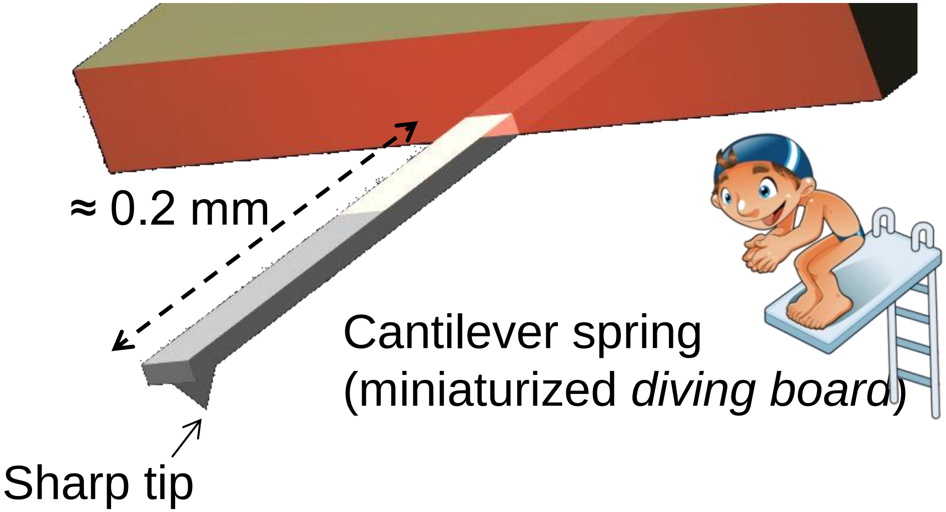
FIBER-TOP TECHNOLOGY:
FROM FUNDAMENTAL PHYSICS TO PRECLINICAL RESEARCH

Davide Iannuzzi
VU University Amsterdam

Atomic force microscopy (1986) (Binning, Quate, Gerber)



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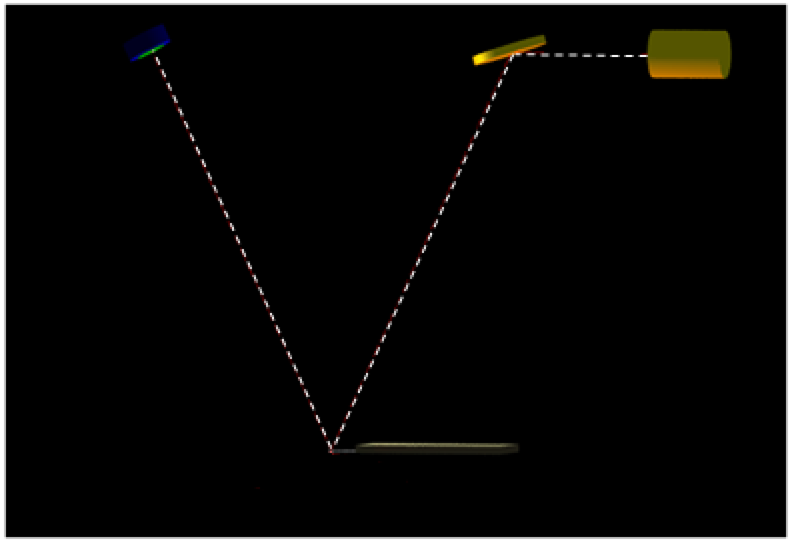

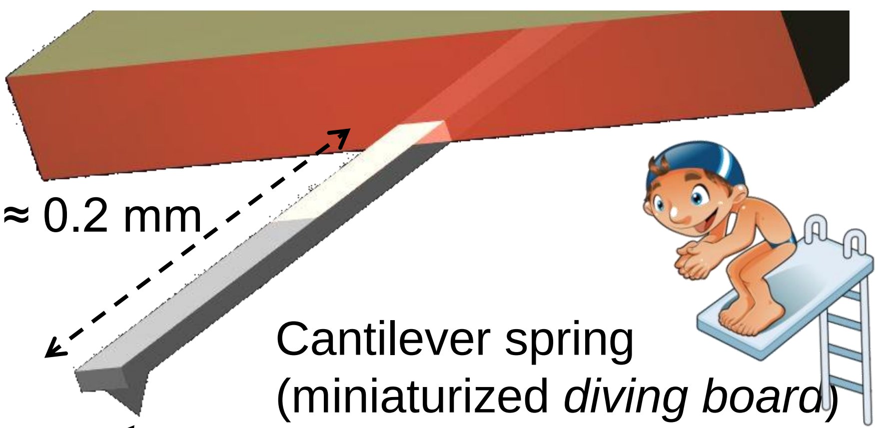

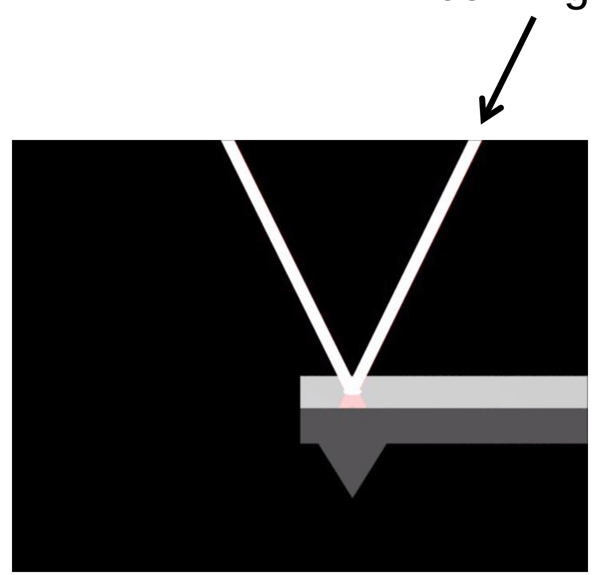

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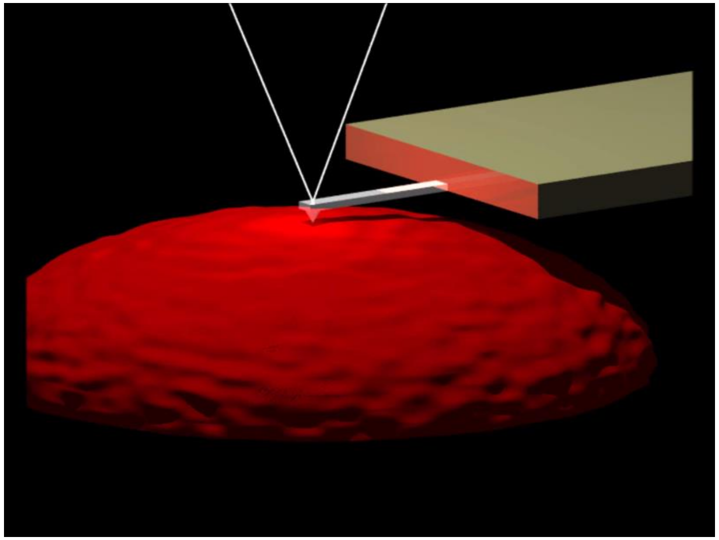
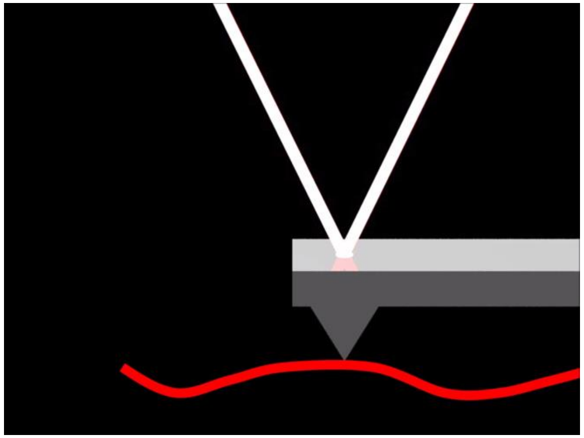
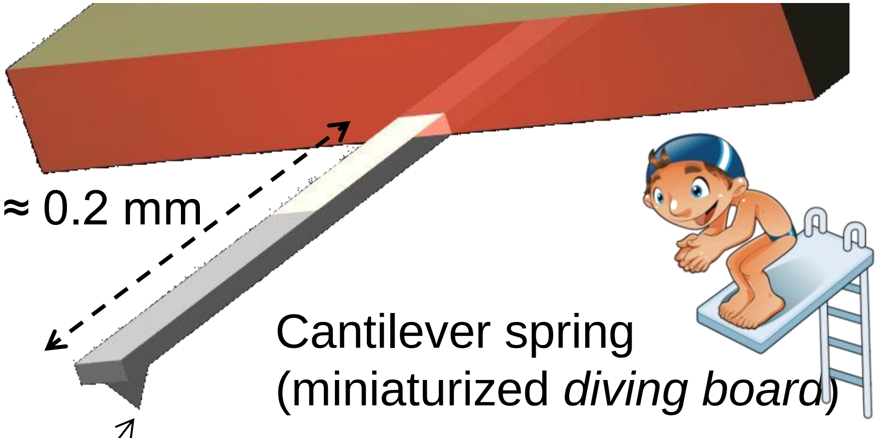


Imaging at the nanoscale
(like vinyl LP players)

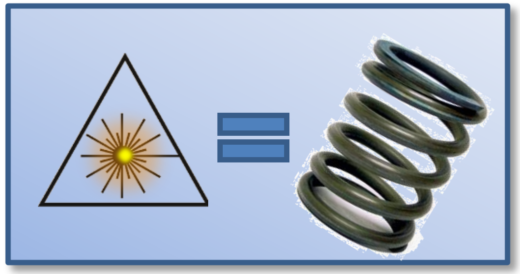




Sharp tip

Atomic force microscopy and the Casimir effect in Amsterdam (2005)

$$
\begin{cases}
\nabla \cdot \mathbf{E} = 0 \\
\nabla \times \mathbf{E} = -\dfrac{\partial \mathbf{B}}{\partial t} \\
\nabla \cdot \mathbf{B} = 0 \\
\nabla \times \mathbf{E} = \dfrac{1}{c^2}\dfrac{\partial \mathbf{B}}{\partial t}
\end{cases}
$$

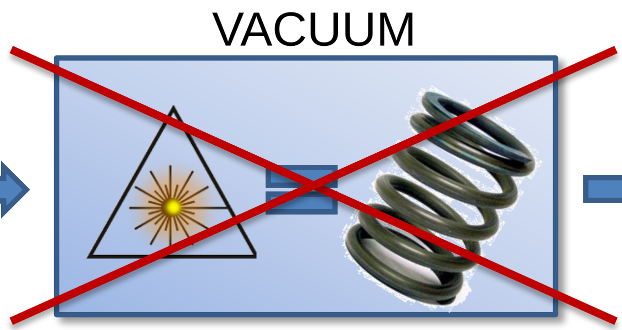


# of photons

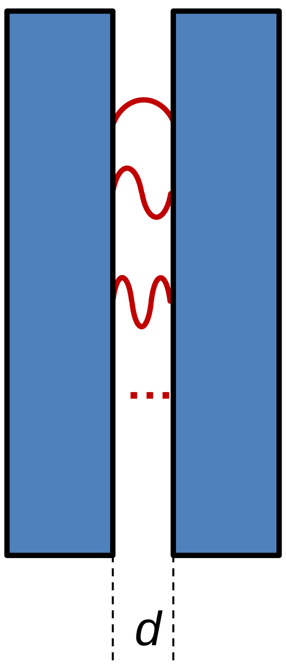
$$E_n = \hbar\omega\left(n + \frac{1}{2}\right)$$

Uncertainty Principle

$$\begin{cases} \nabla \cdot \mathbf{E} = 0 \\ \nabla \times \mathbf{E} = -\dfrac{\partial \mathbf{B}}{\partial t} \\ \nabla \cdot \mathbf{B} = 0 \\ \nabla \times \mathbf{E} = \dfrac{1}{c^2}\dfrac{\partial \mathbf{B}}{\partial t} \end{cases}$$



$$E_0 = \frac{1}{2}\hbar\omega \; ; \; E_{\mathrm{vac.}} = \sum_{all} \frac{1}{2}\hbar\omega_i$$



counting only the modes that fit

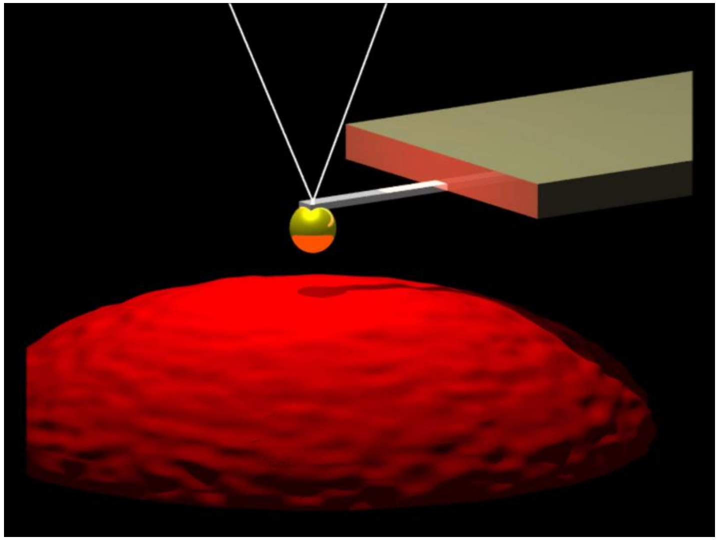
$$\begin{cases} E_{\mathrm{vac.}}^{\mathrm{cavity}} = \sum_m \dfrac{1}{2}\hbar\omega_m \\ \omega_m = c \cdot \sqrt{k_x^2 + k_y^2 + \dfrac{\pi^2}{d^2} m} \\ m = 0, 1, 2, \ldots \end{cases}$$

The energy depends on separation…

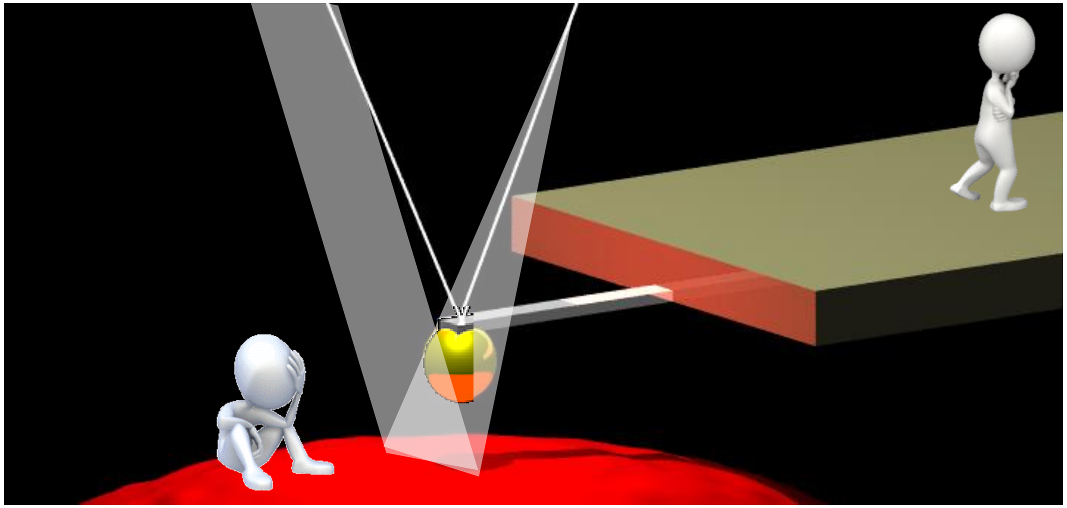
$$F = -\frac{\partial E}{\partial d}$$

…there exists a force

Atomic force microscopy and the Casimir effect in Amsterdam (2005)

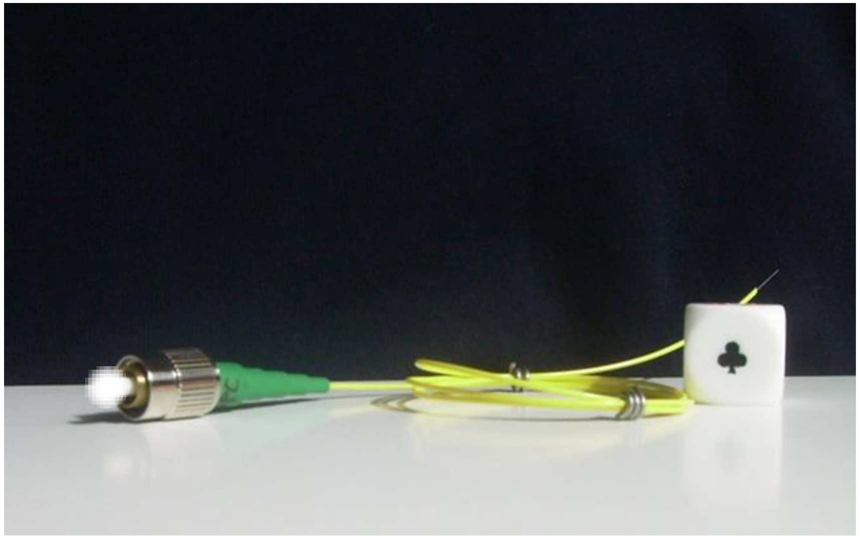


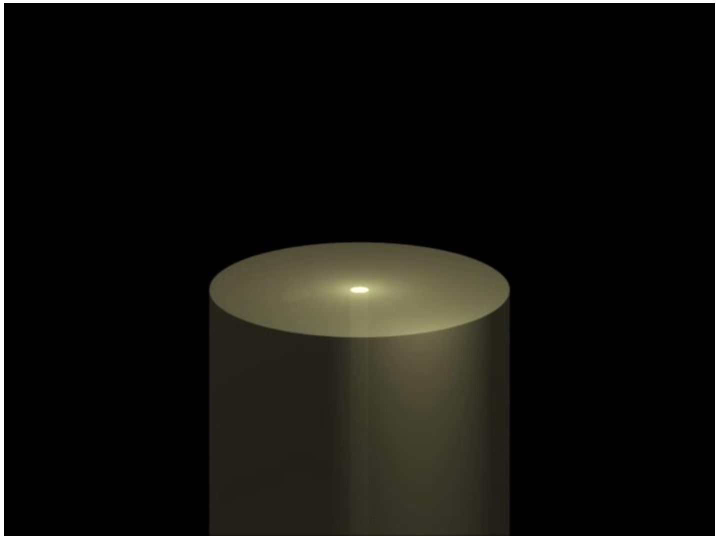
Casimir force measurements (@ 100 nm)

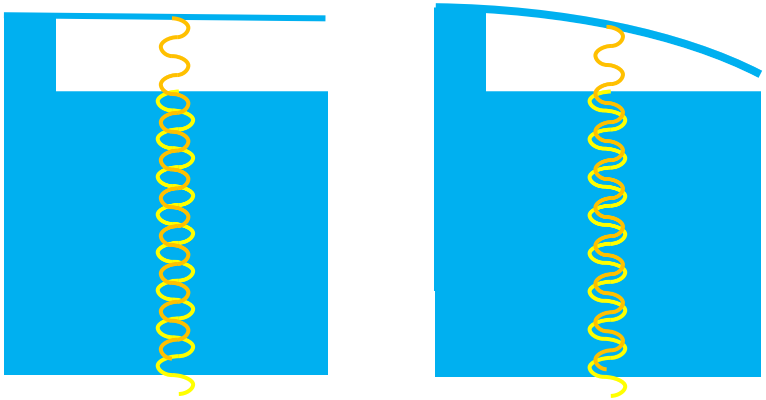


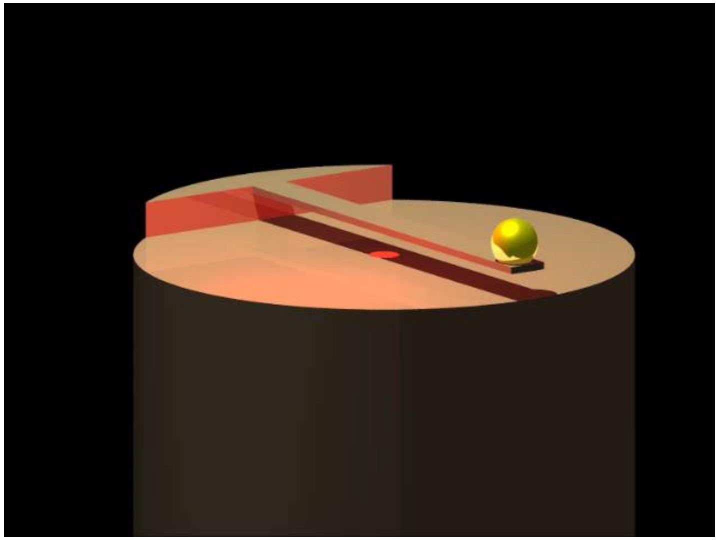
...an annoying problem

Fiber-top technology (2005)









