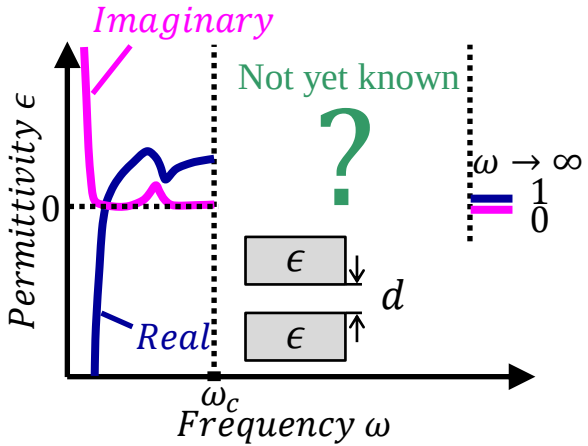
Casimir force computation for emerging materials

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



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

Outline

Brief overview of Casimir forces

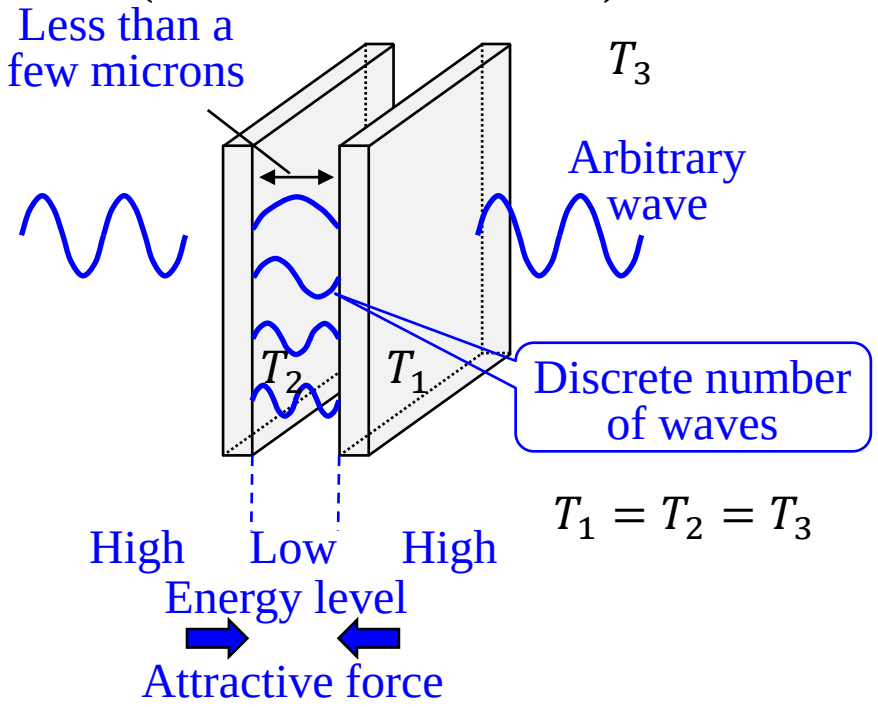
Casimir force computation

Status of experimental setup

Conclusion

Casimir forces and possible applications

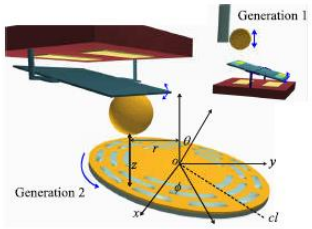
Equilibrium Casimir force (Attractive in vacuum)

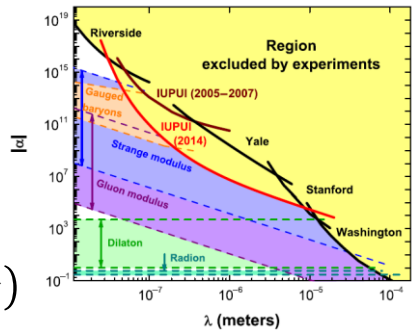


Note: The plates consist of reciprocal materials.

New quantum field search

PRL 116, 221102(2016)



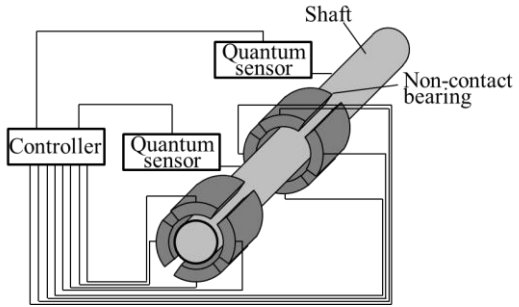


Yukawa type new force

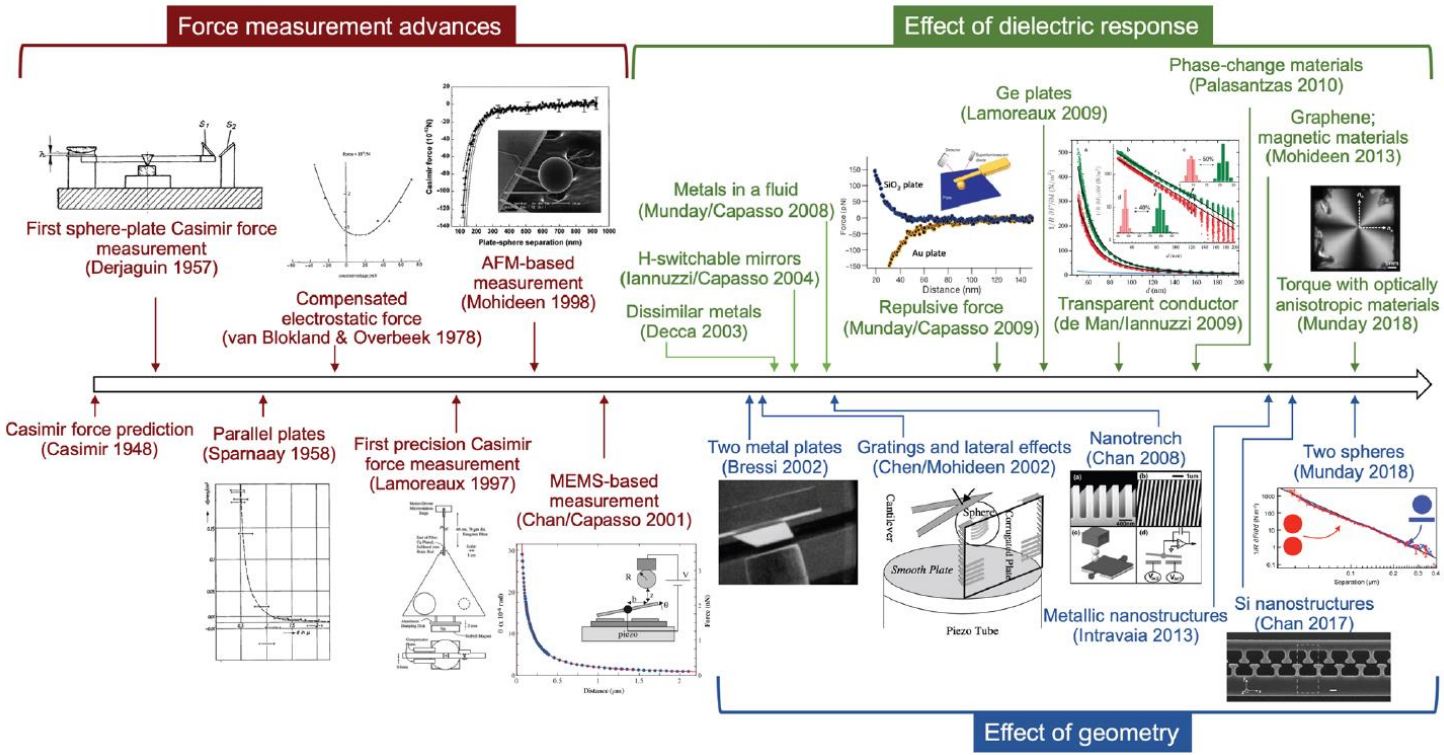
$$V(r) = -G\frac{m_1 m_2}{r}\left(1 + \alpha e^{-r/\lambda}\right)$$

