# Control of equilibrium and non-equilibrium Casimir forces

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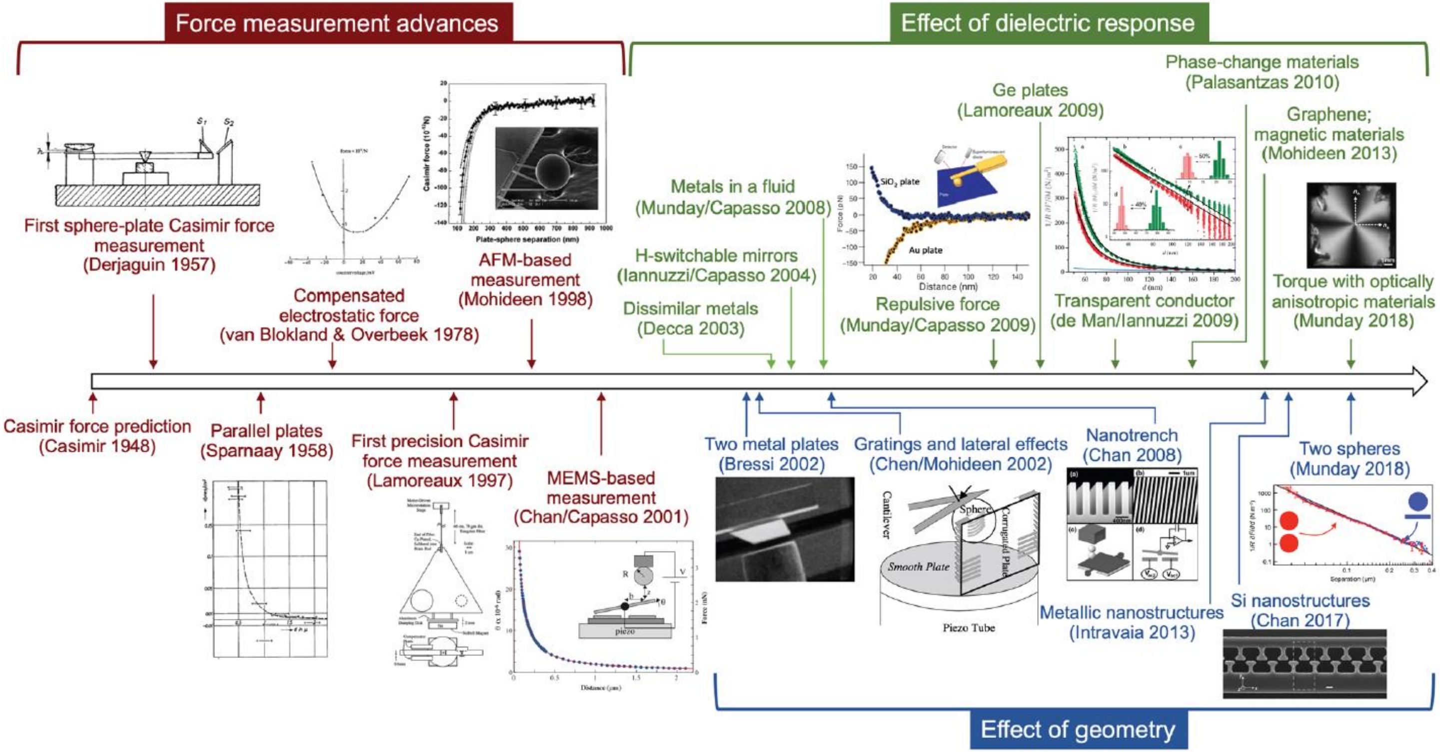
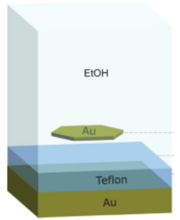
# Outline

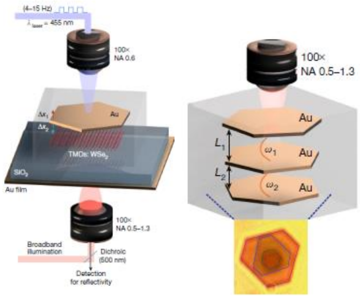
# History of Casimir force research




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.

# Literature of Casimir forces towards new force research



PRL **94**, 240401 (2005) PHYSICAL REVIEW LETTERS week ending 24 JUNE 2005

**Constraining New Forces in the Casimir Regime Using the Isoelectronic Technique**

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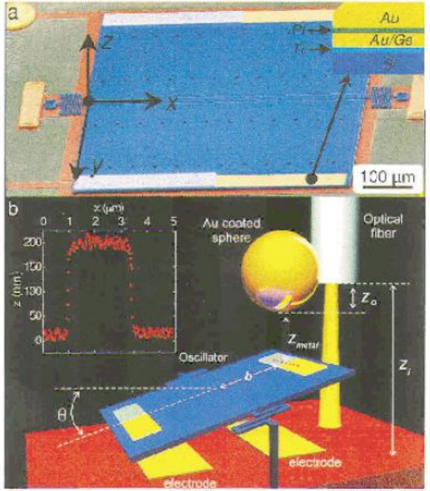



FIG. 1 (color). (a) Scanning electron microscope image of the MTO with the composite sample deposited on it. The coordinate system used in the Letter is indicated. Inset: schematic of the sample deposited on the MTO. The thickness of the different layers are (in order of deposition): $d_{Ti} = 1$ nm, $d_{Ge} = 200$ nm, $d_{Pt} = 1$ nm, and $d^p_{Au} = 150$ nm. The thickness of the layers deposited on the sphere (not shown) are: $d_{Cr} = 1$ nm and $d^s_{Au} = 200$ nm. (b) Experimental setup. The red dotted line indicates where AFM line cuts were taken. Inset: AFM profile of the sample interface.

