IUPAP Commission 15

Atomic, Molecular & Optical Physics

Working Group on Nanoscience

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Commission Conferences

ICPEAC (International Conference on Positrons & Electron Assisted Collisions)

- Stockholm, Sweden 2003
- Rosario, Argentina, 2005

ICAP (International Conference on Atomic Physics)

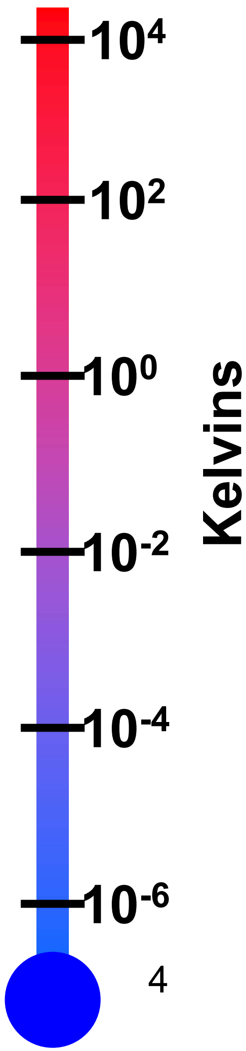
- Rio de Janeiro, Brazil 2004
- Innsbruck, Austria 2006

Sample Invited Sessions at ICAP XX

1. **Bose Einstein condensates**
   a) Atomic Bose Gases in Low Dimensions
   b) Bosonic Josephson Junction at finite temperature
   c) Interference between fluctuating condensates
2. **Fermi Gases**
   a) Superfluidity in a Gas of Fermionic Atoms
   b) Fermi-Bose mixtures in three-dimensional optical lattice
   c) Fermi gas in the BCS-BEC crossover
3. **Quantum information processing with atoms & ions**
   a) Trapped atomic ions & quantum information processing
   b) Entangled states for precision spectroscopy
   c) Quantum bits and quantum wires
4. **Quantum optics and cavity QED with atoms & ions**
   a) Cavity QED
   b) Quantum Optics with Atomic Ensembles
   c) Circuit QED and Prospects for Quantum Circuits
5. **Chip traps for atoms, ions and molecules**
   a) Atom Chip applications
   b) Atom Chips for neutral fermions
   c) Scalable Ion Traps
6. **Atoms in optical lattices**
   a) A Lab in a Trap: Fermions, Molecules & Bose-Fermi mixtures
   b) Strongly correlated atoms in optical lattices
   c) Traveling to exotic places with ultracold atomic gases

Common Theme of Laser Cooling & Trapping of Atoms & Molecules

During 1980s and 1990s techniques were devised to cool atoms by ten orders of magnitude from room temperature to nanoKelvins. Atoms were trapped using magnetic fields.



<u>Nobel Prizes</u>

1999 Laser Cooling
S. Chu, C. Cohen-Tannoudji, W. Phillips

2001 Bose Einstein Condensation
E. Cornell, W. Ketterle & C. Wieman

Criteria for Bose Einstein Condensation

Square Well

Phase Space Density $n\,(\lambda_{dB})^3 > 2.612$

n = atom density

$\lambda_{dB} = h \,/\, (2\pi\, M\, k_B\, T)^{1/2}$

M = atom mass

Superfluid ^{4}He: $n = 2 \times 10^{22}$ atoms/cm^3 $\rightarrow$ Transition Temperature $T_c = 3$ K

