Recent progress in Casimir physics for atom-surface interactions

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Outline of this talk

- Part I

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

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

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- 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

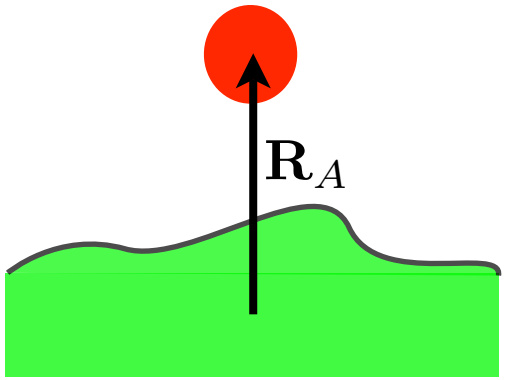
The Casimir-Polder force

vdW - CP interaction

Casimir and Polder (1948)

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

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



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

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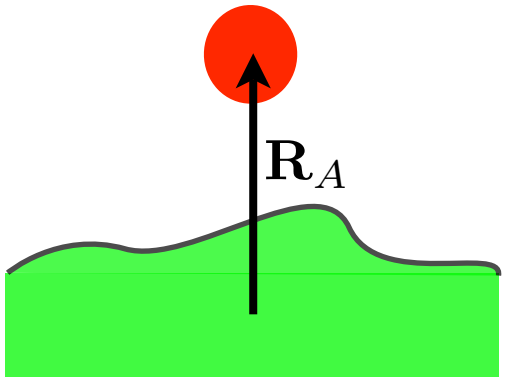

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Eg: Ground-state atom near planar surface @ T=0

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

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

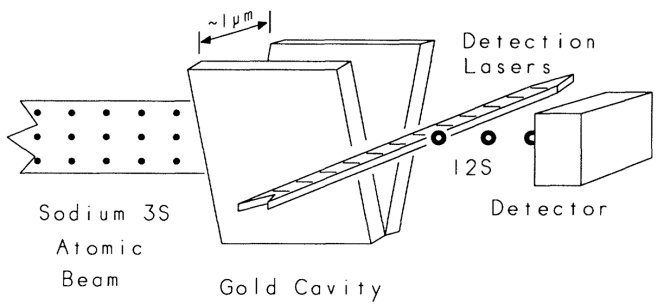
Retarded (CP) limit $z_A \gg \lambda_A$

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

Modern CP experiments

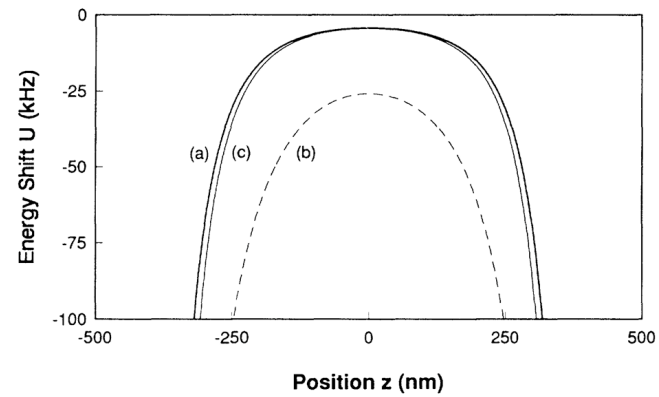
- Deflection of atoms

Hinds et al (1993)



L= 0.7-1.2 um

Exp-Th agreement @ 10%



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

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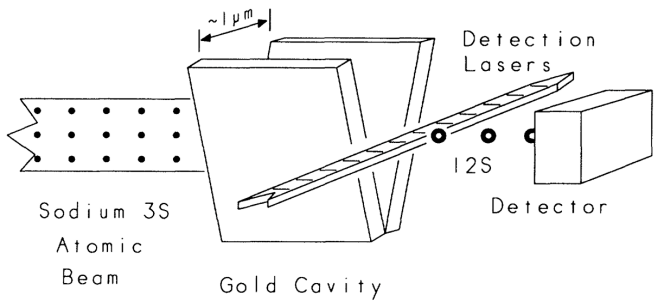

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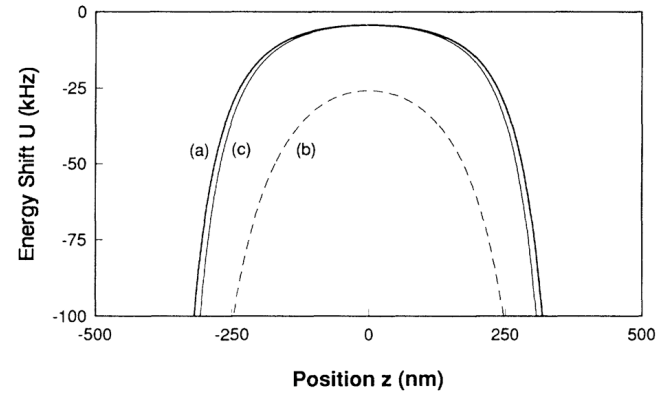

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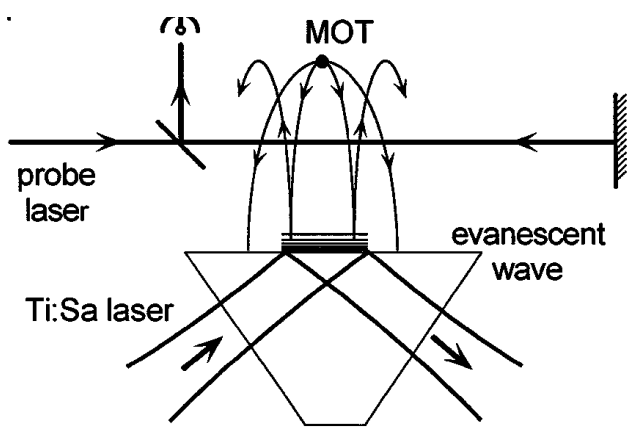
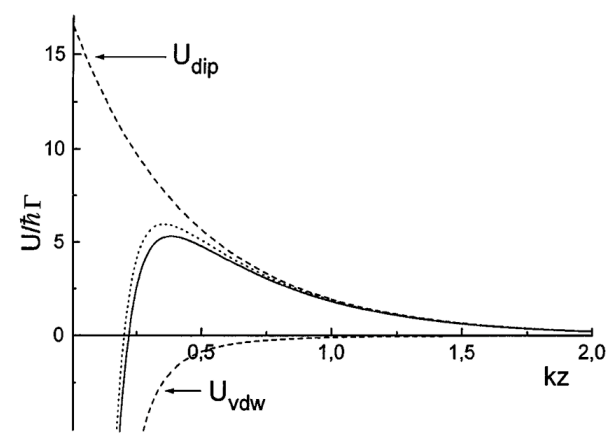
Classical reflection on atomic mirror

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%

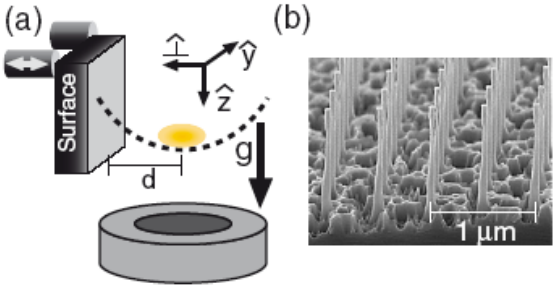
Modern experiments (cont'd)

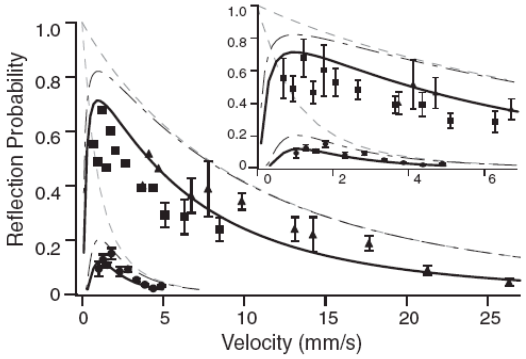
Quantum reflection

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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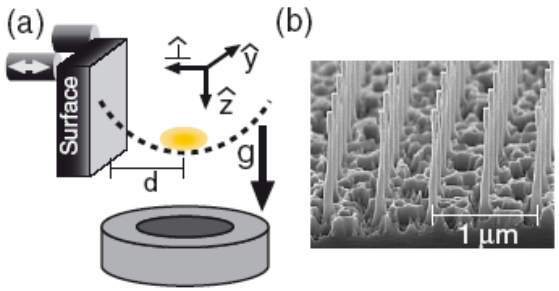

