“Interacting Bose-Einstein condensates - in lattices and atom interferometers“

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Henri Poincare Workshop
Paris

What happens when gases are

Ultracold: nanokelvin
100 million times colder than outer space

Ultralow density: 10^{14} cm^{-3}
100,000 thinner than air

Ultralow pressure: 10^{-14} atmosphere (nanopascal)

Almost nothing

0.01 femtomole

But:

Those atomic gases can be strongly interacting

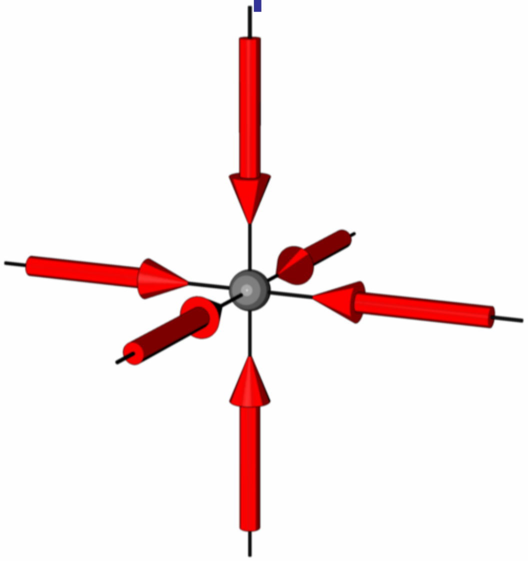
They can show strong correlations

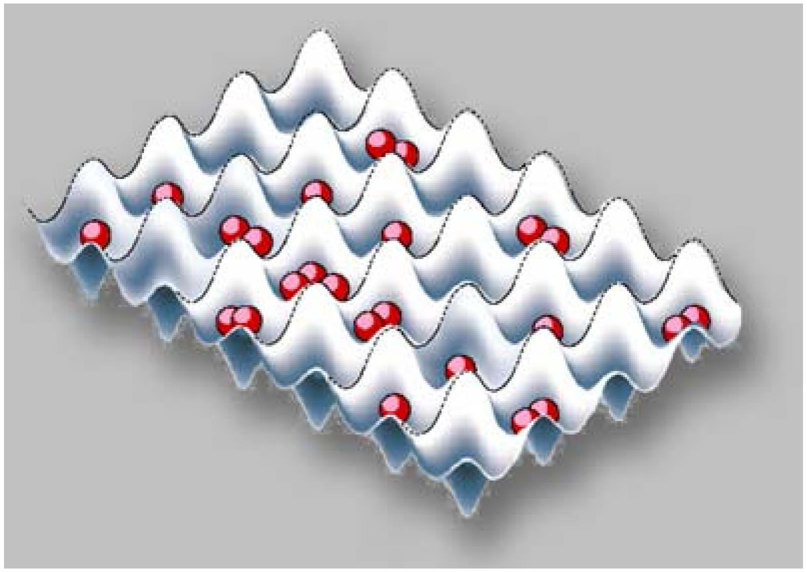
Like liquids
Like solids
Like superconductors

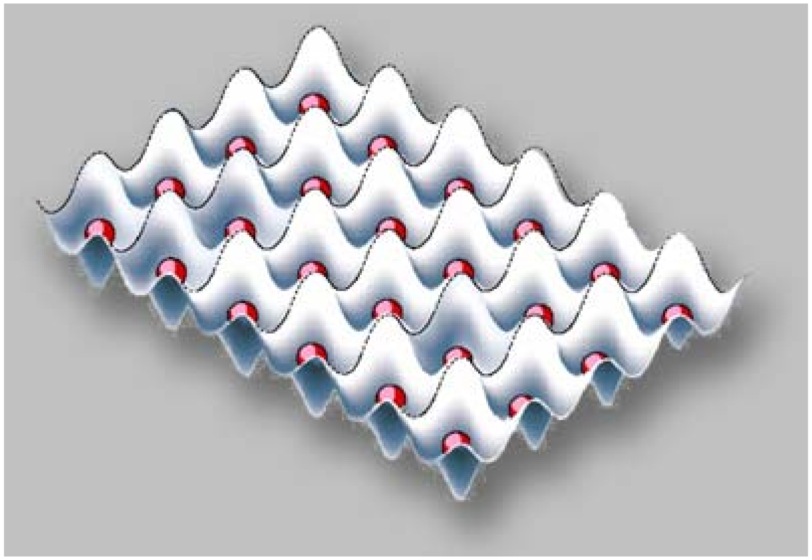
How do get strong interactions and correlations?

- Strong forces
- Optical lattices
- Lower dimensions

BEC in 3D optical lattice



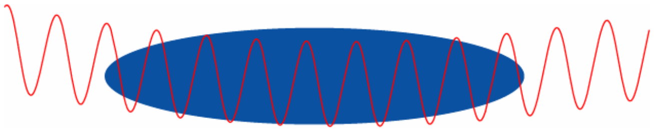




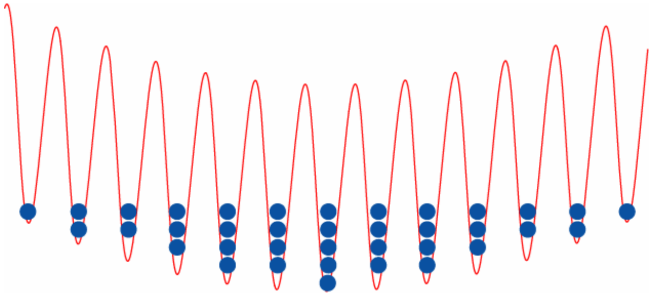
Courtesy Markus Greiner

The Superfluid-Mott Insulator transition

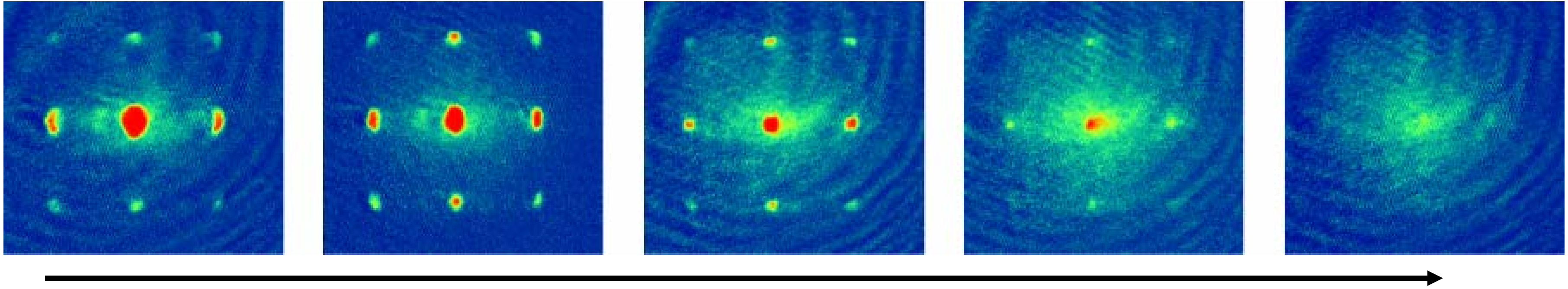
Shallow Lattices - Superfluid



Deep Lattices – Mott Insulator



The Superfluid-Mott Insulator Transition in Optical Lattices



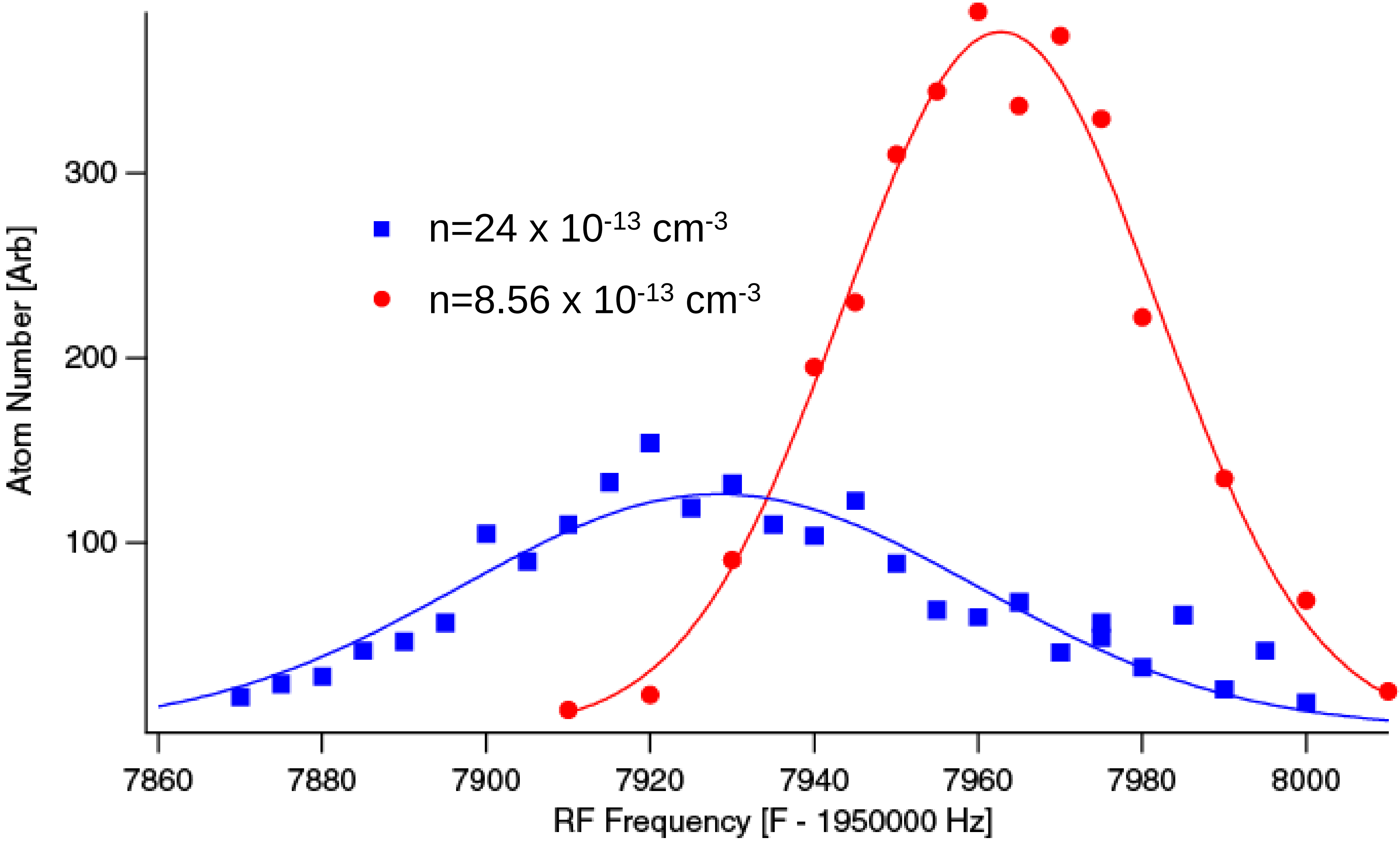
Increase lattice depth

Diagnostics:

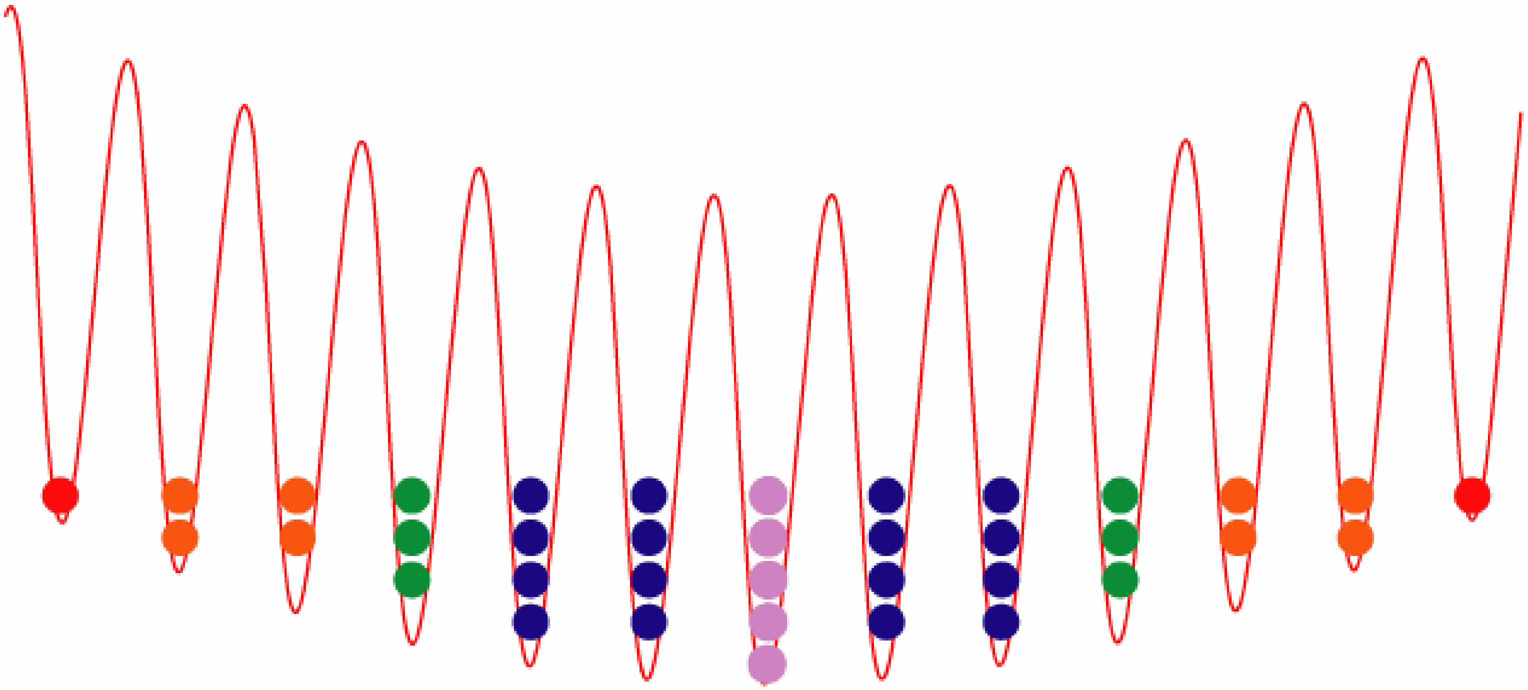
- Loss of Coherence
- Excitation Spectrum
- Noise correlations
- Spin changing collisions
- Microwave Spectroscopy (Atomic clock shifts)

