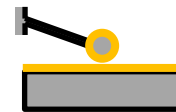
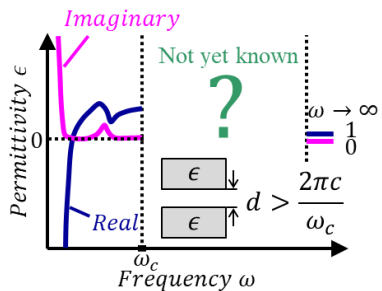


# Study of Casimir forces

## - Computation and experimental setup -



H. Iizuka and S. Fan, Phys. Rev. B 110, 235409 (2024).

## Hideo Iizuka

International Center for Quantum-field Measurement  
Systems for Studies of the Universe and Particles (QUP)



# Outline

Brief overview of Casimir forces

Casimir force computation

Status of experimental setup

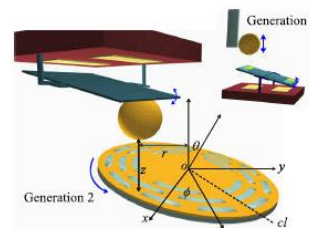
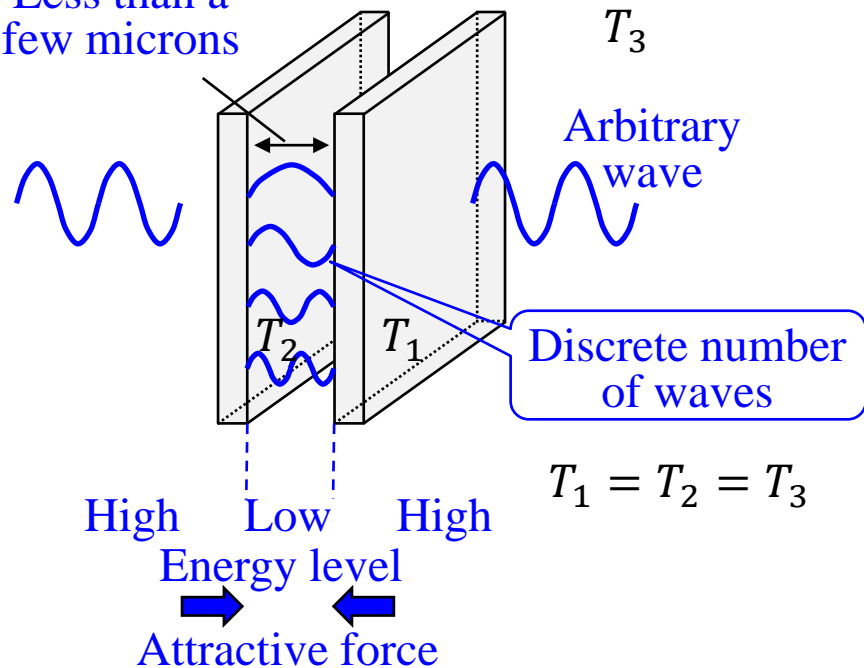
Conclusion

# Casimir forces and possible applications

New quantum field search

Equilibrium Casimir force  
(Attractive in vacuum)

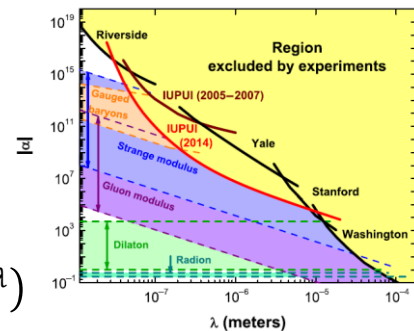
Less than a  
few microns



Yukawa type new force

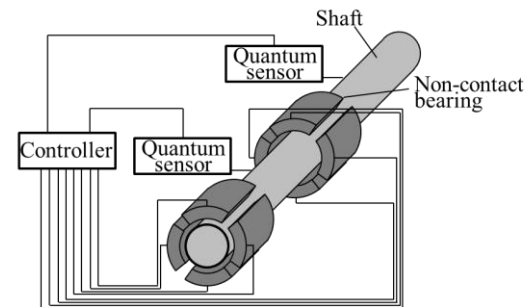
$$V(r) = -G \frac{m_1 m_2}{r} (1 + \alpha e^{-r/\lambda})$$

PRL 116, 221102(2016)



