Probing the screening of the Casimir interaction with optical tweezers

Paulo A. Maia Neto

Quantum and Thermal Electrodynamic Fluctuations - KITP 2022

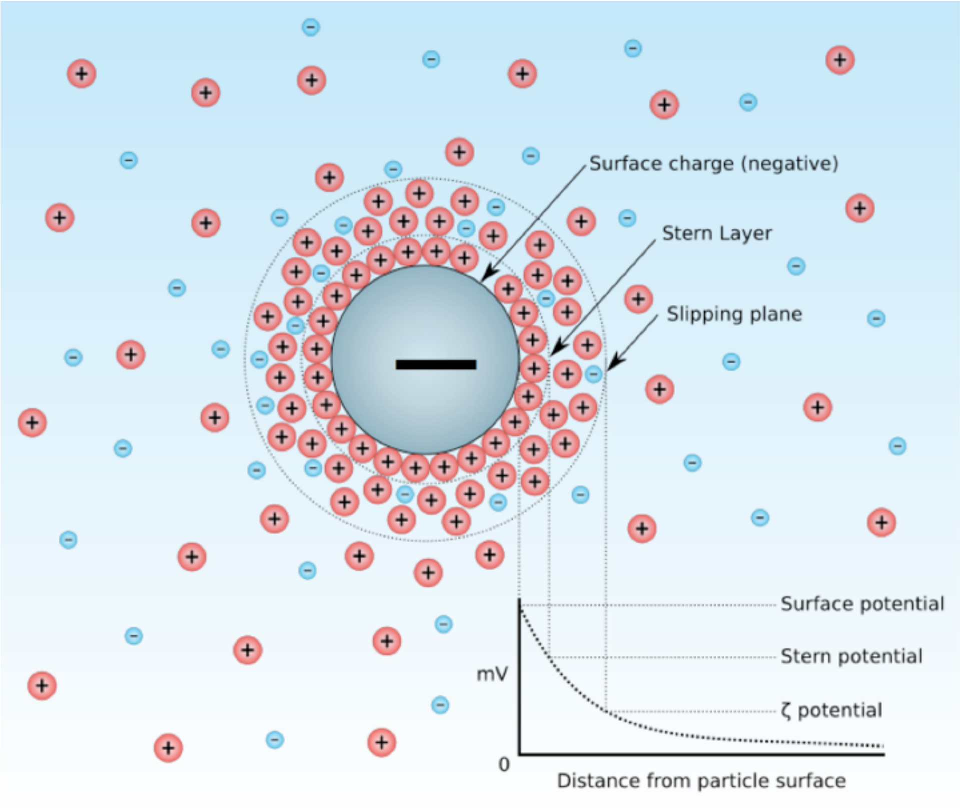
Instituto de Física
Universidade Federal do Rio de Janeiro

Outline

- Introduction
- Theory
- Optical tweezers
- Experimental results
- Conclusion

screening in electrolytes

- ions in solution form a diffuse layer around the charged particle
- characteristic length: Debye screening length λ_D
- electrostatic interaction between two particles exponentially suppressed for distances $> \lambda_D$
- Partial or total (?) screening of the zero-frequency contribution to the Casimir interaction



screening in electrolytes

- Details of screening are essential for understanding the Casimir interaction between dielectric materials across a polar liquid

- Indeed, in this case zero-frequency contribution could be dominant already at distances $> 100\,\mathrm{nm}$ as refractive indexes at positive Matsubara frequencies nearly match

- Example: aqueous solution; biological samples: $\lambda_D < 1\,\mathrm{nm}$
- Is there any interaction left at distances $> 100\,\mathrm{nm}$?

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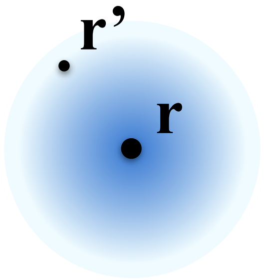
Nonlocal response in aqueous solution

movable ions in solution → **Non-local response**

Bulk approximation: we ignore the presence of boundaries when deriving the constitutive equations (Ohm's law)

real space $$\mathbf{J}(\mathbf{r}) = \int d^3r' \, \sigma(\mathbf{r}-\mathbf{r}') \cdot \mathbf{E}(\mathbf{r}')$$



Fourier $$\mathbf{J}(\mathbf{K},\omega) = \sigma(\mathbf{K},\omega) \cdot \mathbf{E}(\mathbf{K},\omega)$$

↑ K dependence/spatial dispersion

Related problem: non-local response of metals and the Casimir effect

Kats, Barton, Contreras-Reyes, Esquivel-Sirvent, Mochan, Svetovoy, Villareal, Intravaia, Klimchitskaya, Mostepanenko, Henkel

vdW with aqueous solution: B. Davies and B. W. Ninham, J. Chem. Phys. (1972)

Nonlocal response

Electrodynamics in the aqueous solution: movable ions

$$\mathbb{E} = \epsilon_b \, \mathbb{1} + \frac{i}{\omega} \, \mathbb{O}$$

Hydrodynamical model

Transverse permittivity $\epsilon_t(\omega) \;=\; \epsilon_b(\omega) - \frac{\omega_P^2}{\omega(\omega + i\gamma)}$

Longitudinal permittivity: nonlocal, Debye screening length λ_D

$$\epsilon_\ell(\mathbf{K}, \omega) \;=\; \epsilon_b(\omega) - \left(\frac{\omega(\omega + i\gamma)}{\omega_P^2} - \frac{\lambda_D^2}{\epsilon_b} K^2 \right)^{-1}$$

B. Davies and B. W. Ninham, J. Chem. Phys. (1972)

Screening of the Casimir force

Casimir interaction across an electrolyte

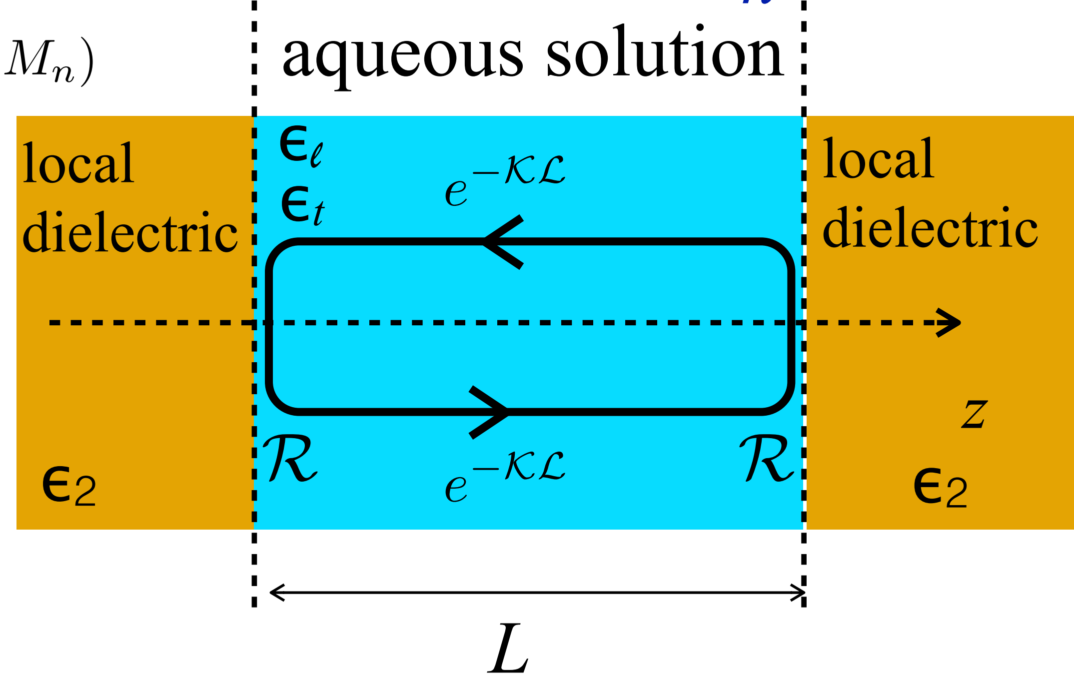
Scattering formula: sum over Matsubara frequencies $\xi_n = 2\pi \frac{k_B T}{\hbar} n$

$$\mathcal{F} = k_B T\, A \sum_{n=0}^{\infty}{}' \int \frac{d^2k}{(2\pi)^2} \ln\det(1 - M_n)$$

$$M_n = \mathcal{R}\, e^{-\mathcal{K}L}\, \mathcal{R}\, e^{-\mathcal{K}L}$$

$$\mathcal{R} = \begin{pmatrix} r_{ss} & 0 & 0 \\ 0 & r_{pp} & r_{p\ell} \\ 0 & r_{\ell p} & r_{\ell\ell} \end{pmatrix}$$

describes the coupling between TM-polarized transverse waves (p) and longitudinal waves



plasma frequency for ions:

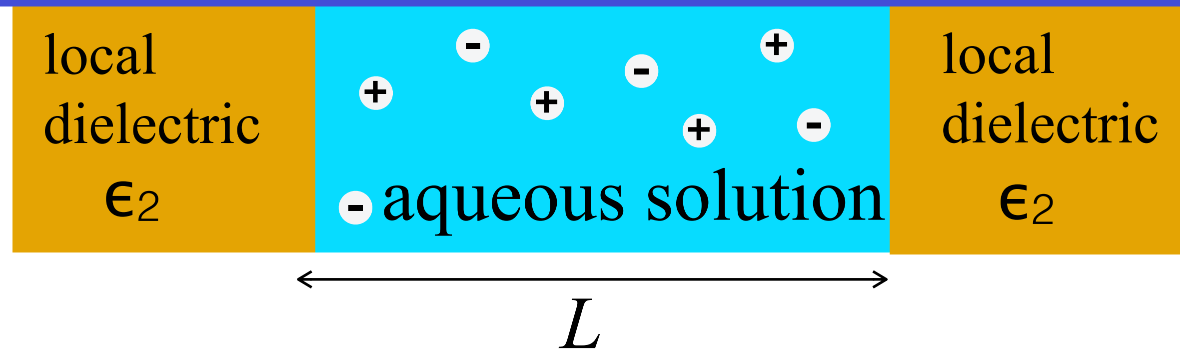
$\omega_P \ll k_B T/\hbar$ ⇨

- only zero-frequency contribution is modified
- no coupling between TM and longitudinal channels

PAMN, Rosa, Pires, Moraes, Canaguier-Durand, Guérout, Lambrecht, Reynaud, EPJD (2019)