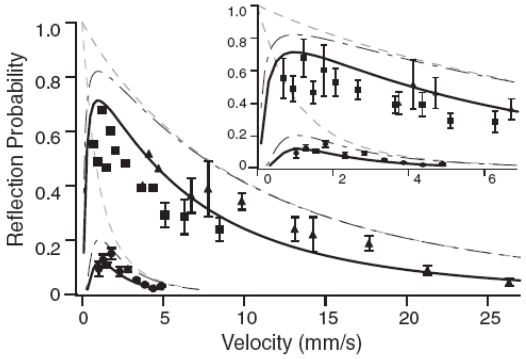

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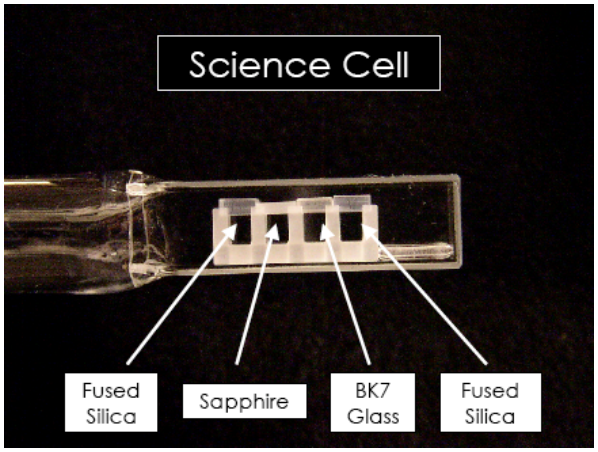
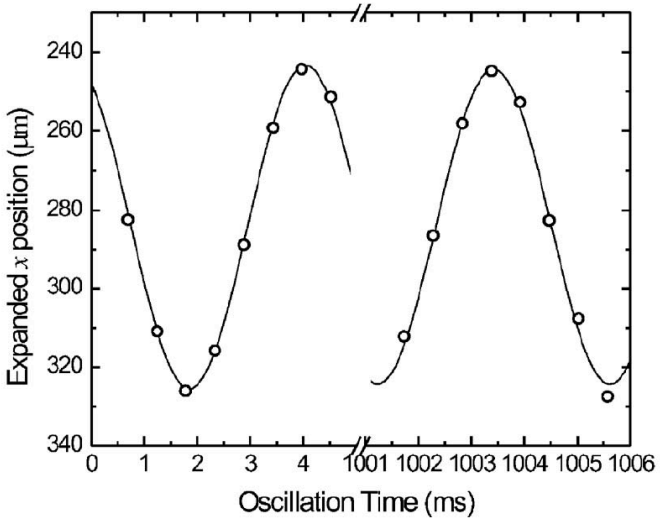
BEC oscillator

Cornell et al (2007)

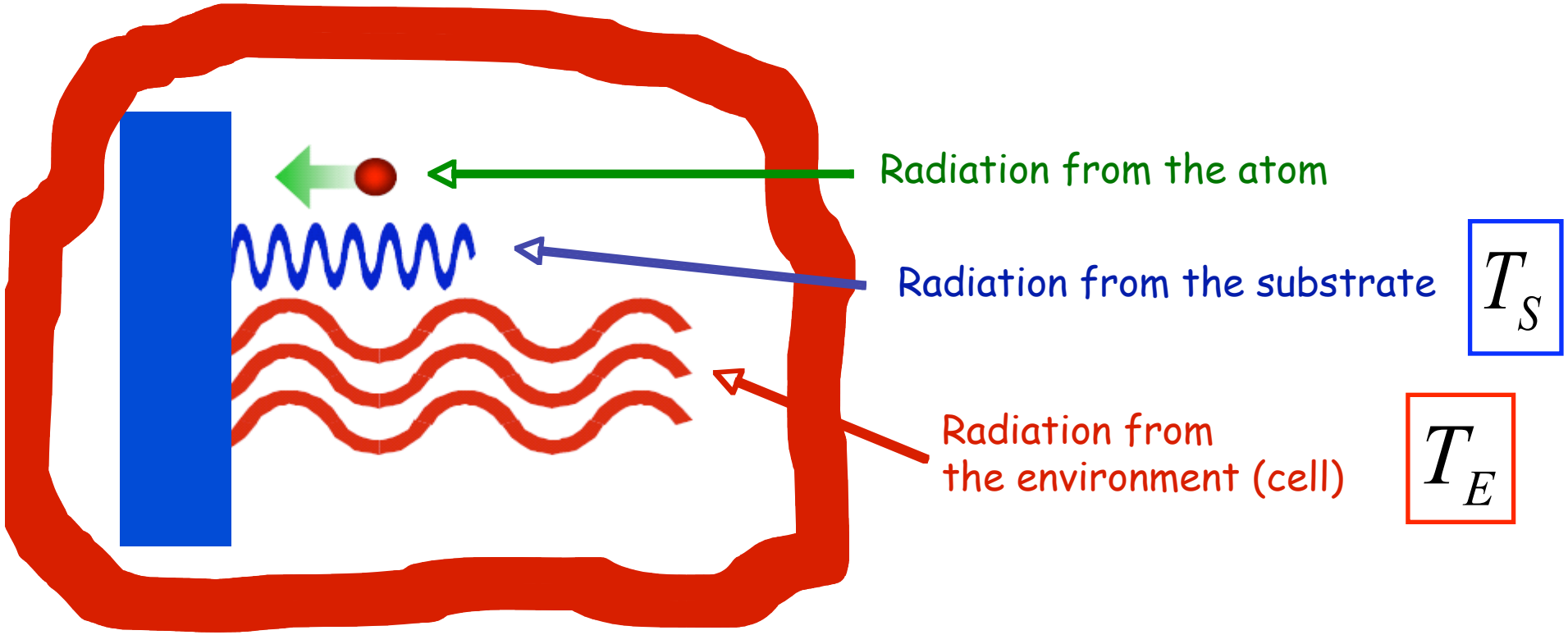


$$\gamma_x \equiv \frac{\omega_x - \omega_x'}{\omega_x} \simeq -\frac{1}{2\omega_x^2 m}\partial_x^2 U^*$$



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

NEW

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

substrate environment

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

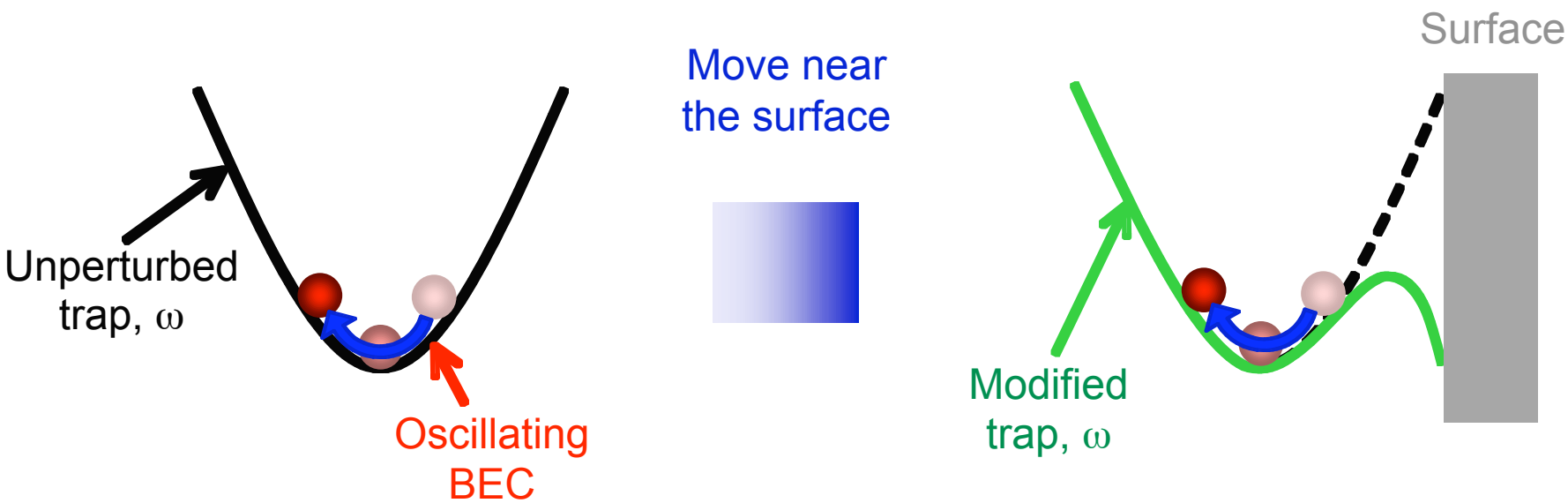
M.Antezza, L.P.Pitaevskii and S.Stringari, PRL. **95**, 093202 (2005)

