Detecting correlated atoms

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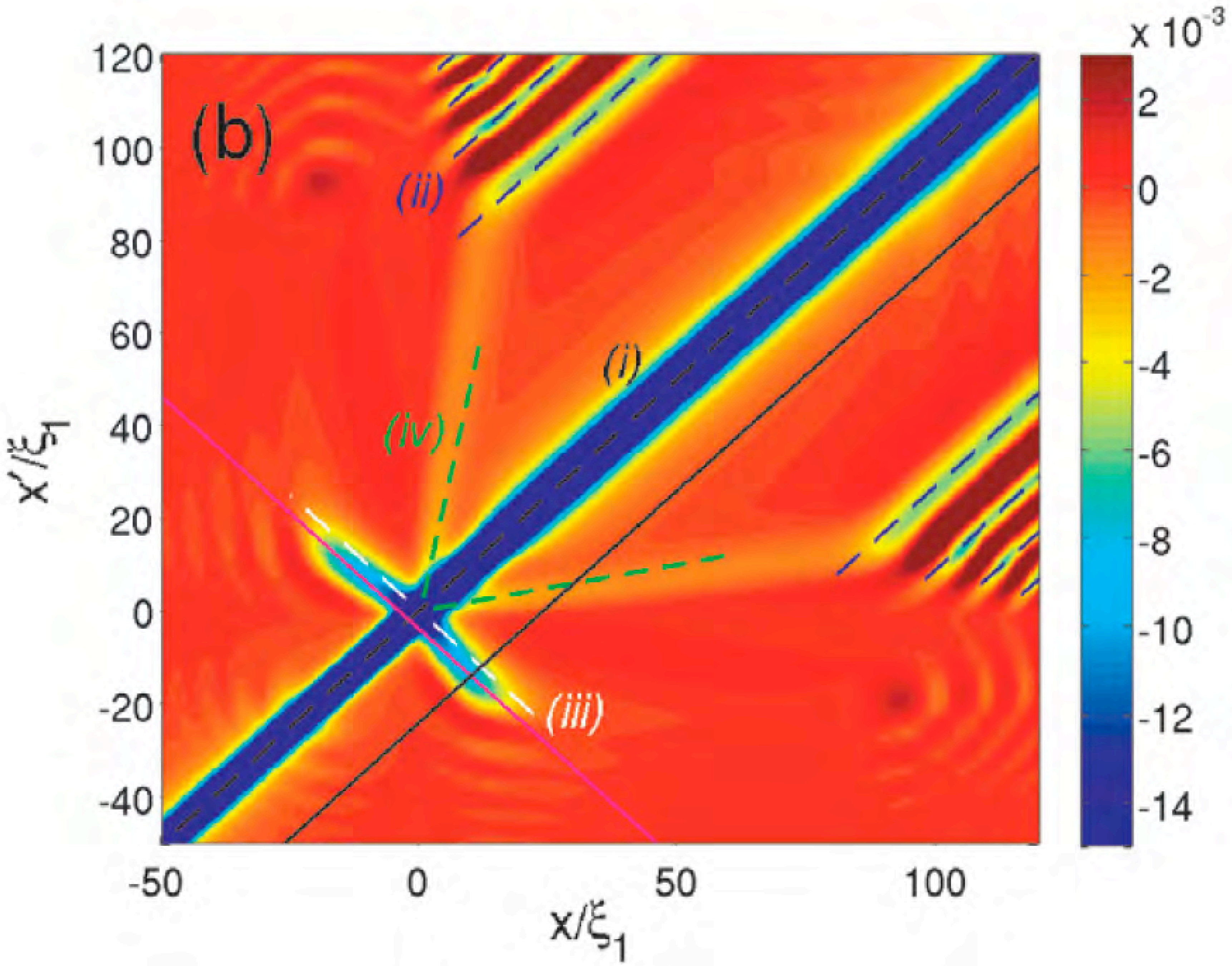
ERH *Valencia 6 Feb 2009*

motivation



Two particle correlation function:
$n\,\xi_1\,g^{(2)}(x,x')$

Numerical observation of Hawking radiation from acoustic black holes in atomic Bose–Einstein condensates
Iacopo Carusotto, Serena Fagnocchi, Alessio Recati, Roberto Balbino and Alessandro Fabbri

***New Journal of Physics* 10 (2008) 103001 (15pp)**

Correlation functions

$$G^{(1)}(x,x') = \langle \psi^\dagger(x)\psi(x')\rangle$$ p-distribution, interference contrast

$$G^{(2)}(x,x') = \langle \psi^\dagger(x)\psi^\dagger(x')\psi(x')\psi(x)\rangle$$

detect one particle at *x* and one at *x*′

$$G^{(2)}(p,p') = \langle \psi^\dagger(p)\psi^\dagger(p')\psi(p')\psi(p)\rangle$$ one at *p* and one at *p*′

$$\langle n(x)^2\rangle = \langle \psi^\dagger(x)\psi(x)\psi^\dagger(x)\psi(x)\rangle$$ squared density at *x*

Relationships (or lack thereof) g is normalized

- for thermal samples: $g^{(2)} = 1 \pm |g^{(1)}|^2$, $\langle n^2\rangle = 2\langle n\rangle^2 \pm \langle n\rangle$
- no general relationship between $g^{(2)}(p,p')$ and $g^{(2)}(x,x')$

