Bath 2004 - POWAG

Ben Gurion University of the Negev

Photonics: the new addition to the *atom chip*

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www.bgu.ac.il/atomchip
www.bgu.ac.il/nanocenter

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Ben Gurion University

The desert….

Archeology, monasteries, geology, 3 seas

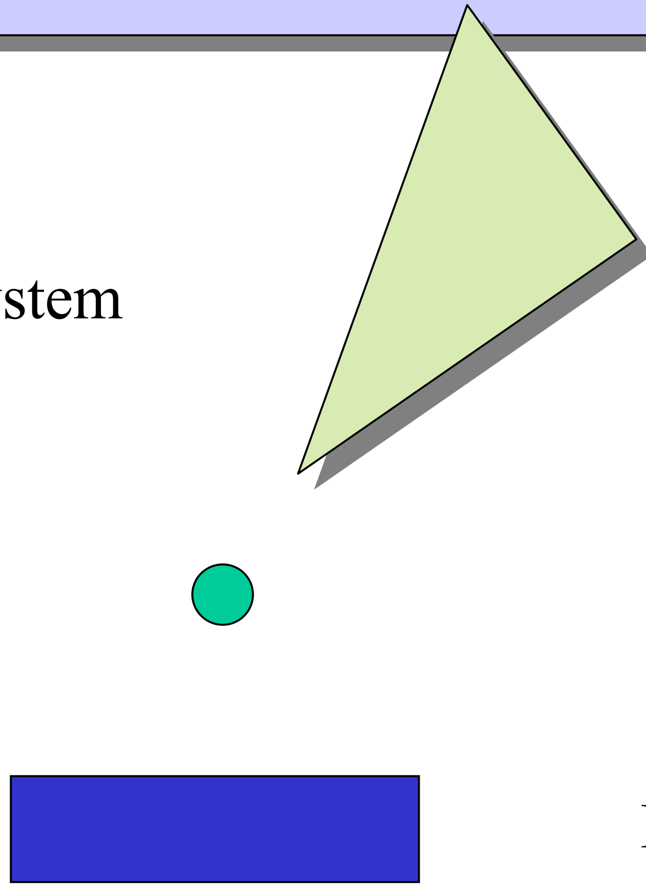
This talk is about Quantum Technology (QT)

What is QT?
It’s the ability to utilize a quantum system.

When can you utilize a quantum system?
When it has very few degrees of freedom so that we can
Initiate, manipulate, anticipate and measure the quantum state.

What can we do with it?
Sensors, communication, computing….

THE slide to remember: Combining 3 fields to make QT



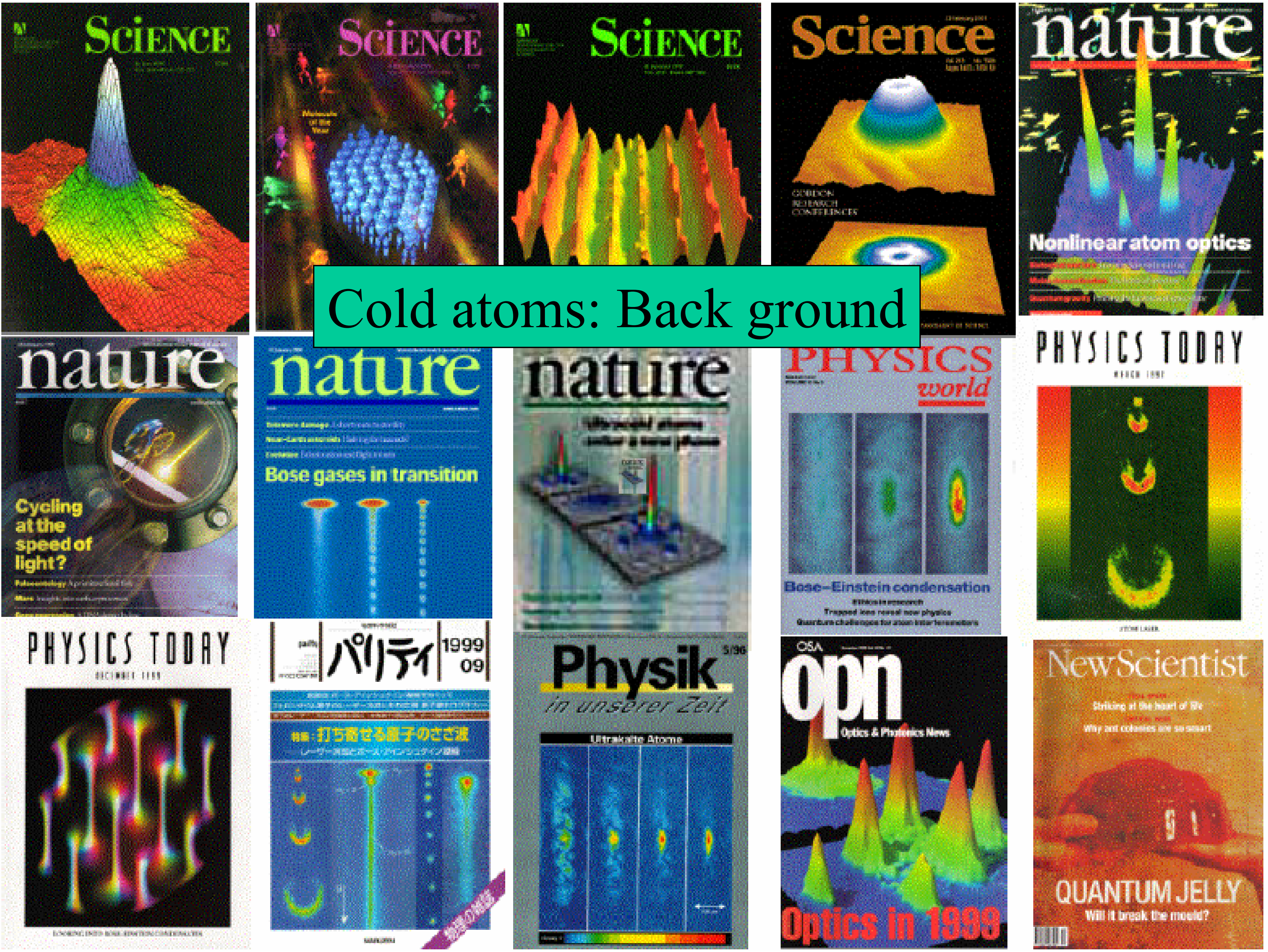
3. Talking to the quantum system (building a dictionary) — Photonics

1. Isolated quantum system — Quantum optics

2. Create magnetic/electric bottles — Planar fabrication & micro electronics

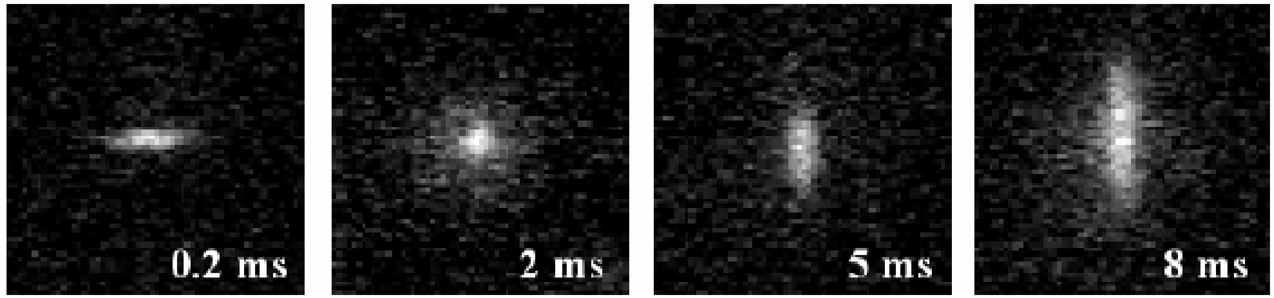
First component:
The quantum system

Cold atoms: Back ground



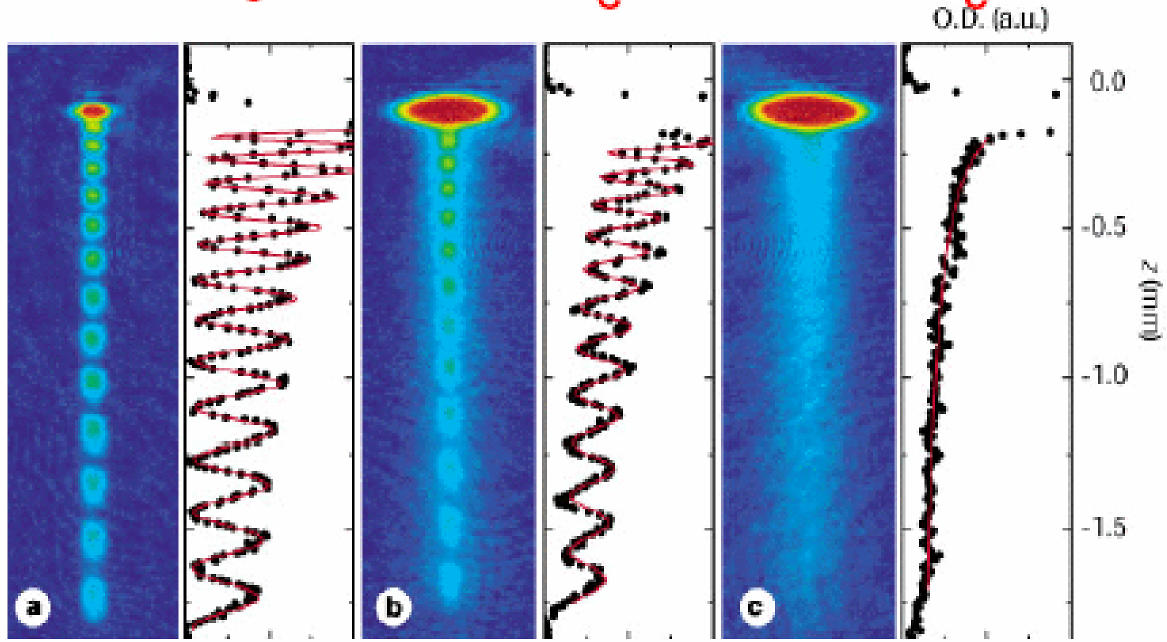
Some detail

He*
Paris



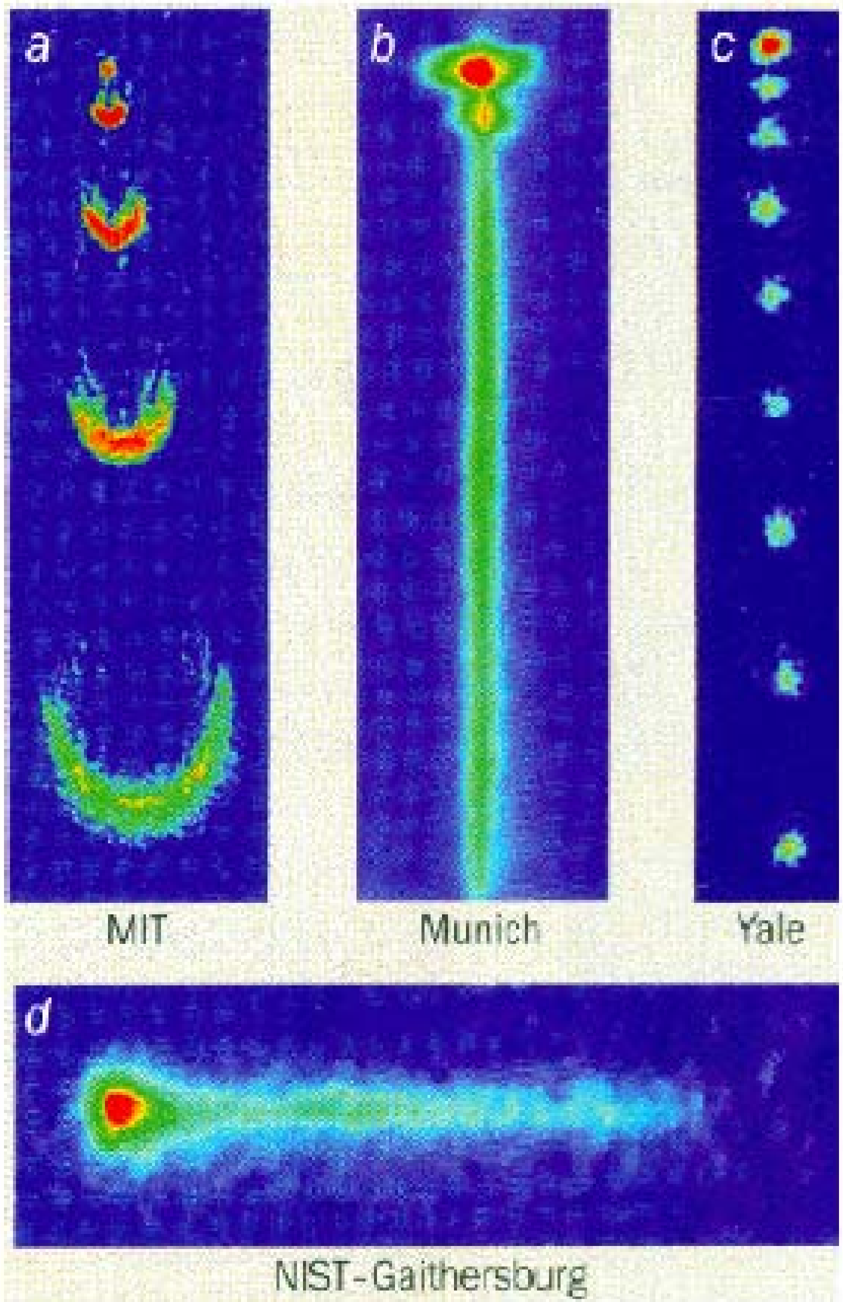
Cigare → Crêpe

$T < T_C$ $T \approx T_C$ $T > T_C$

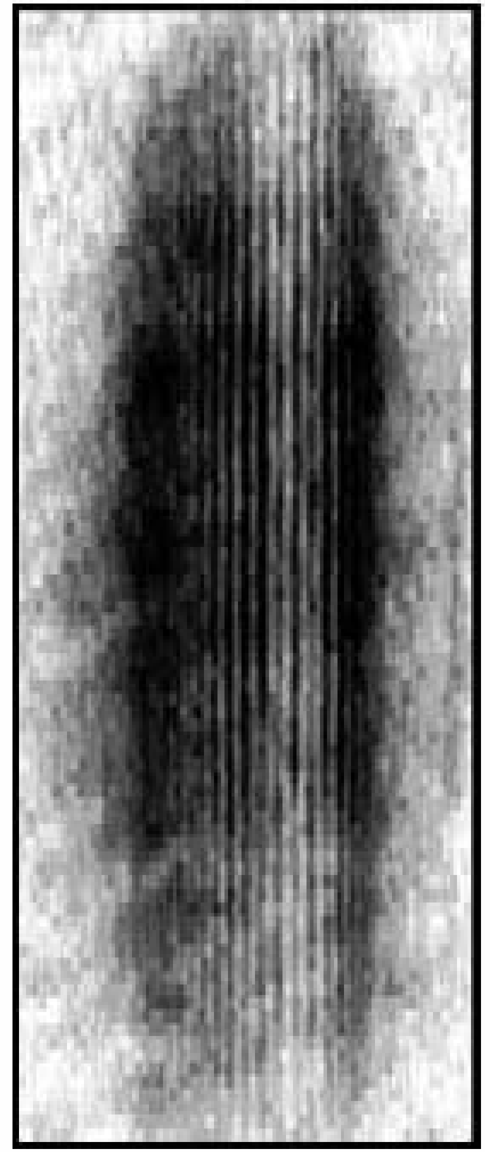


Munich

Atom laser



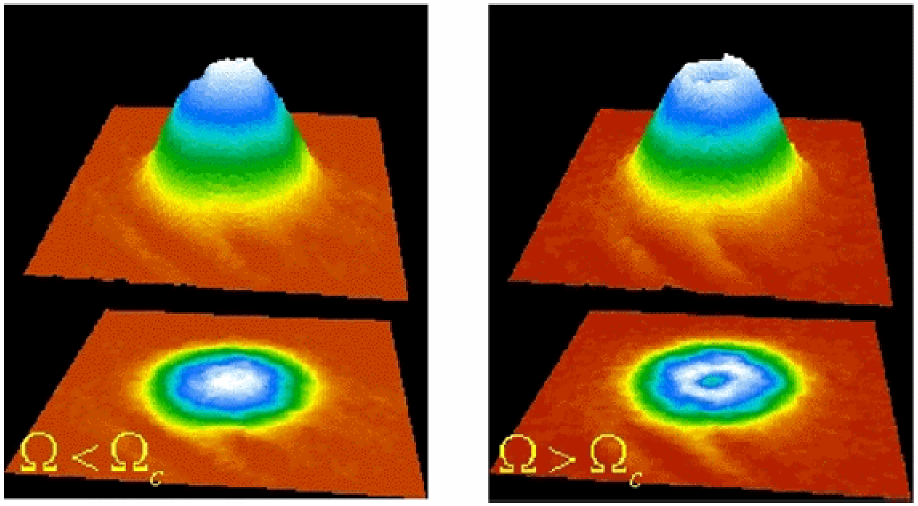
Two source interference



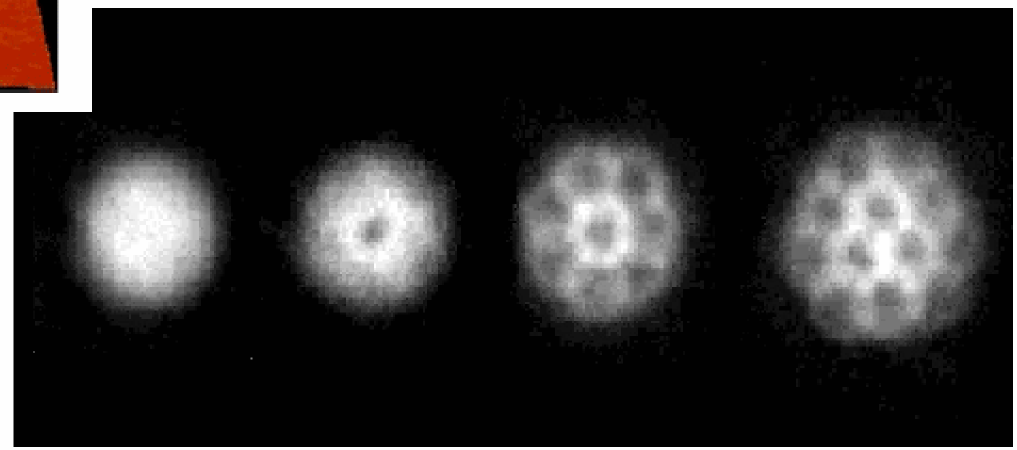
MIT

Vortices

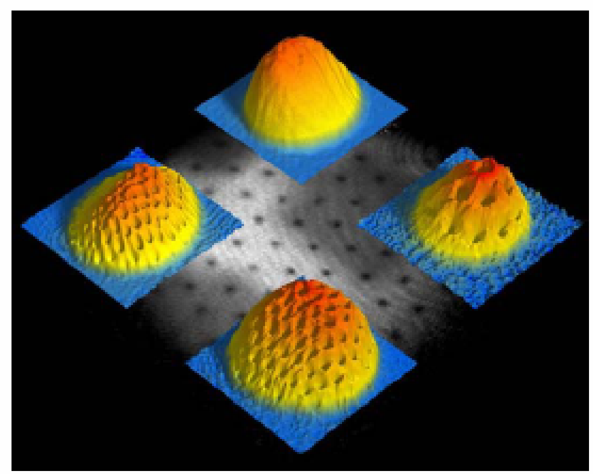
Paris



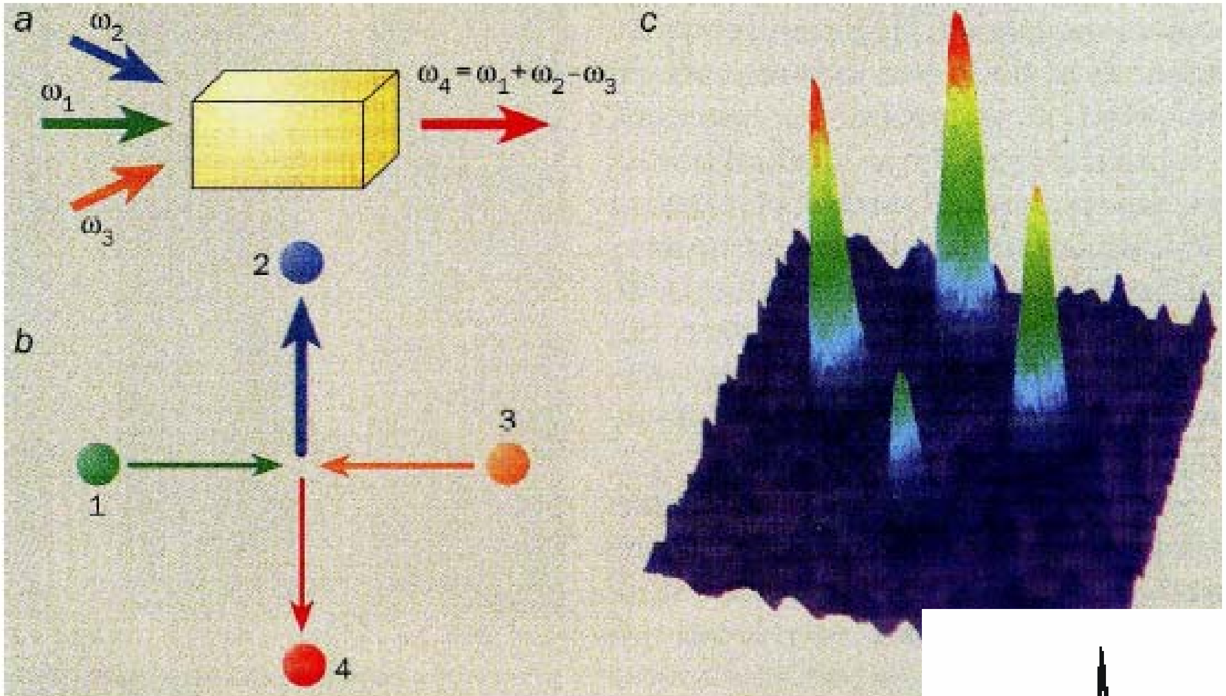
Paris



MIT

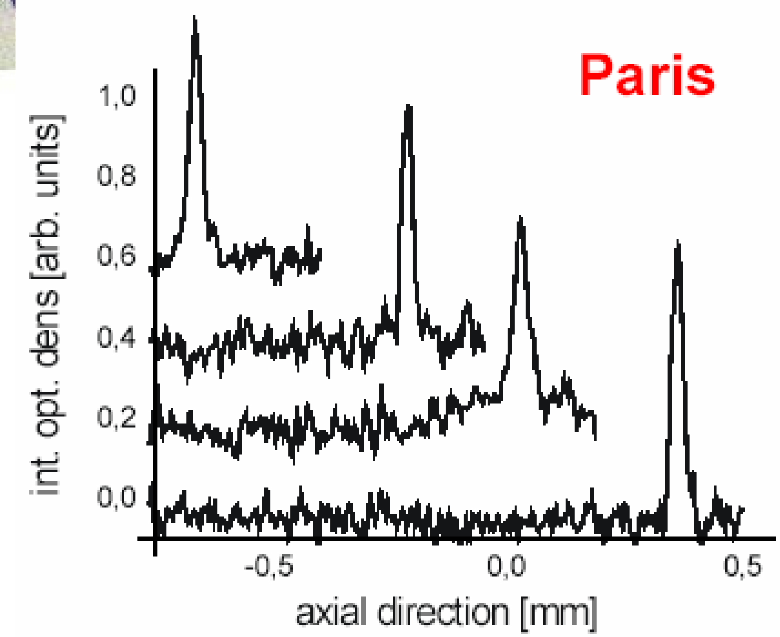


Four wave mixing



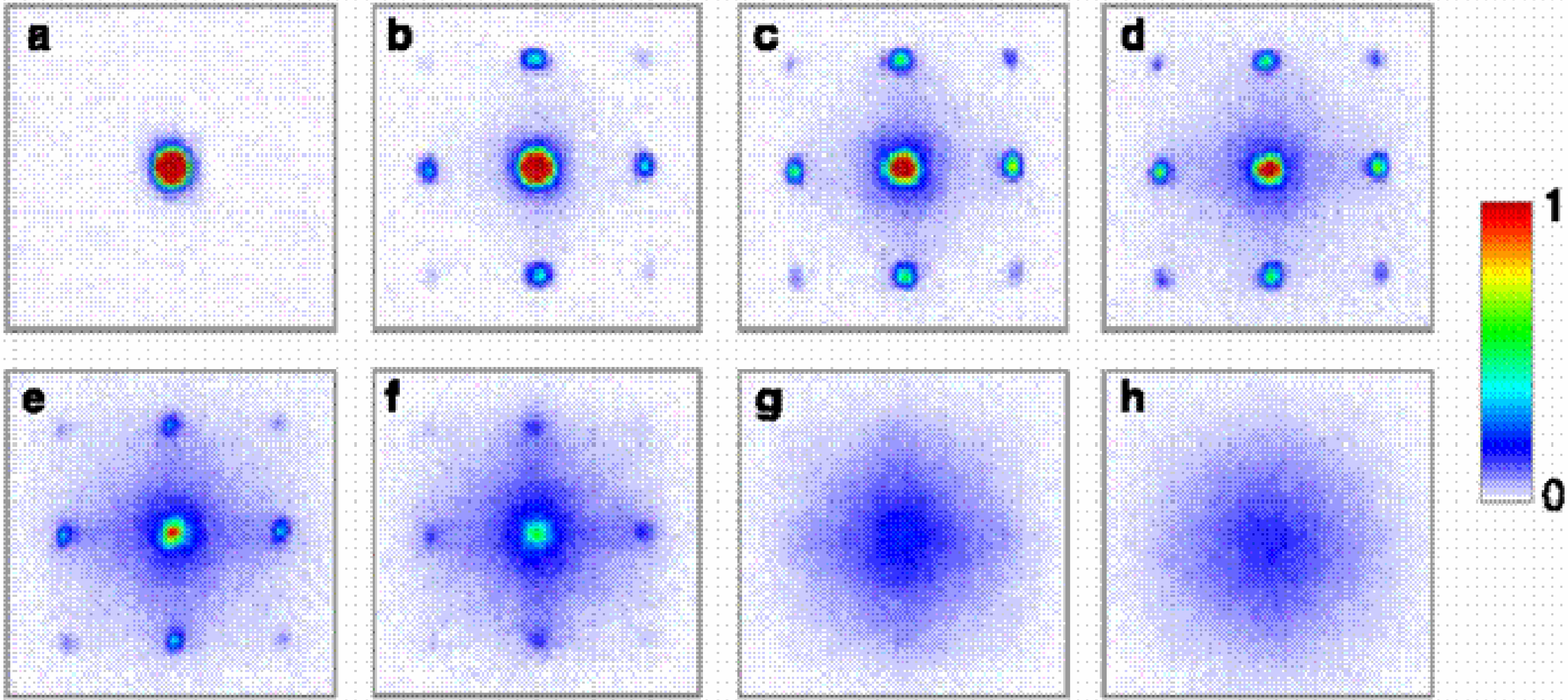
NIST

Paris



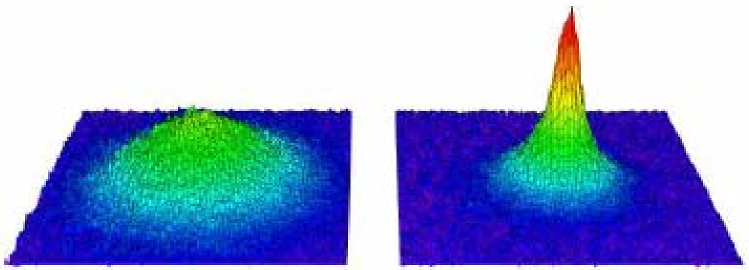
Solitons

Superfluid-isolator Mott transition



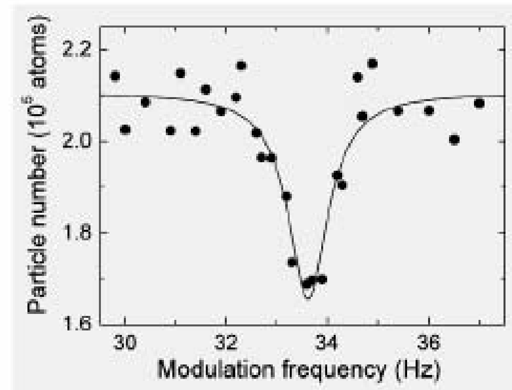
Munich

Molecular BEC



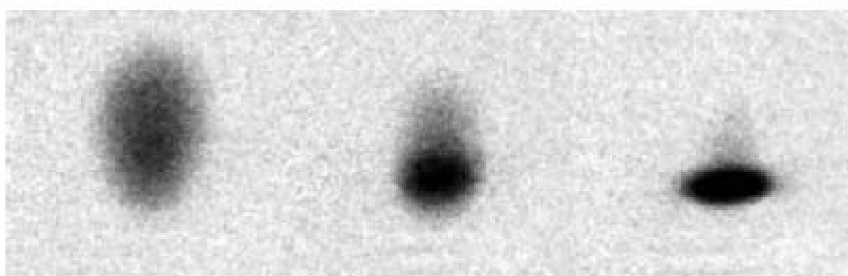
^{40}K

JILA



^{6}Li

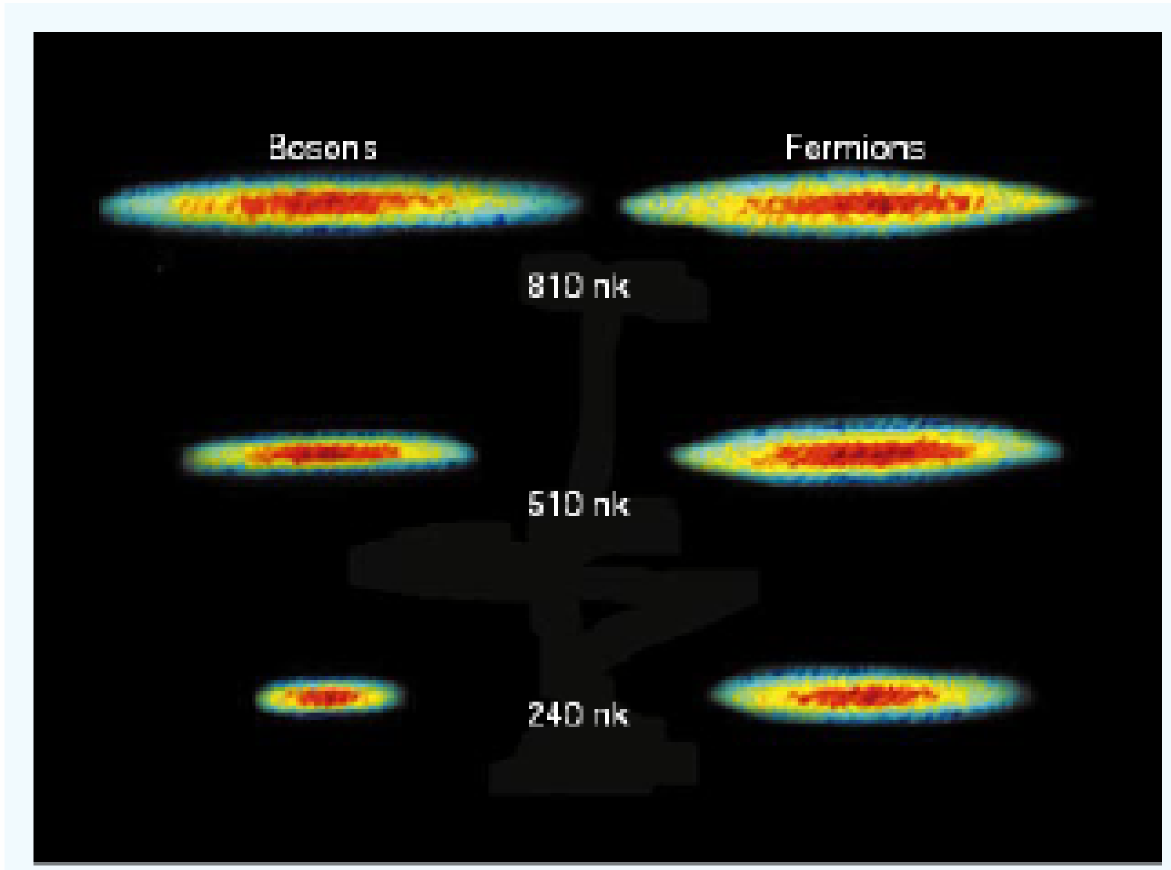
Innsbruck



^{6}Li

MIT

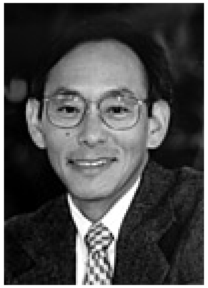
BCS ⟵ Fermi degenerate gas ⟶ Molecules



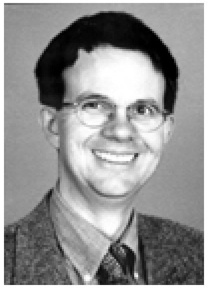
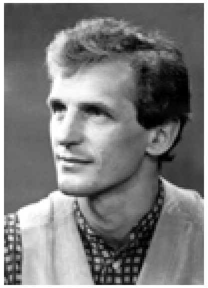
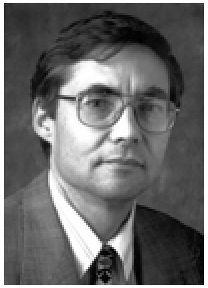
Rice

