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Disordered lattice gases

+ correlations in BEC

J.J. Arlt

T. Schulte, S. Drenkelforth, W. Ertmer
K. Sacha, J. Zakrzewski und M. Lewenstein

Kioloa 2006

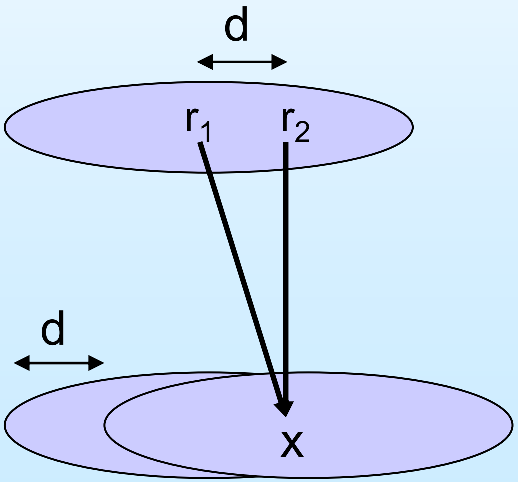
Correlation functions

1st order correlation function:

$$g^{(1)}(\mathbf{r}_1,\mathbf{r}_2) = \frac{\langle \hat{\psi}^\dagger(\mathbf{r}_1)\hat{\psi}(\mathbf{r}_2)\rangle}{\sqrt{\langle \hat{\psi}^\dagger(\mathbf{r}_1)\hat{\psi}(\mathbf{r}_1)\rangle\langle \hat{\psi}^\dagger(\mathbf{r}_2)\hat{\psi}(\mathbf{r}_2)\rangle}}$$

$$\longrightarrow \quad \langle I(x)\rangle$$

Contrast:

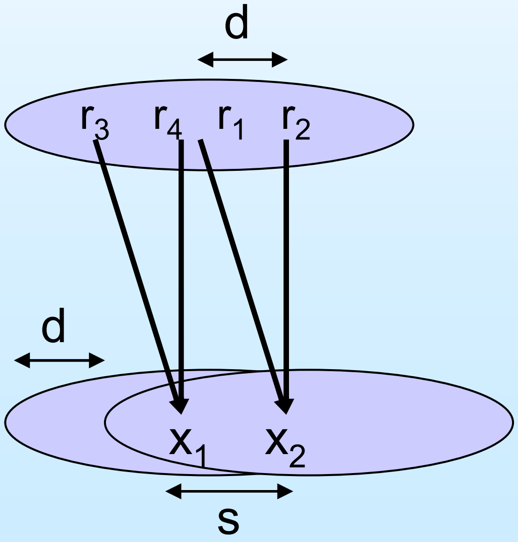


2nd order correlation function:

$$g^{(2)}(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3,\mathbf{r}_4) = \frac{\langle \hat{\psi}^\dagger(\mathbf{r}_1)\hat{\psi}^\dagger(\mathbf{r}_2)\hat{\psi}(\mathbf{r}_3)\hat{\psi}(\mathbf{r}_4)\rangle}{\sqrt{\prod_{i=1}^{4}\langle \hat{\psi}^\dagger(\mathbf{r}_i)\hat{\psi}(\mathbf{r}_i)\rangle}}$$

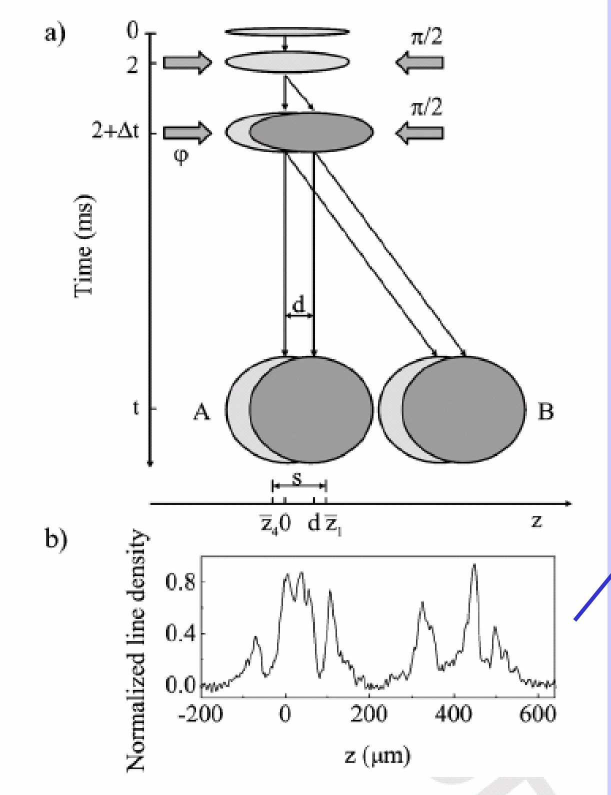
$$\longrightarrow \quad \langle I(x_1)I(x_2)\rangle$$

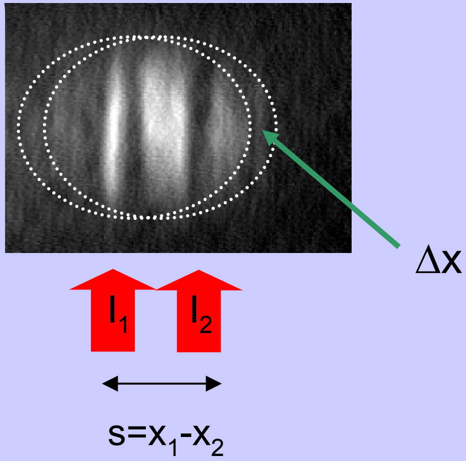
Intensity correlations:



Measurement technique

Interferometric scheme

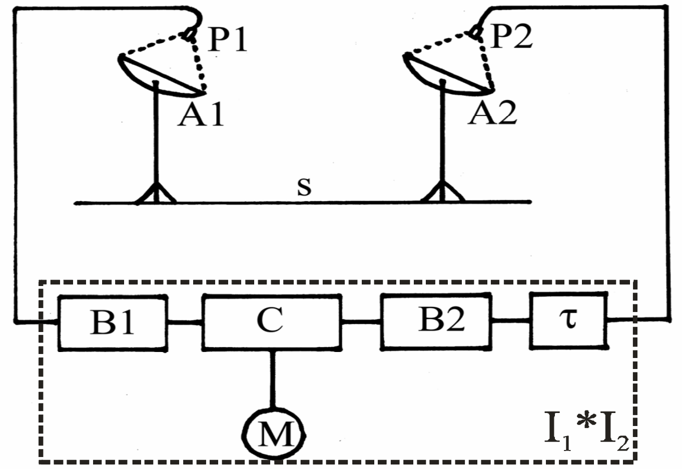




$$\gamma_f^{(2)}(x_1,x_2,\Delta x)=\frac{\left\langle\left(\hat{I}_1-\left\langle\hat{I}_1\right\rangle\right)\left(\hat{I}_2-\left\langle\hat{I}_2\right\rangle\right)\right\rangle}{\sqrt{\left\langle\left(\hat{I}_1-\left\langle\hat{I}_1\right\rangle\right)^2\right\rangle\left\langle\left(\hat{I}_2-\left\langle\hat{I}_2\right\rangle\right)^2\right\rangle}}$$

The normalised intensity correlation function can be measured !

Hanbury-Brown Twiss



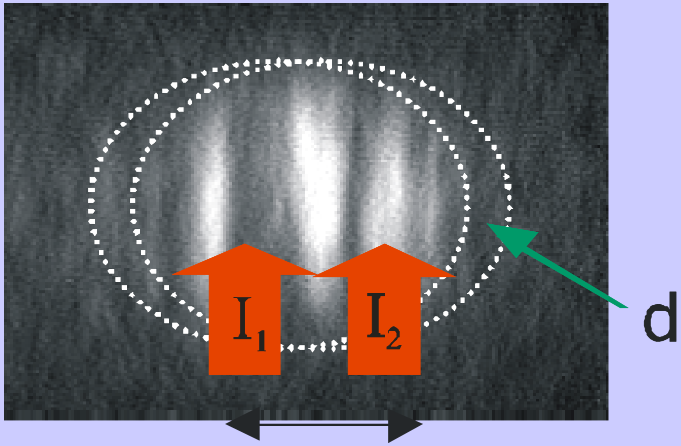
Measurement of intensity correlations

→ transverse coherence length

→ star diameters

Advantage:
insensitive to atmospheric fluctuations

Interferometric scheme



$s = x_1 - x_2$

Measurement of intensity correlations in one output port

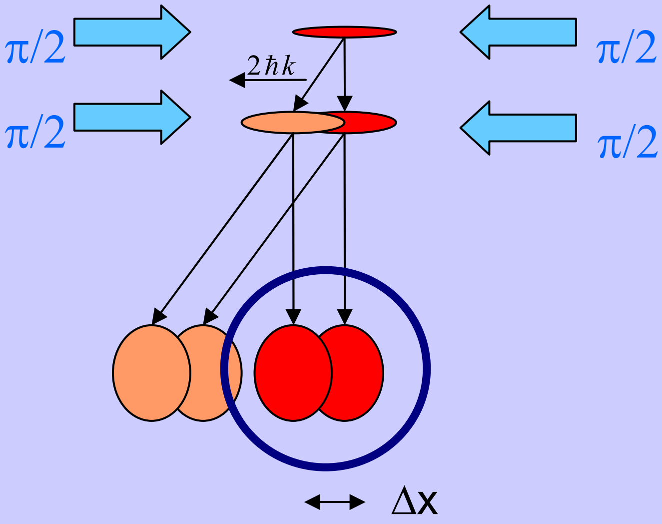
= measurement of the spatial second order correlation function of the original condensate !

→ **coherence length**

Advantage:
insensitive to global phase shifts

Measurement of a general $g^{(2)}$

Interferometric scheme



Measurement of intensity correlations in one output port

= measurement of the second order correlation function of the original condensate !

