Proposal for the search for exotic spin-spin interaction at the micrometer range using a micro-cantilever

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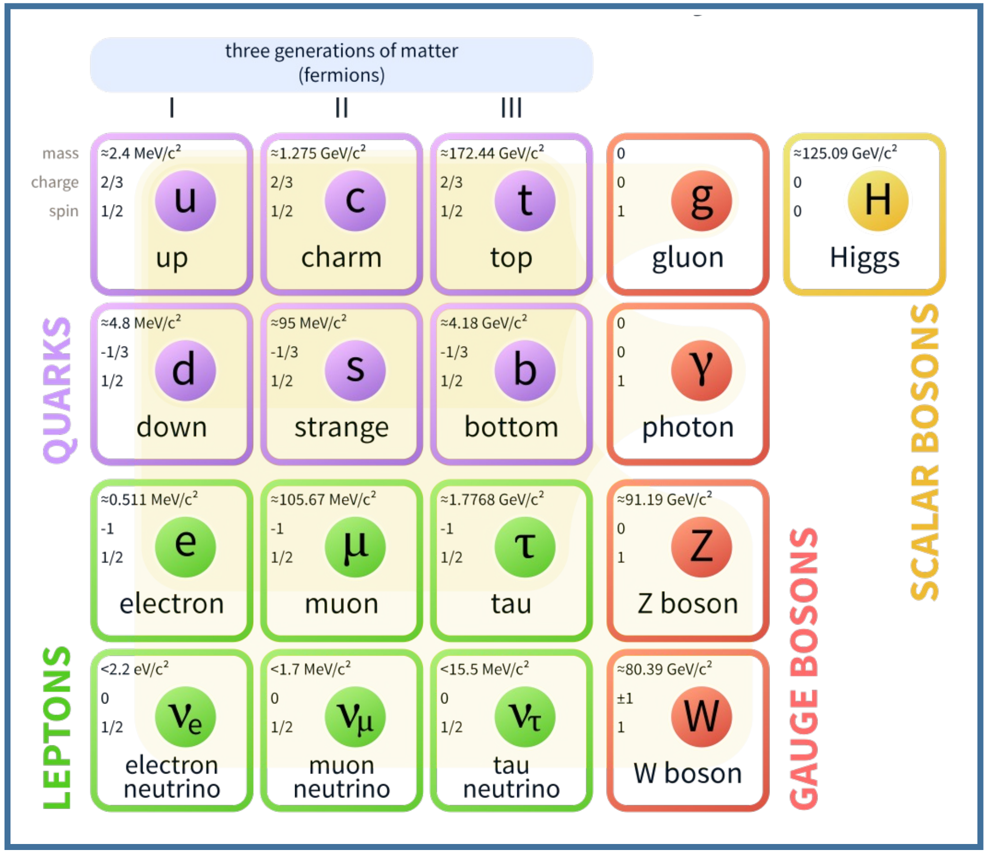
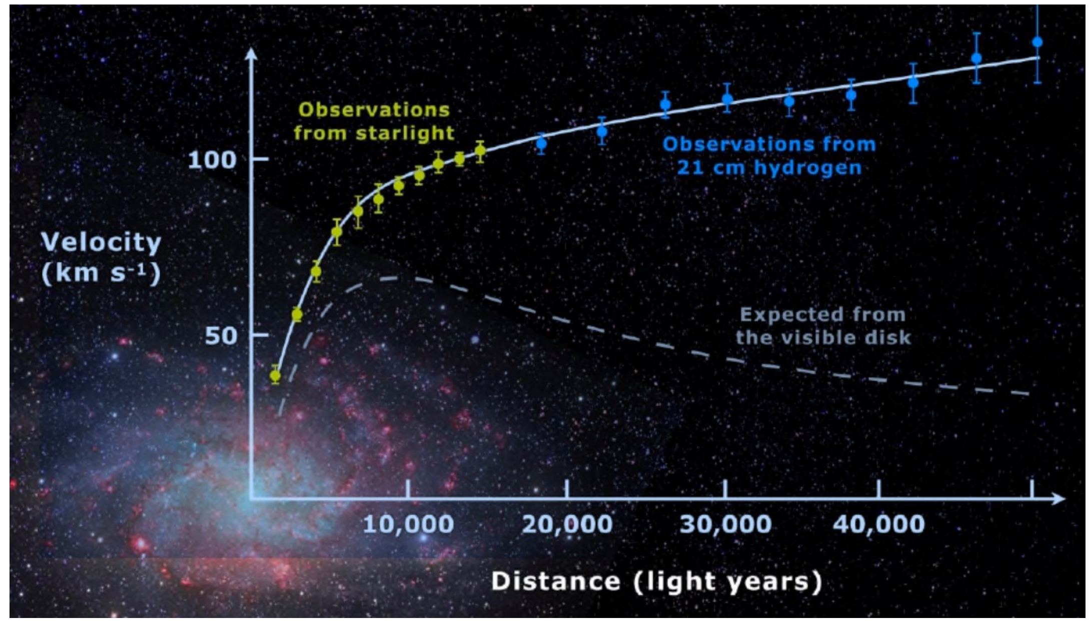
Content

Introduction: beyond SM

Standard model



Unanswered questions[1]



dark matter, dark energy,

strong CP problem, hierarchy problem

asymmetry of matter-antimatter...

Beyond the standard model: new interactions, new particles?

[1]1999 Gaillard et al. *Rev. Mod. Phys*

Introduction: strong CP and axion

Strong CP problem:

$$\mathcal{L}_{\mathrm{QCD}} = \mathcal{L}_0 + \theta_{\mathrm{QCD}} \frac{g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

gauge transform T: $T|\omega\rangle = e^{i\theta_{\mathrm{QCD}}}|\omega\rangle$

Theory: $0 \leq \theta_{\mathrm{QCD}} \leq 2\pi$ → charge-parity odd

Experiment: $\theta_{\mathrm{QCD}} \sim 10^{-10}$ → no indication of the CP odd[1]

Solution: Axion

$U(1)_{\mathrm{PQ}}$ symmetry[2]: $\psi_{\mathrm{PQ}} = |\psi_{\mathrm{PQ}}|\, e^{i\theta_{\mathrm{QCD}}} \simeq f_a\, e^{i\frac{a}{f_a}}$ ← axion field

