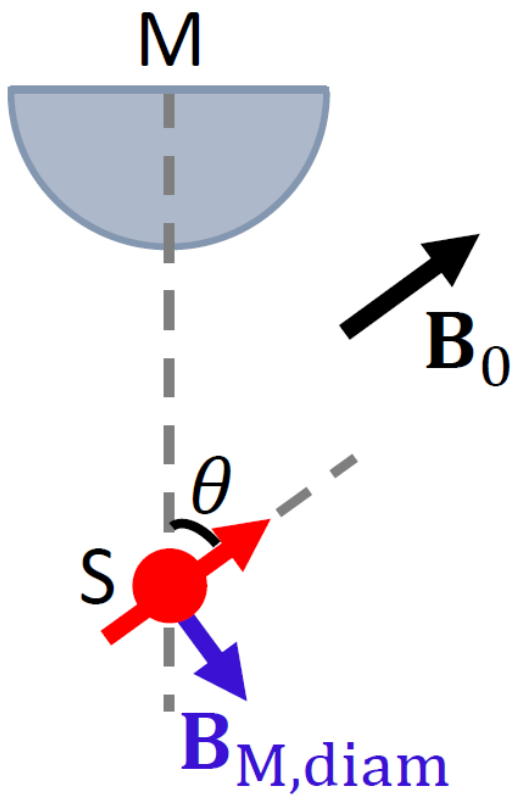
Six separated runs



statistical errors: ～ 0.02 rad

误差分析：抗磁性

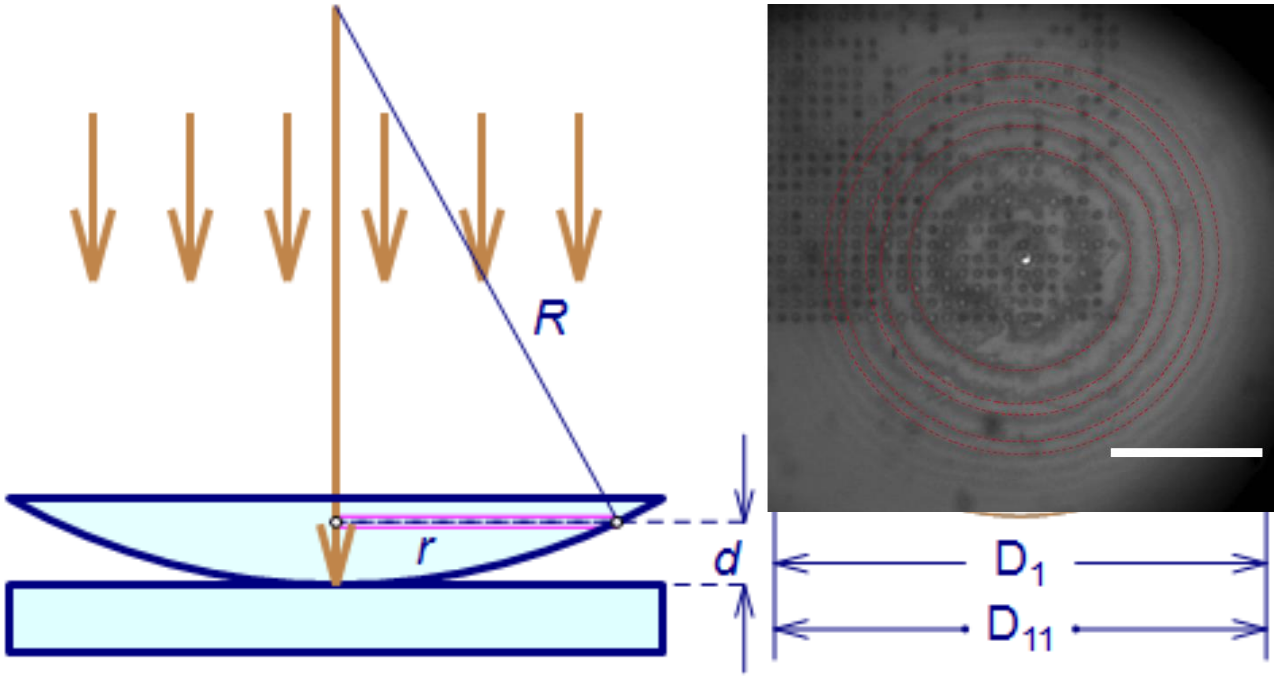
二氧化硅半球抗磁性影响



如果NV正好在半球下方：

- 抗磁性导致的外磁场垂直于NV主轴
- NV 跃迁频率：~ 2 GHz
- $B_{M,diam}$导致的频率移动：~ mHz 对应相位为 10^{-10} rad
- 可以忽略抗磁性影响