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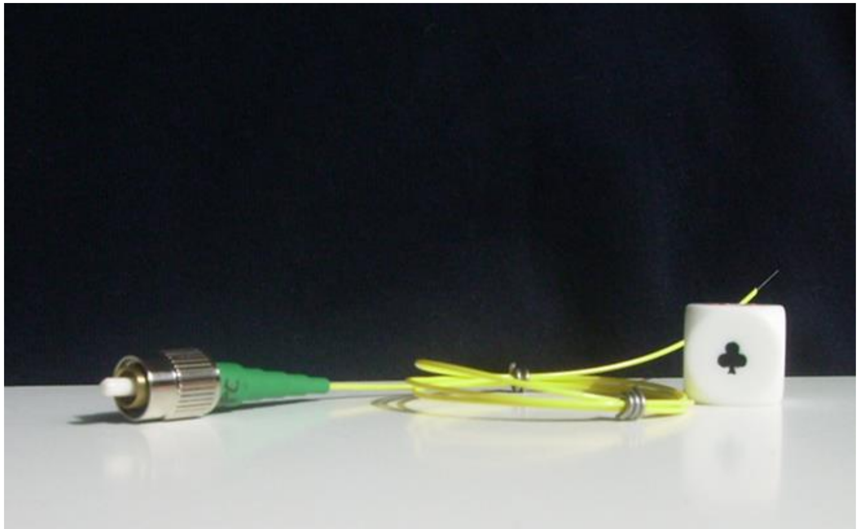
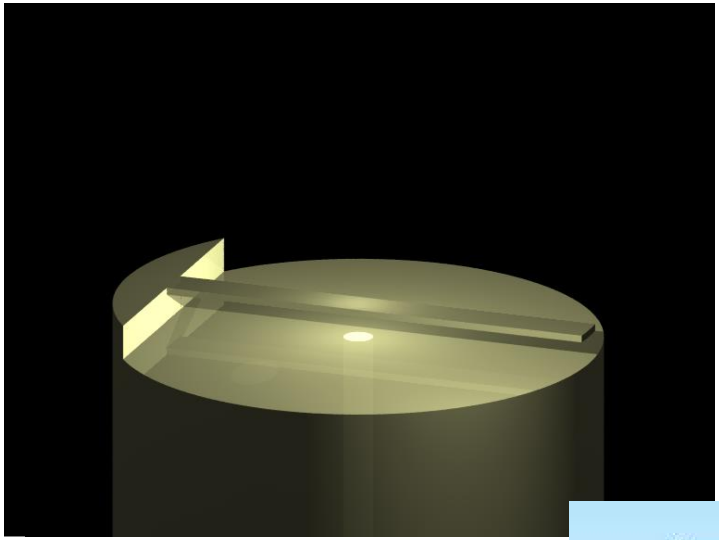
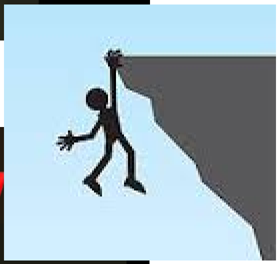
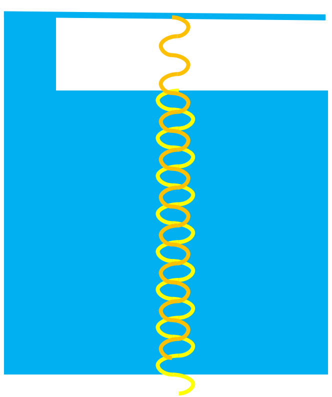
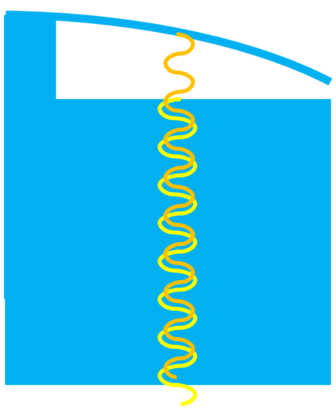




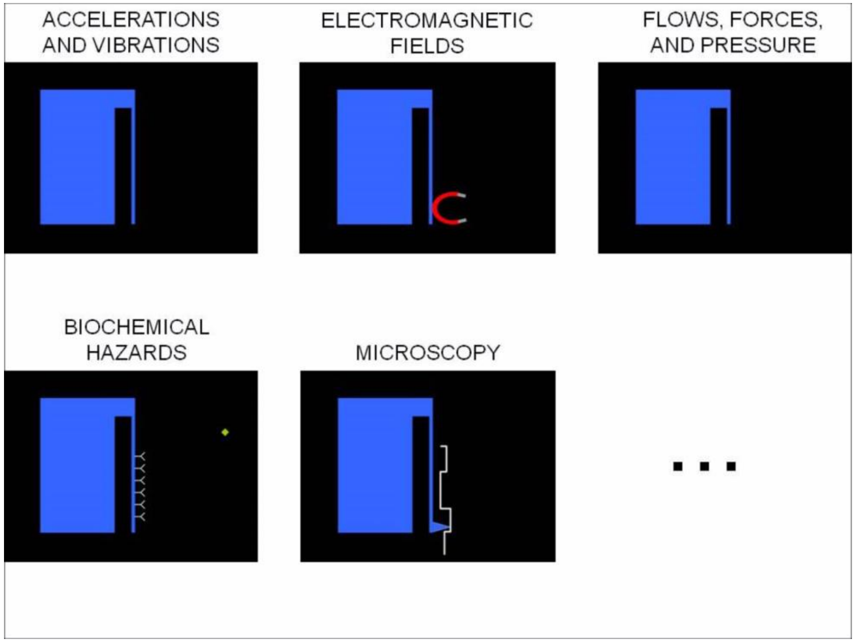


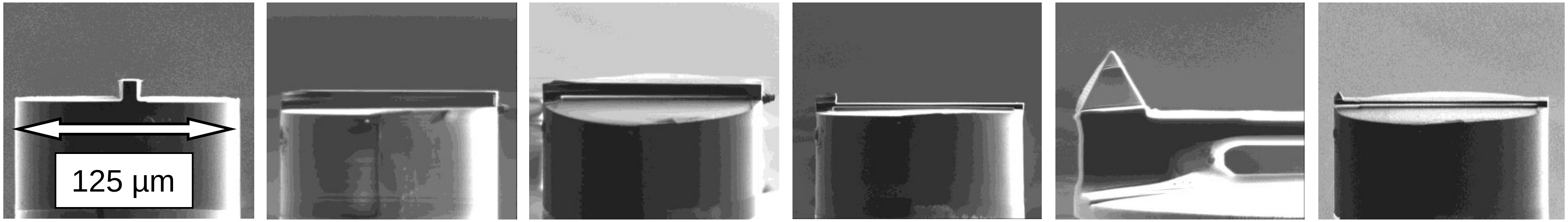




Fiber-top technology: a new platform for all optical sensing

- Extremely small (0.1 mm)
- Easy to use
- Adapt for harsh environments
- Adapt for remote sensing

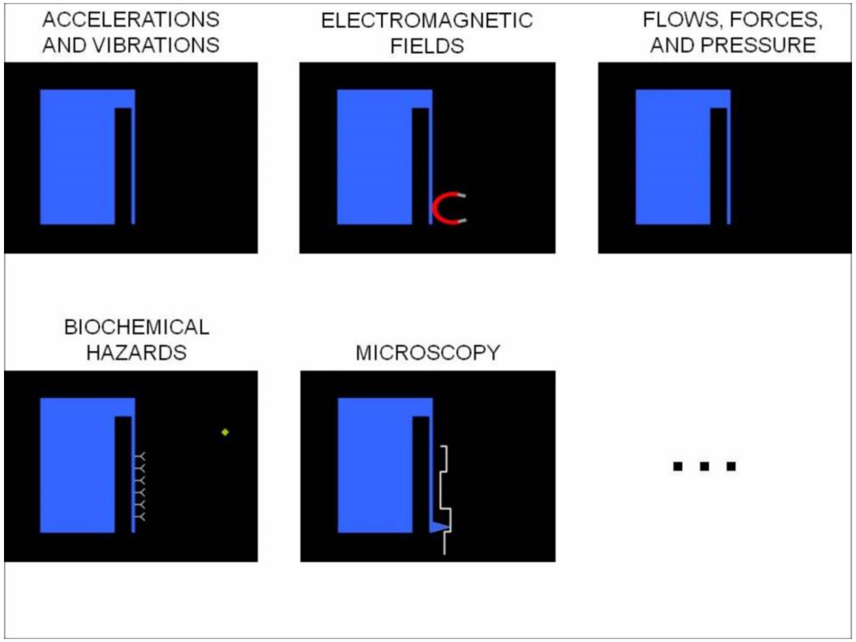


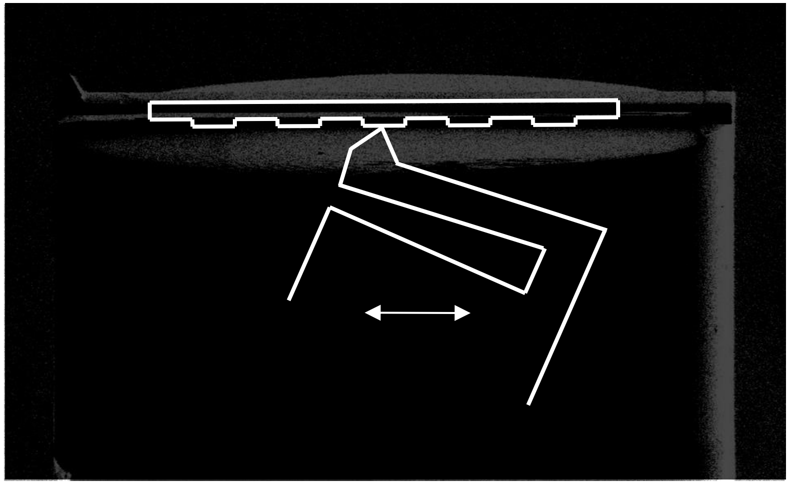


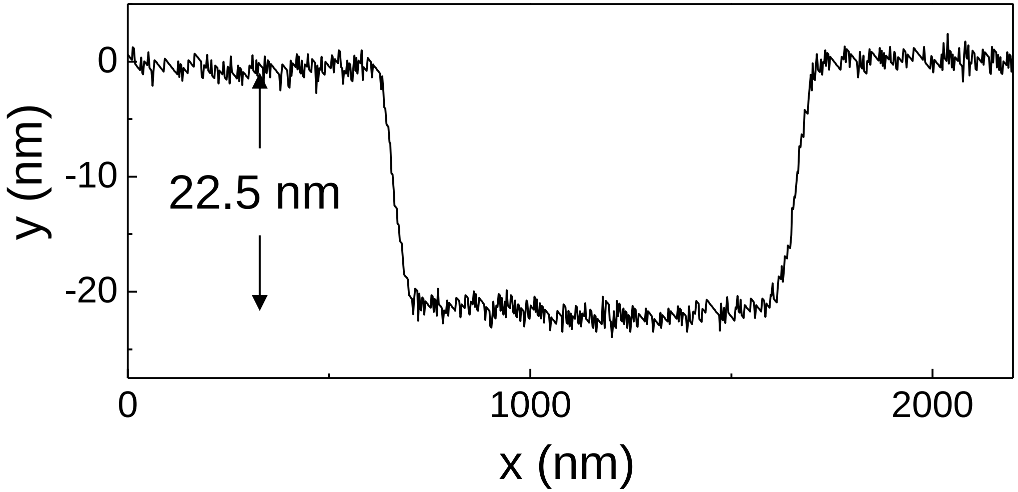
in collaboration with S. Deladi, M. Elwenspoek, E. Berenschot, UTwente

Fiber-top technology: and it even works!

- Extremely small (0.1 mm)
- Easy to use
- Adapt for harsh environments
- Adapt for remote sensing

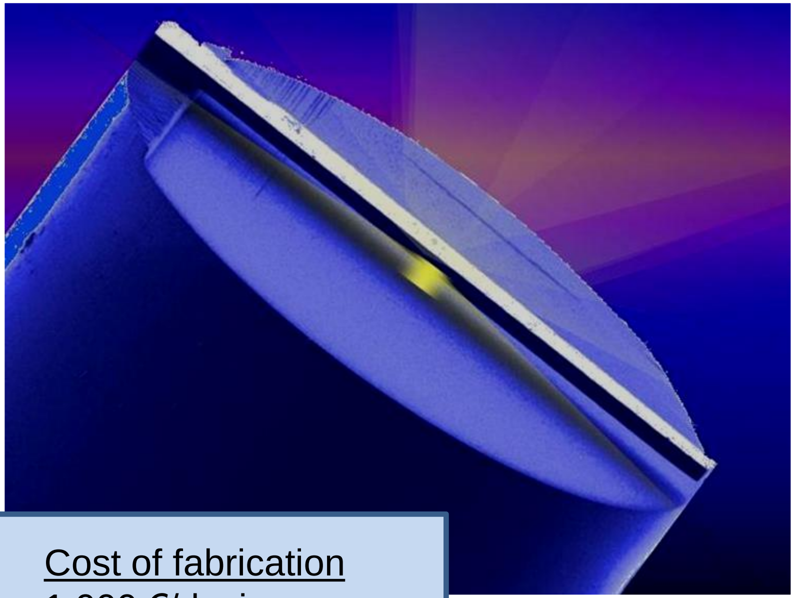






Reality check beyond the comfortable walls of my own laboratory

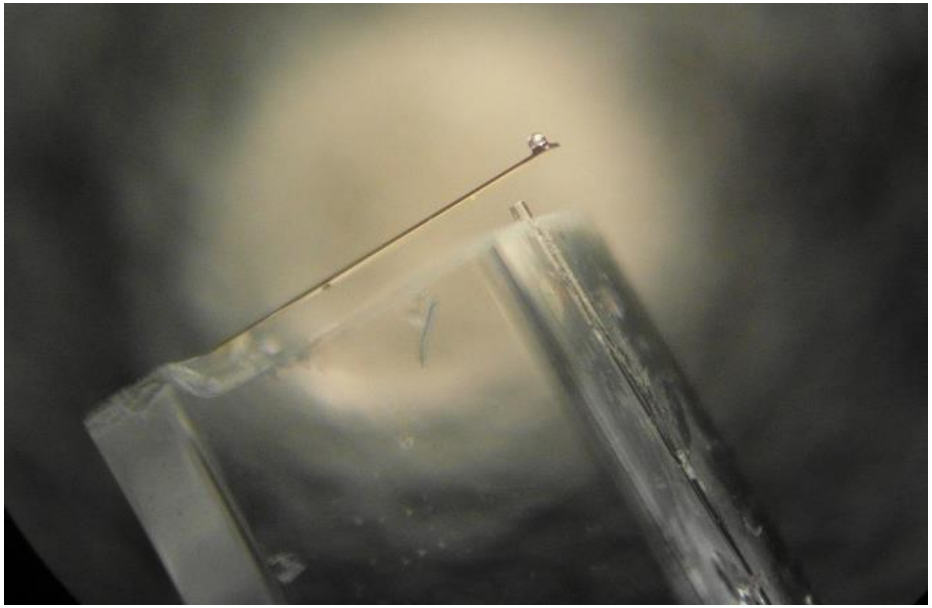
- Extremely small (0.1 mm)
- Easy to use
- Adapt for harsh environments
- Adapt for remote sensing



<u>Cost of fabrication</u>
1,000 €/device, more than one day of work!

Moving outside my research laboratory

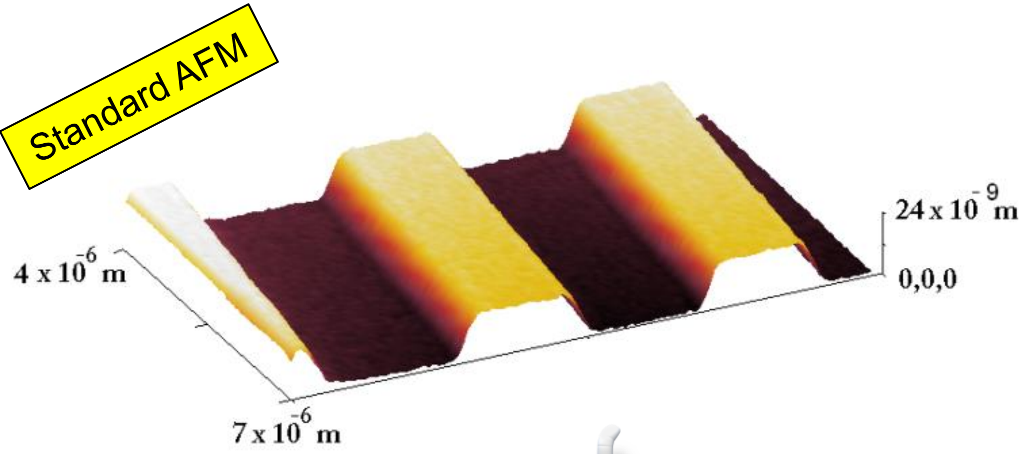
- Extremely small (0.1 ~~mm~~) **3 mm**
- Easy to use
- Adapt for harsh environments
- Adapt for remote sensing

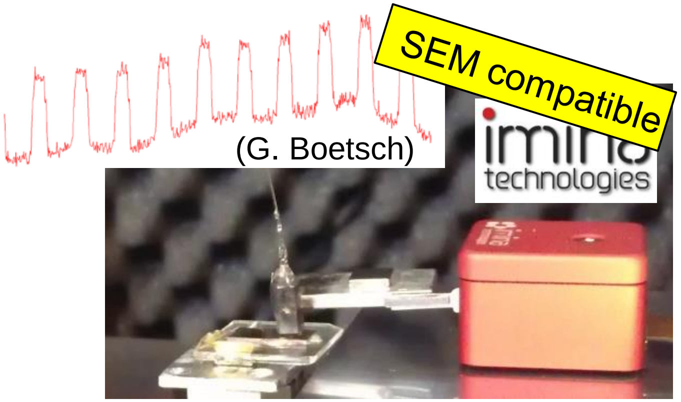


ATOMIC FORCE MICROSCOPY

ALL OPTICAL SENSING

Scanning probe microscopy

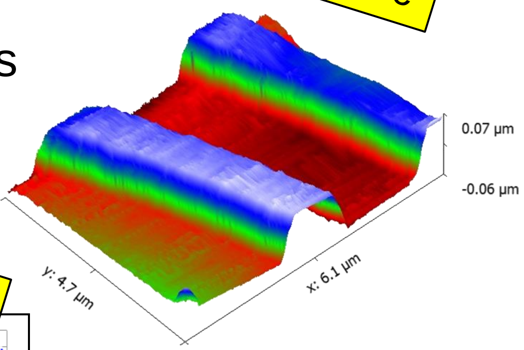


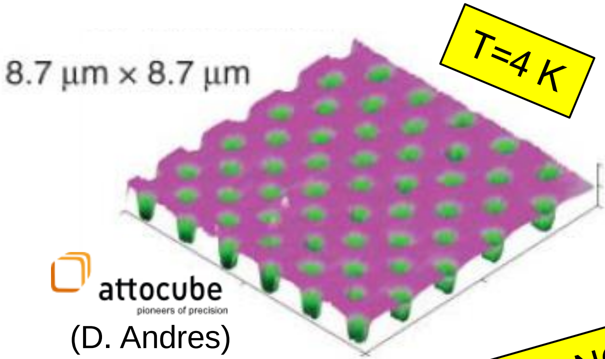


Easy to use

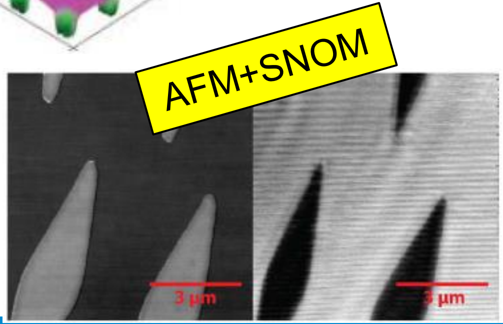
Universiteit Utrecht
(B. Weckhuyzen)

