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IAEA International Atomic Energy Agency

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Conference on Research Frontiers in Ultra-Cold Atoms

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Impurities in a Bose gas

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Impurities in a Bose gas

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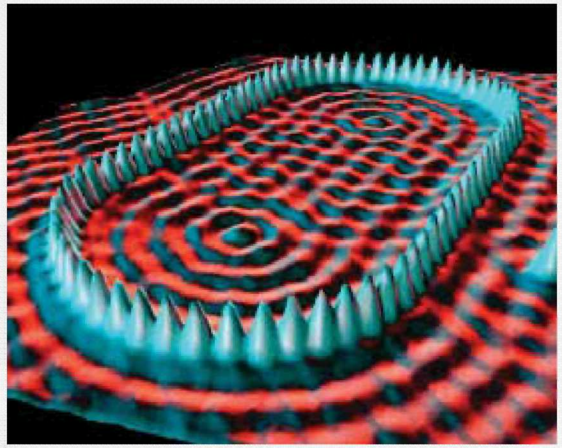
Impurities: why spoiling a clean system?

- Understanding real world systems

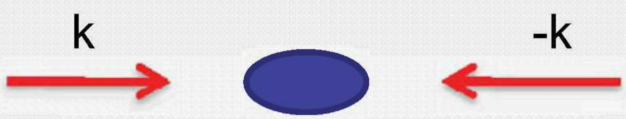
- Test & measurement:
  Impurities as probes and tools

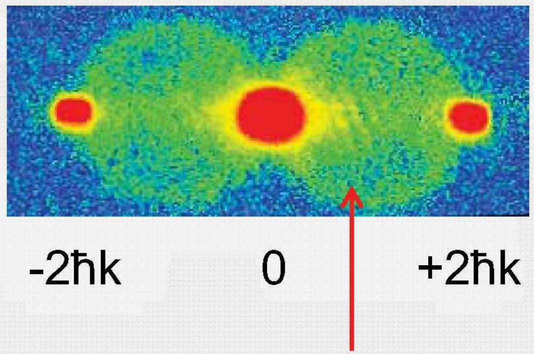
- Transport experiments



Transport experiments in cold atoms

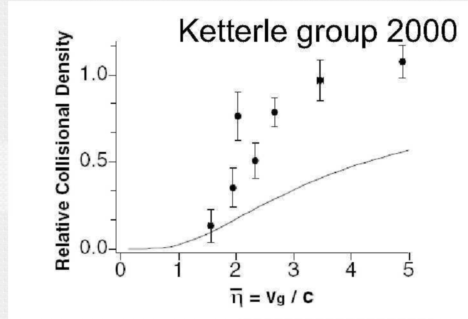
A simple transport experiment



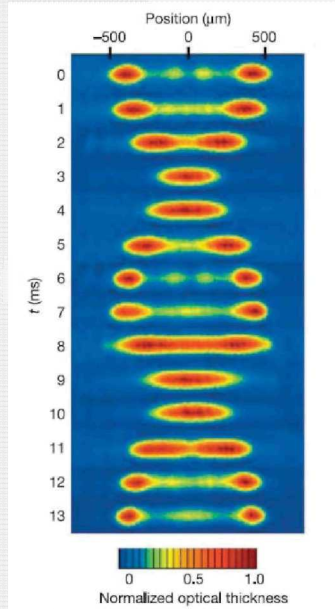


Scattered atoms with spherical (s-wave) symmetry

Three dimensions



One dimension

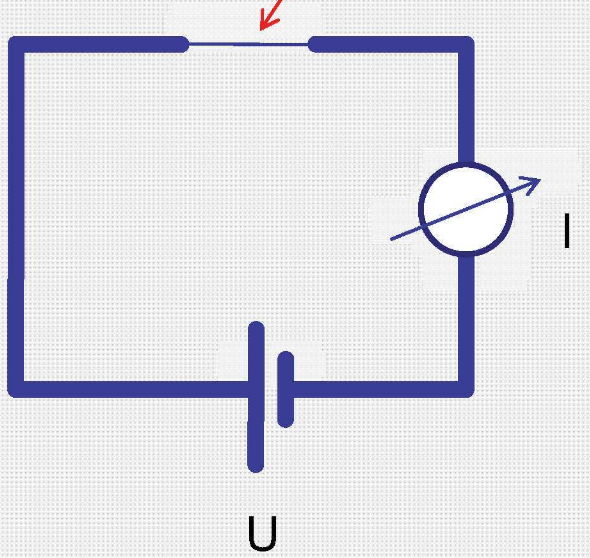


Weiss group 2006

Other transport experiments: ETH, LENS, NIST, Orsay, Pisa, Stanford,, ...

Transport in the solid state

1D quantum wire containing impurities from which electrons scatter



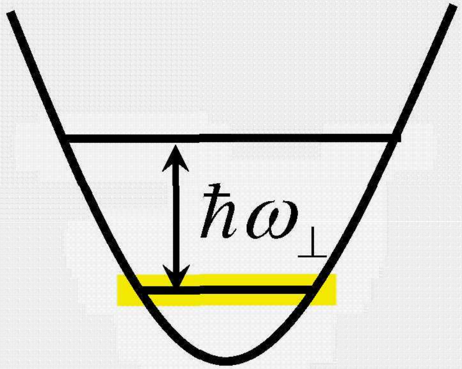
potential difference U continuously accelerates electrons

Open quantum system:
energy is continuously transferred into the system

Quantum transport in a strongly interacting 1D Bose gas

What is a one-dimensional gas?

- transverse degrees of freedom are frozen out



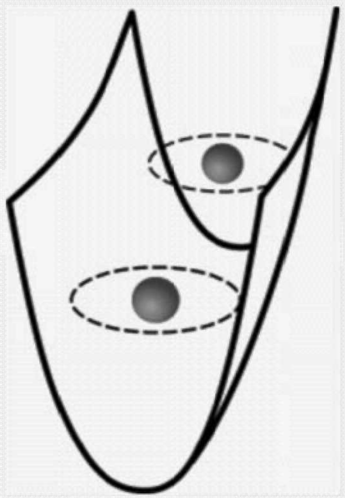
Conditions for 1D

$k_B T < \hbar\omega_\perp$

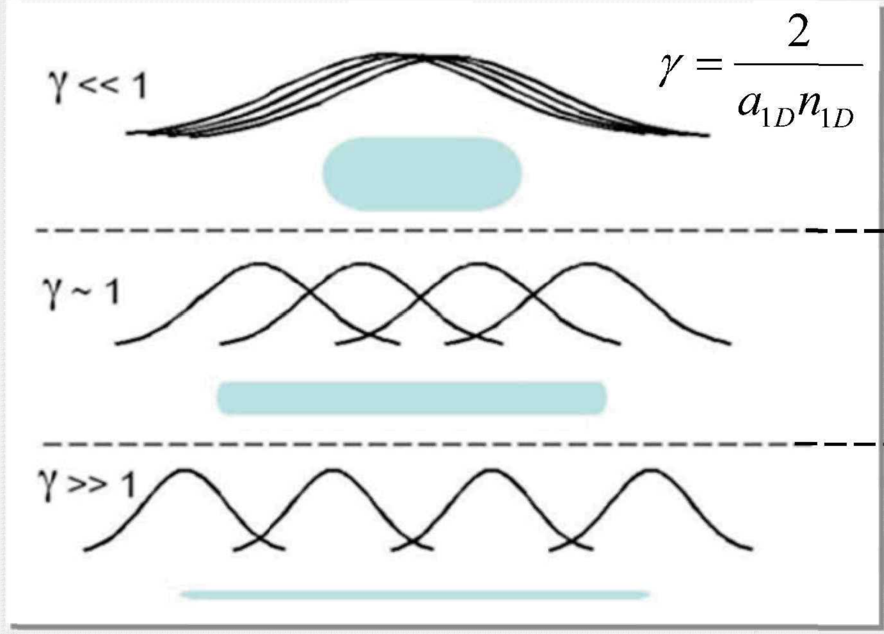
Bosons: $\mu < \hbar\omega_\perp$

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

- asymptotic scattering states are one-dimensional wave functions



Regimes of degeneracy in 1D



weakly interacting Bose gas

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

crossover

Tonks-Girardeau gas
("Fermionized Bosons")