Harmonic Potential

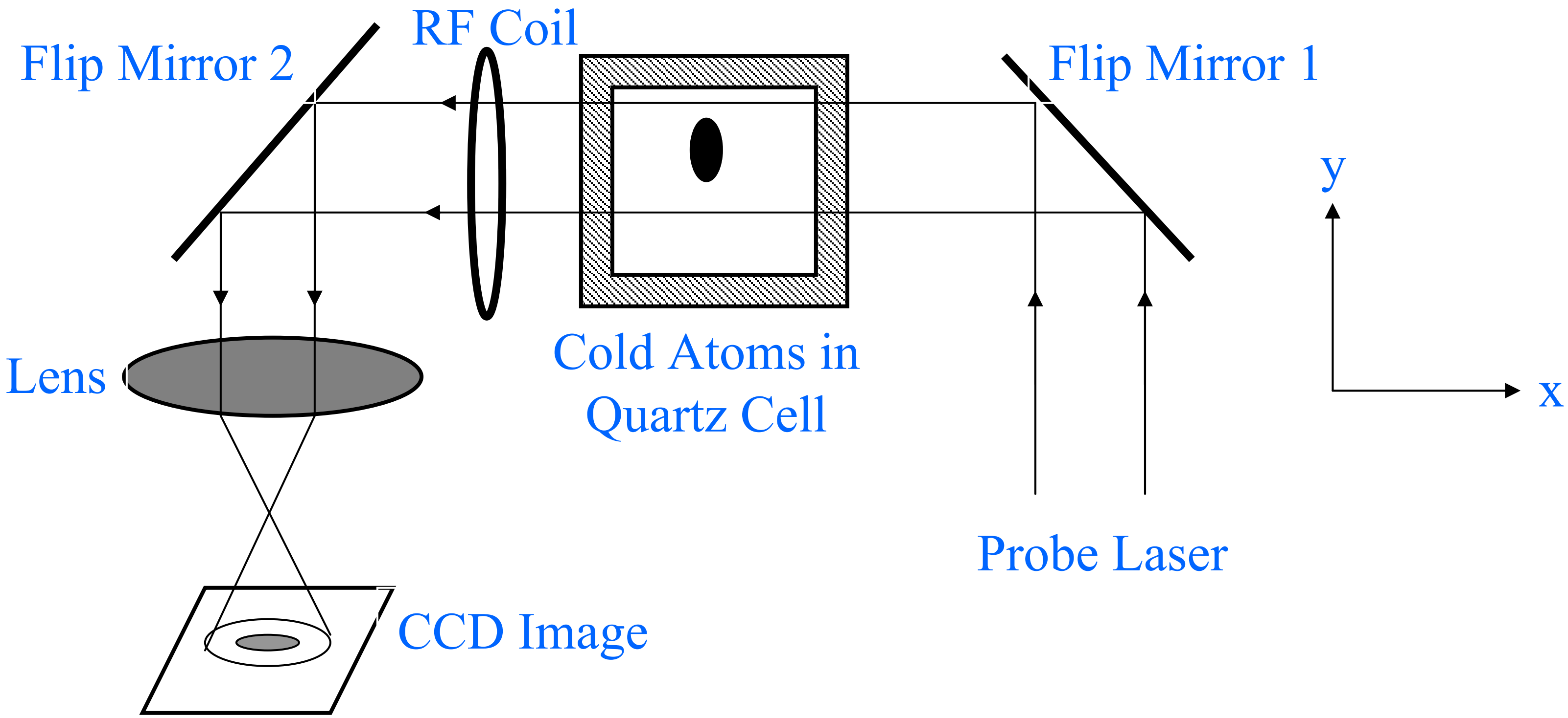
$V = M\,(\omega_x x^2 + \omega_y y^2 + \omega_z z^2) \,/\, 2$

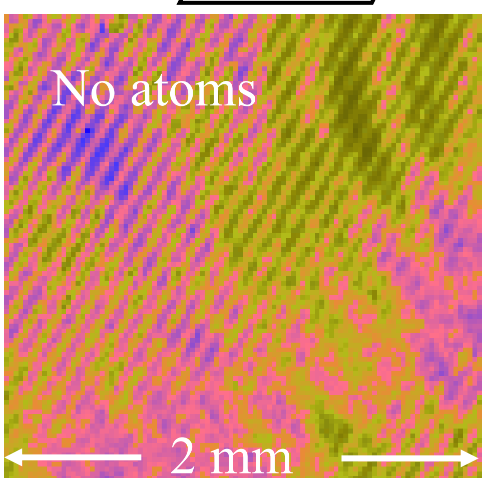
$kT < 0.15\, h\, \varpi\, N^{1/3}$

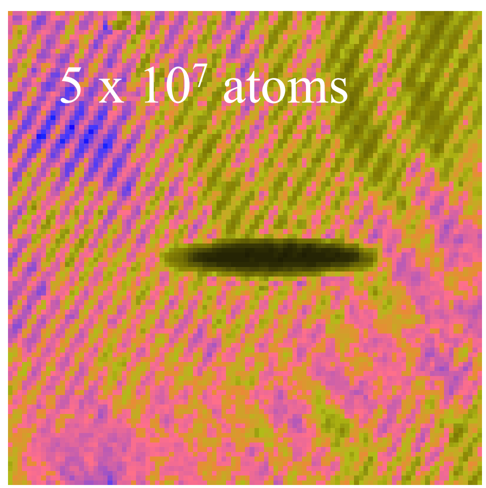
$\varpi = (\omega_x\, \omega_y\, \omega_z)^{1/3}$ N = # trapped atoms