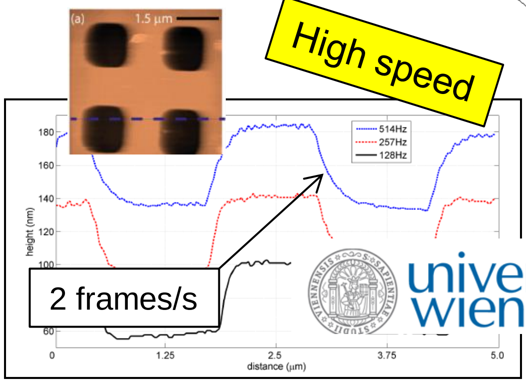
Adapt for harsh environments





attocube
pioneers of precision
(D. Andres)



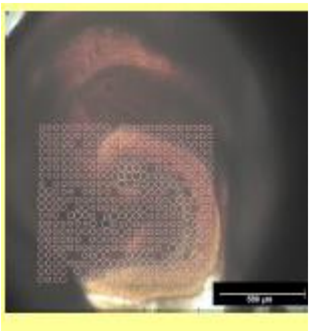


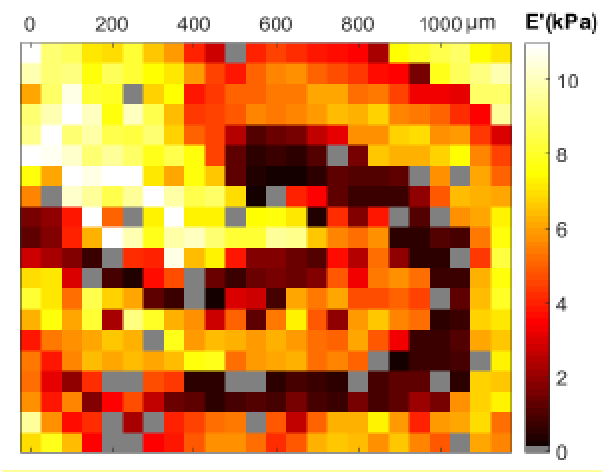
universität wien (G. Schitter)

One application over the others

OPTICS11
ideas on the top of a fiber

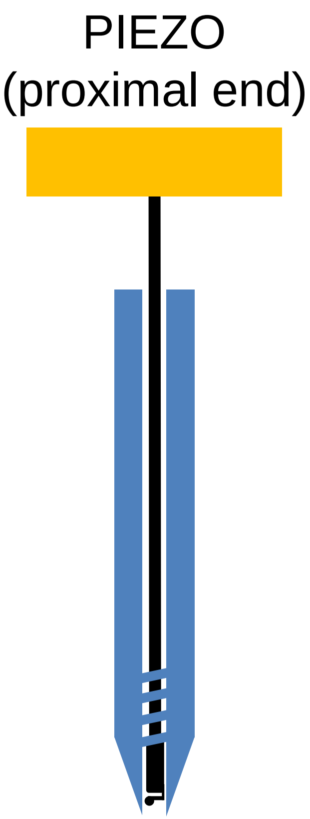
Applications in my group:
- Brain
- Chick embryos

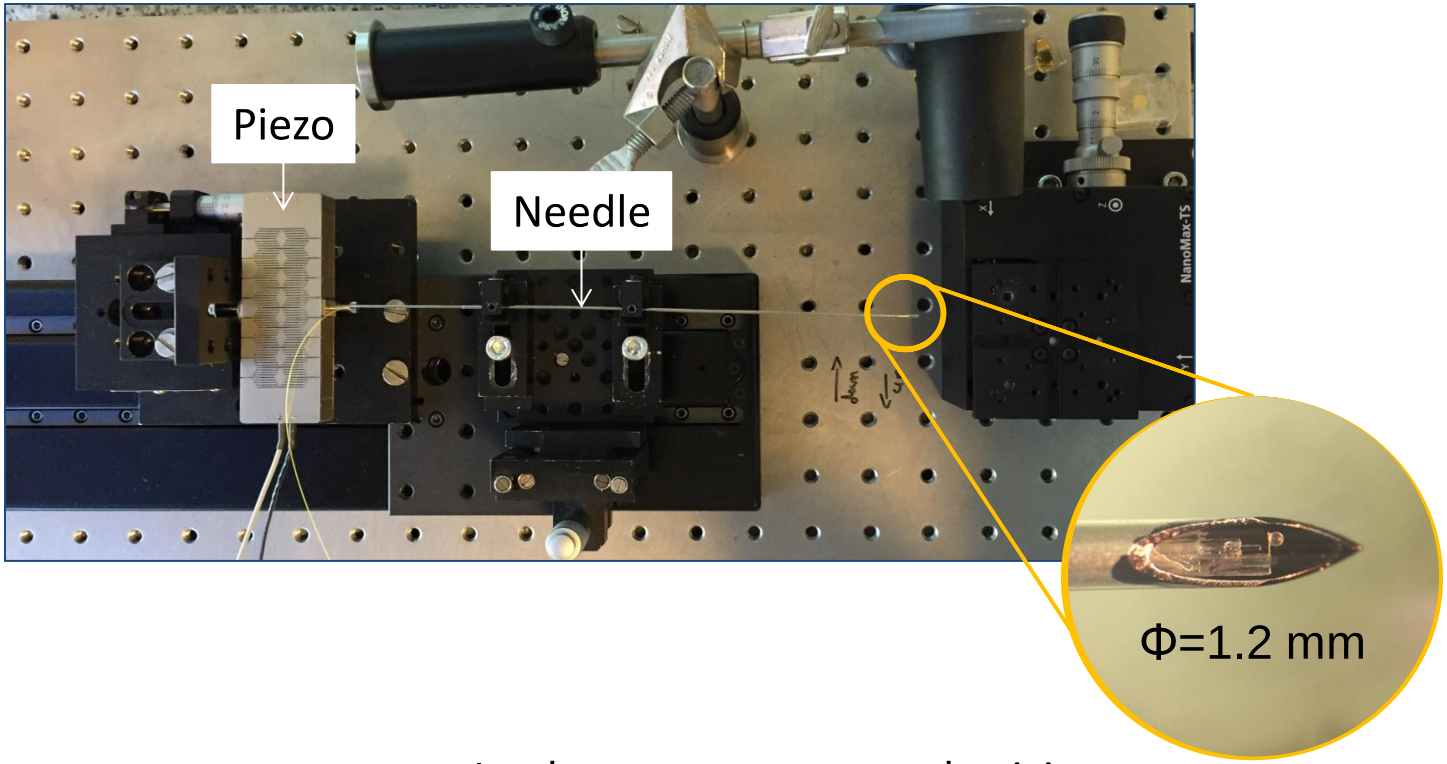


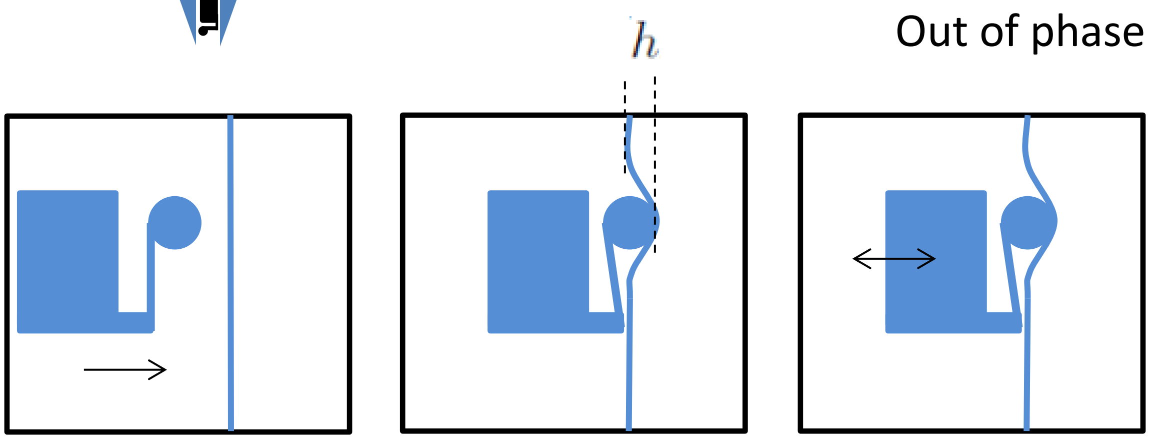


Disclosure: the author is founder and shareholder of Optics11

Indeter in a needle







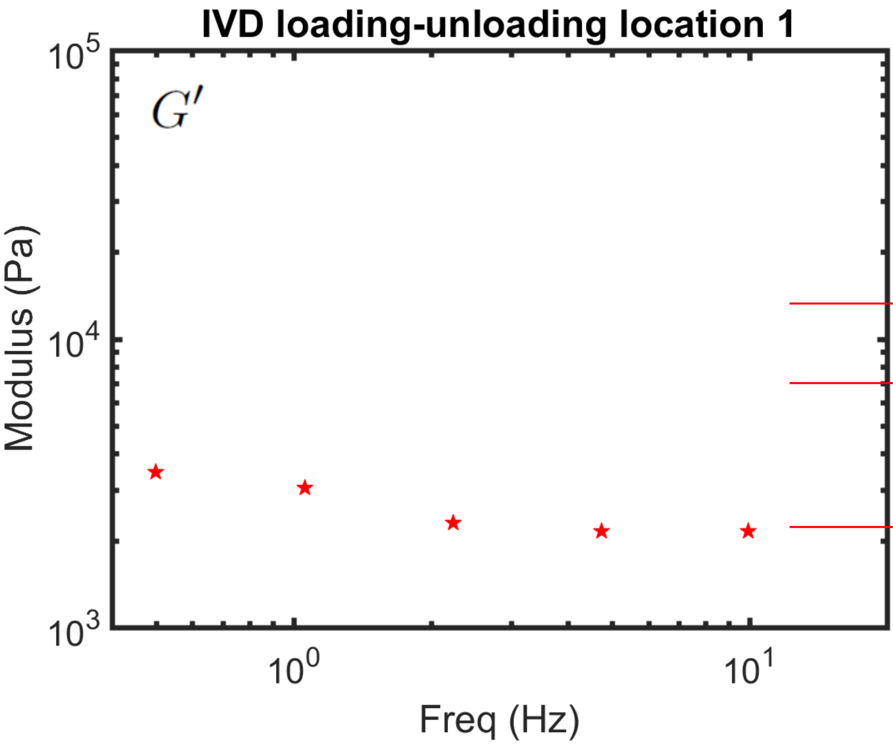
In phase component = elasticity
Out of phase component = viscosity

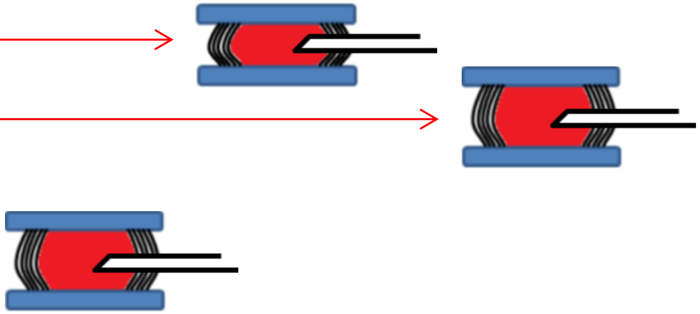
$$G' \propto \frac{P_0}{h_0} \cos(\phi) \frac{1}{\sqrt{hR}} \quad \text{STORAGE}$$

$$G'' \propto \frac{P_0}{h_0} \sin(\phi) \frac{1}{\sqrt{hR}} \quad \text{LOSS}$$

Ex-vivo intervertebral disk experiment

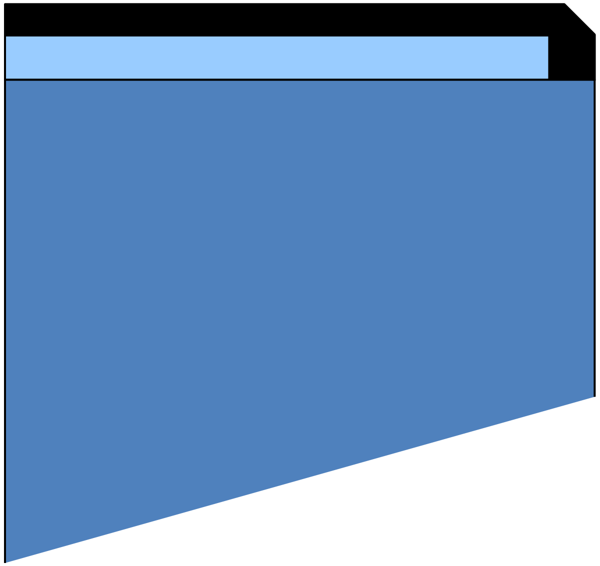
PRELIMINARY RESULTS

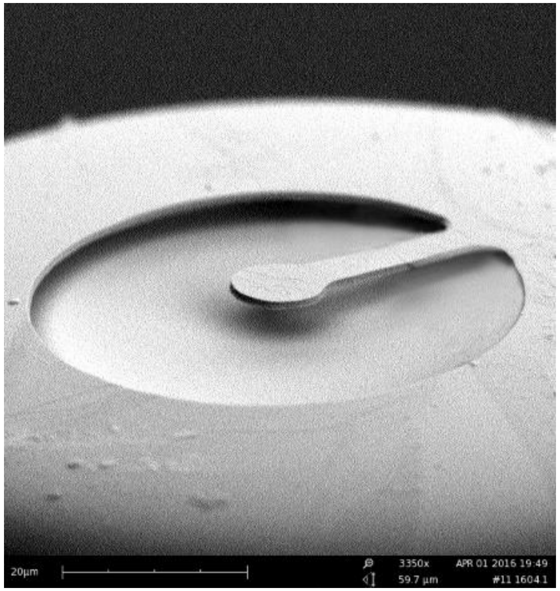


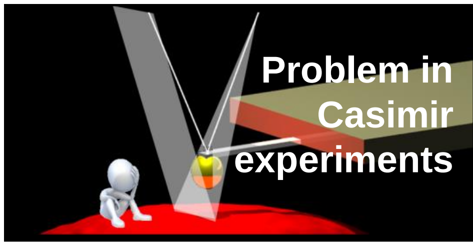


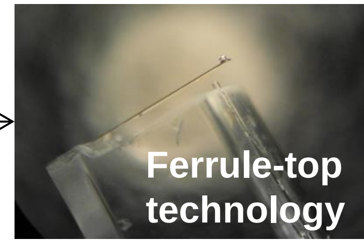
Fiber-top MEMS

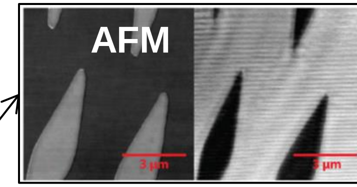
Alternate layers of structural and sacrificial materials
(like in MEMS technology)

