CANNEX

Casimir And Non-Newtonian force EXperiment

Parallel plate force metrology: Status and Perspectives

PIERS 2023
July 03, 2023, Prague

René Sedmik

NWO Nederlandse Organisatie voor Wetenschappelijk Onderzoek
FOM
FWF Der Wissenschaftsfonds.
TU WIEN TECHNISCHE UNIVERSITÄT WIEN

A little repetition

+

Thermal effects

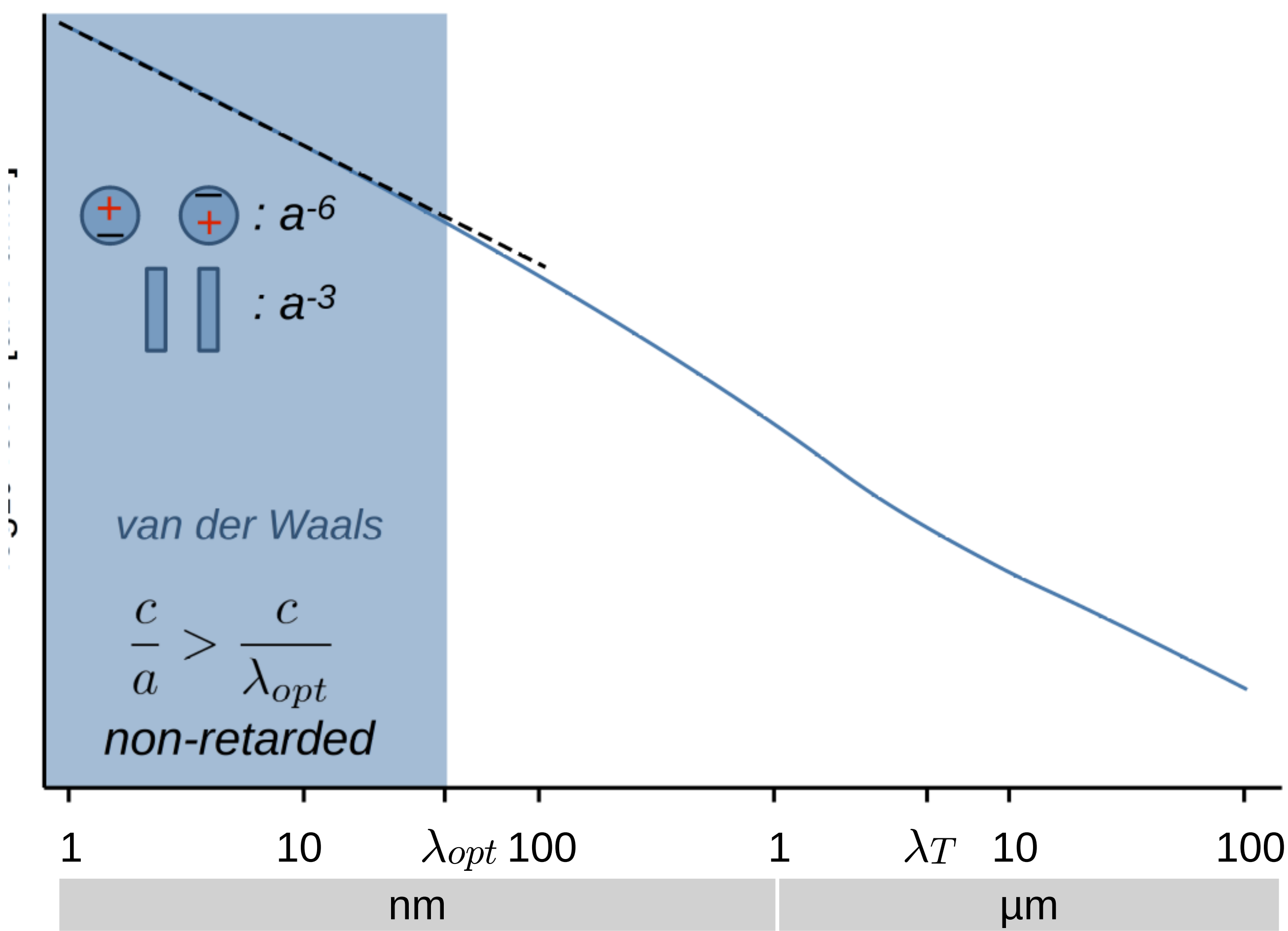
Morphology of dipole interactions:

Dominant source: vacuum fluctuations:

Falloff:

Regime:

Distance:



Distance a

Thermal wavelength: $\lambda_T = \frac{\hbar c}{k_B T}$

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Dominant source: vacuum fluctuations: vacuum fluctuations:

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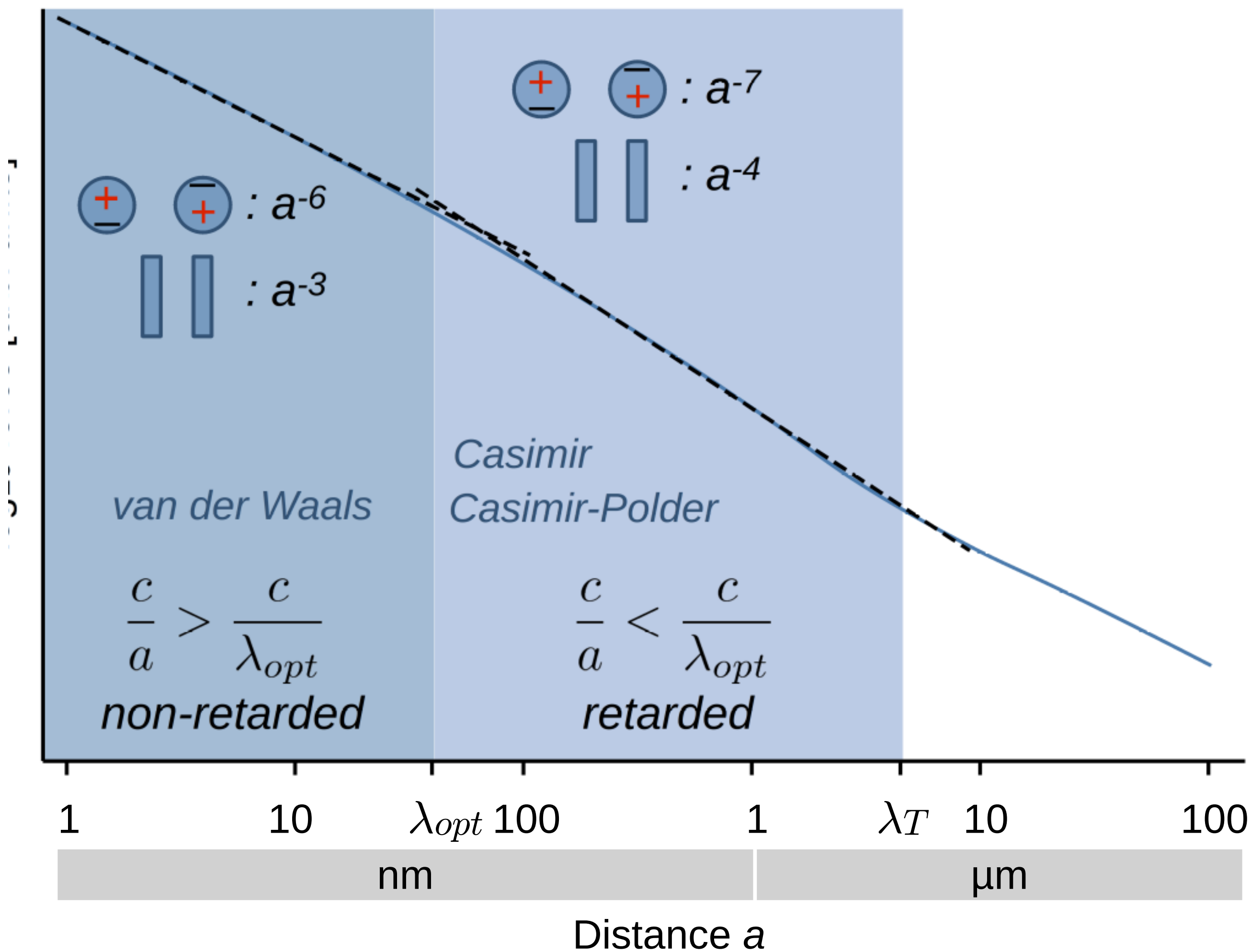

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Dominant source: vacuum fluctuations: vacuum fluctuations: thermal fluctuations:

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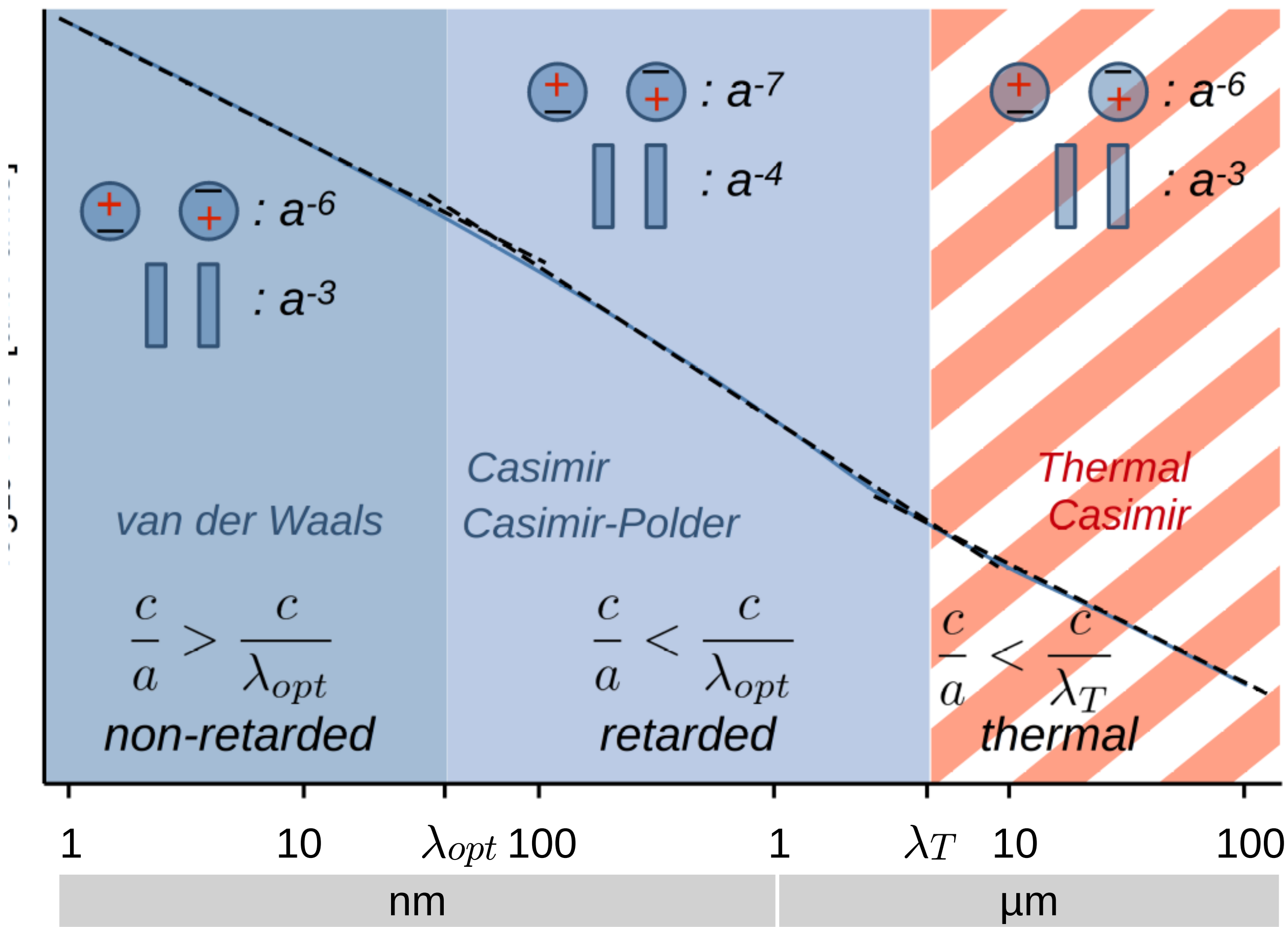
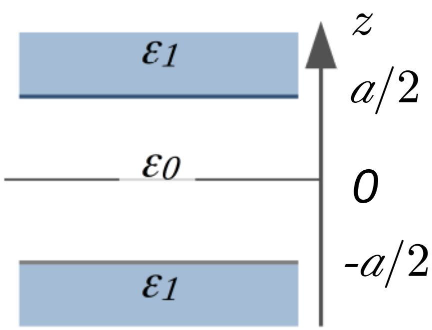


Distance *a*

Thermal wavelength: $\lambda_T = \frac{\hbar c}{k_B T}$

Starting point: Lifshitz theory

Energy per area between plane parallel plates, $T = 0$:



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

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

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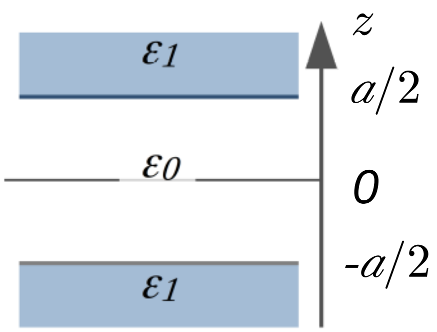

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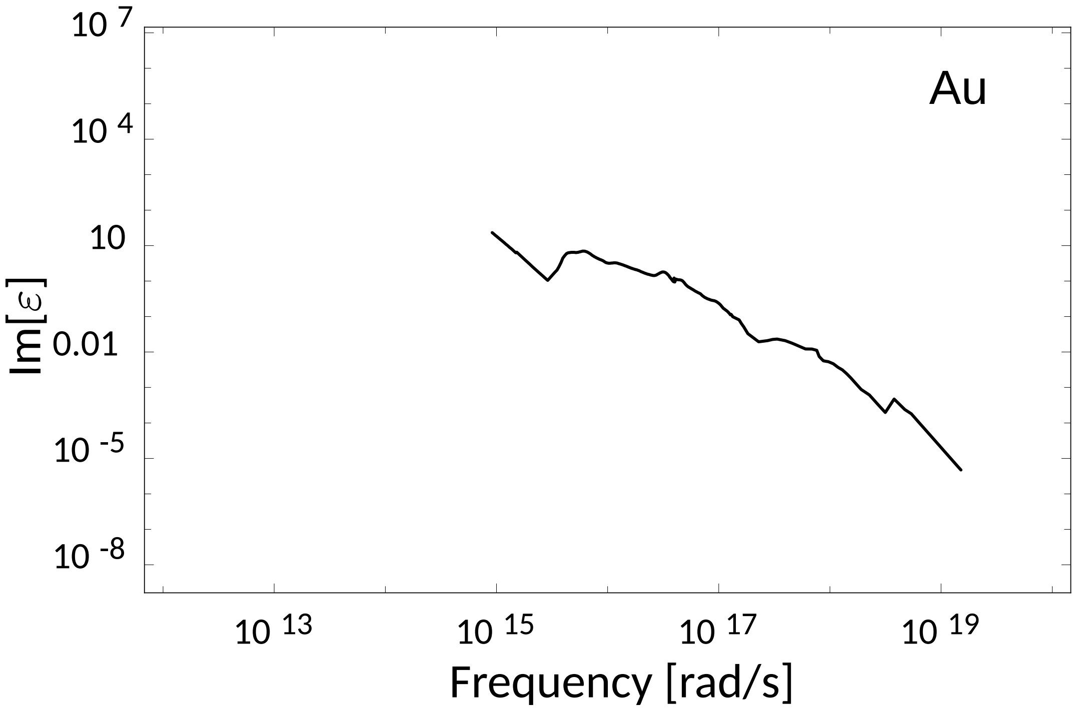
Kramers Kronig transformation:

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

Ellipsometric data: $\mathrm{Im}(\varepsilon) = 2nk$



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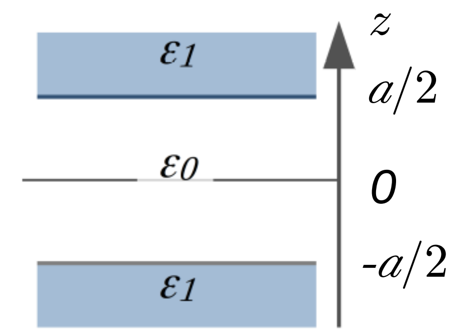

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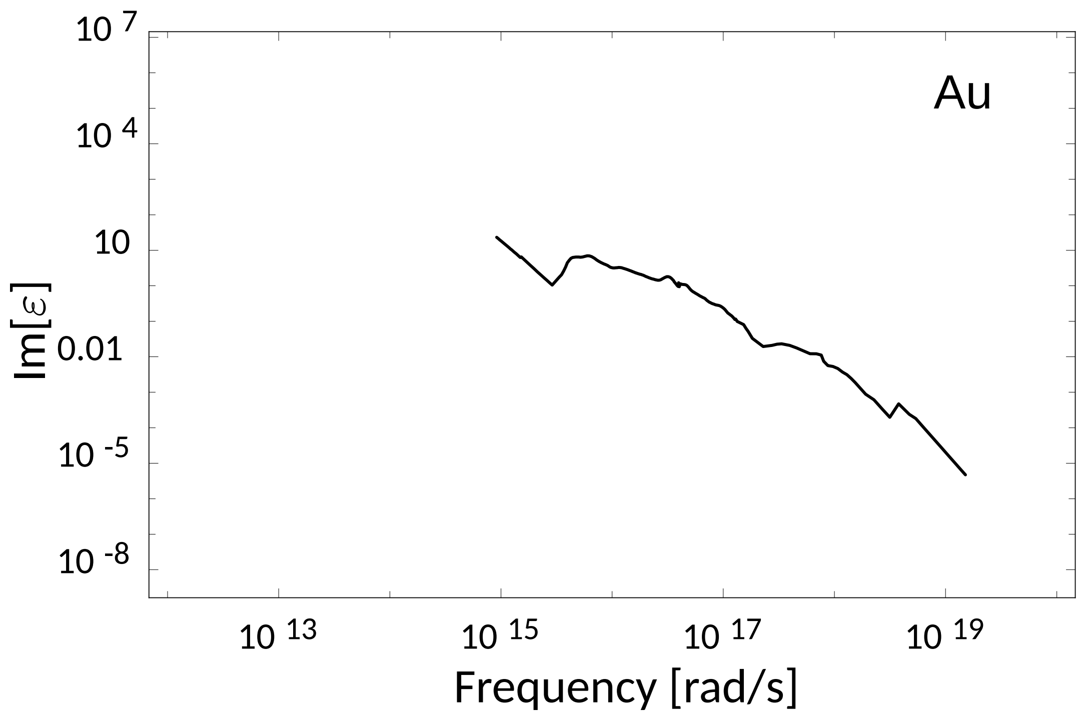

Starting point: The Drude/Plasma debate (Casimir puzzle)

Dissipation at zero frequency or not?