- ✓ 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

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

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

Linear approximation

First non-linear correction

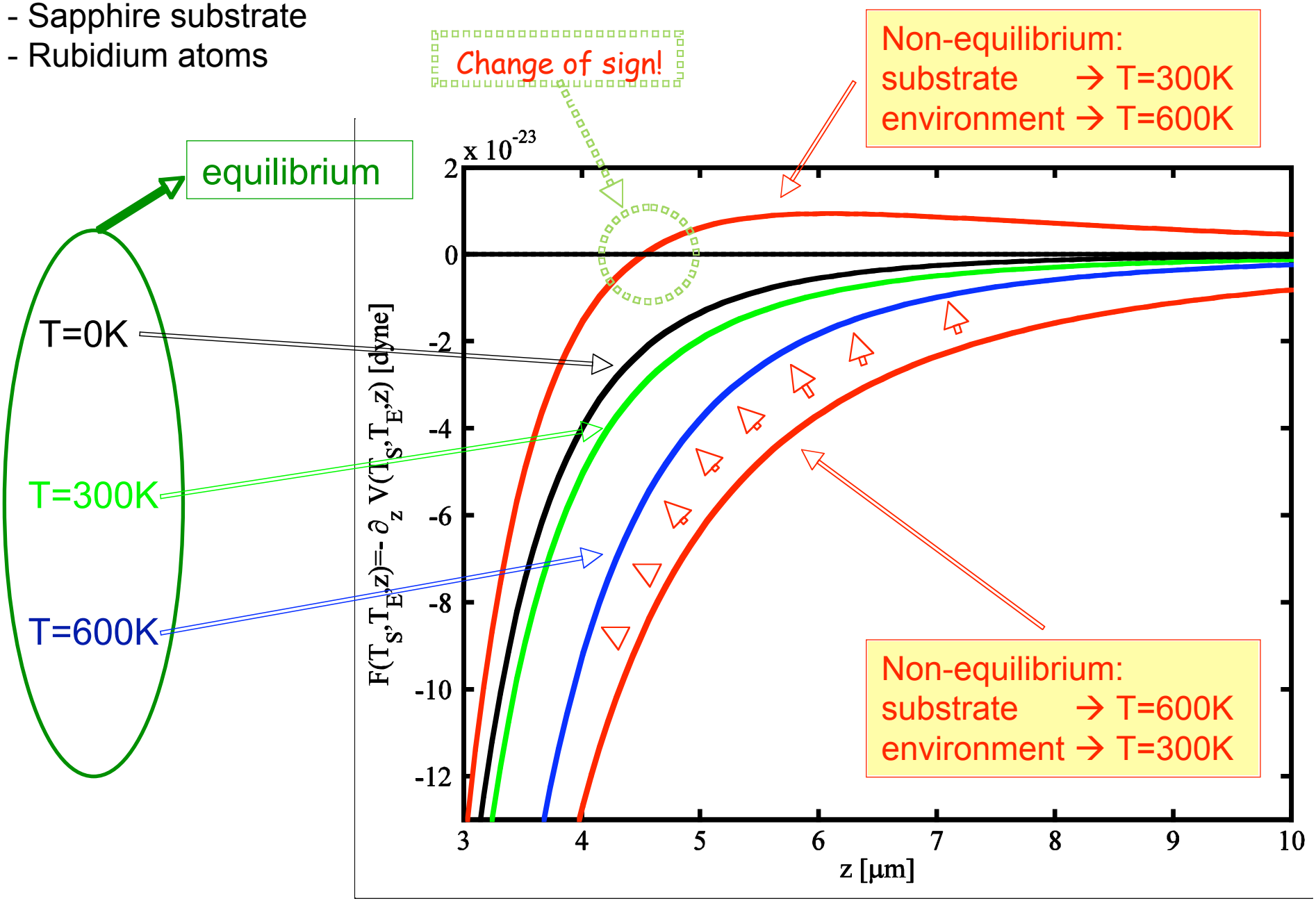
a= amplitude of c.m. oscillation

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

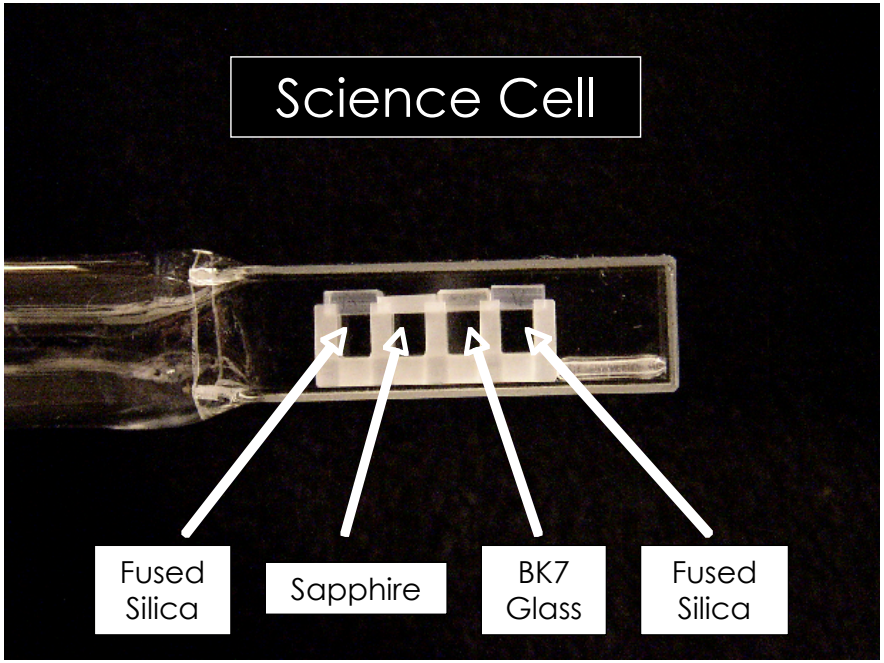
$n_0(r) \equiv$ Thomas-Fermi inverted parabola