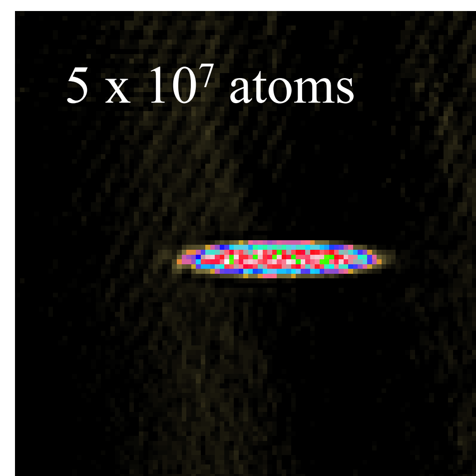
^{87}Rb: $n \approx 10^{14}$ atoms/cm^3 $\rightarrow$ Transition Temperature $T_c \approx 100$ nK

Imaging using Probe Laser Absorption





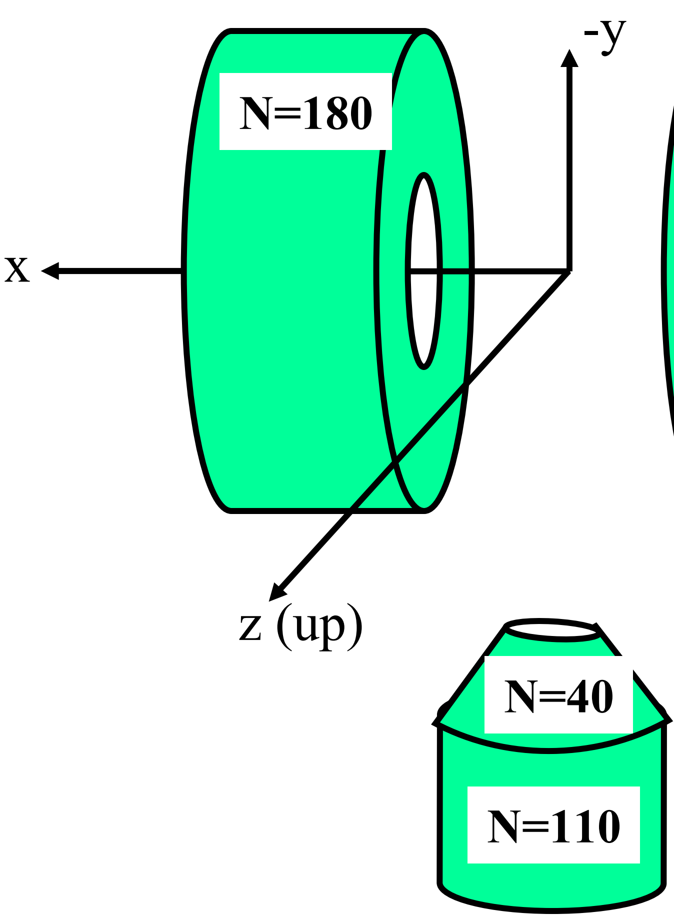




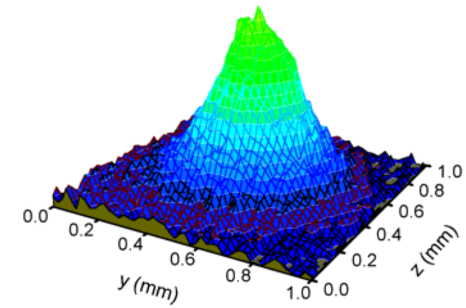
Bose Einstein Condensation

QUIC Trap

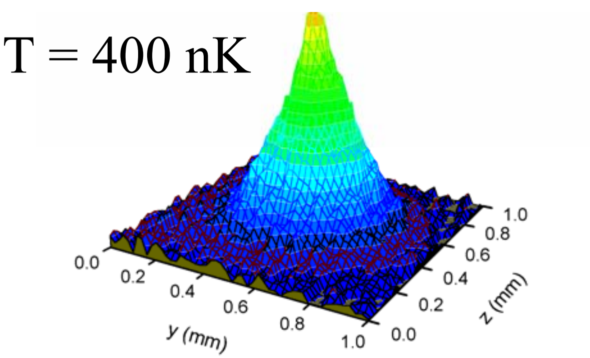
T. Esslinger et al, PRA **58**, R2664 (1998)



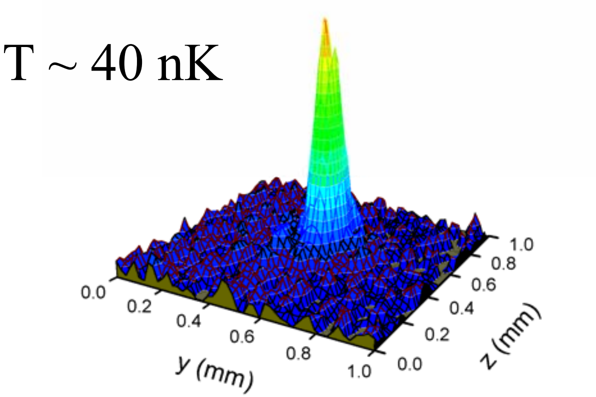
a) T = 449 nK



b) T = 400 nK



c) T ~ 40 nK



Condensate Coherence

Gross-Pitaevskii Equation