Screening of the Casimir force

Parallel planar interfaces



- zero-frequency limit of the longitudinal reflection amplitude:

$$r_{\ell\ell} = \frac{\epsilon_b\sqrt{k^2 + 1/\lambda_D^2} - \epsilon_2 k}{\epsilon_b\sqrt{k^2 + 1/\lambda_D^2} + \epsilon_2 k}$$

- Scattering approach: screened longitudinal contribution and non-screened transverse magnetic (TM) one [Apéry's constant $\zeta(3) \approx 1.20$]

$$\frac{\mathcal{F}_{n=0}}{A} = \frac{k_B T}{2}\left[-\frac{\zeta(3)}{8\pi L^2} + \int \frac{d^2k}{(2\pi)^2} \ln\left(1 - r_{\ell\ell}^2 e^{-2\sqrt{k^2+1/\lambda_D^2}L}\right)\right]$$

- Previous result, from fluctuational electrostatics: zero-frequency completely screened. Mitchell & Richmond (1974), Mahanty & Ninham 1976, Parsegian 2006

$$\frac{\mathcal{F}_{n=0}^{\mathrm{LPB}}}{A} = \frac{k_B T}{2}\int \frac{d^2k}{(2\pi)^2} \ln\left(1 - r_{\ell\ell}^2 e^{-2\sqrt{k^2+1/\lambda_D^2}\,L}\right)]$$

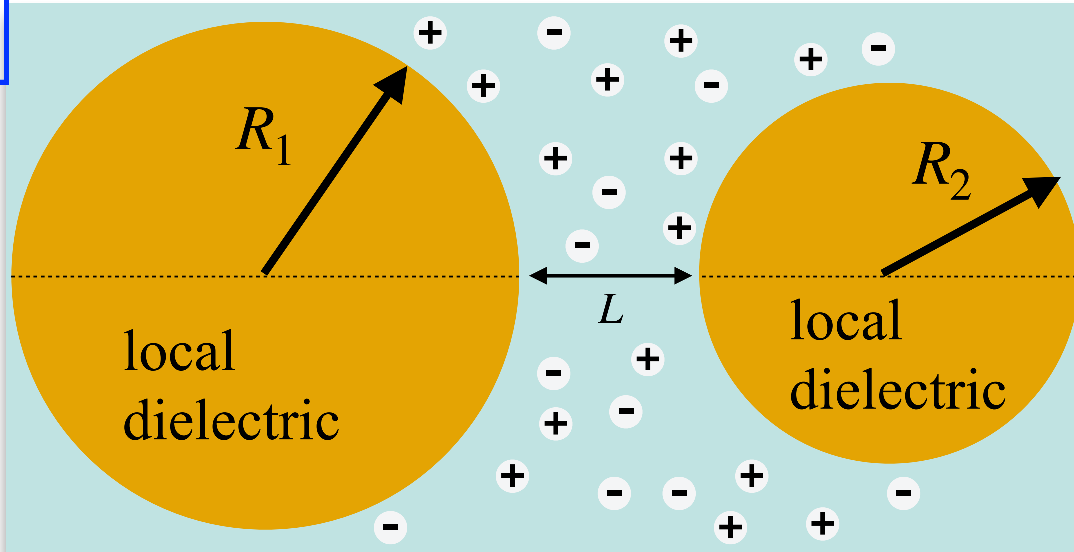
Maia Neto, Rosa, Pires, Moraes, Canaguier-Durand, Guérout, Lambrecht, Reynaud
EPJD (2019)

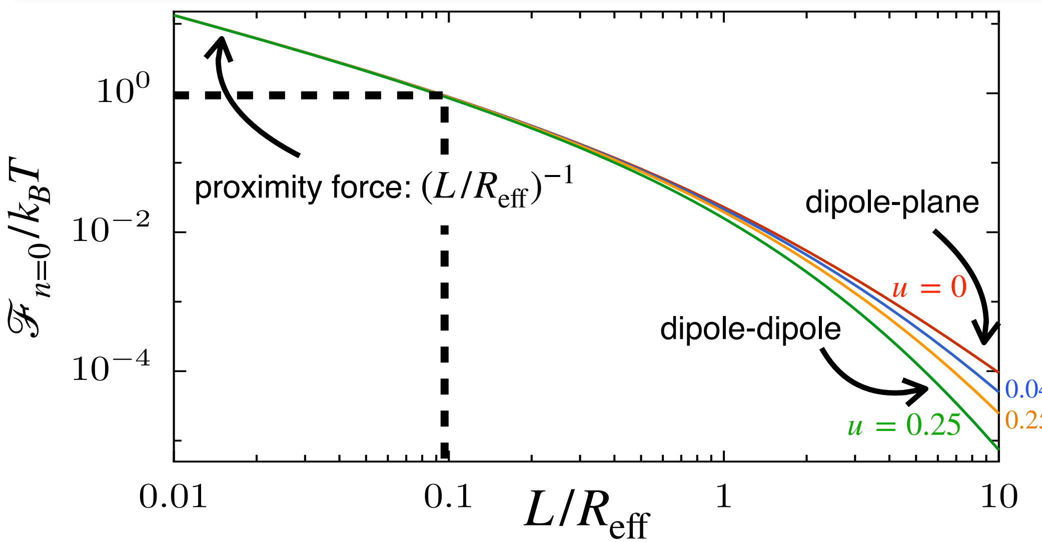
Screening of the Casimir force

two dielectric spheres

- We assume $L \gg \lambda_D \Rightarrow$ longitudinal contribution completely supressed by screening
- More general case: see Larissa Inacio's poster
- The only nonzero contribution modified by the ions is the zero-frequency transverse magnetic contribution
- effective radius $R_{\text{eff}} = \dfrac{R_1 R_2}{R_1 + R_2}$
- Free energy $\mathcal{F}_{n=0}/k_B T$ is an universal function of

$u = \dfrac{R_1 R_2}{(R_1 + R_2)^2}$ AND $x = L/R_{\text{eff}}$





Schoger, Spreng, Ingold, Maia Neto, Reynaud, Phys Rev Lett 2022

Screening of the Casimir force

two dielectric spheres

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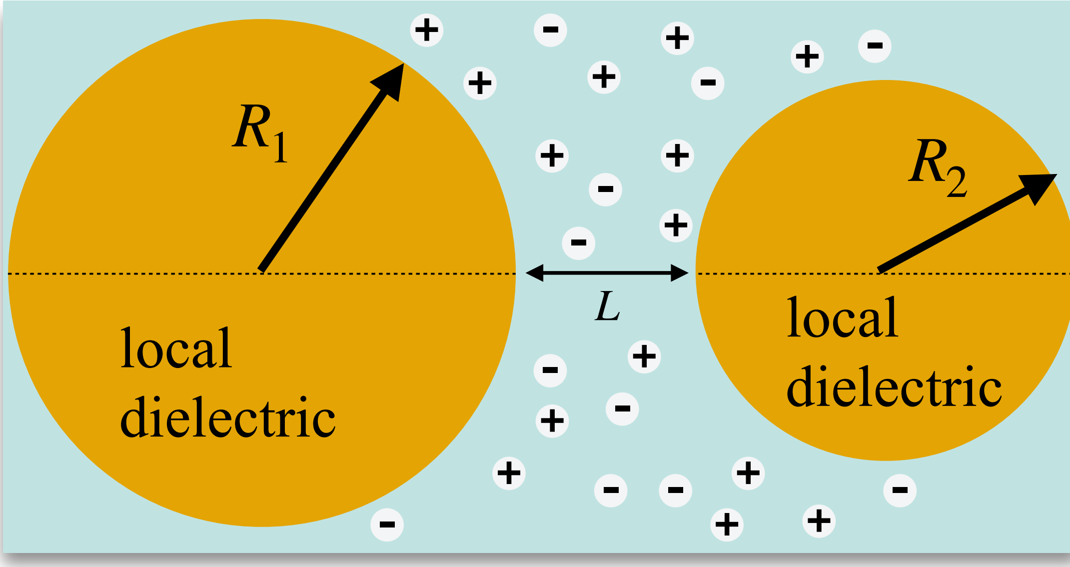
- Free energy $\mathcal{F}_{n=0}/k_B T$ is an universal function of

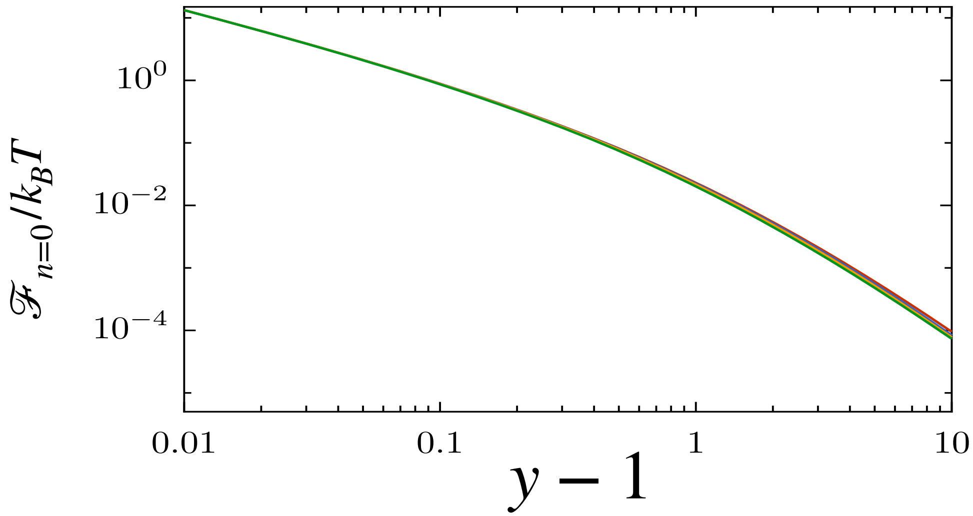
$$u = \frac{R_1 R_2}{(R_1 + R_2)^2} \quad \text{AND} \quad x = L/R_{\text{eff}}$$

- Better representation: conformally-invariant parameter (Fosco, Lombardo & Mazzitelli)

$$y = 1 + x + u\,\frac{x^2}{2}$$

- Similar universal function for Drude-vacuum-Drude configuration: Bimonte & Emig, Schoger & Ingold





