Workshop on Testing Fundamental Physics Principles, Corfu2017

Test of hypothetical forces at short range

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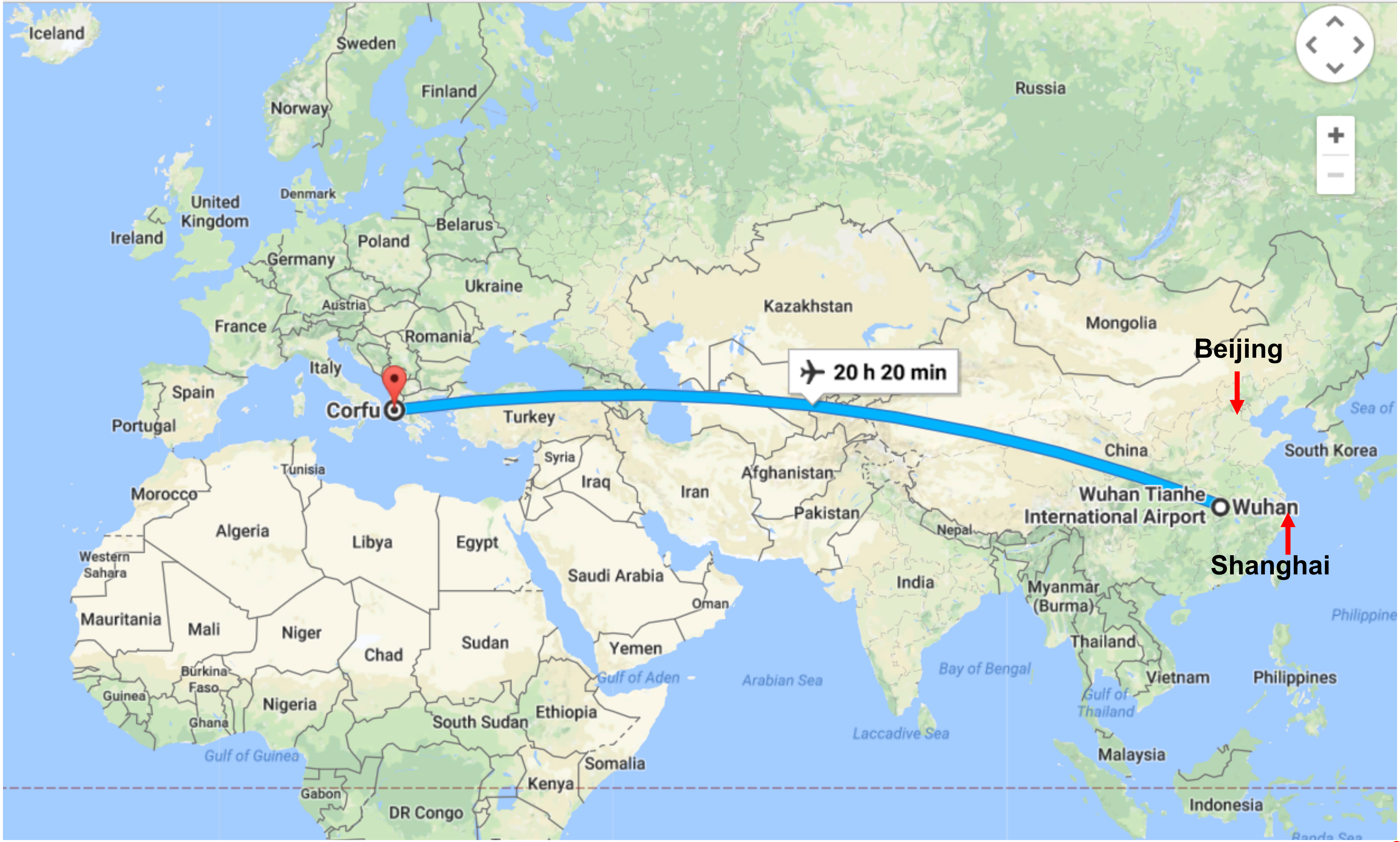
CGE

Where are we from?



Center for gravitational experiments, HUST

- **Precision Gravity Measurement National Facility**

  > Inertial Sensor, Geophysics, ……
- **Test of fundamental principles by precision measurements**

  > Big G measurement

  > Test of Newton's inverse law (hypothetical forces)

  > Test of equivalent principle

  > Test of Lorentz violation

  > Cold atoms and optical clocks

  > ……

Center for gravitational experiments, HUST

- **Precision Gravity Measurement National Facility**

  > Inertial Sensor, Geophysics, ……
- **Test of fundamental principles by precision measurements**

  > Big G measurement

  > Test of Newton's inverse square law (hypothetical forces)

  > Test of equivalent principle

  > Test of Lorentz violation (Shao's talk)

  > Cold atoms and optical clocks

  > ……

Motivations

- **Gravity with *n* extra dimensions**

Yukawa correction

$$V(r) = \begin{cases} -\dfrac{G_4 m_1 m_2}{r}(1 + \alpha e^{-r/\lambda}) & (r \gg R) \\ -\dfrac{G_{4+n} m_1 m_2}{r^{n+1}} & (r \leq R) \end{cases}$$

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

- **Forces mediated by new light bosons**

$$V(r) = -g^2 \frac{e^{-r/\lambda}}{r}$$

New light bosons: moduli, dilatons, scalar axions, …

$$\lambda = h/(mc)$$

$\lambda \sim 1\ \mu m$: $m \sim 0.2\ eV$
$\lambda \sim 1\ nm$: $m \sim 200 eV$

Hypothetical short-ranged forces

Single Boson Exchange Potentials

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:

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

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

Axion, axion-like particle

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

Static, dipole-dipole:

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

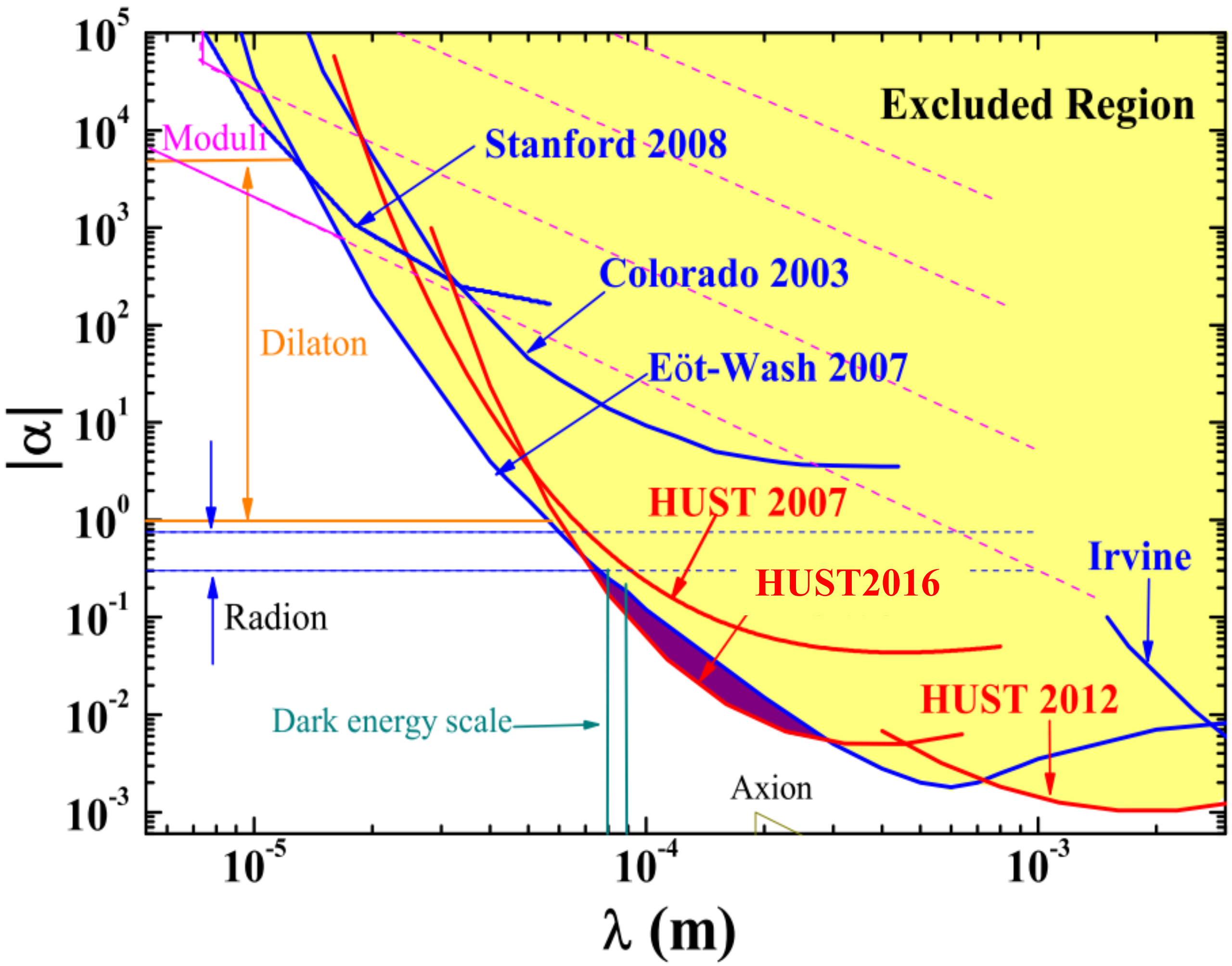
$$V_3 = f_3^{ee} \frac{\hbar^3}{4\pi m_e^2 c}\left[(\hat{\sigma}_1 \cdot \hat{\sigma}_2)\left(\frac{1}{\lambda r^2} + \frac{1}{r^3}\right) - (\hat{\sigma}_1 \cdot \hat{r})(\hat{\sigma}_2 \cdot \hat{r})\left(\frac{1}{\lambda^2 r} + \frac{3}{\lambda r^2} + \frac{3}{r^3}\right)\right] e^{-r/\lambda}$$

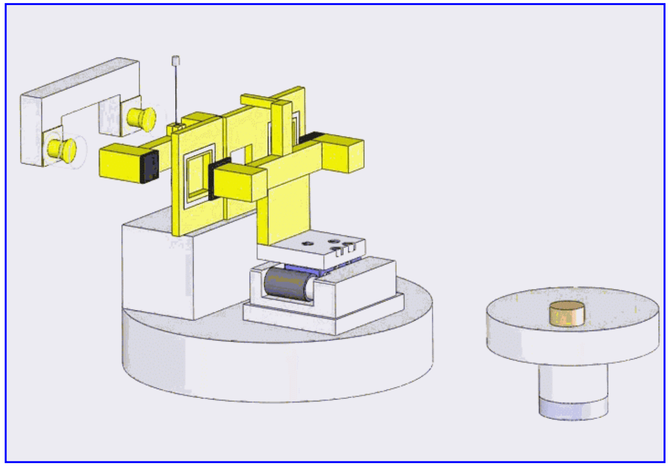
Axion, axion-like particle

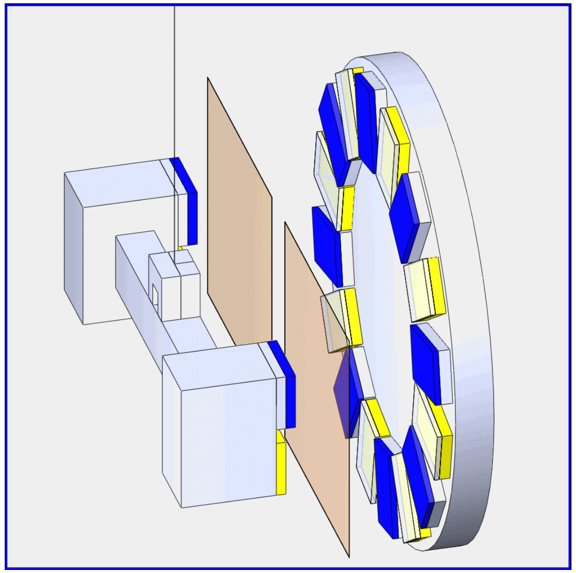
$$V_{11} = -f_{11}^{ee} \frac{\hbar^2}{4\pi m_e}[(\hat{\sigma}_1 \times \hat{\sigma}_2) \cdot \hat{r}]\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right) e^{-r/\lambda}.$$

