# Searching for exotic spin dependent interactions using magnetically levitated force sensor

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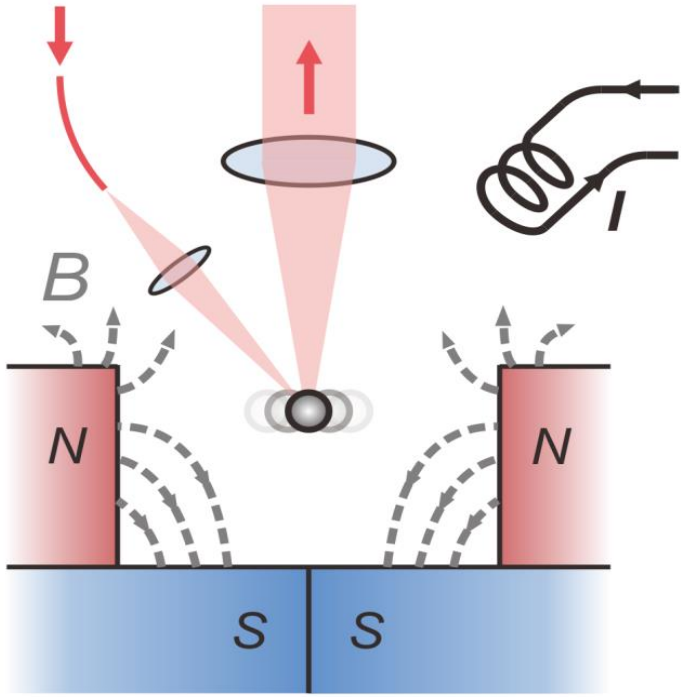
# Force measurement based on magnetic levitation

Since 2018, we develop experimental techniques for precision metrology based on **Mag-levitation**




**Pu Huang's Lab**
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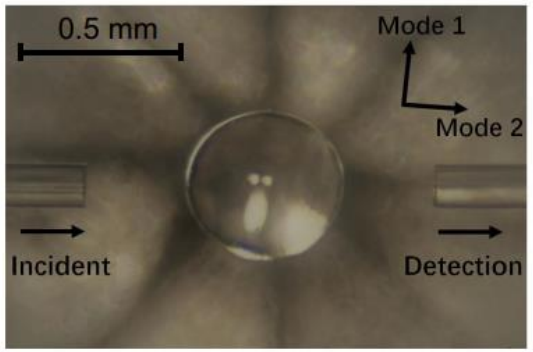
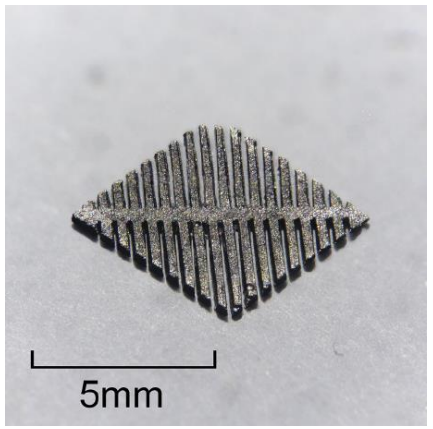
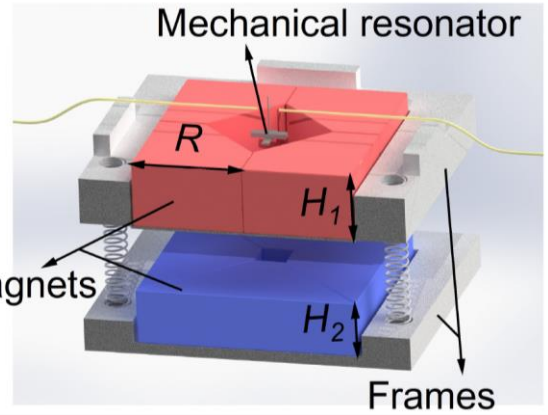
Micro-particle at 3 K (Phys. Rev. Applied 2020)




Sub-mm sphere for inertial sensing (Phys. Rev. Applied 2021)




Mechanical dissipation suppression (Phys. Rev. Res. 2023)




Frequency-adjustable force sensor (2025)

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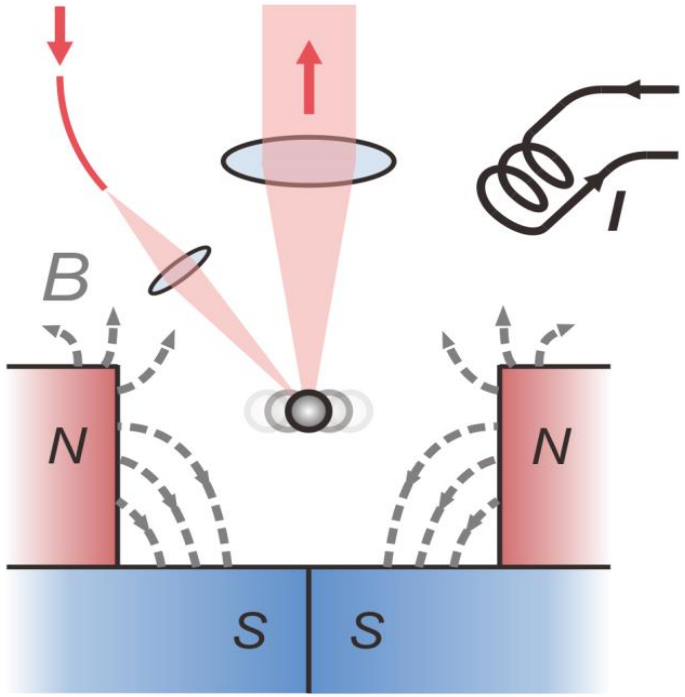


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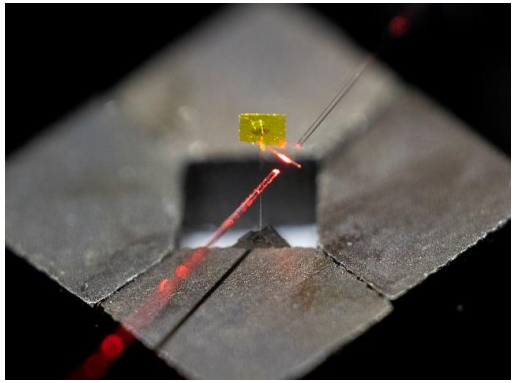
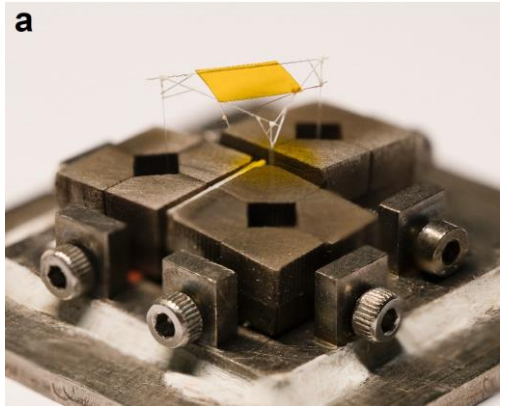
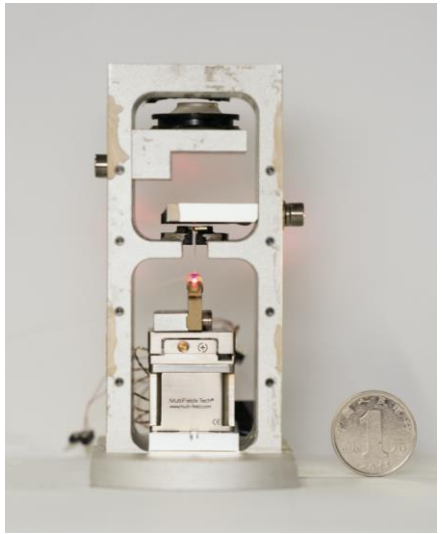


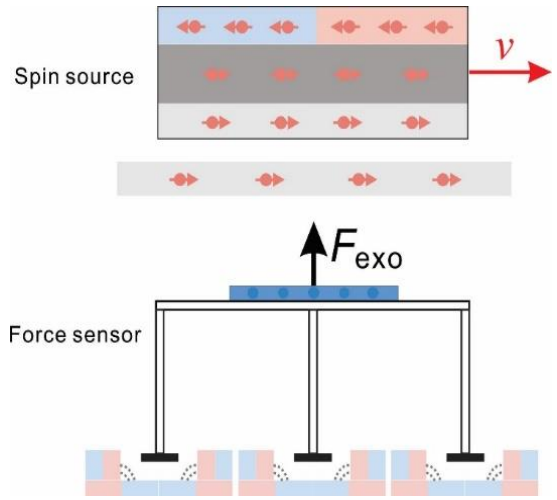
Search for dark energy fifth force (Nat. Phys. 2022)




Search for dark energy fifth force (Nat. Astron. 2025)



Miniaturized gravimetry (Phys. Rev. Lett. 2024)




Searching for exotic interactions ( Phys. Rev. Lett. 2025)

# Outline

- **Exotic spin dependent interactions**
- **Magnetically levitated force sensor**
- **Searching for the exotic interactions**
- **Summary**

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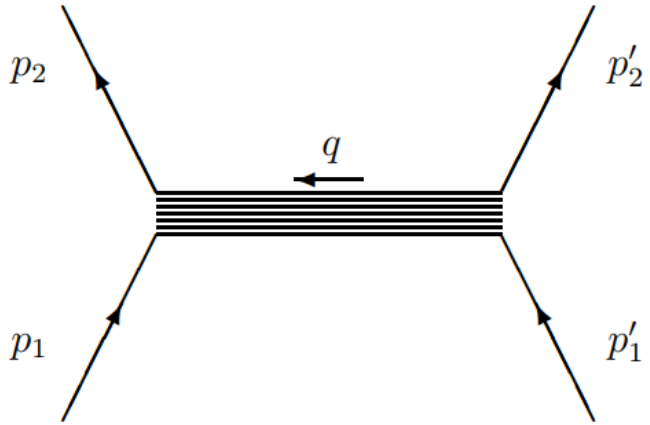
# Exotic spin dependent interactions

The discovery of a new force with a range longer than about a micrometer would have a tremendous impact on our understanding of nature.

