Title: Atom interferometers, atom chips, and Bose-Einstein condensates: from coherent to quantum atom optics

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Abstract:

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Atom interferometers, atom lasers and Bose-Einstein Condensates: from coherent to quantum atom optics

Groupe d'Optique Atomique

…ire Charles Fabry de l'Institut d'Optique - Orsay

http://atomoptic.iota.u-psud.fr

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Atom interferometers, atom lasers and Bose-Einstein Condensates: from coherent to quantum atom optics

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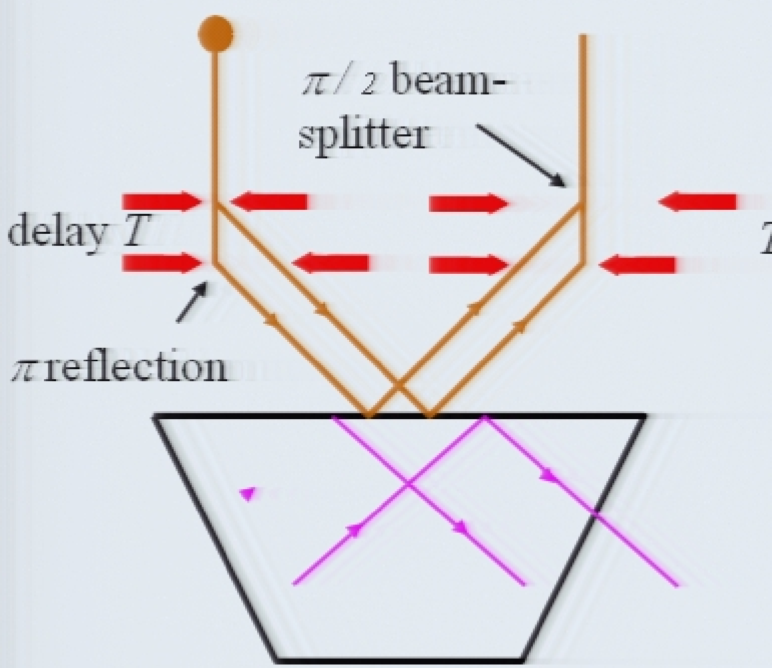
From coherent to quantum atom optics

- Coherent optics with incoherent sources
- BEC and atom lasers
- Coherence of an elongated quasi condensate
- He* BEC: an ideal system for quantum atom optics

Coherent atom optics with incoherent sources (cf. Young Fresnel)

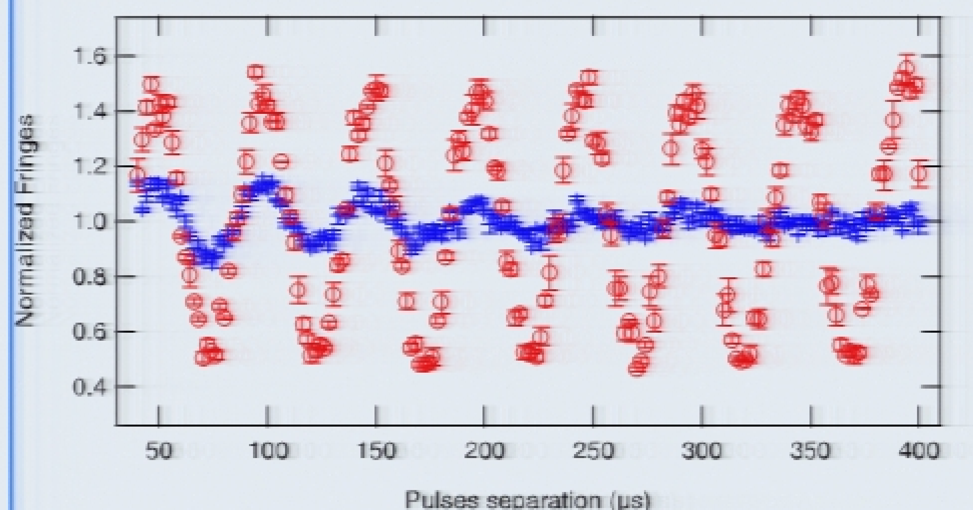
MOT (incoherent atomic source)

Folded Mach-Zehnder interferometer



Evanescent wave atomic mirror

Fringe visibility *vs.* separation at atomic reflection



Study of transverse coherence destruction at reflection on a mirror (roughness, shape defects). Nanometric sensitivity: de Broglie wavelength

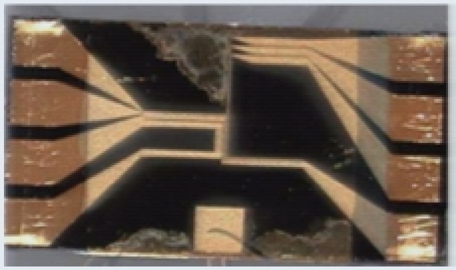
As Photon Optics, Atom Optics can benefit from coherent sources (atom lasers)

Fundamental property of a laser: many photons per elementary mode of the electromagnetic field $(\Delta r^3 \Delta k^3 = 1)$ Dramatic progress in optics:

- Large signal with small aperture interferometers (gravitational wave detection)
- Diffraction limited focusing (CD, DVD, confocal microscope…)
- Possibility to use single mode optical fibers

Bose Einstein Condensates or atom lasers: many atoms per elementary cell of the phase space $(\Delta r^3 \Delta p^3 = \hbar^3)$

- Hopefully improved atom interferometers and atom focusing (nanolithography, nanoprobe…)
- Possibility to use single mode atomic waveguides



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From coherent to quantum atom optics

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BEC: many atoms in the same wave function

density — size of the wave packet $\sim T^{-1/2}$

Bose-Einstein Condensation:

⇒ happens when atomic wave packets overlap $n\Lambda_T^{3} \geq 1$

⇒ increase of density usually leads to molecule (or cluster) formation (except liquid Helium: superfluidity)

⇒ At temperature below 1 μK, BEC with dilute atomic medium

First demonstration in 1995 : evaporative cooling of magnetically trapped alkali atoms (Rb, Na, Li) : Boulder, MIT, Rice

Nobel 2001

BEC of spin polarized hydrogen (MIT, 1998)

BEC of metastable helium (Institut d'Optique, ENS, 2001)

BEC in an optical trap (Georgiatech, 2001)

More: K (Florence 2001), Yb (Kyoto, 2002), Cs (Innsbruck 2002), Cr (Stuttgart, 2004).

Recipe for BEC with a dilute atomic sample

$$n\Lambda_T^3 \geq 1 \quad \Rightarrow$$

decrease temperature and
increase density (moderately)

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- Laser cooling and trapping $\Rightarrow$ $n\Lambda_T^3 \leq 10^{-6}$ (start from 10^{-15})

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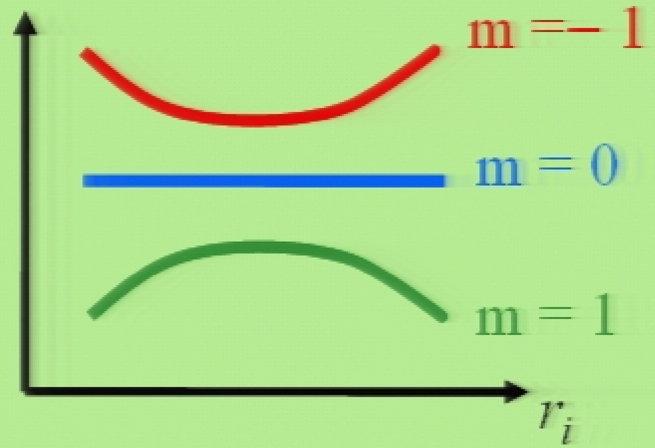
- Turn on a magnetic trap, with a non nul (bias) minimum magnetic field (avoid Majorana non adiabatic losses)

  $n\Lambda_T^{\,3} < 10^{-6}$

$U = g\, m\, \mu_B \,|\mathbf{B}|$



Low field seekers ($g\,m > 0$) trapped at minimum of | B |

Demands large gradients

Recipe for BEC with a dilute atomic sample

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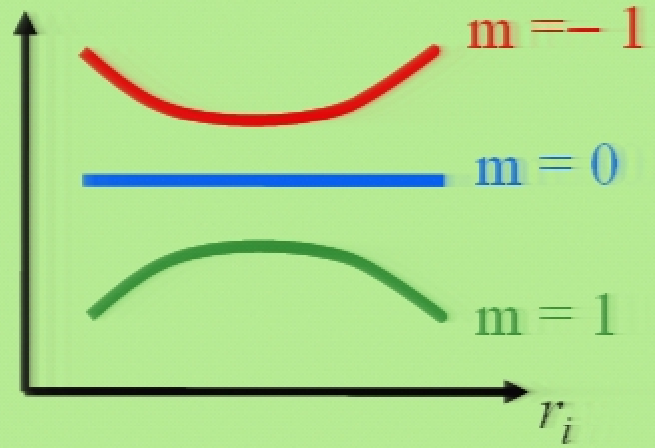
- Non radiative cooling (evaporative, sympathetic…)

$$U = g\, m\, \mu_B \,|\mathbf{B}|$$



Low field seekers ($g\,m > 0$) trapped at minimum of | B |

Demands large gradients

Orsay source for atom lasers: Rb BEC in an iron core electromagnet

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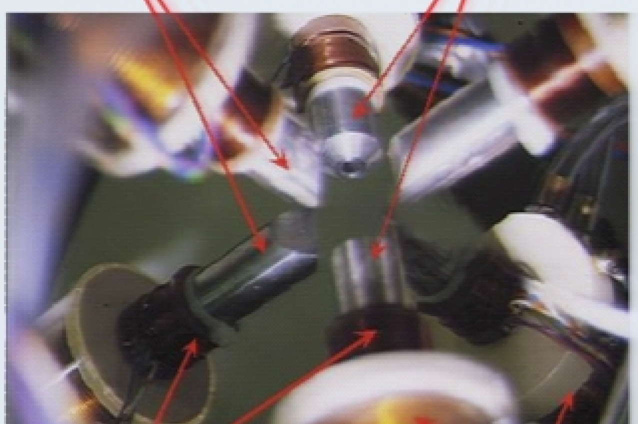
- Low electric power (80 W)
- Strong gradient
- Shielding of the ambient magnetic field

