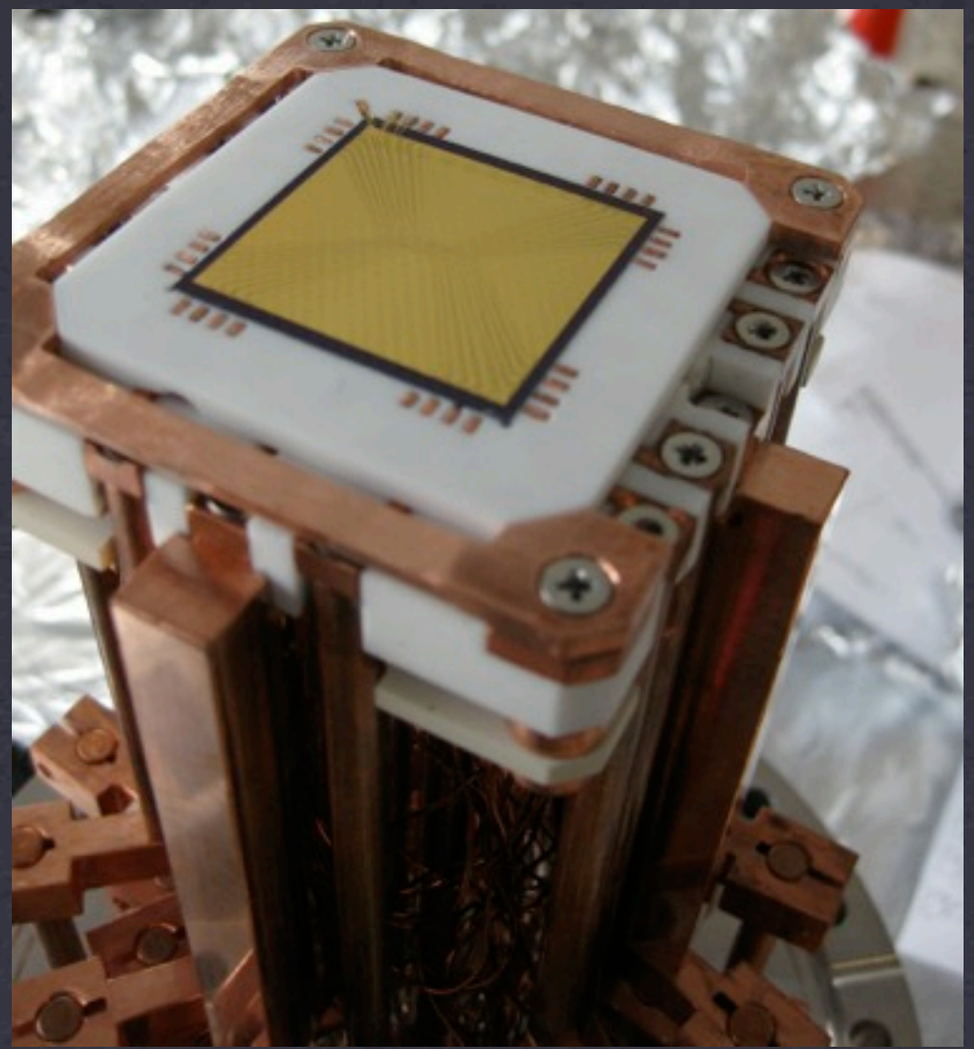
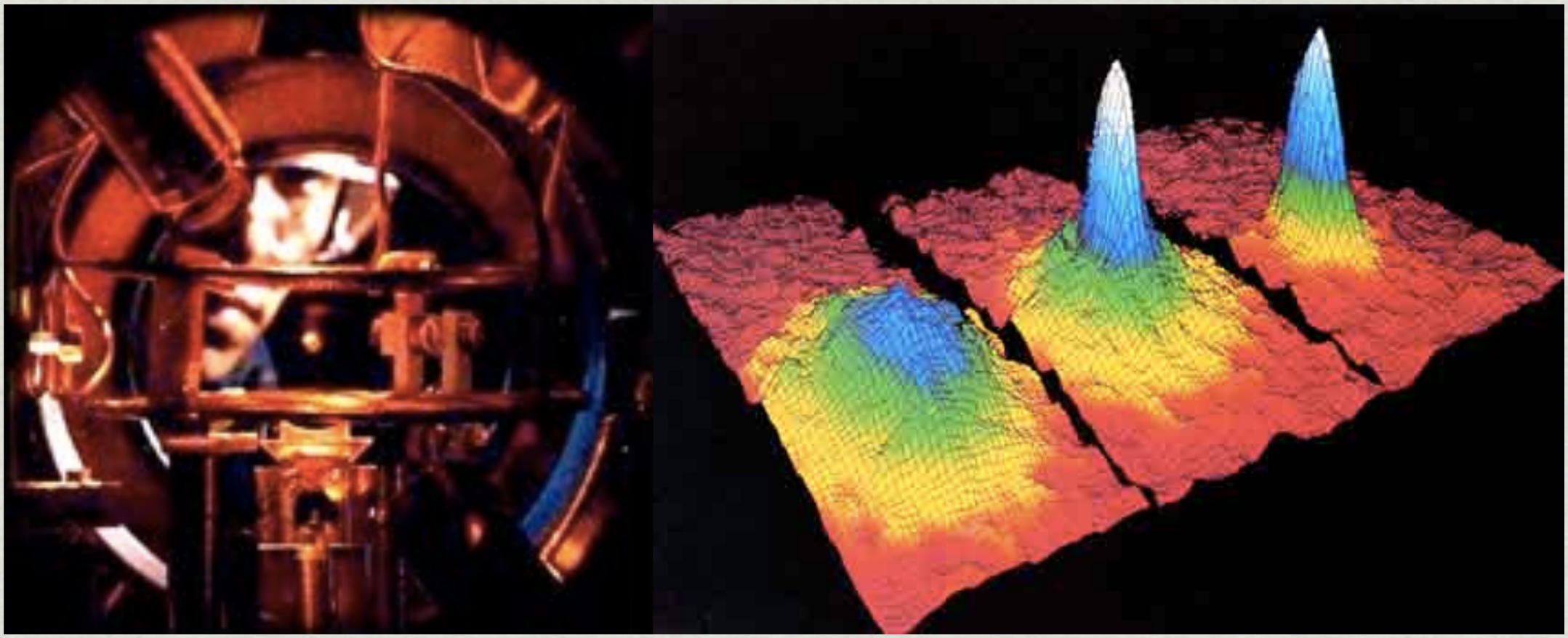
Atom chip: controlling quantum gases on the (sub)micron scale



PETER KRÜGER
MIDLANDS ULTRACOLD ATOM
RESEARCH CENTRE
UNIVERSITY OF NOTTINGHAM, UK

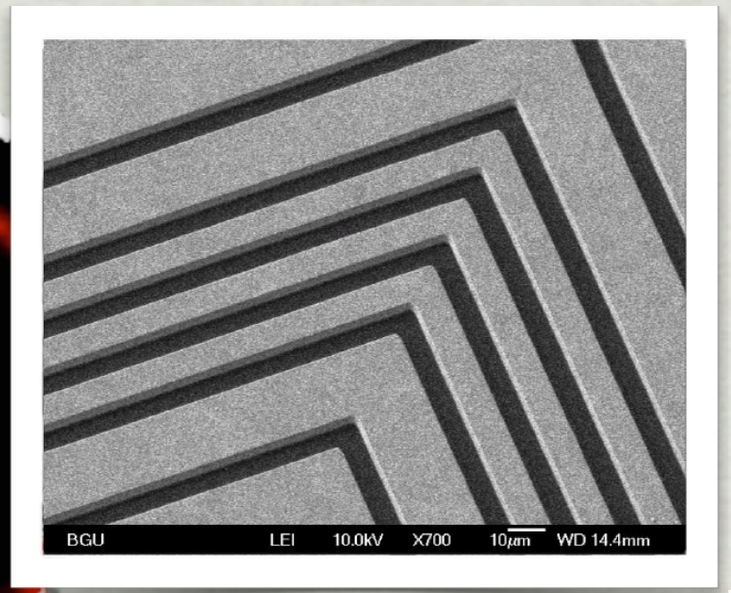
Quantum gases

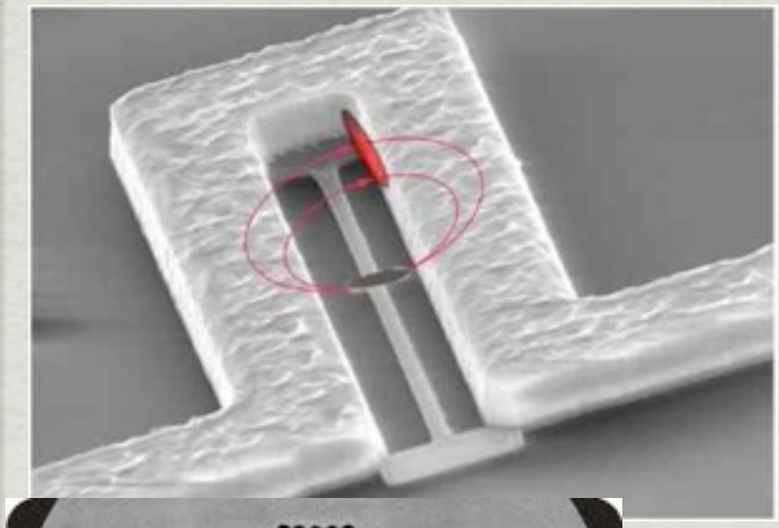


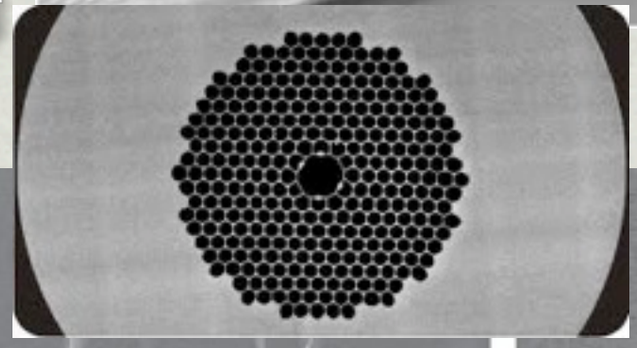
LASER COOLING, OPTICAL/MAGNETIC TRAPPING, EVAPORATIVE COOLING OF ALKALI AND OTHER ATOMS ARE NOW ESTABLISHED TECHNIQUES

