Non ideal trapped quantum gases

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Non ideal trapped quantum gases

1. Critical temperature shift in Rb
2. Penning ionization rate constants and scattering length in He*
3. Roughness of atom chip trapping potential

Non ideal gas

Non ideal trap

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Non ideal trapped quantum gases

standard methods revisited

1. Critical temperature shift and other thermodynamics properties in Rb
2. Penning ionization rate constants and scattering length in He*
3. Roughness of atom chip trapping potential

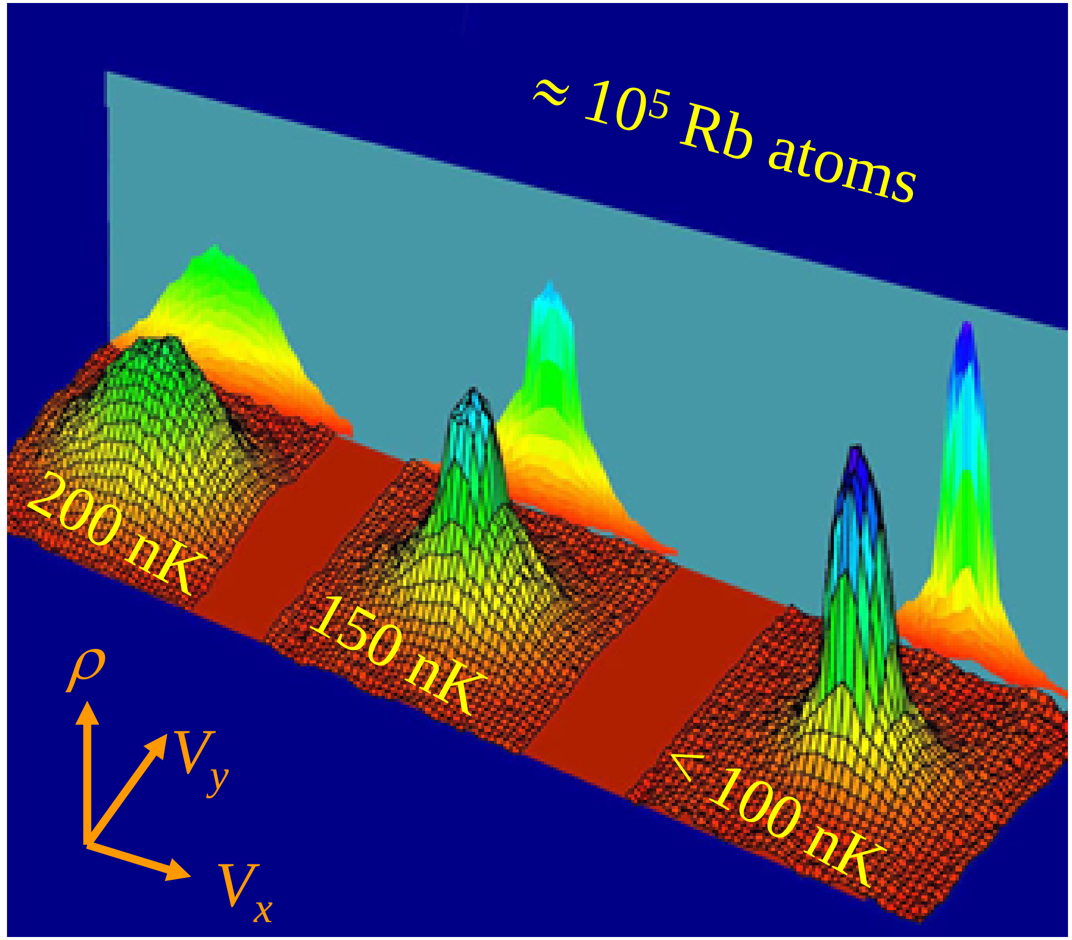
- Critical temperature shift (F. Gerbier et al., PRL 92, 030405, 2004)
- Condensed fraction, interaction energy, equilibrium shape of a mixed profile… (F. Gerbier et al., PRA 70, 013607, 2004)

Trapped BEC: standard measurements

- Turn off the trap at $t = 0$
- Ballistic expansion, duration τ
- Absorption imaging

  *Thermal component (Bose function, Gaussian wings): mostly thermal velocity

  *Condensate (Thomas Fermi profile, inverted parabola): mostly interaction energy



- Measurements difficult at a few percent level
- Theoretical issue: expansion of an interacting mixed cloud?

Critical temperature of a trapped Bose gas

Ideal (non-interacting) trapped Bose gas

$$T_c^{\mathrm{ideal}} = T_c^0 - \frac{\zeta(2)}{\zeta(3)} \frac{\hbar(\omega_z + 2\omega_\perp)}{6 k_B}$$

Thermodynamics limit

$$n\Lambda_T{}^3 = 2.612$$

« Finite size » effects

2% with our parameters

$$\omega_\perp / 2\pi = 413 \text{ Hz}$$

$$\omega_z / 2\pi = 8.69 \text{ Hz}$$

Critical temperature of a non ideal Bose gas

Effect of interactions?

Uniform case (box)

- Theory: T_c □ because of density fluctuations (a hot topics)
- Observed with dilute LHe on Vycor

Harmonic trap

- Theory: T_c □ for repulsive interaction because of density decrease at the trap center (Einstein criterium unchanged):
  W. Krauth; Giorgini et al. (1996)

$$\frac{T_c - T_c^{\text{ideal}}}{T_c^0} \approx -1.33 \frac{a}{a_{\text{HO}}}$$

- Observation?

Critical temperature of a trapped non ideal Bose gas
A "review" of the observations

Inconclusive experiments, except for a pioneering observation (1 standard deviation) by Ensher et al. (1996).

work	**measured $\Delta T_c / T_c^{ideal}$**
Mewes 1996	(assumed 0.0)
Ensher 1996	-0.06 ± 0.05
Han 1998	-0.04 ± 0.15
Shreck 2001	0.0 ± 0.2
Maragò 2001	0.00 ± 0.03

Improved measurements in Orsay: some experimental tips

Fight shape oscillations ocurring at condensation

- Slow down evaporation near condensation (200 kHz / s)
- Hold time (1 s) with RF knife on

Excellent control of the evaporating knife position above trap bottom

- Temperature reproducibility: 20 nK

Accurate absorption measurement of atom number

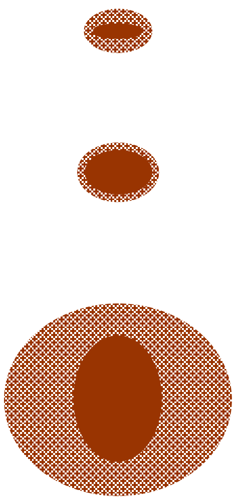
- Careful calibration of absorption cross section by expansion energy measurement (relies on the value of the scattering length, acurately known from spectroscopy)