Velocity dependent, dipole-dipole: …

Short range gravity experiments







Liang-Cheng Tu, Jun Luo *et al.*, PRL 98, 201101 (2007)
Shan-Qing Yang, Jun Luo *et al.*, PRL 108, 081101 (2012)
Wen-Hai Tan, Jun Luo *et al.*, PRL 116, 131101 (2016)

Outlines

- **Experimental Search for Yukawa-type forces at the micrometer range**
- **Constraints on the spin-spin interactions at the nanometer range**

Outlines

- **Experimental Search for Yukawa-type forces at the micrometer scale**

- Constraints on the spin-spin interactions at the nanometer scale

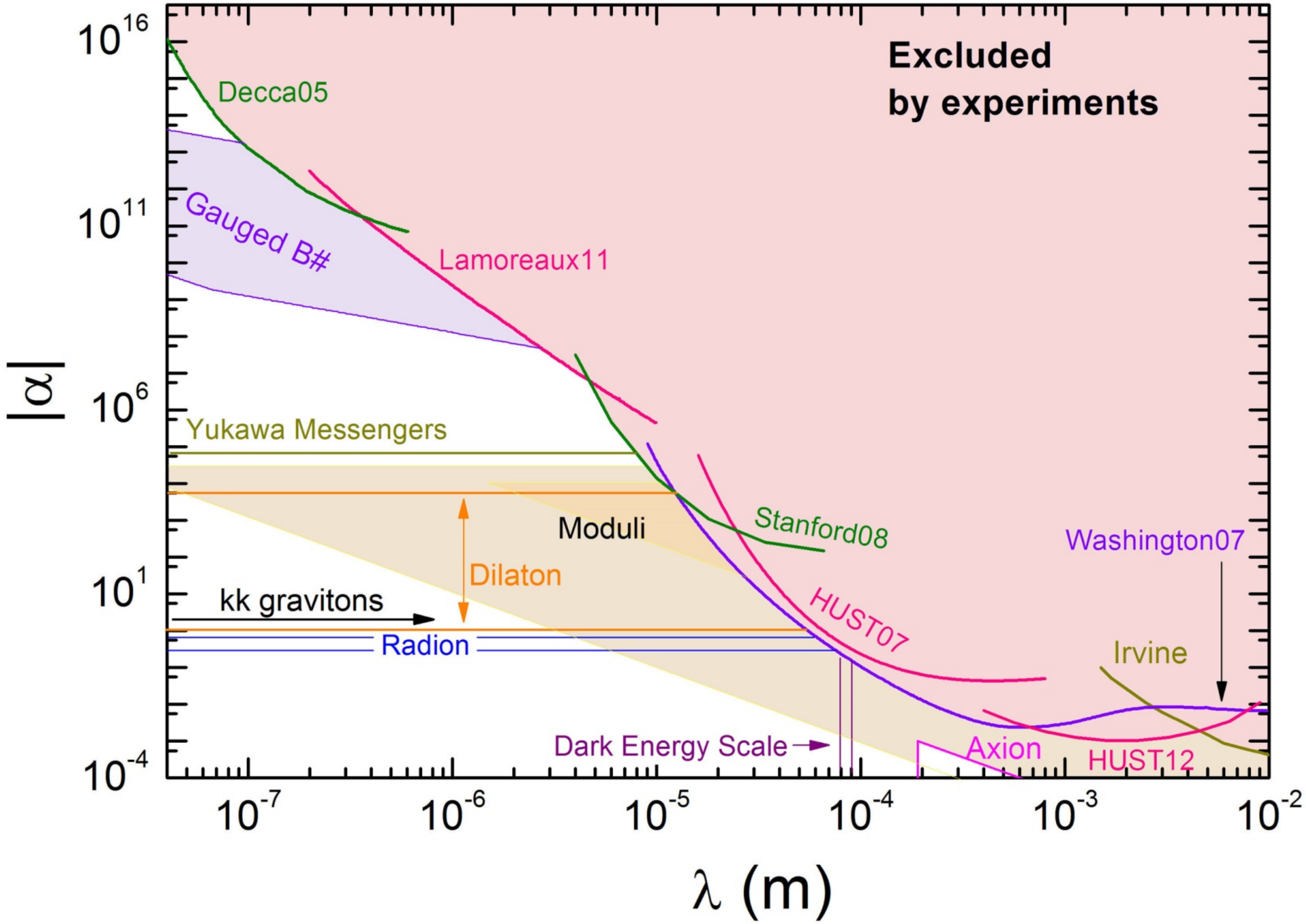
Search for Yukawa forces at micrometer range

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

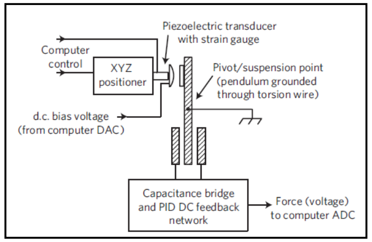
- To be sensitive to forces of range λ, $r \sim \lambda \sim \mu m$
- The force would be small if exists: size of the two interacting bodies $\sim \lambda$
- The disturbance is expected to be large: at such short range, the Casimir force and electrostatic forces contribute
- Approach and alignments: usually adopt a sphere-plate geometry

Constraints at micrometer range

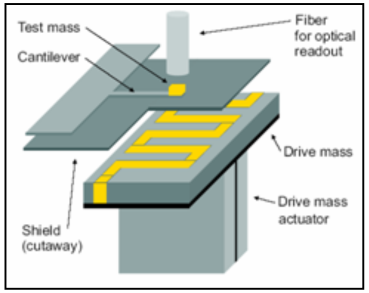
Yukawa Potential: $$V(r) = \frac{Gm_1m_2}{r}(1+\alpha e^{-r/\lambda})$$

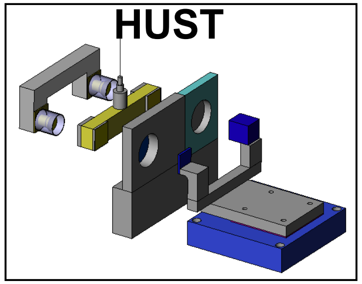


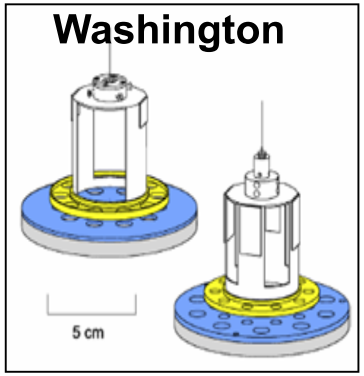
Lamoreaux



Stanford

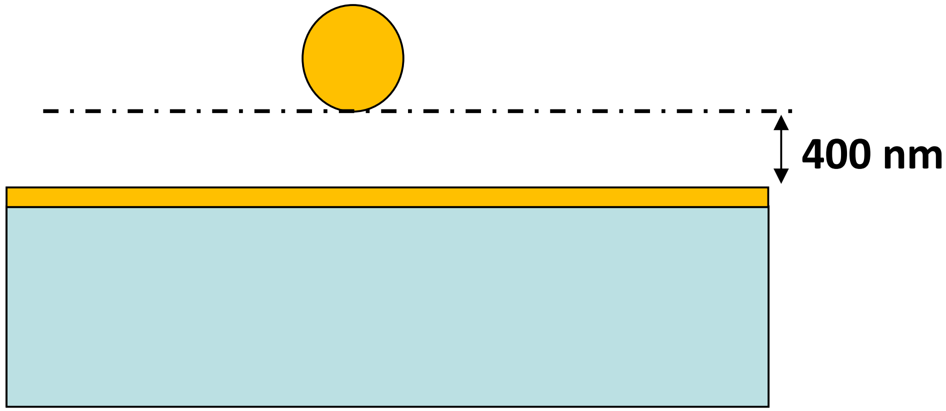




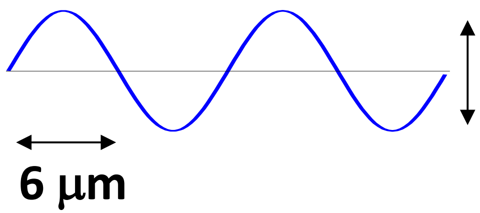


Experimental Scheme

(d_t = 25 μm)



Lateral
Yukawa Force



~ 1.7×10^{-16} N (α =3.0×10^{8} λ = 1 μm)

Casmir： ~ 4.3×10^{-13} N

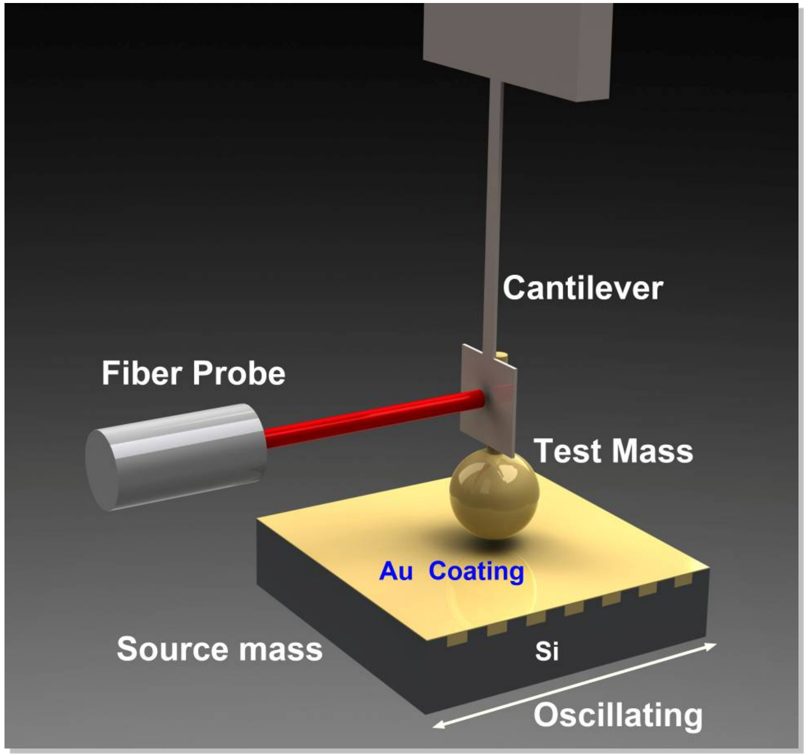
Electrostatic： ~ 3.3×10^{-15} N
(ΔV = 2 mV)