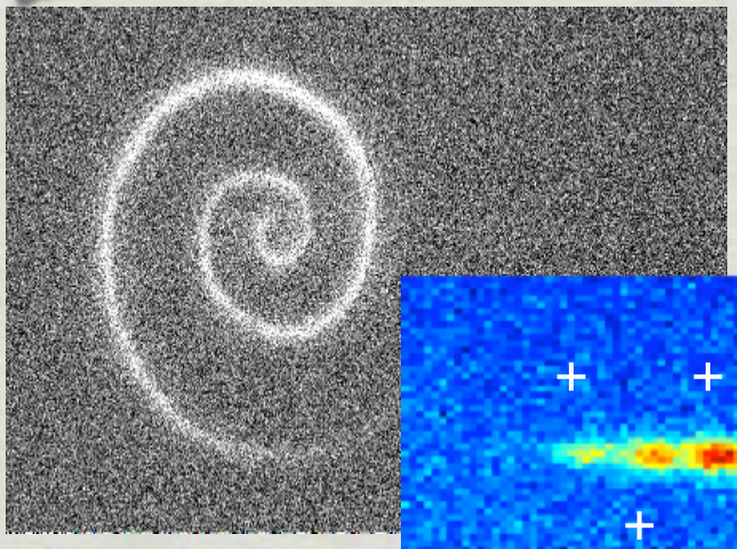
COLD (DEGENERATE) GASES FUNCTION AS HIGHLY CONTROLLED QUANTUM SYSTEM

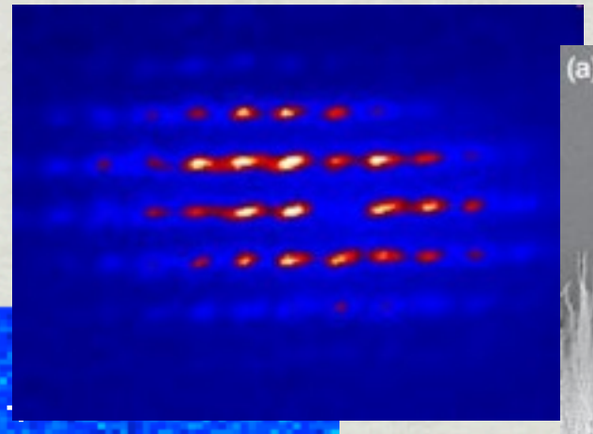
Atom chips

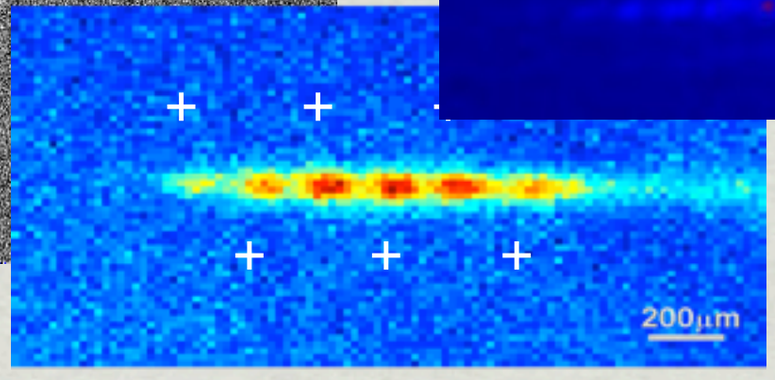


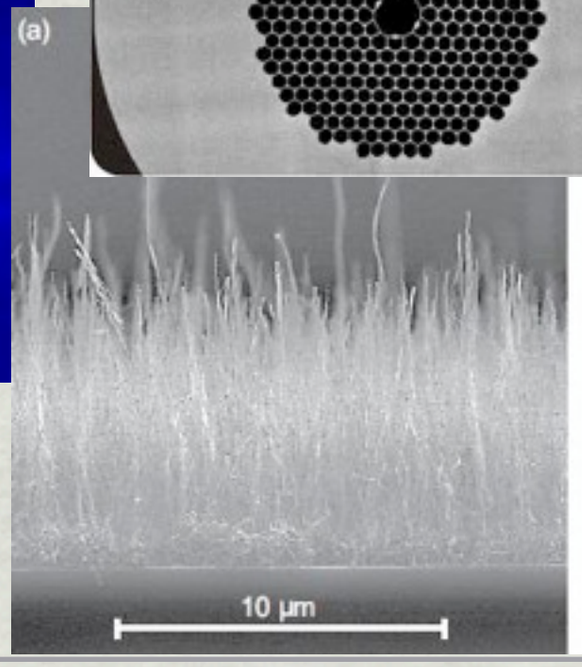




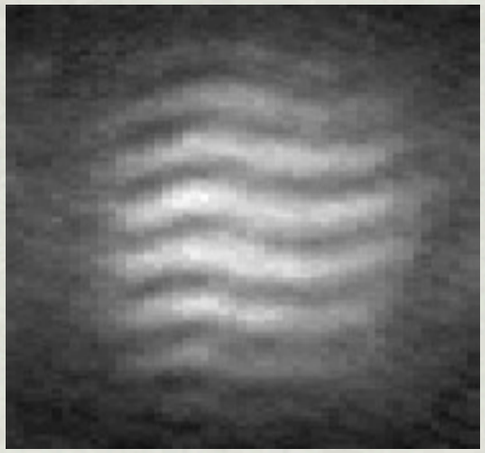




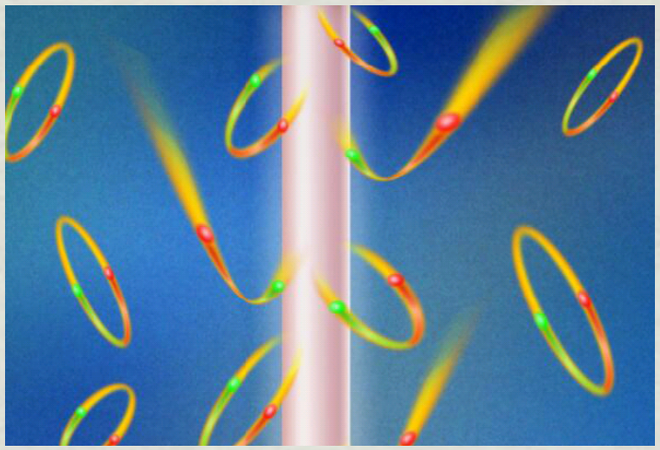




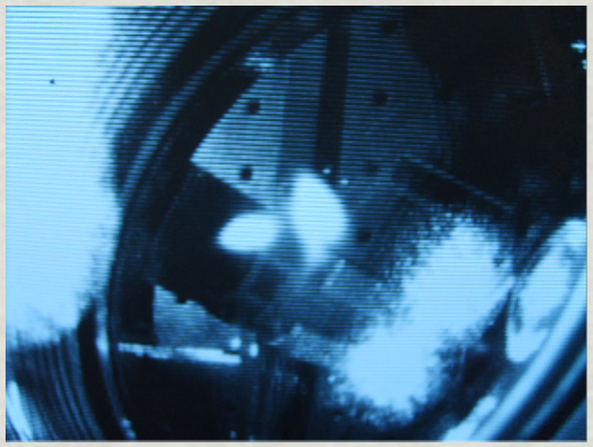
Activities



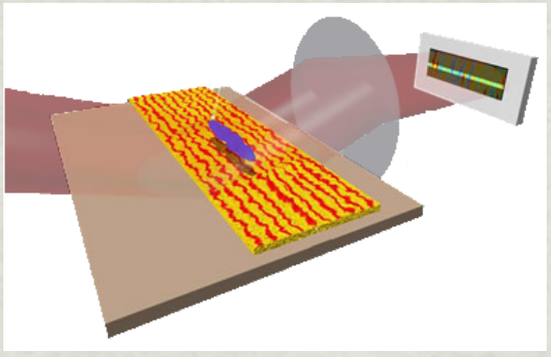
Non-equilibrium phenomenta



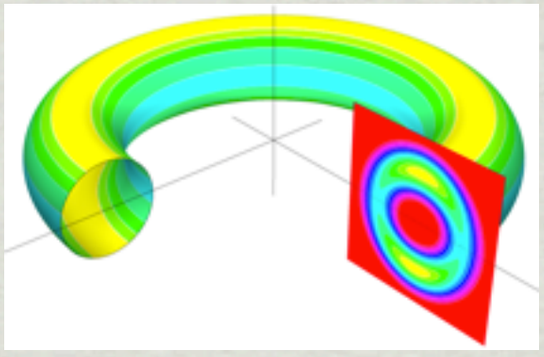
Analog models/ quantum simulators



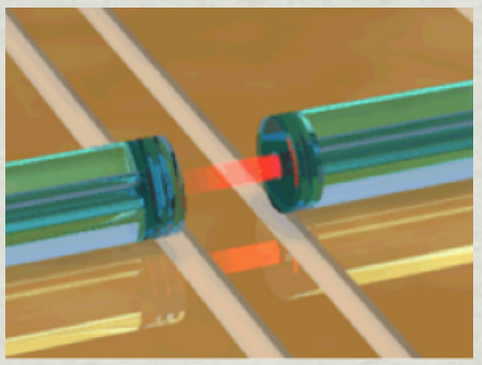
Bose-Fermi mixtures (L. Hackermuller)



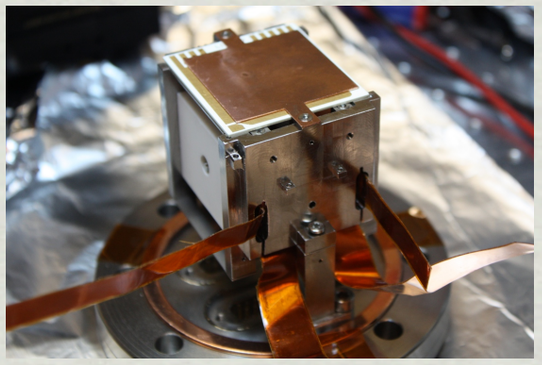
Atom-surface interfaces



Rotation sensors (T. Fernholz)



Atom-light inter-faces (T. Ferholz)

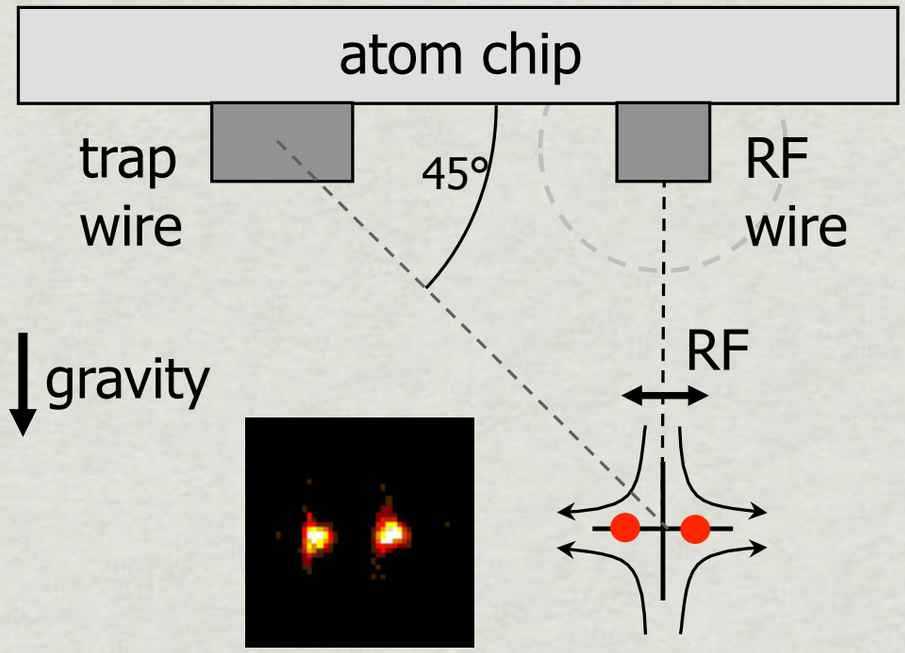


Portable devices

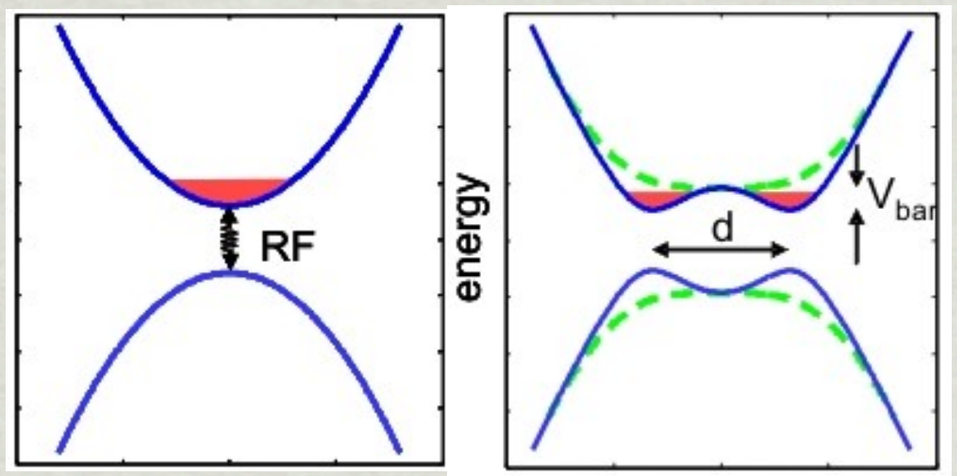
Outline

- Atom chip applications
- Shaping quantum gas environments on a (sub)micron scale
- Supersonic motion
- Bosonic transport
- Challenges on the way to submicron trapping
- Approach to overcome limitations

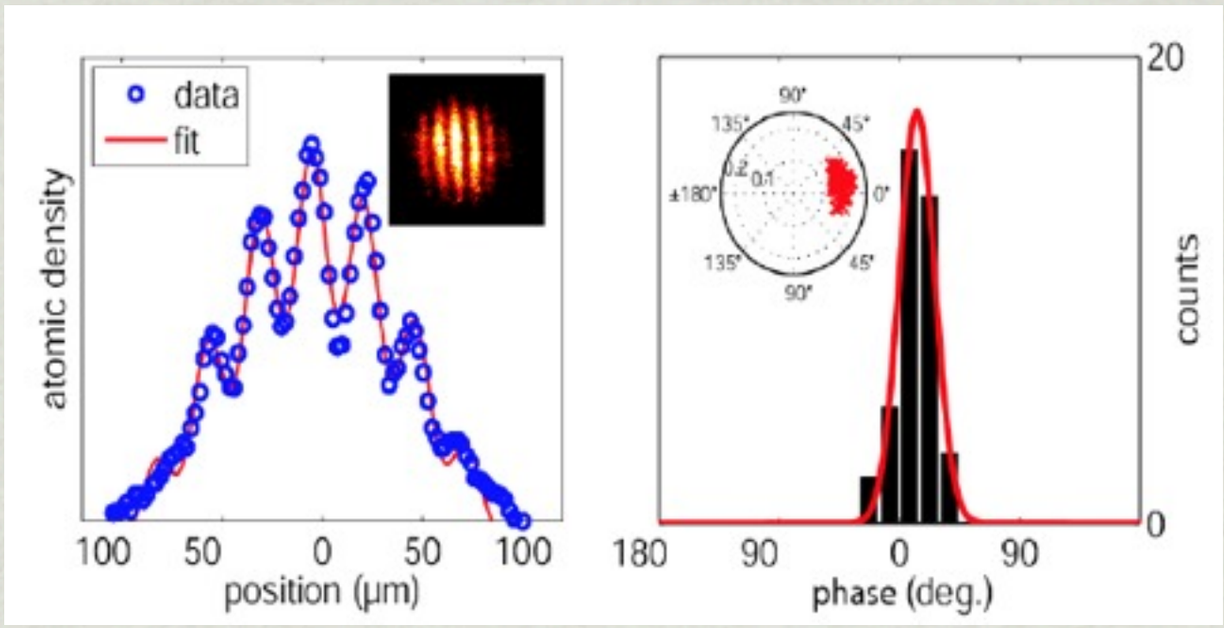
Applications of atom chips: Interferometry