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

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

$+$ oscillator terms

ω_p plasma frequency

γ relaxation frequency (dissipation)

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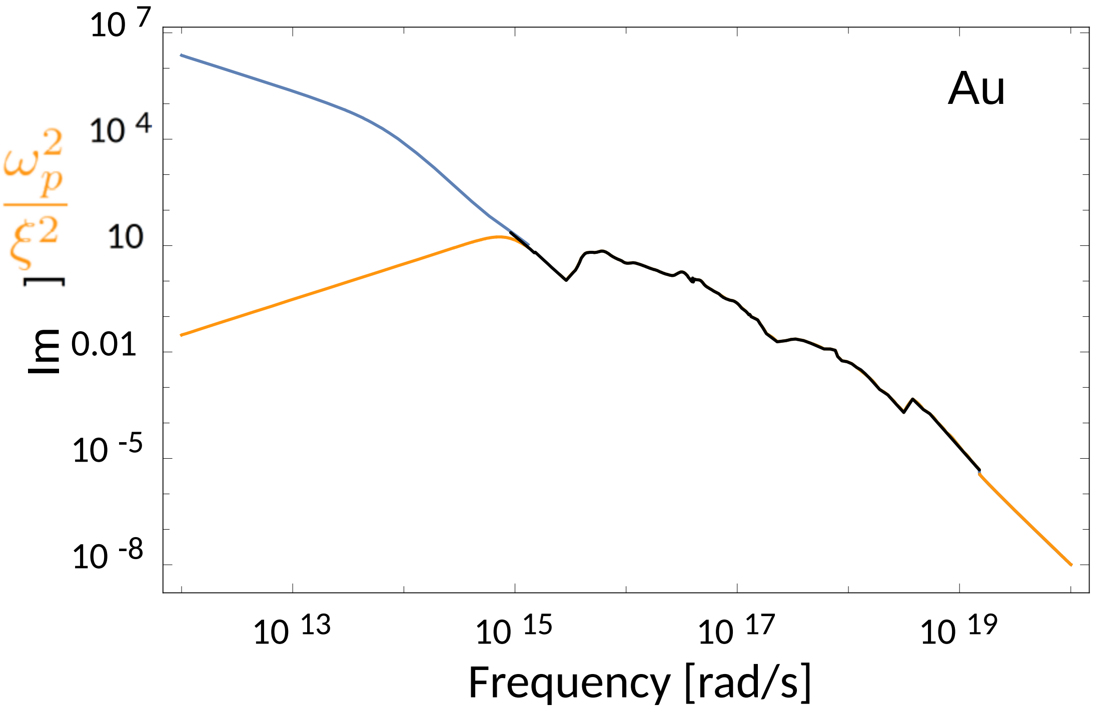

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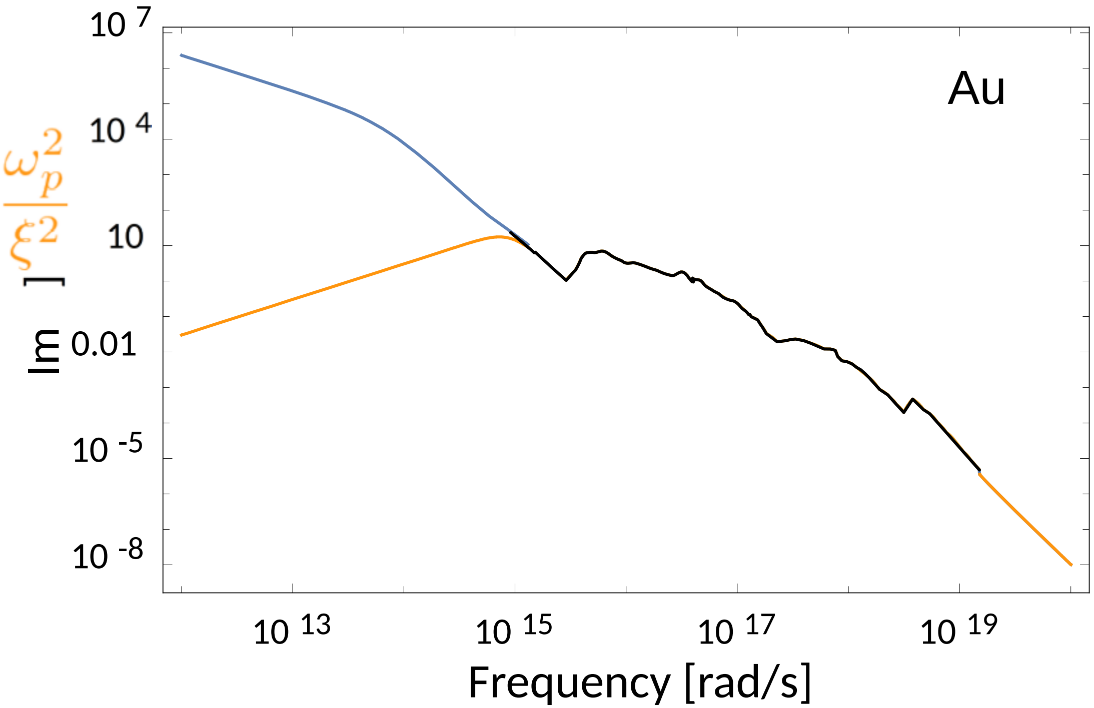

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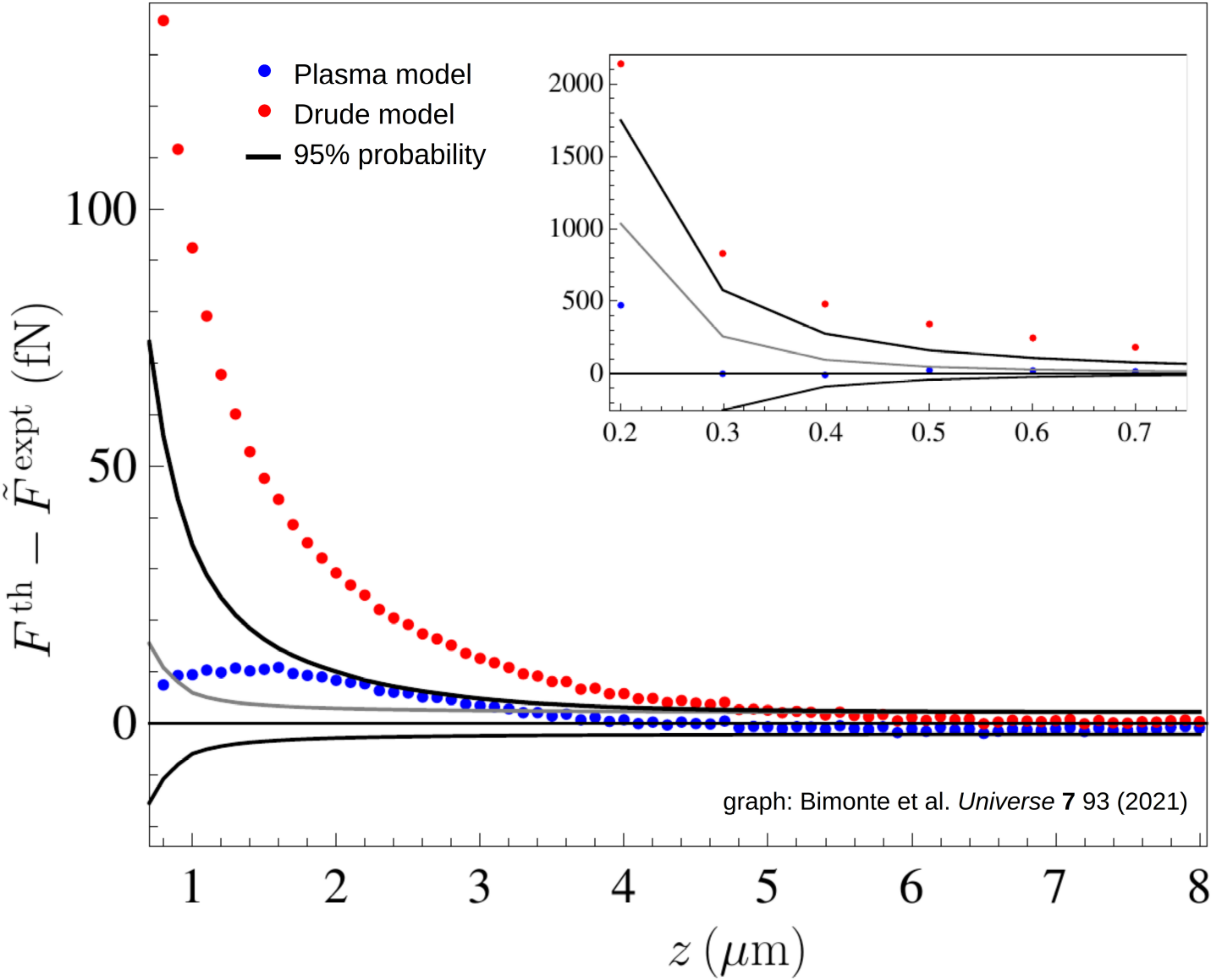
St


Plasma model
Drude model
95% probability
graph: Bimonte et al. *Universe* **7** 93 (2021)
$F^{th} - \tilde{F}^{expt}$ (fN)
z (μm)
100
50
0
1
2
3
4
5
6
7
8
2000
1500
1000
500
0
0.2
0.3
0.4
0.5
0.6
0.7

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

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Recent data suggests:

- No dissipation for vacuum fluctuations (short distance)!

  Bimonte *et al*, Phys. Rev. B **93**, 184434 (2016)
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But ...

- (DC) Dissipation is a proven concept (e.g. Johnson noise)
- ... captured by the Drude model

Q: Why is this still a topic worth investigating?

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Q: Why is this still a topic worth investigating?

A1: Maybe a test of the fluctuation dissipation theorem
A2: Role of Non-locality
A3: Maybe different responses for propagating and evanescent waves?

Thermal Casimir forces (in thermal equilibrium).

Include the spectrum of thermal Planck photons $T \neq 0$

$$\mathcal{F} = -k_B T \ln \sum_{n=0}^{\infty} \mathrm{e}^{-\hbar\omega_n / k_B T}$$ free energy

Formal replacement:

Matsubara frequencies

$$\frac{\hbar}{2\pi} \int_0^{\infty} \mathrm{d}\xi \;\leftrightarrow\; k_B T {\sum_{\ell=0}^{\infty}}{}'$$

$$\xi_\ell = 2\pi \frac{k_B T}{\hbar} \ell$$

Casimir energy at non-zero temperature between parallel plates

$$\frac{\mathcal{F}_{\rm ren}(a,T)}{A} = \frac{k_B T}{(2\pi)c^2} \int_1^{\infty} \mathrm{d}p {\sum_{\ell=0}^{\infty}}{}' p \xi_\ell^2 \left[\ln \frac{\Delta_\perp(i\xi_\ell, a)}{\Delta_{\perp,\infty}(i\xi_\ell)} + \ln \frac{\Delta_\parallel(i\xi_\ell, a)}{\Delta_{\parallel,\infty}(i\xi_\ell)} \right],$$

Split into vacuum and thermal contributions:

$$\mathcal{F}(a,T) = E_{\rm ren}(a, T=0) + \Delta_T \mathcal{F}(a,T)$$

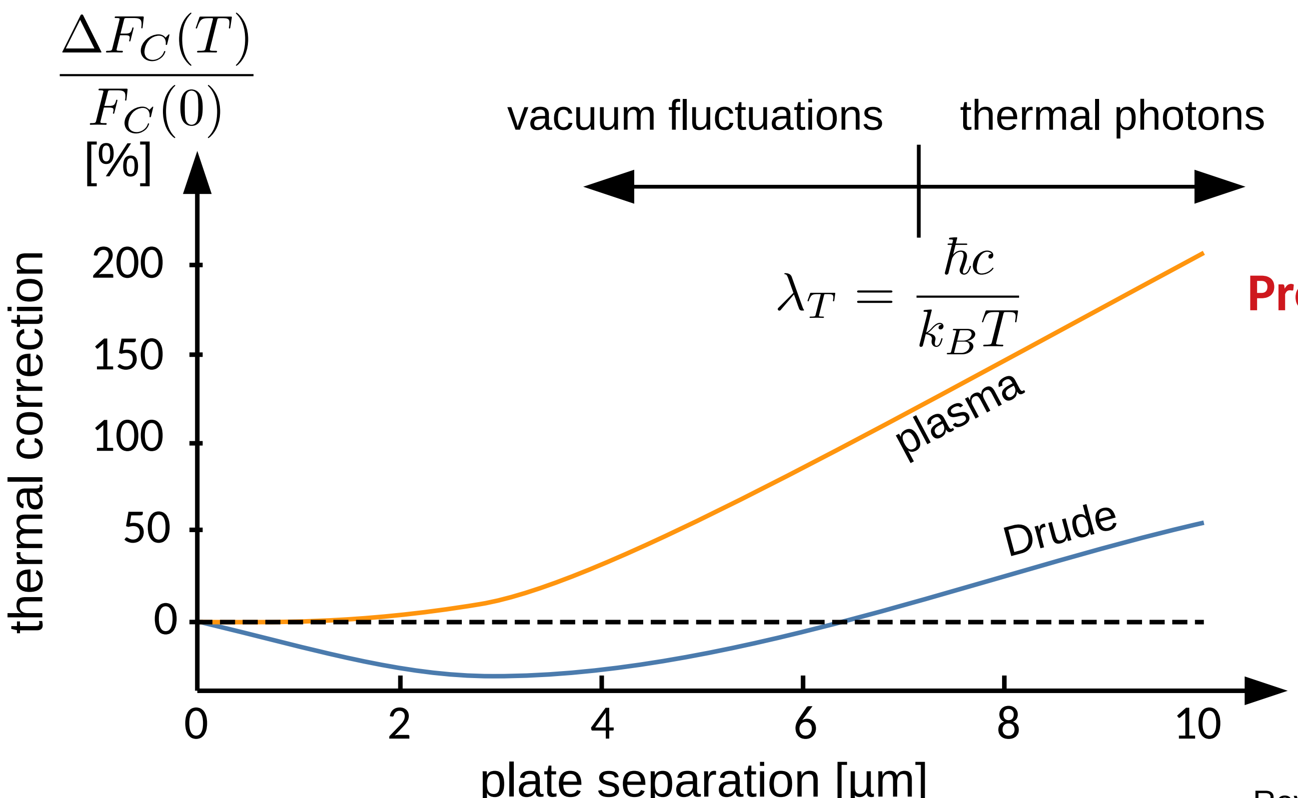
vacuum thermal fluctuations

M.. Bordag et al "Advances in the Casimir effect", *Oxford Science Publications*, (2015).

Thermal Casimir forces and the Casimir Puzzle. Some ideas on what to measure?

Idea 1 (the obvious one)

Measure the force(pressure) at a ~ 10 µm:



Problem: P_C less than 10^{-7} N/m²

Reviews: Mostepanenko, Universe **7**, 84 (2021)

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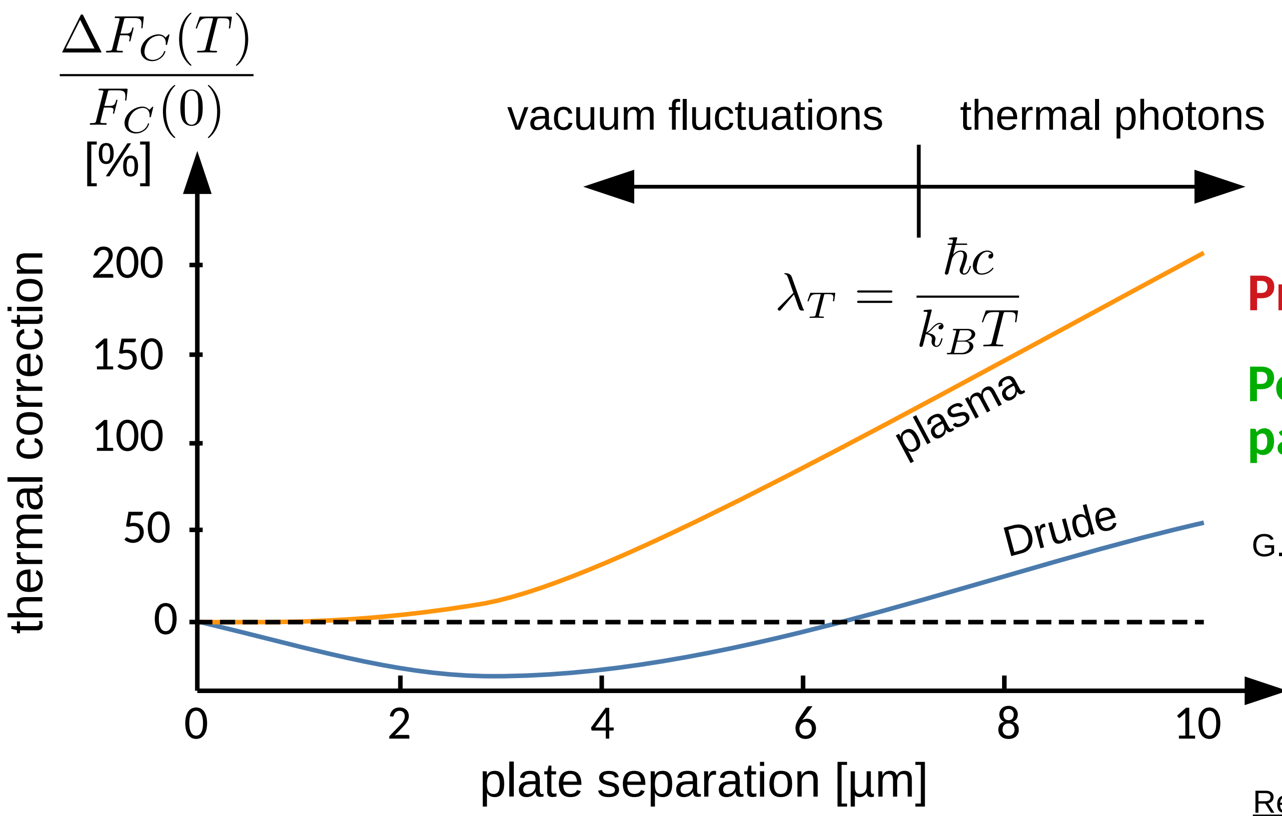

Problem: P_C less than 10^{-7} N/m²

Possible to measure with parallel plates.

