# Recent progress in Casimir physics for atom-surface interactions

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# Collaborators

- Theory:

Engineering the Casimir-Polder force with geometry:

Paulo Maia Neto (Rio de Janeiro)
Astrid Lambrecht (LKB, Paris)
Serge Reynaud (LKB, Paris)

- Experiments:

BECs for Casimir-Polder force:

Malcolm Boshier (LANL)
Matt Blain (Sandia National Labs)

# Outline of this talk

- Part I

- Review of theory and experiment on Casimir atom-surface interactions (see also talks by Stefan Buhmann and Akbar Salam on Thursday)

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- First measurement of thermal effect in Casimir physics (courtesy of Mauro Antezza, JILA-Trento collaboration)

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- Part III

  - Casimir-Polder forces within scattering theory

  - Cold atoms for probing lateral Casimir-Polder forces

# Part I: Review

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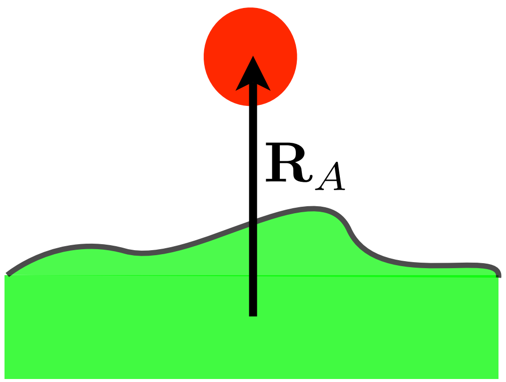
# The Casimir-Polder force

## vdW - CP interaction

Casimir and Polder (1948)

The interaction energy between a ground-state atom and a surface is given by

$$\boxed{U_{\mathrm{CP}}(\mathbf{R}_A) = \frac{\hbar}{c^2\epsilon_0}\int_0^\infty \frac{d\xi}{2\pi}\xi^2\alpha(i\xi)\,\mathrm{Tr}\,\mathbf{G}(\mathbf{R}_A,\mathbf{R}_A,i\xi)}$$




Atomic polarizability: $\alpha(\omega) = \lim_{\epsilon\to 0}\frac{2}{3\hbar}\sum_k \frac{\omega_{k0}|\mathbf{d}_{0k}|^2}{\omega_{k0}^2-\omega^2-i\omega\epsilon}$

Scattering Green tensor: $\left(\nabla\times\nabla\times-\frac{\omega^2}{c^2}\epsilon(\mathbf{r},\omega)\right)\mathbf{G}(\mathbf{r},\mathbf{r}',\omega) = \delta(\mathbf{r}-\mathbf{r}')$

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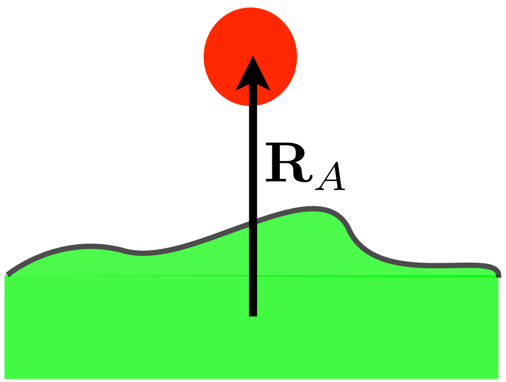


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## Eg: Ground-state atom near planar surface @ T=0

Non-retarded (vdW) limit $z_A \ll \lambda_A$

$$U_{\mathrm{vdW}}(z_A) = -\frac{\hbar}{8\pi\epsilon_0}\frac{1}{z_A^3}\int_0^\infty\frac{d\xi}{2\pi}\alpha(i\xi)\frac{\epsilon(i\xi)-1}{\epsilon(i\xi)+1}$$

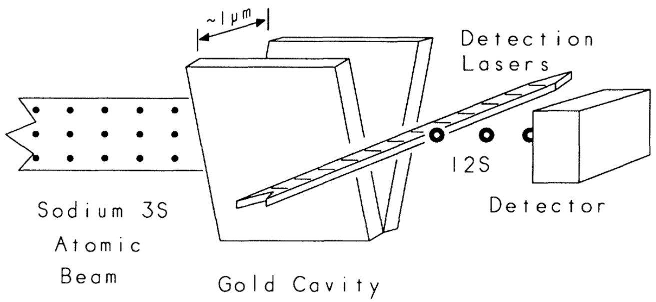
Retarded (CP) limit $z_A \gg \lambda_A$

$$U_{\mathrm{CP}}(z_A) = -\frac{3\hbar c\alpha(0)}{8\pi}\frac{1}{z_A^4}\frac{\epsilon_0-1}{\epsilon_0+1}\phi(\epsilon_0)$$

# Modern CP experiments

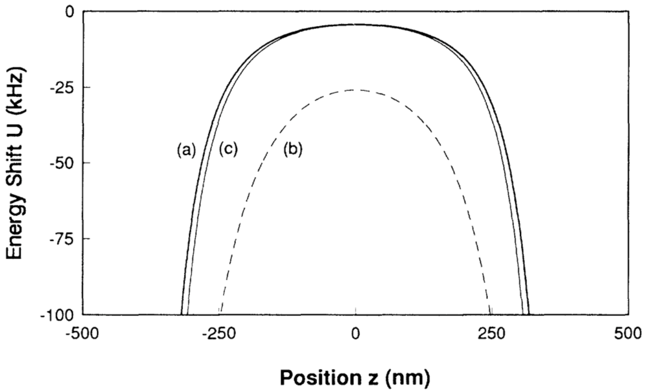
- ## Deflection of atoms

Hinds et al (1993)




L= 0.7-1.2 um

Exp-Th agreement @ 10%




$$U_{CP} = -\frac{1}{4\pi\epsilon_0}\frac{\pi^3\hbar c\alpha(0)}{L^4}\left[\frac{3-2\cos^2(\pi z/L)}{8\cos^4(\pi z/L)}\right]$$

# Modern CP experiments

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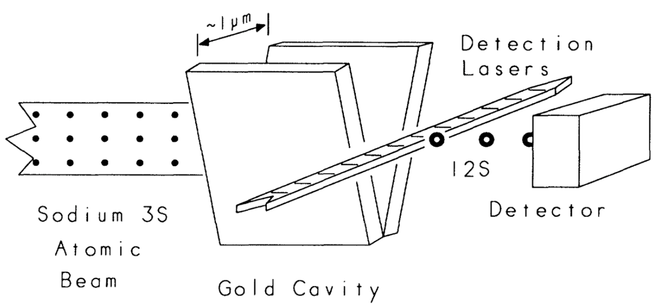


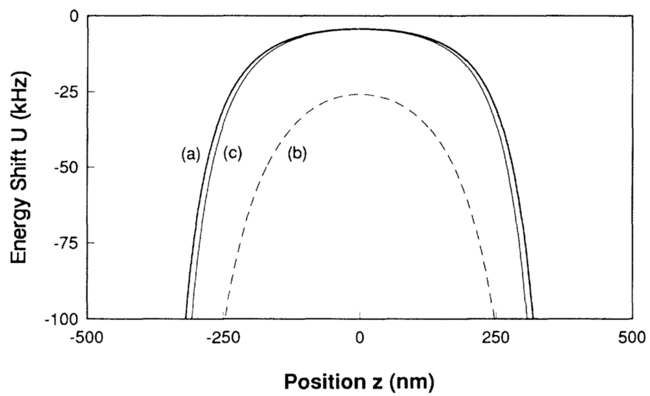


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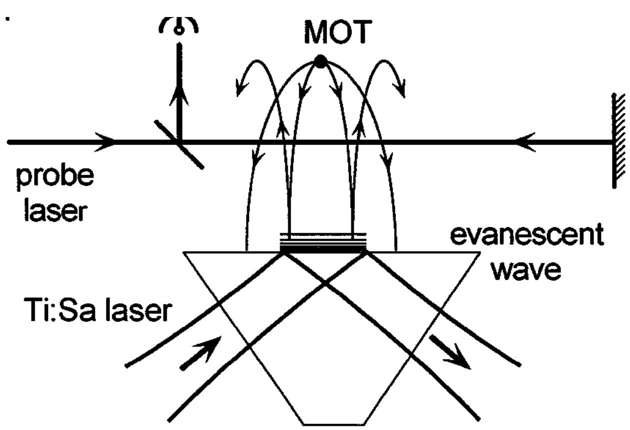
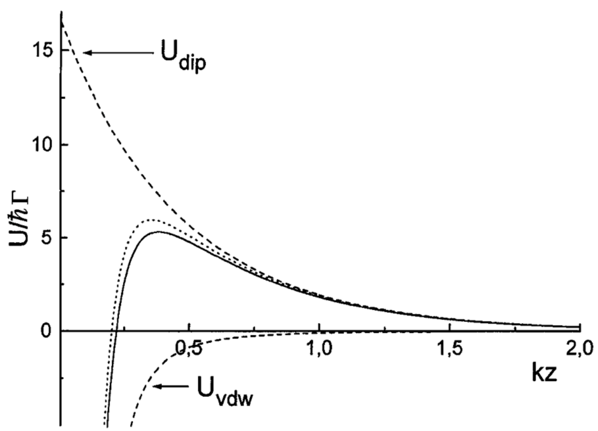
## Classical reflection on atomic mirror

Aspect et al (1996)




$$U_{\rm dip} = \frac{\hbar}{4}\frac{\Omega^2}{\Delta}e^{-2kz}$$

$$U_{\rm vdW} = -\frac{\epsilon-1}{\epsilon+1}\frac{1}{48\pi\epsilon_0}\frac{D^2}{z^3}$$




Exp-Th agreement @ 30%

# Modern experiments (cont'd)

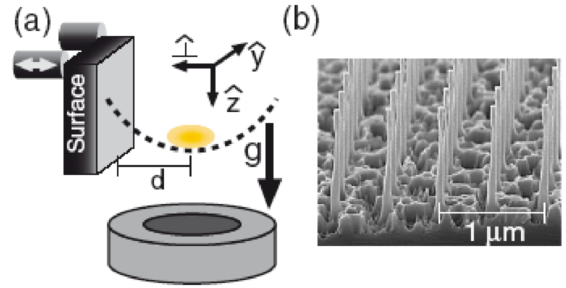


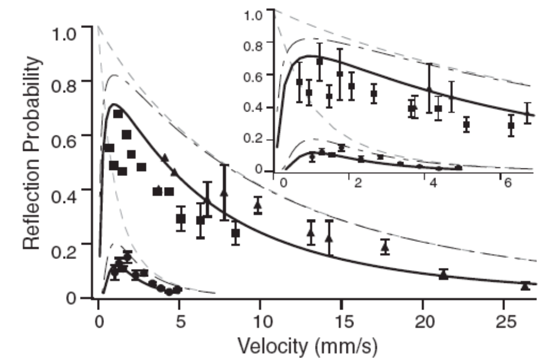
## Quantum reflection

Wave-nature of atoms implies that slow atoms can reflect from purely attractive potentials

$$k = \sqrt{k_0^2 - 2mU/\hbar^2} \qquad \phi = \frac{1}{k^2}\frac{dk}{dr} > 1$$

$$U = -C_n/r^n \ (n > 2)$$




Shimizu (2001) Ketterle et al (2006)

