Probing Atoms with Light

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Outline

In this talk,

- *I will start by showing you the optical lensing effects in systems from cold to hot and from gas to liquid!*

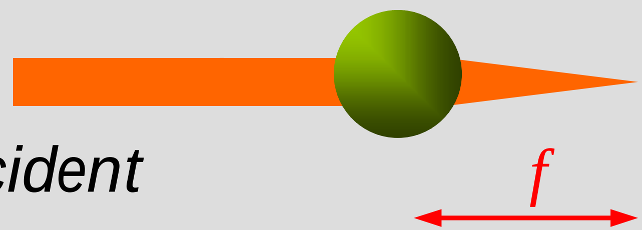
- *Some of the related topics, including the ongoing works and proposed ideas are discussed subsequently!*

The first part of the works shown here began by a coincident conversation with my colleague Prof. T.H. Wei . . .

The second part was initially motivated by simply making an interferometer for phase stabilization. It seems we can do more and do better . . .

Light focusing and defocusing by a small ball (linear optics)

A small uniform ball:



"weak" incident

n_0: *linear* refractive index
R: *radius*
Δ: *light detuning (to the resonance frequency!)*

Effective focal length: $$f = \frac{R}{2(n_0 - 1)}$$

Could be tens of microns!

if R > 0,

$f < 0,$	$n_0 > 1, \ \Delta < 0$
$f > 0,$	$n_0 < 1, \ \Delta > 0$
$f \to \infty,$	$n_0 = 1, \ \Delta = 0$

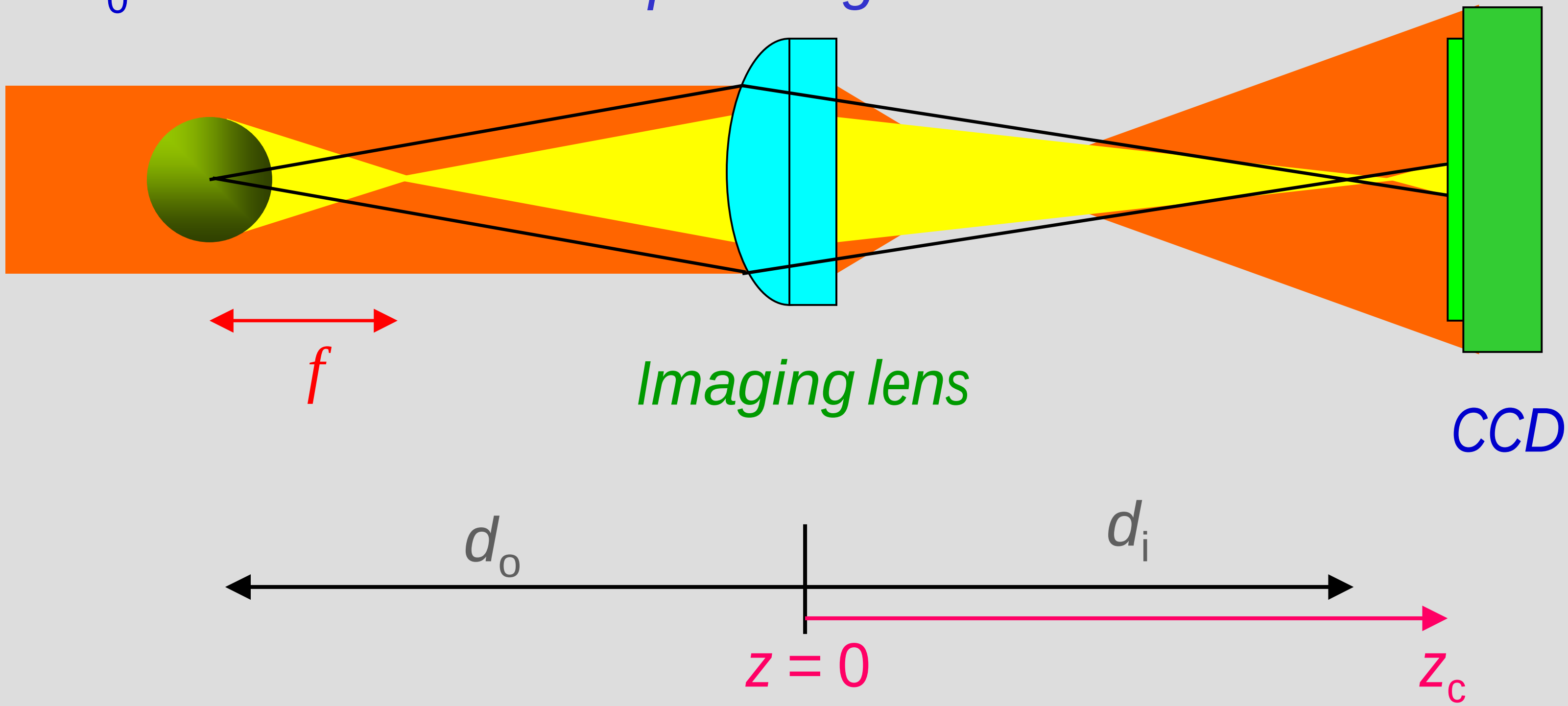
n_0 *is independent of light intensity, but depends on ball parameters !*

Optical lensing effect (1)

A small ball made by cold atoms in high density!

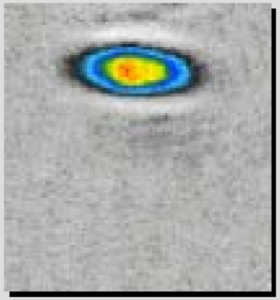
Absorption imaging:

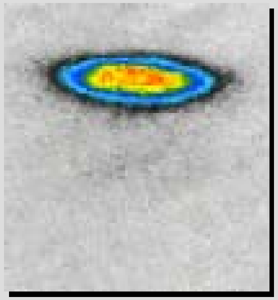
$n_0 > 1$ *for red-detuned probe light*

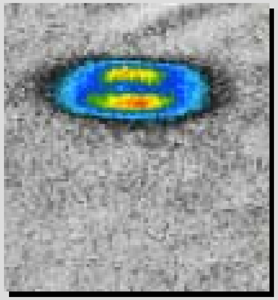


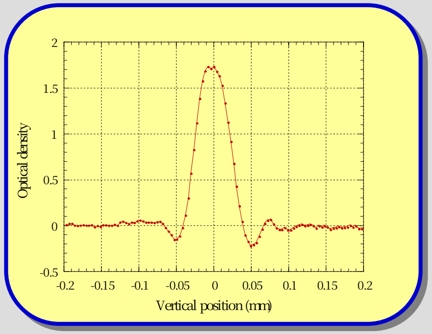
Optical lensing effect (2)

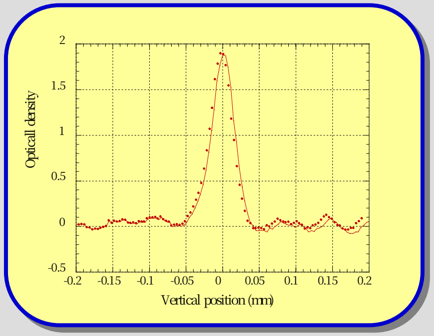
false-color absorption images

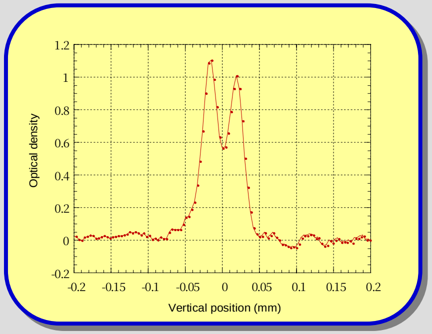








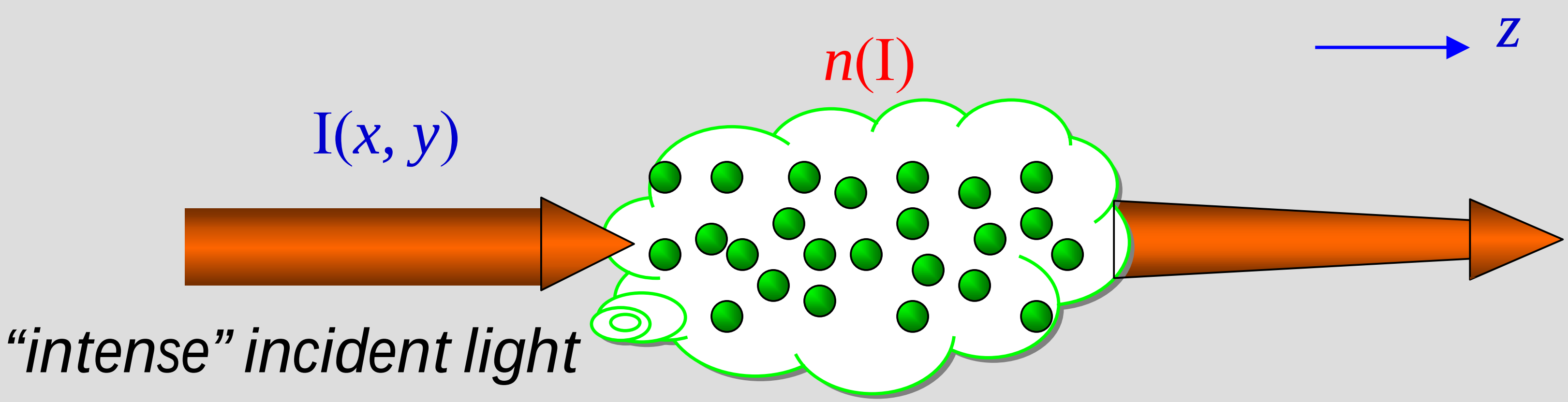




$z_c < d_i$ $z_c = d_i$ $z_c > d_i$

vertical cut profiles

Light focusing and defocusing by uniform medium (nonlinear optics)