in situ absorption image

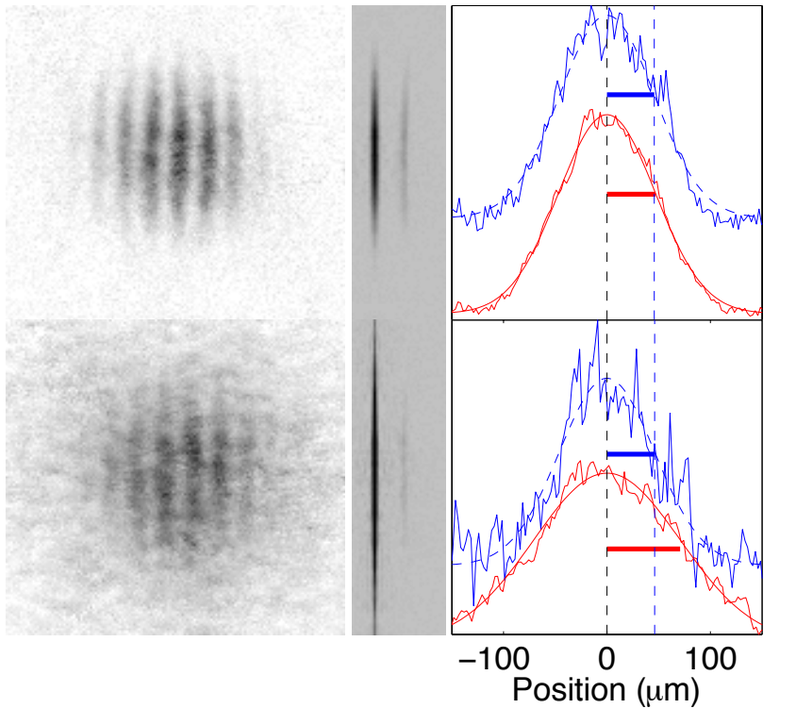


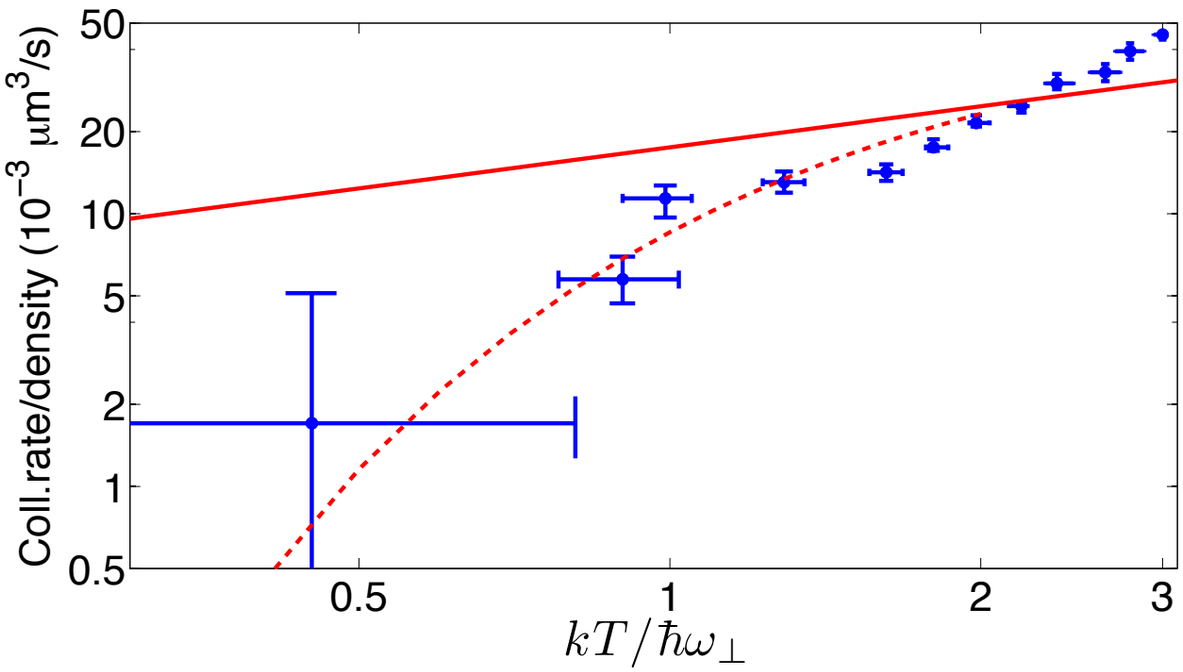
SCHUMM ET AL, NATURE PHYS. 2005



- STABLE FRINGES SHOW THAT SPLITTING IS COHERENT
- COHERENCE PROPERTIES AND EVOLUTION OF 1D GAS
- DIFFERENTIAL FORCES CAN BE MEASURED

Applications of atom chips: 1d dynamics



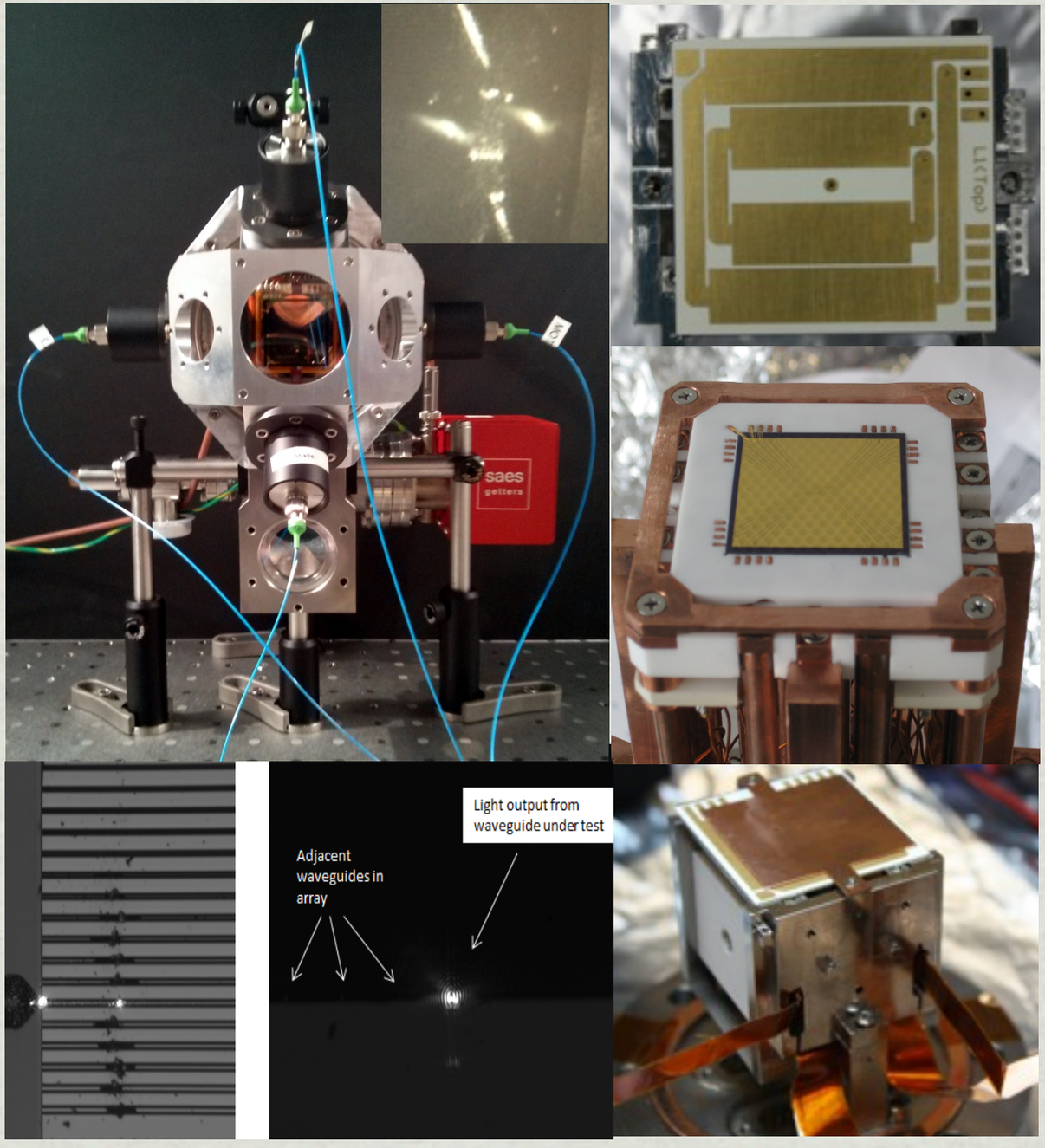


INTERFERENCE ALLOWS FOR SEPARATION OF CONDENSATE FRACTION IN 1D

DECREASED EFFICIENCY OF THERMALIZING COLLISIONS CAN BE OBSERVED

PK AT EL, PRL 2010

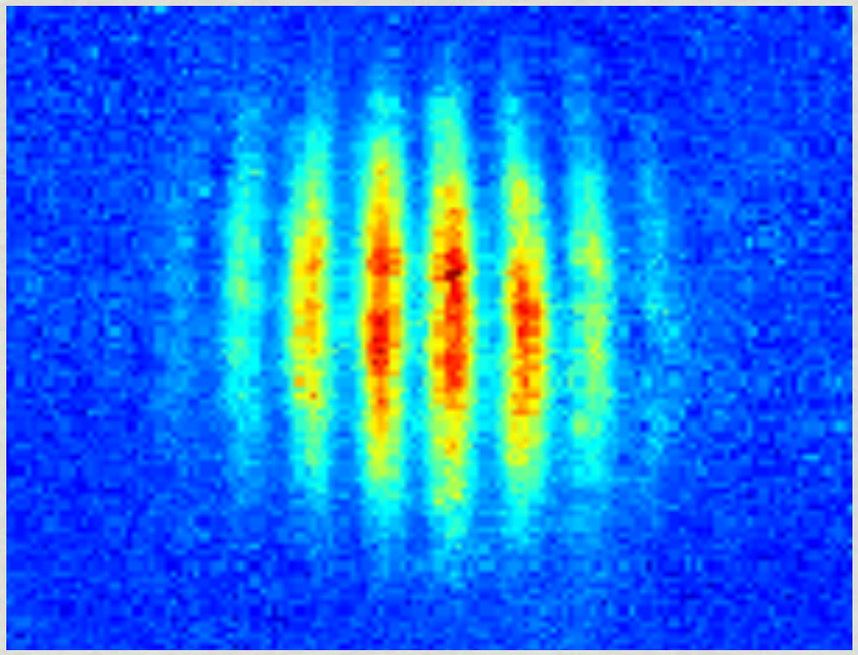
Applications of atom chips: Portable devices



- Atom source for integrated sensor device (total volume < 100 l)
- Chip in combination with mm-cm sized mini-traps (not micro)
- EU-collaboration iSense

