Lecture III
Coherent Manipulation and Interference

Internal states
Qubit
Double well @ chip
RF dressed double well
Coherent splitting and interference

Review:
R. Folman et al. Adv.At.Mol.Opt.Phys. 2002

www.AtomChip.org

Coherent manipulation

internal states
RF dressed state potentials
double well interferometer

Review:
R. Folman et al. Adv.At.Mol.Opt.Phys. 2002

www.AtomChip.org

QUBIT
inernal state

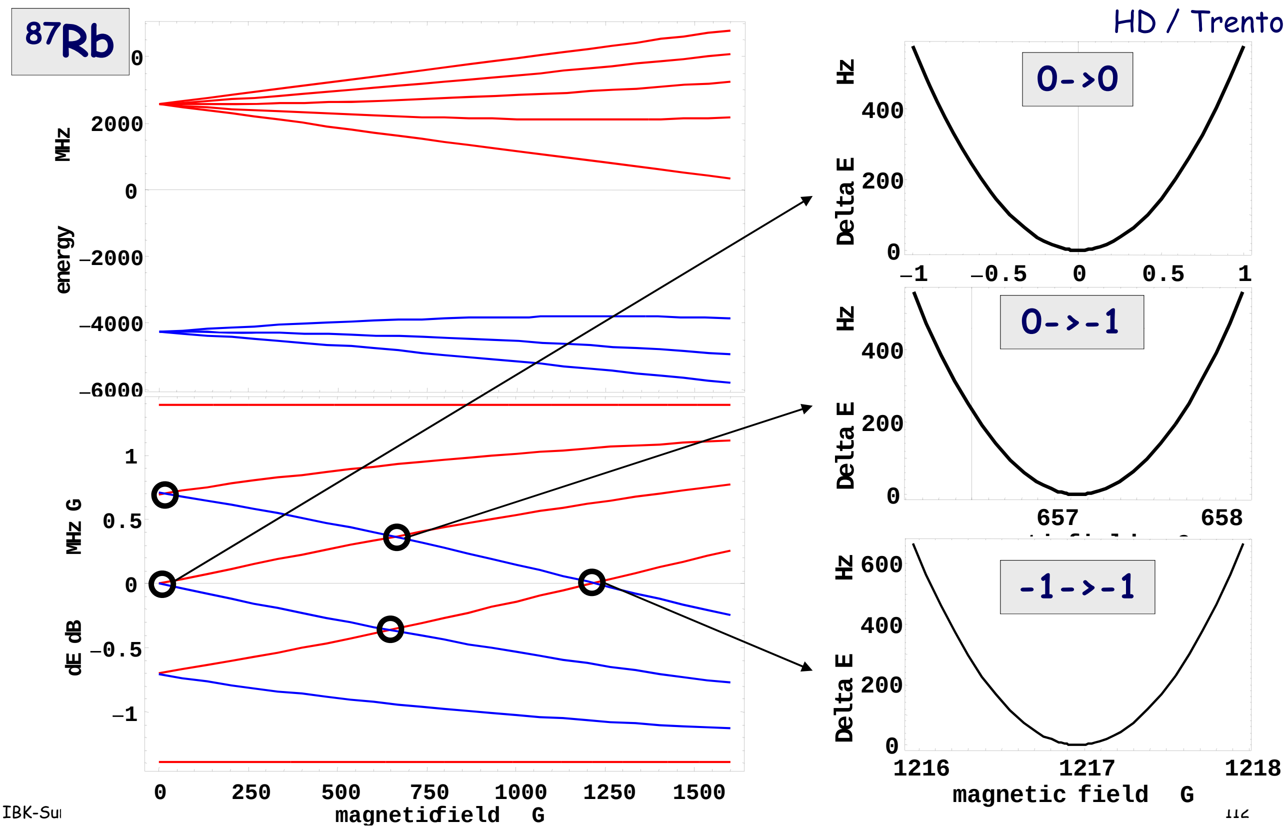
QUBIT = internal state (hyperfine state) of a neutral atom micro manipulated on Atom Chip

Requirements:

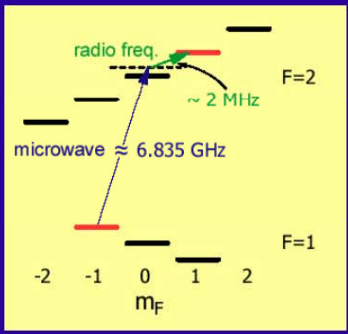
- On Atom Chip trappable states
  - Magnetic trappable states (weak field seeker)
  - Trapping in dipole traps (no restriction)
- Keep the good coherence properties close to the surface of the Atom Chip
  - Magnetic trappable Qubits:
    reduce de-coherence by choosing states with the same magnetic moment ('clock states'). Qubits are then insensitive to local fluctuations (see local magnetic field noise)

Clock States
magnetic field insensitive Qubit transitions

HD / Trento

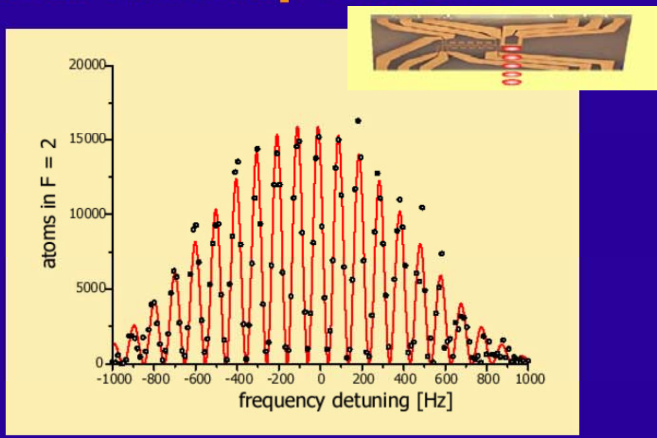


MPQ: Observation of Long Coherence Lifetimes @ 10μm Distance from the Chip Surface



Scan 2-photon detuning

$$\Delta = \nu_{MW} + \nu_{RF} - (\nu_{|2,1>} - \nu_{|1,-1>})$$



First result with ~10,000 atoms, T ~ 450 nK, n ~ 4 x 10^{12} cm^{-3}: coherence time τ ~ 2s at ~40 μm from chip wires (< 10 μm from surface)!

single shot uncertainty: 80 mHz

Precision: $\delta\nu/\nu$ = 2 x 10^{-12}

(integration time ~15 min.)

possible: $\delta\nu/\nu$ < 1 x 10^{-12} $(Hz)^{-1/2}$

Ph. Treutlein, P. Hommelhoff, T. W. Hänsch and J. Reichel, to be published

LMU

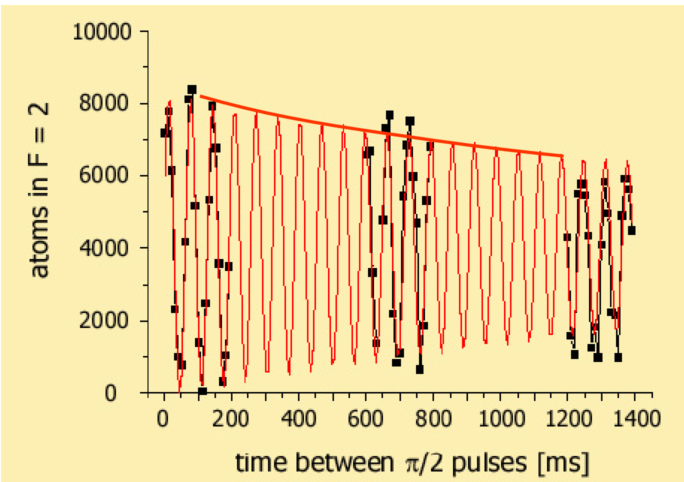
The European Commission Community Research Information society technologies

MPQ

Ramsey oscillations in the time domain

ATOMINSTITUT

MPQ



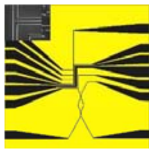
Fit exponential decay of fringe contrast:

→ coherence time τ

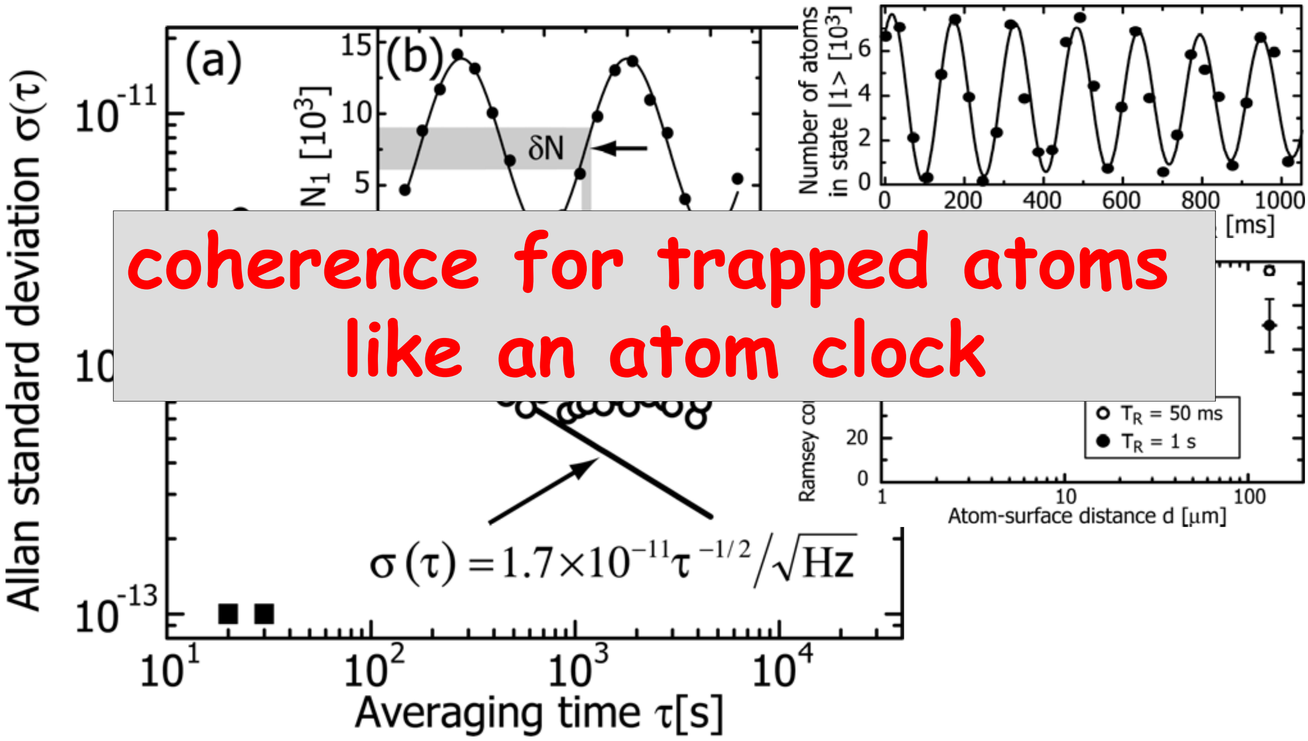
First result: with ~10,000 atoms at T ~ 450 nK, n ~ 4 x 10^{12} cm^{-3} coherence time τ ~ 2s at ~40 μm from chip wires (< 10 μm from surface)!

Coherence time similar to the result measured in Boulder in a macroscopic magnetic trap

One Qubit Rotations
Clock on Chip

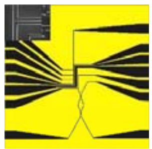


MPQ: Treutlein et al. PRL 2004



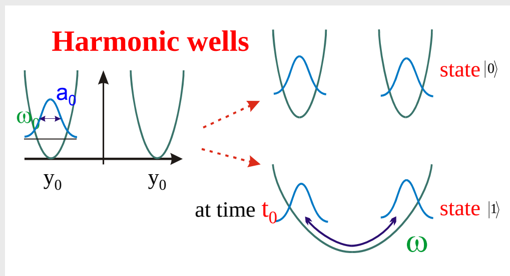
coherence for trapped atoms like an atom clock

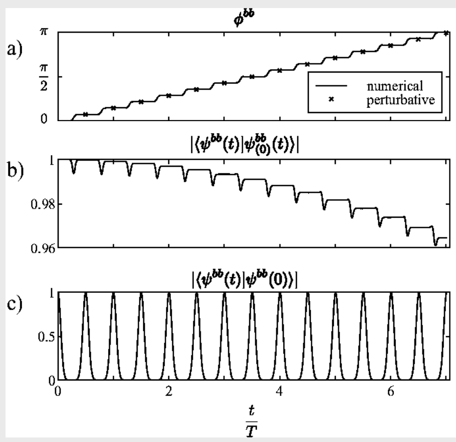
ENTANGLING NEUTRAL ATOMS
controlled collisions



- Neutral atoms can be entangled by their mutual interaction: for example in scattering
- Controlled entanglement: perform scattering experiments in a controlled way
- Gate operation: qubit selective scattering experiment
- Starting with one atom in each well, they will interact (scatter) differently according to their **qubit** state, and thus acquire a conditional phase.
- Requirements:
  - **Harmonic trap** with: ground state size < 100nm trap frequency >100kHz small distance between traps
  - state selective traps or state selective interaction
  - NO loss by scattering

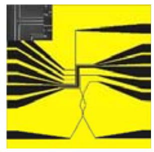
If we go for internal states qubits ^{87}Rb seems to be the only atom so far which satisfies the last requirement. F>0.9999 possible



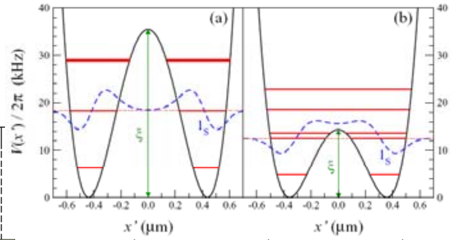


T. Carlarco et al. PRA 61, 022304 (2000)

Motional Gate Operation
implementation on Atom Chip



E. Charron et al. Phys. Rev. A **74**, 012308 (2006)

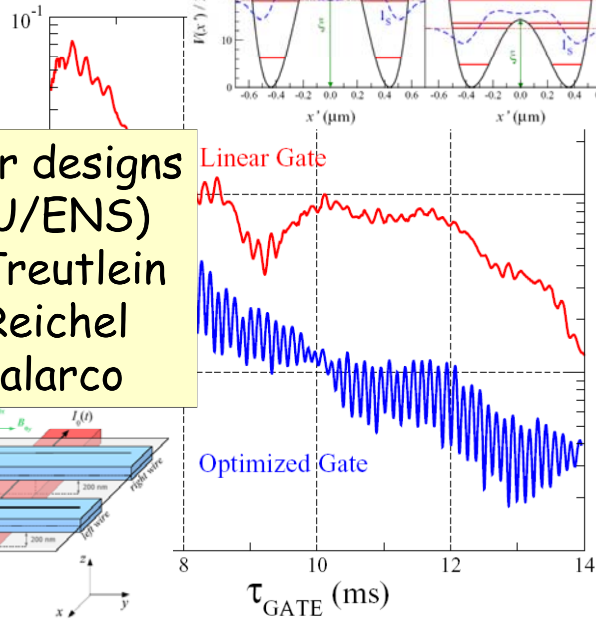


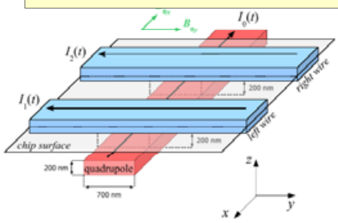
- Store the qubit in a clock state
- Transfer the |1,-1> population to |2,1> in the first excited state (Raman or MW transition)
- Gate operation
- Transfer back

