Supersonic motion of impurities in a Bose gas

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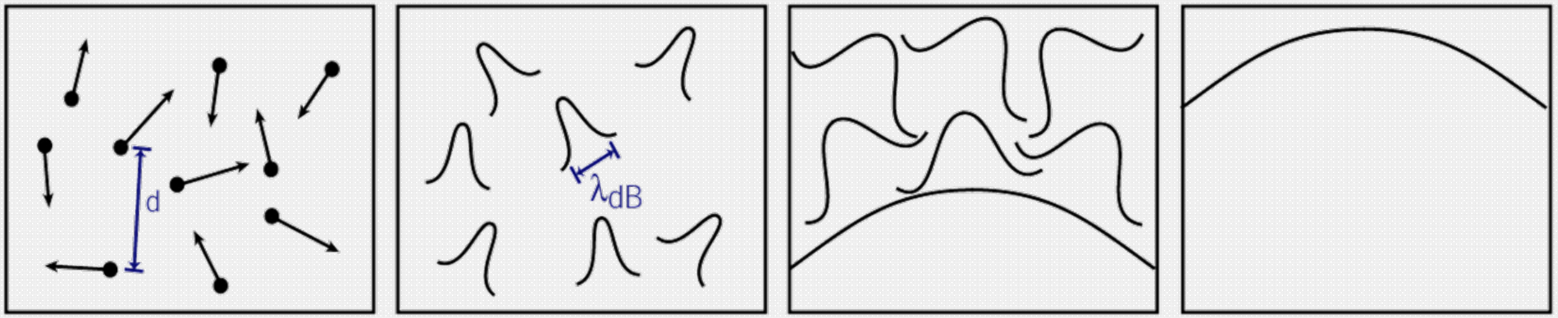
What is a Bose-Einstein condensate?

The „pedestrian“ approach ….



$T >> T_c$:
classical gas

$T > T_c$:
Thermal de-Broglie wavelength
$\lambda_{dB} = h/mv \propto T^{-1/2}$

$T < T_c$: $\lambda_{dB} \approx d$
Bose-Condensate starts growing

$T = 0$:
pure Condensate, coherent matter wave

What is a Bose-Einstein condensate?

Penrose and Onsager (1956):

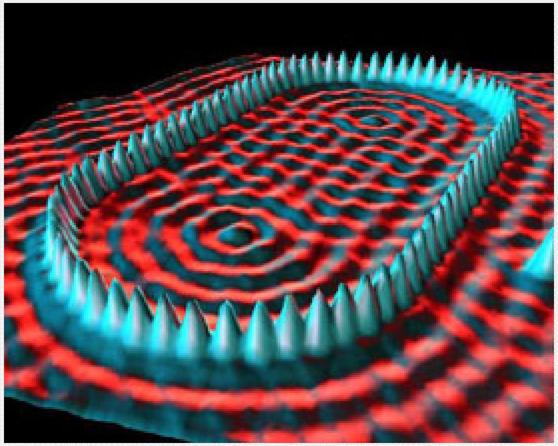
$$\rho(r_1,r_2)=\left\langle\hat{\Psi}^{\dagger}(r_1)\hat{\Psi}(r_2)\right\rangle$$

$$=\underset{\text{condensate wavefunction}}{\underline{\Psi^*(r_1)\Psi(r_2)}}+\underset{\text{fluctuations}}{\underline{\left\langle\delta\hat{\Psi}^{\dagger}(r_1)\delta\hat{\Psi}(r_2)\right\rangle}}$$

off-diagonal long-range order of the density matrix

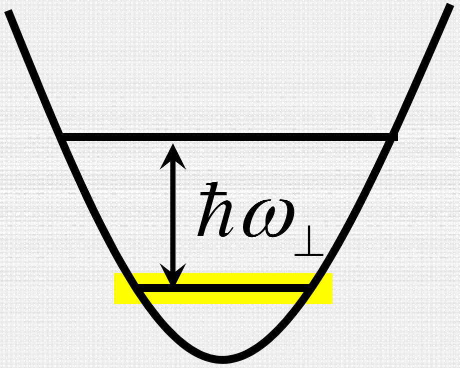
Impurities: why spoiling a clean system?

- Understanding real world systems
- Test & measurement:
  Impurities as probes and tools
- Transport experiments



What is a one-dimensional gas?

- transverse degrees of freedom are frozen out



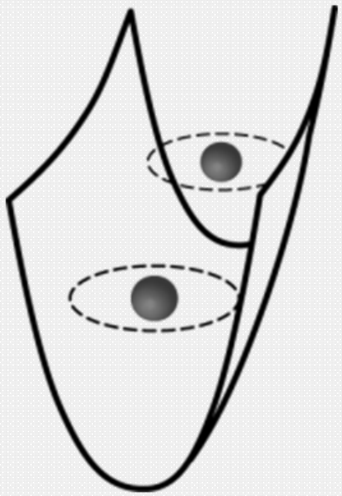
Conditions for 1D

$k_B T < \hbar\omega_\perp$

Bosons: $\mu < \hbar\omega_\perp$

Fermions: $E_F = N\hbar\omega_z < \hbar\omega_\perp$

- asymptotic scattering states are one-dimensional wave functions



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Why 1D?

Many exactly solvable problems

Dimensionality modifies ground state and excitation spectrum

Important role of quantum fluctuations

Mapping of Bose and Fermi systems

Confinement induced scattering phenomena

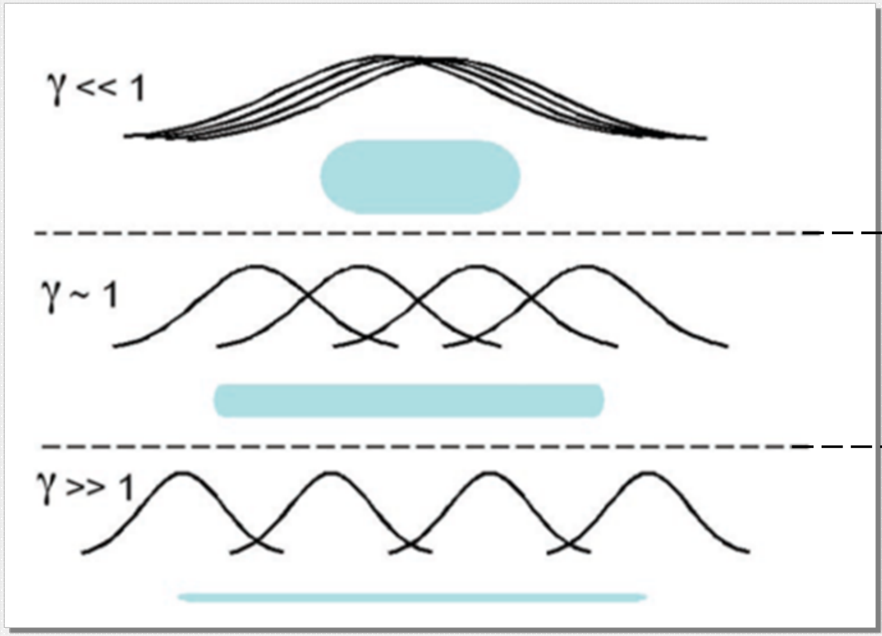
Energy scales in one dimension

	1D	3D
Kinetic energy	$E_{kin} = \frac{\hbar^2 n_{1D}^2}{2m}$	$E_{kin} = \frac{\hbar^2 n_{3D}^{2/3}}{2m}$
Interaction energy	$E_{\text{int}} = \frac{\hbar^2}{m\, a_{1D}} n_{1D}$	$E_{\text{int}} = \frac{4\pi\hbar^2 a}{m} n_{3D}$
	$\gamma = \frac{E_{\text{int}}}{E_{kin}} = \frac{2}{a_{1D} n_{1D}}$	$\frac{E_{\text{int}}}{E_{kin}} = 8\pi a\, n_{3D}^{1/3}$

Strong interaction
at **low density**.

Strong interaction
at **high density**.

