CANNEX

Casimir And Non-Newtonian force EXperiment

A parallel plate approach to physics

Vienna
May 17, 2018

René Sedmik

Atominstitut, TU Vienna
previously: VU Amsterdam

Stay tuned on our website
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NWO
Nederlandse Organisatie voor Wetenschappelijk Onderzoek

FOM

FWF Der Wissenschaftsfonds.

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

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Vacuum energy: The cosmological constant problem

Dark energy and the cosmological constant

$$\mathrm{R}_{\mu\nu} - \left(\frac{1}{2}\mathcal{R} - \Lambda\right) g_{\mu\nu} = \frac{8\pi}{c^4} T_{\mu\nu}$$

Einstein 1918: Absence of gravitational collapse ➡ Phenomenological cosmological constant Λ

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Today:
- Redshift of Type 1a supernovae
- Anisotropy of the cosmic microwave background
- Large scale distribution

...

→ Expansion is accelerating

$$\Lambda \approx 1.8 \times 10^{-52}\,\mathrm{m}^{-2}$$

$$\rho_{vac} \approx 10^{-29}\,\mathrm{g/cm}^3$$

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Quantum mechanics (field theory)

Zero point energies of the EM (and other) fields:

$$\rho_{ZPE} \propto \int_0^{\lambda_c} \mathrm{d}k\, k^3 = \lambda_c^4 \to \infty$$

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Cutoff at the Planck length:

$$\lambda_c \to 2\pi/\ell_P$$

→ $$\rho_{ZPE} \approx 10^{95}\,\mathrm{g/cm^3}$$

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...

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$\Lambda \approx 1.8 \times 10^{-52}\,\mathrm{m}^{-2}$

$\rho_{vac} \approx 10^{-29}\,\mathrm{g/cm^3}$

>120 orders of magnitude off

`worst prediction in the history of physics'

cosmological constant problem

$\rho_{ZPE} \approx 10^{95}\,\mathrm{g/cm^3}$

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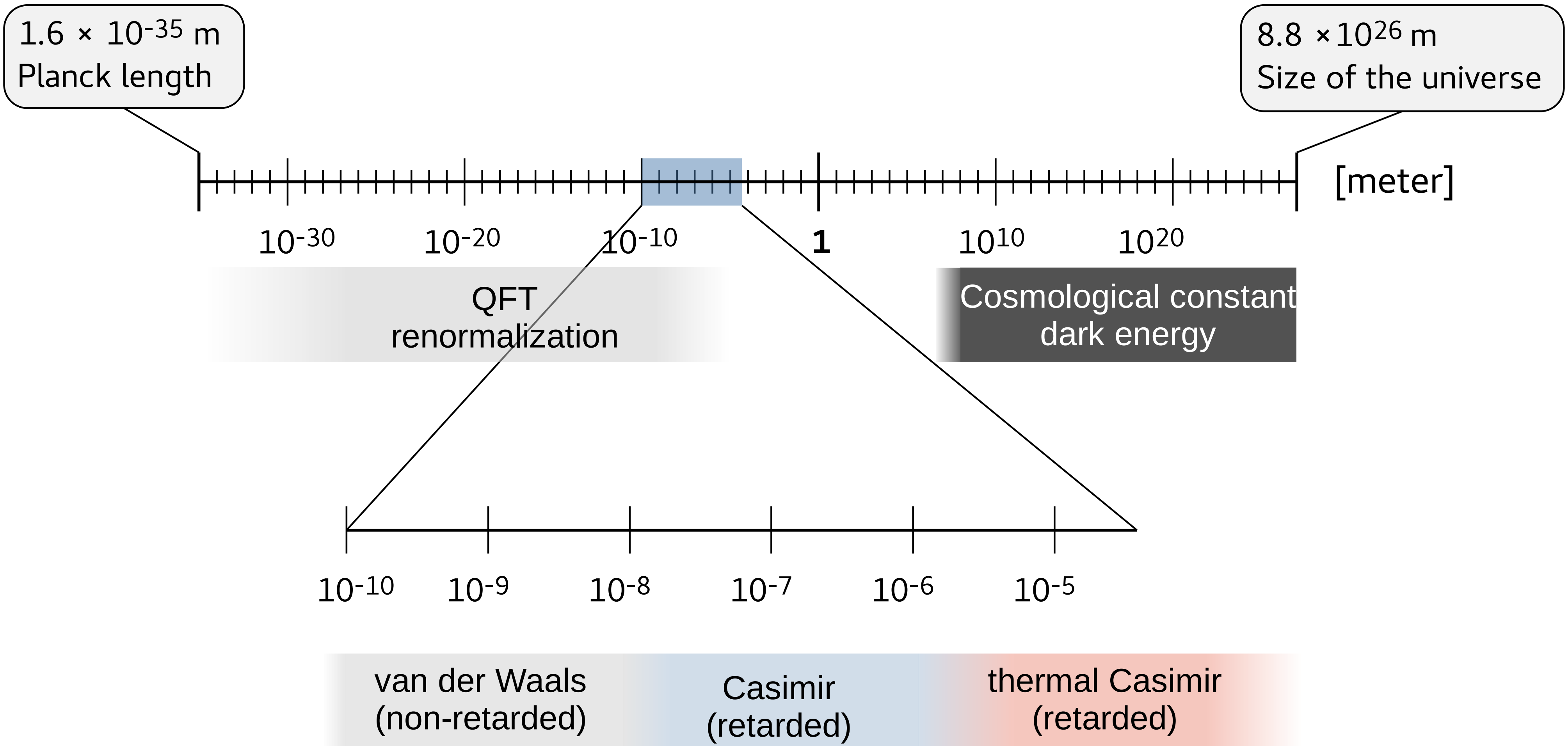
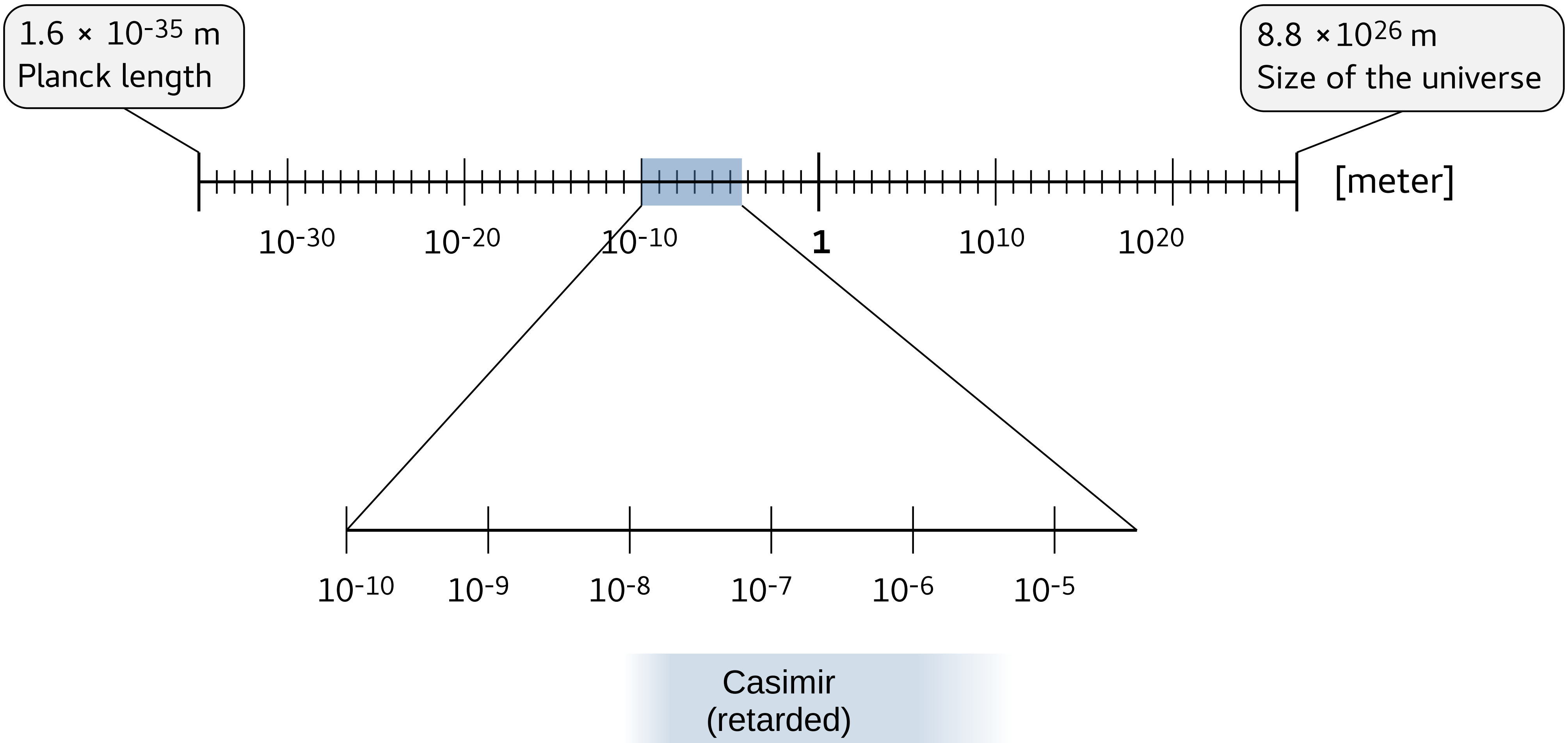
Vacuum energy at different scales

Scale of the universe:



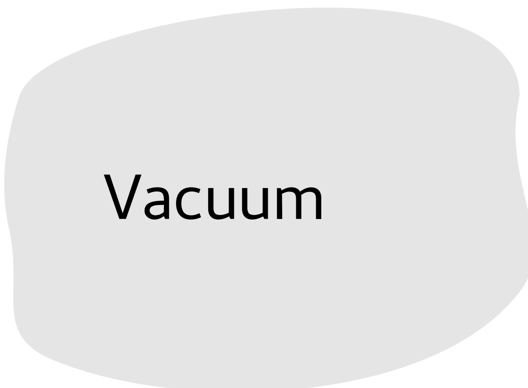
Small surface separations: Casimir effect

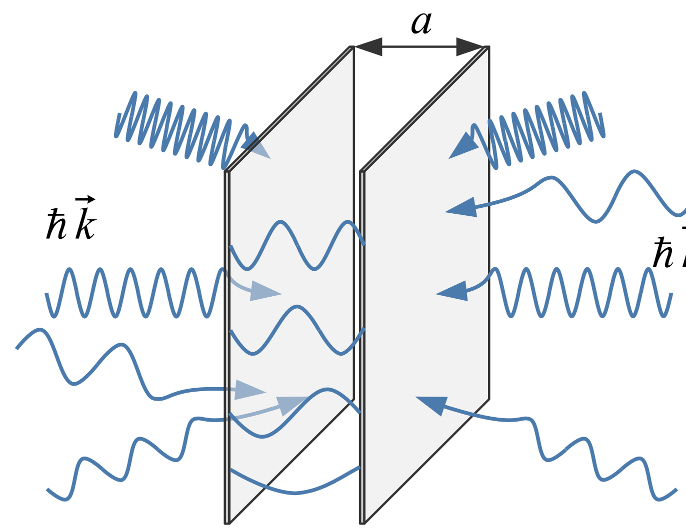
Scale of the universe:



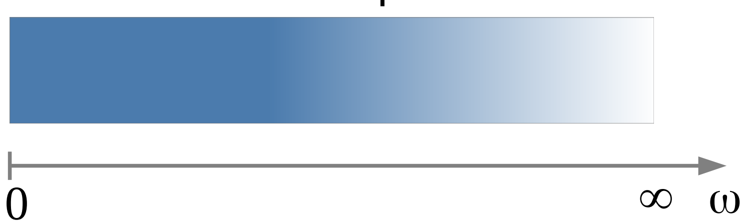
The Casimir effect in a nutshell

Intuitive:

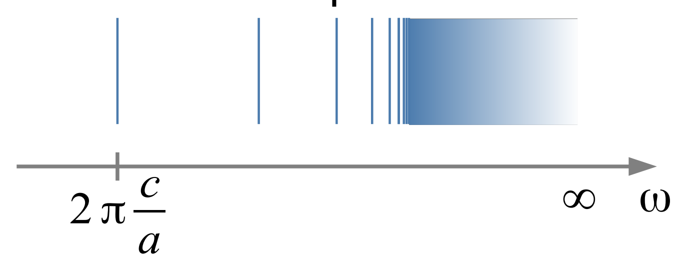




continuous spectrum



discrete spectrum

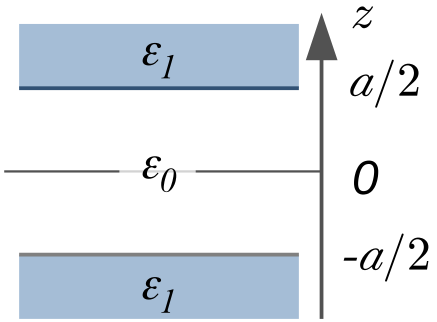


Energy: $E_{vac} = \infty$ $E_{||} = \infty$

Difference: $E_{||} - E_{vac} < 0$ finite

The Casimir effect in a nutshell

Reality (simplest possible case):



- materials with dielectric functions $\varepsilon_r(\omega)$
- extrapolate to zero frequency

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

- need to Wick-rotate by using the Kramers-Kronig relation

$$\varepsilon(\mathrm{i}\xi) = 1 + \frac{2}{\pi}\int_0^\infty \mathrm{d}\omega \frac{\omega \mathrm{Im}\varepsilon_r(\omega)}{\omega^2 + \xi^2}$$

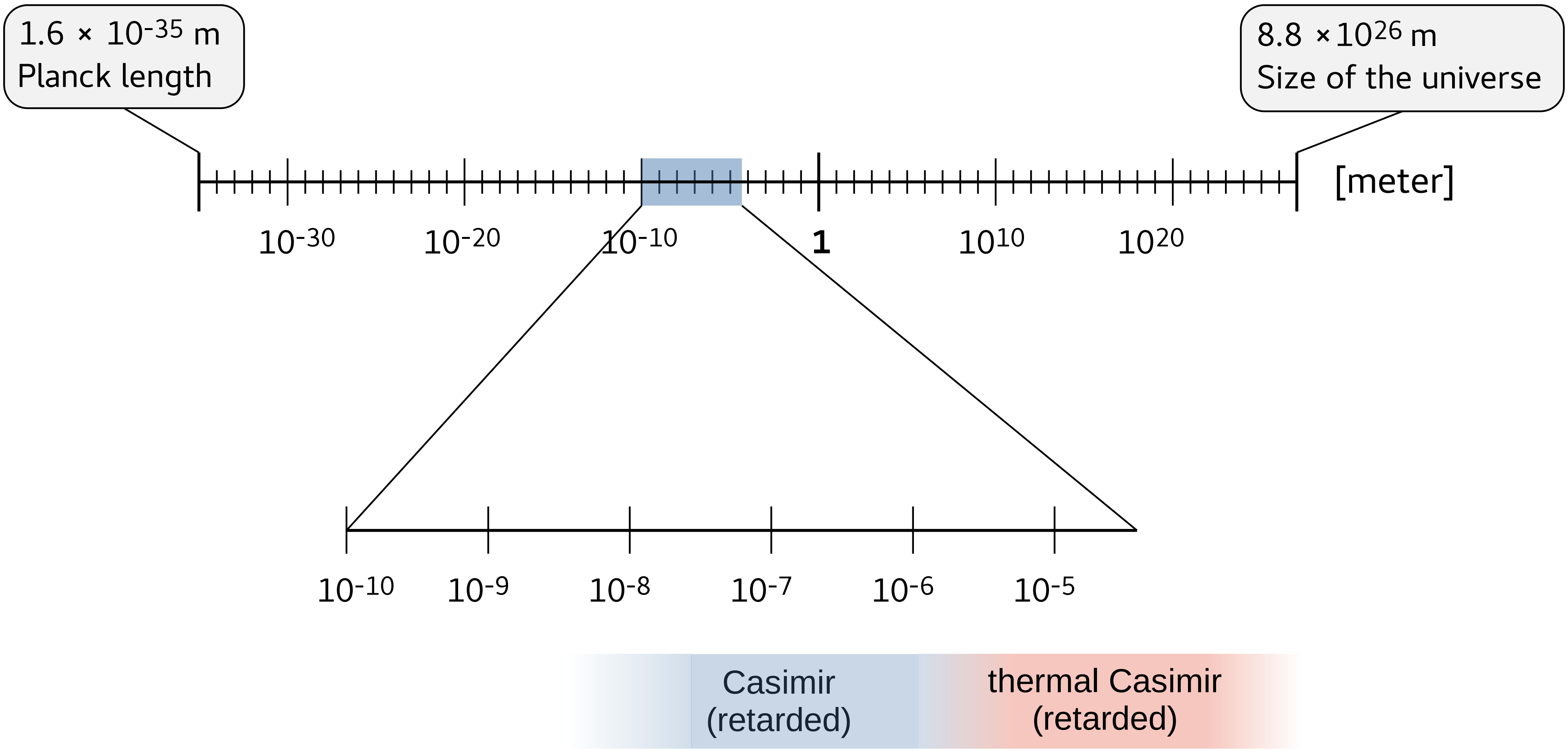
- Compute the energy (force): Lifshitz equation

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

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

Large surface separations: Thermal Casimir effect

Scale of the universe:



More fundamental: The nature of virtual photons

Dissipation at zero frequency or not? Drude vs. plasma debate

Drude

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

plasma

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

ω_p plasma frequency

γ relaxation frequency (dissipation)

Recent data suggests:

- No dissipation for virtual photons (short distance)!
  Bimonte et al, Phys. Rev. B 93, 184434 (2016)
- Situation at large distance ($\gtrsim$2 µm) unclear

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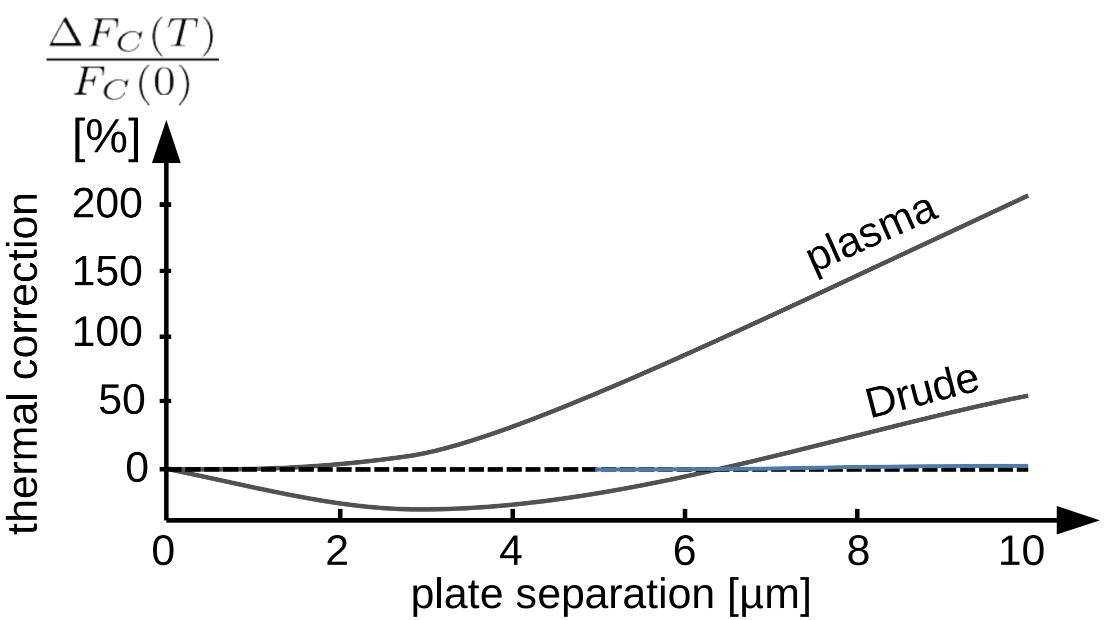
What is different at larger separation?



