Recent progress in Casimir physics for atom-surface interactions

Diego A. R. Dalvit
Theoretical Division
Los Alamos National Laboratory

Los Alamos
NATIONAL LABORATORY

Collaborators

Paulo Maia Neto (Rio de Janeiro)

Astrid Lambrecht (LKB, Paris)

Riccardo Messina (LKB, Paris)

Serge Reynaud (LKB, Paris)

Outline of this talk

- Part I

- Review of theory and experiment on Casimir atom-surface interactions

Outline of this talk

Los Alamos
NATIONAL LABORATORY

- Part I

- Review of theory and experiment on Casimir atom-surface interactions

- Part II

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

Outline of this talk

Los Alamos
NATIONAL LABORATORY

- Part I

  - Review of theory and experiment on Casimir atom-surface interactions

- Part II

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

- Part III

  - Casimir-Polder forces within scattering theory

  - Cold atoms for probing lateral Casimir-Polder forces

Part I: Review

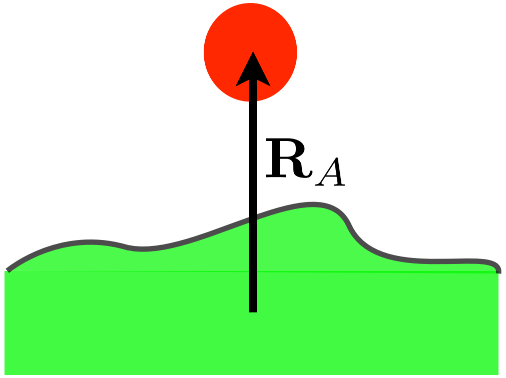
The Casimir-Polder force

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

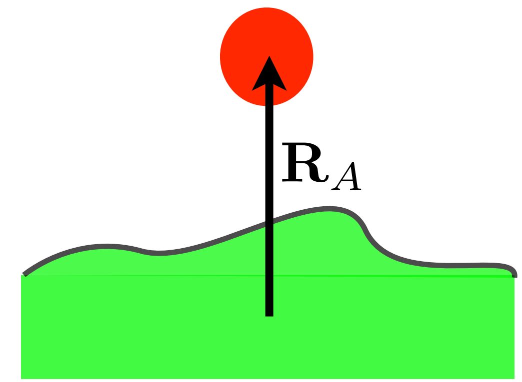
The Casimir-Polder force

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

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

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

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

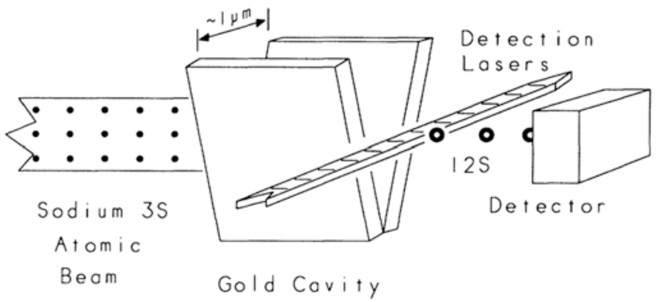
Retarded (CP) limit $z_A \gg \lambda_A$

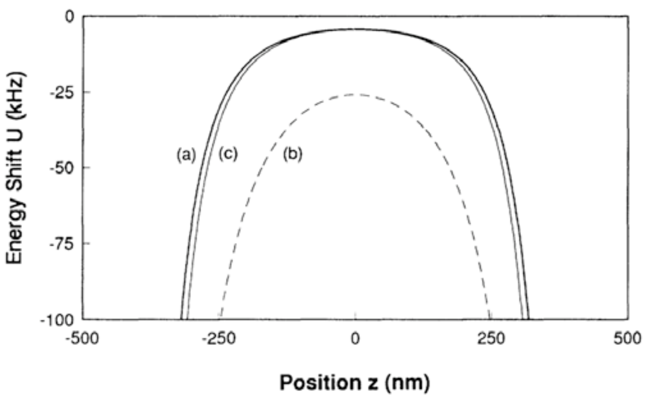
$$U_{\mathrm{CP}}(z_A) = -\frac{3\hbar c\alpha(0)}{8\pi}\frac{1}{z_A^4}\frac{\epsilon_0-1}{\epsilon_0+1}\phi(\epsilon_0)$$

Modern CP experiments

- Deflection of atoms

Hinds et al (1993)





L= 0.7-1.2 um

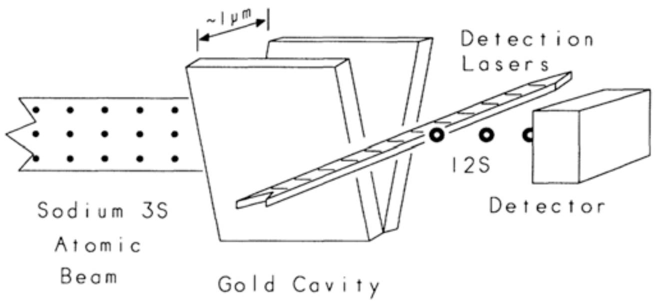
Exp-Th agreement @ 10%

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

Modern CP experiments

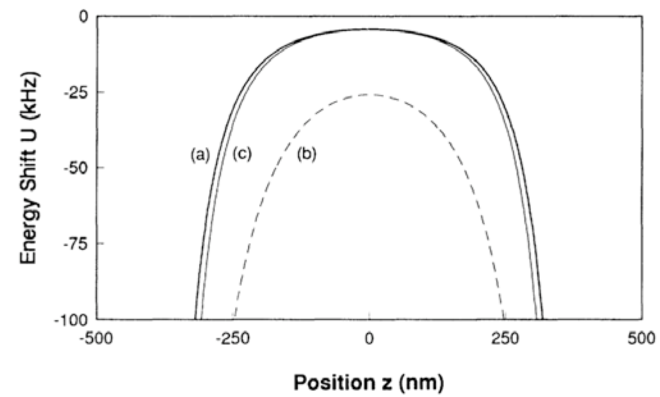
Deflection of atoms

Hinds et al (1993)



L= 0.7-1.2 um

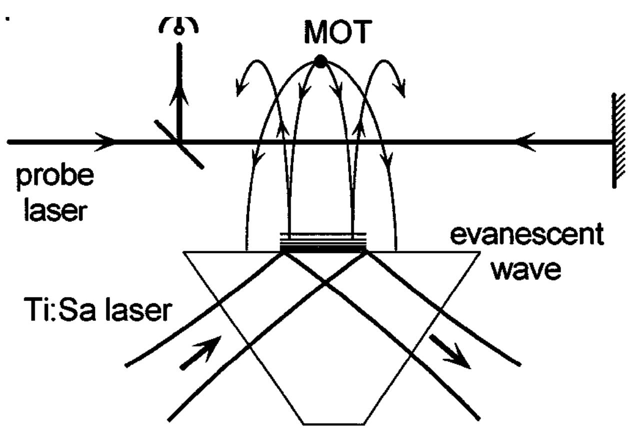
Exp-Th agreement @ 10%



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

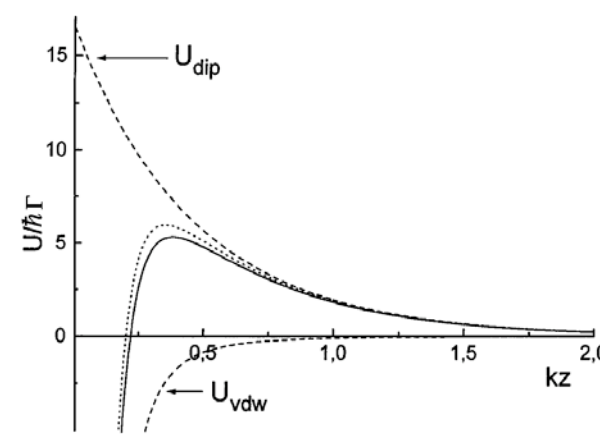
Classical reflection on atomic mirror

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%

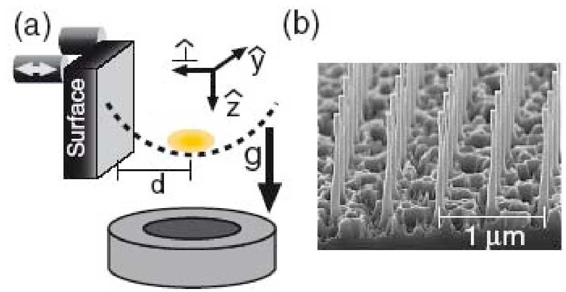
Modern experiments (cont'd)