G. Klimchitskaya *et al,* Symmetry **11**, 407 (2019)

Reviews: Mostepanenko, Universe **7**, 84 (2021)

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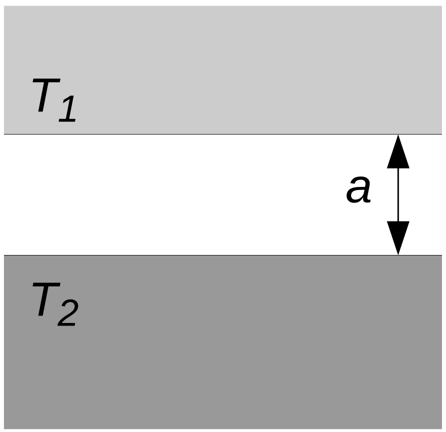
Casimir forces out of thermal equilibrium

pioneering works:
Antezza *et al*, PRL 95, 113202 (2005) , PRA **77**, 022901 (2008),
PRL 97, 223203 (2006)
Krüger et al. EPL 95, 21002 (2011)
Bimonte *et al*, PRA **84**, 042503 (2011), PRA **92**, 032116 (2015)

Idea 2

Two half spaces at **different** temperature



Half spaces:

$$P(a, T_1, T_2) =$$
$$\frac{1}{2}[P_{\rm eq}(a, T_1) + P_{\rm eq}(a, T_2)]$$

equilibrium pressures

Casimir forces out of thermal equilibrium

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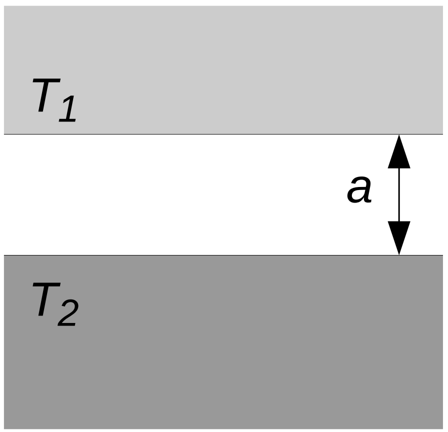
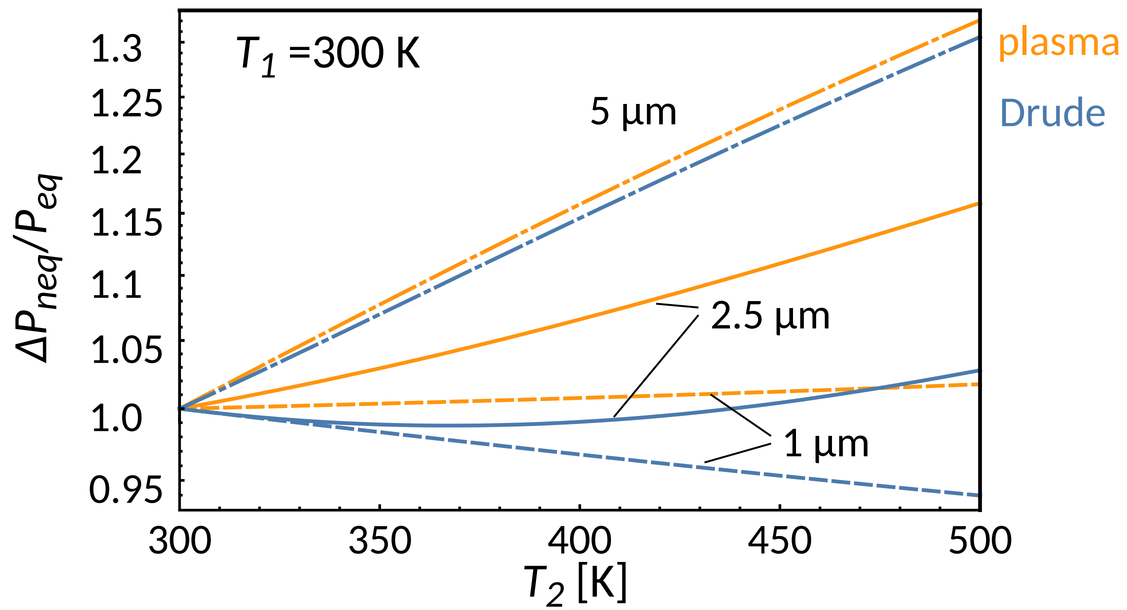




graph data: G. Klimchitskaya, V.M. Mostepanenko, and R.I.P. Sedmik, *PRA* **100**, 022511 (2019)

Half spaces:

$$P(a, T_1, T_2) =$$

$$\frac{1}{2}[P_{\rm eq}(a, T_1) + P_{\rm eq}(a, T_2)] + \Delta P_{\rm neq}(a, T_1, T_2) + \frac{2\sigma}{3c}(T_2^4 + T_1^4)$$

equilibrium pressures   anti-symmetric term   radiation pressure

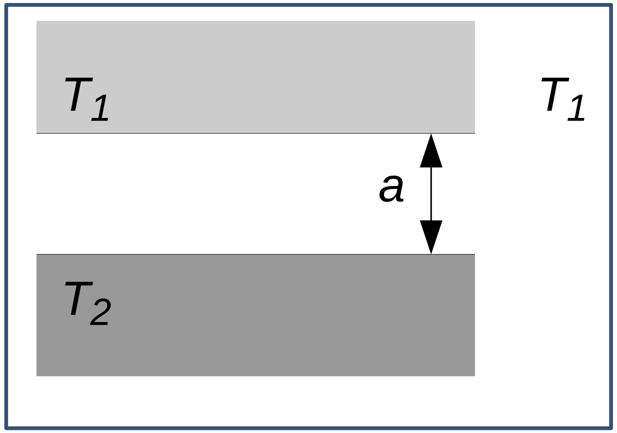
identical plates: $\Delta P_{neq} \rightarrow 0$

Dorofeyev, J. Phys. A **31**, 4369 (1998)

Antezza *et al*, PRA **77**, 022901 (2008)

Casimir forces out of thermal equilibrium

Idea 2
Two plates at **different** temperature
One plate in equilibrium with environment



Finite plates

$$P^{(1)}(a,T_1,T_2) =$$

$$\frac{1}{2}[P_{\rm eq}(a,T_1) + P_{\rm eq}(a,T_2)] + \Delta P_{\rm neq}(a,T_1,T_2) + \frac{2\sigma}{3c}(T_2^4 - T_1^4)$$

equilibrium pressures anti-symmetric term radiation pressure

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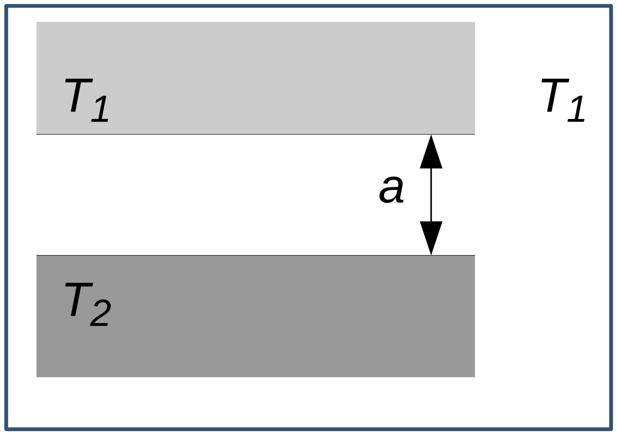

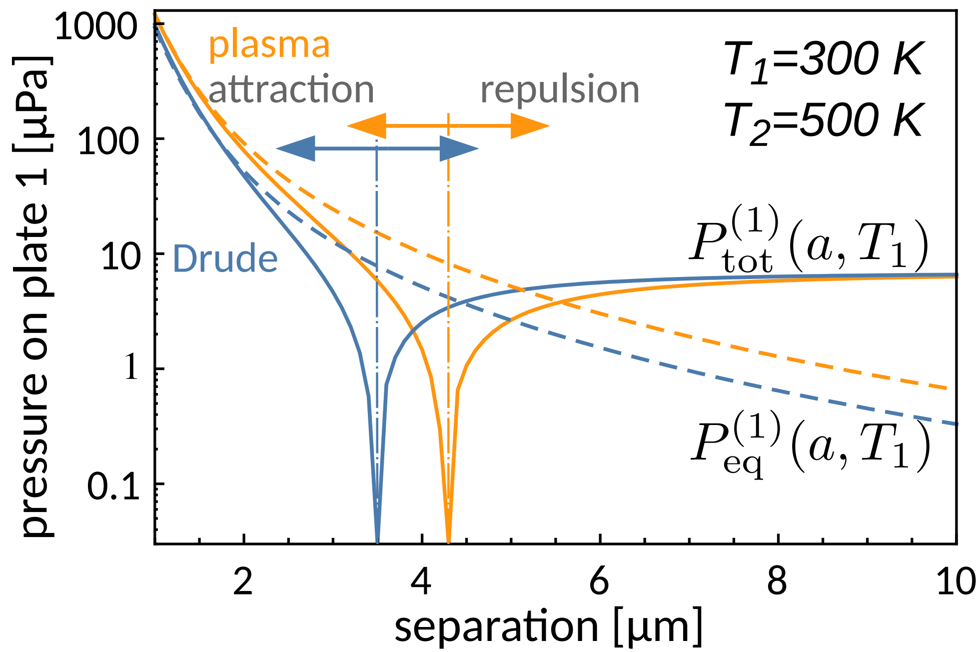

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equilibrium pressures — anti-symmetric term — radiation pressure

identical plates: $\Delta P_{neq} \to 0$

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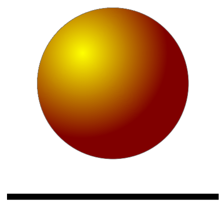
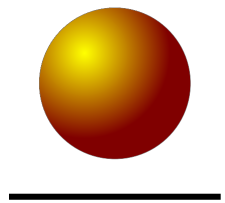
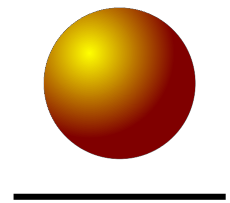
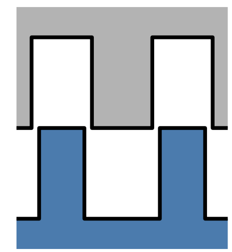
allows for repulsion, spatially oscillating potentials, bound states, self-propulsion...

Can we measure these effects?

How to measure these effects?
A little orders of magnitude comparison

	Torsional balances	AFM-type	Micro-machined oscillators	Micro-beam	Parallel plates
Geometry					
Object size	10 cm	100 µm	100 µm	1 mm	1 cm
Theory	PFA	PFA	PFA	Full Theory	**~exact**
Effective Area [cm²] $A_{eff} \approx \pi R d$	0.01	10^{-6}	10^{-6}	10^{-5}	**1**
Sensitivity [pN]	1	**10^{-2}**	**10^{-3}**	1	0.1 (target)

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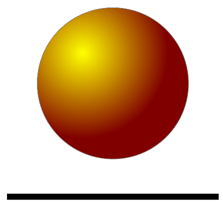
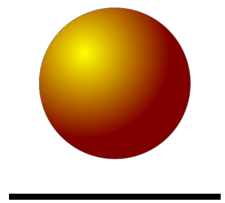
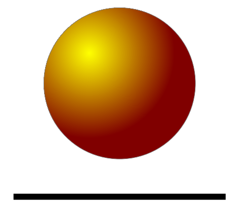
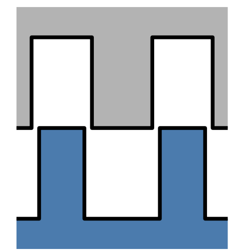
Geometry					
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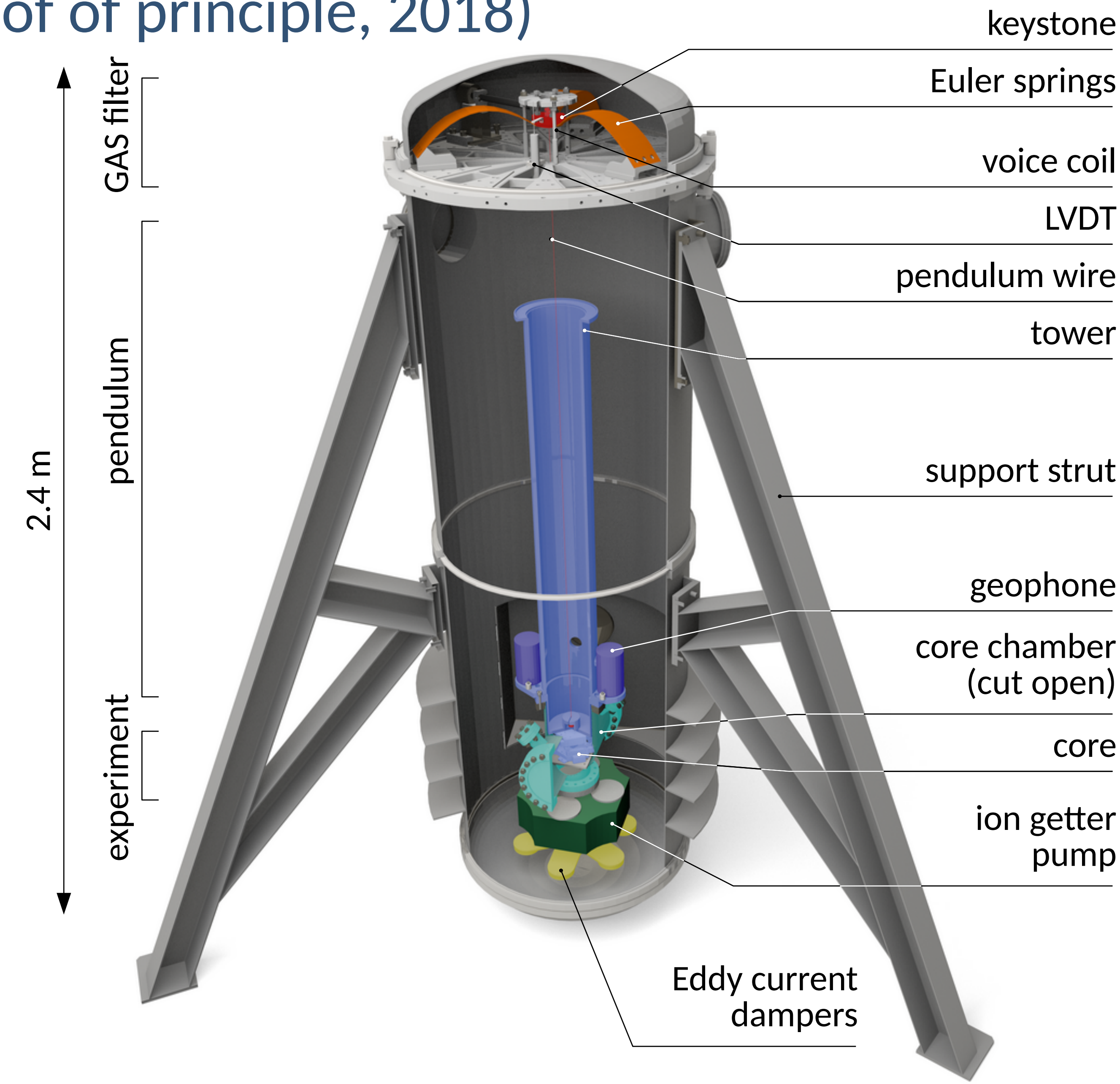
[pN/cm²]	100	10^{4}	1000	10^{5}	**0.1** (target)
Advantage	Precision	Versatility	Precision	Geometry	Precision

The CANNEX Setup

Setup (proof of principle, 2018)

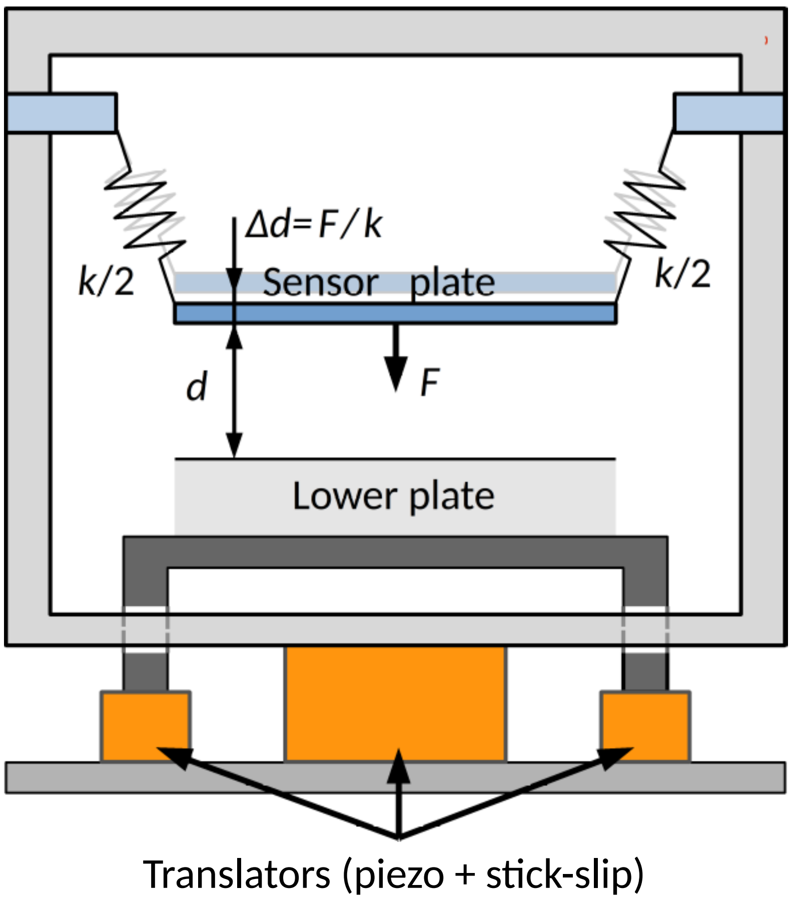


CANNEX overview and isolation system

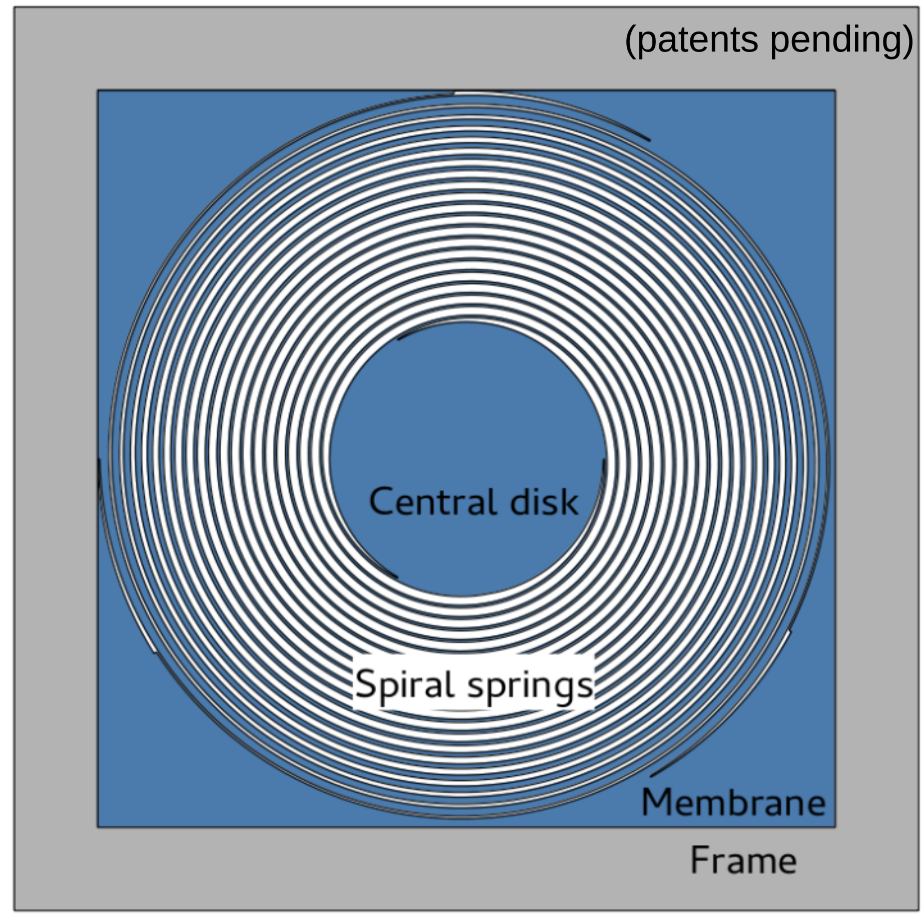
Force detection

Principle:

Measure the displacement
or resonance freq. 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 cm^2
Waviness(disk)	< 15 nm (whole area)
Coating:	10 nm TiW + 65 nm Au