Regimes of degeneracy in 1D



weakly interacting Bose gas

$$\psi_{Bose}(r) = \prod_{i=1\ldots N} \psi_i(r); \quad mc^2 = \mu$$

crossover

Tonks-Girardeau gas
(“Fermionized Bosons”)

$$\psi_{Bose}(r) = |\psi_{Fermi}(r)|$$

$$k_F = \pi n = mc/\hbar$$

1960: $\gamma \to \infty$ limit solved by Girardeau

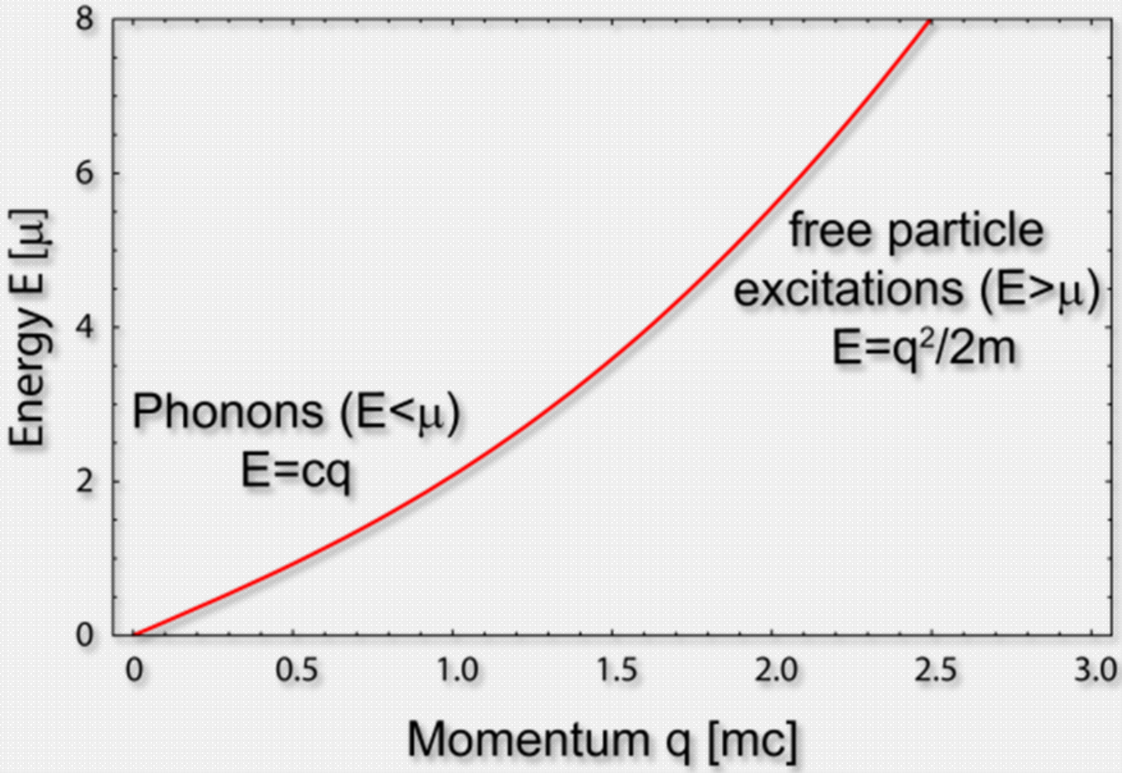
1963: Exactly solved for all values of γ by Lieb & Liniger

2003: 1D Bose gases first realized by Esslinger et al. (ETH Zürich).

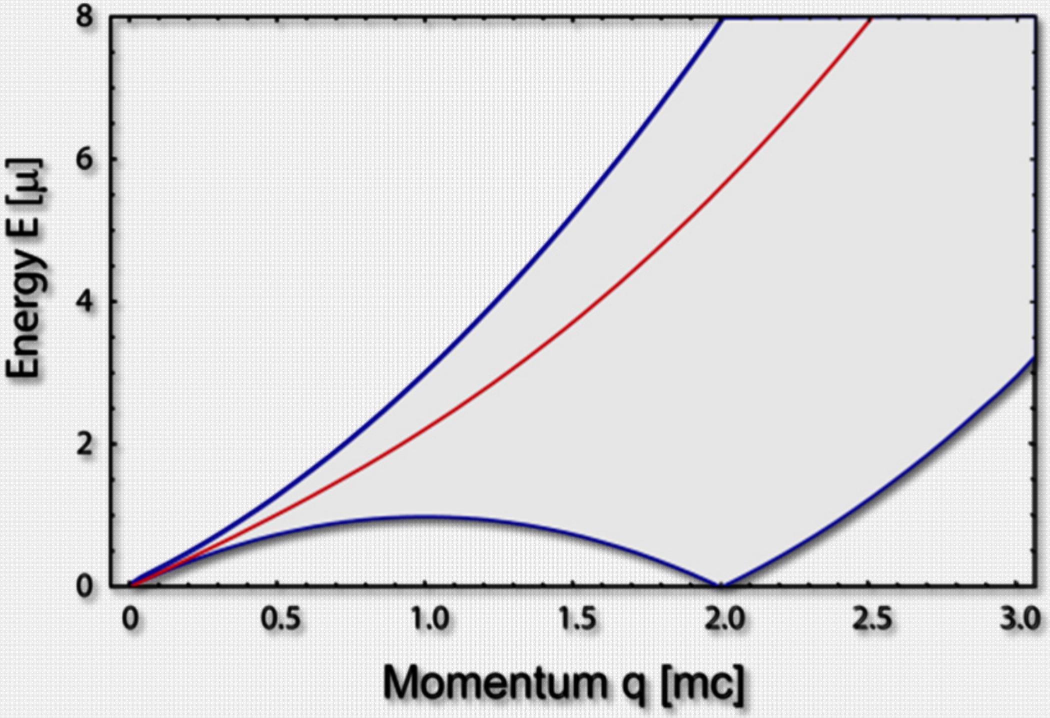
2004: Tonks gas experimentally realized by Weiss et al. (Penn State) & Bloch et al. (Mainz)

