www.bgu.ac.il/atomchip
www.bgu.ac.il/nanofabrication

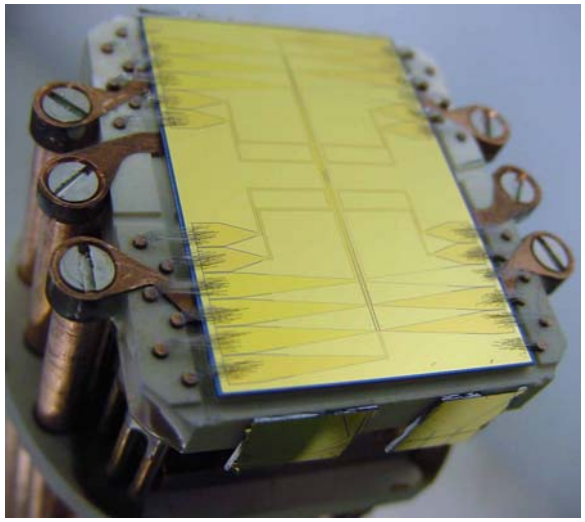
Snowbird January 2010

Ben-Gurion University of the Negev

View of the desert around our university

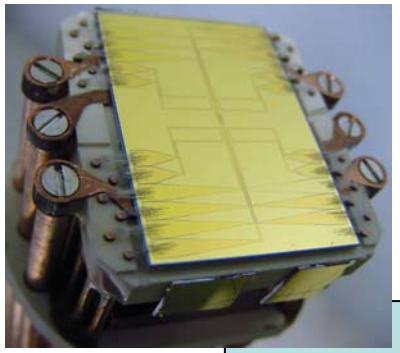
Atom Chips: one decade of ultra cold atoms microns from a surface
Or, do atom chips have a future?
10th anniversary of the AtomChip

Ron Folman



An example of an Atom Chip
Science 2008

Israel Science Foundation
FP6 Research Training Network
German Gov. – DIP, GIF
US-Israeli (BSF)
Center for the Science of Complexity
Converging technologies
FP7 Marie Curie Fellowship
French Government
Defense, Industry



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Atom Chips: one decade of ultra cold atoms microns from a surface
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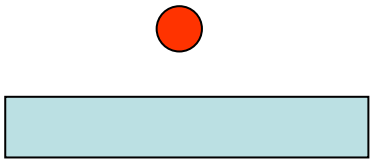
Ron Folman

10 years ago the question was:

Can we make a "***solid state***" room temperature device with long coherence times? (& smooth potentials)

Atom, Ion, Molecule, Electron (>30)



Solid state=
- nano and micro scale potentials
- arbitrary potentials, incl. trapping, guiding, reflection, tunneling
- scalable
- full monolithic integration

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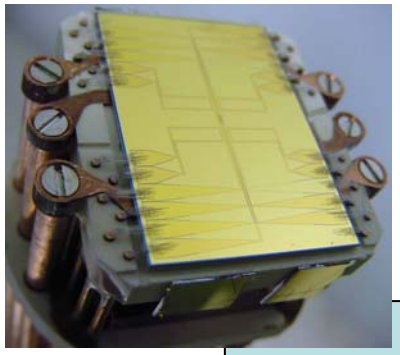

www.bgu.ac.il/atomchip
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Snowbird January 2010

Ben-Gurion University of the Negev

Atom Chips: one decade of ultra cold atoms microns from a surface

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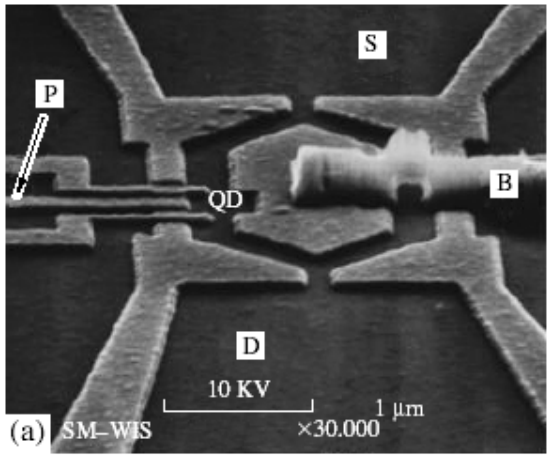
Ron Folman

AB and AC

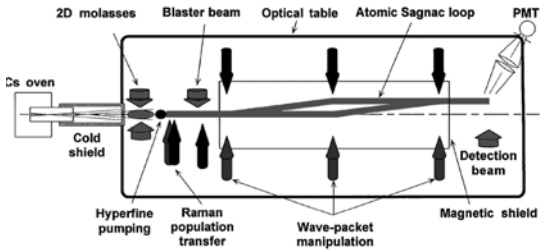


Electrons: Heiblum, Weizmann Inst., 90s
Atoms: Ed Hinds et al. Yale 1993

As a measure of success one may ask about specific tasks such as:

- Can we see the Aharonov-Casher effect?
- Can we match the sensitivities of free space atom interferometers?
- Can we do a high fidelity 2-qubit gate (the base for Quantum computing)?

Acceleration sensing



Kasevich, Ertmer

Israel Science Foundation
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Converging technologies
FP7 Marie Curie Fellowship
French Government
Defense, Industry

Outline:

- What is an atom chip

- What is the community working on

- What has been achieved so far
(see today's evening break-out session for realized matter-wave interferometry)

- Concluding remarks

Outline:

- What is an atom chip
- What is the community work
- What has been achie
(see today's evenin ssion for realized matter-wave interferometry)
- Concludin

I apologize!

In a short talk one cannot do justice to the physics and to the physicists

Basics of the Magnetic Potential

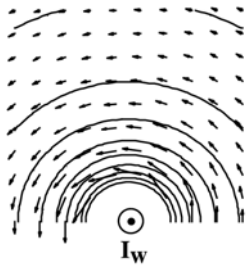
Brief History

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 The name atom chip PRL 84, 4749
2000 ACQUIRE collaboration
2001 Zimmermann, Reichel (BEC, 30μm from surface)
2003 Reichel (Rabi oscillations), Vuletic (0.5μm atom-surface distance)

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: **$Bo^2/I \propto 1/h$**



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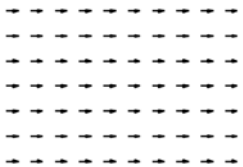

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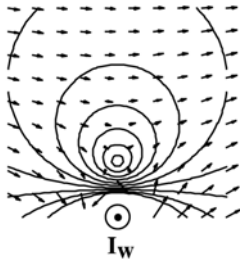
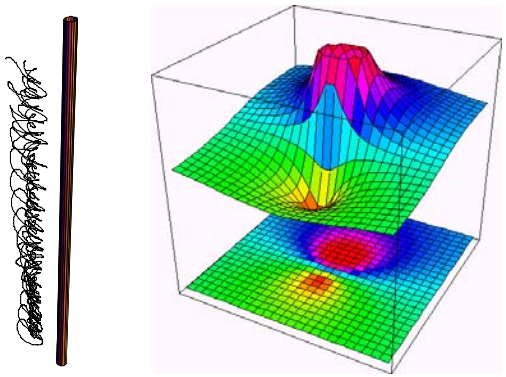
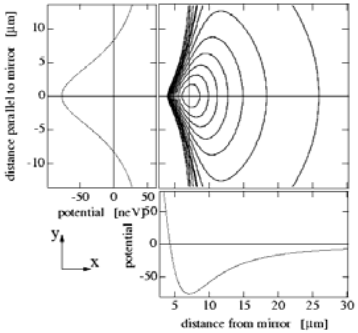


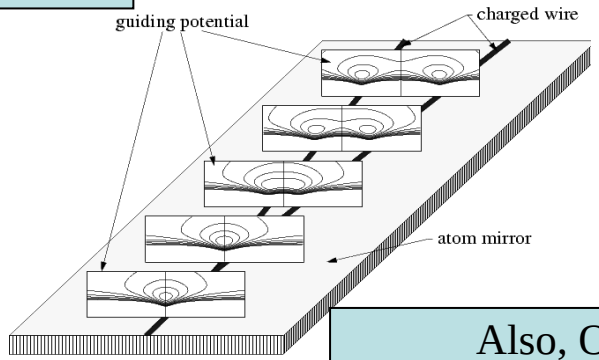


PS additional interactions: electric

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

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





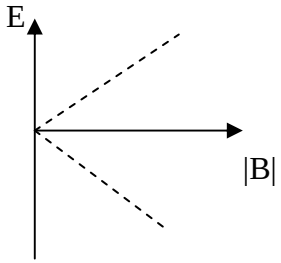
Schmiedmayer EPJ D 4, 57 (1998)

Also, Optical motor/tweezers, Permanent magnets, and more

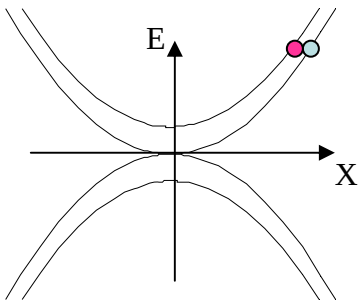
Basics II

The U and Z traps

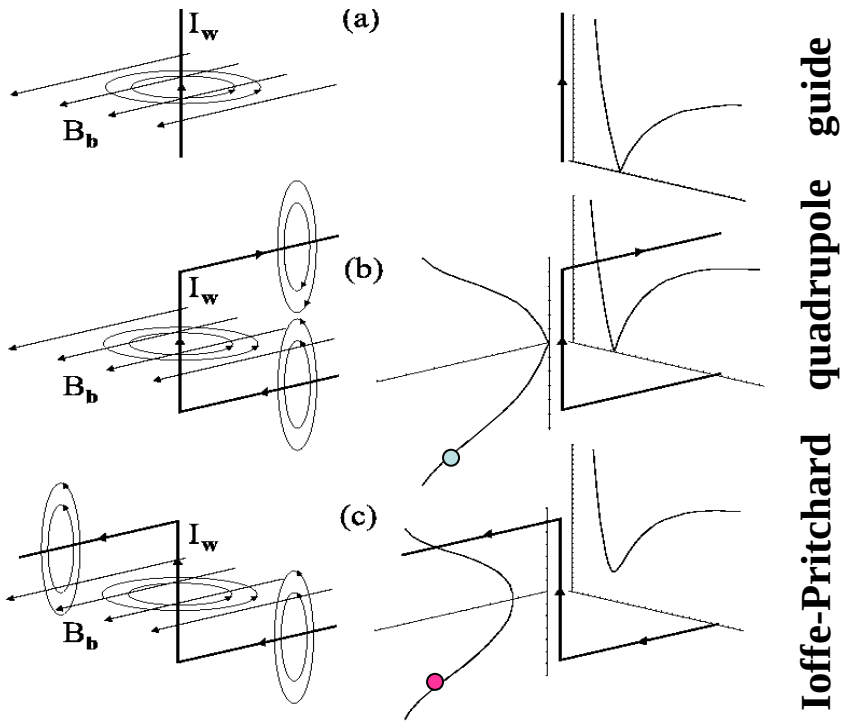
meta stable state

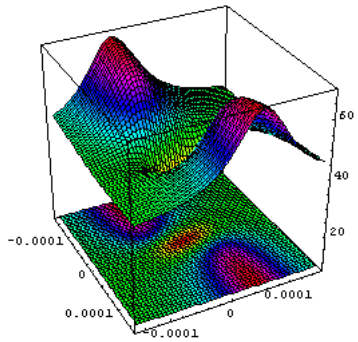


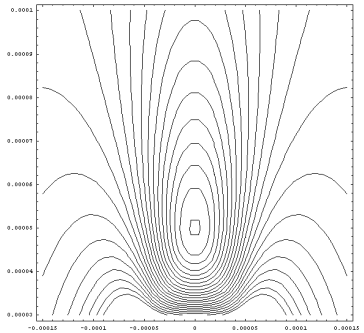
$E = g_F m_F \mu_B |B|$

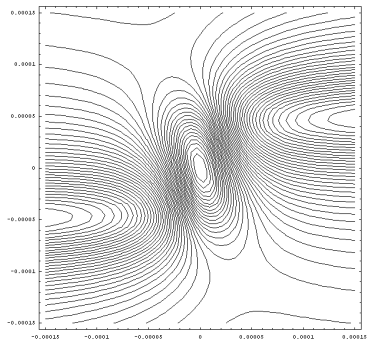


Bending the wire closes the guide and creates 'end caps'









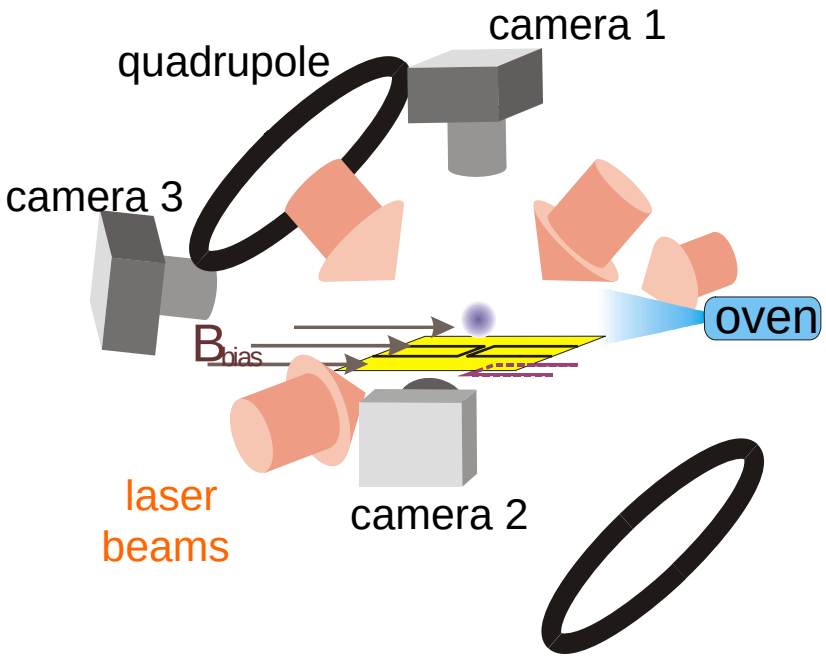
- Adiabaticity
- Earnshaw theorem

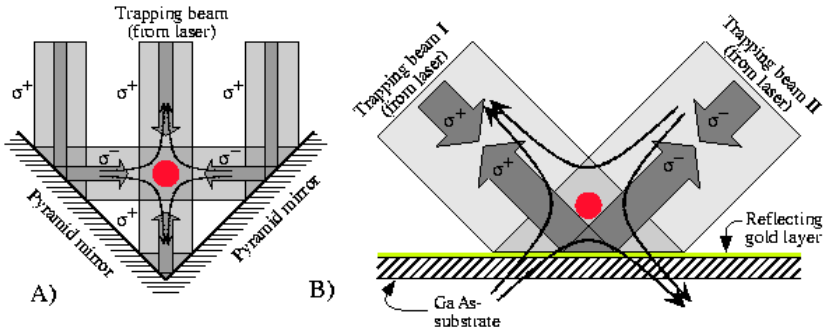
More sophisticated geometries:
Weinstein, Libbrecht PRA 52, 4004 (1995)

MHz traps may be reached!

Trap very weak: atoms at Nano Kelvin temperature!
(device at room temperature – no cryogenics!)

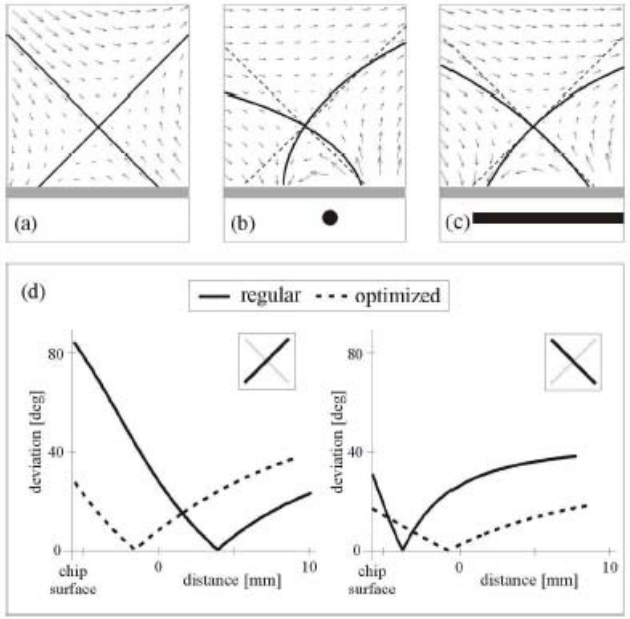
Magneto Optical Trap

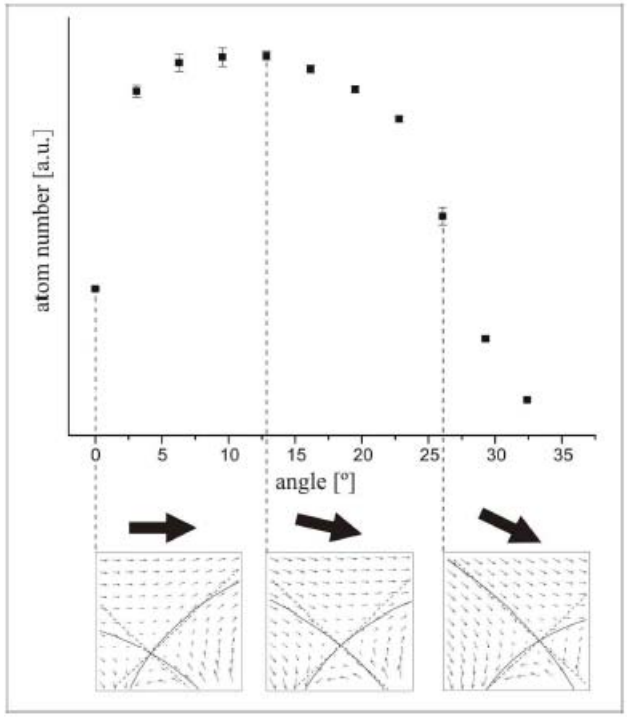


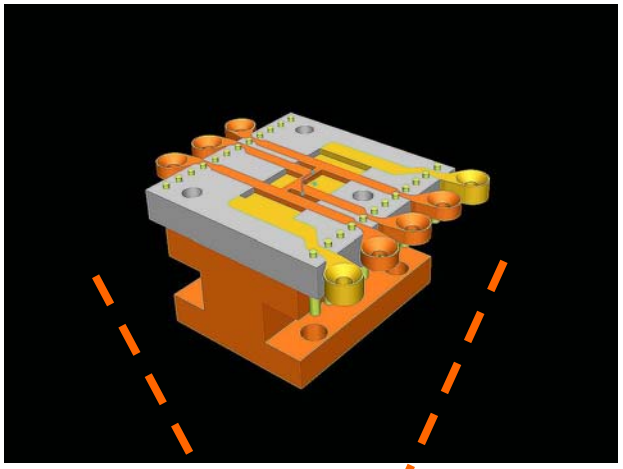


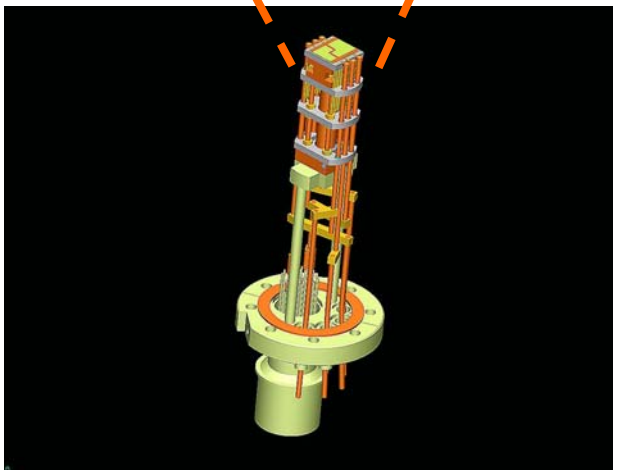
A Coil Free MOT

Old dog... New tricks...



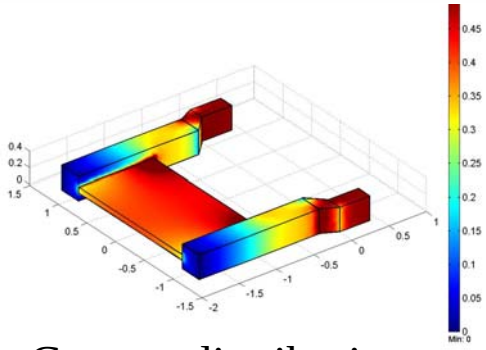






Experimental advantages:

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

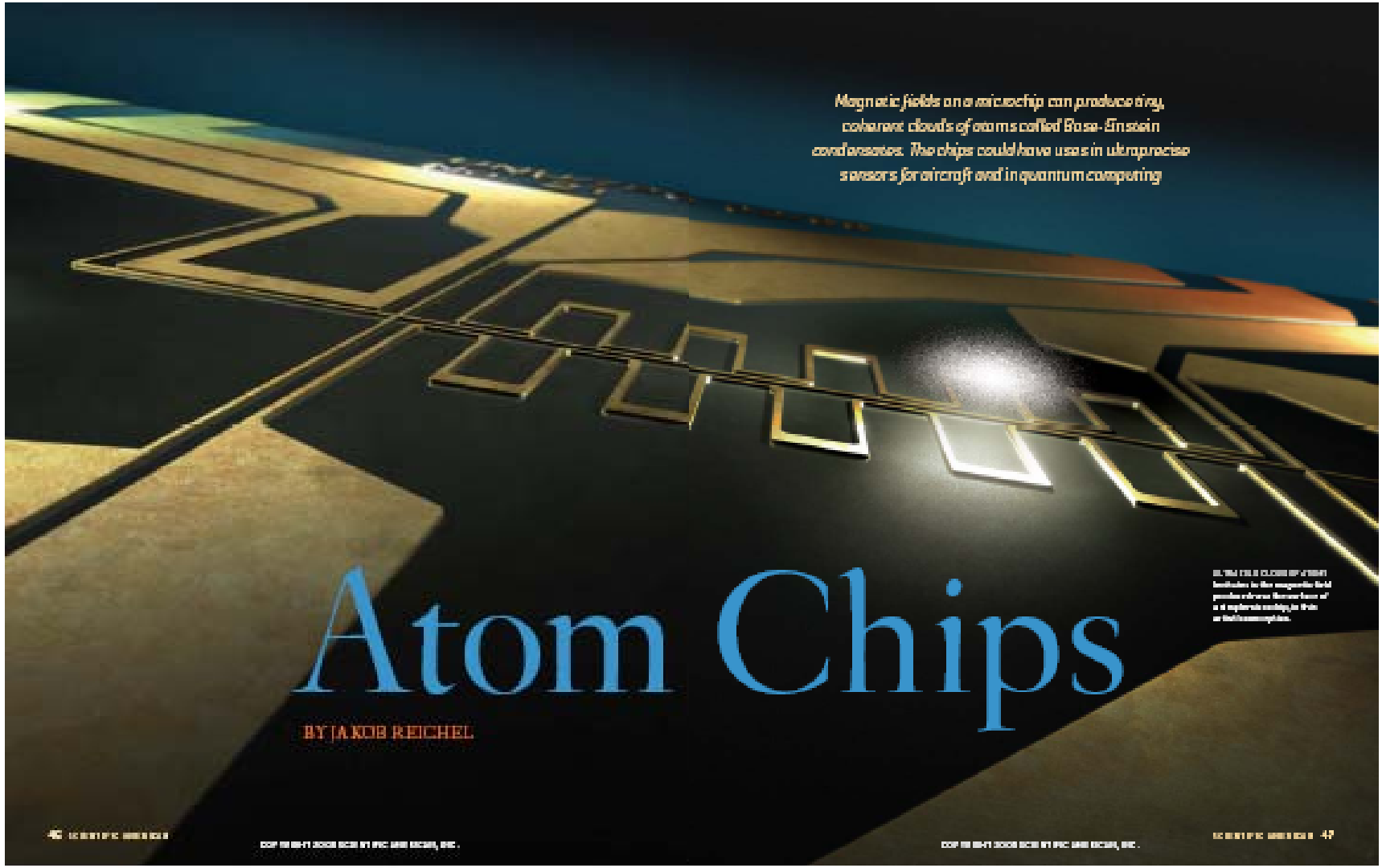


Current distribution

Some atom chip picts:

One of the humble beginnings: R. Folman et al. Phys. Rev. Lett. 84, 4749 (2000)	Atom chip review article: R. Folman et al. Adv. At. Mol. Opt. Phys. 48, 263 (2002)

Drawing from paper by Jakob Reichel; conveyer belt – invention by Ted Haensch



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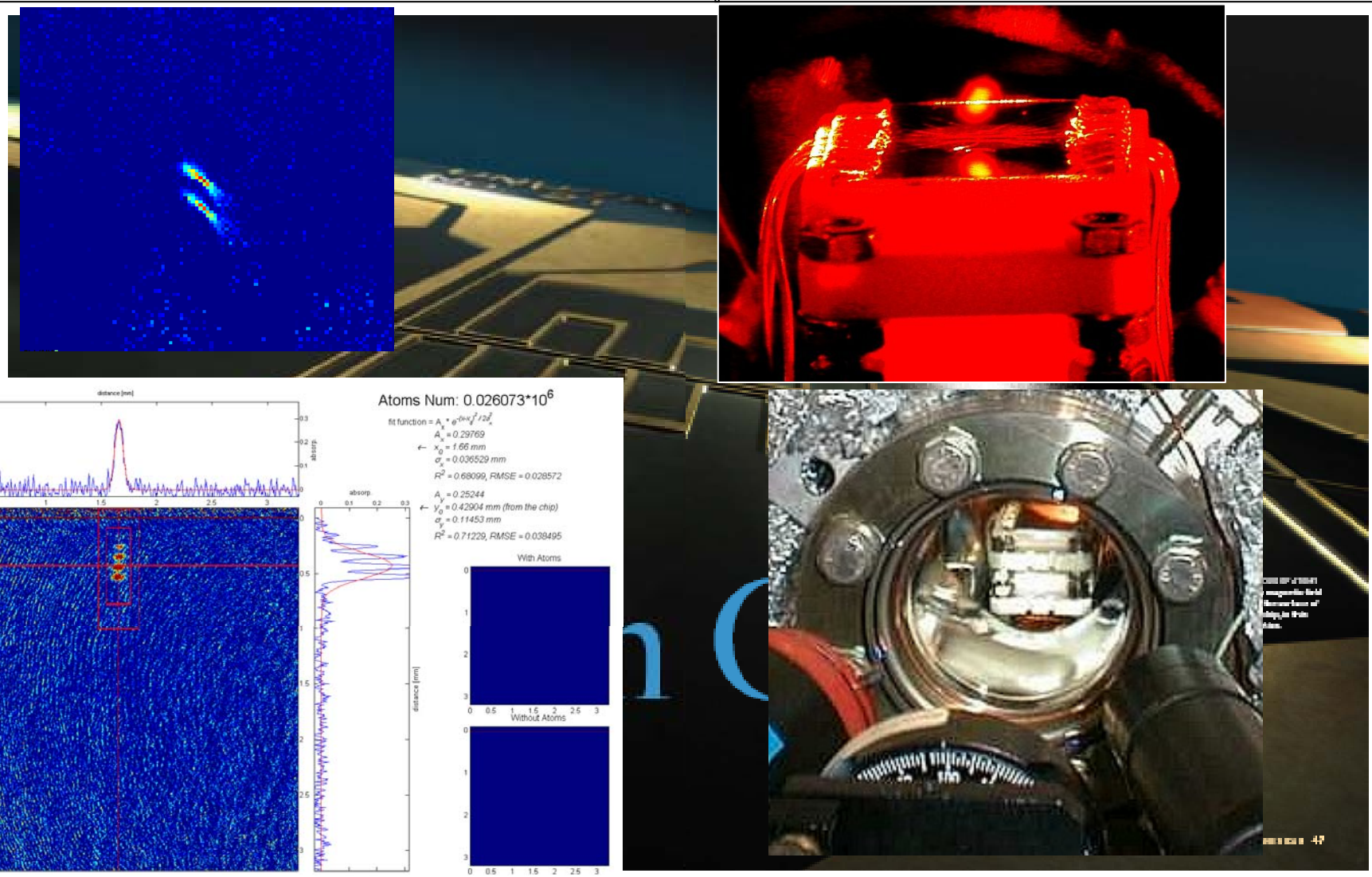