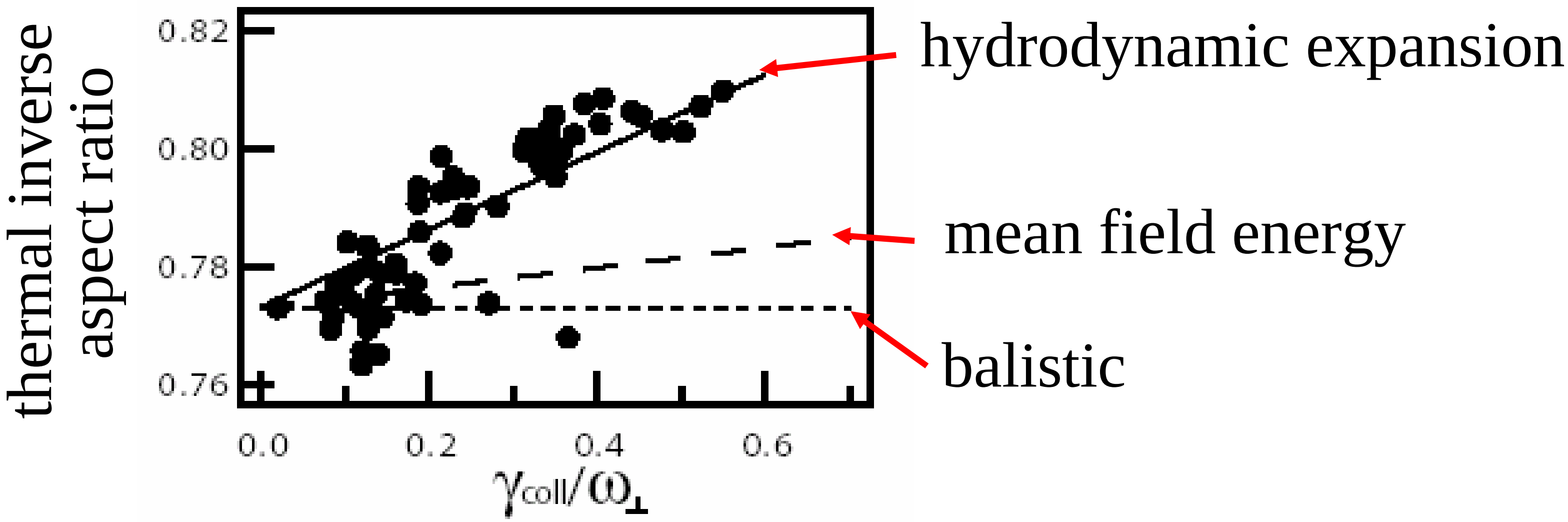
Correction for hydrodynamic effects in temperature measurements

Temperature measurement
Hydrodynamic effects

Temperature measurement: fitting a Bose profile to the wings of the TOF of the cloud around T_c

Necessary to correct hydrodynamic effect for large and dense thermal clouds (elongated trap $\omega_z / \omega_\perp \approx 45$). Also in Amsterdam.

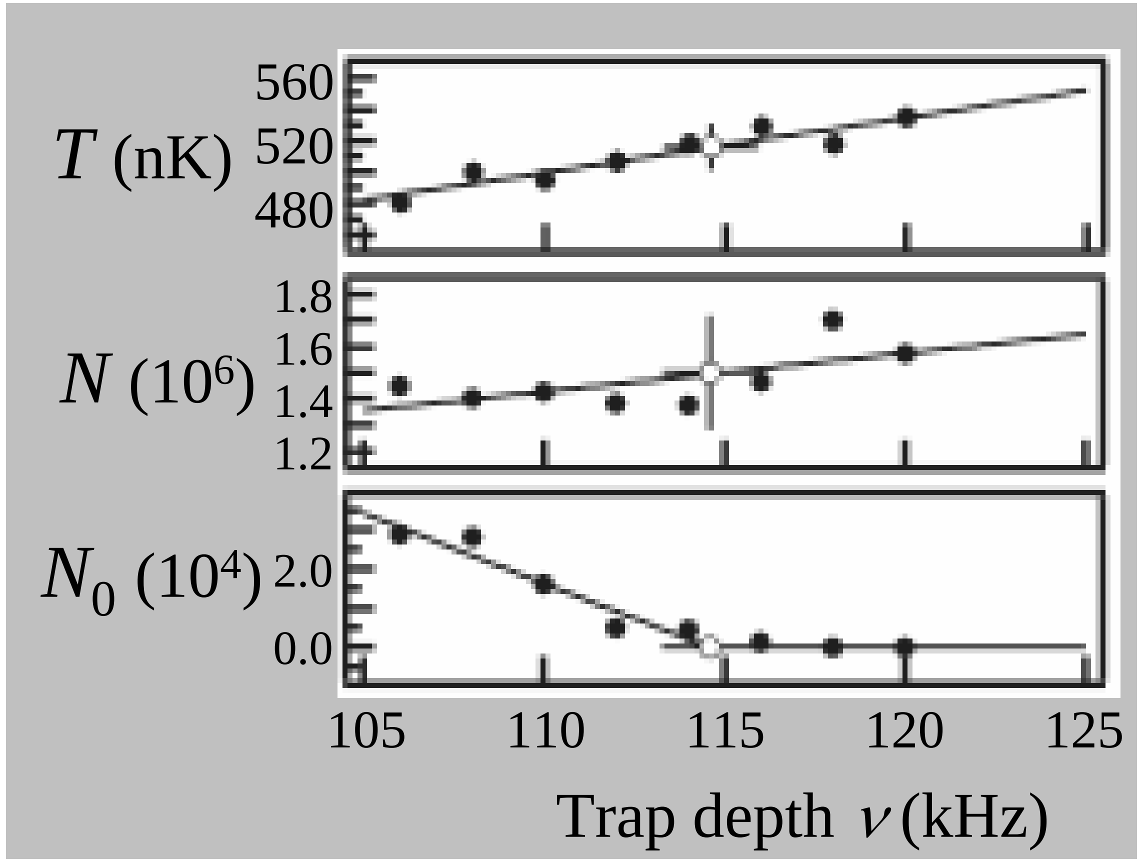




Acurate determination of the critical point

Very reproducible evap. ramps, stopped at different values of trap depth ν:

- plot T, N, N_0 vs. ν
- linear fits
- find ν_c
- derive N_c and T_c



See estimated error bars

Critical temperature of a trapped ^{87}Rb Bose gas: results

- Non ideal behavior (effect of interactions) observed at the level of $2\,\sigma$

- Good agreement with mean field theory: fit of ΔT by $\alpha N^{1/6}$ yields:

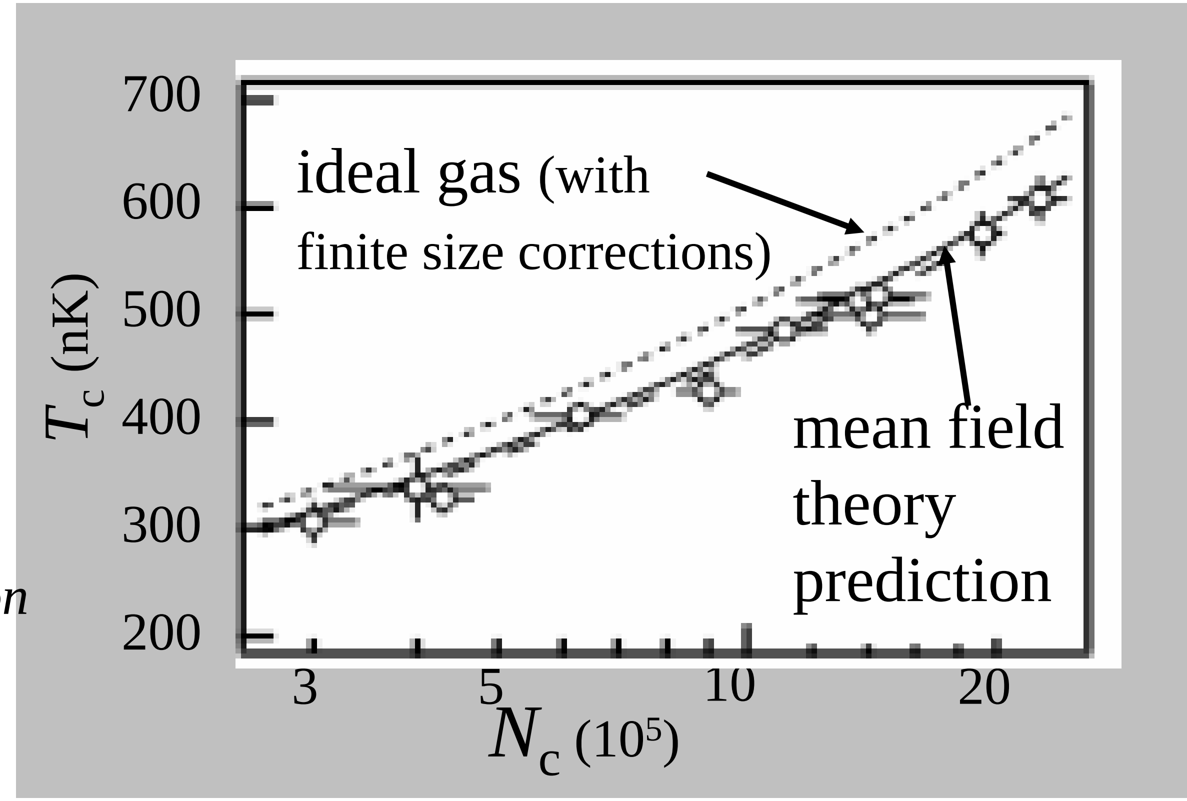
$$\boxed{\alpha_{\rm exp} = -0.009(1)^{+0.003}_{-0.002}}$$