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

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

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

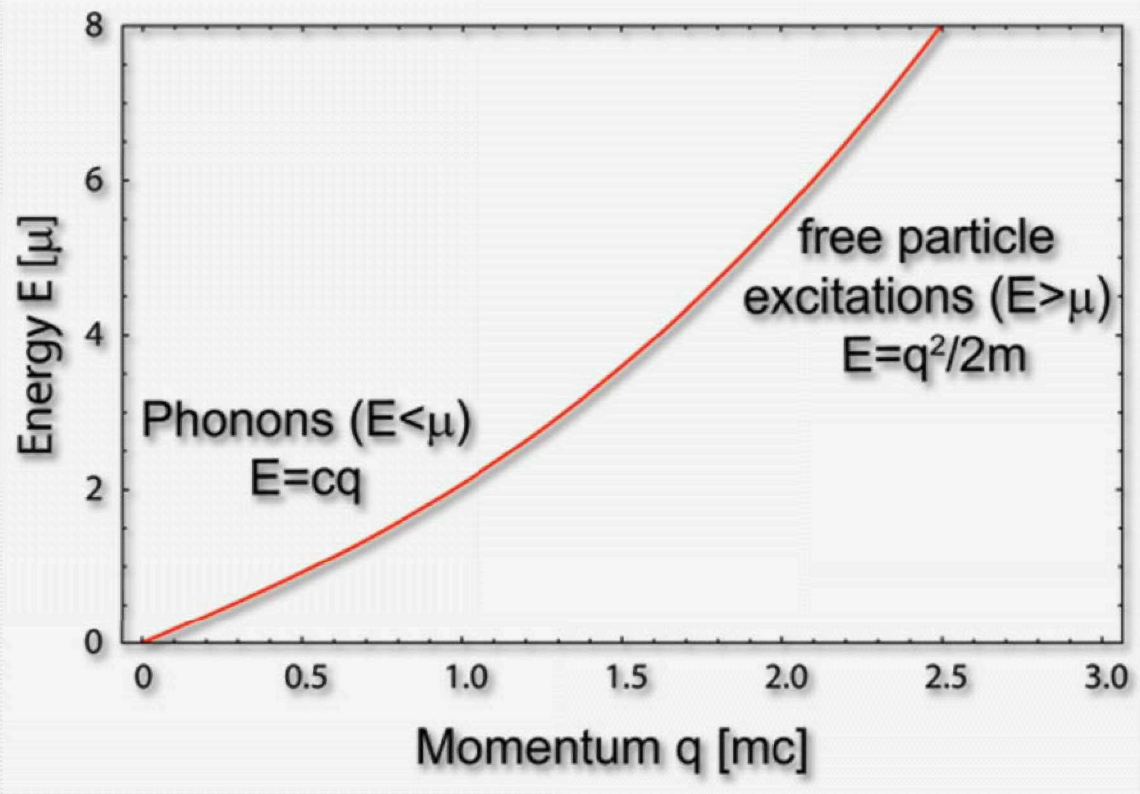
1963: Exactly solved for all values of γ by Lieb & Liniger

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

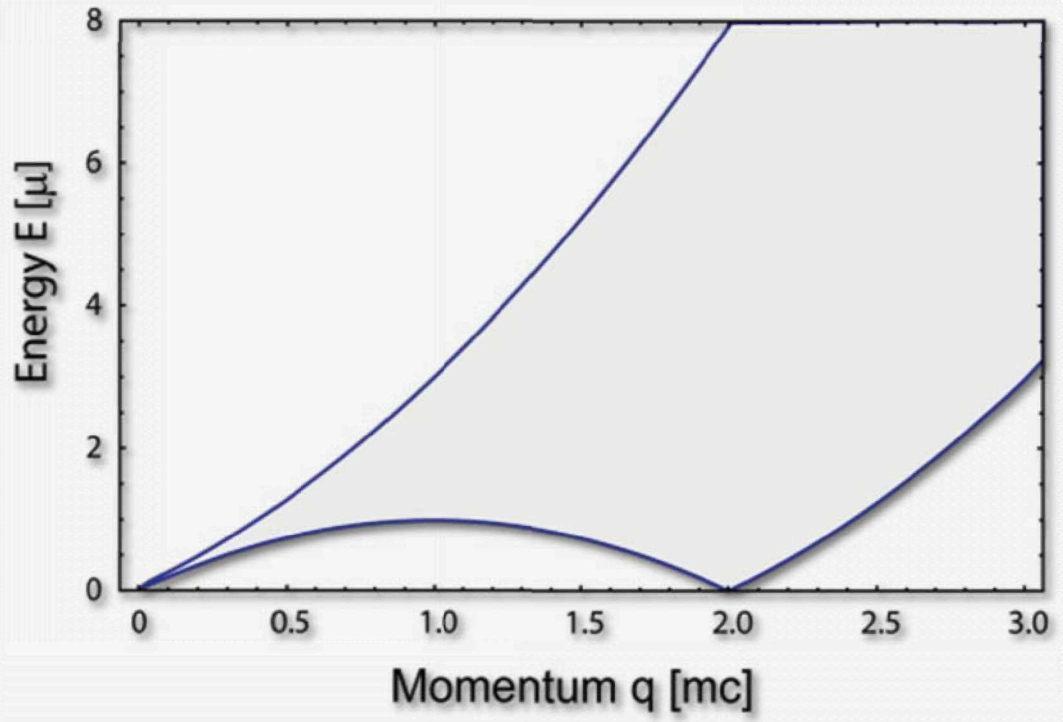
2004: Tonks gas experimentally realized by Weiss et al. (Penn State) & Bloch et al. (Mainz)

Excitations in a weakly interacting Bose gas

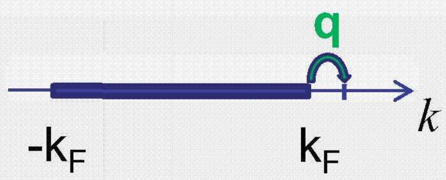
Bogoliubov spectrum

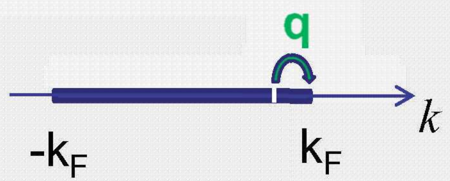


Excitations in a Tonks gas

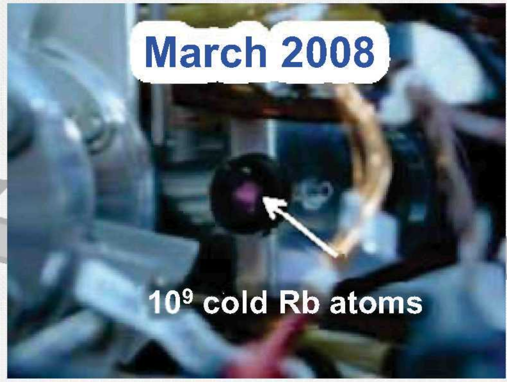


Two branches of excitations: “particle” excitations and “hole” excitations

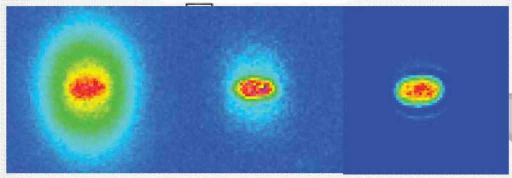




Making a Bose-Einstein condensate



April 2008



Bose-Einstein condensation

Generating tight confining potentials

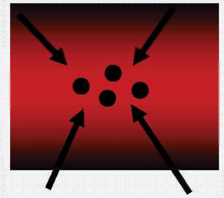
Induced electric dipole potential: $V = -\frac{1}{2}\alpha\left|E\right|^2$

ac polarizability of the atom (α)

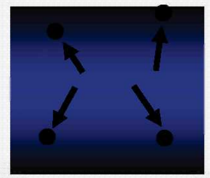
electric field of the laser (E)

Two options:

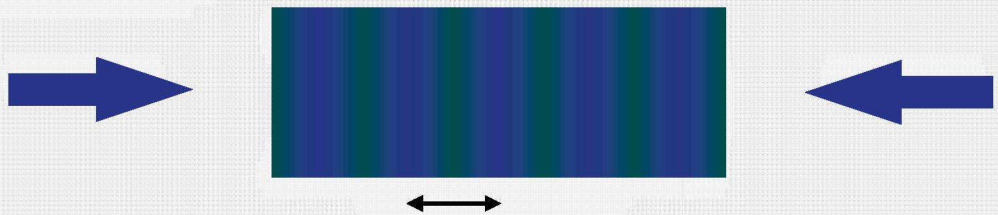
$\omega_L < \omega_A$
„red detuned"



