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Miniworkshop on Strong Correlations in Materials and Atom Traps

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Experiments with cold quantum gases in low dimensions.

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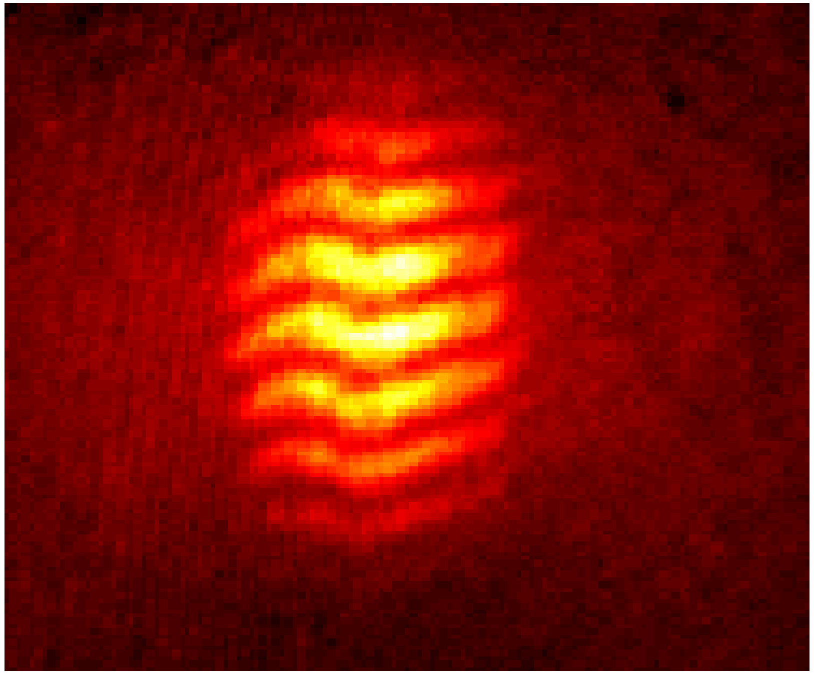
Experiments with cold quantum gases in low dimensions



Peter Krüger

Quantum degenerate cold gases

The achievement of BEC (1995) and DFG (1999) led to studies of

- matter wave coherence → interference of two (independent) BECs, MIT 1997
- Long range phase coherence and superfludity → quantized vortices in Bose (ENS, JILA 2000) and Fermi (MIT 2005) gases
- Basic excitations (Bogoliubov spectrum) of quasi pure Bose-Einstein condensates (Weizmann)
- …

Weakly interacting systems are good model systems for pure quantum gases and single particle description (with mean field) is a good description

Strong correlations

- tuning of interaction strength near Feshbach resonances
- introducing (strong) periodic potentials
- **reducing the dimensionality of the system**

↓

Description based on non-interacting quasi-particles no longer applicable

↓

Strongly correlated systems in dilute gases with much larger control and tuning than in dense quantum liquids

Dimensionality of many body systems

Fluctuations, disorder, interactions play a larger role in reduced dimensions

- quantum transport in 1d
- Tonks-Girardeau gas
- Kosterlitz-Thouless physics (2d)
- …

Dimensionality critically affects order

3d: spontaneous symmetry breaking can lead to the emergence of true long range order

Low d: altered density of states leads to the destruction of long range order, even in the presence of interactions (Mermin-Wagner-Hohenberg)

Order and dimensionality

3d	2d	1d
	True long range order only at T=0	Quasi long range order only at T=0
True long range order below finite T_C	Quasi long range order (algebraic decay of correlations) below $T_{C,2d}$	Exponential decay of correlations at any finite T
Exponential decay of correlations above T_C	Exponential decay of correlations above $T_{C,2d}$	

Outline

- 1d Bose gases
  - Expansion
  - (quasi) condensed vs normal fraction
  - Phase fluctuations

- 2d Bose gases
  - Phase transition? – Bose-Einstein condensation vs Berizinskii-Kosterlitz-Thouless physics
  - Critical atom number measurements
  - Phase dislocations, vortices, and the microscopic basis of the BKT theory

1d Bose gases

1d condition

Transverse confinement strong enough, so that

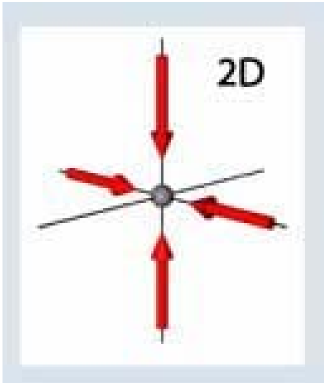
$$\mu, T < \hbar\omega_\perp \quad \Longleftrightarrow \quad n_{1d} a_s < 1$$

$n_{1d} < 100\,\mu m^{-1}$ for ^{87}Rb

Experimental approach

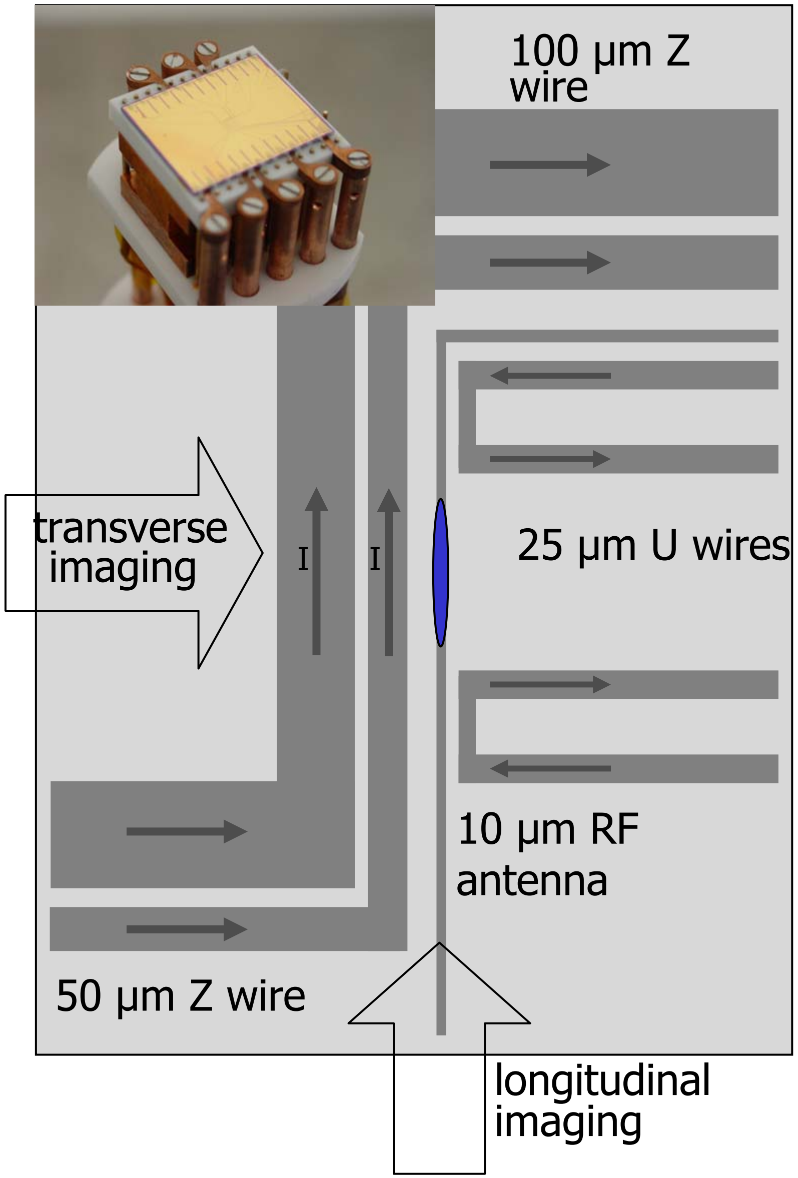
Elongated (macroscopic) magnetic traps: MIT, Hanover, Orsay, …

Optical lattices (2d +): Mainz, Penn State, …

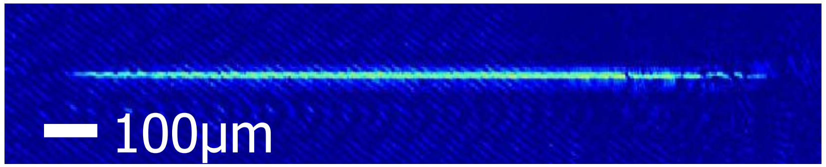


Microtraps, single realisation: Heidelberg, Orsay, Amsterdam, …

One dimensional gases on atom chips



At ~50 microns from the wire very elongated (aspect ratios > 1000) smooth BECs can be formed