Normalised correlation function:

$$\gamma_f^{(2)}(x_1,x_2,\Delta x)=\frac{\left\langle\left(\hat{I}_1-\left\langle\hat{I}_1\right\rangle\right)\left(\hat{I}_2-\left\langle\hat{I}_2\right\rangle\right)\right\rangle}{\sqrt{\left\langle\left(\hat{I}_1-\left\langle\hat{I}_1\right\rangle\right)^2\right\rangle\left\langle\left(\hat{I}_2-\left\langle\hat{I}_2\right\rangle\right)^2\right\rangle}}$$

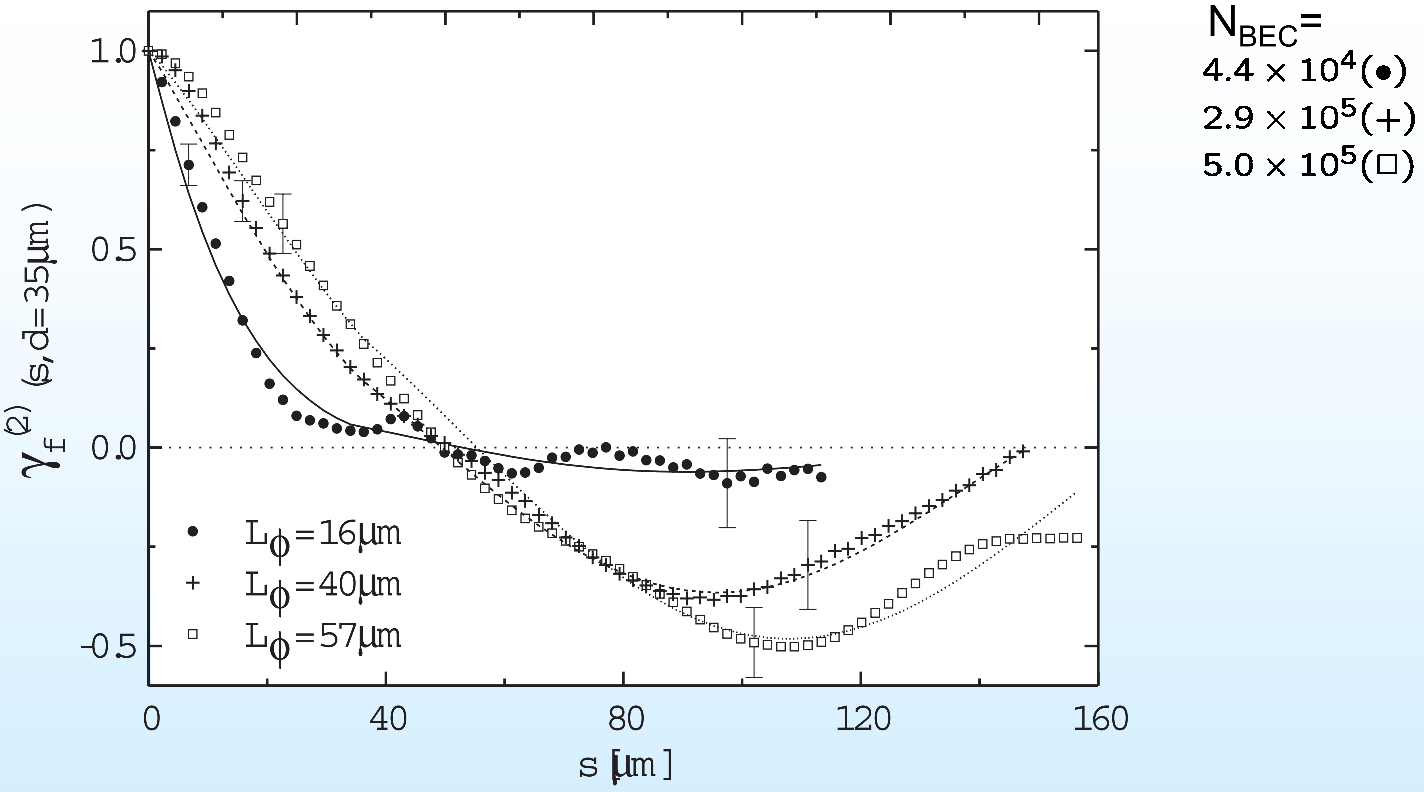
$$=\cos\left[\kappa(x_1-x_2)\right]\ \exp\left[-\frac{\delta_L^2}{2}f^{(2)}(x_1,x_2,\Delta x)\right]$$

$$=\cos\left[\kappa(x_1-x_2)\right]\ g^{(2)}(x_1,x_2,\Delta x)$$

$$g^{(2)}(x_1,x_2,x_3,x_4)=$$

$$\exp\left[-\frac{L}{2L_\phi}f^{(2)}(x_1,x_2,x_3,x_4)\right]$$

correlation function $g^{(2)}$

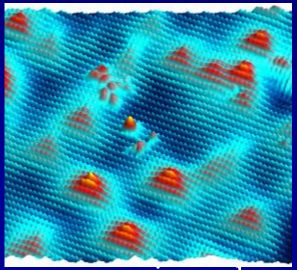


Measurement of the general second order correlation function.

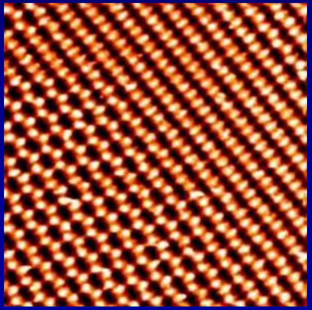
D. Hellweg, L. Cacciapuoti, M. Kottke, T. Schulte, K. Sengstock, W.Ertmer, J. Arlt, Phys. Rev. Lett. **91**, 10406 (2003).

Motivation

- disorder is present in various systems



www.omicron.de



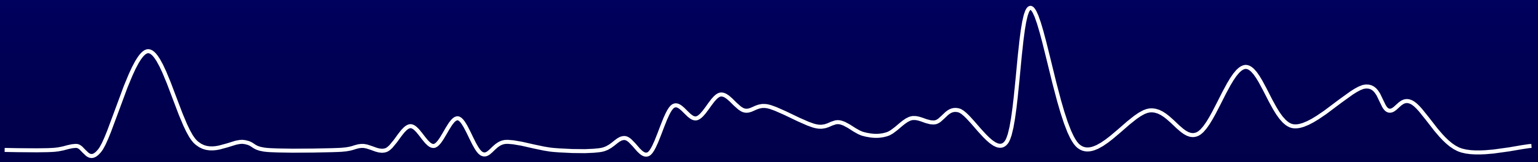
Suppression of superfluidity of ^{4}He in porous media with disorder.

- drastic (non-perturbative) effects on physical properties (e.g. transport, optical)

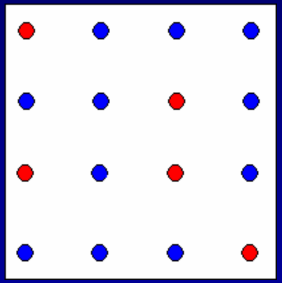
$H(\lambda) = H_0 + \lambda V(\vec{r})$ non-pertubative

$\forall \lambda : \lambda \neq 0$ if $V(\vec{r})$ is random / disordered

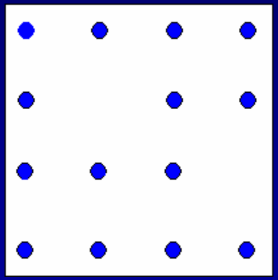
$\Rightarrow$ Effect of <u>controllable</u> disorder on dynamics of quantum many-particle-systems?



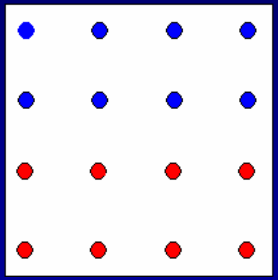
Disorder types



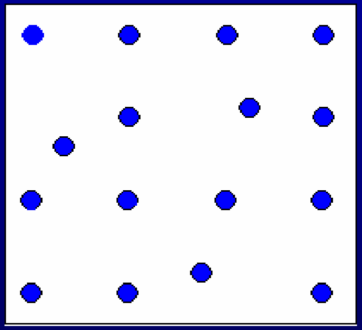
Mixtures



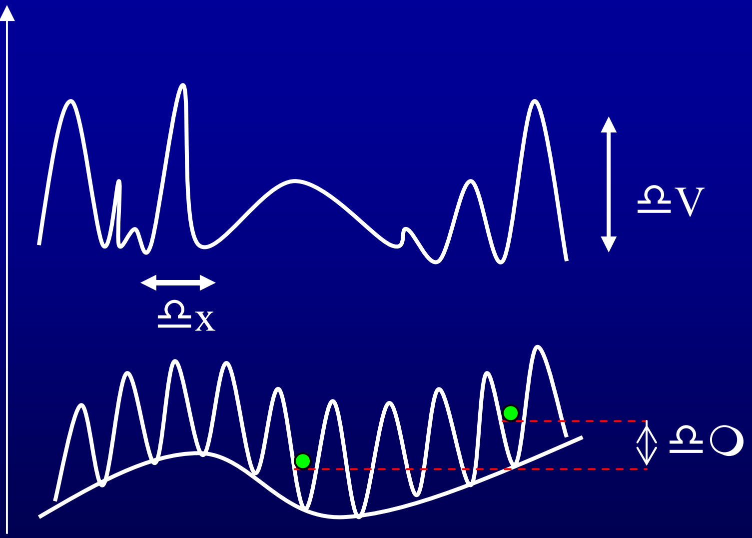
Empty sites



Surfaces, alloys



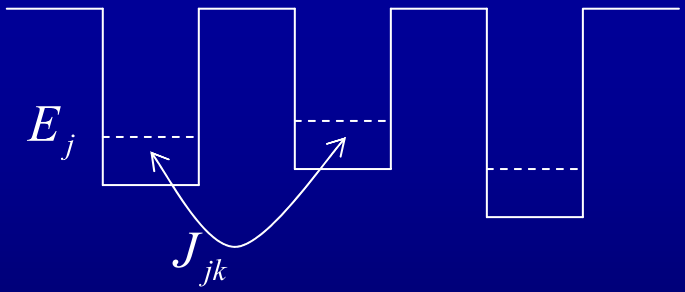
Lattice disorder



Disordered Lattice Gas: Localization

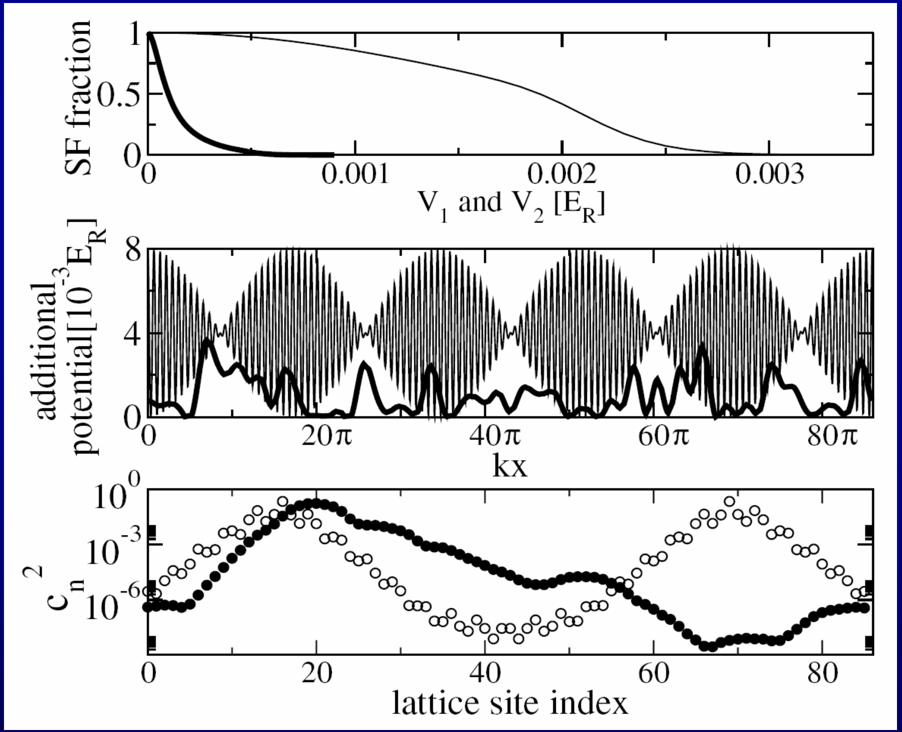
Anderson model :