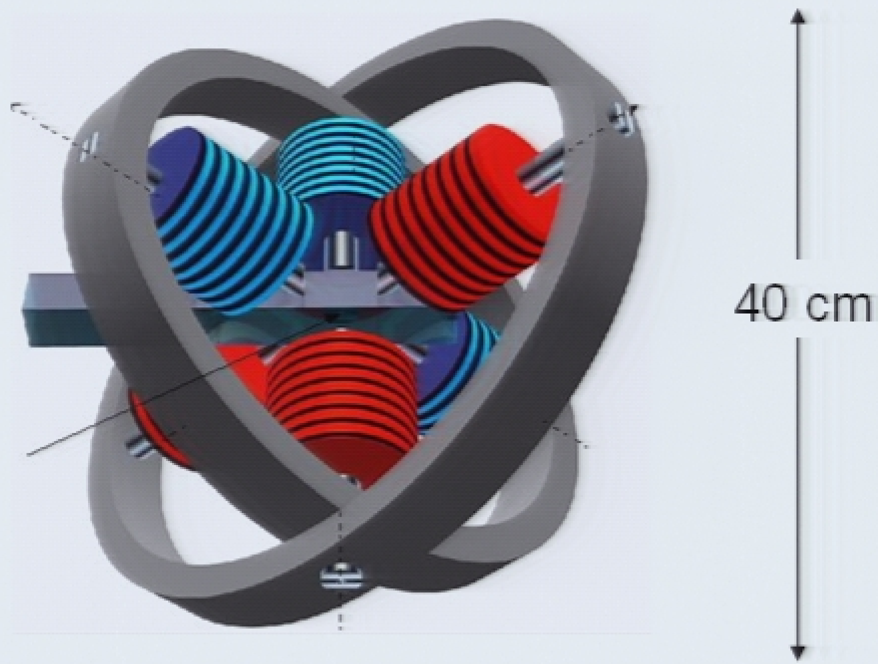
quadripole

dipole



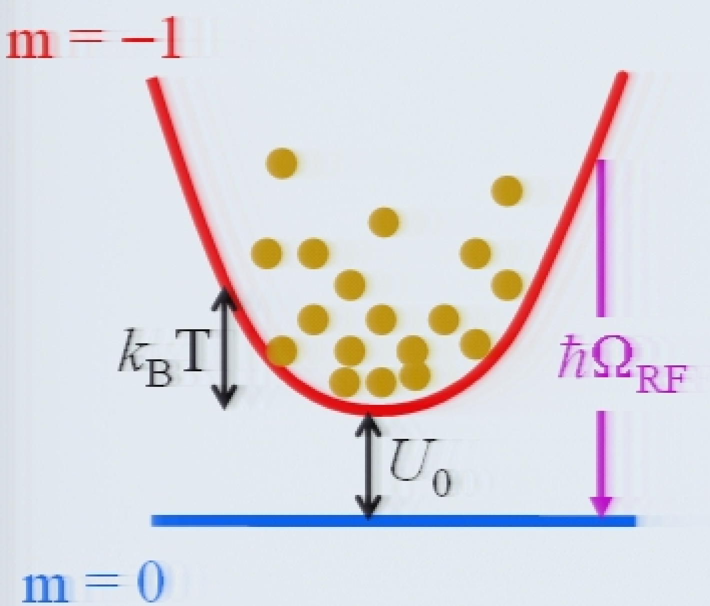
compensating coils

master coils



- Car battery operated BEC (mobile BEC…)
- Low dimensionality possible
- Stability good enough to allow for quasi CW atom laser

Forced evaporative cooling



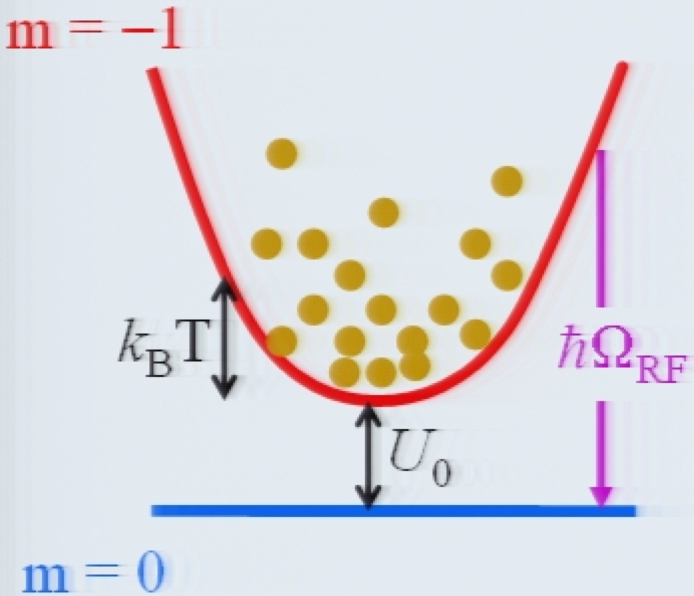
RF eliminates atoms with energy $> \eta k_B T$
(typically $\eta \approx 6$)

After rethermalization (elastic collisions)

- T ↘ $\Rightarrow$ Λ_T ↗
- n ↗ (although N ↘, because T ↘)

$$\Rightarrow \quad n\Lambda_T^{\ 3} \nearrow$$

Forced evaporative cooling



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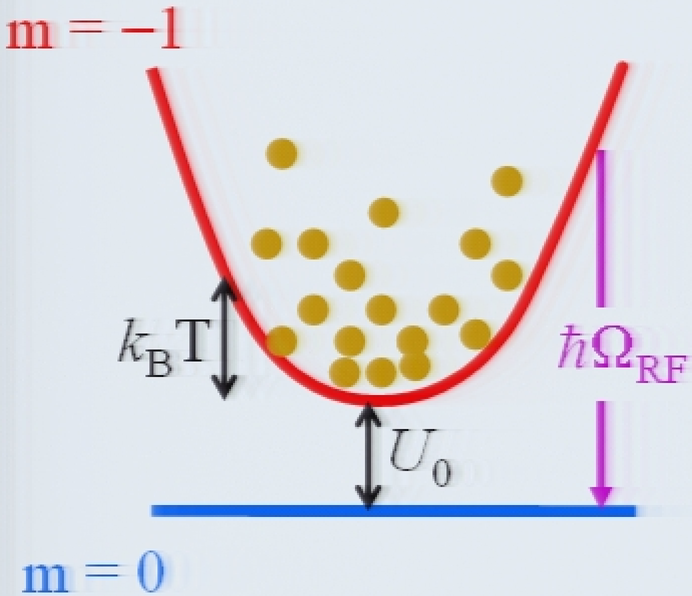
Ω_{RF} ramped down to BEC

$n \Lambda_T^{\,3} > 2.612$

Forced evaporative cooling



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$\Rightarrow$ $n \Lambda_T{}^3$ ↗

Ω_{RF} ramped down to BEC

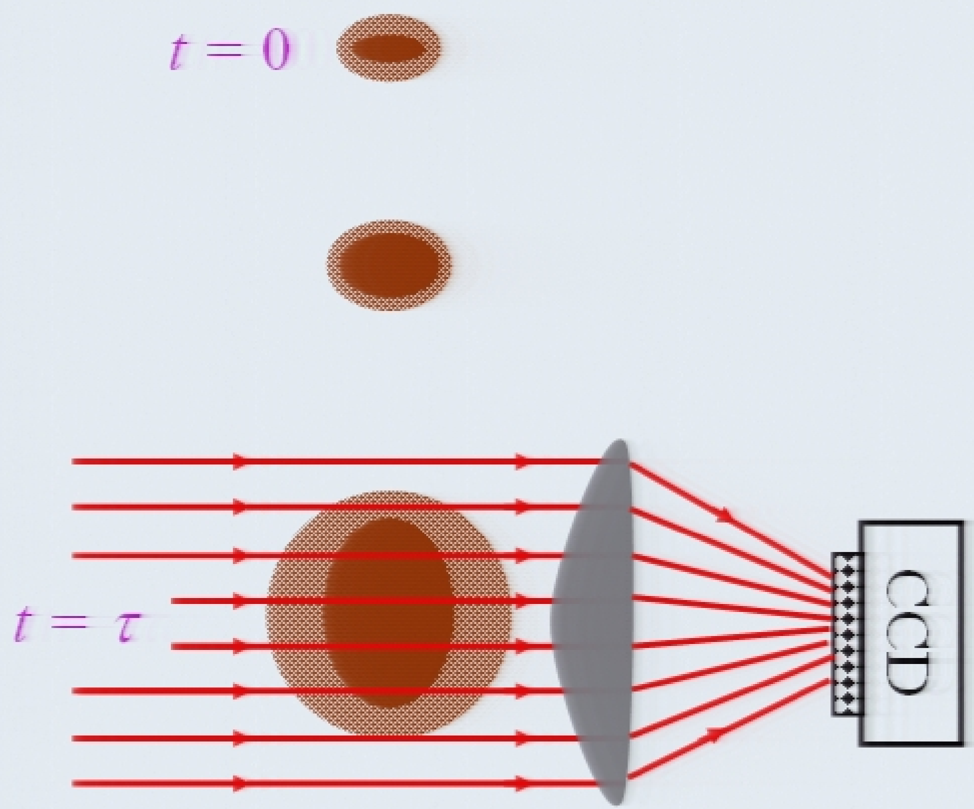
$$n \Lambda_T{}^3 > 2.612$$

Strong demands

- large elastic cross section
- small losses (< 1/300 el.)
  - background pressure ultra low
  - no inelastic processes

