Casimir force experiments:

beyond the accuracy issue

davide iannuzzi - vrije universiteit amsterdam

An interesting (and useful) analogy

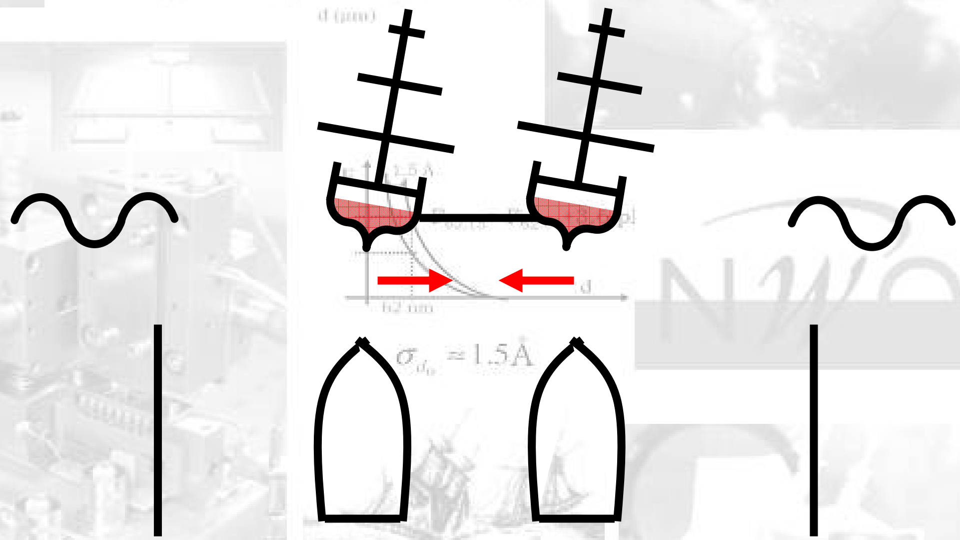
P.C.Caussée (1836)
L'Album du Marin

Two ships, standing parallel in the wavy sea, are driven one against the other by a mysterious attractive force

S. L. Boersma
Am. J. Phys. **64** (1996) 539

The two ships act like barriers

They are pushed one against the other by the waves outside "the gap"



The zero-point energy

Maxwell equations

Uncertainty principle

Energy of a mono-chromatic e.m. wave

$$E_n = \hbar\omega\left(n + \frac{1}{2}\right)$$

→ Vacuum

$$n = 0 \qquad \forall\, \omega$$

$$E_0 = \frac{1}{2}\hbar\omega$$

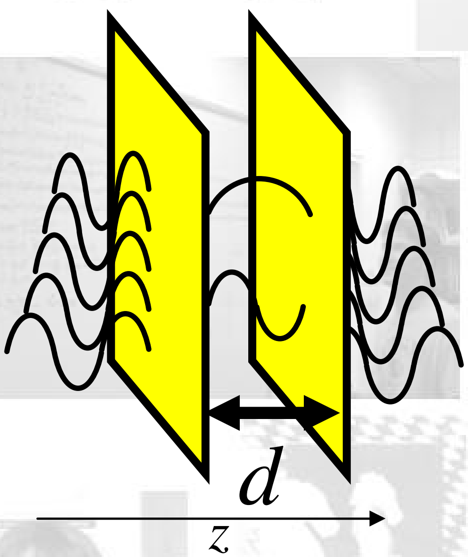
Vacuum is not empty!

Vacuum is filled with the energy produced by the quantum fluctuations of the electromagnetic field

The Casimir effect

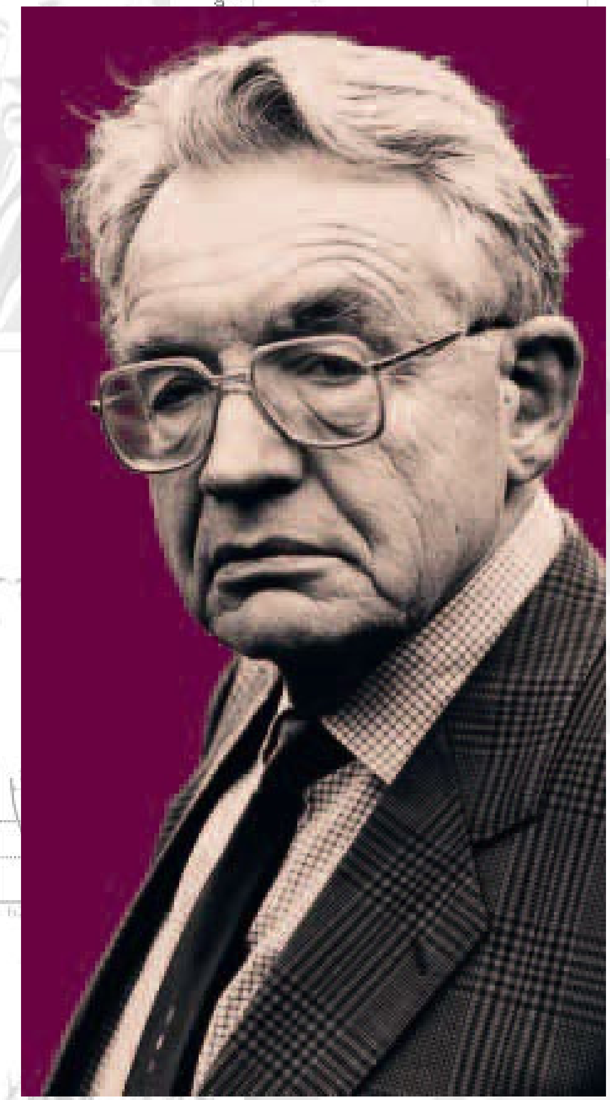
Two metallic parallel plates in vacuum: only some modes can exist

$$E = \sum_{\omega_m} \frac{1}{2}\hbar\omega_m; \quad \omega_m = c\left(k_x{}^2 + k_y{}^2 + \frac{\pi^2}{d^2}m^2\right)^{1/2}$$

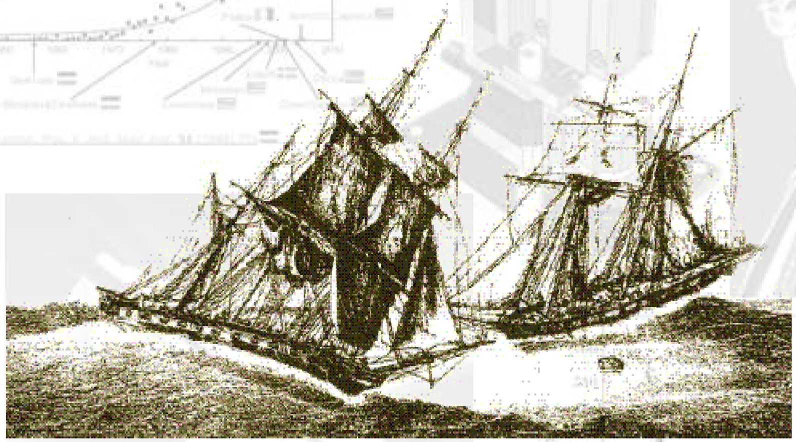


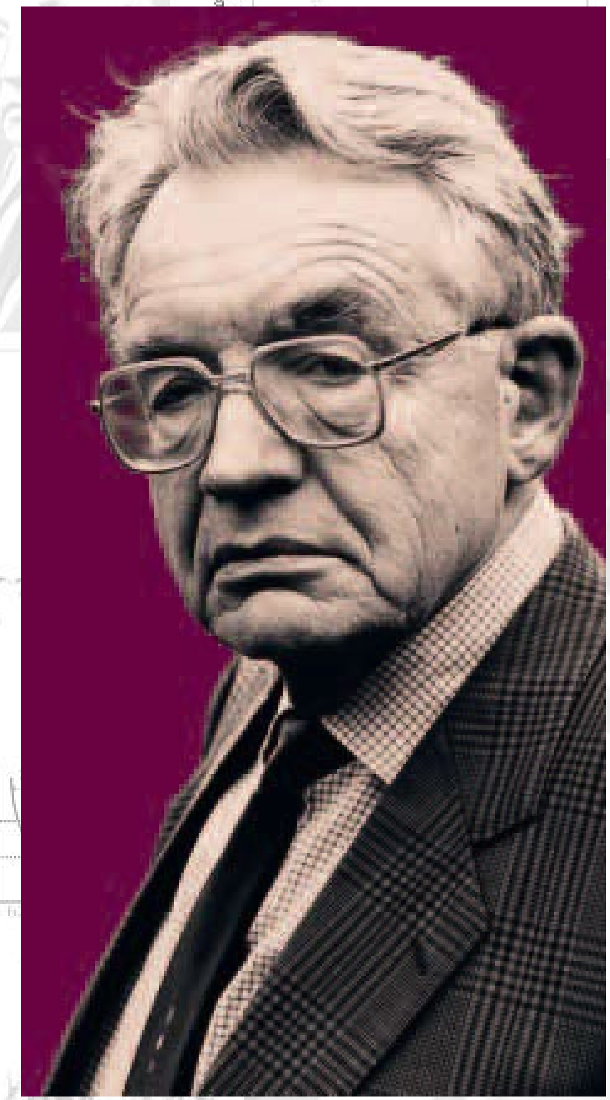
The zero-point energy depends on *d*, therefore:

$$F = -\frac{\partial E}{\partial d} = -\frac{\pi^2\hbar c}{240 d^4}L^2$$



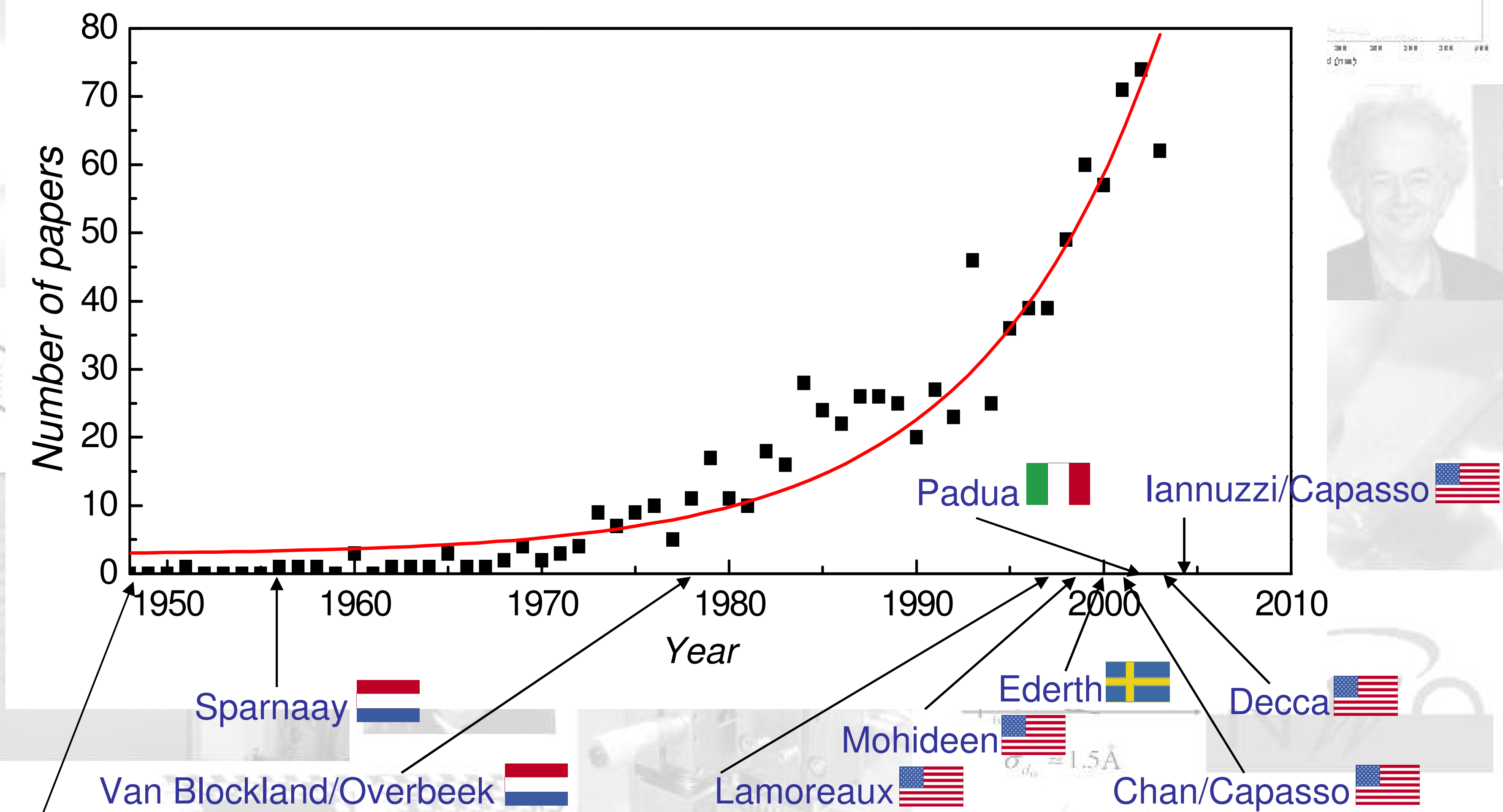
The Casimir effect





The plates act like ships in the wavy sea of electromagnetic quantum fluctuations

The Casimir effect: history of a paper



H. B. G. Casimir, *Proc. K. Ned. Akad. Wet.* **51** (1948) 793

Reasons of this renewed interest

- The only macroscopic manifestation of QED
- Zero-point energy problem
- Gravitation at short distances, extragravitational forces
- Micro- and Nanotechnologies

$$P = \frac{F}{L^2} = -\frac{\pi^2 \hbar c}{240\, d^4}$$

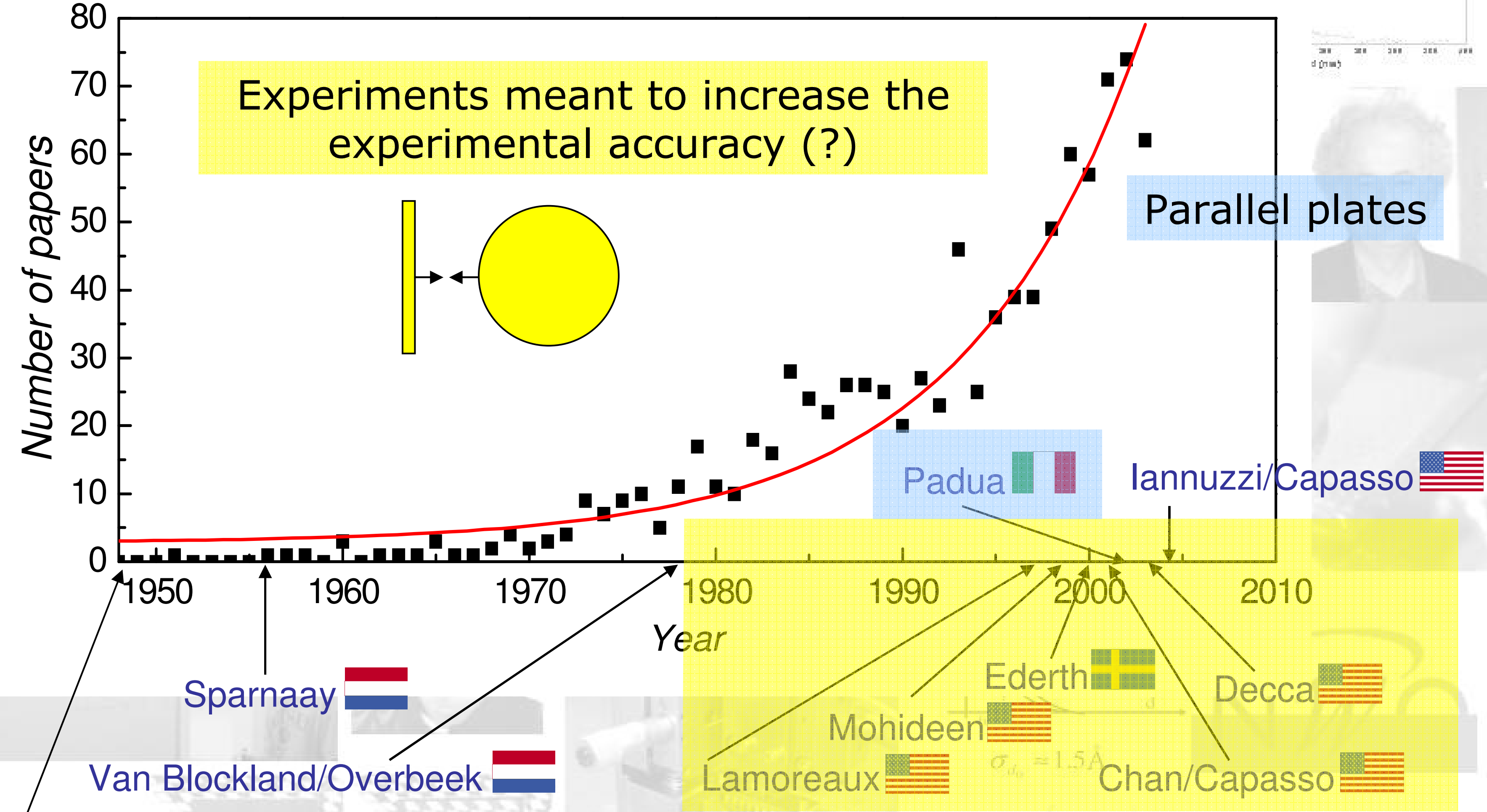
$P \approx 1 \cdot 10^{-15}\ \mathrm{N/m^2}$ at $d = 1\ \mathrm{mm}$