$\omega_L > \omega_A$
„blue detuned"



Optical lattice

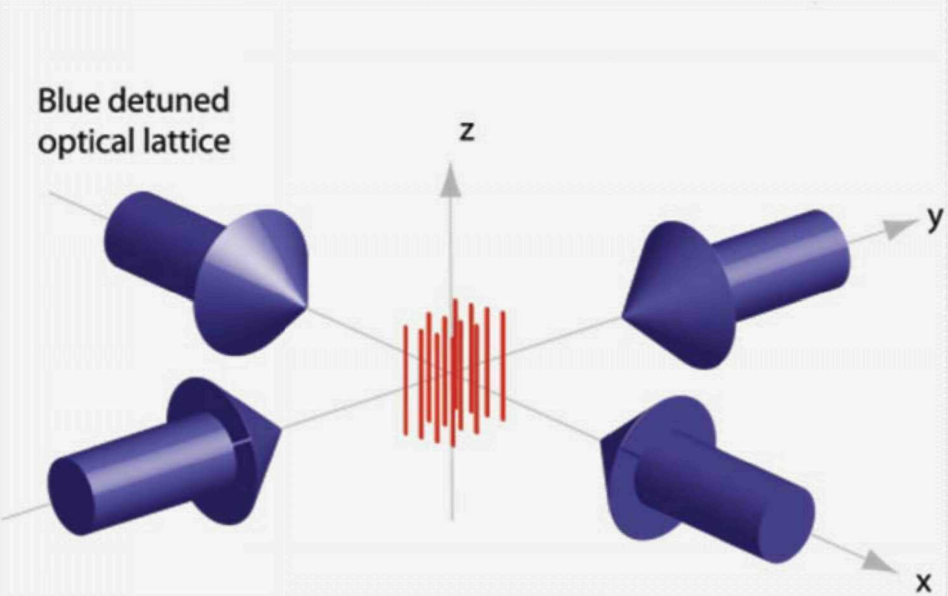


$\lambda/2$=380 nm

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)

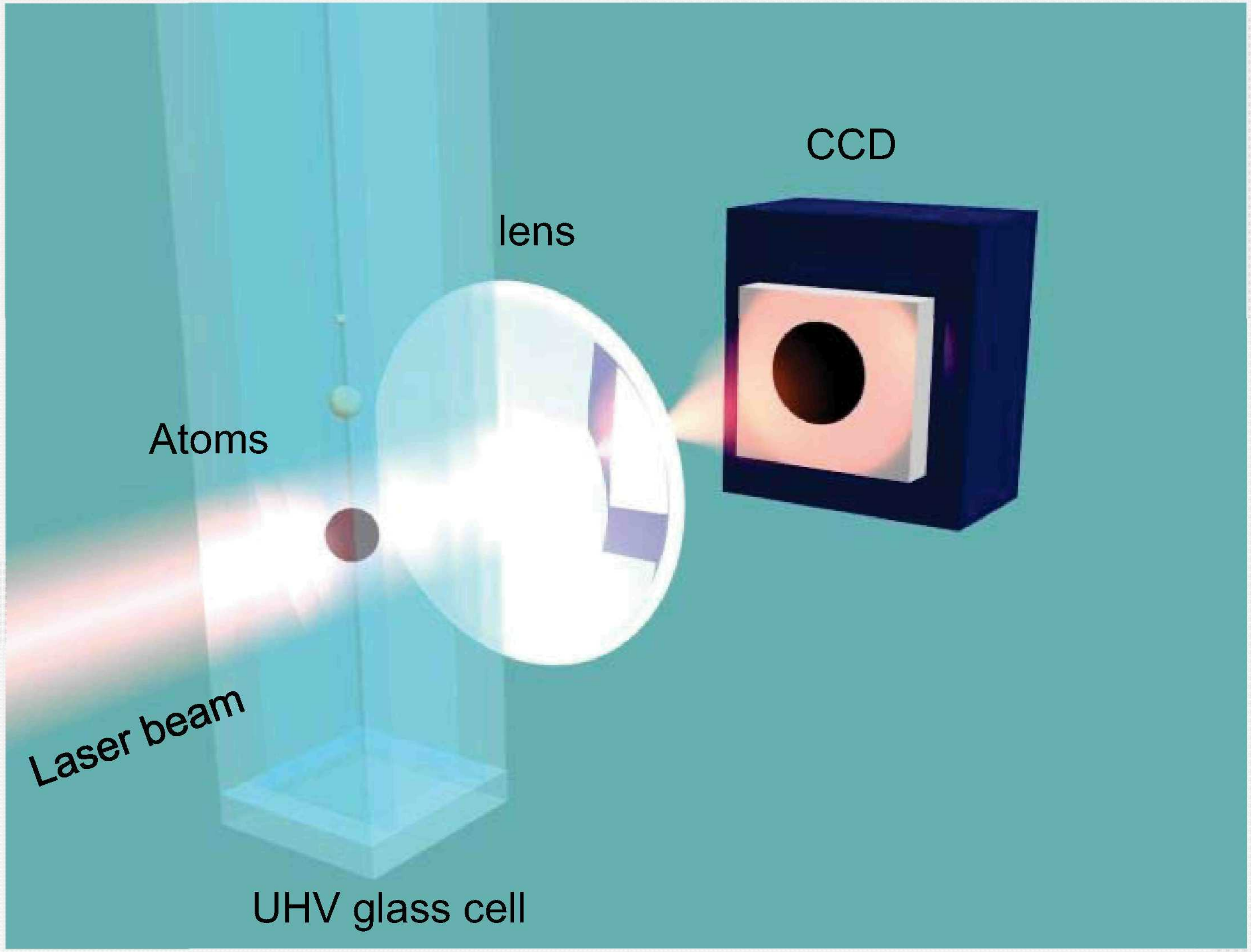
$\omega_z = 2\pi$ 39 Hz (magnetic trap)

N<120 per tube

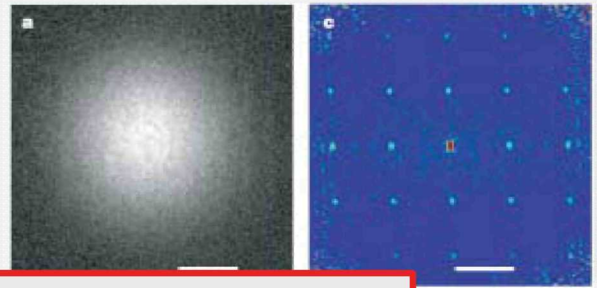
$0.5 < \gamma < 5$

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

Detection



More advanced detection techniques



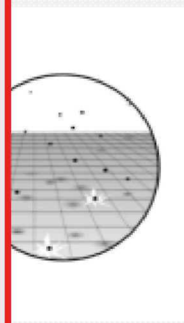
Noise-correlation measurements

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

Hanb

of m

[Aspect



high resolution *in-situ* measurements remain a challenge (the cloud is too small and dense)