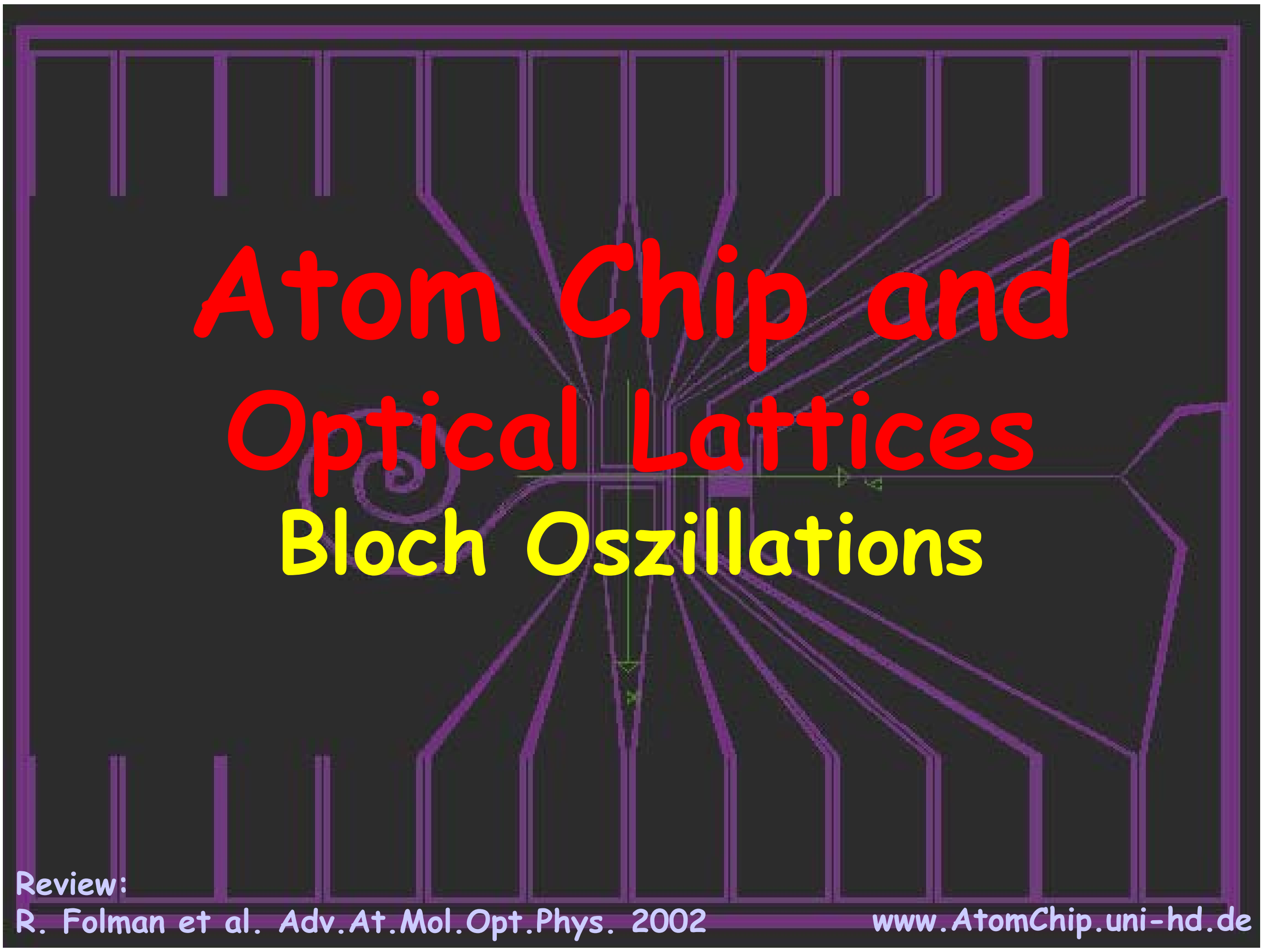
Simplest implementation
H-wire structure
- a = 1.5 μm
- I = 29.9 mA; α=0.093
- B_x=9.91G; B_y=50G
- B_0=3.23G (magic field)
- **Separation** 0.74 μm

Gate operation in 10 ms
Fidelity >99.9%
Surface loss: limit 99.7%

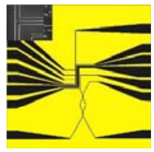
Similar designs
(LMU/ENS)
Ph. Treutlein
J. Reichel
T. Calarco







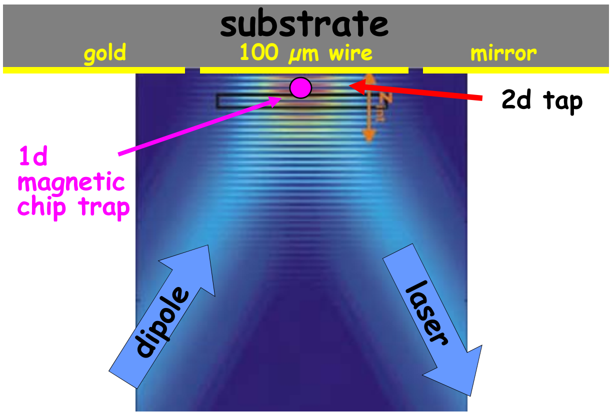
Optical Lattices on Atom Chip

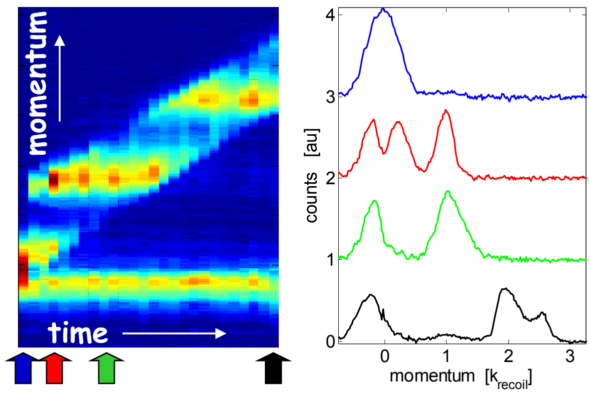


Create a dipole lattice by reflecting a laser beam off the atom chip surface

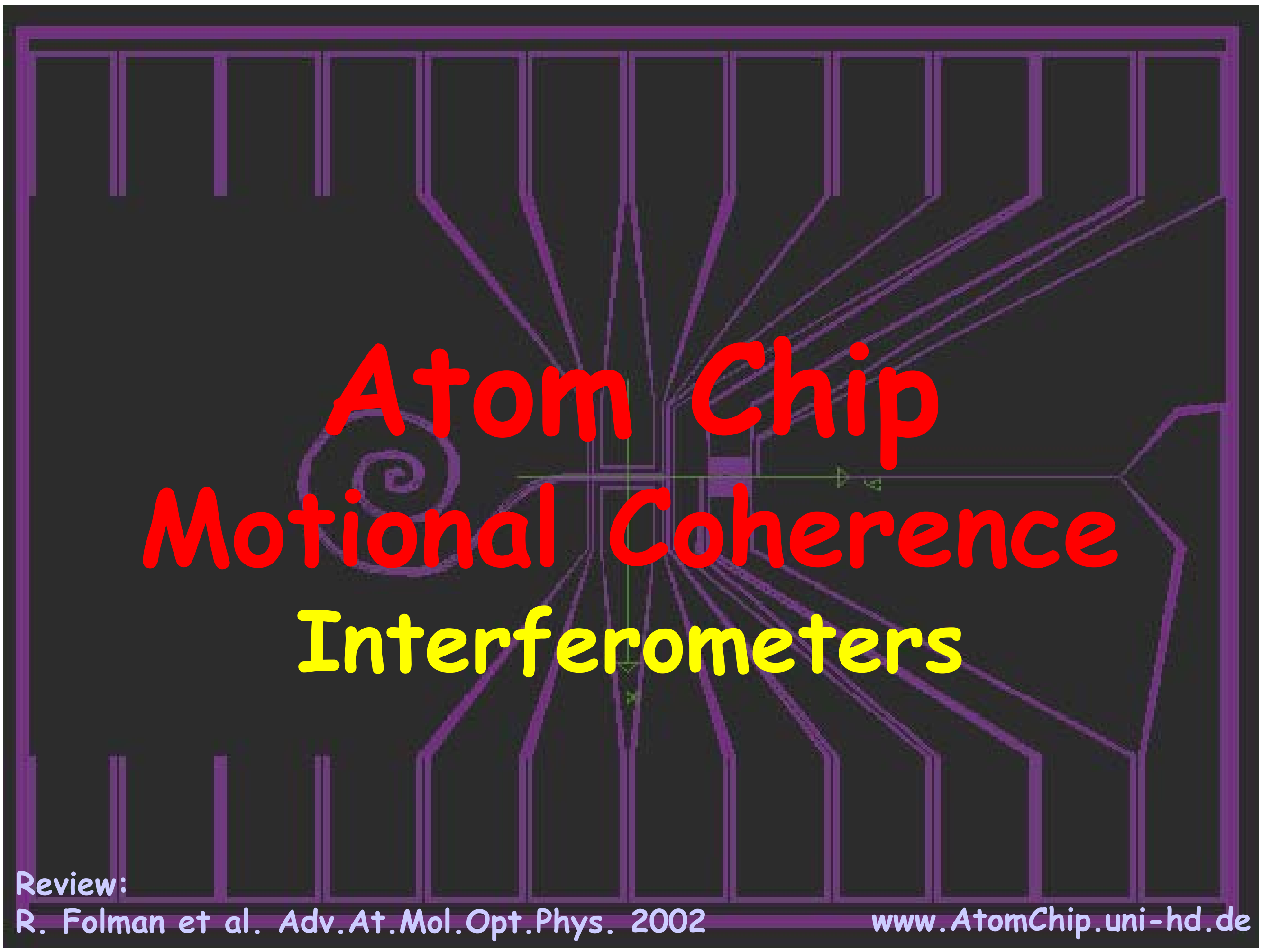
atom chip brings
- site addressability
- selective manipulation, detection

test experiment
(diode laser, 2nm detuning): ω_{trans}~120 kHz ω_{plane}~100Hz
- Rapid evap. cooling (50 ms)
- Final temperature ~trap depth/10
- For low-light intensity (40 kHz trapping) we reach transverse ground state
- Observe Bloch oscillations



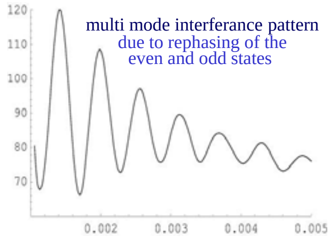


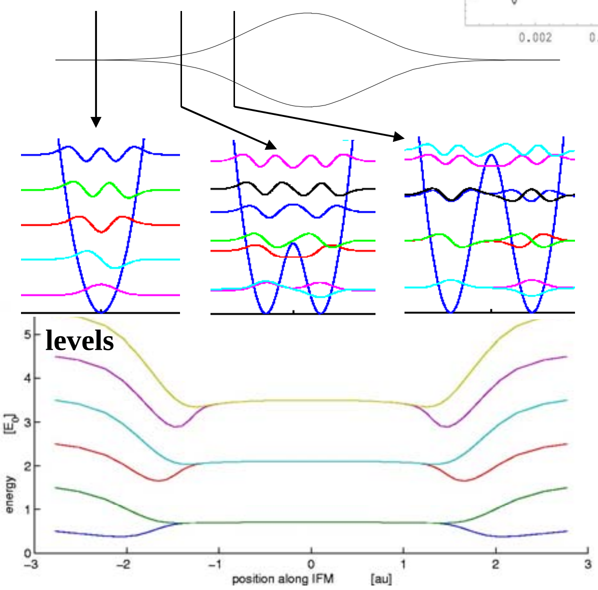
D. Gallego Diplomarbeit Heidelberg (June 2005)

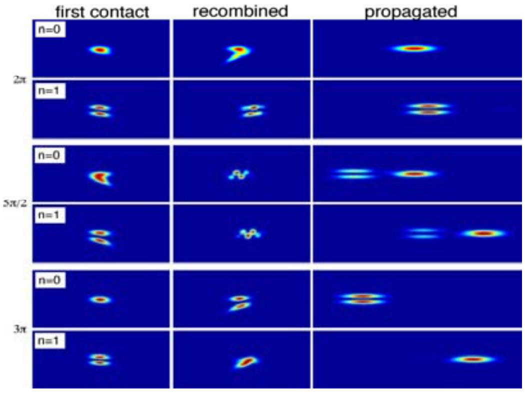


INTERFEROMETER
on the Atom Chip

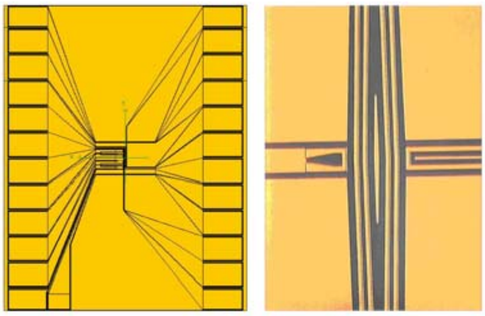
Combine two Y- beam splitters back to back







Real IFM chip designs

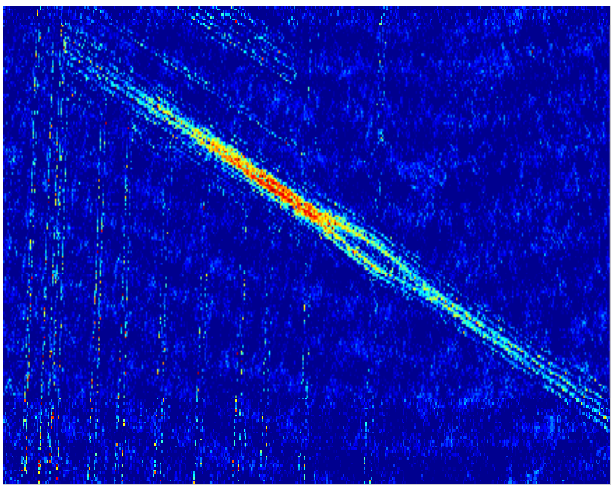


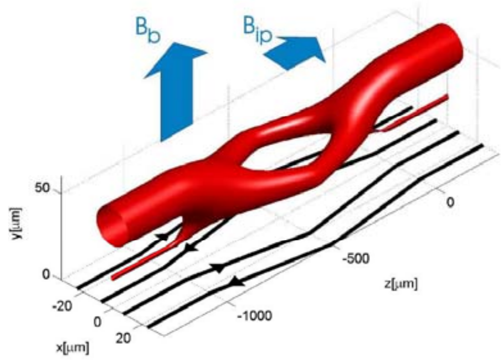
E. Anderson et al. PRL **88** 100401 (2002) quant-ph/0107124

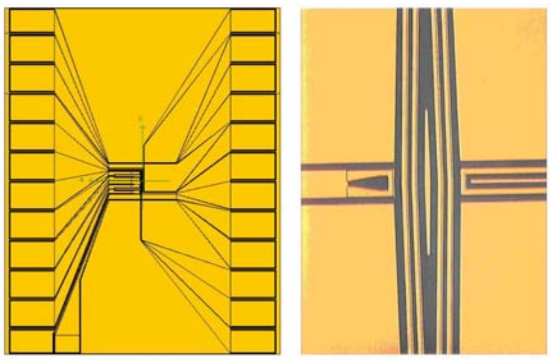
INTERFEROMETER
on the Atom Chip

Real IFM chip designs

Experiment with thermal atoms (2002)



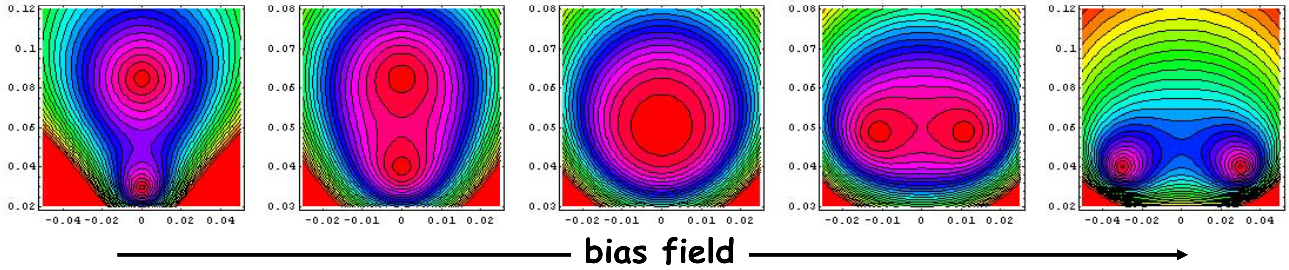




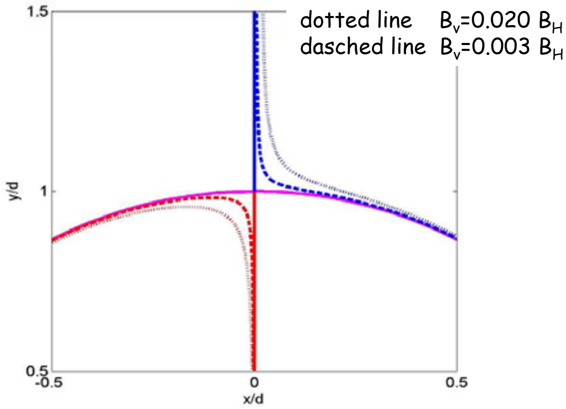
Splitting and Recombining
Time Dependent Potentials