Schoger, Spreng, Ingold, Maia Neto, Reynaud, Phys Rev Lett 2022

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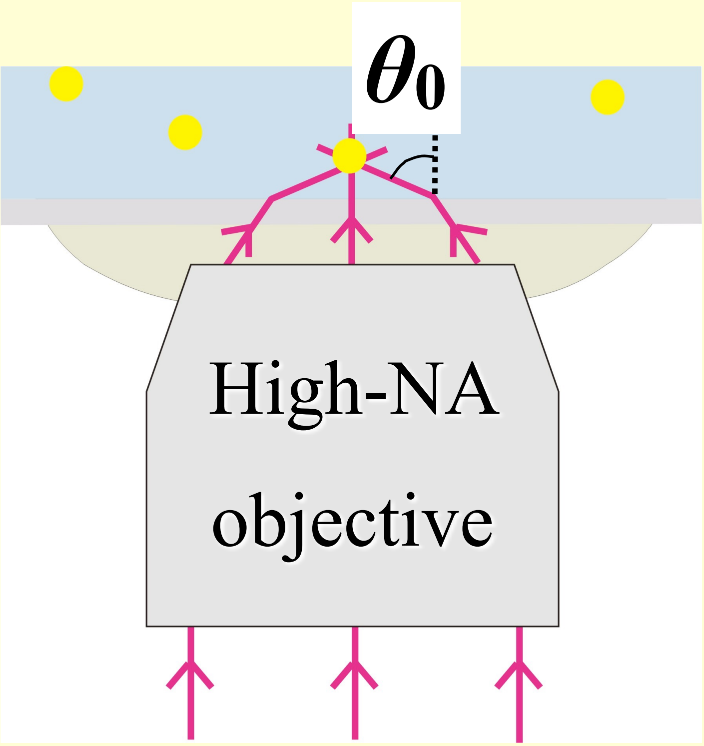
Optical Tweezers

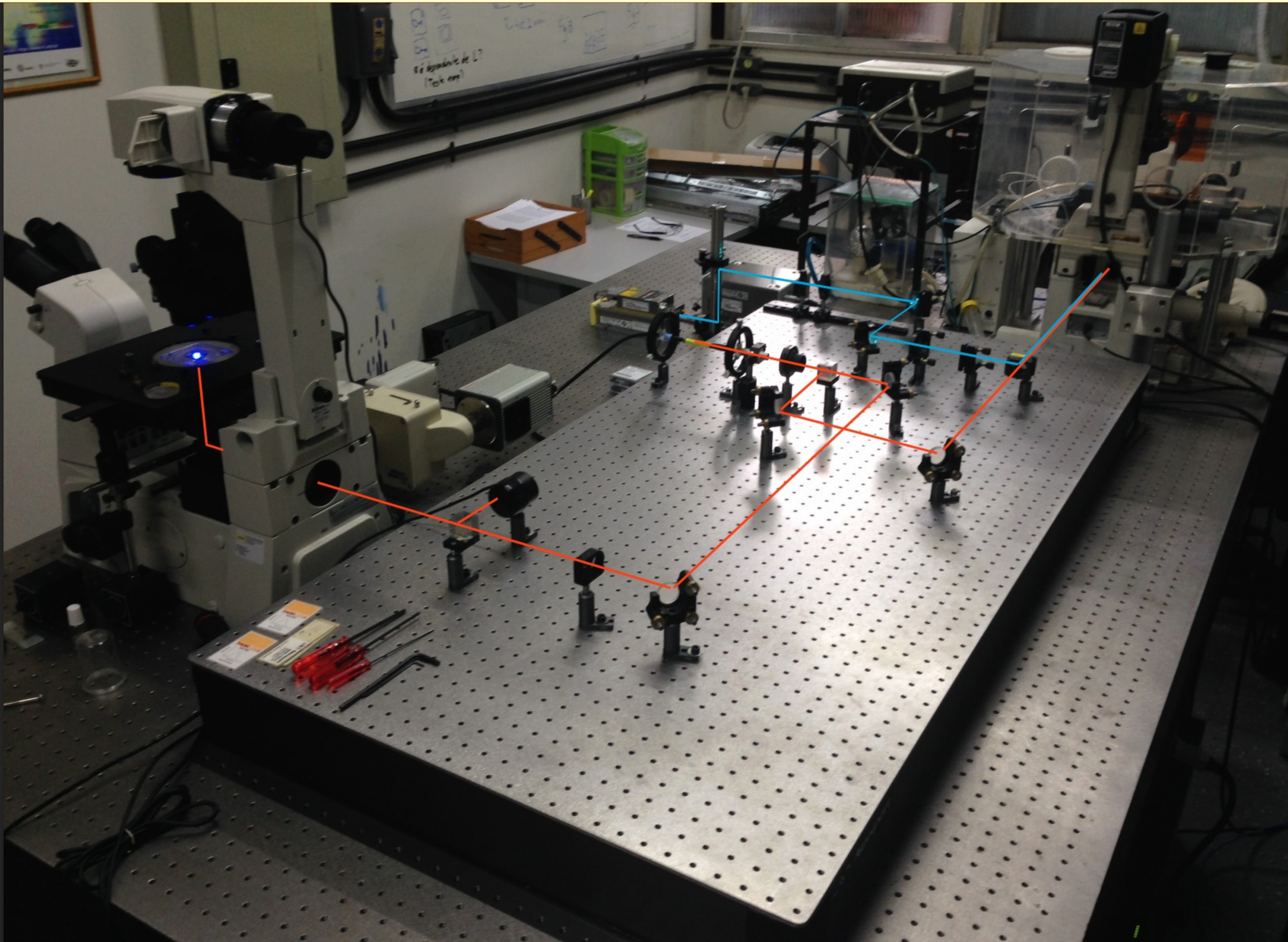
Optical trap with a single strongly focused laser beam...

➡ **"optical tweezers"**



$$\mathrm{NA} = n_{\mathrm{water}} \sin(\theta_0)$$

Optical Tweezers Lab in Rio



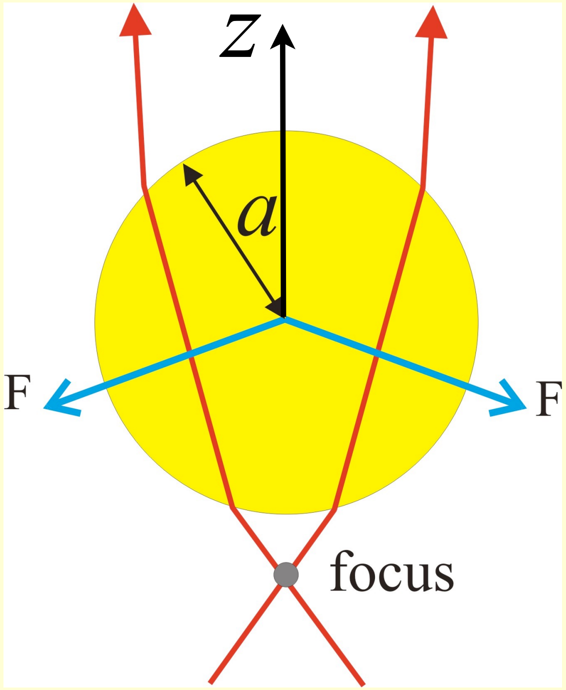
Optical Tweezers

Typically $a \sim \lambda$ ⟹ need many multipole terms (beyond dipole approximation) – **Mie scattering** regime

Physical picture in the ray optics regime $a \gg \lambda$

refracted rays: force **towards** the focus ('gradient force') ...

reflected rays: radiation pressure pushing along the propagation direction



Screening of the Casimir interaction

Motivation: Casimir force experiments with Optical Tweezers

→ material of the trapped microsphere must have refractive index slighlty higher than external medium @ laser wavelength - silica in water

→ materials allowing for trapping are such that positive Matsubara frequencies provide relatively small contribution

Measuring the Casimir interaction

Casimir (van der Waals) experiments with Optical Tweezers

trap stiffness $k \propto$ laser power P

can be tuned to very small values

$k \sim \mathrm{fN/nm}$

measuring fN forces between silica microspheres in aqueous solution at distances ~ 100 nm

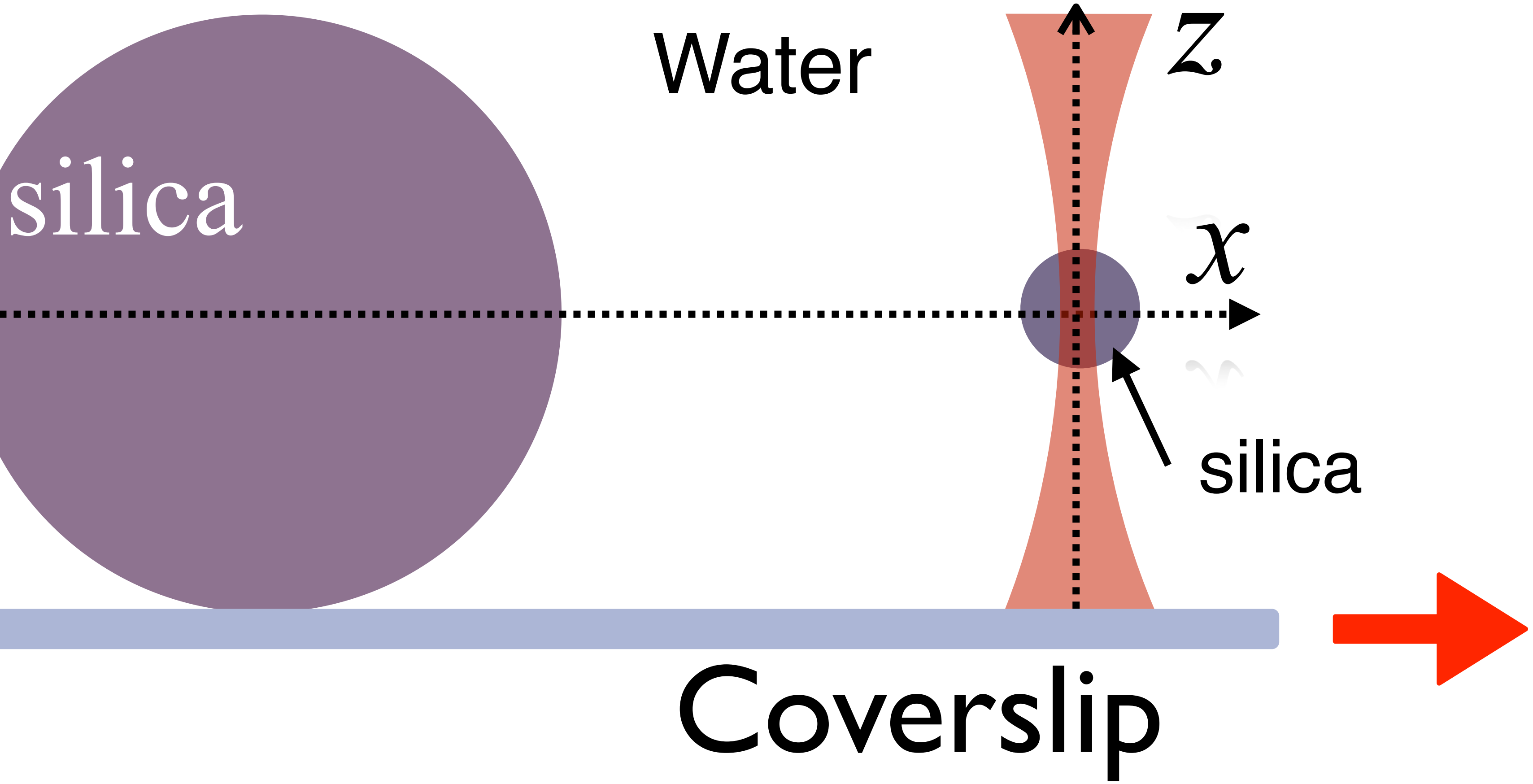
Casimir interaction: radiation pressure of the **quantum electromagnetic field modes in thermal equilibrium**

