# 利用精密弱力测量技术检验新相互作用

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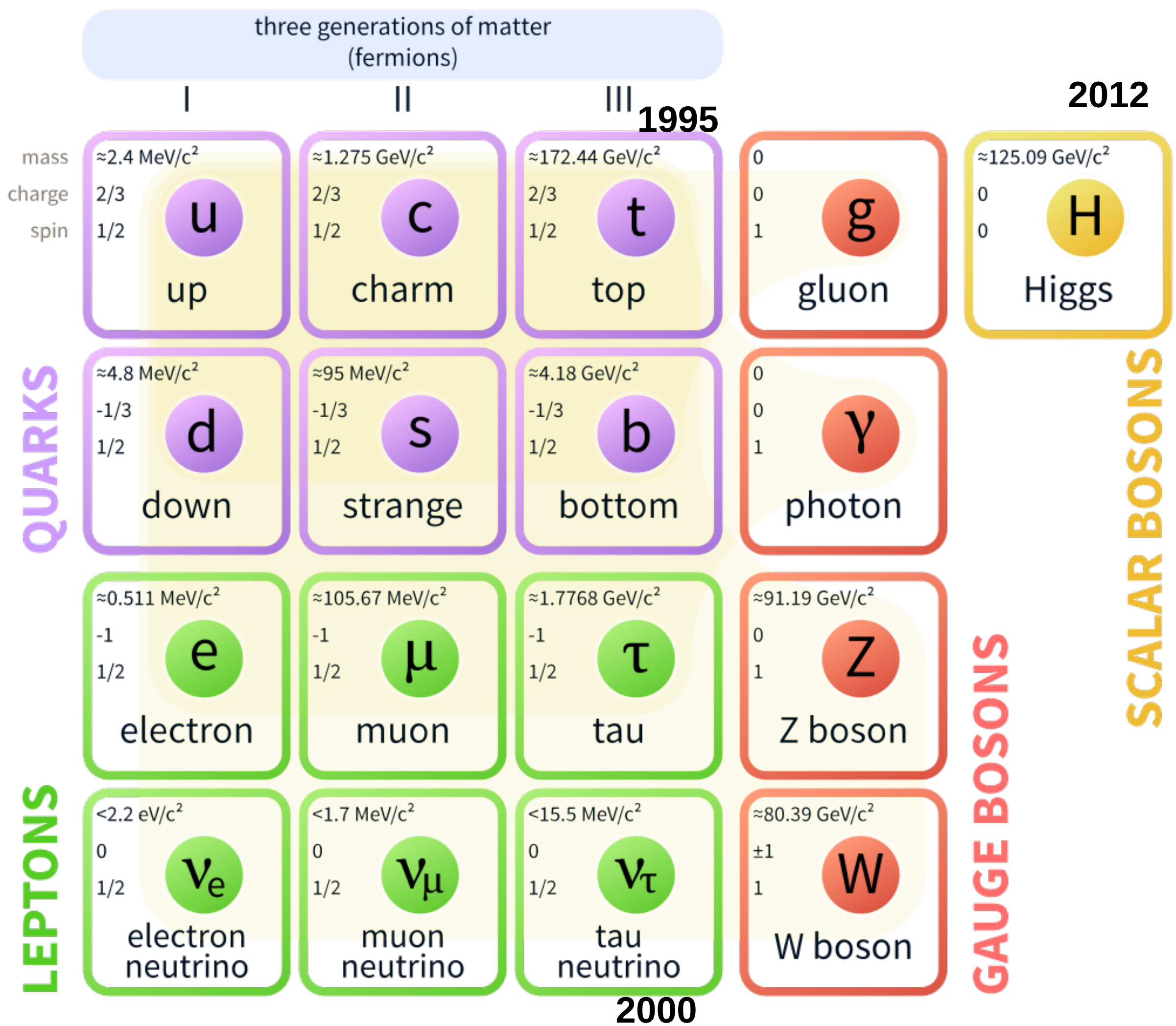
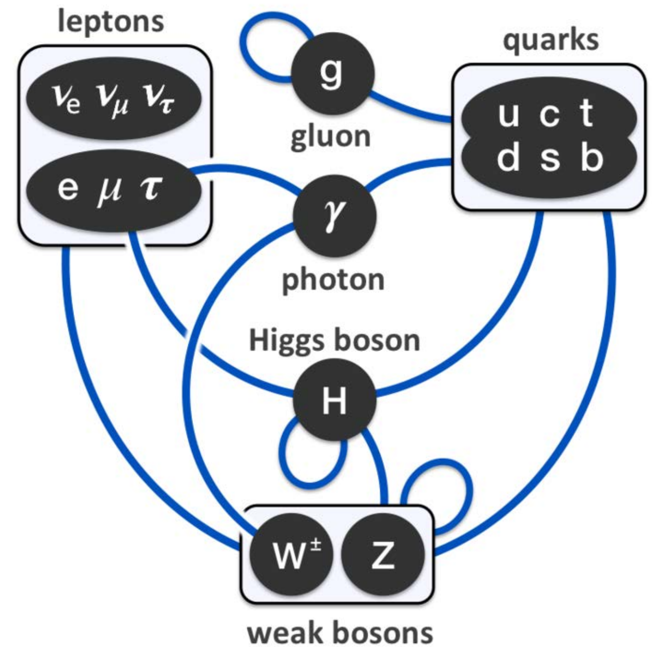
# Standard model of particles

## Standard Model of Elementary Particles

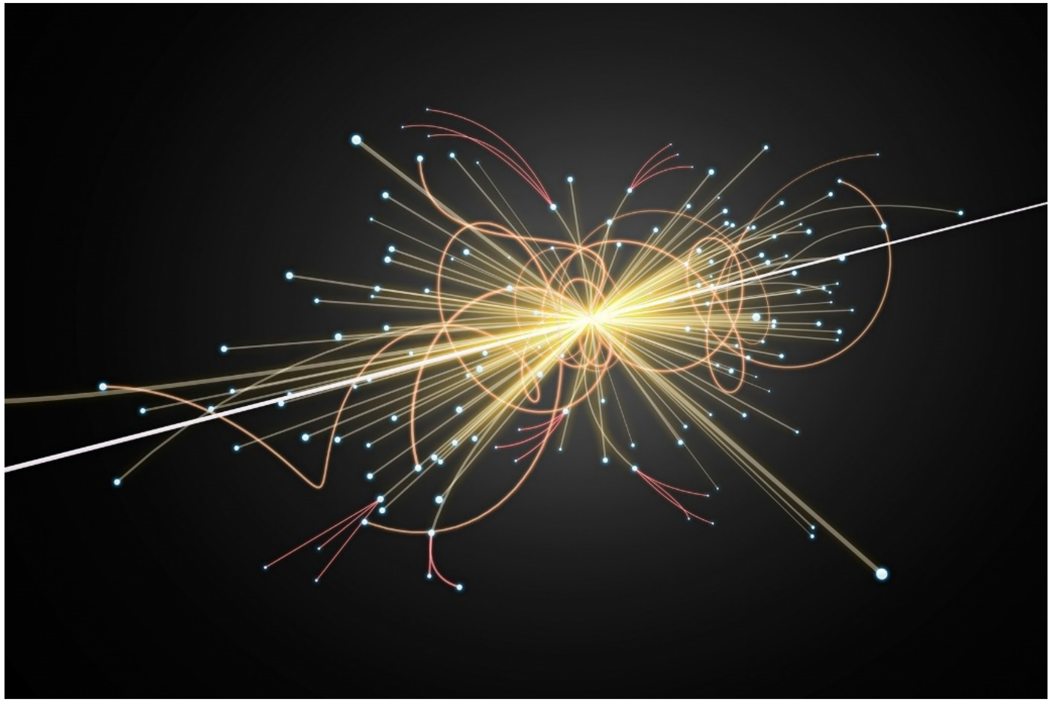


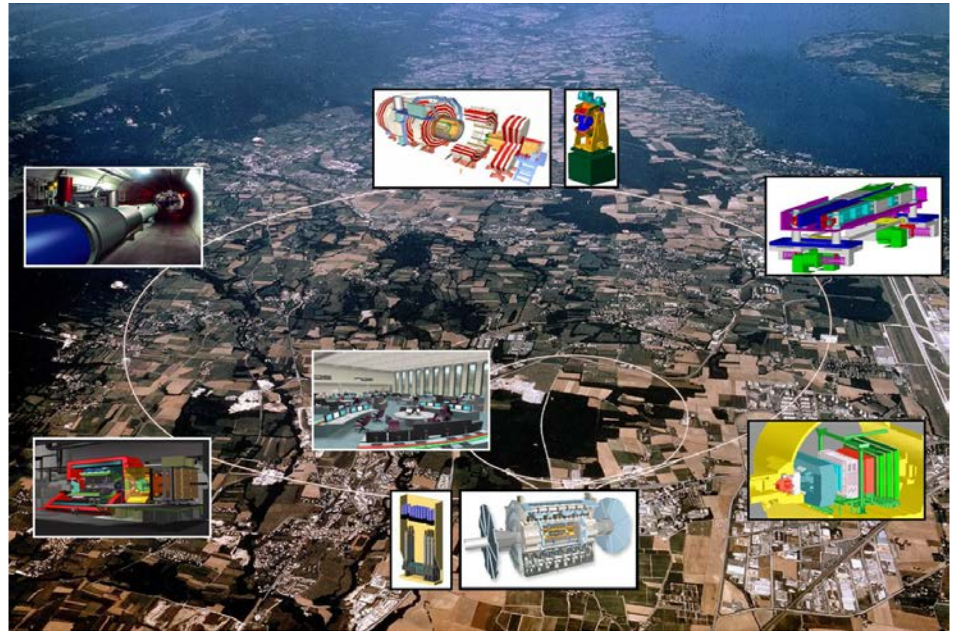

## Fundamental interactions

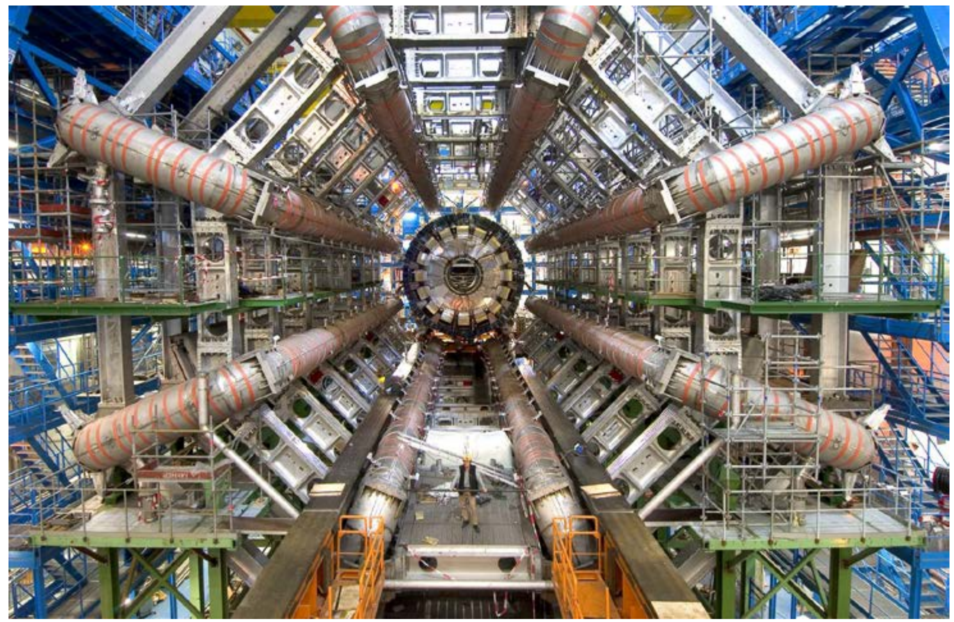



**New particles or interactions?**

# Search for particles: scattering experiment







# Tabletop-scale experiments

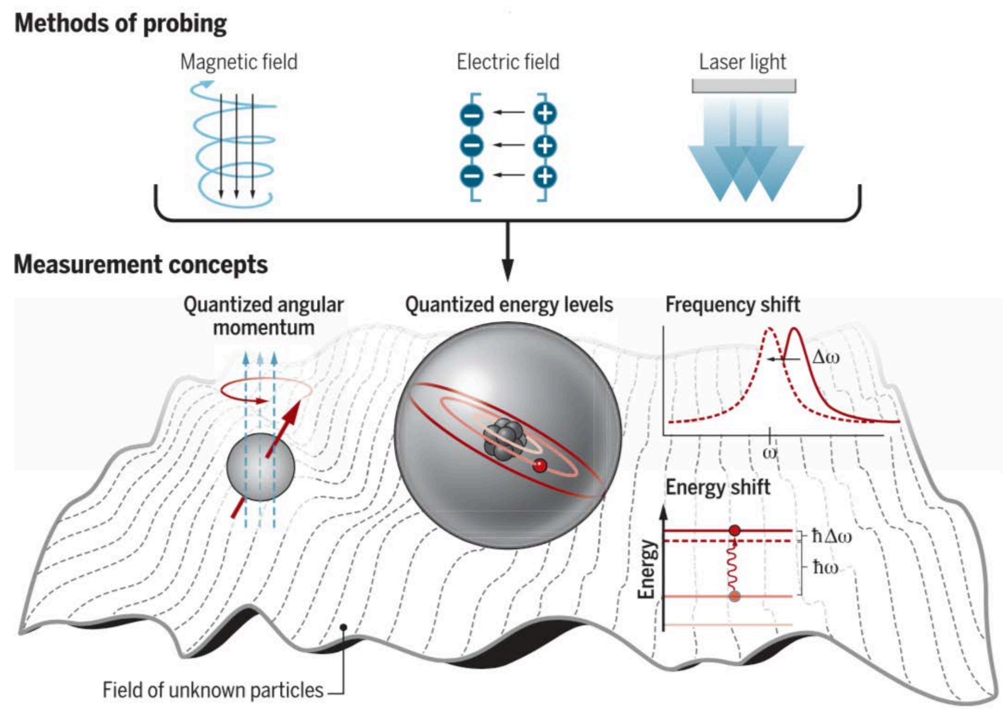
Science 357, 990–994 (2017)

REVIEW

## Probing the frontiers of particle physics with tabletop-scale experiments

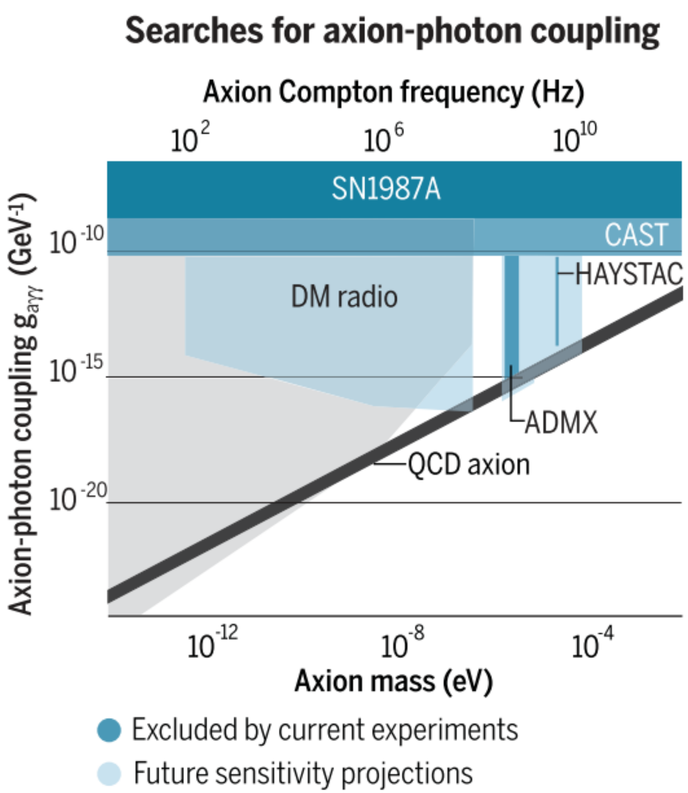
David DeMille,[1]* John M. Doyle,[2]* Alexander O. Sushkov[3,4]*

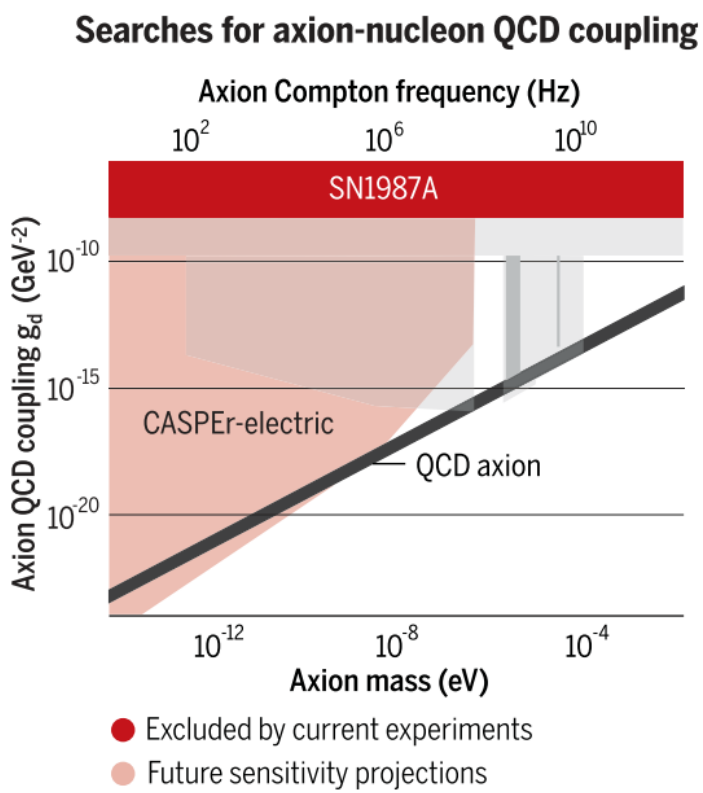
The field of particle physics is in a peculiar state. The standard model of particle theory successfully describes every fundamental particle and force observed in laboratories, yet fails to explain properties of the universe such as the existence of dark matter, the amount of dark energy, and the preponderance of matter over antimatter. Huge experiments, of increasing scale and cost, continue to search for new particles and forces that might explain these phenomena. However, these frontiers also are explored in certain smaller, laboratory-scale "tabletop" experiments. This approach uses precision measurement techniques and devices from atomic, quantum, and condensed-matter physics to detect tiny signals due to new particles or forces. Discoveries in fundamental physics may well come first from small-scale experiments of this type.

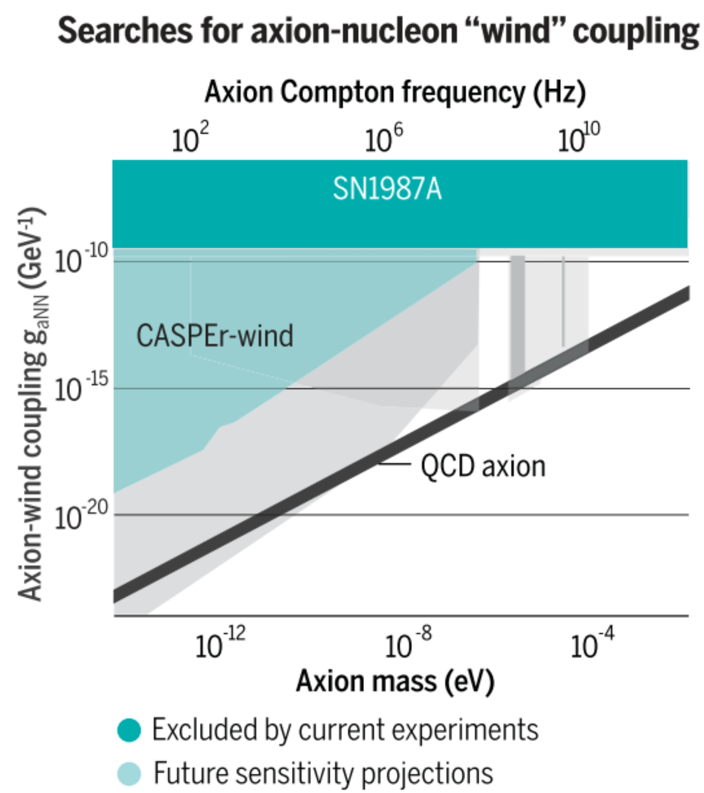


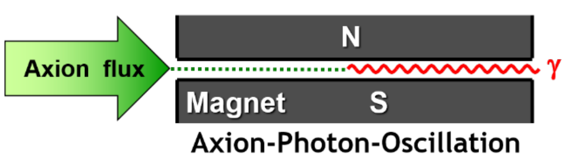
# Axions

- Solution for strong CP problem
- A prime candidate for dark matter




Nucleon EDM from axion field

Axion "wind": effective magnetic field

DeMille *et al.*, Science 357, 990–994 (2017)

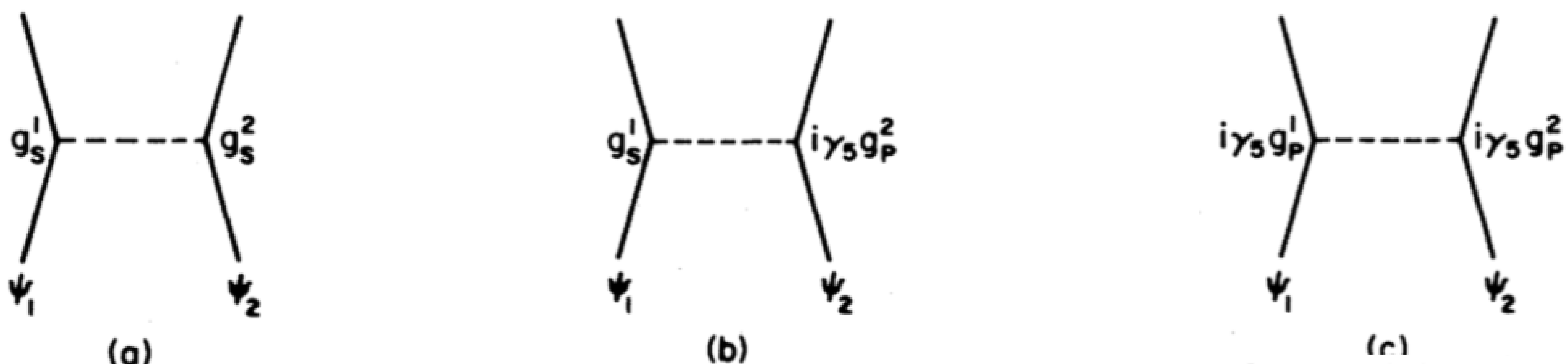
# Axions and new macroscopic forces

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.




$$V(r)=\frac{-g_S^1 g_S^2 e^{-m_\varphi r}}{4\pi r}$$

**monopole**

$$V(r)=(g_S^1 g_P^2)\frac{\hat{\sigma}_2\cdot\hat{r}}{8\pi M_2}\left[\frac{m_\varphi}{r}+\frac{1}{r^2}\right]e^{-m_\varphi r}$$

**Monopole - dipole**

$$V(r)=\frac{g_P^1 g_P^2}{16\pi M_1 M_2}\left[(\hat{\sigma}_1\cdot\hat{\sigma}_r)\left[\frac{m_\varphi}{r^2}+\frac{1}{r^3}+\frac{4\pi}{3}\delta^3(r)\right]-(\hat{\sigma}_1\cdot\hat{r})(\hat{\sigma}_2\cdot\hat{r})\left[\frac{m_\varphi^2}{r}+\frac{3m_\varphi}{r^2}+\frac{3}{r^3}\right]\right]e^{-m_\varphi r}$$

**Dipole - dipole**

# Forces mediated by hypothetical light particles

- **Spin-0 bosons: axions, familon, Majoron, …**
- **Spin-1 bosons: paraphoton ( $\gamma'$ ), $Z'$**
- **Bosons from hidden supersymmetric sectors**
- **Bosons from string theory, moduli (eg. dilaton)**

E.G. Adelberger et al., Annu. Rev. Nucl. Part. Sci. 53, 77 (2003)
B. Dobrescu and I. Mocioiu, J. High Energy Phys. 11 (2006) 005
Wei-Tou Ni, Rep. Prog. Phys. 73, 056901(2010)

# Forces mediated by light particles(spin-0, spin-1)

16 potentials by single boson exchange

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

**Spin-independent**

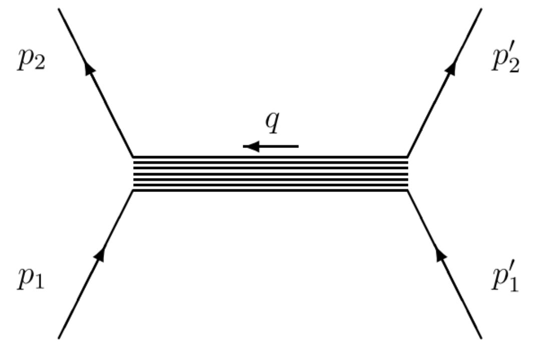
$$V_1 \propto f \frac{1}{r} e^{-r/\lambda}$$

**Monopole-dipole:**

$$V_{4+5} = -Z\left[f_\perp^{ee} + f_\perp^{ep} + \left(\frac{A-Z}{Z}\right) f_\perp^{en}\right] \frac{\hbar^2}{8\pi m_e c}[\hat{\sigma}_1 \cdot (\vec{v} \times \hat{r})]\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right) e^{-r/\lambda}$$

$$V_{9+10} = Z\left[f_r^{ee} + f_r^{ep} + \left(\frac{A-Z}{Z}\right) f_r^{en}\right] \frac{\hbar^2}{8\pi m_e}(\hat{\sigma}_1 \cdot \hat{r})\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right) e^{-r/\lambda}$$

$$V_{12+13} = Z\left[f_v^{ee} + f_v^{ep} + \left(\frac{A-Z}{Z}\right) f_v^{en}\right] \frac{\hbar}{8\pi}(\hat{\sigma}_1 \cdot \vec{v})\left(\frac{1}{r}\right) e^{-r/\lambda},$$




**Static, dipole-dipole:**

$$V_2 = f_2^{ee} \frac{\hbar c}{4\pi}(\hat{\sigma}_1 \cdot \hat{\sigma}_2)\left(\frac{1}{r}\right) e^{-r/\lambda}$$

$$V_3 = f_3^{ee} \frac{\hbar^3}{4\pi m_e^2 c}\left[(\hat{\sigma}_1 \cdot \hat{\sigma}_2)\left(\frac{1}{\lambda r^2} + \frac{1}{r^3}\right) - (\hat{\sigma}_1 \cdot \hat{r})(\hat{\sigma}_2 \cdot \hat{r})\left(\frac{1}{\lambda^2 r} + \frac{3}{\lambda r^2} + \frac{3}{r^3}\right)\right] e^{-r/\lambda}$$

$$V_{11} = -f_{11}^{ee} \frac{\hbar^2}{4\pi m_e}[(\hat{\sigma}_1 \times \hat{\sigma}_2) \cdot \hat{r}]\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right) e^{-r/\lambda}.$$

