Cold atoms in microscopic traps

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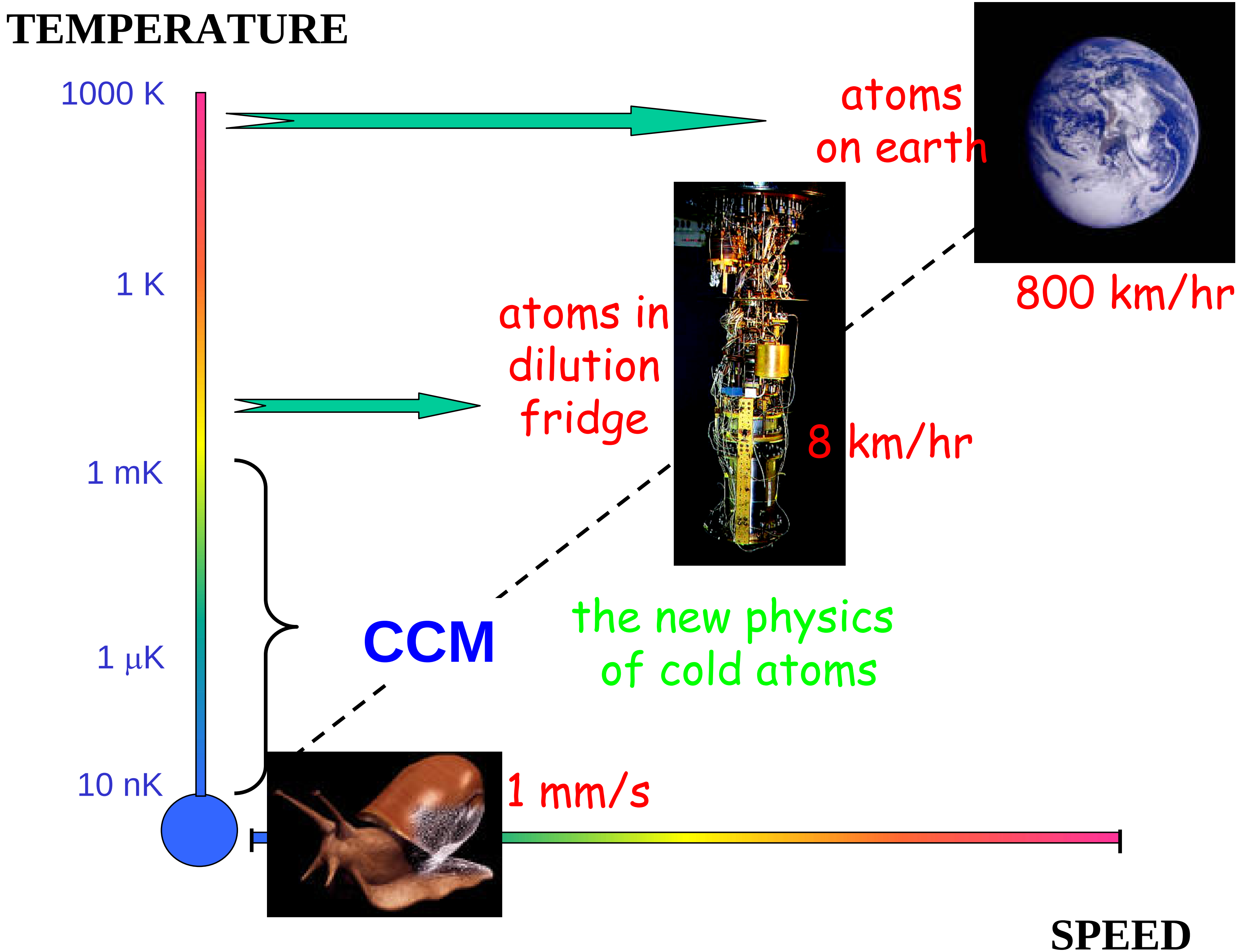
Outline

Part I

- **Introduction**
- **Atom guiding with microscopic wires**
- **Making BEC**

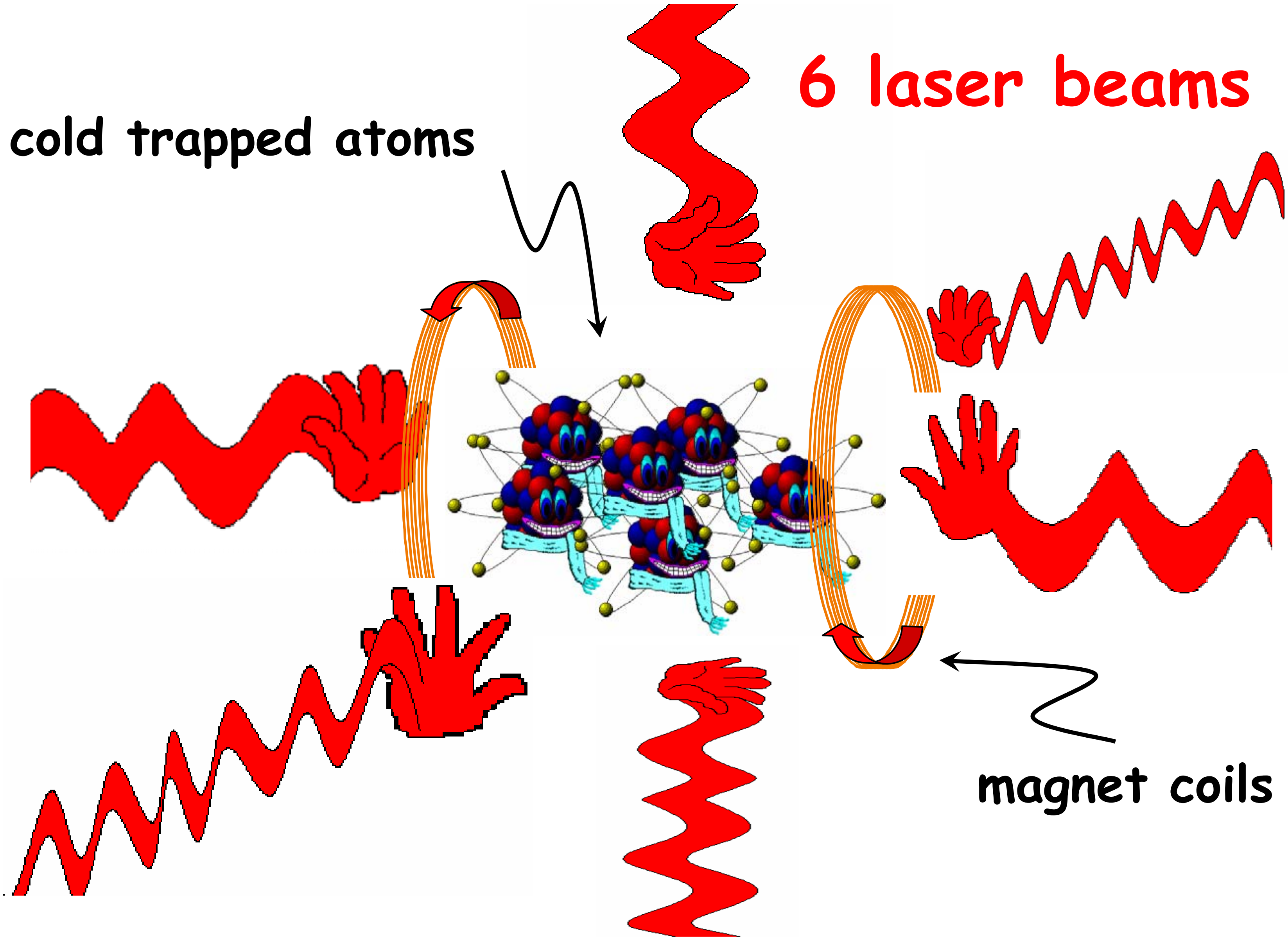
Part II

- **Videotape atom chip**
- **Yet smaller structures**
- **Atom chips for quantum logic?**

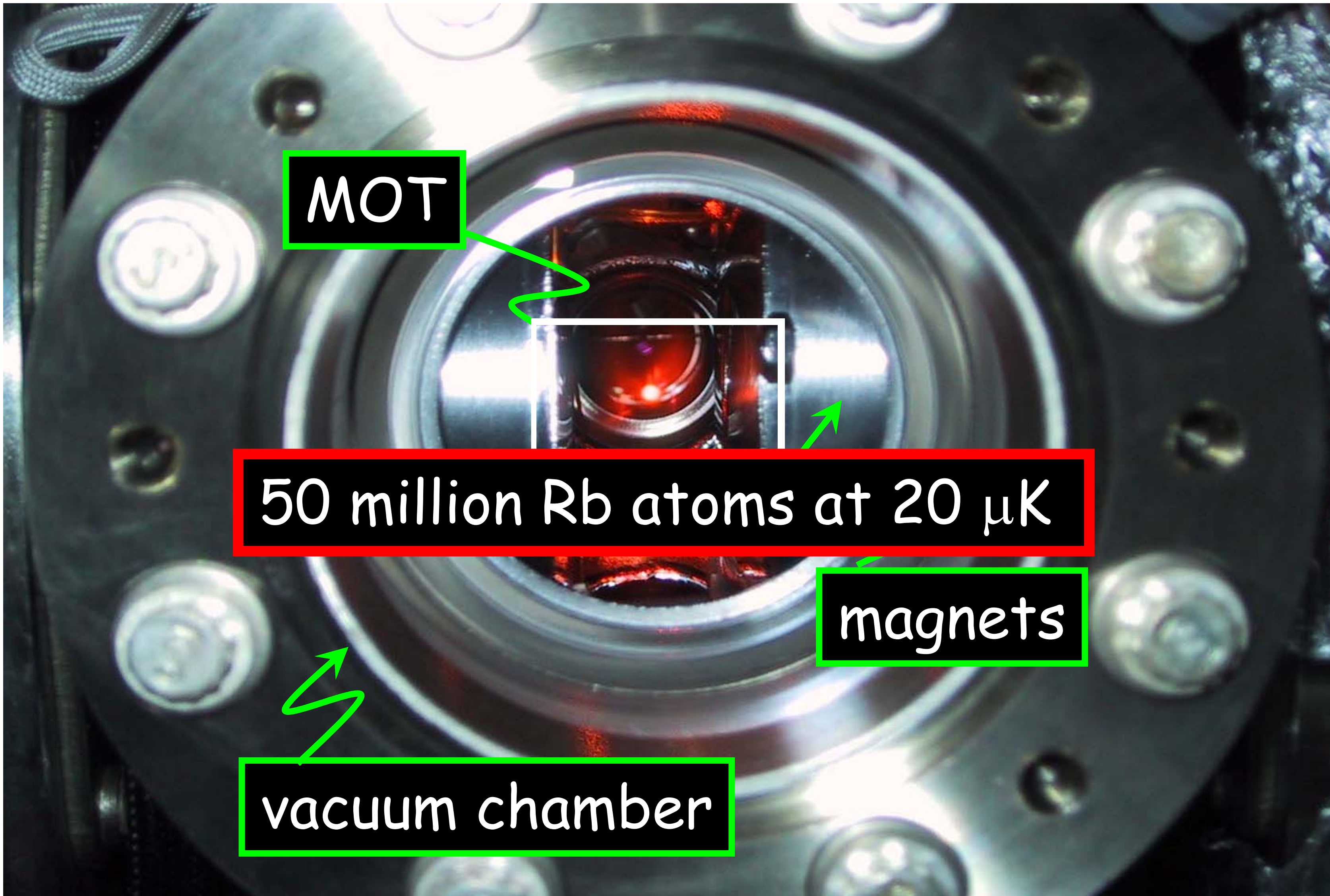

TEMPERATURE
1000 K
1 K
1 mK
1 μK
10 nK
atoms
on earth
800 km/hr
atoms in
dilution
fridge
8 km/hr
CCM
the new physics
of cold atoms
1 mm/s
SPEED

............you need a trap

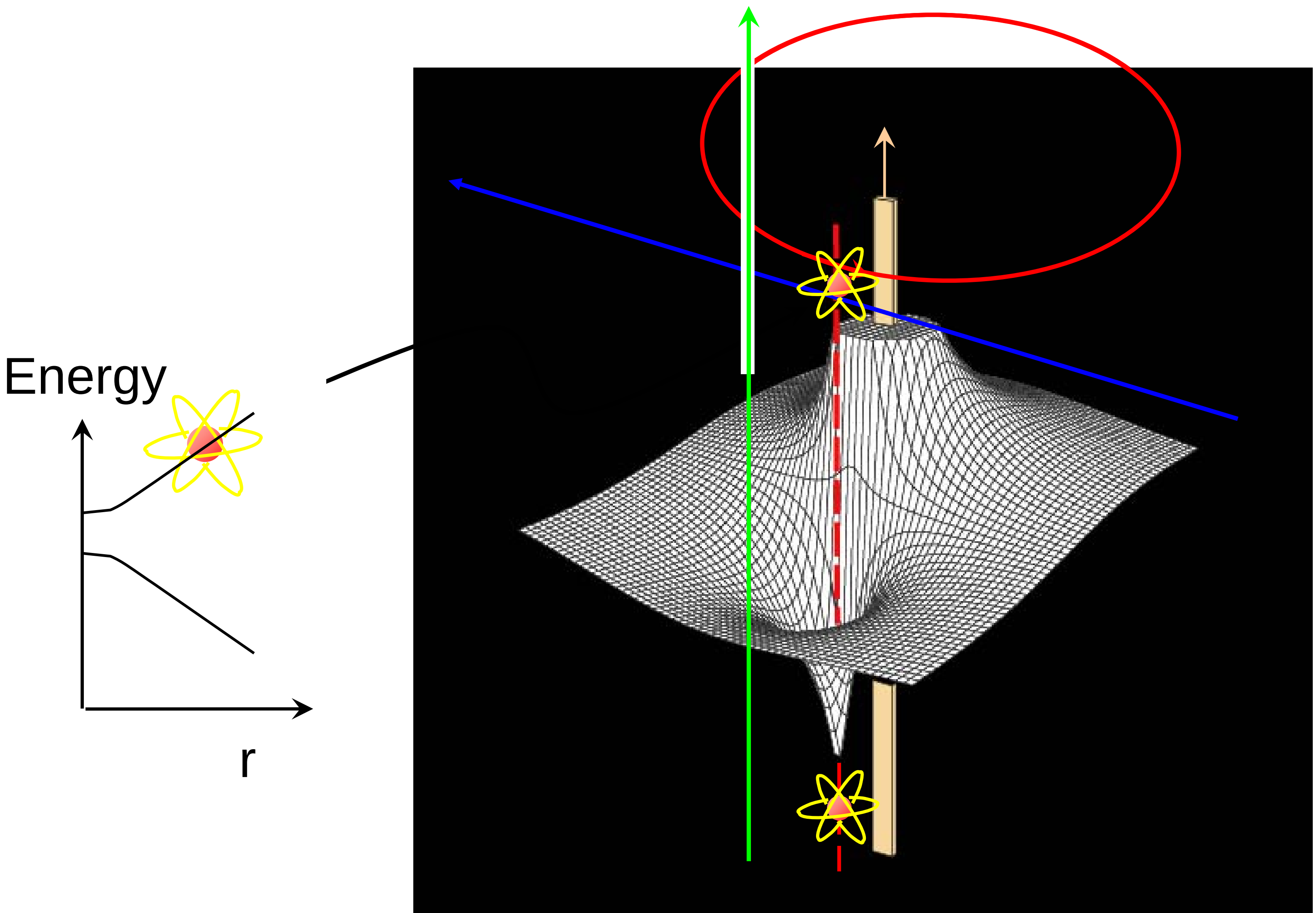
Magneto-optical trap (MOT)