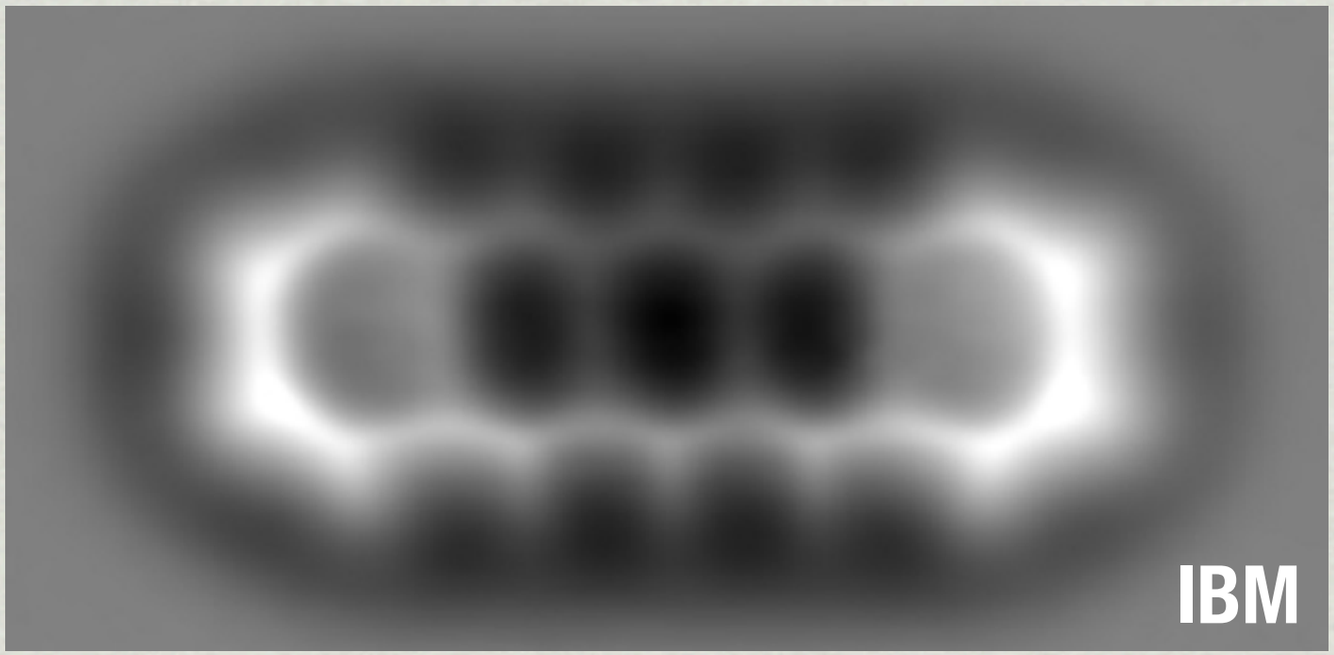
PICCARDO-SELG ET AL., IN PREP 2014

Atoms & surfaces



COLD ATOMS IN VACUUM

Isolated (closed) quantum system, **cm** away from solids



PLACING ATOMS AND BUILDING MOLECULES ON SURFACES

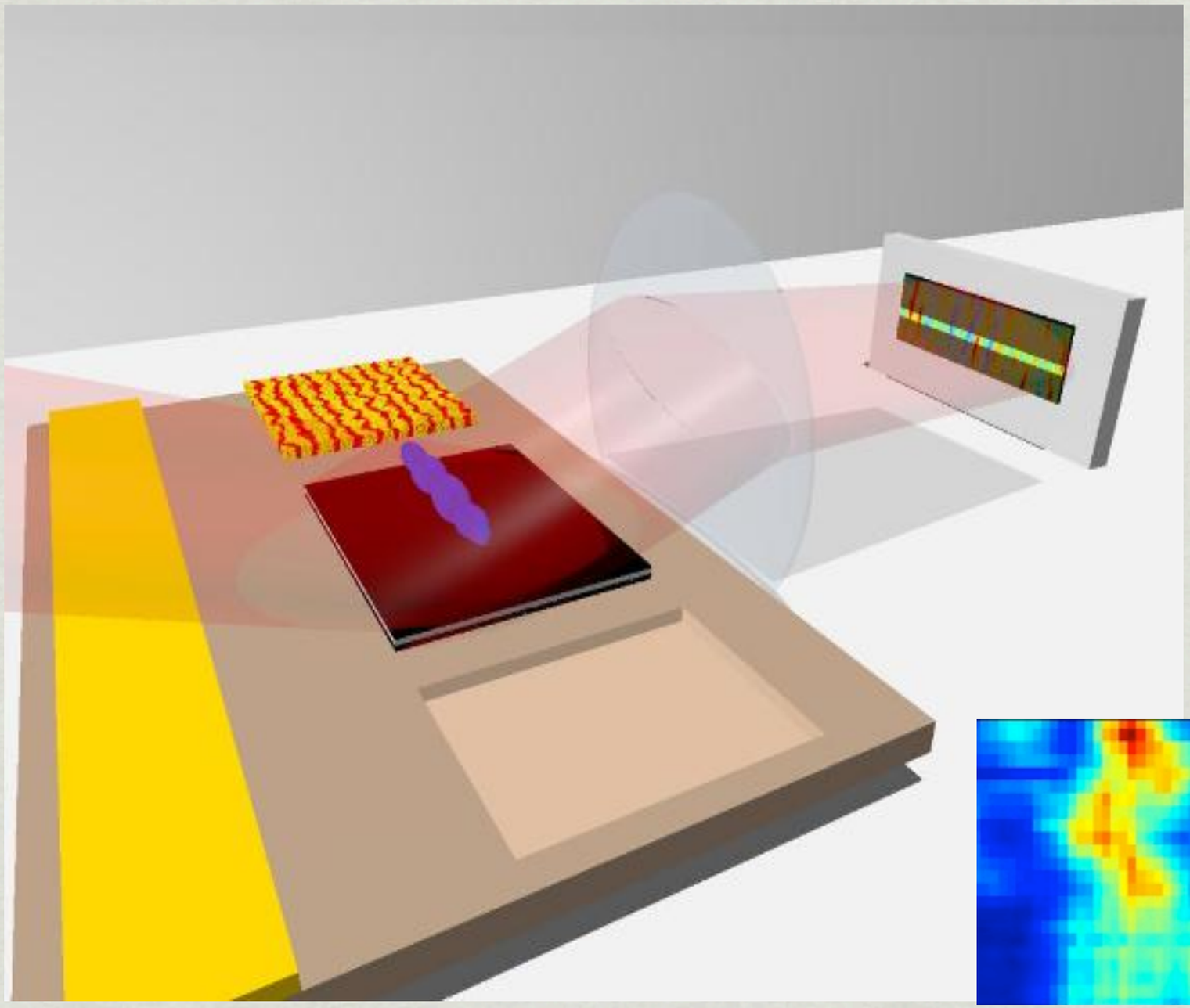
Surface-mounted atoms become part of solid with intimate coupling on **Angstrom** scale

WHAT ABOUT THE GAP IN BETWEEN?

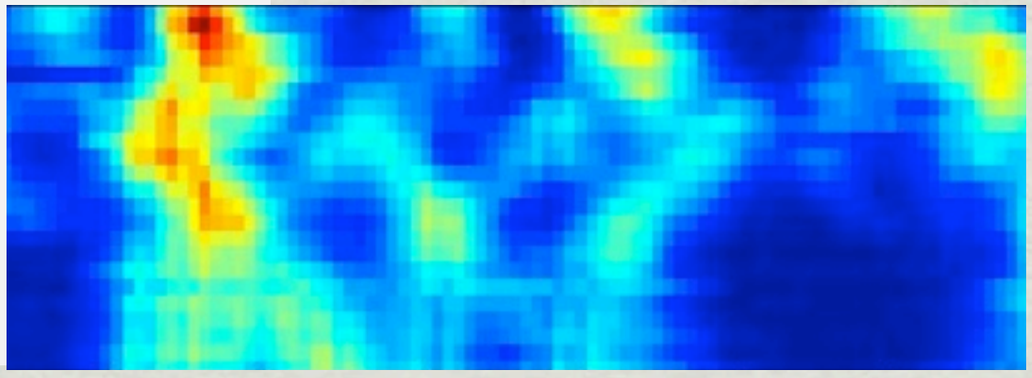
Closer surface approach

- Quantum gases can be structured with high spatial (and temporal) resolution; spatial frequency k is damped exponentially with char. length 1/k
- Small defects, rough disorder, proximity effects
- High resolution, high sensitivity microscopy
- Backaction onto surface: detectors, quantum interfaces

BEC microscope

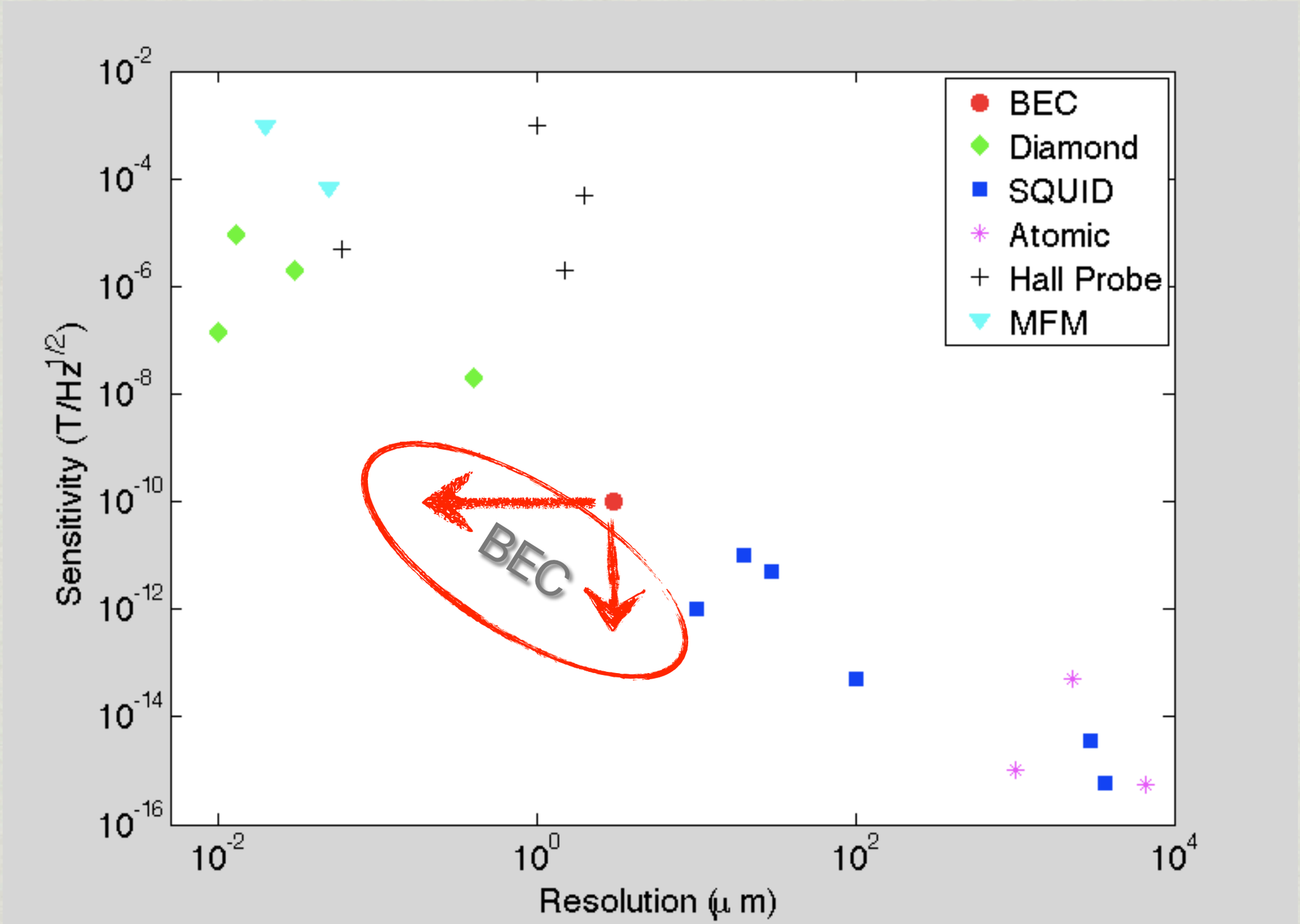


ATOMIC PROBE PROVIDES UNIQUE COMBINATION OF HIGH SENSITIVITY (NANOTESLA) AND HIGH RESOLUTION (MICRONS)



WILDERMUTH ET AL, NATURE 2005

Magnetic sensing

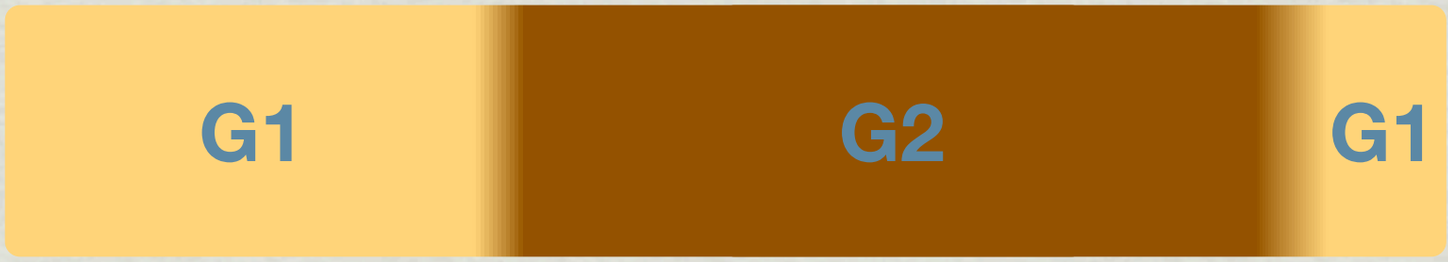


BEC sensor

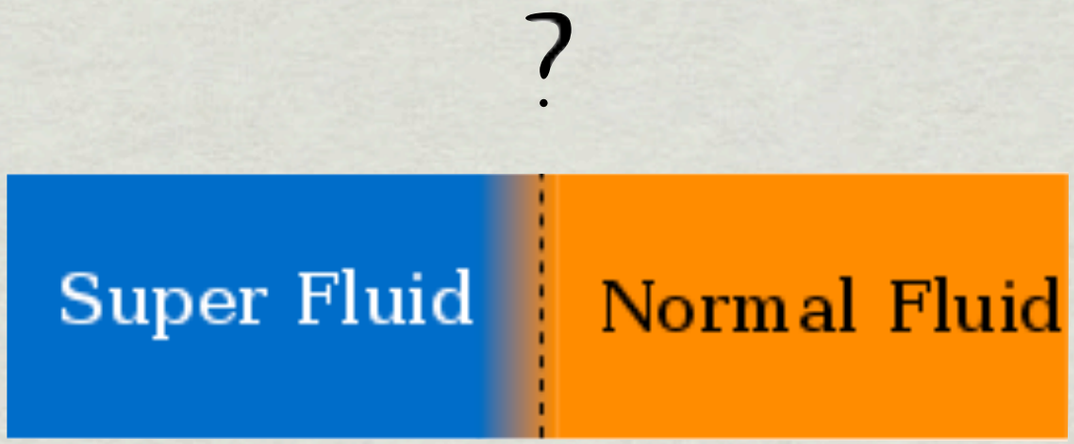
- Single shot image (~10us) contains large field-of-view (>100 um) 1d information
- Resolution in scanning direction given by precisely controllable position and small size (< 100nm) of 1d qBEC
- Good for snapshots of dynamic processes with high resolution & sensitivity over large fields-of-view

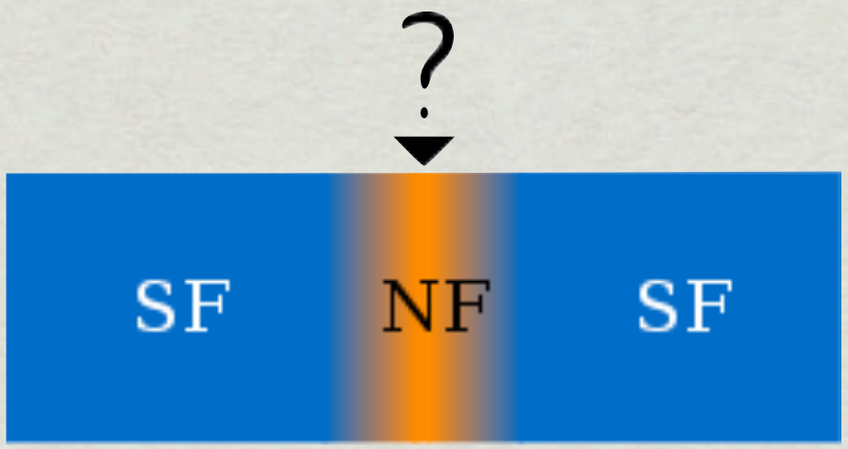
Inhomogeneous interactions

INTER-ATOMIC INTERACTIONS CONTROLLED BY MAGNETIC FIELDS (FESHBACH RESONANCES)