IBK-HD

2 wires + horizontal bias field

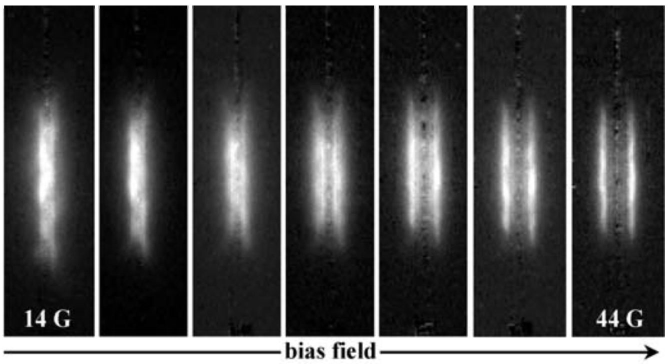


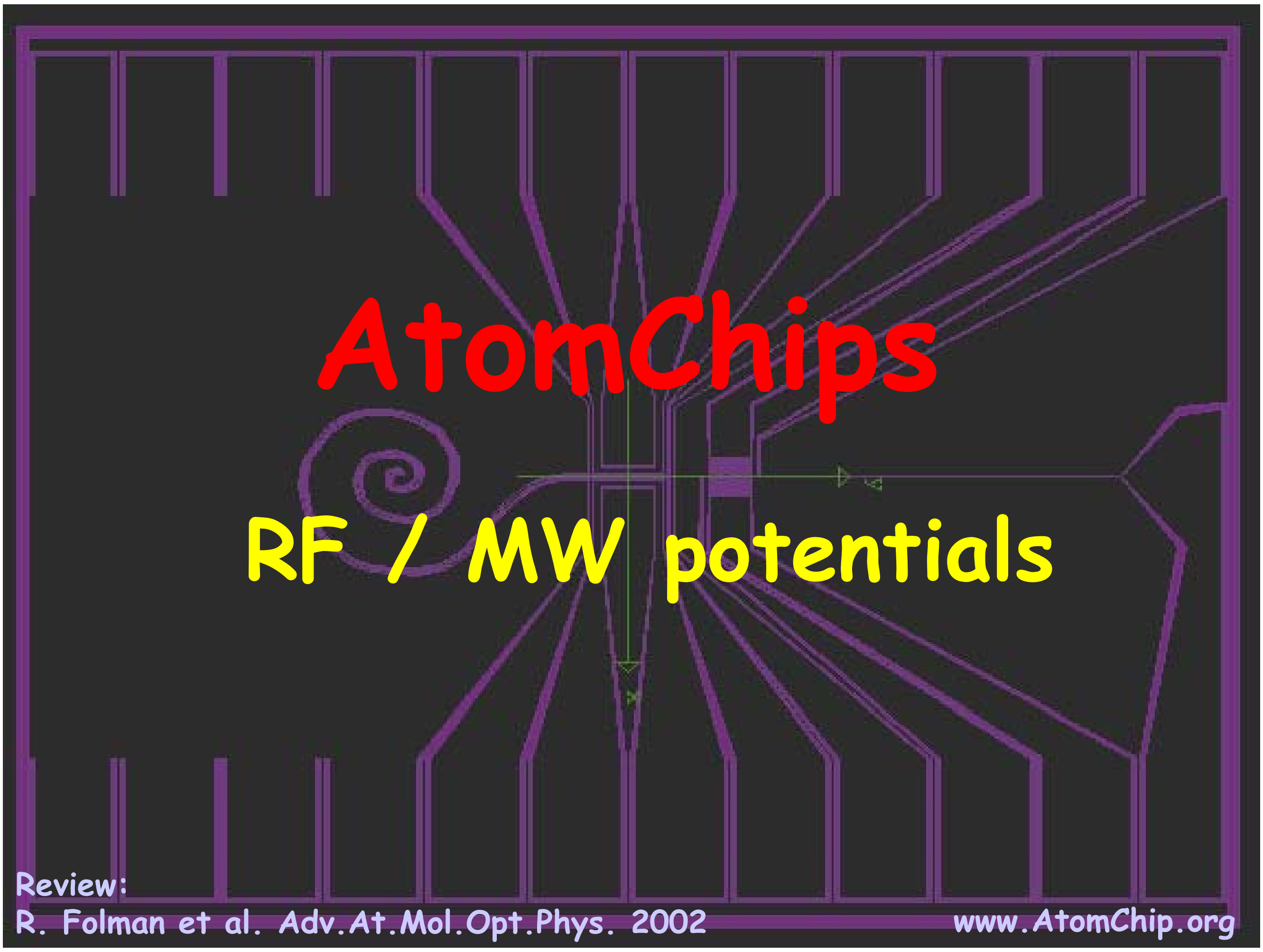
Crossing is highly sensitive to imperfections



experiment

double U-trap; 200 micron wires 2.0 A, 40 Gauss

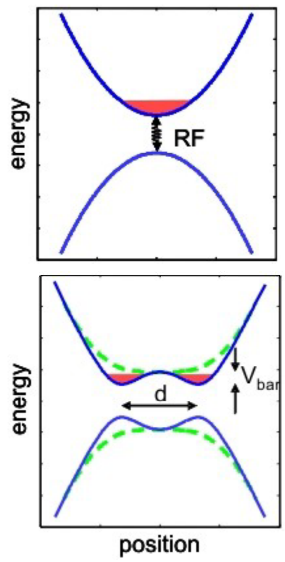




RF and MW induced adiabatic potentials

create adiabatic dressed state potentials by coupling electronic ground states of an atom

- coupling between stable states allows to create conservative potentials even with on resonant radiation
- shaping the potential:
  - detuning the states with an external magnetic field
  - spatial dependent coupling strength (RF field)
    -> allows strong field seeker traps
- coupling is magnetic:
  the amplitude and the relative orientation of the RF field and the detuning field are important

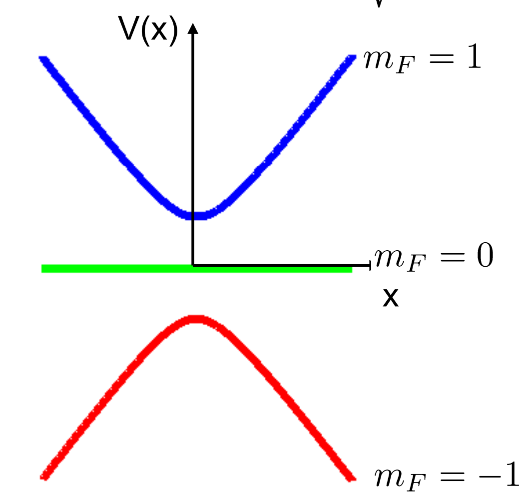


- first experiment: dressed neutrons: E. Muskat et al., PRL **58**, 2047 (1987).
- first proposal of a MW trap (detuned) C. Agosta, et al. PRL. **62**, 2361 (1989).
- MW experiment (Cs, detuned) R. Spreeuw, et al. PRL **72**, 3162 (1994).
- RF dressed state traps O. Zobay, B. M. Garraway, PRL **86**, 1195 (2001).
  (with magnetic field detuning but neglecting polarization)
- RF potentials for thermal Rb atoms: Y. Colombe, et al. Europhys. Lett. **67**, 593 (2004).
- Full implementation T. Schumm et al Nature Physics **1**, 57 (2005)

Combining static and RF fields

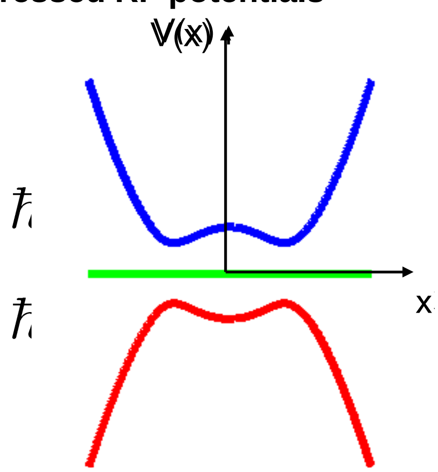
Ioffe-Pritchard trap

$$
\begin{aligned}
\mathbf{B}_S(\mathbf{r}) &= Gx\mathbf{e}_x - Gy\mathbf{e}_y + B_I\mathbf{e}_z \\
V_{\mathrm{ad}}(r) &= g_F\mu_B F_z\,|\mathbf{B}_S(\mathbf{r})| \\
&= g_F\mu_B m_F\sqrt{G^2\rho^2 + B_I^2}
\end{aligned}
$$



- in a source-free region only mag. field minima are achievable
- number of possible trap shapes can be greatly increased by adding an oscillating RF magnetic field

dressed RF potentials



Zobay & Garraway PRL **86**, 1195 (2001)
I. Lesanovsky et al. PRA **73** 033619 (2006)

Dressed adiabatic potentials

Oscillating RF magnetic field

$$\mathbf{B}_{RF}(\mathbf{r},t) = \frac{B_{RF}}{\sqrt{2}}\left[\mathbf{e}_x\cos(\omega t) + \mathbf{e}_y\cos(\omega t + \delta)\right]$$

relative phase shift

Total Hamiltonian

$$H = \frac{\mathbf{p}^2}{2M} + g_F\mu_B\mathbf{F}\cdot\left[\mathbf{B}_S(\mathbf{r}) + \mathbf{B}_{RF}(\mathbf{r},\omega t)\right]$$

1. apply the unitary transformation $U_S(\mathbf{r})$ to diagonalize the static part
2. transform into a rotating frame around the local quantization axis
3. perform the rotating-wave-approximation
4. diagonalize spin-field interaction terms

$$H_{\text{final}} = \frac{1}{2M}\left[\mathbf{p} + \cancel{\mathbf{A}'(\mathbf{r},t)}\right]^2 - \frac{1}{2M}\cancel{\Phi'(\mathbf{r},t)} + \boxed{g_F\mu_B|\mathbf{B}_{\text{eff}}(\mathbf{r})|F_z}$$

adiabatic approximation

dressed adiabatic potentials

B_{eff} does not necessarily obey Maxwell's equations

- potential depends on the relative orientation of the RF and the static field
- spatial dependence gives rise to novel types of RF traps
- free parameter d, i.e. RF polarization can be used to modify the trap shape

theory: I. Lesanovsky et al. PRA **73** 033619 (2006)
I. Lesanovsky et al. PRA **74** 033619 (2006).

experiment: T. Schumm et al. Nature Physics **1**, 57 (2005)
S. Hofferberth et al. Nature Physics **2**, (2006)

RF induced Potentials

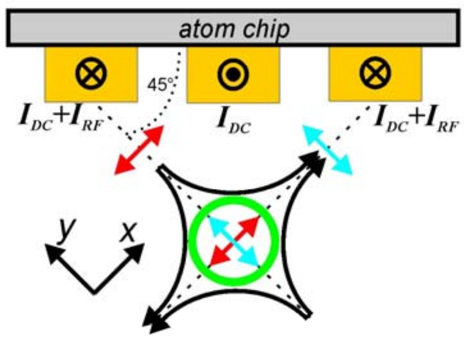
state dependent potentials by RF polarization

Polarization of the RF field gives extra freedom

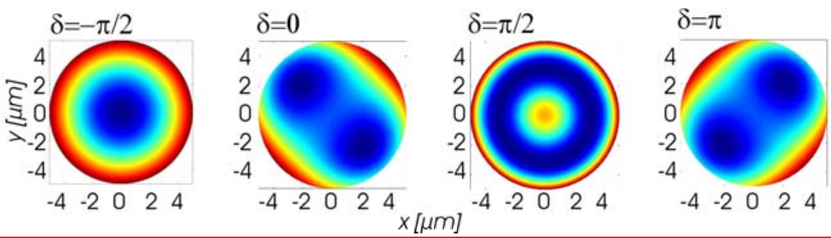
$$\mathbf{B}_S(\mathbf{r}) = Gx\mathbf{e}_x - Gy\mathbf{e}_y + B_I\mathbf{e}_z$$

$$\mathbf{B}_{RF}(\mathbf{r},t) = \frac{B_{RF}}{\sqrt{2}}\left[\mathbf{e}_x\cos(\omega t) + \mathbf{e}_y\cos(\omega t + \delta)\right]$$

$$V_{\text{ad}}(\mathbf{r}) = m_F g_F\mu_B\sqrt{\Omega^2(\mathbf{r}) + \triangle^2(\mathbf{r})}$$



tuning the relative RF phase δ



$$\Omega(\mathbf{r}) = |\mathbf{B}_S(\mathbf{r})| - \frac{\hbar\omega}{|g_F\mu_B|}$$

$$\triangle(\mathbf{r}) = \frac{B_{RF}}{2}\left[1 + \frac{B_I\sin\delta_{eff}}{|\mathbf{B}_S(\mathbf{r})|} + \frac{G^2\rho^2}{2\,|\mathbf{B}_S(\mathbf{r})|^2}\left(\cos\delta_{eff}\sin(2\phi) - 1\right)\right]$$

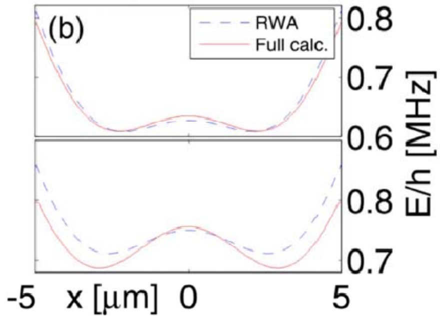
state dependent

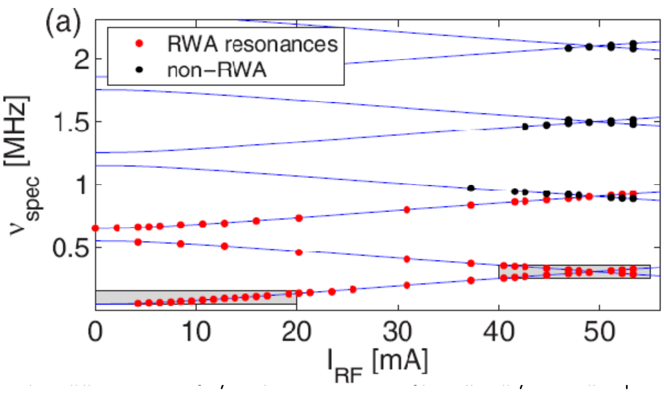
$$\delta_{eff} = \frac{g_F}{|g_F|}\delta$$