Atomic clock as diagnostics tool for many-body physics

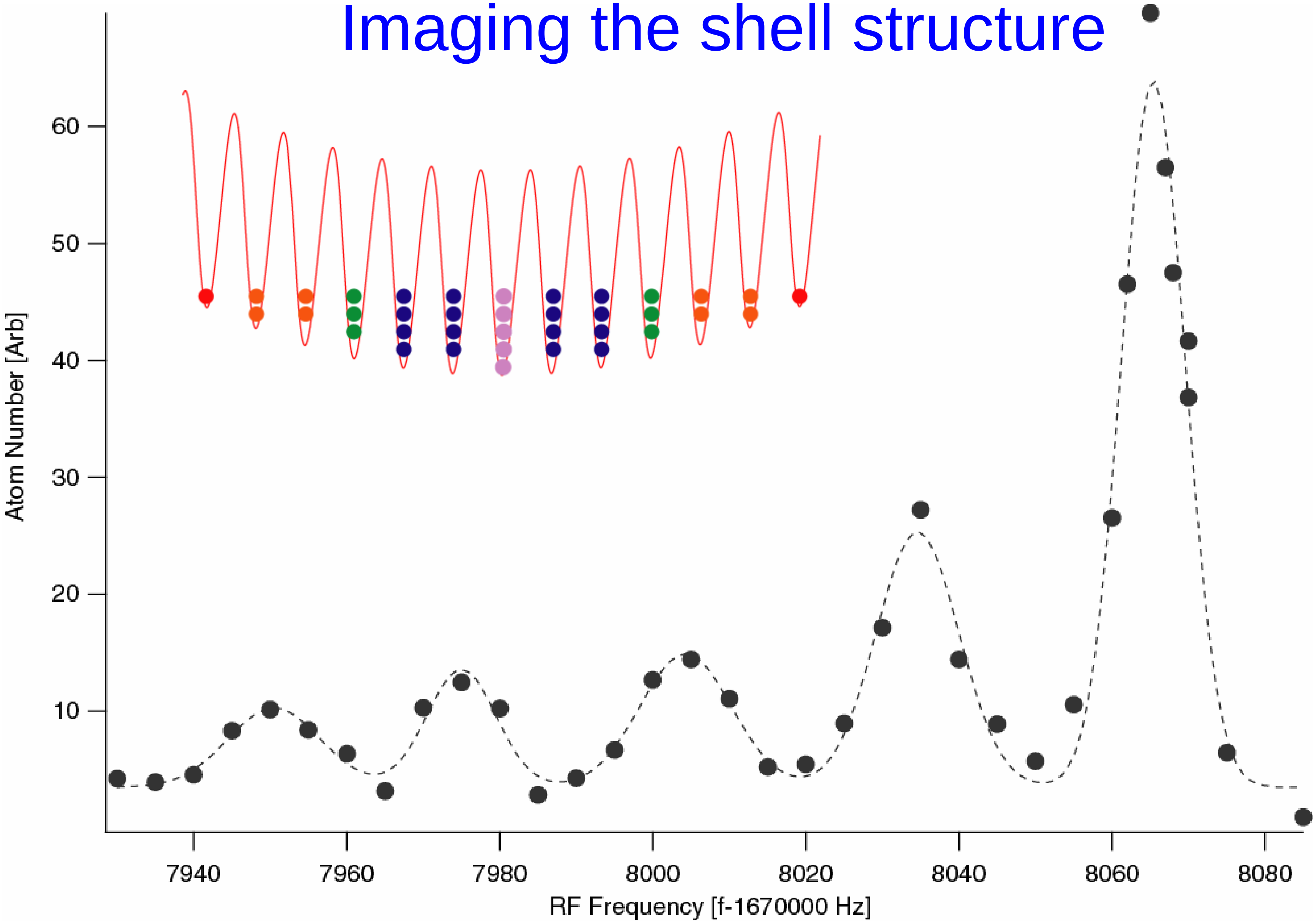
2-photon Microwave Spectroscopy



Imaging the shell structure

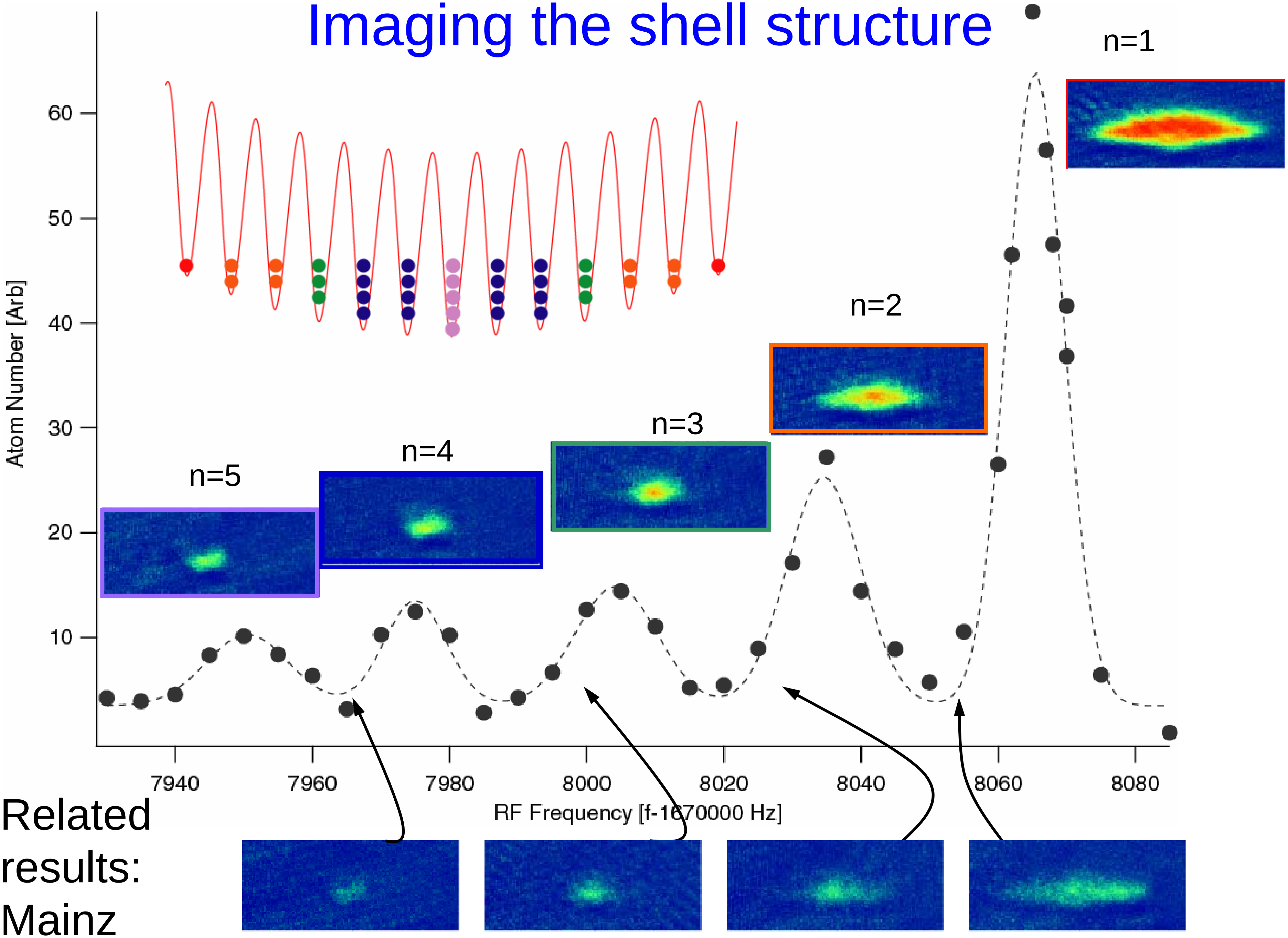


Imaging the shell structure



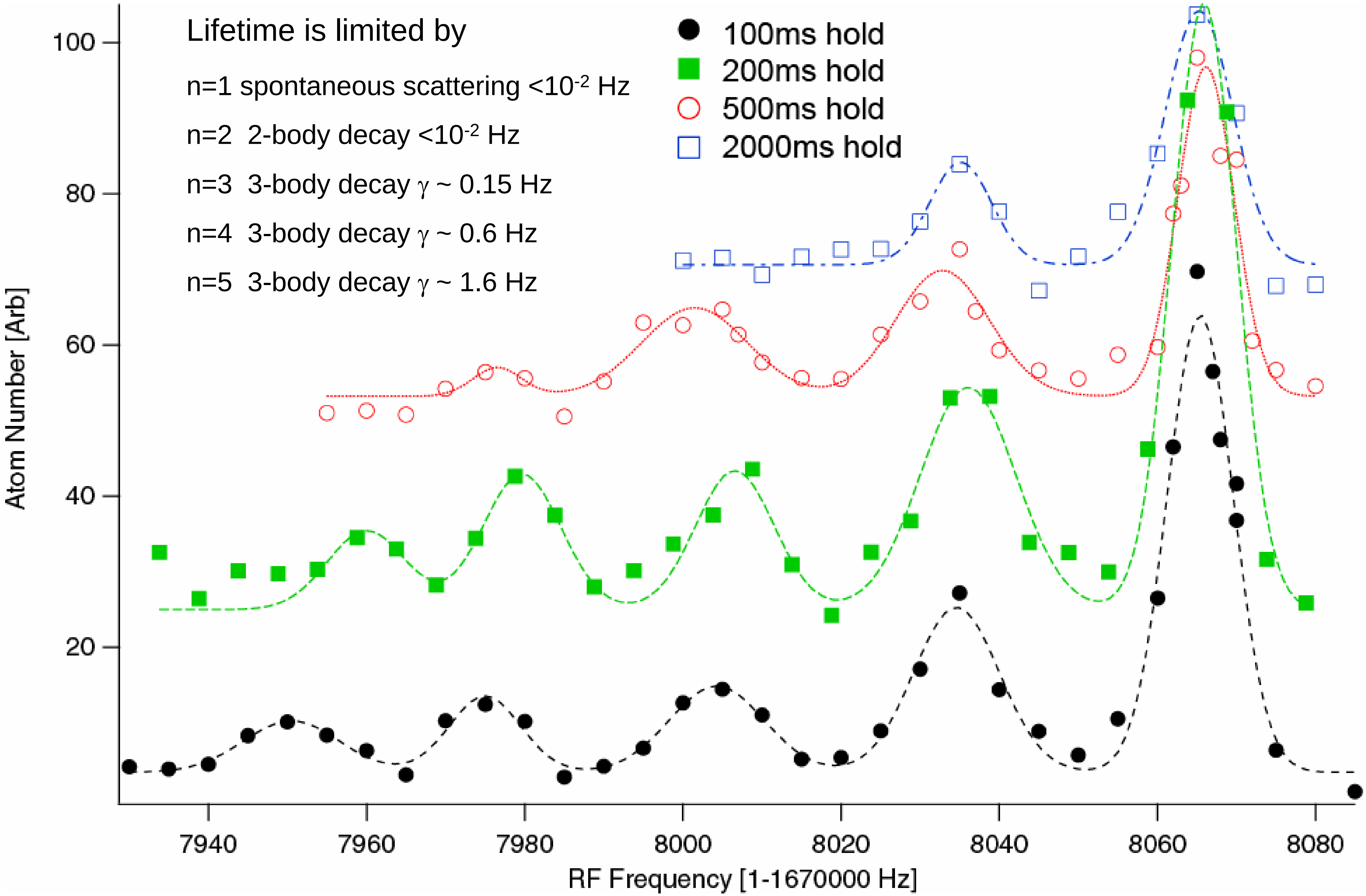
G.K. Campbell, J. Mun, M. Boyd, P. Medley, A.E. Leanhardt, L. Marcassa, D.E. Pritchard, W.K., Science 313, 649-652 (2006).

Imaging the shell structure



Related results: Mainz

Lifetime of shells



Lifetime is limited by

n=1 spontaneous scattering <10^{-2} Hz

n=2 2-body decay <10^{-2} Hz

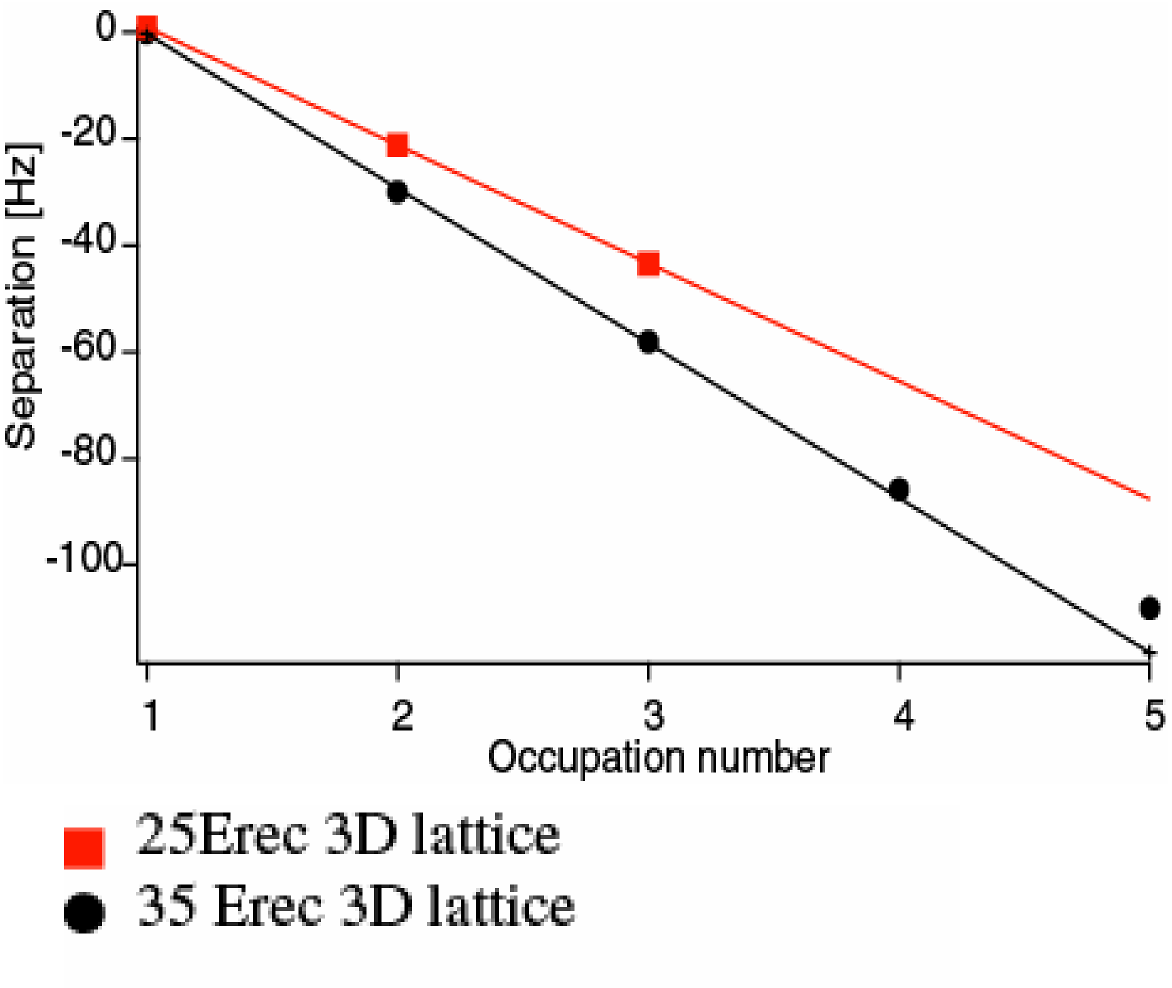
n=3 3-body decay γ ~ 0.15 Hz

n=4 3-body decay γ ~ 0.6 Hz

n=5 3-body decay γ ~ 1.6 Hz

Measuring the Onsite Interaction

Separation between peaks

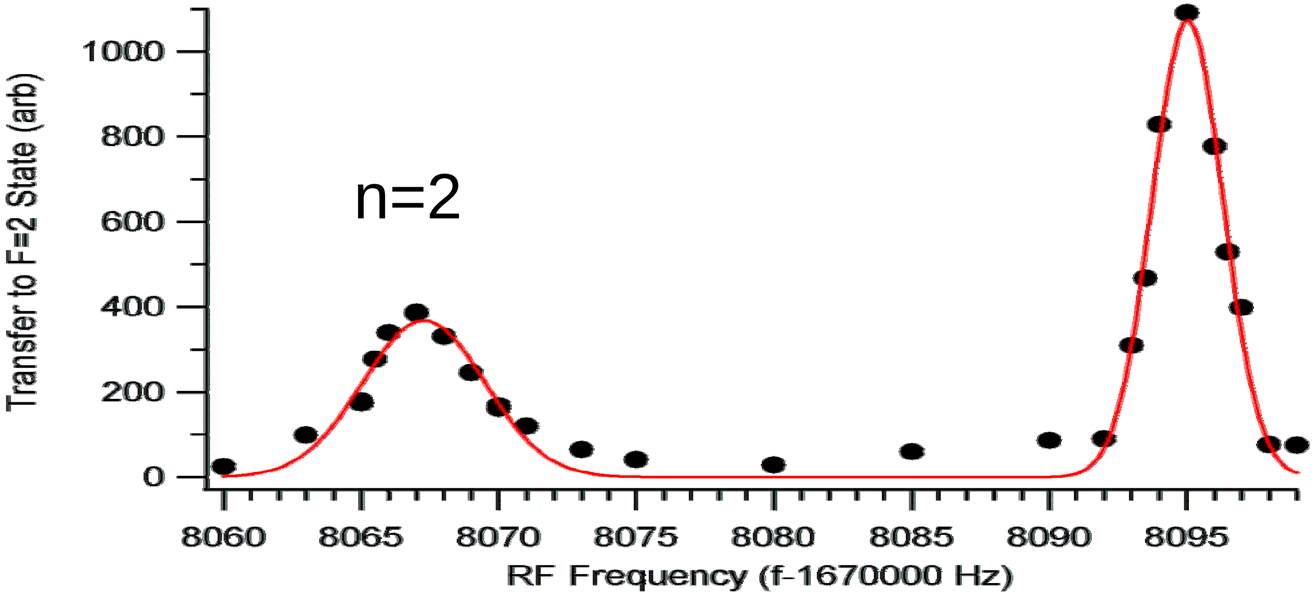


Many-body physics to enhance an atomic clock

An Atomic clock using a Mott insulator state

Advantages:

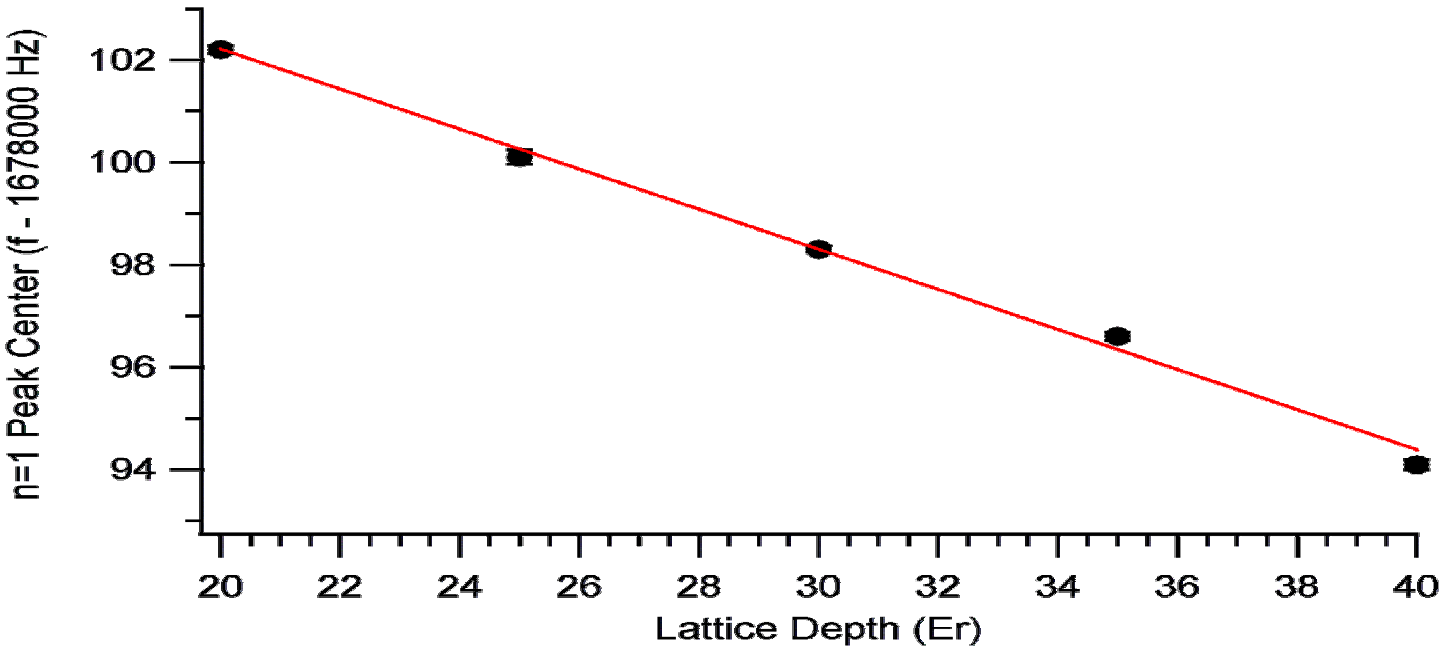
- High density, but no clock shift for the n=1 peak
- Pulse length can be much longer than tunneling time