$$-\hbar^2/2m\, \nabla^2 \Psi(r,t) + V(r)\, \Psi(r,t) + U_o\, |\Psi(r,t)|^2\, \Psi(r,t) = i\,\hbar\, \delta\Psi(r,t)/\delta t$$

$$U_o = 4\pi\, \hbar^2\, a / M$$

a = scattering length $a>0$ ($a<0$) if interaction between atoms is repulsive (attractive)

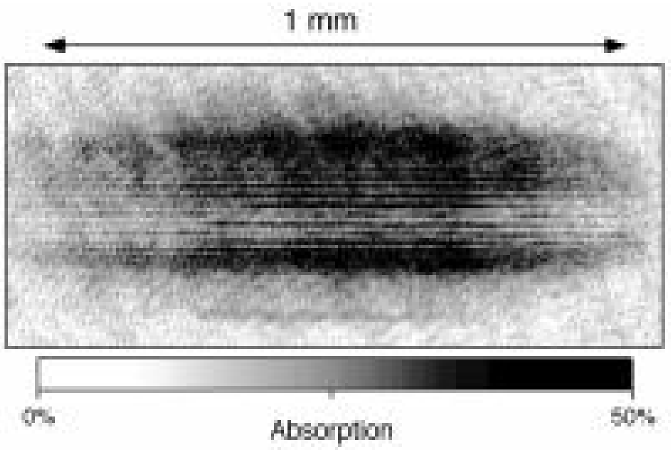
Atom Interferometry

Two condensates have atom density

$$|\Psi_{tot}|^2 = |\Psi_1|^2 + |\Psi_2|^2 + 2\,\mathrm{Re}\,(\Psi_1 \Psi_2{}^*)$$

Interference term gives rise to density variations.

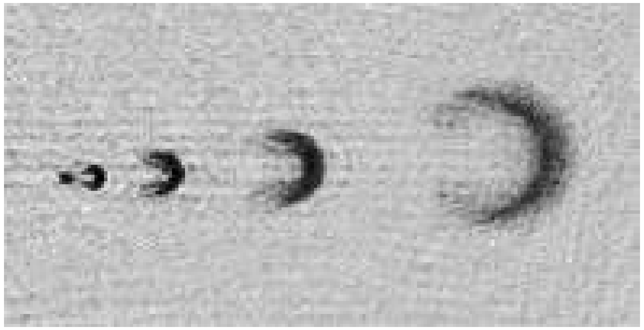
M. Andrews et al, Science **275**, 637 (1997)



Atom Laser

One can generate pulses of coherent atoms analogous to a laser beam.