calibration

statistical

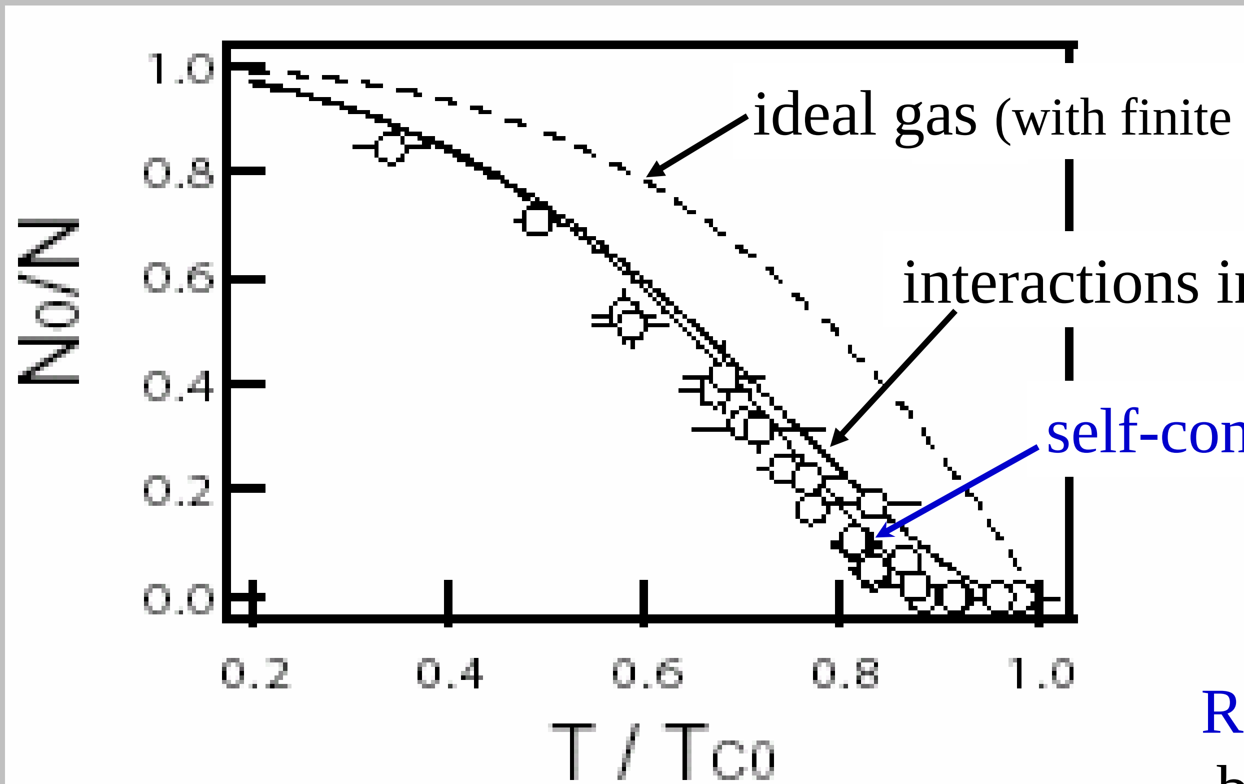
to be compared to

$$\boxed{\alpha_{\rm th} = -0.007}$$



- No upwards shift due to density fluctuations as predicted for homogeneous case: in agreement with predicted suppression for trapped Bose gases (Giorgini, Pitaevski, Stringari; Arnold and Tomasik)

Trapped ^{87}Rb Bose gas: condensed fraction



ideal gas (with finite size corrections)

interactions in the condensate only

self-consistent Hartree-Fock

Reasonable agreement

but…

…experiment systematically (slightly) below theory

Error in temperature measurement due to interaction between thermal cloud and BEC during expansion? Theory is missing for expansion of a mixed cloud!

Trapped interacting degenerate Bose gas (Rb): conclusions

Deviation from ideal gas clearly observed

Agreement with mean field theory

- Shift of critical temperature
- Self consistent Hartree Fock modeling of condensed fraction and mixed cloud profile

Observation of hydrodynamics effects in TOF of dense thermal cloud

Theory needed to better understand TOF of mixed sample (condensate and thermal cloud)

No effect observed beyond mean field for a trapped BEC: agreement with theory

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Non ideal trapped quantum gases

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new methods

O. Sirjean et al., PRL 89(22): 220406 (2002)

S. Seidelin et al., PRL in print

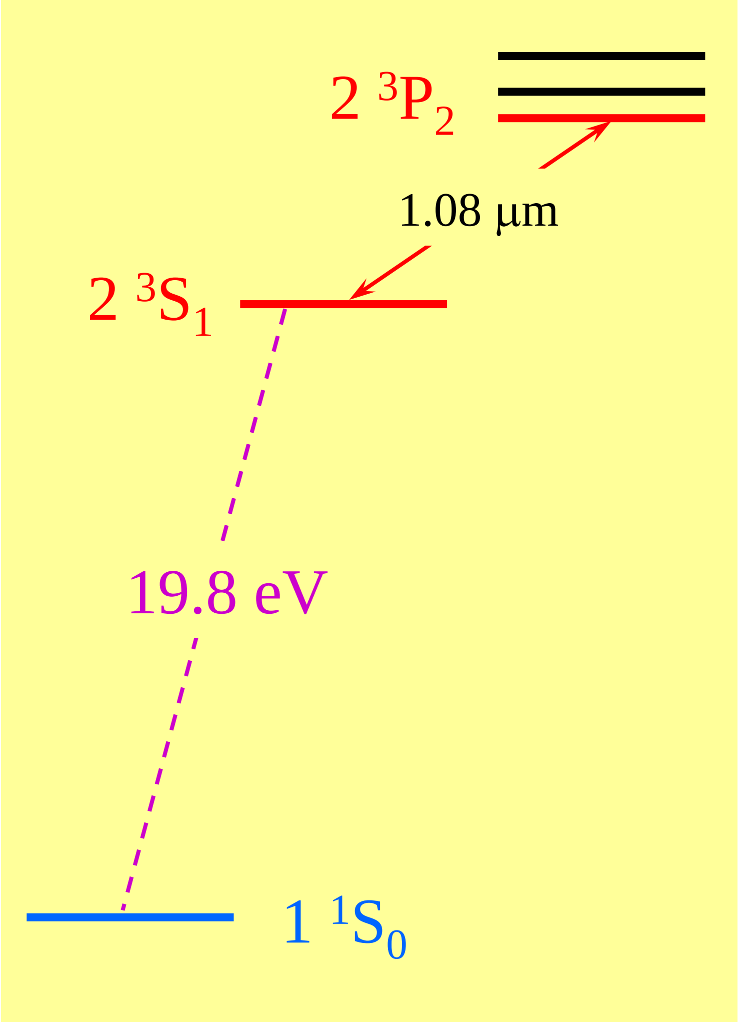
Metastable Helium $2\ ^3S_1$

- Triplet (↑↑) $2\ ^3S_1$ cannot *radiatively* decay to singlet (↑↓) $1\ ^1S_0$ (lifetime 9000 s)
- Laser manipulation on closed transition $2\ ^3S_1 \rightarrow 2\ ^3P_2$ at 1.08 μm (lifetime 100 ns)