Hypothetical force difference

$$\Delta F_h = -4\pi^2 G\alpha\lambda^3 e^{-z/\lambda} R K_s K_p,$$

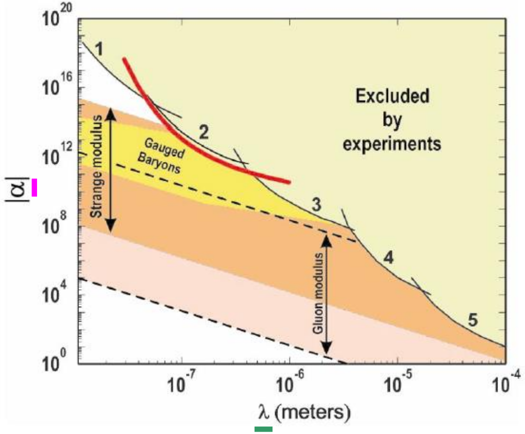
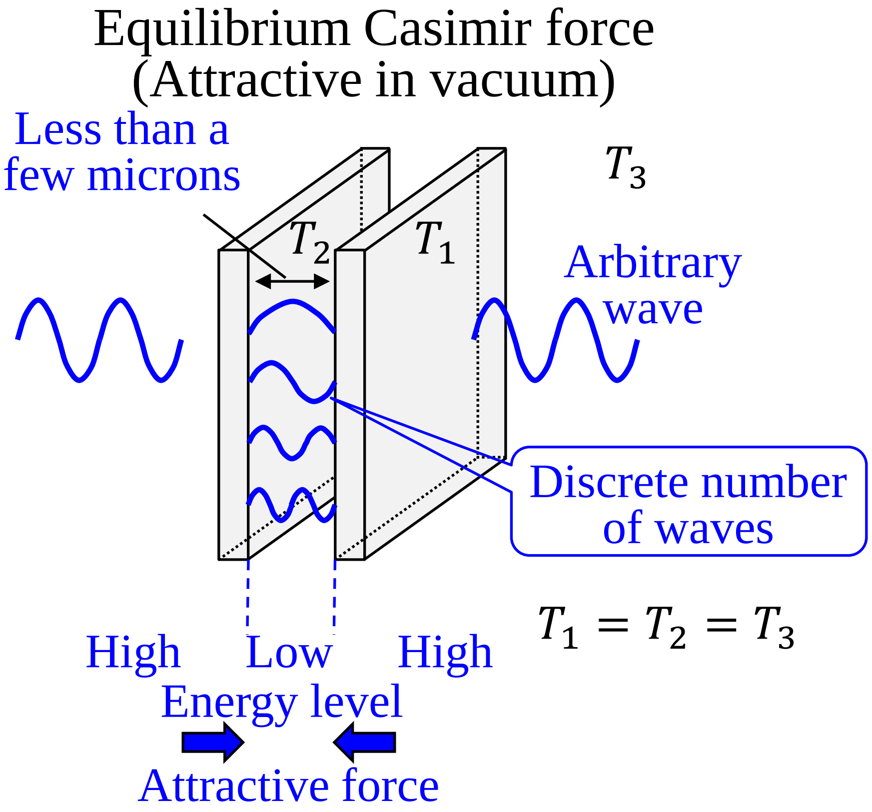
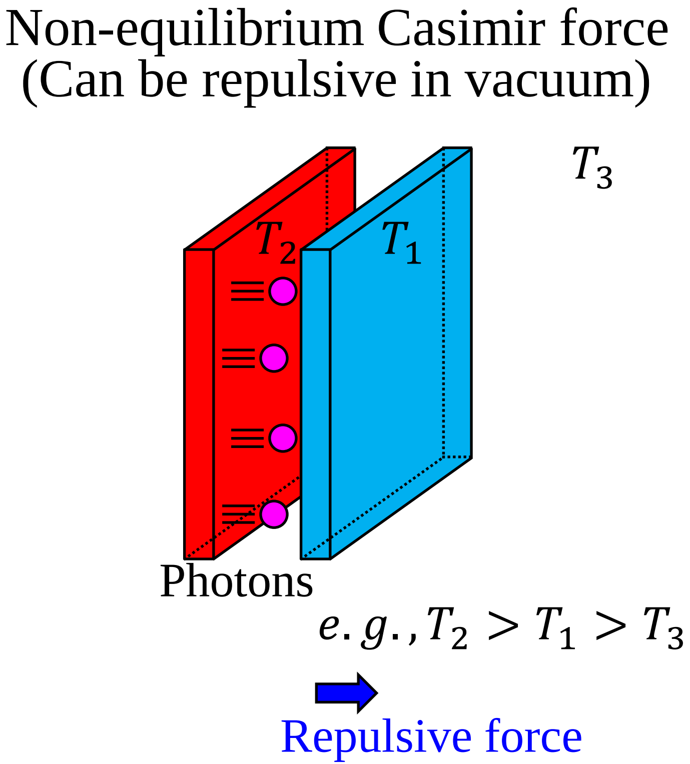



FIG. 4 (color). Values in the $\{\lambda, \alpha\}$ space excluded by experiments. The red curve represents limits obtained in this work. Curves 1 to 5 were obtained by Mohideen's group [7], our group [1], Lamoreaux [6], Kapitulnik's group [8], and Price's group [5], respectively. Also shown are theoretical predictions [21].

$G$: Gravitational constant
$K_s, K_p$: Terms relating to densities of the sphere and the plate
$R$: Radius of the sphere

# Equilibrium and non-equilibrium Casimir forces

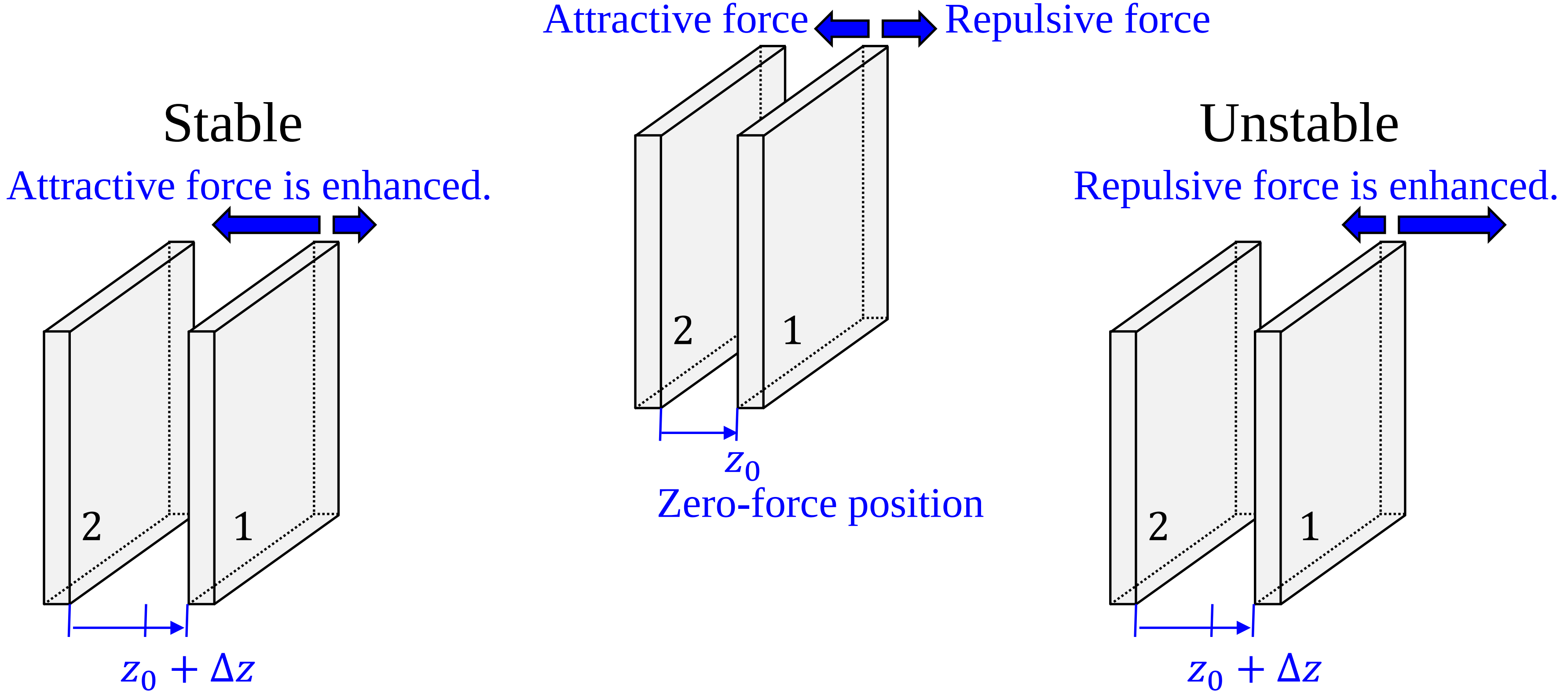



Note: The plates consist of reciprocal materials.

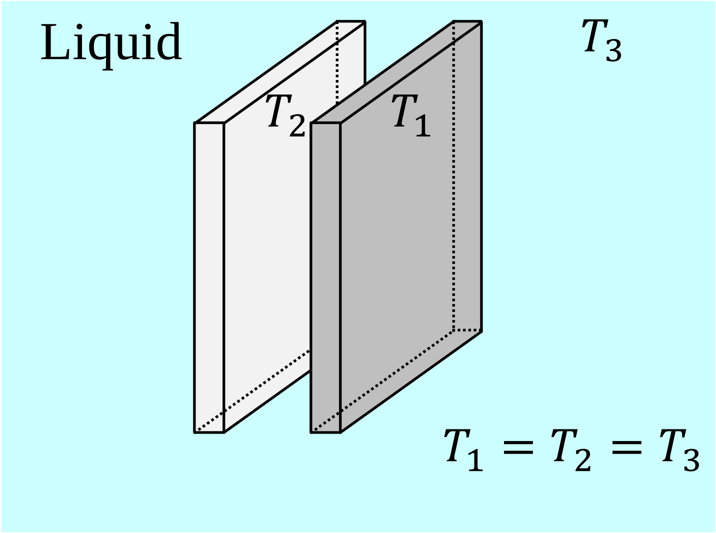
# Stable and unstable Casimir force systems