Projected: 1.0×10^{-16} N

Density modulation

Signal of interest @ $n\times f_d$

Experimental Scheme



Density modulation

Oscillating amplitude: 18.4 μm

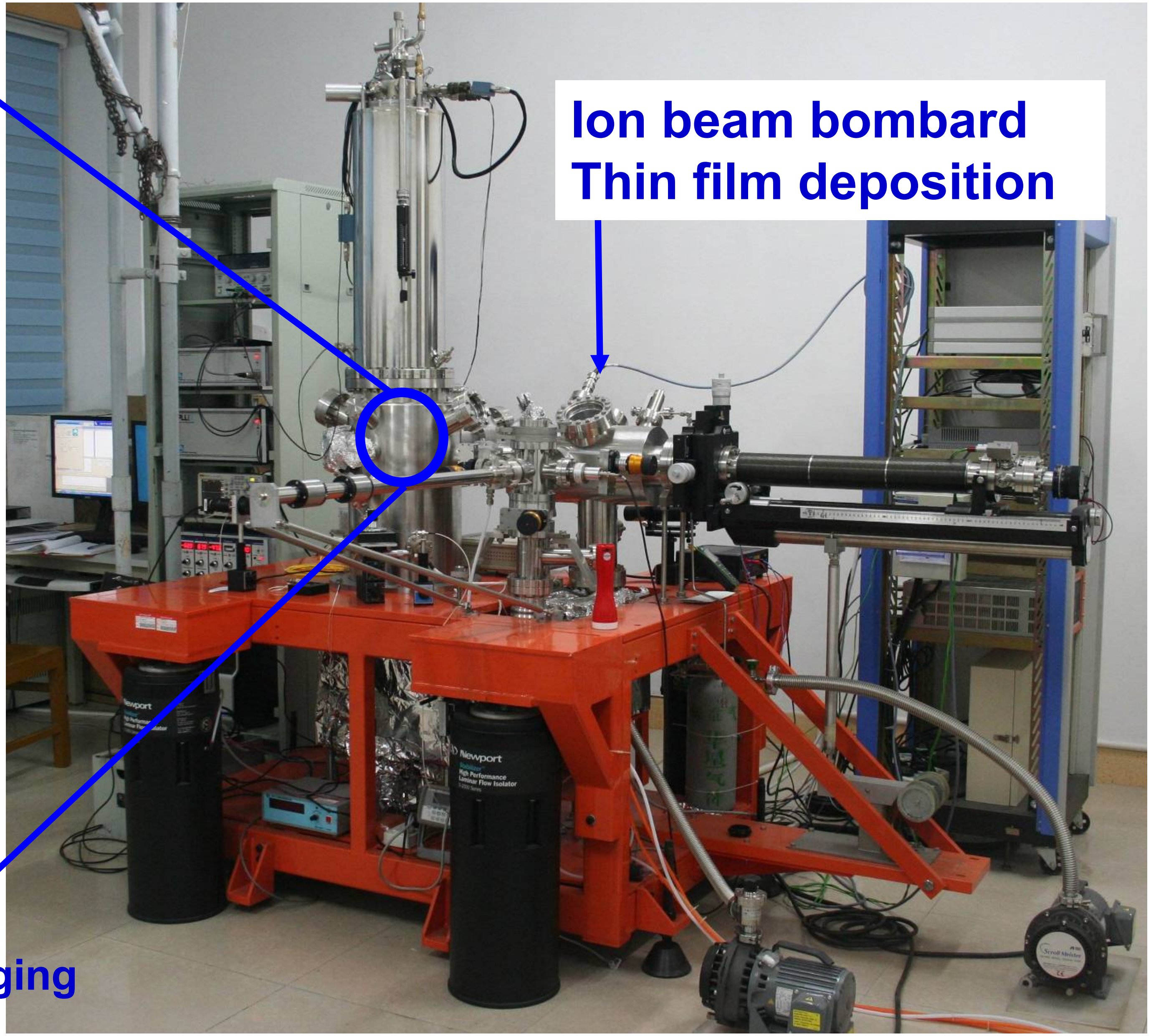
Signal frequency：$8f_d$

- Cantilever: ~ mN/m
- Pendulum-like: sensitive to lateral force
- Laser interferometer: ~2 pm/$Hz^{1/2}$ @16.8 Hz
- Density modulation: period ~12μm
- Isoelectronic surface: gold coating

make the Casimir & electrostatic forces constant

→ "null" test

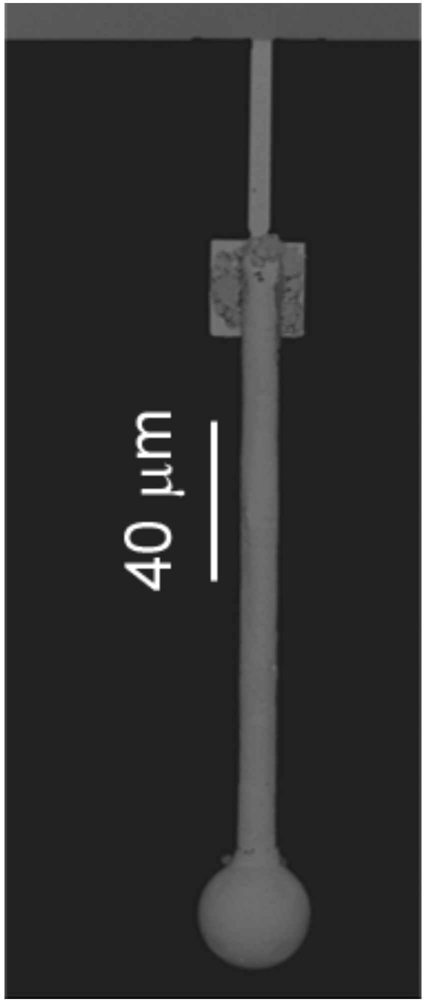
Apparatus

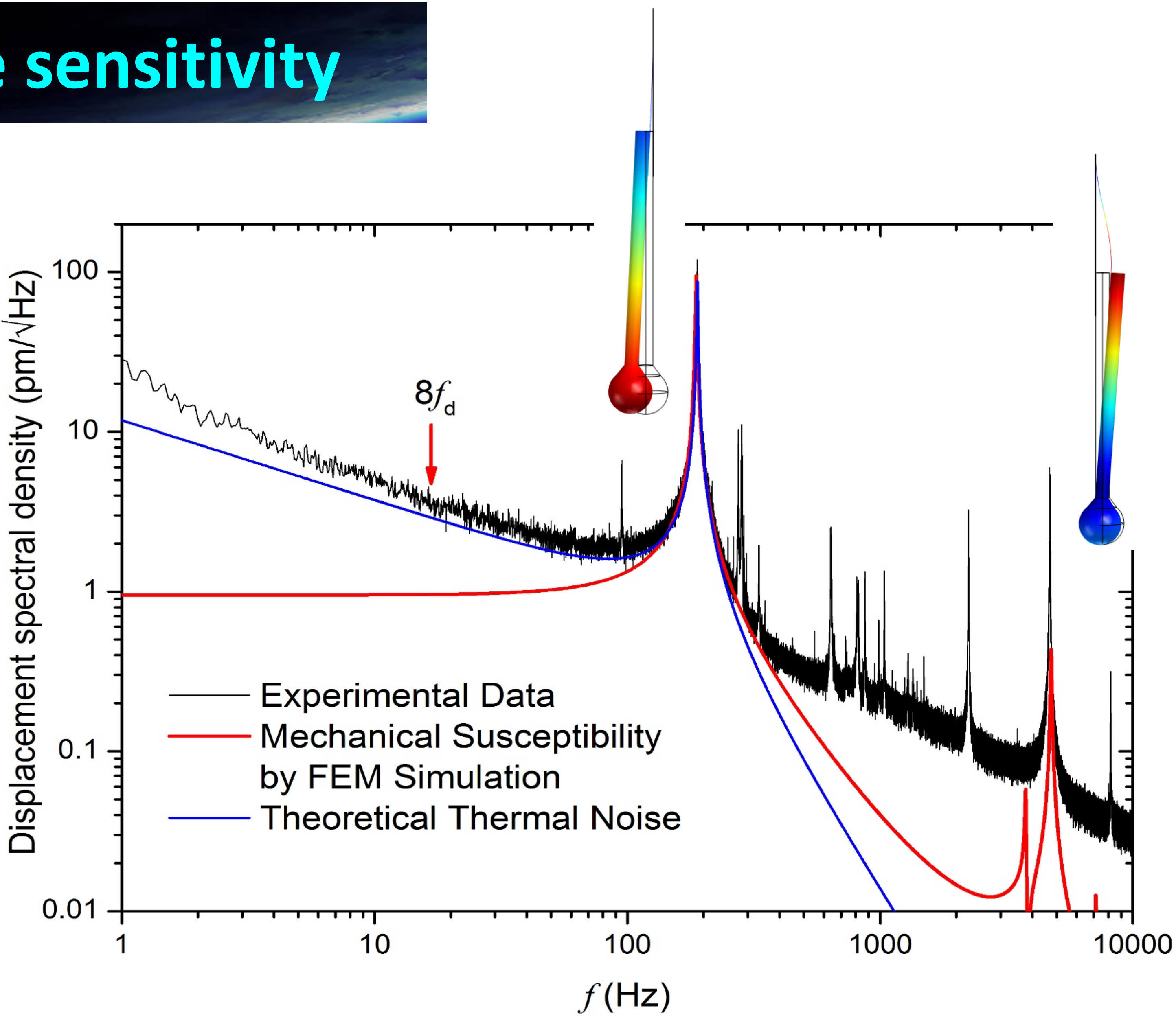


Ion beam bombard
Thin film deposition

Surface imaging
Surface potential imaging
ISL exp.

Cantilever: force sensitivity



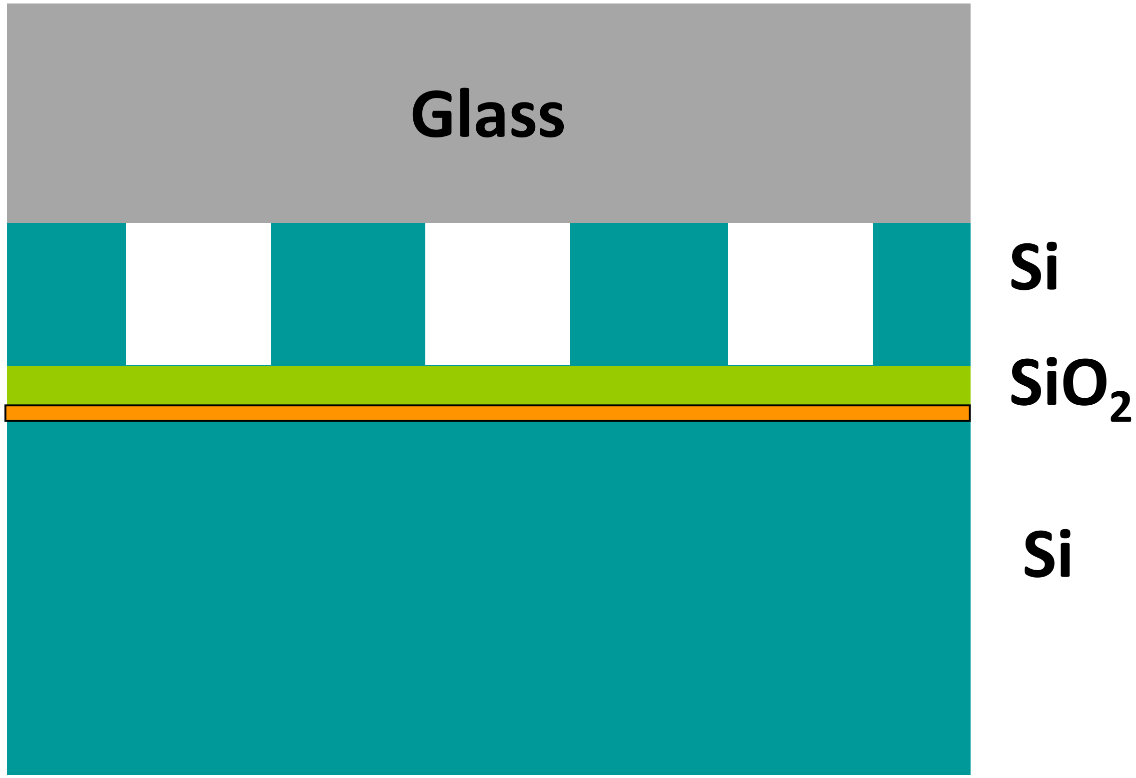


k = 1.3 (2) mN/m

Force noise level: 6×10^{-15} N/ √Hz

Density modulated source mass

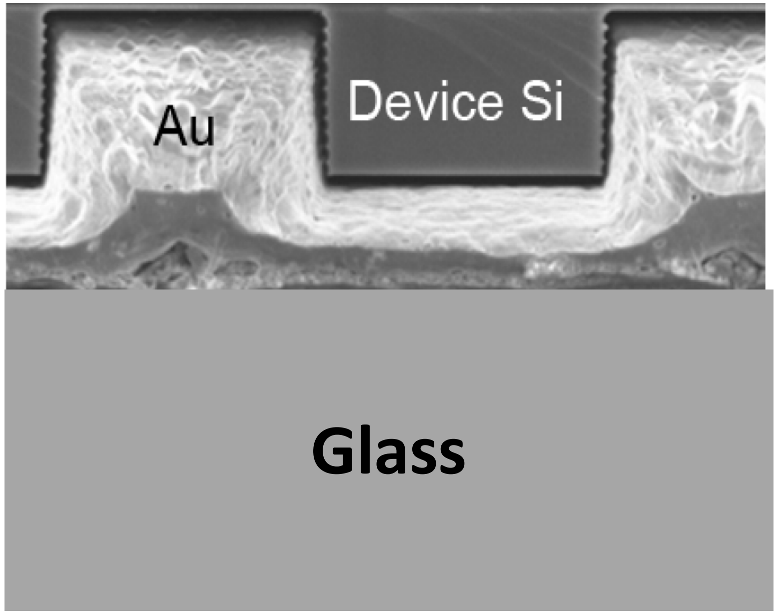
Density modulation + Flat + isoelectronic