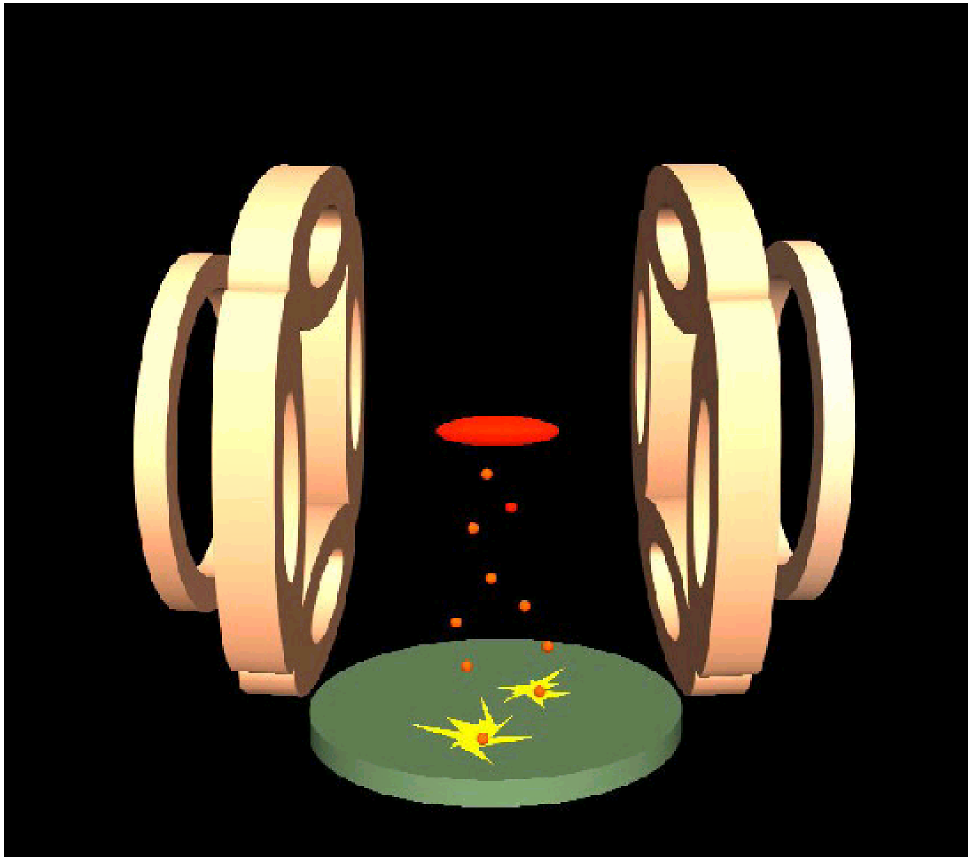
- Large electronic energy stored in He*

  ⇒ ionization of colliding atoms or molecules

  ⇒ extraction of electron from metal: single atom detection with Micro Channel Plate detector



He* trap and MCP detection



Clover leaf trap

@ 240 A : B_0 : 0.3 to 200 G ;

B' = 90 G / cm ; B'' = 200 G / cm^2

$\omega_z / 2\pi$ = 50 Hz ; $\omega_\perp / 2\pi$ = 1800 Hz

(1200 Hz)

He* on the Micro Channel Plate detector:

$\Rightarrow$ an electron is extracted

$\Rightarrow$ multiplication

$\Rightarrow$ observable pulse

Single atom detection of He*

The route to He* BEC: not such an easy way

Pros:

- Strong magnetic trap (2 Bohr magnetons)
- Ultrasensitive detection scheme
- Very rapid release scheme

$\Rightarrow$ Excellent TOF diagnostic

Cons:

- Source of cold He* not as simple as alkalis'; vacuum challenges
- Elastic cross section *a priori* unknown at low temperature

  Direct measurement of rethermalization of the energy distribution after RF knife disturbance (A. Browaeys et al., PRA…): $a \approx 20$ nm (as predicted by Shlyapnikov 95, Venturi …)

- Penning ionization

Penning ionization of He*

$$\boxed{He^* + He^* \rightarrow He(1\,^1S_0) + He^+ + e^-}$$

Reaction constant ≈ 5 x 10 $^{-10}$ cm^3.s^{-1} @ 1 mK

Impossible to obtain a sample dense enough for fast thermalization?

Solution (theory, Shlyapnikov et al., 1994; Leo el al.):

Penning ionization strongly suppressed (10^{-5} predicted!) in spin polarized He* because of selection rule (spin conservation)

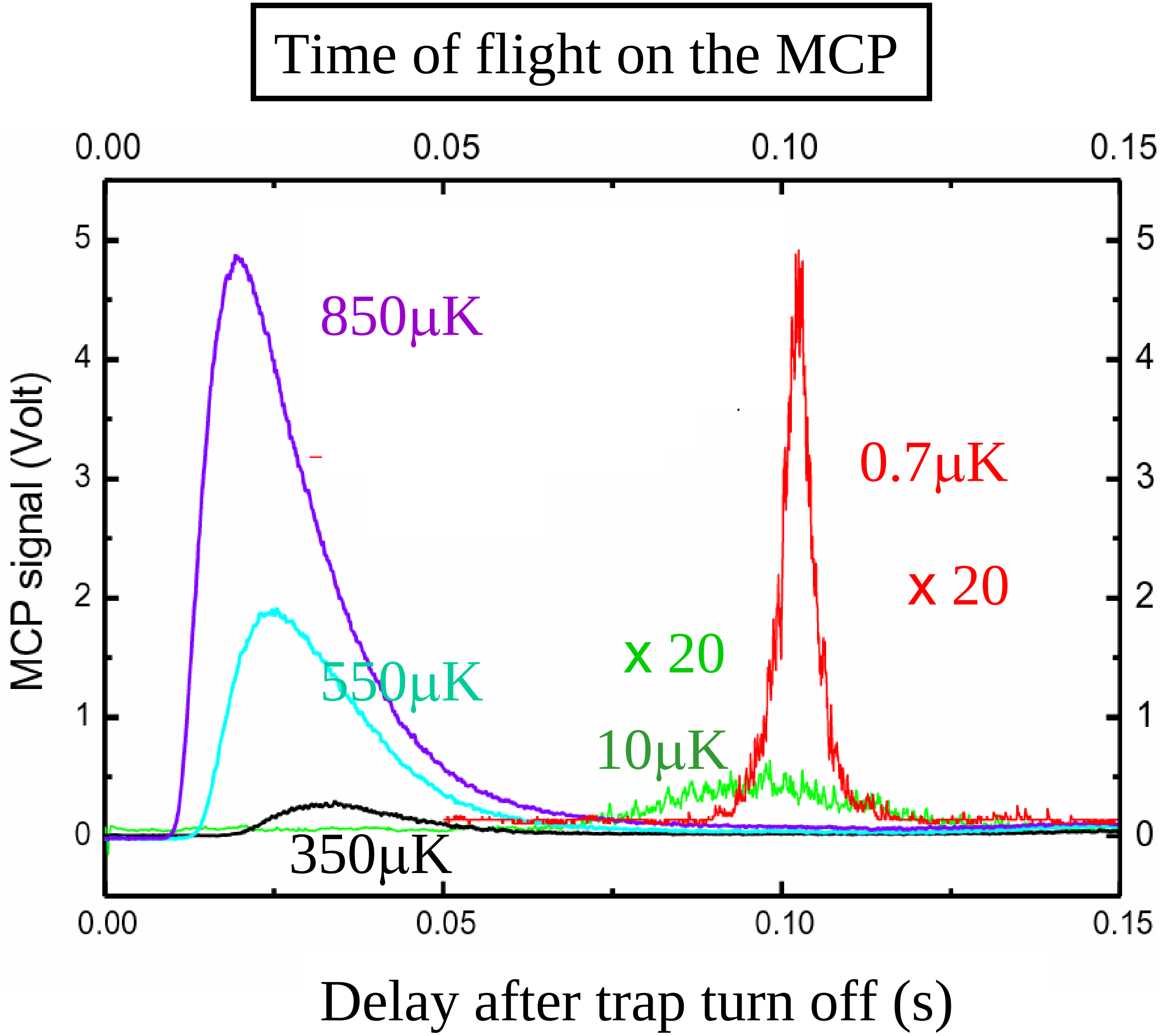
$$\boxed{m = 1 \;+\; m = 1 \;\not\rightarrow\; s = 0 \;+\; s = 1/2 \;+\; s = 1/2}$$