**Long-range forces between two fermions**




$$\mathcal{A}\left(\vec{q},\vec{P}\right)=\mathcal{P}(\vec{q}^{\,2})\sum_{i=1}^{16}\mathcal{O}_i\left(\vec{q},\vec{P}\right)\,f_i\left(\vec{q}^{\,2}/m^2,\,\vec{P}^2/m^2\right)$$

**16 independent scalars that include all possible spin configurations**

**Forces between one polarized and one unpolarized object :**

Parity-even

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

Parity-odd

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

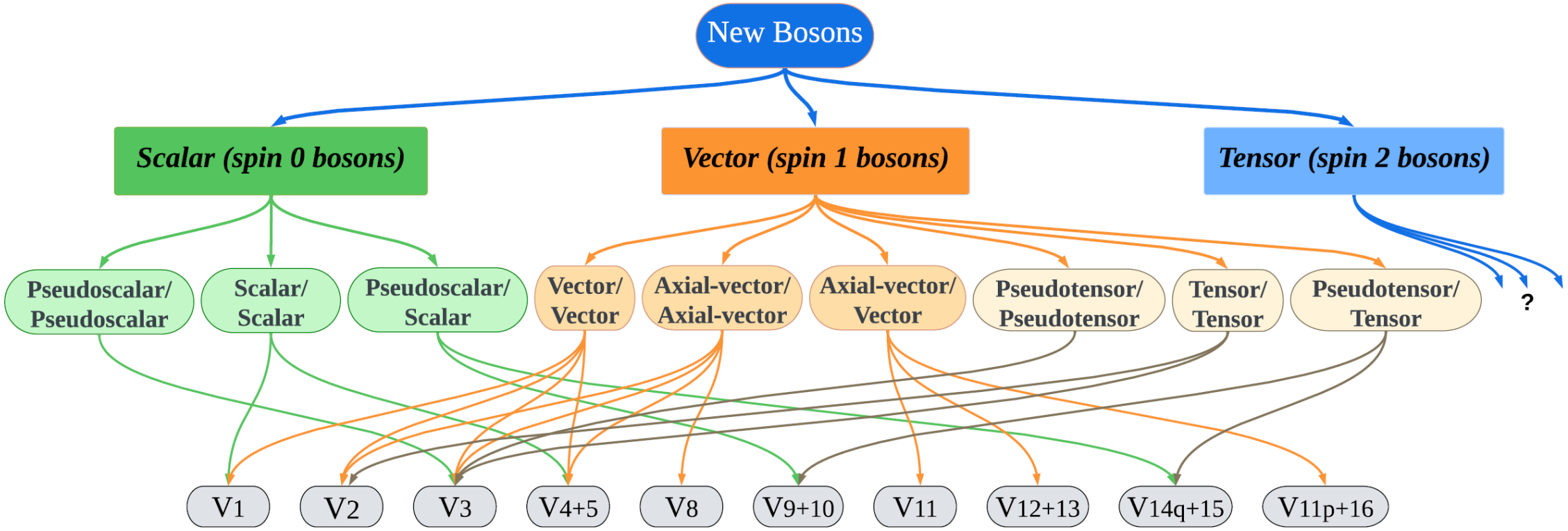
$$\mathcal{V}_{12,13}=\frac{1}{2r}\left(\vec{\sigma}\pm\vec{\sigma}\,'\right)\cdot\vec{v}\,y(r)$$

J. High Energy Phys. 11(2006) 005.

# Exotic spin dependent interactions

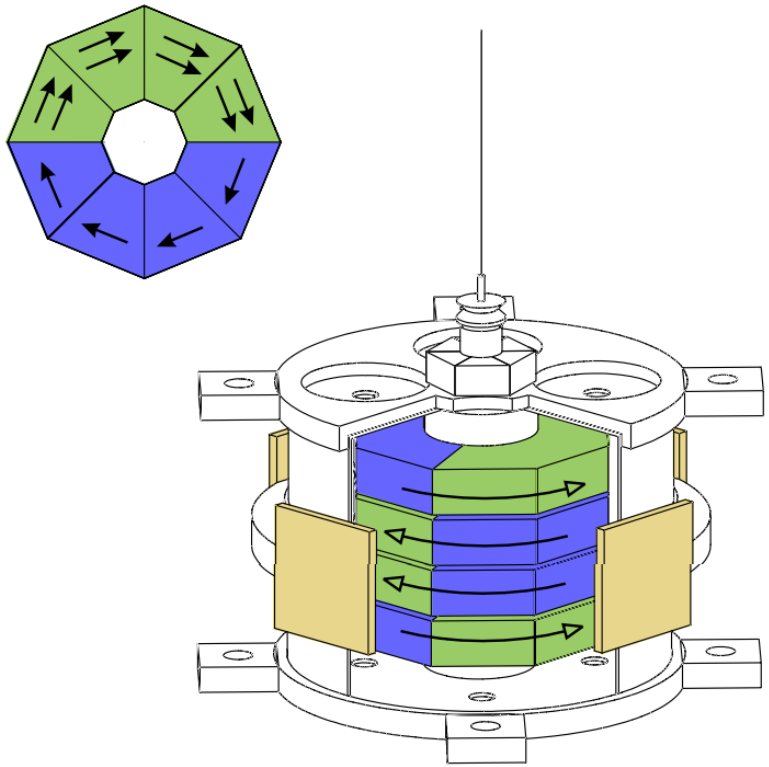
## Interactions through exchange of light bosons

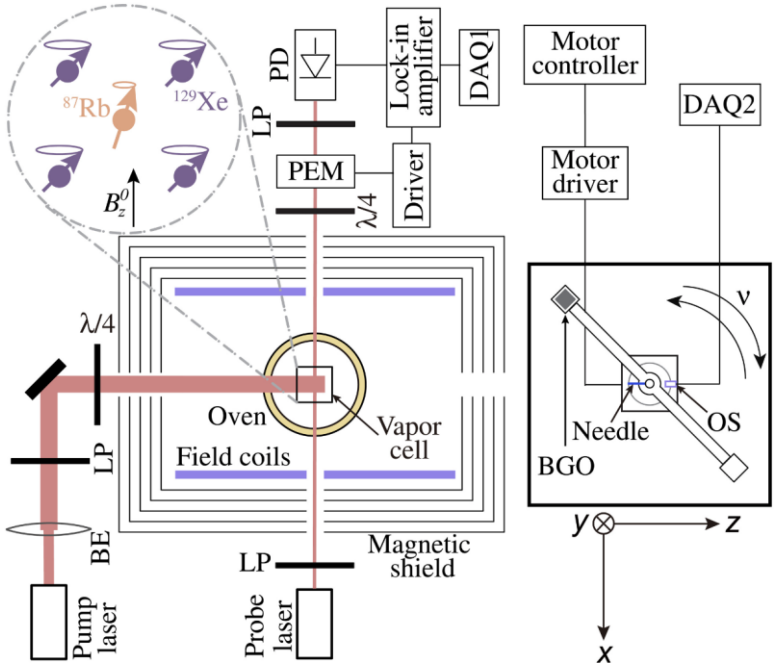
Such as: axions, ALPs, dark photons, Z' bosons, etc.