RF dressed states beyond RWA

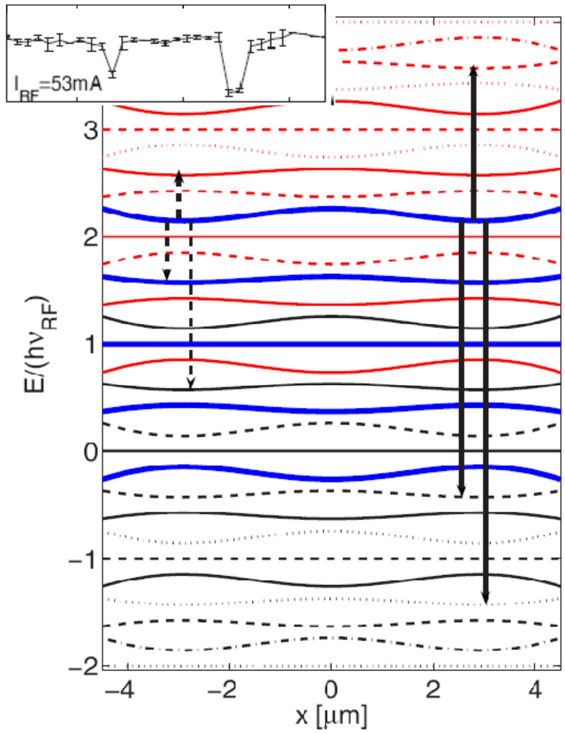
Hofferberth et al. Phys. Rev. A **76**, 013401 (2007)

change in potential





spectroscopy



RF and MW induced state dependent potentials

The two clock states have

$\left|F=2, m_F=1\right\rangle$

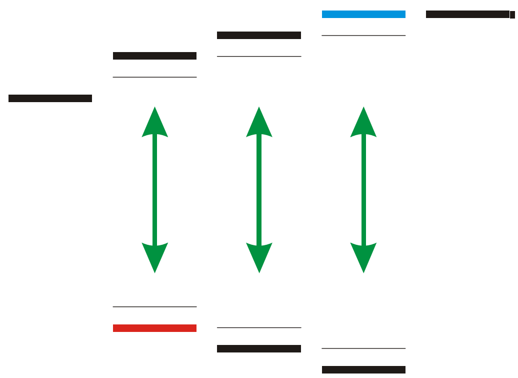
$\left|F=1, m_F=-1\right\rangle$

- Identical Zeeman shift
- Identical Stark shift
- Identical light shift (for large detuning)

Radio Frequency (RF) and Micro Wave (MW) fields can couple differently

On chip: local RF and MW field for manipulaion

Linear polarized micro wave



AC-Zeeman shift:

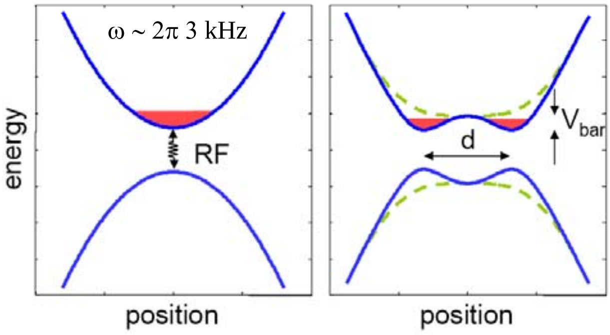
$$\Delta E = \pm \frac{\hbar \Omega_R^2}{4\Delta}, \quad \text{with } (|\Delta| >> \Omega_R)$$

$$\hbar \Omega_R \sim \mu_B \cdot B_{MW}$$

M. Cirone et al. quant-ph/0505194 (EPJ D special issue atom chip)
RF idea: M. Anderson (HD)

RF-Dressed State Potentials
Creating a Double Well

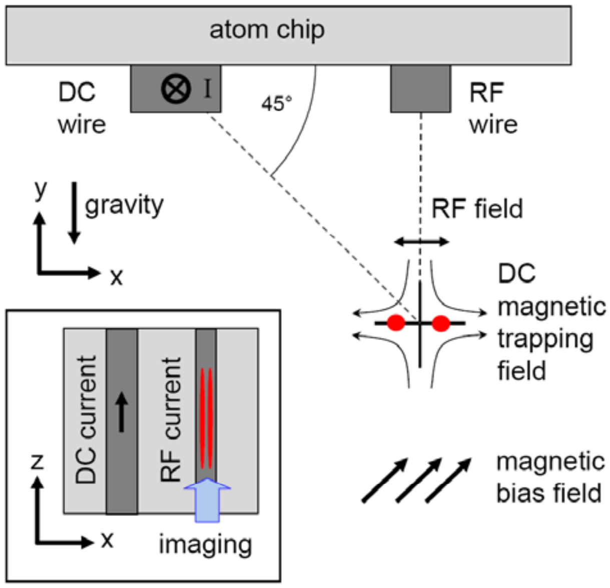
Couple atomic states by RF / MW



- The minumum of the adiabatic potential is at iso-B surfaces
- The minmum value at the iso-B surface depends on the **RF** couppling strength
- The couppling strength depends on the **orientation** of the RF field relative to the trap field

$$V_{\text{ad}}(\mathbf{r}) = m_F g_F \mu_B \sqrt{\Omega^2(\mathbf{r}) + \triangle^2(\mathbf{r})}$$

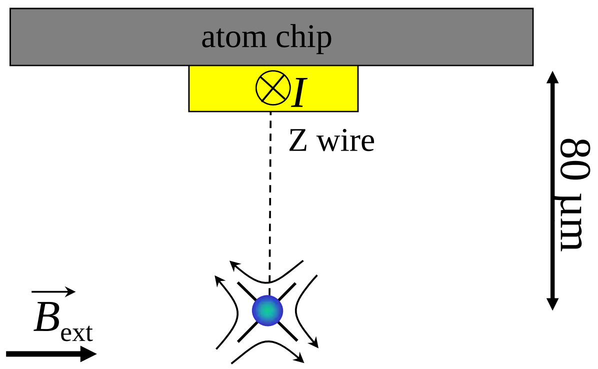
realization on AtomChip



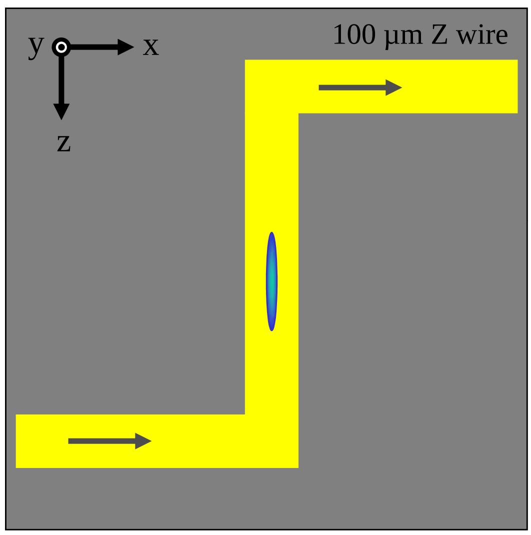
'Matter-wave interferometry in a double well on an atom chip', T. Schumm, et al., Nature Physics. **1**, 57 (2005)

Interferometry with BEC
Implementation on the atom chip

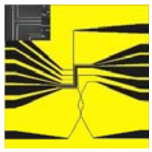
side view



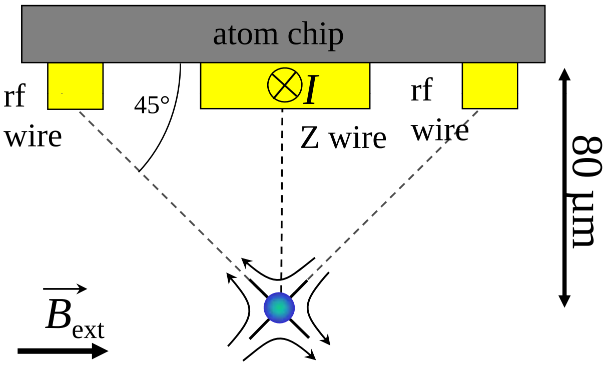
top view



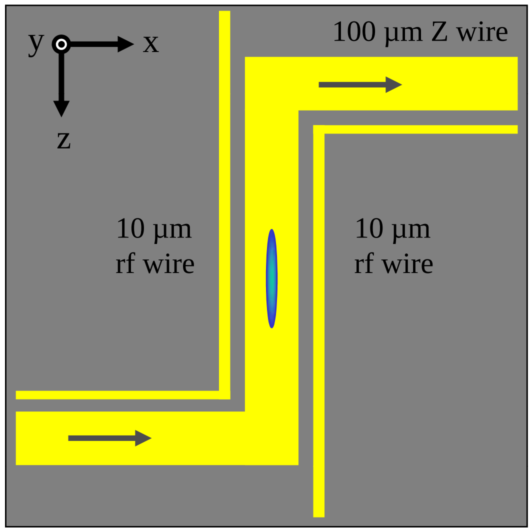
Interferometry with BEC
Implementation on the atom chip



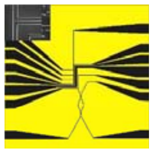
side view



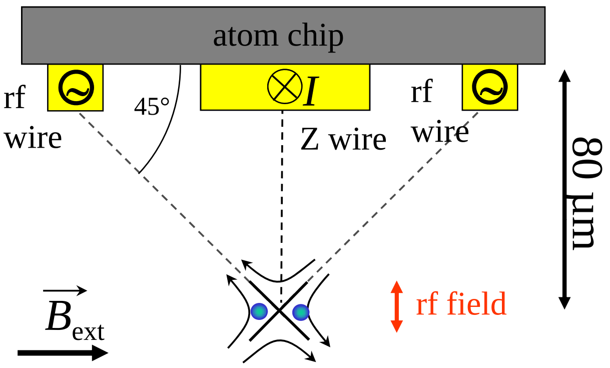
top view



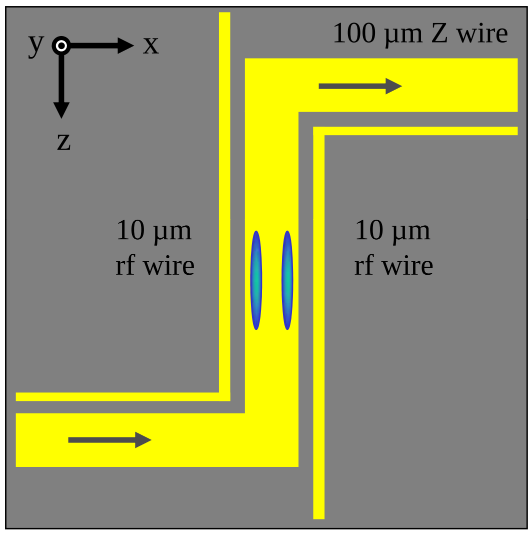
Interferometry with BEC
Implementation on the atom chip



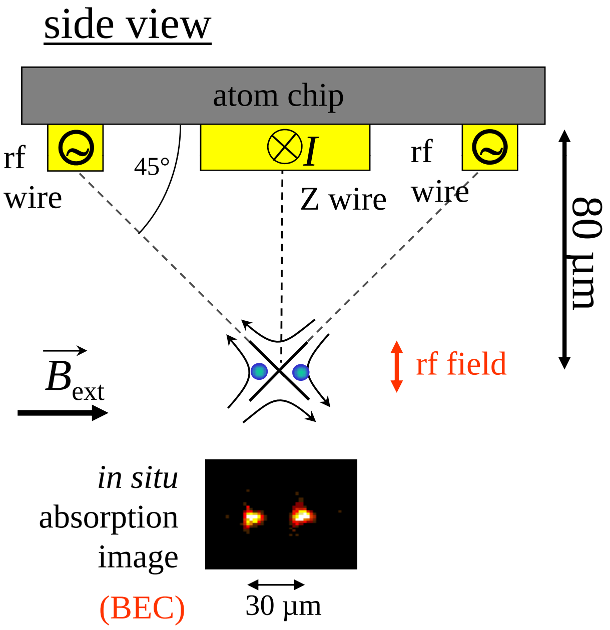
side view

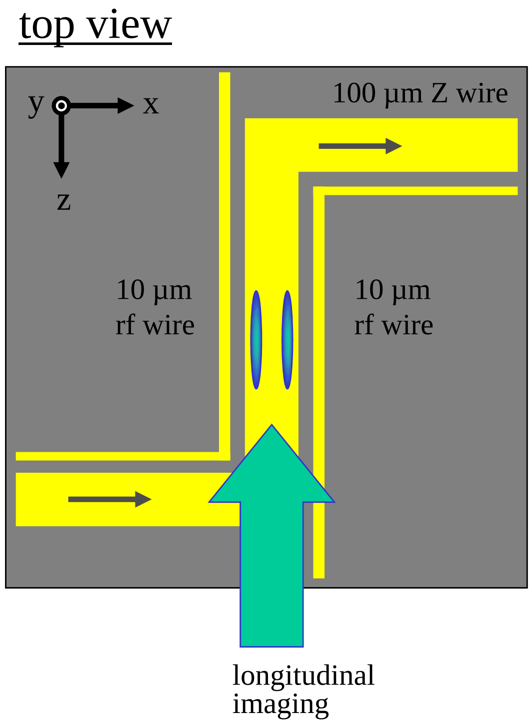


top view

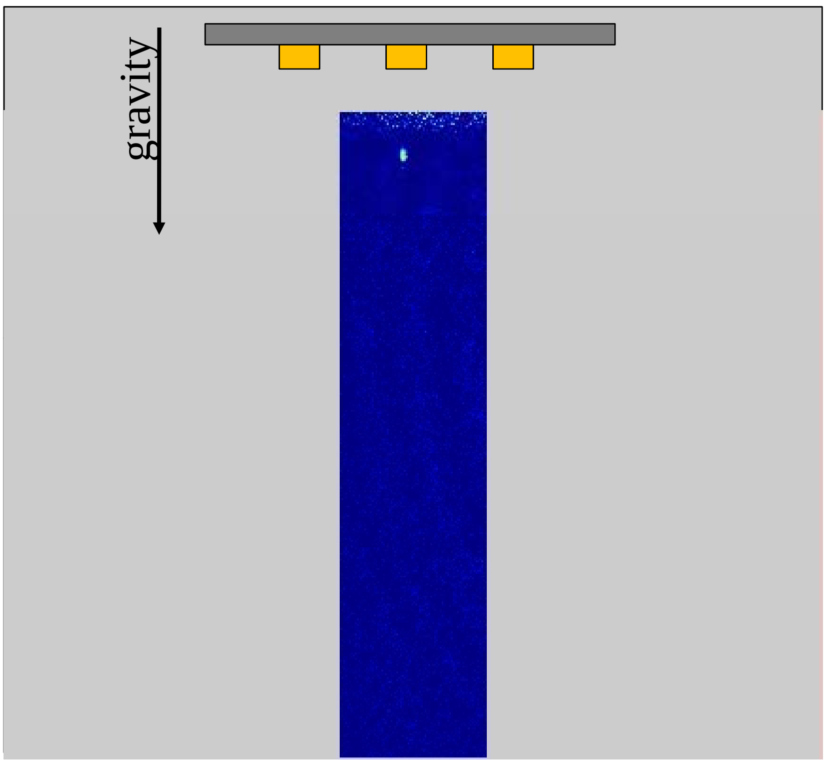


Interferometry with BEC
Implementation on the atom chip

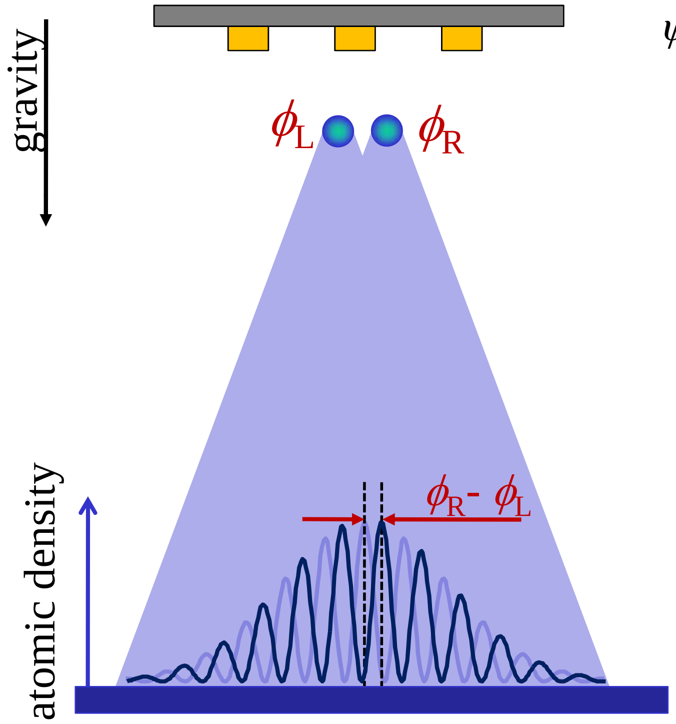




Splitting Bose-Einstein condensates:
Youngs double slit for matter waves



Splitting Bose-Einstein condensates:
Youngs double slit for matter waves



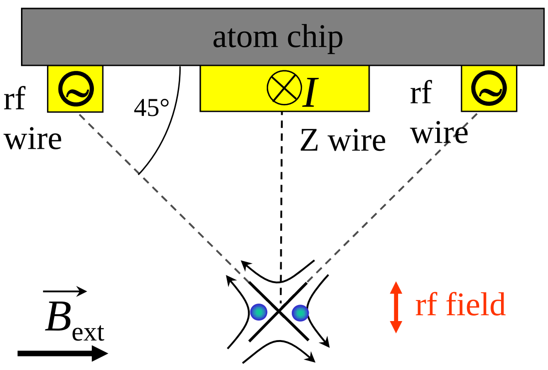
$$\psi_{L/R} = \sqrt{n_{L/R}} \cdot e^{i\phi_{L/R}}$$