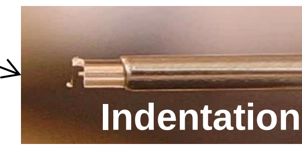


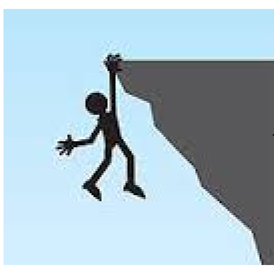






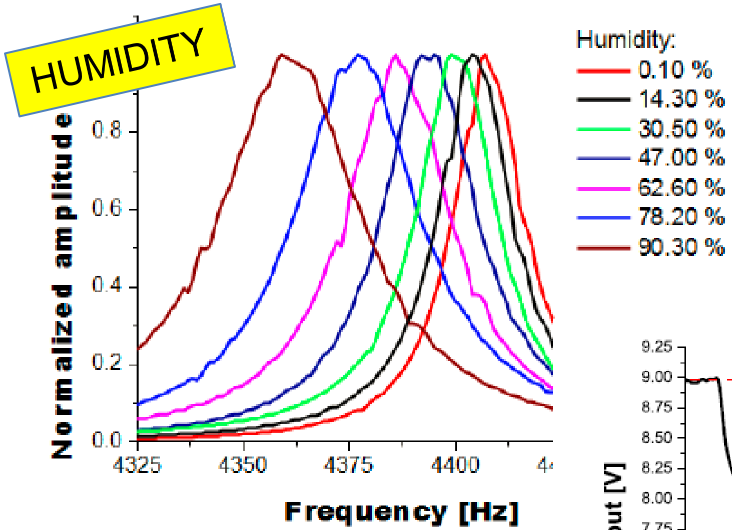


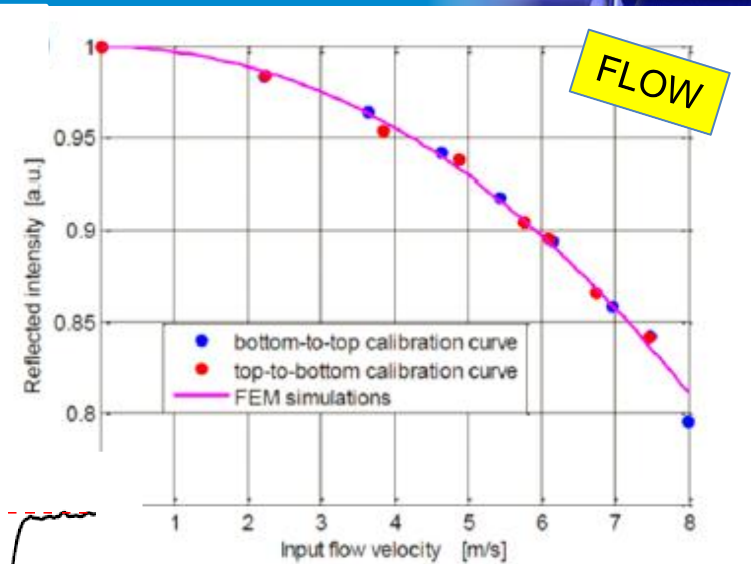




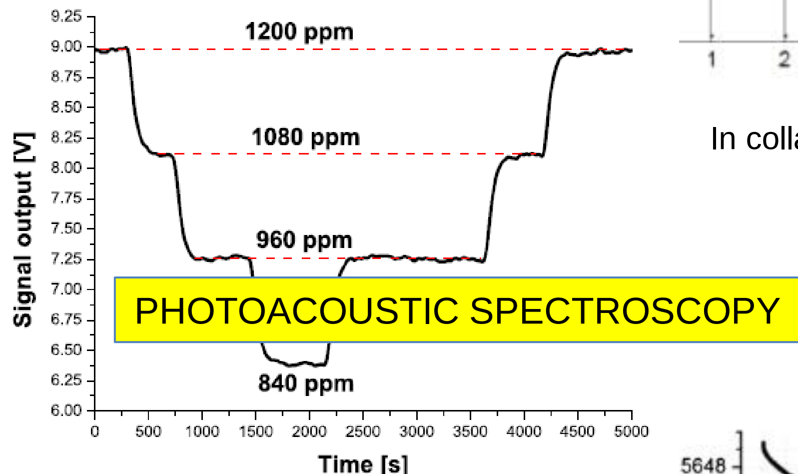
COMING UP:
All-optical sensing

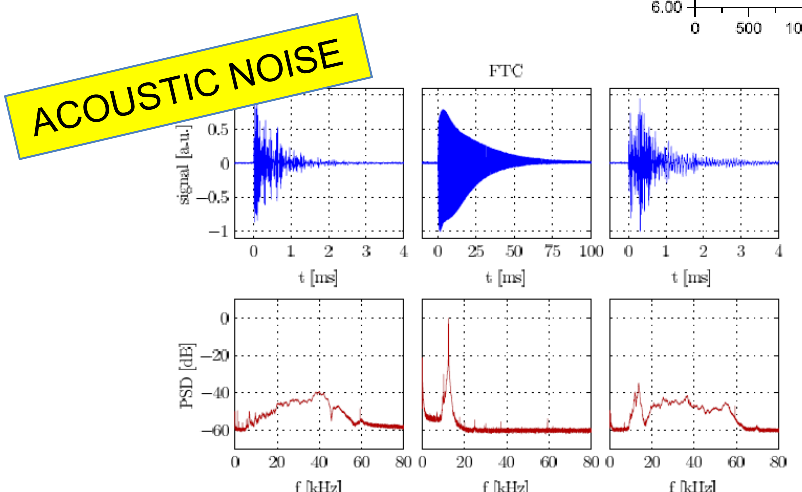
All optical sensors

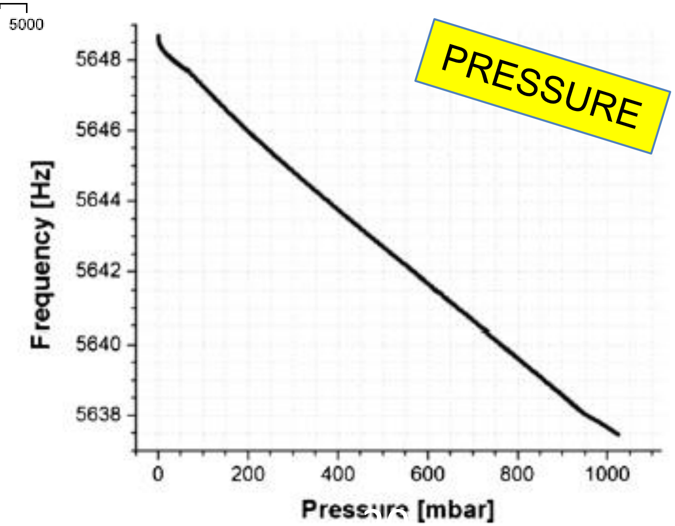




In collaboration with the group of L. Zeni





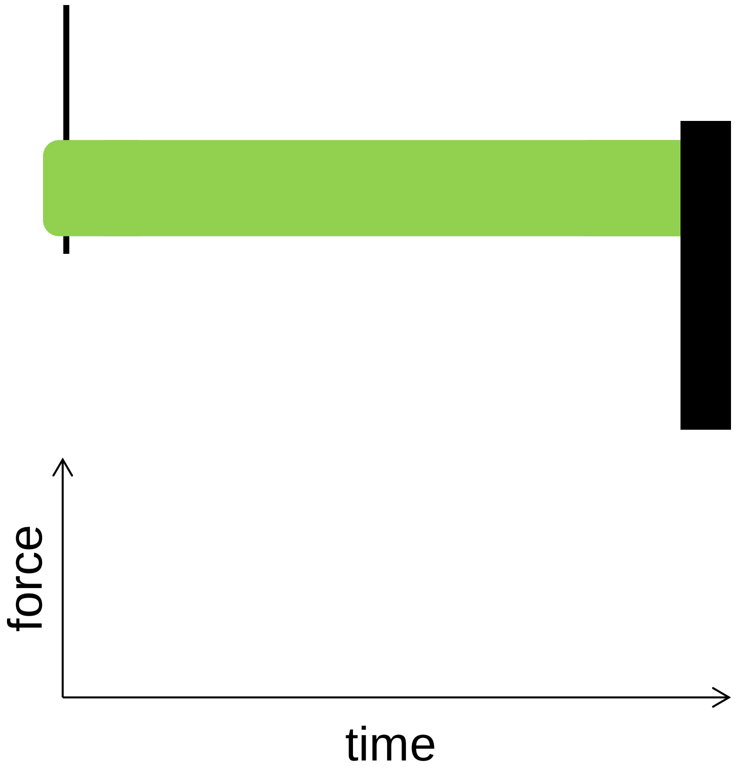


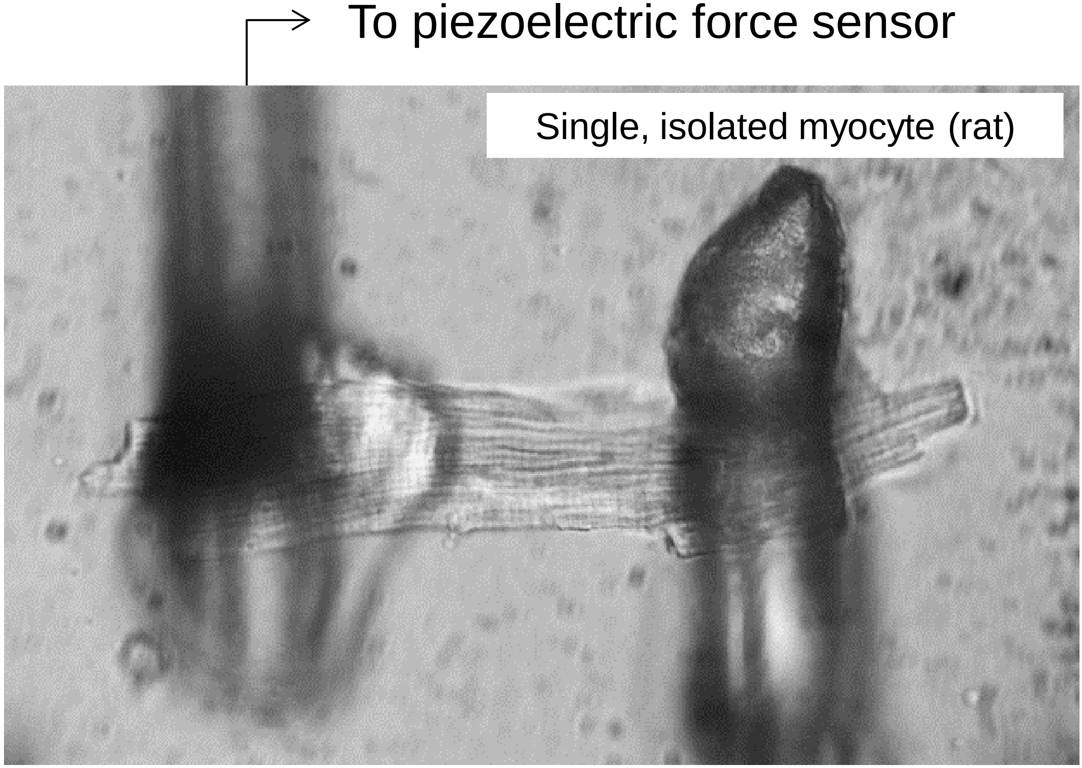
In collaboration with the group of L. Palmieri

In collaboration with

and with J. van der Velden, A. Najafi, and M. Helmes (VUmc)

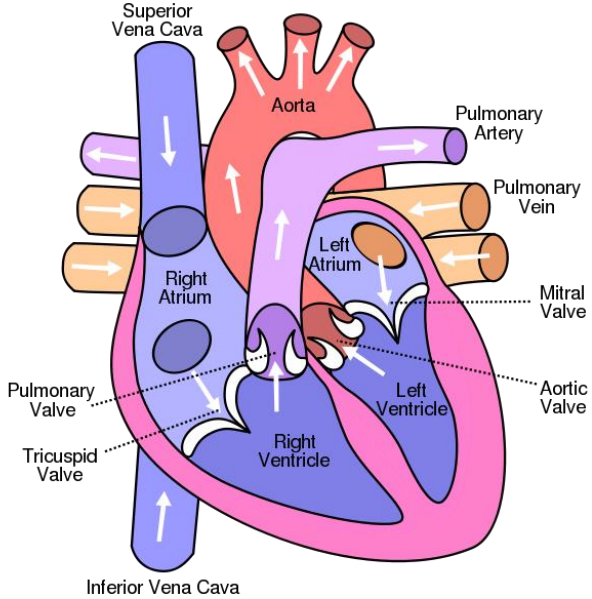
Previous state-of-the-art

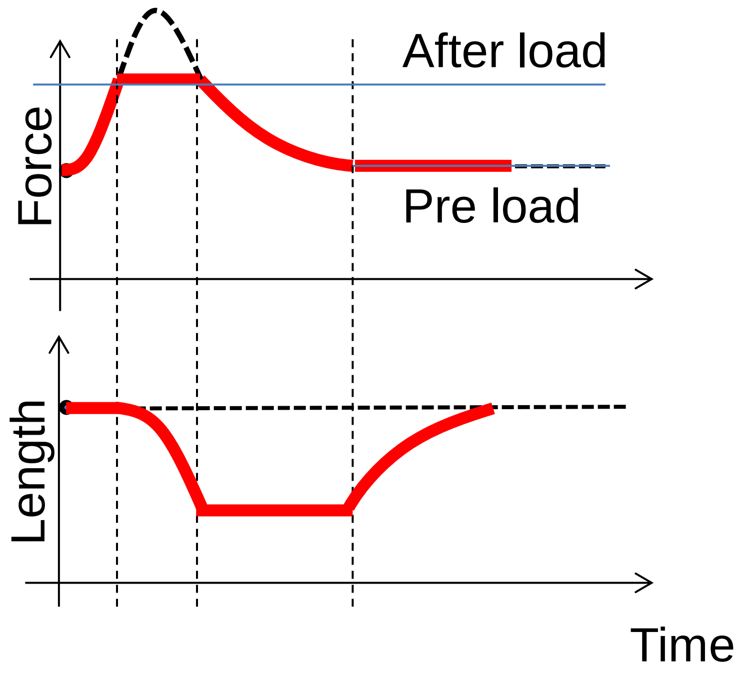




(note: the change in length is negligible!)
ISOMETRIC CONTRACTION!

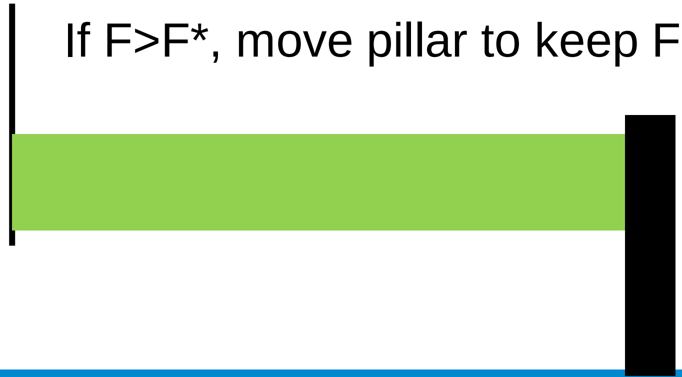
Are we doing the right thing?



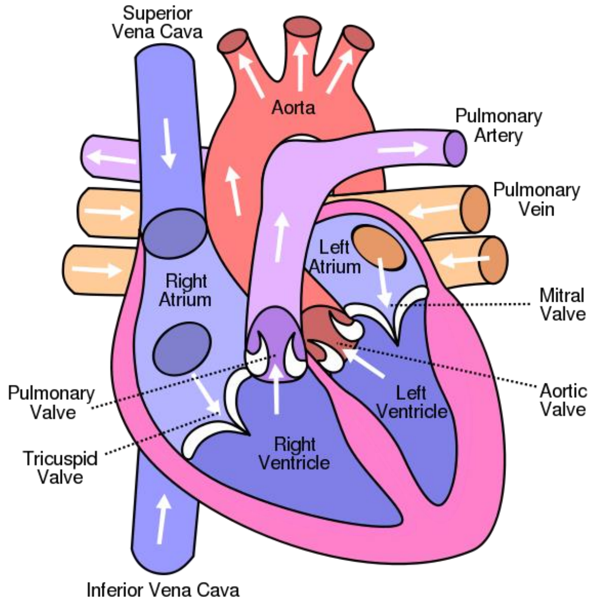


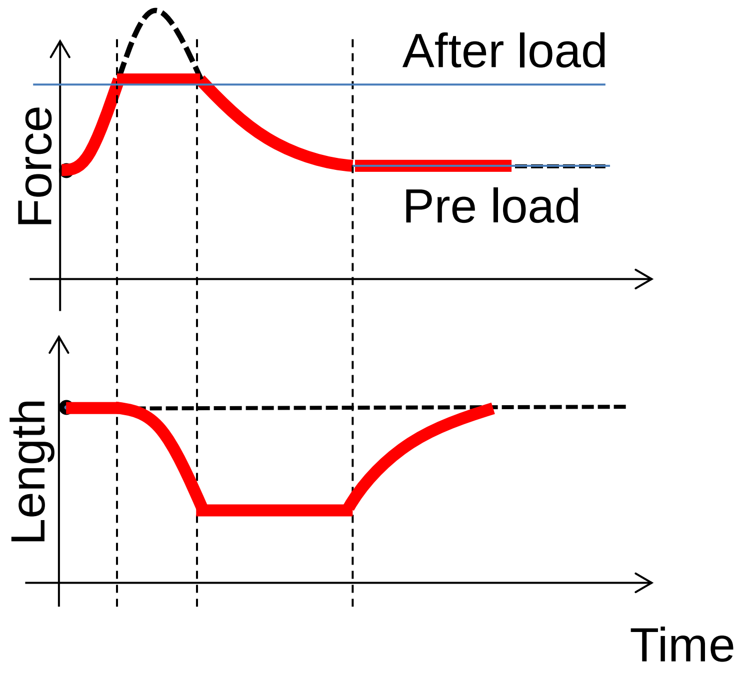
Measure F real time

If F>F*, move pillar to keep F=F*



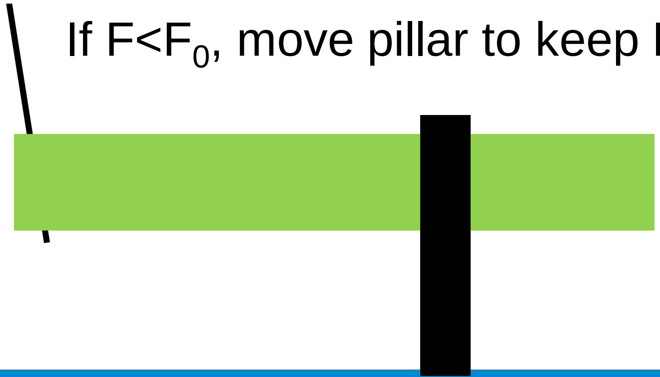
The cardiac cycle



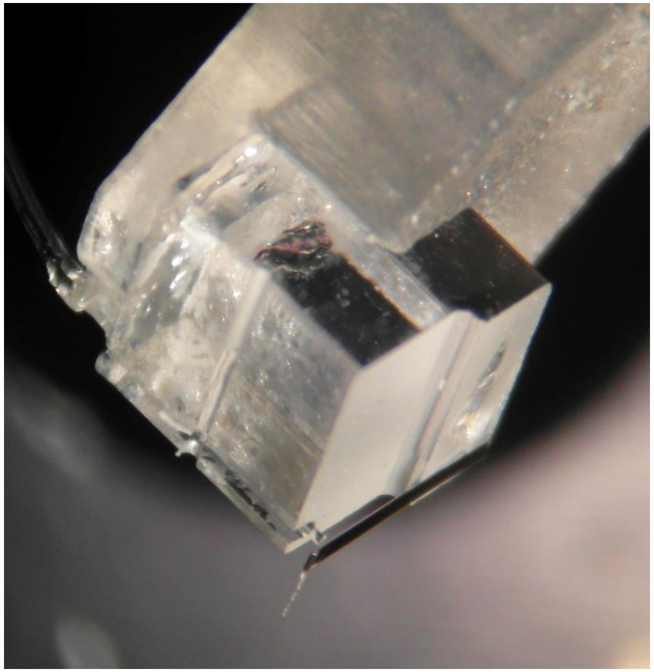


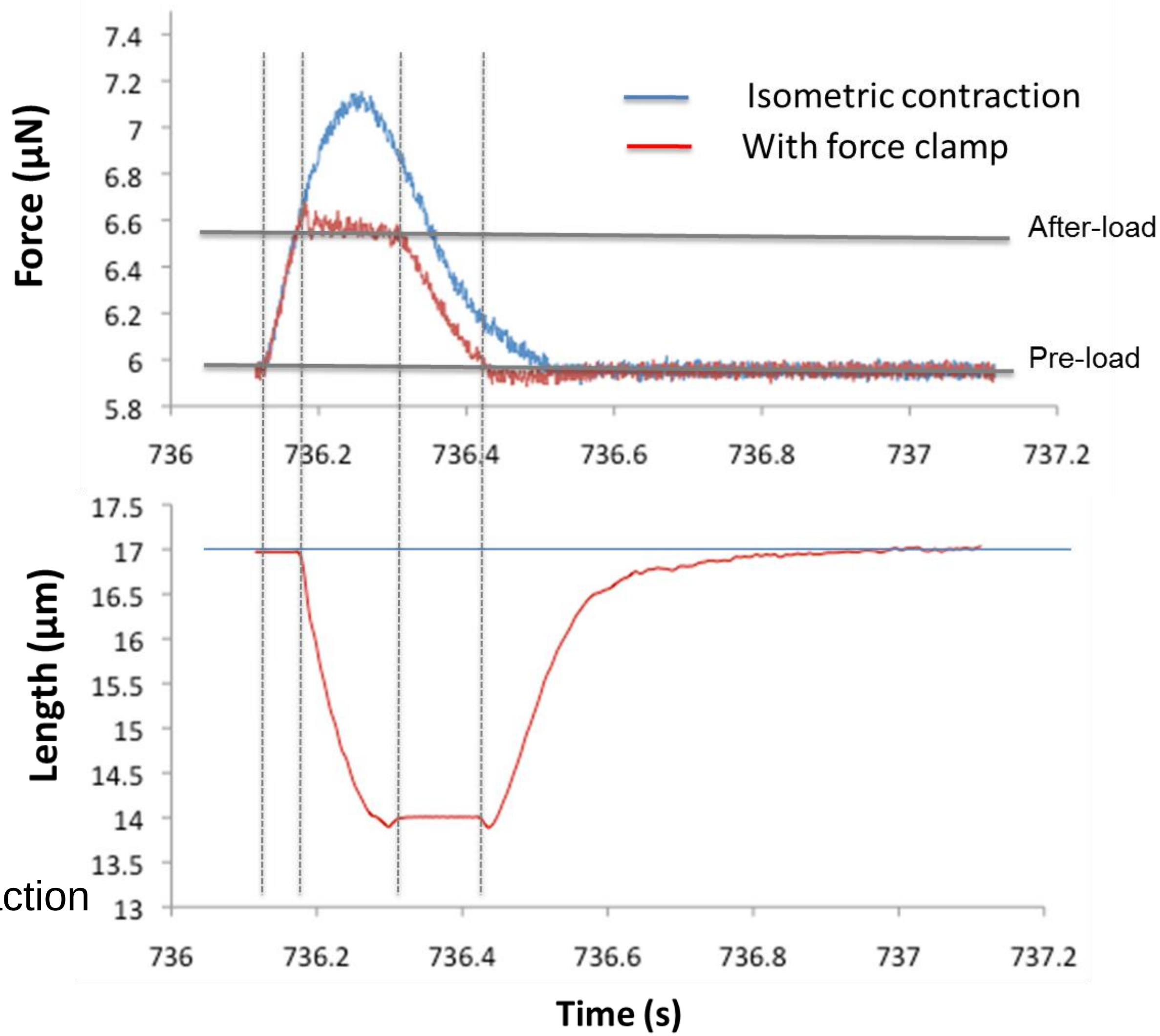
Measure F real time

If $F<F_0$, move pillar to keep $F=F_0$



Piezoelectric force sensor:
- Too slow
- Not sensitive enough
- Remote → more noise/drift