Excitations in a weakly interacting Bose gas

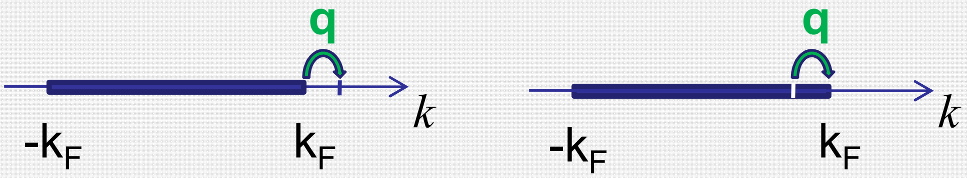
Bogoliubov spectrum



Excitations in a Tonks gas



Two branches of excitations: “particle” excitations and “hole” excitations



Tools of the trade

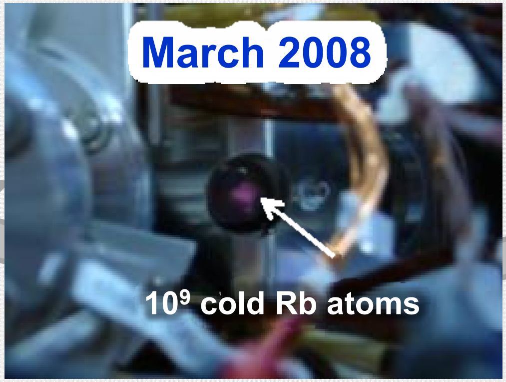
Making a Bose-Einstein condensate


March 2007


June 2007

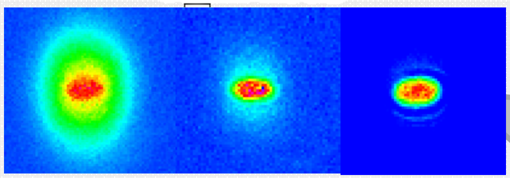

October 2007


November 2007

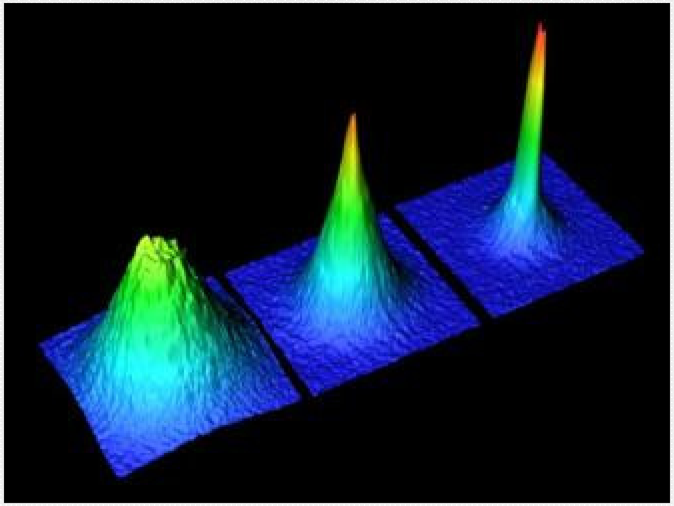

March 2008

10^9 cold Rb atoms

April 2008

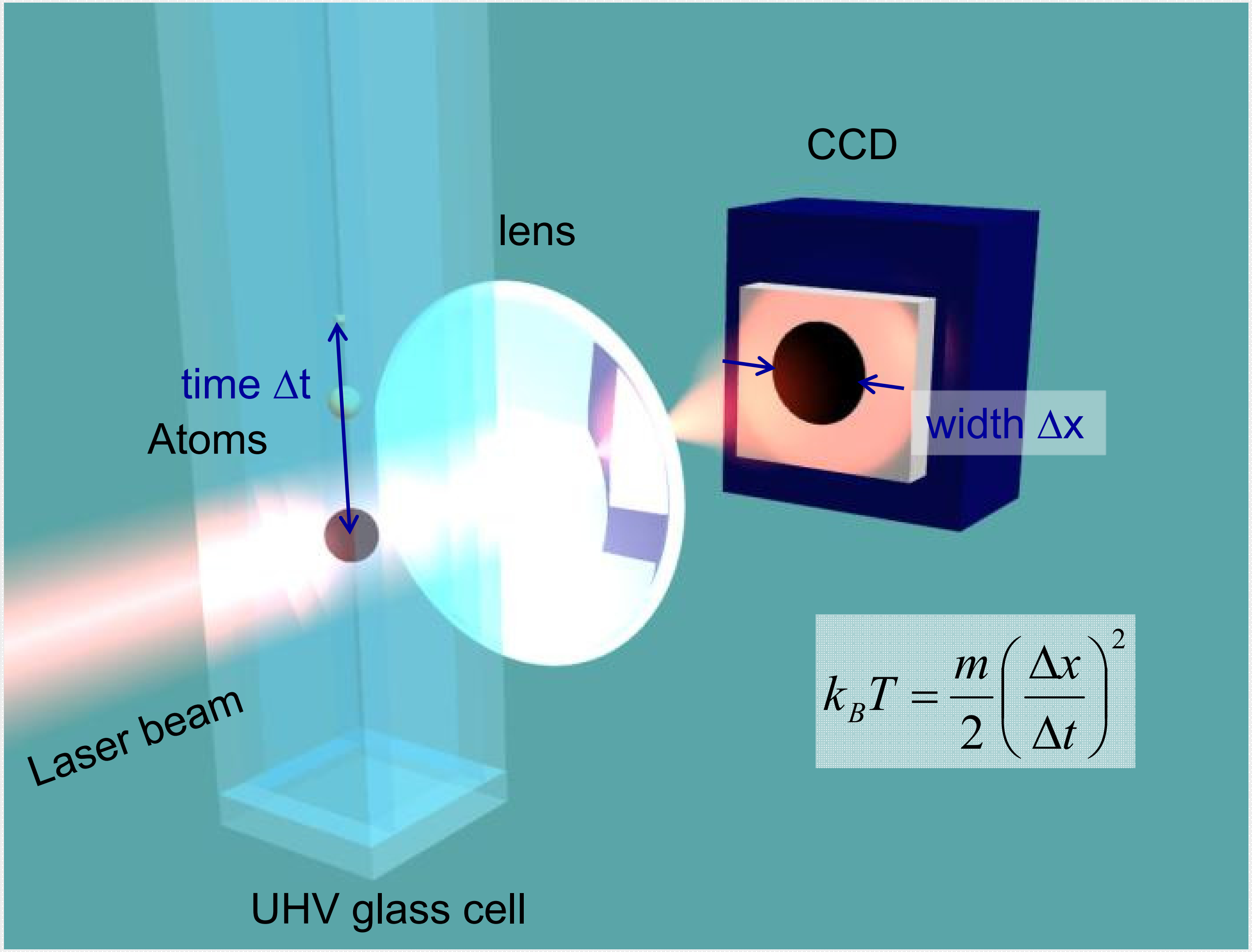

Bose-Einstein condensation

Cold atomic gases



- Dilute gases: $n \approx 10^{14}\ \mathrm{cm}^{-3}$
- Tunable from weak to strong interactions
- Ultracold: $T_{\mathrm{degeneracy}} \approx 100\ \mathrm{nK}$
- Detection by absorption imaging

How to detect ultracold atoms



$$k_B T = \frac{m}{2}\left(\frac{\Delta x}{\Delta t}\right)^2$$

Absorption imaging

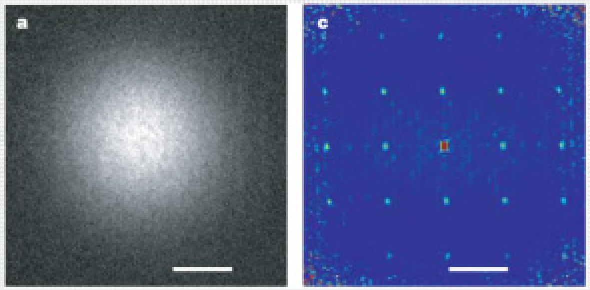
Advantages

- precise atom number determination
- good momentum resolution
- technically very simple

Disadvantages

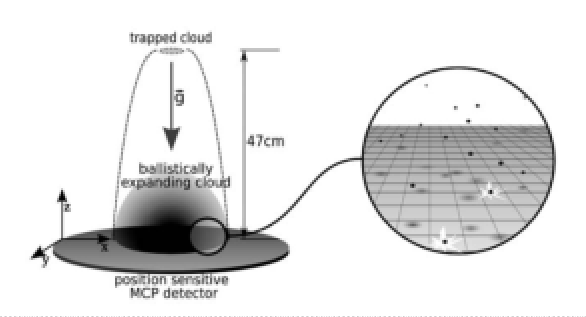
- integration along the line of sight
- no in-situ measurements: cloud is too small and dense
- correlation measurements are difficult

More advanced detection techniques



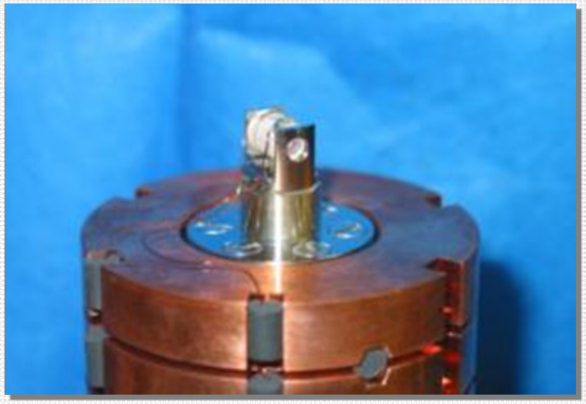
Noise-correlation measurements

[Altman et al. PRA (2004); Bloch group (Mainz), Nature (2005 & 2006)]



Hanbury Brown and Twiss correlations of metastable atoms

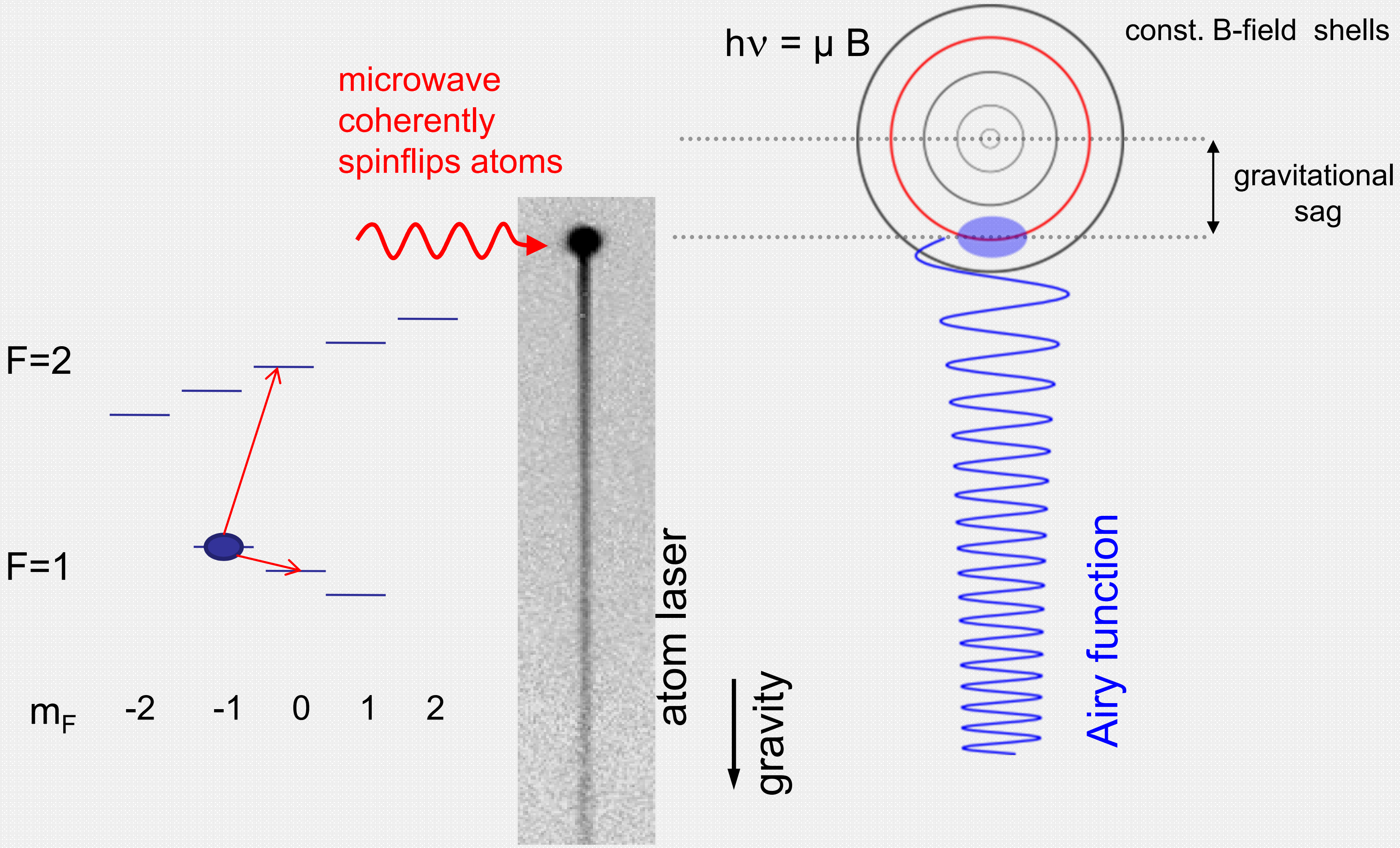
[Aspect group (Orsay), Science (2005) & Nature (2006)]



Single atom counting by cavity QED

[A. Öttl, S. Ritter, M. Köhl, T. Esslinger, PRL (2005)
S. Ritter, T. Donner, A. Öttl, M. Köhl, T. Esslinger, PRL (2007)
T. Donner, S. Ritter, T. Bourdel, A. Öttl, M. Köhl, T. Esslinger, Science (2007)].