U = 35 E_{recoil}, N=~100,000, pulse length = 300 ms

Systematic AC Stark shift

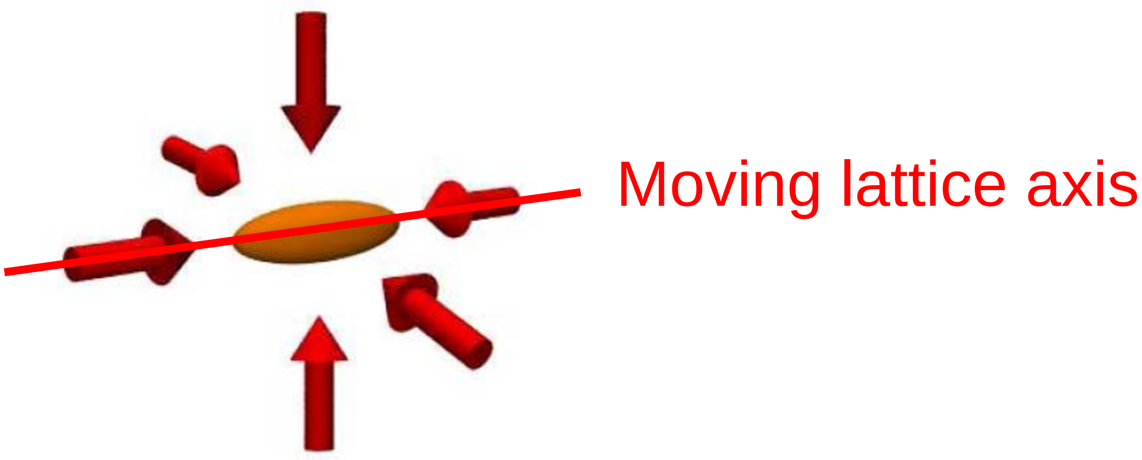
Resonance frequency vs lattice depth

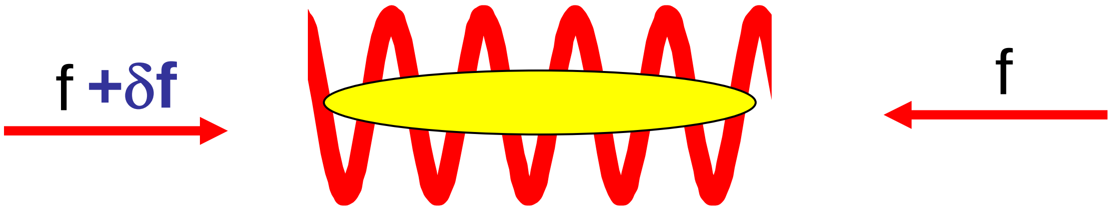


Micah Boyd et al., Ph.D. thesis

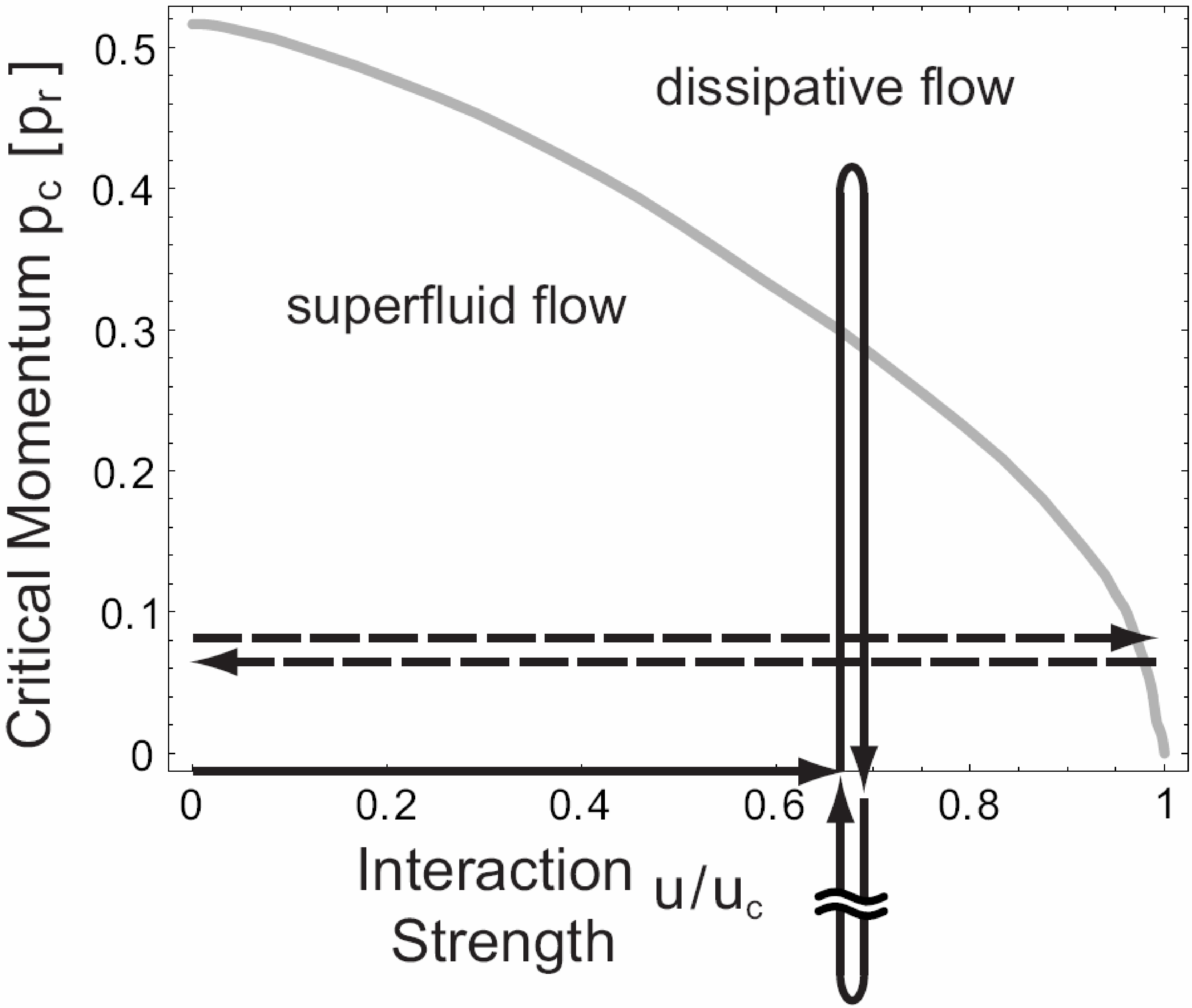
Superfluid to Mott Insulator Transition

Superfluid flow?
Precise location of Mott insulator phase transition



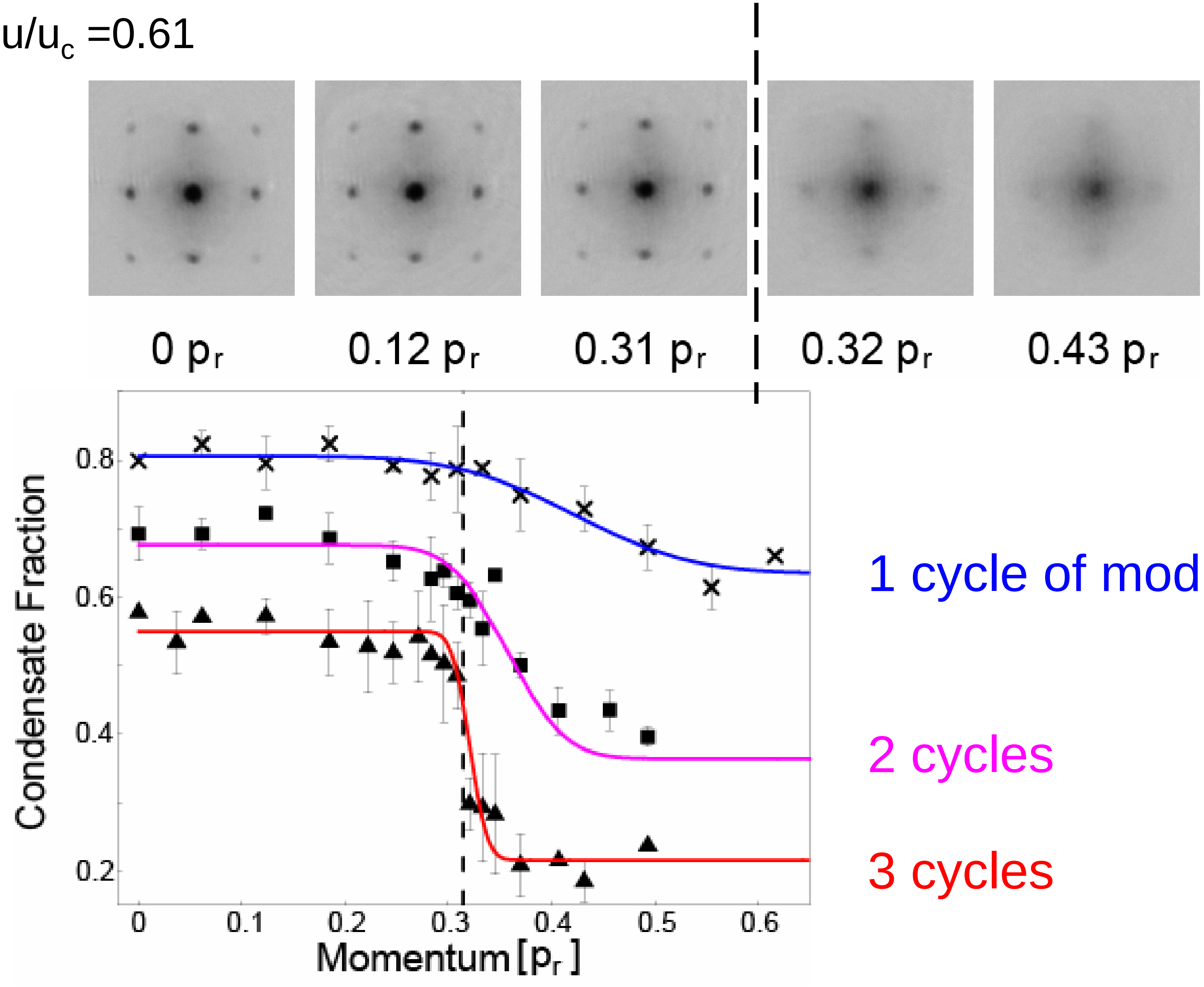


J. Mun, P. Medley, G.K. Campbell, L.G. Marcassa, D.E. Pritchard, WK, preprint.


Critical Momentum p_c $[p_r]$
0.5
0.4
0.3
0.2
0.1
0
dissipative flow
superfluid flow
0
0.2
0.4
0.6
0.8
1
Interaction Strength u/u_c