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



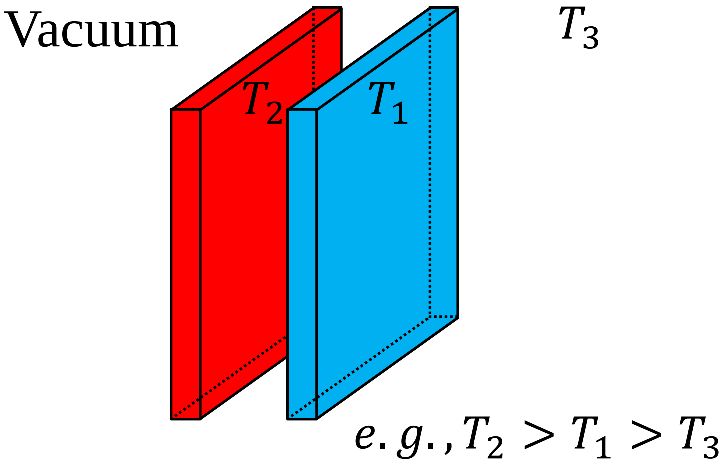
# Examples of stable and unstable systems

Equilibrium Casimir force in liquid
(Can be stable)




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

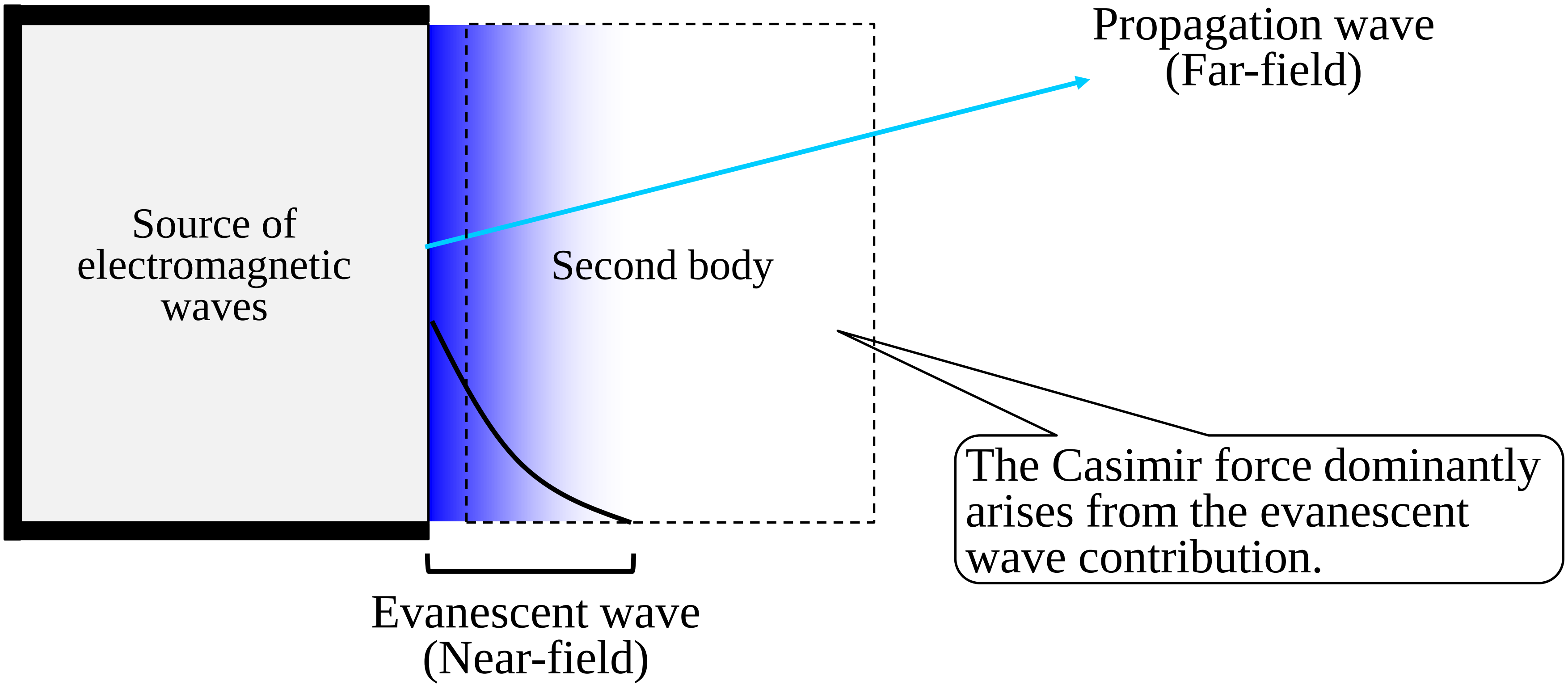
Non-equilibrium Casimir force in vacuum
(Unstable)



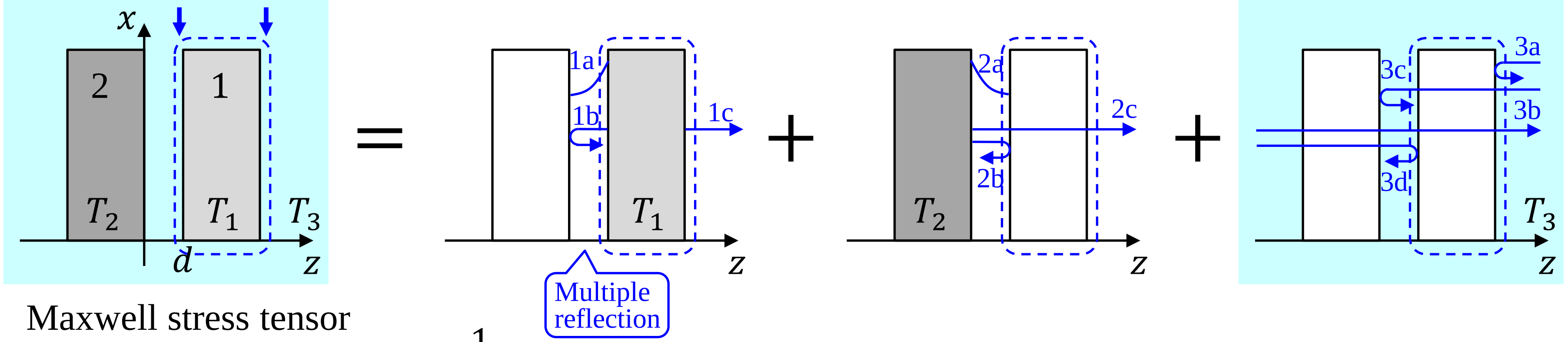

Note: The plates consist of reciprocal materials.

# Propagation and evanescent waves

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



# Casimir force calculation




Maxwell stress tensor

$$T_{ij}=\epsilon_0 E_i E_j+\mu_0 H_i H_j-\delta_{ij}\frac{1}{2}\left(\epsilon_0 E^2+\mu_0 H^2\right), (1)$$

Casimir force acting on body 1 in the two-body system (isotropic materials)

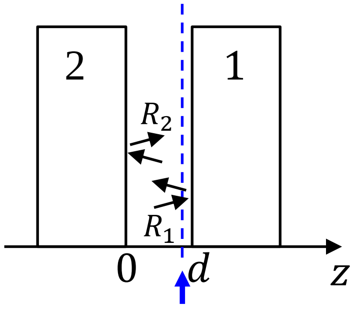
$\tilde{r}_{0j}$: reflection coefficient
$\tilde{t}_{0j}$: reflection coefficient