At d>10 µm
less than 10^{-7} N/m²

Only possible with parallel plates.

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

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

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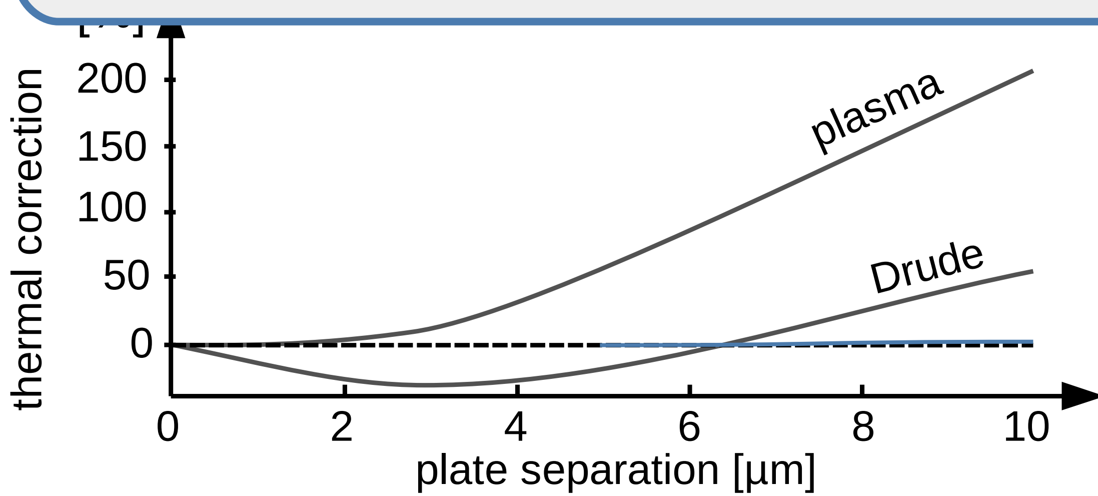

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Very large scales: 1 AE to the size of the universe

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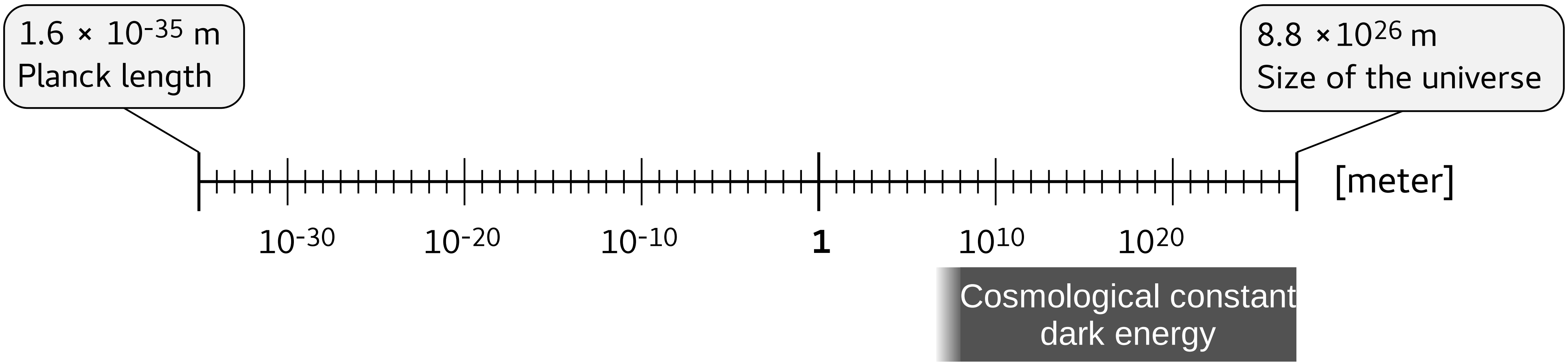
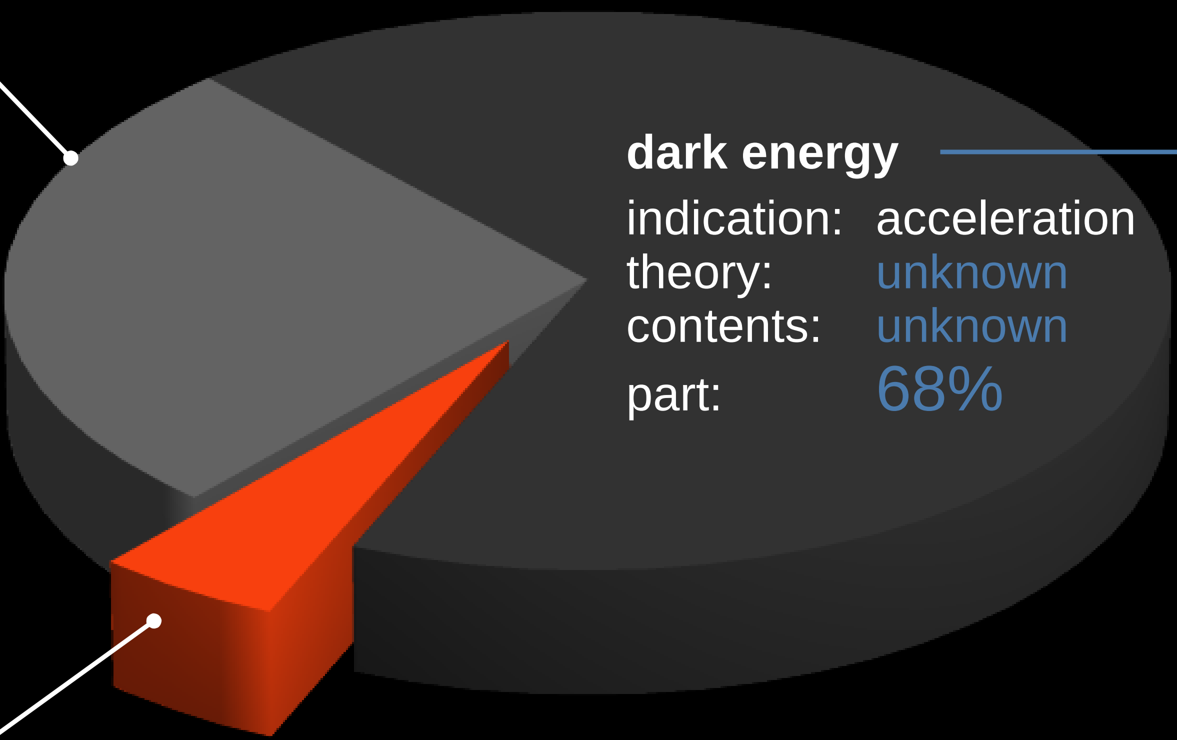


Very large scales: 1 AE to the size of the universe

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: $\mathcal{L}_{\rm SM}$
contents: particles of the SM
part: 5%

proposition:

add a new scalar
particle with Yukawa coulings

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

New dynamics:

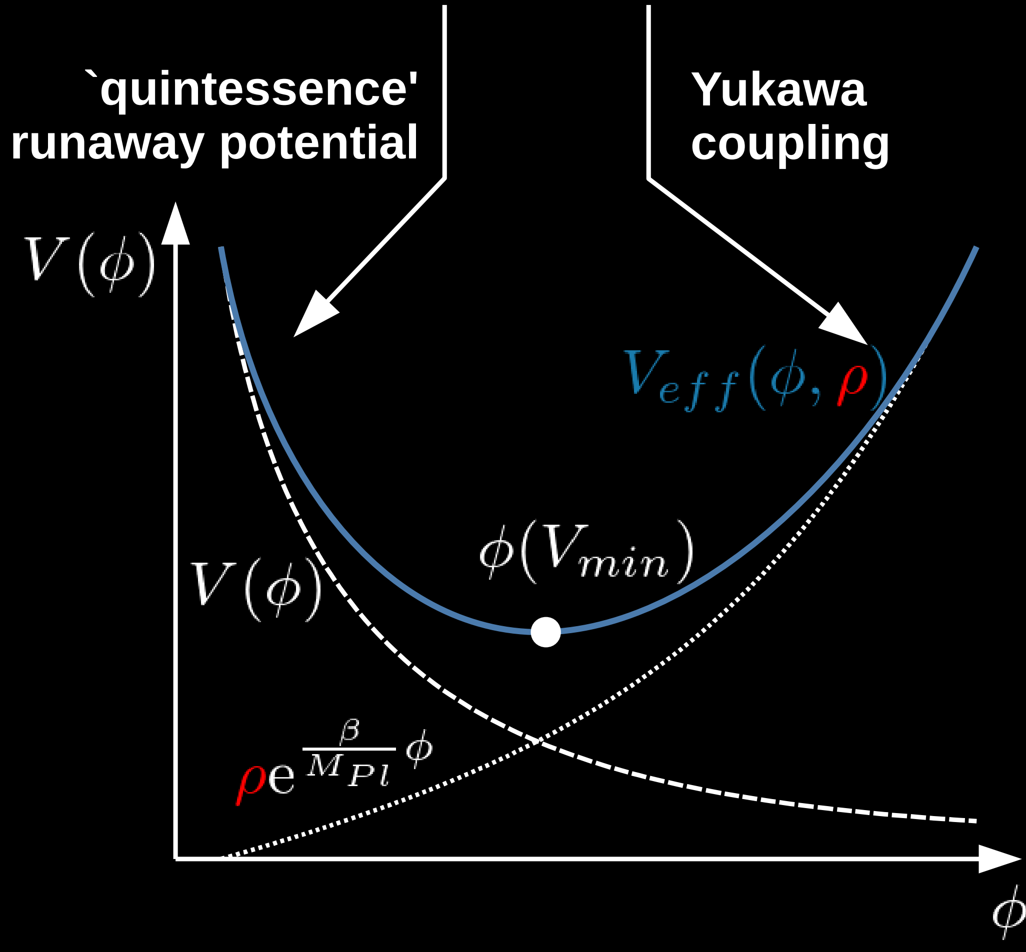
$$\mathcal{L}_\phi = \sqrt{-g}\left[\mathcal{R}\frac{M_{Pl}^2}{2} - \frac{(\partial\phi)^2}{2} - V(\phi)\right]$$

Yukawa couplings:

$$\mathcal{L}_{EM} = \frac{-e^{\frac{\beta_\gamma}{M_{Pl}}\phi}}{4}F_{\mu\nu}F^{\mu\nu}$$

Result 1 : effective potential

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



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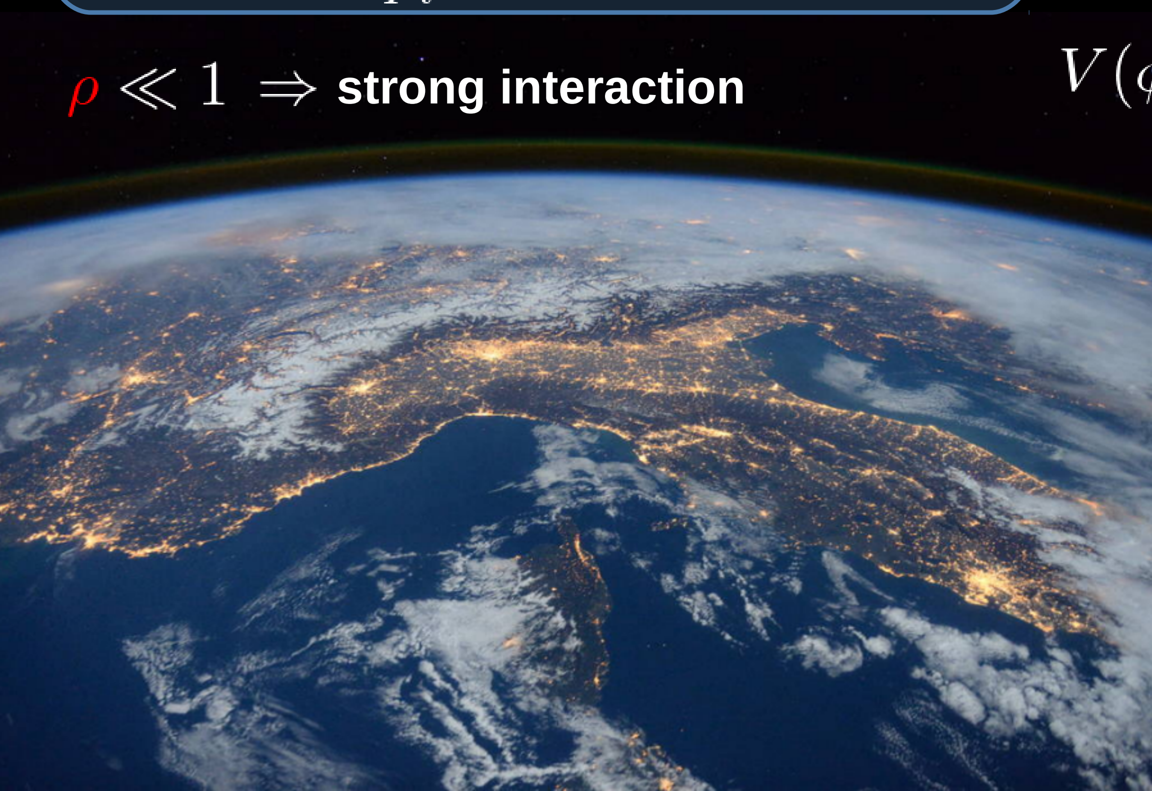
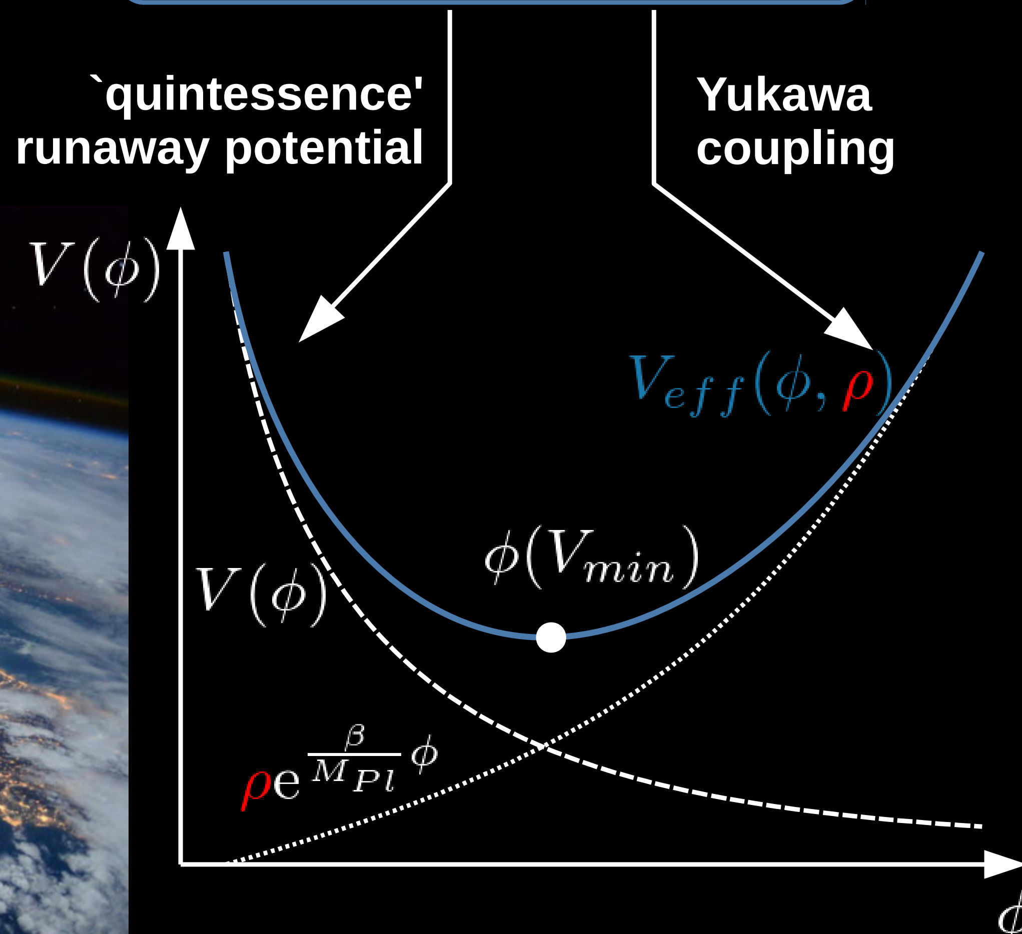
Result 2: `Newtonian' potential:

$$V(r) \propto \beta \frac{M}{M_{Pl}} \frac{\mathrm{e}^{-\sqrt{\partial V_{eff}(\rho)/\partial\phi^2}\, r}}{r}$$

