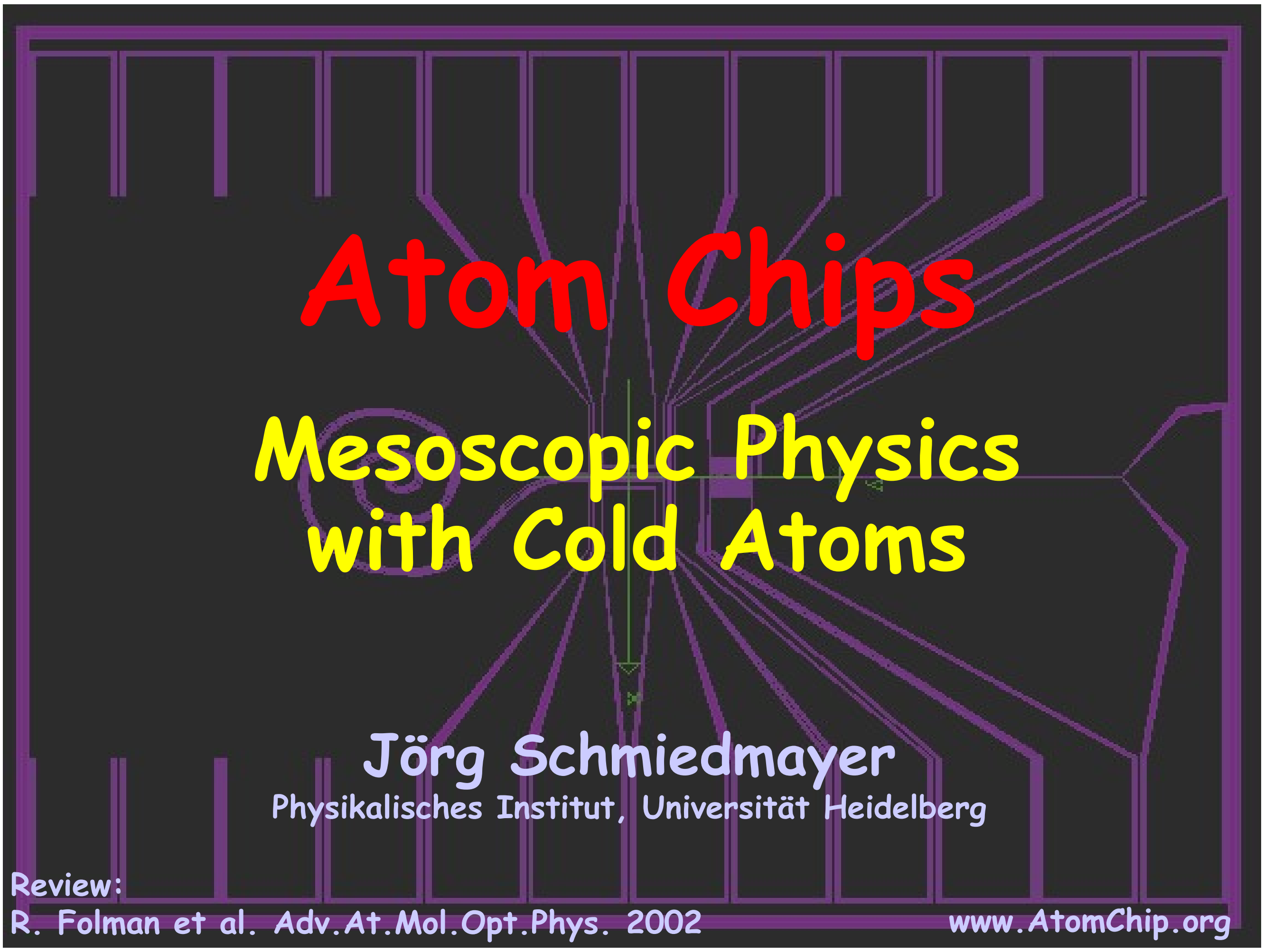


Atom Chips

Mesoscopic Physics with Cold Atoms

Jörg Schmiedmayer

Physikalisches Institut, Universität Heidelberg

Review:
R. Folman et al. Adv.At.Mol.Opt.Phys. 2002

www.AtomChip.org

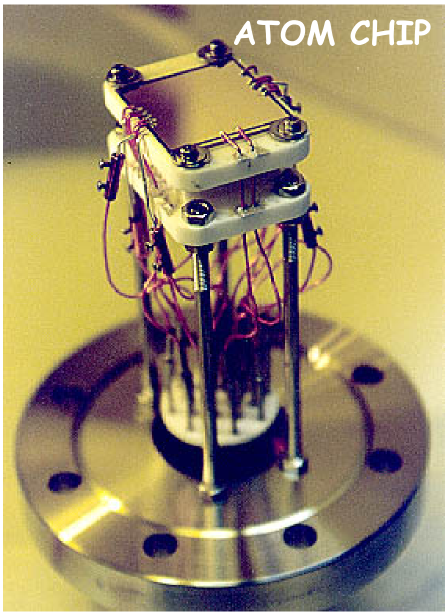
THE VISION

Atom Chip

neutral-atom manipulation using integrated micro-devices

combining the best of two worlds:

- **cold neutral atoms** - a well controllable quantum system
- technologies of **nano-fabrication, micro-electronics, micro-optics**

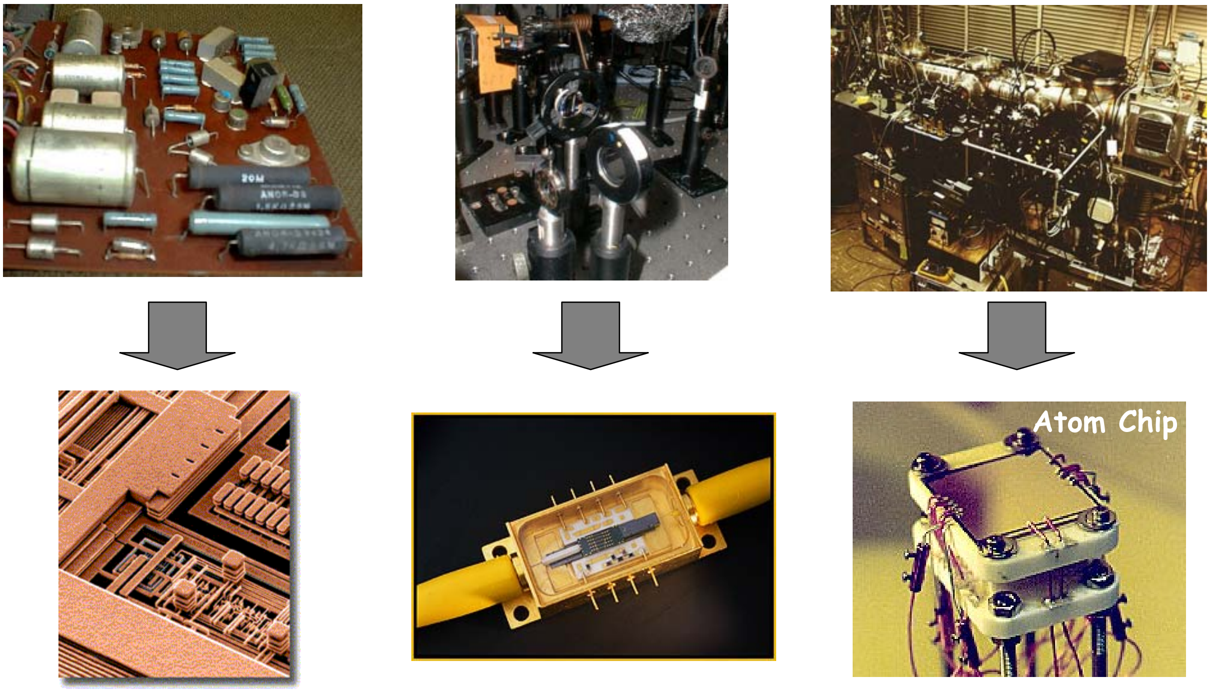


Take the tools of quantum optics and atomic physics and make them robust and applicable by miniaturizing and integrating them using the techniques of nano-fabrication, micro-electronics and micro-optics.

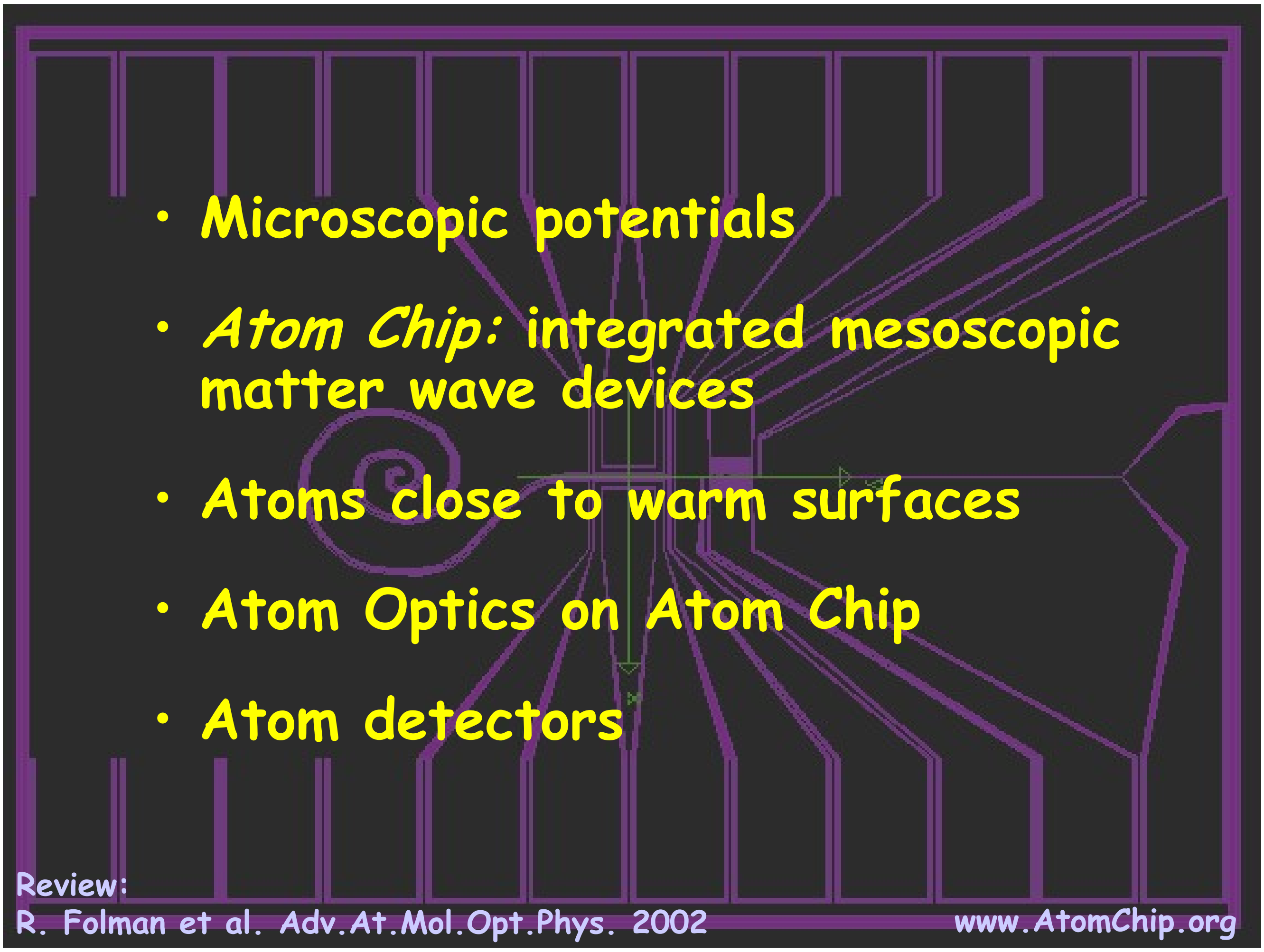
- create a **tool box** for building quantum devices

MINIATURIZATION and INTEGRATION

Electronics Optics Matter waves



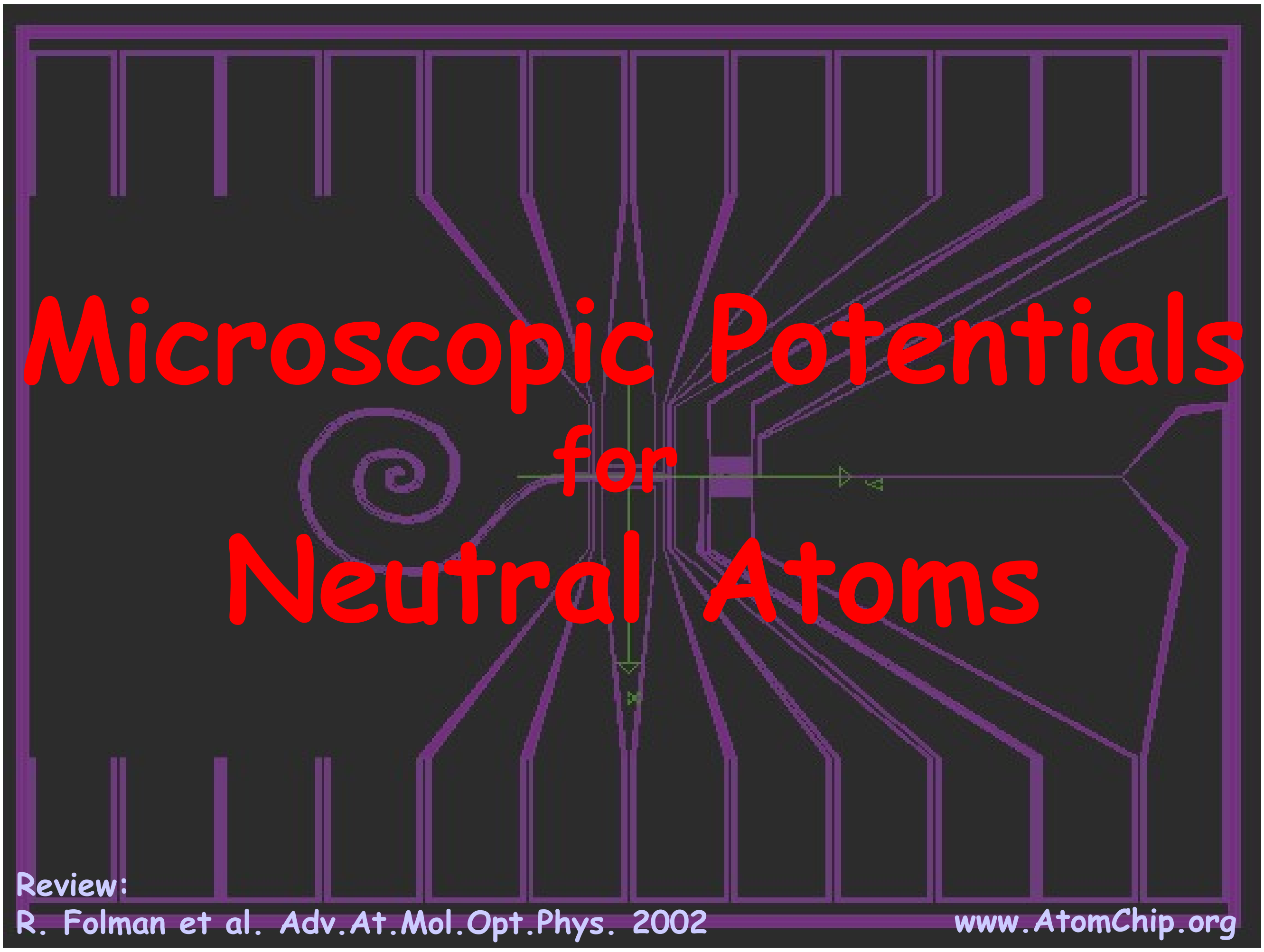
mesoscopic matter wave optics similar to quantum electronics



- Microscopic potentials
- *Atom Chip:* integrated mesoscopic matter wave devices
- Atoms close to warm surfaces
- Atom Optics on Atom Chip
- Atom detectors

Review:
R. Folman et al. Adv.At.Mol.Opt.Phys. 2002

www.AtomChip.org



Microscopic Potentials for Neutral Atoms

Review:
R. Folman et al. Adv.At.Mol.Opt.Phys. 2002

www.AtomChip.org

Interactions for micro traps

Magnetic Potentials

Magnetic moment of the atom interacting with the magnetic field

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

$U_B[\mu K] \propto 67\, B \quad [G]$

strong field seeker: $U_{mag} < 0$

weak field seeker: $U_{mag} > 0$

Electric Potentials

Electric polarizability interacting with an electric field

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

Li-Atom: $\alpha = 24 A^3$

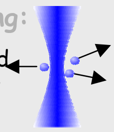
$U_E[\mu K] \propto 98\, E^2\, [V/\mu m]$

Optical Dipole Potentials

Dipole potential: $U_{dip} \propto -\alpha(\omega) I(\vec{r})$

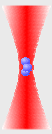
Blue detuning:

Atoms repelled from intensity maxima

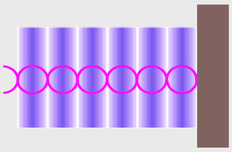


Red detuning:

Atoms trapped in intensity maxima



Use reflective properties of Atom Chip for 1D, 2D and 3D standing-wave-potentials