Industry/Social implementation

Non-contact shaft-bearing system

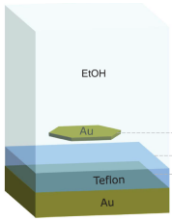


History of Casimir force research

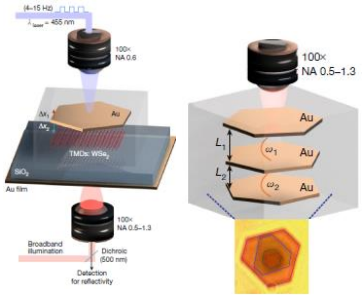


T. Gong, M. R. Corrado, A. R. Mahbub, C. Shelden, and J. N. Munday, Nanophotonics 10, 523 (2021).
J. N. Munday, KEK IPNS-IMSS-QUP joint workshop Feb. 8-10, 2022.

Past few years

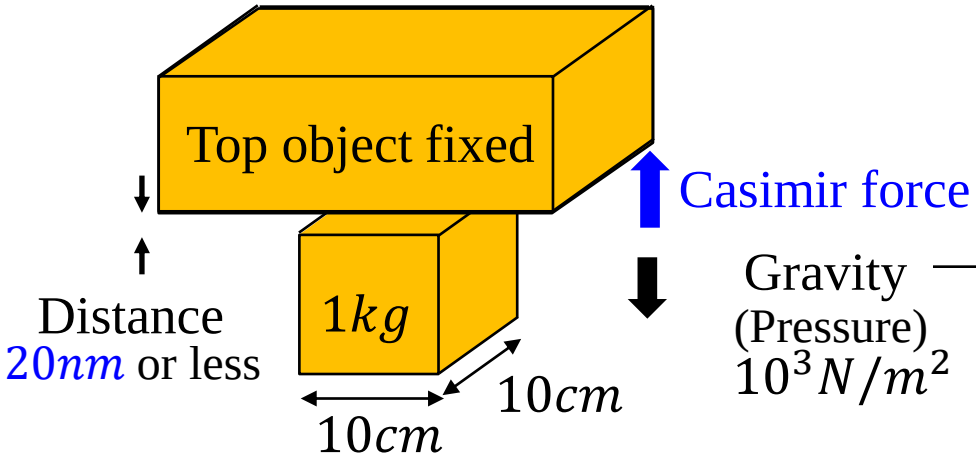


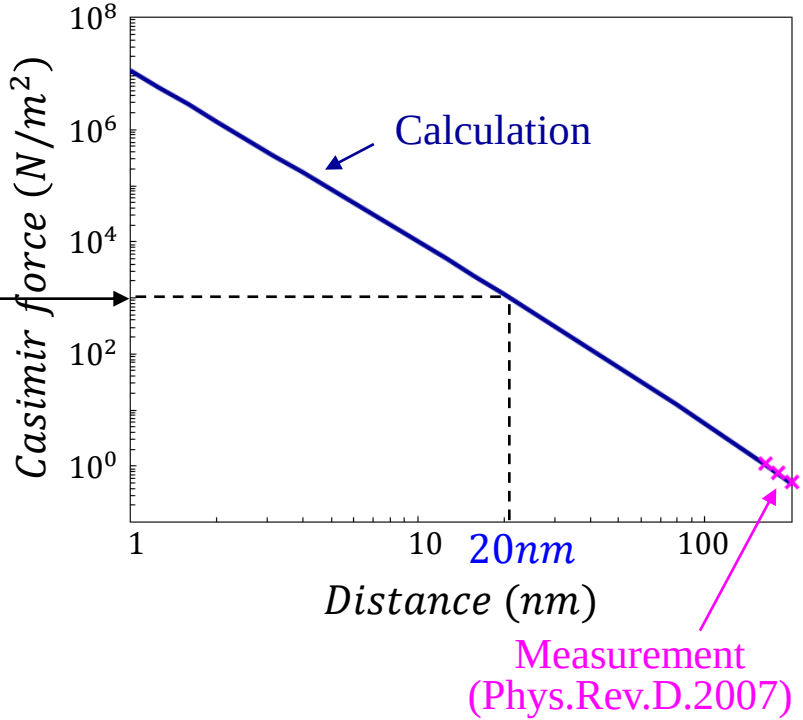
Levitation in liquid
[Science 364, 984 (2019)]



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

How large is Casimir force?