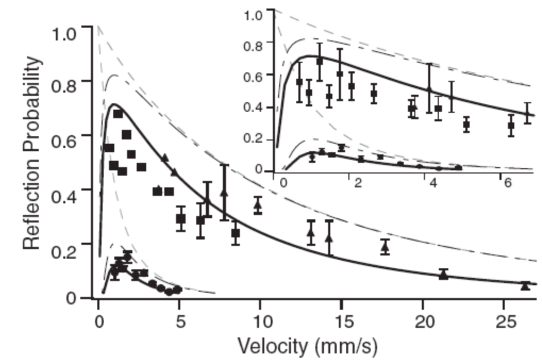
Quantum reflection

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)

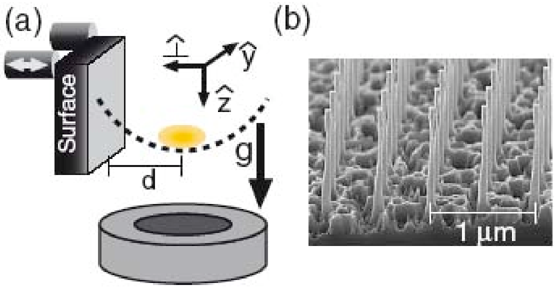
Ketterle et al (2006)

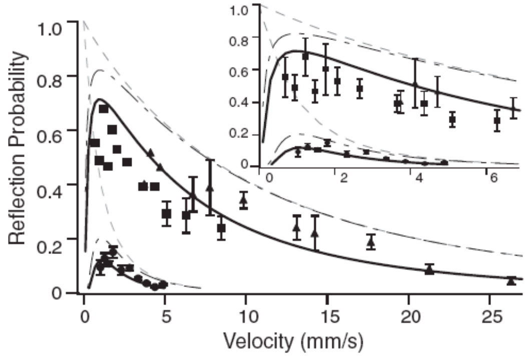
DeKievet et al (2003)

Modern experiments (cont'd)

Quantum reflection

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





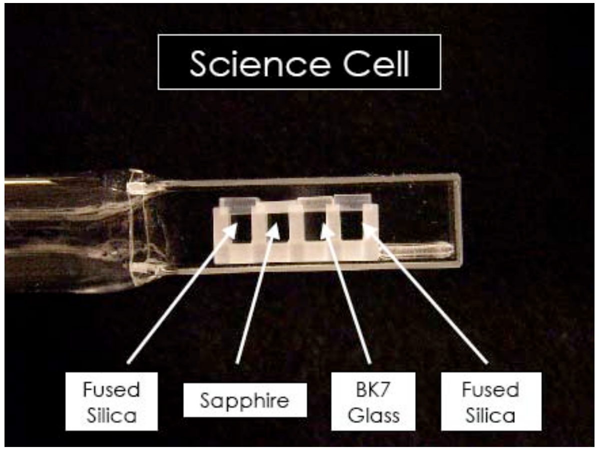
$$k = \sqrt{k_0^2 - 2mU/\hbar^2} \qquad \phi = \frac{1}{k^2}\frac{dk}{dr} > 1$$

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

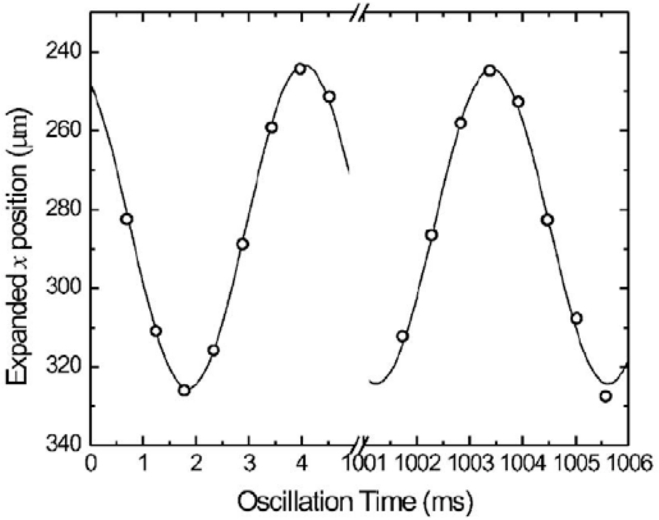
Shimizu (2001) Ketterle et al (2006)
DeKievet et al (2003)

BEC oscillator

Cornell et al (2007)

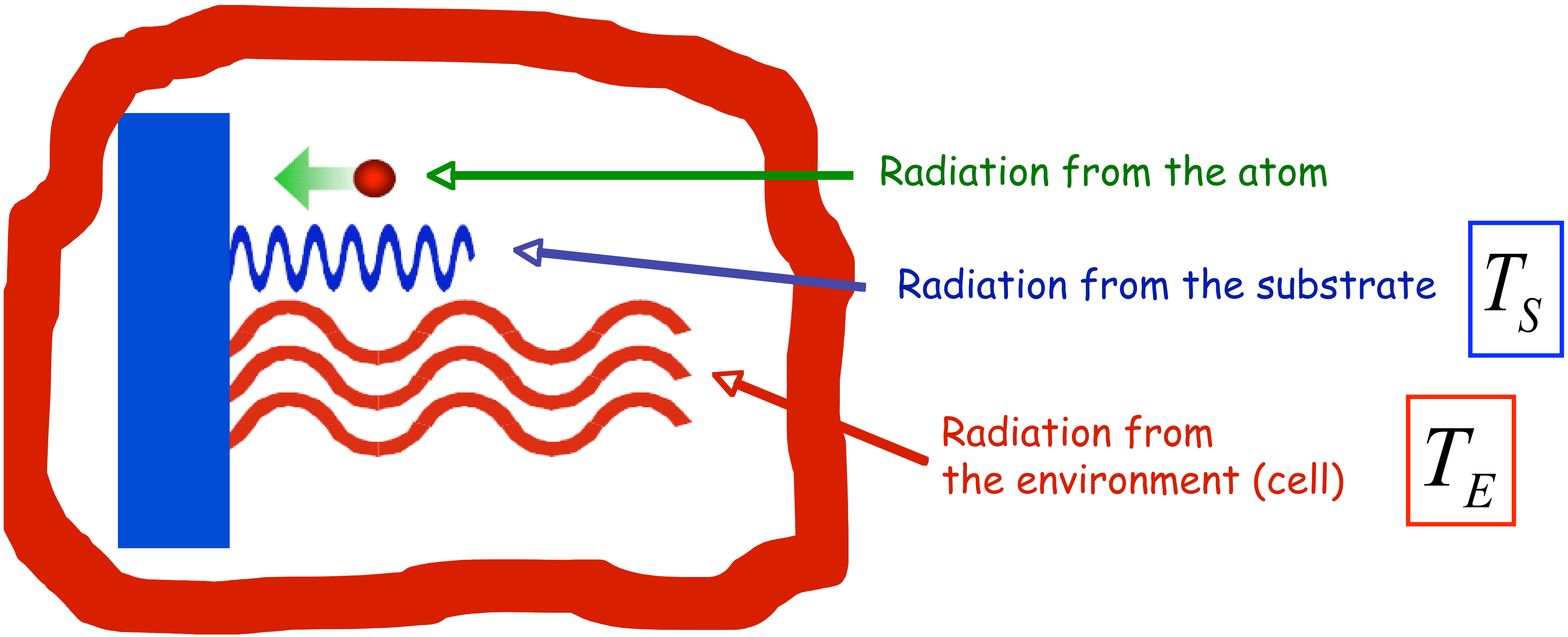


$$\gamma_x \equiv \frac{\omega_x - \omega_x'}{\omega_x} \simeq -\frac{1}{2\omega_x^2 m}\partial_x^2 U^*$$