$P \approx 1\ \mathrm{mN/m^2}$ at $d = 1\ \mu\mathrm{m}$

$P \approx 1\ \mathrm{atm}$ at $d = 10\ \mathrm{nm}$

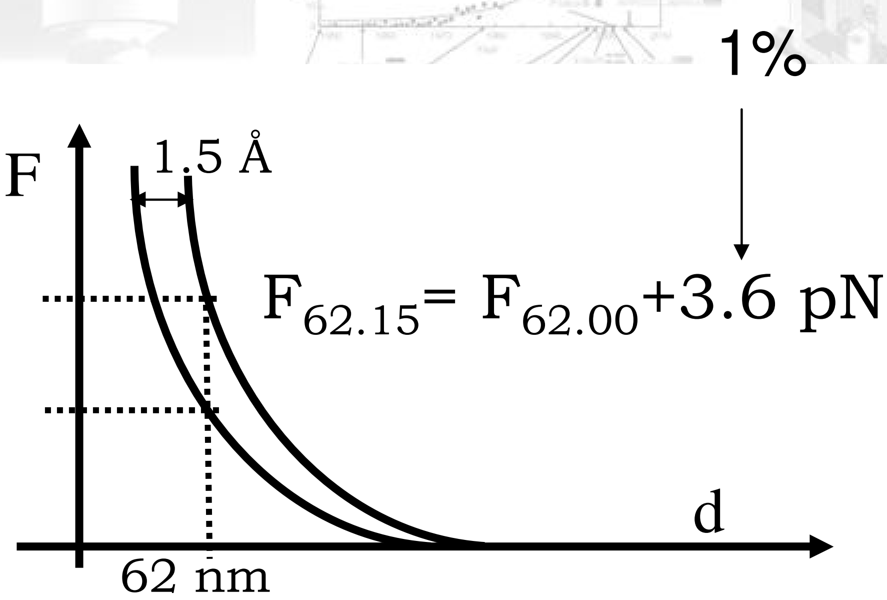
(for ideal metals)

The trend



H. B. G. Casimir, *Proc. K. Ned. Akad. Wet.* **51** (1948) 793

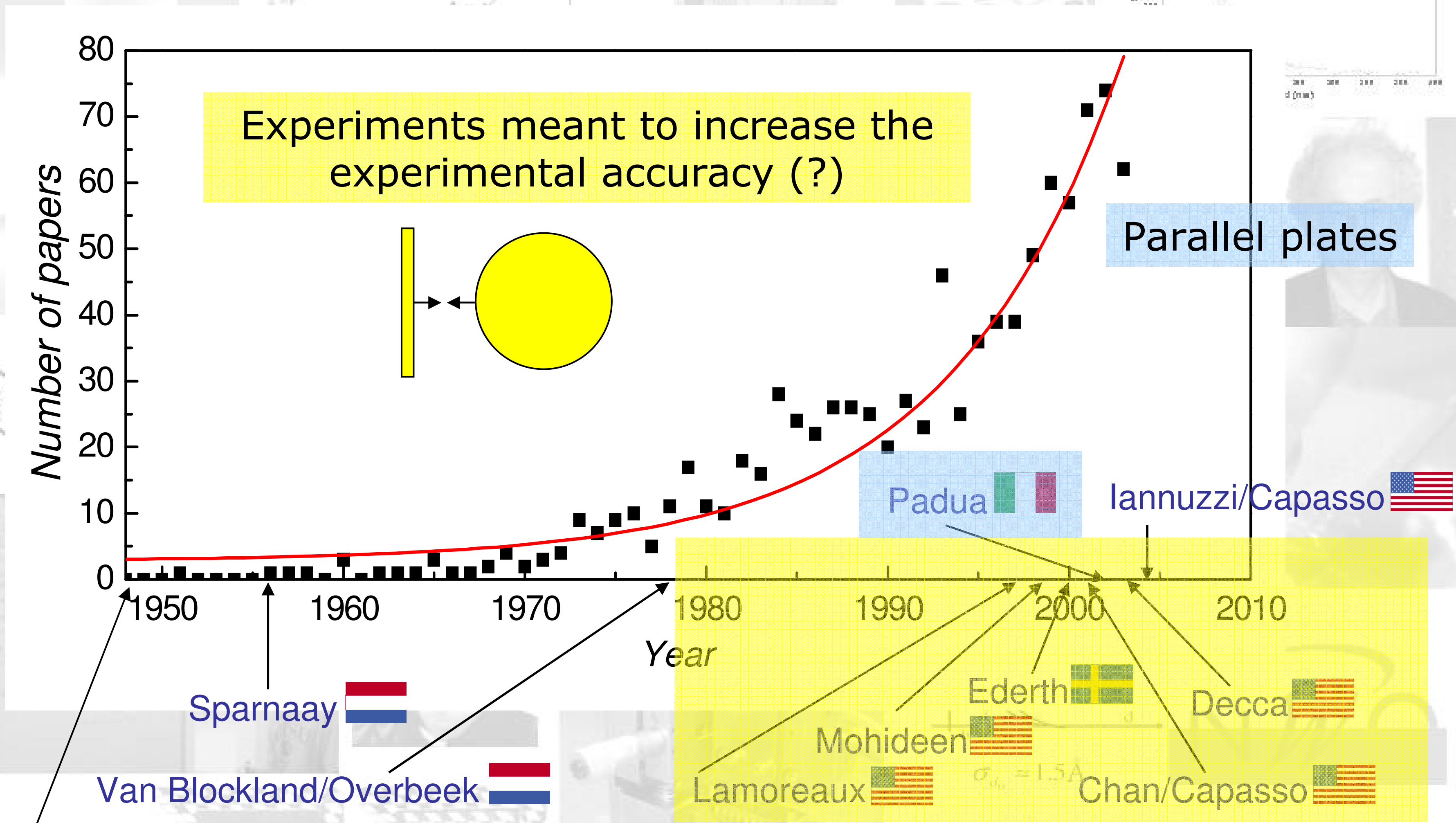
The accuracy issue



$$\sigma_{d_0} \approx 1.5\text{Å}$$

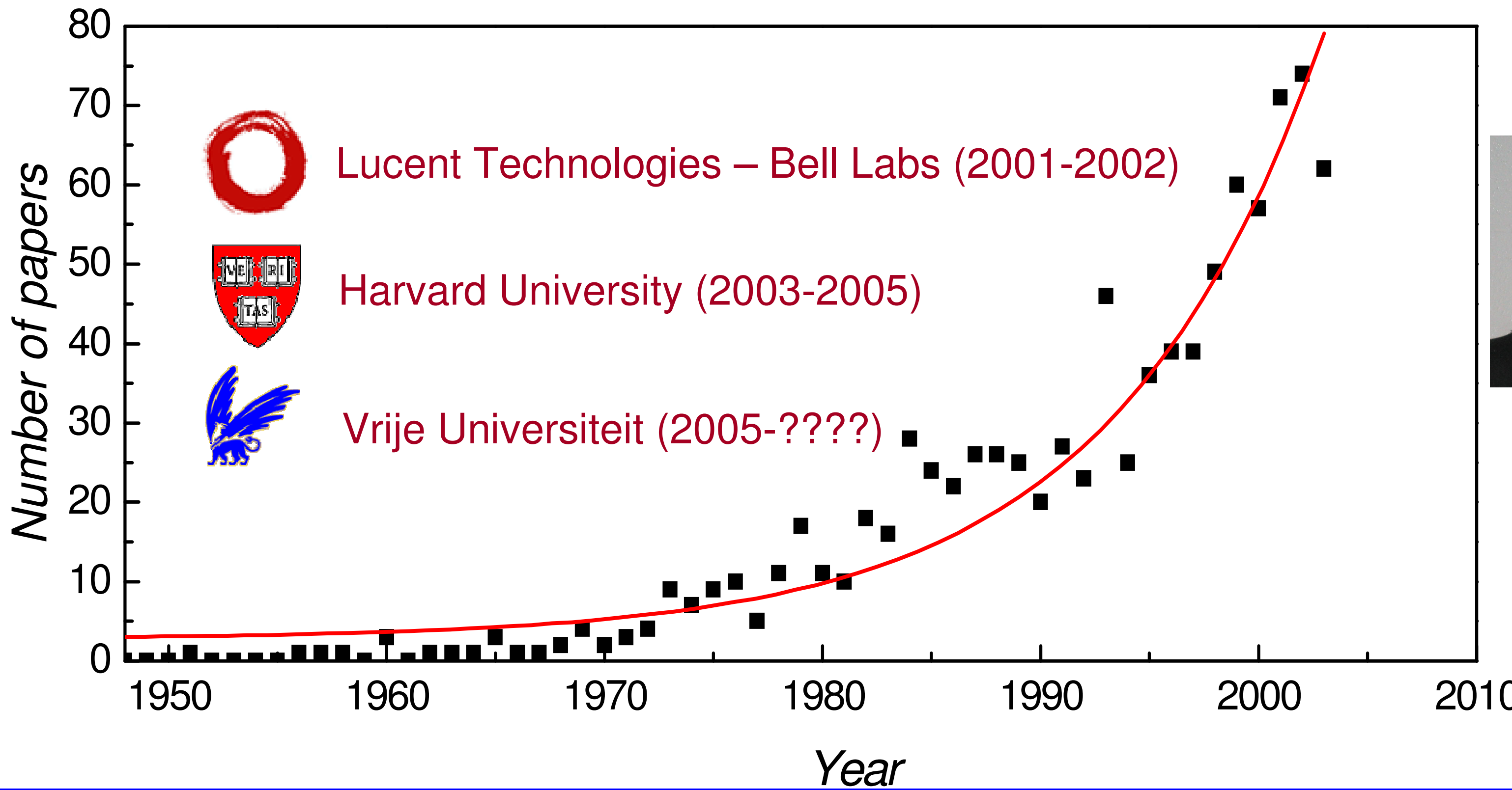
- No direct measurement of *d*
- Surface roughness corrections
- Finite conductivity corrections
- Electrostatic under control?

The trend



H. B. G. Casimir, *Proc. K. Ned. Akad. Wet.* **51** (1948) 793

A different approach



QUANTUM FLUCTUATIONS ENGINEERING

Design of the interacting surfaces → Design of the Casimir interaction

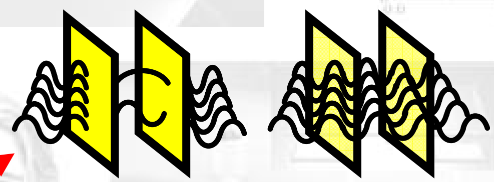
Review papers:
- Iannuzzi, Lisanti, Munday, Capasso, *Solid State Comm.* **135** (2005) 618
- Iannuzzi, Lisanti, Munday, Capasso, *J. Phys.* **A39** (2006) 6445

Quantum fluctuations engineering

Casimir paper: two PERFECT CONDUCTORS

Real materials $\varepsilon(\omega)$ ⟷ Boundary conditions

$\varepsilon(\omega)$ ⟷ F ⟹ The Casimir force depends on which materials the interacting surfaces are made of (Lifshitz theory)



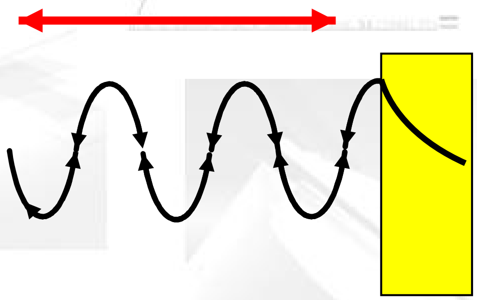
Highly reflective

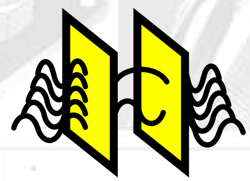
Transparent

Conductive surfaces are needed
(charge accumulation on the surfaces mimics the Casimir effect)

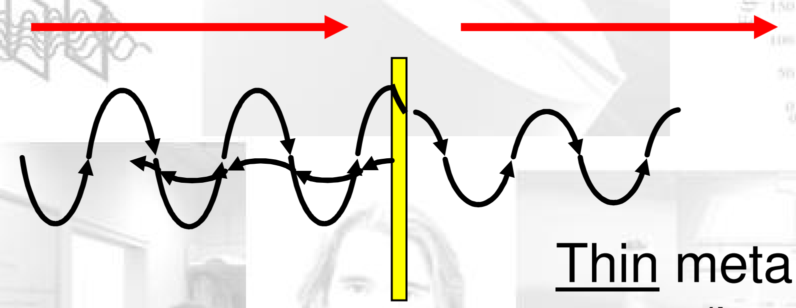
Casimir force: skin-depth effect

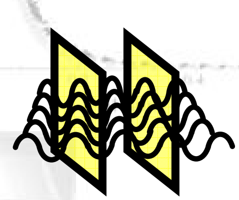
When is a metallic layer really a mirror?





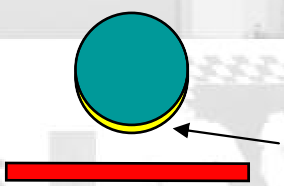
Thick (bulk-like) metallic film: reflective





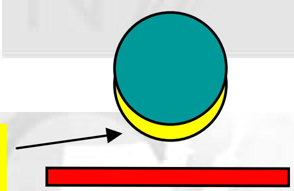
Thin metallic film: transparent
(but still metallic!)