Optical observation of Rb condensation

- Turn off the trap at $t = 0$
- Ballistic expansion, duration τ
- Absorption imaging
  - *Thermal component (Bose function, Gaussian wings): mostly velocity
  - *Condensate (Thomas Fermi profile, inverted parabola): mostly interaction energy



Measurement difficult for less than 10^4 atoms

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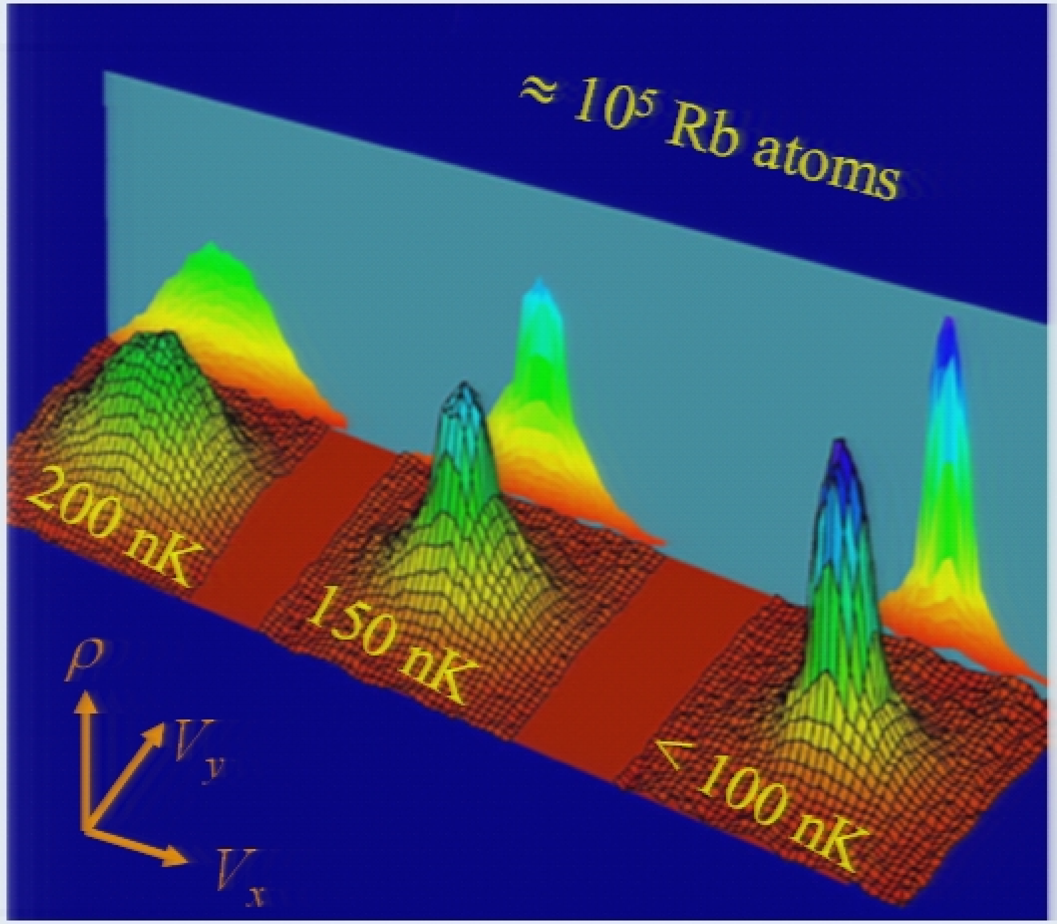
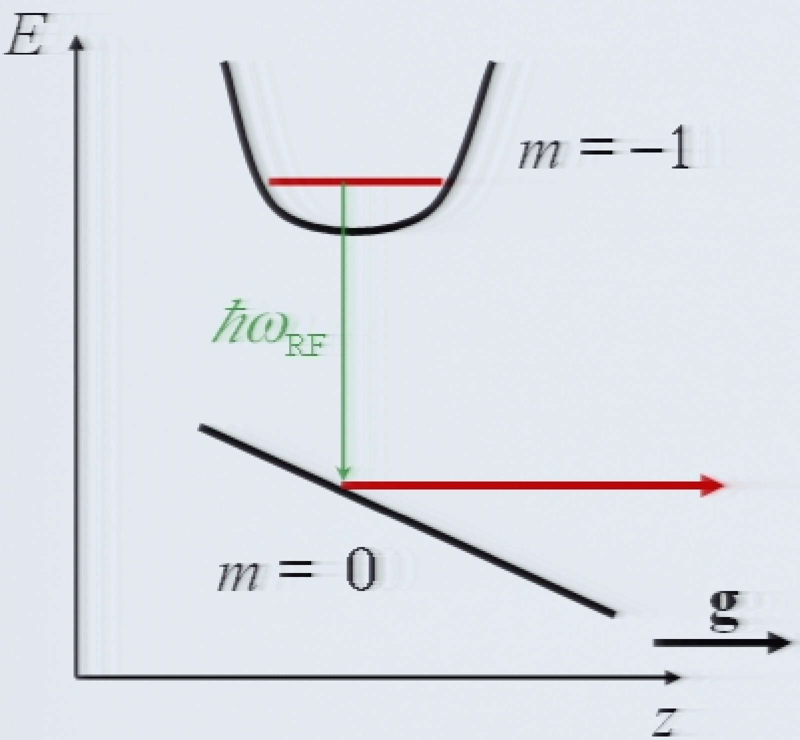
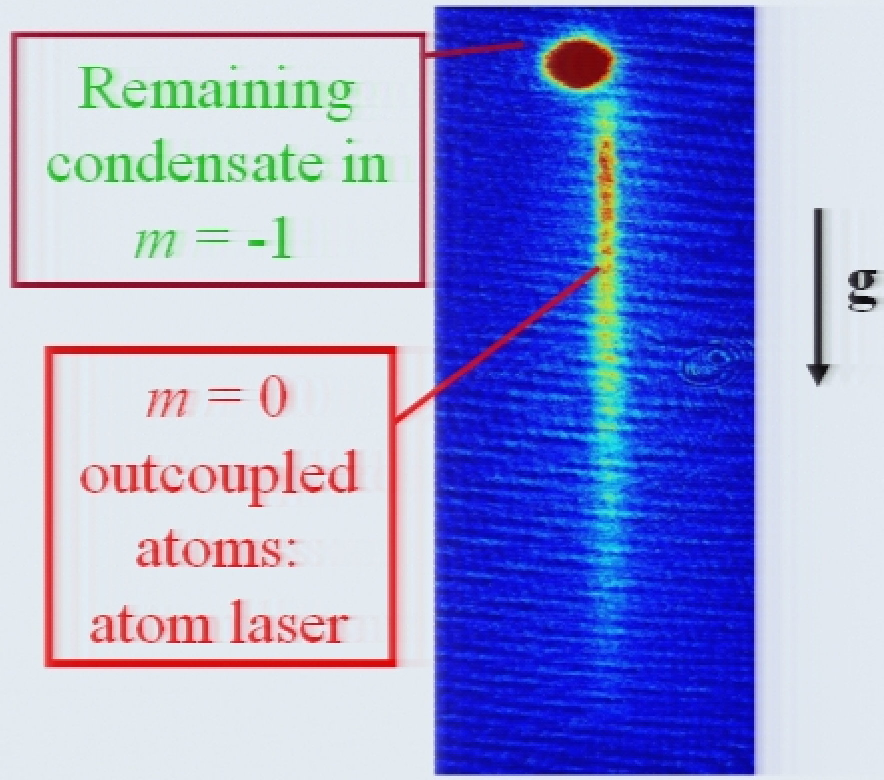