DeKievet et al (2003)

# Modern experiments (cont'd)

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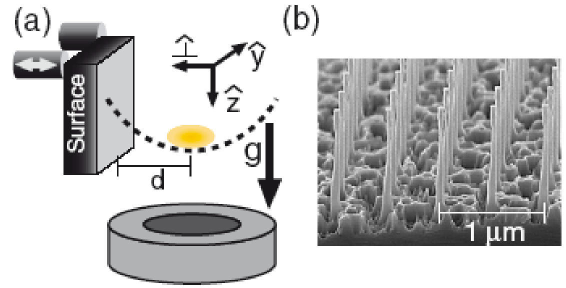


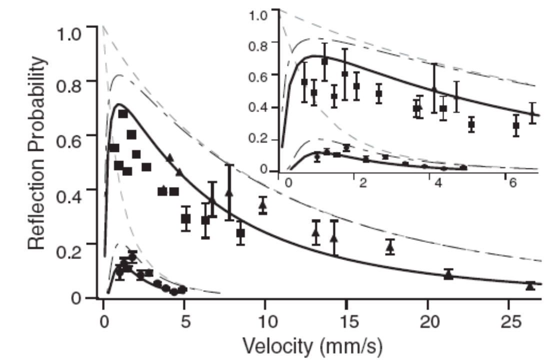


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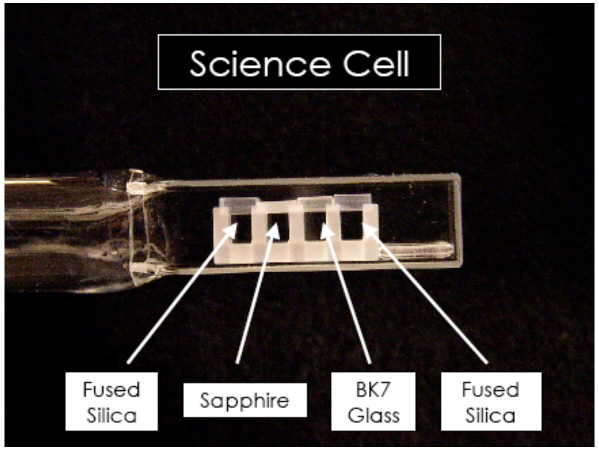
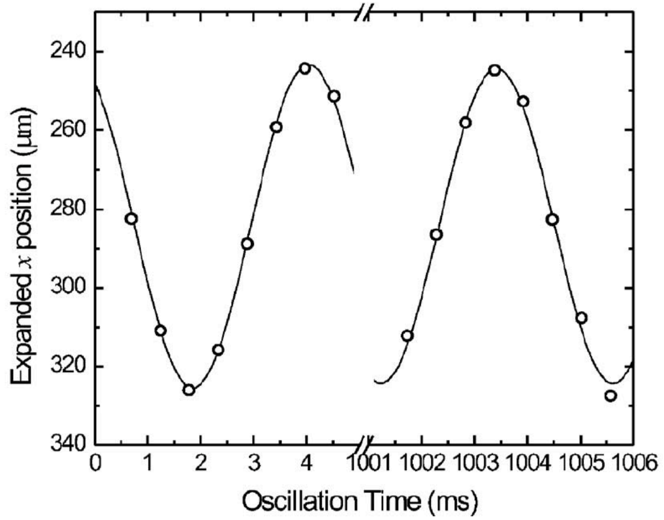
## BEC oscillator

Cornell et al (2007)

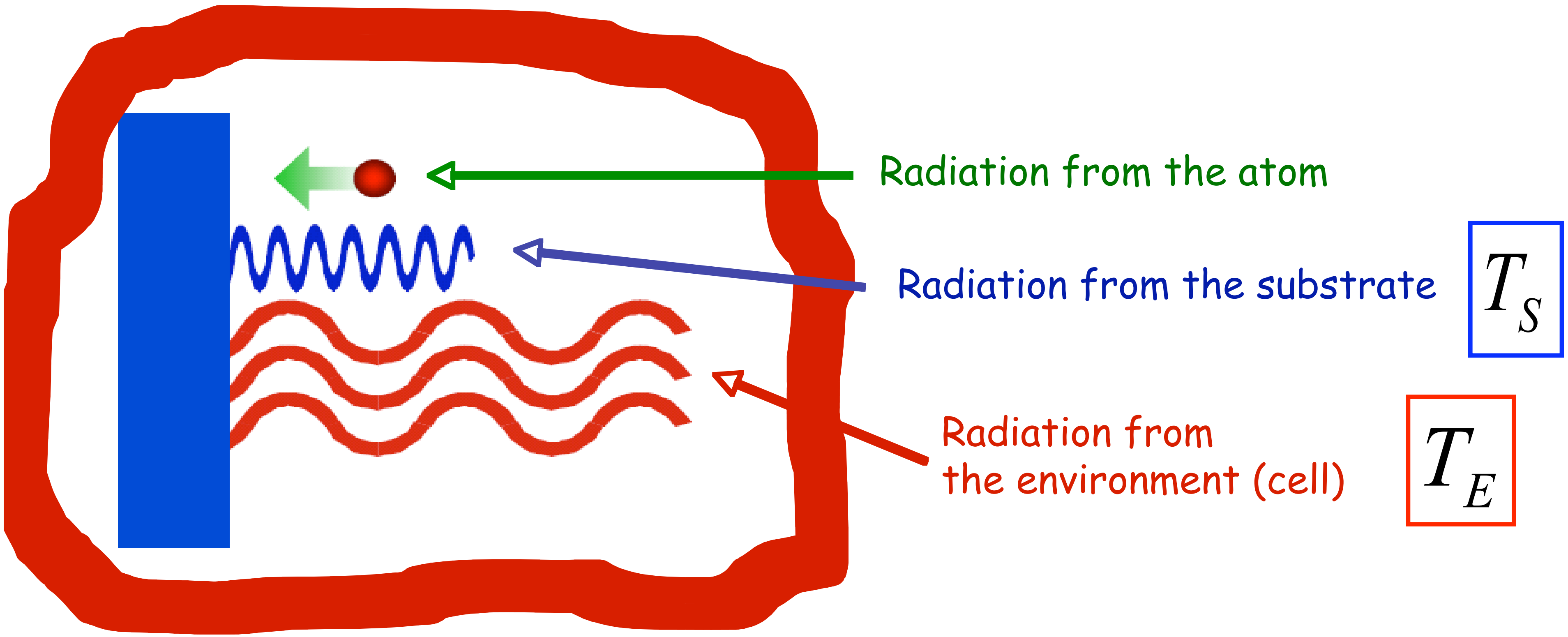



$$\gamma_x \equiv \frac{\omega_x - \omega_x'}{\omega_x} \simeq -\frac{1}{2\omega_x^2 m}\partial_x^2 U^*$$



# Part II: Thermal CP force

# Surface-atom force




$$\vec{F}(\vec{r}) = \left\langle d_i^{tot}(t)\vec{\nabla}E_i^{tot}(\vec{r},t)\right\rangle \approx \left\langle d_i^{ind}(t)\vec{\nabla}E_i^{fl}(\vec{r},t)\right\rangle + \left\langle d_i^{fl}(t)\vec{\nabla}E_i^{ind}(\vec{r},t)\right\rangle$$

Force includes **zero-point** (**or vacuum**) fluctuations effects +
**thermal** (**or radiation**) fluctuations effects (**crucial at large distance!**)

# Large distance asymptotic behaviours

**System at equilibrium**

$$F^{eq} = -\frac{3k_B T\alpha_0(\varepsilon_0 - 1)}{4z^4(\varepsilon_0 + 1)}$$

E.M. Lifshitz, Dokl. Akad. Nauk. **100**, 879 (1955)

**System out of equilibrium** NEW

substrate environment

$$F^{neq} = -\frac{\pi}{6}\frac{\alpha_0 k_B^2(T_S^2 - T_E^2)}{z^3 c\hbar}\frac{\varepsilon_0 + 1}{\sqrt{\varepsilon_0 - 1}}$$

M.Antezza, L.P.Pitaevskii and S.Stringari, PRL. **95**, 093202 (2005)

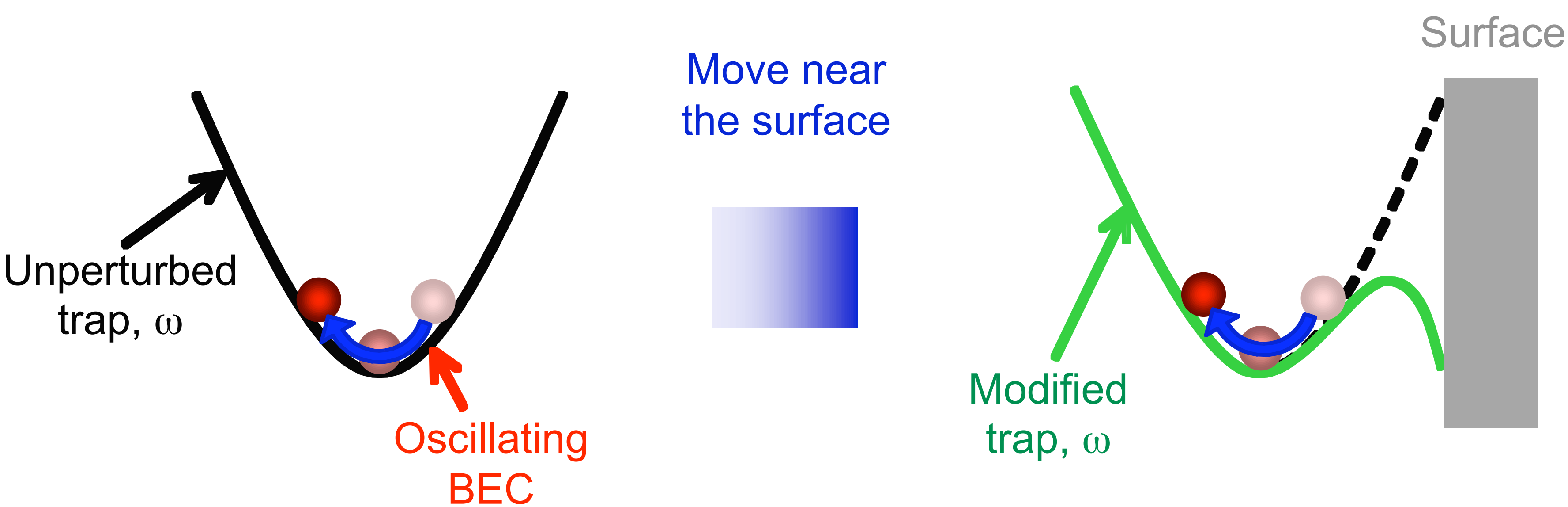
- ✓ force decays slower than at thermal equilibrium:
- ✓ force depends on temperature more strongly than at equilibrium
- ✓ force can be attractive or repulsive depending on relative temperatures of substrate and environment
- ✓ simple extension to metals (Drude model $\varepsilon'' = 4\pi\sigma/\omega$ )

# Measuring atom-surface interactions: dipolar oscillations of a BEC

**Use trapped BEC as a mechanical oscillator:**

Measure changes in oscillation frequency

**Attractive force ->** Trap frequency decrease




Total force on the BEC is the sum of the forces on individual atoms. Role of BEC coherence/superfluidity not central. A BEC is convenient since it is a spatially compact collection of large number of particles, well controlled.