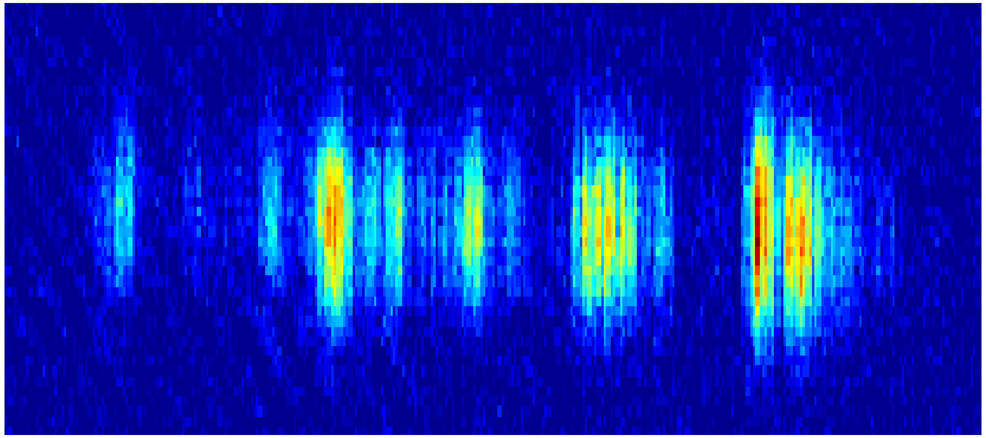


1d: $\mu \ll \hbar\omega$

Momentum distribution: TOF

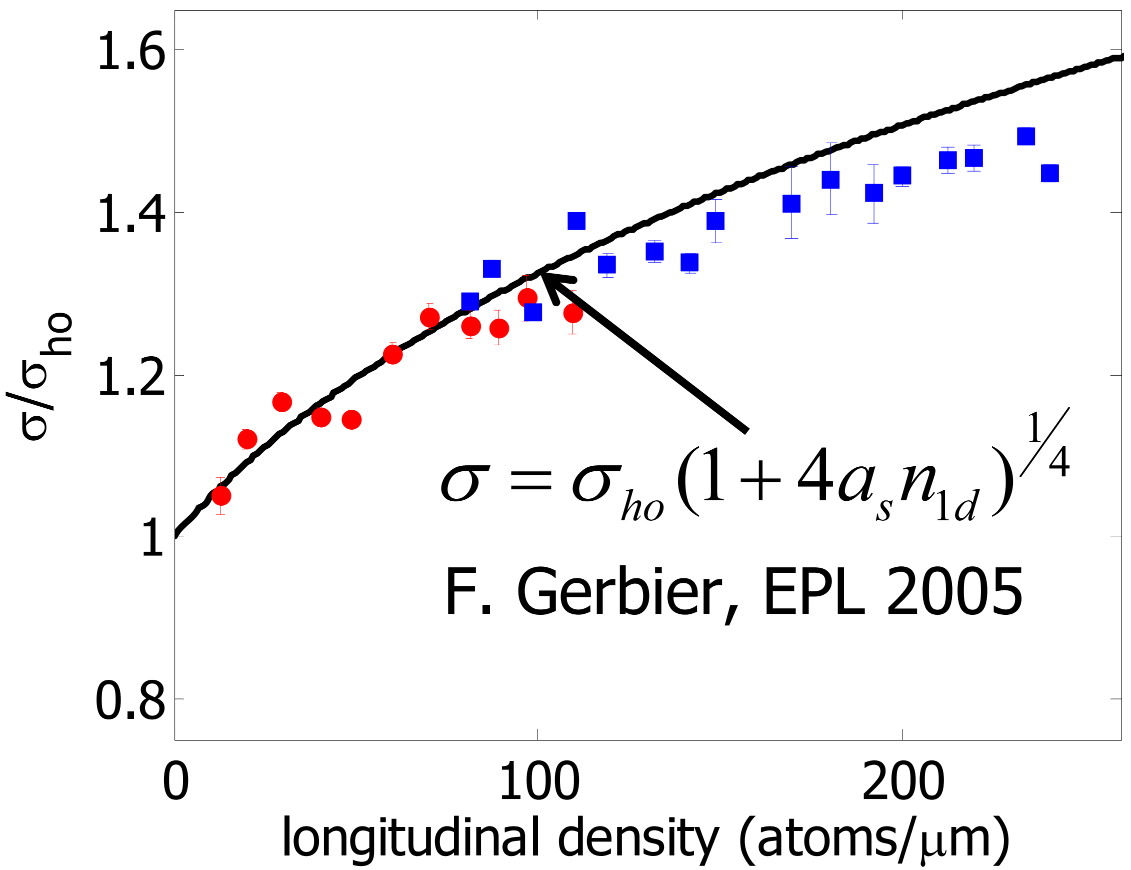
$\mu \ll \hbar\omega$ ➡ Momentum distribution of the ground state ?

Experiment: Measure density dependence of transverse cloud width after TOF expansion



Fragmented cloud gives (almost) single shot measurement of large density span

1d time of flight: widths

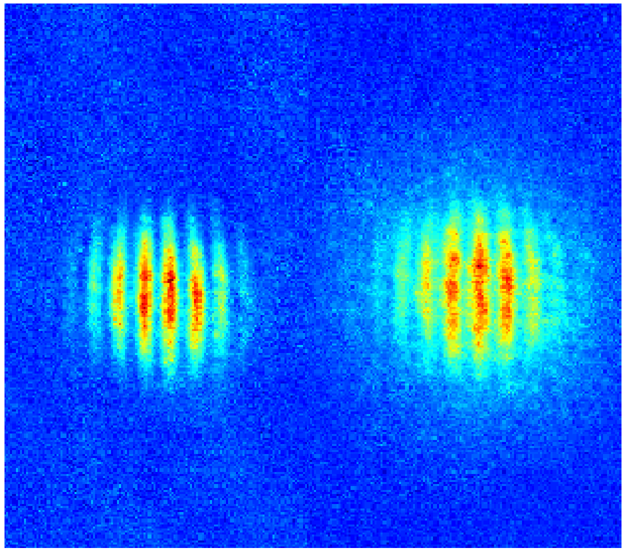


Even in purely 1d, there is a mean field correction

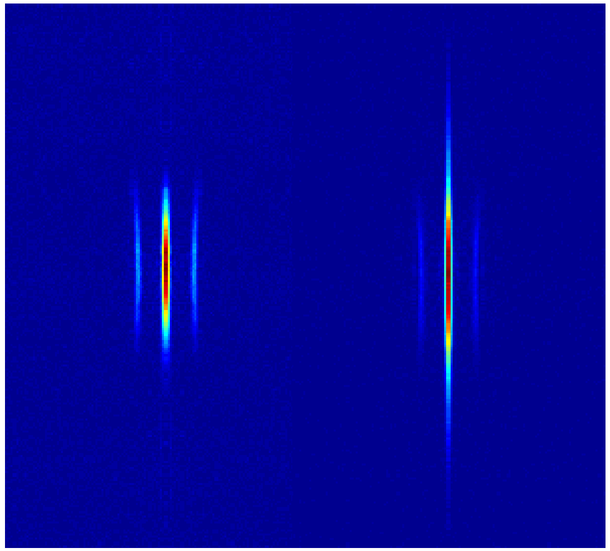
Finite T: bimodal 1d clouds

If the expansion for both a quasi-BEC and a thermal cloud is gaussian, how can they be distinguished ($kT \sim \hbar\omega$) ?

Discern the interferable fraction !