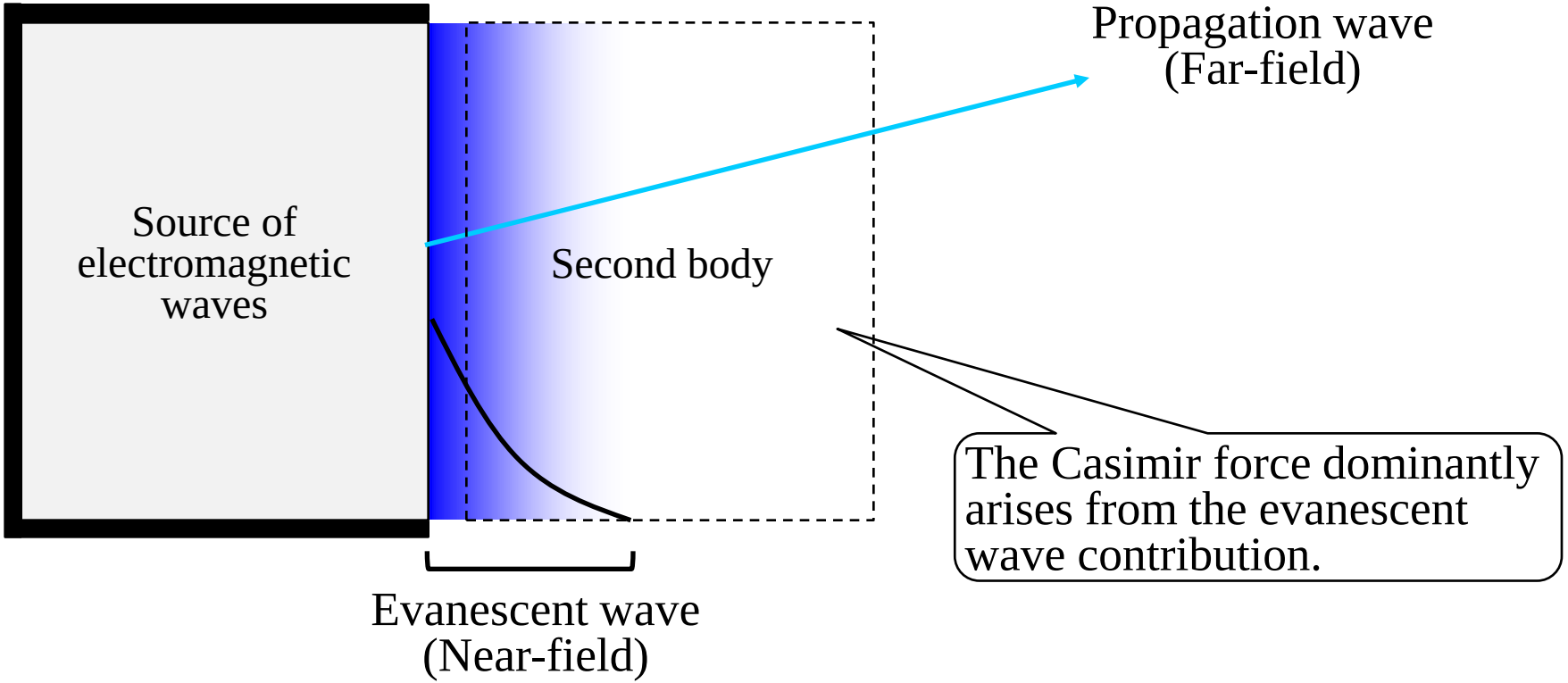
The bottom object moves up!

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

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

Propagation and evanescent waves

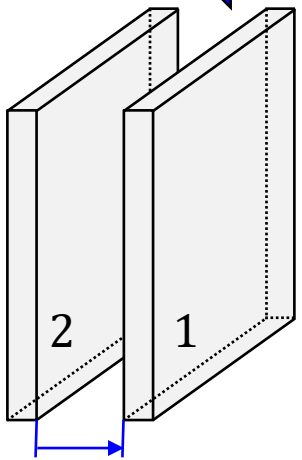
The propagation wave goes away from the electromagnetic source.
The evanescent wave stays around the electromagnetic source.



Stable and unstable Casimir force systems

When attractive and repulsive force components acting on body 1 are balanced, zero-force position can exist.

Attractive force ⟵ ⟶ Repulsive force

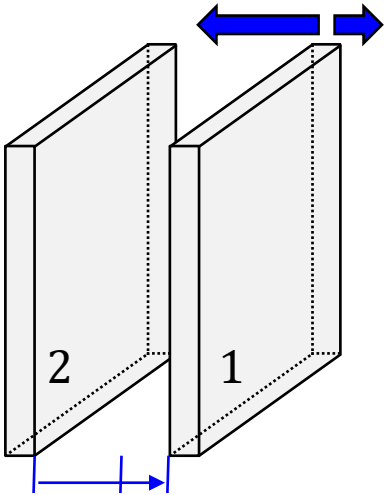


z_0

Zero-force position

Stable

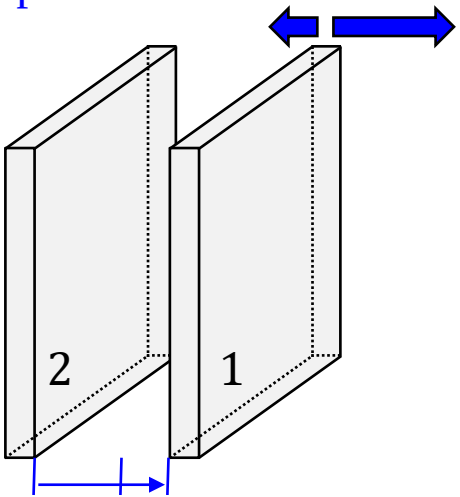
Attractive force is enhanced.



$z_0 + \Delta z$

Unstable

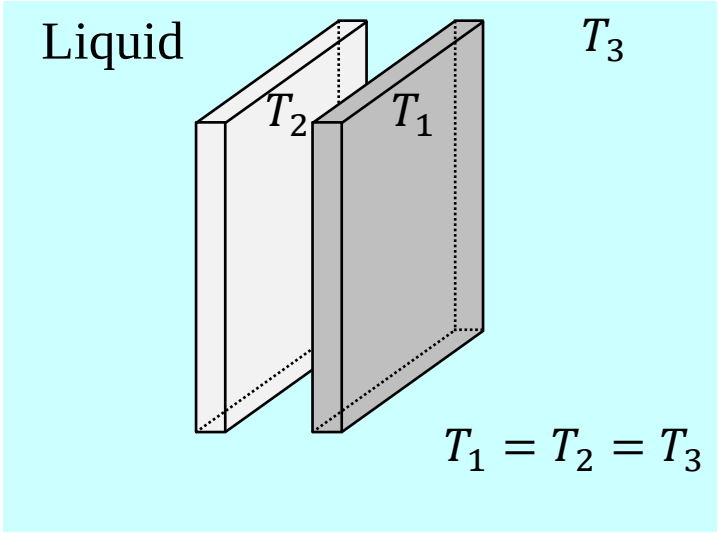
Repulsive force is enhanced.



$z_0 + \Delta z$

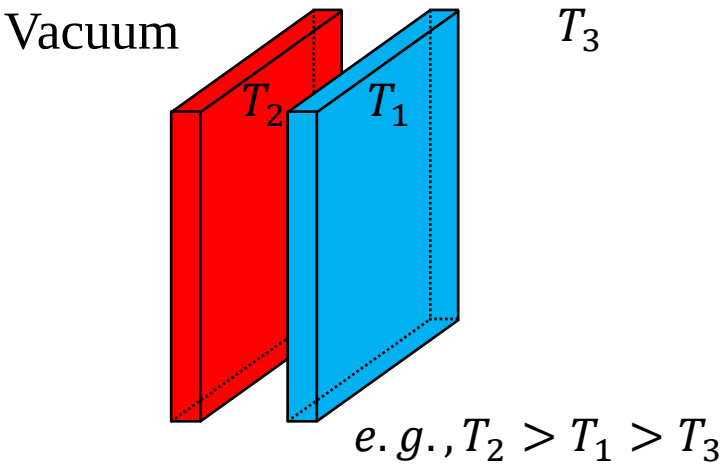
Examples of stable and unstable systems

Equilibrium Casimir force in liquid
(Can be stable)



[See *Science* 364, 984 (2019)]

Non-equilibrium Casimir force in vacuum
(Unstable)

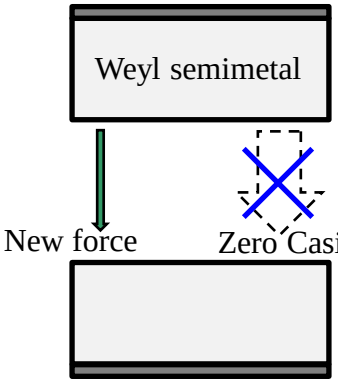


Note: The plates consist of reciprocal materials.