Spectroscopic detection



$h\nu = \mu B$

const. B-field shells

microwave coherently spinflips atoms

gravitational sag

atom laser

gravity

Airy function

Experimental realization of 1D Bose gases

Generating tight confining potentials

Induced electric dipole potential: $V = -\frac{1}{2}\alpha\left|E\right|^2$

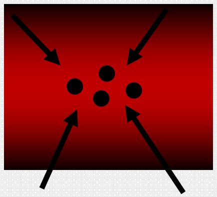
ac polarizability of the atom

electric field of the laser

Two options:

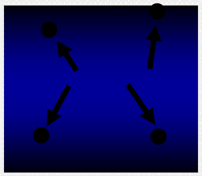
$\omega_L < \omega_A$

„red detuned“

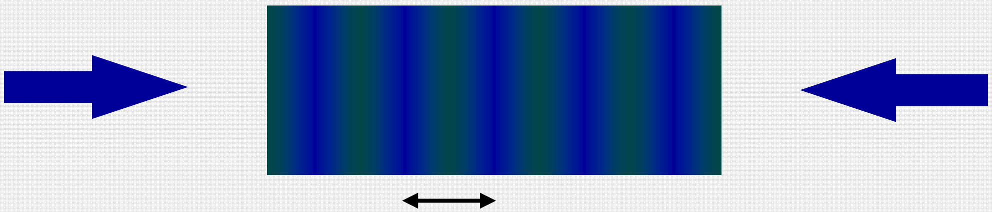


$\omega_L > \omega_A$

„blue detuned“



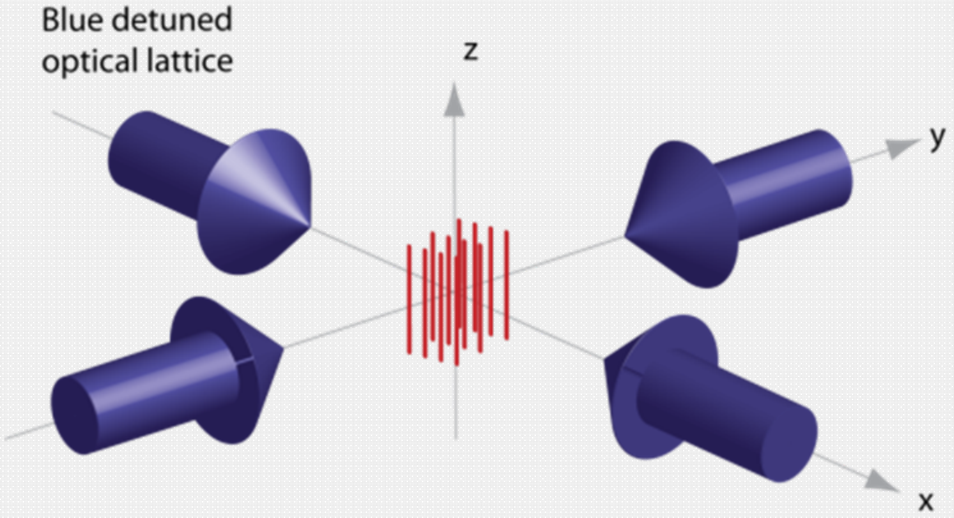
Optical lattice



Energy scale:

$$E_{rec} = \frac{\hbar^2 k^2}{2m}$$

Hybrid optical/magnetic trap



Experimental parameters:

Atoms: ^{87}Rb (bosons)

Wavelength of lattice: 764 nm

$\omega_x = \omega_y \leq 2\pi$ 65 kHz (optical lattice)

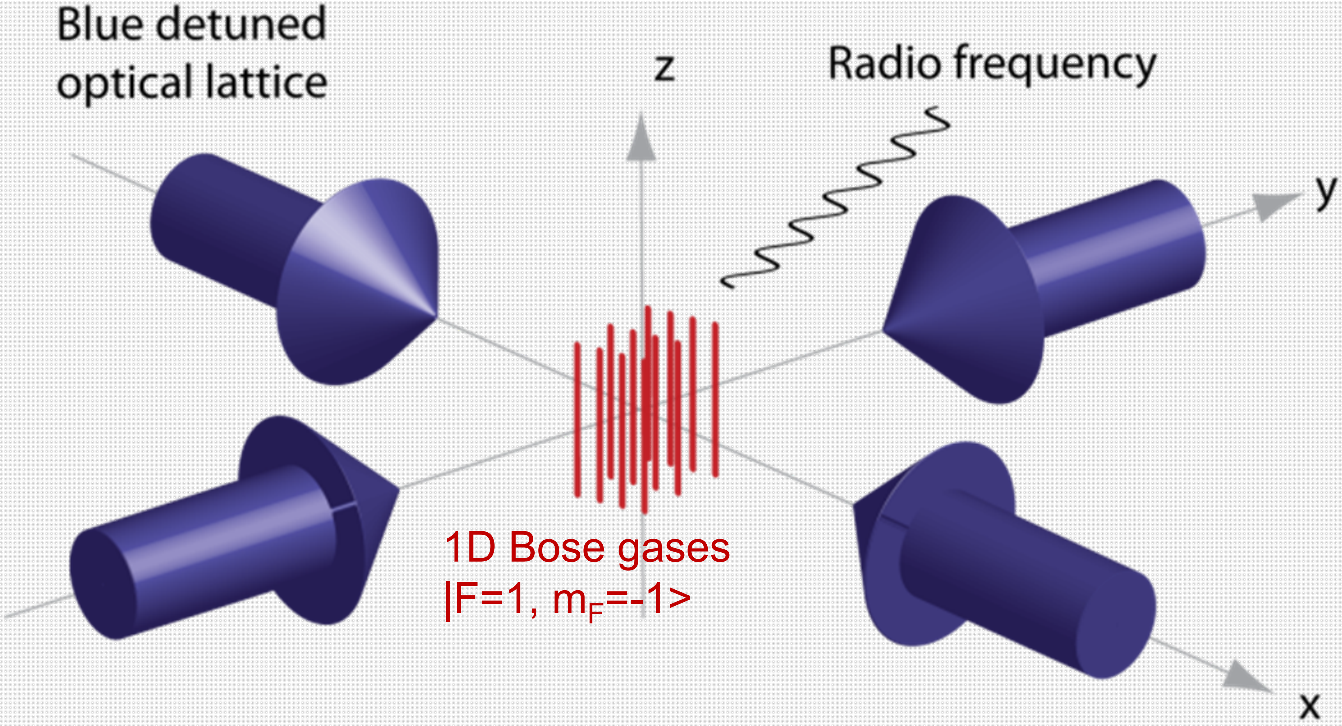
$\omega_z = 2\pi$ 39 Hz (magnetic trap)

$N<120$ per tube

$0.5 < \gamma < 5$

Other experiments in 1D: ETH, ENS, Mainz, MIT, NIST, Penn State, Rice, Vienna …

Spatial addressing



1D Bose gases
$|F=1, m_F=-1>$

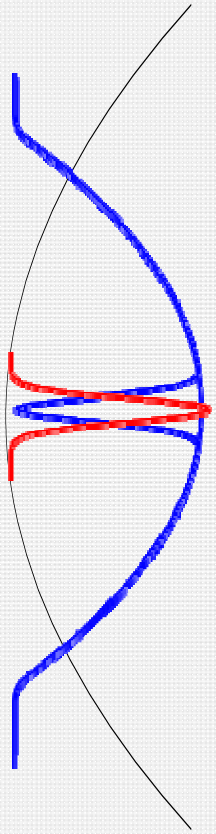
Radio frequency resonance: $|F=1, m_F=-1> \rightarrow |F=1, m_F=0>$
at $\hbar\nu_{RF} = g_F\mu_B B(x,y,z) \approx \mu_B B(z)/2$