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

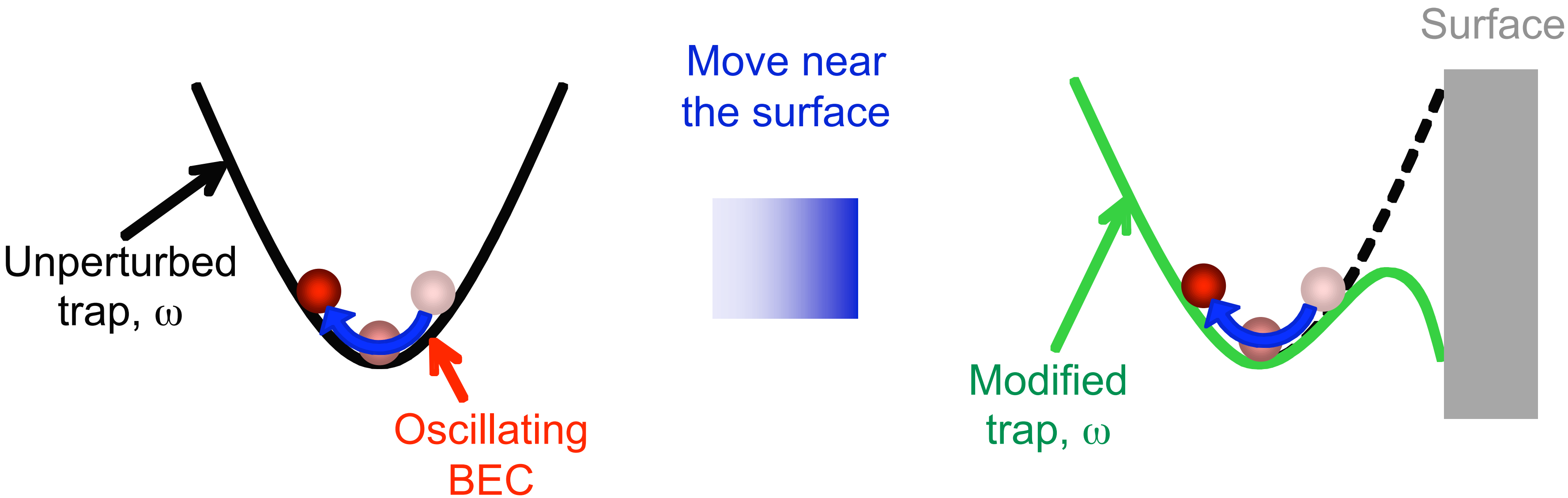
System at equilibrium	System out of equilibrium
$$F^{eq} = -\frac{3k_B T\alpha_0(\varepsilon_0 - 1)}{4z^4(\varepsilon_0 + 1)}$$	substrate, environment $$F^{neq} = -\frac{\pi}{6}\frac{\alpha_0 k_B^2(T_S^2 - T_E^2)}{z^3 c\hbar}\frac{\varepsilon_0 + 1}{\sqrt{\varepsilon_0 - 1}}$$
E.M. Lifshitz, Dokl. Akad. Nauk. **100**, 879 (1955)	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

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

$$\omega_{cm}^2 - \omega_z^2 = \frac{1}{m}\int n_0(\vec{r})\partial_z^2 V_{surf-at}(z)d\vec{r} + \frac{a^2}{8m}\int n_0(\vec{r})\partial_z^4 V_{surf-at}(z)d\vec{r}$$

Linear approximation

First non-linear correction

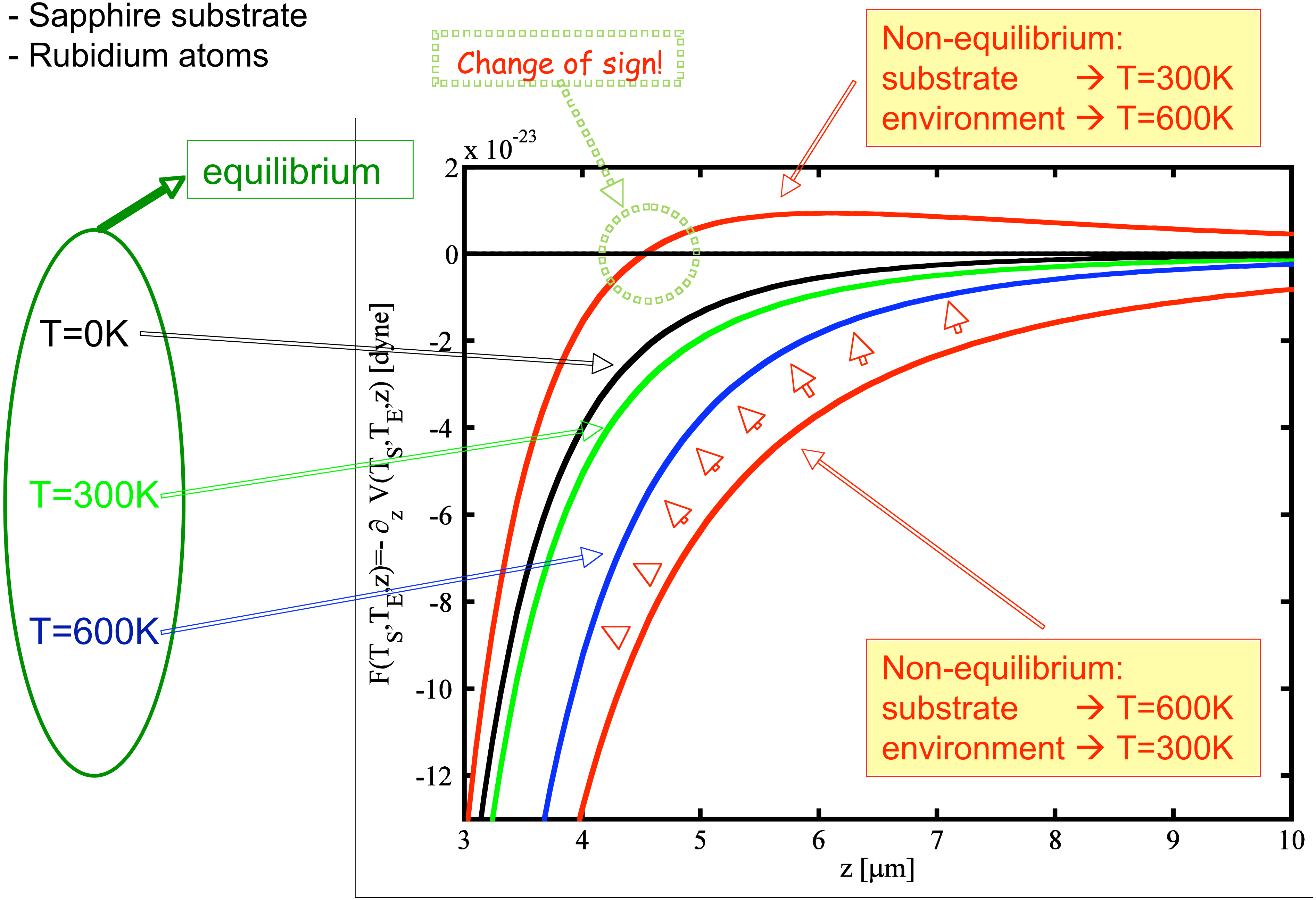
a= amplitude of c.m. oscillation

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

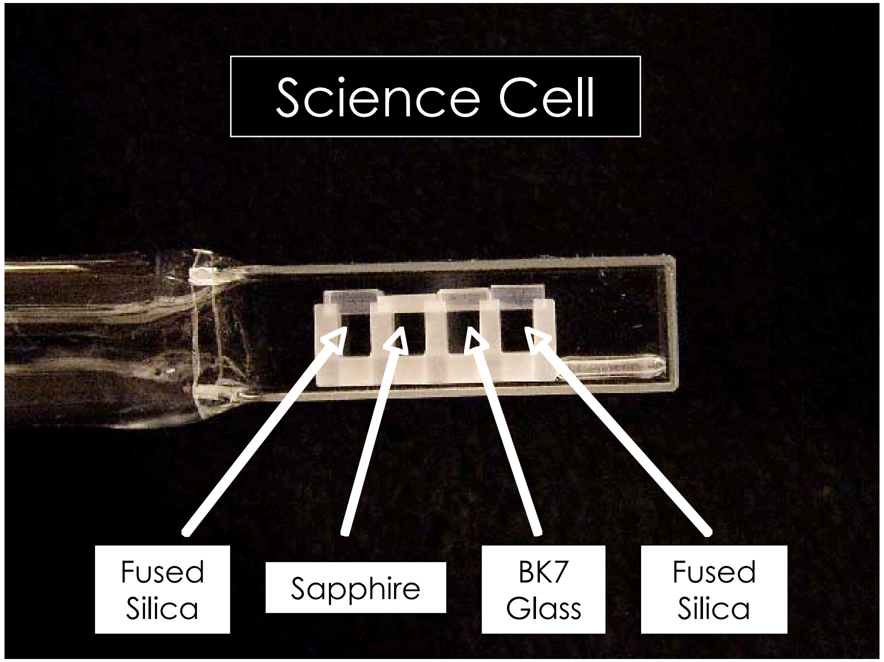
$n_0(r) \equiv$ Thomas-Fermi inverted parabola