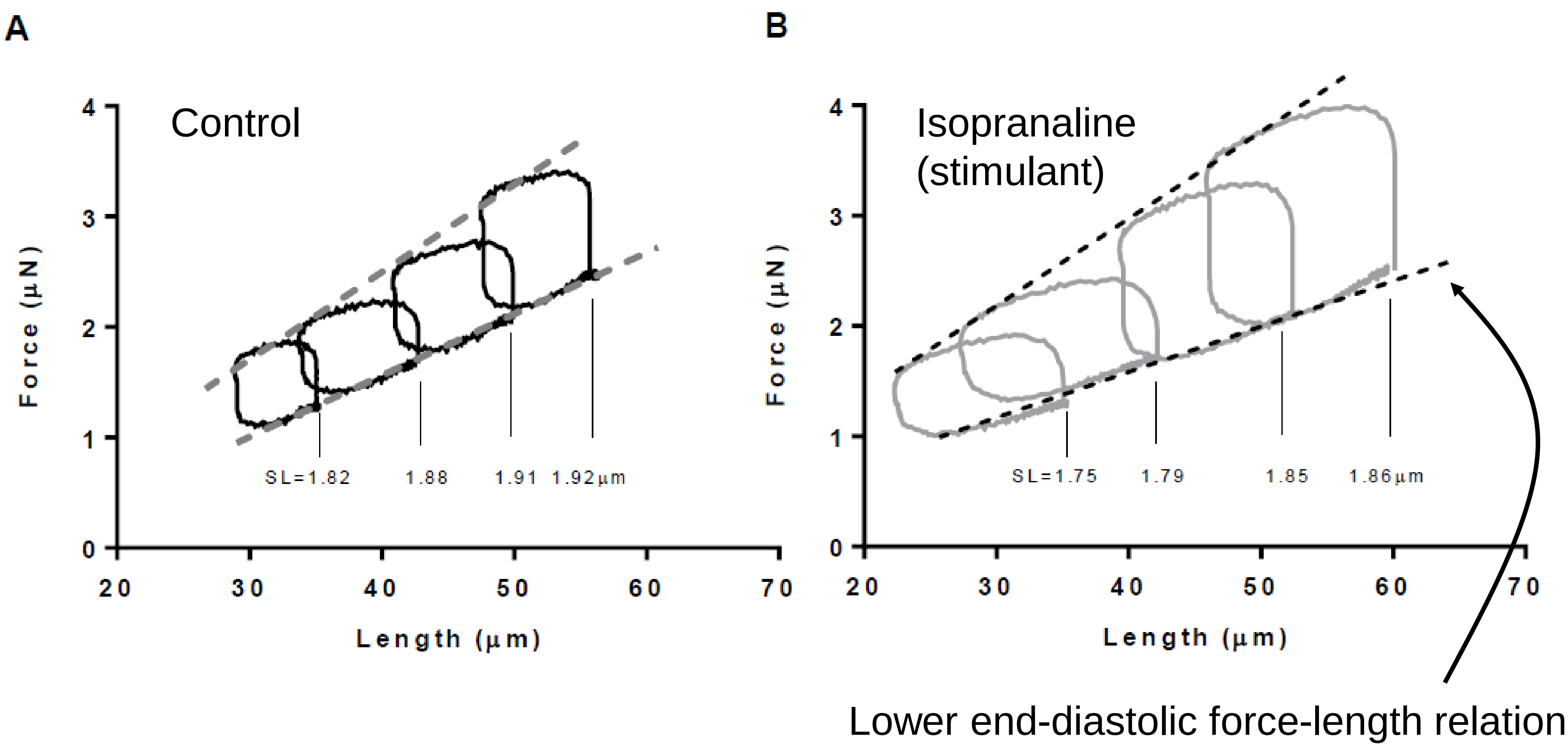


We can mimic, EXACTLY, the heart cycle at physiological conditions at the single cell level (no extracellular matrix)!

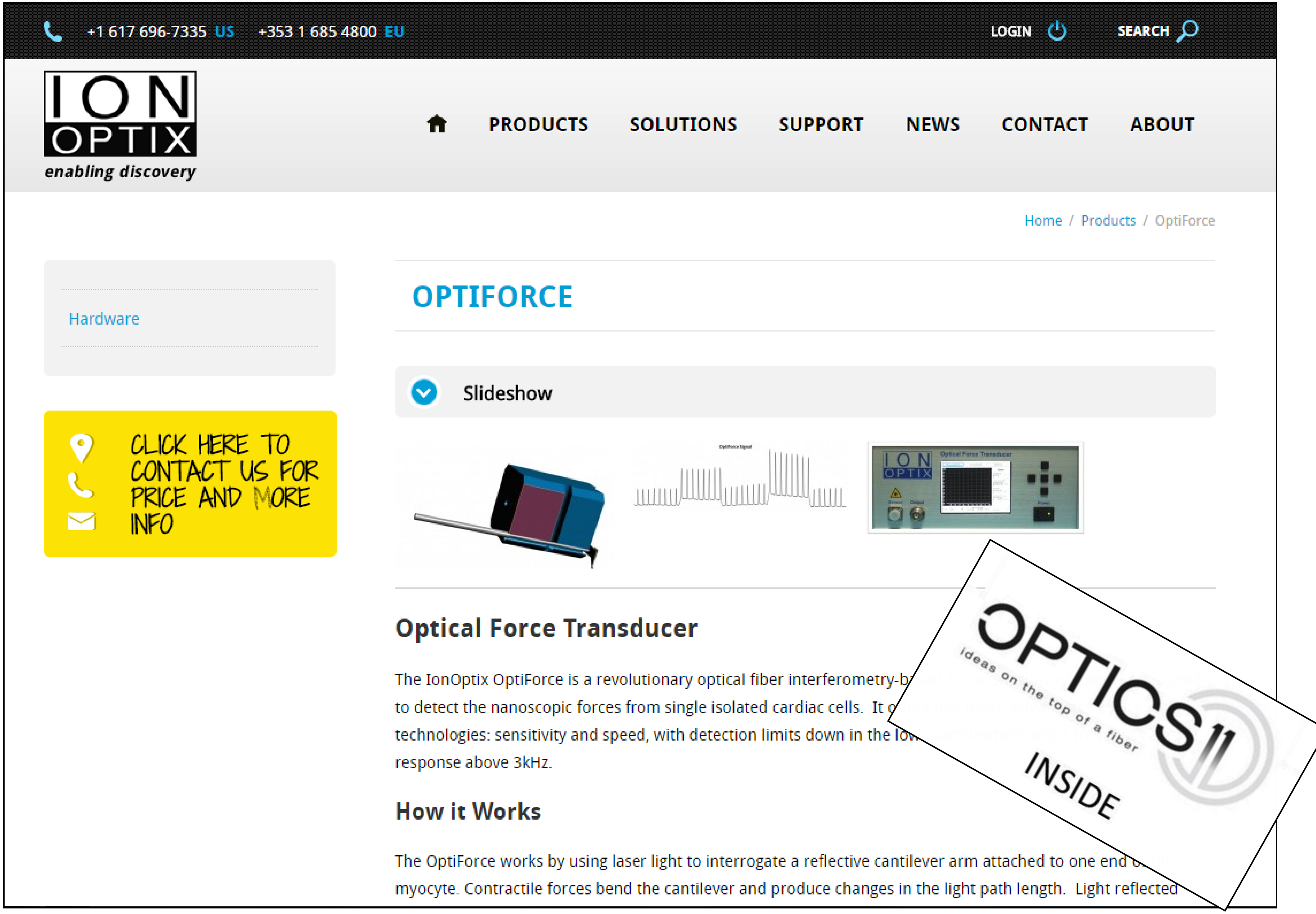
<u>Study regarding</u>:

- Chemical signaling during contraction
- Disease animal models
- Pharmaceutical

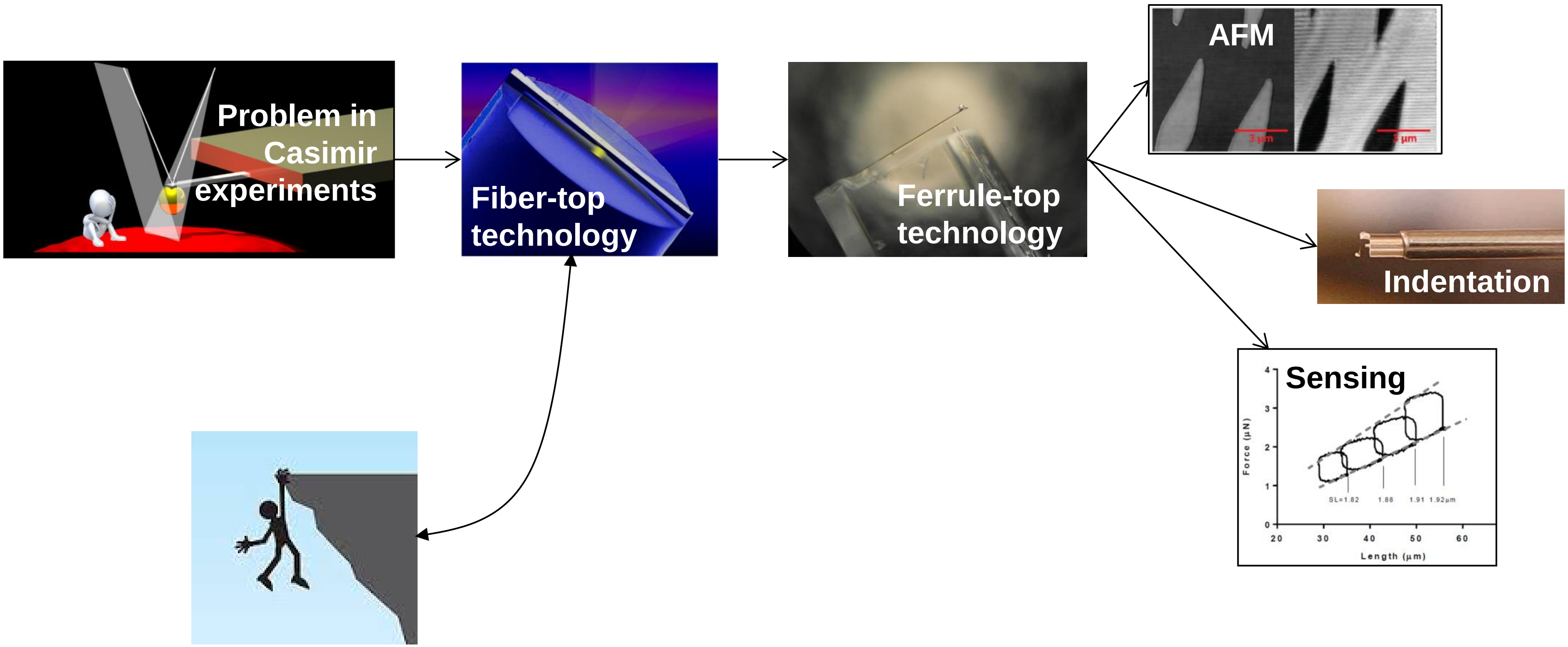
Ferrule-top force sensor for the study of heart cells



Ferrule-top force sensor for the study of heart cells



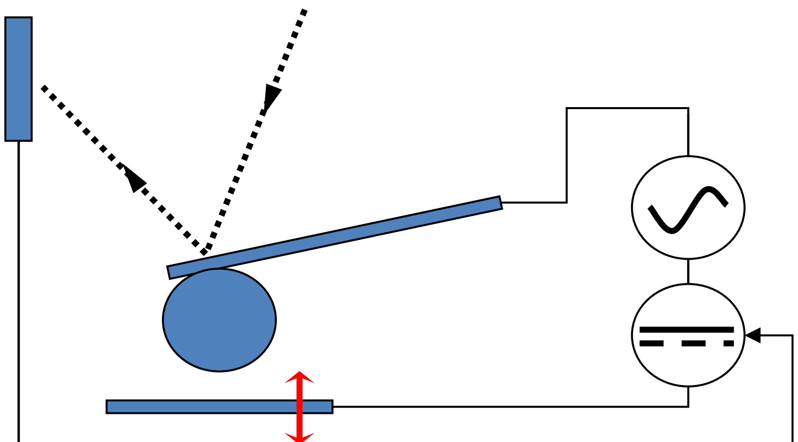
Update on the temporary summary

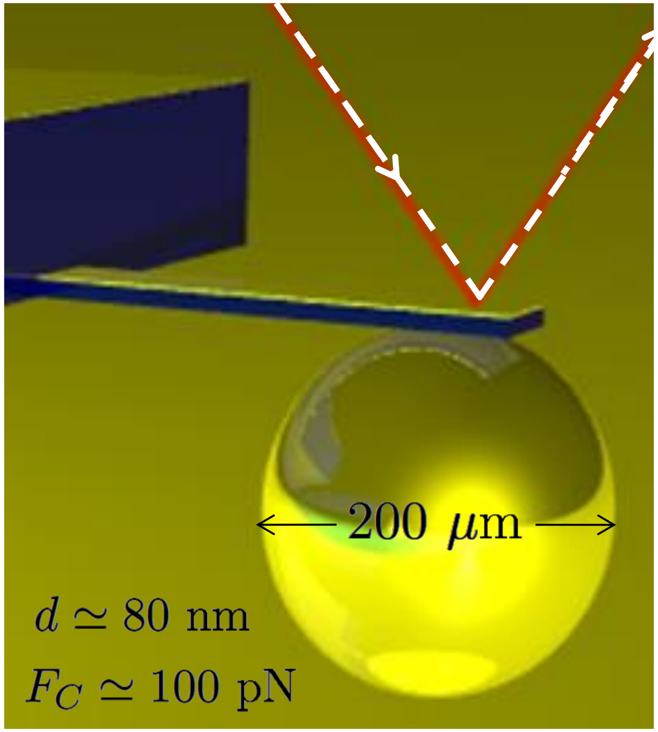


COMING UP:
Solve the cliffhanger

Back to Casimir: a better solution

Measurements with a standard AFM in Amsterdam





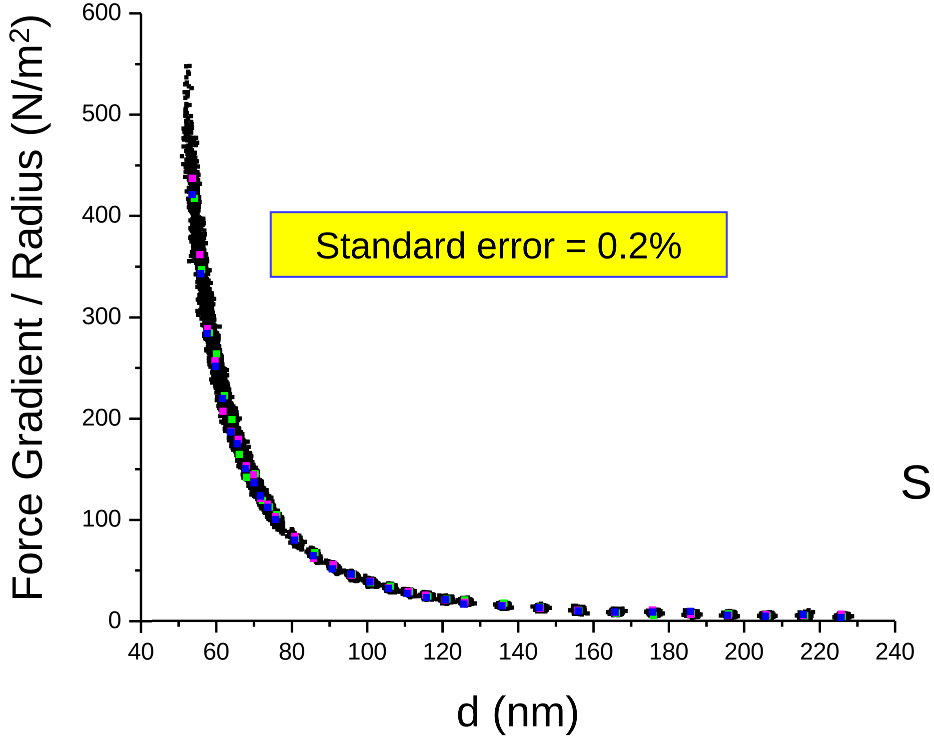
V_0 feedback — TO ELIMINATE ELECTROSTATIC RESIDUAL FORCE

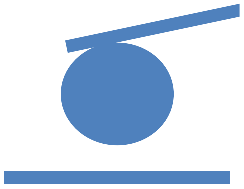
Measure $S(2\omega_1)$ — TO CALIBRATE THE INSTRUMENT

Measure $S(\omega_2)$ — TO MEASURE THE CASIMIR FORCE

The Amsterdam method

$$F_C(t) = F_C(d^* + \delta\cos(\omega_2 t)) \simeq F_C(d^*) + \boxed{\left.\frac{\partial F_C}{\partial d}\right|_{d^*} \cdot \delta\cos(\omega_2 t)}$$





Casimir

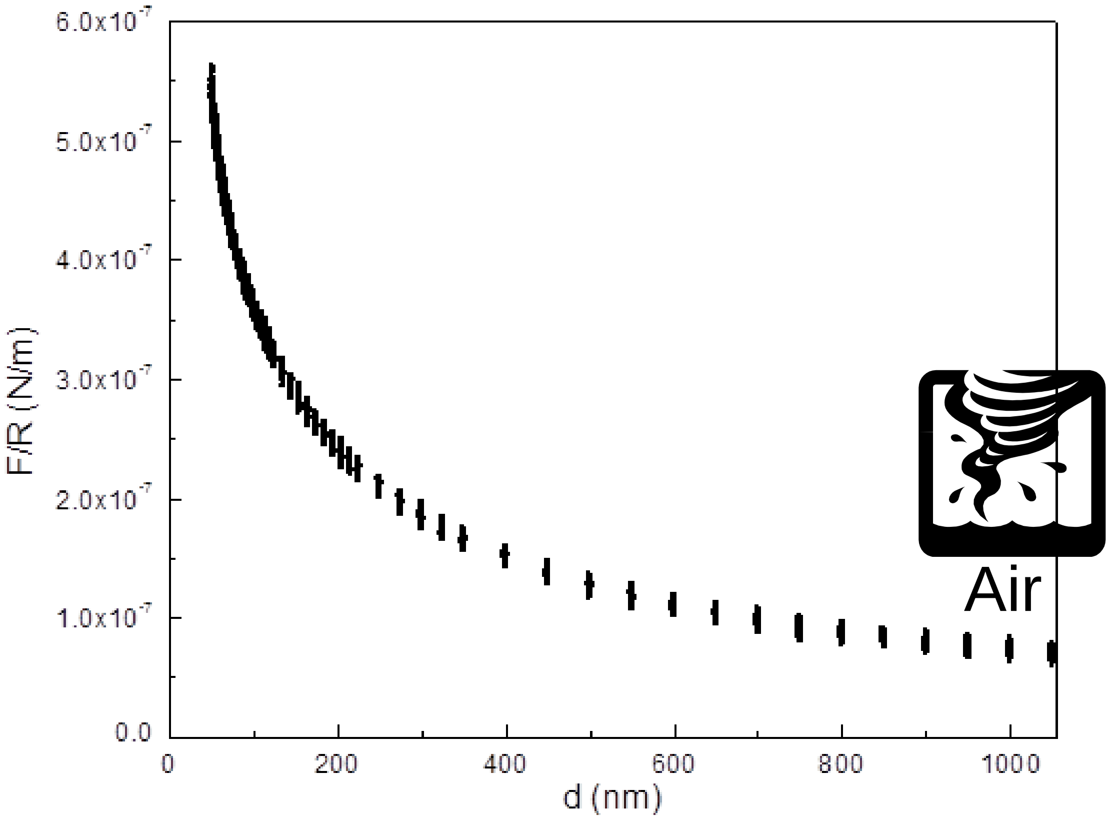
IN PHASE

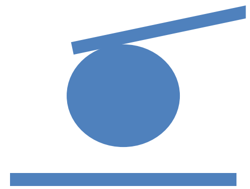
Shadow? Minimized (small oscillations)

The Amsterdam method: hydrodynamic force

$$F_C(t) = F_C(d^* + \delta\cos(\omega_2 t)) \simeq F_C(d^*) + \boxed{\left.\frac{\partial F_C}{\partial d}\right|_{d^*} \cdot \delta\cos(\omega_2 t)}$$