Generation of spin impurities

|F=1, m_F=-1>
V= m/2 ω_z^2 z^2 - m g z

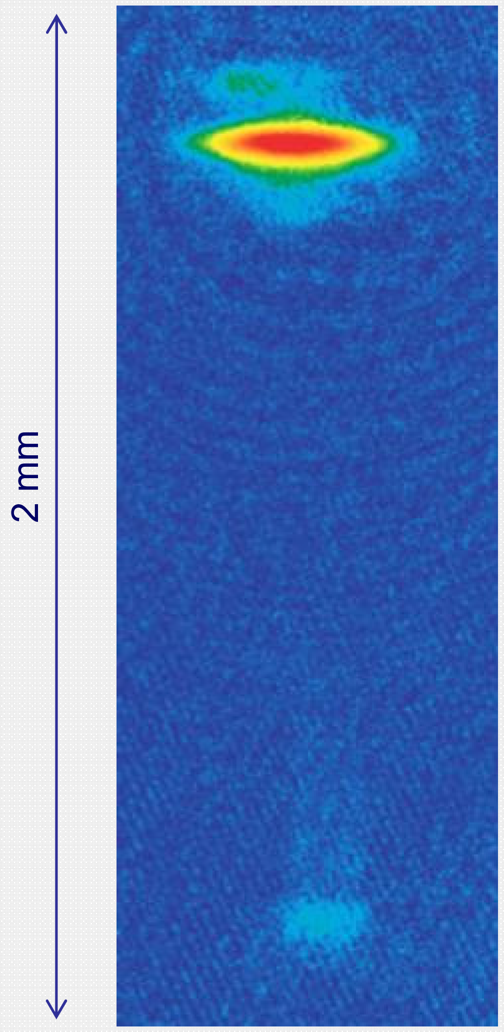
|F=1, m_F=0>
V=- m g z

quick transfer
(RF π-pulse, 200 μs)

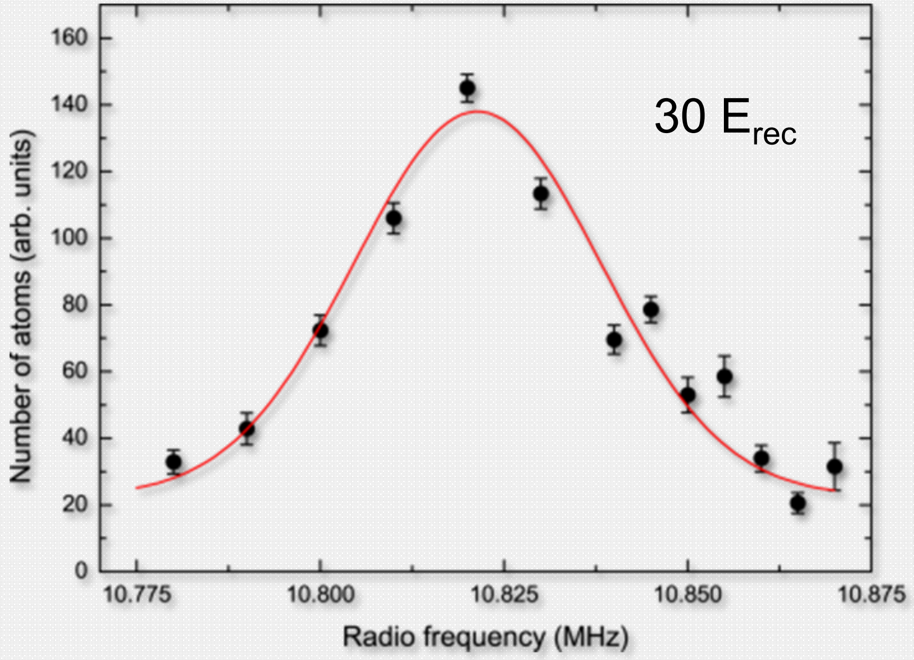


- width of impurity wave packet: 2.5 μm (≈ 3 atoms)
- same transverse confinement: propagation of impurities is purely one-dimensional
- same scattering lengths: $a_{-1,-1} \approx a_{-1,0} \approx a_{0,0}$