$$F_z=\int_S \langle T_{zz}\rangle dz\,, (2)$$

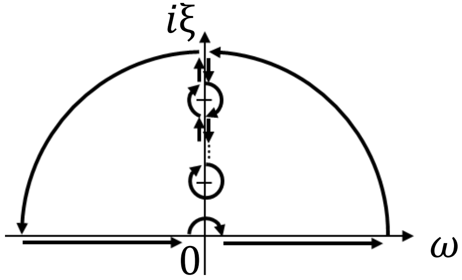
$$\begin{aligned}
&= -\sum_{p,s}\frac{\hbar}{\pi^2}\int_0^\infty d\omega\Bigg\{\left[n(\omega,T_1)+\frac{1}{2}\right]\Bigg[\overbrace{\int_{k_0}^{\infty} k_\parallel dk_\parallel \kappa_0\frac{Im(\tilde{r}_{01})Re(\tilde{r}_{02})e^{-2\kappa_0 d}}{|1-\tilde{r}_{01}\tilde{r}_{02}e^{-2\kappa_0 d}|^2}}^{\text{Evanescent waves: 1a}}+\int_0^{k_0} k_\parallel dk_\parallel k_{z0}\frac{1}{4}\Bigg(\overbrace{-\frac{(1-|\tilde{r}_{01}|^2-|\tilde{t}_{01}|^2)(1+|\tilde{r}_{02}|^2)}{|1-\tilde{r}_{01}\tilde{r}_{02}e^{i2k_{z0}d}|^2}}^{\text{Propagation waves: 1b}}\overbrace{+1-\left|\tilde{r}_{31}+\frac{\tilde{r}_{02}\tilde{t}_{01}^2e^{i2k_{z0}d}}{1-\tilde{r}_{01}\tilde{r}_{02}e^{i2k_{z0}d}}\right|^2-\frac{|\tilde{t}_{01}|^2(1-|\tilde{r}_{02}|^2)}{|1-\tilde{r}_{01}\tilde{r}_{02}e^{i2k_{z0}d}|^2}}^{\text{1c}}\Bigg)\Bigg]\\
&+\left[n(\omega,T_2)+\frac{1}{2}\right]\Bigg[\overbrace{\int_{k_0}^{\infty} k_\parallel dk_\parallel \kappa_0\frac{Im(\tilde{r}_{02})Re(\tilde{r}_{01})e^{-2\kappa_0 d}}{|1-\tilde{r}_{01}\tilde{r}_{02}e^{-2\kappa_0 d}|^2}}^{\text{2a}}++\int_0^{k_0} k_\parallel dk_\parallel k_{z0}\frac{1}{4}\Bigg(\overbrace{-\frac{(1-|\tilde{r}_{02}|^2-|\tilde{t}_{02}|^2)(1+|\tilde{r}_{01}|^2)}{|1-\tilde{r}_{01}\tilde{r}_{02}e^{i2k_{z0}d}|^2}}^{\text{2b}}+\overbrace{\frac{|\tilde{t}_{01}|^2(1-|\tilde{r}_{02}|^2-|\tilde{t}_{02}|^2)}{|1-\tilde{r}_{01}\tilde{r}_{02}e^{i2k_{z0}d}|^2}}^{\text{2c}}\Bigg)\Bigg]\\
&+\left[n(\omega,T_3)+\frac{1}{2}\right]\int_0^{k_0} k_\parallel dk_\parallel k_{z0}\frac{1}{4}\Bigg(\overbrace{1+\left|\tilde{r}_{31}+\frac{\tilde{r}_{02}\tilde{t}_{01}^2e^{i2k_{z0}d}}{1-\tilde{r}_{01}\tilde{r}_{02}e^{i2k_{z0}d}}\right|^2}^{\text{3a}}+\overbrace{\frac{|\tilde{t}_{01}|^2|\tilde{t}_{02}|^2}{|1-\tilde{r}_{01}\tilde{r}_{02}e^{i2k_{z0}d}|^2}}^{\text{3b}}-\overbrace{\frac{|\tilde{t}_{01}|^2(1+|\tilde{r}_{02}|^2)}{|1-\tilde{r}_{01}\tilde{r}_{02}e^{i2k_{z0}d}|^2}}^{\text{3c}}-\overbrace{\frac{|\tilde{t}_{02}|^2(1+|\tilde{r}_{01}|^2)}{|1-\tilde{r}_{01}\tilde{r}_{02}e^{i2k_{z0}d}|^2}}^{\text{3d}}\Bigg)\Bigg\}(3)
\end{aligned}$$

# Casimir force calculation in equilibrium

Calculations of equilibrium Casimir forces can be simplified since photon exchange is balanced at the exterior boundary. (The interior boundary is only considered.)




$T \equiv T_1 = T_2 = T_3$




**Casimir force formula, integration along the real frequency axis**

$$P_t = -\sum_{j=p,s}\int_0^{\infty}\frac{k_\parallel dk_\parallel}{2\pi}\int_0^{\infty}\frac{d\omega}{2\pi}4\hbar\left[n(\omega,T)+\frac{1}{2}\right]Re[k_z Z(\omega,\beta)], (11a)$$

$$Z(\omega,\beta) = \frac{R_1(\omega,\beta)R_2(\omega,\beta)e^{i2k_z d}}{1-R_1(\omega,\beta)R_2(\omega,\beta)e^{i2k_z d}}, (11b)$$

- Understanding the mechanism
- Long calculation time

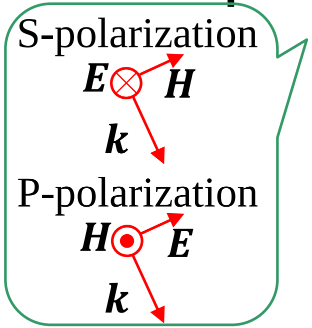
**Wick rotation approach, integration along the imaginary frequency axis (E.M. Lifshitz, Sov. Phys. 1956)**

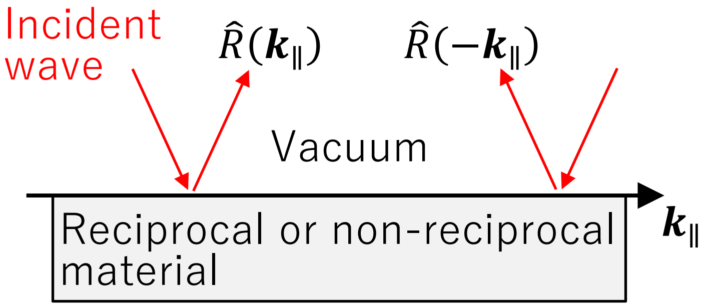
$$P_t = \sum_{j=p,s}\int_0^{\infty}\frac{k_\parallel dk_\parallel}{2\pi}2k_B T\sum_{n=0}^{\infty\prime} q_{0,n}\, Z(i\xi_n,\beta), (12a)$$

$$Z(i\xi_n,\beta) = \frac{R_1(i\xi_n,\beta)R_2(i\xi_n,\beta)e^{-2q_{0,n}d}}{1-R_1(i\xi_n,\beta)R_2(i\xi_n,\beta)e^{-2q_{0,n}d}}, (12b),$$

- Significantly reduced calculation time
- Little observation of the mechanism

# Reciprocal and non-reciprocal materials




## Reflection matrix

$$\hat{R}(\boldsymbol{k}_\parallel) = \begin{bmatrix} R^{s\to s}(\boldsymbol{k}_\parallel) & R^{p\to s}(\boldsymbol{k}_\parallel) \\ R^{s\to p}(\boldsymbol{k}_\parallel) & R^{p\to p}(\boldsymbol{k}_\parallel) \end{bmatrix}, \quad (21)$$

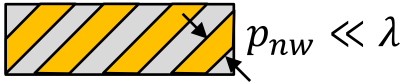
## Reciprocal materials

$$\hat{R}(-\boldsymbol{k}_\parallel) = \hat{\sigma}_z \hat{R}^T(\boldsymbol{k}_\parallel)\hat{\sigma}_z, \quad (22)$$

$$\left(\hat{\sigma}_z = \begin{bmatrix} 1 & \\ & -1 \end{bmatrix}\right)$$

Bulk (Isotropic)

Inclined nanowires (Anisotropic)

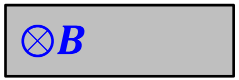



$$\hat{\epsilon}_i = \begin{bmatrix} \epsilon_p & & \\ & \epsilon_p & \\ & & \epsilon_p \end{bmatrix}, \quad (23) \qquad \hat{\epsilon}^S = \begin{bmatrix} \epsilon_d & & \epsilon_f \\ & \epsilon_p & \\ \epsilon_f & & \epsilon_d \end{bmatrix}, \quad (24)$$

## Non-reciprocal materials

Eq. (22) can be violated.

