

Confining ultracold atoms on a ring in reduced dimensions

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Charge and heat dynamics in nano-systems
Orsay, October 11, 2011



What are ultracold atoms?

- low temperature: **cold**: below 1 mK ; **ultracold**: below $1 \mu\text{K}$
- **dilute** gases \implies metastable state (low molecular formation rate)
- cold collisions (described by *s*-wave scattering)
- atoms trapped by light or magnetic fields in ultra high vacuum chambers

How are they produced?

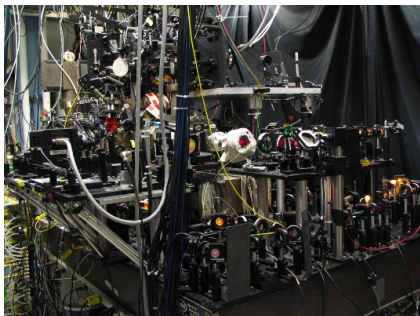
A schematic recipe

- bake a ultrahigh vacuum chamber, pump down to 10^{-11} mbar
- laser cooling in a magneto-optical trap (MOT): 10^8 – 10^{10} atoms @ 1–100 μK
- transfer into a conservative trap (light trap, magnetic trap...)
- evaporative cooling
- transition for degeneracy in a harmonic trap: $k_B T \sim N^{1/3} \hbar \omega$

Result: 10^5 – 10^7 atoms at degeneracy @ 1–100 nK.

How are they produced?

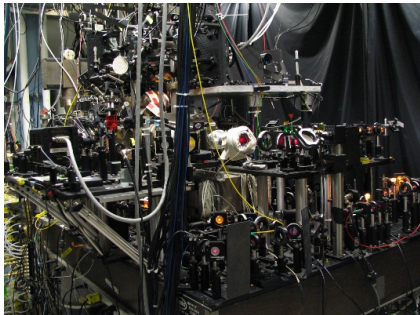
A "typical" experimental setup



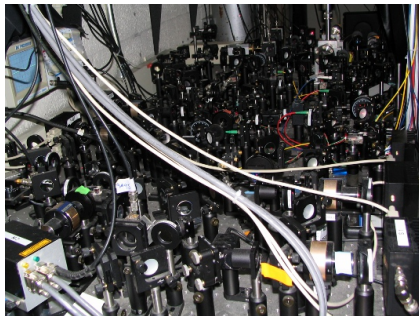
vacuum system

How are they produced?

A "typical" experimental setup



vacuum system



laser table

Outline

OUTLINE OF THE TALK

- 1 Ultracold atoms as a model system
- 2 A ring trap in reduced dimensions

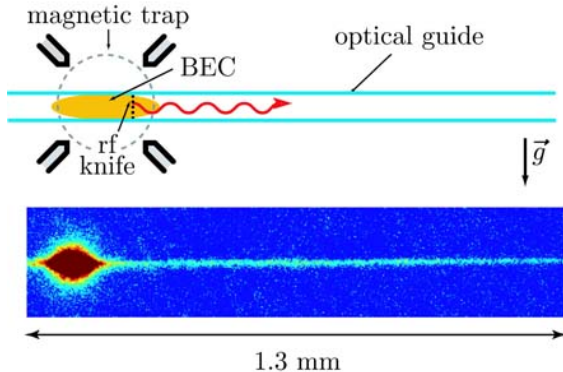
Ultracold atoms as a model system

Which tools?