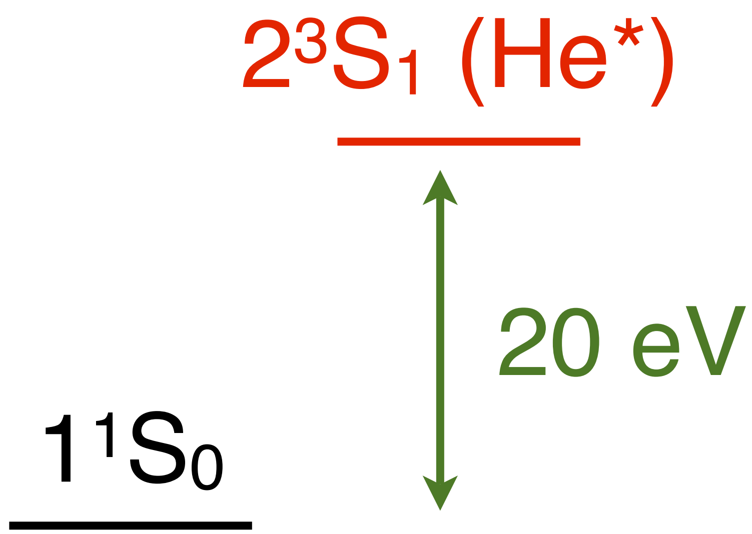
The team

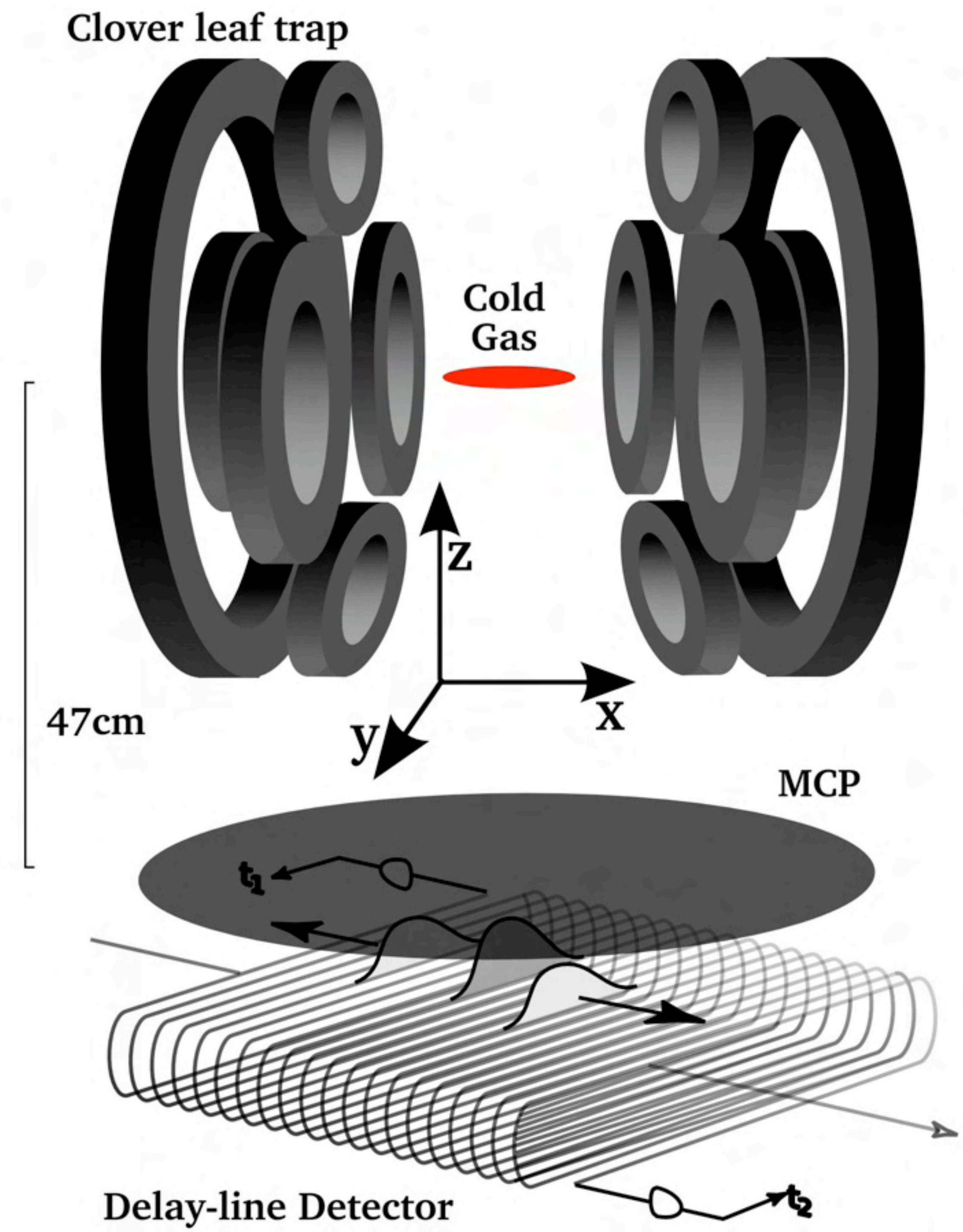
- Valentina Krachmalnicoff, Jean-Christoph Jaskula, Marie Bonneau, Karim El Amili, Julien Armijo
- Vanessa Leung, Guthrie Partridge, Carlos Garrido Alazar, Sébastien Gleyzes
- Denis Boiron, Isabelle Bouchoule, Alain Aspect