Alkaline gas:

$$n(I)=n_0+n_2 I$$

nonlinear coefficient of refractive index

Clear measurements on detuning and polarization are still not well established!

We are interested in the two mechanisms:

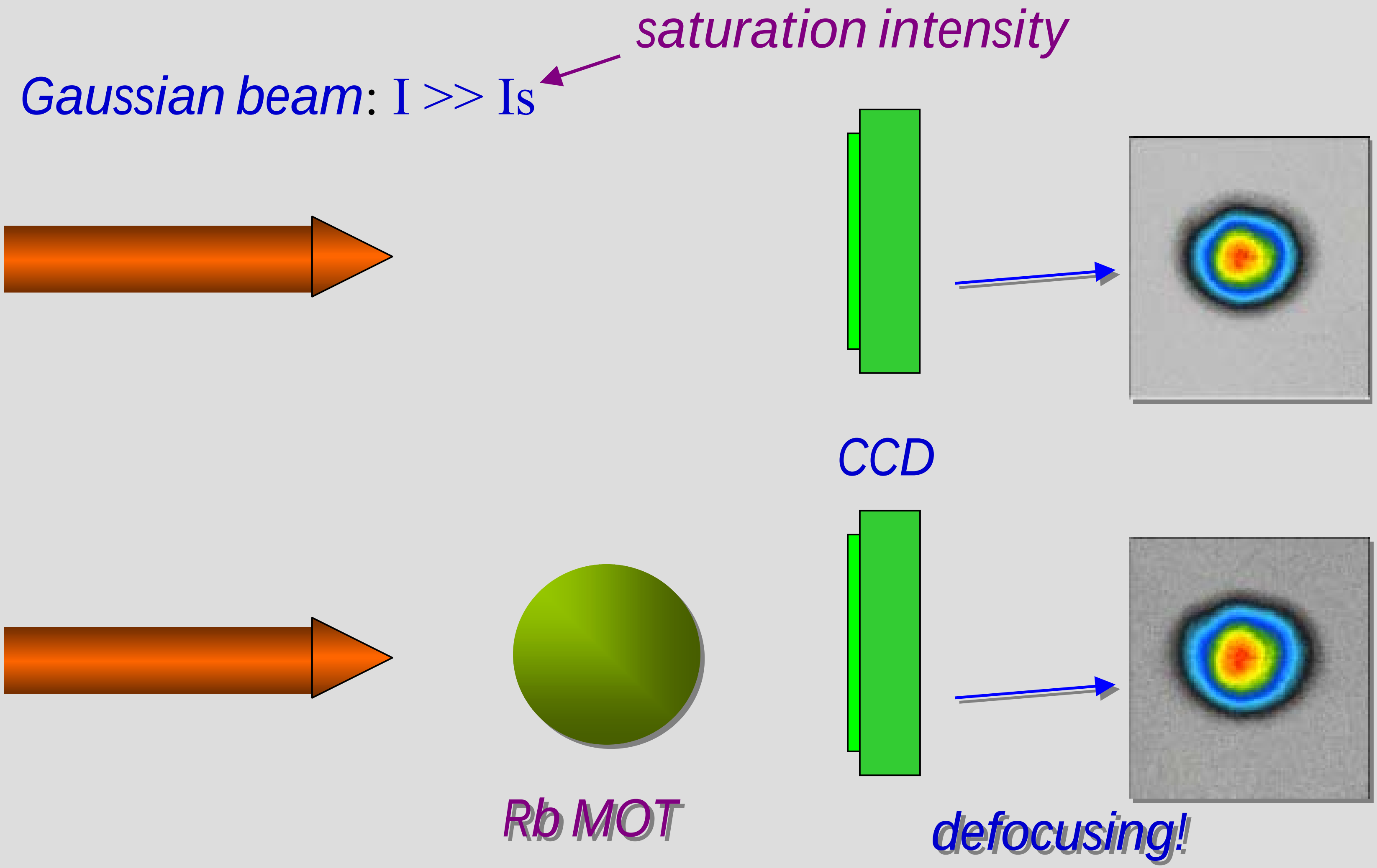
1. Saturated atomic absorption: response time 10^{-8} sec, $n_2 \sim 10^{-7}$ cm^2/W,

2. Thermal effects: response time 10^{-3} sec, $n_2 \sim 10^{-6}$ cm^2/W.

cold atom Calorimetry!?

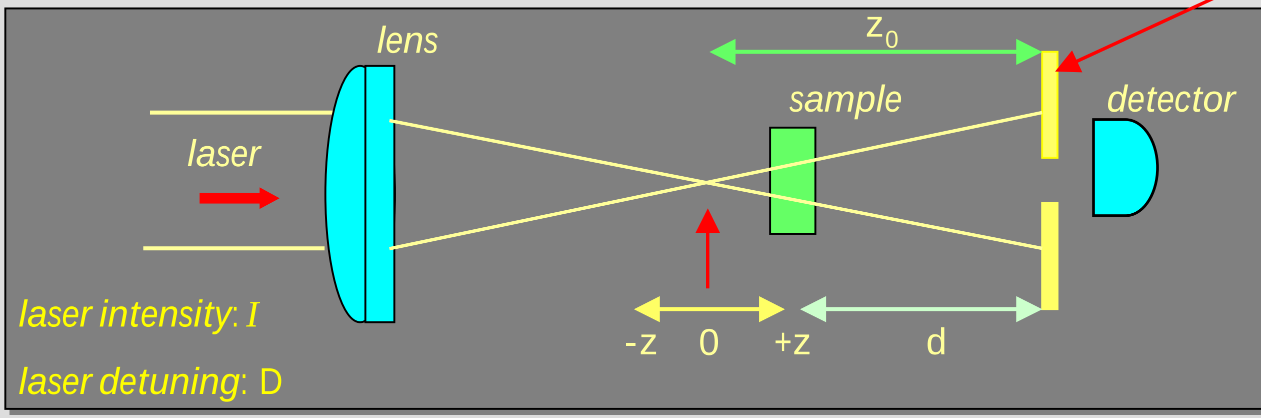
Optical lensing effect (3)

Gaussian beam: I >> Is



Measure the nonlinear lensing effect: Z-scan method

*Stryland et al., IEEE J. of Quantum Electronics **26**, 760 (1990)*



For a saturable Kerr medium (3rd order nonlinearity), the refractive index n(I) and absorption coefficient a(I) are

$$n(I) = n_0 + \Delta n(I) \quad \text{and} \quad \Delta n(I) = \frac{n_2 I}{1 + \frac{I}{I_{s\Delta}}}$$

$$\alpha(I) = \frac{\alpha_0}{1 + \frac{I}{I_{s\Delta}}}, \qquad I_{s\Delta} = I_s\left(1 + \frac{4\Delta^2}{\Gamma^2}\right)$$

I_s: *saturation intensity*
a_0: *linear absorption coefficient*
n_2: *Kerr index,* G: *spontaneous decay rate*