A MOT of rubidium atoms

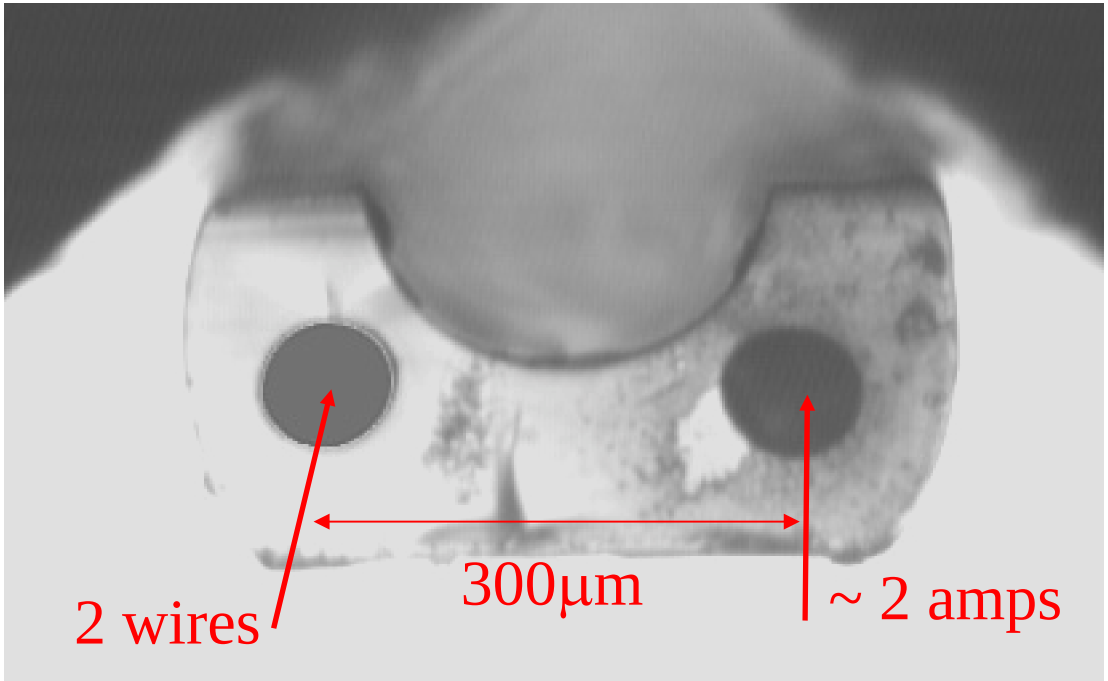


Principle of the magnetic guide for atoms



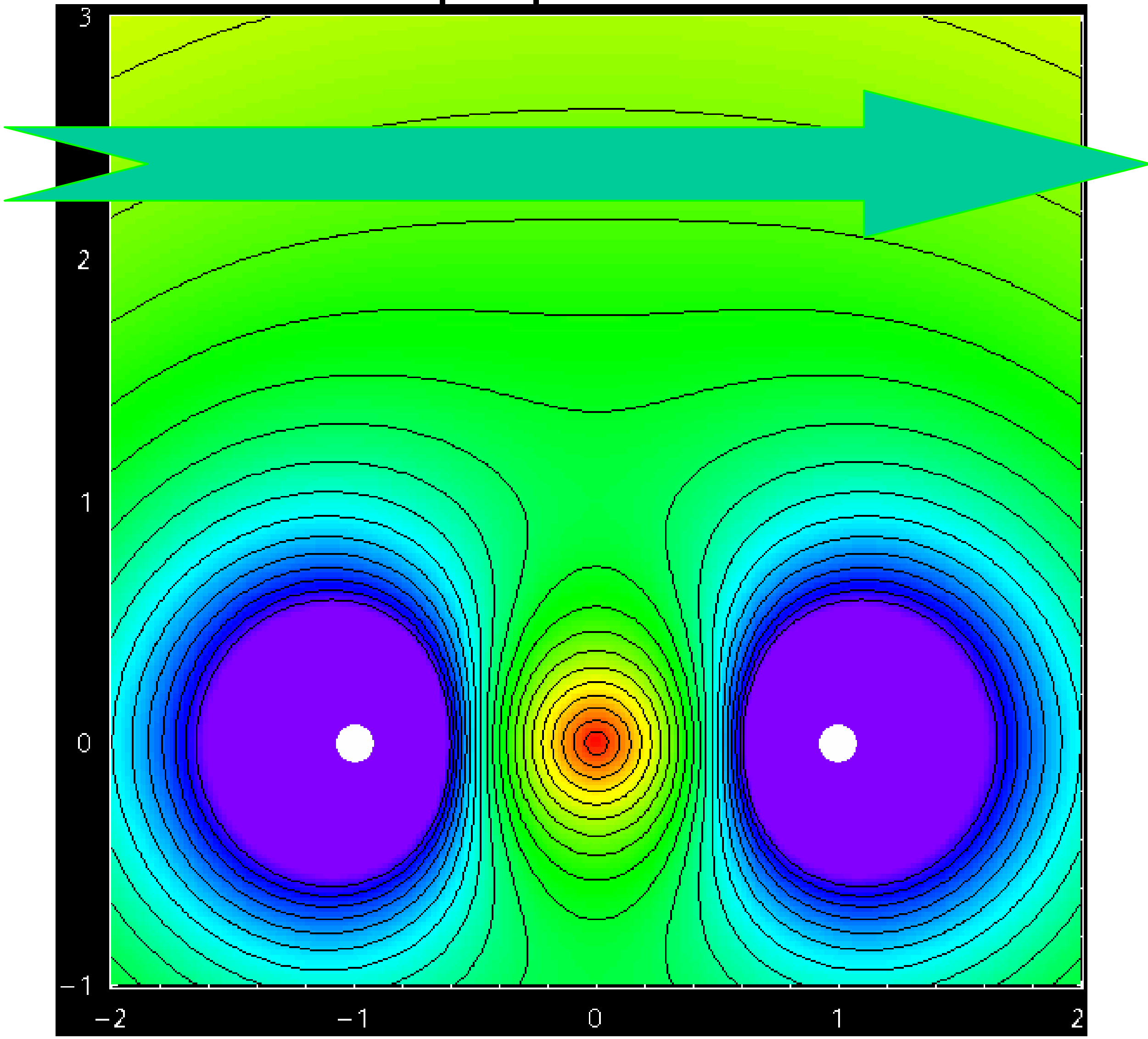
Two wire guide

Hollow silica fibre fabricated at the ORC, Southampton University



Basis for a de Broglie wave interferometer

Contours of |**B**|

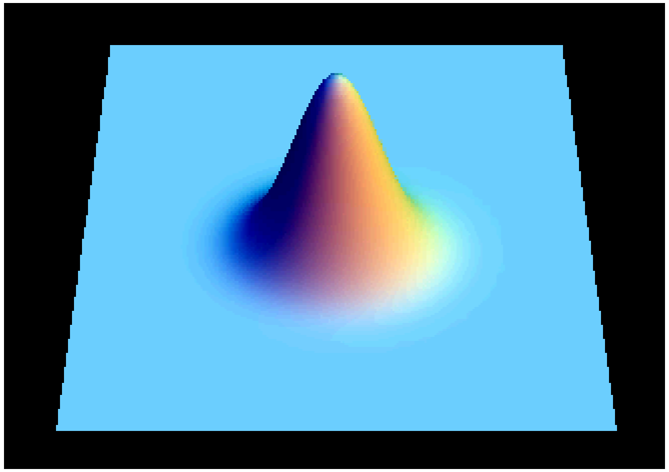


Add a horizontal uniform field

Great potential for coherent splitting

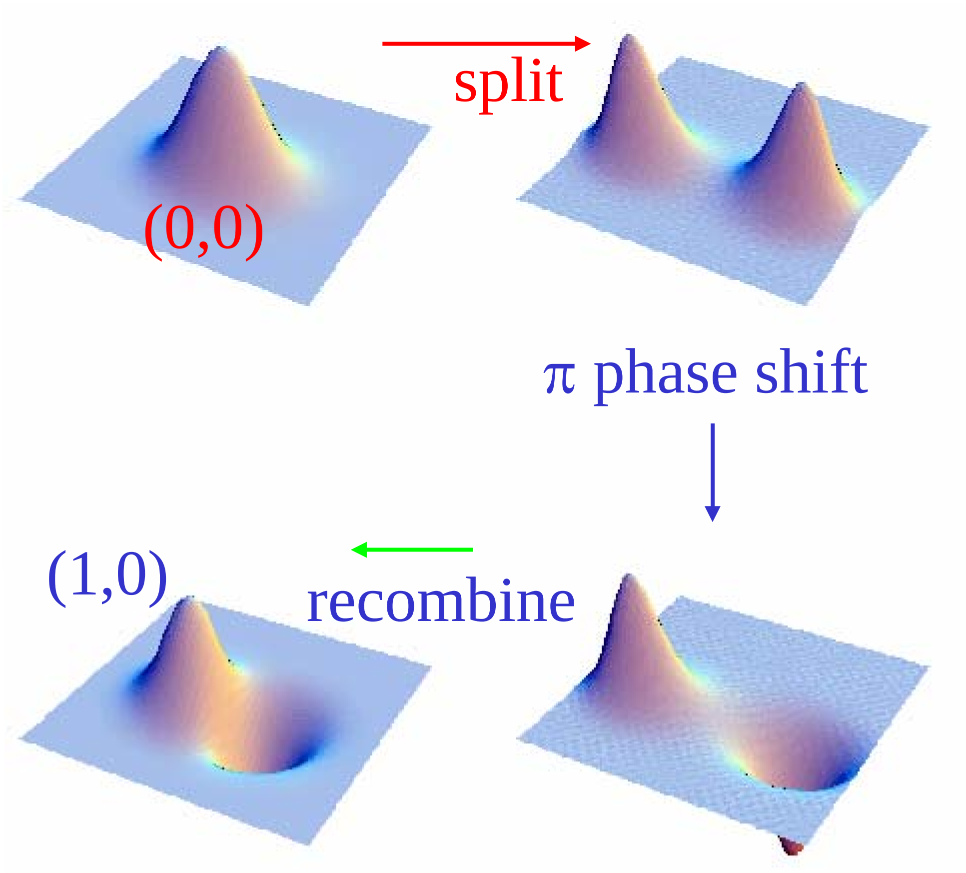
Hinds, Vale, and Boshier PRL Feb 2001

Splitting the Ground State
$\psi(0,0)$



Horizontal bias field increases to make horizontal splitting

Interferometry



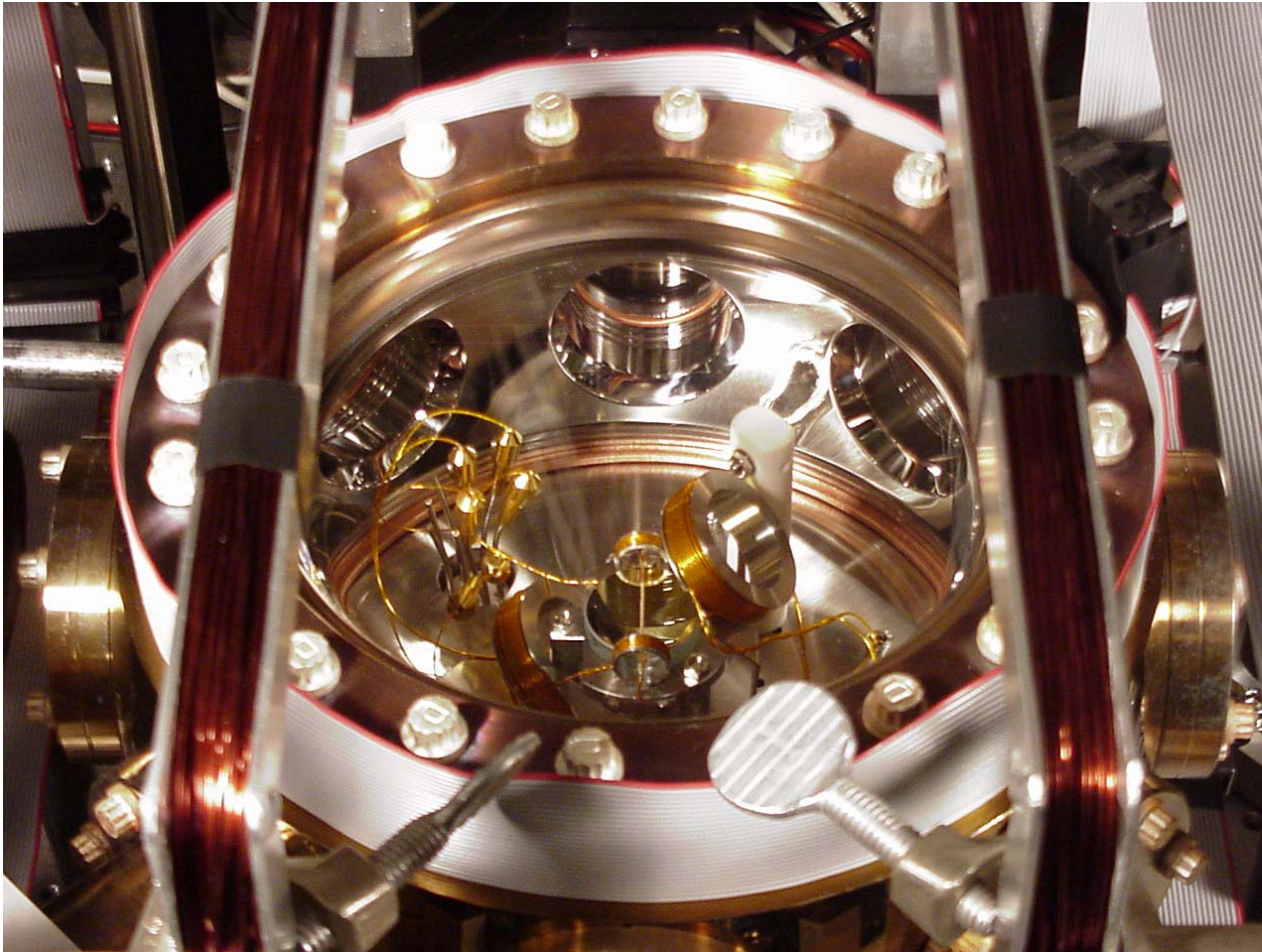
Extremely sensitive to

- Gravity
- EM fields
- Other feeble forces

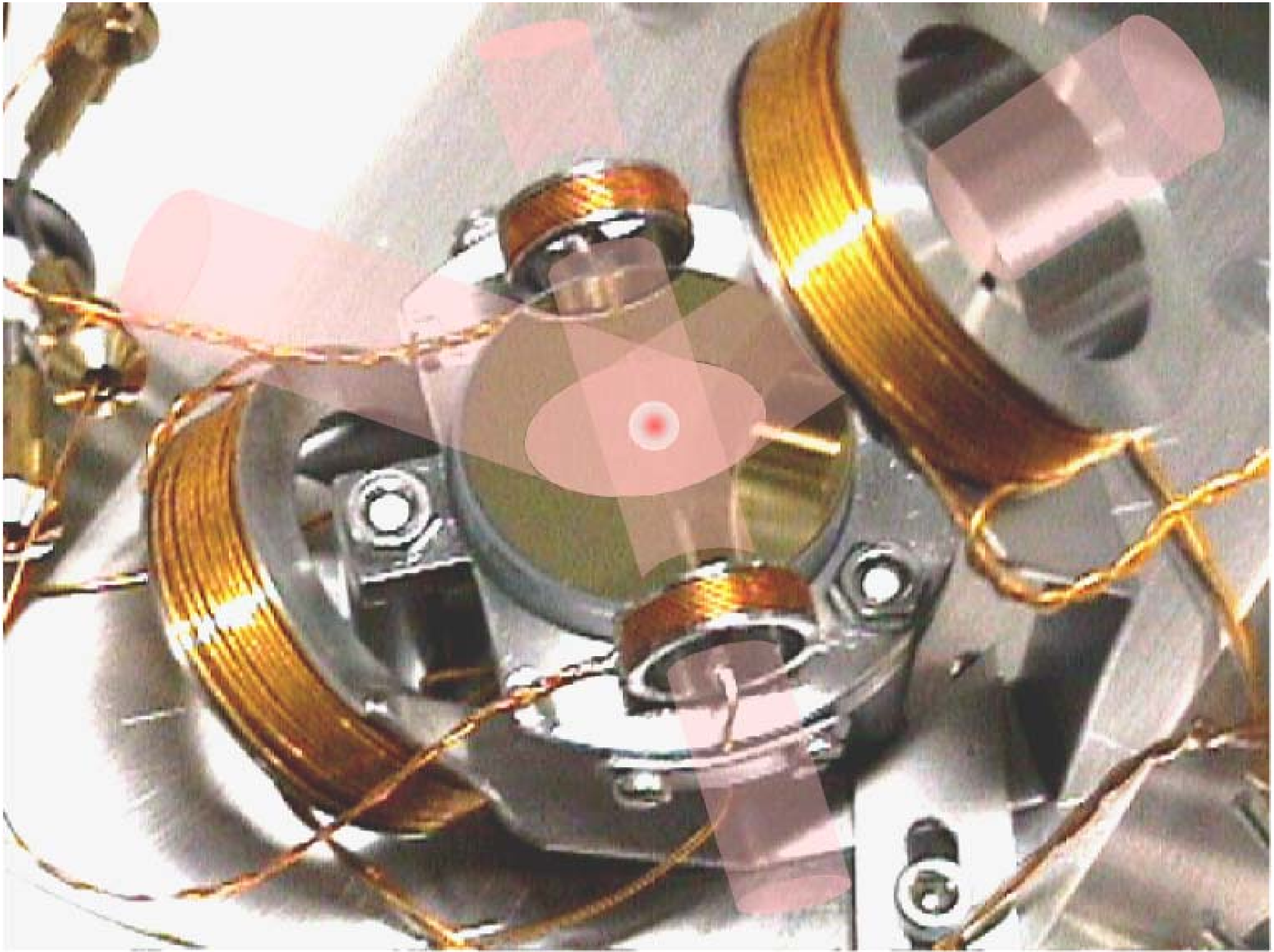
Nonlinear quantum games:
number squeezing
Heisenberg sensitivity
etc.

The output ports are the (0,0) and (1,0) vibration states of the guide.

The 2-wire interferometer at CCM



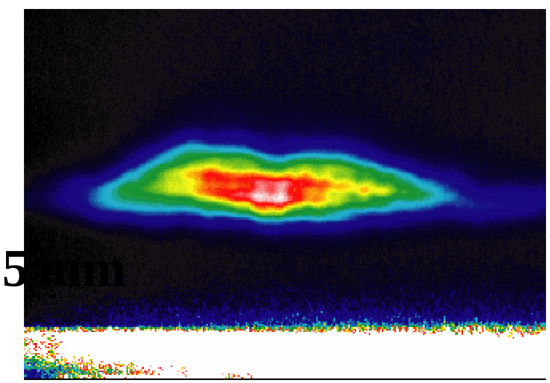
The Mirror MOT



Loading the guide

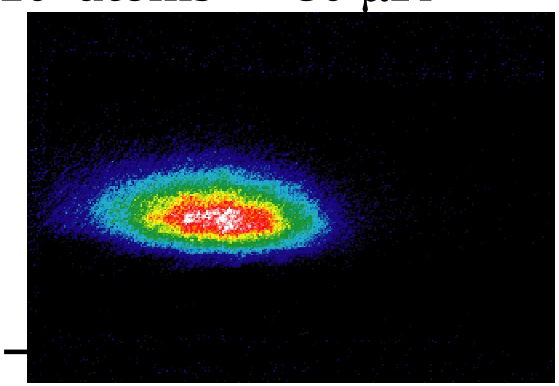
Mirror MOT

$1\ 10^8$ atoms 70 µK

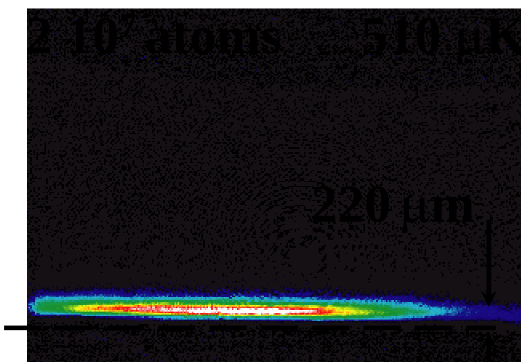


Magnetic trap

$2\ 10^7$ atoms 80 µK



Compressed Magnetic trap



………..the next step is evaporation

This means allowing the fastest atoms to escape

The remaining ones are slower ………

……… and therefore colder

http://www.colorado.edu/physics/2000/applets/bec.html

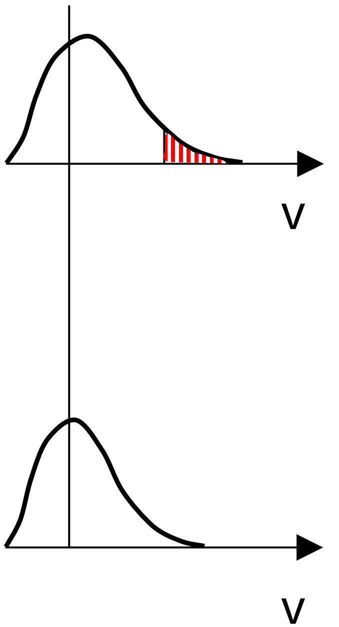
Evaporative cooling

Principle

Throw away the fastest atoms in the velocity distribution

Let the remaining atoms rethermalise through collisions

→ fewer atoms and lower temperature



Cooling rate is controlled by the elastic scattering rate γ_{el}

runaway evaporation

$$\gamma_{el} = n\, \mathrm{v}\, \sigma_{el}$$

peak number density n

$$n = \frac{N}{(2\pi)^{3/2} w_x w_y w_z}$$

rms width

$$w_x = \sqrt{\frac{k_B T}{m\omega_x^2}}$$

$$\therefore \quad n \propto N\, T^{-3/2}$$

collision velocity v

$$\mathrm{v} = \sqrt{\frac{6 k_B T}{m}}$$

$$\therefore \quad \mathrm{v} \propto T^{1/2}$$

collision cross section σ_{el}

$$\sigma_{el} = \frac{8\pi a^2}{1 + \left(\frac{2\pi a}{\lambda_{dB}}\right)^2}$$

thermal wavelength

$$\lambda_{dB} = \frac{h}{\sqrt{2\pi m k_B T}}$$

For ^{87}Rb, a = 5.6 nm

∴ below ~10 μK

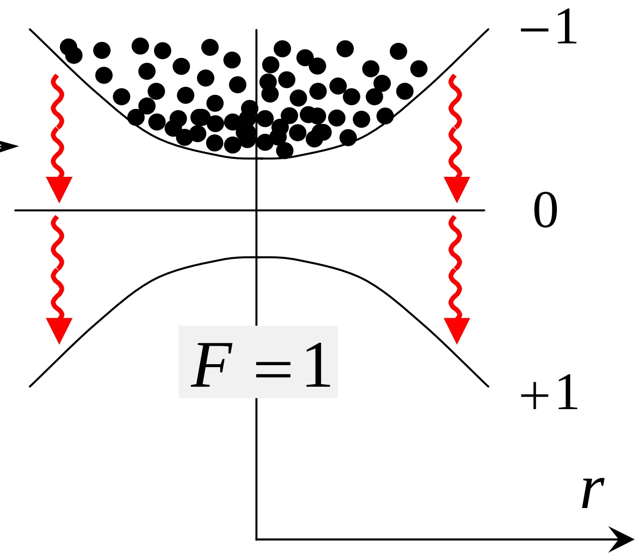
$$\sigma_{el} \approx 8\pi a^2 = \text{constant}$$

$$\gamma_{el} \propto N / T$$

If the temperature falls faster than we lose atoms, the evaporation runs away

forced evaporation by rf transitions

rf magnetic field
makes a leak



Sweep the frequency down
to force cooling

Typical initial elastic collision rate $\gamma_{el} = 1 - 100\ \mathrm{s}^{-1}$

Typical cooling time $\sim 100 / \gamma_{el} \sim 1 - 100\,\mathrm{s}$

Lifetime for loss from background gas collisions must be longer than this

→ Background pressure <10^{-9} – 10^{-11} torr.