Outline

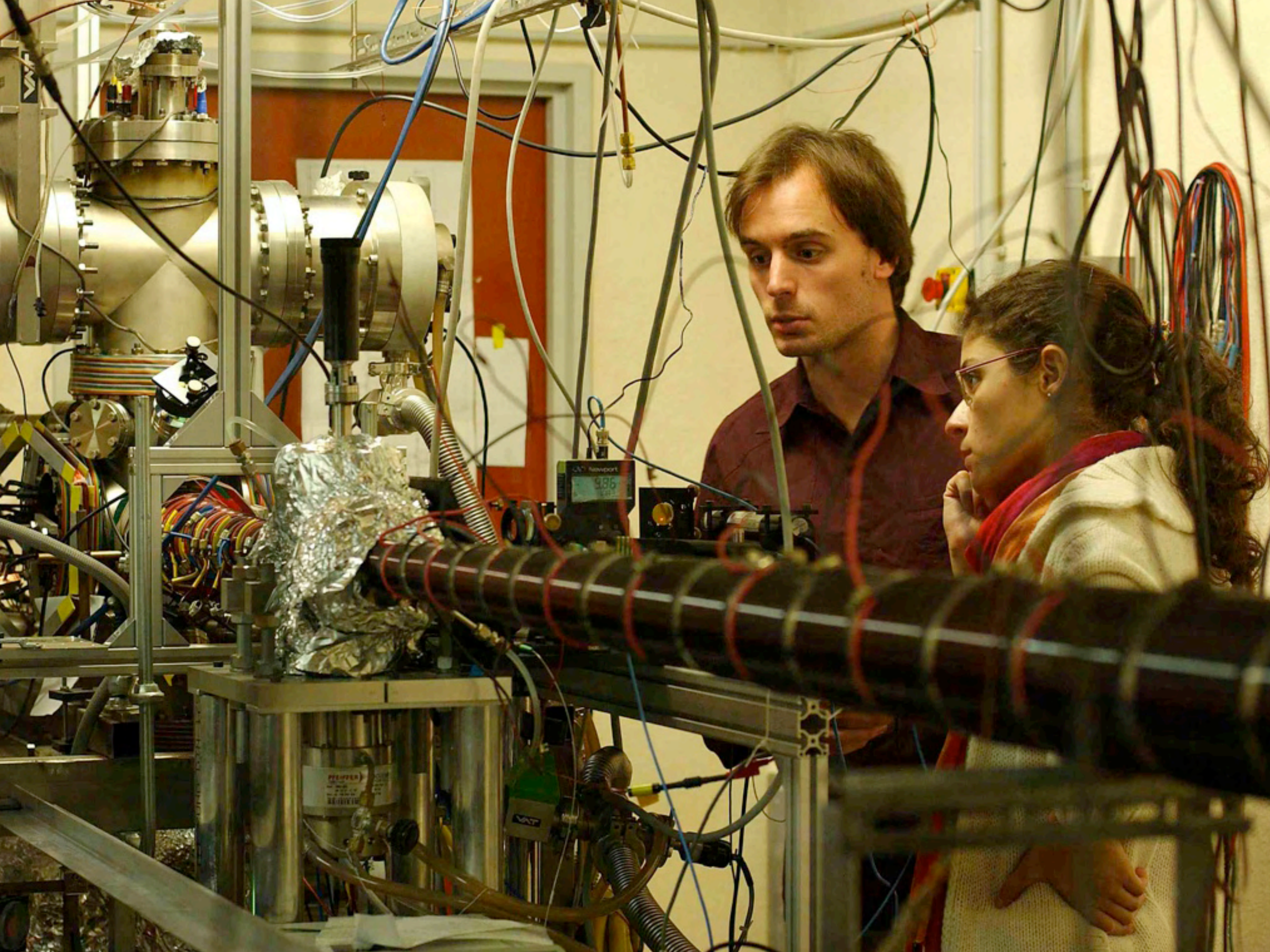
- Metastable He, after expansion, $g^{(2)}(p,p')$
  - Hanbury Brown Twiss
  - Other experiments
  - Correlated pairs
  - Other experiments
- Rb on an atom chip, in situ, $\langle n(x)^2 \rangle$.
- More other experiments