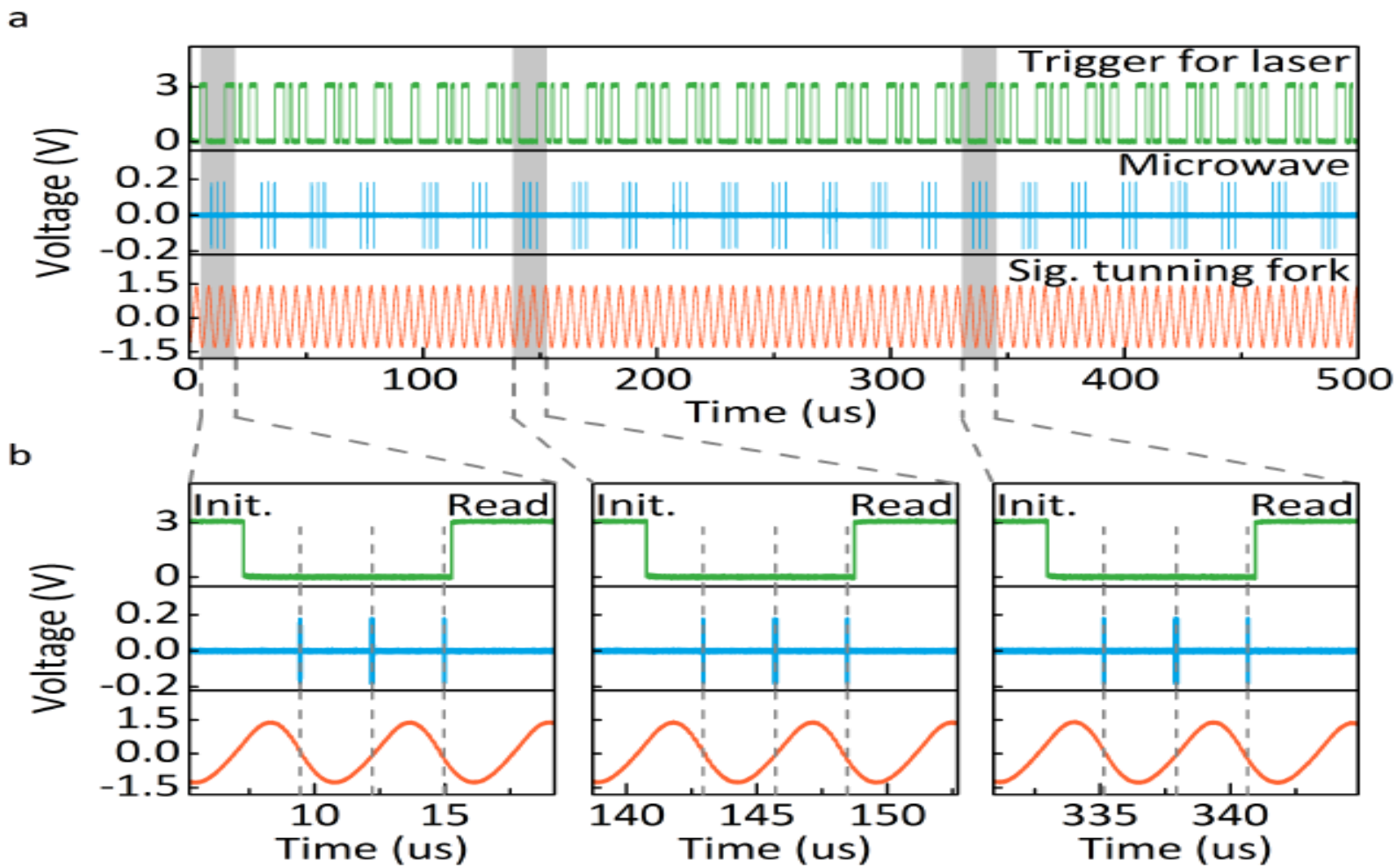
误差分析：定位误差



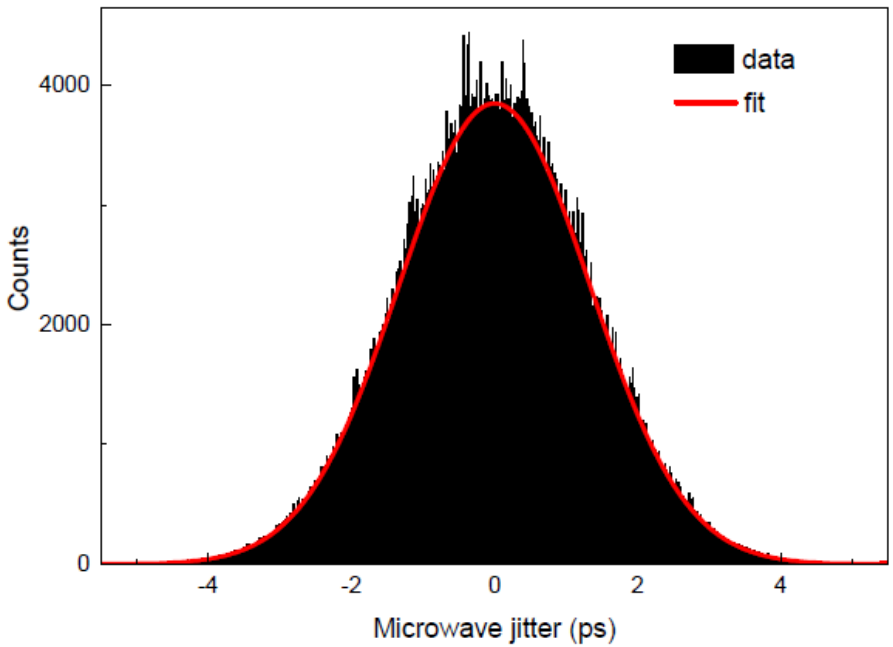
定位误差为 0.7(8) μm

定位误差导致抗磁性对最终相位测量的误差为 3(3) $\times 10^7$ rad 远小于0.02 rad，可以忽略。

误差分析：时序


a
Trigger for laser
Microwave
Sig. tunning fork
Voltage (V)
3
0
0.2
0.0
-0.2
1.5
0.0
-1.5
0
100
200
300
400
500
Time (us)
b
Init.
Read
Voltage (V)
10
15
140
145
150
335
340
Time (us)