$$i\hbar\dot{a}_j = E_j\,a_j + \sum_{k\neq j} J_{jk}\,a_k$$



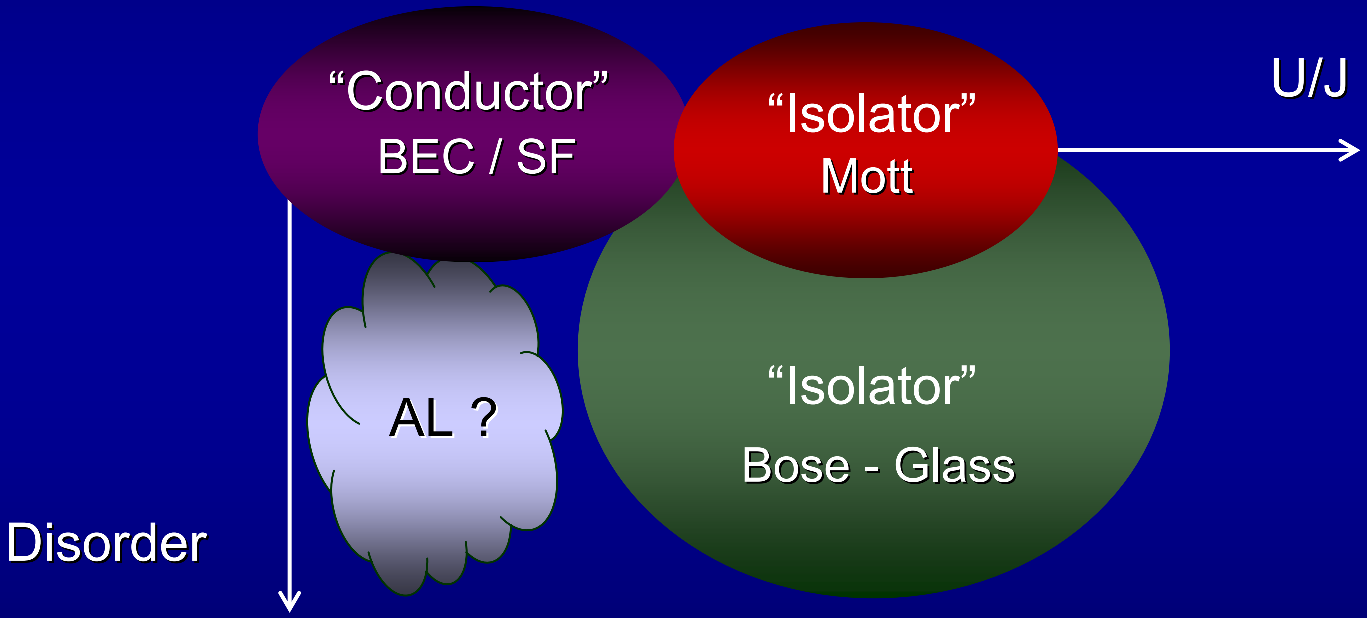
Non-interacting particles in 1D lattices :

- inhibition of transport , vanishing SF
- associated with localized states



B. Damski, J. Zakrzewski, L. Santos, P. Zoller and M Lewenstein; Phys. Rev. Lett. 91 8 (2003)

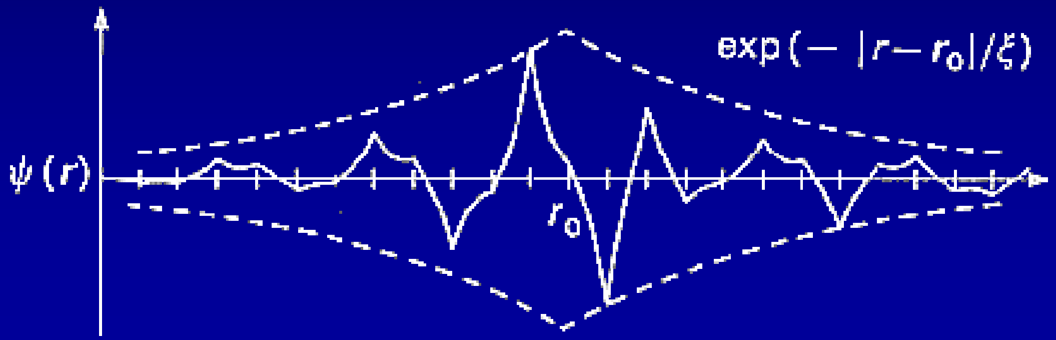
Disorder and Interactions



Can there be an Anderson Localization regime ?

Disorder : Basic effect

→ It strongly enhances the existence of localized states !

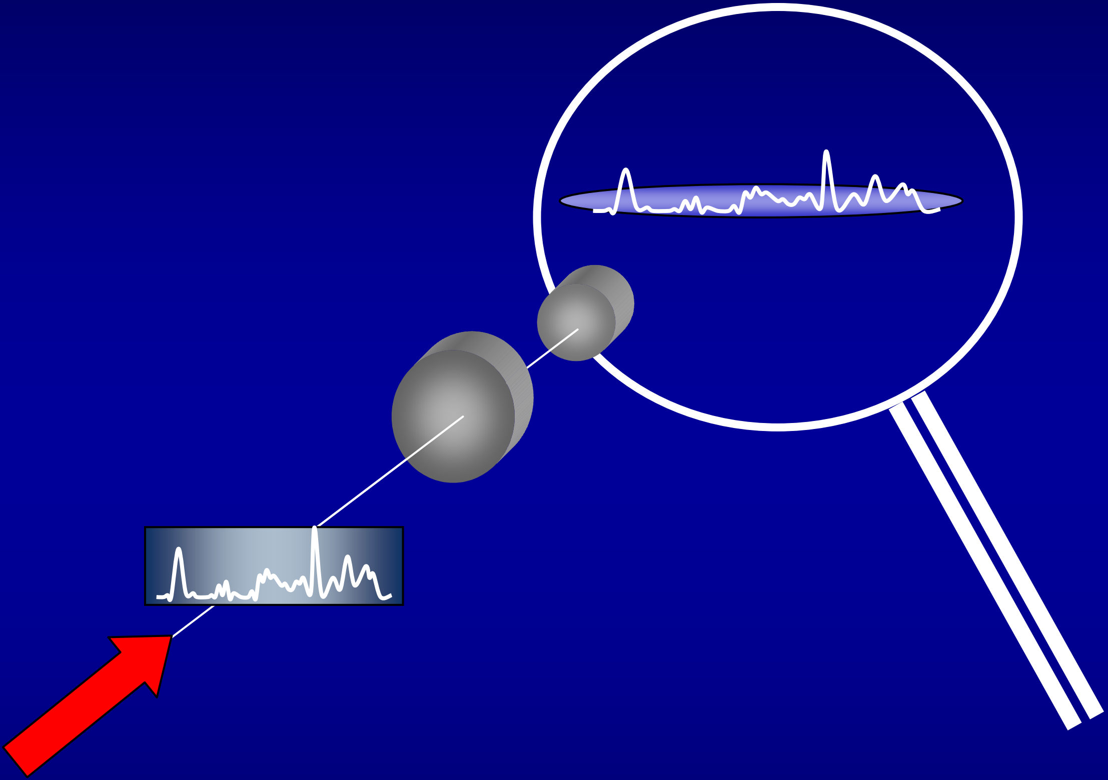


Wave function : $$\psi(r) = \varphi(r)\exp\left(\frac{-|r-r_0|}{\xi}\right)$$ ξ **localization length**

Anderson Localization is characterized by:

- vanishing superfluid fraction
- localization of atoms due to interference
- gapless excitation spectrum

Disorder : Experimental realisation



this work:

T. Schulte et al.
Phys. Rev. Lett. 95, 170411 (2005),
cond-mat/0507453.

similar investigations:

J. E. Lye et al. Phys. Rev. Lett. 95, 070401 (2005)
C. Fort et al. Phys. Rev. Lett. 95, 170410 (2005)

D. Clément et al. Phys. Rev. Lett. 95, 170409 (2005)

Disorder : Experimental realisation

Disorder potential :

Wavelength : 825 nm

Waist : ~ 480 µm

Theo. modulation depth : ~ 3 E_{Rec}

Smallest structure : ~ 7 µm

Modulations over cloud size : ~ 20

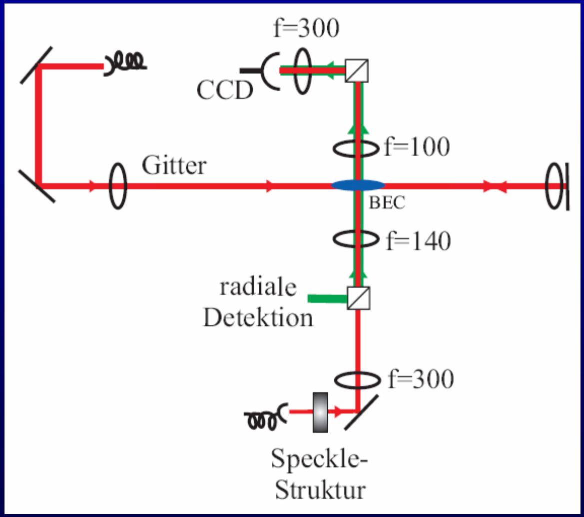
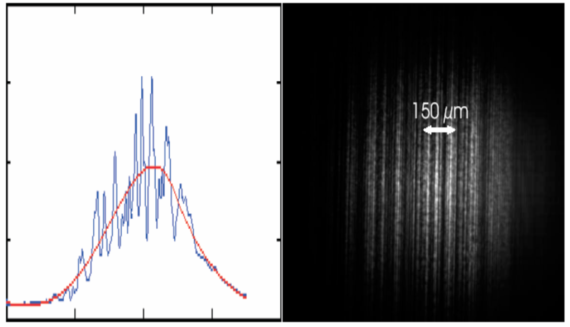
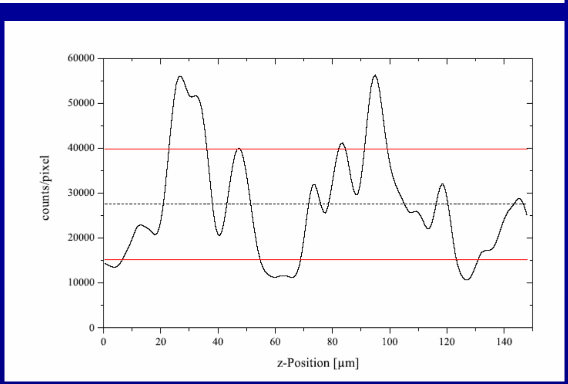