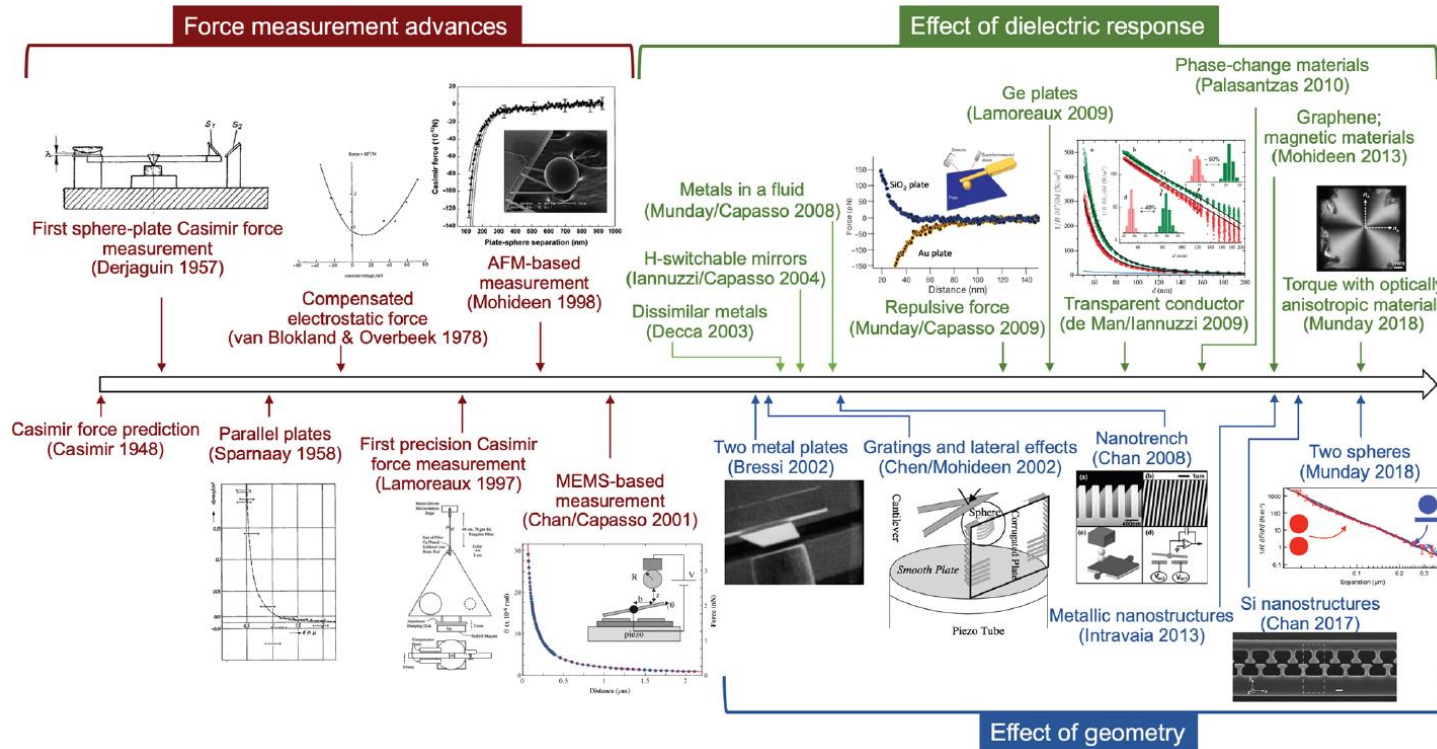
Industry/Social implementation

Non-contact shaft-bearing system

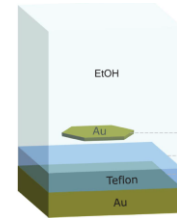


Note: The plates consist of reciprocal materials.

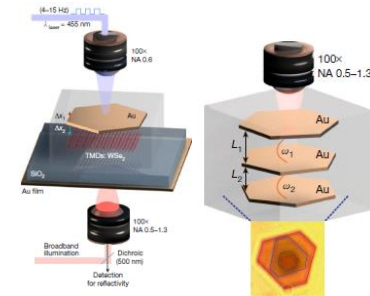
# History of Casimir force research



## Past few years



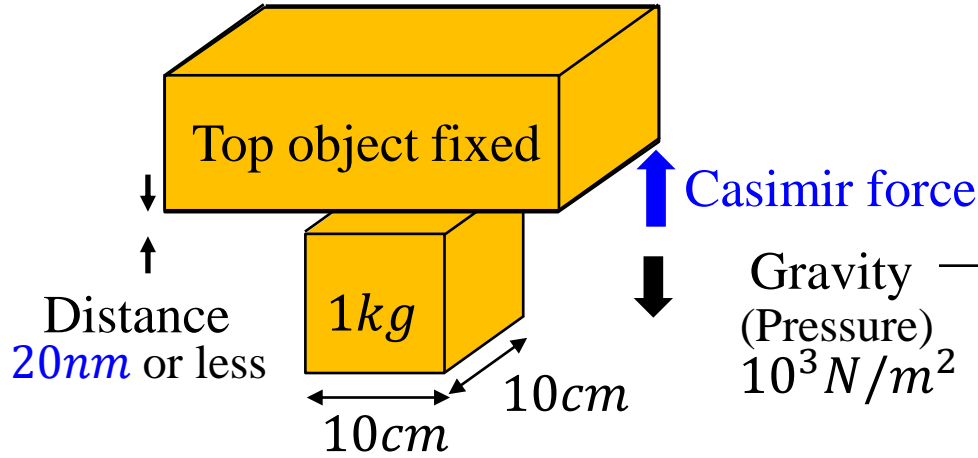
Levitation in liquid  
[Science 364, 984 (2019)]



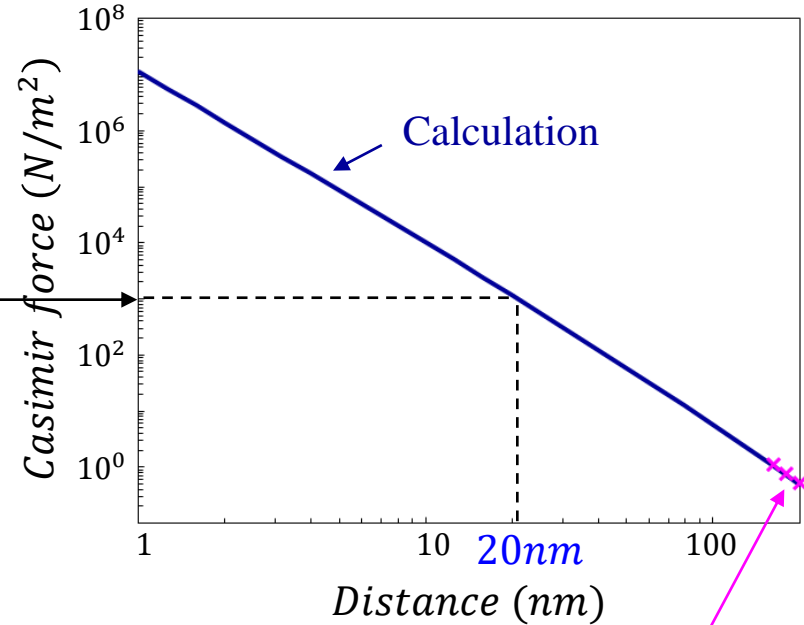
Active control, many-body in liquid  
[Nature, 597, 214 (2021)]

T. Gong, M. R. Corrado, A. R. Mahbub, C. Shelden, and J. N. Munday, *Nanophotonics* 10, 523 (2021).  
J. N. Munday, KEK IPNS-IMSS-QUP joint workshop Feb. 8-10, 2022.

# How large is Casimir force?



The bottom object moves up!