Measurement difficult for less than 10^4 atoms

From BEC to atom laser: a quasi CW gravity driven atom laser





RF (weak) outcoupler from BEC: falling single mode matter wave

cf. Munich experiments

for a simple analytical 3D theory including gravity see Gerbier et al., PRL 2001

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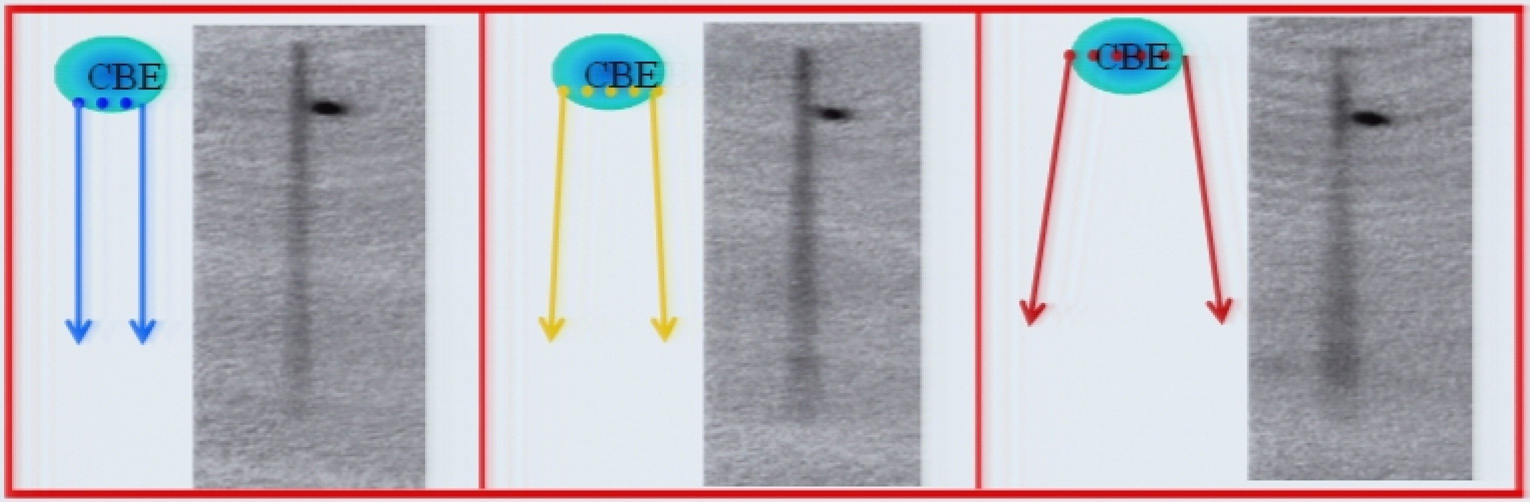
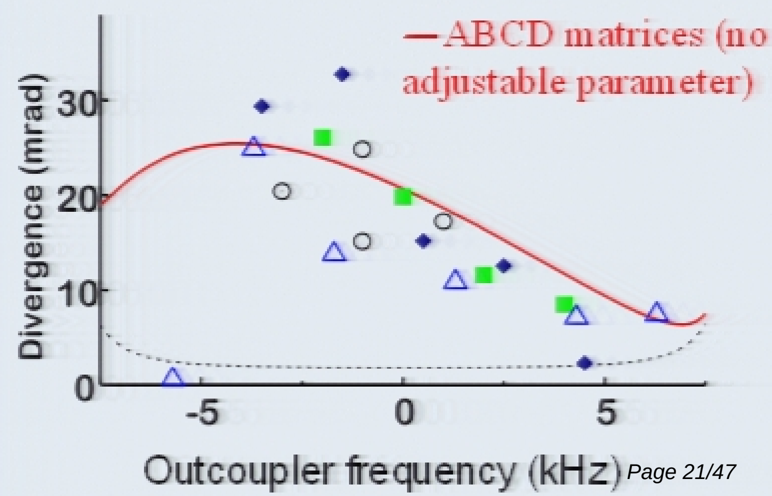
Divergence of a cw atom laser



Divergence clearly increases with height z_{out} of the RF knife

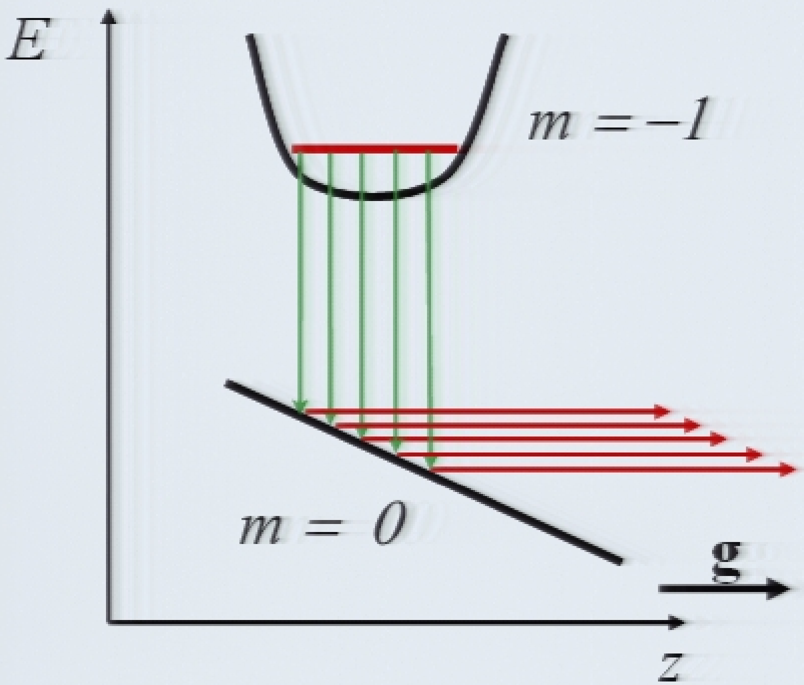
Divergence due to interaction with the remaining condensate

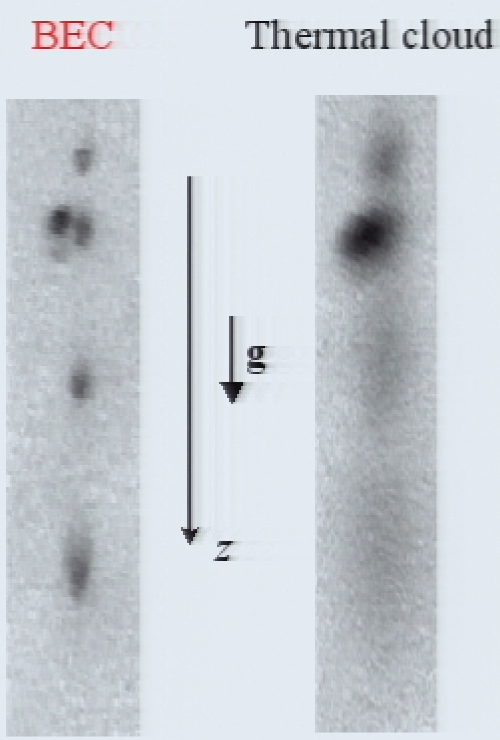
A fruitful analogy: condensate acts as a diverging lens.
Quantitative analysis with a straightforward extension of the ABCD matrices treatment of the propagation of usual (photon) laser beams (see also C. Bordé)



Mode locked atom laser

- Comb of coherent RF outcouplers





FM = 200 Hz

Interference between coherent lasers at different frequencies: analogy to mode locked laser (cf Kasevich et al.)

Quantitative analysis: dephasing due to interaction of each laser with remaining condensate easily calculated with « thin phase object » approximation (*cf.* Raman-Nath)

Atom Optics has much to learn from Photon Optics

- Do not forget your Optics classes
- There is a whole host of concepts, models, approximations… yielding useful analogies

Not all Atom Optics has analogues in Photon Optics

A striking example:

- Phase fluctuations for a BEC in a quasi 1 D trap

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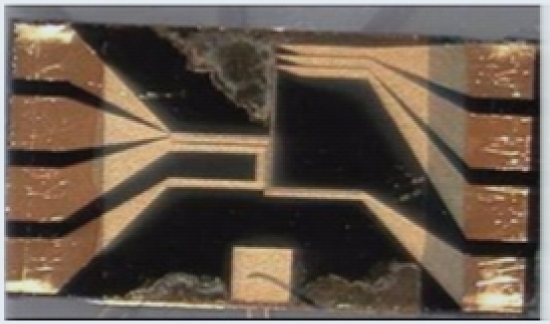
1D BEC: an important problem

Theoretical issues

- No homogeneous 1D BEC (uniform potential)
- 1D BEC possible in a trapping potential with a large aspect ratio: intermediate regime of phase fluctuating « quasicondensates »

Application issues: coherence in integrated atom optics

- Atom interferometers for inertial and gravitational sensors have a potential sensitivity larger than photon gyros → $\frac{M_{at} c^2}{\hbar \omega} \sim 10^{11}$
- Applications demand integrated devices
- Integrated atom optics, atom wave guides, BEC « on a chip » (analogy to integrated photon laser): strong transverse confinement for single mode regime (analogy with single mode optical fibers).

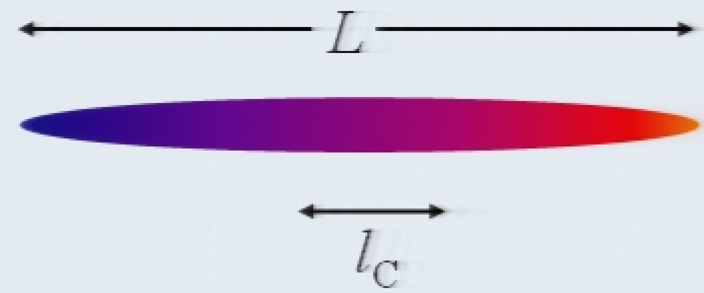


Phase fluctuations in 1D systems → reduced coherence: an issue to address

Phase fluctuations in a quasi 1D BEC

Theoretical prediction for an elongated condensate

« Smooth » density, but axial phase fluctuations thermally excited



Coherence length l_C smaller than condensate size L

$$l_C = L\frac{T_\phi}{T} < L \quad \text{for} \quad T_{BEC} > T > T_\phi = \frac{15N_0(\hbar\omega_z)^2}{16\mu k_B}$$

(D. Petrov, J. Walraven, G. Shlyapnikov)

Reminiscence of no 1D homogeneous BEC

First experimental evidence (Hannover)

Density fluctuations after free expansion (phase fluctuations convert into density fluctuations in the far field diffraction pattern)

