Casimir and Chameleon forces - the universe on the tabletop

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on behalf of the

Cannex team

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NWO Nederlandse Organisatie voor Wetenschappelijk Onderzoek

FOM

FWF Der Wissenschaftsfonds.

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Outline

Part I: Scientific background

Casimir physics, Chameleon model and dark energy

What are the goals?

Part II: Setup

Core: Principle of measurement, Control of parallelism,

Vibration insulation: Mechanisms, Preliminary characterization

Status

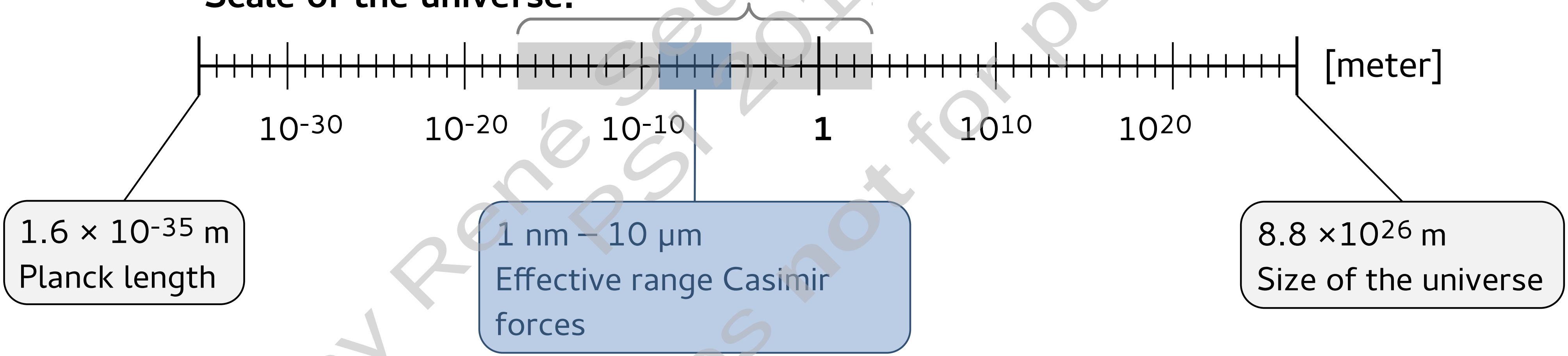
Outline

Part I: Scientific background

Casimir physics, Chameleon model and dark energy

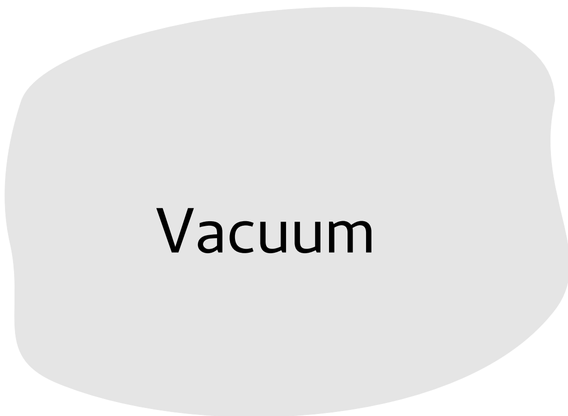
What are the goals?

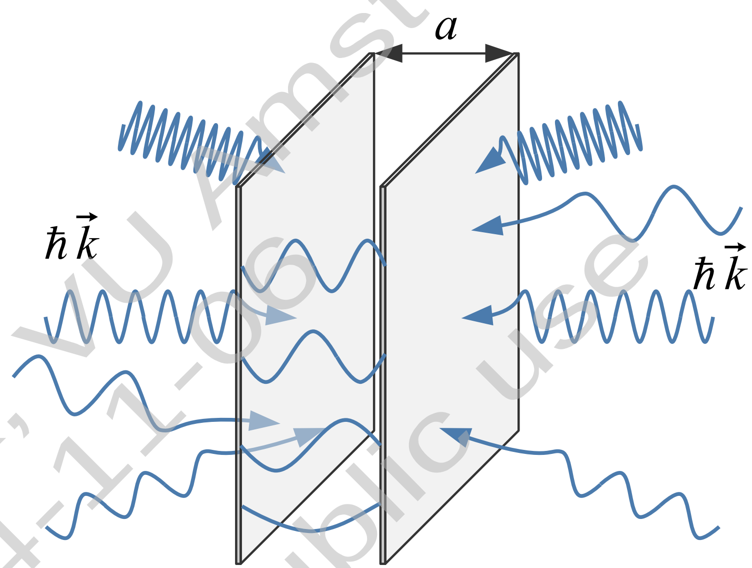
Scale of the universe:



Casimir force

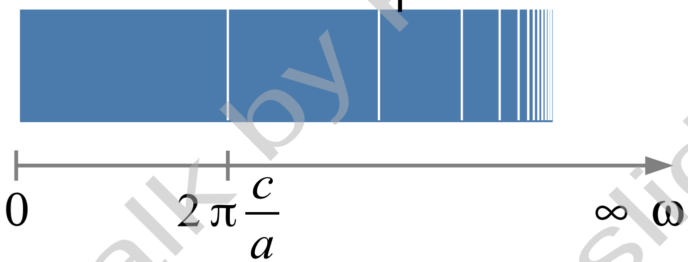
An intuitive approach ...





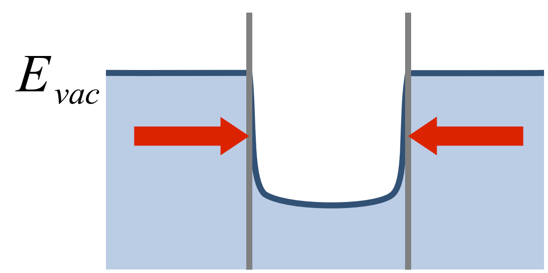
continuous spectrum

difference spectrum

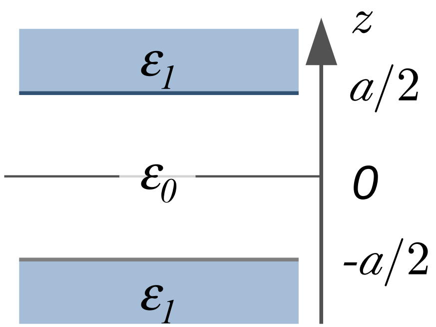


discrete spectrum

attractive potential:



The realistic approach ...



Electric field:

$$E_\alpha(k,x) = f(k,z)\mathrm{e}^{i(k_x x + k_y y - \omega t)}$$

Wave equation:

$$\frac{d^2 f(k,z)}{dz^2} - K^2(k) f(k,z) = 0\,, \quad K^2(k) = k_x^2 + k_y^2 - \varepsilon(\omega)\frac{\omega^2}{c^2}$$

Ansatz:

$$f(k,z) = c_1 \mathrm{e}^{Kz} + c_2 \mathrm{e}^{-Kz}$$

Boundary conditions at surfaces:

$$\left.\begin{array}{r} \varepsilon(z)E_\perp(z),\ E_\parallel(z) = \text{const.} \\ \dfrac{\partial E_\perp(z)}{\partial z},\ \dfrac{\partial E_\parallel(z)}{\partial z} = \text{const.} \end{array}\right\} \Rightarrow$$

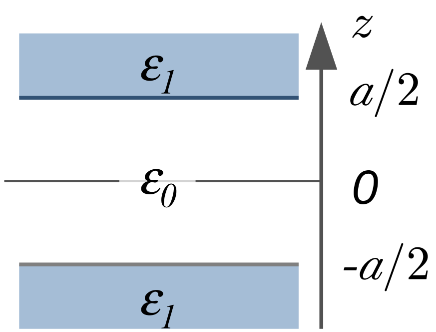
Homogeneous set of eqns.

$$\det C = 0 \equiv \Delta_{\perp,\parallel}(\varepsilon, k, \omega, a)$$

(and similar for the magnetic field)

Review: M. Bordag, U. Mohideen, V.M. Mostepanenko, "New Developments in the Casimir Effect", *Phys. Rep.* **353**, pp. 1–205, (2001) arxiv:quant-ph/0106045

The realistic approach: Lifshitz theory



Sum over modes:

$$\frac{E}{A} = \frac{\hbar}{2} \int_0^\infty \frac{\mathrm{d}k_x\,\mathrm{d}k_y}{(2\pi)^2} \underbrace{\sum_{n=0}^{\infty} \omega_n(a)}$$

Argument Theorem: $\frac{1}{2\pi i}\left[\int_{-\infty}^{\infty} \omega \mathrm{d}\ln\Delta(\omega) + \oint_C \omega \mathrm{d}\ln\Delta(\omega)\right]$

infinite

Renormalization: divide $\Delta(\omega)$ by the expression $\Delta_\infty(\omega) \equiv \Delta(\omega, a)|_{a\to\infty}$

$$\frac{E_{\mathrm{ren}}(a)}{A} = \frac{\hbar}{(2\pi)^2 c^2} \int_1^\infty \mathrm{d}p \int_0^\infty \mathrm{d}\xi\, p\xi^2 \left[\ln\frac{\Delta_\perp(i\xi, a)}{\Delta_{\perp,\infty}(i\xi)} + \ln\frac{\Delta_{\|}(i\xi, a)}{\Delta_{\|,\infty}(i\xi)}\right],\ F(a) = -\frac{\partial E_{\mathrm{ren}}(a)}{\partial a}$$

$$\frac{\Delta_\perp(p, i\xi, a)}{\Delta_{\perp,\infty}(p, i\xi)} = 1 - \left(\frac{K_1\varepsilon_0(i\xi) - K_0\varepsilon_1(i\xi)}{K_1\varepsilon_0(i\xi) + K_0\varepsilon_1(i\xi)}\right)^2 \mathrm{e}^{-2a\frac{\xi}{c}K_0}, \quad K_j(p, i\xi) = \sqrt{p^2 - 1 + \varepsilon_j(i\xi)}$$

Casimir vs. van der Waals

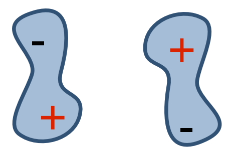
Morphology of dipole interactions:

Interacting media

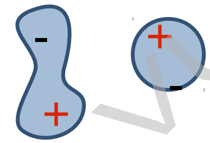
sparse

sparse media → single dipole interactions — *van der Waals* interactions

described by dipole moments and polarizability α, **additive**



fixed dipoles



fixed and induced dipoles

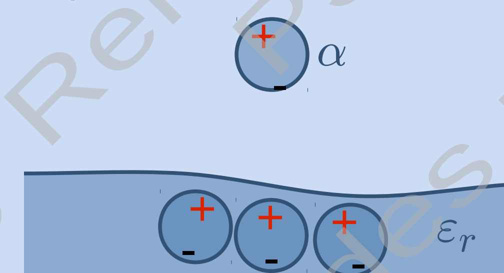
induced dipoles

Dispersion forces

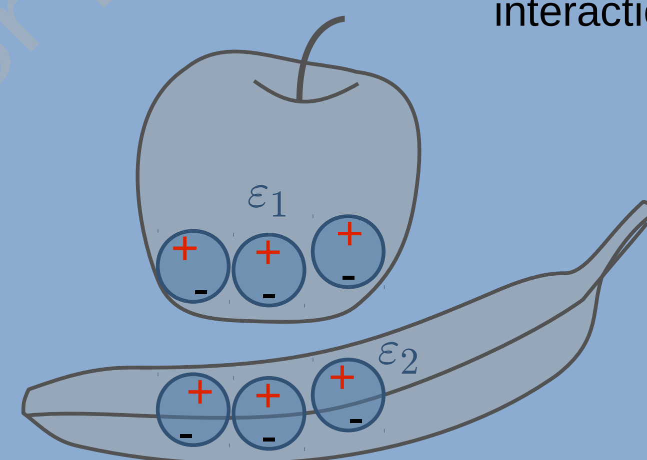
dense

single dipole with dense medium — *Casimir-Polder* interaction

→ **non-additive** collective response depending on the spectral dielectric function ε_r



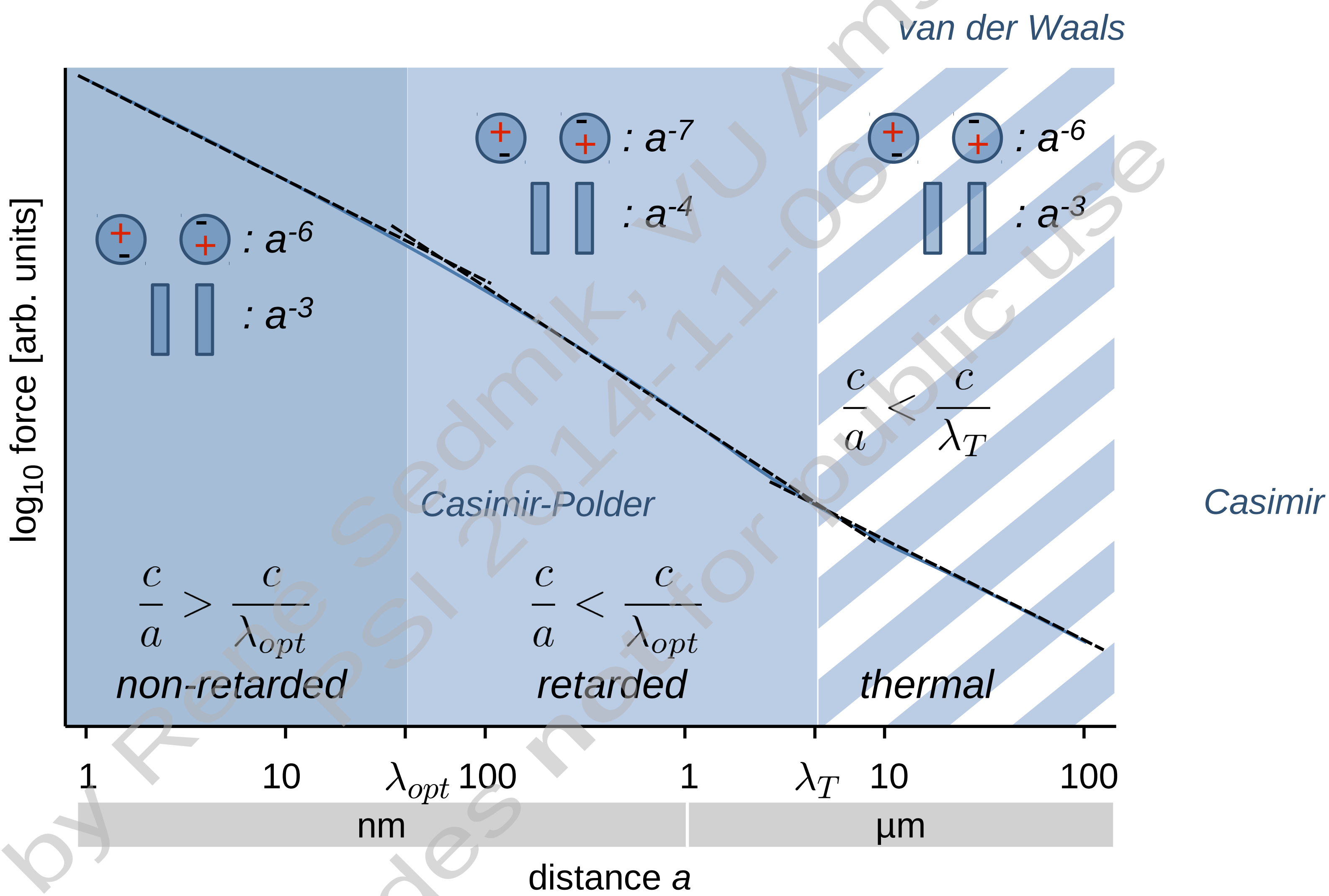
dense media — *Casimir* interaction



Casimir vs. van der Waals

Morphology of dipole interactions:

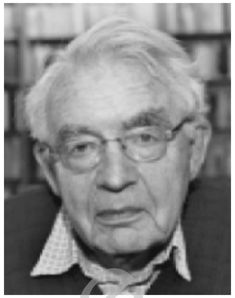
Interaction distance



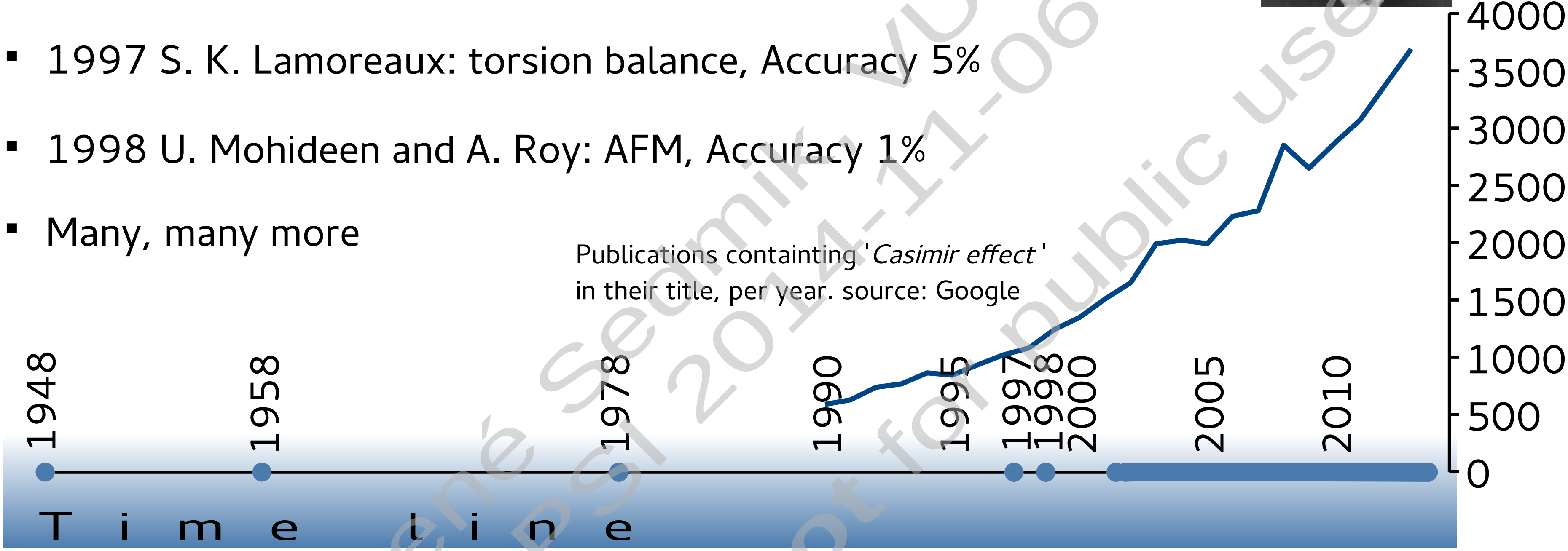
$$\lambda_T = \frac{\hbar c}{k_B T}$$

Casimir force – a long history

Landmark contributions



- 1948 H.B.G. Casimir $\dfrac{F(a)}{A} = -\dfrac{\pi^2 \hbar c}{240 a^4}$
- 1958 - 1978 Sparnaay, Blokland and Overboek, qualitative
- 1997 S. K. Lamoreaux: torsion balance, Accuracy 5%
- 1998 U. Mohideen and A. Roy: AFM, Accuracy 1%
- Many, many more



H. B. G. Casimir, "On the attraction between two perfectly conducting plates", *Proc. Royal Ned. Acad. Sci.*, Vol. **51**, pp. 793–795 (1948).

M. J. Spaarnay: "Measurement of attractive forces between flat plates", *Physica,* Vol **24**, pp. 751 (1958)

P. H. G. M van Blokland and J. T. G. Overbeek "The measurement of the van der Waals dispersion forces in the range 1.5 to 130 nm", *J. Chem. Soc. Faraday Trans.*, **I74**, pp. 2637(1978)

S. K. Lamoreaux, "Demonstration of the Casimir Force in the 0.6 to 6 µm Range", *Phys. Rev. Lett.* **78**, 5–8 (1997)

U. Mohideen and Anushree Roy, "Precision Measurement of the Casimir Force from 0.1 to 0.9 µm", *Phys. Rev. Lett.* **81**, 004549 (1998)

Over 3600 articles in 2013
Steadily growing interest in the field

Casimir force – why is it interesting?