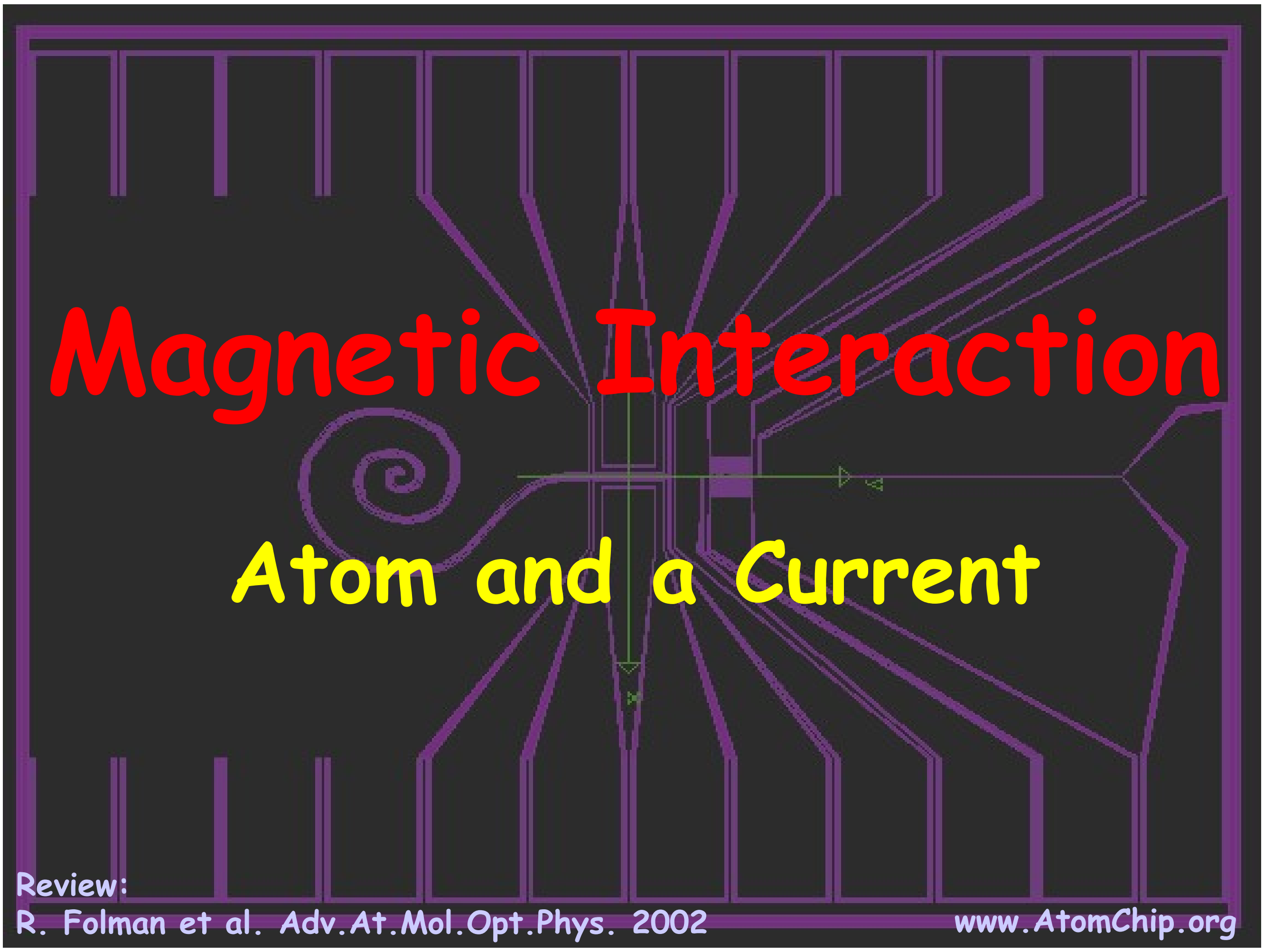
$$U(x) = \frac{\hbar\Omega_0^2}{4\Delta}\left(1+\cos\vec{G}\vec{x}\right)$$

Modulate ***magnetic* traps** using *optical* potentials (Optical lattice QIP on chip)

Modify ***optical* traps** with *magnetic (electric)* potentials

Structure the dipole traps by holographic means (spatial light modulators)

For a review see R. Grimm et al.
Adv. At. Mol. Opt. Phys. 42, 95-170 (2000).



Magnetic Interaction

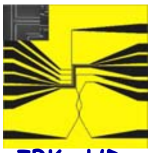
Atom and a Current

Review:
R. Folman et al. Adv.At.Mol.Opt.Phys. 2002

www.AtomChip.org

MAGNETIC INTERACTION

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



IBK, HD

Vladimirskii Sov. Phys. JETP 12, 740 (1961)
Experiment: Schmiedmayer IQEC 92; PRA 52, R13 (1995)
Denschlag et al. PRL 82, 2014 (1999)

Quantum wire:

current carrying wire

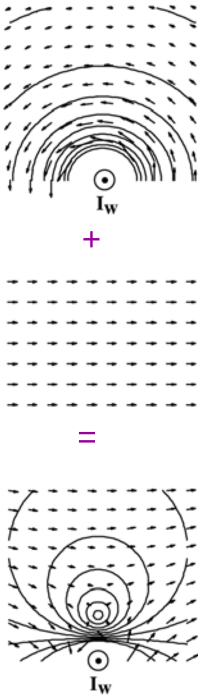
$$\vec{B}(\rho) \propto I \frac{1}{\rho} \hat{e}_{\varphi}$$

Vector Coulomb Problem

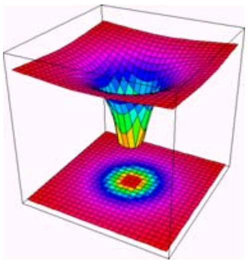
adding a bias field creates a potential minimum on side of wire (Frisch, Segre 1932)

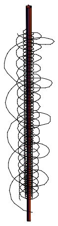
potential depth: bias field
potential gradient: $1/I$

Mount wire on a surface:
Use nanofabrication to build mesoscopic structures.

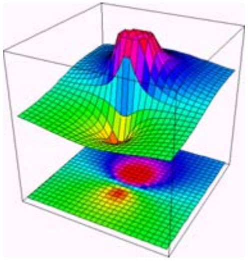


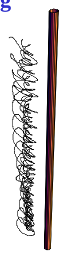
strong field seeker: $U_{mag} < 0$





weak field seeker: $U_{mag} > 0$





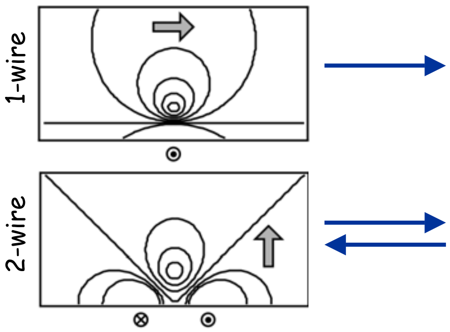
Achievable: level spacing of >1 MHz

DESIGNS

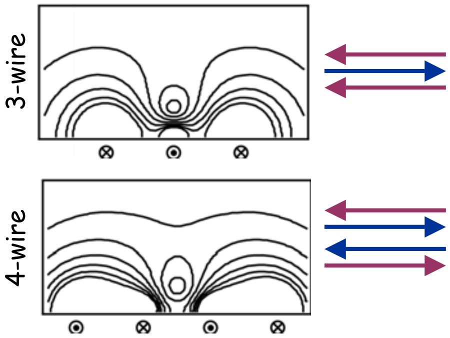
Surface Mounted Atom Optics

Guides

with external bias field



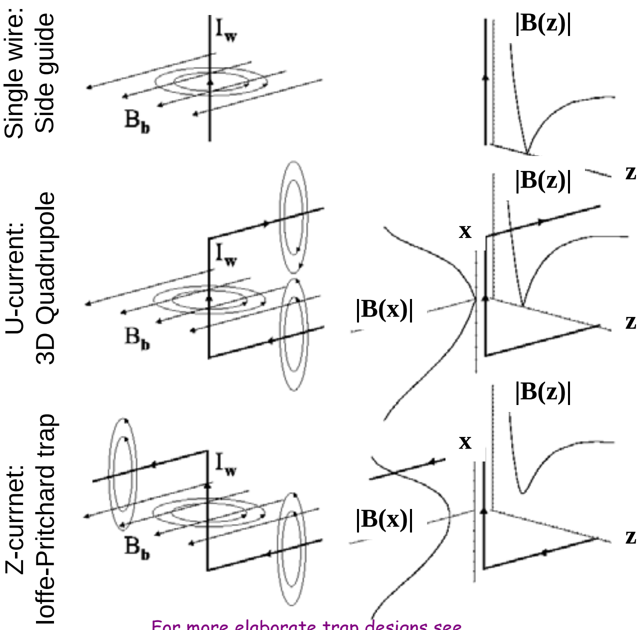
with on chip bias field



See also: J.H. Thywissen et al., EPJ D **7**, 361 (1999)

How to build a trap

minimum of the potential is given by the angle between the wire and the bias field



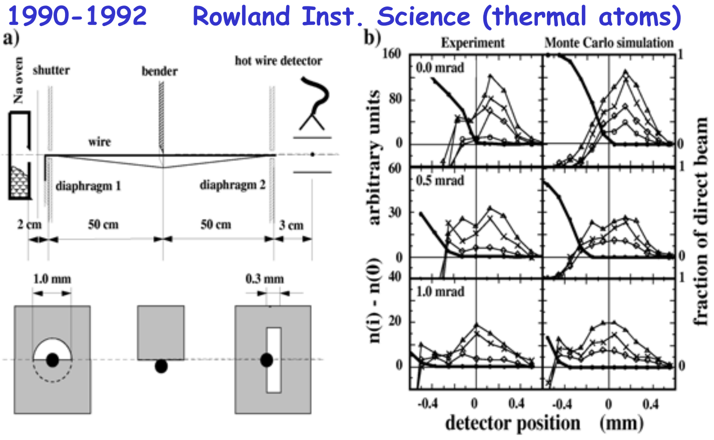
For more elaborate trap designs see
J. Weinstein, K. Libbrecht, Phys.Rev. A 52, 4004 (1995)

ATOMS and WIRES

microscopic guides and traps

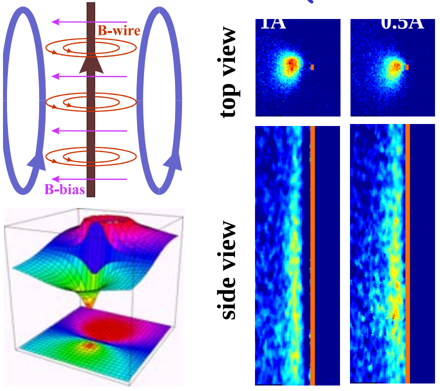
1990-1999

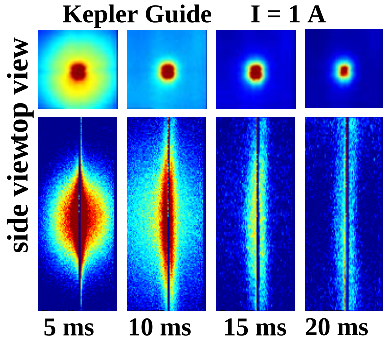
1990-1992 Rowland Inst. Science (thermal atoms)

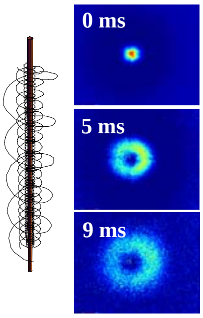


Innsbruck

1995-99 Innsbruck (cold atoms)

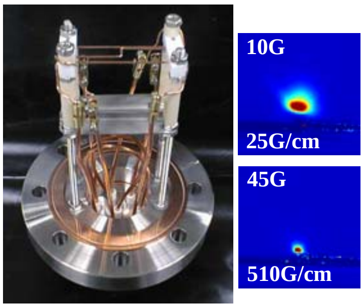


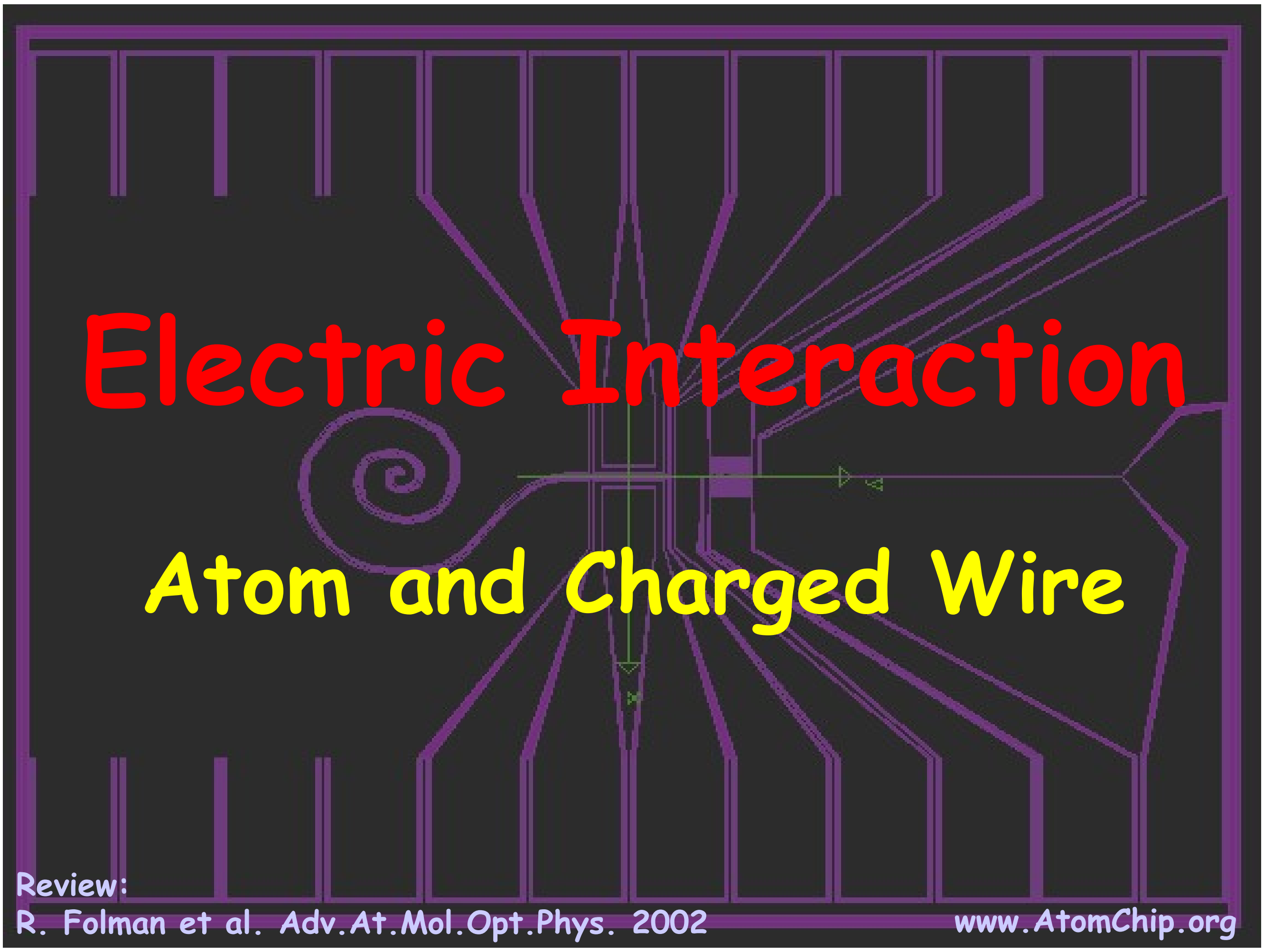




Schmiedmayer **IQEC 92**;
PRA **52**, R13 (1995)
Denschlag et al. PRL **82**, 2014 (1999)
Appl.Phys. B **69** 291 (1999)
A. Haase Diplomarbeit (2000)

Z-trap





Electric Interaction

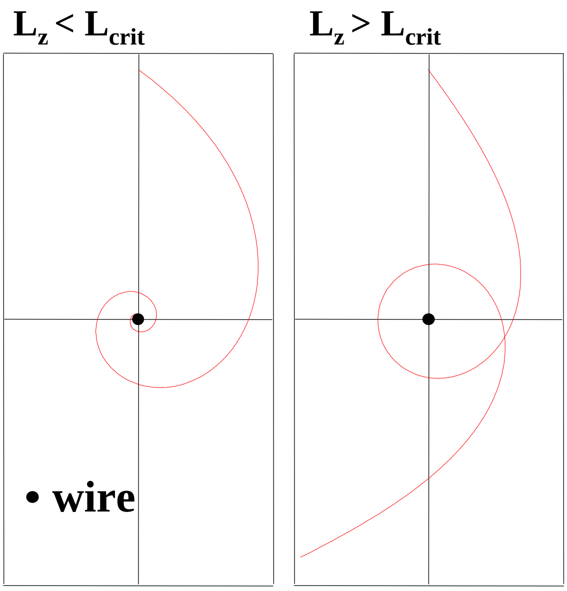
Atom and Charged Wire

Review:
R. Folman et al. Adv.At.Mol.Opt.Phys. 2002

www.AtomChip.org

Neutral Atom and Charged Wire

$1/r^2$ Potential



$L_z < L_{crit}$ $L_z > L_{crit}$

Classical Trajectories

No stable orbits!