误差分析：相位抖动



微波源的相位抖动

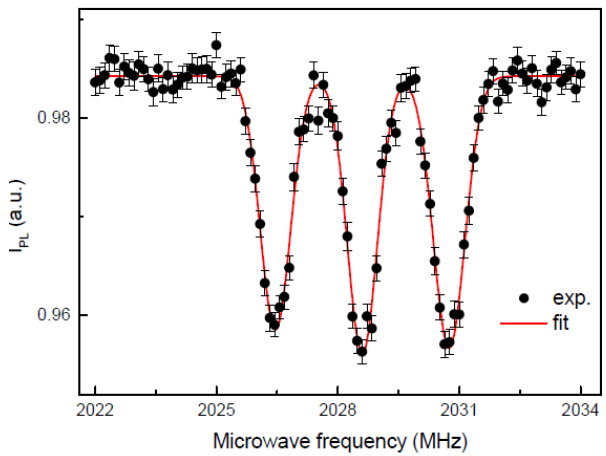
Observer operator: <Sx>

微波源相位抖动导致
观测算符不完美：
<Cos(δ) Sx + Sin(δ) Sy>

相位抖动导致测量误差：
$3.5\times10^{-5} \pm 7.6\times10^{-15}$ rad

远小于 0.02 rad，可以忽略

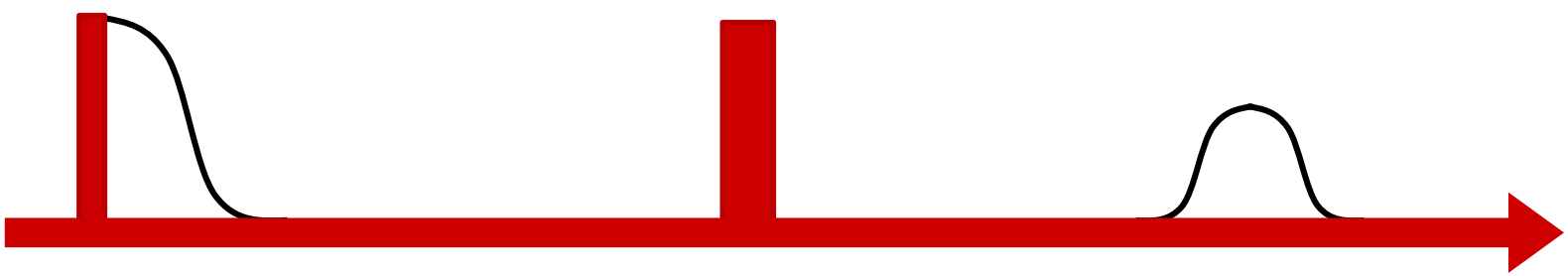
误差分析：退相干效应



核自旋热库诱导的展宽

$T_2^* = 0.67\ \mu s$

使用动力学解耦技术后可以极大提升相干时间至 8.3 μs



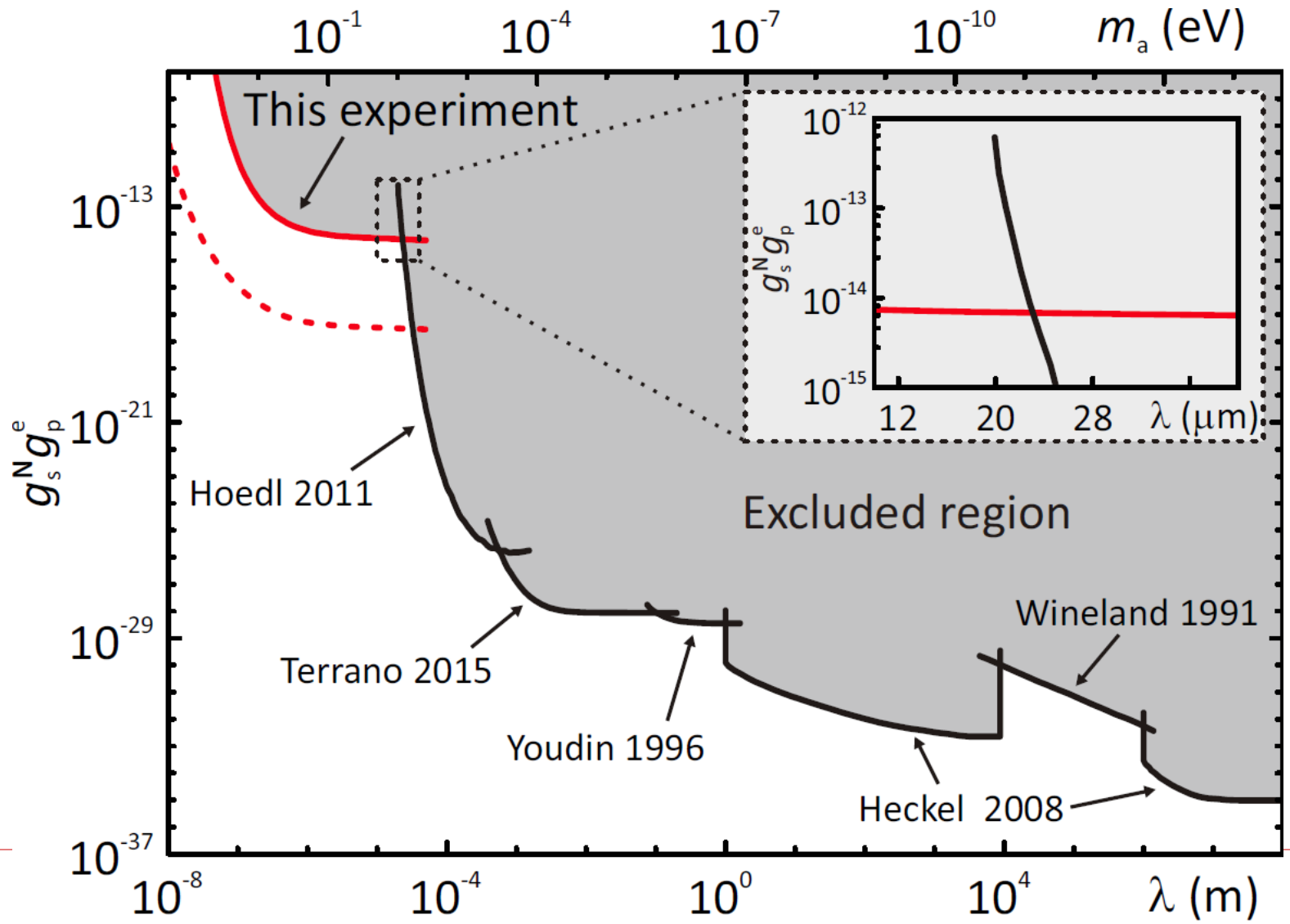
核自旋热库导致的误差 $0 \pm 1.3 \times 10^{-14}$ rad

系统误差分析表

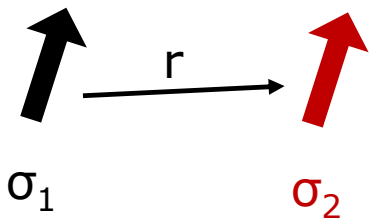
Table 1: Systematic error summary.

Systematic error	Size of effect	Correction to $g_s^N g_p^e$ for $20\ \mu$m
diamagnetism of M	-11.28×10^{-6}	$(5 \pm 5) \times 10^{-20}$
diamagnetism of the tuning fork	-11.28×10^{-6}	$(3.8 \pm 0.3) \times 10^{-20}$
phase jitter of microwave	1.3 ps	$(0.0 \pm 1.7) \times 10^{-27}$
T_2^* dephasing	670 ± 41 ns	$(0.0 \pm 1.9) \times 10^{-27}$
shortest distance between M and S	$0.5 \pm 0.1\ \mu$m	$(0.1 \pm 3.0) \times 10^{-17}$
the amplitude of the modulation of M	41.1 ± 0.1 nm	$(0.0 \pm 1.3) \times 10^{-17}$
the radius of M	$250 \pm 2.5\ \mu$m	$(0.1 \pm 3.7) \times 10^{-18}$
the angle between $\mathbf{B}_{\mathrm{eff}}$ and NV axis	$54.7 \pm 3°$	$(0.4 \pm 4.2) \times 10^{-16}$