InSb



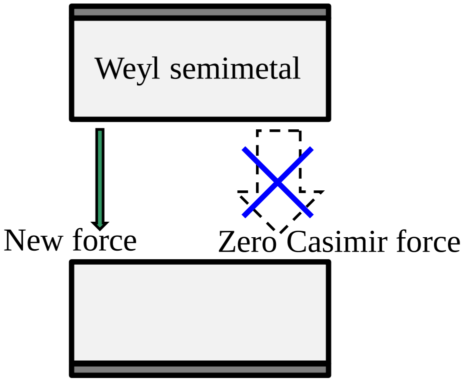

Magnetic Weyl semimetals

$$\hat{\epsilon}^A = \begin{bmatrix} \epsilon_d & & i\epsilon_f \\ & \epsilon_p & \\ -i\epsilon_f & & \epsilon_d \end{bmatrix}, \quad (25)$$

# Our Casimir force research

## Particle physics

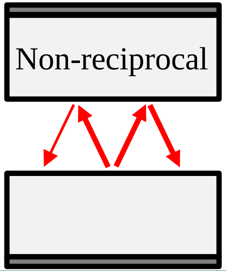
New force search via zero Casimir force[1]




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

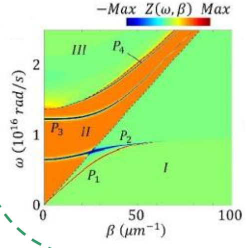
## Fundamental understanding

[2] Symmetry argument in Casimir forces

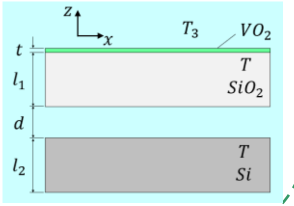



Show details

[3]Casimir force is insensitive to material loss



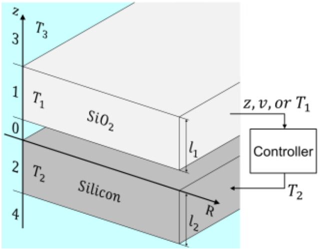

[4]Exterior control of non-equilibrium Casimir force



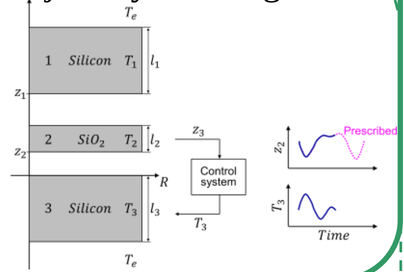

## Toward industry

Dynamic control of Casimir forces in vacuum

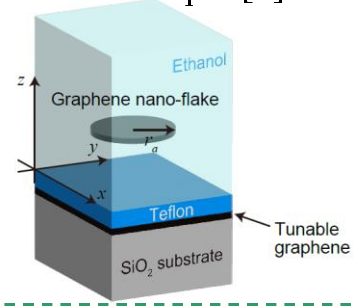
Control theory[5]




Trajectory tracking[6]




Dynamic control of Casimir forces in liquid[7]




[2] H. Iizuka and S. Fan, Phys. Rev. B 108, 075429 (2023).
[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, Applied Physics Letters 118, 144001 (2021).
[6] H. Iizuka and S. Fan, J. Quantitative Spectroscopy Radiative Transfer 289, 108281 (2022).
[7] H. Toyama, T. Ikeda, and H. Iizuka, Phys. Rev. B 108, 245402 (2023).

# Outline

Brief overview of Casimir forces

Control theory for Casimir forces

Symmetry of Casimir forces in wavevector space

Conclusions

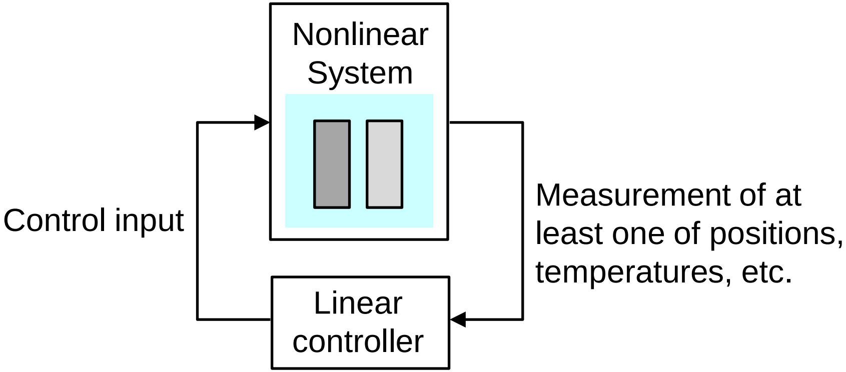
# Casimir force to Industries

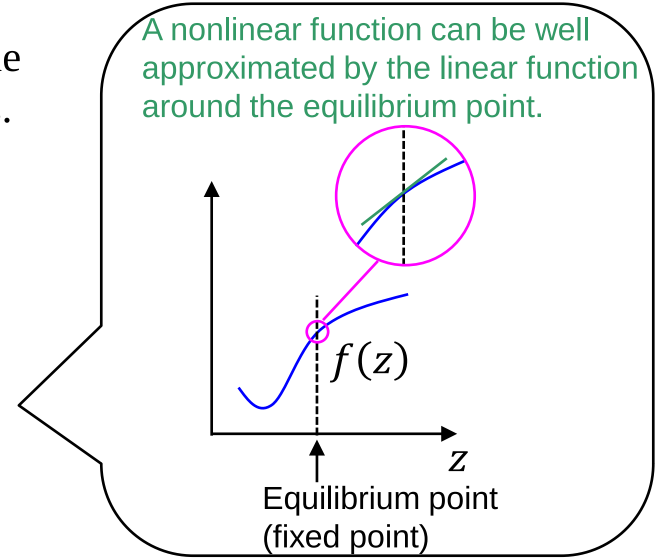
Control theory has been widely used in industries.

We introduce control theory to manipulate Casimir forces for the first time.

We show that a linear controller enables a nonlinear system interacting through non-equilibrium Casimir forces to be stable around the equilibrium point with a limited number of sensors.

└ zero force, zero net heat transfer



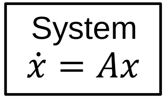



# Linear control system (1/2)

Dynamics of a linear system is given by

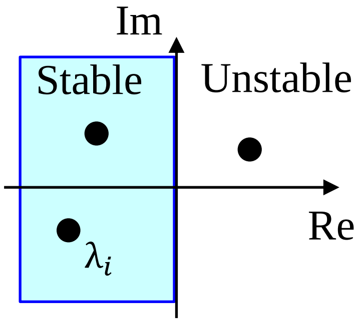
$$\frac{dx}{dt} = Ax, (51)$$

$A$: $n \times n$ matrix; State vector $x = \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix}$




The system is stable if all eigenvalues meet

$$Re[\lambda_i] < 0, (52)$$




Eigenvalues (unstable)

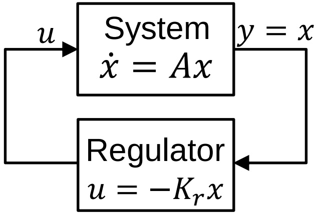
The controller changes the dynamics.

$$\frac{dx}{dt} = Ax + Bu, (53)$$

$u$: Control input

$$u = -K_r x, (54)$$

$K_r$: Gain matrix of the regulator

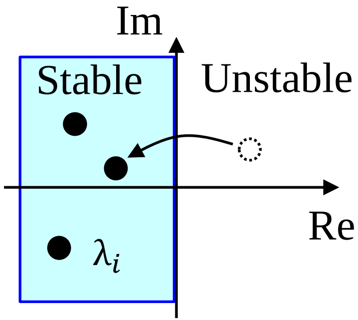



Eqs. (53),(54) give

$$\frac{dx}{dt} = \underline{(A - BK_r)}x, (55)$$

If the controllability matrix is full ranked, the system is “controllable”. (All $\lambda_i$ can have negative real parts.)

$$Q = [A, AB, \ldots AB^{n-1}], (56)$$




Eigenvalues (stable)

Steve Brunton, Control bootcamp, YouTube.
B. Friedland, Control System Design: An Introduction to State-Space Methods (McGraw-Hill, New York, 1986).

# Linear control system (2/2)

The estimator (Kalman filter) enables the system to be stable with limited measurement results.

$$\frac{dx}{dt} = Ax + Bu, (61)$$

$C = [0\ \ 1\ \ 0 \ldots]$

$$y = Cx, (62)$$

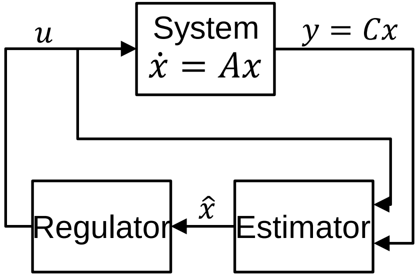
Observation vector

Gain matrix of the estimator

$$\frac{d\hat{x}}{dt} = (A - K_f C)\hat{x} + [B \quad K_f]\begin{bmatrix} u \\ y \end{bmatrix}, (63)$$

Estimated state vector

$$u = -K_r \hat{x}, (64)$$




If the observability matrix is full ranked, the system is “observable”.
(The system is stable with limited measurement results.)