He* apparatus

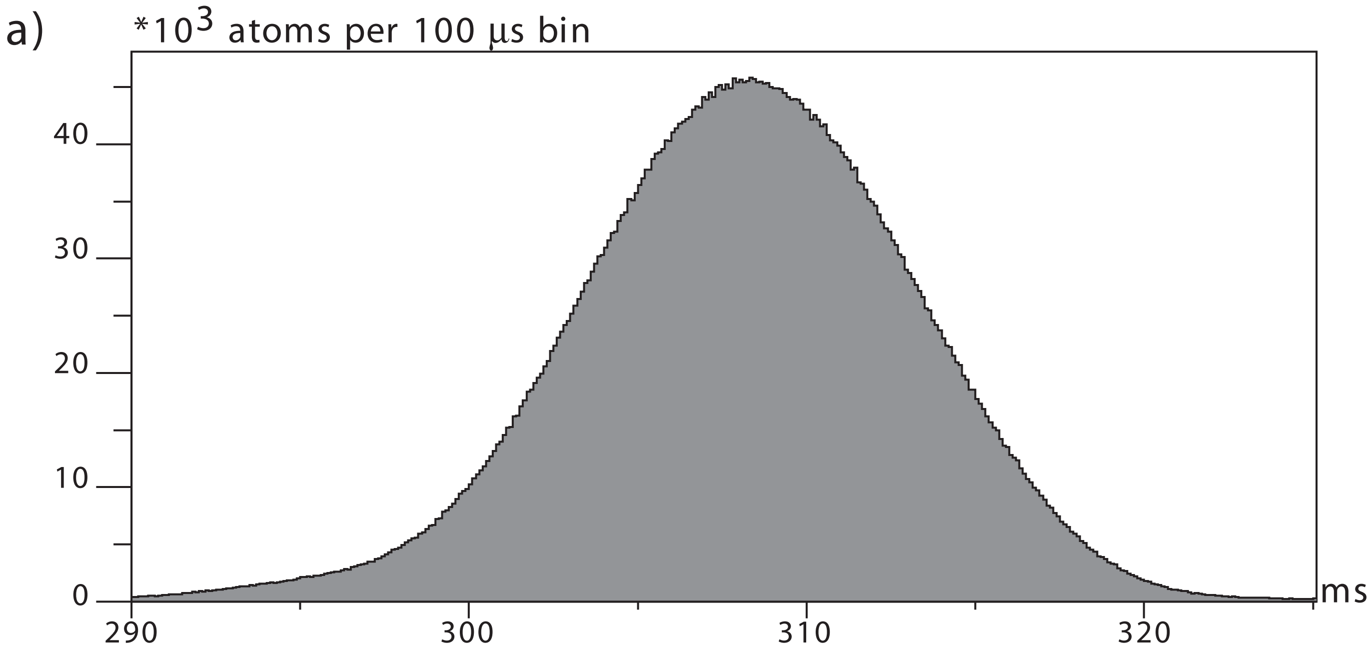


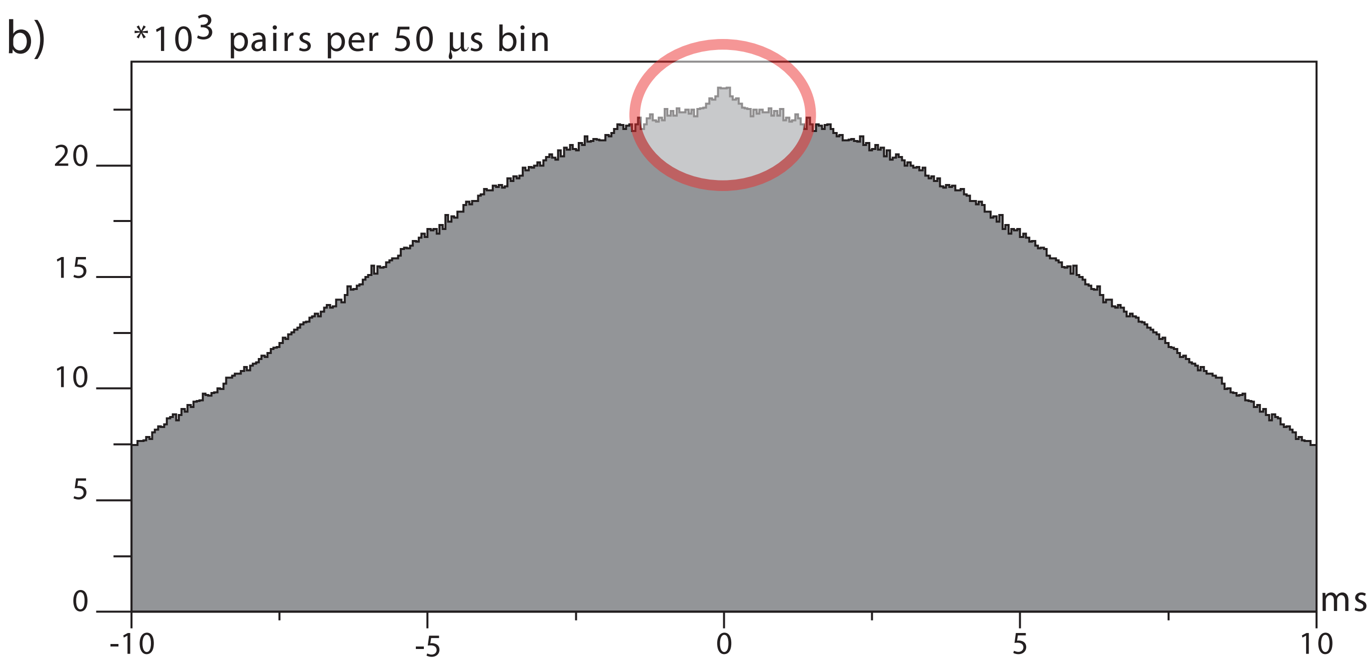


- detection by μ-channel plate (He* has 20 eV)
- excellent time (vertical) resolution
- ~ 500 μm horiz. res. $5*10^4$ detectors in //
- long time of flight
- lots of data


Newport
VAT

1st expt: drop the atoms on the detector





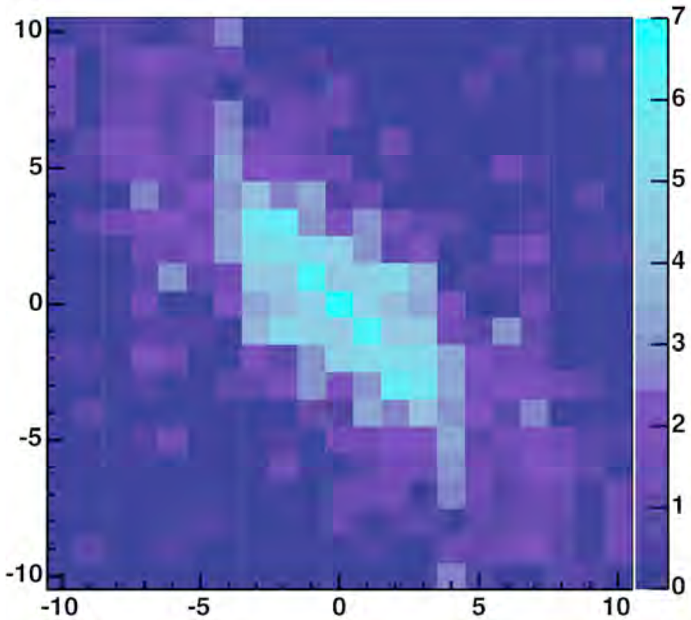
$n(p_z)$

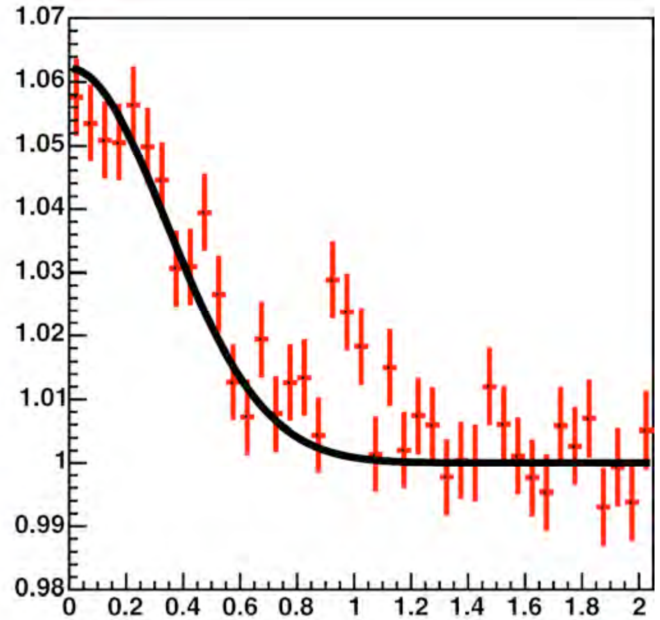
Actually, the arrival time distribution integrated over the detector, summed ~1000 times

$G^{(2)}(p-p')$

Actually the number of pairs within a small volume: $(500\times500\times150\ \mu m^3)$.