- simple systems, where input ingredients are well understood
- adjustable (low) temperature, down to 1 nK
- bosons, fermions, or mixtures of both trappable and coolable to degeneracy
- tuneable interactions
- wide variety of trapping geometries
- various direct or indirect diagnostics
- analogy with **optics** (atom laser experiments, quantum atom optics...)
- analogy with **condensed matter** systems (atoms play the role of electrons in solids)
- Feynman's idea of **quantum simulator** becomes within reach

Ultracold atoms as a model system

Example: an atom laser

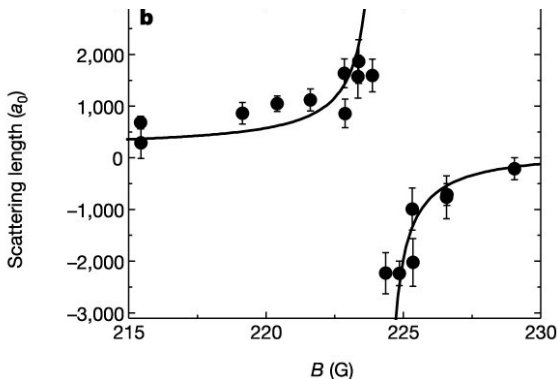


Orsay 2006: Atom laser, which can be sent to an interaction zone (including disordered potential...)

Ultracold atoms as a model system

Controlling interactions

- s-wave collisions: contact interaction $g\delta(r)$ is an accurate model
- $g = \frac{4\pi\hbar^2 a}{M}$ a : scattering length
- Feshbach resonances allow the tuning of the scattering length with a magnetic field



Ultracold atoms as a model system

Controlling interactions

Many systems with **controllable contact interactions**

- bosons: ^{85}Rb , ^{87}Rb , Cs, Na, ^{52}Cr ...
- fermions: ^6Li ...
- interspecies resonances: bosons: Rb - Cs, boson-fermion: Li - Na, Li - Rb, K - Rb...

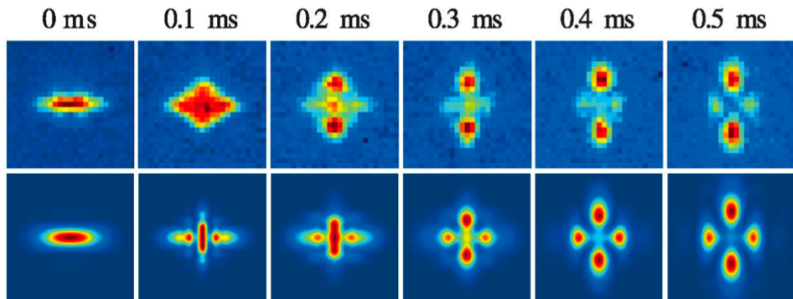
Dipolar interactions also important in some systems:

- atoms with large magnetic moment: Cr, Dy
- heteronuclear molecules in an electric field
- can be made dominant by tuning a to 0

Ultracold atoms as a model system

Example: collapse of a dipolar gas

Collapse of a dipolar (chromium) gas

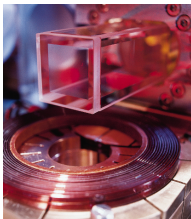


Pfau (Stuttgart), 2008

See also: chromium experiment at LPL

Conservative atom traps

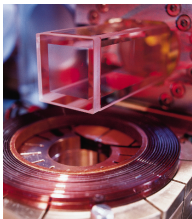
- magnetic traps



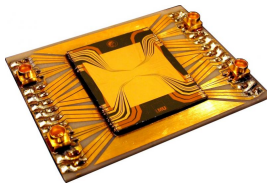
macroscopic coils

Conservative atom traps

- magnetic traps



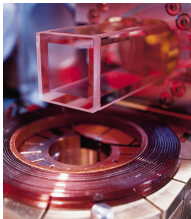
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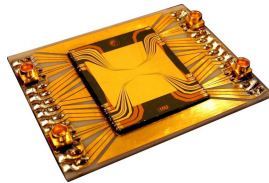
atom chip

Conservative atom traps

- magnetic traps



macroscopic coils

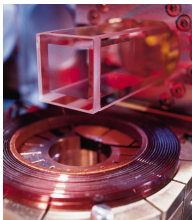


atom chip

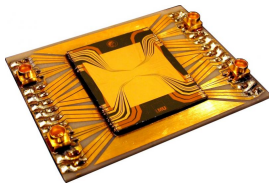
- laser traps: potential \propto intensity; either repulsive or attractive depending on the frequency