EXAMPLE: STEPS IN THE COUPLING CONSTANT





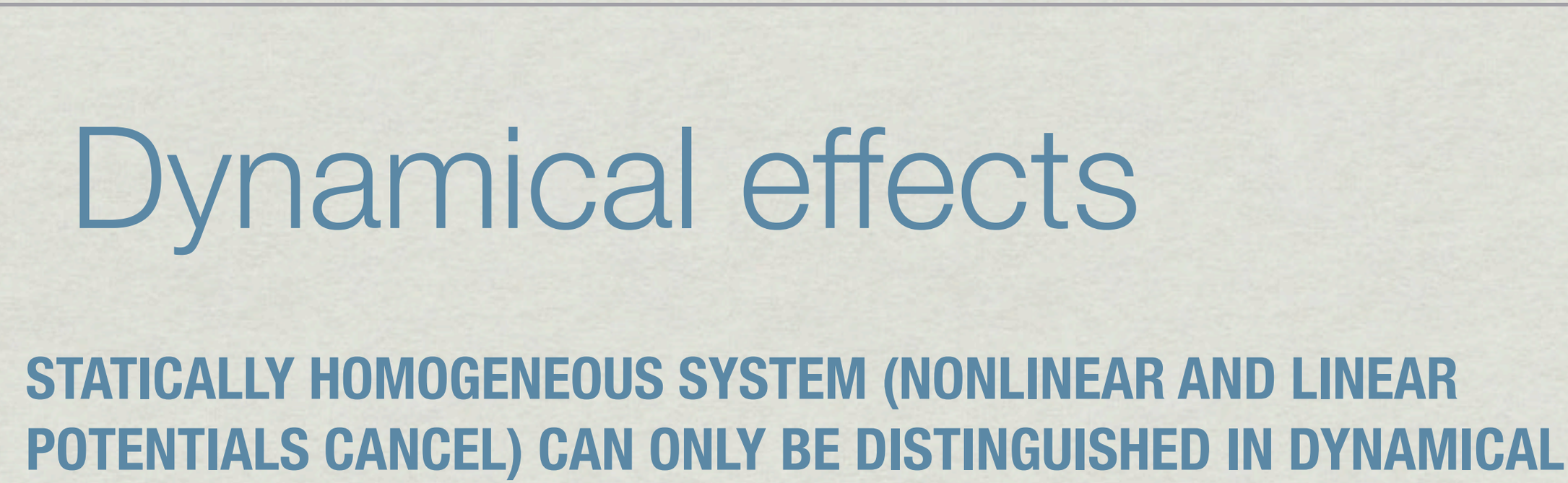
TRANSITION TEMPERATURE TO BEC DEPENDS ON INTERACTIONS

$$T_c^1 < T < T_c^2$$

Dynamical effects

STATICALLY HOMOGENEOUS SYSTEM (NONLINEAR AND LINEAR POTENTIALS CANCEL) CAN ONLY BE DISTINGUISHED IN DYNAMICAL SITUATIONS

NUMERICAL EXPERIMENT: DRAGGING A DEFECT THROUGH A GAS

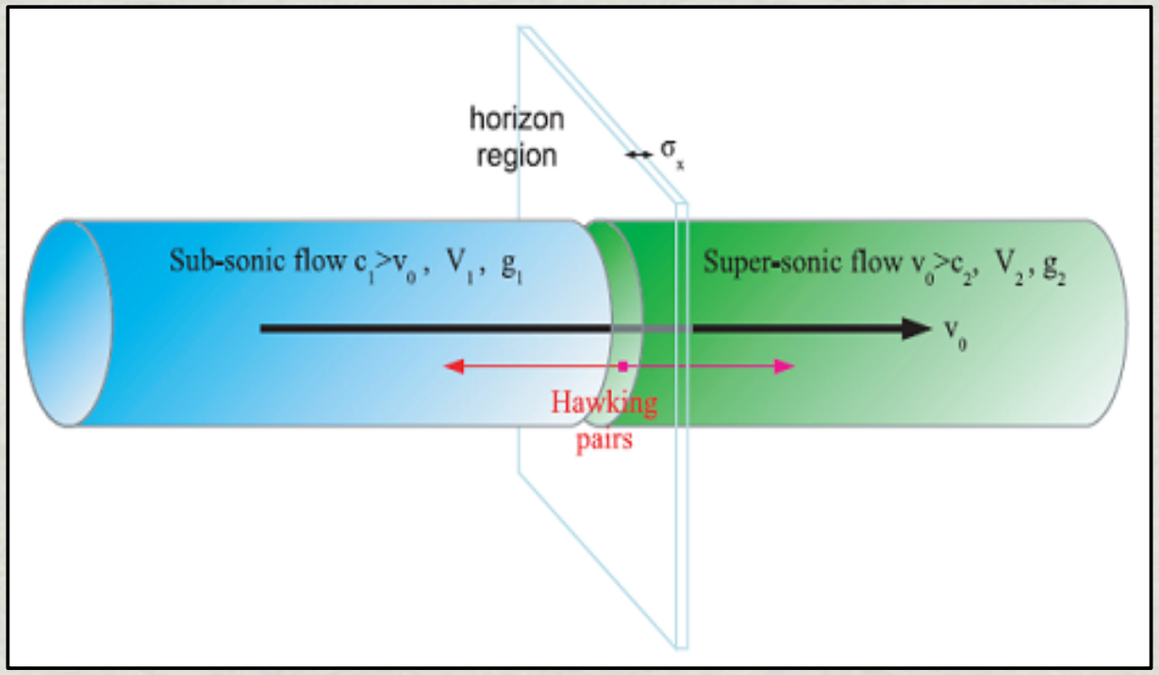


WITH STEP IN NONLINEARITY

WITHOUT STEP

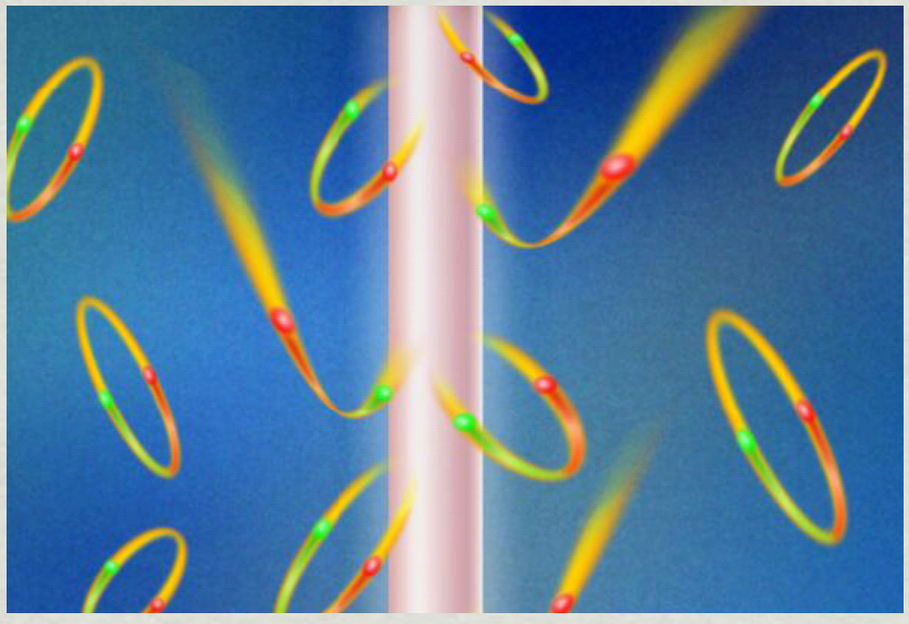
PORTER ET AL, PRA 2013

Dynamical effects



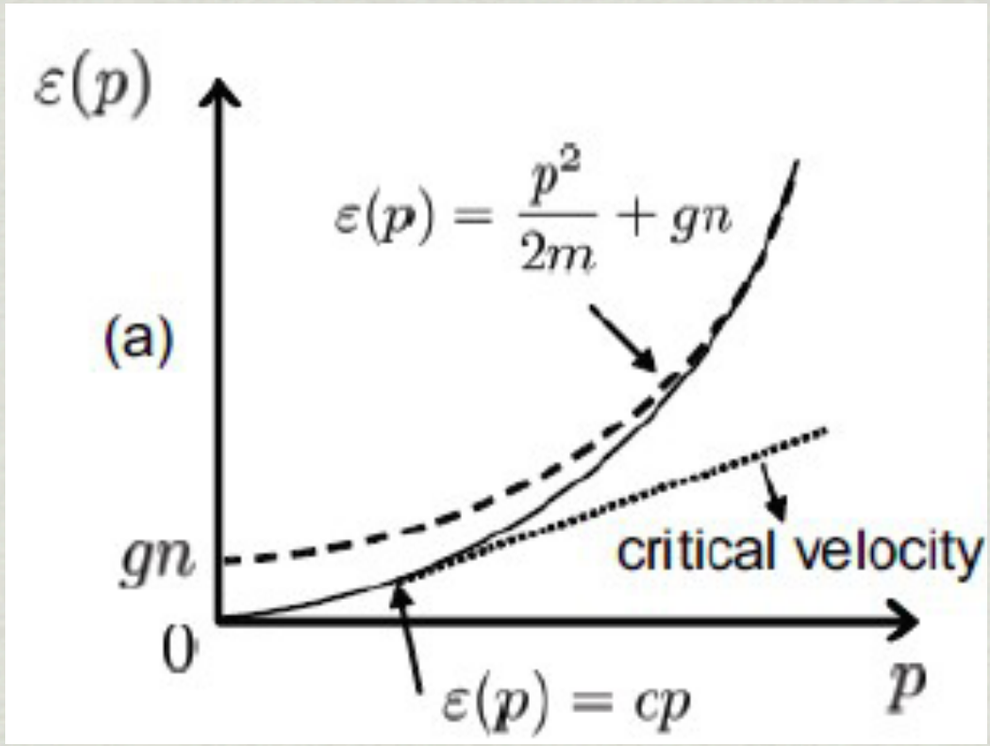
CONSTANT VELOCITY FLOW IN A POTENTIAL TUBE WITH INHOMOGENEOUS SPEED OF SOUND

PHONON PAIR PRODUCTION AT BOUNDARY ANALOGOUS TO HAWKING RADIATION EMERGING FROM BLACK HOLE EVENT HORIZON



Landau criterion

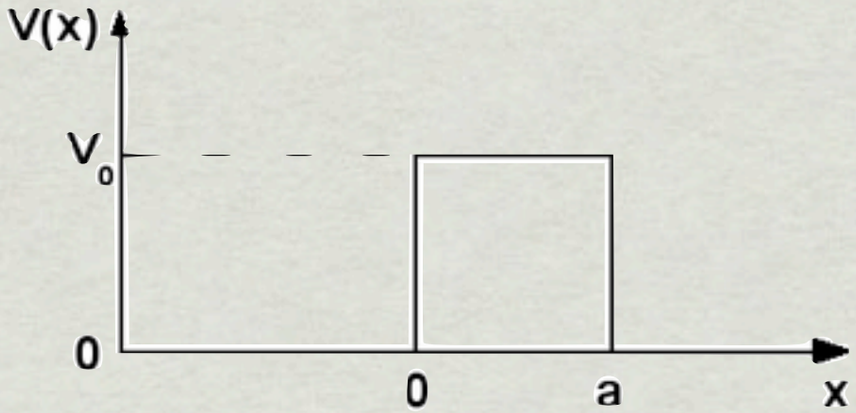
$$v_c = \min_{\mathbf{p}} \frac{\epsilon(\mathbf{p})}{|\mathbf{p}|}$$

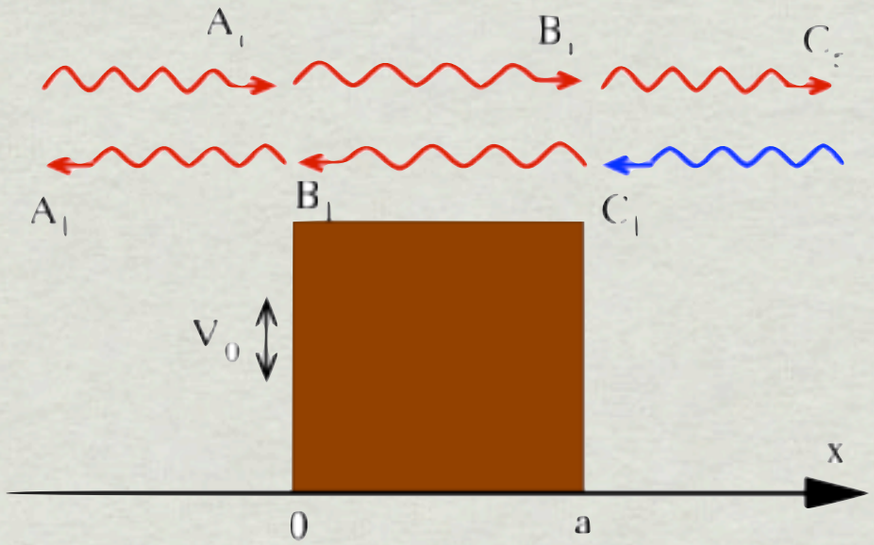


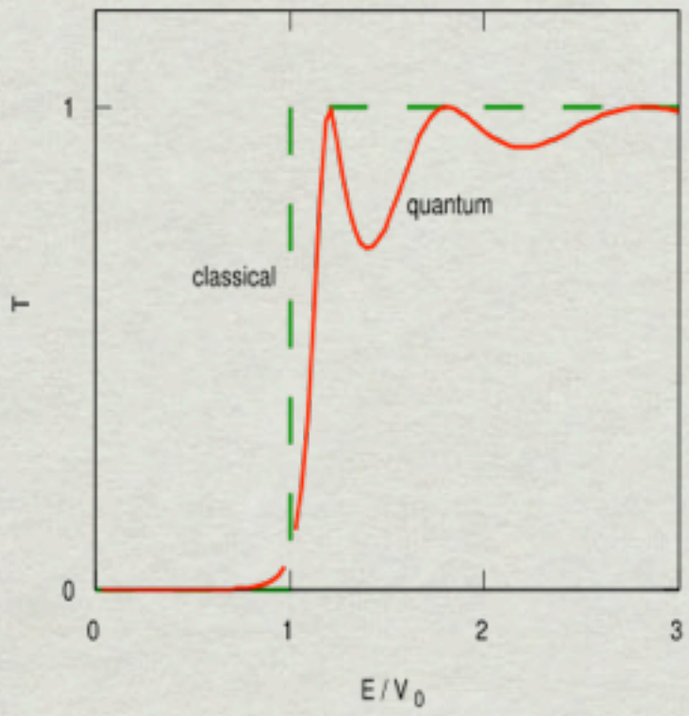
FOR BEC LANDAU CRITICAL VELOCITY IS SPEED OF SOUND