Two nobel prizes

<u>1997 Light Cooling</u>
- **Steven Chu**
- **Claude Cohen-Tannoudji**
- **William D. Phillips**

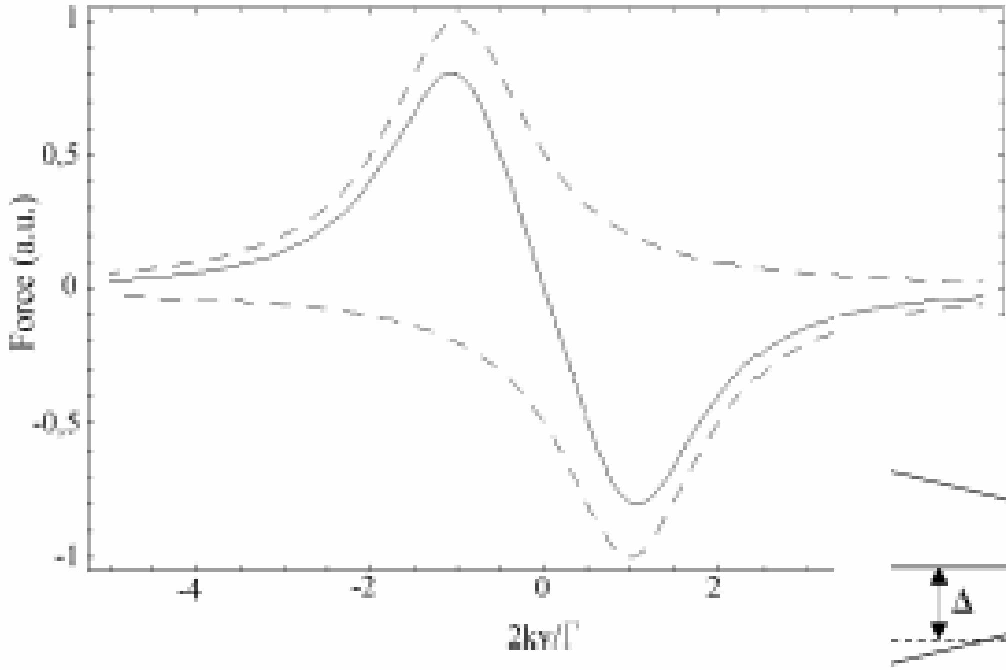


<u>2001 BEC</u>
- **Eric A. Cornell**
- **Wolfgang Ketterle**
- **Carl E. Wieman**

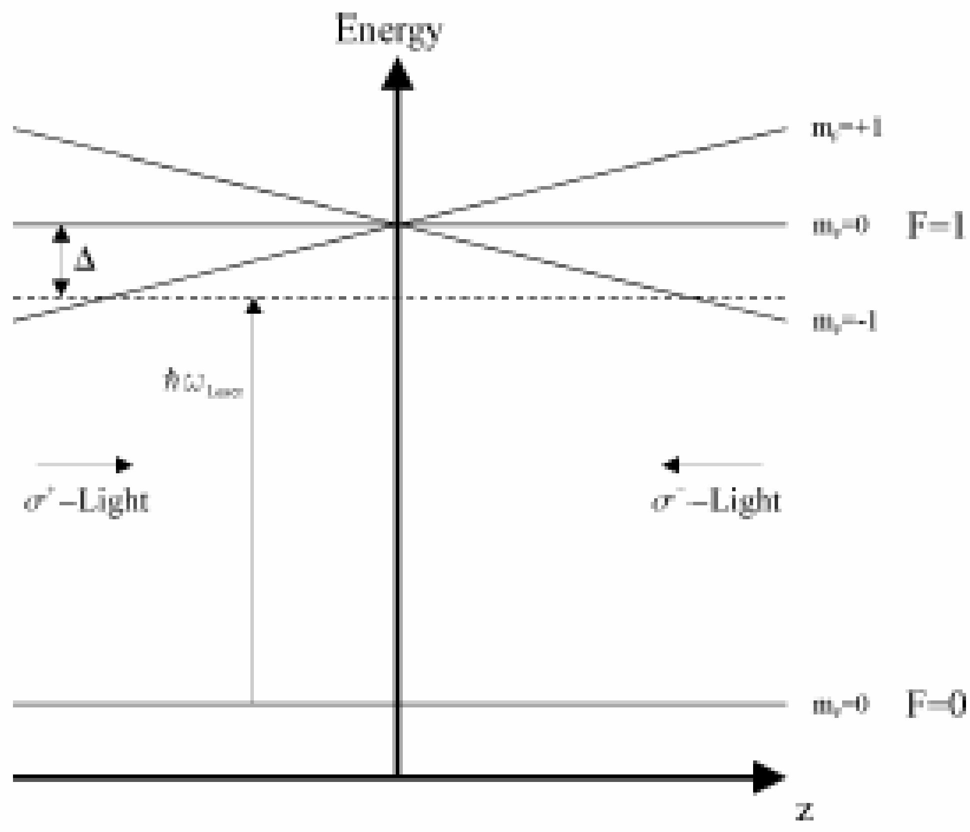
Next??? Ultra cold molecules?

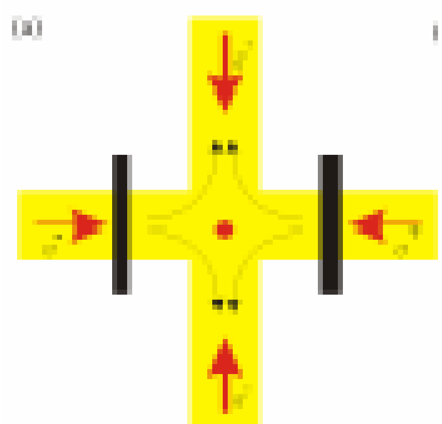
Light cooling



Molasses

Magneto-Optical-Trap

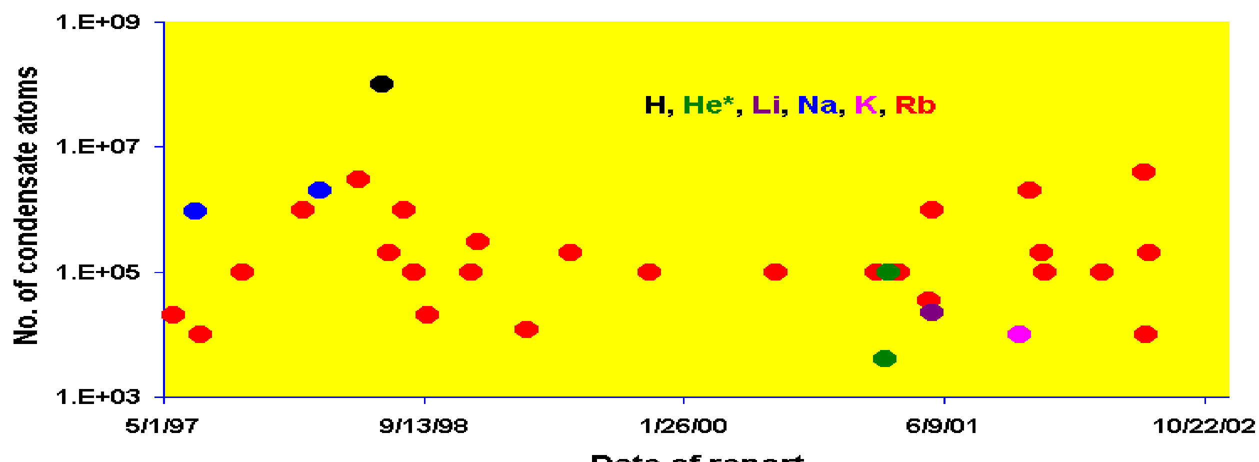




Bose Einstein Condensation

		1995	1997	1998	1998	1998	1998	1999	1999	2001	2001	2002	2002	2002
Rb	1995	9	8	3	1	3	5	2	1	1	1	1		1
Na	1995	3												
Li	1995/97	1		1										
H	1998	1												
He*	2001			2										
K	2001							1						
Cs	2002											Innsbruck 05. Oct. 2002	1	

New MOTs: Fr, Mg, Ca, Sr, Cr, Eu, Ag, Yb, Ne…

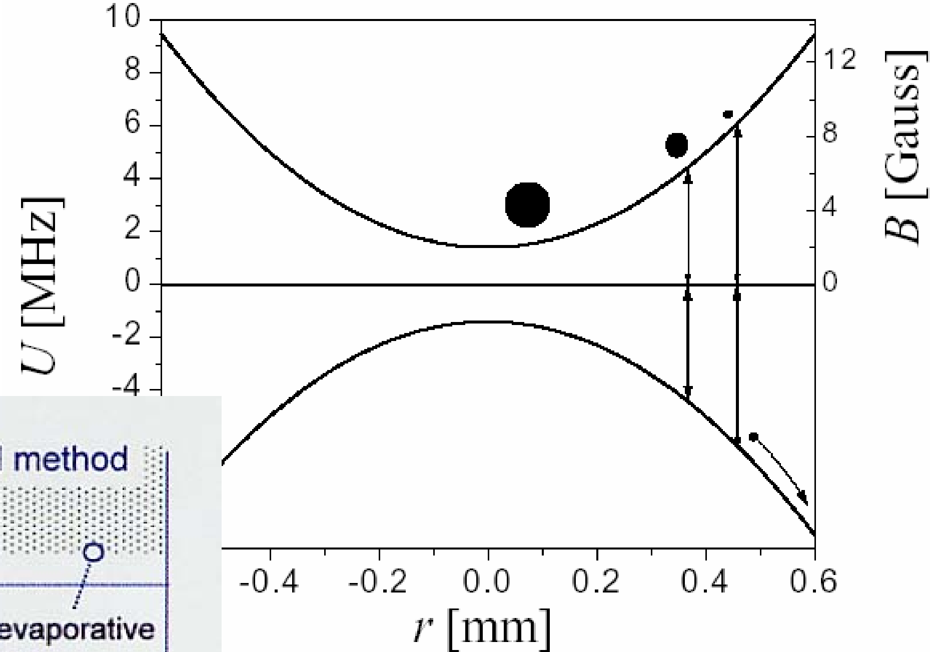


New state of matter: See Kishan Dholakia's talk

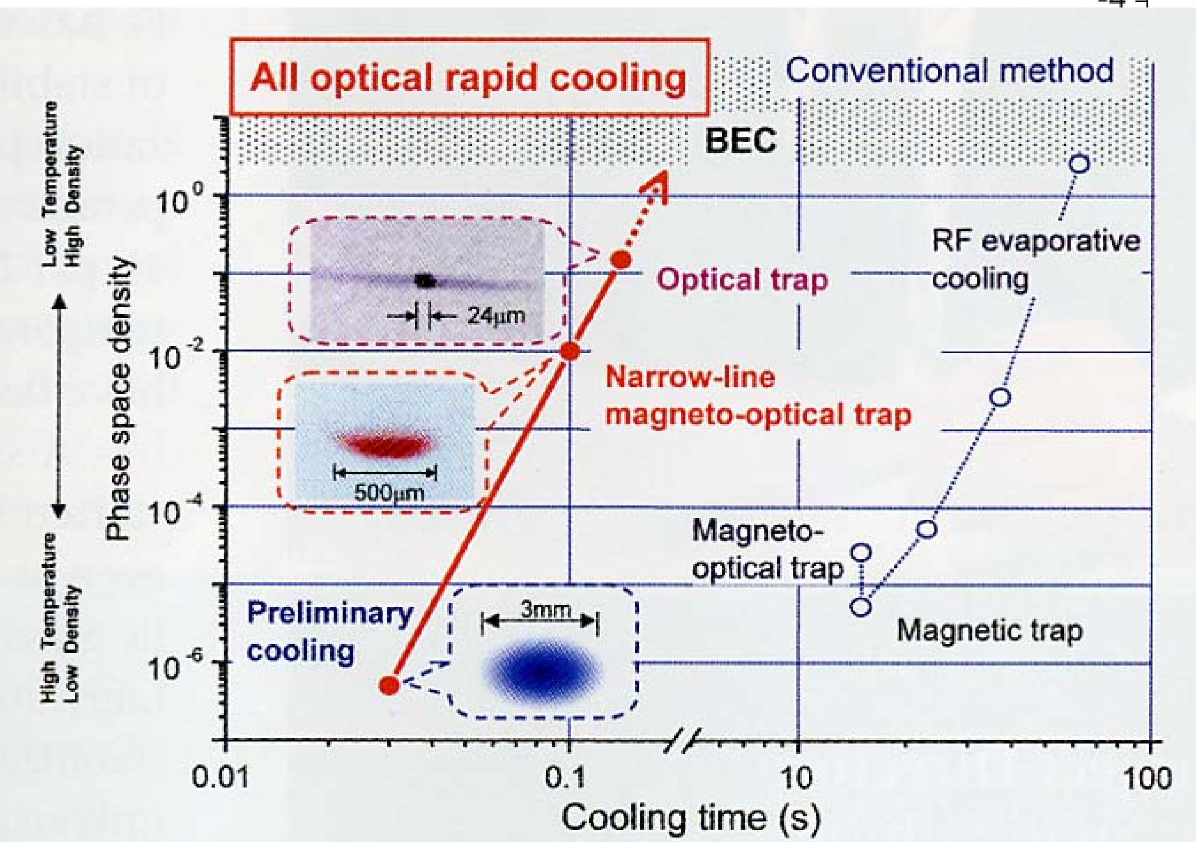
$$U = \mu\left|\vec{B}\right|$$

Forced evaporative cooling of Bosons, and beyond…

$$\mu = \mu_B g_F m_F$$

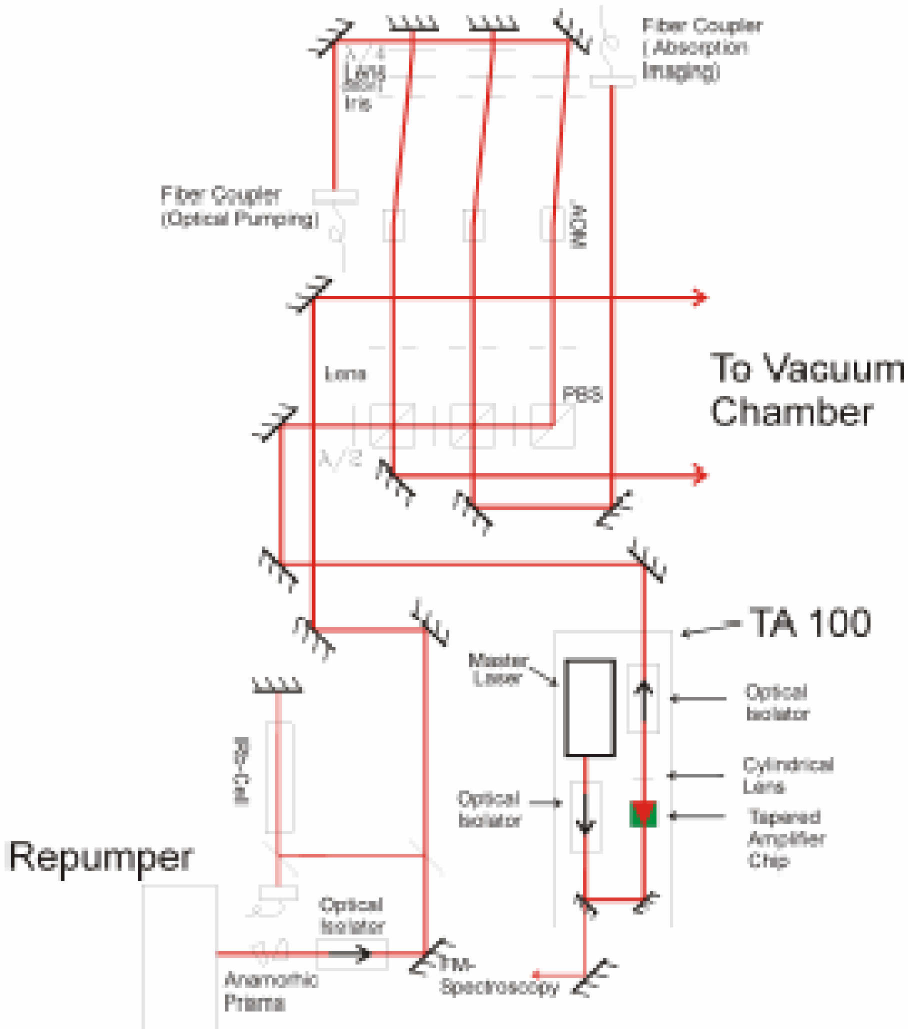


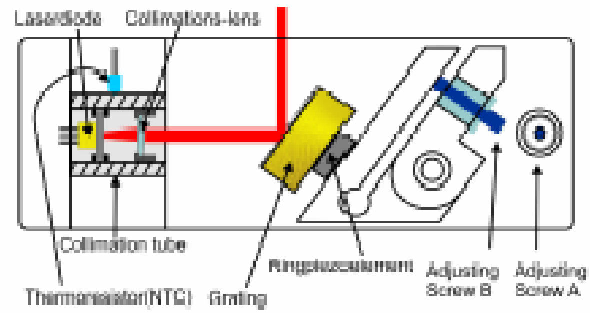
Japan: Yb.

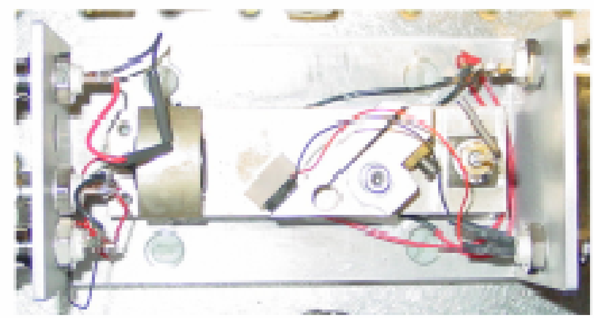


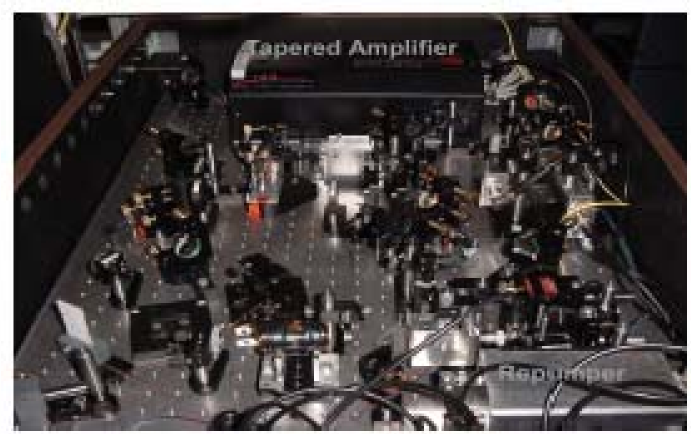
- New particles: Fermi gas, molecules…
- New methods: Optical, buffer gas, cavities, head-on collisions…

Lasers


Fiber Coupler
(Absorption
Imaging)
λ/4
Lens
Iris
Fiber Coupler
(Optical Pumping)
AOM
To Vacuum
Chamber
Lens
PBS
λ/2
TA 100
Master
Laser
Optical
Isolator
Cylindrical
Lens
Tapered
Amplifier
Chip
Optical
Isolator
Rb-Cell
Repumper
Optical
Isolator
Anamorphic
FM-
Spectroscopy


Laserdiode
Collimations-lens
Collimation tube
Grating
Adjusting
Screw B
Adjusting
Screw A




Tapered Amplifier
Repumper

Some technological applications...

What can we do with them?
(aside from a lot of exciting fundamental physics
e.g. Even nuclear! 219 hits on the web...)

- Metrology (time)
- Navigation (acceleration)
- Geology (gravitation)
- Super chemistry
- Secure communications (quantum cryptography)
- Super computers (quantum computing)

Ps Also non quantum single particle applications:

- Lithography (no diffraction, no proximity effects)
- Deterministic doping

“Future "matter wave sensors" could include a new class of compact atom-laser gyroscopes at least a million times more sensitive than current laser gyroscopes and ultra-sensitive gravity-measuring sensors for detecting underground tunnels and chambers or undiscovered oil and mineral deposits.

All the individual steps to do this with non-linear atom optics have been demonstrated. Its just a matter of making it work all together. I think it will happen in the next two or three years.”
(Pierre Meystre, Chair of the Quantum Optics center at the university of Arizona)

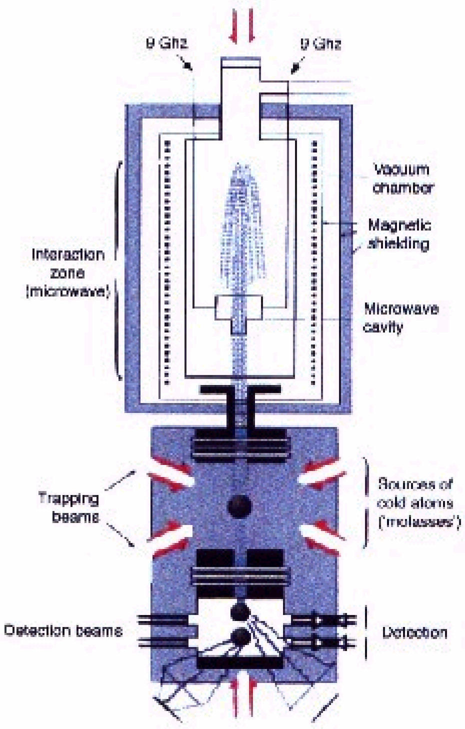
Example of grants:
The Department of Defense, established a 5-year, $5 million research consortium of Harvard, MIT, Stanford, UA and Yale to develop novel high technology sensing devices that will make current state-of-the-art sensors used for strategic navigation, guidance, detection and mapping obsolete.

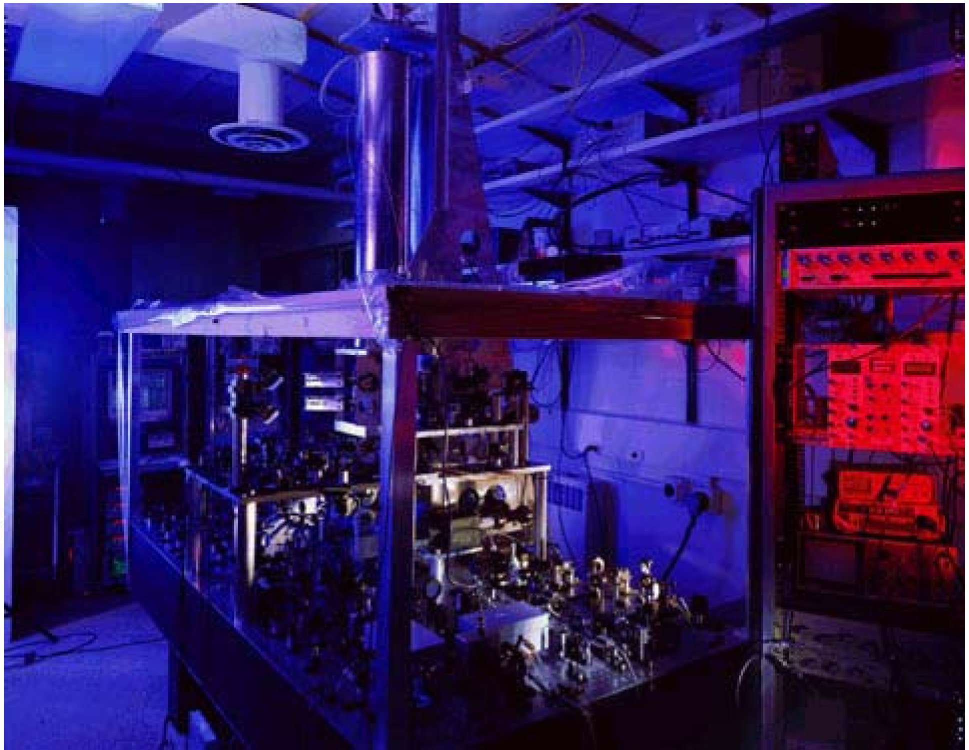
A few examples:

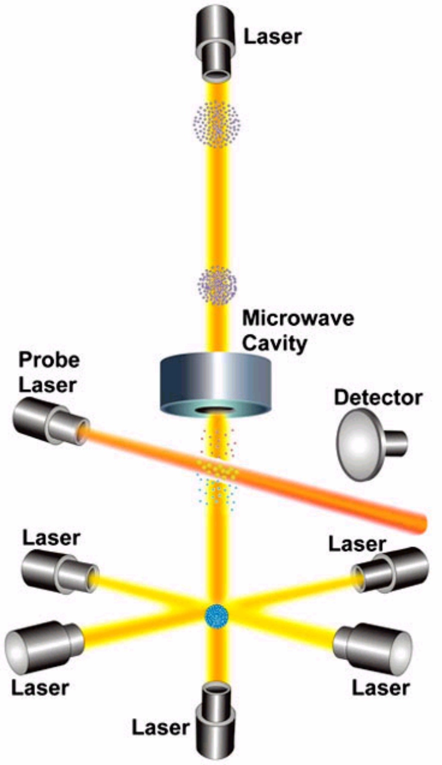
- Time standards

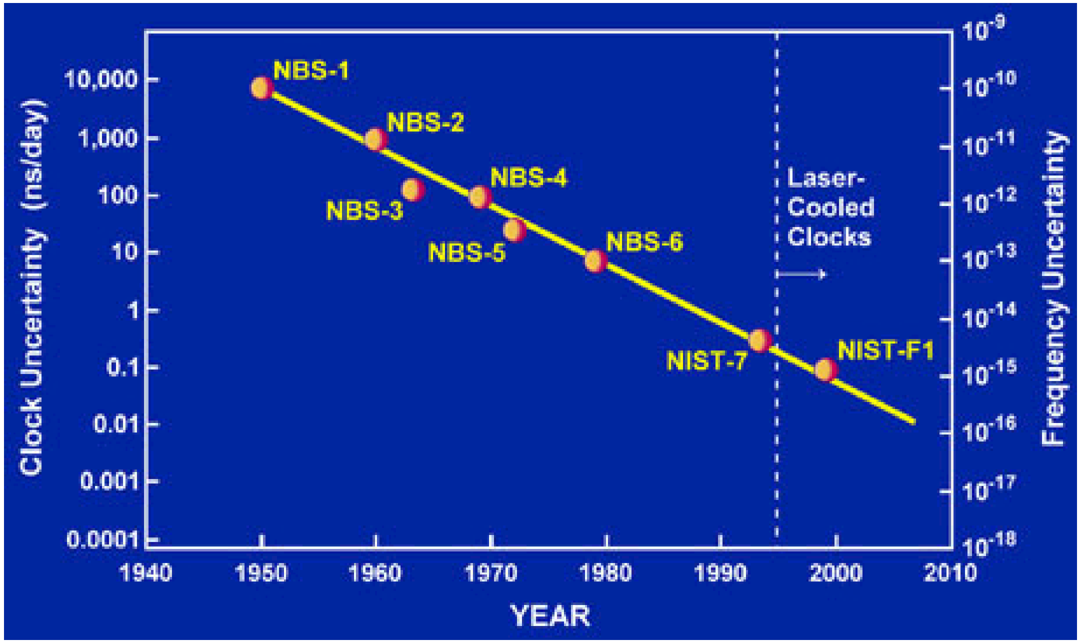
Since October 13, 1967, the primary standard of time has been based on the transition frequency between two levels of energy, very close to the minimum energy of a cesium 133 atom.Thus a second is equal to 9192631770 times this transition period. Some fifteen laboratories around the world are currently developing this type of clock, which has an accuracy of 10^{-15}

(NIST-F1, Boulder, Colorado)









Each of the 24 GPS satellites carries 4 atomic clocks on board. By triangulating time signals broadcast from orbit, GPS receivers on the ground can pinpoint their own location.