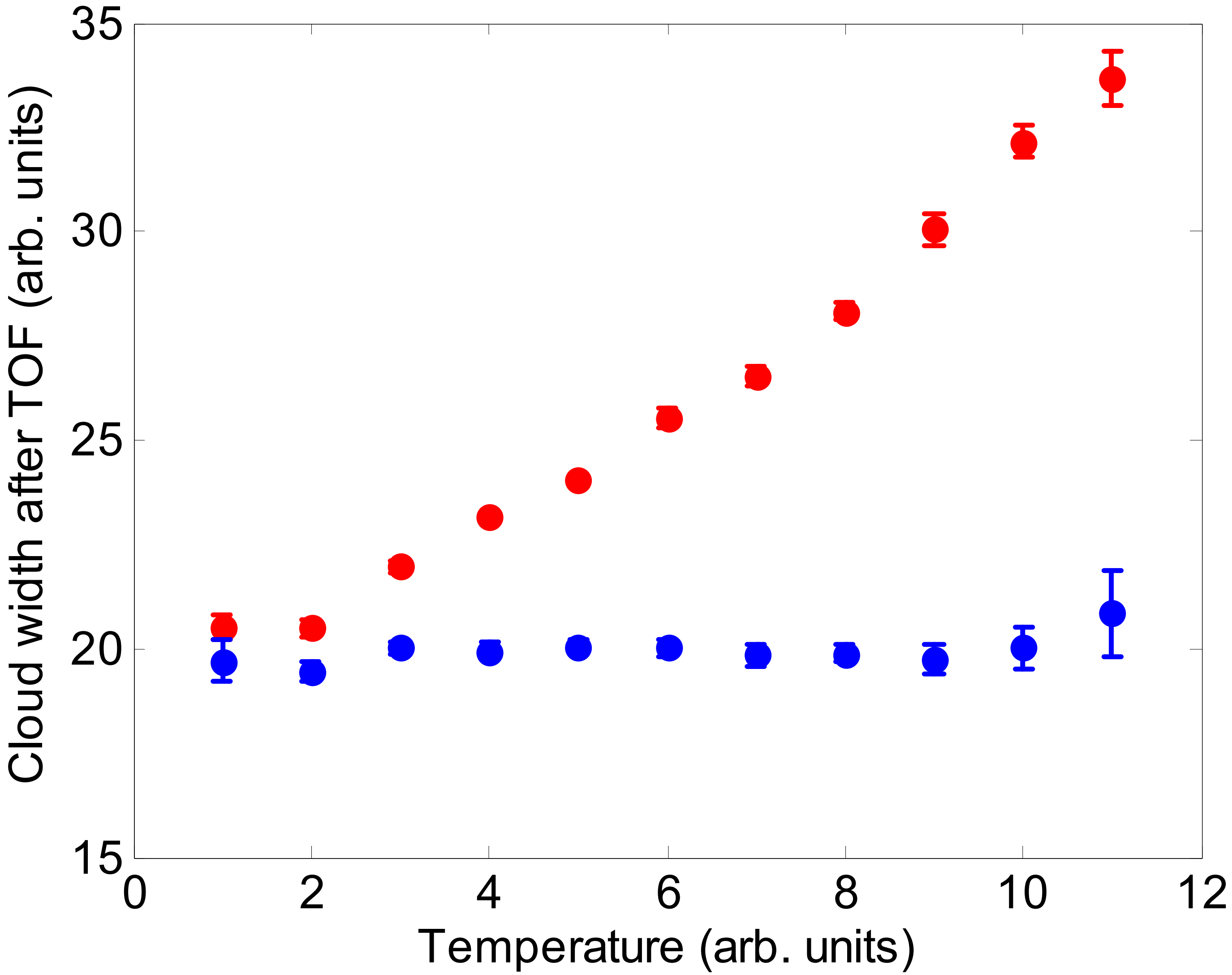


cold **hot**

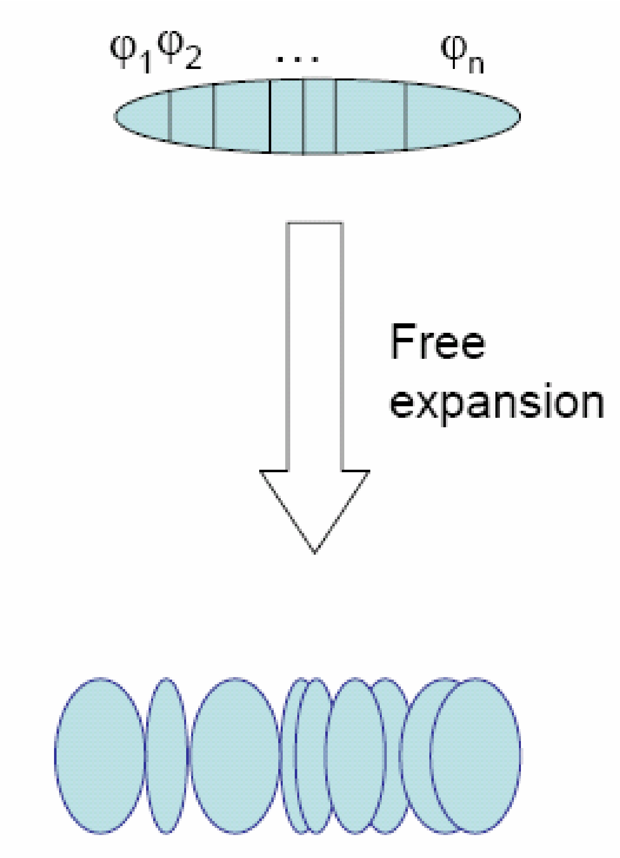


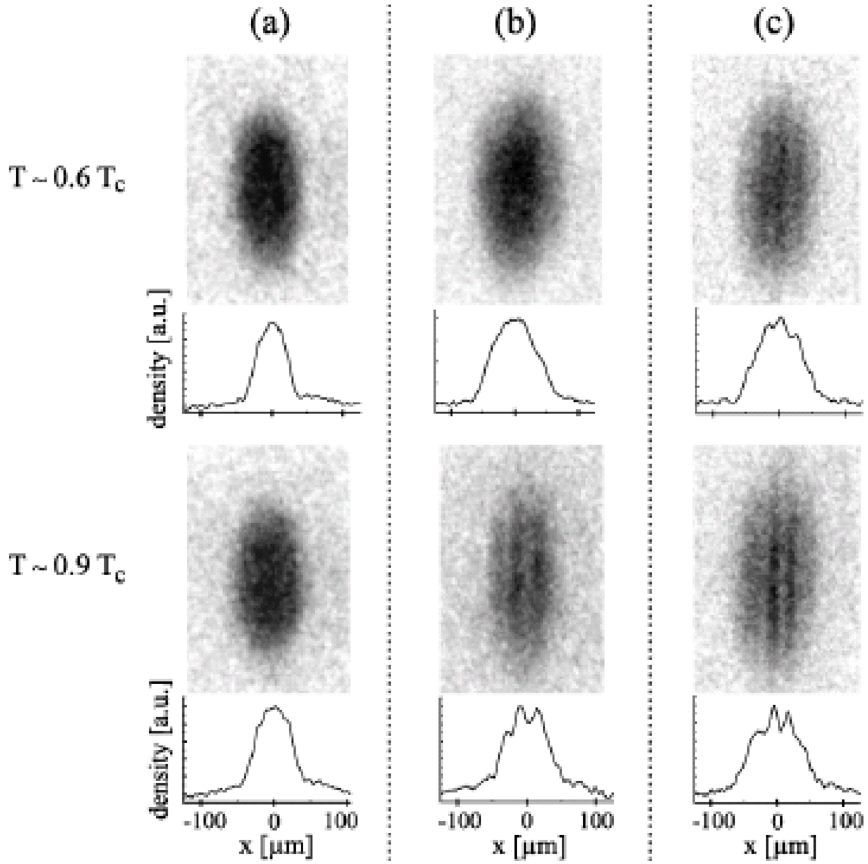
Fourier transform

1d gases at finite temperature



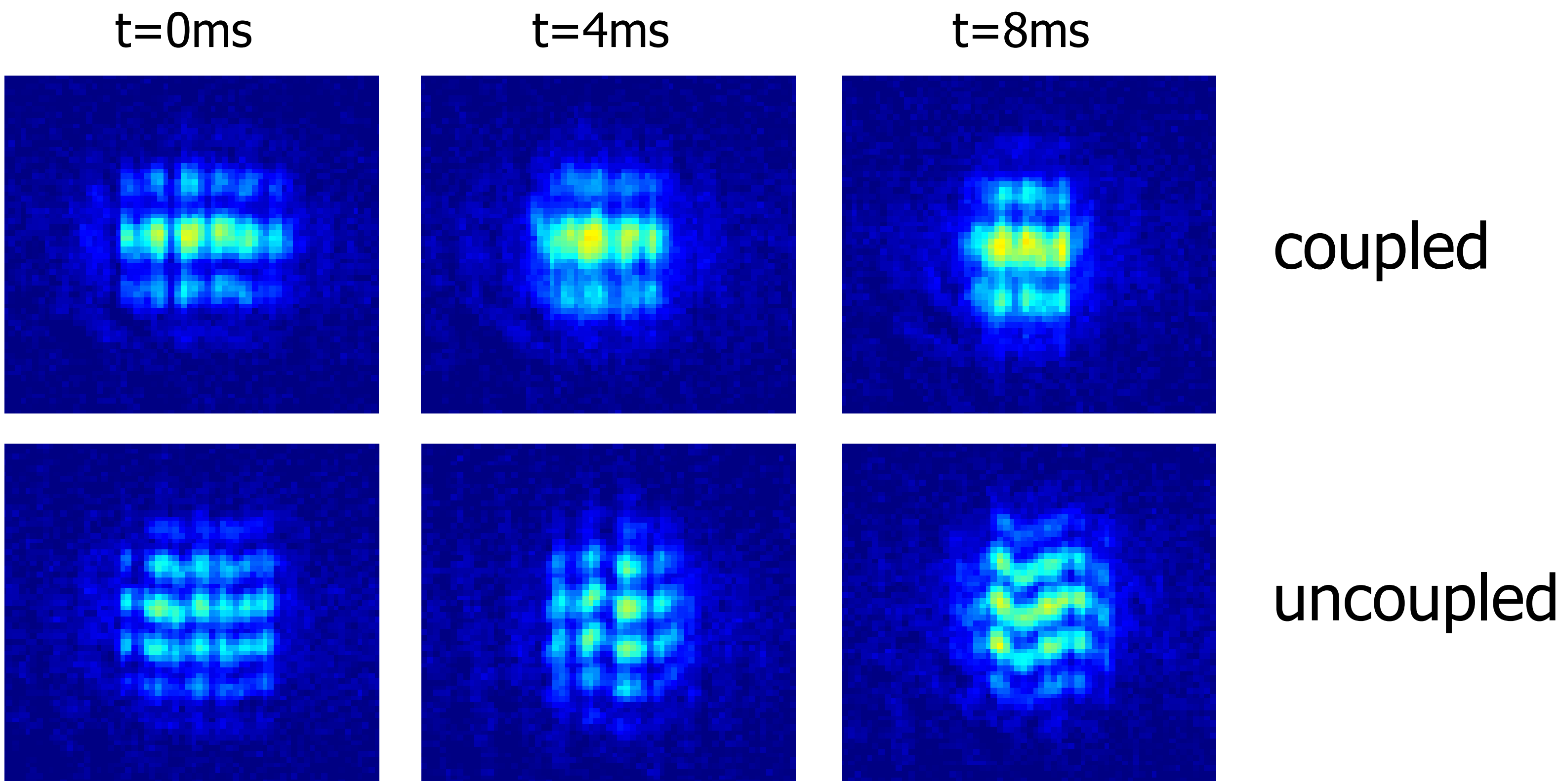
Phase fluctuations





Dettmer et al., PRL 2001
Richard et al., PRL 2003

Time evolution



Schumm et al., Nature Physics 2005
Hofferberth et al., Nature 2008

2d Bose gases

BEC in 2d ? – The ideal Bose gas

Homogeneous system:

3D: BEC occurs when the phase space density reaches $n\lambda^3 = 2.6$

2D: no BEC for any phase space density $n\lambda^2$

In a harmonic trap:

3D: BEC occurs when $N = 1.2\left(\frac{k_B T}{\hbar\omega}\right)^3$

2D: BEC occurs when $N = 1.6\left(\frac{k_B T}{\hbar\omega}\right)^2$ Bagnato, Kleppner 1991

Does the trapping potential obscure the dimensionality difference?

Interactions

Treat the interactions at the mean field level:

$$V_{\text{eff}}(r) = \frac{m\omega^2 r^2}{2} + 2gn_{\text{mf}}(r)$$

where the mean field density is obtained from the self-consistent equation

$$n_{\text{mf}}(r) = \int \rho_{\text{mf}}(r,p)\frac{d^2p}{h^2} \qquad \rho_{\text{mf}}(r,p) = \left[e^{\beta(\frac{p^2}{2m}+V_{\text{eff}}(r))} - 1\right]^{-1}$$

Two remarkable results

- One can accommodate an arbitrarily large atom number.

Badhuri et al

- The effective frequency deduced from $V_{\text{eff}}(r) \simeq m\omega_{\text{eff}}^2 r^2/2$ tends to zero when $\mu \to 2gn_{\text{mf}}(0)$

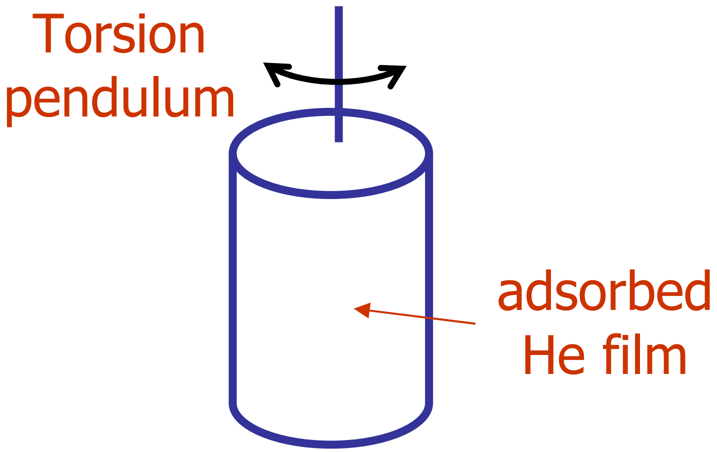
Holzmann et al

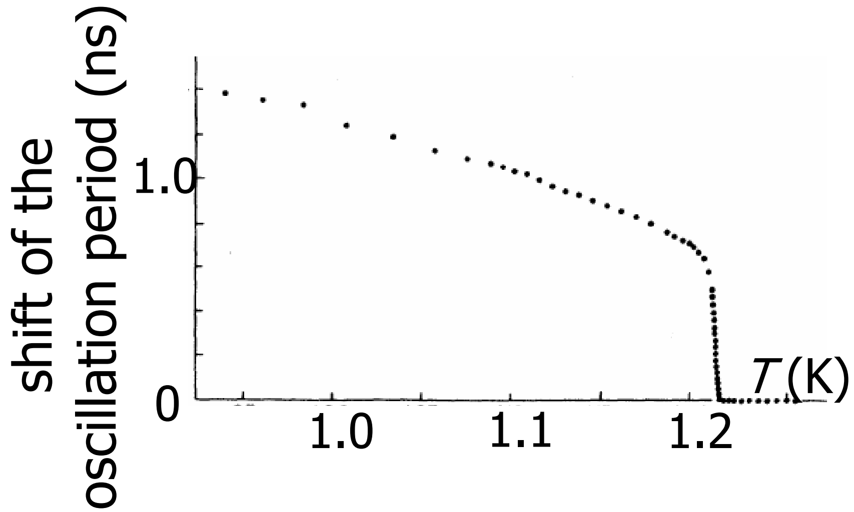
Similar to a 2D gas in a flat potential…

Does this mean there's no 2d BEC, even in the trap?