**Velocity dependent, dipole-dipole: ...**

# Forces mediated by light particles

Scalar-scalar:

$$V_{ss}(\boldsymbol{r}) = -g_1^s g_2^s \underbrace{\frac{e^{-Mr}}{4\pi r}}_{\mathcal{V}_1}, \tag{4}$$

pseudoscalar-scalar:

$$V_{ps}(\boldsymbol{r}) = -g_1^p g_2^s \underbrace{\boldsymbol{\sigma}_1 \cdot \hat{\boldsymbol{r}} \left(\frac{1}{r^2} + \frac{M}{r}\right) \frac{e^{-Mr}}{8\pi m_1}}_{\mathcal{V}_{9,10}}, \tag{5}$$

pseudoscalar-pseudoscalar:

$$V_{pp}(\boldsymbol{r}) = -\frac{g_1^p g_2^p}{4} \underbrace{\left[\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \left[\frac{1}{r^3} + \frac{M}{r^2} + \frac{4\pi}{3}\delta(\boldsymbol{r})\right] - (\boldsymbol{\sigma}_1 \cdot \hat{\boldsymbol{r}})(\boldsymbol{\sigma}_2 \cdot \hat{\boldsymbol{r}}) \left[\frac{3}{r^3} + \frac{3M}{r^2} + \frac{M^2}{r}\right]\right] \frac{e^{-Mr}}{4\pi m_1 m_2}}_{\mathcal{V}_3}, \tag{6}$$

vector-vector:

$$V_{VV}(\boldsymbol{r}) = g_1^V g_2^V \underbrace{\frac{e^{-Mr}}{4\pi r}}_{\mathcal{V}_1} + \frac{g_1^V g_2^V}{4} \underbrace{\left[\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \left[\frac{1}{r^3} + \frac{M}{r^2} + \frac{M^2}{r} - \frac{8\pi}{3}\delta(\boldsymbol{r})\right] - (\boldsymbol{\sigma}_1 \cdot \hat{\boldsymbol{r}})(\boldsymbol{\sigma}_2 \cdot \hat{\boldsymbol{r}}) \left[\frac{3}{r^3} + \frac{3M}{r^2} + \frac{M^2}{r}\right]\right] \frac{e^{-Mr}}{4\pi m_1 m_2}}_{\mathcal{V}_2 + \mathcal{V}_3}, \tag{7}$$

axial-vector:

$$V_{AV}(\boldsymbol{r}) = g_1^A g_2^V \underbrace{\boldsymbol{\sigma}_1 \cdot \left\{\frac{\boldsymbol{p}_1}{m_1} - \frac{\boldsymbol{p}_2}{m_2}, \frac{e^{-Mr}}{8\pi r}\right\}}_{\mathcal{V}_{12,13}} - \frac{g_1^A g_2^V}{2} \underbrace{(\boldsymbol{\sigma}_1 \times \boldsymbol{\sigma}_2) \cdot \hat{\boldsymbol{r}} \left(\frac{1}{r^2} + \frac{M}{r}\right) \frac{e^{-Mr}}{4\pi m_2}}_{\mathcal{V}_{11}}, \tag{8}$$

axial-axial:

$$V_{AA}(\boldsymbol{r}) = -g_1^A g_2^A \underbrace{\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \frac{e^{-Mr}}{4\pi r}}_{\mathcal{V}_2} - \frac{g_1^A g_2^A m_1 m_2}{M^2} \underbrace{\left[\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \left[\frac{1}{r^3} + \frac{M}{r^2} + \frac{4\pi}{3}\delta(\boldsymbol{r})\right] - (\boldsymbol{\sigma}_1 \cdot \hat{\boldsymbol{r}})(\boldsymbol{\sigma}_2 \cdot \hat{\boldsymbol{r}}) \left[\frac{3}{r^3} + \frac{3M}{r^2} + \frac{M^2}{r}\right]\right] \frac{e^{-Mr}}{4\pi m_1 m_2}}_{\mathcal{V}_3}, \tag{9}$$

tensor-tensor:

$$V_{TT}(\boldsymbol{r}) = \frac{4 v_h^2 \mathrm{Re}(C_1) \mathrm{Re}(C_2) m_1 m_2}{\Lambda^4} \underbrace{\left[\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \left[\frac{1}{r^3} - \frac{8\pi}{3}\delta(\boldsymbol{r})\right] - (\boldsymbol{\sigma}_1 \cdot \hat{\boldsymbol{r}})(\boldsymbol{\sigma}_2 \cdot \hat{\boldsymbol{r}}) \frac{3}{r^3}\right] \frac{1}{4\pi m_1 m_2}}_{\mathcal{V}_2 + \mathcal{V}_3}, \tag{10}$$

Fadeev et al., PRA 99, 022113 (2019)

# Experimental tests

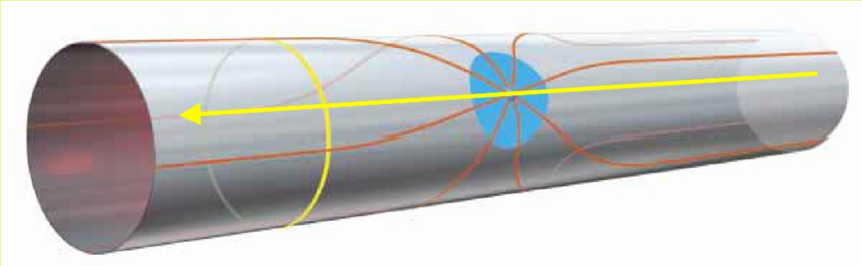
- **Spin-independent interaction**
- **Spin-dependent interaction: measure the spin response to an effective magnetic field** $V(r) = -\mu\hat{\sigma} \cdot \vec{B}_{eff}$
- **Spin-dependent interaction: measure the macroscopic force or torque** $F_i = -\frac{\partial V(\vec{r})}{\partial x_i}$ $\tau = -\frac{\partial V(\vec{r})}{\partial \theta}$

# Test of spin-independent interaction

Test of short range gravity:

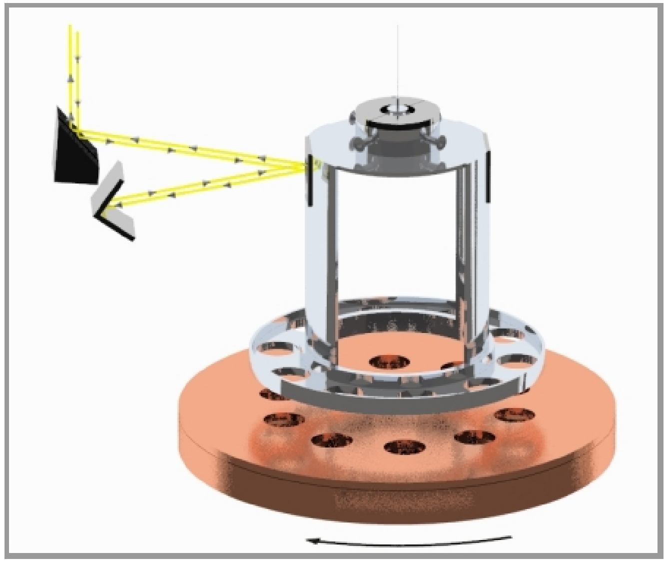
$$V(r) = \frac{Gm_1m_2}{r}(1+\alpha e^{-r/\lambda})$$

Compacted extra dimension

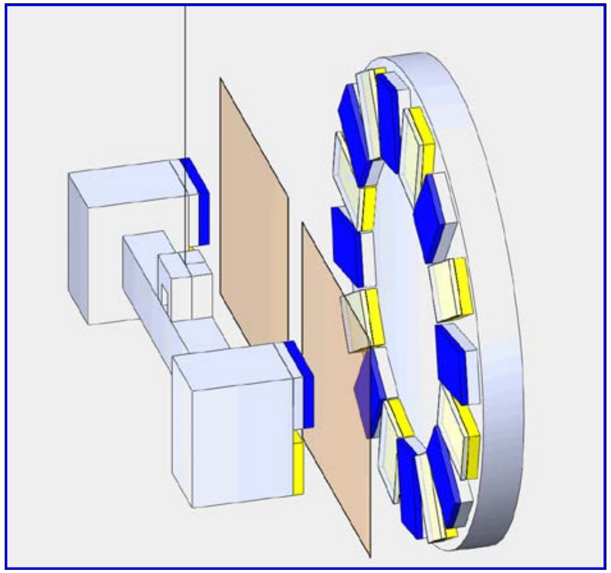


N. Arkani-Hamed, S. Dimopoulos, G. Dvali, PLB 429(1998) 263

**Torsion Balance Experiments**



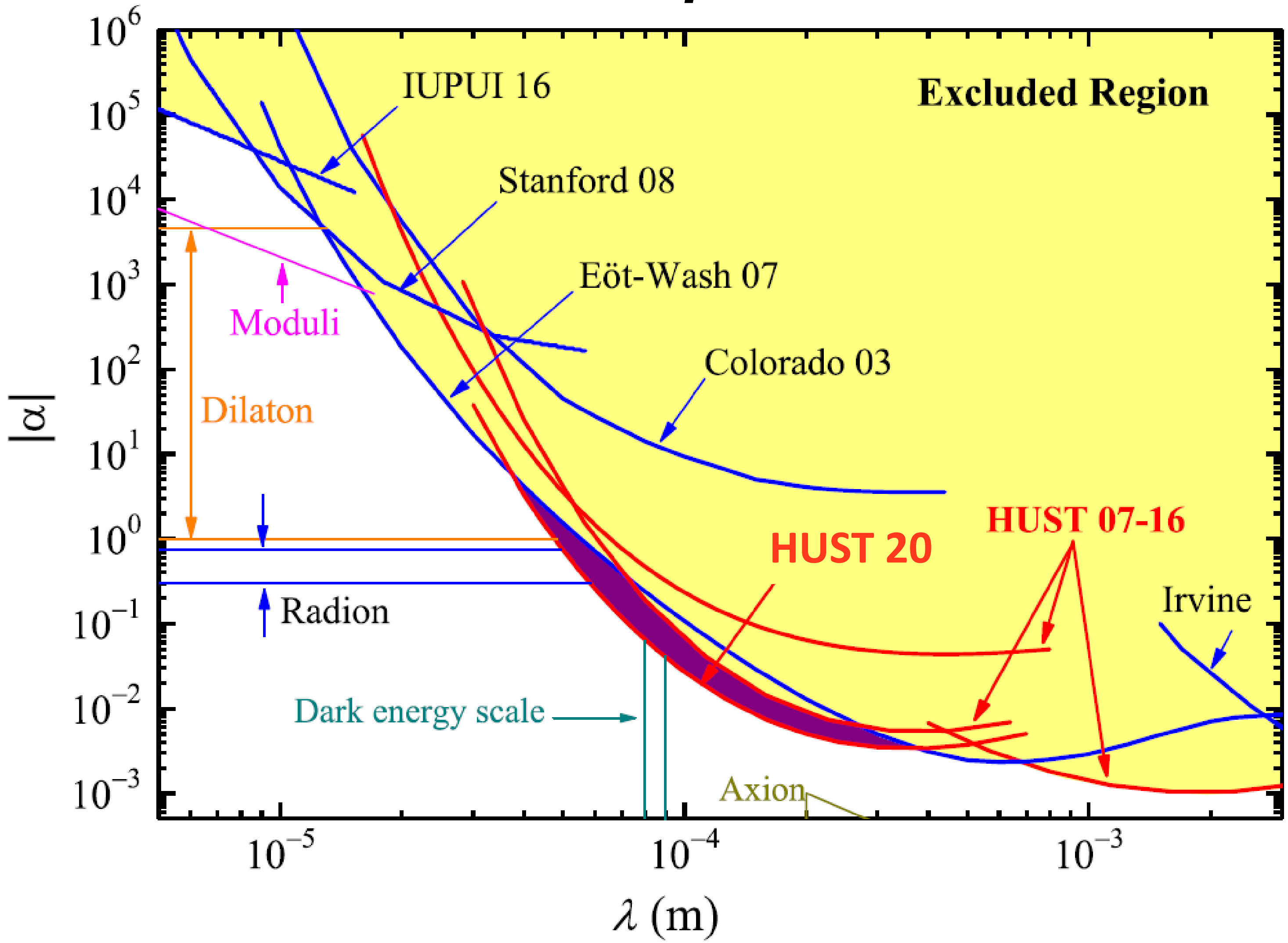
The Eöt-Wash Group, Washington University



CGE, HUST

# Test of newton's inverse square law

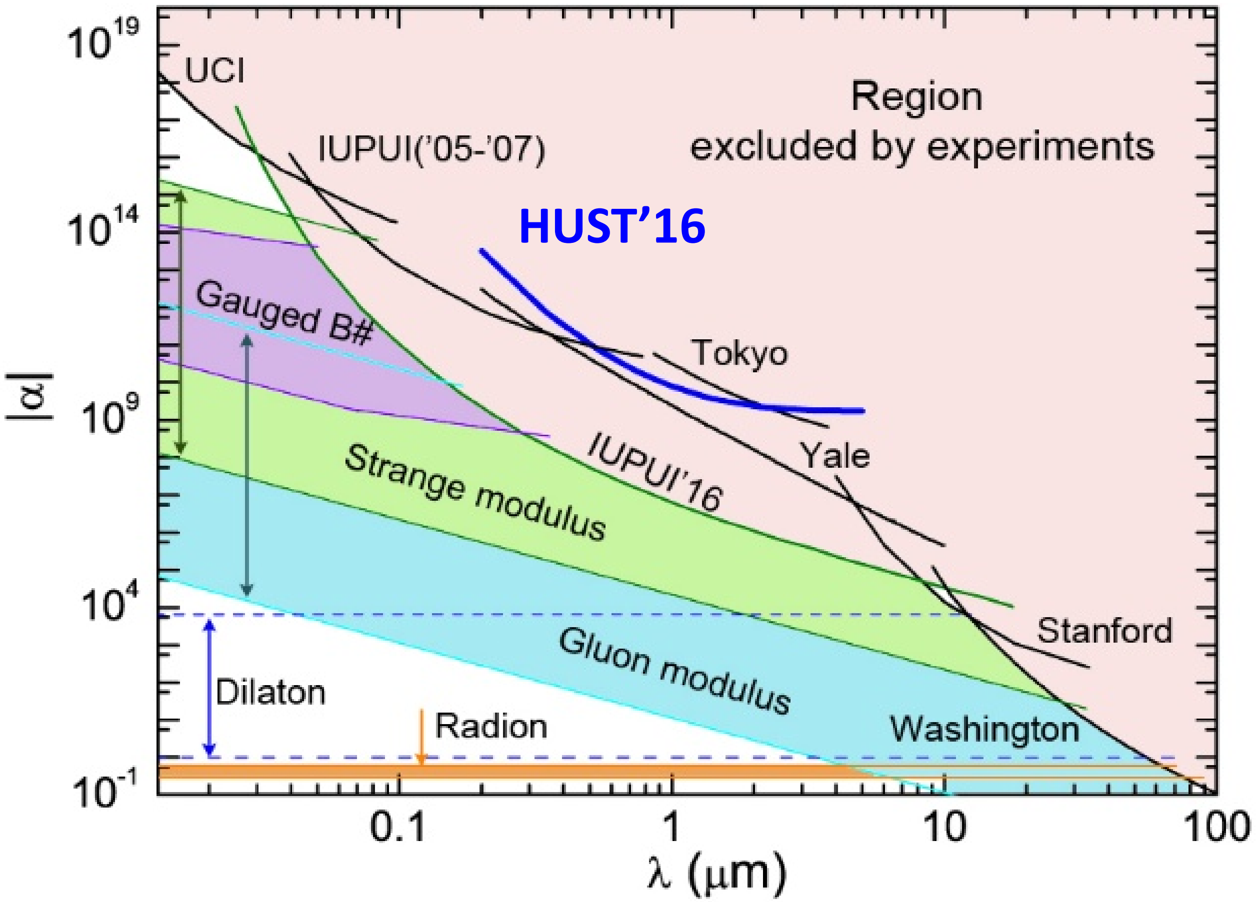
$$V(r) = \frac{Gm_1m_2}{r}(1+\alpha e^{-r/\lambda})$$

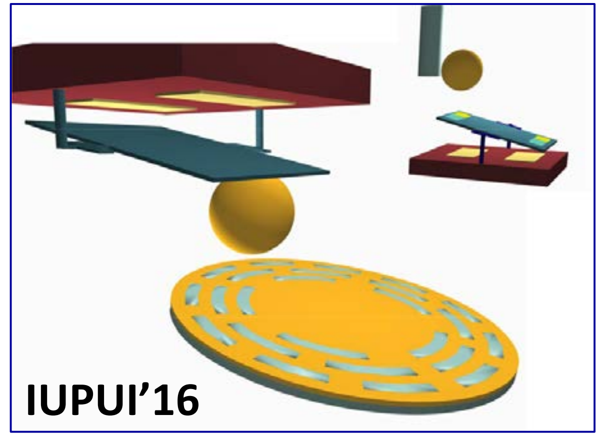


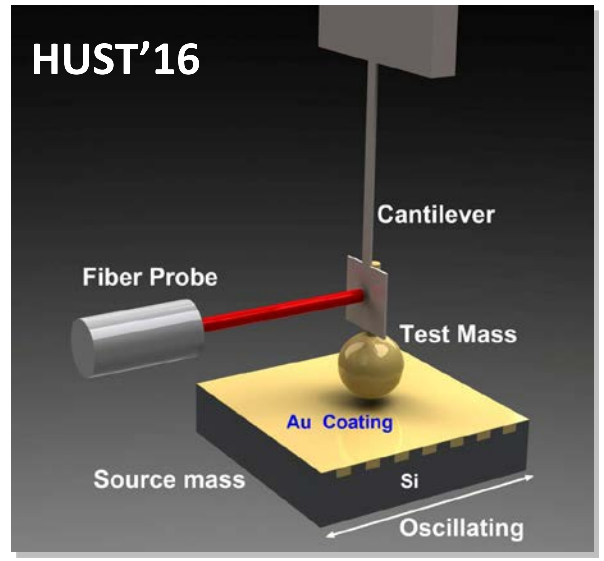

Wen-Hai Tan et al., 124, 051301 (2020)

# Micrometer range experiment

$$V(r)=\frac{Gm_1m_2}{r}(1+\alpha e^{-r/\lambda})$$




Jianbo Wang *et al.*, PRD 94, 122005 (2016)

# Search for spin-dependent interactions

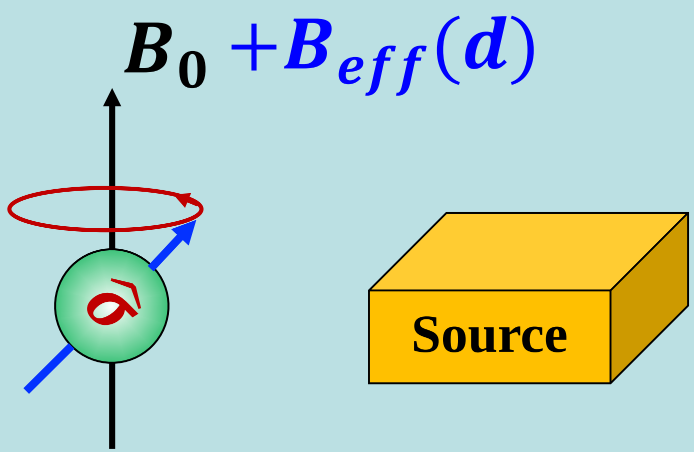
$$V_2 = f_2^{ee}\frac{\hbar c}{4\pi}(\hat{\sigma}_1\cdot\hat{\sigma}_2)\left(\frac{1}{r}\right)e^{-r/\lambda}$$

$$V_3 = f_3^{ee}\frac{\hbar^3}{4\pi m_e^2 c}\left[(\hat{\sigma}_1\cdot\hat{\sigma}_2)\left(\frac{1}{\lambda r^2}+\frac{1}{r^3}\right)-(\hat{\sigma}_1\cdot\hat{r})(\hat{\sigma}_2\cdot\hat{r})\left(\frac{1}{\lambda^2 r}+\frac{3}{\lambda r^2}+\frac{3}{r^3}\right)\right]e^{-r/\lambda}$$

$$V_{4+5} = -Z\left[f_\perp^{ee}+f_\perp^{ep}+\left(\frac{A-Z}{Z}\right)f_\perp^{en}\right]\frac{\hbar^2}{8\pi m_e c}\hat{\sigma}_1\cdot(\vec{v}\times\hat{r})]\left(\frac{1}{\lambda r}+\frac{1}{r^2}\right)e^{-r/\lambda}$$

$$V_{9+10} = Z\left[f_r^{ee}+f_r^{ep}+\left(\frac{A-Z}{Z}\right)f_r^{en}\right]\frac{\hbar^2}{8\pi m_e}(\hat{\sigma}_1\cdot\hat{r})\left(\frac{1}{\lambda r}+\frac{1}{r^2}\right)e^{-r/\lambda}$$

$$\Rightarrow \quad V(r) = -\mu\hat{\sigma}\cdot\vec{B}_{eff}$$

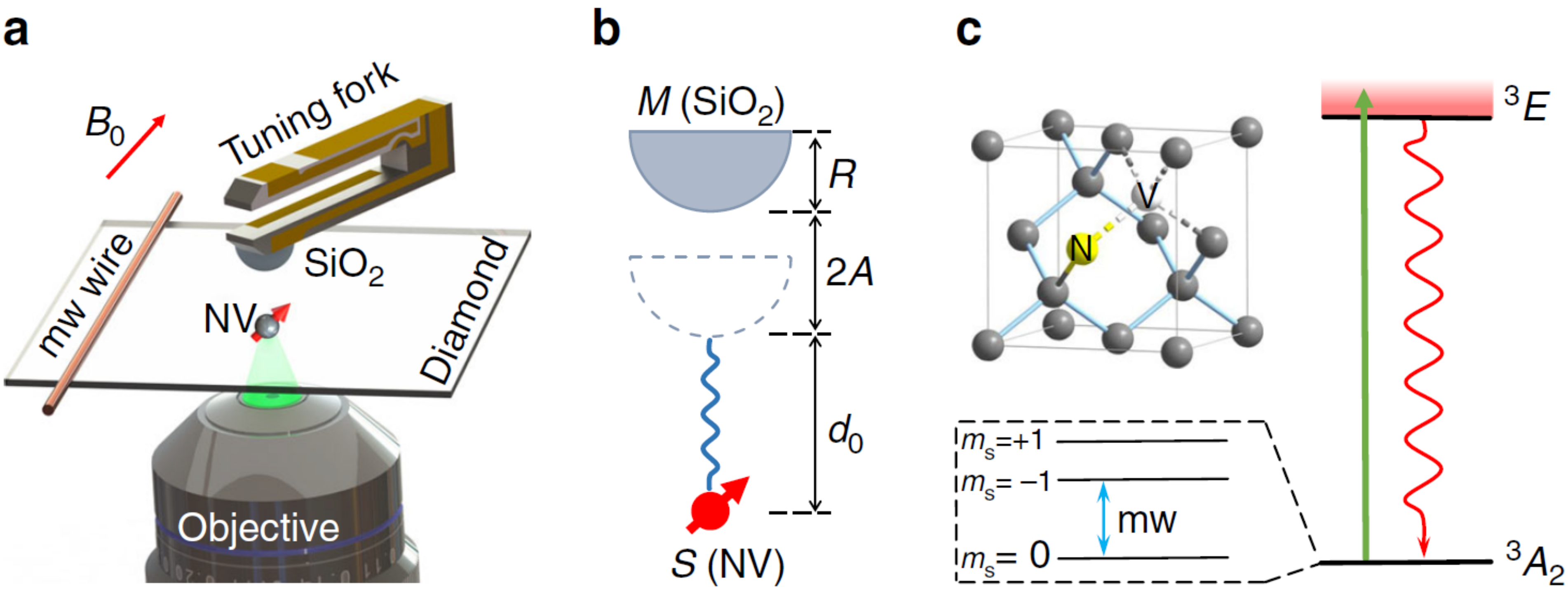



- Atom magnetometer
- NV center quantum sensor
- Neutron Ramsey interferometer: spin precession
- SQUID

# NV quantum sensor

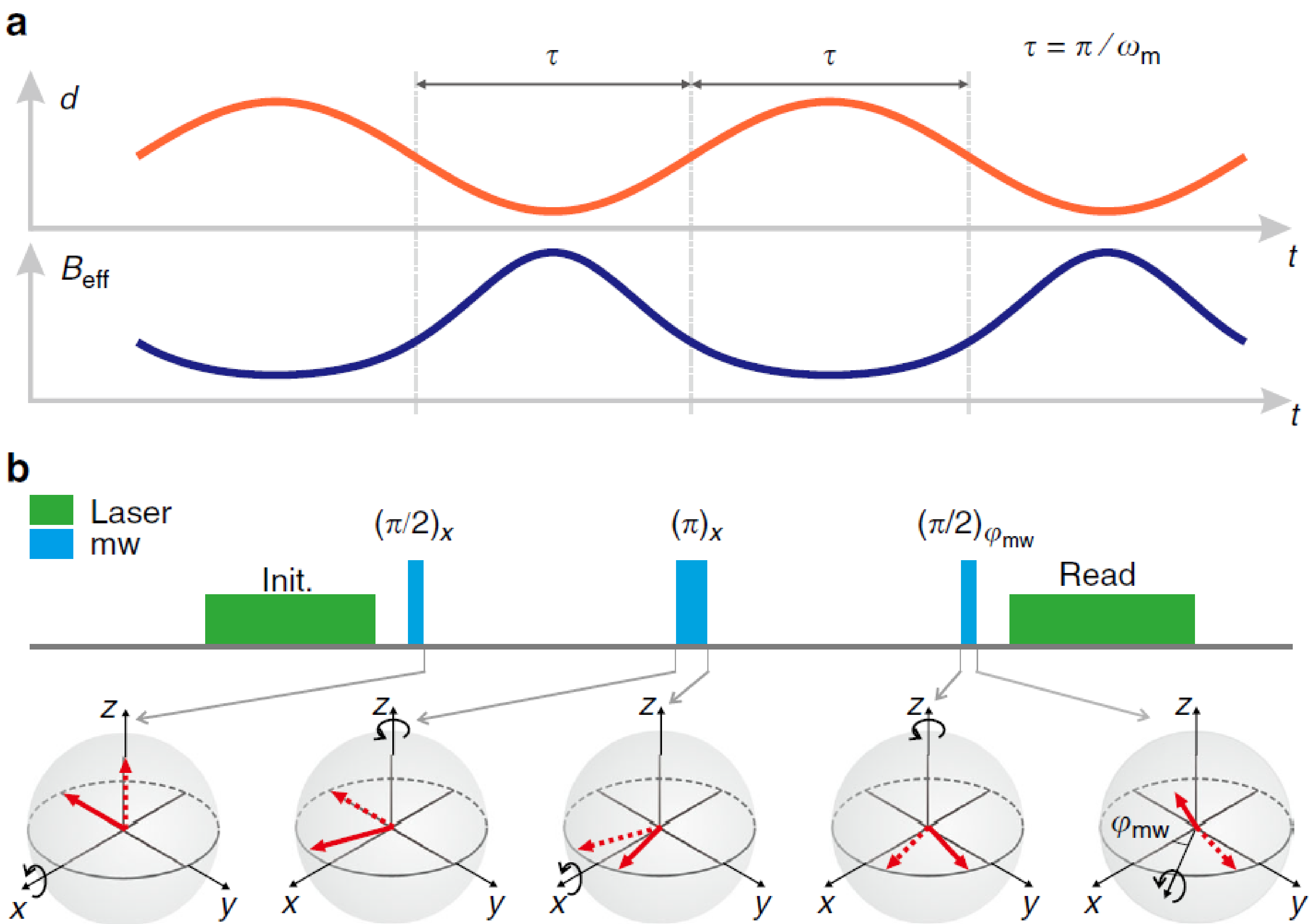
$$V_{\rm sp}(\mathbf{r}) = \frac{\hbar^2 g_s^N g_p^e}{8\pi m}\left(\frac{1}{\lambda r}+\frac{1}{r^2}\right)e^{-\frac{r}{\lambda}}\boldsymbol{\sigma}\cdot\mathbf{e}_r,$$

$$\mathbf{B}_{\rm sp}(\mathbf{r}) = \frac{\hbar g_s^N g_p^e}{4\pi m\gamma}\left(\frac{1}{\lambda r}+\frac{1}{r^2}\right)e^{-\frac{r}{\lambda}}\mathbf{e}_r,$$