Tiny instabilities in those orbiting clocks contribute at least a few meters of error to single-receiver GPS measurements. Making the clocks smaller (so that more of them can fit on each satellite) and increasing their stability could reduce such errors to fractions of a meter.

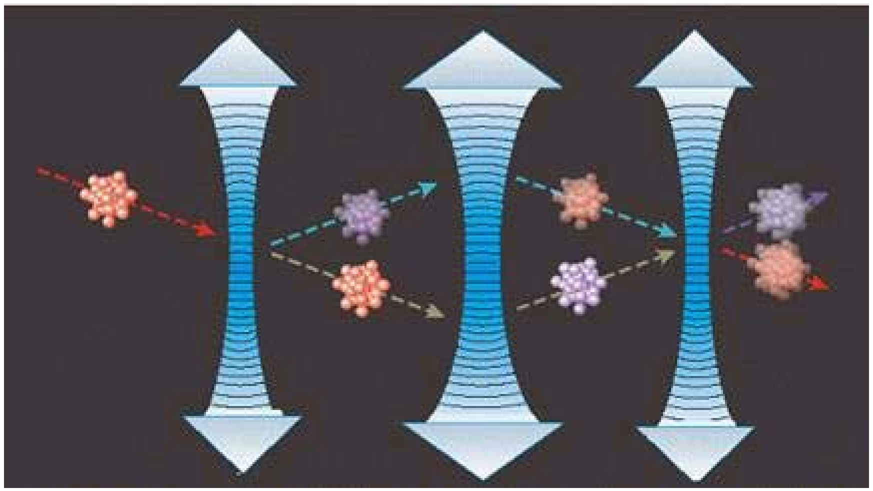
A cold atom clock in space by 2005 (ESA/NASA)

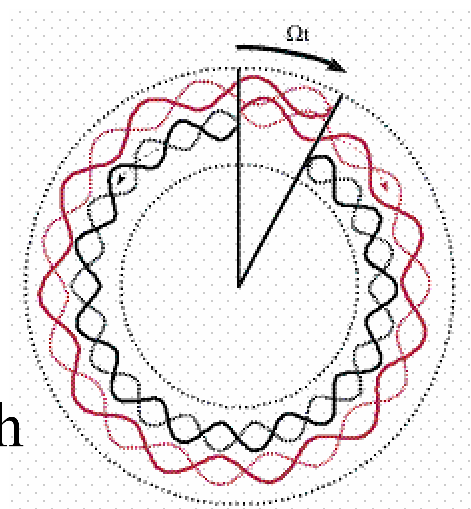
To improve the clock's performance, scientists have to increase the interaction time. One of the limiting factors is gravity, hence the idea of working in space - the objective of a new program, called PARCS/RACE PHARAO/HYPER. A prototype clock has already been tested in microgravity on the Zero G Airbus A300 during a parabolic flight, proving that the team can miniaturise the whole unit to fit into an aeroplane and make it robust enough to stand up to the accelerations involved. Based on this prototype, another fountain of atoms is currently being studied, designed to operate on the International Space Station in the year 2003, aiming at an accuracy of 10^{-17} (1 second in 3000 Million years!).

(http://atomoptic.iota.u-psud.fr/hyper)

• Gyroscope in space

10^3-10^{10} increase in sensitivity over light based ring gyros.





The hyper project 1.5m x 1.5m.

$\Delta\phi_{rot}=4\pi\, m_{at} A\bullet\Omega/h$

• Geodesy

Oribit: 300 km

Measurement baseline:

100 m (ISS)

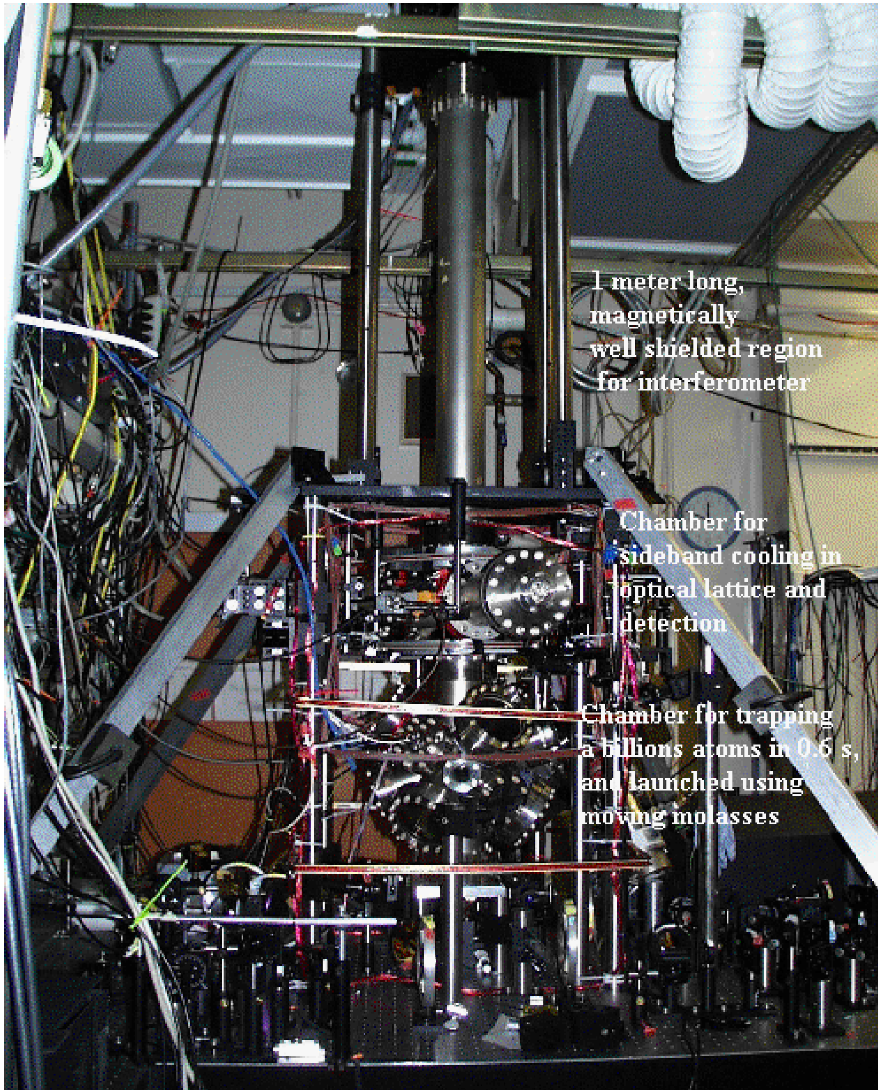
100 km (Satellite constellation)

Sensitivity: 10^{-4} E/Hz $^{1/2}$ (ISS) ,

10^{-7} E/Hz $^{1/2}$ (Satellite constellation)

Earthquake, water table monitoring

and military applications.

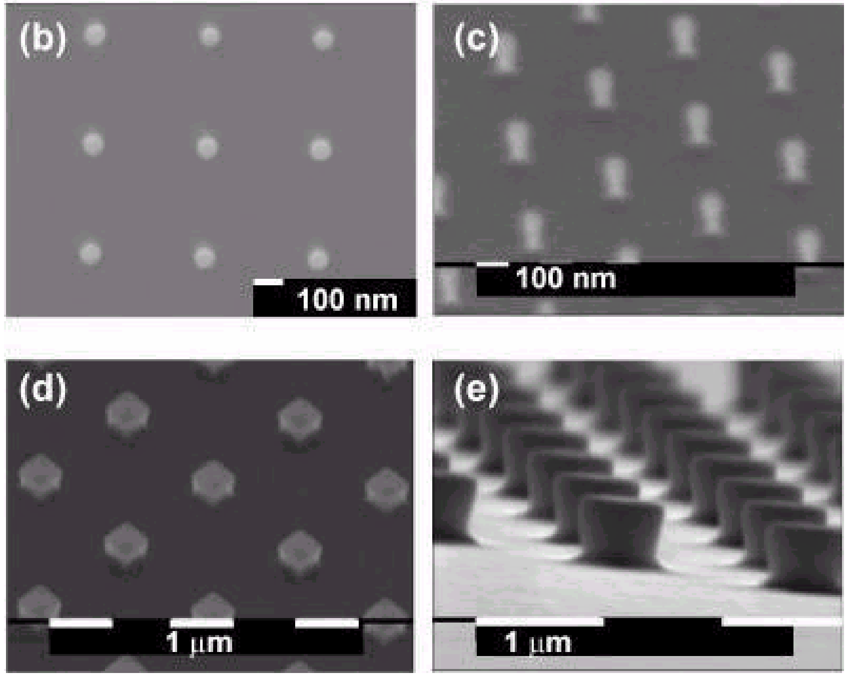


Gravitation sensor, Stanford

Non quantum:

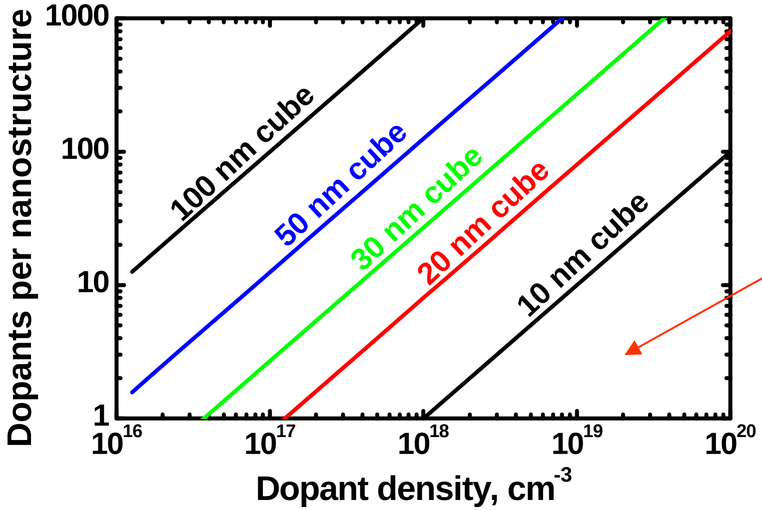
• Atom lithography

No diffration and
no proximity effects
cornel, NIST



• Deterministic doping: a solution to...

The nanoscale semiconductor catastrophe



Danger zone – Fluctuations ~ $N^{1/2}$ > 30%

Final example: One long term motivation – Quantum Information Processing (QIP)

What do many people mean by quantum information?

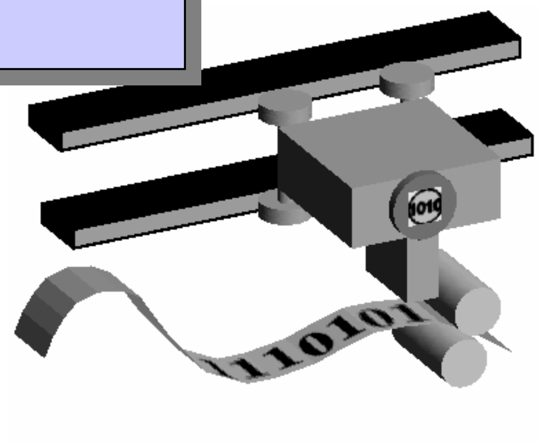
Put the library of congress on the tip of a pencil...
Namely: they mean efficient memory...

Naive example of quantum memory profit in case 1Atom=1Byte:
1CD ~ 10^{-2}m^2 ~ 10^{17} bytes
> 10^7 profit factor (27GB with 405nm laser) ...not true!
Classical memory can be almost as good.

e.g. IBM's future single atom classical memory:

However,
Moore's law will make information processing quantum anyway....
But in an uncontrolled way!
λ_dB=7nm (electron @ 300K), already now: 2nm thickness
Width now: 130nm (193nm light) 10y: 10nm (100GHz)

Quantum ??
Information ??



Usually we mean:
Small and well isolated system
(i.e. Finite # of degrees of freedom)
for which we have a clear view
of the Schrödinger evolution and how
to alter it.

Bytes (Qubits):

- Write & Read
- Store
- Compute
- Communicate x2

The monk story:
Non destructive measurement
with high Q photonics

A little history

Feynman's question.

R.P. Feynman, 1982

Simulating physics with computers, Int. J. Theor. Phys. **21**, 467 (1982).

Can a *quantum* system be simulated *exactly* by a classical computer ? NO !

- Cannot simulate a large quantum process.
- A physical computer operating by quantum rules.
- Could it compute more *efficiently* than a classical computer ?

D. Deutsch, 1985

Quantum theory, the Church-Turing principle and the universal quantum computer. Proc. Roy. Soc. A**400**, 97, (1985).

Computational basis

Direct product Hilbert space of N two-level systems:

$$|S_N\rangle \otimes |S_{N-1}\rangle \otimes \ldots |S_1\rangle; \quad S_i \in \{1,0\}$$

Quantum computer

arbitrary superpositions of computational basis...

explore all 2^N dimensions !

Quantum parallelism

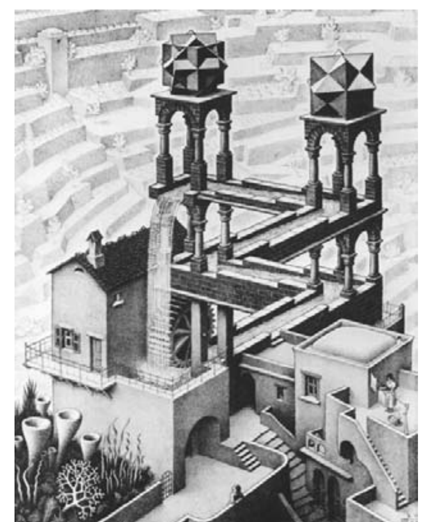
$$f: \sum_{k=0}^{2^{N-1}} |k\rangle_{input} \otimes |0\rangle_{output} \to \sum_{k=0}^{2^{N-1}} |k\rangle_{input} \otimes |f(k)\rangle_{output}$$

Example of magic

$$f : \{0,1\} \to \{0,1\}$$

Is f EVEN, $f(0) = f(1)$ or ODD, $f(0) \neq f(1)$?

Only evaluate f once!



Implementation of Deutsch algorithm.

- quant- ph/ 9801027 14 Jan 1998

“Implementation of a Quantum Algorithm to Solve Deutsch's Problem on a Nuclear Magnetic Resonance Quantum Computer”

  – J. A. Jones & M. Mosca, Oxford

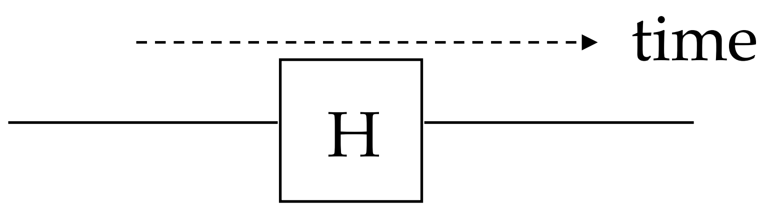
The elementary single qubit operation

- The Hadamard transform.

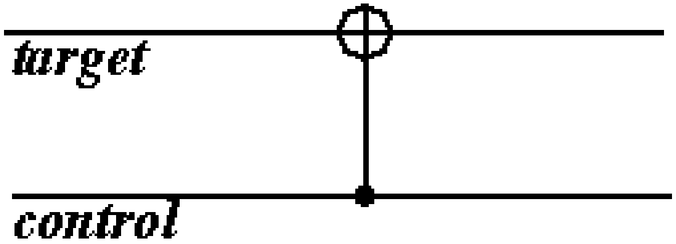
$$|0\rangle \rightarrow \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

$$|1\rangle \rightarrow \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$$

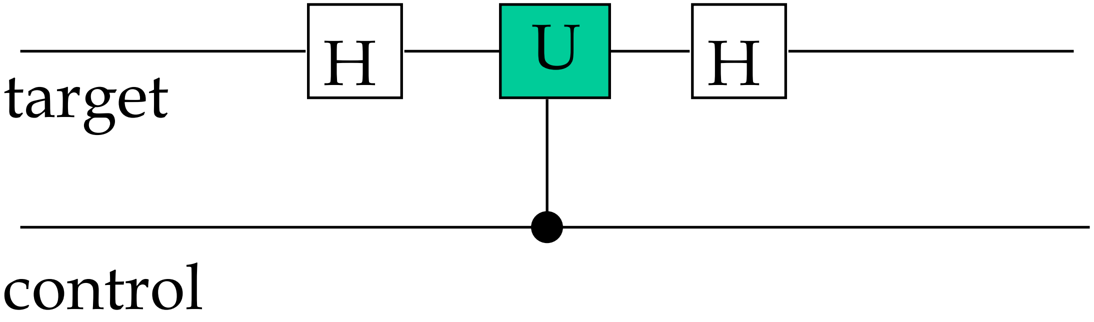
- Quantum circuit:



The elementary two qubit operation: The quantum gate



Quantum circuit for Controlled NOT.



- Step 1: Hadamard transform of target, $|0\rangle_T \otimes |1\rangle_C \rightarrow (|0\rangle_T + |1\rangle_T) \otimes |1\rangle_C$
- Step 2: Spin-spin coupling to control, $U_\pi = \exp\left(-i\pi\ |1\rangle_T\langle 1| \otimes |1\rangle_C\langle 1|\right)$
  $U_\pi(|0\rangle_T + |1\rangle_T) \otimes |1\rangle_C \rightarrow (|0\rangle_T - |1\rangle_T) \otimes |1\rangle_C$
- Step 3: Hadamard transform of target, $(|0\rangle_T - |1\rangle_T) \otimes |1\rangle_C \rightarrow |1\rangle_T \otimes |1\rangle_C$

- Peter Shor, AT&T, 1994
  - –a quantum algorithm to find prime factors of large composites *N* in polynomial time (e^N improvement over best known classicaly)
  - –public key cryptography no longer safe !
- Grover (search), …..?

Perhaps the most advanced realization yet:
Ion traps – Dave Wineland (Boulder)
Rainer Blatt (Innsbruck)

Theory of Physical realizations of a gate:

+Ion traps … Cirac & Zoller 1994, Phys. Rev. Lett **74**, 4094

+Cavity QED … Turchette et al. 1995, Phys. Rev. Lett **75**, 4710

+NMR … Gershenfeld & Chuang 1997, Science **275,** 350

+SQUID … Rouse et al.,1995 Phys. Rev. Lett **75**, 1614

+Quantum dots … Loss & Di Vincenzo, cond-mat/9701055

+Since then, many more. Specifically to neutral atoms:

Motional (Williams), Rydberg (Deutsch, Cirac-Zoller), Contact (Zoller), Dipole blockade – ensembles (Cote-Lukin-Zoller), etc.

Some neutral atom examples (theory)

Controlled collisions contact interact. T. Calarco et al. PRA 61, 02234 (2000)

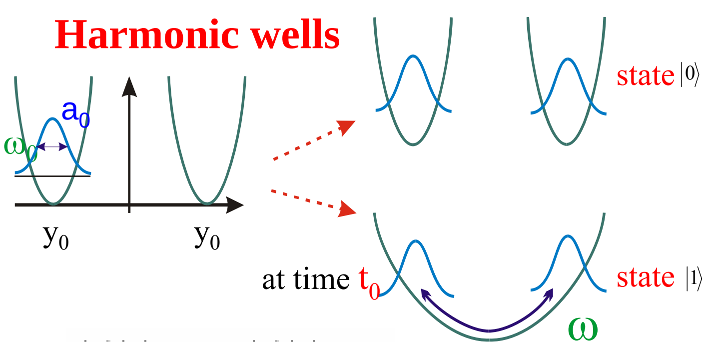
E. Charron et al., PRL 88, 077901 (2002)

Switchable interactions

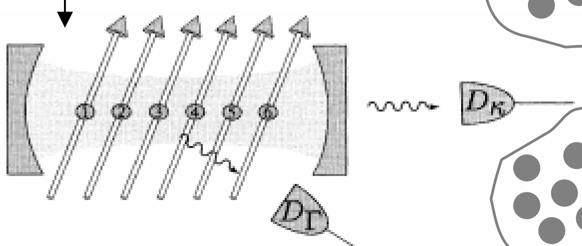
Rydberg Atoms D. Jaksch et. al, PRL 85, 2208 (2000)
G.K. Brennen et. al, PRL 82, 1060 (1999)

Mesoscopic ensembles M. D. Lukin, et. al, PRL 87, 37901 (2001)

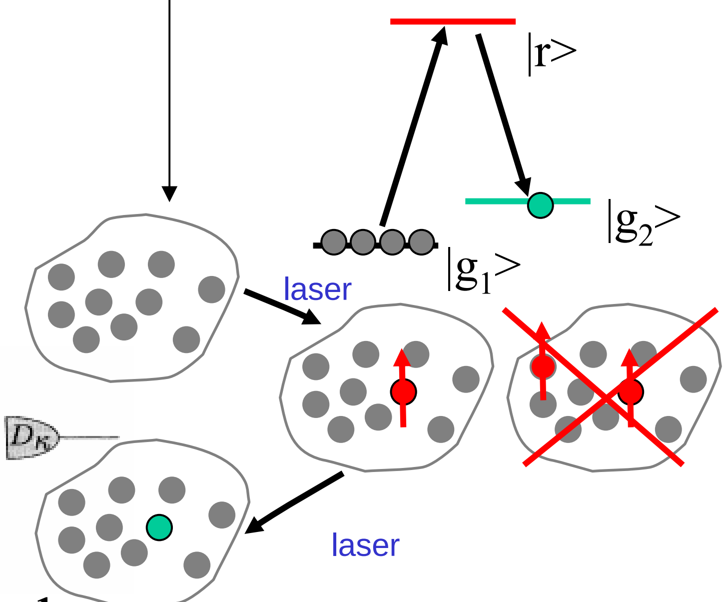
Cavity mediated interactions Th. Pellizzari et al, PRL 75, 3788 (1995)



$$
\begin{aligned}
|0\rangle|0\rangle &\rightarrow |0\rangle|0\rangle, \\
|0\rangle|1\rangle &\rightarrow |0\rangle|1\rangle, \\
|1\rangle|0\rangle &\rightarrow |1\rangle|0\rangle, \\
|1\rangle|1\rangle &\rightarrow e^{i\phi}|1\rangle|1\rangle.
\end{aligned}
$$



qubit=hyperfine levels



THE slide to remember: Combining 3 fields to make QT

3. Talking to the quantum system (building a dictionary)

Photonics

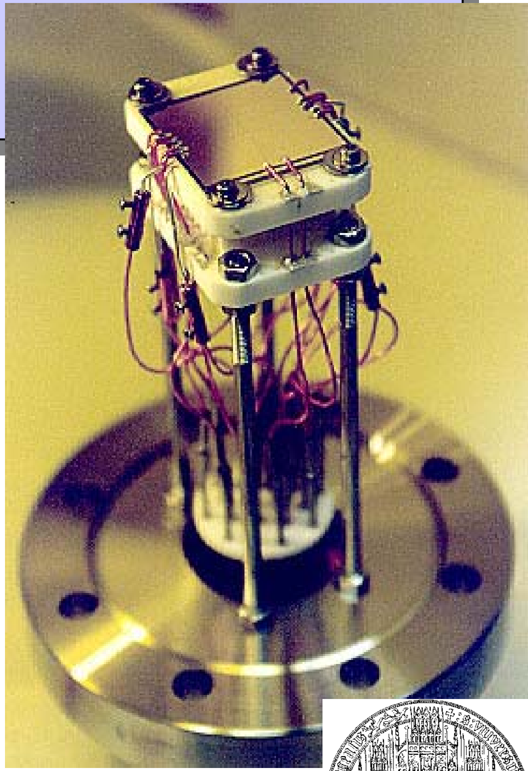
1. Isolated quantum system

Quantum optics

2. Create magnetic/electric bottles

Planar fabrication & micro electronics

Second component: Atoms trapped, manipulated & measured by surfaces - The Atom Chip



• Setup:
miniaturization, integration, monolithic, arrays, low power…

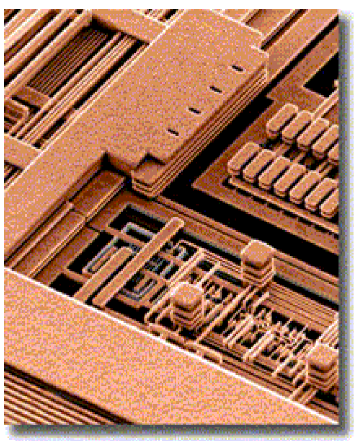
• Advantages:
arbitrary (e.g. non periodic) potentials, sub-100nm potentials (e.g. double well barrier), near field imaging, high frequency traps, high aspect ratio traps (i.e. low dimensions), single site addressability

R. Folman et al., Advances in Atomic, Molecular and Optical Physics, Vol. 48, 263 (2002); J. Reichel, Appl. Phys. B 74, 469 (2002).