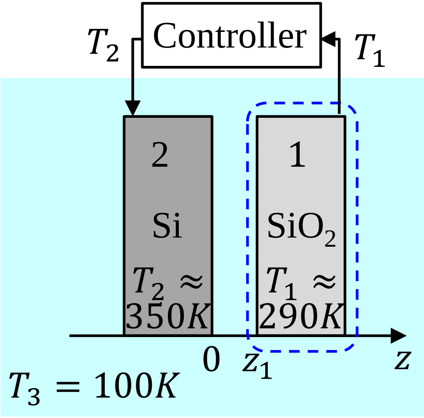
$$N = [C, CA, \ldots CA^{n-1}], (65)$$

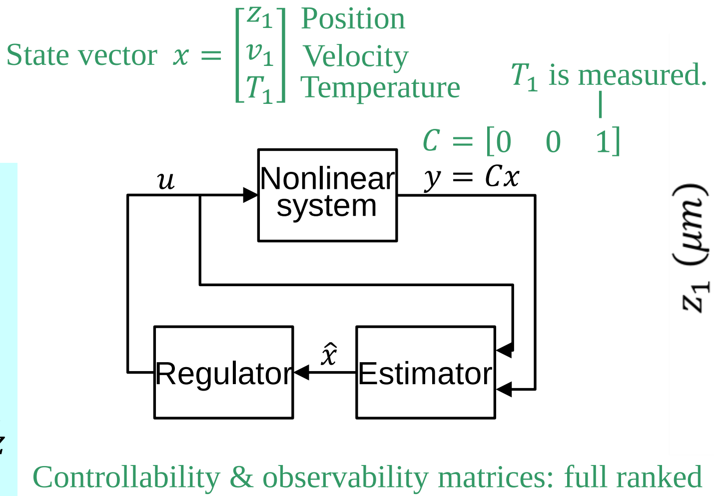
Steve Brunton, Control bootcamp, YouTube.
B. Friedland, Control System Design: An Introduction to State-Space Methods (McGraw-Hill, New York, 1986).

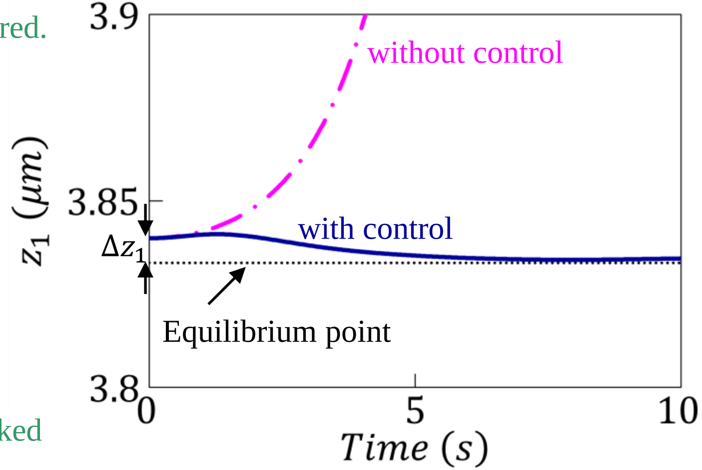
# Control of non-equilibrium Casimir force

Consider a system consisting of a silicon plate and a $SiO_2$ plate in a low-temperature environment. The silicon plate is fixed and the temperature can be adjusted while the $SiO_2$ plate is moved and the temperature is determined through the thermal emission exchange.

We theoretically prove that the $SiO_2$ plate can stay at a distance away from the silicon plate indefinitely by monitoring the temperature of the $SiO_2$ plate and adjusting the temperature of the silicon plate.



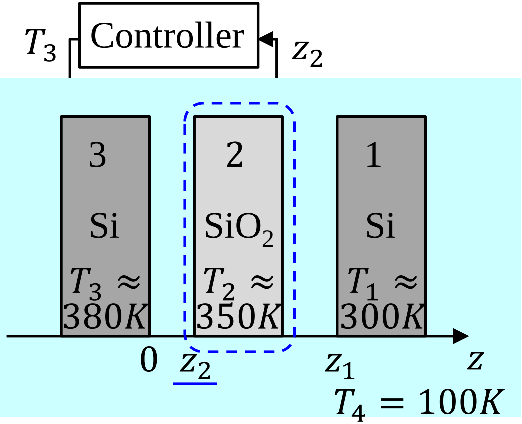

H. Iizuka and S. Fan, “Control of non-equilibrium Casimir force,” Applied Physics Letters 118, 144001 (2021).

# Trajectory tracking through the control of Casimir force

An autonomous vehicle can follow a path as we set by control theory, which is called trajectory tracking.

Quantum world

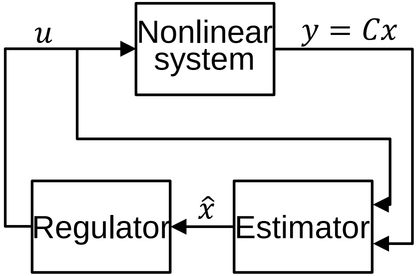
Trajectory tracking is applied to a three-body system interacting through non-equilibrium Casimir forces.




$x = [z_1\ v_1\ T_1\ z_2\ v_2\ T_2]^T$

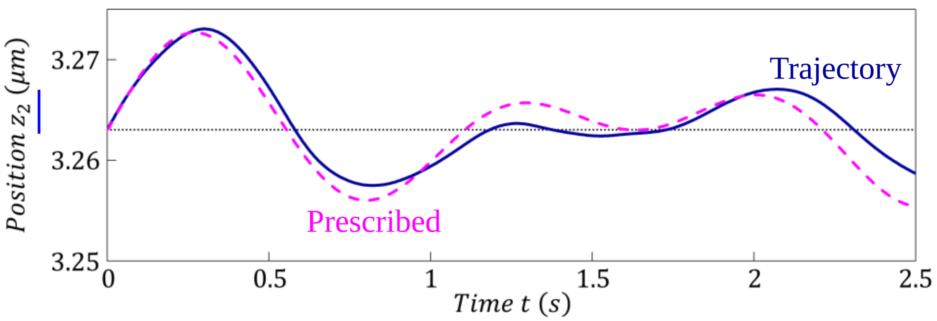
$C = [0\ \ 0\ \ 0\ \ 1\ \ 0\ \ 0]$

$z_2$ is measured.




Controllability & observability matrices: full ranked

The position of the middle $SiO_2$ plate (blue line) follows a prescribed trajectory (pink dashed line) by adjusting the temperature of the left silicon plate (single parameter) while the right silicon plate is kept around the equilibrium position.




H. Iizuka and S. Fan, "Trajectory tracking through the control of non-equilibrium Casimir force," Journal of Quantitative Spectroscopy and Radiative Transfer 289, 108281 (2022).

# Outline



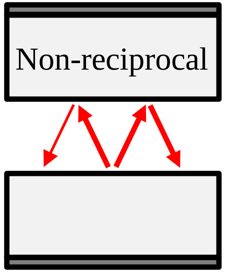
Brief overview of Casimir forces

Control theory for Casimir forces

Symmetry of Casimir forces in wavevector space

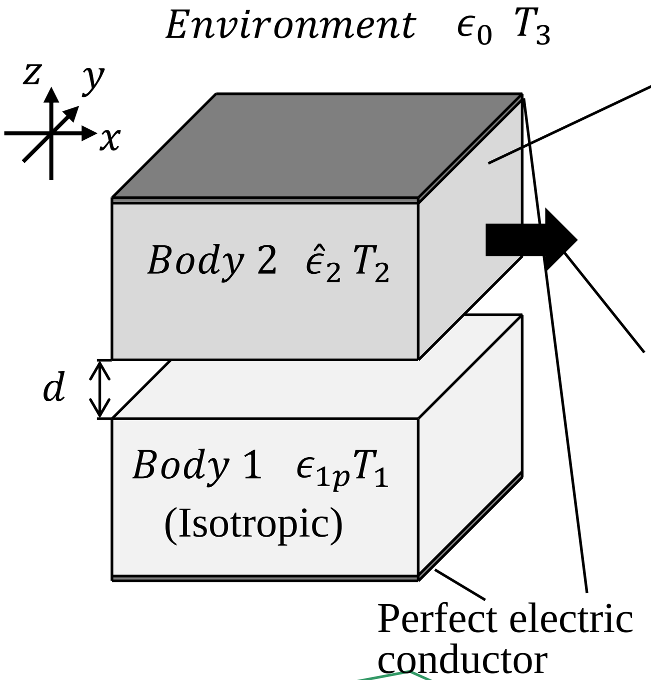
Conclusions

[2] Symmetry argument in Casimir forces

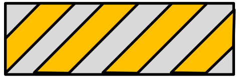



[2] H. Iizuka and S. Fan, Phys. Rev. B 108, 075429 (2023).