Typical (usually AFM) measurements of the van-der-Waals/Casimir interaction across an electrolyte (polar liquid)

- **metallic surfaces**: distance ~ 100 nm (Munday, Palasantzas, Svetovoy, Ciliberto,…)
- **dielectric surfaces**: distance ~ 1 nm (Borkovec, Trefalt,…)

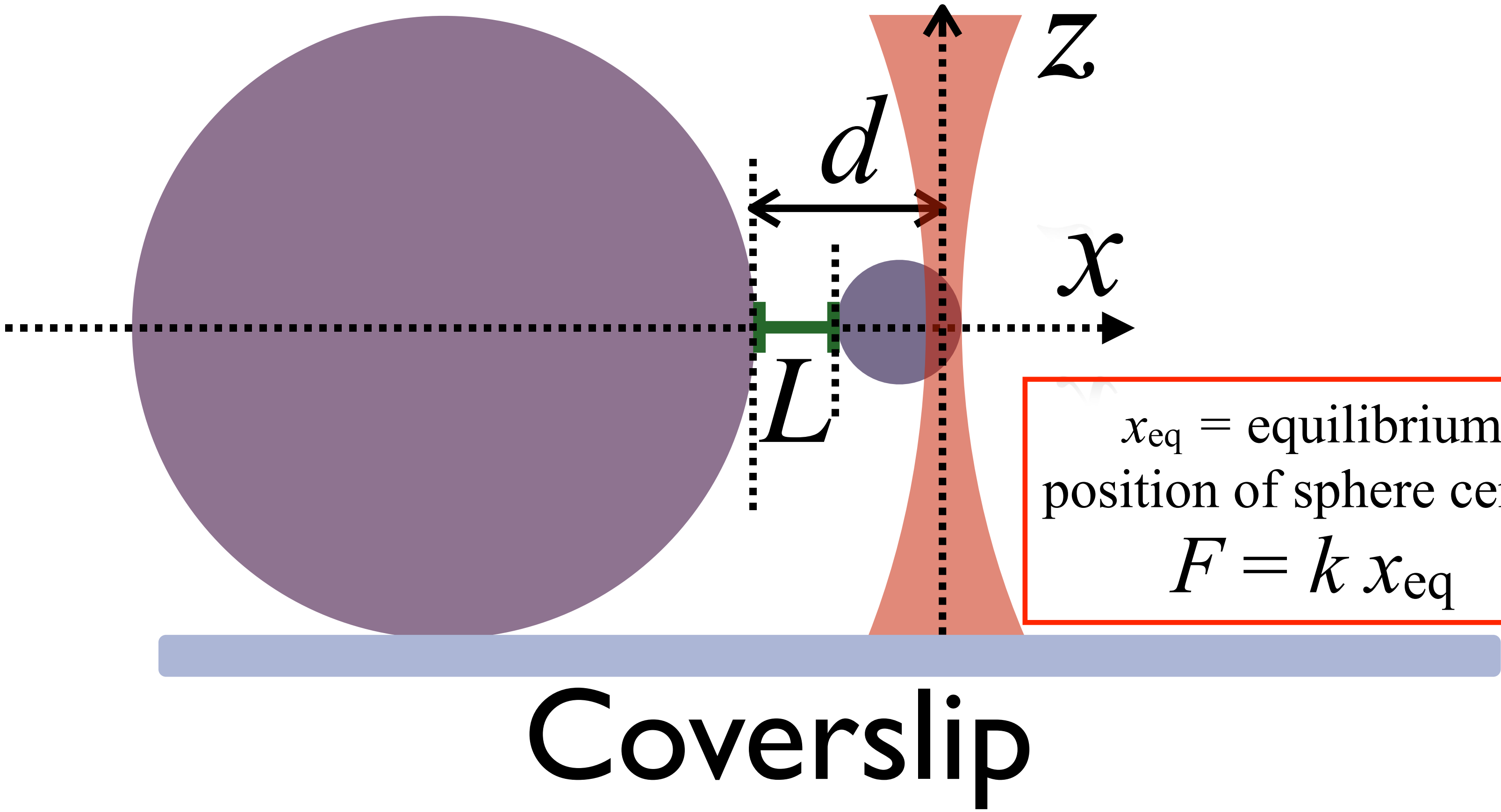
In both cases, Matsubara zero frequency contribution is usually negligible, and so is screening!

Measuring the Casimir force



D. S. Ether Jr, L. B. Pires, S. Umrath et al., EPL **112**, 44001 (2015)

Measuring the Casimir force



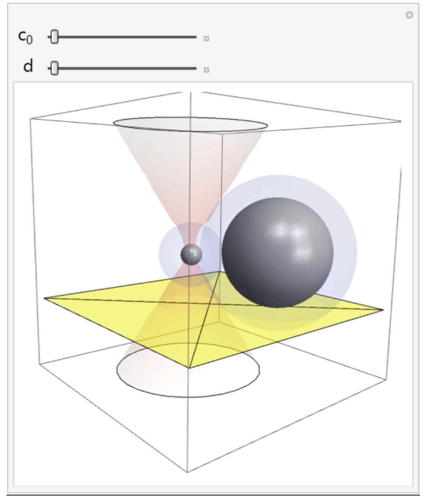
x_{eq} = equilibrium position of sphere center

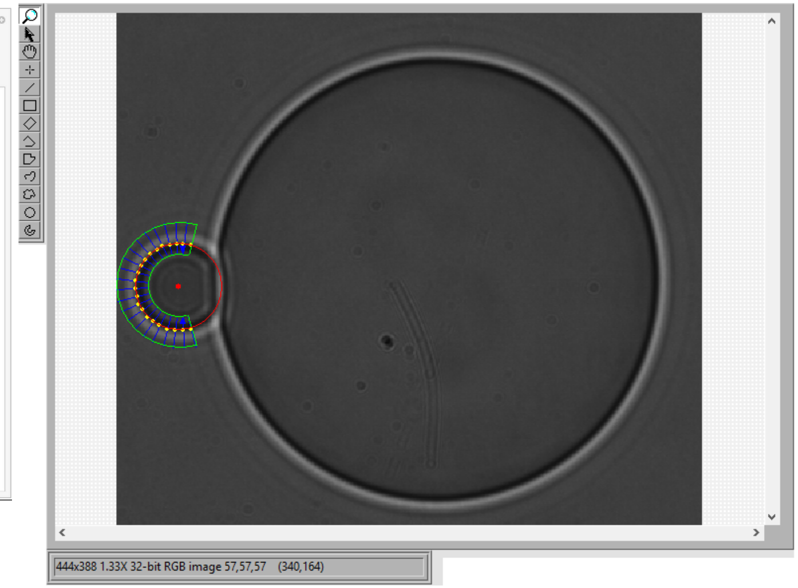
$$F = k\, x_{\text{eq}}$$

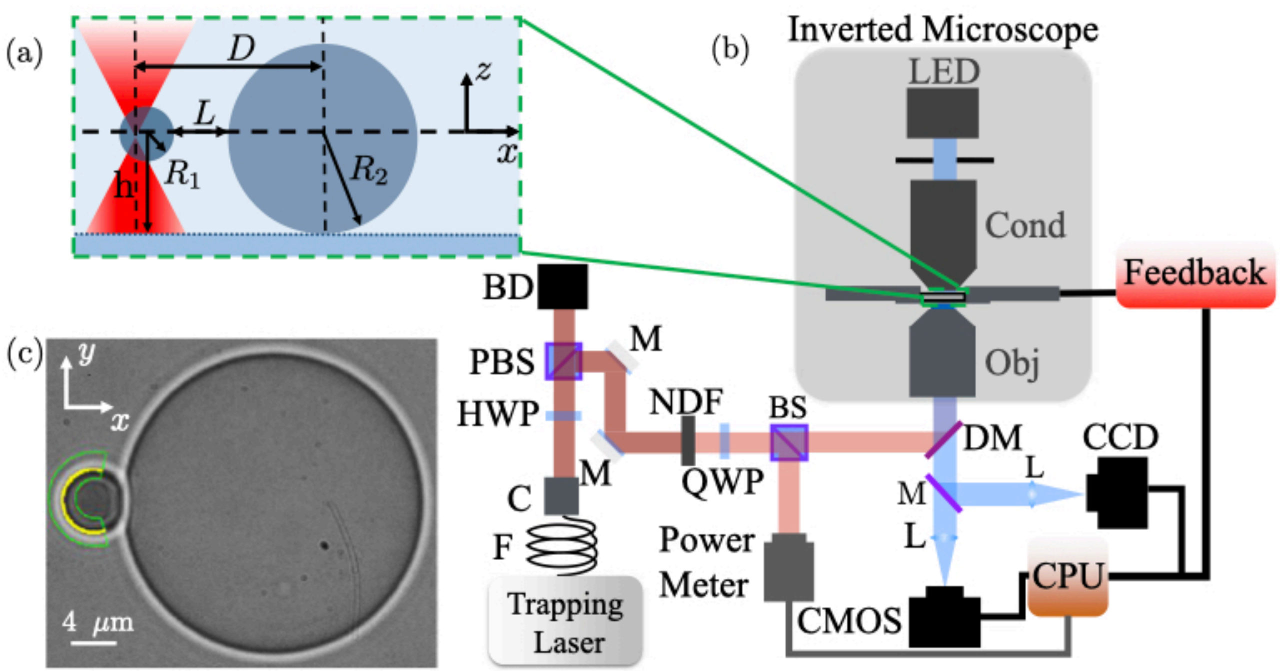
D. S. Ether Jr, L. B. Pires, S. Umrath et al., EPL **112**, 44001 (2015)

measuring the interaction energy from fluctuations

Fluctuations of a trapped sphere near a bigger sphere attached to the glass slide