Phase space density and BEC

The phase space volume occupied by one atom is $V\,\dfrac{h^3}{\lambda_{dB}^3}$

So with N atoms, a volume h^3 contains $\dfrac{N}{V}\lambda_{dB}^3$ atoms

$\propto N/T^{3/2}$ $\qquad\qquad$ $\propto 1/T^{3/2}$

And atom density in phase space is $\propto N/T^3$

If N goes down by 10^3 and T by 2⑨$10^3$, phase space density

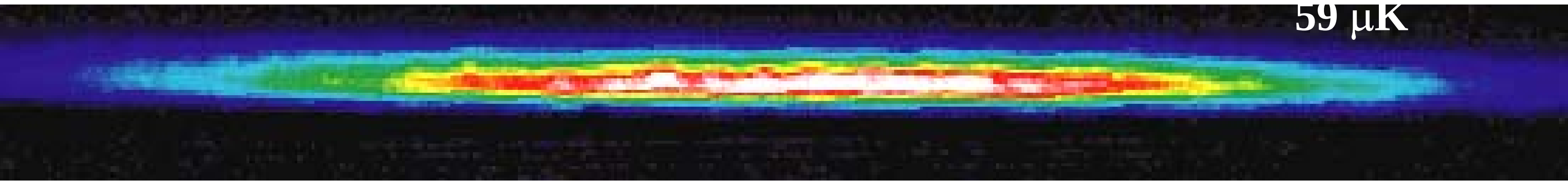
⟹ phase space density goes up by 8⑨$10^6$

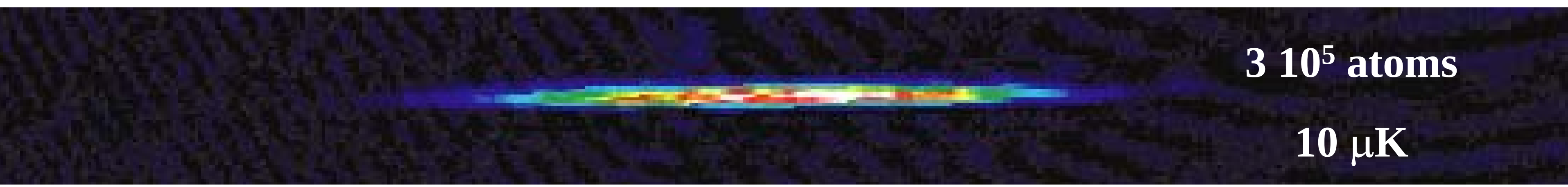
With more than 1 atom per cell of phase space, the gas can Bose condense.

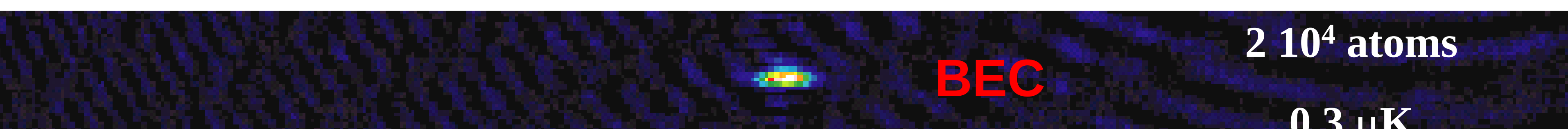
Evaporating to the ground state

1 mm

3 10^6 atoms





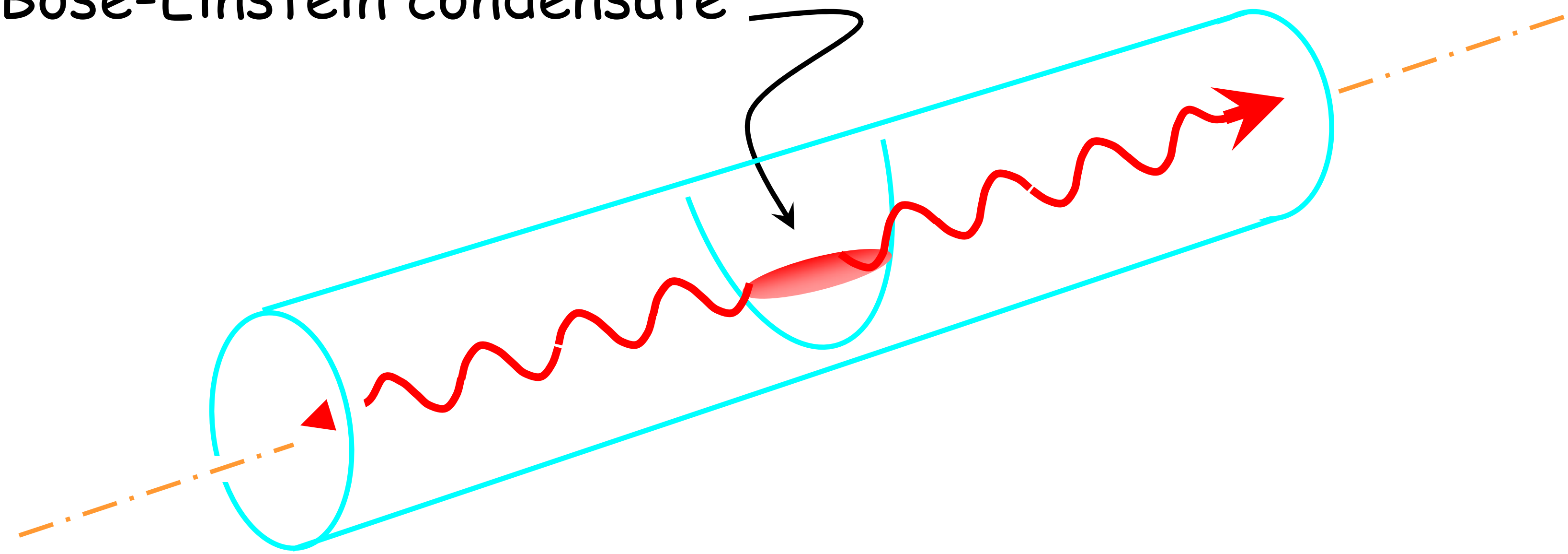


2 μm × 60 μm

Below 380 nK the atoms all jump into the ground state

The atoms behave collectively as a single quantum wave

……Bose-Einstein condensate

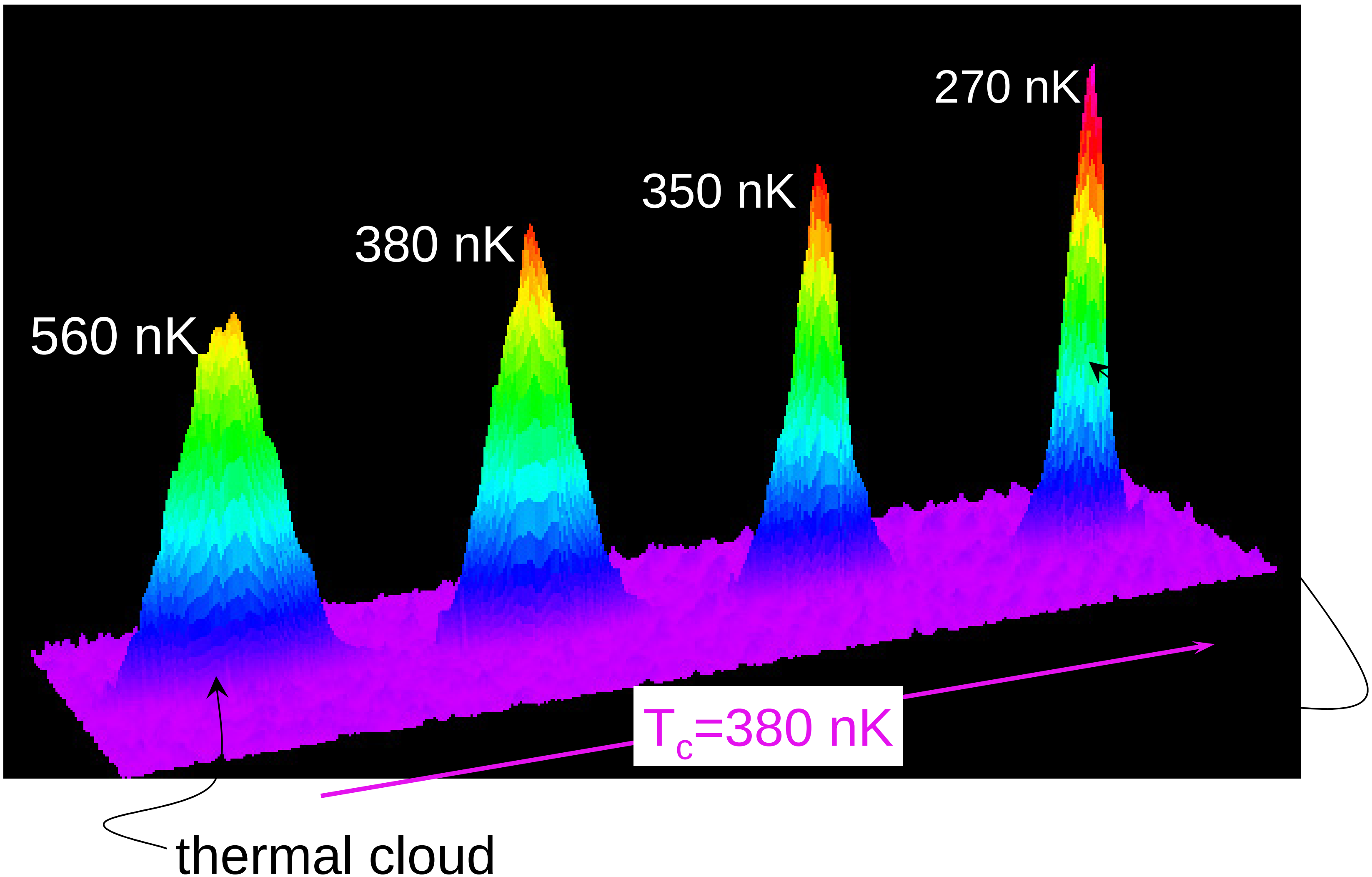


Switch off the axial trap …….

….matter wave propagates along magnetic guide

ATOM LASER

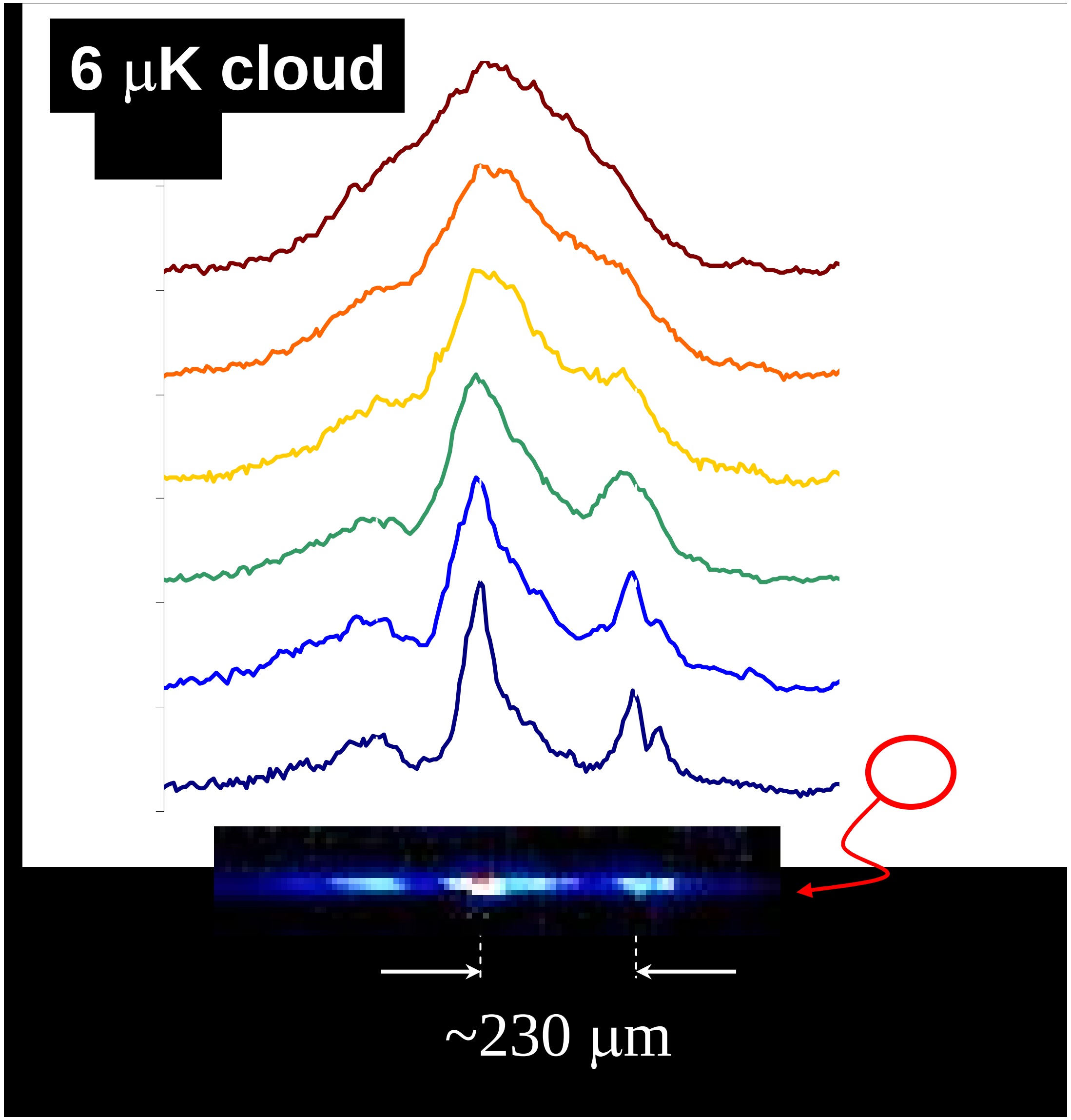
Below 380 nK the cloud Bose condenses



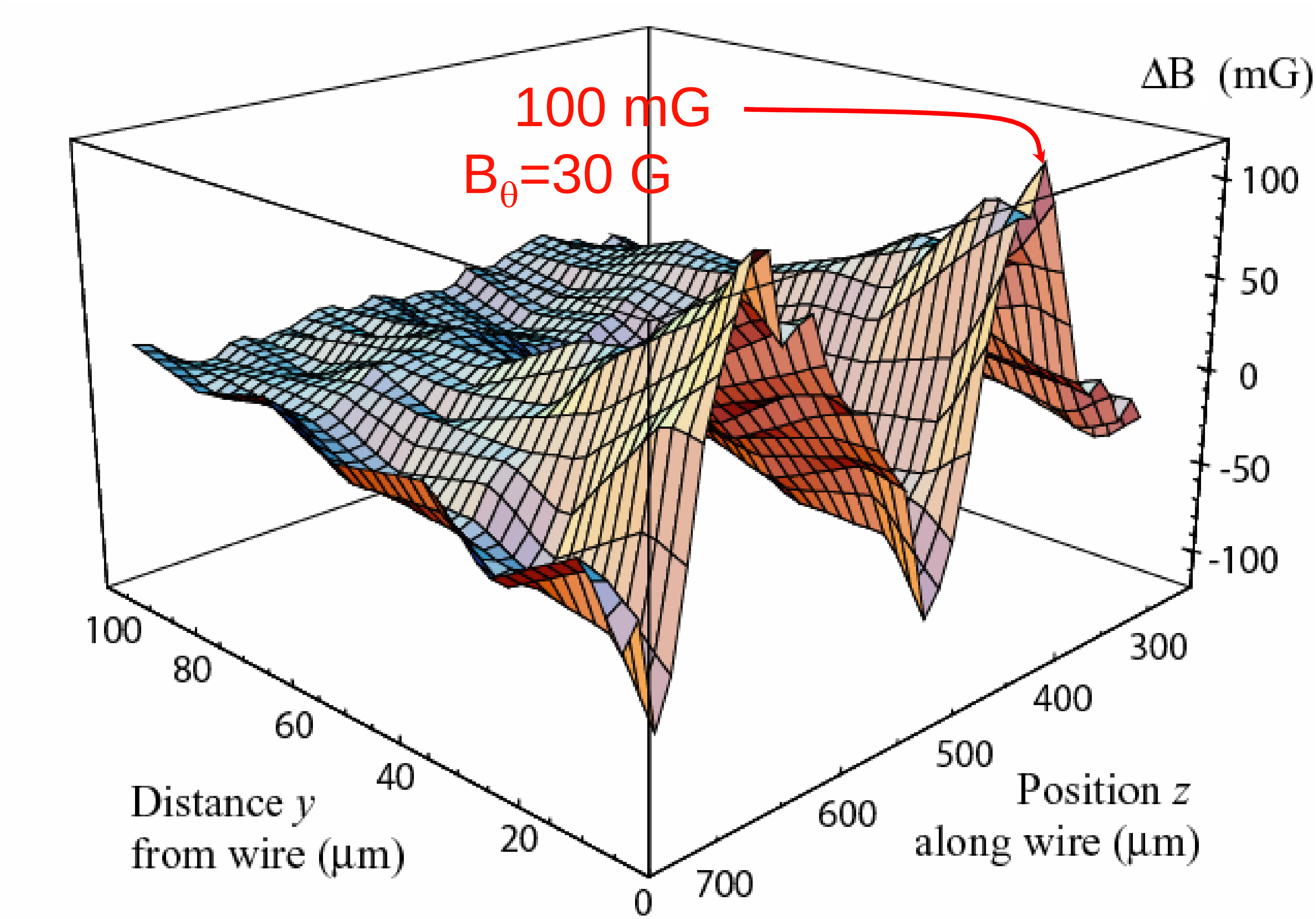
the interferometer should now be ready, however ….

. . . . the atoms interact with the wire

The cloud breaks up when lowered



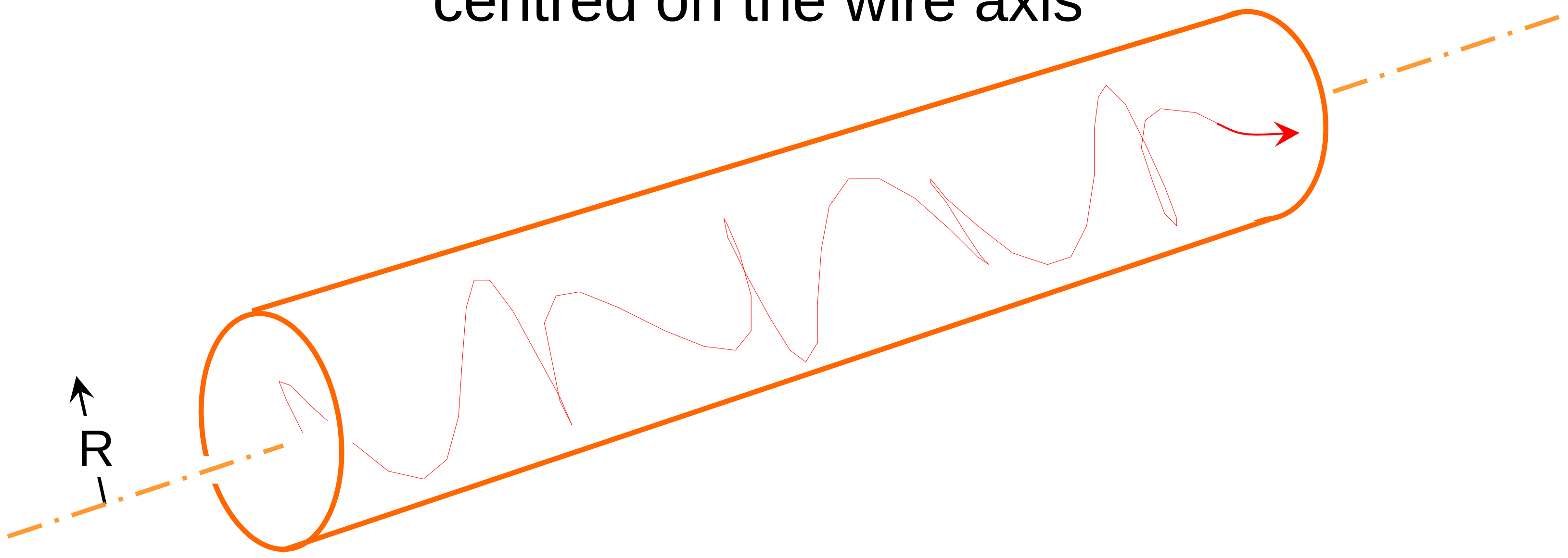
. . . . the lumps are due to ΔB_z - *along* the wire



. . . . this decays as $K_1(ky)$

Conclusions about ΔB_z

Produced by transverse current (or spin)
centred on the wire axis

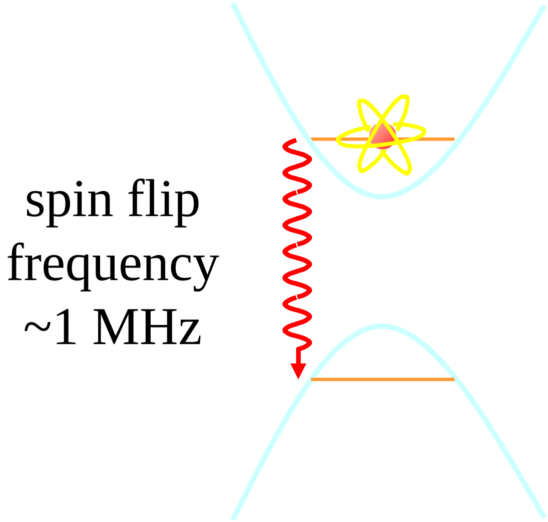


Amplitude ~R/2

But we still don't know why the transverse current ….