Superfluidity in 2d

A 2D film of helium becomes superfluid at sufficiently low temperature (Bishop and Reppy, 1978)





"universal" jump to zero of superfluid density at $T = T_c$

BKT theory

topological phase transition associated with the binding/unbinding of vortex pairs

0 — *superfluid* — T_c — *normal* — T

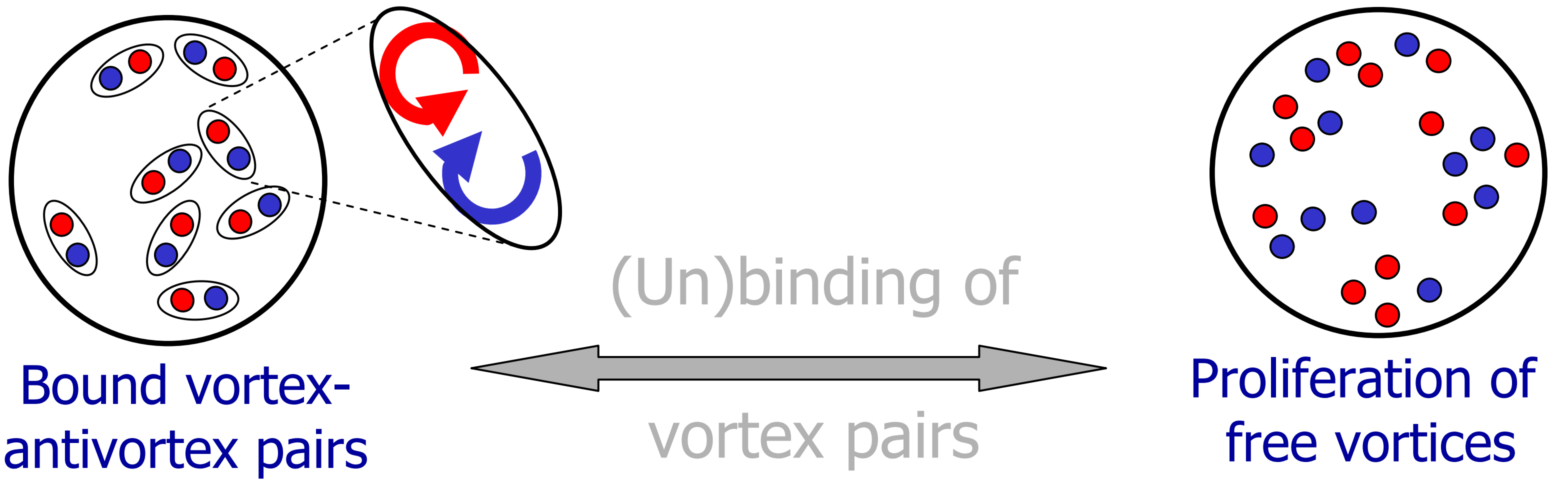
algebraic decay of g_1 — *exponential decay of g_1*

$$n_{\text{superfluid}}\lambda^2 = 4$$

$$g_1(r) \propto \frac{1}{r^\alpha}$$

$$\alpha = \frac{1}{n_s\lambda^2}$$

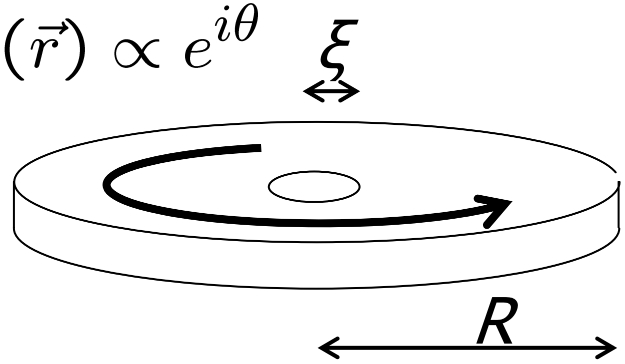
$$g_1(|\vec{r} - \vec{r}\,'|) = \langle \psi^*(\vec{r})\psi(\vec{r}\,') \rangle$$



Simplified picture

Probability of thermal excitation of a free vortex

$\psi(\vec{r}) \propto e^{i\theta}$



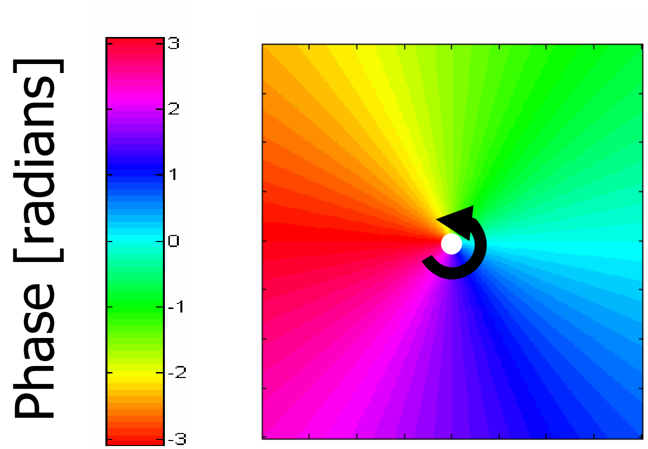
$$v = \frac{\hbar}{mr} \qquad n_s = \frac{N}{\pi R^2}$$

Energy: $E = \int n_s \frac{mv^2}{2} 2\pi r \, dr \sim \frac{\pi\hbar^2}{m} n_s \log(R/\xi)$

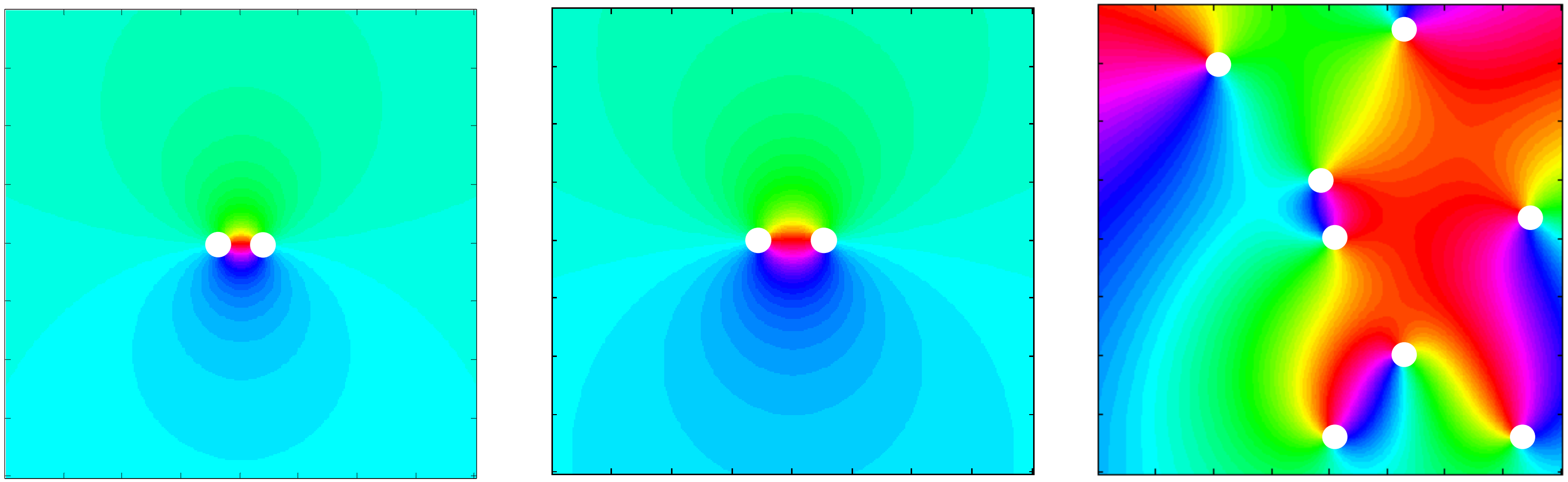
Entropy: $S = k \log(W) \sim k \ln(R^2/\xi^2) = 2k \log(R/\xi)$

Free energy: $\frac{E - TS}{kT} \sim \frac{1}{2}\left(n_s \lambda^2 - 4\right) \ln(R/\xi)$

Vortices and long range order

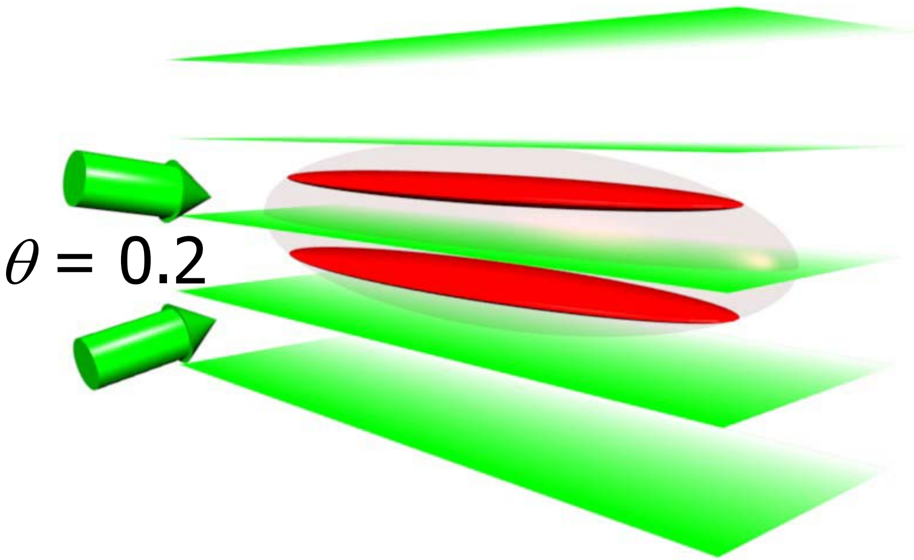


Phase winding around a vortex



Increasing temperature →

The Paris experiment



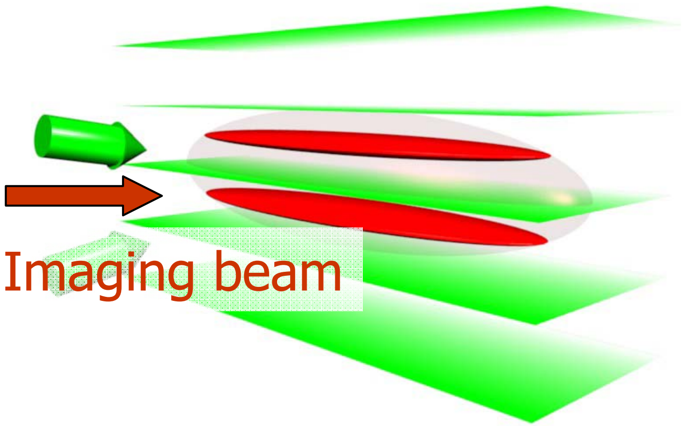
- A regular 3d BEC is split into two by super-imposing a blue detuned 1d optical lattice
- Ramping up the lattice compresses the cloud into 2d