$\rho \ll 1 \Rightarrow$ **strong interaction**





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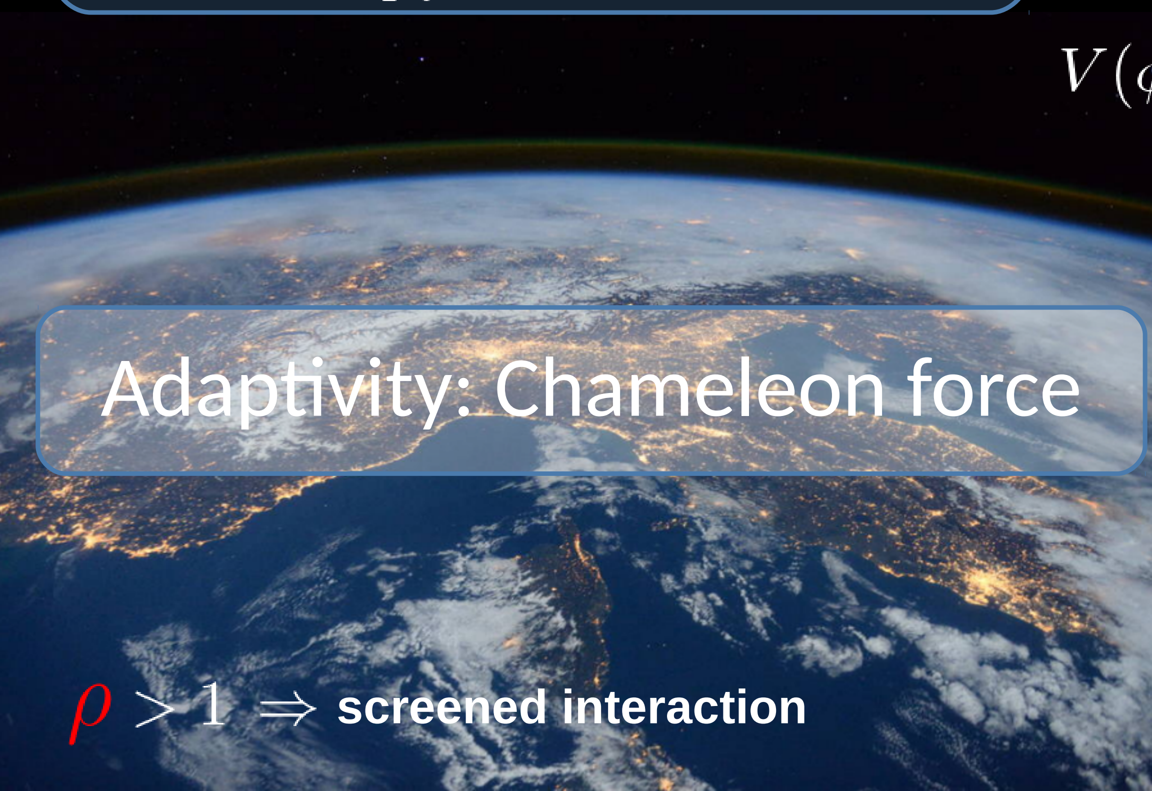
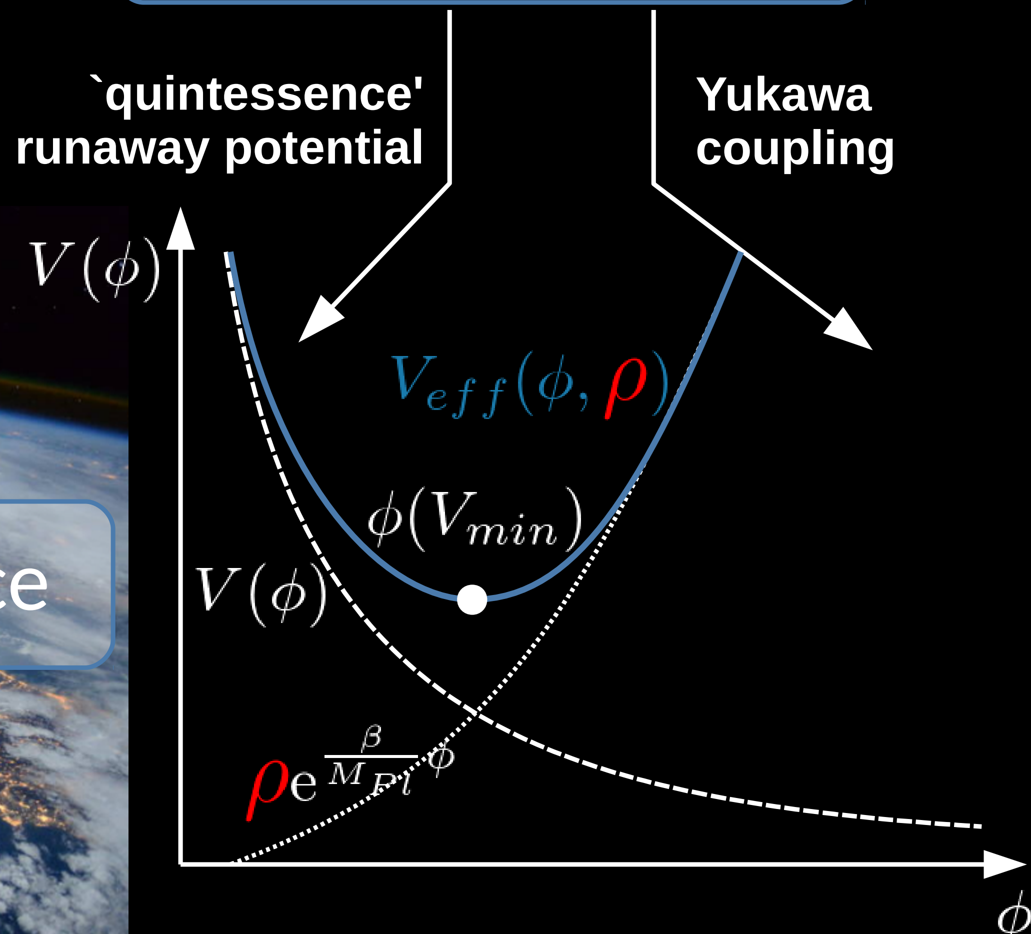
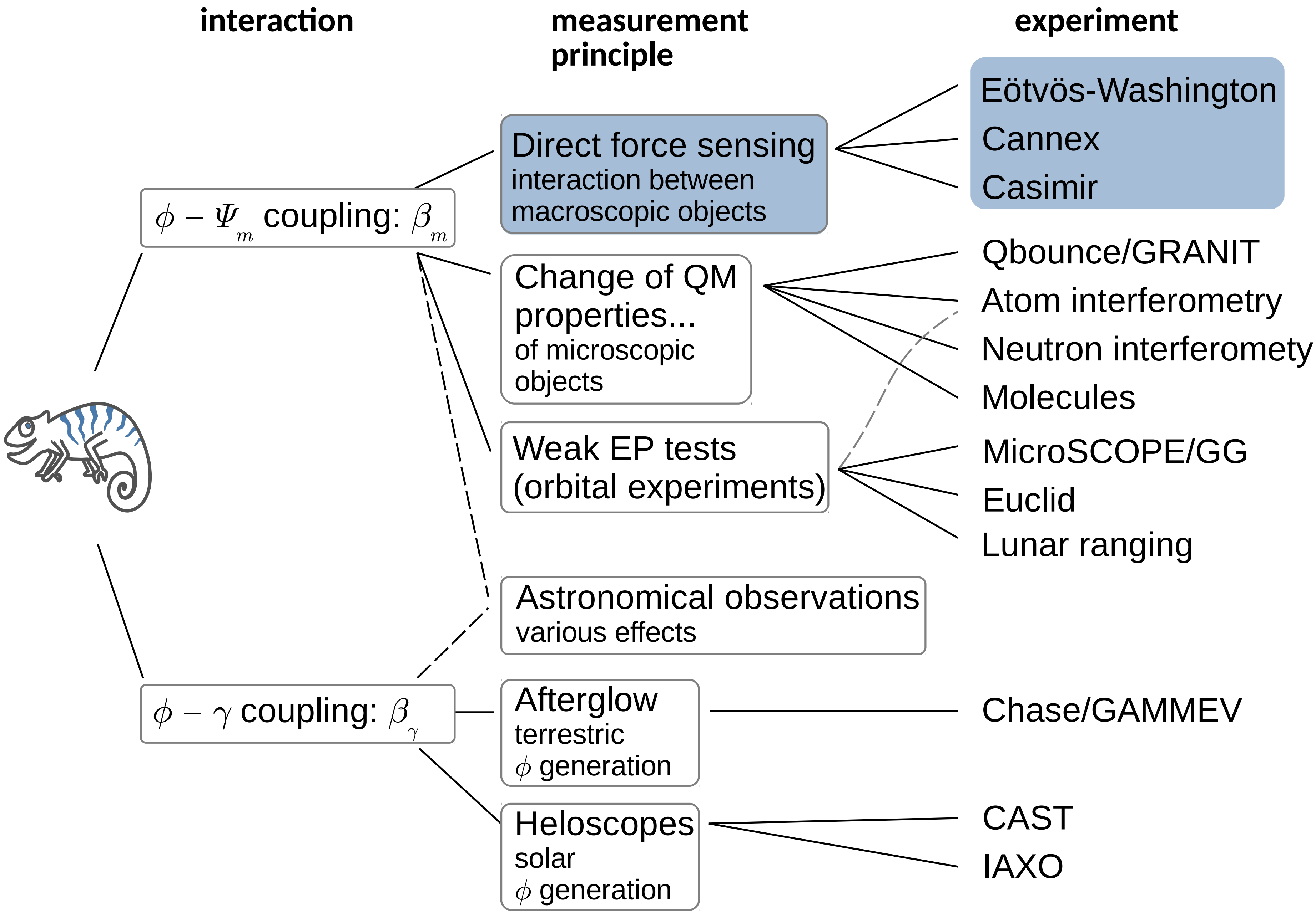


Adaptivity: Chameleon force

$\rho > 1 \Rightarrow$ **screened interaction**



Prospects for chameleon detection

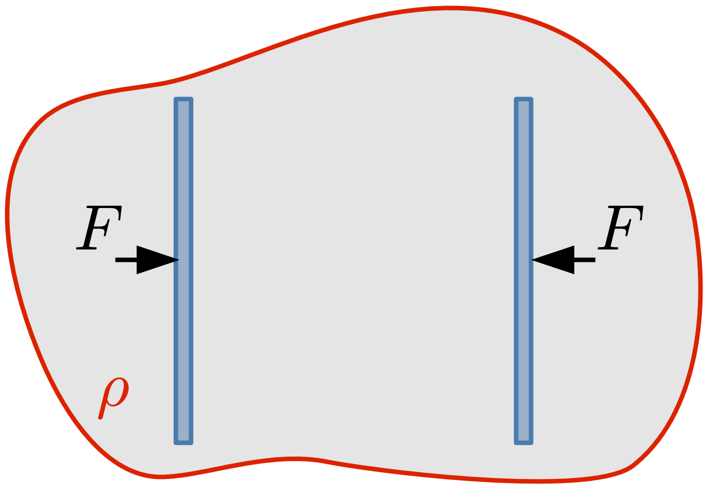


Our approach

Principle:
Measure at **constant plate separation**
the change in the force for **different gas density ρ**
Brax, van de Bruck, Davis, Shaw, Iannuzzi,
PRL. **104,** 241101(2010)

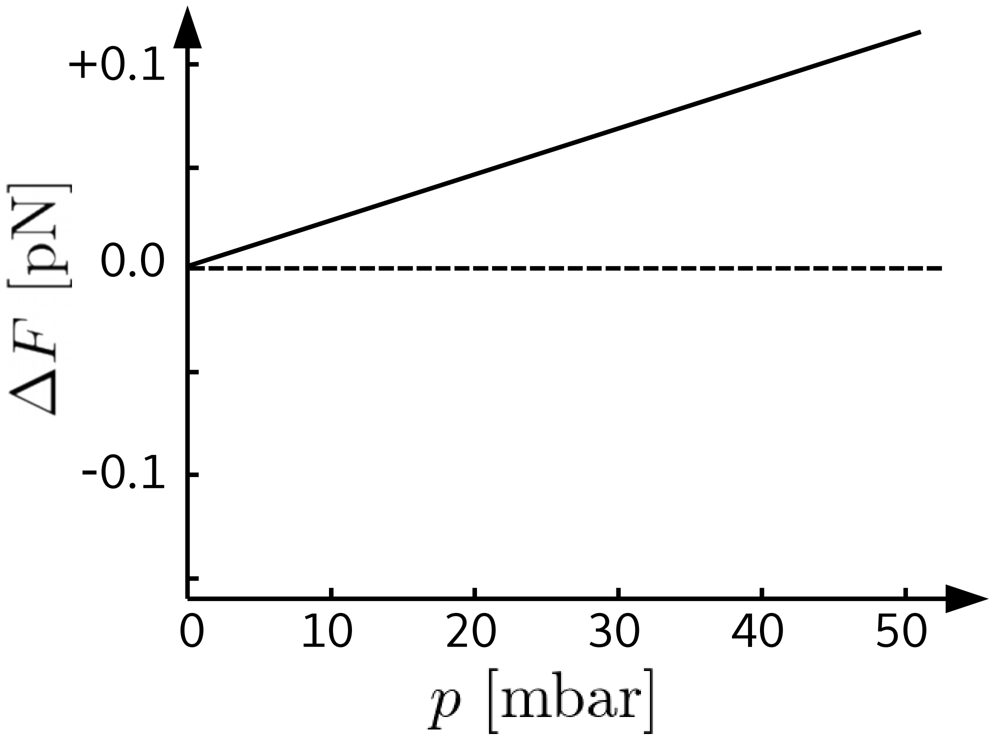
$$F(\rho) = F_{ES} + F_C + F_G$$

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



Assumptions:

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



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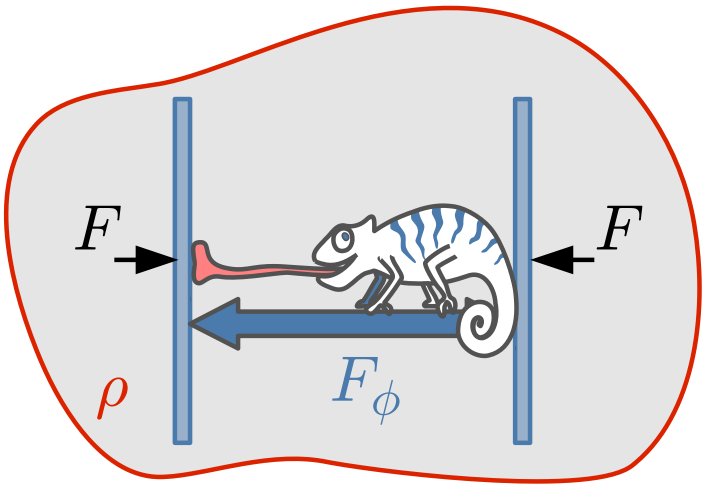

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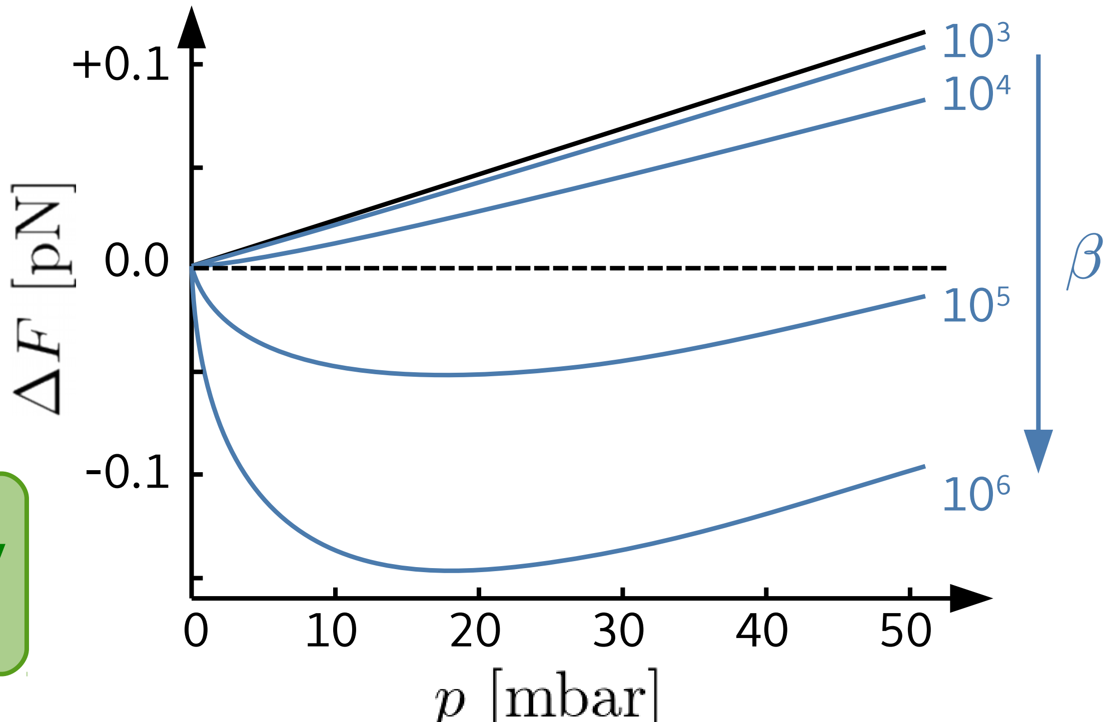
✓ high sensitivity



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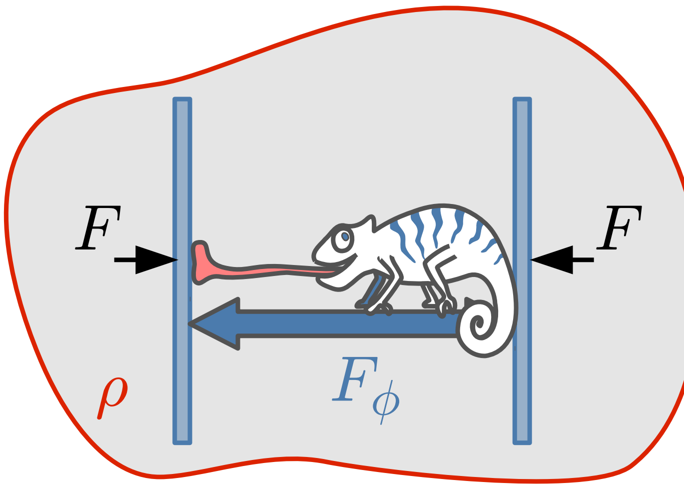