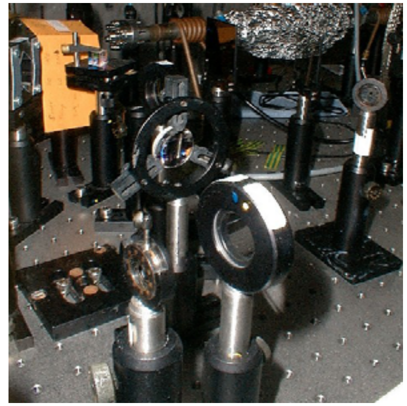
Joerg Schmiedmayer

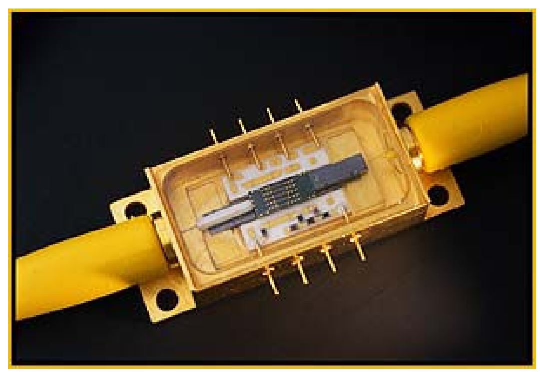
miniaturization, integration, monolithic ➔

Electronics

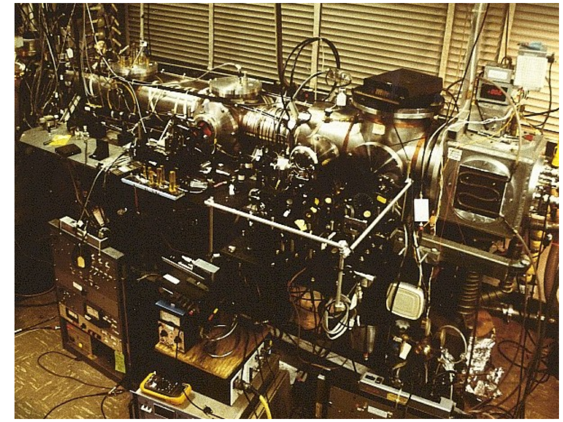


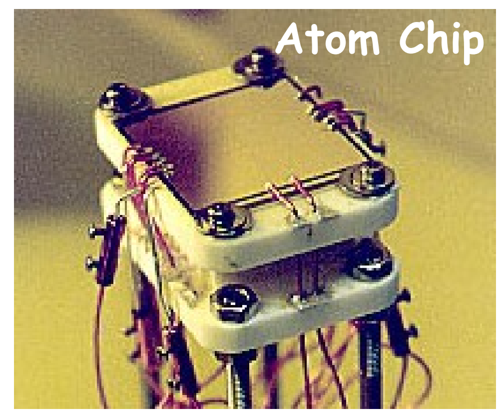
Optics





Matter waves





➔ accuracy, complexity ➔ novel functionality

How to make a magnetic bottle

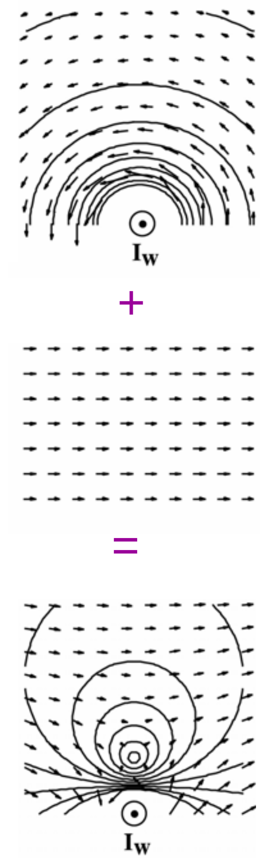
Brief History

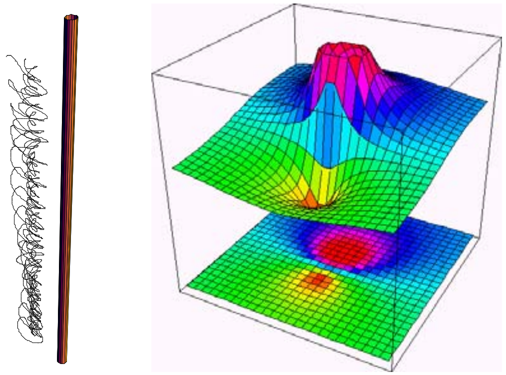
1921 Stern-Gerlach
1932 Frisch & Segre (bias field and a wire)
1961 Vladimirskii (neutrons)
1992 Opat 1995 Hinds 1999 Prentiss (atom mirrors)
1992 Schmiedmayer (wires)
1995 Weinstein & Librecht 1999 Prentiss (micro traps)
1996-7 Wonho, Pfau (surface MOT)
1999 Reichel (chip MOT)
2000 atom chip PRL 84, 4749 (complex manipulation, fabrication limit<atom de-Broglie wave length)
2000 ACQUIRE collaboration
2001 Zimmermann, Reichel (BEC, 30μm from surface)
presently: at least 6 atom chip surface BECs.
2003 Reichel (Rabi oscillations), Vuletic (0.5μm)

Magnetic Interaction

$$U_{mag} = -\vec{\mu} \cdot \vec{B}$$

potential depth: **bias field Bo**
potential height: **$h=\mu_o/2\pi \quad I/Bo$**
potential gradient: **$Bo^2/I \propto 1/h$**

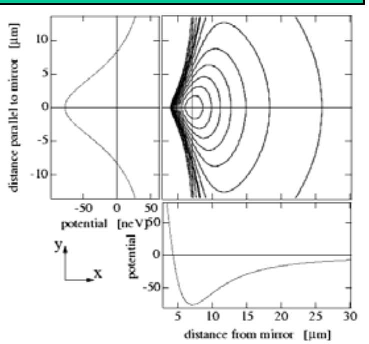


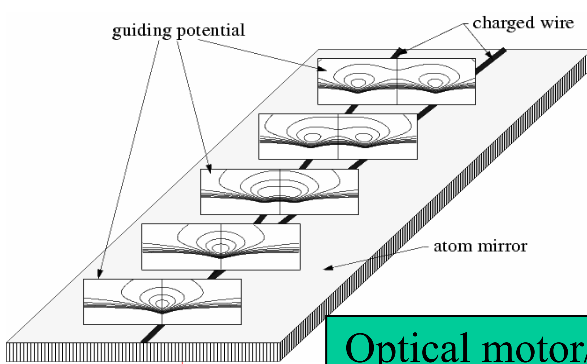


Electric Interaction

$$U_{el} = -\frac{1}{2}aE^2$$

$$U_{mirror} \propto e^{-\kappa_m z}$$





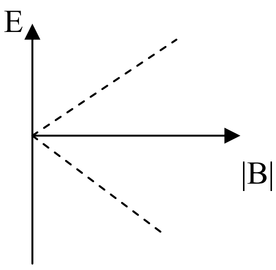
Schmiedmayer EPJ D 4, 57 (1998)

Optical motor/tweezers, Permanent magnets, and more

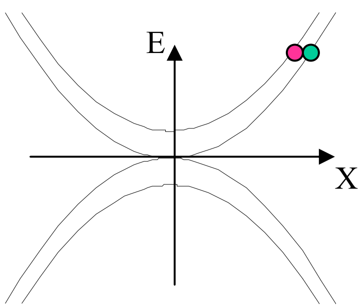
Magnetic bottle II

The U and Z traps

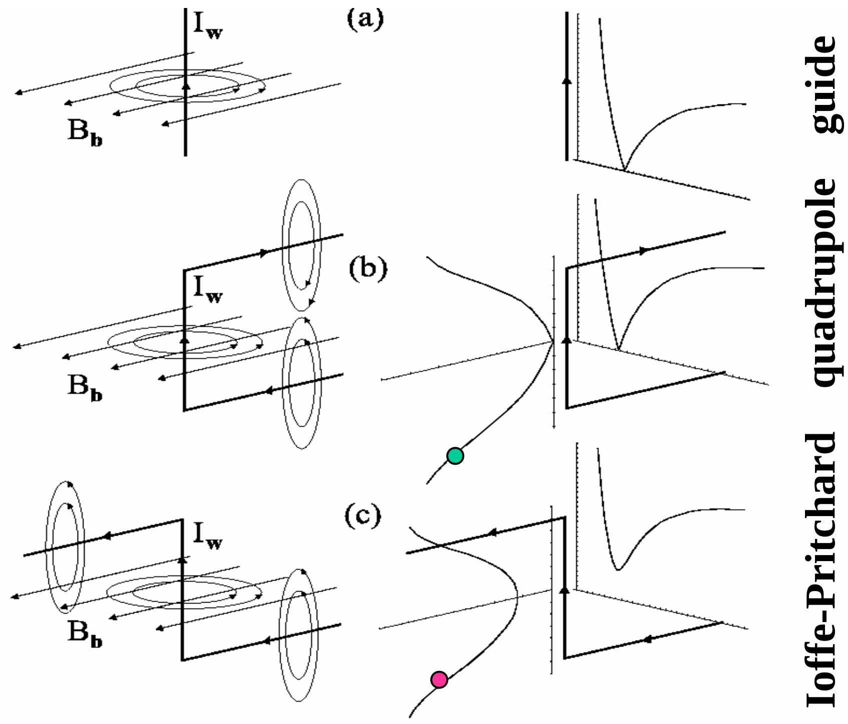
meta stable state

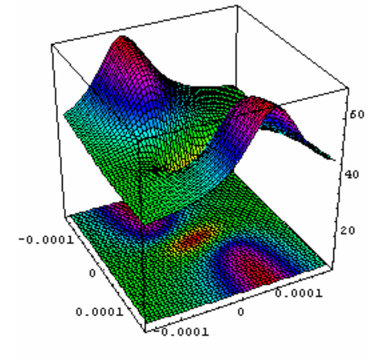


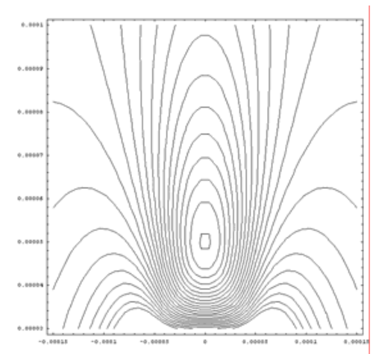
$E=g_F m_F \mu_B |B|$

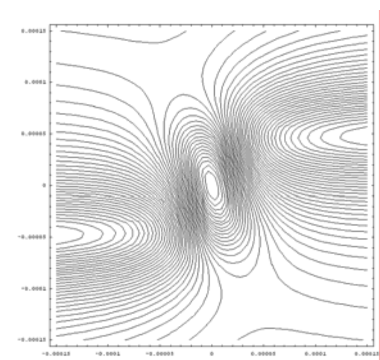


Bending the wire closes the guide and creates 'end caps'







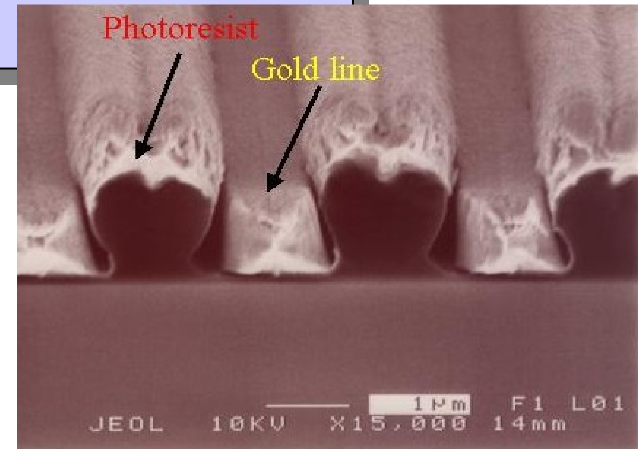


- Adiabaticity
- Earnshaw theorem

More sophisticated geometries:

Weinstein, Libbrecht PRA 52, 4004 (1995)

Fabrication



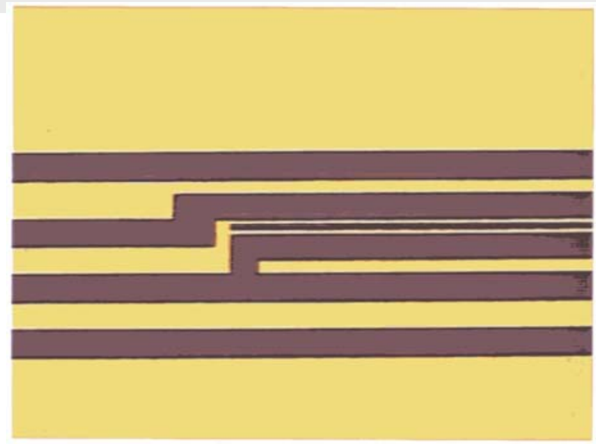
Motivation

Israel Bar Joseph, Weizmann
Soenke Groth et al. (2004)

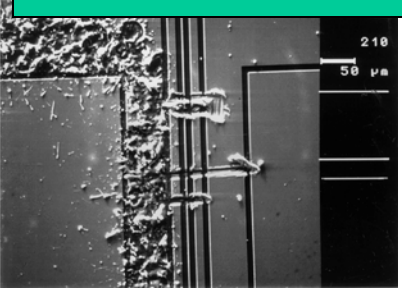
- Miniaturization (<100nm):
  - $I^2R \ \alpha$ width & $B' \ \alpha \ 1/h \ \alpha \ 1/\text{width}$
  - nm scales between well localized sites for entanglement.
  - accuracy of the de-Broglie wave length scale
- Heat sink
- Robustness
- Scalability (arrays)
- 3d (multi layers)
- Photonics (monolitic)

currently

- current densities $> 10^7$ A/cm^2
- high voltages > 600V
- starting light elements
- starting multi layer designs

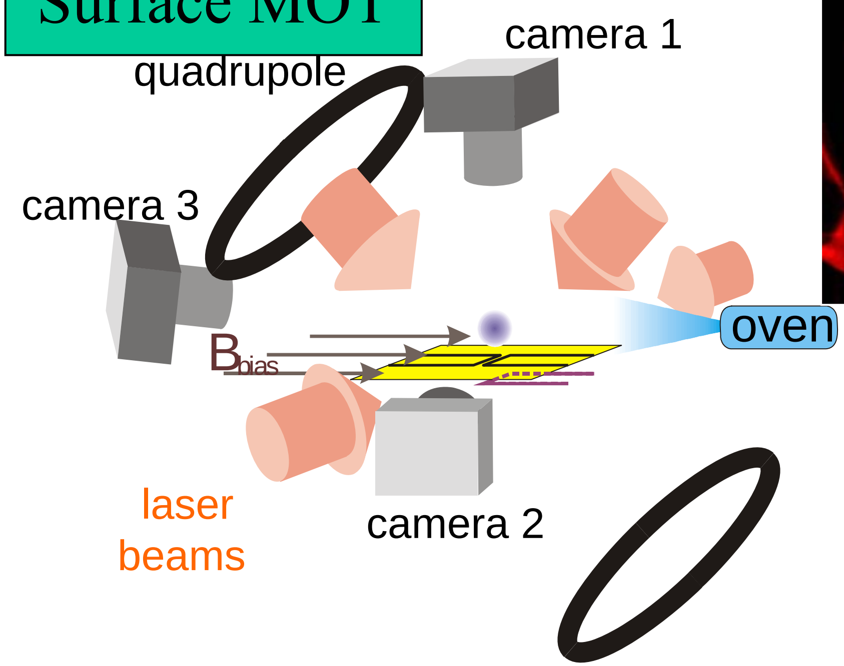


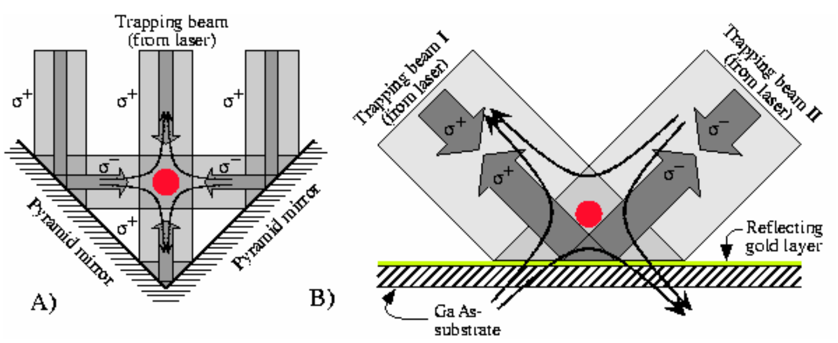
Burning: Moon craters and stars

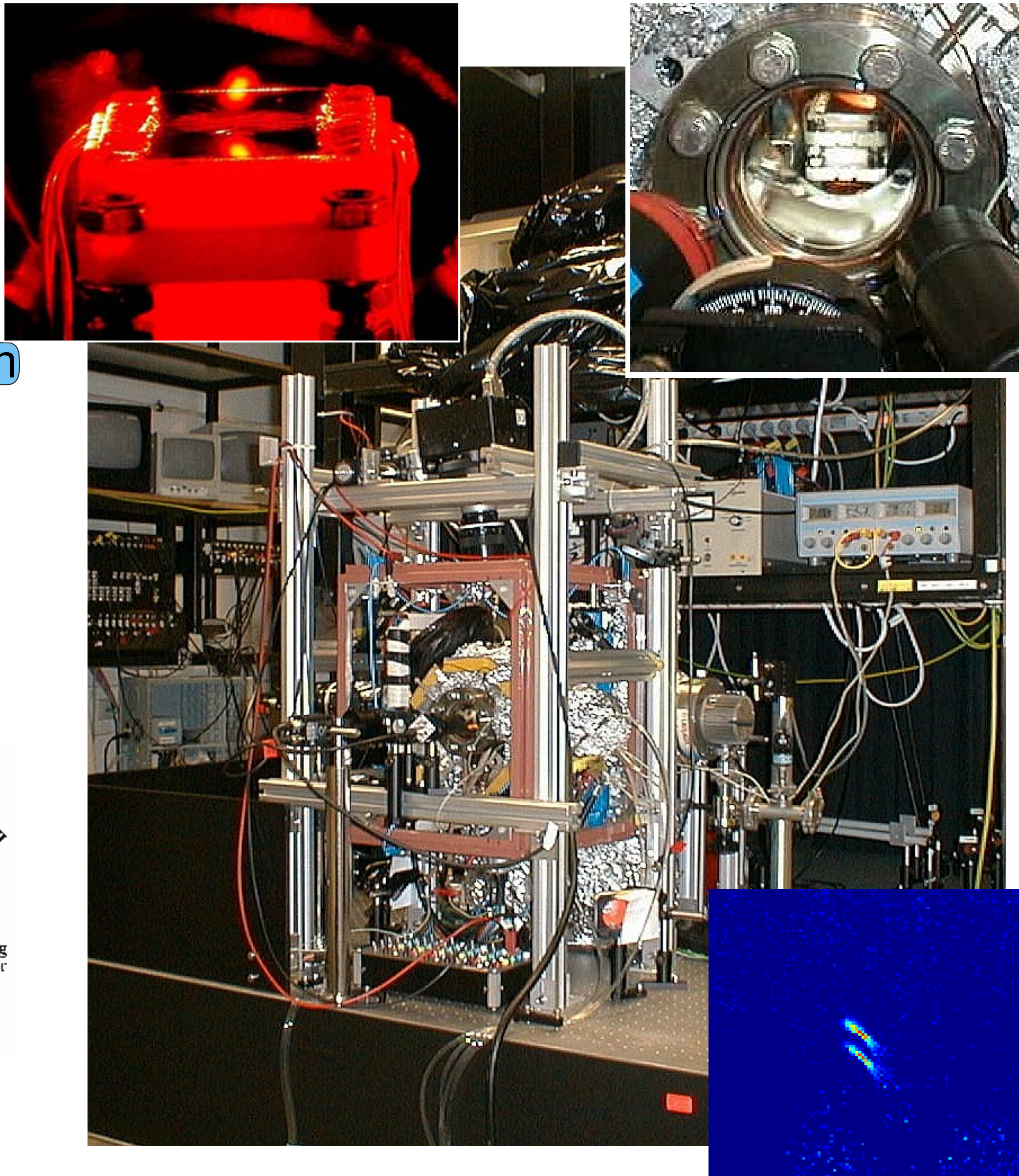


Loading the chip (Lithium)

Surface MOT







(1+2) Neutral atom & chip: Why is this combination good?

Best of two worlds:

- **Well isolated system**

Stable quantum state evolution

- **Well established control of external and internal degrees of freedom**

For writing of information and for initiating quantum state evolution

- **Well established miniaturization techniques**

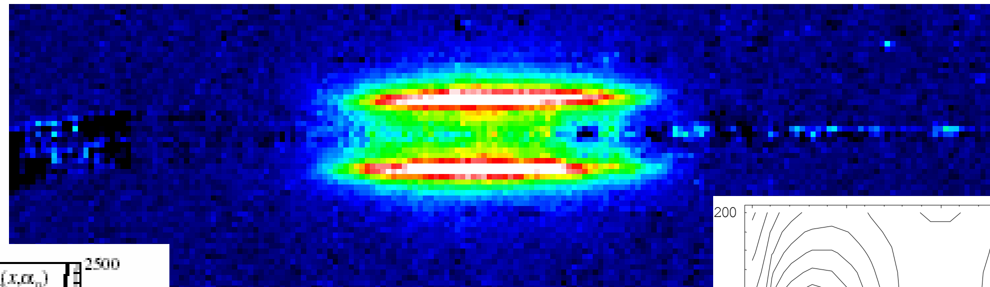
For highest density packing and addressability

→ **The atom chip**

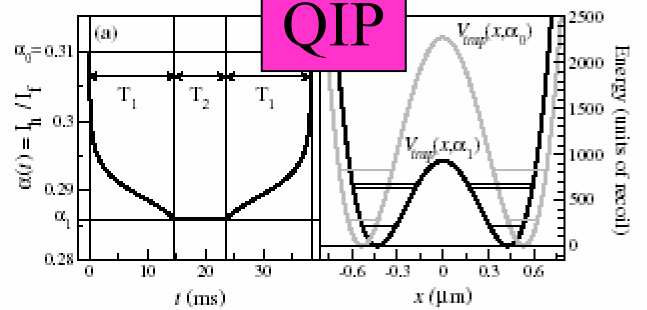
Atom chip results so far:

Complex potentials

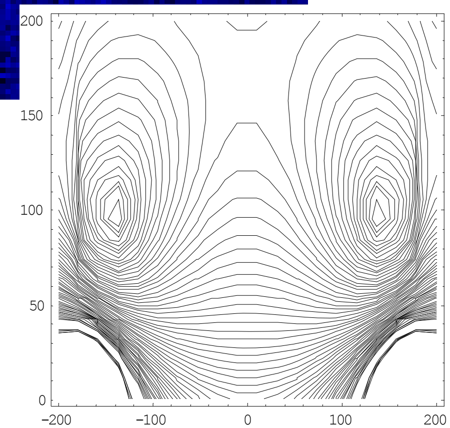
Splitting in a time dependent potential



QIP



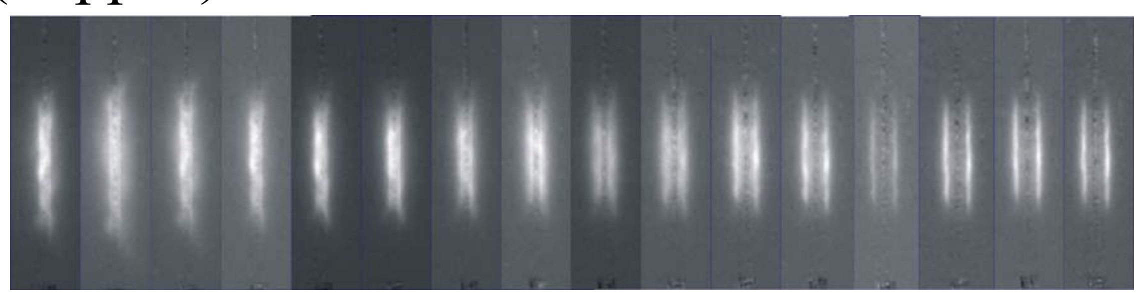
2.0A, 40G, 100μm



|0>, |1> Motional gate (trapped)

C. Williams

In our lab (thermal):

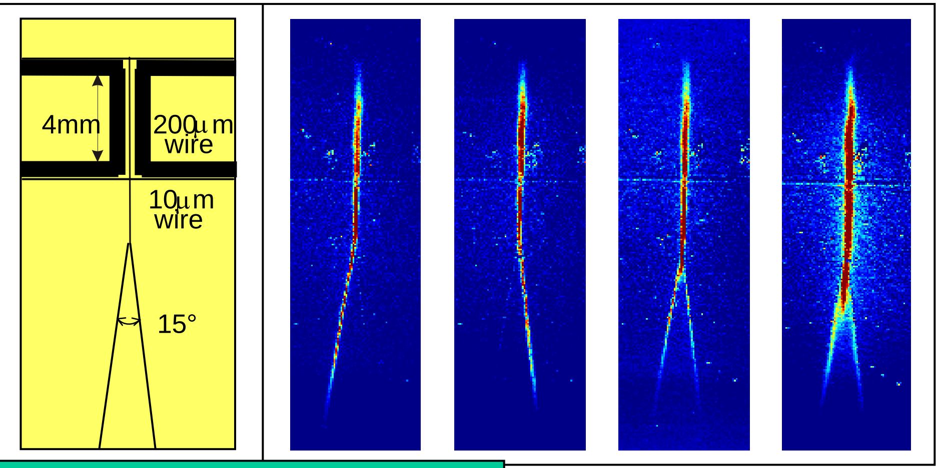


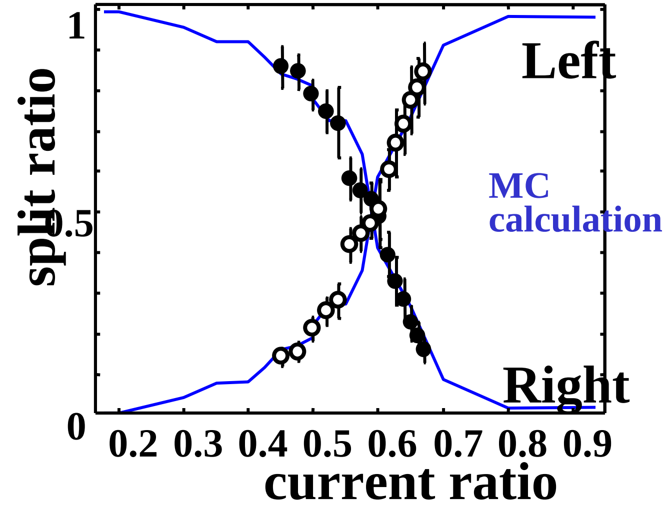
14G

44G

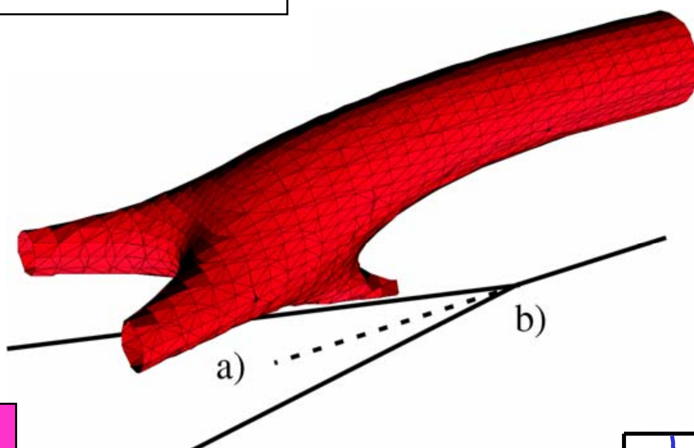
Beam splitter for guided atoms

D. Cassettari et al. PRL 85, 5483 (2000)
Nature 409 (2001).

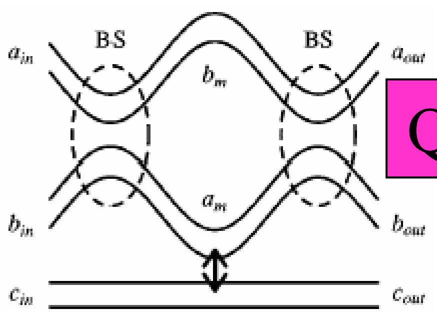




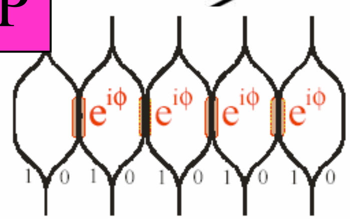
Coherent??

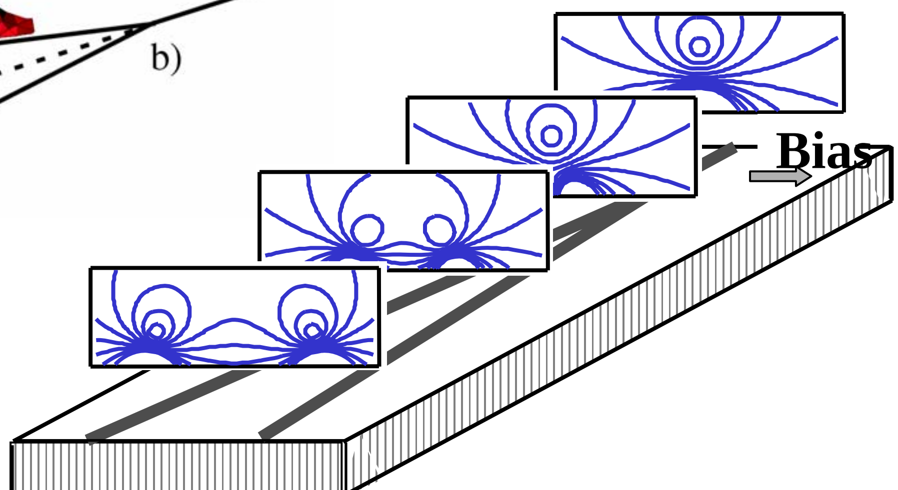


E. Andersson



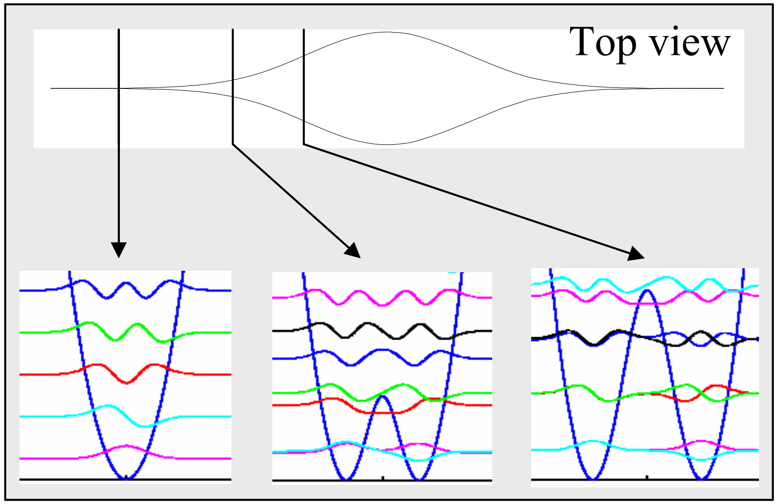
QIP



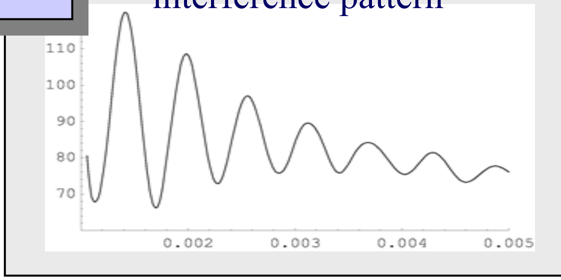


|L>, |R> Motional gate (propagating)

Some theory of an Interferometer

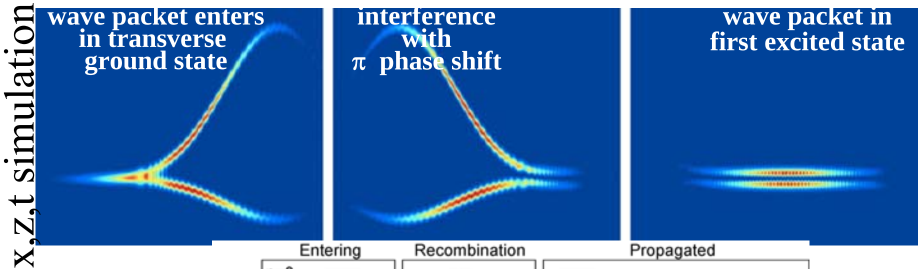


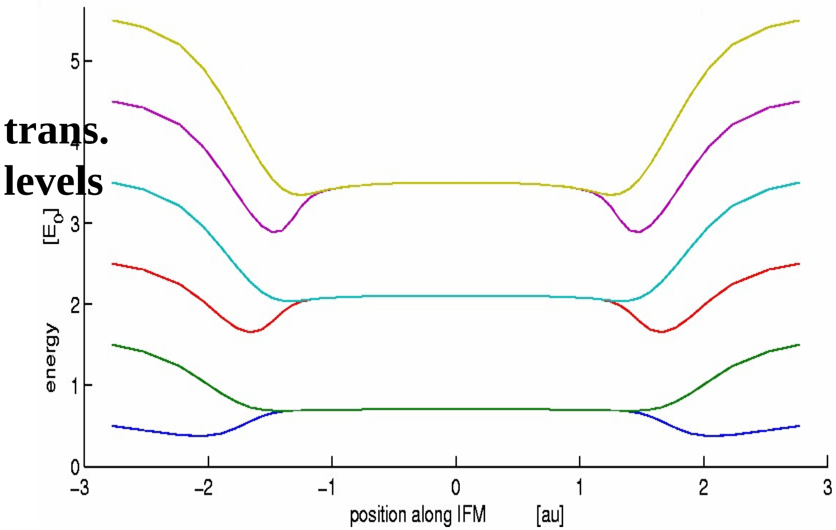
multi mode
interference pattern

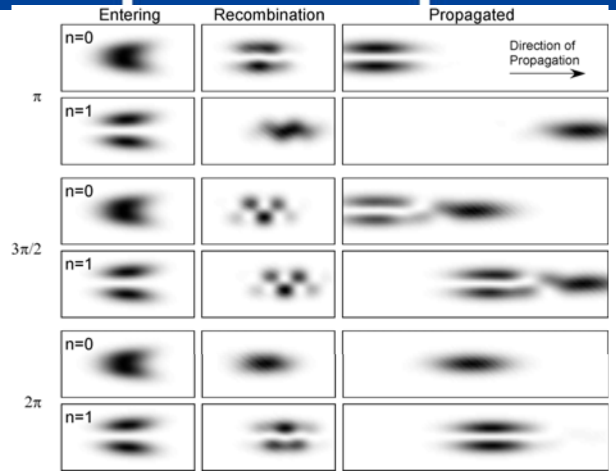


E. Andersson et al. PRL 88, 100401 (2002)

due to rephasing of the even and odd states







Interferometers inherently connected to QIP

Why have we not seen an interference pattern yet? 3 possible reasons

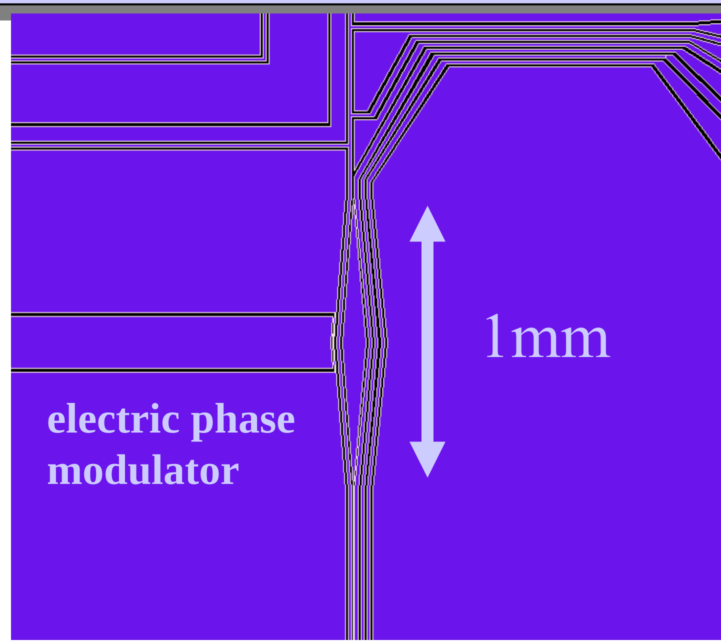
Answer I: Beam splitters are non trivial