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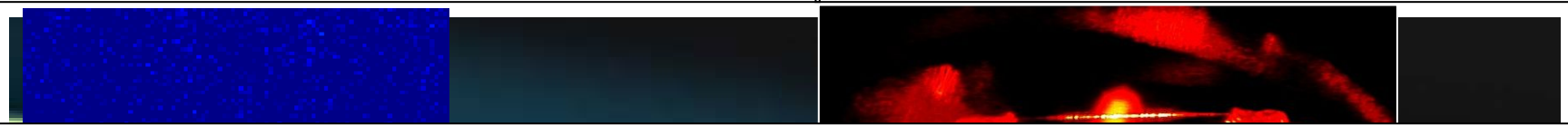
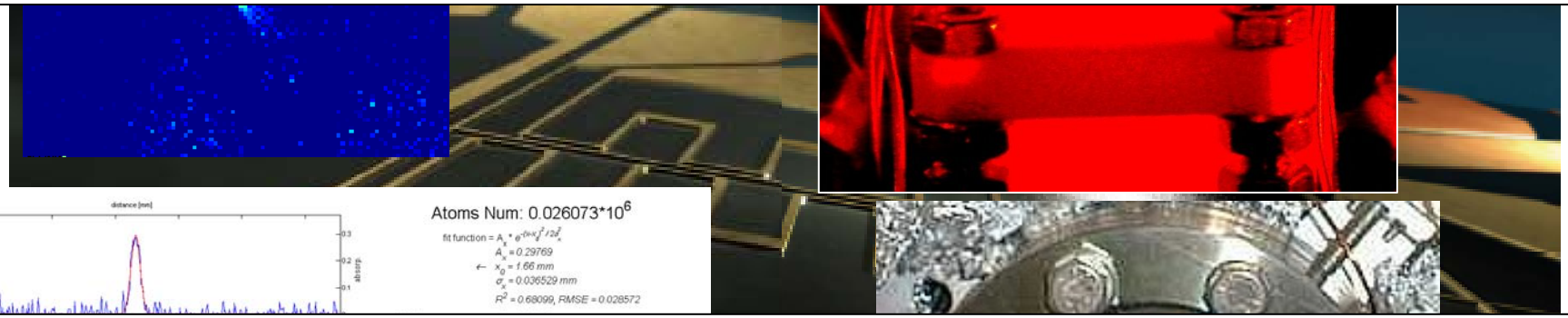
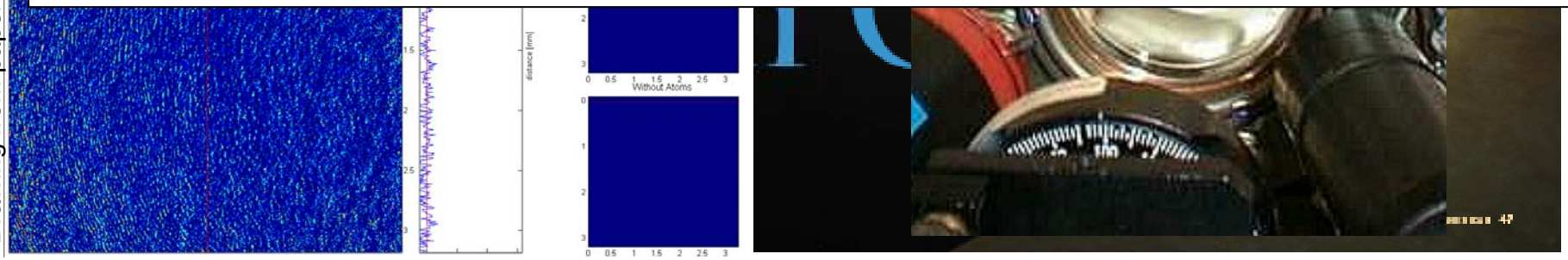


Applications: clocks, acceleration sensors, gravitational sensors, magnetic sensors, quantum memory and communications, quantum computing



Fundamental science: Decoherence, interferometry, many body, atomic physics, low dimensional systems, atom-surface physics, surface physics, symmetries and fundamental constants



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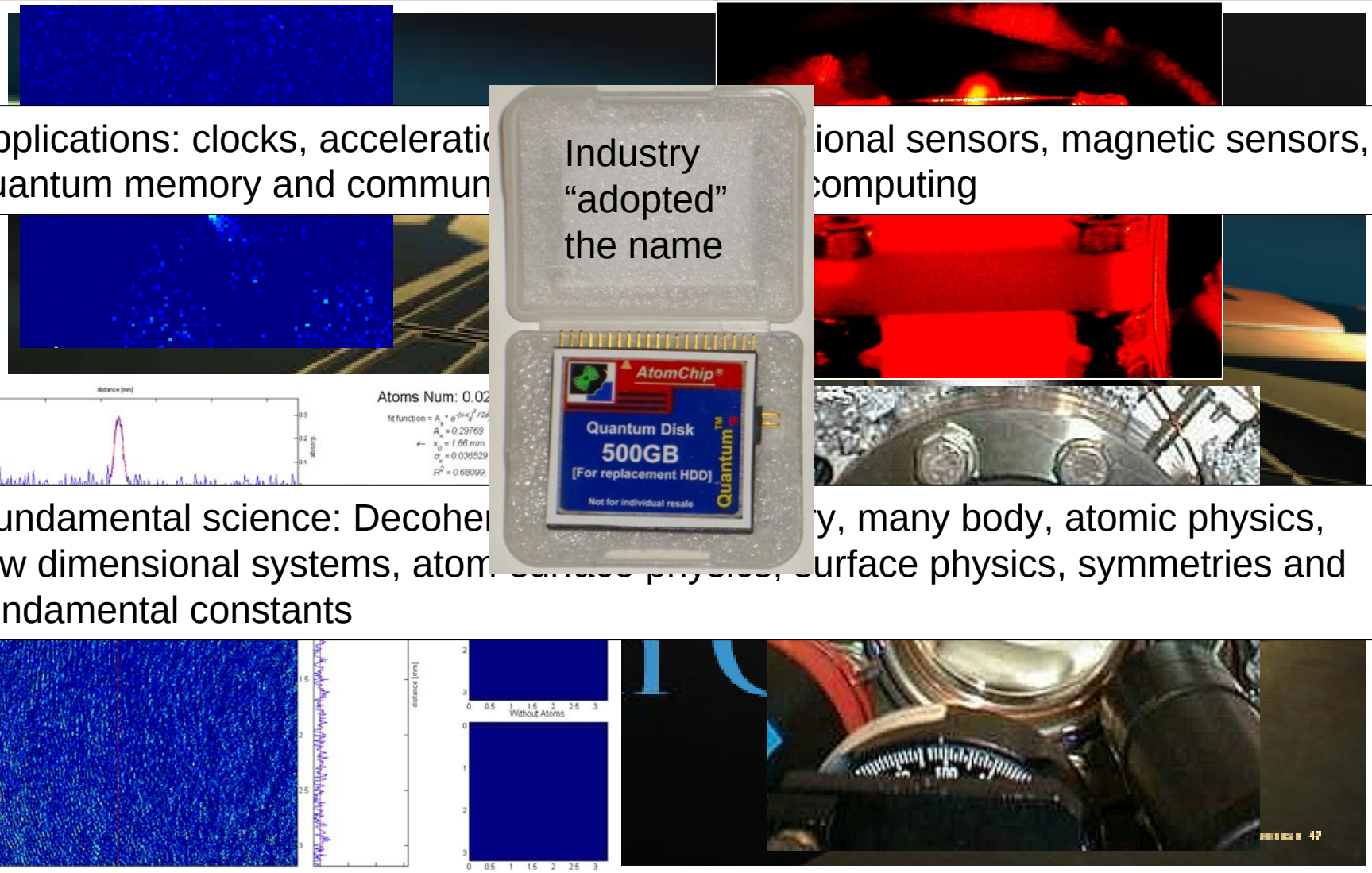
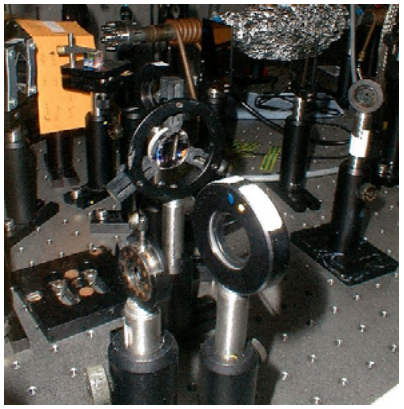
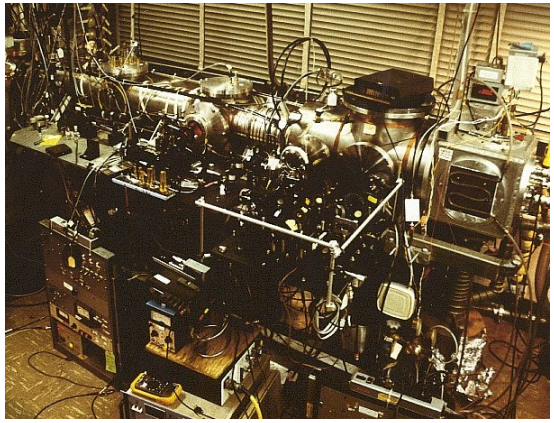
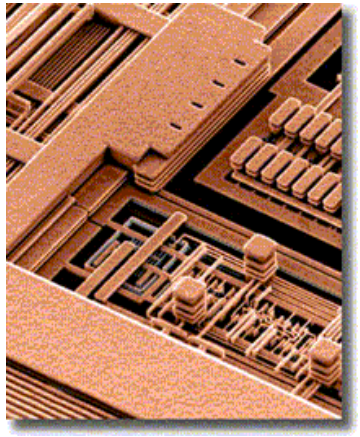
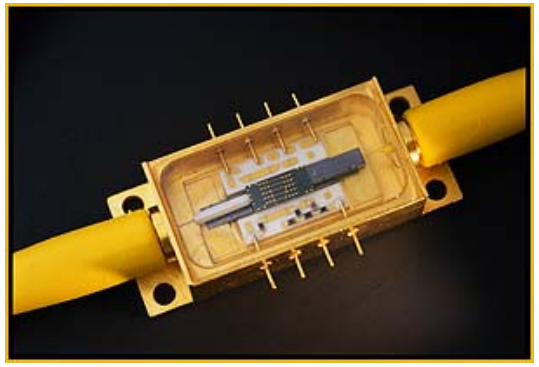
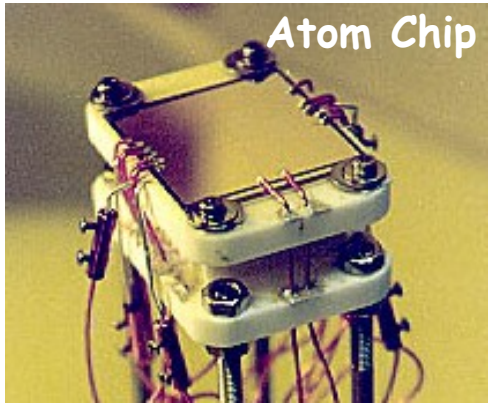


Applications: clocks, acceleratio[illegible]ional sensors, magnetic sensors, quantum memory and commun[illegible]computing

Fundamental science: Decohe[illegible]y, many body, atomic physics, low dimensional systems, atom[illegible]urface physics, symmetries and fundamental constants

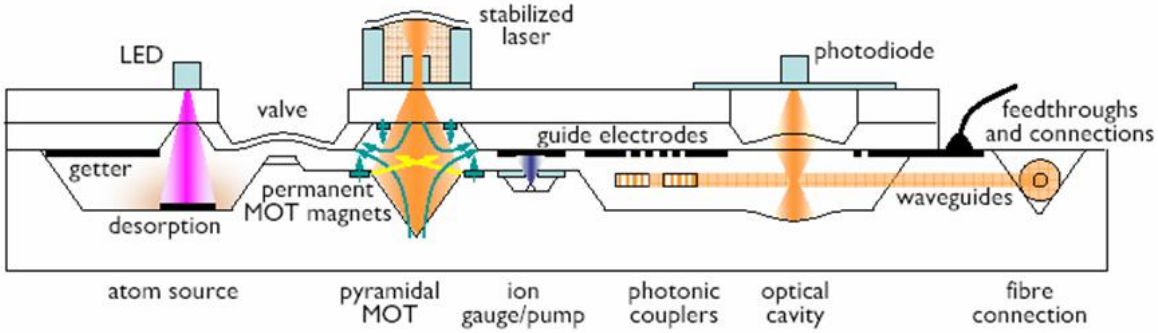
Drawing from paper by Jakob Reichel; conveyer belt – invention by Ted Haensch

AtomChips: miniaturization, integration, monolithic ➔

Electronics	Optics	Matter waves
		
		

➔ accuracy, complexity ➔ novel functionality

The monolithic integration dream



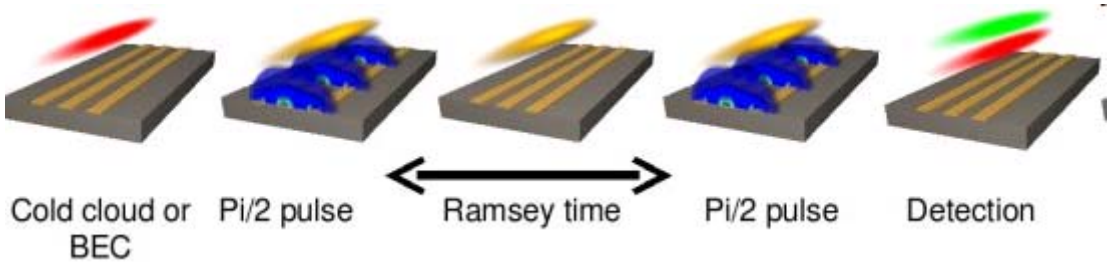
Schematic diagram of an integrated atom chip with pumps, guides, MOT, integrated lasers and fibre connections.

Courtesy of Tim Freegarde

Some of the many things The community is working on

Technology

Clocks

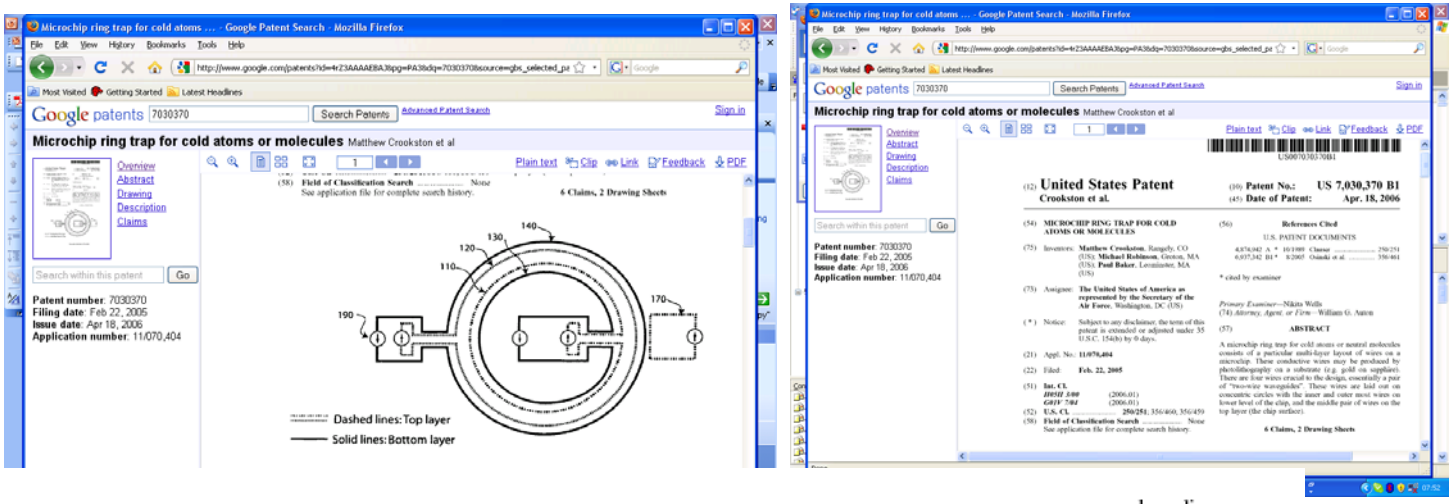


Reichel

QIP

Navigation systems: Sagnac (2 out of many proposals)

Paul Baker
and US AirForce



PRL 99, 060402 (2007) PHYSICAL REVIEW LETTERS week ending 10 AUGUST 2007

Using Time-Reversal Symmetry for Sensitive Incoherent Matter-Wave Sagnac Interferometry

Y. Japha, O. Arzouan, Y. Avishai, and R. Folman
Department of Physics, Ben-Gurion University, Be'er-Sheva 84105, Israel
(Received 6 December 2006; published 8 August 2007)

Phase rigidity

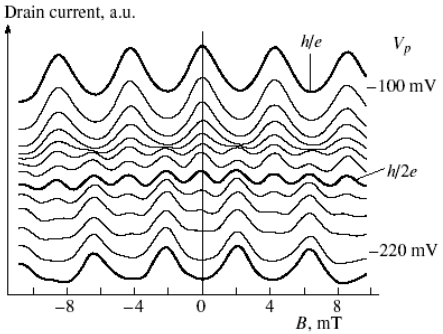
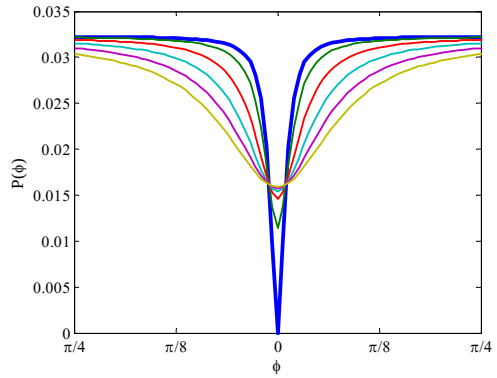
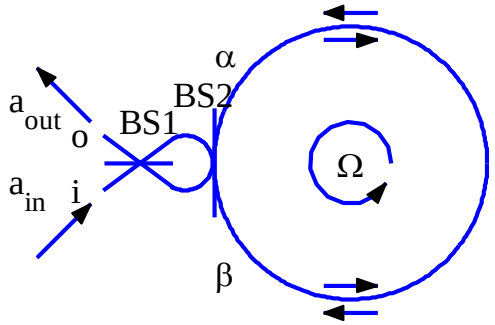


Fig. 4. Current through the closed interferometer of Fig. 3(a) as a function of the magnetic field. The various traces show the current at various settings of the plunger gate potential V_p across a resonance of the QD. The phase as a function of V_p does not change gradually, but jumps by π.

White light fringe allows the use of a high flux thermal source



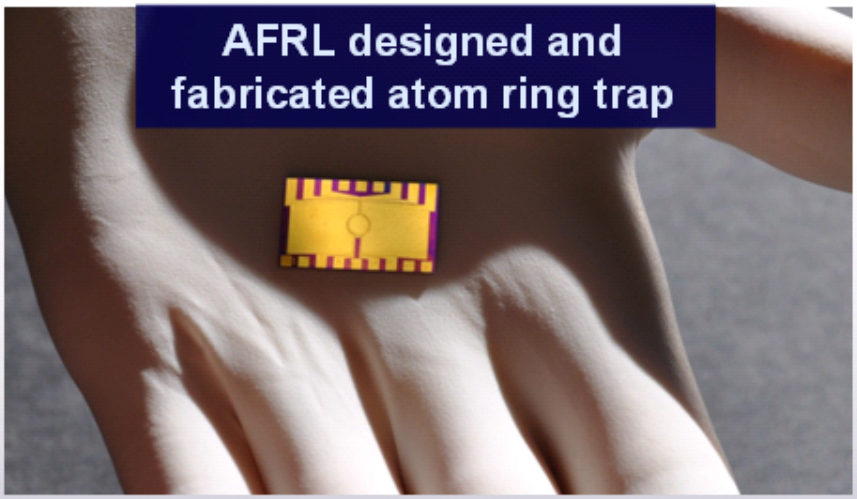
Rotation sensitivity grows as the square root of the finesse



Cold Atom Inertial Navigation Systems (INS)

Ultra-accurate Low-power Autonomous Jam-free

- Cold atoms: a gas of atoms slowed by lasers
- Cold atoms are incredibly sensitive to inertial forces
- Cold atom sensors enable ultra-accurate navigation w/o external reference (e.g., GPS-denied environments, space)
- Adaptable to multiple platforms



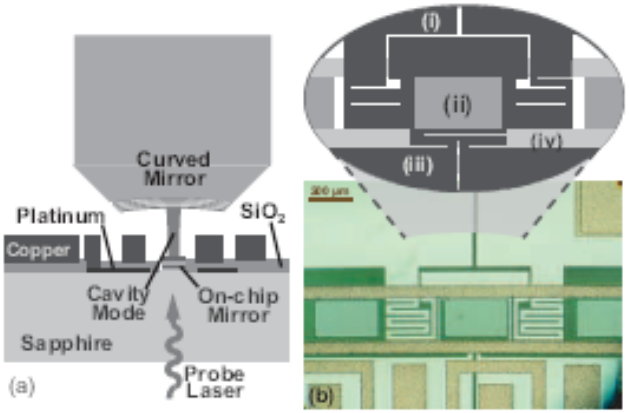
- Current accuracies equivalent to most accurate mechanical gyros at significantly reduced cost
- Performance headroom for future improvements

AFRL Focus: Reduced Size & Cost, Increased Sensitivity

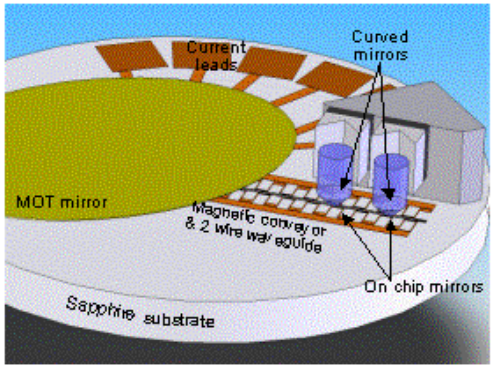
Atom - Light

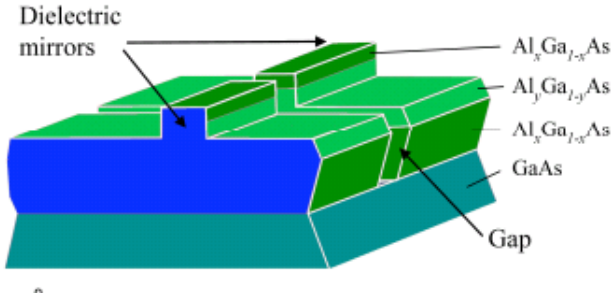
For trapping, manipulation, measurement and state transfer e.g. for quantum communication

Dan Stamper-Kurn

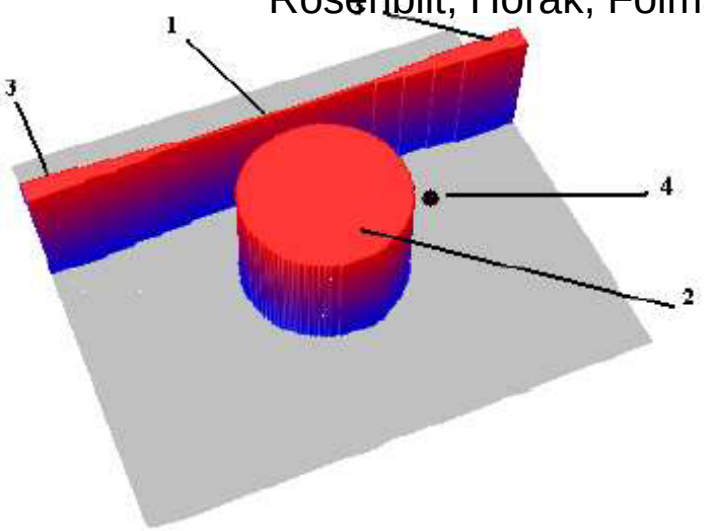


Westbrook, Aspect

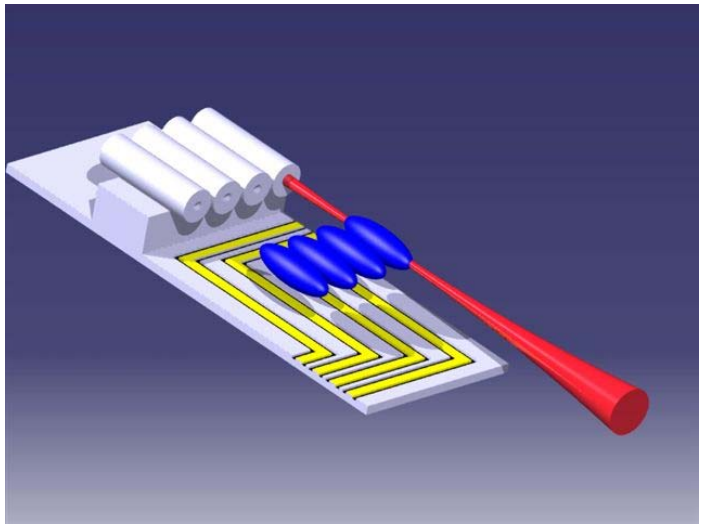




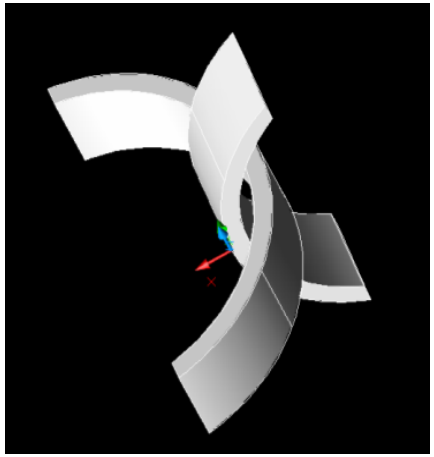
Rosenblit, Horak, Folman

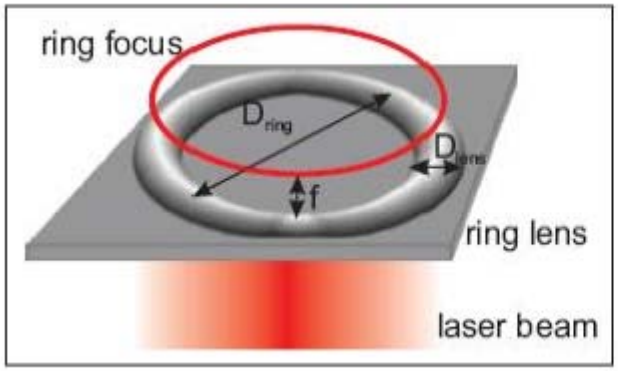


Schmiedmayer



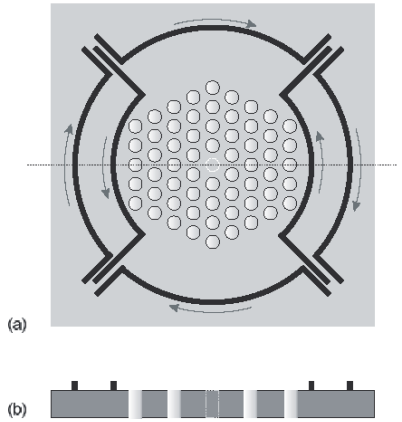
Rosenblit, Folman





Birkl, Ertmer

My favorite proposal:



Mabuchi

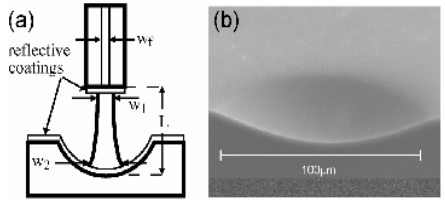
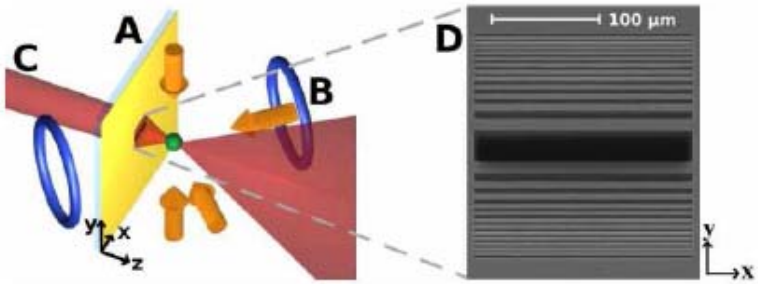
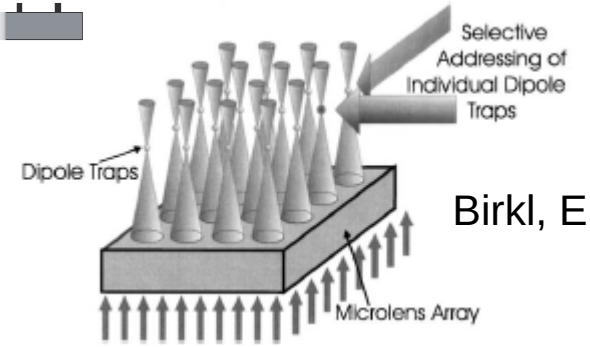


Figure 1 (a) Schematic diagram of the cavity. The light field drops to 1/e of its central value at radii w_f=2.65 μm in the fibre, $w_1=(\lambda/\pi)^{1/2}(LR\text{-}L^2)^{1/4}$ at the waist of the cavity mode and $w_2=(\lambda/\pi)(L/R)^{1/2}/w_1$ on the concave mirror. Here L is the cavity length and R is the radius of curvature of the lower mirror. **(b)** Scanning electron microscope image of an uncoated mirror template cleaved almost across the diameter.

Hinds

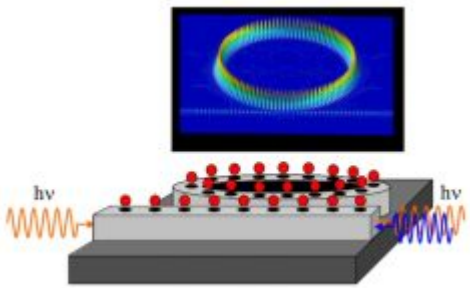


John Weiner



Birkl, Ertmer

Bi-chromatic evanescent field trapping



Also Rosenblit, Horak, Folman

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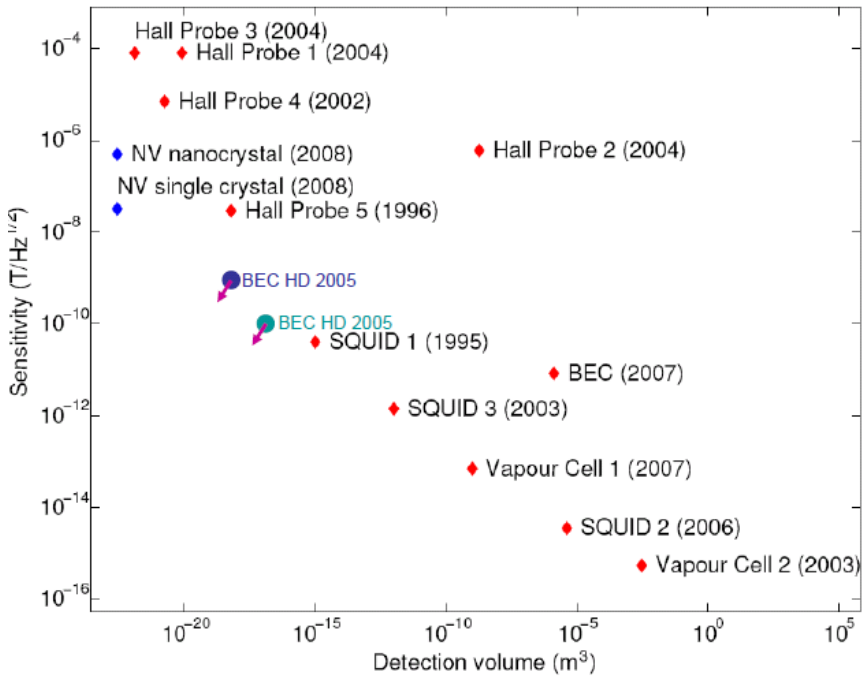
Probing surface physics

Magnetic probing

e.g. electron transport

Comparison



Noise probing

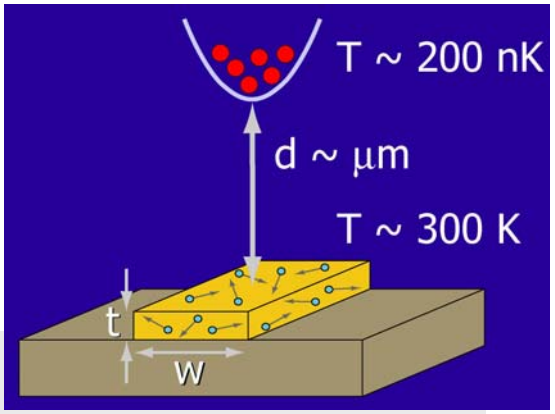
On the feasibility of studying vortex noise in 2D superconductors with cold atoms

Stefan Scheel,* Rachele Fermani, and E.A. Hinds
Quantum Optics and Laser Science, Blackett Laboratory,
Imperial College London, Prince Consort Road, London SW7 2BW

(Dated: April 6, 2007)

We investigate the feasibility of using ultracold neutral atoms trapped near a thin superconductor to study vortex noise close to the Kosterlitz-Thouless-Berezinskii transition temperature. Alkali atoms such as rubidium probe the magnetic field produced by the vortices. We show that the relaxation time T_1 of the Zeeman sublevel populations can be conveniently adjusted to provide long observation times. We also show that the transverse relaxation times T_2 for Zeeman coherences are ideal for studying the vortex noise. We briefly consider the motion of atom clouds held close to the surface as a method for monitoring the vortex motion.

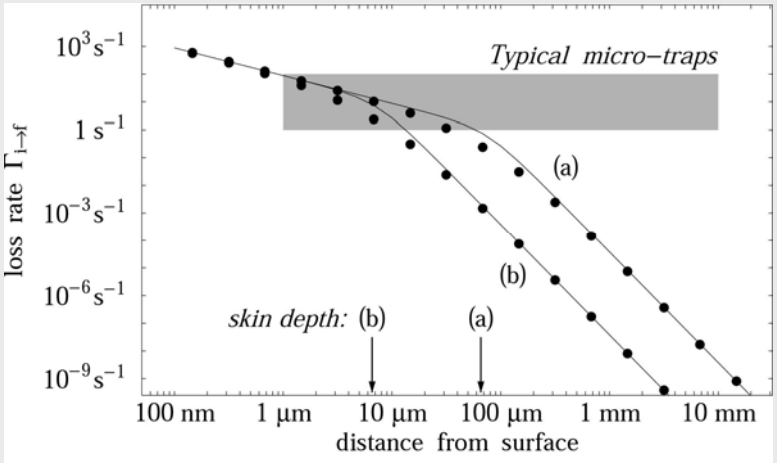
Theory of thermal noise – Carsten Henkel



Loss due to Johnson noise magnetic fields

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

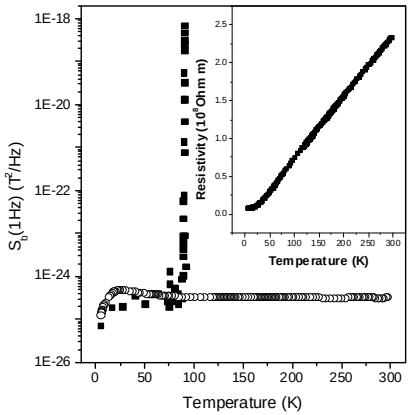
Geometry	Tr Y_{ij}
Half-space	π/h
Layer	$\pi d/h^2$
Wire	$\pi^2 a^2/(2h^3)$



Similarly for heating and decoherence!

Carsten Henkel

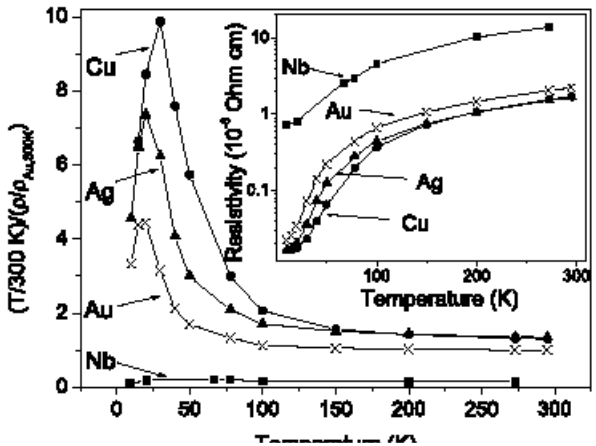
The noise at the SC phase transition point

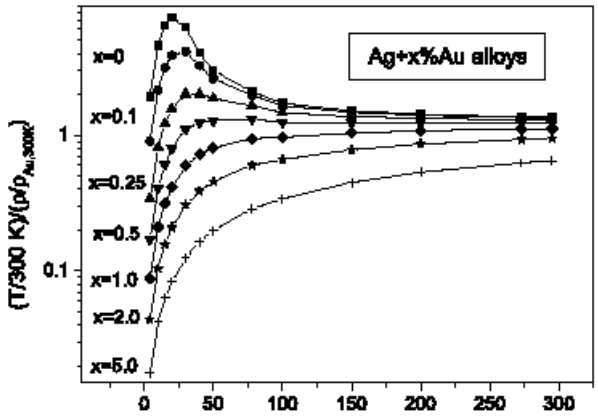


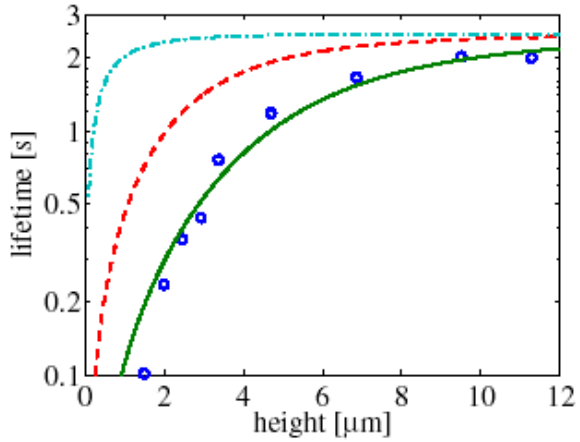
Another example, do cooler metals produce less magnetic noise?

$$S_B^{ij}(\mathrm{x},\omega) = \frac{\mu_0^2 k_B T}{4\pi^2 \rho} Y_{ij}(\mathrm{x})$$

The answer is NO, unless we contaminate the sample!

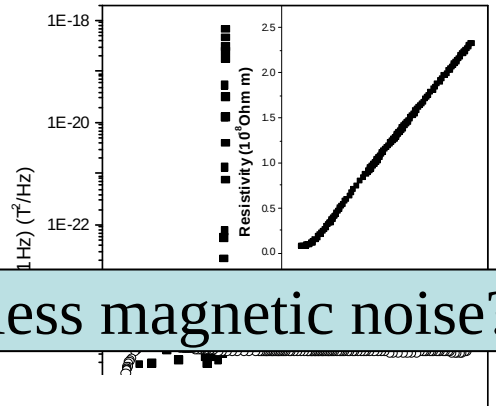






SC and Alloys: V. Dikovsky et al., EPJD (2005, 2009)

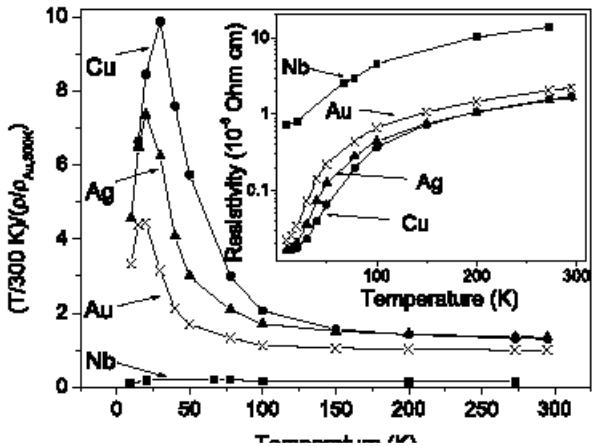
The noise at the phase transition point

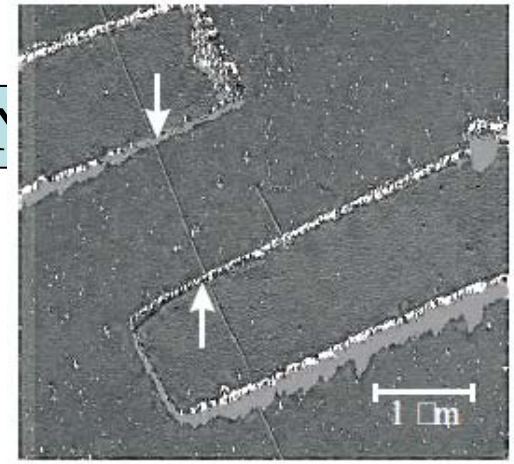


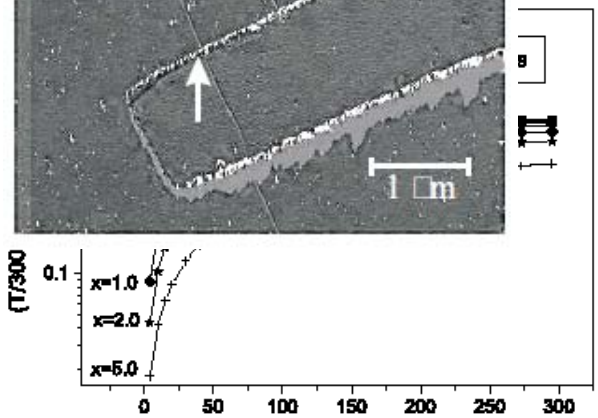
Another example, do cooler metals produce less magnetic noise?

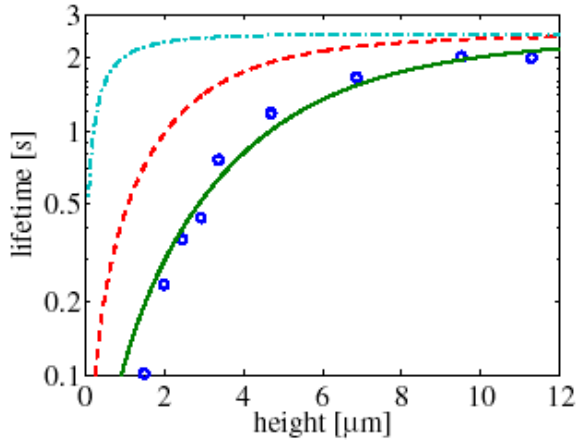
It would also be interesting to measure the noise and electron transport in molecules

The answer is N minate the sample!









SC and Alloys: V. Dikovsky et al., EPJD (2005, 2009)

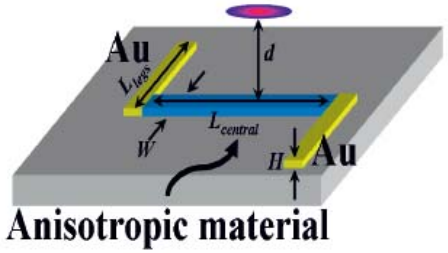
Atom - Surface

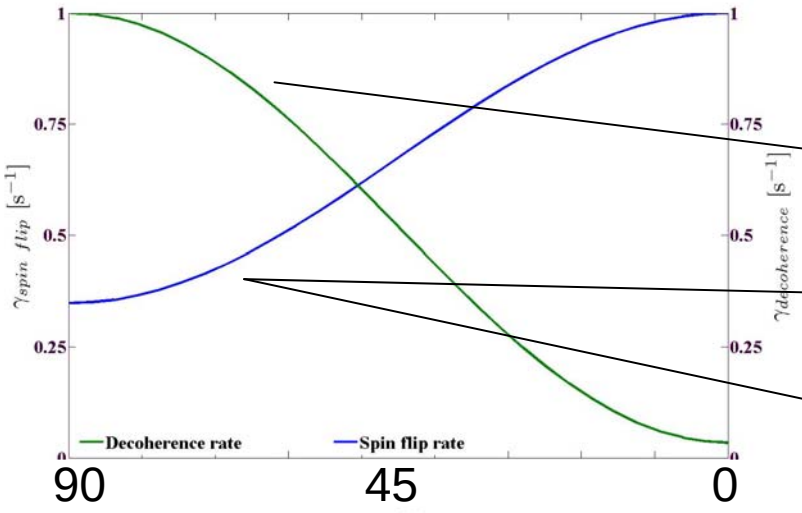
Can we suppress decoherence at room temperature?

NO! Because it has exactly the same T dependence as in the spin flip rate.

$$\gamma_{\text{spin decoherence}} = \frac{\Delta\mu_{\parallel}^2}{2\hbar^2} S_{\parallel}(\vec{r};0) \qquad \Delta\mu_{\parallel} = \langle 2|\mu_{\parallel}|2\rangle - \langle 1|\mu_{\parallel}|1\rangle$$

Not true! The little parallel sign makes the difference!
Take anisotropic material:





follow the tensor

$$S_{xx}^{(\parallel)} \propto T\left(\sigma_{zz} X_{yy} + \sigma_{yy} X_{zz}\right)$$

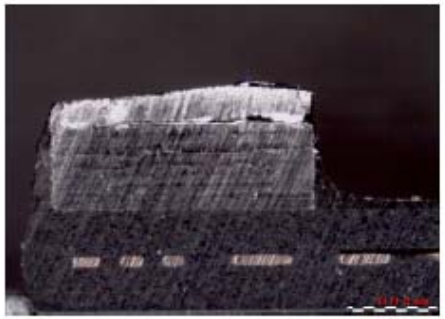
$$S_{yy}^{(\perp)} \propto T\left(\sigma_{zz} X_{xx} + \sigma_{xx} X_{zz}\right)$$

$$S_{zz}^{(\perp)} \propto T\left(\sigma_{yy} X_{xx} + \sigma_{xx} X_{yy}\right)$$

Angle between magnetic moment and the good conductivity axis

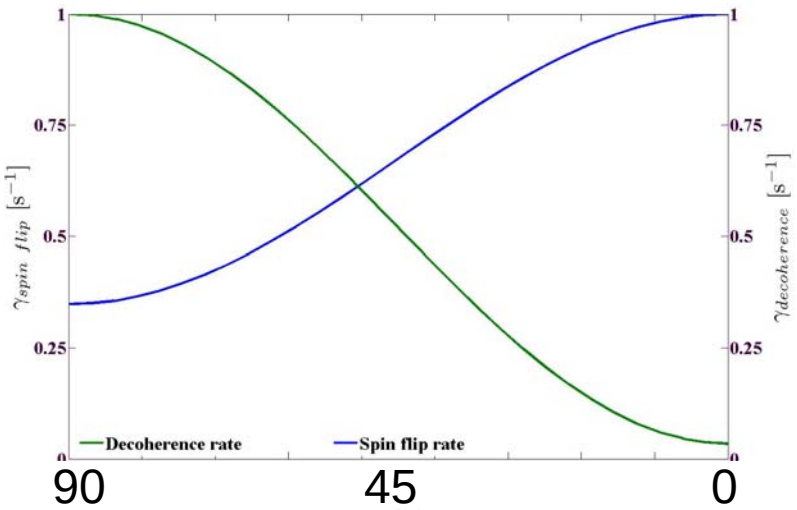
S – noise power spectrum T – temperature
σ – conductivity X – geometrical factor

Life time prediction may be readily verified if one can fabricate the surface:



highly oriented pyro-graphite (HOPG)

ρ_{HOPG}/ρ_{Au} =18 ρ_a/ρ_b =3750



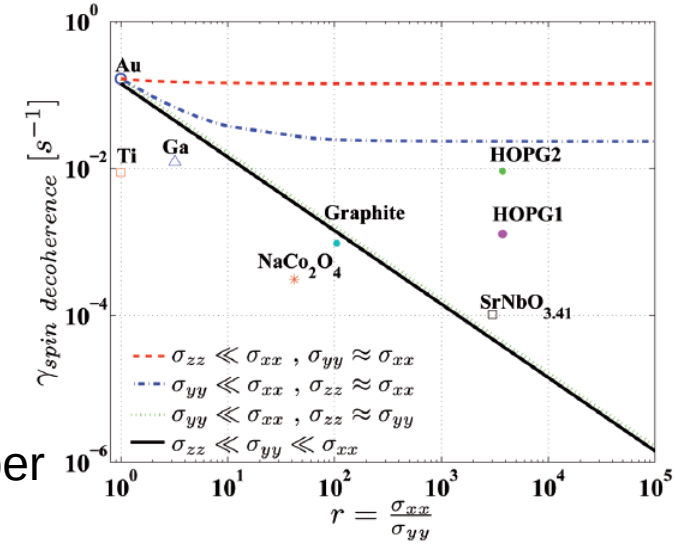
Angle between magnetic moment and the good conductivity axis

But to measure decoherence suppression, may not be easy

|1> = |2,1> and |2> = |2,2> : first order Zeeman

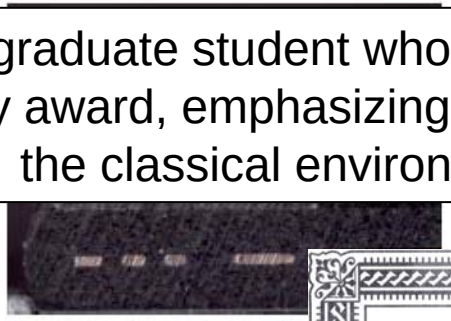
But strong masking by broadening due to inhomogeneous trap (mag. field)

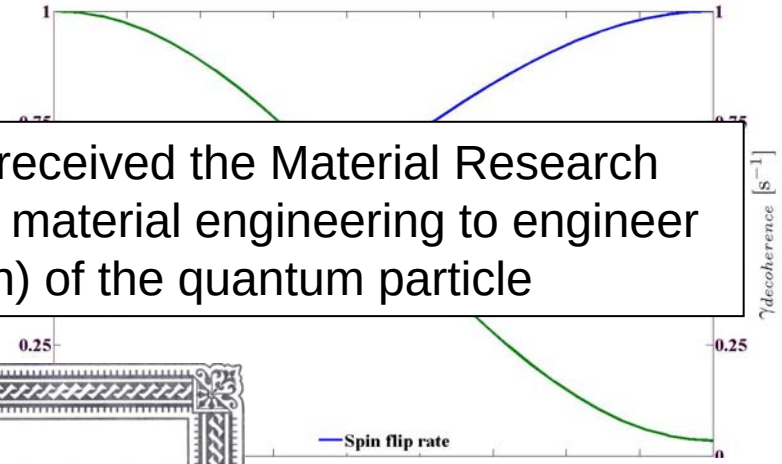
T. David et al., EPJD (2008) – chosen as highlight paper



Life time prediction may be readily verified if one can fabricate the surface:

The graduate student who developed this idea received the Material Research Society award, emphasizing the concept of using material engineering to engineer the classical environment (or thermal bath) of the quantum particle





45 0

highly oriented pyro-gra

ρ_{HOPG}/ρ_{Au} =18 $\rho_{a'}$

tween magnetic moment

ood conductivity axis

But to mea

t be easy

|1> = |2,1> and |2>

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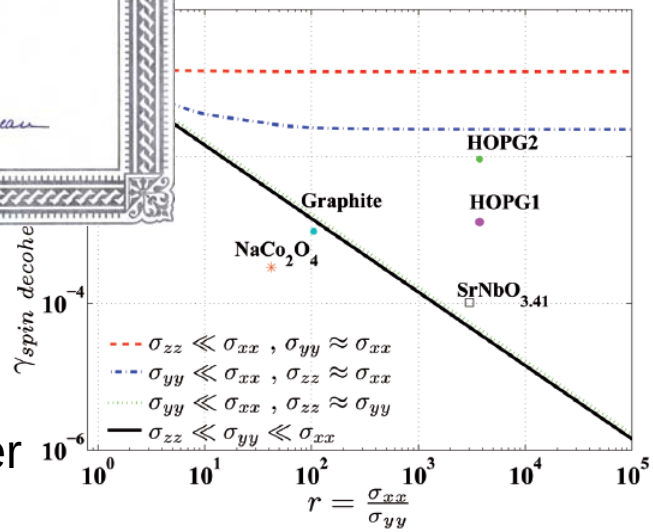


Final examples of hard to do proposals

Fabry-Perot for atoms

PHYSICAL REVIEW A VOLUME 47, NUMBER 3 MARCH 1993

Fabry-Pérot interferometer for atoms

M. Wilkens, E. Goldstein, B. Taylor, and P. Meystre
Optical Sciences Center, University of Arizona, Tucson, Arizona 85721
(Received 5 June 1992; revised manuscript received 20 October 1992)

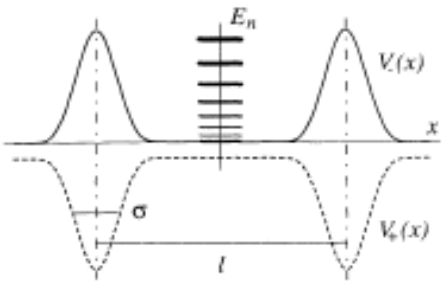


FIG. 1. Possible geometry of a Fabry-Pérot device for atoms, illustrating the potentials V_+ and V_- due to the optical fields, and sketching the resonant modes for the dressed state $|-\rangle$.