Jones et al. J. Phys B 37, L15 (2004)

Loss due to spin flips



First, in free space

At zero temperature

$$\Gamma_0 = \frac{\mu_0}{3\pi\hbar c^3}\,\omega_{if}^3 \left|\vec{\mu}_{if}\right|^2 \approx 5\times10^{-24}\ s^{-1}$$

At room temperature

photons / mode

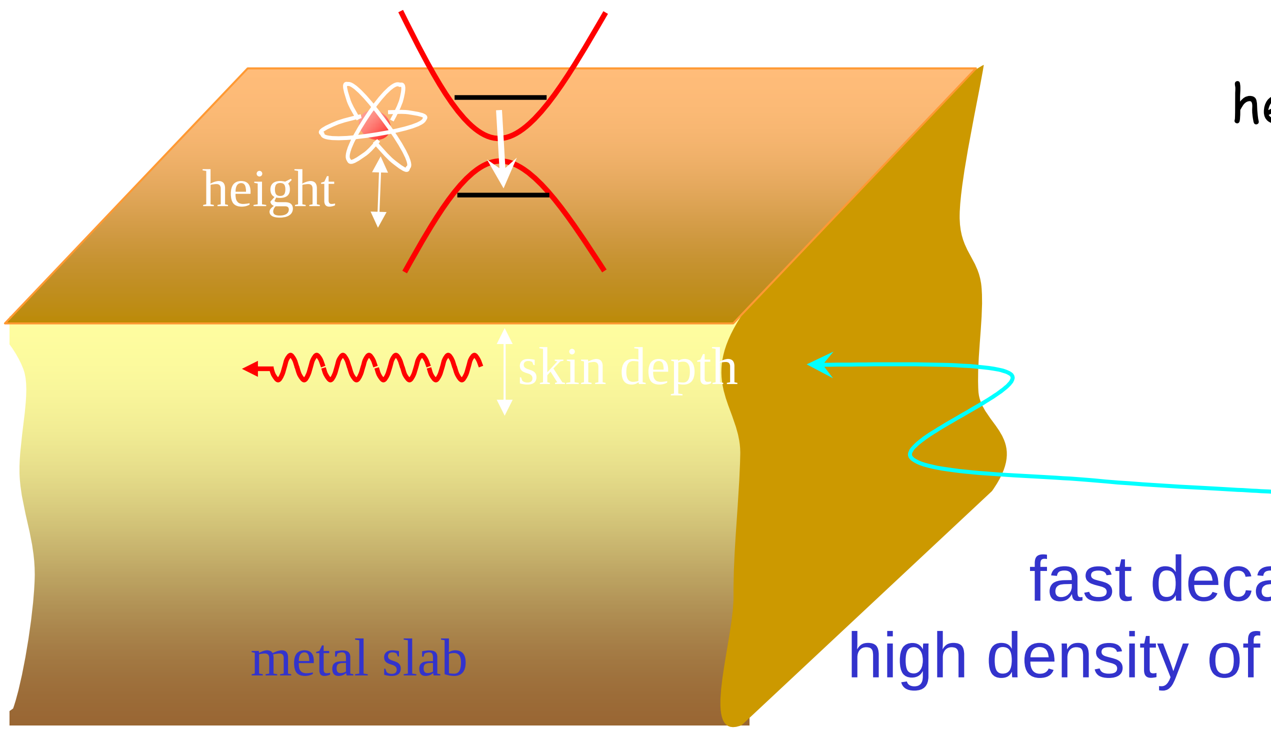
$$\times \frac{kT}{\hbar\,\omega_{if}} \approx 3\times10^{-18}\ s^{-1}$$

Now, near a surface

Johnson noise

Hugely increases the spin flip rate

resistivity of metal
↓
dissipation
↓
fluctuating field outside
↓
heating and spin flips

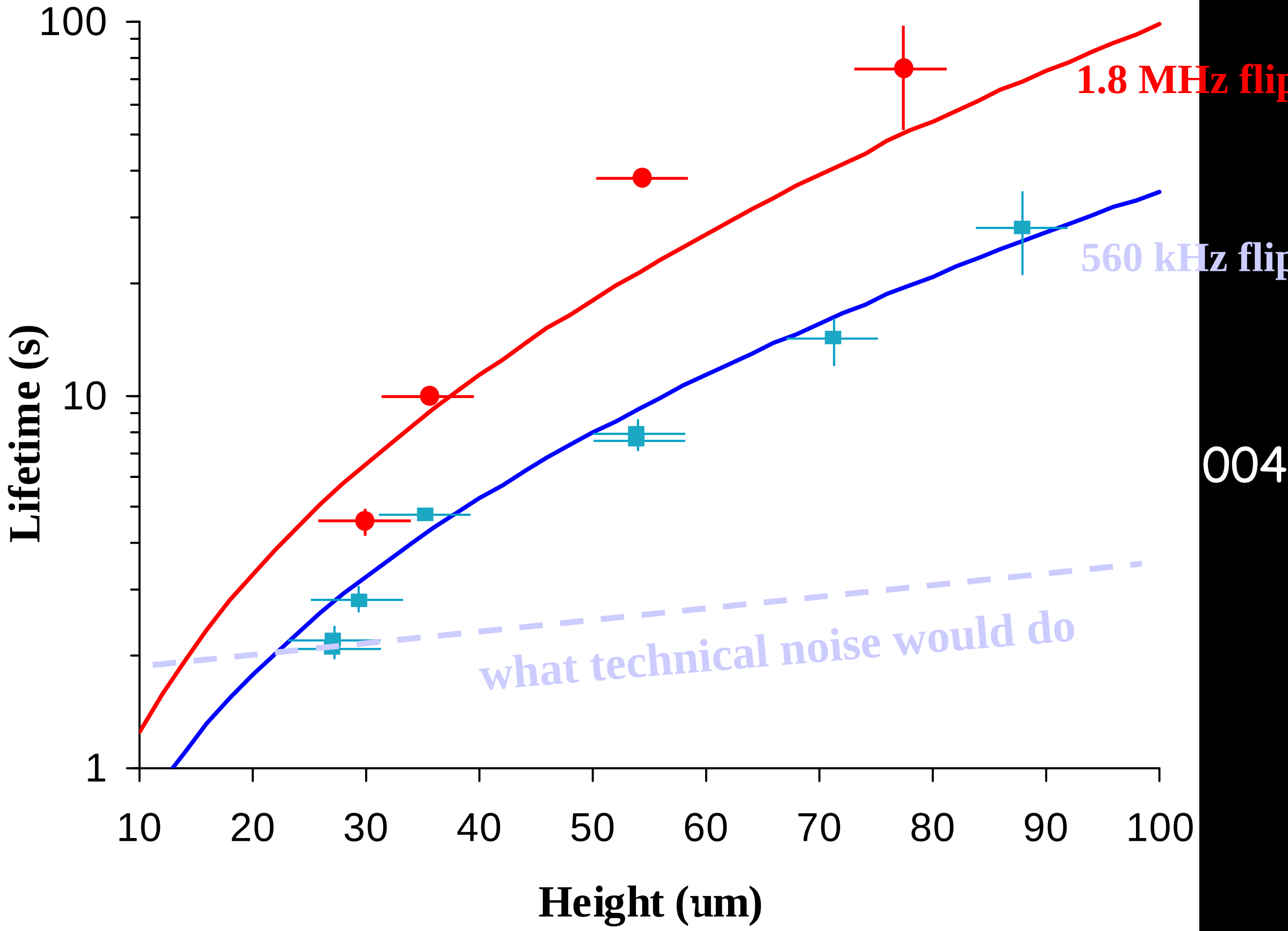


$$\Gamma \approx 1\,s^{-1}$$

fast decay due to
high density of surface modes

Henkel, Pötting and Wilkens Appl. Phys B 69,379 (1999)

Spin flip lifetime above metal wire

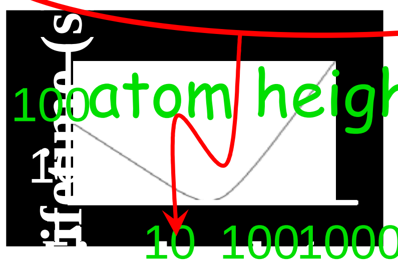


004)

Atom/surface impedance matching

perfect conductor ← → insulator

skin depth ~ atom height



atom height = 50 μm, say

And what material has ~ 50 μm skin depth?

gold, aluminium, copper,...

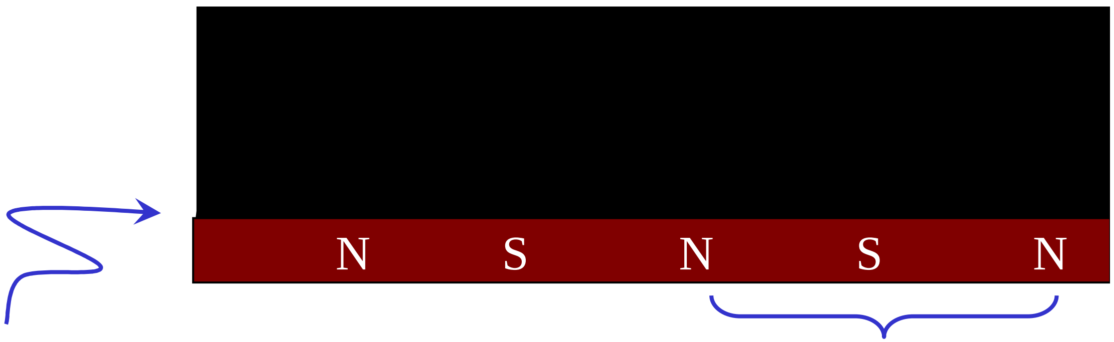
Ways to improve the traps near a surface:

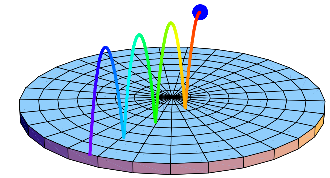
(i) Keep the metal thin

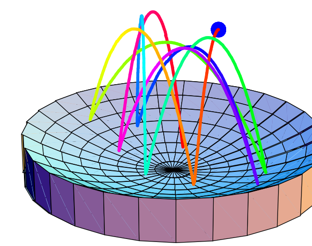
(ii) Use insulating surface

the subject of part II

• Videotape atom chip



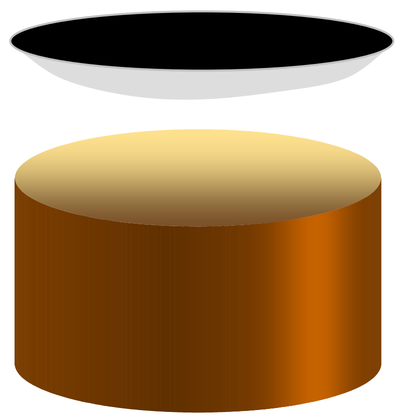




• ~500 G at surface• Period ~10 μm

Lens to make curvature

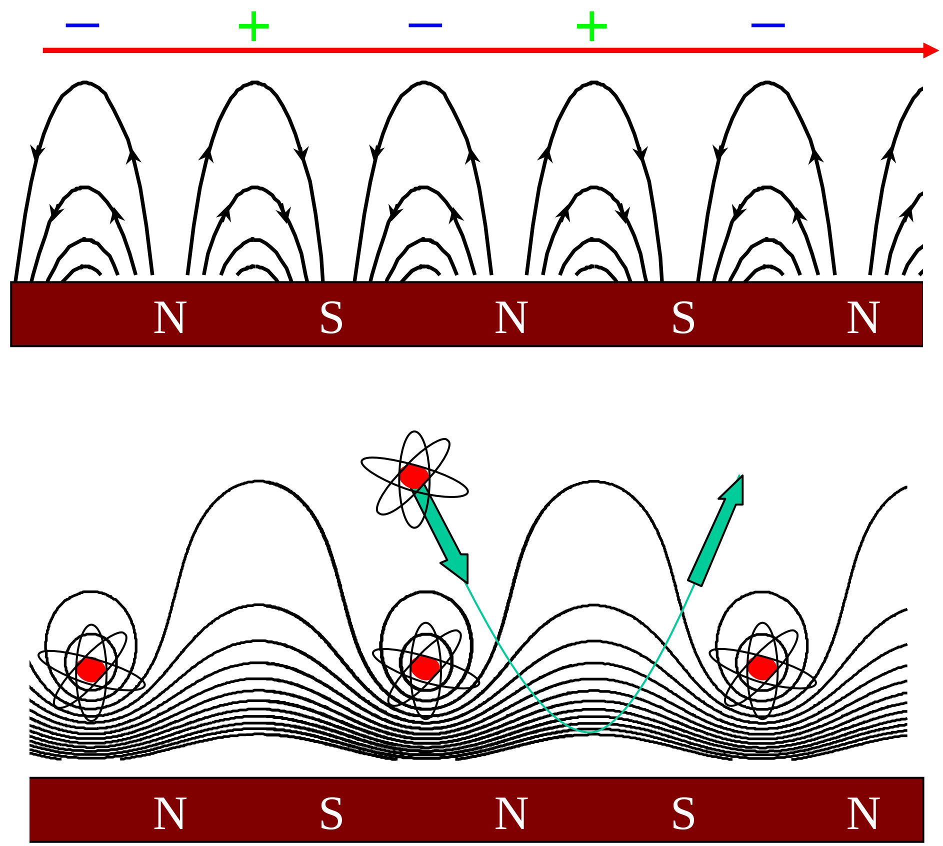
Video tape glued to ring



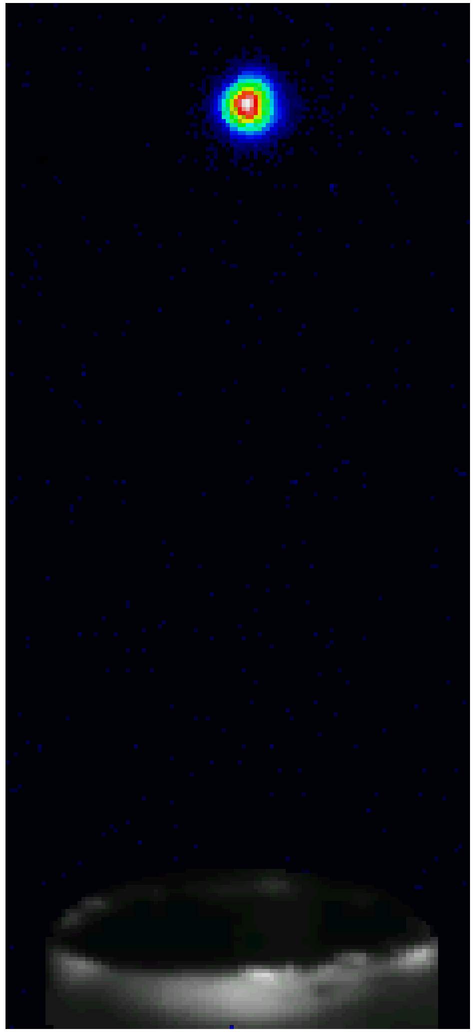
Sinusoidally magnetised videotape makes an atom mirror

An extra, constant field corrugates the mirror

and makes an array of atom guides



Bouncing atoms on the chip

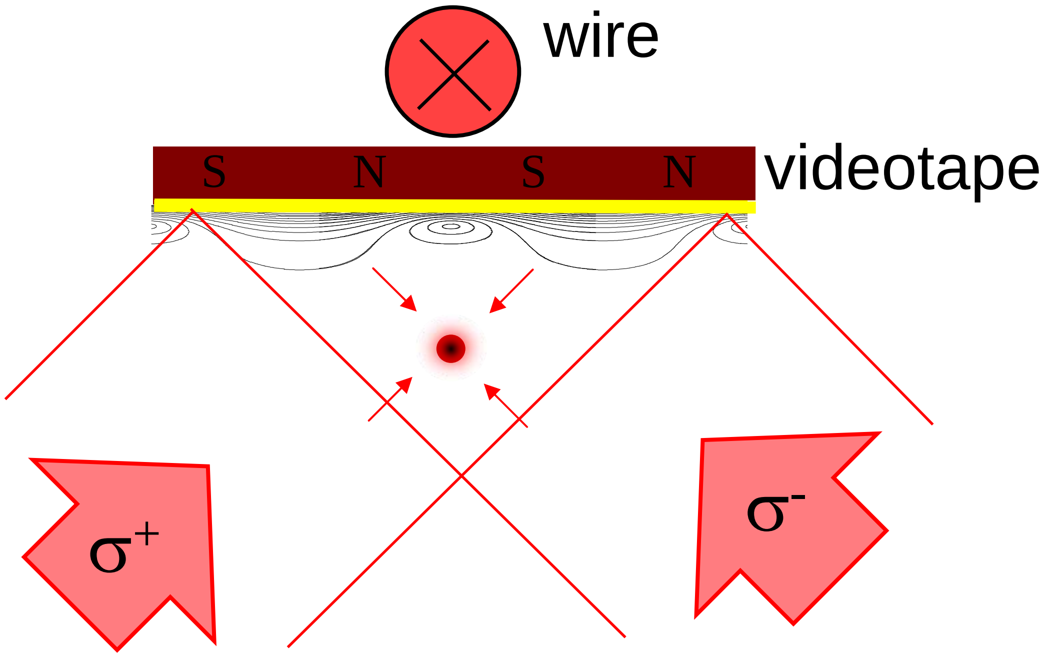


smooth reflector
(bias field = 0)

corrugated reflector
(bias turned on)

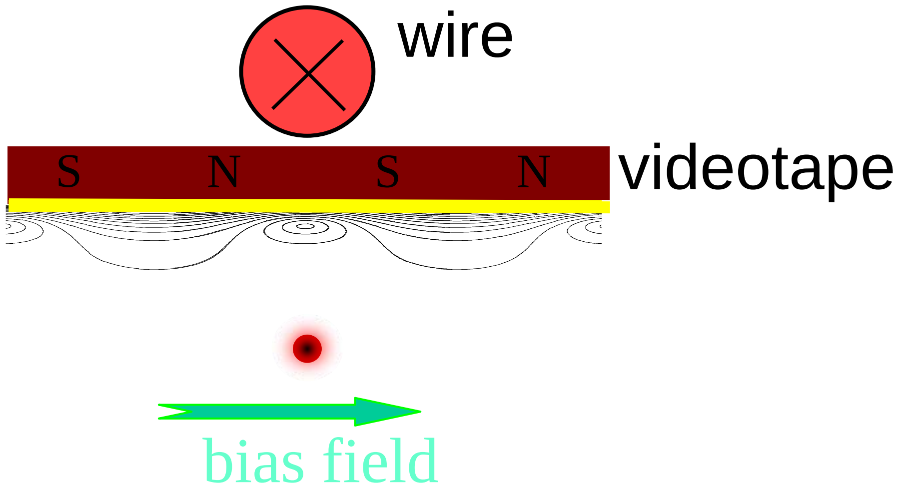
PRA 61 R31404 (2000) with Peter Rosenbusch, Brenton Hall, Ifan Hughes and Carlos Saba