Interaction Potential

$$U_{INT} = -\frac{1}{2}\alpha E^2 = -\frac{2\alpha q^2}{r^2}$$

Angular momentum

$$U_{Lz} = \frac{L_z^2}{2Mr^2}$$

Total potential

$$U_{Eff} = U_{L_z} + U_{INT}$$

$$= \frac{1}{2Mr^2}\left[L_z^2 - L_{crit}^2(q)\right]$$

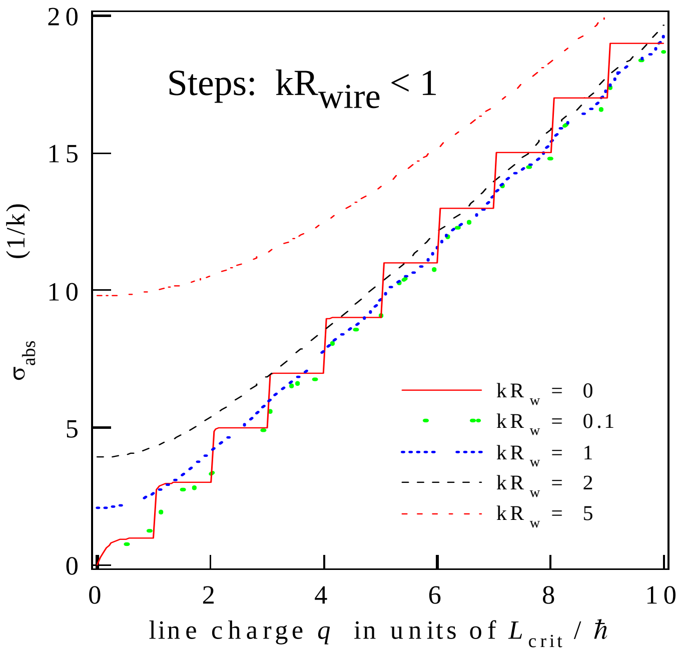
Critical angular momentum:

$$L_{crit} = 2\sqrt{\alpha M} \quad q$$

$1/r^2$ potential
quantum fall towards the center

Quantized of Absorption Cross Section for $R_{wire} \rightarrow 0$

quantum limit for $R_{wire} << \lambda_{dB}$



Linecharge: $U_{Eff} = \left[L_z^2 - L_{crit}^2(q) \right]$
(R_{wire} =0)

$$L_{crit} = 2\sqrt{\alpha M}\, q$$

One partial wave after the other ($\hbar\ell < L_{crit}$) is absorbed
→ *quantum steps* in absorption cross section

$$q_{\Delta\ell=1} = \frac{\hbar}{2\sqrt{\alpha M}}$$

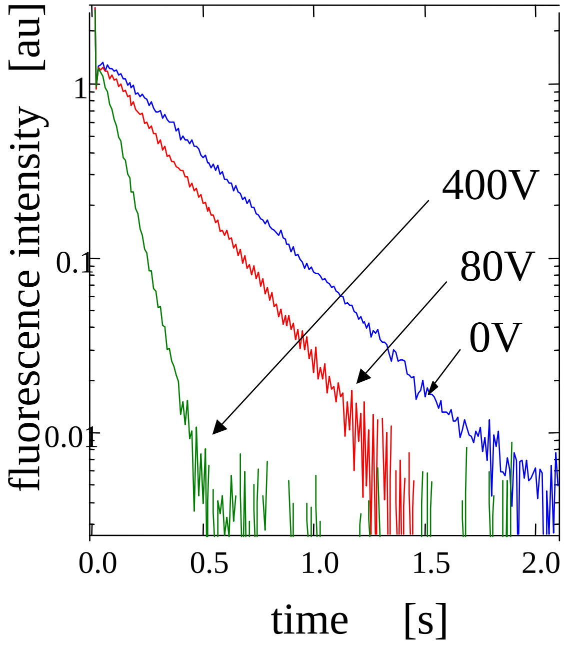
Li:
$\Delta q_{\Delta\ell=1}$~1pC
$\Delta U_{\Delta\ell=1}$~0.2V

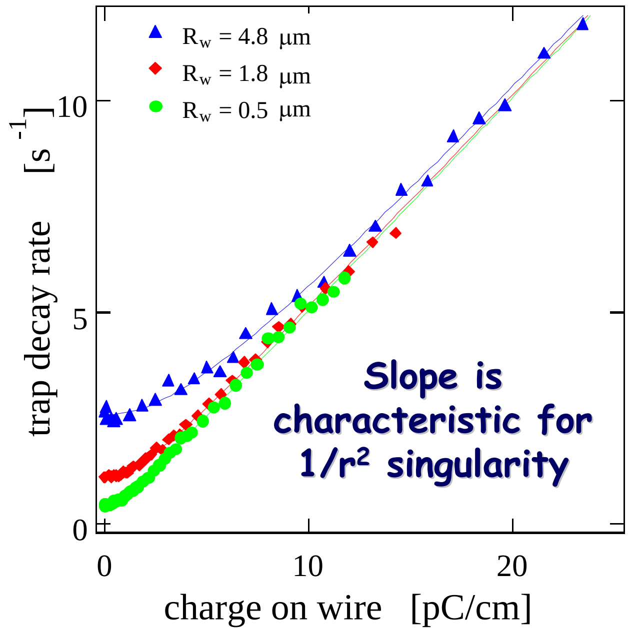
For k R_{wire} >1 the steps wash out but reappear for high ℓ

J. Denschlag, J.Schmiedmayer, EPL, **36**, 407 (1996)

Decay experiments
3 different wire diameters

Measuring the fall onto the wire by trap devay



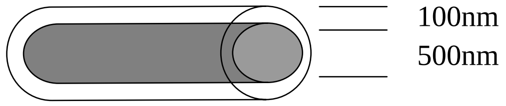


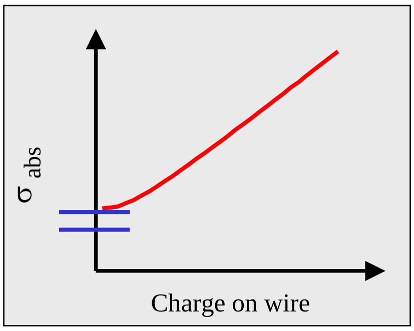
Slope is characteristic for $1/r^2$ singularity

Denschlag et al. PRL **81**, 737 (1998)

Measuring Van der Waals Forces between an Atom and a Mesoscopic Wire

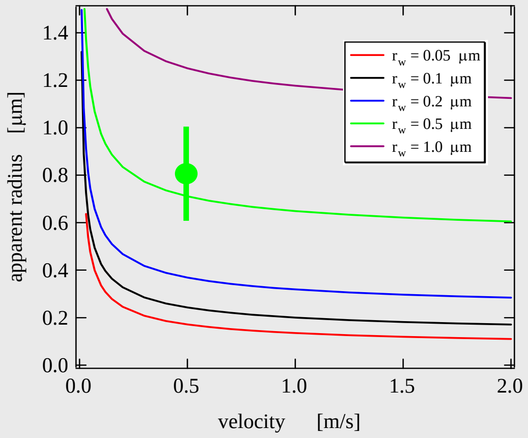
Van der Waals Potential will make wire radius appear thicker





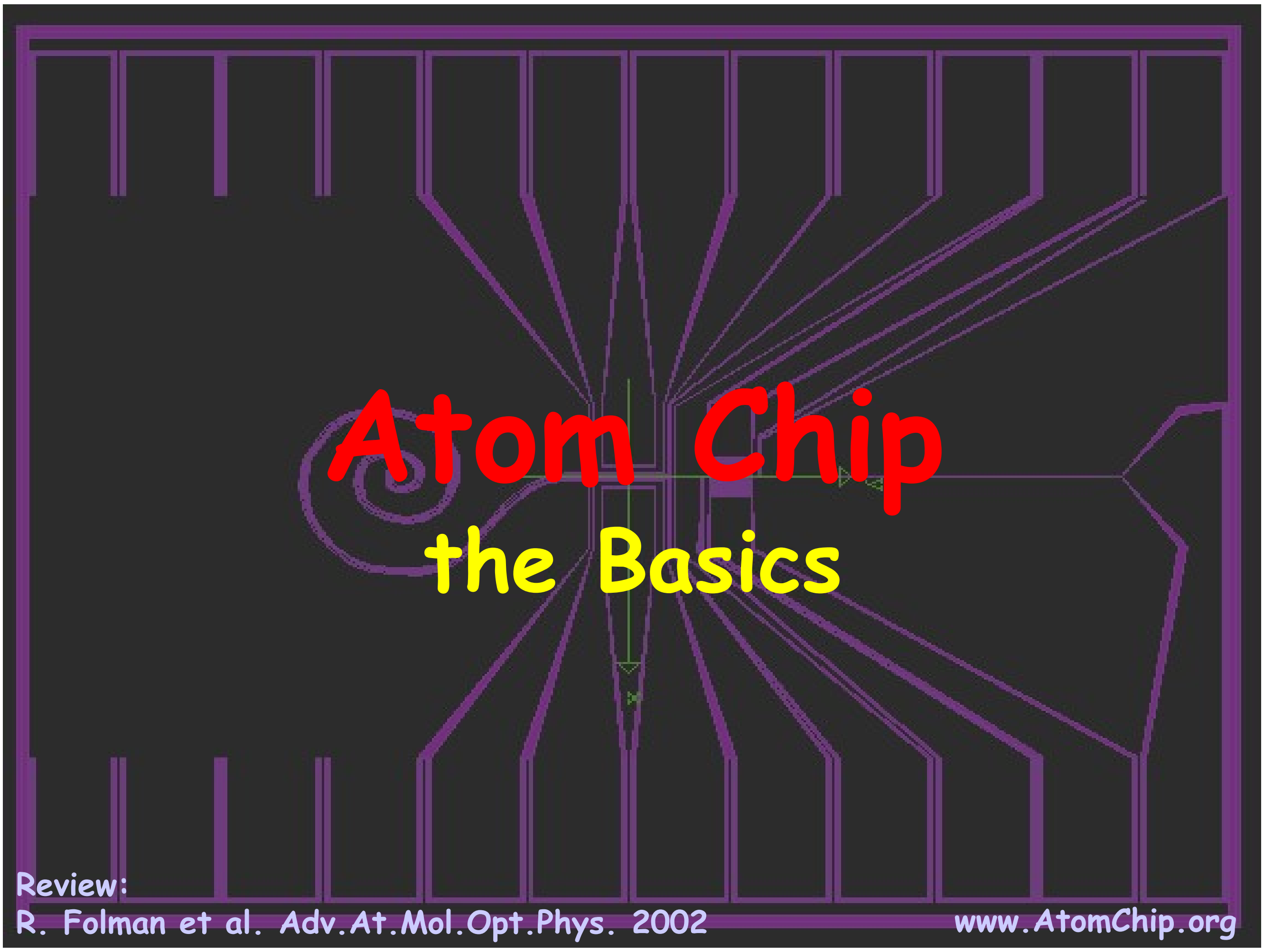
Simple model:

Integrating the contribution over the finite size of the wire



large effect for thin wires

Preliminary data (v=50 cm/s):
r_w = 0.5 µm ❾ r_{eff} ~ 0.8 µm
r_w = 1.8 µm ❾ r_{eff} ~ 2.3 µm



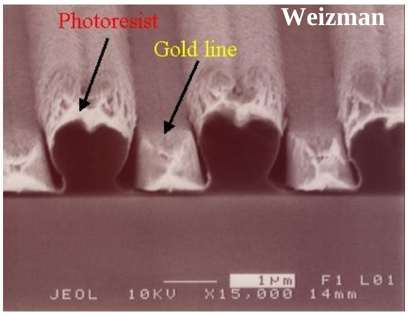
Atom Chip
the Basics

Review:
R. Folman et al. Adv.At.Mol.Opt.Phys. 2002

www.AtomChip.org

ATOM CHIP
fabrication of microscopic atom traps

Adapted nanofabrication technique to needs of Atom Chip (Weizman, Innsbruck/Heidelberg, TU-Vienna)



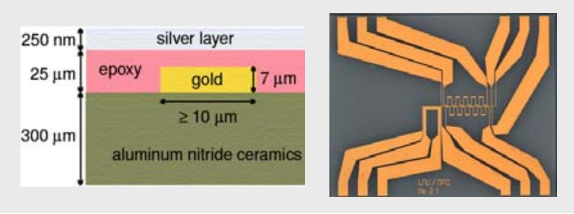
Features:

- Chip = mirror ⟶ wires are defined by etchings
- structures down to 1 μm
- current densities > 3 10^7 A/cm^2
- high voltages > 500V
- trap frequencies > 1MHz
  ground state size ~10 nm
- multi layer possible

Other techniques (MPQ, Orsay, Tübingen …):

Thin film hybrid technology

- Larger structures
- Large cross section
- High currents

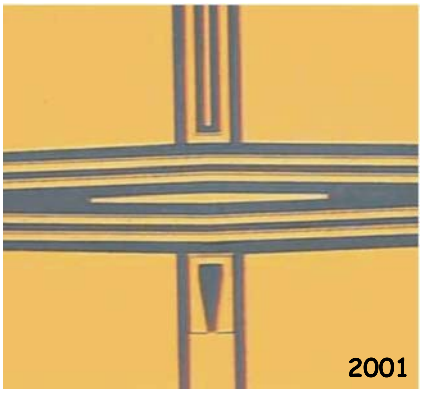


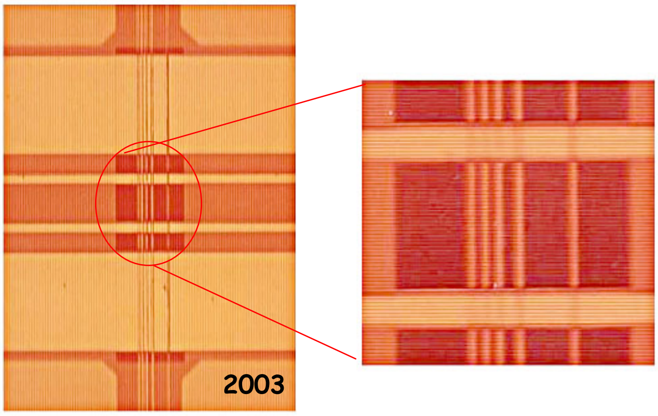
Atom Chip Fabrication

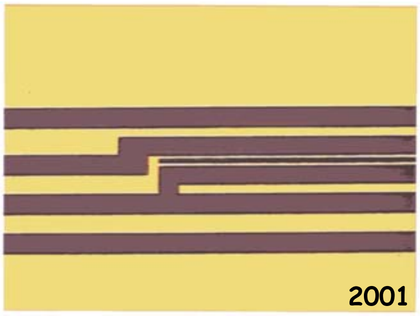
S. Groth et al. Cond-mat/0404141 (2004)

WIS - HD

Adapted from standard semiconductor nanofab.
Innsbruck, Heidelberg, Weizmann, TU-Wien







Heating of the Wire
a simple model

Model the heat transfer to the substrate:

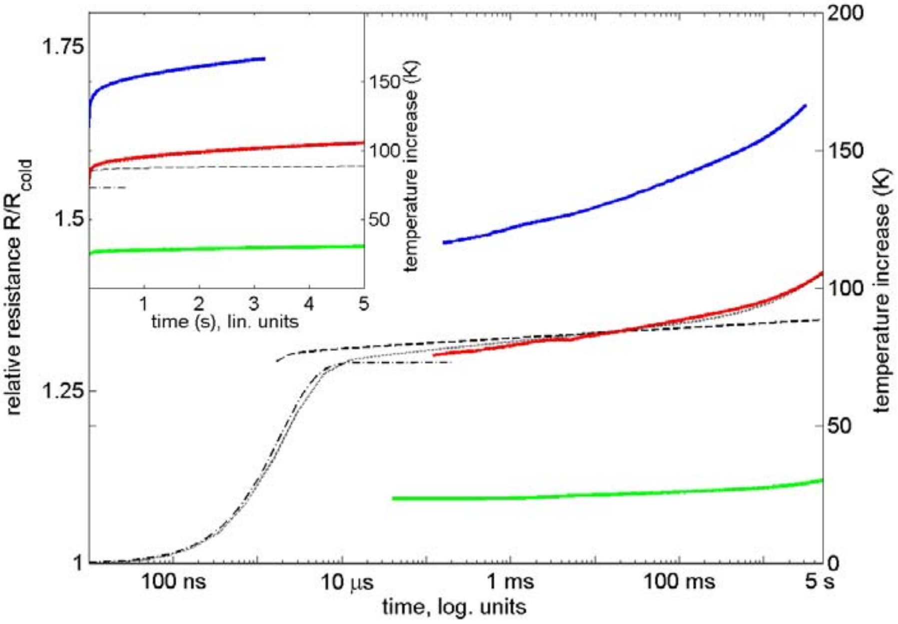
- Contact resistance (fast time scale)
- Heat conductivity into the sample (slow time scale)
- Finite thickness of sample

Important:

- Heat capacity
- Heat conductivity

For us the choice:

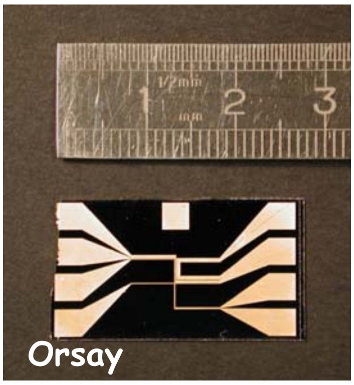
- Si
- GaAs

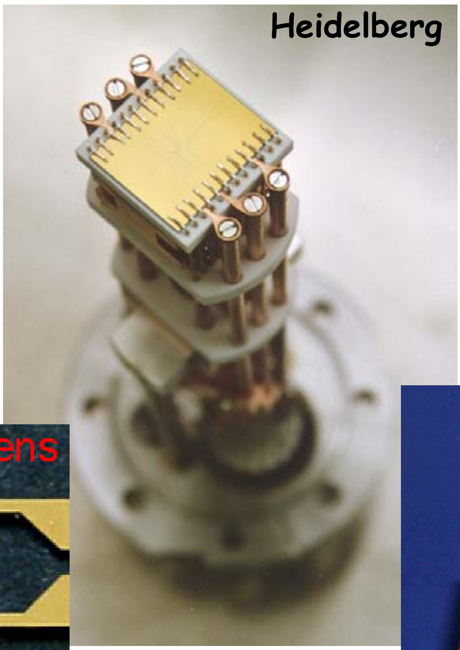


Thin wires are limited by fast heating: $j_{max} > 10^8$ is possible

S. Groth et al. Cond-mat/0404141 (2004)

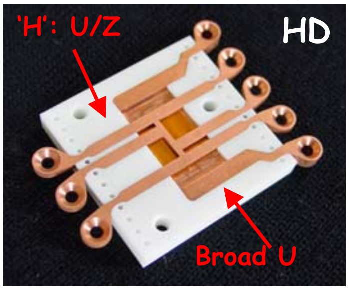
ATOM CHIP
implementation

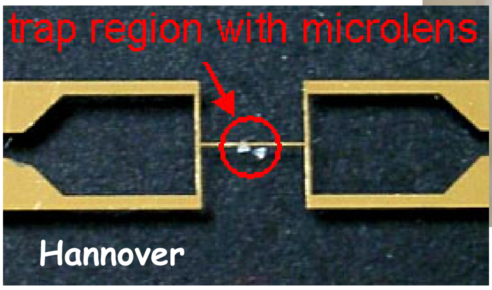




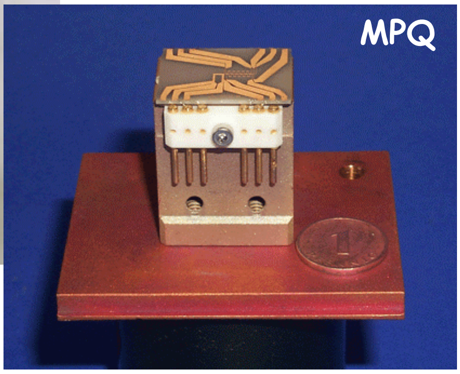
nano fabricated chip compatible with $p < 10^{-11}$ torr