In-situ spectroscopy of the Tonks gas

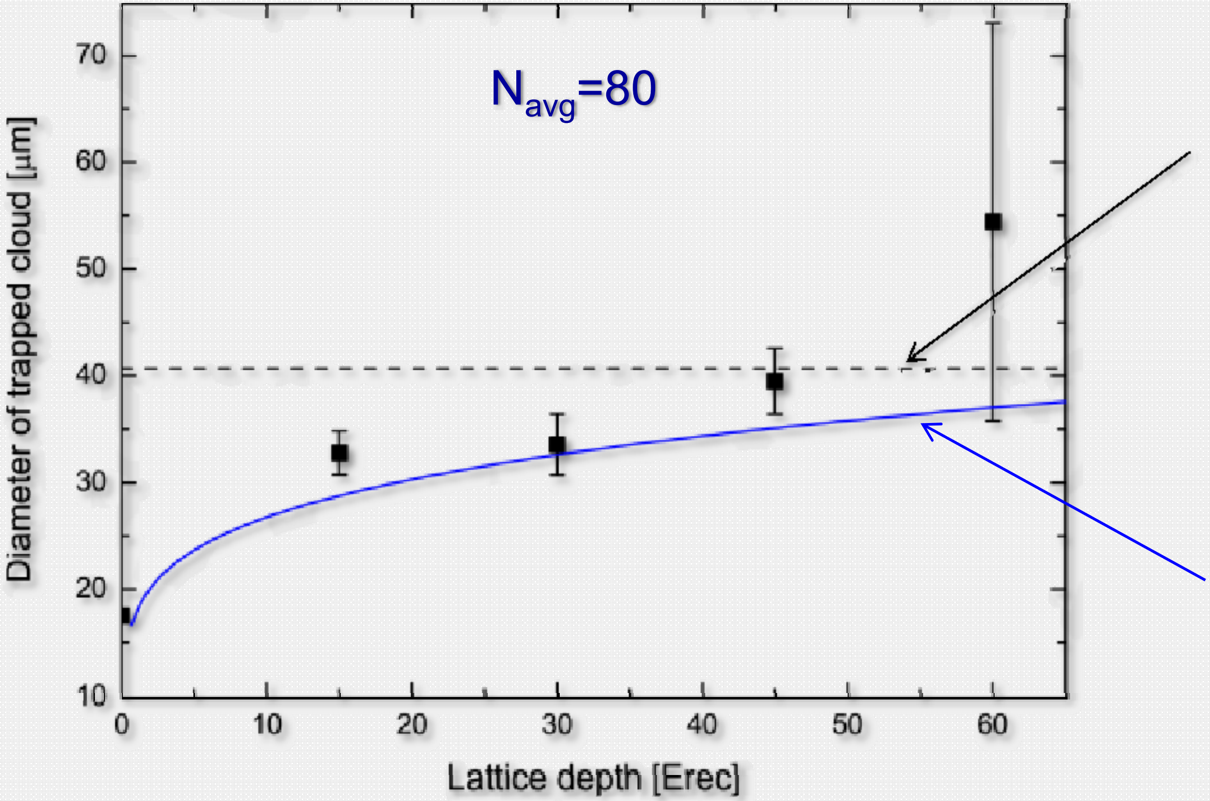


Bose gases



Impurity atoms after
19 ms ballistic expansion

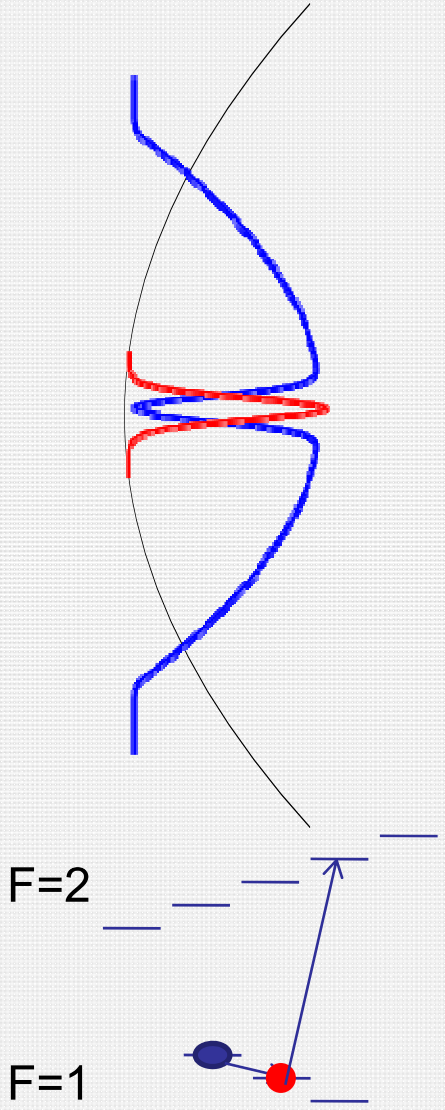
In-situ spectroscopy of the Tonks gas

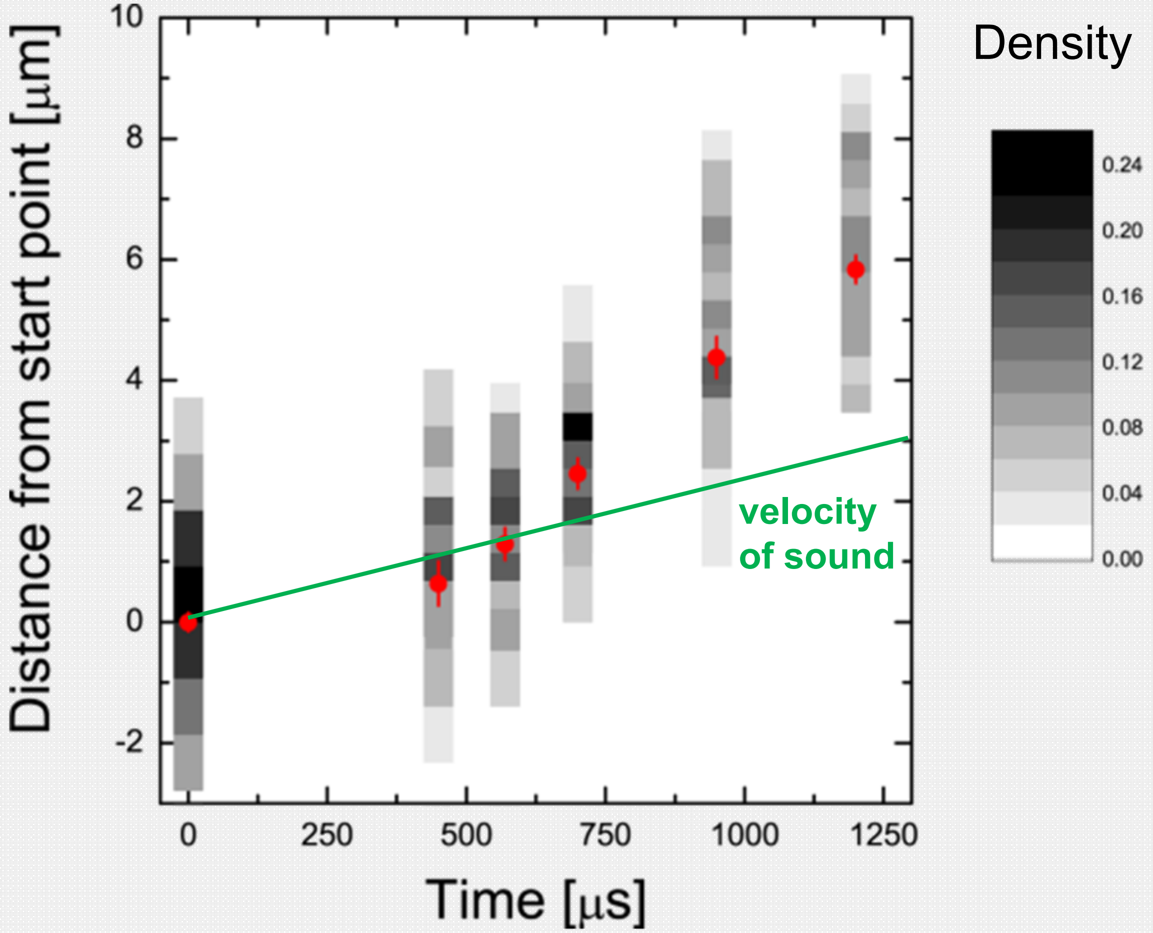


Tonks (fermionic) limit
$d = (8\ N\ a_{HO})^{1/2}$

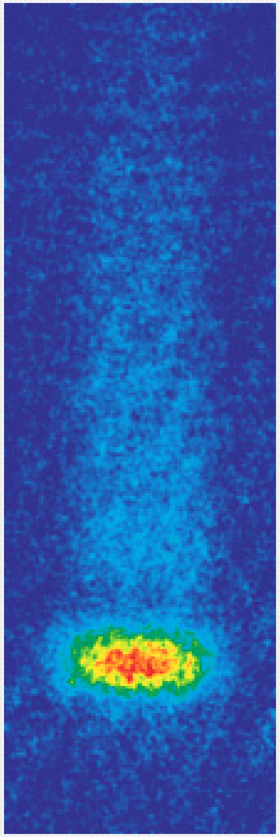
Weakly interacting
(Thomas Fermi) limit
$d = (8\mu/(m\omega_z^2))^{1/2}$

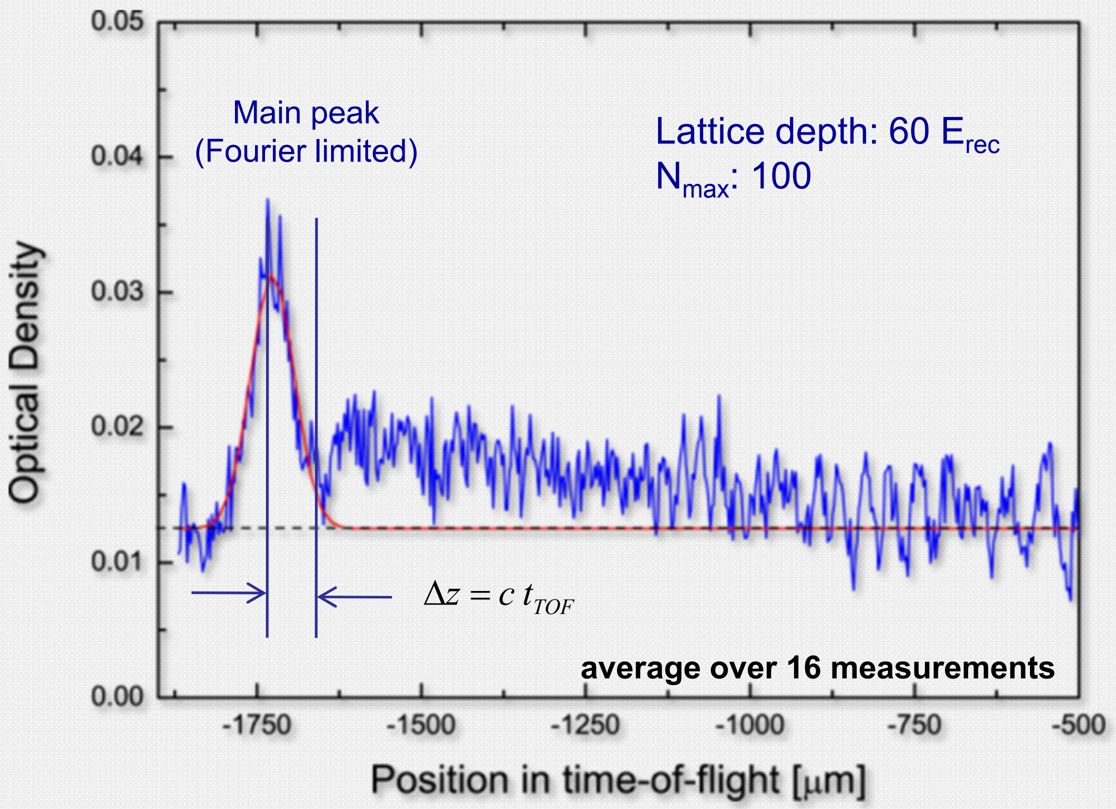
Propagation of a density wave packet





Impurity momentum distribution





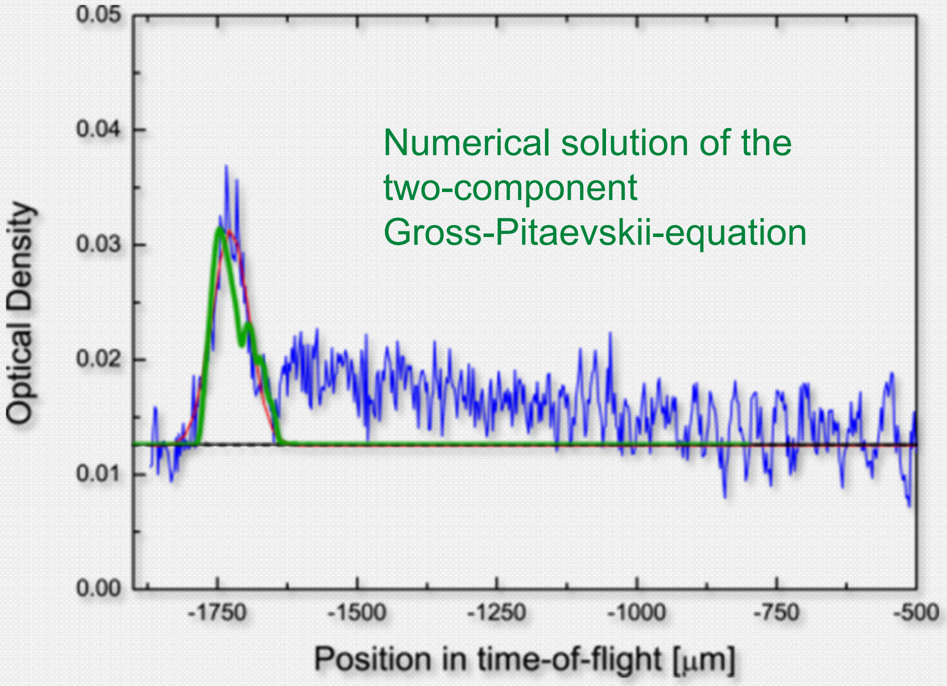
Main peak
(Fourier limited)