Q: Why is there such a huge interest in the Casimir effect **?**

A: Because ...

- it is one of very few **quantum effects with macroscopic action.**
- **it has applications.**
- it becomes the **dominating force** at very small surface separations (<100 nm).

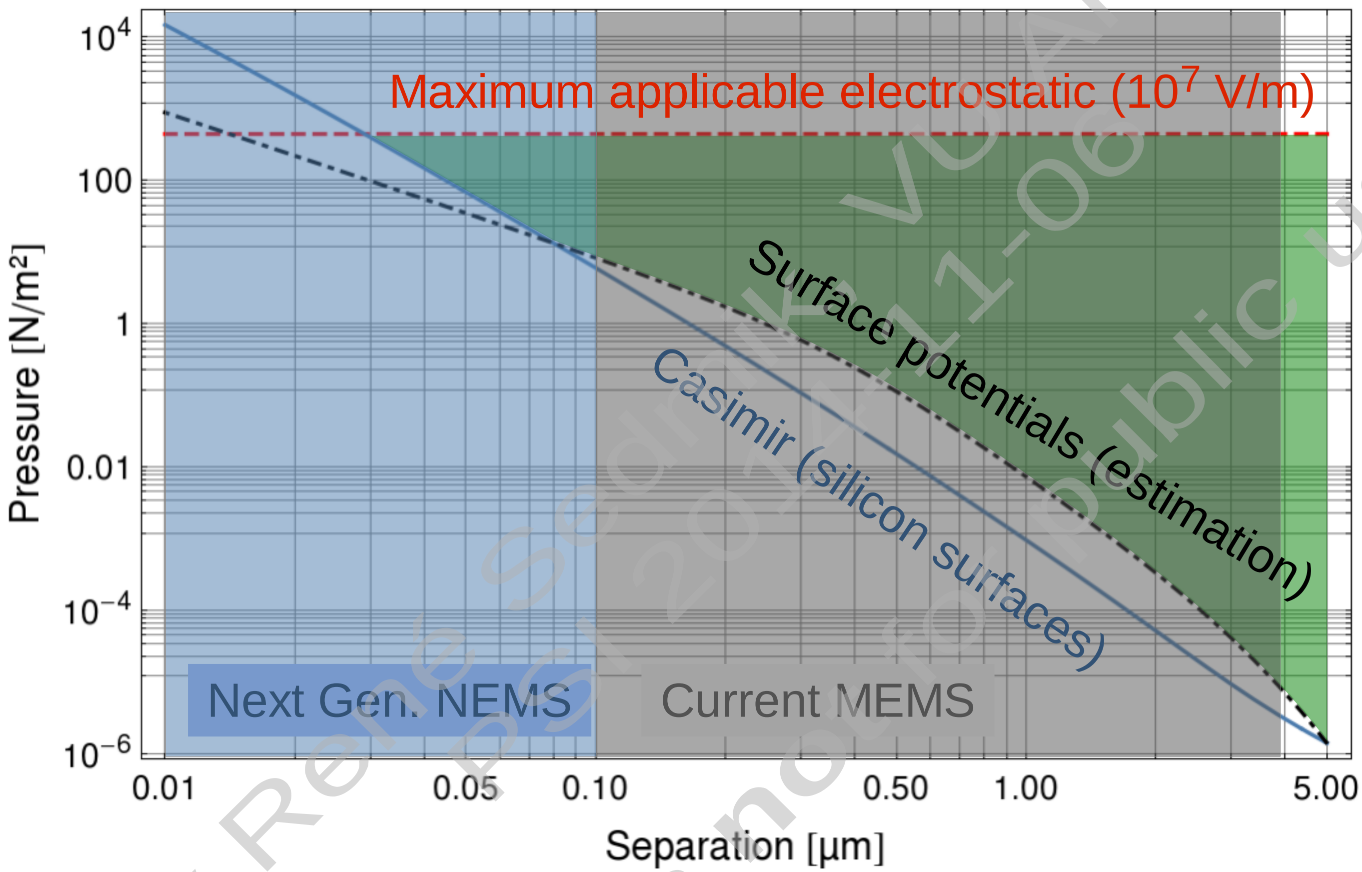
- the Casimir force causes `stiction' and therefore...

→ **it is a nuisance for the development of (M)NEMS**

Casimir force – why is it interesting?

Micro-electromechanical devices (MEMS)

Comparison of amplitudes:



Implications:

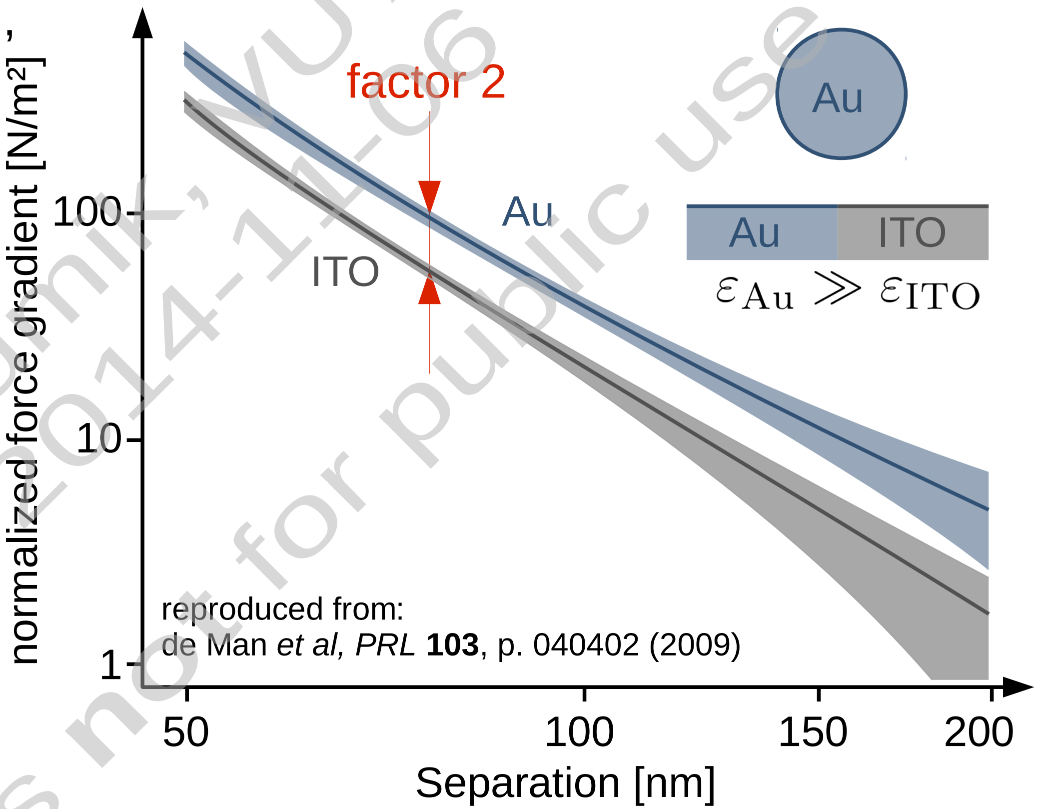
- Need to find ways to **eliminate/reduce the Casimir force**
- Find a way to **use the force** to drive actuators

Casimir force – what has been done already?

Experiments
... what influences the Casimir force?

Dependence on dielectric functions ε_r

- Range for tunability in vacuum limited, narrow spectral range of differences



$$\frac{E_{\text{reg}}(a)}{A} \propto \int_1^\infty \mathrm{d}p \int_0^\infty \mathrm{d}\xi\, p\xi^2 \left[\ln\left(1 - \left(\frac{K_1\varepsilon_0(i\xi) - K_0\varepsilon_1(i\xi)}{K_1\varepsilon_0(i\xi) + K_0\varepsilon_1(i\xi)}\right)^2 \mathrm{e}^{-2a\frac{\xi}{c}K_0}\right) + \ldots \right],$$

Casimir force – what has been done already?

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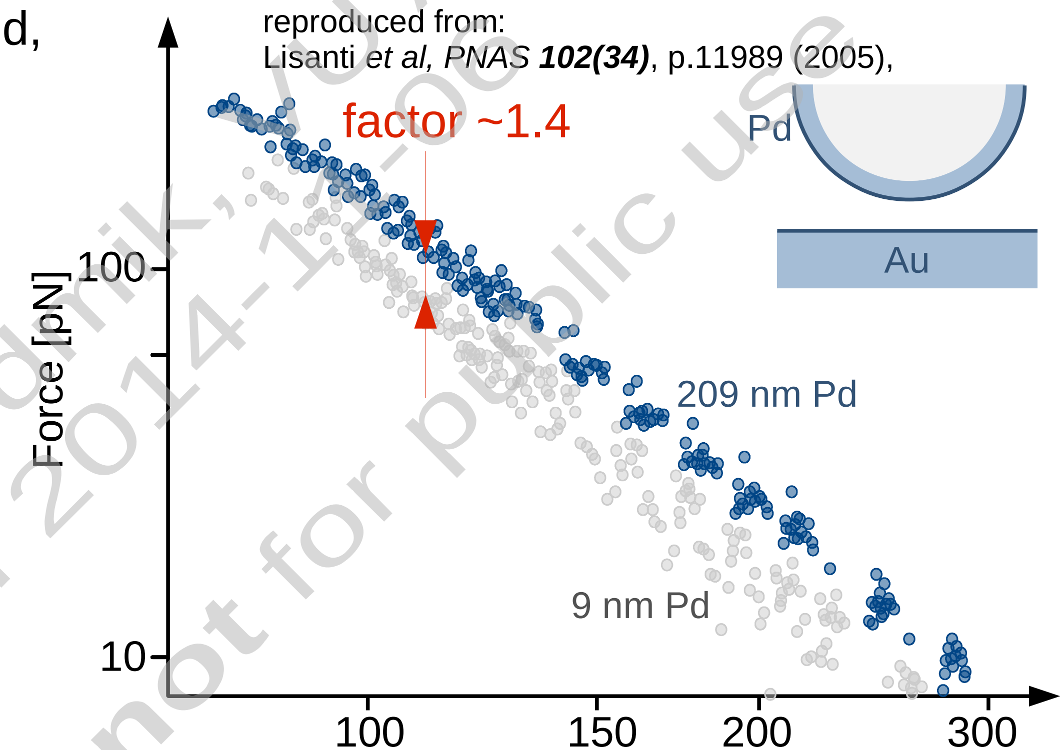
Skin-depth effect

- materials respond only as bulk if thicker than the penetration depth $\delta_p = \frac{c}{\omega_p}$~100 nm

with $\omega_p^2 = \frac{4\pi n_e e^2}{m^*}$



Casimir force – what has been done already?

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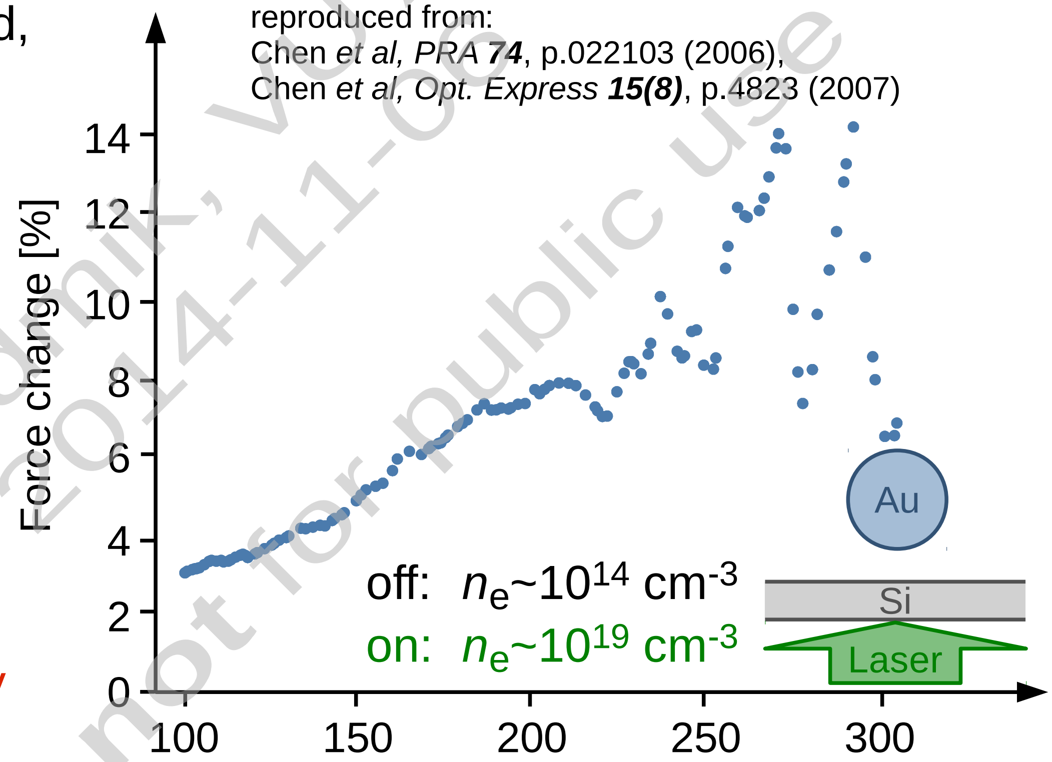
Modulation of Casimir forces

- possible but limited again by
  narrow spectral range of conductivity



Casimir force – what has been done already?

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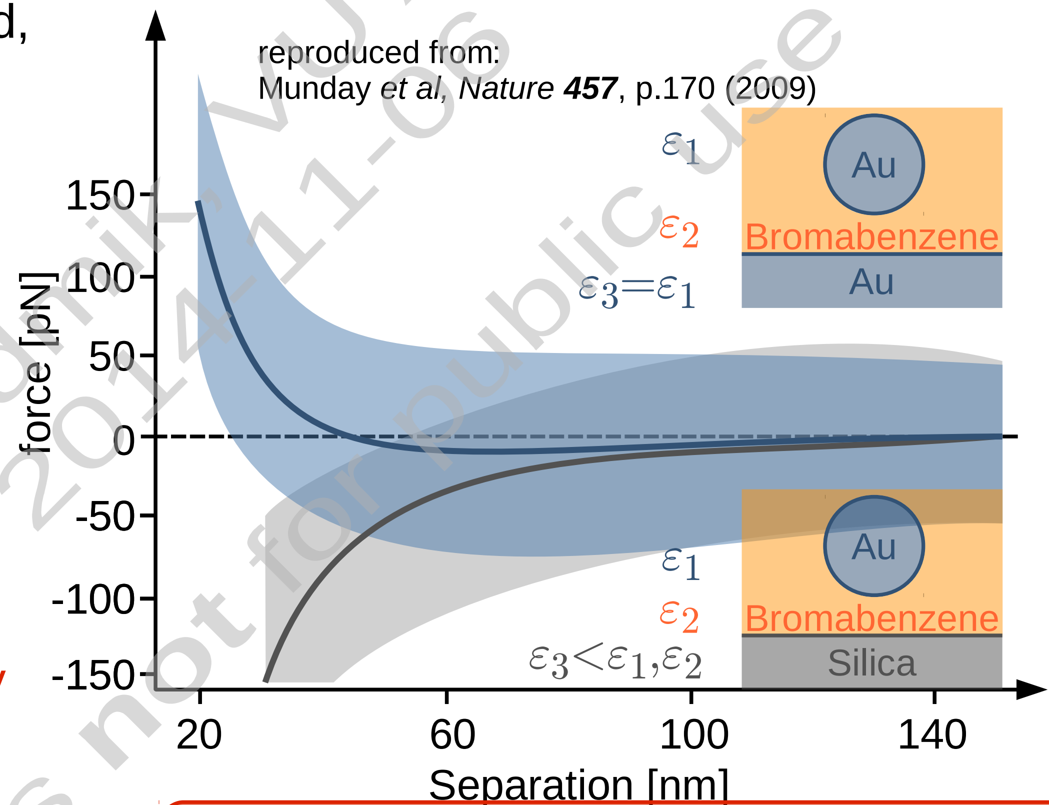
Modulation of Casimir forces

- possible but limited again by narrow spectral range of conductivity

Repulsive Casimir forces

- possible using liquids $\varepsilon_1 < \varepsilon_2 < \varepsilon_3$

$F(a) \propto -(\varepsilon_1 - \varepsilon_2)(\varepsilon_3 - \varepsilon_2)$



No obvious solution for NEMS yet.

Roughness, temperature, magnetic materials, torques, metamaterials, ...

More physical problems in Casimir physics:

1. The infamous Drude vs. plasma debate

Review: Klimchitskaya *et al*, Int. J. Mod. Phys. Conf. Ser. **3**(2011), 515

- The Casimir force F_C depends on dielectric properties via $\varepsilon_r(\omega)$
- There are two main models to extrapolate experimental data on $\varepsilon_r(\omega)$

Drude

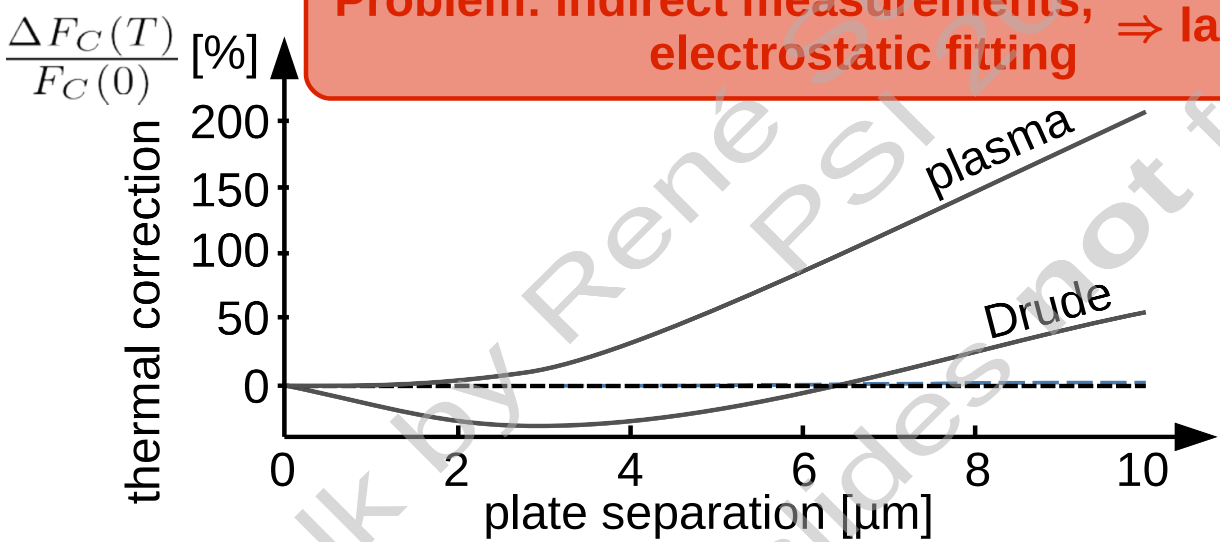
$$\varepsilon_r(\omega) = \varepsilon_0 - \frac{\omega_p^2}{\omega^2 + i\gamma\omega}$$

plasma

$$\varepsilon_r(\omega) = \varepsilon_0 - \frac{\omega_p^2}{\omega^2}$$

ω_p plasma frequency
γ relaxation frequency (dissipation)

Problem: indirect measurements, electrostatic fitting ⇒ large uncertainties



An **absolute measurement** with **$\mathcal{O}$(1%) accuracy at d > 3 μm** is required

M.. Bordag et al "Advances in the Casimir effect", *Oxford Science Publications*, (2009).