$$\Psi = \psi_L + \psi_R$$

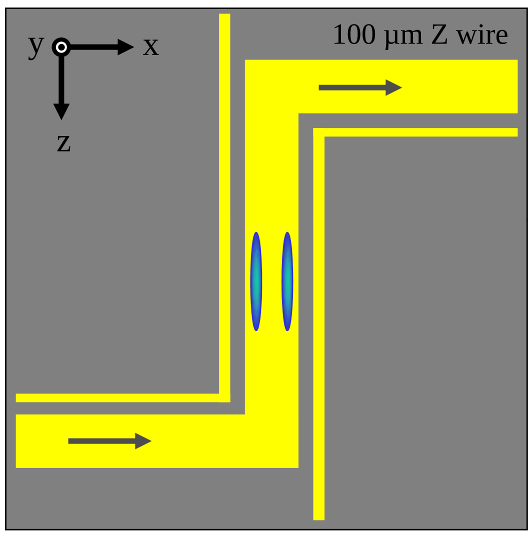
screen / detector

Interferometry with 1D gases
Implementation on the atom chip

side view

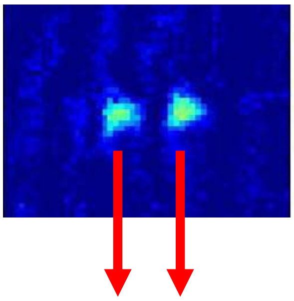


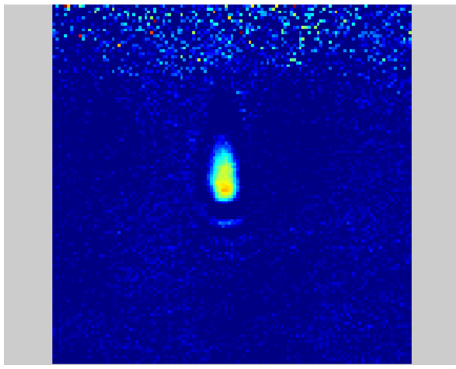
top view

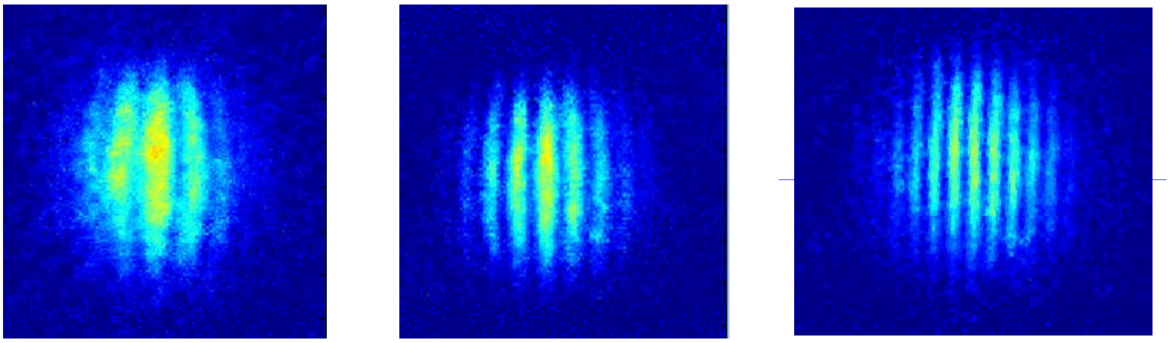


Observe interference in time of flight

Condensates released
from double well
fall and expand





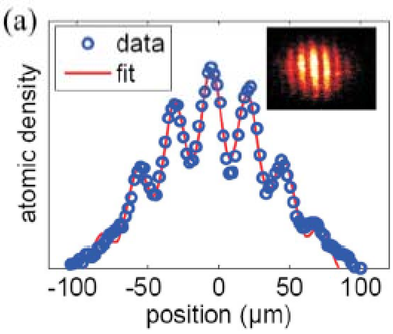


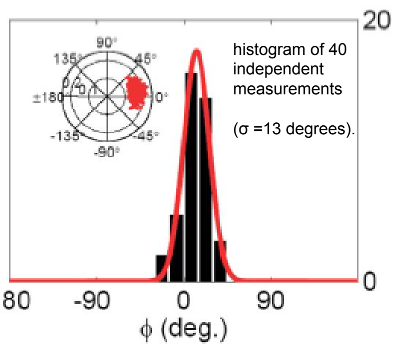
Interference between overlapping BECs

TOF = 16ms

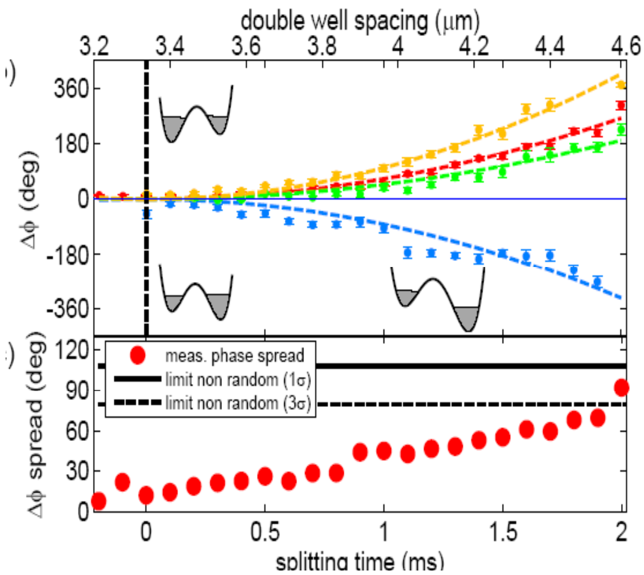
Coherent Splitting

After the BECs has been split far enough to inhibit tunneling (d=3.4 μm),
atoms are released and an interference pattern is observed after a time of flight.





Evolution of the differential phase
throughout the splitting process

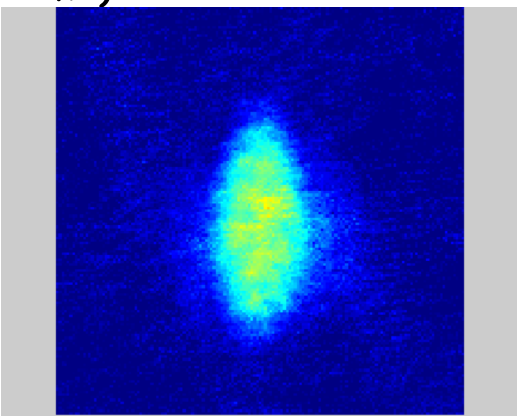


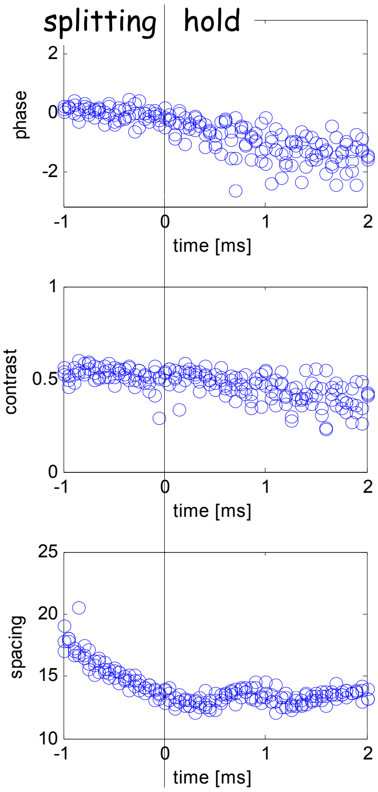
'Matter-wave interferometry in a double well on an atom chip',
T. Schumm, et al., Nature Physics. **1**, 57 (2005)

ATOMINSTITUT

Splitting prozess

- Splitting of the quasi 1d BEC is very robust
- Coherent splitting seen in time-scales from 5-50 ms RF ramp time
- The actual splitting then occures in the last part of the RF ramp (0.5-5ms)



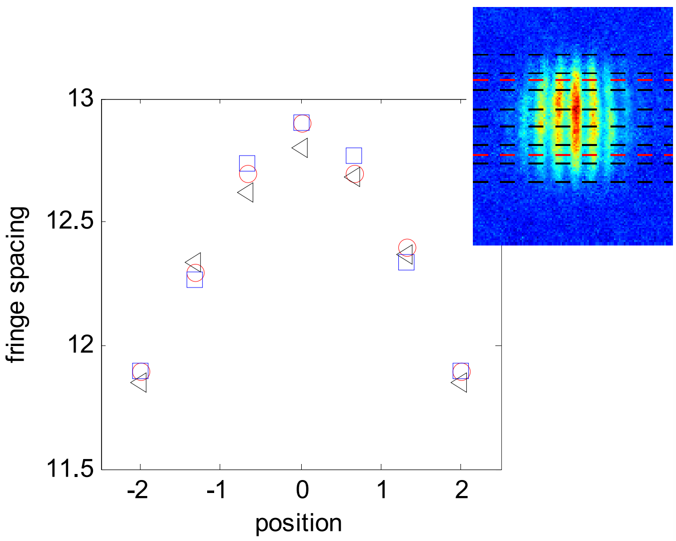


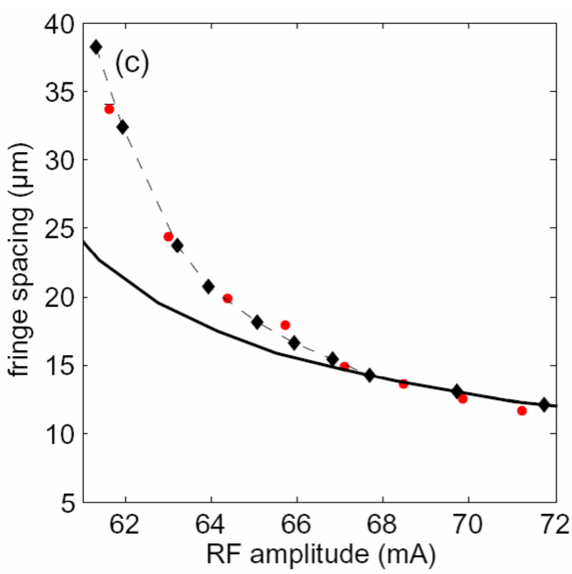
ATOMINSTITUT

Measuring the collisional phase

The **non linear** phase shift results in

- bending of the fringes
- changing fringe spacing





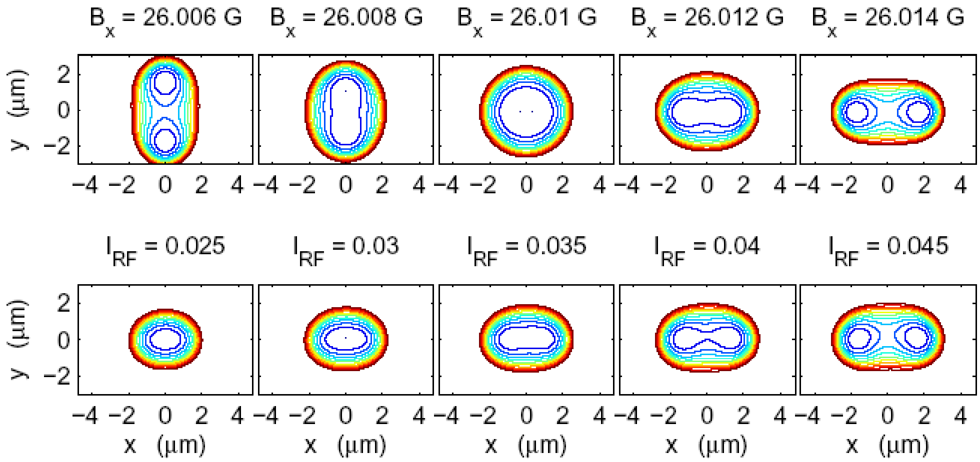
Advantages of RF potentials
splitting a trap

Hoffererth et al. Naure Physics 2, 710 (2006)

- True spliting 1 trap -> 2 traps
  - Confinement in transvrsal direction stays the same
  - Confinement in splitting direction is significantly tighter
- splitting potential: $V(x)=A(t)\ x^2+\mathbf{B}\ x^4$
  the size of the x^4 term determines the confinement
  In RF potentials **B** is factor ~1000 larger

2-wire
beam splitter
contours 5 Hz

RF
beam splitter
contours 5 kHz



State-dependent double well interference

„effective" polarization depends on g_F

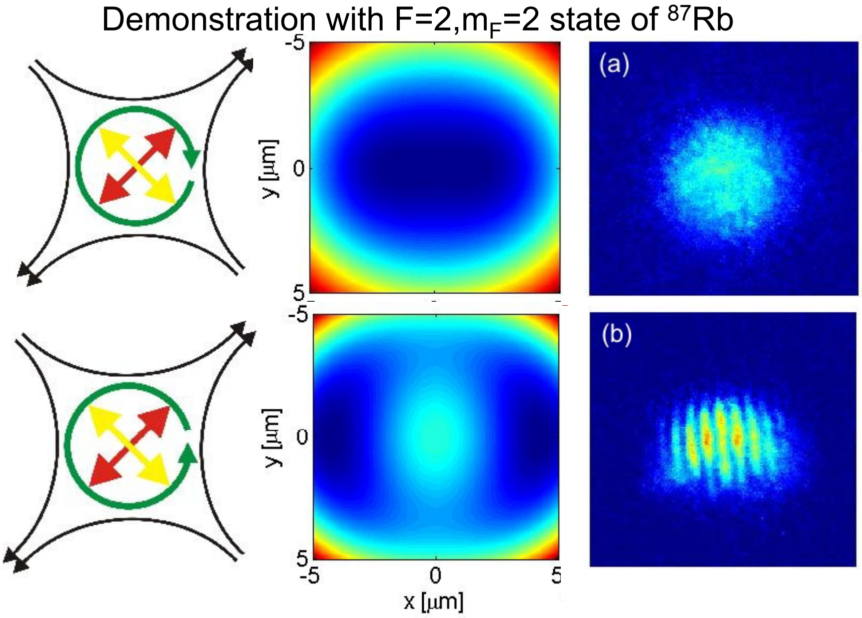
$$\delta_{eff} = \frac{g_F}{|g_F|}\delta$$

RF-potentials allow state-dependant manipulation

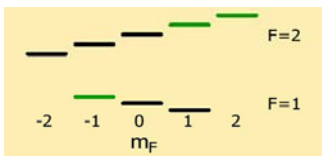
elliptical polarization:

state-dependant double well

Demonstration with F=2,m_F=2 state of ^{87}Rb



possible application:
collisional phase gate



Hofferberth et al. Nature physics Oct. (2006)