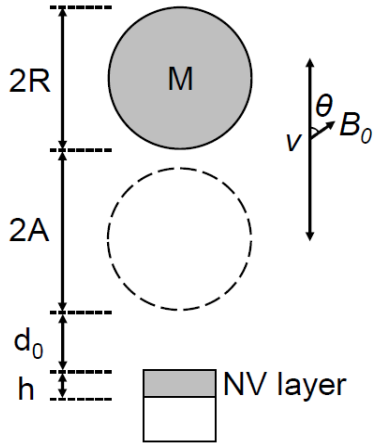


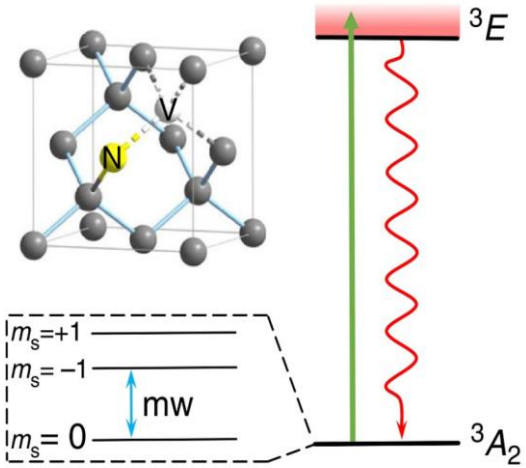

Physical couplings between fermions and bosons

# Experiments for the Exotic spin dependent interactions: dedicated source-sensor experiments





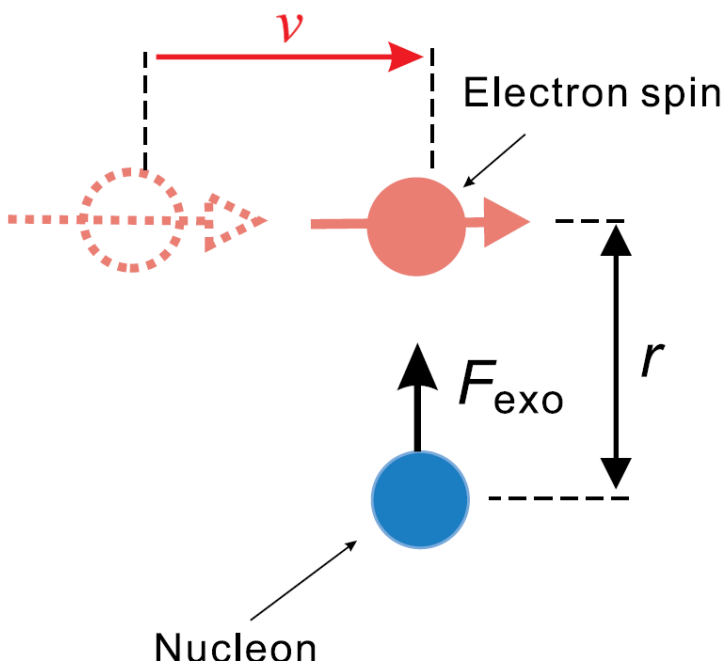



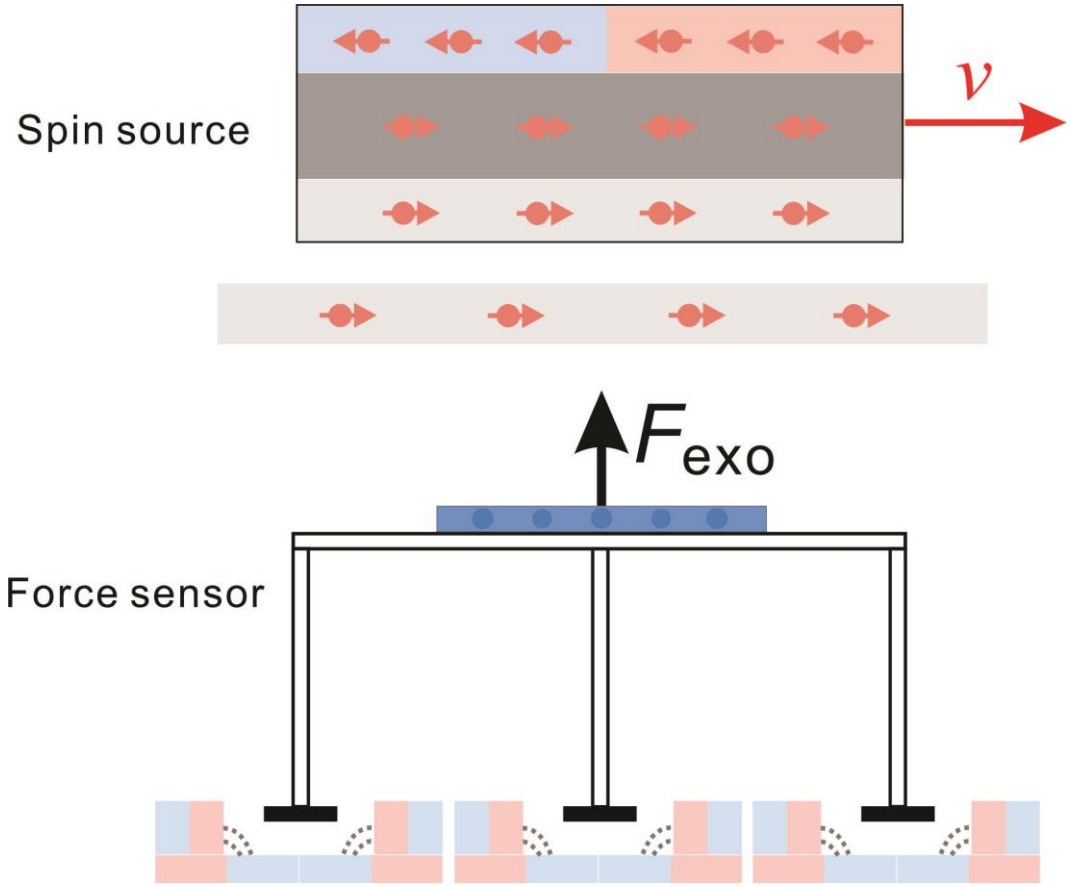

**Torsional balance** **spin-exchange relaxation-free magnetometers** **NV centers**

# Our methods: Mag-levitation Force sensor

## Velocity and Spin Dependent Exotic Interaction at the Millimeter scale




$$V = g_A^e g_V^N \frac{\hbar}{4\pi r}(\hat{\boldsymbol{\sigma}} \cdot \boldsymbol{v}) e^{-\frac{r}{\lambda}}.$$



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# Mechanism of diamagnetically levitation

Principle：

Magnetic + gravitational energy:

$$U(\mathbf{x}) = -\frac{\chi}{2\mu_0} V |\boldsymbol{B}(\mathbf{x})|^2 + mgz$$

Thermal energy:

$$k_B T$$

Trapping condition:

$$U \gg k_B T$$

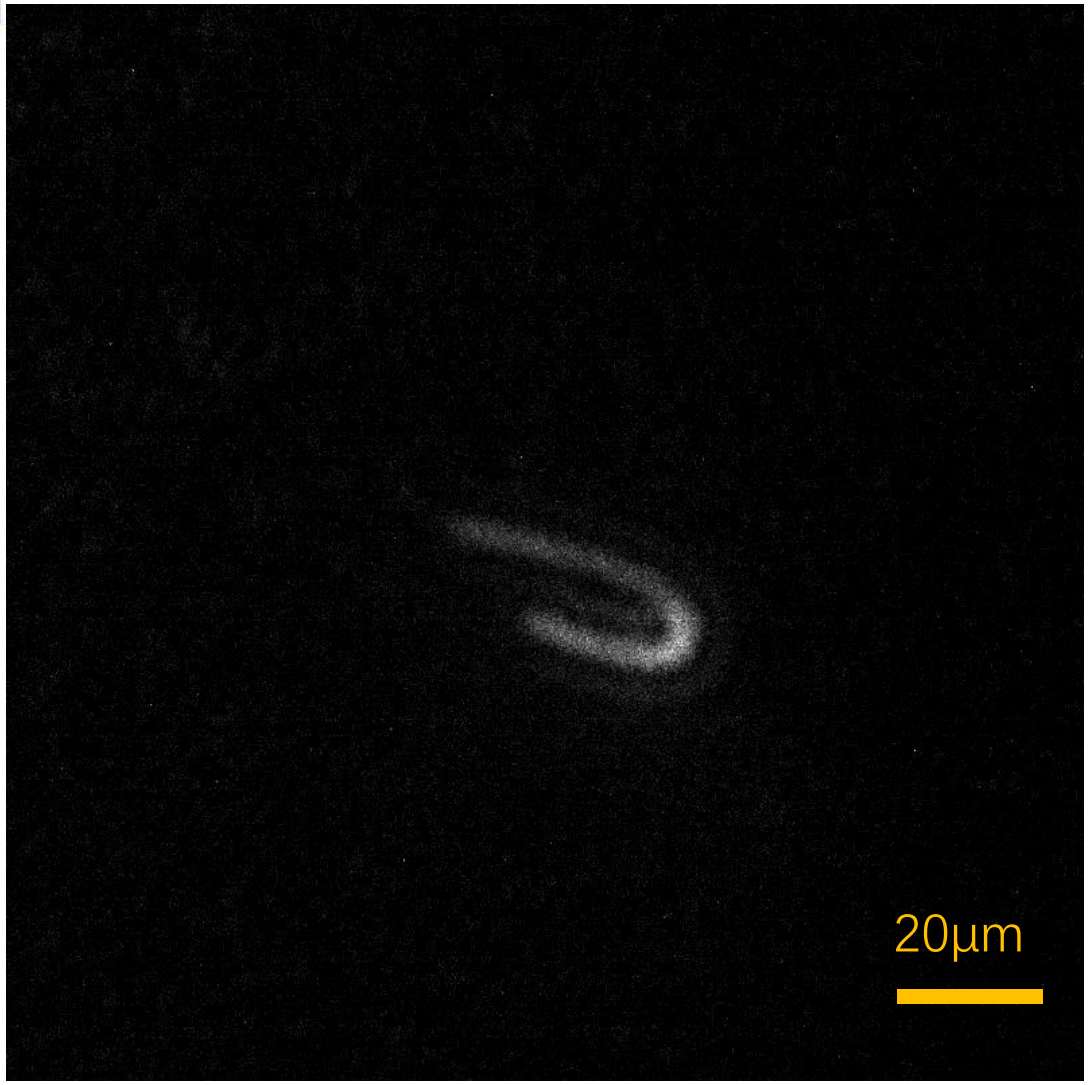

Magnetic energy of a frog : U~$10^{-9}$J

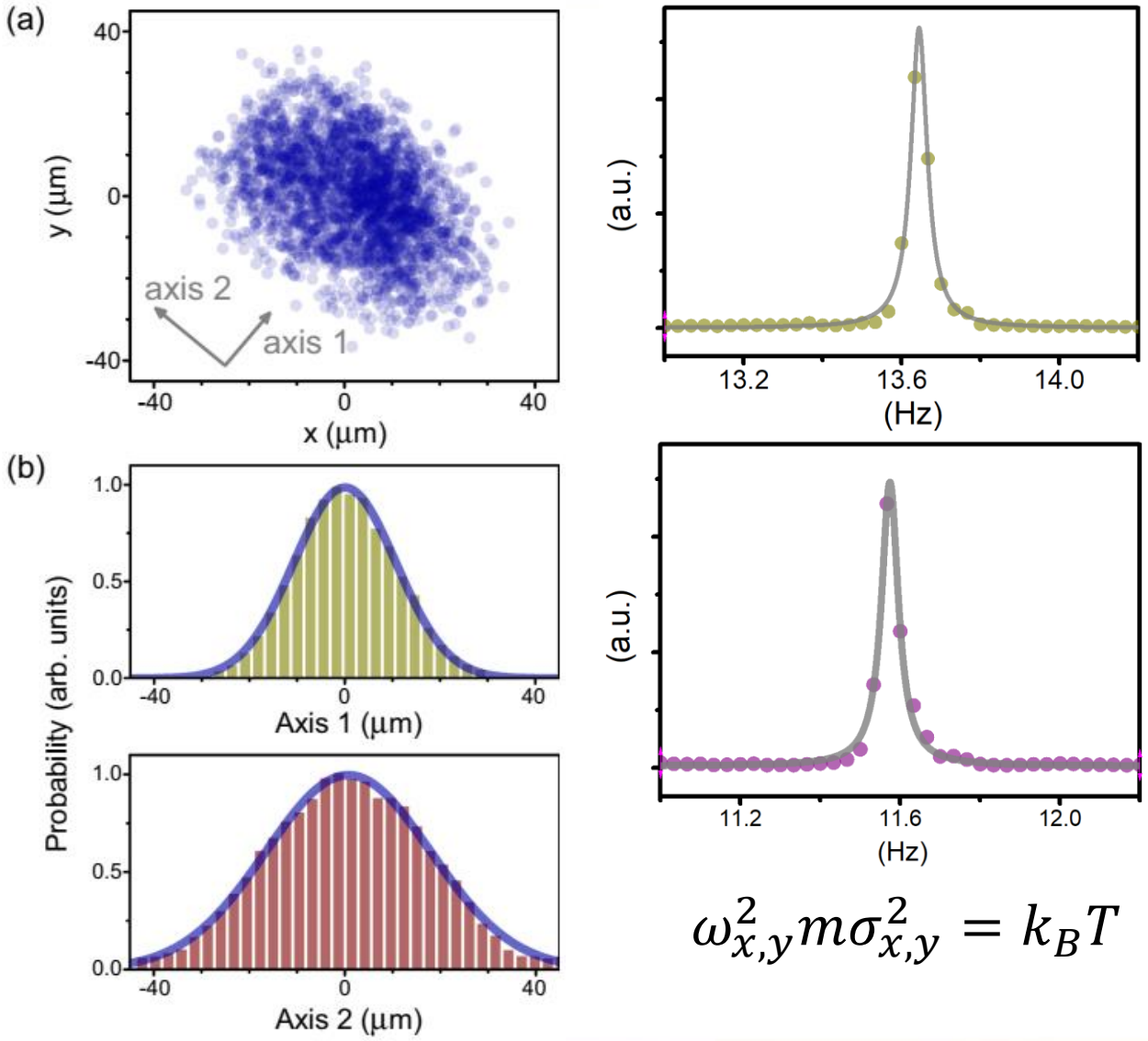
Magnetic energy of a particle with 1um diameter : U~$10^{-21}$J