约束


10^{-1}
10^{-4}
10^{-7}
10^{-10}
m_a (eV)
This experiment
10^{-13}
10^{-21}
10^{-29}
10^{-37}
$g_s^N g_p^e$
Hoedl 2011
Terrano 2015
Youdin 1996
Heckel 2008
Wineland 1991
Excluded region
10^{-12}
10^{-13}
10^{-14}
10^{-15}
$g_s^N g_p^e$
12
20
28
λ (μm)
10^{-8}
10^{-4}
10^{0}
10^{4}
λ (m)

Constraint on exotic interaction between electrons



Magnetic dipole-dipole coupling

$$-\frac{\mu_0\gamma_e\gamma_e\hbar^2}{16\pi r^3}[3(\vec{\sigma_1}\cdot\hat{r})(\vec{\sigma_2}\cdot\hat{r})-(\vec{\sigma_1}\cdot\vec{\sigma_2})],$$

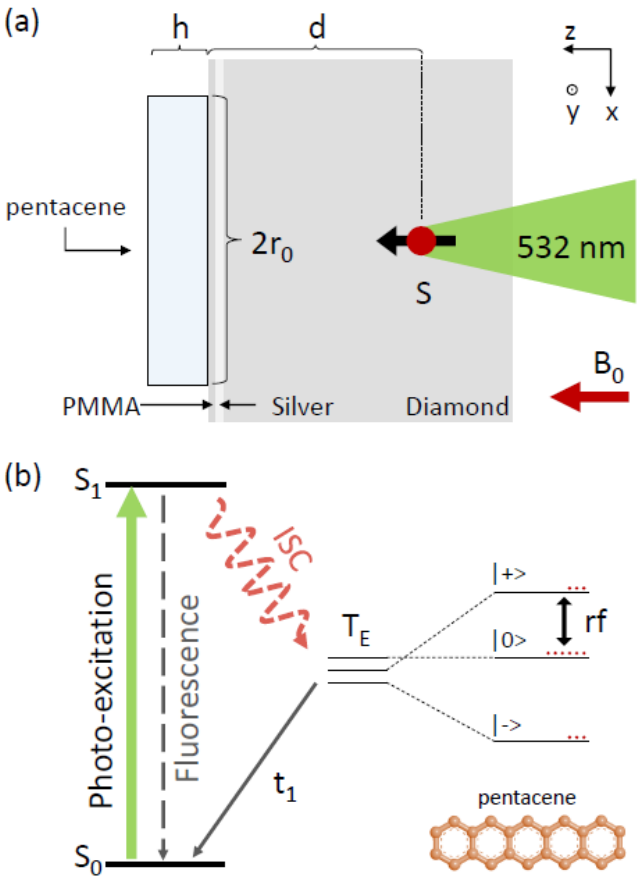
Exotic dipole-dipole coupling [1]

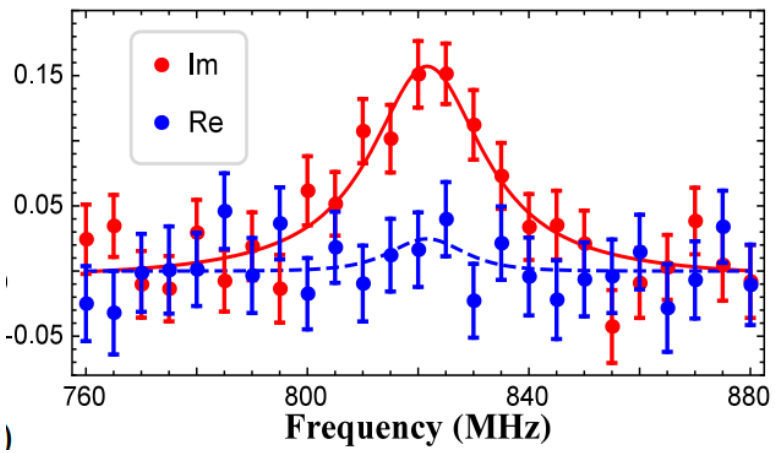
$$\frac{g_A^e g_A^e}{4\pi\hbar c}\frac{\hbar c}{r}(\vec{\sigma_1}\cdot\vec{\sigma_2})e^{-\frac{r}{\lambda}},$$

We now experimentally search for this type of exotic dipole-dipole coupling [2].