Can we make curved light mirrors?
With what corrugation?
Dispersion of mirrors?
Is there importance to deBroglie length vs. cavity length?
How would atom-atom collisions enter?
How do we load?
What beam will come out?

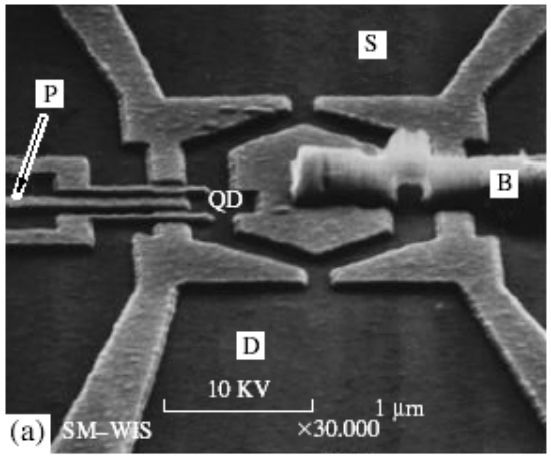
Atom-Electron Entanglement

Reversible state transfer between superconducting qubits and atomic ensembles

David Petrosyan,[1,2] Guy Bensky,[1] Gershon Kurizki,[1] Igor Mazets,[3,4] Johannes Majer,[3] and Jörg Schmiedmayer[3]

[1] *Department of Chemical Physics, Weizmann Institute of Science, Rehovot 76100, Israel*
[2] *Institute of Electronic Structure & Laser, FORTH, 71110 Heraklion, Crete, Greece*
[3] *Atominstitut der Österreichischen Universitäten, TU-Wien, A-1020 Vienna, Austria*
[4] *A.F. Ioffe Physico-Technical Institute, 194021 St.Petersburg, Russia*

(Dated: December 20, 2009)



Or perhaps to QD or mesoscopic states?

Bose-Einstein condensate coupled to a nanomechanical resonator on an atom chip: a proposal

Philipp Treutlein,[1,*] David Hunger,[1] Stephan Camerer,[1] Theodor W. Hänsch,[1] and Jakob Reichel[2]

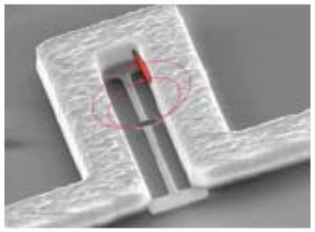
[1] *Max-Planck-Institut für Quantenoptik and Fakultät für Physik der Ludwig-Maximilians-Universität, Schellingstr. 4, 80799 München, Germany*

[2] *Laboratoire Kastler Brossel de l'E.N.S, 24 Rue Lhomond, 75231 Paris Cedex 05, France*

(Dated: July 10, 2007)

We theoretically study the coupling of Bose-Einstein condensed atoms to the mechanical oscillations of a nanoscale cantilever with a magnetic tip. This is an experimentally viable hybrid quantum system which allows one to explore the interface of quantum optics and condensed matter physics. We propose an experiment where easily detectable atomic spin-flips are induced by the cantilever motion. This can be used to probe thermal oscillations of the cantilever with the atoms. At low cantilever temperatures, as realized in recent experiments, back-action of the atoms onto the cantilever is significant and the system represents a mechanical analog of cavity quantum electrodynamics. With high but realistic cantilever quality factors, the strong coupling regime can be reached, either with single atoms or collectively with BECs. We discuss an implementation on an atom chip.

PACS numbers: 85.85.+j, 03.75.Nt, 39.90.+d, 42.50.Pq
Keywords: atom chip, NEMS, Bose-Einstein condensate, cavity quantum electrodynamics



Can we cool the resonator?
Can we go quantum?

Quantum optics and condensed matter physics presently show strong convergence. On the one hand, quantum optical systems, most notably neutral atoms in optical lattices, have been used to experimentally investigate concepts of condensed matter physics such as Bloch oscillations and Fermi surfaces [1]. On the other hand, micro- and nanostructured condensed matter systems enter a regime described by concepts of quantum optics, as exemplified by circuit cavity quantum electrodynamics [2], laser-cooling of mechanical resonators [3], and measurement back-action effects in cryogenic mechanical resonators [4]. A new exciting possibility beyond this successful conceptual interaction is to *physically couple* a quantum optical system to a condensed matter system. Such a hybrid quantum system can be used to study fundamental questions of decoherence at the transition between quantum and classical physics and has possible applications in precision measurement [5] and quantum information processing [6].

Atom chips [7] are ideally suited for the implementation of hybrid quantum systems. Neutral atoms can be

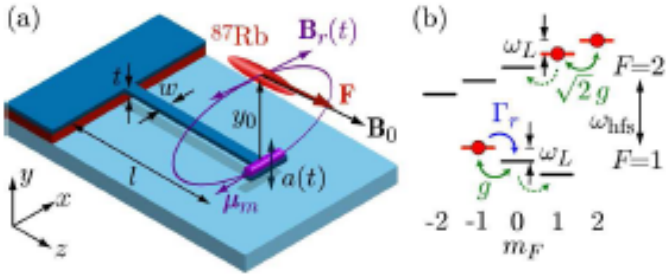
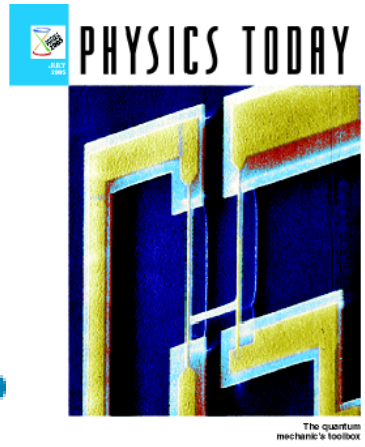


FIG. 1: (color online) BEC-resonator coupling mechanism. (a) Atom chip with a BEC of ^{87}Rb atoms (red: BEC wave function) at a distance y_0 from a nanomechanical resonator. The free-standing structure (dark blue) is supported at one end to form a cantilever-type resonator that performs out-of-plane mechanical oscillations $a(t)$. The single-domain ferromagnet (purple) on the resonator tip creates a magnetic field with oscillatory component $\mathbf{B}_r$ spin $\mathbf{F}$. (b) Hyperfine structu $\mathbf{B}_0$. Hyperfine levels $|F, m_F\rangle$ rows, depending on experimer is tuned to the oscillation fre netically trappable states indi

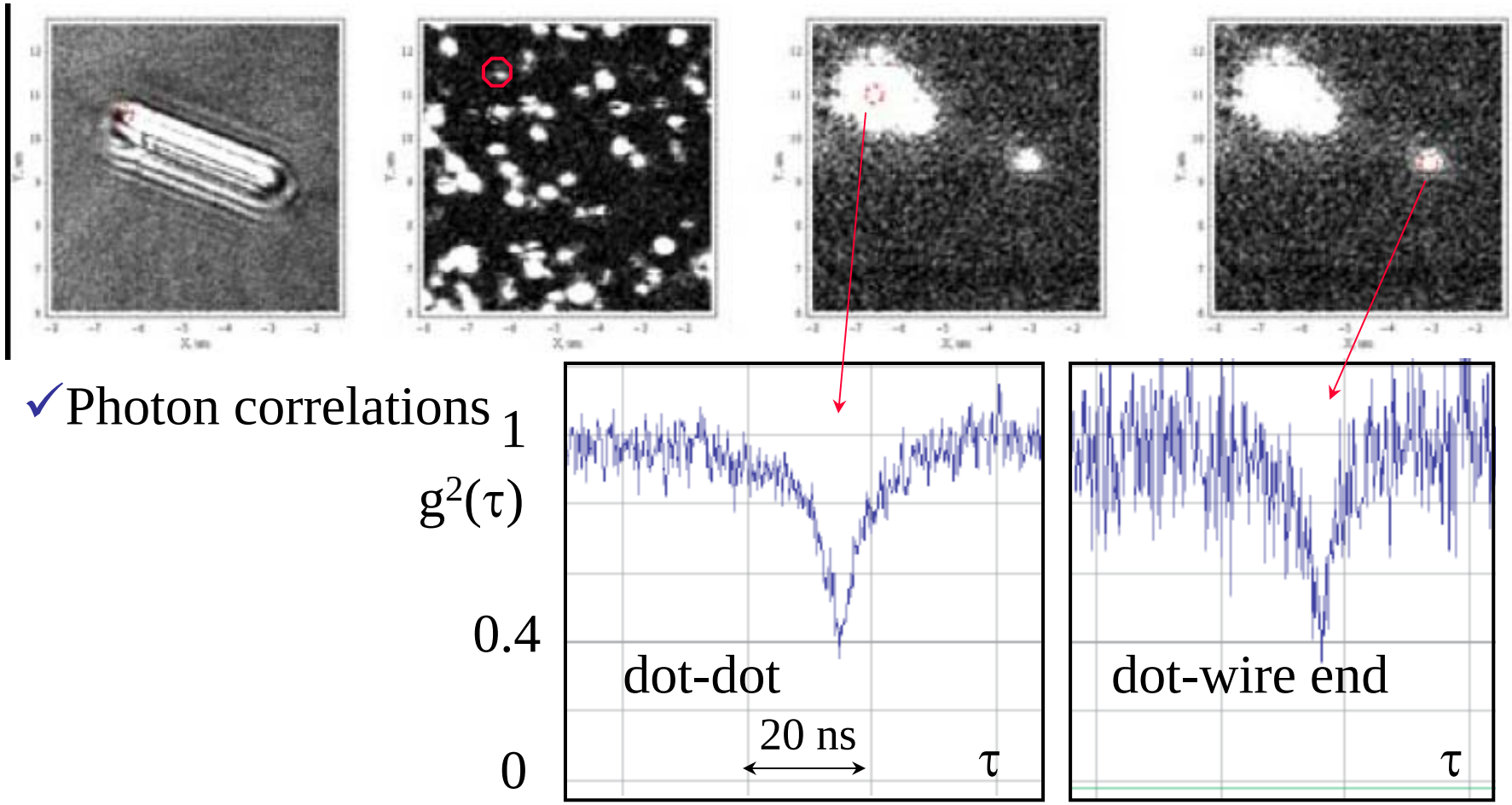


Atomic trapping and Cavity QED with plasmons

Trapping and manipulation of isolated atoms using nanoscale plasmonic structures

D.E. Chang,[1] J.D. Thompson,[2] H. Park,[2,3] V. Vuletić,[4] A.S. Zibrov,[2] P. Zoller,[5] and M.D. Lukin[2]

First experiments with a QD emitter



✓Photon correlations

One-mirror Fabry-Perot and one-slit Young interferometry

Or an alternative title….

PRL 96, 173601 (2006) PHYSICAL REVIEW LETTERS week ending 5 MAY 2006

Interference Swapping in Scattering from a Nonlocal Quantum Target

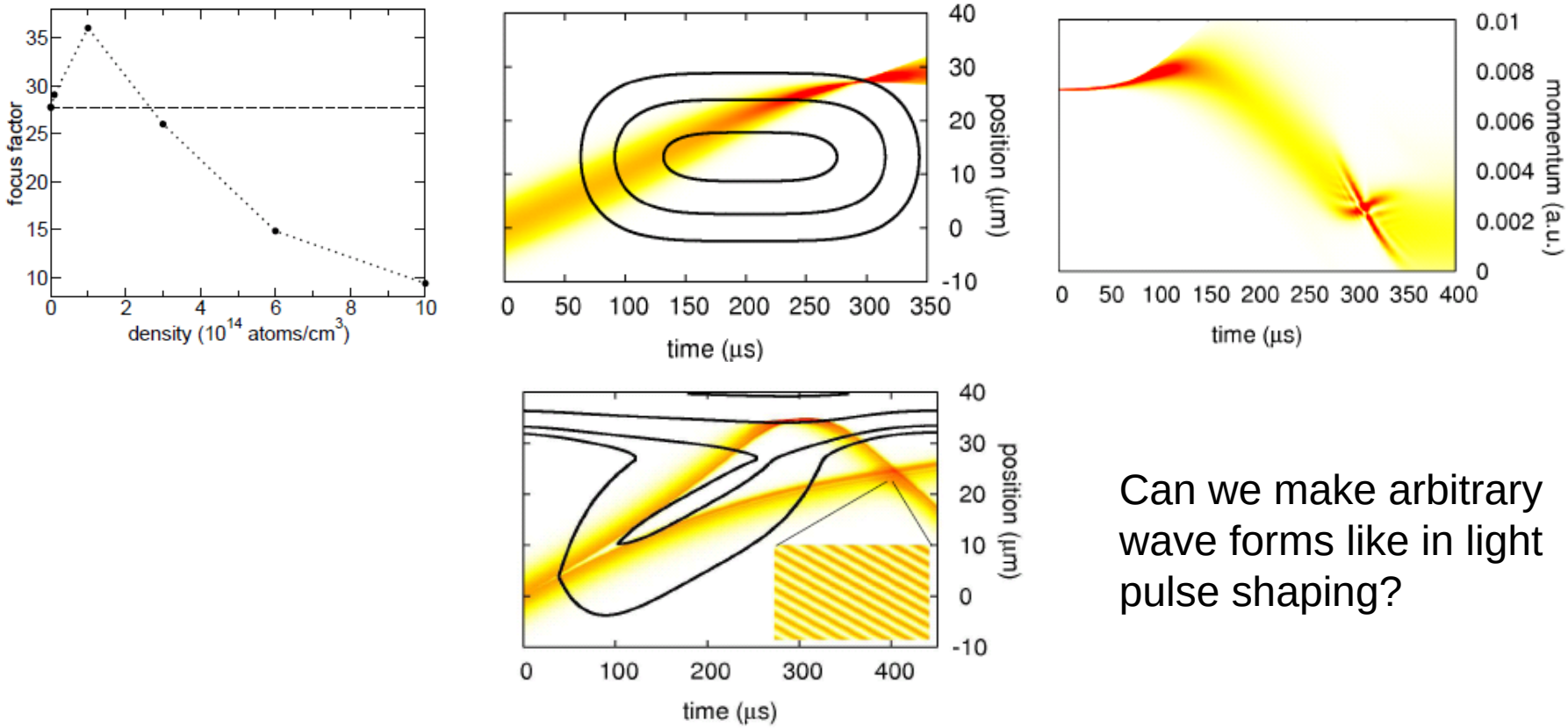
Daniel Rohrlich, Yakov Neiman, Yonathan Japha, and Ron Folman
Department of Physics, Ben-Gurion University, Beer-Sheva 84105, Israel
(Received 23 January 2006; published 5 May 2006)

We describe a new and distinctive interferometry in which a probe particle scatters off a *superposition* of locations of a *single* free target particle. Probe particles scattering off a single free "mirror" (in one dimension) or a single free "slit" (in two dimensions) can "swap" interference with the superposed target states. The condition for interference is *loss* of orthogonality of the target states and reduces, in simple examples, to *transfer* of orthogonality from target to probe states. We analyze experimental parameters and conditions necessary for interference to be observed.

Matter Wave Pulse Shaping

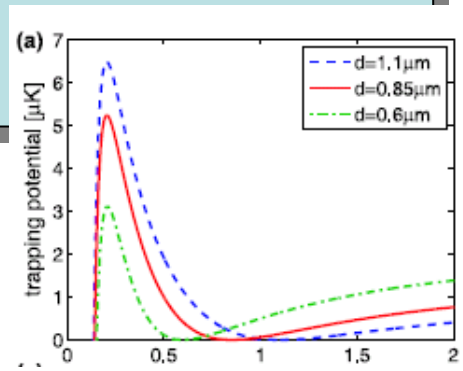
Dynamic Matter-Wave Pulse Shaping

M. Nest[1], Y. Japha[2], R. Folman[2], R. Kosloff[3]



Can we make arbitrary wave forms like in light pulse shaping?

My personal favorite item on the wishlist: Altering the CP force



The problem

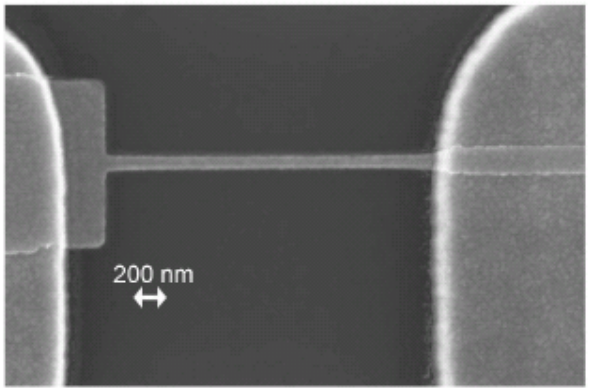
Beyond the trivial concept of using less material?????

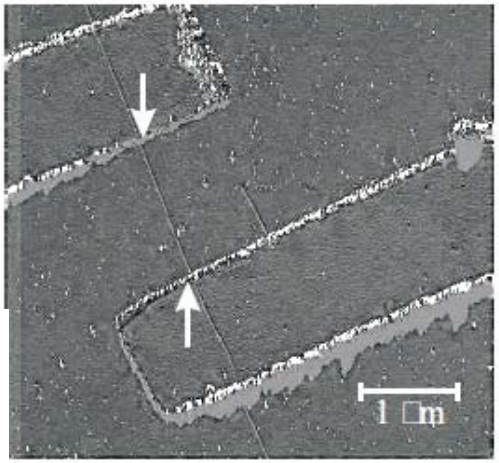
Using less material: CNTs and nano gold wires

Trapping cold atoms using surface-grown carbon nanotubes

P. G. Petrov,[1,*] S. Machluf,[1] S. Younis,[1,2] R. Macaluso,[1,2] T. David,[1]
B. Hadad,[2] Y. Japha,[1] M. Keil,[1,†] E. Joselevich,[3] and R. Folman[1]

Also Tubingen





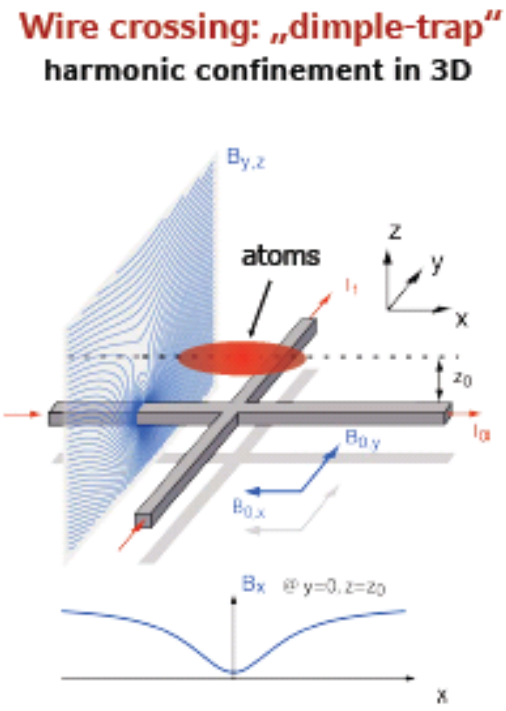
Nanowire atomchip traps for sub-micron atom-surface distances

R. Salem,[1,*] Y. Japha,[1] J. Chabé,[1] B. Hadad,[2] M. Keil,[1] K. A. Milton,[3] and R. Folman[1]

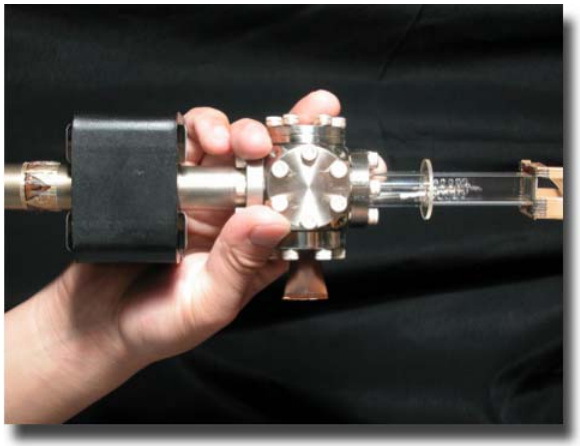
Some of the many achievements

The BEC survives 10 orders of magnitude in temperature difference over a few micro meters

Fast BEC (e.g. 100,000 atoms in a few secs)



Portable BECs



www.coldquanta.com

The first coherent splitting on a chip:

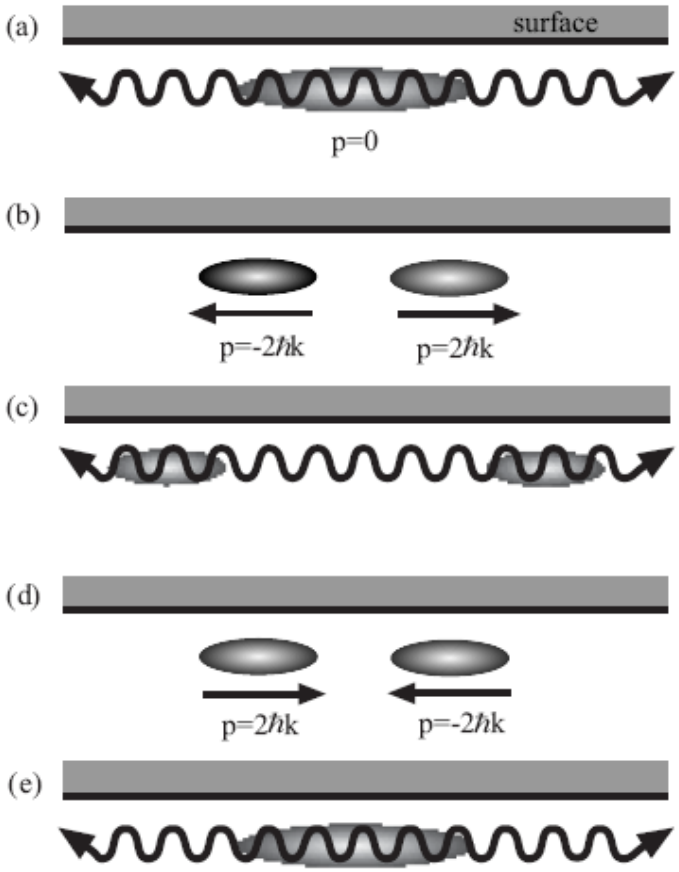
An Atom Michelson Interferometer on a Chip Using a Bose-Einstein Condensate

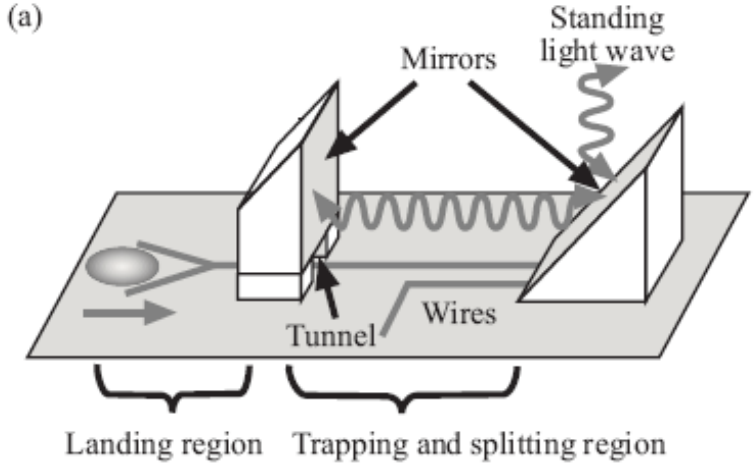
Ying-Ju Wang,[1] Dana Z. Anderson,[1] Victor M. Bright,[2] Eric A. Cornell,[1] Quentin Diot,[1] Tetsuo Kishimoto,[1*]
Mara Prentiss,[3] R. A. Saravanan,[2] Stephen R. Segal,[1] and Saijun Wu[3]

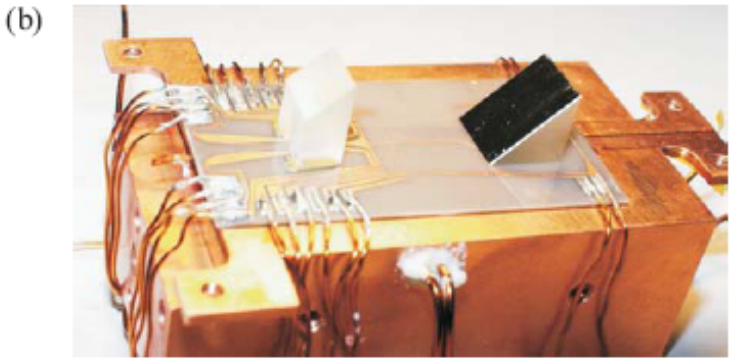
[1] *Department of Physics, University of Colorado, and JILA, National Institute of Standards and Technology and University of Colorado, Boulder, Colorado 80309-0440, USA*

[2] *Department of Mechanical Engineering, University of Colorado, Boulder, Colorado 80309-0427, USA*