Thermal energy @300K: $k_B$T~$10^{-21}$J

M.V. Berry and A.K. Geim, Eur. J. Phys. 18 (1997)

# Motion measurement

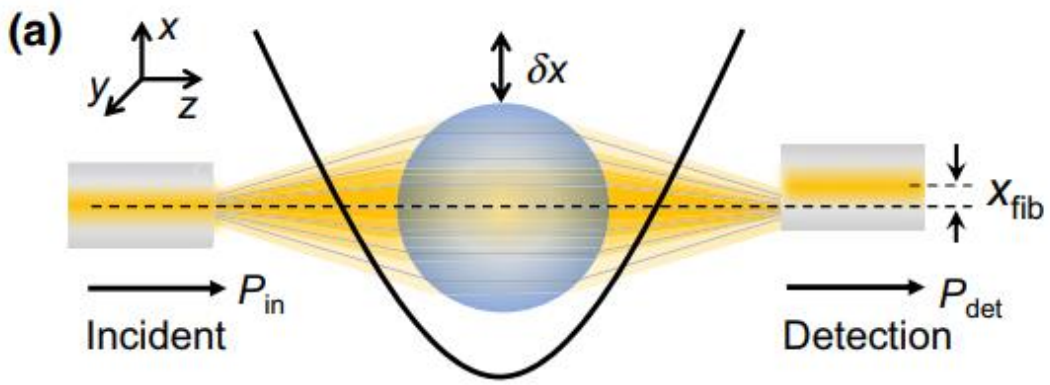


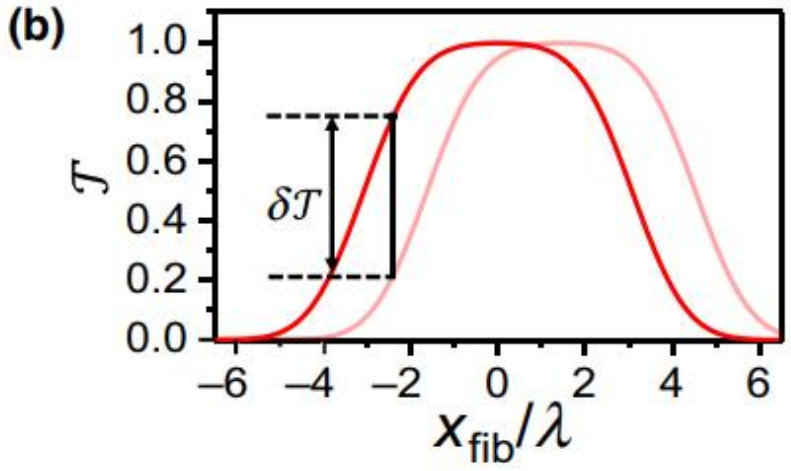



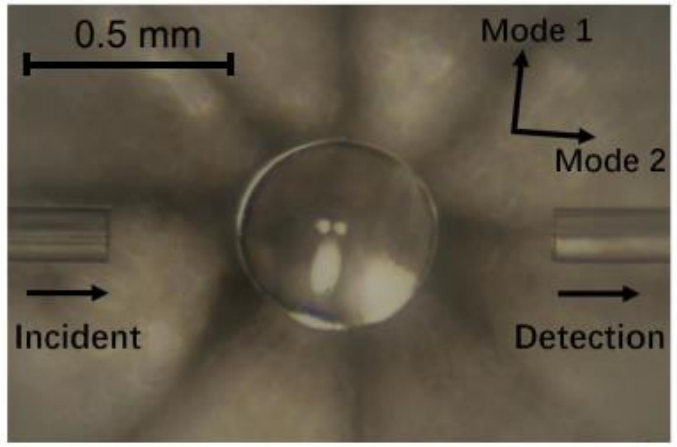

$$\omega_{x,y}^2 m\sigma_{x,y}^2 = k_B T$$

Phys. Rev. Res. **2**, 013057 (2020)

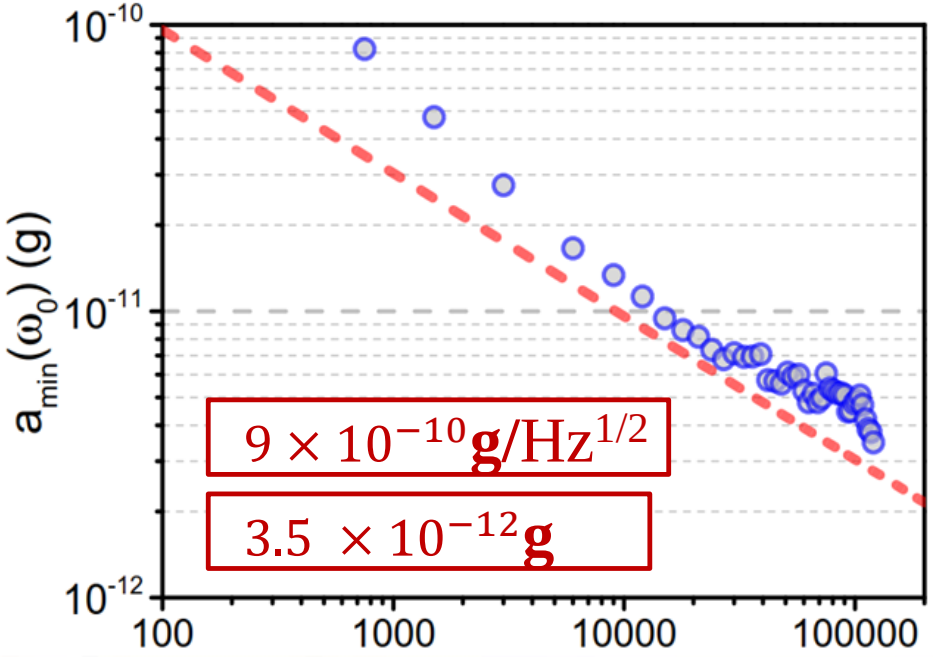
# Millimeter and sub-millimeter oscillator




Diameter: 0.5 mm
Mass: 80 ug



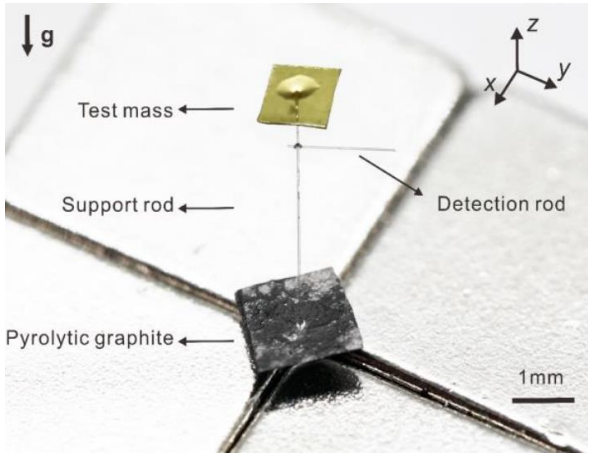

**Acceleration sensitivity** $S_{aa} = \sqrt{4k_B T\gamma/m}$

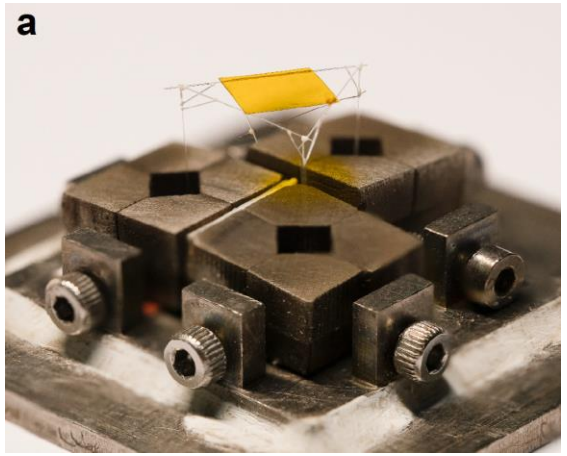


Phys. Rev. Applied **12,** 044017 (2021)