# Frequency shift of collective oscillations of a BEC

In M. Antezza, L.P. Pitaevskii and S. Stringari, PRA 70, 053619 (2004), the surface-atom force has been calculated and used to predict the frequency shift of the center of mass oscillation of a trapped Bose-Einstein condensate, including:

- Effects of finite size of the condensate
- Non harmonic effects due to the finite amplitude of the oscillations
- Dipole (center of mass) and quadrupole (long living mode) frequency shifts

In the presence of harmonic potential + surface-atom force frequency of center of mass motion is given by

$$V_{ho}(\vec{r}) = \frac{m}{2}\omega_x^2 x^2 + \frac{m}{2}\omega_y^2 y^2 \frac{m}{2}\omega_z^2 z^2$$

$$\omega_{cm}^2 - \omega_z^2 = \frac{1}{m}\int n_0(\vec{r})\partial_z^2 V_{surf-at}(z)d\vec{r} +$$

Linear approximation

$$\frac{a^2}{8m}\int n_0(\vec{r})\partial_z^4 V_{surf-at}(z)d\vec{r}$$

First non-linear correction

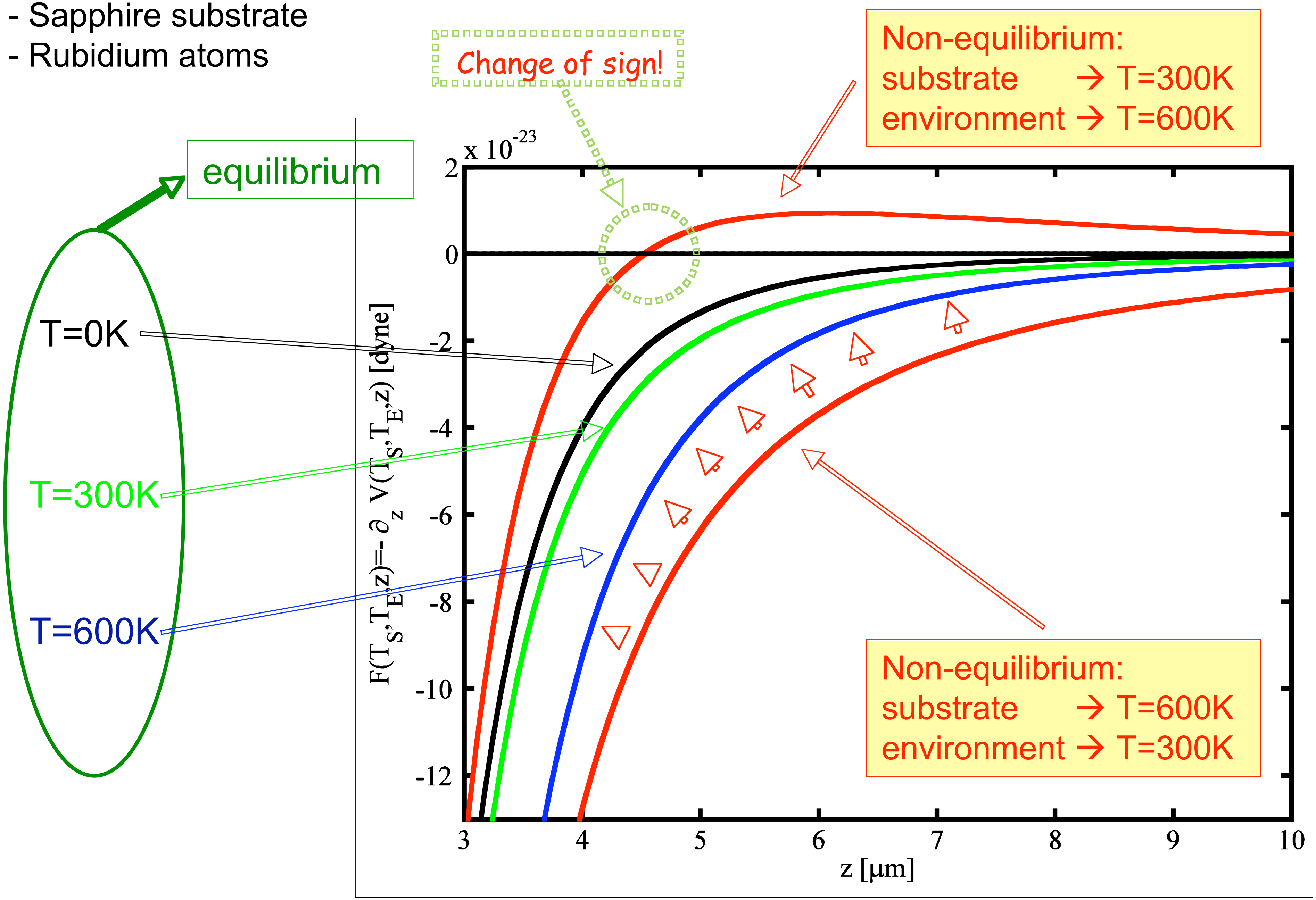
a= amplitude of c.m. oscillation

$$Z_{cm} = Z_0 + a\cos(\omega t)$$

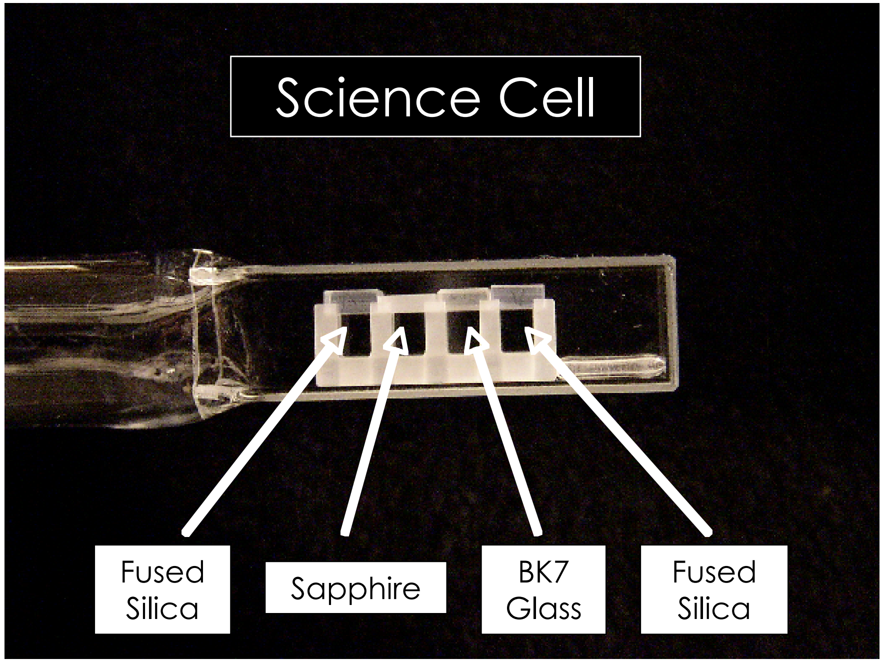
$n_0(r) \equiv$ Thomas-Fermi inverted parabola

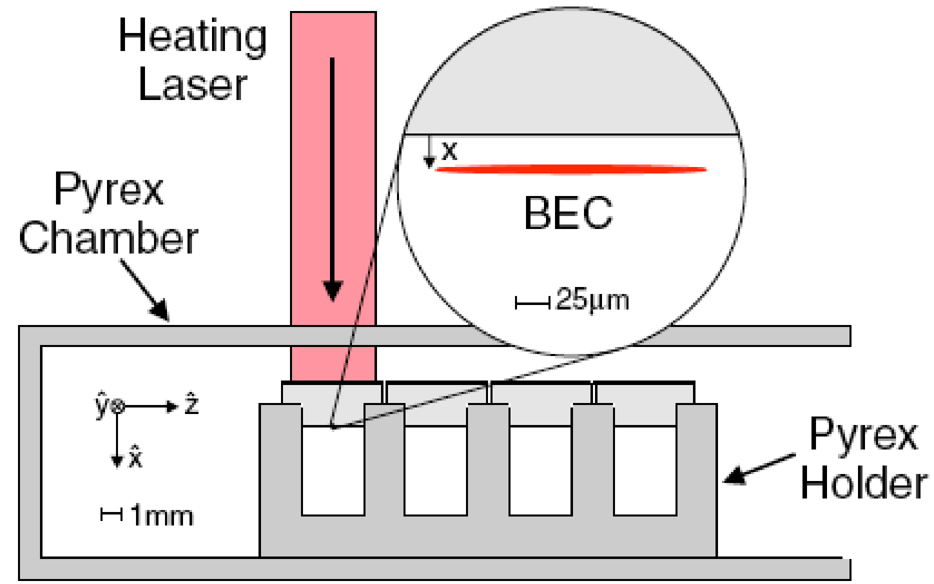
# Thermal effects on the surface-atom force