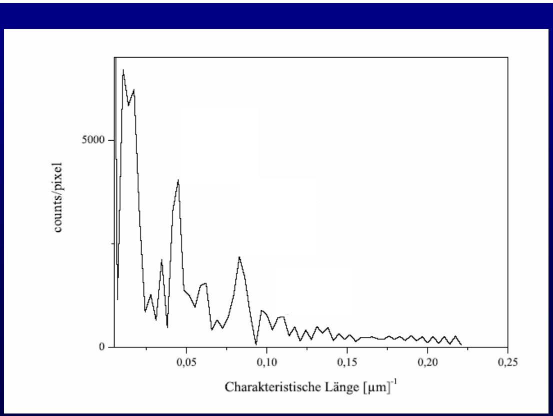
Image of total beam profile



Intensity modulations over cloud size



Fourier analysis of profile

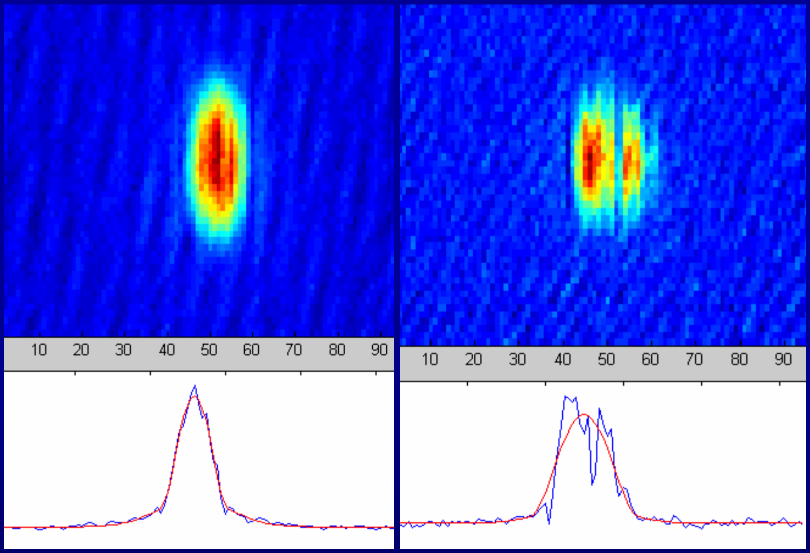


Disorder : First results

Absorption images :

TOF = 20.4 ms

Modulation depth 0.2 E_{rec}



N = 5 10^4

N = 2.6 10^4

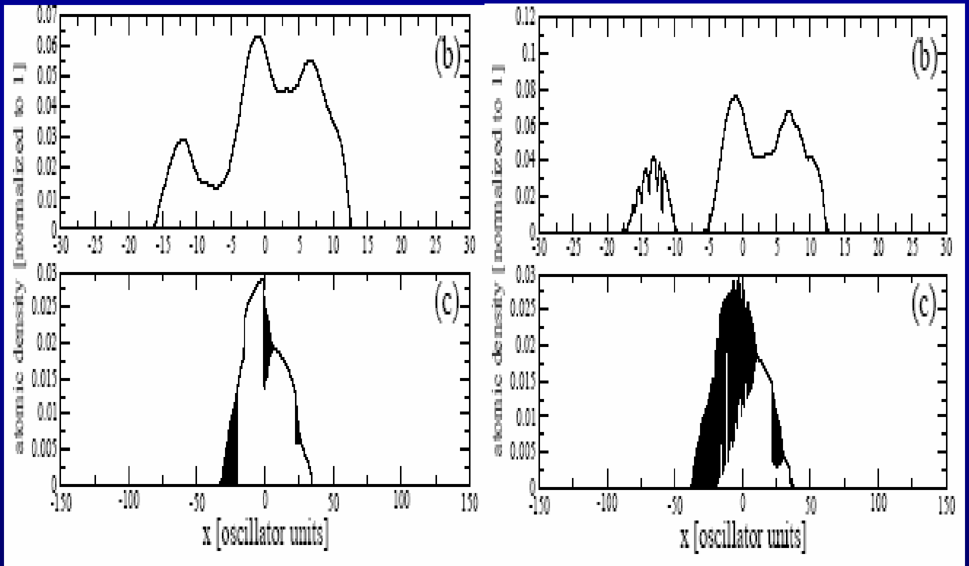
Numerical simulation :

TOF = 20.4 ms

Modulation depth

0.2 E_{rec}

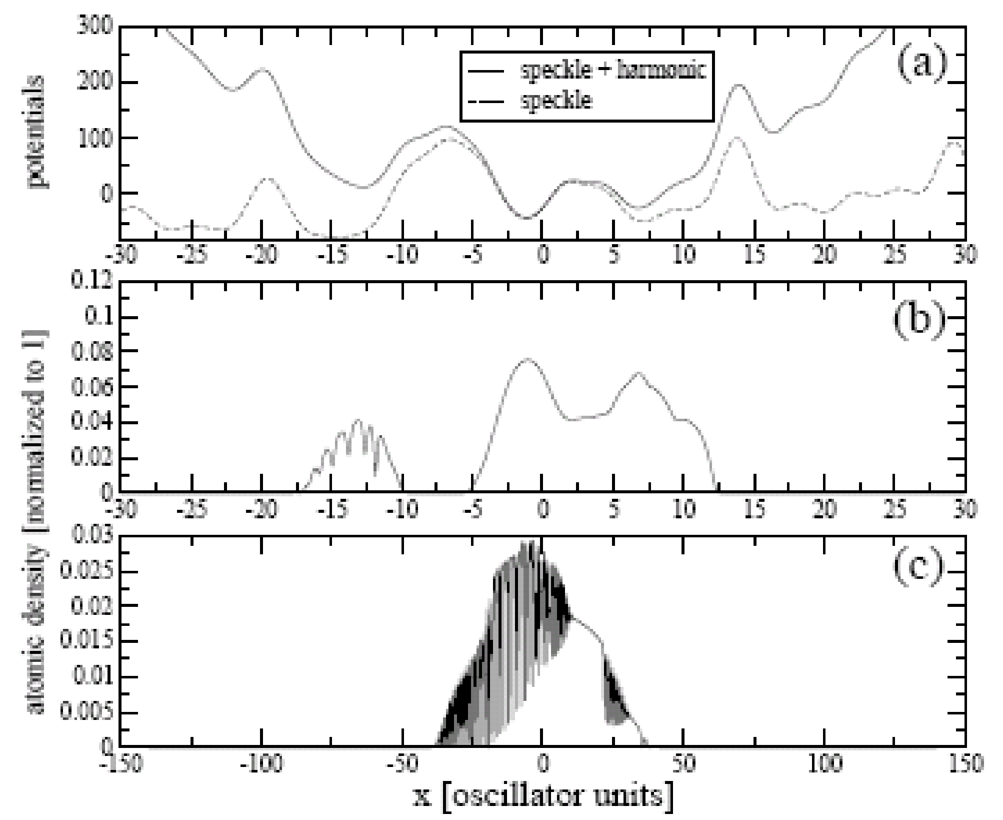
0.4 E_{rec}



Parameters adjusted for proper TF - radius

Disorder : First results

Numerical simulation : 1D GPE

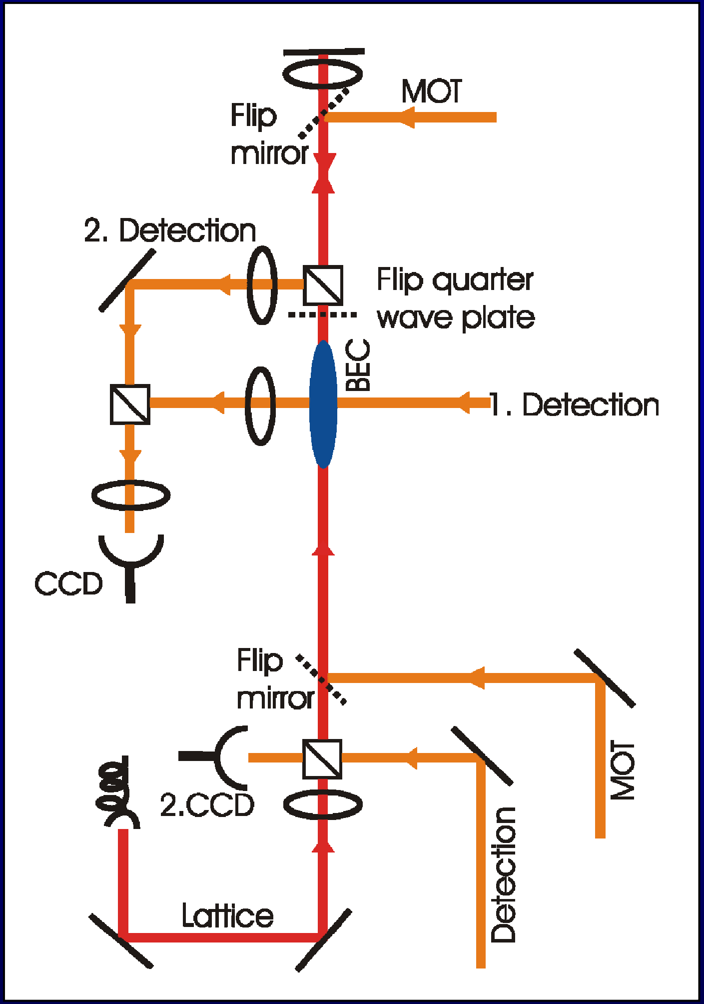


Potential:
magnetic trap + disorder 0.4 Er

atomic density in trap

atomic density after 20.4 ms TOF

Experimental challenge



1D optical lattice:

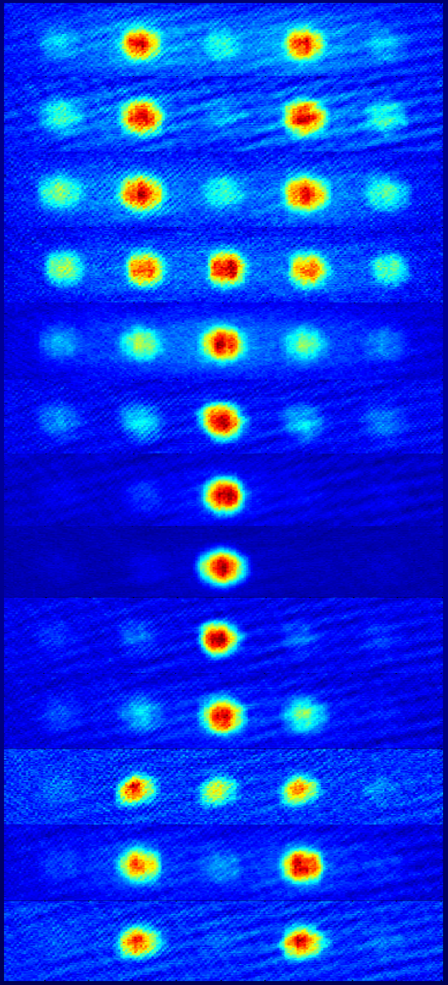
Wavelength λ = 825 nm

Waist ω ~ 140 µm

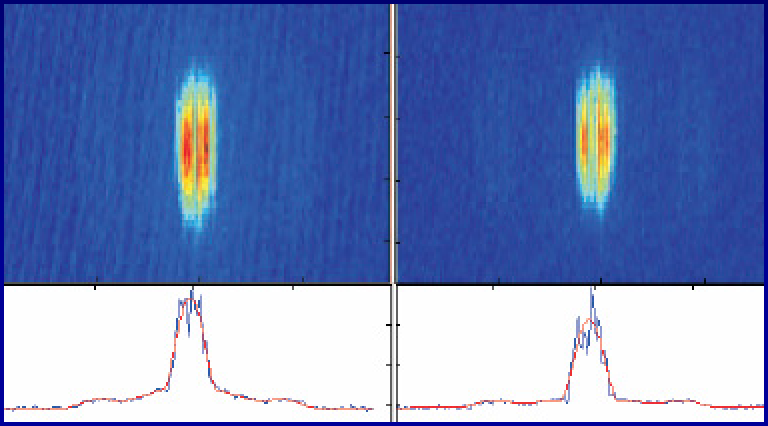
theo. lattice depth : ~ 100 E_{Rec}

Occupied lattice sites <N> ~ 200

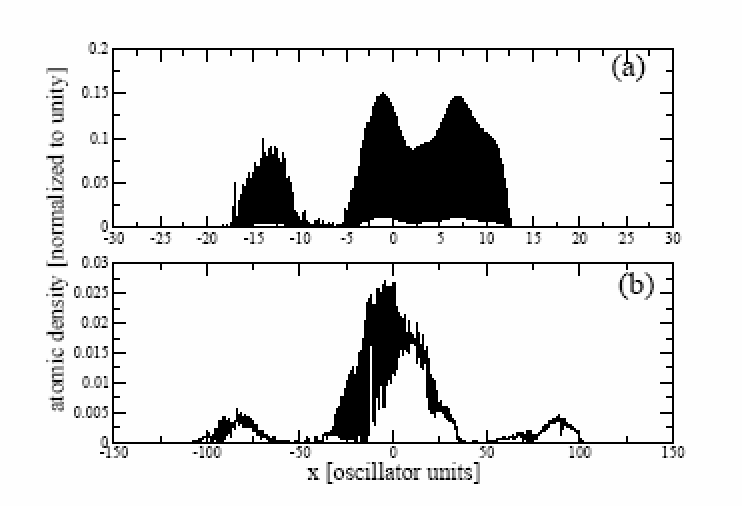
Atoms per site N/200 ~ 50 … 500



Disorder + Lattice : First results



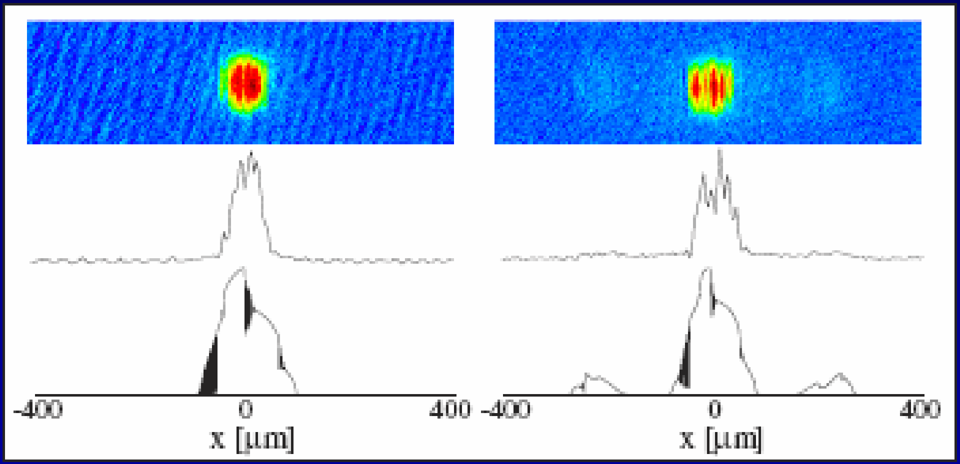
Modulation depth 0.09 E_{rec}



atomic density in
MT + disorder + lattice

atomic density after 20.4 ms TOF

Experimental results



Experimental parameters:

ν_z = 14 Hz; ν_{rad} = 200 Hz

N_{BEC} ~ 1,5 - 8·10^4

Modification of density profile:

- Pronounced fringes
- Axial expansion of ground state

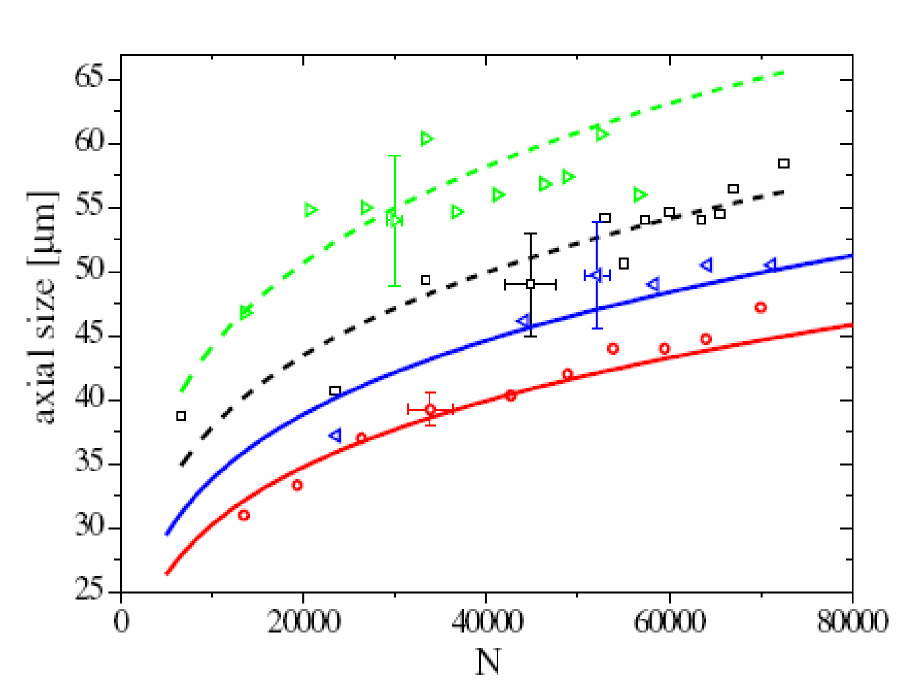
- **no Anderson-localized regime**

🟥 pure MT
🟦 MT + OL
⬛ MT + DP
🟩 MT + DP + OL

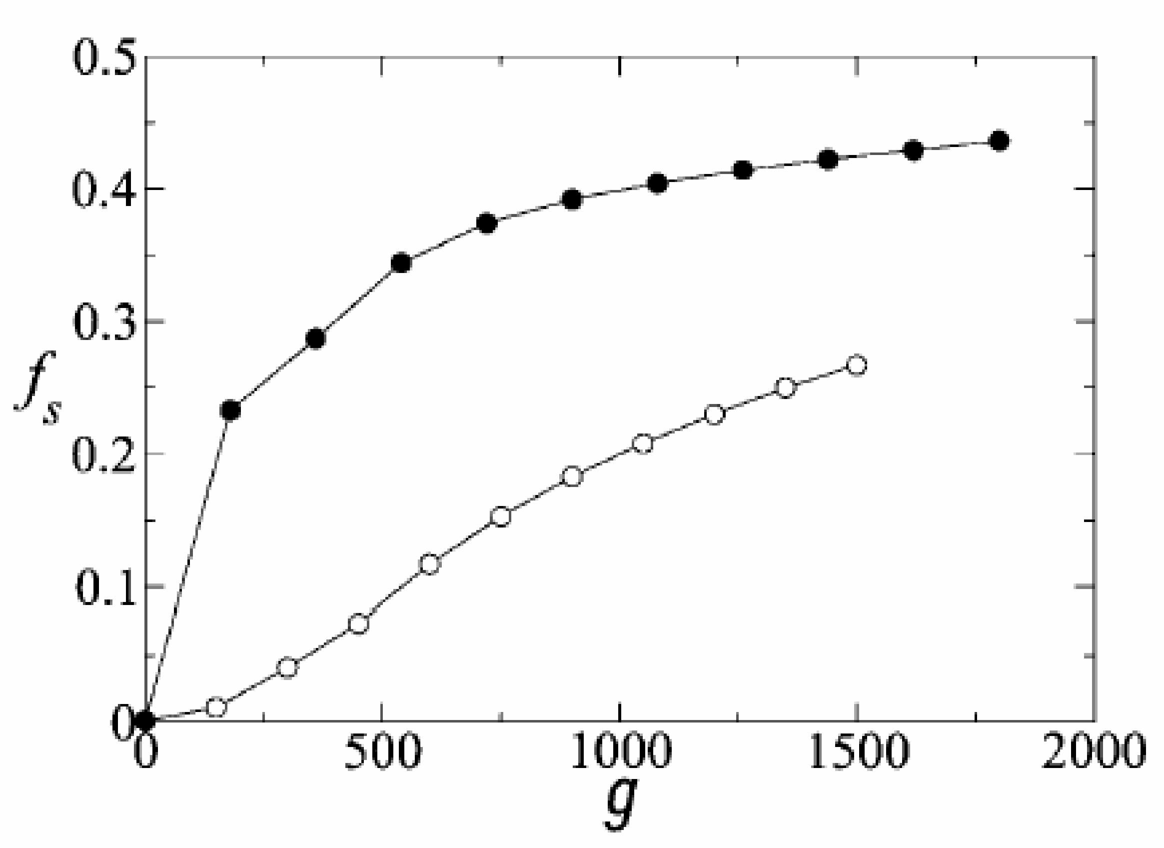
Increase : 25 %

Increase : 28 %

axial width after 20.4 ms TOF :