Real designs

for elecrons: E. Buks et al. Nature (1998)

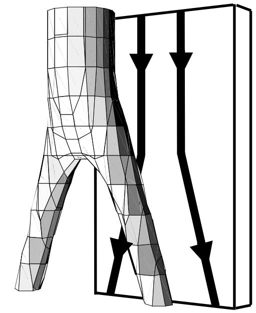
Multi Mode IFM:

One input - one output



improved 3-port:

- no 4th port
- no height change



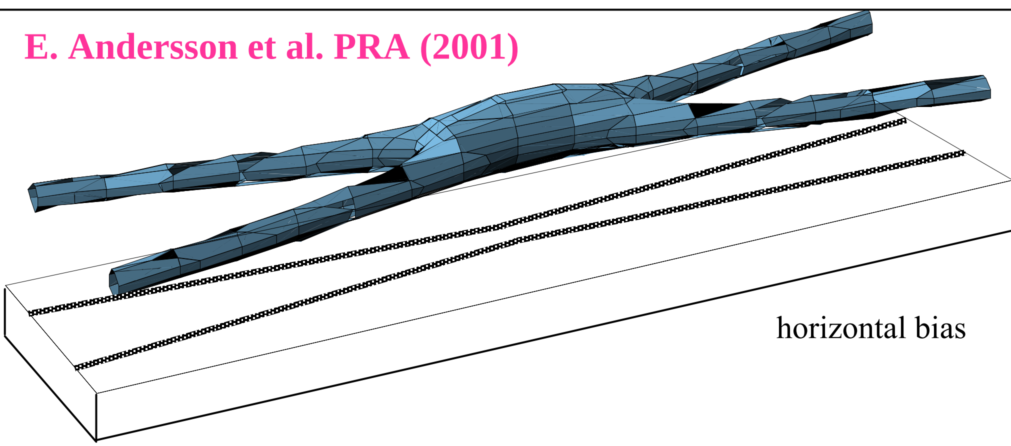
horizontal bias

Mach-Zehnder

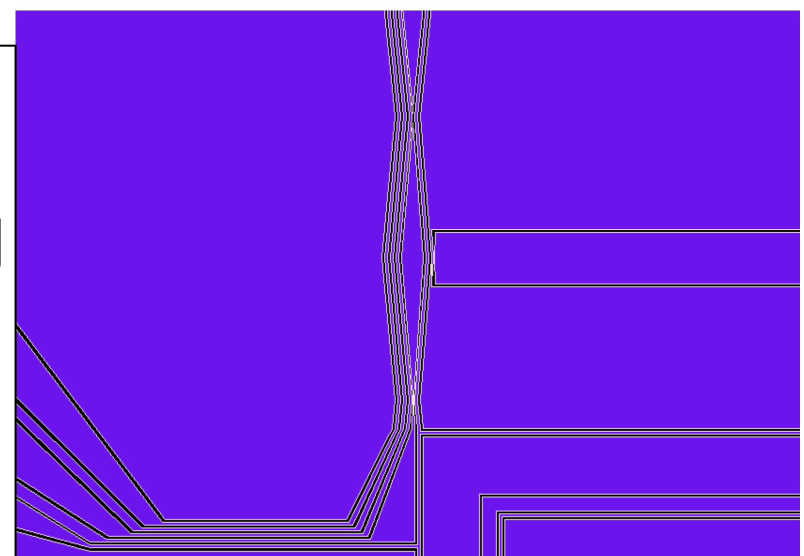
Single Mode IFM:

Two input - two output

E. Andersson et al. PRA (2001)

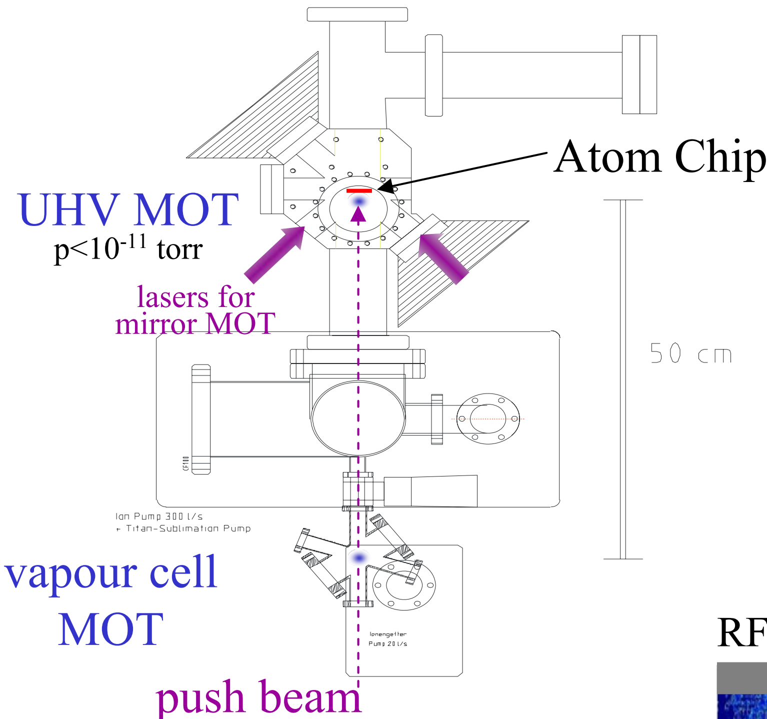


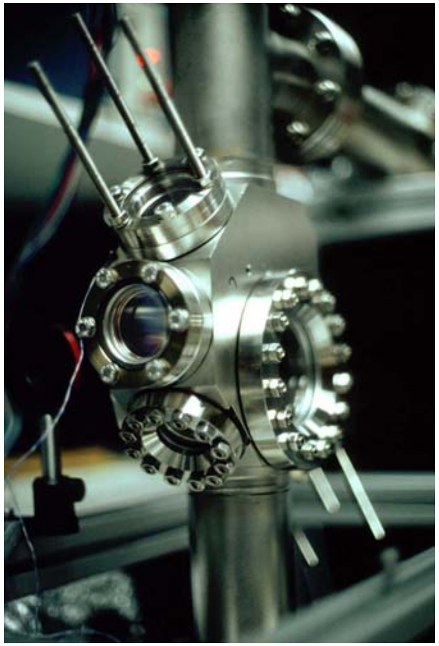
Single mode tunneling beam splitter

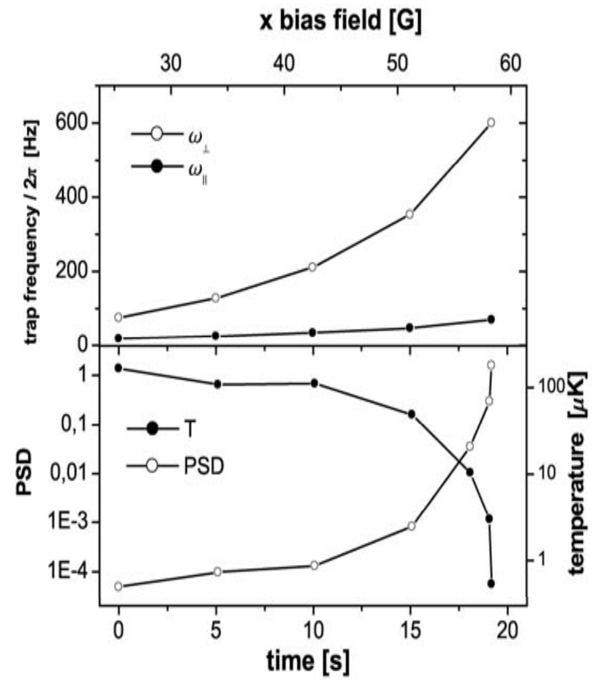


Answer II: we have a BEC but no real single mode propagation

Rb 2 MOT, BEC experiment





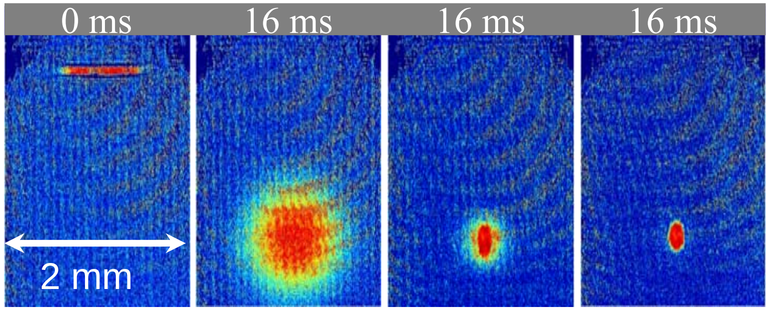


transversal: 2π x 600 Hz

longitudinal: 2π x 70 Hz

Gradient (transv.): 400G/cm

RF start at 19MHz/4x10^7 atoms, and continue for 19s



RF end frequency 800 kHz 650 kHz 630 kHz

BEC:
3 x 10^5 Atoms
T_c ~ 600 nK
d_{chip} ~ 300 μm

New state of matter: See Kishan Dholakia's talk

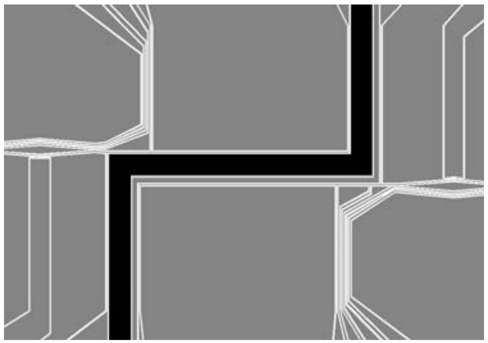
BEC – Cont.

On the surface

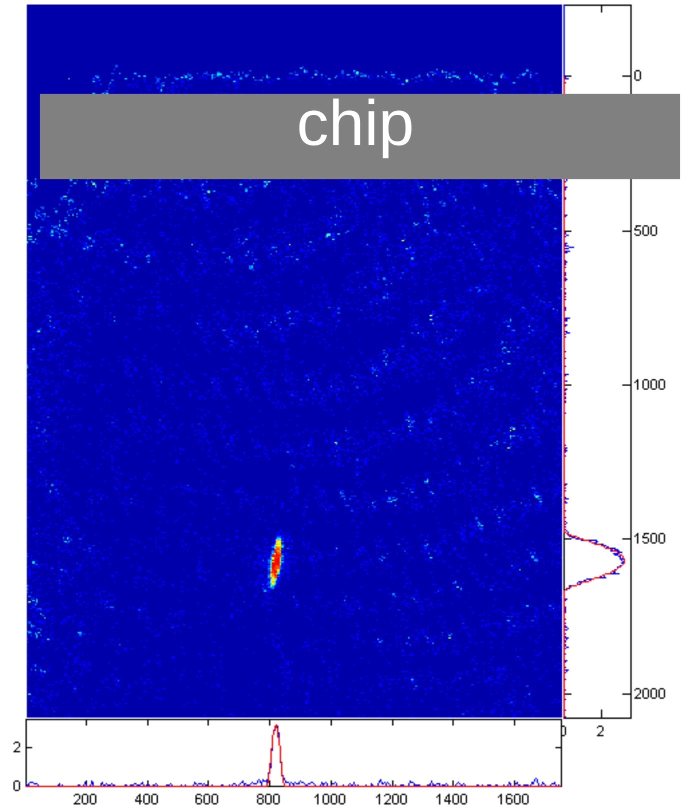
S. Schneider et al.,

Phys. Rev. A 67, 023612 (2003), (cond-mat/0210488).

Atom Chip layout

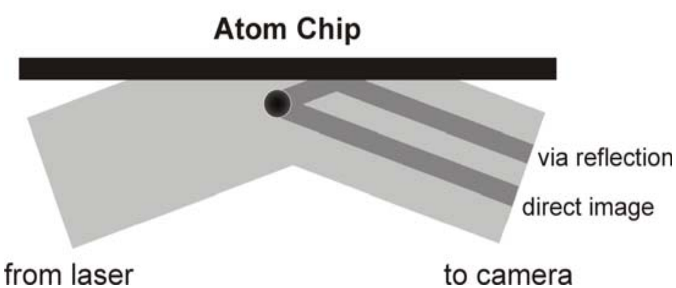


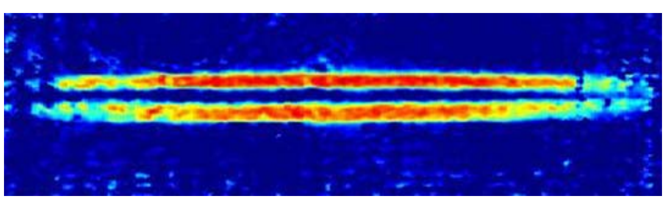
2 mm Z
200 x 2 μm^2 wire
I_W = 2 A
B_{bias} = 15 G
height = 250 μm
N = 4 x 10^4



BEC after the transfer to the 200μm gold wire and 15 ms expansion

‚Reflection imageing‘ of a thermal cloud (Cu-Z-trap) on the chip surface





Answer III: Surface effects, but before that a look at some new tricks

- P. Krueger, X. Luo, M. W. Klein, K. Brugger, A. Haase, S. Wildermuth, S. Groth, I. Bar-Joseph, R. Folman, J. Schmiedmayer, 'Trapping and manipulating neutral atoms with electrostatic fields', to appear, Phys. Rev. Lett. (2004) quant-ph/0306111.

- X. Lou, P. Krueger, K. Brugger, S. Wildermuth, H. Gimpel, M.W. Klein S. Groth, R. Folman, I. Bar-Joseph, J. Schmiedmayer, 'An atom fiber for guiding cold neutral atoms', quant-ph/0311174 (2004).

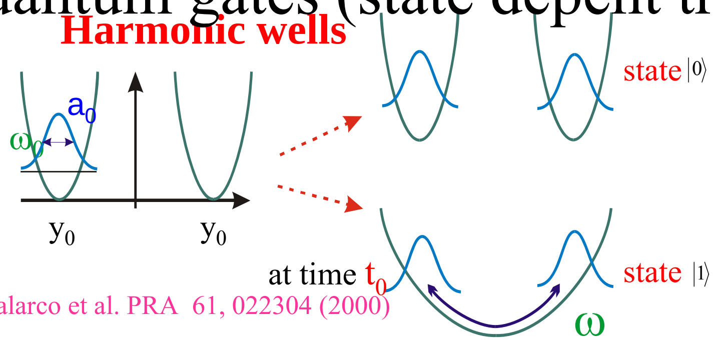
- S. Wildermuth, P. Krueger, C. Becker, M. Brajdic, S. Haupt, A. Kasper, R. Folman, J. Schmiedmayer, 'Optimized U-MOT for experiments with ultracold atoms near surfaces', to appear, Phys. Rev A., cond-mat/0311475 (2004).

Combined E&M traps

Another degree of freedom

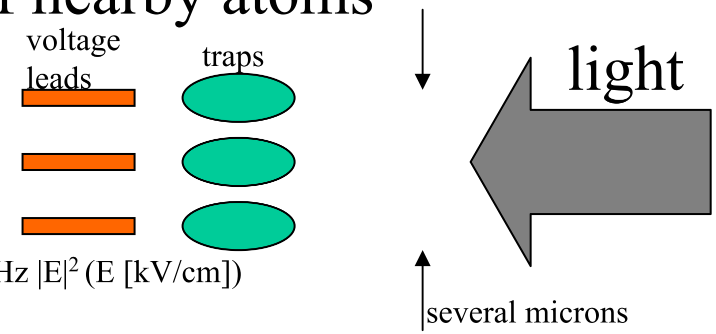
$$U_{el} = -\frac{1}{2}aE^2$$

e.g.1 controlled collision for quantum gates (state depent trap)



T. Calarco et al. PRA 61, 022304 (2000)

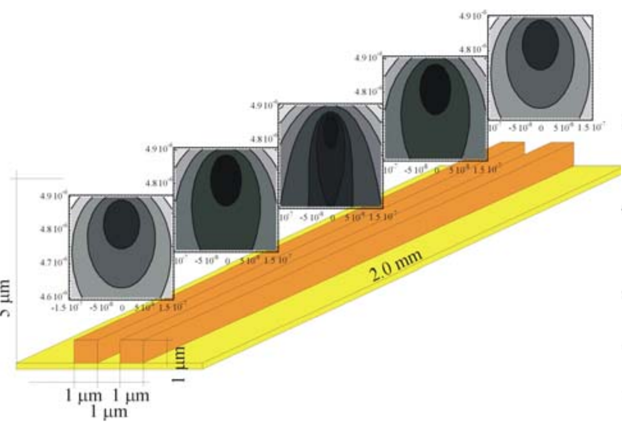
e.g.2 Individual hyperfine manipulation of nearby atoms

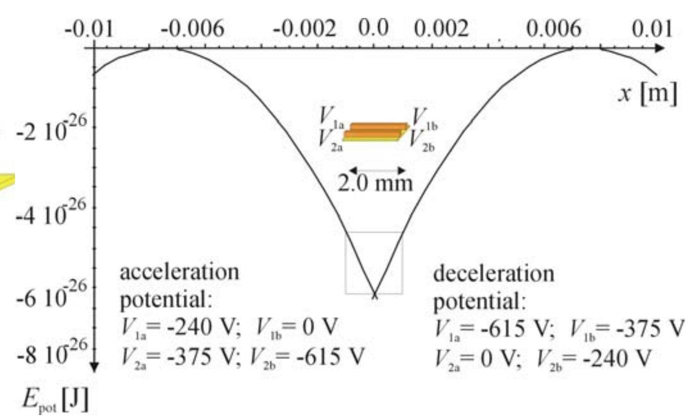


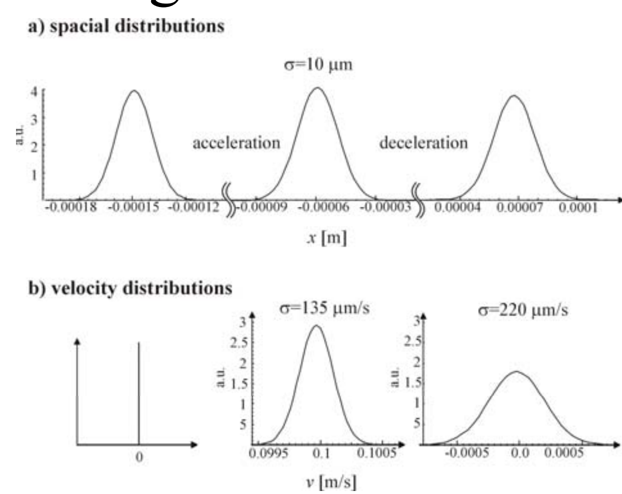
Δf=100kHz $|E|^2$ (E [kV/cm])

e.g.3 the electric motor (no additional wires): 200µm in 3.6ms (<600V)

vertical magnetic guide + electric variations in the magnetic minimum

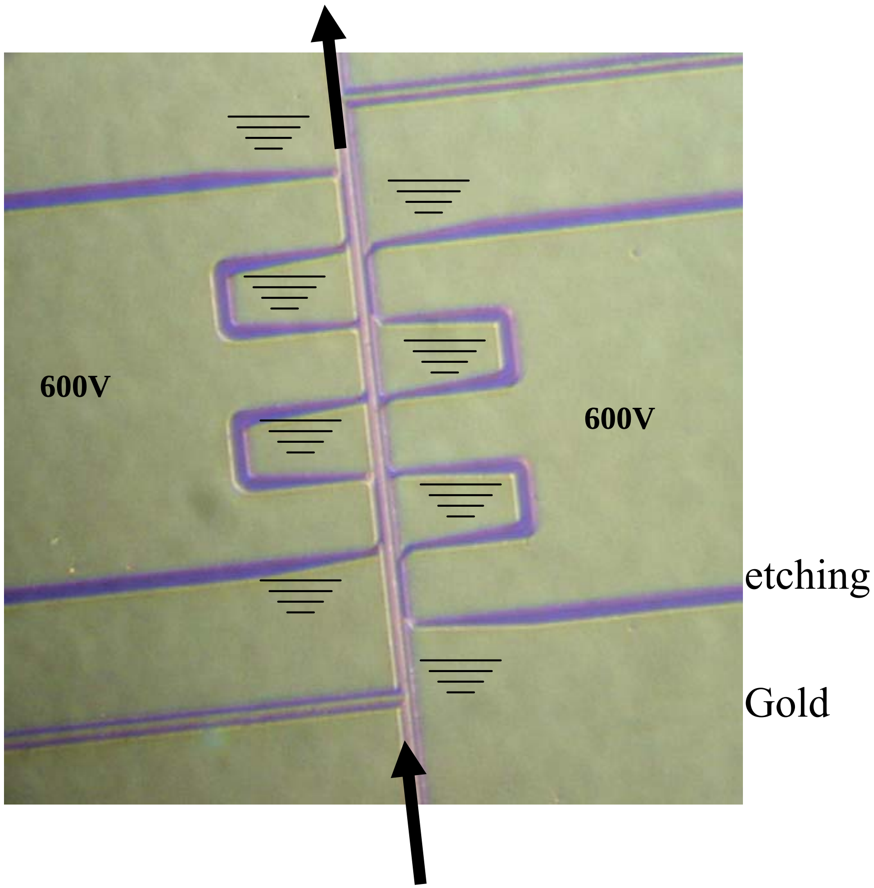




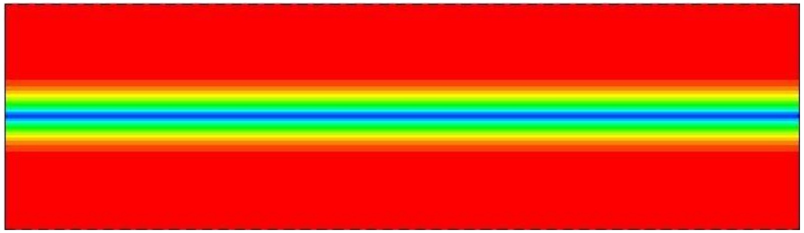


Combined E&M traps II

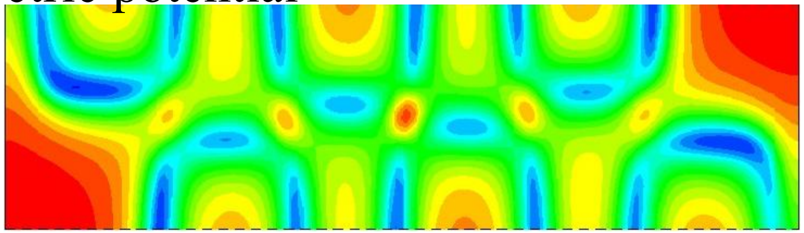
Experimental configuration

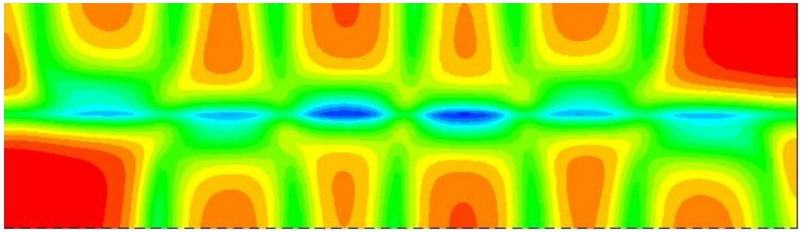


magnetic potential



electric potential





Combined E and B potential

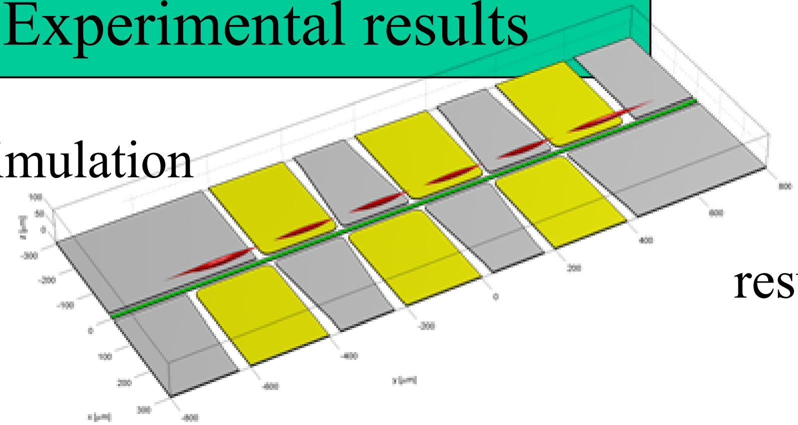
Combined E&M traps III

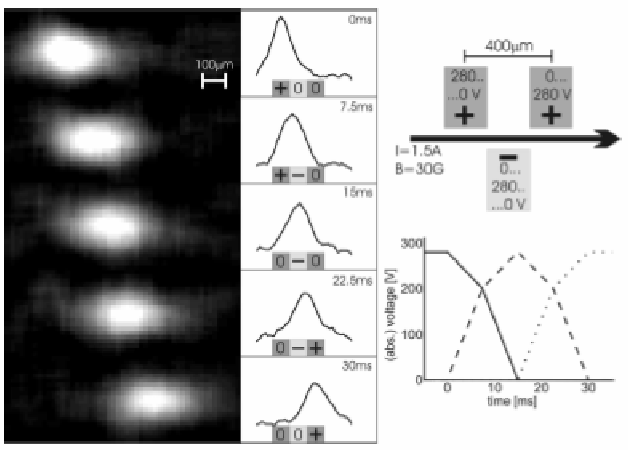
Experimental results

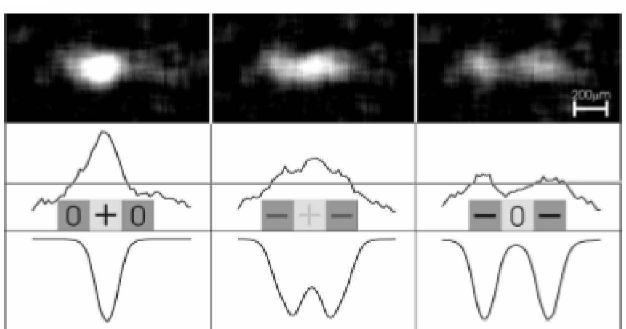
P. Krueger et al.
(quant-ph/0306111)

electric traps: 300 V
magnetic guide: 1.6 A, 44 G
height: 70µm

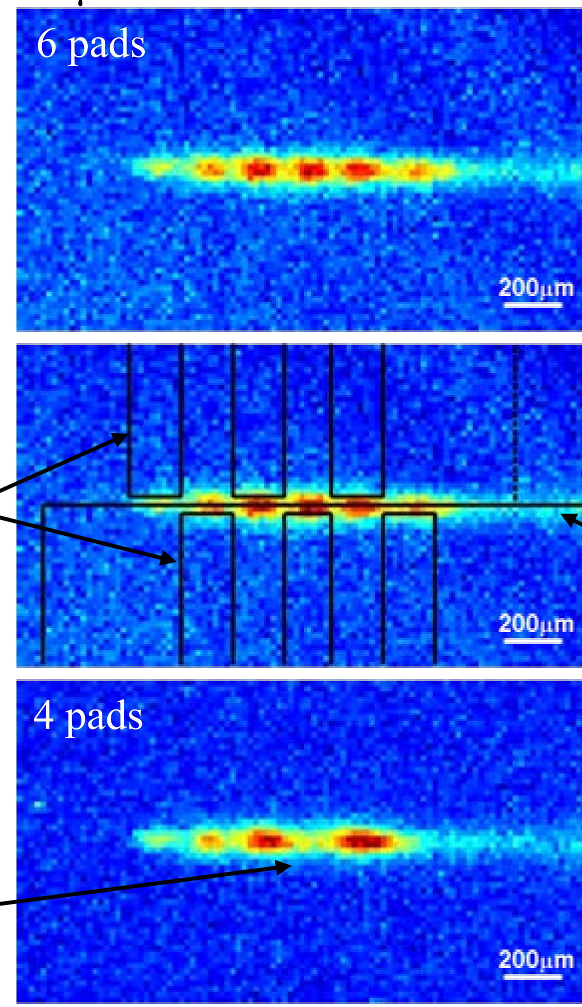
simulation







results



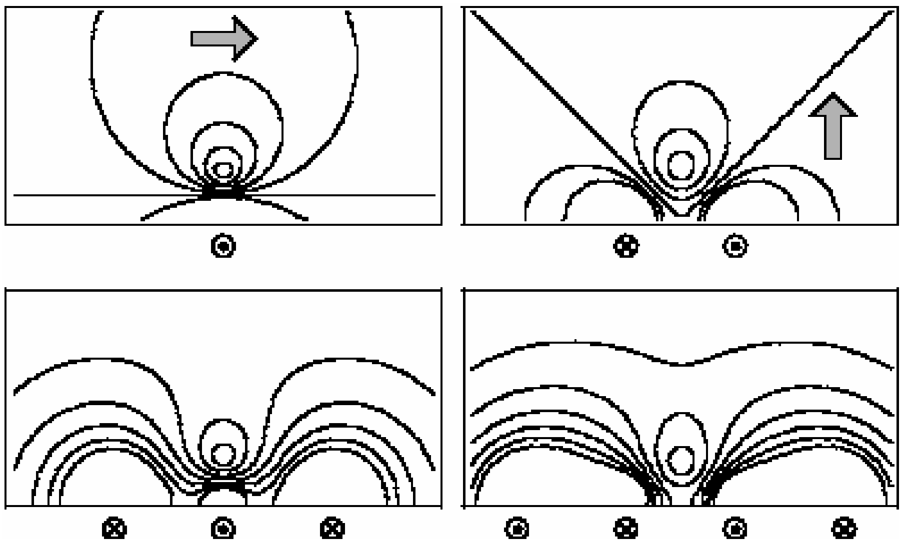
HV electrodes

side guide wire

de-focusing of the electric field lines

Atom fiber: Vertical traps

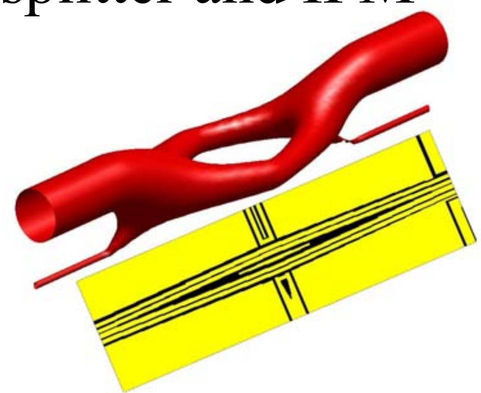
Motivation: full use of available surface and directions