M. Mewes et al, PRL **78**, 582 (1997)



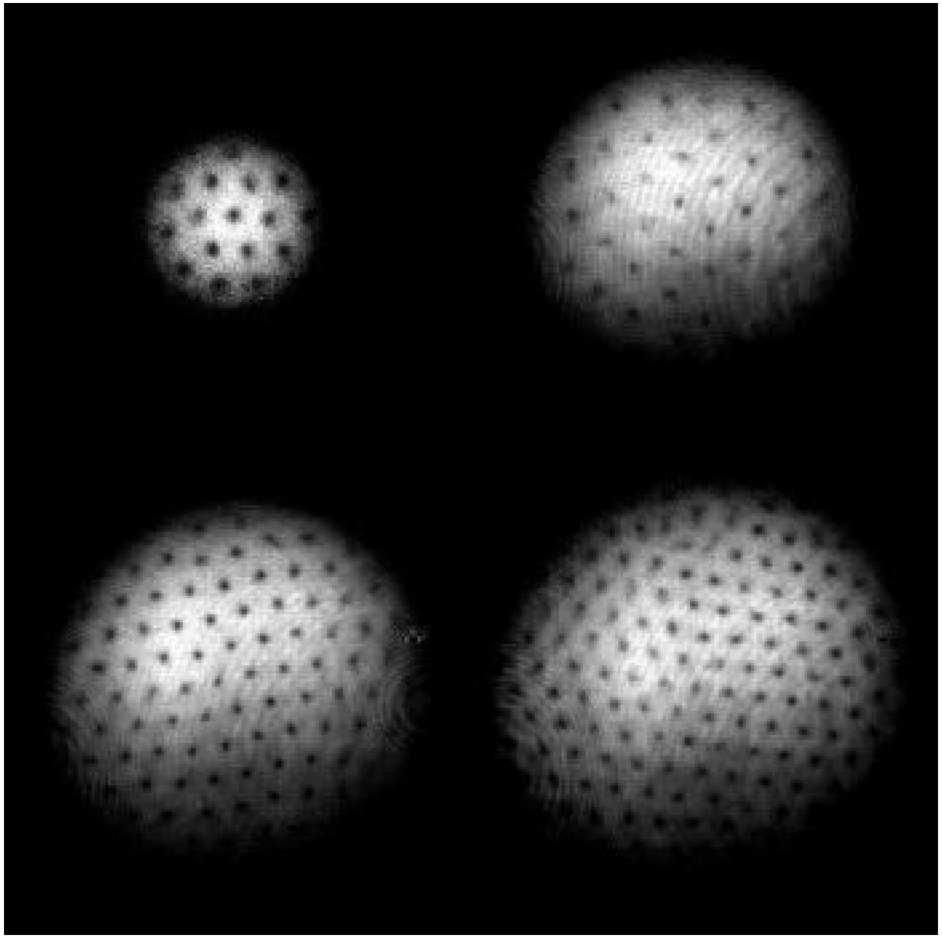
Vortices

J. R. Abo-Shaeer et al, Science **292**, 476 (2001)

Superfluid properties of a BEC were shown using a spatially rotated probe laser beam that generated moving potential. Condensate velocity is given by

$$\mathbf{v} = \hbar / M \nabla\phi$$

where ϕ is condensate phase. Images of a ^{23}Na BEC after a free expansion revealed an array of up to 130 vortices each having one unit of quantized circulation h/M.



Superfluid Mott Insulator Transition

M. Greiner et al, Nature 415, 39 (2002)

Optical Lattice

Create 3 dimensional array of condensates using a standing laser wave.

$V = V_o \{\sin^2 kx + \sin^2 ky + \sin^2 kz\}$ where $k = 2\pi/\lambda$ & $V_o \sim$ laser intensity

Condensate atoms tunnel between neighbouring lattice sites. Tunneling decreases as laser power increases causing transition from superfluid to Mott insulator.

Bose-Hubbard Model

$H = - J \Sigma_{ij} a_i^t a_j + \Sigma \varepsilon_i n_i + ½ U \Sigma_i n_i (n_i - 1)$

First term describes tunneling between neighbouring sites i & j. a_i^t (a_i) is atom creation (destruction) operator. Second term is energy ε_i of n_i atoms at site i. Last term describes repulsion between atoms at site i.