Critical velocity for superfluid flow

$u/u_c = 0.61$

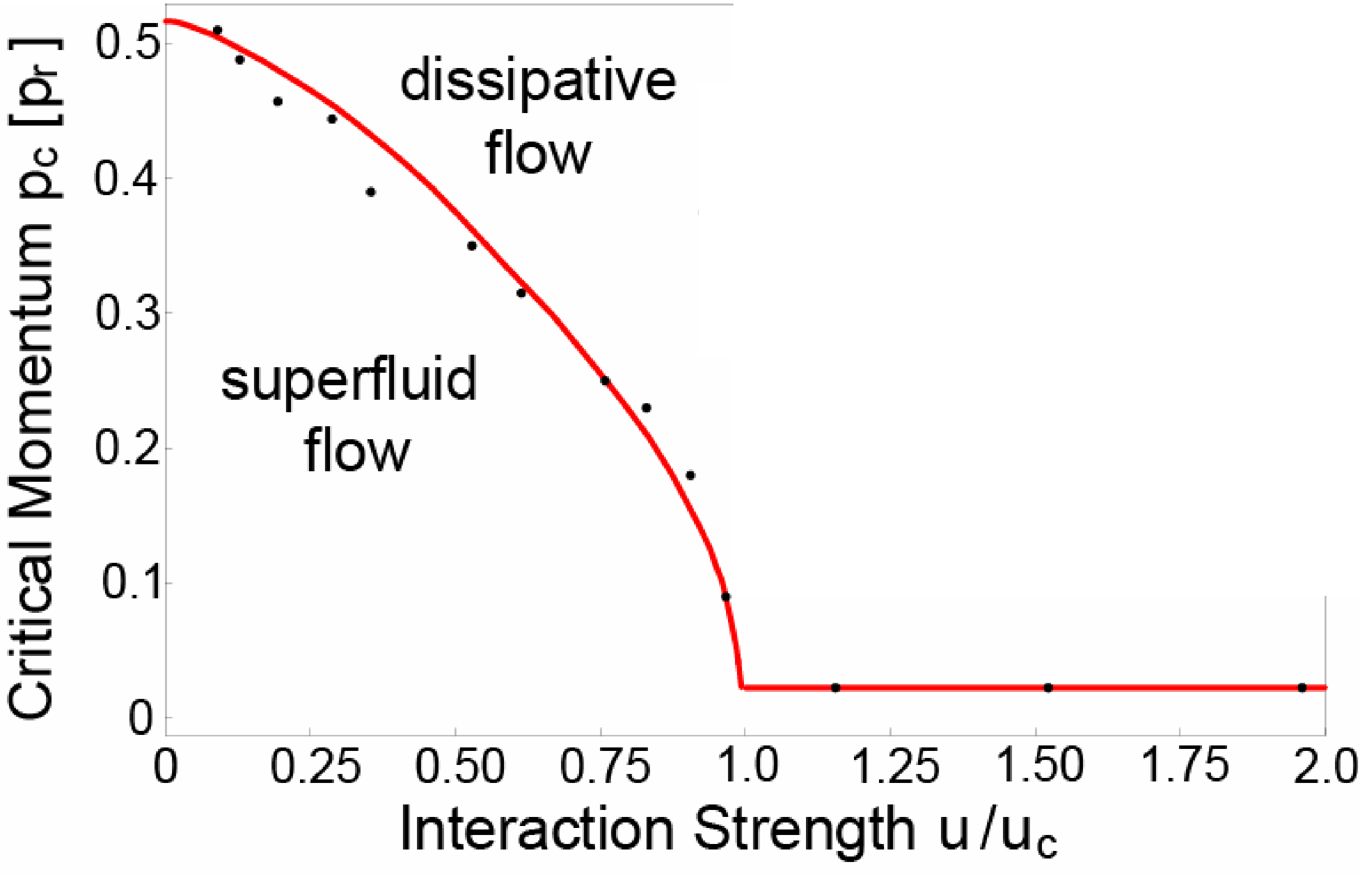


1 cycle of modulation

2 cycles

3 cycles

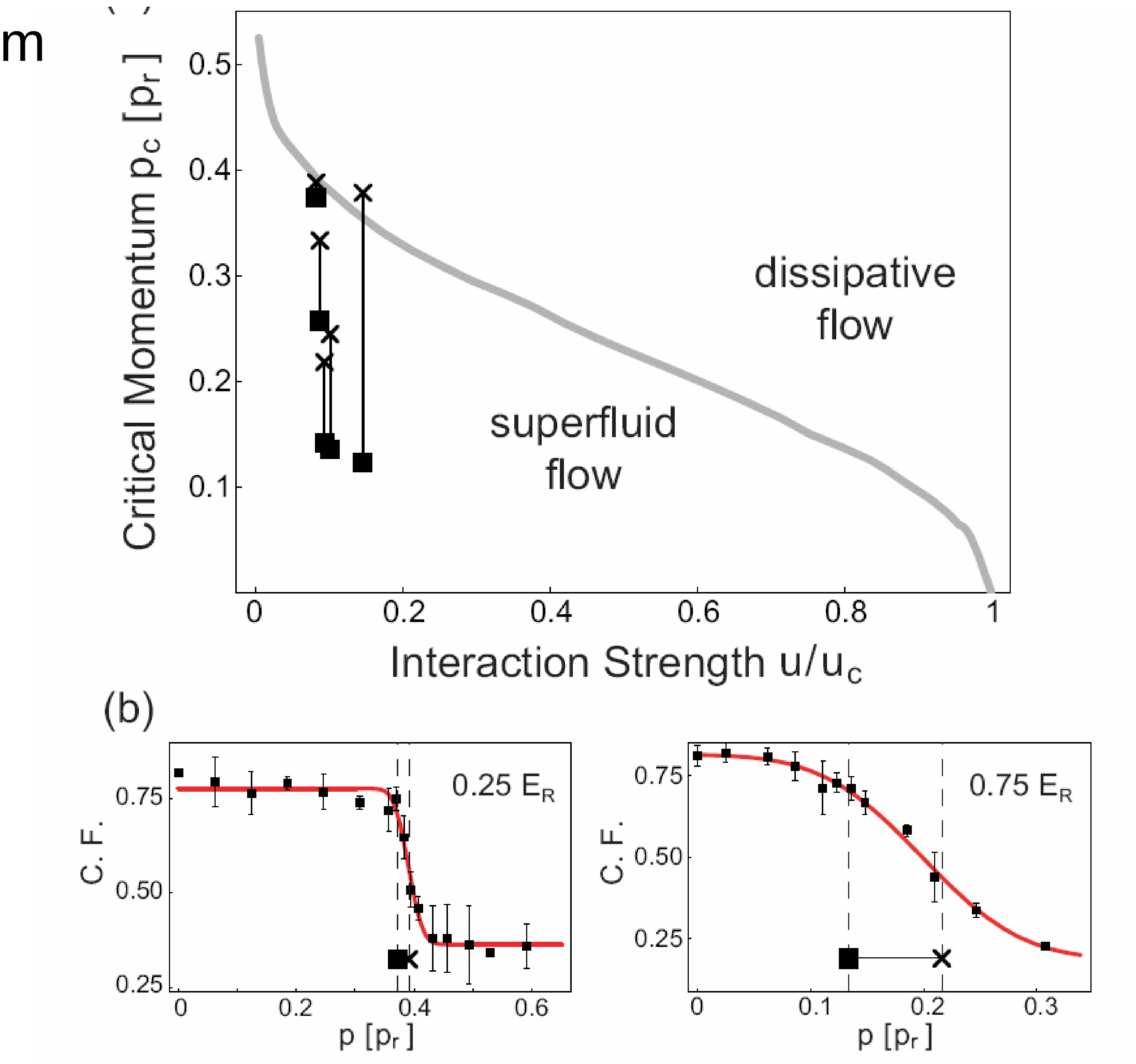
Superfluid phase diagram



Critical lattice depth for the phase transition
13.5 (+/- 0.2) E_R

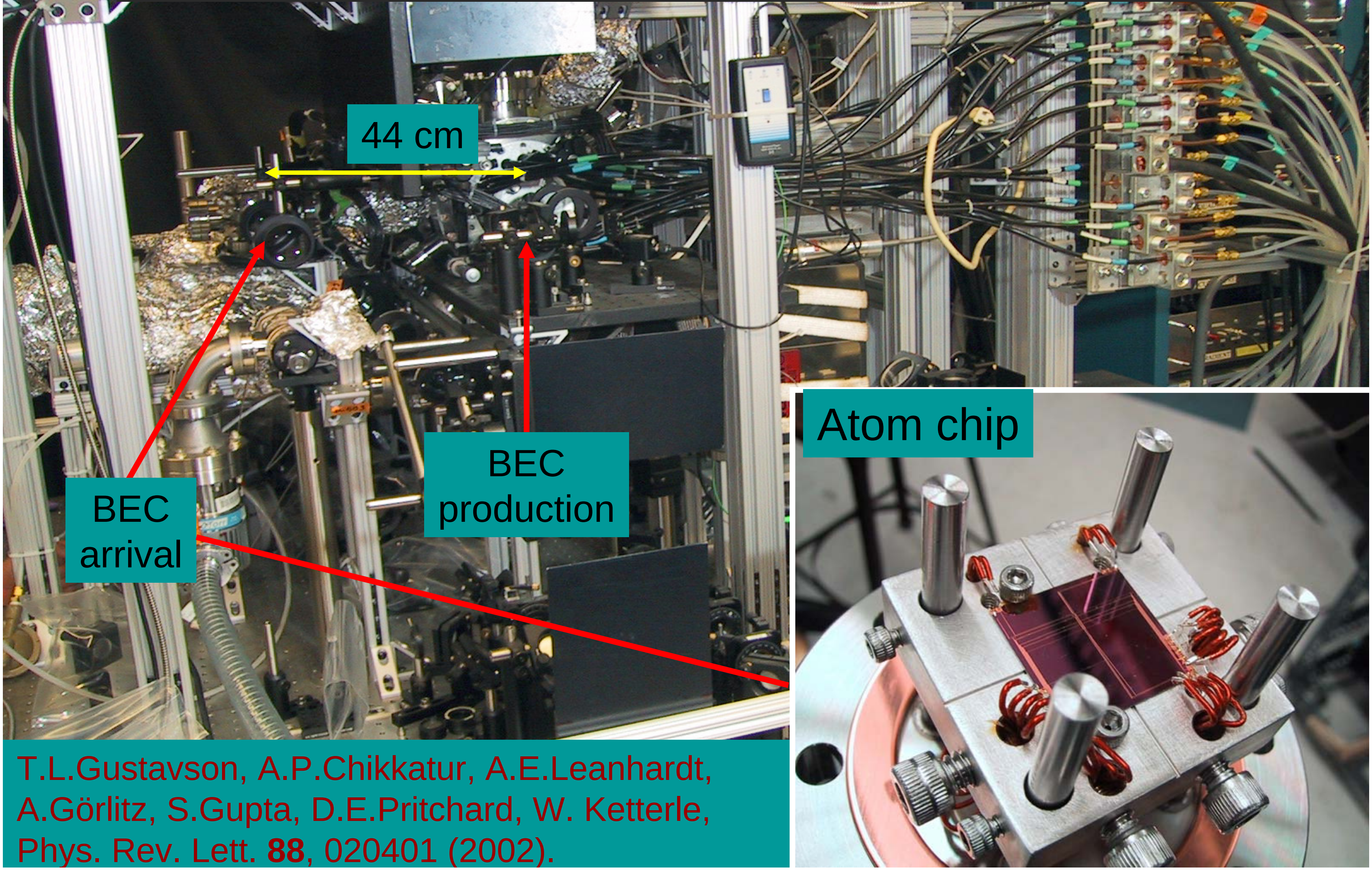
Mean field theory : 13.6 E_R (Jaksch, 1998)
Qauntum Monte Carlo : 13.0 E_R (Capogrosso-Sansone, 2007)

1D System


Critical Momentum p_c [p_r]
0.5
0.4
0.3
0.2
0.1
0
0.2
0.4
0.6
0.8
1
Interaction Strength u/u_c
dissipative flow
superfluid flow
(b)
C. F.
0.75
0.50
0.25
0
0.2
0.4
0.6
p [p_r]
0.25 E_R
C. F.
0.75
0.50
0.25
0
0.1
0.2
0.3
p [p_r]
0.75 E_R

Many-body physics to enhance an atom interferometer

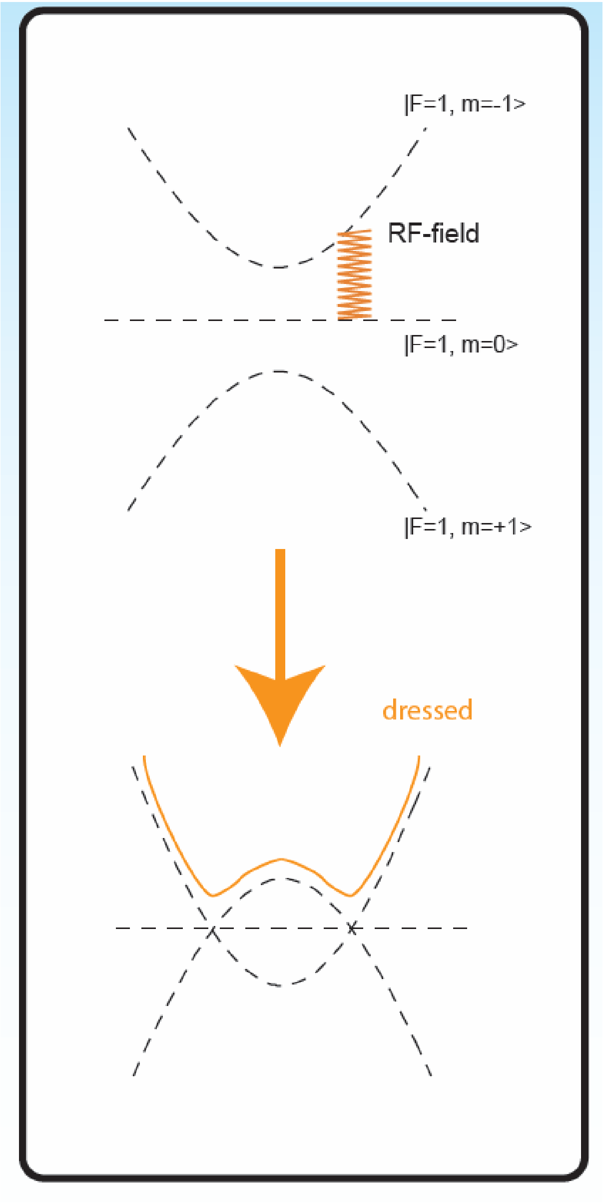
Loading sodium BECs into atom chips with optical tweezers

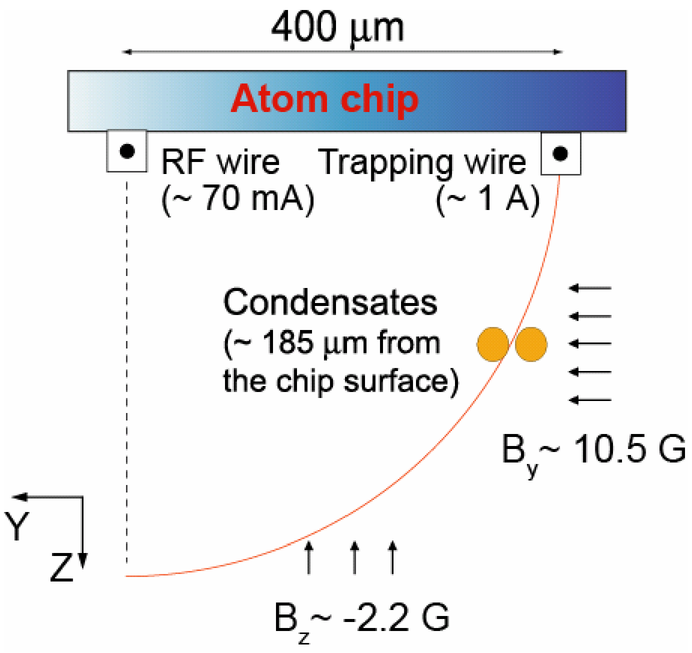


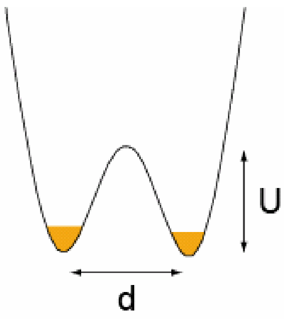
T.L.Gustavson, A.P.Chikkatur, A.E.Leanhardt, A.Görlitz, S.Gupta, D.E.Pritchard, W. Ketterle, Phys. Rev. Lett. **88**, 020401 (2002).

Coherent splitter and our double well system

RF dressed potential (Zobay, Garraway; Perrin, Schmiedmayer)

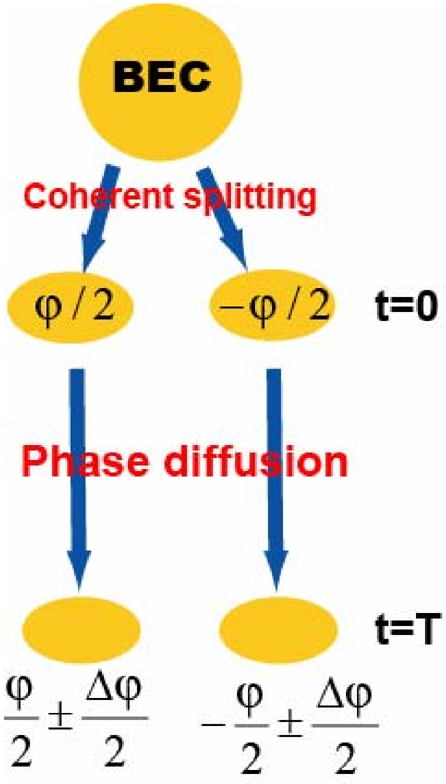






- Atom # : ~ **400,000**
- **Chemical potential : ~ $h\times$6 kHz**
- **Trap frequency : 2.1 kHz (radial), 9 Hz (axial)**
- **Lifetime at the splitting position: ~1.8 s**
- **d ~ 8.7 um U ~ $h\times$30 kHz**

Mean-field interactions → Phase diffusion



Fixed total atom number N (Fock state)

Phase coherent state (Well-defined relative phase)

$$|\varphi(t=0)\rangle = \frac{1}{2^{N/2}}\sum_{k=0}^{N}\sqrt{\binom{\mathrm{N}}{\mathrm{k}}}\,e^{i\varphi k}\,|k, N-k\rangle$$

Each of the number states $|k, N-k\rangle$ has different energy depending the relative number of atoms. (dephasing)

$$|\varphi(T)\rangle = \frac{1}{2^{N/2}}\sum_{k=0}^{N}\sqrt{\binom{\mathrm{N}}{\mathrm{k}}}\,e^{i\varphi k}\,\boxed{e^{-i\xi T(k-N/2)^2}}\,|k, N-k\rangle \quad \text{where} \quad \xi = \frac{1}{\hbar}\frac{d\mu}{dk}\bigg|_{k=N/2}$$

μ : chemical potential

Atom-atom interactions $\xi \neq 0$
scrambles the relative phase

For a harmonic trap and phase coherent state :

$$R = \frac{4\mu}{5\hbar}\frac{1}{\sqrt{N}}$$

Typical coherence time ~ 20ms

Phase diffusion rate $R = \tau_c^{-1} = \frac{1}{\hbar}\left(\frac{d\mu}{dN_i}\right)_{N_i = N/2} \Delta N_r$

Extending Coherence time & Number squeezing

Classical state vs **Non-classical state**

phase coherent state

Uncertainty $\Delta N \sim \sqrt{N}$

$\Delta\varphi \sim 1/\sqrt{N}$

τ_c

atom shot-noise limit

$1/\sqrt{N}$

Coherence time

Quantum measurements

Number-squeezed state

Uncertainty $(s>1)$ $\Delta N \sim \sqrt{N}/s$

$\Delta\varphi \sim s/\sqrt{N}$

$\tau_c \times s$

Heisenberg limit

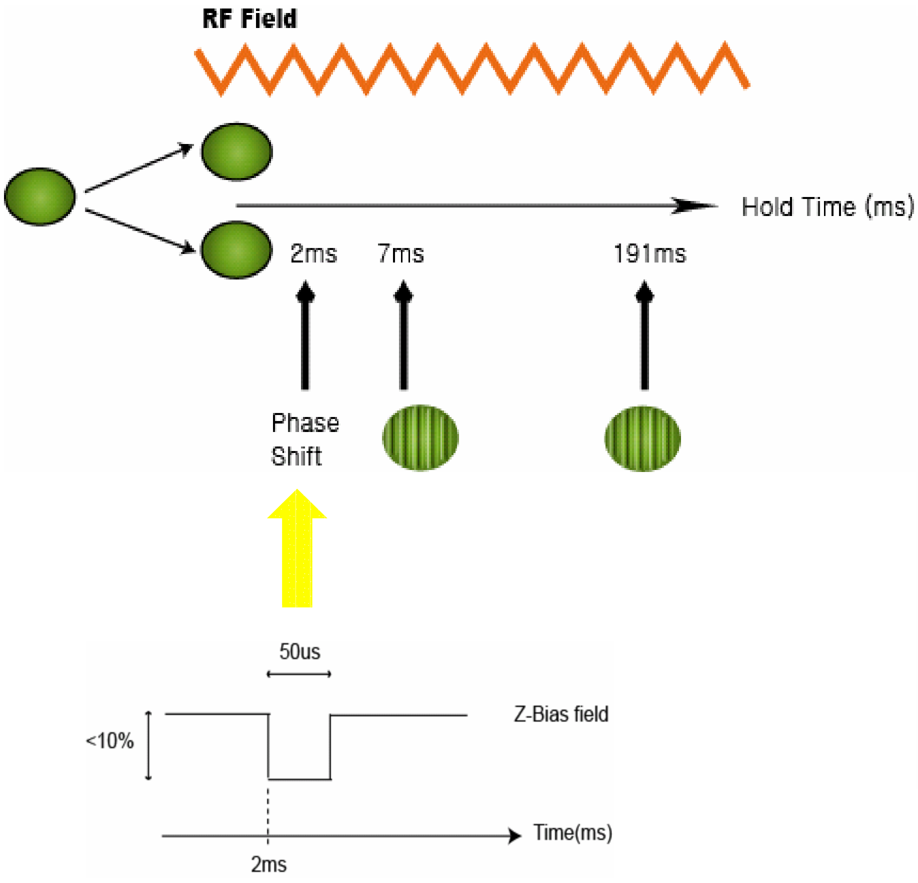
$1/N$

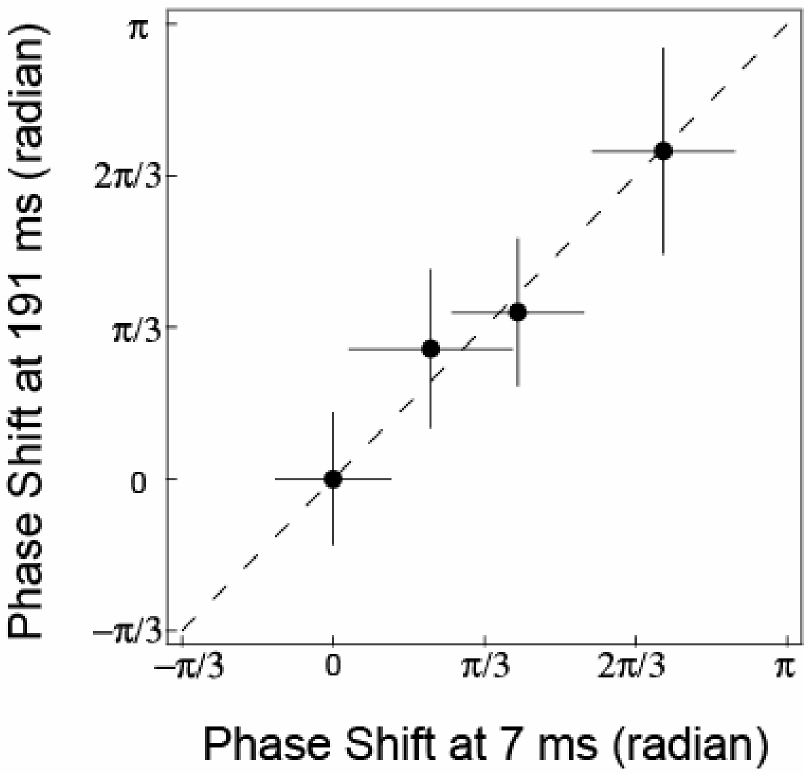
Observed number squeezed state in an atomic sample

Optical lattice (C.Orzel et al., Science **291**, 2386
M.Greiner et al., Nature **415**, 39)
Optical trap (C.-S.Chuu et al., PRL **95**, 260403)

Small atom # < 1000

Applying various phase shifts on the condensates at 2ms after splitting, the shifts of the relative phase were measured at 7ms and 191ms





Strong correlation !