[3] *Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*



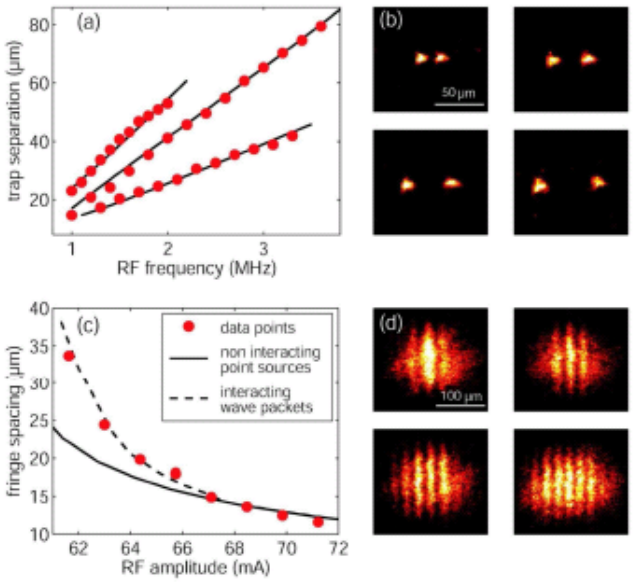


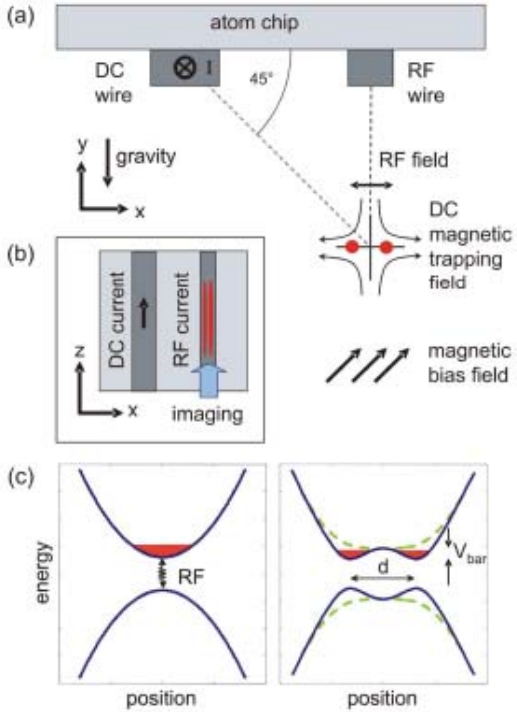


The first “in the dark” deterministic spatial fringes on an atomchip:

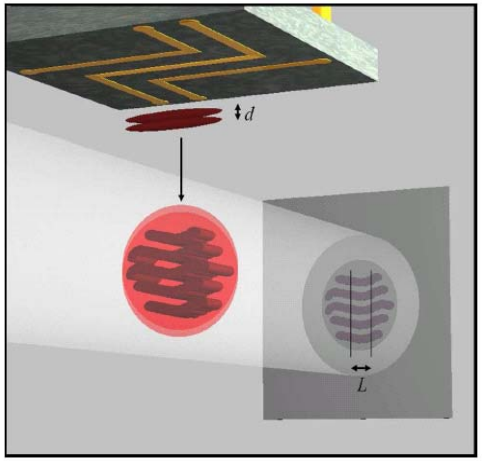
Matter-wave interferometry in a double well on an atom chip

T. Schumm,[1,2] S. Hofferberth,[1] L. M. Andersson,[1] S. Wildermuth,[1]
S. Groth,[1,3] I. Bar-Joseph,[3] J. Schmiedmayer,[1,*] and P. Krüger[1,4,†]



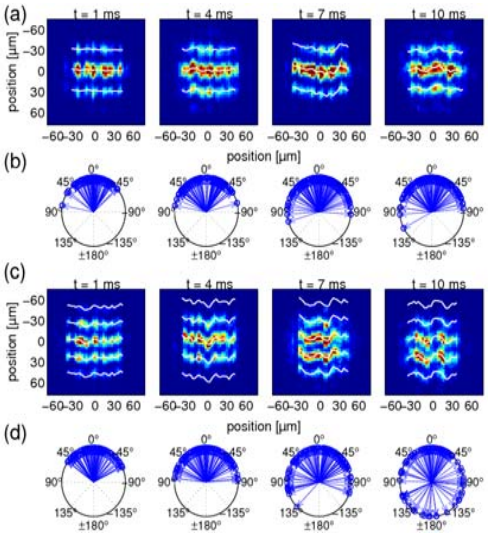


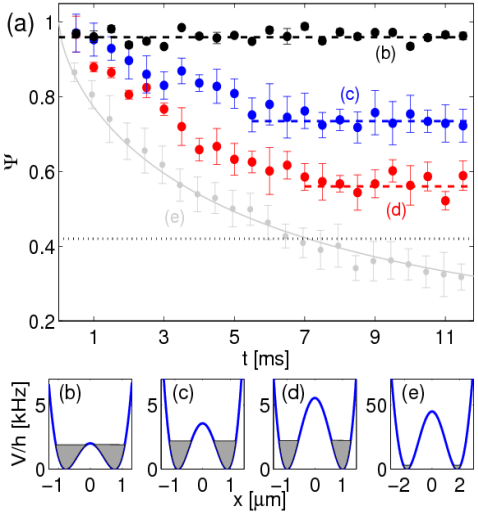
Non equilibrium coherence dynamics in 1d super fluid

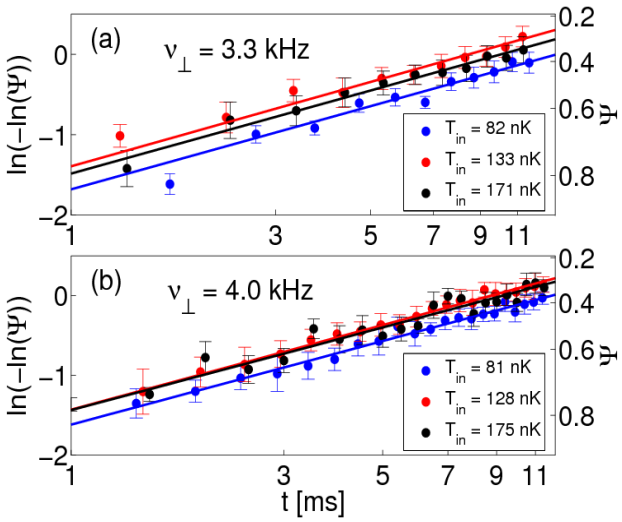


Splitting a 1d degenerate Bose gas initializes the system in a phase coherent state coherent

- Observe the universal parameters of the relaxation to thermal equilibrium in 1d systems:
  - phase locking
  - sub exponential coherence decay with a universal exponent 2/3
- Continuous array of Josephson oscillators coupled to a ‘quantum bath’ (=a few phonons)



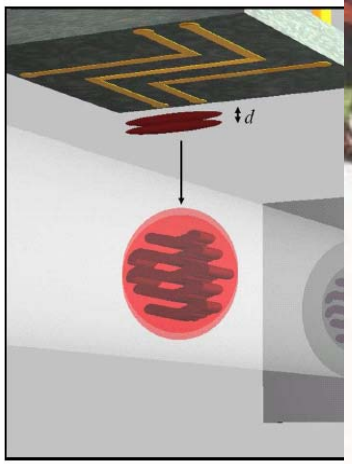




Hofferberth et al. arXiv:0706.2259 Schmiedmayer group

Non equilibrium coherence dyna

Cant resist the temptation to show you how they ski in Tyrol…

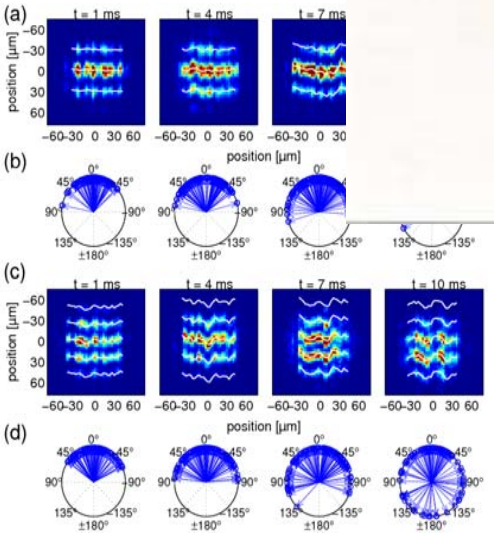


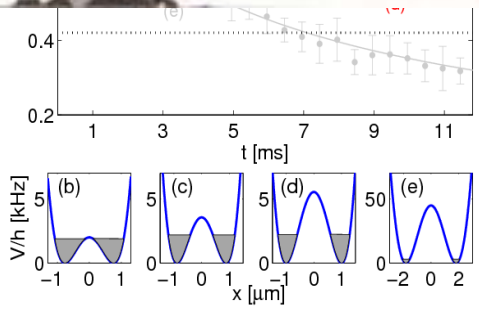
es the system

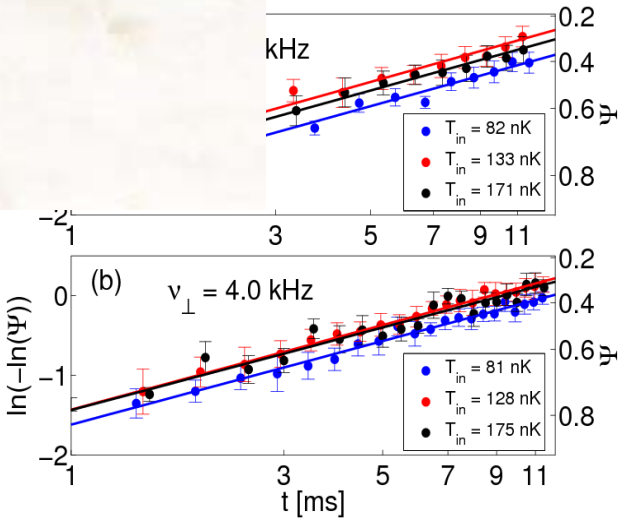
e relaxation to

universal

ors coupled to a



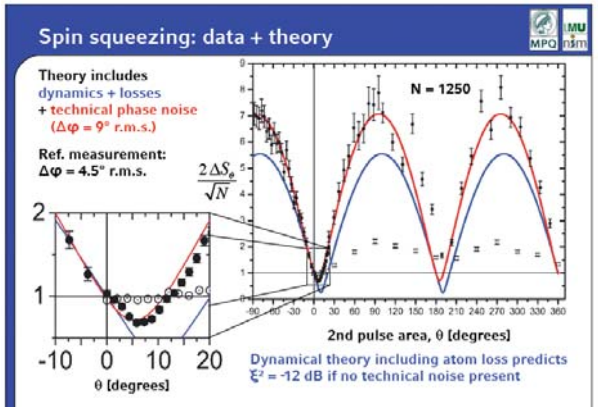


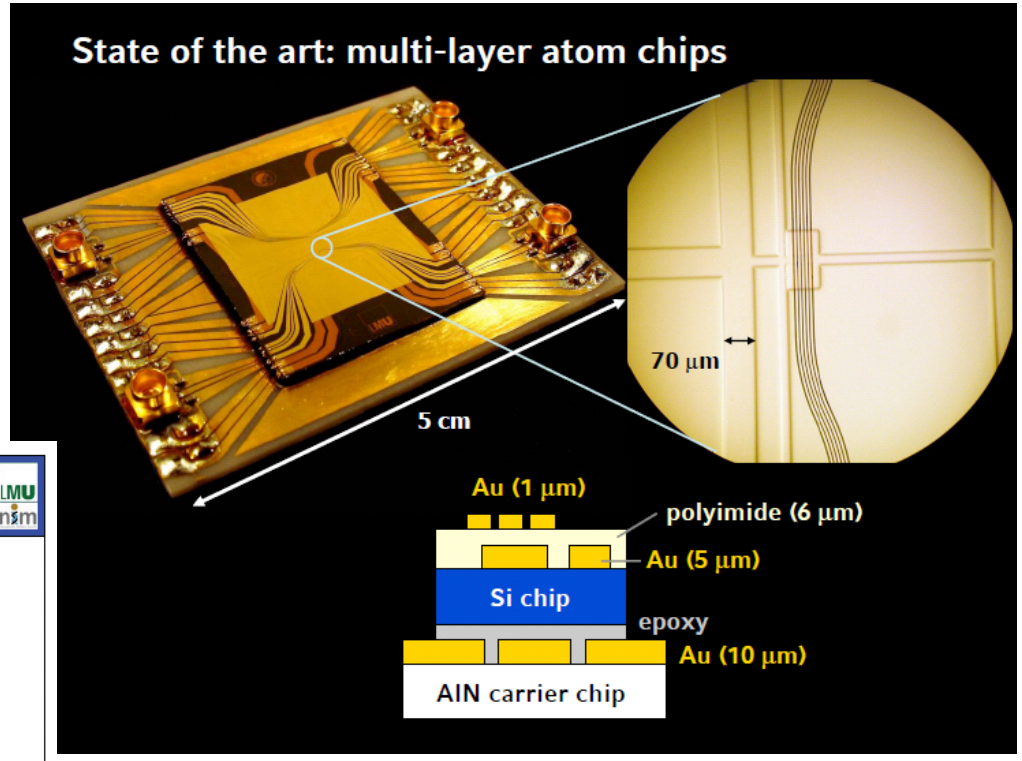


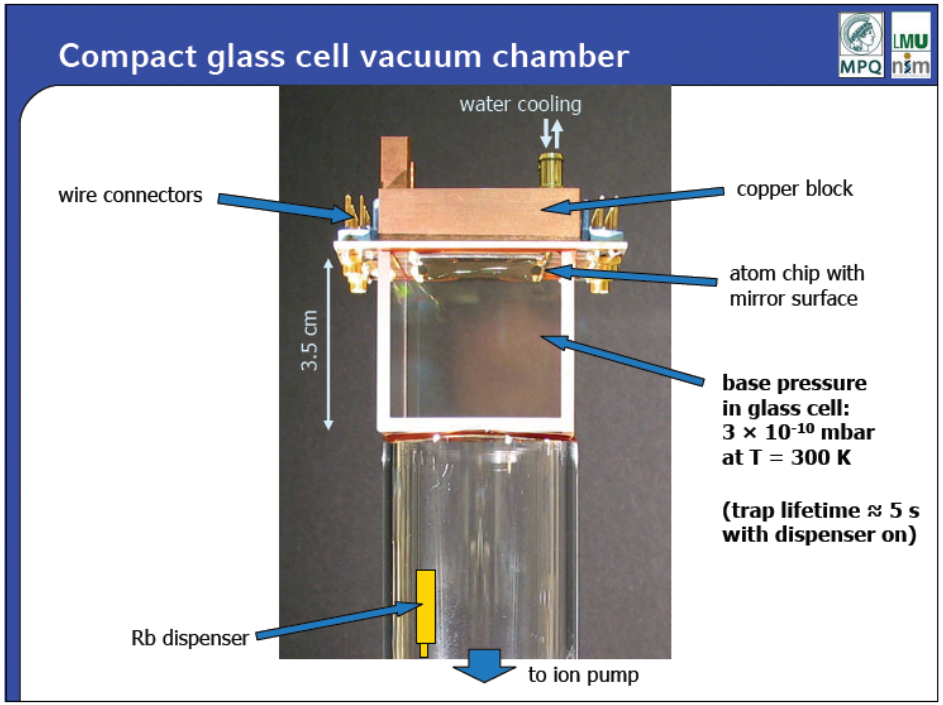
Hofferberth et al. arXiv:0706.2259 Schmiedmayer group

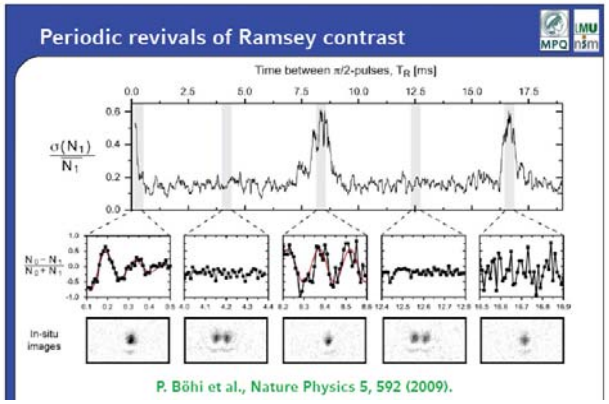
Coherent manipulation of Bose-Einstein condensates with state-dependent microwave potentials on an atom chip

Pascal Böhi,[1] Max F. Riedel,[1] Johannes Hoffrogge,[1] Jakob Reichel,[2] Theodor W. Hänsch,[1] and Philipp Treutlein[1,*]

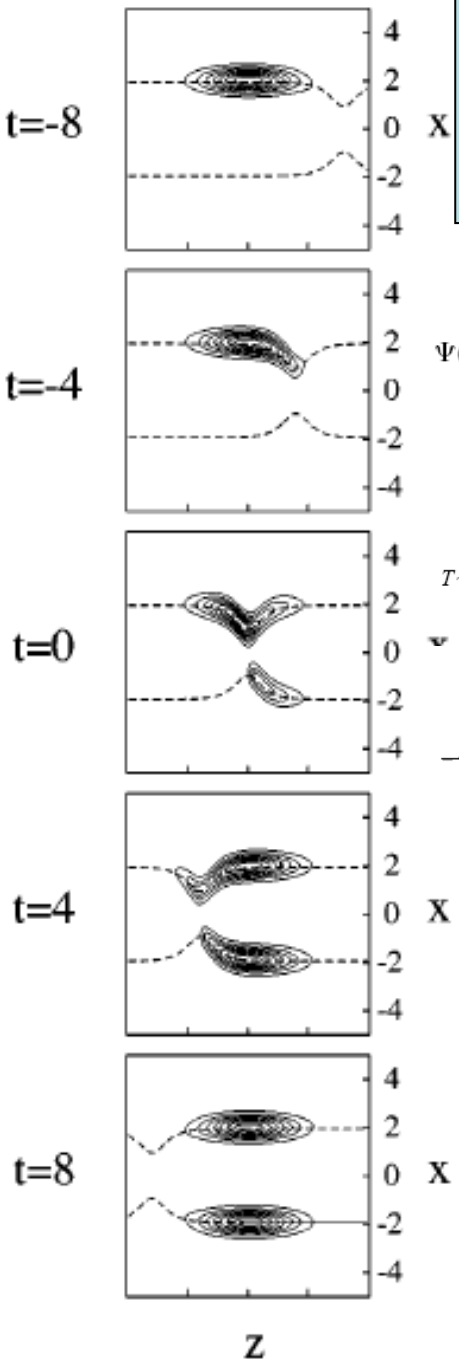








DC splitting (static magnetic tunneling barrier): why has it never worked? (although many simulations showed feasibility)

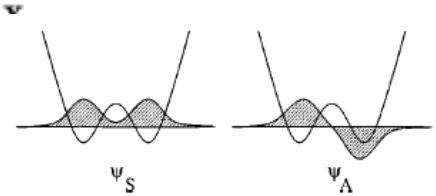


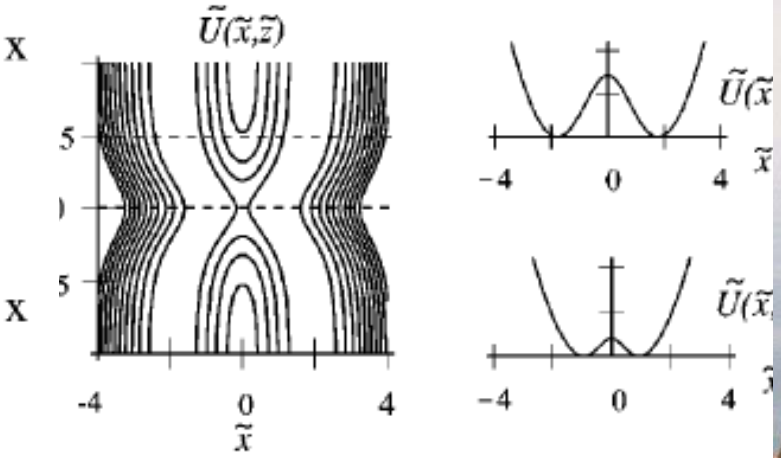
$$\Psi(t) = \exp(-iHt/\hbar)\varphi_L$$

$$= \frac{1}{\sqrt{2}}\exp(-i\bar{E}t/\hbar)(e^{i\Omega t}\psi_S + e^{-i\Omega t}\psi_A)$$

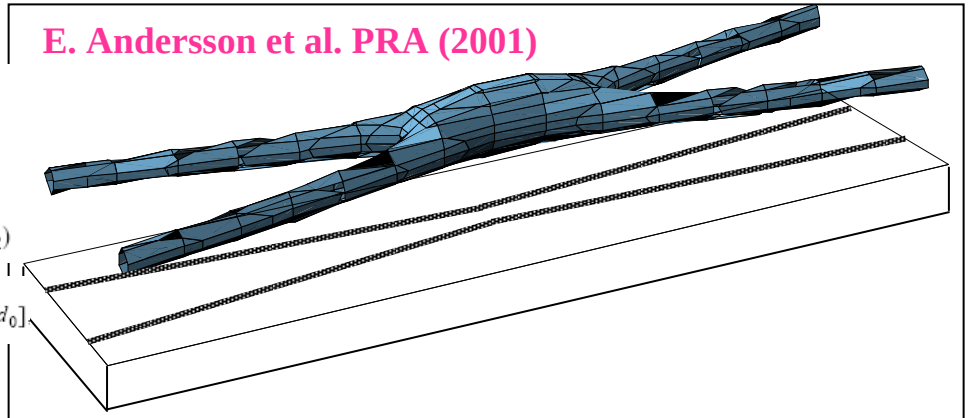
$$= \exp(-i\bar{E}t/\hbar)(\cos\Omega t\varphi_L + i\sin\Omega t\varphi_R)$$

$$T \sim \exp\left[-\int\sqrt{2mU(x,0)}dx\right] \approx \exp[-\kappa\sqrt{U(0,0)}d_0]$$





E. Andersson et al. PRA (2001)



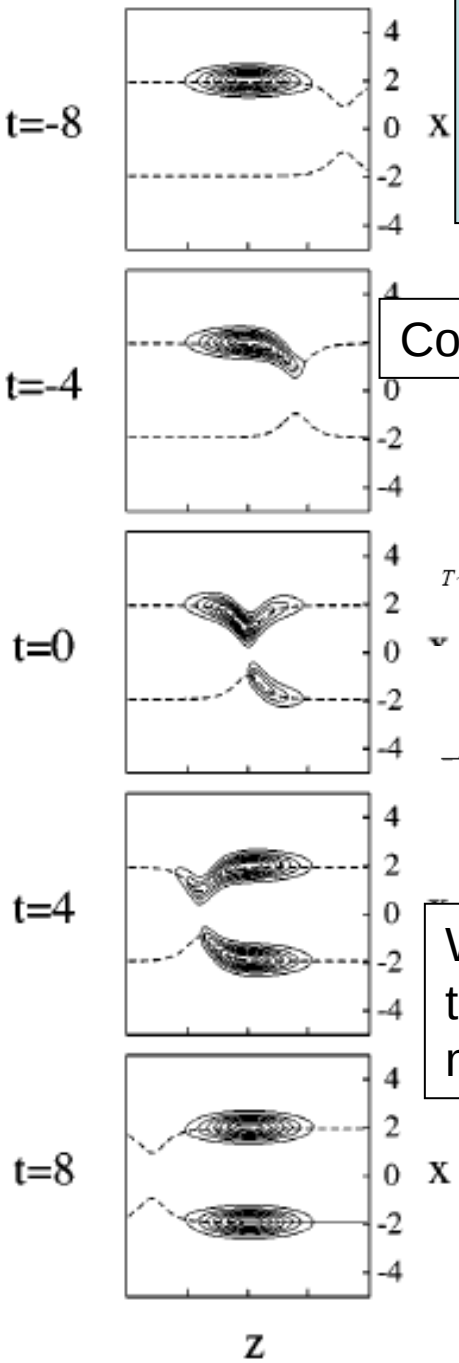
Single mode tunneling beam splitter

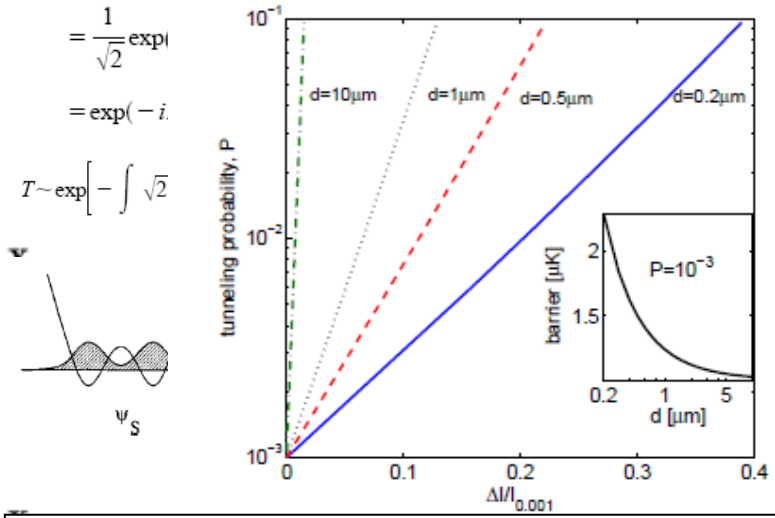
RF

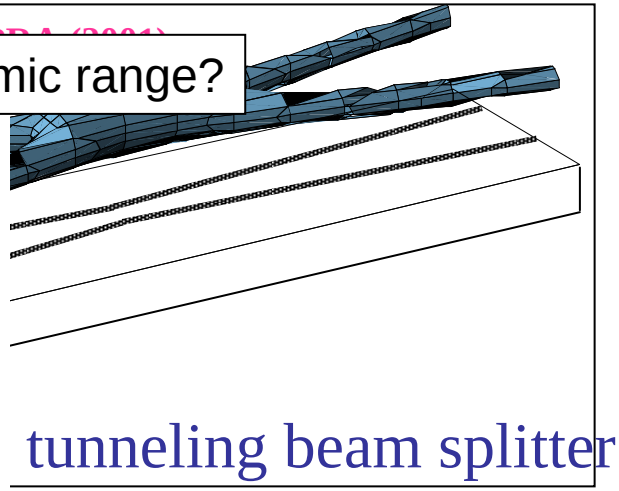
Erika Andersson

DC splitting (static magnetic tunneling barrier): why has it never worked?