- 10^5 atoms/plane
- plane thickness: 0.1mm
- plane separation: 3 μm (lattice period @ small angle)
- barriers broad and high → no tunneling

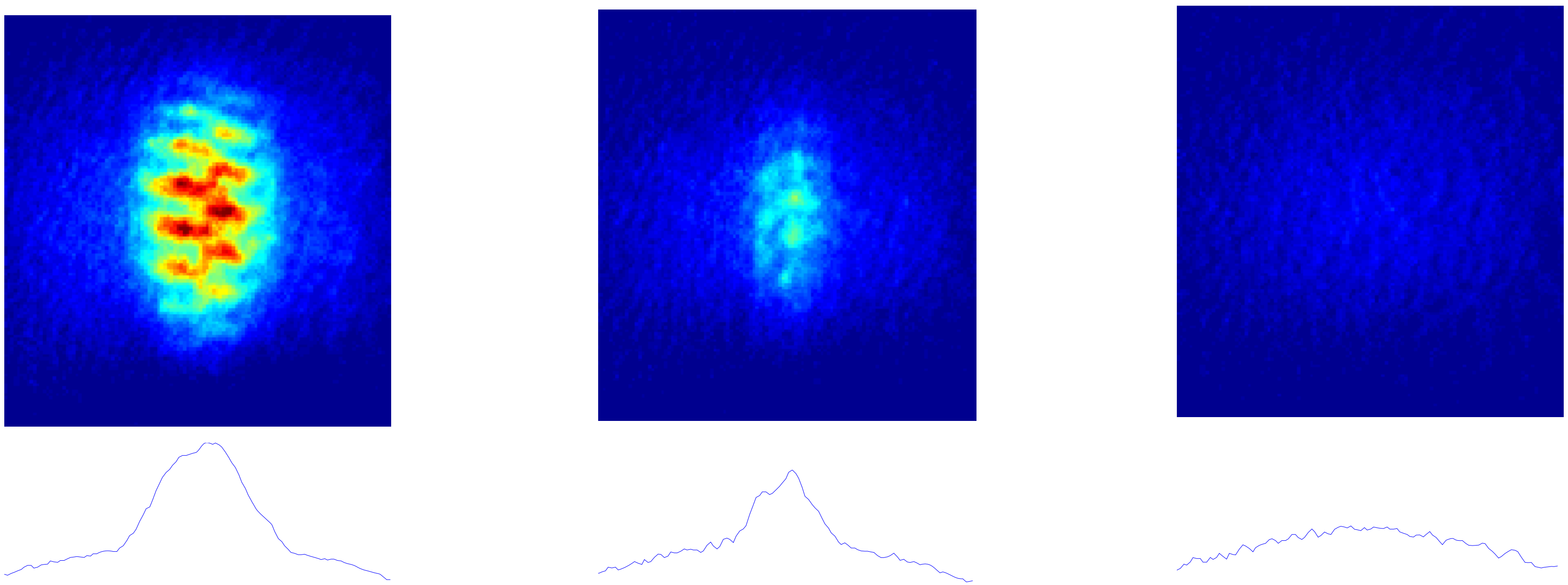
$$\mu \sim 2\ \text{kHz} \quad < \quad \hbar\omega \sim 4\ \text{kHz} \quad \ll \quad V_0 \sim 50\ \text{kHz}$$

Experiments also at MIT, Oxford, Innsbruck, Heidelberg, Florence, NIST, …

Measuring critical atom numbers

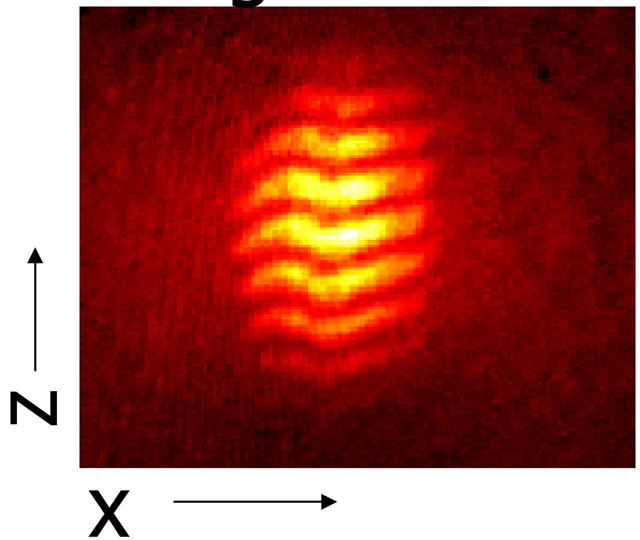


Produce 2d cloud, wait for atom number to reduce (~ 10s) RF knife on to keep T constant

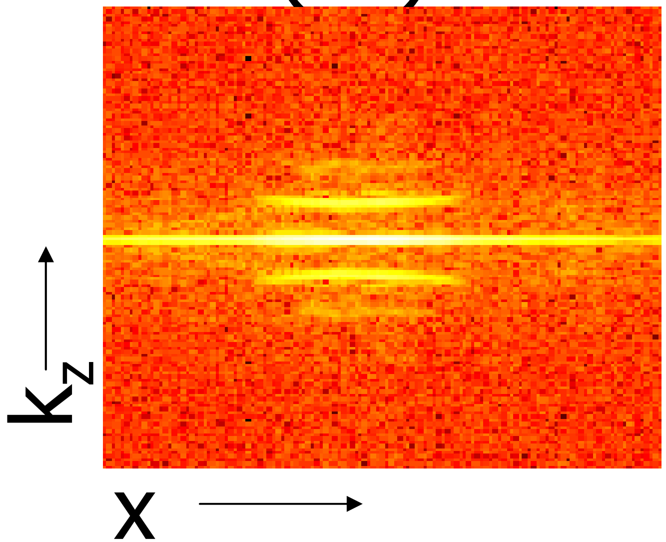


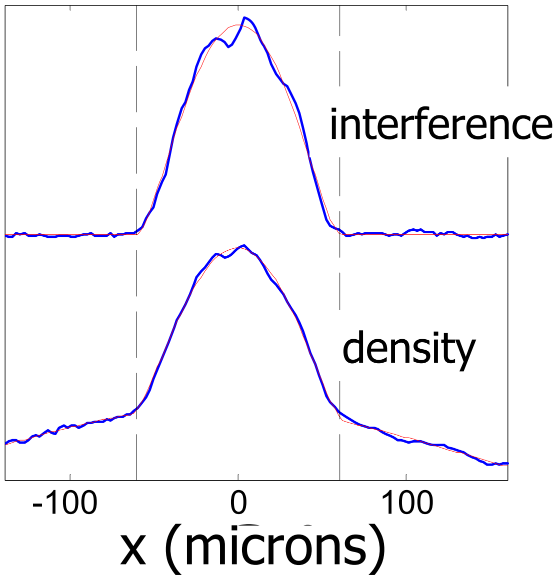
Interference

image



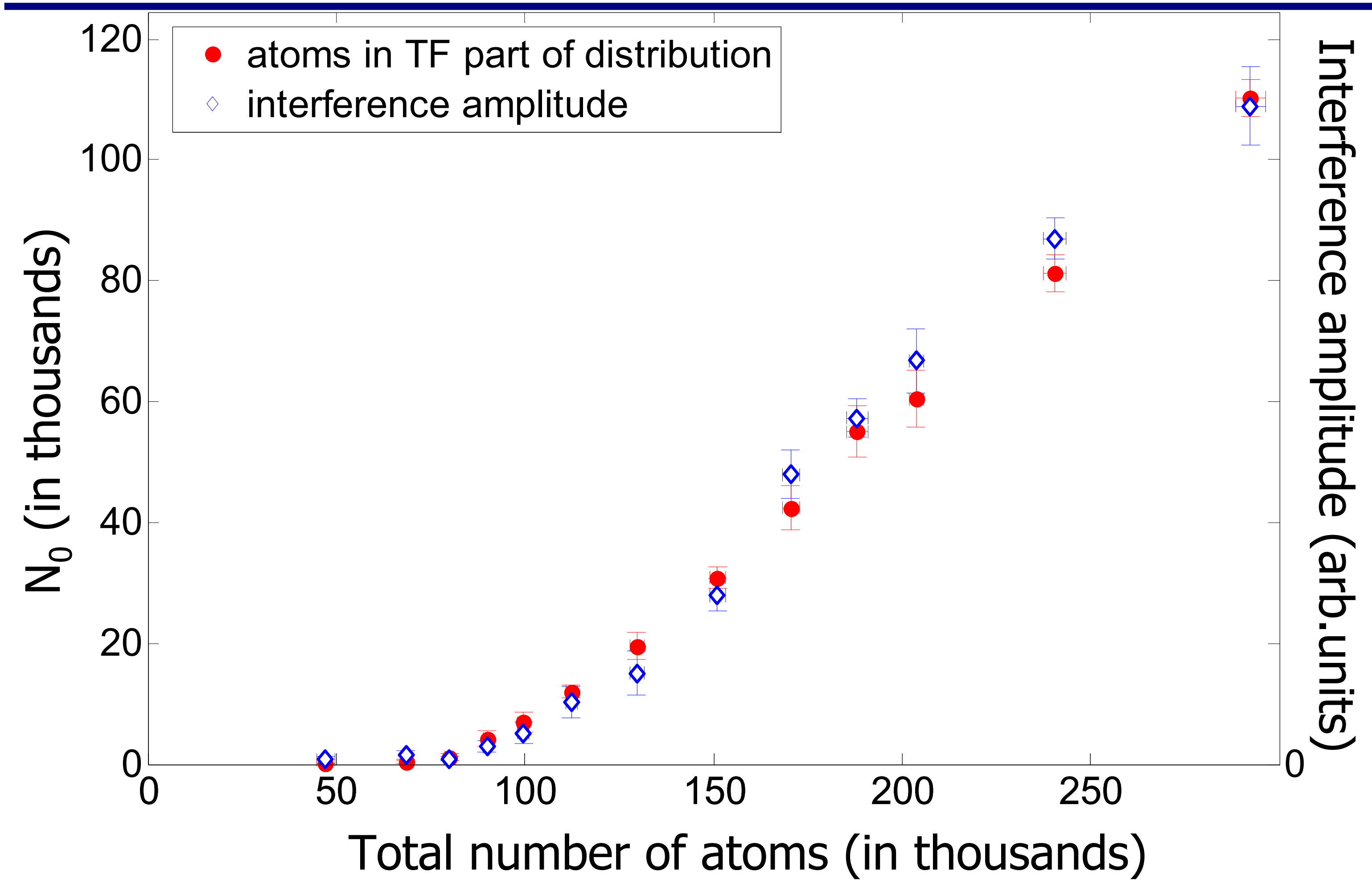
FFT (1d)