Transparent sphere coated with

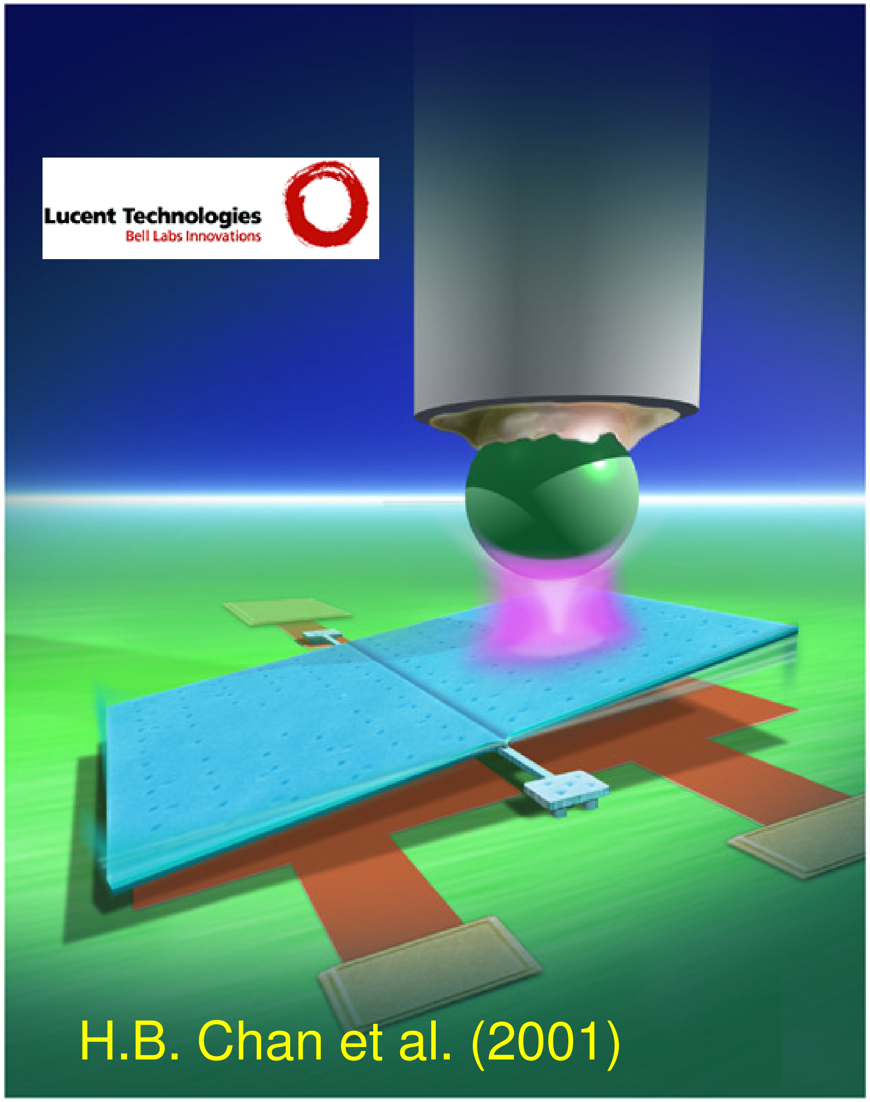


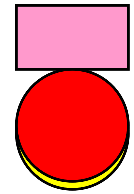
Thin metallic layer

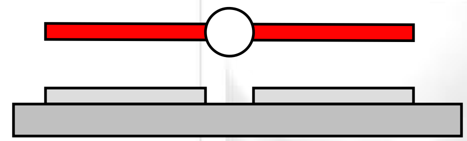
Thick metallic layer



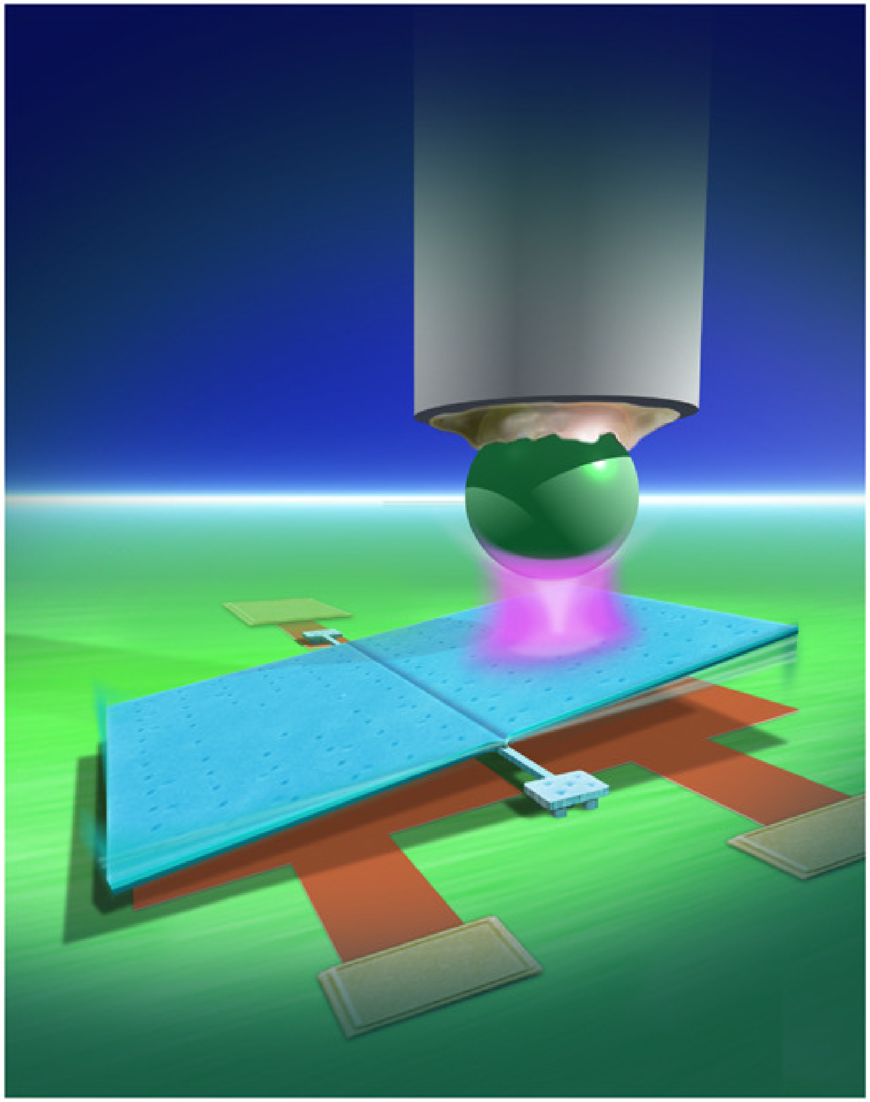
Casimir force: experimental set-up

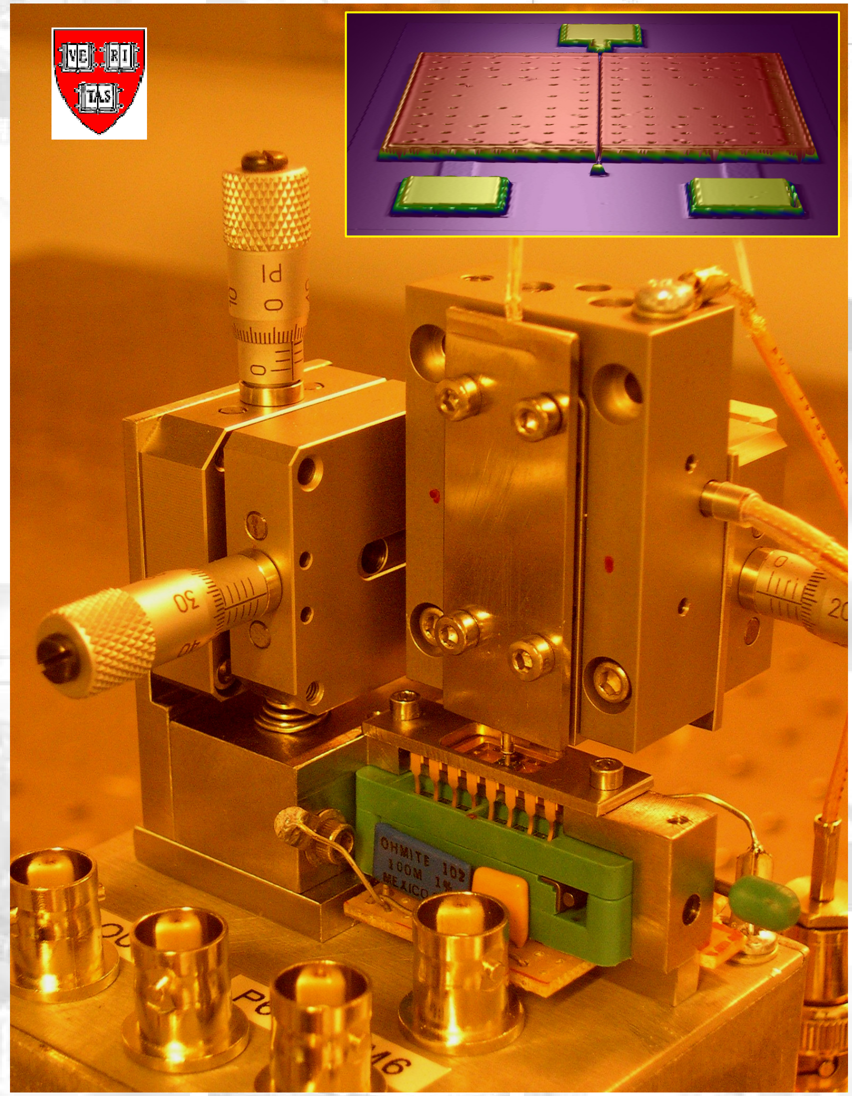






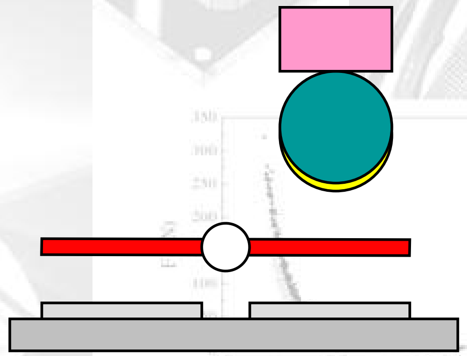
Casimir force: experimental set-up



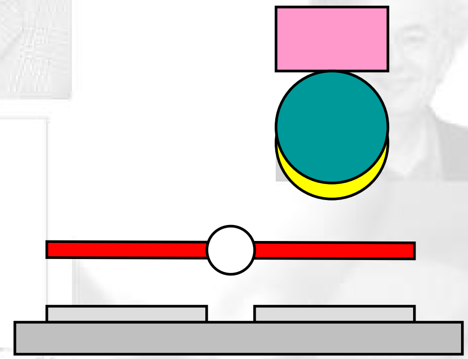


Casimir force: skin-depth effect

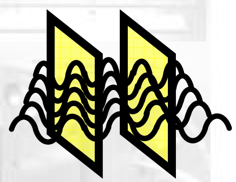
Mariangela Lisanti
(now at Stanford)

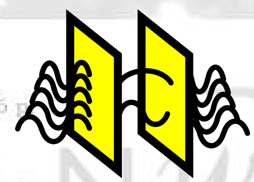


Thin film of Pd



Thick film of Pd

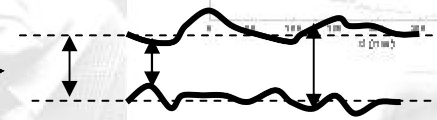




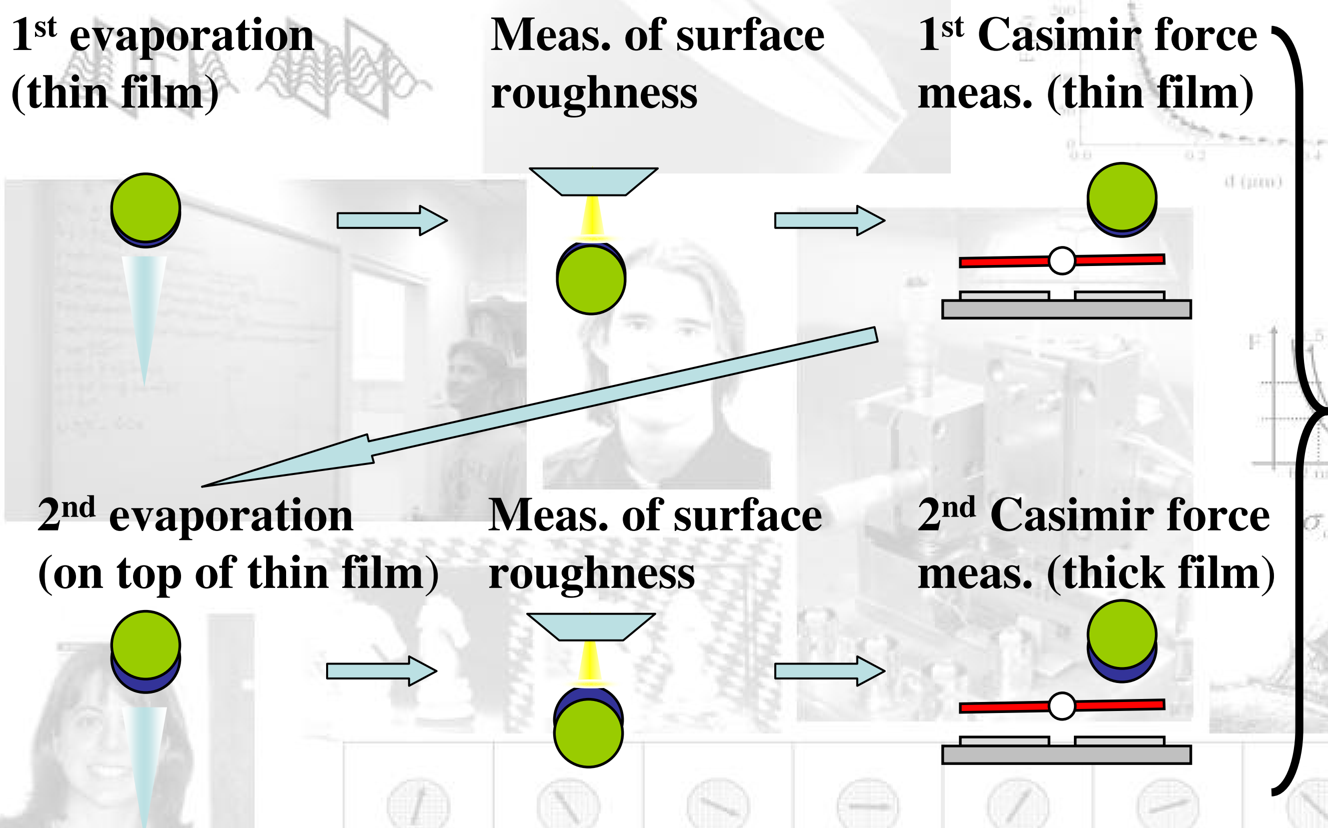
Thin and thick film should behave differently:
skin-depth effect in the Casimir force

Casimir force: skin-depth effect

Main problems:
- surface roughness
- radius of the sphere



$$F = -\frac{\pi^3 \hbar c}{360 d^3} R$$

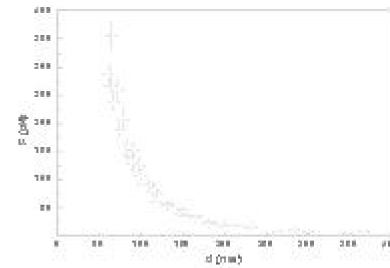


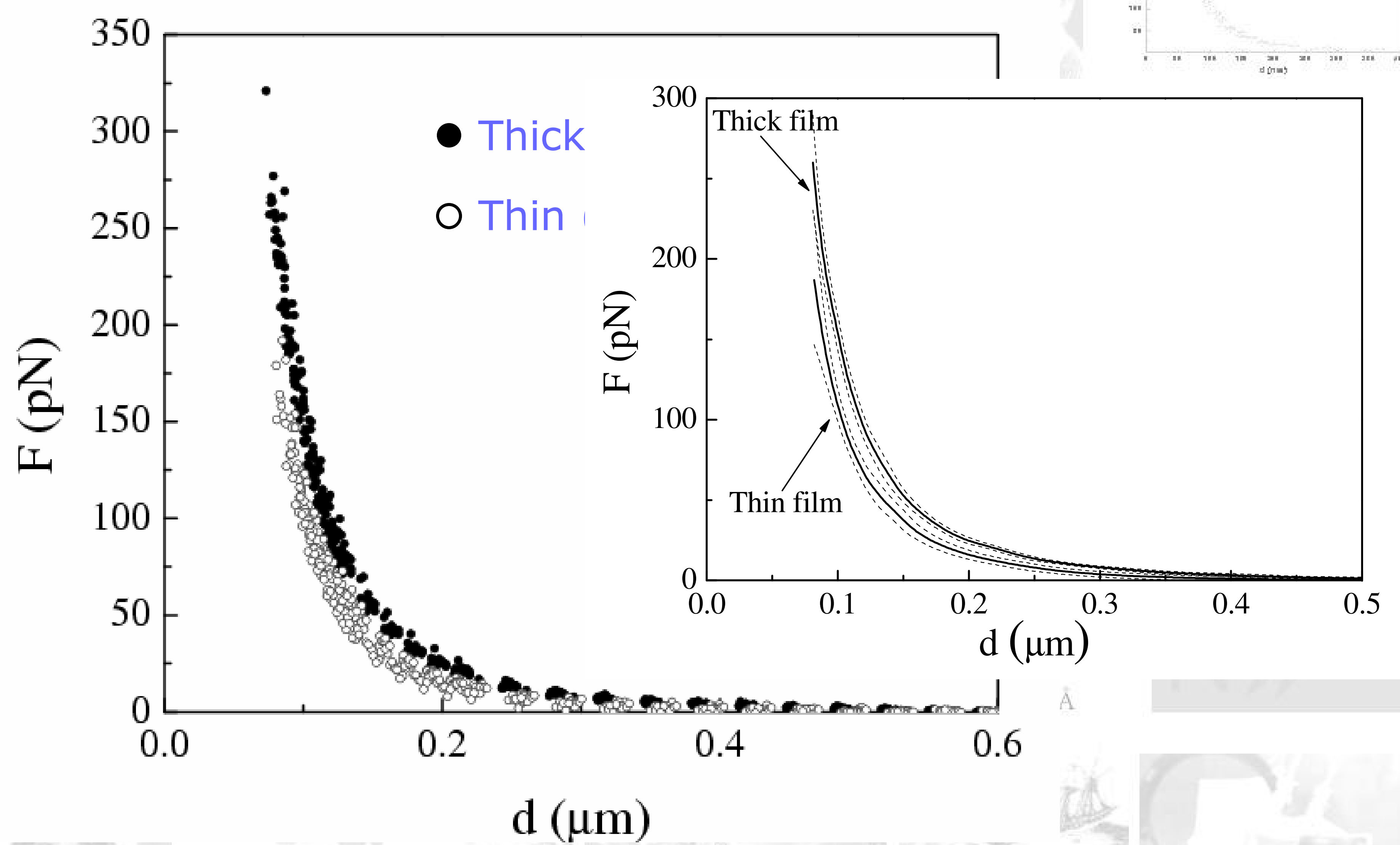
-Data with thick film are taken only if the **surface roughness is the same**