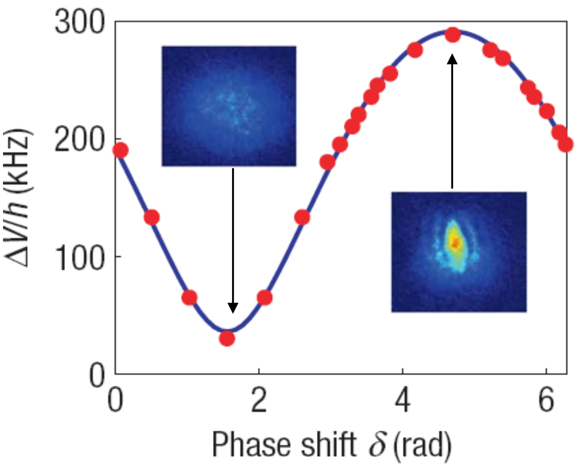
State dependent traping and manipulatipon

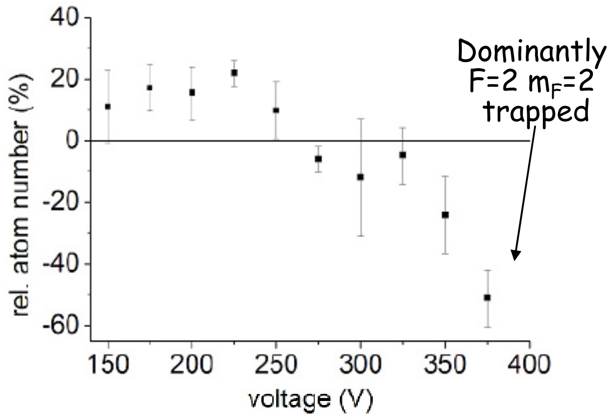
HD

RF polarization
changing the RF polarization dramatically changes the dressed state potential

Combined electric-magnetic trap
difference in the number of atoms in an electric trap depending on the magnetic state

$U(\mathbf{r}) = gF\ mF\ \mu B\ B(\mathbf{r}) - ½\ \mathbf{a}\ E(\mathbf{r})2$





Hofferberth et al. Nature physics Oct. (2006)

P. Krüger PhD thesis (2004)

RF potential characteristics

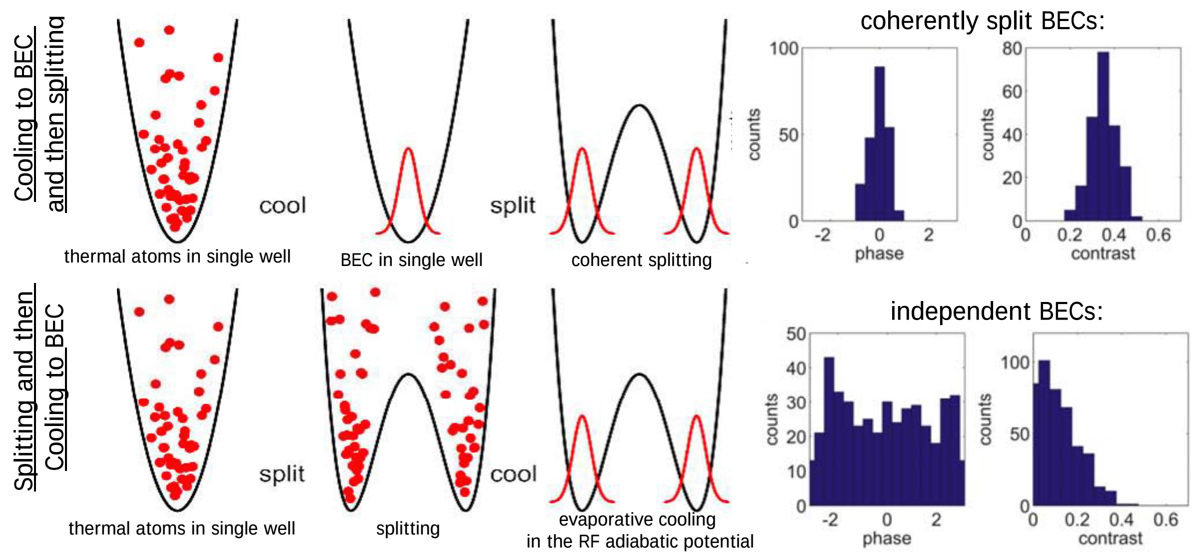
Typical Parameters:
$\omega_L \sim 640$ kHz $\quad \Delta_{RF} \sim 40$ kHz $\quad \Omega_{RF} \sim 500$ kHz

$(\Delta < \omega_L < \Omega_R)$

- dressed states are a superposition of **all** sub-states !
- should lead to additional loss (ms) due to collisions
- at a density of 10^{15} atoms/cm^3 we do not see any additional loss caused by the RF dressing.
- RF creates new collisional stable states from a set of other states. The superposition can be controlled by changing the RF parameters
- should allow to change scattering parameters
- no additional heating

Evaporative cooling in RF adiabatic potentials

S. Hofferberth et al. Nature Physics **2**, 710 (2006)

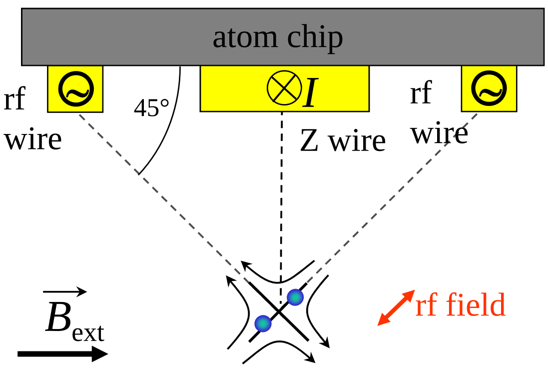


cooling in double well leads to two fully independent (1d)-BECs

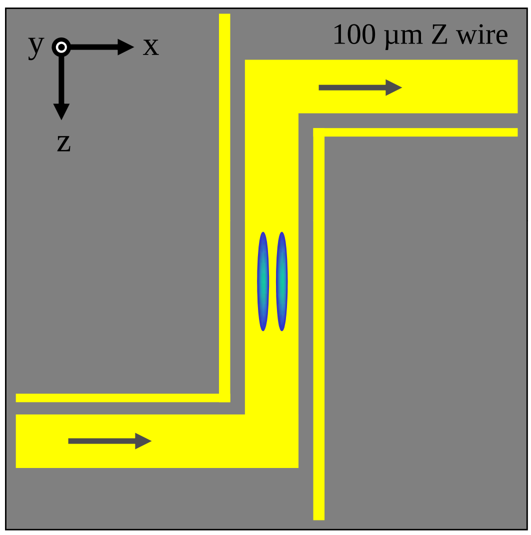
- Coherently split BECs allow study of 1d-phase diffusion dynamics
- Independent BECs allow study of 1d-coherence length and (local) phase locking between BECs
- Tunnel coupling between the wells can be changed dynamically with high precision

Interferometry with 1D gases
Implementation on the atom chip

side view

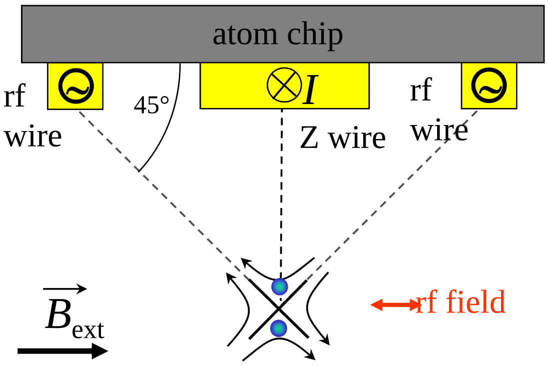


top view

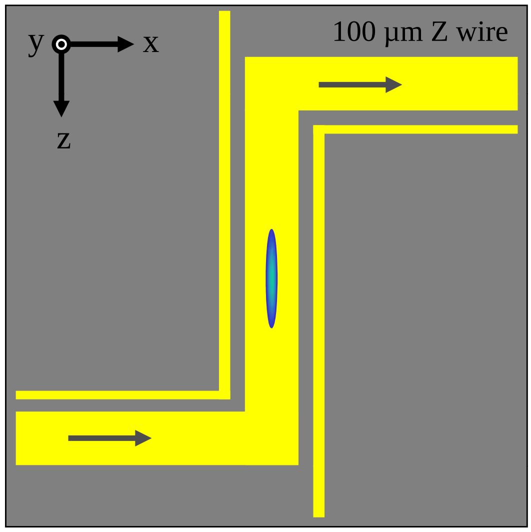


Interferometry with 1D gases
Implementation on the atom chip

side view

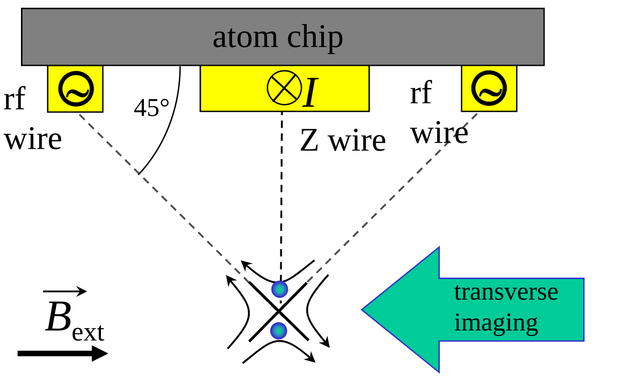


top view

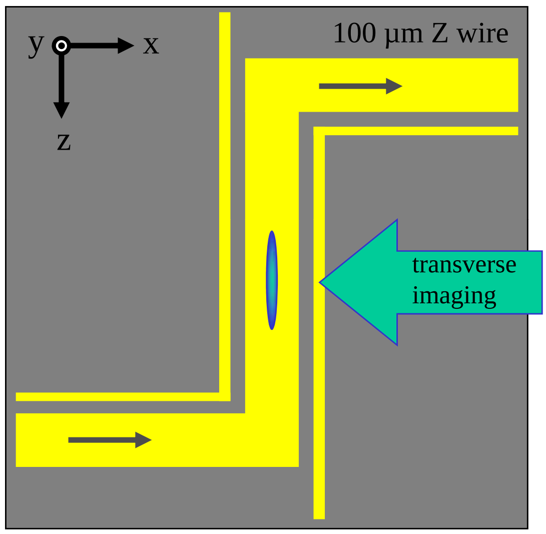


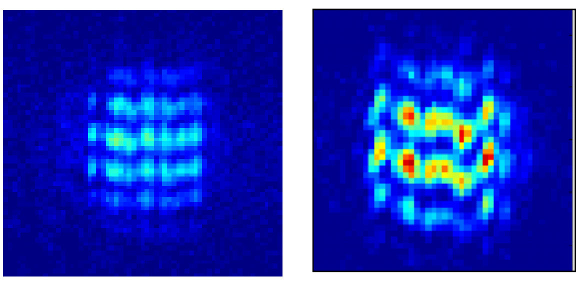
Interferometry with 1D gases
Implementation on the atom chip

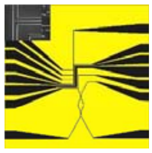
side view



top view





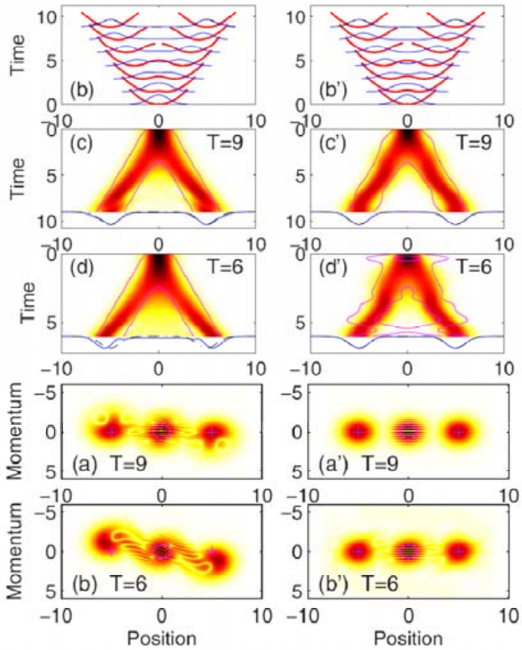


Control of the Splitting

Optimal quantum control of Bose Einstein condensates in magnetic microtraps
U. Hohenester et al. Phys. Rev.A **75**, 023602 (2007)

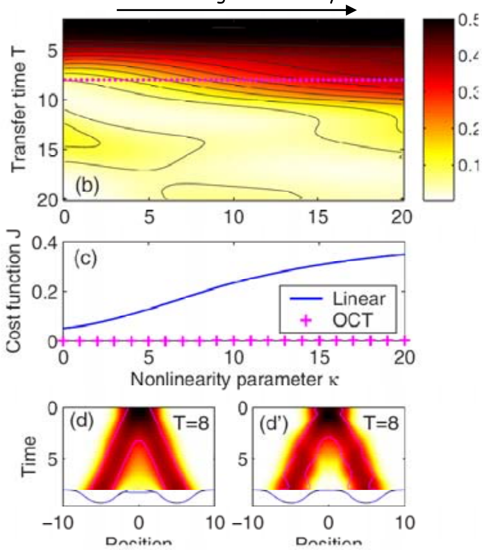
Spliting is 'quite violent'

→ apply optimal quantum control to improve the coherence



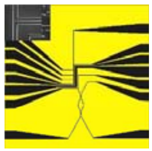
algotithm works also for non linear Schrödinger equation

increasing non linearity



how good can we controll the splitting beyond mean field ?

can we controll quantum noise?
achieve optimal squeezing
optimal sensitivity of an interferometer

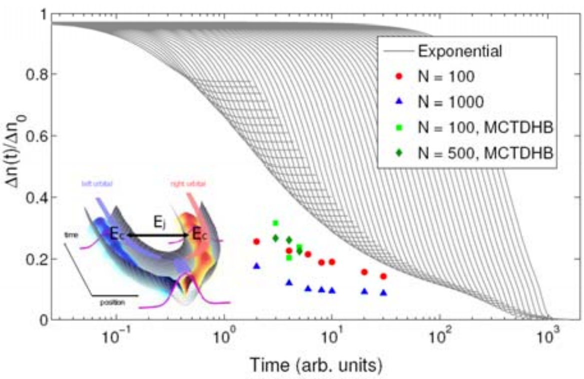


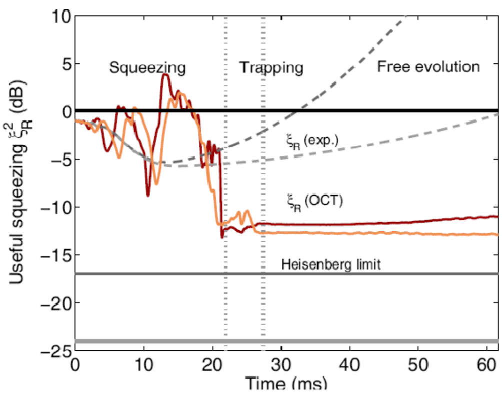
Optimal Control of Squeezing

J. Grond PRA **79**, 021603 (2009)

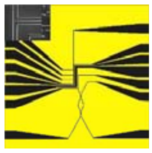
significant **squeezing** can be achieved by applying an optimal control strategy during the splitting minimizing the number fluctuations

- split by about one order of magnitude faster then adiabatic
- OCT follows closely a parametric oscillator model to obtain number squeezing + a stabilization step
- few mode model and a full MCTDHB model give similar results
- phase coherence time of an interferometer should be considerable enhanced compared to regular splitting