- Sapphire substrate
- Rubidium atoms



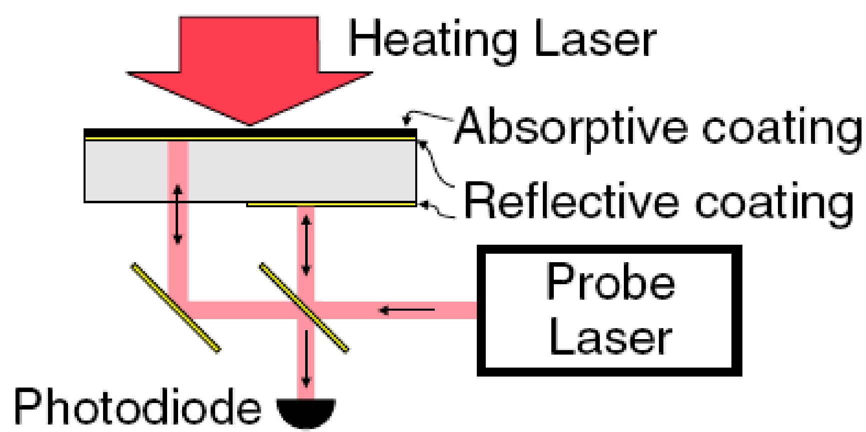
## The experimental apparatus



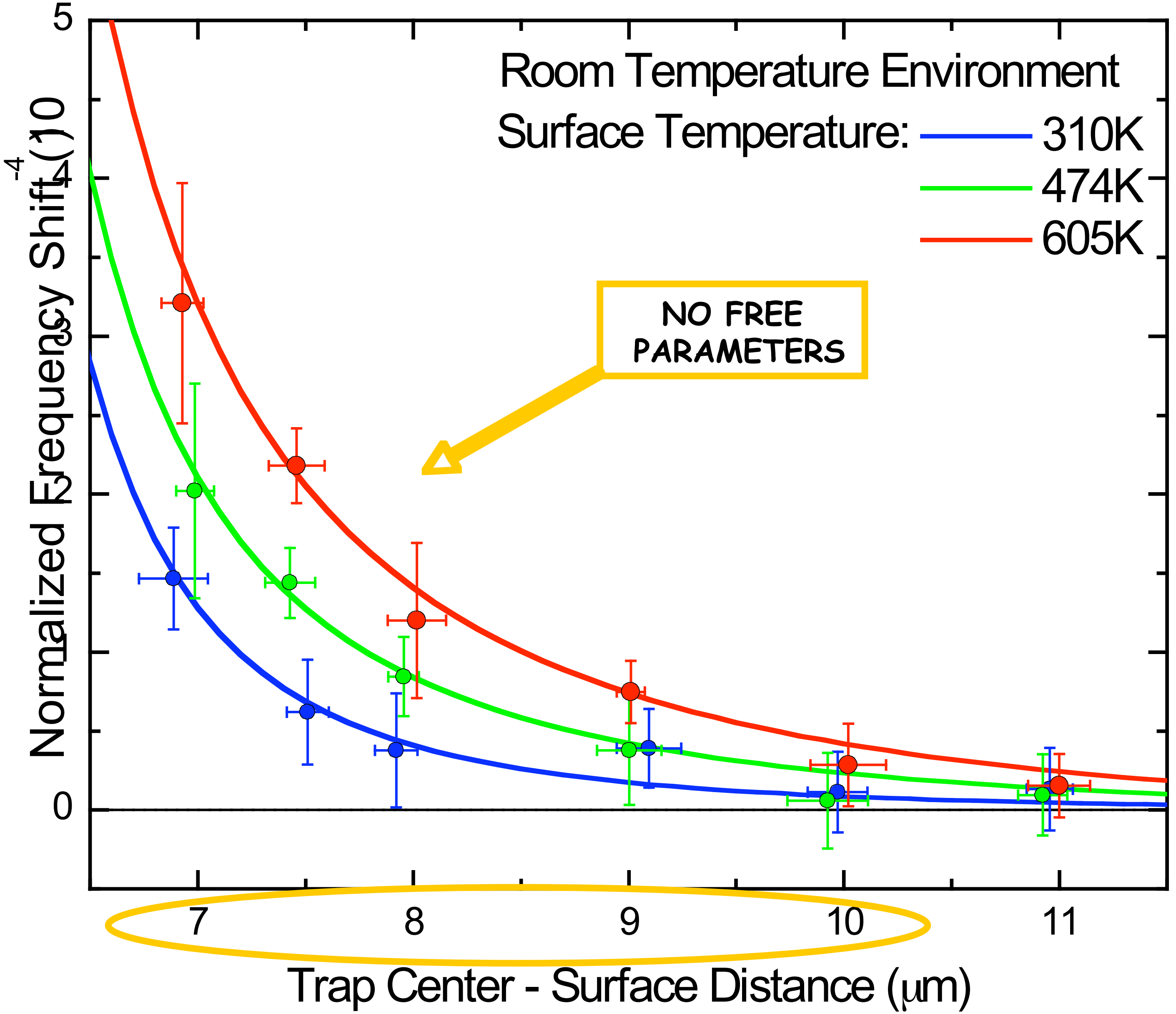

- ✓ Multiple dielectric surfaces! Amorphous glass, crystalline sapphire.
- ✓ No conducting objects near atoms!

Interferometric measurement of temperature of substrate:



Experimental results from JILA

OUT OF EQUILIBRIUM



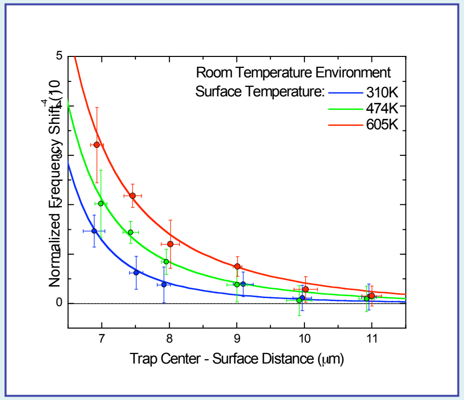

J.M. Obrecht, R.J. Wild, M. Antezza, L.P. Pitaevskii, S. Stringari, and E.A. Cornell, Phys. Rev. Lett 98, 063201 (2007)

# Conclusions

- ✓ Surface-atom force out of thermal equilibrium exhibits new asymptotic (large distance) behaviour and can provide a new way to measure thermal effects

$$F(T_S, T_E, z) \rightarrow \frac{(T_S^2 - T_E^2)}{z^3}$$

- ✓ Center of mass oscillation of a trapped Bose-Einstein condensate provides a powerful mechanical tool to detect surface-atom force at large distances, and agrees with theoretical predictions for Casimir-Polder force
(first measurement of thermal effect) Trento−Boulder collaboration

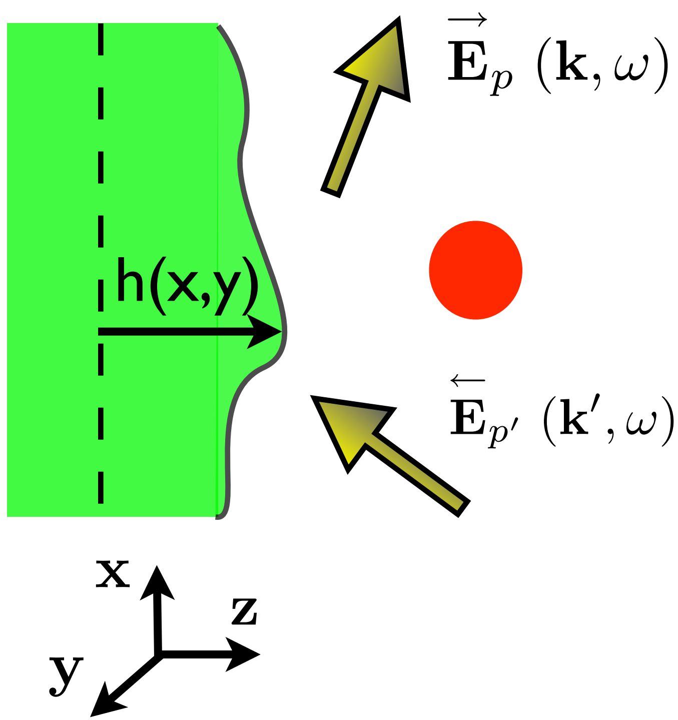



- ✓ Recent realizations of ultra-sensitive atomic interferometers based on Bloch oscillations of weakley interacting BEC are encuraging for higher precision measuments of small forces (surface-atom, possible non-Newtonian, etc. etc.)

# Part III: Lateral CP force

# CP within scattering theory






**Output fields:** $\overrightarrow{\mathbf{E}}\,(\mathbf{R},\omega) = \int \frac{d^2\mathbf{k}}{(2\pi)^2} e^{-i\mathbf{k}\cdot\mathbf{r}}\,\overrightarrow{\mathbf{E}}\,(\mathbf{k},z,\omega)$

$$\overrightarrow{\mathbf{E}}\,(\mathbf{k},z,\omega) = [\overrightarrow{E}_{\mathrm{TE}}\,(\mathbf{k},\omega)\,\hat{\epsilon}^{+}_{\mathrm{TE}}(\mathbf{k}) + \overrightarrow{E}_{\mathrm{TM}}\,(\mathbf{k},\omega)\,\hat{\epsilon}^{+}_{\mathrm{TM}}(\mathbf{k})]\; e^{ik_z z}$$

$$\hat{\epsilon}^{+}_{\mathrm{TE}}(\mathbf{k}) = \mathbf{z}\times\mathbf{k} \qquad \hat{\epsilon}^{+}_{\mathrm{TM}}(\mathbf{k}) = \hat{\epsilon}^{+}_{\mathrm{TE}}(\mathbf{k})\times\mathbf{K} \qquad (\mathbf{K} = \mathbf{k} + k_z\mathbf{z})$$

**Input fields:** idem with $k_z \to -k_z$

**Input and output fields related via reflection operators**

$$\boxed{\overrightarrow{\mathbf{E}}_p\,(\mathbf{k},\omega) = \int \frac{d^2\mathbf{k}'}{(2\pi)^2} \sum_{p'} \langle \mathbf{k},p|\mathcal{R}(\omega)|\mathbf{k}',p'\rangle\; \overleftarrow{\mathbf{E}}_{p'}\,(\mathbf{k}',\omega)}$$

**Casimir-Polder force:**

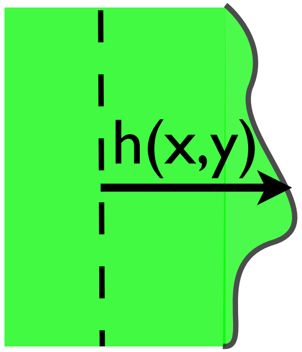
$$\boxed{U_{\mathrm{CP}}(\mathbf{R}_A) = \frac{\hbar}{c^2\epsilon_0}\int_0^\infty \frac{d\xi}{2\pi}\xi^2\alpha(i\xi)\int\frac{d^2\mathbf{k}}{(2\pi)^2}\int\frac{d^2\mathbf{k}'}{(2\pi)^2} e^{i(\mathbf{k}-\mathbf{k}')\cdot\mathbf{r}_A} e^{-(\kappa+\kappa')z_A}\frac{1}{2\kappa'}\sum_{p,p'}\hat{\epsilon}^{+}_p(\mathbf{k})\cdot\hat{\epsilon}^{-}_{p'}(\mathbf{k}')\,R_{p,p'}(\mathbf{k},\mathbf{k}')}$$

with $\kappa \equiv \sqrt{\xi^2/c^2 + k^2}$ and $R_{p,p'}(\mathbf{k},\mathbf{k}')$ dependent on material properties at freq. $i\xi$