-**Same radius** because it is the same sphere

(note: thickness is measured with RBS)

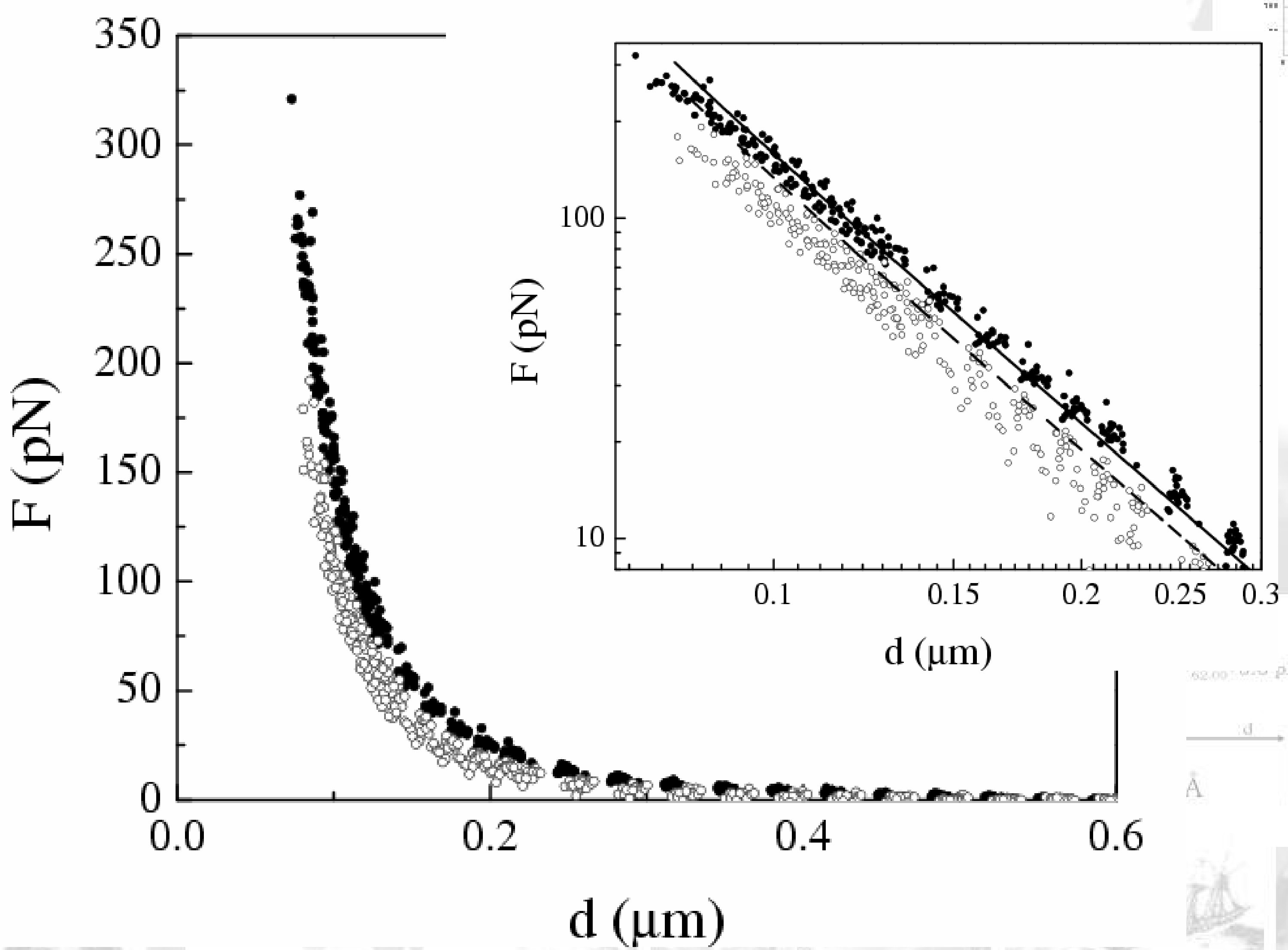
Casimir force: skin-depth effect





Lisanti, Iannuzzi, Capasso, PNAS **102** (2005) 11989

Casimir force: skin-depth effect



Lisanti, Iannuzzi, Capasso, PNAS **102** (2005) 11989

CONCLUSION 1

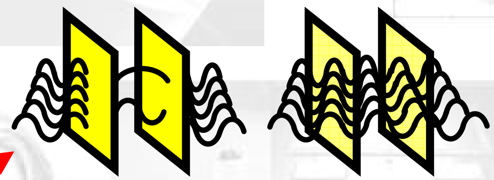
First evidence of the skin-depth effect on the Casimir force

Casimir force with H-switchable mirrors

Casimir paper: two PERFECT CONDUCTORS

Real materials $\varepsilon(\omega) \leftrightarrow$ Boundary conditions

$\varepsilon(\omega) \leftrightarrow F \rightarrow$ The Casimir force depends on which materials the interacting surfaces are made of (Lifshitz theory)



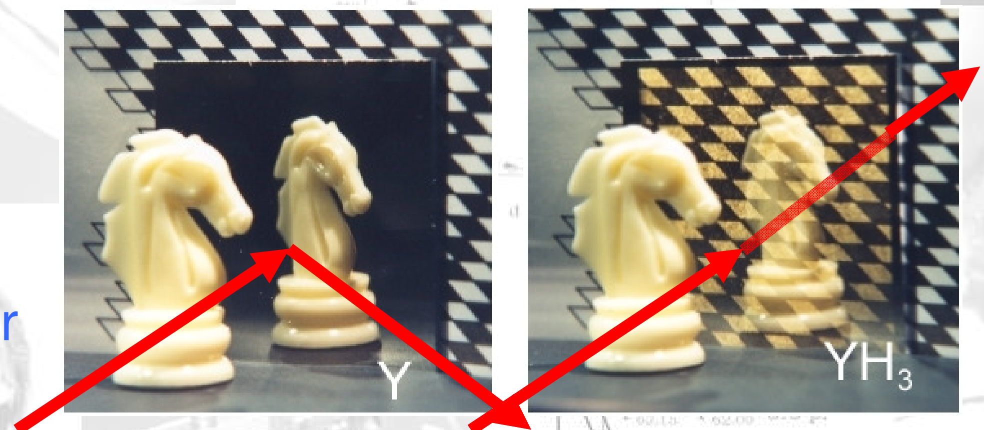
Highly reflective

Transparent

Is it possible to do it in situ?
We need metallic surfaces that can be switched from reflective to transparent!

Casimir force with H-switchable mirrors

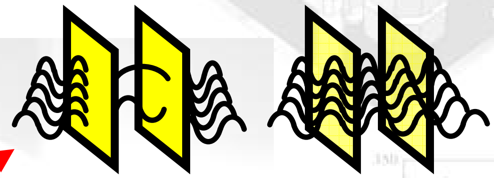
Hydrogen Switchable Mirrors



R. Griessen, J. H. Rector
and J. Huiberts
(Vrije Universiteit)

Casimir force with H-switchable mirrors

The idea: measurement of the Casimir force in air and in hydrogen



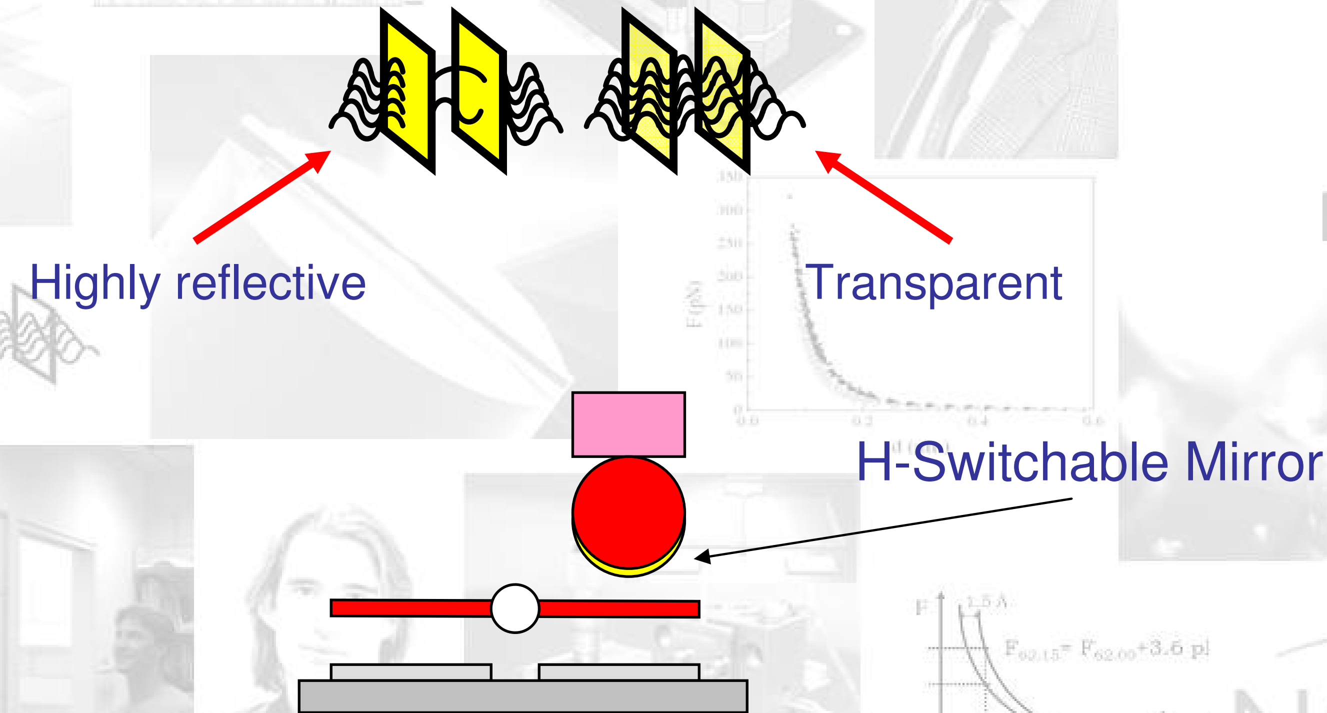
Highly reflective

Transparent

The goal: tuning the Casimir force *in situ*, from strong to weak

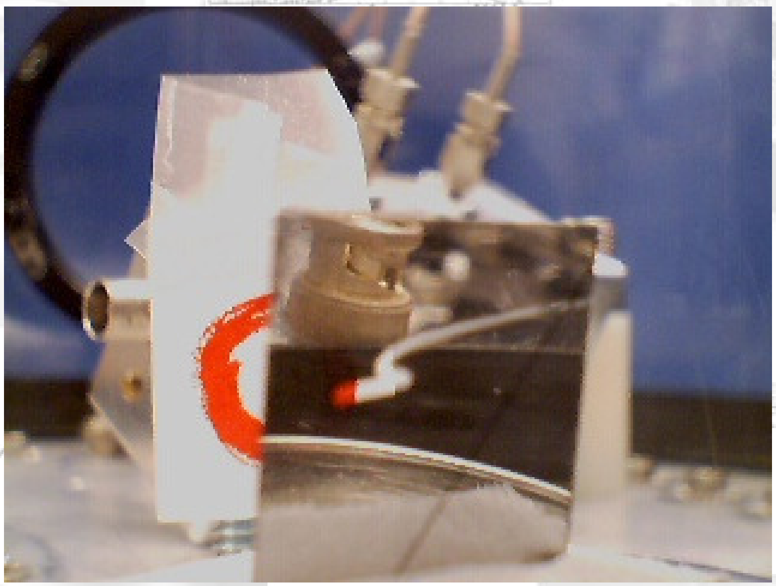
Casimir force with H-switchable mirrors

The idea: measurement of the Casimir force in air and in hydrogen

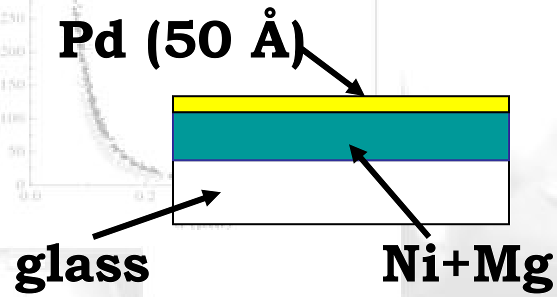


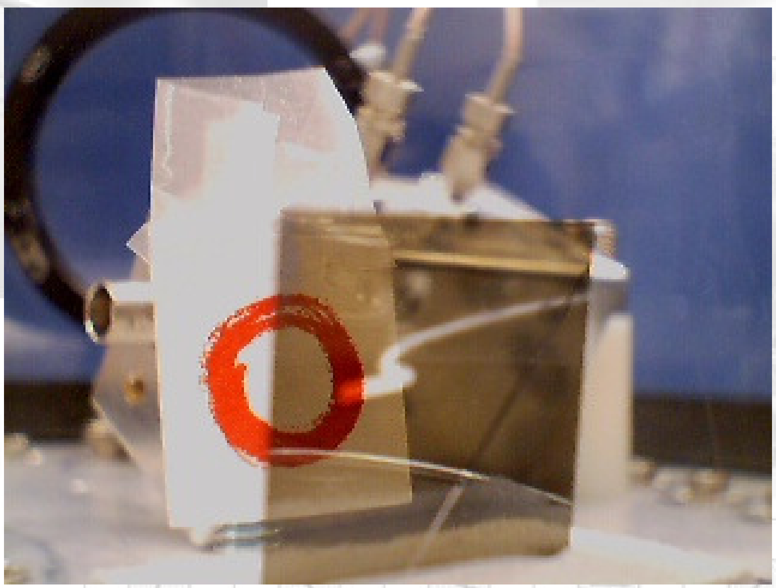
The goal: tuning the Casimir force *in situ*, from strong to weak

Casimir force with H-switchable mirrors



Mirror in air

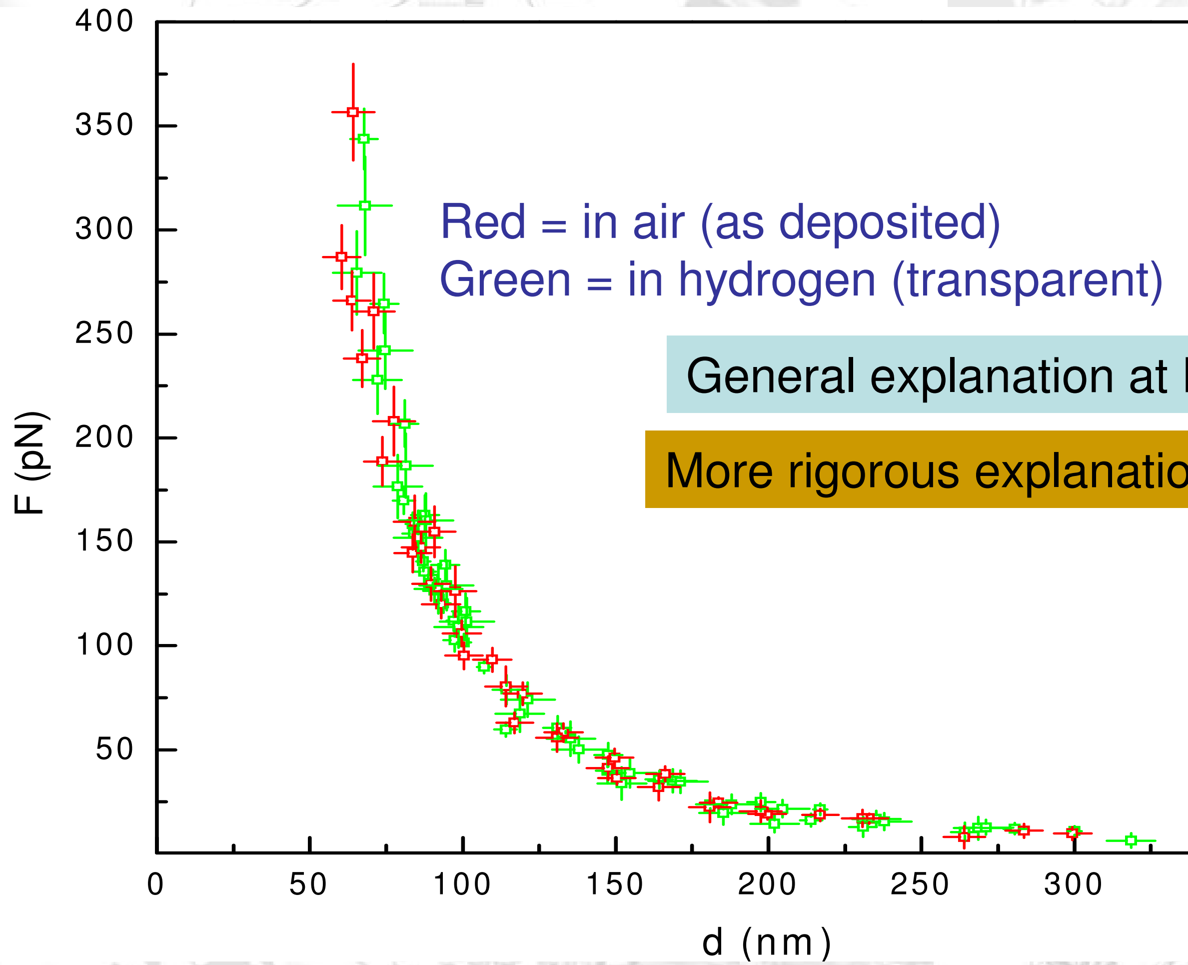




Same mirror
in H atmosphere

Casimir force with H-switchable mirrors

Results: Why is the change below experimental sensitivity?