THIS TYPE OF *ENERGETIC* INSTABILITY ARISES WHEN EXCITATIONS BECOME ENERGETICALLY FAVORABLE, THE GROWTH WITH TIME IS *POLYNOMIAL*

Linear case: Ramsauer-Townsend Effect



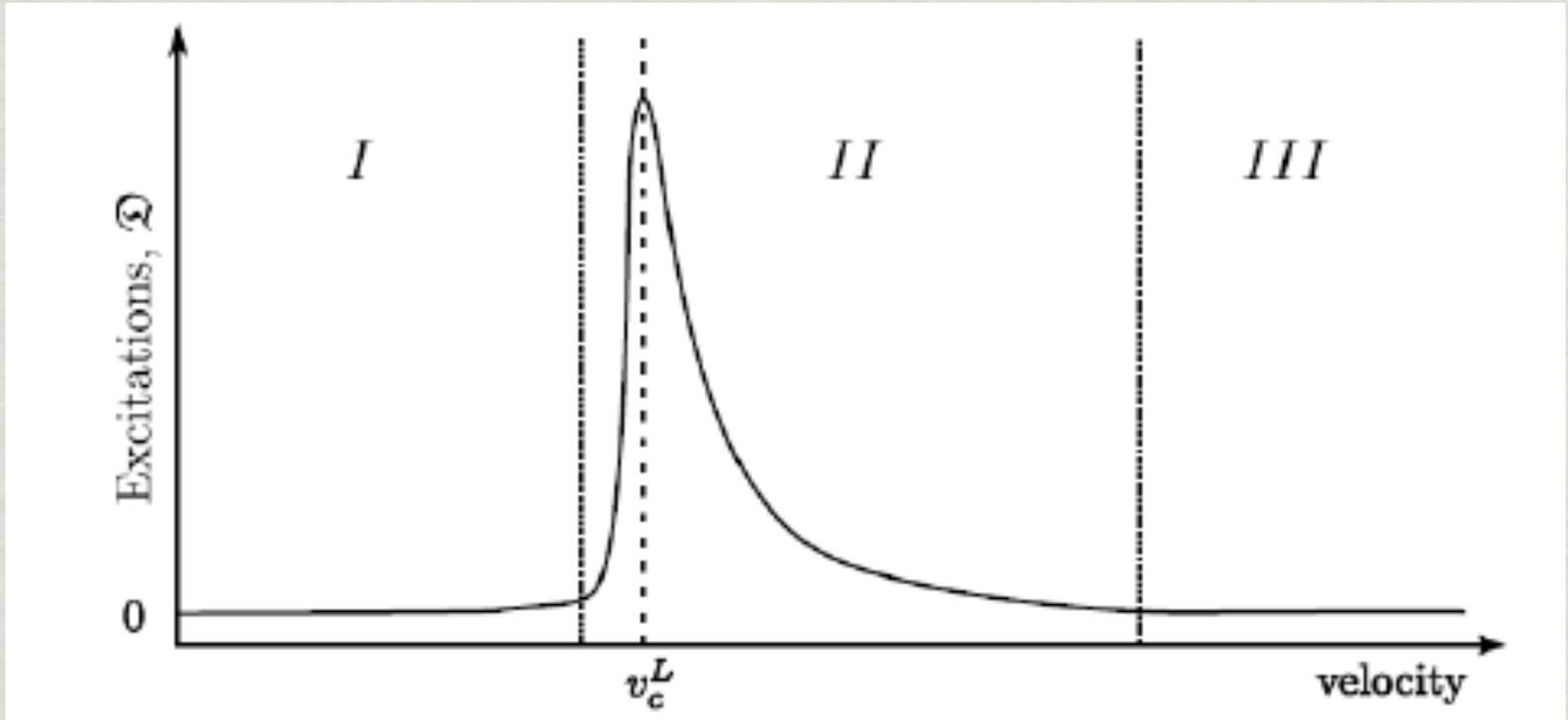




ARE THERE CONTINUATIONS OF BASIC QUANTUM EFFECT INTO NON-LINEAR REGIME ?

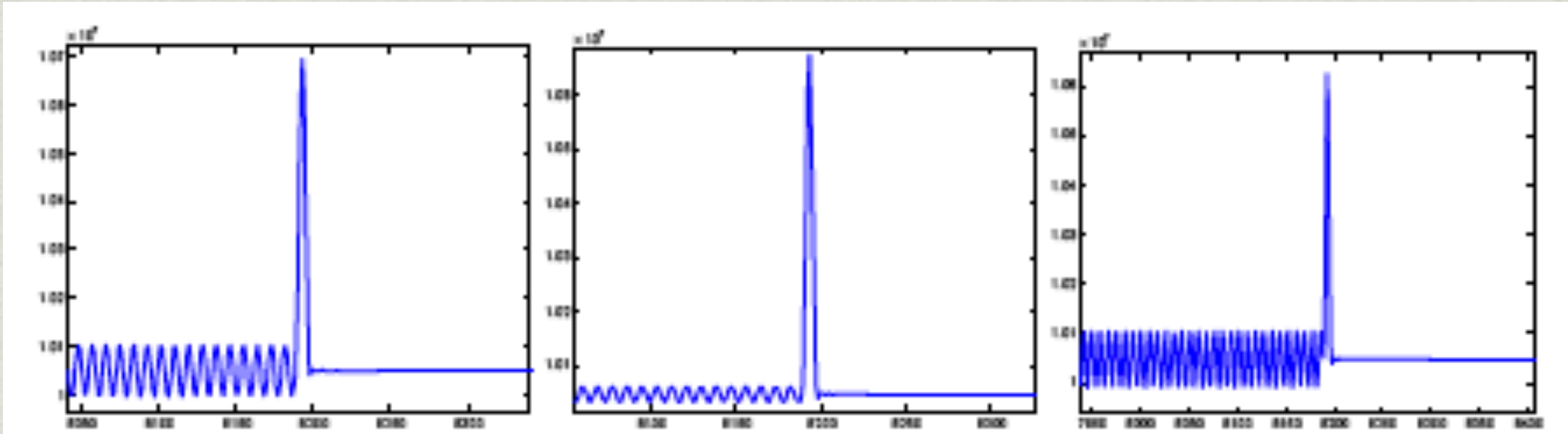
Interacting gas: Do resonances persist ?

CASE STUDY: (SLOWLY) RAISE RECTANGULAR BARRIER INTO FLOWING GAS



$$D = \int dx \left(|\psi(x,t)|^2 - |\psi_{v=0}|^2 \right)$$

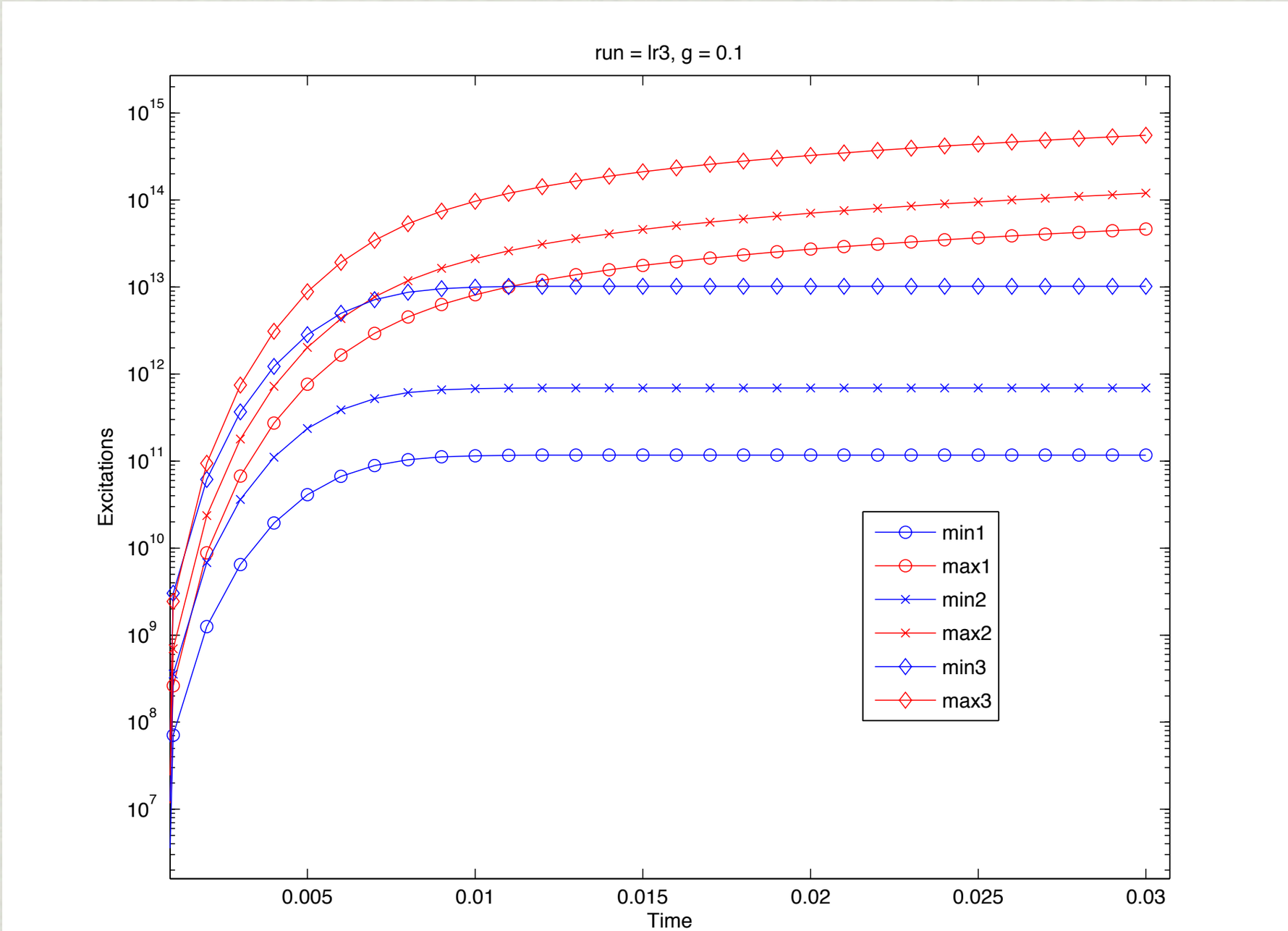
Numerical experiment



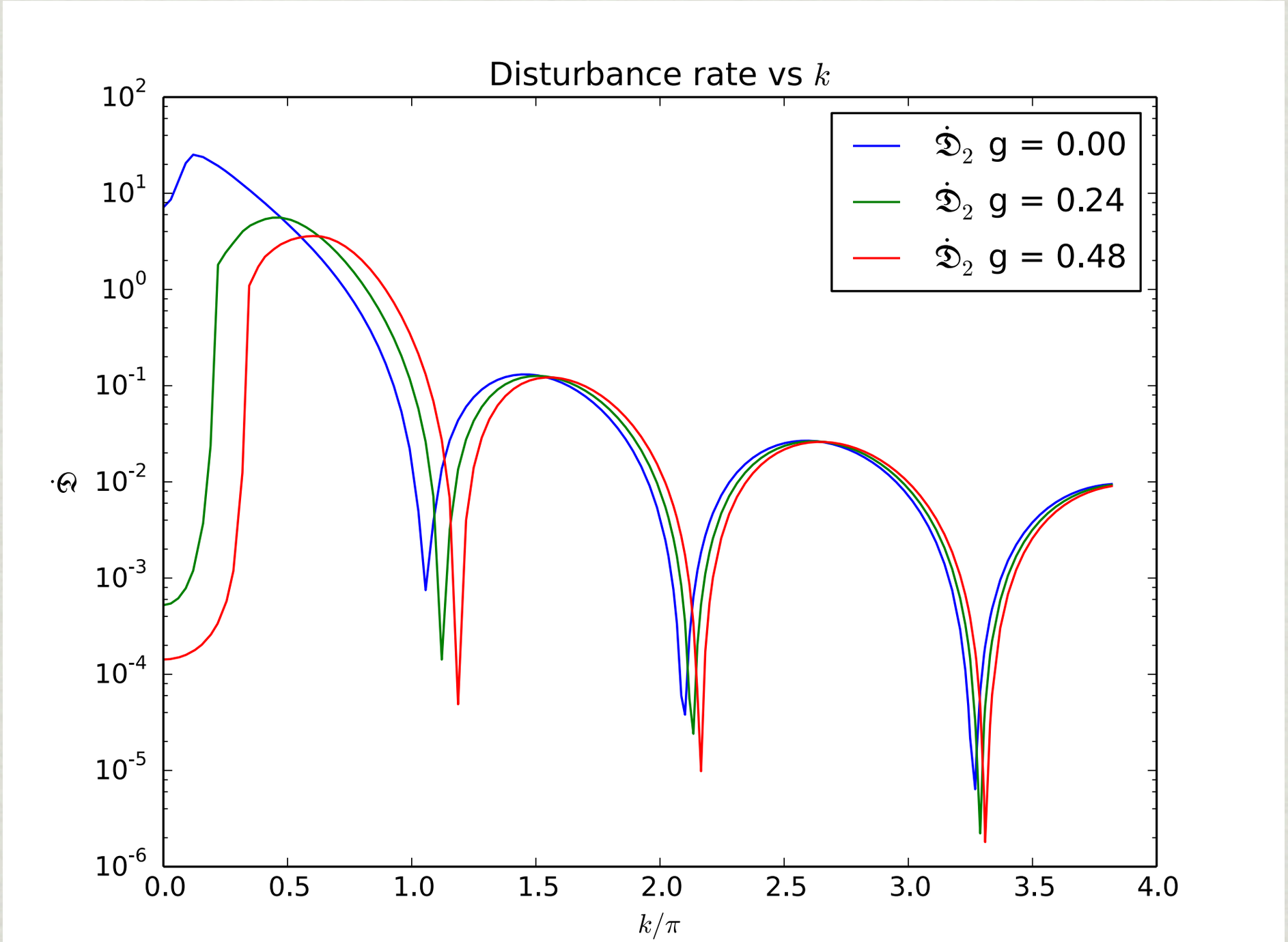
(a) $\alpha = 2.5142$ (b) $\alpha = 2.5554$ (c) $\alpha = 2.6378$