Normalized correlation functions

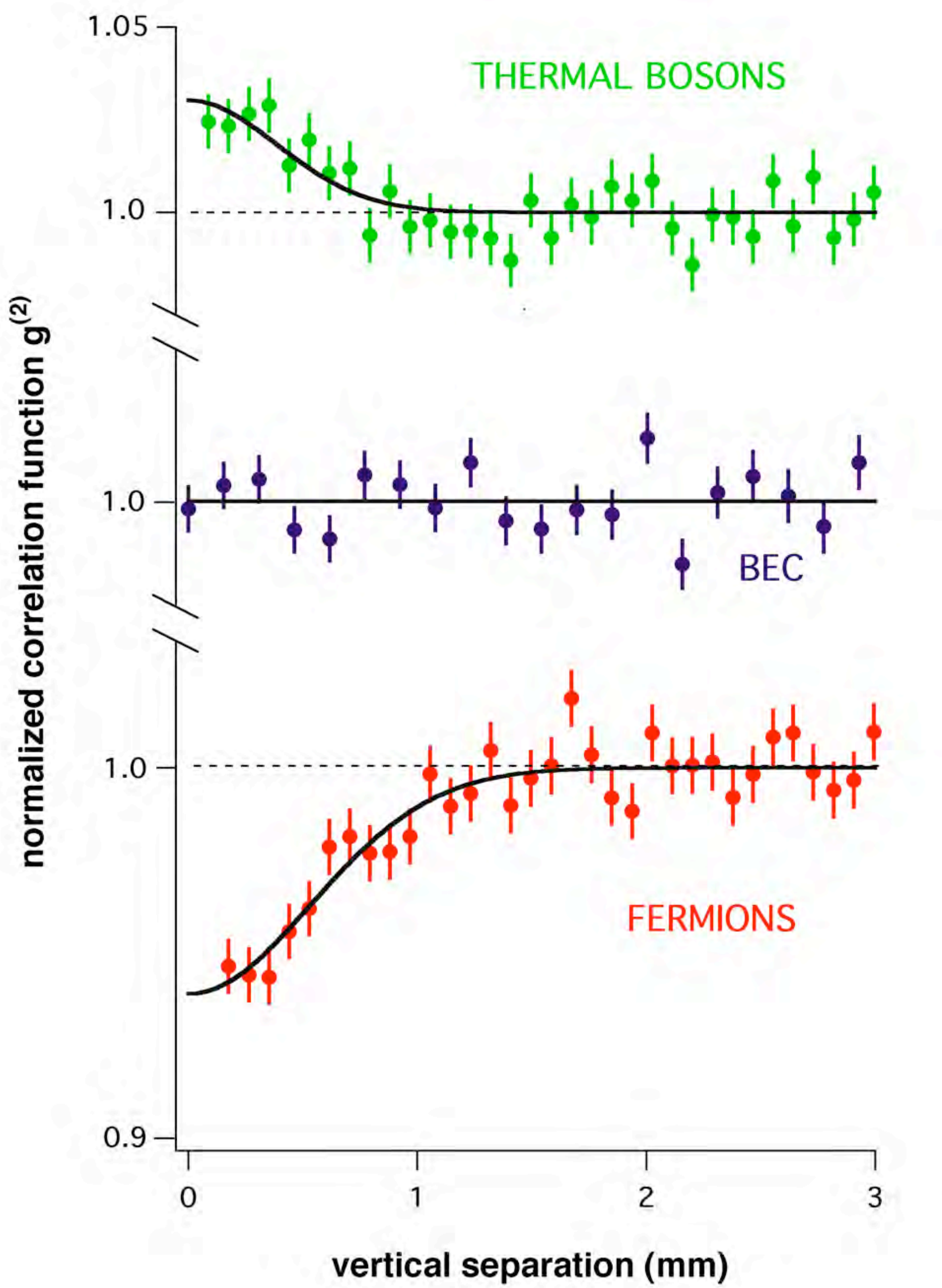




in detector plane

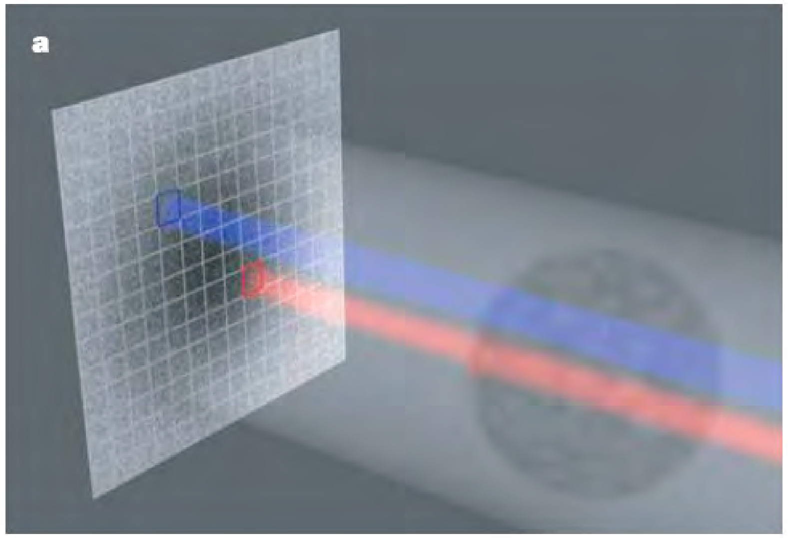
vertical

$g^{(2)}(p-p')$

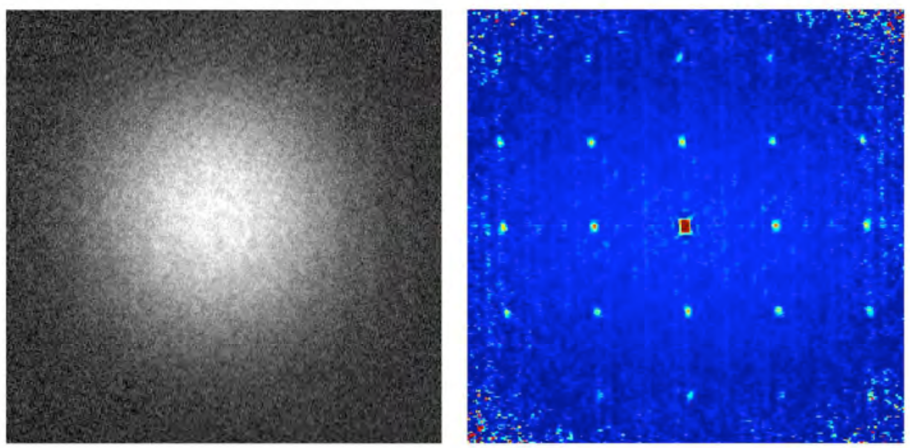


M. Schellekens et al. *Science*, **310**, 648 (2005)
T. Jeltes et al. *Nature* **445**, 402 (2007)