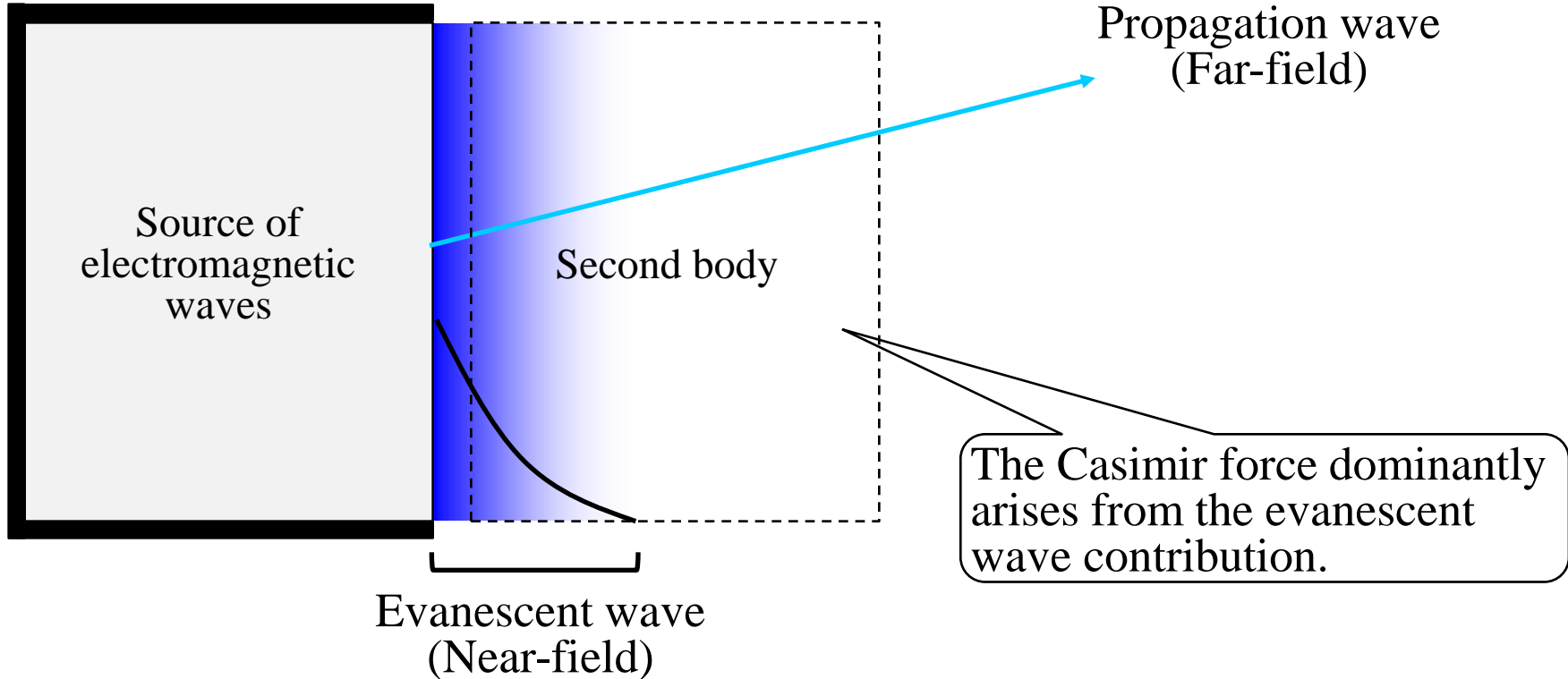


$$\text{Gravity: } 10\text{N} = 1\text{kg} \times 10\text{m/s}^2$$

$$\text{Pressure: } 10^3\text{N/m}^2 = \frac{10\text{N}}{0.1\text{m} \times 0.1\text{m}}$$

# Propagation and evanescent waves

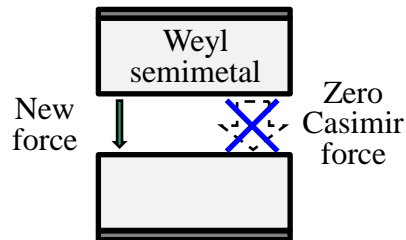
The propagation wave goes away from the electromagnetic source.  
The evanescent wave stays around the electromagnetic source.



# Our Casimir force research

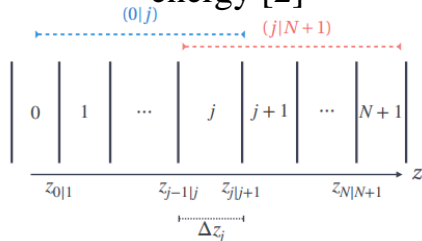
## Particle physics

New force search via zero Casimir force[1]



[1] Y. Ema, M. Hazumi, H. Iizuka, K. Mukaida, and K. Nakayama, Phys. Rev. D 108, 016009 (2023).

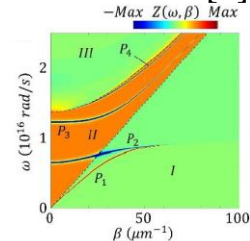
## Multilayers in Casimir energy [2]



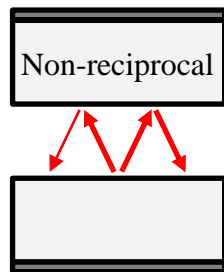
[2] K. Mukaida, H. Iizuka, and K. Nakayama, arXiv:2503.03853 (2025).

## Fundamental understanding

Casimir force is insensitive to material loss [3]



Symmetry argument in Casimir forces [5]



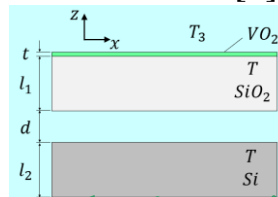
[3] H. Iizuka and S. Fan, J. Optical Society of America B 36, 2981 (2019).

[4] H. Iizuka and S. Fan, J. Optical Society America B 38, 151–158 (2021).

[5] H. Iizuka and S. Fan, Phys. Rev. B 108, 075429 (2023).

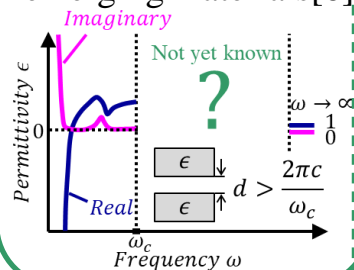
[6] H. Iizuka and S. Fan, Phys. Rev. B 110, 235409 (2024).

Exterior control of non-equilibrium Casimir force [4]



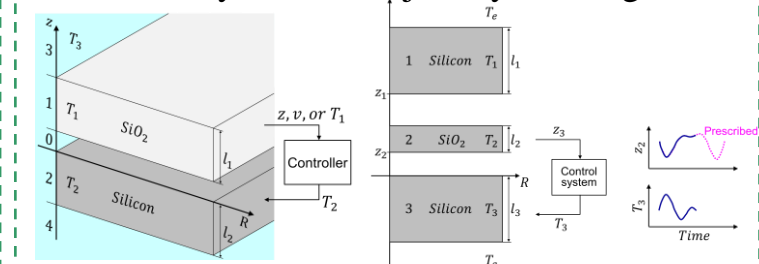
## Today's topic

Casimir force computation for emerging materials[6]

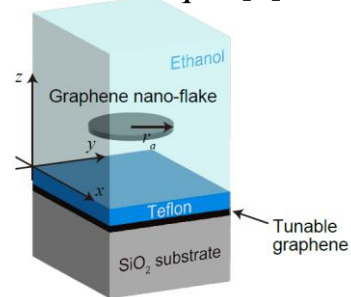


## Toward industry

Dynamic control of Casimir forces in vacuum



Dynamic control of Casimir forces in liquid[9]



[7] H. Iizuka and S. Fan, Applied Physics Letters 118, 144001 (2021).