TF radii of density (DC peak) and interfering region (1^{st} harmonic) coincide

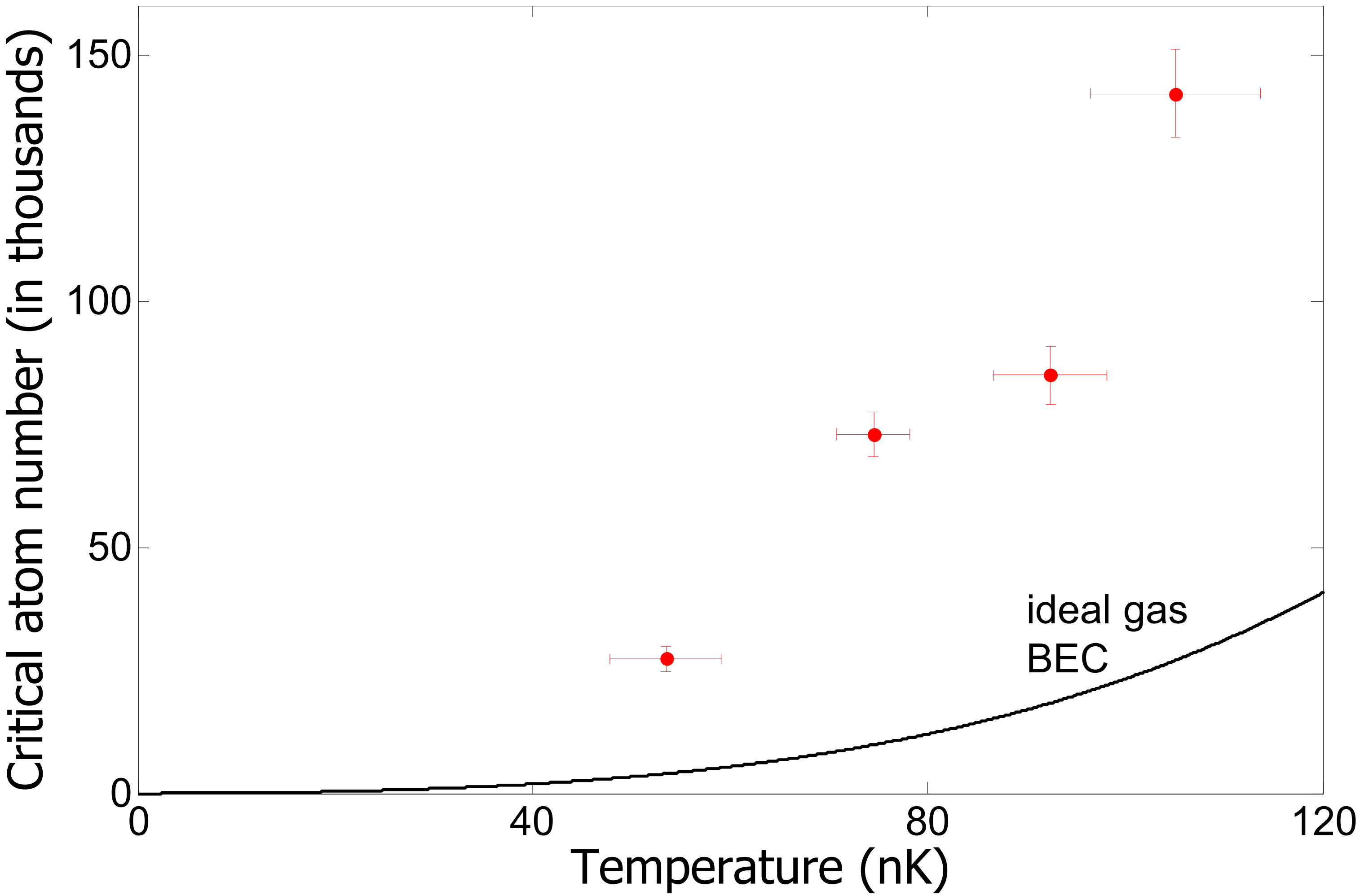
Comparing critical numbers



Within our accuracy, onset of bimodality and interference agree

P. Krüger, Z. Hadzibabic, J. Dalibard, PRL 2007

Temperature dependence of N_c



critical atom numbers are systematically higher than ideal gas prediction (multiple planes taken into account)

Critical density: BKT

universal jump in superfluid density from $\rho_s\lambda^2=0$ to $\rho_s\lambda^2=4$, but total density at transition depends on interactions:

$$\rho_{tot}\lambda^2 = \ln\left(C/\tilde{g}\right)$$

Fisher and Hohenberg

for sufficiently weak interactions

$\tilde{g} < 1; \tilde{g} = 0.13$ in our case

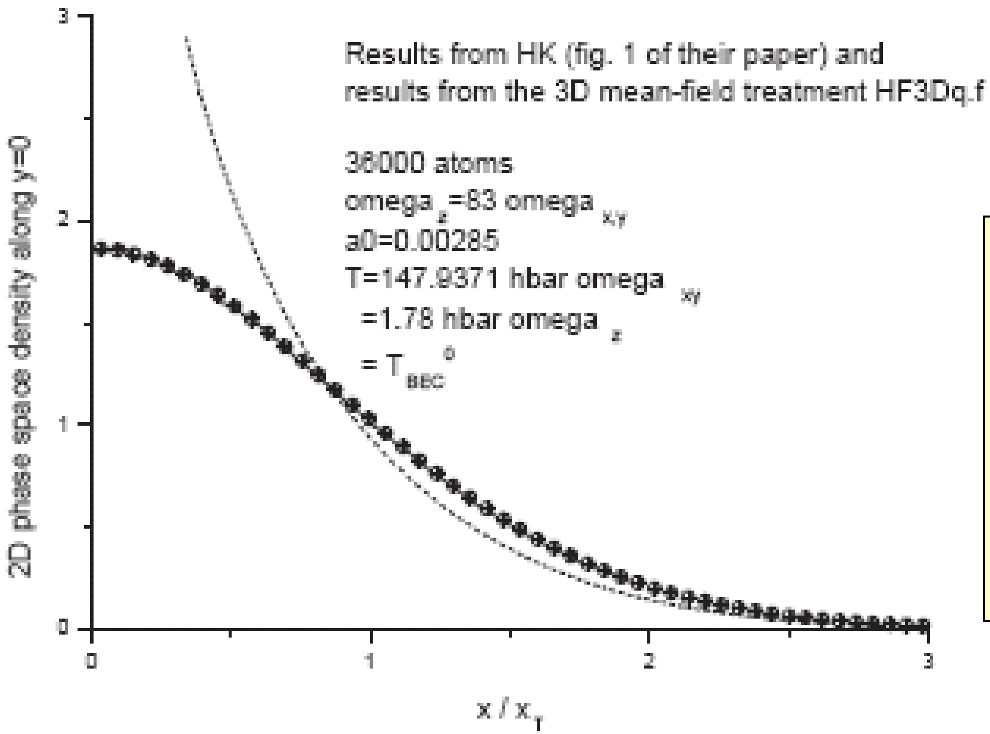
Quantum Monte-Carlo calculations give C=380:

$$\rho_{tot}\lambda^2 = 8.0$$

Svistunov et al.

Hatree-Fock analysis and QMC

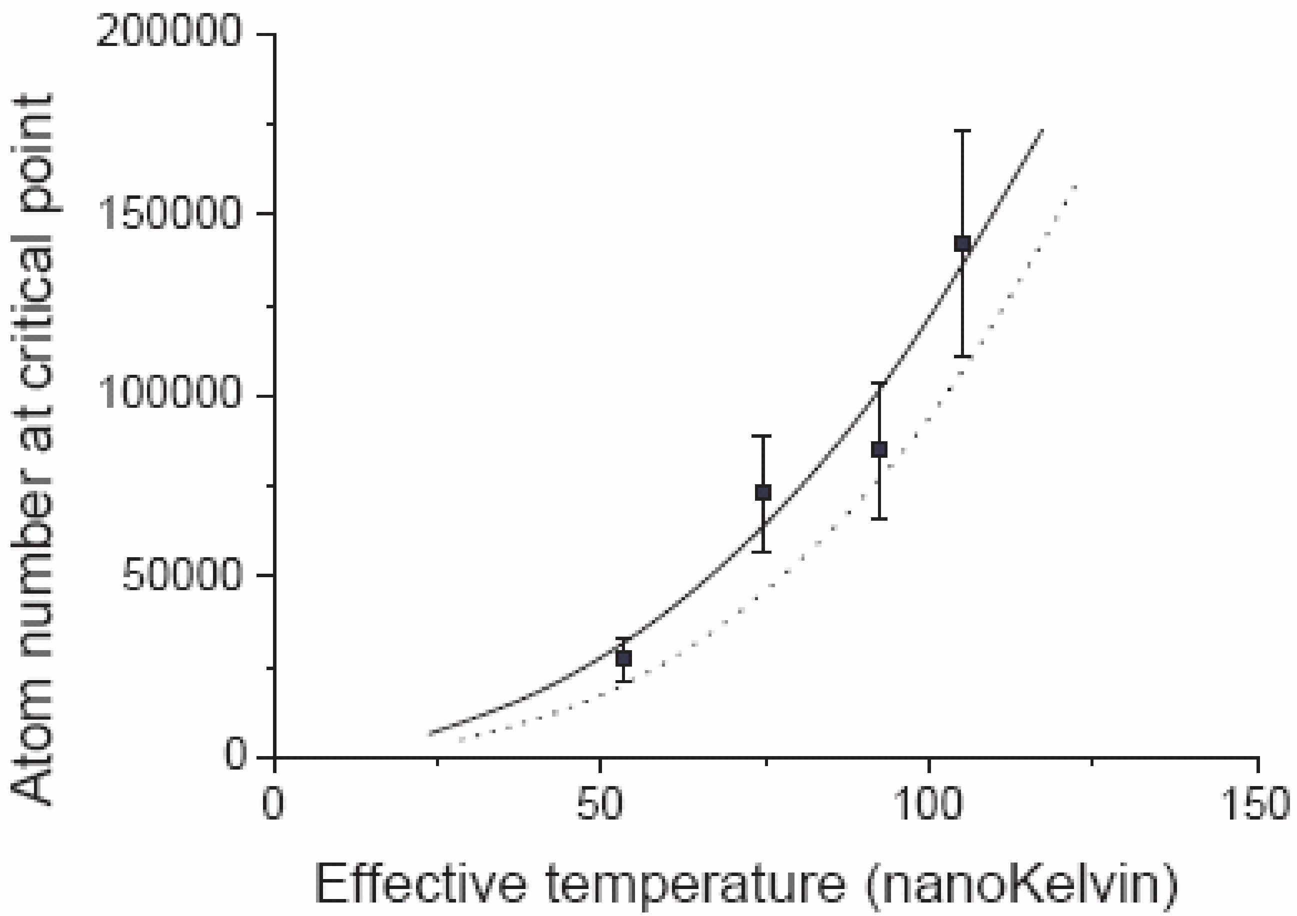
Solve HF equations self-consistently in hybrid approach: semi-classical (continuous) treatment in xy, quantum in z