Our Casimir force research

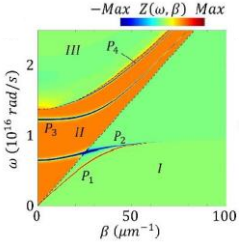
Particle physics

New force search via zero Casimir force[1]

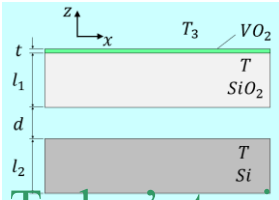


Fundamental understanding

Casimir force is insensitive to material loss [2]

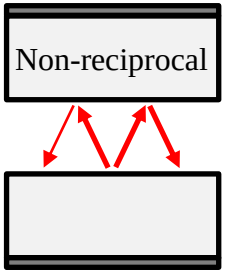


Exterior control of non-equilibrium Casimir force [3]

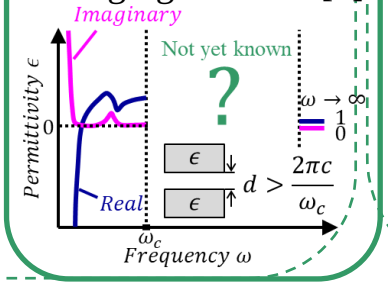


Today's topic

Symmetry argument in Casimir forces [4]



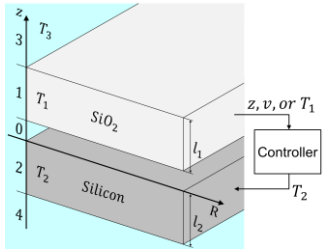
Casimir force computation for emerging materials[5]



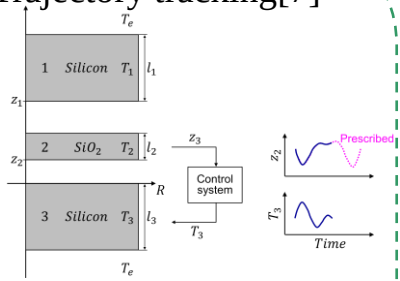
Toward industry

Dynamic control of Casimir forces in vacuum

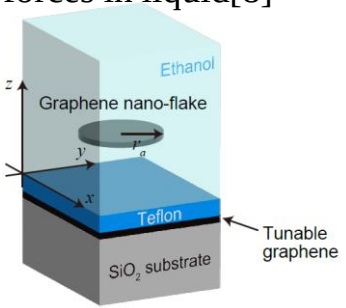
Control theory[6]



Trajectory tracking[7]



Dynamic control of Casimir forces in liquid[8]



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

[2] H. Iizuka and S. Fan, J. Optical Society of America B 36, 2981 (2019).
[3] H. Iizuka and S. Fan, J. Optical Society America B 38, 151–158 (2021).
[4] H. Iizuka and S. Fan, Phys. Rev. B 108, 075429 (2023).
[5] H. Iizuka and S. Fan, Phys. Rev. B 110, 235409 (2024).

[6] H. Iizuka and S. Fan, Applied Physics Letters 118, 144001 (2021).
[7] H. Iizuka and S. Fan, J. Quantitative Spectroscopy Radiative Transfer 289, 108281 (2022).
[8] H. Toyama, T. Ikeda, and H. Iizuka, Phys. Rev. B 108, 245402 (2023).

Outline

Brief overview of Casimir forces

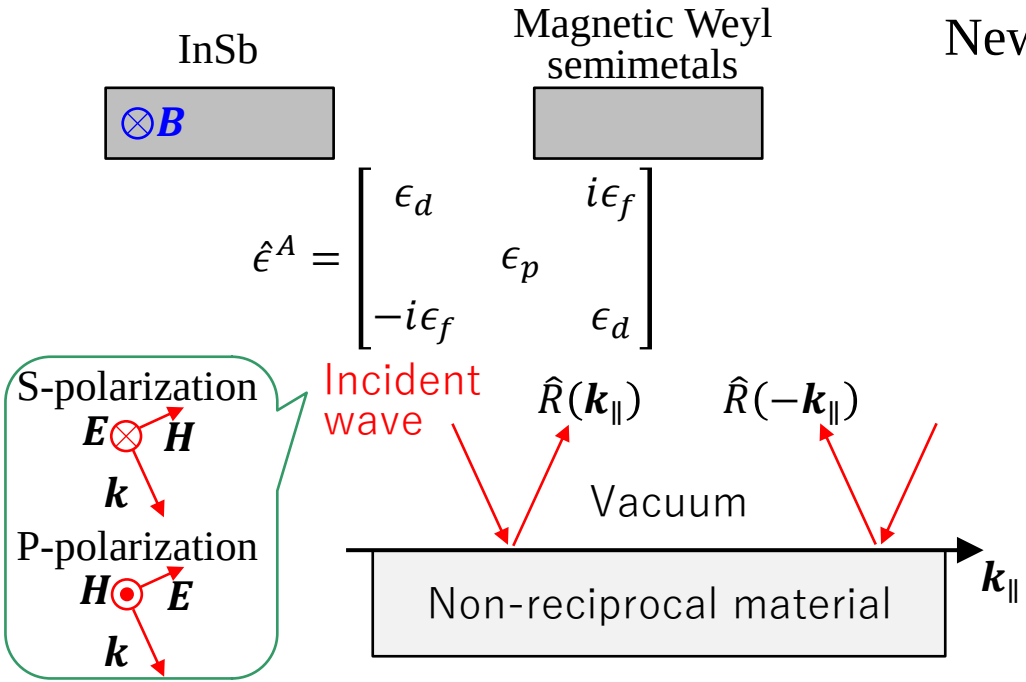
Casimir force computation

Status of experimental setup

Conclusion

Weyl semimetals for Casimir forces

Non-reciprocal materials

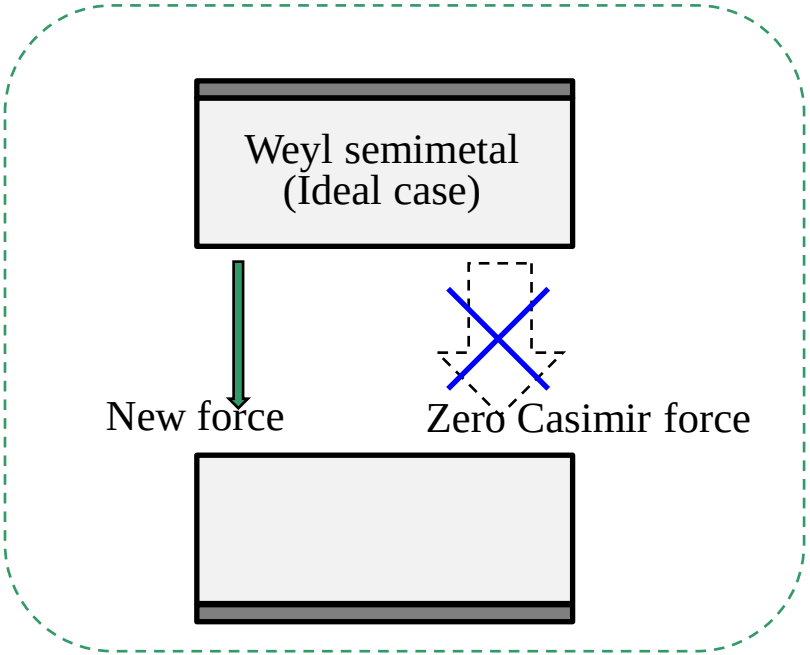


Reciprocity can be violated.