[8] H. Iizuka and S. Fan, J. Quantitative Spectroscopy Radiative Transfer 289, 108281 (2022).

[9] H. Toyama, T. Ikeda, and H. Iizuka, Phys. Rev. B 108, 245402 (2023).

# Outline

Brief overview of Casimir forces

**Casimir force computation**

Status of experimental setup

Conclusion

# Weyl semimetals for Casimir forces

Non-reciprocal materials

InSb



Magnetic Weyl semimetals



$$\hat{\epsilon}^A = \begin{bmatrix} \epsilon_d & i\epsilon_f \\ -i\epsilon_f & \epsilon_d \\ & \epsilon_p \\ & \epsilon_d \end{bmatrix}$$

S-polarization



$\mathbf{k}$

P-polarization



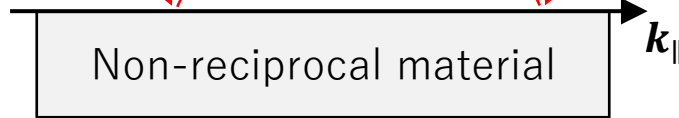
$\mathbf{k}$

Incident wave

$\hat{R}(\mathbf{k}_{\parallel})$

$\hat{R}(-\mathbf{k}_{\parallel})$

Vacuum



Non-reciprocal material

Proposal of QUP:  
New force search via zero Casimir force[1]

Weyl semimetal  
(Ideal case)

New force

~~Zero Casimir force~~

Reciprocity can be violated.

$$\hat{R}(-\mathbf{k}_{\parallel}) \neq \hat{\sigma}_z \hat{R}^T(\mathbf{k}_{\parallel}) \hat{\sigma}_z$$

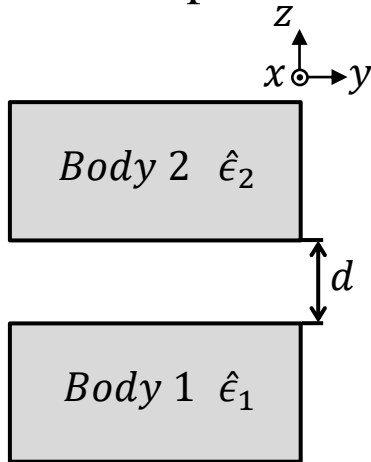
$$\left( \hat{R}(\mathbf{k}_{\parallel}) = \begin{bmatrix} R^{s \rightarrow s} & R^{p \rightarrow s} \\ R^{s \rightarrow p} & R^{p \rightarrow p} \end{bmatrix}, \hat{\sigma}_z = \begin{bmatrix} 1 & \\ & -1 \end{bmatrix} \right)$$

[1] Y. Ema, M. Hazumi, H. Iizuka, K. Mukaida, and K. Nakayama, Phys. Rev. D 108, 016009 (2023).

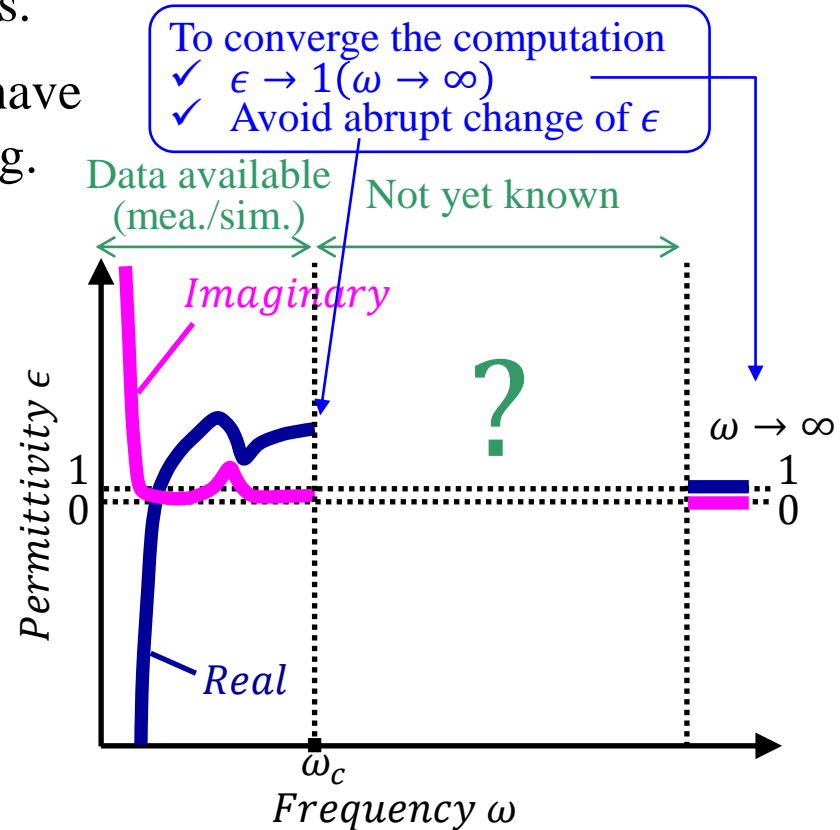
# Challenge in Casimir force computation

Casimir force computation, in principle, needs very wide frequency range of material permittivities.

However, most of emerging materials do not have high frequency range of their permittivities, e.g. Weyl semimetals up to 1eV.



Can we compute Casimir forces?



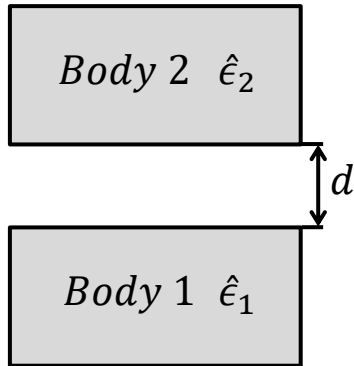
# Accurate computation is possible!