Loading a videotape microtrap



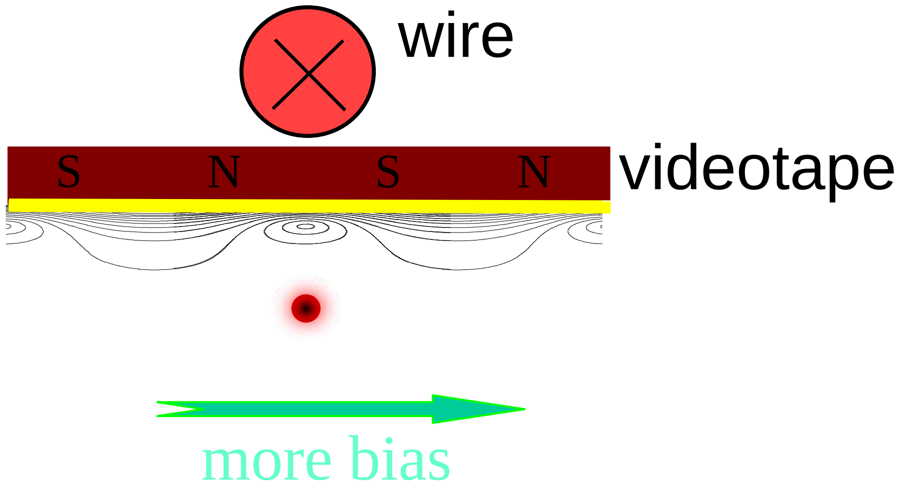
collect atoms in mirror MOT

Loading a videotape microtrap

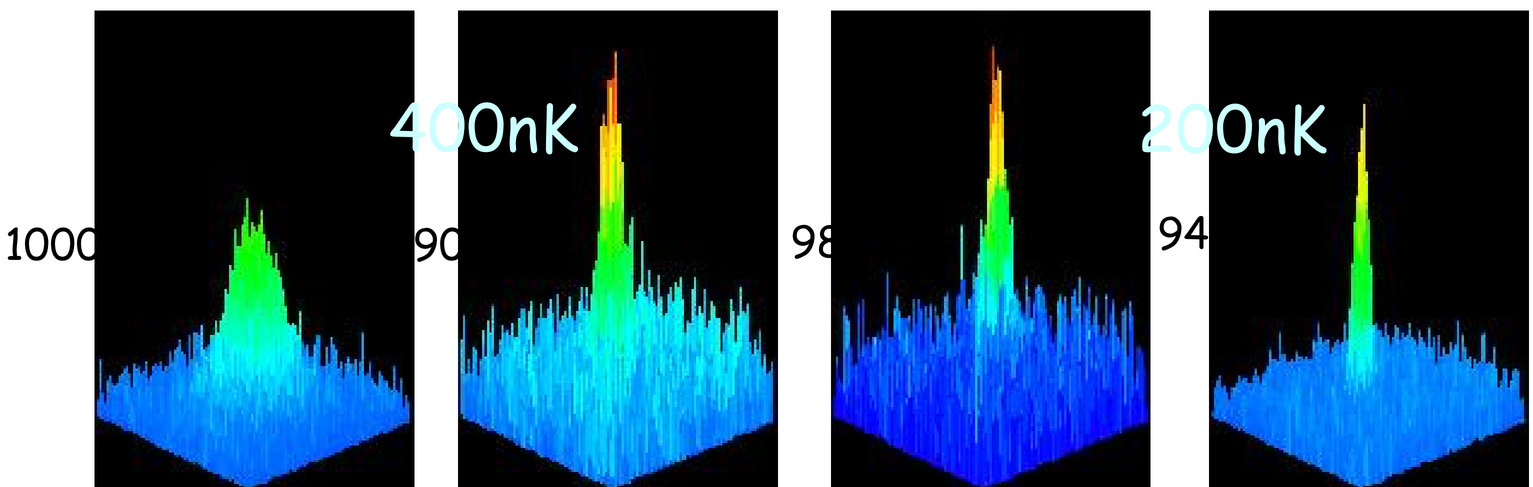


transfer to wire trap

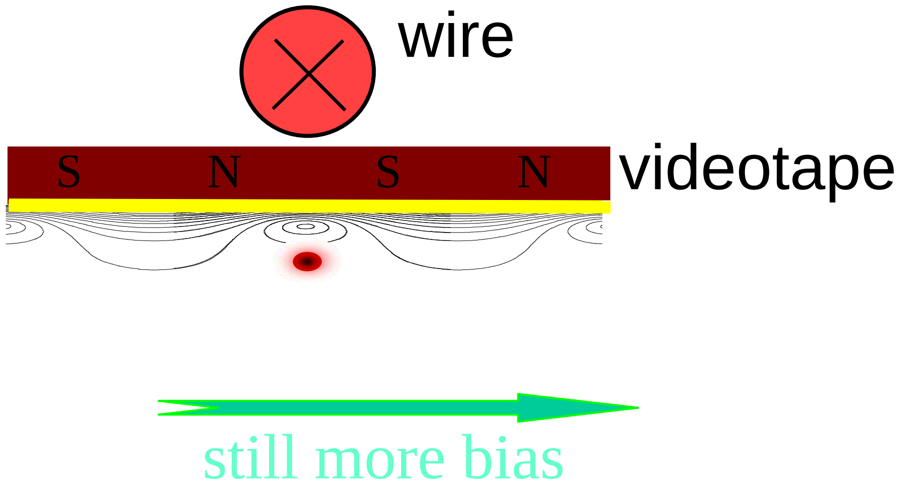
Loading a videotape microtrap



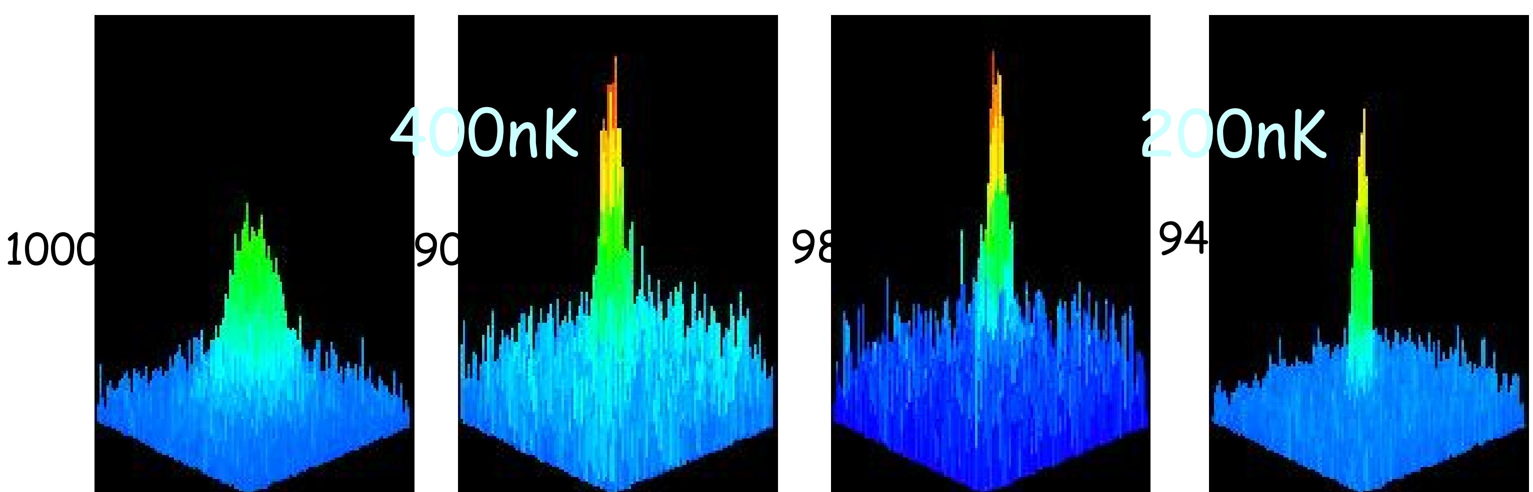
Evaporate to make BEC



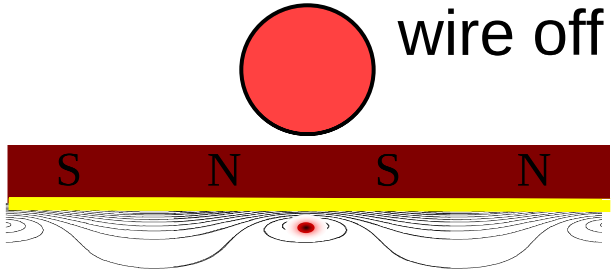
Loading a videotape microtrap



Evaporate to make BEC



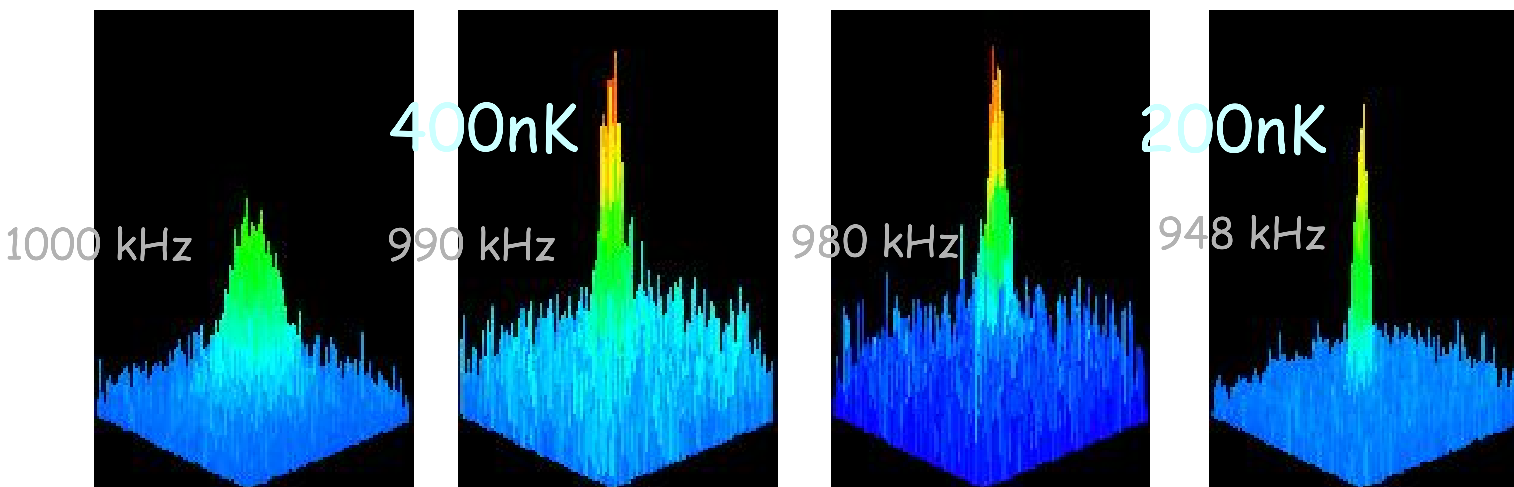
Loading a videotape microtrap



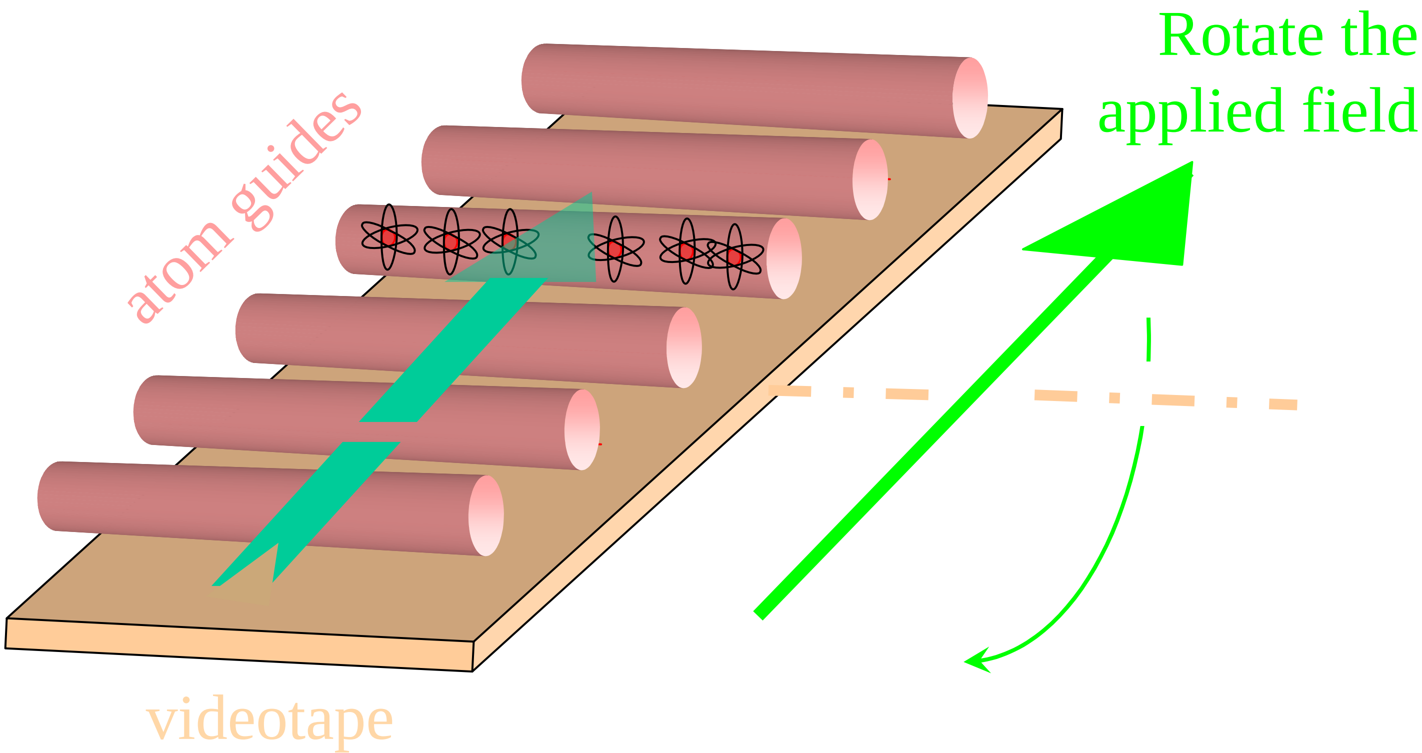
keep bias

atoms now in microtrap

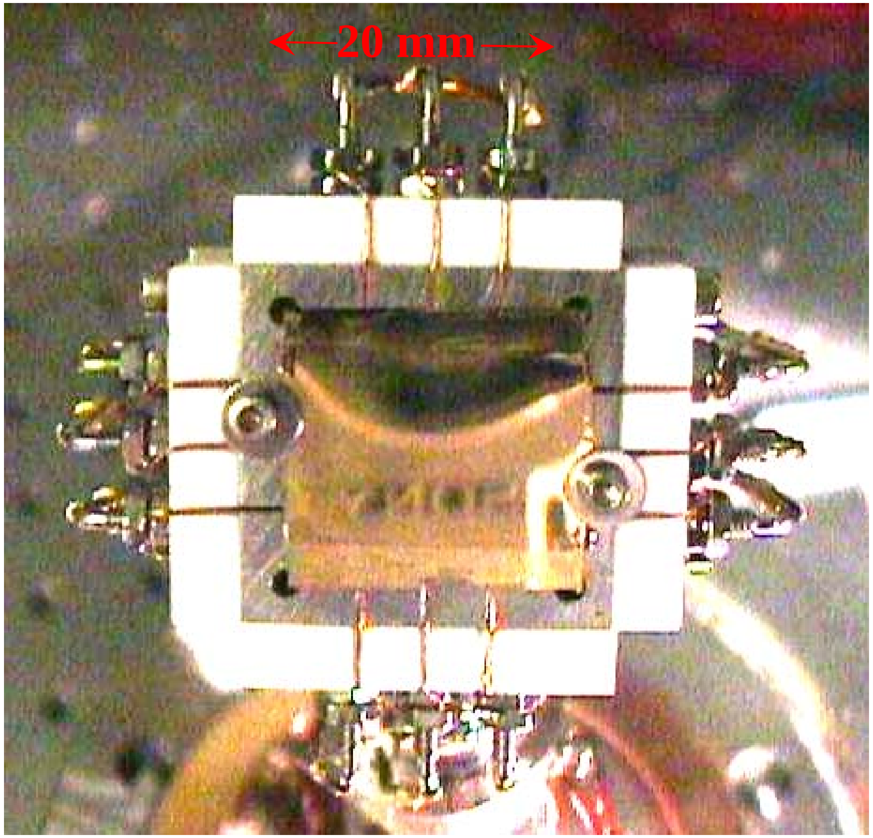
Evaporate to make BEC



Videotape atom transporter

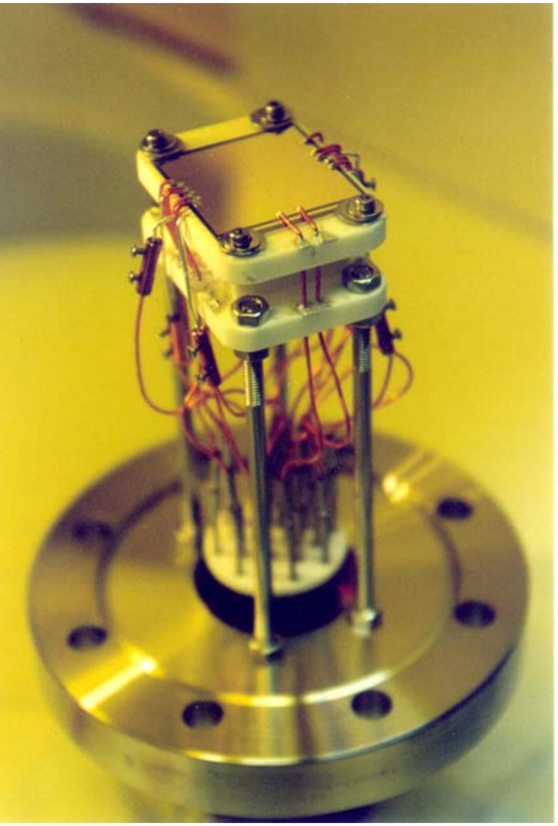


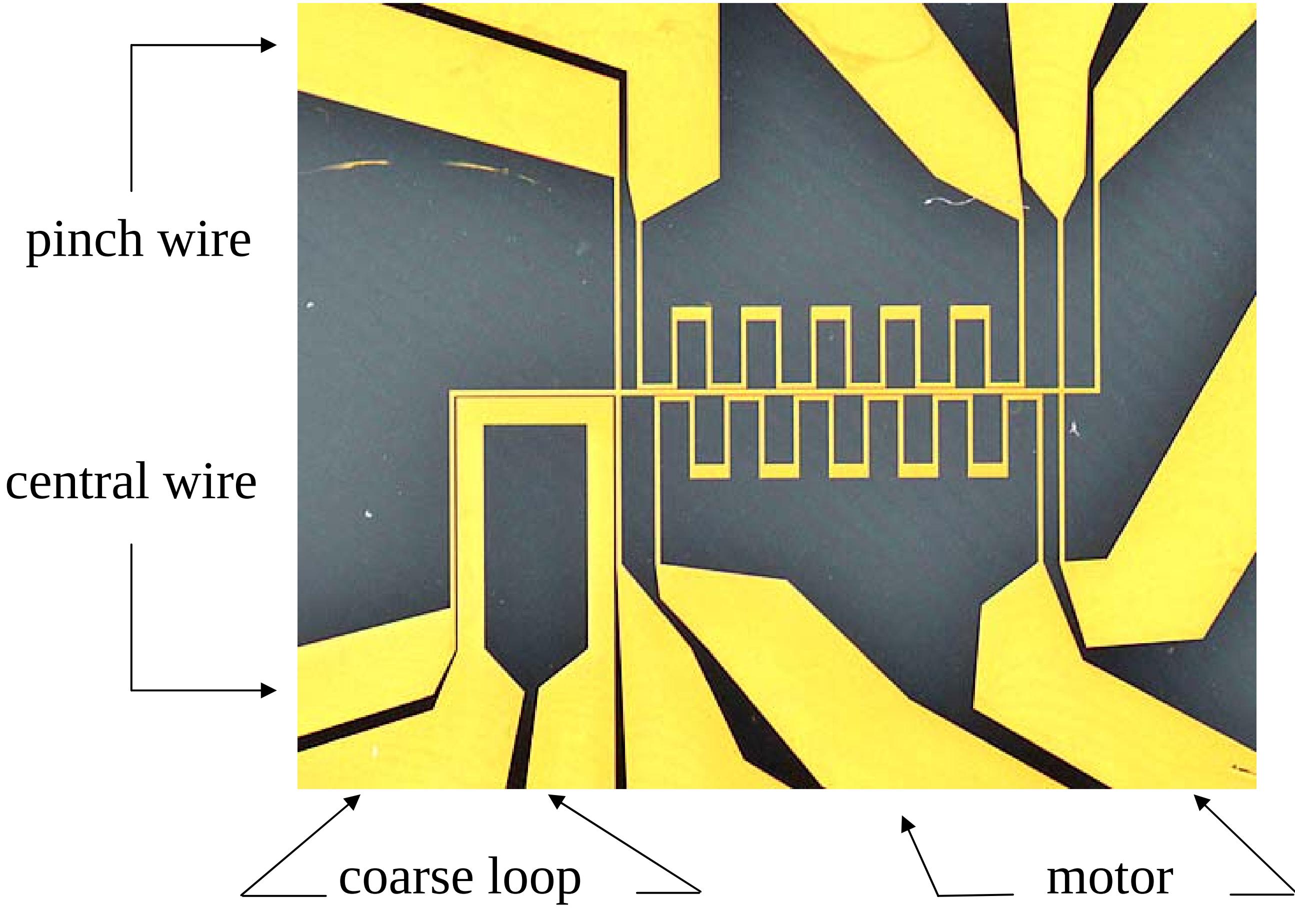
This videotape chip has a 250 guides on it



We are transporting cold atoms around above it …..