Experimental difficulties in detecting AL-regime



full: ν_z = 14 Hz

open: ν_z = 4 Hz

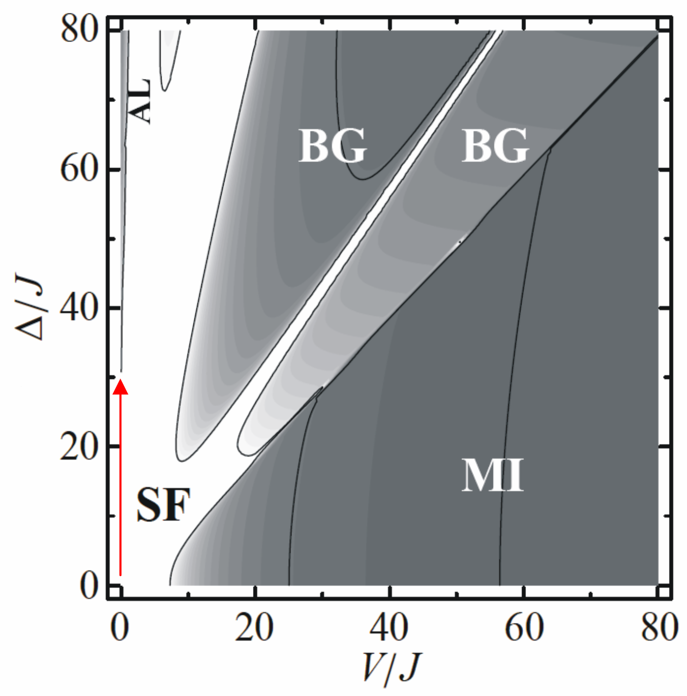
Phase diagram for ultra-cold gases

ANDERSON LOCALISATION

1. Long-range phase coherence
2. High number fluctuations
3. gapless excitation spectrum

BOSE-GLASS PHASE

1. No phase coherence
2. Low number fluctuations
3. continuous excitation spectrum



*(R. Roth and K. Burnett, PRA **68**, 023604 (2003))*

SUPERFLUID PHASE

1. Long-range phase coherence
2. High number fluctuations
3. continuous excitation spectrum

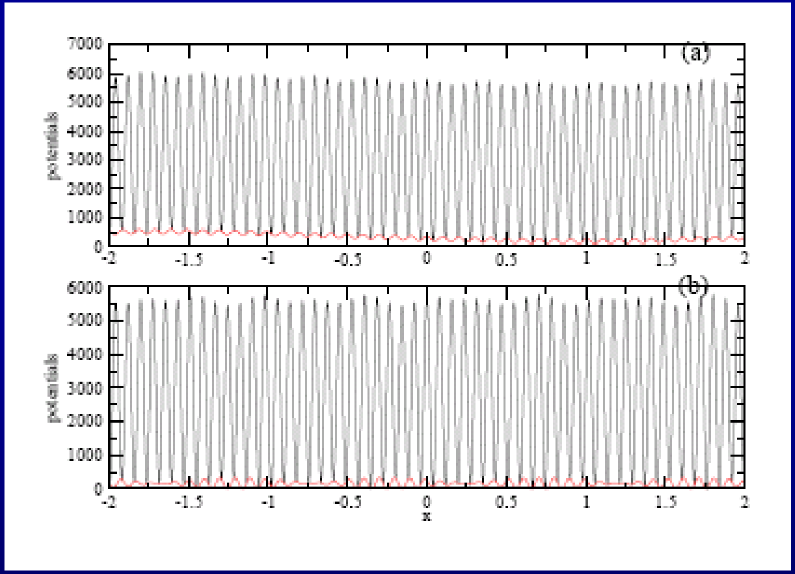
MOTT INSULATOR PHASE

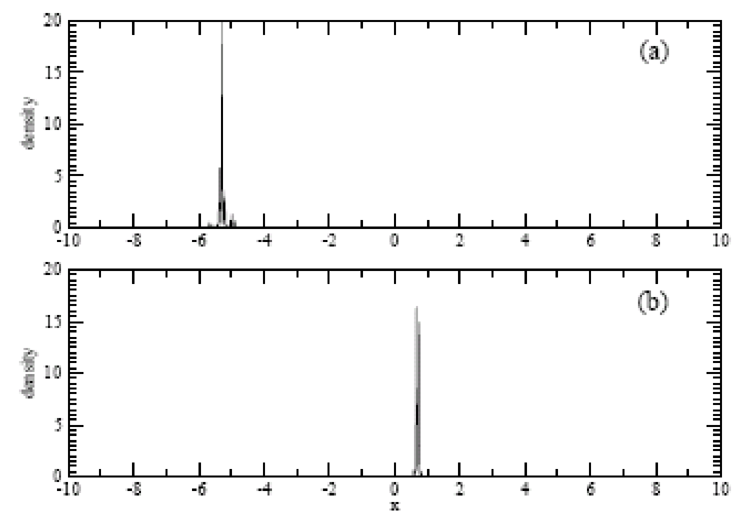
1. No phase coherence
2. Zero number fluctuations
3. discrete excitation spectrum

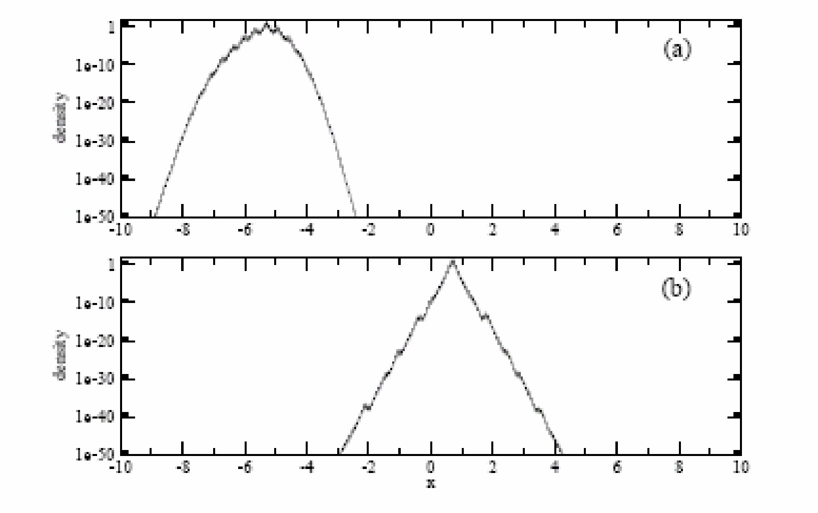
Disorder without Interactions

Simulation using **small scale disorder without interactions** to find localization regime.

g=0



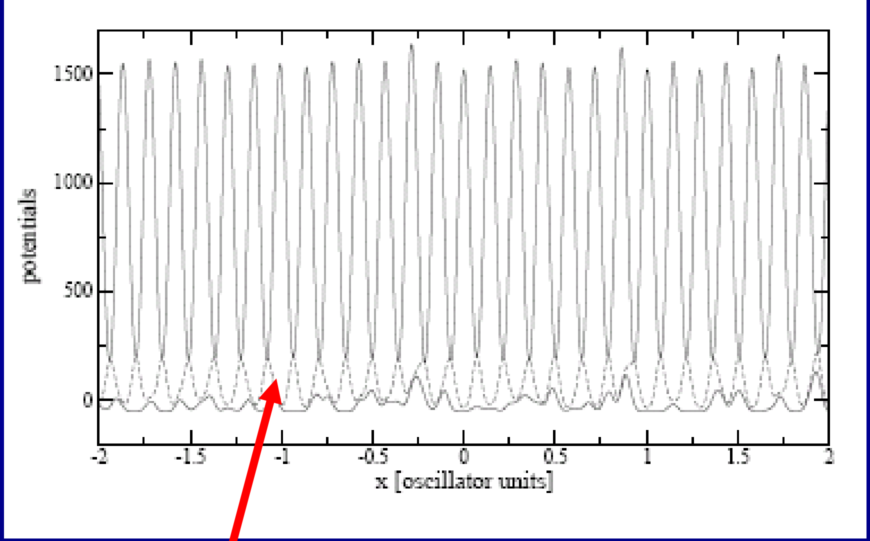




a) Speckle pattern.
b) Pseudorandom potential 1060nm + 960nm

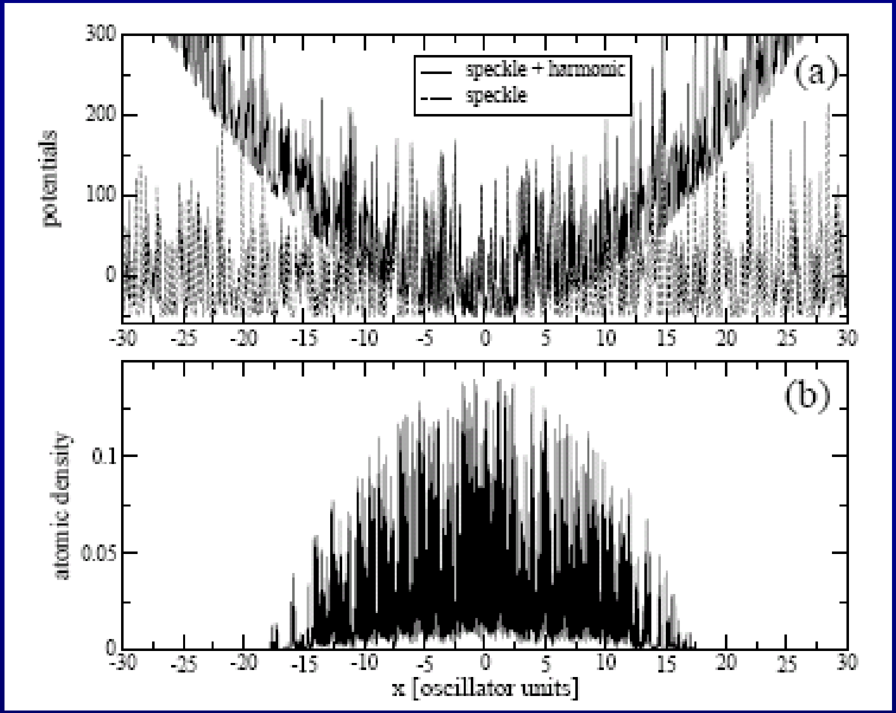
Disorder and Interactions

Simulation using small scale disorder to find localization regime



$V_{speckle}(x) + g|\phi_0|^2$

Smoothing of the potential due to interactions!



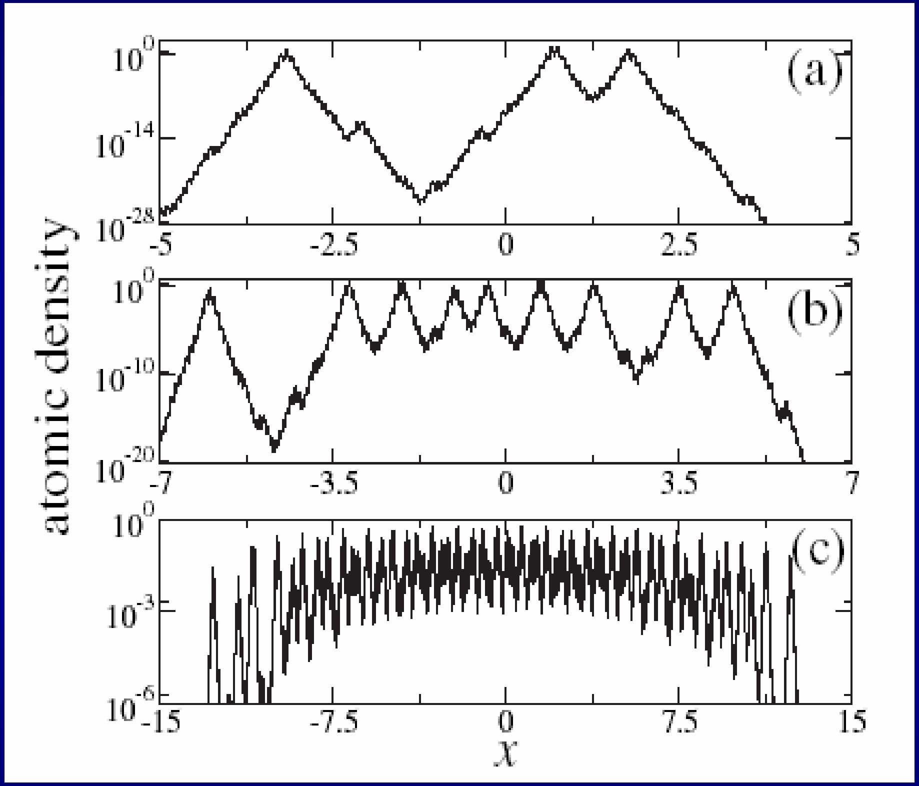
Is there localization?

Theoretical analysis of interaction-dependence

g=8

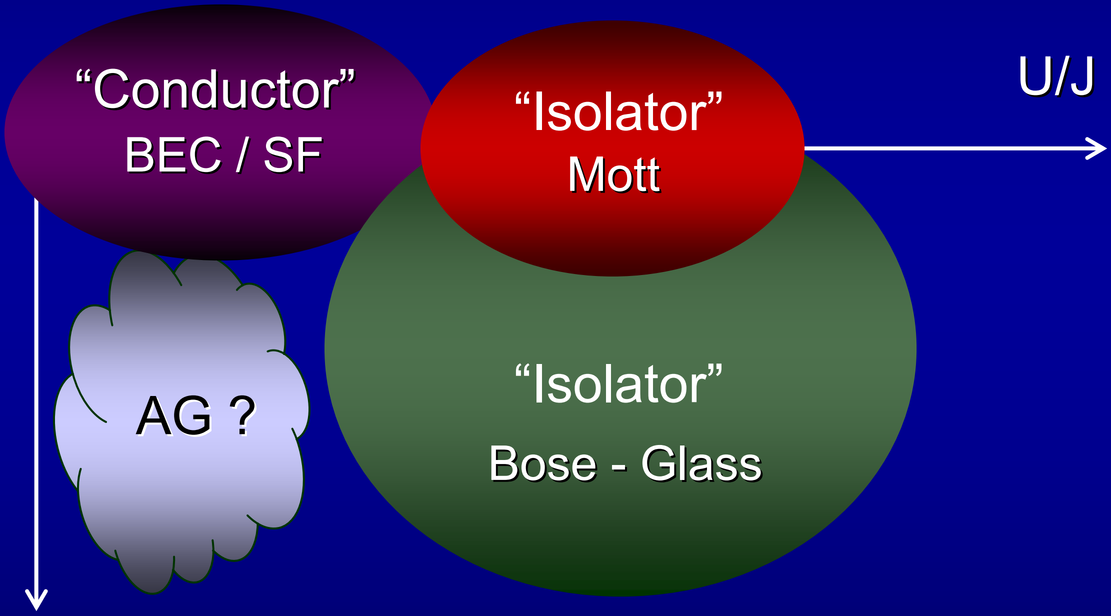
g=128

g=256



Are there experimentally reasonable parameters to observe the AL-regime?