[1] B. A. Dobrescu and I.Mocioiu, J. High Energy Phys. 11, 005 (2006)
[2] Xing Rong et al., arXiv:1804.07026 (2018)

Experiment technique and setup

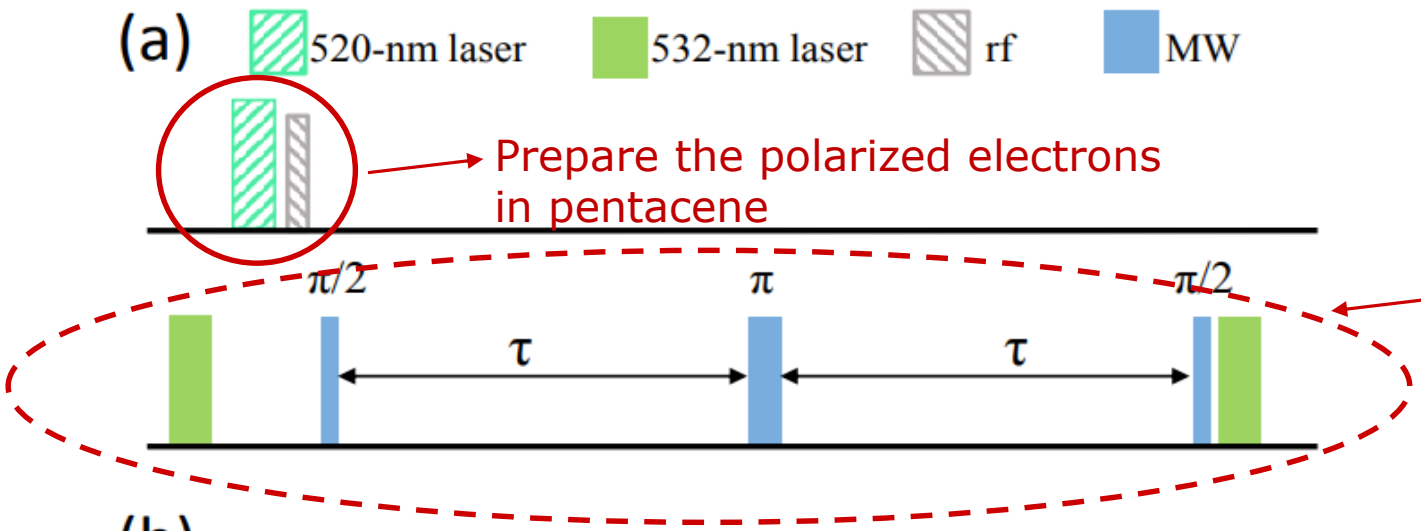


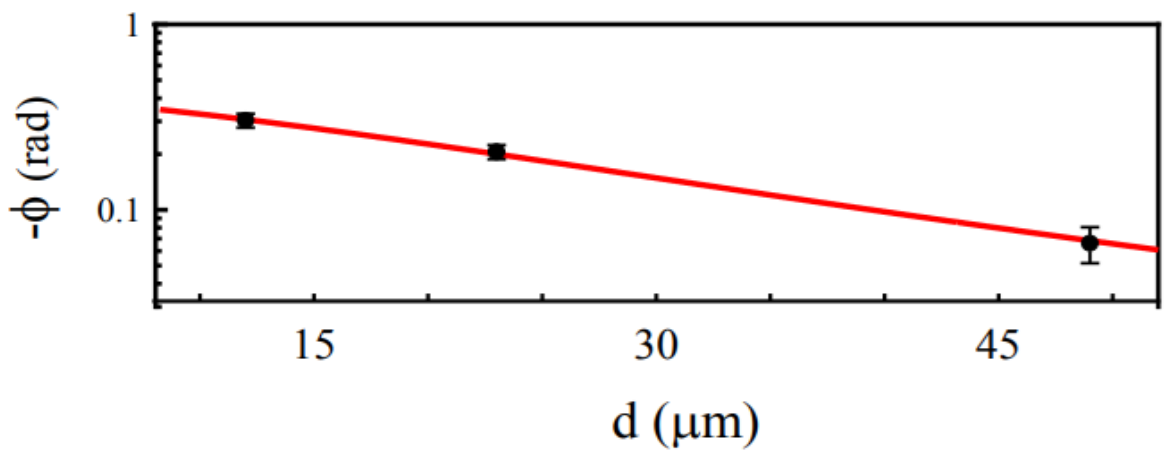


The measured polarized signal

T. Xie, et al., arXiv:1706,03939 (2017).

Experimental pulse sequence for searching exotic interactions





The fitting provides:

$$g_A^e g_A^e / 4\pi\hbar c = (0.04 \pm 2.16) \times 10^{-19}.$$

Xing Rong et al., arXiv:1804.07026 (2018)