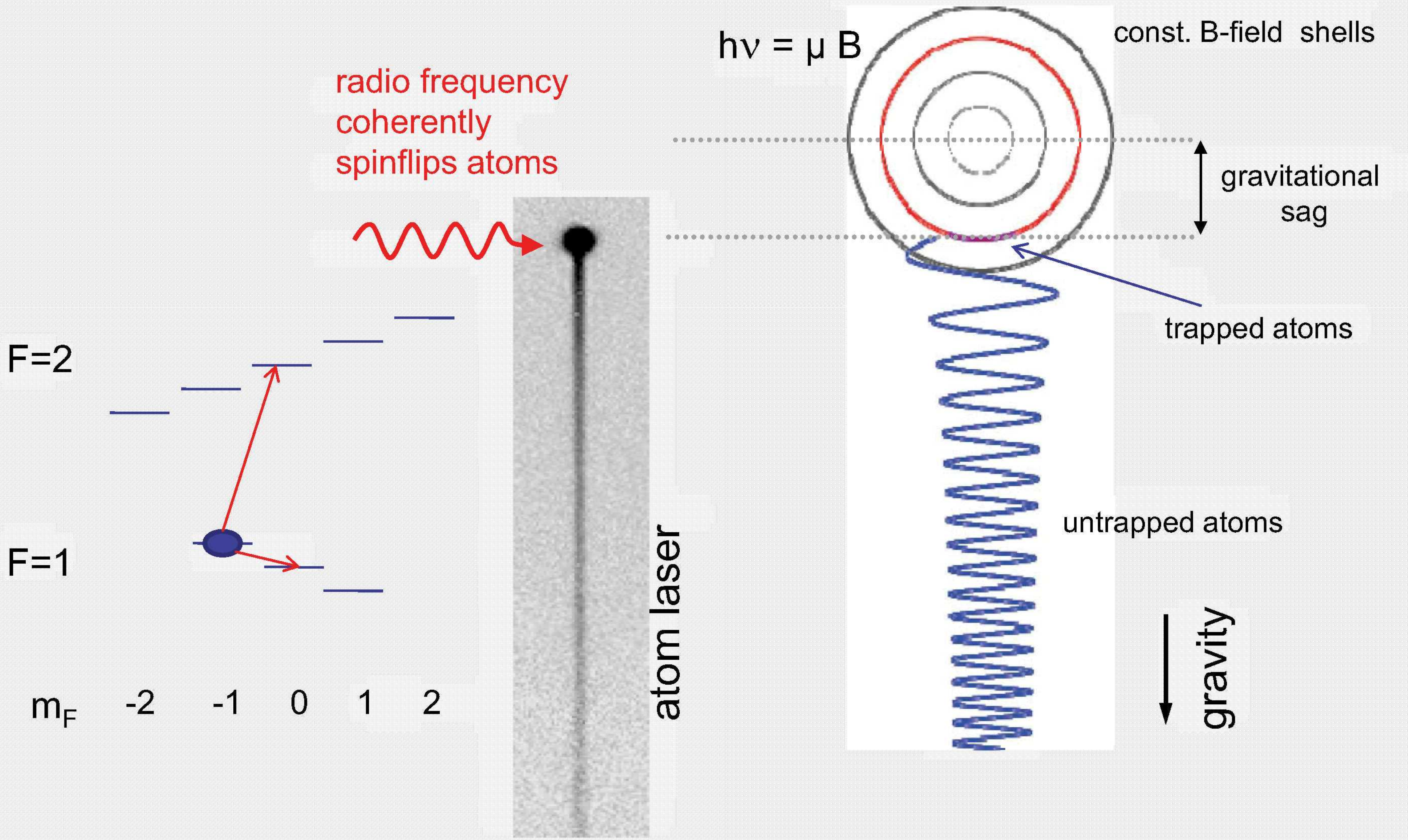
Single atom counting by cavity QED

[A. Öttl, S. Ritter, M. Köhl, T. Esslinger, PRL (2005)

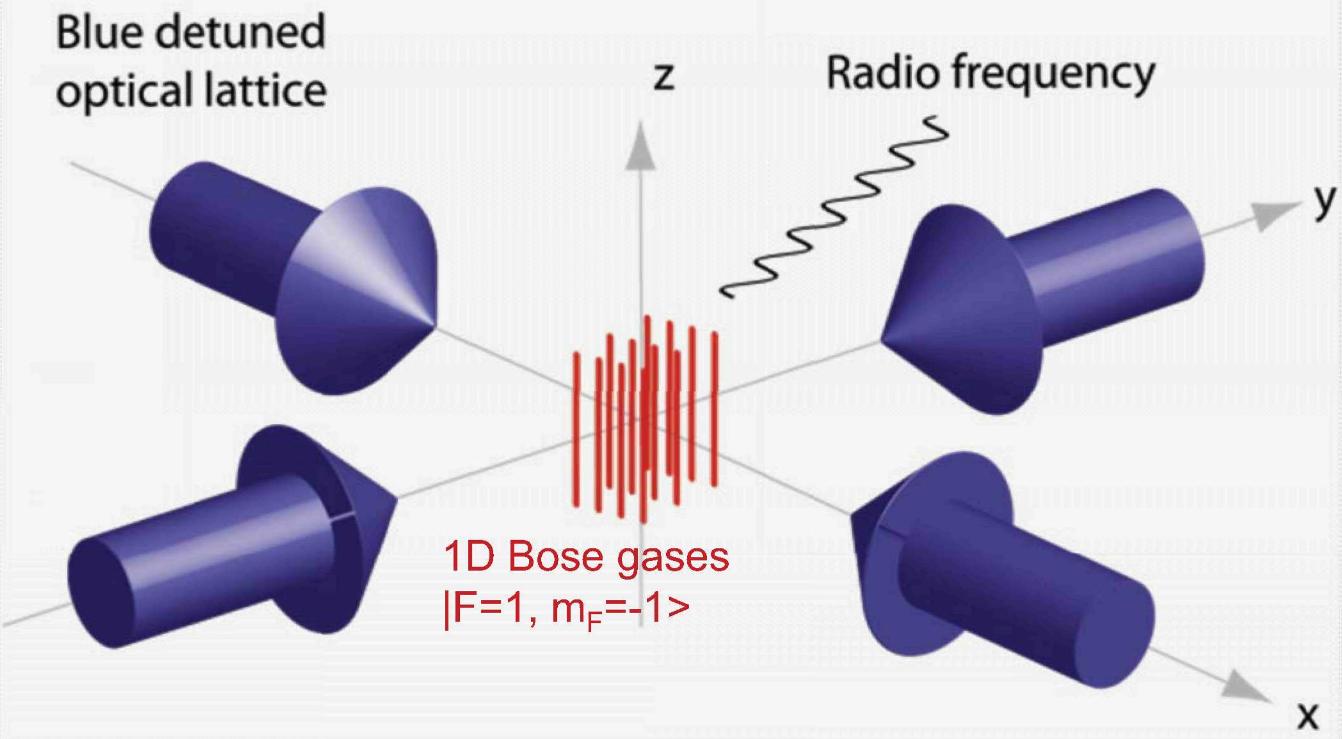
S. Ritter, T. Donner, A. Öttl, M. Köhl, T. Esslinger, PRL (2007)

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

Tomographic in-situ measurements



Spatial addressing



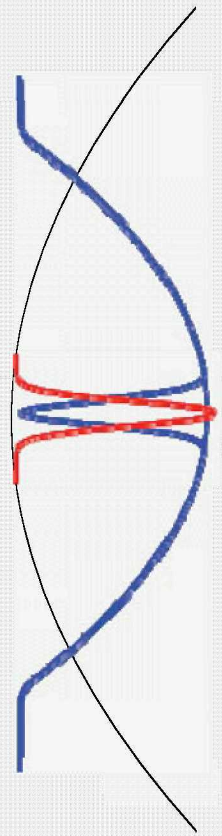
Radio frequency resonance: $|F=1, m_F=-1\rangle \rightarrow |F=1, m_F=0\rangle$
at $\hbar\nu_{RF} = g_F\mu_B B(x,y,z) \approx \mu_B B(z)/2$

Generation of spin impurities

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

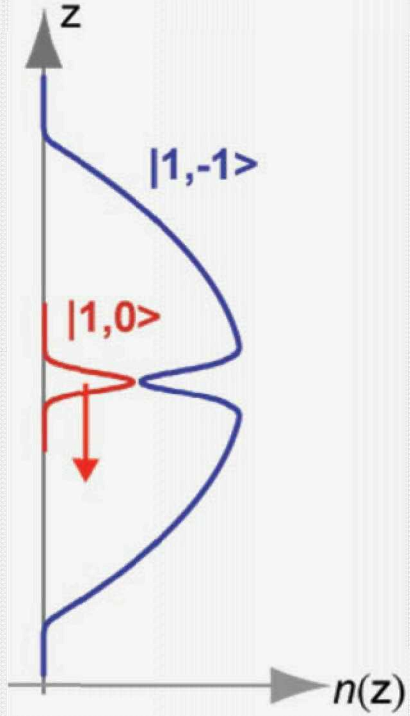
|F=1, m_F=0>
V=- m g z

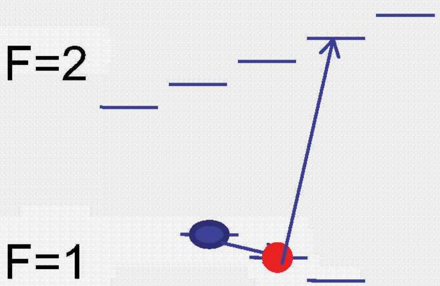
quick transfer
(RF π-pulse, 200 μs)