$$\alpha = v/c$$

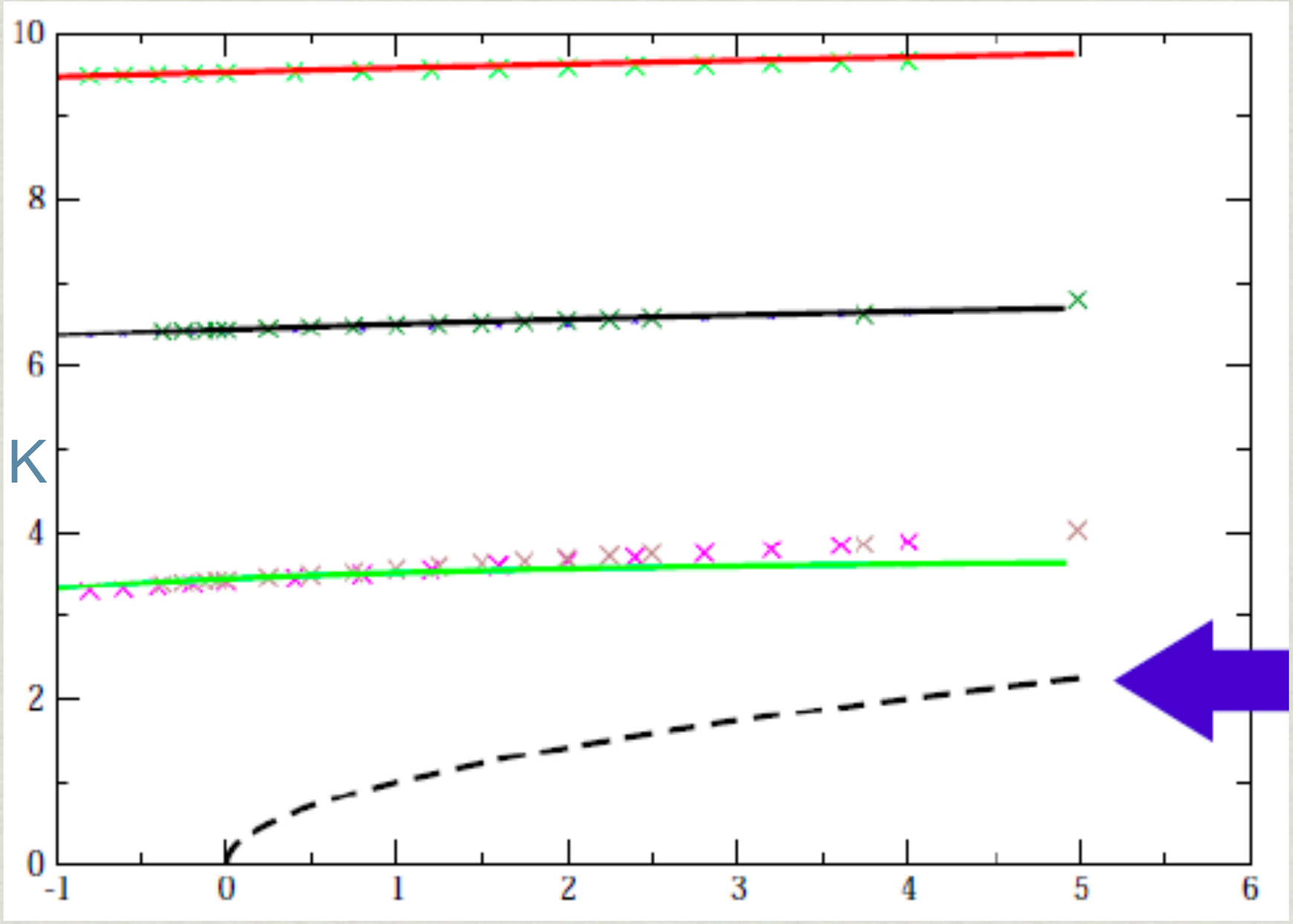
Bounded growth rates



Velocity dependence

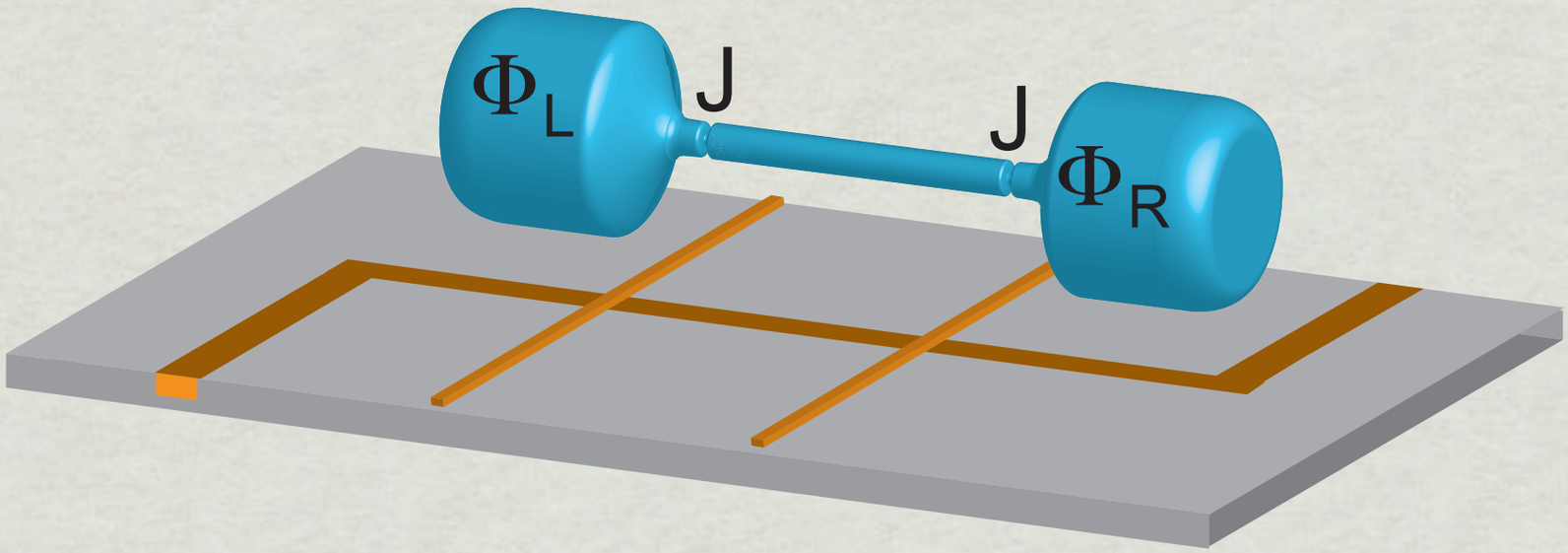


Interaction dependence



PARIS-MANDOKI ET AL, IN PREP 2014

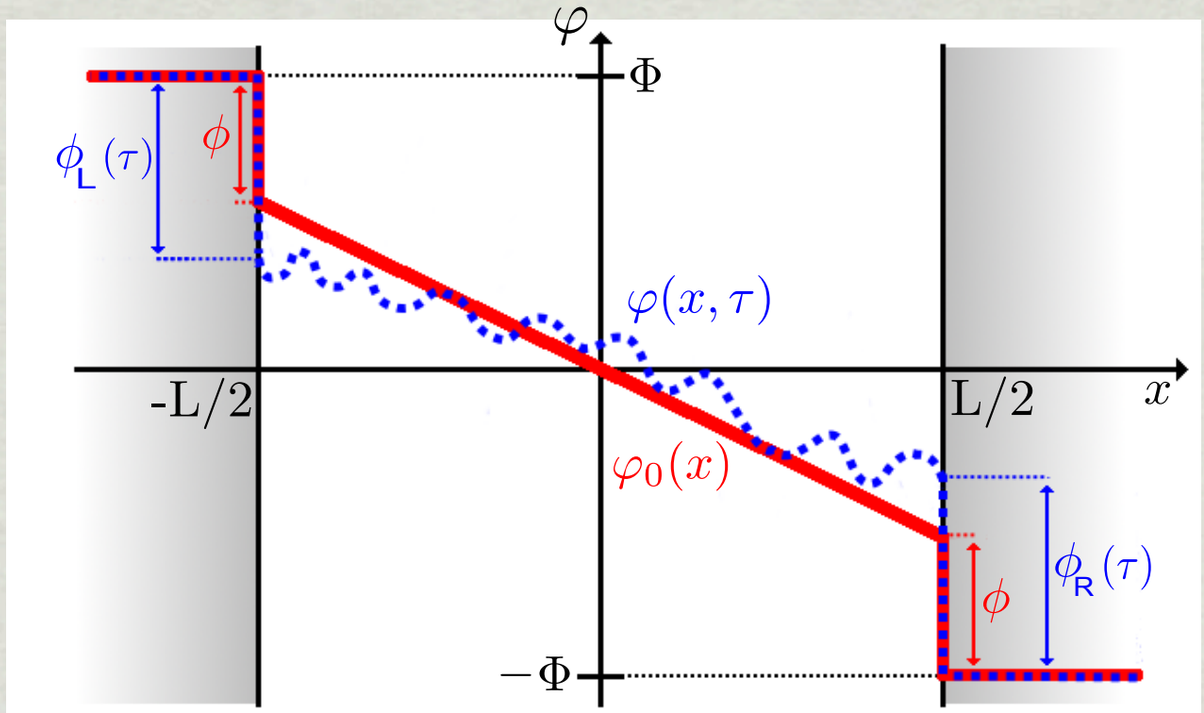
1d transport of bosons



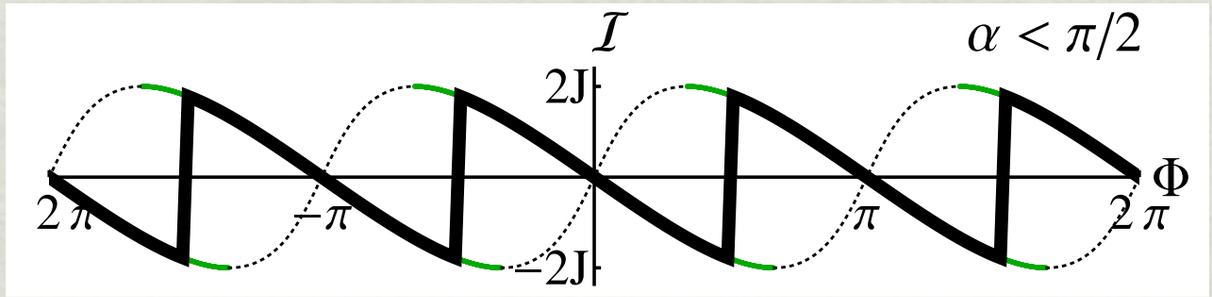
TWO 3D RESERVOIRS ARE CONNECTED VIA 1D CHANNEL WITH WEAK LINK CONNECTIONS
PHASE DIFFERENCE AT EQUAL CHEMICAL POTENTIAL DRIVES CURRENT
JOSEPHSON LIKE BEHAVIOR FOR BOSONS?