Disorder and Interactions



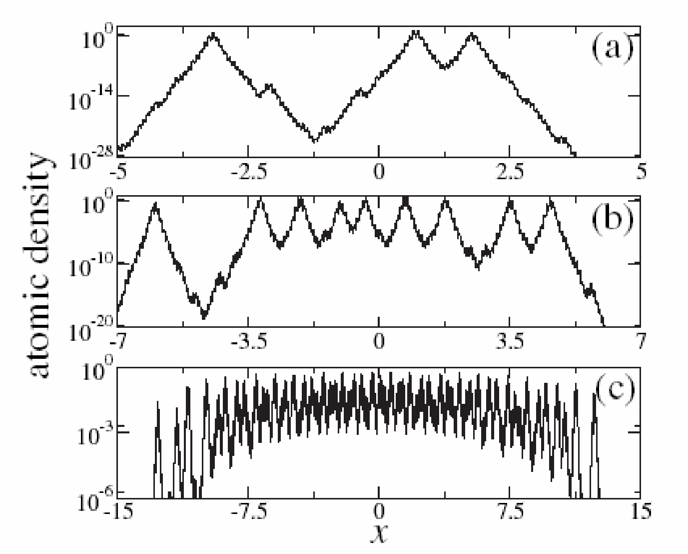
Can there be an Anderson Localization regime ?

Theoretical analysis of interaction-dependence

g=8

g=128

g=256

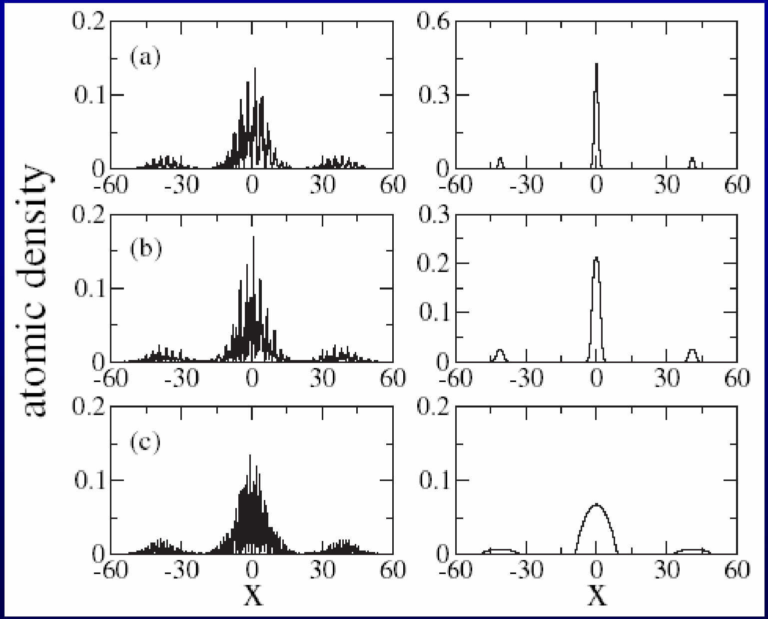


Are there experimentally reasonable parameters to observe the AL-regime?

$\nu_z = 4$ Hz; $\nu_{rad} = 40$ Hz
g = 256

<u>Free (but limited) parameters</u>:

- Lowering interaction-strength *g* by Feshbach-resonance
- Variation of trap frequencies



g=8

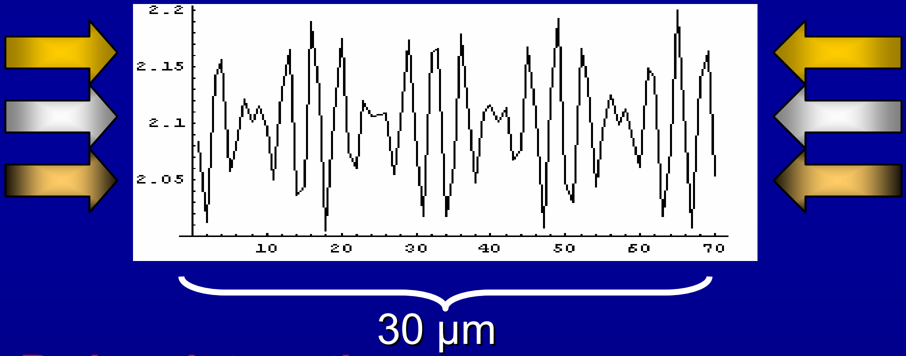
g=128

g=256

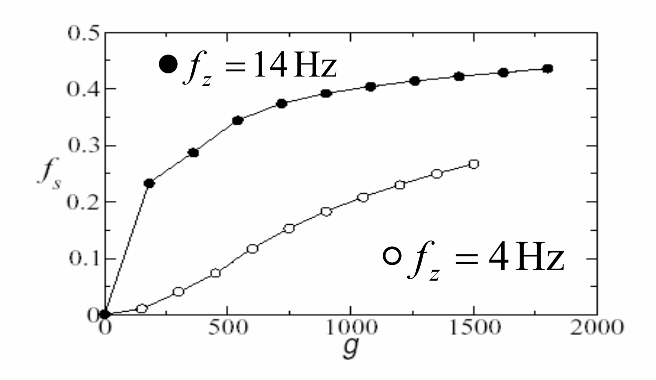
Towards Anderson localization :

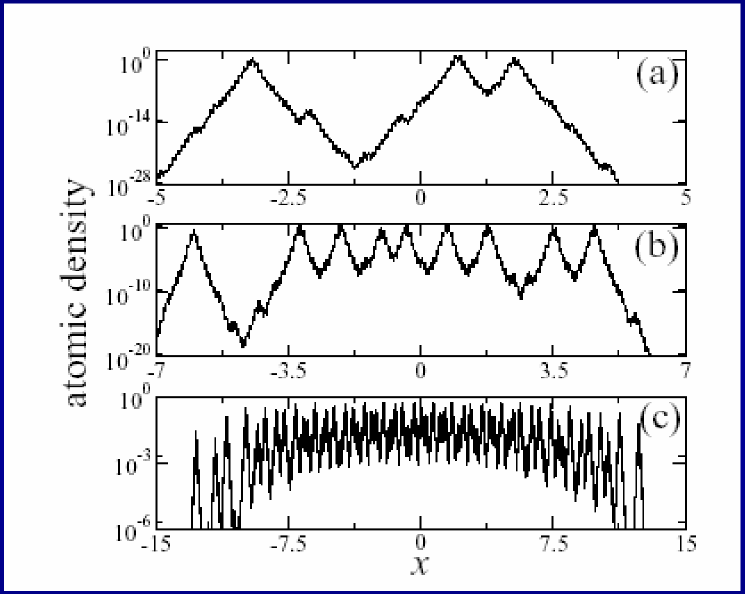
- **Realization of fine scaled disorder**

→ 2 incommensurate
super lattices
e.g. @ 1040 nm + 980 nm



- **Reduce interactions**





a) g = 0.5

b) g = 8

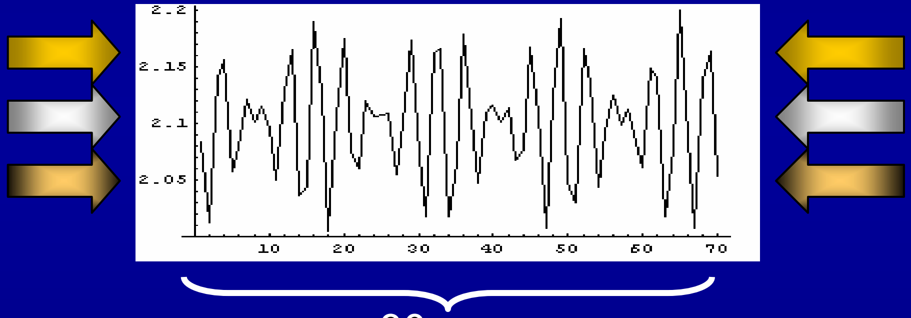
c) g = 256

Disordered Lattice Gas: Localization

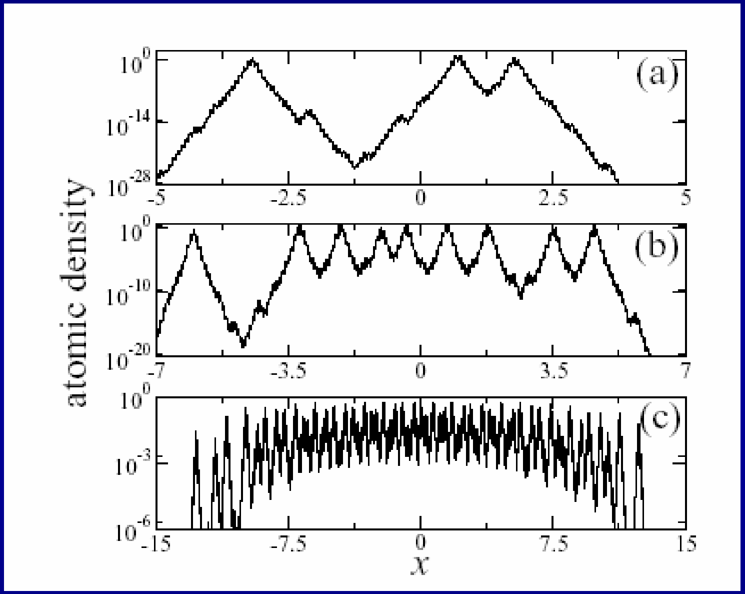
Towards Anderson localization :

- **Realization of fine scaled disorder**

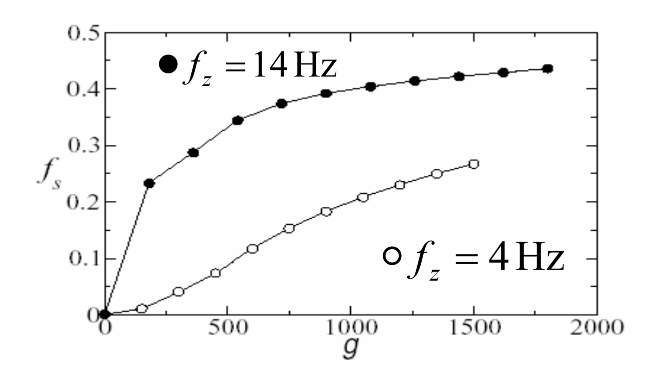
→ 2 incommensurate
super lattices
e.g. @ 1040 nm + 980 nm