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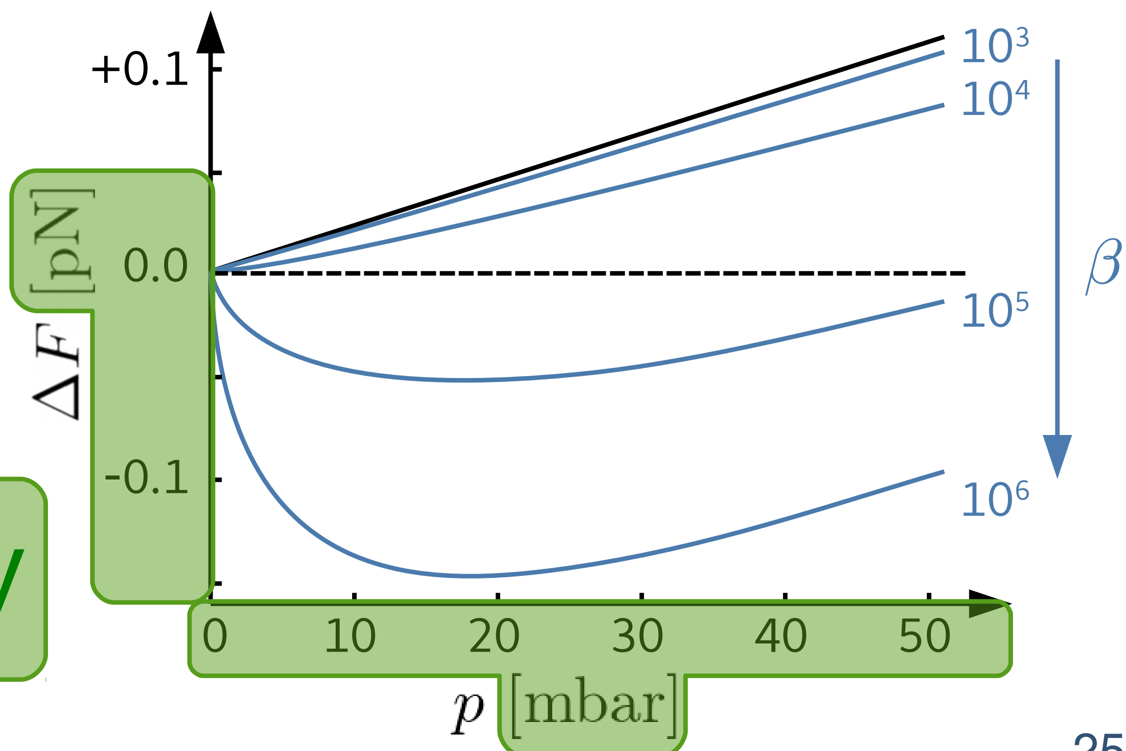

Our approach

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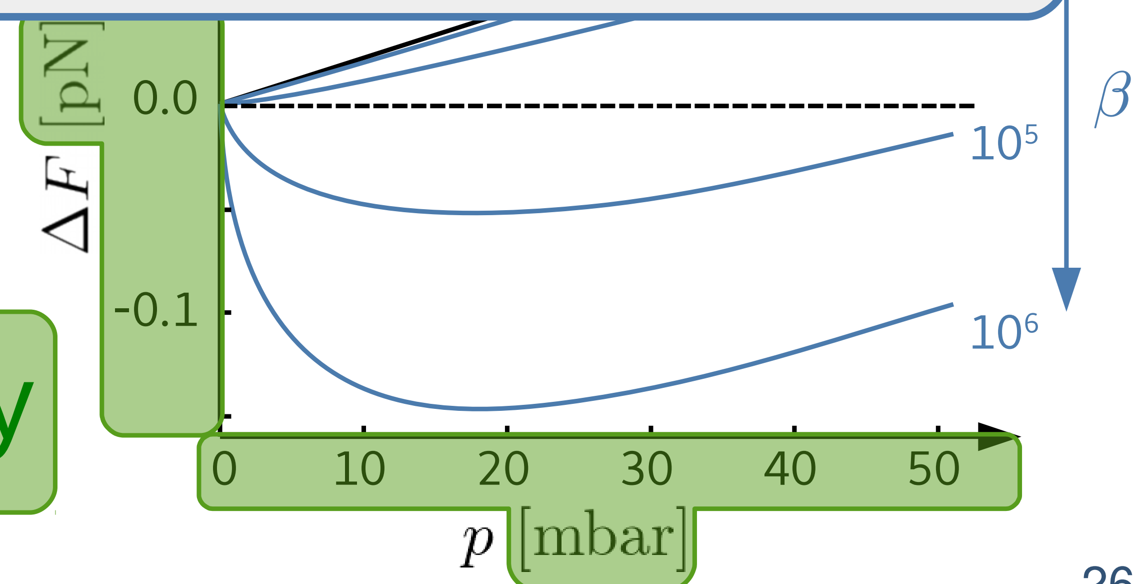
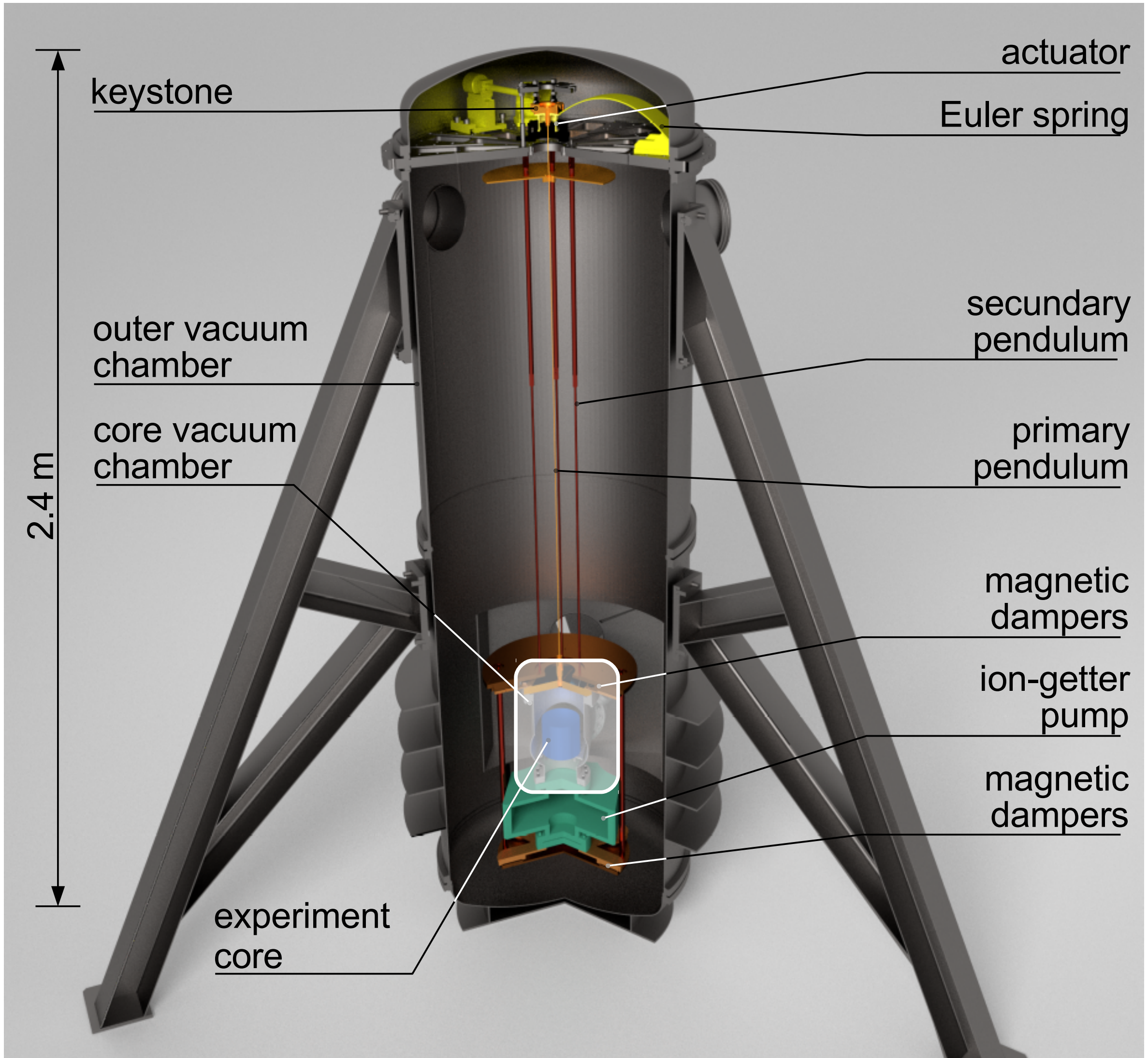
2. Force measurements at constant separation, modulated gas density, **precision <0.1 pN**

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

✓ high sensitivity



Setup (located at VU Amsterdam)

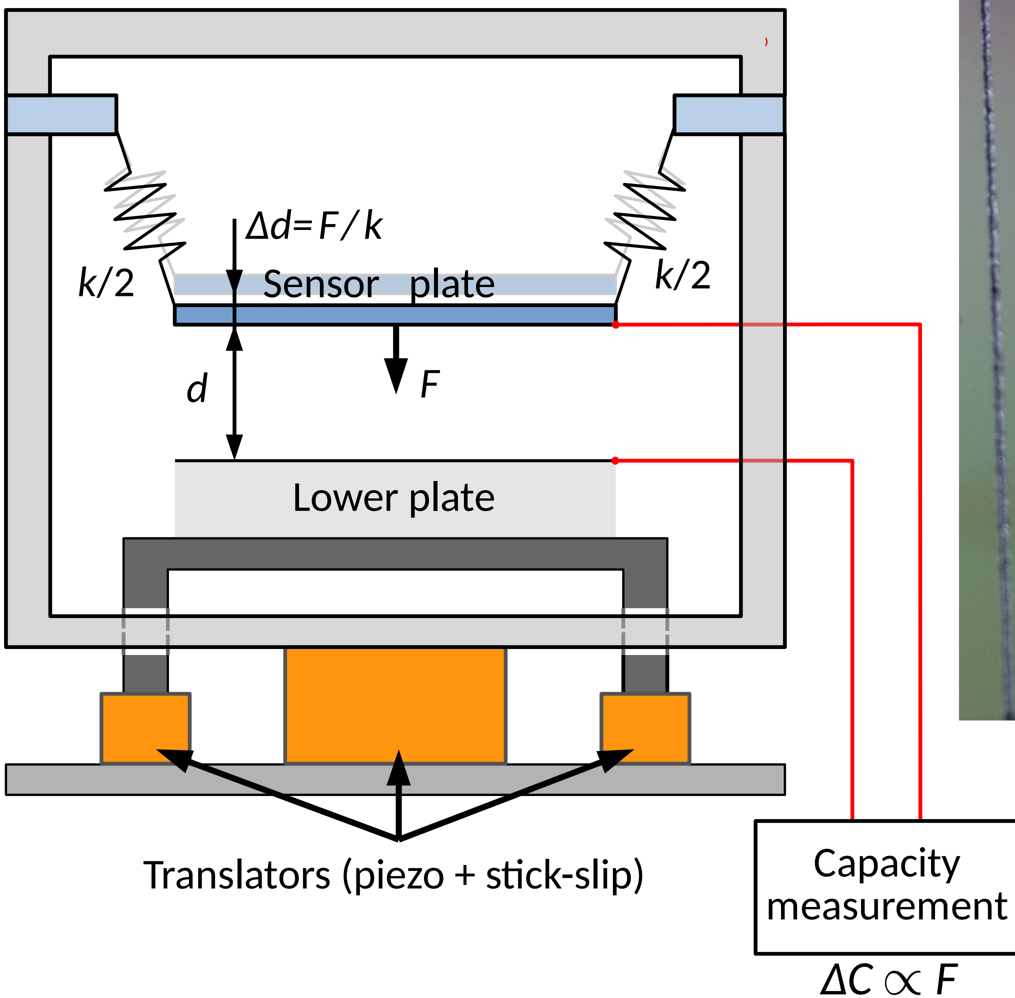


CANNEX overview and isolation system

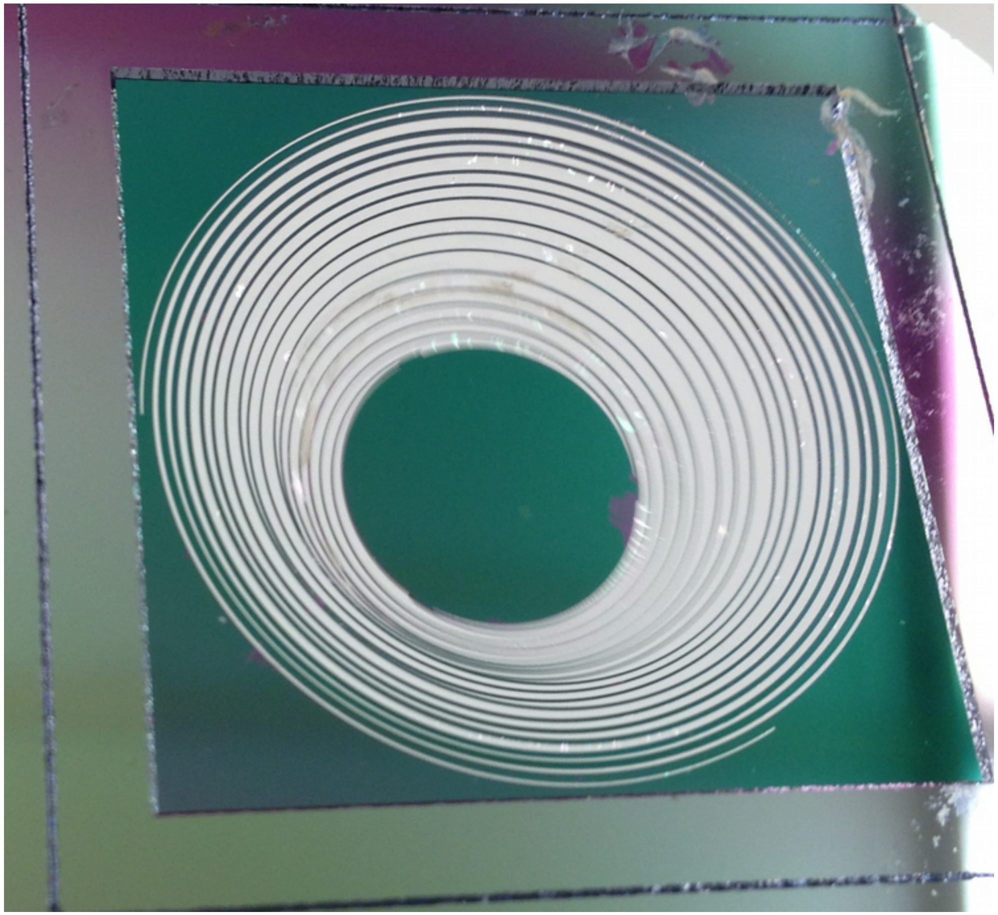
Force detection (one year ago)

Principle:

Measure capacitively the displacement of a spring.



Implementation: upper plate (sensor)



Custom-fabricated Silicon membrane

Force constant: 0.22±0.02 N/m

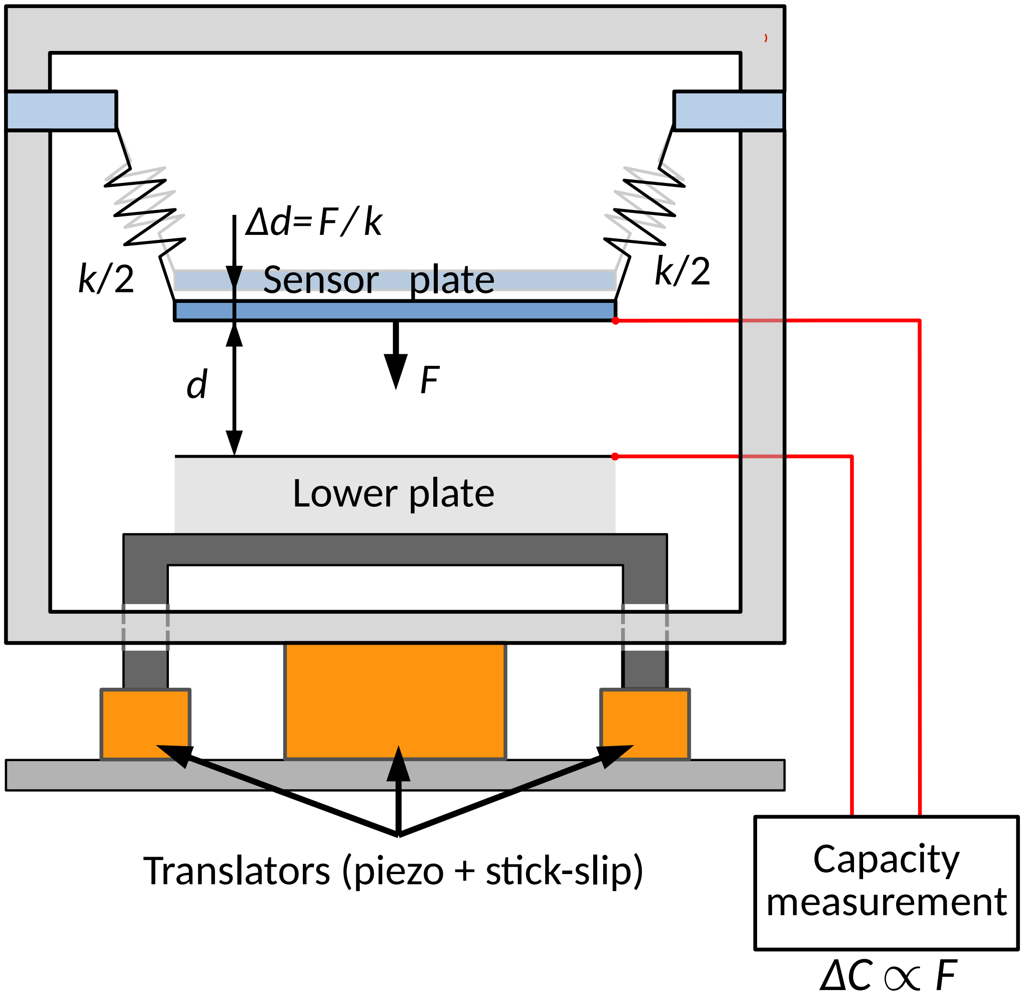
Disk area: 1.0834±0.0005 cm²

Waviness(disk) < 15 nm (whole area)

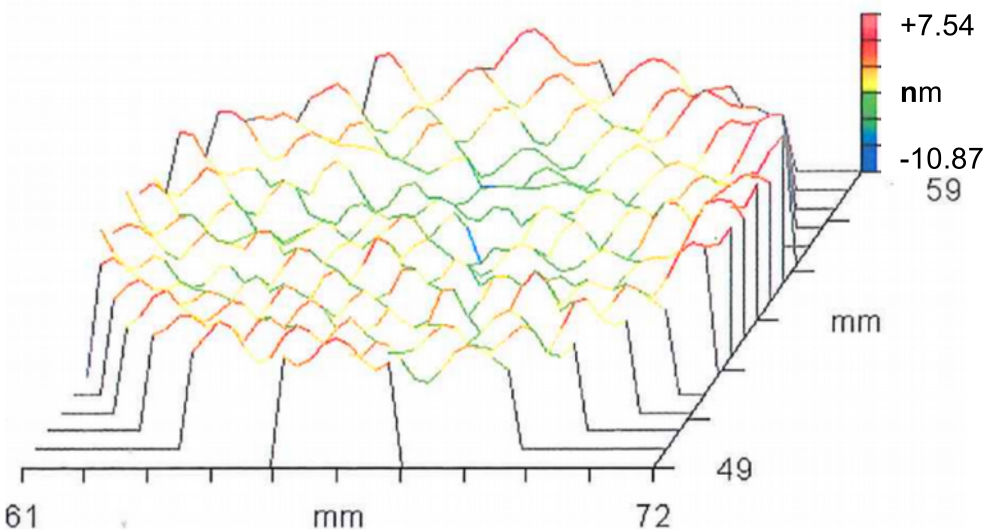
Force detection

Principle:

Measure optically the displacement of a spring.