Suppose available material permittivities up to cutoff frequency  $\omega_c$ .

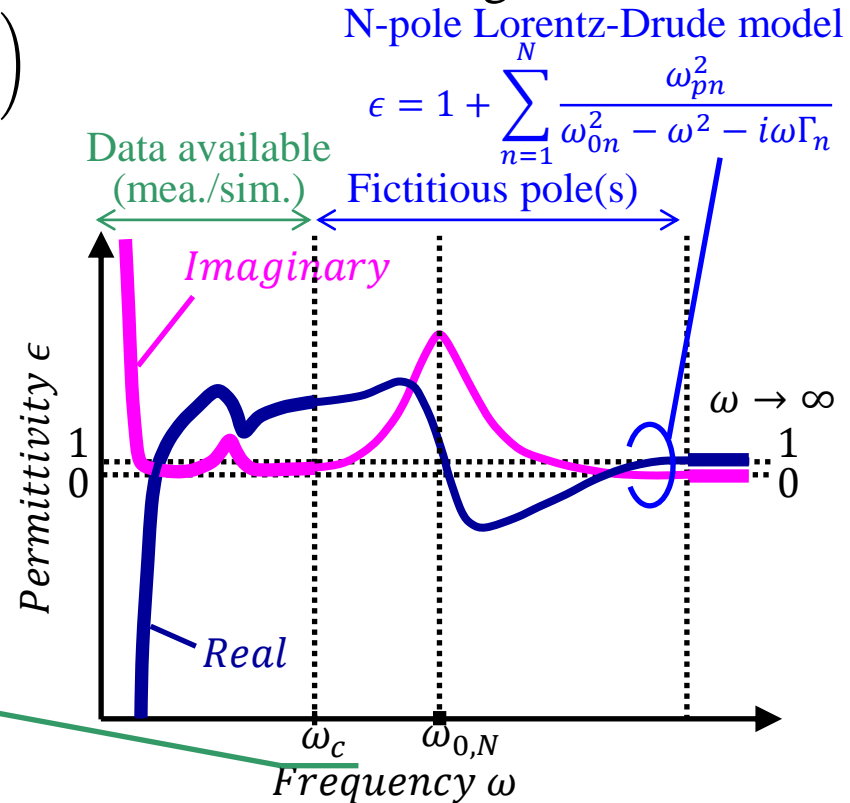
The Casimir force can be accurately computed for the distance range

$$d > \lambda_c \left( = \frac{2\pi c}{\omega_c} \right)$$

Casimir forces should be independent of fictitious pole(s).



Cutoff frequency



# Case I, Isotropic material (typical metal)

Plasma

frequency

1<sup>st</sup> pole fixed2<sup>nd</sup> pole varied

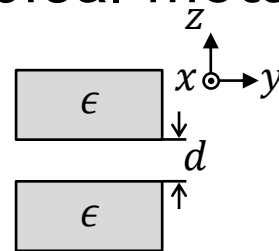
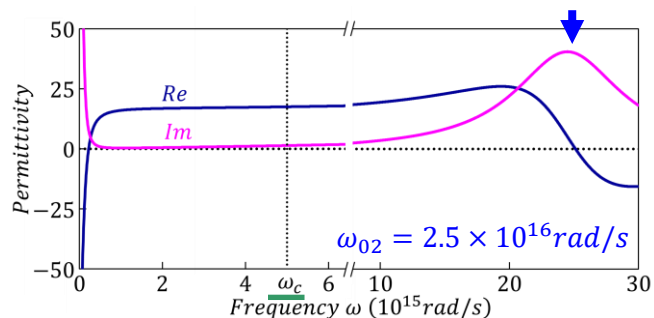
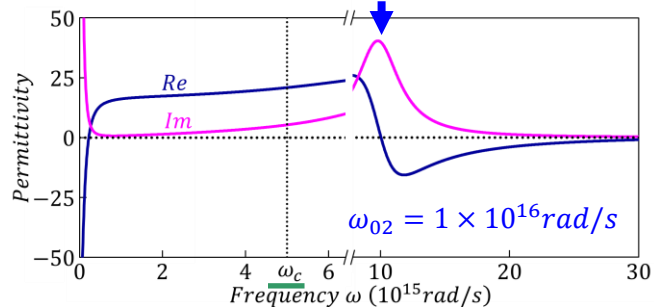
$$\epsilon = 1 + \frac{\omega_{p1}^2}{\omega_{01}^2 - \omega^2 - i\omega\Gamma_1} + \frac{\omega_{p2}^2}{\omega_{02}^2 - \omega^2 - i\omega\Gamma_2}$$

Resonant frequency

Loss rate

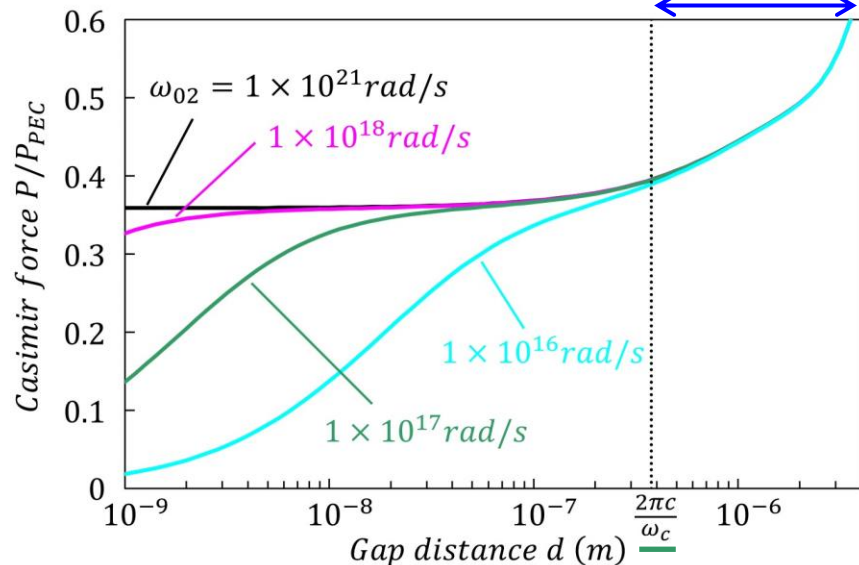
Fictitious pole

Two permittivity examples



The Casimir force is independent of the fictitious pole  $\omega_{02}$ !