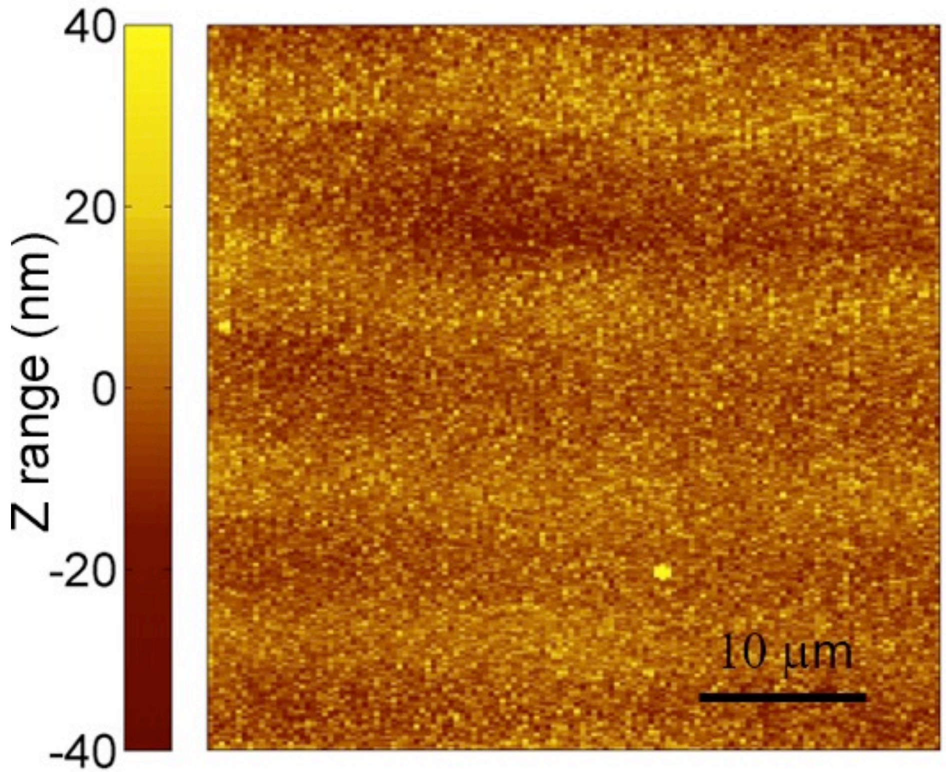
Process based on silicon on insulator (SOI) wafer

Density modulated source mass

SEM Image

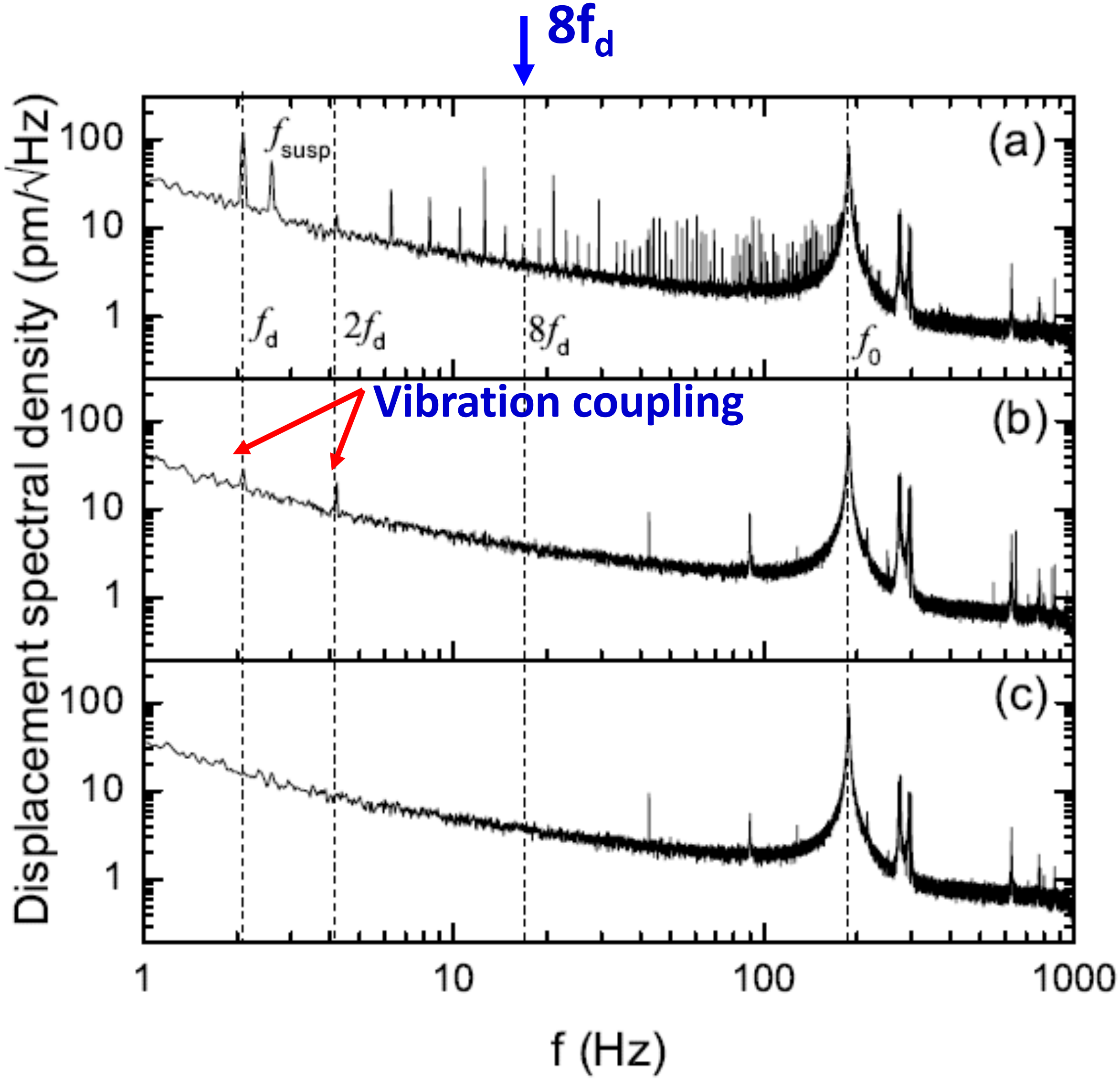


AFM Image



Averaged corrugation: ~3 nm

Control experiments



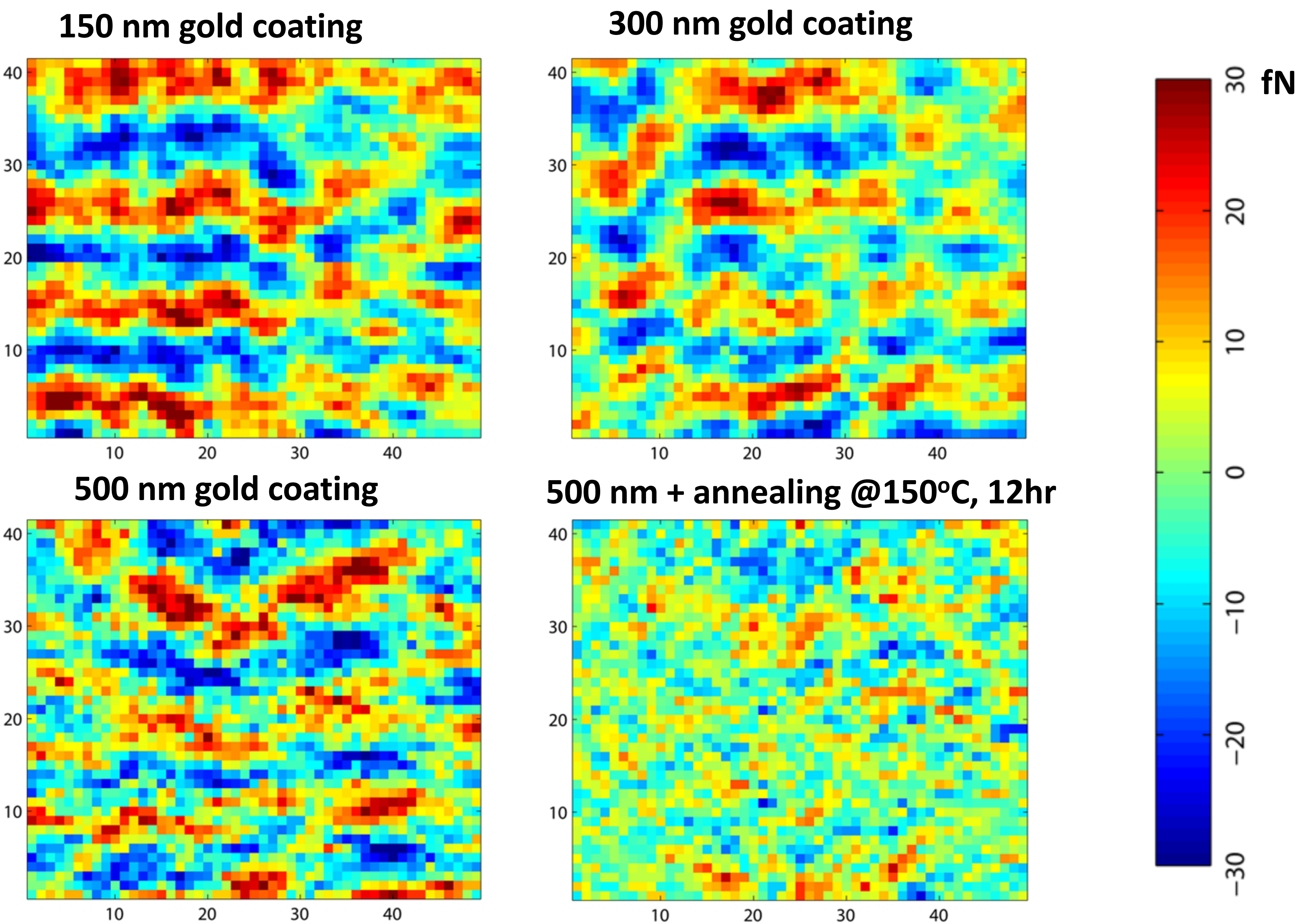
Oscillating
d ~ 640 nm

Oscillating
d ~ 3μm

at rest

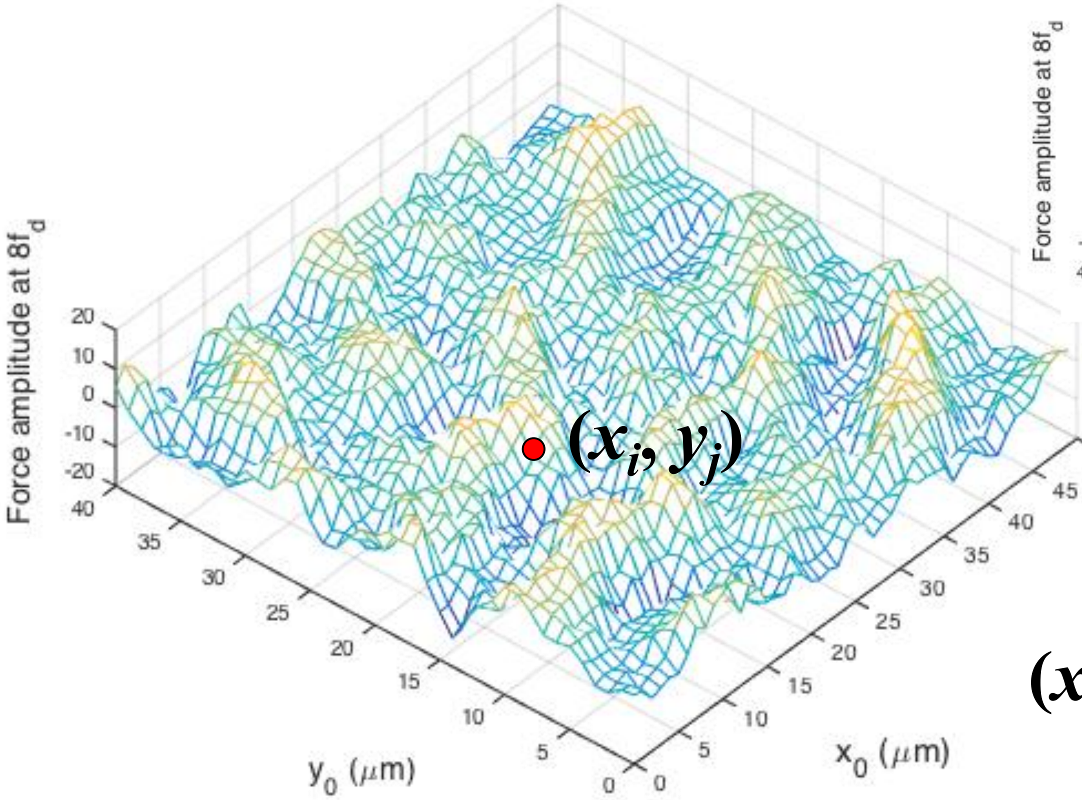
Observed non-zero signal at $8f_d$ where signal of interest is expected.