Implementation lower plate:

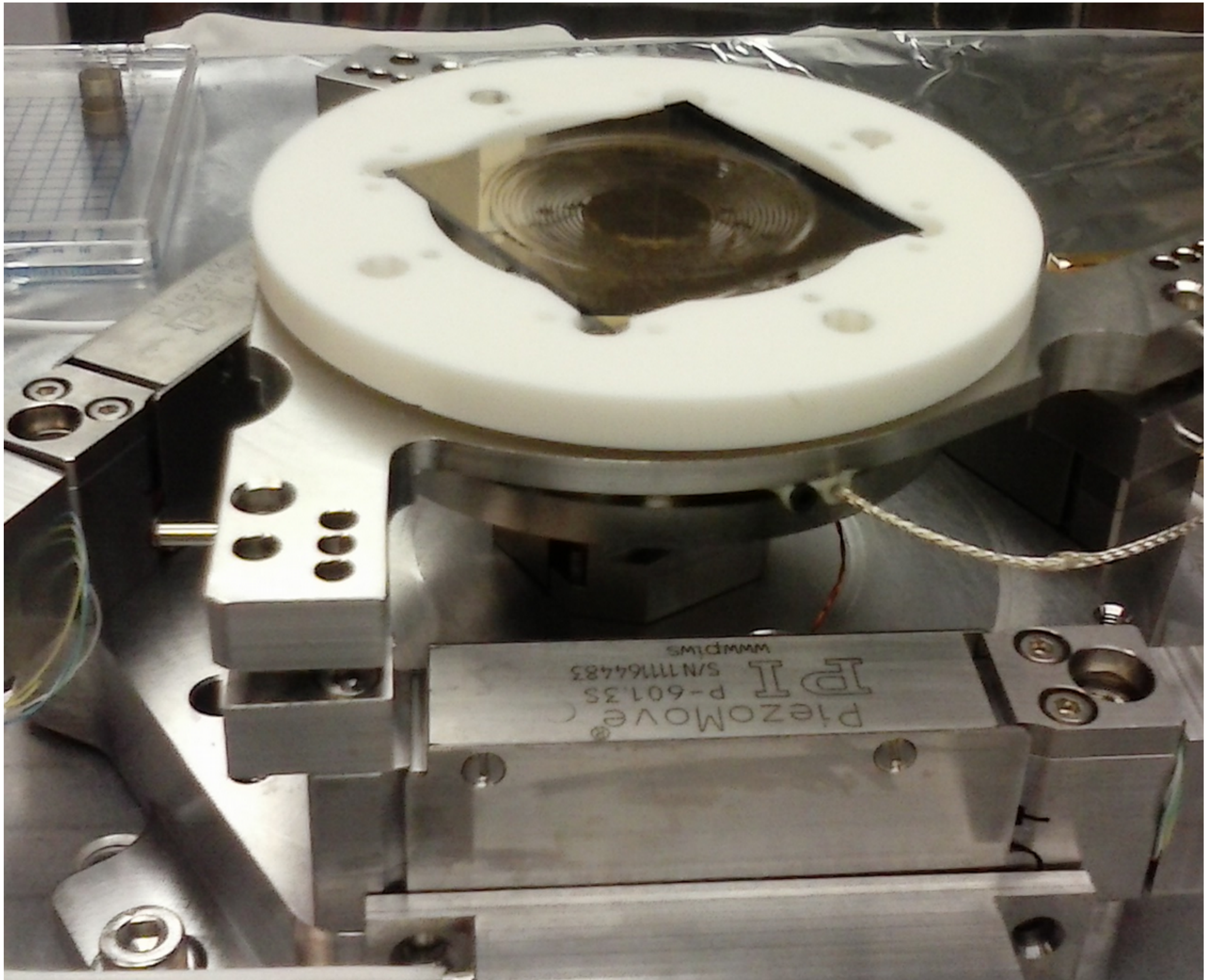


Custom-fabricated SiO_2 disk

Thickness	6 mm
Disk area	1 cm²
Waviness(disk)	< 18 nm (whole area)

Force detection

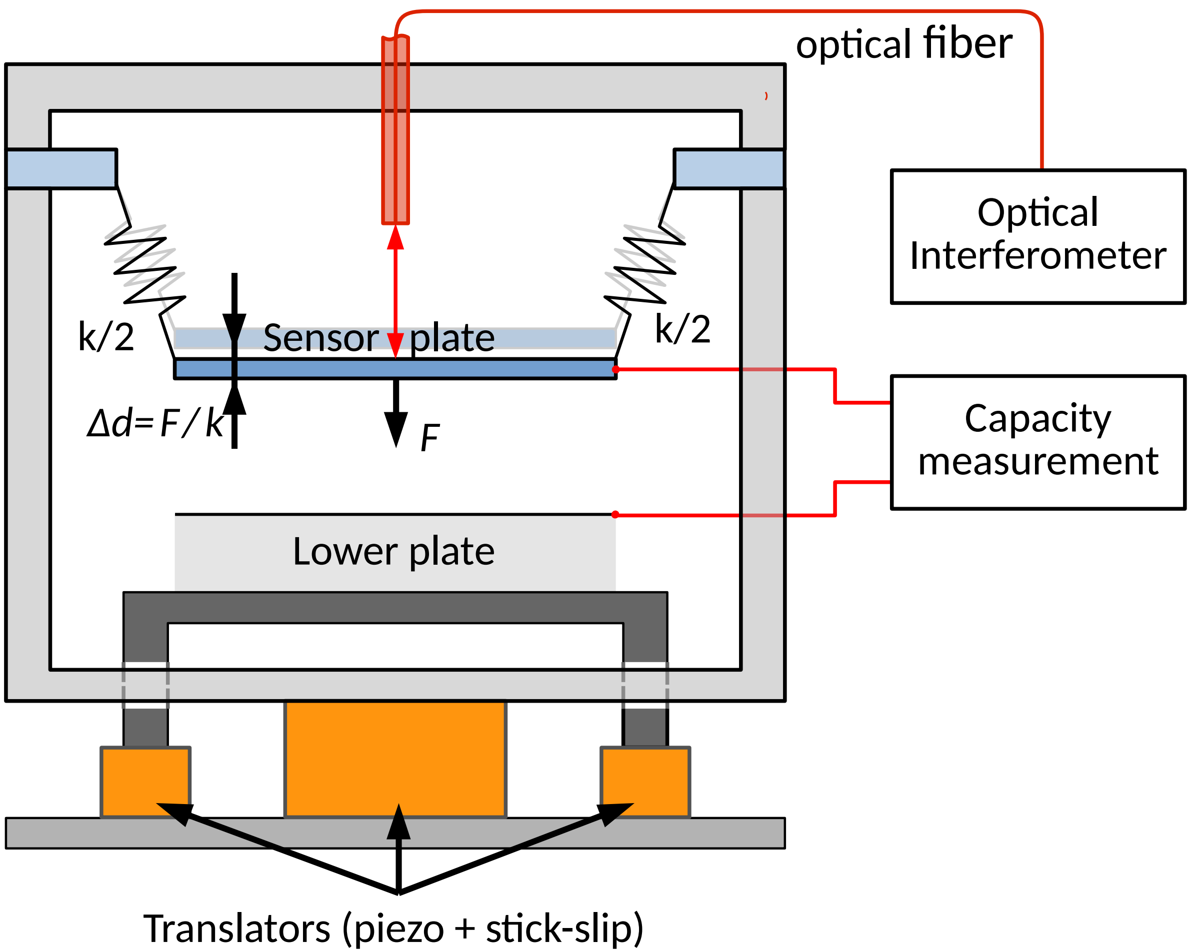
Implementation: core



Force detection

Principle:

Measure ~~capacitively~~ optically the displacement of a spring.



Casimir:
resonance frequency shift

$$\omega_0 = \sqrt{\frac{k}{m} - \frac{1}{m}\frac{\partial F(d)}{\partial d}}$$

Chameleon:
adiabatic pressure modulation

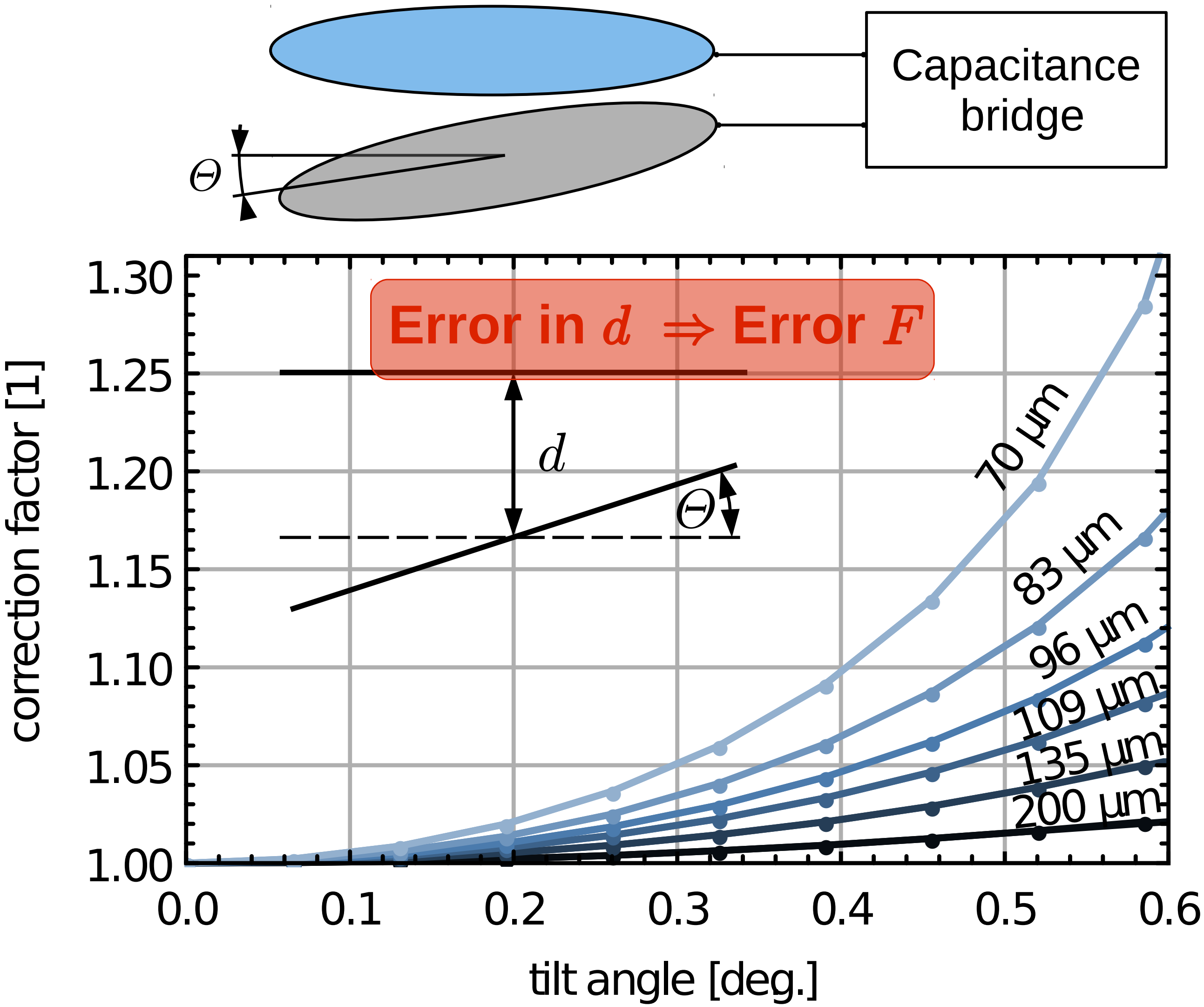
$$\Delta F_\phi \approx \frac{\partial F_\phi(p)}{\partial p}\Delta p$$

Homodyne detection

→ Able to measure below the thermal noise level

Parallelism: Importance

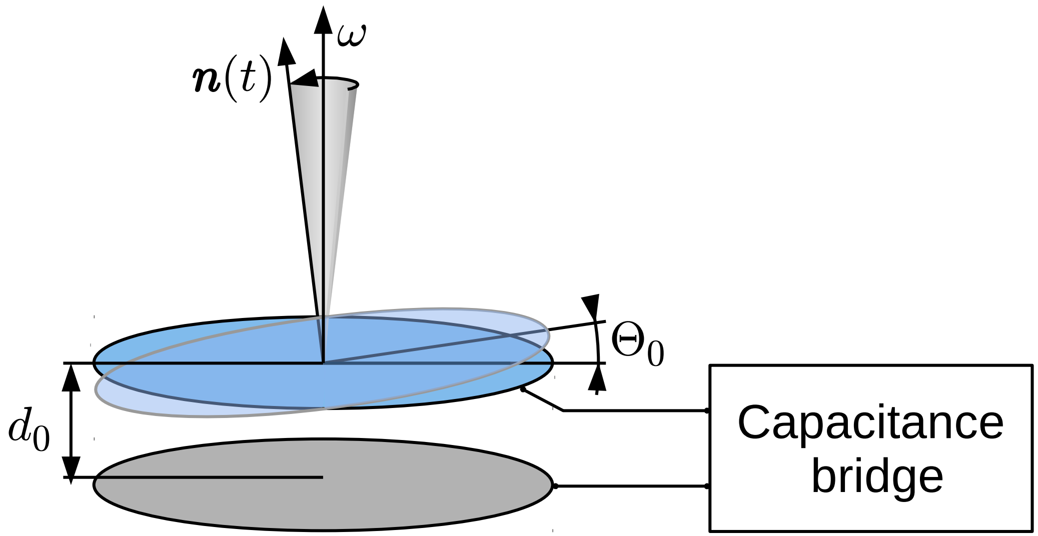
parallel plates with small tilt Θ



Target **0.1 pN:** max deviation **0.1 µrad**

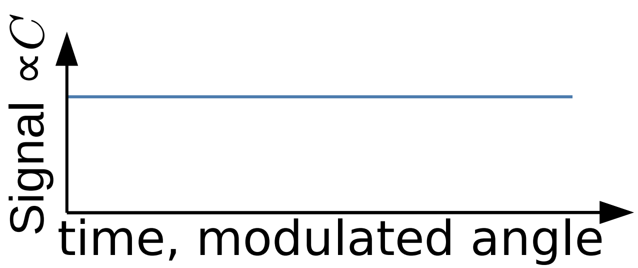
Parallelism control: Principle

assume: **parallel plates**



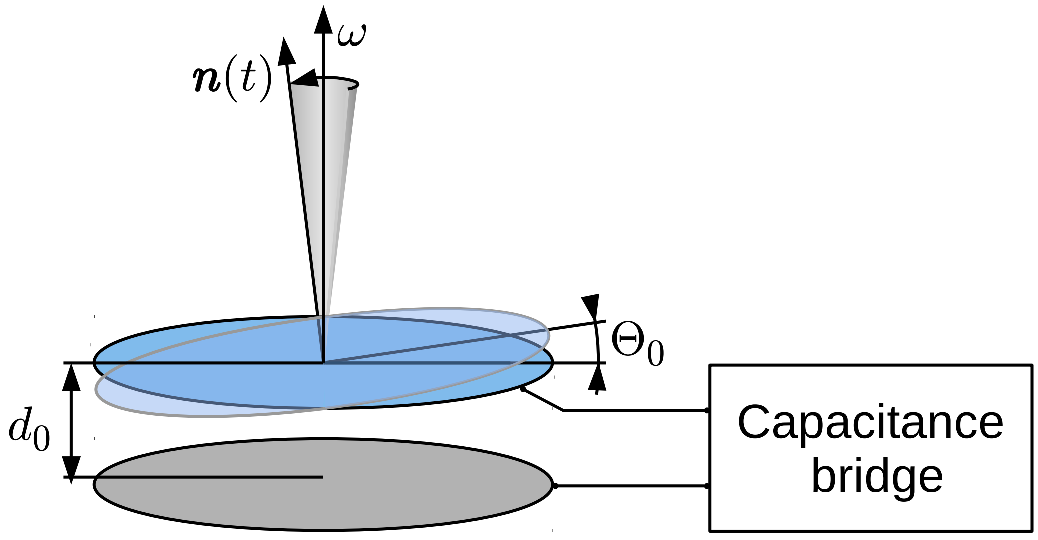
$$\Theta(t) = \Theta_0 = \text{const.}$$

$$C(t) = \varepsilon_0 \frac{R^2 \pi}{d} \left[1 + \left(\frac{R}{2d} \Theta(t) \right)^2 \right] + \mathcal{O}\left(\Theta(t)^4 \right)$$