Solved strong CP problem by absorbing θ_{QCD} into axion field term, thus there is no charge-parity odd

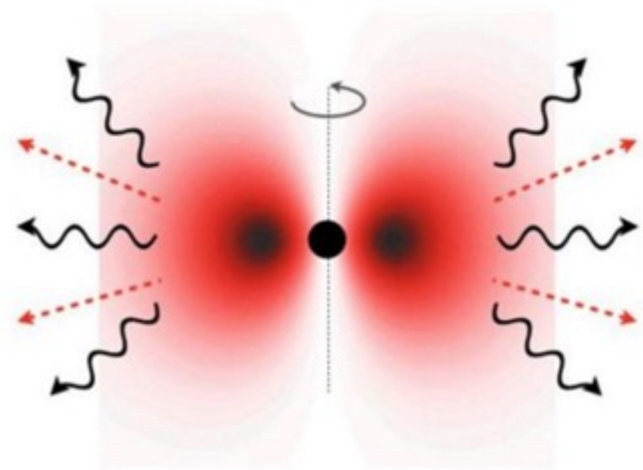
[1]2015 Pendlebury et al. *Phys. Rev. D*

[2]1977 Peccei et al. *Phys. Rev. D*

Introduction: axion

Axion: hypothetical spin-0 boson

1. Solution to Strong CP problem
2. Dark matter candidate
3. **Mediating new interactions**



Axion mediated exotic spin-spin interaction[1]

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

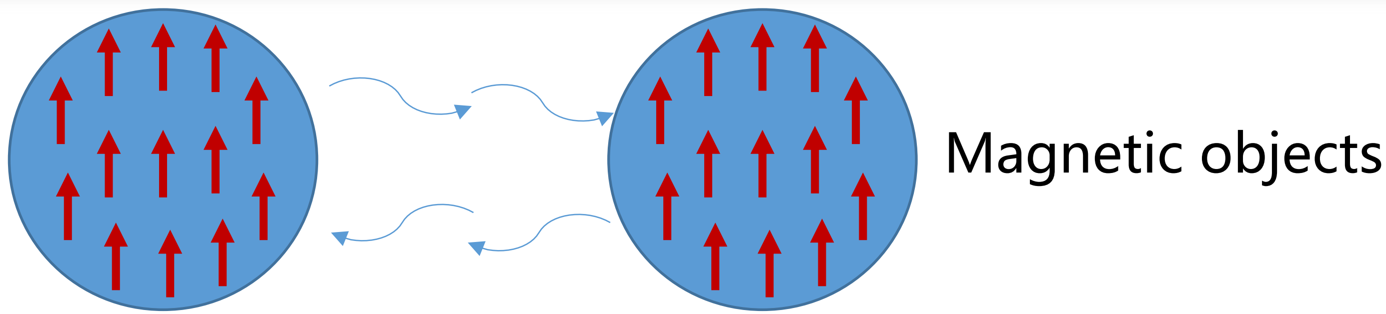
Long range interaction between fermions, $\lambda = \frac{\hbar}{m_a c}$

[1]1984 Moody et al. *Phys. Rev. D*

Experimental scheme: experimental steps

Proposed experimental steps:

Convert the V_{axion} into macroscopic force between spin-polarized objects



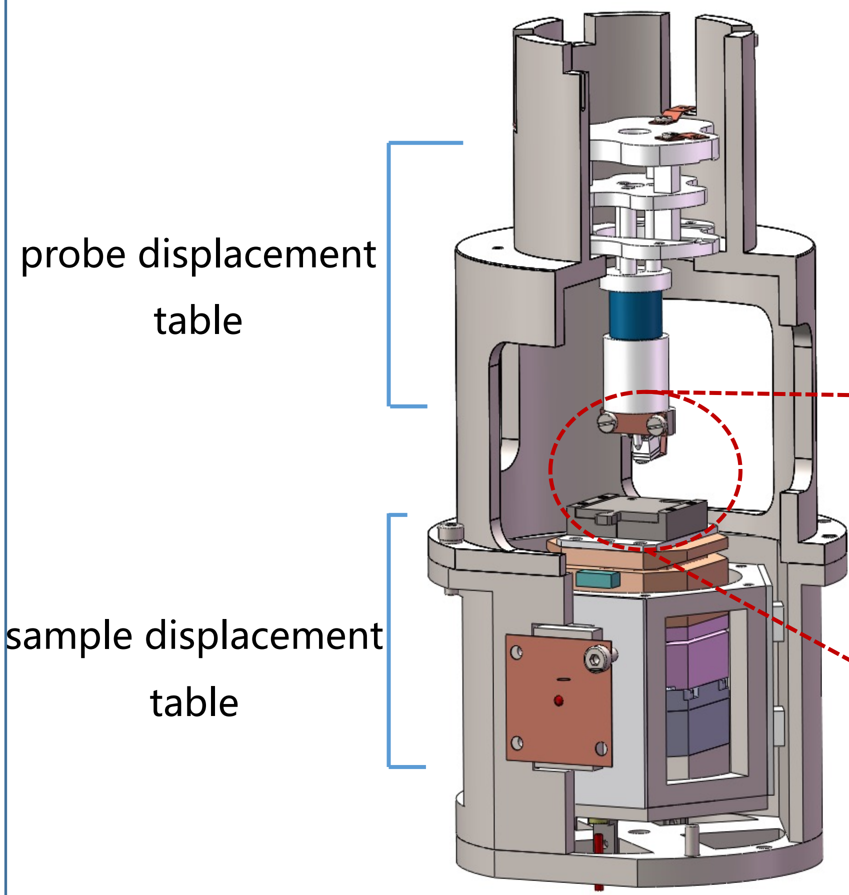
Measure the exotic spin-spin force via a **micro-cantilever**