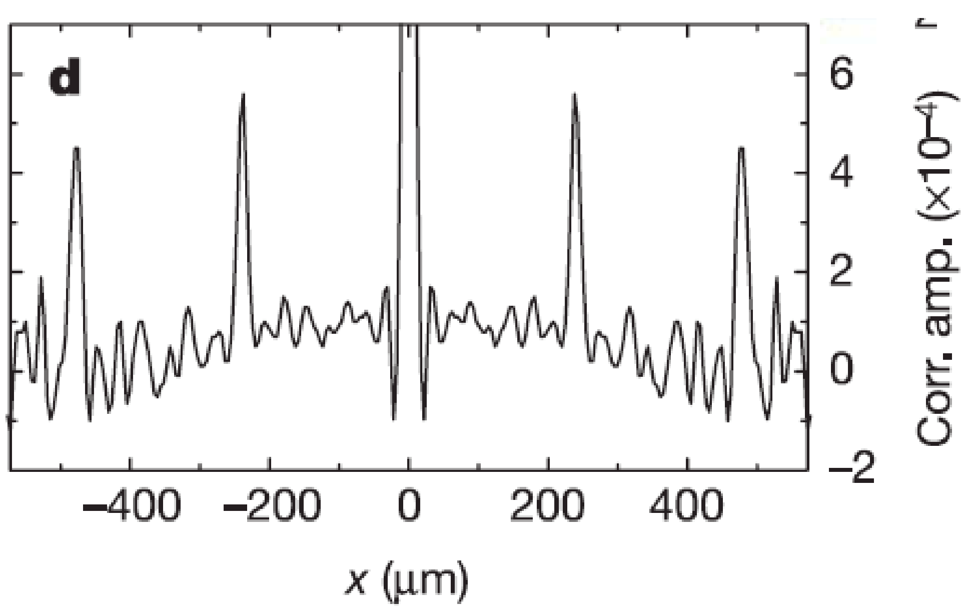
Other experiments



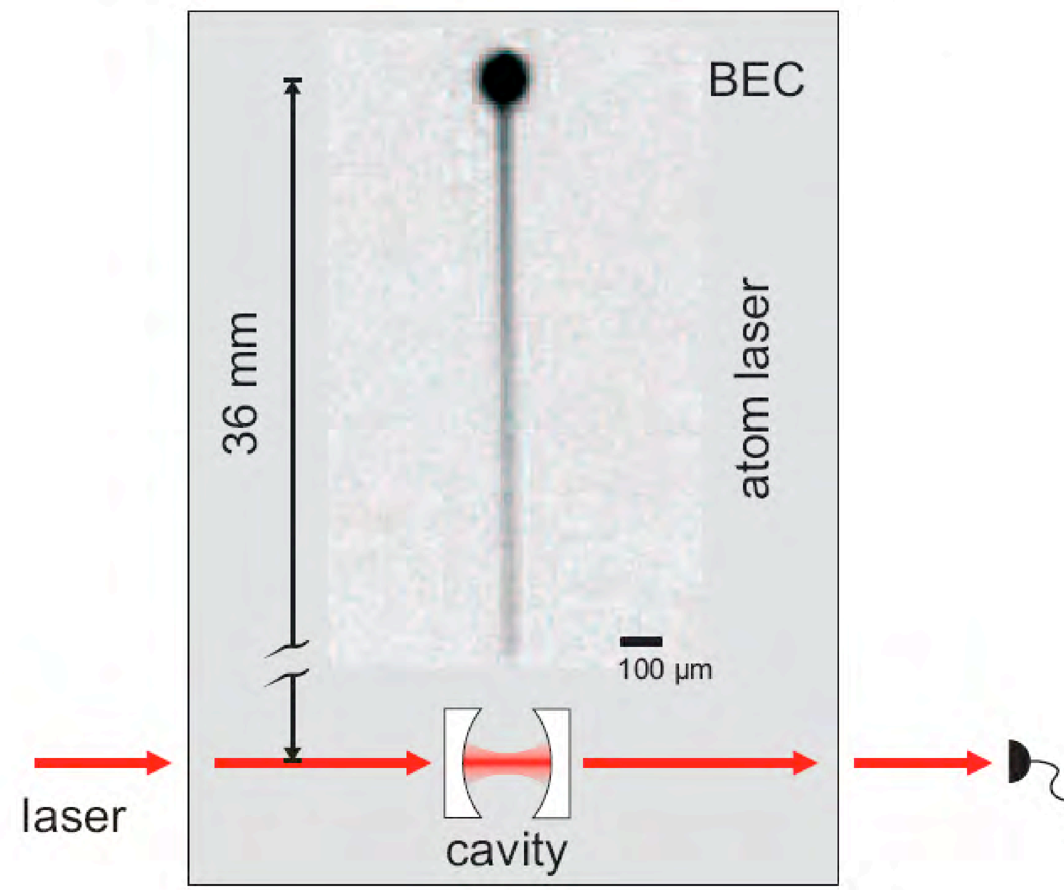
Optical lattice, Mott state, using absorption imaging. You see the FT of the density distribution (Mainz, NIST, LENS ..



$n(p)$ $G^{(2)}(p-p')$



Fölling et al. *Nature* **434**, 481-484 (2005)