# Casimir lateral force




Anisotropic reciprocal material



non-reciprocal material

InSb/Weyl

$$\epsilon_2^S = \begin{bmatrix} \epsilon_d & & \epsilon_f \\ & \epsilon_p & \\ \epsilon_f & & \epsilon_d \end{bmatrix}, (24) \quad \text{or} \quad \epsilon_2^A = \begin{bmatrix} \epsilon_d & & i\epsilon_f \\ & \epsilon_p & \\ -i\epsilon_f & & \epsilon_d \end{bmatrix}, (25)$$

Casimir lateral force acting on body 2

$$\boldsymbol{F}_2^{\parallel}(T_1, T_2) = \int_0^{\infty} d\omega \int_{-\infty}^{\infty} d\boldsymbol{k}_{\parallel} \boldsymbol{F}_2^{\parallel}(\omega, \boldsymbol{k}_{\parallel}, T_1, T_2), (41)$$

$$\boldsymbol{F}_2^{\parallel}(\omega, \boldsymbol{k}_{\parallel}, T_1, T_2) = -\boldsymbol{F}_{1\to 2}^{\parallel}(\omega, \boldsymbol{k}_{\parallel}, T_1) - \boldsymbol{F}_{2\to 1}^{\parallel}(\omega, \boldsymbol{k}_{\parallel}, T_2), (42)$$

$$\boldsymbol{F}_{1\to 2}^{\parallel}(\omega, \boldsymbol{k}_{\parallel}, T_1) = \left[n(\omega, T_1) + \frac{1}{2}\right] \frac{\hbar \boldsymbol{k}_{\parallel}}{8\pi^3} \tilde{F}_{1\to 2}^{\parallel}(\omega, \boldsymbol{k}_{\parallel}), (43)$$

$$\tilde{F}_{l\to m}^{\parallel}(\omega, \boldsymbol{k}_{\parallel}) = \begin{cases} Tr\left[(-1)^l \left(\hat{I} - \hat{R}_m^{\dagger}\hat{R}_m\right)\hat{D}_{lm}\left(\hat{I} - \hat{R}_l\hat{R}_l^{\dagger}\right)\hat{D}_{lm}^{\dagger}\right], & (k_{\parallel} < k_0) \\ Tr\left[(-1)^l \left(\hat{R}_m^{\dagger} - \hat{R}_m\right)\hat{D}_{lm}\left(\hat{R}_l - \hat{R}_l^{\dagger}\right)\hat{D}_{lm}^{\dagger} e^{-2\kappa_{z0} d}\right], & (k_{\parallel} > k_0) \end{cases}, (44)$$

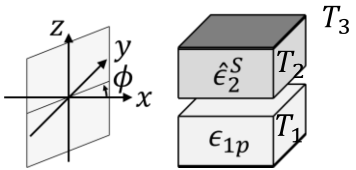
Exchange function

No photon exchange between the two-body system and the environment.

$T_1 = T_2 = T_3 = T$ (Equilibrium)

$T_1 \neq T_2$ (Non-equilibrium)

# Casimir lateral force, reciprocal




Casimir lateral force is symmetric for reciprocal systems in equilibrium and non-equilibrium.

$\tilde{F}^{\parallel}_{1\to 2} + \tilde{F}^{\parallel}_{2\to 1}$    $a\tilde{F}^{\parallel}_{1\to 2} + b\tilde{F}^{\parallel}_{2\to 1}$

Casimir lateral force in $(\omega, \boldsymbol{k}_\parallel)$ space

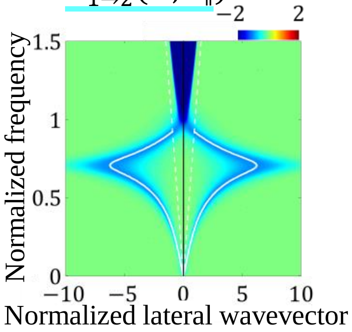
$F^{\parallel}_2(\omega, \boldsymbol{k}_\parallel, T_1, T_2, T_3)$

$$F^{\parallel}_2(\omega, \boldsymbol{k}_\parallel, T_1, T_2) = -F^{\parallel}_2(\omega, -\boldsymbol{k}_\parallel, T_1, T_2), (45)$$

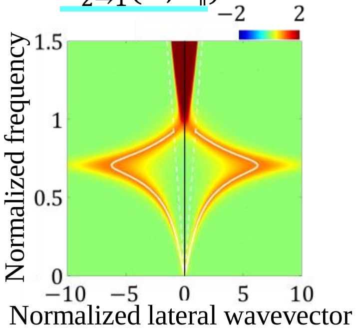
Symmetric for $\boldsymbol{k}_\parallel$

Exchange function $\tilde{F}^{\parallel}_{l\to m}(\omega, \boldsymbol{k}_\parallel)$

$\tilde{F}^{\parallel}_{1\to 2}(\omega, \boldsymbol{k}_\parallel)$

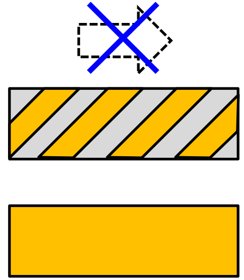



$\tilde{F}^{\parallel}_{2\to 1}(\omega, \boldsymbol{k}_\parallel)$

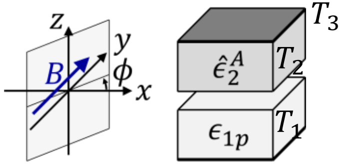



White lines:
Dispersion curves

Lateral force does not occur in equilibrium and nonequilibrium for reciprocal systems.



# Casimir lateral force, non-reciprocal




Casimir lateral force in $(\omega, \boldsymbol{k}_\parallel)$ space

$F_2^\parallel(\omega, \boldsymbol{k}_\parallel, T_1, T_2, T_3)$

Exchange function

$\tilde{F}_{l\to m}^\parallel(\omega, \boldsymbol{k}_\parallel)$

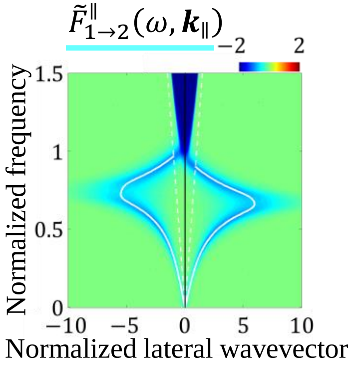
White lines:
Dispersion curves

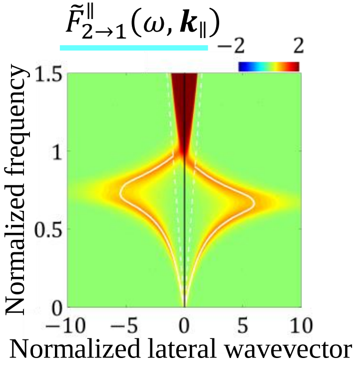
Symmetry of the Casimir lateral force is broken for non-reciprocal systems in equilibrium and non-equilibrium.

$\tilde{F}_{1\to 2}^\parallel + \tilde{F}_{2\to 1}^\parallel$ $\quad$ $a\tilde{F}_{1\to 2}^\parallel + b\tilde{F}_{2\to 1}^\parallel$

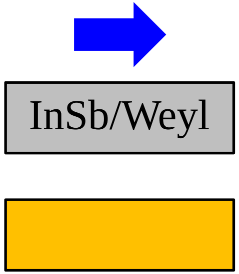
Cancelled out

Asymmetric for $\boldsymbol{k}_\parallel$




Lateral force can occur in non-equilibrium for non-reciprocal systems.