Mapping the force at $8f_d$



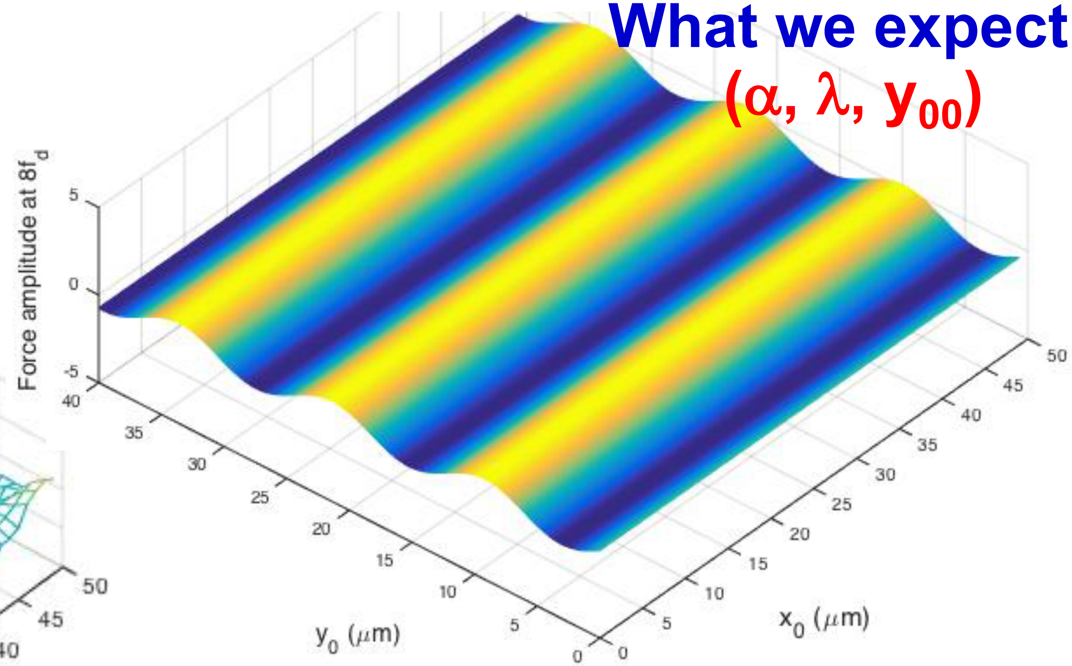
Maximum likelihood estimation

What we observed



What we expect

(α, λ, y_{00})



$$(x_i, y_j):\quad P_{i,j}(F_{i,j}^{\exp} \mid y_{00}, \alpha) = \frac{1}{\sqrt{2\pi}\sigma_{i,j}} e^{-\frac{F_{i,j}^{\exp} - F_{i,j}^{T}}{\sigma_{i,j}}}$$

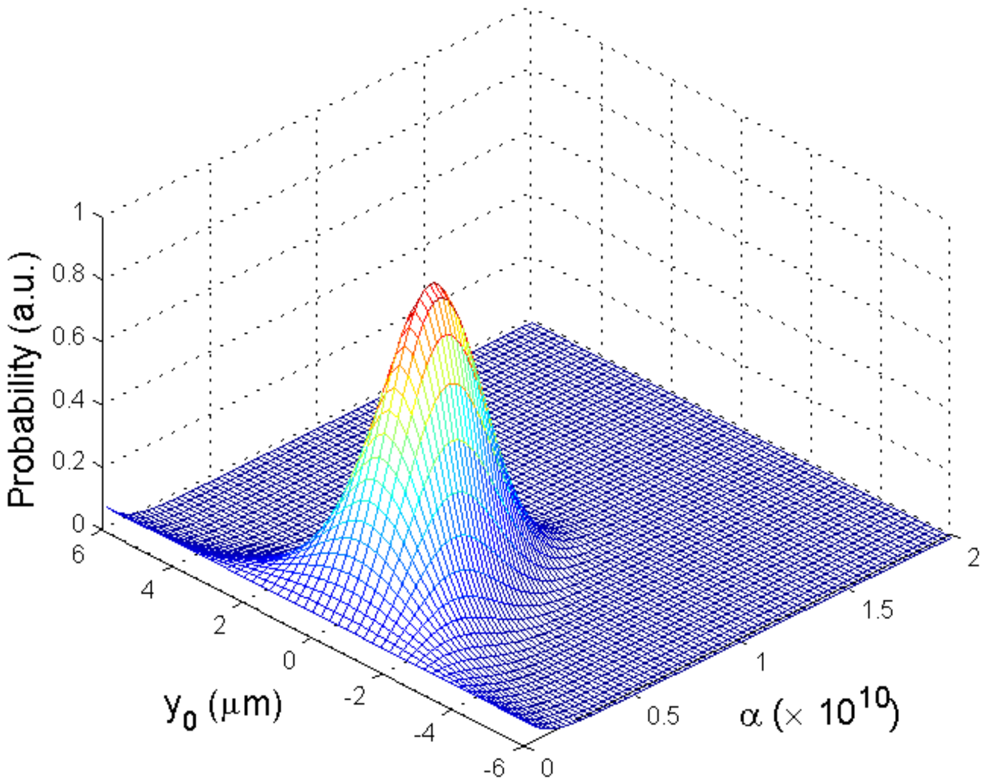
$$\sigma_{i,j} = \sqrt{\left(\delta F_{i,j}^{\exp}\right)^2 + \left(\delta F_{i,j}^{T}\right)^2}$$

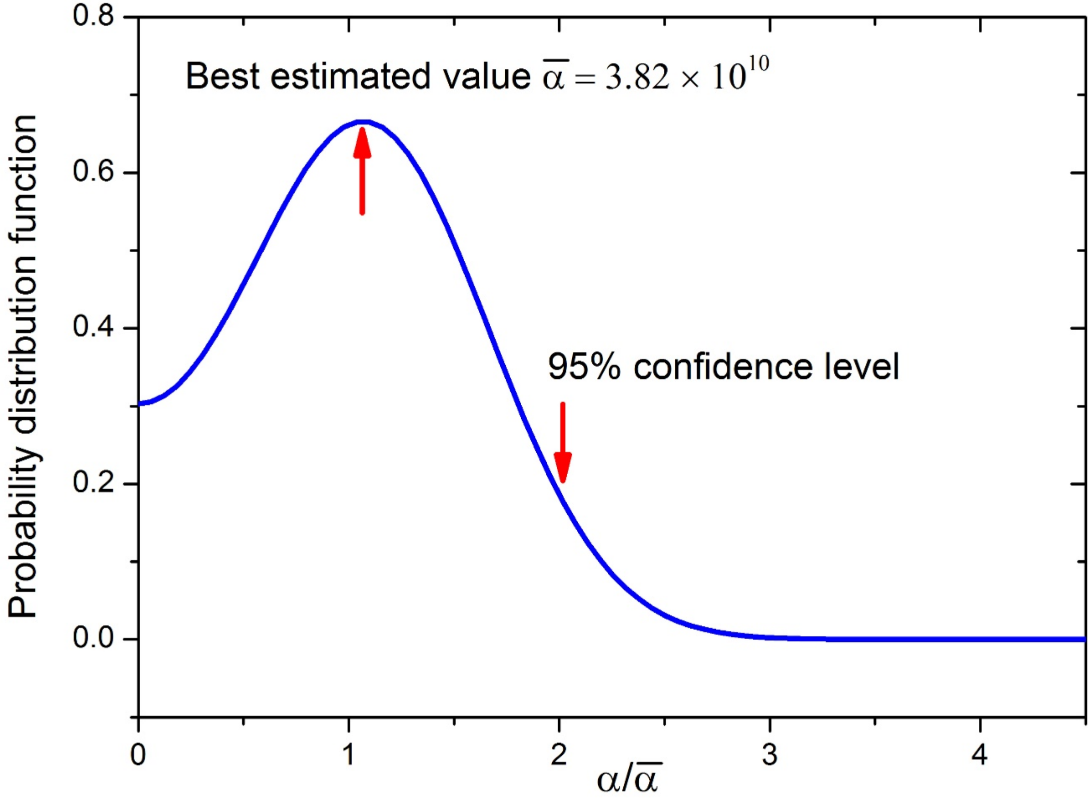
Conditional probability:
(for a fixed λ)

$$P(y_{00}, \alpha) = \frac{1}{A} \prod_{i,j} P_{i,j}(F_{i,j}^{\exp} \mid y_{00}, \alpha)$$