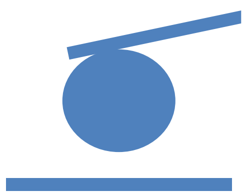
10^{-7}





Casimir

IN PHASE

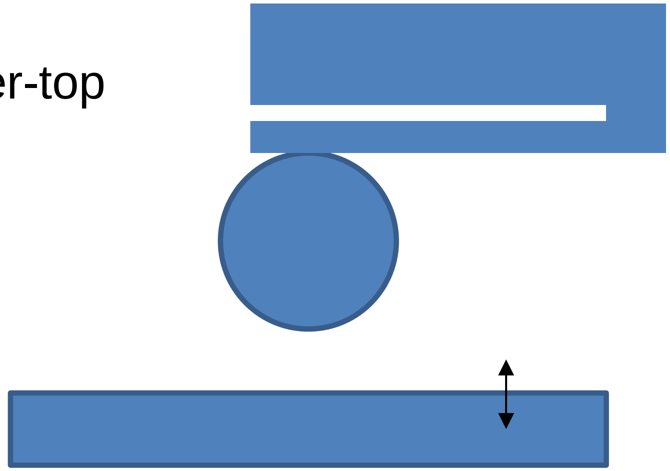


Hydrodynamic

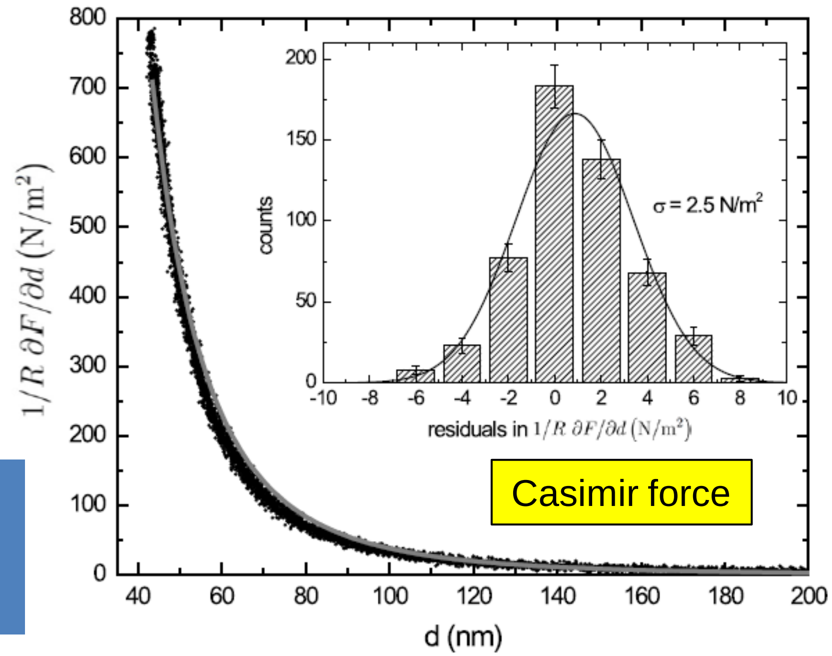
PHASE SHIFT=90º

Amsterdam method: problem with fiber-top

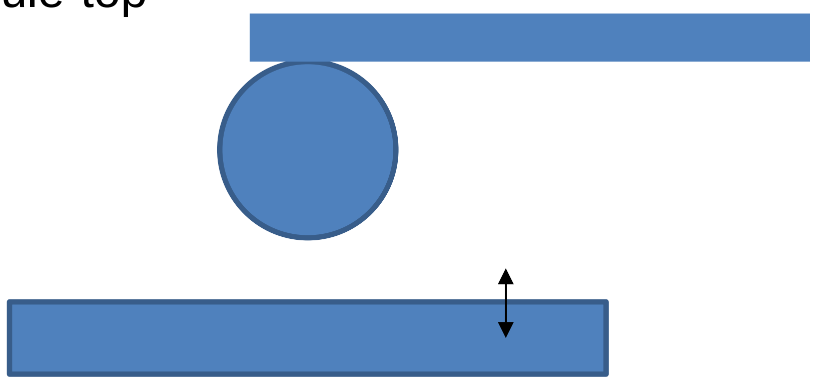
Fiber-top



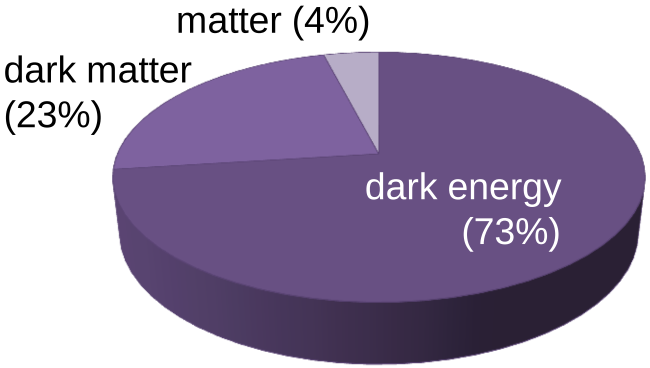
...which is not a problem with ferrule-top



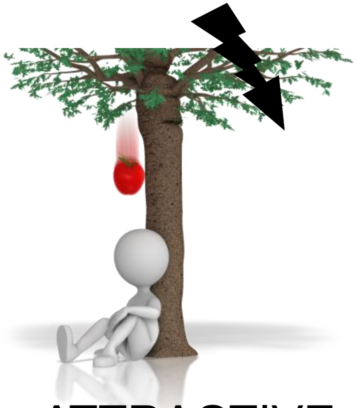
Ferrule-top



From Casimir to dark energy

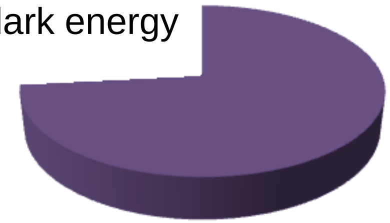


Remote galaxies: the Universe is expanding at accelerated rate

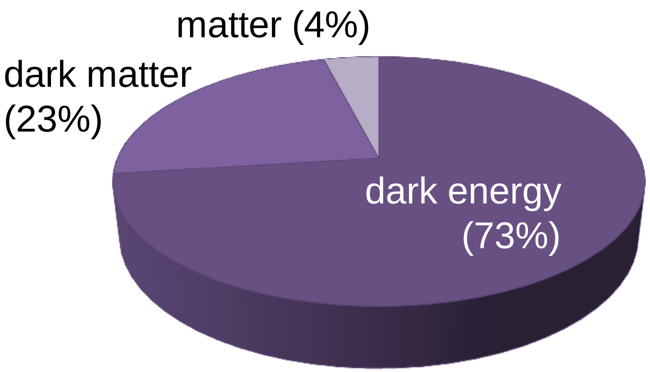


<

Something else: dark energy

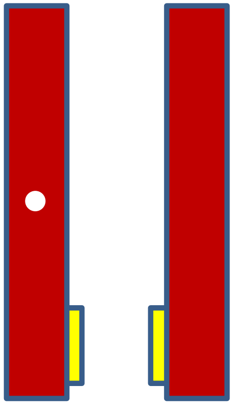


ATTRACTIVE < REPULSIVE



Dark energy: a particle with a small mass?

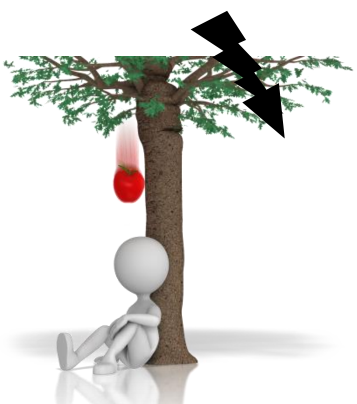
$$m_\phi \simeq 10^{-33}\ \mathrm{eV} \Rightarrow \boxed{5^{th}\ \text{force}}$$



$$F_{d.e.}/A \simeq 1\mathrm{pN}/\mathrm{cm}^2$$

10-30 µm

Remote galaxies: the Universe is expanding at accelerated rate



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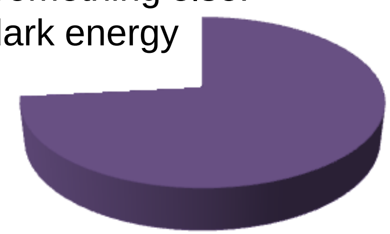
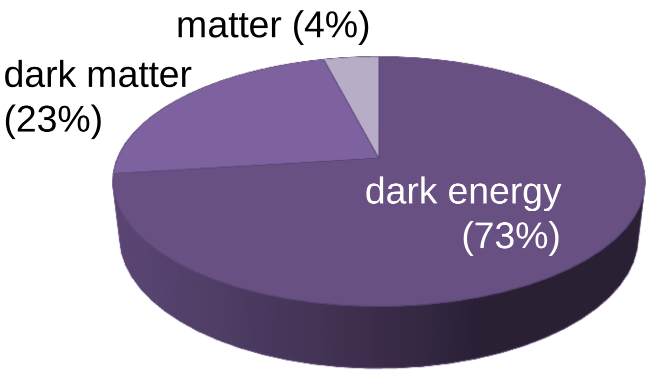
Something else: dark energy

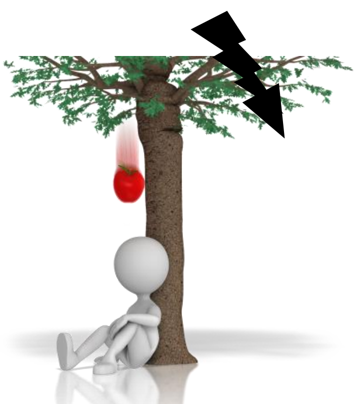


ATTRACTIVE < REPULSIVE

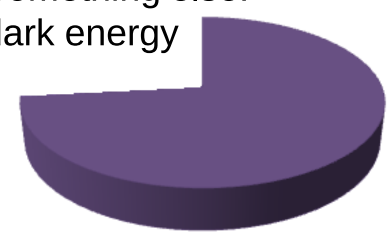
Dark energy and 5th force



Remote galaxies: the Universe is expanding at accelerated rate



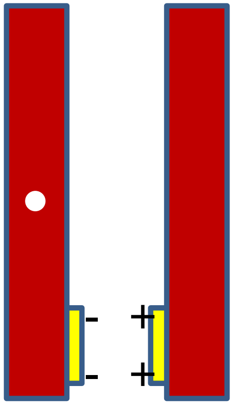
Something else: dark energy



ATTRACTIVE < REPULSIVE

Dark energy: a particle with a small mass?

$$m_\phi \simeq 10^{-33}\ \mathrm{eV} \Rightarrow$$ 5th force



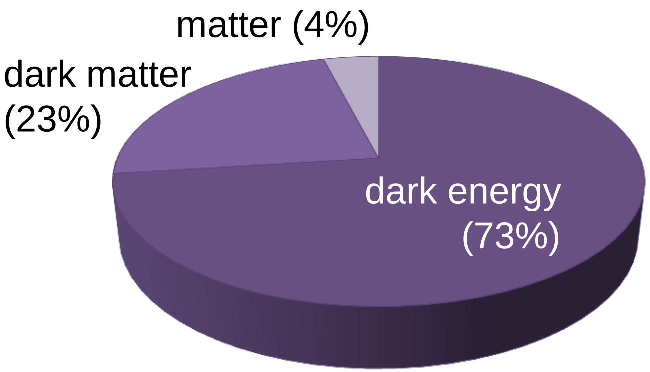
10-30 μm

$$F_{d.e.}/A \simeq 1\mathrm{pN}/\mathrm{cm}^2$$

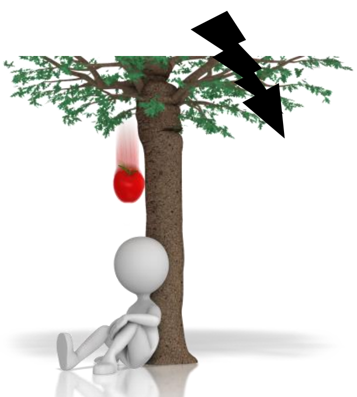
$$F_{el}/A \simeq 1000 \times F_{d.e.}/A$$

$$\frac{F_{\mathrm{el}}}{A} = \epsilon_0\left(\frac{\sigma_L^2}{2d^2} + \frac{2\sigma_S^2}{k_{\max}^2 - k_{\min}^2}\int_{k_{\min}}^{k_{\max}} \frac{k^3}{\sinh^2(kd)}\,dk\right)$$

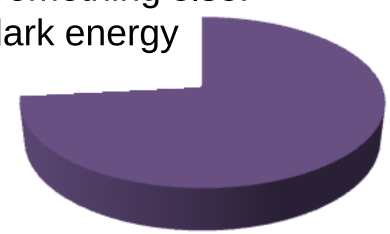
We cannot test it...or can we?



Remote galaxies: the Universe is expanding at accelerated rate



Something else: dark energy



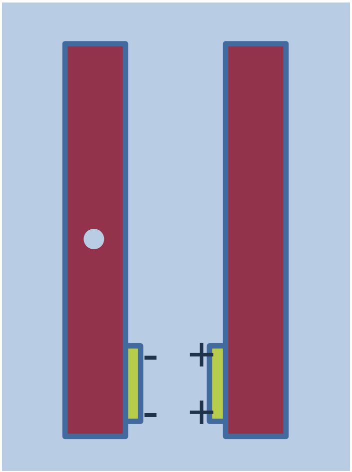
ATTRACTIVE < REPULSIVE

Dark energy: a particle with a variable mass?

$m_\phi \simeq 10^{-33}$ eV in vacuum

$m_\phi \leftrightarrow \rho_{\mathrm{matter}}$

J. Khoury and A.Weltman,
Phys. Rev. Lett. **93** (2004) 171104



$\rho_{\mathrm{matter}} \Uparrow \quad m_\phi \Uparrow$

$F_{d.e.} \Downarrow$

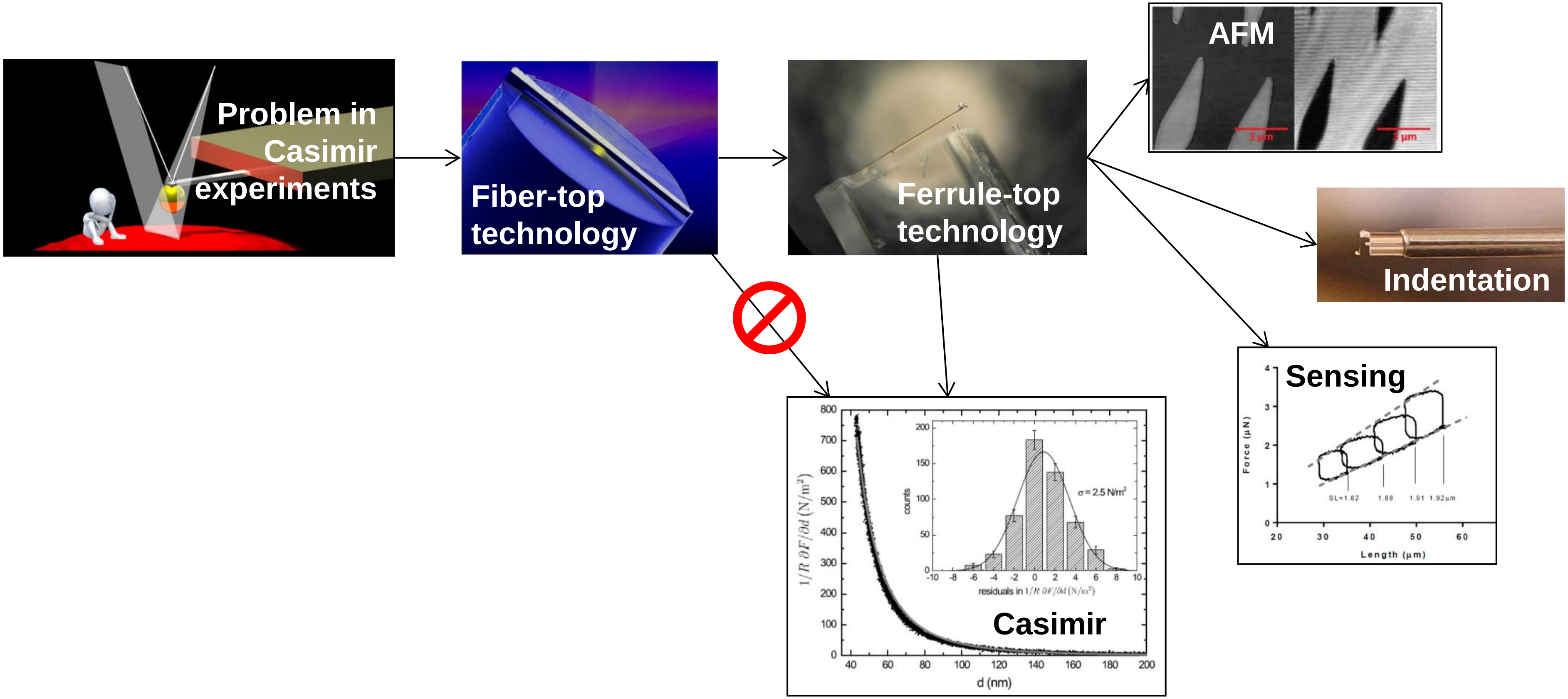
$F_{el} =$

COMPARE TOTAL FORCE WITH AND WITHOUT GAS

If  does not exist → no change of force

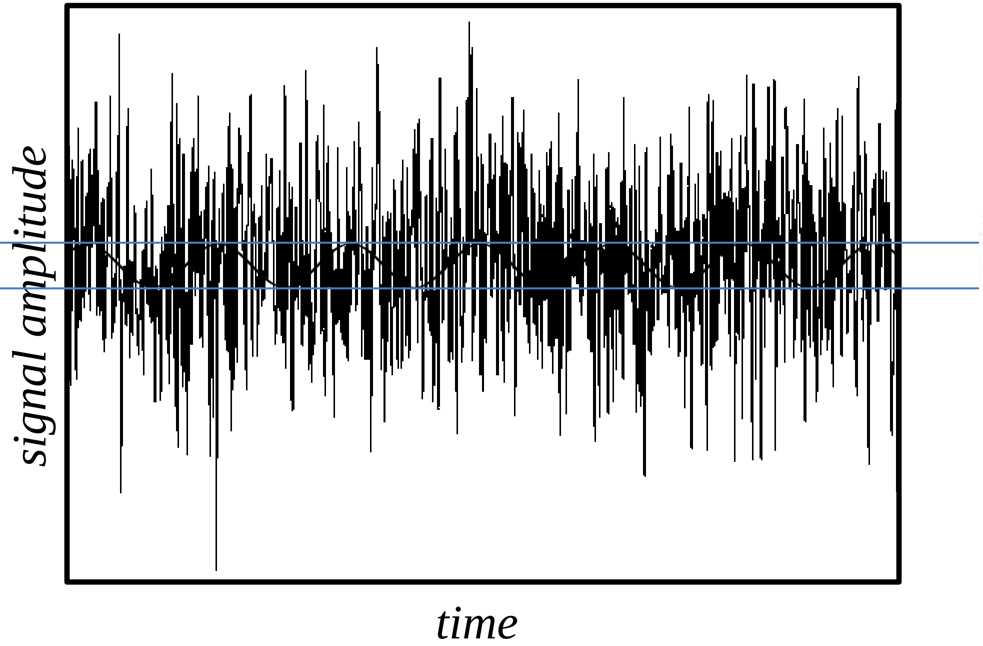
If  exists → the force changes

New update on the temporary summary



COMING UP:
Social sciences

Lock-in amplifiers



$$y(t) = A\cos(\omega t)$$

$$\times \cos(\omega t)$$

$$\int dt$$

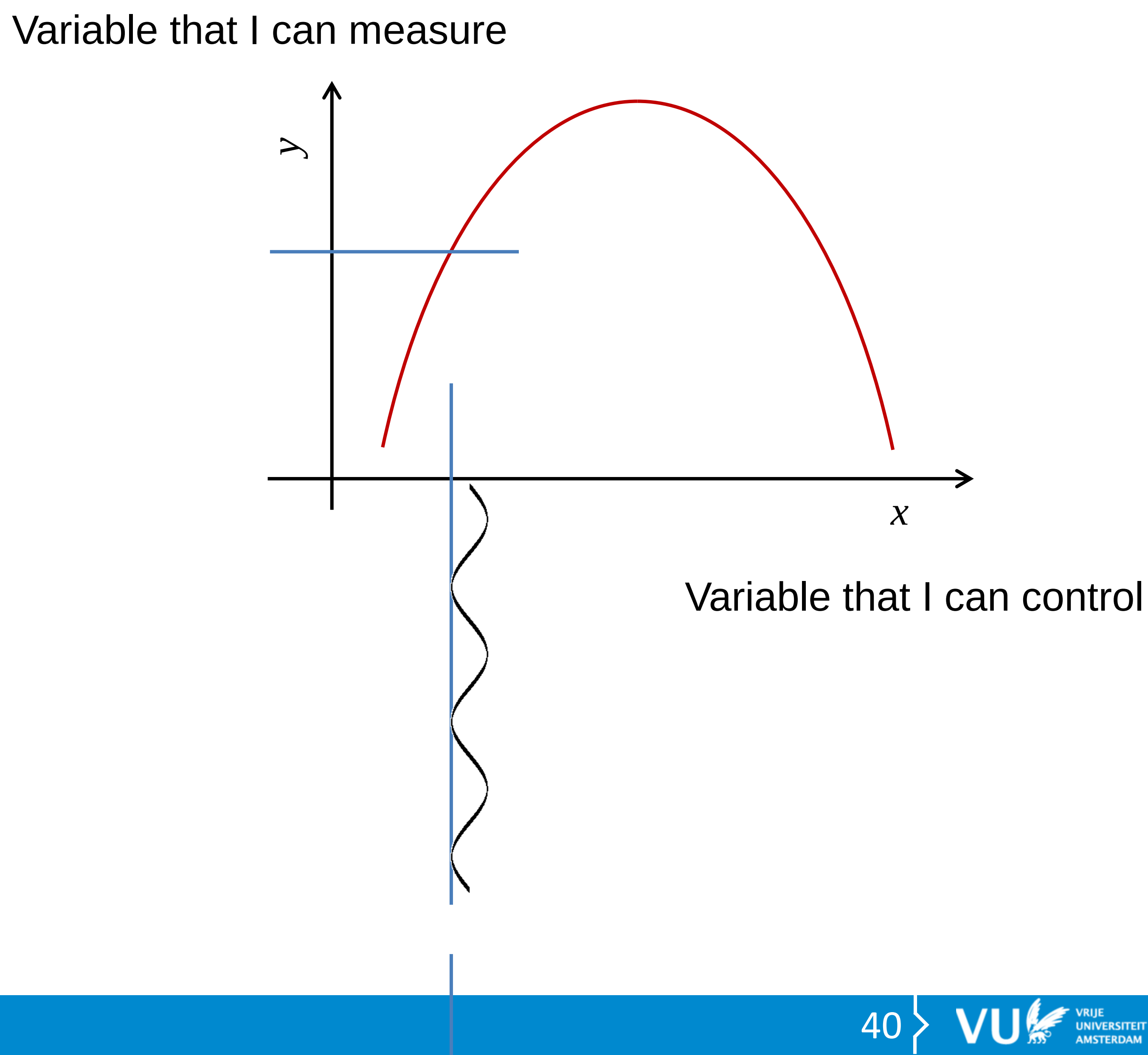
$$y_{\times}(t) = A\cos^2(\omega t) + f(t)\cos(\omega t)$$