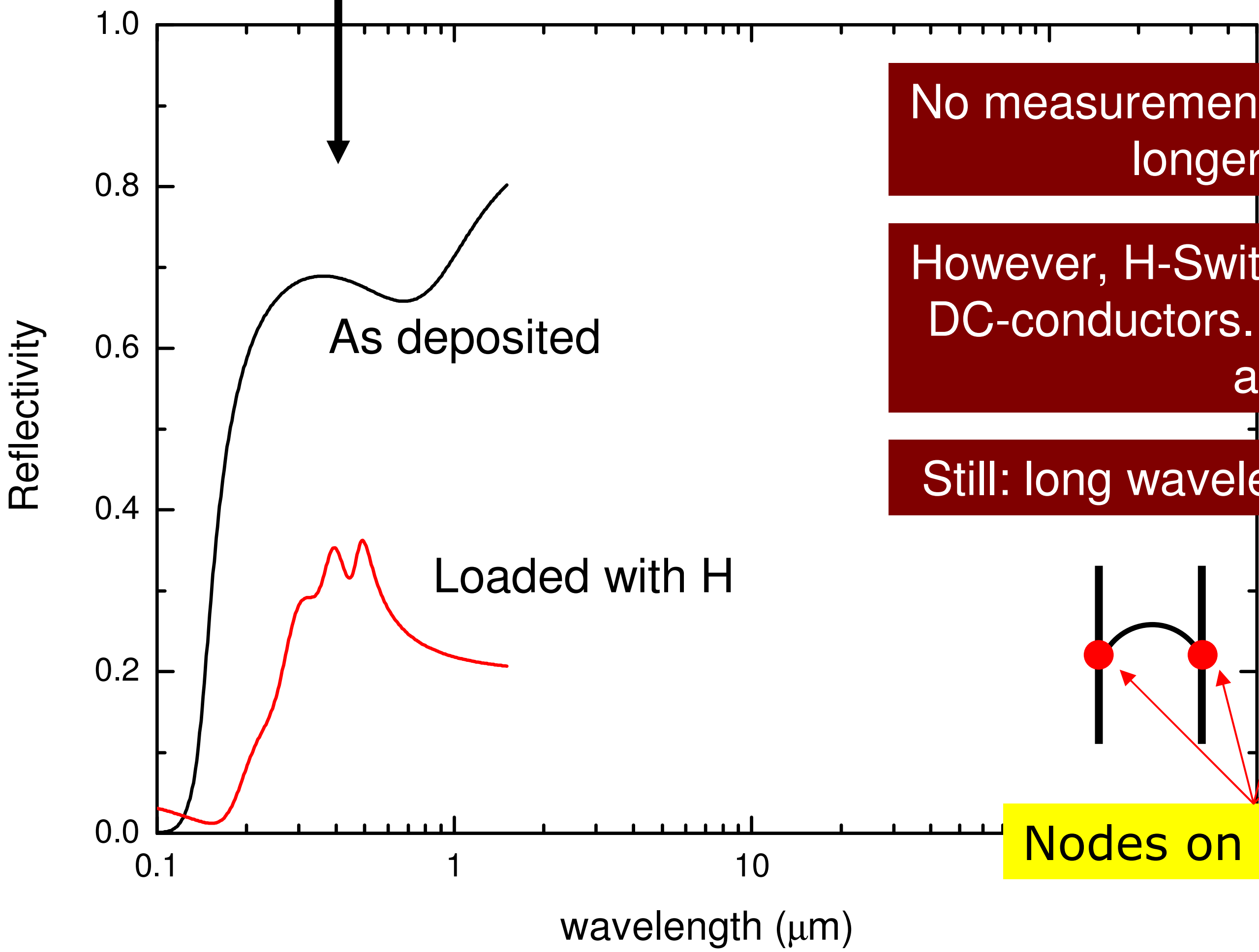
General explanation at Harvard

More rigorous explanation at VU

Iannuzzi, Lisanti, Capasso, *PNAS* **101** (2004) 4019
De Man, Iannuzzi, *New J. Phys.*, in press (2006)

Casimir force with H-switchable mirrors

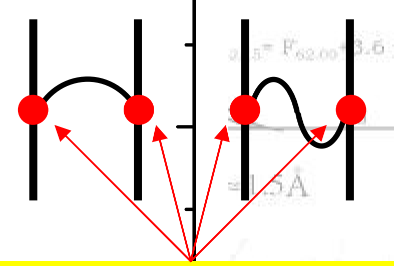
Dielectric functions of H-Switchable Mirrors are known to switch in visible and near-IR



No measurement has been performed at longer wavelengths

However, H-Switchable Mirrors are good DC-conductors. Reflectivity must go up at some λ

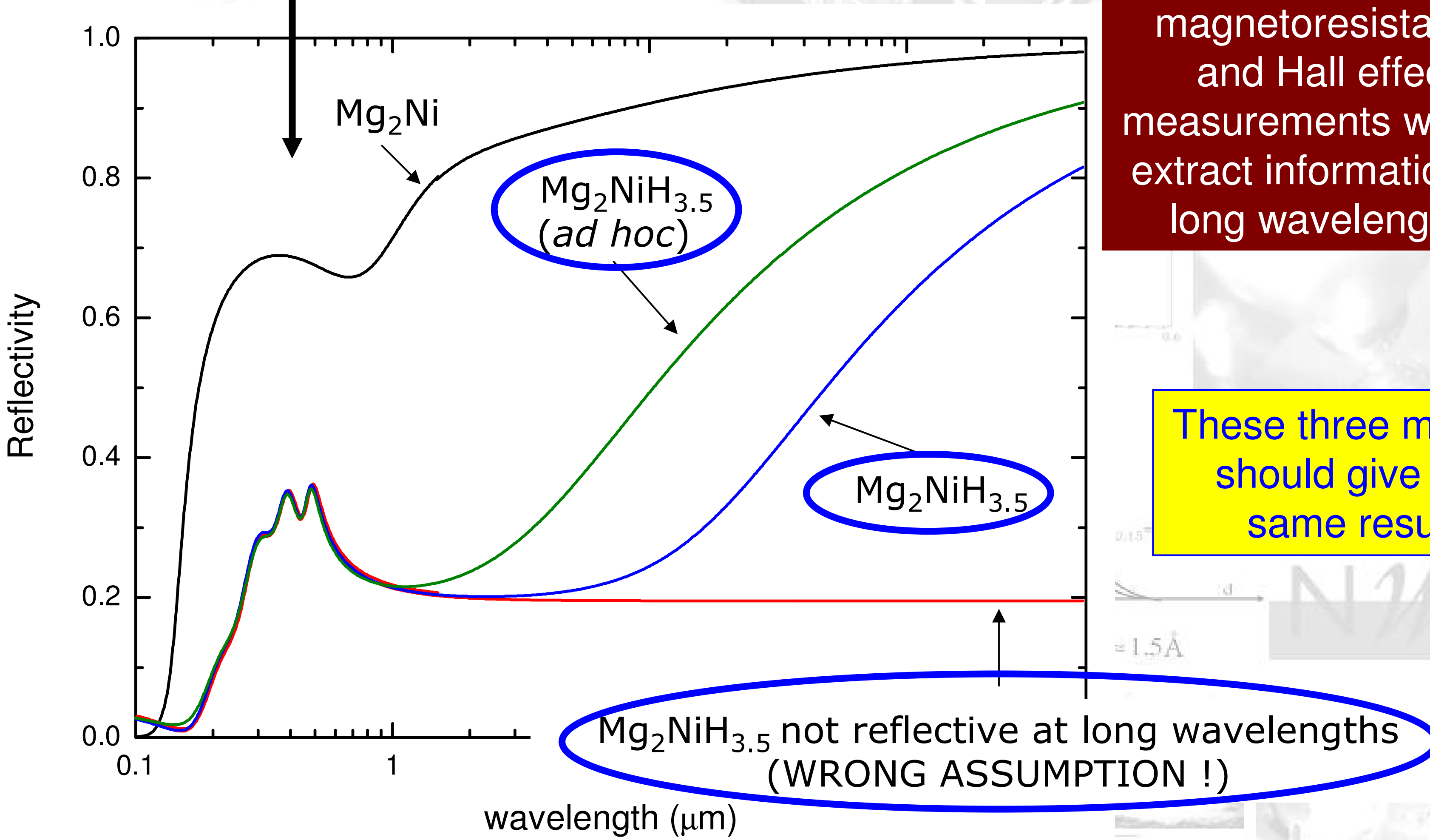
Still: long wavelengths should not count



Nodes on the plates

Casimir force with H-switchable mirrors

Dielectric functions of H-Switchable Mirrors are known to switch in visible and near-IR



From magnetoresistance and Hall effect measurements we can extract information on long wavelengths

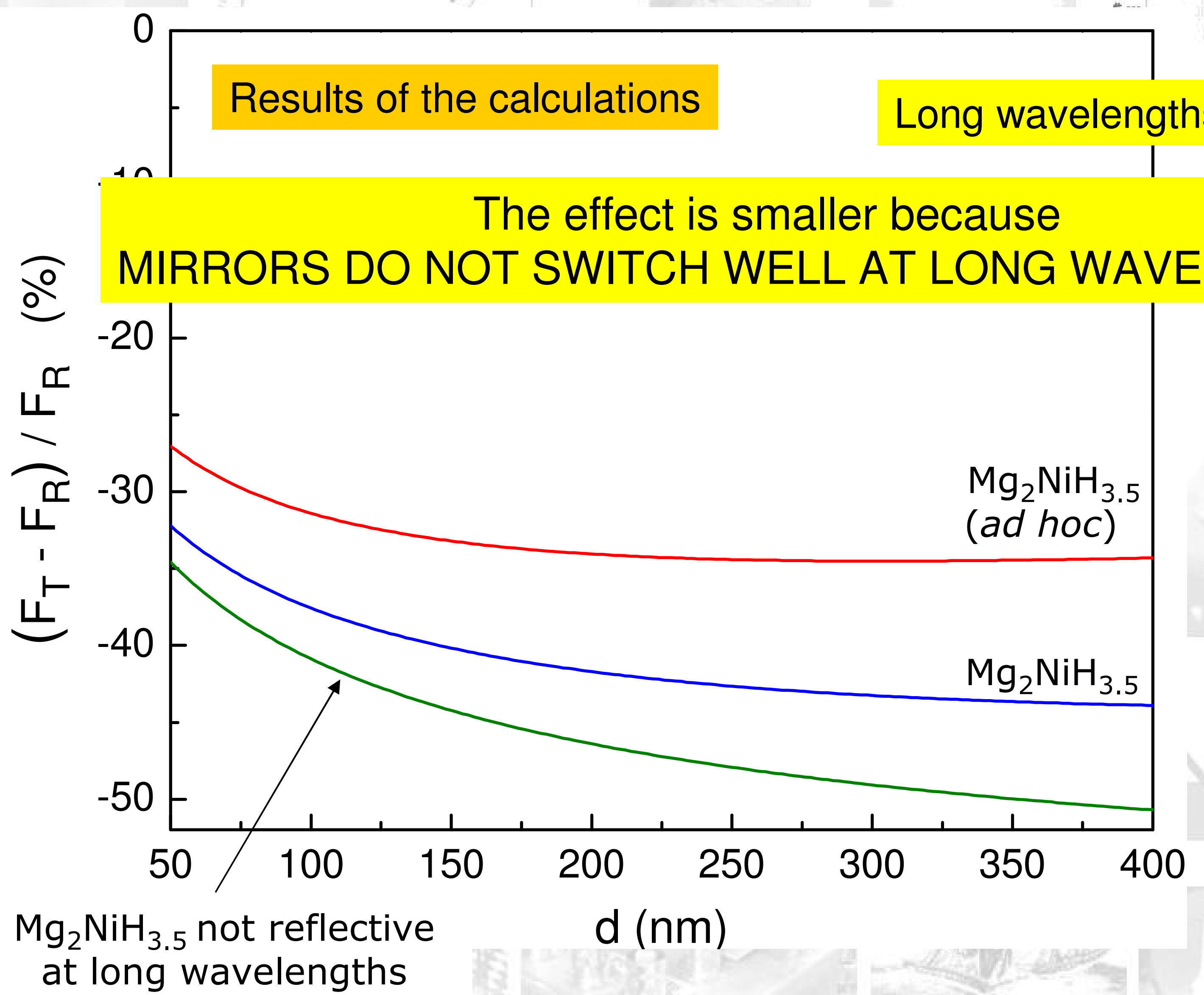
These three models should give the same result

Casimir force with H-switchable mirrors

Results of the calculations

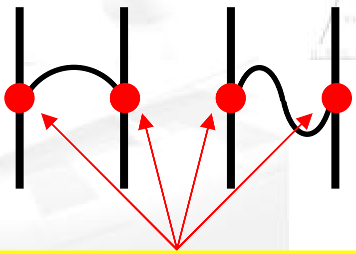
Long wavelengths count!

The effect is smaller because
MIRRORS DO NOT SWITCH WELL AT LONG WAVELENGTHS



WHY?