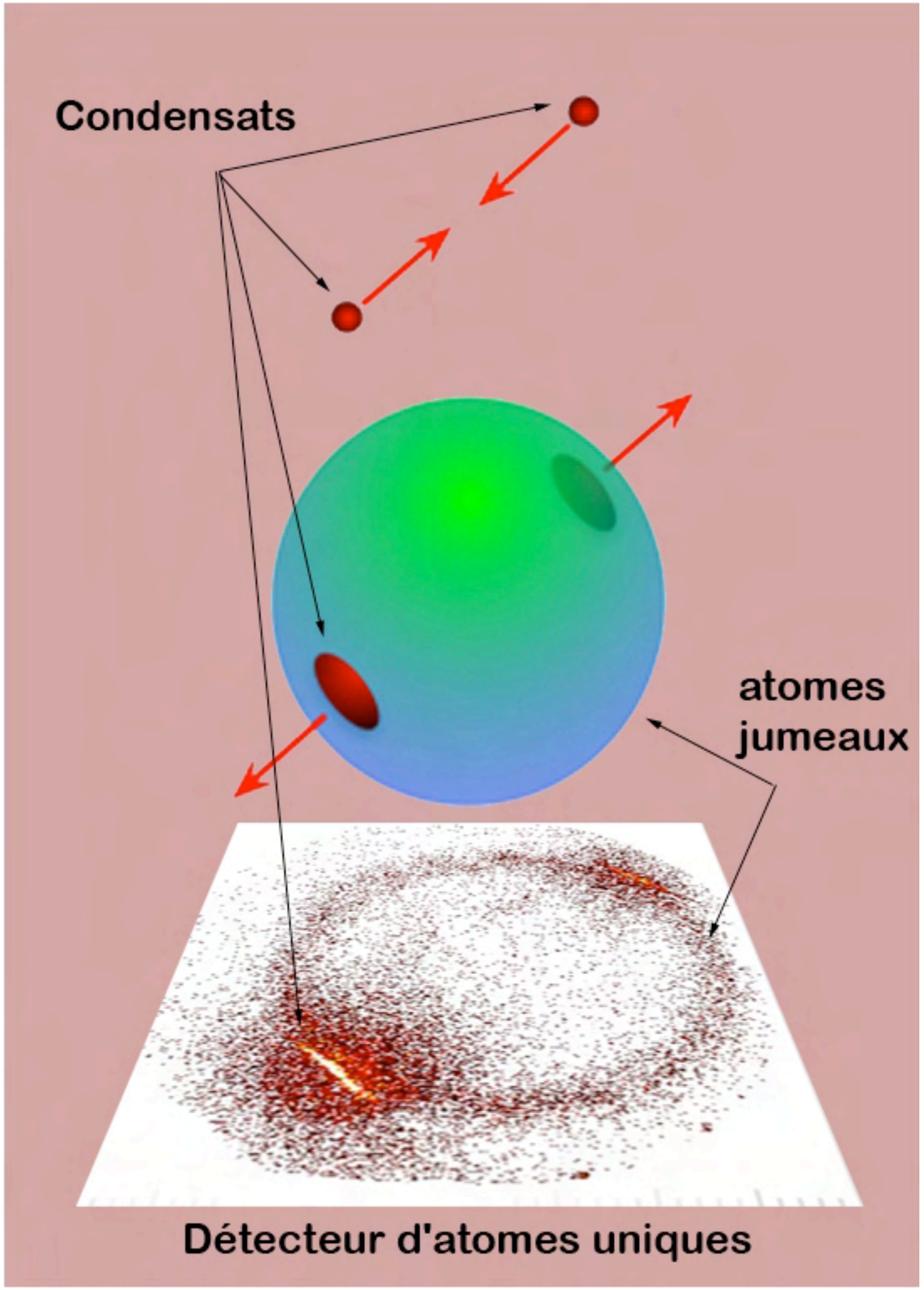


Zürich, atom laser, single atom detection with optics

Öttl et al. *Phys. Rev.Lett.* **95**, 090404 (2005)

Produce pairs by collisions

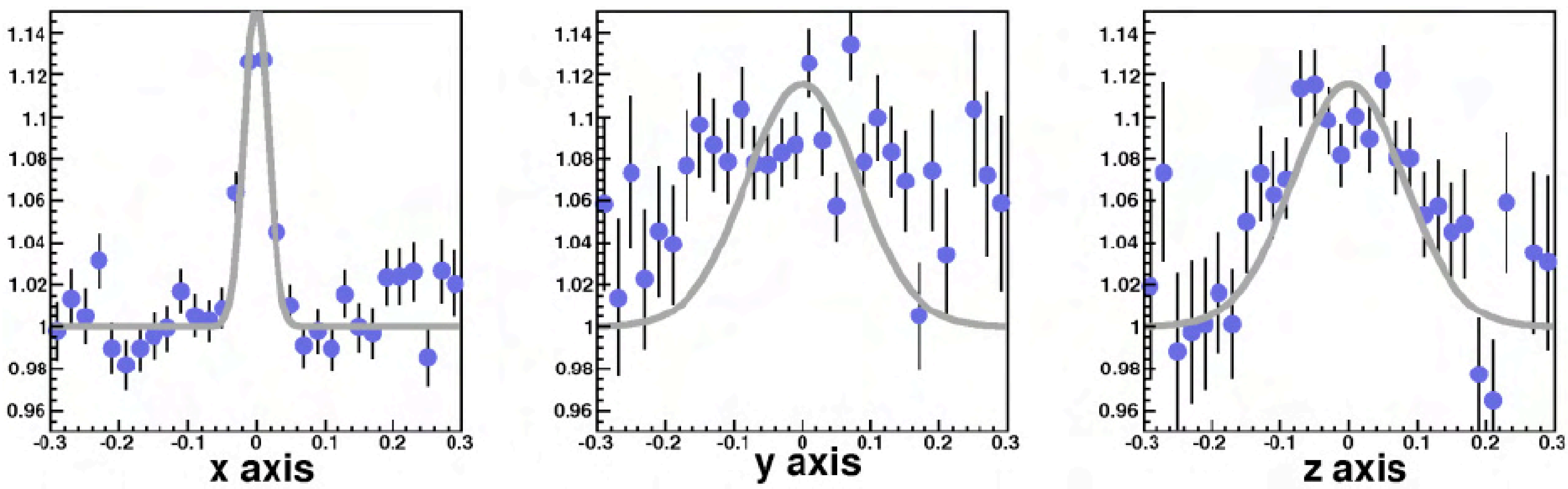
- collision of 2 condensates at 9 cm/s
- atom pairs are scattered on a spherical shell



Movie available at

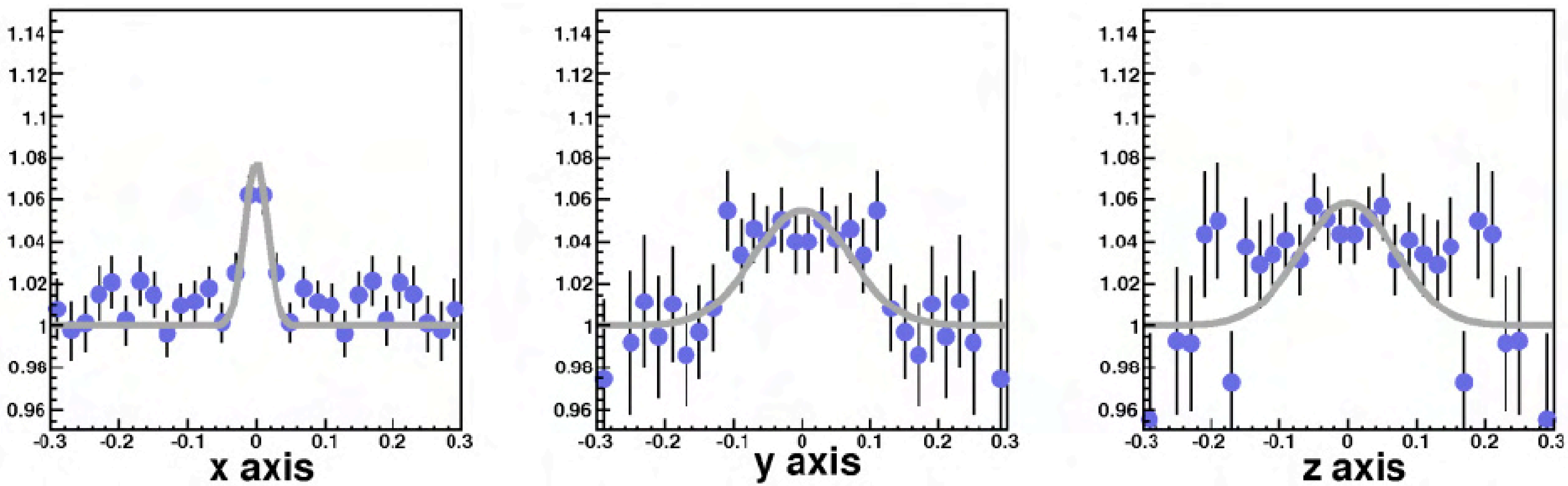
http://atomoptic.iota.u-psud.fr/research/helium/helium.html