Also qualitatively observed in Amsterdam

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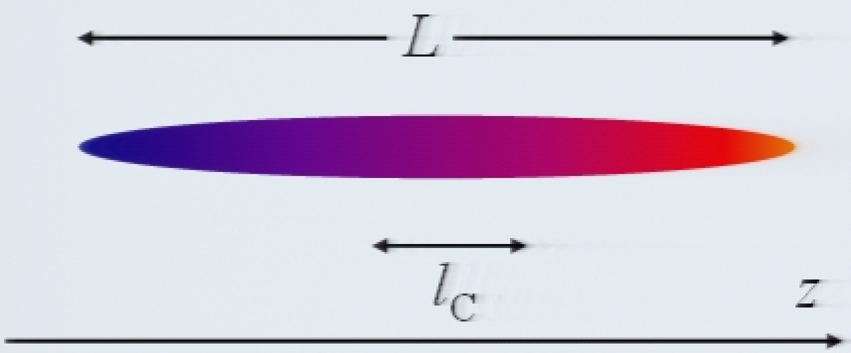
Momentum distribution measurement: a way to measure the coherence length



Momentum distribution $\left\langle \left|\tilde{\psi}(p_z)\right|^2 \right\rangle$

= Fourier transf. of correlation function

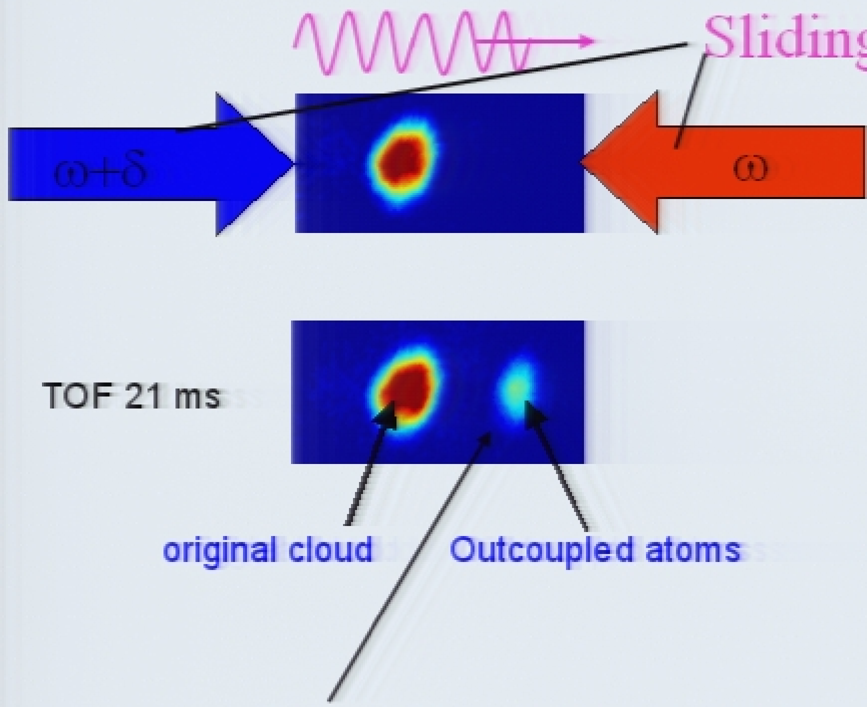
$$C^{(1)}(\delta z) = \int dz_0 \left\langle \psi^*(z_0 + \delta z)\,\psi^*(z_0) \right\rangle$$

Fully quantitative method (cf MIT: transverse coherence length)

Analogous to traditional (dispersion) spectroscopy – *i.e.* meas. of $S(\omega)$ – compared to Fourier transform spectroscopy – *i.e.* meas. of $\Gamma(\tau)$.

Decrease of coherence length:
⇒ increase of momentum distribution width $\quad l_C < L \;\Rightarrow\; \Delta p_z > \dfrac{\hbar}{L}$

Bragg spectroscopy of the momentum distribution: principle



Sliding standing wave = moving periodic potential for the atoms

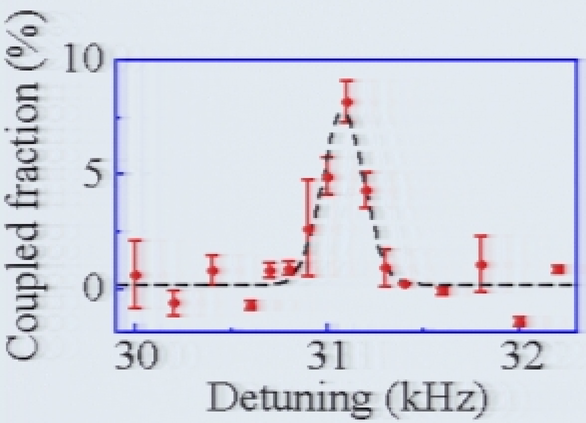
Periodic potential: selective reflection of atoms with a given momentum (Bragg reflection of matter waves with de Broglie wavelength matching the grating period)

Number of extracted atoms = magnitude of the p_z component

By scanning δ one can measure the momentum distribution $\mathcal{P}(p_z)$

cf MIT and NIST

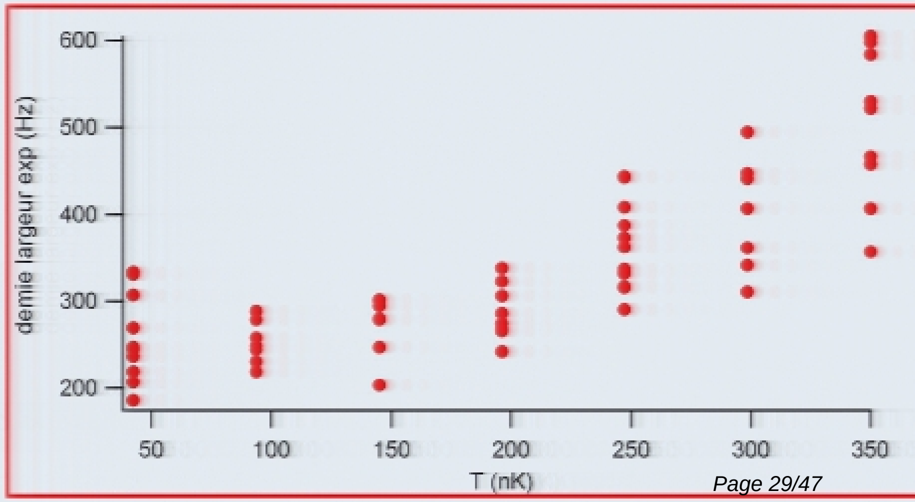
Bragg spectroscopy of the momentum distribution: results



Example of result

resolution of 120 Hz (equivalent to the axially released expansion velocity): 3 mm / mn

- Large a. ratio : 200 (800 Hz / 4 Hz)
- Atom number: a few 10^4

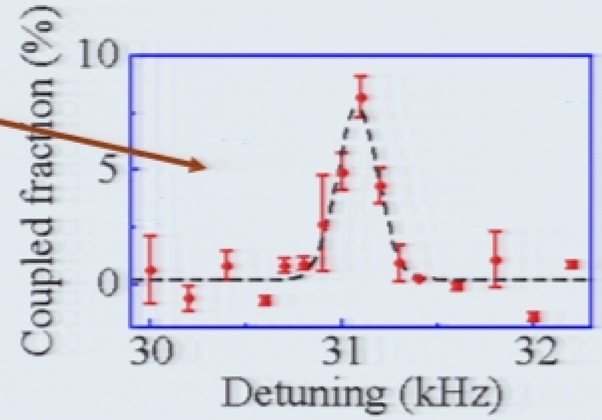


☺ Width clearly increases with *T*

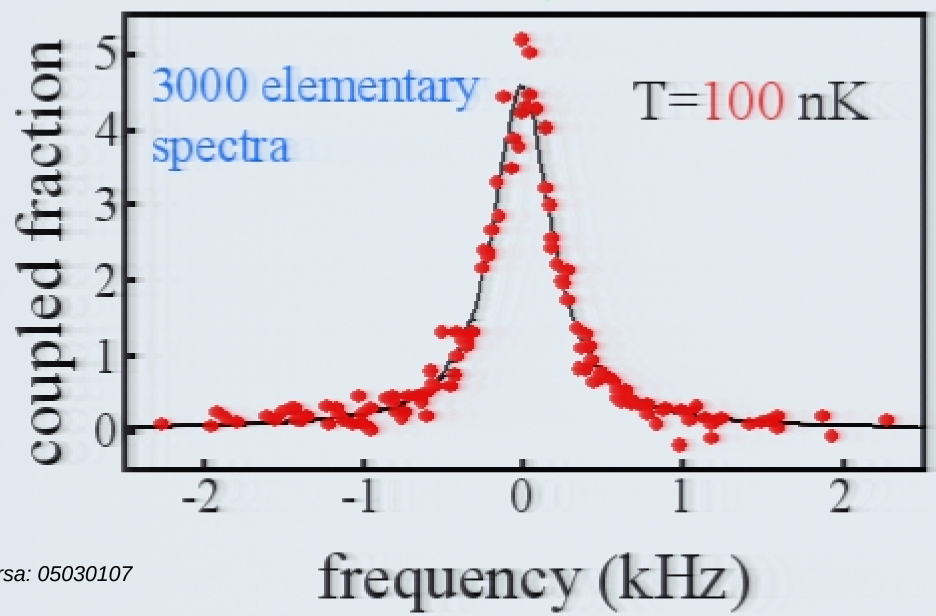
☹ Large dispersion of individual results

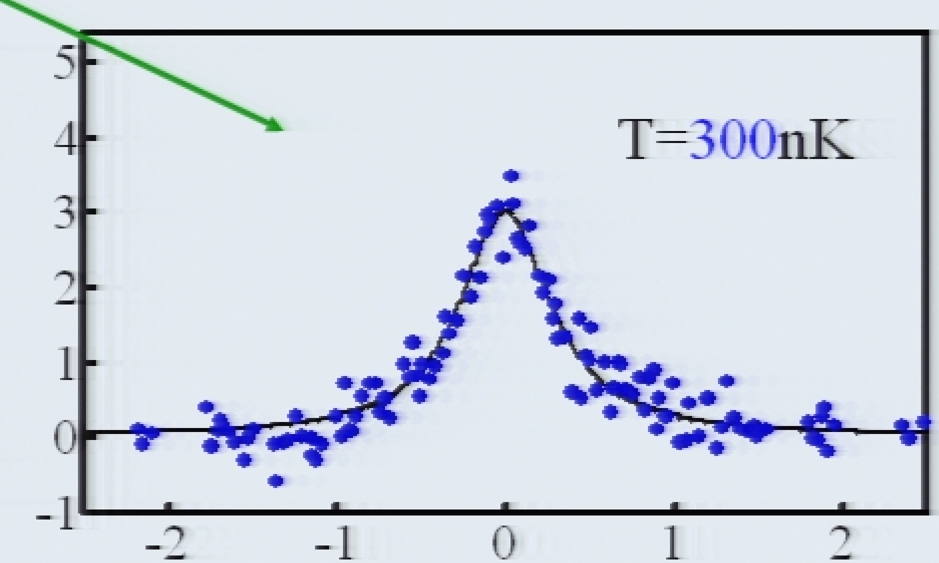
Averaging: fantastic!

