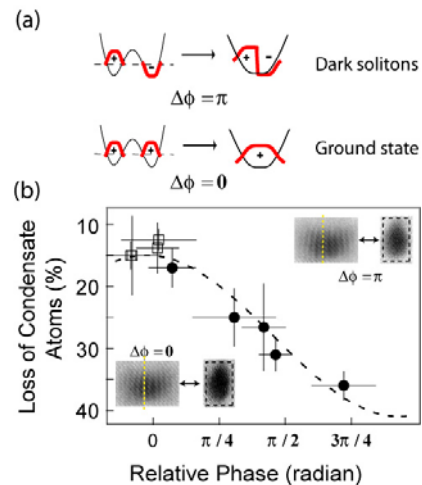


## Progress in year 2007

### 1. Phase Sensitive Recombination of Two Bose-Einstein Condensates on an Atom Chip

Most experiments in atom interferometry use freely propagating atom clouds. Alternative geometries are confined-atom interferometers where atoms are guided or confined in trapping potentials, often realized by using atom chips. Many discussions of confined-atom interferometers proposed a readout by merging the two separated atomic clouds, but it was also shown that the recombination process is very sensitive to atomic interactions which can lead to exponential growth of unstable modes.

The present work demonstrates that interactions between atoms and collective excitations are not necessarily deleterious to direct recombination of separated trapped condensates that have acquired a relative phase in atom interferometry. We show that in-trap recombination leads indeed to heating of the atomic cloud. However, this heating is phase dependent and can be used as a robust and sensitive readout of the atom interferometer. The resulting oscillations of the condensate atom number are dramatic (typically  $\sim 25\%$  contrast), occur over a wide range of recombination rates, and permit high signal to noise ratios since they simply require a measurement of the total number of condensate atoms in the trap [1].



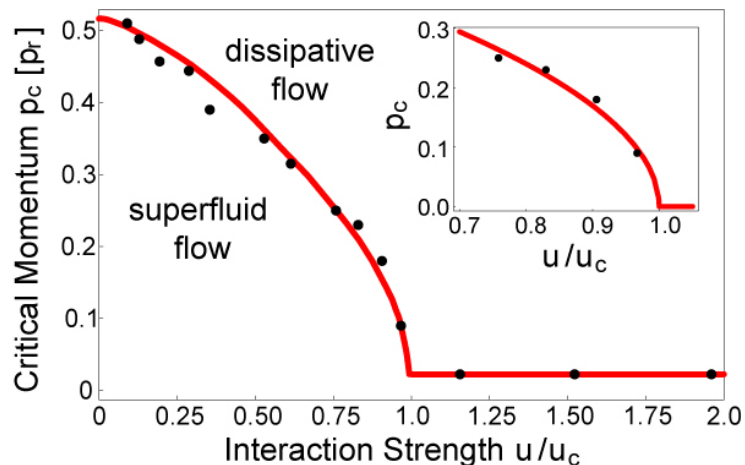
Concept and results on phase-sensitive recombination of two condensates. (a) The merged matter-wave functions are shown for the case of a sudden merger of interacting condensates leading to soliton formation for a relative phase of  $\pi$ . (b) The relative phase of two split condensates was monitored for various hold time after splitting by suddenly releasing the two condensates and observing interference. The heating during recombination (observed through the loss of condensate atoms) was correlated with the relative phase and can be used as in situ read out the atom interferometer.

### 2. Phase diagram for a Bose-Einstein condensate moving in an optical lattice

Mott insulator (MI) physics is an important paradigm for the suppression of transport by particle correlations. So far, with ultracold atoms, the superfluid to MI transition has

been studied mostly in a stationary system. In this work, we study the stability of superfluid currents in a moving optical lattice, as suggested in ref. [2], and extend previous studies in two regards. First, superfluidity near the MI transition has only been indirectly inferred from coherence measurements, whereas in this work, we characterize the superfluid regime by observing a critical current for superfluid flow. Second, previous studies were not able to precisely locate the phase transition partially due to the inhomogeneous density, while the sudden onset of dissipation provides a clear distinction between the two quantum phases.