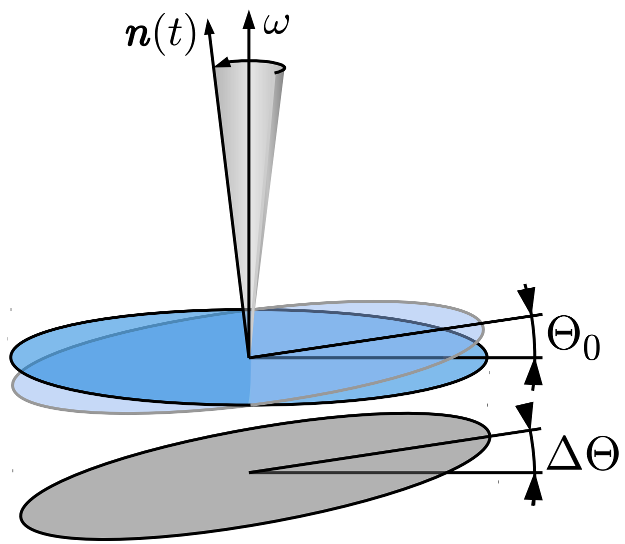


Parallelism control: Principle

assume: **parallel plates**



plates with relative tilt ΔΘ

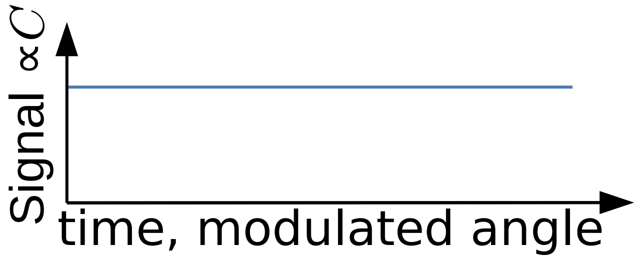


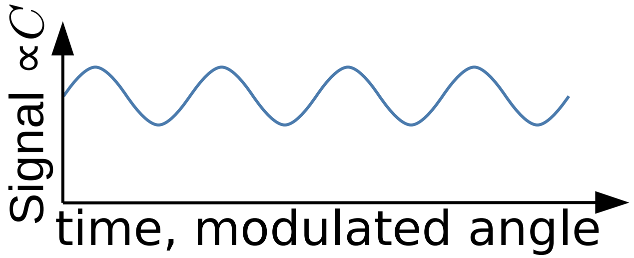
$$\Theta(t) = \Theta_0 = \text{const.}$$

$$C(t) = \varepsilon_0 \frac{R^2\pi}{d}\left[1 + \left(\frac{R}{2d}\Theta(t)\right)^2\right] + \mathcal{O}\left(\Theta(t)^4\right)$$

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

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





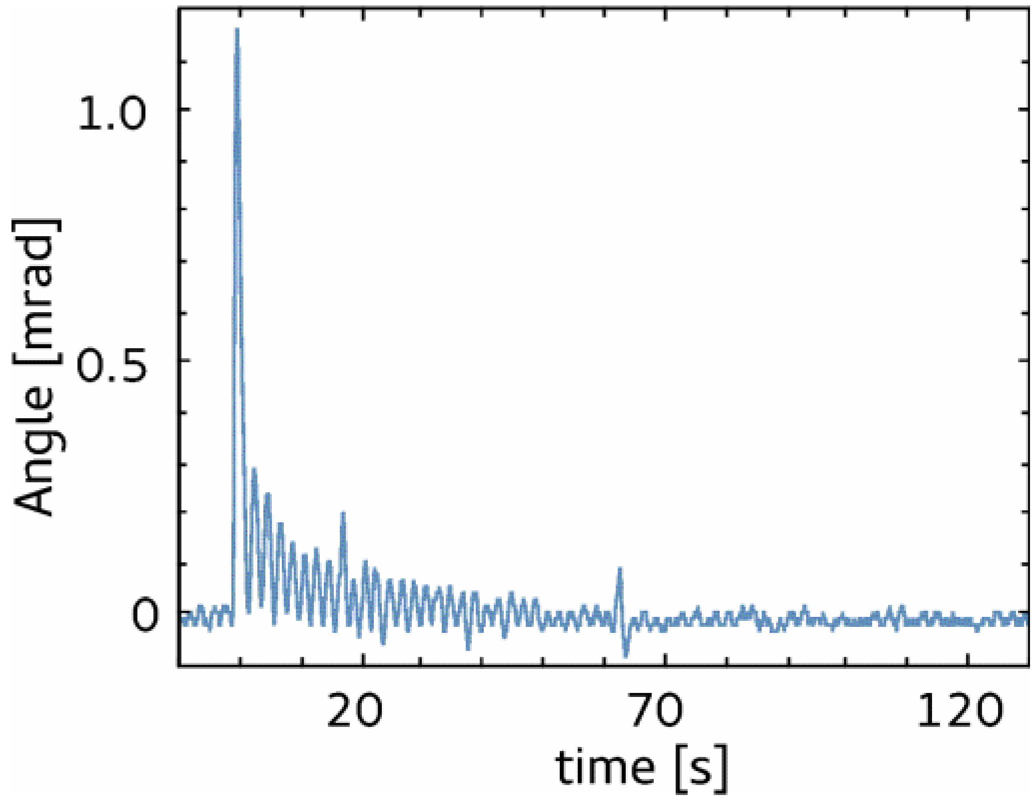
Idea: Use feedback circuit to compensate ΔΘ

Parallelism control: Performance

Proof of principle/preliminary results

Step response
under very bad conditions

- First test
  - in air
  - without anti-vibration
  - with thick testing plates
- 6 µm single-sided step
- nominal distance 90 µm



Long-term stability

- Same conditions
- **3 µrad(RMS)**

Target

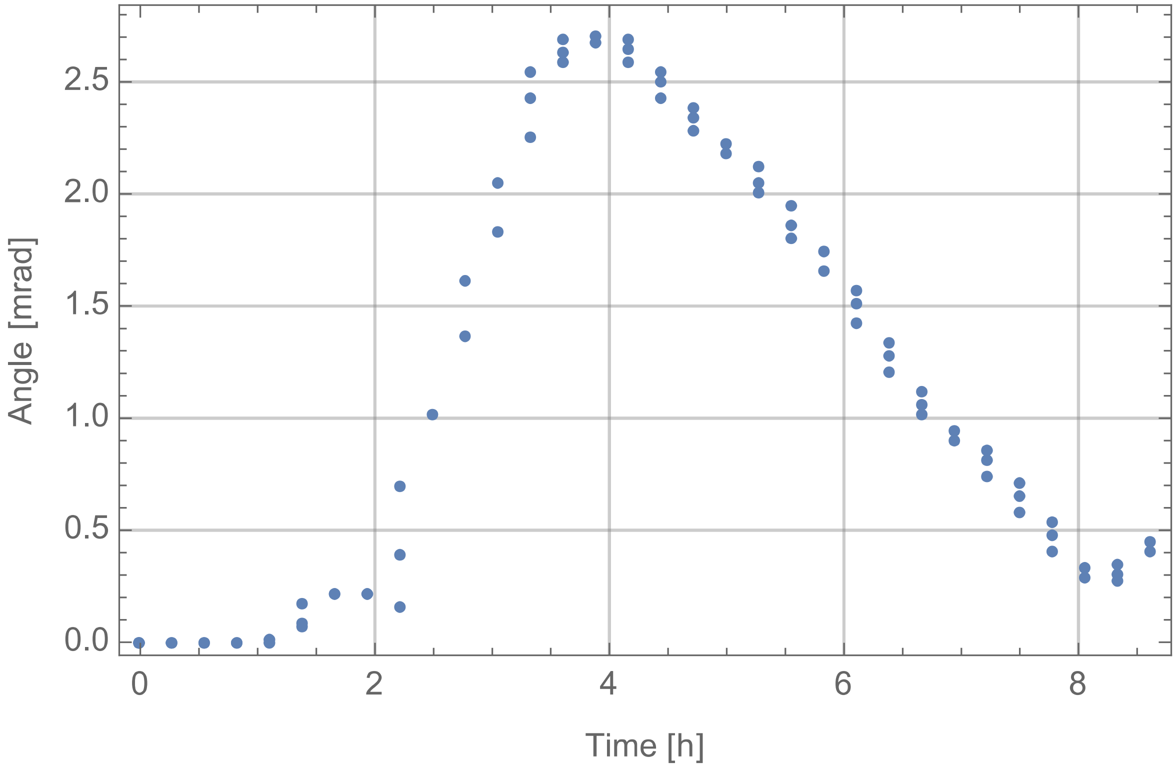
- Assumptions: vacuum, anti-vibration
- **0.1 µrad (~1 nm total tilt)**

Parallelism control: Performance

Proof of principle/preliminary results

Practical operation

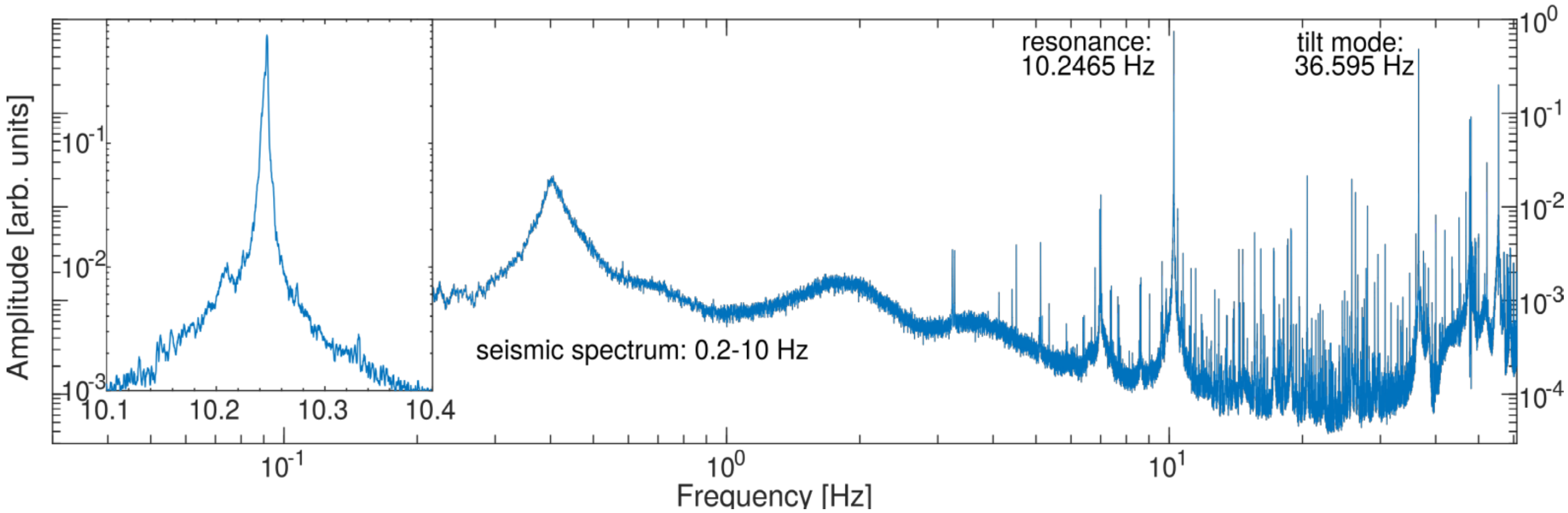
- Works as expected
- **currently ~200 µrad long term**



Limiting factor: Vibrations, Drift

Force detection

Sensor characterization: noise spectrum



Custom-fabricated Silicon membrane

Force constant: 0.22±0.02 N/m

Eigenfrequency: 10.2465 Hz ± 0.1 mHz

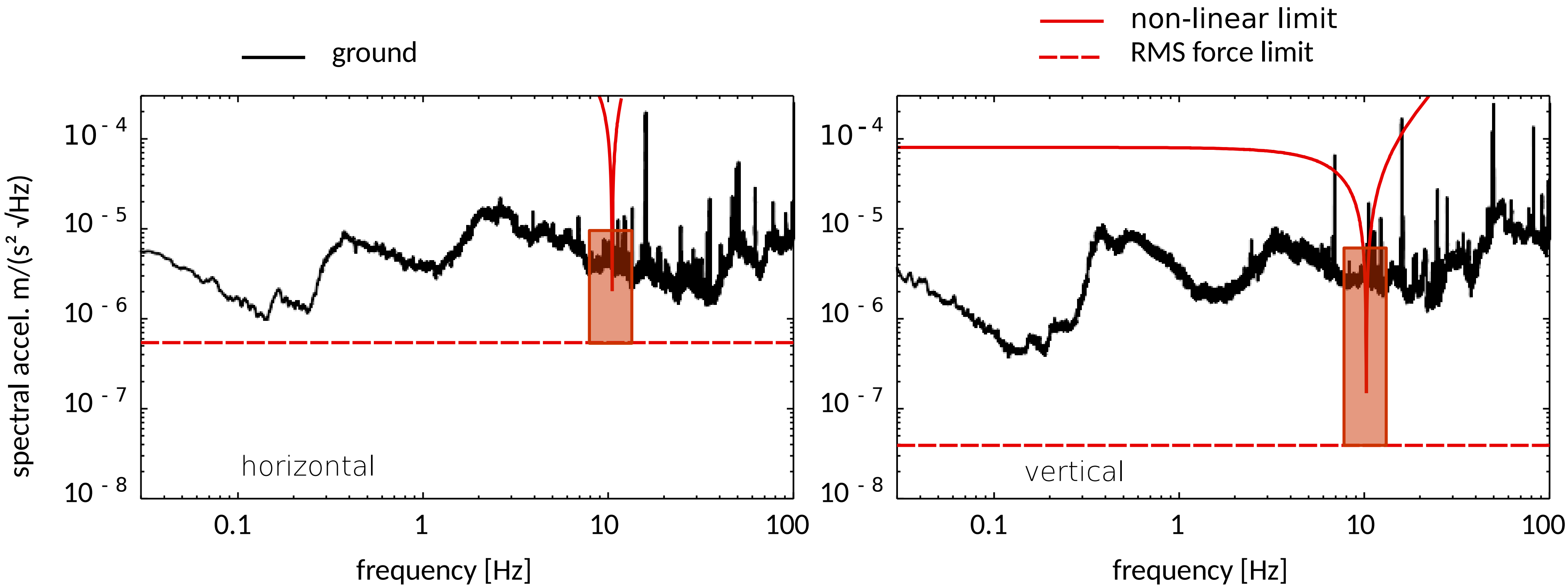
Q-factor: 5 k—15 k

Disk area: 1.0834±0.0005 cm²

Waviness(disk) < 15 nm (whole area)

Vibrations 1: The background

Noise levels and limits:



2 limits:

1: non-linearities: $F(d+\delta d) \approx F(d) + \delta d \partial_d F(d) + 1/2\, \delta d^2\, \partial_d^2 F(d)$

< **1 pN** @ d=10 µm

2: equivalent RMS noise: $\delta a_{n,RMS}(F) \gtrsim \int_{f_0 - f_{BW}/2}^{f_0 + f_{BW}/2} \delta a_n \approx \sqrt{f_{BW}}\, \delta a_n(f_0)$ $\quad f_{BW} \sim 5$ mHz

< **0.1** pN @ d=10 µm

required improvement: factor 10 horizontal, 100 vertical around 10 Hz

Vibrations 2: The unlucky first system

Vertical seismic:

- GAS* filter
- ~~active $\mathcal{H}_\infty$ feedback~~

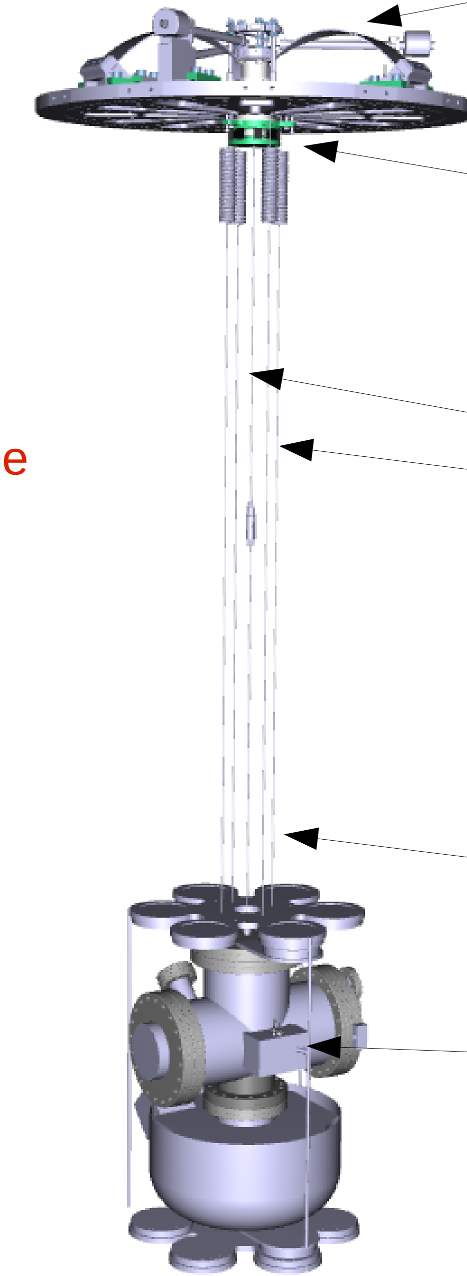
still missing

Horizontal seismic:

- ~~double-pendulum~~ single
- Eddy current dampers

Acoustic:

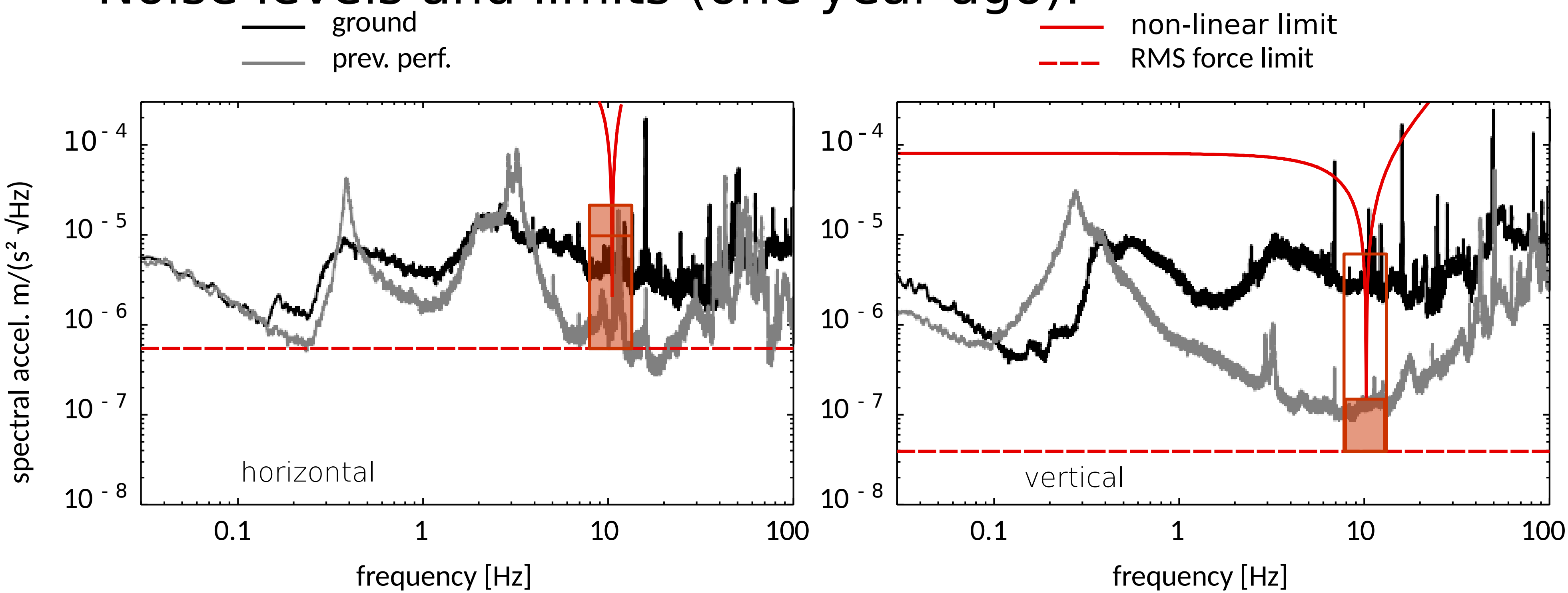
- rigid all-enclosing vacuum chamber 10^{-5} mbar (not shown)