Lattice depth: 60 E_{rec}
N_{max}: 100

$\Delta z = c\, t_{TOF}$

average over 16 measurements

Comparison with numerical calculations

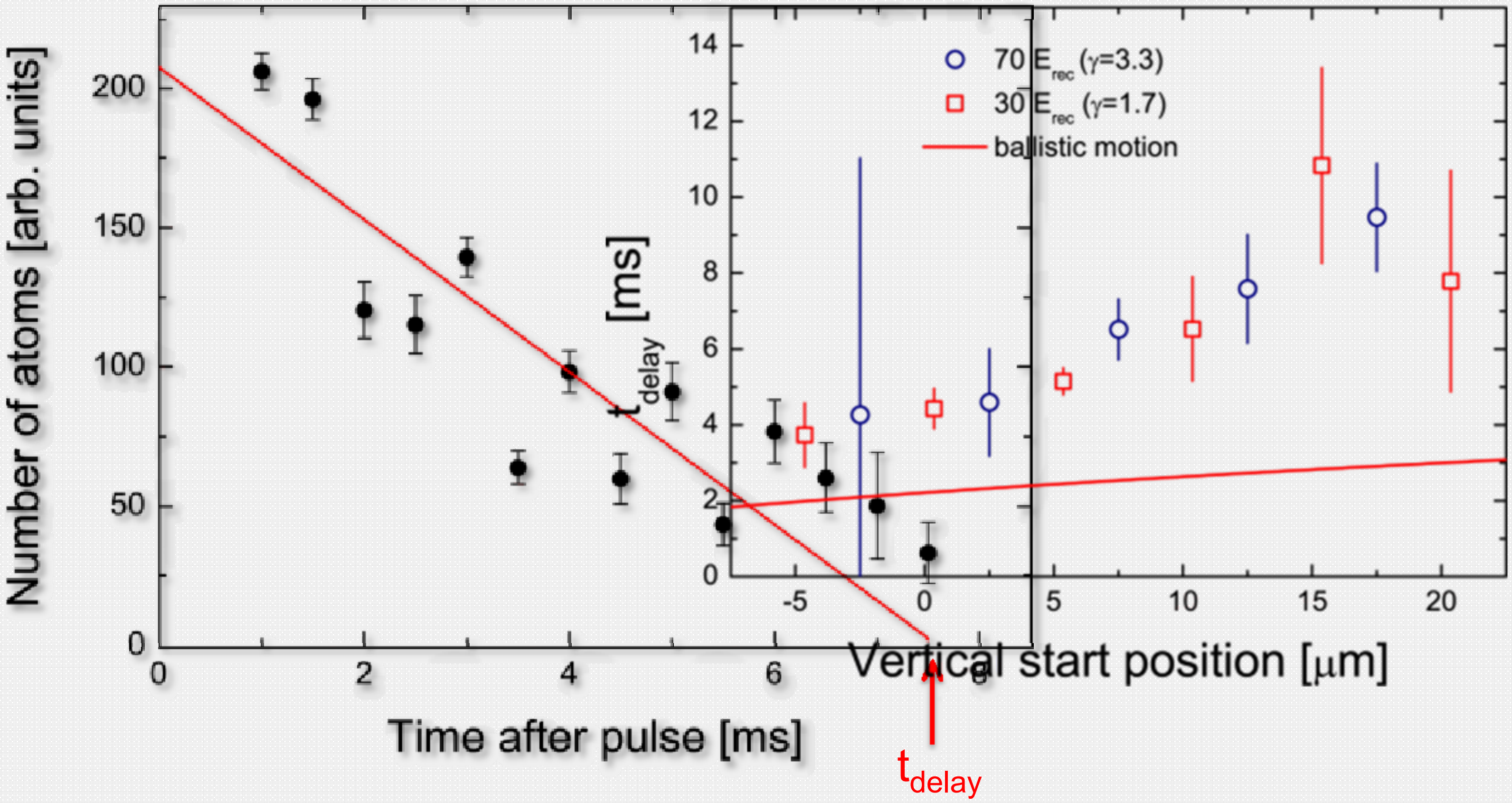


Numerical solution of the two-component Gross-Pitaevskii-equation

Gross-Pitaevskii equation does not account for

- strong interactions (γ>>1)
- excitations of wave vector $k > \pi$ n

Length of the “tail”: Release measurement



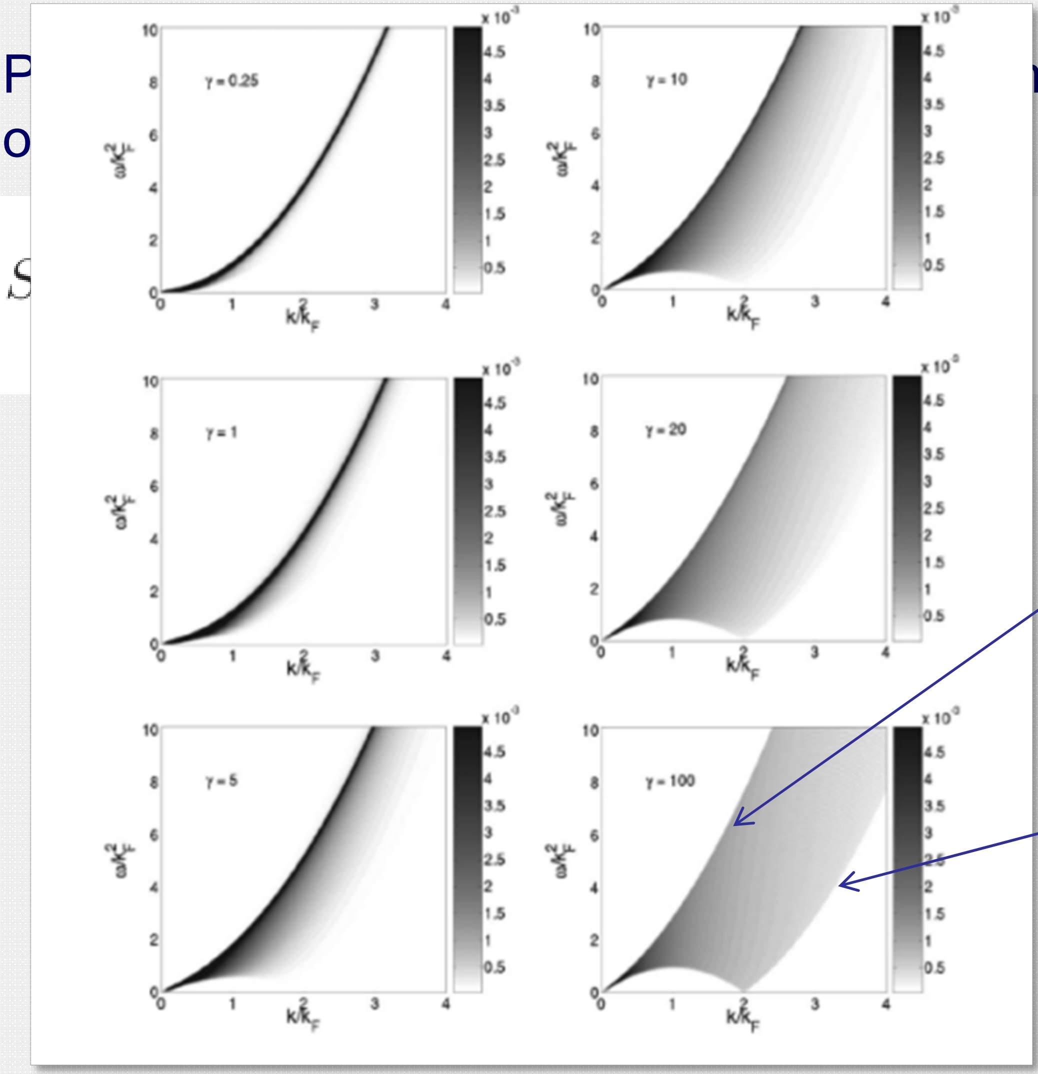
t_{delay}

Dynamic structure factor

P all) excitation

o

S

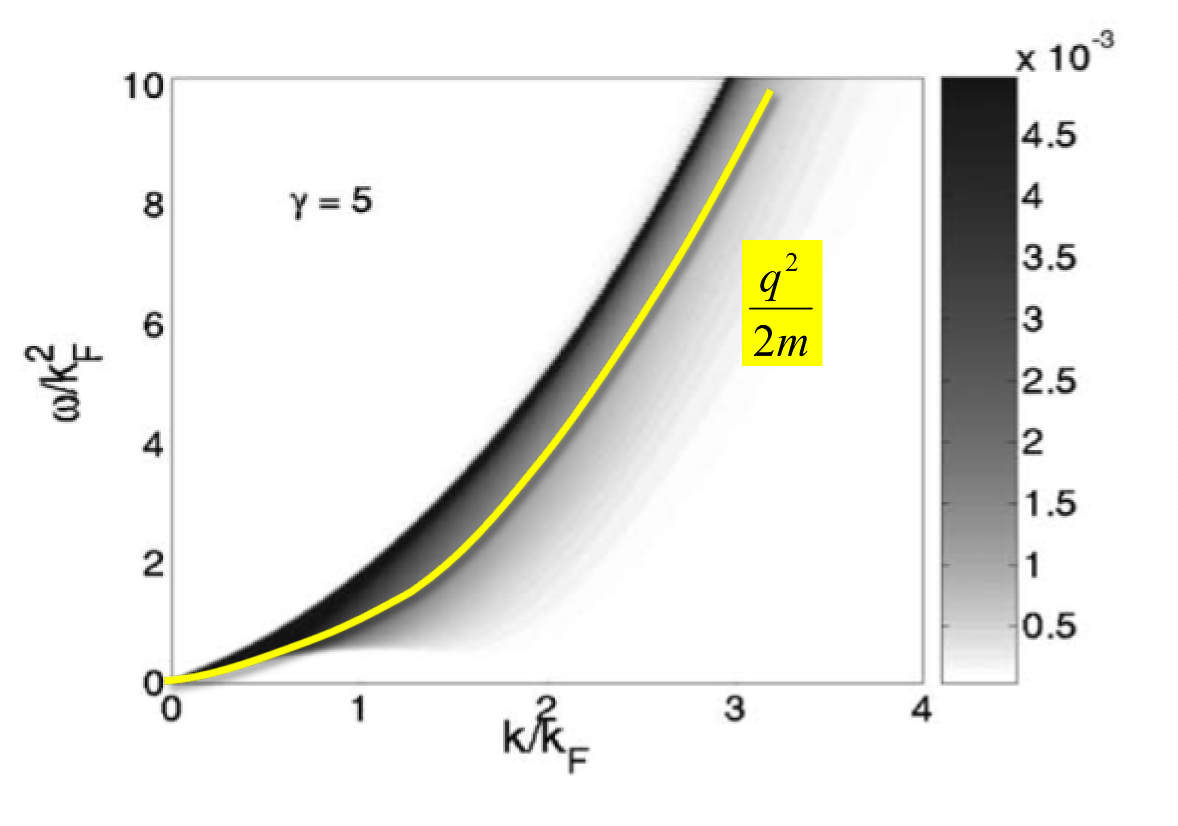


$$E_{particle}(q) = \left| \frac{\hbar k_F}{m} q + \frac{q^2}{2m} \right|$$

$$E_{hole}(q) = \left| \frac{\hbar k_F}{m} q - \frac{q^2}{2m} \right|$$

Dynamic structure factor calculation:
Brand & Cherny, PRA (2004);
Caux & Calabrese, PRA (2006).

Dynamic structure factor

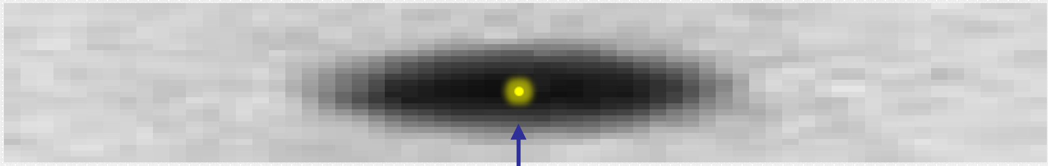


Towards immersing single ions into a Bose-Einstein condensate