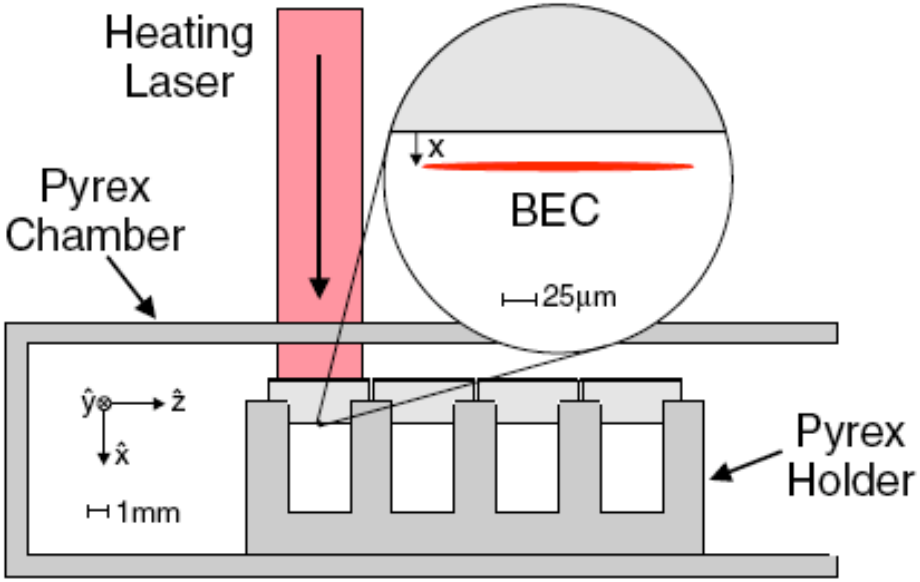
Thermal effects on the surface-atom force

- Sapphire substrate
- Rubidium atoms



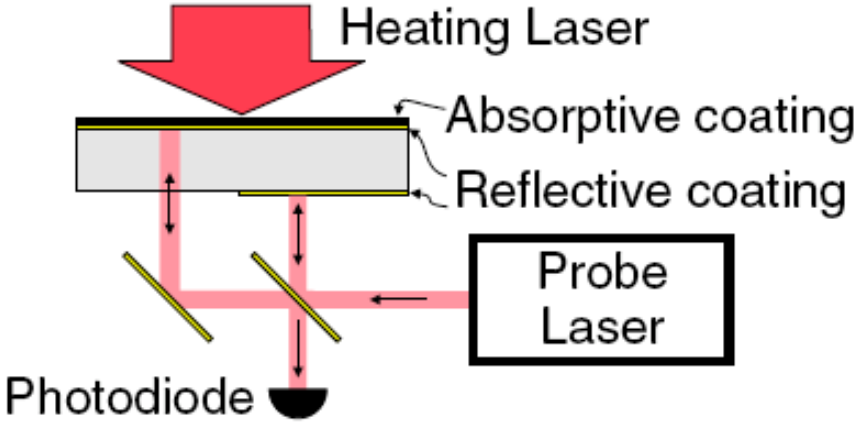
The experimental apparatus





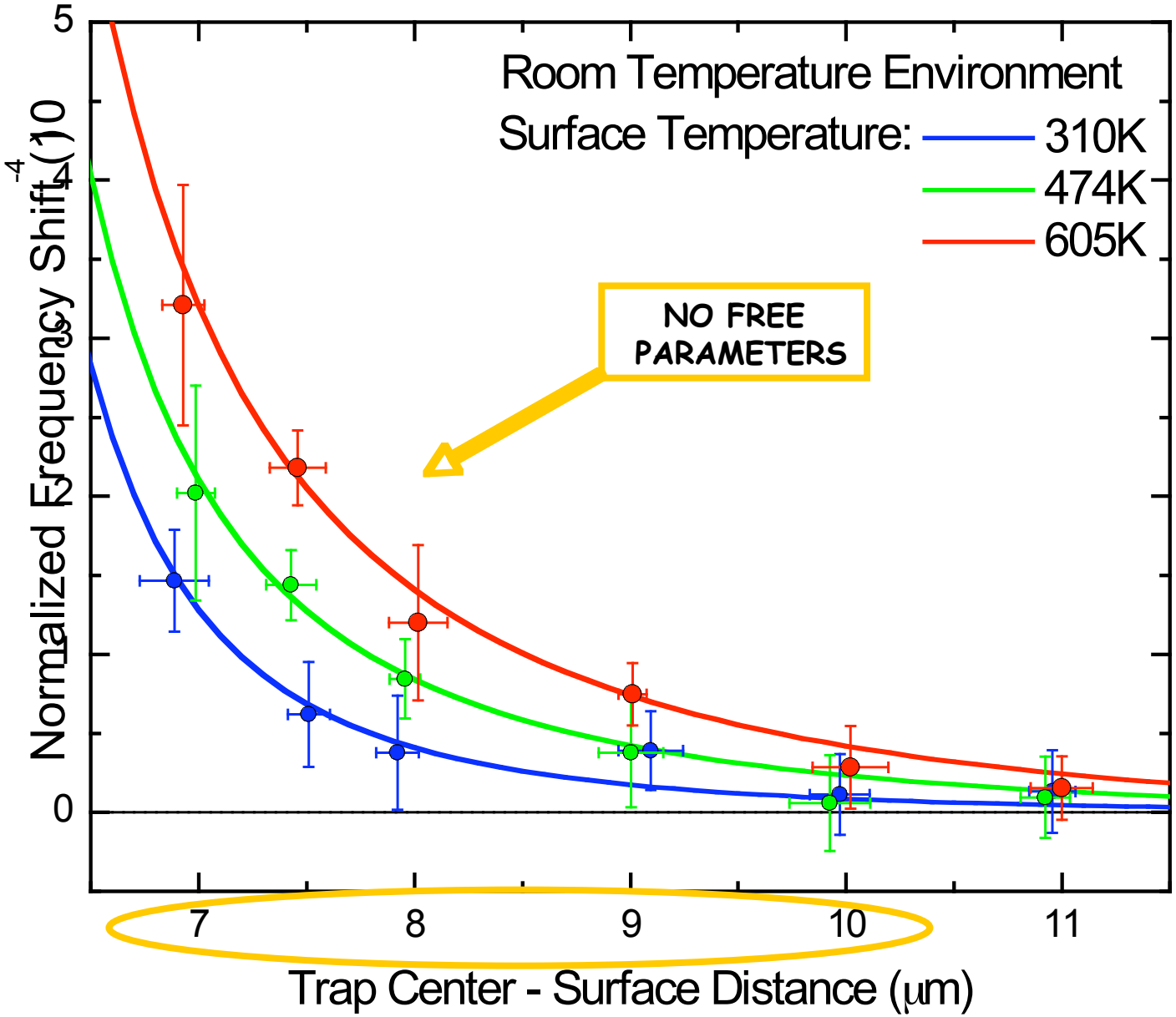
- ✓ Multiple dielectric surfaces! Amorphous glass, crystalline sapphire.
- ✓ No conducting objects near atoms!

Interferometric measurement of temperature of substrate:



Experimental results from JILA

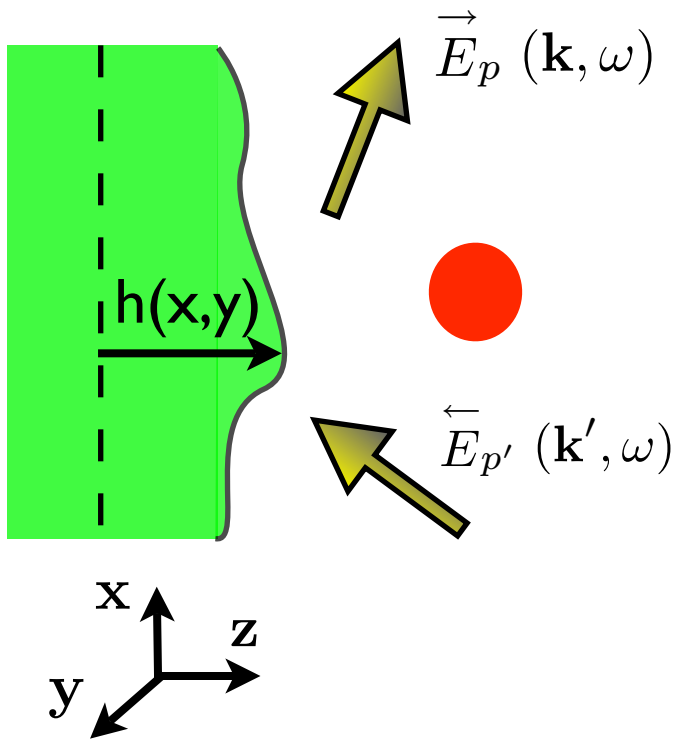
OUT OF EQUILIBRIUM



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

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

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

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

Input-output fields related via reflection operators for the surface

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

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

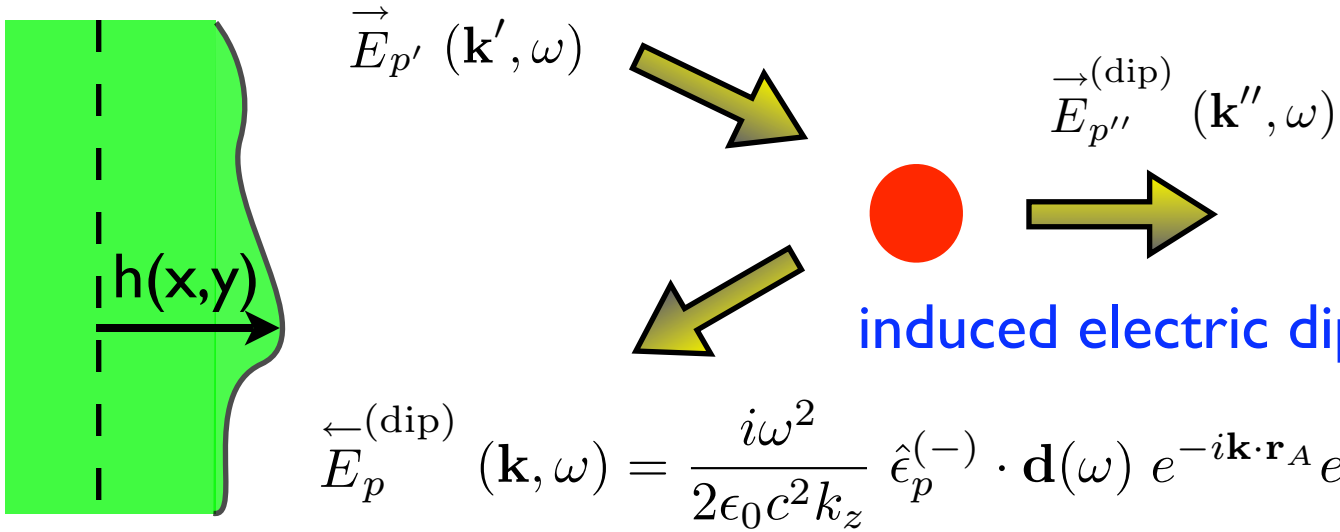
aka "TGTG" formula

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

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

Atom reflection operator

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



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

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

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

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

From TGTG to GTG

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Exact expression for the atom-surface interaction energy:

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

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

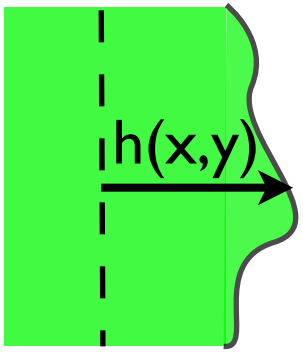
$$U_{\rm CP}(\mathbf{R}_A) = \frac{\hbar}{c^2\epsilon_0}\int_0^\infty \frac{d\xi}{2\pi}\xi^2\alpha(i\xi)\,\mathrm{Tr}\,\mathbf{G}(\mathbf{R}_A,\mathbf{R}_A,i\xi)$$

- 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)

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



- Specular reflection:

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

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:

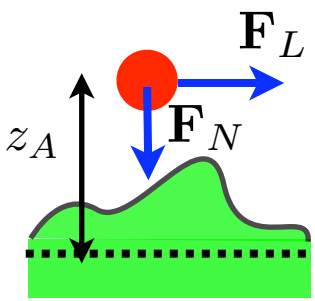
$$\langle \mathbf{k}, p | \mathcal{R}^{(1)} | \mathbf{k}', p' \rangle = R_{p,p'}(\mathbf{k}, \mathbf{k}')\, H(\mathbf{k} - \mathbf{k}')$$

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

Response function g:

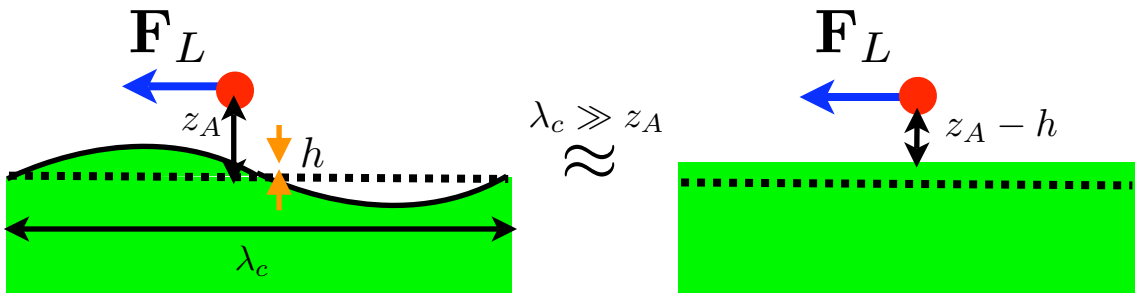
$$g(\mathbf{k}, z_A) = \frac{\hbar}{c^2\epsilon_0}\int_0^\infty \frac{d\xi}{2\pi}\xi^2\alpha(i\xi)\int\frac{d^2\mathbf{k}'}{(2\pi)^2}\; a_{\mathbf{k}',\mathbf{k}'-\mathbf{k}}(z_A,\xi)$$

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

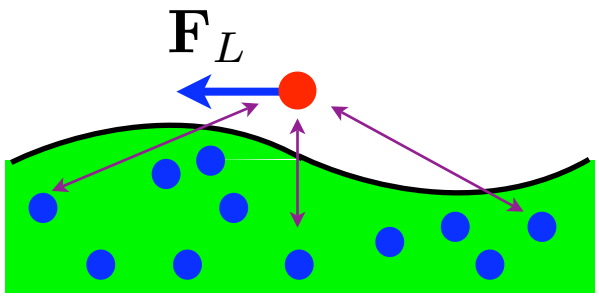
Our approach is perturbative in h(x,y), which should be the smallest length scale in the problem $h \ll z_A, \lambda_c, \lambda_A, \lambda_0$

Approx. methods: PFA & PWS

- Proximity Force Approximation (PFA)

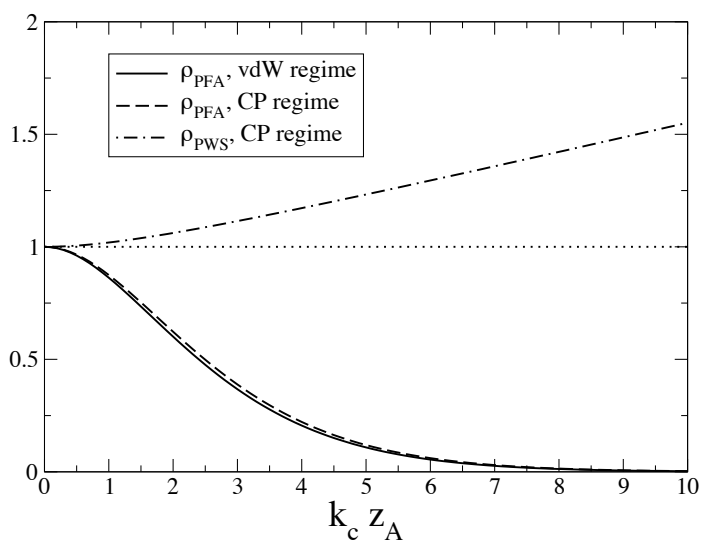


- Pair-wise Summation (PWS)



- 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 $\lambda_c = 3.5\mu\mathrm{m}$