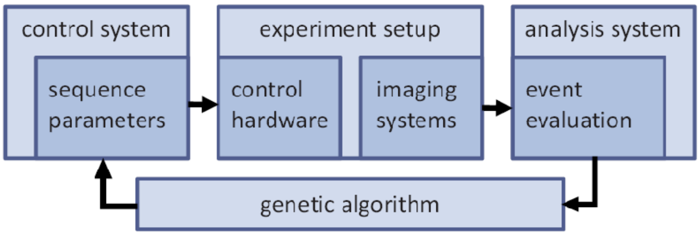
Optimization by Generic Algorithms

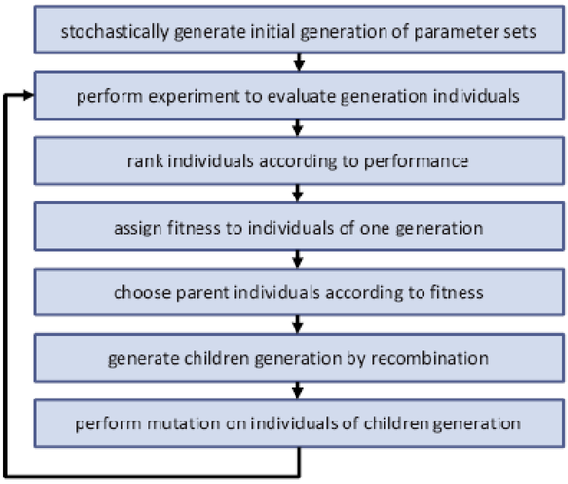


W. Rohringer Appl.Phys.Lett, **93**, 264101 (2008)
NatPhys **4**, 901 (2008)

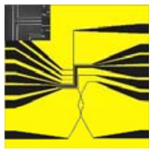
Controlling a complex experiment

- making a complete search of the parameter space is impractical
- close the loop in the experiment by use generic algorithms to find an optimum





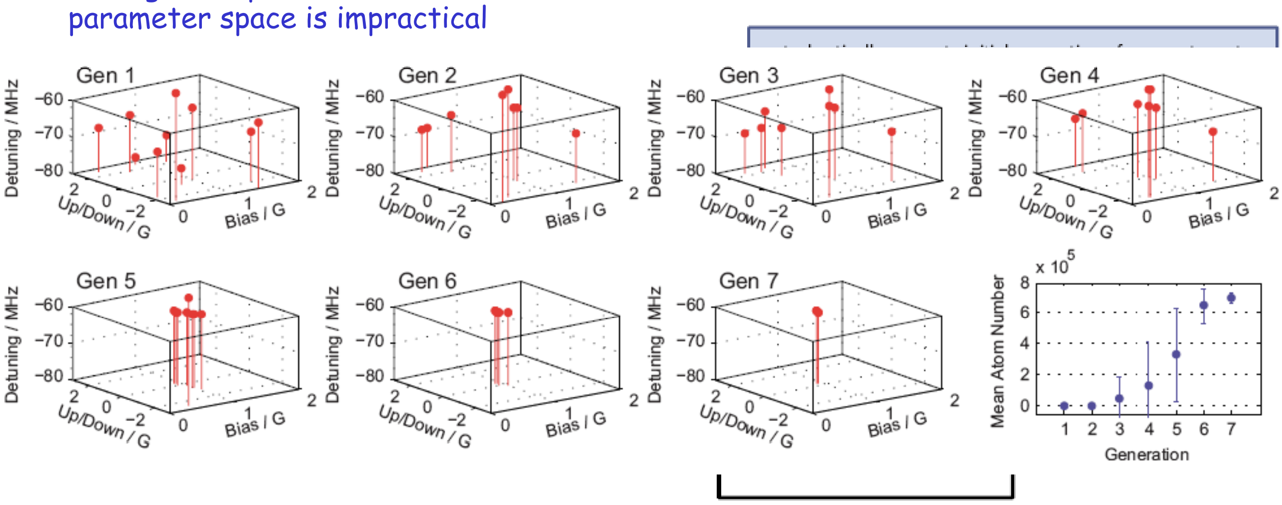
Optimization by Generic Algorithms



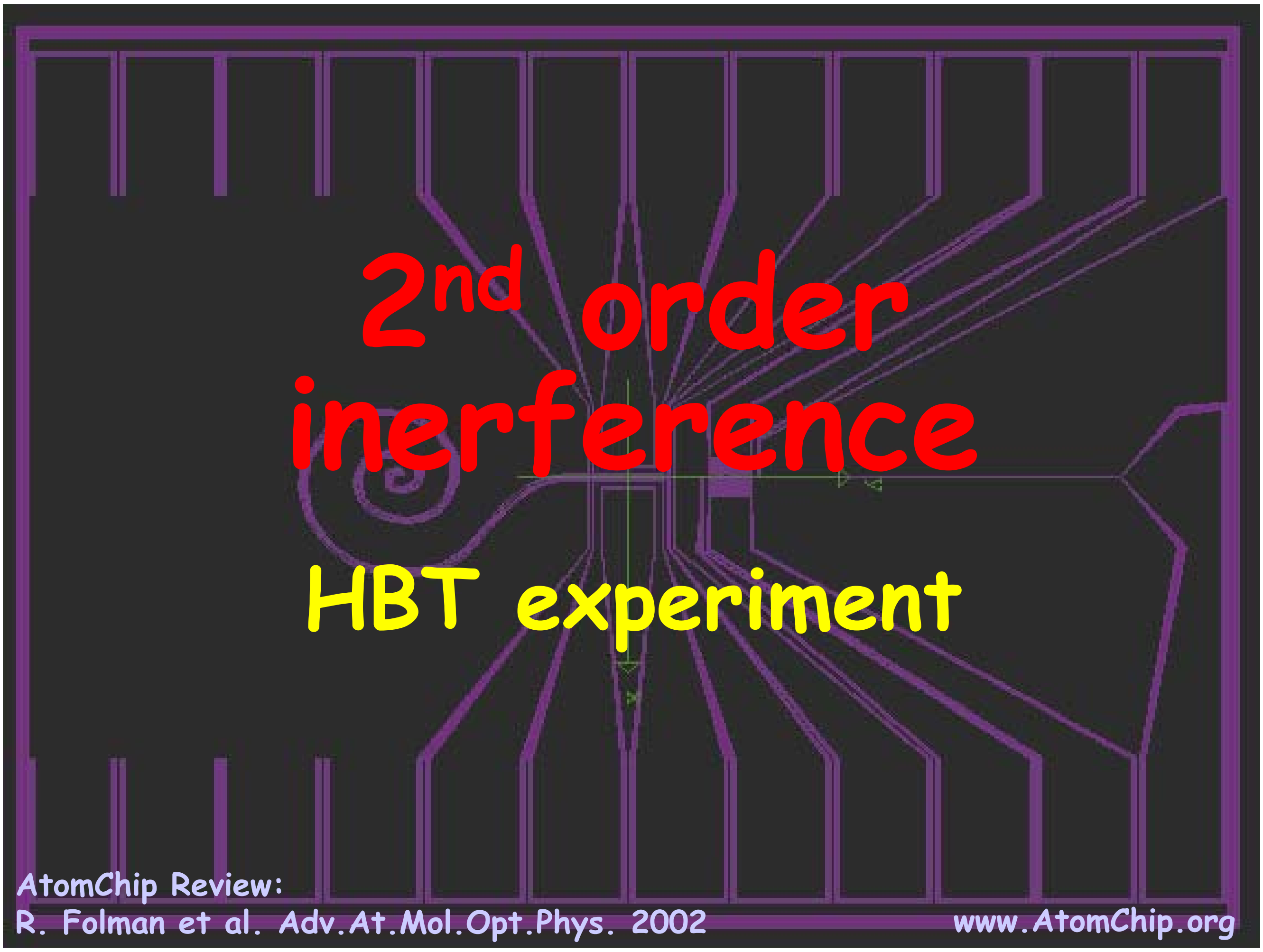
W. Rohringer Appl.Phys.Lett, **93**, 264101 (2008)
NatPhys **4**, 901 (2008)

Controlling a complex experiment

- making a complete search of the parameter space is impractical



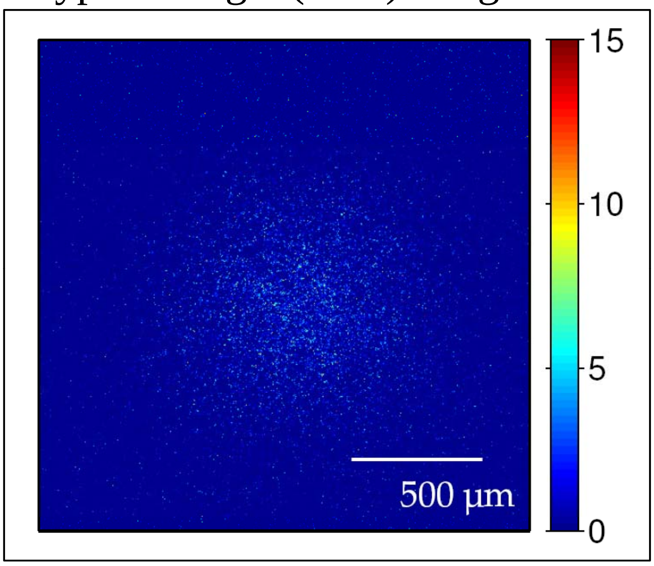
after only a few generation the algorithm finds parameters for the experiment that are at least as good as by manual optimization



ATOMINSTITUT

Measuring two-particle correlation functions
How to obtain $g^{(2)}$(r)...

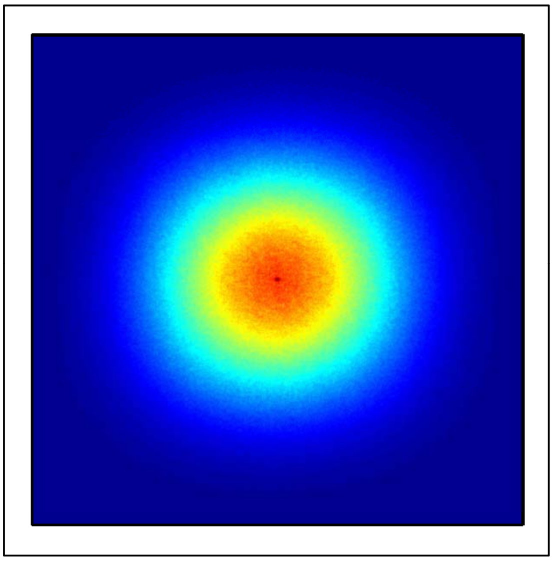
a typical single (slice) image...



... gives $\rho(\vec{r})$

temperature (and condensate fraction) can be derived from individual images (binning)

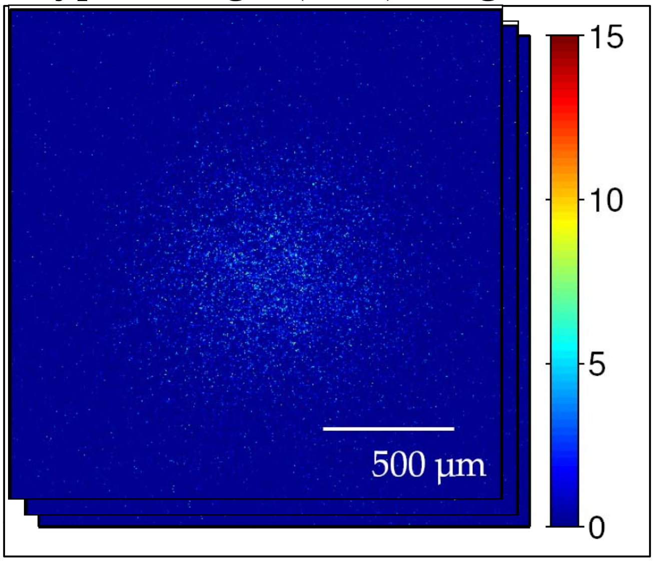
it's autocorrelations...



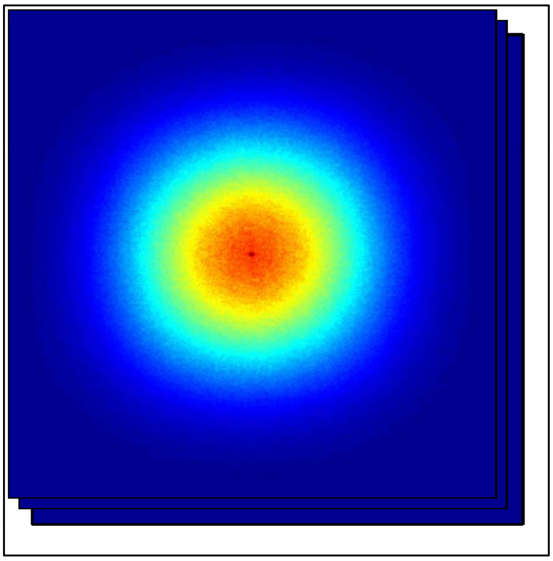
...gives $\int \rho(\vec{u})\rho(\vec{u}+\delta\vec{r})d\vec{u}$

How to obtain $g^{(2)}(\mathrm{r})$...
...gives the expectation values...

a typical single (slice) image...



it‘s autocorrelations...

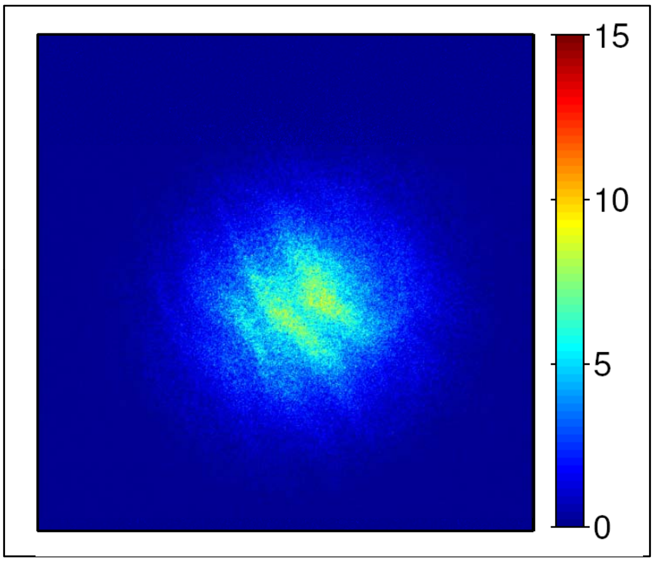


... gives $\rho(\vec{r})$

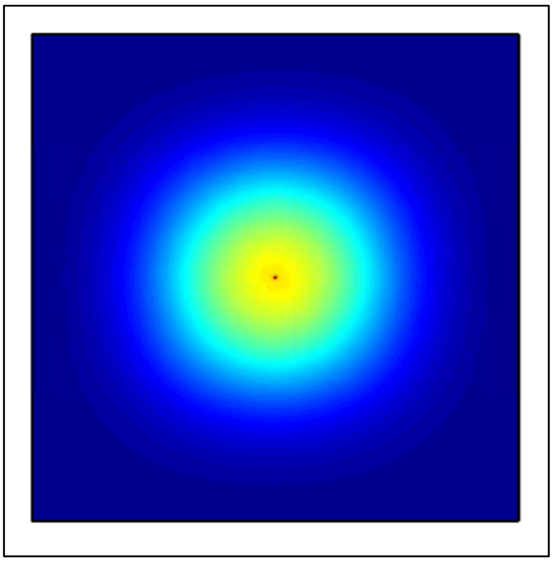
...gives $\int \rho(\vec{u})\rho(\vec{u}+\delta\vec{r})d\vec{u}$

How to obtain $g^{(2)}(\mathrm{r})$...
...gives the expectation values...

mean atomic density



mean autocorrelation



... gives $\langle \rho(\vec{r}) \rangle$

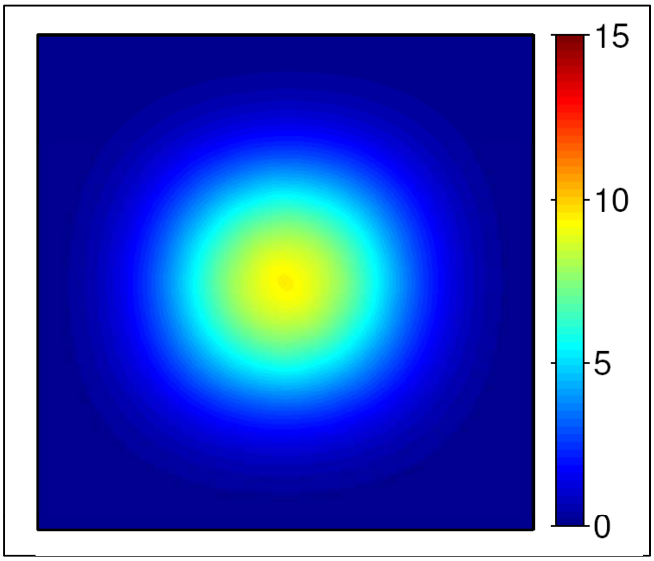
(note fringes due to single photon interference!)