# Specular/non specular scattering

In order to treat a general rough or corrugated surface, we make a perturbative expansion in powers of h(x,y)

$$\mathcal{R} = \mathcal{R}^{(0)} + \mathcal{R}^{(1)} + \dots$$




## Specular reflection:

$$\boxed{\langle \mathbf{k}, p | \mathcal{R}^{(0)} | \mathbf{k}', p' \rangle = (2\pi)^2 \delta^{(2)}(\mathbf{k} - \mathbf{k}')\, \delta_{p,p'}\, r_p(\mathbf{k}, \xi)}$$

Fresnel coefficients $r_{\mathrm{TE}} = \dfrac{\kappa - \kappa_t}{\kappa + \kappa_t} \qquad r_{\mathrm{TM}} = \dfrac{\epsilon(i\xi)\kappa - \kappa_t}{\epsilon(i\xi)\kappa + \kappa_t} \qquad (\kappa_t = \sqrt{\epsilon(i\xi)\xi^2/c^2 + k^2})$

## Non-specular reflection:

$$\boxed{\langle \mathbf{k}, p | \mathcal{R}^{(1)} | \mathbf{k}', p' \rangle = R_{p,p'}(\mathbf{k}, \mathbf{k}')\, H(\mathbf{k} - \mathbf{k}')}$$

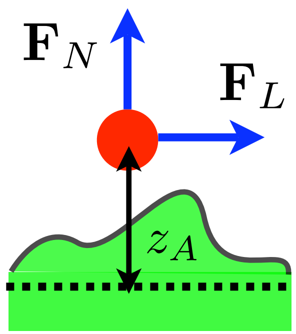
Fourier transform of h(x,y)

The non-specular reflection matrices depend on the geometry and material properties.

Greffet (1988), Reynaud et al (2005)

- See talk by Valery Marachevsky for an exact calculation of the Casimir force between real plates with rectangular corrugation (experiment by H. Chen for beyond-PFA forces)

# Lateral Casimir-Polder force




$$U_{\rm CP} = U^{(0)}_{\rm CP}(z_A) + U^{(1)}_{\rm CP}(z_A, x_A)$$

- **Normal CP force:** $$U^{(0)}_{\rm CP}(z_A) = \frac{\hbar}{c^2\epsilon_0}\int_0^\infty \frac{d\xi}{2\pi}\xi^2\alpha(i\xi)\int \frac{d^2\mathbf{k}}{(2\pi)^2}\frac{1}{2\kappa}\sum_p \hat{\epsilon}^+_p\cdot\hat{\epsilon}^-_p\; r_p(\mathbf{k},\xi)\; e^{-2\kappa z_A}$$

- **Lateral CP force:** $$\boxed{U^{(1)}_{\rm CP}(z_A, x_A) = \int \frac{d^2\mathbf{k}}{(2\pi)^2}\; e^{i\mathbf{k}\cdot\mathbf{r}_A}\; g(\mathbf{k}, z_A)\; H(\mathbf{k})}$$

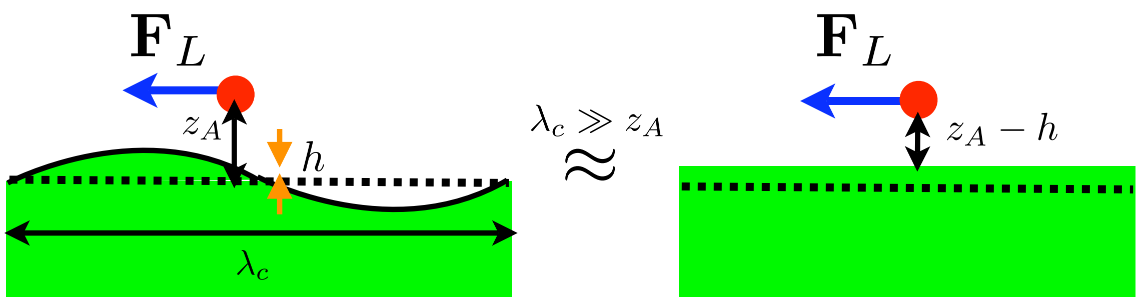
**Response function g:**

$$\boxed{\begin{aligned} g(\mathbf{k}, z_A) &= \frac{\hbar}{c^2\epsilon_0}\int_0^\infty \frac{d\xi}{2\pi}\xi^2\alpha(i\xi)\int \frac{d^2\mathbf{k}'}{(2\pi)^2}\; a_{\mathbf{k}',\mathbf{k}'-\mathbf{k}}(z_A,\xi) \\ a_{\mathbf{k}',\mathbf{k}''} &= \sum_{p',p''}\hat{\epsilon}^+_{p'}\cdot\hat{\epsilon}^-_{p''}\;\frac{e^{-(\kappa'+\kappa'')z_A}}{2\kappa''}\; R_{p',p''}(\mathbf{k}',\mathbf{k}'') \end{aligned}}$$

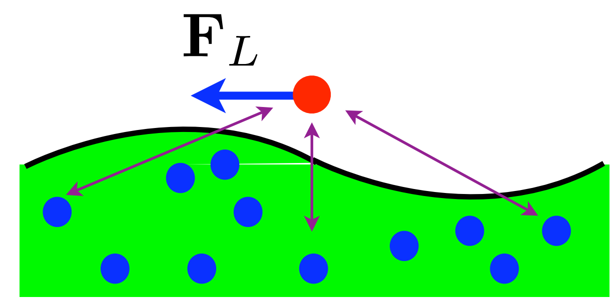
Our approach is perturbative in h(x,y), which should be the smallest length scale in the problem $h \ll z_A, \lambda_c, \lambda_A, \lambda_0$

# Approx. methods: PFA & PWS

- Proximity Force Approximation (PFA)

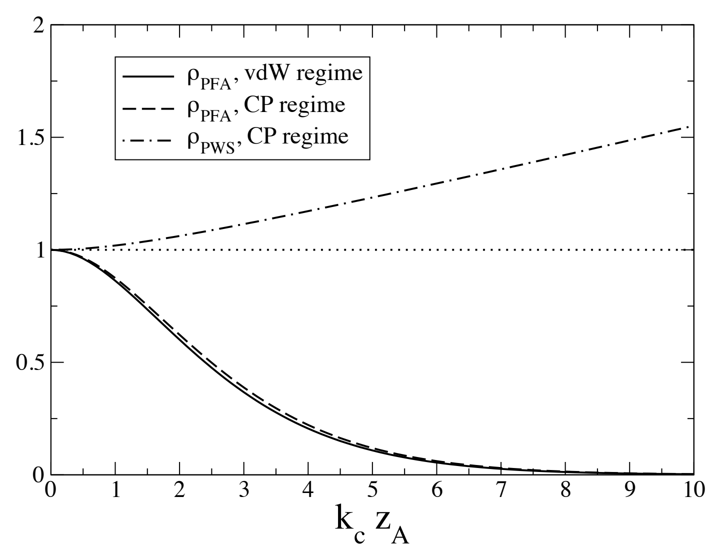



- Pair-wise Summation (PWS)




- Deviations from PFA and PWS

$$\rho_{\rm PFA} = \frac{g(k_c, z_A)}{g(0, z_A)} \qquad \rho_{\rm PWS} \equiv \frac{g(k_c, z_A)}{g_{\rm PWS}(k_c, z_A)}$$




Example:

atom-surface distance $z_A = 2\mu\text{m} \gg \lambda_A$

corrugation wavelength $\lambda_c = 3.5\mu\text{m}$

$\rho_{\rm PFA} \approx 30\% \qquad \rho_{\rm PWS} \approx 115\%$

PFA largely overestimates the lateral CP force
PWS underestimates the lateral CP force

# Real materials

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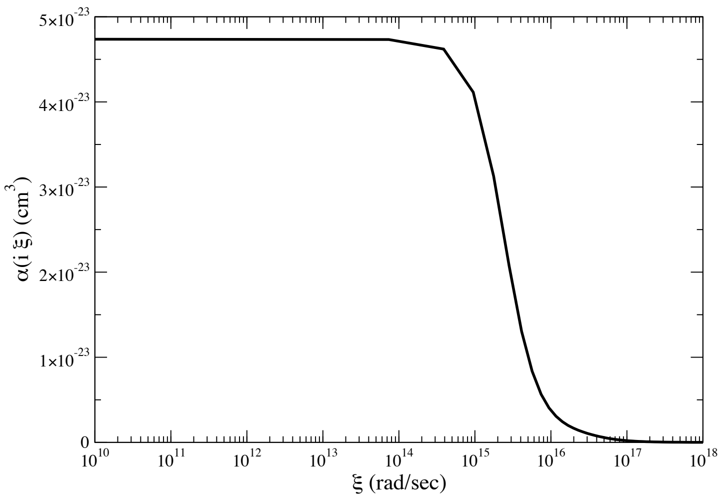
- Dynamic polarizability of Rb

Babb et al (1999)




- Calculation of $R^{(1)}_{p,p'}(\mathbf{k},\mathbf{k}',\xi)$ in terms of $\epsilon(i\xi)$ of bulk materials Reynaud et al (2005)

$$R^{(1)}_{\mathrm{TE,TE}}(\mathbf{k},\mathbf{k}';\xi) = 2\kappa\, C\, h_{\mathrm{TE,TE}}(\mathbf{k},\mathbf{k}',\xi)$$

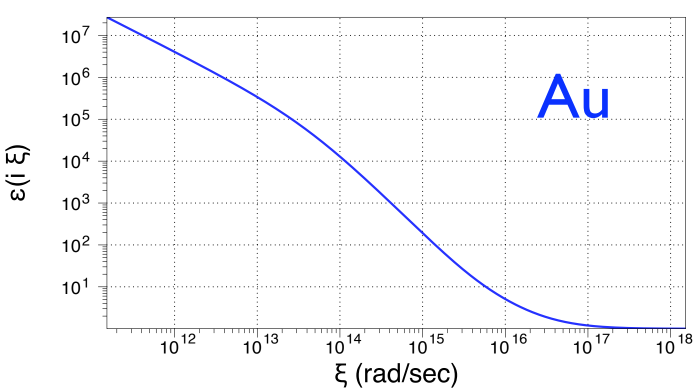
$$R^{(1)}_{\mathrm{TE,TM}}(\mathbf{k},\mathbf{k}';\xi) = 2\kappa S\, \frac{c\kappa_t'}{\sqrt{\epsilon}\xi}\, h_{\mathrm{TE,TM}}(\mathbf{k},\mathbf{k}',\xi)$$