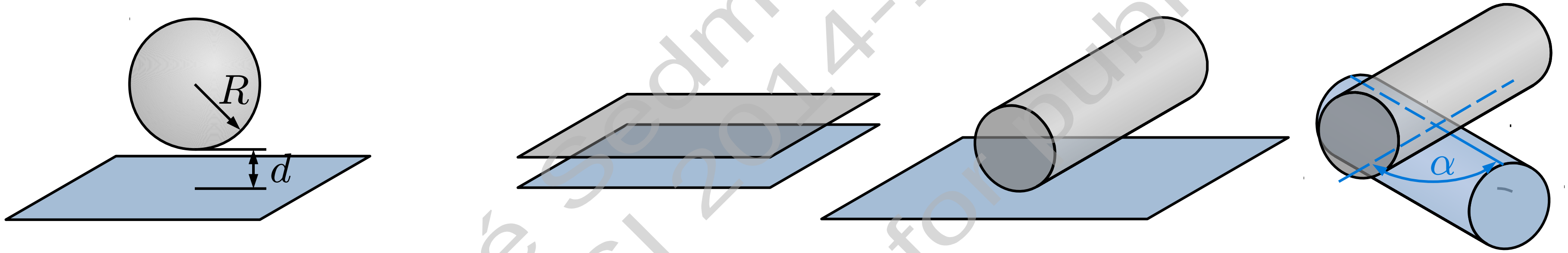
Casimir physics – what problems are we after?

More physical problems in Casimir physics:

2. Geometries without symmetry

- Several numerical approaches for precise computation of forces need experimental verification
- Data on different geometries, some involving parallelism, are required

most experiments: required data:



Need a precision experiment allowing for **control of relative orientation**

Casimir physics – what do we need?

More specifically...

- Sensitivity: Drude vs. Plasma problem
  measurement at **d > 3 μm** with **accuracy < 1 %** (1 pN/cm^2)

  Sushkov *et al*, Nature Physics **7** (2011), 230, Klimchitskaya *et al*, arXiv:1108.5696 (2011)

- Geometry: Parallelism (plates, cylinders, ...)
  measurement at **d > 3 μm** with **max. deviation 0.1 µrad**

  Rodriguez-Lopez Emig Phys. Rev. A **85** (2012), 032510, Bimonte *et al*, EPL **97** (2012), 50001

Need a high-precision, high-accuracy experiment with control of orientation (parallelism)

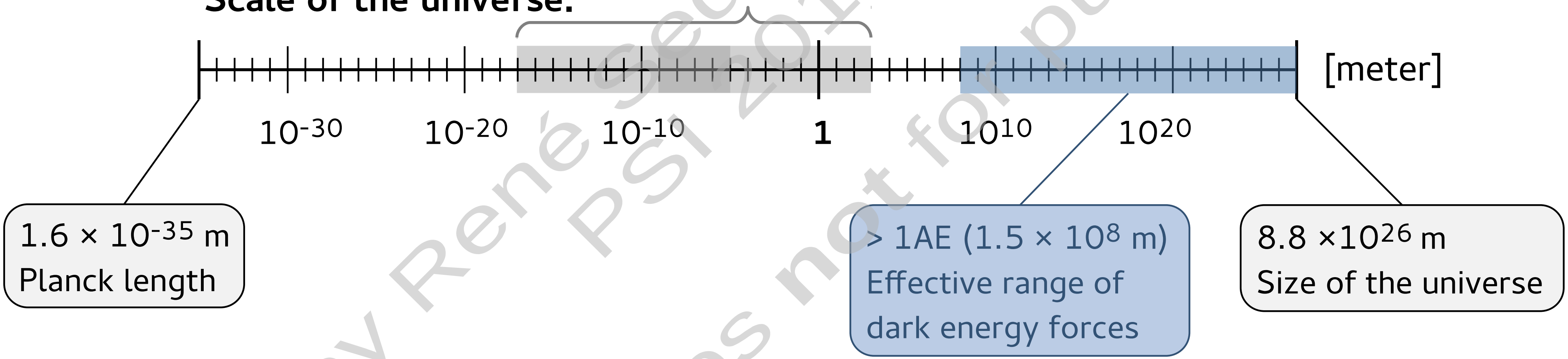
Outline

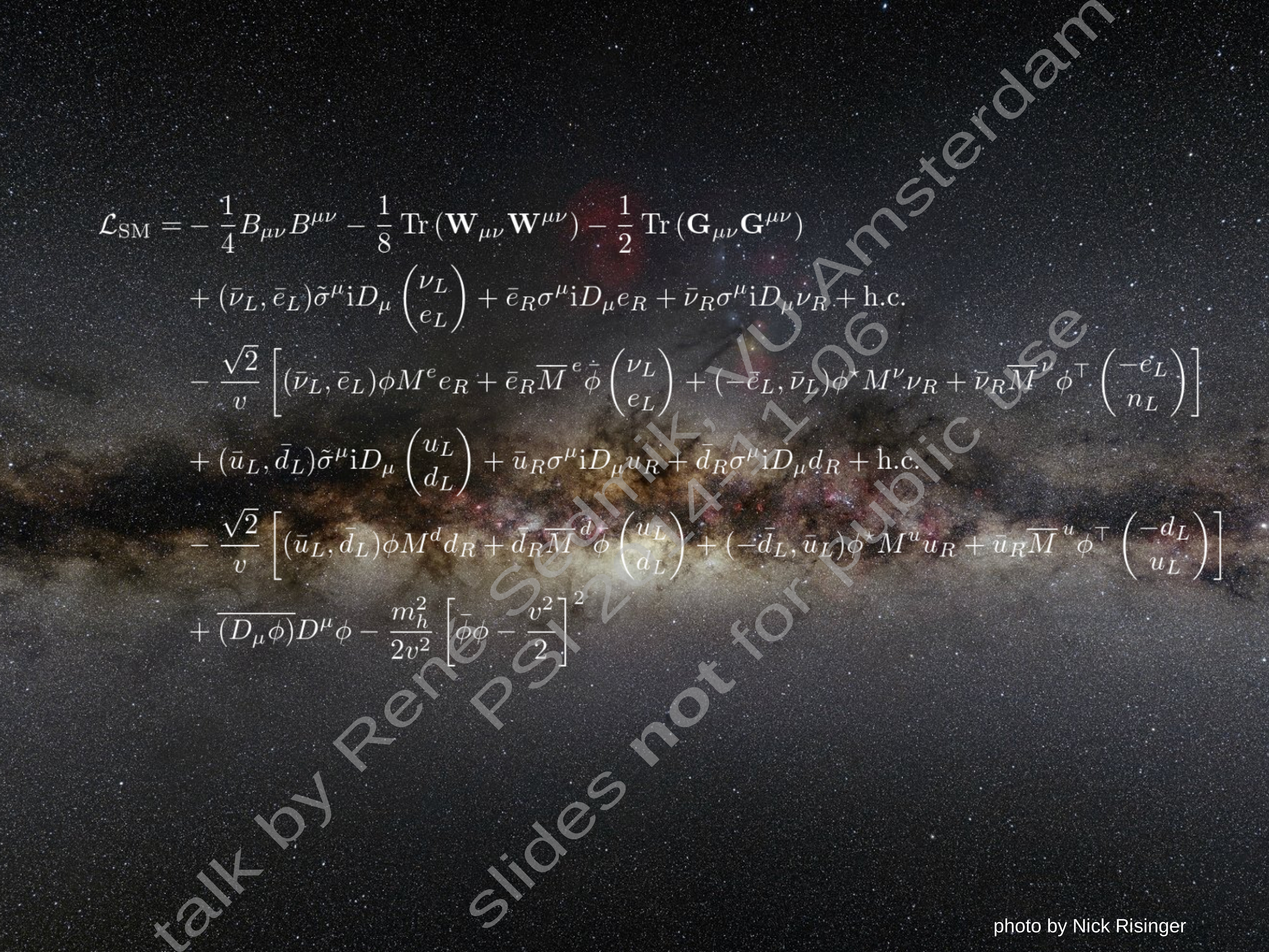
Part I: Scientific background

Casimir physics, **Chameleon model and dark energy**

What are the goals?

Scale of the universe:





$$\mathcal{L}_{\mathrm{SM}} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}\,\mathrm{Tr}\left(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}\right) - \frac{1}{2}\,\mathrm{Tr}\left(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}\right)$$

$$+ (\bar\nu_L, \bar e_L)\tilde\sigma^\mu \mathrm{i}D_\mu \begin{pmatrix}\nu_L\\ e_L\end{pmatrix} + \bar e_R \sigma^\mu \mathrm{i}D_\mu e_R + \bar\nu_R \sigma^\mu \mathrm{i}D_\mu \nu_R + \mathrm{h.c.}$$

$$- \frac{\sqrt{2}}{v}\left[(\bar\nu_L, \bar e_L)\phi M^e e_R + \bar e_R \overline{M}^e \bar\phi \begin{pmatrix}\nu_L\\ e_L\end{pmatrix} + (-\bar e_L, \bar\nu_L)\phi^\star M^\nu \nu_R + \bar\nu_R \overline{M}^\nu \phi^\top \begin{pmatrix}-e_L\\ n_L\end{pmatrix}\right]$$

$$+ (\bar u_L, \bar d_L)\tilde\sigma^\mu \mathrm{i}D_\mu \begin{pmatrix}u_L\\ d_L\end{pmatrix} + \bar u_R \sigma^\mu \mathrm{i}D_\mu u_R + \bar d_R \sigma^\mu \mathrm{i}D_\mu d_R + \mathrm{h.c.}$$

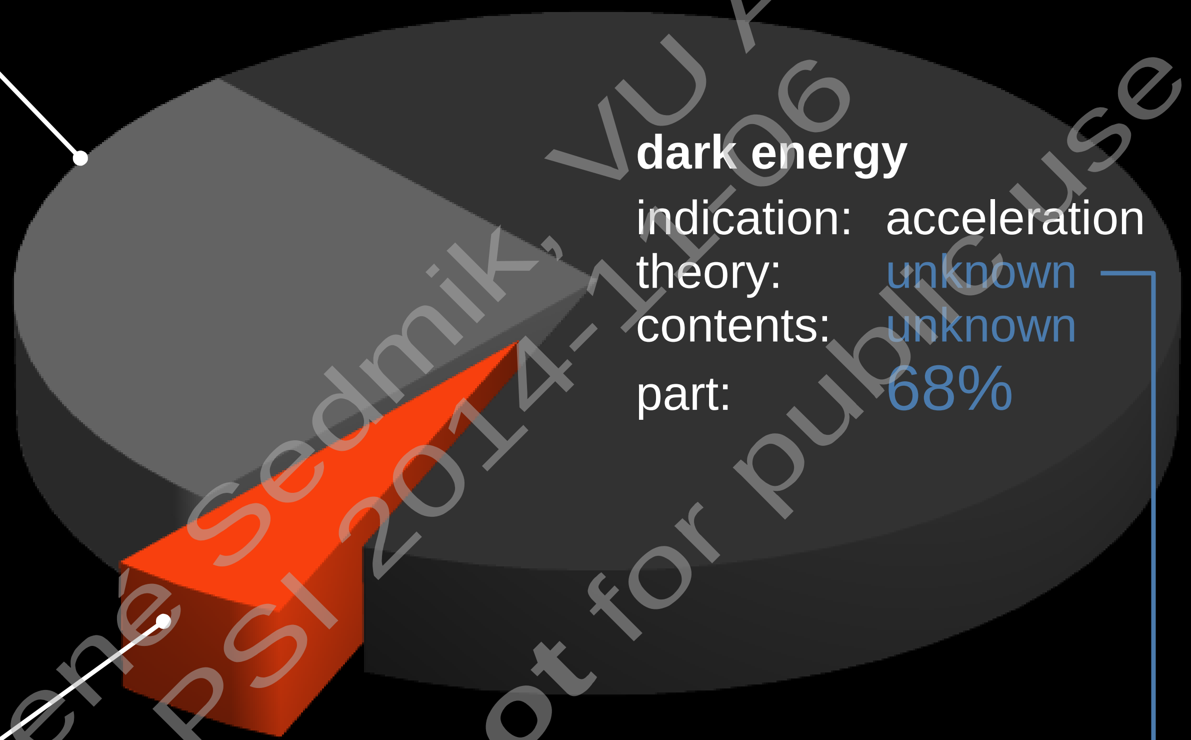
$$- \frac{\sqrt{2}}{v}\left[(\bar u_L, \bar d_L)\phi M^d d_R + \bar d_R \overline{M}^d \bar\phi \begin{pmatrix}u_L\\ d_L\end{pmatrix} + (-\bar d_L, \bar u_L)\phi^\star M^u u_R + \bar u_R \overline{M}^u \phi^\top \begin{pmatrix}-d_L\\ u_L\end{pmatrix}\right]$$

$$+ \overline{(D_\mu\phi)}D^\mu\phi - \frac{m_h^2}{2v^2}\left[\bar\phi\phi - \frac{v^2}{2}\right]^2$$

photo by Nick Risinger

dark matter

indication: grav. pull
theory: unknown
contents: unknown
part: 27%



dark energy

indication: acceleration
theory: unknown
contents: unknown
part: 68%

visible universe

indication: em radiation, gravity
theory: $\mathcal{L}_{\mathrm{SM}}$
contents: particles of the SM
part: 5%

proposition:

add a new scalar
Yukawa interaction: $\mathcal{L}_{\mathrm{C}}$

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

$$\mathcal{L}_{\rm SM} \rightarrow \mathcal{L}'_{\rm SM} + \mathcal{L}_{\rm C}$$

$$\frac{\mathrm{e}^{\frac{\beta_\gamma}{M_{Pl}}\phi}}{4} F^2 + \sum_i \mathcal{L}^{(i)} \left(\mathrm{e}^{\frac{\beta_i}{M_{Pl}}\phi}, \psi^{(i)} \right)$$

~ Einstein-Hilbert action with **added dynamics:**

$$\sqrt{-g}\left[\mathcal{R}\frac{M_{Pl}^2}{2} - \frac{1}{2}(\partial\phi)^2 - V(\phi)\right]$$

Λ

equations of motion for ϕ:

$$\partial^2\phi = \frac{\partial V(\phi)}{\partial\phi} + \frac{\beta}{M_{Pl}}\rho \mathrm{e}^{\frac{\beta}{M_{Pl}}\phi}$$

effective potential

$$V_{eff} = V(\phi) + \rho \mathrm{e}^{\frac{\beta}{M_{Pl}}\phi}$$

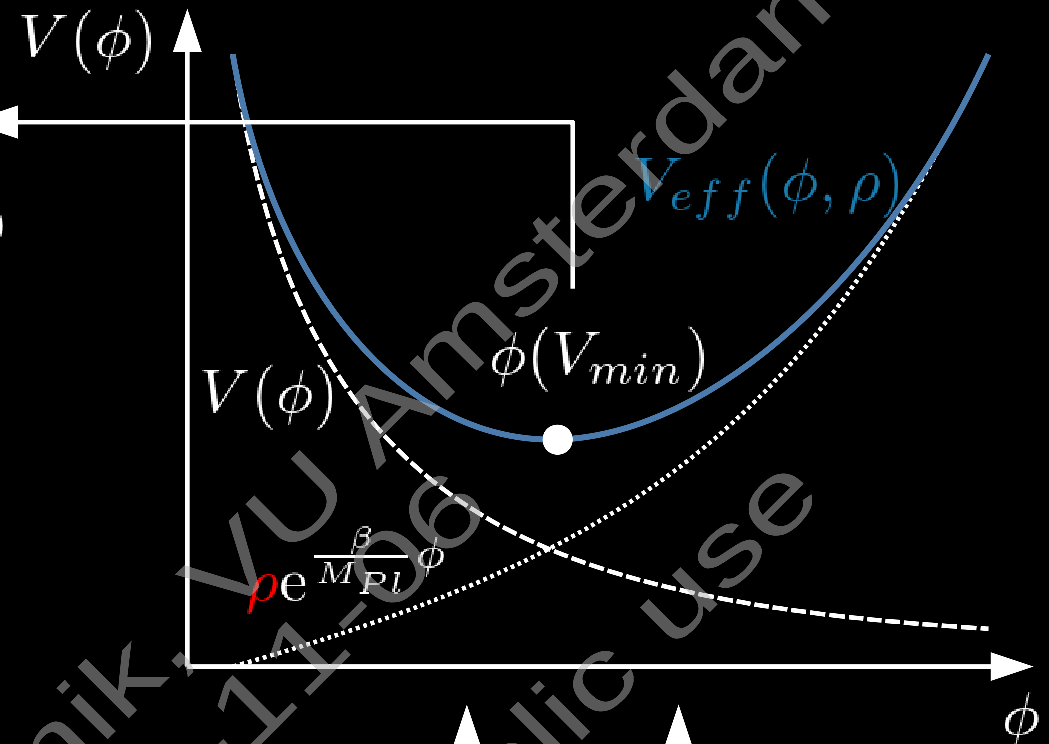
depend on the local mass density ρ

$\mathcal{L}_{\rm SM}$

$\mathcal{L}_{\rm C}$

$$m_\phi(\rho) = \sqrt{\frac{\partial^2 V_{eff}(\phi)}{\partial \phi^2}}\Bigg|_{\phi=\phi_{min}(\rho)}$$

$$\propto \frac{\beta}{M_{Pl}}\rho$$



Chameleon potential:

$$V(r) \propto \beta \frac{M}{M_{Pl}} \frac{e^{-m_\phi(\rho) r}}{r}$$

\`quintessence' runaway potential

Yukawa coupling

$$\partial^2 \phi = \frac{\partial V(\phi)}{\partial \phi} + \frac{\beta}{M_{Pl}} \rho e^{\frac{\beta}{M_{Pl}}\phi}$$

equations of motion for ϕ:

$$V_{eff} = V(\phi) + \rho e^{\frac{\beta}{M_{Pl}}\phi}$$

effective potential

Q: What does that mean?

$$V(r) \propto \beta \frac{M}{M_{Pl}} \frac{\mathrm{e}^{-m_\phi(\rho) r}}{r}$$

free space:

$\rho \ll 1 \Rightarrow m_\phi \ll 1$

strong interaction

large massive object:

$\rho \gg 1 \Rightarrow m_\phi \gg 1$

weak interaction

For this adaptivity, the model is dubbed **Chameleon**

A: The interaction strength is inversely dependent on the local mass (energy) density.

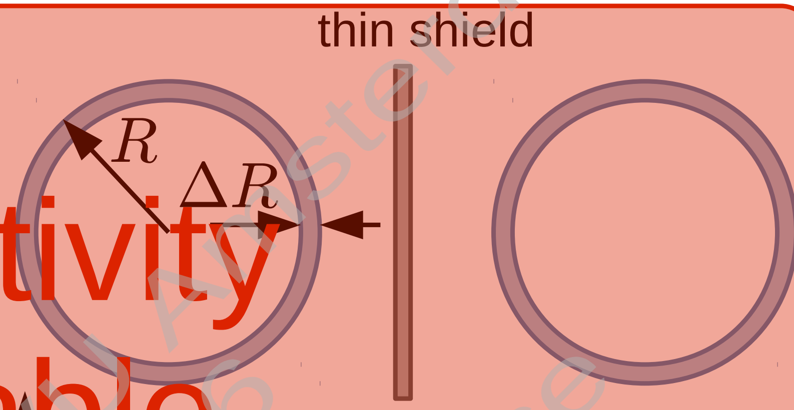
Q: What does that mean?

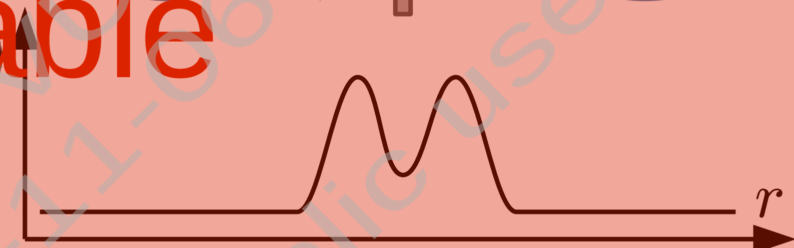
How can we detect the Chameleon on Earth?