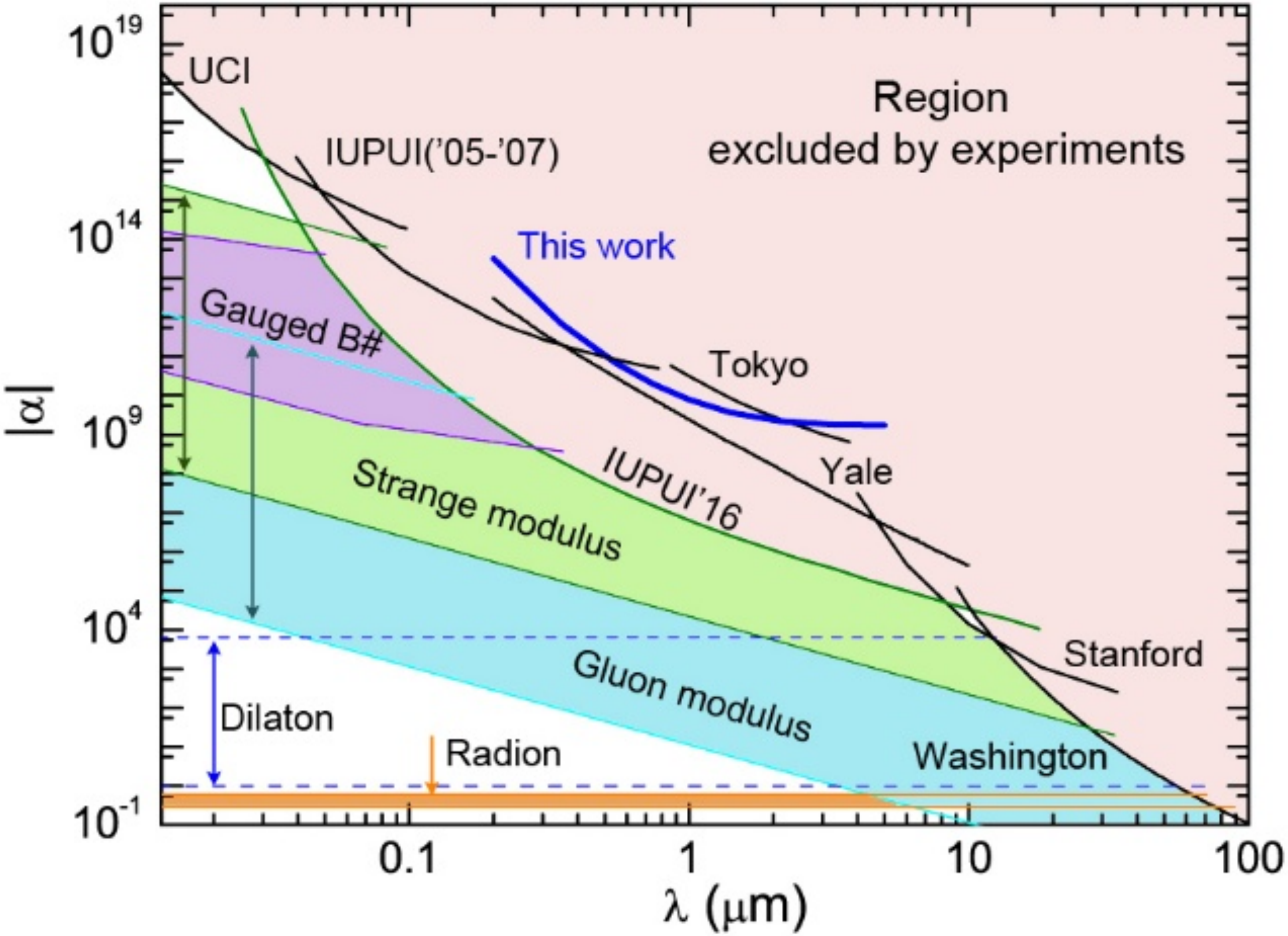
Maximum likelihood estimation

$\lambda = 1\ \mu m$





Constraints on the Yukawa-type forces



Yale: derived from Casimir experiment

IUPUI'16: current strongest constraints

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

Outlines

- Experimental Search for Yukawa-type forces at the micrometer scale

- **Constraints on the spin-spin interactions at the nanometer scale**

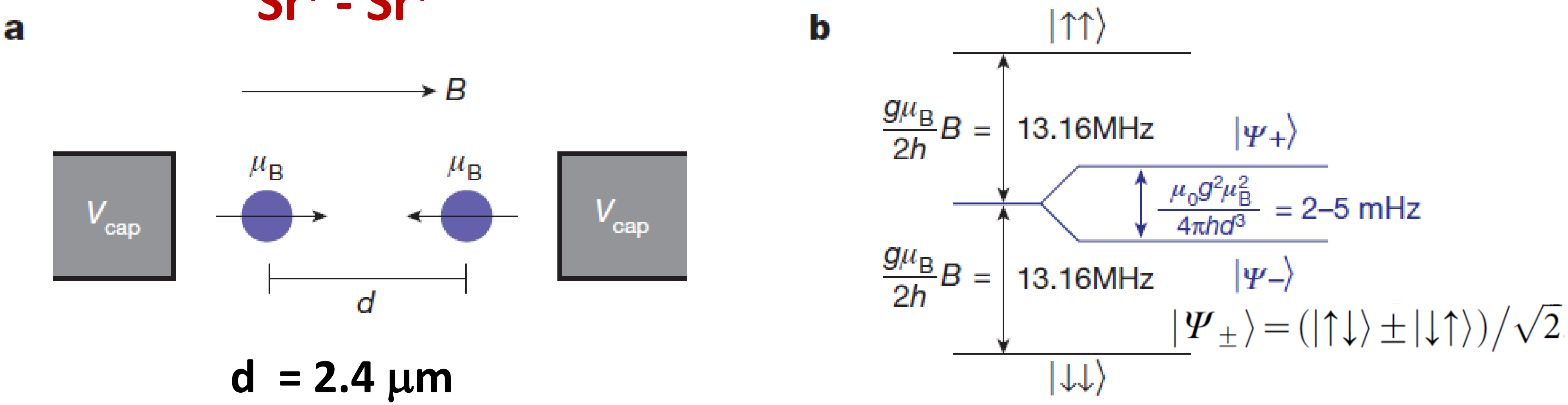
PRL **115,** 081801 (2015) PHYSICAL REVIEW LETTERS week ending 21 AUGUST 2015

Constraints on Exotic Dipole-Dipole Couplings between Electrons at the Micrometer Scale

Shlomi Kotler,[1] Roee Ozeri,[2] and Derek F. Jackson Kimball[3]
[1]National Institute of Standards and Technology, 325 Broadway Street, Boulder, Colorado 80305, USA
[2]Department of Physics of Complex Systems, Weizmann Institute of Science, P.O. Box 26, Rehovot 76100, Israel
[3]Department of Physics, California State University, East Bay, Hayward, California 94542-3084, USA

$$|\uparrow\downarrow\rangle \Rightarrow |\Psi(T)\rangle = \cos(2\xi T)|\uparrow\downarrow\rangle + i\sin(2\xi T)|\downarrow\uparrow\rangle$$

Sr^+ - Sr^+



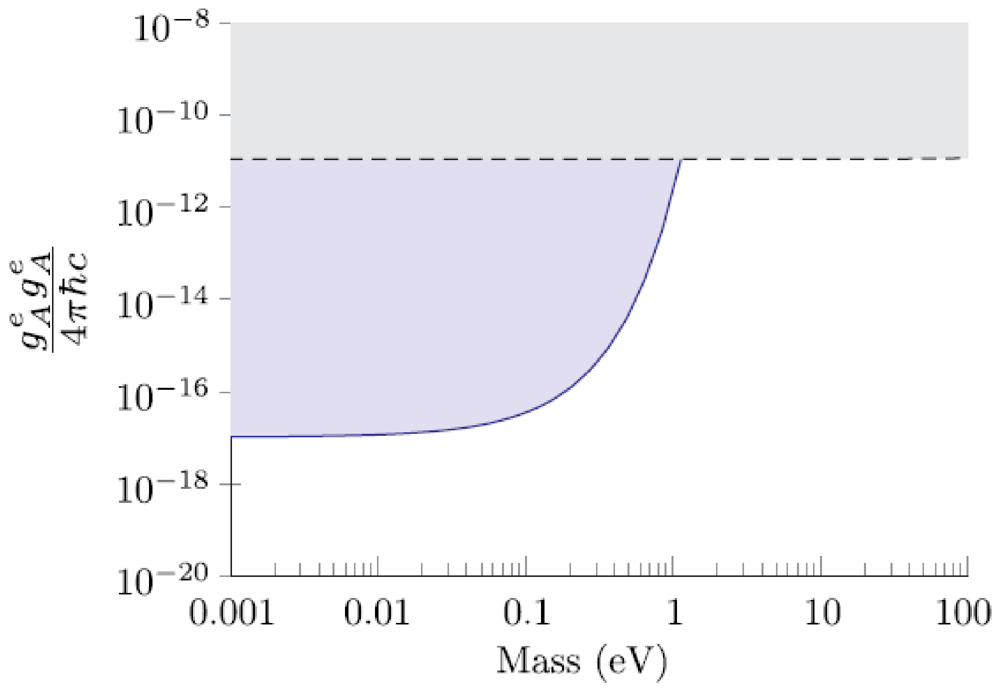
d = 2.4 μm

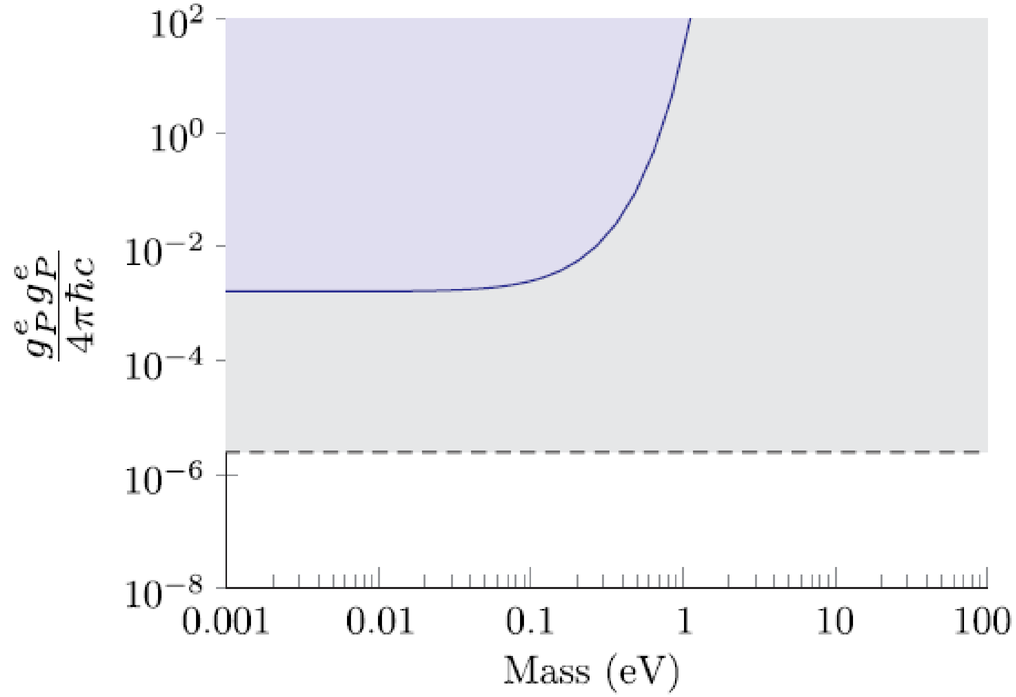
Coupling strength: $\xi = 2\pi \times 1.020(95)_{\rm stat}$ mHz

Constraints on hypothetical force: $\xi_h \leq 2\delta\xi$

Kotler *et al.*, Nature 510， 376（2014）

Constraints on spin-spin interaction





Pseudovector coupling

$$\mathcal{V}_A(r) = \frac{g_A^e g_A^e}{4\pi\hbar c}\frac{\hbar c}{r}\mathbf{S}_1 \cdot \mathbf{S}_2 e^{-r/\lambda}$$

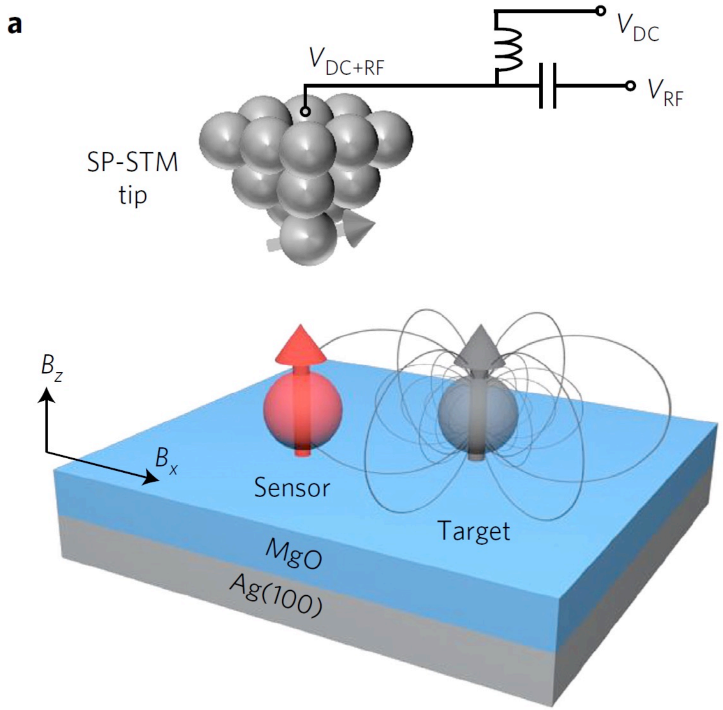
Pseudoscalar coupling

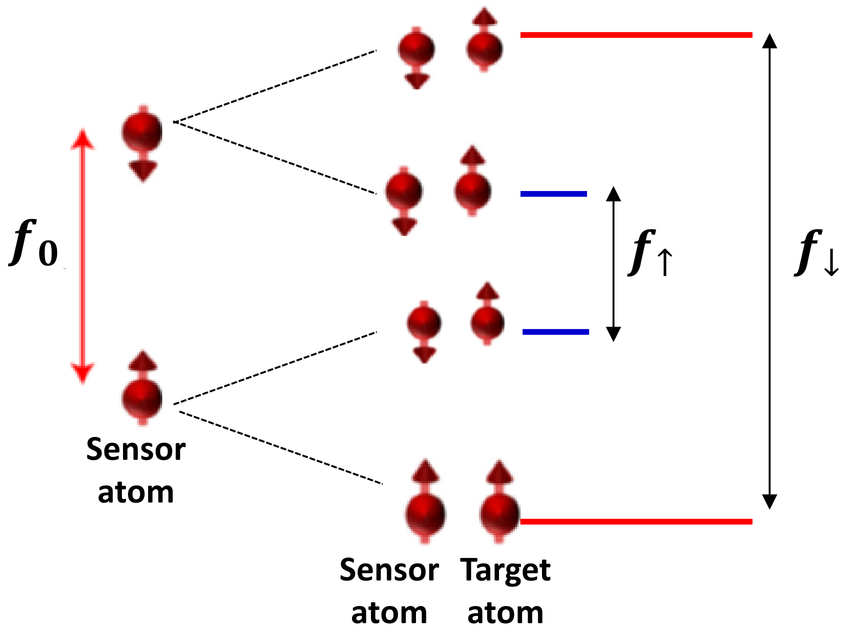
$$\mathcal{V}_P(\mathbf{r}) = \frac{g_P^e g_P^e}{4\pi\hbar c}\frac{\hbar^3}{4m_e^2 c}\left[\mathbf{S}_1 \cdot \mathbf{S}_2\left(\frac{1}{\lambda r^2} + \frac{1}{r^3} + \frac{4\pi}{3}\delta^3(r)\right) - (\mathbf{S}_1 \cdot \hat{\mathbf{r}})(\mathbf{S}_2 \cdot \hat{\mathbf{r}})\left(\frac{1}{\lambda^2 r} + \frac{3}{\lambda r^2} + \frac{3}{r^3}\right)\right] e^{-r/\lambda},$$

nature nanotechnology
LETTERS
PUBLISHED ONLINE: 6 MARCH 2017 | DOI: 10.1038/NNANO.2017.18