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

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

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

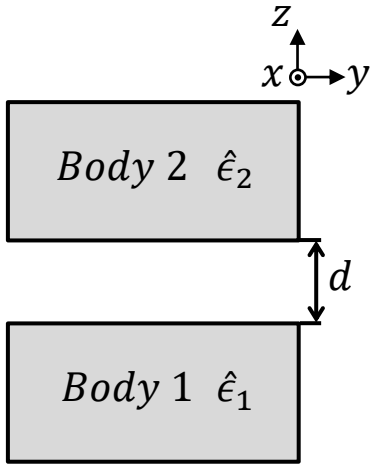


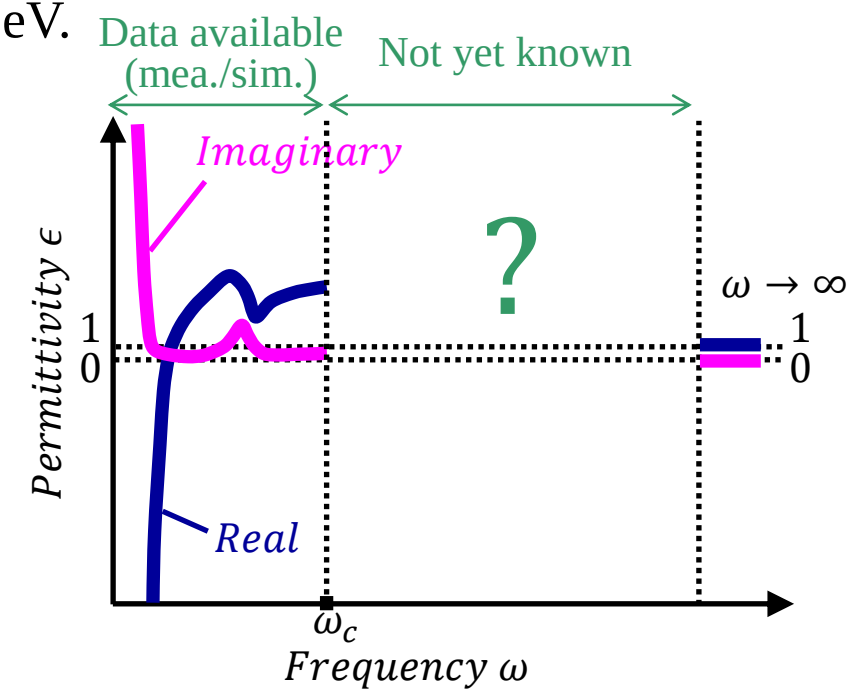
[1] Y. Ema, M. Hazumi, H. Iizuka, K. Mukaida, and K. Nakayama, Phys. Rev. D 108, 016009 (2023).

Challenge

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.

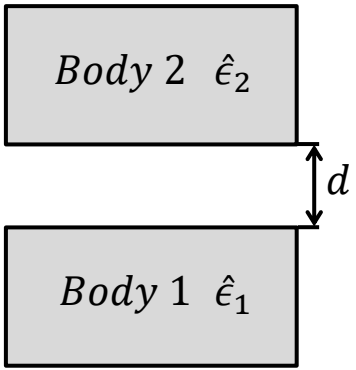


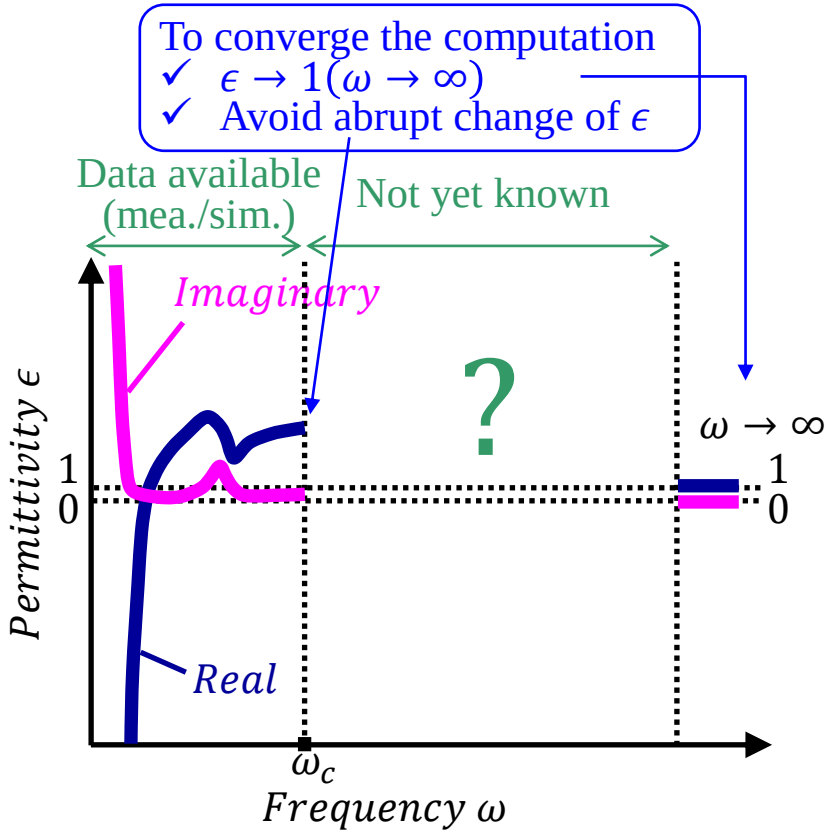


Can we compute Casimir forces?

Objective

To establish a Casimir force computation method for plate materials that lack their permittivities in high frequencies.