$$d > \lambda_c \left( = \frac{2\pi c}{\omega_c} \right)$$



(1<sup>st</sup> pole:  $\omega_{01} = 0$ ,  $\omega_{p1} = 1 \times 10^{15}$  rad/s,  $\Gamma_1 = 1 \times 10^{14}$  rad/s, 2<sup>nd</sup> pole:  $\omega_{p2} = 4\omega_{02}$ , and  $\Gamma_2 = 0.4\omega_{02}$ , Ref. force:  $P_{PEC} = \frac{\hbar c \pi^2}{240 d^4}$ )

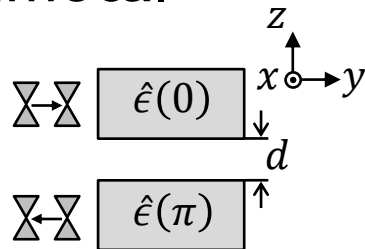
# Case II, Weyl semimetal

$$\hat{\epsilon} = \begin{bmatrix} \epsilon_d & 0 & -i\epsilon_a \\ 0 & \epsilon_d & 0 \\ i\epsilon_a & 0 & \epsilon_d \end{bmatrix}$$

$$\epsilon_d = 1 + \frac{\omega_{p1}^2}{\omega_{01}^2 - \omega^2 - i\omega\Gamma_1} + \frac{\omega_{p2}^2}{\omega_{02}^2 - \omega^2 - i\omega\Gamma_2}$$

Fictitious pole

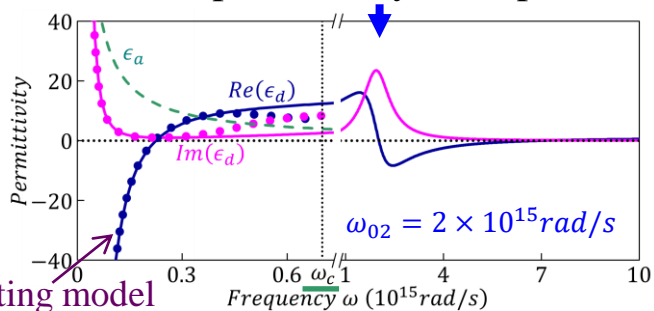
$$\epsilon_a = \frac{2\pi^2\epsilon_0\hbar\omega}{b e^2}$$



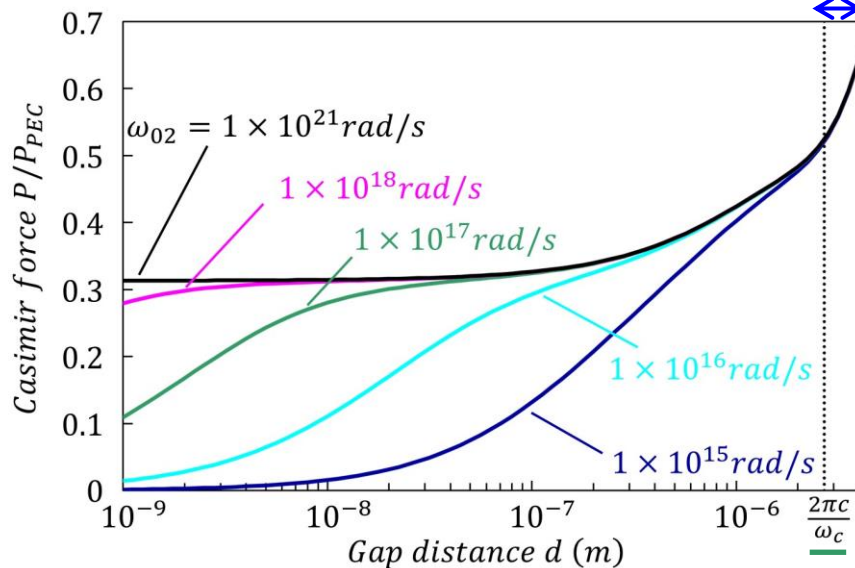
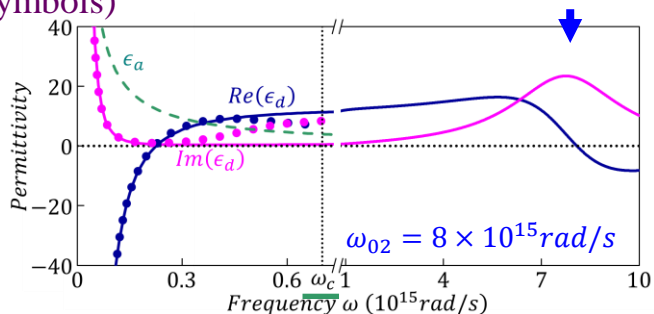
The Casimir force is independent of the fictitious pole  $\omega_{02}$ !

$$d > \lambda_c \left( = \frac{2\pi c}{\omega_c} \right)$$

Two permittivity examples



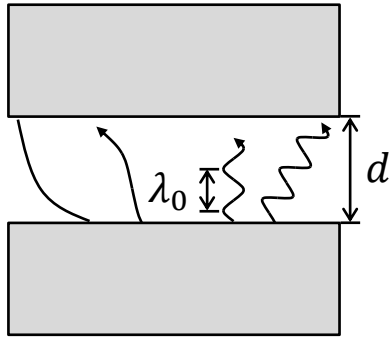
Existing model (symbols)