*Geometric anti-spring

Vibrations 2: The unlucky first system

Noise levels and limits (one year ago):



New problem: **resonances**

⇒ Could not approach

separations < 50 µm

required improvement: factor 30 horizontal, 3 vertical around 10 Hz

Vibrations 3: The hopeful update:

Vertical seismic:

- GAS* filter (Euler springs)
- active feedback

Horizontal seismic:

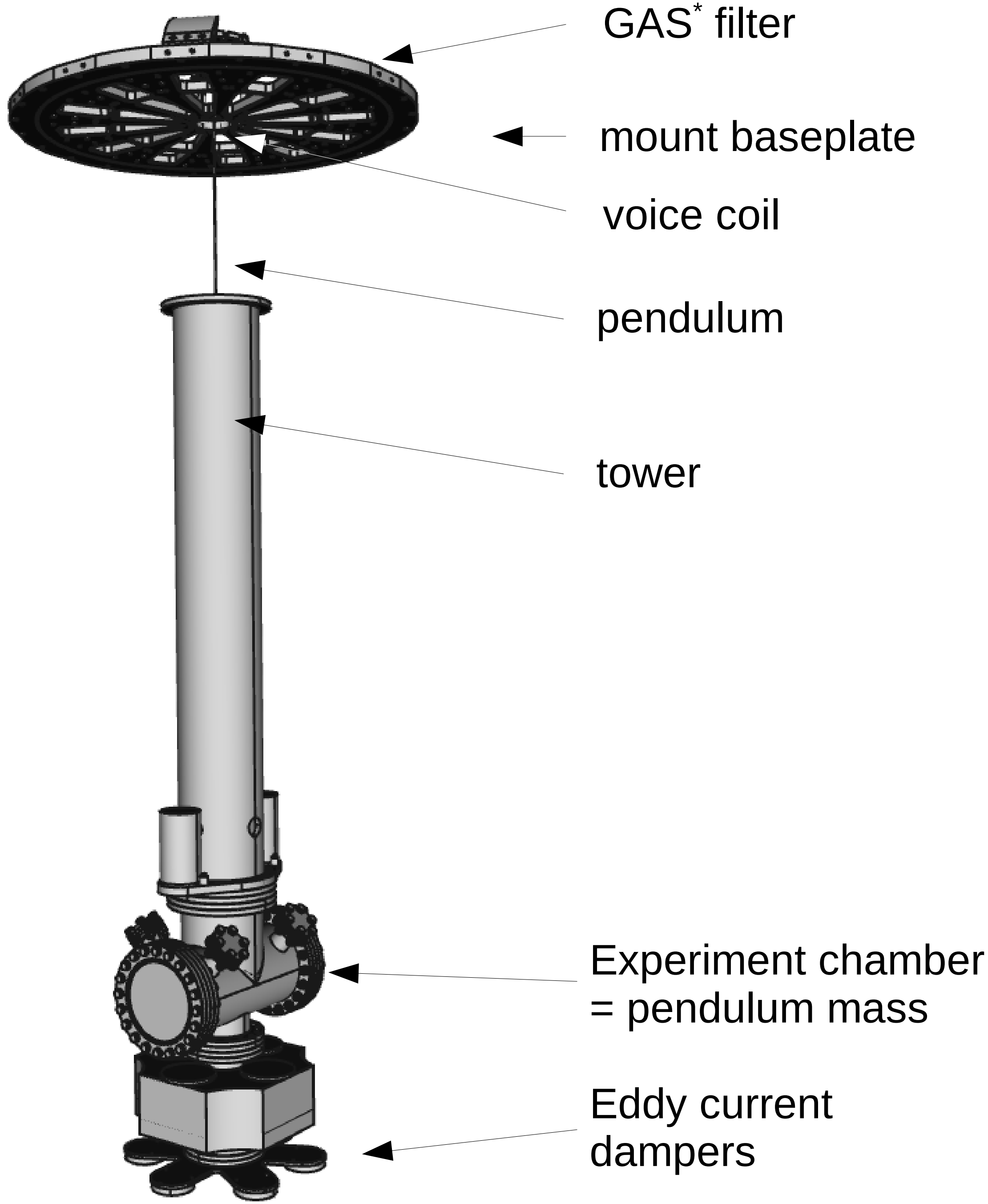
- single-pendulum
  thinner wire
- Eddy current dampers

Tilt seismic:

- tower on core chamber
- Eddy current dampers

Acoustic:

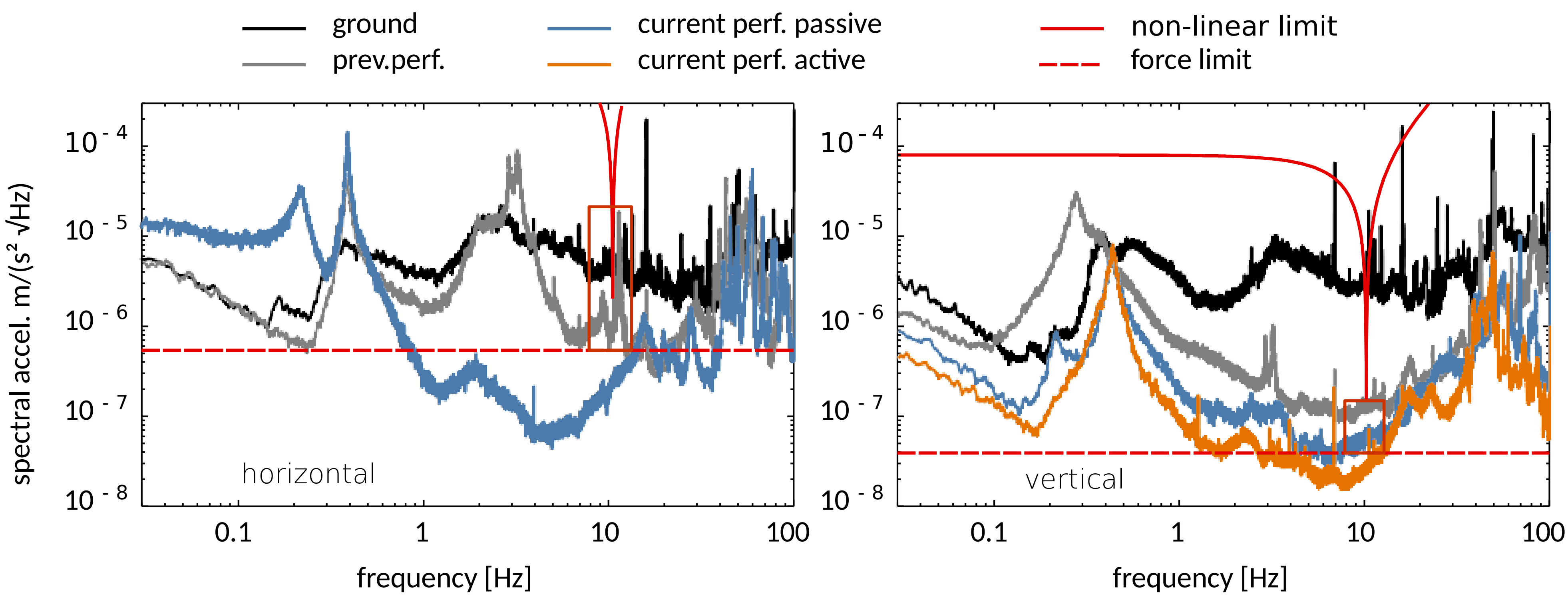
- rigid all-enclosing
  vacuum chamber
  10^{-5} mbar
  (not shown)



*Geometric anti-spring

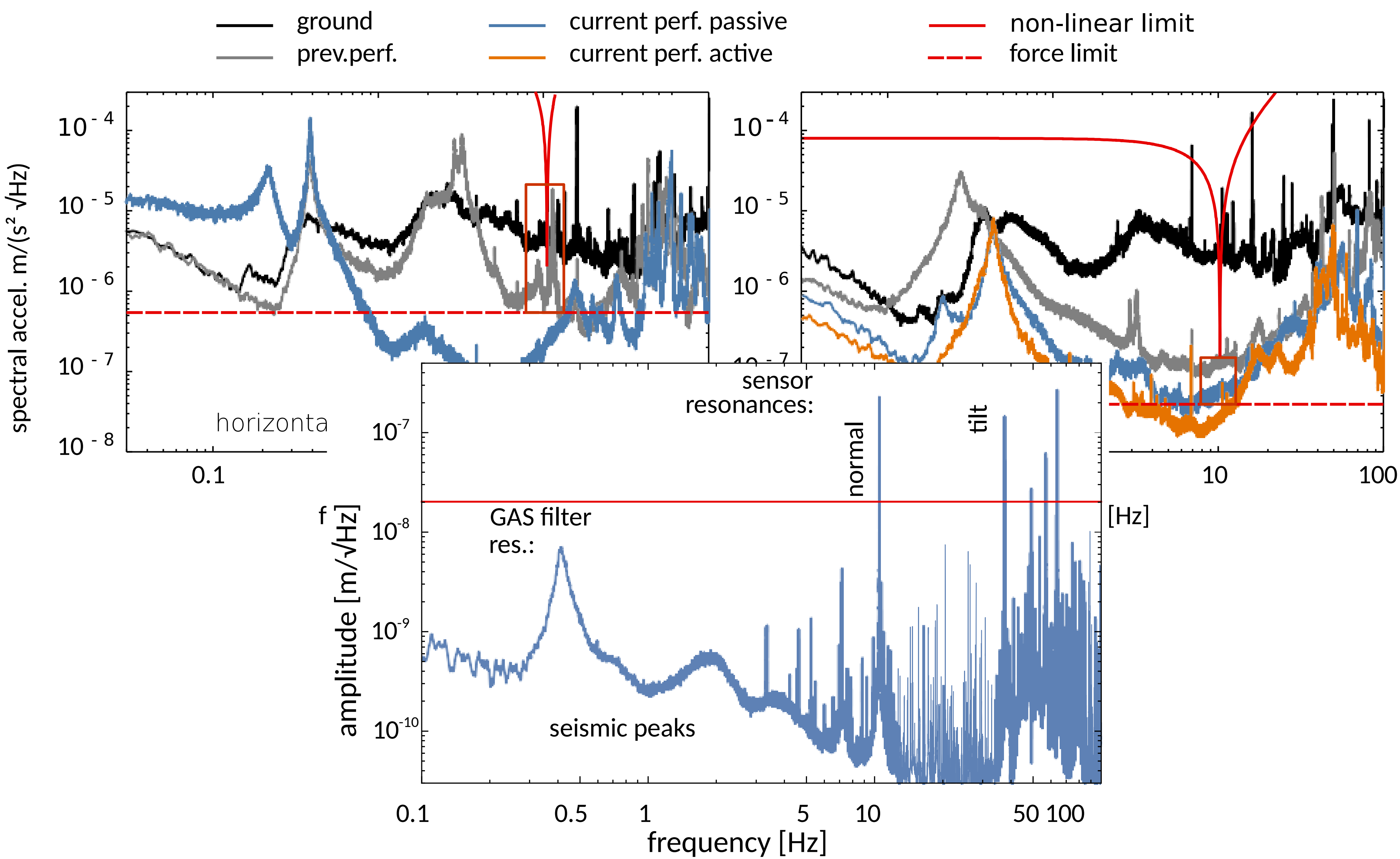
Vibrations 3: The hopeful update

Noise levels and limits:



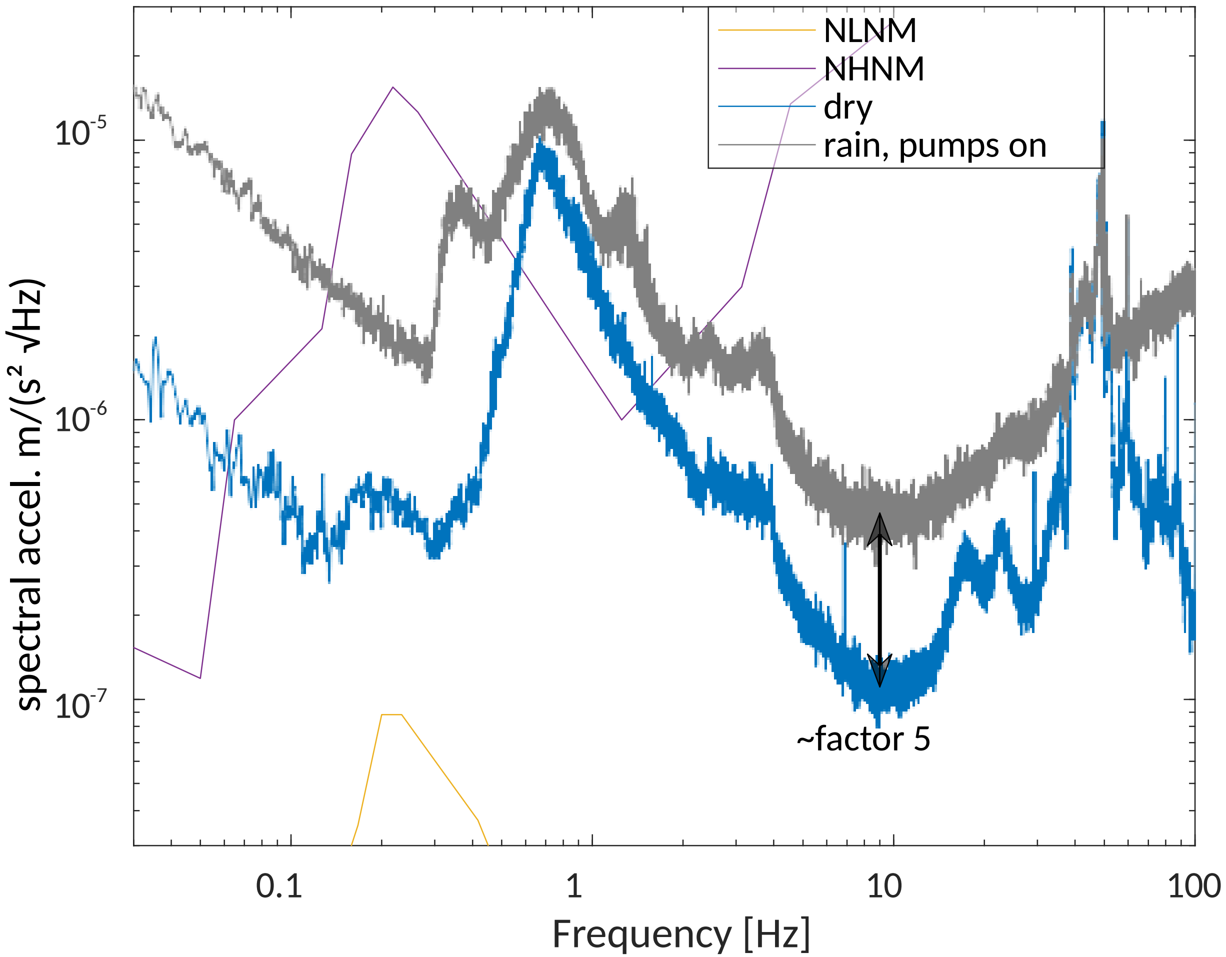
Vibrations 3: The hopeful update

Noise levels and limits:

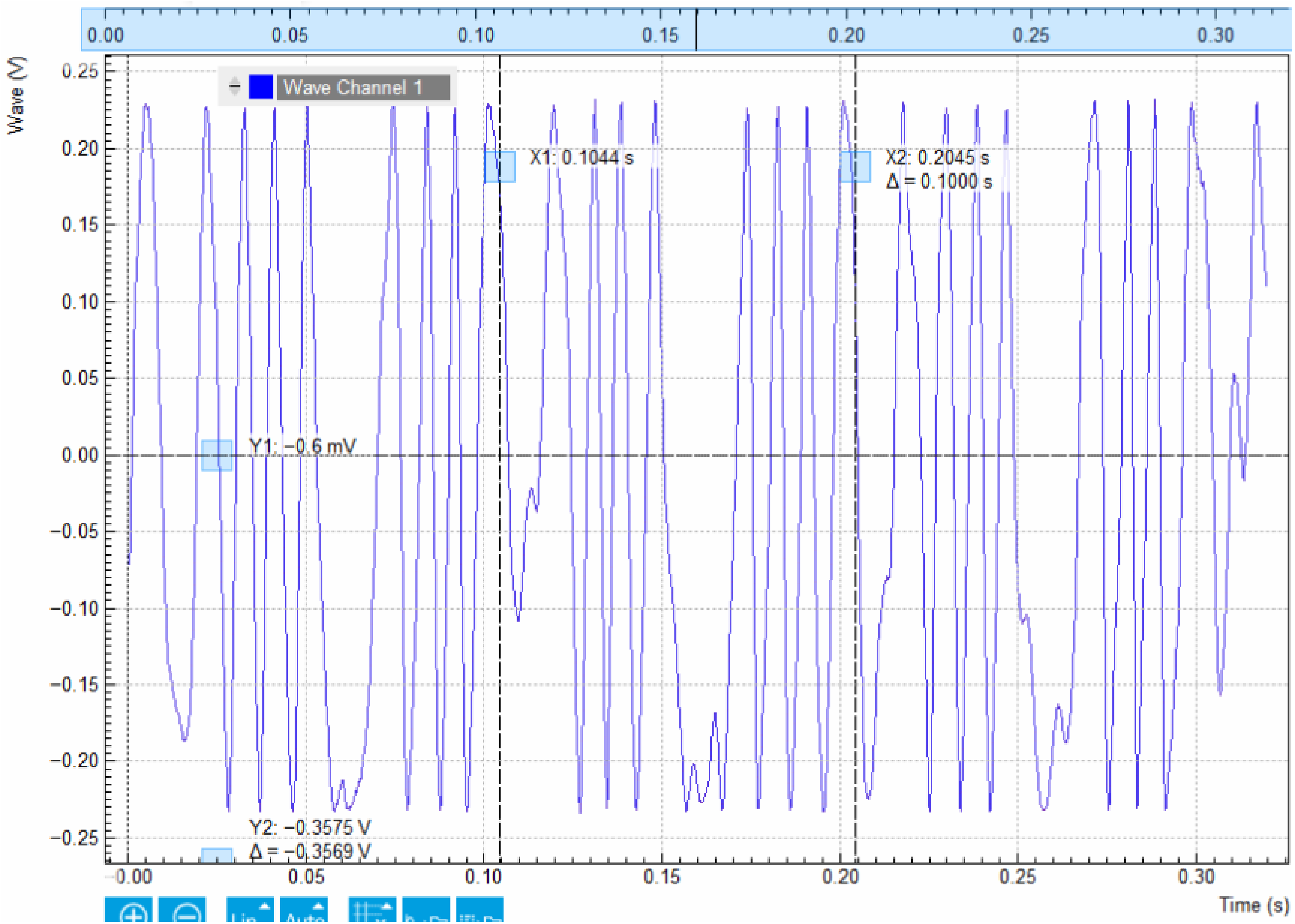


Still an improvement of 30 required (depending on the background)

Vibrations 4: The bitter end



Vibrations 4: The bitter end



Remote operation

Setup completely automized.