Idea #1:
Precision Cavendish-type 5th force experiment
Measure force as a **function of distance**

$$V(r) \propto \beta \frac{M}{M_{Pl}} \frac{\Delta R}{R} \frac{\mathrm{e}^{-m_\phi(\rho) r}}{r}$$

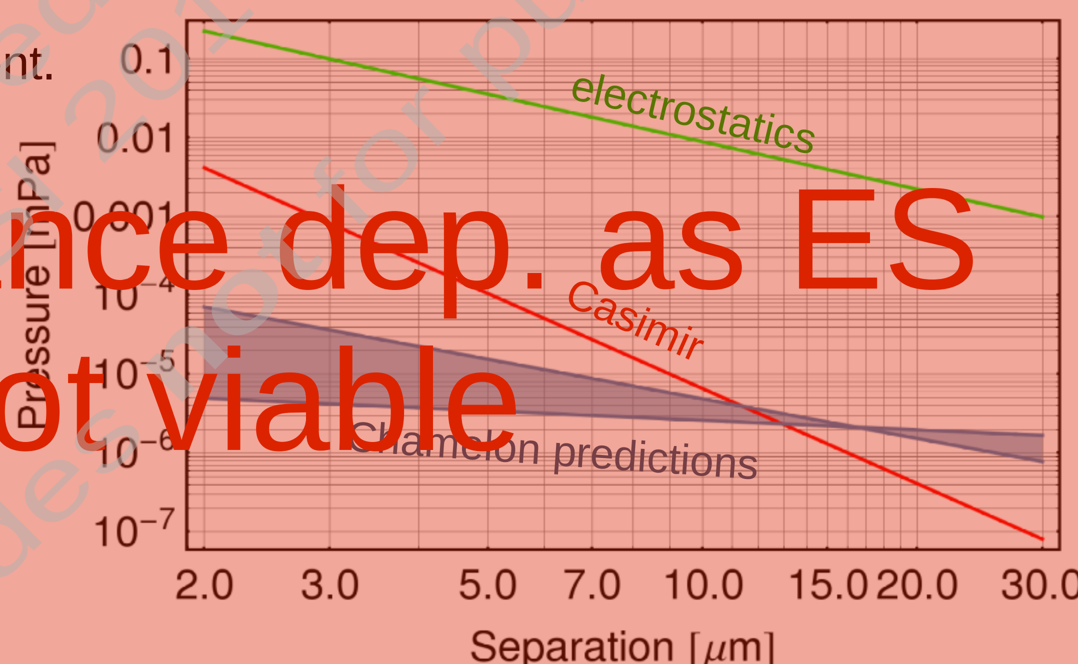
↳ `thin shell effect'





low sensitivity
► not viable

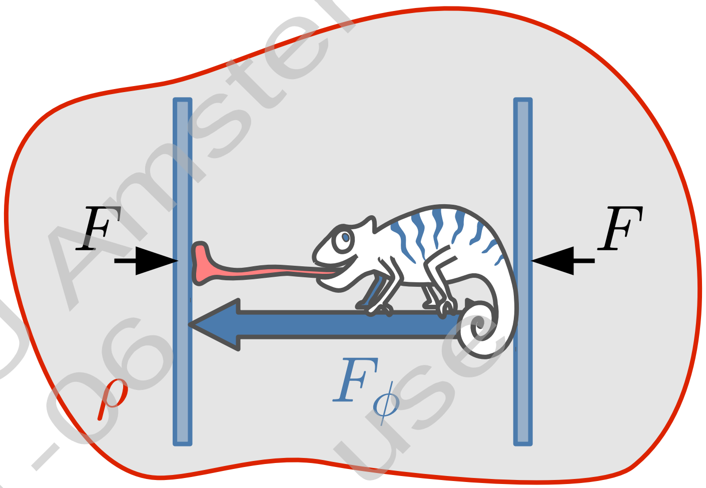
Idea #2:
Precision Casimir-type force experiment.
Measure force as a
function of distance without shield



same distance dep. as ES
► not viable

de Man, Heeck, Wijngarden, Iannuzzi,
PRL. **103** (2009), 040402

Idea #3:
Measure at **constant plate separation**
the change in the force for **different gas density ρ**
Brax, van de Bruck, Davis, Shaw, Iannuzzi,
Phys. Rev. Lett. **104** (2010) 241101



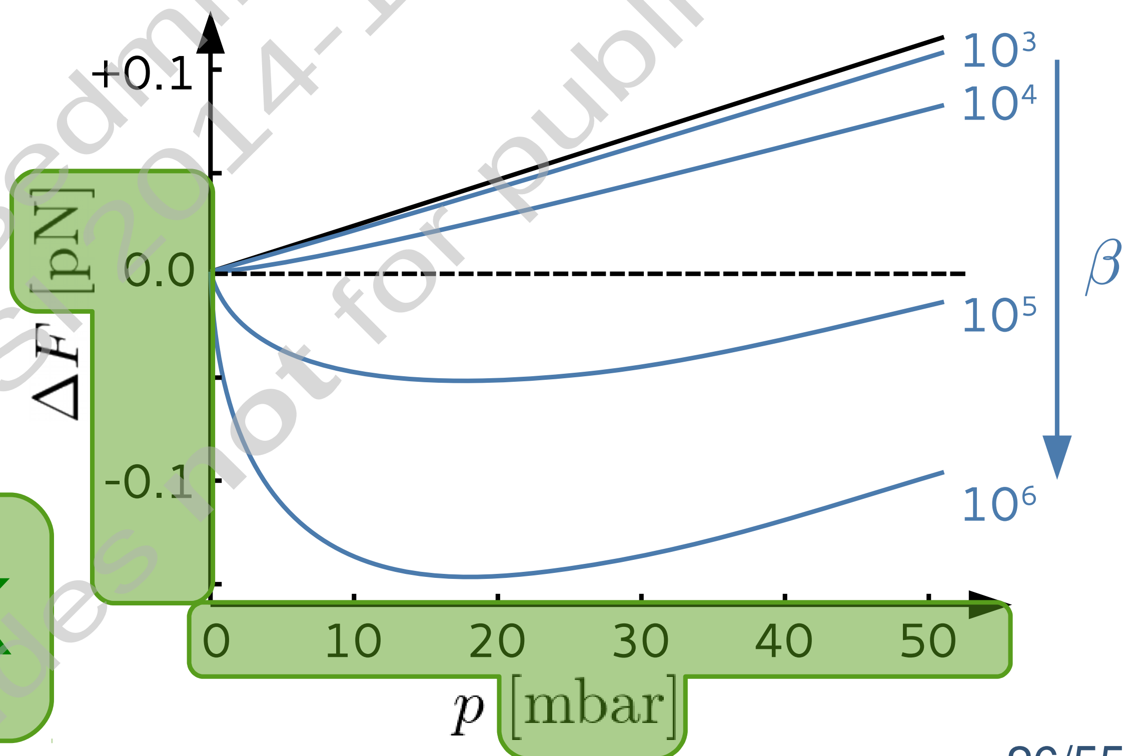
$$F(\rho) = F_{ES} + F_C + F_G + F_\phi$$

$$\Delta F(\rho) = F(\rho) - F(0)$$

Assumptions:

- Xe gas
- plate area 1 cm²
- $V(\phi) = \Lambda^4 \left(1 + \frac{\Lambda^n}{\phi^n}\right)$
- Λ = 2.4 meV

✓ can work

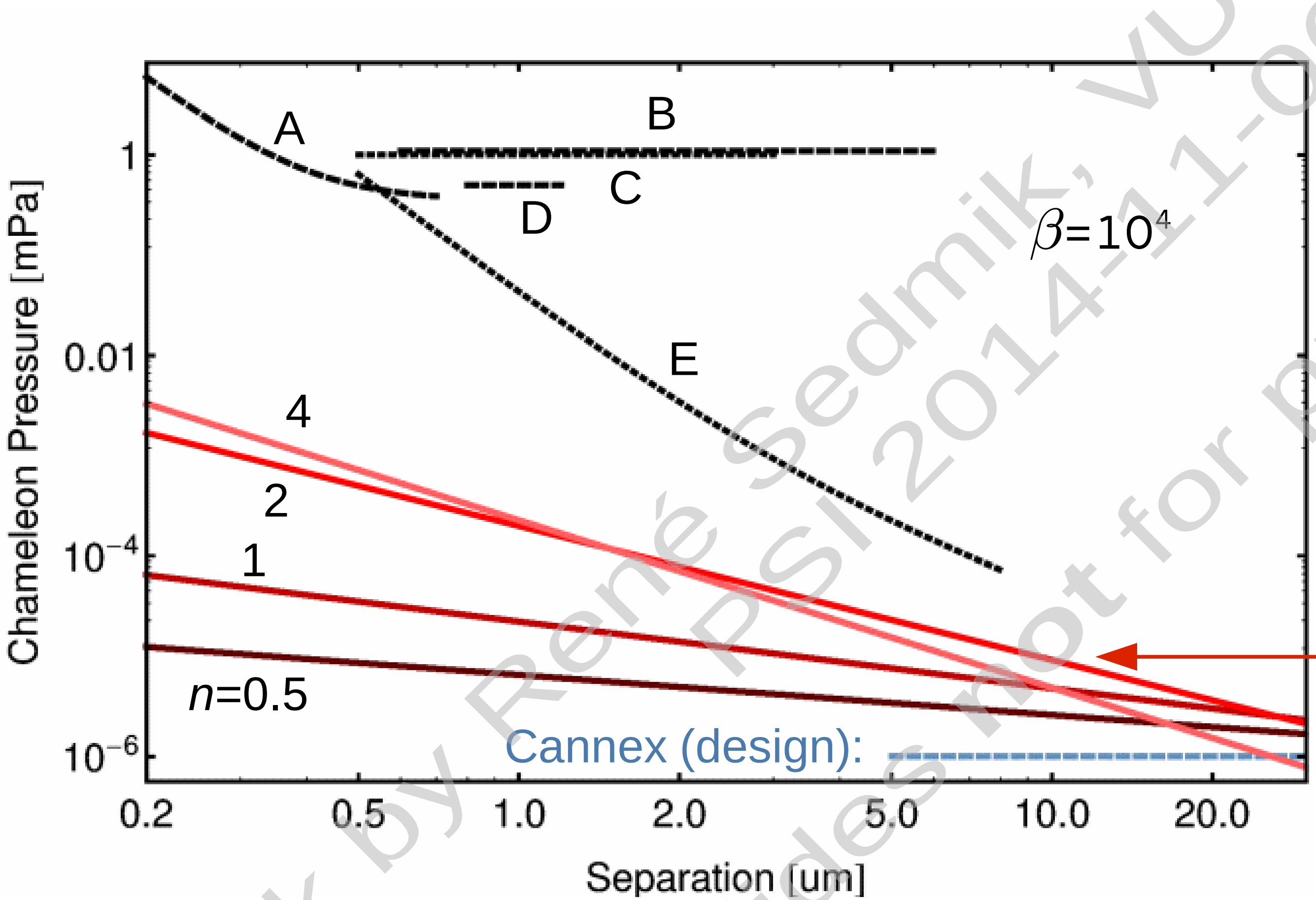


What can we reach?

New limits...

- to the interaction parameter β
- to the form of potentials $V(\phi)$, exclusion of specific n

$$V(\phi) = \Lambda^4 \left(1 + \frac{\Lambda^n}{\phi^n}\right)$$



A: Decca *et al*, Ann. Phys. (N.Y.) **318** (2005), 37
B: Lamoreaux PRL. **78**(1997), 5
C: Bressi *et al*, PRL. **88** (2002), 041804
D: Decca *et al*, PRL. **91** (2003), 050402
E: Sushkov et al, Nature Phys. **7** (2011), 230

Parameter range not excluded by any experiment

Chameleon physics – what do we need?

More specifically...

- Sensitivity: New limits can be seen for a measurement at d > 10 μm with **accuracy < 0.1 pN/cm²**.
  Brax *et al*, Phys. Rev. D **76** (2007), 124034
- Geometry: Parallel plates give the maximum force sensitivity. Measurement at d > 10 μm with **max. deviation 0.1 µrad**.
  Brax *et al*, Phys. Rev. Lett. **104** (2011), 241101

compare: Casimir

d > 3 μm, 1 pN/cm²

0.1 µrad

Again: Need a high-precision, high-accuracy experiment with control of orientation (parallelism)

Both forces could be measured with the same setup

CANNEX

Casimir And
Non-Newtonian force
EXperiment

Aim: Measure Casimir as well as Chamelon forces with the same setup

Outline

Part I: Scientific background

Casimir physics, Chameleon model and dark energy

What are the goals?

Part II: Setup

Core: Principle of measurement, Control of parallelism,

Vibration insulation: Mechanisms, Preliminary characterization

Status

What do we need to implement Cannex?

Cooking recipe:
sub-pN Force measurement in parallel plates geometry

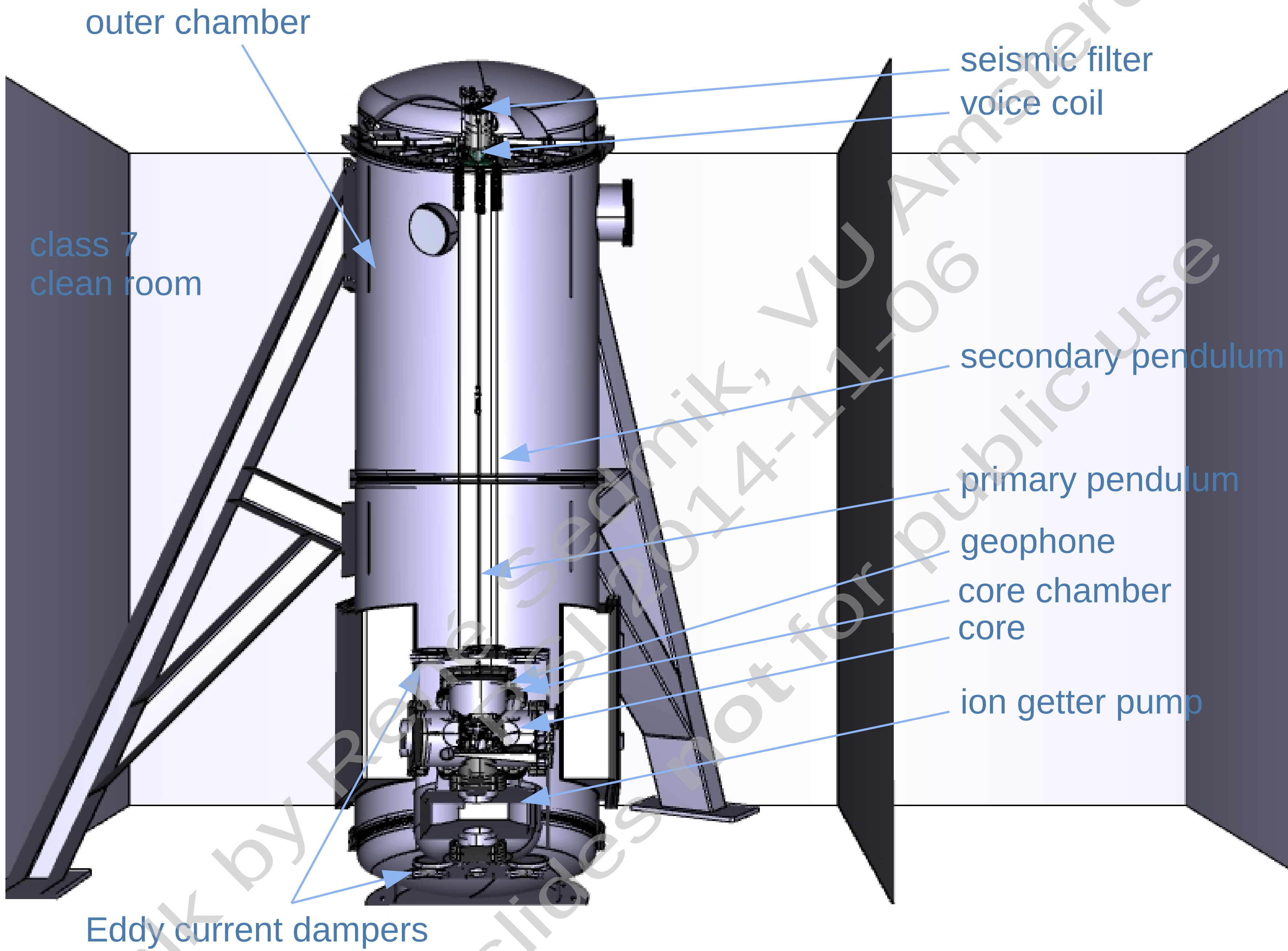
Sensitivity:	**0.1 pN**
Geometry:	flat, parallel plates
Area:	1 cm²
Separation:	3-30 µm
Pressure:	vacuum – ambient

difficulty level: **challenging**
preparation time: **3 years**

Shopping List:

- Force transducer for <1 N/m
- Capacitive detection system: (C-bridge 1 aF at nom. 100 pF)
- Parallelism control ~0.1 µrad
- Ultra-flat surfaces (waviness < 20 nm)
- Vibration isolation (-60 dB at 1 Hz)

Setup


outer chamber
seismic filter
voice coil
class 7
clean room
secondary pendulum
primary pendulum
geophone
core chamber
core
ion getter pump
Eddy current dampers

Outline

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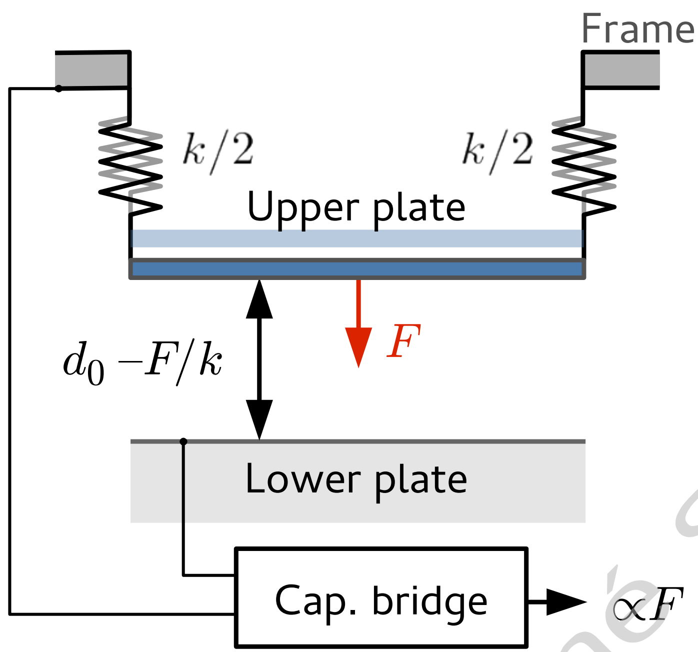
Principle:

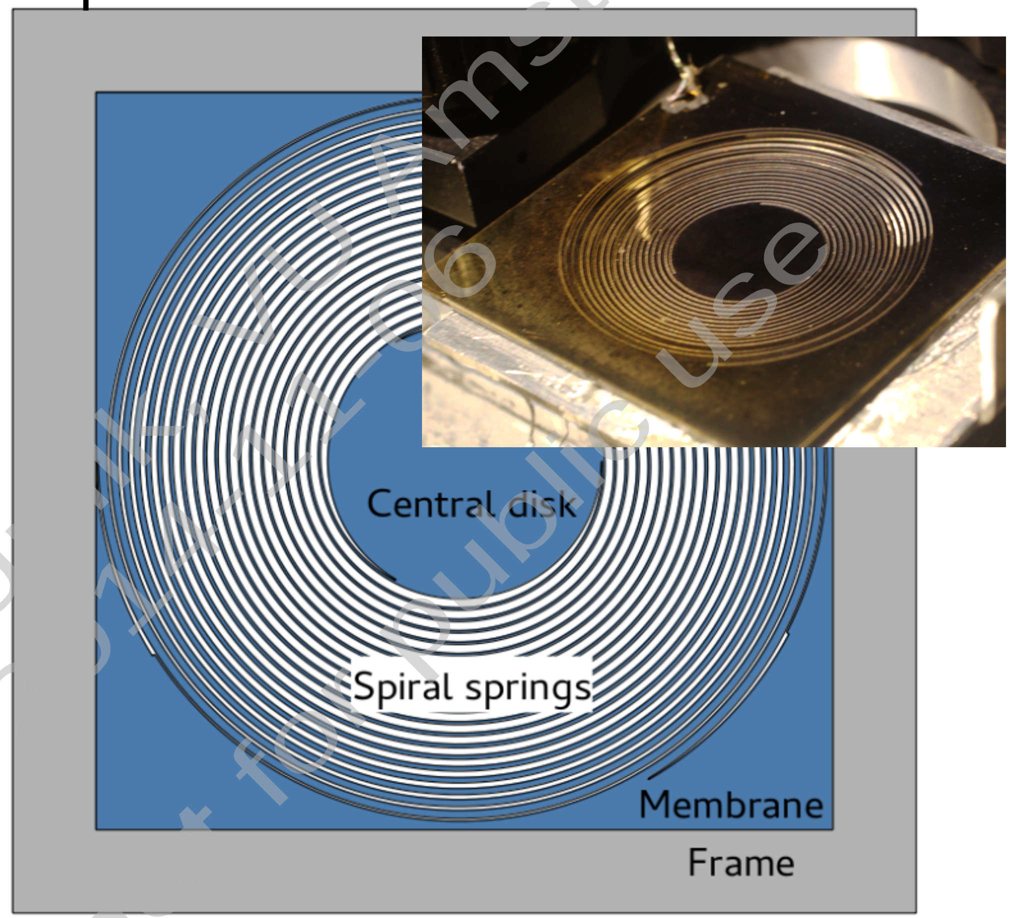
Measure capacitively the displacement of a spring.