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Measure the displacement
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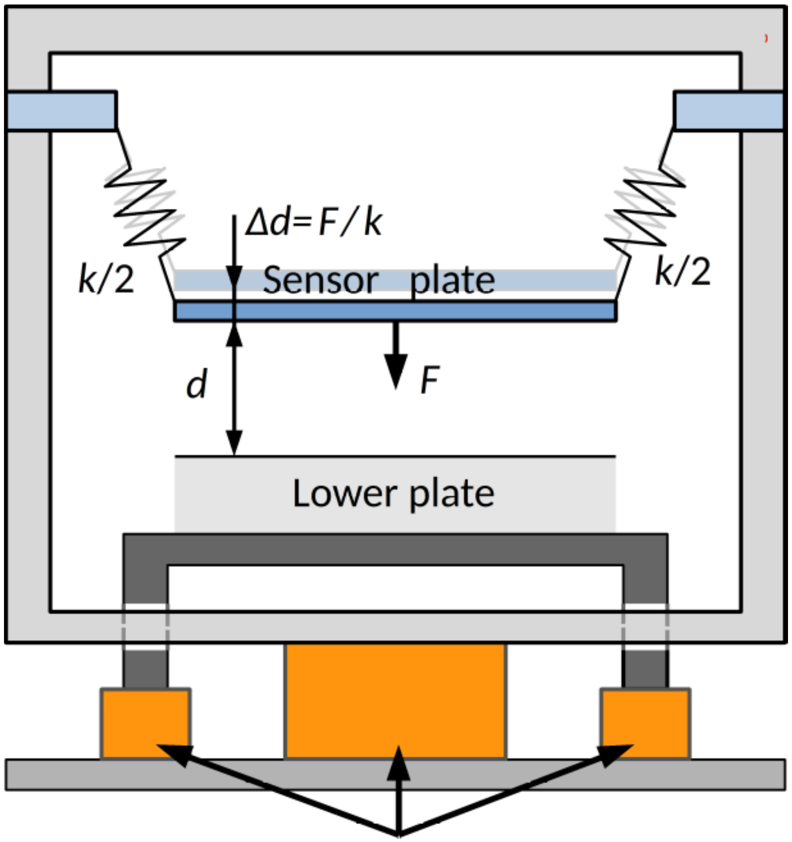
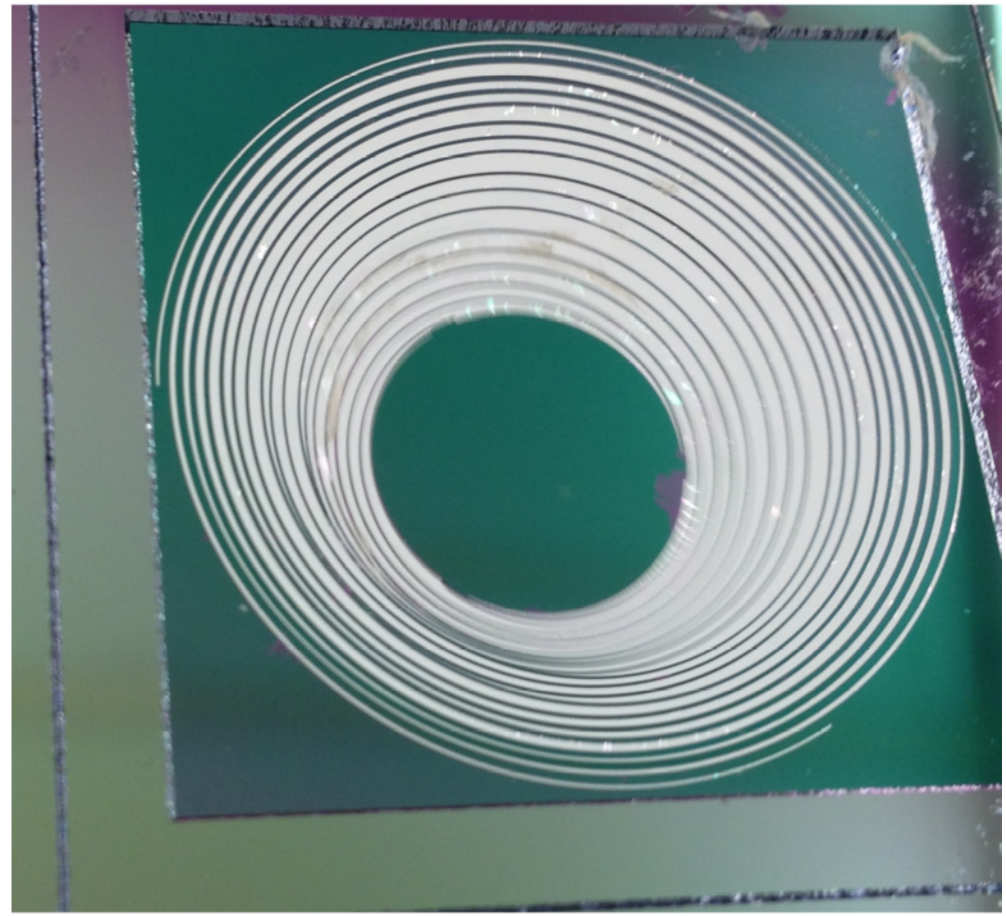


Implementation: upper plate (sensor)



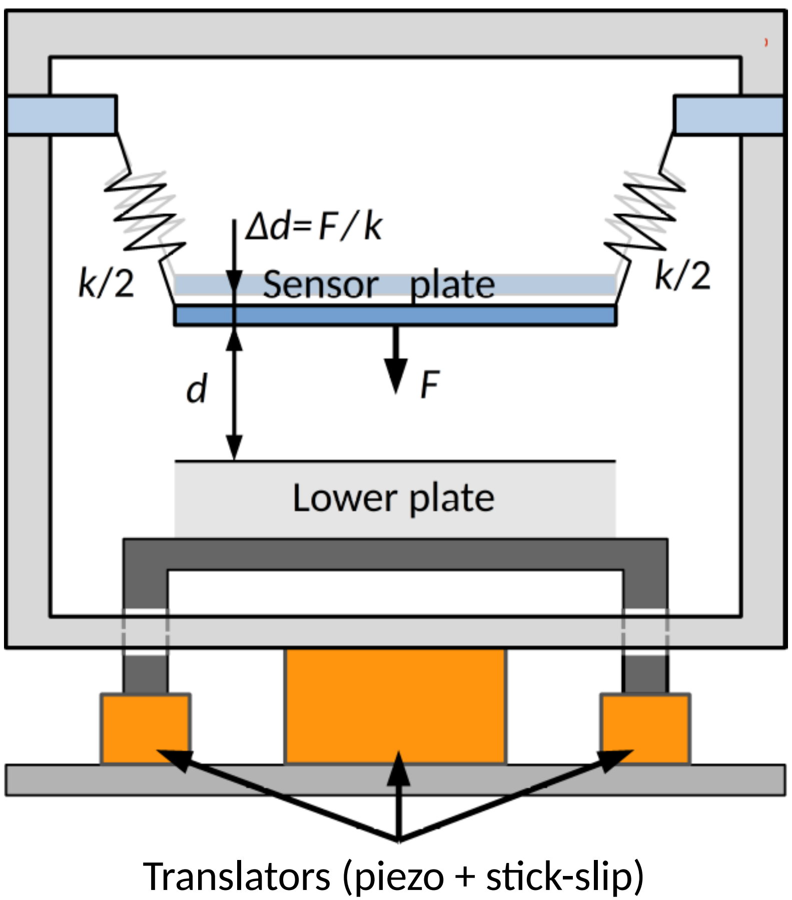
Custom-fabricated Silicon membrane

Force constant:	0.22±0.02 N/m
Disk area :	1.0834±0.0005 cm^2
Waviness(disk)	< 15 nm (whole area)
Coating:	10 nm TiW + 65 nm Au

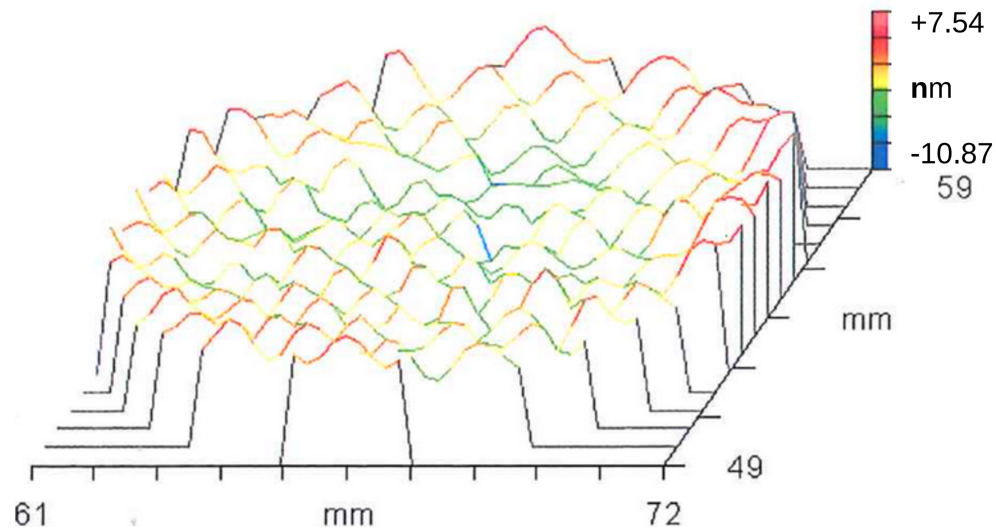
Force detection

Principle:

Measure the displacement
or resonance frequency of a spring.



Implementation lower plate:



Custom-fabricated SiO_2 disk

Thickness	6 mm
Disk area	1 cm^2
Waviness(disk)	< 18 nm (whole area)
Coating	5 nm Cr + 100 nm Au

Force detection (2018)

Detection Principle:

Forces

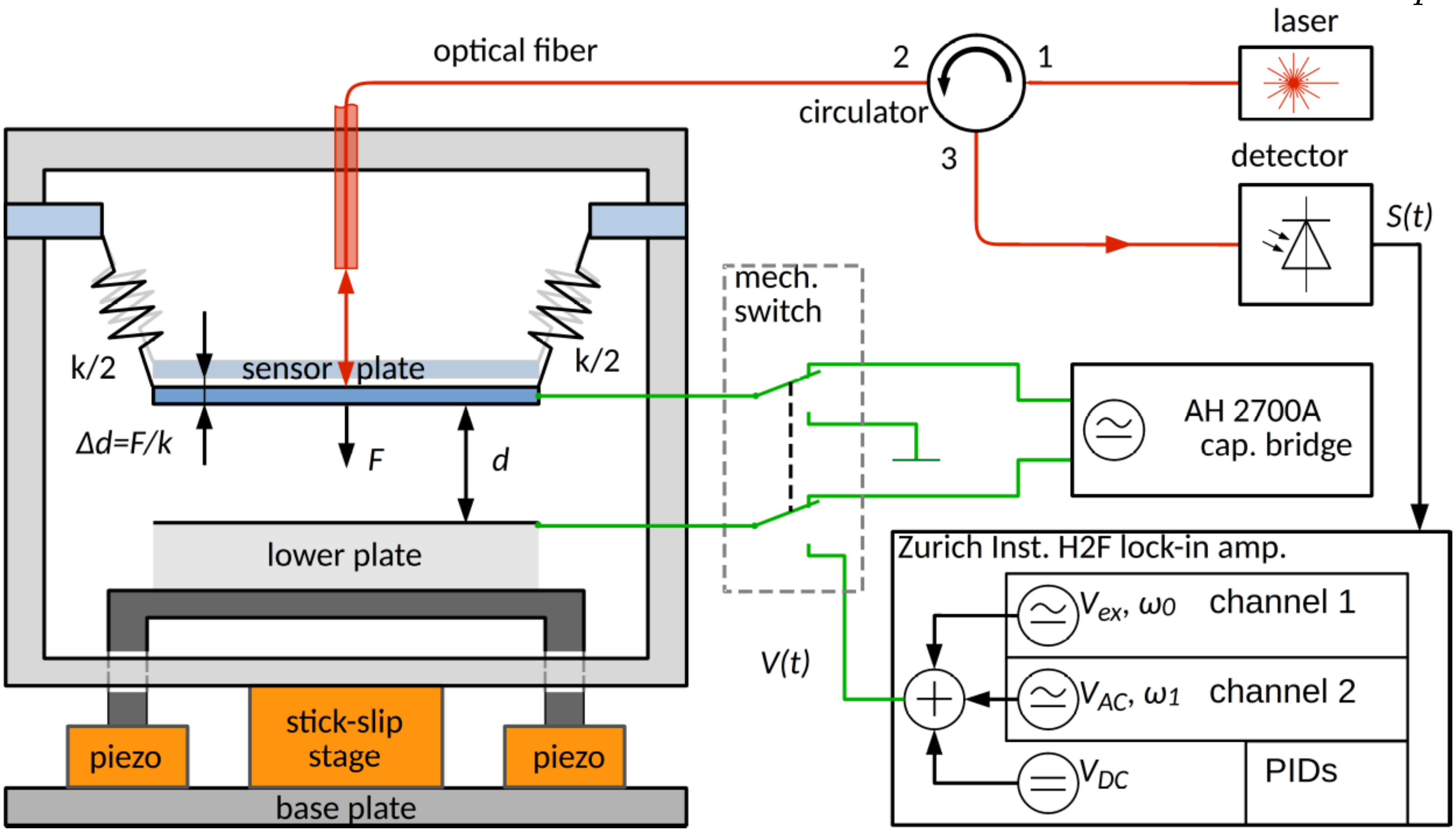
$$F(d) = \Delta d\, k$$

Force gradients

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

Chameleon: pressure modulation

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



Control: **Parallelism:** tilt modulation + feedback **Separation:** Electrostatic fit ***V*₀:** feedback

Force detection concepts

Detection Principle:

Forces

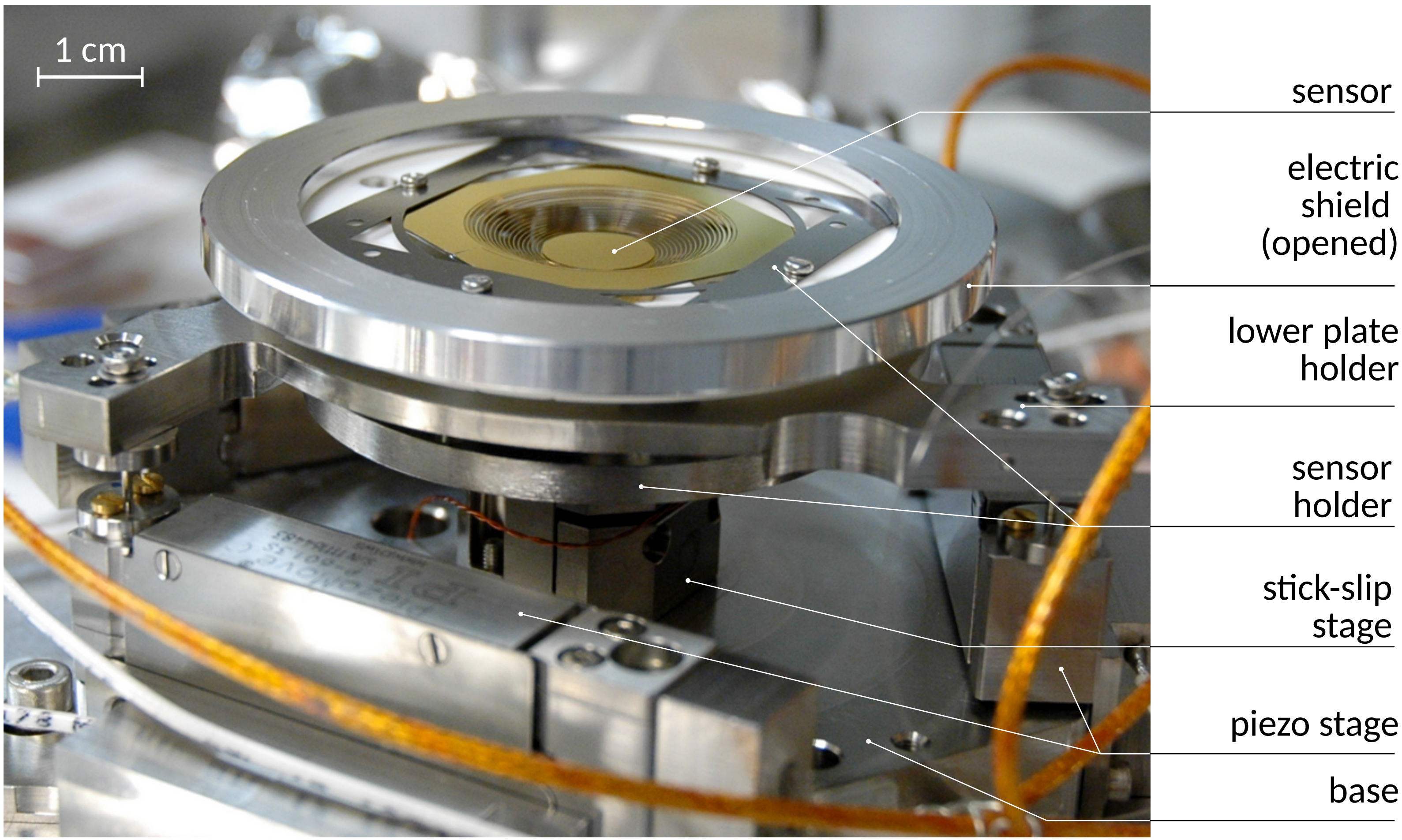
$$F(d) = \Delta d \, k$$

Force gradients

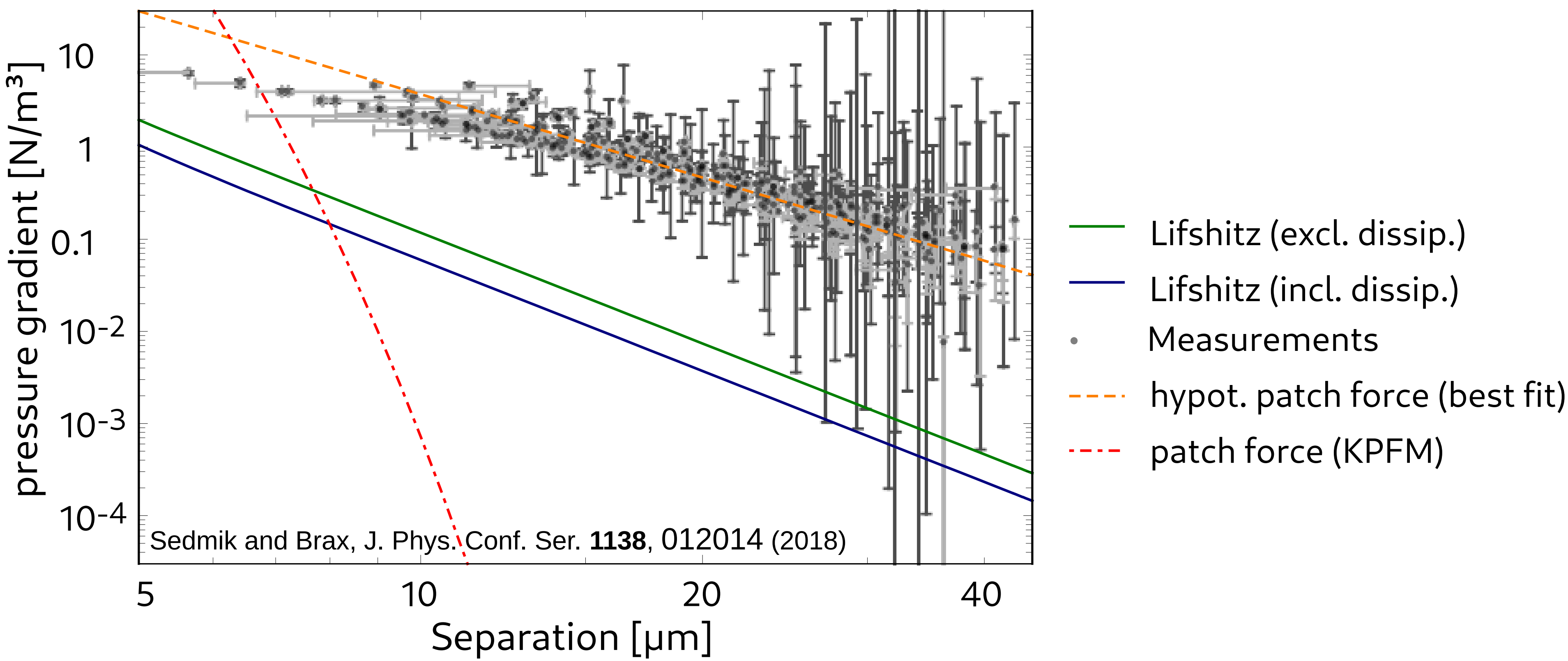
$$\omega_0 = \sqrt{\frac{k}{m} - \frac{1}{m}\frac{\partial F(d)}{\partial d}}$$

Chameleon: pressure modulation

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



First results (under far from ideal conditions)



Take-home message:

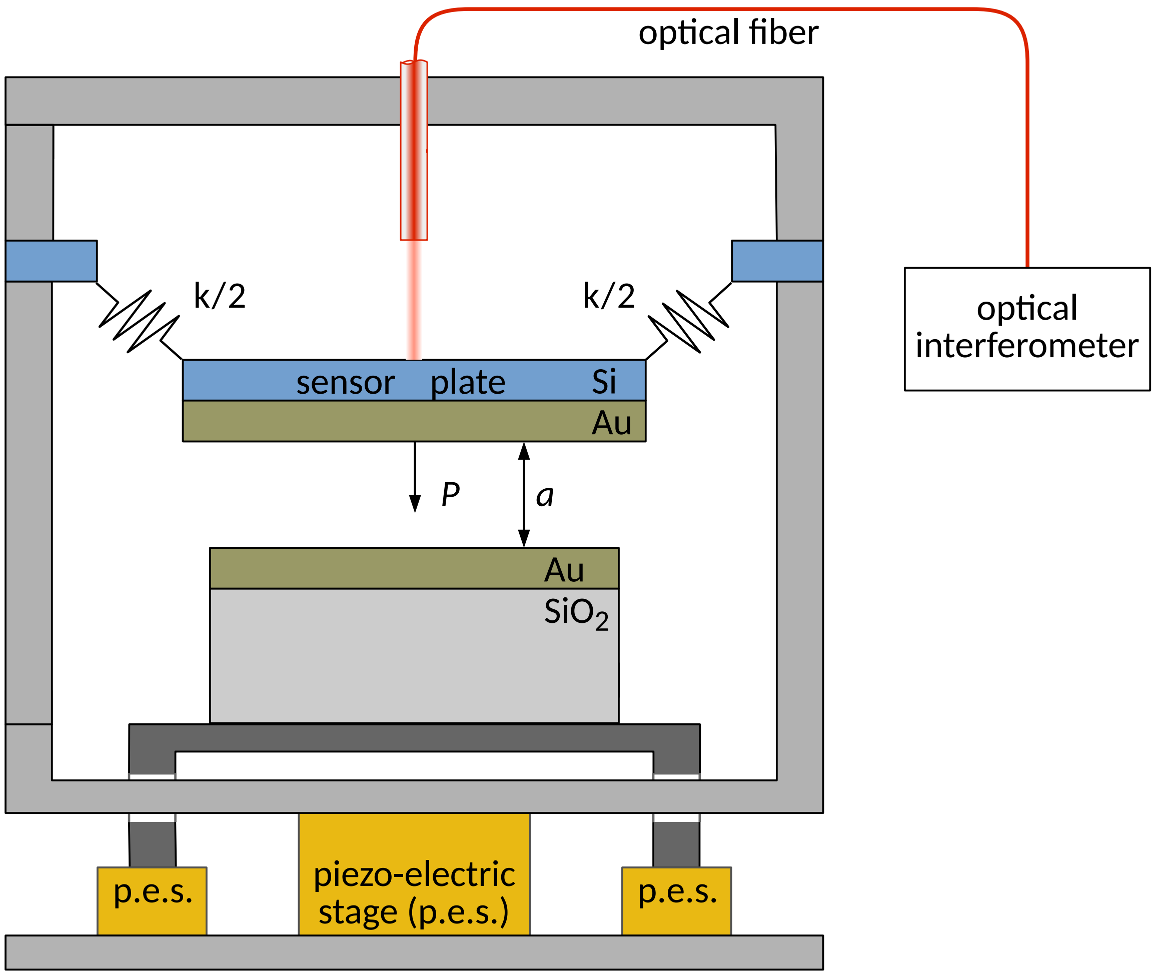
CANNEX works in principle.
Proof of concept successful.

Calibrated / Measured Parameters

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

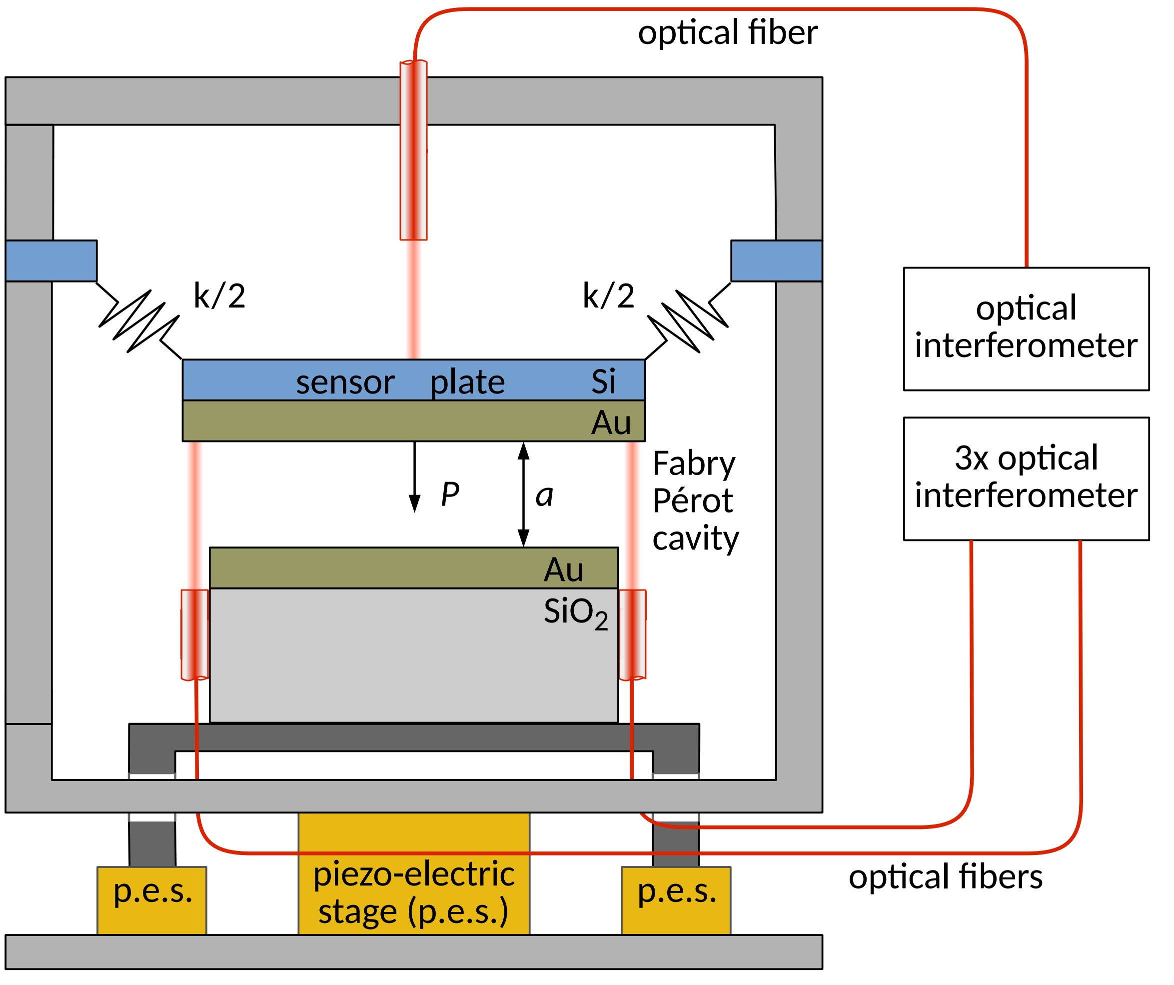
Updates – a new setup

Planed technical improvements (core)



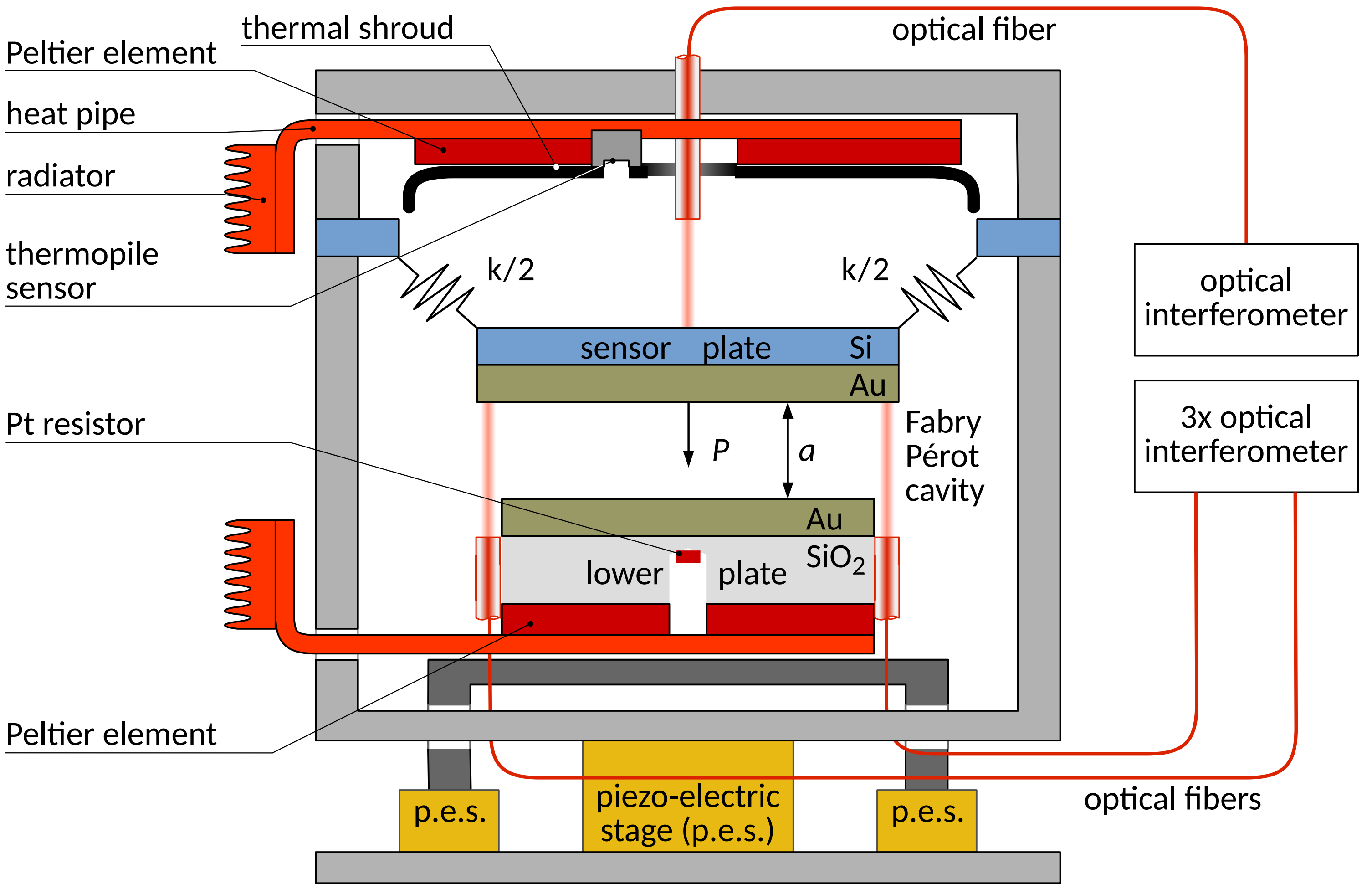
Planed technical improvements (core)

- All-optical sensing for parallelism and frequency shift → Less ES background



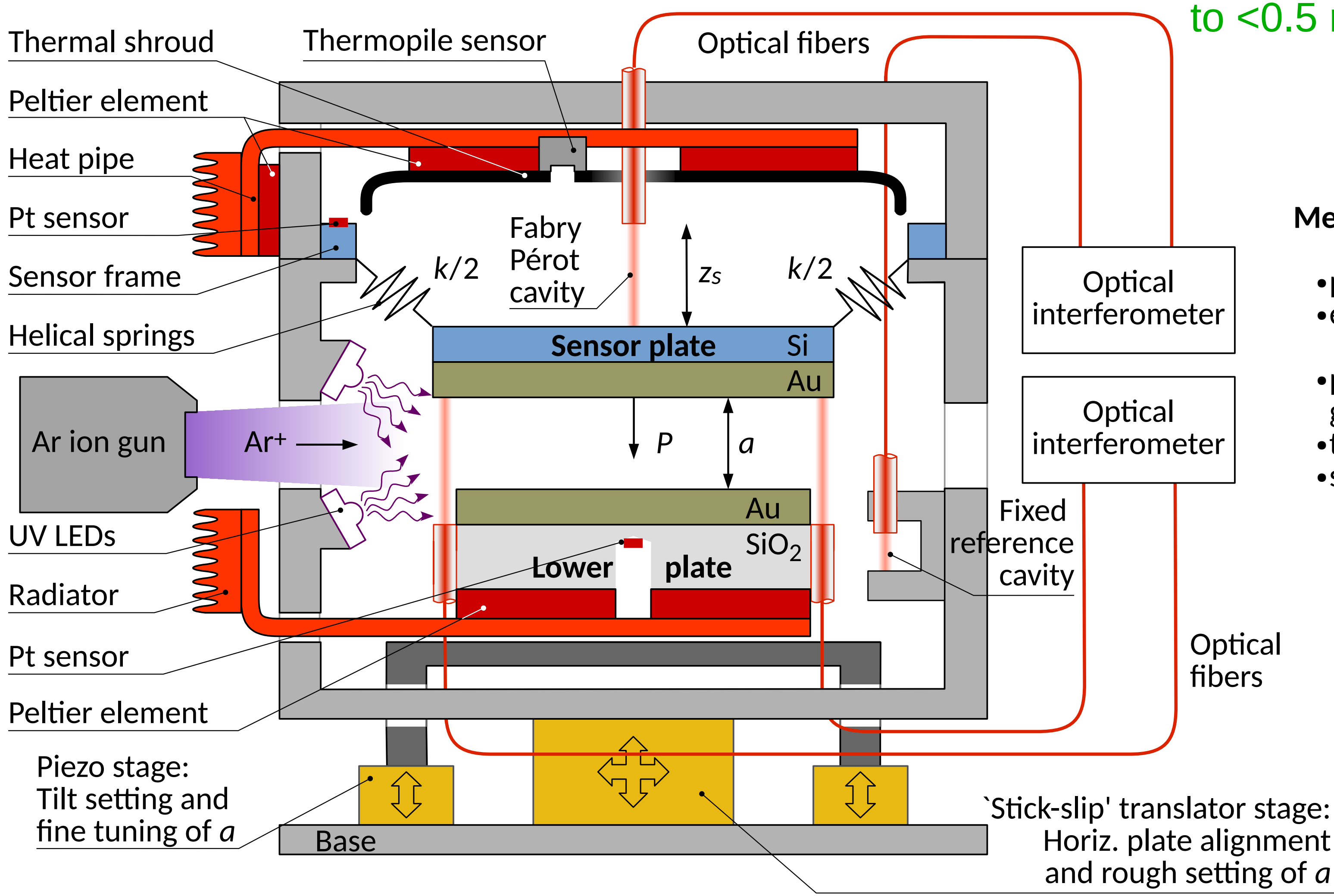
Planed technical improvements (core)

- All-optical sensing for parallelism and frequency shift → Less ES background
- Independent thermal controls for both plates → Enable $\Delta T = 10$ K with < 1mK precision

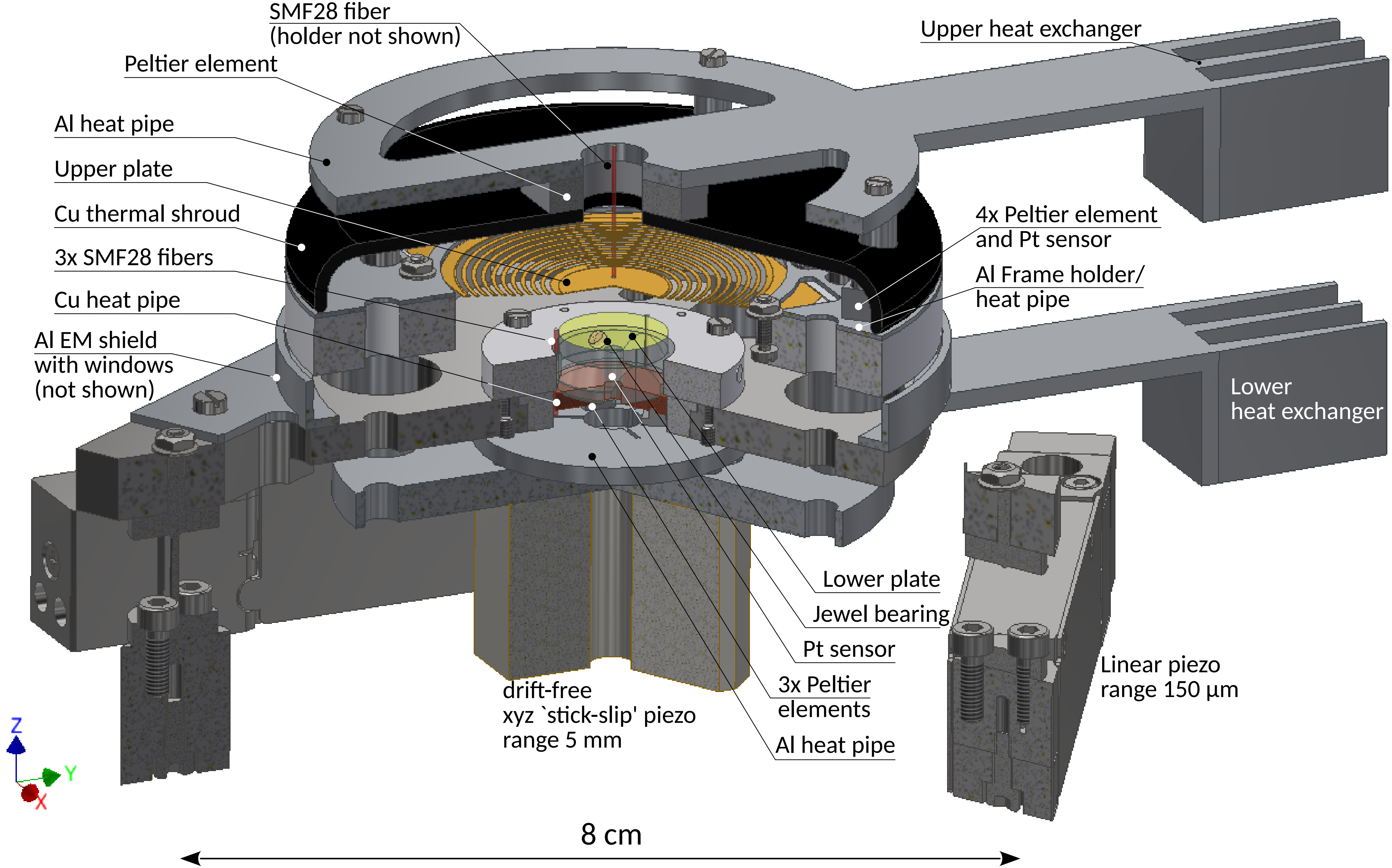


Planed technical improvements (core)

- All-optical sensing for parallelism and frequency shift → Less ES background
- Independent thermal controls for both plates → Enable ΔT = 10 K with < 1mK precision
- In-situ Ar-Ion cleaning and UV irradiation → Reduce surface pot. to <0.5 mV$_{RMS}$