Conservative atom traps

- magnetic traps



macroscopic coils



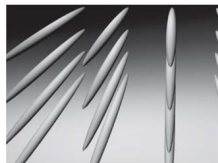
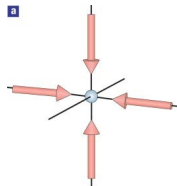
atom chip

- laser traps: potential \propto intensity; either repulsive or attractive depending on the frequency
- adiabatic potentials (RF traps)

Trapping geometries

- **harmonic:** 3D, 2D, 1D

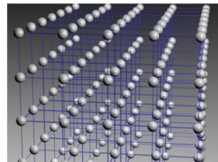
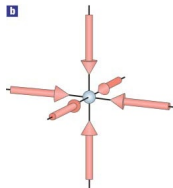
Ex: series of 1D tubes



Trapping geometries

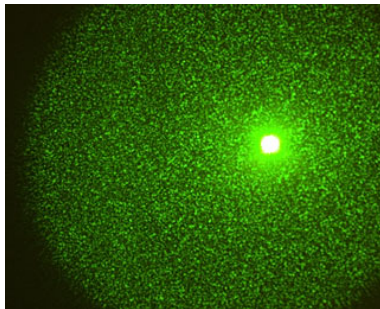
- harmonic: 3D, 2D, 1D
- **optical lattices**

a 3D lattice
mimics a solid



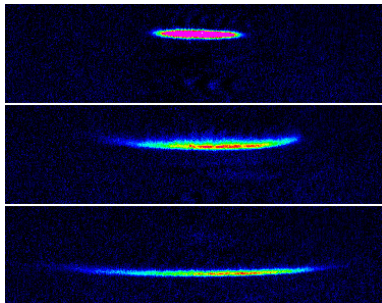
Trapping geometries

- harmonic: 3D, 2D, 1D
- optical lattices
- **disorder potentials**



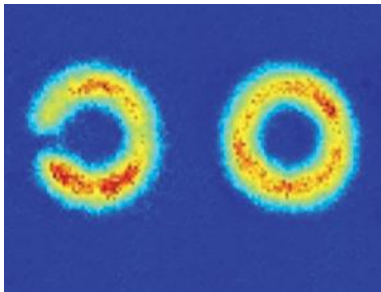
Trapping geometries

- harmonic: 3D, 2D, 1D
- optical lattices
- disorder potentials
- **curved traps: LPL**



Trapping geometries

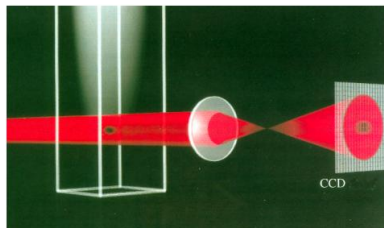
- harmonic: 3D, 2D, 1D
- optical lattices
- disorder potentials
- curved traps
- **ring traps**: NIST 2011



Dynamically adjustable potentials if required.

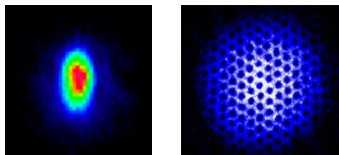
Diagnostic tools

- **Absorption imaging**
- Time of flight
- High resolution imaging
- Bragg spectroscopy
- RF spectroscopy
- correlation measurements
- ...