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*]

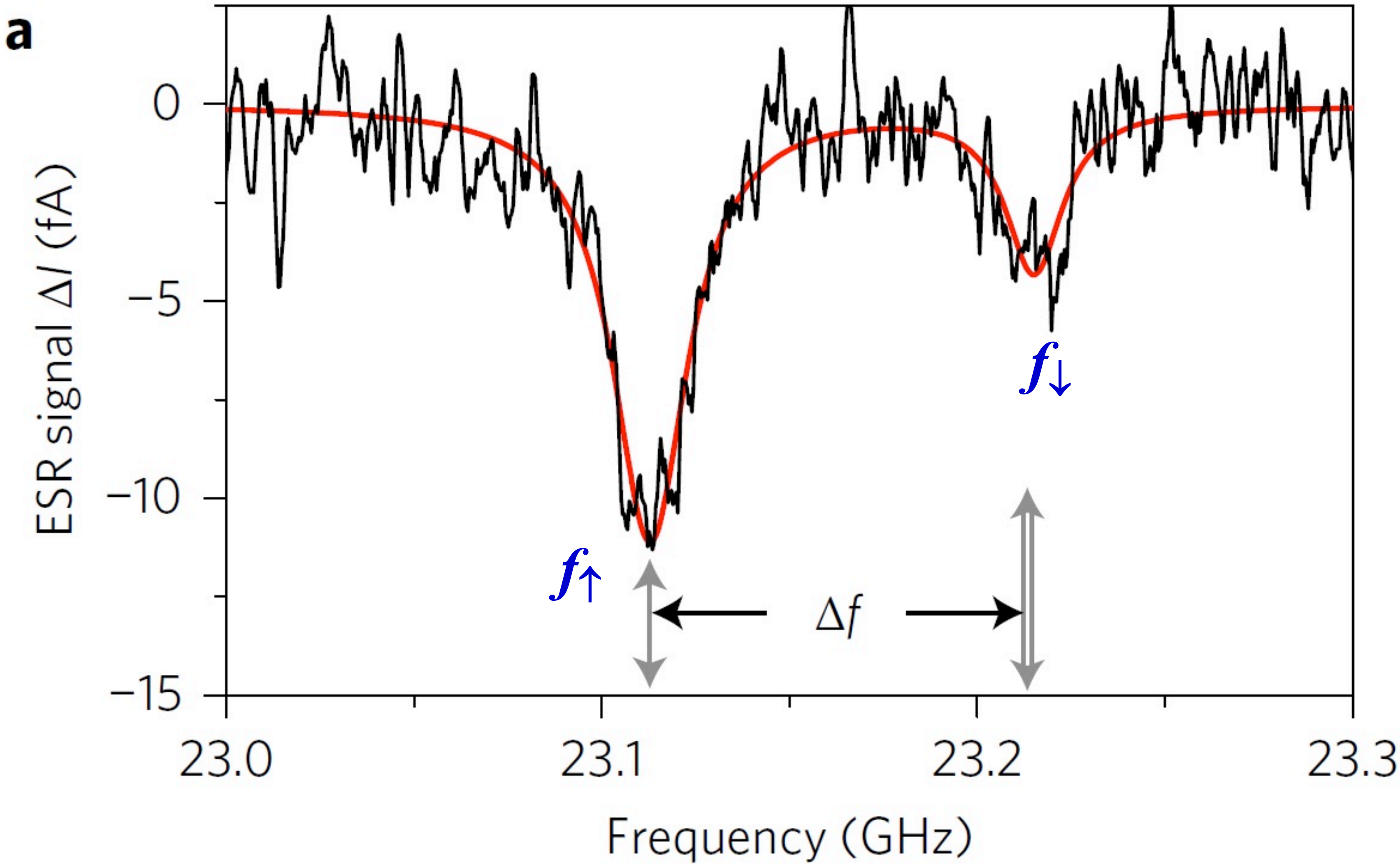




$$\Delta f = f_\downarrow - f_\uparrow = \frac{4E_{dd}}{h}$$

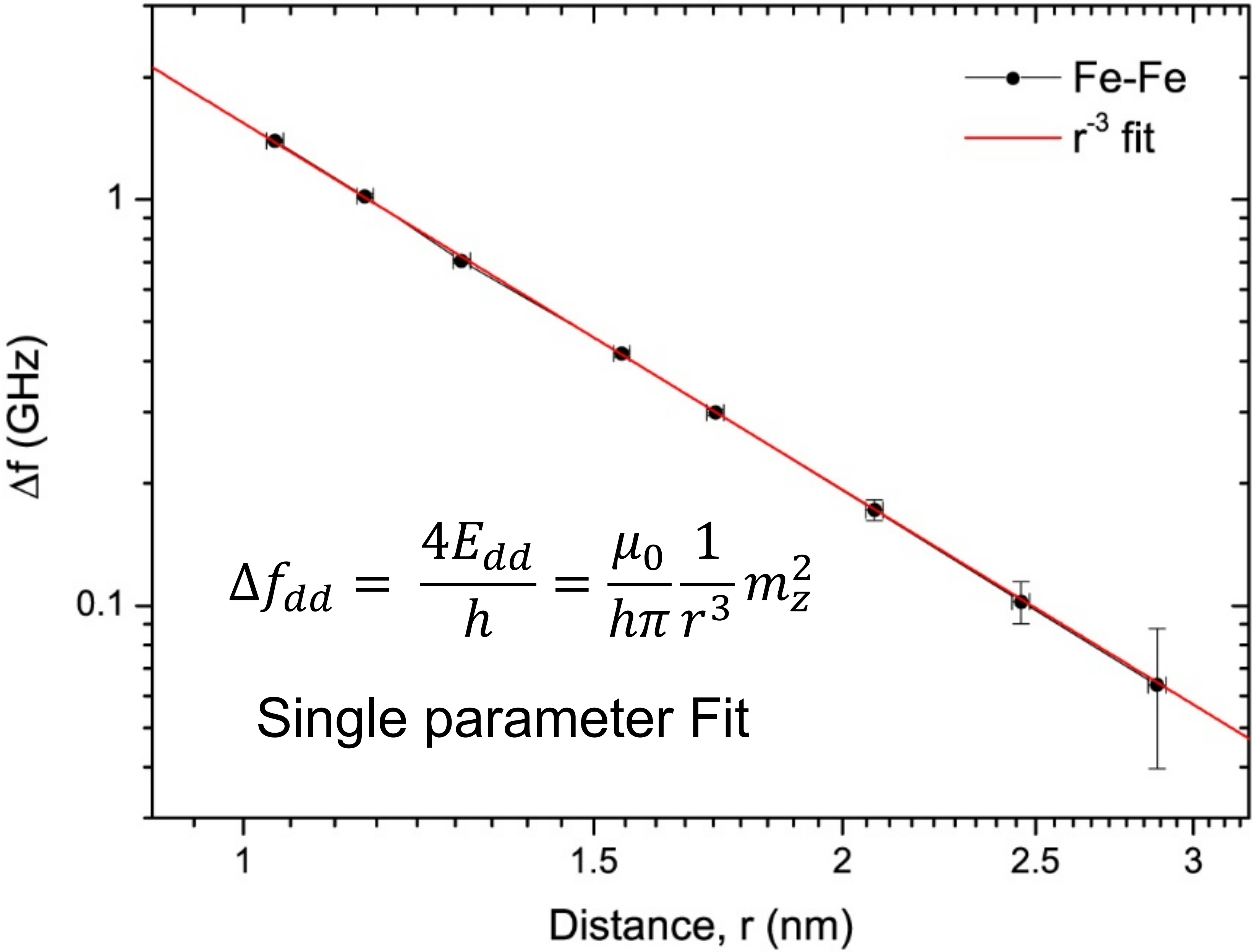
Dipole-dipole: $E_{dd} = \frac{\mu_0}{4\pi}\frac{1}{r^3}\left[\left(\vec{m}^{(1)}\cdot\vec{m}^{(2)}\right) - 3\left(\vec{m}^{(1)}\cdot\hat{r}\right)\left(\vec{m}^{(2)}\cdot\hat{r}\right)\right] = \frac{\mu_0}{4\pi}\frac{1}{r^3}m_z^2$

ESR Spectroscopy of Fe atom



$$\Delta f = 4\, E_{dd}/h$$

Magnetic dipole-dipole interaction



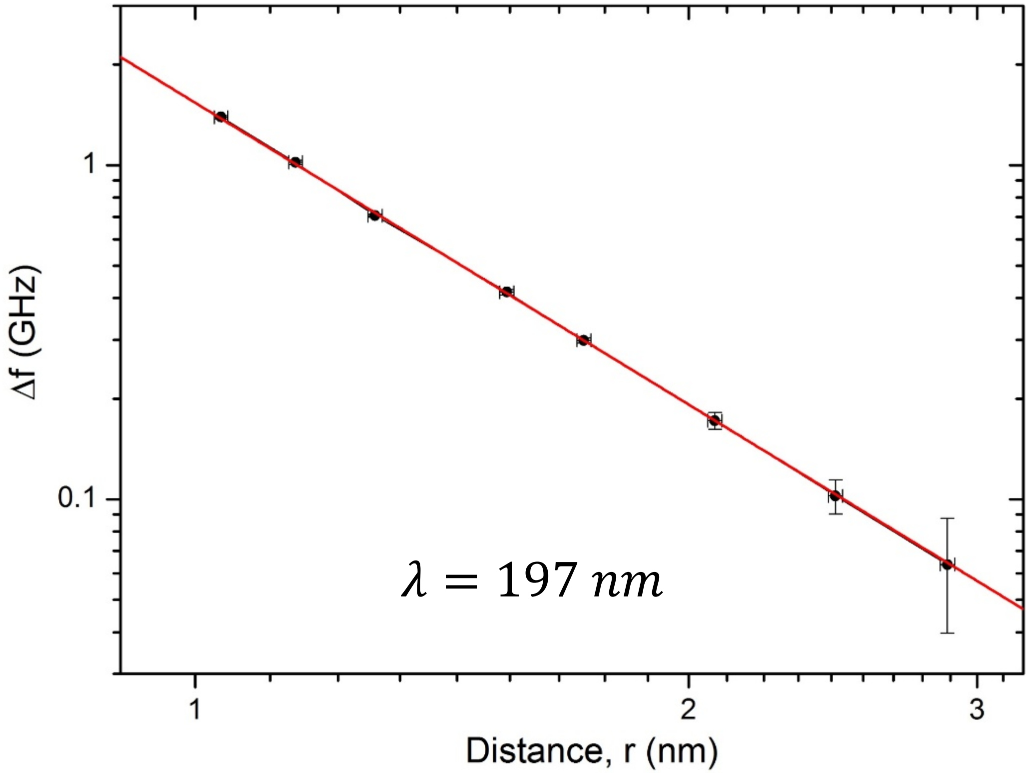
$$\Delta f_{dd} = \frac{4E_{dd}}{h} = \frac{\mu_0}{h\pi}\frac{1}{r^3}m_z^2$$