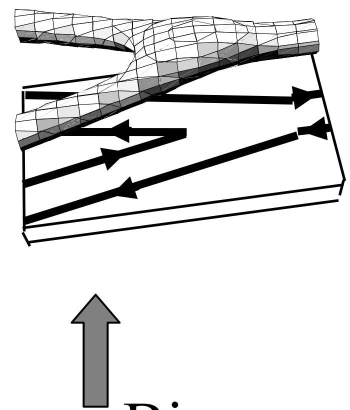


vertical bias field perpendicular to wires
whatever their direction on the chip

Prentiss. PRL 84, 1124 (2000)

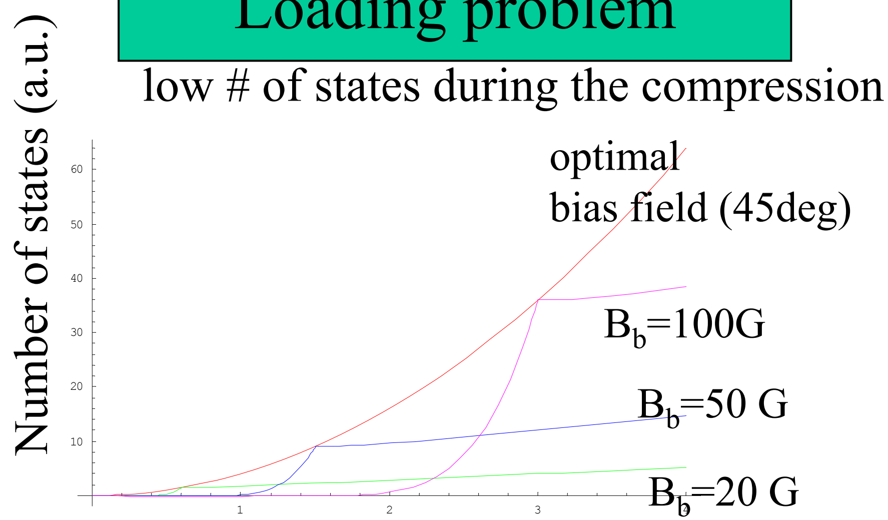
e.g. optimal beam splitter and IFM





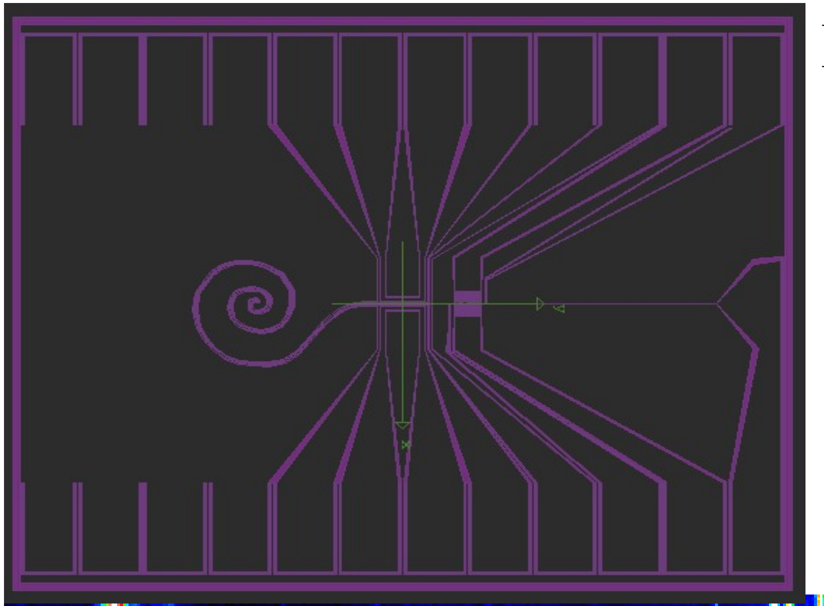
Loading problem

low # of states during the compression



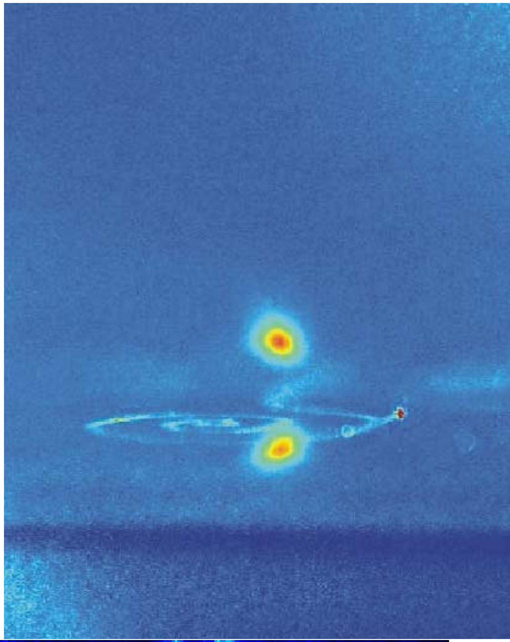
\# of states according to PRA 53, 381 (1996)
Model: quadrupole trap with constant harm. confinement in longitudinal direction. Reality: *no* confinement in longitudinal dir., i.e. non-equilibrium problem. In the model: rho(E)=const. E^3/grad^2
\# of states = const. $\text{barrier}^4/\text{grad}^2$
Here: 120 micron wire distance (center to center)

Vertical traps II

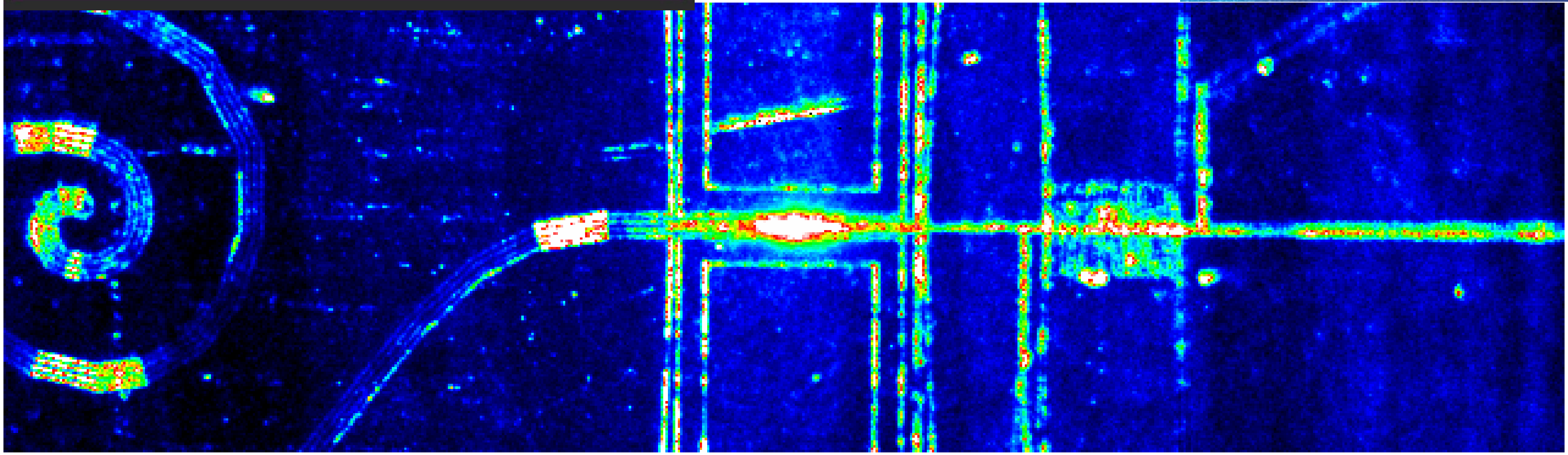


Design

Loading I:
Silver U



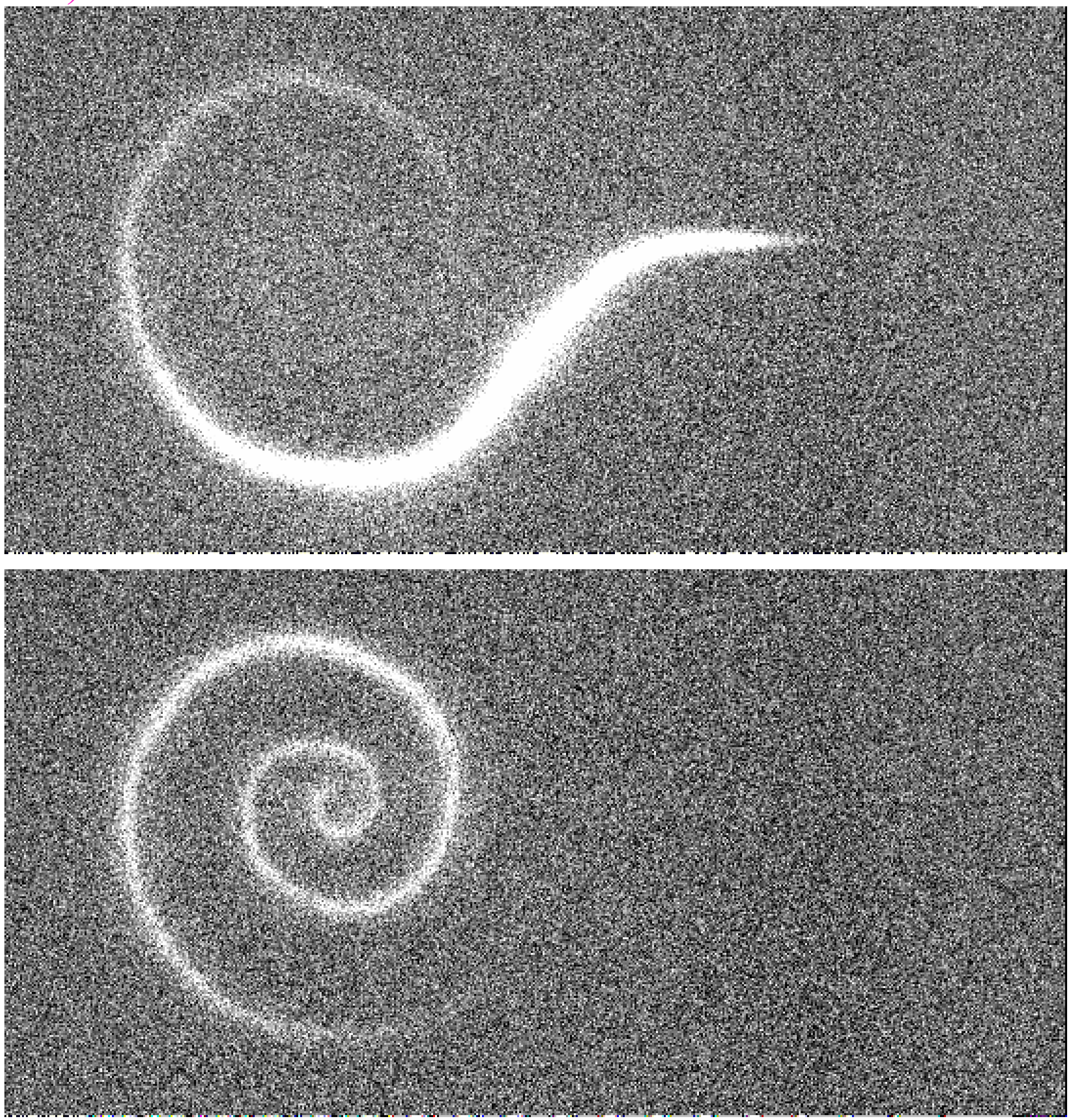
Loading II:
50μm U



Vertical traps III

X. Lou et al,
quant-ph/0311174 (2004)

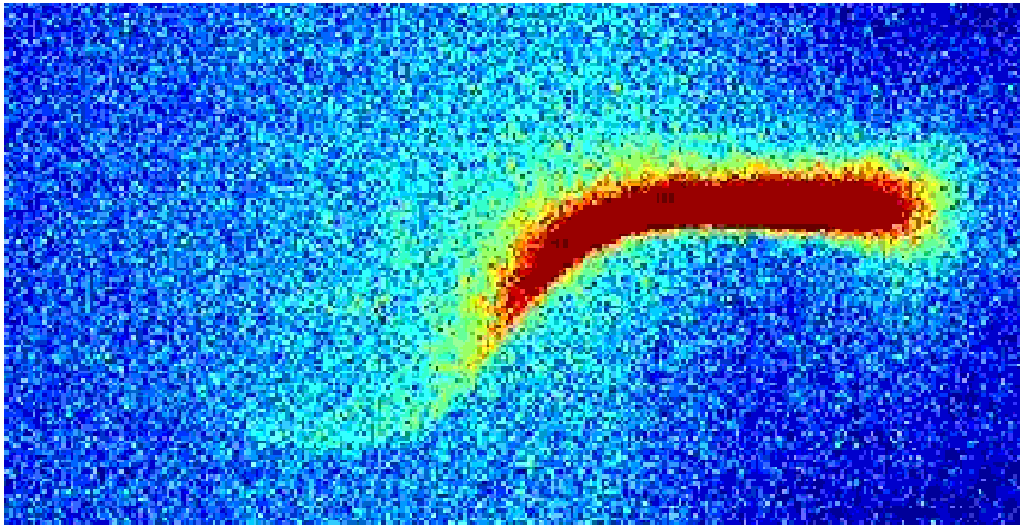
Height of 35-450 microns



30ms

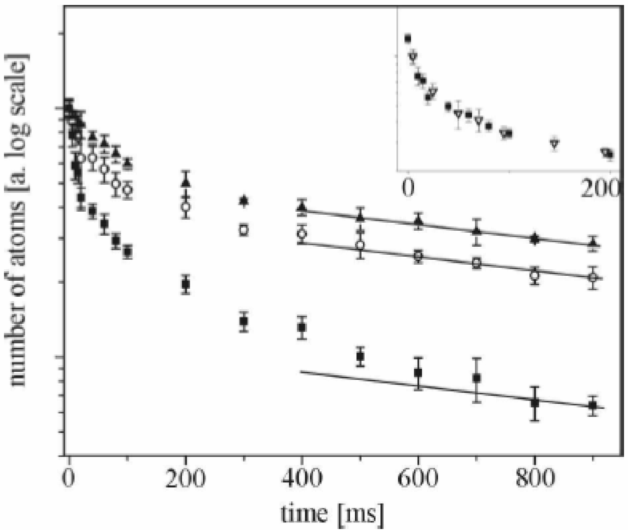
65ms

1.0A 8-35G

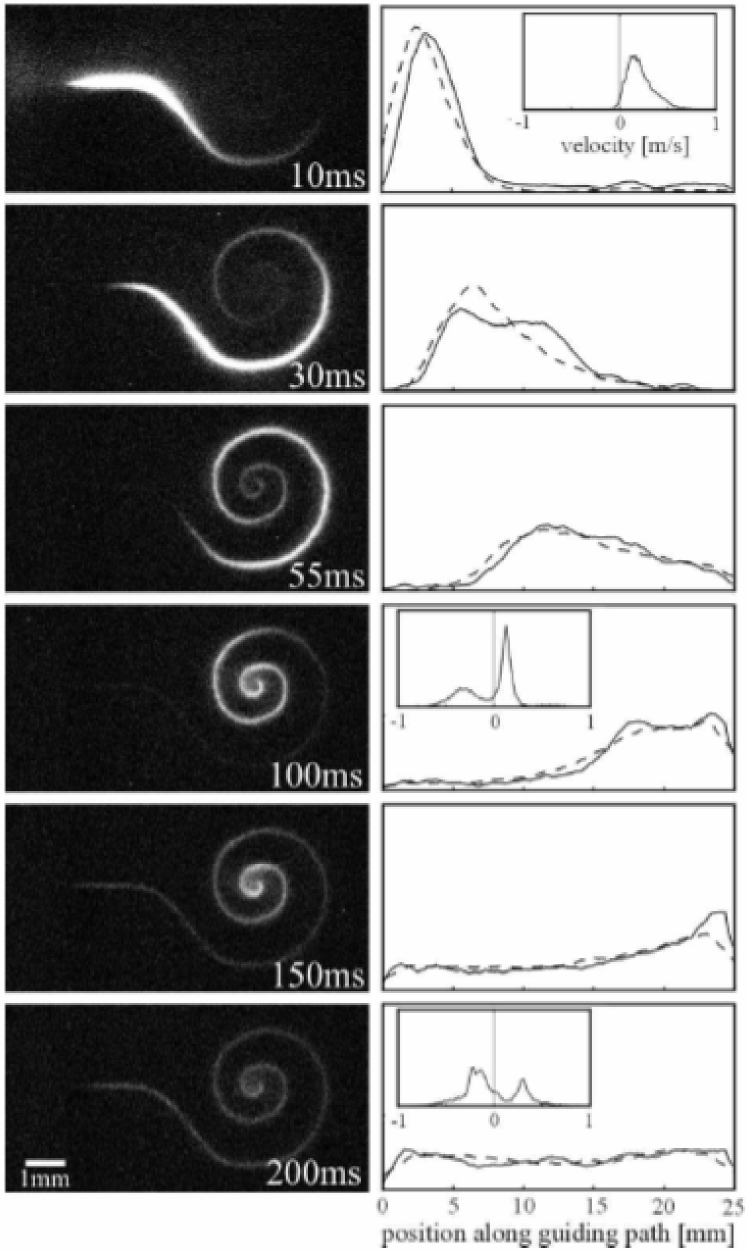


Vertical traps IV

Lifetime

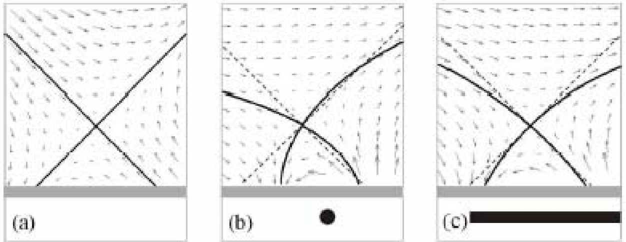


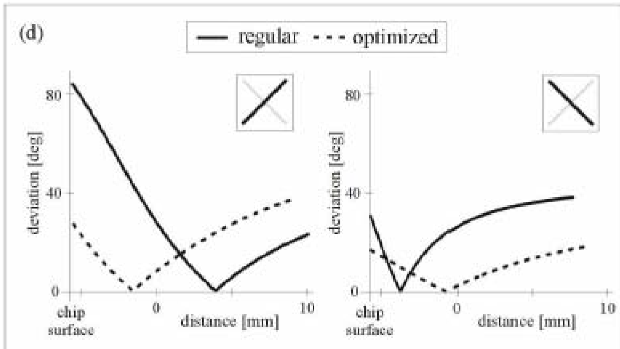
Way Back...

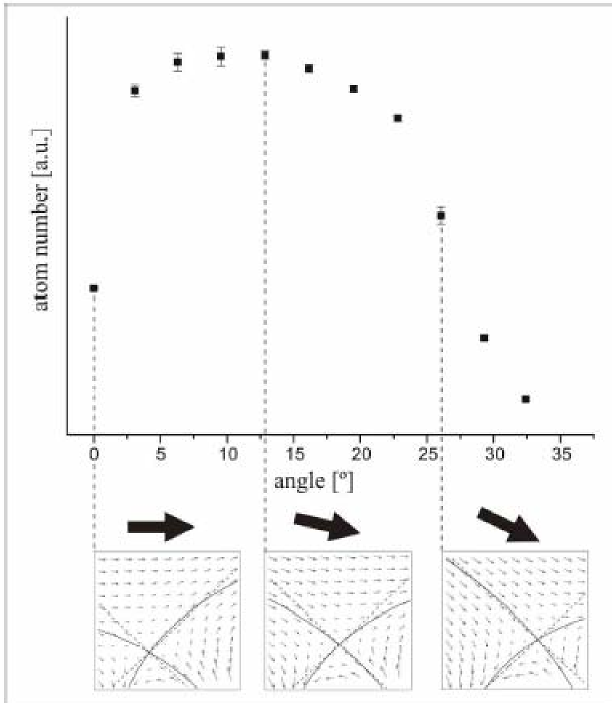


A Coil Free MOT

Old dog... New tricks...

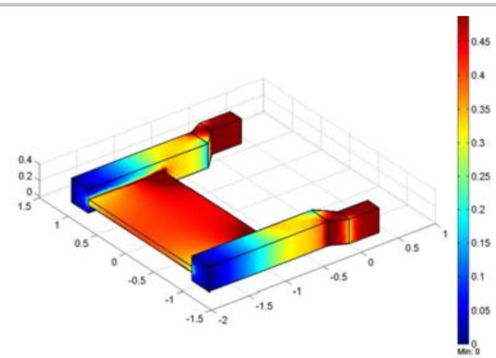




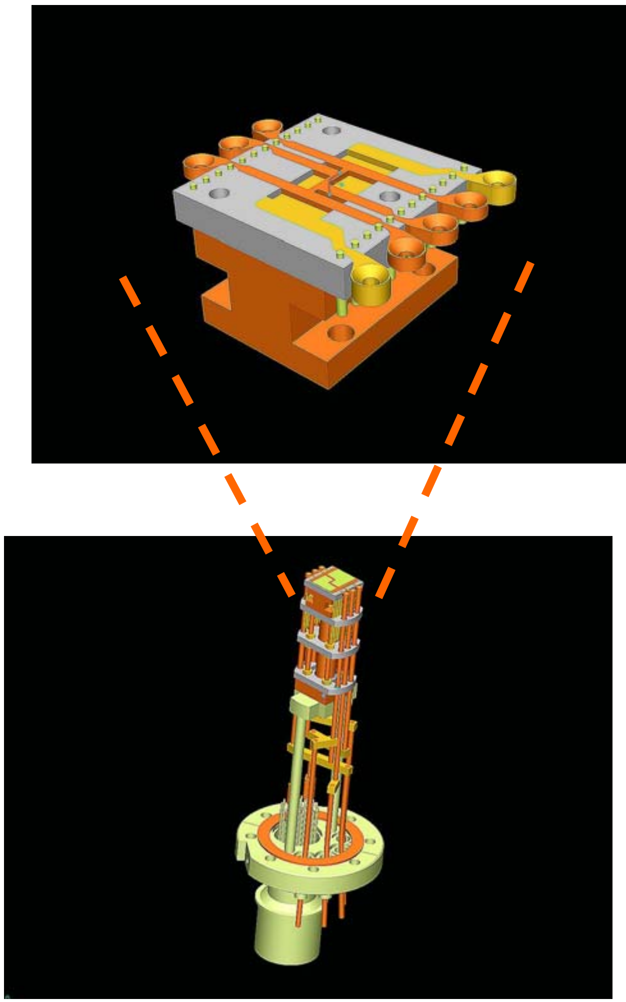


Experimental advantages:

- can be switched on/off immediately
- no quadrupol coils required any more
- 1kW ⟶ 1W



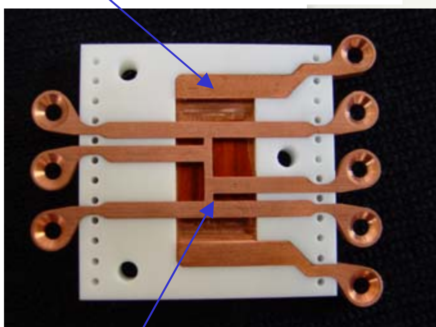
Current distribution

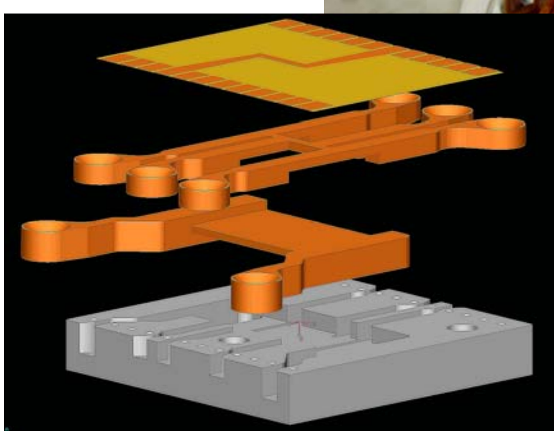


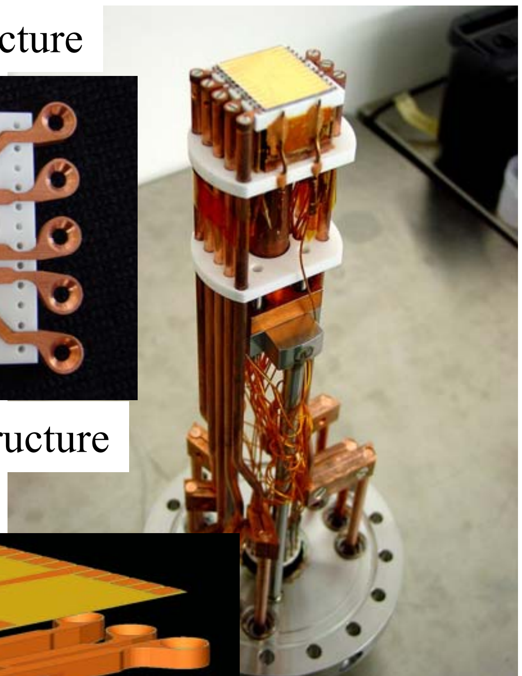
A Coil Free MOT II

Experimental realization

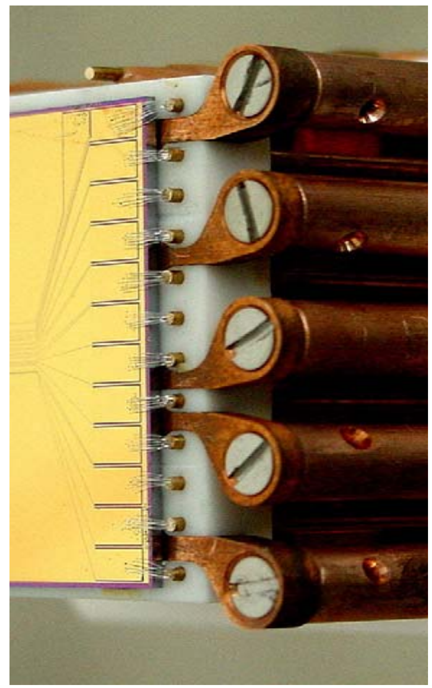
S. Wildermuth et al., cond-mat/0311475 (2003)







the complete chip mounting



detailed picture of chip bondings

„Quadrupole coil free MOT“ with up to 10^9 atoms (note shadows).
Gradients 10-25 G/cm.
After 10s evaporation, 10^5 in BEC (2π x 150-1500Hz, 35-50Hz, 190-450G/cm)

Back to our third problem: surface effects

The short DiVincenzo list for QIP (quant-ph/0002077, 2000):

- storage of the quantum information in a 2-level system (qubit)
- manipulating the state through 1-qubit operations
- processing the information using 2-qubit gates
- reading out the results
- <u>long coherence times relative to the gate (‘clock‘) time (10^4!!!)</u>

$\longrightarrow$ Decoherence (de-phasing), Zeh, Zurek, Aharonov...

The tibetian monk....