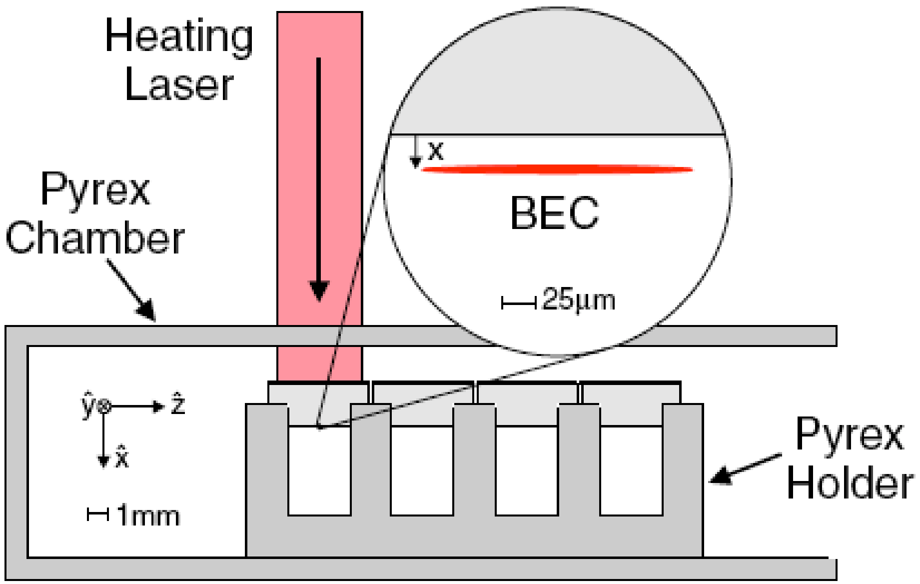
Thermal effects on the surface-atom force

- Sapphire substrate
- Rubidium atoms



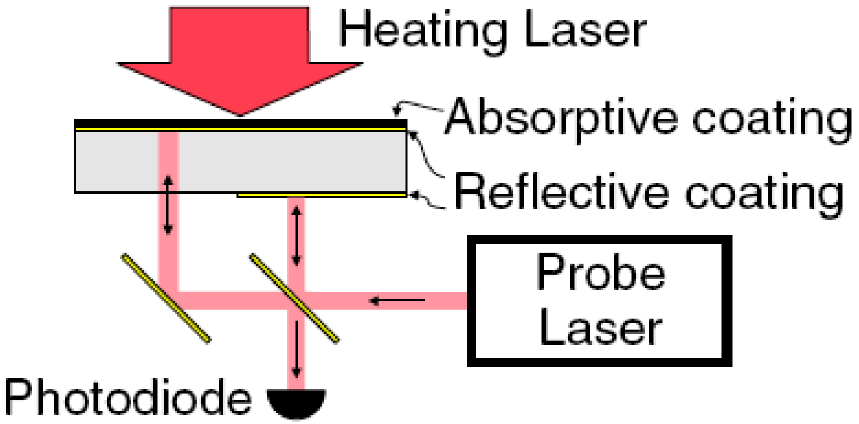
The experimental apparatus





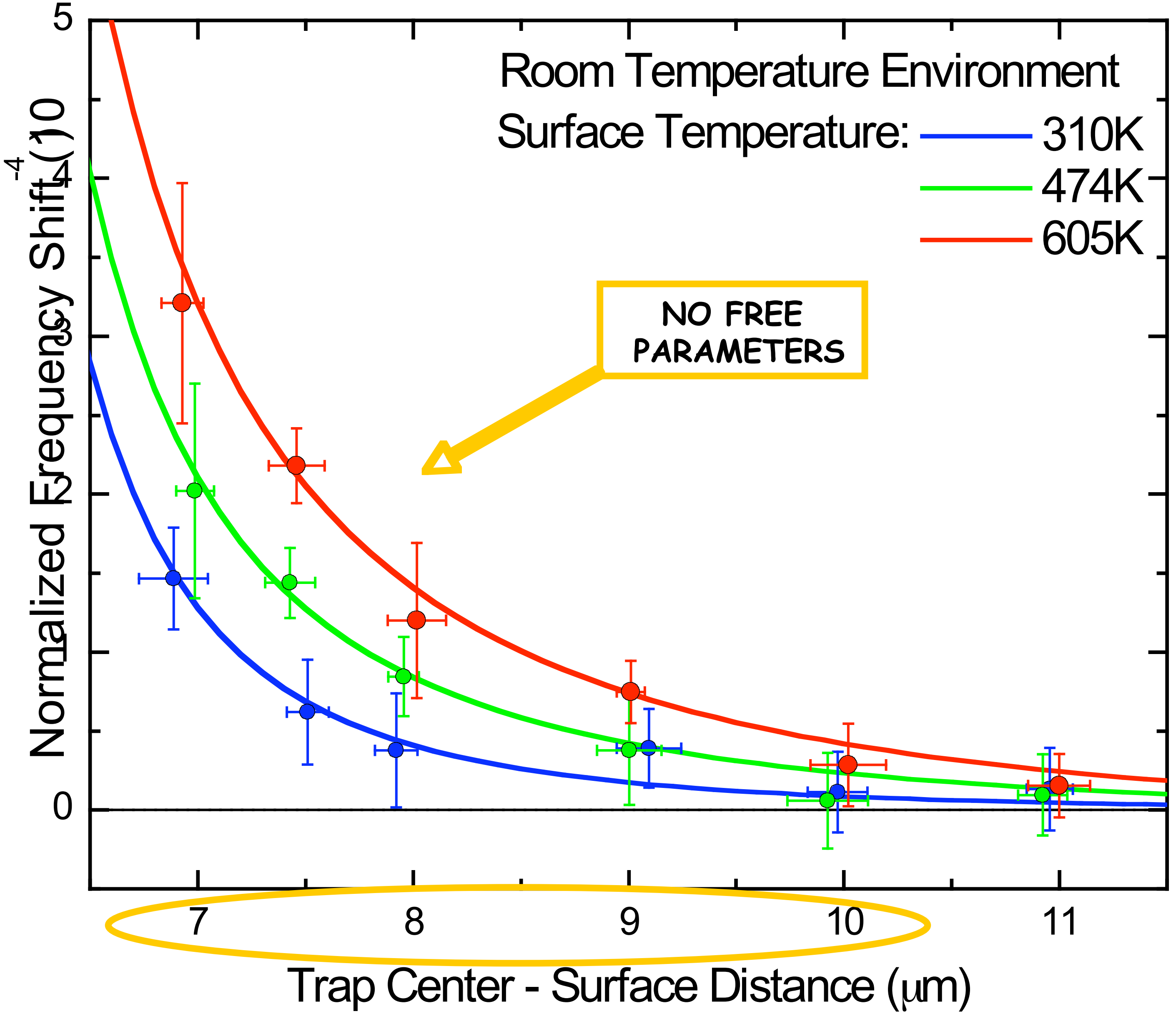
- ✓ Multiple dielectric surfaces! Amorphous glass, crystalline sapphire.
- ✓ No conducting objects near atoms!

Interferometric measurement of temperature of substrate:



Experimental results from JILA

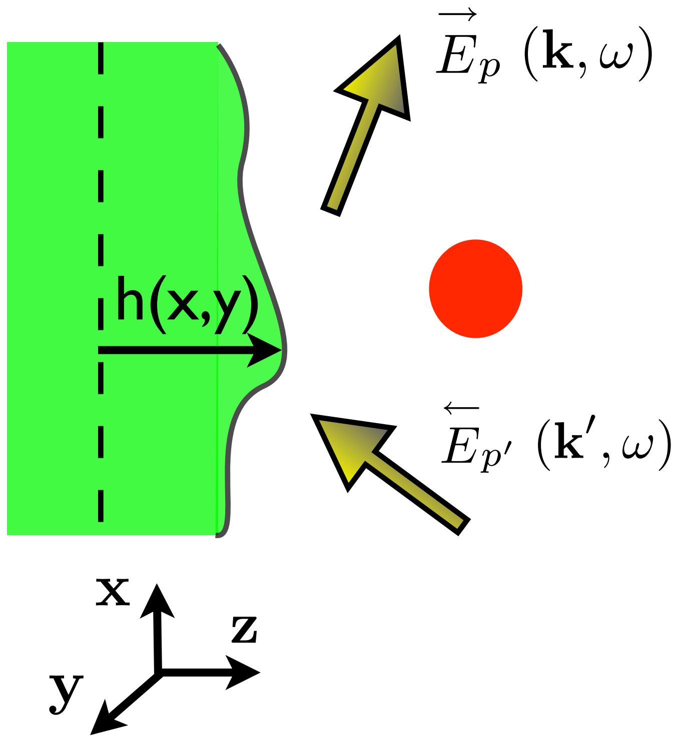
OUT OF EQUILIBRIUM



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

Part III: CP and scattering theory

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-output fields related via reflection operators for the surface

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

$$\boxed{\mathcal{E} = \hbar \int_0^\infty \frac{d\xi}{2\pi} \mathrm{Tr}\log(1 - \mathcal{R}e^{-\mathcal{K}z_A}\mathcal{R}_{\mathrm{at}}e^{-\mathcal{K}z_A})}$$