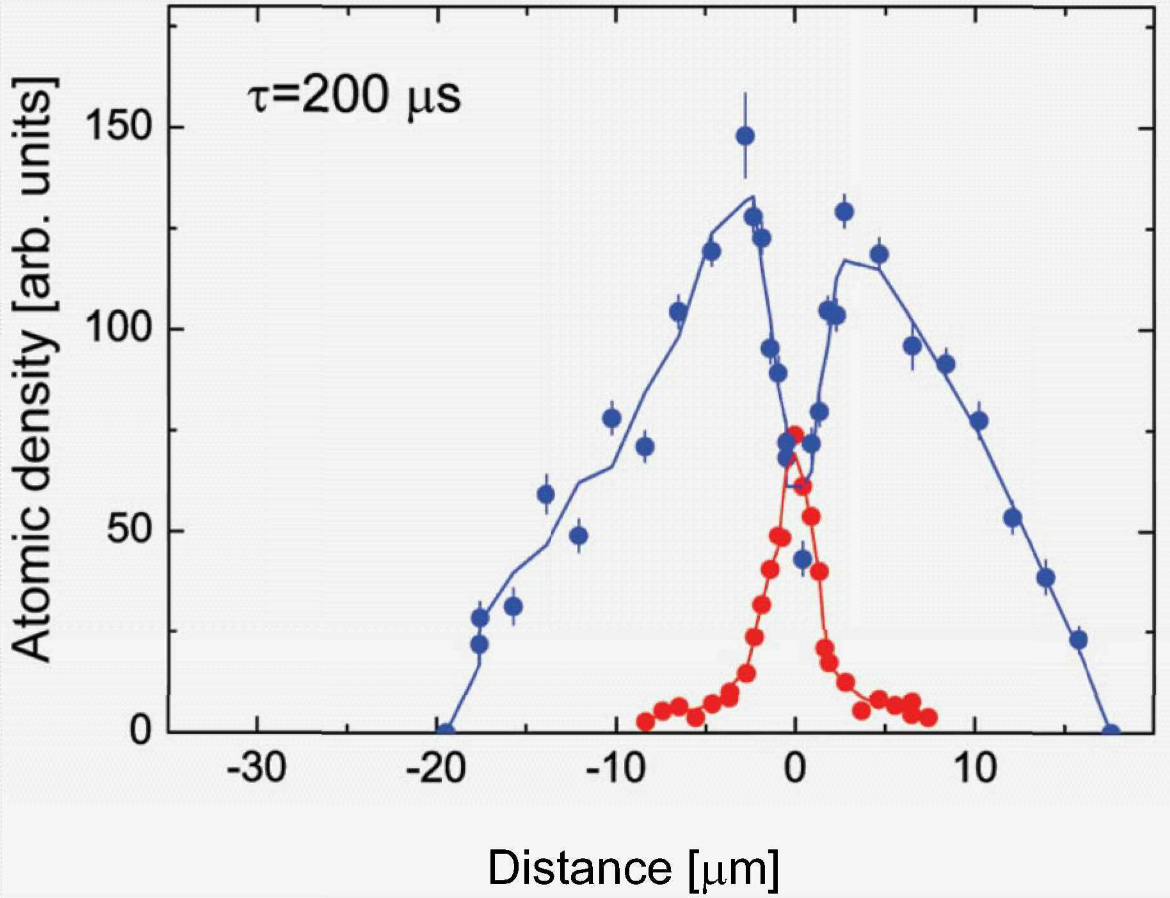


- width of impurity wave packet: 2.5 μm (≈ 3 atoms)
- same transverse confinement: propagation of impurities is purely one-dimensional
- same scattering lengths: $a_{-1,-1} \approx a_{-1,0} \approx a_{0,0}$
- accelerated impurity breaks integrability of the 1D Bose gas → **interesting dynamics**

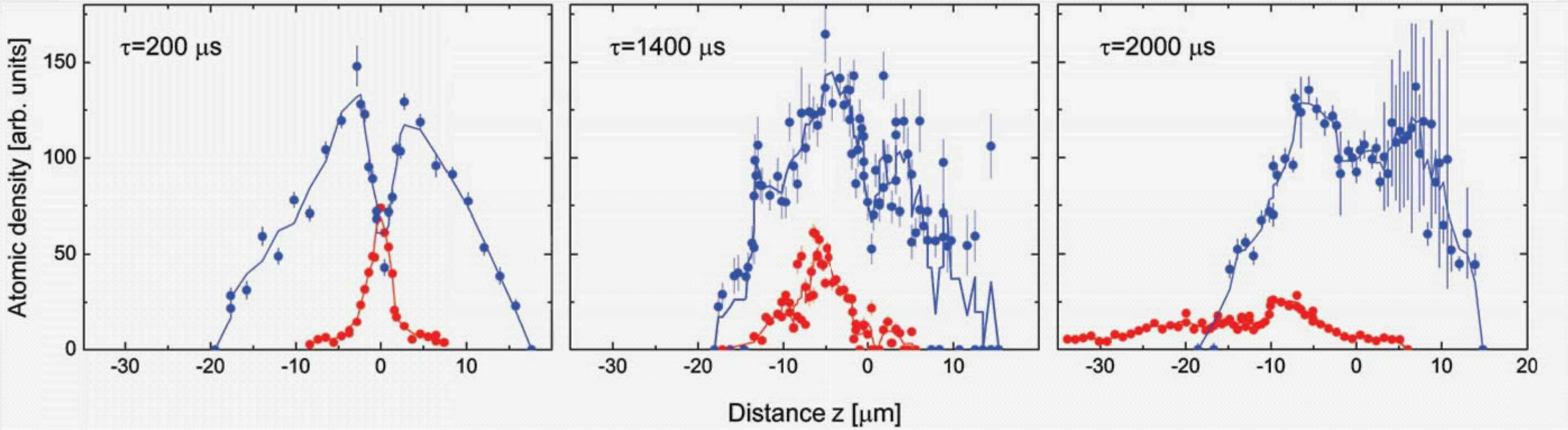
In situ detection of the spin wave packet







Time evolution



- strong interaction-induced dynamics
- significant back action of the impurity onto the majority component
- open quantum system: impurity atoms can transfer continuously energy into trapped component by collisions