Support structure underneath the chip



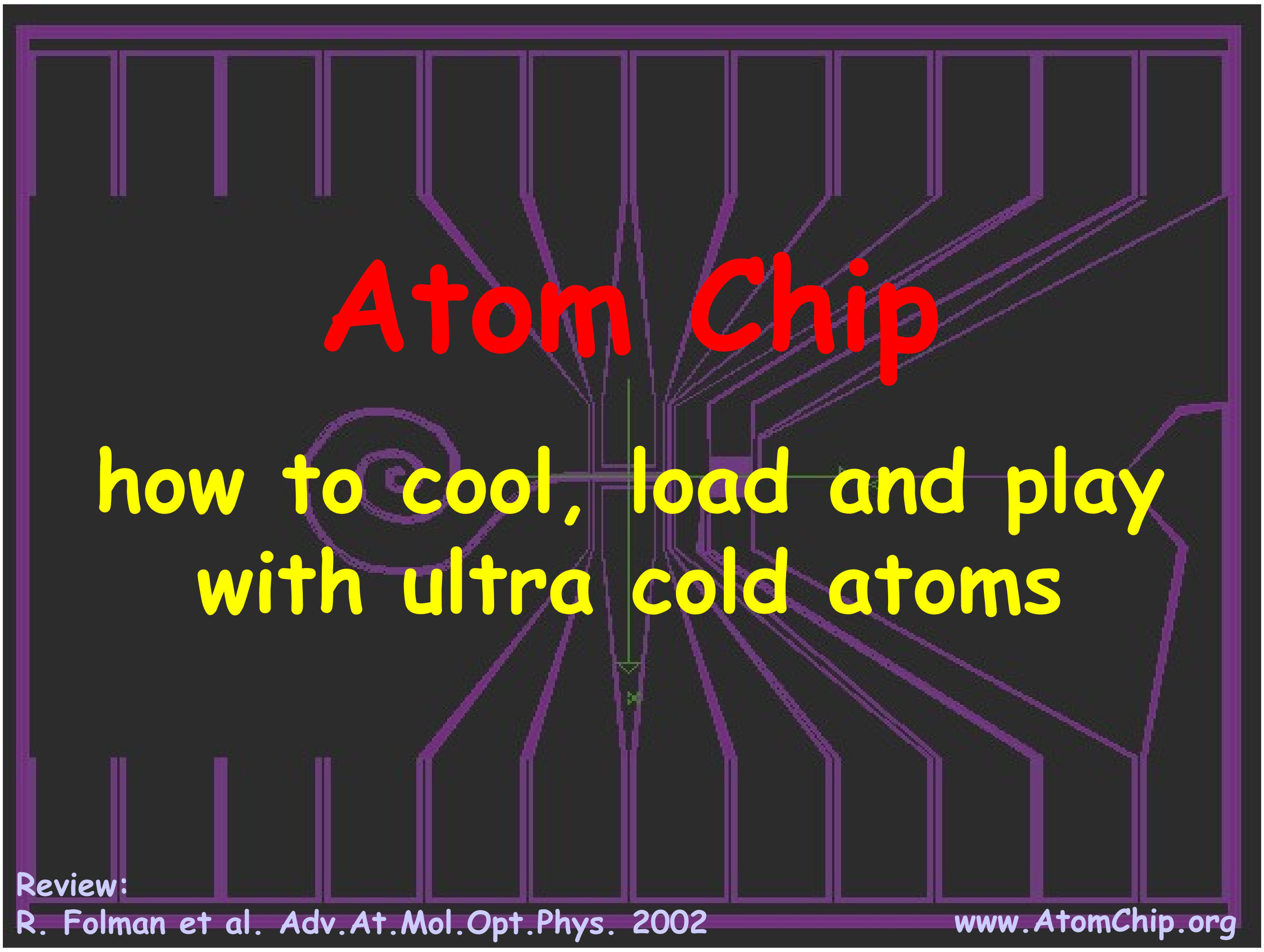


Chip with integrated lens



thin film hybrid technology

ACQUIRE, ACQP



Atom Chip

how to cool, load and play with ultra cold atoms

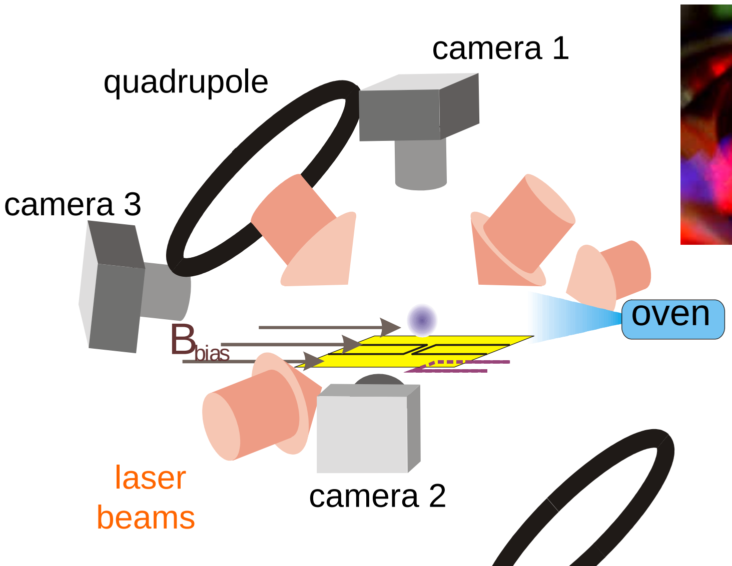
Review:
R. Folman et al. Adv.At.Mol.Opt.Phys. 2002

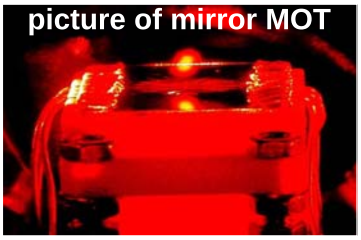
www.AtomChip.org

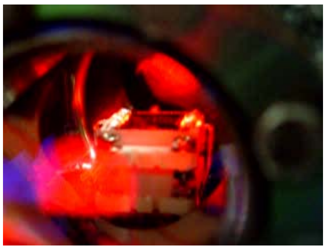
EXPERIMENTAL SETUP

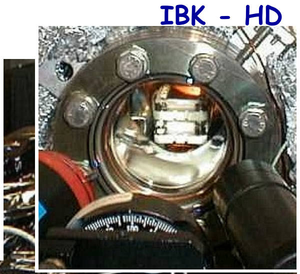
cooling close to surface

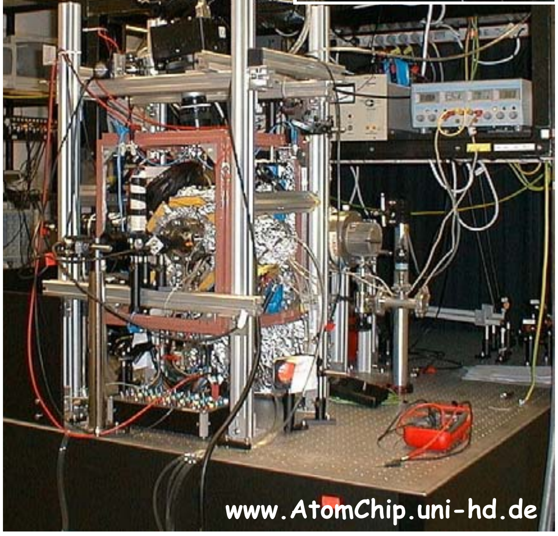
IBK - HD




picture of mirror MOT

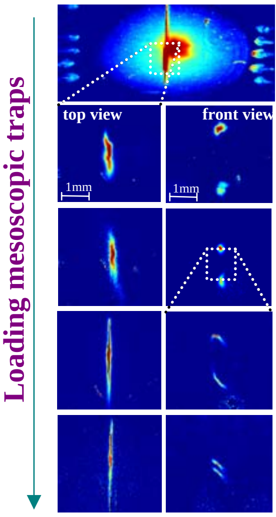




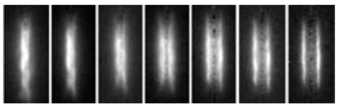

www.AtomChip.uni-hd.de

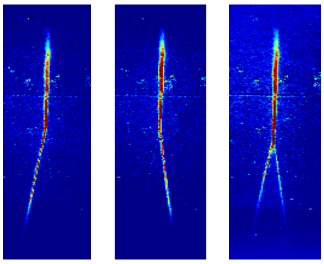
ATOM CHIP STATUS
experiments with thermal atoms

Innsbruck
Heidelberg



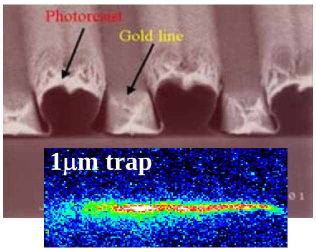
Dynamic Beam Splitter



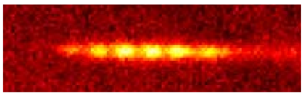


Beam Splitter

1µm structures

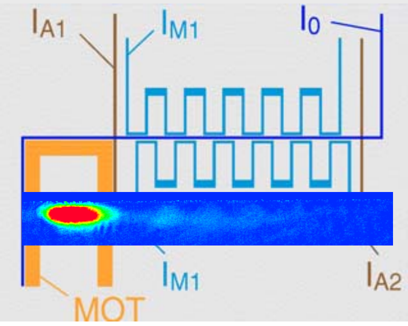


Electric traps

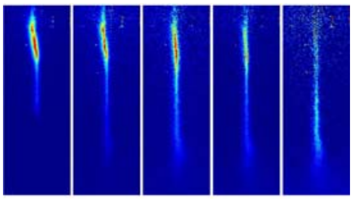


- trap frequencies > 1 MHz
- trap ground state < 30 nm
- trapping with on-board bias field
- structures down to 1 µm
- moving, splitting etc …

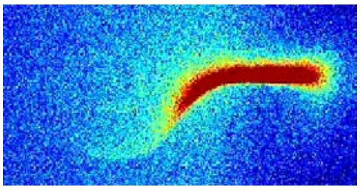
MPQ Munich
Moving atoms (conveyor belt)



Continuous Loading



Vertical traps
guiding in arbitrary direction

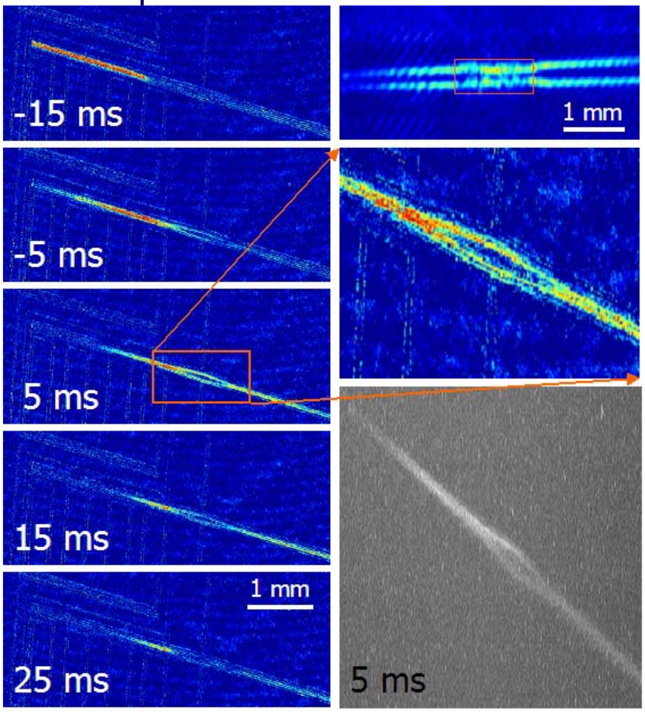


www.AtomChip.org

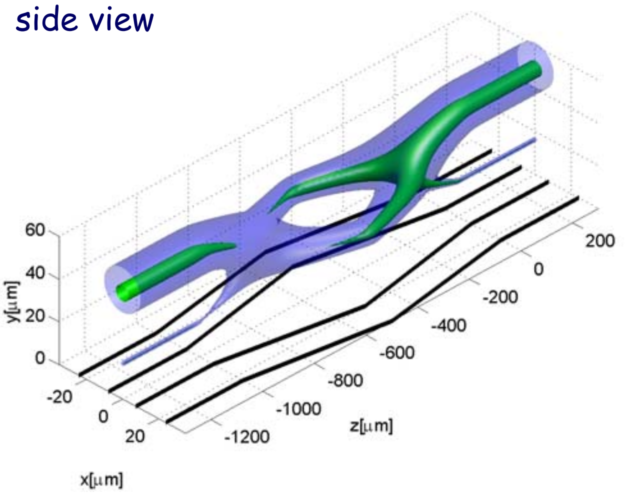
INTERFEROMETER
on the Atom Chip

Experiment with thermal atoms

Top view



side view



Problem: minimum of the potential changes during the splitting.

Manipoulation with Electric Fields

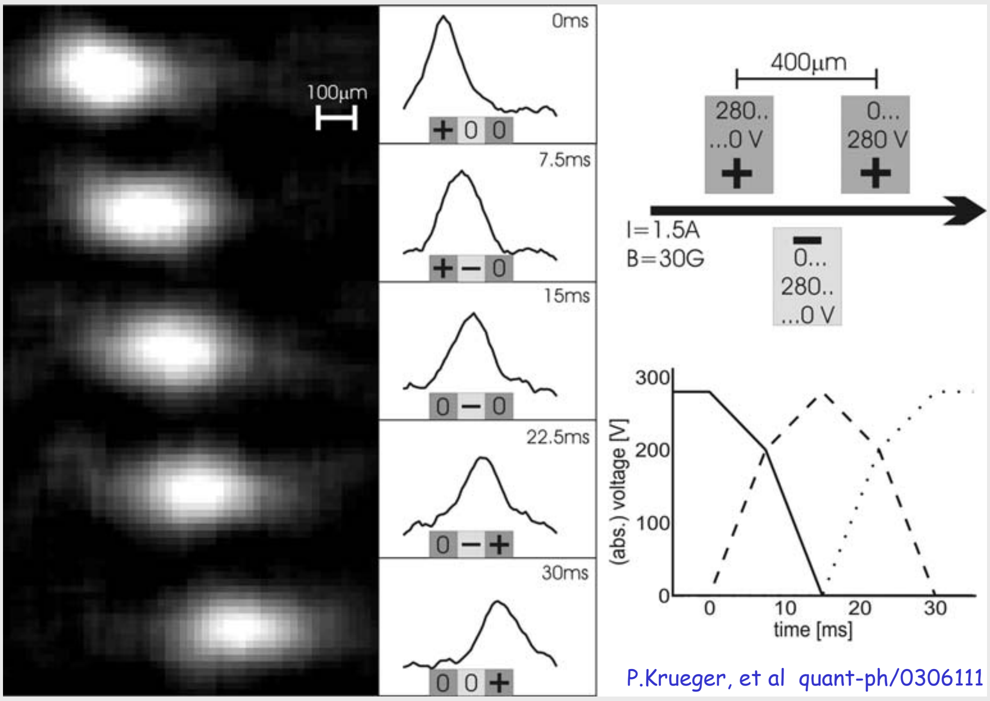
Heidelberg

Dynamics

- Electric fields can be varied
- linearly summed

- Atomic transport 'motors'
- Splitting and recombining

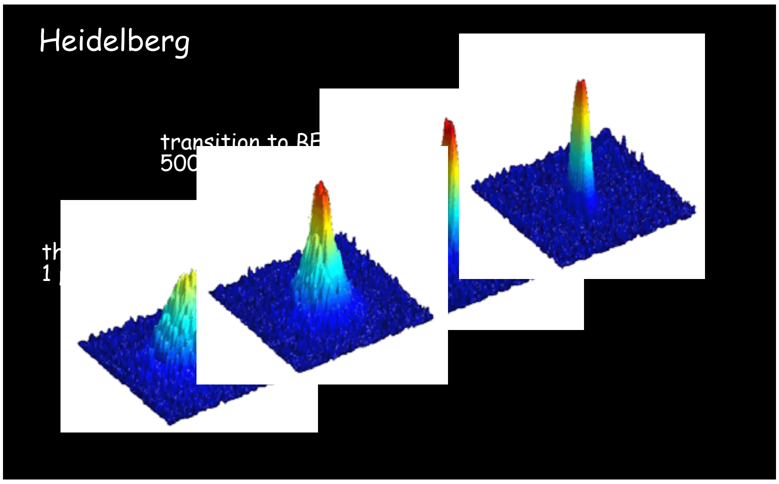
Electric Motor



P.Krueger, et al quant-ph/0306111

BEC in MICRO TRAP

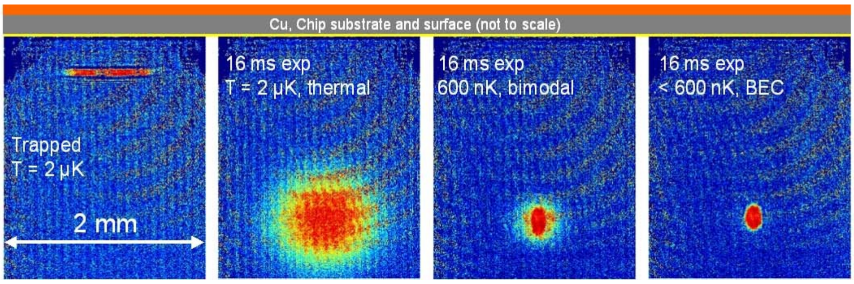
Heidelberg



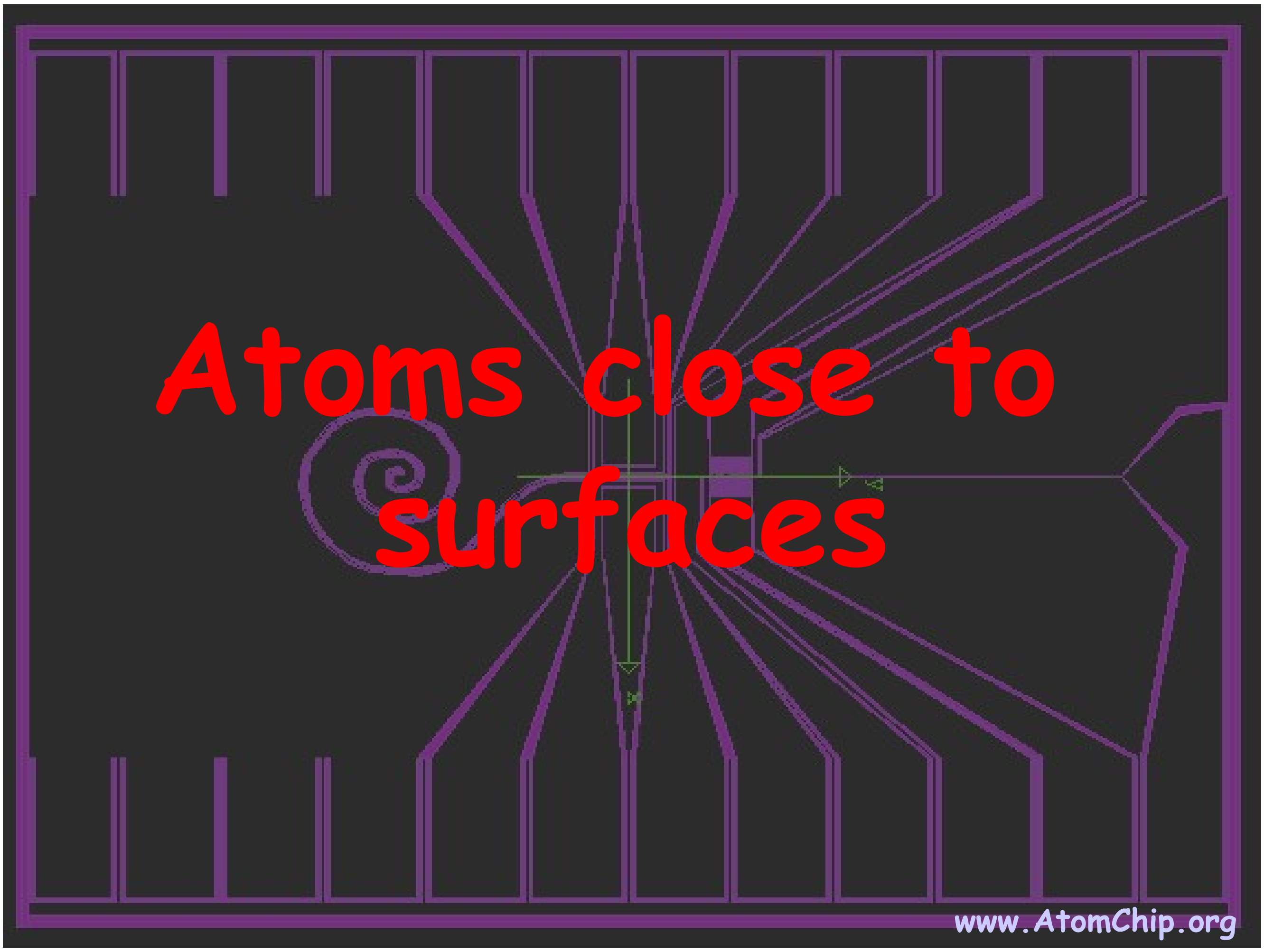
Many groups:
Tübingen, MPQ, ORSAY, IC, MIT, JILA, Brisbane ...