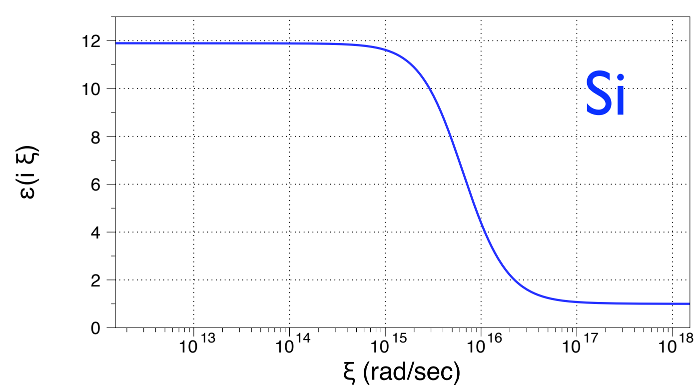
$$R^{(1)}_{\mathrm{TM,TE}}(\mathbf{k},\mathbf{k}';\xi) = \frac{2\sqrt{\epsilon}\kappa\kappa_t \frac{\xi}{c} S}{(\frac{\xi}{c})^2 - (\epsilon+1)\kappa^2} h_{\mathrm{TM,TE}}(\mathbf{k},\mathbf{k}',\xi)$$

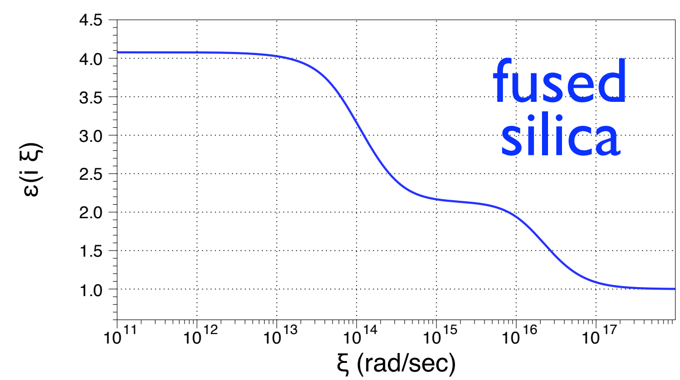
$$R^{(1)}_{\mathrm{TM,TM}}(\mathbf{k},\mathbf{k}';\xi) = -2\kappa \frac{\epsilon k k' + \kappa_t \kappa_t' C}{(\frac{\xi}{c})^2 - (\epsilon+1)\kappa^2}\, h_{\mathrm{TM,TM}}(\mathbf{k},\mathbf{k}',\xi)$$

$$h_{pp'}(\mathbf{k},\mathbf{k}') = \frac{r^p(\mathbf{k}) t^{p'}(\mathbf{k}')}{t^p(\mathbf{k})}$$

- Optical data + Kramers-Kronig relations



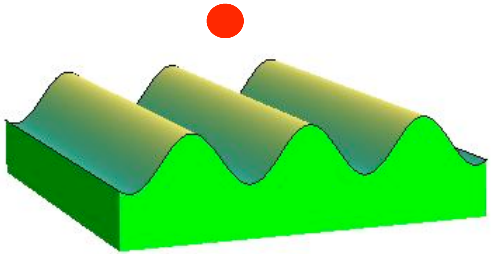



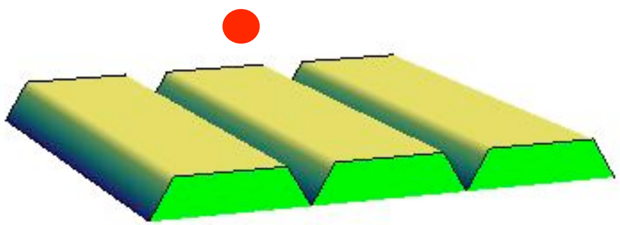
# Atoms as local probes

In contrast to the case of the lateral Casimir force between corrugated surfaces, an atom is a local probe of the lateral Casimir-Polder force. Deviations from the PFA can be much larger than for the force between two surfaces!

- ☑ Deviations from PFA/PWS can be obtained for a sinusoidal corrugated surface.



- ☑ Even larger deviations from PFA/PWS can be obtained for a periodically grooved surface.



- If the atom is located above one plateau, the PFA predicts that the lateral Casimir-Polder force should vanish. A non-vanishing force appearing when the atom is moved above the plateau thus clearly signals a deviation from PFA!

- A lateral force appears for PWS, but it should be much smaller than the exact result.

# CP energy for grooved surface

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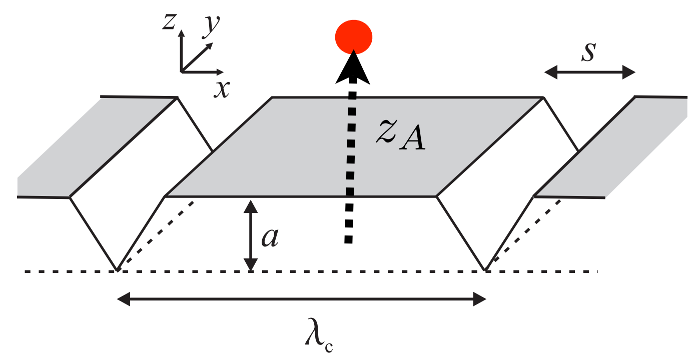
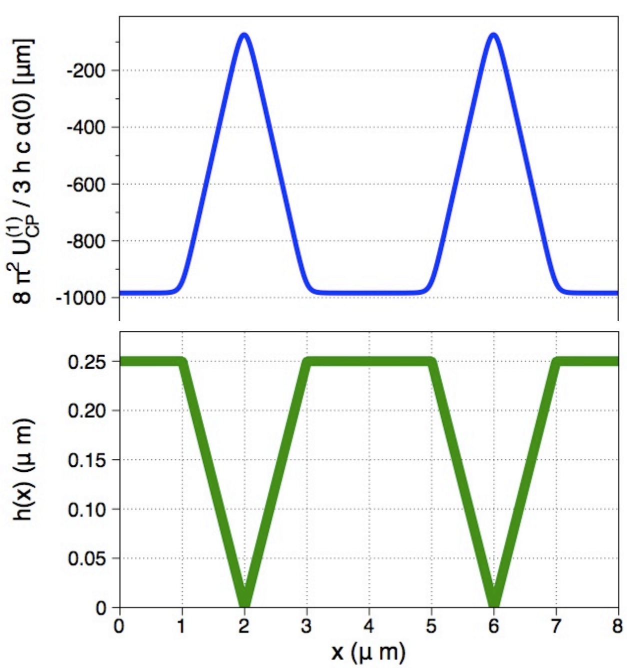
- Surface profile for periodical grooved corrugation

$$h(x) = a\left(1 - \frac{s}{2\lambda_c}\right) + \frac{2a\lambda_c}{\pi^2 s}\sum_{n=1}^{\infty}(-1)^{n+1}\frac{1-\cos(n\pi s/\lambda_c)}{n^2}\cos\left(\frac{2\pi n x}{\lambda_c}\right)$$

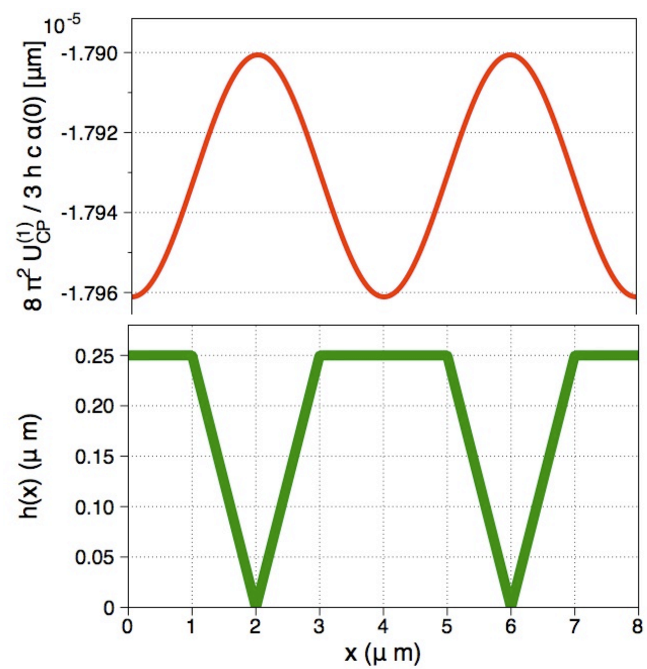



- Single-atom lateral CP energy: it can be easily calculated using that the first order lateral CP energy $U^{(1)}_{\rm CP}(\mathbf{R}_A) = \int \frac{d^2\mathbf{k}}{(2\pi)^2} e^{i\mathbf{k}\cdot\mathbf{r}_A} g(\mathbf{k}, z_A)\, H(\mathbf{k})$ is linear in $H(\mathbf{k})$

$k_c z_A = 0.3$




$k_c z_A = 10$

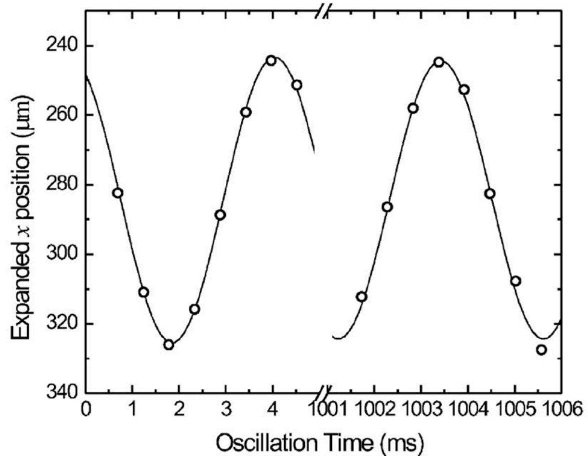


# BEC as a field sensor

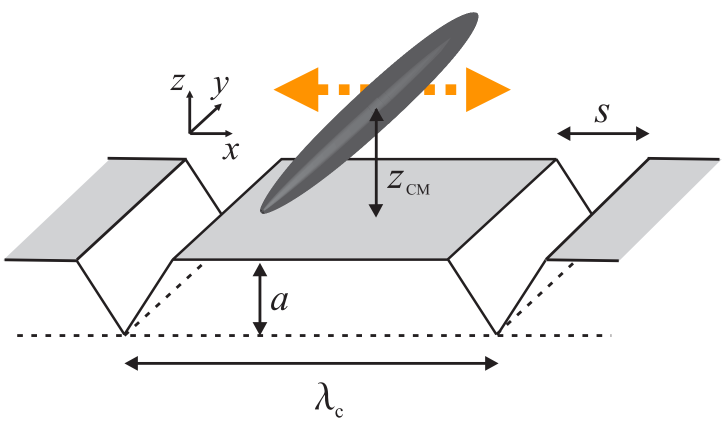
## BEC oscillator

- The normal component of Casimir-Polder force $U_{\rm CP}^{(0)}(z)$ shifts the normal dipolar oscillation frequency of a BEC trapped above a surface