Other atom circuits on a chip

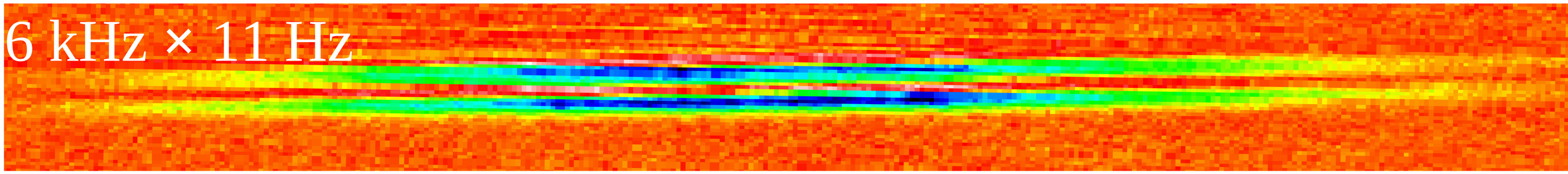




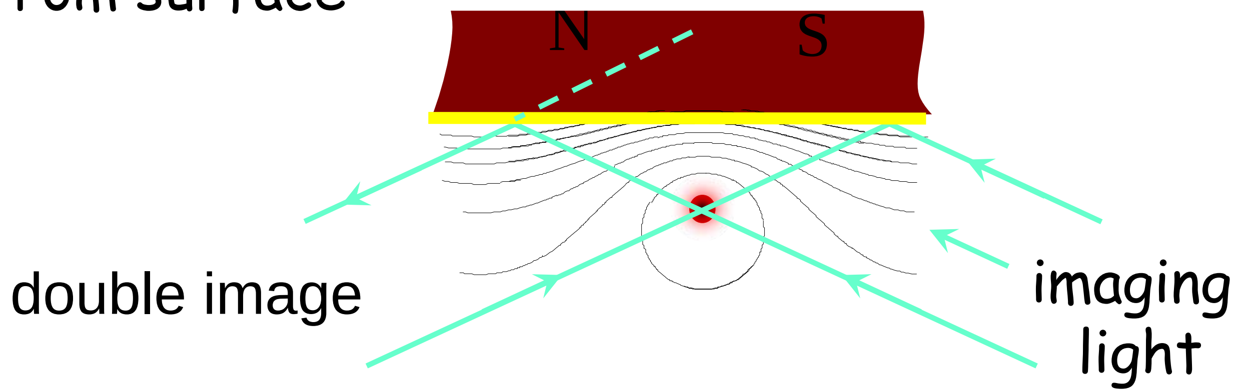
courtesy of
Schmiedmayer *et al.* Heidelberg

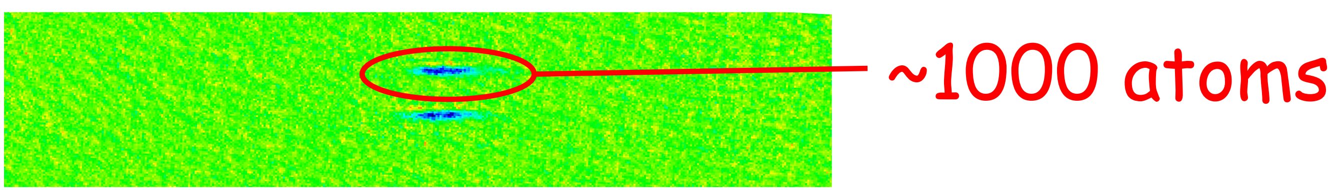
courtesy of
Reichel *et al.* Munich

Imaging in the videotape trap



10 μK cloud, 45 μm from surface



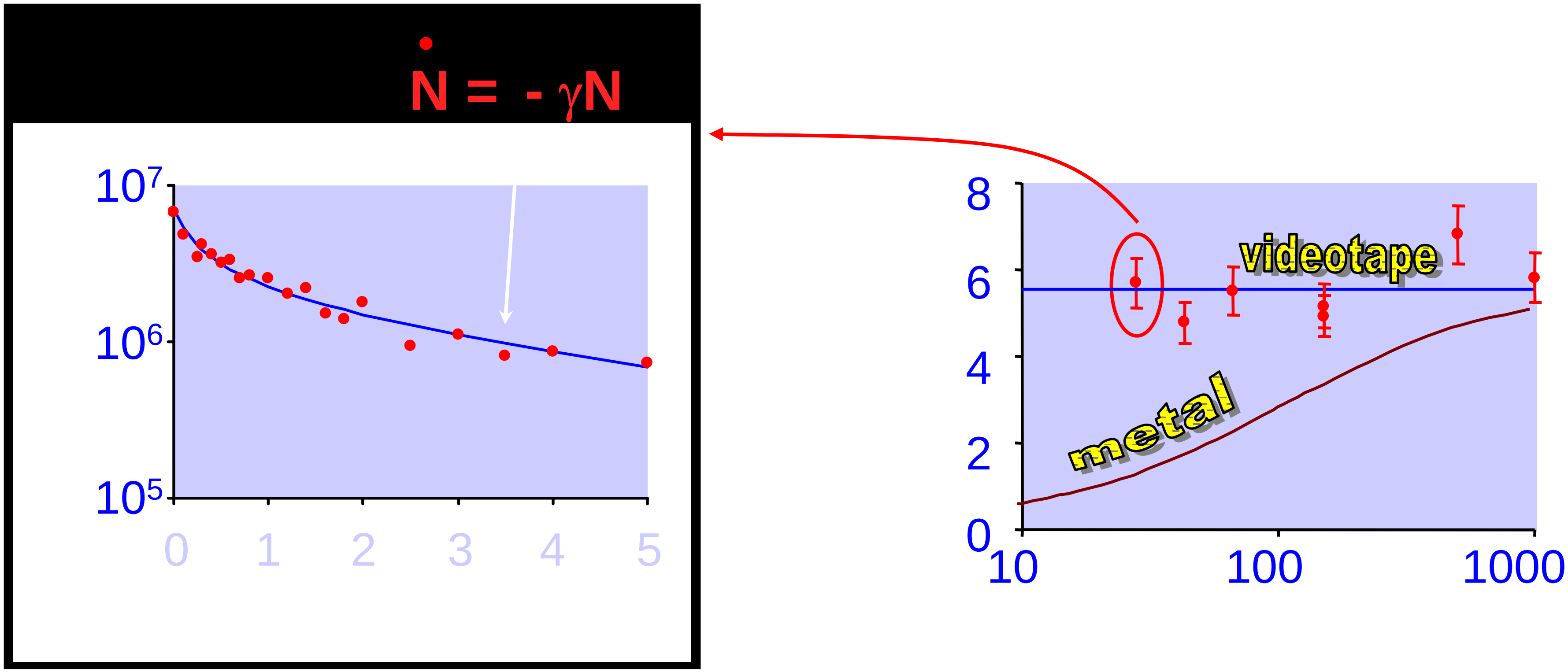


200 nK cloud, 45 μm from surface

Videotape trap has no lumps (well < 50 nK at 45 μm)

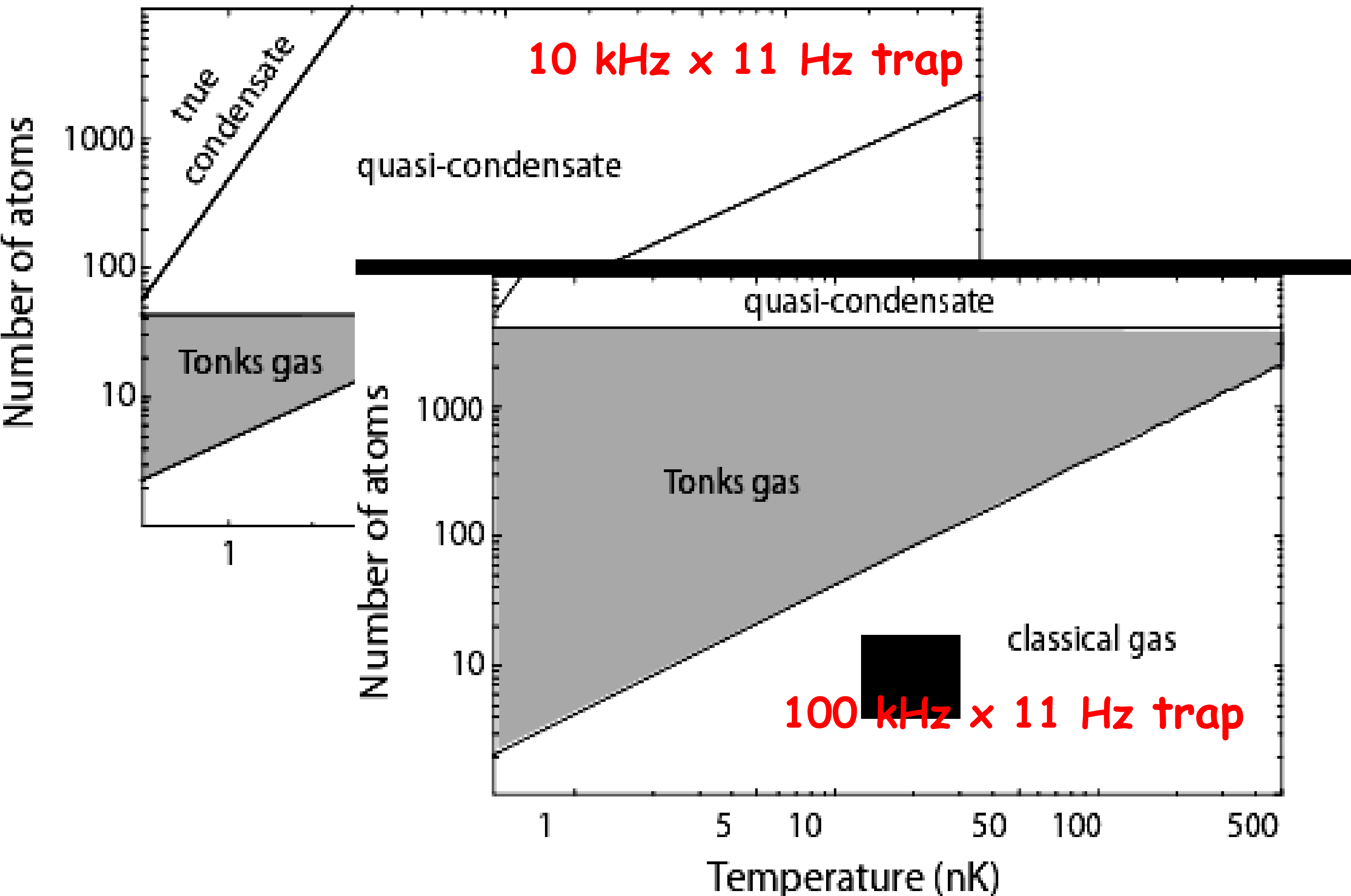
Videotape also gives low spin-flip loss

$h = 28\mu m, \quad \omega_r = 2\pi \times 31$ kHz



Much lower spin flip loss due to surface

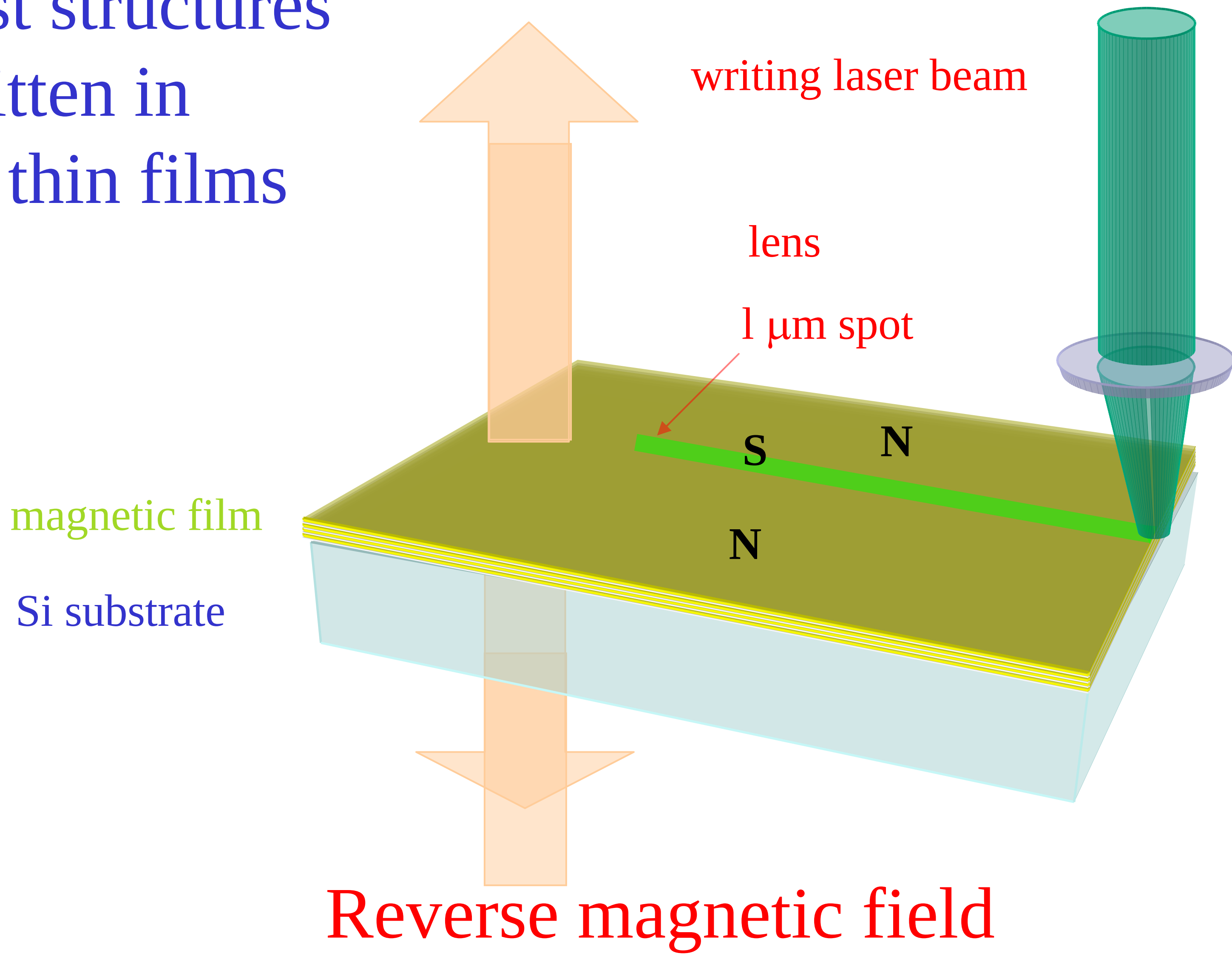
Physics of long, thin clouds



• Yet smaller structures

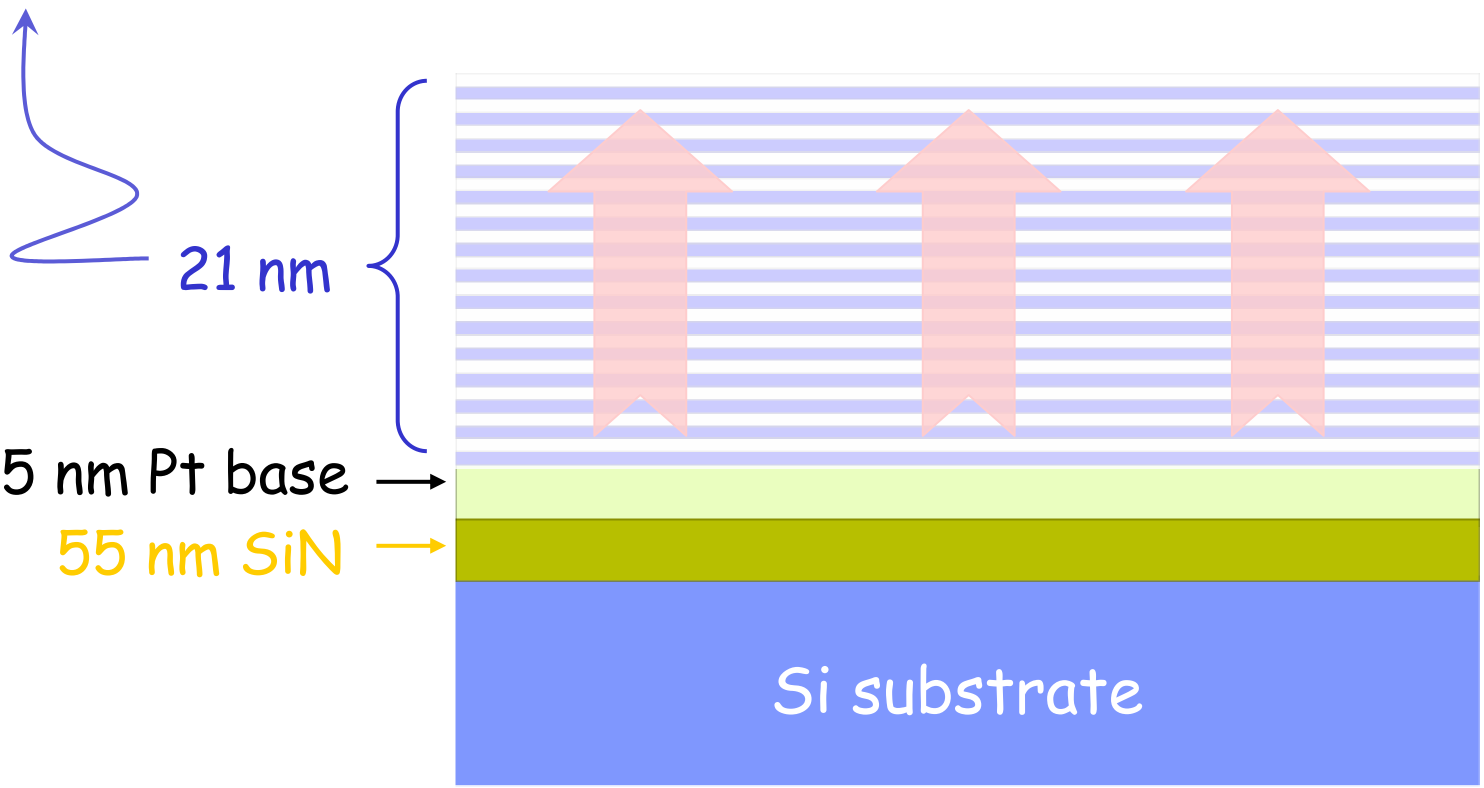
(towards QIP)