Casimir force with H-switchable mirrors



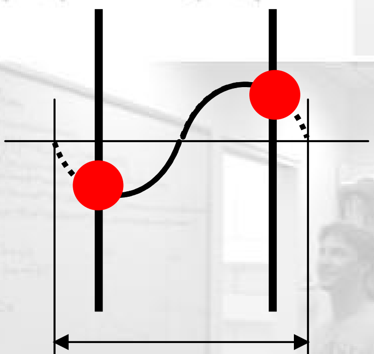
Nodes on the plates

These are the modes considered so far

This is a constraint due to the hypothesis of PERFECT CONDUCTORS

For “real” materials:

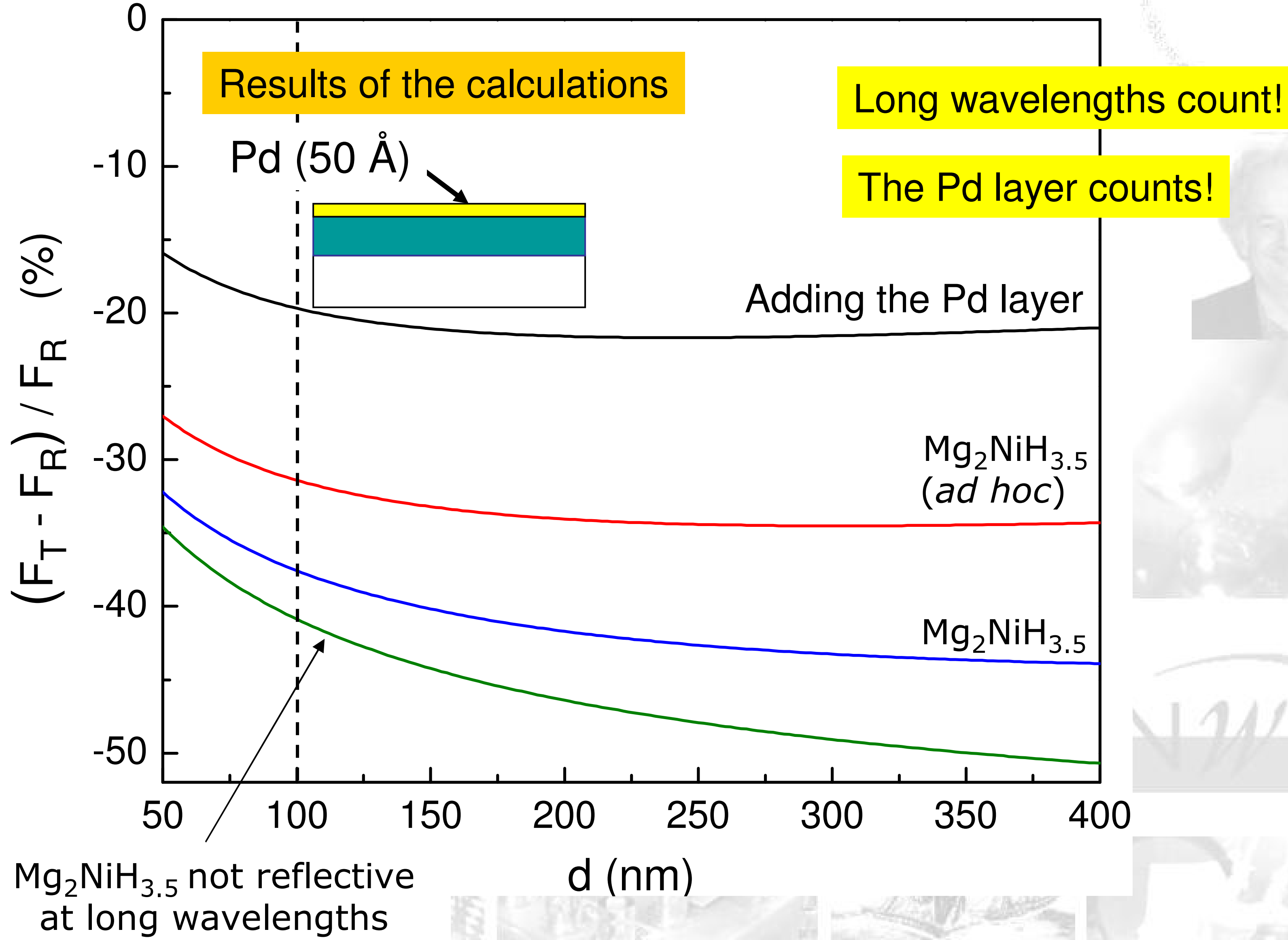
$$\varepsilon(\omega)$$ determines the boundary conditions



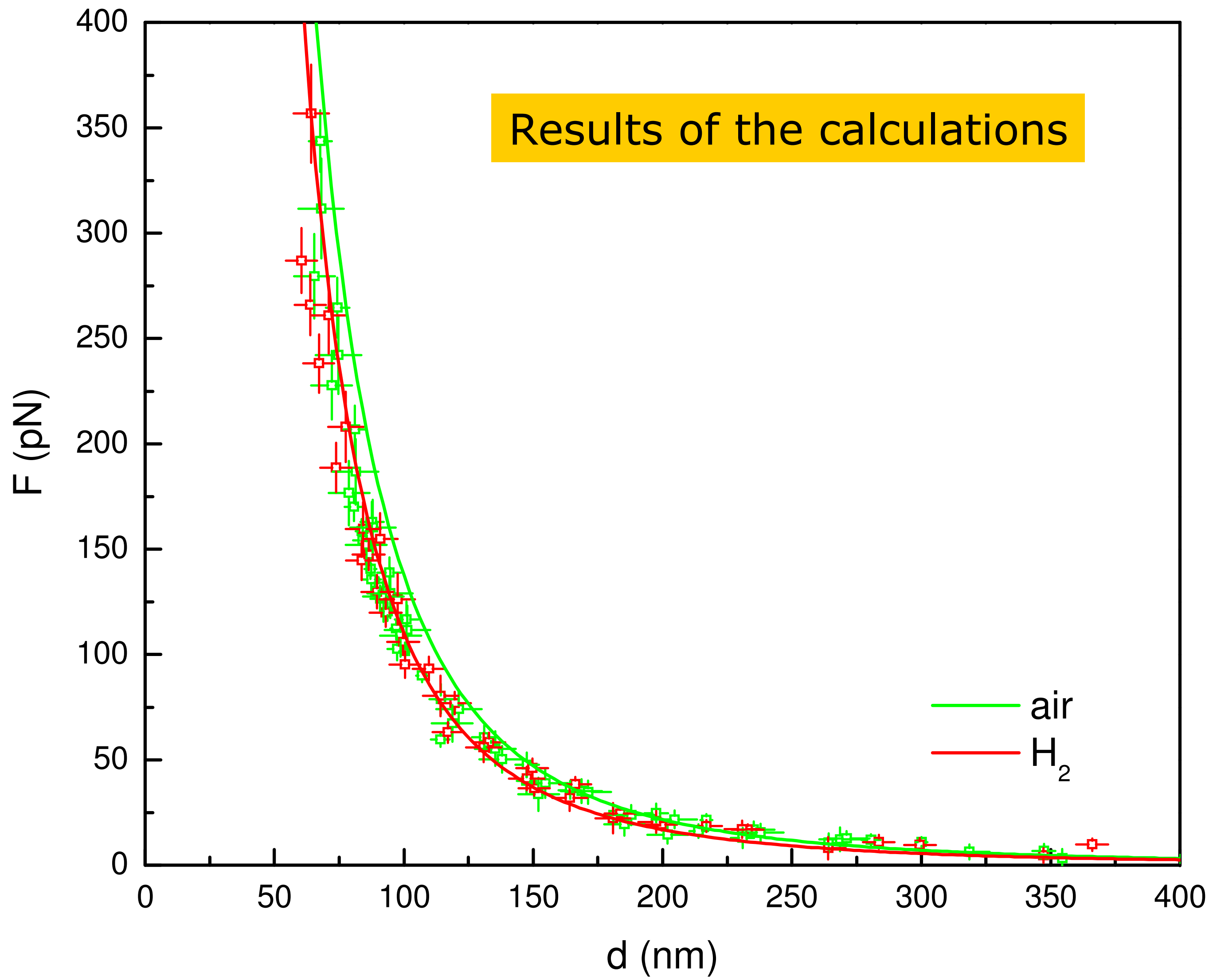
$\lambda > d$

Longer wavelength modes are allowed and will thus contribute to the force

Casimir force with H-switchable mirrors



Casimir force with H-switchable mirrors



CONCLUSION 2

Hydrogen Switchable Mirrors offer the possibility to tune the Casimir force

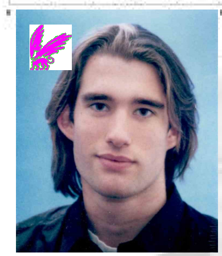
First experiment: no effect observed

Reasons:
long wavelengths count
thin metallic layers count

Effects at 20% expected (should be measurable)

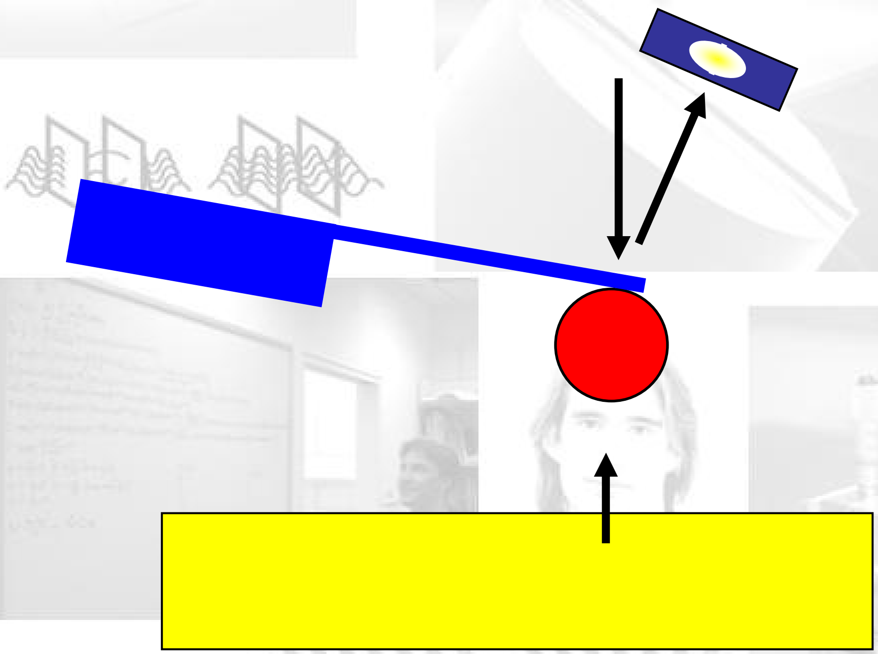
Game is not over

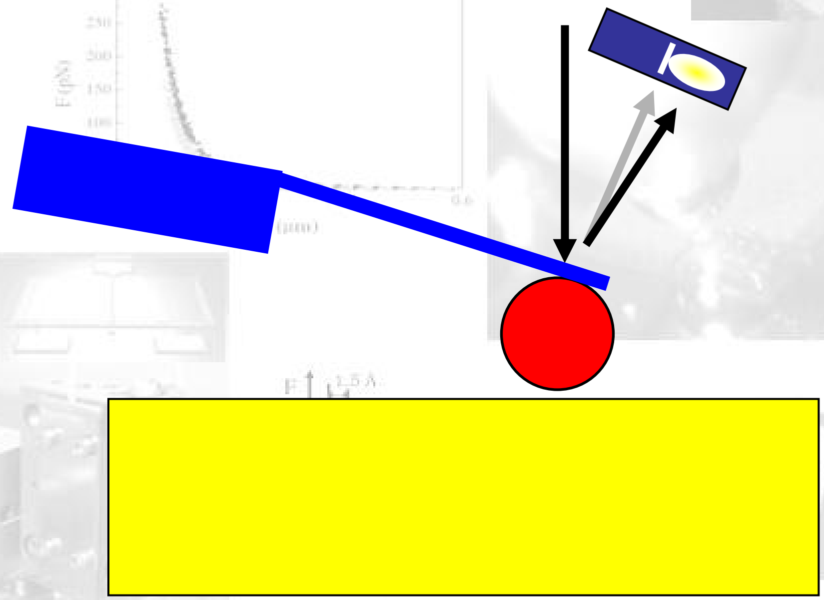
Casimir force with H-switchable mirrors II



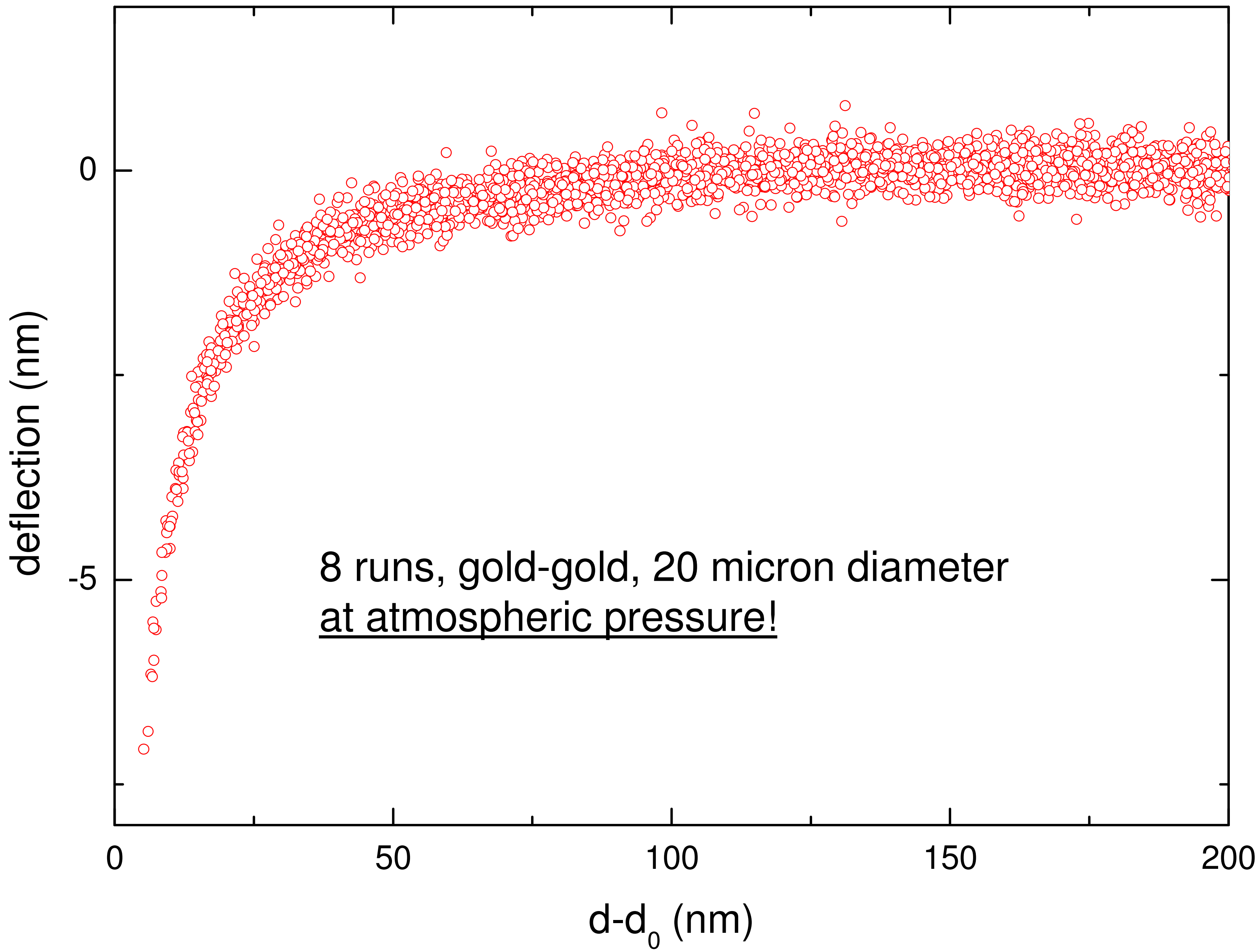
Casimir force with H-Switchable Mirrors Episode II