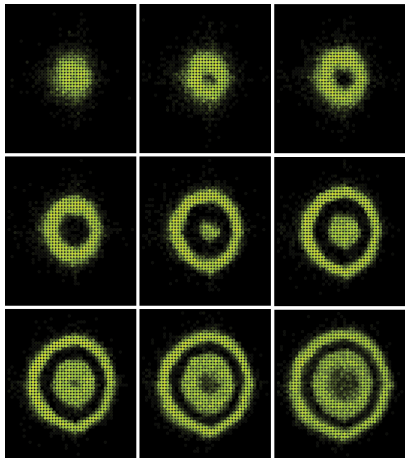
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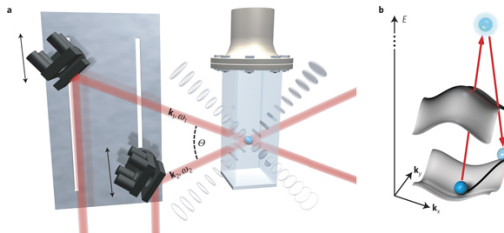
- Absorption imaging
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- ...



M. Greiner, Harvard

Diagnostic tools

- Absorption imaging
- Time of flight
- High resolution imaging
- **Bragg spectroscopy**
- RF spectroscopy
- correlation measurements
- ...



reconstruction of dispersion relation

Model system for solid state physics

- Mott insulator
- Bloch oscillations
- Josephson oscillations
- Anderson localization
- spins on lattices
- superfluidity of bosons or of paired fermions (BCS)
- low-D physics (2D: BKT, FQHE; 1D: Tonks-Girardeau)
- ...

Ring geometry

Motivation

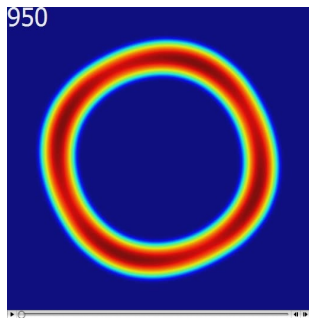
- true periodic boundary conditions
- study of persistent current / superfluid flow
- inertial sensors (interferometry)
- SQUID geometry
- macroscopic quantum superpositions

⇒ Study superfluidity by persistent flow, with **arbitrary rotation** frequency and possible tuning to **lower dimensions**.

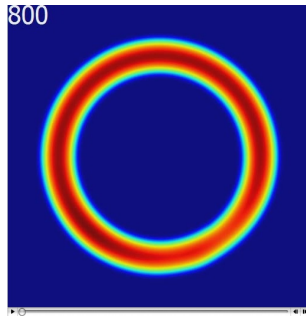
Vortices entering a rotating ring

Numerical simulation of Gross-Pitaevskii equation

Simulate GPE in 2D: $i\hbar\partial_t\Psi = \left(-\frac{\hbar^2}{2M}\Delta + V(\mathbf{r}, t) + g|\Psi|^2\right)\Psi$
 Excitation rotating at frequency Ω



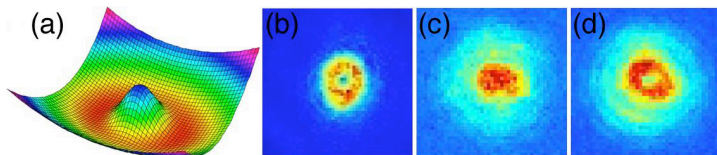
$\ell = 4$ excitation



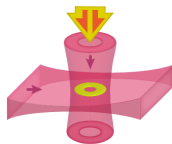
rotating barrier

Ring geometry

Possible implementation



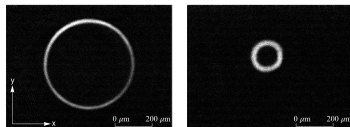
magnetic trap plugged by a blue detuned laser NIST 2007



all optical ring trap with two red detuned lasers NIST 2011

Ring geometry

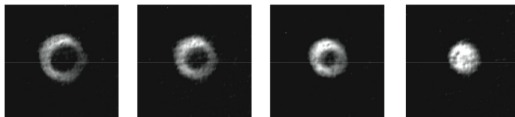
Possible implementation



a)

b)