Our smallest structures are written in magnetic thin films



structure of the magnetic film

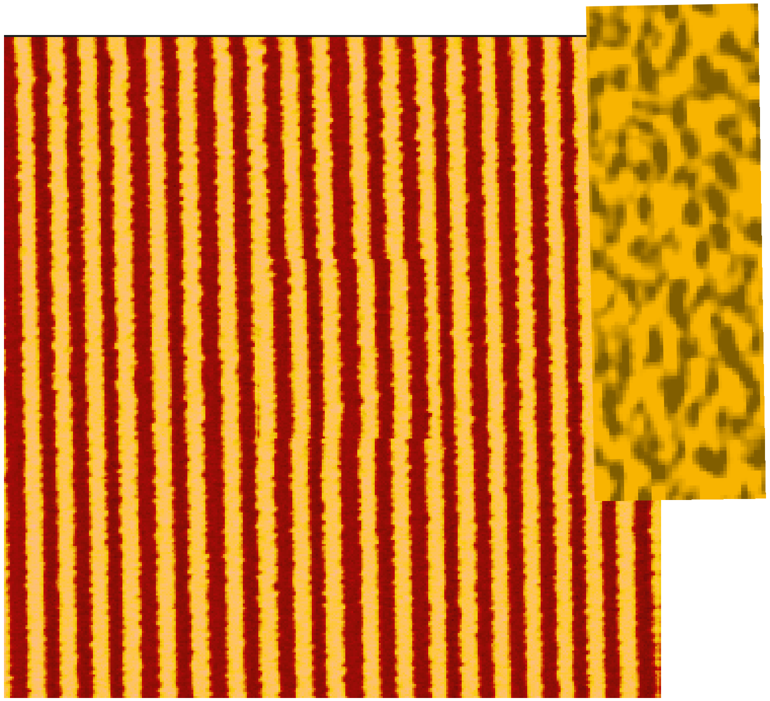
15 bilayers of cobalt (0.4 nm) and platinum (1.0 nm)



This structure has
Strong perpendicular remanence & high coercivity

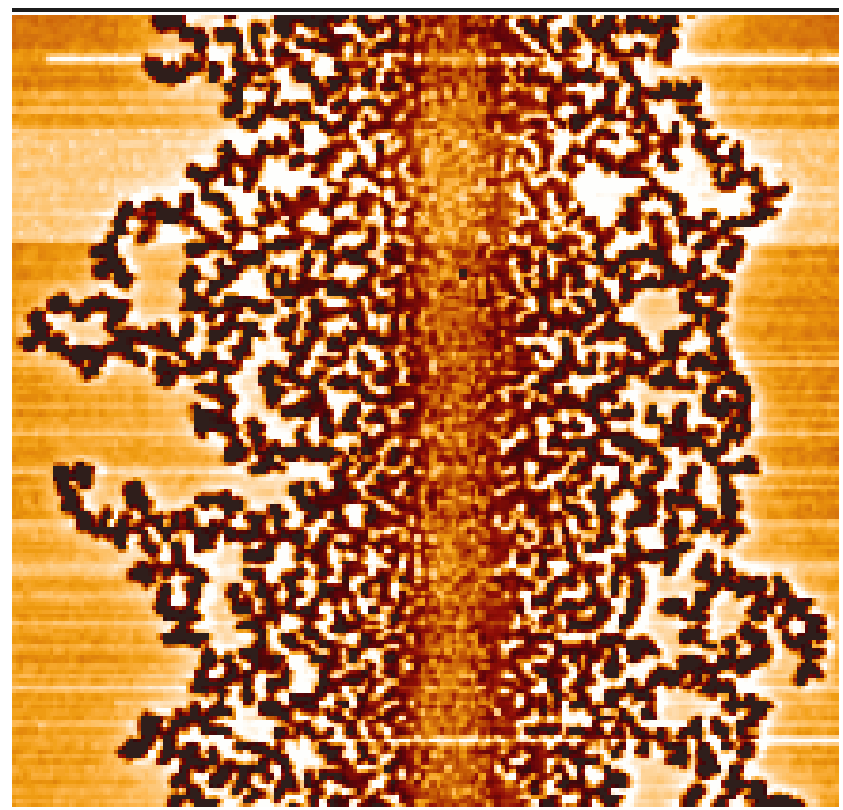
an array of lines written in M-O film

MFM Image



The period is 2 μm

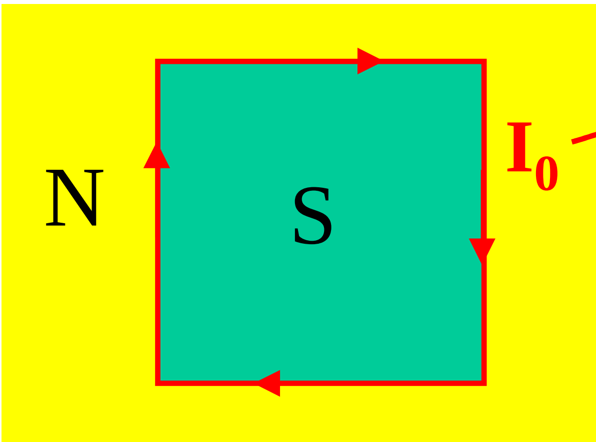
Demagnetised film shows natural domain size: typically 250 nm



too much laser power

Microscopic circuits

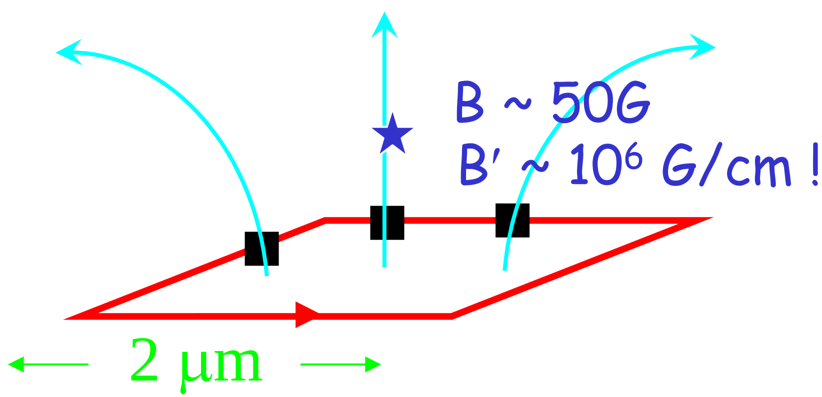
The boundary of a magnetised region carries equivalent current $\mathbf{I_0}$



$2\,M_0\,t$ → ~ 22 mA in our films

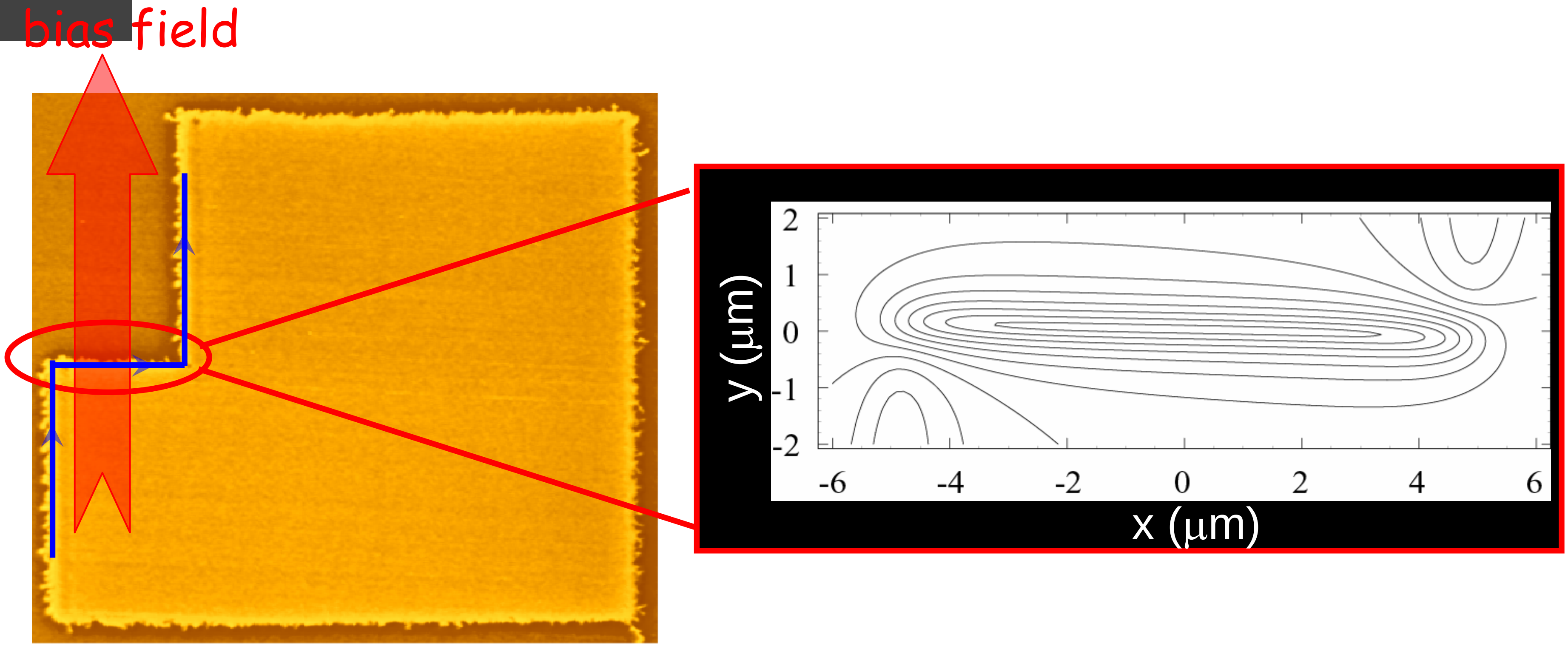
magnetisation

thickness



We can write any arbitrary pattern of 22 mA current loops, including large arrays of traps and guides

e.g here is a z-trap we have made on M-O film



radial trap frequency f = 1 MHz at 1 μm height

cond-matt 0406482 (2004)

• Atom chips for quantum logic?

SOME REQUIREMENTS

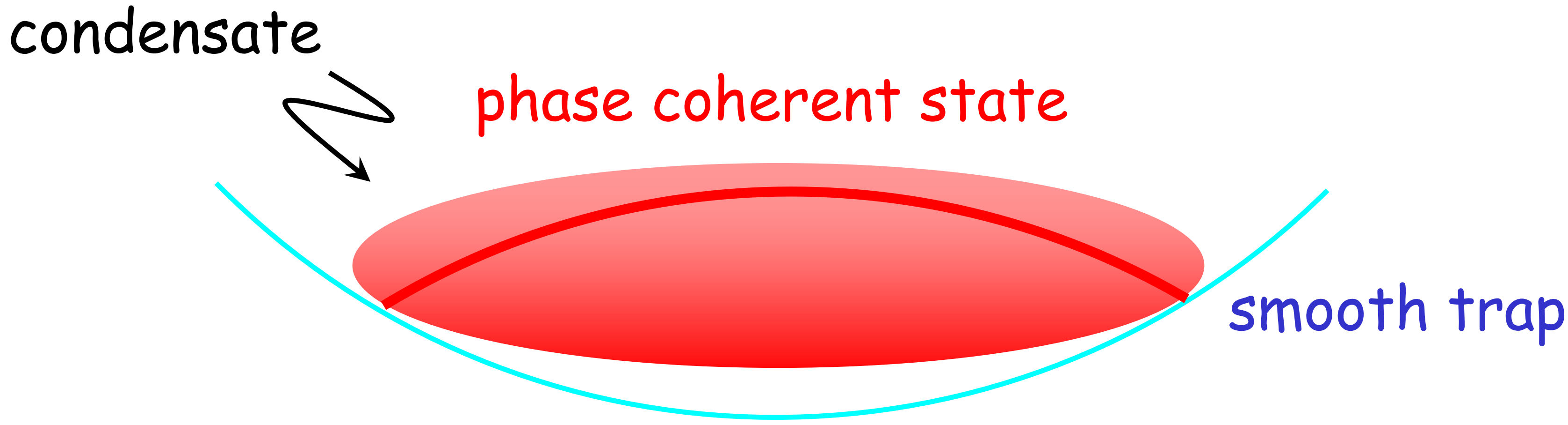
1. many gates ✓

2. single atom preparation and readout ✓ ?

3. controlled entanglement of 2 qubits ?

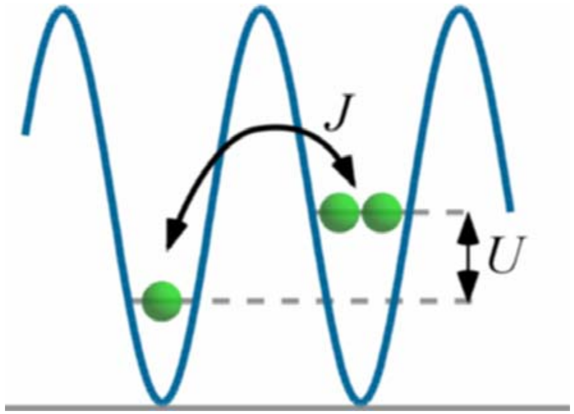
Single atom preparation

Take a condensate in a smooth trap



Gradually corrugate the trap

this phase transition is driven by quantum fluctuations



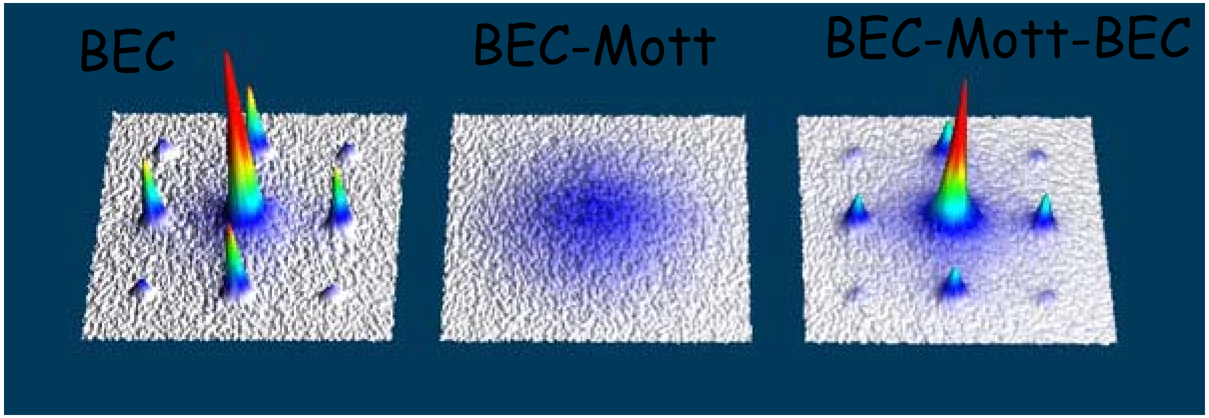
Bose-Hubbard model

$$H = -J\sum_{\langle i,j\rangle} \hat{a}_i^\dagger \hat{a}_j + \frac{1}{2}U\sum_i \hat{n}_i(\hat{n}_i - 1) + \sum_i \varepsilon_i \hat{n}_i$$

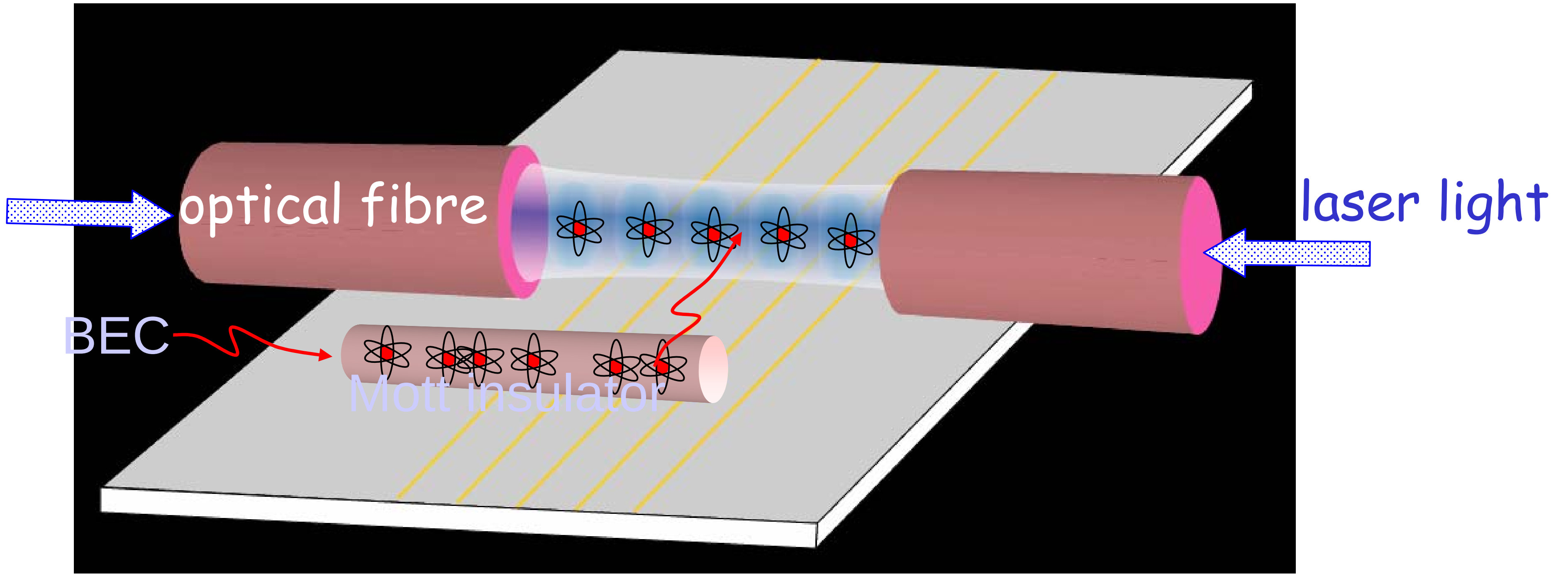
it has been made in the lab using a 3D lattice of light

.......here are the patterns made by the matter waves scattering from the lattice:

courtesy of I. Bloch *et al.* Munich



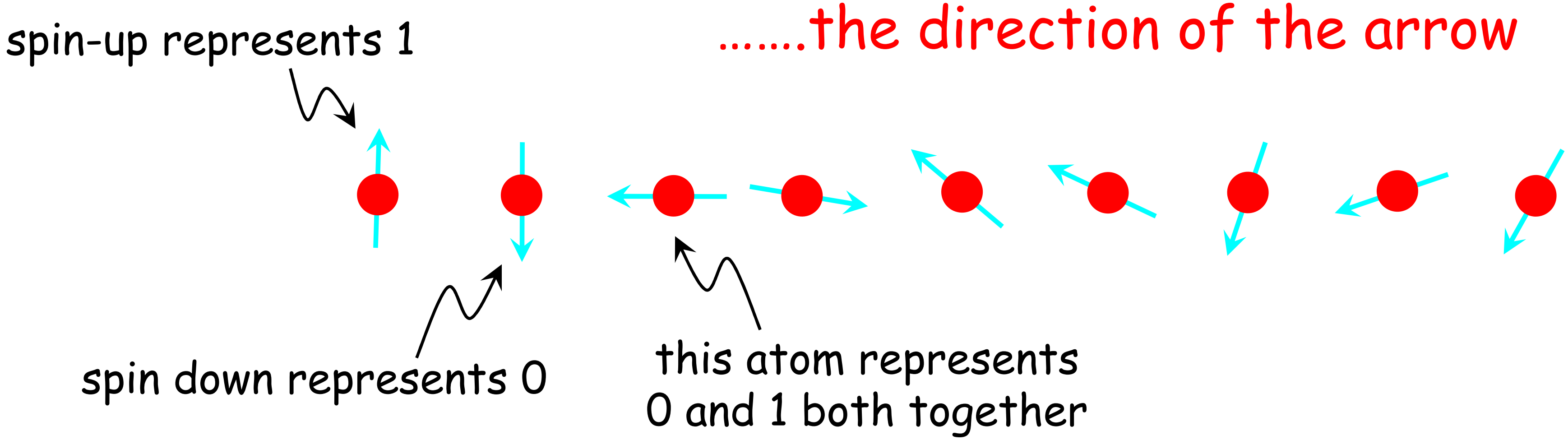
...........we will do it on a videotape chip