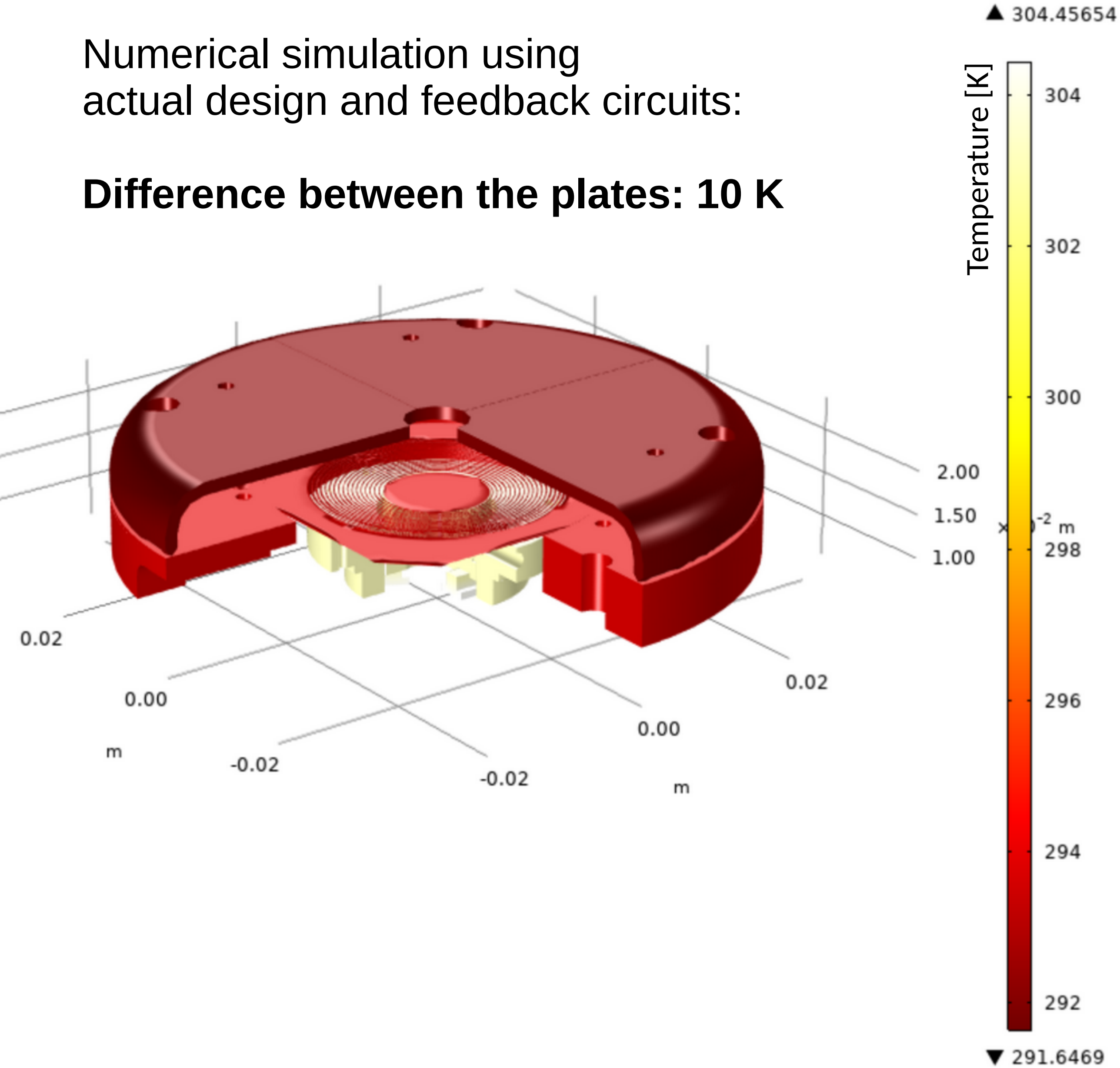
Planned technical improvements (core) Realization

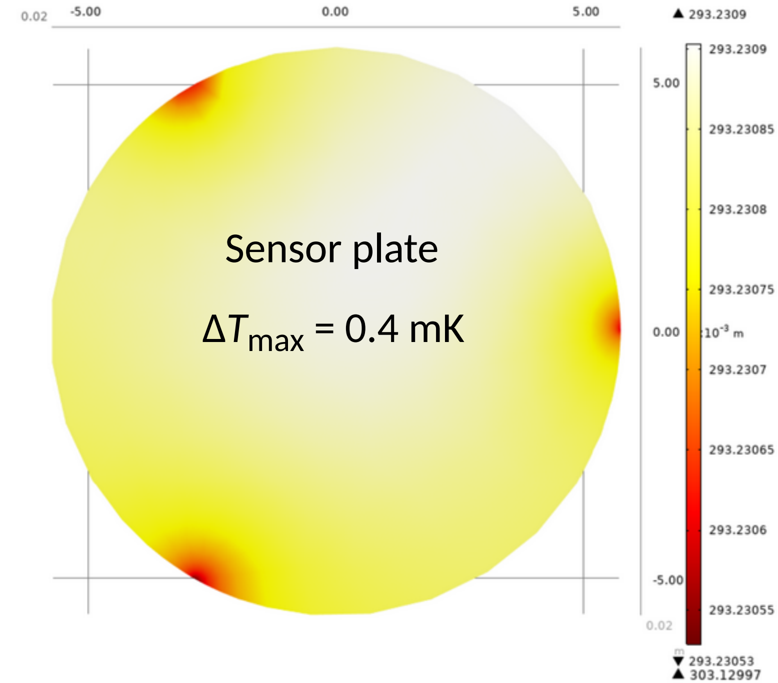


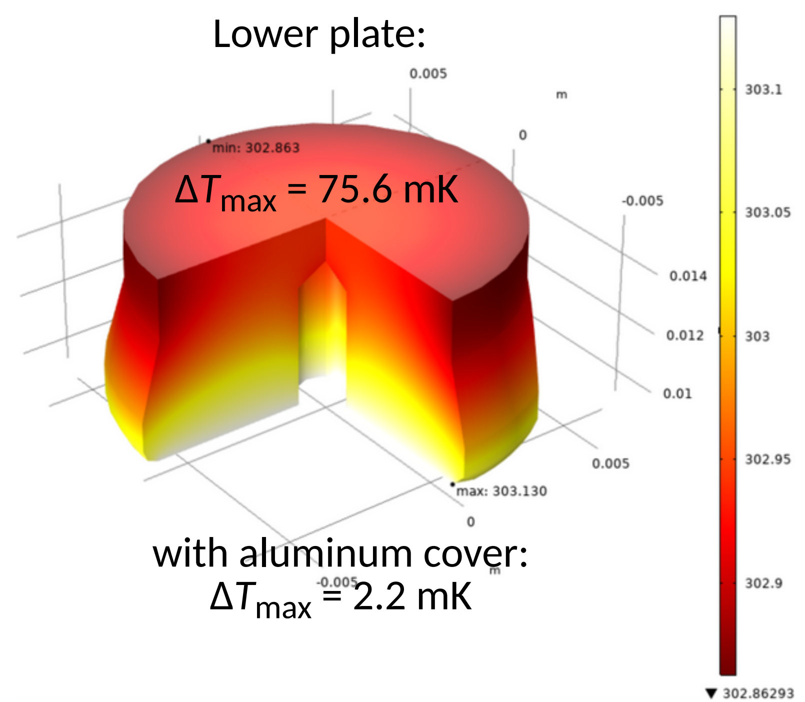
Planned technical improvements (core) Realization

Numerical simulation using
actual design and feedback circuits:

Difference between the plates: 10 K

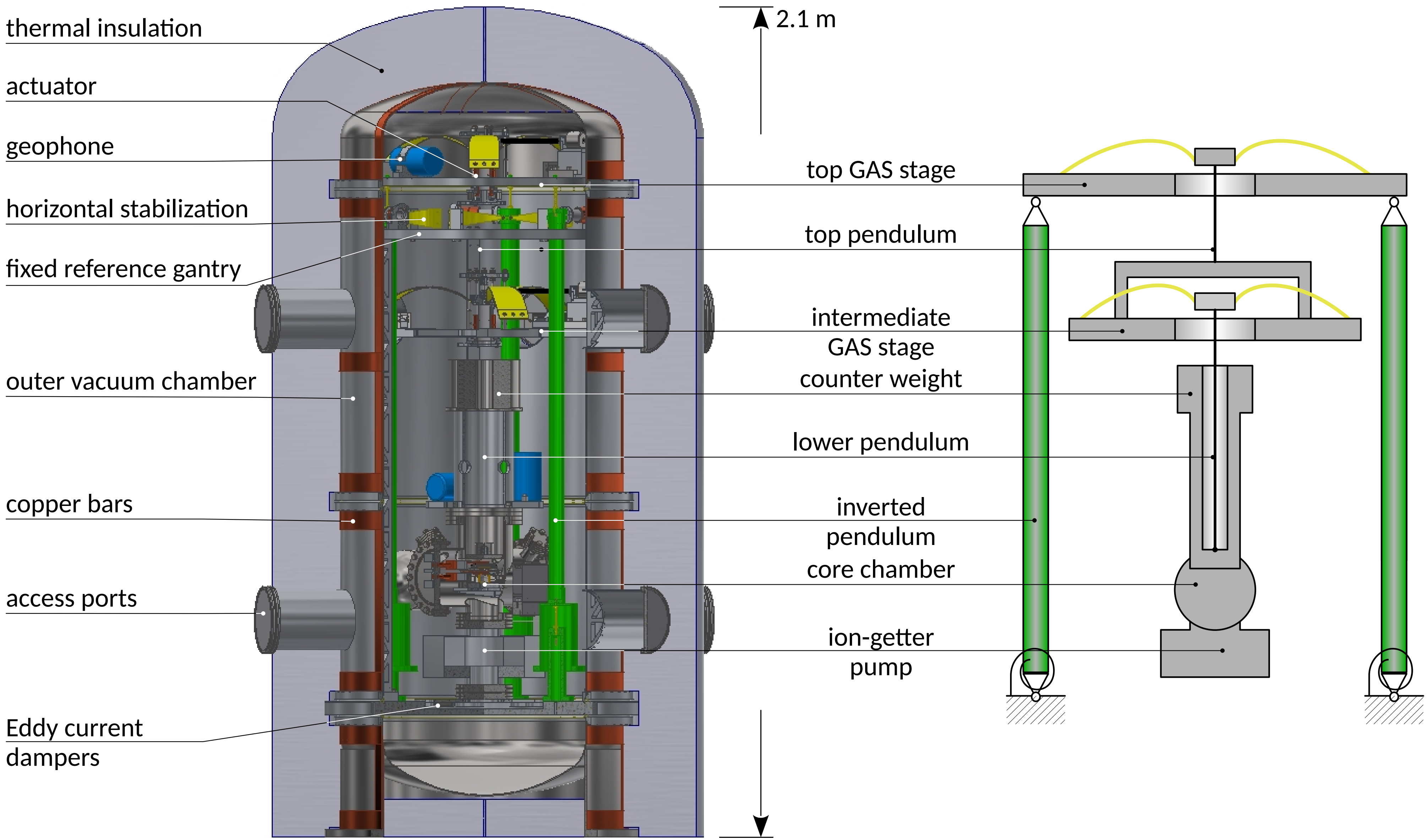




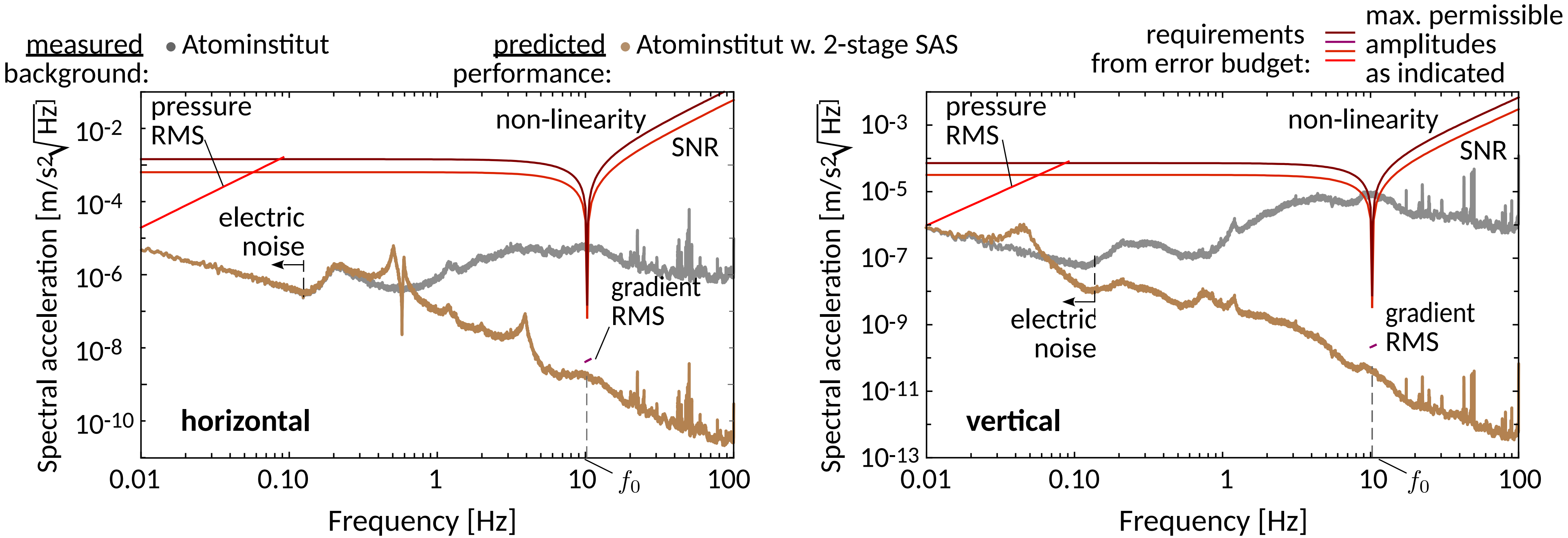


Goal: <1 mK difference on each surface

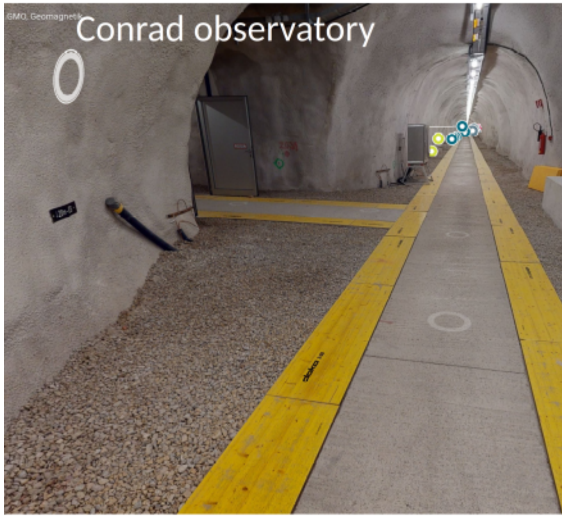
Planned technical improvements: Vibration isolation



Planned technical improvements: Vibration isolation (preliminary)



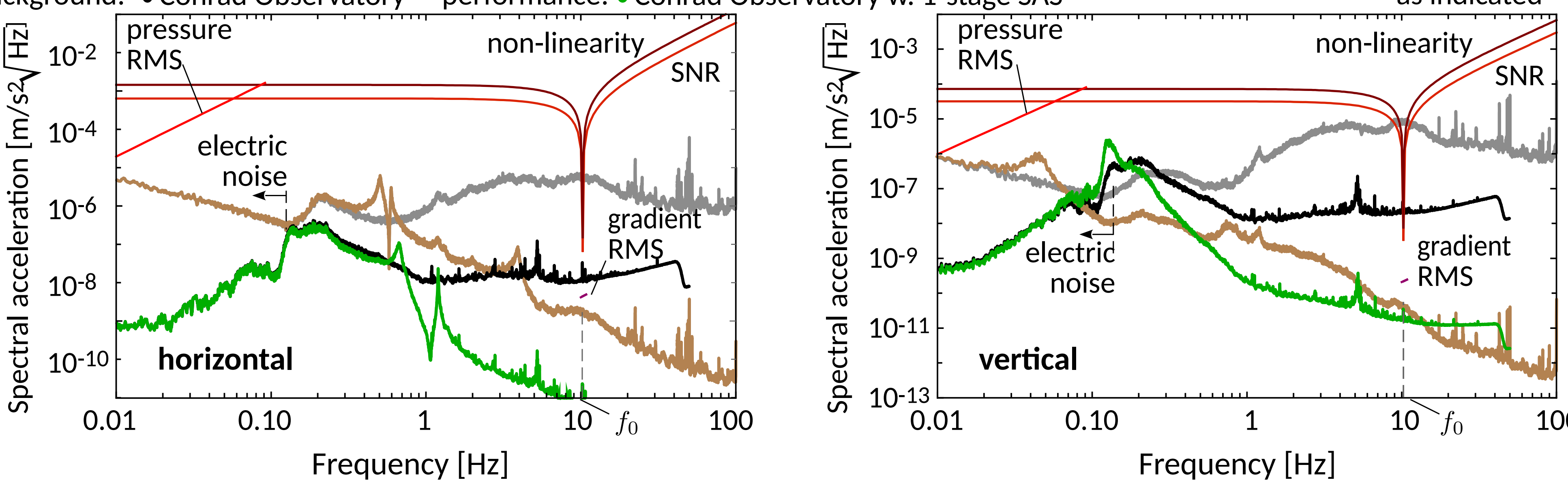
Planned technical improvements: Vibration isolation (preliminary)



<u>measured</u> background: • Atominstitut • Conrad Observatory

<u>predicted</u> performance: • Atominstitut w. 2-stage SAS • Conrad Observatory w. 1-stage SAS

requirements from error budget: max. permissible amplitudes as indicated



Metrology

Considered detailed data and models on all relevant systematic and statistical noise sources
For force measurements and gradient measurements different:

- **Seismic:**
  - Non-linearity (stat.)
  - RMS noise in different bandwidths (stat.)
  - Direct force noise (stat.)
  - Phase noise (stat.)
- **Surface deformations:**
  - Stochastic roughness (stat.)
  - large-scale deformations (sys. + stat.)
- **Residual tilt** (stat.)
- **Thermal fluctuations:**
  - Thermal expansion (stat.)
  - Changes of the Young's modulus (stat.)
- **Mechanical Brownian noise:** (stat.)
- **Detector noise** (stat. + sys.)
- **Phase resolution (PLL)** (sys.)
- **Calibration uncertainties** (stat.)
- **Laser stability/Allen deviation** (stat.)
- **Optical path variations** (sys.)
- **Electrostatic surface potentials** (sys.)
- **Voltage noise** (stat.)