Antezza et al (2004) Cornell et al (2005, 2007)




- In order to measure the lateral component $U_{\rm CP}^{(1)}(x,z)$ , a cigar-shaped BEC could be trapped parallel to the corrugation lines, and the lateral dipolar oscillation measured as a function of time




$$V(\mathbf{r}) = V_{\rm ho}(\mathbf{r}) + U_{\rm CP}(\mathbf{r})$$

$$V_{\rm ho}(\mathbf{r}) = \frac{m}{2}(\omega_x^2 x^2 + \omega_y^2 y^2 + \omega_z^2 z^2) \quad \omega_y \ll \omega_x = \omega_z$$

Lateral frequency shift:

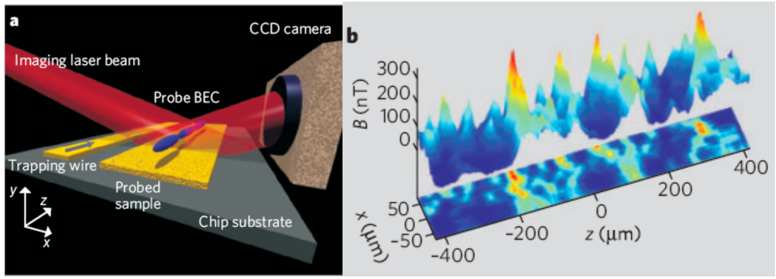
$$\omega_{x,\rm CM}^2 = \omega_x^2 + \frac{1}{m}\int dx dz\, n_0(x,z) \frac{\partial^2}{\partial x^2} U_{\rm CP}^{(1)}(x,z)$$

# BEC as a field sensor (cont'd)

## Density variations of a BEC above an atom chip

- For a quasi one-dimensional BEC, the potential is related to the 1D density profile as

$$V_{\mathrm{ho}}(x) + U_{\mathrm{CP}}(x) = -\hbar\omega_x\sqrt{1 + 4a_{\mathrm{scat}}n_{1d}(x)}$$




Measurement of the magnetic field variations along a current-carrying wire

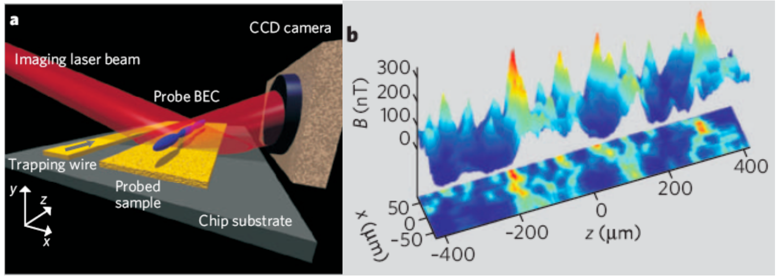
Schmiedmayer et al (2005)

# BEC as a field sensor (cont'd)

## Density variations of a BEC above an atom chip

- For a quasi one-dimensional BEC, the potential is related to the 1D density profile as

$$\boxed{V_{\rm ho}(x) + U_{\rm CP}(x) = -\hbar\omega_x\sqrt{1 + 4a_{\rm scat}n_{1d}(x)}}$$



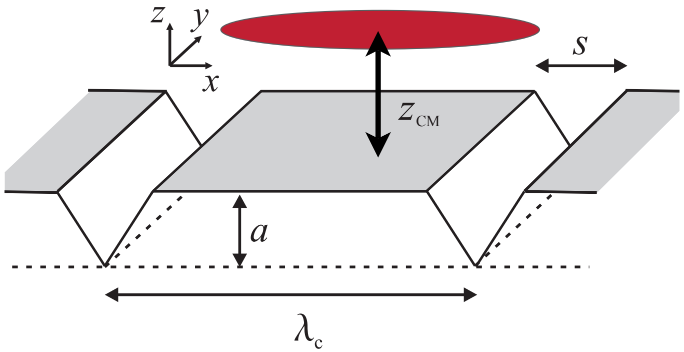

Measurement of the magnetic field variations along a current-carrying wire

Schmiedmayer et al (2005)

For the lateral CP force, perfect conductor, sinusoidal corrugation ( $a = 100\mathrm{nm}$), distance $z_A = 2\mu\mathrm{m}$, PFA limit $(k_c z_A \ll 1)$

$$\Delta U^{(1)}_{\rm CP} \simeq 10^{-14}\,\mathrm{eV}$$

- To measure the lateral CP force, the elongated BEC should be aligned along the x-direction, and a density modulation along this direction above the plateau would be a signature of a nontrivial (beyond-PFA) geometry effect.



# Single-atom/BEC frequency shift

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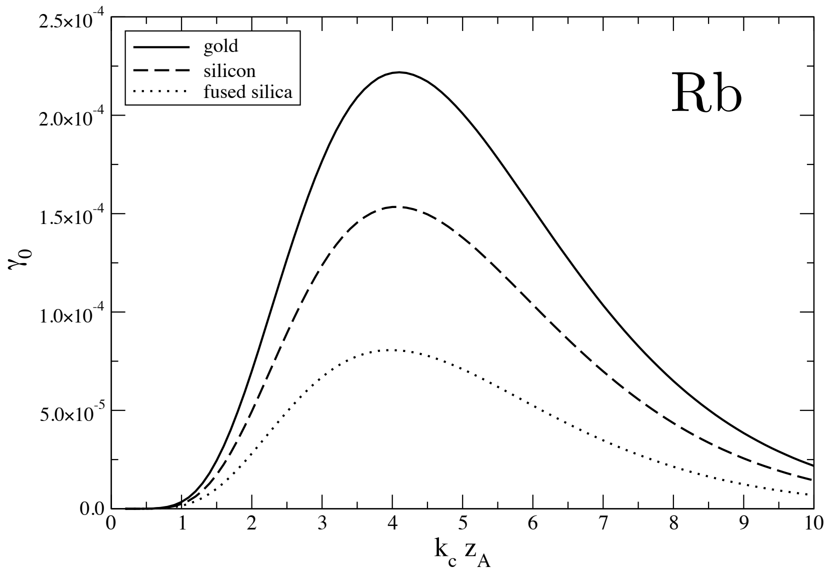
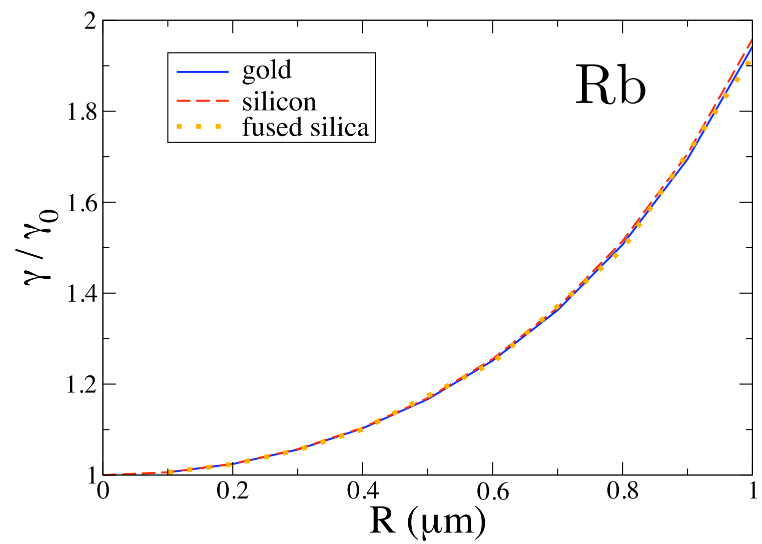
$$\boxed{\gamma_0 \equiv \frac{\omega_{x,\mathrm{CM}} - \omega_x}{\omega_x}}$$

## Single-atom lateral freq. shift




$$\omega_x/2\pi = 229\,\mathrm{Hz}$$
$$z_{\mathrm{CM}} = 2\mu\mathrm{m}$$
$$\lambda_c = 4\mu\mathrm{m}$$
$$a = 250\mathrm{nm}$$
$$s = \lambda_c/2$$

## Single-atom / BEC comparison



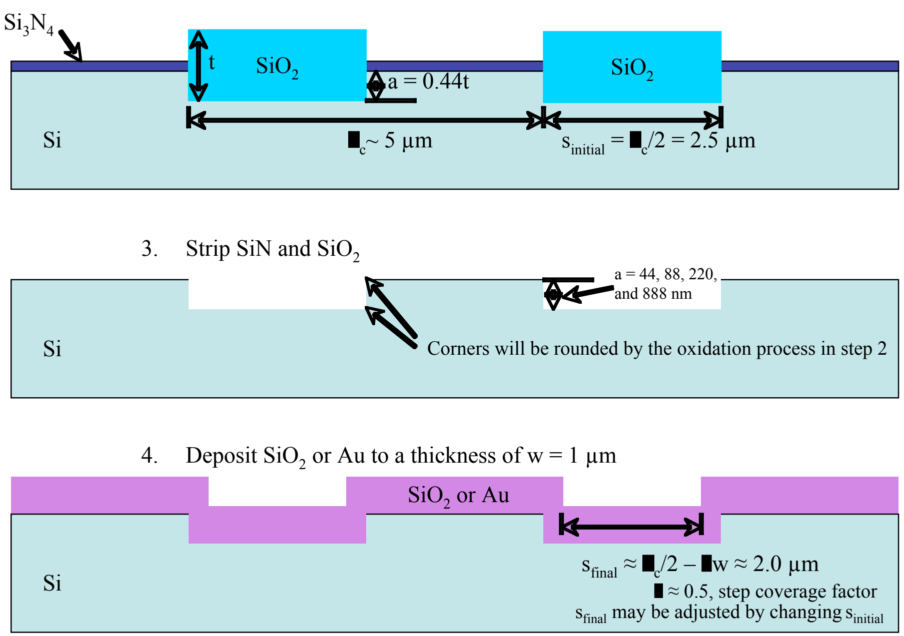

Given the reported sensitivity $\gamma = 10^{-5} - 10^{-4}$ for relative frequency shifts from E. Cornell's experiment, we expect that beyond-PFA lateral CP forces on a BEC above a plateau of a periodically grooved silicon surface should be detectable for distances $z_{\mathrm{CM}} < 3\mu\mathrm{m}$, groove period $\lambda_c = 4\mu\mathrm{m}$, groove amplitude $a = 250\mathrm{nm}$, and a BEC radius of, say, $R \approx 1\mu m$