# Newton's third law

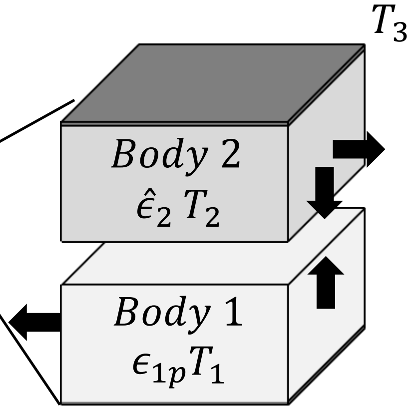
Newton's third law holds for every frequency and wavevector, as long as no exchange of photons occurs between the two-body system and the environment.

Casimir pressure: $F_1^z(\omega, \boldsymbol{k}_\parallel, T_1, T_2, T_3) = -F_2^z(\omega, \boldsymbol{k}_\parallel, T_1, T_2, T_3)$

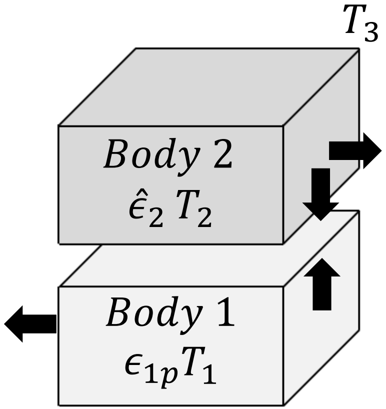
Casimir lateral force: $F_1^\parallel(\omega, \boldsymbol{k}_\parallel, T_1, T_2) = -F_2^\parallel(\omega, \boldsymbol{k}_\parallel, T_1, T_2)$

Newton's third law does not hold.

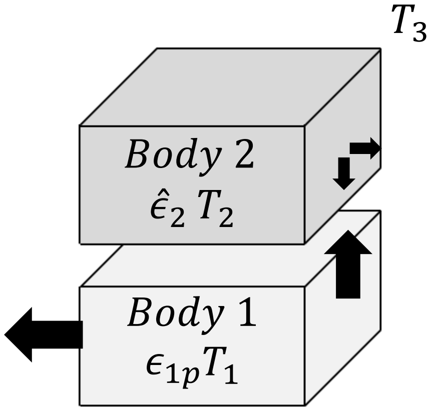
Perfect electric conductor




Equilibrium ($T_1 = T_2 = T_3$) and non-equilibrium ($T_1 \neq T_2$)




Equilibrium ($T_1 = T_2 = T_3$)




Non-equilibrium ($T_1 \neq T_3$ or $T_2 \neq T_3$)

No exchange of photons

Exchange of photons

The above is true for both reciprocal $\hat{\epsilon}_2 = \hat{\epsilon}_2^S$ and non-reciprocal $\hat{\epsilon}_2 = \hat{\epsilon}_2^A$ materials.

# Conclusions

A brief overview of Casimir forces was presented.

Parallel-plate systems for non-equilibrium Casimir forces are controllable and observable by introducing a linear controller.

Symmetry of Casimir forces in wavevector space was discussed. This understanding is helpful for investigating Casimir forces using Weyl semimetals.

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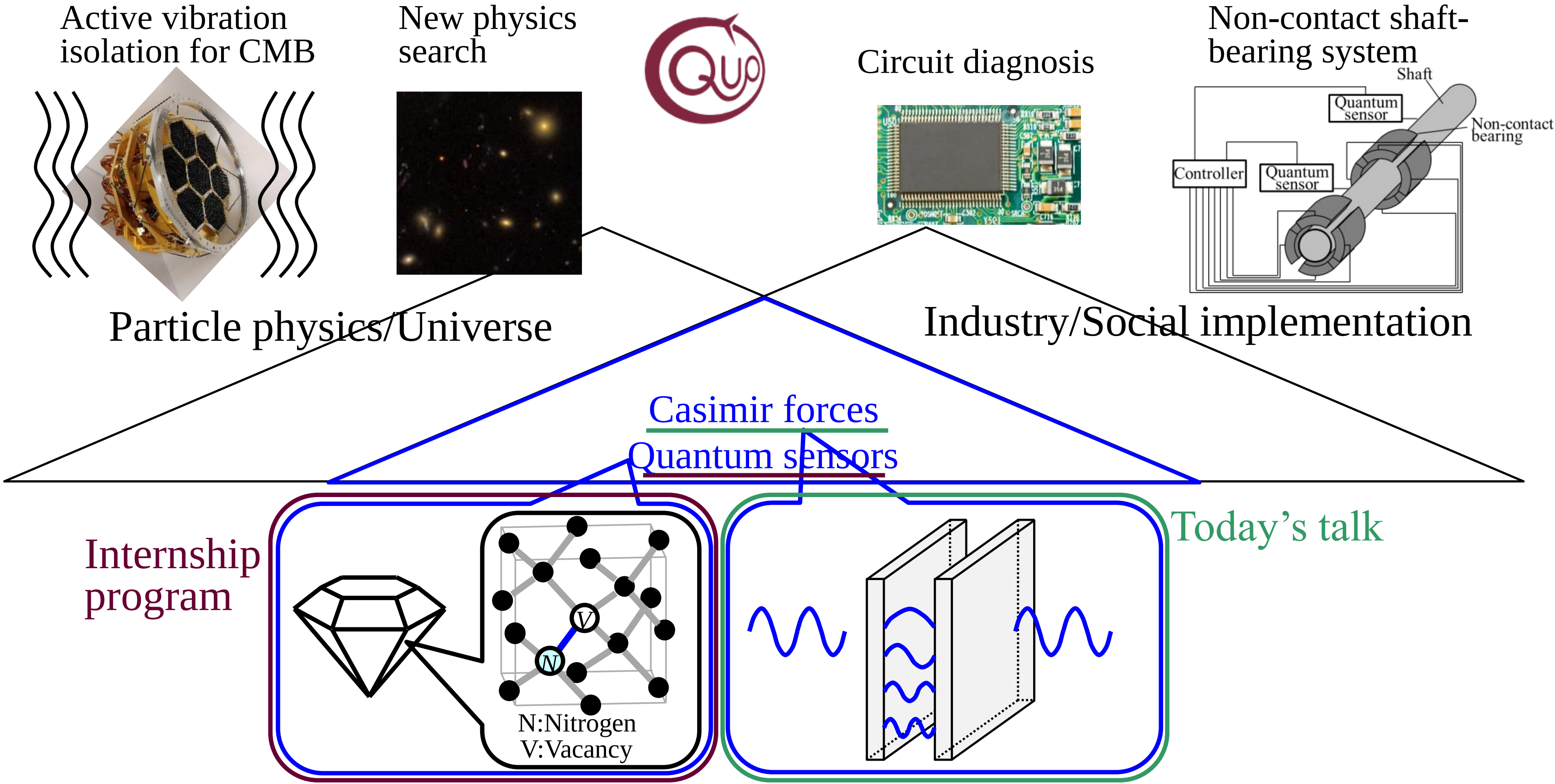
# Research scope of QUP quantum sensor cluster



# QUP Internship program



https://www2.kek.jp/qup/en/jobs/qupip.html

Jobs | **QUPIP**

Announcement 2023.10.18

**QUP Internship Program (QUPIP)**

The International Center for Quantum-field Measurement Systems for Studies of the Universe and Particles (WPI-QUP) invites applications for young researchers (post-doctoral fellows and graduate students) to stay and work with QUP researchers. QUP is developing a new measurement system using existing quantum fields to explore unknown quantum fields under "Bringing New Eyes to Humanity."

**Hideo Izuka** (Research Location: KEK Tsukuba, Japan)
Our aim is to search for new quantum fields enabled by quantum effects in a single lab space. We have started setting up a measurement system using nitrogen-vacancy centers in diamond for light dark matter search.

Example study subjects for the young researchers

- Setup of the ODMR (optically detected magnetic resonance) measurement system.
- Evaluation of optical properties of diamond samples.

## Quantum sensors