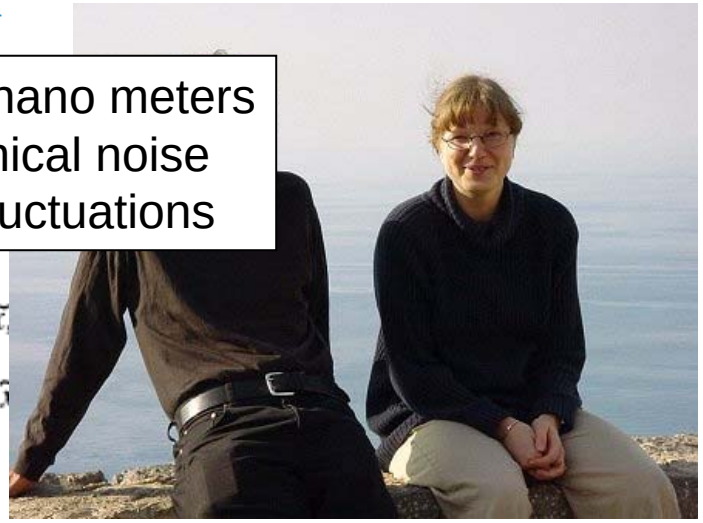
Could the answer be as simple as dynamic range?



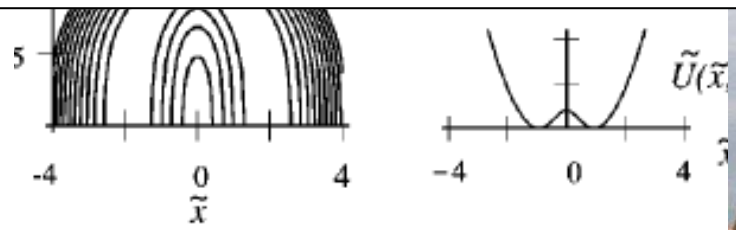




Erika Andersson

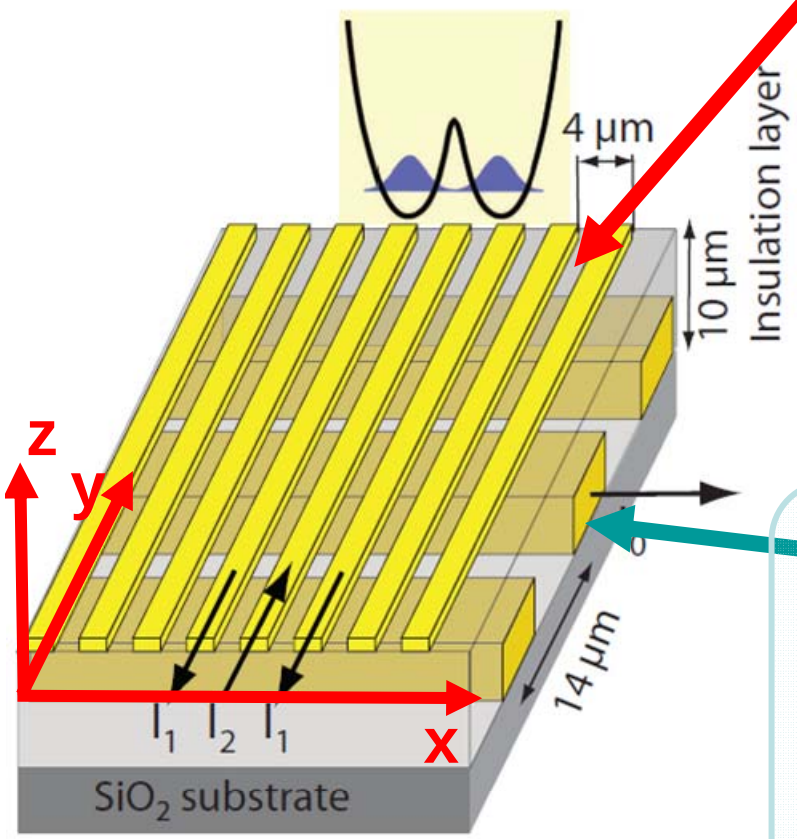


We see that above a few hundred nano meters the dynamic range is low and technical noise may be causing severe tunneling fluctuations

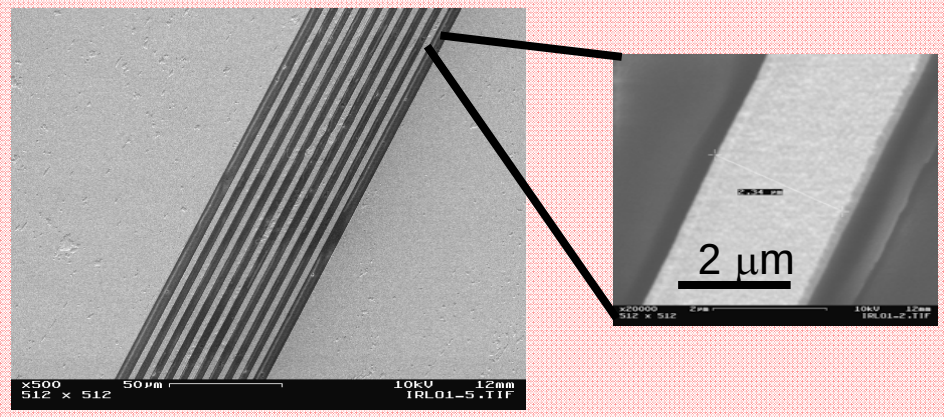


First successful step : 2-layer atom chip

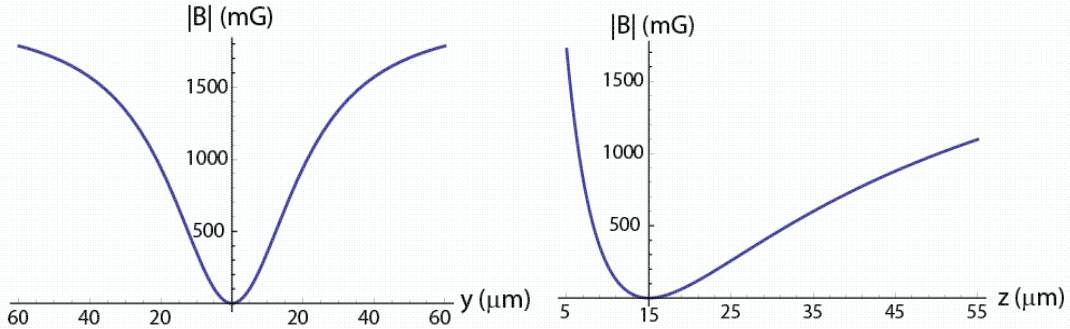
Jakob Reichel, Romain Long



Top Layer : trapping in x direction

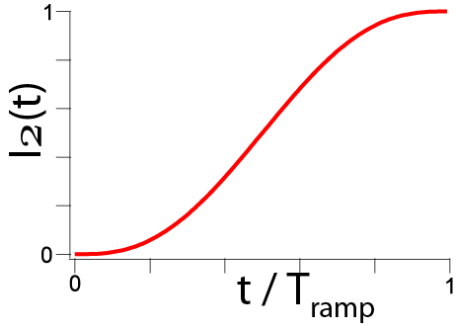


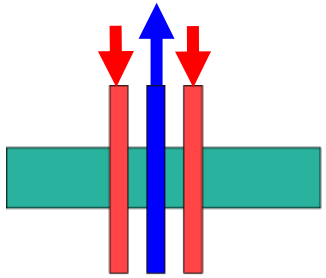
Bottom layer : trapping in y, z



Squeezing vs. Ramping Time

Ramp of the current in the middle wire : I_2



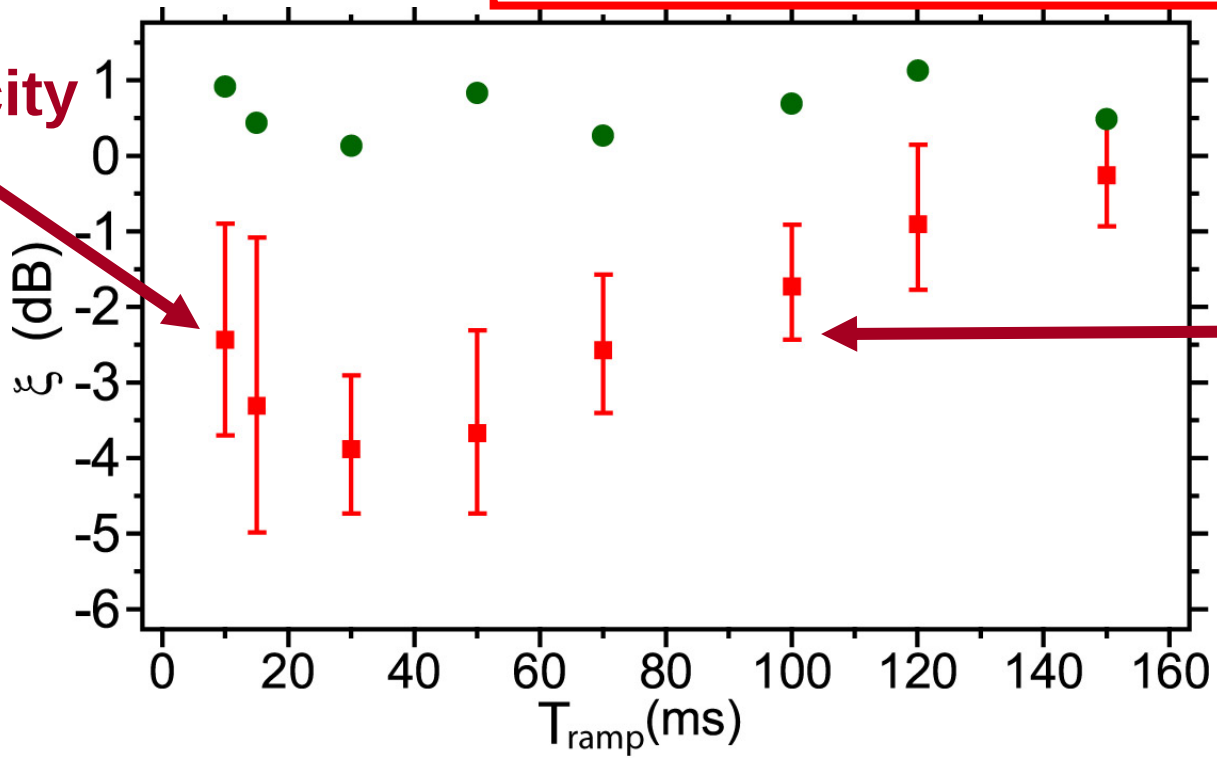


$$\xi = \left\langle \frac{n^2}{N_L + N_R} \right\rangle$$

Variance of n

Expected Variance for a binomial distribution

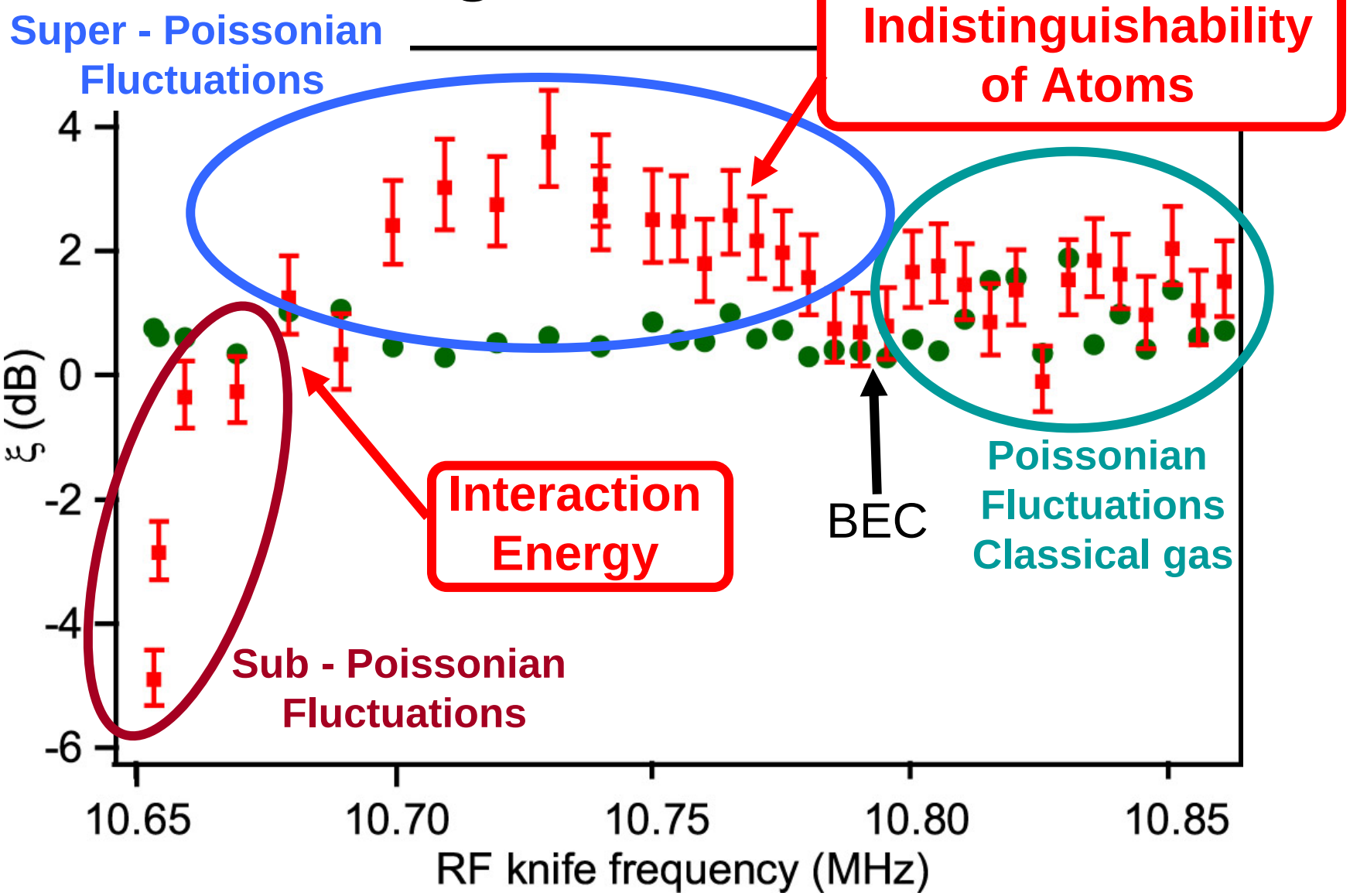
Non - Adiabaticity



Technical Heating

Technical detection noise estimation

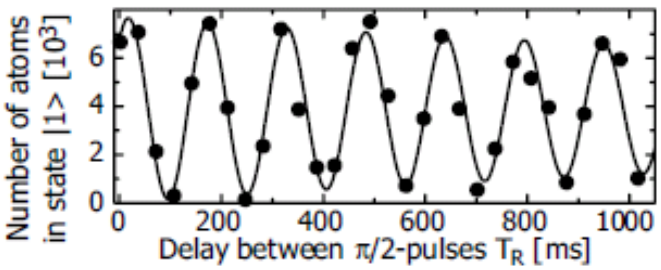
Squeezing vs. Temperature

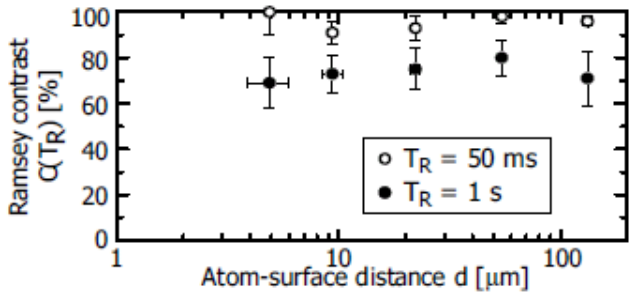


Coherence of internal degrees of freedom

Coherence in Microchip Traps

Philipp Treutlein,* Peter Hommelhoff,† Tilo Steinmetz, Theodor W. Hänsch, and Jakob Reichel
Max-Planck-Institut für Quantenoptik und Sektion Physik der Ludwig-Maximilians-Universität, Schellingstr.4, 80799 München, Germany
(Dated: April 22, 2004)





Probing the surface and atom-surface physics

Measuring electric fields from surface contaminants with neutral atoms

J. M. Obrecht*, R. J. Wild, E. A. Cornell†
JILA, National Institute of Standards and Technology and University of Colorado, Boulder, Colorado 80309-0440, USA and Department of Physics, University of Colorado, Boulder, Colorado 80309-0390, USA
(Dated: June 25, 2007)

Measurement of the Temperature Dependence of the Casimir-Polder Force

J. M. Obrecht[1,*], R. J. Wild[1], M. Antezza[2], L. P. Pitaevskii[2,3], S. Stringari[2], E. A. Cornell[1,†]
[1] *JILA, National Institute of Standards and Technology and University of Colorado, Boulder, Colorado 80309-0440, USA and Department of Physics, University of Colorado, Boulder, Colorado 80309-0390, USA*
[2] *Dipartimento di Fisica, Università di Trento and CNR-INFM BEC Center, Via Sommarive 14, I-38050 Povo, Trento, Italy*
[3] *Kapitza Institute for Physical Problems, ulitza Kosygina 2, 119334 Moscow, Russia*
(Dated: April 3, 2007)

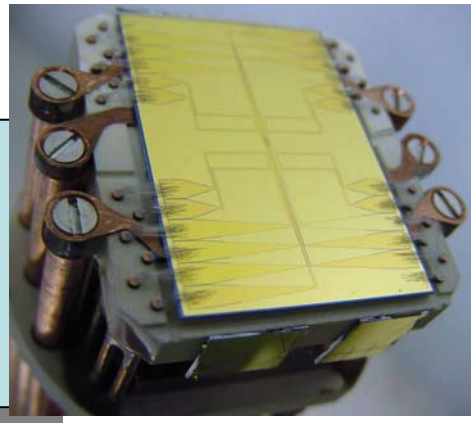
Thermally induced spin flips above an atom chip

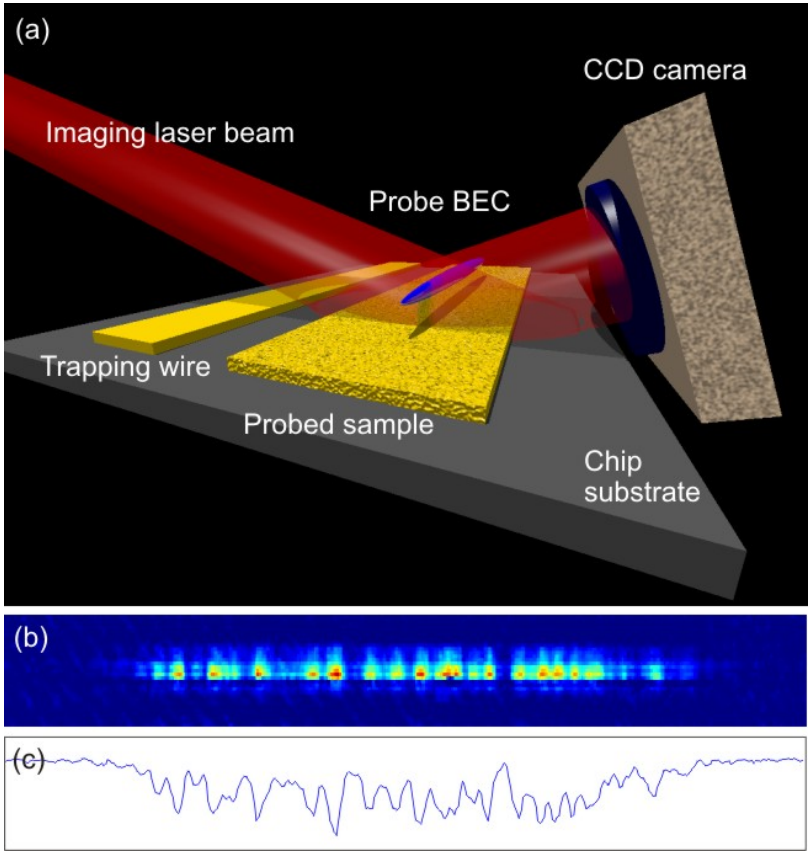
M. P. A. Jones, C. J. Vale, D. Sahagun, B. V. Hall and E. A. Hinds*
Blackett Laboratory, Imperial College, London SW7 2BW, United Kingdom
(Dated: December 15, 2009)

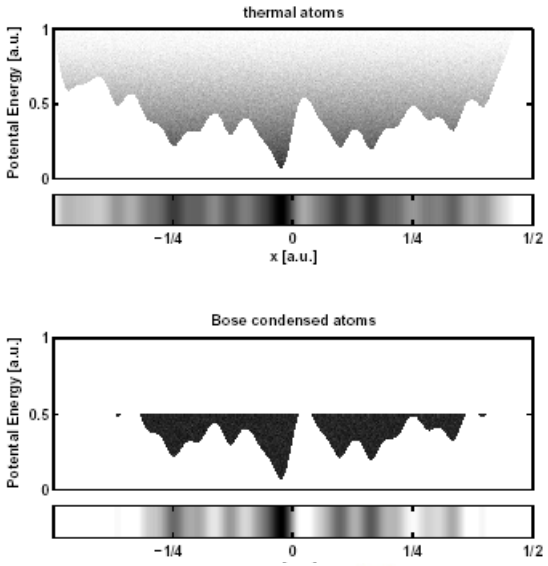
Impact of the Casimir-Polder Potential and Johnson Noise on Bose-Einstein Condensate Stability near Surfaces

Yu-ju Lin, Igor Teper, Cheng Chin, and Vladan Vuletić
*Department of Physics, Stanford University, Stanford, California 94305-4060**

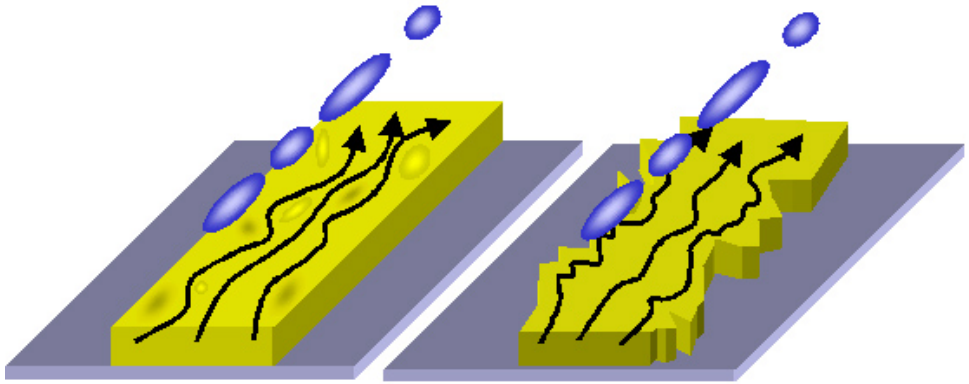
Probing electron transport





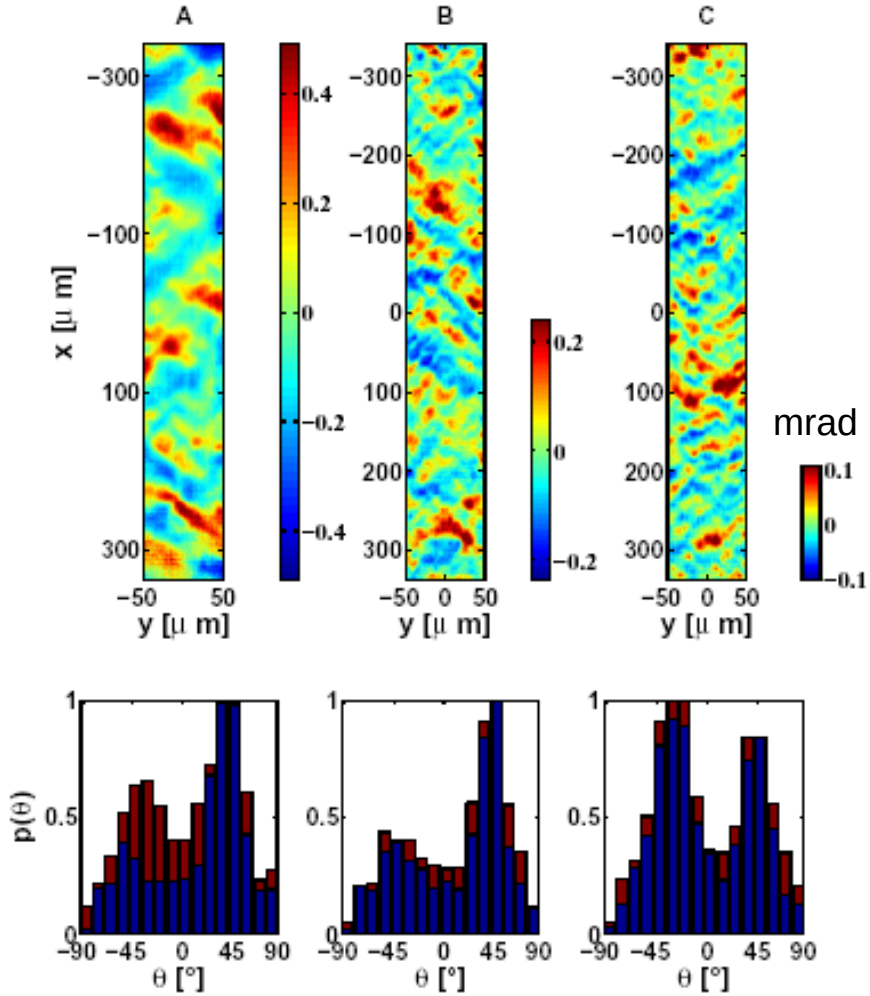


Schmiedmayer
Folman
Science 2008



The surprise: long range order in electron flow in a wire without any structural long range order

$$\beta(x, y, z_0) = \delta B_x(x, y, z_0)/B_y$$



$\lambda_\beta = 77\mu$m, 46μm 48μm $\lambda_\beta = 2\pi/\sqrt{\langle k^2 \rangle}$.