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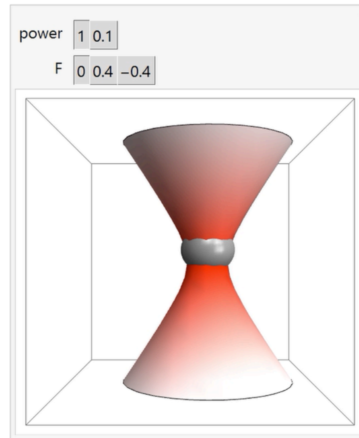
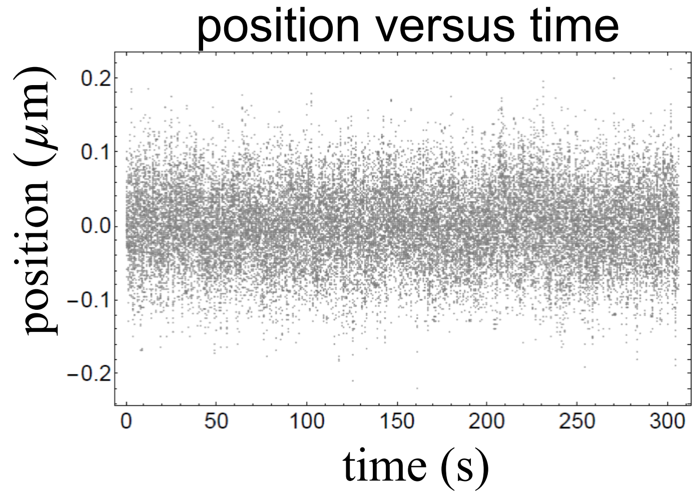
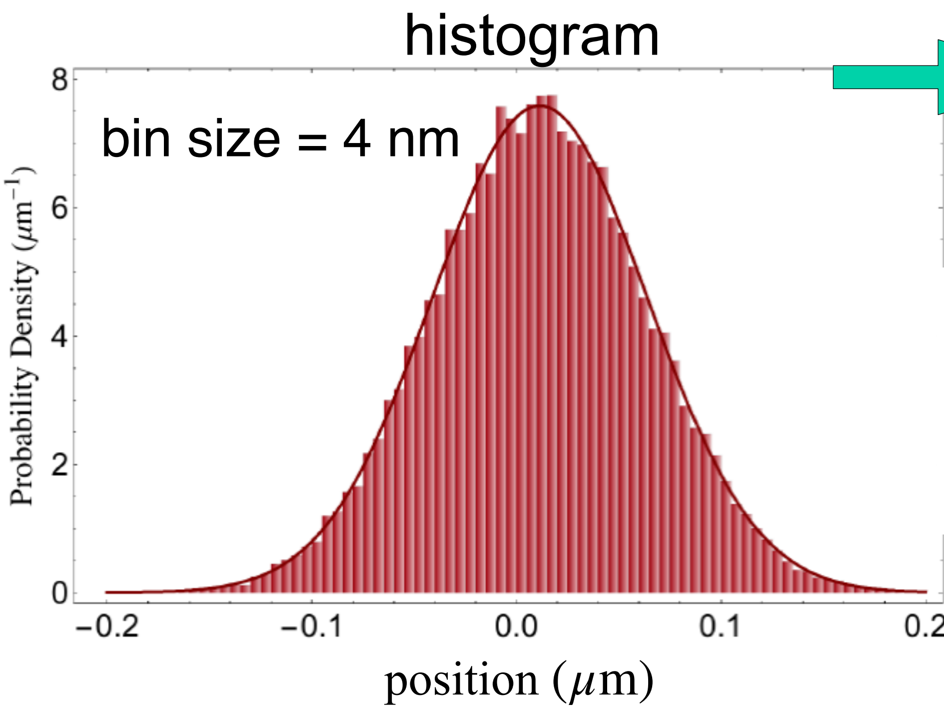
measuring the fluctuations

Isolated trapped sphere: Brownian fluctuations at thermal equilibrium

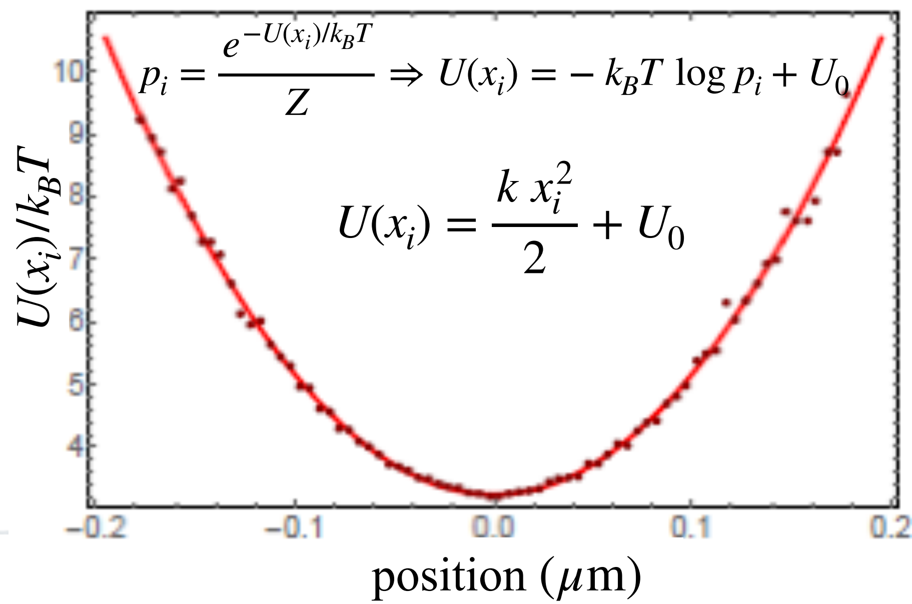






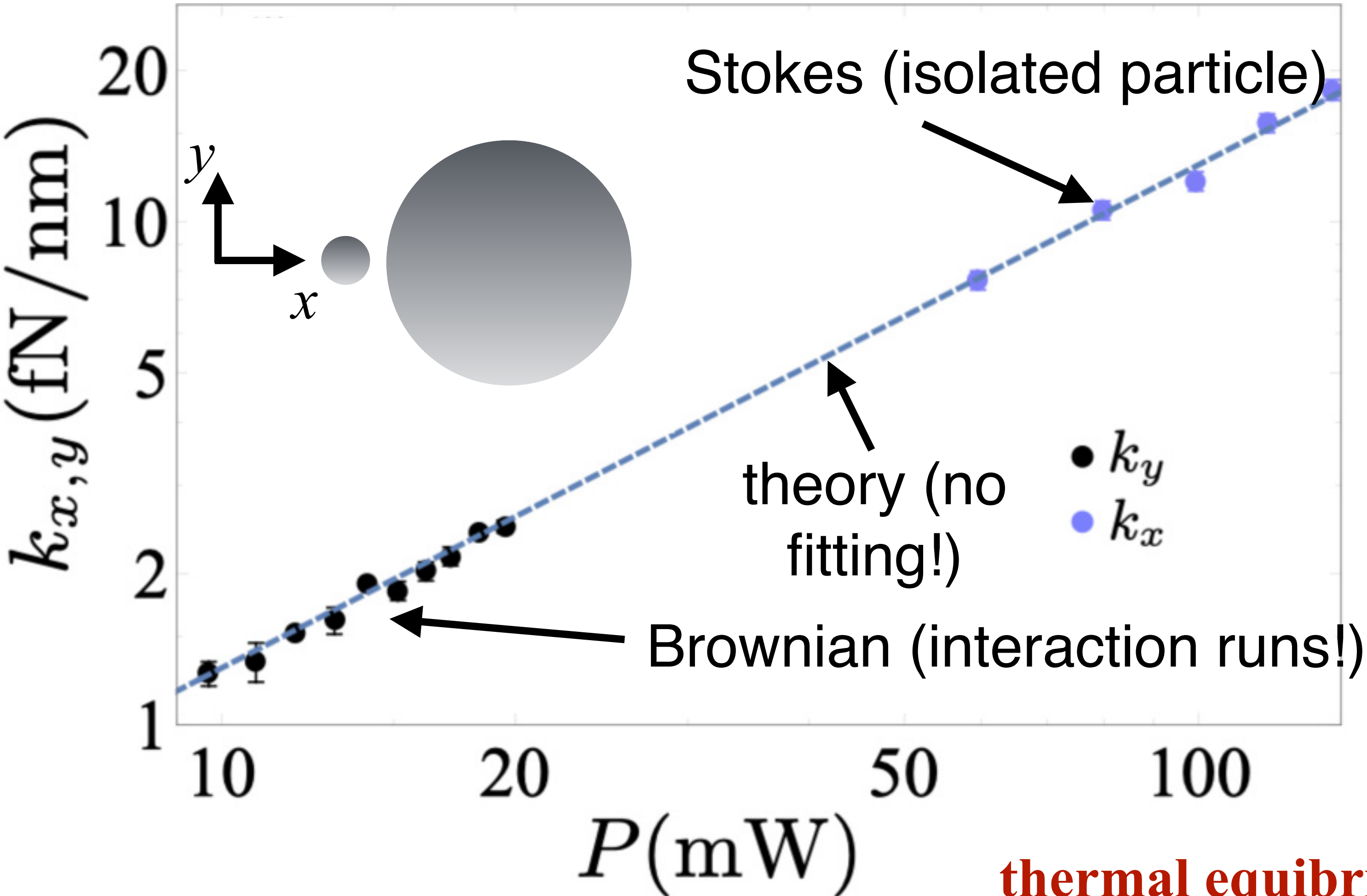
probability distribution p_i

$$\lim_{N\to\infty} \frac{N_i}{\sum_{i=1}^{N} N_i} = p_i$$



Brownian and Stokes calibrations

Since the trapping beam is circularly polarized, we expect $k_x = k_y$



thermal equibrium!