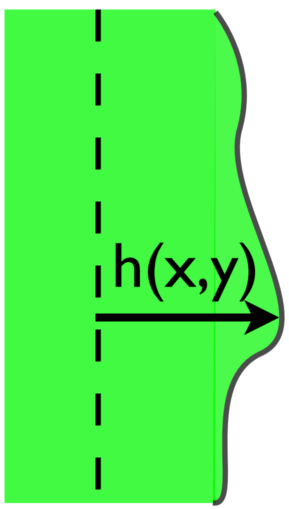
aka “TGTG” formula

$$\langle \mathbf{k},p|\mathcal{K}|\mathbf{k}',p'\rangle = \delta^2(\mathbf{k}-\mathbf{k}')\delta_{pp'}\sqrt{k^2+\xi^2/c^2}$$

$\mathcal{R}_{\mathrm{at}}$ $(z_A = 0)$ reflection operator for the atom

Atom reflection operator

Calculating reflection operator for the atom: $(\forall\, \mathbf{R}_A)$



$$\overrightarrow{E}_{p'}(\mathbf{k}',\omega)$$

$$\overrightarrow{E}^{(\mathrm{dip})}_{p''}(\mathbf{k}'',\omega)$$

induced electric dipole $\mathbf{d}(\omega) = \alpha(\omega)\mathbf{E}(\mathbf{R}_A,\omega)$

$$\overleftarrow{E}^{(\mathrm{dip})}_{p}(\mathbf{k},\omega) = \frac{i\omega^2}{2\epsilon_0 c^2 k_z}\, \hat{\epsilon}^{(-)}_p \cdot \mathbf{d}(\omega)\, e^{-i\mathbf{k}\cdot\mathbf{r}_A} e^{ik_z z_A}$$

$$\overleftarrow{E}^{(\mathrm{dip})}_{p}(\mathbf{k},\omega) = \frac{i\omega^2\alpha(\omega)}{2\epsilon_0 c^2 k_z} \int \frac{d^2\mathbf{k}'}{(2\pi)^2} e^{-i(\mathbf{k}-\mathbf{k}')\cdot\mathbf{r}_A} e^{i(k_z+k_z')z_A} \sum_{p'} \hat{\epsilon}^{(-)}_p(\mathbf{k})\cdot\hat{\epsilon}^{(+)}_{p'}(\mathbf{k}')\, \overrightarrow{E}_{p'}(\mathbf{k}',\omega)$$

$$\boxed{\langle \mathbf{k},p|\mathcal{R}_{\mathrm{at}}(\omega)|\mathbf{k}',p'\rangle = \frac{i\omega^2\alpha(\omega)}{2\epsilon_0 c^2 k_z} e^{-i(\mathbf{k}-\mathbf{k}')\cdot\mathbf{r}_A} e^{i(k_z+k_z')z_A}\; \hat{\epsilon}^{(-)}_p(\mathbf{k})\cdot\hat{\epsilon}^{(+)}_{p'}(\mathbf{k}')}$$

From TGTG to GTG

Los Alamos NATIONAL LABORATORY

Exact expression for the atom-surface interaction energy:

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

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

- Analogous to known expressions based on Green function formalism

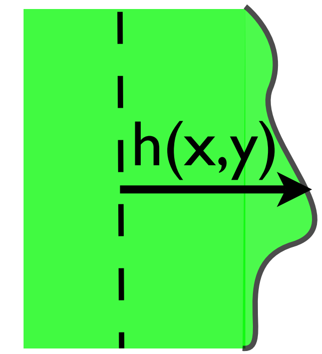
$$U_{\mathrm{CP}}(\mathbf{R}_A) = \frac{\hbar}{c^2\epsilon_0}\int_0^\infty \frac{d\xi}{2\pi}\xi^2\alpha(i\xi)\ \mathrm{Tr}\,\mathbf{G}(\mathbf{R}_A,\mathbf{R}_A,i\xi)$$

- Remaining difficulty: calculation of the surface reflection matrix

Perturbation theory

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

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



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

- Non-specular reflection:

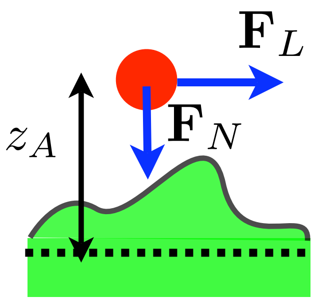
$$\boxed{\langle \mathbf{k}, p | \mathcal{R}^{(1)} | \mathbf{k}', p' \rangle = R_{p,p'}(\mathbf{k}, \mathbf{k}')\, H(\mathbf{k} - \mathbf{k}')}$$

Fourier transform of h(x,y)

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

Greffet (1988), Reynaud et al (2005)

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:

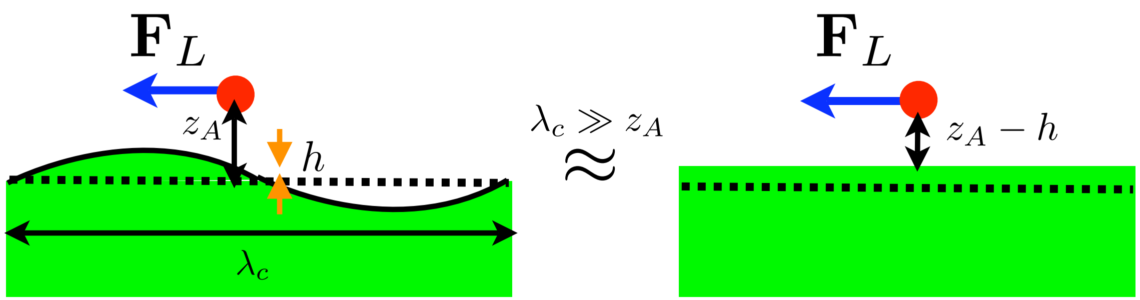
$$g(\mathbf{k}, z_A) = \frac{\hbar}{c^2\epsilon_0}\int_0^\infty \frac{d\xi}{2\pi}\xi^2\alpha(i\xi)\int\frac{d^2\mathbf{k}'}{(2\pi)^2}\ a_{\mathbf{k}',\mathbf{k}'-\mathbf{k}}(z_A,\xi)$$

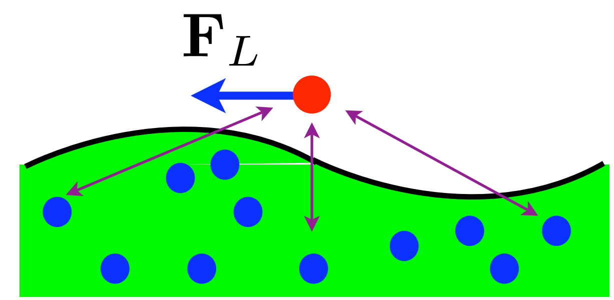
$$a_{\mathbf{k}',\mathbf{k}''} = \sum_{p',p''}\hat{\epsilon}^+_{p'}\cdot\hat{\epsilon}^-_{p''}\ \frac{e^{-(\kappa'+\kappa'')z_A}}{2\kappa''}\ R_{p',p''}(\mathbf{k}',\mathbf{k}'')$$

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

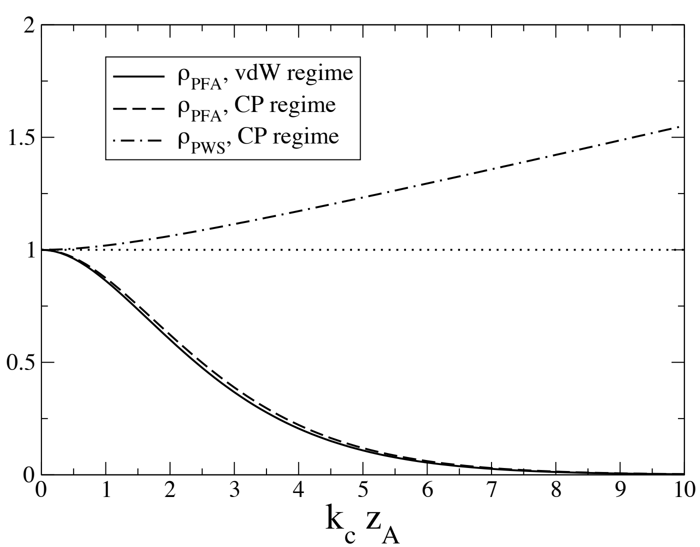
- Proximity Force Approximation (PFA)
- Pair-wise Summation (PWS)





- 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 $z_A = 2\mu\mathrm{m} \gg \lambda_A$