Experimental pulse sequence for searching exotic interactions

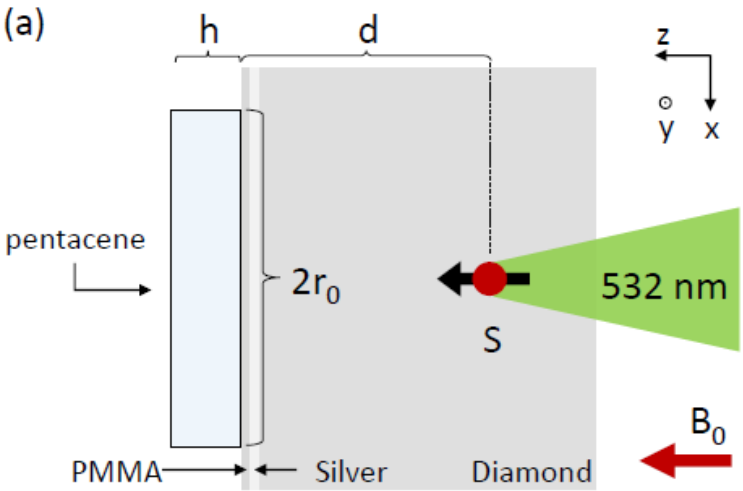
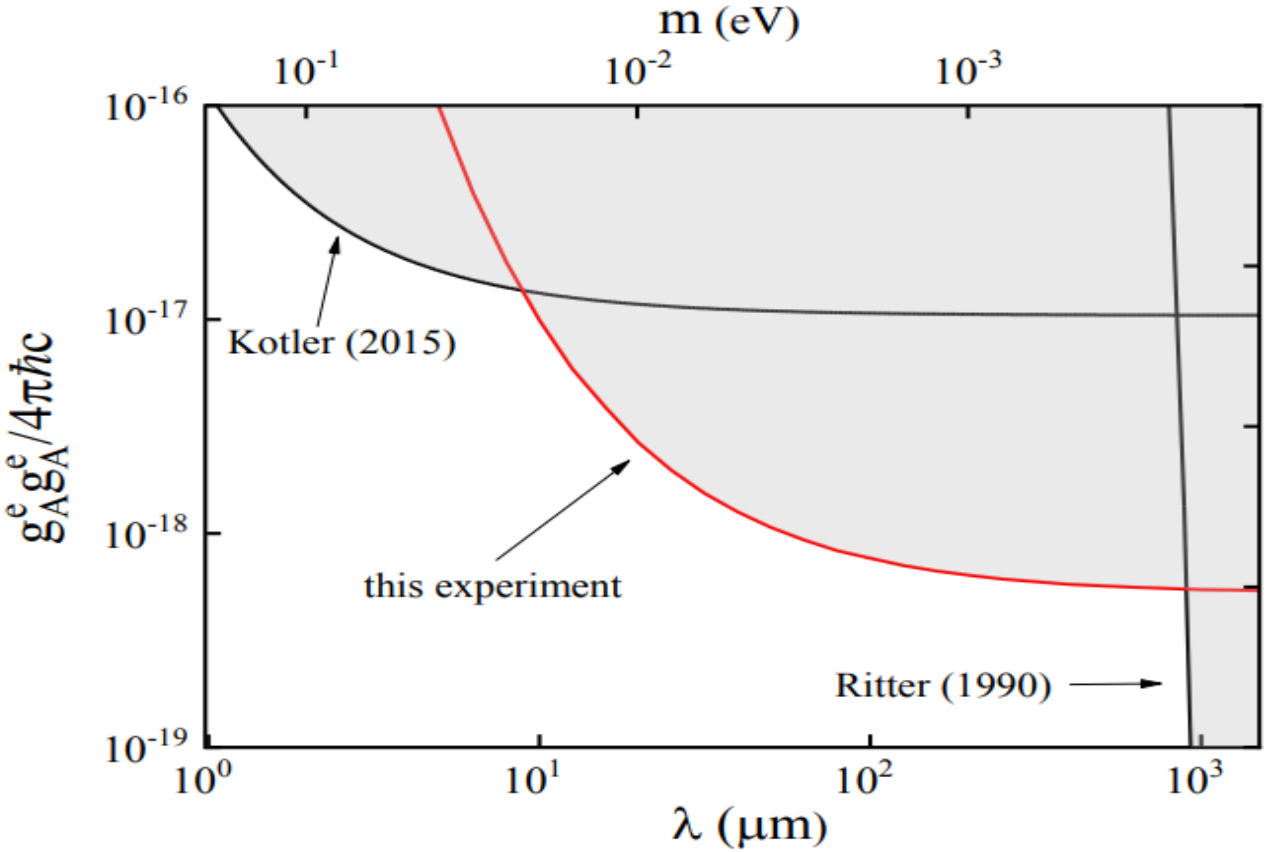


TABLE I. Summary of the systematic errors in our experiment. The corrections to $g_A^e g_A^e/4\pi\hbar c$ at $\lambda = 500\ \mu m$ are listed.