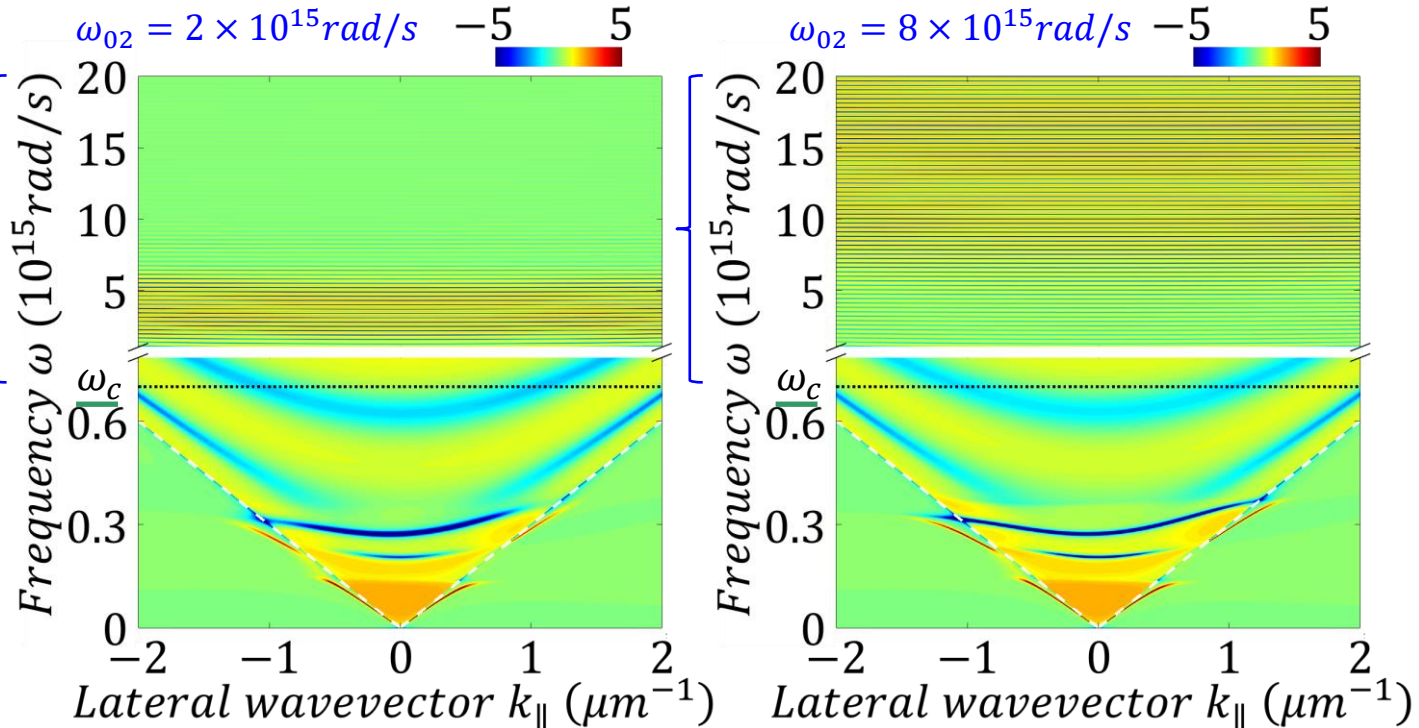
$$(\omega_{01} = 0, \omega_{p1} = 8 \times 10^{14} \text{ rad/s}, \Gamma_1 = 7 \times 10^{12} \text{ rad/s}, \omega_{p2} = 3.4\omega_{02}, \Gamma_2 = 0.5\omega_{02}, b = 2 \times 10^9 \text{ m}^{-1} \text{ and } P_{PEC} = \frac{\hbar c \pi^2}{240 d^4})$$

# Cancellation of force components in high frequency

In high frequency range, Casimir force components have positive and negative values, resulting in cancellation and negligible contribution.



$$d > \lambda_c \left( = \frac{2\pi c}{\omega_c} \right)$$



# Outline

Brief overview of Casimir forces

Casimir force computation

**Status of experimental setup**

Conclusion

# Experimental setup of Casimir forces

Our Casimir force experimental setup is going on in the QUP satellite of Toyota Central R&D Labs.

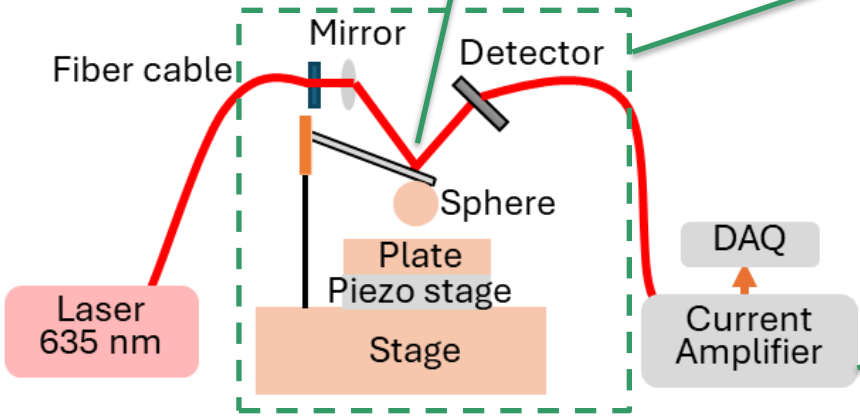
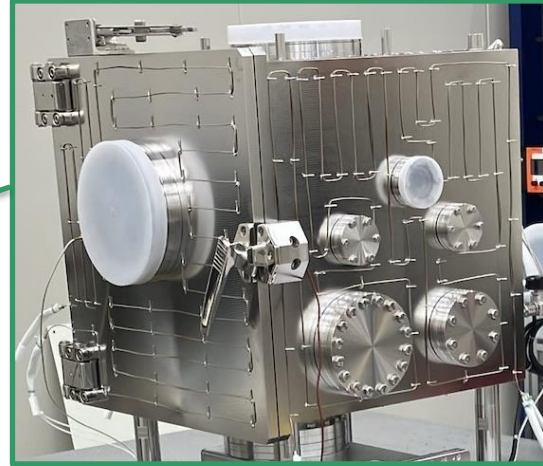


Shrinathan E. M. Pandara Kone  
(Toyota Central R&D Labs. )

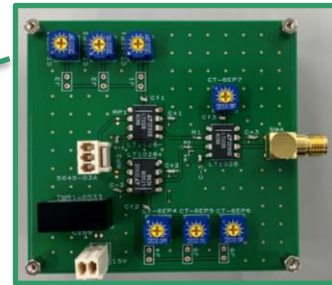
Laser spot on the cantilever



Vacuum chamber,  $10^{-7}$  Torr



Collaborator: Prof. Pramod Reddy  
(Univ. Michigan)



# Strategy toward new force search

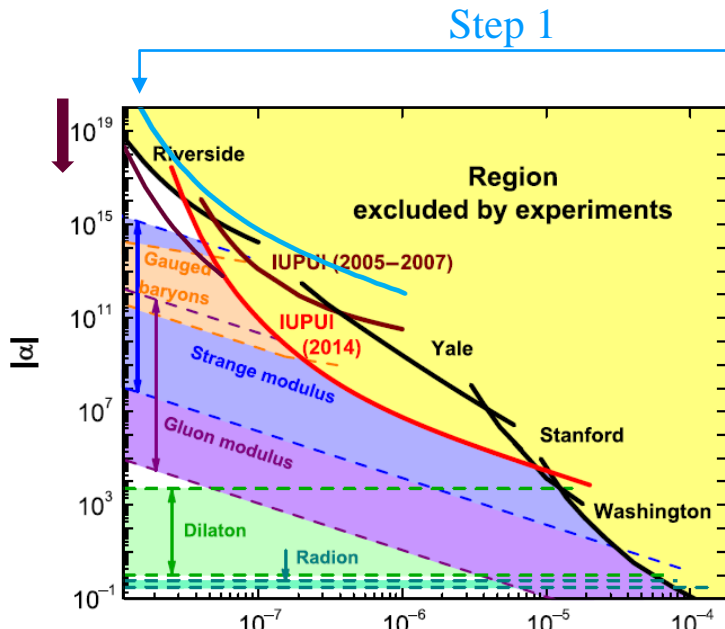
Step 2 target:

3-order improvement via

- Lock-in amp.