# Millimeter and sub-millimeter oscillator

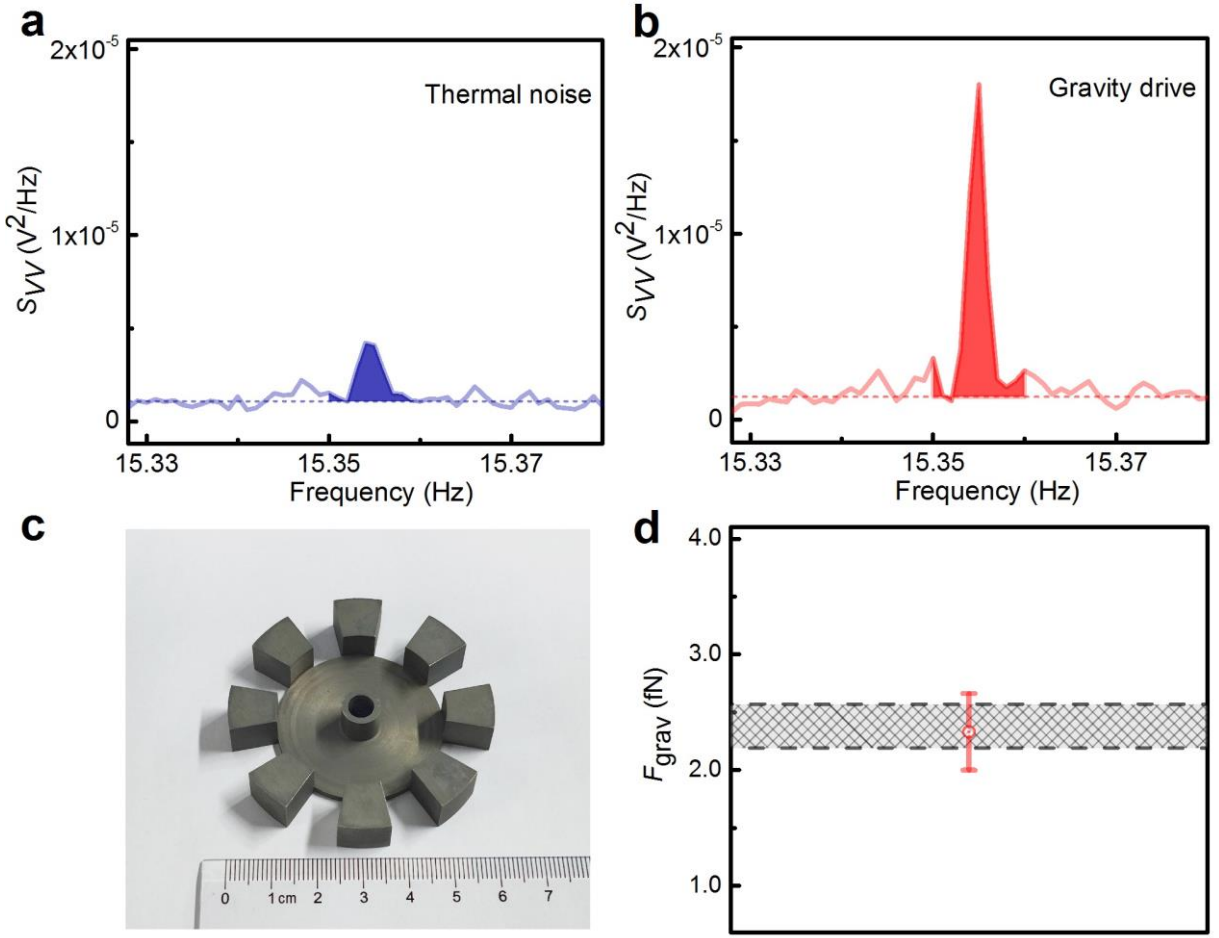
## Mag-Levitation Force sensors




Mass: 0.35 mg
Frequency: 10.8 Hz
$S_{aa} = 5 \times 10^{-9}\ \mathrm{g}/\sqrt{\mathrm{Hz}}$

Mass: 5.4 mg
Frequency: 15.3 Hz
$S_{aa} = 5 \times 10^{-10}\ \mathrm{g}/\sqrt{\mathrm{Hz}}$



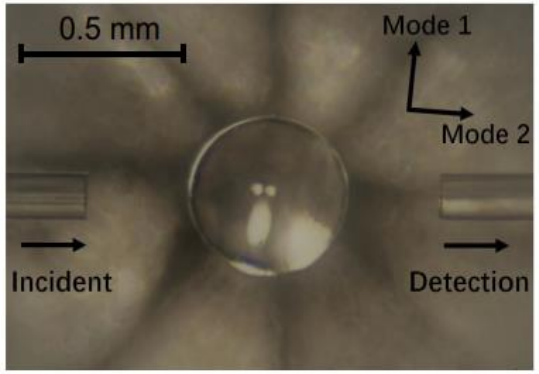

Newtonian gravity measurements: $2.3 \pm 0.3$ fN

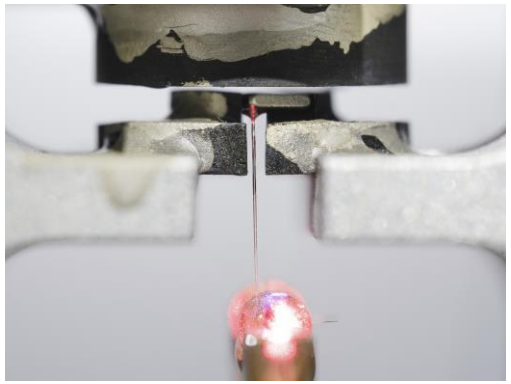


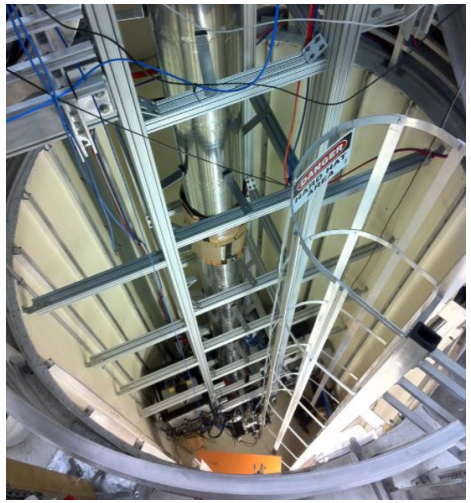
Peiran Yin et al., *Nat. Phys.* **18**, 1181 (2022) Peiran Yin et al., *Nat. Astron.* (2025)