Solutions:

- realistic estimate of the coupling to noisy environment
- environment engineering
- non-destructive measurements
- error correction

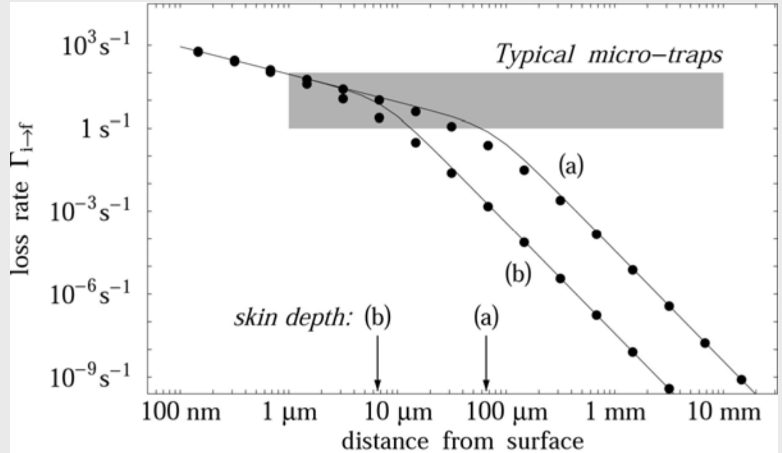
Loss: Spin flips (fluctuations perpendicular to the spin)

Loss due to Johnson noise magnetic fields

C. Henkel et al., Applied Physics B76, 173 (2003)

$$\gamma \simeq 75\mathrm{s}^{-1} \frac{(\mu/\mu_\mathrm{B})^2 (T_s/300\mathrm{K})}{(\varrho/\varrho_\mathrm{Cu})} (\mathrm{Tr} Y_{ij} \times 1\mu\mathrm{m})$$

Geometry	Tr Y_{ij}
Half-space	π/h
Layer	$\pi d/h^2$
Wire	$\pi^2 a^2/(2h^3)$



Majorana transitions in a harmonic trap

$$\gamma = \frac{\pi\omega}{2\sqrt{\mathrm{e}}} \exp(-\mu_{\|} B_{ip}/\hbar\omega)$$

$$= 6 \times 10^5 \mathrm{s}^{-1} \frac{\omega/2\pi}{100\mathrm{kHz}} \exp\left(-14 \frac{(\mu_{\|}/\mu_B)(B_{ip}/\mathrm{G})}{\omega/2\pi\, 100\mathrm{kHz}}\right)$$

ω_L=10ω $\gamma \sim 10^{-4}\,\omega$

Technical current noise

$$\gamma \simeq \frac{\mu^2}{2\hbar^2} \left(\frac{\mu_0}{2\pi h}\right)^2 S_I(\omega_L)$$

$$\simeq 1.3\mathrm{s}^{-1} \frac{(\mu/\mu_B)^2}{(h/1\mu\mathrm{m})^2} \frac{S_I(\omega_L)}{S_{\mathrm{SN}}}$$

S_{SN}=3.2 10^{-19} A^2/Hz

Loss mechanisms for the atom chip (overview). The columns 'Scaling' and 'Magnitude' refer to loss rates per atom at typical atom chip traps: density $n = 10^{10}\text{cm}^{-3}$, height $h = 10\mu\text{m}$, trap frequency $\omega/2\pi = 100\text{kHz}$, Larmor frequency $\omega_L/2\pi = 5\text{MHz}$.

Mechanism	Scaling	Magnitude	Workaround
Spilling over			deep trap potential
Background collisions[a]	p_{bg}	0.01s^{-1}	ultra-high vacuum
Majorana flips[b]	$\omega\, \mathrm{e}^{-\omega_L/2\omega}$	$\simeq 1\text{s}^{-1}$	avoid $B_{ip} = 0$
Near field noise[c]	$T_s/\varrho h^\alpha$	10s^{-1}	little metal
Current noise[d]	$S_I(\omega_L)/h^2$	$\simeq 3\text{s}^{-1}$	quiet drivers
2-body spin exchange[e].	n	10^{-4}s^{-1}	spin polarize
2-body spin relaxation[f].	n	$10^{-2} - 10^{-4}\text{s}^{-1}$	
3-body collisions[g]	n^2	$10^{-9} - 10^{-7}\text{s}^{-1}$	
Tunneling		10^{-3}s^{-1}	deep, thick potential
Stray light	I_{stray}		keep in the dark

[a]Eq.(25).
[b]Flip rate (18) from trap ground state
[c]Eq.(22). The exponent $\alpha = 1, 2, 3$ for metal half-space, layer, and wire (see table II). The estimate 10s^{-1} is for a half-space.
[d]Eq.(24).
[e]Experimental result for ^{87}Rb (Myatt et al., 1997)
[f]Experimental result for Cs and ^{7}Li, respectively (Söding et al., 1998; Gerton et al., 1999)
[g]Experimental result for ^{87}Rb and ^{7}Li, respectively (Burt et al., 1997; Söding et al., 1999; Gerton et al., 1999)

MIT observed life times of 20s at 70μm height (cond-mat/0211345)

MIT conclusions: at that height, lifetime limited by technical noise spin flips (current drivers connected but not on). $1/h^2$ law confirmed.
At this height our theory predicts 2s from thermally induced near field and S_I/S_{SN}=188 for 20s technical noise related lifetime.
See also Imperial College (Ed Hinds) quant-ph/0301018, Stanford (Vuletic) cond-mat/0308457, Munich (J. Reichel), etc.

Heating: vibrational excitations (frequency dependent)

Harmonic oscillator model

$$\Gamma_{0\to1} = \frac{M\omega^3}{4\hbar} S_x(\omega) = \frac{\omega^2}{8} S_{x/a_0}(\omega)$$

$$\Gamma_{0\to2} = \frac{1}{4} S_\omega(2\omega)$$

Johnson noise

$$\Gamma_{0\to1} \simeq 0.7\mathrm{s}^{-1} \times$$
$$\times \frac{(\mu/\mu_B)^2 (T_s/300\mathrm{K})}{(M/\mathrm{amu})(\omega/2\pi\,100\mathrm{kHz})(\varrho/\varrho_{\mathrm{Cu}})(h/1\mu\mathrm{m})^3}$$

Technical current noise

$$\Gamma_{0\to1} = 1.4\mathrm{s}^{-1} \times$$
$$\times (M/\mathrm{amu})(\omega/2\pi\,100\mathrm{kHz})^3 \frac{S_I(\omega)/S_{\mathrm{SN}}}{(B_b/\mathrm{G})^2}$$

$$\Gamma_{0\to2} \simeq 10^{-7}\mathrm{s}^{-1} \frac{(\omega/2\pi\,100\mathrm{kHz})^2}{(I_w/\mathrm{A})^2} \frac{S_I(2\omega)}{S_{\mathrm{SN}}}$$

Heating mechanisms for the atom chip (overview). The columns 'Scaling' and 'Magnitude' refer to transition rates from the ground state of a typical atom chip trap: lithium atoms, height $h = 10\mu$m, trap frequency $\omega/2\pi = 100$kHz. Harmonic confinement is assumed throughout.

Mechanism	Scaling	Magnitude	Workaround
Near field noise[a]	$T_s/\omega\varrho h^3$	$10^{-4}\mathrm{s}^{-1}$	
Current noise[b]	$\omega^3 S_I/B_b^2 \sim \omega S_I/h^2$	$1\mathrm{s}^{-1}$	correlate currents
Trap frequency noise[c]	$\omega^2 S_I/I_w^2 \sim S_I/h^4$	$10^{-5}\mathrm{s}^{-1}$	
Light scattering	$1/\omega\lambda^2$		reduce stray light

[a]Eq.(31), for a metal half-space.
[b]Eq.(33). Note the scalings $\omega \sim B_b^2/I_w$ and $h \sim I_w/B_b$ for trap frequency and height.
[c]Eq.(35).

Decoherence: fluctuations parallel to the spin (mainly near field)

internal states

$$\gamma_{\rm dec} = \frac{\langle \Delta\varphi^2 \rangle}{2t} = \frac{S_{\dot\varphi}(\omega \to 0)}{4}$$

SAI, PRA 90 $\quad \langle e^{i\Delta\varphi} \rangle = e^{-\gamma_{\rm dec} t}$ ← Multiplies the Interference term

same as spin flip rate

Δφ - accumulated phase difference due to noise

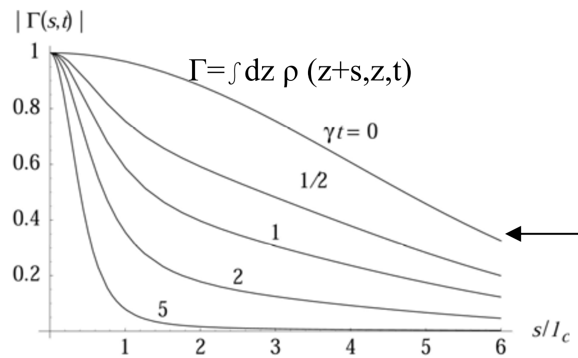
$dt/t\ \Delta\varphi = g\mu_B\,(m_f - m'_f)\ \Delta B/h$

external states

transverse and longitudinal

For separation larger than correlation length l_c:
-> same as spin flip rate

For thermal currents $l_c \cong h$



Note the effect of gravity and cloud size on wire contribution

← Initial finite off diagonal width

TABLE V. Decoherence mechanisms for atom chip interferometers (overview). The column 'Magnitude' refers to the decoherence rate $\gamma_{\rm dec}(s)$ for a typical guided interferometer: lithium atoms, height $h = 10\mu$m, separation $s = 10\mu$m, transverse guide frequency $\omega/2\pi = 100$kHz. Along the waveguide axis, the atomic motion is free.

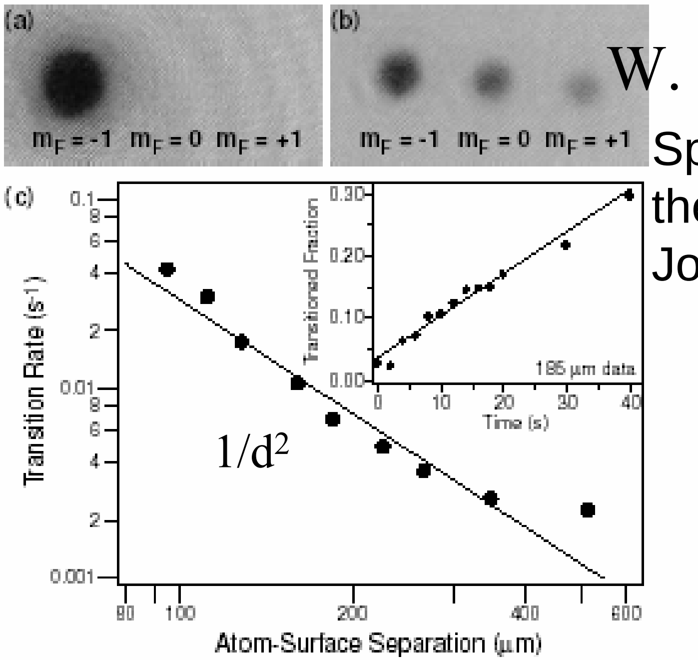
Mechanism	Scaling	Magnitude [a]	Remedy
Substrate fields [b]			
$s \ll h$	$T_s s^2/\varrho h^{\alpha+2}$	$\ll 10\ {\rm s}^{-1}$	little metal,
$s \gg h$	$T_s/\varrho h^{\alpha}$	$10\ {\rm s}^{-1}$	small splitting
Current noise [c]	$\omega^3 S_I/B_b^2 \sim \omega S_I/h$	$1\ {\rm s}^{-1}$	correlate currents
Bias fluctuations [d]	$s^2 B_b^2 S_I/R^2 I_b^2 \sim s^2 S_I/R^4$	$10^{-8}\ {\rm s}^{-1}$	
Trap frequency noise [e]	$\omega^2 S_I/I_w^2 \sim S_I/h^4$	$10^{-5}\ {\rm s}^{-1}$	

[b] Exponent $\alpha = 1, 2, 3$ for metal half-space, layer, and wire (Eq. 22 and table 2).
[c] Eq. (34).
[d] Eq. (56). The bias field scales as $B_b \sim I_b/R$ where R is the size of the bias coils.
[e] Eq. (36).

To conclude: height, frequency, temperature, direction, separation

Use interferometer to study!!!

Surface losses: experimental results

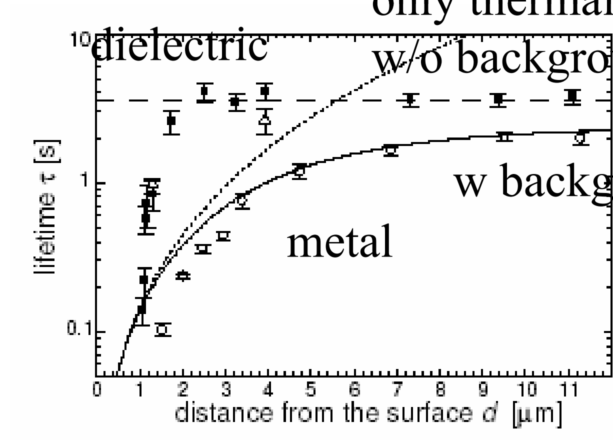


W. Ketterle 2002

Spin flips due to thermally induced Johnson noise.

$1/d^2$

Dipole trap, connections w/o current



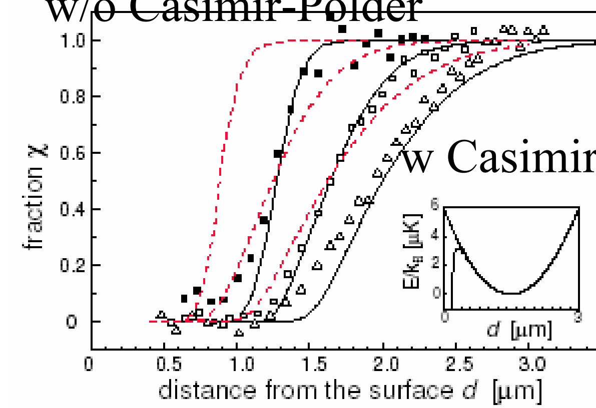
dielectric

only thermal noise w/o background

w background

metal

w/o Casimir-Polder



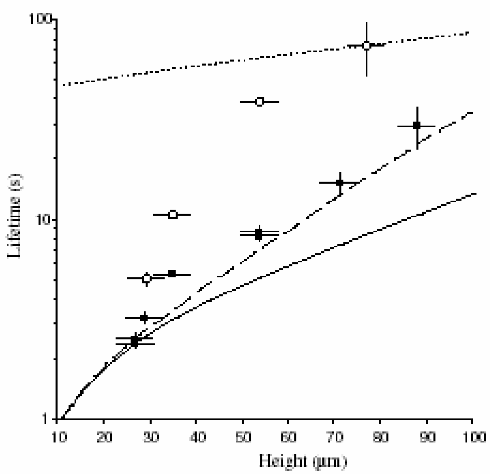
w Casimir-Polder

Above a dielectric for BEC, 2.1, 4.6μK

V. Vuletic 2003

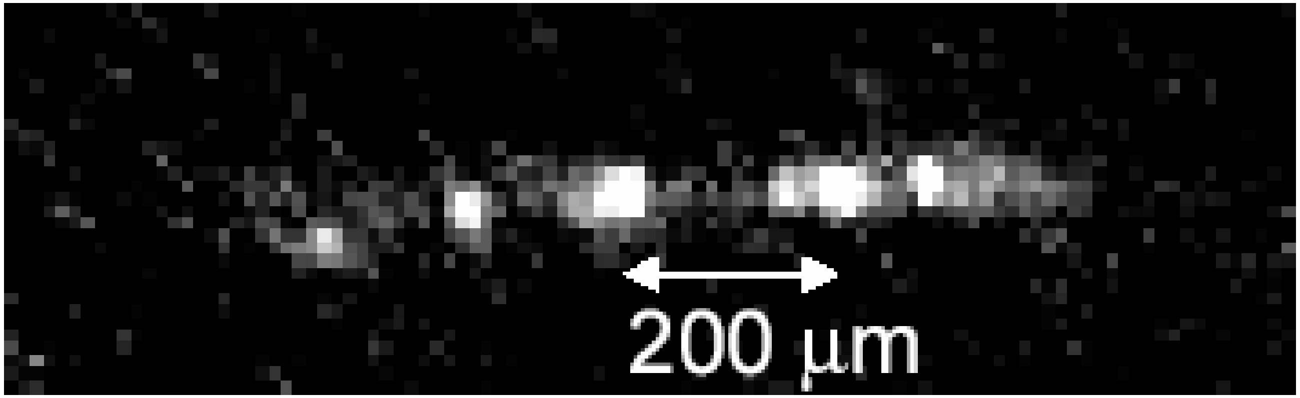
Losses do to tunneling to the surface

Spin flips due to thermal and technical noise

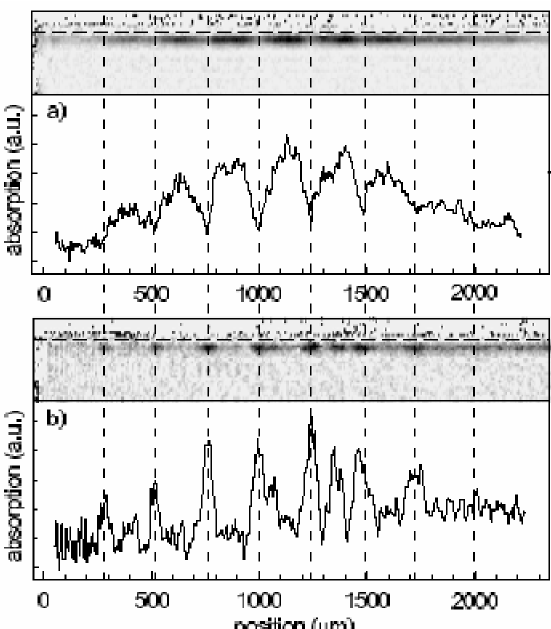


E. Hinds 2003

Fun Riddle: fragmentation



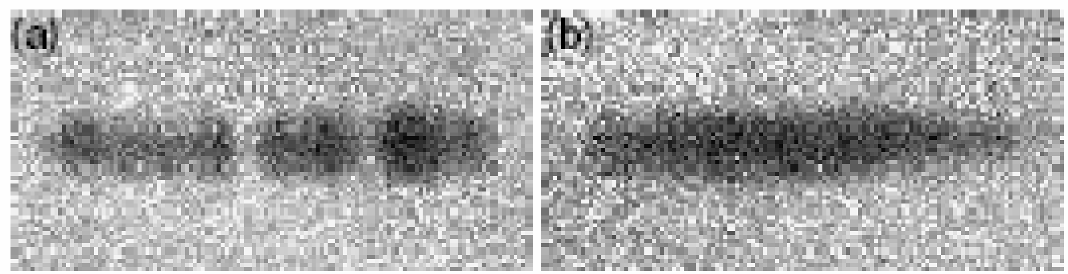
Fragmented ultra cold atomic cloud 37 micro-meters above the chip surface (Source: PhD thesis of Peter D.D. Schwindt, Boulder, Colorado (2003)).



+1.3G

-1.3G

C. Zimmermann 2002



Magnetic trap

Optical trap (same height)

W. Ketterle 2002

Opposite longitudinal field shifts by pi the location of the nodes

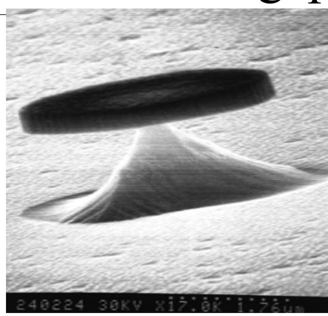
THE slide to remember: Combining 3 fields to make QT

3. Talking to the quantum system (building a dictionary)	Photonics
1. Isolated quantum system	Quantum optics
2. Create magnetic/electric bottles	Planar fabrication & micro electronics

The third component: Light

Measurement

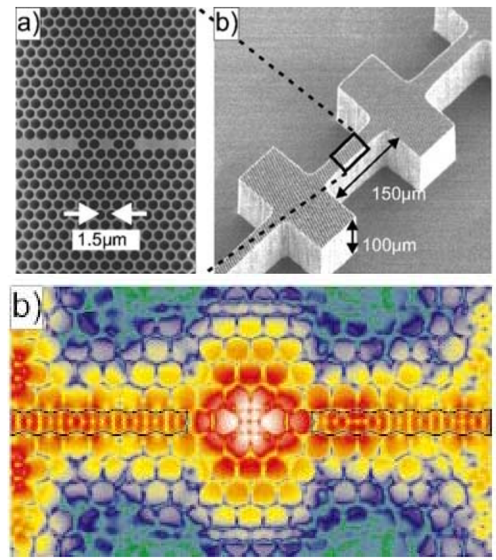
Coupling to evanescent fields of microdiscs, -spheres, photonic band gap structures; SNOM techniques; monolithic integration.

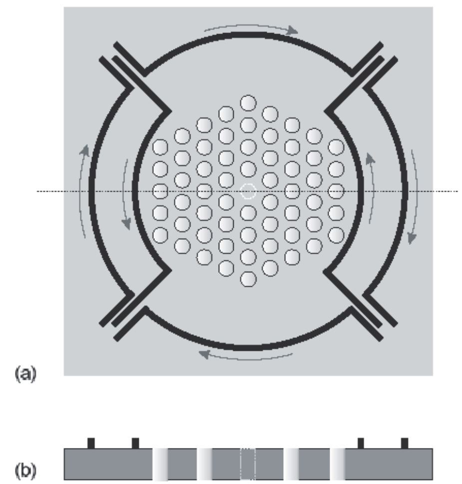


Diameter of the Ta_2O_5 disk : 3 microns

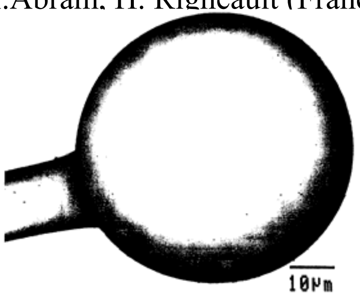
I.Abram, H. Rigneault (France Telecom)

V. Sandoghdar

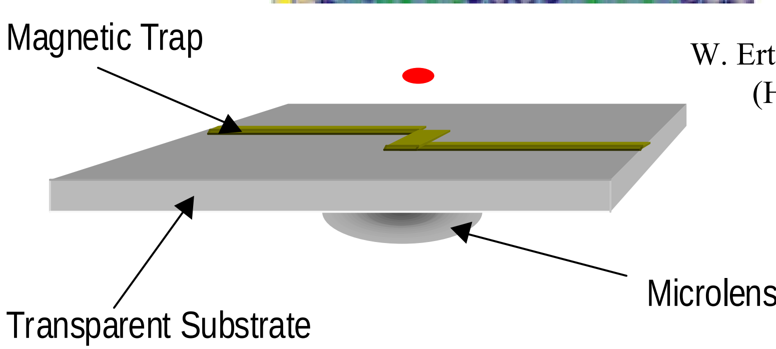




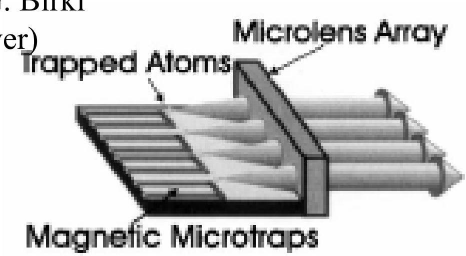
H. Mabuchi (Cal-Tech)



F. Treussart (ENS),
J. Reichel (Munich)

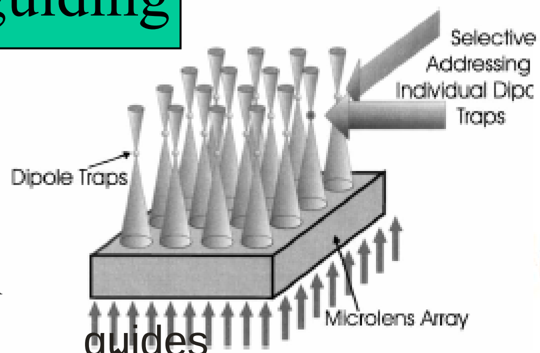


W. Ertmer, G. Birkl (Hannover)



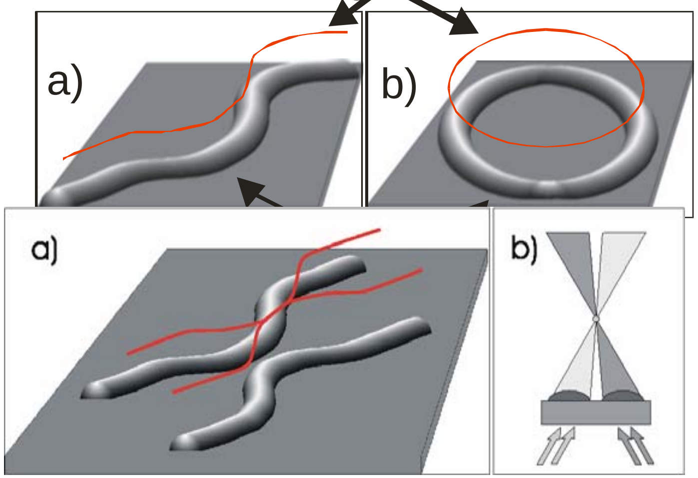
Why high Q?

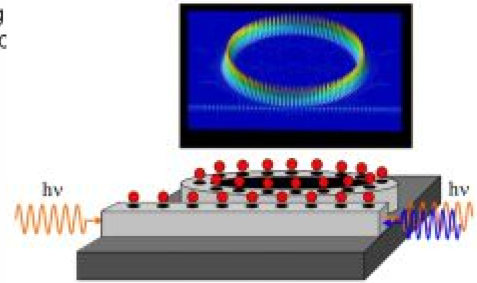
Trapping/guiding



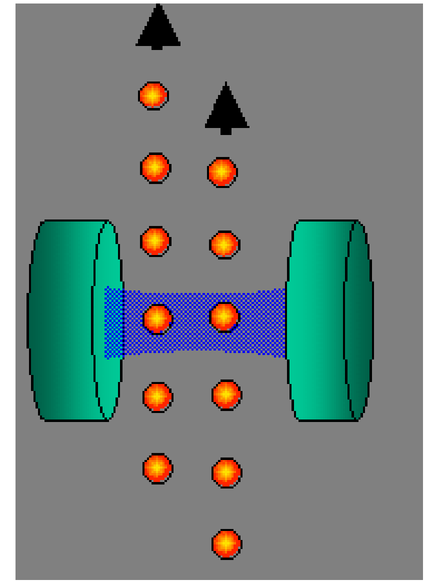
W. Ertmer, G. Birkl
(Hannover)

guides





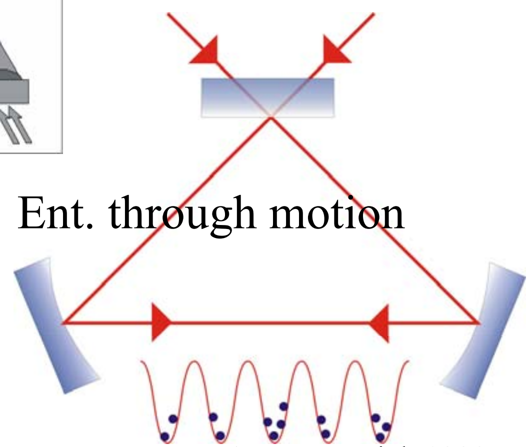
NIST



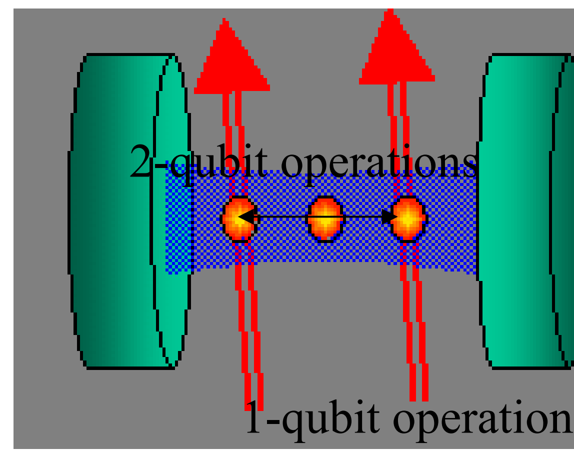
Computing....

(artist: Chapman group)

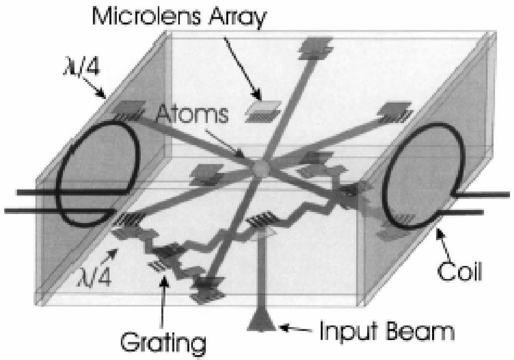
P. Zoller 1995



A. Hemmerich 1999
H. Ritsch, C. Zimmermann



Atom source....



W. Ertmer, G. Birkl
(Hannover)

Communication....

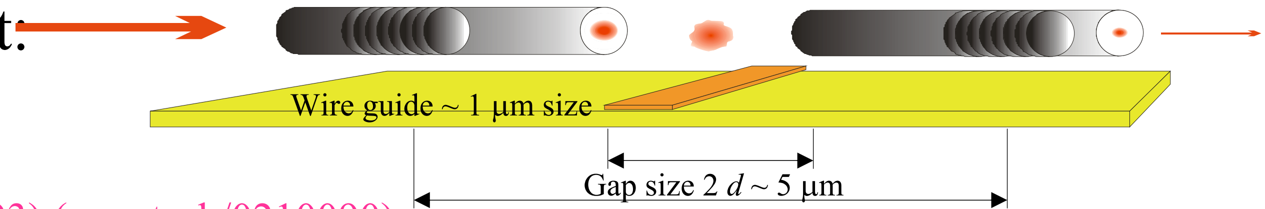
Light: our humble begining with the FP

Our first experiment:

Opto electronics center SH

Peter Horak, Bruce Klappauf

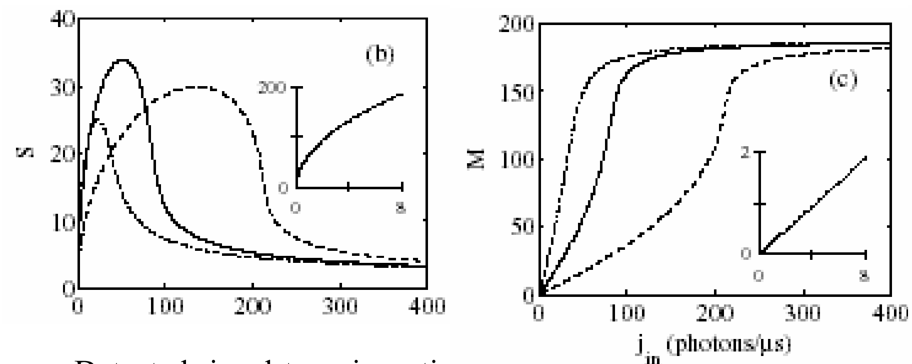
Phys. Rev. A 67, 043806 (2003) (quant-ph/0210090).