With a BEC we have a reservoir of motional ground state atoms as a source for the experiments

High atom density
-> the matter wave optics will be non linear
-> if interactions dominate: strongly correlated systems



MOT $> 3\ 10^8$ atoms @ 70 µK
Magn. Z trap $> 10^8$ at. @ 250 µK
Compress
trans.: ~500 Hz ~400 G/cm
long.: ~ 50 Hz
RF-Evaporation ~10 sec
BEC $3\ 10^5$ atoms @ T_c ~ 500 nK
Independent of chip structure



Atoms close to surfaces

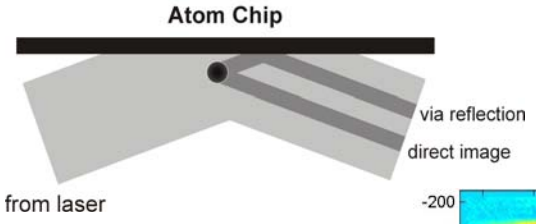
www.AtomChip.org

Why go close to surface

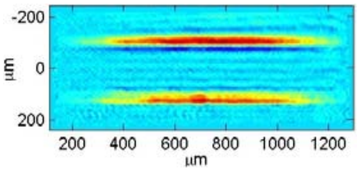
- **Tight confinement (transversal)**
  1d-physics, QuInfo
  - Confinement proportional to current density *j*
  - *j* depends on the removal of Ohmic heat better for small wires
- **Small potentials for tunnelling coupling**
  - Minimum structure size of the potentials ~ distance to the surface
  - size ~ 1μm
- **Small potentials for quantum tweezer**
  loading single atoms
- **Manipulating mesoscopic ensambles**
- ....

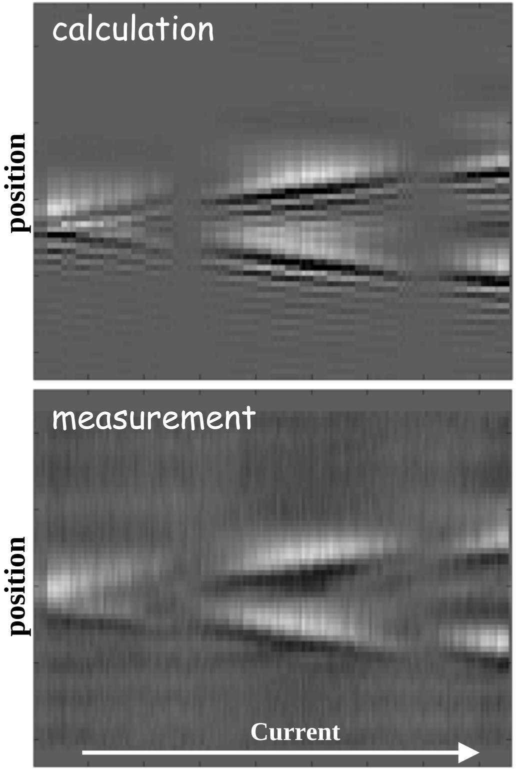
Measure Distance from the Surface

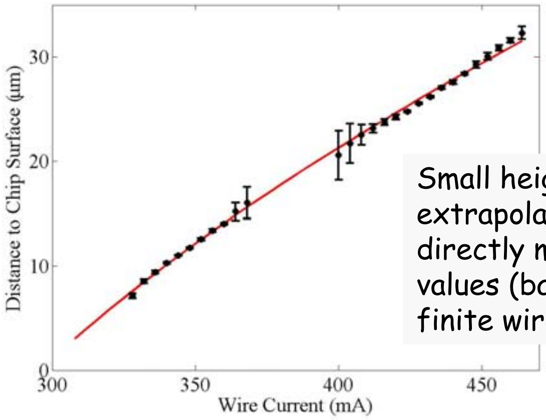
HD



Need to consider the light wave close to the surface







Small heights are extrapolated from directly measurable values (based on finite wire size)

Atoms close to surface

The bad guy: Johnson Noise life time of trap

$$\tau \sim \rho h^x / T_S$$

Theory: C. Henkel (Potsdam)

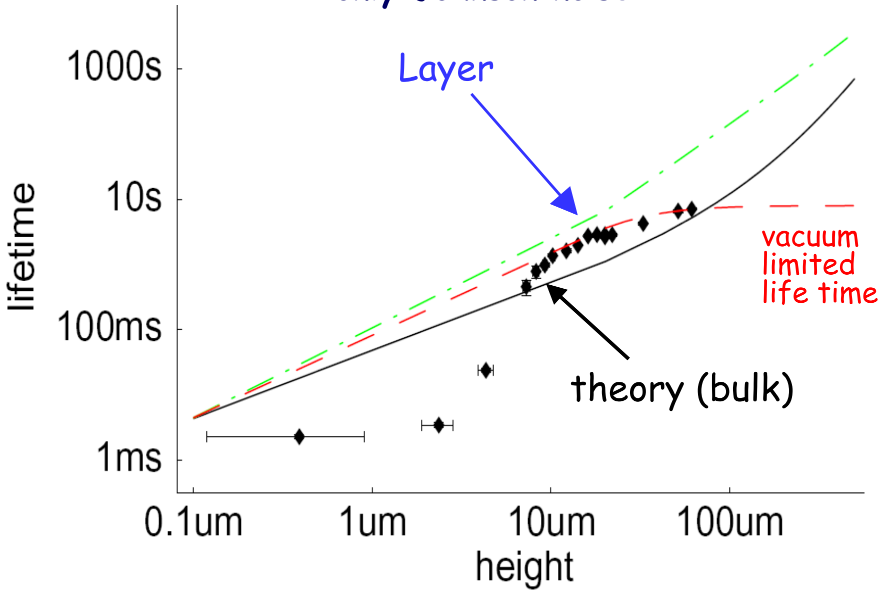
Pure exponential decay of trap observed over up to >2 orders of magnitude

Qualitatively the same behaviour but quantitative differences

- Steeper dependence with hight
- Shorter lifetime vor small distances
- Long lifetime for moderate distances (1s at ~5µm)
- Differences between wires (tech. noise?)

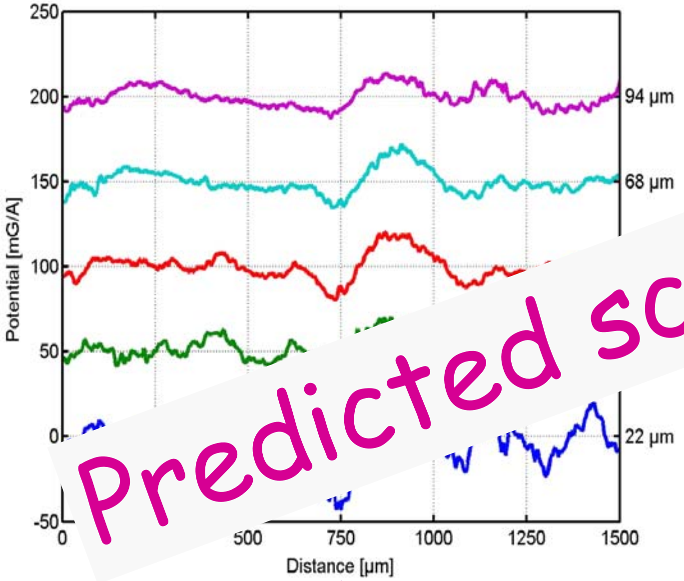
Hight calibration still uncertain by ~ 1µm

Grounded metal layer
only Johnson noise

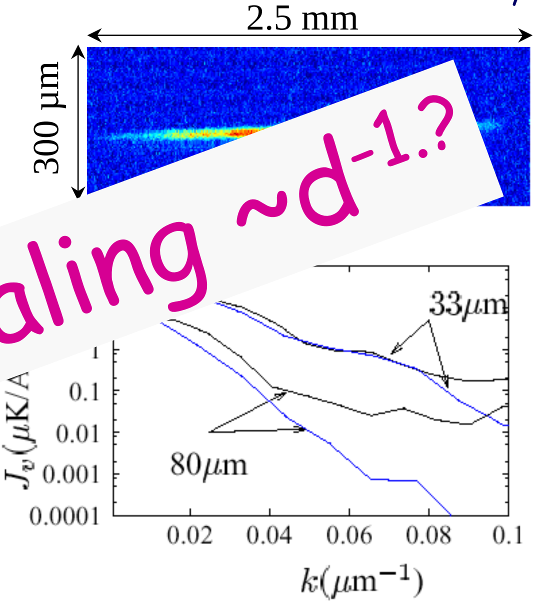


Atoms Approaching the Surface
Roughness of the magnetic potential

electro-plated wires



Orsay



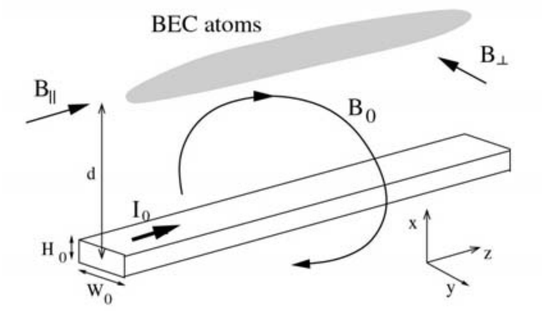
Predicted scaling ~d^{-1}?

Observed potential at different heights

Seen by many other groups
Tübingen, Susex/IC, JILA, MIT, ...

Power spectrum of roughness in terms of potential energy (1 μK = 15 mG)

From where do the disorder potentials come from



- Atoms are trapped in the minima of potentials created by the subtraction of two large fields.
- Minimum in that plane depends on the angle between these two fields.
- Sensitivity to changes in the current direction which are **not** orthogonal to the bias field.
- Sensitivity: thermal atoms: 1G ~ 67 μK
  BEC: chem. potential (~1-10 mG) sensitivity < 10^{-5} rad

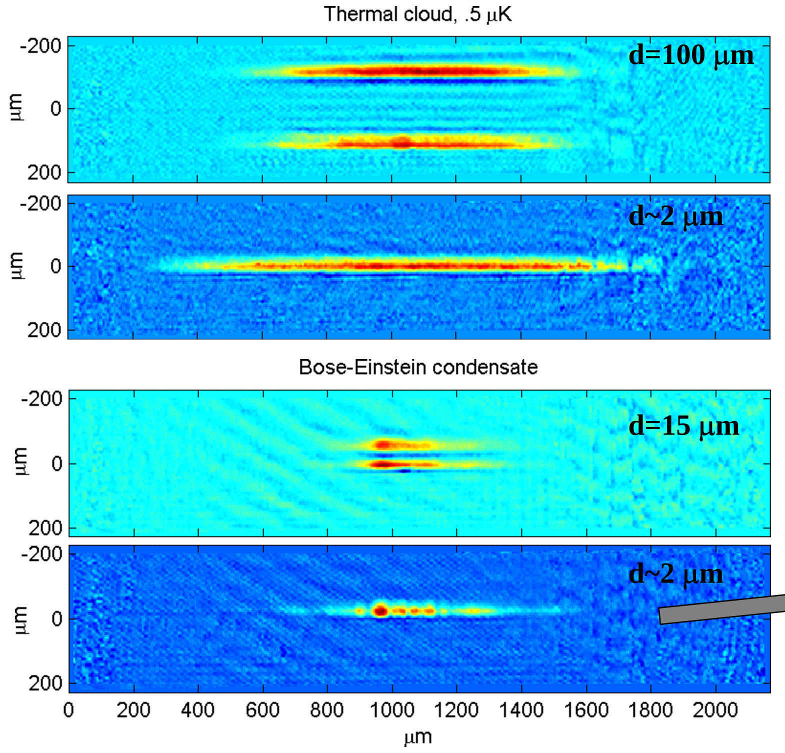
Proposal:

- Roughness of the wire edge causes the current to deviate from a straight flow (we choose evap. gold and nanofab.) for theory see: Daw-Wie Wang et al. PRL 92, 076802 (04).
- Imperfections in the surface of substrate (we chose Si and GaAs).
- Disordered current flow due to grain size, inhomgeneities, ... in the wire.

Roughness of the magnetic potential

evaporated gold Atom Chips

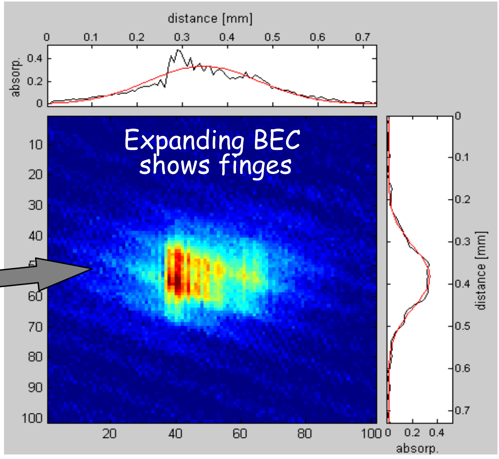
Heidelberg/WIS



No fragmentation for a thermal cloud even at T~500nK

Some fragmentation for a BEC below 10 μm from surface

Disorder potentials ~ 100nK or smaller



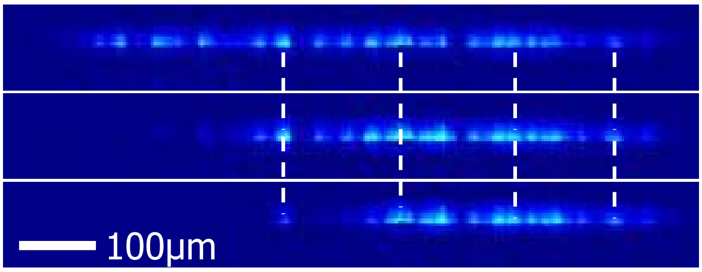
Expanding BEC shows finges

BEC near surfaces

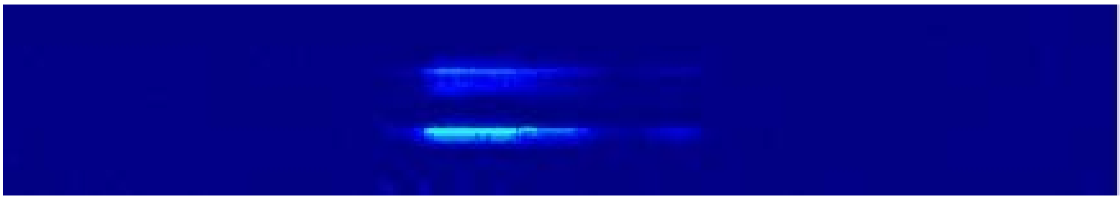
Heidelberg

BECs are a more sensitive probe $\Delta U < 10^{-13}$ eV

Fragmentation becomes visible
typical scale given by chem. potential of BEC (~100nK)



- Wire can be scanned by variation of longitudinal confinement
- disorder potentials are stable in position and time

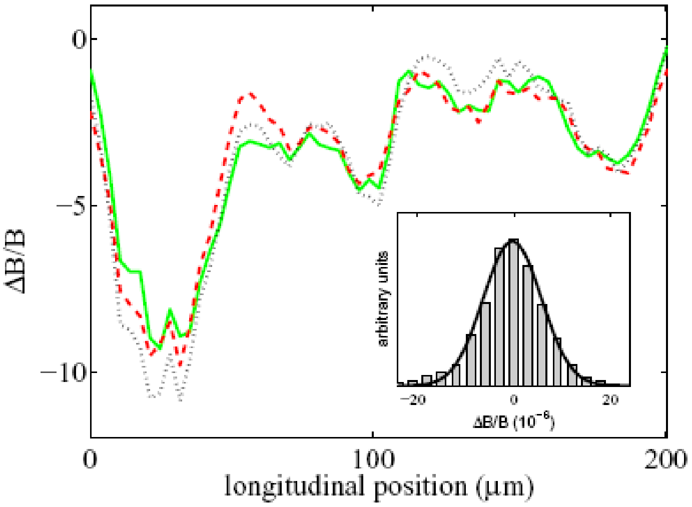


Origin of disorder potentials

Heidelberg

Possible sources:

- gravitation (~100nK/μm)
- electric fields
- magnetic fields (irregular currents)



scan at equal height but varied currents

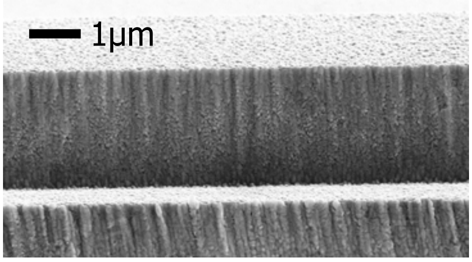
disorder potentials normalized to ΔB/B

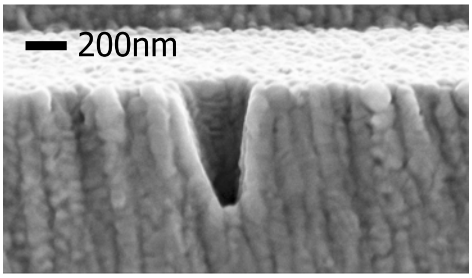
traces equal within $\Delta B/B \sim 3\ 10^{-6}$

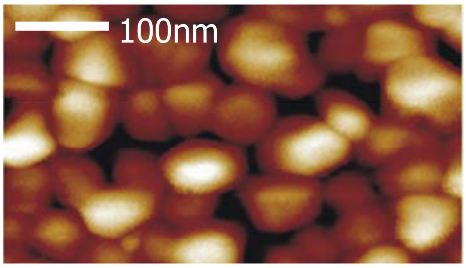
$\Delta U < 10^{-13}$ eV down to d<5μm

Chip surfaces

lithographically pattered atom chips
Innsbruck-Heidelberg-Weizman

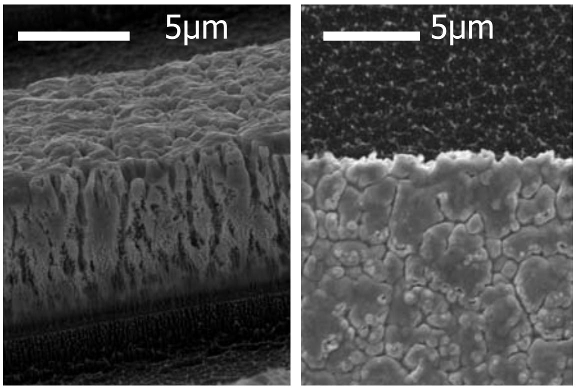




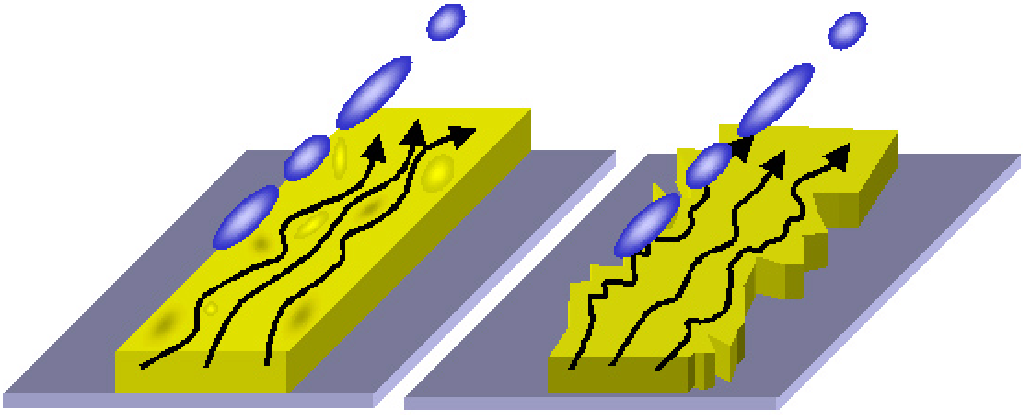


electroplated chips (Orsay)

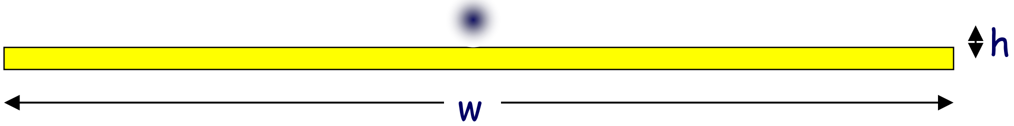
Estève et al., cond-mat 2004



What causes the disorder potentials?

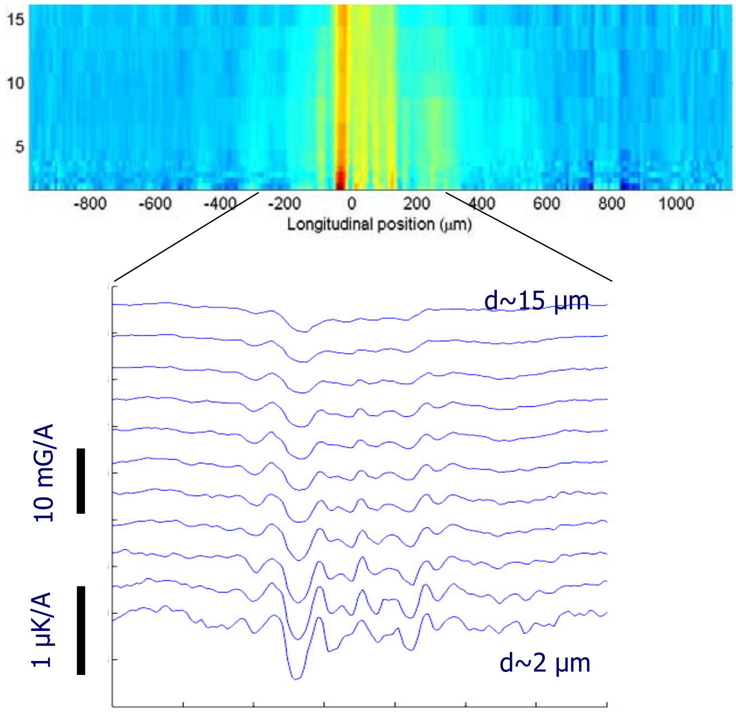


How to decide?
Measure potentials on a wide wire (width >> hight of atoms)
will see the local properties of the current

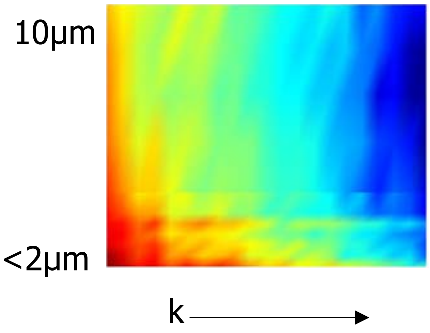


Mapping disorder potentials
100µm wide wire

Heidelberg



frequency dependent
power spectra

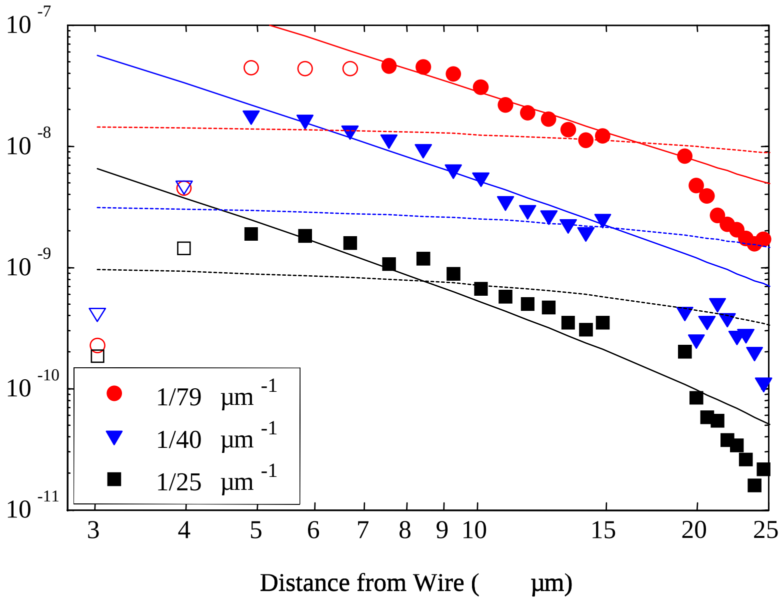


Strong height scaling even though the distance to wire is much smaller than the wire width

? Can the edge of wire be the cause of the disorder potential ?

Edge or local effect?

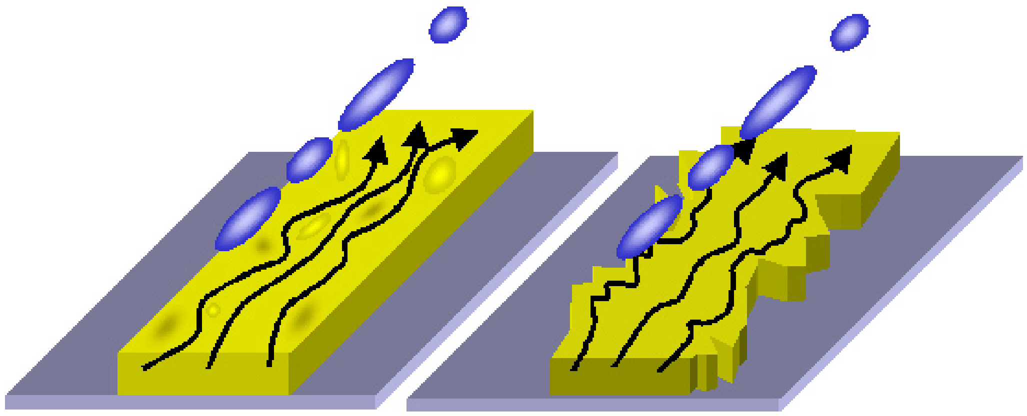
Heidelberg



Scaling of disorder potentials near a broad wire (100μm)

- fragmentation increases as the surface (not edge) is approached
- pure edge effect leads to different scaling
- Simple local model gives better agreement
- k-dependence ~1/k^2

What causes the disorder potentials?

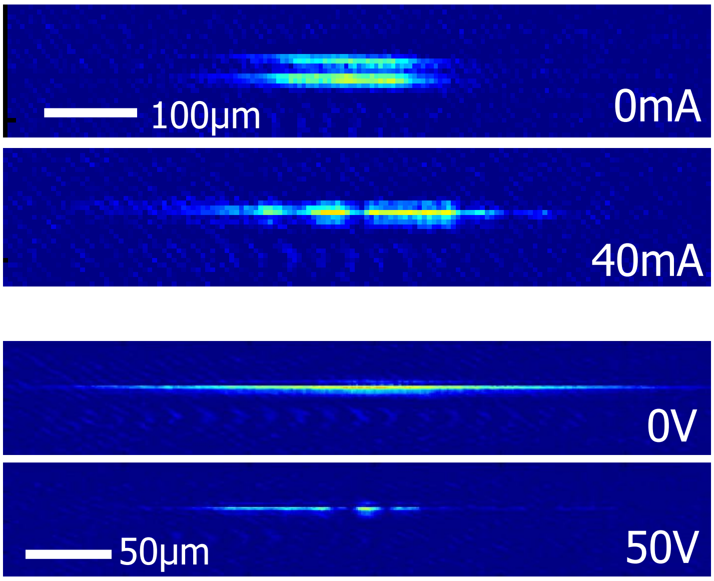


Important contribution from the local properties

Trap independent disorder probe

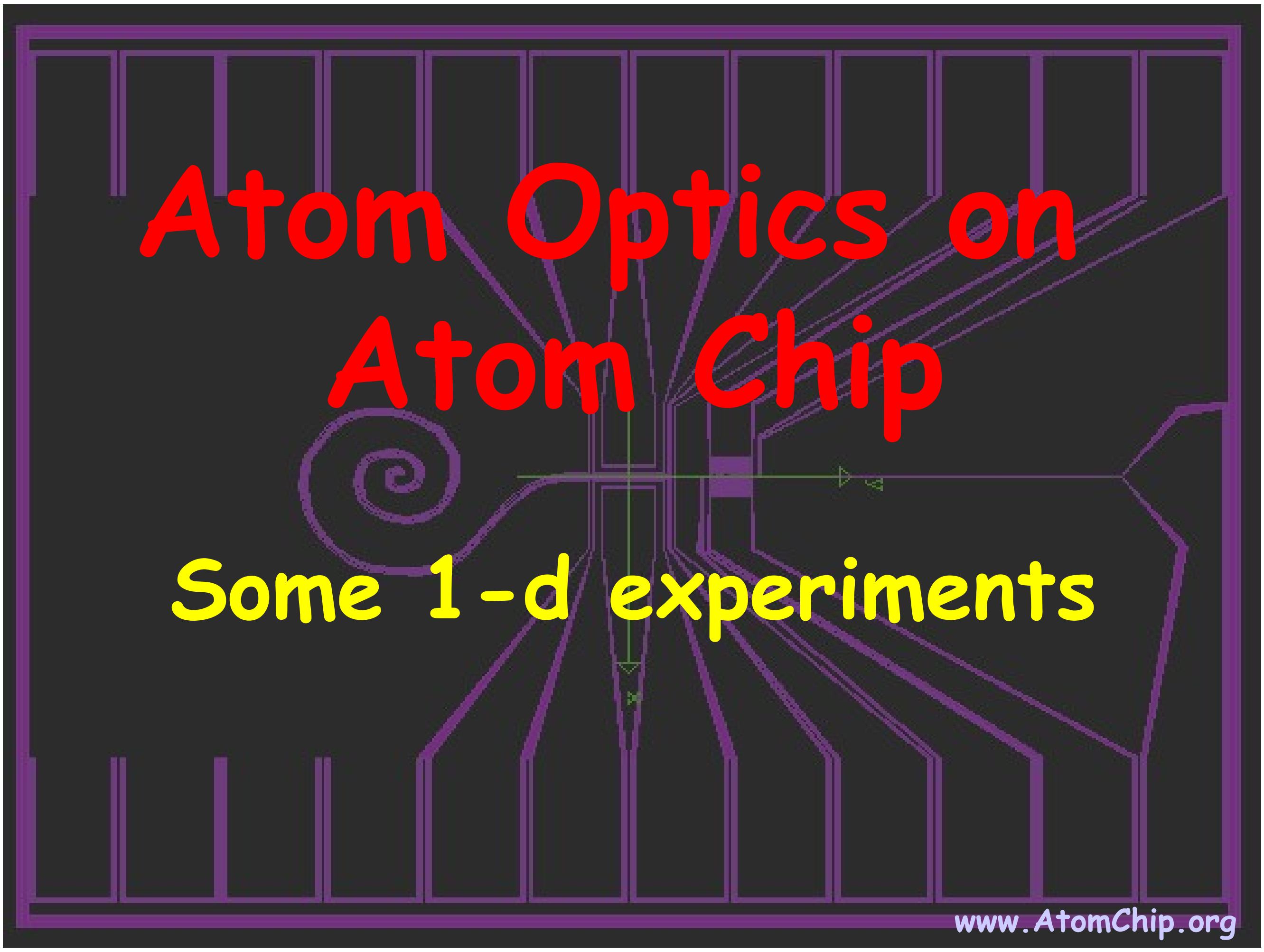
Heidelberg

BEC can be placed far from trapping wire but close to a different structure by rotating the bias field
Atoms held with 10µm wire above 100µm wire



Magnetic disorder

Electric disorder



Atom Optics on Atom Chip

Some 1-d experiments

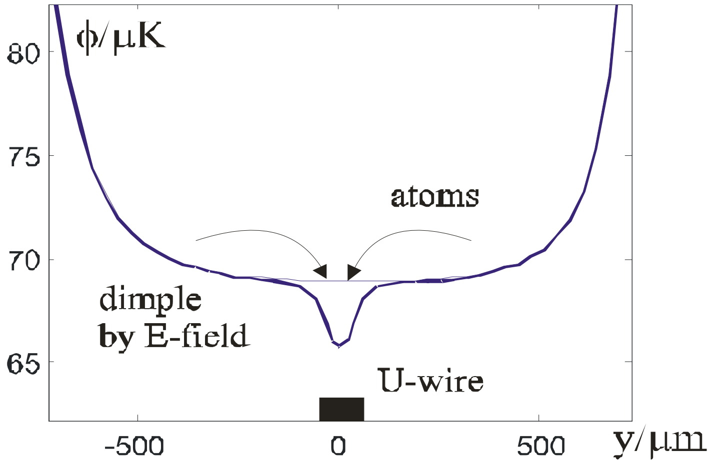
www.AtomChip.org

Condensing with E-field

Heidelberg

Thermal cloud

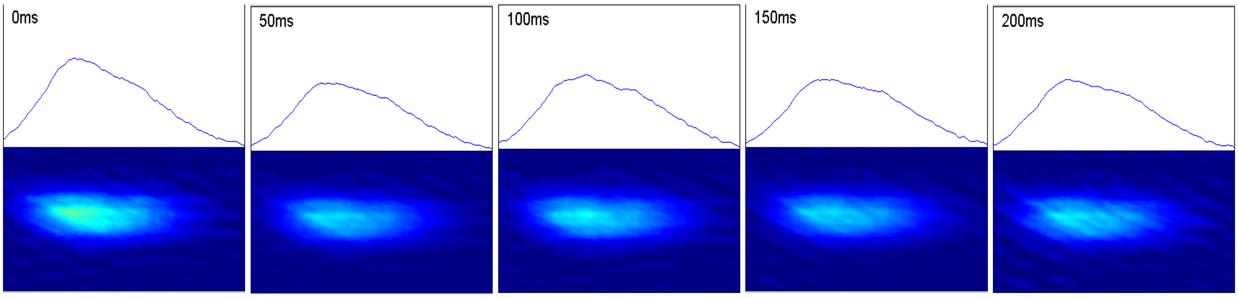
- N = $1.3 \cdot 10^5$
- T = 1.1 µK
- Height = 10 µm
- ν_{long} ~ 5 Hz
- ν_{trans} = 17 kHz
- TOF = 10ms