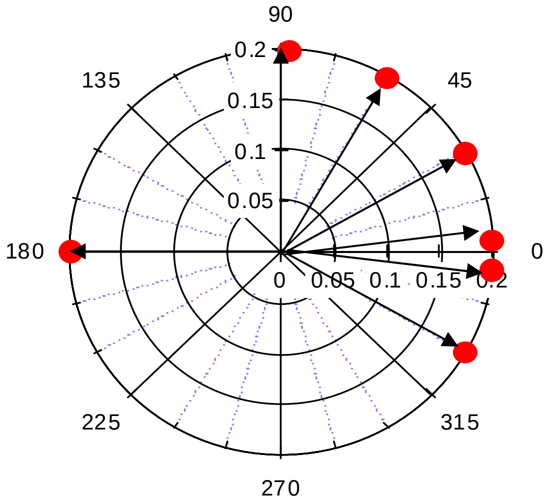
Phase coherence time ~ 200 ms

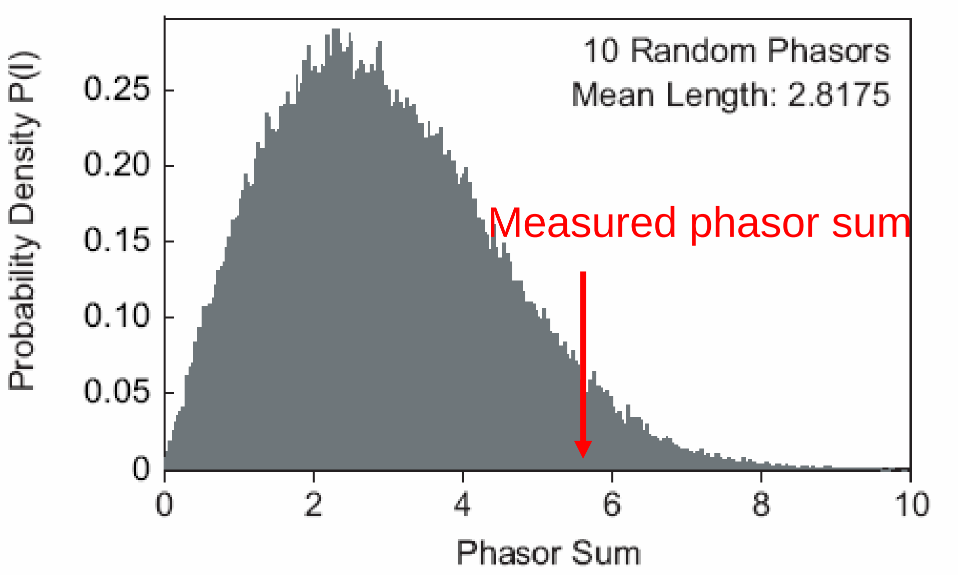
← Number squeezing?

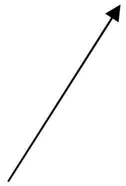
Quantitative study of phase fluctuation : Circular data analysis

- **Relative phase : measured modulo 2π**

Randomness (Rayleigh Test)

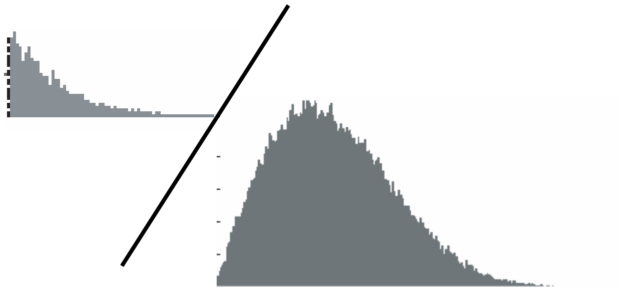


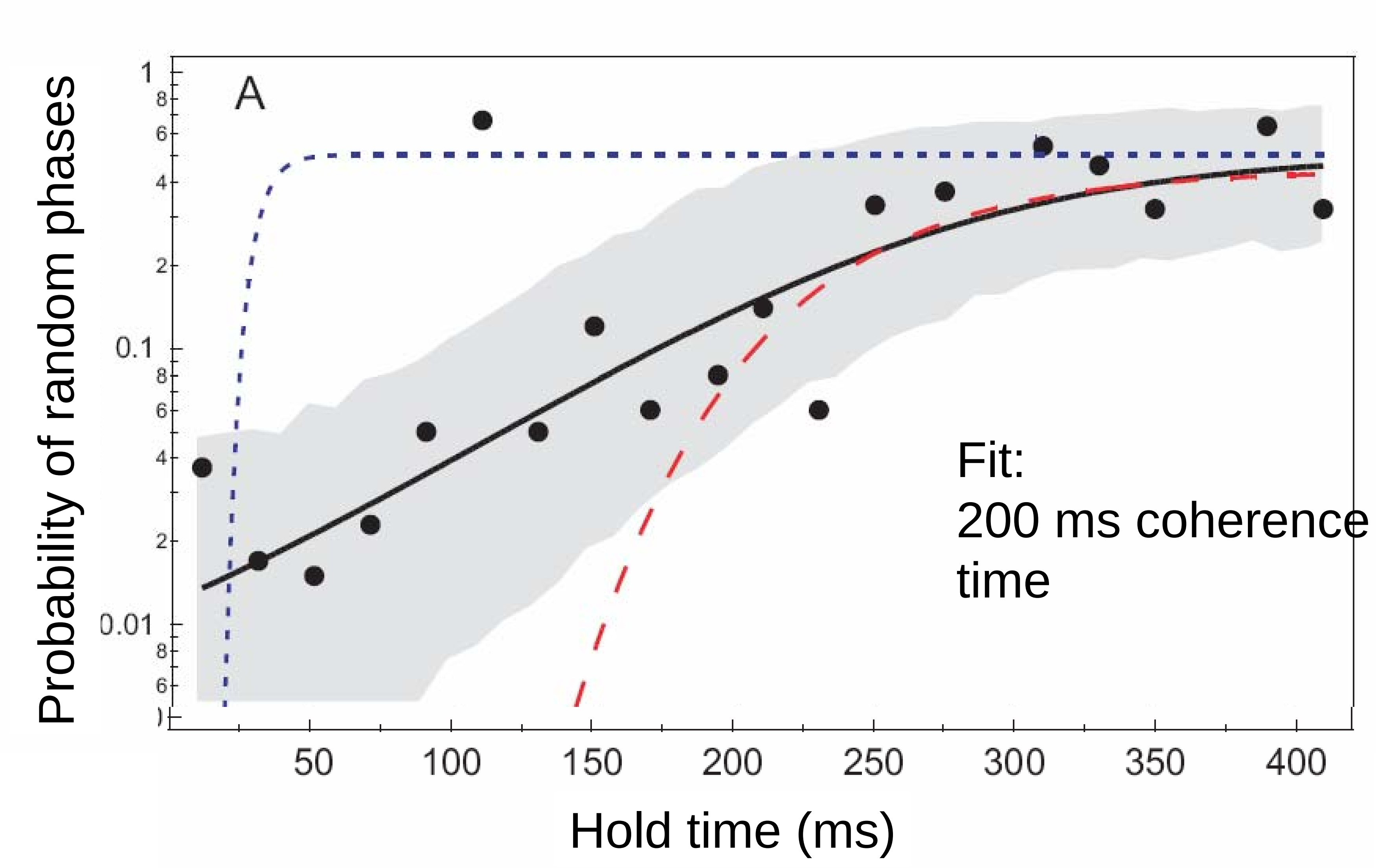




: Phasor vector

Randomness =





Fit:
200 ms coherence time

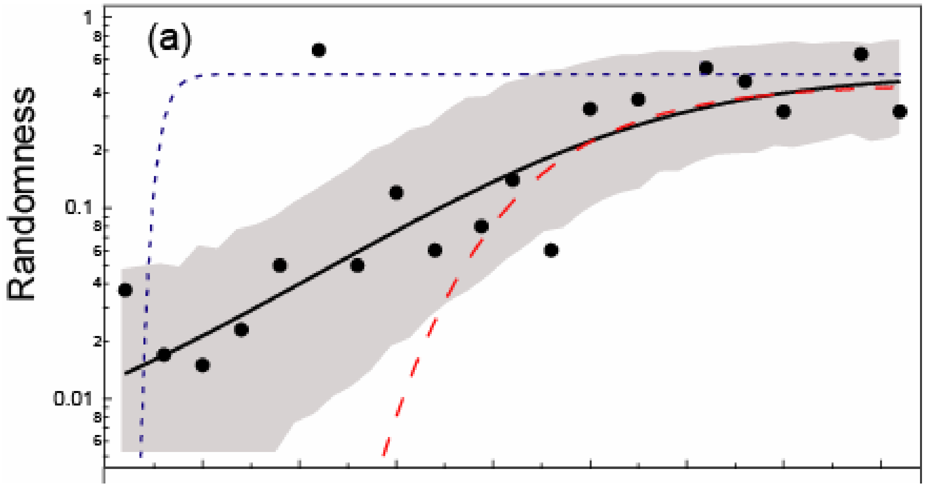
Squeezing by a factor of 10: $\Delta N = \sqrt{N}\,/10$

G.-B. Jo, Y. Shin, S. Will, T. A. Pasquini, M. Saba, M. Vengalattore,
M. Prentiss, W. K., D. E. Pritchard, Phys. Rev. Lett. 98, 030407 (2007)

Phase diffusion and Number squeezing

Phase diffusion model

$$\Delta\phi(t)^2 = \Delta\phi_0{}^2 + (Rt)^2$$



Blue curve : phase coherent state

$$R \cong 50 \quad \tau_c \cong 20\ ms$$

Red curve : Number squeezed state (s=10)

$$R \cong 5 \quad \tau_c \cong 200\ ms$$

Black curve : fitted curve including the initial variance $\Delta\phi_0{}^2$

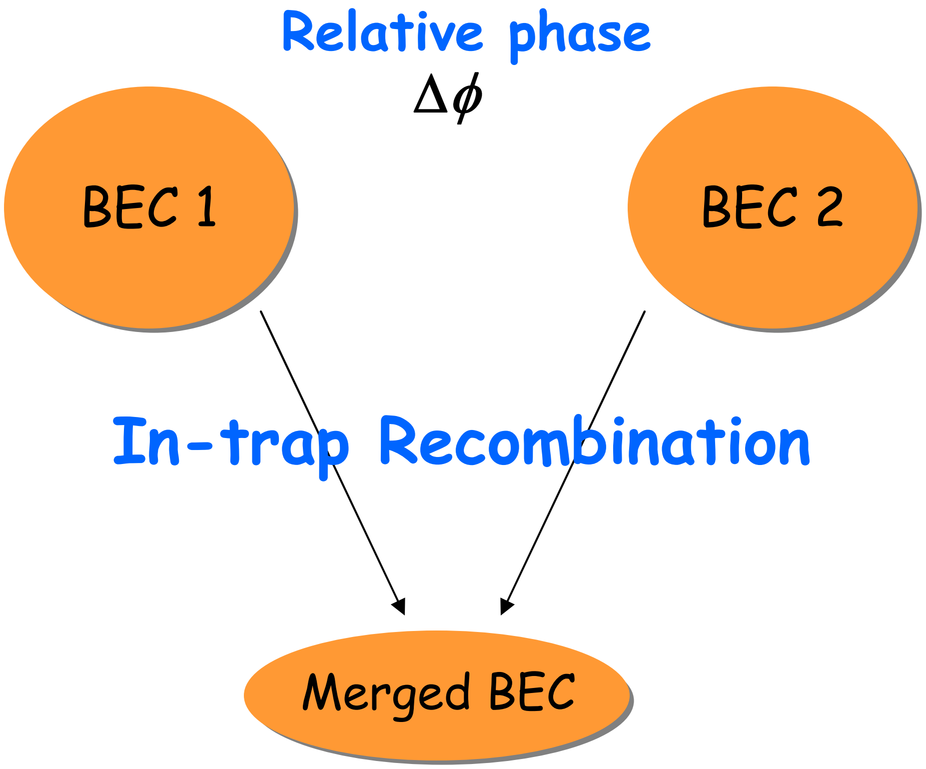
$$\Delta\phi_0{}^2 = (0.28\pi)^2, \quad R = 5$$

- **Number squeezing factor s > 10**

How to read out an atom interferometer using many-body physics

G.-B. Jo, J.-H. Choi, C.A. Christensen, T.A. Pasquini, Y.-R. Lee, W. K, D.E. Pritchard: *Phase Sensitive Recombination of Two Bose-Einstein Condensates on an Atom Chip, Phys. Rev. Lett. 98, 180401 (2007).*

Motivation 1 : Fundamental aspect



Relative phase

$\Delta\phi$

BEC 1

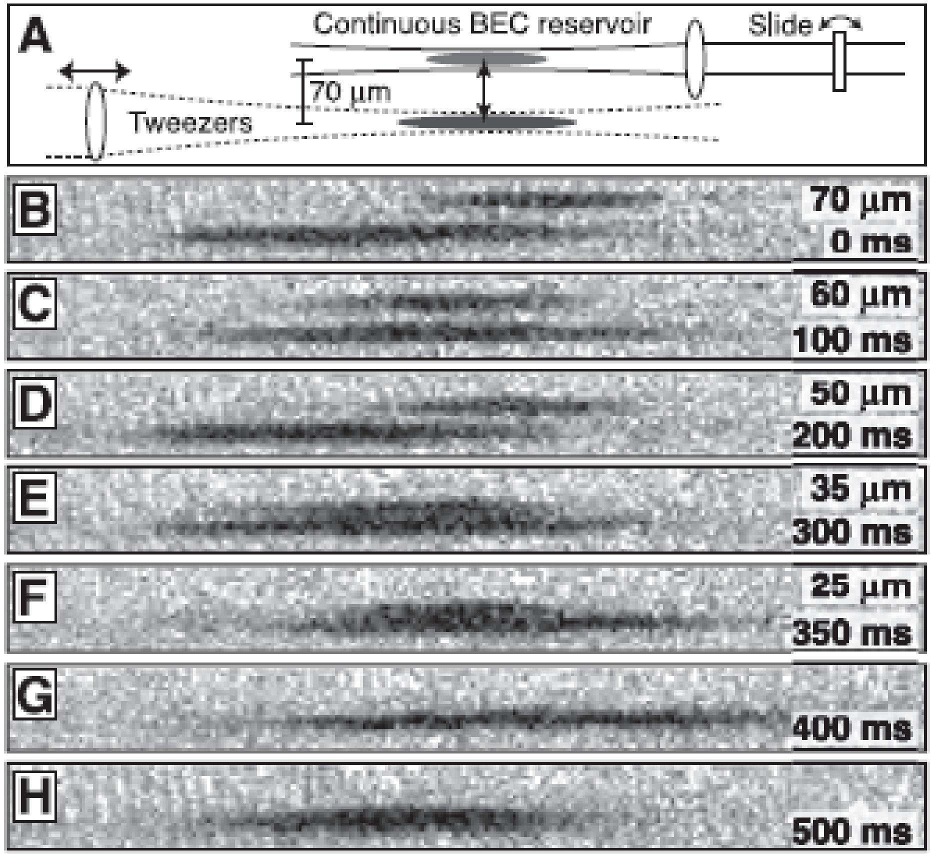
BEC 2

In-trap Recombination

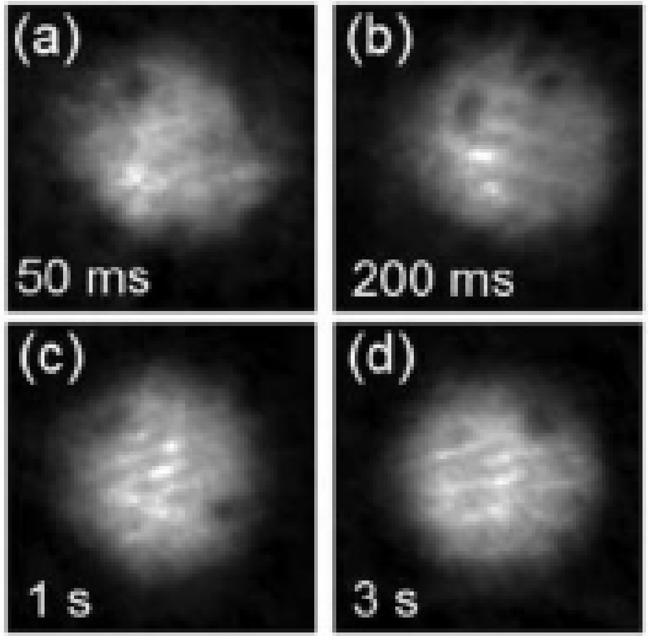
Merged BEC

What happens in the recombination process ?