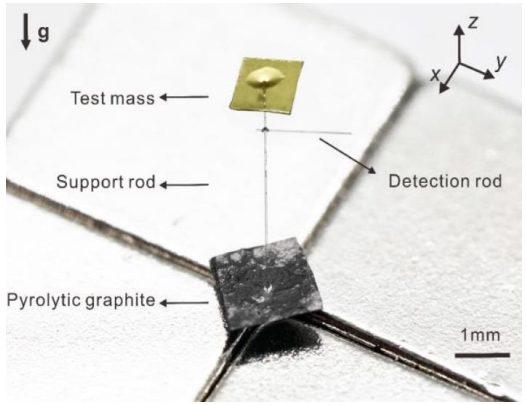
# Acceleration sensitivity

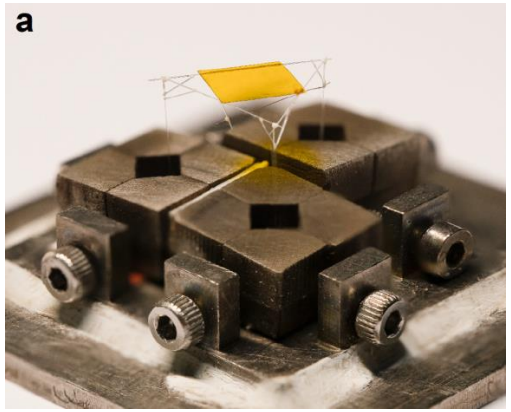
## Comparisons with other systems








**LIGO**
**System size: >4km; Sensitivity: ~$10^{-15}$g/Hz$^{1/2}$**

**Cold atom Interferometry**
**System size: >10m; Sensitivity: ~$10^{-10}$g /Hz$^{1/2}$**

**Magnetic levitation system:**
**System size: <1mm; Sensitivity: ~ $10^{-11}$g/Hz$^{1/2}$**

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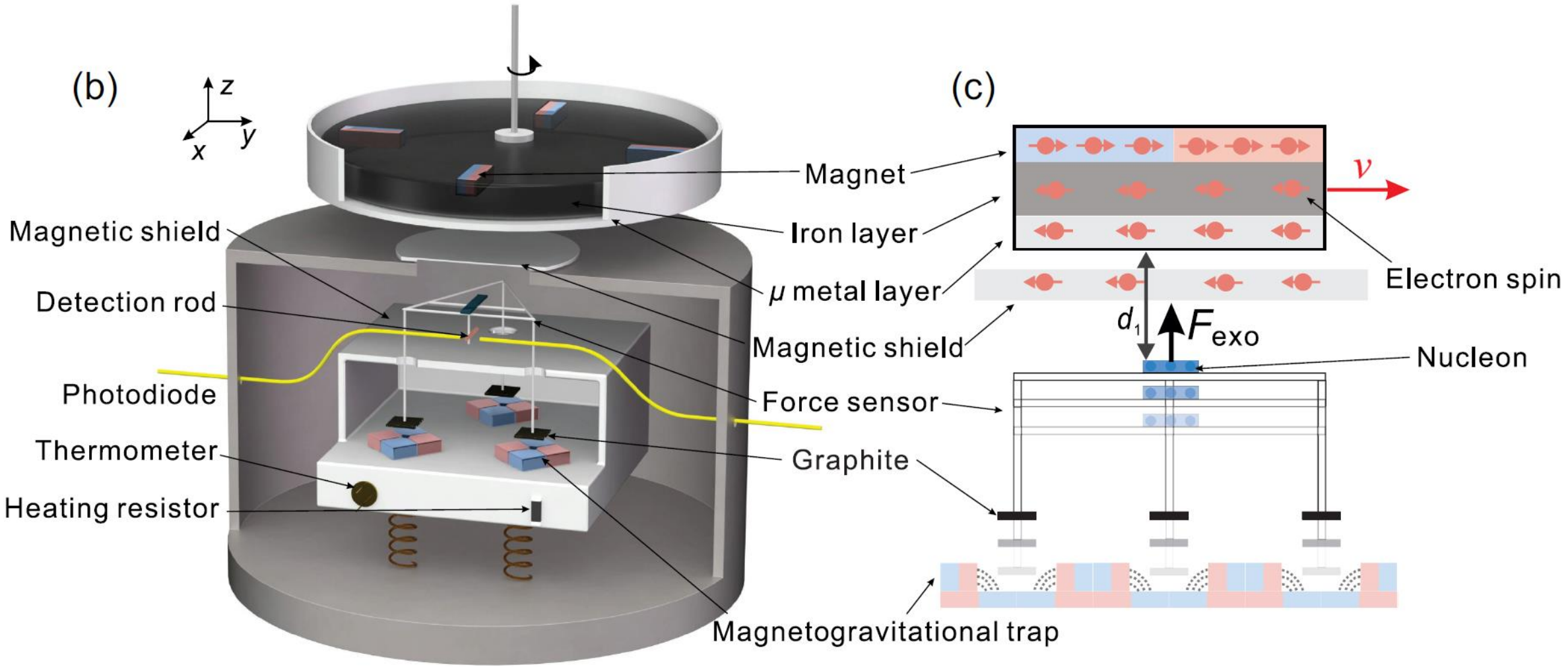
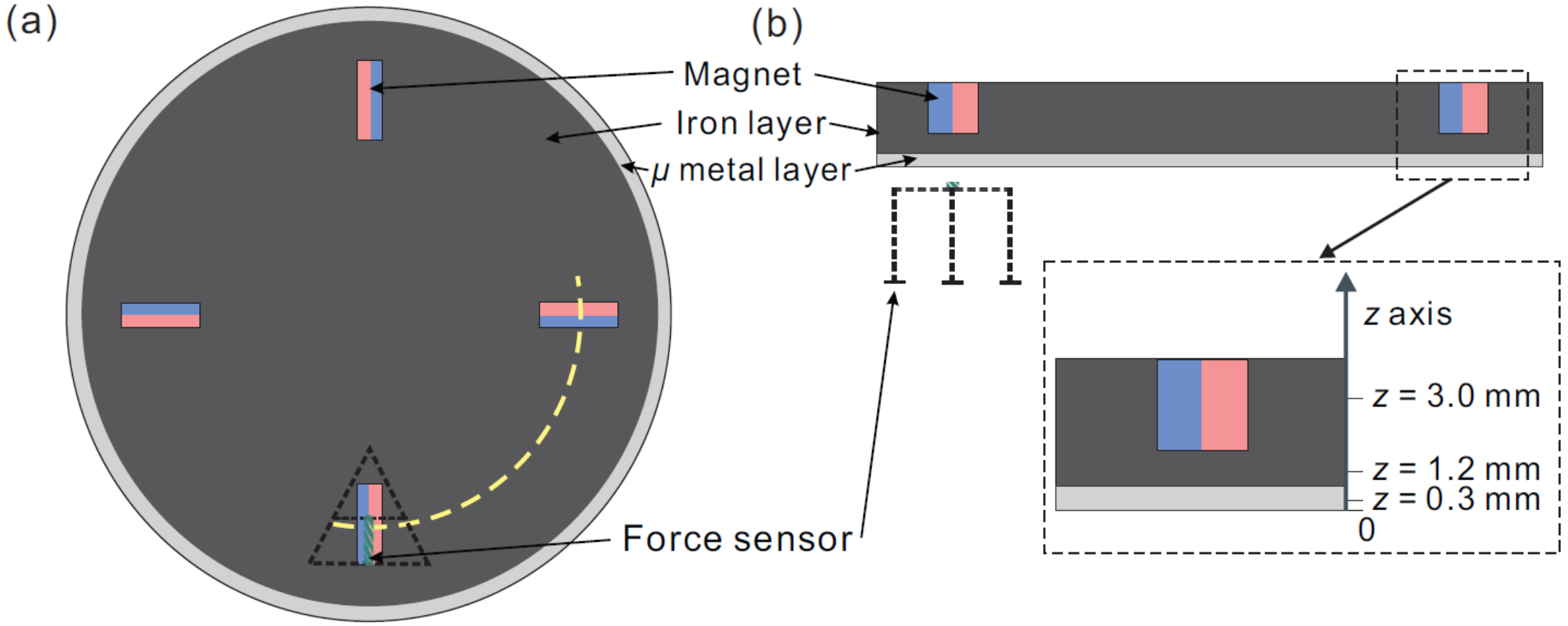
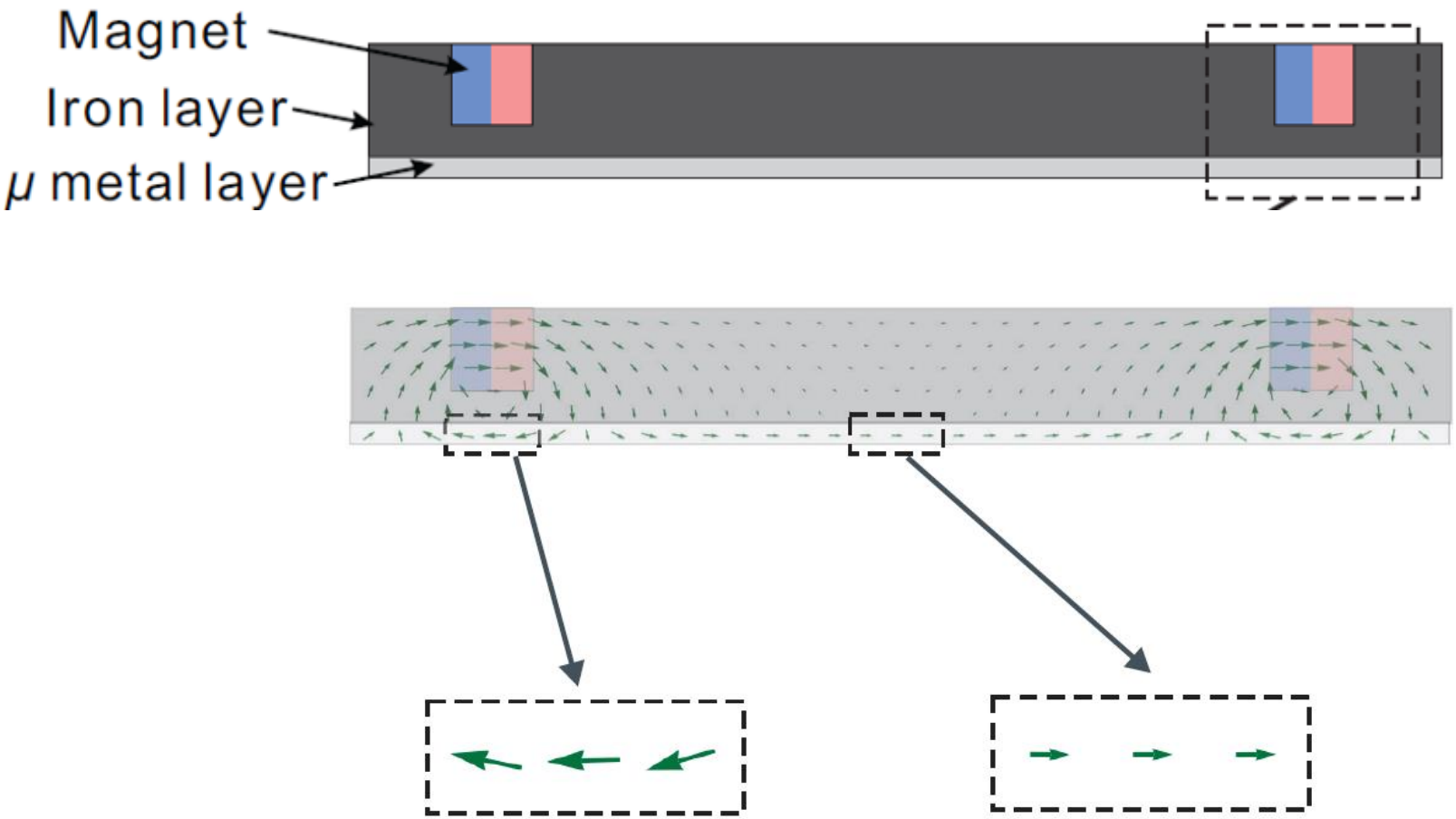
# Experimental setup

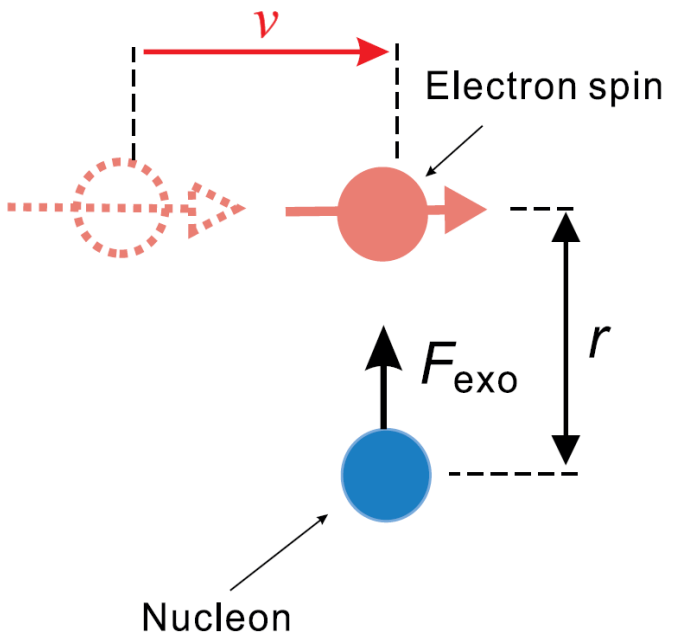


# Experimental setup: detection mechanism



# Experimental setup: detection mechanism

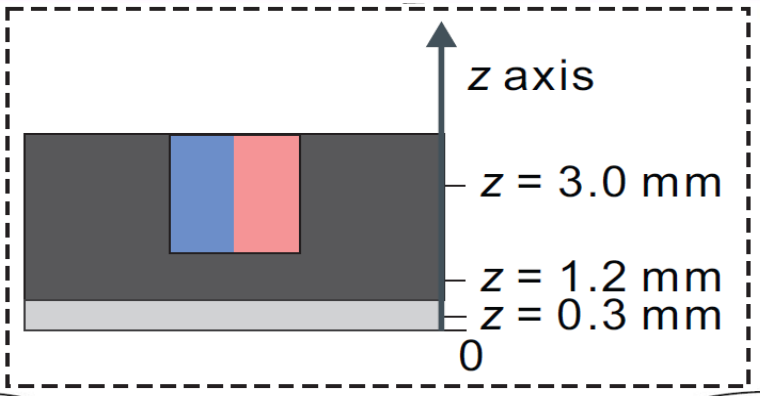


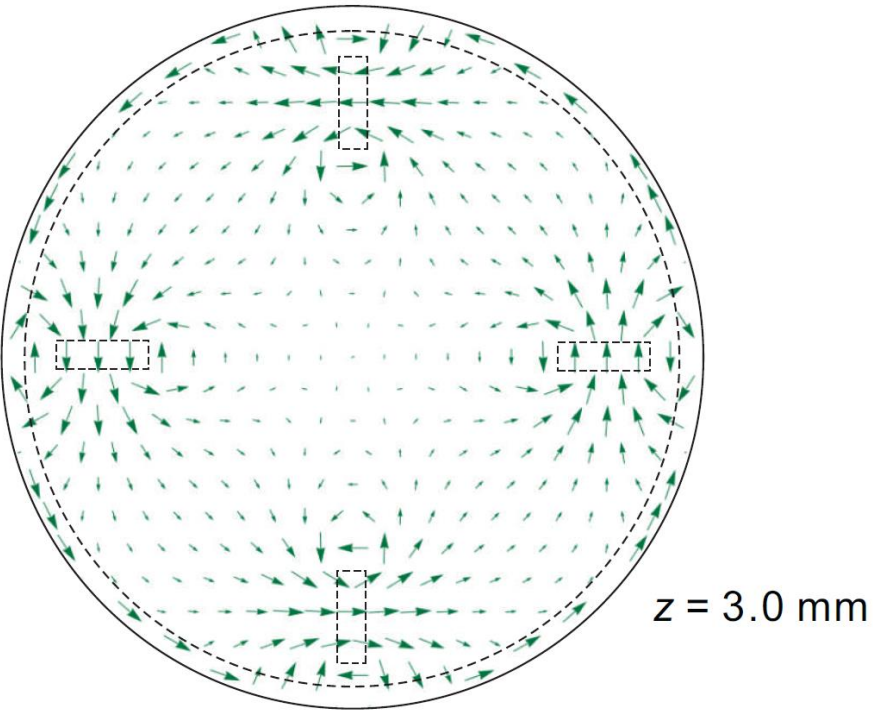




$$V = g_A^e g_V^N \frac{\hbar}{4\pi r}(\hat{\boldsymbol{\sigma}} \cdot \boldsymbol{v}) e^{-\frac{r}{\lambda}}.$$