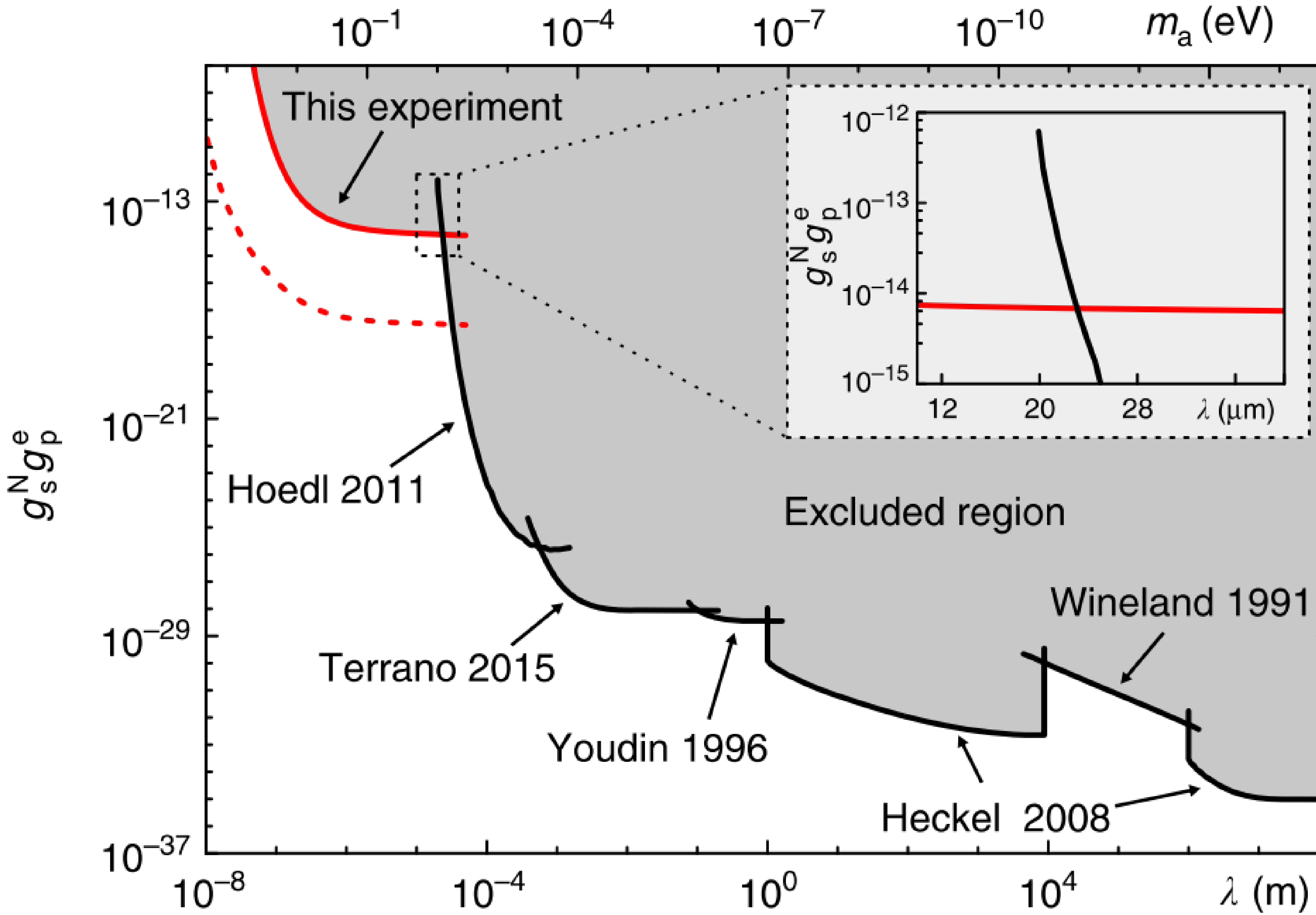



Xing Rong *et al.*, Nat. Commun. 9, 739 (2018)

# NV quantum sensor



# NV quantum sensor



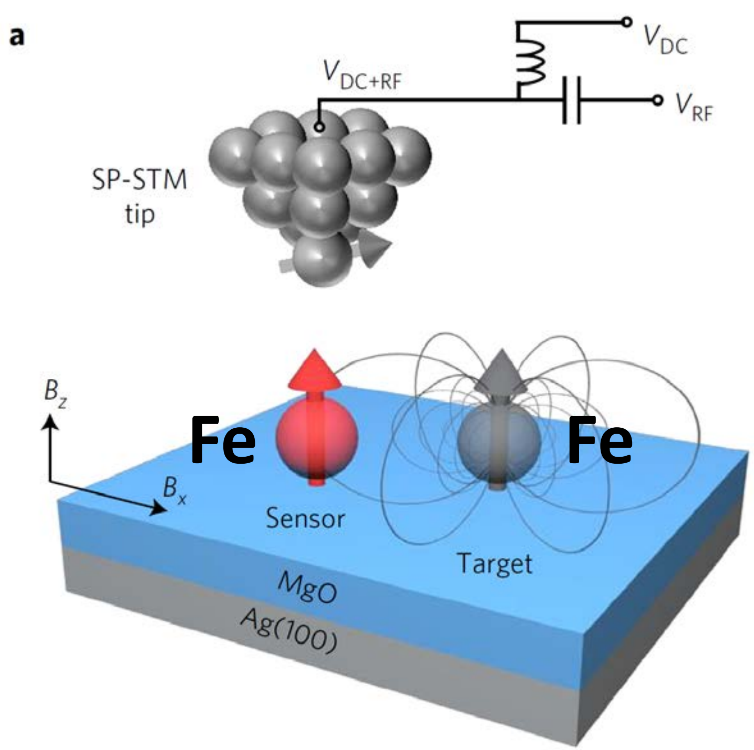
# Search with ESR-STM at nm range

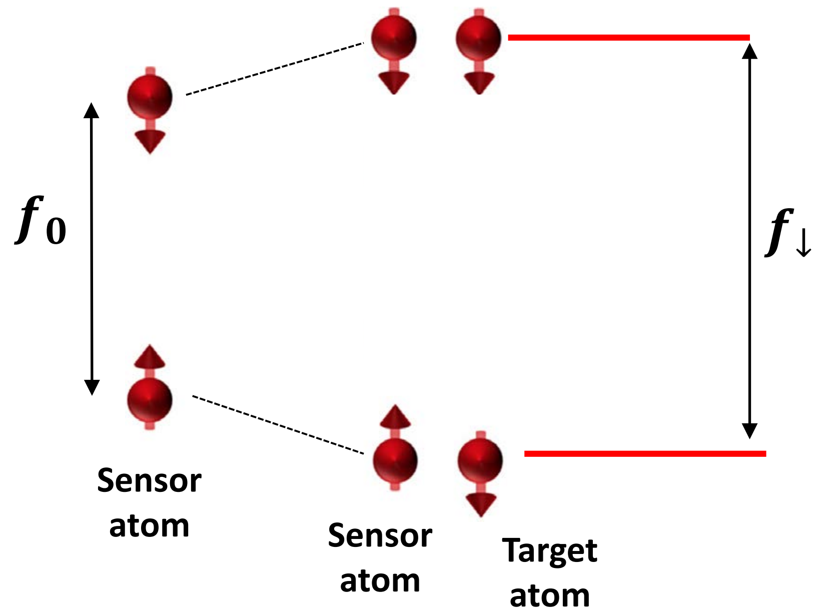
## Atomic-scale sensing of the magnetic dipolar field from single atoms

Taeyoung Choi[1†], William Paul[1], Steffen Rolf-Pissarczyk[2,3], Andrew J. Macdonald[4], Fabian D. Natterer[1,5], Kai Yang[1,6], Philip Willke[1,7], Christopher P. Lutz[1*] and Andreas J. Heinrich[8,9*]

IBM Almaden Research Center

Nat. Nanotechnol. 12, 420 (2017)




**Dipole-dipole:** $E_{dd} = \frac{\mu_0}{4\pi}\frac{1}{r^3}\left[\left(\vec{m}^{(1)}\cdot\vec{m}^{(2)}\right) - 3\left(\vec{m}^{(1)}\cdot\hat{r}\right)\left(\vec{m}^{(2)}\cdot\hat{r}\right)\right] = \frac{\mu_0}{4\pi}\frac{1}{r^3}m_z^2$

# Search with ESR-STM at nm range

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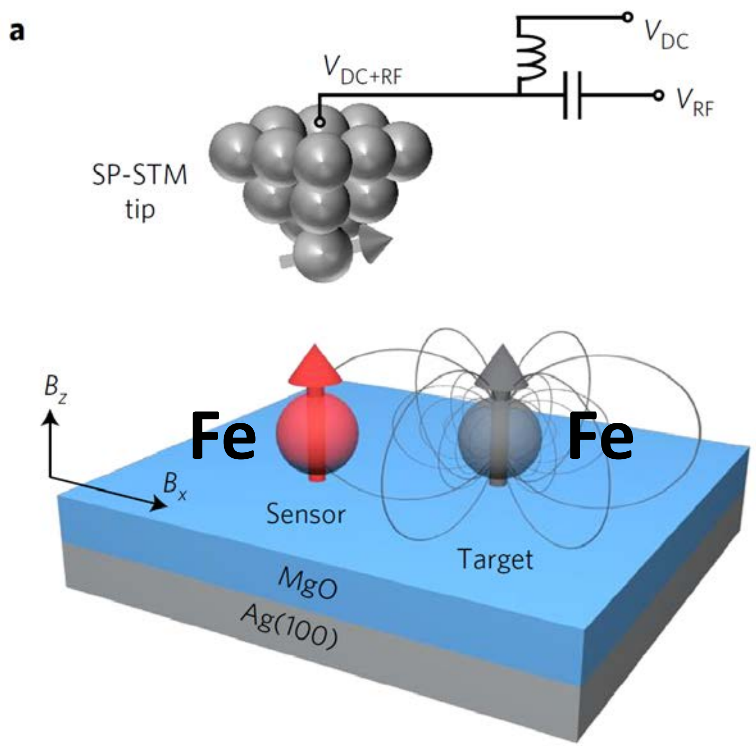
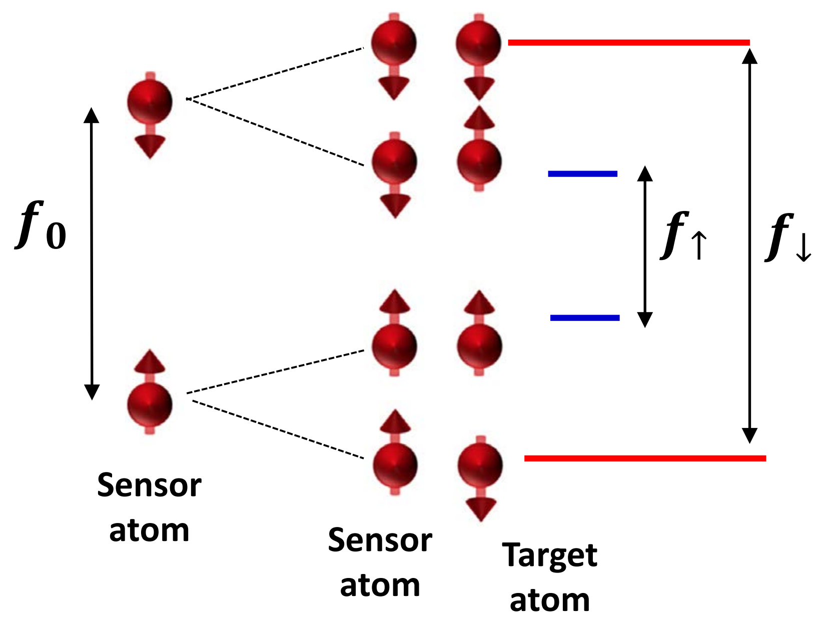
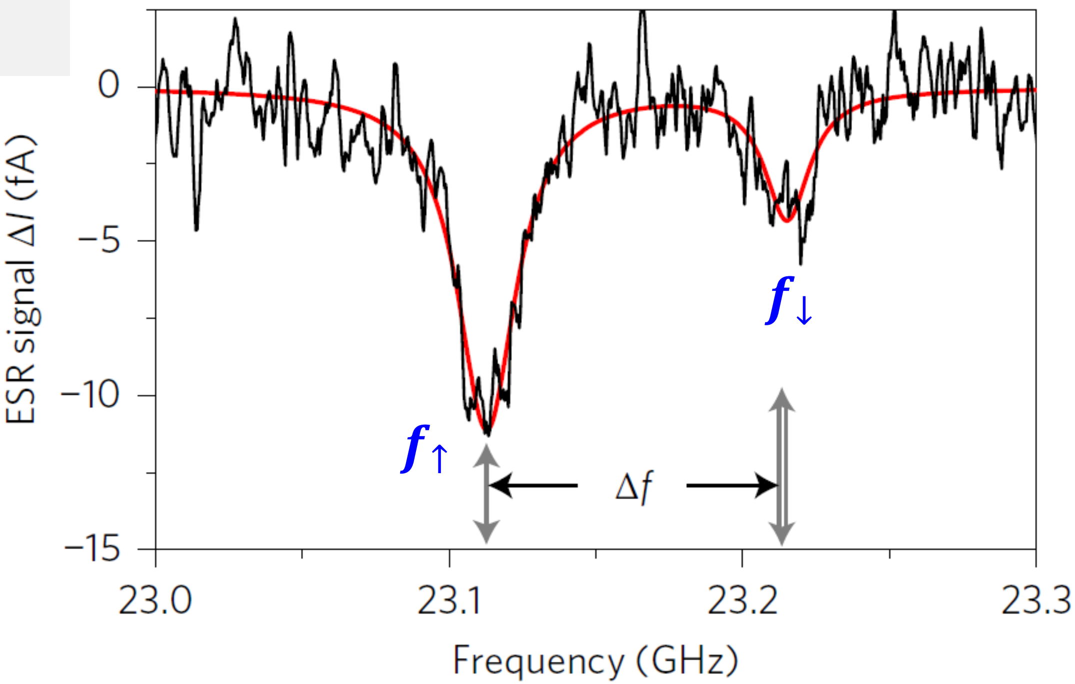


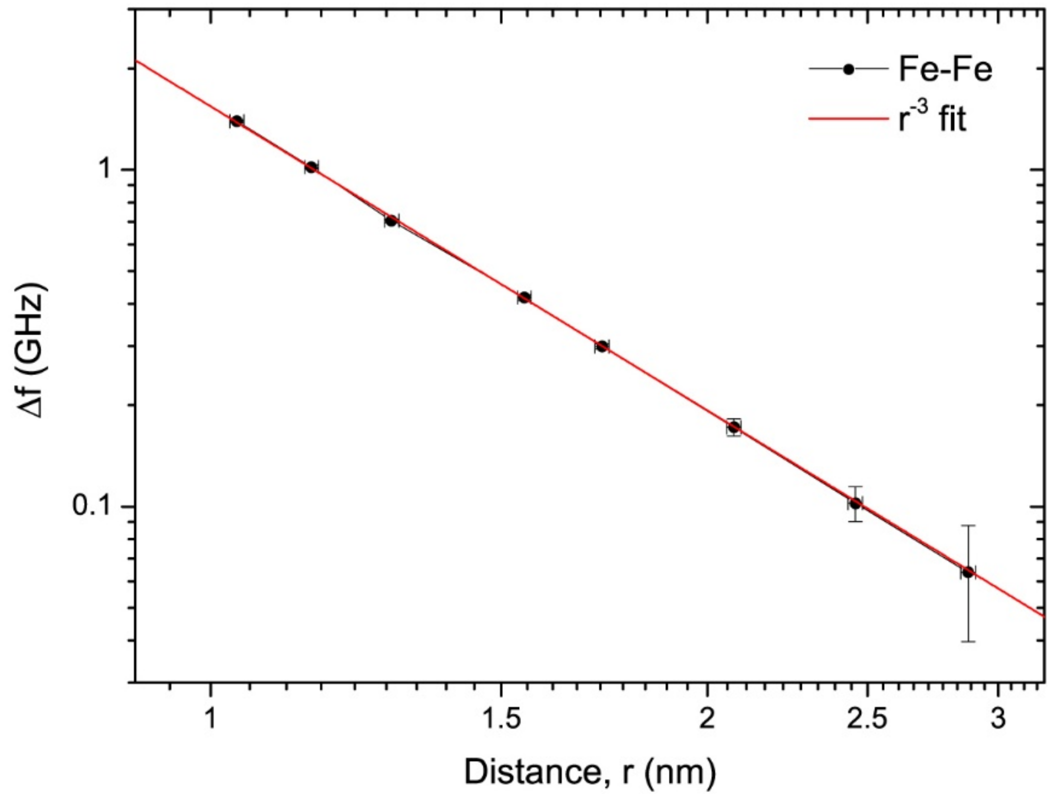




$$\Delta f = f_\downarrow - f_\uparrow = \frac{4E_{dd}}{h}$$

**Dipole-dipole:** $E_{dd} = \frac{\mu_0}{4\pi}\frac{1}{r^3}\left[\left(\vec{m}^{(1)}\cdot\vec{m}^{(2)}\right) - 3\left(\vec{m}^{(1)}\cdot\hat{r}\right)\left(\vec{m}^{(2)}\cdot\hat{r}\right)\right] = \frac{\mu_0}{4\pi}\frac{1}{r^3}m_z^2$

# ESR signal

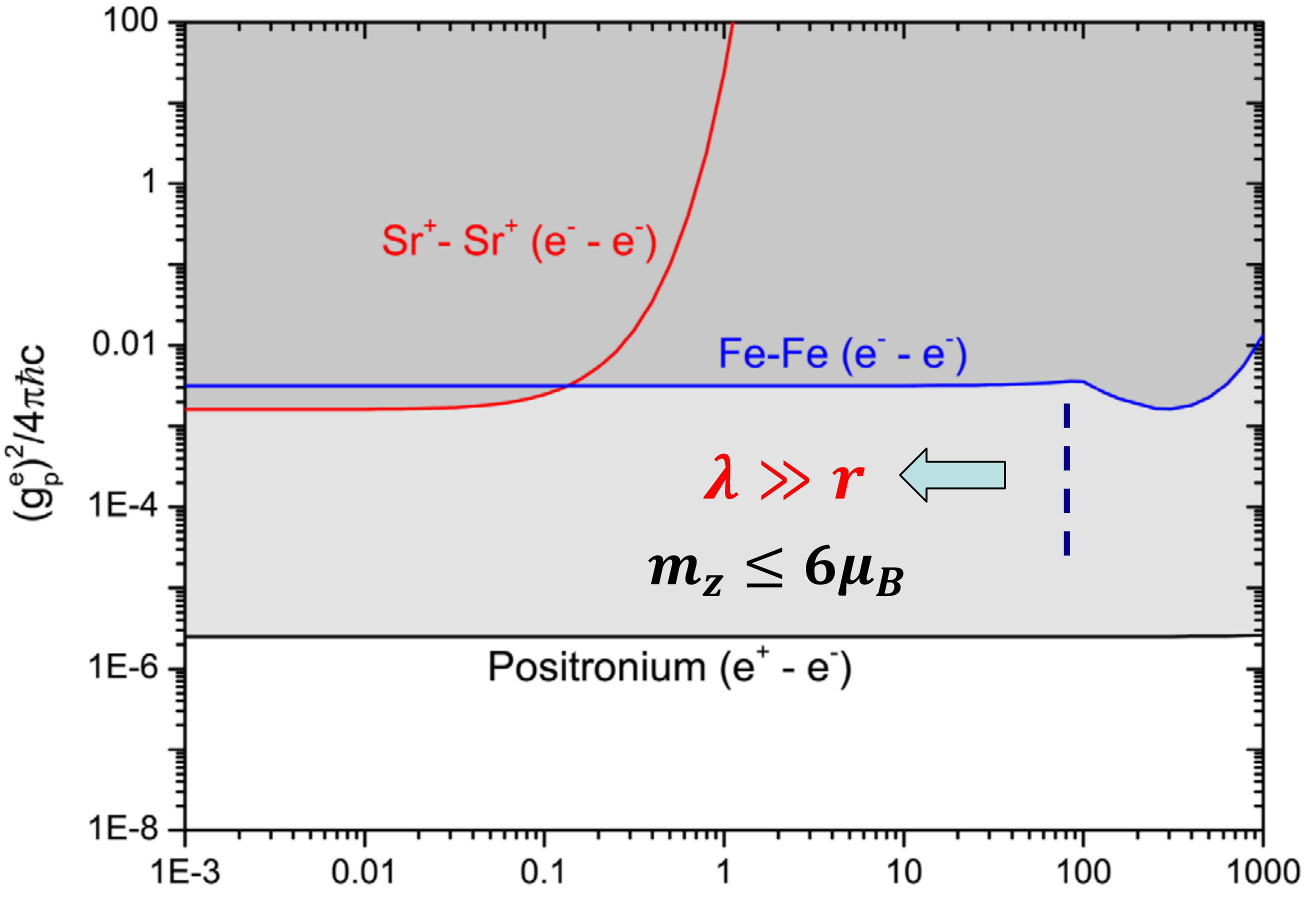



$$\Delta f = \frac{\mu_0}{h\pi}\frac{1}{r^3}m_z^2 + \Delta f_{exotic}$$

# Constraints on $V_{pp}$

$$V_{pp}(r) = -\frac{g_p^2}{4\pi\hbar c}\frac{\hbar^3}{4m_f^2 c}\left[\hat{\sigma}_1\cdot\hat{\sigma}_2\left(\frac{1}{\lambda r^2}+\frac{1}{r^3}\right) - (\hat{\sigma}_1\cdot\hat{r})(\hat{\sigma}_2\cdot\hat{r})\left(\frac{1}{\lambda^2 r}+\frac{3}{\lambda r^2}+\frac{3}{r^3}\right)\right]e^{-r/\lambda}$$




$\lambda = 200\ \mu m$ $\lambda = 0.2\ nm$

$$\Delta f = \frac{\mu_0}{h\pi}\frac{1}{r^3}m_z^2 + \Delta f_{V_{dd}}$$

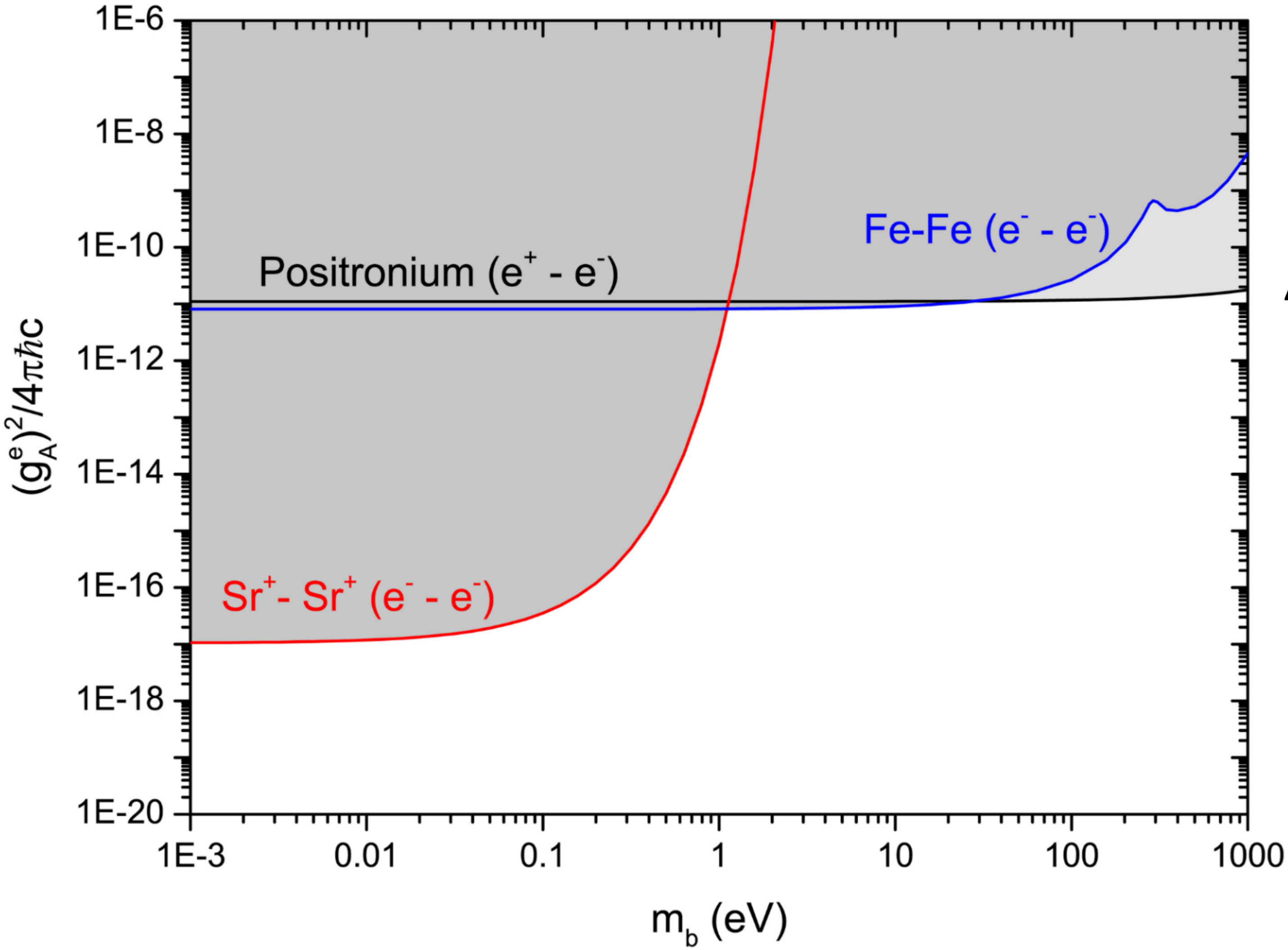
**Mass of Axion-like particle:**

$$m_b = \frac{\hbar}{\lambda c}$$

Pengshun Luo *et al.*, PRD 96, 055028 (2017)