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

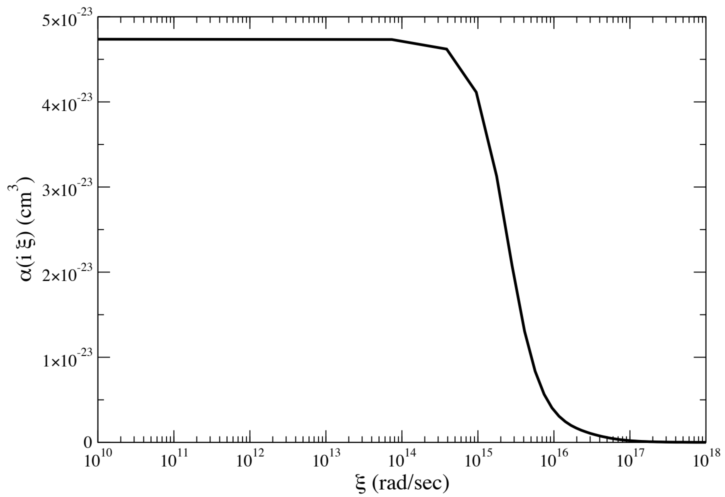
$\rho_{\rm PFA} \approx 30\% \qquad \rho_{\rm PWS} \approx 115\%$

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

Real materials

- 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)

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

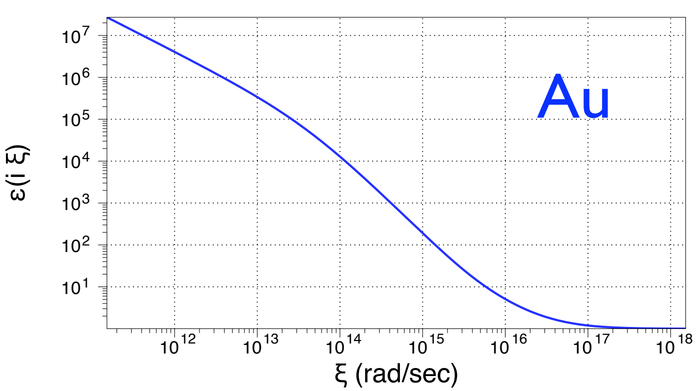
$$R^{(1)}_{\mathrm{TE,TM}}(\mathbf{k},\mathbf{k}';\xi) = 2\kappa S\, \frac{c\kappa_t'}{\sqrt{\epsilon}\xi}\, h_{\mathrm{TE,TM}}(\mathbf{k},\mathbf{k}',\xi)$$

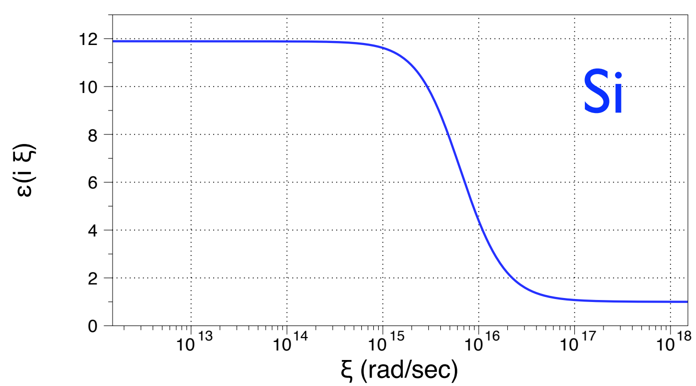
$$R^{(1)}_{\mathrm{TM,TE}}(\mathbf{k},\mathbf{k}';\xi) = \frac{2\sqrt{\epsilon}\kappa\kappa_t \frac{\xi}{c} S}{(\frac{\xi}{c})^2 - (\epsilon+1)\kappa^2} h_{\mathrm{TM,TE}}(\mathbf{k},\mathbf{k}',\xi)$$

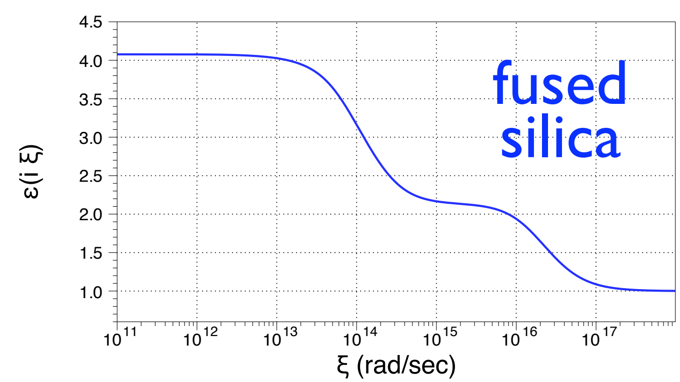
$$R^{(1)}_{\mathrm{TM,TM}}(\mathbf{k},\mathbf{k}';\xi) = -2\kappa\frac{\epsilon k k' + \kappa_t\kappa_t' C}{(\frac{\xi}{c})^2 - (\epsilon+1)\kappa^2}\, h_{\mathrm{TM,TM}}(\mathbf{k},\mathbf{k}',\xi)$$

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

- Optical data + Kramers-Kronig relations



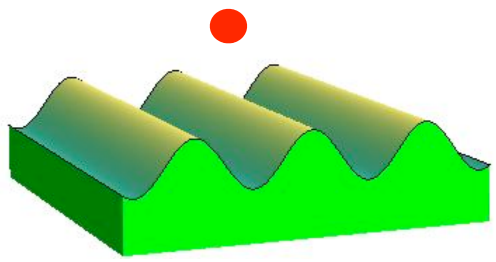




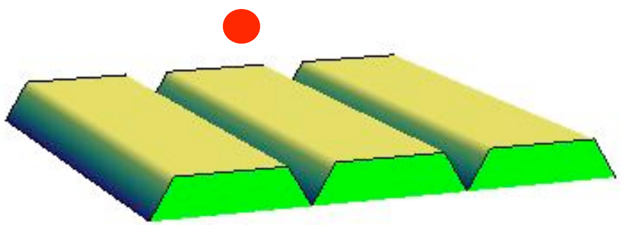
Atoms as local probes

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.



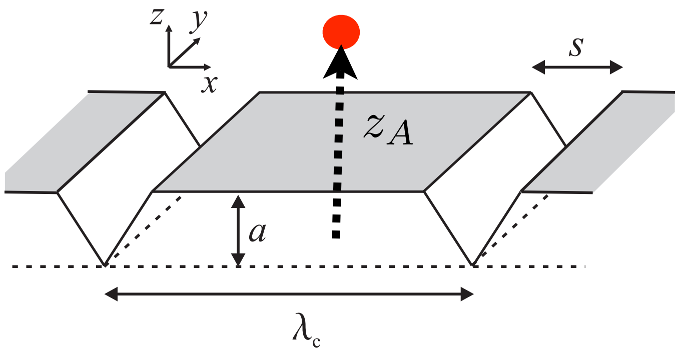
- If the atom is located above one plateau, the PFA predicts that the lateral Casimir-Polder force should vanish. A non-vanishing force appearing when the atom is moved above the plateau thus clearly signals a deviation from PFA!

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

CP energy for grooved surface

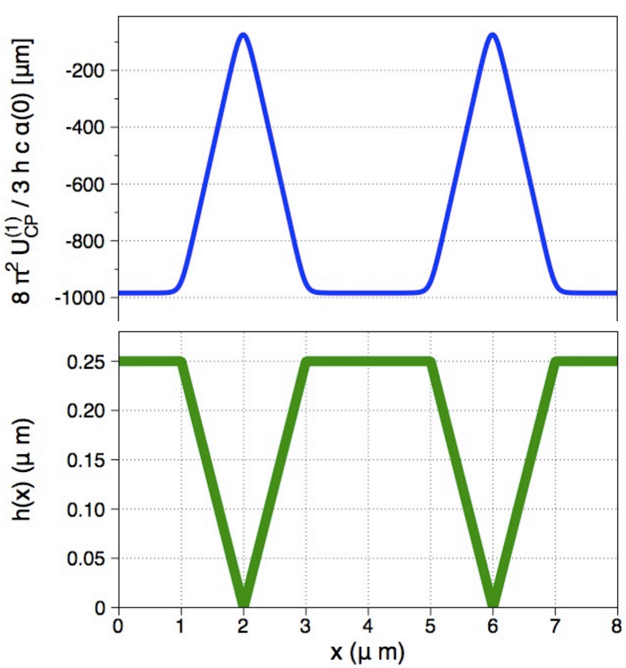
- Surface profile for periodical grooved corrugation