One elementary spectrum



3000 elementary spectra

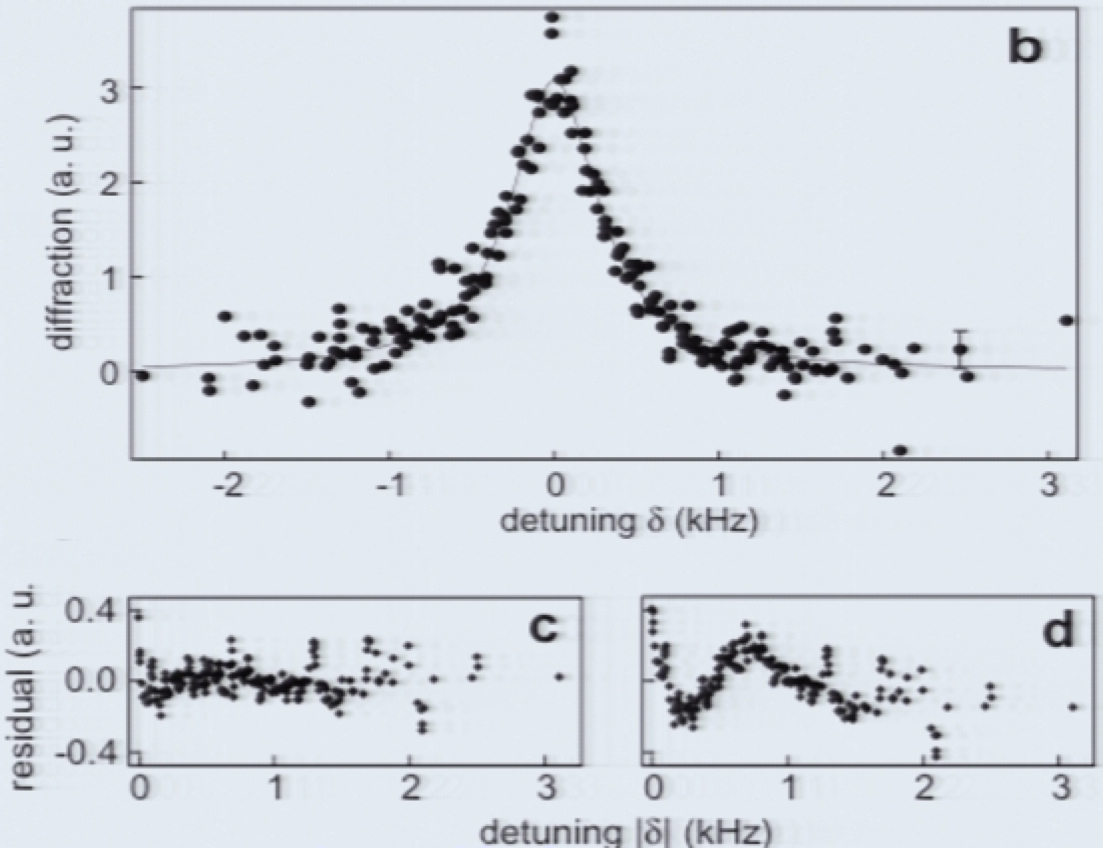




Lorentzian lineshape of momentum distribution

After averaging:
unambiguous discrimination between Gaussian and Lorentzian : exponential decrease of correlation function; phase fluctuations dominate.

As predicted by theory for $T / T_\phi \gg 1$



Lorentzian residual   Gaussian residual

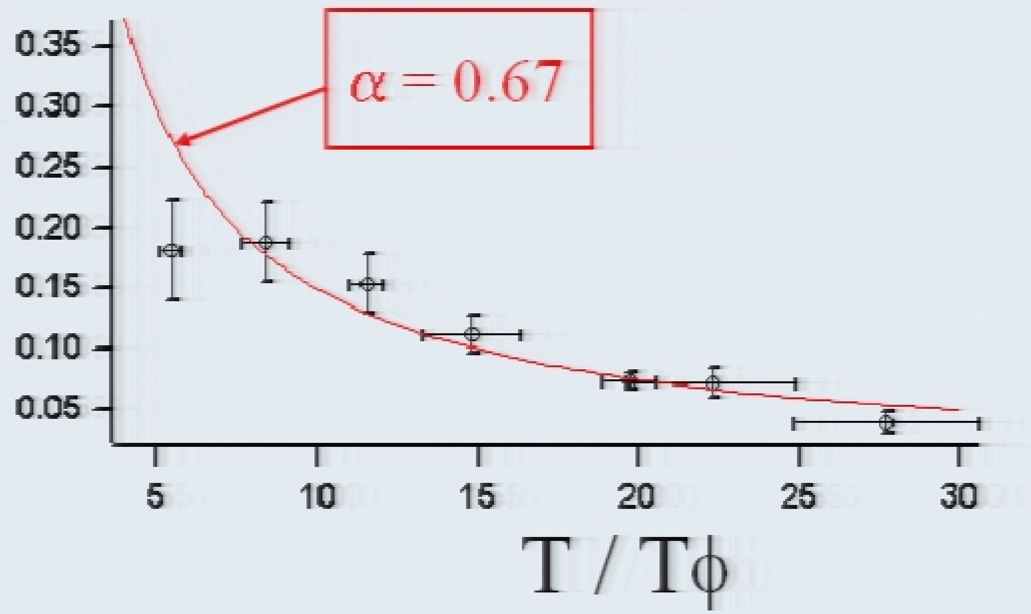
Fit: quantitative measurement of $\Delta p \Rightarrow$ coherence length $l_c = \hbar / \Delta p$

Coherence length *vs.* temperature

Agreement with theory $\frac{l_c}{L_{BEC}} = \frac{1}{\alpha}\frac{T_\phi}{T}$

with $\alpha = 0.67$ (density profile)

Also checked suppression of density fluctuations $\langle n^2 \rangle \simeq \langle n \rangle^2$



- Coherence length definitely smaller than condensate size
- Analogy with laser beam with stable intensity but large phase fluctuations
- Interferometry possible with small path difference designs

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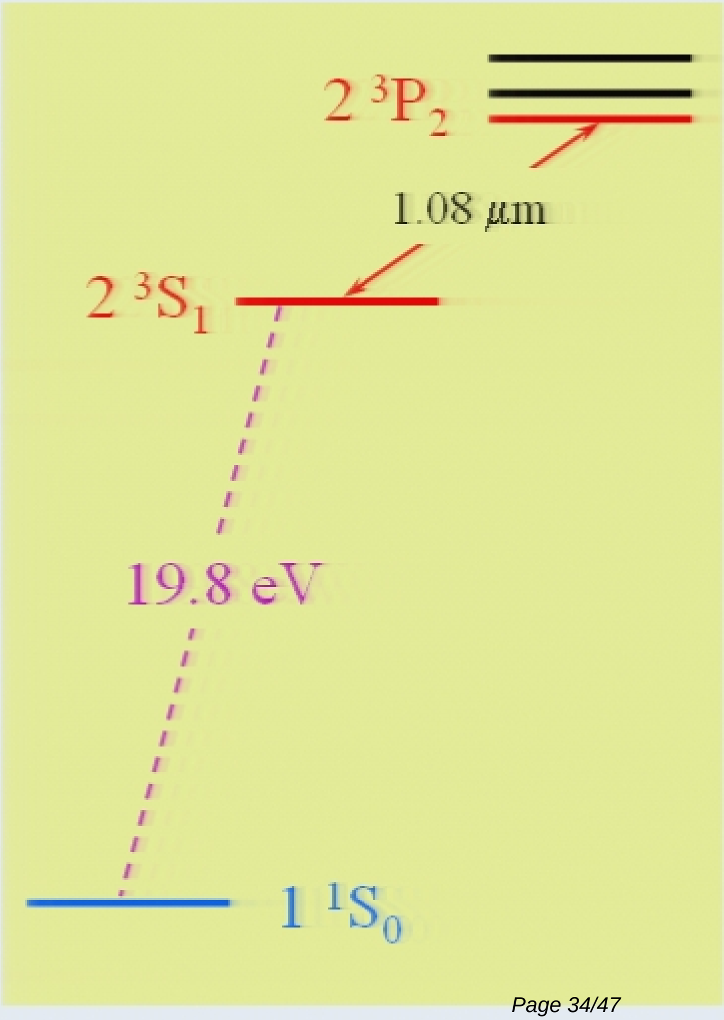
Metastable Helium $2\,^3S_1$