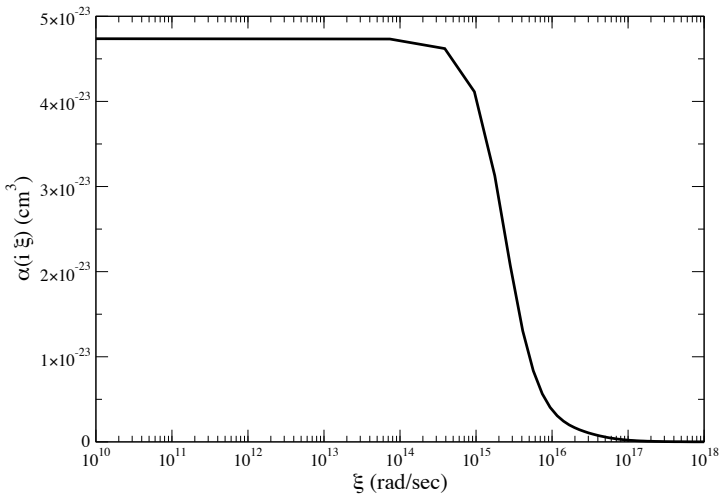
$\Rightarrow$ $\rho_{\rm PFA} \approx 30\%$ $\quad \rho_{\rm PWS} \approx 115\%$

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)

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

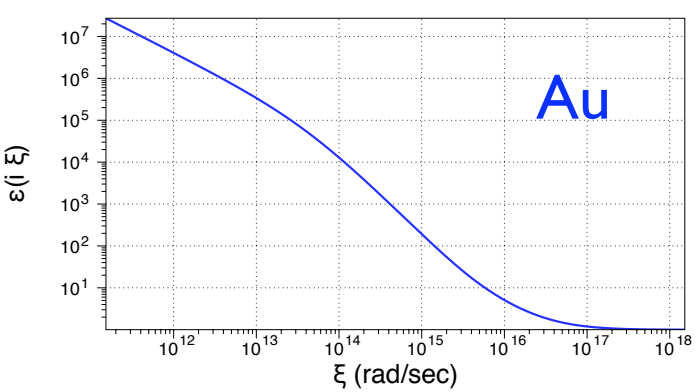
$$R^{(1)}_{\mathrm{TE,TM}}(\mathbf{k},\mathbf{k}';\xi) = 2\kappa S\, \frac{c\kappa_t'}{\sqrt{\epsilon}\xi}\, h_{\mathrm{TE,TM}}(\mathbf{k},\mathbf{k}',\xi)$$

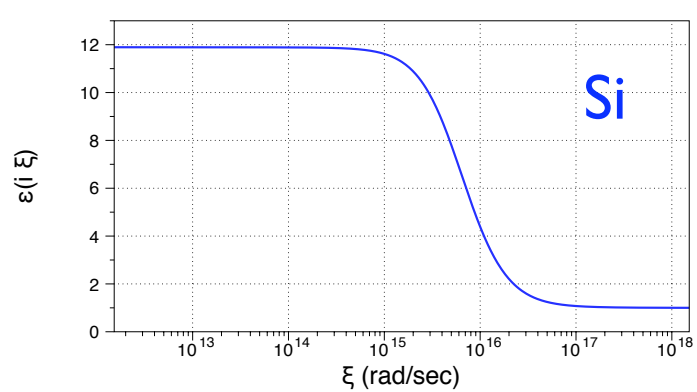
$$R^{(1)}_{\mathrm{TM,TE}}(\mathbf{k},\mathbf{k}';\xi) = \frac{2\sqrt{\epsilon}\kappa\kappa_t \frac{\xi}{c} S}{(\frac{\xi}{c})^2 - (\epsilon+1)\kappa^2} h_{\mathrm{TM,TE}}(\mathbf{k},\mathbf{k}',\xi)$$

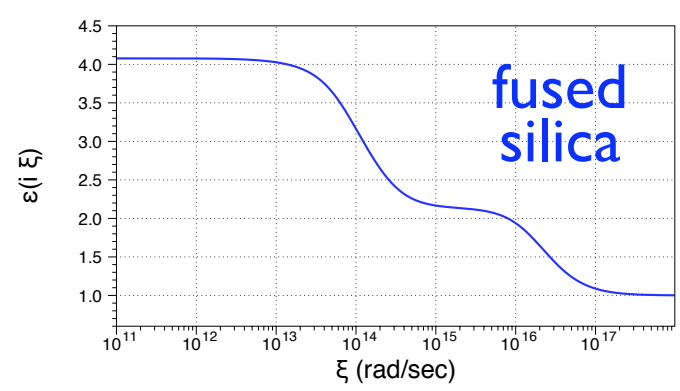
$$R^{(1)}_{\mathrm{TM,TM}}(\mathbf{k},\mathbf{k}';\xi) = -2\kappa \frac{\epsilon k k' + \kappa_t \kappa_t' C}{(\frac{\xi}{c})^2 - (\epsilon+1)\kappa^2}\, h_{\mathrm{TM,TM}}(\mathbf{k},\mathbf{k}',\xi)$$

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

- Optical data + Kramers-Kronig relations



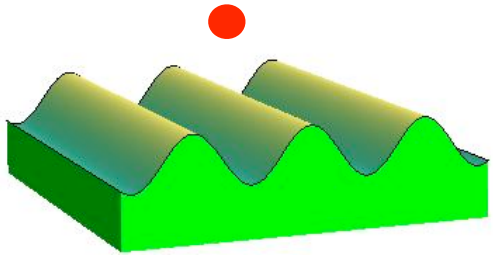




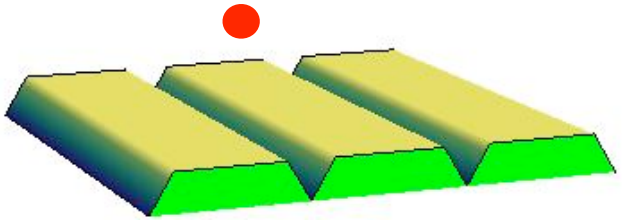
Atoms as local probes

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.



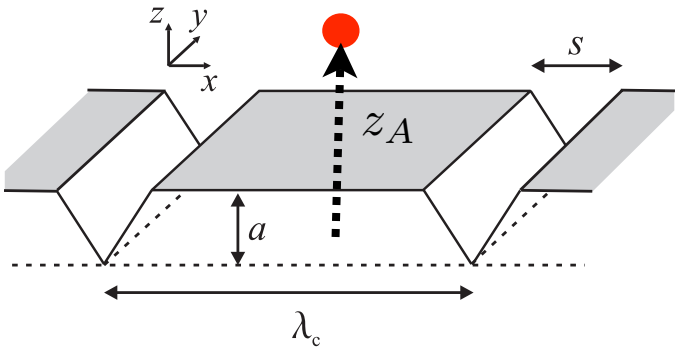
- If the atom is located above one plateau, the PFA predicts that the lateral Casimir-Polder force should vanish. A non-vanishing force appearing when the atom is moved above the plateau thus clearly signals a deviation from PFA!

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

CP energy for grooved surface

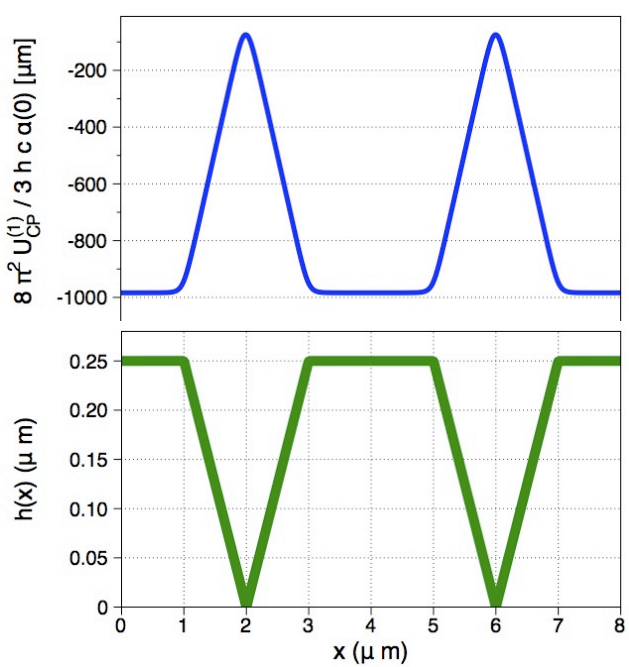
- Surface profile for periodical grooved corrugation