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

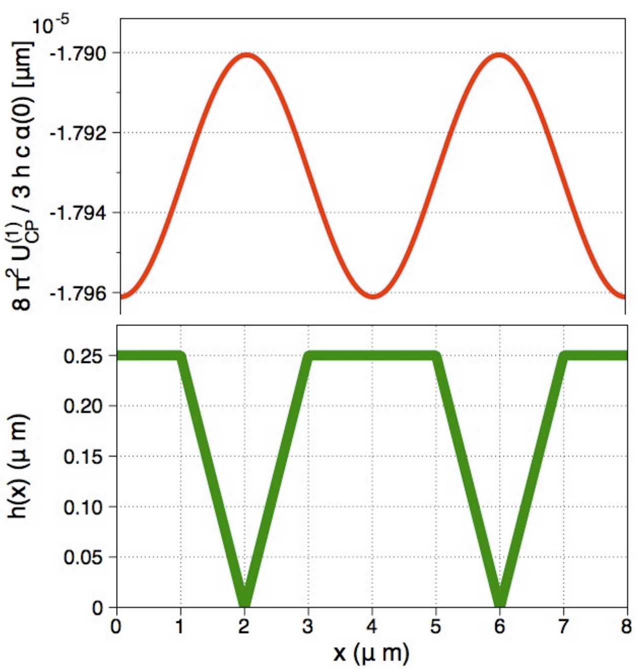


- Single-atom lateral CP energy: it can be easily calculated using that the first order lateral CP energy $U^{(1)}_{\rm CP}(\mathbf{R}_A) = \int \frac{d^2\mathbf{k}}{(2\pi)^2} e^{i\mathbf{k}\cdot\mathbf{r}_A}\, g(\mathbf{k}, z_A)\, H(\mathbf{k})$ is linear in $H(\mathbf{k})$

$k_c z_A = 0.3$



$k_c z_A = 10$

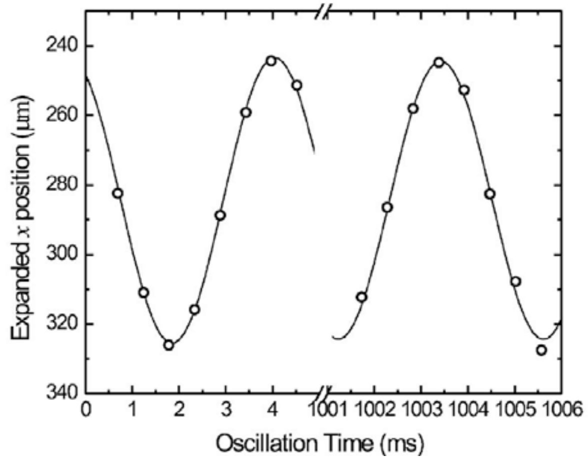


BEC as a field sensor

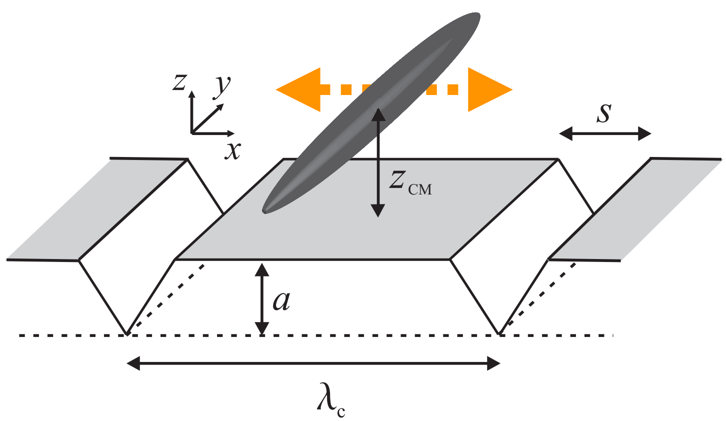
BEC oscillator

- 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:

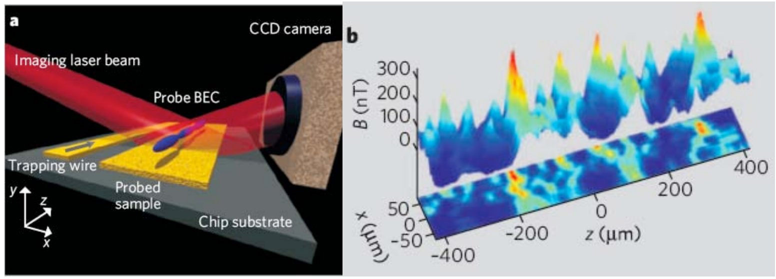
$$\omega_{x,\rm CM}^2 = \omega_x^2 + \frac{1}{m}\int dx dz\, n_0(x,z) \frac{\partial^2}{\partial x^2} U_{\rm CP}^{(1)}(x,z)$$

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

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



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

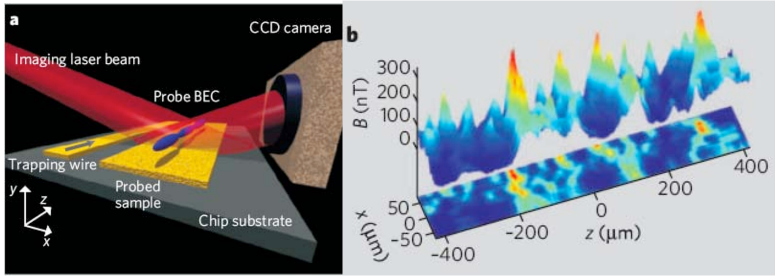
Schmiedmayer et al (2005)

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

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



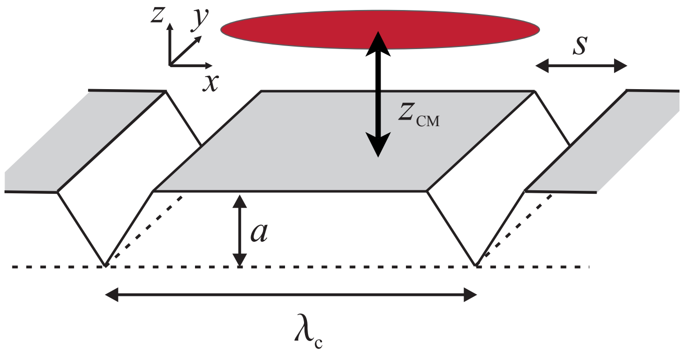
Measurement of the magnetic field variations along a current-carrying wire

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 $(k_c z_A \ll 1)$

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

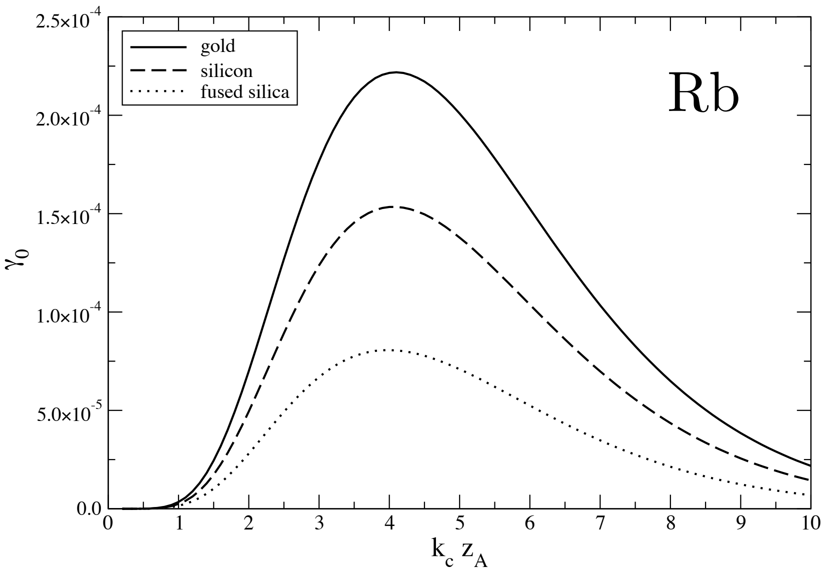
- To measure the lateral CP force, the elongated BEC should be aligned along the x-direction, and a density modulation along this direction above the plateau would be a signature of a nontrivial (beyond-PFA) geometry effect.