...gives

$$G^{(2)}(\delta\vec{r}) = \left\langle \int \rho(\vec{u})\rho(\vec{u}+\delta\vec{r})d\vec{u} \right\rangle$$

How to obtain $g^{(2)}$(r)...
...another autocorrelation…

autocorrelation of the mean

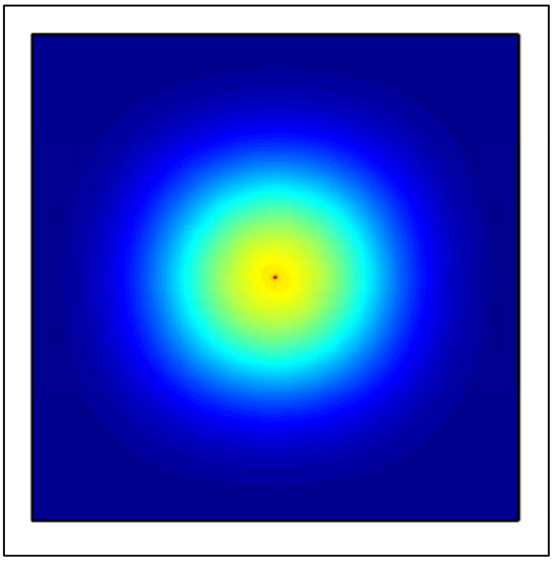


... gives

$$\int \langle \rho(\vec{u}) \rangle \langle \rho(\vec{u}+\delta\vec{r}) \rangle d\vec{u}$$

(after filtering)

mean autocorrelation



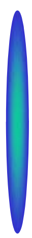
...gives

$$G^{(2)}(\delta\vec{r}) = \left\langle \int \rho(\vec{u}) \rho(\vec{u}+\delta\vec{r}) d\vec{u} \right\rangle$$

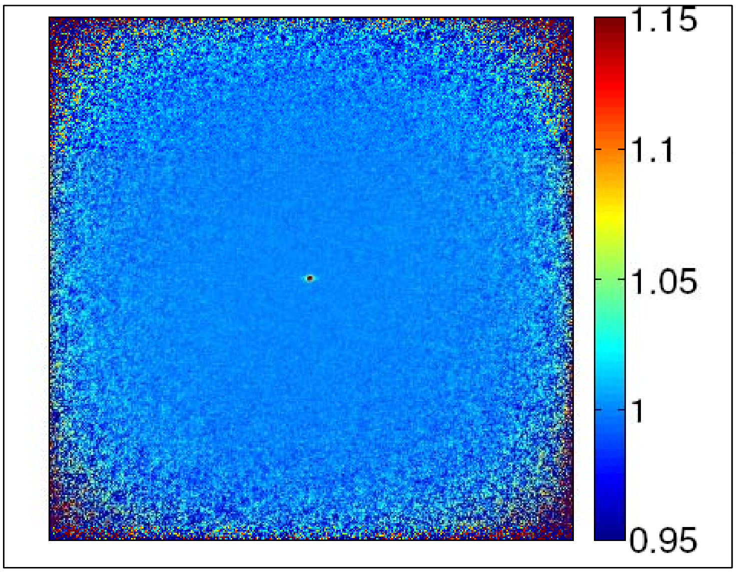
...finally gives $g^{(2)}$(r)
Signature of Hanbury-Brown-Twiss?

„Normalized autocorrelation" $g^{(2)}(\delta\vec{r}) = \dfrac{G^{(2)}(\delta\vec{r})}{\int \langle \rho(\vec{u}) \rangle \langle \rho(\vec{u}+\delta\vec{r}) \rangle d\vec{u}}$

hot thermal cloud (1.6 µK)



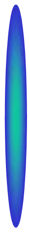
in-trap orientation



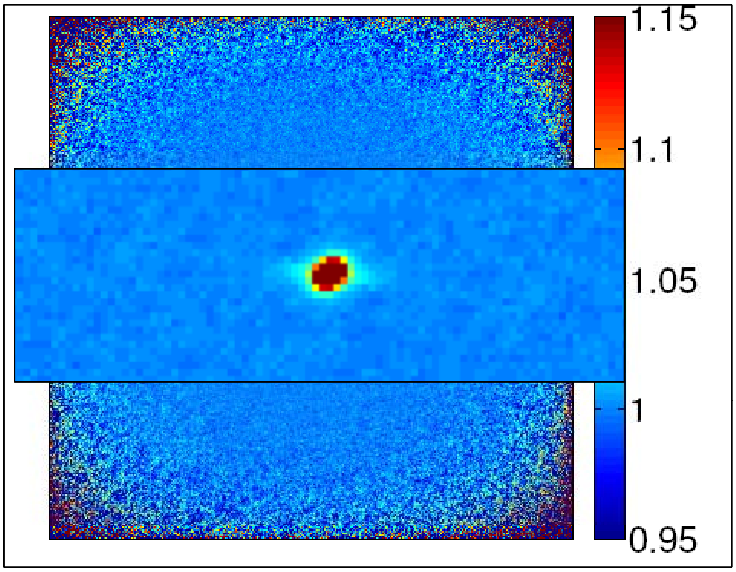
...finally gives $g^{(2)}$(r) Signature of Hanbury-Brown-Twiss?

„Normalized autocorrelation $g^{(2)}(\delta\vec{r}) = \dfrac{G^{(2)}(\delta\vec{r})}{\int \langle \rho(\vec{u}) \rangle \langle \rho(\vec{u}+\delta\vec{r}) \rangle d\vec{u}}$

hot thermal cloud (1.6 µK)



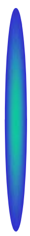
in-trap orientation



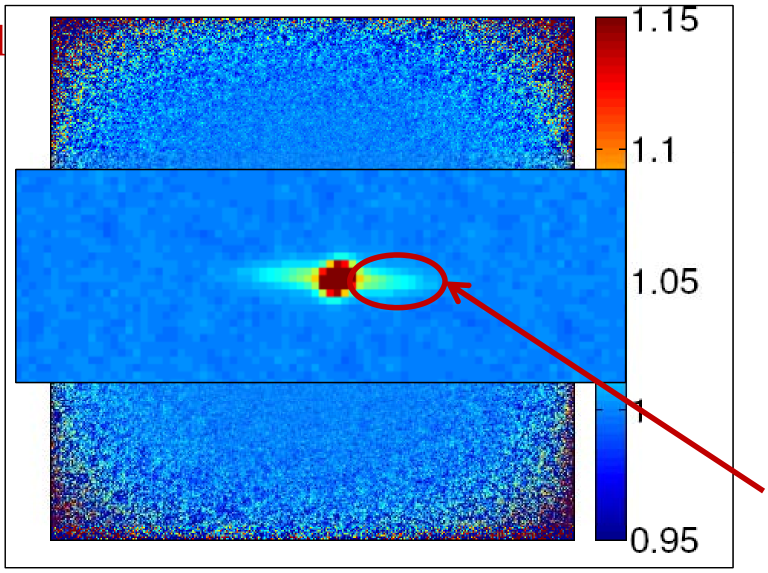
...finally gives $g^{(2)}$(r) Signature of Hanbury-Brown-Twiss?

„Normalized autocorrelation $g^{(2)}(\delta\vec{r}) = \dfrac{G(2)(\delta\vec{r})}{\int \langle \rho(\vec{u}) \rangle \langle \rho(\vec{u}+\delta\vec{r}) \rangle d\vec{u}}$

colder thermal cloud (1.0 µK)



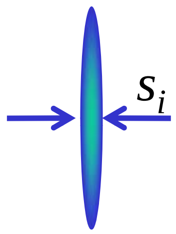
in-trap orientation



measure width and amplitude of bunching...

Hanbury-Brown-Twiss for thermal bosons: Bunching coherence length and amplitude

in-trap cloud



source size

$$s_i = \sqrt{\frac{k_B T}{m\omega_i^2}}$$

coherence length

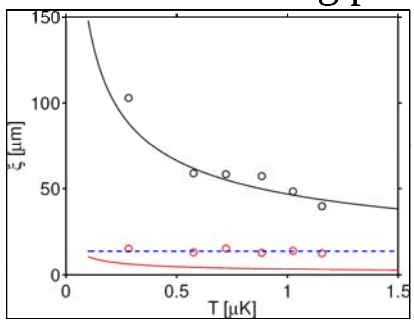
$$\xi = \frac{\hbar t}{m s_i}$$

$\omega_{\|}=2\pi \cdot 160$ Hz
$\omega_{\perp}=2\pi \cdot 2180$ Hz
aspect ratio 1:15

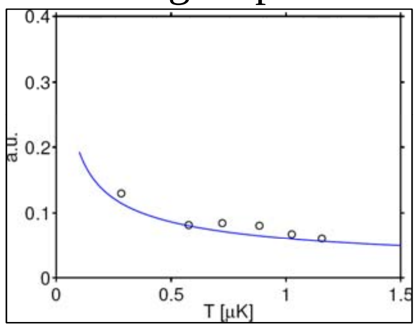
scaling of thermal bunching with temperature well understood
(finite optical resolution)

same results as He*

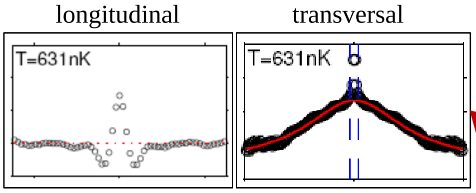
width of bunching peak



bunching amplitude

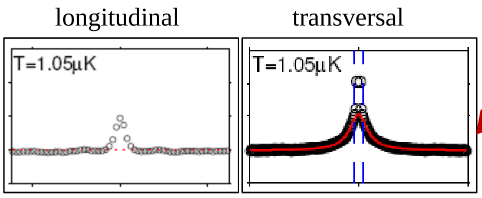


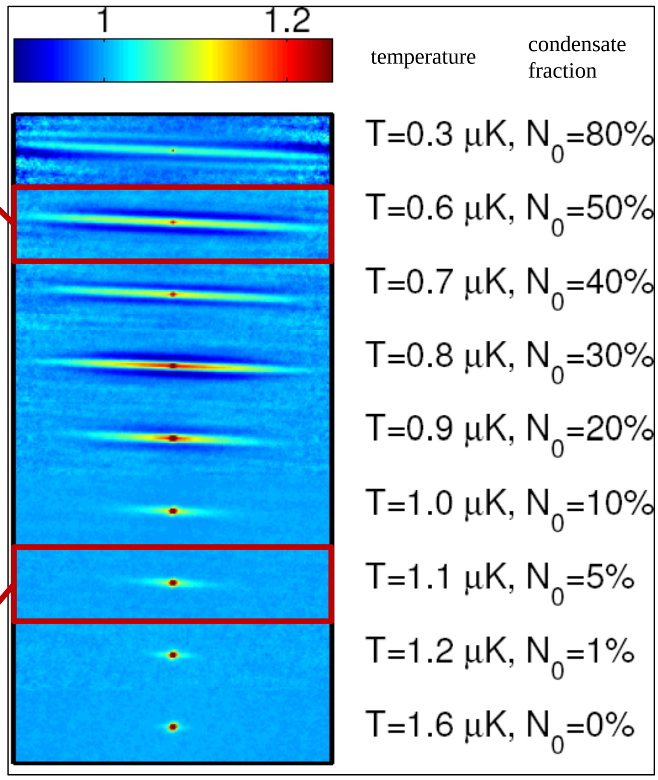
Hanbury-Brown-Twiss for condensed bosons: What happens at T_c ? (priliminary)



qualitative observations:

- coherence length jumps from thermal bunching to size of the condensate
- significant bunching even for almost pure BEC
- g(2) drops below 1 in the longitudinal direction
- no theory for shape of profiles



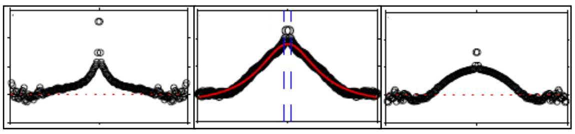


What happens at T_c ? (priliminary)
What happens in the 3D case?

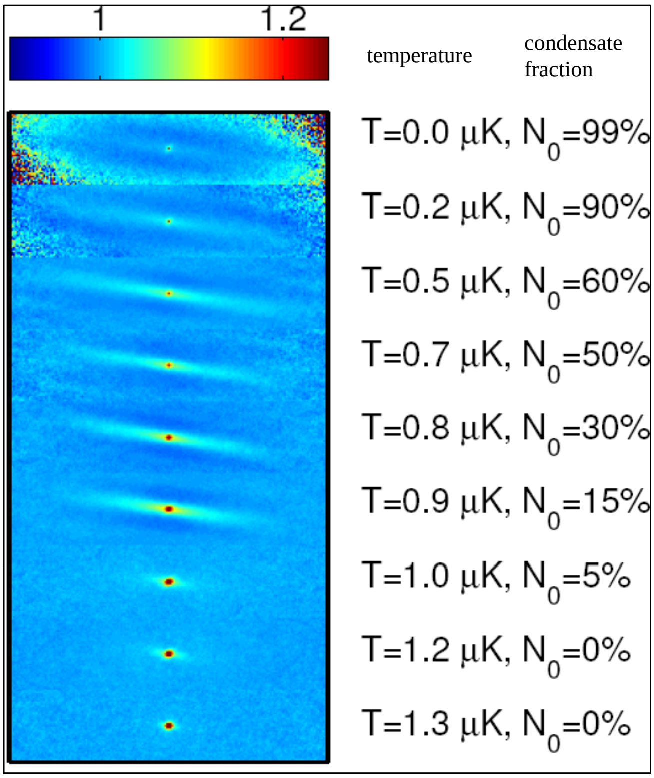
more qualitative observations:

- coherence length jumps from thermal bunching to size of the condensate
- **still true (even more striking)**
- significant bunching even for almost pure BEC
- **bunching fades away at very low temperatures**
- g(2) drops below 1 in the longitudinal direction
- **still true in a weaker form**
- no theory for shape of profiles
- **profiles a mystery!**

3D 1D

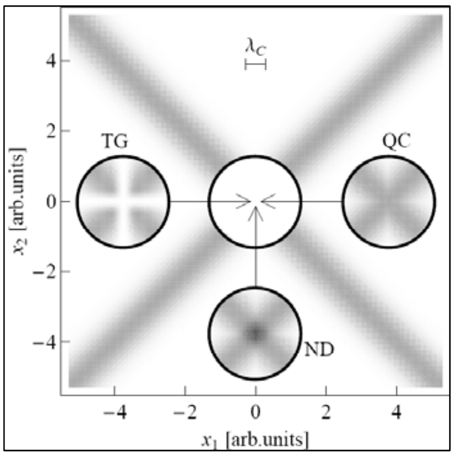


1:5 1:15 1:100



Correlations as a 1D probe:
what's left after expansion?

I. Mazets, in preparation...



numerical propagation of the 2-point density matrix

relevant timescale:

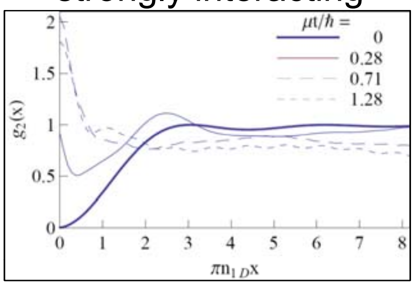
$$\boxed{m\lambda_c^2/\hbar}$$

strongly interacting:
λ_c: particle distance

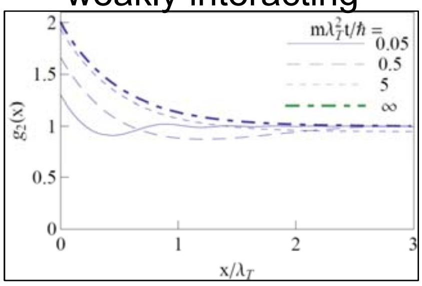
weakly interacting
λ_c: coherence length

A. Imambekov et al. arXiv:0904.1723

strongly interacting



weakly interacting



Conclusion: don't take TOF too long or look in-situ

for long TOF, everything looks like an ideal gas