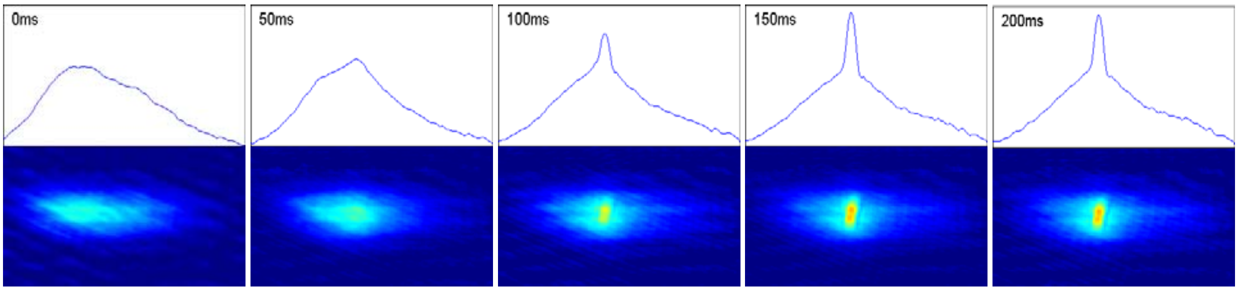
Condensing with E-field

Heidelberg

U = 0 V



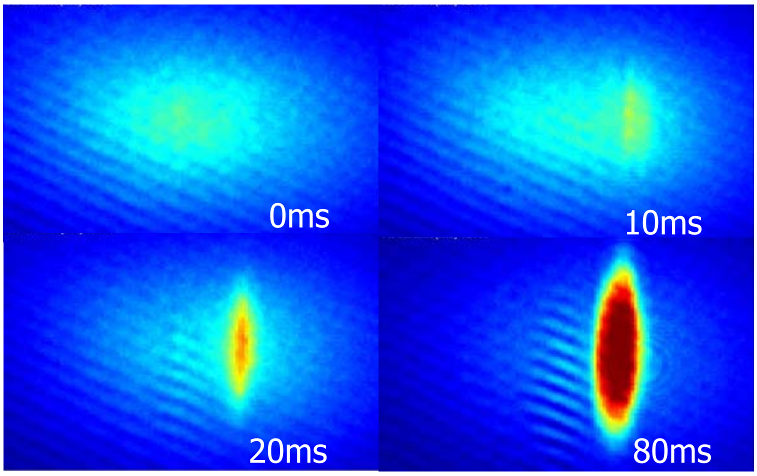
U = 3.5 V



16.4.04
#1001
Mean of 10

Condensate formation in dimple trap

- thermal atoms just above T_C in a 1d trap
- at 0ms electric dimple is suddenly created
- 1d BEC forms slowly
- BEC becomes larger and 3d
- equilibrium reached after ~80ms



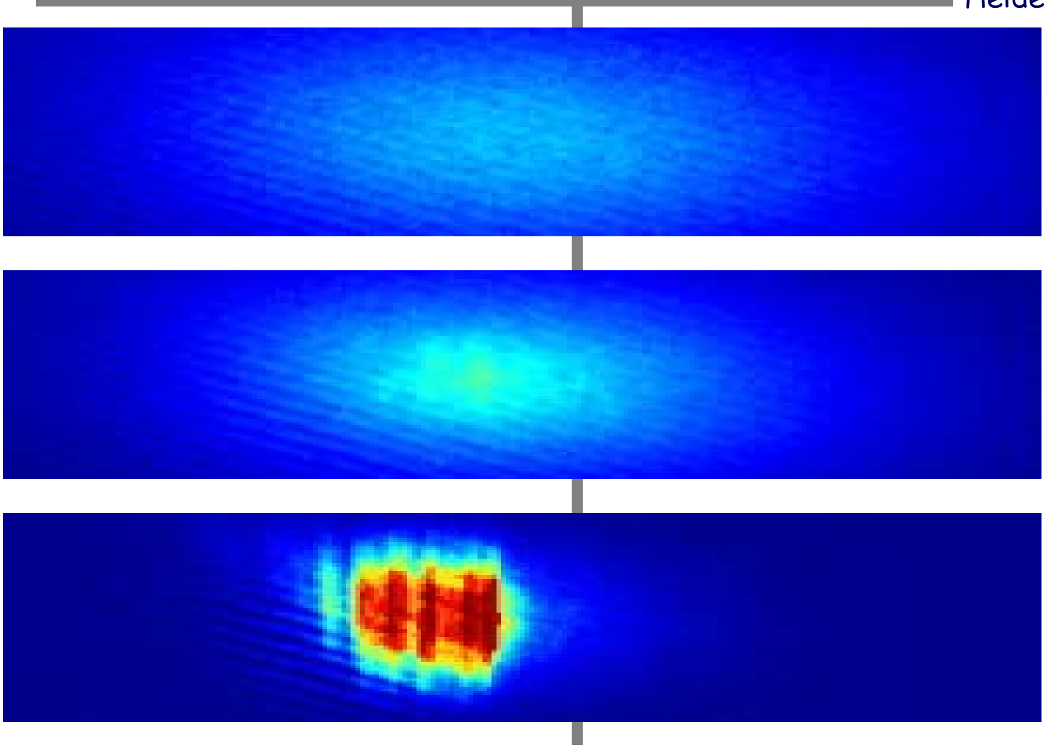
Condensate formation in dimple trap

Final cooling

825 kHz

792 kHz

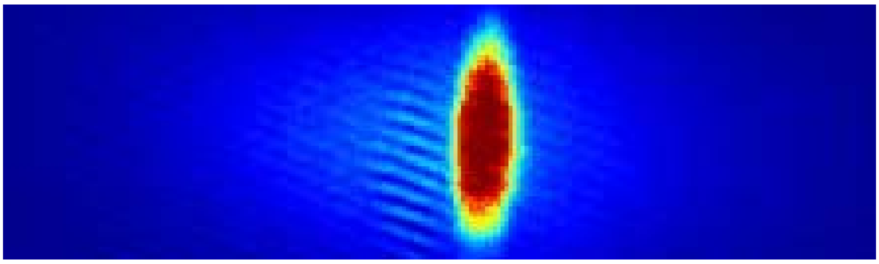
760 kHz



TOF = 16ms Duration of sequence 60 ms

BEC propagation in 1d guide
against a background

Heidelberg



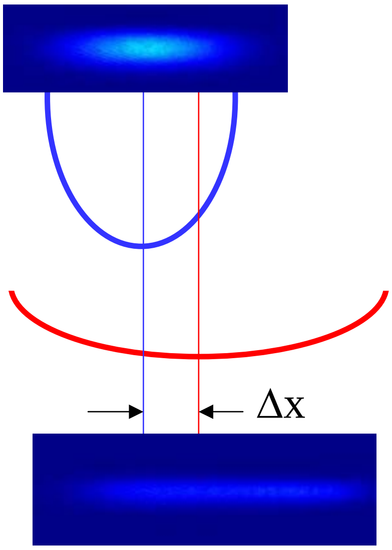
TOF = 16ms
Duration of sequence 5ms

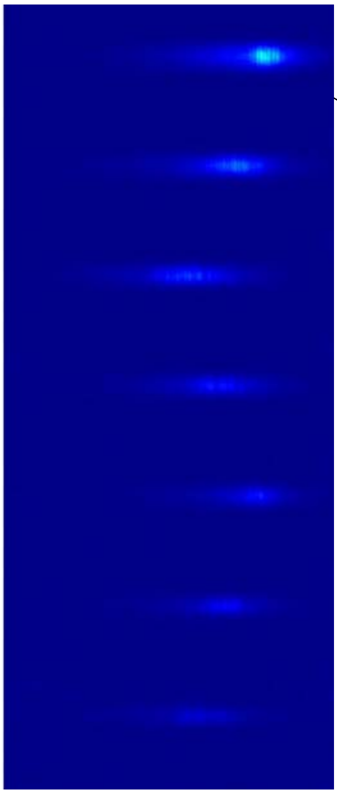
- BEC is formed in 3d dimple
- off-center release to elongated (1d) trap by sudden (<1µs) switching off of dimple voltage
- background gas temperature ~T_C
- movement of edge at ~5cm/s
- thermalization into equilibrium state (centered cloud at T_C) on slower time scale (~100ms)

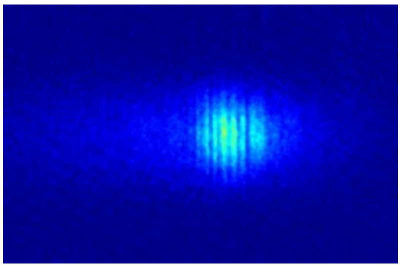
Moving cloud in 1-d

Heidelberg

Displace the potential longitudinally



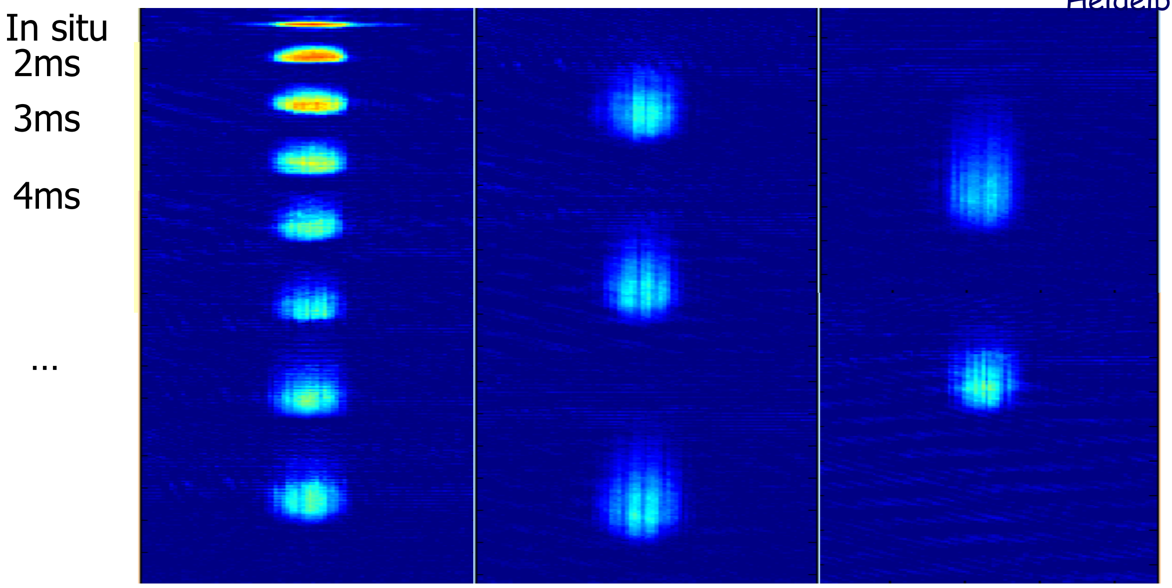




See the formation of a dense core at first ‘reflection‘
Appearance of regular fringes

TOF expansion: 1-d BEC
sharp lines in expansion after fast cooling

Heidelberg



Parameters: fast cooling time (start of ramp to picture as short as 10ms)
sound propagation along condensate >200ms
1-d regime: $\mu \kappa \hbar\omega$
Suggestion: sharp lines are a sign of domain formation in the order parameter during the phase transition

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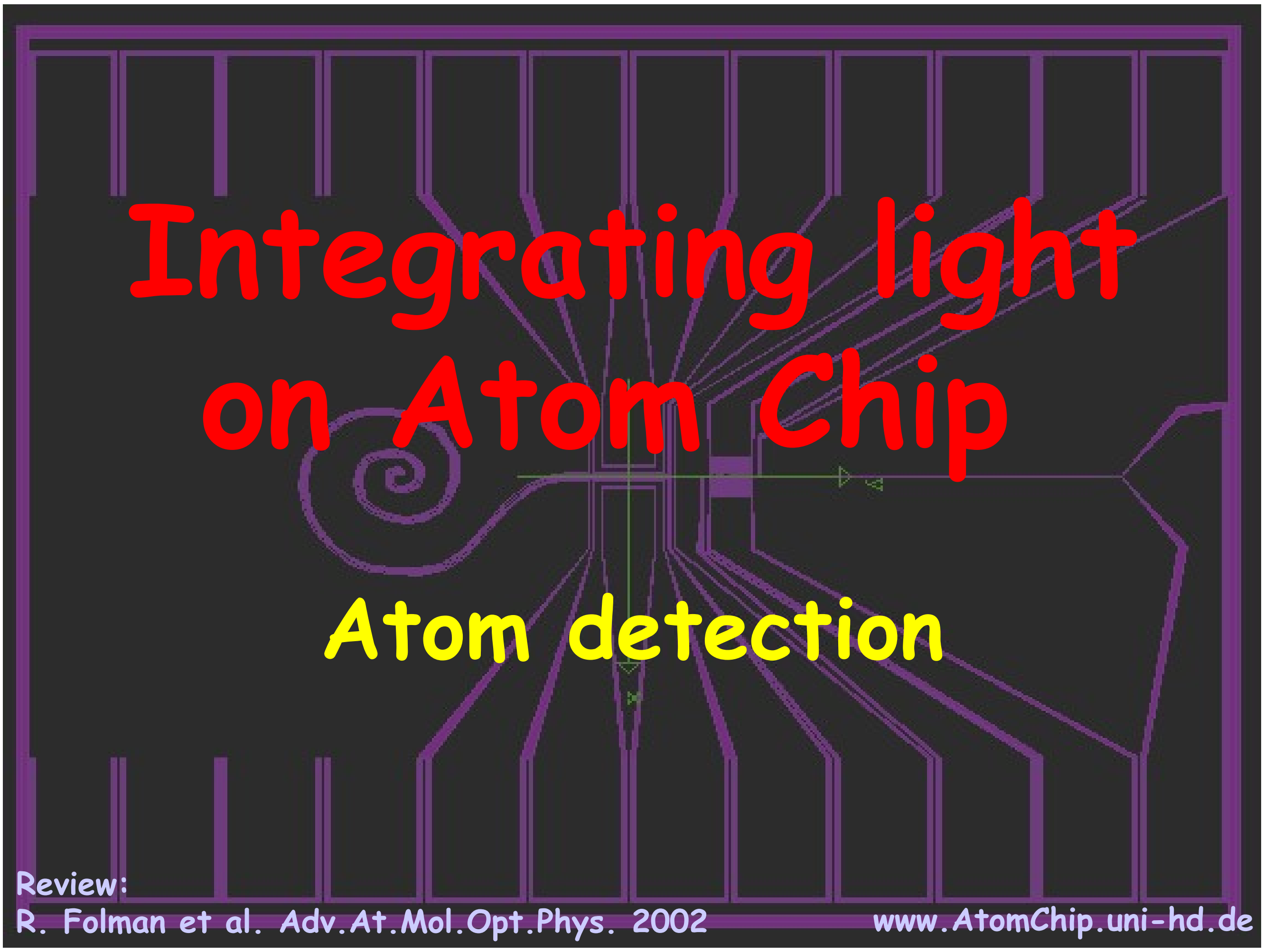


Integrating light on Atom Chip

Atom detection

Review:
R. Folman et al. Adv.At.Mol.Opt.Phys. 2002

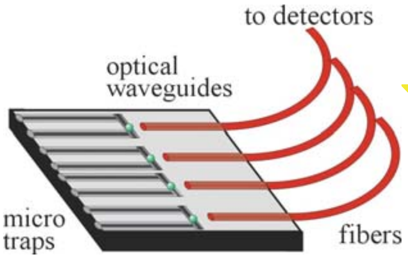
www.AtomChip.uni-hd.de

INTEGRATION OF LIGHT ON THE ATOM CHIP

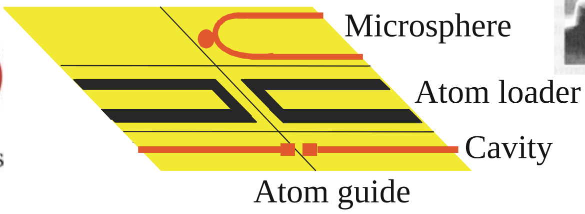
Goals: Preparation, Manipulation, Detection of atomic states on the Atom Chip

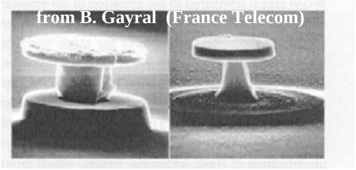
Tools: Micro optics: cavities, lenses, waveguides

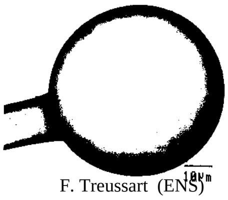
Techniques of coupling to the atoms: Two mirror resonators, evanescent fields of micro spheres or micro discs, SNOM techniques, fiber cavities



Hannover




from B. Gayral (France Telecom)



F. Treussart (ENS)

Longtime goals:

State selective, non-demolishing, single atom detection; Integration of all micro optical elements, including light sources, onto the Atom Chip

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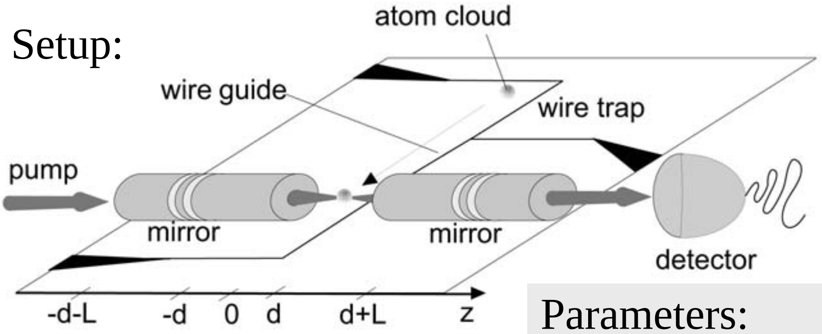
ATOM DETECTION

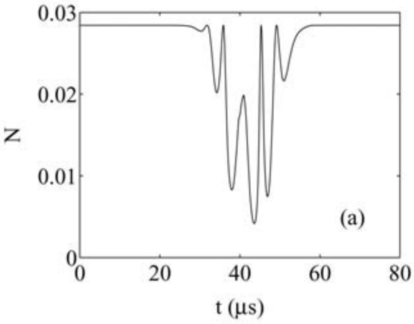
micro cavity on chip: basic calculation

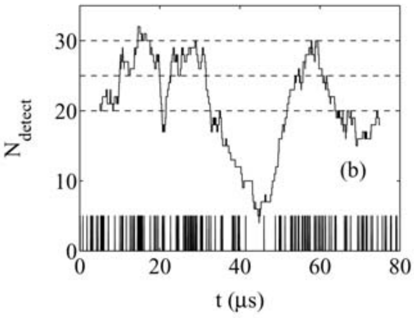
Heidelberg

Detection of atomic states on the Atom Chip
Micro optics: cavities, lenses, waveguides
- Two mirror resonators
- fiber cavities
- SNOM techniques

Setup:







Parameters:
- 5 μm core
- 5 μm gap
- finesse 500
- >3σ detection

A. Haase, R. Folmann J.Schmiedmayer (Heidelberg)
P. Horak, B. Klappauf, P. Kazansky (ORC, Southampton)
P. Domokos (Innsbruck)
E. Hinds (Sussex)

www.AtomChip.uni-hd.de

Experiment with a macroscopic cavity

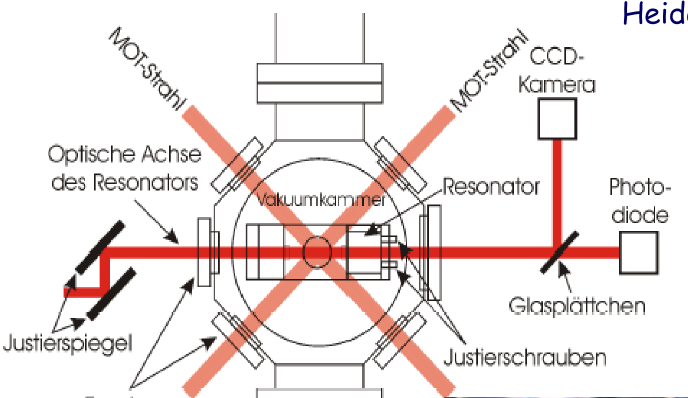
Heidelberg

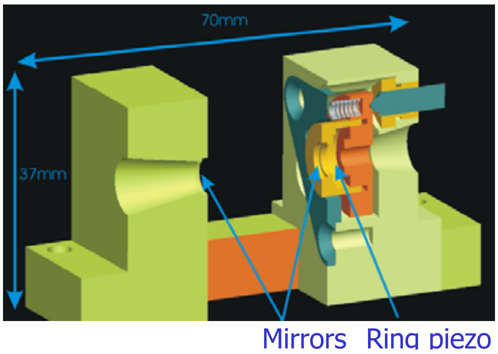
Test Setup

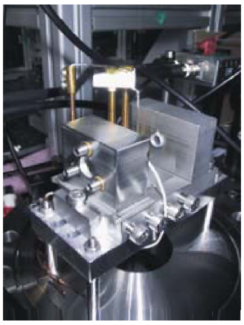
To learn stabilization schemes for the cavity, preliminary experiments are performed using a standard mirror cavity and cold atoms being dropped from a 6-beam MOT above.