Excellent agreement of mean field with QMC for non-degenerate gas

Result for ideal gas critical atom #, PSD < 8

Comparison to the experiment



P. Krüger, Z. Hadzibabic, J. Dalibard, PRL 2007
Z. Hadzibabic, P. Krüger, M. Cheneau, P.S. Rath, J. Dalibard, NJP 2008

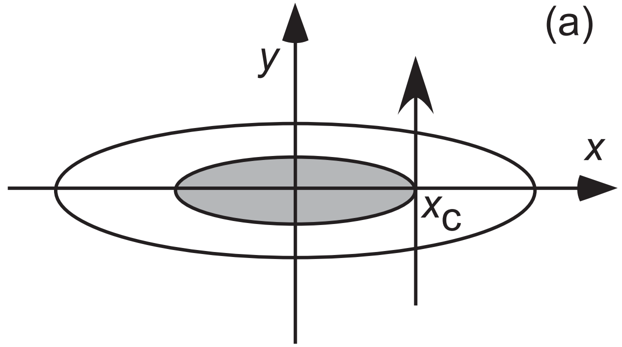
BEC – BKT crossover

A mean field calculation yields that in general (low and high interactions)

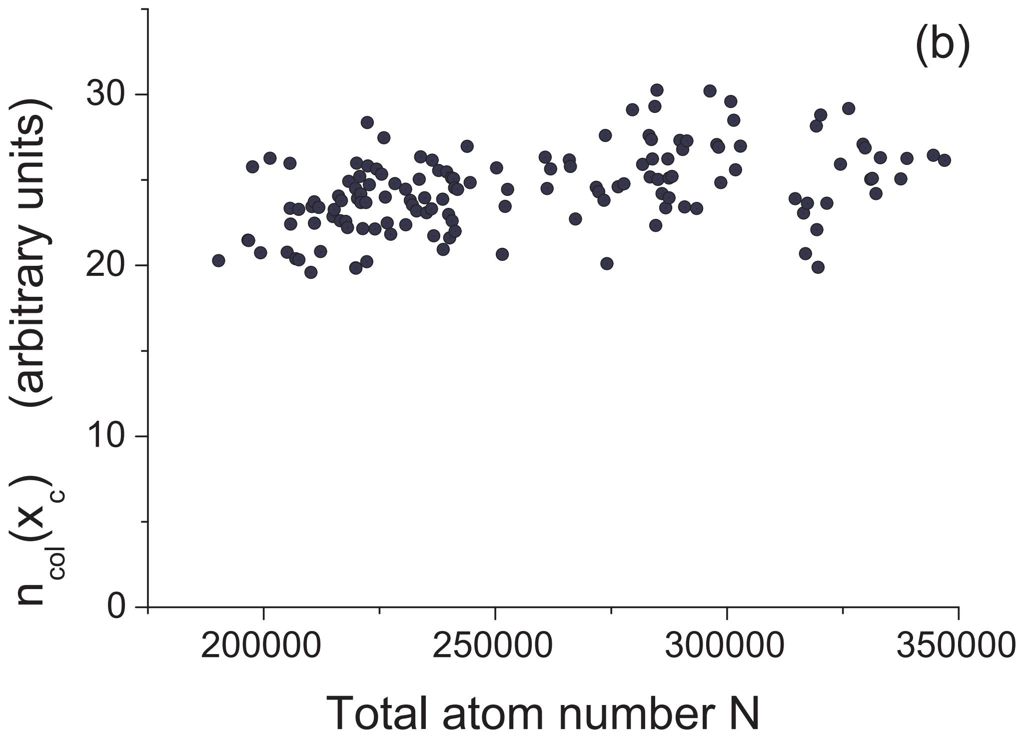
$$\frac{N_c^{mf}}{N_c^{id}} = 1 + \frac{3\tilde{g}}{\pi^3}\rho_{tot,crit}\lambda^2$$

Holzmann et al.

Local density approximation

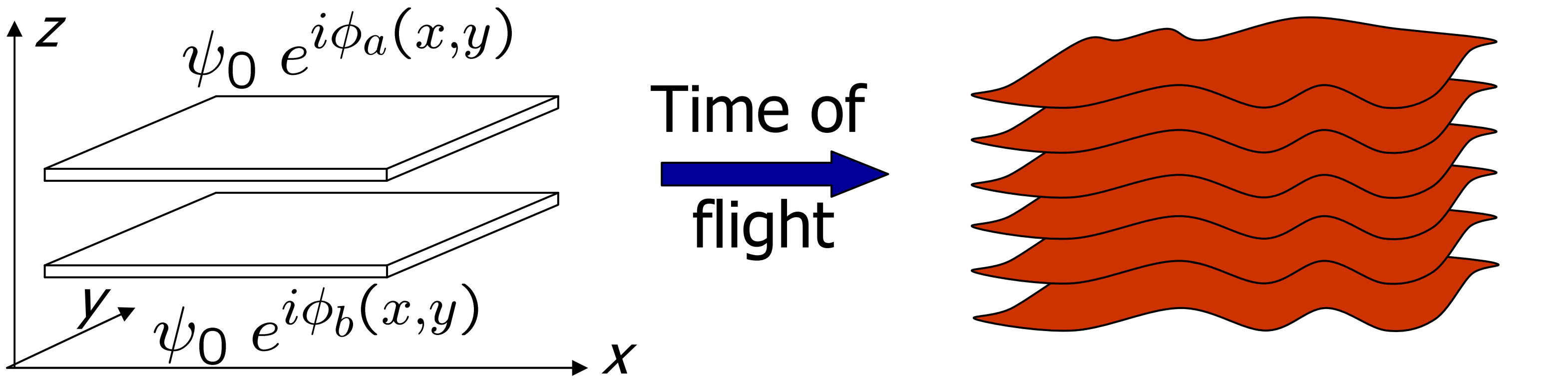


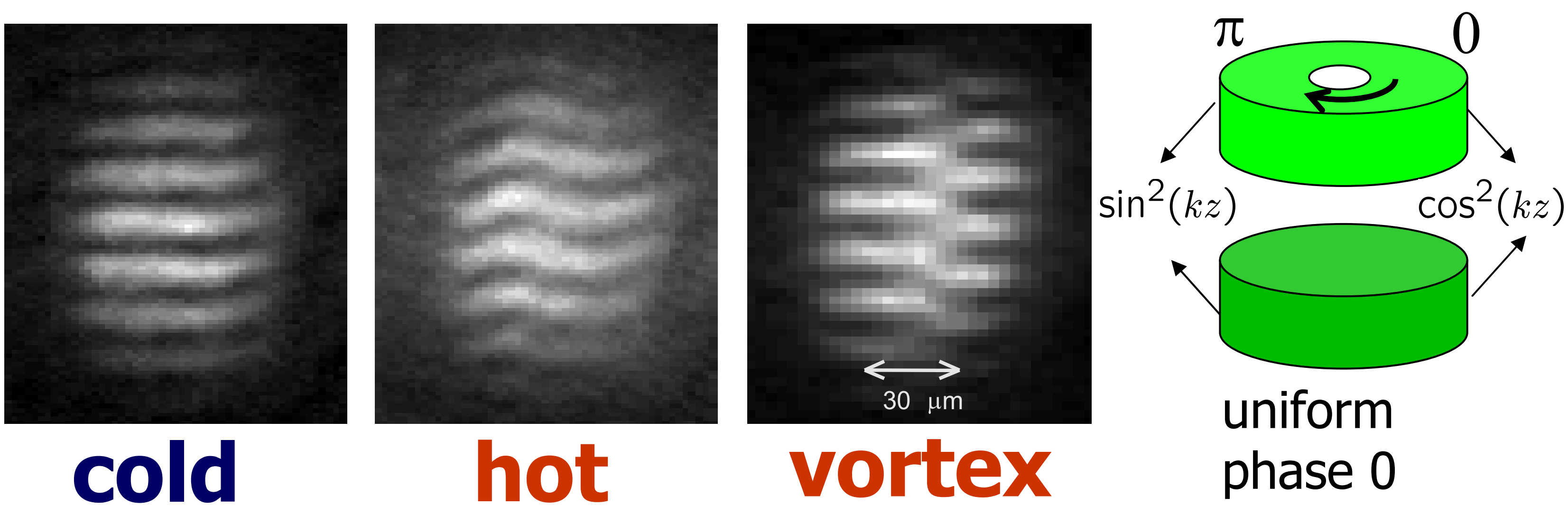
Determine (column) density at the edge of core for varied atom numbers



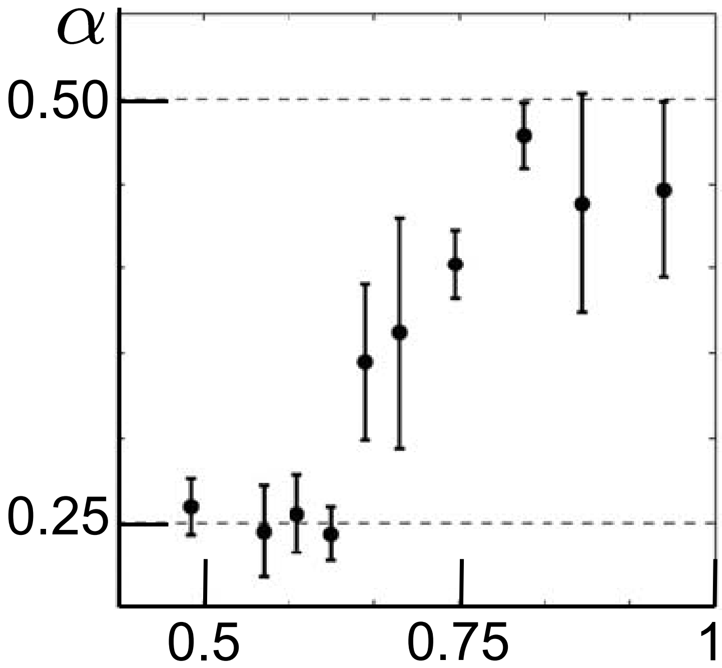
There's no significant dependence of onset of bimodality on atom number