Now: Andeen-Hagerling 2700A (0.4 ppm resolution ~ 1 pN)

Target: Custom differential bridge (0.01 ppm resolution <0.1 pN)

Implementation: (patents pending)



Custom-fabricated Silicon membrane

Force constant	0.25 N/m
Eigenfrequency	11.4 Hz
Disk area	1 cm^2
Waviness(disk)	< 15 nm (whole area)

Principle:

Measure capacitively the displacement of a spring.

Frame

Shopping List:

✓ Force transducer for < 1 N/m
0.25 N/m

Capacitive detection system:
(C-bridge 1 aF at nom. 100 pF)

Parallelism control ~0.1 µrad

✓ Ultra-flat surfaces (waviness < 20 nm)

Vibration isolation (-60 dB at 1 Hz)

Implementation:

(patents pending)

Frame

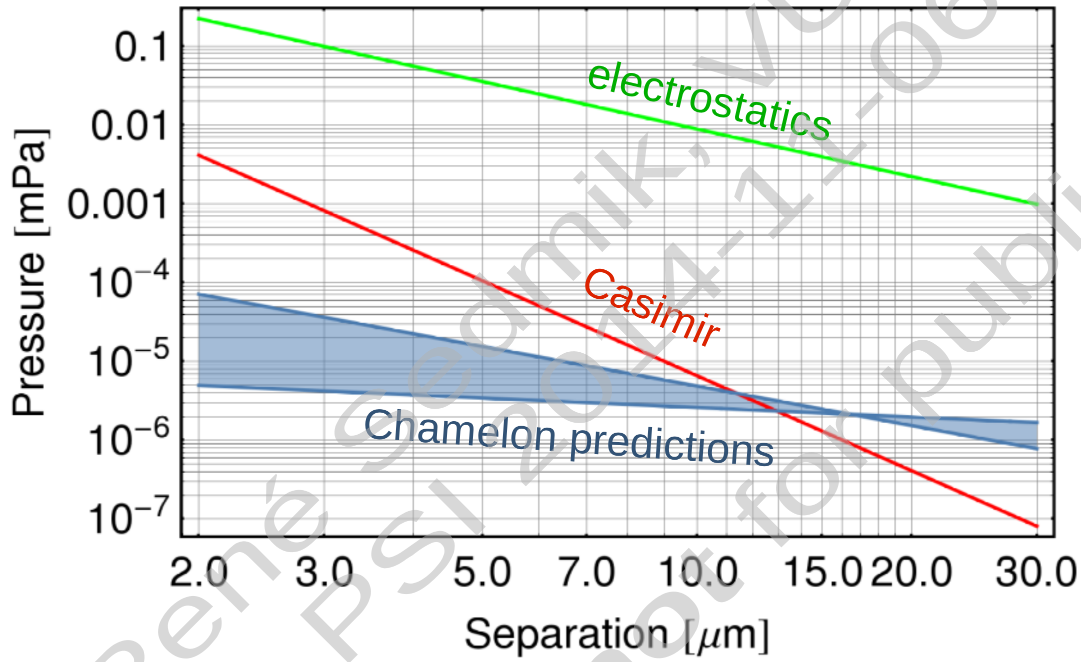
…stom-fabricated Silicon membrane

…e constant	0.25 N/m
…nfrequency	11.4 Hz
…area	1 cm²
…ness(disk)	< 15 nm (whole area)

Force detection: Elimination of parastitic forces

Problem diagnosis:

- Omnipresent varying Fermi potentials V_0 give rise to parasitic electrostatic forces.
- Electrostatic and hydrodynamic effects are normally far stronger than Casimir or Chameleon interactions.

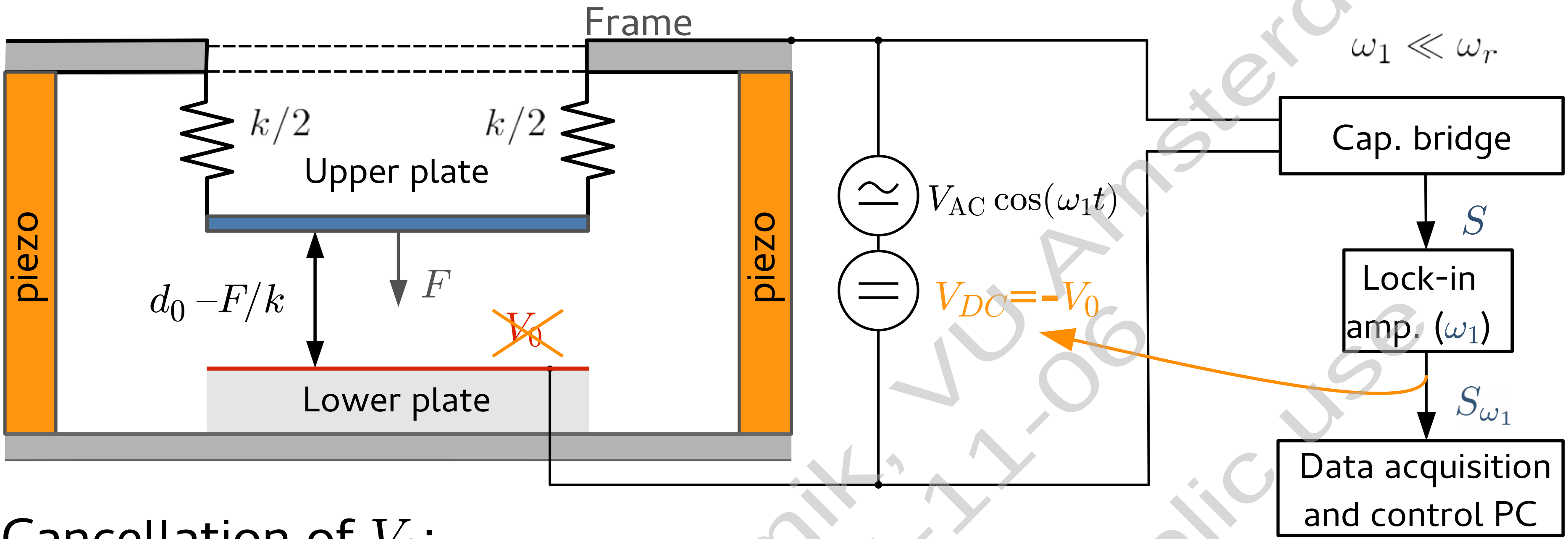


Solution:

de Man, Heeck, Iannuzzi, *Phys. Rev. A* **79**,(2009), 024102

- **Active feedback circuit** to cancel electrostatics
- Use **UHV** (10^{-9} mbar) for Casimir measurements to cancel hydrodynamics
- Chameleon measurements at **quasi-DC** (<100 mHz) frequencies

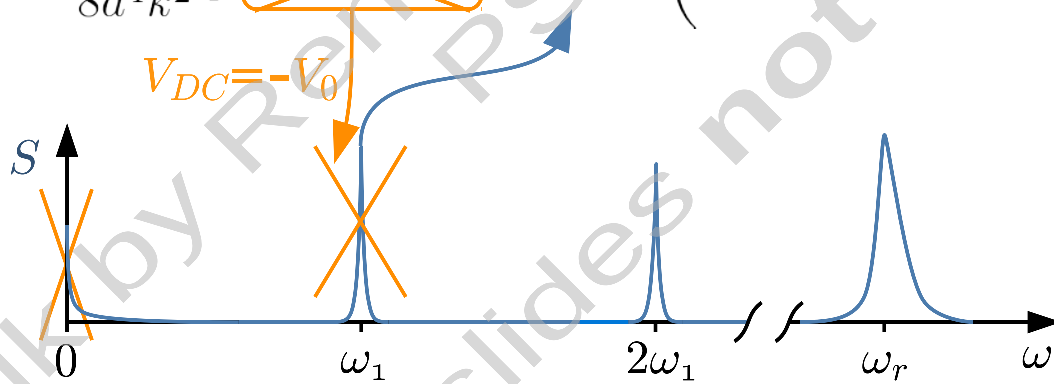
Force detection – AC measurements



Cancellation of V_0:

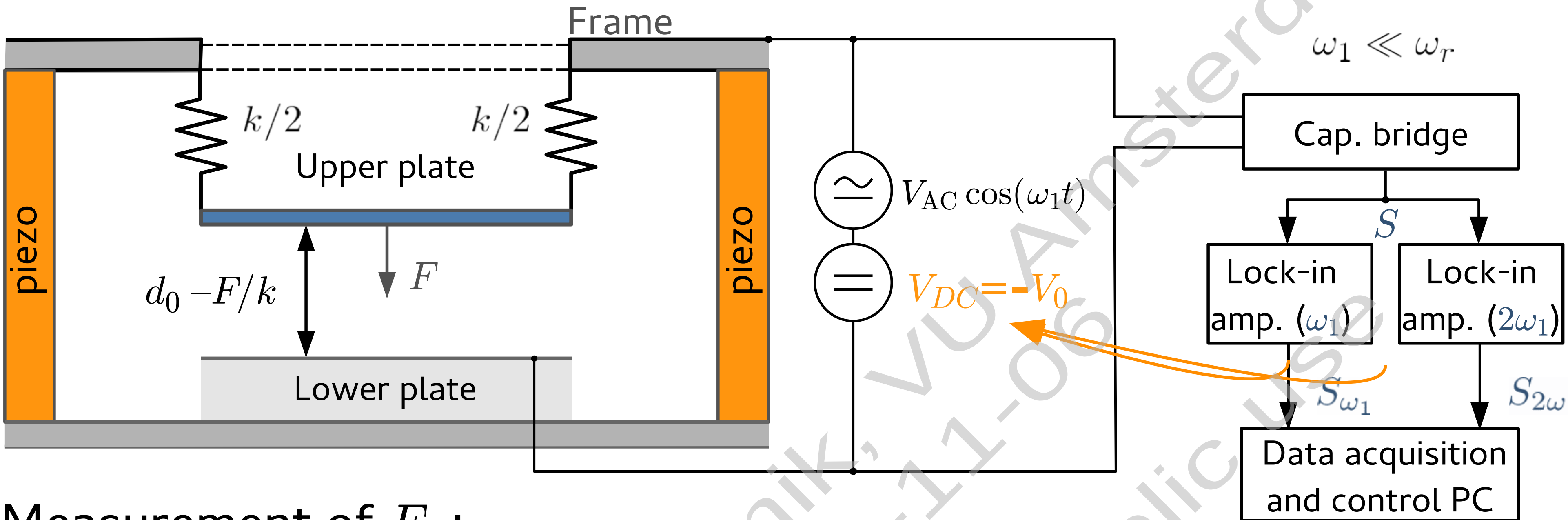
Signal: $S \equiv C(F) \underset{F/k \ll d}{\approx} \frac{\varepsilon_0 A}{d - F/k}$ **Force:** $F = \frac{\epsilon_0 A}{d^2}[V_0 + V_{DC} + V_{AC}\cos(\omega_1 t)]^2$

$$= \frac{\varepsilon_0^2 A^2}{8 d^4 k^2}\left[2(V_0 + V_{DC})\cos(\omega_1 t)\left(4k + \frac{\varepsilon_0 A(3V_{AC}^2 + 4[V_0 + V_{DC}]^2}{d^3}\right) + \ldots\right.$$



Effect:
- Replace unknown force by small known one.
- Residual potential < 50 µV (compared to initially >10 mV)
- Experience shows that the residual force << Casimir force

Force detection – AC measurements



Measurement of F_C:

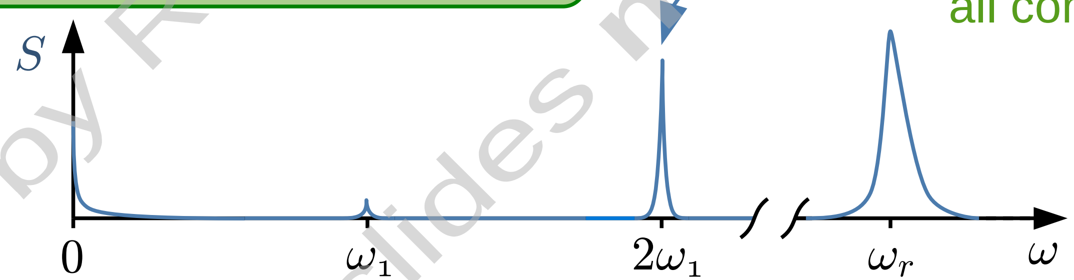
Signal: $S \equiv C(F) \underset{F/k \ll d}{\approx} \frac{\varepsilon_0 A}{d - F/k}$

Force: $F = \frac{\epsilon_0 A}{d^2}[V_{AC}\cos(\omega_1 t)]^2 + F_C(d)$

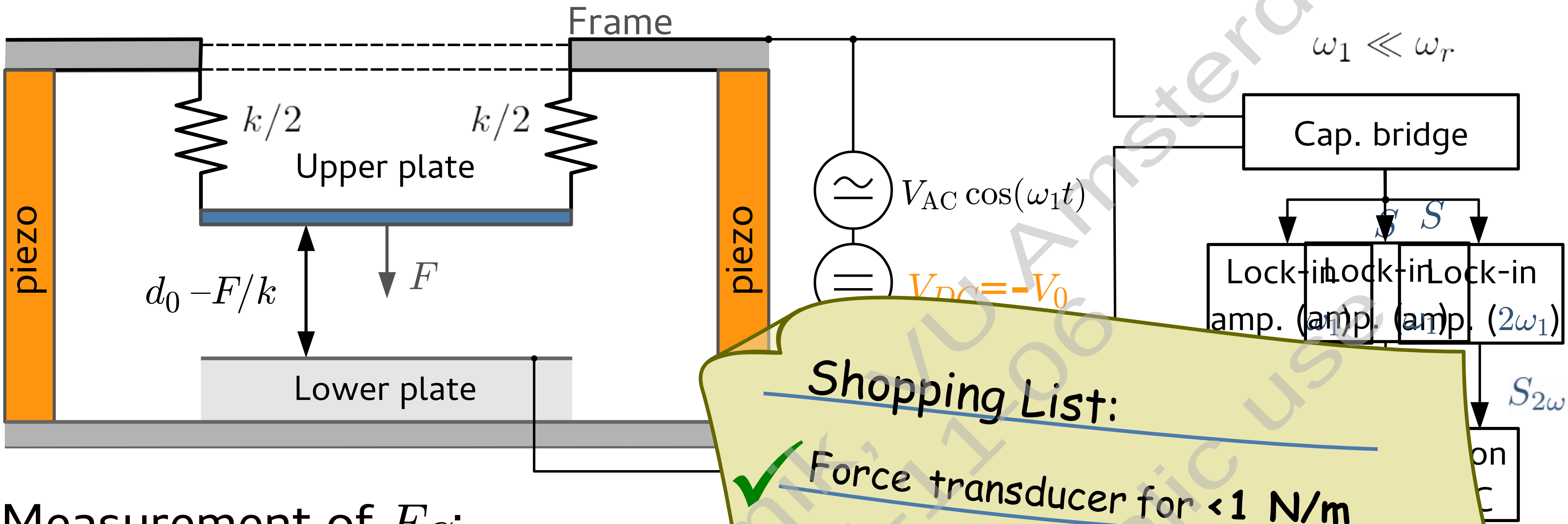
$$F_C = -\frac{dk}{2} - \frac{\varepsilon_0 A}{4d^2}V_{AC}^2 + \frac{2d^5k^2}{\varepsilon_0^2 A^2 V_{AC}^2} S_{2\omega_1}$$

all components known!