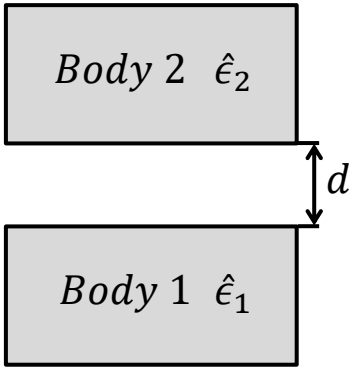


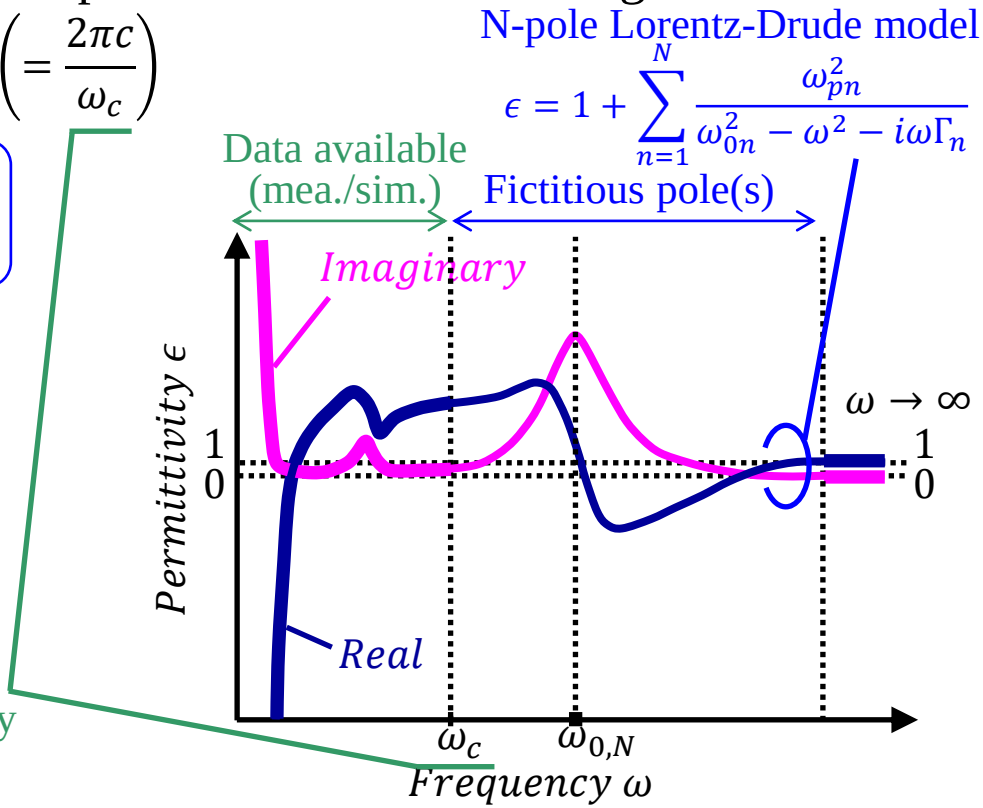
Main result

Suppose available material permittivities up to cutoff frequency ω_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).





Case I, Isotropic material (typical metal)

Plasma frequency

1st pole fixed

2nd pole varied

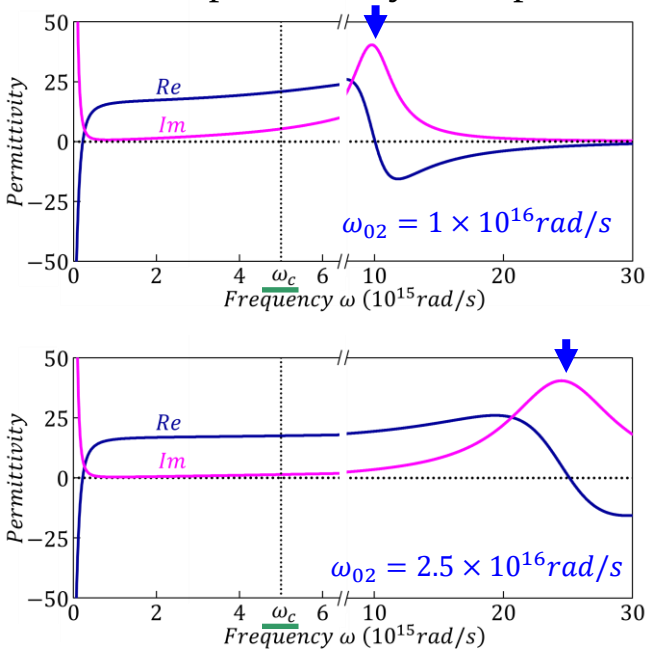
$$\epsilon = 1 + \frac{\omega_{p1}^2}{\omega_{01}^2 - \omega^2 - i\omega\Gamma_1} + \frac{\omega_{p2}^2}{\omega_{02}^2 - \omega^2 - i\omega\Gamma_2}$$

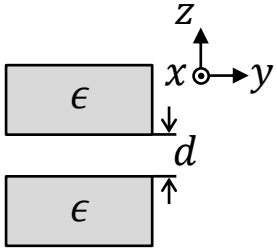
Resonant frequency

Loss rate

Fictitious pole

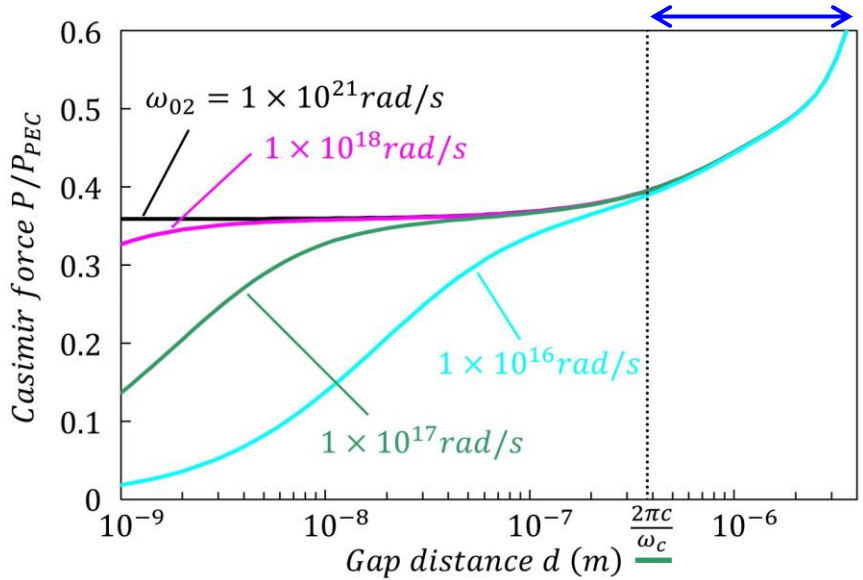
Two permittivity examples





The Casimir force is independent of the fictitious pole ω_{02}!