SIMPSON ET AL, PRL 2014

Predictions



EXAMPLE OF PHASE PROFILE IN THE CHANNEL

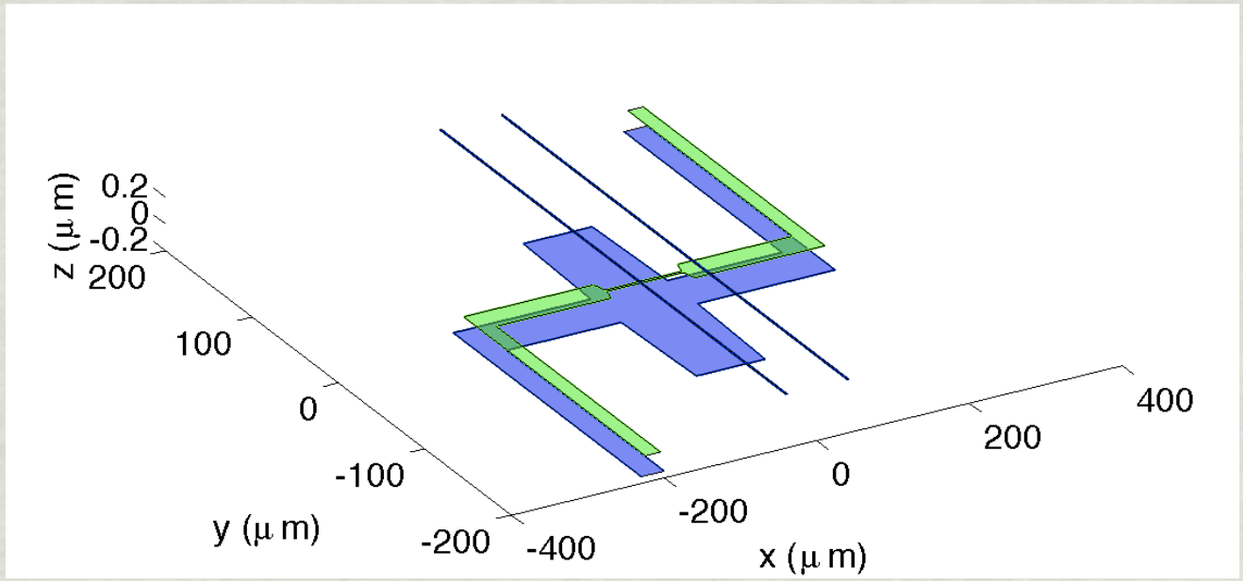


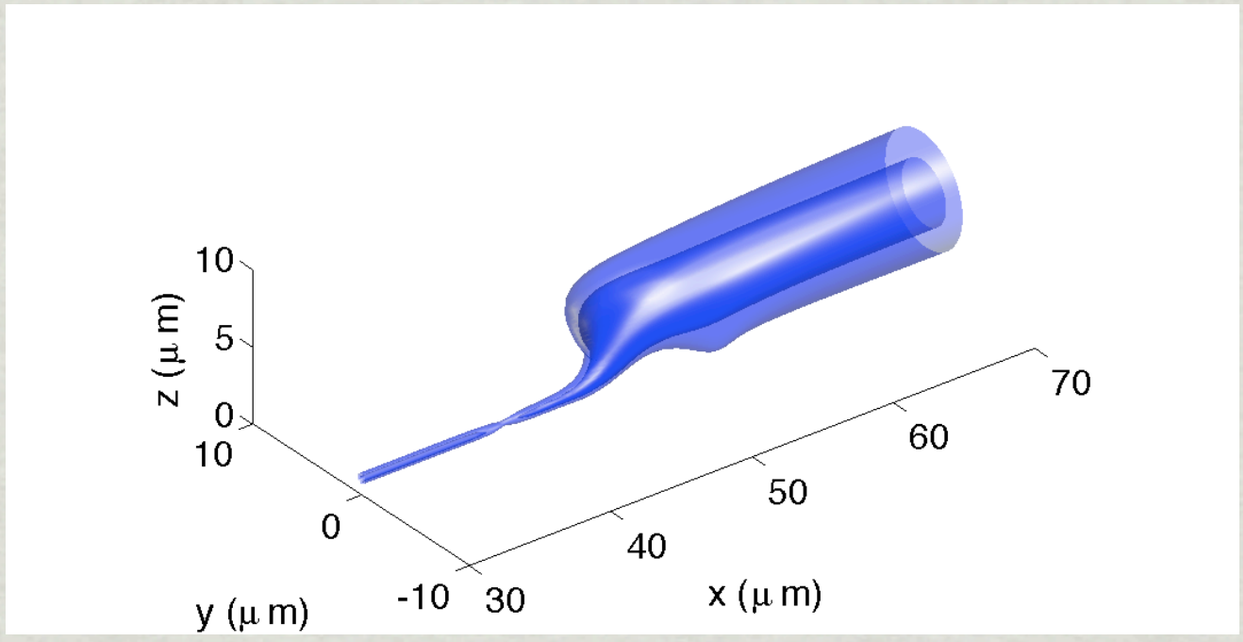
CURRENT AS A FUNCTION OF IMPRINTED PHASE

- Mean field treatment (not perturbative) leads to linear (in J) scaling of current
- Spontaneous flip of direction, metastable states and hysteresis instead of sinusoidal current

SIMPSON ET AL, PRL 2014

Experimental realization





- Double layer trapping wires with varying width
- Third layer barrier wires on micron scale
- Direct or interferometric readout

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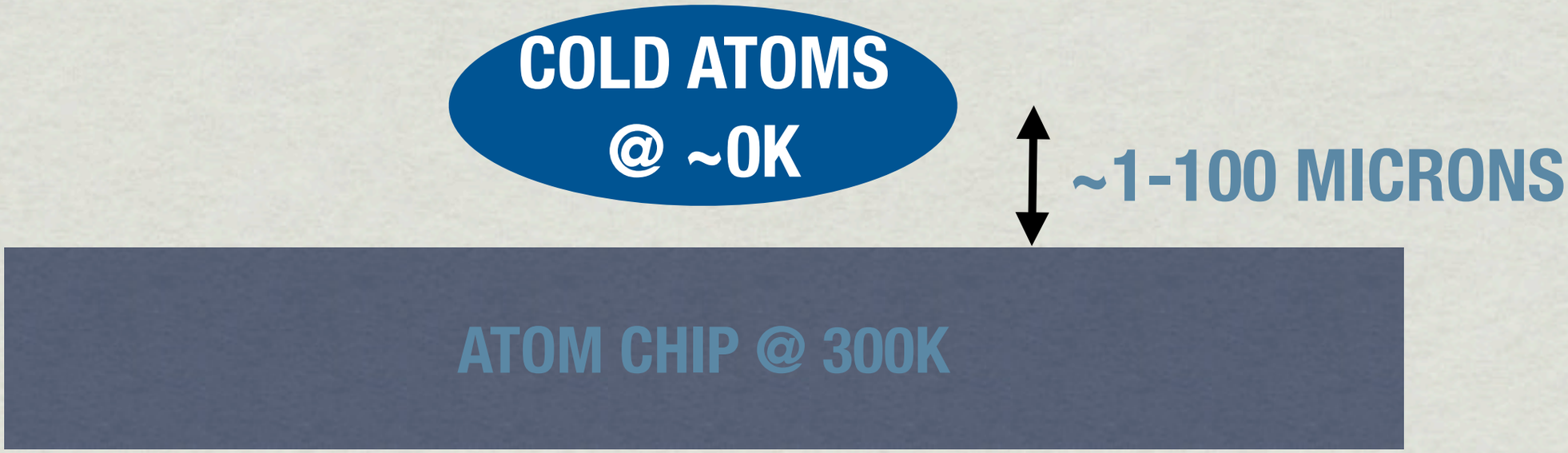
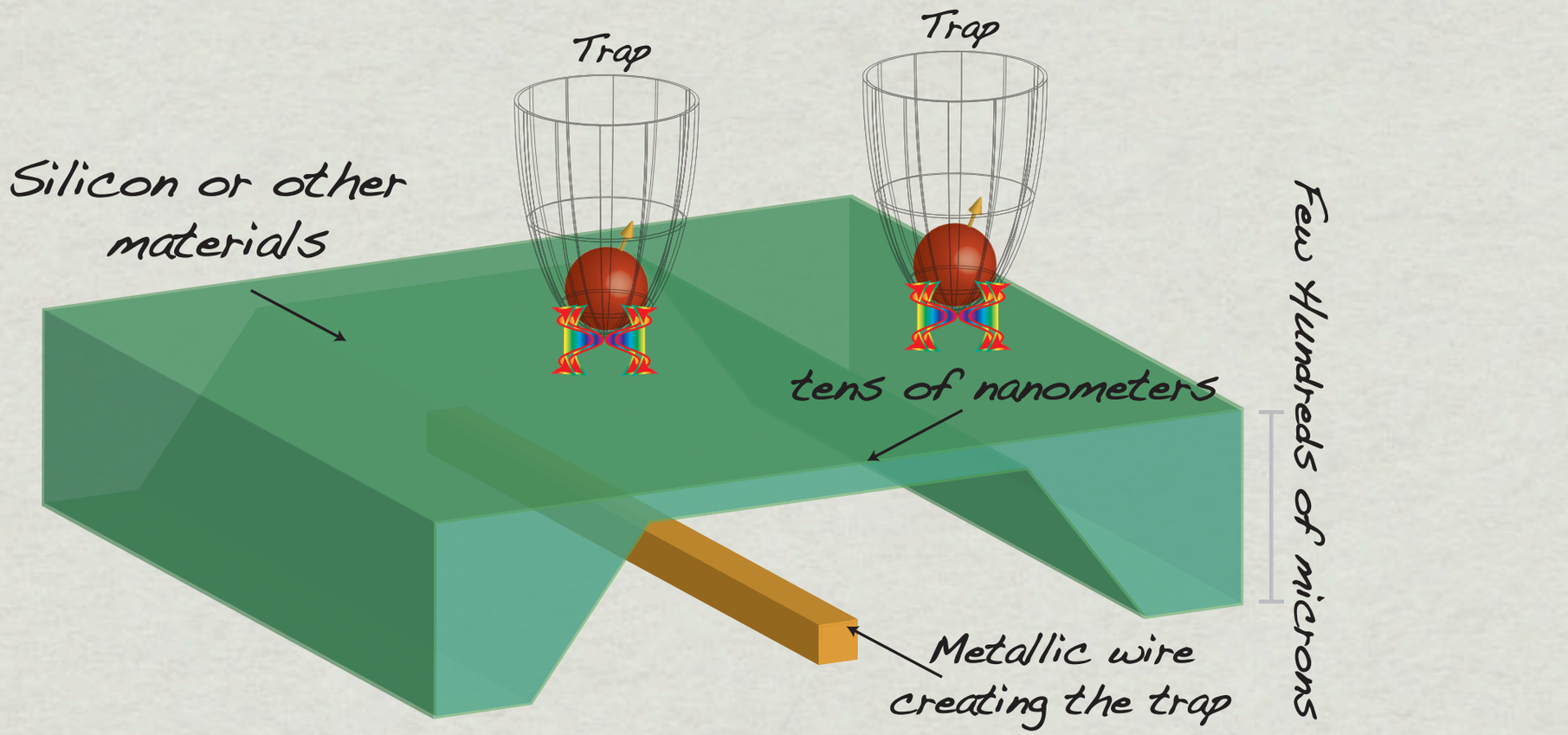
Challenges

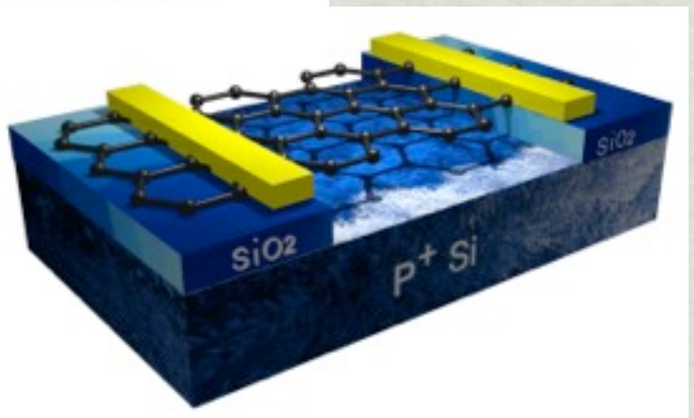


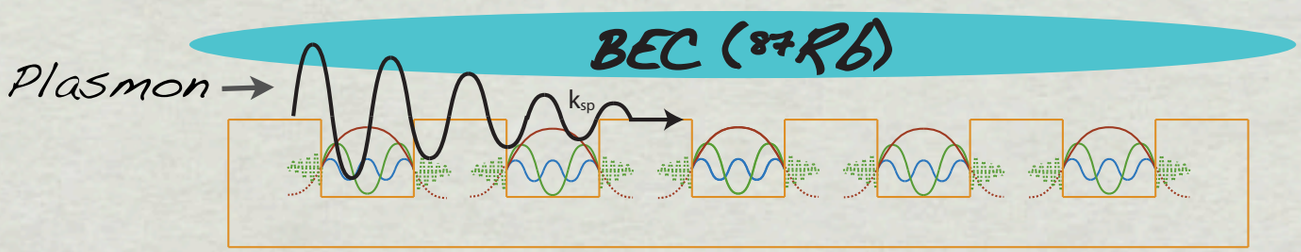
- Potential corrugation
- Attractive surface forces
- Johnson noise

Geometries & materials



Graphene





F. INTRAVAIA ET AL, IN PREP 2014

Summary

- Atom chips have been demonstrated to be versatile tools for fundamental studies on complex quantum systems and for device applications alike
- Further miniaturization opens new prospects for engineered environments for quantum gases, for microscopic sensing, and ultimately for atom-surface interfaces

People

- **Atom chips exp:** Anton Piccardo-Selg, Gal Aviv, Tom Barrett, Fedja Orucevic, Thomas Fernholz
- **Surface exp:** Samanta Piano, Robert Hollenstein, Amruta Gadge, Lu Bo, Christian Koller
- **Fabrication:** Jessica Maclean, Chris Mellor
- **Theory:** Francesco Intravaia, Mark Fromhold; David Simpson, Dima Gangardt, Igor Lerner (Birmingham); Andrea Trombettoni (SISSA)
- **Collaborators:** Jorg Schmiedmayer, Ron Folman, Thomas Fernholz, Igor Lesanovsky, Kai Bongs