# Constraints on axial coupling force

$$V_{AA}(r) = \frac{g_A^2}{4\pi\hbar c}\frac{\hbar c}{r}e^{-r/\lambda}\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2$$




$$\Delta f = \frac{\mu_0}{h\pi}\frac{1}{r^3}m_z^2 + \Delta f_{V_2}$$

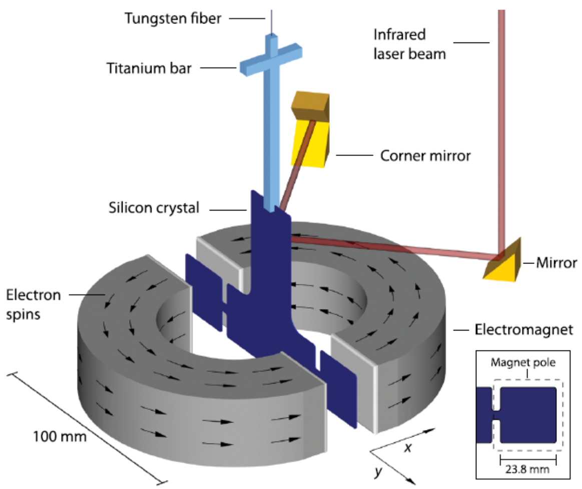
$$m_b = \frac{\hbar}{\lambda c}$$

# Macroscopic force or torque measurement

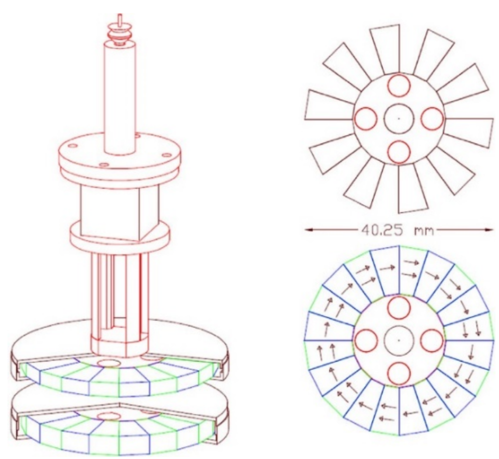
$$F_i = -\frac{\partial V(\vec{r})}{\partial x_i} \qquad \tau = -\frac{\partial V(\vec{r})}{\partial \theta}$$

# Torsion balance

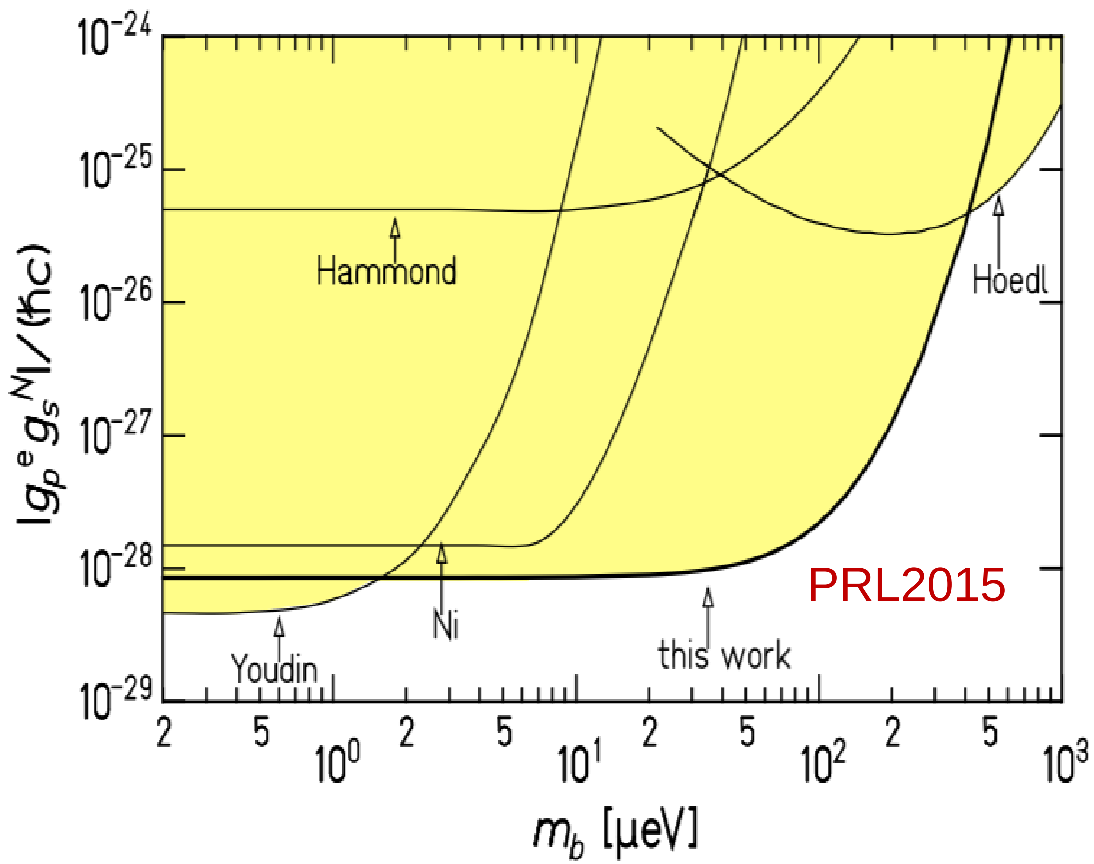
$V_{md}(r)$




$V_{md}(r), V_{dd}(r)$



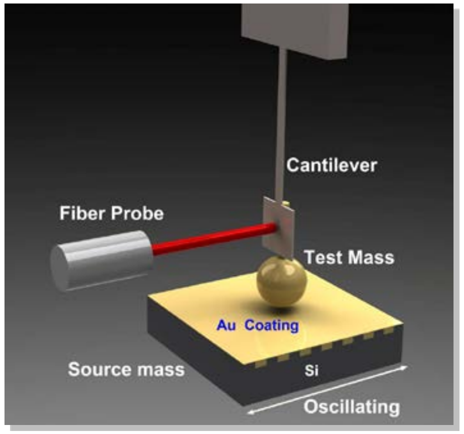

$\lambda = 100\ mm$ $\lambda = 200\ \mu m$

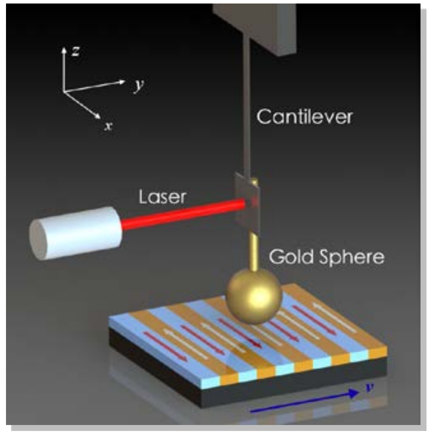


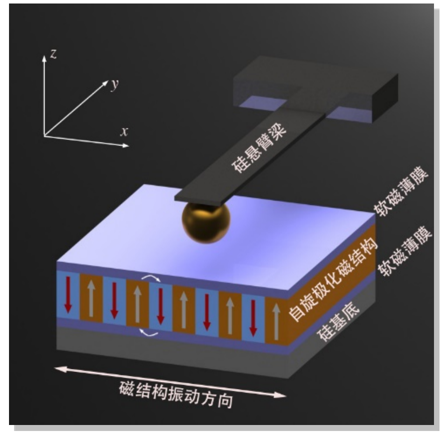

The Eöt-Wash Group, Washington Univ.

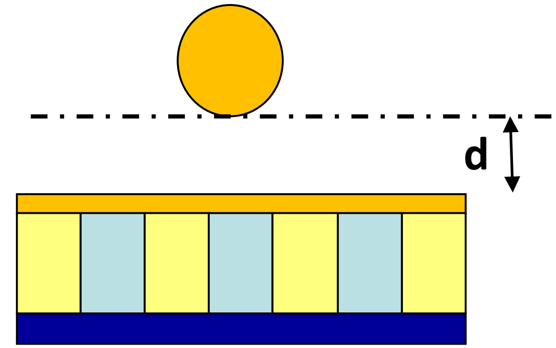
PRL 106, 041801 (2011)
PRL 111, 151802 (2013)
PRL 115, 201801 (2015)

# Micro cantilever/ Atomic force microscope



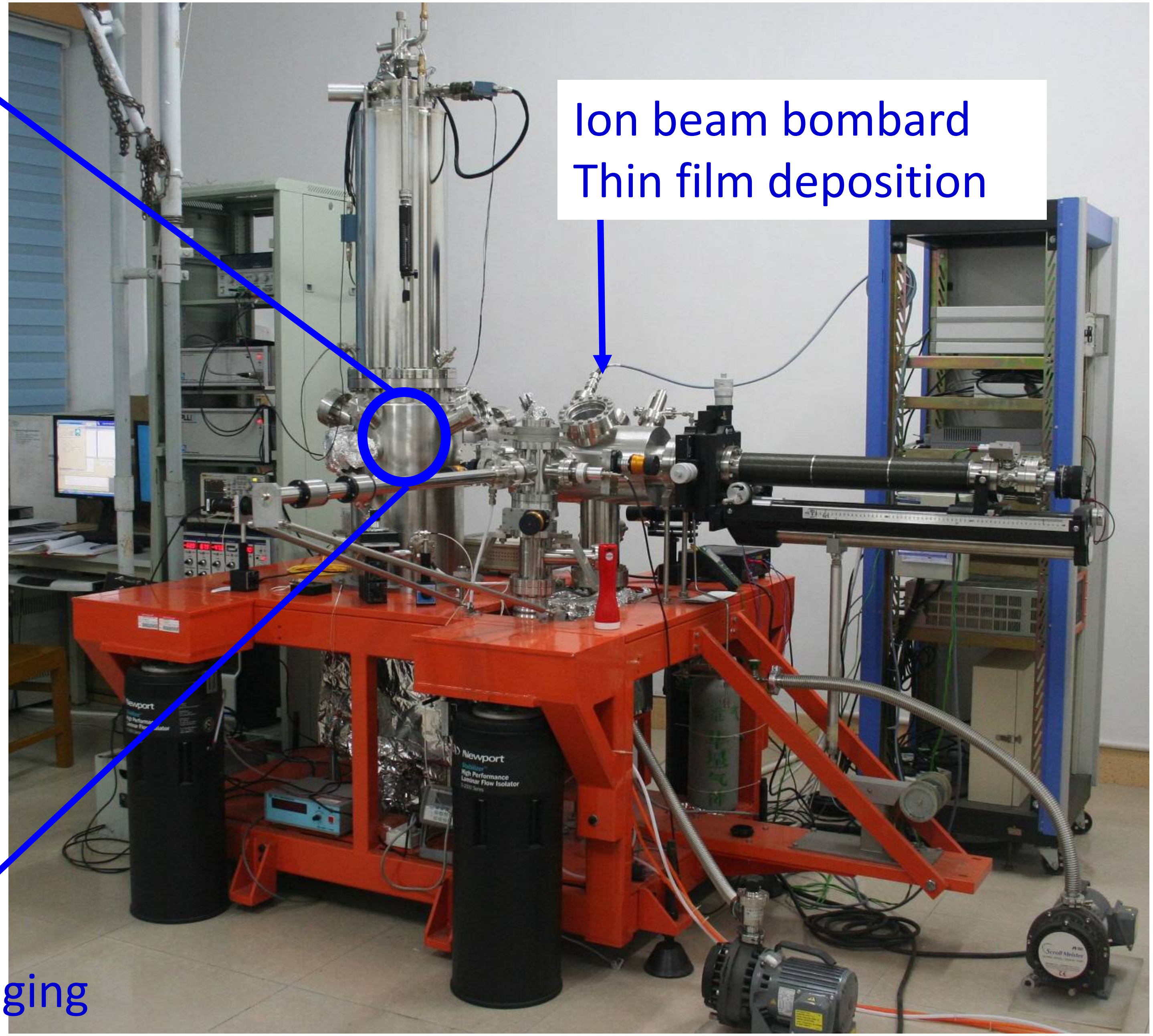




- Soft cantilever： k ~ mN/m
- Fiber laser interferometer： ~ 4 pm/√Hz (@~20 Hz)
- Source: periodic structures, to separate the signal from well-known forces
- Microsphere: close distance (μm)

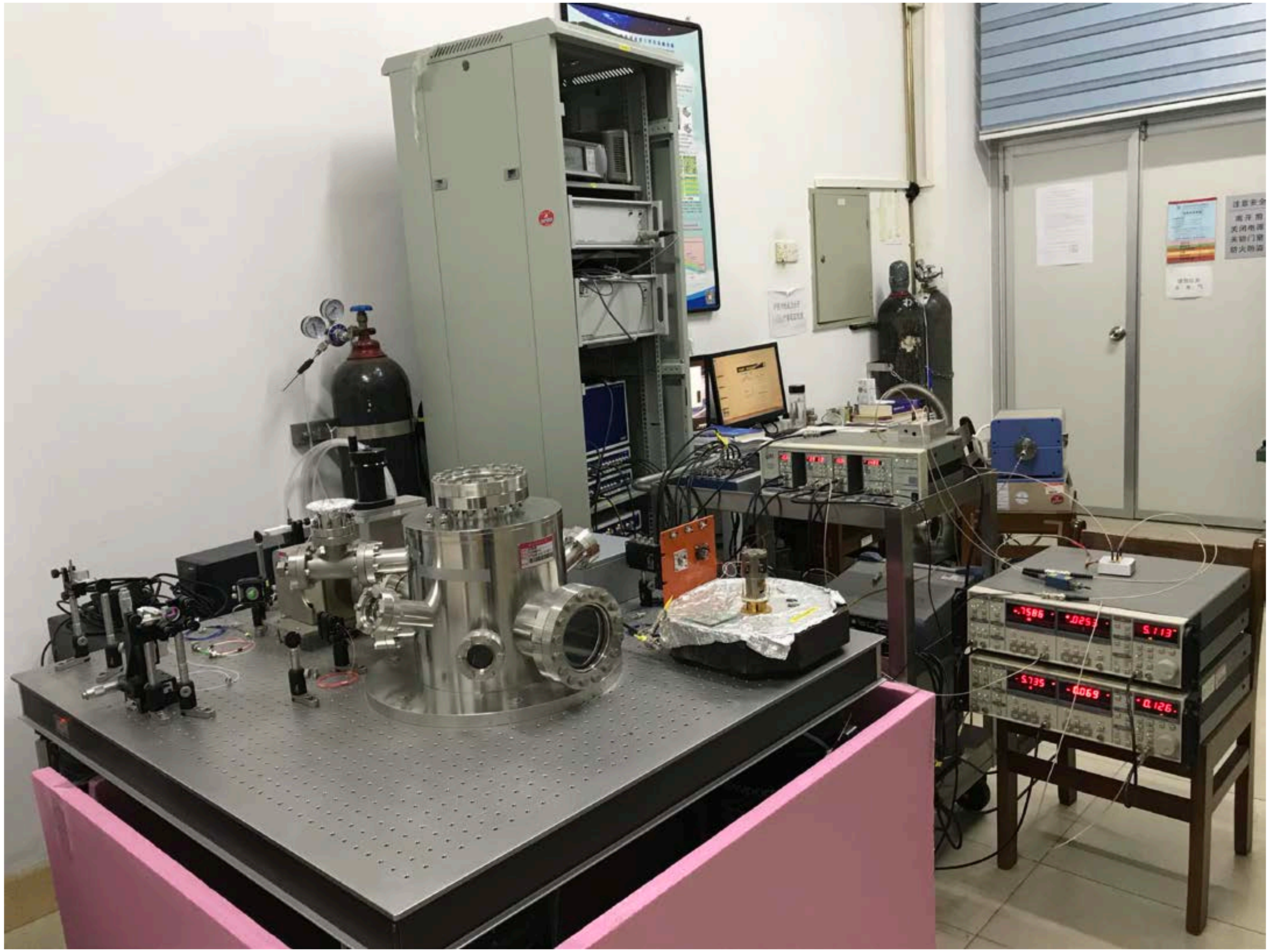
# Apparatus: low temperature SPM



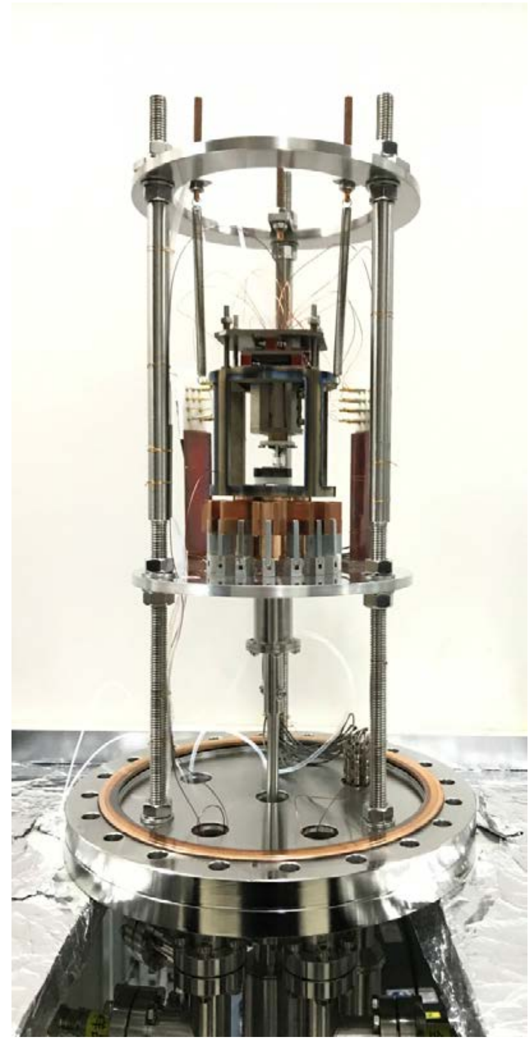
Ion beam bombard
Thin film deposition

Surface imaging
Surface potential imaging
ISL exp.

# Room temperature SPM

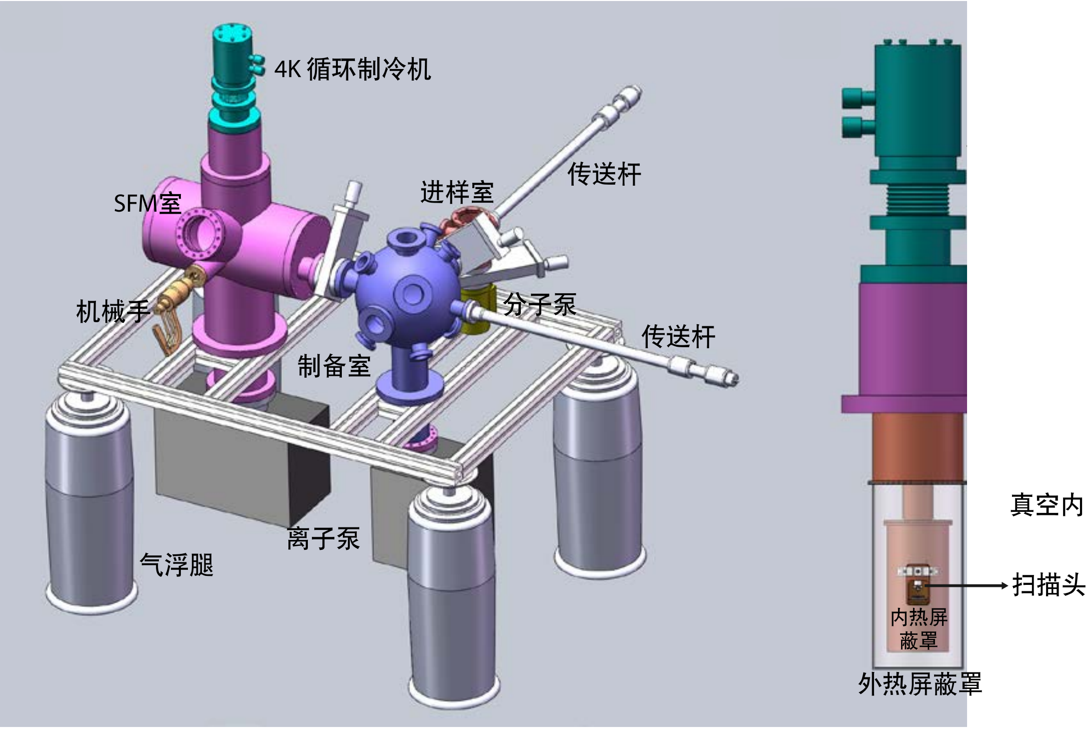


High Vacuum Atomic Force Microscope



Scanning Head

# Low temperature SPM under design



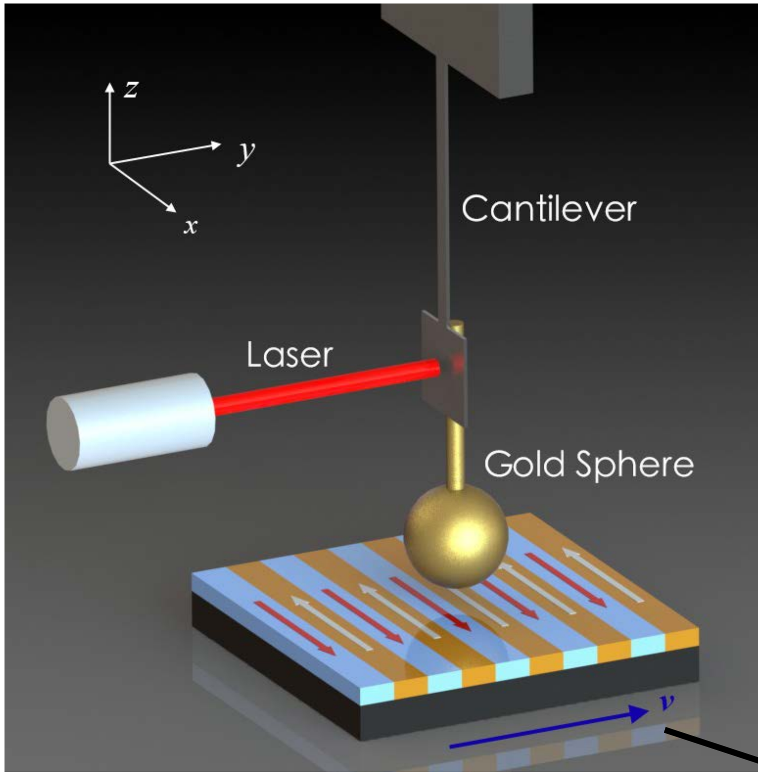


- Low temperature: Helium-free cryostat
- Improve cantilever displacement sensitivity
- Rigid design
- More displacement sensors

# $V_{4+5}$

$$V_{4+5} = -Af_{\perp}^{eN}\frac{\hbar^2}{8\pi m_e c}\hat{\sigma}\cdot(\vec{v}\times\hat{r})\left(\frac{1}{\lambda r}+\frac{1}{r^2}\right)e^{-r/\lambda}$$

$$f_{\perp}^{eN}\begin{cases}\frac{1}{2}g_V^e g_V^N \\ -\frac{1}{4}g_s^e g_s^N\end{cases}$$




Spin-polarized electrons($\hat{\sigma}$)

- **Measure lateral force**
- **Periodic spin-polarization：**

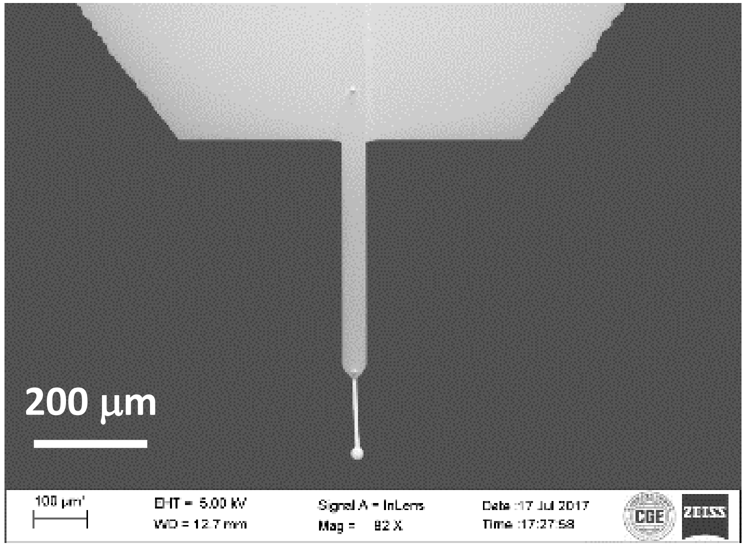
$$f_{signal} = 6f_d$$

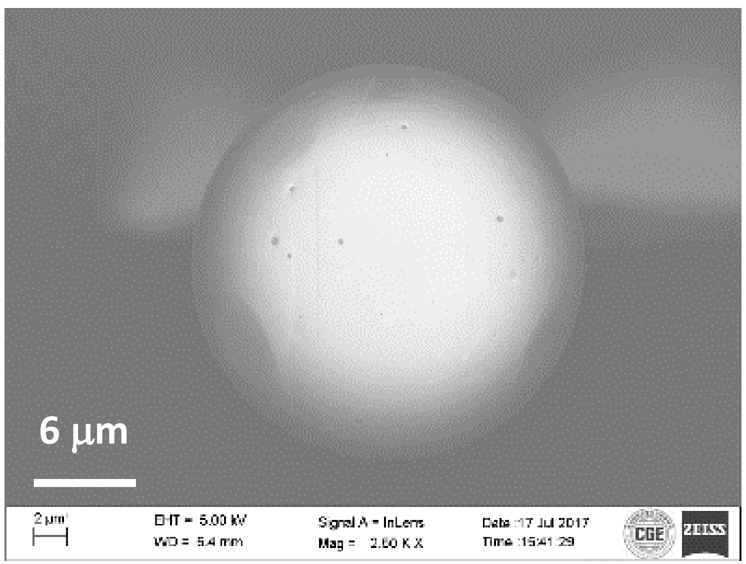
**Separate the signal of interest from the disturbing background**