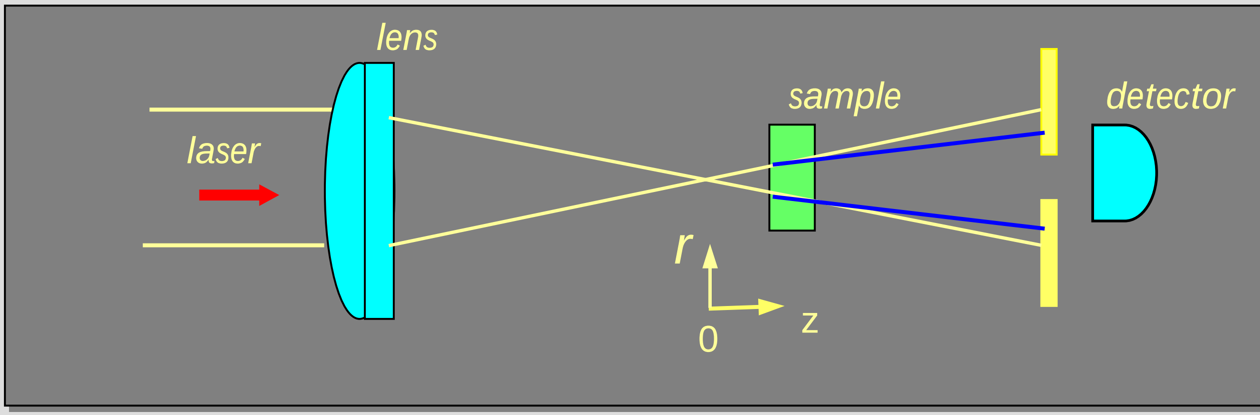
Na atoms	*Sinha et al., Opt. Comm. **203**, 427 (2002).*
Rb atoms	*Chiao et al., JOSA **20**, 2480 (2003).*
Cs MOT	*Saffman et al., PRA **70**, 013801 (2004).*

Positive Lensing

positive lensing: sample works as a positive lens!

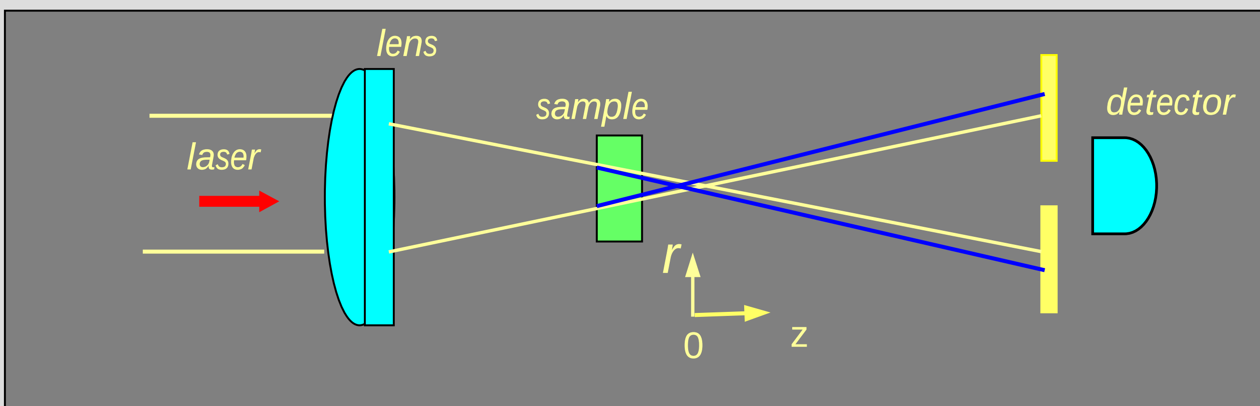
sample position: z,   beam waist position: z = 0!

z > 0



size ↓
signal ↑

z < 0



size ↑
signal ↓

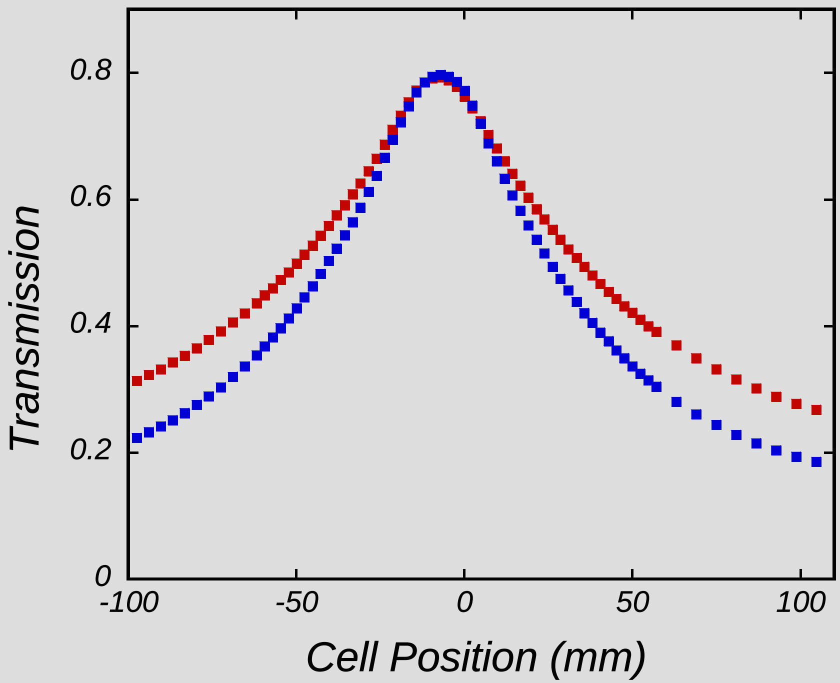
A Gaussian beam produces an r-dependent refractive index at each position z!

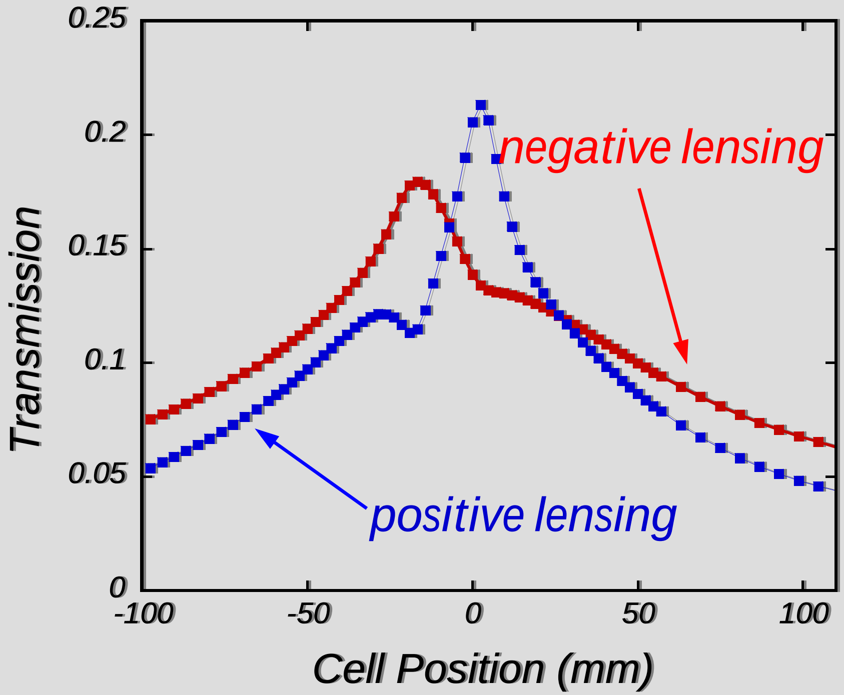
Z-scan measurement in hot atoms (heated Rb cell)

+/– 480 MHz to ^{85}Rb F=3 → F'=4 transition

$I \sim 0.2\, I_{s\Delta}$ cw measurement

measured by photodiode!





open aperture

closed aperture

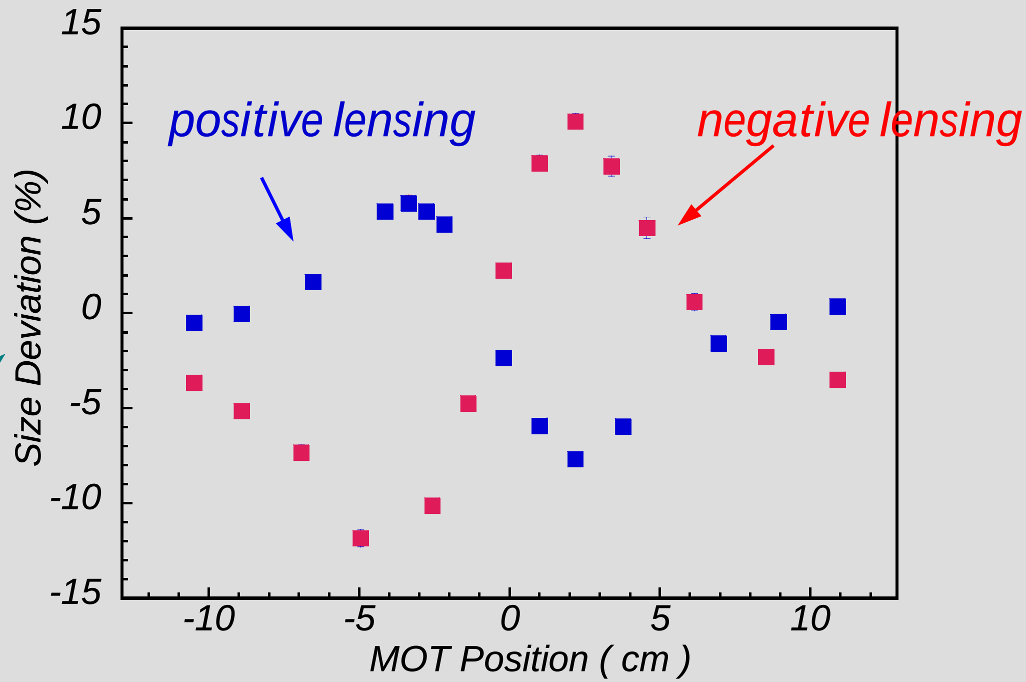
T~ 80 °C → significant Doppler broadening!