: uncontrolled relative phase



Replenish a continuous BEC
(MIT, 2002)



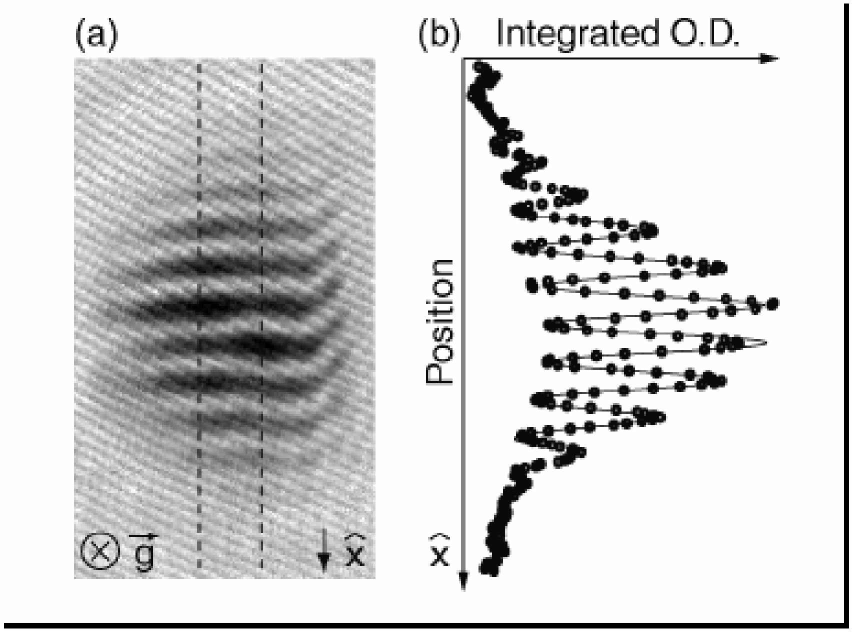
Vortex Formation by Merging BECs
(Arizona, 2007)

In-trap Recombination of two BECs with well-defined relative phase

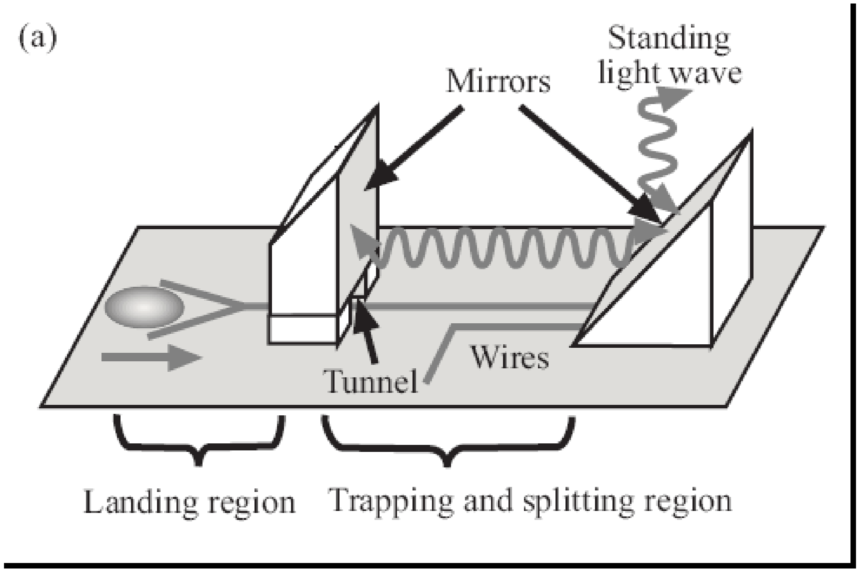
Motivation 2 : Atom Interferometer

Reliable Phase Read-out

Reduce the atomic density before recombination
(avoid the deleterious effect of atom-atom interactions)



Matter-wave Interference
(MIT, 2004)



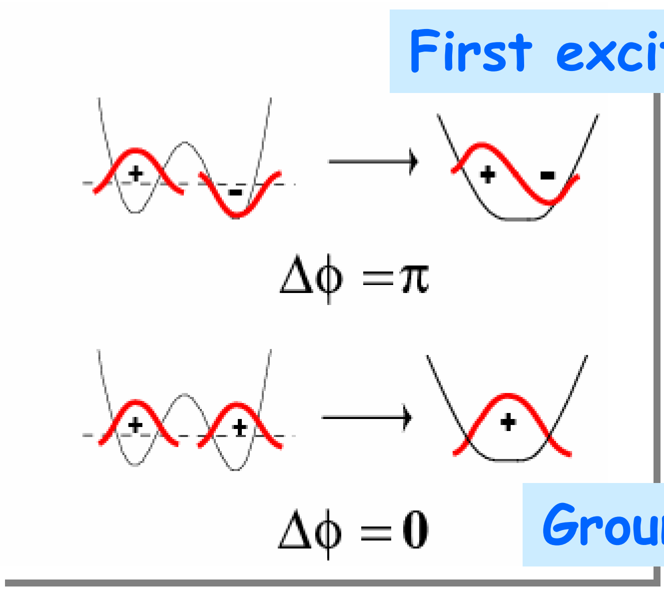
Atom Michelson Interferometer
(JILA, 2004)

In-trap Recombination of Two Bose-Einstein Condensates

: Two extreme cases

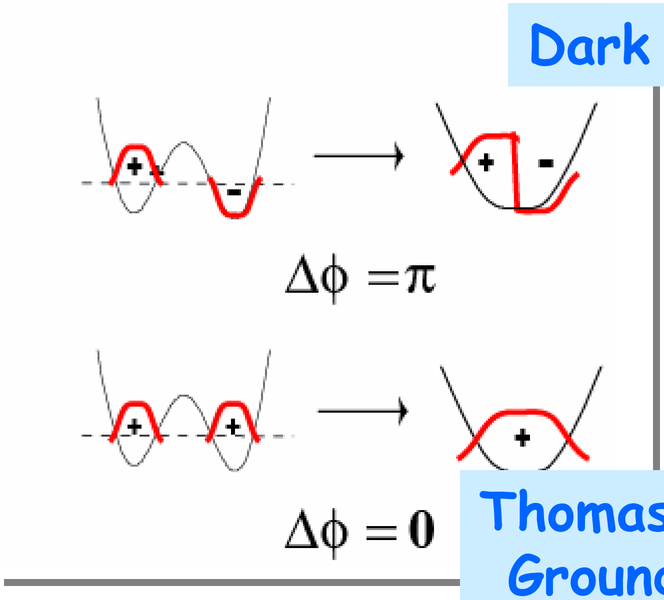
Adiabatic merger of non-interacting condensates