Single parameter Fit

Constraints on pseudo-vector mediated force

$$V_A(r) = \frac{g_A^2}{4\pi\hbar c}\frac{\hbar c}{r}e^{-r/\lambda}\boldsymbol{\sigma_1}\cdot\boldsymbol{\sigma_2}$$

$$\Delta f_A = \frac{g_A^2}{4\pi\hbar c}\frac{8c}{\pi r}S_z^2 e^{-r/\lambda}$$



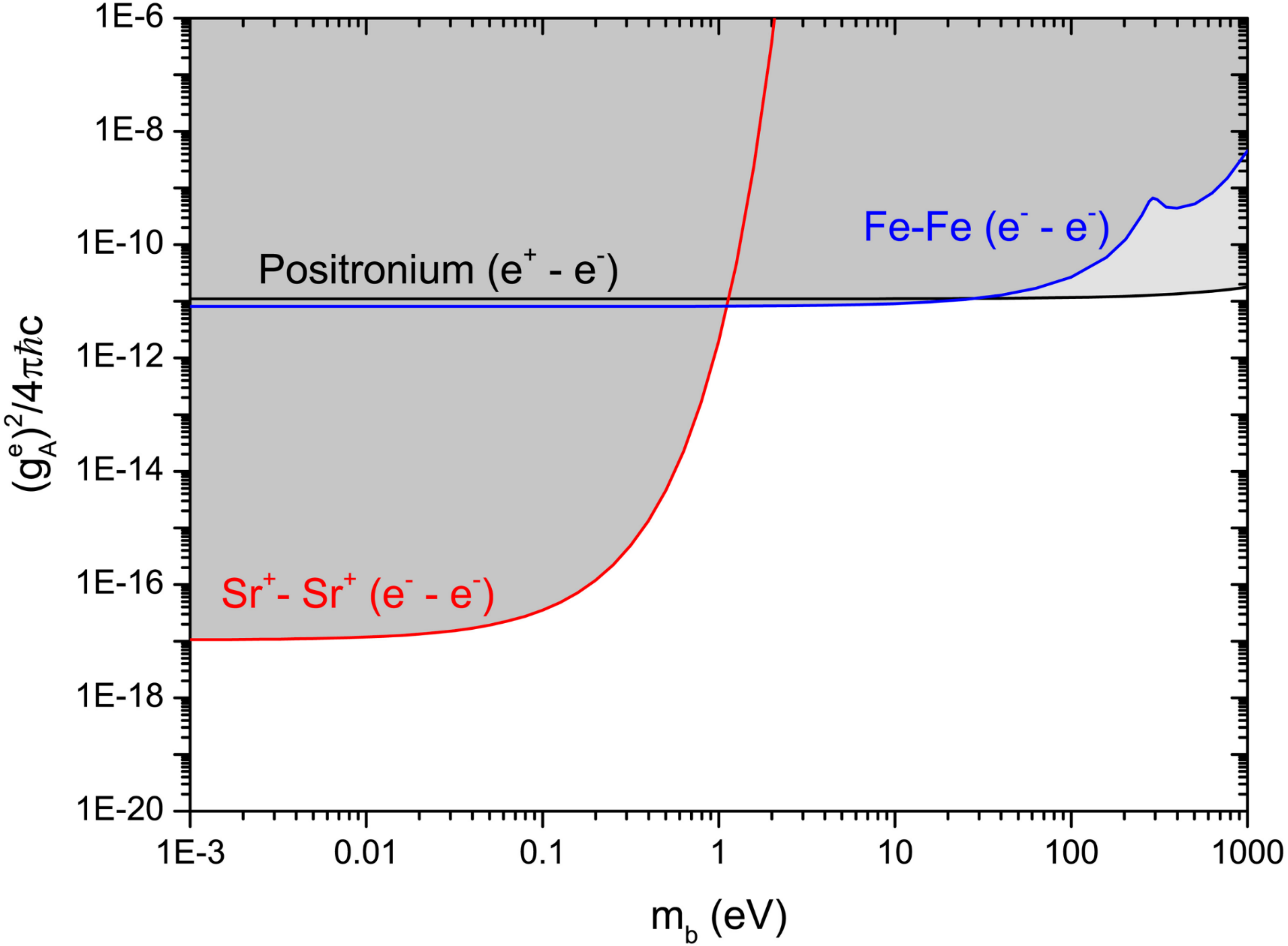
Assume

$$\Delta f_{exp} = \Delta f_{dd}(m_z) + \Delta f_{PP}(\lambda, g_p^2)$$

$$\frac{g_A^2}{4\pi\hbar c} = (0 \pm 4.1)\times 10^{-12}$$

$$\frac{g_A^2}{4\pi\hbar c} \leq 8.1\times 10^{-12}$$

Constraints on pseudo-vector mediated force



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

Constraints on pseudo-scalar mediated force

$$V_P(r) = -\frac{g_p^2}{4\pi\hbar c}\frac{\hbar^3}{4m_f^2 c}\left[\boldsymbol{\sigma_1}\cdot\boldsymbol{\sigma_2}\left(\frac{1}{\lambda r^2}+\frac{1}{r^3}\right)-(\boldsymbol{\sigma_1}\cdot\hat{\boldsymbol{r}})(\boldsymbol{\sigma_2}\cdot\hat{\boldsymbol{r}})\left(\frac{1}{\lambda^2 r}+\frac{3}{\lambda r^2}+\frac{3}{r^3}\right)\right]e^{-r/\lambda}$$

$$V_P(r) = -\frac{g_p^2}{4\pi\hbar c}\frac{\hbar^3}{4m_f^2 c}\boldsymbol{\sigma_1}\cdot\boldsymbol{\sigma_2}\left(\frac{1}{\lambda r^2}+\frac{1}{r^3}\right)e^{-r/\lambda}$$

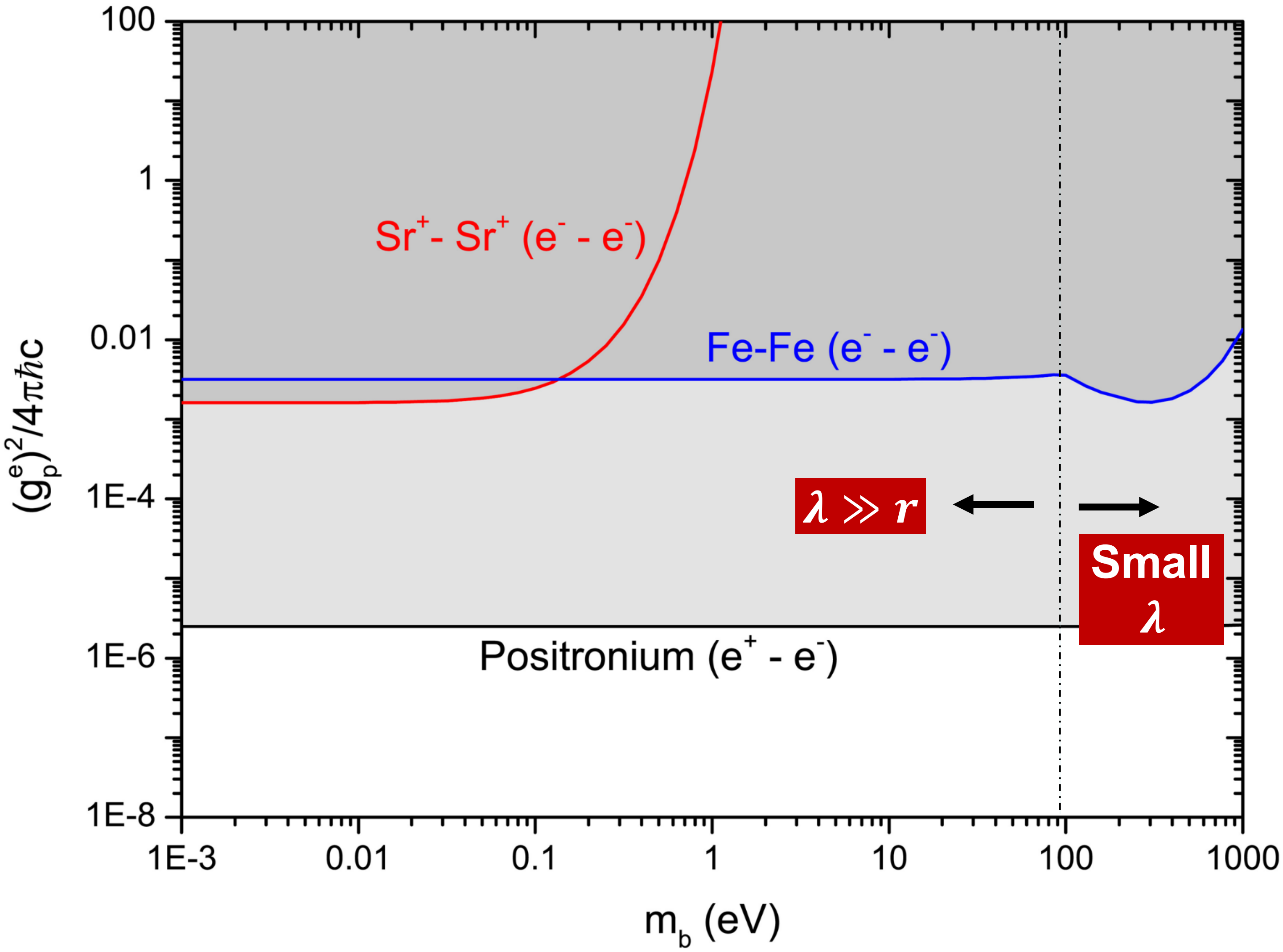
$$\Delta f_P = -\frac{g_p^2}{4\pi\hbar c}\frac{2\hbar^2}{\pi m_e^2 c}S_z^2\left(\frac{1}{\lambda r^2}+\frac{1}{r^3}\right)e^{-r/\lambda} \xrightarrow{\lambda \gg r} \propto \frac{1}{r^3}$$

Small λ : $\Delta f_{exp} = \Delta f_{dd}(m_z) + \Delta f_A(\lambda, g_A^2)$

$\lambda \gg r$: $\Delta f_{exp} = \Delta f_{dd}(m_z = 6\mu_B) + \Delta f_A(\lambda, g_A^2)$

Maximum DD contribution

Constraints on pseudo-scalar mediated force



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

Stellar cooling rates imposed rather stronger constraints than laboratory experiments [G. Raffelt, Phys. Rev. D 86, 015001 (2012)].

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

Summary

- Performed a experimental search for the Yukawa-type forces at the micrometer range.
- Constraints were derived without the need to subtracting the Casimir and electrostatic force background.

- Derived the constraints on the pseudoscalar and pseudovector coupling between electrons by analyzing the ESR-STM data.
- The constraints on the pseudovector coupling are the strongest for bosons with mass range from 1 eV to 20 eV.

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Dr. Wenjie Wu
Jihua Ding
Huixing Fu
Xiaofang Ren
Zhaoyang Tian
……

Institute of Physics, CAS:

Dr. Aizi Jin

SPBSTU, Saint Petersburg:

Prof. G. Klimchitskaya
Prof. V. Mostepaneko

Micrometer range experiment

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

Parameter	Value	Error	Units
Parameters in force measurement			
Effective spring constant (k)	1.3	0.2	mN/m
Interferometer sensitivity (S_{int})	12.0	0.9	nm/V
Other parameters			
Separation (d)	905	54	nm
Test mass radius (R)	13.7	0.1	μm
Silicon mass width (W_{Si})	5.9	0.2	μm
Gold mass width (W_{Au})	6.3	0.2	μm
Electroplated gold density (ρ_{Au})	19.1	0.9	g/cm^3
Source mass depth (t)	3.3	0.1	μm
Drive amplitude (A_d)	18.4	0.1	μm
Tilt about the y-axis (θ_y)	0.0	0.7	mrad