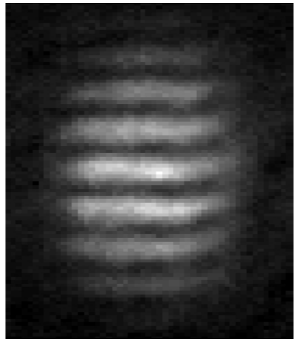
A closer look at interference

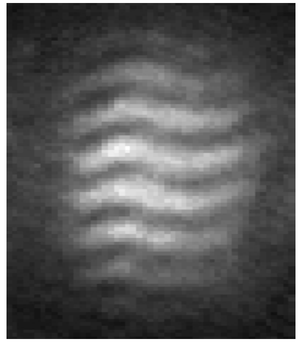




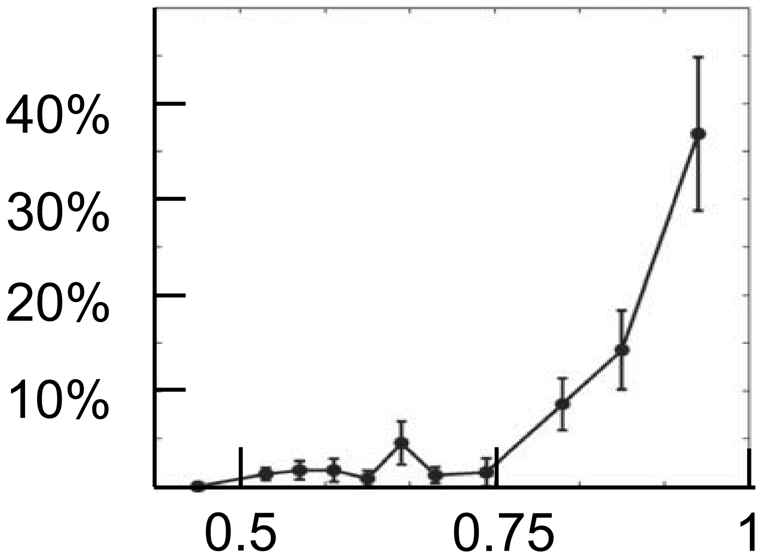
Correlations and Vortices

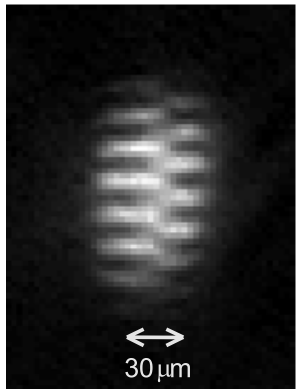






Loss of quasi long range order

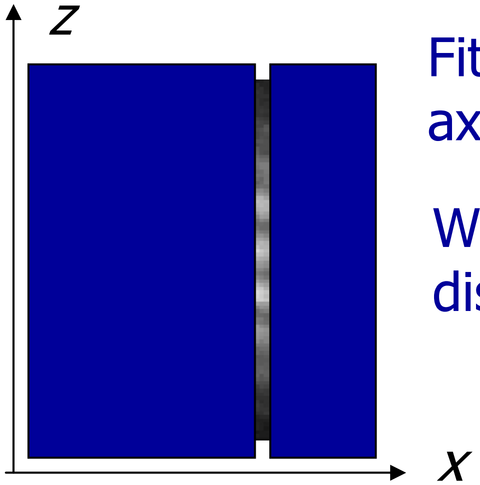




Proliferation of vortices

Hadzibabic, Krüger, Cheneau, Battelier, Dalibard, Nature 2006

Local analysis of interference



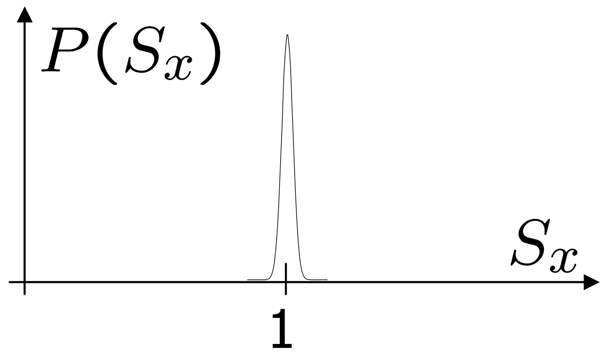
Fit the modulation along the z axis with

$$C_x \; e^{ikz} + \text{c.c.}$$

What is the statistical distribution of

$$S_x = \frac{|C_x|^2}{\langle |C_x|^2 \rangle}$$

➡ Straight fringes with full contrast:

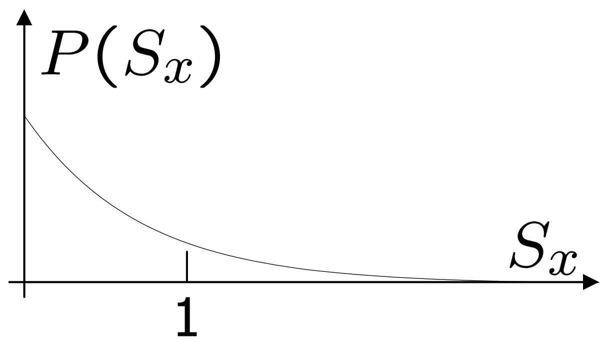


➡ Pattern resulting from many uncorrelated elements along the line of sight

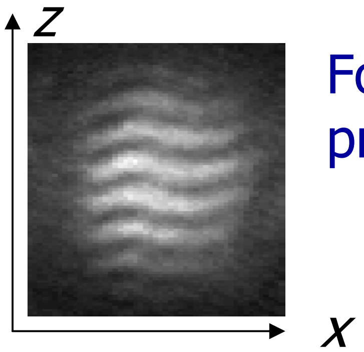
$C_x^{(\text{real})}$ and $C_x^{(\text{imag})}$ are two independent gaussian variables.

Exponential distribution for:

$$|C_x^{(\text{real})}|^2 + |C_x^{(\text{imag})}|^2$$



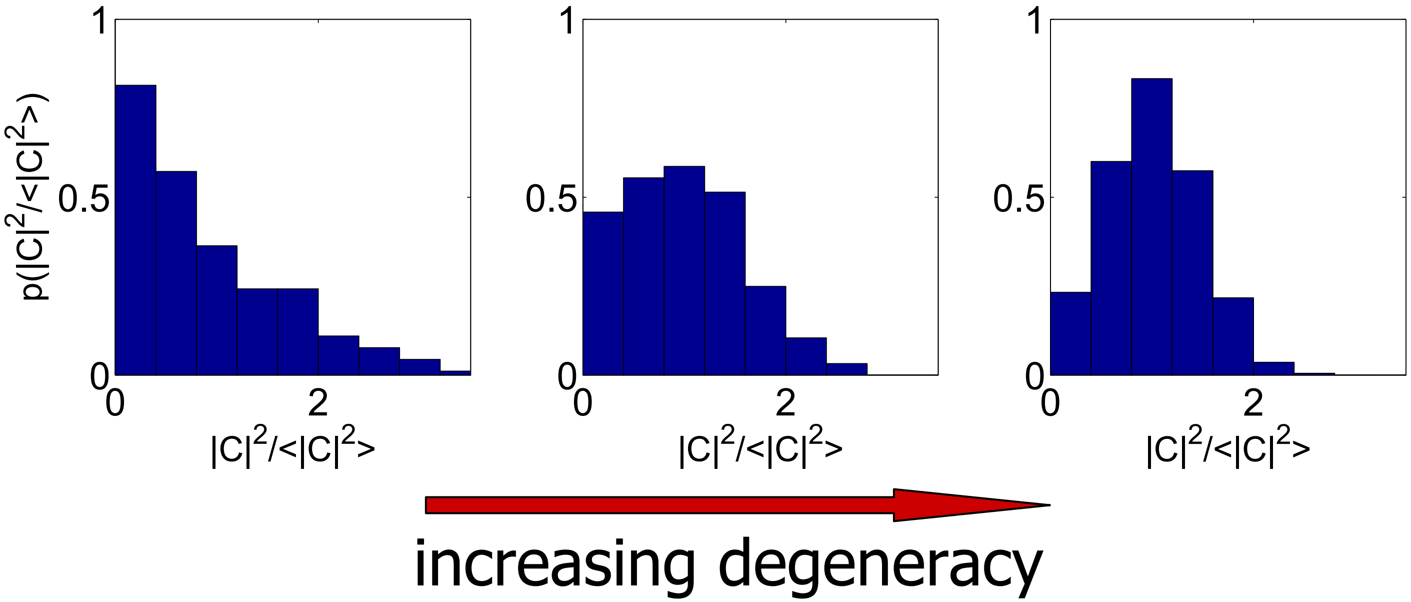
Distribution of local contrast



For each image we have ~ 30 useful columns, each providing a local $\bar{\rho}_s(x)$ and a local contrast C_x

We use 300 images all at the same temperature

We sort all 9000 couples $(\bar{\rho}_s(x), C_x)$ into groups of increasing $\bar{\rho}_s(x)$



P. K., Hadzibabic, Dalibard, Demler et al., in prep. 2008

Conclusion

- Low dimensional systems can be formed, controlled, and studied with high versatility in cold atomic gases
- Beyond mean-field effects, i.e. ‘true’ many-body physics become important in low d
- Example 1d: phase fluctuations
- Example 2d: Berizinskii-Kosterlitz-Thouless physics and BEC-BKT crossover

Acknowledgements

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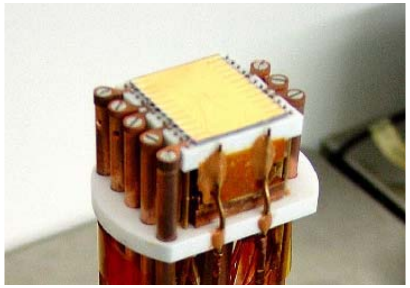
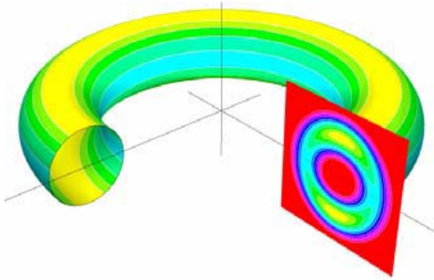
Thorsten Schumm
Jörg Schmiedmayer

New group & experiments at Nottingham

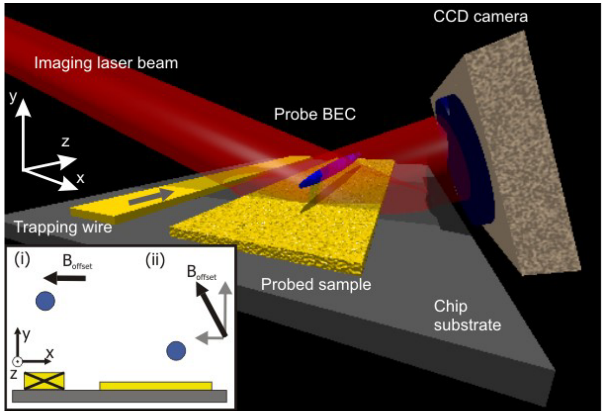
Atom chips



Non-trivial potentials, topologies



Surface probes, atom-surface interaction/coupling



Hybrid atom-semiconductor chips
Chip based atom-light interfaces