Z-scan measurement in cold atoms

+/– 30 MHz to ^{87}Rb F=2 → F'=3 transition

Measured by CCD at 70 ms after MOT turned off!

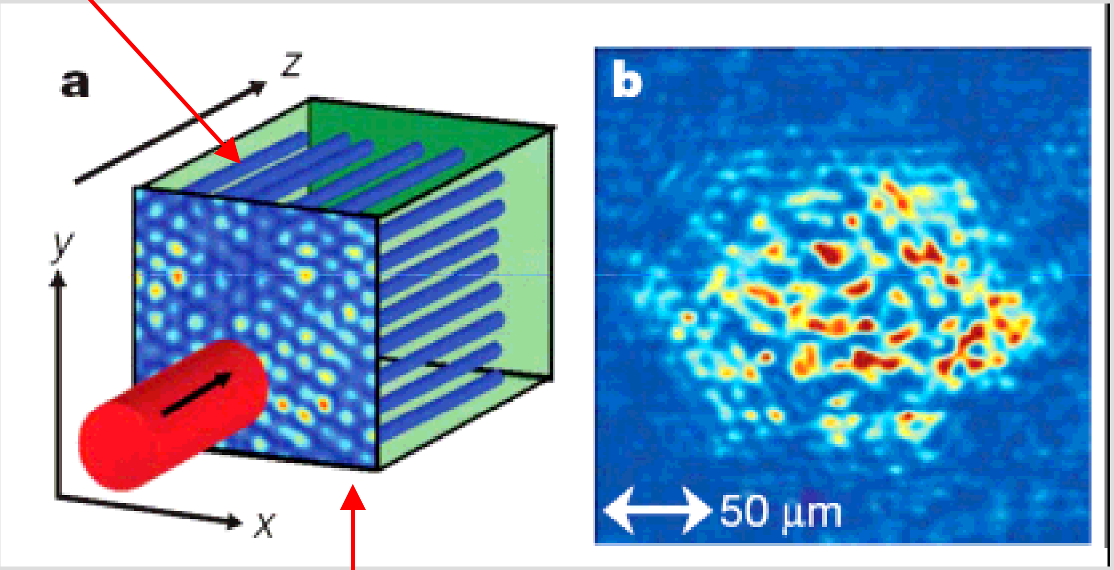
Compared the beam size with and without MOT atoms!



$I \sim 10\ I_{s\Delta}$, 3 ms duration
MOT density ~ 1.1×10^{10} atoms/cm^3
MOT temperature ~ 300 mK → *no Doppler broadening!*

Diffraction from a 2D lattice

Lattice with periodicity in the two transverse dimensions x and y!

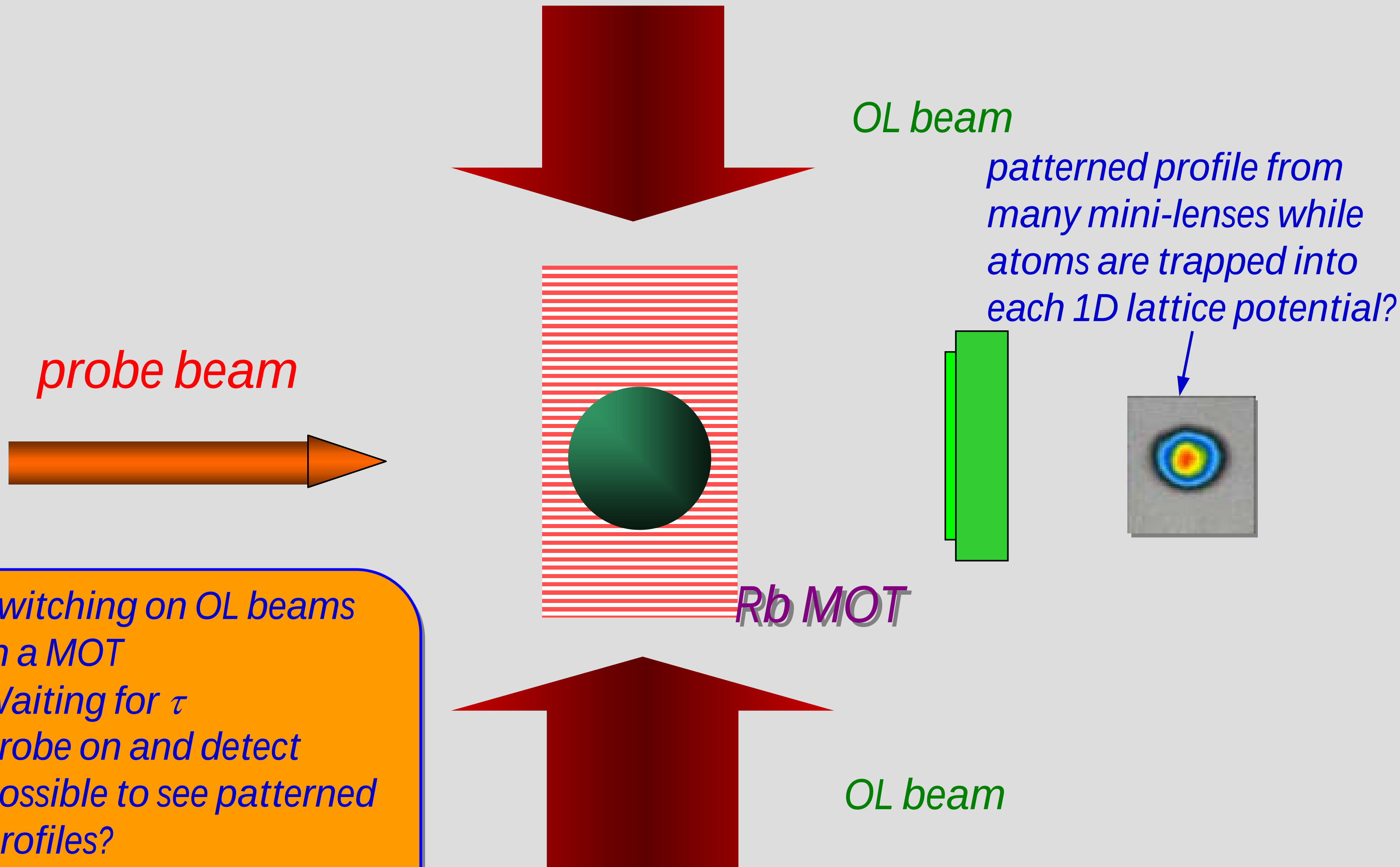


Far-field diffraction pattern!

photorefractive crystal

Schwartz et al., *Nature* 446, 52 (2007)

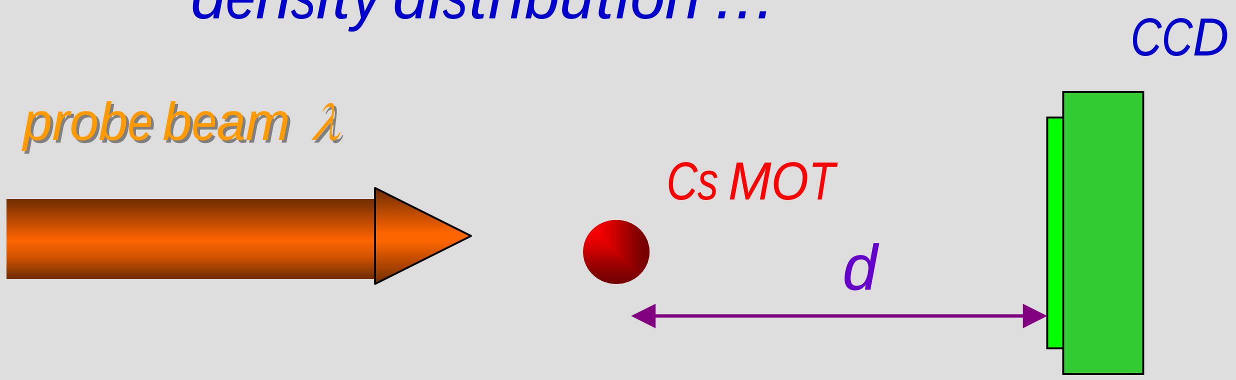
Dynamics of optical lattice loading?