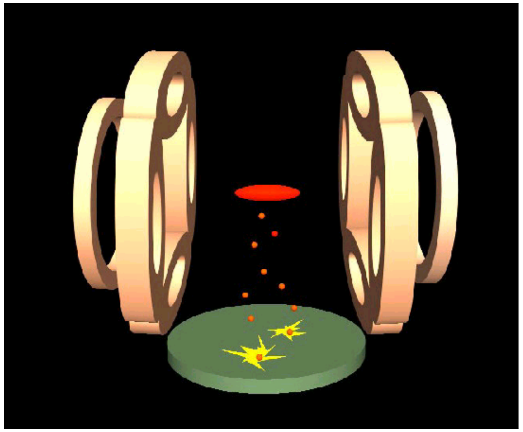
Magnetically trapped He* ***is*** spin polarized

Preliminary experimental evidence (Amsterdam, Orsay, 1999): suppr. < 10^{-2}

Definitive evidence of supression (< 10^{-4}) : BEC of He* observed (Orsay, Paris, 2001)

Evaporative Cooling to BEC





- RF ramped down from 130 MHz to ~ 1 MHz in 70 s (exponential 17 s)

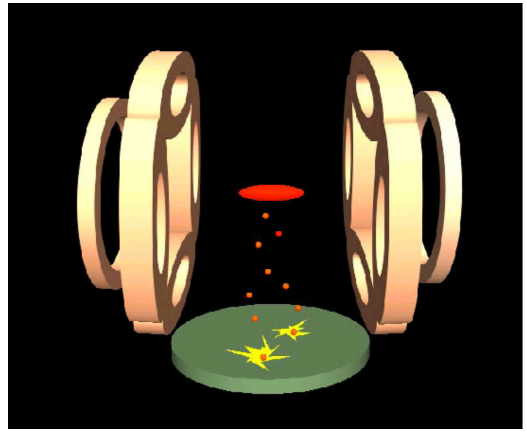
  ⇒ less atoms, colder

- Small enough temp. (about 2µK): all atoms fall on the detector, better detectivity
- At 0.7µK: narrow peak, BEC

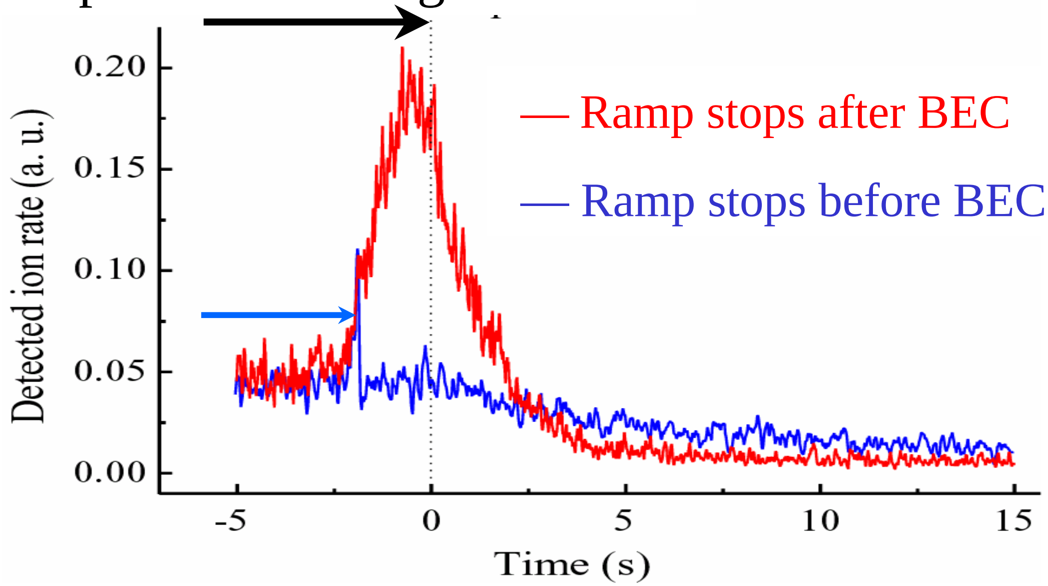
Residual Penning ionization

A new tool for monitoring a trapped He* BEC

- Residual ionization (He+): detected with negatively biased grid (2keV) in front of MCP in counting mode (from 10^2 to $10^3\ s^{-1}$)



evaporative cooling



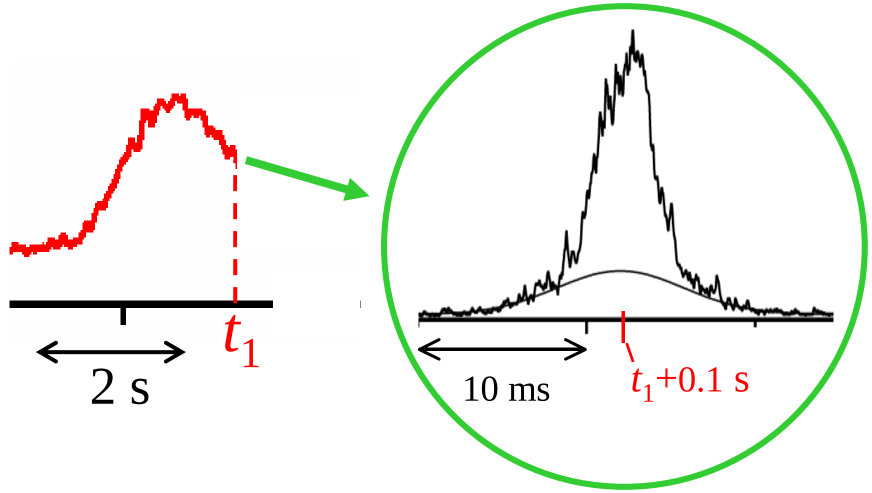
Real time observation of BEC birth and death on a single sample