Measurement of F_C from the $S_{2\omega_1}$ signal



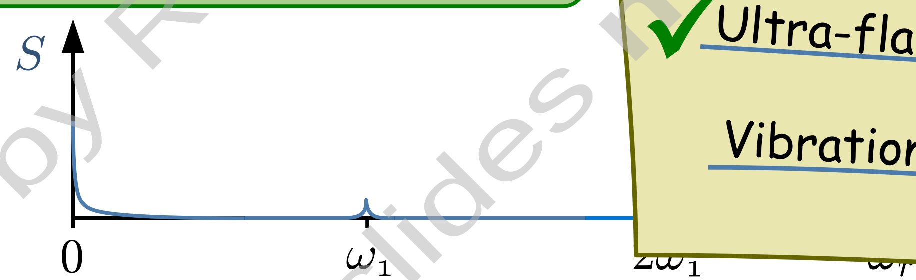
Force detection – AC measurements



Measurement of F_C:

Signal: $S \equiv C(F) \underset{F/k \ll d}{\approx} \frac{\varepsilon_0 A}{d - F/k}$

Measurement of F_C from the $S_{2\omega_1}$ signal



Shopping List:

- ✓ Force transducer for <1 N/m — 0.25 N/m
- Capacitive detection system: (C-bridge ~~1 aF~~ at nom. 100 pF) currently 40 aF, need to improve
- Parallelism control ~0.1 µrad
- ✓ Ultra-flat surfaces (waviness < 20 nm)
- Vibration isolation (-60 dB at 1 Hz)

Outline

Part I: Scientific background

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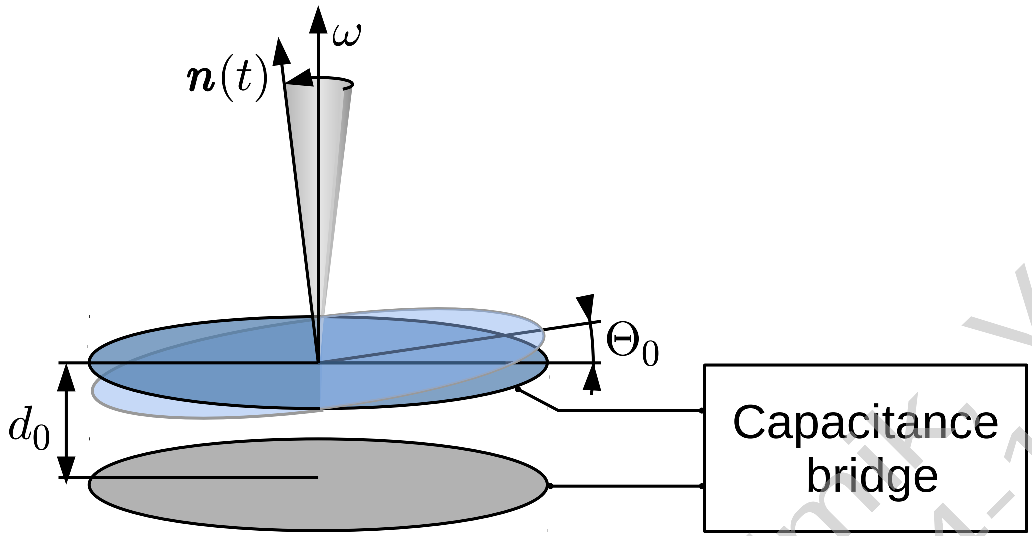
Vibration insulation: Mechanisms, Preliminary characterization

Status

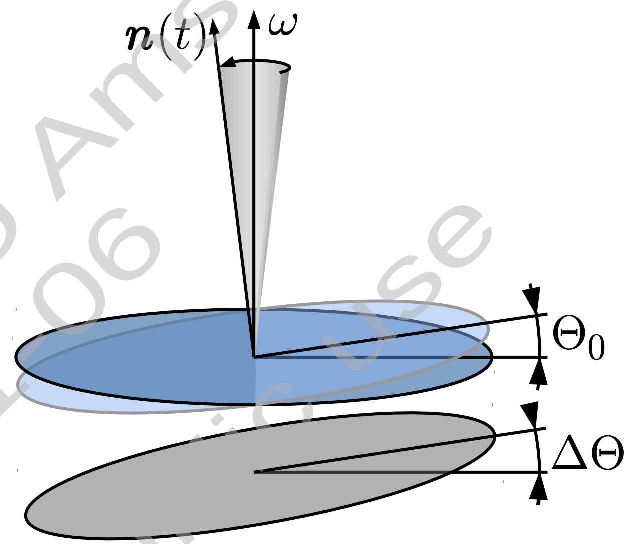
Parallelism control: Principle

assume: **parallel plates**



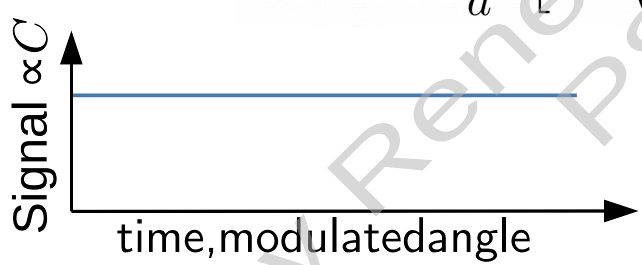
$\Theta(t) = \Theta_0 = \text{const.}$

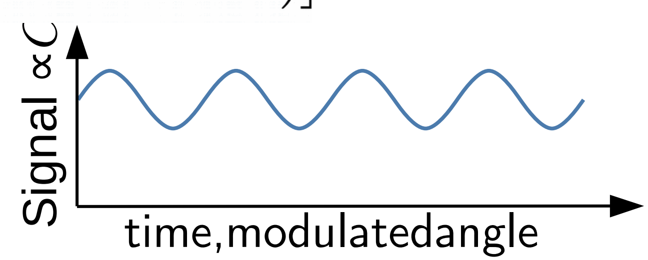
plates with relative tilt $\Delta\Theta$



$\Theta(t) = \Theta_0 + \Delta\Theta \cos \omega t$

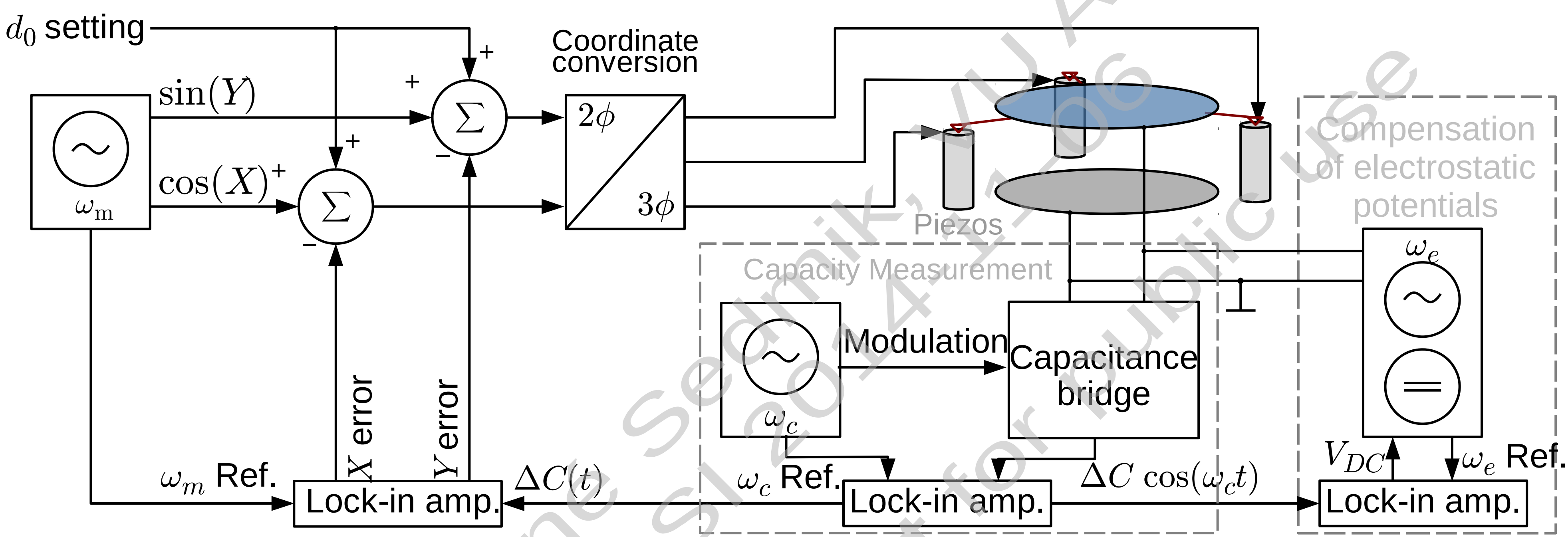
$$C(t) \approx \varepsilon_0 \frac{R^2 \pi}{d} \left[1 + \left(\frac{R}{2d} \right)^2 \left(\Theta_0^2 + \Delta\Theta^2 + 2\Theta_0 \Delta\Theta \cos \omega t \right) \right]$$





Idea: Use feedback circuit to compensate $\Delta\Theta$

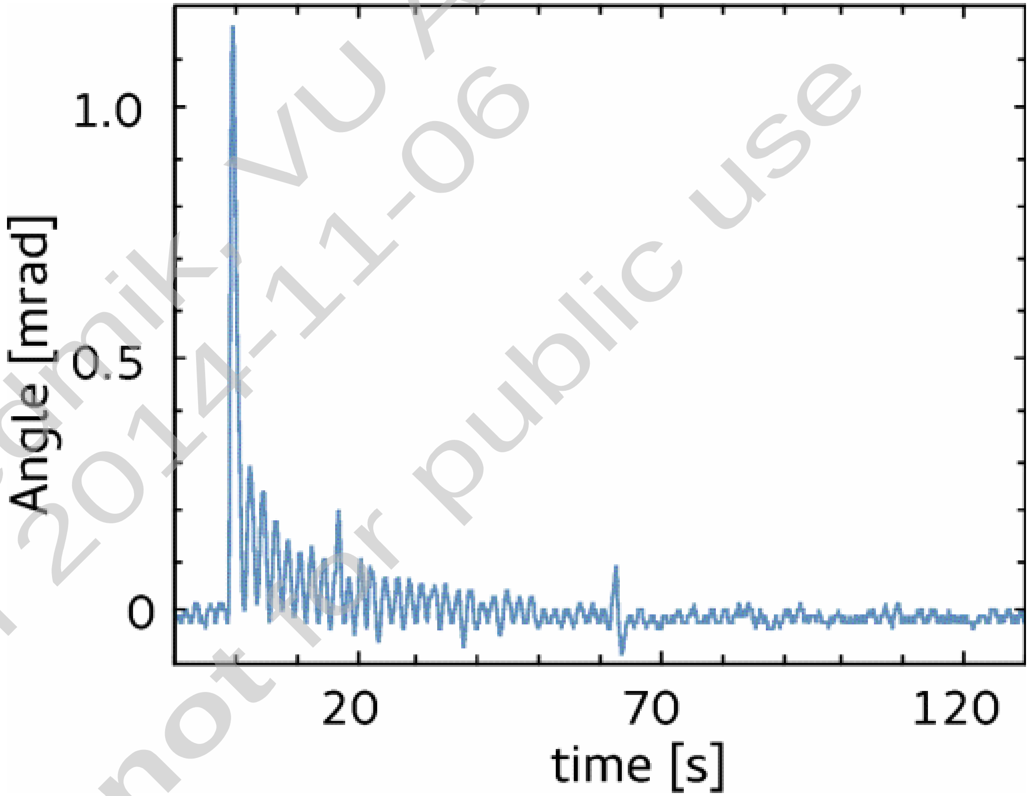
A feedback circuit



Proof of principle

Step response
under very bad conditions

- First test
  - in air
  - without anti-vibration
  - with rough surfaces
  - insufficient shielding
- 6 µm single-sided step
- nominal distance 90 µm
- plate area 1 cm²



Long-term stability

- Same conditions
- **3 µrad(RMS)**

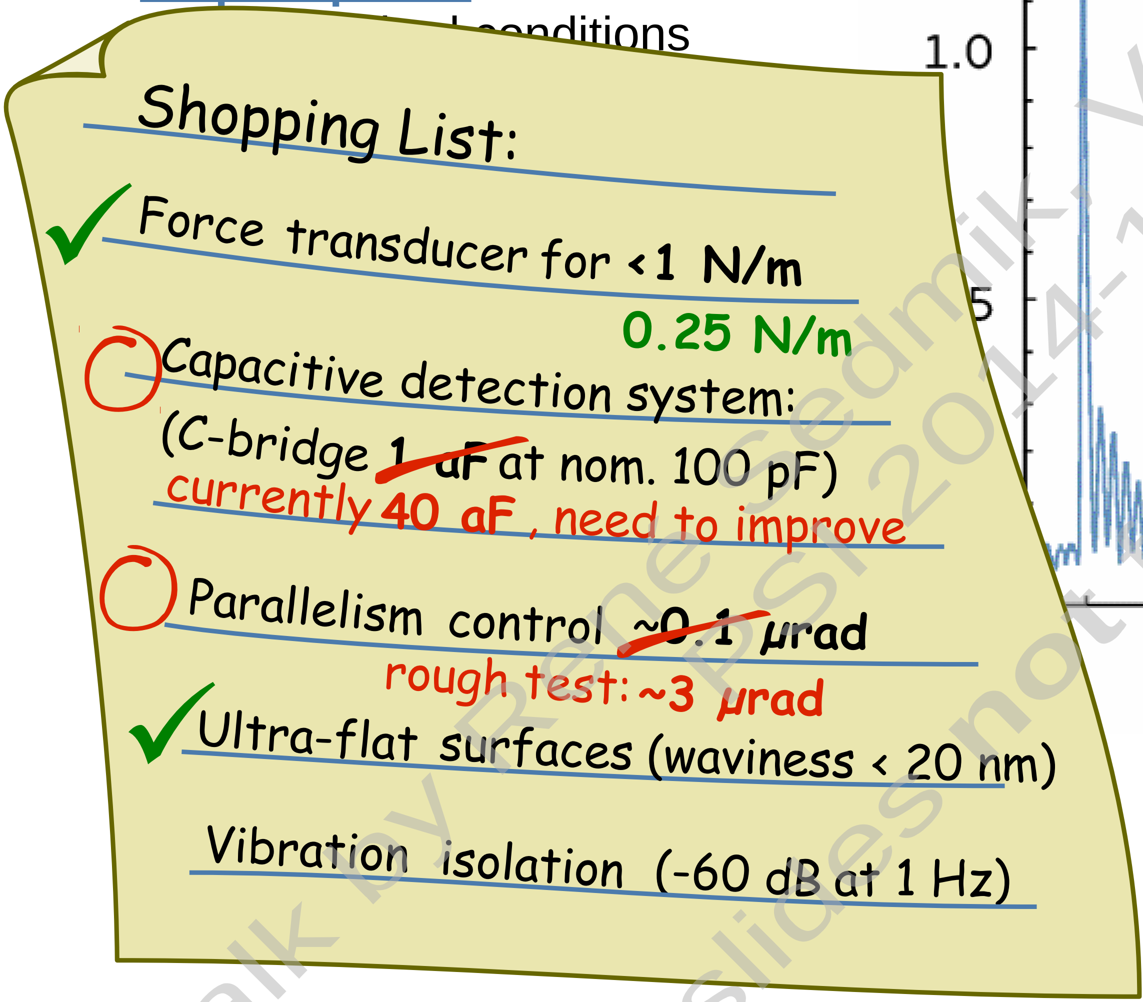
Target

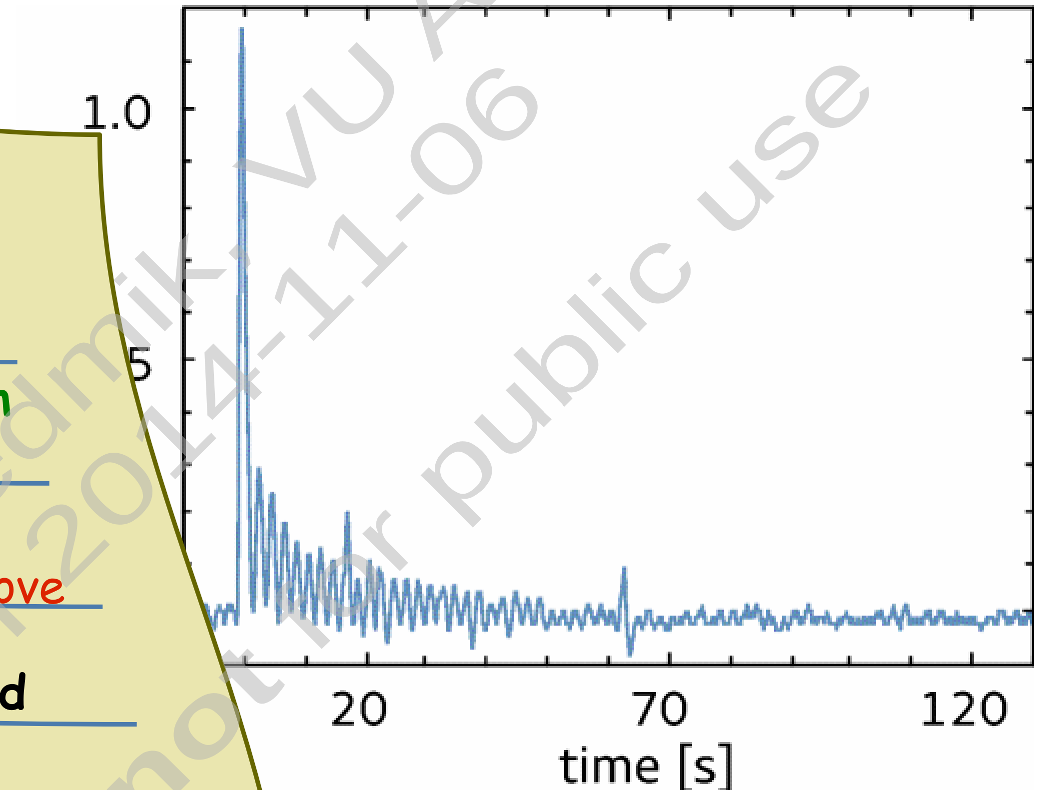
- Assumptions: good surface quality, vacuum, anti-vibration
- **0.1 µrad (~1 nm total tilt)**

Proof of principle

Step response

...conditions





anti-vibration

Outline

Part I: Scientific background

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What are the goals?

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Vibration insulation: Mechanisms, Preliminary characterization

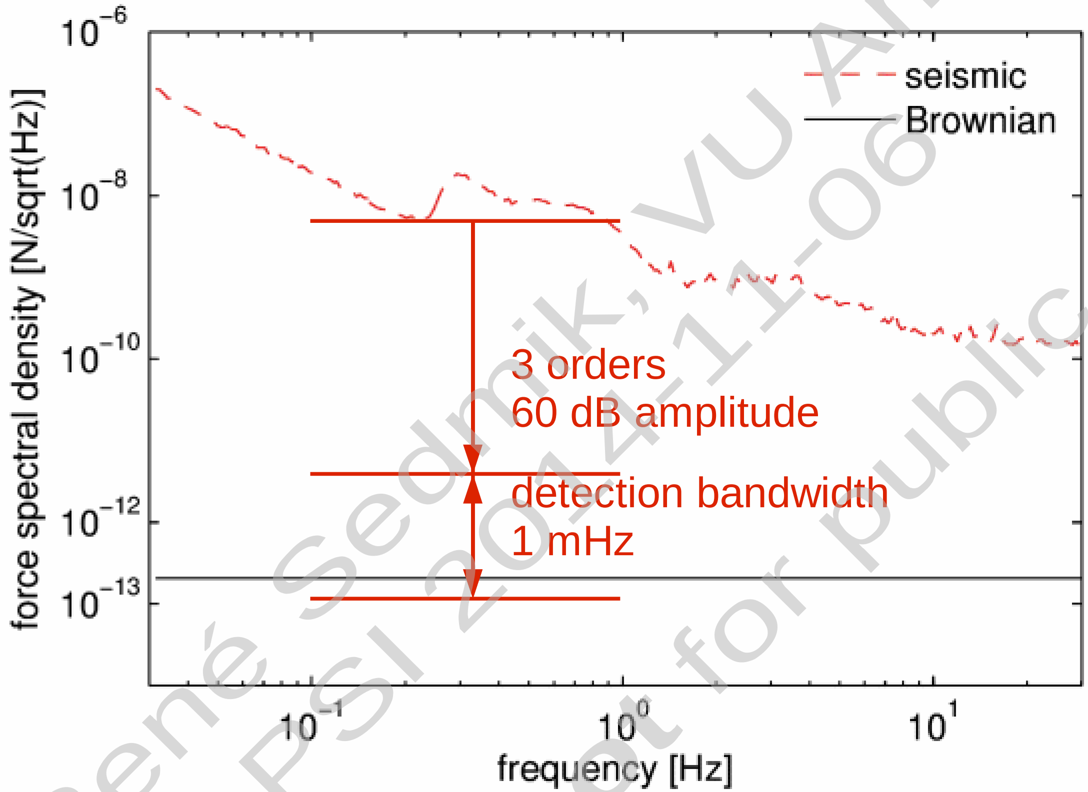
Status

Vibration insulation: Required performance

Q: What performance do we need?