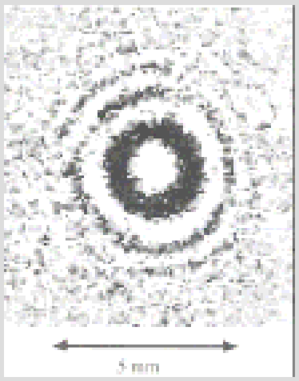


1. Switching on OL beams in a MOT
2. Waiting for τ
3. Probe on and detect
4. Possible to see patterned profiles?
5. Allows to trace the density distribution with τ?

Far-field diffraction pattern through a cold atom cloud (1)

- *Single beam detection*
- *Probe beam size larger than cloud size*
- *Allows to measure the cloud parameters, such as density distribution …*





$$n = n_0 + i\alpha_0 = 1 + \frac{3N\lambda^3}{8\pi^2}\,\frac{i - 2\Delta/\Gamma}{1 + (2\Delta/\Gamma)^2}\,.$$

$N \sim 10^{10}$ *atoms/cm*^{3}

$\Delta = 0.5\,\Gamma$

Stable intensity is required!

Strauch et al., Opt. Commun. 145, 57 (1998)

Far-field diffraction pattern through a cold atom cloud (2)

probe beam:

size (1/e^2 radius): 710 μm

detuning: -50 MHz

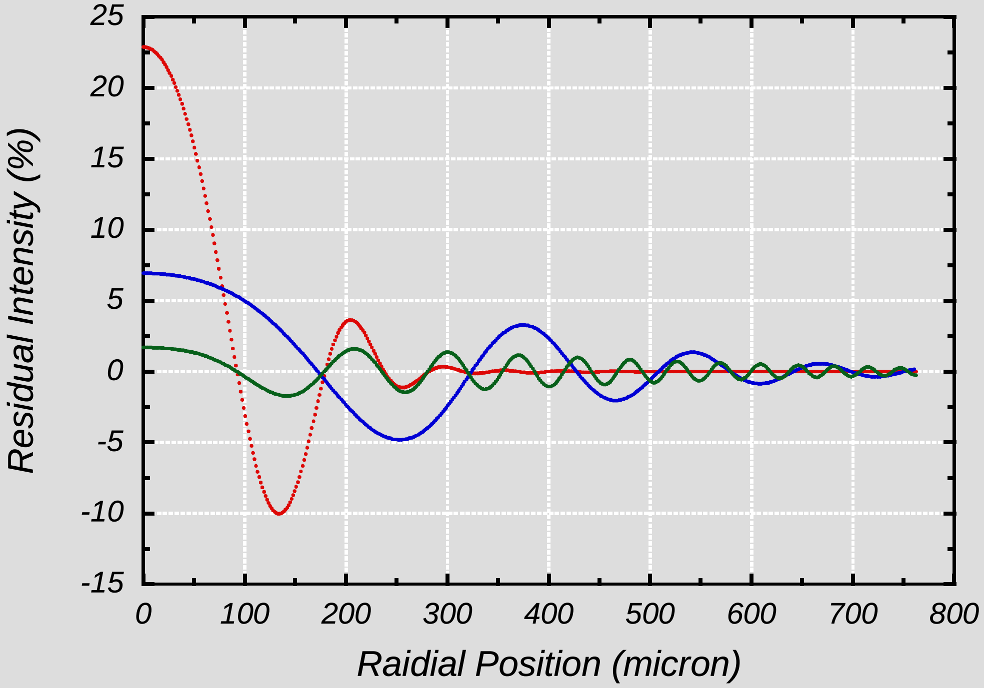
Rb cloud

red : d= 3 cm, N=5$\times$10^6 atoms
n=10^{12} atoms/cm^3

blue : d= 10 cm, N=5$\times$10^6 atoms
n=10^{12} atoms/cm^3

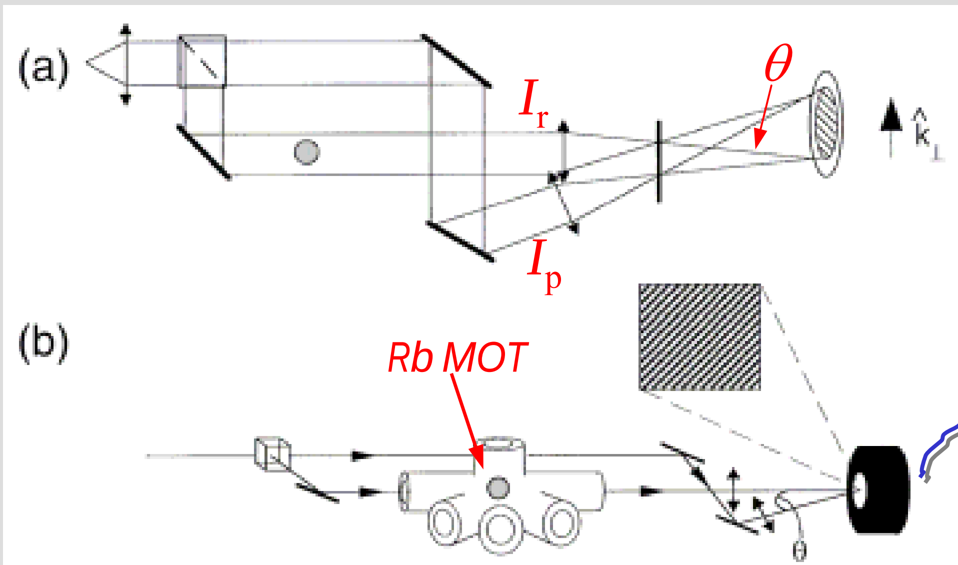
green : d= 3 cm, N=4$\times$10^5 atoms
n=10^{13} atoms/cm^3

Simulation



Spatial heterodyne imaging of cold atoms

$$I(x) = I_r + I_p + 2\sqrt{I_r I_p}\cos[\Delta\varphi + 2\pi\theta\hat{k}_\perp\frac{\vec{x}}{\lambda} - \phi(\vec{x})]$$



$\Delta\varphi = \varphi_1 - \varphi_2$
=phase difference
between the two beams!

position-dependent
phase shift: phase image
$\phi(\vec{x})$

Kadlecek et al.,
Opt. Lett. 26, 137 (2001)