Detection (Detector noise through Optical path variations)

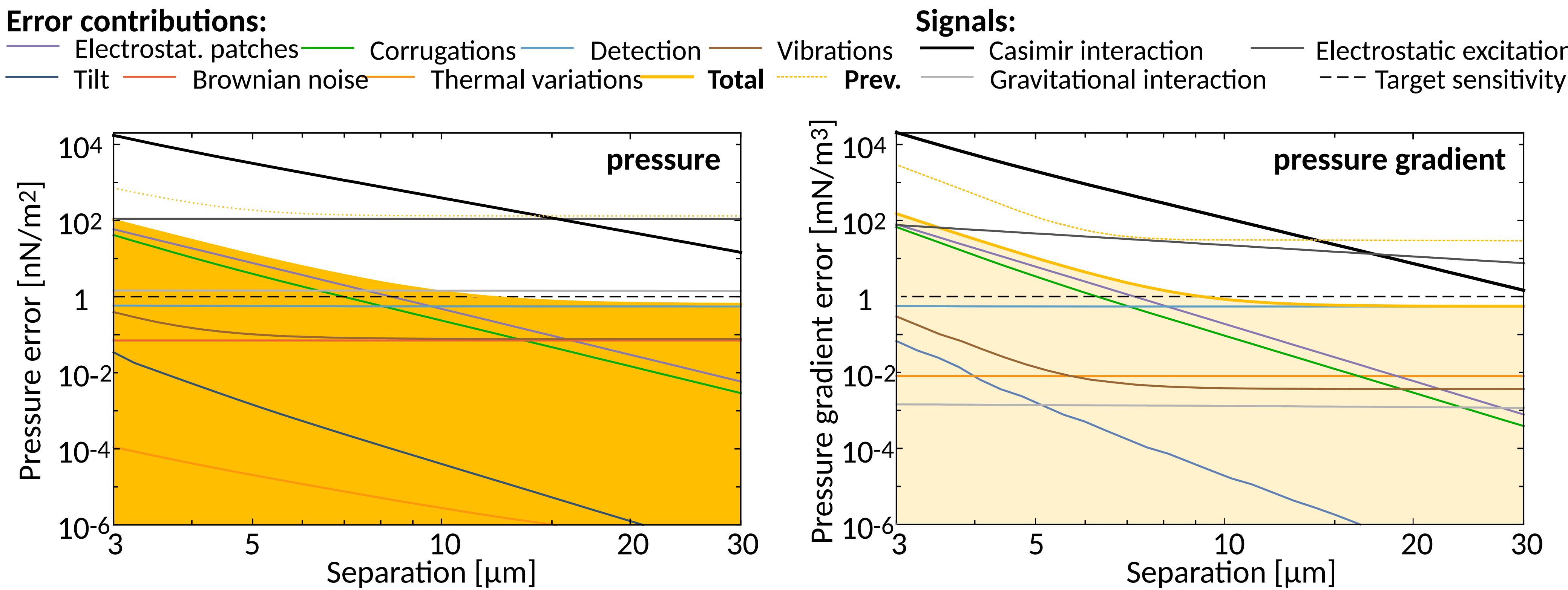
Total error:

$$\delta_{\text{tot}} = \left[\sum(\text{stat.})^2\right]^{1/2} + \sum(\text{sys.})$$

Details: Sedmik and Pitschmann, *Universe*, **7**(7), 234 (2021)

Metrology

Considered detailed data and models on all systematic and statistical noise sources
For force measurements and gradient measurements different:



Targeted sensitivity 1 nN/m² and 1 mN/m³ achievable at >10 µm

At all separations Measurement of the Casimir force at % level

Measurement options: $g_S^2,\ g_P^2,\ g_S g_P,\ g_V^2,\ G(r)$

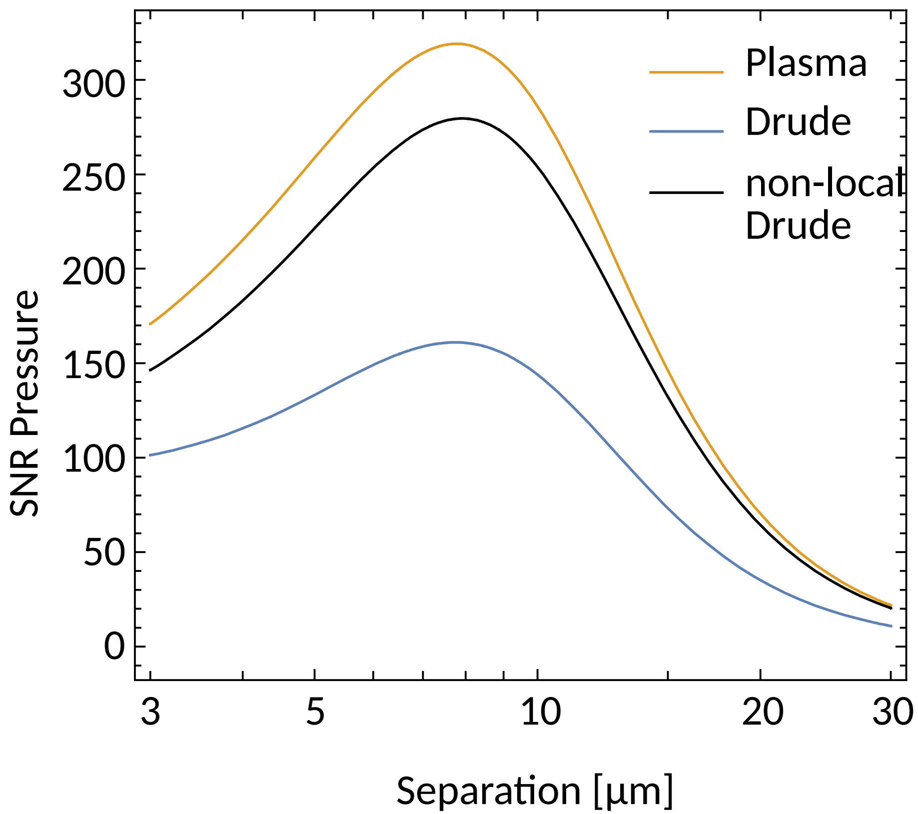
Advantage: $N = 10^{23}$ amplification factor

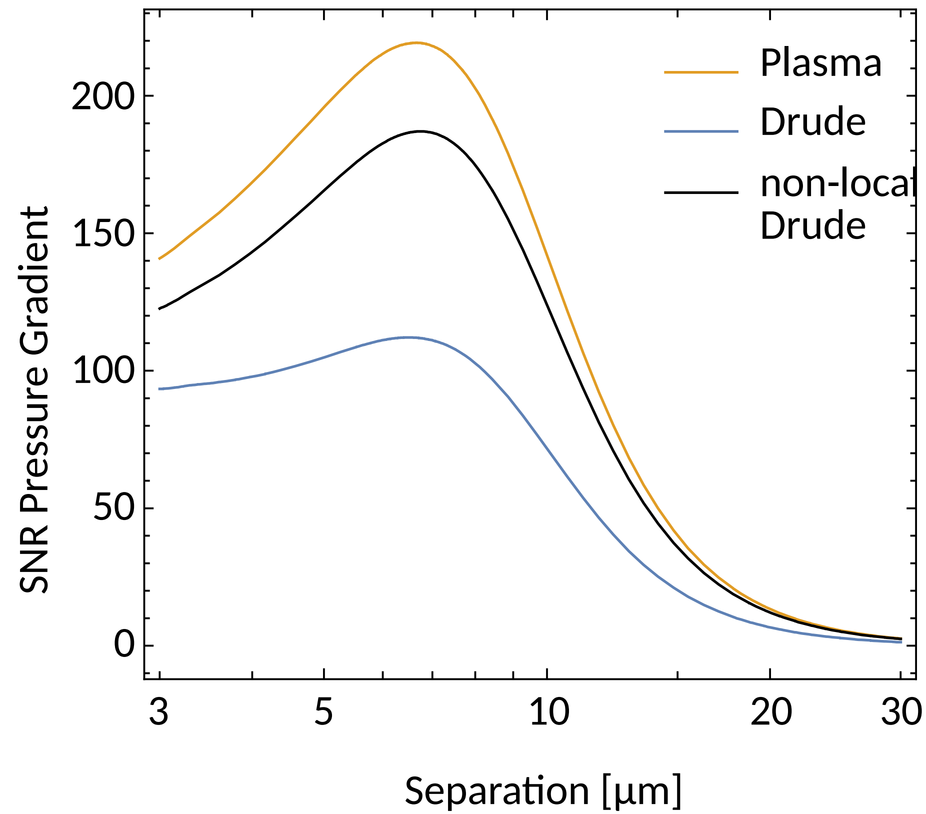
What can be achieved?

First accurate Casimir measurement beyond 10 µm with parallel plates

Cannex is the only experiment that can distinguish all available models

Klimchitskaya and Mostepanenko *EPJ* **80** 900 (2020)
Sedmik and Pitschmann, *Universe*, **7** 234 (2021)





+ First accurate Casimir measurement out of thermal equilibrium (ΔT = 10 K)

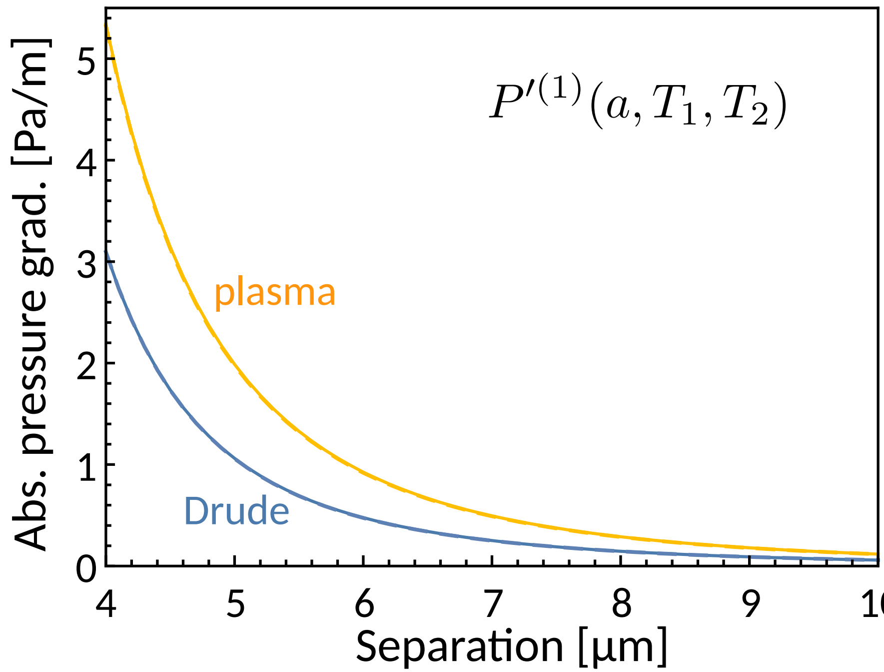
G. Klimchitskaya, V.M. Mostepanenko, R.I.P. Sedmik, and H. Abele, *Symmetry*, **11**(3) 407 (2019)

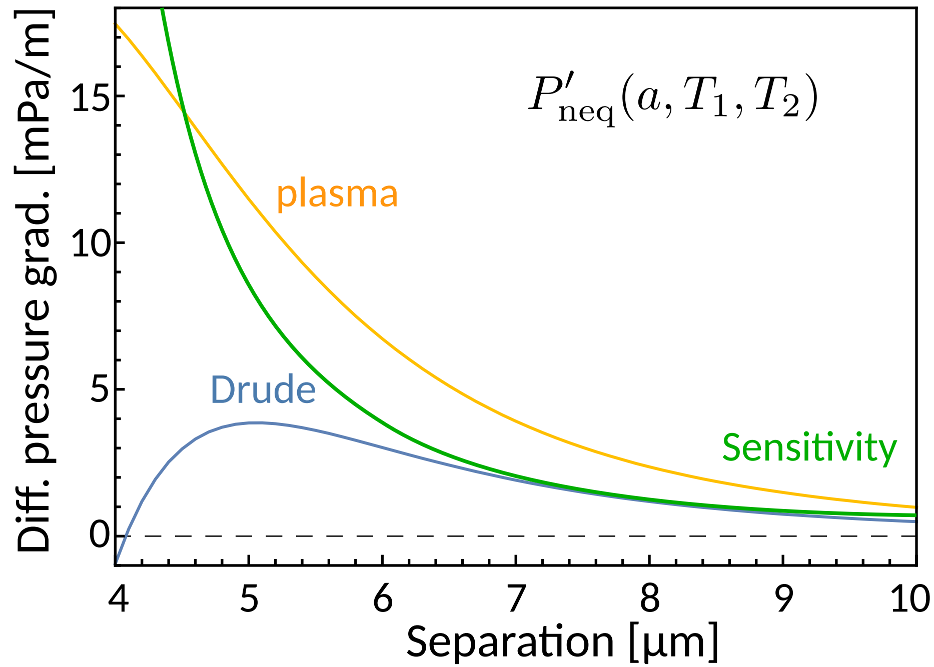
What can be achieved?

First measurement of non-equilibrium thermal contributions: **gradient**

$$P'^{(1)}(a,T_1,T_2) = \frac{1}{2}[P'_{\rm eq}(a,T_1) + P'_{\rm eq}(a,T_2)] + \boxed{P'_{\rm neq}(a,T_1,T_2)}$$

T_1 = 300 K (sensor), T_2 = 310 K (plate)





graph data: G. Klimchitskaya, V.M. Mostepanenko, and R.I.P. Sedmik, *PRA* **100**, 022511 (2019)

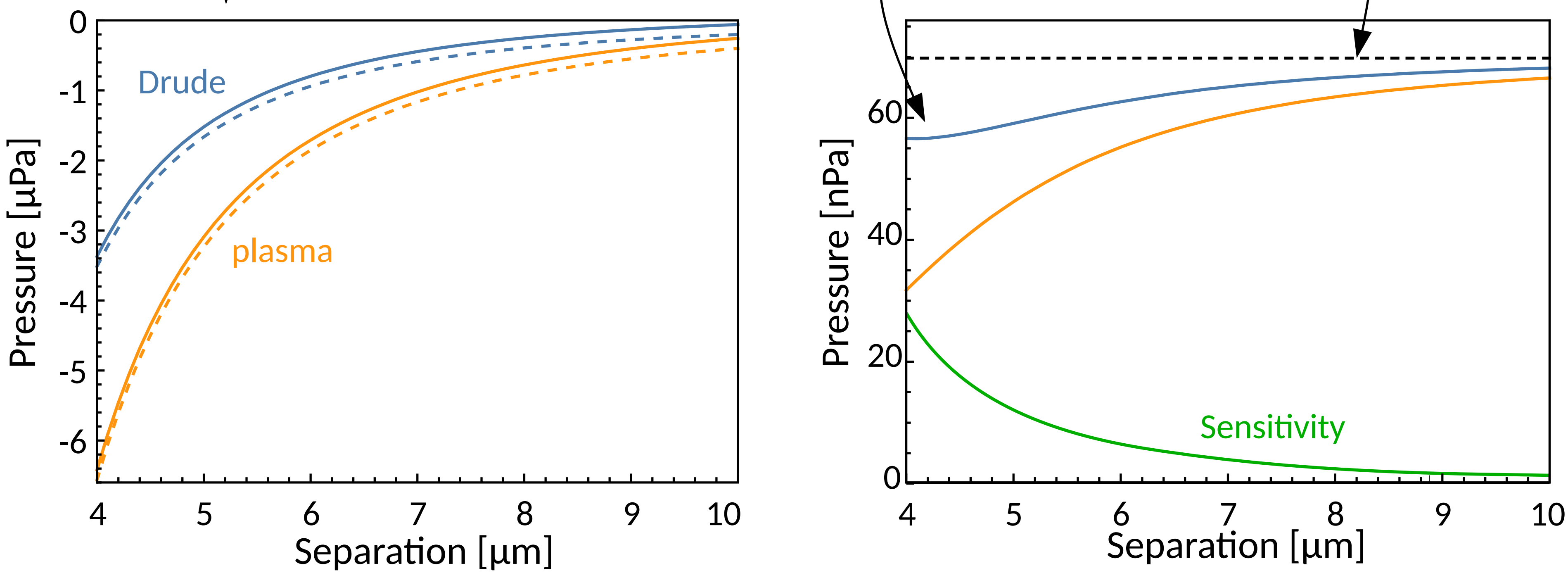
Difficult but possible with SNR ~ 1.8 (plasma)

What can be achieved?

Measurement of separation-independent radiation **pressure**

$$P'^{(1)}(a,T_1,T_2) = \frac{1}{2}[P'_{\rm eq}(a,T_1) + P'_{\rm eq}(a,T_2)] + \Delta P'_{\rm neq}(a,T_1,T_2) + \frac{2\sigma}{3c}(T_2^4 - T_1^4)$$

T_1 = 300 K (sensor), T_2 = 310 K (plate)

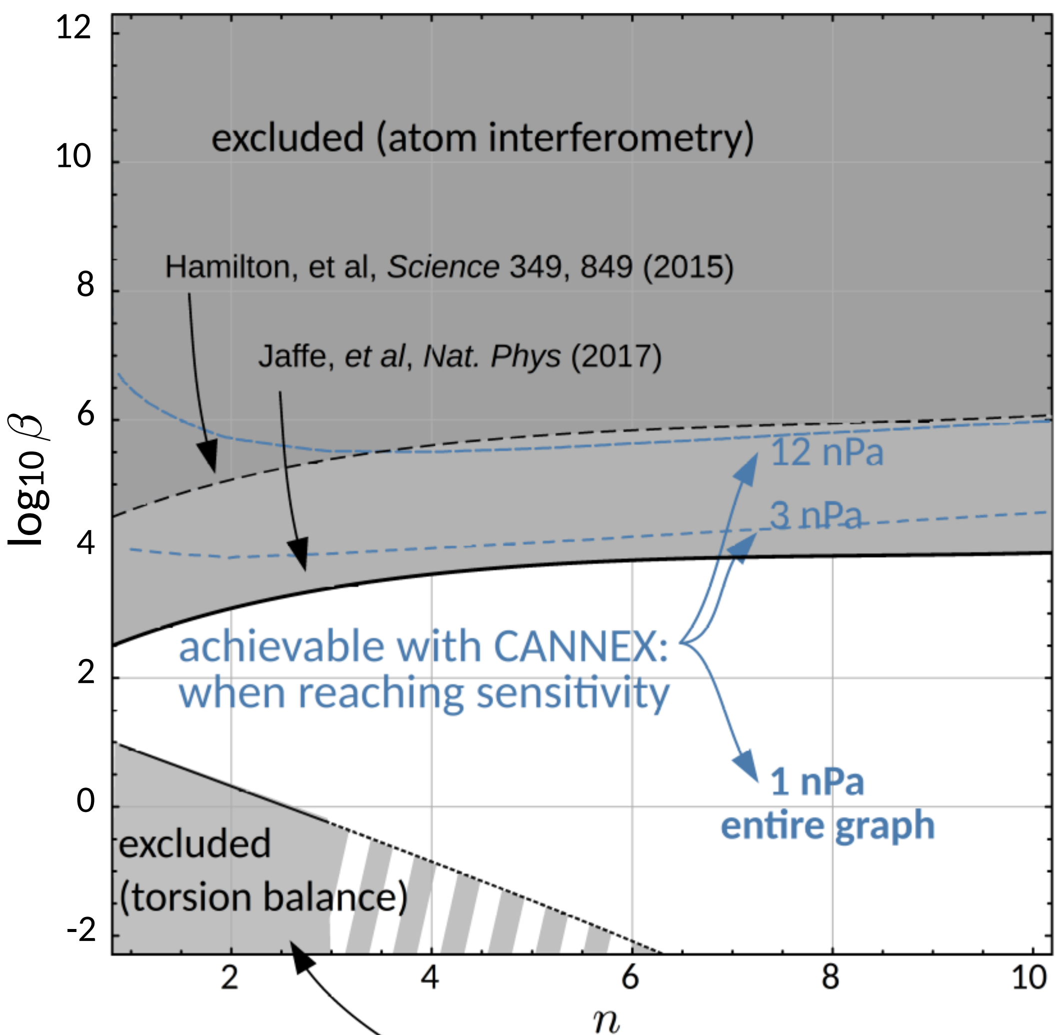


graph data: G. Klimchitskaya, V.M. Mostepanenko, and R.I.P. Sedmik, *PRA* **100**, 022511 (2019)

Clearly possible to measure (SNR ~ 5)

What can be achieved?