$$y = y_0 + A_d \cos\omega_d t$$

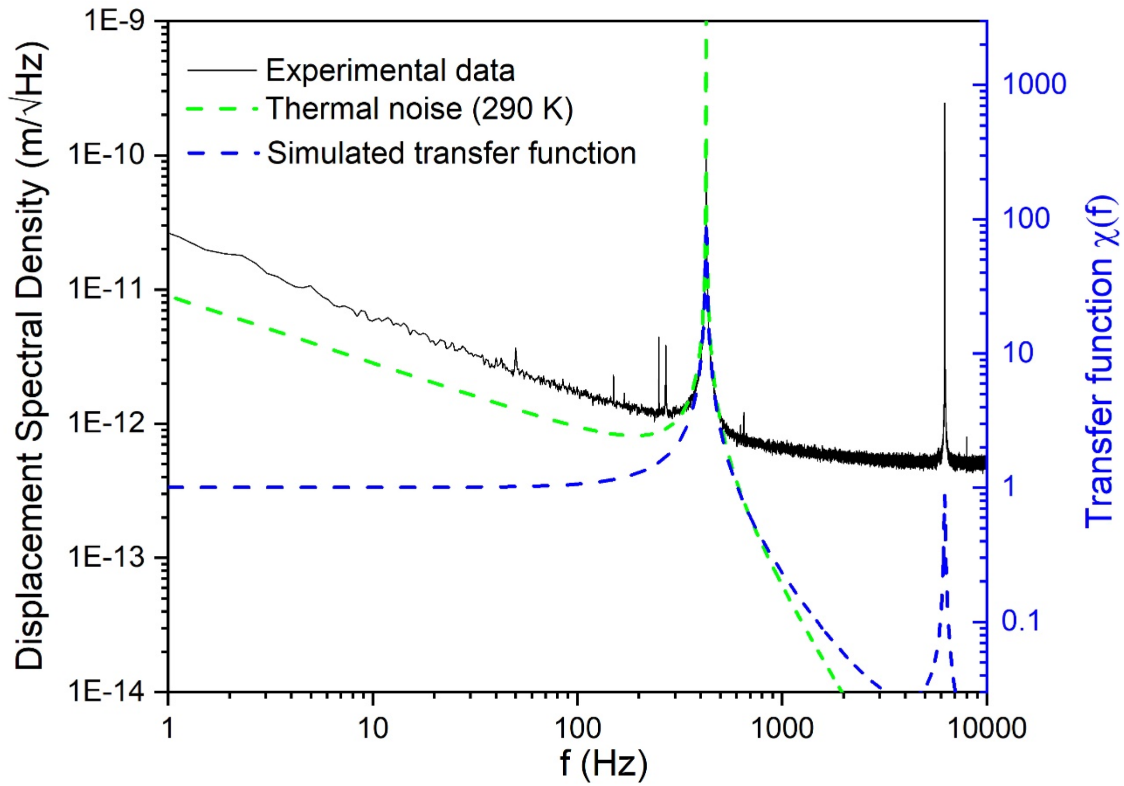
$$v = -A_d\omega_d \sin\omega_d t$$

# Cantilever + Gold sphere




Thermal noise： $S_x^{1/2} = |\chi(f)| \sqrt{\frac{2kk_BT}{\pi f Q}}$

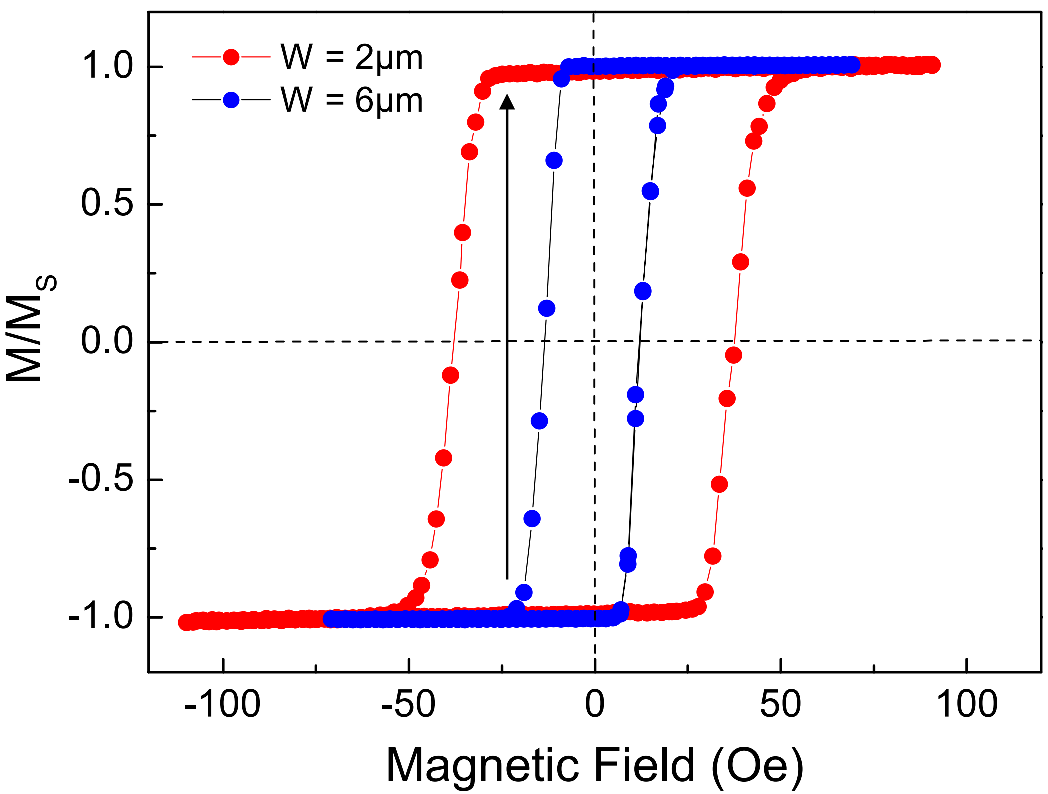



k = 3.3(3) mN/m, $f_0$ = 426 Hz, Q = 6134

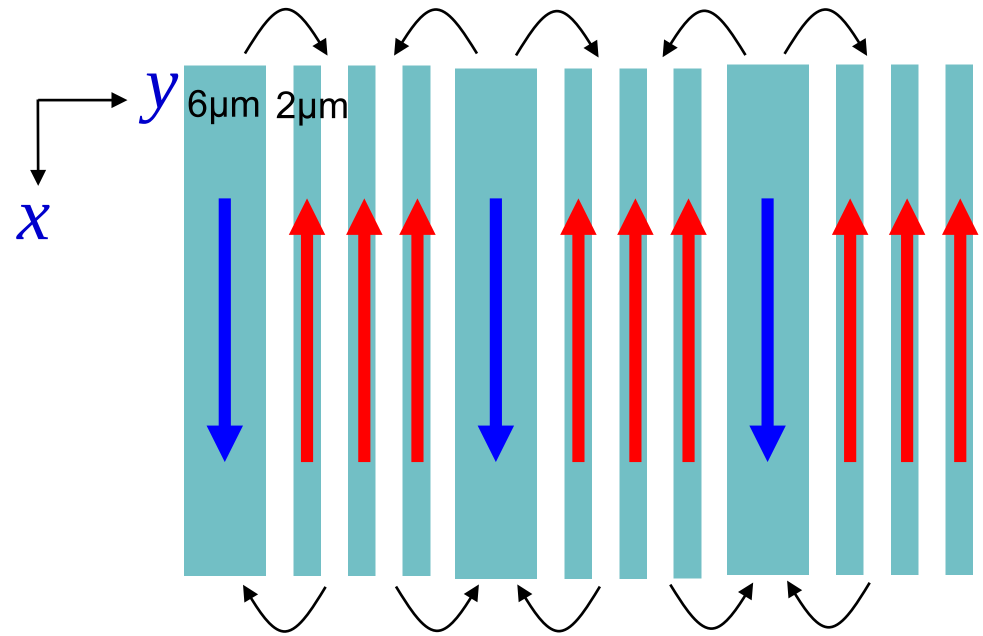
Noise floor： $4\ \mathrm{pm}/\sqrt{\mathrm{Hz}}$

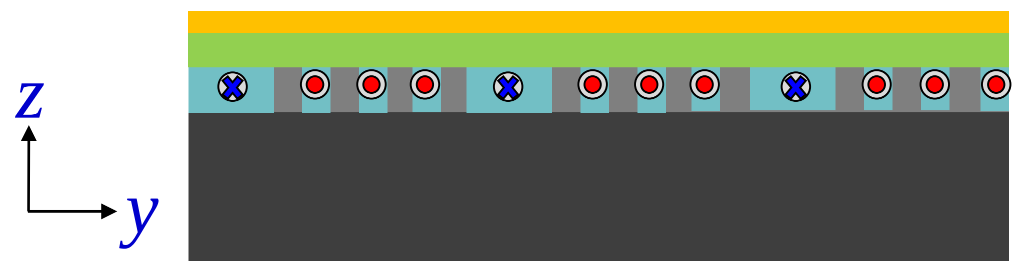
# Magnetic periodic structure

## Shape anisotropy




Thin film(~62 nm)： $Ni_{77}Fe_{23}$

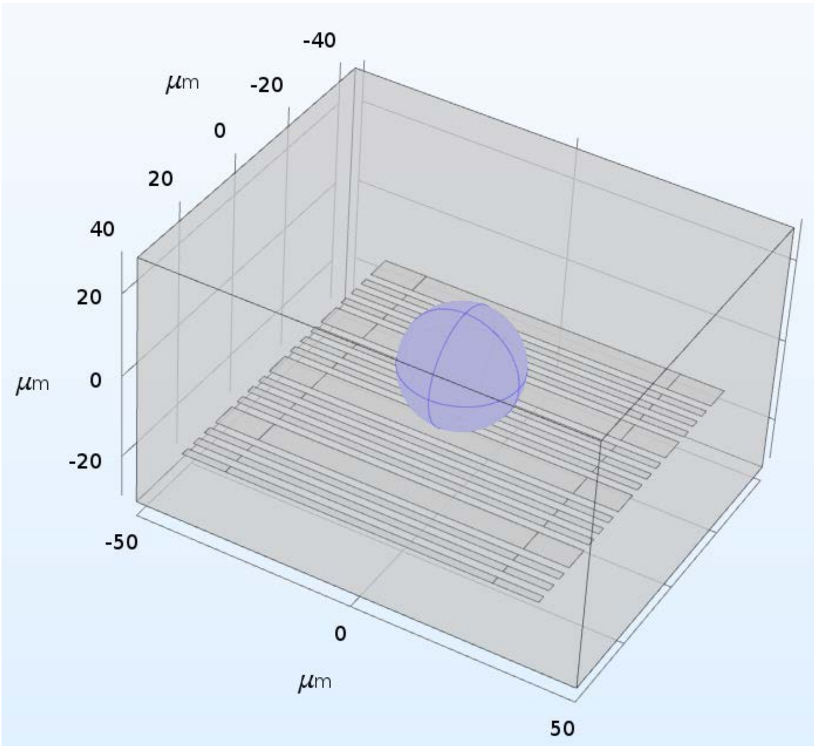


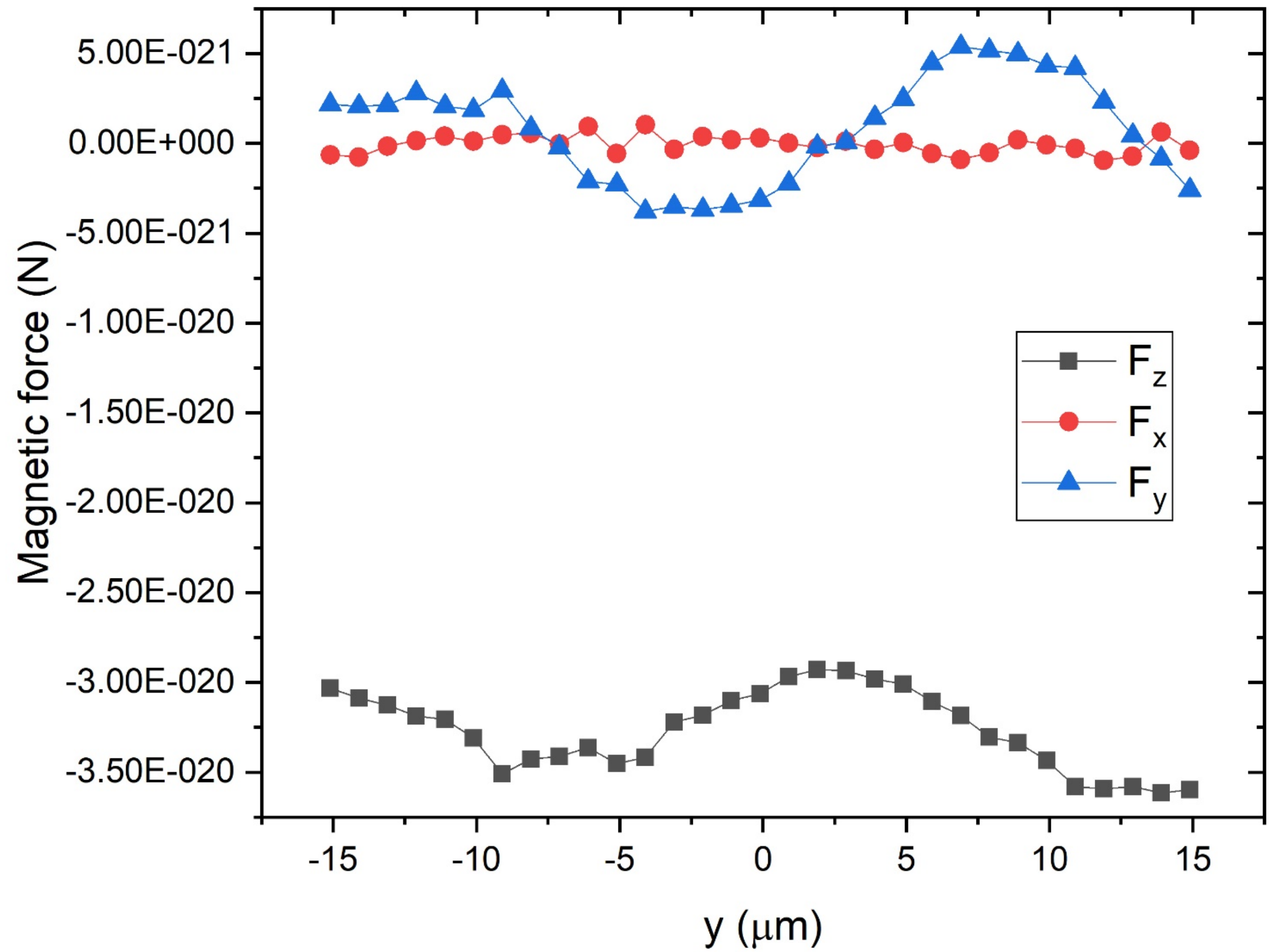

- In plane magnetic field
- Magnetic flux close at the ends

# Magnetic force

**COMSOL Multiphysics Simulation**



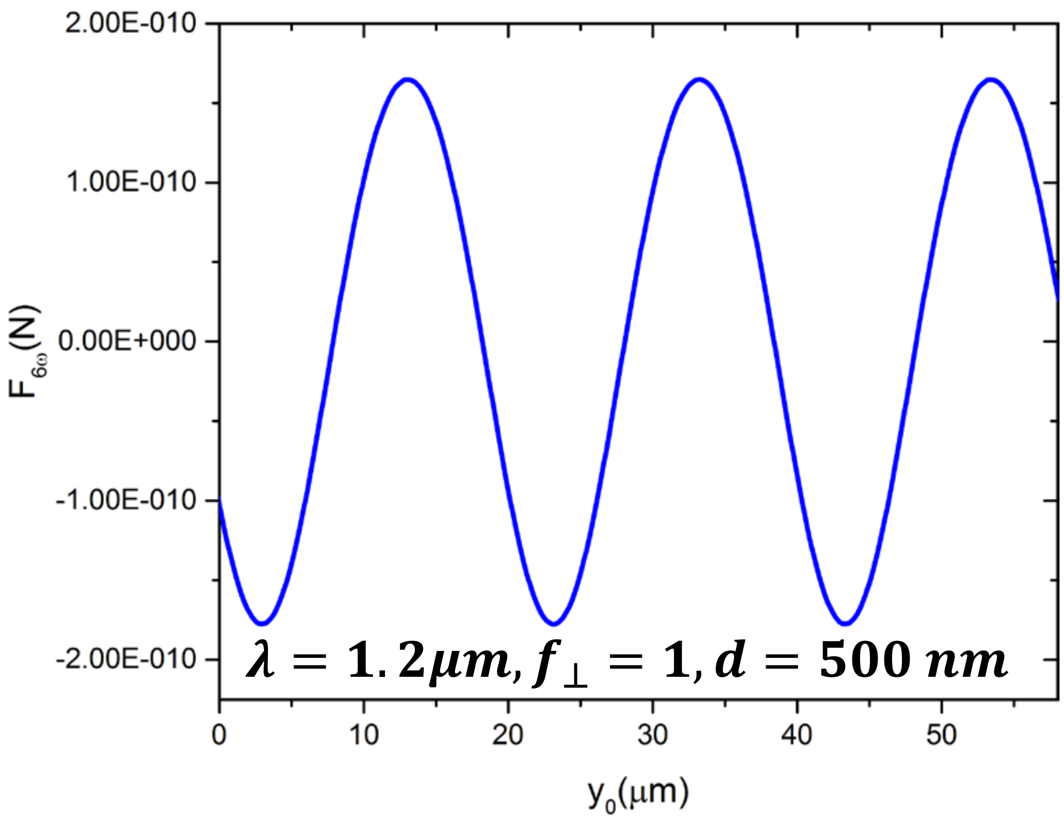

$\chi=1.6 \times 10^{-3}$

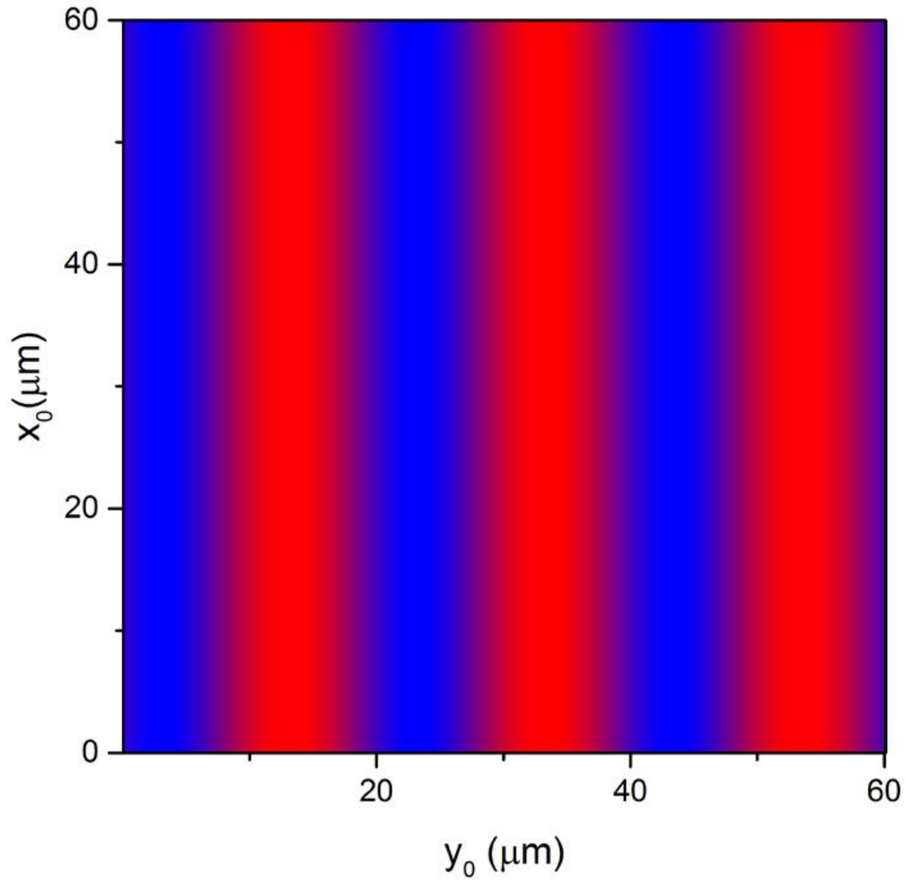



The magnetic susceptibility is less than $1.6 \times 10^{-3}$ for a concentration of 1% [Journal of Applied Physics 42, 1689 (1971)]

# Expected exotic force signal

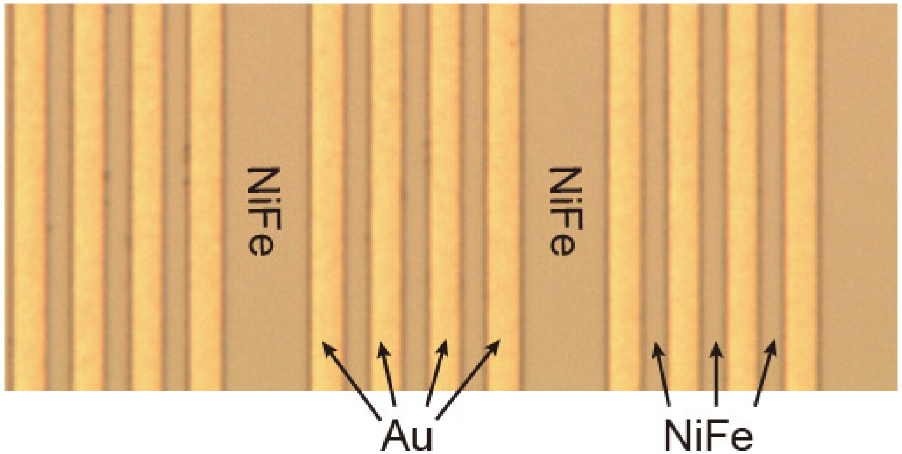
$$F_{4+5}(6\omega_d, y_0) = -\boldsymbol{i}\sum_{n=1}^{\infty} A_d\omega_d \mathrm{Im}\left[f_{4+5}(k_n)e^{ik_n y_0}\right]\left(J_5(k_n A_d) + J_7(k_n A_d)\right)$$

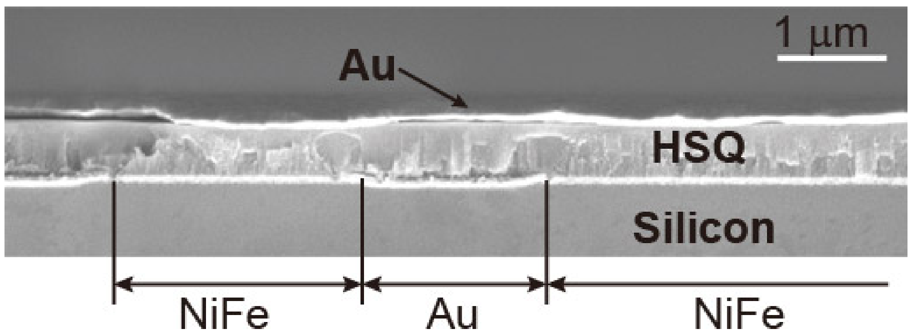


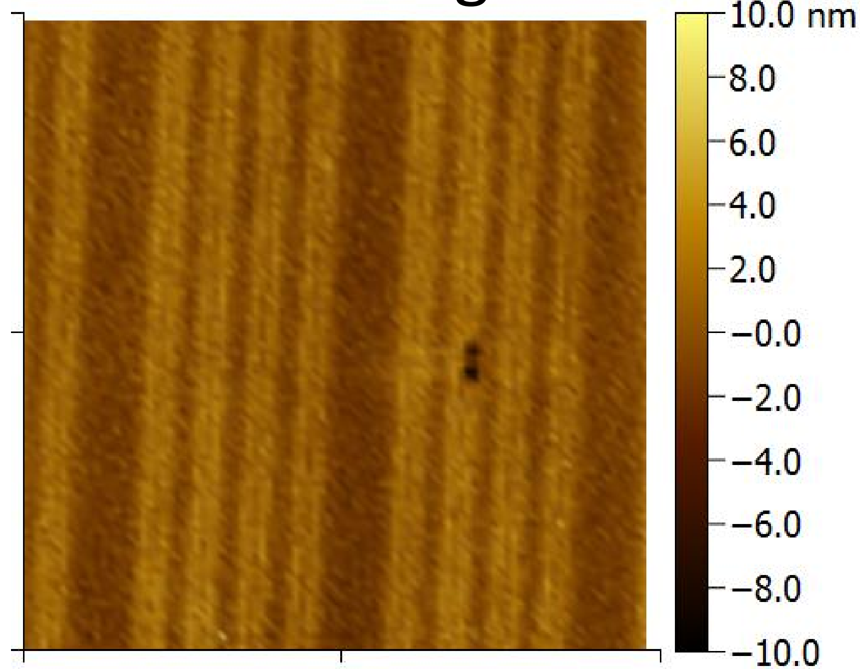

- Extract the sin component from the data
- Most spurious signals appear in cos component

# Fabrication of the magnetic structure



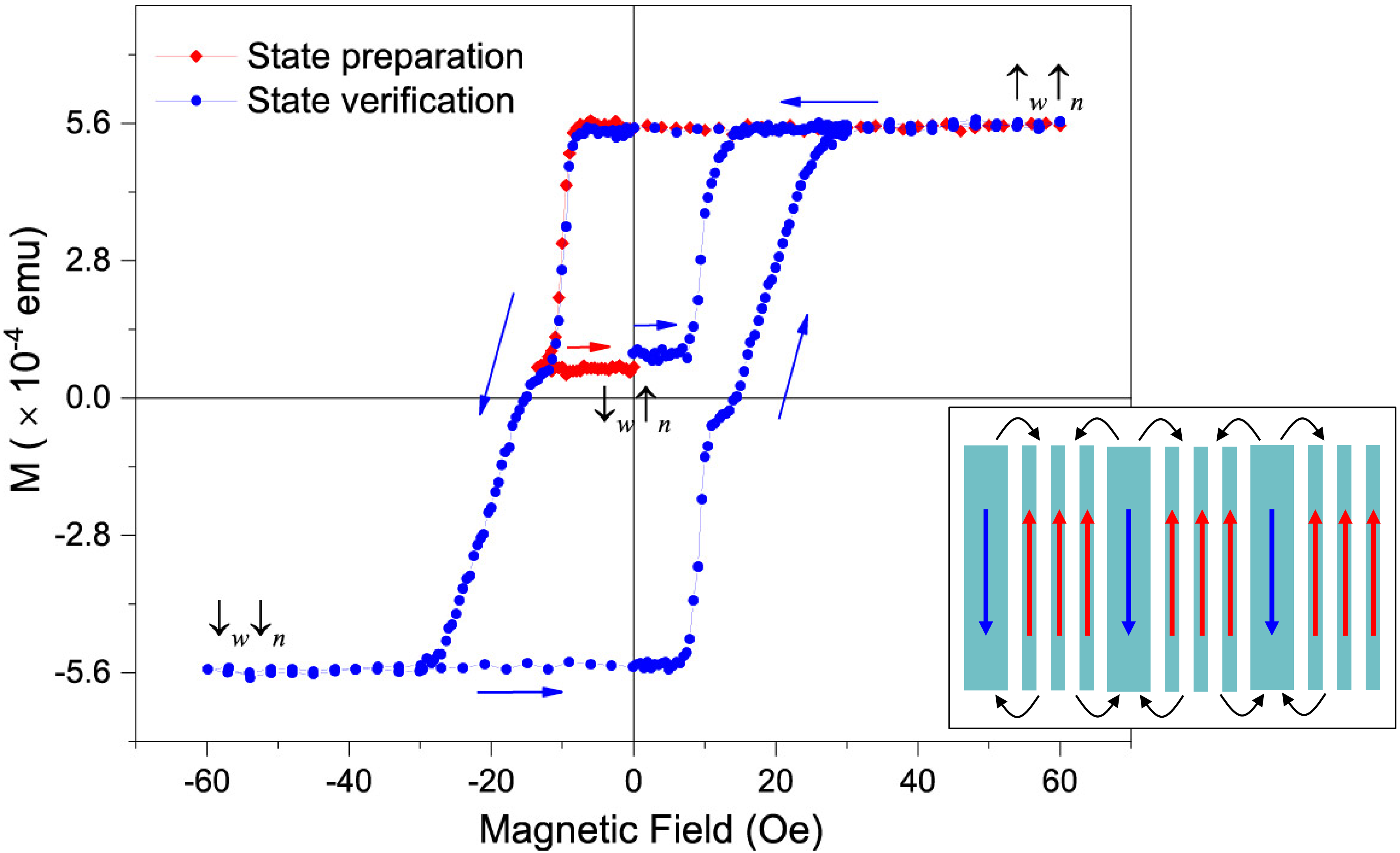

AFM image




corrugation： ~3.3 nm

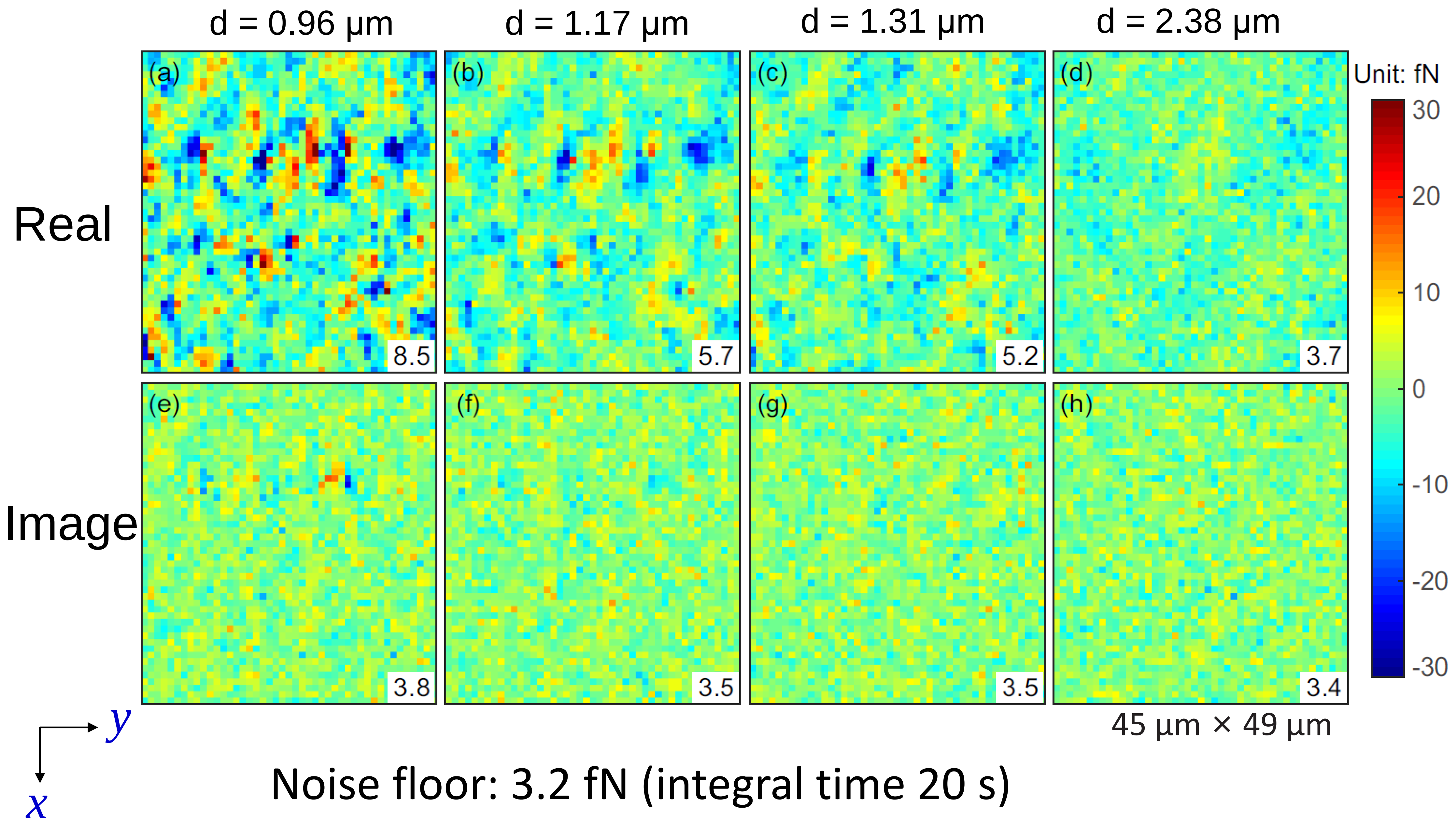
| item | $W_1$ (μm) | | $W_2$ (μm) | | $W_{gap}$ (μm) | | $T_{HSQ}$ (nm) | $T_{Au}$ (nm) | $T_{FeNi}$ (nm) |
|---|---|---|---|---|---|---|---|---|---|
| | top | bottom | top | bottom | top | bottom | | | |
| dimension | 5.91(2) | 6.03(4) | 2.01(2) | 2.12(2) | 2.06(3) | 1.94(2) | 471(8) | 157(7) | 62(4) |