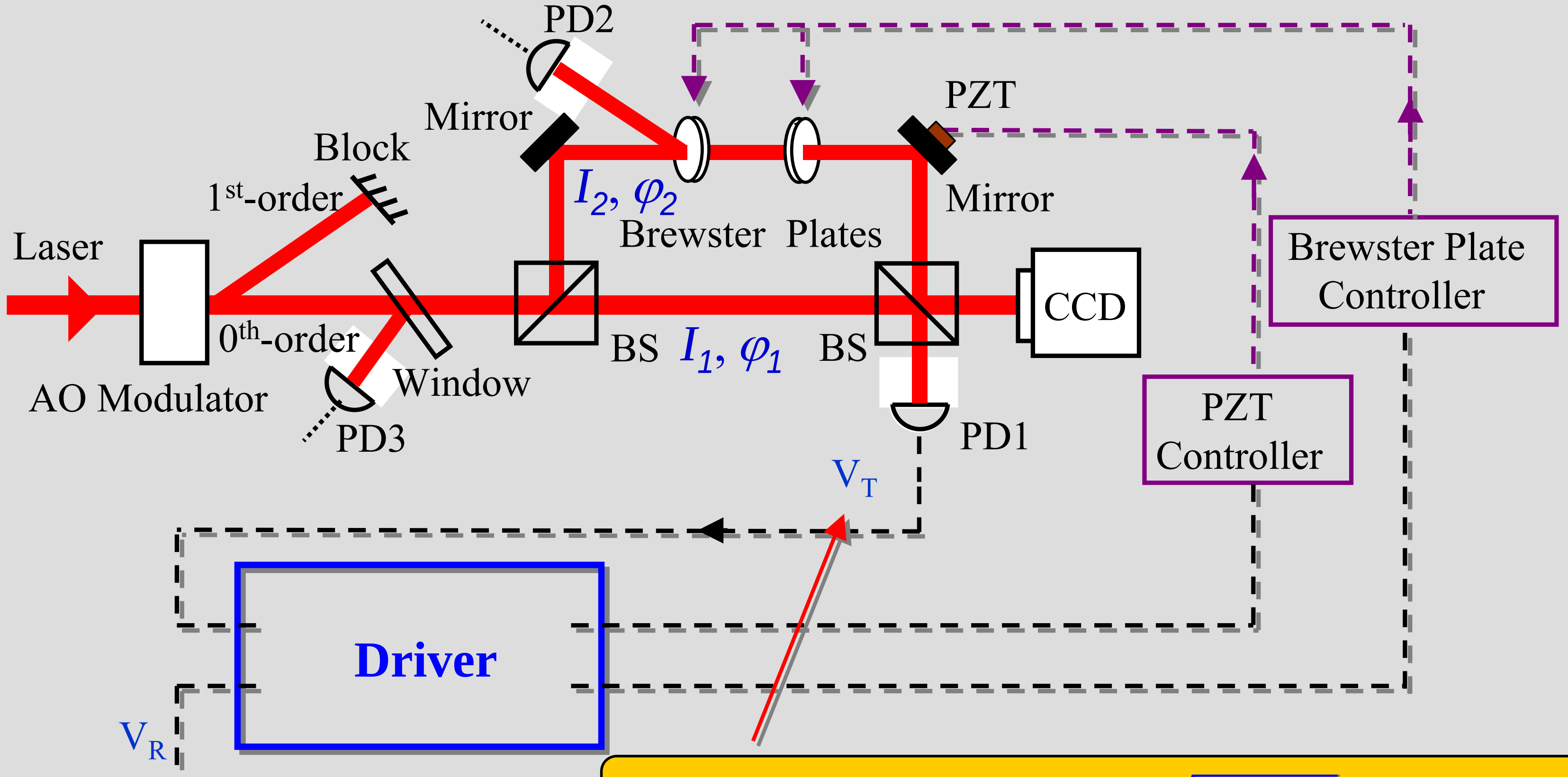
- two-beam detection
- possibly nondestructive
- high S/N ratio → even better than the phase contrast imaging!

In general, it requires a little complicated algorithm for phase-shift retrieval!

However, direct phase shift imaging is possible if $\theta \rightarrow 0$, and $\Delta\varphi$ is stabilized to $\pi/2$!
We can do this as seen in the next page!

Adjustable Phase difference using a Mach-Zehnder Interferometer (1)

$\Delta\varphi = \varphi_1 - \varphi_2$ =phase difference

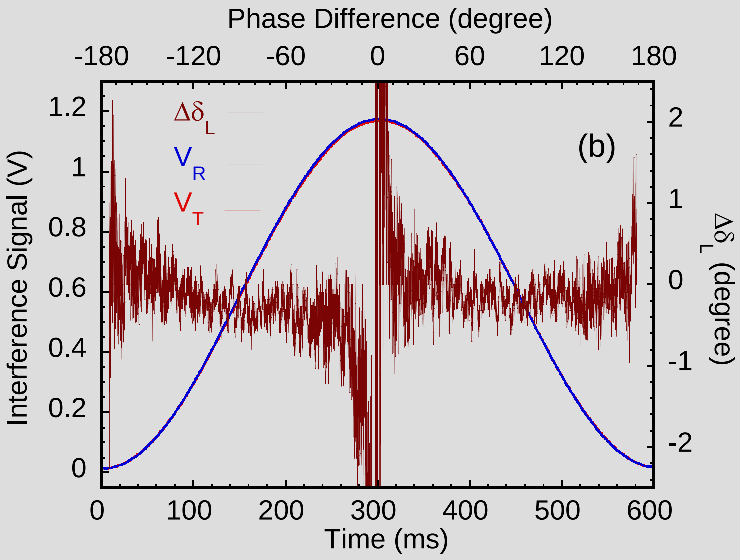


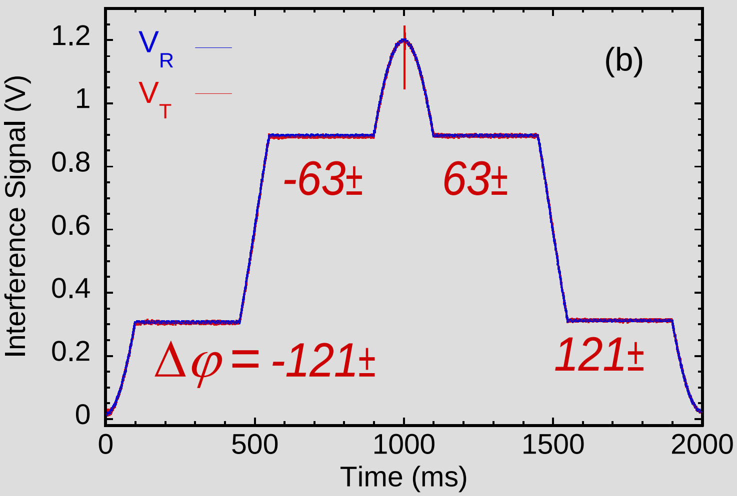
$$\propto I_T = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\Delta\varphi)$$

Tunable while with high phase stability!

Adjustable Phase difference using a Mach-Zehnder Interferometer (2)

Phase stability of 0.2° (*rms*) *is achieved!*

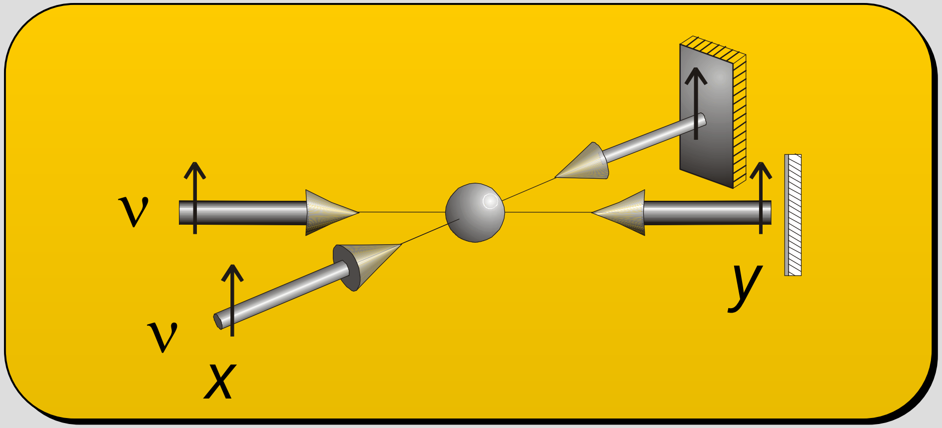




continuous sweep

step-wise sweep

2D optical lattice: two dimensional optical standing wave



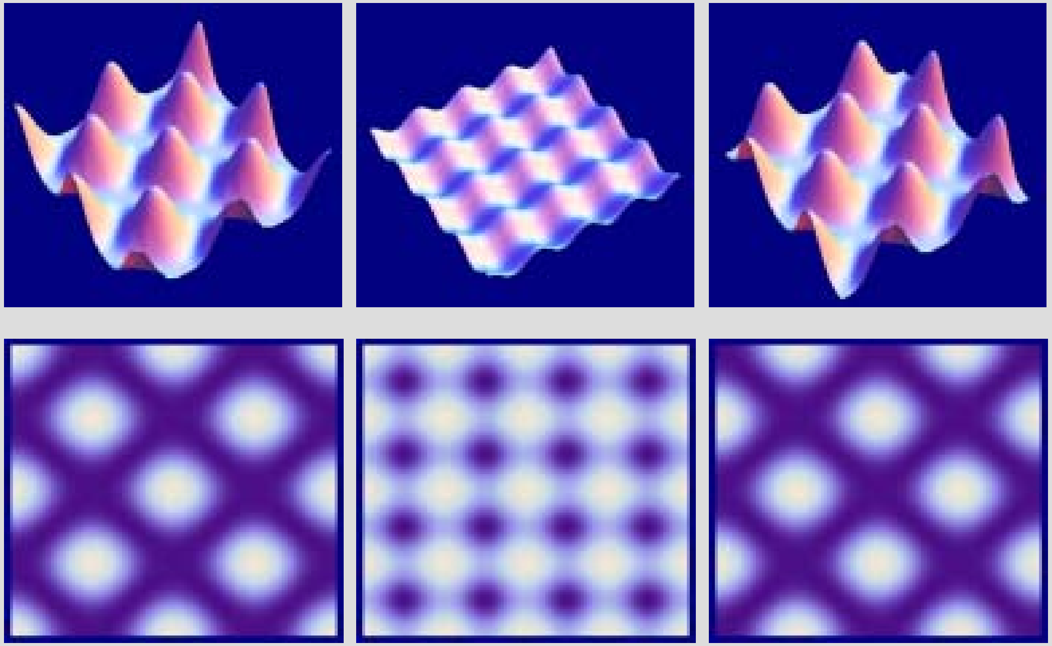
$$U \approx U_o \cdot [\cos^2(k_x x) + \cos^2(k_y y) + 2\cos(k_x x)\cdot\cos(k_y y)\cos(\Delta\varphi)],$$

$$\Delta\varphi = \varphi_x - \varphi_y = \text{phase difference.}$$

The phase difference locking scheme shown above can be directly applied to the 2D OL by injecting the locking beam into the OL!