We observed that superfluid current became unstable if the momentum exceeded a critical momentum, and the critical momentum varied from 0.5 recoil momentum in a very weak lattice to zero in the Mott insulator phase. We study the phase diagram for the stability of superfluid current as a function of momentum and lattice depth. Our phase boundary extrapolates to the critical lattice depth for the SF-to-MI transition, which was measured with high precision to be 13.5 (+/- 0.2) recoil energy [3]

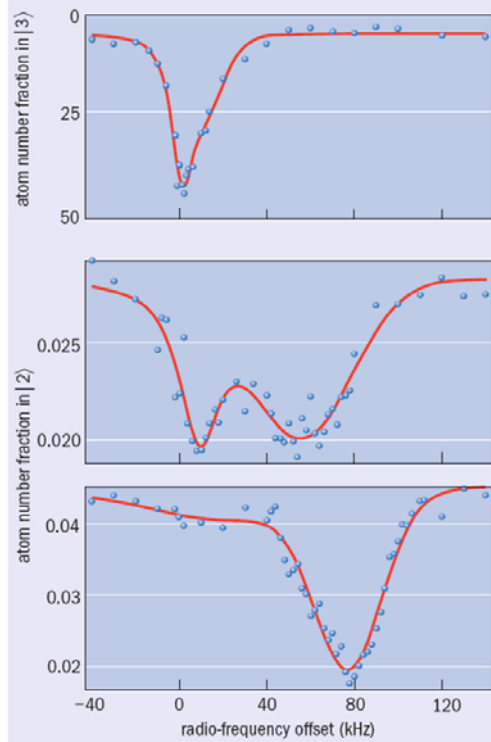


Critical momentum for a condensate in a three-dimensional moving lattice. The solid line shows the theoretical prediction for the superfluid region. The horizontal solid line is a fit to the data points in the MI phase. (Inset) Fit of critical momenta near the SF-MI phase transition.

### 3. Pairing without superfluidity for ultracold fermionic atoms

We have used radio-frequency spectroscopy to study pairing in the normal and superfluid phases of a strongly interacting Fermi gas with imbalanced spin populations. At high spin imbalances, above the so-called Chandrasekhar-Clogston limit of superfluidity, the system does not become superfluid even at zero temperature. In this normal phase pairing of the minority atoms is observed: While isolated atoms show a narrow peak in the radio-frequency spectrum, those that are bound in pairs produce a second peak at a higher frequency due to the extra energy required to break the bond. At the lowest temperature we found almost complete pairing of the minority atoms, indicated by the remaining frequency-shifted peak [4]. Since the system is beyond the Chandrasekhar-Clogston limit, this normal state consists of fermion pairs that do not undergo condensation and form a superfluid even at the lowest temperature: pairing can occur without superfluidity.

We have also studied whether radio frequency spectroscopy can reveal the onset of superfluidity. As we crossed the phase transition by varying population imbalance and temperature we found almost identical spectra, suggesting that radio-frequency spectroscopy cannot distinguish between the two phases.

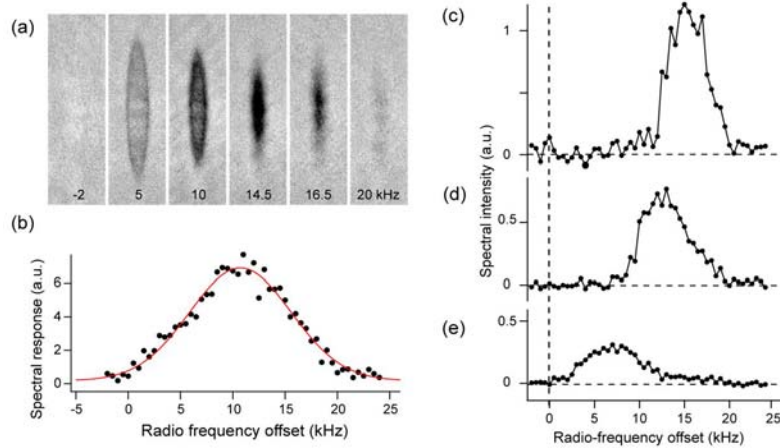


Radio-frequency spectroscopy was used to study pairing in the normal phase of a strongly interacting Fermi gas with highly imbalanced spin populations. At high temperatures (top) only a single atomic “peak” is present, indicating that no pairing has taken place. As the temperature is lowered (middle) a second peak emerges, reflecting the existence of pairs that require additional excitation energy. At sufficiently low temperatures (bottom) only the pairing peak remains, demonstrating that full pairing develops in the absence of superfluidity.