- 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

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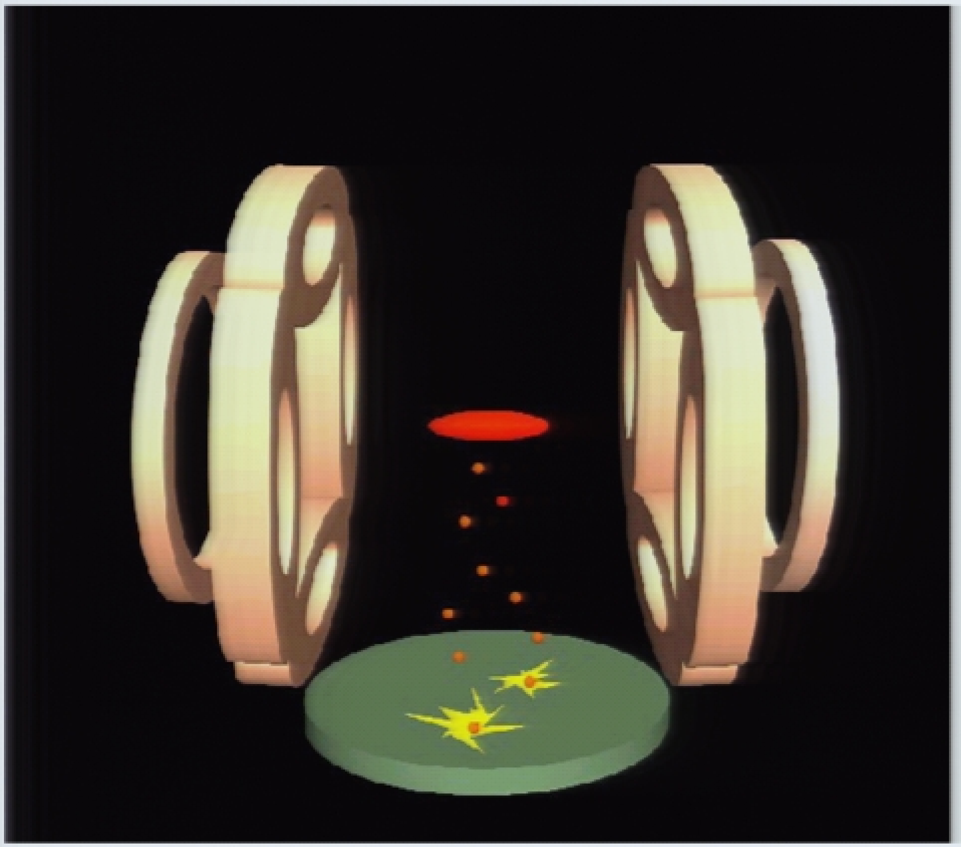


Clover leaf trap

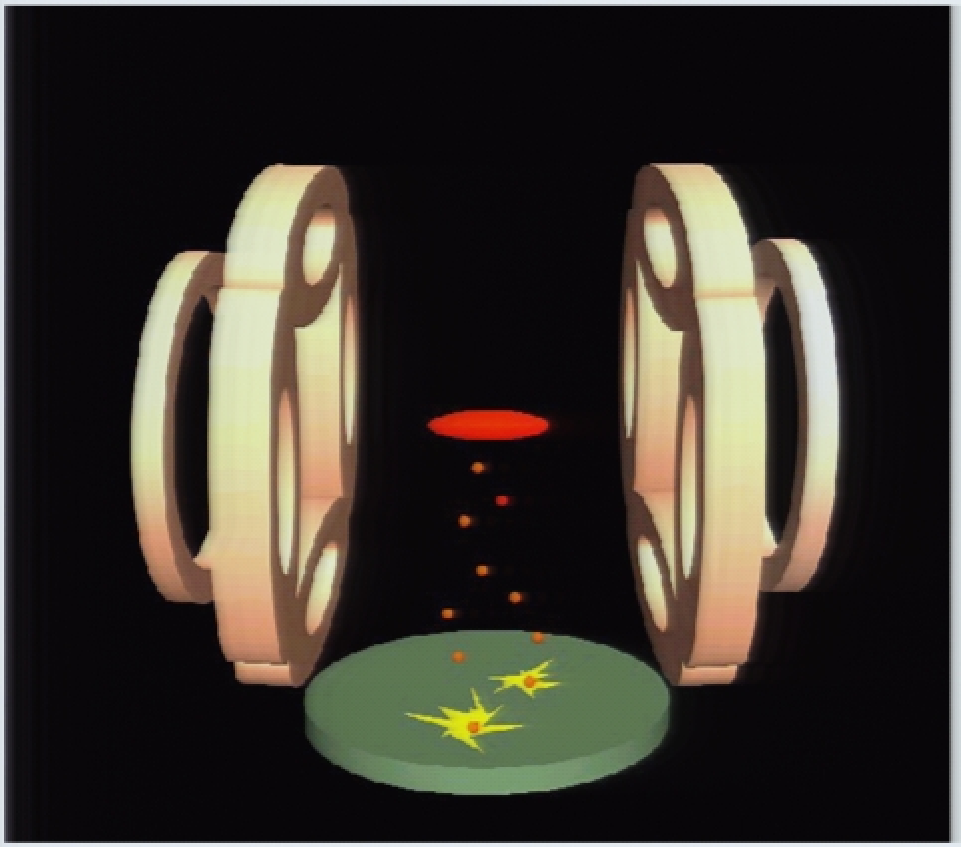
@ 240 A : B_0 : 0.3 to 200 G ;

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

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

(1200 Hz)

He* trap and MCP detection



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(1200 Hz)

He* on the Micro Channel Plate detector:

⇒ an electron is extracted

⇒ multiplication

⇒ 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

⇒ 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*

$$He^{*} + He^{*} \rightarrow He(1^{1}S_{0}) + He^{+} + e^{-}$$

Reaction constant ≈ 5×10^{-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 spin conservation:

$$m = 1 + m = 1 \not\rightarrow s = 0 + s = 1/2 + s = 1/2$$

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Magnetically trapped He* *is* spin polarized

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

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Definitive evidence of supression ($\sim 10^{-4}$) :

BEC of He* observed (Orsay, Paris, 2001)

$a \approx 10 \pm 10$ nm

Evaporative Cooling to BEC

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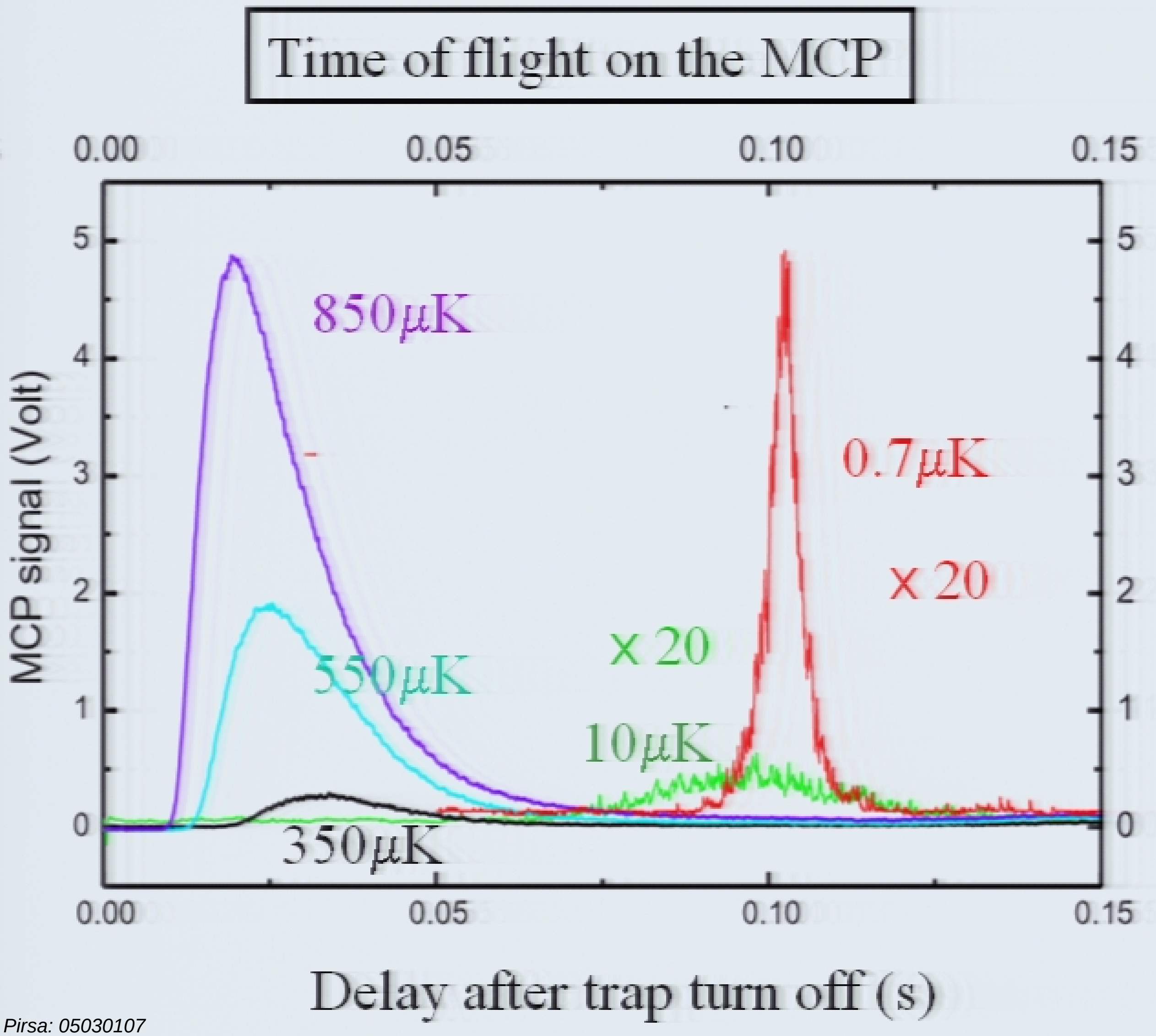
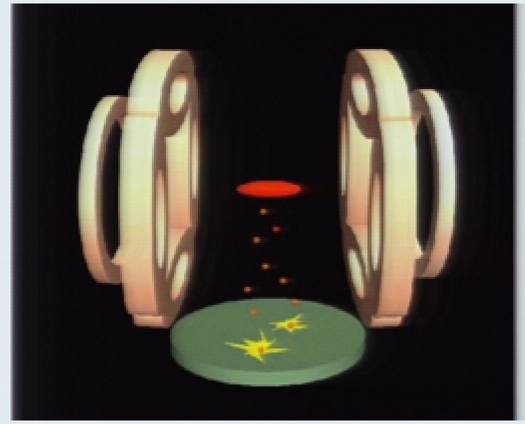