Either find the new interaction

Or set the constraint on the coupling constant based on a Null result

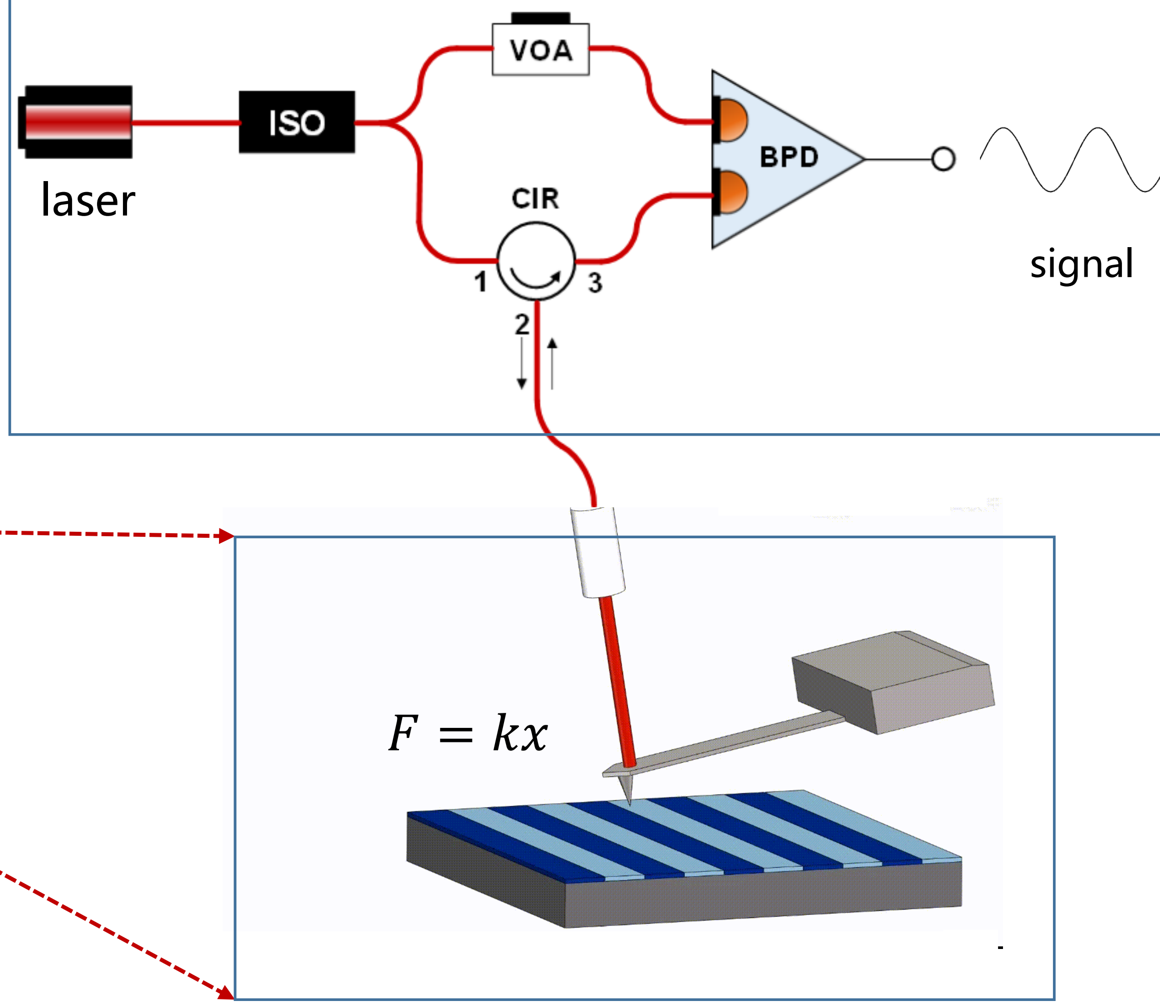
Experimental scheme: SPM

Scanning probe microscopy

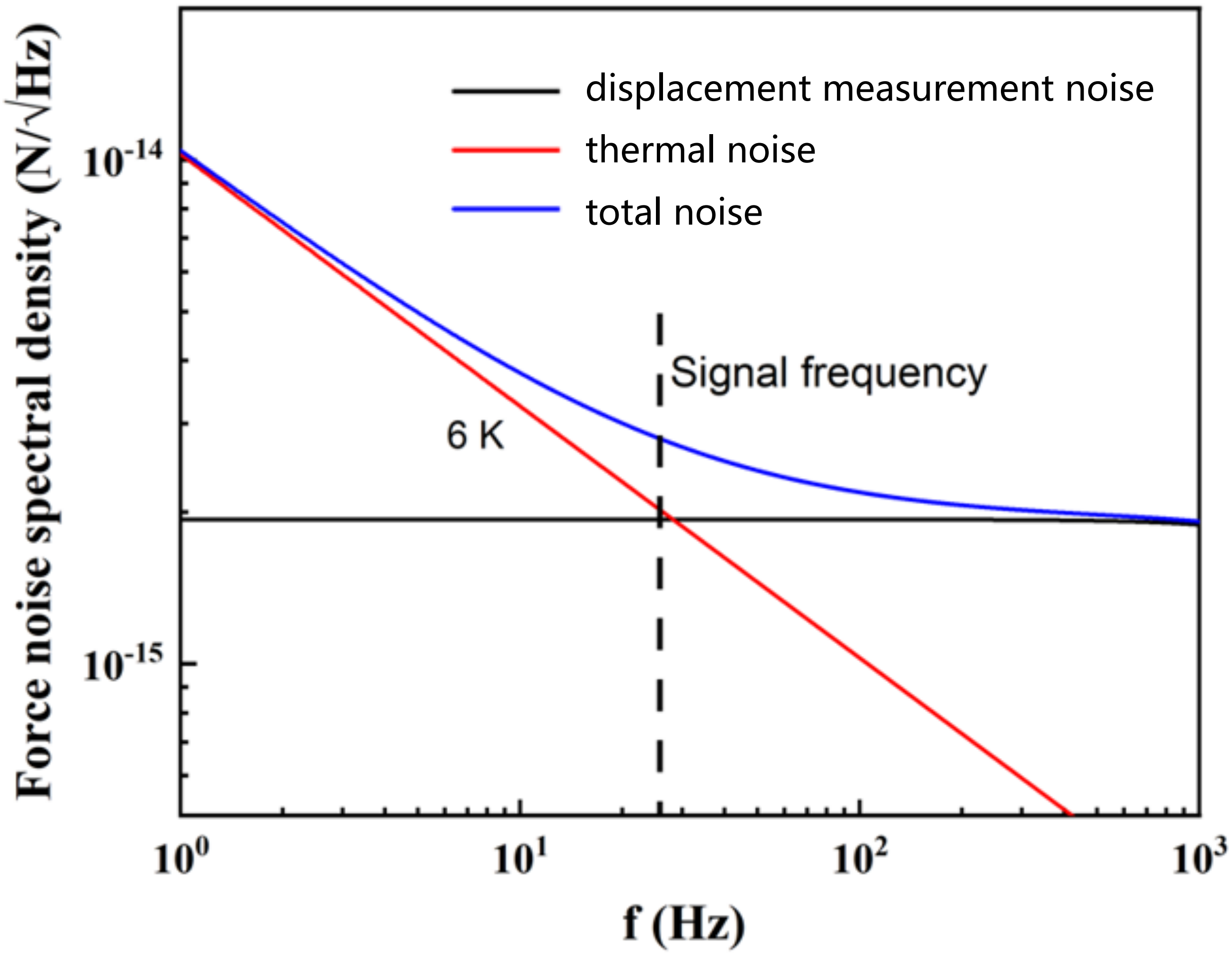


ultra high vacuum and cryogenic (6K)