Interpretation: ionization increases with density (2 and 3 body Penning ionization)

Quantitative if one knows the Penning ionisation rate constants

Ionization monitoring plus TOF: a measurement of Penning ionization constants

Complete ion rate measurement $I(t_1)$ by measurement of the spatial distribution of atoms at t_1



$\Rightarrow$ Switch off the trap at t_1 and observe Time of Flight of the released atoms:

$\Rightarrow$ Atom number in the condensate

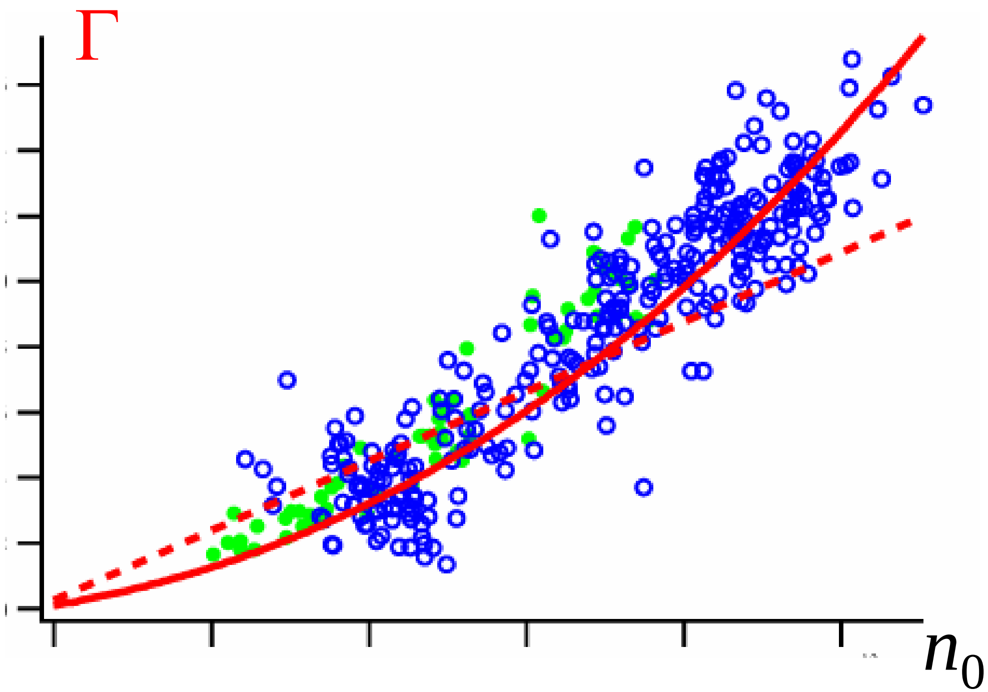
$\Rightarrow$ Atom number and temperature in the thermal cloud

One can then know, in a given situation (at t_1) :

- the ion rate per atom $\Gamma(t_1)$
- the atomic density $n(\mathbf{r},t_1)$

$\Rightarrow$ ionization rate constants β and L

Ion rate per atom *vs* peak density in a quasi pure BEC



For each ion rate I , TOF:

$\Rightarrow$ N_0 (atom number)

$\Rightarrow$ n_0 (density)

$\Rightarrow$ check pure BEC (thermal cloud not visible, i. e. < 10%)

$\Rightarrow$ ion rate per atom $\Gamma = \dfrac{W}{N_0}$

Fit to $G = \dfrac{2}{7} k_2 b\, n_0 + \dfrac{8}{63} k_3 L\, n_0^{\,2}$ $\Rightarrow$ β, L : 2 and 3 body ionization

The detection efficiency and scattering length issue

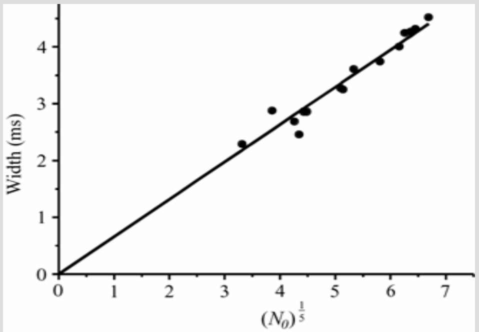
A serious difficulty: determining the absolute atom number

- Absolute detection efficiency of MCP known within a factor of 2

Another difficulty: determining the absolute atomic density in the BEC

- Depend on scattering length a

Scattering length obtained from measurement of expansion velocity of a pure condensate



$$W_i \propto \left(N_0 a\right)^{1/5}$$

Coefficient accurately known: accuracy on a depends on accuracy on atom number N_0

$$a = 20 \pm 10\,\text{nm}$$

Detection efficiency and scattering length issue: a solution

Our results on Penning ionization constants depend dramatically on the value of *a*. Photoassociation spectroscopy measurements of *a* ?

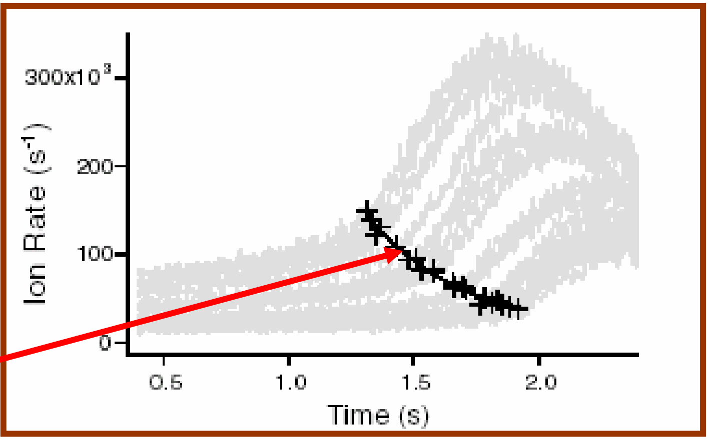
Another solution: improve the accuracy on atom detection efficiency

Calibration based on absolute atom number derived from thermodynamics relation at BEC transition

$$N_c = f(T_c)$$

accurately measured by TOF

accurately located by sudden rise of ion current



$$\Rightarrow \quad \boxed{a = 11.3^{+2.5}_{-1.5}\ \mathrm{nm}}$$

Reasonable agreement with theory and previous measurements.
Reduced error bars

Interest of independent measurements of *a*

A photoassociation spectroscopy measurement of *a* will be very interesting (in progress at ENS)

⇒ More accurate value expected

⇒ Independent measurement: will allow us to reinterpret our results and test various effects depending on *a* :

- critical temperature correction
- quantum depletion (30% correction in 3-body Penning ionization)

Combining different methods: a great tool

Penning ionization: an original tool for « non destructive » monitoring of a trapped He* gas

Non ideal trapped quantum gases

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3. Roughness of atom chip trapping potential

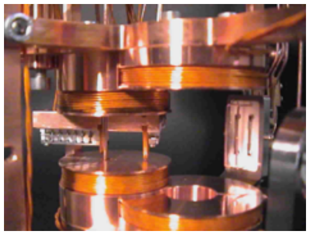
mesoscopic cold atoms ensemble

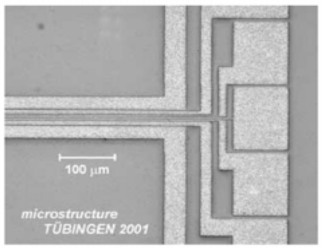
J. Estève et al., Phys. Rev. A, in press