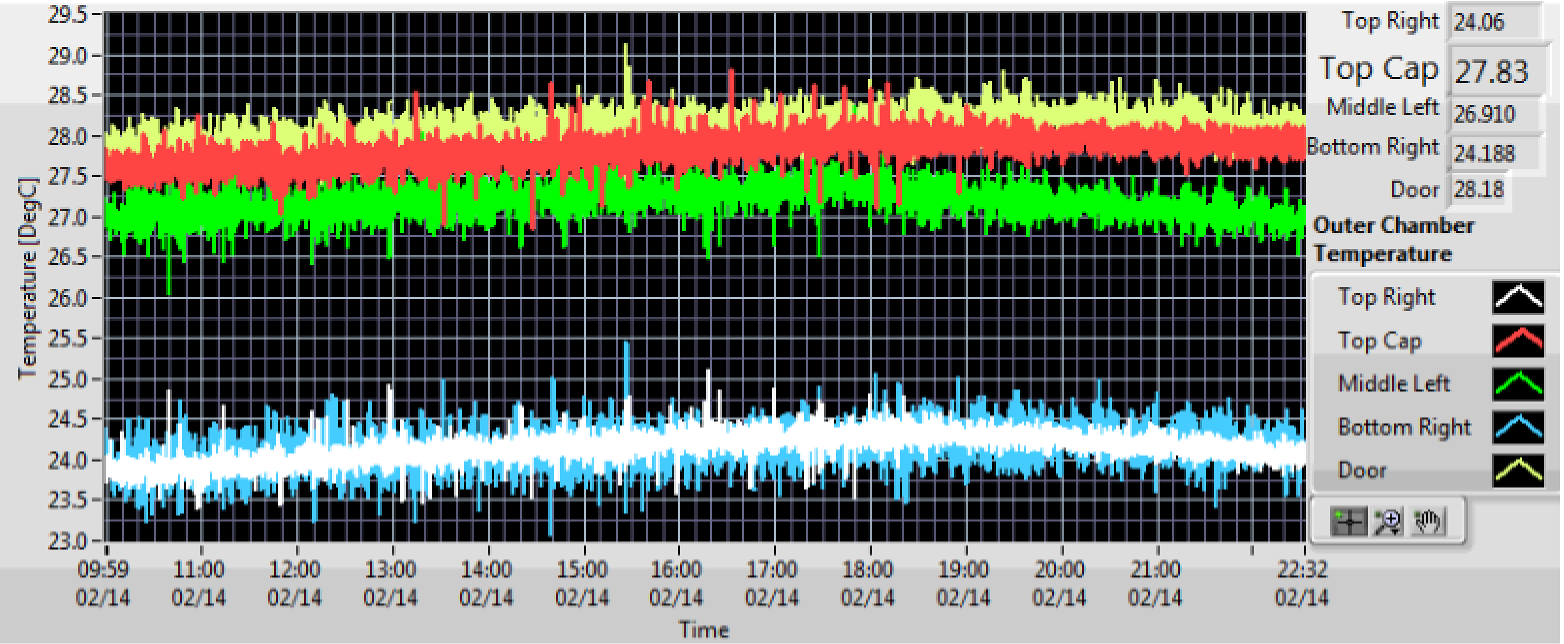
Data acquisition without physical access to the setup.
What can go wrong?

Remote operation

Setup completely automized.

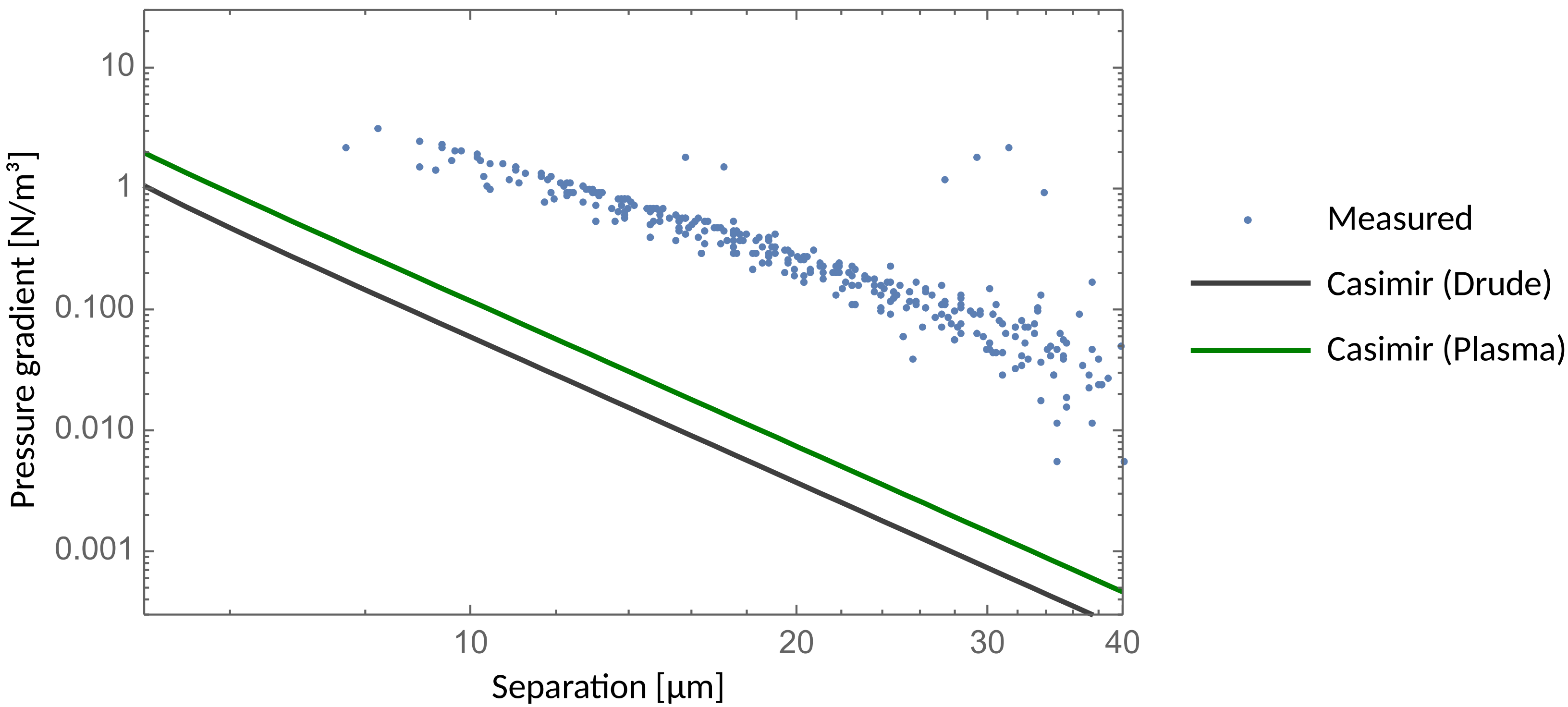
Data acquisition without physical access to the setup.
What can go wrong?

Rain water pipe rupture → Lab flooded → Thermal controls broken



Required stability (sensor spring constant) in sensor spring constant: < 10 mK
Actual stability ~ 500 mK

However, there is hope



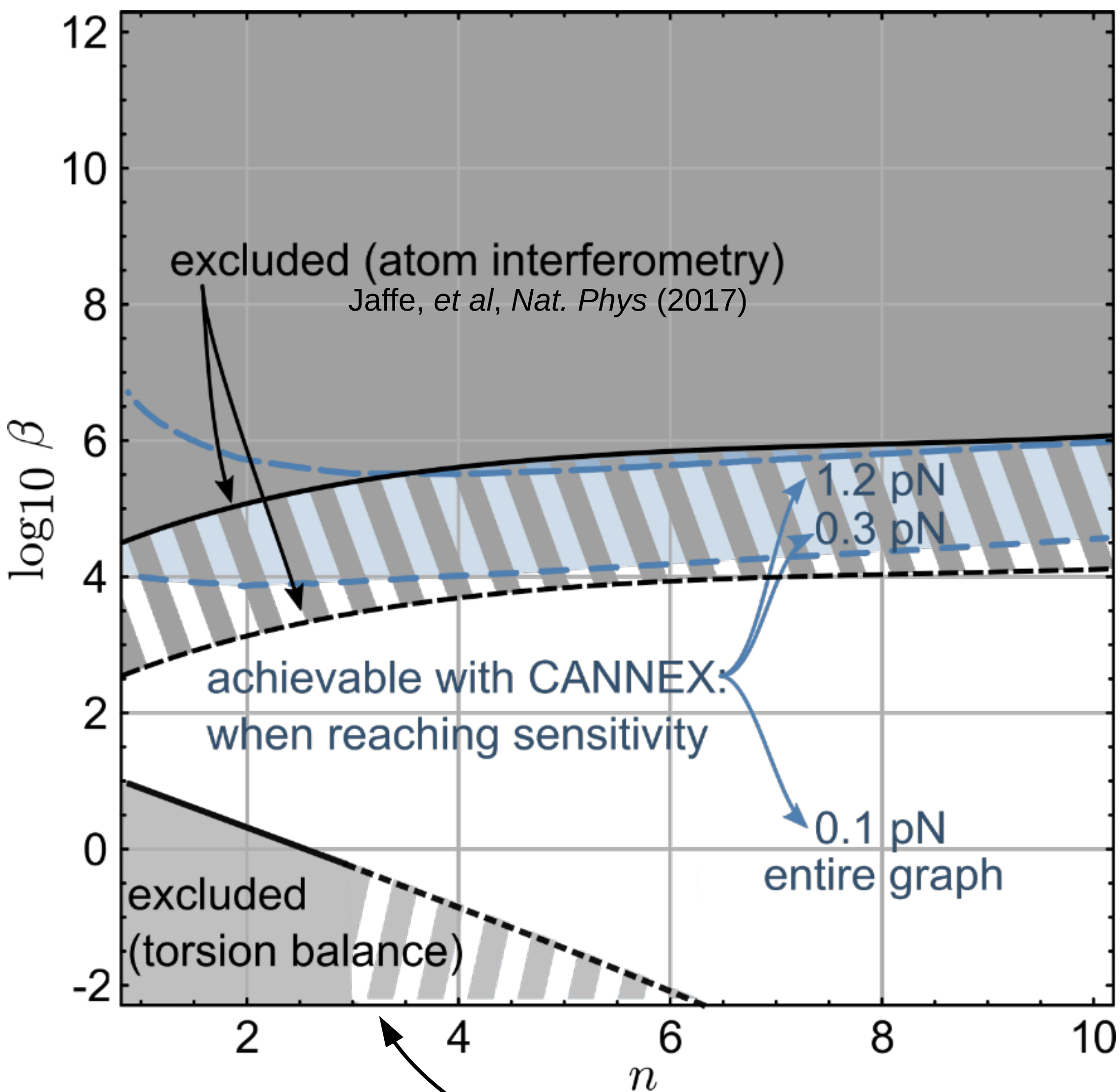
First evaluation. Preliminary!

Calibrated / Measured Parameters

Parallelism (calibrated):	< 200 µrad
Residual electrostatic potential:	< 8 µV
Drift	< 500 nm/h
Total thermal drift error	< 2.5 µm/run

What could we reach?

New limits...



Adelberger, *et al*, Prog. Part. Nucl. Phys. **62**, 102 (2009)

Assumptions:

- $V(\phi) = \Lambda^4 \left(1 + \frac{\Lambda^n}{\phi^n}\right)$
- **Active vibration insulation > 30dB at 1 Hz**
- **Sensitivity limited only by**

  1) Brownian sensor noise

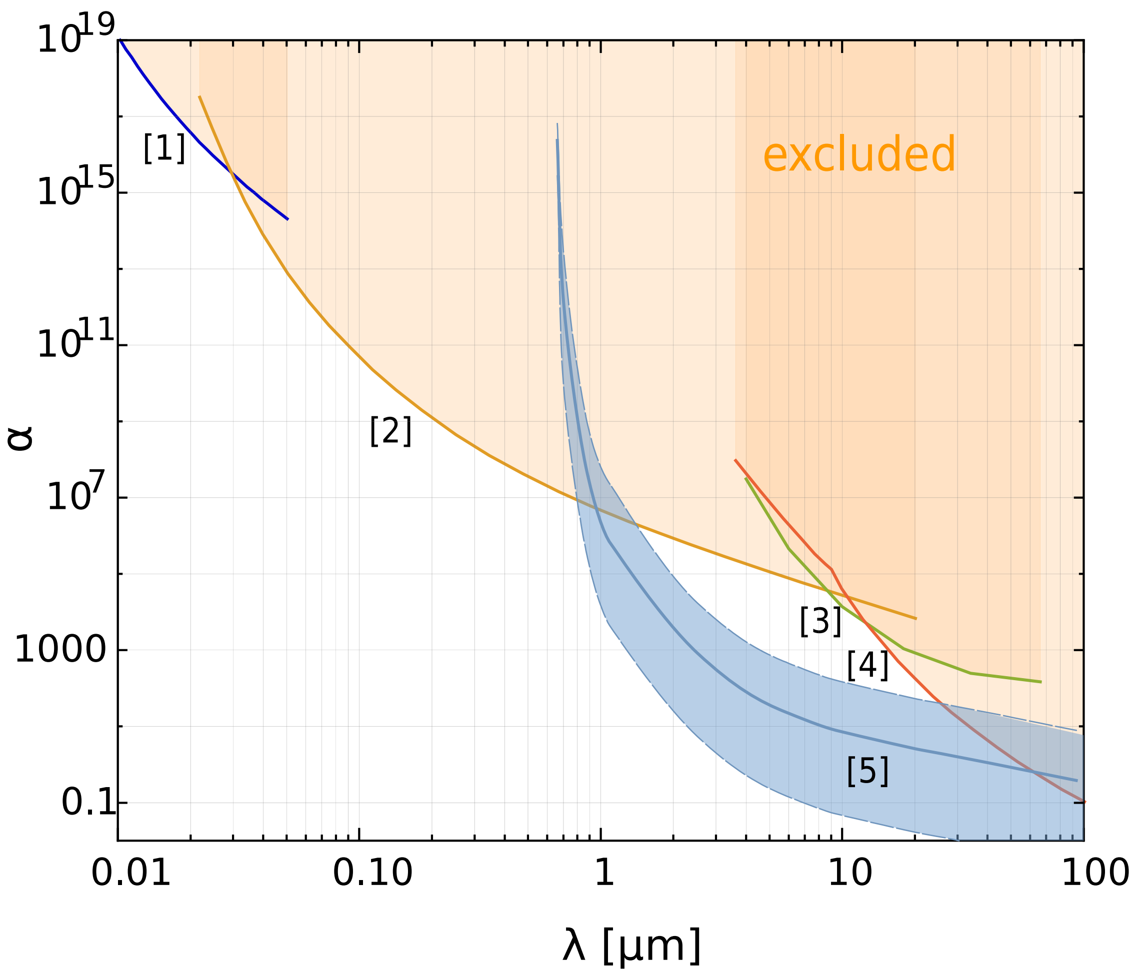
  2) C-bridge electronic noise

Room for improvements:

- **Even better vibration insulation (6 axis, two-staged)**
- **Optical readout**
- **Sensor design with larger mass**

What could we reach?

New limits possible... $\alpha = 2\beta^2 \quad \lambda = m_\phi^{-1}$



— [1] Sushkov et al, *PRL* **107**, 171101 (2011)
— [2] Chen et al, *PRL*, **116**, 221102 (2016)
— [3] Gerarci er al, *PRD* **78**, 022002 (2008)
— [4] Kapner et al, *PRL*, **98**, 021101 (2007)
— [5] Cannex (estimated) d=10 μm, 0.1pN

Assumptions:

- $V(\phi) = -G\frac{m_1 m_2}{d}\left(1 + \alpha e^{-d/\lambda}\right)$
- **Sensitivity limited only by**
  1) Brownian sensor noise
  2) C-bridge electronic noise
- **PRELIMINARY!**

Room for improvements:

- **Even better vibration insulation (6 axis, two-staged)**
- **3 interferometer optical readout**
- **Sensor design with larger mass**

Outlook & Conclusion

Refurbished Cannex:

Improvements:

6 axis active feedback system to cancel resonances

Fully optical measurements

Pressure modulation system

Measurements:

Frequency shift force measurements 10-30 µm, 1 pN

Pressure modulation measurement at 10 µm, 0.1 pN

Possible Results:

Exclusion of Chameleon forces $n \leq 10$, $\beta > 10^{-2}$

Indication if virtual photons behave differently from real ones

Possibly new limits on Yukawa forces

Acknowledgments

Thank you for your attention!

Stay tuned on our website
cannex.vu.nl

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