L. B. Pires, D. S. Ether Jr, B. Spreng et al., Phys Rev Res. 2021

measuring the interaction energy from fluctuations

each run: 5000 frames

sampling time = 100 ms

correlation time @ 1 micron: $\tau = \gamma_{\text{drag}}/k = 100\,\text{ms}$

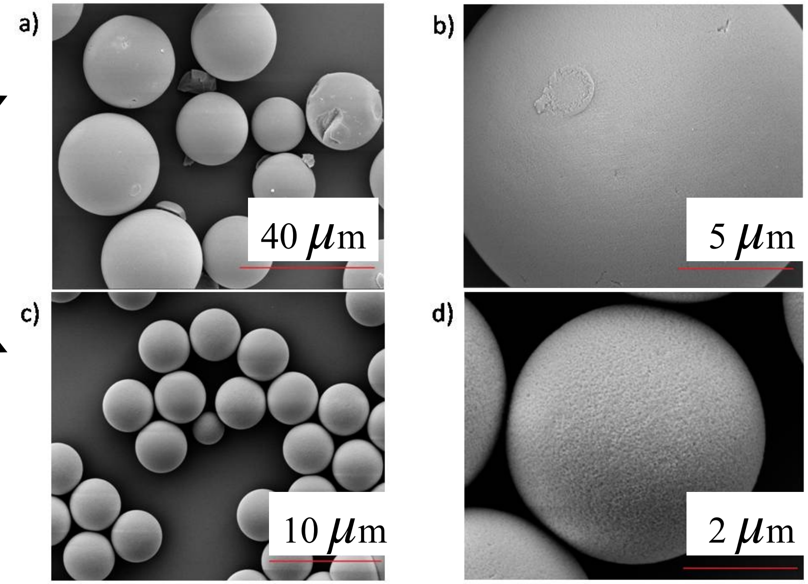
exposure time = 1 ms

HRSEM images of silica microspheres

Radii:

$R_1 = (11,74 \pm 0,09)\ \mu\text{m}$

$R_2 = (2,35 \pm 0,02)\ \mu\text{m}$



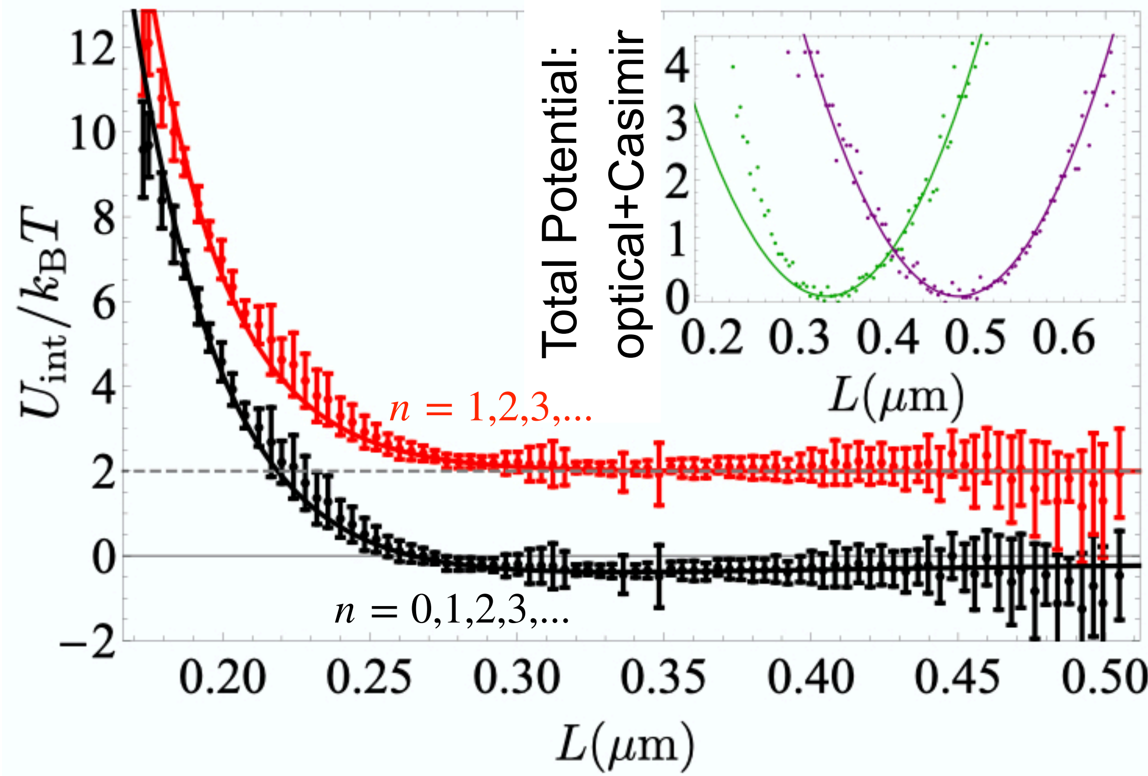
measuring the interaction energy from fluctuations

Low salt concentration:

Debye length

$$\lambda_D \sim 30\,\text{nm}$$

- several runs
- subtract optical potential



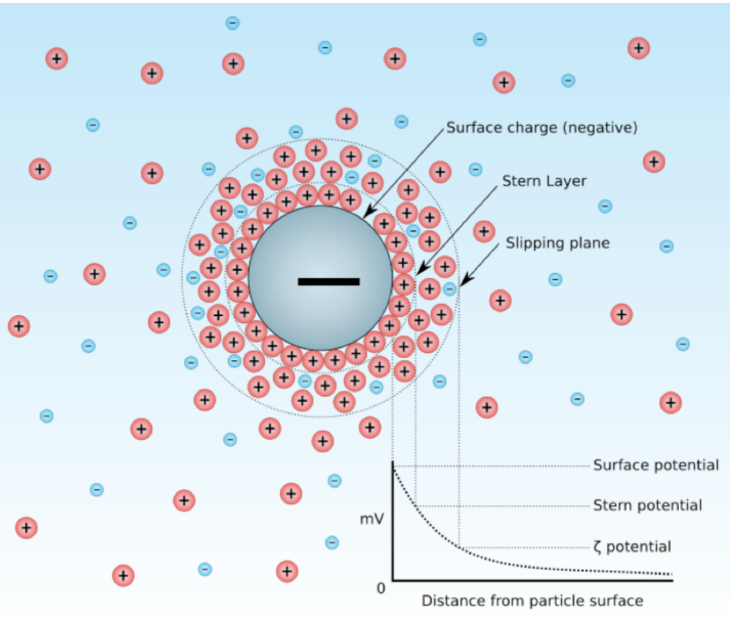


TABLE II: Parameters employed for the curve fit of the measured interaction energy: charge density σ and Debye screening length $\lambda_{\rm D}$. In addition to the double-layer interaction energy (3), we also consider the Casimir interaction either with or without the zero-frequency TM contribution.

Casimir model	σ (mC/m^2)	$\lambda_{\rm D}$ (nm)
$n = 1, 2, \ldots$	-1.7 ± 0.3	25.0 ± 0.9
$n = 0, 1, 2, \ldots$	-0.8 ± 0.1	29.3 ± 0.6

L. B. Pires, D. S. Ether Jr, B. Spreng et al., Phys Rev Res. 2021

measuring the interaction energy from fluctuations

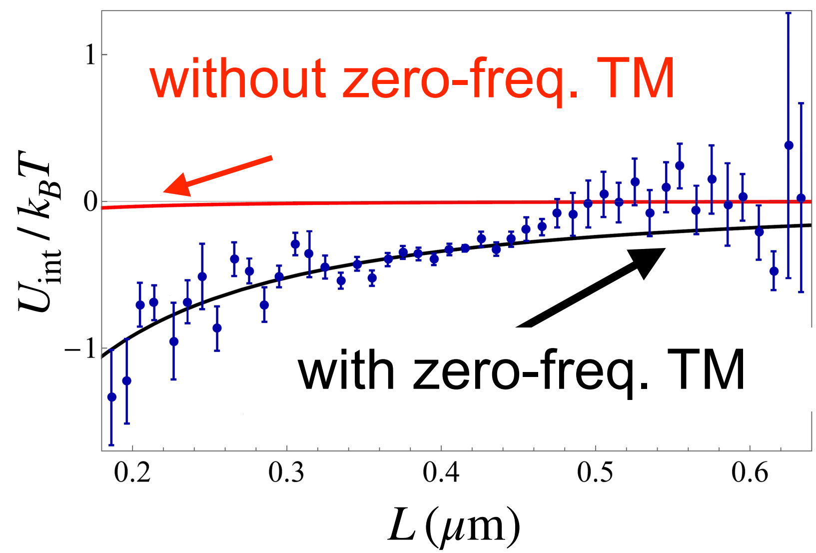
High salt concentration (0.22 M):

Debye screening length $\lambda_D = 0.64\,\mathrm{nm}$

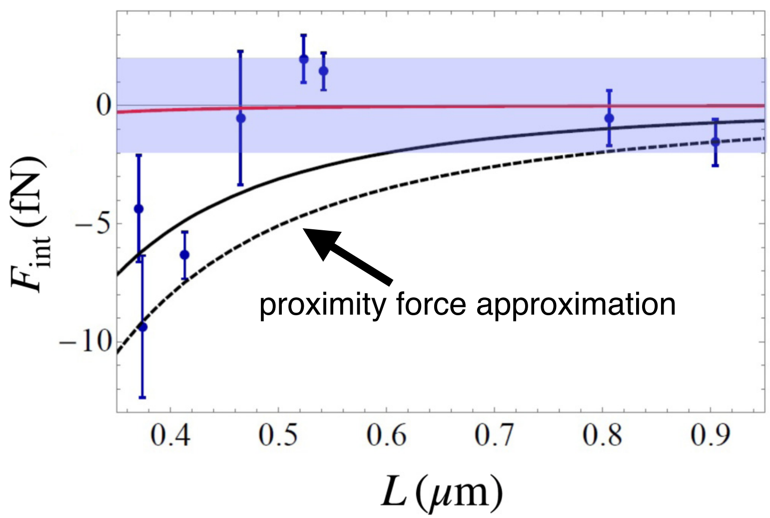
- several runs
- subtract optical potential

no fitting!!