^{87}Rb Lattice (150,000 sites)

After free expansion, interference pattern disappeared when lattice depth exceeded critical value. Interference reappeared when laser intensity lowered below transition intensity. Observed time of 14 ms to restore coherence comparable to tunneling time between neighbouring lattice sites proportional to ħ / J.

Ultracold Fermions

A. Truscott et al, Science 291, 2570 (2001)

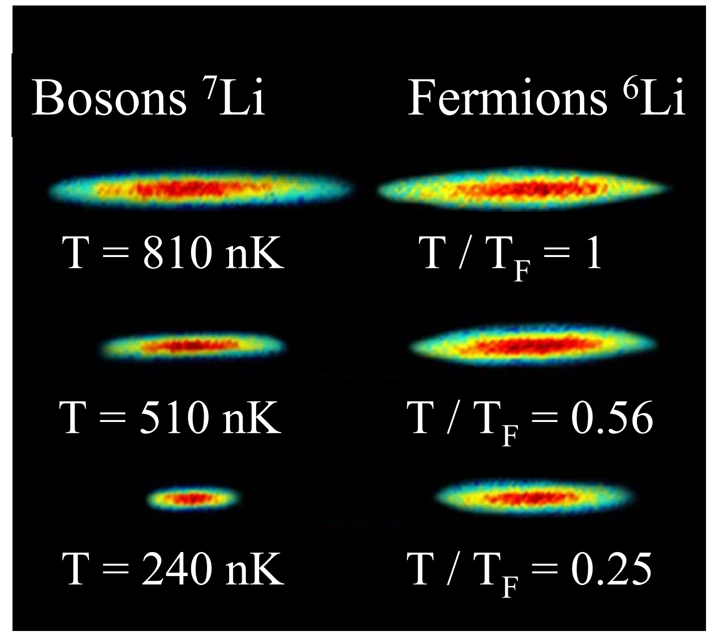
1. A vapour of ^6Li and ^7Li was loaded into a magnetic trap.

2. The boson ^7Li was cooled in the "standard" way using laser cooling and evaporative cooling. Evaporative cooling doesn't work well for fermions since identical fermions are unable to undergo collisions necessary to rethermalize the gas during evaporation.

3. ^6Li cools as a result of collisions with ^7Li called sympathetic cooling.

Picture at right illustrates Pauli Exclusion Principle. As bosons cool, they bunch together while fermions keep their distance.

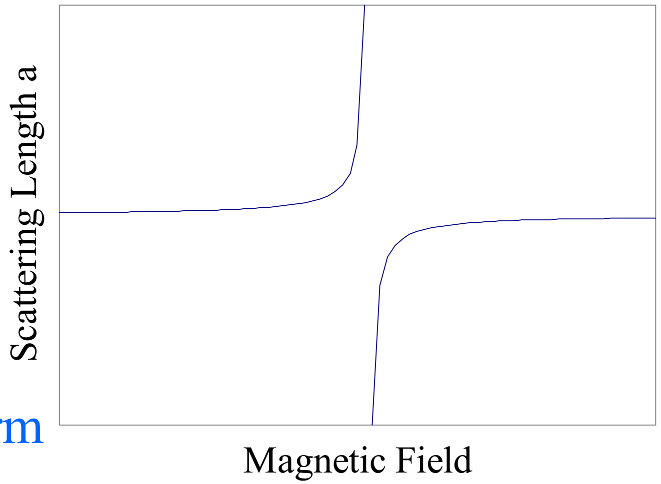
"Astronomy Picture of the Day"



$$k_B T_F = 1.817\, \hbar\varpi\, [^6Li]^{1/3}$$

Molecular BEC

C. Regal et al, PRL, 2004.



Scattering Length a

-Atoms repel (attract) if a>0 (a<0)

-Magnetic field tunes molecular & atomic energies

Feshbach Resonance: $E_{\text{molecular state}} = E_{\text{colliding atoms}}$

-During collision, atoms stick together briefly & can form molecule enhancing scattering

Creation of Molecular BEC

- ^{40}K atoms cooled evaporatively in an optical trap to temperature $T/T_F = 0.07$
- K cooled into two magnetic sublevels.
- Feshbach resonance controls atom-atom interactions.
- Molecules detected by probing photodissociation spectra.
- Transition to condensation of fermionic atom pairs (i.e. molecule) mapped as a function of temperature enables study of BCS- BEC crossover transition.