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

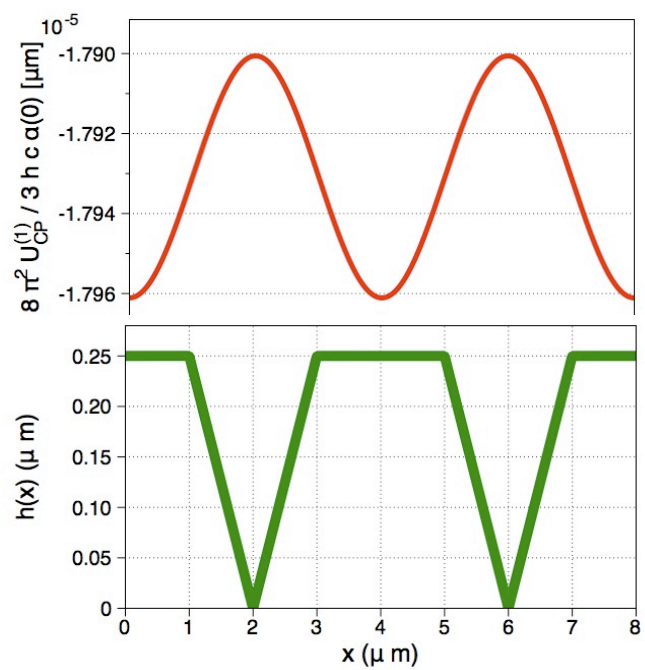


- Single-atom lateral CP energy: it can be easily calculated using that the first order lateral CP energy $U^{(1)}_{\rm CP}(\mathbf{R}_A) = \int \frac{d^2\mathbf{k}}{(2\pi)^2} e^{i\mathbf{k}\cdot\mathbf{r}_A}\, g(\mathbf{k}, z_A)\, H(\mathbf{k})$ is linear in $H(\mathbf{k})$

$k_c z_A = 0.3$



$k_c z_A = 10$

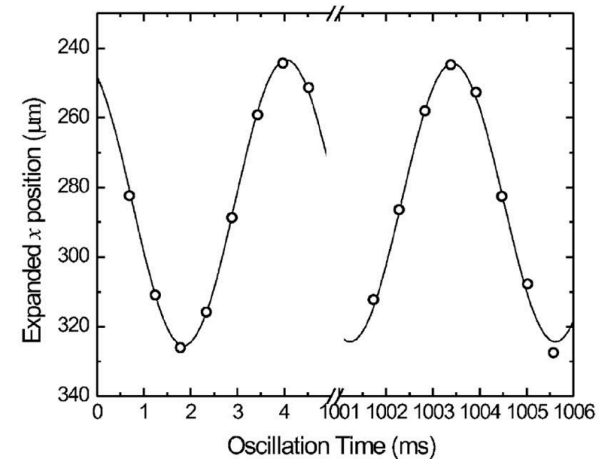


BEC as a field sensor

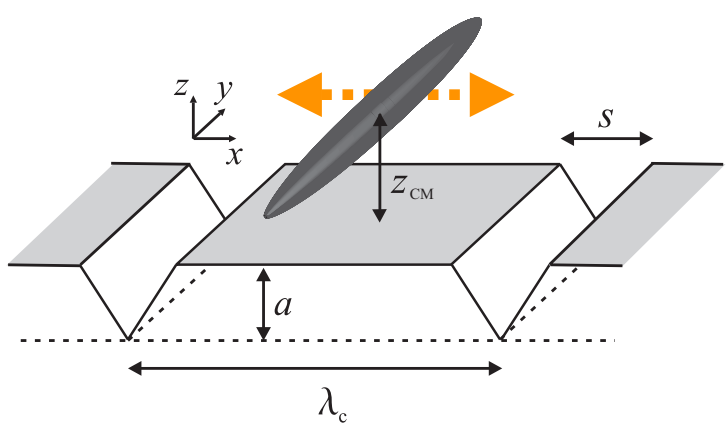
BEC oscillator

- 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:

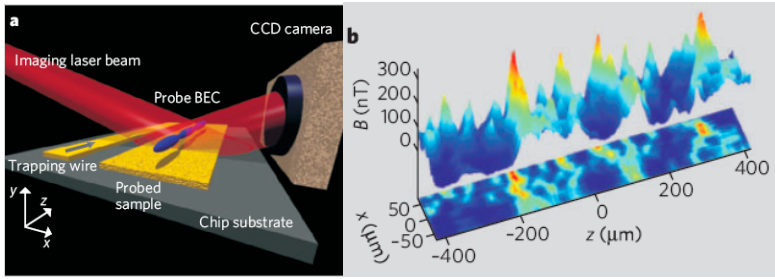
$$\omega_{x,\rm CM}^2 = \omega_x^2 + \frac{1}{m}\int dxdz\, n_0(x,z)\frac{\partial^2}{\partial x^2}U_{\rm CP}^{(1)}(x,z)$$

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

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



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

Schmiedmayer et al (2005)

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

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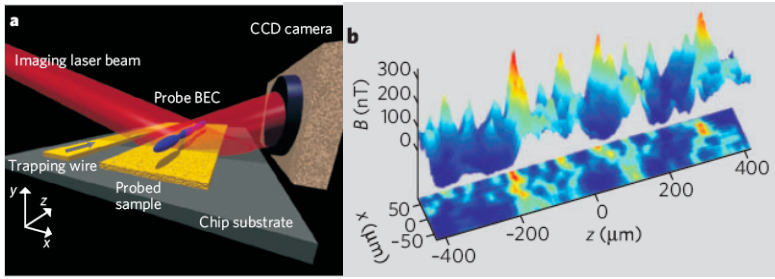


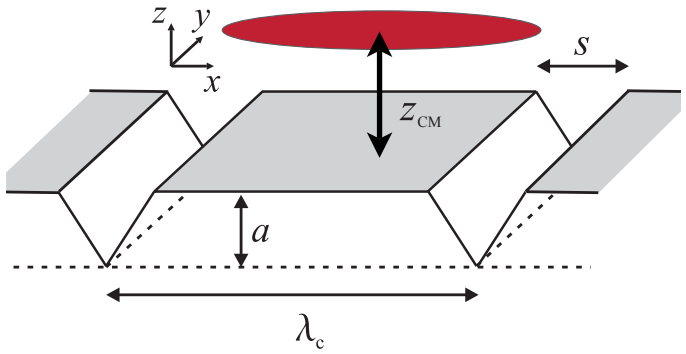
Measurement of the magnetic field variations along a current-carrying wire

Schmiedmayer et al (2005)

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

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

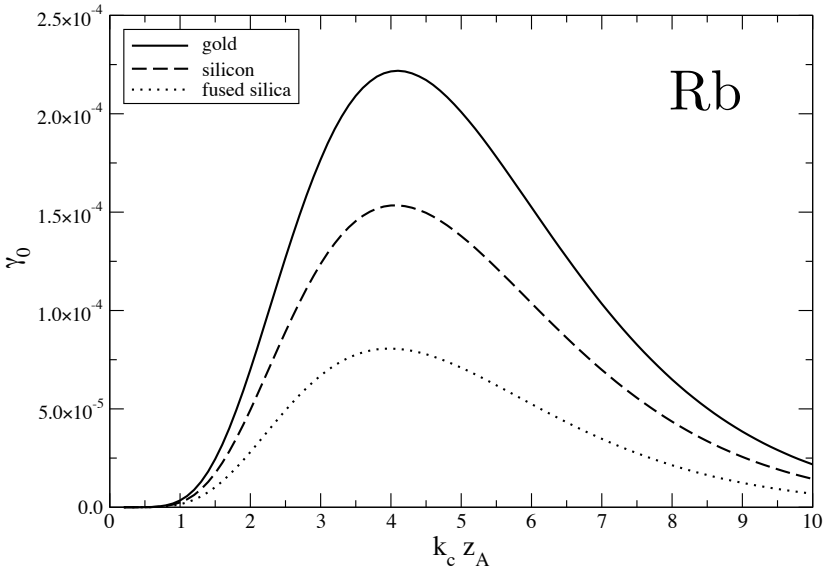
To measure the lateral CP force, the elongated BEC should be aligned along the x-direction, and a density modulation along this direction above the plateau would be a signature of a nontrivial (beyond-PFA) geometry effect.