Laser interferometer



Experimental scheme: detection noise



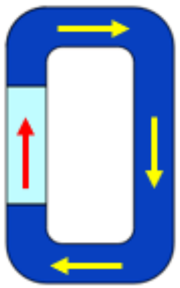
Cantilever parameters	
elastic coefficient	0.02 N/m
length	450 μm
width	48 μm
thickness	1.0 μm
resonance frequency	6.5 kHz
quality factor	10000

detection noise

$\sim 8.9\times10^{-17}$ N,

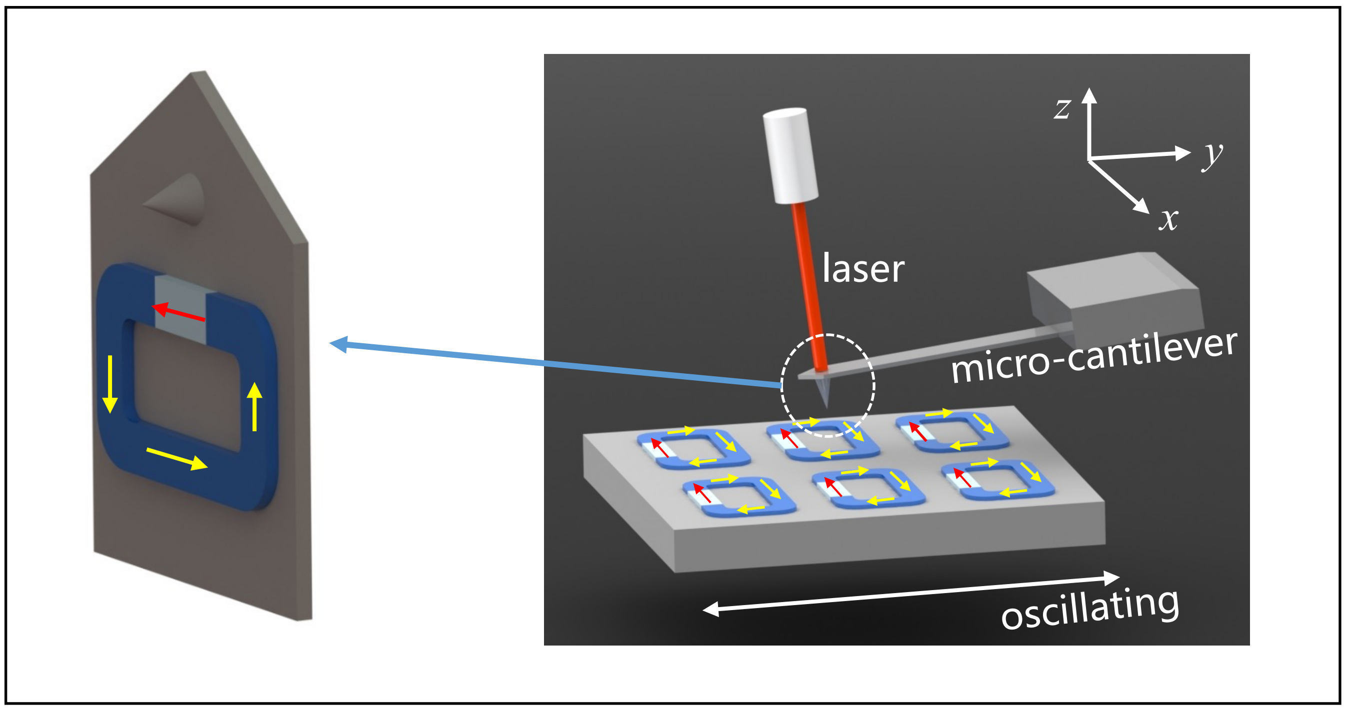
integral time ~1000s

Experimental scheme: new structure



Closed loop magnetic structure (CLMS):