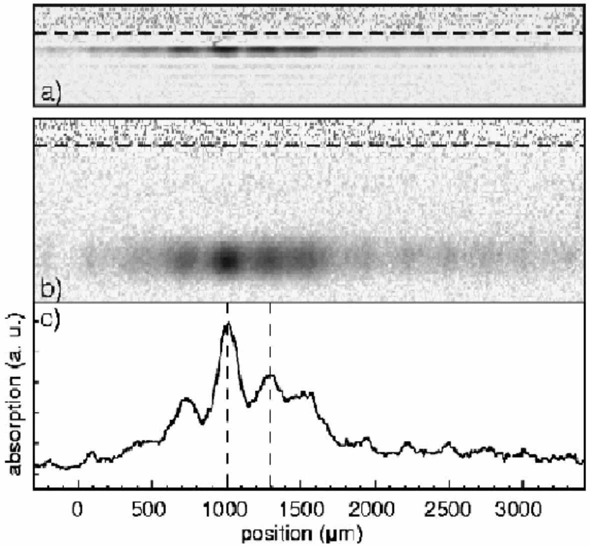
T. Schumm et al., Physics/0407094

BEC on a chip: fragmentation

Tübingen







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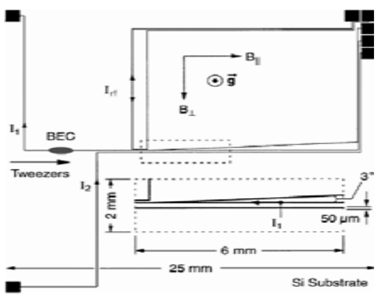
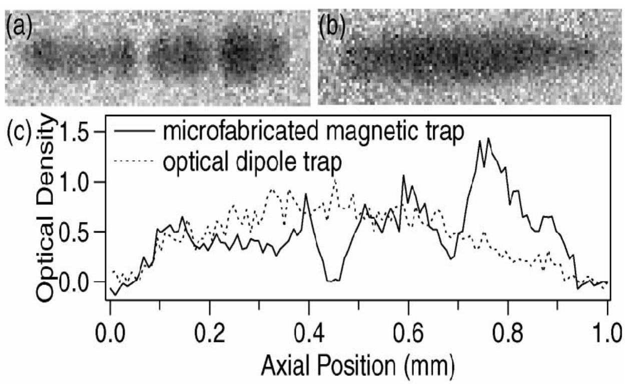
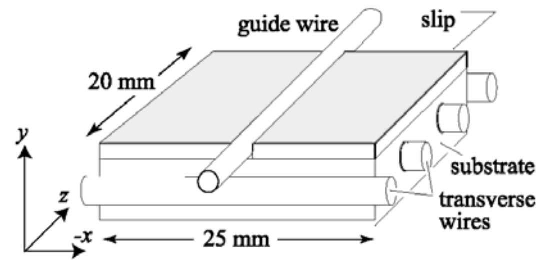
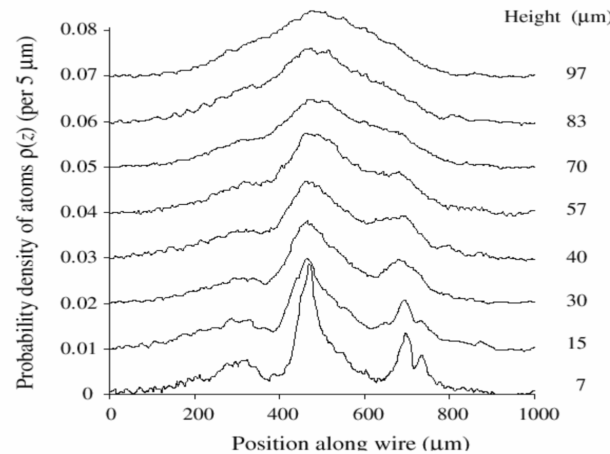




Sussex / London





Orsay

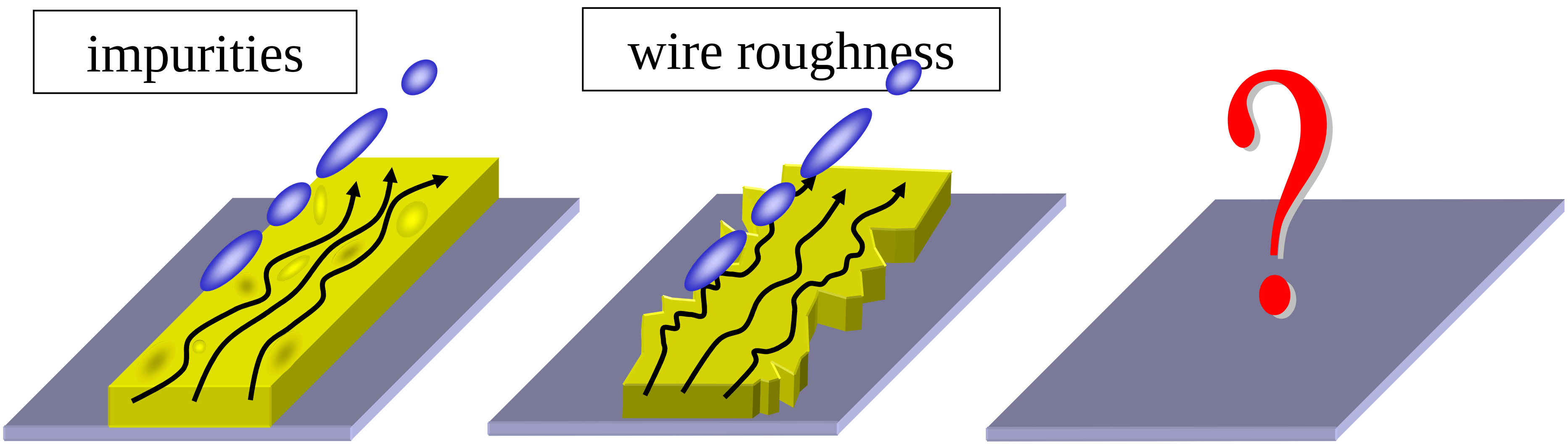
also!

. . .

In search of the cause of fragmentation

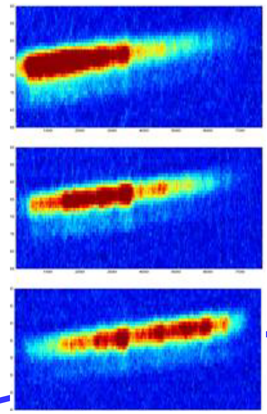
Fragmentation due to roughness of the magnetic trapping potential, due to deviations of the current flow (static, linear in current, decreasing with distance to the wire…)

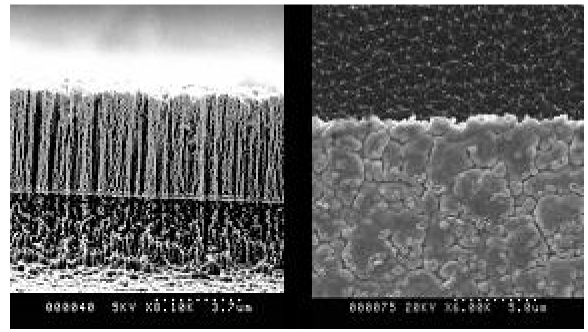
Cause of deviations in current flow?