# Anti-parallel state preparation




$$M_n = 8.7(3)\times 10^5\ \mathrm{A/m},\ \ M_w = 6.3(7)\times 10^5\ \mathrm{A/m}$$

# 2D Mapping (distance dependence)

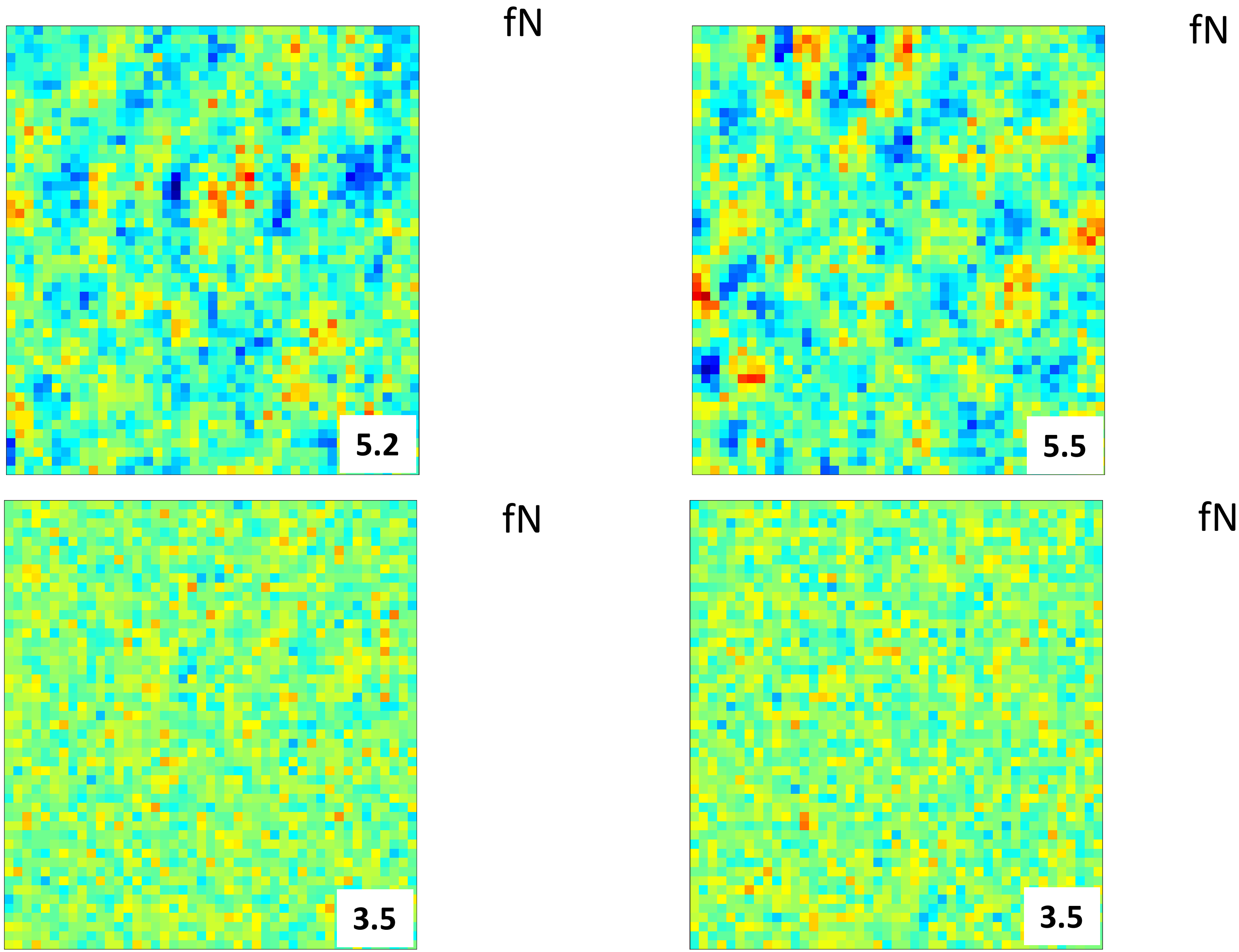



Noise floor: 3.2 fN (integral time 20 s)

# 2D Mapping (location dependence)

Real

Image



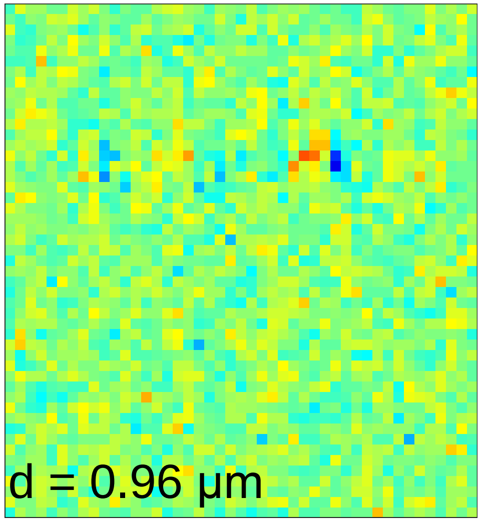

(2222, 2269) μm

(3638, 2168) μm

d ~ 1.31 μm

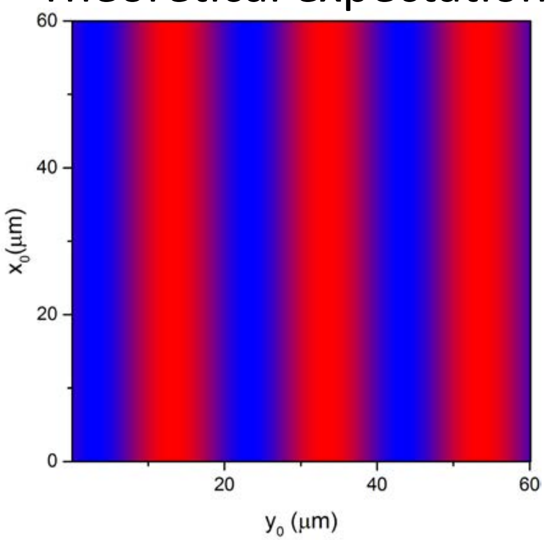
# Maximum likelihood estimation

Experimental data

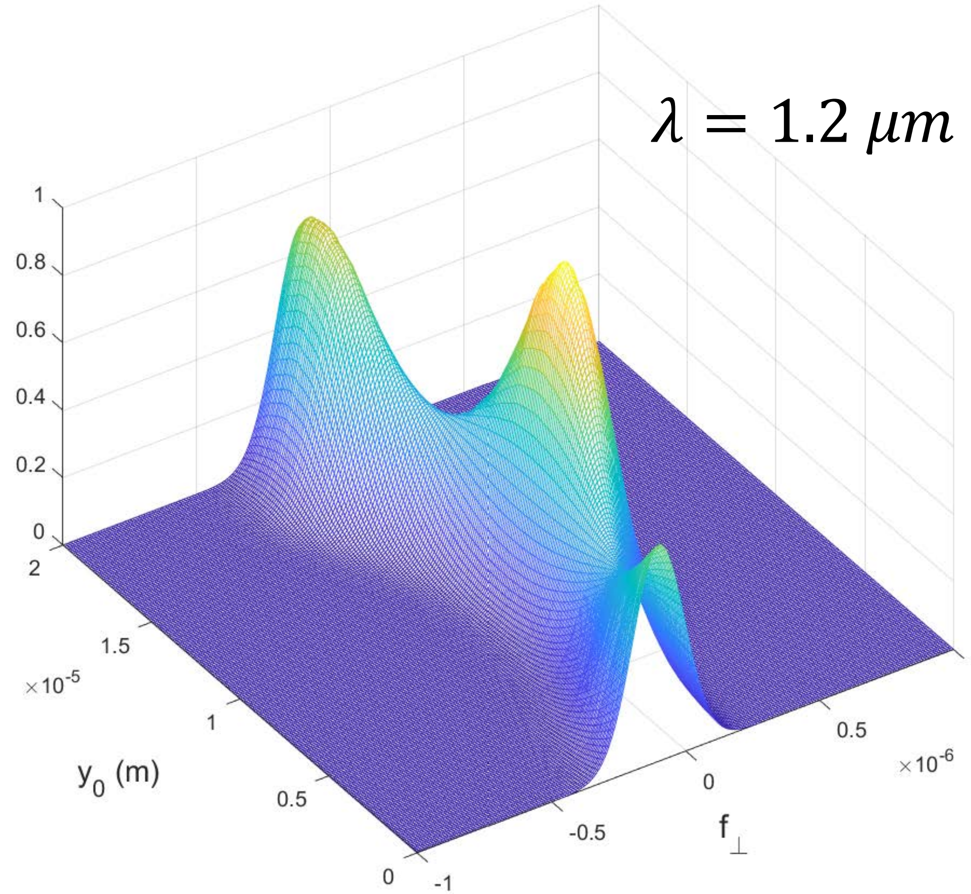



fN

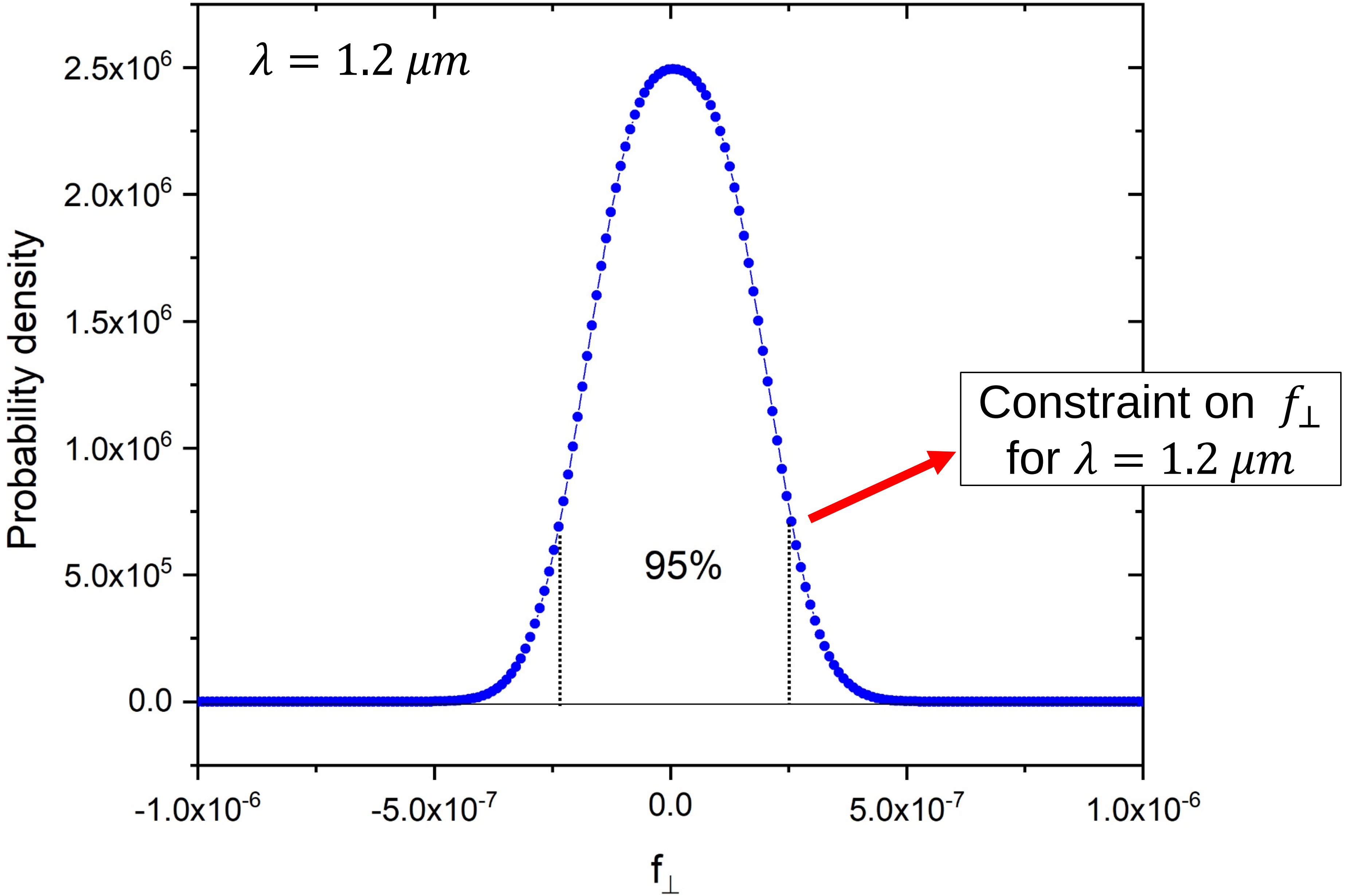
Theoretical expectation




$$P(y_0, f_\perp, \lambda) = \frac{1}{A}\prod_{i,j}\frac{1}{\sqrt{2\pi}\sigma_{ij}}e^{-\frac{(F_{ij}^{exp}-F_{ij}^{T}(f_\perp,\lambda))^2}{2\sigma_{ij}^2}}$$



# Maximum likelihood estimation



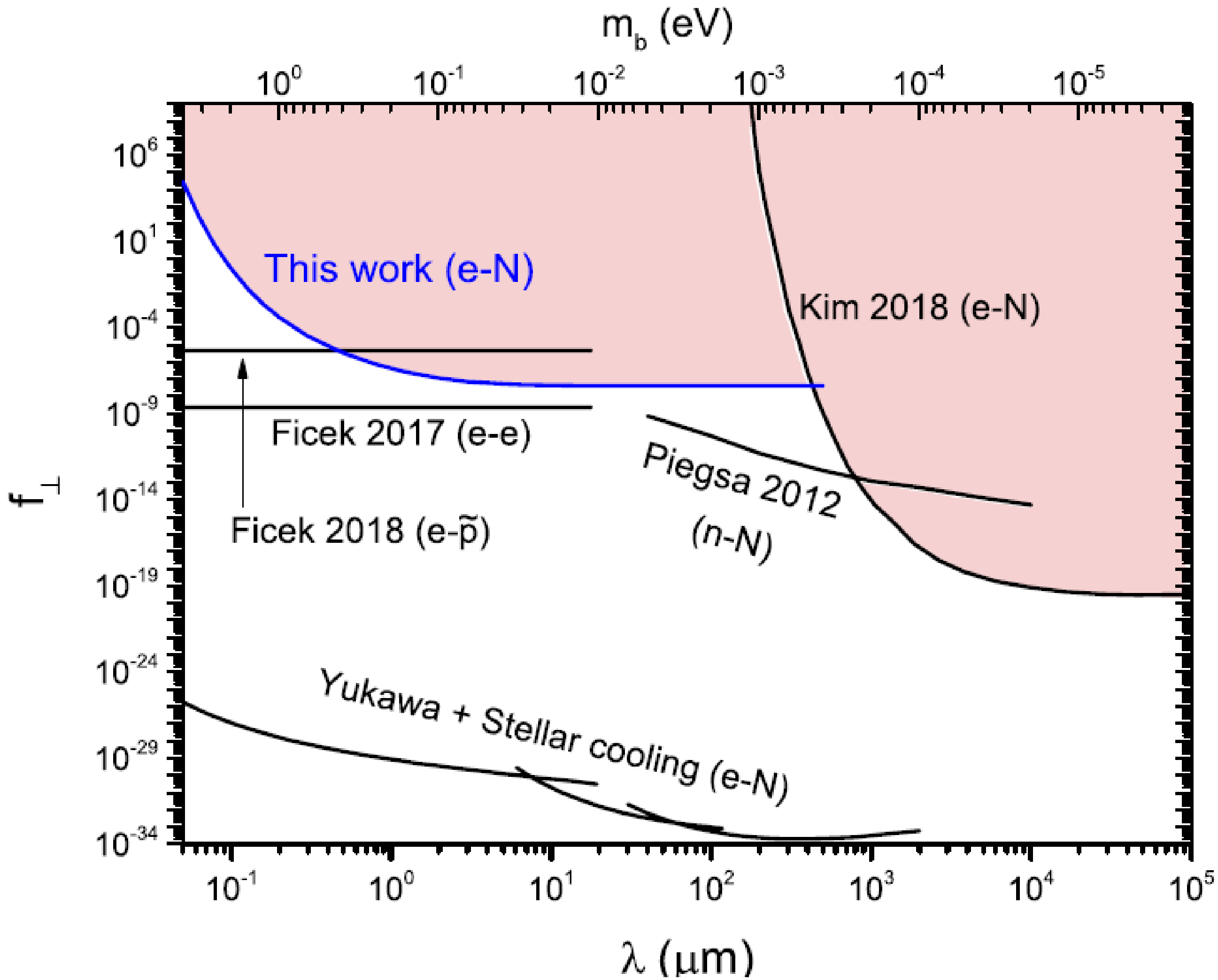
# Experimental parameters

TABLE I. Table of the mean values and uncertainties of the main experimental parameters.

| Parameter | Value | Error | Unit |
|---|---|---|---|
| Sphere radius | 12.26 | 0.03 | $\mu$m |
| Period of structure | 20.46 | 0.08 | $\mu$m |
| Width of the wide stripe | 5.92 | 0.01 | $\mu$m |
| Width of the narrow stripe | 2.02 | 0.01 | $\mu$m |
| $Fe_{24}Ni_{76}$ thickness | 64 | 2 | nm |
| Spin density of the wide stripe | 6.3 | 0.7 | $10^{28}/m^3$ |
| Spin density of the narrow stripe | 8.8 | 0.3 | $10^{28}/m^3$ |
| Distance | 0.96 | 0.04 | $\mu$m |
| Drive amplitude | 24.0 | 0.2 | $\mu$m |

# Constraints on the coupling constant

$$V_{4+5} = -Af_{\perp}^{eN}\frac{\hbar^2}{8\pi m_e c}\hat{\sigma}_1\cdot(\vec{v}\times\hat{r})\left(\frac{1}{\lambda r}+\frac{1}{r^2}\right)e^{-r/\lambda}$$



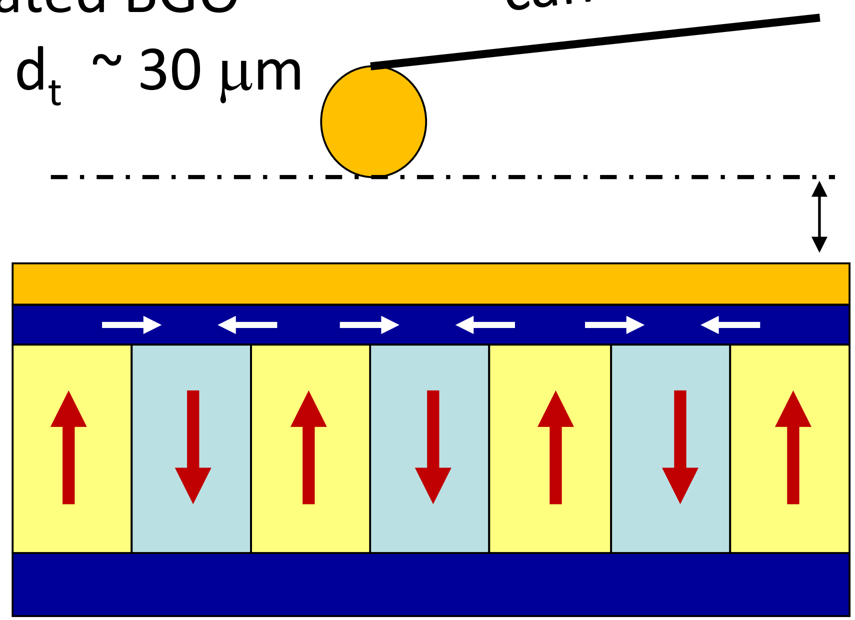

$$f_{\perp}^{eN}\begin{cases}\frac{1}{2}g_V^e g_V^N\\ -\frac{1}{4}g_s^e g_s^N\end{cases}$$

J. Ding *et al.*, Phys. Rev. Lett. 124, 161801 (2020)

# $V_{9+10}$

$$V_{md}(r) = g_p^e g_s^N \frac{\hat{\sigma}\cdot\hat{r}}{8\pi m}\left[\frac{1}{\lambda r}+\frac{1}{r^2}\right]e^{-r/\lambda}$$

axion mediated interaction



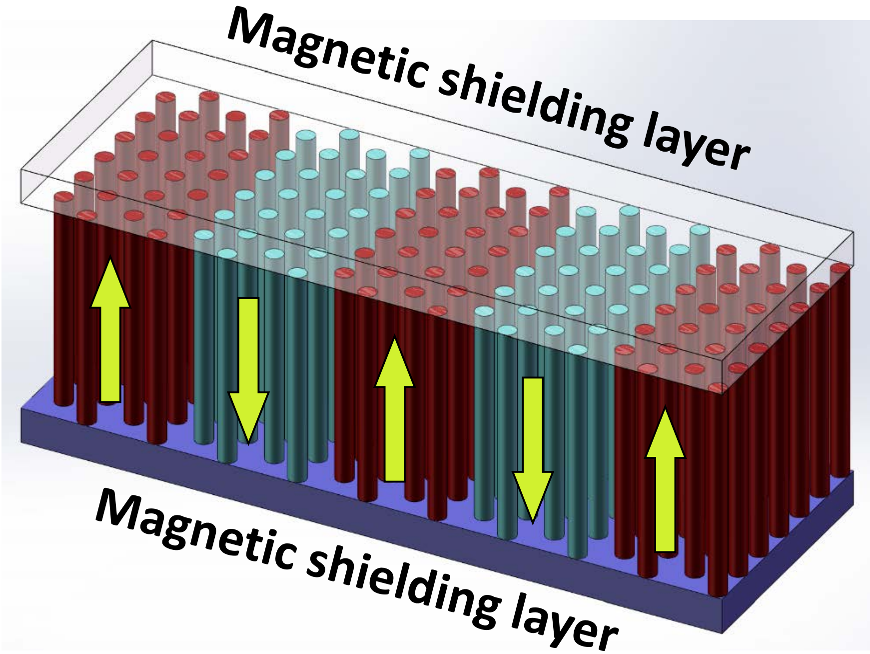

$Bi_4Ge_3O_{12}$(BGO) : high number density of nucleons, 4.3 ×$10^{24}$ $cm^{-3}$