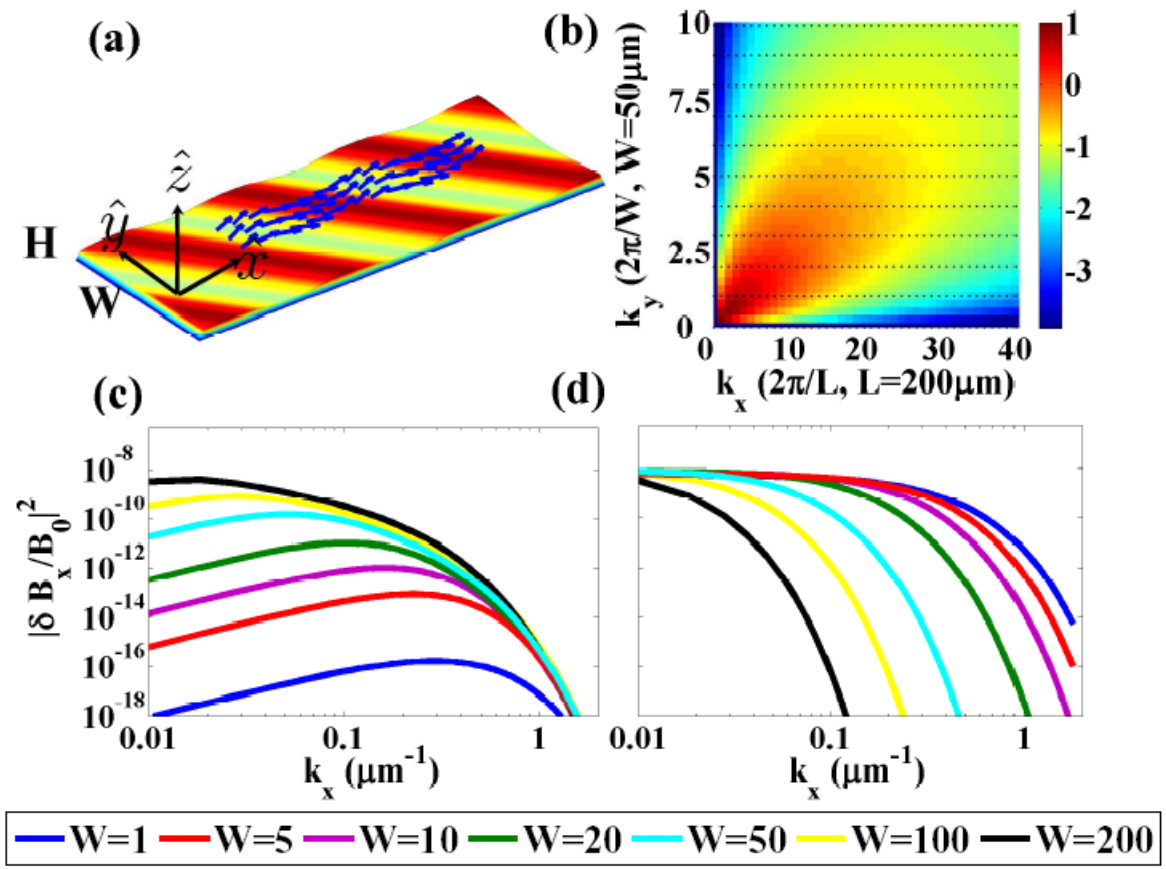
First mystery:
Why correlation length
1000 times more than expected
from grain size or diffusion length?

Second mystery:
Why 45 degrees?

Third mystery:
Why does the wire with largest
grains has smallest corrugation?

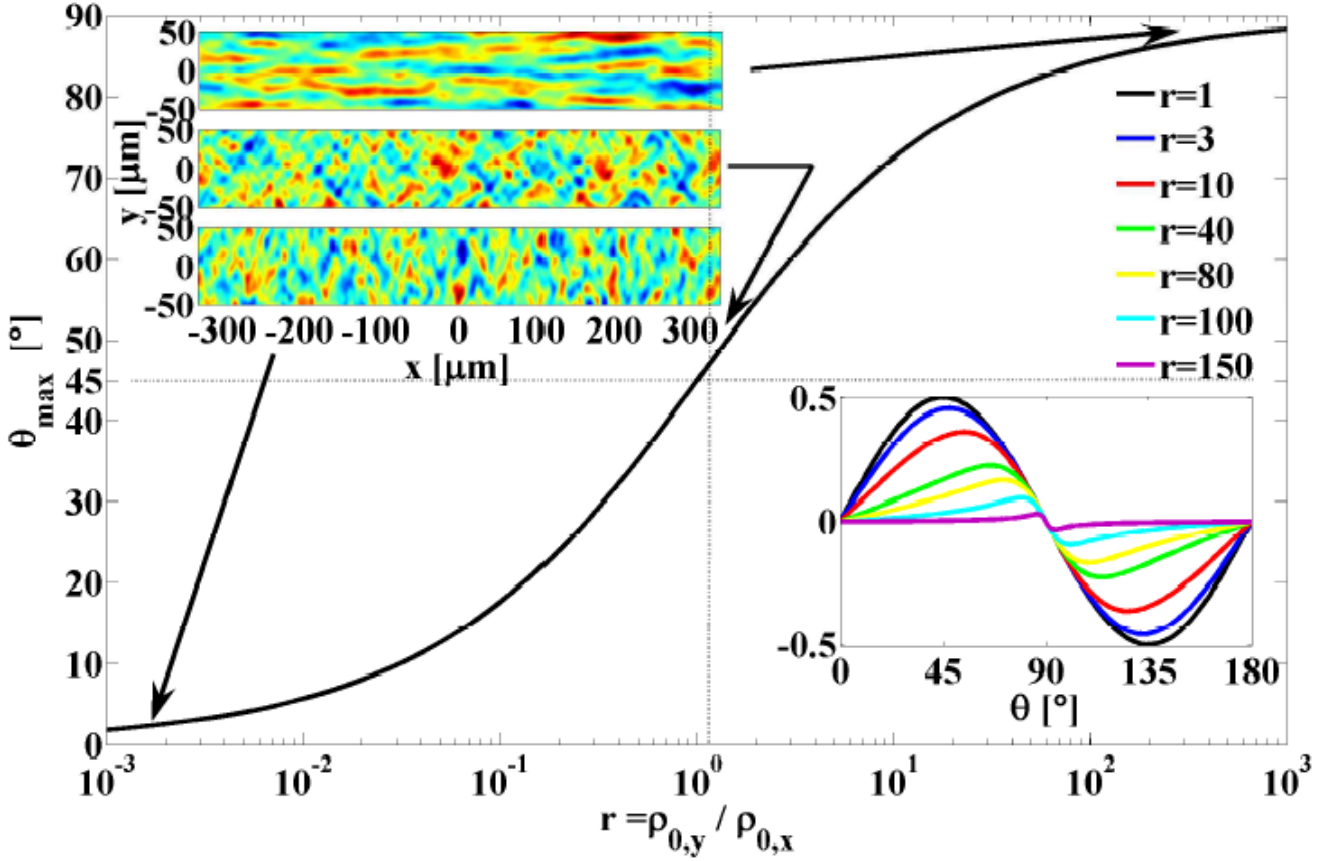
Fourth mystery:
Why do the wires have such a
different spectral behavior?

Predictions of our model: less width=less scattering



Y. Japha et al., PRB (2008)

Predictions of our model: anisotropic materials change the 45 and the corrugation amplitude

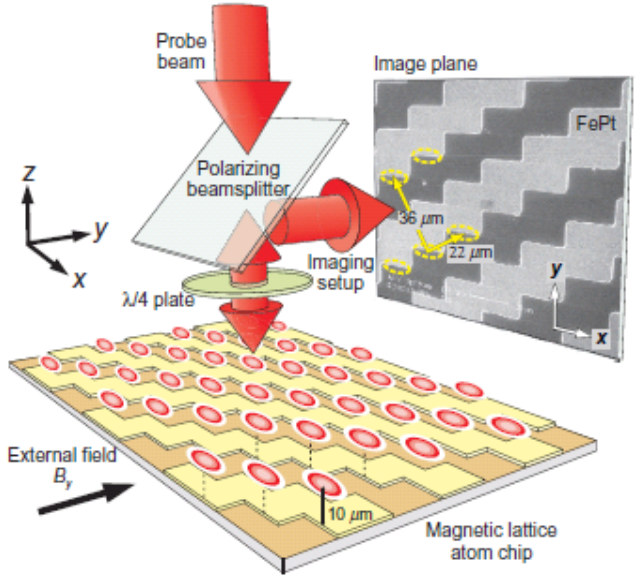


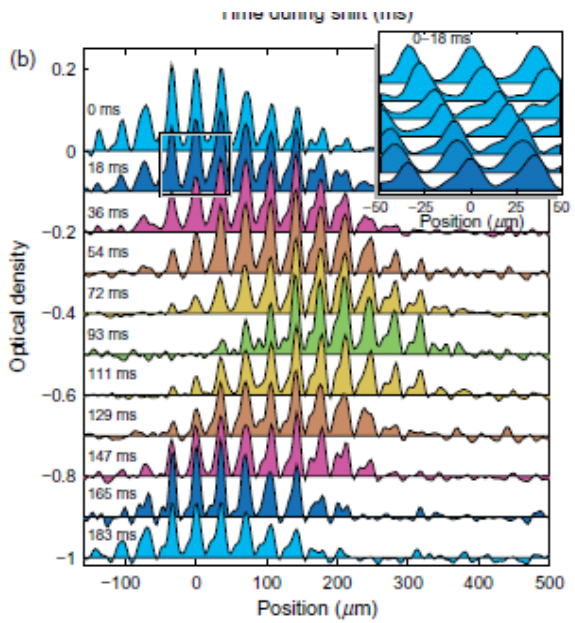
Y. Japha et al., PRB (2008)

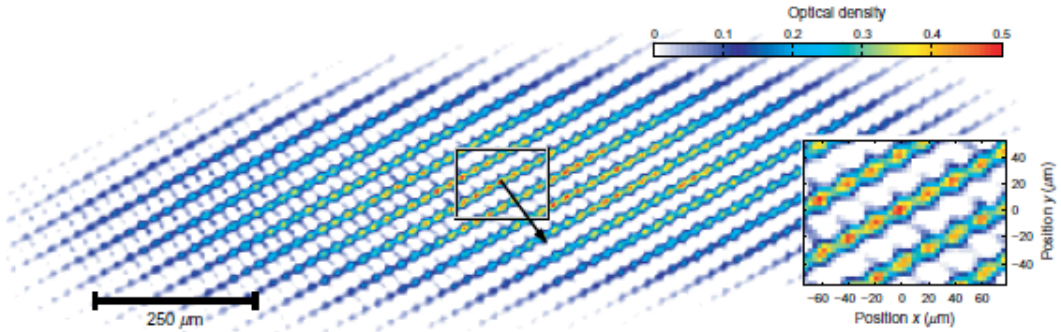
Novel potentials: permanent magnets, electric, SC vortex, multi directional

Two-dimensional array of microtraps with atomic shift register on a chip

S Whitlock[1], R Gerritsma[2], T Fernholz[3] and R J C Spreeuw
Van der Waals-Zeeman Institute, University of Amsterdam, Amsterdam, The Netherlands
E-mail: S.M.Whitlock@uva.nl







Electric traps

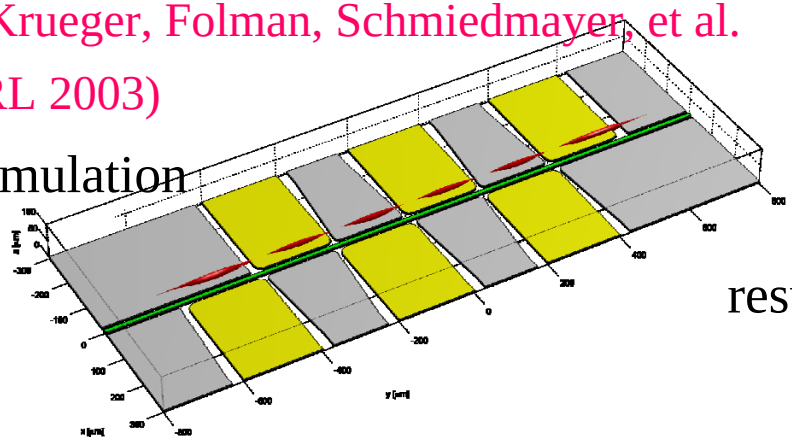
P. Krueger, Folman, Schmiedmayer, et al.

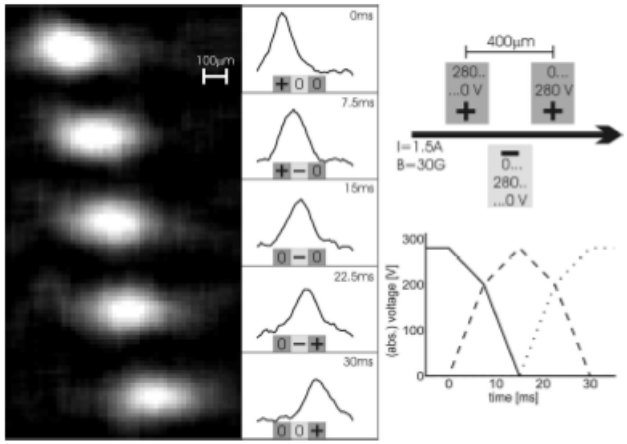
(PRL 2003)

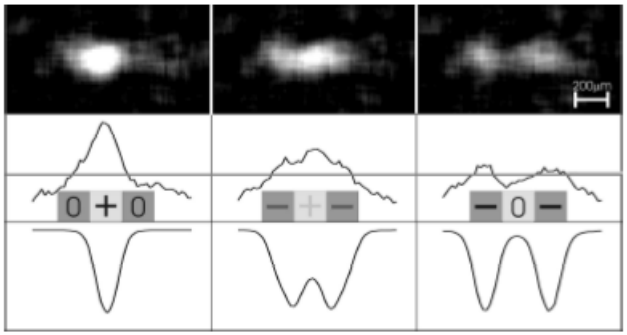
The matter-wave pulse shaping discussed earlier is based on this

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

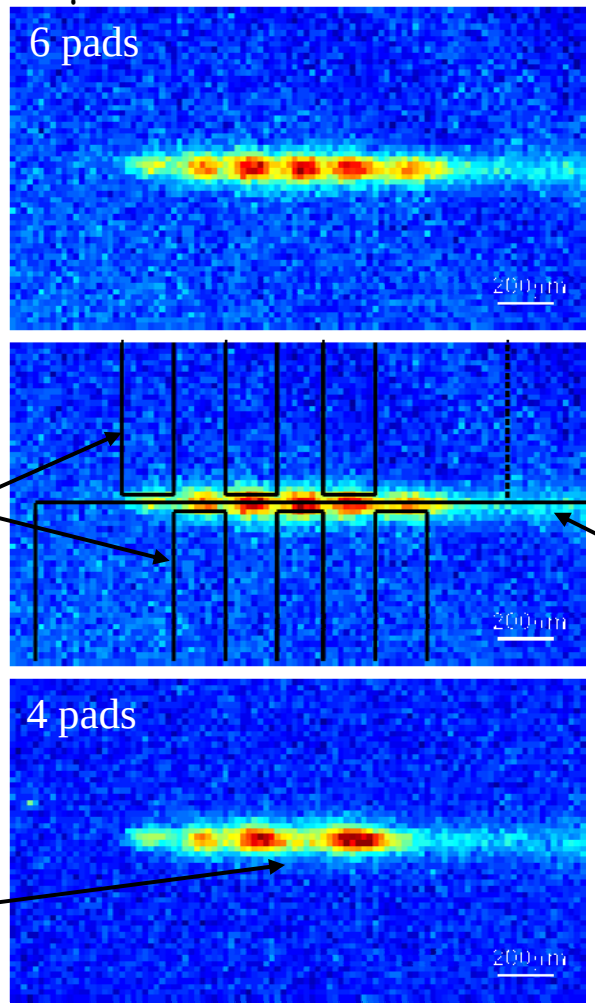
simulation







results



HV electrodes

side guide wire

de-focusing of the electric field lines

Trapping of ultra-cold atoms with the magnetic field of vortices in a thin film superconducting micro-structure

T. Müller,* B. Zhang, R. Fermani,* K.S. Chan, Z.W. Wang, C.B. Zhang, M.J. Lim,† and R. Dumke‡
Nanyang Technological University, Division of Physics and Applied Physics, 21 Nanyang Link, Singapore 637371
(Dated: December 22, 2009)

Could this be the first step towards the Atom-Electron entanglement we discussed previously?

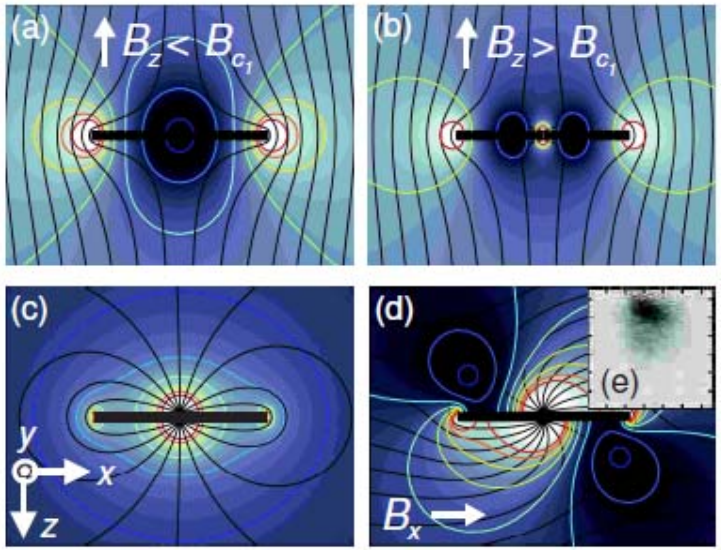
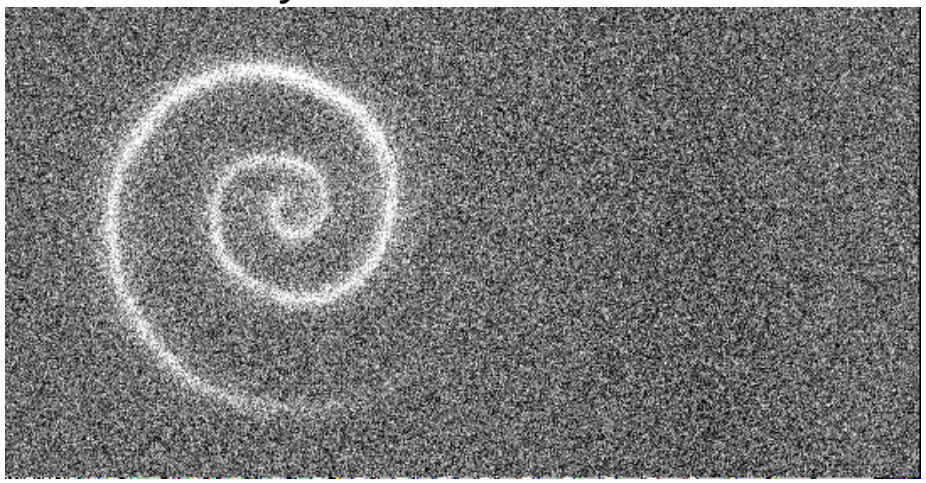


FIG. 1: (Color online) Schematic illustration of the magnetic field distribution during the preparation of the remanent-state superconductor (a)-(c) and the vortex-based micro-trap (d). Illustrated are the field lines (black lines) and equipotentials (colored lines and grayscale) of the magnetic field. An absorption image of $6 \cdot 10^5$ atoms recorded 1ms after release from the vortex-based micro-trap is shown in (e).

Multi directional guiding: an atom fiber
Schmiedmayer, Folman

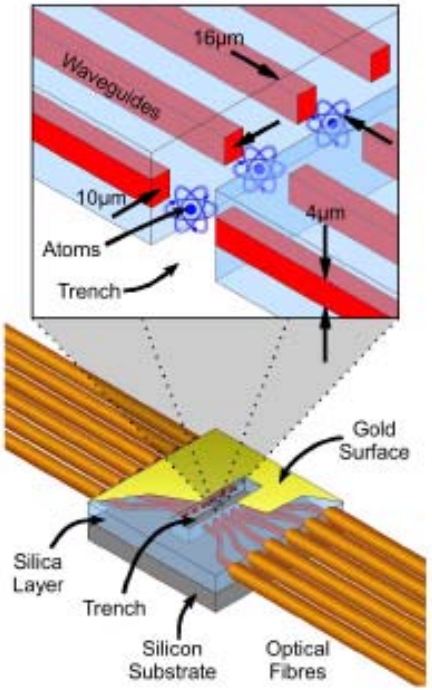


Atom-Light

The first real integrated device:

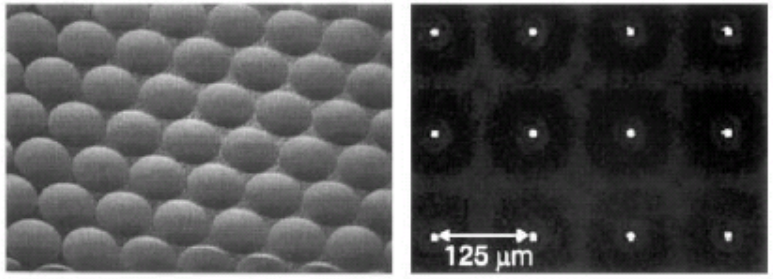
An integrated atom-photon junction

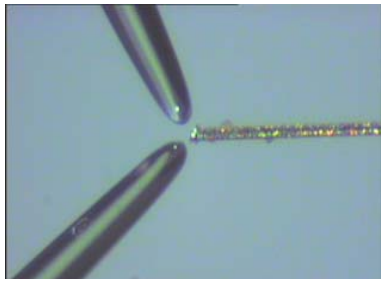
M. Kohnen, M. Succo, P. G. Petrov, R. A. Nyman, M. Trupke, and E. A. Hinds
Centre for Cold Matter, Blackett Laboratory, Imperial College London, Prince Consort Road, SW7 2BW, United Kingdom
(Dated: December 23, 2009)



Many previous works, e.g.:

Birkl, Ertmer

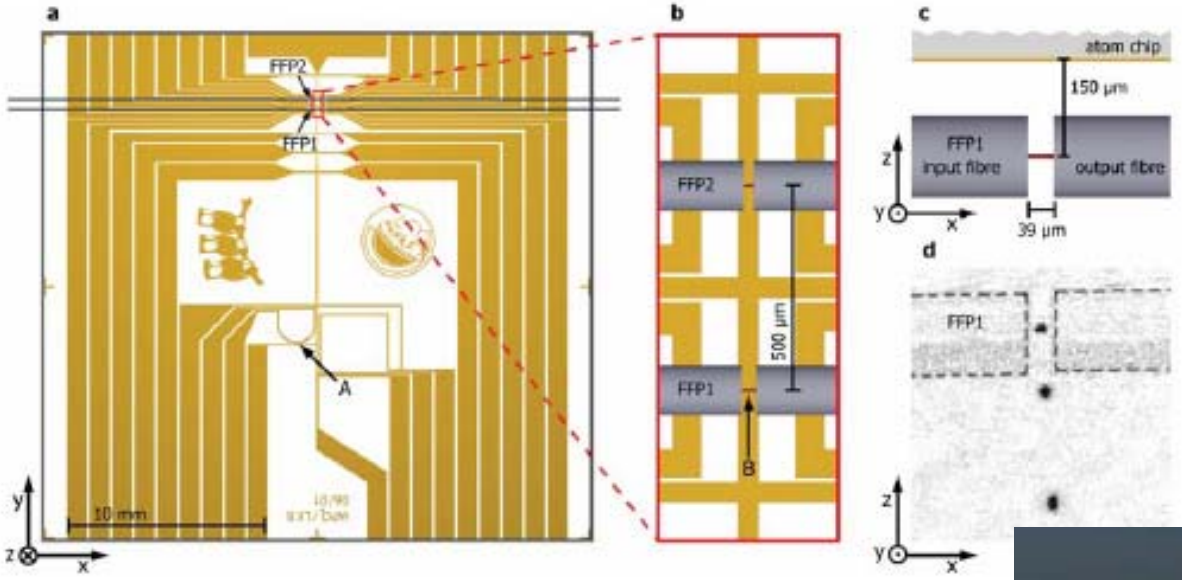


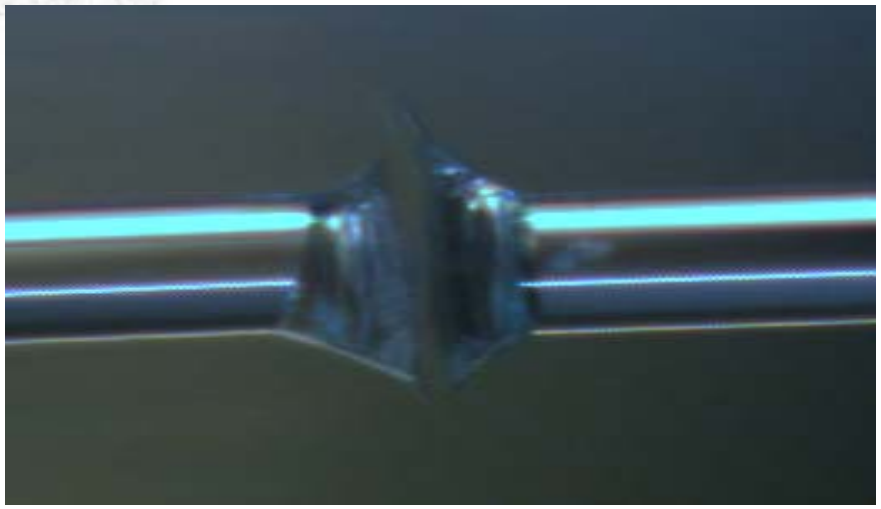


Vienna and Rochester

Strong atom-field coupling for Bose-Einstein condensates in an optical cavity on a chip

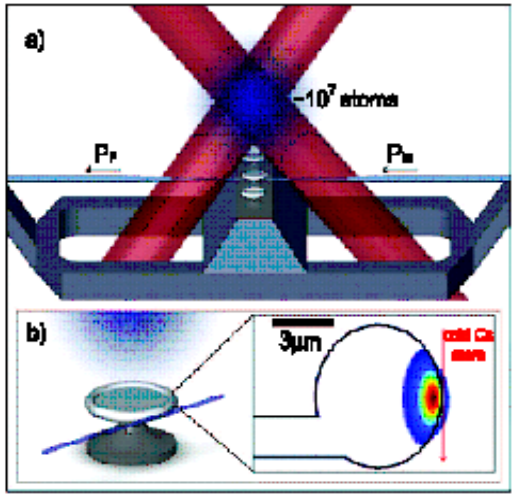
Yves Colombe[1,*], Tilo Steinmetz[1,2,*], Guilhem Dubois[1], Felix Linke[1,†], David Hunger[2] & Jakob Reichel[1]





Observation of strong coupling between one atom and a monolithic microresonator

Takao Aoki[1]†, Barak Dayan[1], E. Wilcut[1], W. P. Bowen[1]†, A. S. Parkins[1]†, T. J. Kippenberg[2]†, K. J. Vahala[2] & H. J. Kimble[1]



Integration of fiber coupled high-Q SiN_X microdisks with magnetostatic atom chips

Paul E. Barclay,* Kartik Srinivasan, and Oskar Painter
Thomas J. Watson, Sr. Laboratory of Applied Physics, California Institute of Technology, Pasadena, CA 91125, USA.

Benjamin Lev and Hideo Mabuchi
Norman Bridge Laboratory of Physics, California Institute of Technology, Pasadena, CA 91125, USA.