$$\cos^2(\omega t) = \frac{1+\cos(2\omega t)}{2}$$

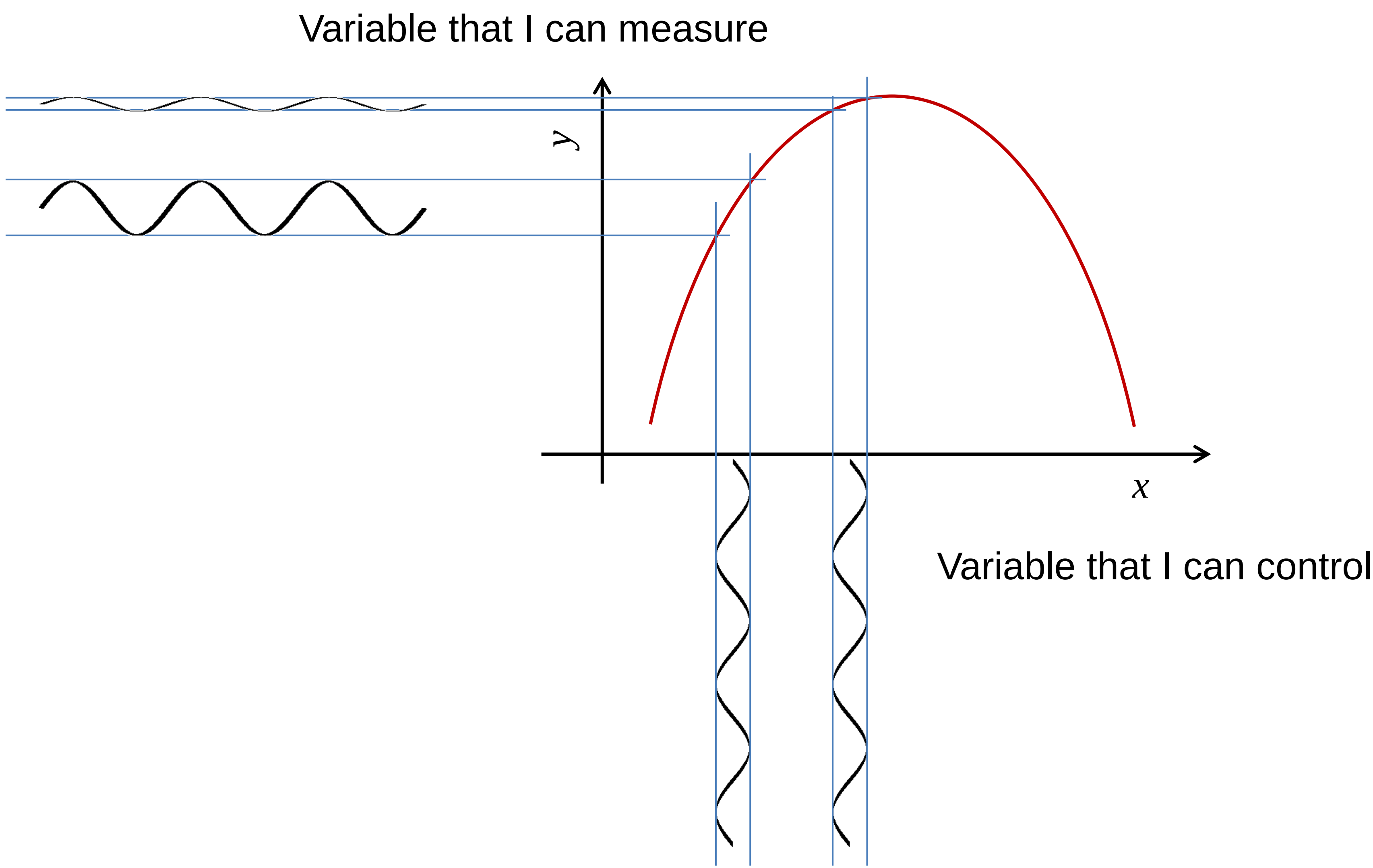
constant

oscillating around zero

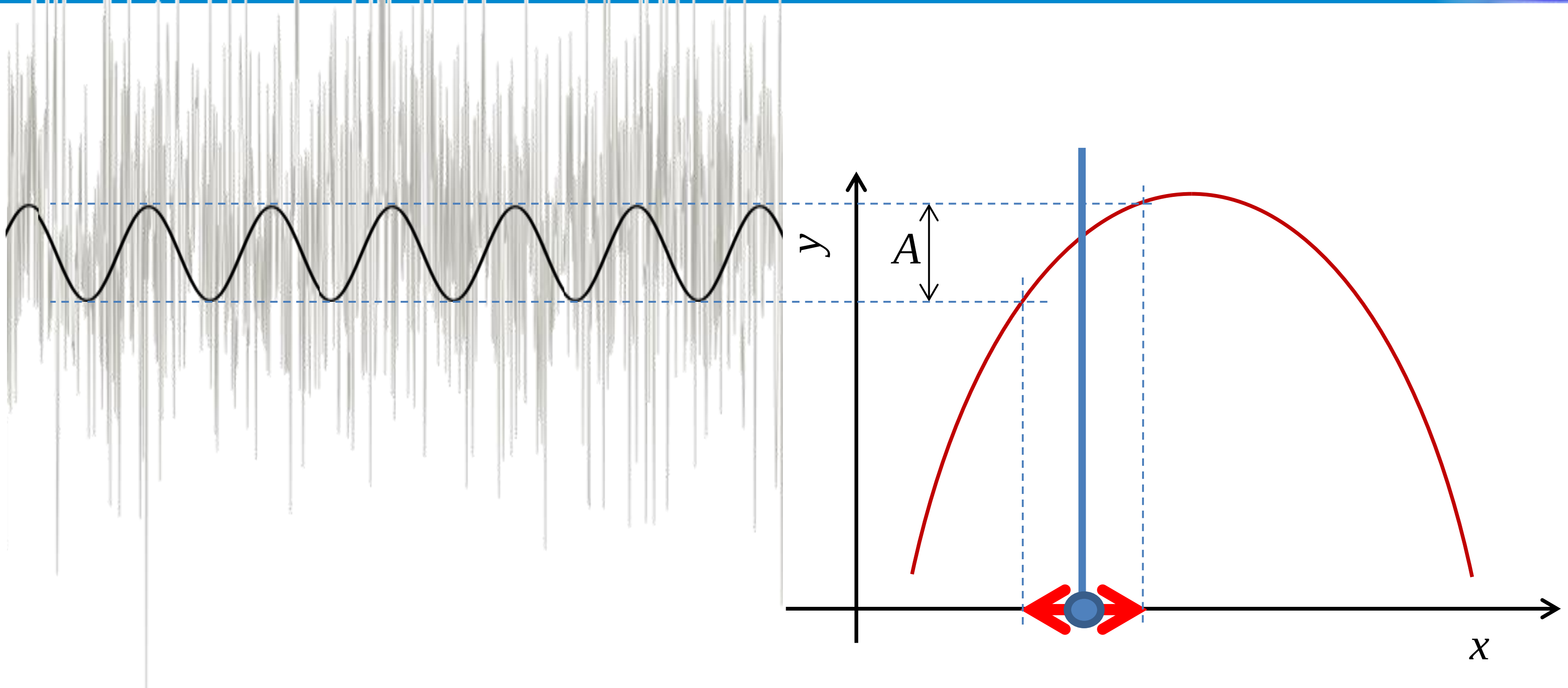
Lock-in amplifiers feedback loop



Lock-in amplifiers feedback loop



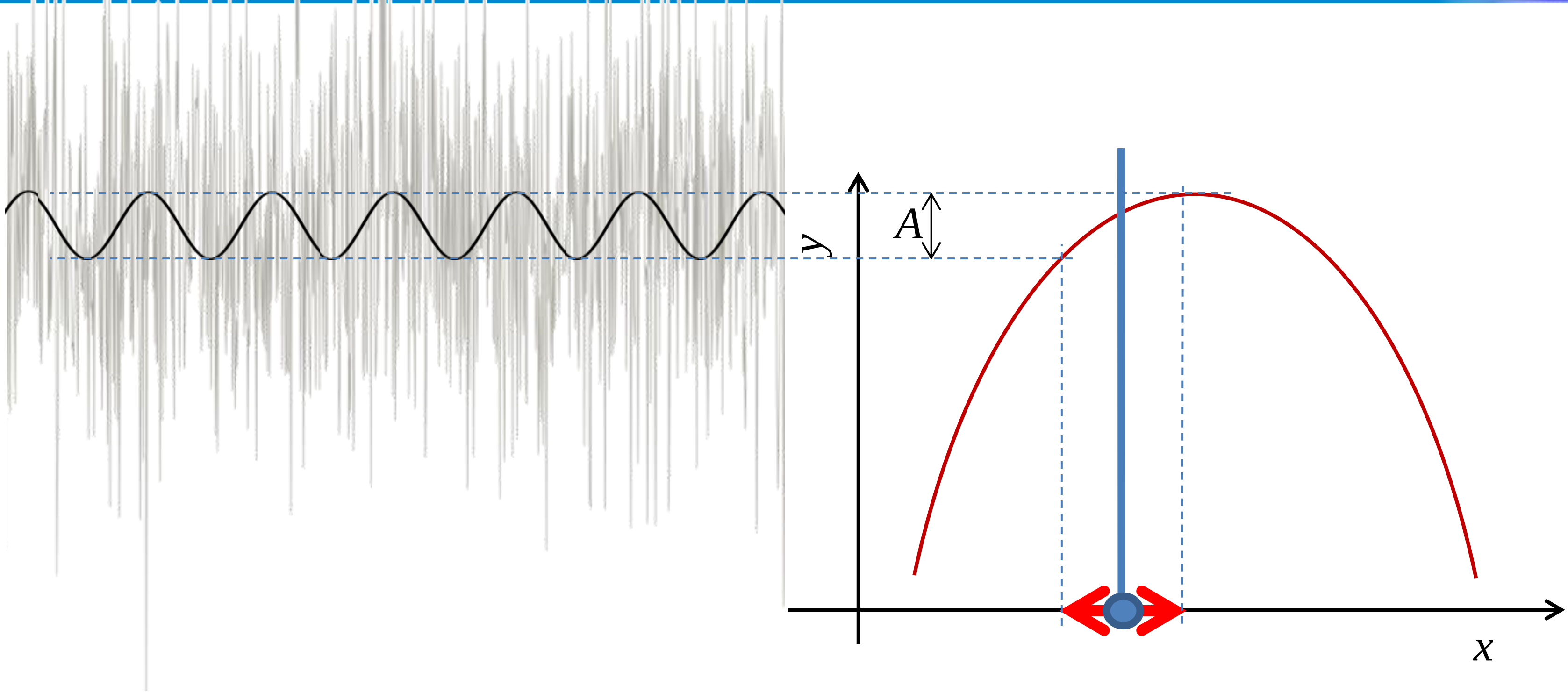
Lock-in amplifiers feedback loop



Oscillate x around x_0

Measure y at ω
(Lock-in amplifier) $\longrightarrow A$

Lock-in amplifiers feedback loop

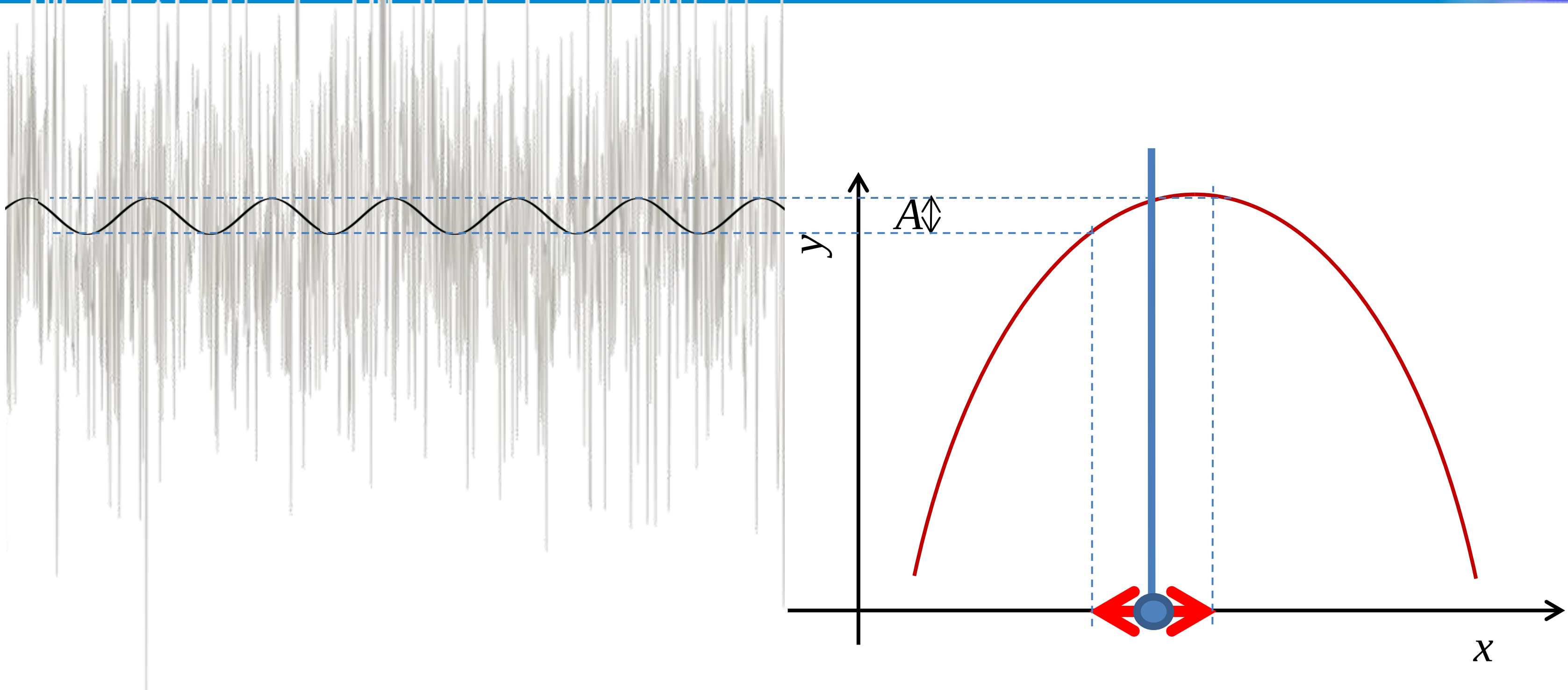


Oscillate x around x_0

Measure y at ω
(Lock-in amplifier) $\longrightarrow A$

Set $x_0 = x_0 + \gamma A$

Lock-in amplifiers feedback loop

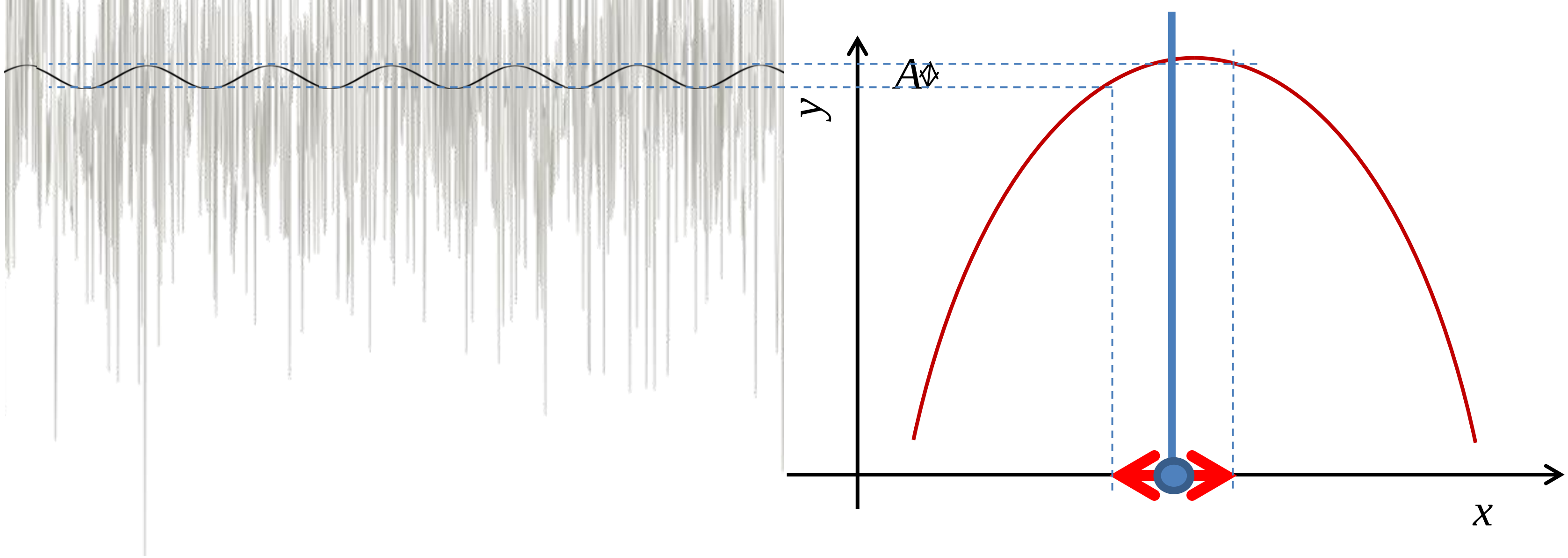


Oscillate x around x_0

Measure y at ω
(Lock-in amplifier) $\longrightarrow A$

Set $x_0 = x_0 + \gamma A$

Lock-in amplifiers feedback loop

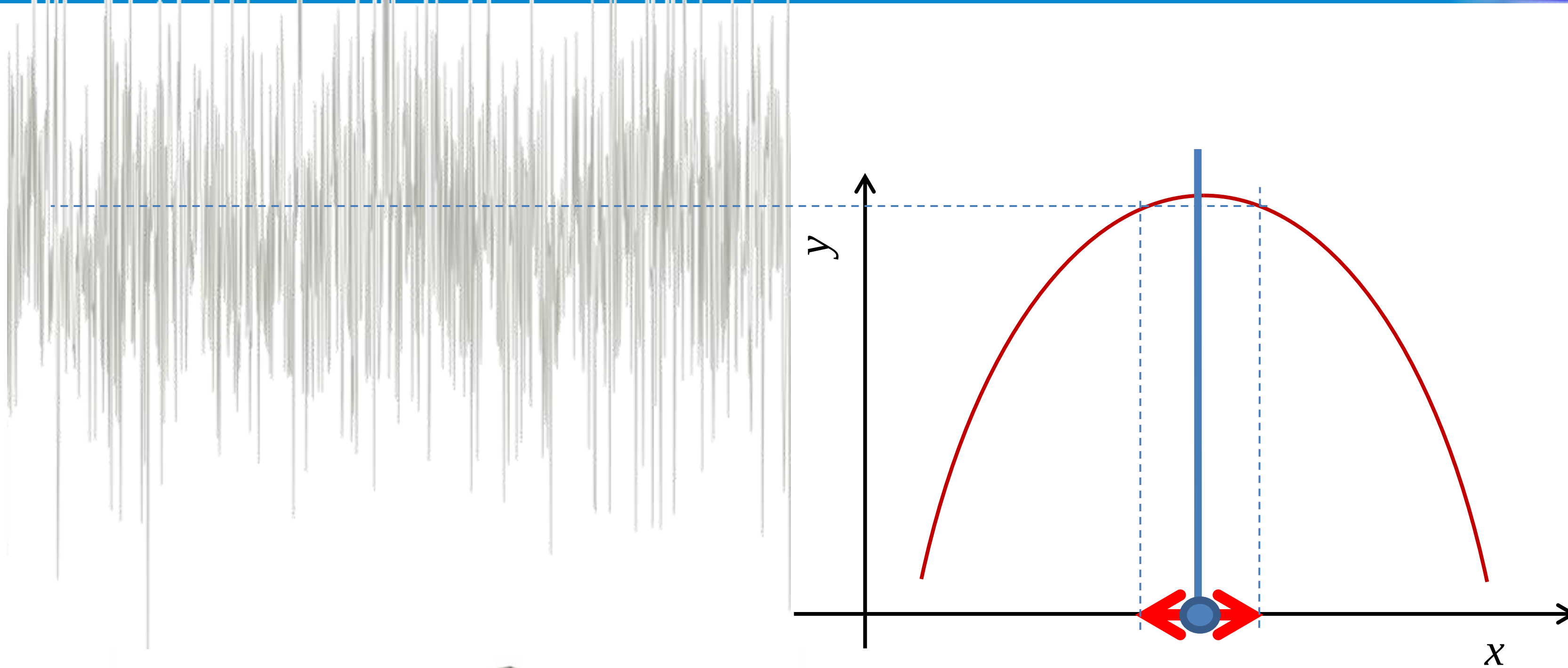


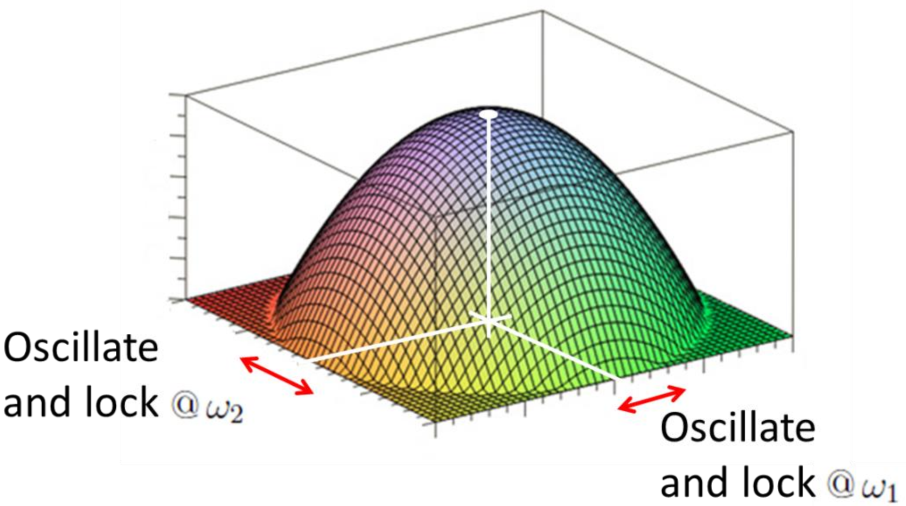
Oscillate x around x_0

Measure y at ω
(Lock-in amplifier) $\longrightarrow A$

Set $x_0 = x_0 + \gamma A$

Lock-in amplifiers feedback loop



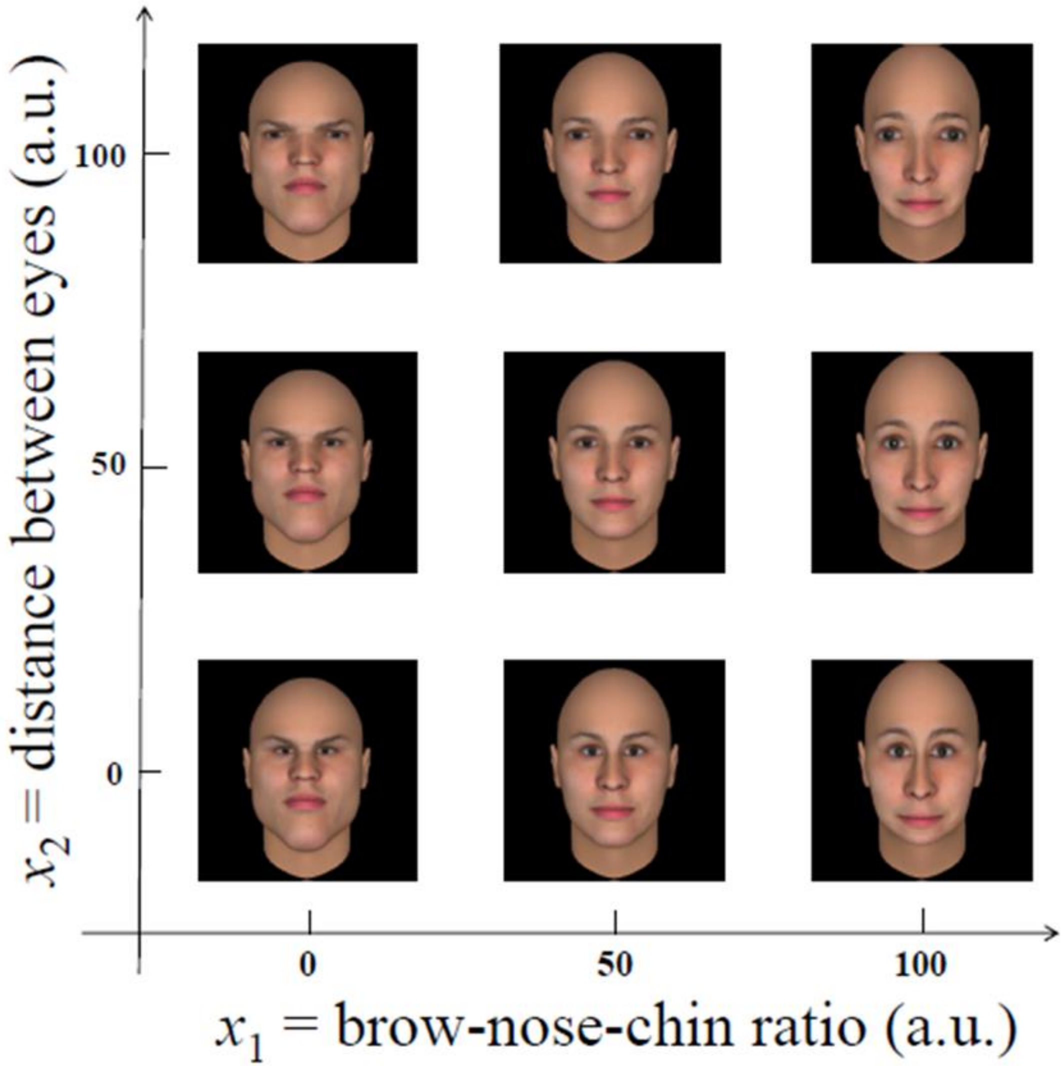


Oscillate x around x_0

Measure y at ω
(Lock-in amplifier) $\longrightarrow$ $A=0$

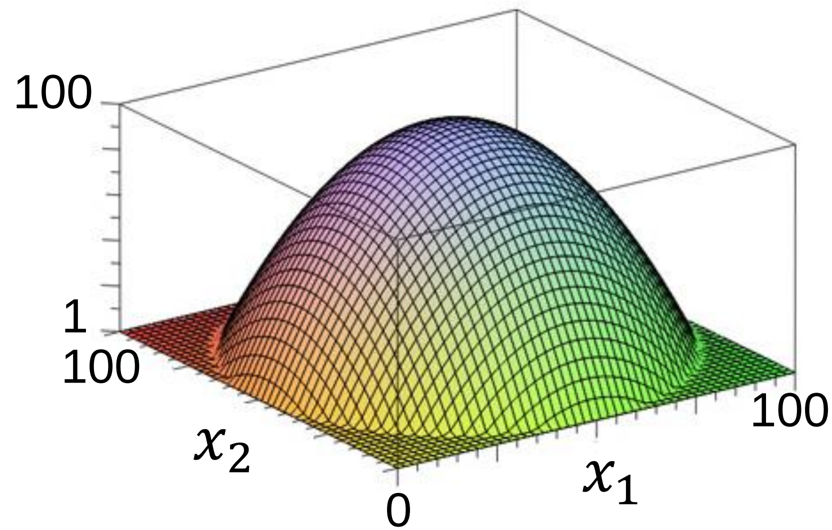
Set $x_0=x_0$

The beauty contest experiment: idea



Which of these avatars
is the most attractive?

AVERAGE PEOPLE'S VOTE
(1=ugly, 100=beautiful)



GOAL OF THE EXPERIMENT:
Lock-in feedback loop →
Find values of x_1 and x_2 that
maximizes the average vote

The beauty contest experiment: method

Survey – VU University 2016

How attractive would you rate the computer generated face to the left, on a scale **from 1 to 100.**