"Warming-up" with an atomic force microscope

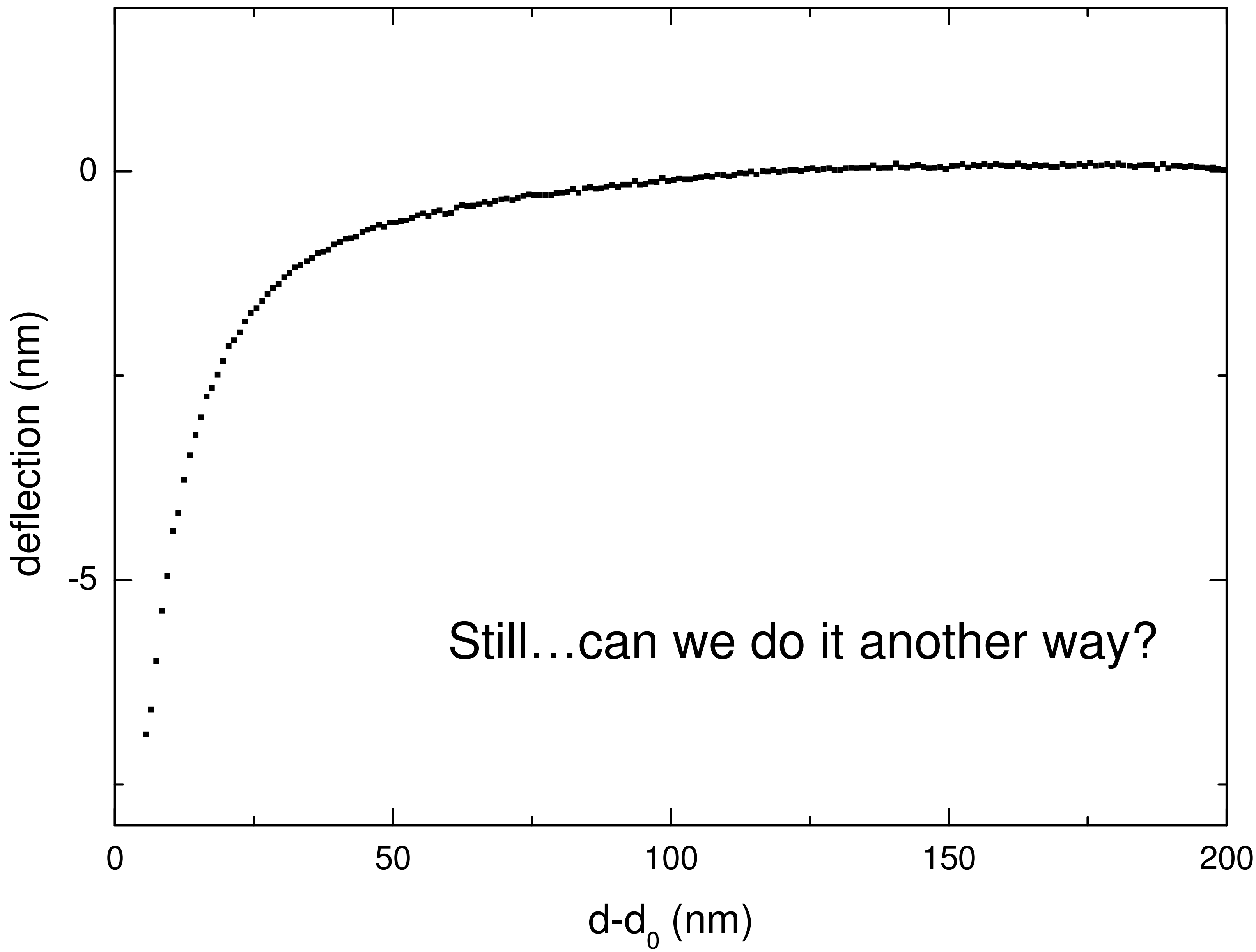




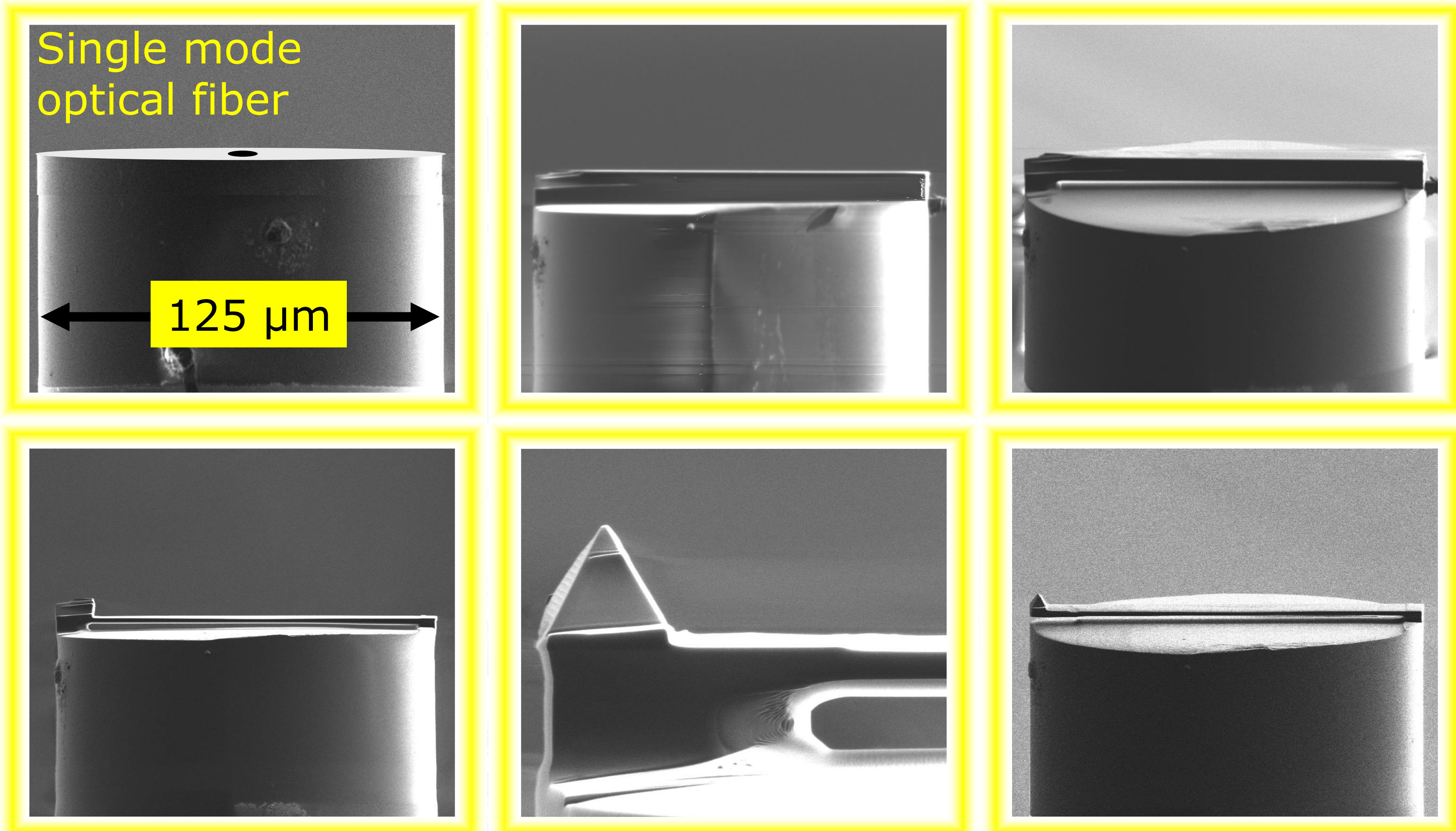
Casimir force with H-switchable mirrors II



Casimir force with H-switchable mirrors II



A new Casimir setup: let's get to work…



A new sensor for Casimir experiments and…

A conceptually new Casimir force apparatus (…and much more than that !)

K. Heeck, J.H. Rector, H. Schreuders, M. Slaman

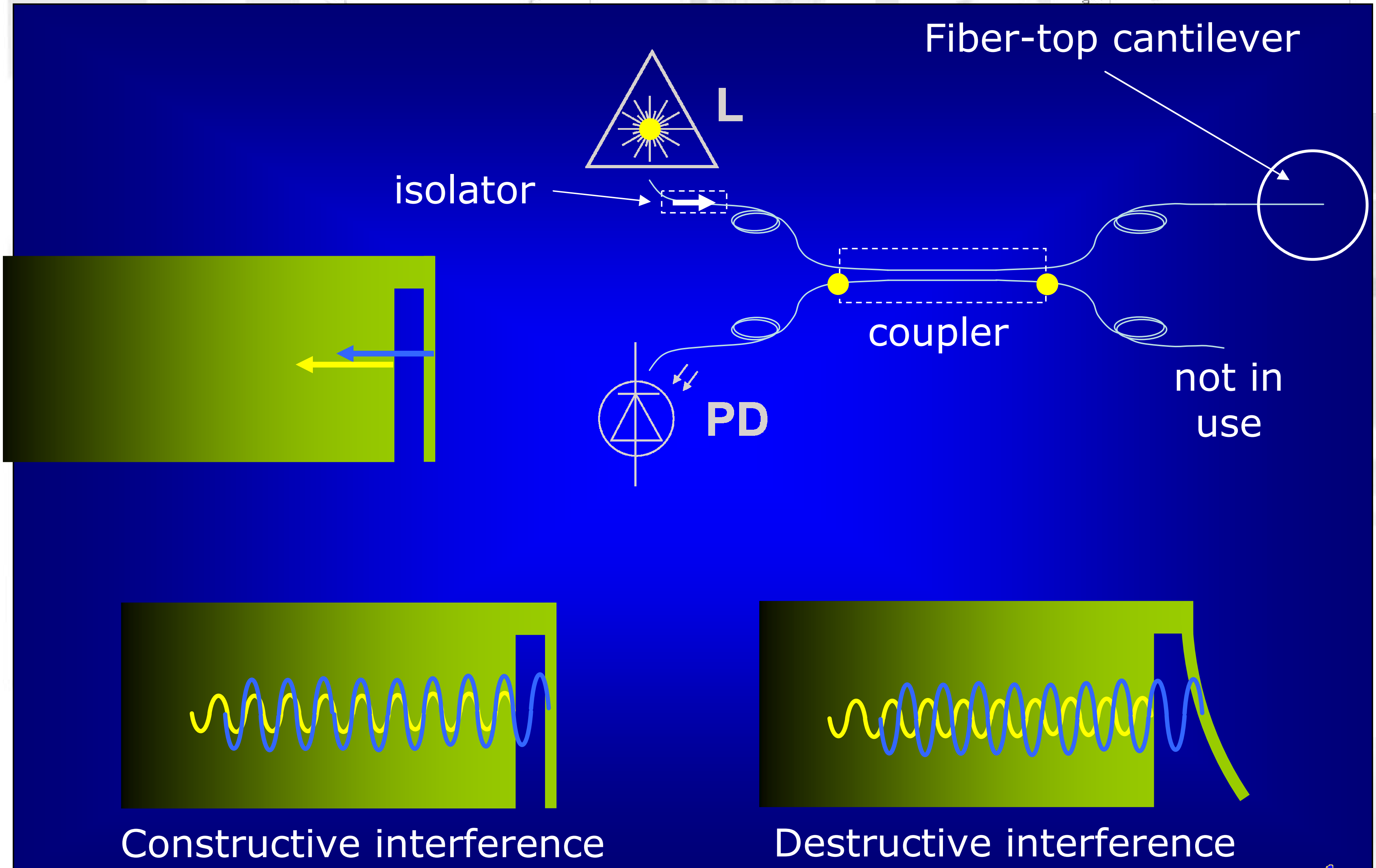
Szabolcs Deladi

Miko Elwenspoek

Iannuzzi et al., Appl. Phys. Lett. **88** (2006) 053052
Deladi et al., J. Micromech. Microeng. **16** (2006) 886
Iannuzzi et al., Rev. Sci. Instr. **77** (2006) 106105
Iannuzzi et al., OSF-18 Technical Digest (2006) TuB2
Iannuzzi et al., accepted for publication in Sensors & Act. **B** (2006)
Iannuzzi et al., accepted for publication in Optics & Photonics News (2006)

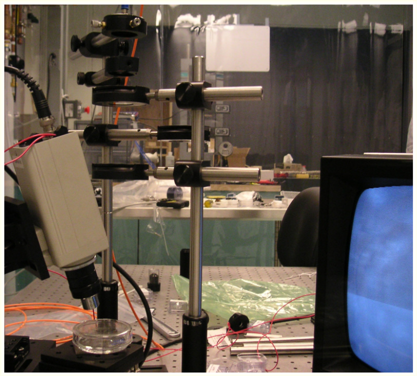
2006 Rhenaphotonics Alsace Best Design Award
2006 Rhenaphotonics Alsace Best Technology Award
Iannuzzi, Deladi, Elwenspoek, patent PCT/NL2005/000816 (filed)

A new sensor for Casimir experiments and…



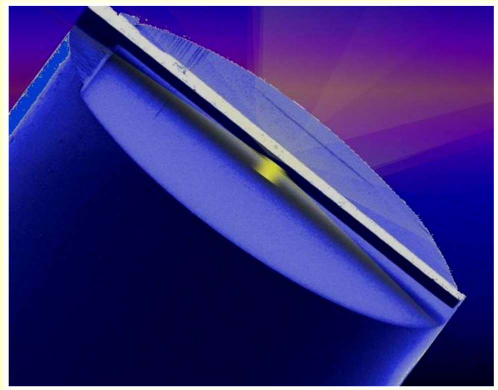
A new sensor for Casimir experiments and…

Research laboratories

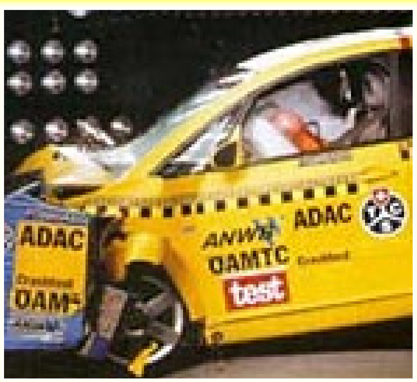


Space missions

Homeland security



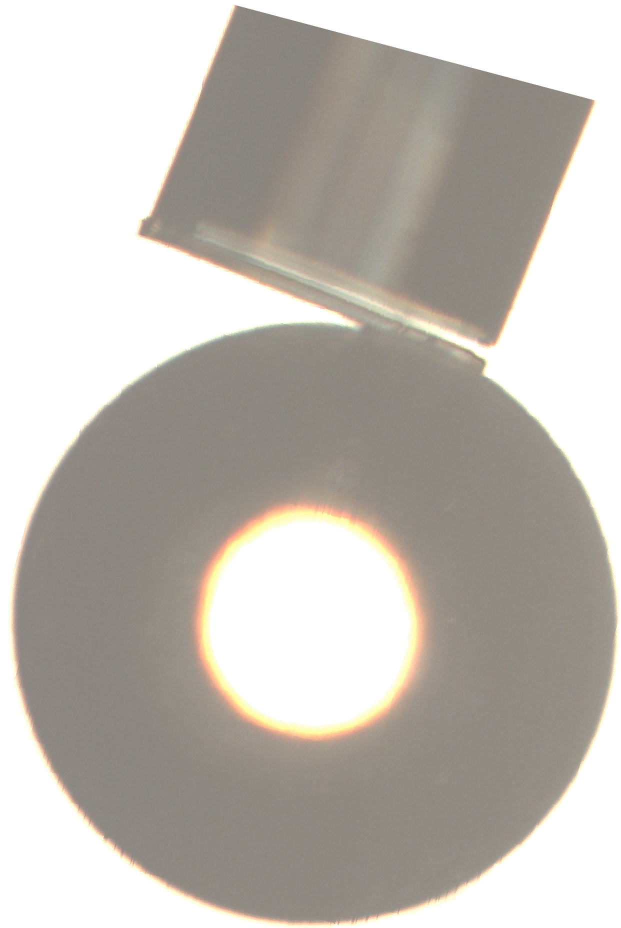
Quality inspection



Surgery rooms & medical applications

Environmental analysis

A new sensor for Casimir experiments

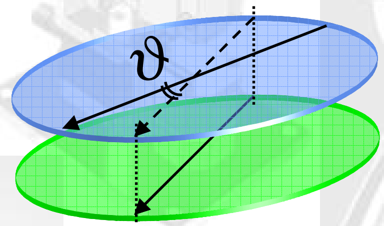


CONCLUSION 3

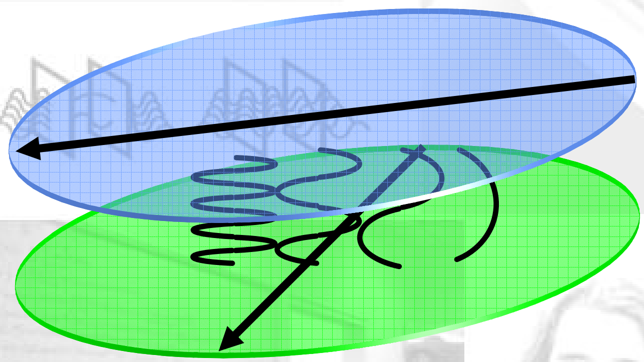
We have developed a new sensor for multipurpose applications, among which Casimir force measurements in vacuum, gases, and liquids.