(Dated: May 30, 2006)

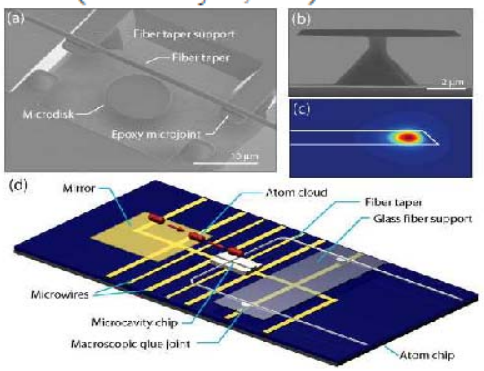


FIG. 1: (a) Scanning electron microscope (SEM) image of a SiN_x cavity coupled to an optical fiber taper. The fiber taper is permanently aligned a few hundred nanometers from the microdisk circumference with epoxy microjoints to SiN_x supports. (b) Side-view SEM image of a 9 μm diameter mircodisk. (c) FEM calculated field distribution ($|E|^2$) of a $m = 50$, $p = 1$, TE-like mode of the microdisk in (b). (d) Schematic of the integrated hybrid atom-cavity chip.

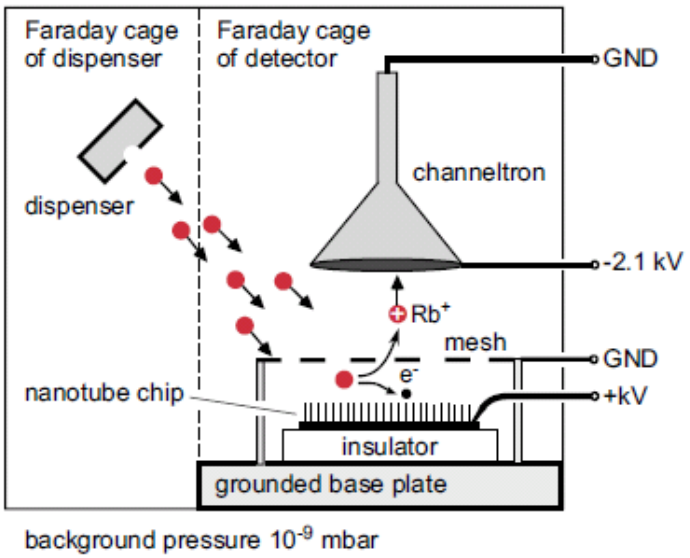
Novel atom detection
Another example of „where material engineering meets atom optics“

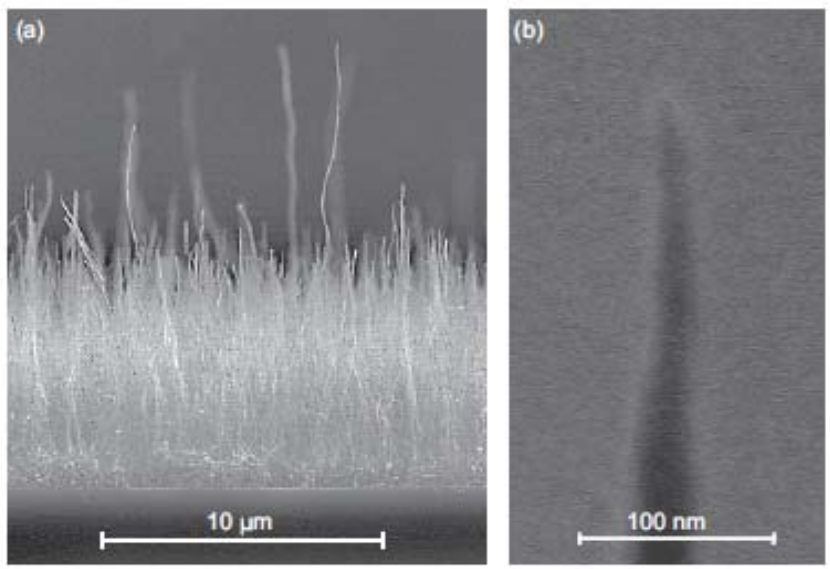
Integrated Atom Detector Based on Field Ionization near Carbon Nanotubes

B. Grüner,[1] M. Jag,[1] A. Stibor,[1] G. Visanescu,[1] M. Häffner,[1] D. Kern,[1] A. Günther,[1,*] and J. Fortágh[1]

[1] *CQ Center for Collective Quantum Phenomena and their Applications, Eberhard-Karls-Universität Tübingen, Auf der Morgenstelle 14, D-72076 Tübingen, Germany*

(Dated: November 9, 2009)

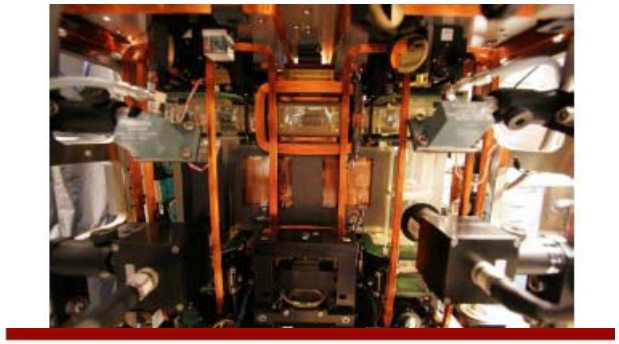


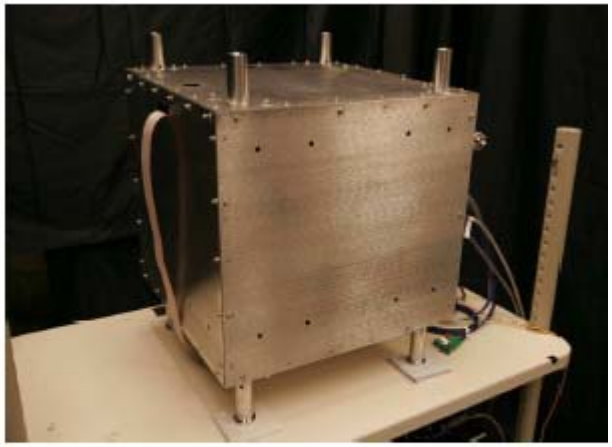


Always note the alternatives to AtomChips

Miniaturization of non guided atoms

All in a box, Mark Kasevich





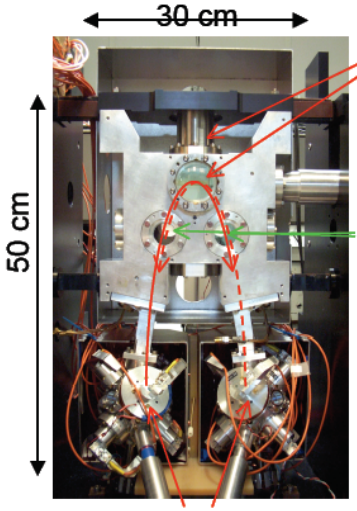
Multi-function sensor measures gravity gradient, rotation and linear acceleration along a single input axis.

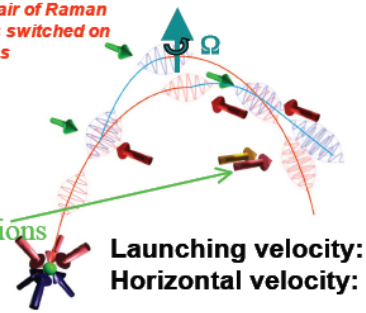
e.g. single path vs. multi path interferometers

A compact dual atom interferometer gyroscope based on laser-cooled rubidium

T. Müller[a], M. Gilowski[b], M. Zaiser, P. Berg, Ch. Schubert, T. Wendrich, W. Ertmer, and E.M. Rasel

Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany





Launching velocity: 2.4 m.s^{-1}
Horizontal velocity: 0.33 m.s^{-1}

Maximum interaction time : 90 ms
3 rotation axes
2 acceleration axes
Cycling frequency 2Hz

Expected sensitivity (10^6 at):
- gyroscope : 4 10^{-8} rad.s^{-1}.Hz$^{-1/2}$
- accelerometer : 3 10^{-8} m.s^{-2}.Hz$^{-1/2}$

Hot atoms: clocks, magnetic sensors, gyros

TOPICAL REVIEW

The development of micro-gyroscope technology

Kai Liu, Weiping Zhang, Wenyuan Chen, Kai Li, Fuyan Dai, Feng Cui, Xiaosheng Wu, Gaoyin Ma and Qijun Xiao

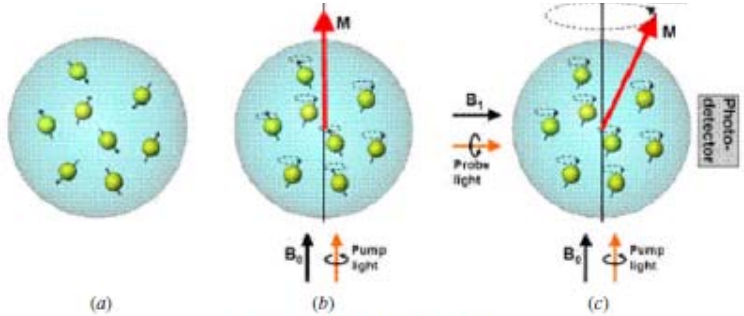


Figure 26. NMRG principle.

PRL 95, 230801 (2005) PHYSICAL REVIEW LETTERS week ending 2 DECEMBER 2005

Nuclear Spin Gyroscope Based on an Atomic Comagnetometer

T. W. Kornack, R. K. Ghosh, and M. V. Romalis
Department of Physics, Princeton University, Princeton, New Jersey 08550 USA
(Received 6 May 2005; published 29 November 2005)

Also Kitching

Real solid state

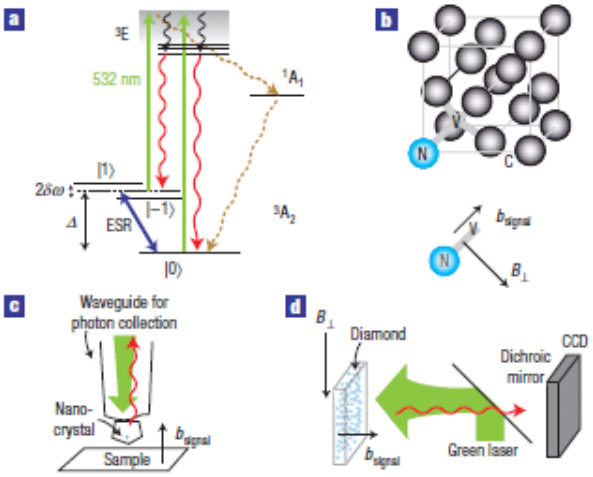
ARTICLES

High-sensitivity diamond magnetometer with nanoscale resolution

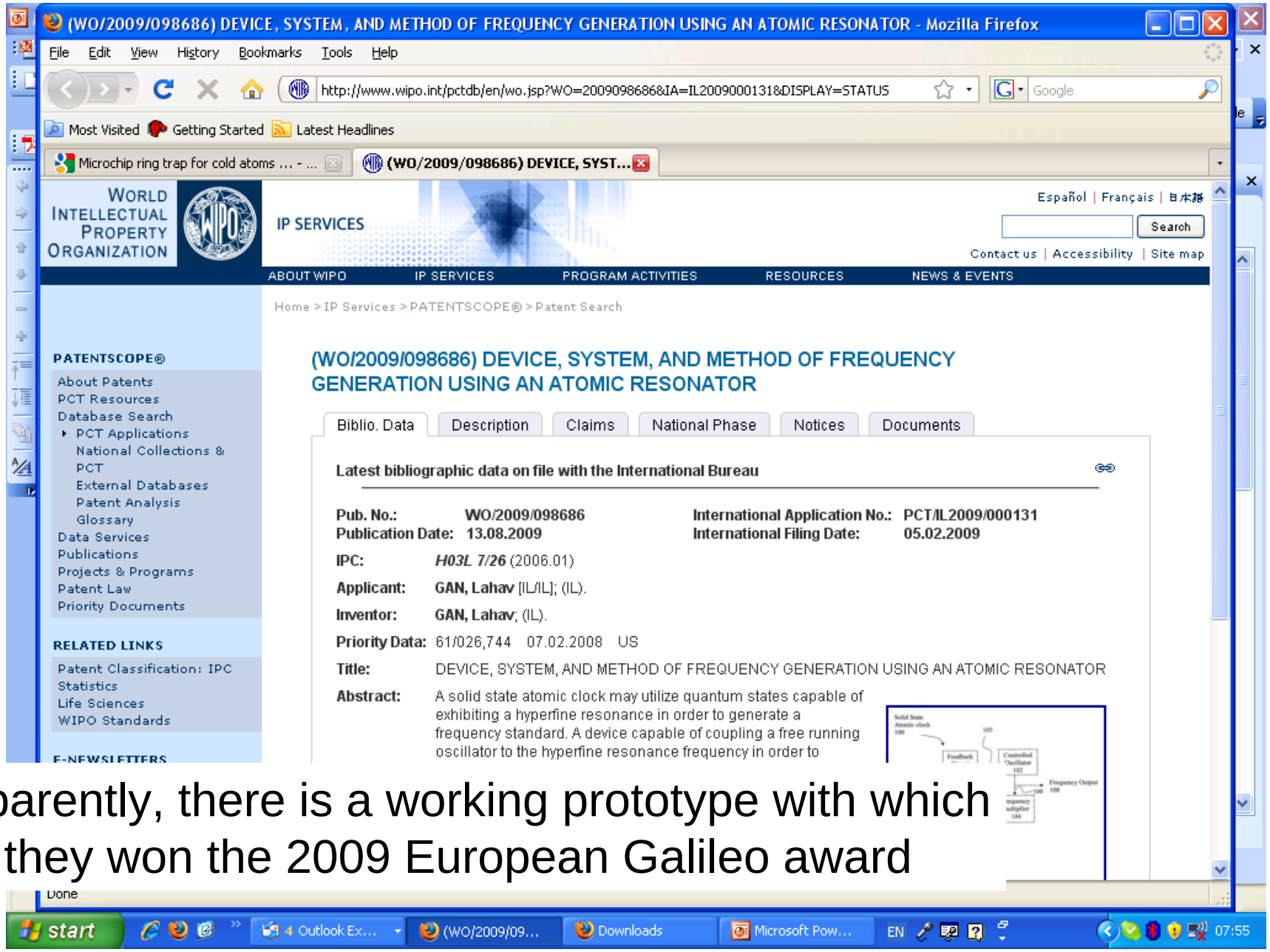
J. M. TAYLOR[1]*, P. CAPPELLARO[2,3]*, L. CHILDRESS[2,4], L. JIANG[2], D. BUDKER[5], P. R. HEMMER[6], A. YACOBY[2], R. WALSWORTH[2,3] AND M. D. LUKIN[2,3]†

[1] Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
[2] Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
[3] Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138, USA
[4] Department of Physics, Bates College, Lewiston, Maine 04240, USA
[5] Department of Physics, University of California, Berkeley, California 94720, USA
[6] Department of Electrical and Computer Engineering, Texas A&M University, College Station, Texas 77843, USA
* These authors contributed equally to this work
† e-mail: lukin@physics.harvard.edu

Published online: 14 September 2008; doi:10.1038/nphys1075

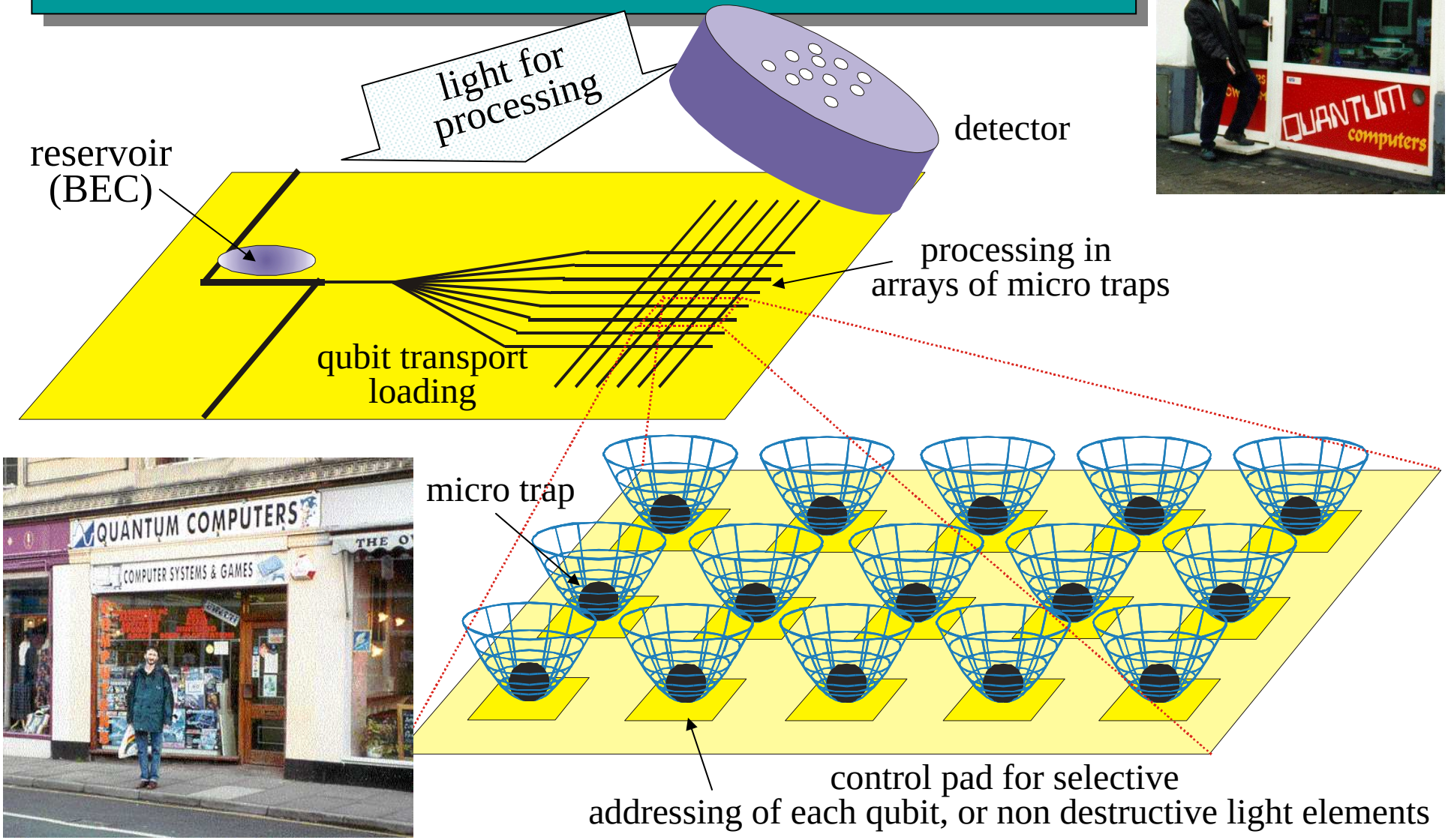


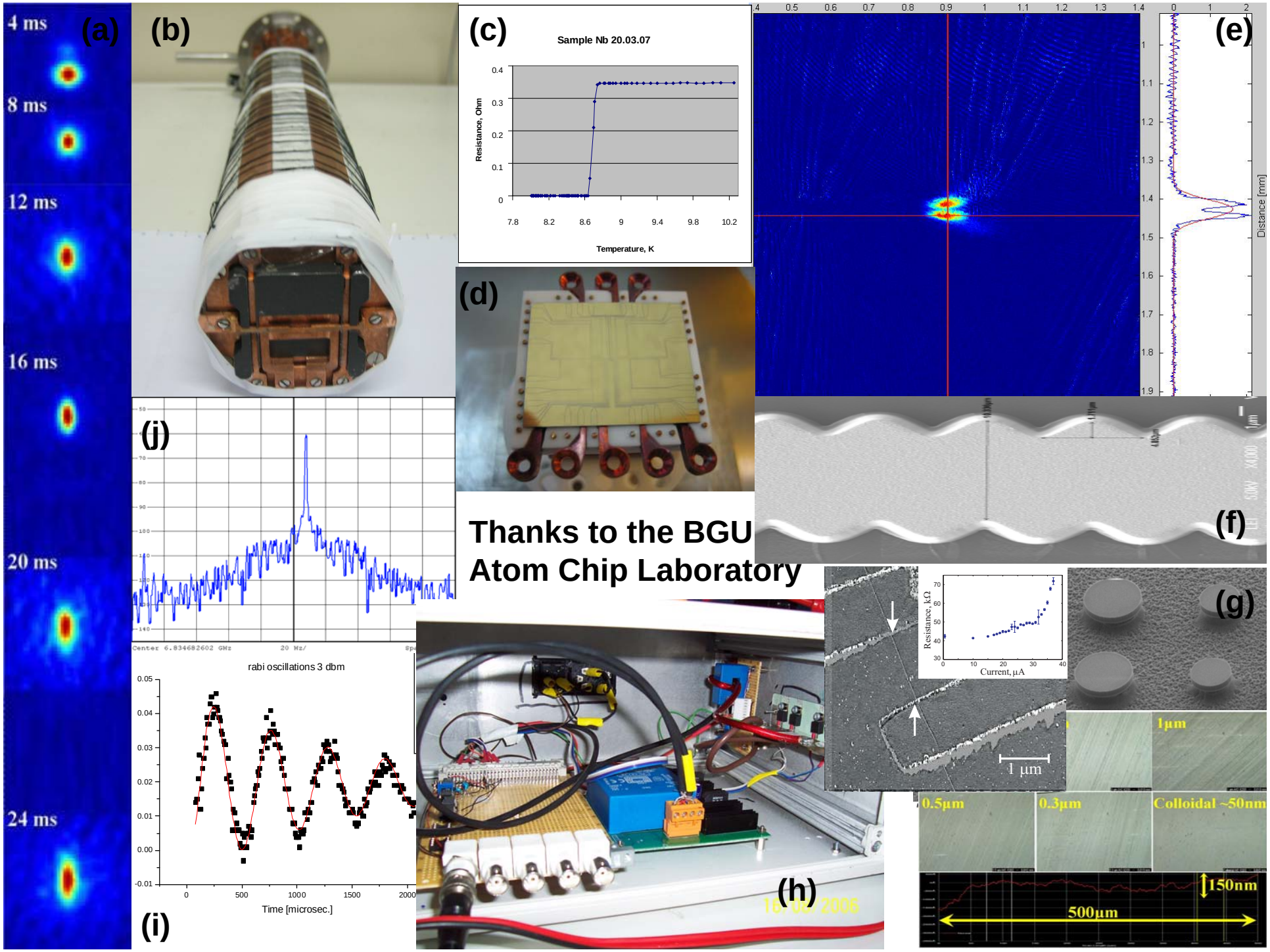
Israeli company named 4D, uses NV centers for a solid state atomic clock:

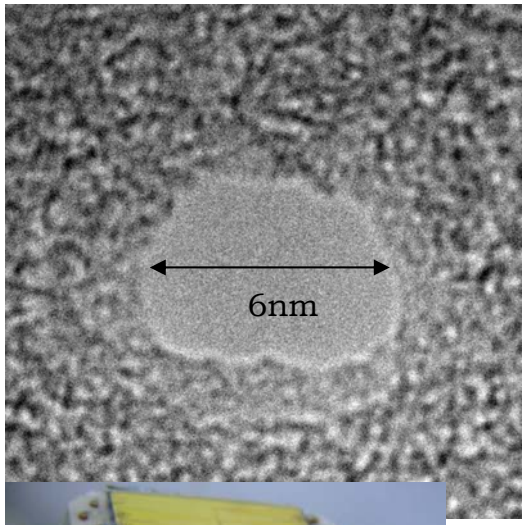


Apparently, there is a working prototype with which they won the 2009 European Galileo award

Take home message: A lot of great physics, however
Ultimate atom chip...
is not in the labs or the shops just yet,
But recent 10 years give room for optimism

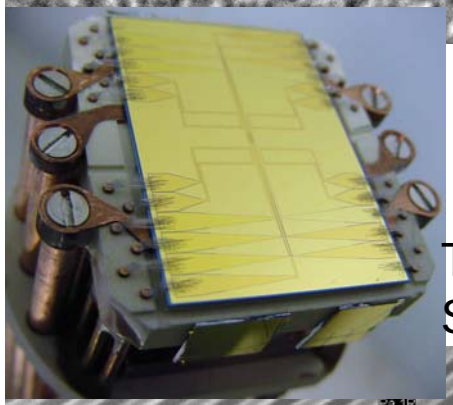



(a)
4 ms
8 ms
12 ms
16 ms
20 ms
24 ms
(b)
(c)
Sample Nb 20.03.07
Resistance, Ohm
Temperature, K
(d)
(e)
Distance [mm]
(f)
(g)
1 µm
1µm
0.5µm
0.3µm
Colloidal ~50nm
150nm
500µm
Resistance, kΩ
Current, µA
(h)
(i)
rabi oscillations 3 dbm
Time [microsec.]
(j)
Thanks to the BGU
Atom Chip Laboratory



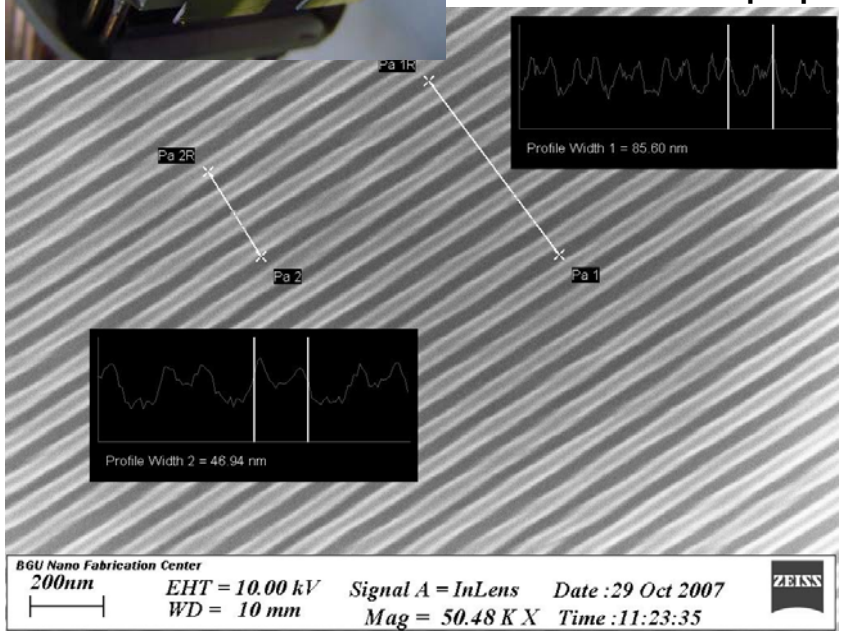
Our smallest structure to date
(a 6nm hole through a SiN membrane)

Thankyou also to the fab team!



The chip used in our Science 2008 paper

We go on hikes in the desert around our university and
learn fabrication from mother nature
…and you are welcome to join!



Our smallest periodical structure to date
(a 45nm wires)

Thanks for your attention!

Positions for PhD/Post-Docs
in theory and experiment