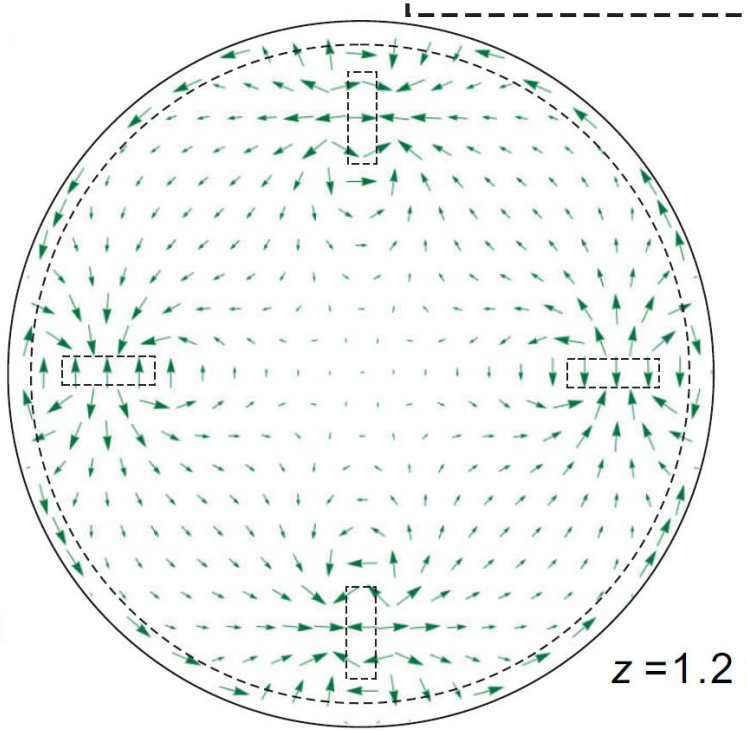
# Experimental setup: detection mechanism