1. Supply spin-polarized electrons
2. Suppress magnetic force by forming a circular $\vec{B}$ field

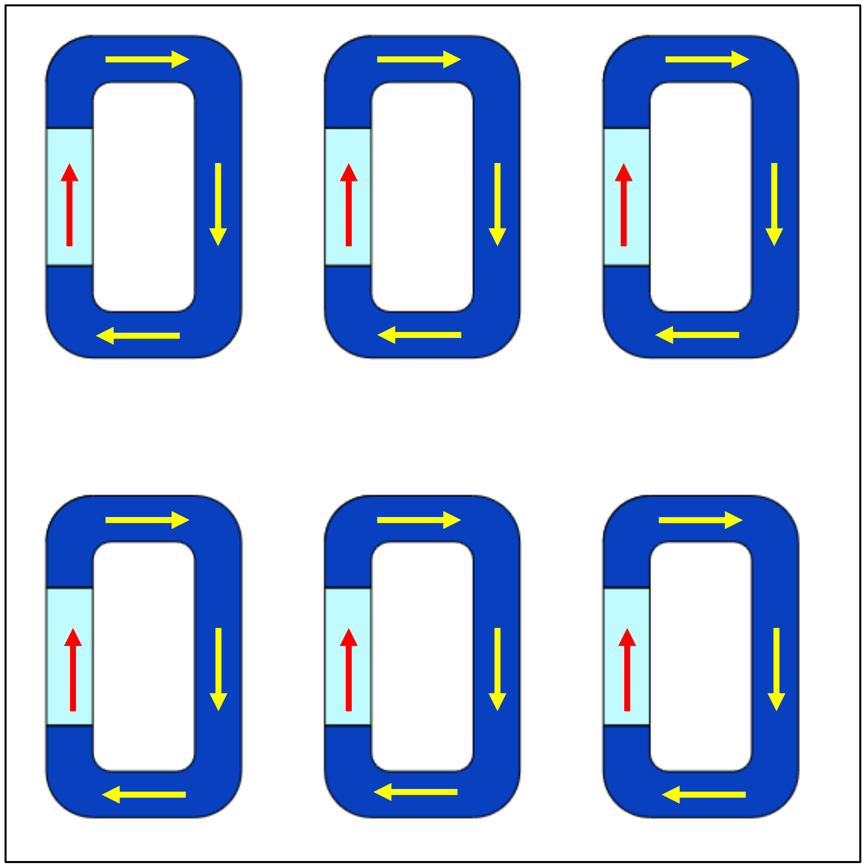


Measure the force along the z axis

Experimental scheme: expected signal

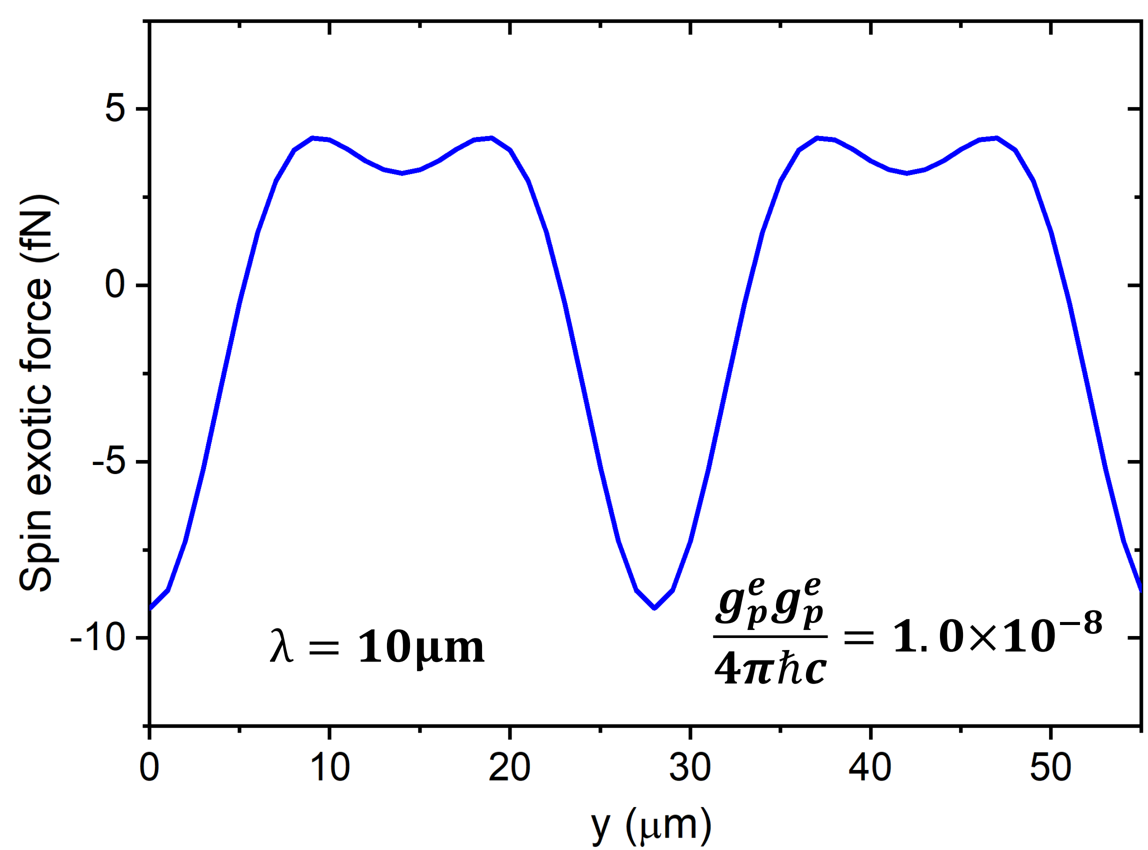
$$V_{axion} = -\frac{g_p^2}{4\pi\hbar c}\frac{\hbar^3}{4m_f^2 c}\left[\hat{\sigma}_1\cdot\hat{\sigma}_2\left(\frac{1}{\lambda r^2}+\frac{3}{r^3}\right)-(\hat{\sigma}_1\cdot\hat{r})(\hat{\sigma}_2\cdot\hat{r})\left(\frac{1}{\lambda^2 r}+\frac{3}{\lambda r^2}+\frac{3}{\lambda^3}\right)\right]e^{-r/\lambda}$$

$$F_Z = \frac{g_p^e g_p^e}{4\pi\hbar c}\cdot n_1 n_2\frac{\hbar^3}{4m_e^2 c}\int dV_1\int dV_2\frac{\partial}{\partial Z}\left[(\hat{\sigma}_1\cdot\hat{\sigma}_2)\left(\frac{1}{\lambda r^2}+\frac{1}{r^3}\right)-(\hat{\sigma}_1\cdot\hat{r})(\hat{\sigma}_2\cdot\hat{r})\left(\frac{1}{\lambda^2 r}+\frac{1}{\lambda r^2}+\frac{3}{r^3}\right)\right]e^{-r/\lambda}$$