Sudden merger of interacting condensates



First excited state

Ground state

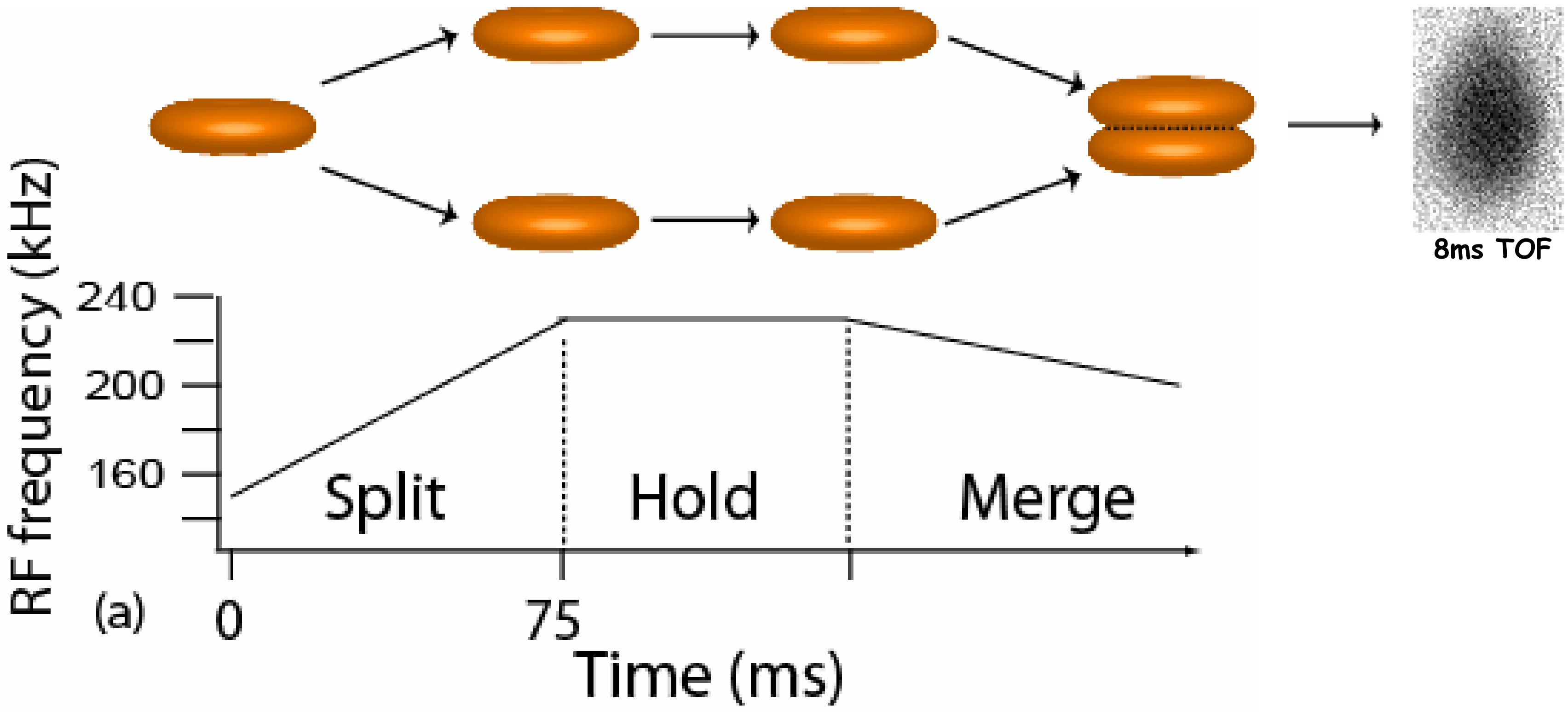


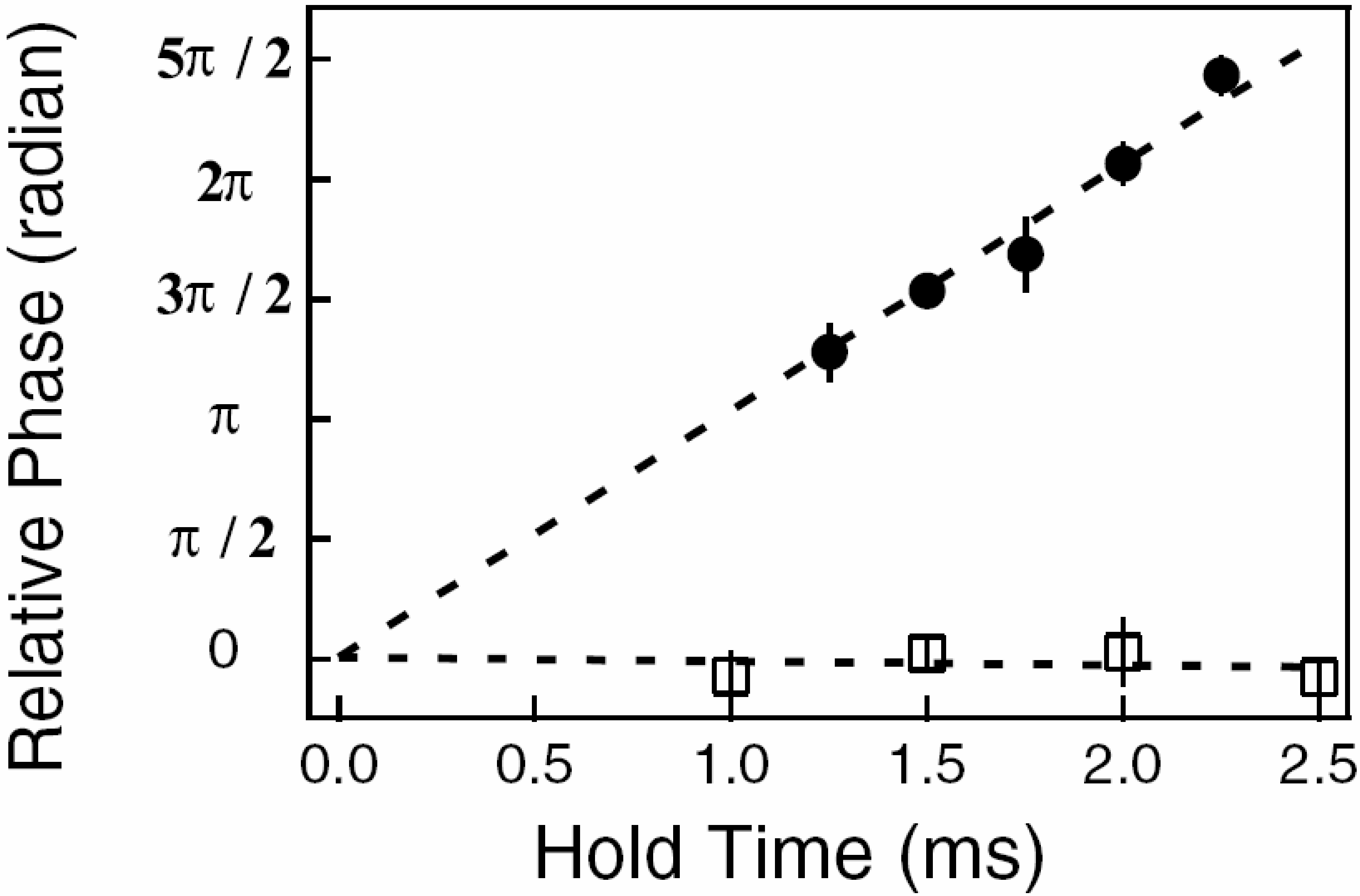
Dark Soliton

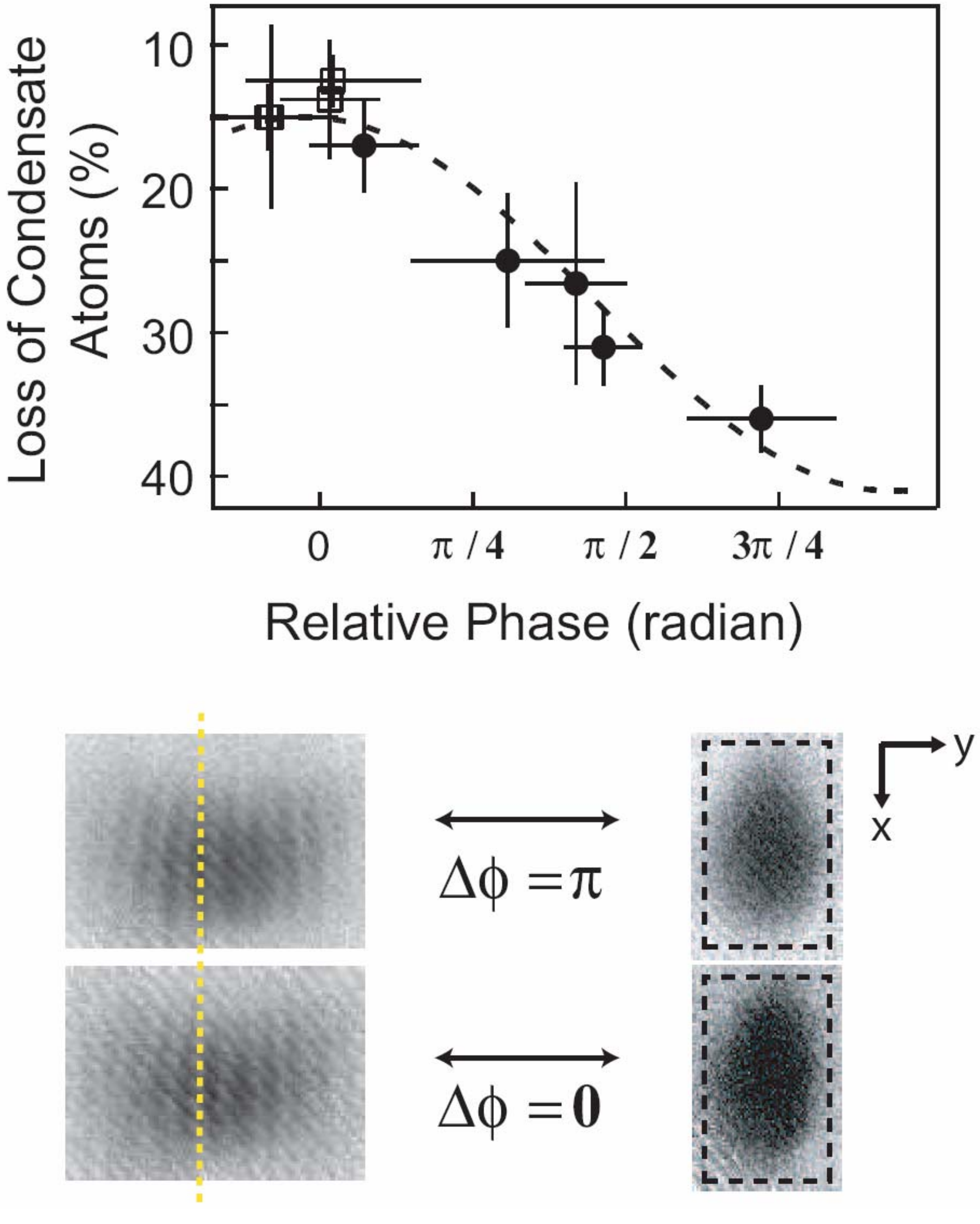
Thomas-Fermi Ground state

Energy scale : 100 nK per particle

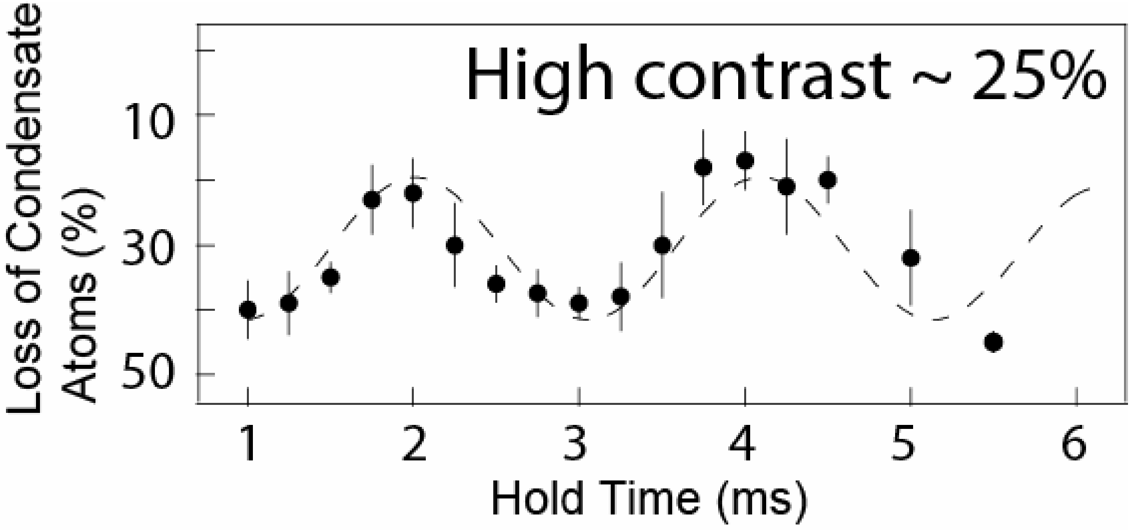
Our working assumption
: Phase-sensitive excitation of the cloud decays quickly and leads to an Increase in temperature


8ms TOF
RF frequency (kHz)
240
200
160
Split
Hold
Merge
(a)
0
75
Time (ms)


Relative Phase (radian)
5π / 2
2π
3π / 2
π
π / 2
0
0.0
0.5
1.0
1.5
2.0
2.5
Hold Time (ms)


Loss of Condensate Atoms (%)
10
20
30
40
0
π / 4
π / 2
3π / 4
Relative Phase (radian)
Δϕ = π
Δϕ = 0
y
x

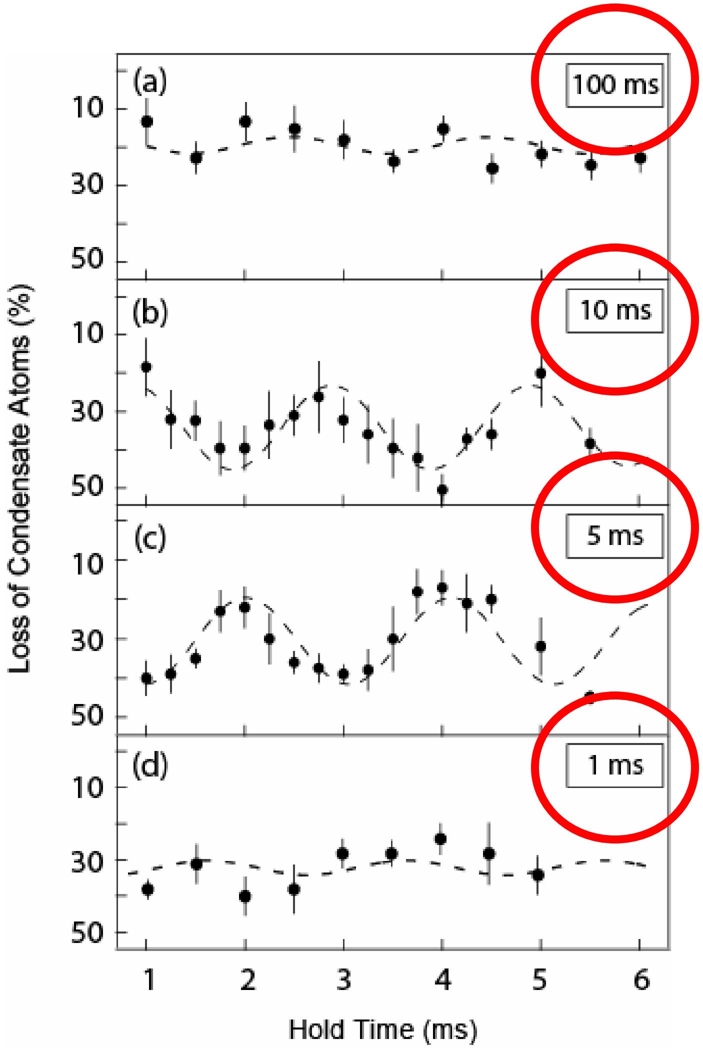
New Phase Read-out for an Atom Interferometer

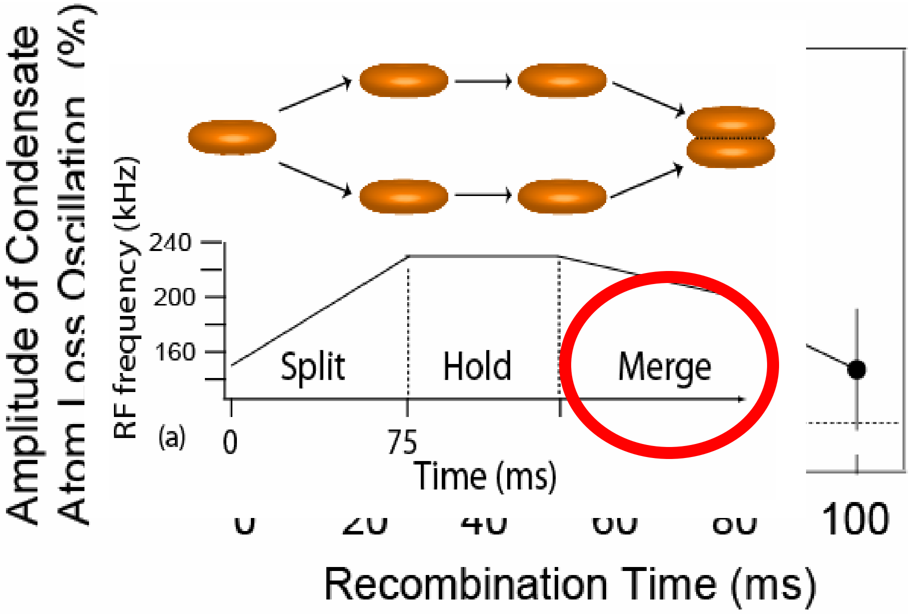


New Phase readout method possible without ballistic expansion

- **Atom recycling possible**
- **Cavity enhanced detection possible**

Recombination Time and Condensate Atom Loss



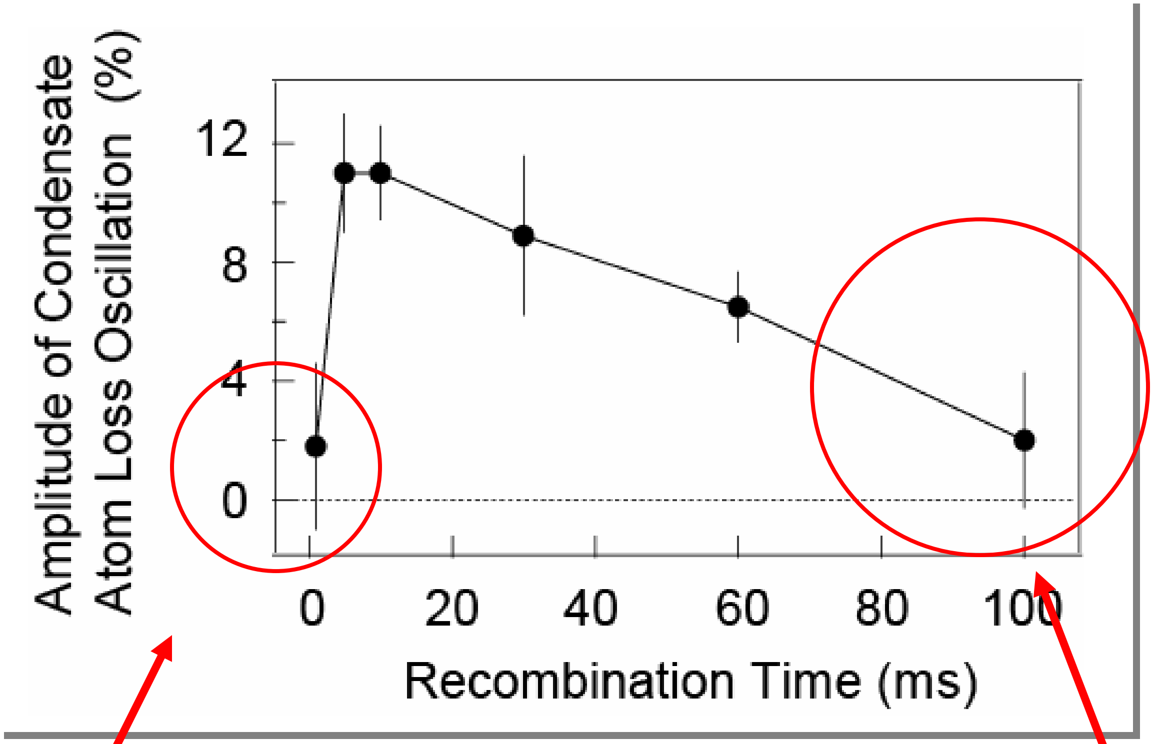


Phase sensitive recombination works over a wide range of Recombination rates.

5 ~ 30 ms recombination time

Recombination Time and Condensate Atom Loss

The dependence of the condensate atom loss on the recombination time allows us to speculate about different excitations caused by the merging process.



Significant loss
due to mechanical
excitations

Small loss
Relaxation of the phase-sensitive
excitation ?

Atom interferometry with phase-fluctuating Bose-Einstein condensates

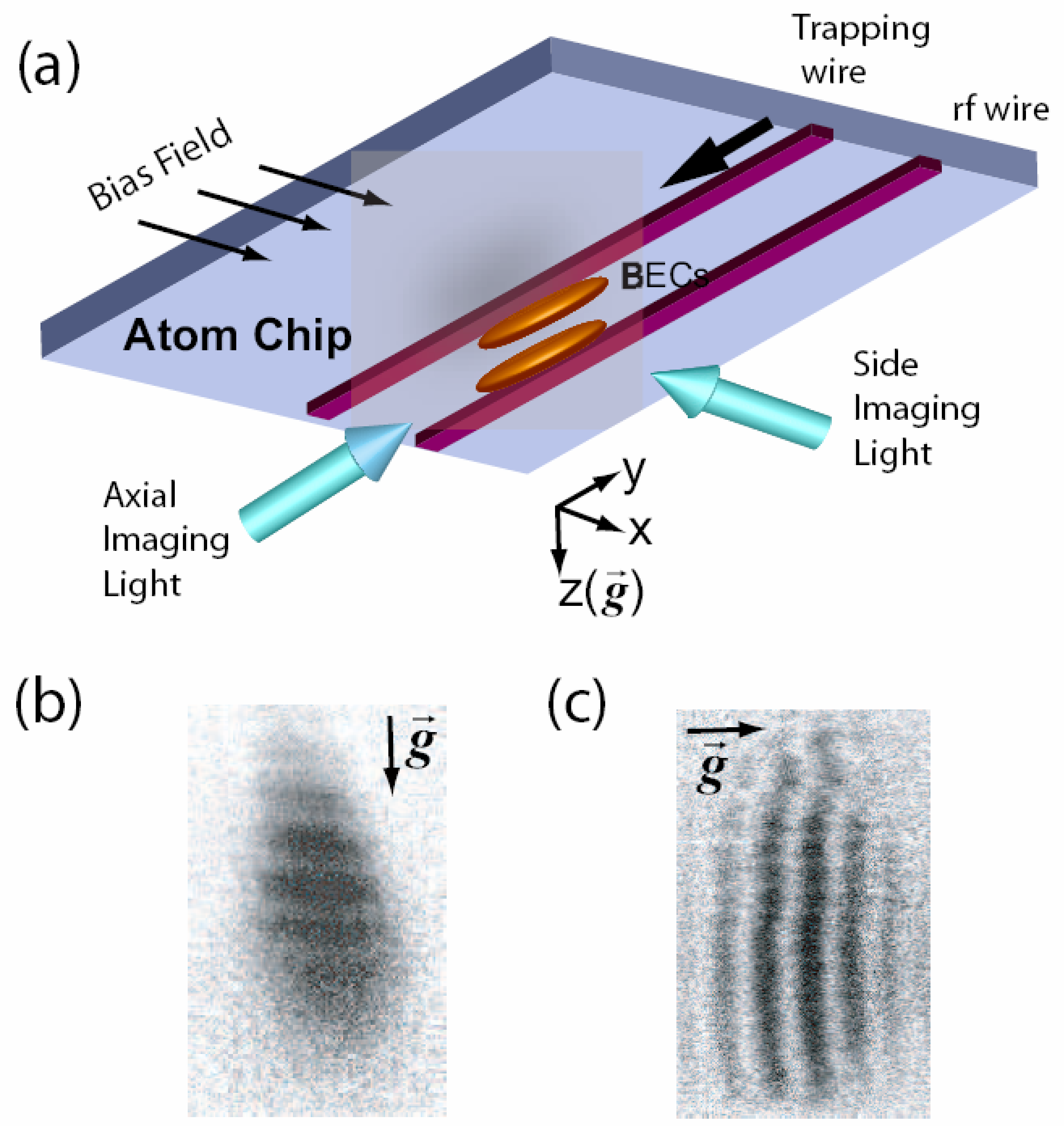
G.-B. Jo, J.-H. Choi, C.A. Christensen, Y.-R. Lee, T.A. Pasquini, W. K, D.E. Pritchard, to be published.