S. Palzer, C. Zipkes, C. Sias, M.K., arXiv:0903.4823

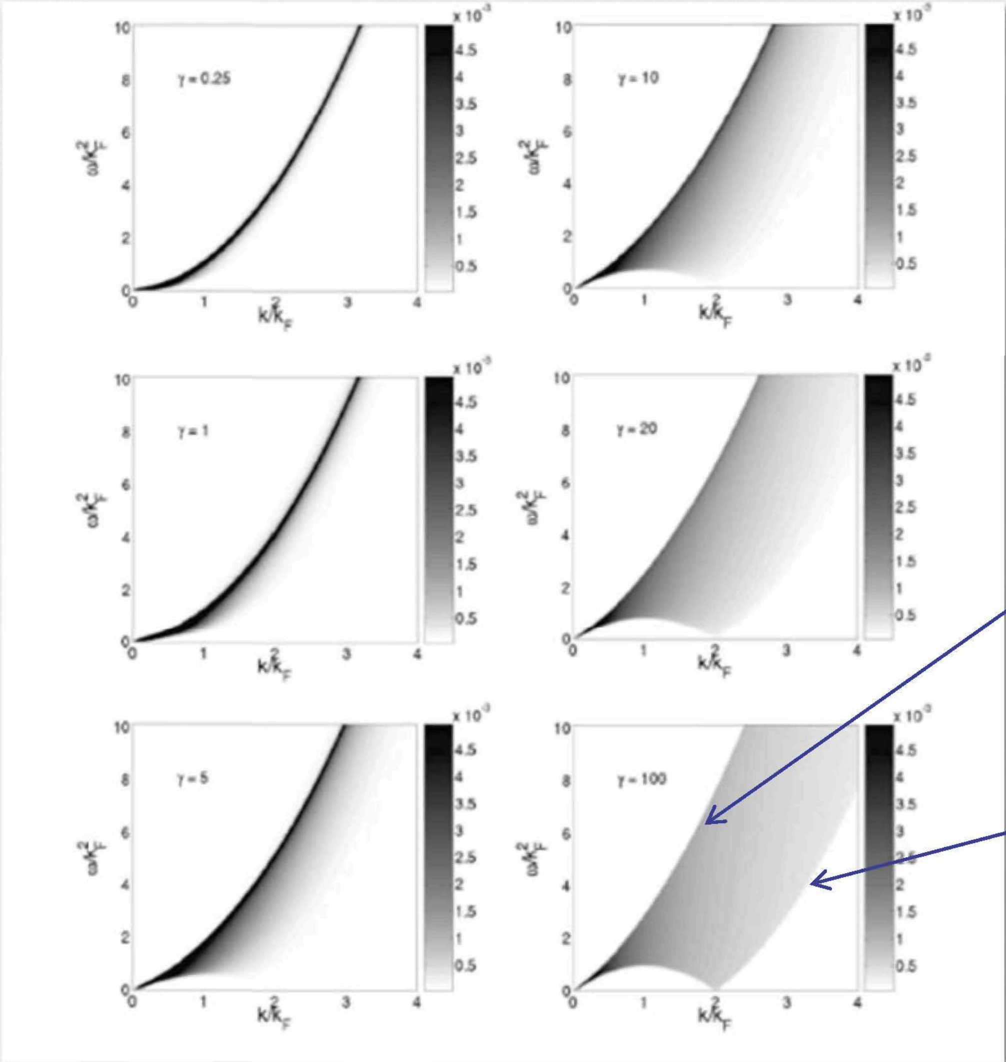
Dynamic structure factor

Scattering rate of an impurity (Fermi's golden rule):

$$\Gamma \propto \int dq\, d\omega\, S(\omega, q)\, \delta(\varepsilon(k_i) - \varepsilon(k_f) - \hbar\omega(q))$$

$S(q,\omega)$: dynamic structure factor
k_i , k_f : initial and final momentum of the impurity
$\omega(q)$: excitation spectrum of the gas

Dynamic structure factor in 1D



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

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

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

Collision rate and energy dissipation

For equal masses:
impurities move collisionless through a superfluid **and** a Tonks-Girardeau gases for v<c.

Collision rate (v>c)

$$\Gamma = \begin{cases} \dfrac{\hbar^2 n_{1D}}{m^2 a_{1D}^2 \mathrm{v}} & \text{weakly interacting Bose gas} \\ \dfrac{\hbar n_{1D}}{2 m a_{1D}^2 k_F} \ln\left(\dfrac{k_i / k_F + 1}{k_i / k_F - 1} \right) & \text{Tonks – Girardeau gas} \end{cases}$$

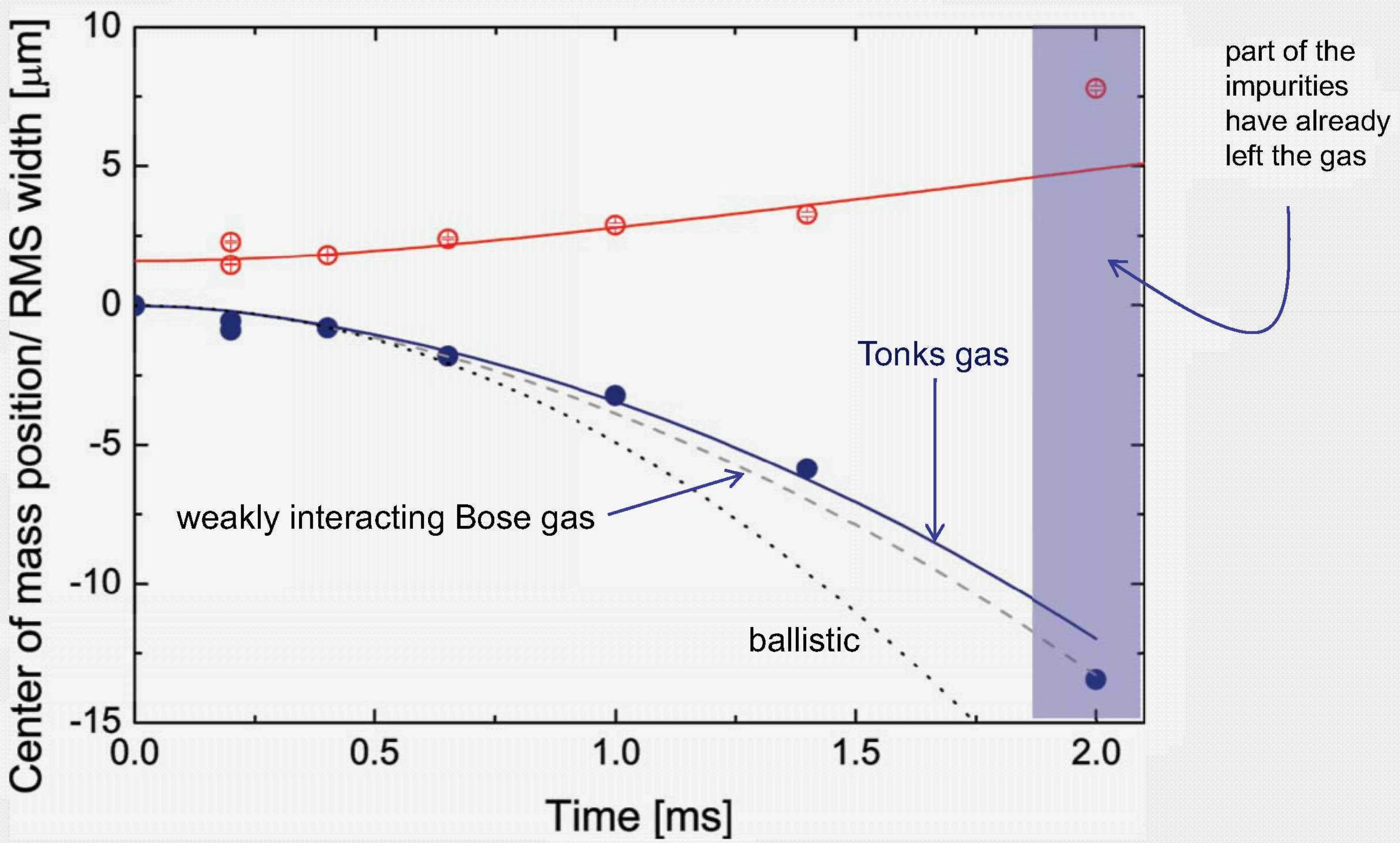
Energy dissipation (v>c)

$$\dot{E} = \begin{cases} \dfrac{\hbar^2 n_{1D}}{m a_{1D}^2} \dfrac{\mathrm{v}}{2} \left(1 - \left(\dfrac{c}{\mathrm{v}} \right)^4 \right) & \text{weakly interacting Bose gas} \\ \dfrac{\hbar^2 n_{1D}}{m a_{1D}^2} \dfrac{\mathrm{v}}{2} & \text{Tonks – Girardeau gas} \end{cases}$$

constant force
≈ 50% of gravity

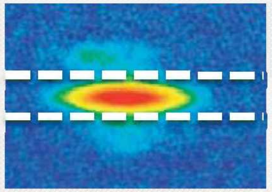
for heavy impurities: Astrakharchik & Pitaevskii, Davis et al., ...