Magnetic shielding layer

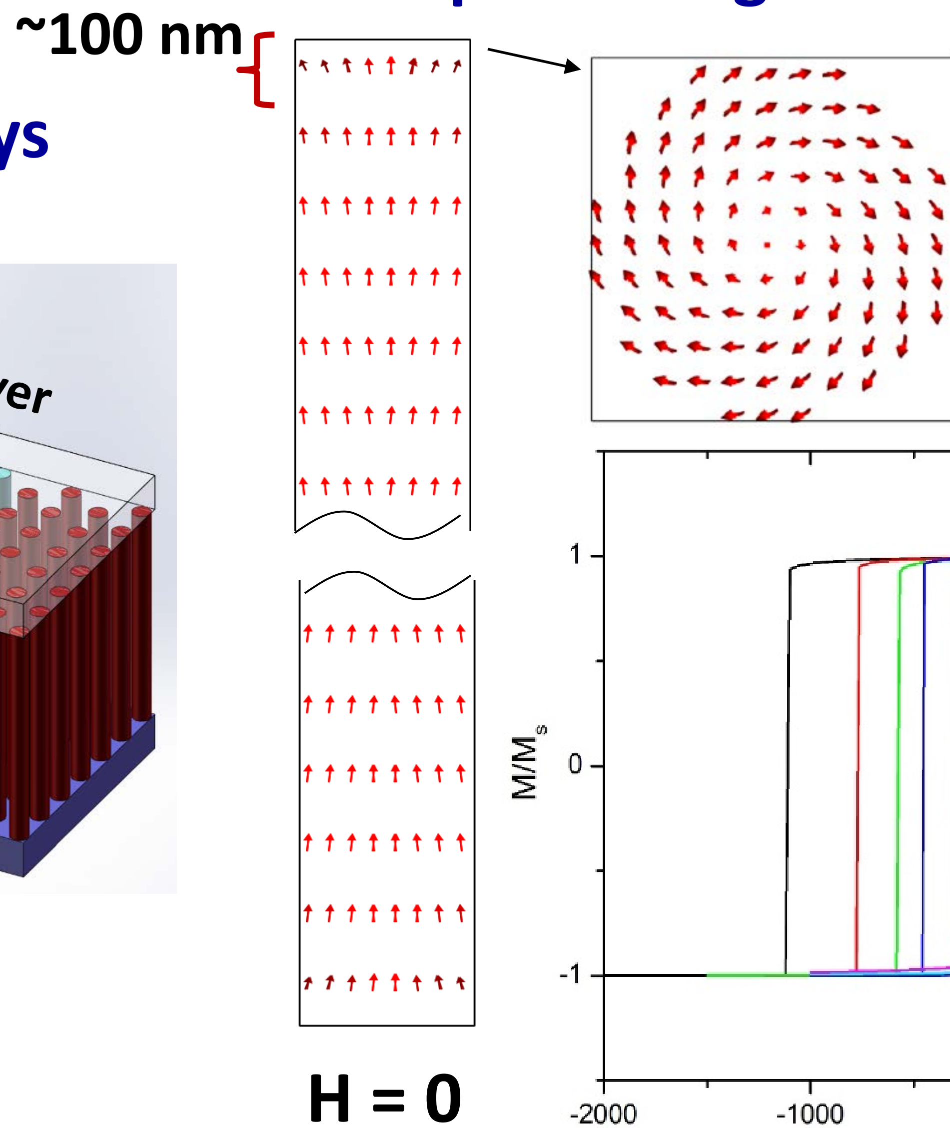
Gold coating

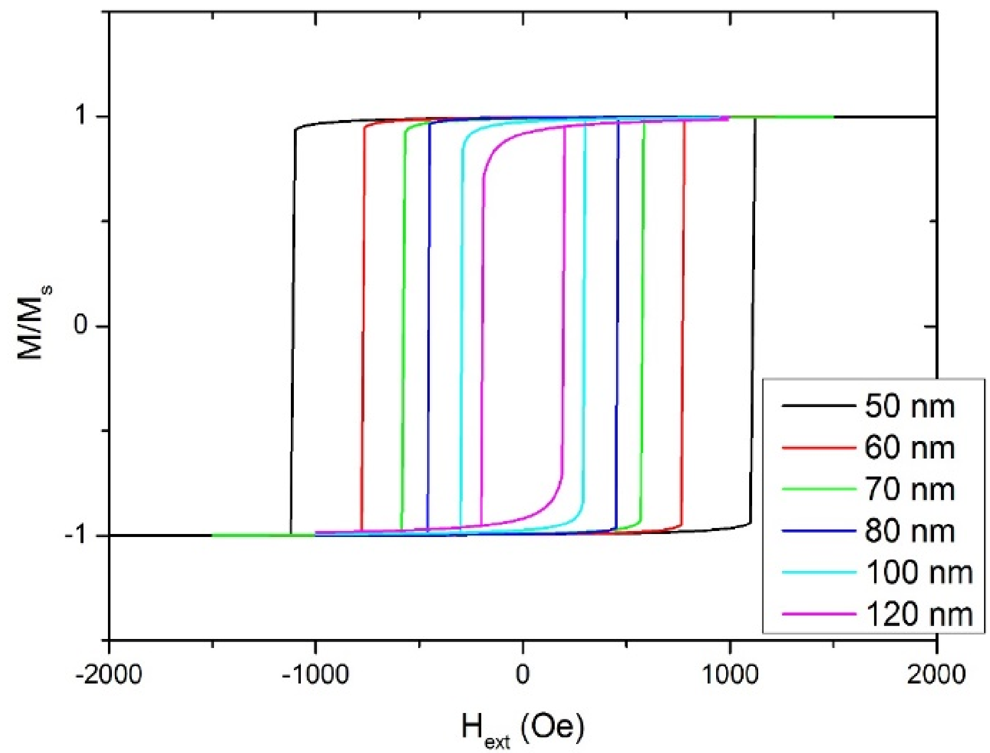
# Magnetic structure: nanopillar arrays

## Nanopillar arrays




## Nanopillar: single domain magnet

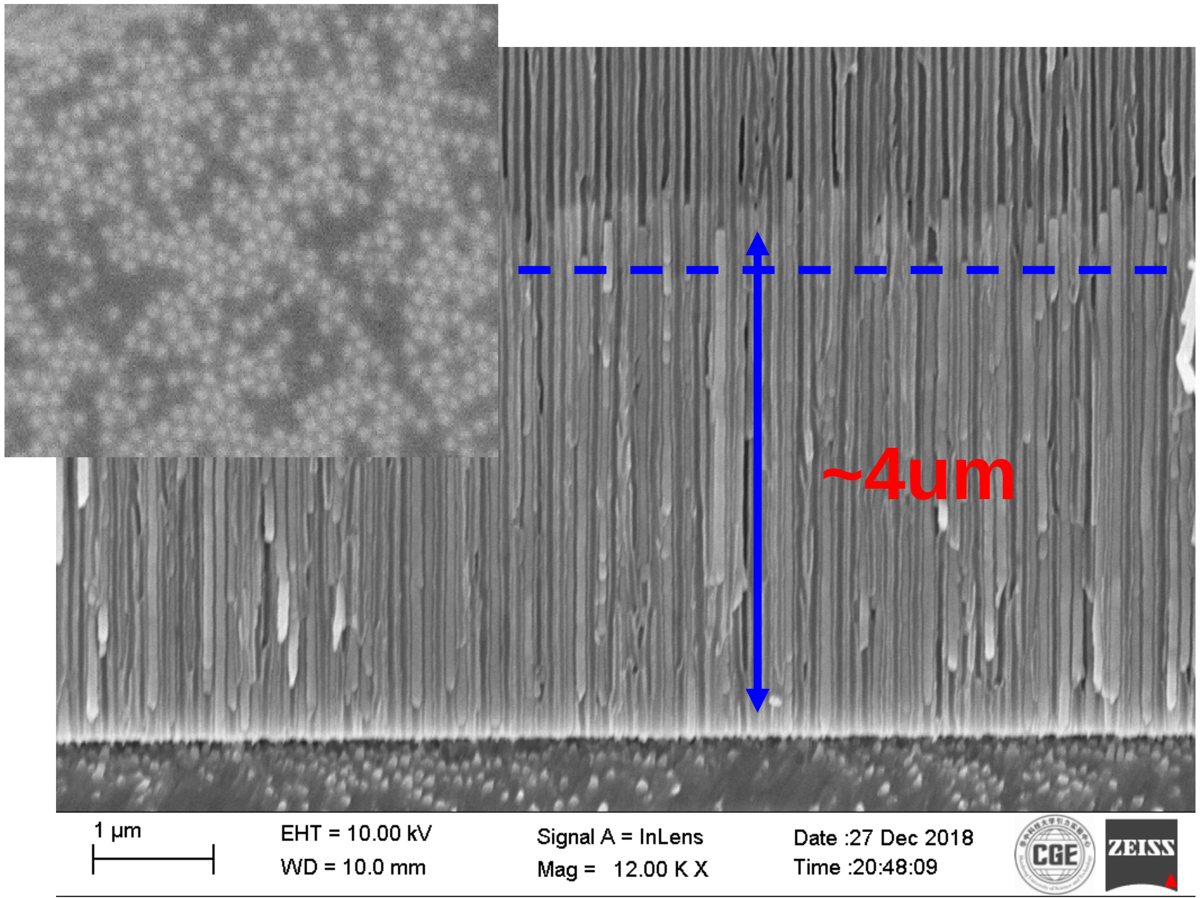


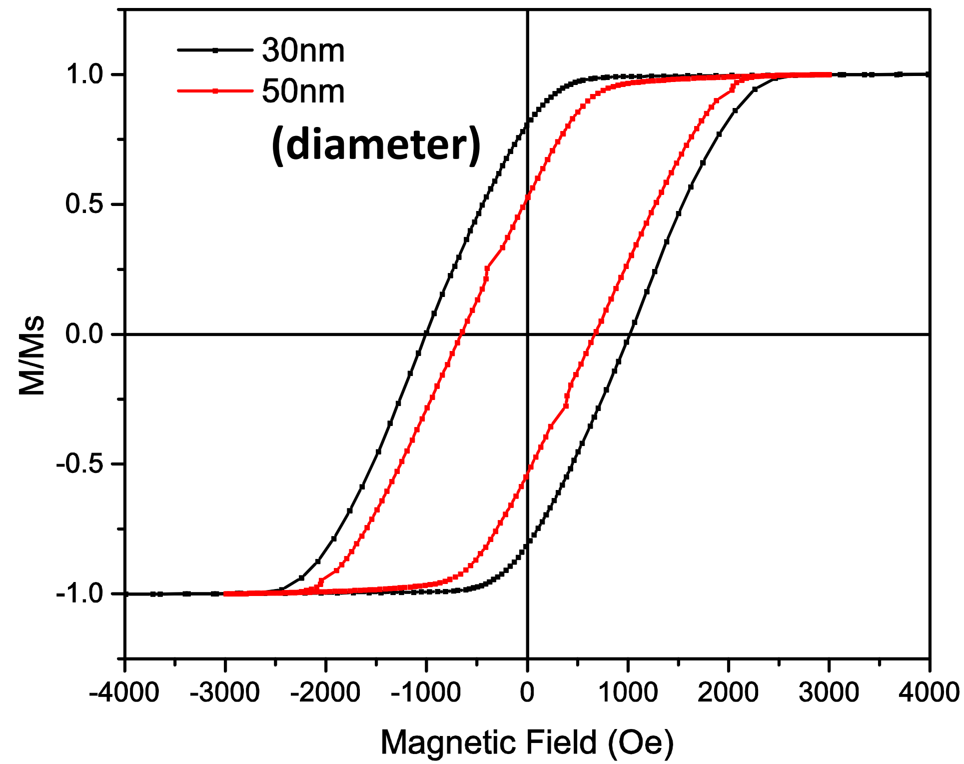




micromagnet simulation

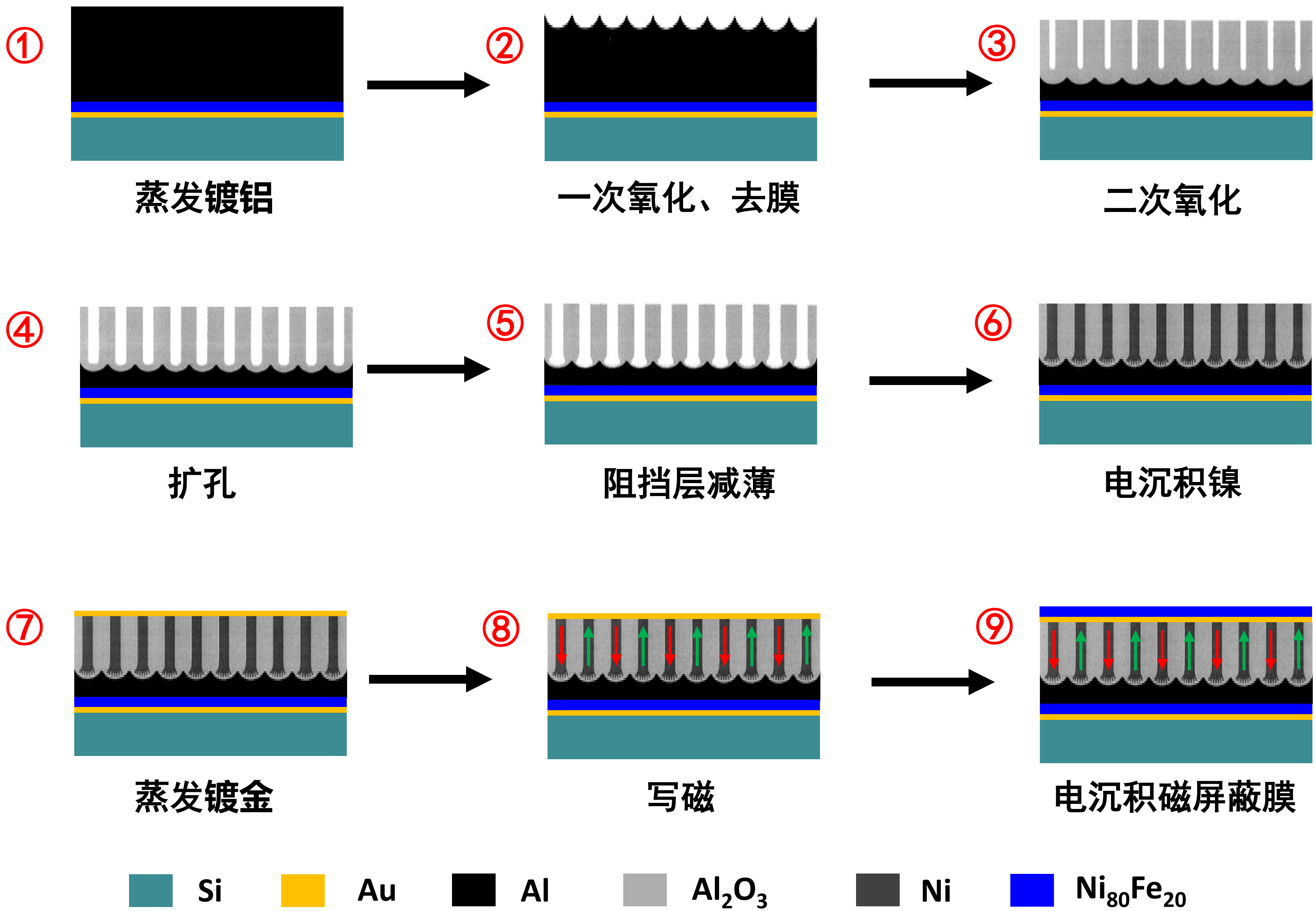
# Magnetic structure fabrication

## Anodic Aluminum Oxide (AAO) template filled with Ni



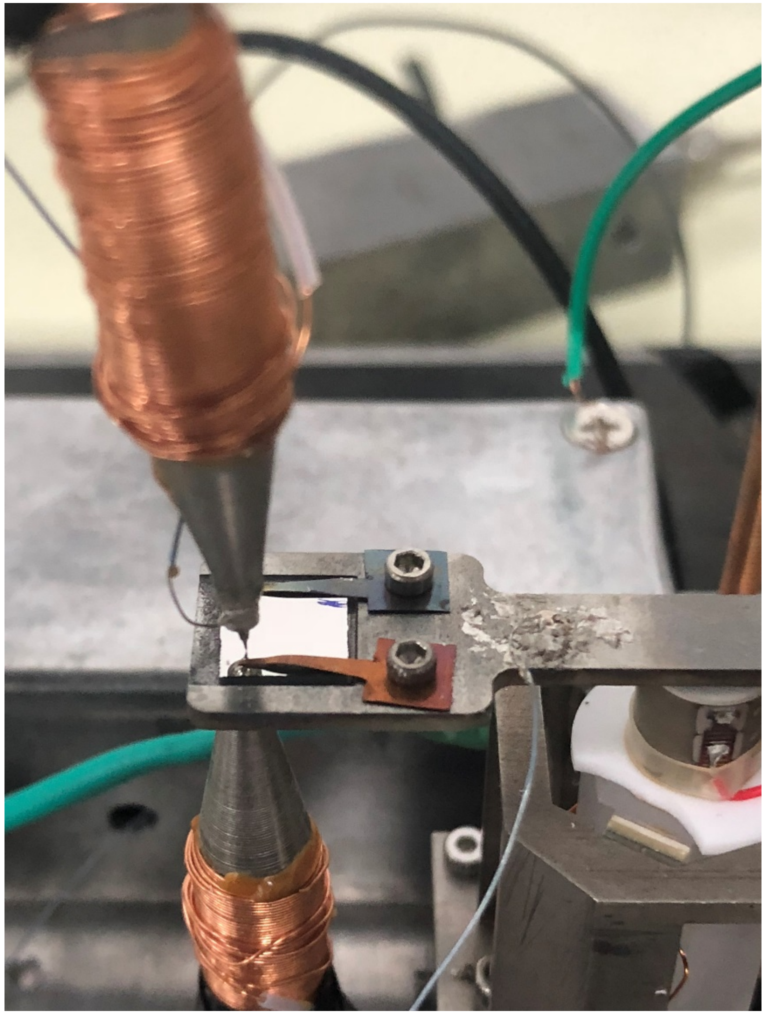



# Magnetic structure fabrication

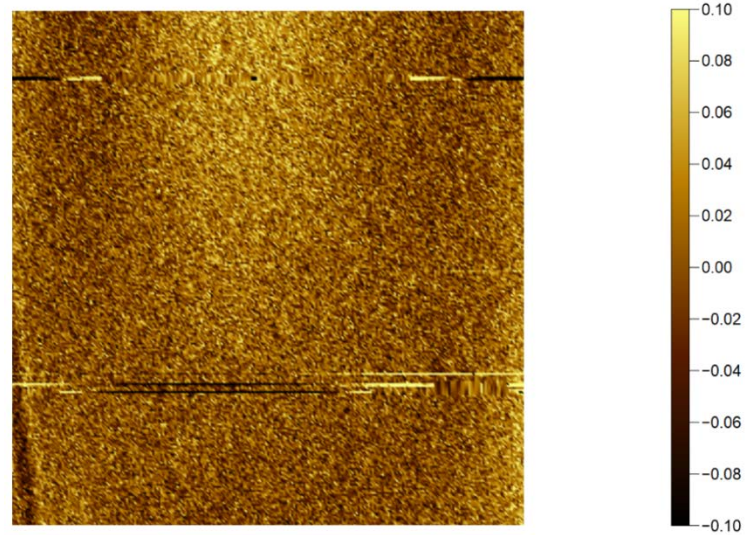


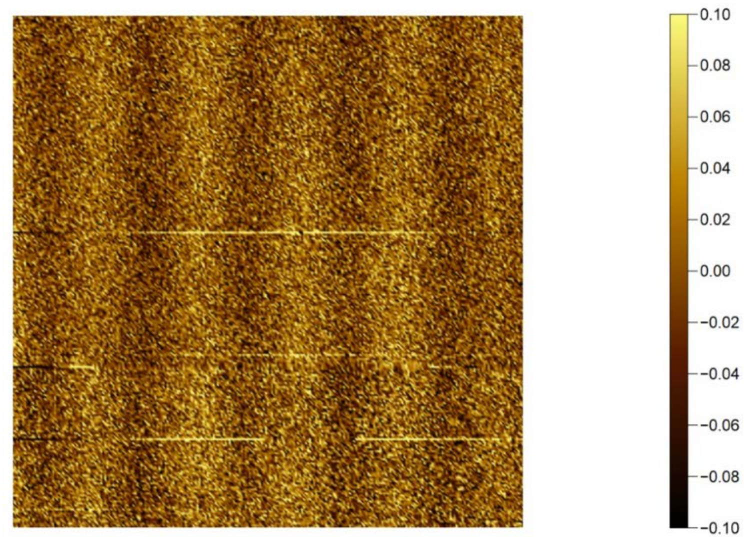
# Periodic magnetic structure

Magnetization Writing



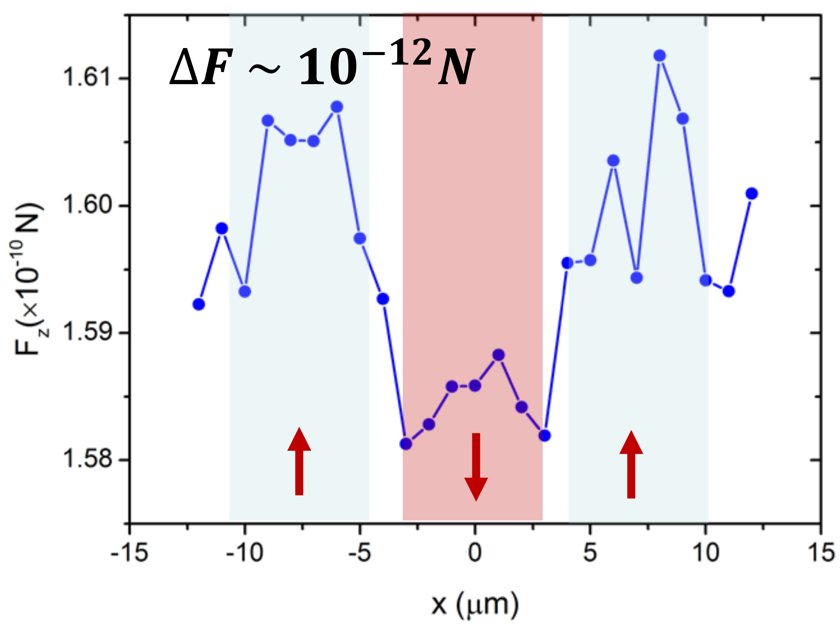
Pattern writing on hard disk

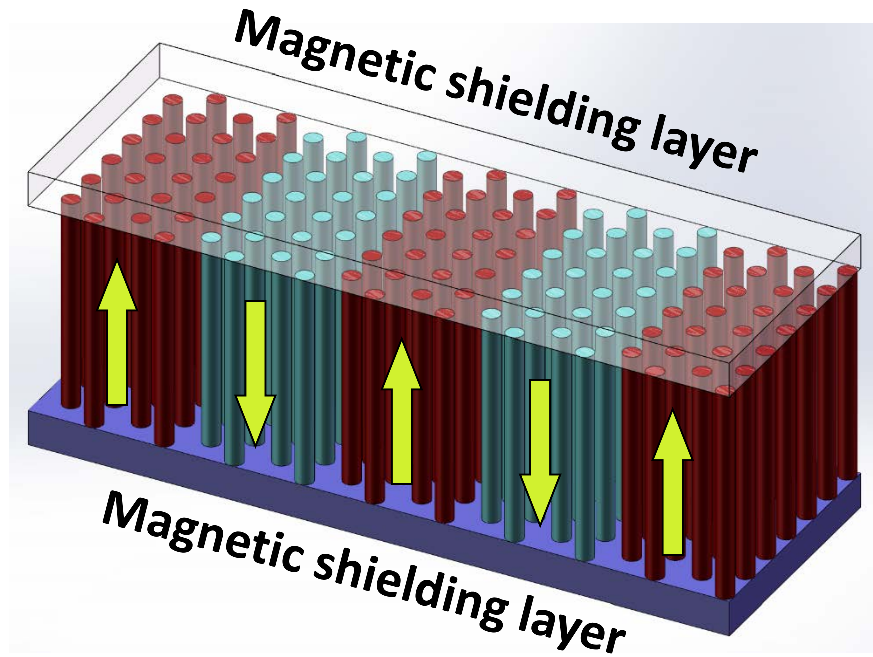


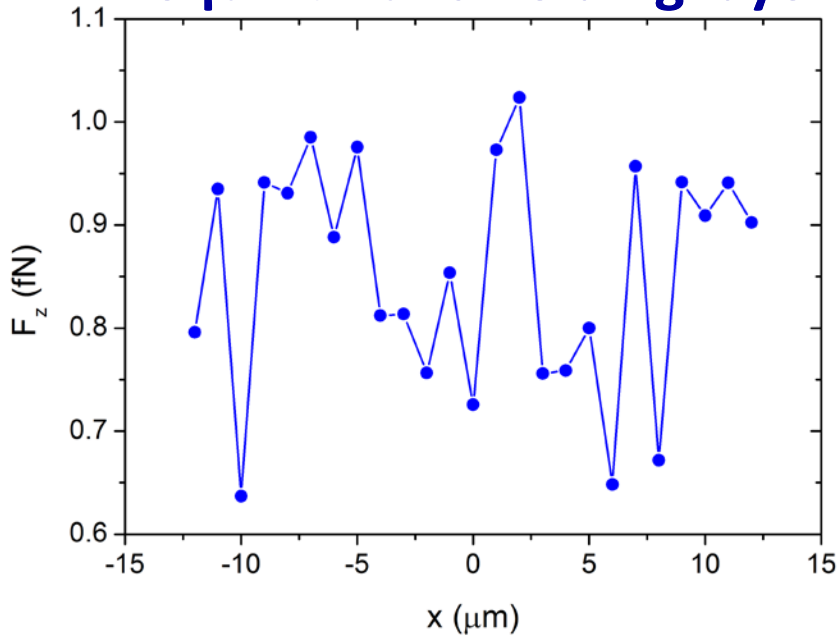
# Shielding the normal magnetic force

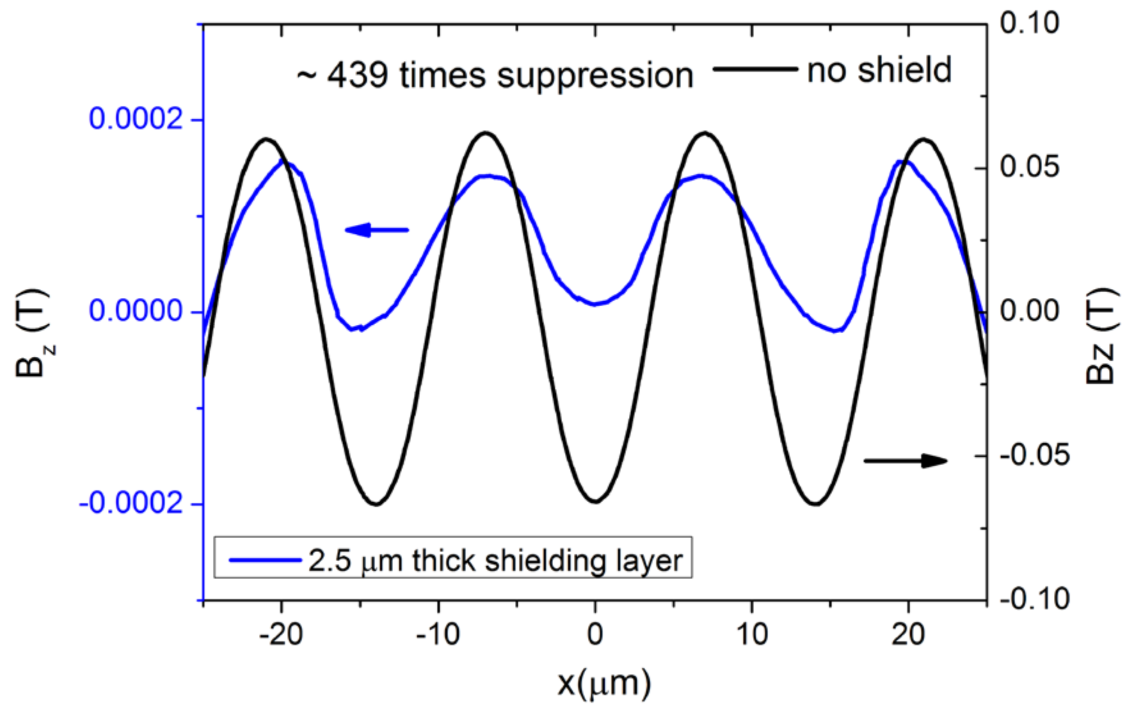
## Without magnetic shielding



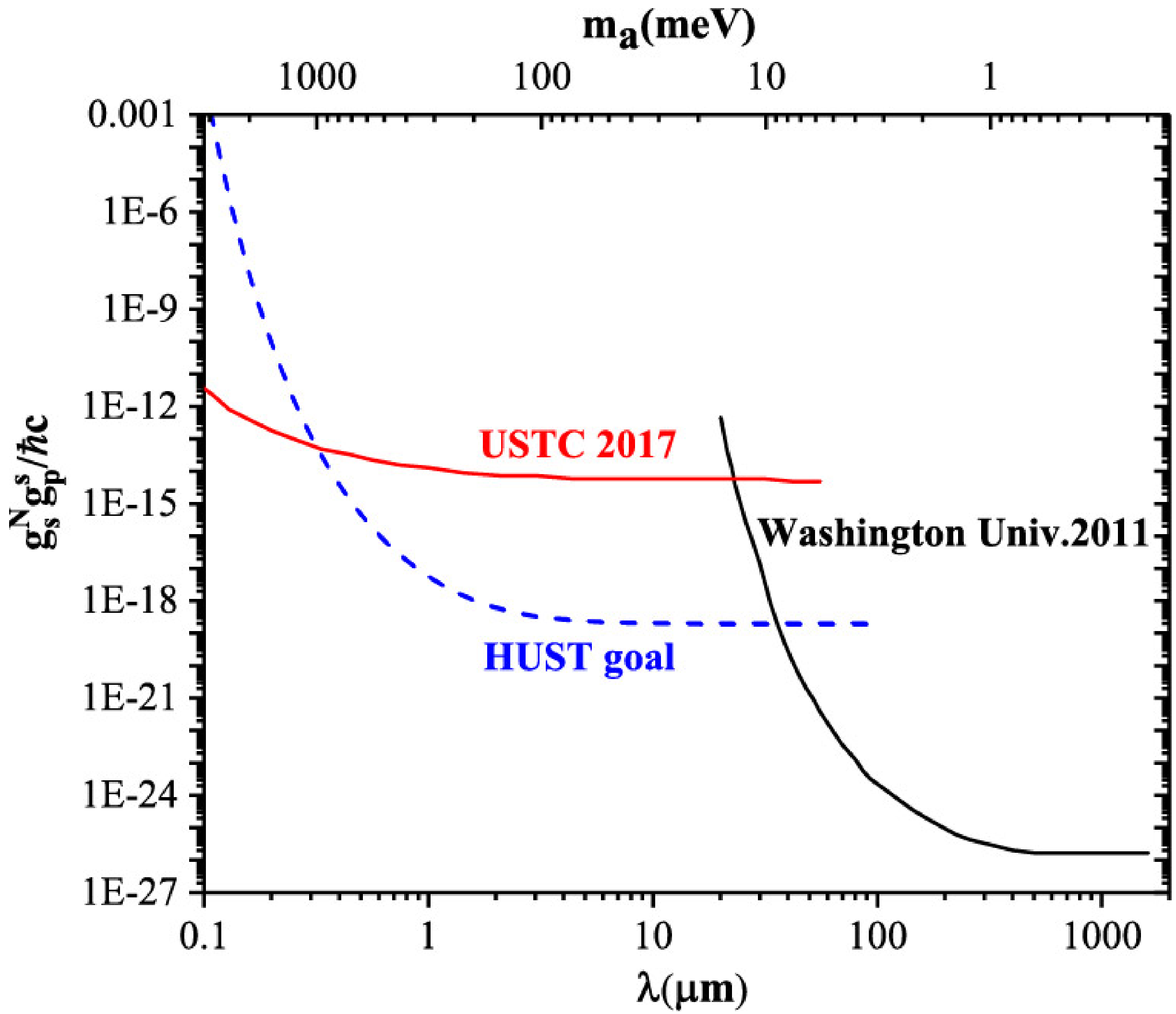




## 2.5 μm thick shielding layer



# Projected goal




Nanopillar arrays：

Φ = 30 nm

L= 4 μm

d = 65 nm

$n_e$ : $6\times10^{28}$ /$m^3$

Period： ~ 12 μm

Separation ： 3 μm

Force sensitivity： 1 fN

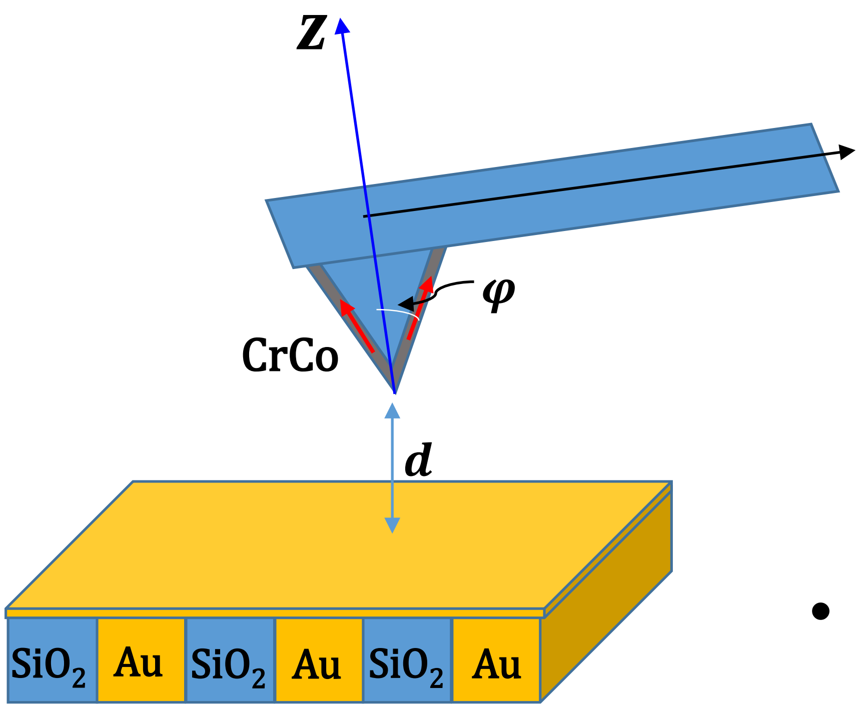
(Electromagnetic force noise)

Rui Luo *et al.*, Int. J. Mod. Phys. A 35, 2040003 (2020)

# $V_{12+13}$

$$V_{12+13} = 2g_A^e g_V^N \frac{\hbar}{8\pi}[\hat{\sigma} \cdot \vec{v}]\left(\frac{1}{r}\right)e^{-\frac{r}{\lambda}} \qquad F_z = f_{spin}(g_A^e g_V^N, d, \dots)\dot{z}$$

$$m\ddot{z} + m\gamma\dot{z} + kz = F_{drive}\cos(\omega_d t) + f_{spin}\dot{z}$$




Drive at resonance: $f_d = f_0 = 139.44$ kHz

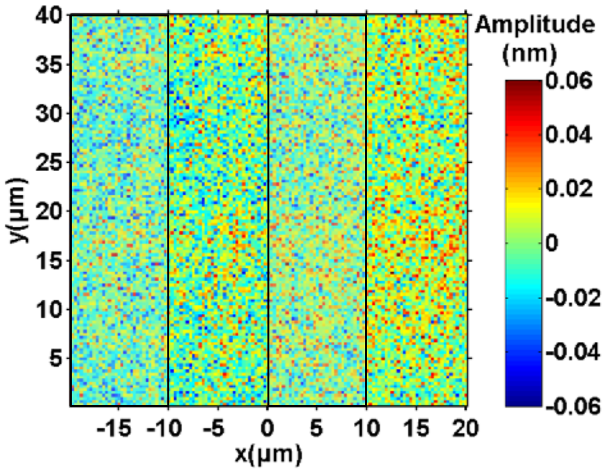
Drive amplitude: ~ 3 nm

$$|z|_{amp} \approx |z_0|_{far}\left(1 + Q\frac{f_{spin}}{\omega_0 m}\right)$$