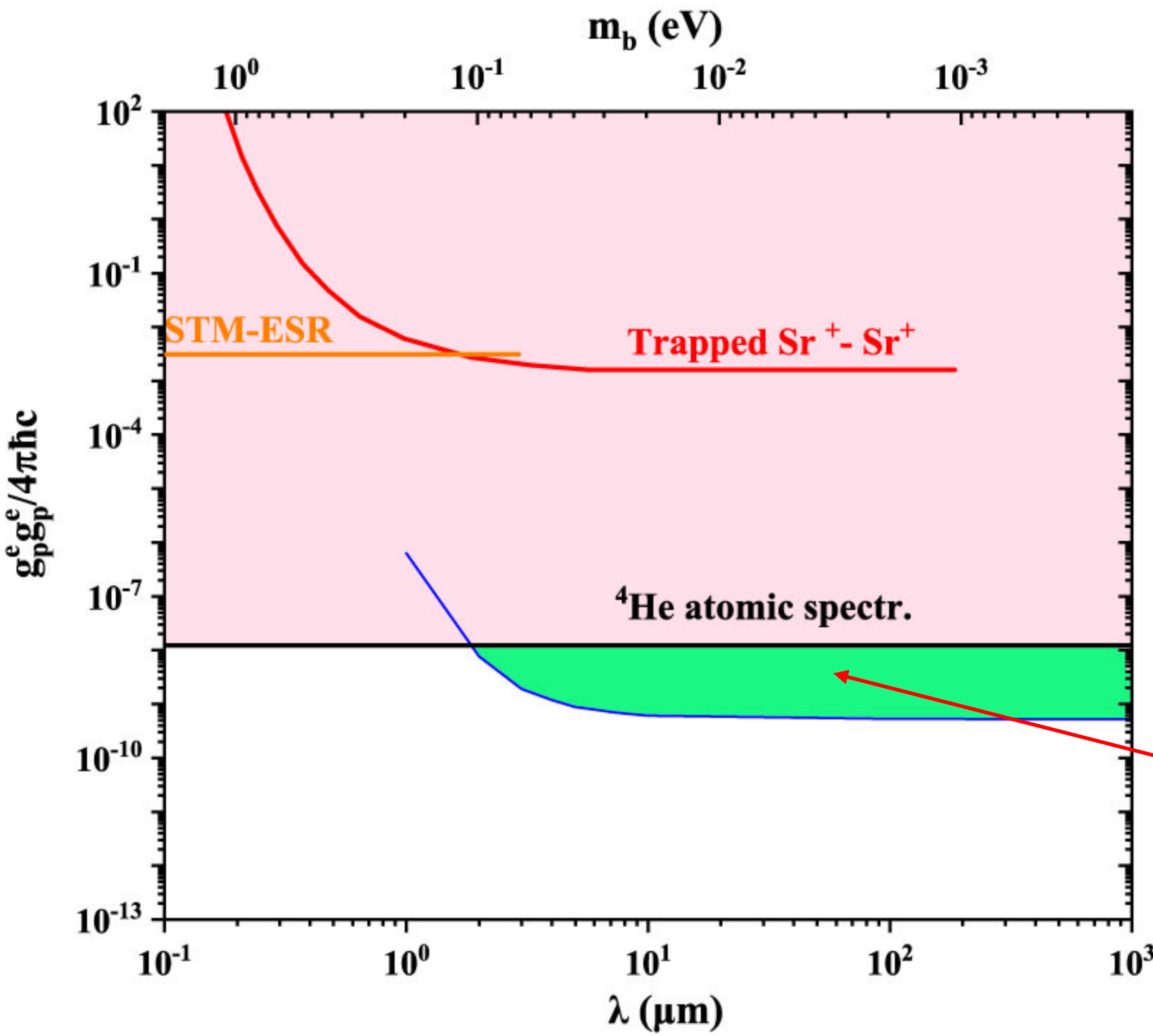
Spatial modulated force

Expected signal



Experimental scheme: expected signal

Parameter space of V_{axion}



expected **constraint** on the coupling constant based on a Null result at $\lambda = 10\mu\text{m}$ and 95% CL

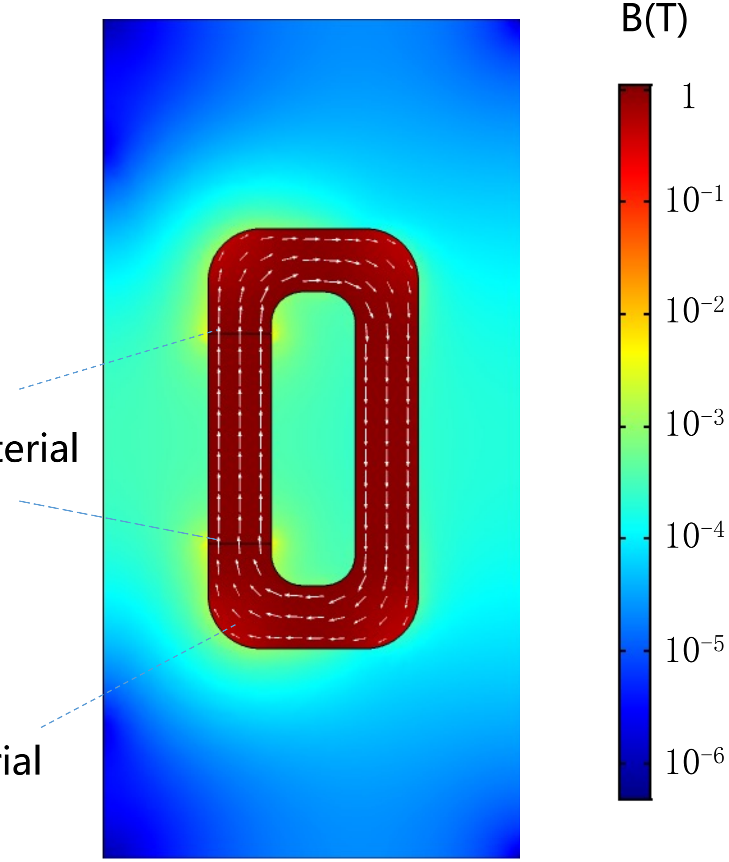
$$\left|\frac{g_p^e g_p^e}{4\pi\hbar c}\right| \leq 6.1\times10^{-10}$$