Systematic error	Size of effect	Corrections
Deviation in x-y plane	$0 \pm 10\ \mu m$	$(0.6 \pm 1.3) \times 10^{-20}$
Distance	$12 \pm 1.3\ \mu m$	$(-1 \pm 80) \times 10^{-22}$
Decoherence of S	$405 \pm 23\ \mu s$	$(8.0 \pm 1.0) \times 10^{-22}$
Decay time	$7 \pm 1\ \mu s$	$(5 \pm 36) \times 10^{-21}$
Radius	$35 \pm 5\ \mu m$	$(3 \pm 7) \times 10^{-21}$
Thickness	$15 \pm 3\ \mu m$	$(9 \pm 45) \times 10^{-21}$
Total		$(2.4 \pm 6.0) \times 10^{-20}$

Xing Rong et al., arXiv:1804.07026 (2018)

New constraint on exotic interaction between electrons



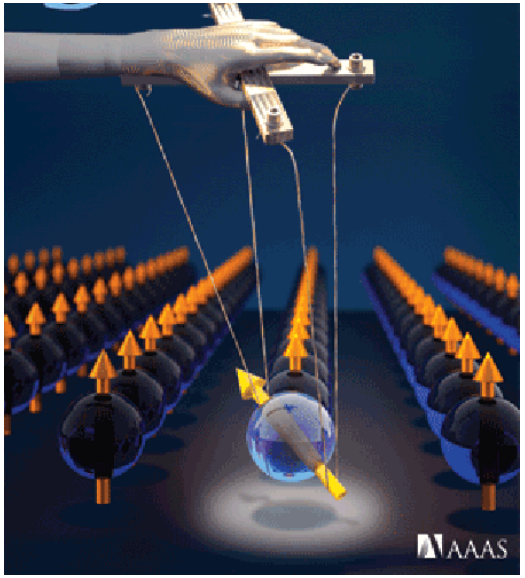
We established upper limits on this type of exotic spin-dependent interaction in the force range 10 to 900 μm.

Xing Rong et al., arXiv:1804.07026 (2018)

总结

宏观世界 “陀螺”

空间尺度：厘米
时间尺度：秒
特征频率：百赫兹



微观世界 “自旋”

空间尺度：纳米
时间尺度：纳秒
特征频率：吉赫兹

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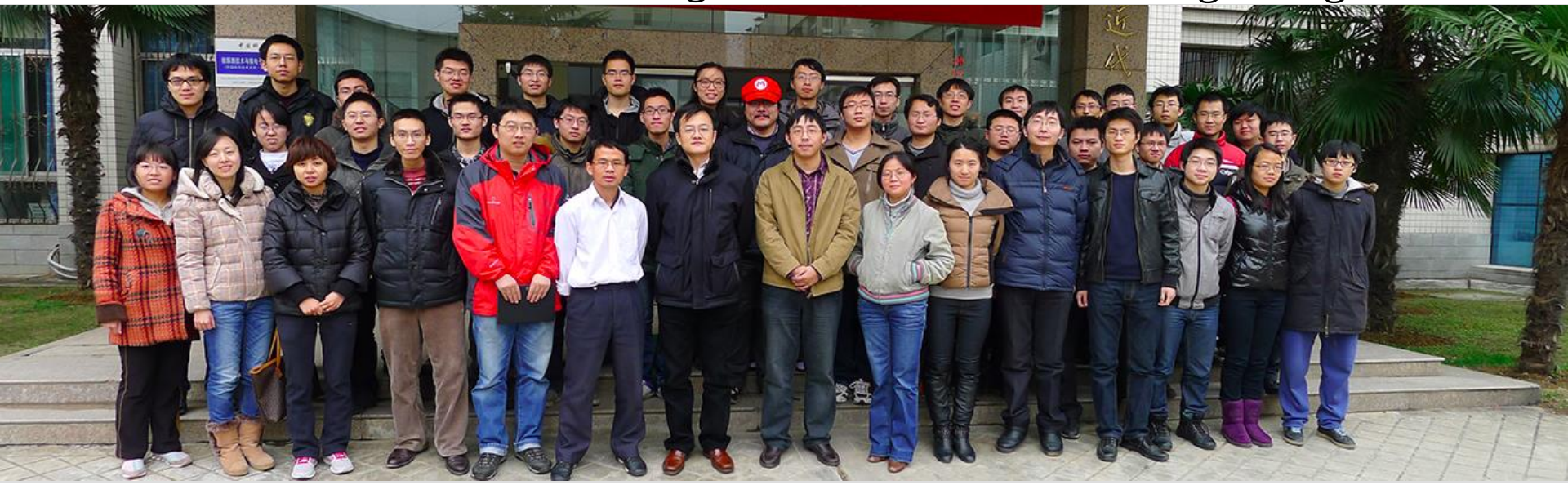

Hope for collaborations with you!

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The Ministry of Science and Technology of the People's Republic of China