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



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

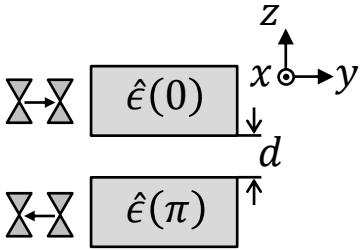
Case II, Weyl semimetal

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

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

Fictitious pole

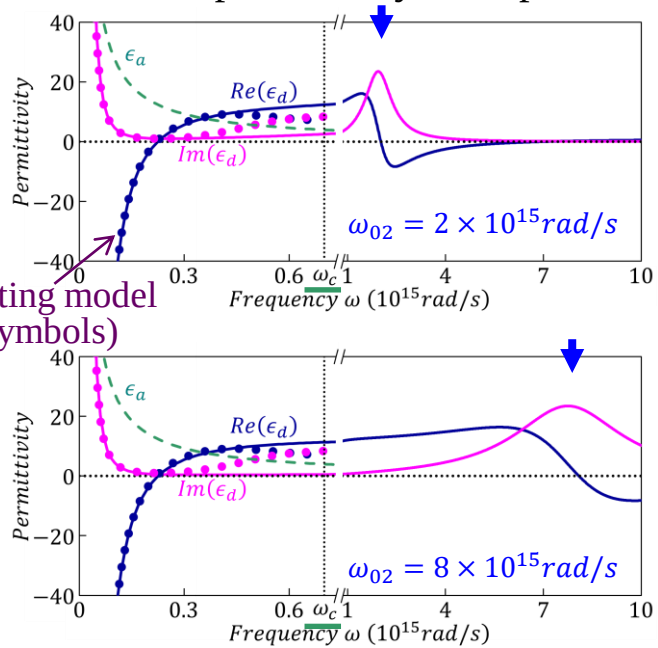
$$\epsilon_a = \frac{be^2}{2\pi^2\epsilon_0\hbar\omega}$$

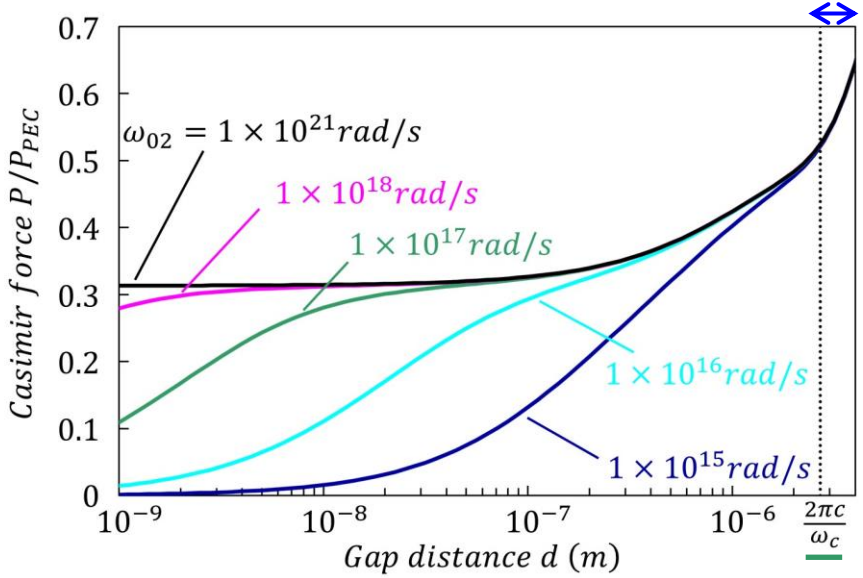


The Casimir force is independent of the fictitious pole ω_{02}!

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

Two permittivity examples

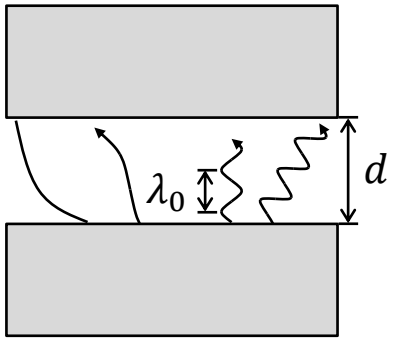




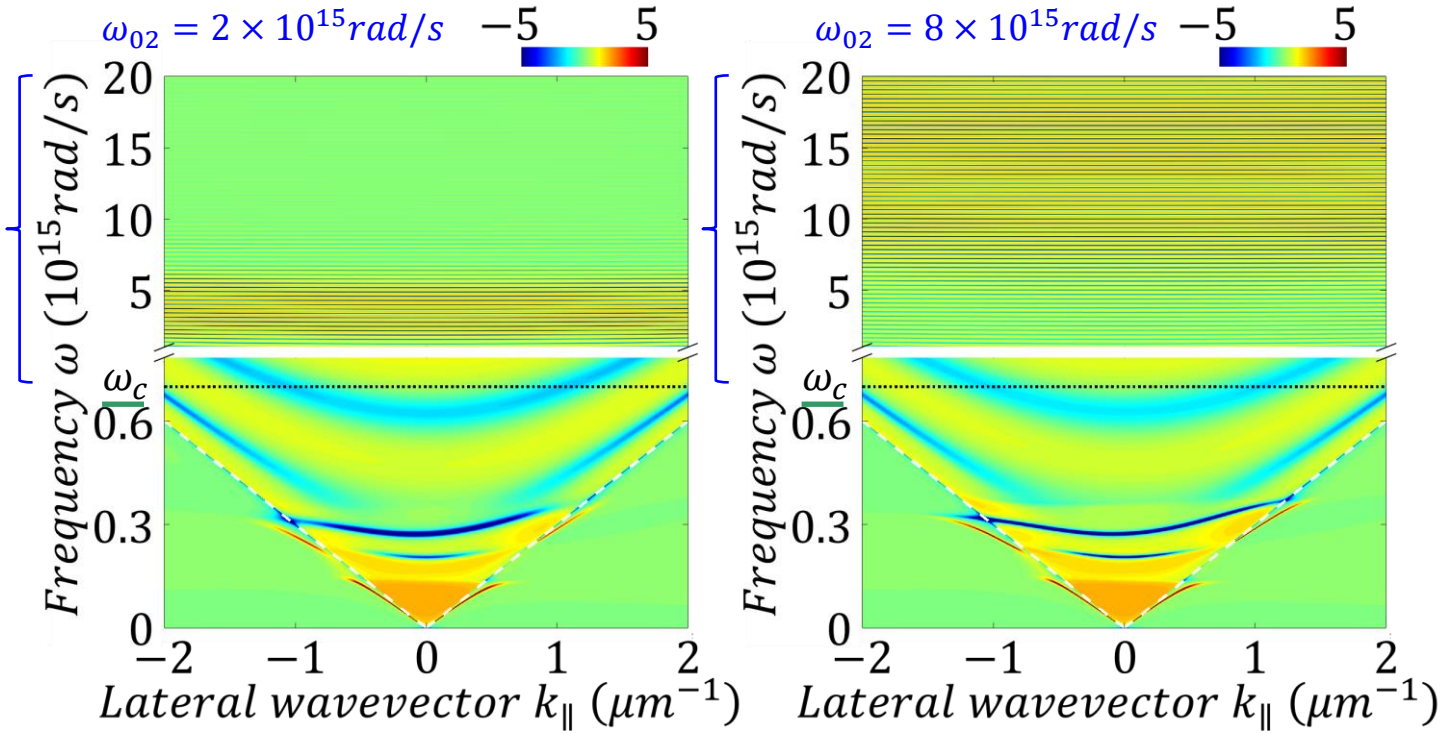
($\omega_{01} = 0$, $\omega_{p1} = 8 \times 10^{14} rad/s$, $\Gamma_1 = 7 \times 10^{12} rad/s$, $\omega_{p2} = 3.4\omega_{02}$, $\Gamma_2 = 0.5\omega_{02}$, $b = 2 \times 10^9 m^{-1}$ and $P_{PEC} = \frac{\hbar c \pi^2}{240 d^4}$)

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.