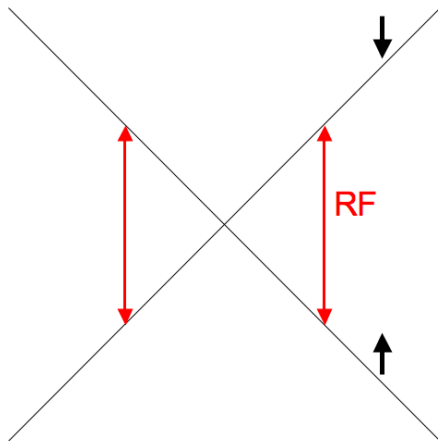
time averaged adiabatic potentials Oxford 2011

(a) $B_0^{\text{DC}} = 1.0 \text{ G}$ (b) $B_0^{\text{DC}} = 1.1 \text{ G}$ (c) $B_0^{\text{DC}} = 1.2 \text{ G}$ (d) $B_0^{\text{DC}} = 1.3 \text{ G}$

combination of optical + adiabatic potentials LPL 2006 / Oxford
2008

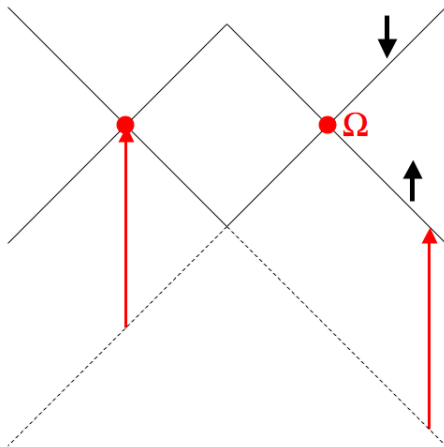
Ring geometry

Ring trap for dressed atoms



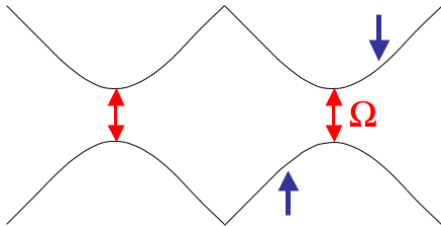
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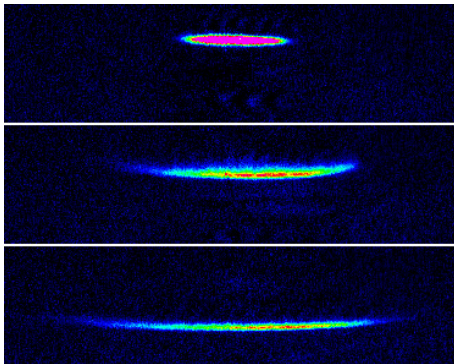
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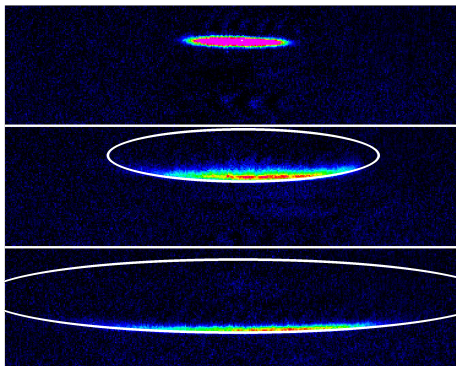
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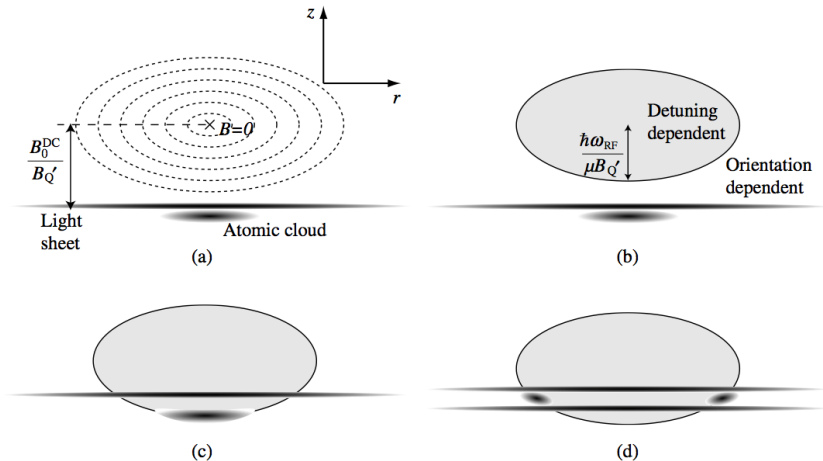
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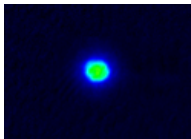
Typical figures:

- oscillation frequencies: $\nu_z = 1$ to 40 kHz / $\nu_{\perp} = 0.5$ to 2 kHz
- ν_z, ν_{\perp} adjustable independently
- ring radius: $r_0 = 20$ to 200 μm , $r_0 \propto \nu_{\text{RF}}$
- low dimensionality: μ compared to $h\nu_z, h\nu_{\perp}$
 - 3D for $N > N_{2D} = \frac{\pi r_0}{2a} \frac{\nu_z}{\nu_{\perp}} \sim 10^5 - 10^6$
 - 2D for $N_{2D} > N > N_{1D} = \frac{4\sqrt{\pi} r_0}{3a} \sqrt{\frac{\nu_z}{\nu_{\perp}}} \sim 10^4 - 10^5$
 - 1D for $N < N_{1D}$
- rotation by deformation of the trap

Current status

A BEC in a dressed quadrupole trap

- BEC with 2×10^5 in a plugged quadrupole trap

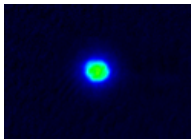


Lifetime 30 s.

Current status

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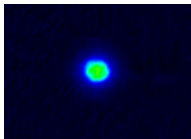
Lifetime 30 s.

- transfer in a dressed state

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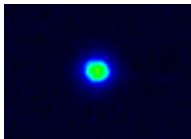
Lifetime 30 s.

- transfer in a dressed state
- slow switch off of the plug laser

Current status

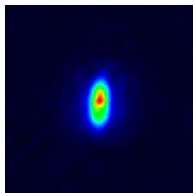
A BEC in a dressed quadrupole trap

- BEC with 2×10^5 in a plugged quadrupole trap



Lifetime 30 s.

- transfer in a dressed state
- slow switch off of the plug laser
- BEC in a pure quadrupole trap, in a dressed state



Lifetime 140 s!

Summary and prospects

- degenerate gases can be a useful model system with tunable parameters

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- an interesting case: the ring geometry
- GPE simulations: how does a vortex enter the ring

Summary and prospects

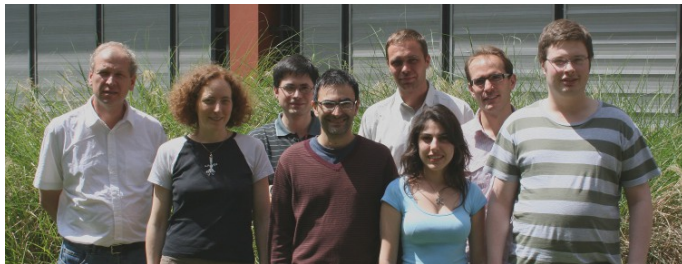
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- GPE simulations: how does a vortex enter the ring
- a ring trap relying on adiabatic potentials and standing waves
- 1st step: **BEC in the dressed potential**

Summary and prospects

- degenerate gases can be a useful model system with tunable parameters
- an interesting case: the ring geometry
- GPE simulations: how does a vortex enter the ring
- a ring trap relying on adiabatic potentials and standing waves
- 1st step: **BEC in the dressed potential**
- **Prospects:** add the standing wave to obtain a ring, and make it rotate!

Acknowledgments

The BEC group in Villeteuse



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www-lpl.univ-paris13.fr/bec