**B field lines in the x-y plane at different z coordinate**

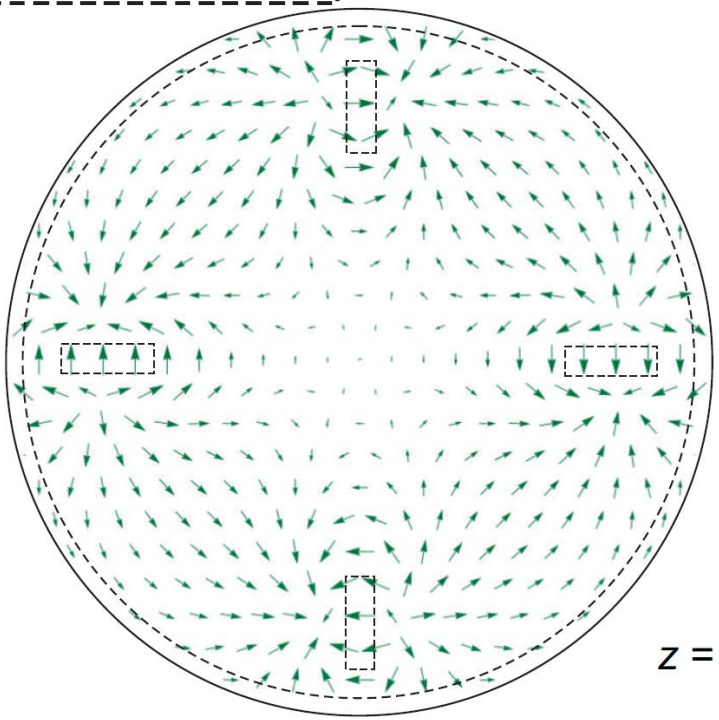


z = 3.0 mm



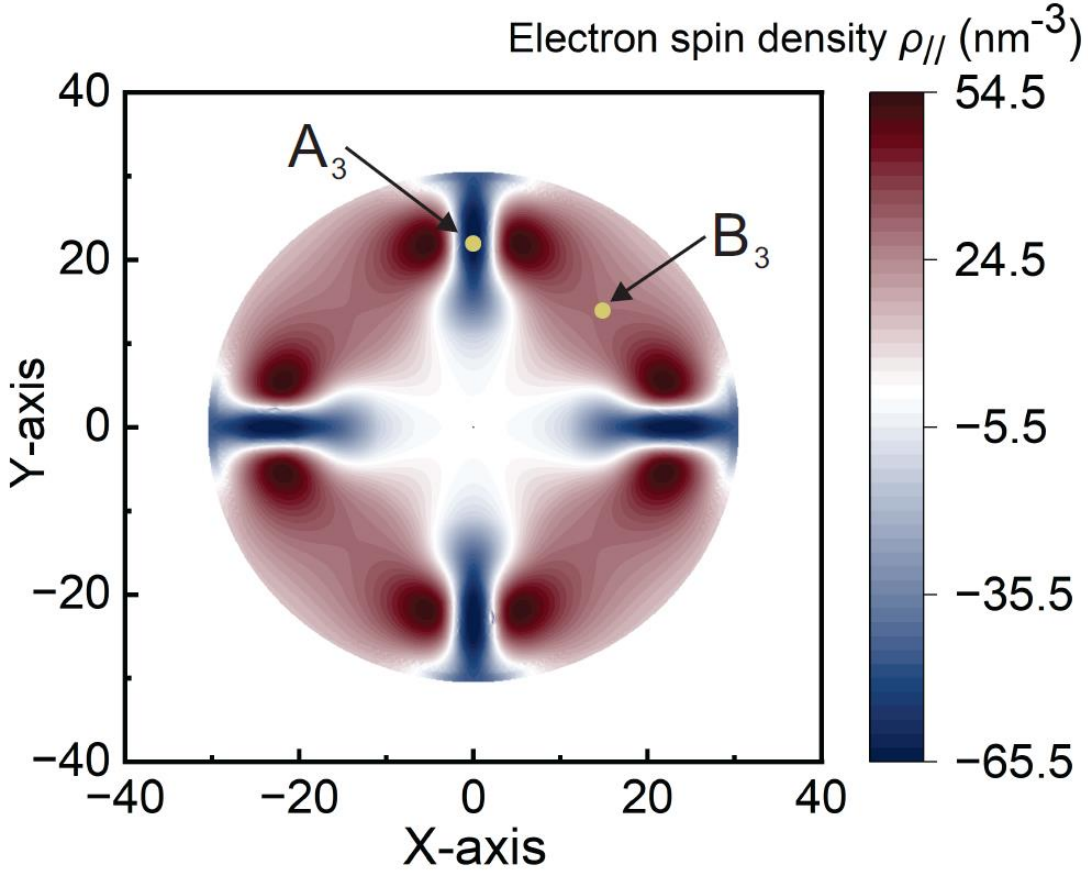
z =1.2 mn

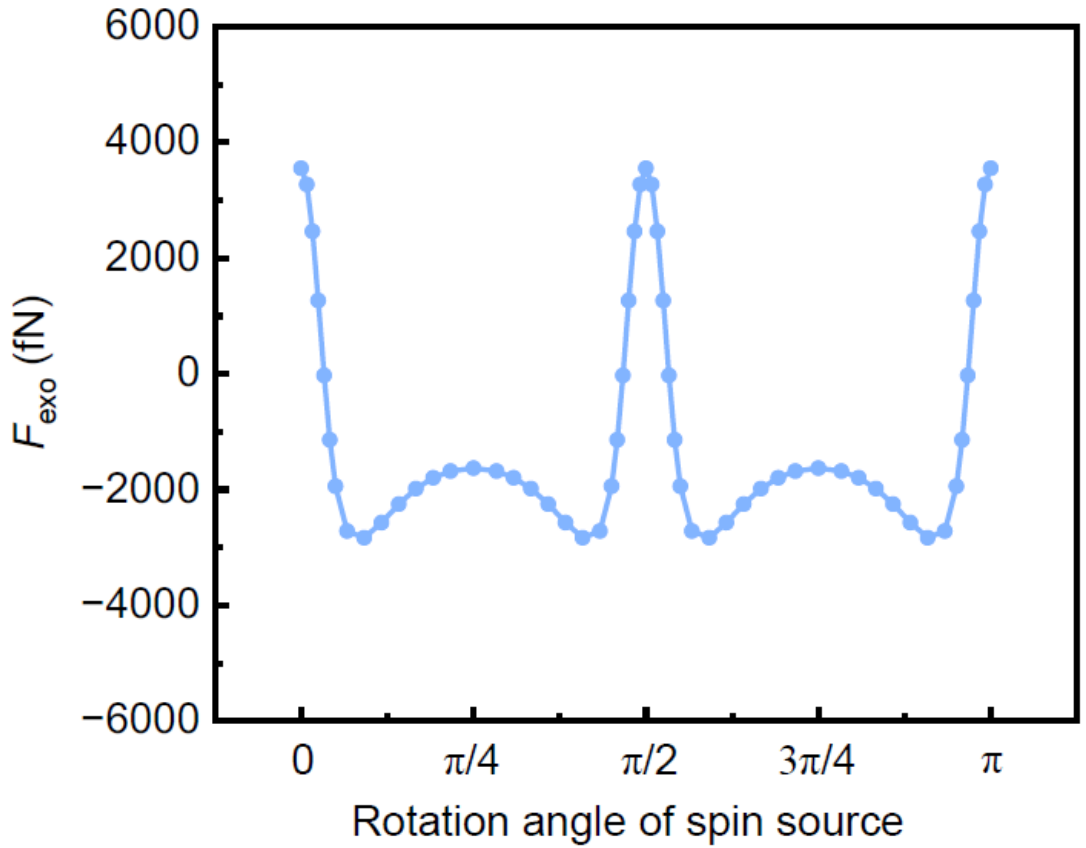


z = 0.3 mm

# Experimental setup: detection mechanism

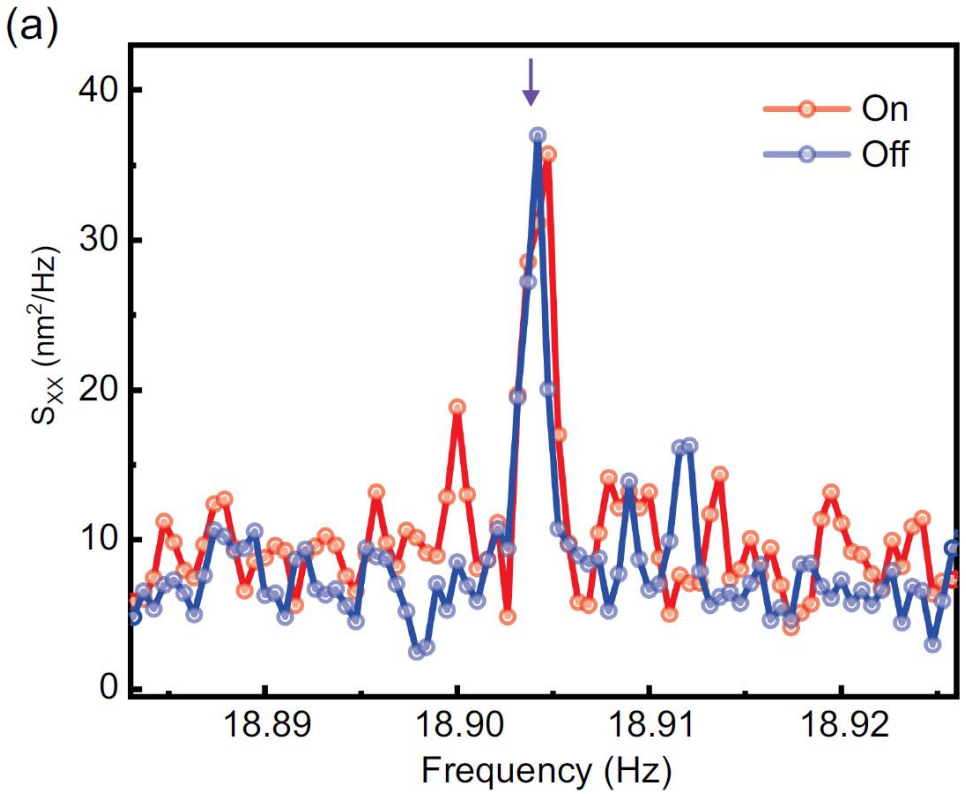
## Exotic force: numerical results



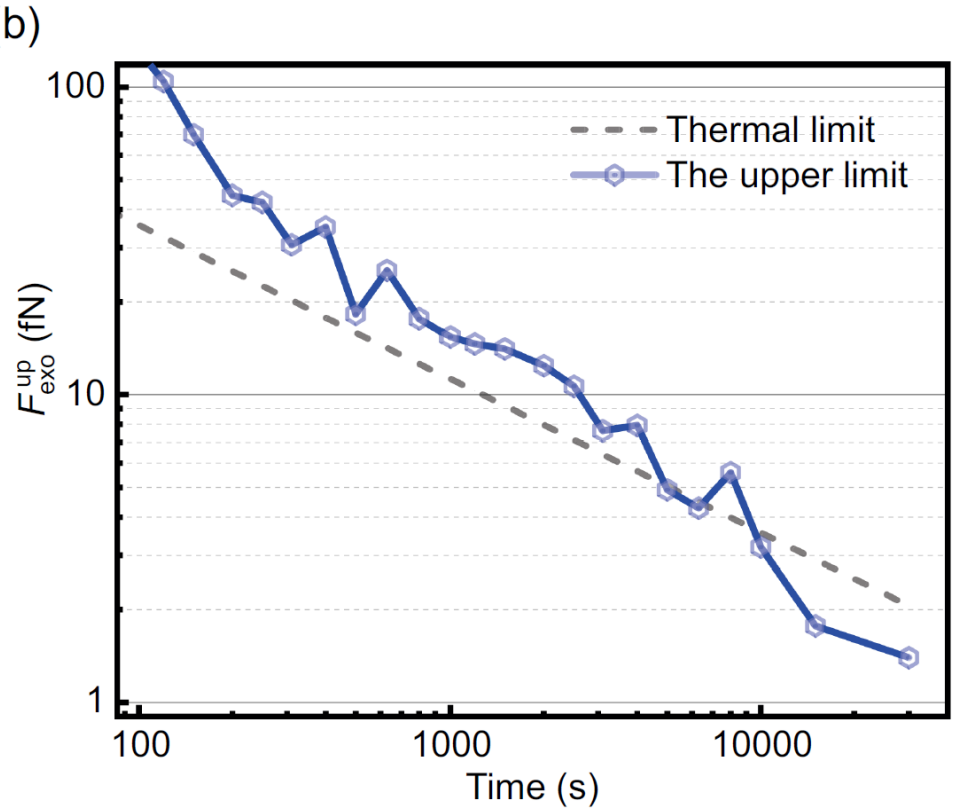



# Experimental results

**We conducted two continuous measurements, each 30000 s.**



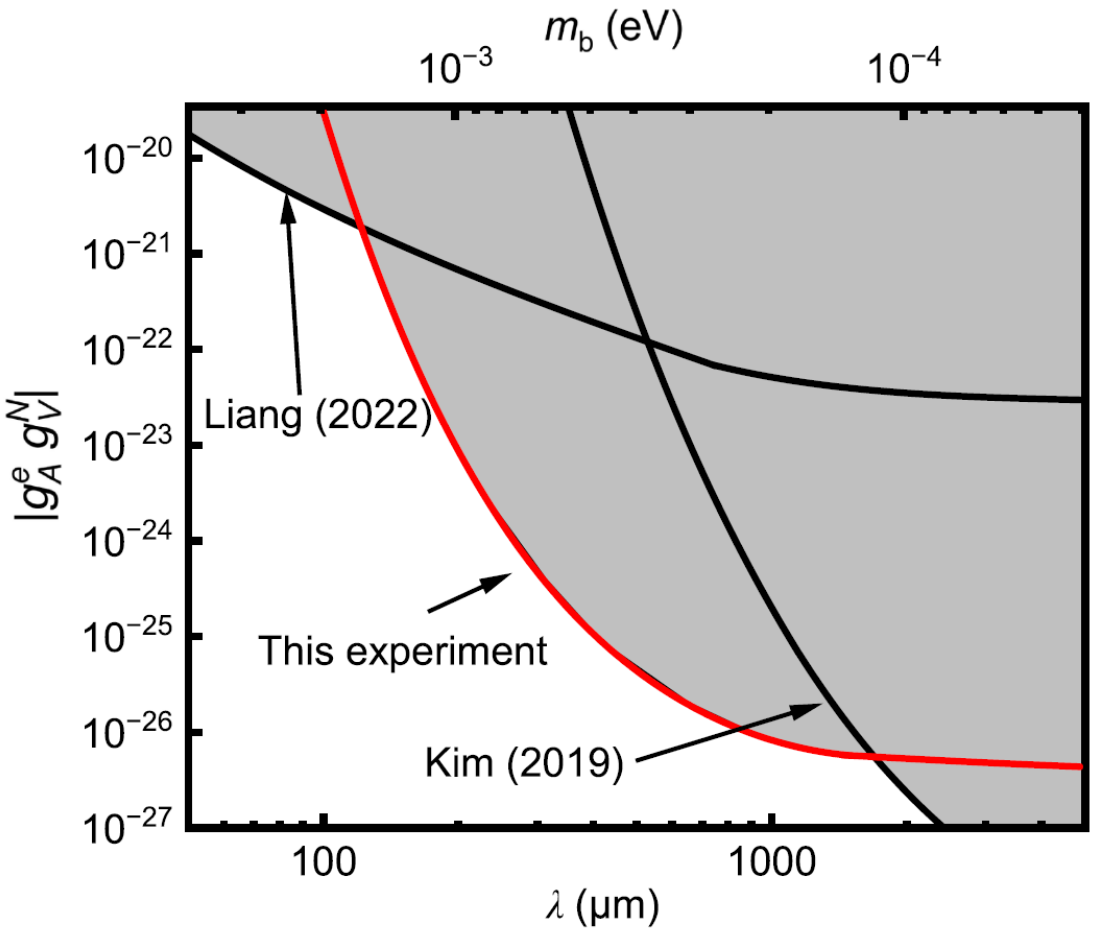

The power spectral density of the displacement of the force sensor.




The upper limit of the exotic interaction at the 95% confidence level: **1.40 fN**

# Experimental results

## The upper limit on the exotic spin and velocity dependent interaction




- The constraint $|g_A^e g_V^N| \leq 4.39 \times 10^{-26}$ at $\lambda = 0.5$ mm significantly surpasses previous results **by more than 3 orders of magnitude.**
- **For the first time**, levitated force sensor has been used to search for the exotic interactions.
- Other exotic spin dependent interactions, such as the exotic **spin-spin interaction.**

# Summary

- Mag-levitation system is becoming an emerging ultra-sensitive force sensor
- Detecting “fifth force” beyond the Standard Model, looking for clues to new physics at low energy
- In the future, equivalence principle, gravitational force at sub-milligram scale will be studied

## References:


**Nat. Astron.** (2025)

**Phys. Rev. Lett.** 134, 111001 (2025)

**Phys. Rev. Lett. 132,** 123601 (2024)

**Phys. Rev. Res. 5**, 013030 (2023)

**Nature Phys. 18,** 1181 (2022)

**Phys. Rev. Res. 3**, 013205 (2021)

**Phys. Rev. Appl. 16**, L011003 (2021)

**Phys. Rev. Appl. 15,** 024061 (2021)

**Phys. Rev. Res. 2**, 013057 (2020)

**Phys. Rev. Appl. 12,** 044017 (2019)