Application to 2D and 3D optical lattice construction

Lattice configuration changes while $\Delta\varphi$ varies!



$\Delta\varphi = 0°$ $\Delta\varphi = 90°$ $\Delta\varphi = 180°$

Related applications (1)

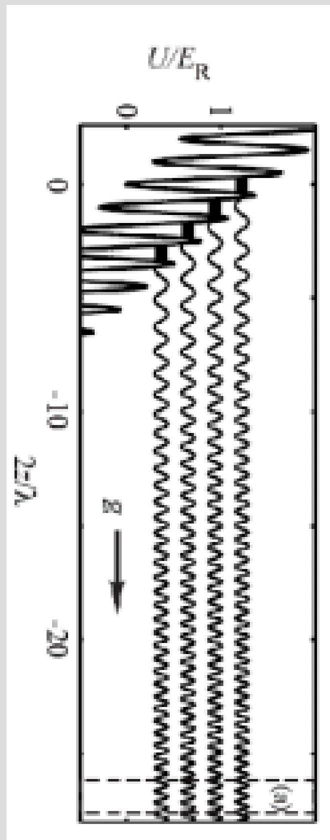
Atomic tunneling …

1D optical lattice
+
gravity g

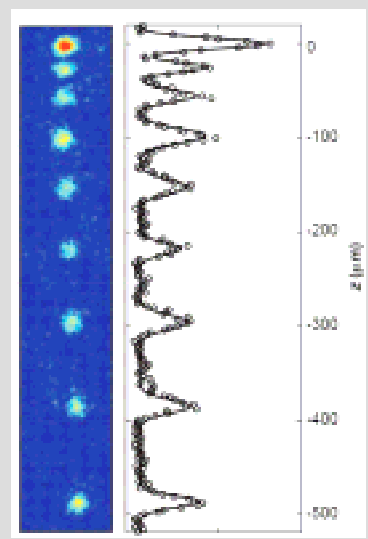
Tunneling probability per oscillation:

$P=\exp(-\lambda\varepsilon^2/8\hbar^2 g)$,

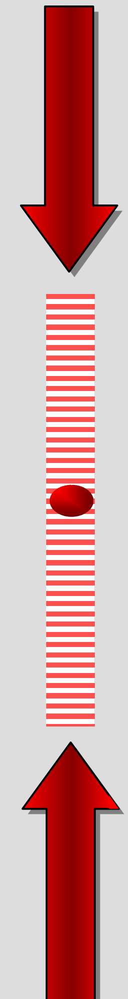
ε: *energy gap between the ground state band and the continuum states!*



matter wave interference due to tunneling!



OL beam



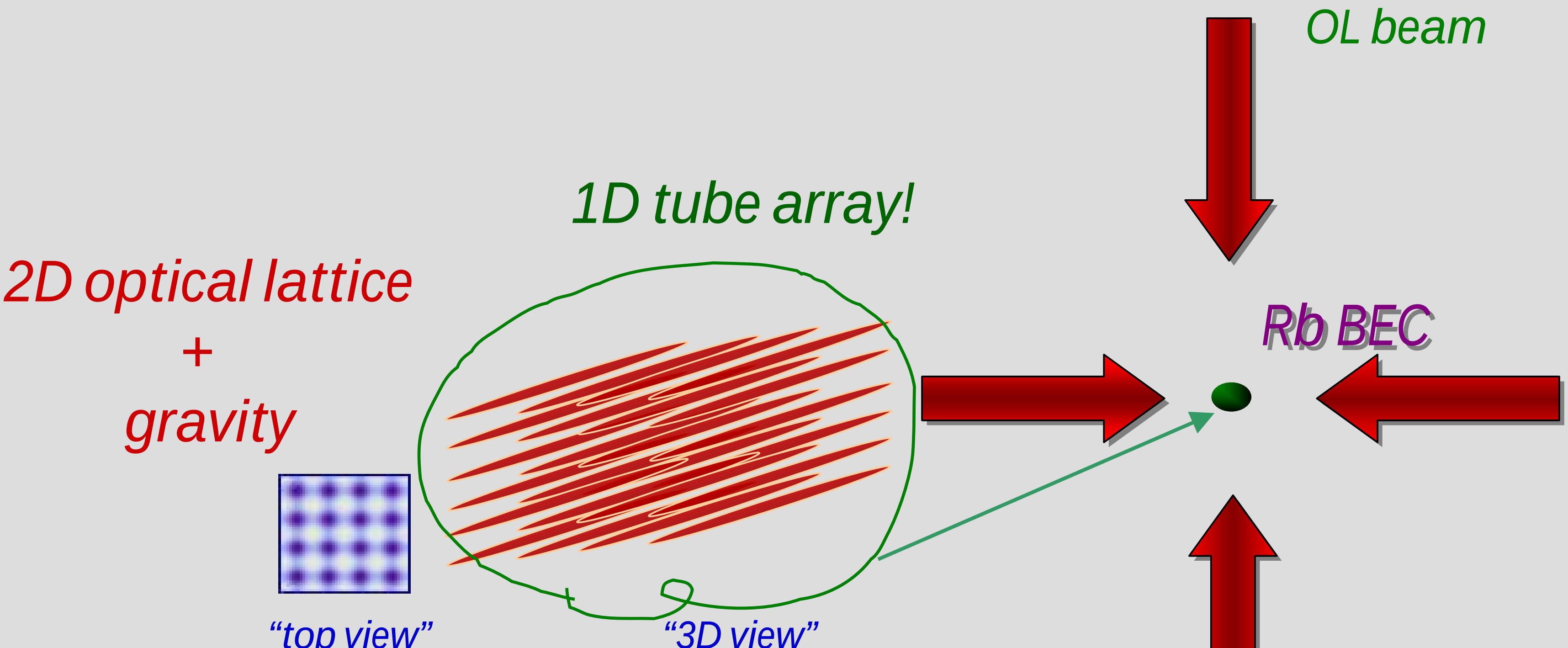
Rb BEC

OL beam

Anderson et al., Science ***282***, *1686 (1998)*

Related applications (2)

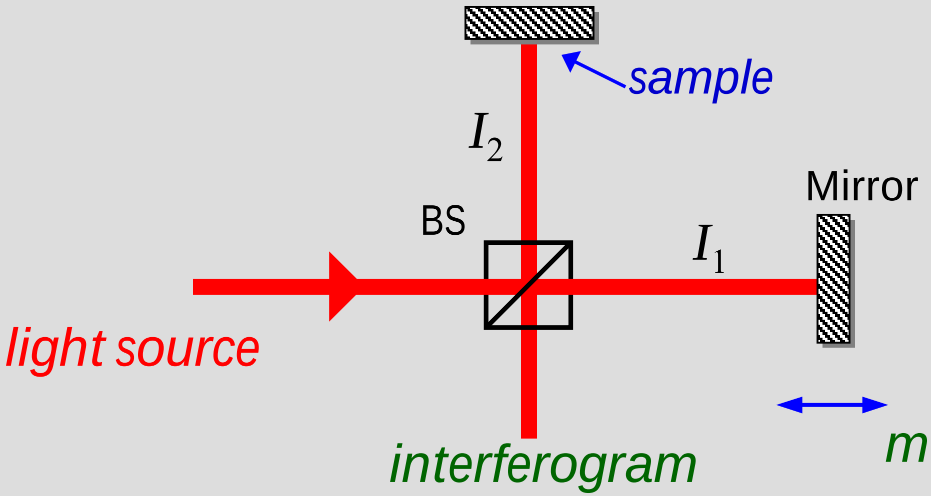
Atomic tunneling …



1. *Matter wave Interference while tunneling out?*
2. *Matter wave interference under different $\Delta\varphi$?*

Atom Grating?