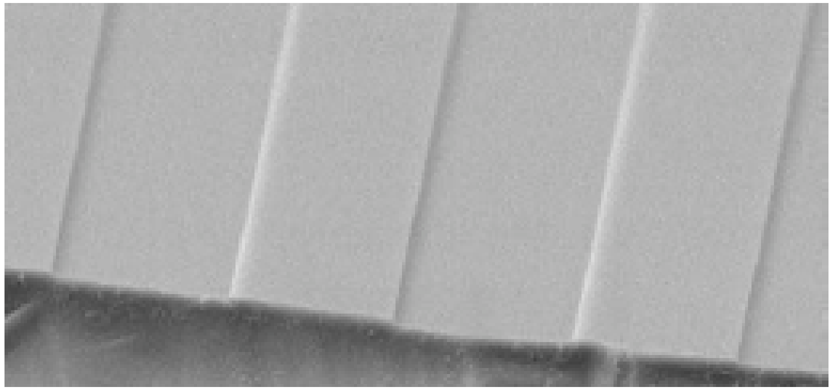
# Towards the experiment

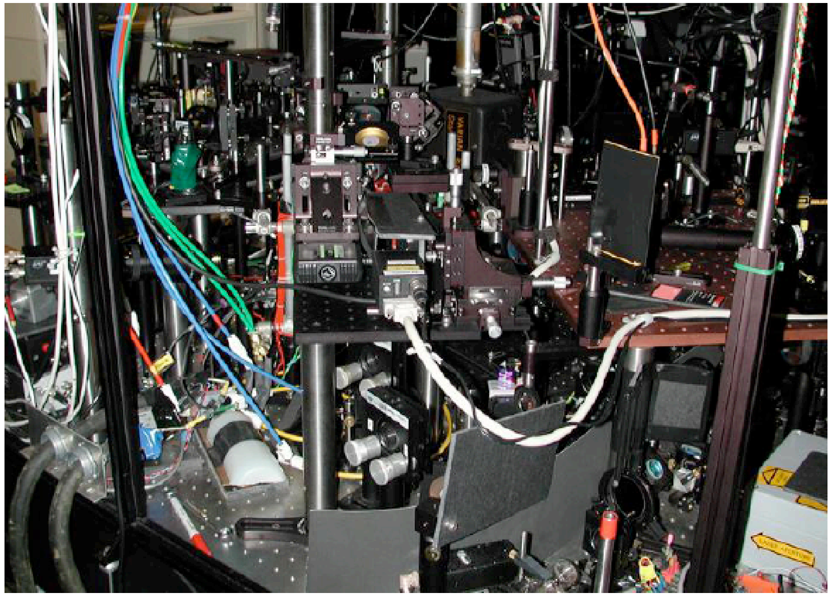
- Surfaces are being fabricated by Matt Blain
- CP force measurements with BEC will be done by Malcolm Boshier

Number of periods, 100/set
•Length of “grooves”, 2 mm
•see next slide

Process sequence
1. Deposit/pattern SiN oxidation mask
2. Grow $SiO_2$ in exposed Si to thicknesses of t = 100, 200, 500 and 2000 nm





# Summary part III

- Novel cold atoms techniques open a promising way of investigating nontrivial geometrical effects on quantum vacuum
- Important feature of atoms: they can be used as local probes of quantum vacuum fluctuations
- Non-trivial, beyond-PFA effects should be measurable using a BEC as a vacuum field sensor with available technology

For more details see:

Dalvit, Maia Neto, Lambrecht, and Reynaud,
Phys. Rev. Lett. 100, 040405 (2008)
J. Phys. A 41, 164028 (2008)

# Part IV: Carrier drift in SC

In collaboration with Steve Lamoreaux
(theoretical and experimental work in progress)

Some preliminary results in arXiv: 0805.1676

# Part IV: Carrier drift in SC

- Maxwell eqns
- Boltzmann eqn

$$\nabla \times \mathbf{E} = i\mu_0\omega\mathbf{H}, \quad \nabla \times \mathbf{H} = -i\overline{\epsilon}(\omega)\omega\mathbf{E} + \mathbf{J},$$

$$\nabla \cdot \mathbf{E} = -en/\overline{\epsilon}(\omega). \qquad \mathbf{J} = -en\mathbf{v}$$

$$\left(\frac{\partial}{\partial t} + \mathbf{v}\cdot\nabla\right)\mathbf{v} = -\frac{e}{m}\mathbf{E} - \frac{v_T^2}{n}\nabla n - \frac{\mathbf{v}}{\tau},$$

$$\boxed{\left[\nabla^2 + \mu_0\overline{\epsilon}(\omega)\omega^2\left(1 + i\frac{\tilde{\omega}_c}{\omega}\right)\right]\mathbf{E} = [1+i\mu_0\overline{\epsilon}(\omega)\omega\tilde{D}]\nabla\cdot(\nabla\cdot\mathbf{E})}$$

$\tilde{D} = D/(1 - i\omega\tau)$ $\qquad D = v_T^2\tau$ $\qquad$ Diffusion constant

$\tilde{\omega}_c = \omega_c/(1 - i\omega\tau)$ $\qquad \omega_c = 4\pi e n_0\mu/\overline{\epsilon}(\omega)$ $\qquad \mu = e\tau/m$ $\qquad$ Mobility

$\omega_c/D = 4\pi e^2 n_0/\overline{\epsilon}(\omega)k_B T = \kappa^2 = 1/R_{\mathrm{D}}^2$ $\qquad$ Debye length

The equation for the field allows TE and TM solutions.

# Reflection coefficient w/ drift

- TE modes

$$\boxed{r_{\mathbf{k}}^{\mathrm{TE}}(i\xi) = \frac{\sqrt{k^2+\xi^2/c^2}-\eta_T}{\sqrt{k^2+\xi^2/c^2}+\eta_T}.}$$

$$\eta_T^2 = k^2 - \mu_0\overline{\epsilon}(\omega)\omega^2\left(1+i\frac{\tilde{\omega}_c}{\omega}\right)$$

- TM modes

$$\boxed{r_{\mathbf{k}}^{\mathrm{TM}}(i\xi) = \frac{\overline{\epsilon}(i\xi)\sqrt{k^2+\xi^2/c^2}-\chi}{\overline{\epsilon}(i\xi)\sqrt{k^2+\xi^2/c^2}+\chi},}$$

$$\eta_L^2 = k^2 - i\frac{\omega}{\tilde{D}}\left(1+i\frac{\tilde{\omega}_c}{\omega}\right)$$

$$\chi = \frac{1}{\eta_L}\left[k^2+\overline{\epsilon}(i\xi)\frac{\xi^2}{c^2}\frac{\eta_L\eta_T-k^2}{\eta_T^2-k^2}\right]$$

- Quasi-static limit - Application to thermal CP force for surfaces with small density of carriers (semiconductors, dielectrics) L.P. Pitaevskii, arXiv:0801.0656v2.

$$r_{\mathbf{k}}^{\mathrm{TE}}(0) = 0 \text{ and } r_{\mathbf{k}}^{\mathrm{TM}}(0) = (\overline{\epsilon}_0 q - k)/(\overline{\epsilon}_0 q + k). \qquad q = \sqrt{k^2+\kappa^2},$$

$d \ll R_{\mathrm{D}}$ (ideal dielectric limit)

$d \gg R_{\mathrm{D}}$ (good conductor limit)

- Relation to spatial dispersion in Casimir physics.

# Carrier drift / conduc. in SC

- Application to intrinsic semiconductors: Ge and Si

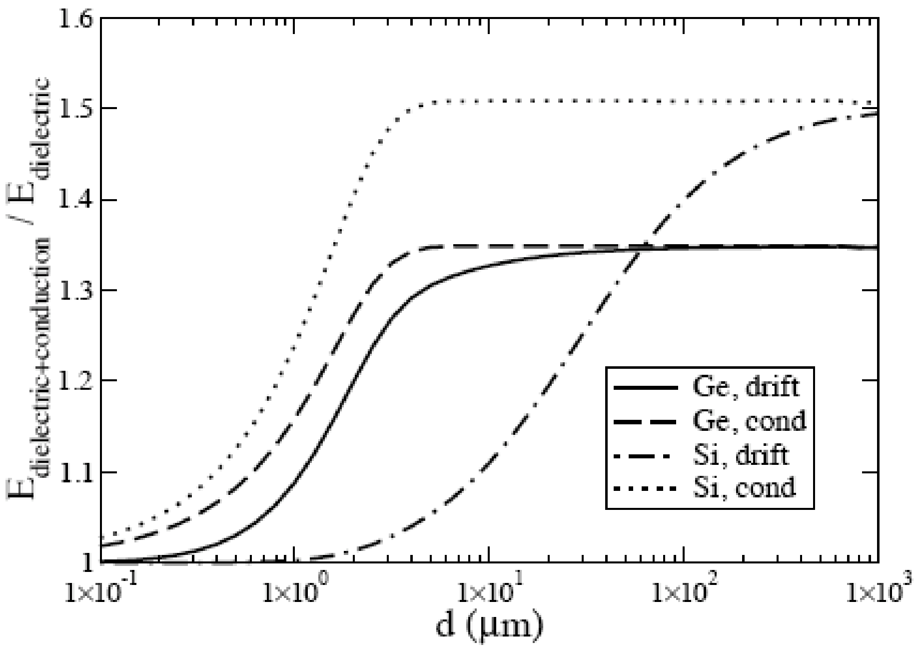



FIG. 2: The ratio of Casimir-Lifshitz free energies at $T = 300$K for intrinsic semiconductor parallel plates for different conductivity models as follows: Carrier drift with Debye-Hückle screening, and a Drude-like model where a term $4\pi\sigma/\xi$ is added to the bare permittivity. Parameters are as follows: For Ge, the Debye length is $R_D = 0.68\mu$m and the conductivity is $\sigma = 1/(43\ \Omega\ \text{cm})$; For Si, $R_D = 24\mu$m and $\sigma = 1/(2.3\times10^5\ \Omega\ \text{cm})$.

Including the effect of conductivity $4\pi\sigma/\xi$ leads to an increase of the force in disagreement with Cornell's experiment

G.L. Klimchitskaya and V.M. Mostepanenko, arXiv:0801.1978.

In the near future we plan to apply these results to an ongoing measurement of the Casimir-Lifshitz force between pure germanium plates.