- Materials

etc.



Yukawa type new force  $\lambda$  (meters)

$$V(r) = -G \frac{m_1 m_2}{r} (1 + \alpha e^{-r/\lambda})$$

PRL 116, 221102(2016)

Step 1:  
Reproduce PRA 2000 result (Dec. 2025).

PHYSICAL REVIEW A, VOLUME 62, 052109

## Precision measurement of the Casimir force using gold surfaces

B. W. Harris, F. Chen, and U. Mohideen  
 Department of Physics, University of California, Riverside, California 92521  
 (Received 19 May 2000; published 17 October 2000)

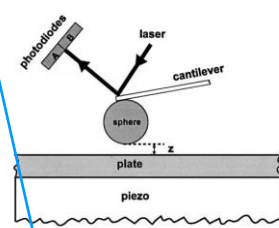


FIG. 1. Schematic diagram of the experimental setup. Application of voltage to the piezoelectric tube results in the movement of the plate toward the sphere. A force on the sphere leads to flexing of the cantilever.

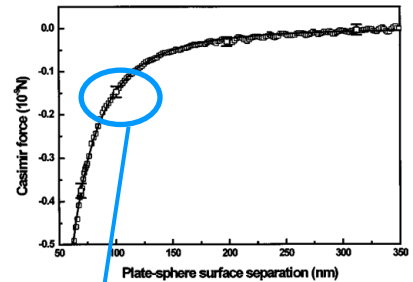
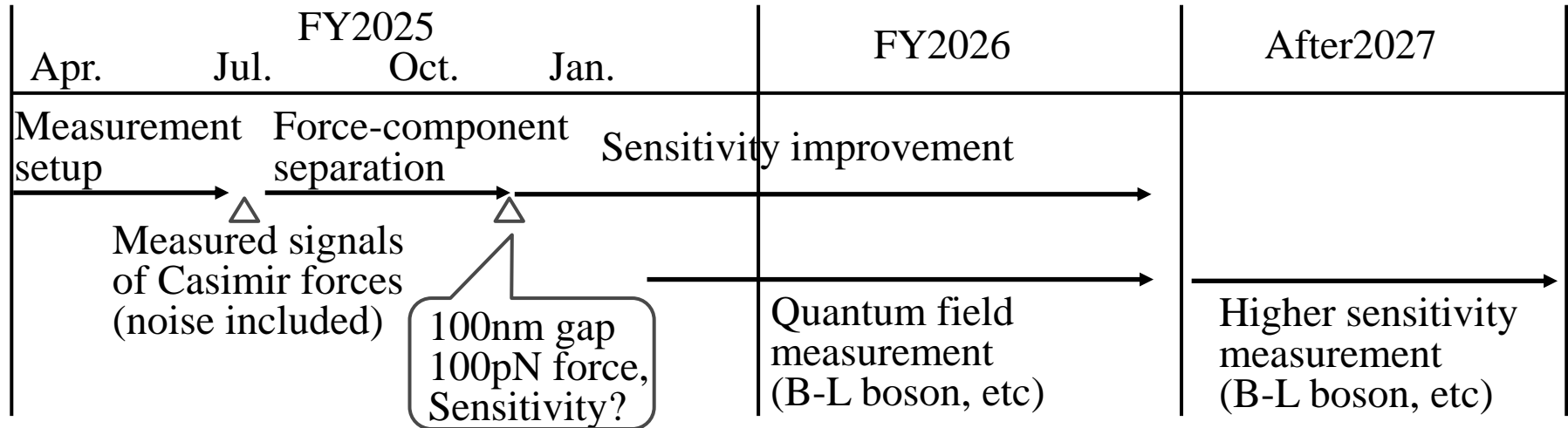
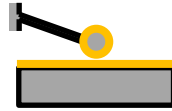


FIG. 5. The measured average Casimir force as a function of plate-sphere separation is shown as squares. For clarity, only 10% of the experimental points are shown in the figure. The error bars represent the standard deviation from 30 scans. The solid line is the theoretical Casimir force from Eq. (2).

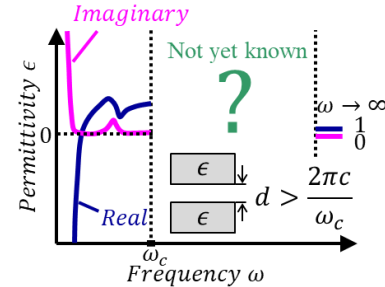
Force: 100pN  
 Force sensitivity: 10pN (error bar)  
 at a 100nm gap

# FY25–27 plan, Casimir forces



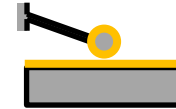
# Conclusions

A Casimir force computation method has been presented for plate materials that lack their permittivities in high frequencies.



H. Iizuka and S. Fan, Phys. Rev. B 110, 235409 (2024).

The experimental setup for Casimir force is going on.



# Acknowledgement

This work was supported by World Premier International Research Center Initiative (WPI), MEXT, Japan. I sincerely thank my collaborators and colleagues for conducting researches together.

Prof. Shanhui Fan (Stanford Univ.), Prof. Pramod Reddy (Univ. Michigan), Dr. Shrinathan E. M. Pandara Kone (Toyota Central R&D Labs), Dr. Kenichi Yatsugi (Toyota Central R&D Labs), Dr. Kyohei Mukaida (KEK), Dr. Yohei Ema (Univ. Minnesota), Prof. Kazunori Nakayama (Tohoku Univ./QUP), Masashi Hazumi (KEK)