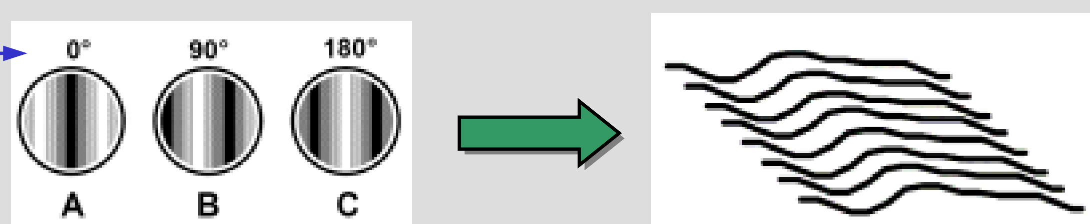
Phase-shifting Interferometry (PSI)



- Fast measurement allowed
- High longitudinal accuracy
- Offset effects from the detected signal are cancelled out by subtraction
- Gain effects are eliminated by taking the ratio

$$I_T(x, y) = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos[\Delta\varphi + \Theta(x, y)]$$

$\Delta\varphi$ →



Phase image Q(x, y)

minimum 3 frames required!

optical phase difference $Q(x, y) = \frac{\lambda}{2\pi}\tan^{-1}\left(\frac{C - B}{A - B}\right)$

Useful for 2D surface cold atoms imaging? (Michelson type)

Conventional PSI

Silicone chip

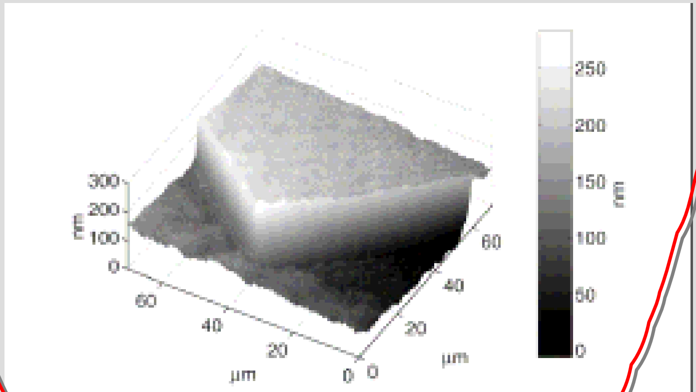
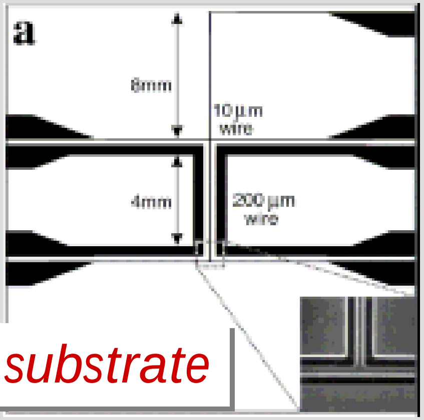
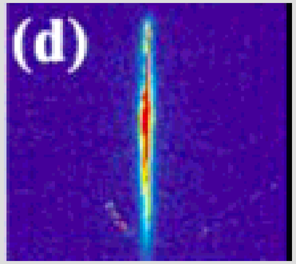


Fig. 3. Reflection phase image at the corner of a micro-fabricated silicon structure. The phase distribution is expressed as a surface height profile.

Iwai et al., Opt. Lett. ***29***, 2399 (2004)

Li MOT with 10^8 atoms!





top view

fluorescence!
destructive!

Folman et al., PRL ***84***, 4749 (2000)

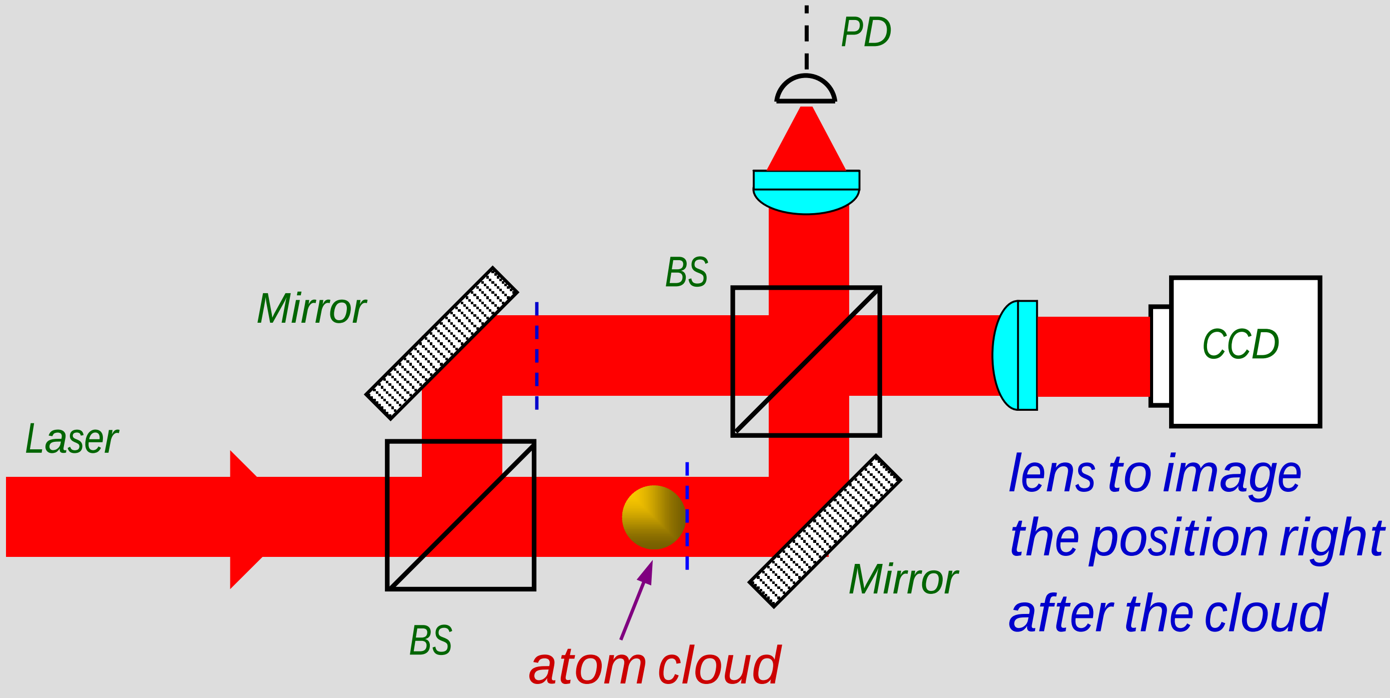
possible for PSI?

Less destructive!

Trap can leave on!

Direct diagnosis of wiring!

Phase-shifting Interferometry on cold atoms (Mach-Zehnder type)



Similar to the heterodyne method!

However, possible to mapping out other phase disturbances other than pure density distribution, such as magnetic field distribution …

Phase-shifting Interferometry on cold atoms (Mach-Zehnder type)

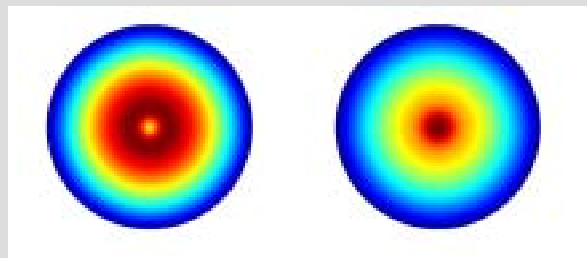
Simulation:

Rb cloud

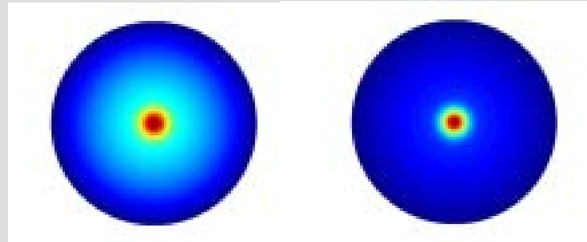
$N \sim 5 \times 10^6$ atoms

density $\sim 10^{12}$ atoms/cm^3

false color images



(*a*) $\Delta\varphi=0°$ (*b*) $\Delta\varphi=45°$



(*c*) $\Delta\varphi=90°$ (*d*) $\Delta\varphi=135°$

The probe laser has a radius of 710 μm *and –50 MHz detuning.*

Acknowledgements

nonlinear optical refraction and absorption of atoms

林志杰 *(Rb cell)*
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phase difference adjustment, stabilization, and imaging

蕭博文
顧子平

atom tunneling

吳欣澤
丁威志