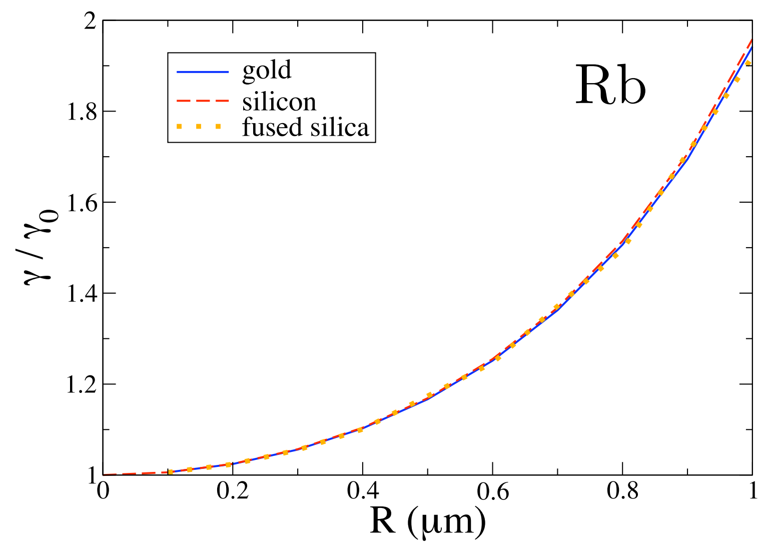
Single-atom/BEC frequency shift

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

- Single-atom lateral freq. shift
- Single-atom / BEC comparison



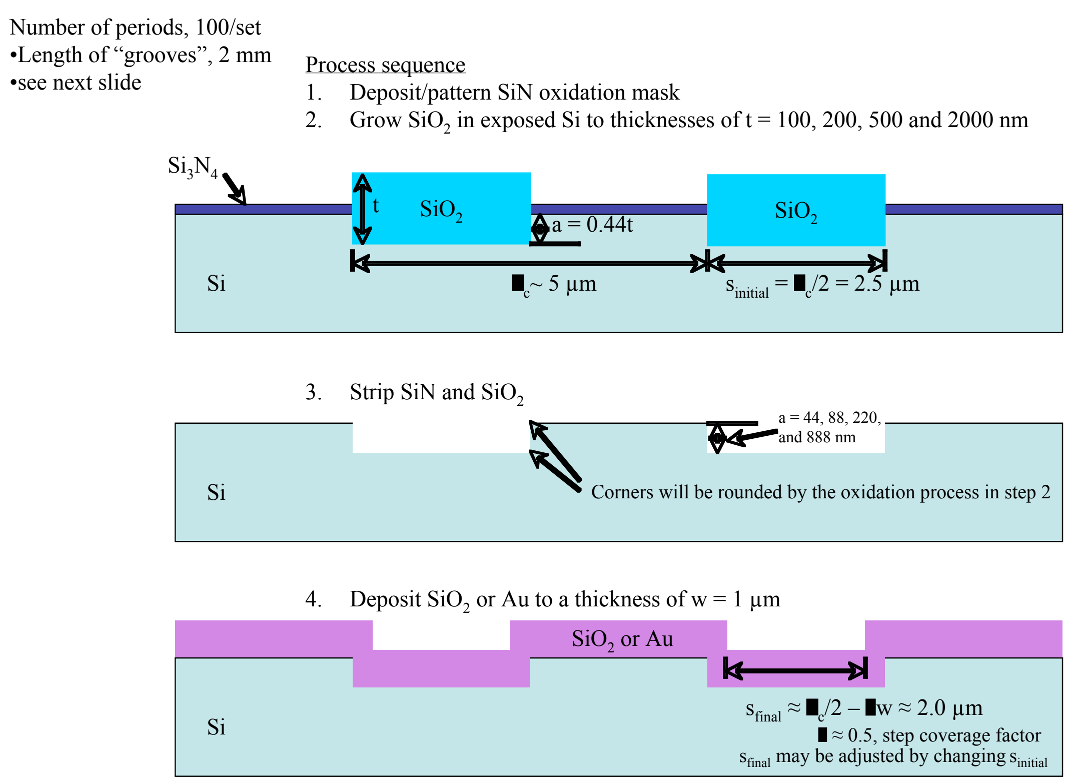
$$\omega_x/2\pi = 229\,\mathrm{Hz}$$
$$z_{\mathrm{CM}} = 2\mu\mathrm{m}$$
$$\lambda_c = 4\mu\mathrm{m}$$
$$a = 250\mathrm{nm}$$
$$s = \lambda_c/2$$

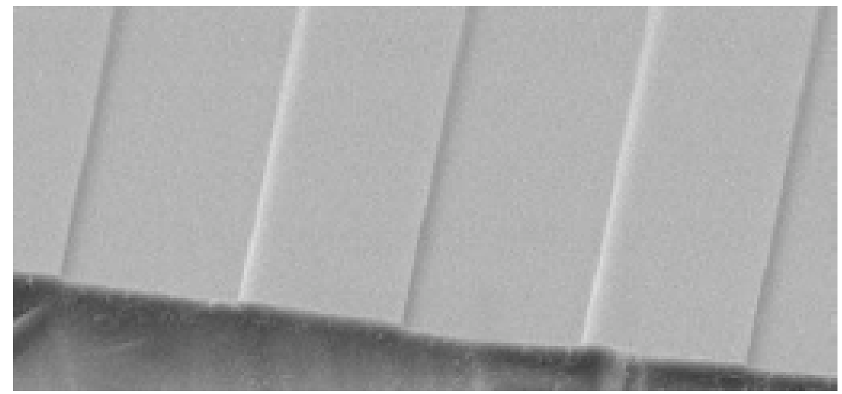


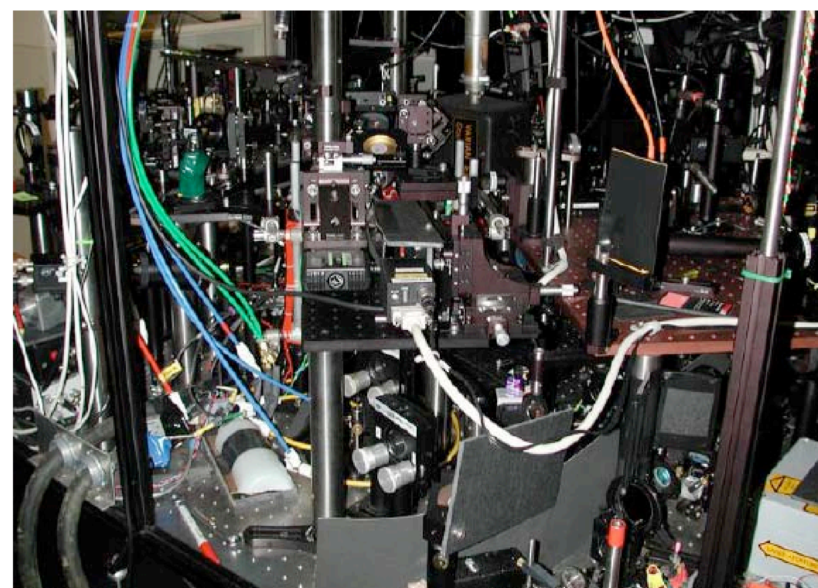
Given the reported sensitivity $\gamma = 10^{-5} - 10^{-4}$ for relative frequency shifts from E. Cornell's experiment, we expect that beyond-PFA lateral CP forces on a BEC above a plateau of a periodically grooved silicon surface should be detectable for distances $z_{\mathrm{CM}} < 3\mu\mathrm{m}$,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

Towards an experiment

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

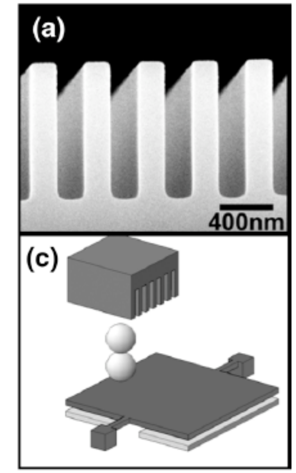




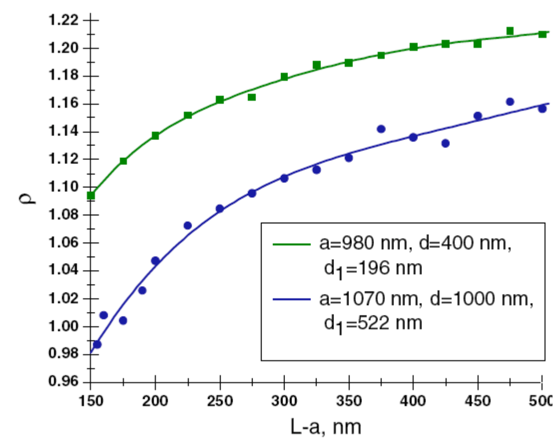


Exact analytical results

- Large corrections to PFA/PWS have been recently observed in the Casimir force between a Au sphere and a Si uniaxial corrugated surface   Chan et al (2008)



- Exact analytical expressions for the Casimir force for uniaxial corrugations have been derived:
  - Ideal reflectors   Buscher+Emig (2004)
  - Real materials   Lambrecht+Marachevsky (2008)



- We have already computed the <u>exact</u> CP force for an atom above uniaxial corrugated surfaces taking into account optical data of the materials   Dalvit, Maia Neto, Lambrecht, Marachevsky (to be submitted)

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 <u>local</u> probes of quantum vacuum fluctuations

- Non-trivial, beyond-PFA/PWS 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)