Aim: Want to measure 0.1 pN at < 1 Hz, vertical direction

Disturbances:



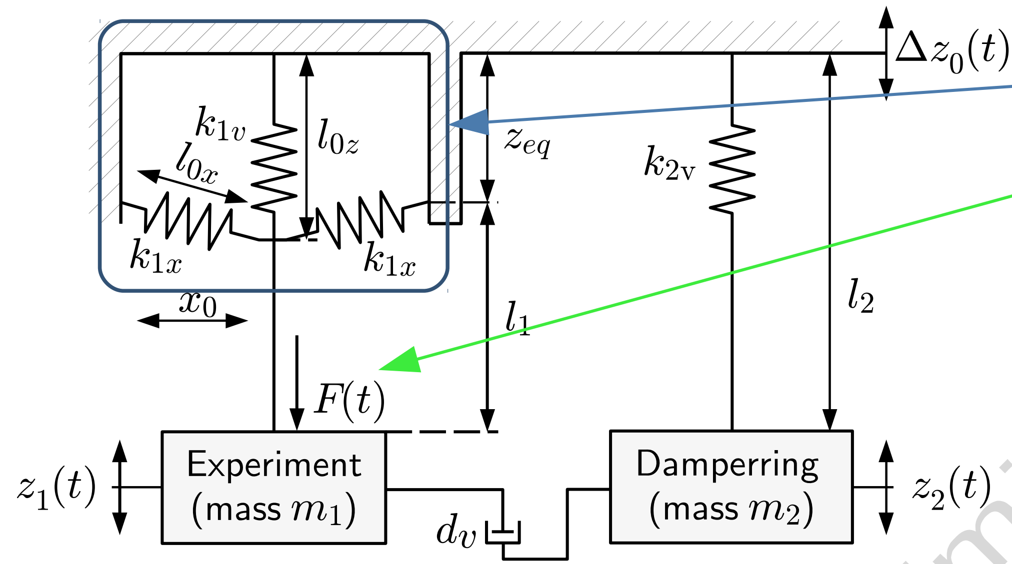
geophone measurement

$$F_B = \sqrt{4k_B T \frac{\gamma}{k}}$$

γ ... structural damping
k ... spring constant

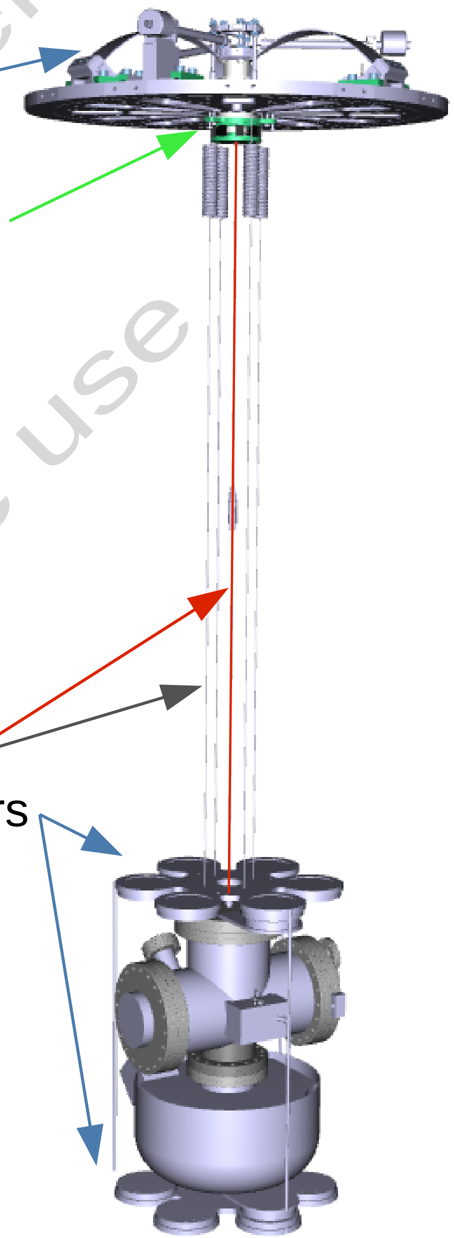
A: Improvement by 3 orders in vertical amplitude, 0.1 Hz – 1 Hz.

Vibration insulation: Principle



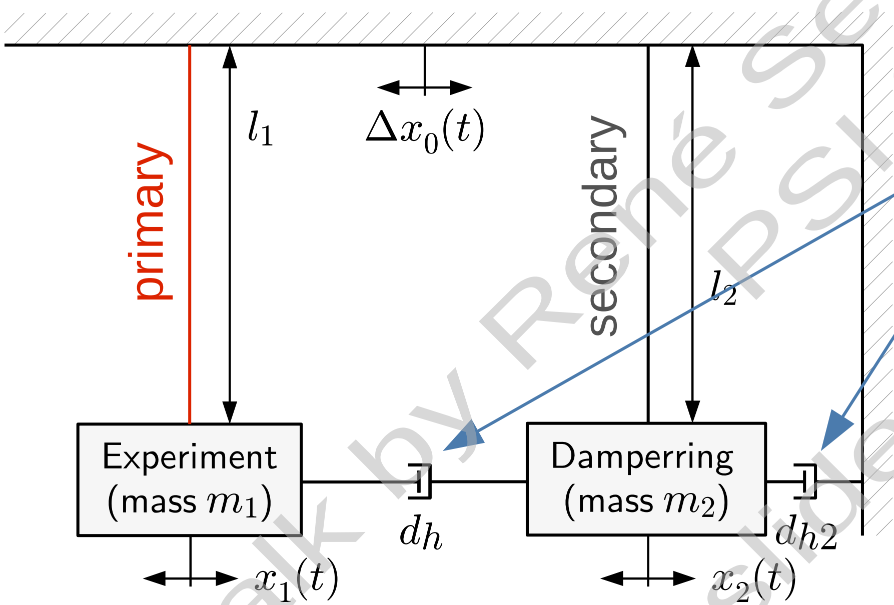
Vertical seismic:

- GAS* filter
- active $\mathcal{H}_\infty$ feedback with voice coil driver



Horizontal seismic:

- Double-pendulum
- Eddy current dampers



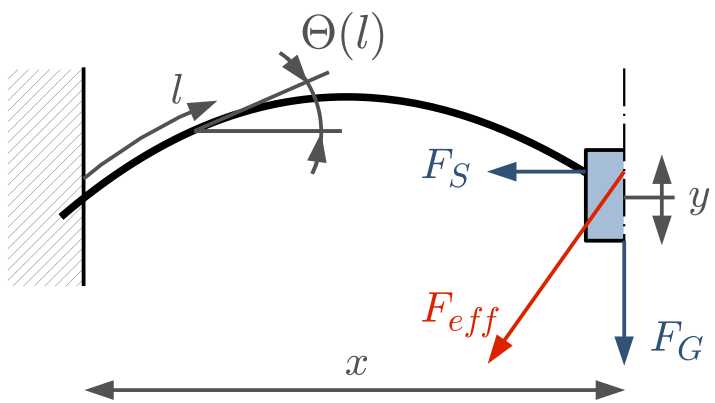
Acoustic:

- rigid all-enclosing vacuum chamber 10^{-5} mbar (not shown)

*Gravimetric anti-spring

Vibration insulation: Vertical: GAS filter

Principle: Euler spring

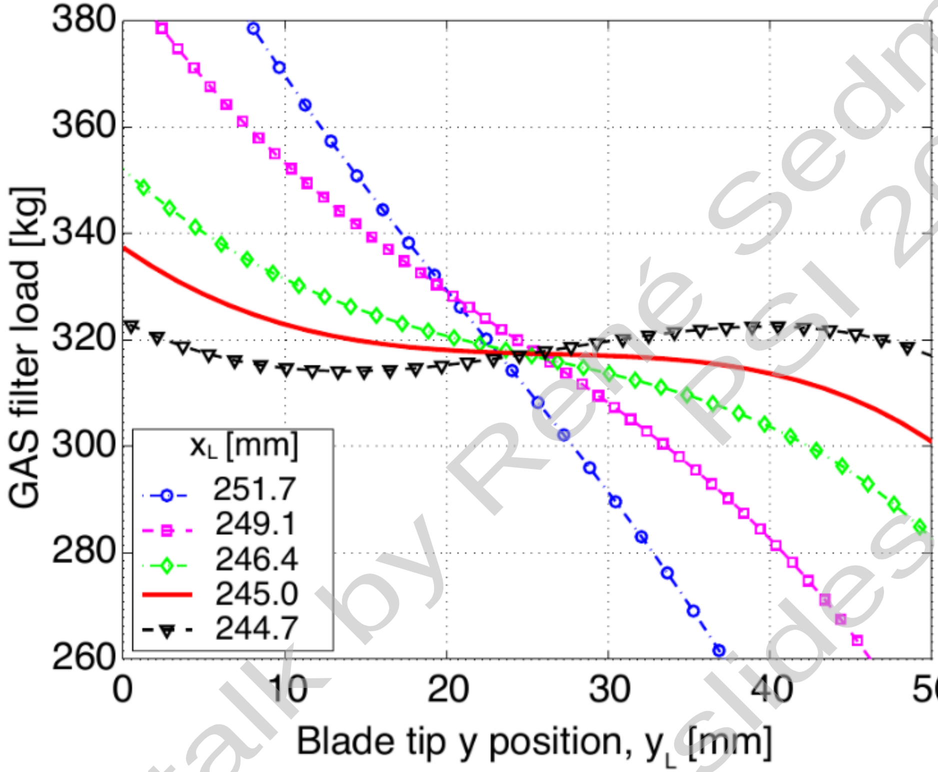


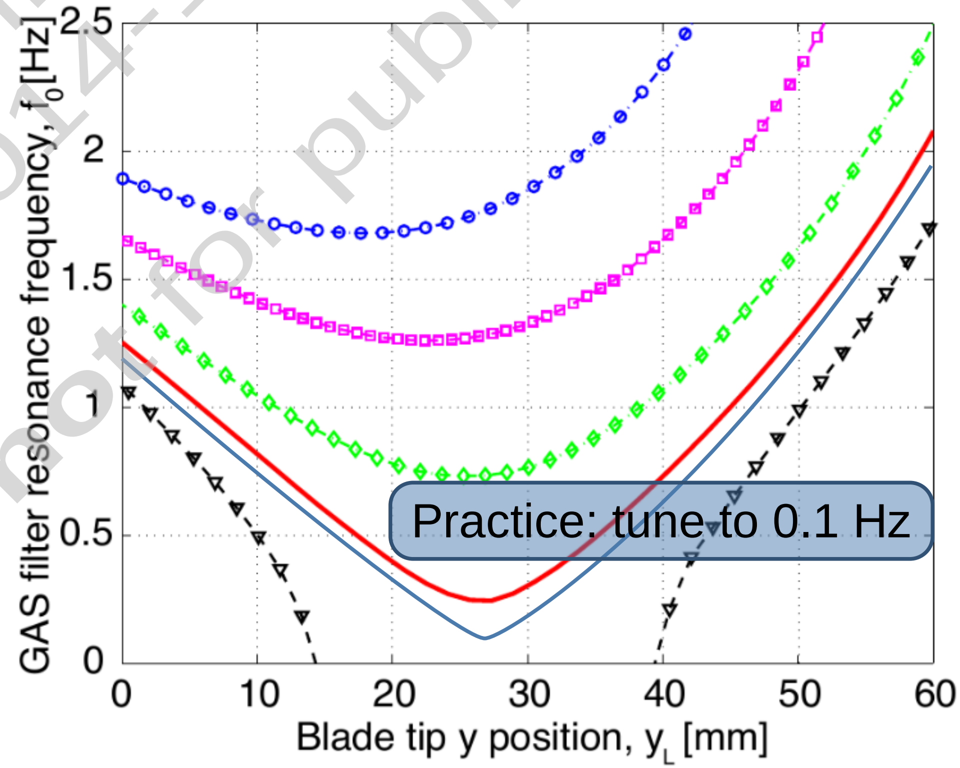
Model:

$$U = \int_0^L \mathrm{d}l \, \frac{EI(l)}{2} \left(\frac{\partial \Theta(l)}{\partial l} \right)^2 - F_S \cos \Theta(l) - F_G \sin \Theta(l)$$

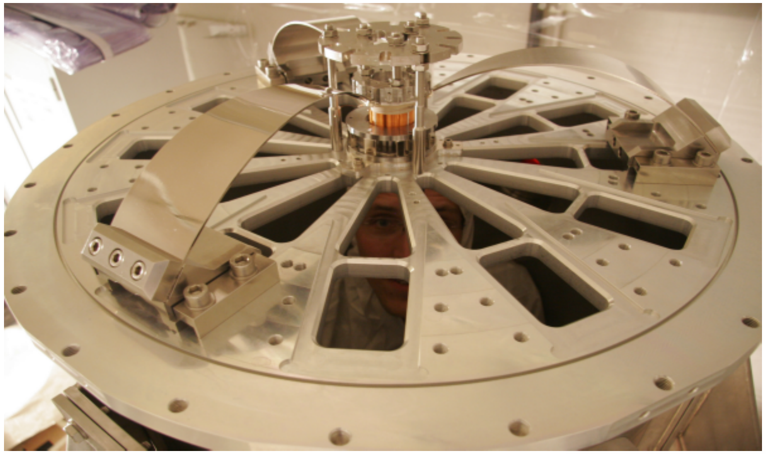
Solution for dynamics from: $\dfrac{\delta U(\Theta)}{\delta \Theta} = 0$

Bertolini *et al*, *Nucl. Inst. Meth. Phys. Res A*, **435** (1999), 475
Beker, PhD Thesis, VU Amsterdam (2013)





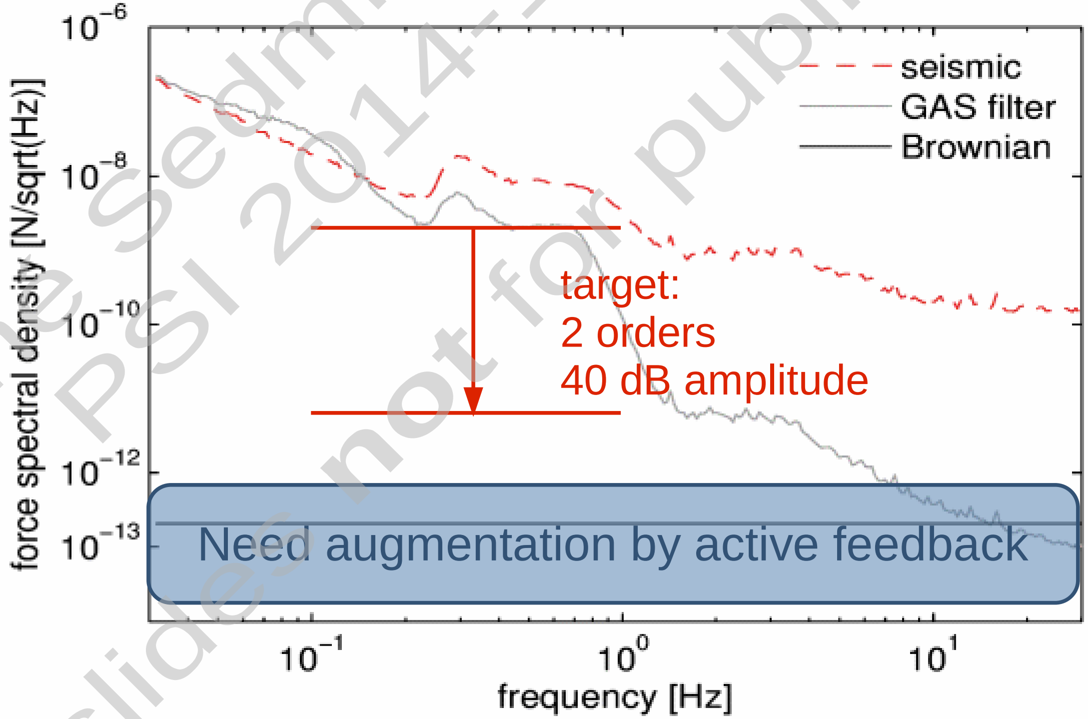
Performance



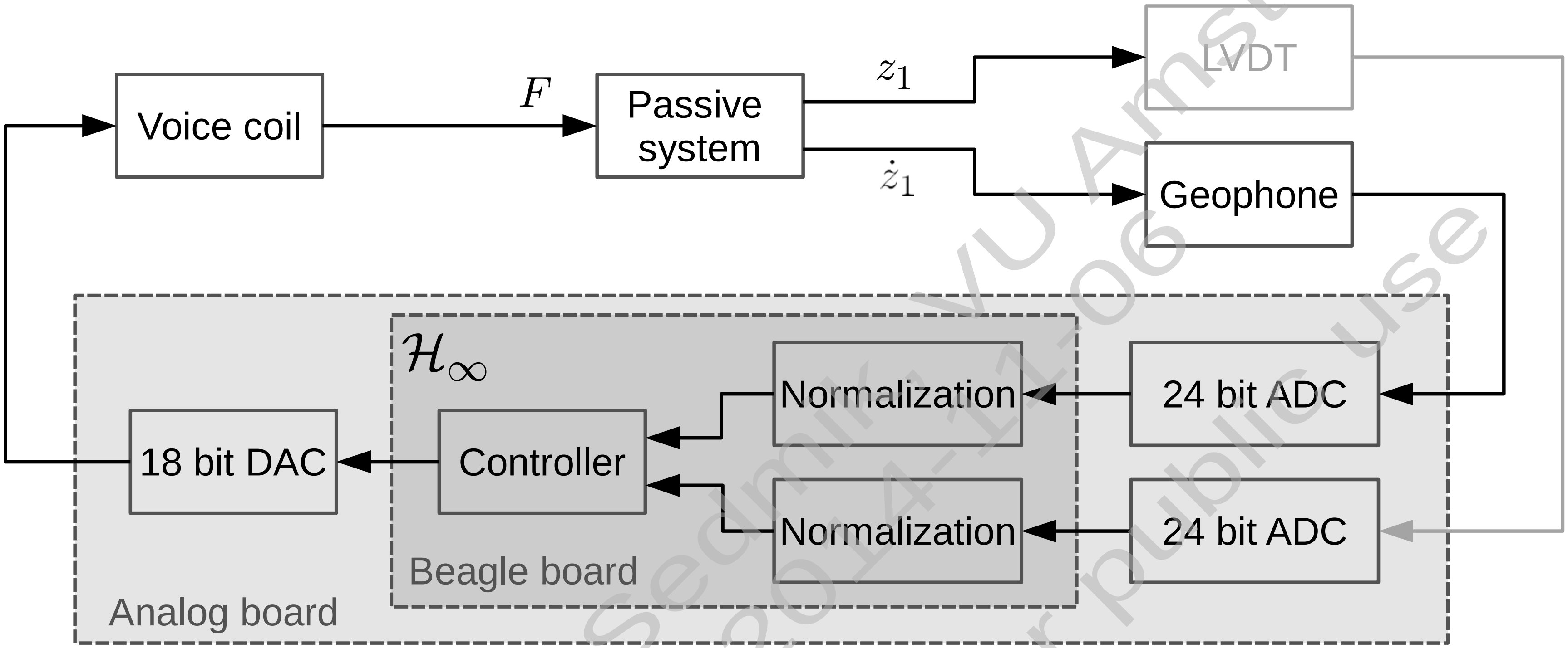
Implementation:

- 3 springs
- suspended mass 85 kg
- tuning in air: 150 mHz

Numerical results:



Schematic



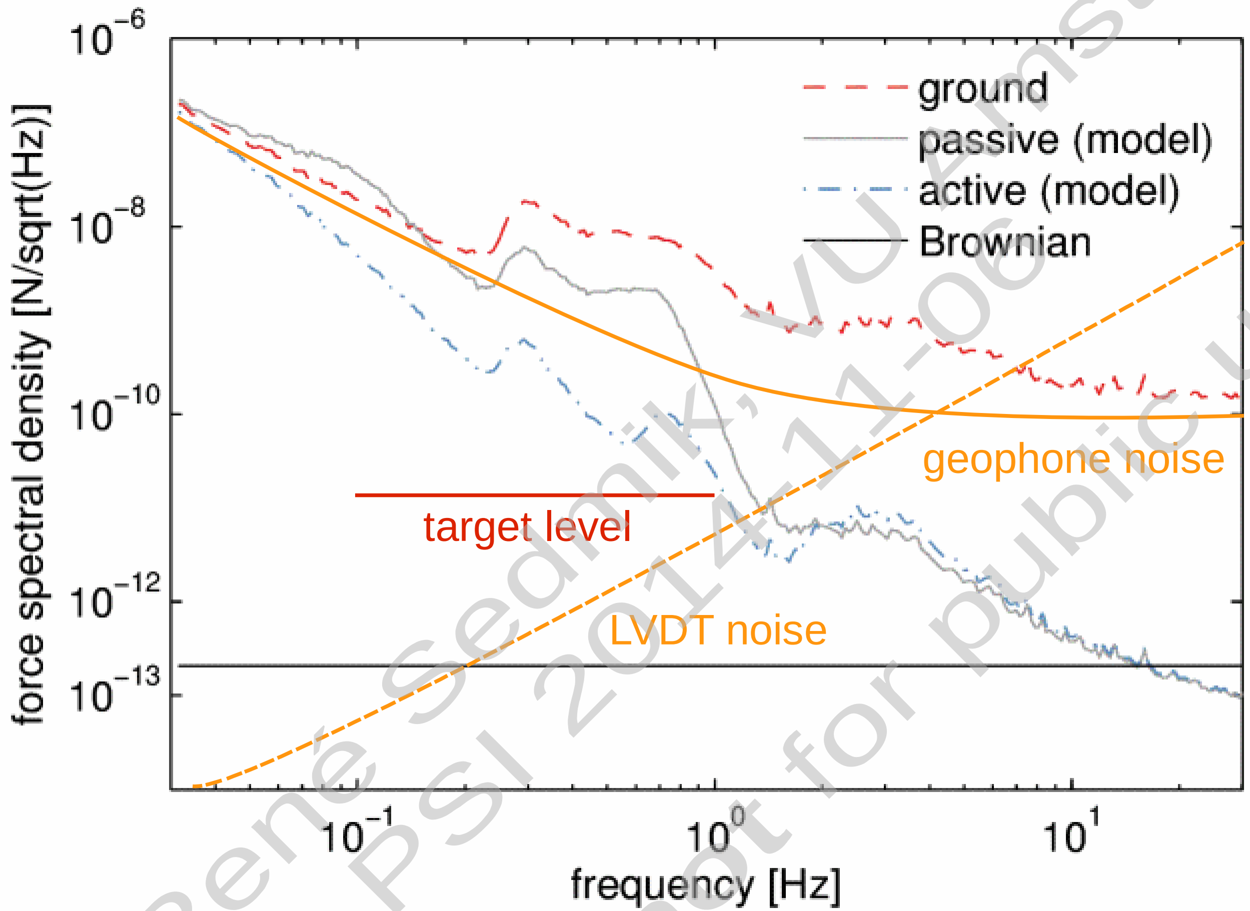
Q: Why is a simple PID-controller not enough?