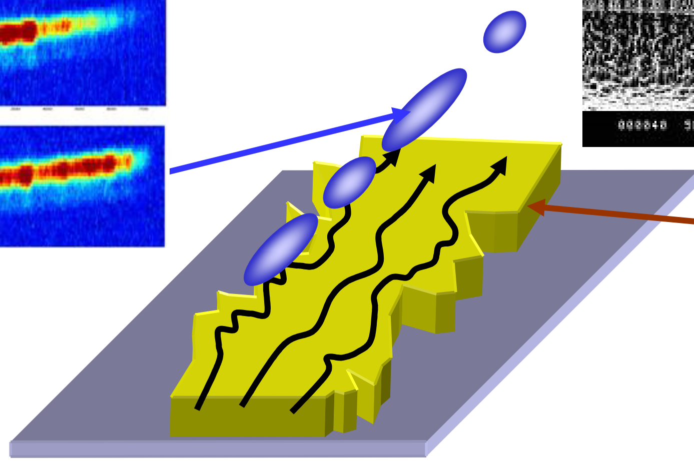


proposed D. Wang, M. Lukin, and E. Demler, cond-mat/0307402

Our approach: measure trapping potential roughness and wire edges roughness







cold atoms density distribution

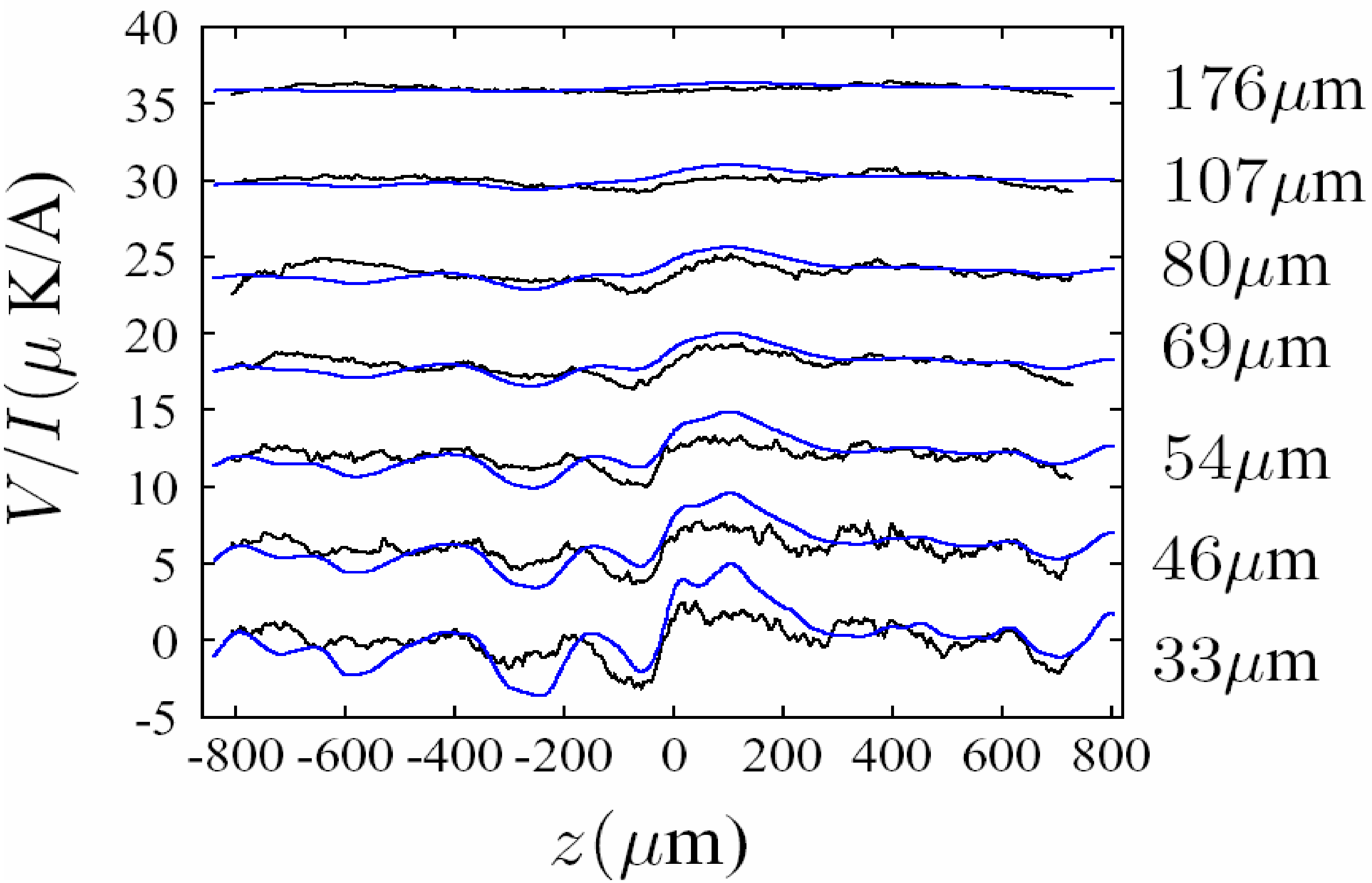
wire edges roughness
(electron microscope)

Boltzmann law

Maxwell equations

trapping potential roughness

Our conclusion: wire edges roughness suffices to explain trapping potential roughness (for our chip)



reconstructed from density profiles of cold atoms

reconstructed from measurement of edges roughness

no free parameters!

Comparison of roughness power spectrum also convincing

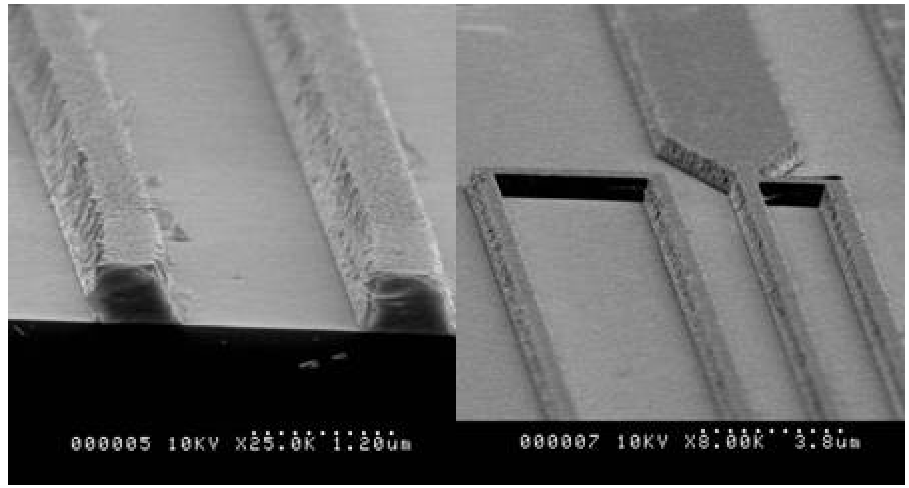
Conclusion

For our atom chip made with electroplated gold wires (5 μm x 50 μm) on silicon wafer:

wire edges roughness suffices to explain trapping potential roughness.

New generation of trapping wires (700 nm width evaporated gold wires, pattern witten with e beam)

Encouraging results



To know more, visit Thorsten Schumm's poster

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Post doc applications encouraged

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ATOM CHIP BEC

Jérome Estève
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Jean-Baptiste Trebia
Hai Nguyen

BEC VERSATILE SOURCE

Yann Le Coq
Marie Fauquembergue
Jean Felix Riou
William Guérin

Electromagnet Rb BEC

Mathilde Hugbart
Andres Varon
David Clément
Jocelyn Retter

K-Rb MIXTURES

Gaël Varoquaux
Rob Nyman
Yann Le Coq

He* BEC

Signe Seidelin
Jose Gomes
R. Hoppeler
M. Schellekens
A. Perrin

BIOPHOTONICS

Karen Perronet

That's all