- RF ramped down from 130 MHz to ~ 1 MHz in 70 s (exponential 17 s)

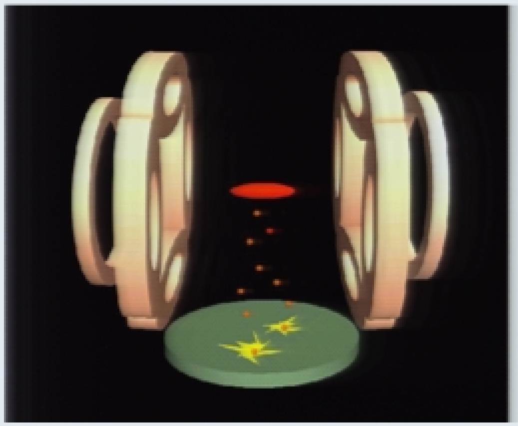
  $\Rightarrow$ less atoms, colder

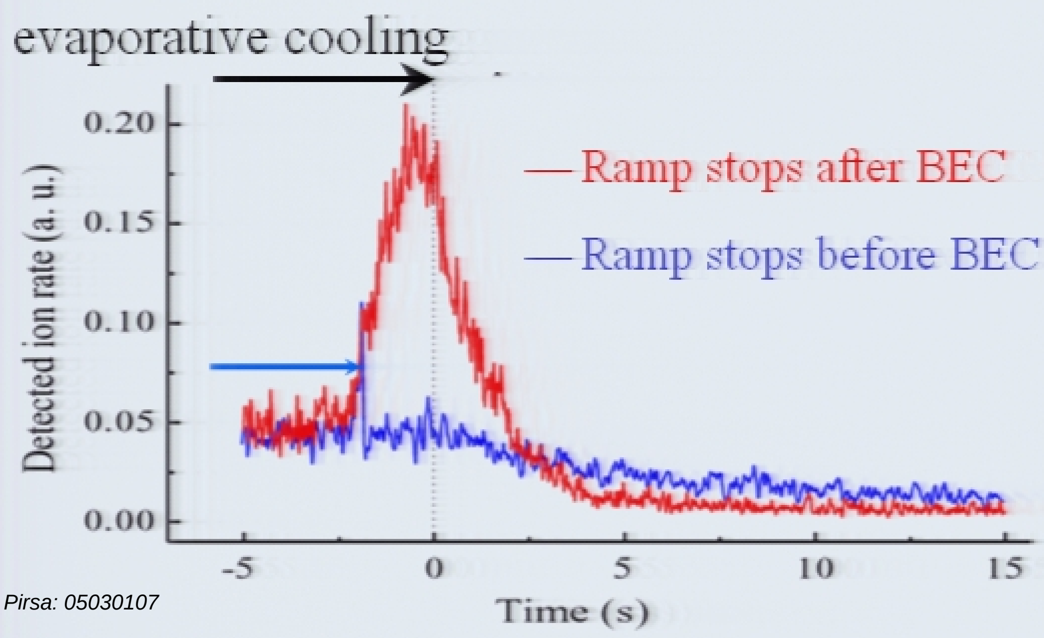
- Small enough temp. (about 2µK): all atoms fall on the detector, better detectivity

- At 0.7µK: narrow peak, BEC

Residual ionization of trapped He*
A new tool for monitoring a BEC

- Residual ionization of trapped atoms → He^+ detected with negatively biased grid (2keV) in front of MCP in counting mode (from 10^2 to 10^3 s^{-1}): signal proportional to density





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

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

Quantitative

Single He* detection: breakthrough in quantum atom optics

Photon counting (1950-): start of modern quantum optics

Correlated photon pairs

- Bunching in thermal light (Hanburry-Brown and Twiss)
- Time correlated photon pairs (Burnham, Mandel)
- Entangled pairs (violation of Bell's inequalities)
- Entanglement as a resource for quantum information (cryptography, teleportation, quantum gates…)

Single photon effects

Single He* detection: breakthrough in quantum atom optics

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Photon counting (1950-): start of modern quantum optics

Correlated photon pairs

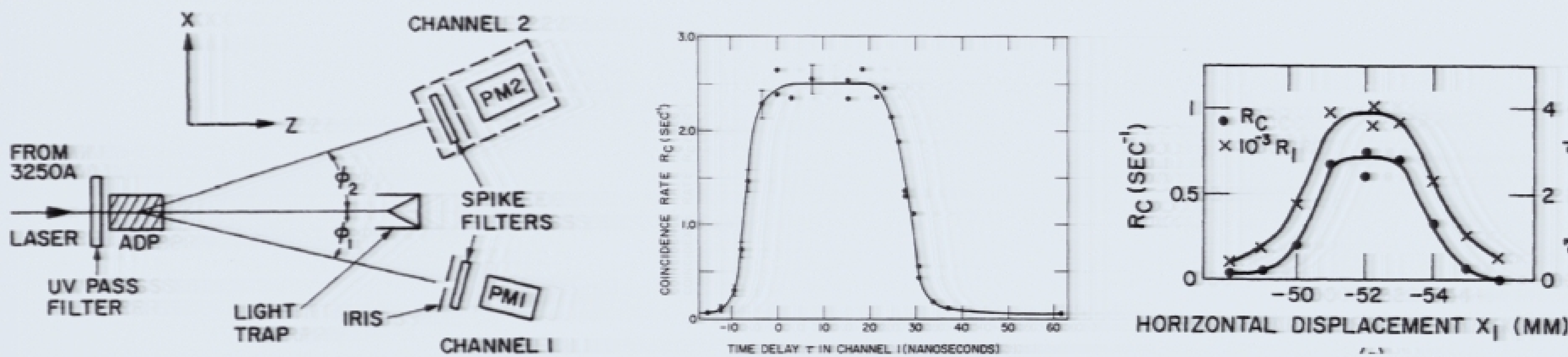
Single photon effects

- Antibunching in resonance fluorescence (Kimble, Dagenais, Mandel)
- Anticorrelation on a beam splitter, wave-particle duality (Grangier-A.)
- Single photon "on demand" (Moerner, Orrit…)
- Single photon as a resource for quantum information (cryptography…)

Single He* detection: breakthrough in quantum atom optics

Photon counting (1950-): start of modern quantum optics

Correlation function resolved in space and time $g^{(2)}(\mathbf{r}_1, t_1; \mathbf{r}_2, t_2)$



OBSERVATION OF SIMULTANEITY IN PARAMETRIC PRODUCTION OF OPTICAL PHOTON PAIRS

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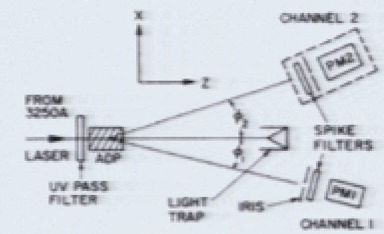
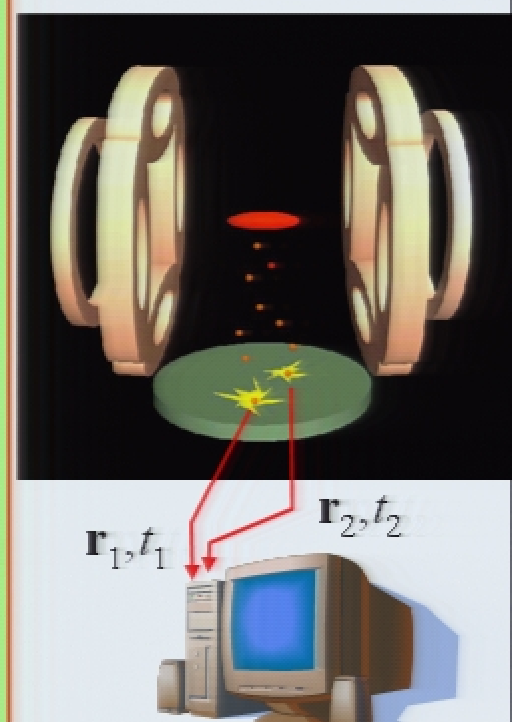
Single He* detection: breakthrough in quantum atom optics

Photon counting (1950-): start of modern quantum optics $g^{(2)}(\mathbf{r}_1, t_1; \mathbf{r}_2, t_2)$



Single He* atom detection, resolved in time and space (2005-)

- Study of any correlation function of atomic field
  - Hanburry-Brown & Twiss type experiments
  - Fluctuations of atom laser around BEC transition
  - Detection of correlated atom pairs in 4-wave mixing
  - Entangled atomic pairs? Bell's inequalities violation? A ressource for quantum information?



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