A: 1. Sensors and system give too much phase delay.
2. SNR is ~1 at low frequencies

Need a predictive system for the passive dynamics for stability

Vibration insulation: Augmentation: $\mathcal{H}_\infty$ feedback

Performance:

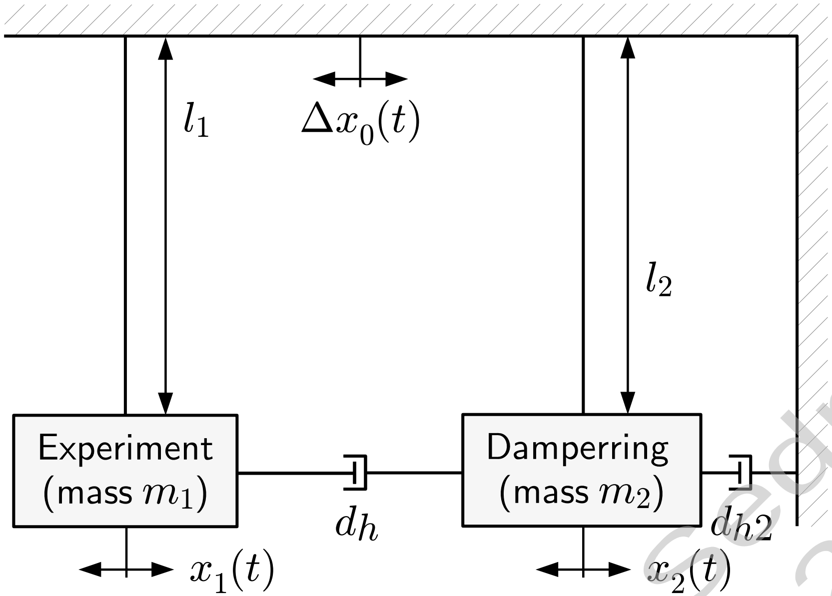


Still ~ one order of magnitude missing
Problem: sensor noise of the geophone

Approach to improve:

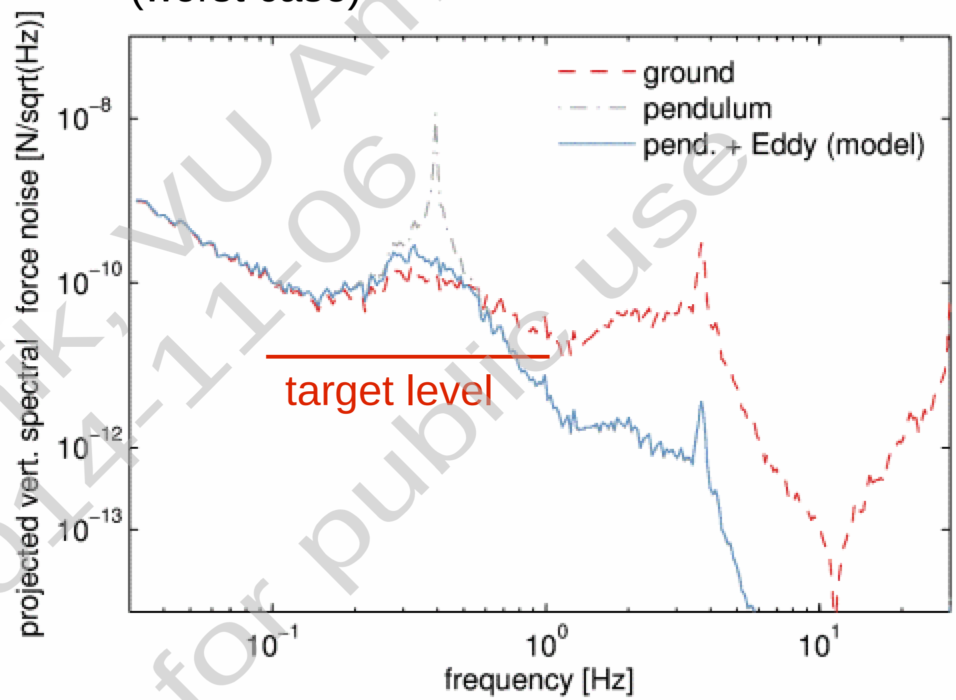
- enhance preamplifiers (factor 10)
- Add LVDT for better signal at low frequencies

Principle: Low-pass
and energy dissipation



Performance:

projected to vertical, 10% coupling (worst case)



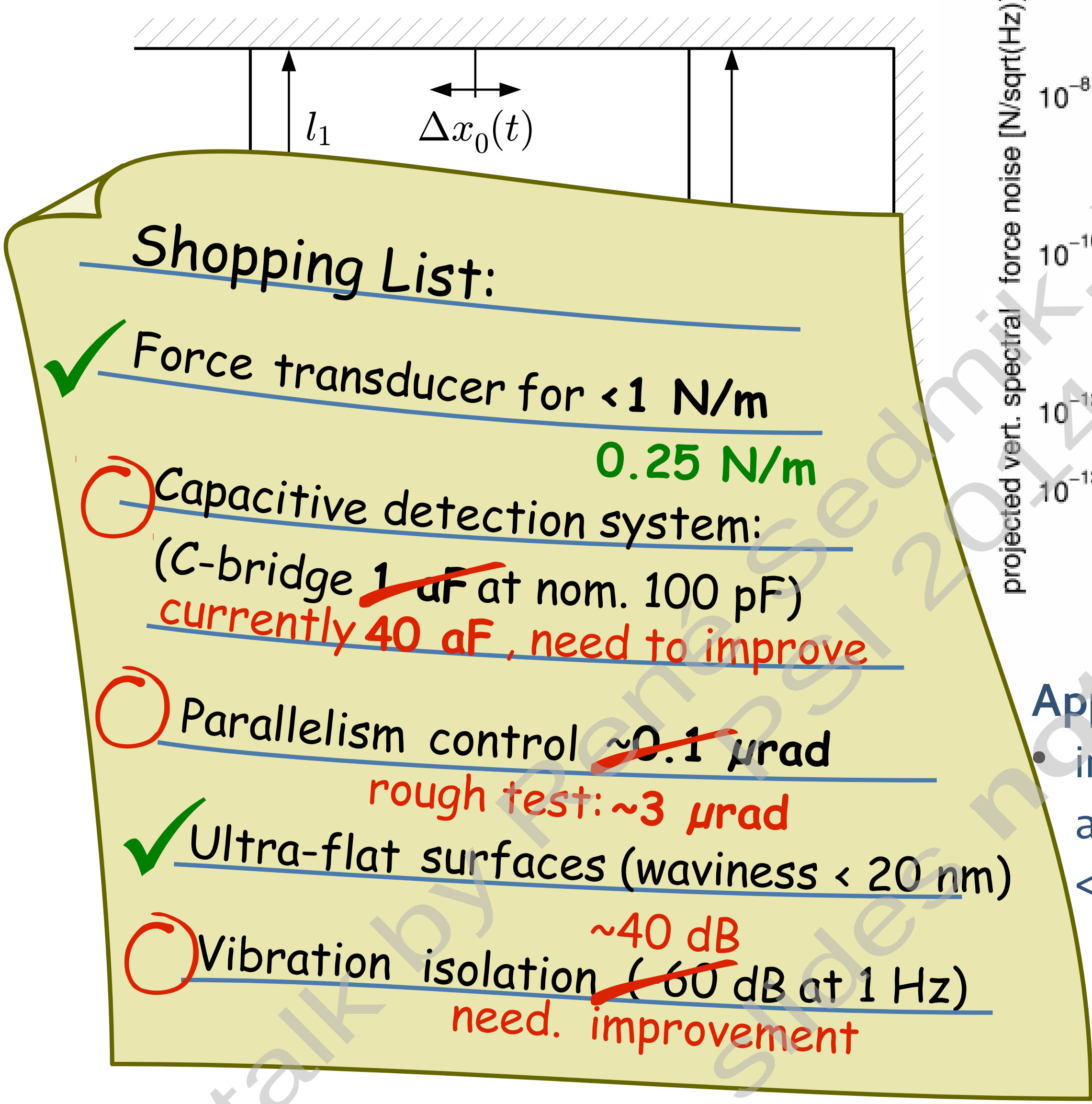
Requirements:

10^{-11} N/√Hz at 0.1 Hz – 1 Hz

Approach for improvement:

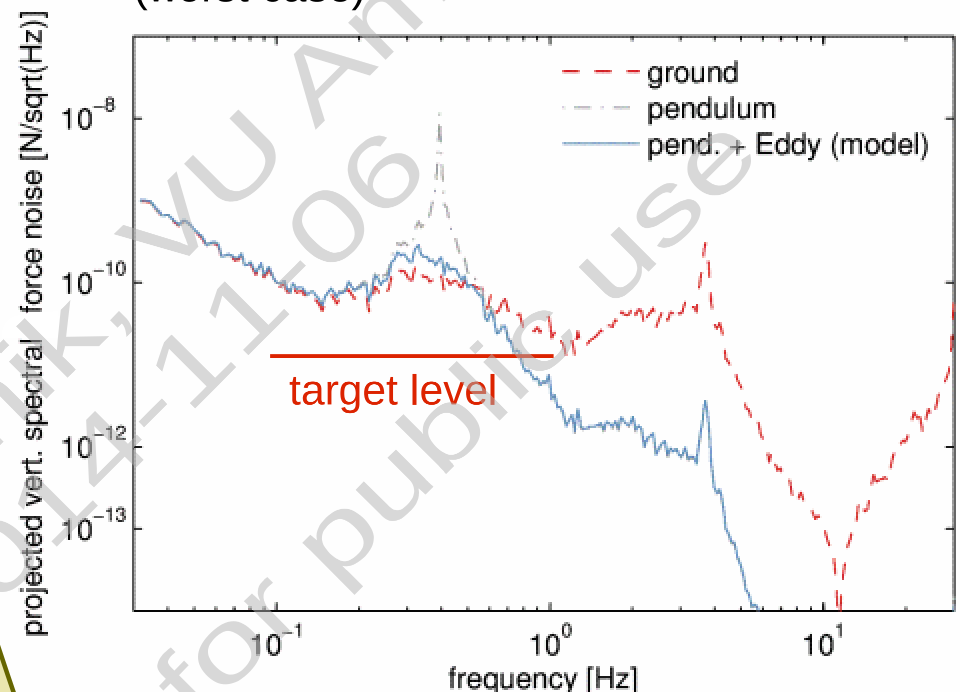
- increase damping
- assure that sensor has < 3% coupling H → V

Principle: Low-pass and energy dissipation



Performance:

projected to vertical, 10% coupling (worst case)



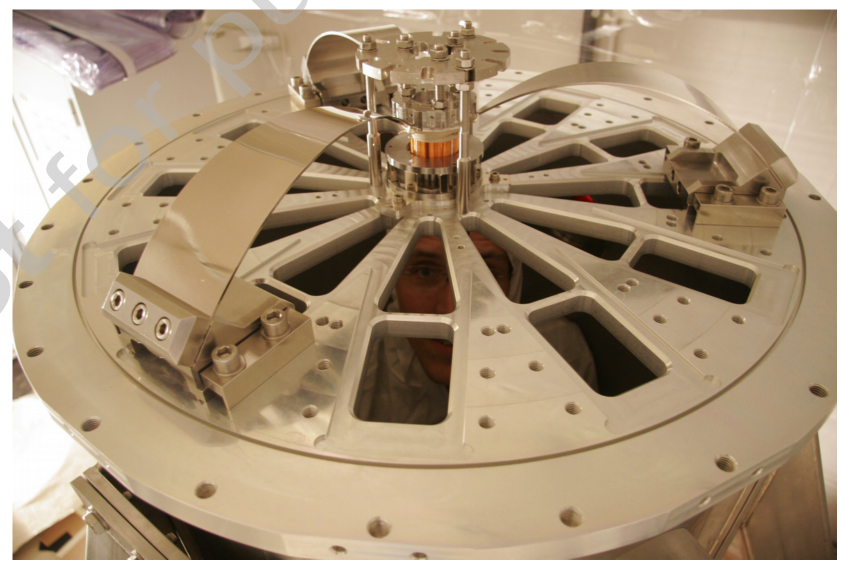
Approach for improvement:

- increase damping
- assure that sensor has < 3% coupling H → V

Outlook & Conclusion

Status:

- The experiment is still under construction
- Subsystems are being tested
- **First force measurements planned still this yer: Proof of principle**
- For final sensitivity, several improvements required (long term)



Outlook & Conclusion

Conclusion:

- Casimir forces potentially play a role in the development of MEMS
  but are interesting in many ways.
- Chameleon forces could explain the accelerated expansion of the universe.
- Both forces could be measured in a high-accuracy parallel plate experiment
- Status: Experiment has been designed and built, close to turning the switch
- First preliminary results (hopefully) later this year.

Acknowledgments

Thank you for your kind attention!

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Davide Iannuzzi

Nikhef:

Alessandro Bertolini
Eric Hennes
Arnold Rietmeijer
Martin Duets
Johannes v. d. Brand

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Nederlandse Organisatie voor Wetenschappelijk Onderzoek

FOM

FWF Der Wissenschaftsfonds.

partially crowd-funded via Flintwave Make Research & Innovation Visible and ASML

Finite Temperature

Gibbs free energy

Remember Lifshitz at T=0

$$\frac{E_0}{A} = \frac{\hbar}{2}\int_0^\infty \frac{\mathrm{d}k_x\,\mathrm{d}k_y}{(2\pi)^2}\sum_{n=0}^{\infty}\omega_n(a)$$

Lifshitz at $T \neq 0$

$$\frac{\mathcal{F}(T)}{A} = \frac{\hbar}{2}\int_0^\infty \frac{\mathrm{d}k_x\,\mathrm{d}k_y}{(2\pi)^2}\sum_{n=0}^{\infty}\left[\omega_n(a) + \frac{k_B T}{\hbar}\left(1+\mathrm{e}^{\frac{\hbar\omega_n(a)}{k_B T}}\right)\right]$$

$$\mathcal{F}(T) = E_0 + \Delta\mathcal{F}(T)$$

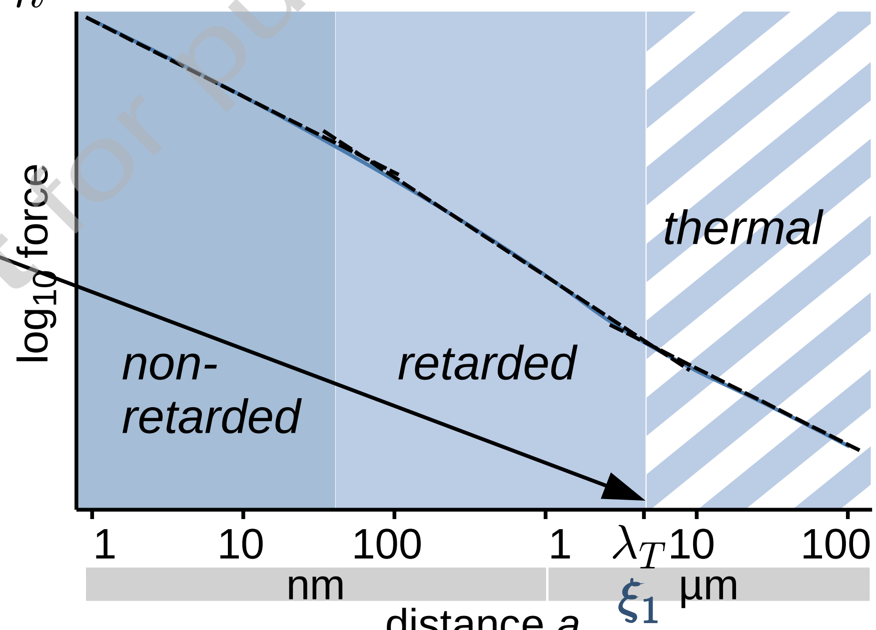
Matsubara formalism: Formal substitution

term at n=0 has an additional factor 1/2

$$\frac{\hbar}{2\pi}\int_0^\infty \mathrm{d}\xi \to k_B T {\sum_n}'$$ and $$\xi \to \xi_n := 2\pi\frac{k_B T}{\hbar}n$$ ... *Matsubara* frequencies

$$\xi_0 = 0$$

$$\xi_1|_{T=300\,\mathrm{K}} \approx 2.5\times 10^{14}\,\mathrm{rad/s} \quad \Rightarrow 7.6\,\mu\mathrm{m}$$



$$\mathcal{L}_{\mathrm{SM}} \rightarrow \mathcal{L}'_{\mathrm{SM}} + \mathcal{L}_{\mathrm{C}}$$

$$\frac{\mathrm{e}^{\frac{\beta_\gamma}{M_{Pl}}\phi}}{4} F^2 + \sum_i \mathcal{L}^{(i)}\left(\mathrm{e}^{\frac{\beta_i}{M_{Pl}}\phi}, \psi^{(i)}\right) \qquad \sqrt{-g}\left[\mathcal{R}\frac{M_{Pl}^2}{2} - \frac{1}{2}(\partial\phi)^2 - V(\phi)\right]$$

modified metric $\tilde{g}^{(i)}_{\mu\nu} = \mathrm{e}^{\frac{2\beta^{(i)}\phi}{M_{Pl}}} g_{\mu\nu}$ $\qquad g = \det g_{\mu\nu}$

energy momentum tensor $T_{\mu\nu} = \frac{2}{\sqrt{-\tilde{g}}}\frac{\delta\mathcal{L}}{\delta\tilde{g}^{\mu\nu}}$

Energy (natural units) $\tilde{\rho} = \tilde{g}^{\mu\nu} T_{\mu\nu}$ $\qquad \rho_i \equiv \tilde{\rho}\,\mathrm{e}^{\frac{3\beta_i}{M_{Pl}}}$

effective potential

$$V_{eff} = V(\phi) + \sum_i \rho_i \mathrm{e}^{\frac{\beta_i}{M_{Pl}}\phi}$$