Casimir potential versus distance



Casimir force



$\} \; \sigma_x \sim 2\,\mathrm{nm} \Rightarrow \sigma_F \sim 2\,\mathrm{fN}$

L. B. Pires, D. S. Ether Jr, B. Spreng et al., Phys Rev Res. 2021

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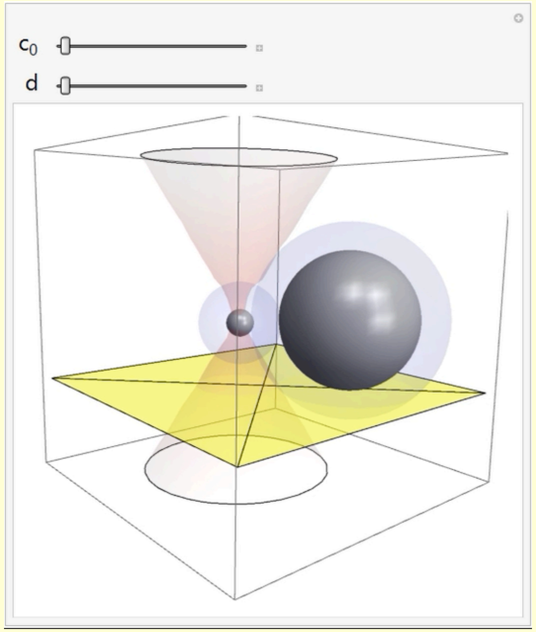
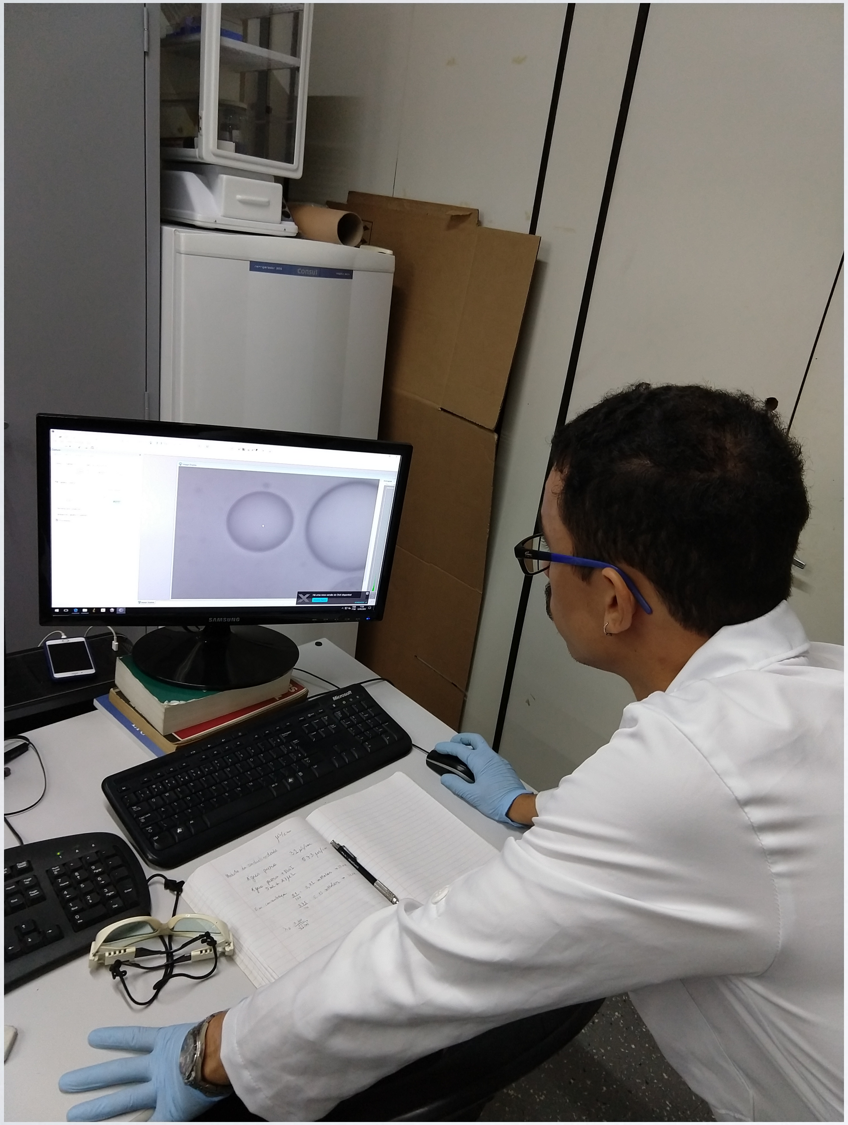
Conclusion

Casimir interaction between dielectric microspheres in aqueous solution: **contribution from transverse magnetic polarization at zero frequency**

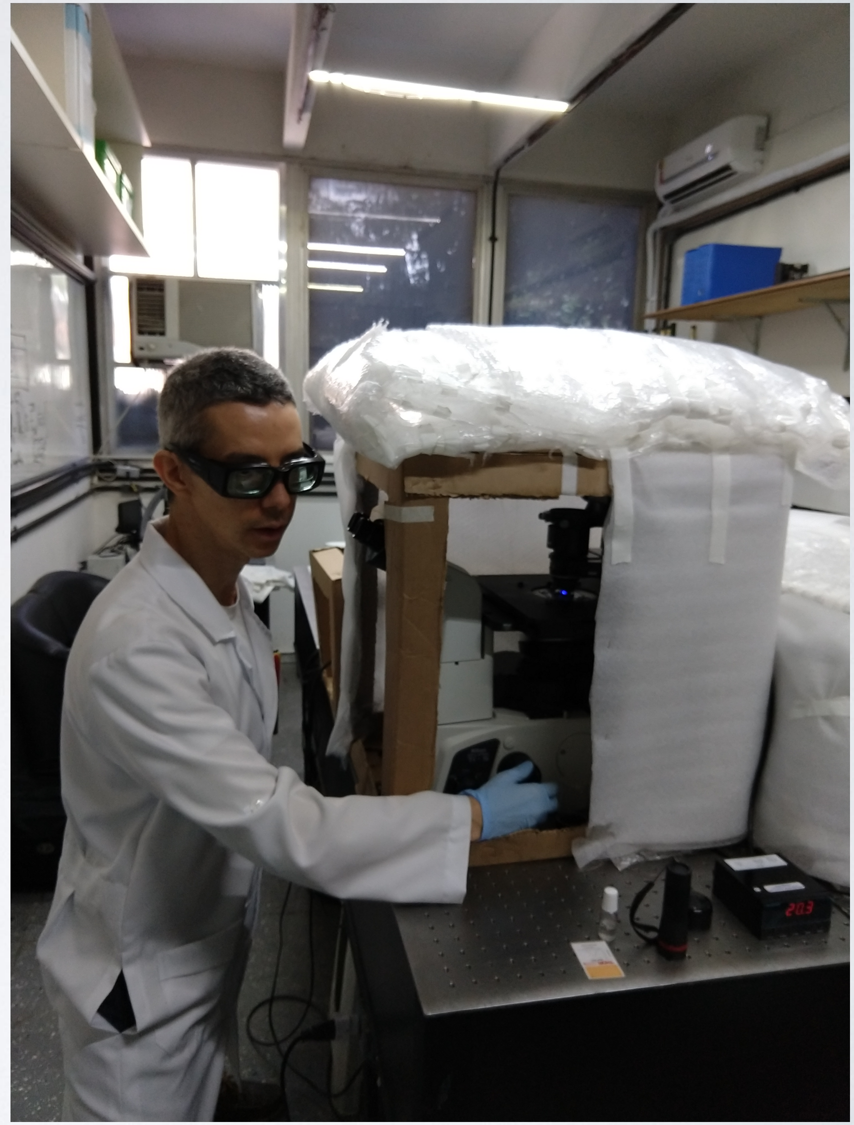
- unscreened !
- interaction is of a longer range than previously thought
- zero frequency dominant at distances > 100 nm
- universal function of geometric aspect ratios
- interaction energy ~ $k_B T$ at $L/R_{\mathrm{eff}} \sim 0.1$
- measured with optical tweezers for silica microspheres in the distance range 200 - 500 nm



Measuring the Casimir force

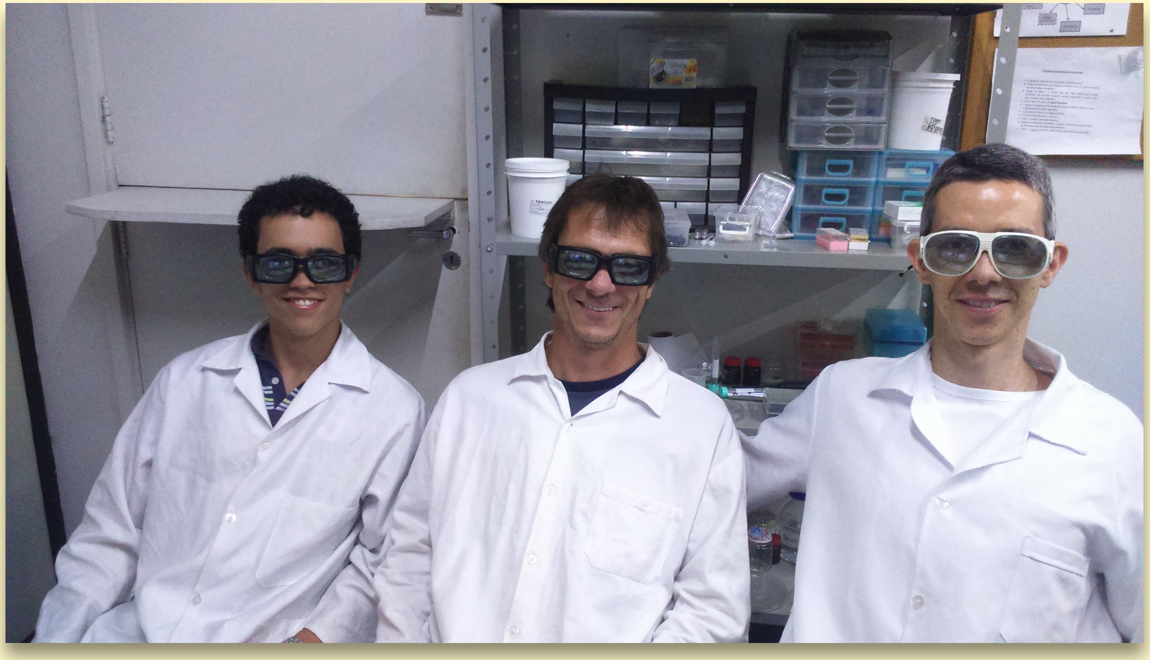


Luis Pires



Diney Ether Jr

Optical Tweezers UFRJ



Nathan Viana

Luis Pires

Ricardo Decca
IUPUI
Indianapolis
USA

Diney Ether

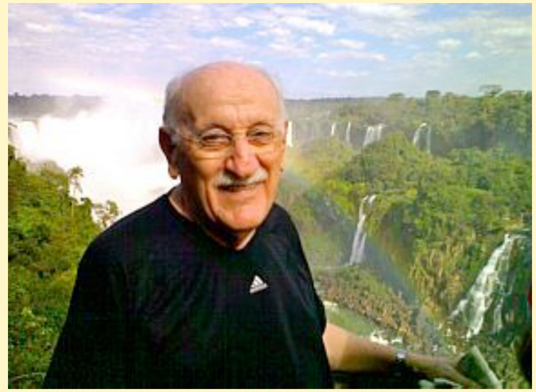
Kainã Diniz

Fran Gomez

Arthur Luna

Bruno Pontes

Instituto de Ciências Biomédicas -UFRJ



H. Moysés Nussenzveig

Instituto de Física

Susana Frases

Instituto de Biofísica Carlos Chagas Filho - UFRJ

Glauber Araújo (D)

Instituto de Biofísica Carlos Chagas Filho - UFRJ

Theory

IFRJ

Rafael Dutra

UFRJ

Felipe S. Rosa

Uni. Augsburg

Benjamin Spreng

Gert Ingold

Tanja Schoger

Stefan Umrath

LKB - ENS - Sorbonne

Serge Reynaud

Astrid Lambrecht

Antoine Canaguier-Durand

Romain Guerout

EPFL

Anne-Florence Bitbol

LPTMC - Sorbonne

Hélène Berthoumieux

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Thank you!