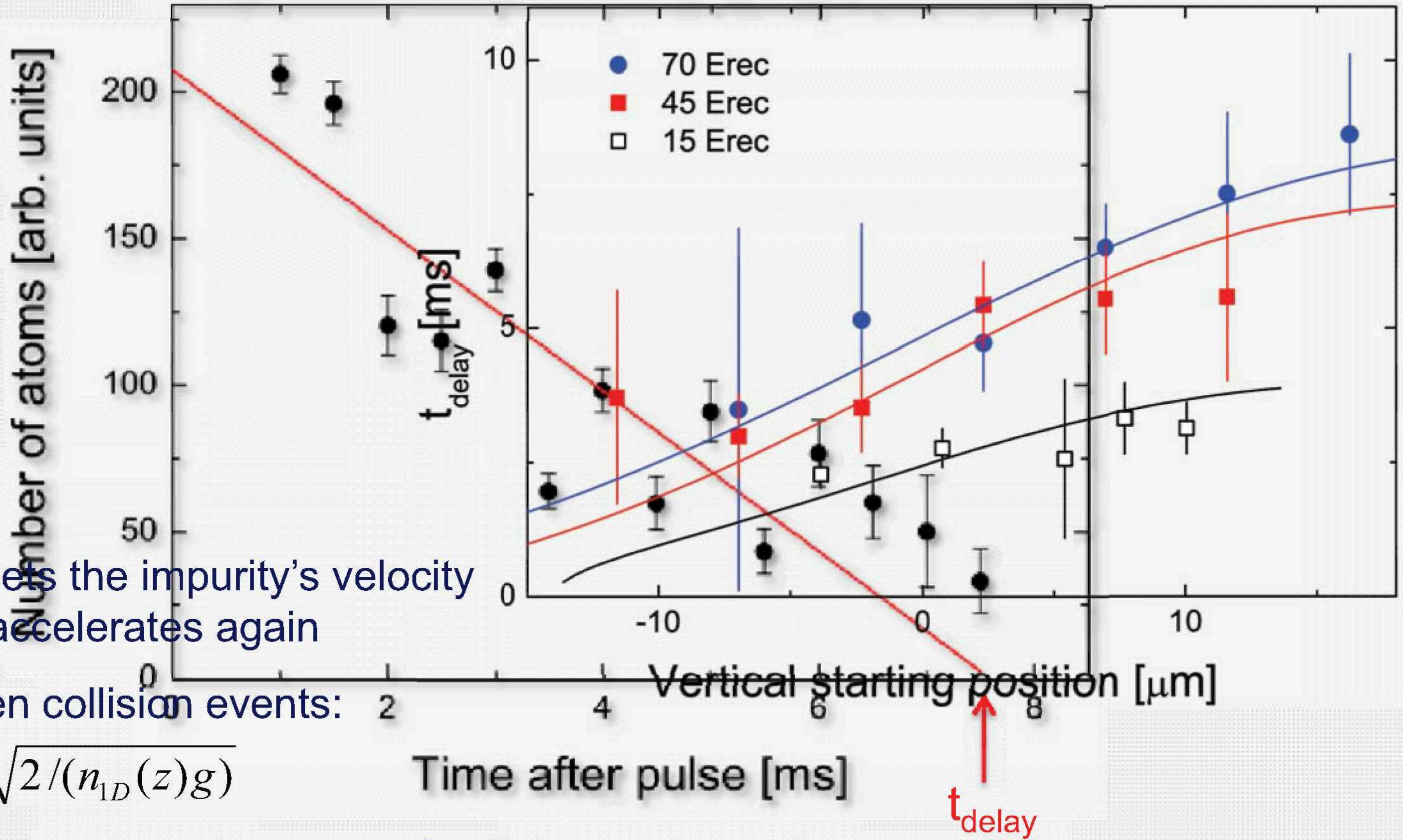
Center-of-mass motion of the impurities



S. Palzer, C. Zipkes, C. Sias, M.K., arXiv:0903.4823

Release measurement





Simple model

Every collision resets the impurity's velocity to 0, then gravity accelerates again

Mean time between collision events:

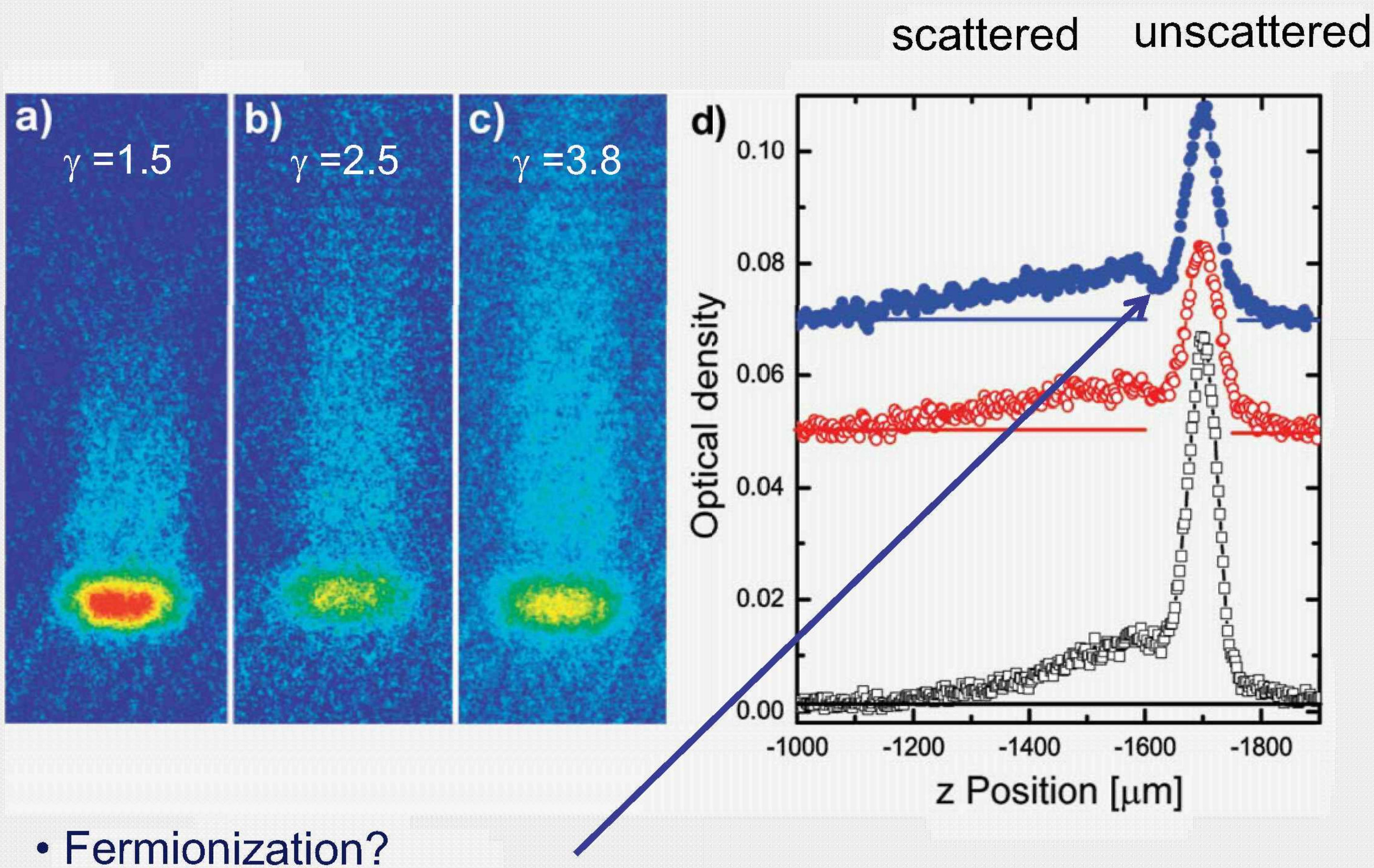
$$t_{coll} \approx \sqrt{2/(n_{1D}(z)g)}$$