#### 4. Tomographic RF Spectroscopy of a Trapped Fermi Gas at Unitarity

Experiments on trapped ultracold atoms deal with samples with inhomogeneous density, leading to a broadening of spectral features and a smear-out of phase transitions. We show here that spatial imaging and tomographic reconstruction can eliminate inhomogeneous broadening and observe the homogeneous excitation spectrum of strongly interacting Fermi gases [5].

The spatial distribution of the rf-induced excited region in the trapped gas was recorded with in situ phase-contrast imaging and the local rf spectra were tomographically compiled after 3D image reconstruction. In contrast to the inhomogeneous rf spectrum, the homogeneous local rf spectrum shows a clear spectral gap with an asymmetric line shape.



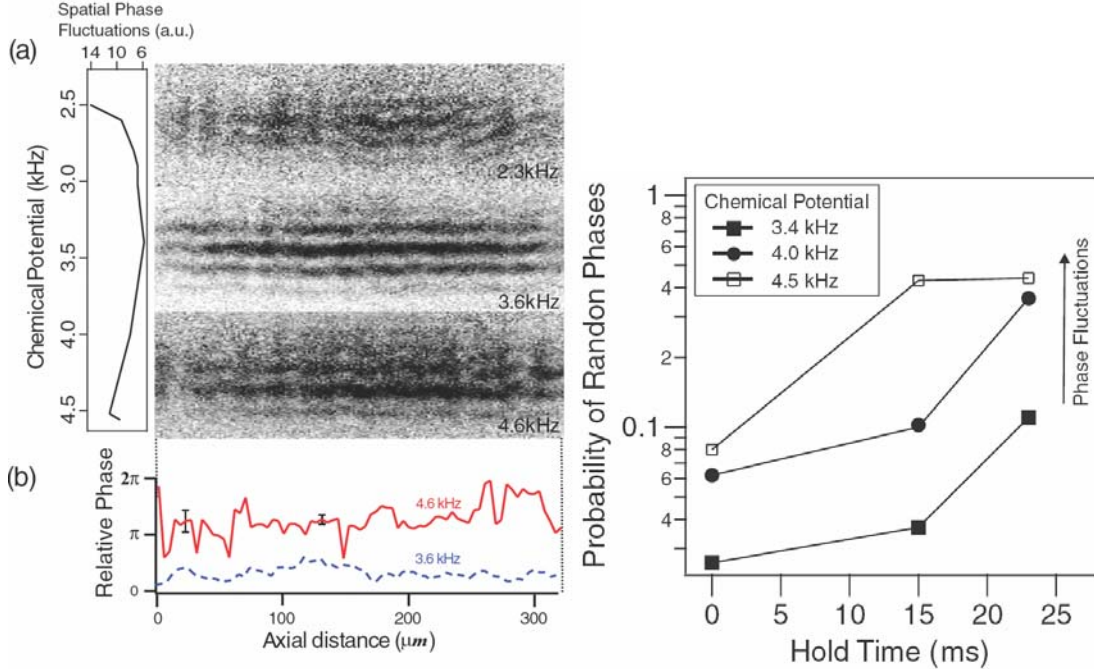
Tomographic radio-frequency (rf) spectroscopy of a trapped Fermi gas. (a) *in situ* phase-contrast images show the spatial structure of the spin excitation induced by an rf pulse, demonstrating the inhomogeneous density broadening effect in (b) the overall rf spectrum. Local rf spectra are tomographically reconstructed from the images. Local spectra at (c)  $r=0 R$ , (d)  $r=0.4 R$ , and (e)  $r=0.7 R$  ( $R$ : the radius of the cloud).

## 5. Matter-Wave Interferometry with Phase Fluctuating Bose-Einstein Condensates

A non-interacting zero-temperature Bose-Einstein condensate is the matter-wave analogue to the optical laser, and therefore the ideal atom source for matter-wave interferometry. However, at finite temperature elongated condensates (e.g. in wave guides) suffer from phase fluctuations.

We observed directly axial phase fluctuations and characterized their effect on the coherence time of the atom interferometer. We demonstrated that atom interferometry can be performed in the presence of phase fluctuations [6].