30 µm



- **Reduce interactions**



a) g = 0.5

b) g = 8

c) g = 256

→ Corresponding 3D trap :

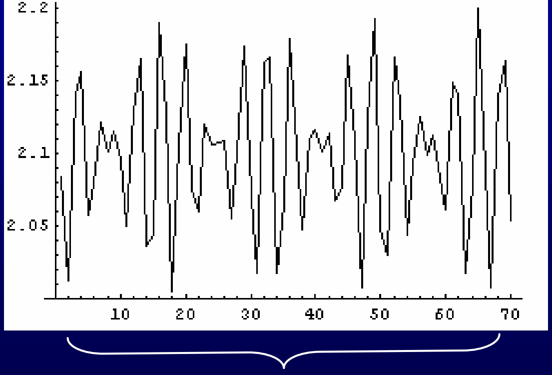
$$f_\rho = 40\,\mathrm{Hz}\ ,\ f_z = 4\,\mathrm{Hz}\ ,\ \mathrm{N} = 10.000$$

Outlook

Anderson Localization :

- decrease mean density
- work at small U/J
- use appropriate disorder potential

⟶ 2 incommensurate
super lattices
e.g. @ 1040 nm + 980 nm



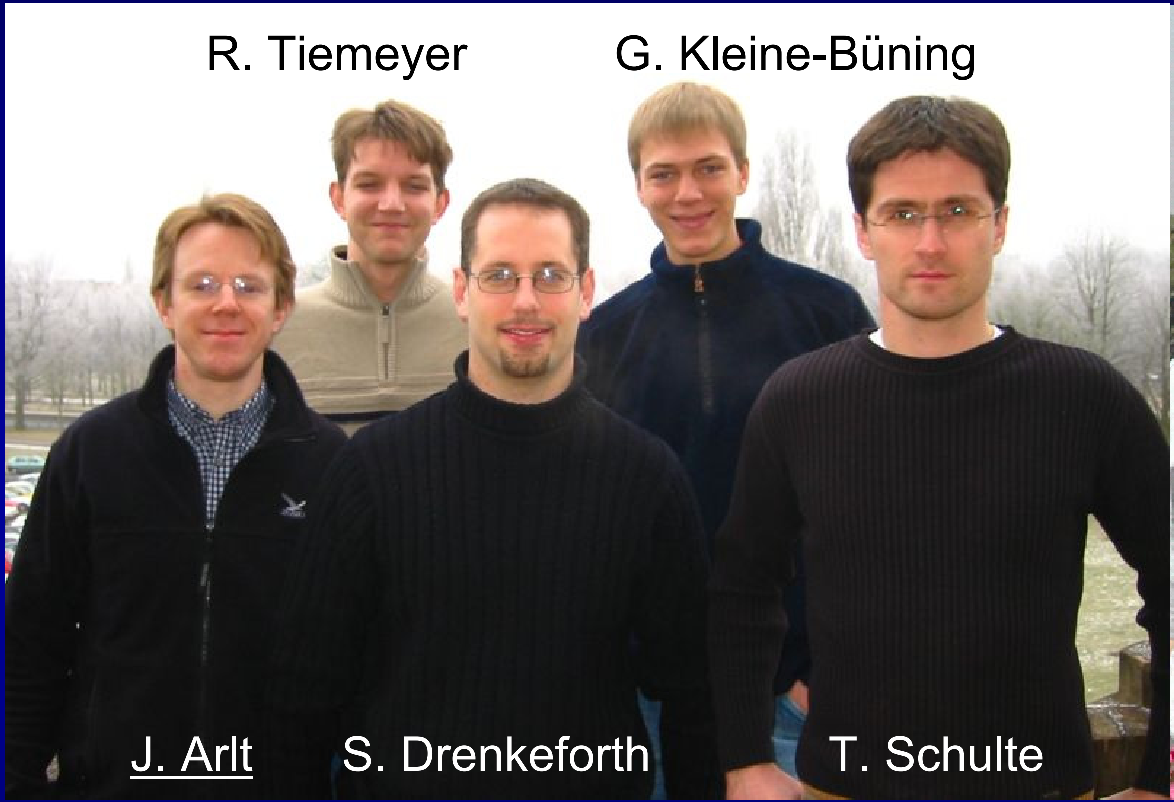
30 µm

…towards Bose Glass :

- high mean density
- work at large U/J
- find appropriate disorder potential

⟶ 2 incommensurate
super lattices
e.g. @ 1040 nm + 980 nm

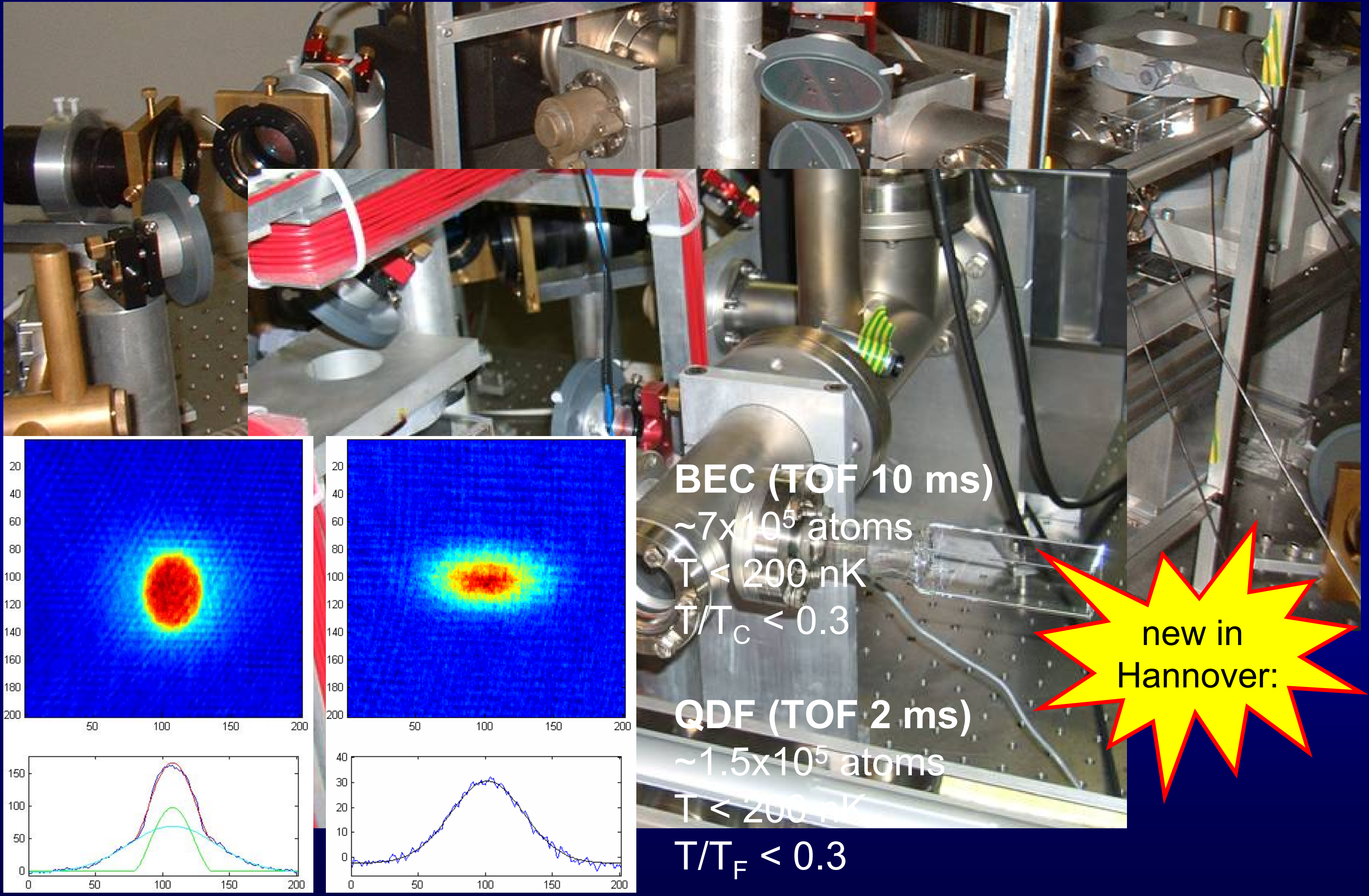
Rb BEC team in Hannover



in close collaboration with: K. Sacha, J. Zakrzewski und M. Lewenstein, L. Santos

former members: D. Hellweg, L. Cacciapuoti

A quantum degenerate Boson (^{87}Rb) and Fermion (^{40}K) - mixture



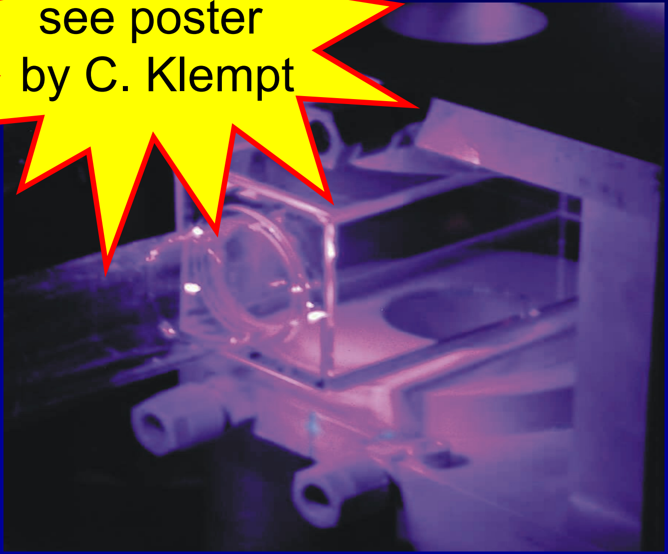
new in Hannover:

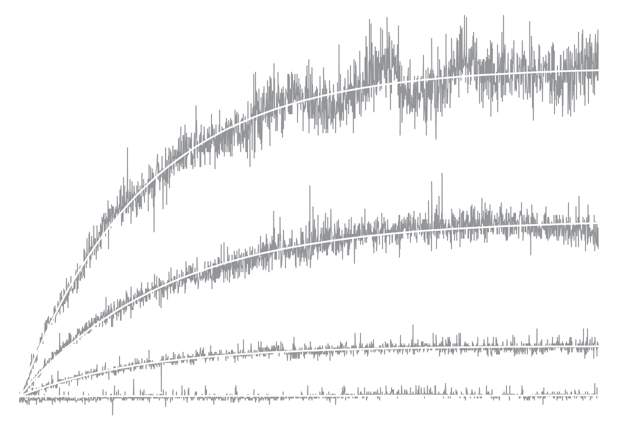
BEC (TOF 10 ms)
~7x10^5 atoms
T < 200 nK
$T/T_C < 0.3$

QDF (TOF 2 ms)
~1.5x10^5 atoms
T < 200 nK
$T/T_F < 0.3$

UV light-induced atom desorption (LIAD) for large rubidium and potassium MOTs

see poster
by C. Klempt





Number of atoms in a Rb MOT for various LIAD wavelengths

LIAD intensity dependence

C. Klempt, T. van Zoest, T. Henninger, O. Topic, E. Rasel,
W. Ertmer, and J. Arlt, Phys. Rev. A 73, 013410 (2006)