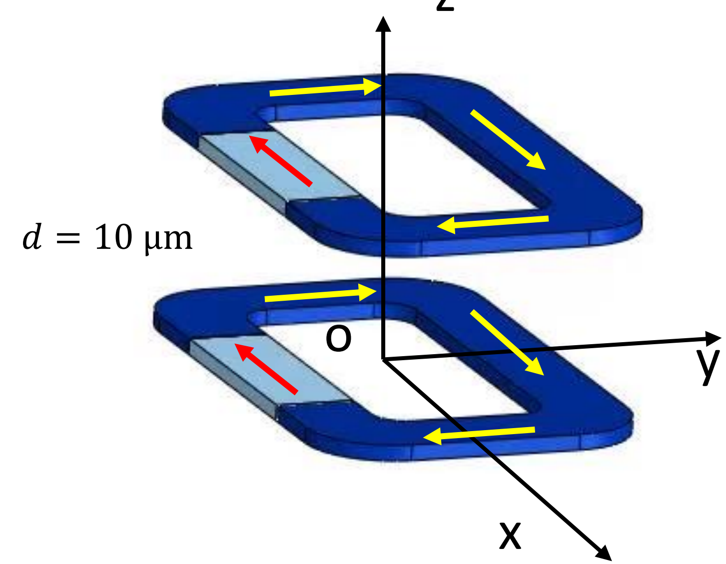
parameter space to explore

Error analysis: magnetic force

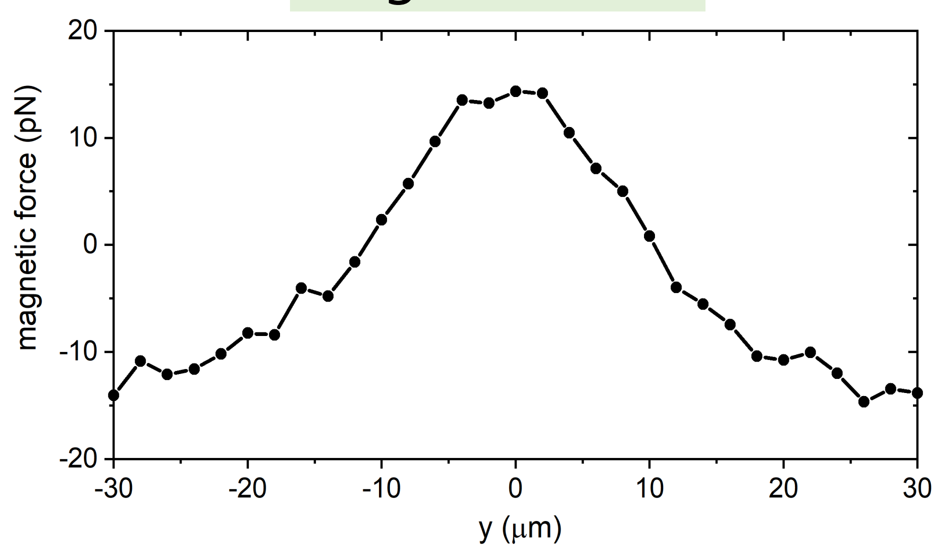
$$V_{magnetic} = -\frac{\mu_0 \gamma_e \gamma_e \hbar^2}{16\pi r^3}[3(\hat{\sigma}_1 \cdot \hat{r})(\hat{\sigma}_2 \cdot \hat{r}) - (\hat{\sigma}_1 \cdot \hat{\sigma}_2)]$$