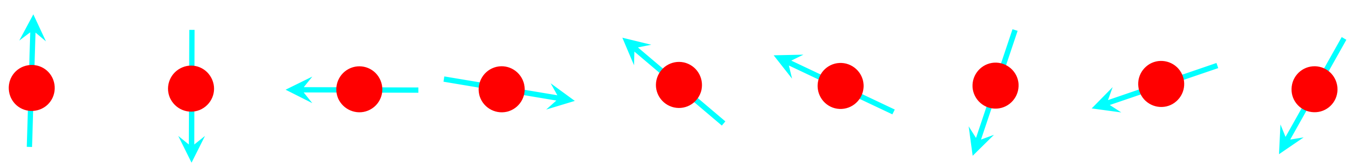
The atom string can be a quantum information register

each atom stores a bit of quantum information

.......the direction of the arrow

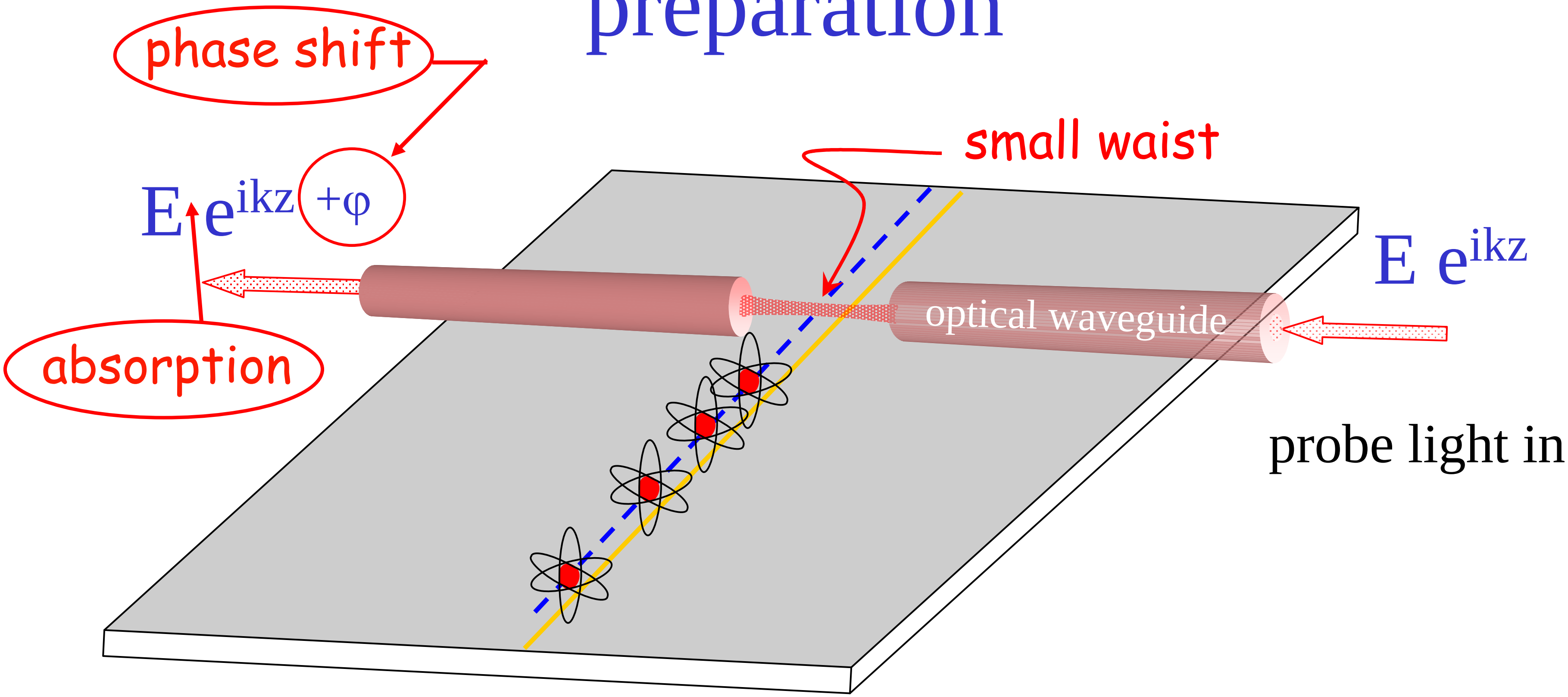


controlled collisions can do calculations



.......this leaves each atom entangled with its neighbour

Single atom detection and preparation

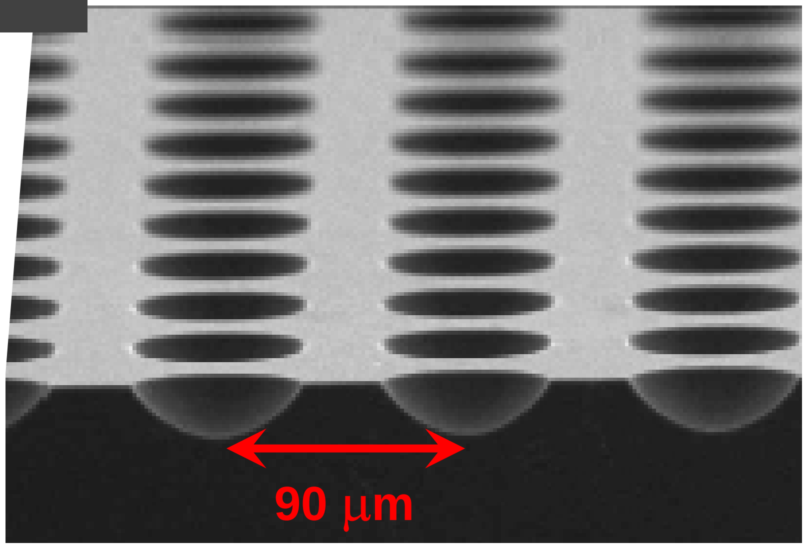


With 1μm waist, 5-10 atoms can be seen in a single-pass

But single atom sensitivity will need a cavity

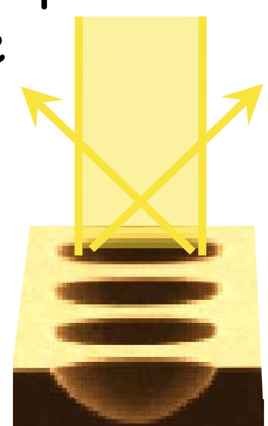
Horak et al. Phys. Rev. **A 67**, 043806 (2003)

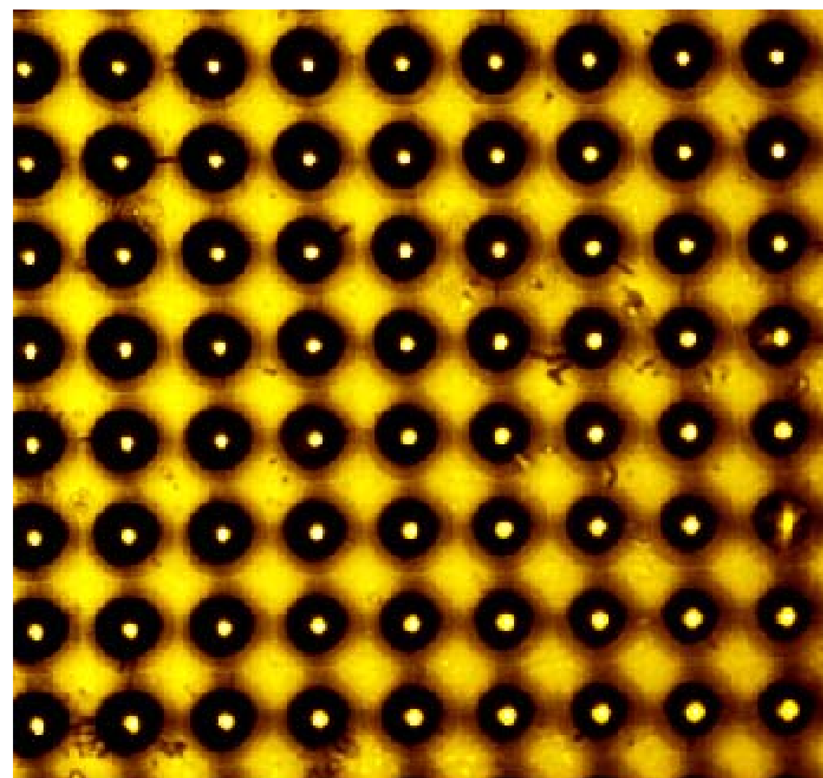
[redacted]rds single atom sensitivity on a chip:



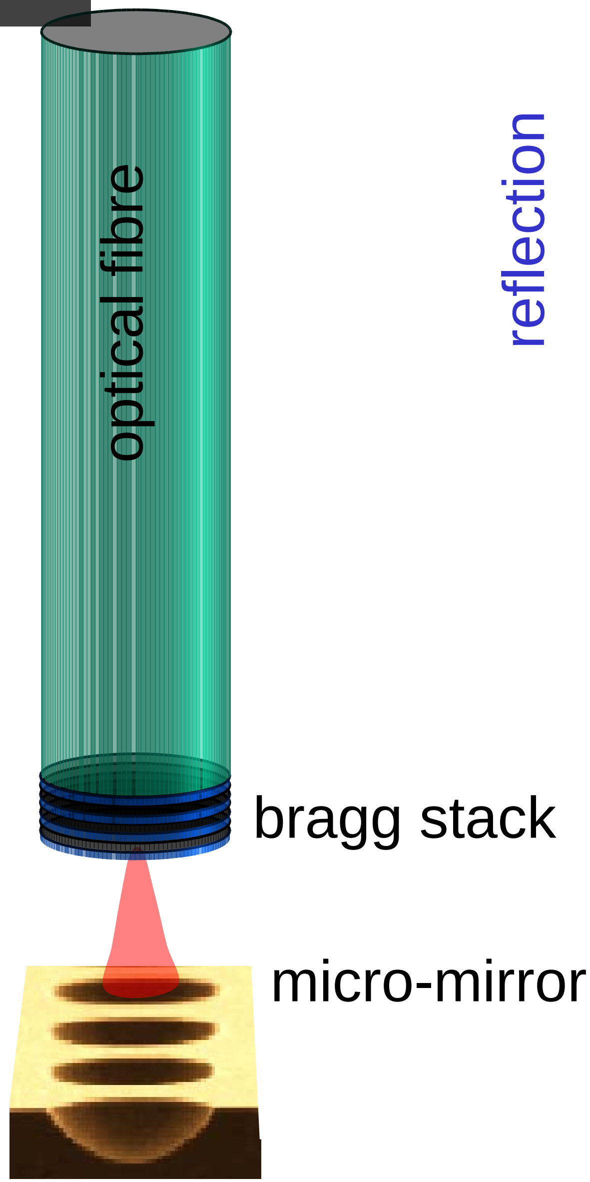
concave mirrors
etched in silicon

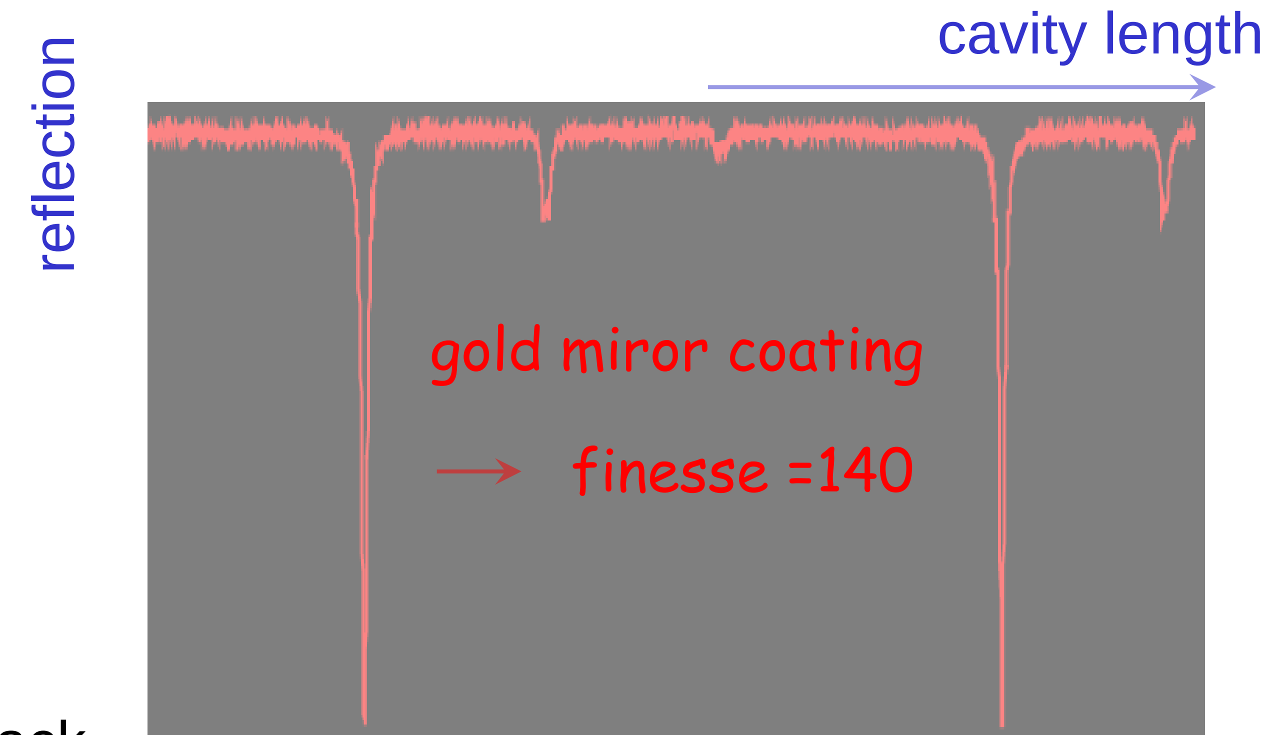
after coating with gold,
we see focal spots under
a microscope





……these mirrors form optical microcavities

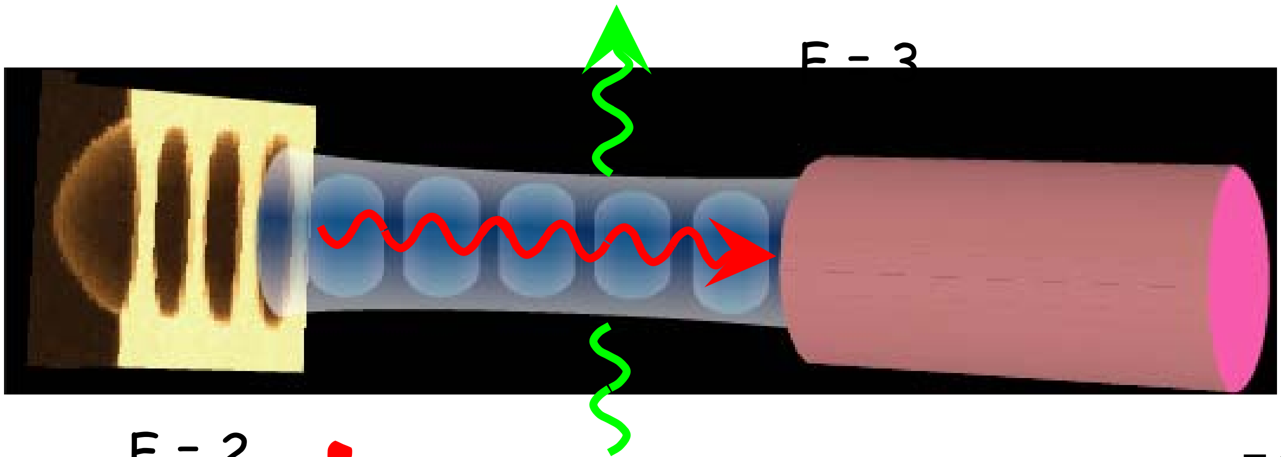




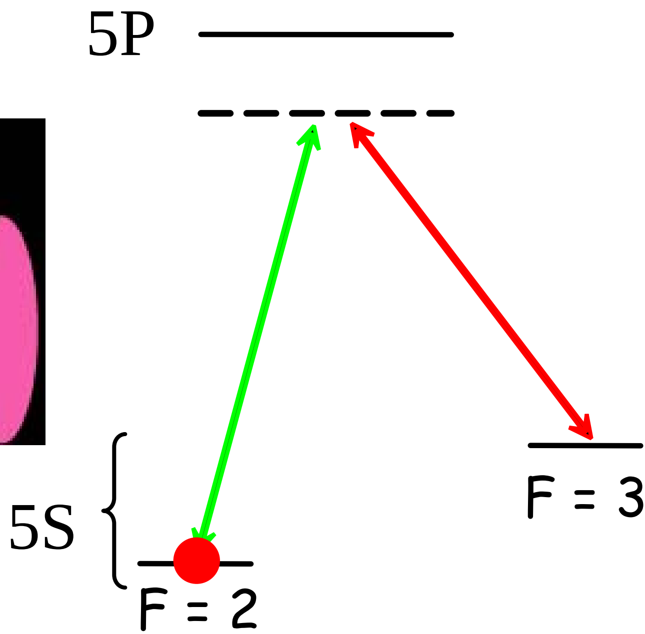
easily detects 1 atom

with dielectric coating we expect to reach cavity QED strong coupling regime

e.g. photon pistol



F = 2



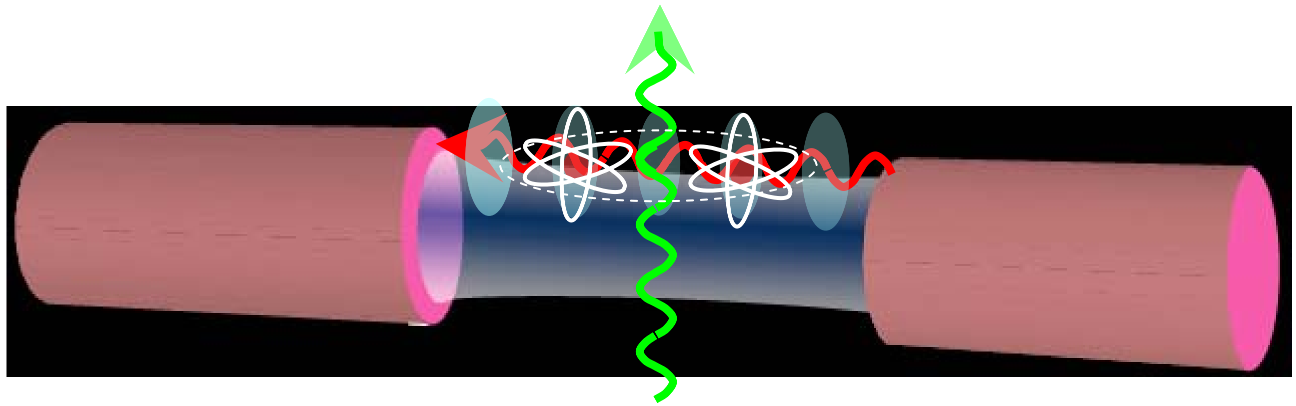
this idea leads to

Coherent exchange of quantum information between atom and photon

optical interface to atom quantum memory

[redacted]..2 atoms in optical microcavity

an alternative quantum logic gate



atoms can be entangled through a shared cavity photon

Summary

The present

- We can make circuits of quantum gas floating above wires and permanent magnets on atom chips

Microscopic atom waveguides, motors, interferometers etc. are starting to make spectacular new instruments

The future

- It will soon be possible to prepare atom arrays on chips.
- Single atoms will be moved in controlled ways.
- They will be coupled to each other and to light cavities.

Quantum computing with neutral atoms will take a bit longer.

Many colleagues, postdocs and students have worked on these experiments

I thank them all

particular thanks go to

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£ { EPSRC, PPARC, Royal Society }