Where **100** would represent a very attractive face. And the face below would represent a face with an attractiveness score of about **25.**

≈25

Always the same

1 100

40

Continue

Sequentially adjusted via lock-in feedback loop to converge to maximizing features

Voter i

Sees avatar with

$$x_1 = \tilde{x}_1 + A_1 \cos(\omega_1 i)$$

$$x_2 = \tilde{x}_2 + A_2 \cos(\omega_2 i)$$

Gives his vote

y_i

@ ω_1

@ ω_2

New values for

$\tilde{x}_1$

$\tilde{x}_2$

Voter i+1

Sees avatar with

$$x_1 = \tilde{x}_1 + A_1 \cos(\omega_1 (i+1))$$

$$x_2 = \tilde{x}_2 + A_2 \cos(\omega_2 (i+1))$$

Gives her vote

$y_{(i+1)}$

@ ω_1

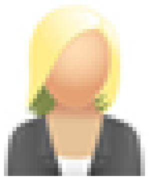
@ ω_2

New values for

$\tilde{x}_1$

$\tilde{x}_2$

Voter i+2

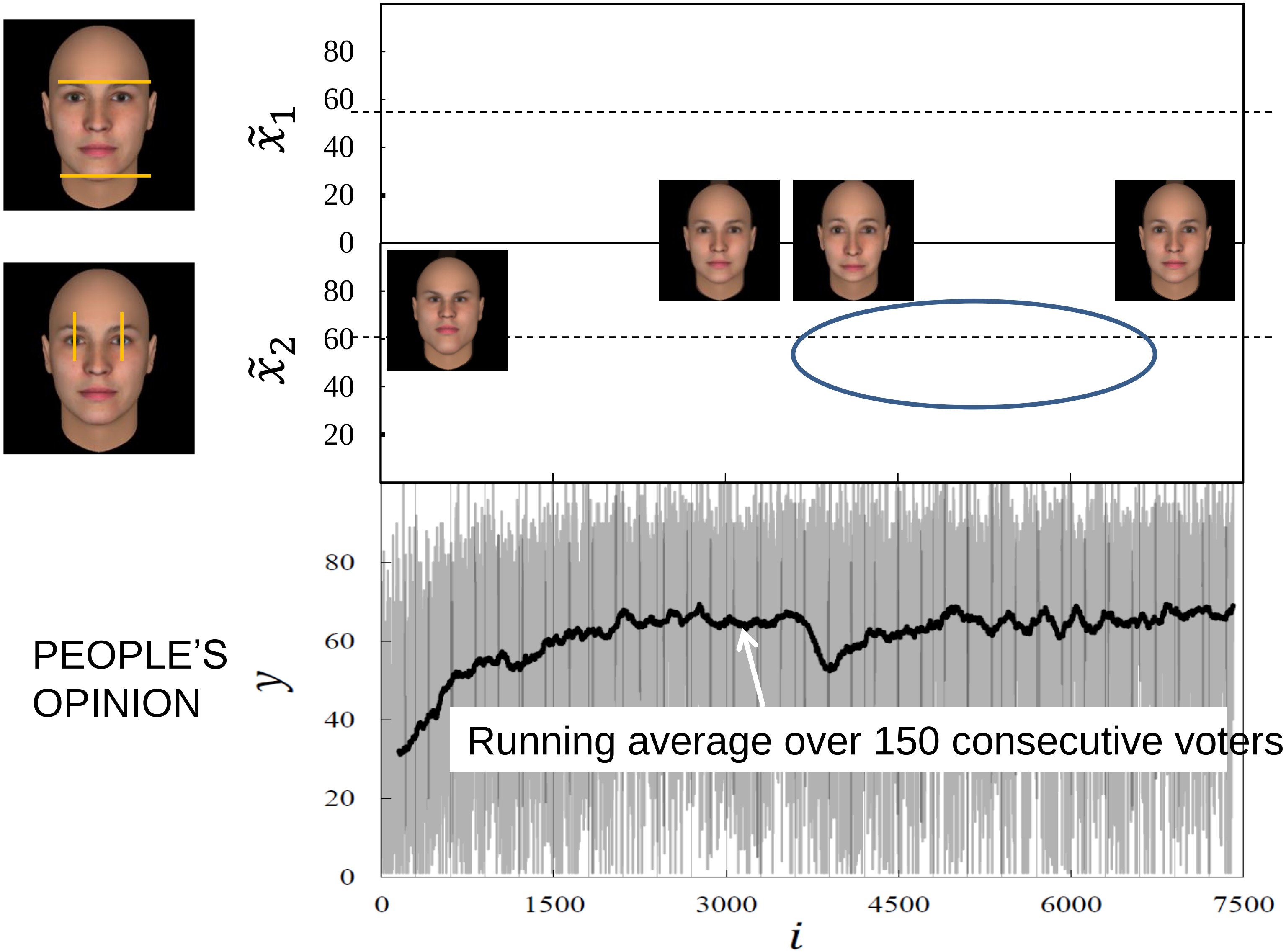


. . .

. . .

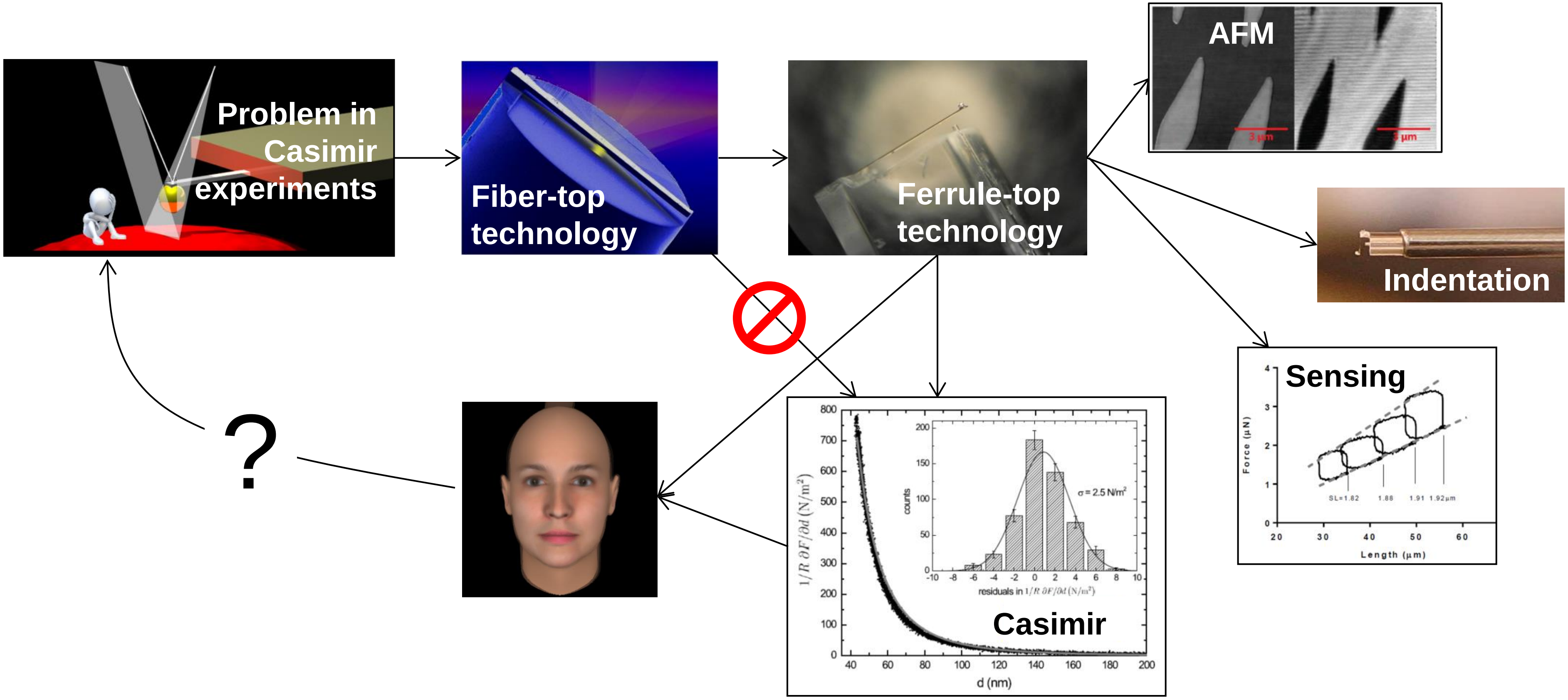
. . .

The beauty contest experiment: results



PEOPLE'S OPINION

Summary


Problem in Casimir experiments
Fiber-top technology
Ferrule-top technology
AFM
3 µm
Indentation
Sensing
Force (µN)
Length (µm)
SL=1.82
1.88
1.91
1.92µm
Casimir
d (nm)
counts
σ = 2.5 N/m²
residuals in 1/R ∂F/∂d (N/m²)
?

Acknowledgements (of collaborators not already mentioned in the slides!)

VU
A. Almasi
N. Antanovaite
K. Babaei Gavan
L. Bartolini
S. Beekmans
A. F. Borghesani
D. Chavan
S. de Man
K. Heeck
M. Marrese
A. Petrusis
J. H. Rector
R. Sedmik
M. Slaman
C. Van Hoorn
H. van Hoorn
K. Zhou
P. Zuurbier

Optics11
N. Rijnveld
G. Gruca
K. van der Laan
E. Breel
T. van der Wardt
E. Labordus
E. Leeferink
M. Stoffel
H. Brouwer
...

erc

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Nederlandse Organisatie voor Wetenschappelijk Onderzoek

FOM

STW
connecting innovators

URC PROGRAM

Giacomo Bressi – amico e maestro