Finesse=140, $\kappa=2\pi$ 5.5MHz, g= 2π 12MHz, T=0.1-10^{-3} Waist: 2-5μm

Resonant case $\Delta_c=\Delta_a=0$, τ = 10 μs

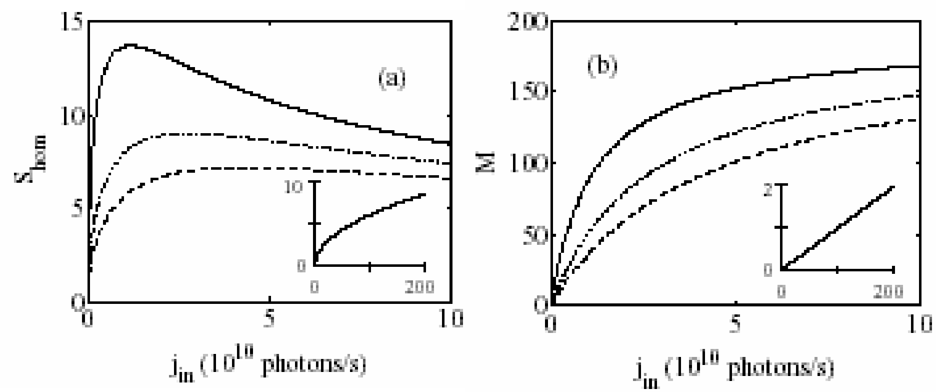
Nonresonant case $\Delta_a=50\Gamma$, $\Delta_c=0$, τ = 10 μs



Detected signal-to-noise ratio in intensity measurement

Spontaneous emission

For kappa = 1 MHz (dashed), 3 MHz (solid), 10 MHz (dash-dotted)



Detected signal-to-noise ratio in a homodyne measurement

Spontaneous emission

For kappa = 6 MHz (solid), 14 MHz (dotted), 22 MHz (dashed)

	Mod. vol. (E-14)	g [MHz]	κ [MHz]	Length [μm]	Finesse
Heidelberg	18	12	5.5	30000	140
Rempe	8	16	1.4	116	430000
Kimble	0.2	120	40	10	180000

saturation parameter $M= 2 g^2 n \Gamma \tau / [(\omega-\omega_A)^2+\Gamma^2]$

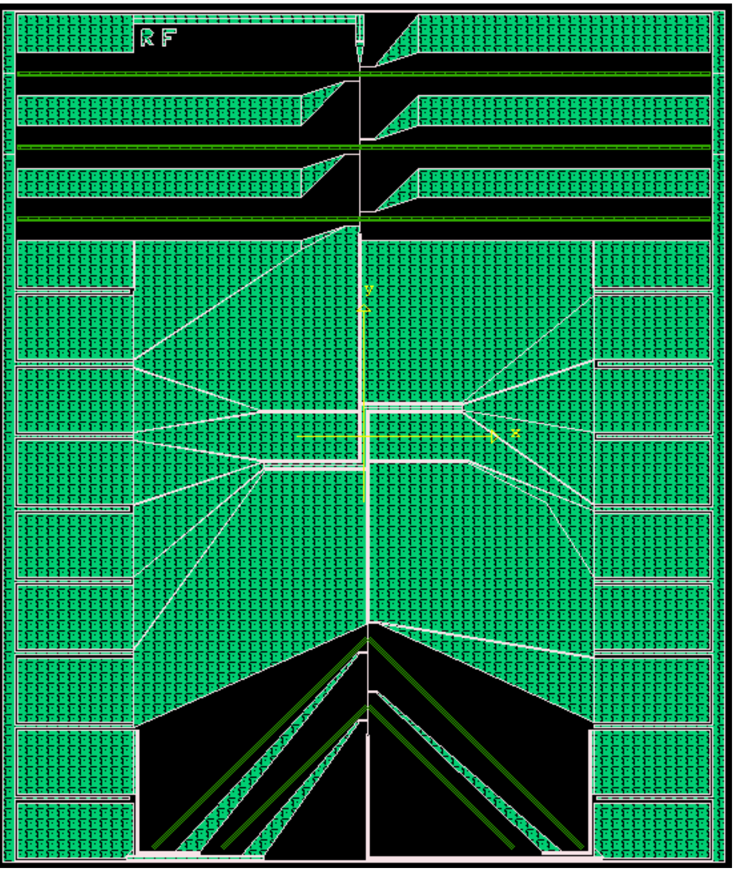
Non-destructive for 1μm gap!

First chip

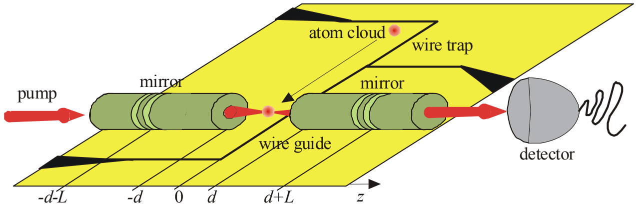
Including V-grooves for mounting of

- fibre cavities of different gap sizes
- flourescence detectors using 90° fibres with tapered fibre lenses for focussing

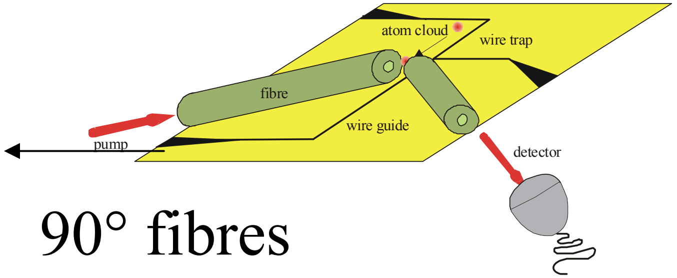
chip mask



fibre cavities

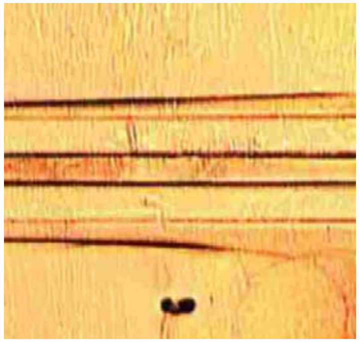


chip loading (Z-,U-Traps)

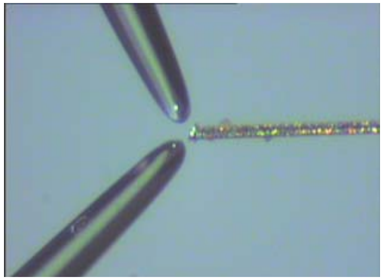


90° fibres

first etchings



Sönke Groth



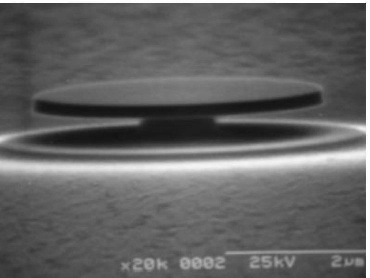
Bruce Klappauf

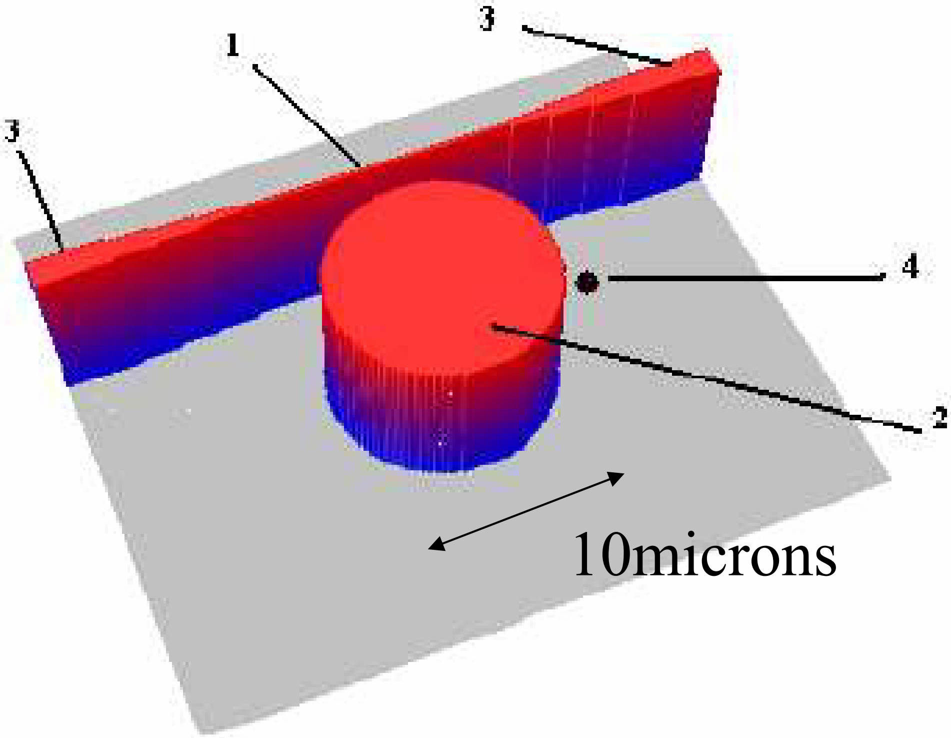
(Focal length=15 μm)

Another option: The micro disk

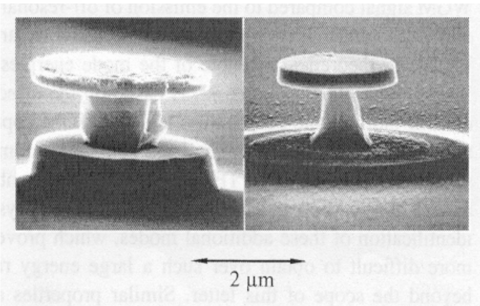
Single-atom detection using whispering gallery modes of microdisk resonators

Michael Rosenblit,[1] Peter Horak,[2] Steve Helsby,[2] and Ron Folman[1]
[1] Department of Physics and Ilse Katz Center for Meso- and Nanoscale Science and Technology, Ben Gurion University of the Negev, P.O.Box 653, Be'er Sheva 84105, Israel
[2] Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, United Kingdom
(Dated: July 9, 2004)





from B. Gayral (France Telecom)



Finite difference time domain (FDTD) & Couple mode theory (CMT)

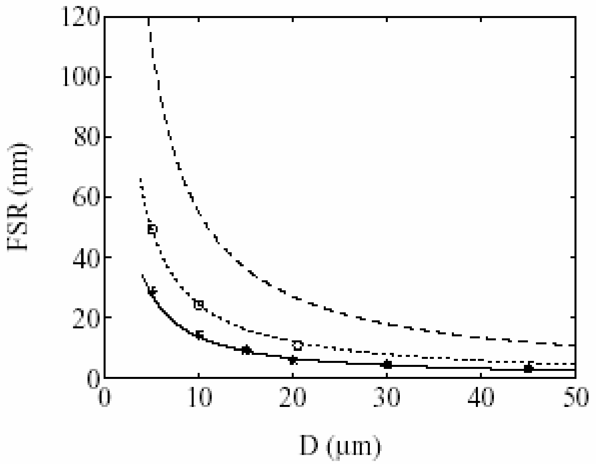


FIG. 2: Free spectral range versus disk diameter. The lines present results of analytical calculations at wavelengths 780nm (solid line) and 1550nm (dashed) in fused silica and at 1550nm for $n_c = 3.2$ (dotted). Corresponding FDTD results are indicated by ($*$), and experimental data [20] by ($\circ$).

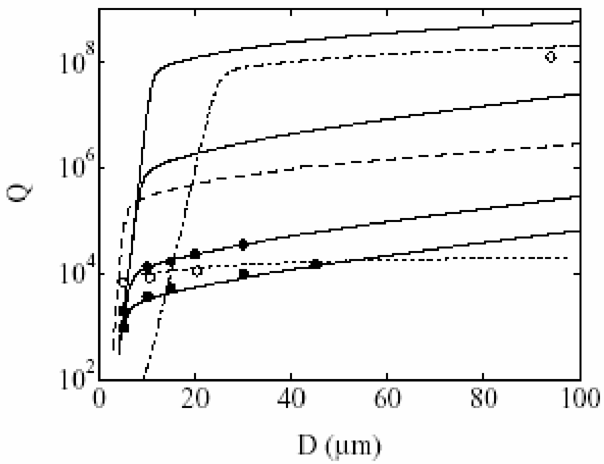


FIG. 3: Quality factor Q versus disk diameter for various gap sizes and materials. Solid curves (from bottom to top): CMT results for gap sizes 0.1μm, 0.2μm, 0.5μm, and for the uncoupled disk for λ = 780nm, n_c = 1.454, σ = 1nm, L_c = 5nm, ($\bullet$) represent FDTD simulations. Dashed curve: n_c = 2.17, gap size 0.2μm. CMT results for λ = 1550nm, σ = 2nm, L_c = 10nm: uncoupled disk with n_c = 1.444 (dash-dotted curve), n_c = 3.2 and gap size 0.1μm (dotted curve). Corresponding experimental data is given by ($\diamond$) [8] and ($\circ$) [20], respectively.

Good agreement between FDTD & CMT and Data

Conclusion: very high Qs possible for small diameters!

Coupling to an atom

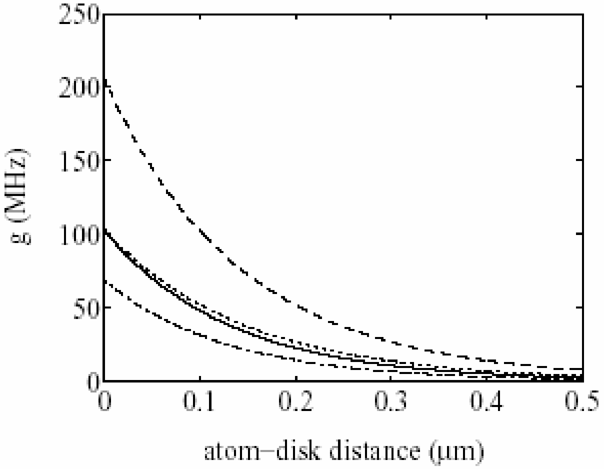


FIG. 4: Rabi frequency versus atom-disk distance. Solid curve: $D = 30\mu\text{m}$, mode indices $(l, q) = (167, 1)$; dotted: $D = 30\mu\text{m}$, $(l, q) = (159, 2)$; dashed: $D = 15\mu\text{m}$, $(l, q) = (81, 1)$; dash-dotted: $D = 45\mu\text{m}$, $(l, q) = (253, 1)$.

D (μm)	l	q	λ (nm)	Q_1	Q_2	g_0 (MHz)
30	167	1	778.73	1.55×10^5	8.44×10^6	102.6
30	166	1	783.27	1.47×10^5	8.05×10^6	103.2
30	159	2	780.04	1.83×10^5	8.85×10^6	102.8
15	81	1	780.41	7.66×10^4	3.82×10^6	205.7
45	253	1	780.15	2.66×10^5	1.40×10^7	68.5

TABLE I: Optical properties of selected WGM. Q_1 (Q_2) is the quality factor Q for a gap size of 0.3μm (0.6μm), l and q are the longitudinal and radial mode index, respectively, g_0 is the single-photon Rabi frequency for an atom at the disk boundary. Surface parameters are $\sigma = 2$nm, $L_c = 10$nm. Results are obtained using CMT.

Non-destructive

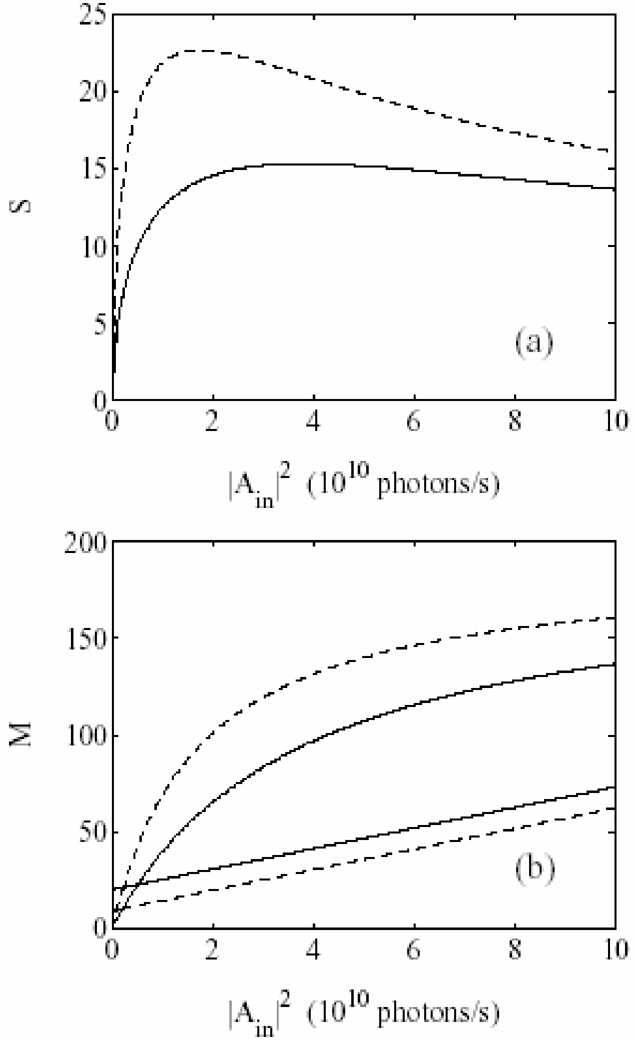


FIG. 5: (a) Signal-to-noise ratio versus pump intensity for disk diameter 30μm (solid line) and 15μm (dashed). (b) Corresponding photon scattering M (top curves) and M_{10} (bottom). Gap size is 0.3μm, waveguide width is 0.6μm, $\sigma = 2$nm, $L_c = 10$nm, $\Delta_a = 100\Gamma$, $\tau = 10\mu s$, and the atom is assumed to sit 50nm away from the disk surface.

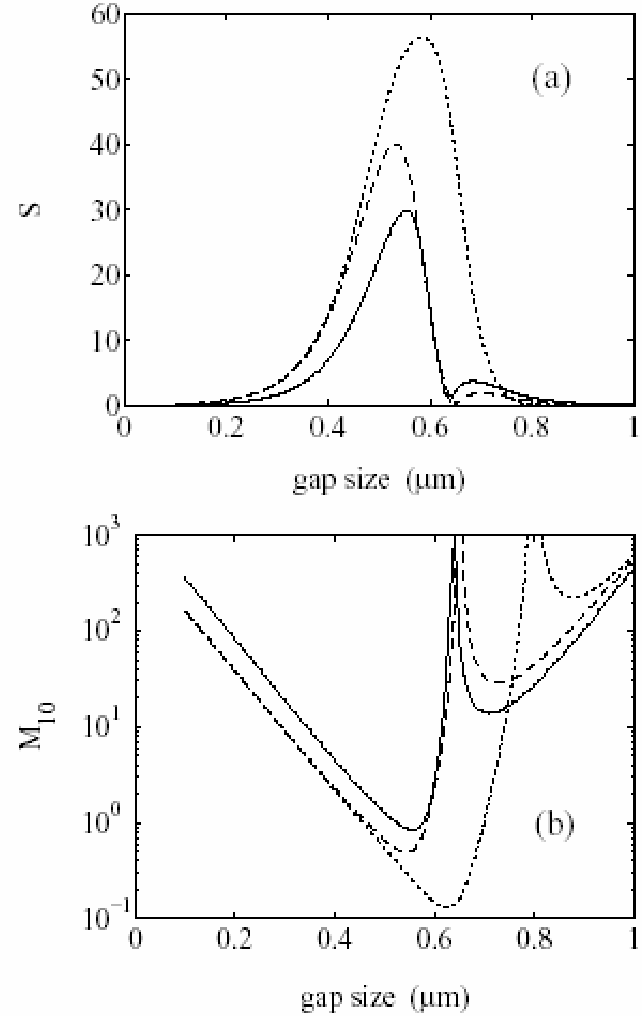
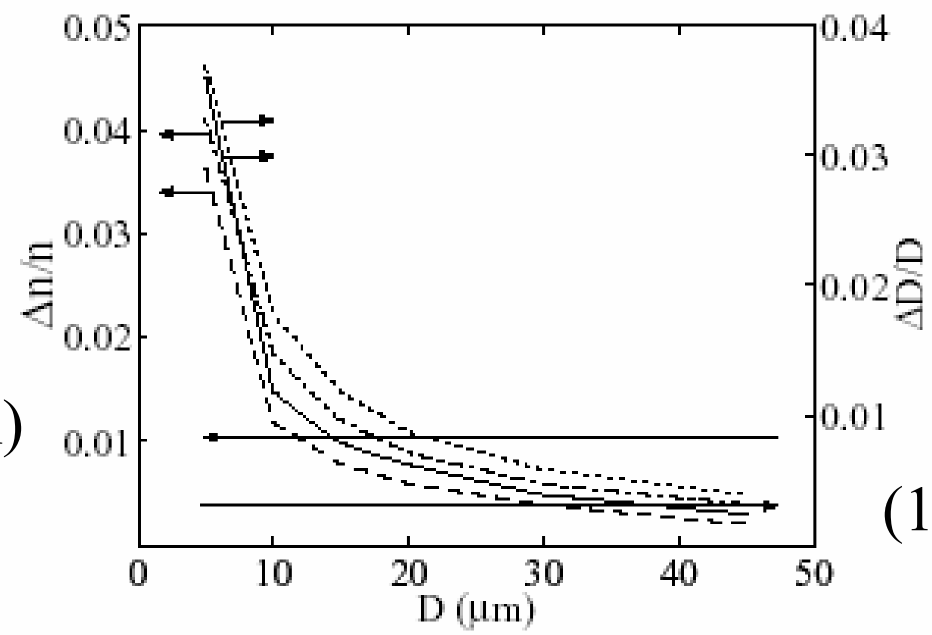


FIG. 6: (a) Signal-to-noise ratio S and (b) scattered photons M_{10} versus gap size for weak pumping ($|A_{in}|^2 = 10^8$ photons/s). Solid curve: $D = 30\mu m$, dashed: $D = 15\mu m$ for $\sigma = 2$nm, $L_c = 10$nm. Dotted curve: $D = 15\mu m$, $\sigma = 1$nm, $L_c = 5$nm. Waveguide width is 0.6μm, distance atom-disk is 50nm, interaction time is 10μs.

FSR Tuning: fighting permanent flaws e.g. fabrication, and fluctuating flaws e.g. temperature

Poling???

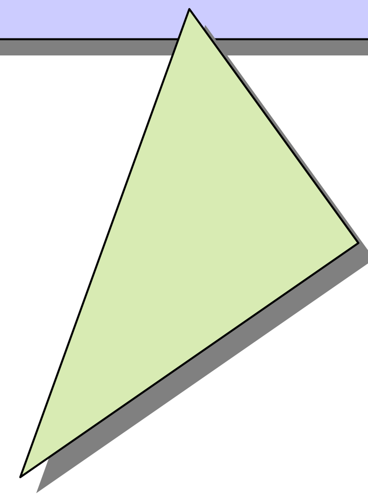
(5V=10^6V/m)



(100V=20 10^6V/m)

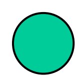
FIG. 8: Required change of disk diameter and refractive index for a full FSR scan versus disk diameter at $\lambda = 780$nm. $\Delta D/D$ and $\Delta n/n$ are presented by dotted and dash-dotted curves for $n = 1.454$, and by solid and dashed curves for $n = 2.17$, respectively. Typical values for actual materials are also presented by the long base arrows.

THE slide to remember: Combining 3 fields to make QT



3. Talking to the quantum system (building a dictionary)

Photonics



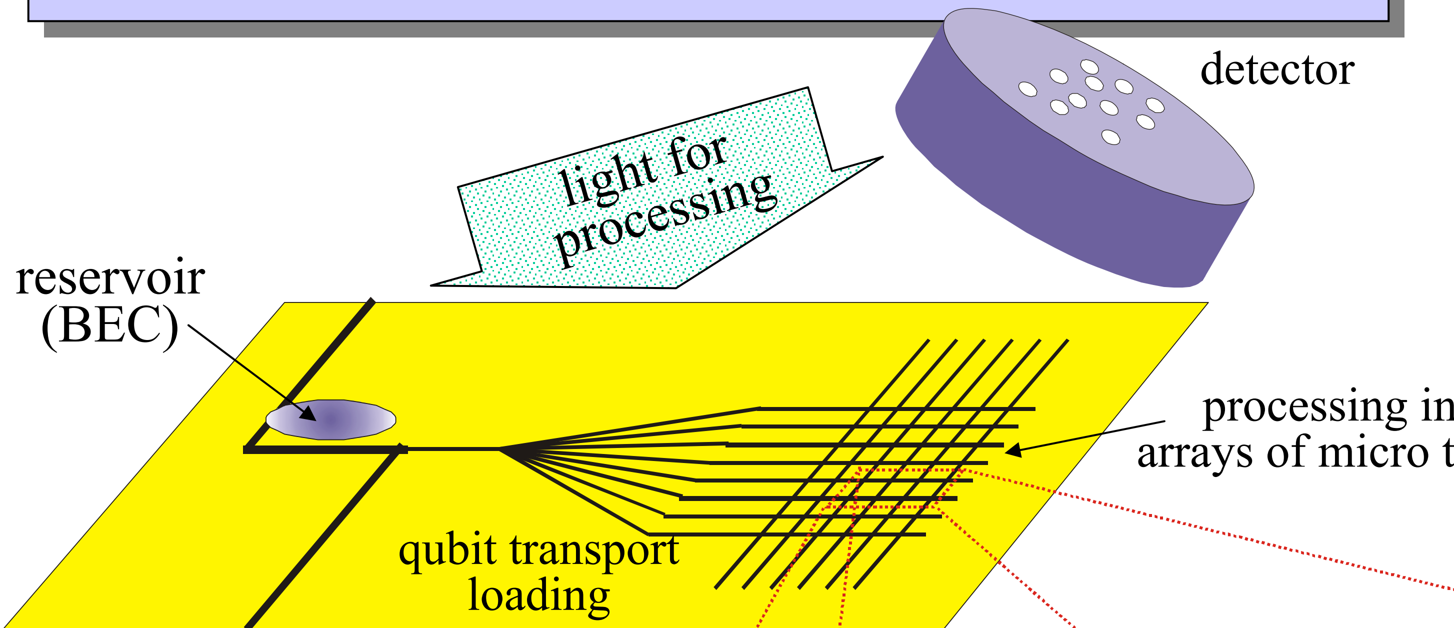
1. Isolated quantum system

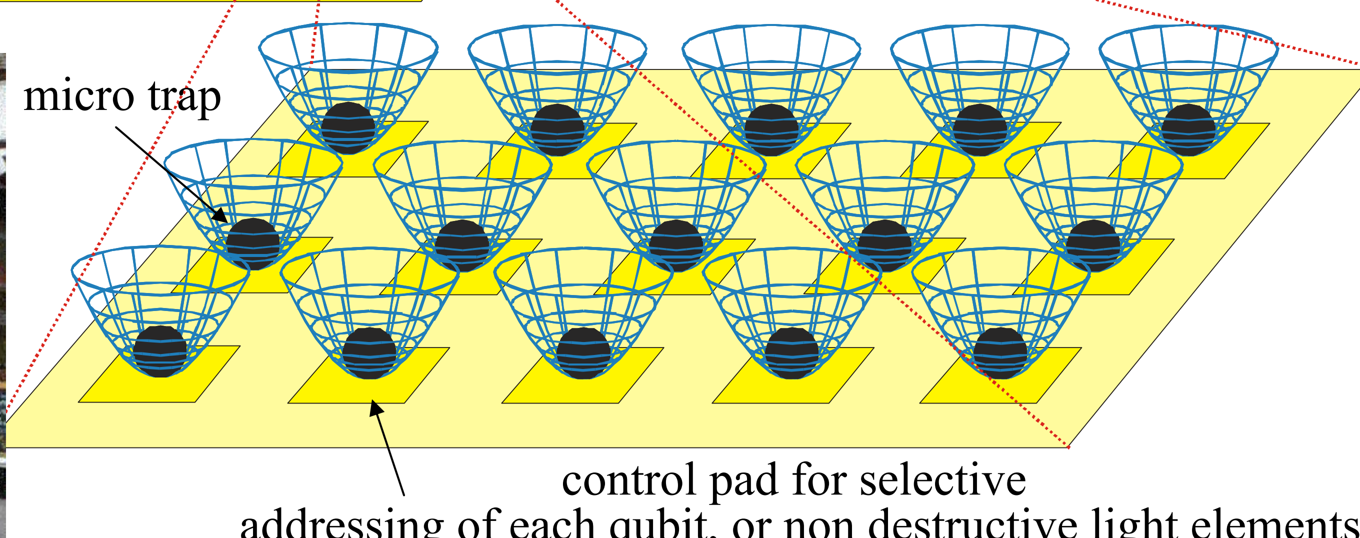
Quantum optics

2. Create magnetic/electric bottles

Planar fabrication & micro electronics

Final product...





Conclusion & Outlook

Demonstrated principles of microfabricated atom optics

- **Adapted state-of-the-art fabrication to atom optics**
- **Built and tested Atom Chips down to 1μm**
including traps, guides, beam splitters, vertical & electric traps
- **Simplified the set up**
- **Reached a regime interesting for QIP**
  - **trap frequencies > 1 MHz**
  - **trap ground state ~ 10 nm**

In the pipe line

- **Light resonator (to initiate, manipulate and measure the qubit)**
- **Interferometer (to measure decoherence)**
- **Controlled collisions (the basis for a 2-qubit gate)**

Other types of information

- **Understanding of entanglement, squeezing, fermi gas, superchemistry…**
- **Sensing of time, gravitational fields, navigation…**

Reviews: R. Folman et al., Advances in Atomic, Molecular and Optical Physics, Vol. 48, 263 (2002); J. Reichel, Appl. Phys. B 74, 469 (2002).

Generous EU funding received for post docs

…So, you are welcome to come

www.bgu.ac.il/atomchip