Mie theory of image formation

aligning the sphere centers: image contains info about z

PHYSICAL REVIEW APPLIED **15,** 064012 (2021)

Nonparaxial Mie Theory of Image Formation in Optical Microscopes and Characterization of Colloidal Particles

F. Gómez,[1] R.S. Dutra,[2] L.B. Pires,[1] Glauber R. de S. Araújo,[3] B. Pontes,[4,5] P.A. Maia Neto,[1,5] H.M. Nussenzveig,[1,5] and N.B. Viana[1,5,*]

[1] *Instituto de Física, Universidade Federal do Rio de Janeiro, Rio de Janeiro, RJ 21941-972, Brazil*
[2] *LISComp-IFRJ, Instituto Federal de Educação, Ciência e Tecnologia, Rua Sebastião de Lacerda, Paracambi, RJ 26600-000, Brazil*
[3] *Instituto de Biofísica Carlos Chagas Filho, Rio de Janeiro, RJ 21941-901, Brazil*
[4] *Instituto de Ciências Biomédicas, Universidade Federal do Rio de Janeiro, Rio de Janeiro, RJ, 21941-902, Brazil*
[5] *CENABIO—Centro Nacional de Biologia Estrutural e Bioimagem, Universidade Federal do Rio de Janeiro, Rio de Janeiro, RJ, 21941-902, Brazil*

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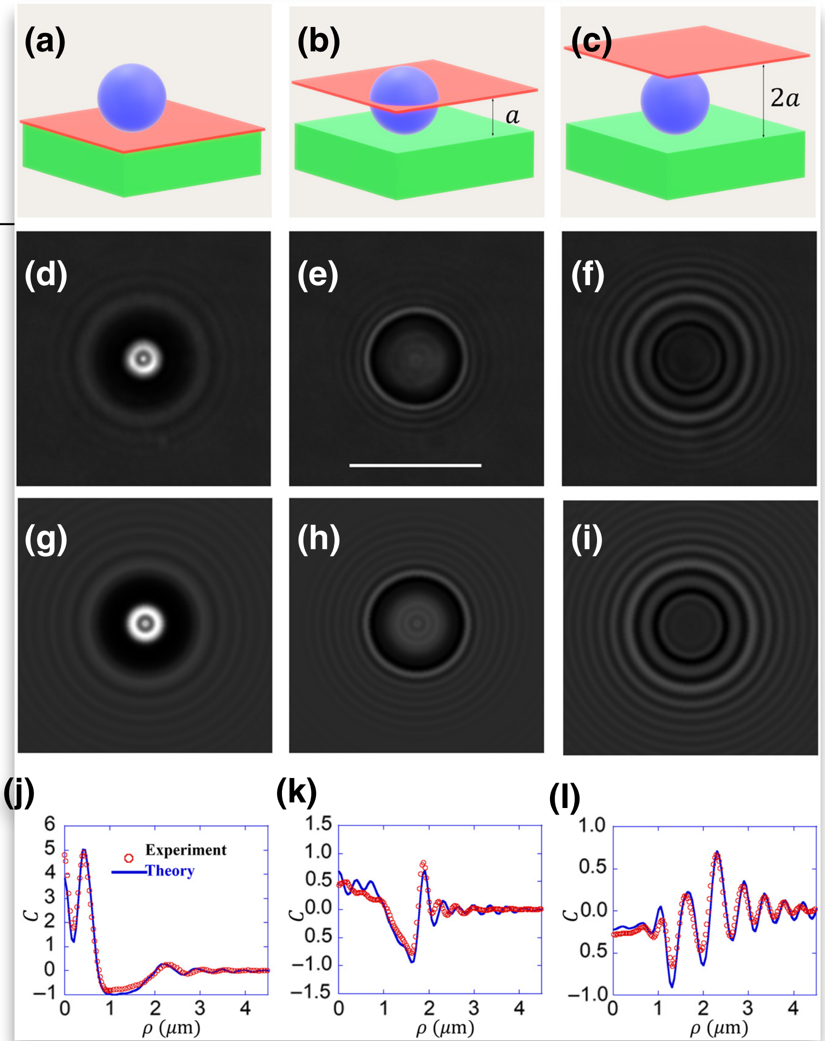


sensitivity of the position measurement

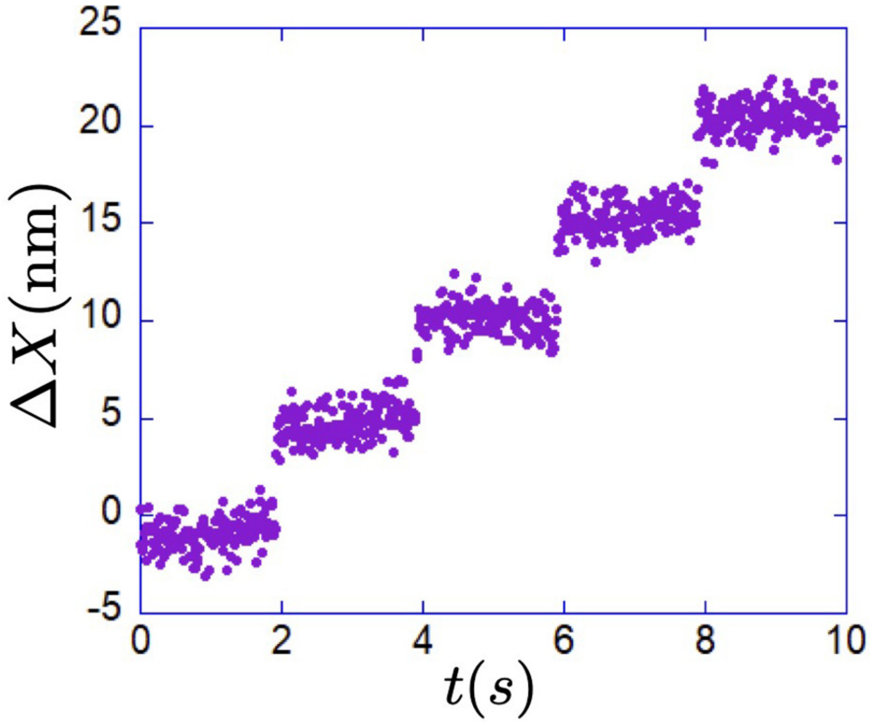


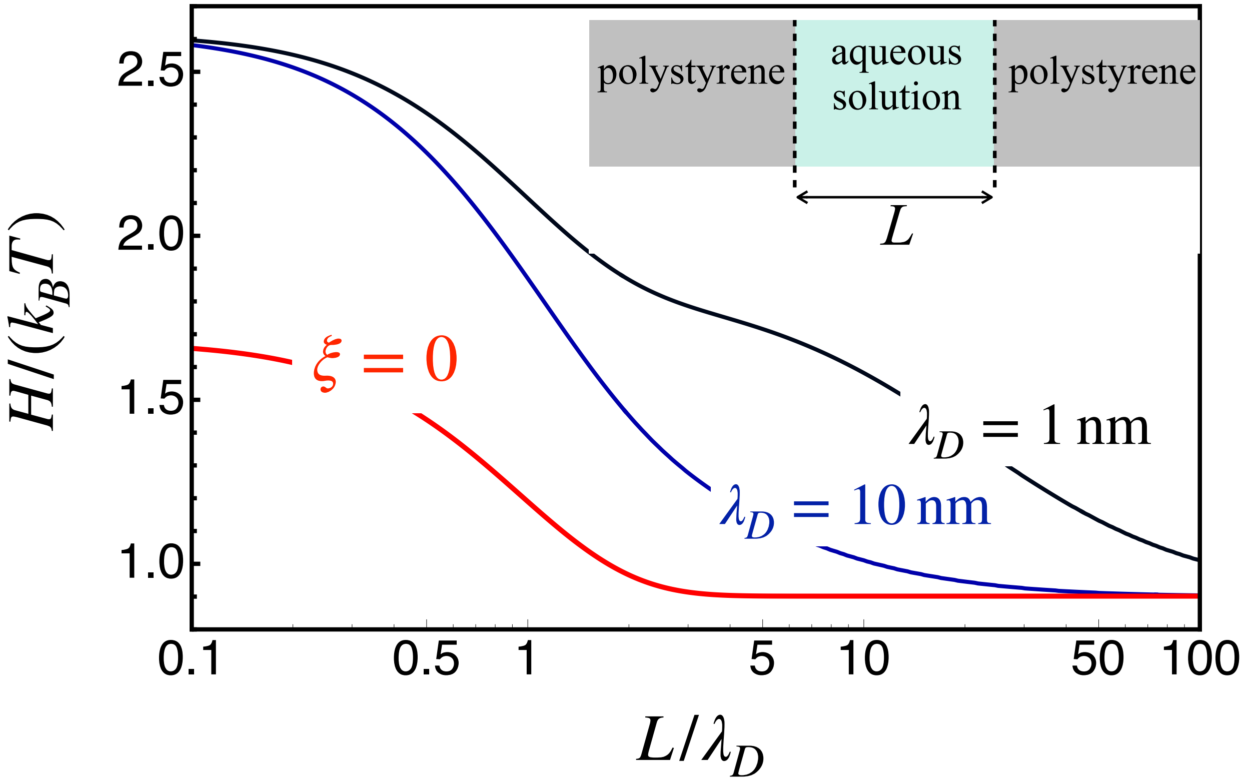
FIG. 7. Microsphere position versus time. A silica microsphere is adhered to the cover slip, which is driven laterally by 5 nm every 2 s with the help of a piezoelectric nanopositioning system.

Screening of the Casimir force

Numerical example Polystyrene - aqueous solution - Polystyrene $T = 293\,\text{K}$

Lorentz model for water and polystyrene - parameters taken from P.J. van Zwol and G. Palasantzas, PRA **81,** 062502 (2010)

$$\text{Hamaker constant}: \; H = -12\pi L^2 \frac{\mathcal{F}_{PP}}{A}$$



Maia Neto, Rosa, Pires, Moraes, Canaguier-Durand, Guérout, Lambrecht, Reynaud EPJD (2019)