Preparation of the CLMS



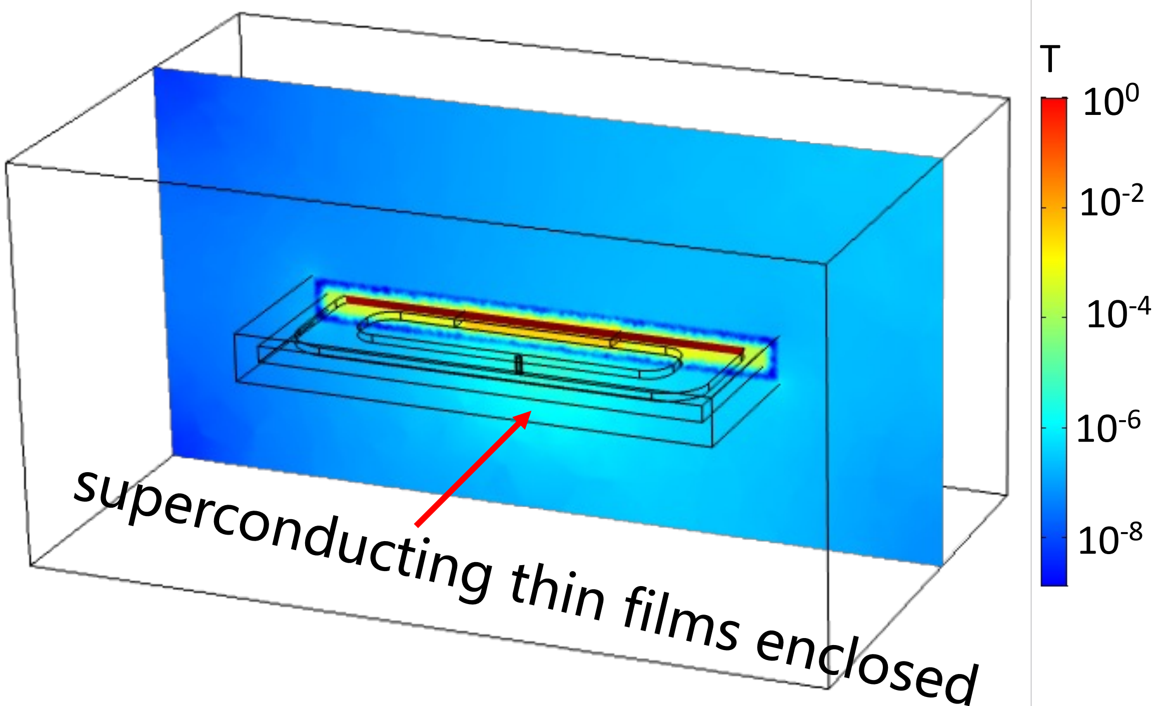


Magnetic force

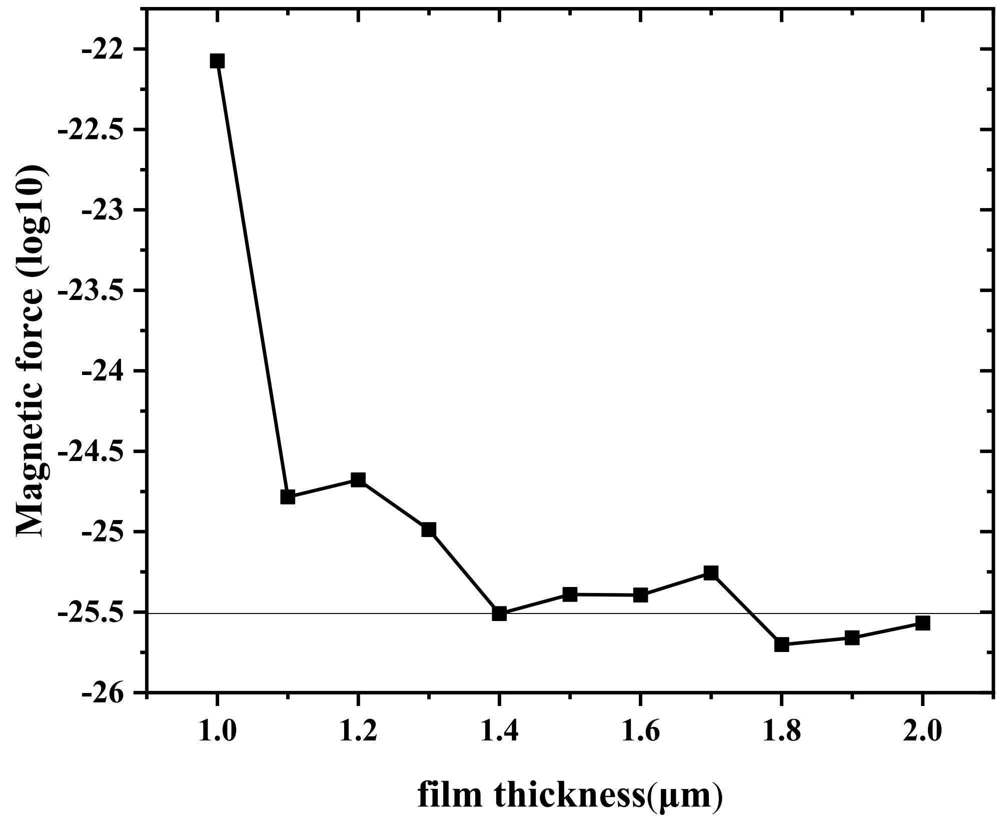


Error analysis: superconducting films

The superconducting thin films are used to suppress magnetic force by the perfect diamagnetism of superconducting state materials.

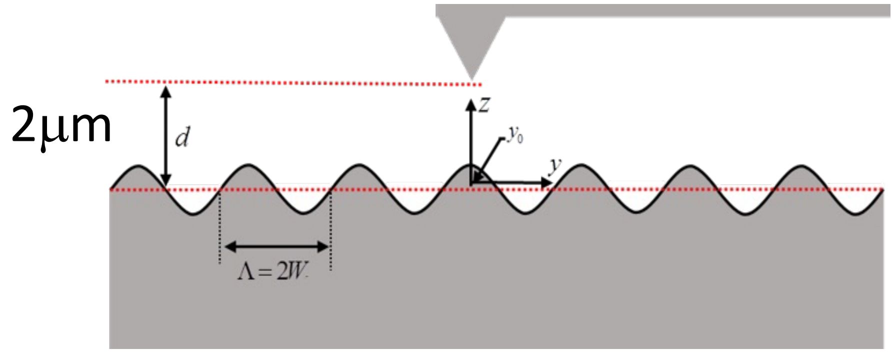


Magnetic force



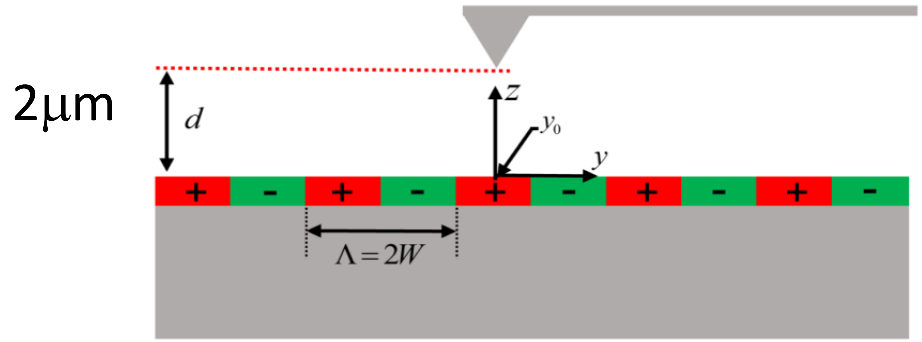
external B field can be decreased to ~1μT

Error analysis: other forces



Height fluctuation[1]

leads to → Casimir force & electrostatic force



Charge fluctuation

leads to → electrostatic force

Terms		Amplitude	ΔF_z(N)
Casimir force	Height	3 nm	5.0×10^{-17}
electrostatic force	Height	3 nm	1.7×10^{-17}
	Charge	2 mV	3.0×10^{-17}

[1]2016 Jianbo Wang et al. *Phys. Rev. D*

Conclusion

1. We proposed a method to search for axion mediated spin-dependent interaction, based on specially designed probe and spin-polarized electron source.
2. Our result showed the potential of such method, improving the constraints at the micrometer range by about 1 order of magnitude.
3. Spurious noise was analyzed and suppressed.
4. Our work is in preparation to be submitted.

Proposal for the search for exotic spin-spin interactions at the micrometer scale using functionalized cantilever force sensors

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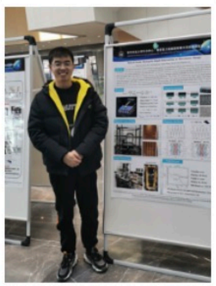

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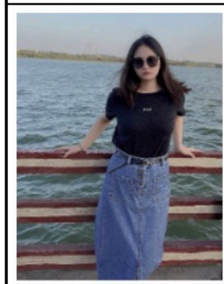

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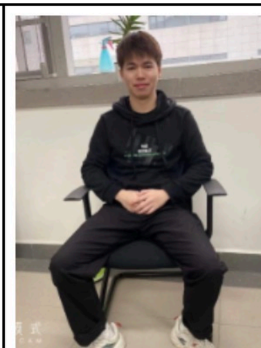

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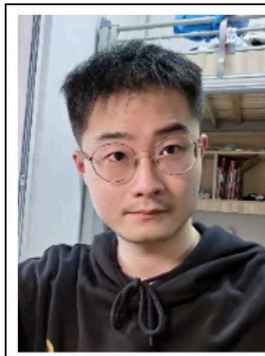

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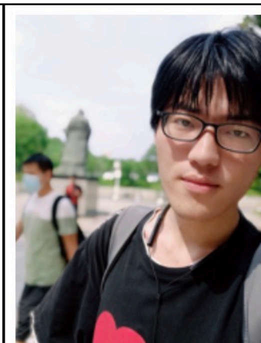

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