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



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Brief overview of Casimir forces

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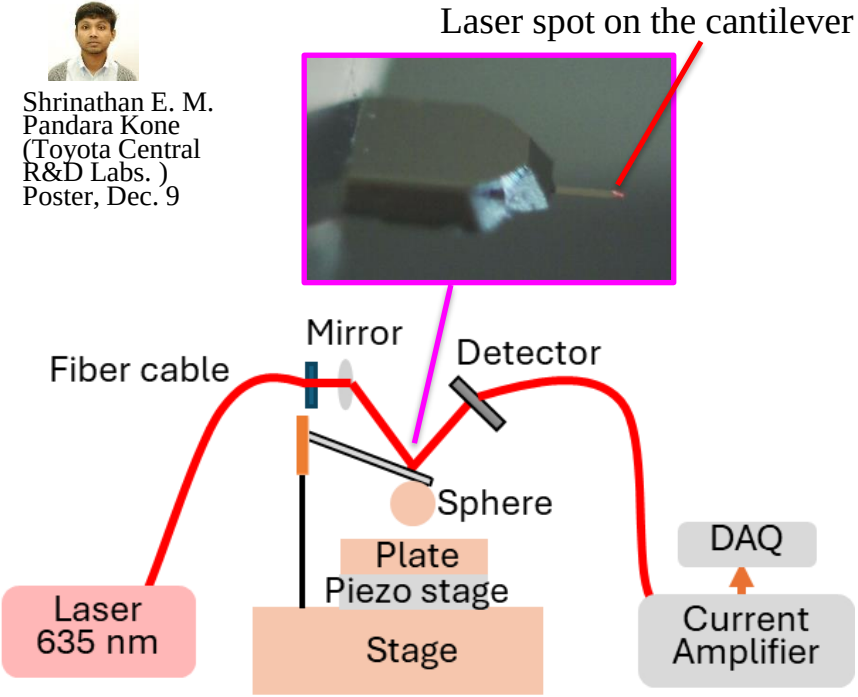
Experimental setup of Casimir forces in QUP (1/2)

Our Casimir force experimental setup is under preparation.

Shrinathan E. M.
Pandara Kone
(Toyota Central R&D Labs.)
Poster, Dec. 9



Collaborator: Prof. Pramod Reddy
(Univ. Michigan)

Step 1:
Reproduce PRA 2000 result (Aug. 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)

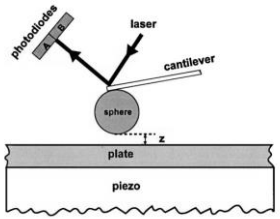


FIG. 1. Schematic diagram of the experimental setup. Application of voltage to the piezoelectric tube results in the movement of the plate toward the sphere. A force on the sphere leads to flexing of the cantilever.

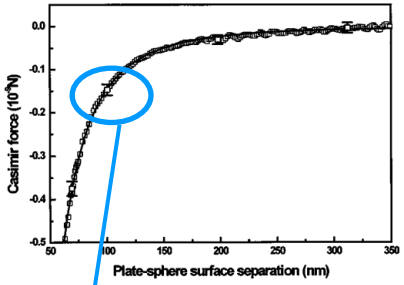


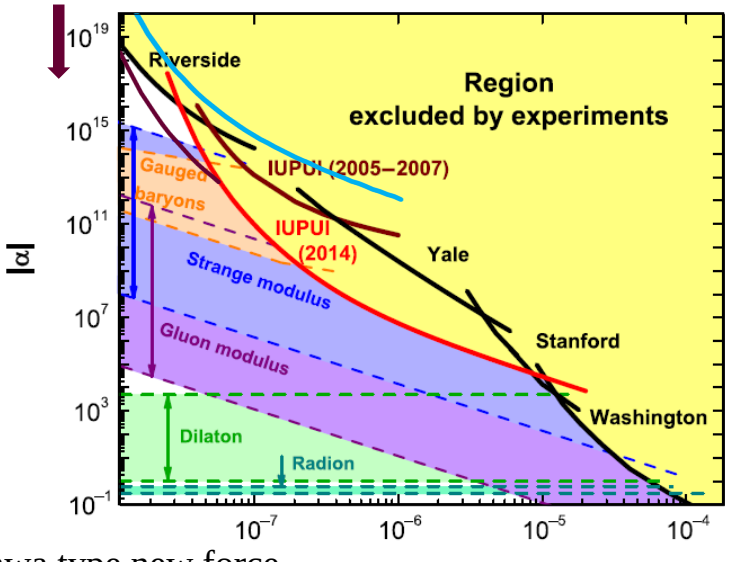
FIG. 5. The measured average Casimir force as a function of plate-sphere separation is shown as squares. For clarity, only 10% of the experimental points are shown in the figure. The error bars represent the standard deviation from 30 scans. The solid line is the theoretical Casimir force from Eq. (2).

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

Experimental setup of Casimir forces in QUP (2/2)

Step 2 target:
3-order improvement via
·Lock-in amp.
·Weyl semimetals
etc.

Step 1



Yukawa type new force

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

PRL 116, 221102(2016)

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

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Precision measurement of the Casimir force using gold surfaces

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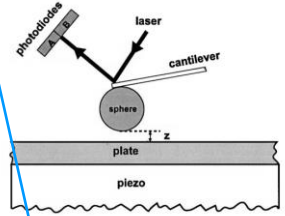

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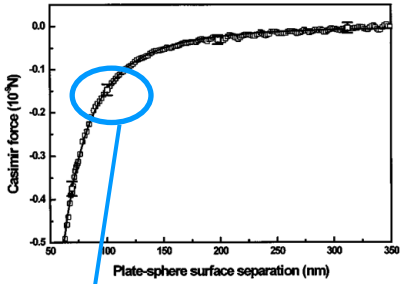

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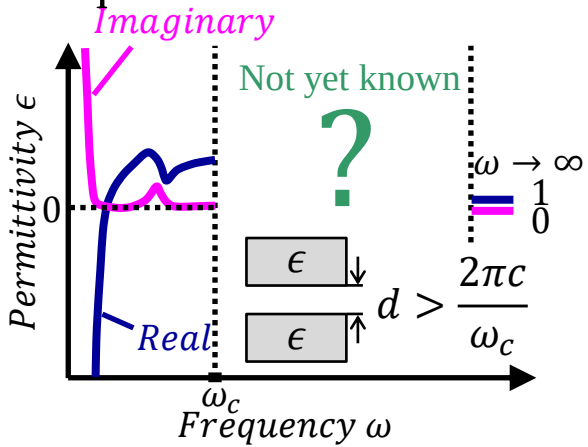
Force: 100pN
Force sensitivity:10pN
(error bar)

at a 100nm gap

Conclusions

We presented a Casimir force computation method for plate materials that lack their permittivities in high frequencies.



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

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