We found some degradation of the fringe contrast due to phase fluctuations. However, it appears that for our experimental conditions, this degradation is not due to the quantum limit of phase fluctuations, but is rather caused by asymmetries in the double-well potential leading to relative motion of the divided condensates.



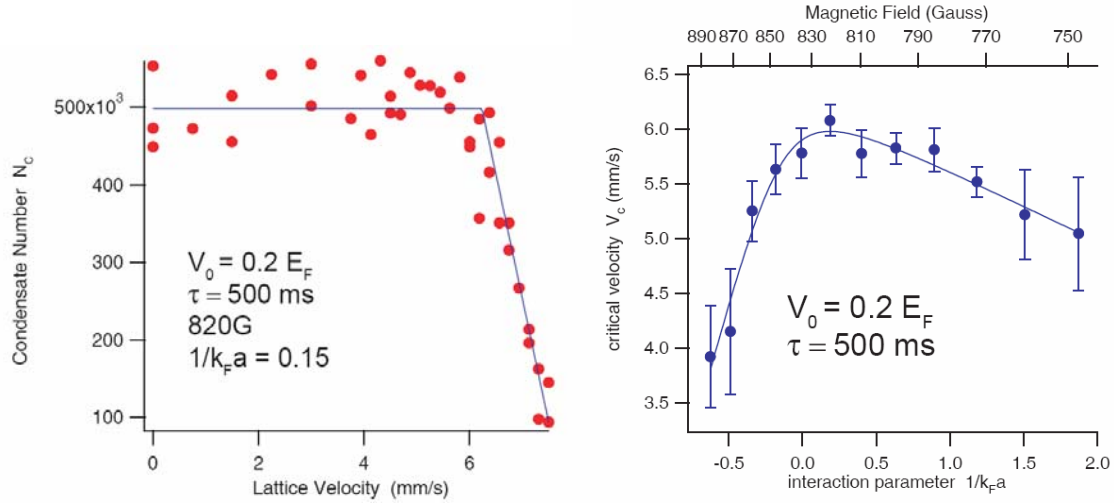
Effect of longitudinal phase fluctuations on the performance of the matter-wave interferometry. (Left) Effect of spatial phase fluctuation on the waviness of interference fringes. Interference fringes obtained right after splitting a condensate in (a). For large spatial phase fluctuation (e.g., 4.6 kHz), the fringe pattern shows more significant wiggles than for smaller phase fluctuations (e.g., 3.6 kHz). From the fringes for 3.6 kHz (dashed line) and 4.6 kHz (solid line) chemical potentials, relative phases are obtained along the axial direction in (b) (Right) Effect of longitudinal phase fluctuations on the coherence time between the split condensates. The probability for a random phase for ten measurements of the relative phase is shown for three different amounts of the longitudinal phase fluctuations.

## 6. Critical velocity for superfluid flow across the BEC-BCS crossover

The recent realization of the BEC-BCS crossover in ultracold atomic gases allows one to study how bosonic superfluidity transforms into fermionic superfluidity. Many quantities, such as the speed of sound and the transition temperature, vary monotonously through the crossover. In contrast, the critical velocity for superfluid flow has been predicted to show a pronounced maximum [7]. This maximum occurs at the transition from a “bosonic” region where excitation of sound limits superfluid flow to a “fermionic” region where pair breaking dominates.

By crossing two tightly focused laser beams, we exposed only the central region to a 1D moving optical lattice and could observe the response of the superfluid at a well-defined density. In this way, critical velocities were obtained throughout the BEC-BCS crossover [8].

In good agreement with theoretical predictions we found a pronounced peak of the critical velocity at unitarity which confirms that superfluidity is most robust for resonant atomic interactions. The dependence of the critical velocity on lattice depth and on the inhomogeneous density profile was carefully studied.



(left) Onset of dissipation for superfluid fermions in a moving optical lattice. Shown is the number of fermion pairs which remained in the condensate after being subjected to a moving optical lattice at variable velocity. The abrupt onset of dissipation occurred at the critical velocity.

(right) Critical velocities throughout the BEC-BCS crossover. A pronounced maximum was found at resonance. Data are shown for a lattice with a depth of  $0.2 E_F$  deep lattice. The solid line is a guide to the eye.

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