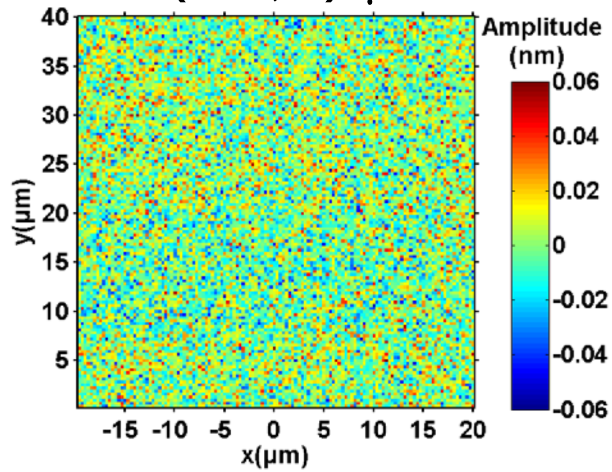
- EM forces: force gradient matters (in 3 nm)
- Exotic Force: proportion to $v$ and then $f_0$
- $|z|_{amp}$: proportion to $Q$

# Preliminary results

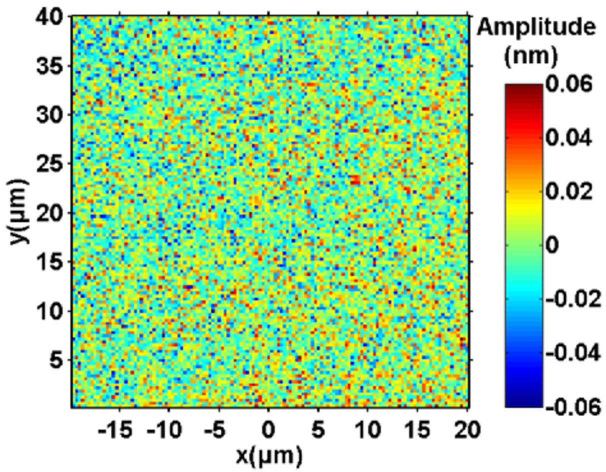
(0 , 0 ) μm



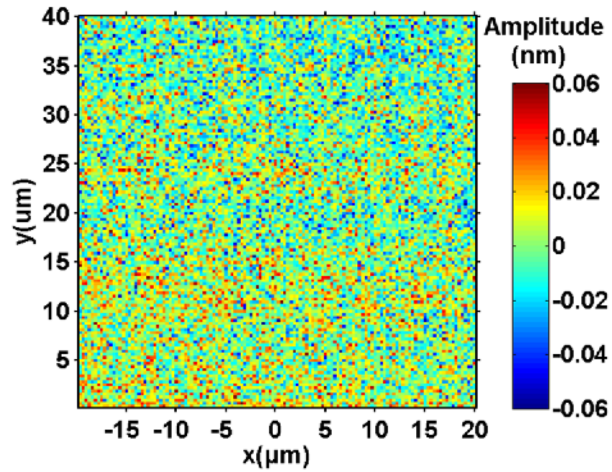

(-133, 0 ) μm



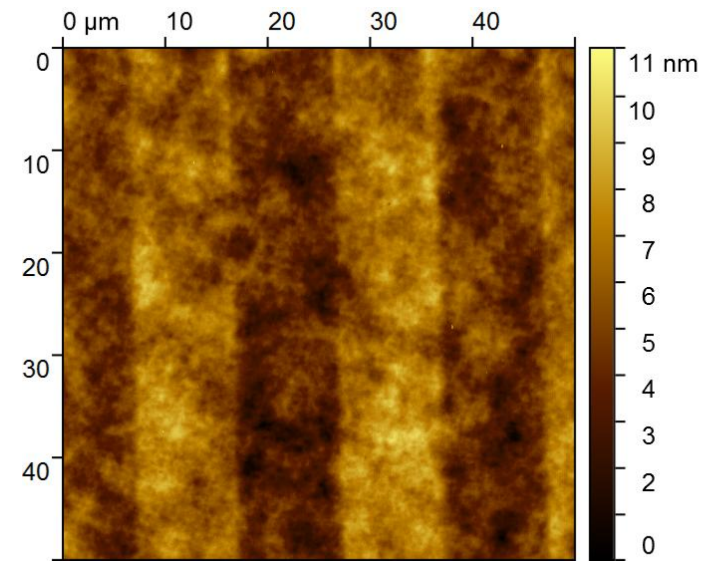

(-129, 214) μm




(-120 , -276 ) μm

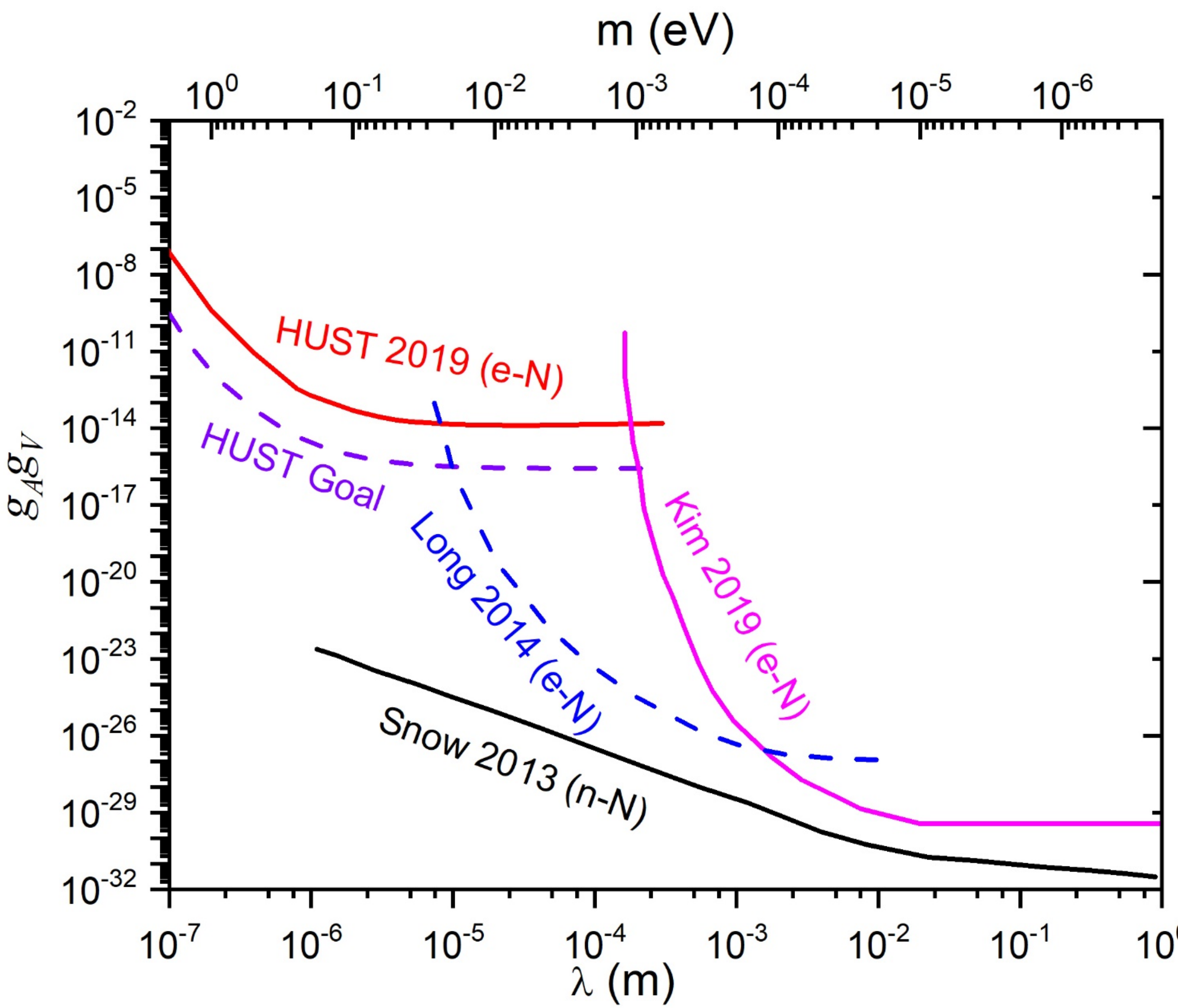


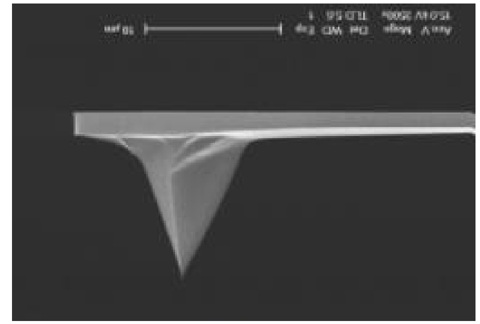

Period: 20 μm




$$d = 642(73)\ \text{nm}$$

# Preliminary analysis



**MFM tip (estimated)**

$t_s = 40$ nm

$h = 12.5$ μm

$n_e = 5.6 \times 10^{28}/m^3$

**Periodic structure**

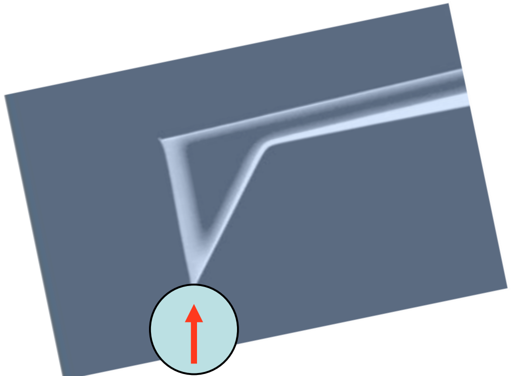
Period: 20 μm

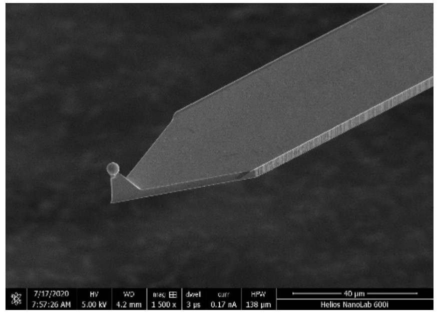
$n_{Au} = 11.6 \times 10^{31}/m^3$

$n_{SiO_2} = 1.6 \times 10^{30}/m^3$

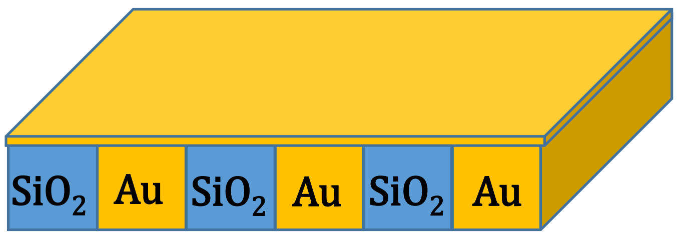
**Separation： 642 nm**

# Future improvement



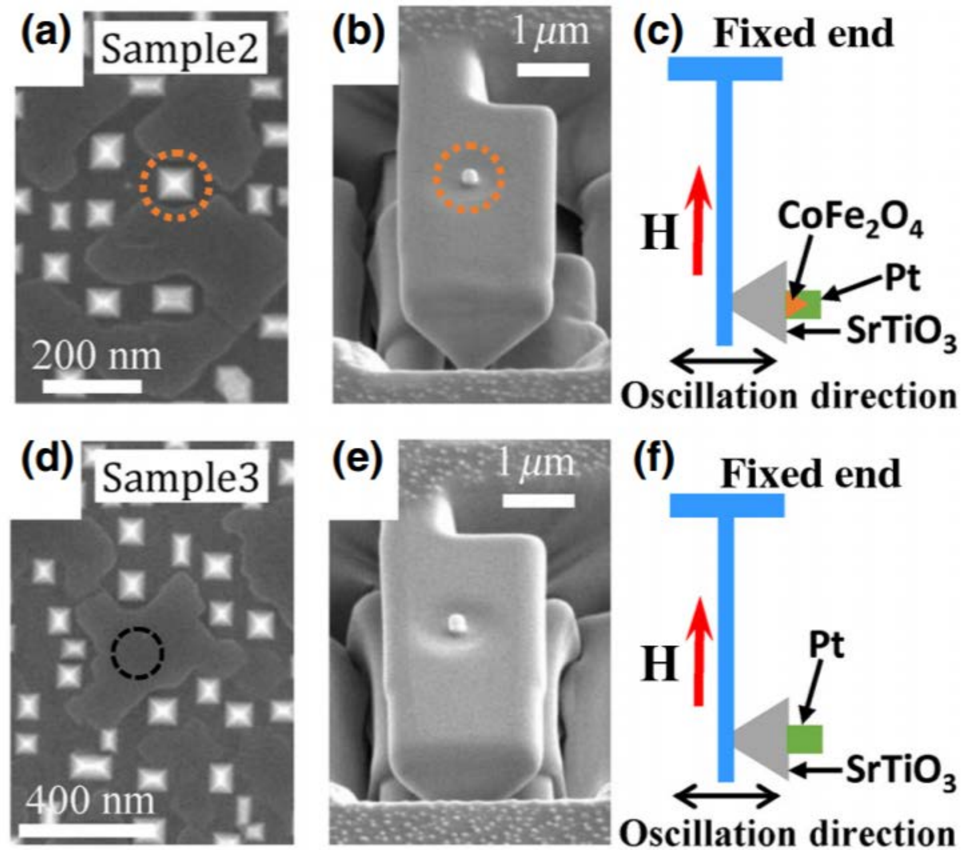


Magnetic microsphere




Magnetic microsphere: single domain magnet

Dynamic Cantilever Magnetometry

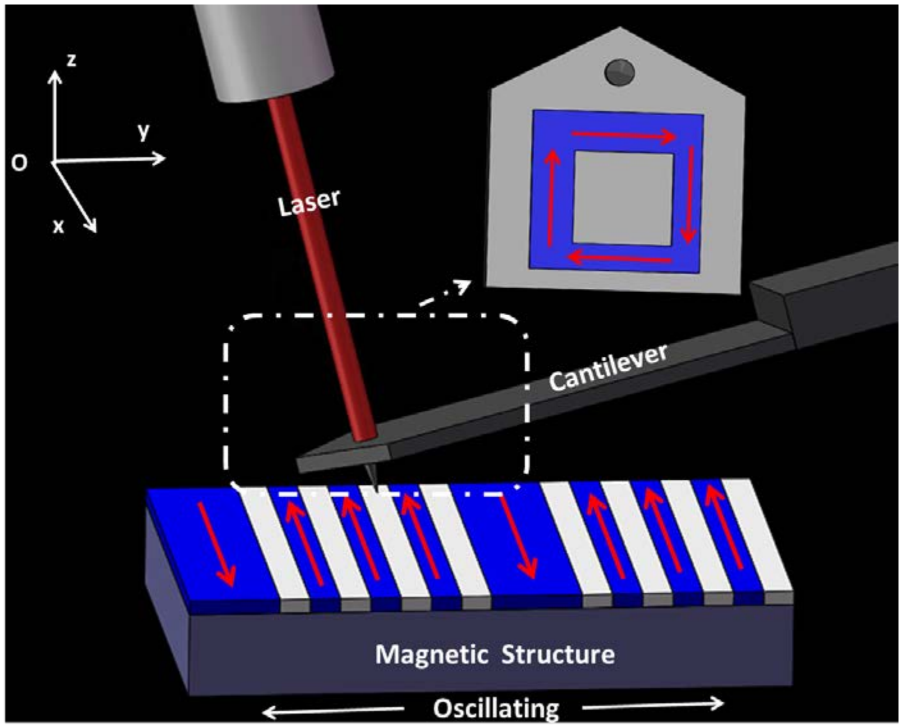


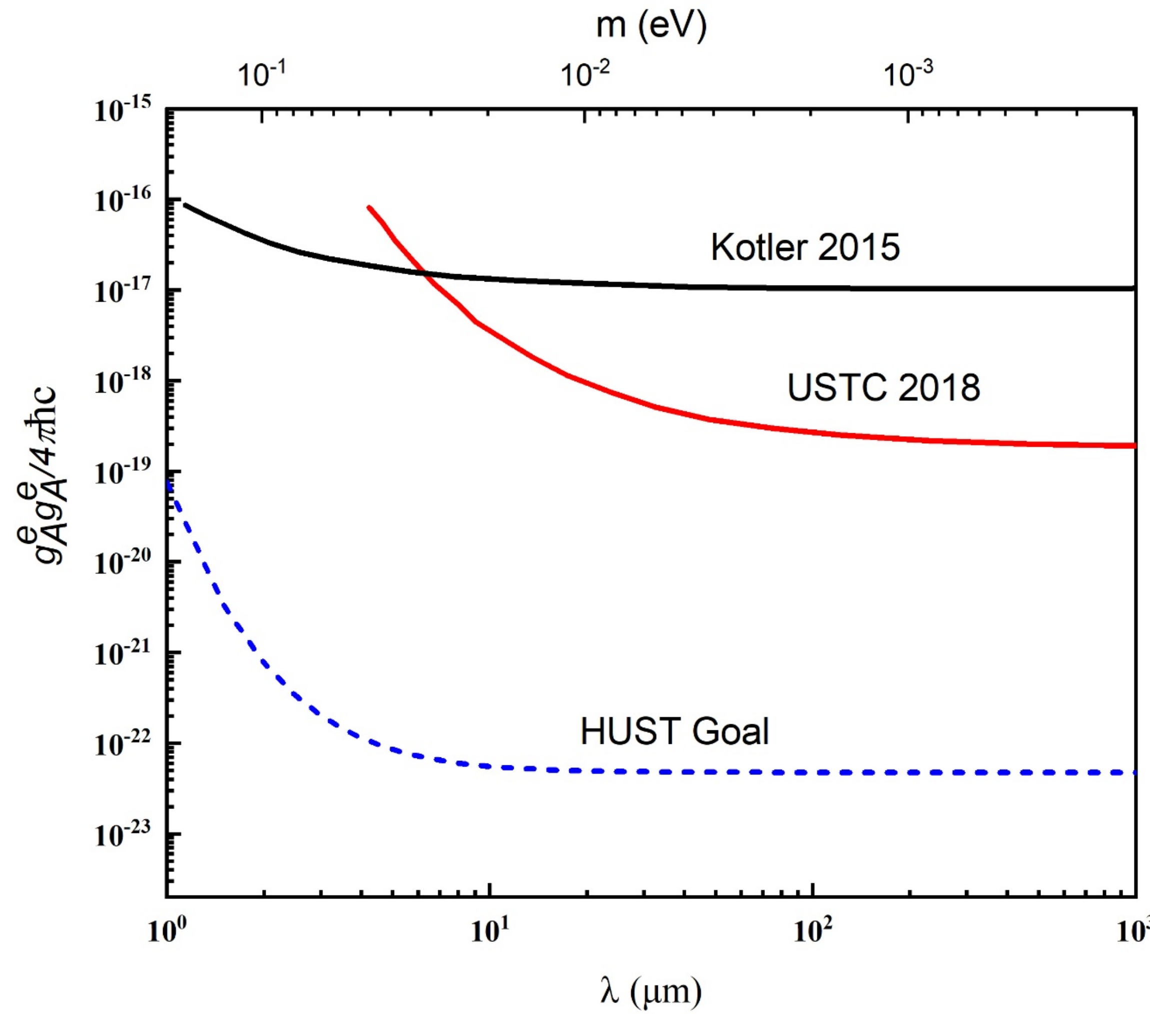

Sensitivity: $1.7 \times 10^{-15}$ emu

Feng Xu *et al.*, Phys. Rev. Appl. 11, 054007 (2019)

# $V_2$

$$V_2 = \frac{g_A^e g_A^e}{4\pi\hbar c} \cdot \hbar c(\hat{\sigma}_1 \cdot \hat{\sigma}_2)\frac{e^{-r/\lambda}}{r}$$



# Summary

- Spin-dependent exotic forces may exist, and can be searched by tabletop scale experiments.
- Micro-cantilever is a suitable sensor to perform the experiment at the micrometer range.
- Improvement needed: cantilever displacement measurement, low thermal noise, high stability etc.

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N S F C

"May the Force be with you." ?


**Thanks for listening!**