A new hybrid system: Atoms and ions

Quantum technology

- Cooling ions by superfluid immersion
- Ion as scanning probe

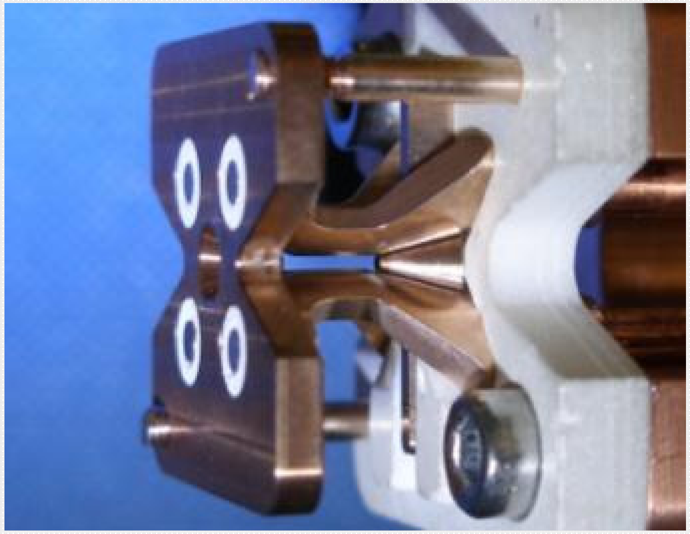


Fundamental physics

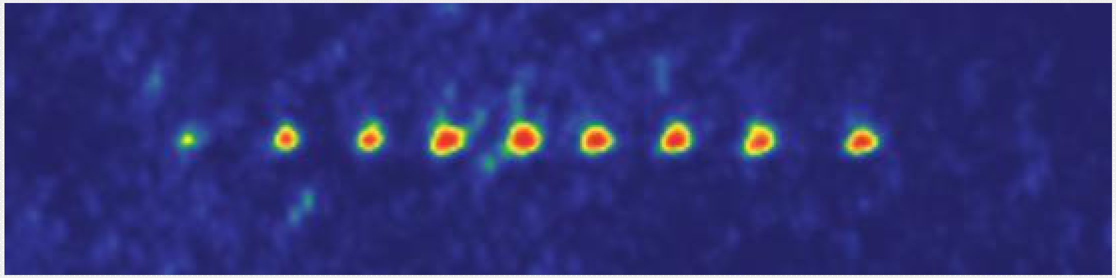
- Ultracold atom-ion interactions
- Ions provide tunable nano-potential

position accuracy
of the ion: <10 nm

Trapping ion crystals

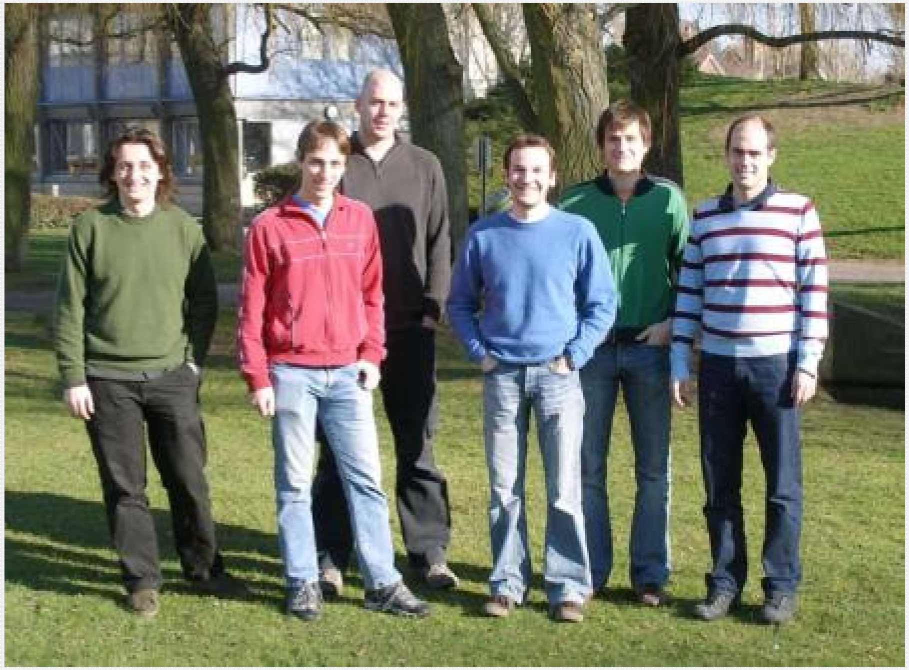


- Linear Paul trap with 0.8 mm spacing between electrodes
- RF drive: 750 V @ 42 MHz
- Trap loading by photo-ionization from an atomic beam



Axial trap frequency: $\omega_z = 2\pi\cdot45$ kHz
Radial trap frequency: $\omega_\perp = 2\pi\cdot1$ MHz

Thanks!



Carlo Sias (Postdoc), Christoph Zipkes (PhD), Stefan Palzer (PhD), Michael Feld (PhD), Bernd Fröhlich (PhD), M.K., not in the picture: Alexander Beck (undergraduate)

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