Single-atom/BEC frequency shift

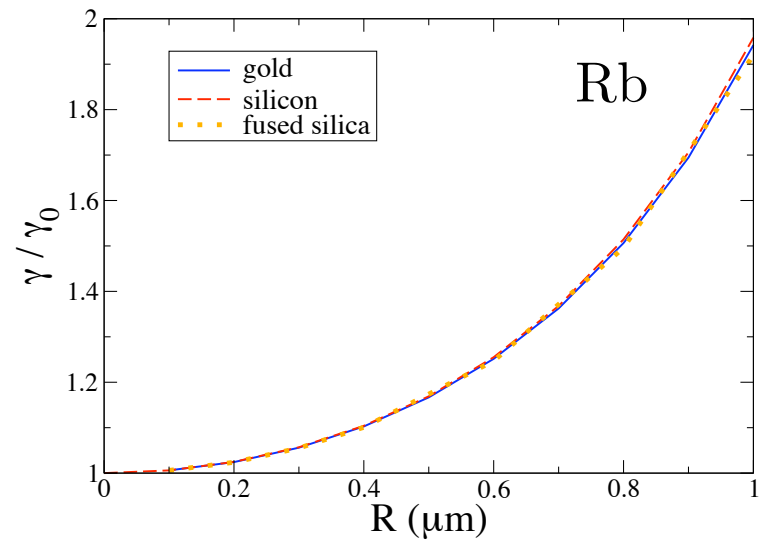
$$\gamma_0 \equiv \frac{\omega_{x,\mathrm{CM}} - \omega_x}{\omega_x}$$

- Single-atom lateral freq. shift



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

- 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, $R \approx 1\mu\mathrm{m}$

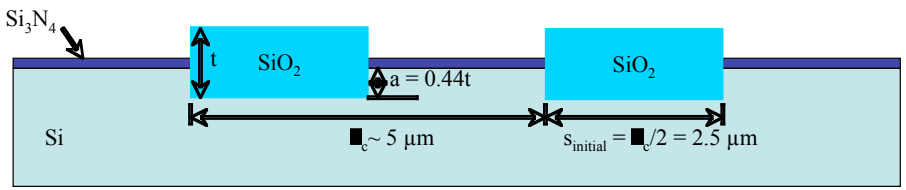
Towards an experiment

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

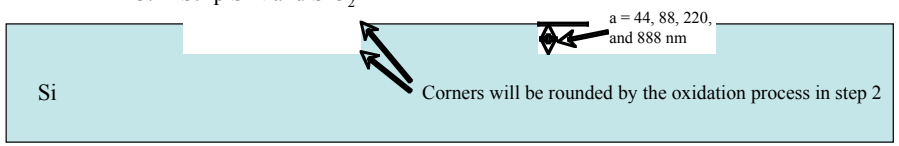
Number of periods, 100/set
•Length of "grooves", 2 mm
•see next slide

Process sequence

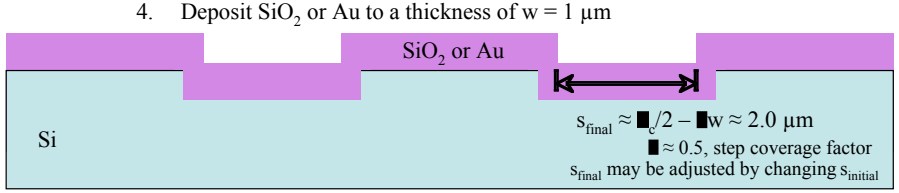
1. Deposit/pattern SiN oxidation mask
2. Grow SiO_2 in exposed Si to thicknesses of t = 100, 200, 500 and 2000 nm

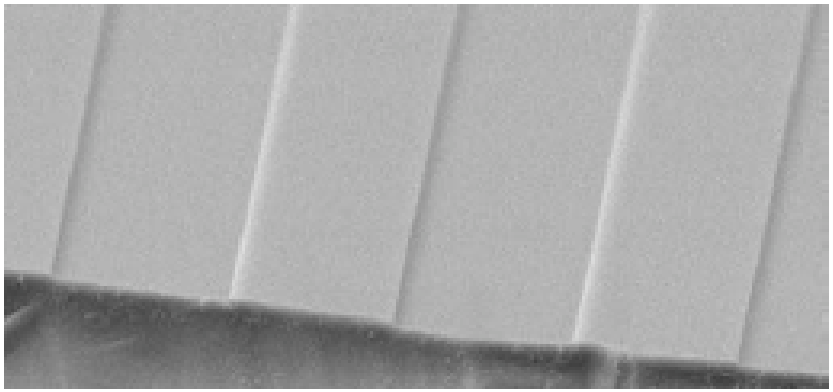


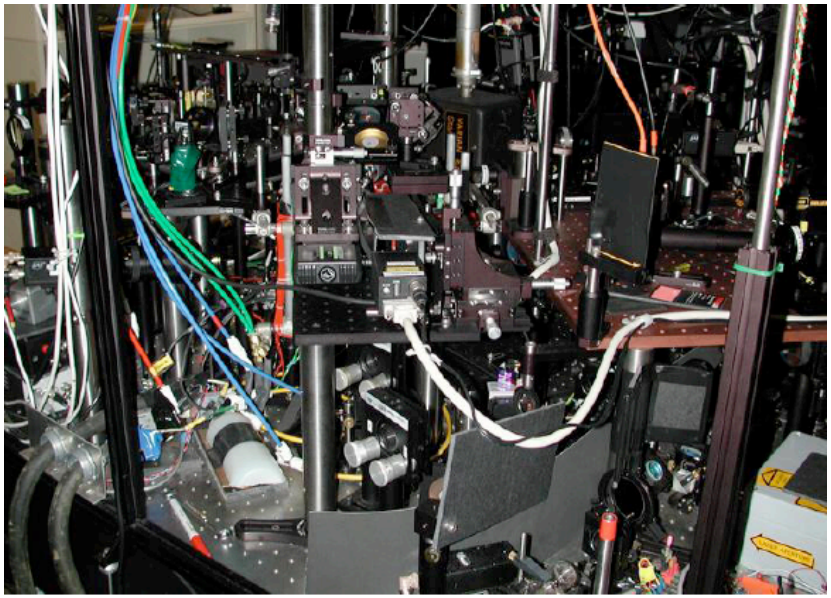
3. Strip SiN and SiO_2



4. Deposit SiO_2 or Au to a thickness of w = 1 µm

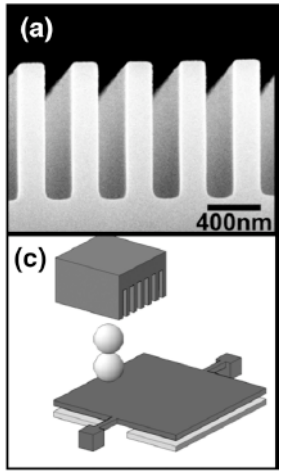




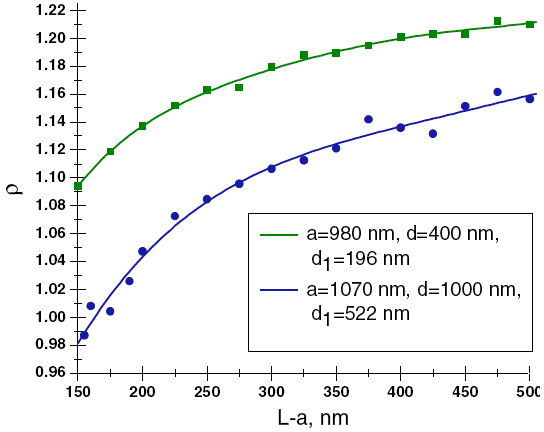


Exact analytical results

- 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 local 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)