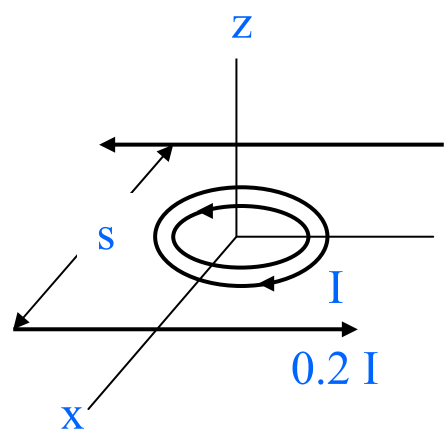
Miniaturization

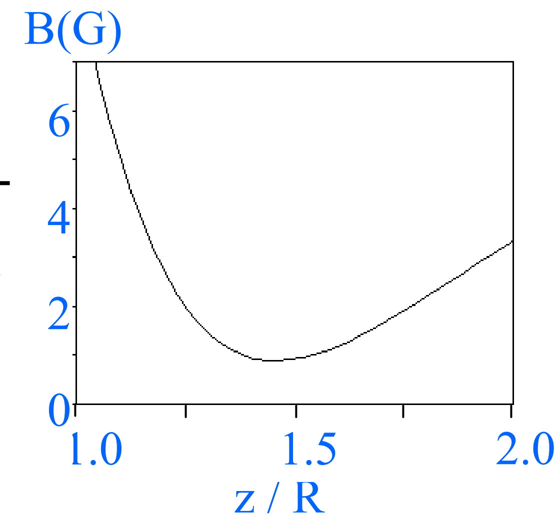
Microtrap

Micron sized gold wires deposited using lithography create trap.

-BEC generation in 700 ms
(W. Hänsel et al, Nature **413**, 498 (2001))

-order of magnitudes smaller current & power consumption



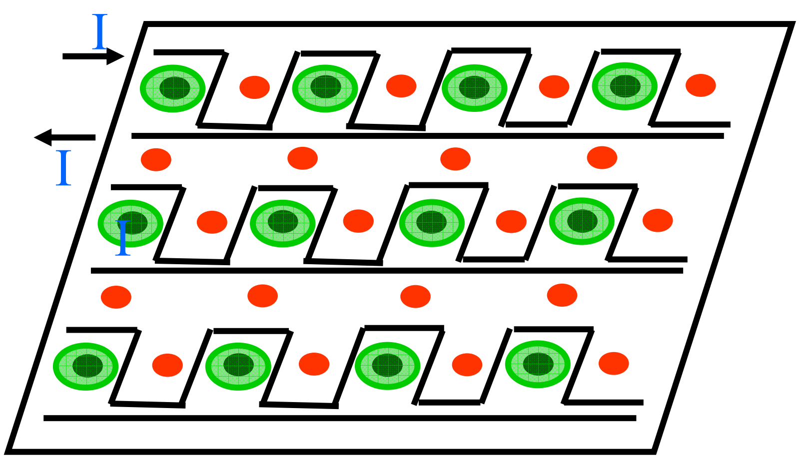


Proposed Microtrap Array (Atom Chip)

One or two dimensional lattice of traps for quantum information.

-neutral atoms easier than ions
(J. Cirac & P. Zoller, Phys. Today **3**, 38 (2004))

-Desirable to include diode lasers on chip to cool, probe & control coupling of lattice sites (WvW, Phys. in Can. **60**, (2004))