Time delay accumulated: total number of collisions x time delay per collision

$$t = \int_{-R}^{z_0} dz\, n_{1D}(z)\Gamma(z)t_{coll}^2$$

S. Palzer, C. Zipkes, C. Sias, M.K., arXiv:0903.4823

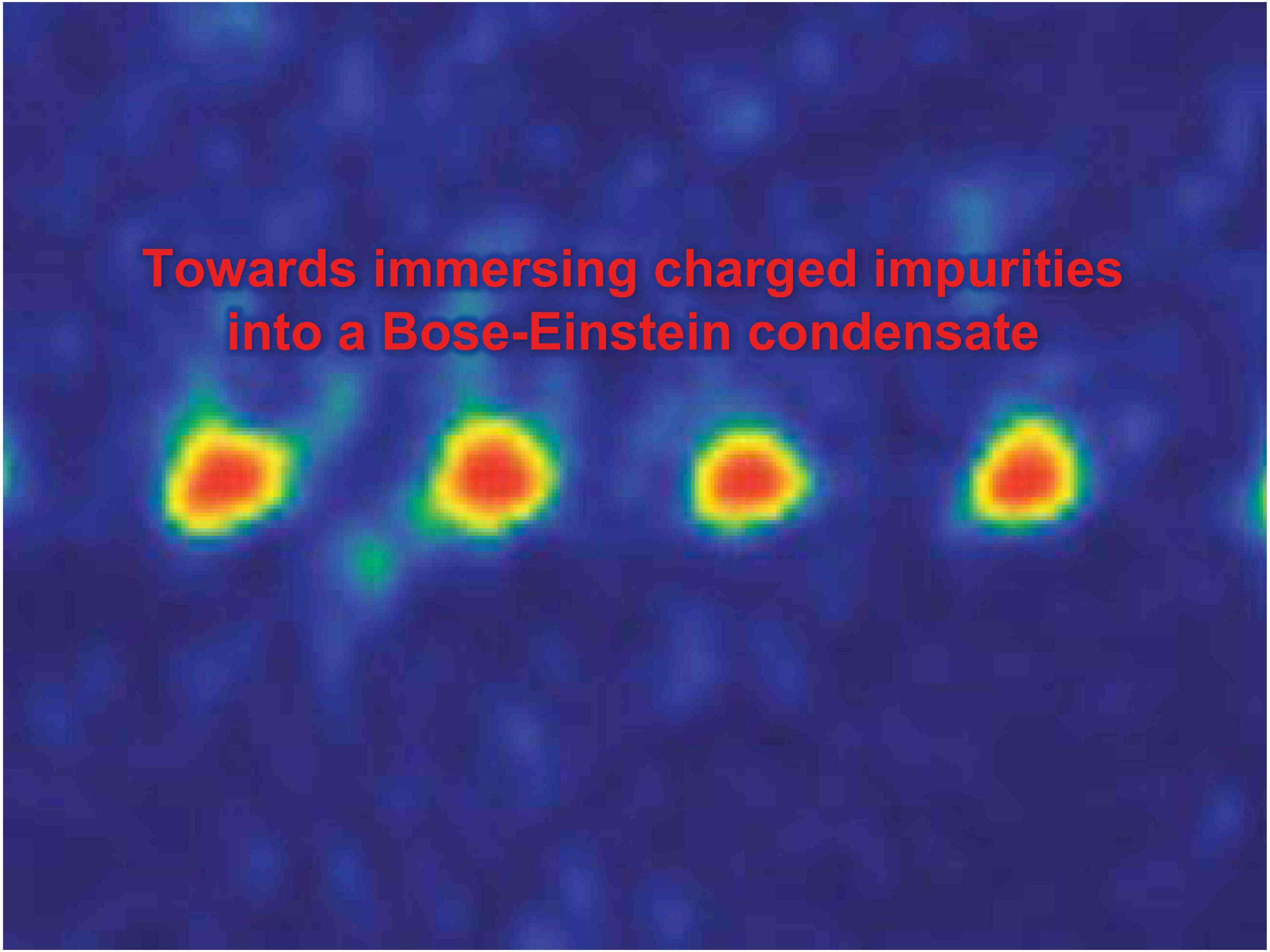
"Far field" distribution of the impurities



- Fermionization?
- Enhancement of multiple collision events due to strong interactions?
- ?

S. Palzer, C. Zipkes, C. Sias, M.K., arXiv:0903.4823

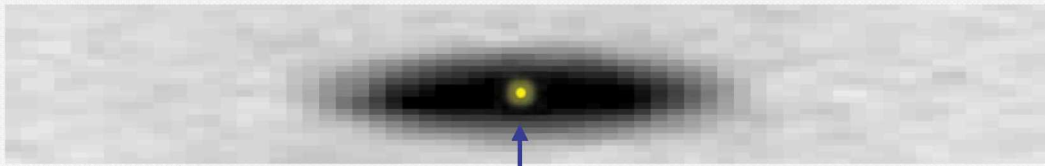
Towards immersing charged impurities into a Bose-Einstein condensate



A new hybrid system: Atoms and ions

Quantum technology

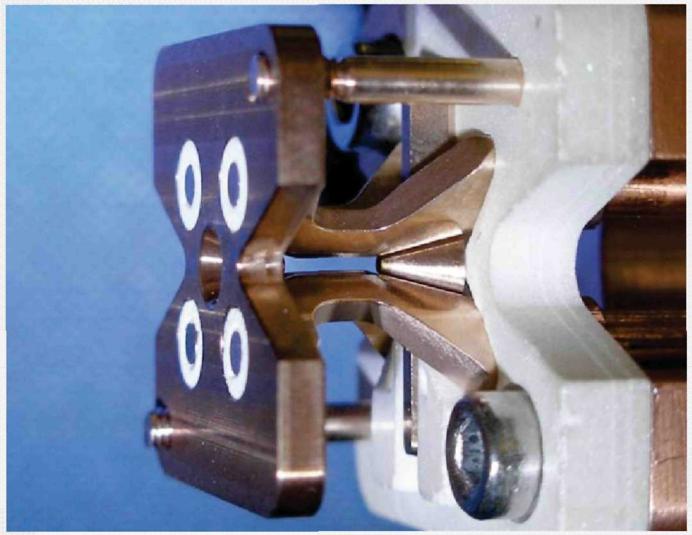
- Cooling ions by superfluid immersion
- Ion as scanning probe



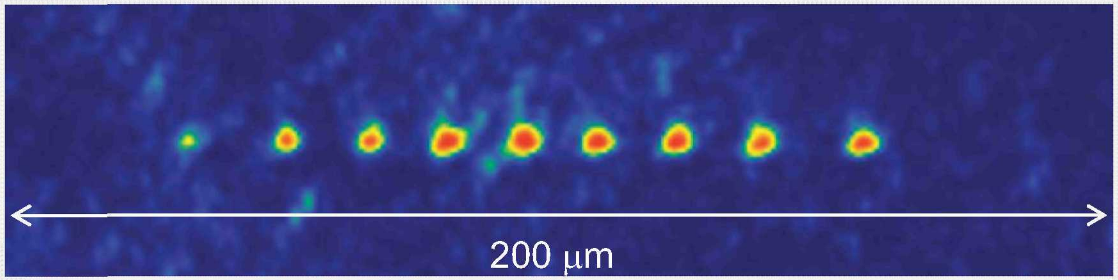
Fundamental physics

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

Ion crystals of $^{174}Yb^{+}$



- Linear Paul trap with 0.8 mm spacing between electrodes
- Axial trap frequency: $\omega_z = 2\pi \cdot 45$ kHz
  Radial trap frequency: $\omega_\perp = 2\pi \cdot 1$ MHz
- Preparation of a deterministic number of impurities

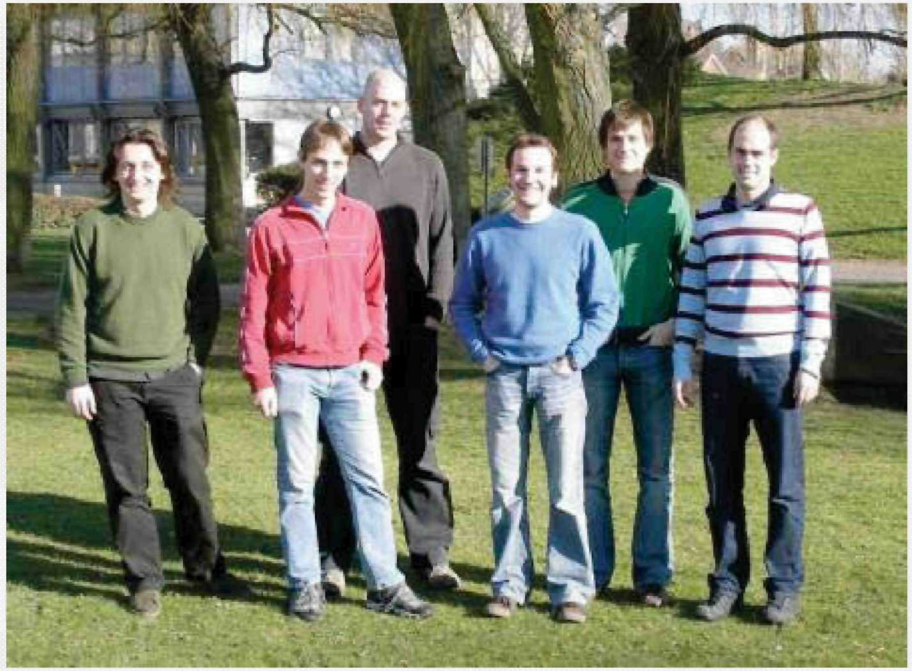


One-dimensional Coulomb crystal of singly charged ions

Summary

- Quantum transport in a strongly interacting Bose gas with an accelerated impurity
- High resolution tomography
- Strong dynamics and back action of the impurity
- Work towards deterministic implantation of impurities is on the way

Thanks!



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Michael Feld (PhD), Bernd Fröhlich (PhD), M.K.

www.quantumoptics.eu

Postdoc position available.

£££: EPSRC, University of Cambridge, Herchel-Smith Fund