Exclusion of the Chameleon as dark energy candidate



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

Dynamic scalar field:

$$\mathcal{L} = \sqrt{-g}\left[\frac{R}{16\pi G} - \frac{(\partial\phi)^2}{2} + V(\phi)\right] + \mathcal{L}_{\rm sm}(\psi, \tilde{g}_{\mu\nu})$$

$$\tilde{g}_{\mu\nu} = A^2(\phi) g_{\mu\nu}$$

Coupling: $A(\phi) = \mathrm{e}^{\beta\phi/m_{\rm pl}}$

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

$\Lambda = \Lambda_0 \approx$ 2.4 meV

Effective potential:

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

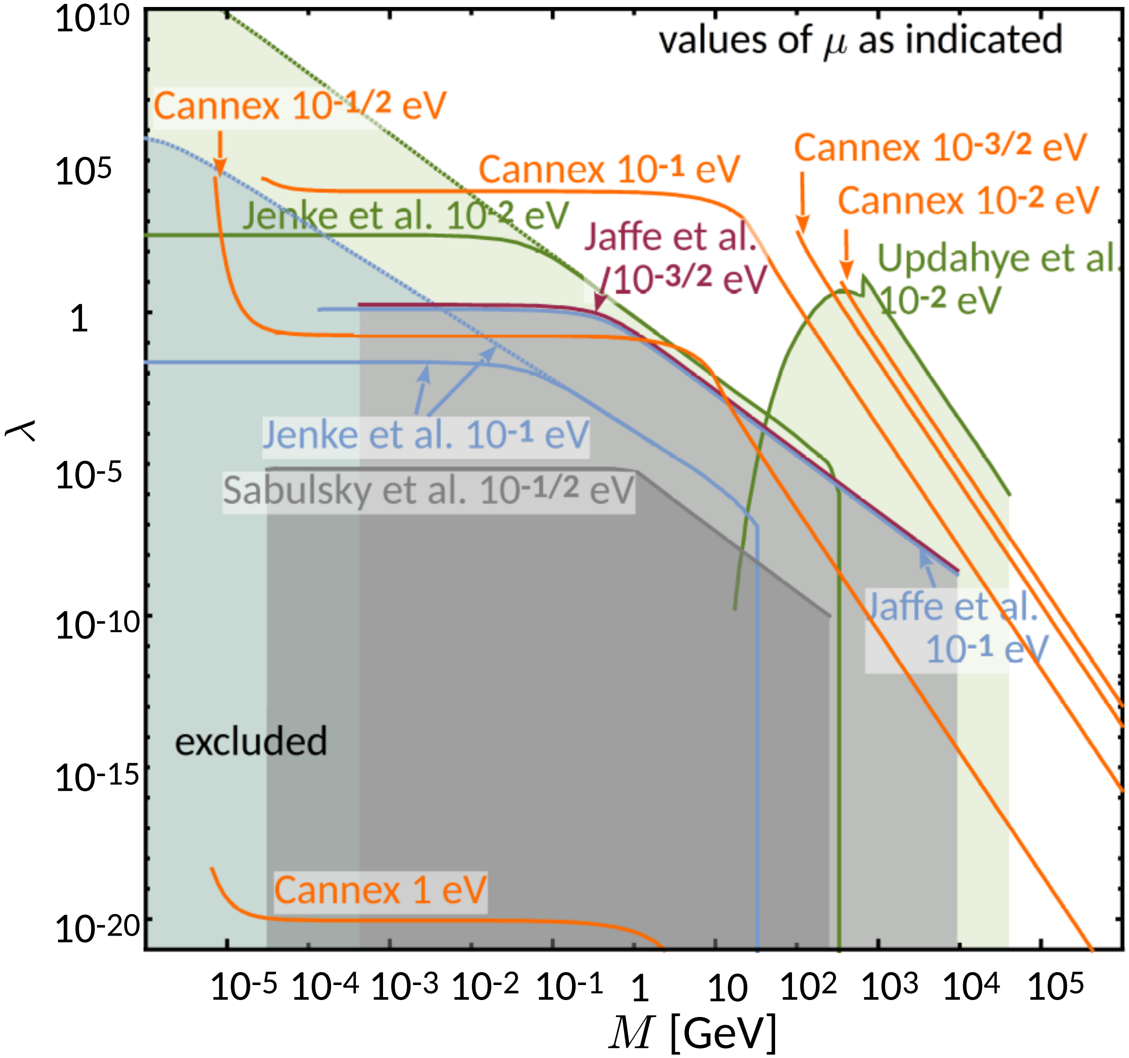
Measurement via vacuum pressure modulation

Complete exclusion possible

What can be achieved?

Limits on the Symmetron as dark energy candidate

Sedmik and Pitschmann, *Universe* 7, 234 (2021)



Dynamic scalar field:

$$\mathcal{L} = \sqrt{-g}\left[\frac{R}{16\pi G} - \frac{(\partial\phi)^2}{2} + V(\phi)\right] + \mathcal{L}_{\rm sm}(\psi, \tilde{g}_{\mu\nu})$$

$$\tilde{g}_{\mu\nu} = A^2(\phi) g_{\mu\nu}$$

Coupling: $A(\phi) = 1 + \frac{\phi^2}{2M^2}$

Potential: $V(\phi) = -\frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4$

At $\rho < M^2\mu^2$ symmetry spontaneously broken and acquires $\langle\phi\rangle_{\rm vac.} = \sqrt{\mu^2/\lambda}$

At $\rho \gg M^2\mu^2$ symmetry restored, $\langle\phi\rangle_{\rm vac.} = 0$ no coupling to matter

Effective potential:

$$V_{\rm eff} = \frac{1}{2}\left(\frac{\rho}{M^2} - \mu^2\right)\phi^2 - \frac{\lambda}{4}\phi^4$$

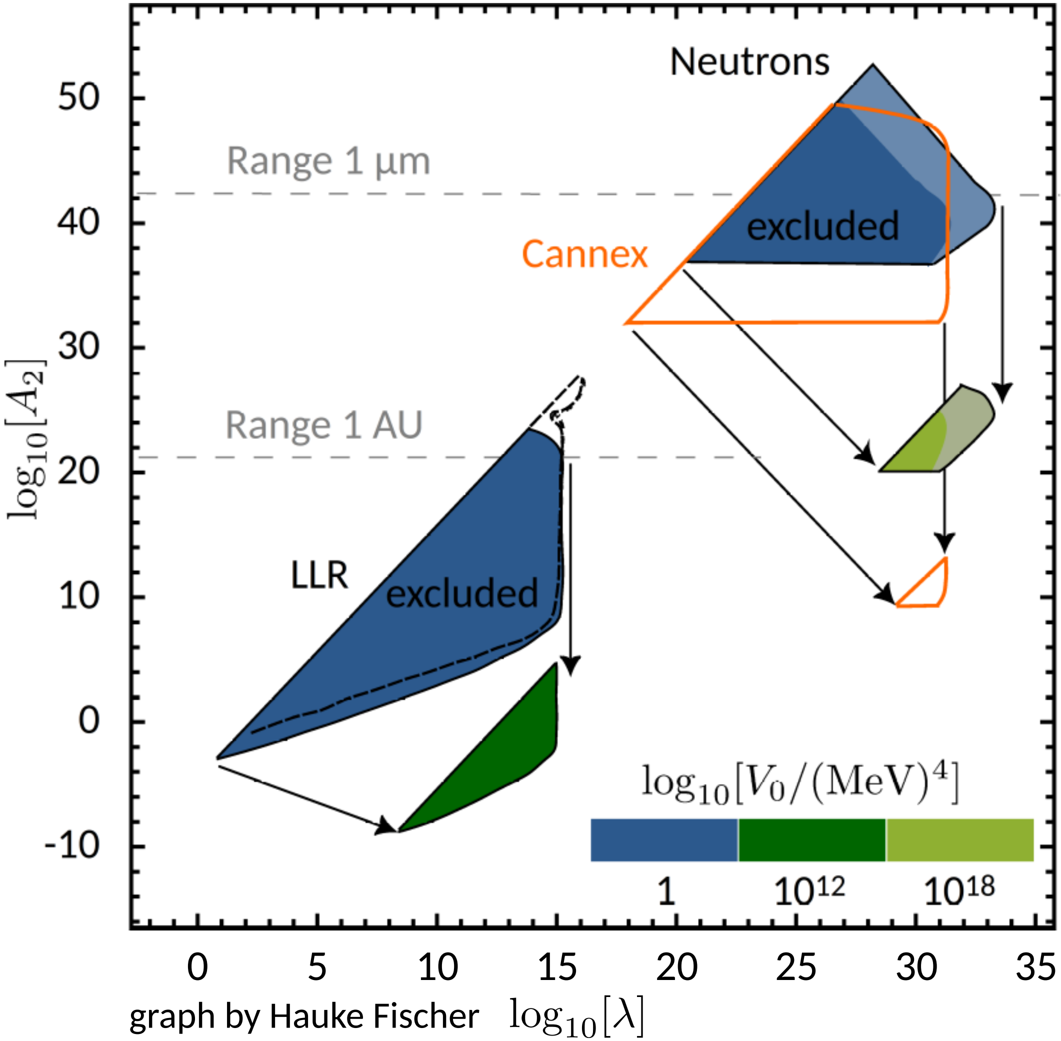
Measurement via vacuum pressure modulation

New limits possible

What can be achieved?

Limits on the Dilaton as dark energy candidate

Fischer *et al*. submitted.



graph by Hauke Fischer

Dynamic scalar field:

$$\mathcal{L} = \sqrt{-g}\left[\frac{R}{16\pi G} - \frac{(\partial\phi)^2}{2} + V(\phi)\right] + \mathcal{L}_{\mathrm{sm}}(\psi, \tilde{g}_{\mu\nu})$$

$$\tilde{g}_{\mu\nu} = A^2(\phi) g_{\mu\nu}$$

Coupling: $A(\phi) = 1 + \frac{A_2 \phi^2}{2 m_{\mathrm{pl}}^2}$

Potential: $V(\phi) = V_0 \mathrm{e}^{-\lambda\phi/m_{\mathrm{pl}}}$

Effective potential:

$$V_{\mathrm{eff}} = V_0\, e^{-\lambda\phi/m_{\mathrm{pl}}} + A_2 \frac{\phi^2}{2m_{\mathrm{pl}}^2}\, \rho$$

Measurement via vacuum pressure modulation

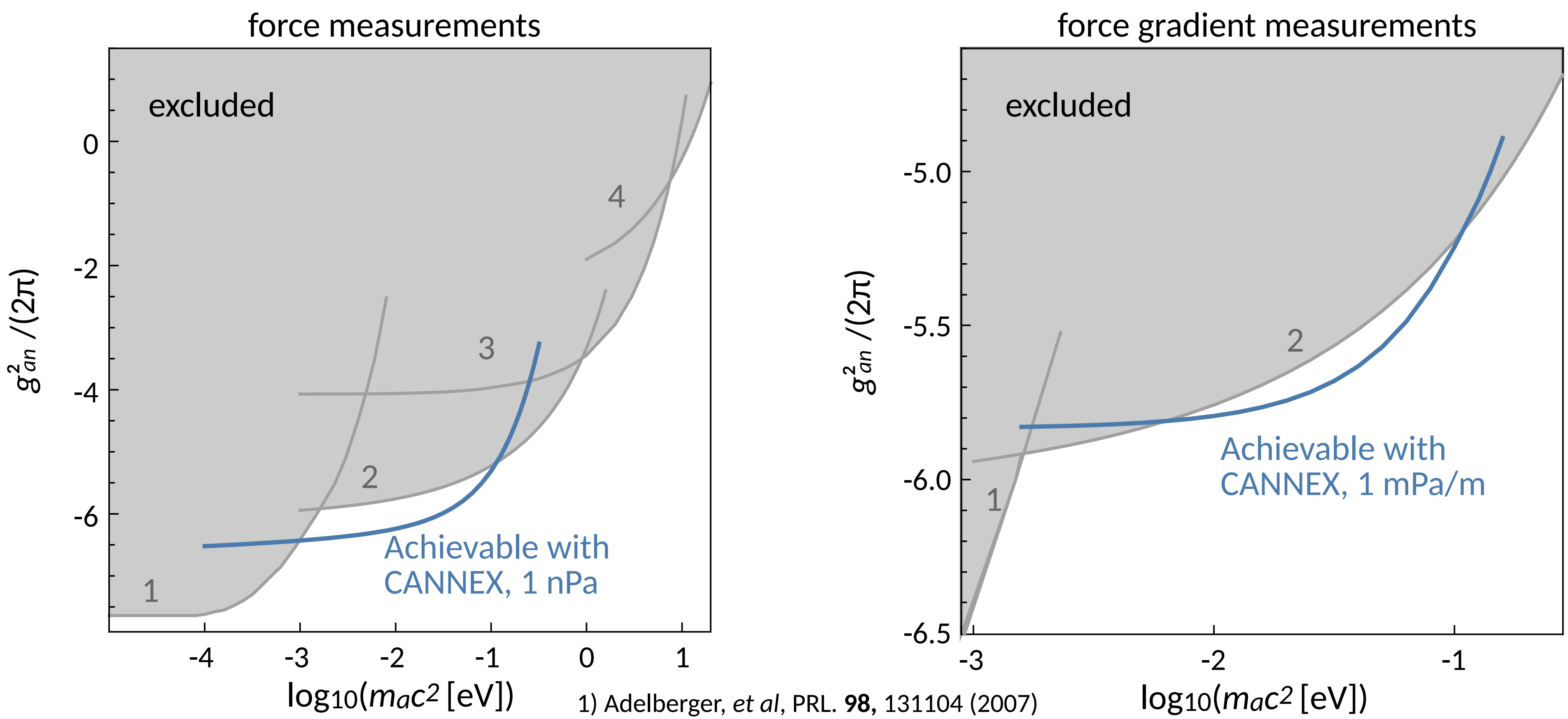
New limits possible

What can be achieved?

Improved limits on Axion-nucleon (scalar-pseudoscalar) interactions

G. Klimchitskaya, V.M. Mostepanenko, R.I.P. Sedmik, and H. Abele, Symmetry, 11(3) 407 (2019)

$$V_{an}(r) = -\frac{{g_{an}}^4}{32\pi^3}\frac{\hbar^2 m_a}{m^2}(\boldsymbol{r}_1 - \boldsymbol{r}_2)^{-2} K_1\left(\frac{2m_a c|\boldsymbol{r}_1 - \boldsymbol{r}_2|}{\hbar}\right).$$



1) Adelberger, *et al*, PRL. **98,** 131104 (2007)
2) Chen, *et al*, PRL. **116**, 221102 (2016)
3) Bezerra, *et al*, EPJC **74**, 2859 (2014)
4) Bezerra, *et al*, PRD **90**, 055013 (2014)

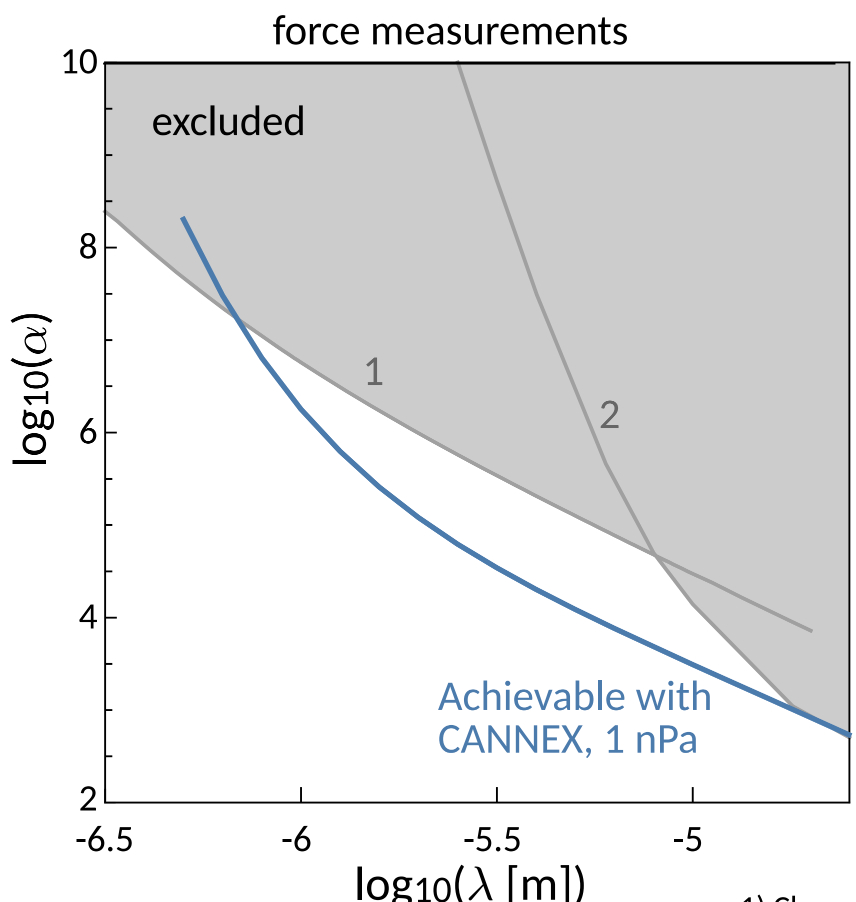
New limits achievable

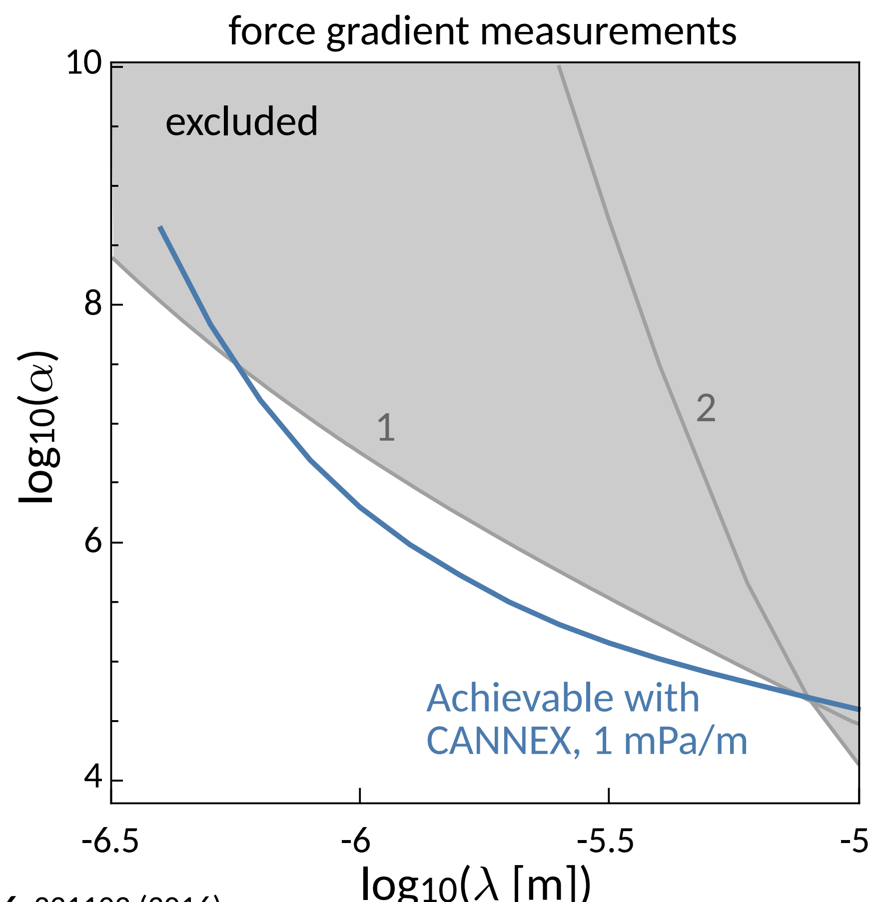
What can be achieved?

Improved limits on Yukawa interactions

G. Klimchitskaya, V.M. Mostepanenko, R.I.P. Sedmik, and H. Abele, Symmetry, 11(3) 407 (2019)

$$V_{\mathrm{Yu}}(r) = -\alpha \frac{G m_1 m_2}{|\boldsymbol{r}_1 - \boldsymbol{r}_2|} \exp\left(-\frac{(|\boldsymbol{r}_1 - \boldsymbol{r}_2|}{\lambda}\right)$$





1) Chen, *et al*, PRL. **116**, 221102 (2016)
2) Geraci, *et al*, PRD **78**, 022002 (2008)

New limits achievable

Conclusion

- CANNEX is about to become
  the **first metrological plane parallel plate Casimir experiment**

- The proof of principle was successful
  (though solvable technical problems encountered)

- Setup **is being rebuilt** with many enhancements

- First setup to **detect force and force gradient in one measurement**
  Interfacial and Cavendish configuration possible.

- CANNEX will allow to measure:
  - **Casimir forces at large separations (>10 µm)**
  - **Thermal effects**
  - Dark matter and dark energy "fifth" forces
  - Gravity

Acknowledgments

Thank you for your your attention!

Present and former team members

ATI:

René Sedmik
Hamid Haghmoradi
Mario Pitschmann
Andrzej Pelczar
Ivica Galic
Roman Gergen
Thomas Dokulil
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Lex v. d. Gracht
Davide Iannuzzi
Rogier Elsinga
Rob Limburg

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

Berlin:

Francesco Intravaia

Paris Saclay:

Philippe Brax

St. Petersburg

Galina Klimchitskaya
Vladimir M. Mostepanenko

NWO Nederlandse Organisatie voor Wetenschappelijk Onderzoek

FOM

FWF Der Wissenschaftsfonds.

TU WIEN TECHNISCHE UNIVERSITÄT WIEN

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