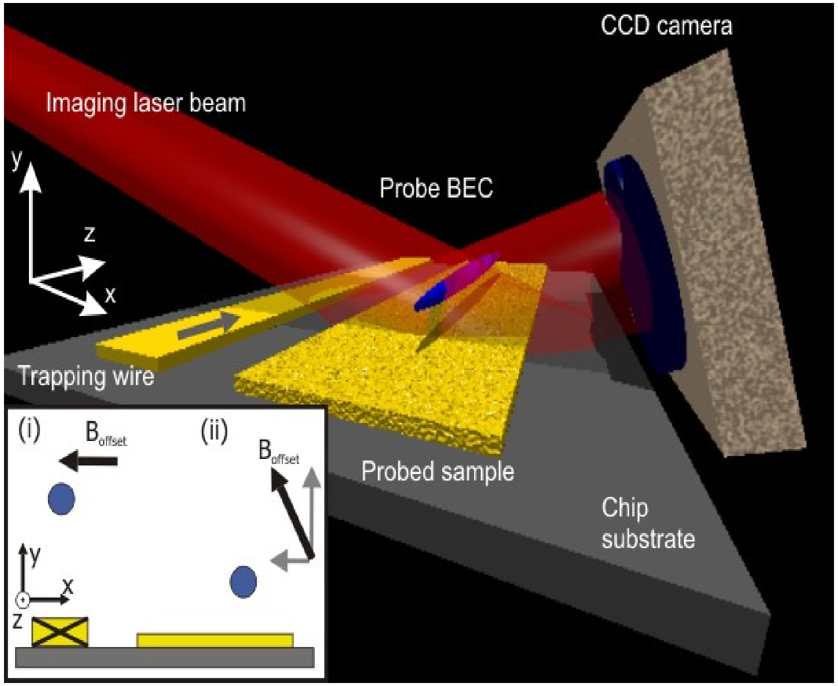
● Laser detuned from resonance controls coupling between BECs

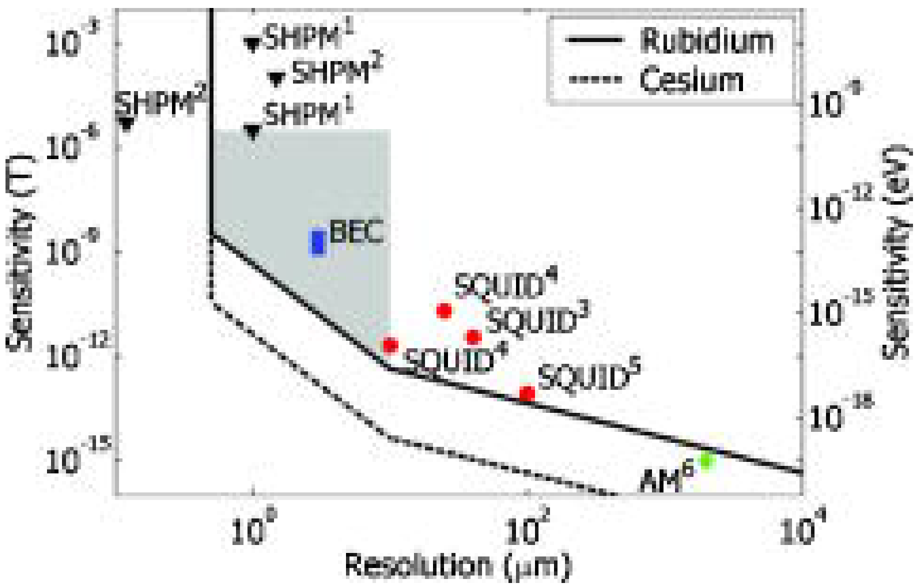
● Cooling/Probe Laser

BEC

BEC Magnetometer

S. Wildermuth et al, Appl. Phys. Lett. 88, 264103 (2006)





1. BEC sensitive to magnetic field created by microwires on atom chips (10^{-14} eV at 3 μm)
2. Two dimensional magnetic field map measured 10 μm above 100 μm wide wire

Greater sensitivity than scanning Hall probe microscope (SHPM) at smaller distance scale than SQUIDs

Conclusions

- Exciting & rapid developments affecting pure & applied physics
- This talk is very incomplete!!! A few of important topics omitted are:
  - Solitons K. Strecker et al, Nature **417,** 150 (2002)
  - Stopping light C. Liu et al, Nature **409**, 490 (2001)
  - Optical traps for BEC

    Yb Y. Tahasa et al, PRL **91**, 040404 (2003)

    Cs T. Weber et al, Science **299**, 232 (2003)
  - Biophysical applications, lab on a chip development etc.
- Very interdisciplinary impinging on many fields
- Continued close interactions essential between theoreticians & experimentalists of disciplines represented in Working Group.

Development of microtraps requires nanoscience expertise!