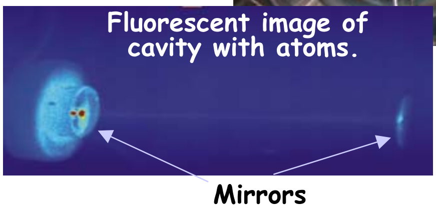
Cavity parameters

Chosen to be comparable with fibre setup: spherical mirrors with transmission T=0,001, radius of curvature r=10 mm at a distance of L~19,9 mm form a waist of w_0~10 μm. A Finesse of up to F~2000 was measured.





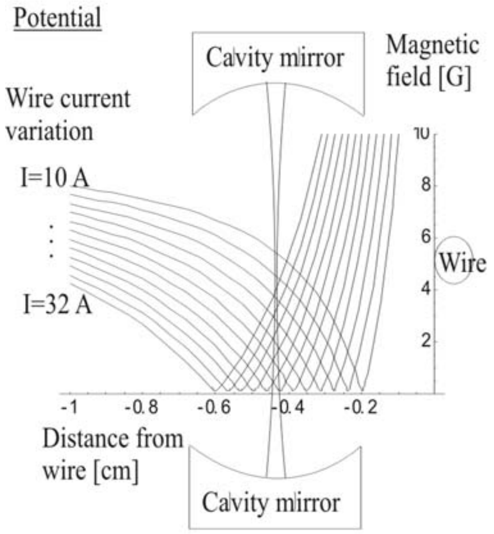


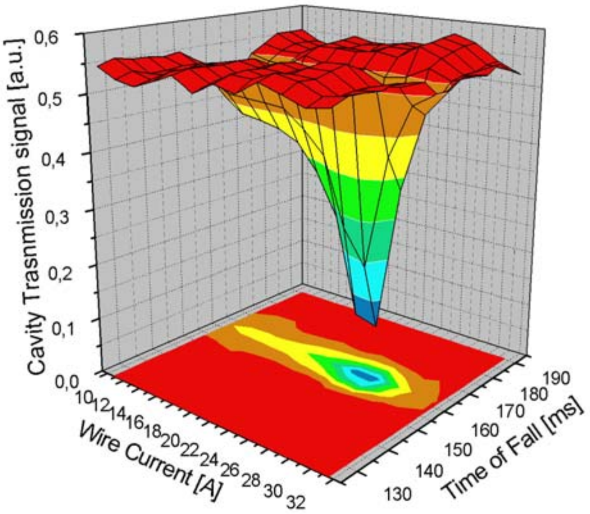


Detecting Atoms in micro traps
First signals

Heidelberg

Regime of bistability



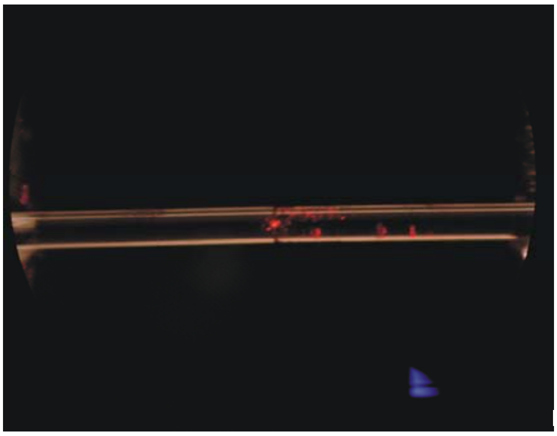


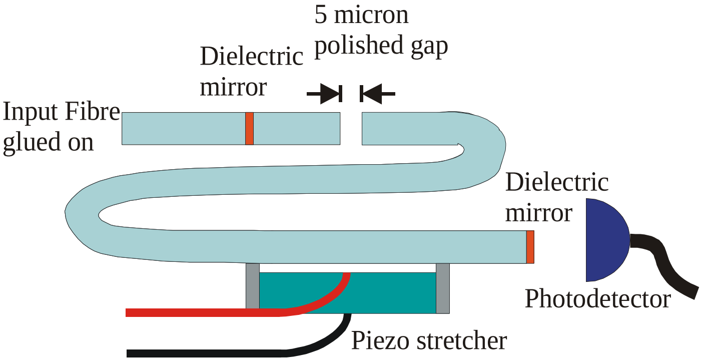
Cavity with Finess ~500 w~12 μm

A. Haase 2003

First fiber cavity test experiments

HD

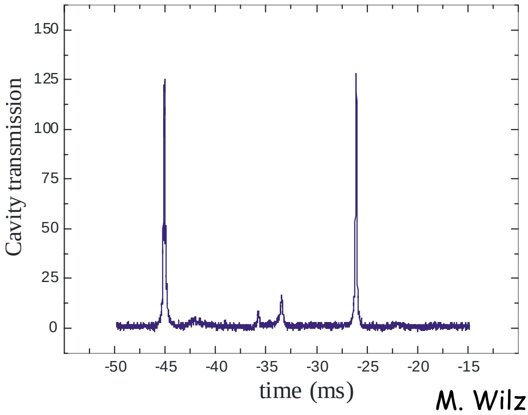




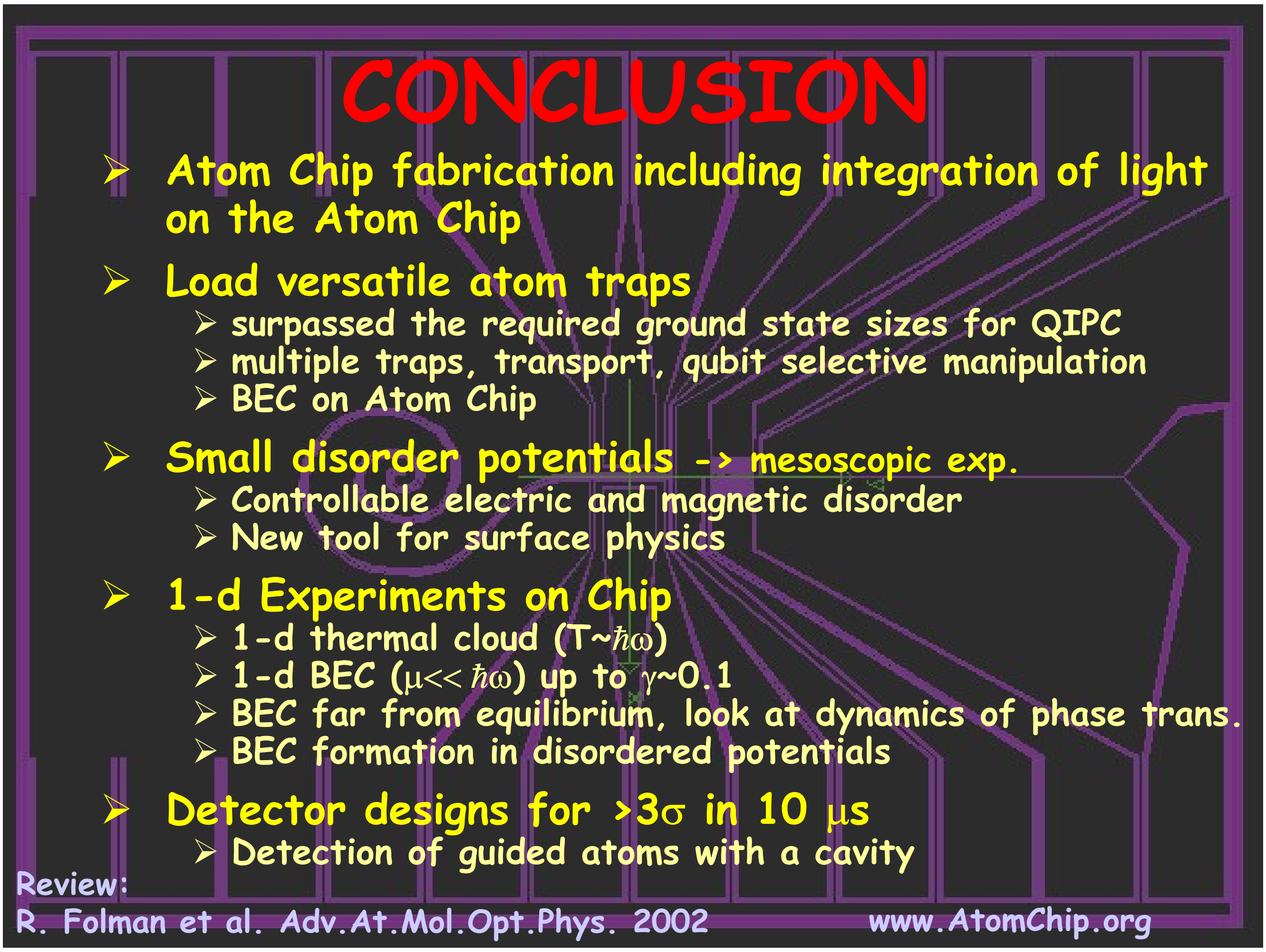
Fibre cavity of finesse 110 formed by dielectric mirrors at the outer fibre ends. A gap of 5 microns is included. The cavity length is scanned using a piezo stretcher, no alignment needed

8σ detection of a single atom in 10 μs

Finess > 1000, w~2.5 µm with front mirrors and gap up to >50 µm



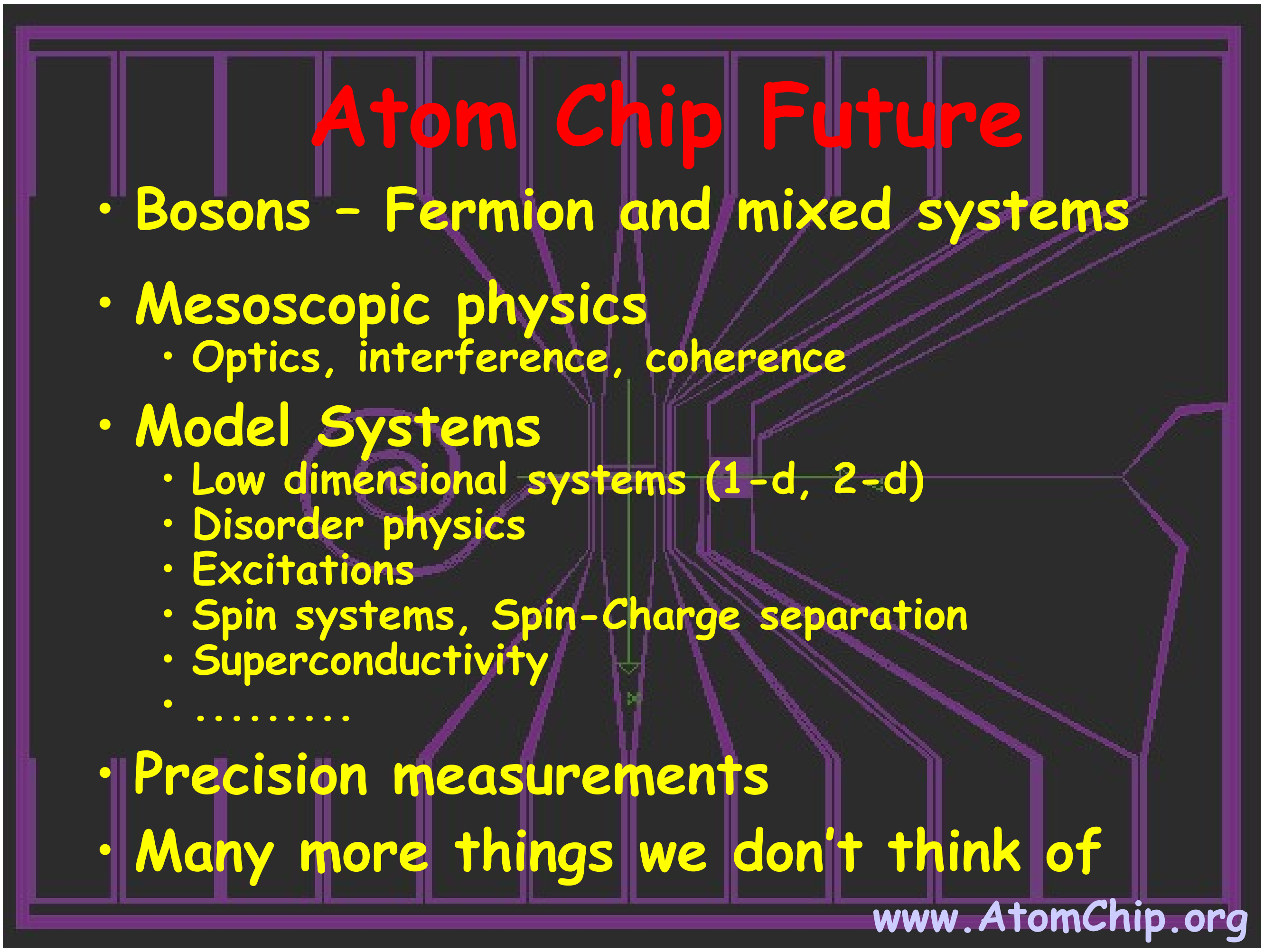
M. Wilzbach 2003



CONCLUSION

- Atom Chip fabrication including integration of light on the Atom Chip
- Load versatile atom traps
  - surpassed the required ground state sizes for QIPC
  - multiple traps, transport, qubit selective manipulation
  - BEC on Atom Chip
- Small disorder potentials -> mesoscopic exp.
  - Controllable electric and magnetic disorder
  - New tool for surface physics
- 1-d Experiments on Chip
  - 1-d thermal cloud ($T\sim\hbar\omega$)
  - 1-d BEC ($\mu \ll \hbar\omega$) up to $\gamma\sim0.1$
  - BEC far from equilibrium, look at dynamics of phase trans.
  - BEC formation in disordered potentials
- Detector designs for $>3\sigma$ in 10 μs
  - Detection of guided atoms with a cavity

Review:
R. Folman et al. Adv.At.Mol.Opt.Phys. 2002 www.AtomChip.org



Atom Chip Future

- Bosons – Fermion and mixed systems
- Mesoscopic physics
  - Optics, interference, coherence
- Model Systems
  - Low dimensional systems (1-d, 2-d)
  - Disorder physics
  - Excitations
  - Spin systems, Spin-Charge separation
  - Superconductivity
  - ....
- Precision measurements
- Many more things we don't think of

www.AtomChip.org

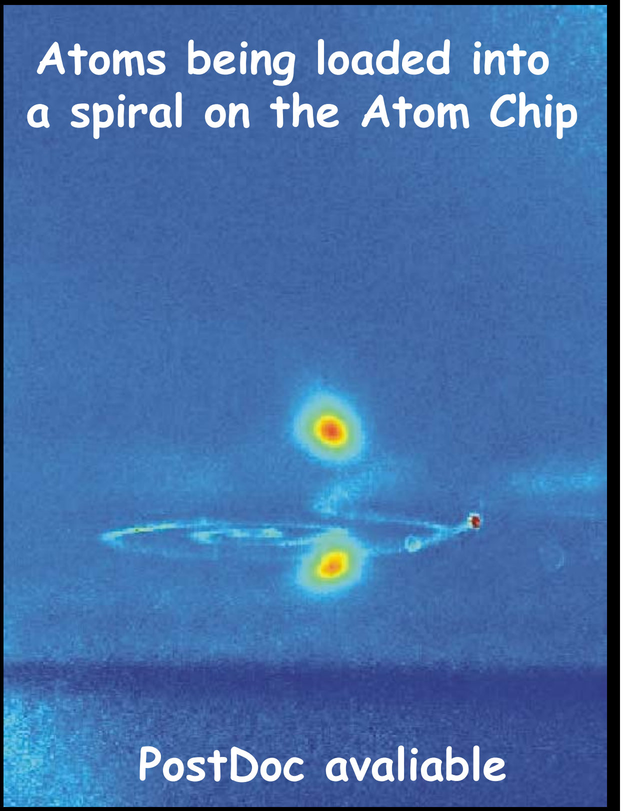
Atom Chip Experiment
Peter Krüger
Stephan Wildermuth
Elmer Haller
Sebastian Hofferberth
Mauritz Anderson

Atom Chip Detector
Albrecht Haase
Marco Wiltzbach
Bjorn Hessmo

Atom Chip Fabrication
Sönke Groth
Israel Bar Joseph (WIS)

Former:
K. Brugger, D. Cassetari, R. Folman, X. Lou
series of undergrad students in Heidelberg

EU: ACQUIRE, ACQP, FASTnet
DFG: QIPC, Cold Quantum Gases
Landesstiftung BW



Atoms being loaded into a spiral on the Atom Chip

PostDoc avaliable

www.AtomChip.org