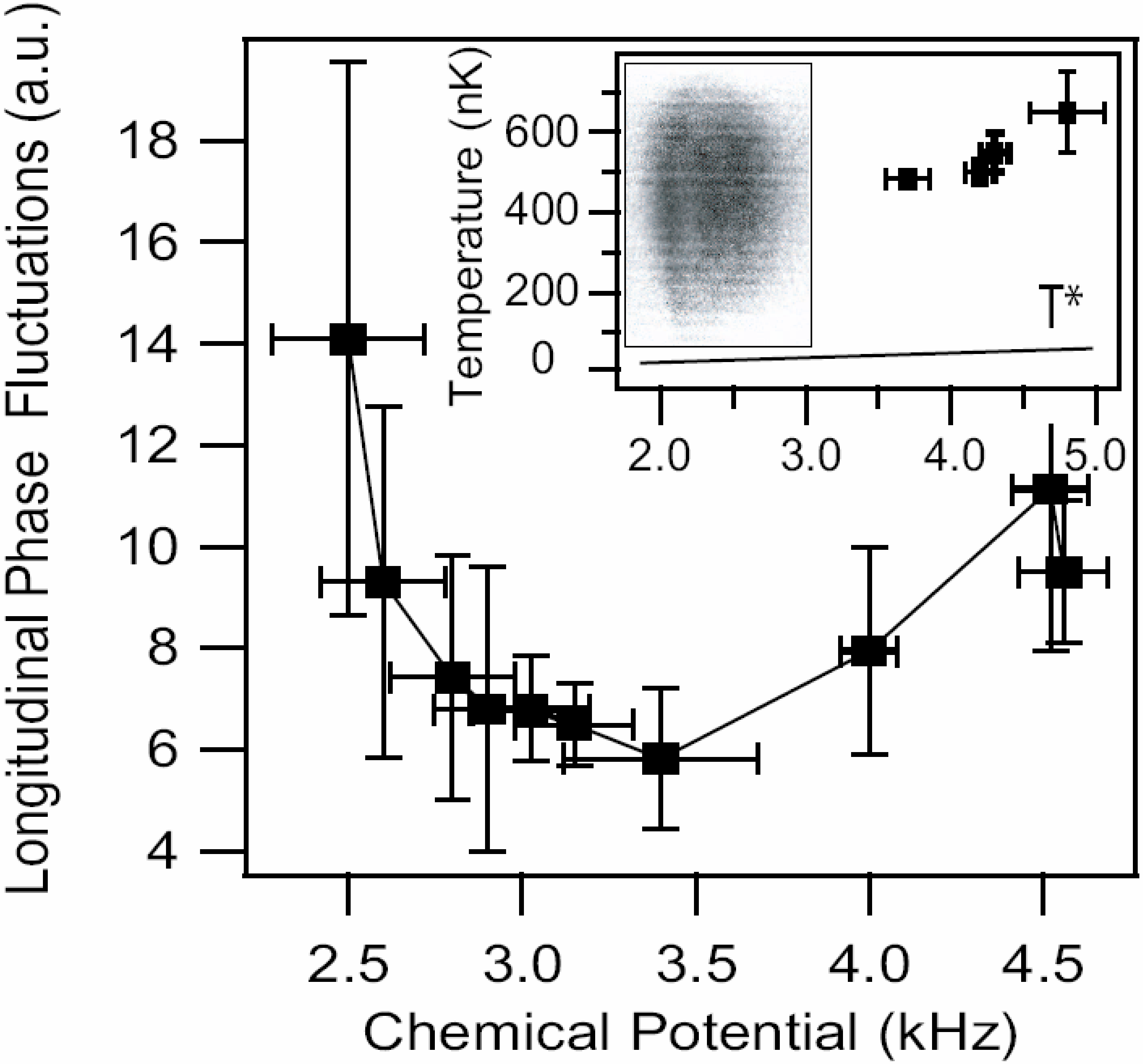
For highly elongated BECs:

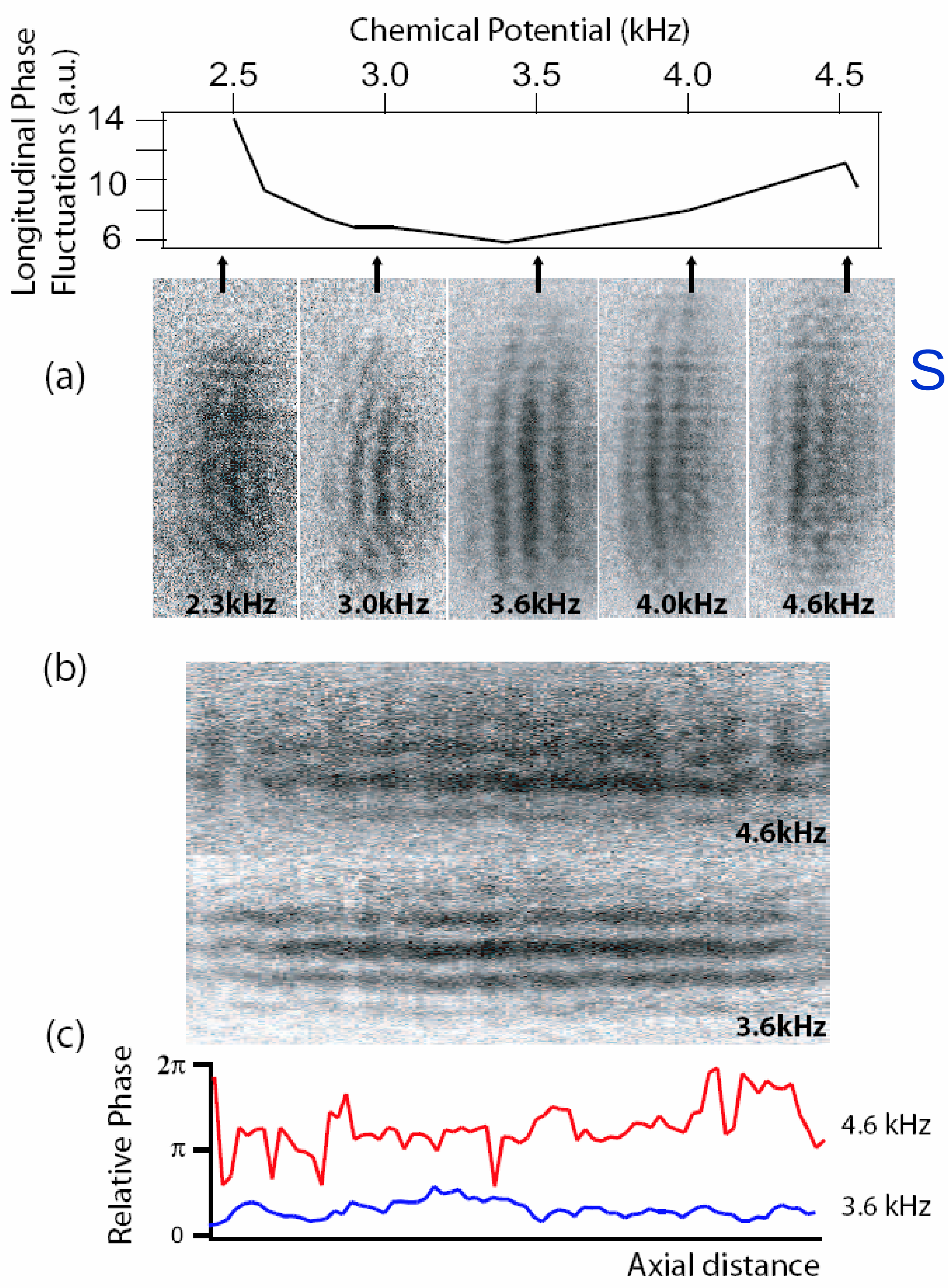
$T^* << T_c$

$$T^* = \frac{15N(h\omega_z)^2}{32\mu}$$

$$L_{coh}/L_{cond} = T^*/T$$

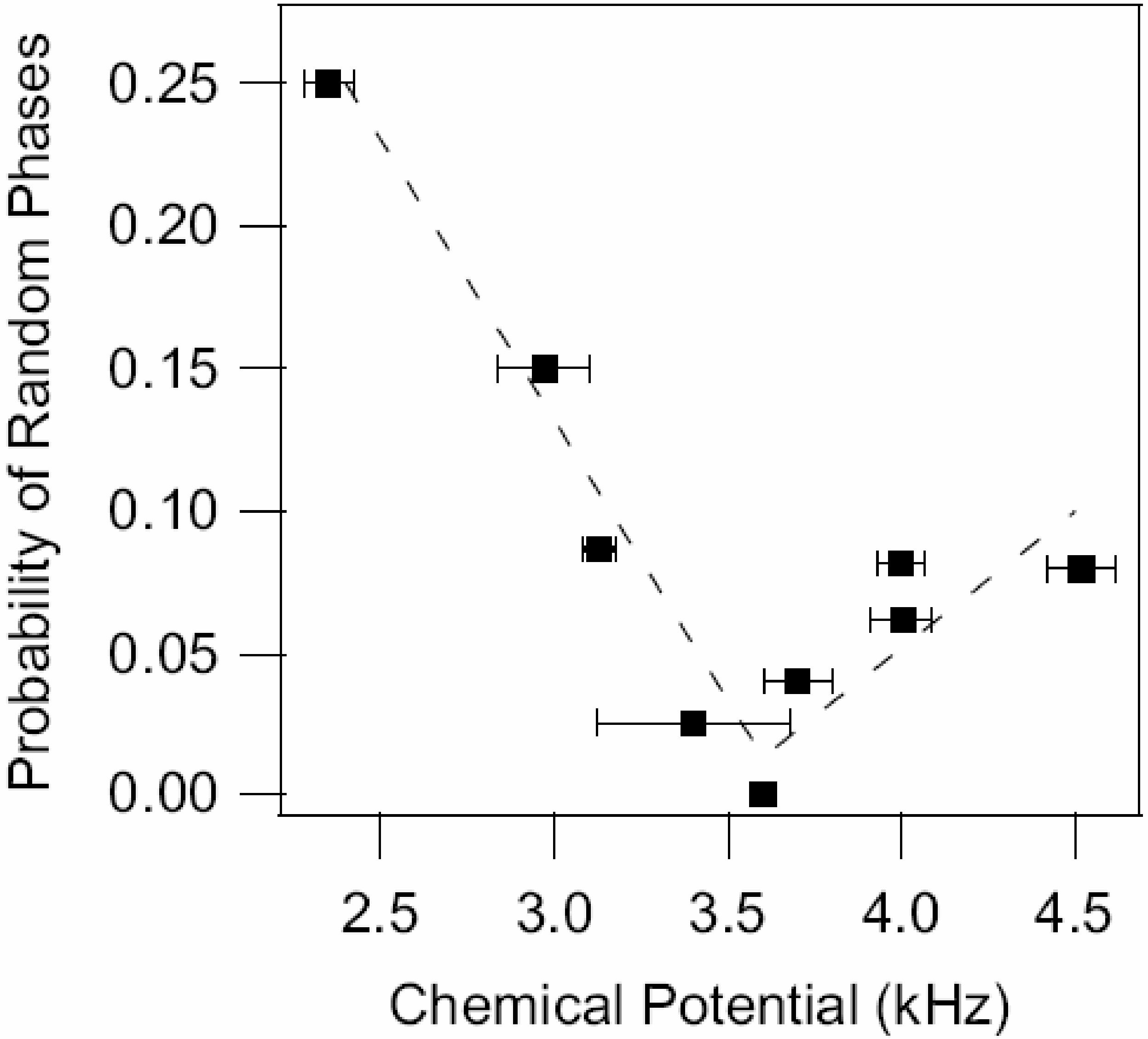

(a)
Trapping wire
rf wire
Bias Field
BECs
Atom Chip
Side Imaging Light
Axial Imaging Light
y
x
z($\vec{g}$)
(b)
$\vec{g}$
(c)
$\vec{g}$

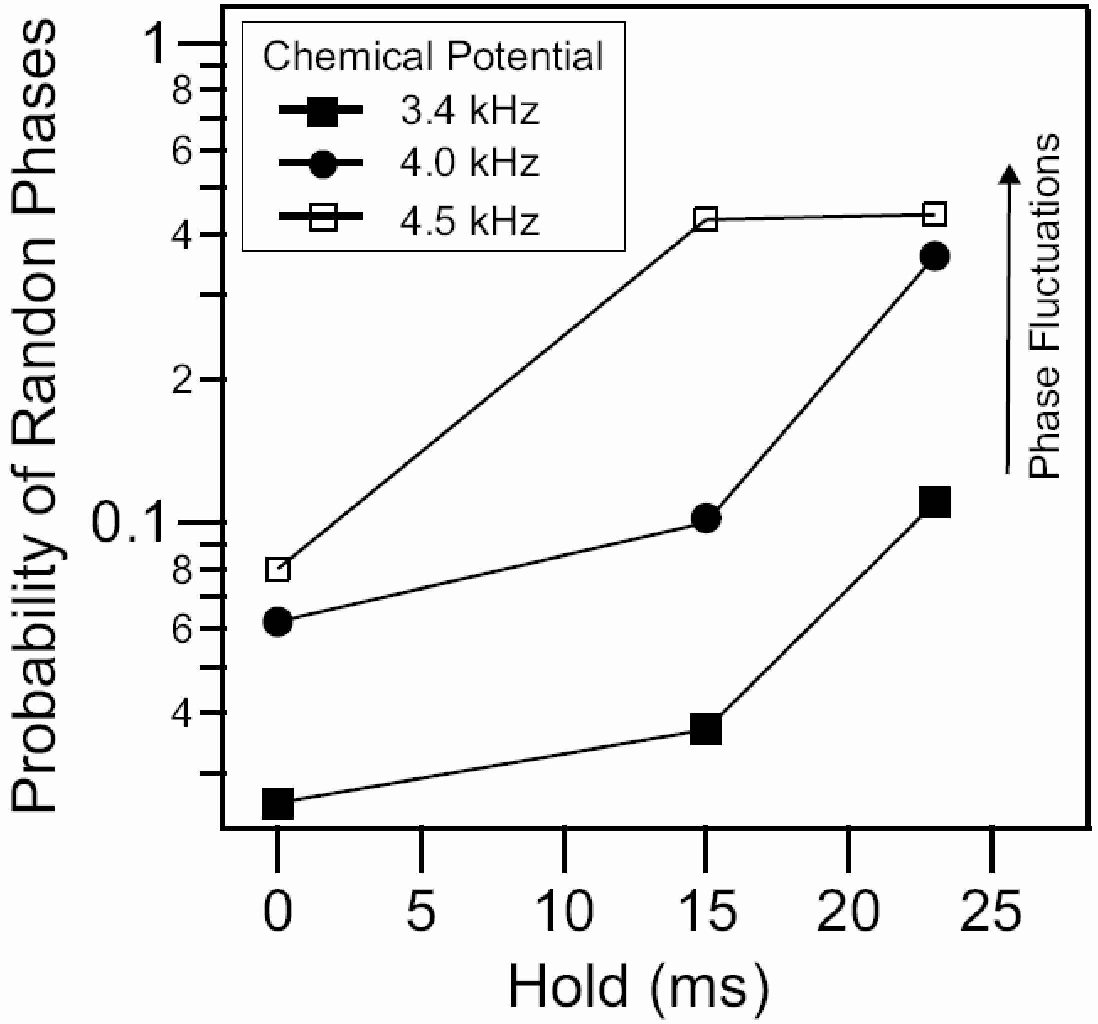

Longitudinal Phase Fluctuations (a.u.)
18
16
14
12
10
8
6
4
2.5
3.0
3.5
4.0
4.5
Chemical Potential (kHz)
Temperature (nK)
600
400
200
0
T*
2.0
3.0
4.0
5.0

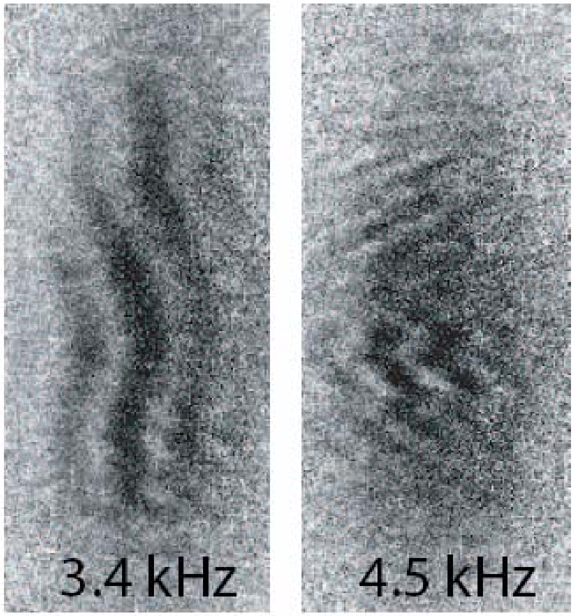


Spatial phase fluctuations are common mode for relative phase

Atom interferometer is robust against phase fluctuations


Probability of Random Phases
0.25
0.20
0.15
0.10
0.05
0.00
2.5
3.0
3.5
4.0
4.5
Chemical Potential (kHz)


Chemical Potential
3.4 kHz
4.0 kHz
4.5 kHz
Phase Fluctuations
Probability of Randon Phases
1
8
6
4
2
0.1
8
6
4
0
5
10
15
20
25
Hold (ms)


3.4 kHz
4.5 kHz

23ms Hold

Interpretation:

Quantum fluctuation suppressed by strong squeezing
Squeezing factor of 30!

Interferometer with phase-fluctuating condensates is very sensitive to relative displacements!

Conclusions

Atom interferometry is robust against

- High density, atom interactions
- Phase fluctuations

Interesting physics mitigates bad effect of interactions

BEC I

Ultracold fermions

Christian Schunck
Andre Schirotzek
Yong-Il Shin

BEC II

Na, Li
Optical Lattices

Jit Kee Chin
Daniel Miller
Yingmei Liu
Widagdo Setiawan
Christian Sanner
Aviv Keshet

BEC III

Atom chips, surface atom optics

Tom Pasquini
Gyu-Boong Jo
Caleb Christensen
Ye-ryoung Lee
Jae Choi
Tony Kim
D.E. Pritchard

BEC IV

Atom optics and optical lattices

Jongchul Mun
Patrick Medley
David Hucul
David Weld
D.E. Pritchard

$$
NSF
ONR
DARPA