Quantum electrodynamical torque

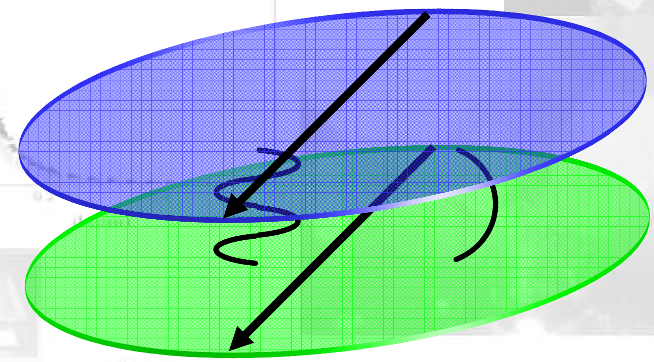
Birefringent materials: reflection, absorption, transmission depend on orientation



Zero-point energy depends on the orientation too!



$$M = -\frac{\partial E}{\partial \vartheta}$$



V. A. Parsegian and G. H. Weiss, *J. Adhesion* **3** (1972) 259 (non-retarded limit)
Y. Barash, *Izvestiya vuzov, Radiofizika*, Tom **XXI** (1978) 1637

Quantum Electrodynamical torque

Quantum electrodynamical torque

A simplified equation (non-retarded, slightly birefringent materials)

$$M = -\frac{\hbar\overline{\omega}\sin 2\theta}{64\pi^2 d^2} A$$

$$\overline{\omega} = \int_0^\infty d\omega \frac{-(\varepsilon_1-\varepsilon_2)^2}{(1+\varepsilon_2)^2(1-\varepsilon_2)^2} \ln\left(1-\left(\frac{1-\varepsilon_2}{1+\varepsilon_2}\right)^2\right)$$

Important features

$$M \propto \frac{1}{d^2}$$

Small separations are necessary

$$M \propto A$$

Area of the surfaces must be relatively large

Make the experiment difficult (surfaces tend to come into contact)

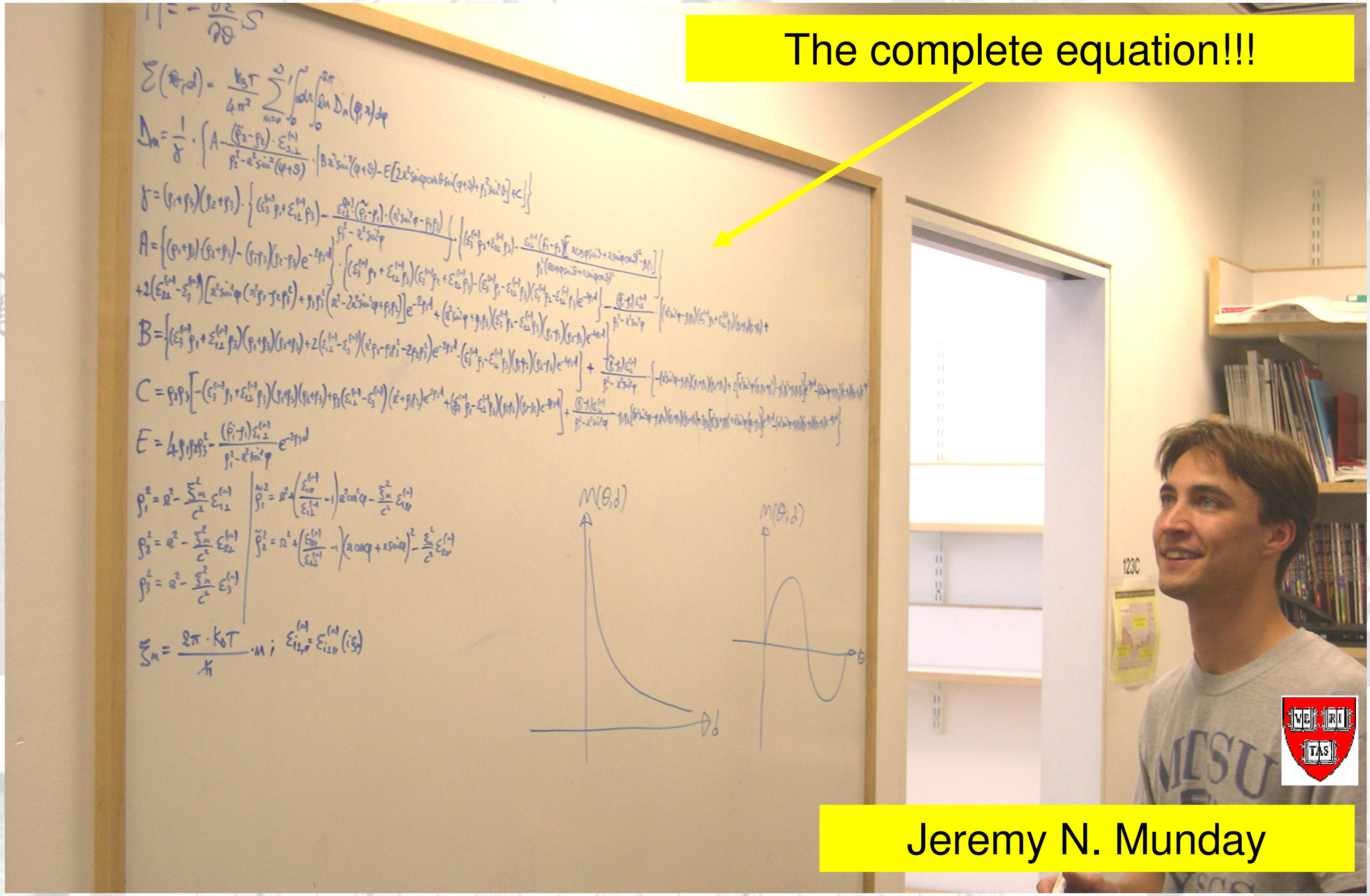
$$M \propto \sin 2\theta$$

Strong signature

Can help to distinguish spurious effects

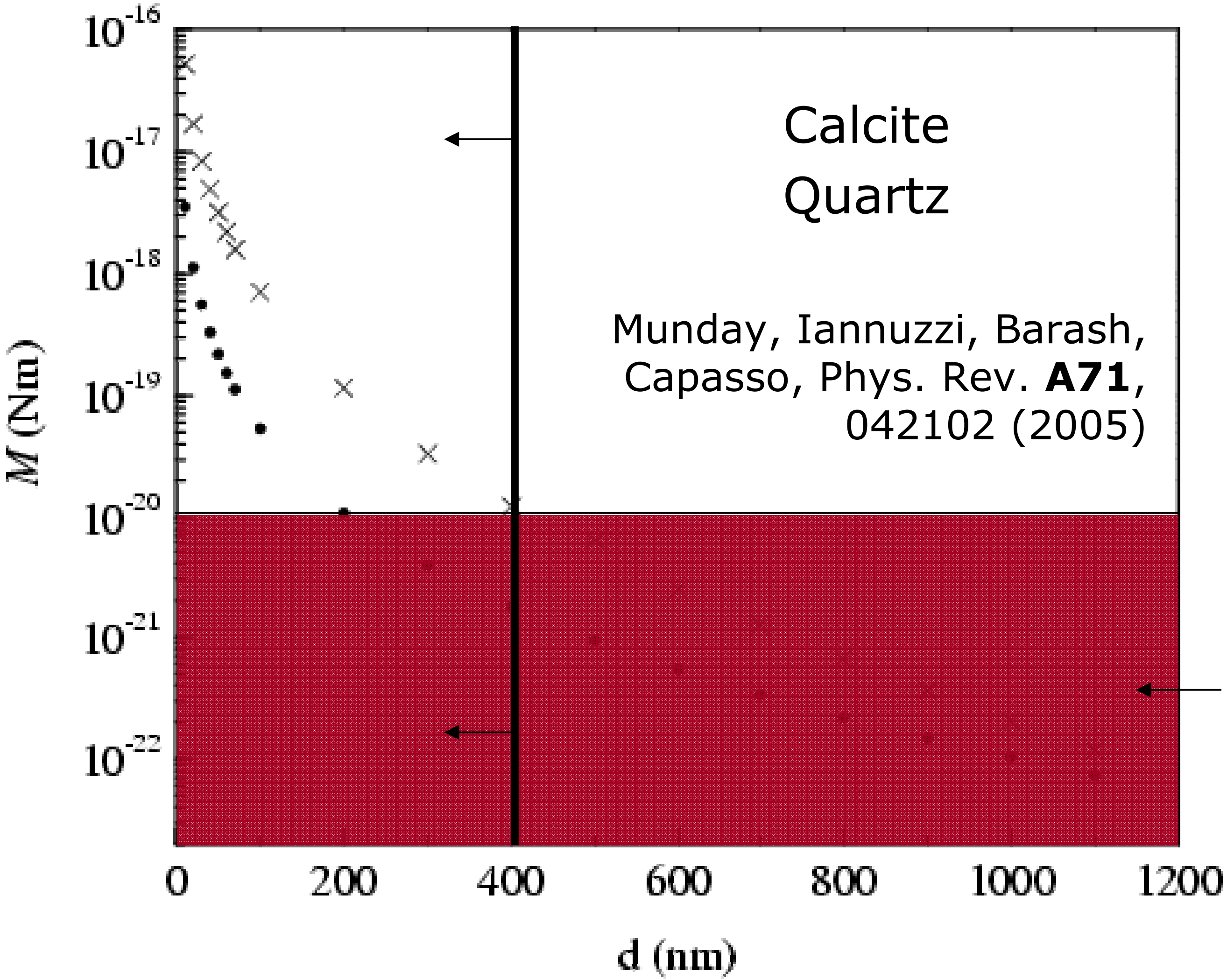
The complete equation?

Quantum electrodynamical torque



Quantum electrodynamical torque

Quartz or calcite disk (Ø=40µm,t=20µm) on top of barium titanate



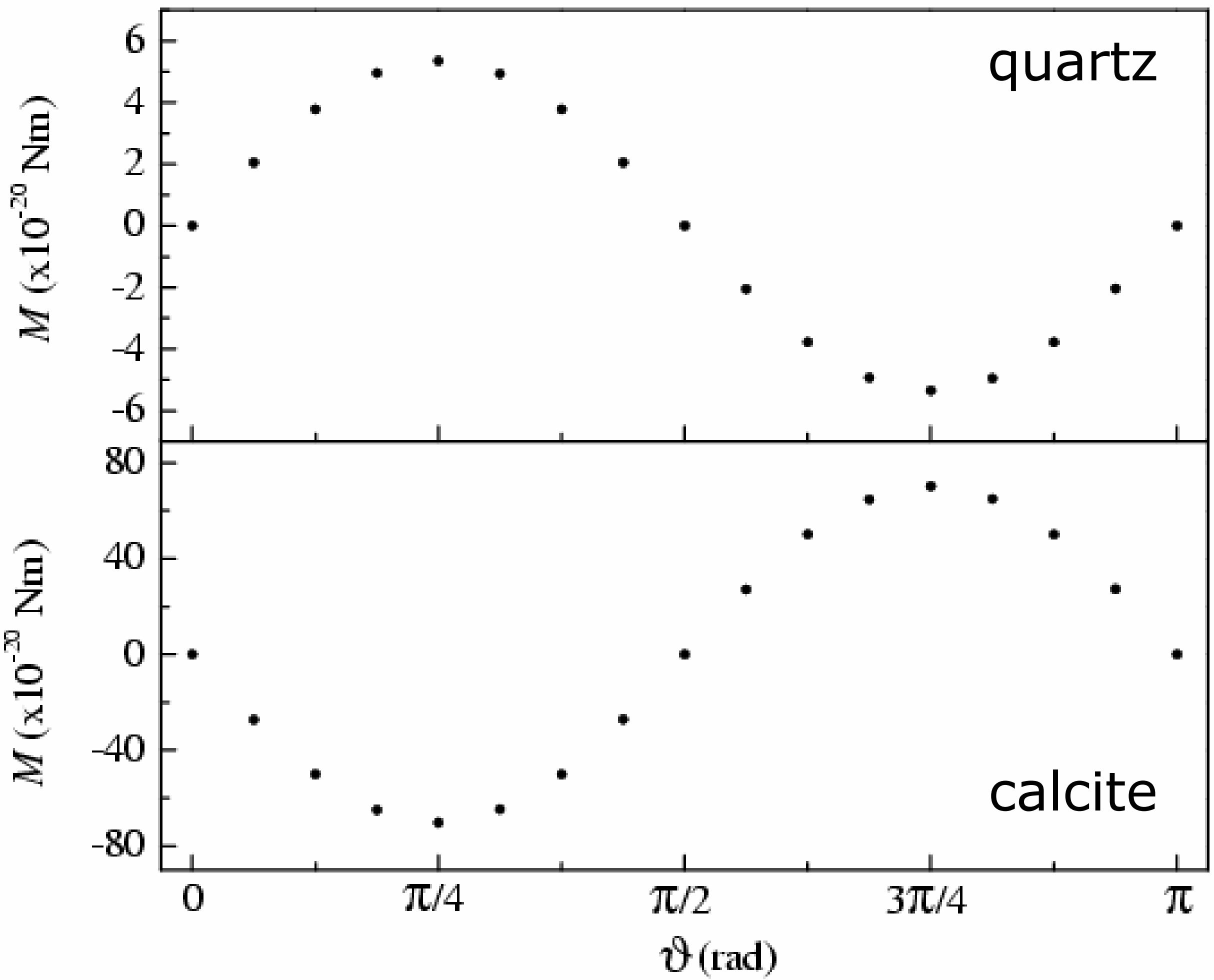
Bad news

Quite a technical challenge!

The effect is too small for currently available technologies

Quantum electrodynamical torque

Quartz or calcite disk (Ø=40µm,t=20µm) on top of barium titanate



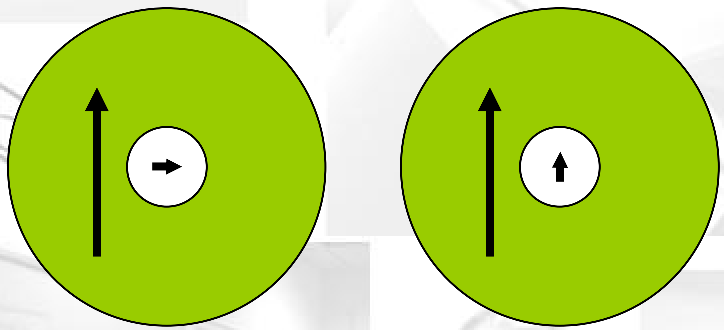
Good news

Torque versus angle for d = 100 nm

$$M \propto \sin 2\theta$$

Quantum electrodynamical torque

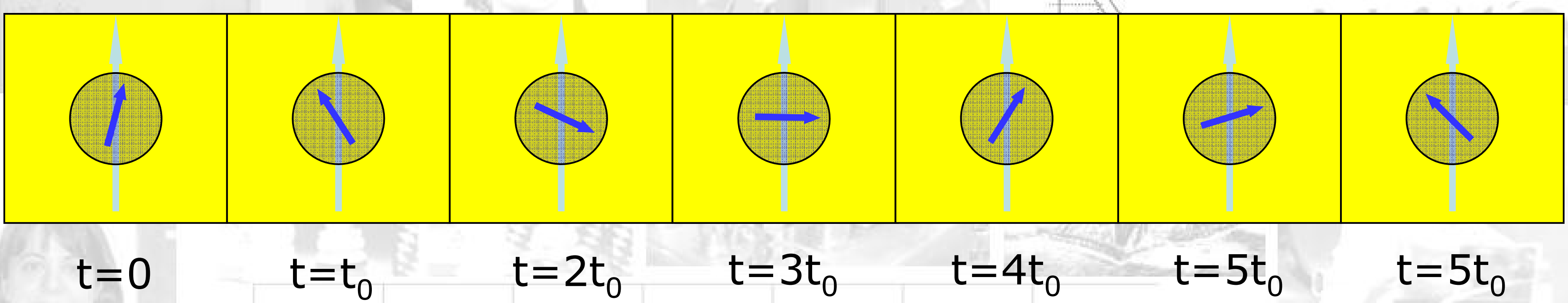
- Smaller surfaces: a better choice?
  - Let’s take a small disk *(Ø<1 μm,t~100nm)*



Itan Barmes

$$E(\pi/2) - E(0) \approx k_B T$$

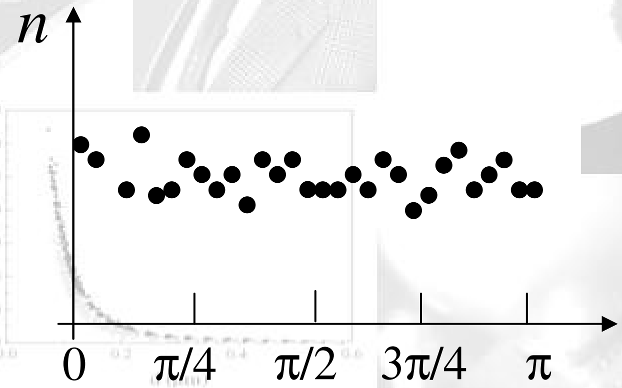
Still in collaborations with



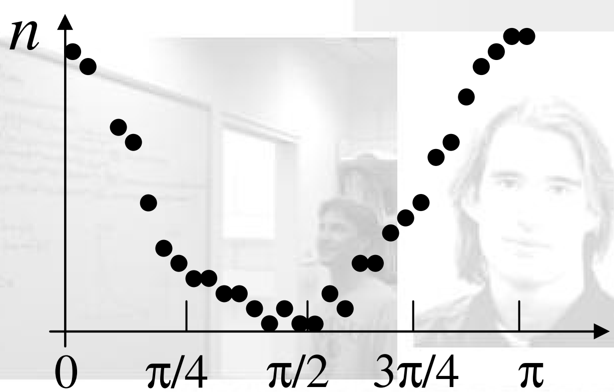
Quantum electrodynamical torque

Measure the position as a function of time

If energy did not depend on θ



But energy depends on θ



$$p(\vartheta) \propto \exp\left(-\frac{E(\vartheta)}{k_B T}\right)$$

CONCLUSION 4

Quantum electrodynamical torque: an interesting phenomenon that has not received adequate attention

Rotation is weak: tricks are needed

One possible solution: Brownian motion

Experiment running at Harvard

CONCLUSIONS

There is plenty of room…

…beyond the accuracy issue!

Thank you for your kind attention
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