Back to back correlations ($p \sim -p'$)



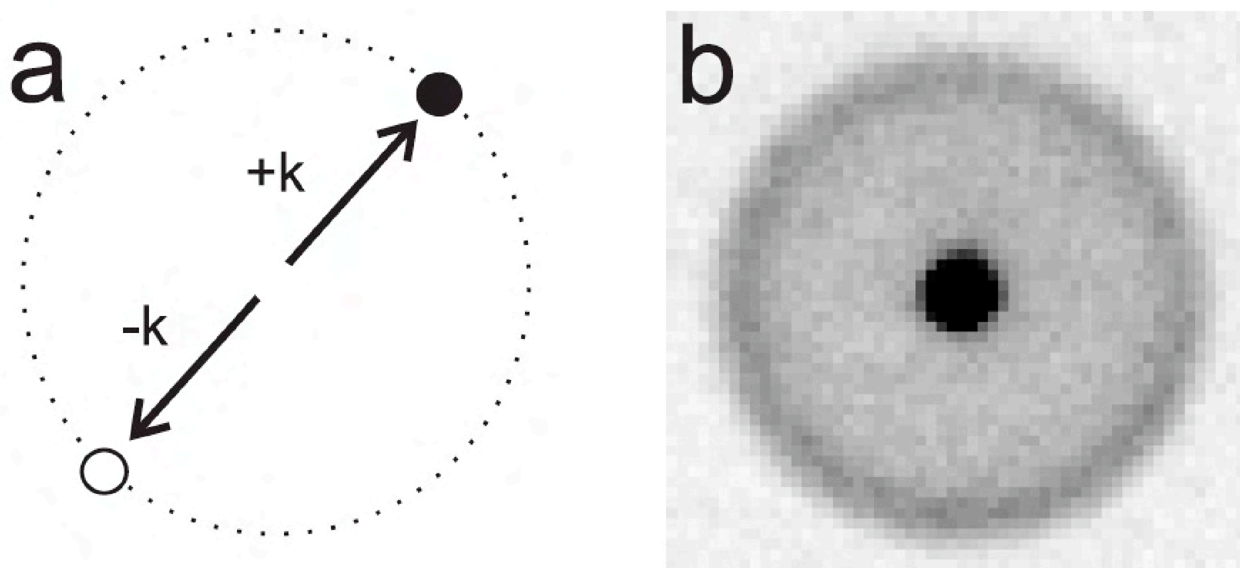
Perrin et al. PRL 99, 150405 (2007)
Perrin et al. New J. Phys. 10, 045021 (2008)

Collinear correlation (HBT, $p \sim p'$)

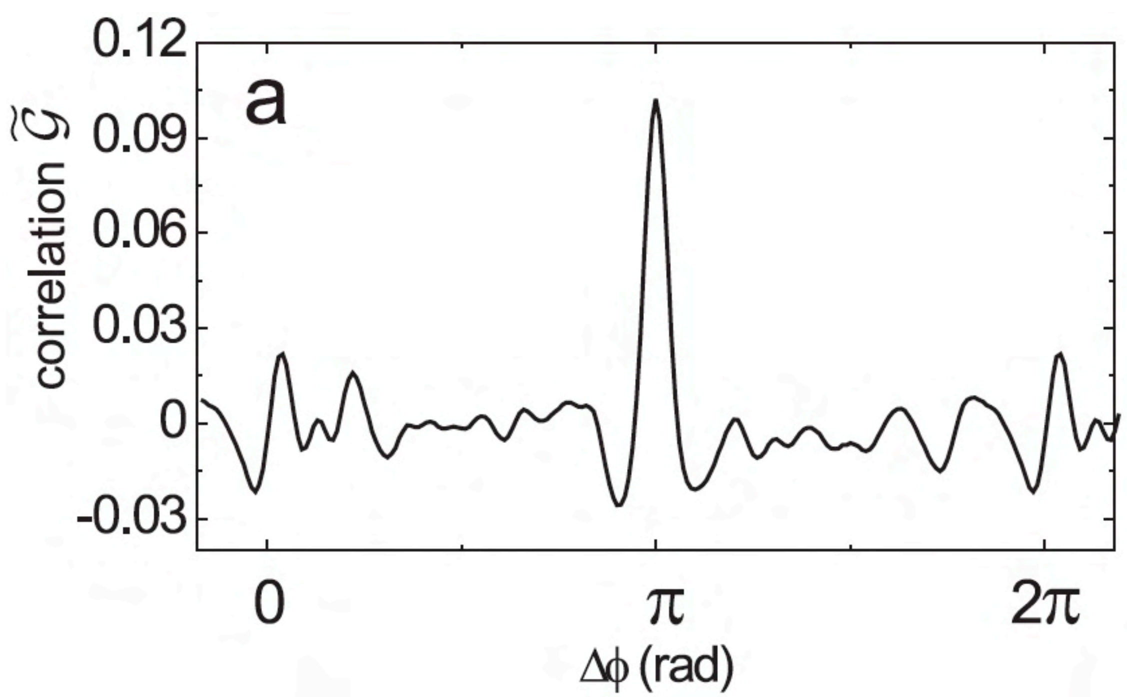


Indicates thermal population of mode

Another experiment



Breakup of $^{40}K_2$ molecule near Feshbach resonance gives back to back m=9/2, m=5/2 pairs. Very analogous to parametric fluorescence

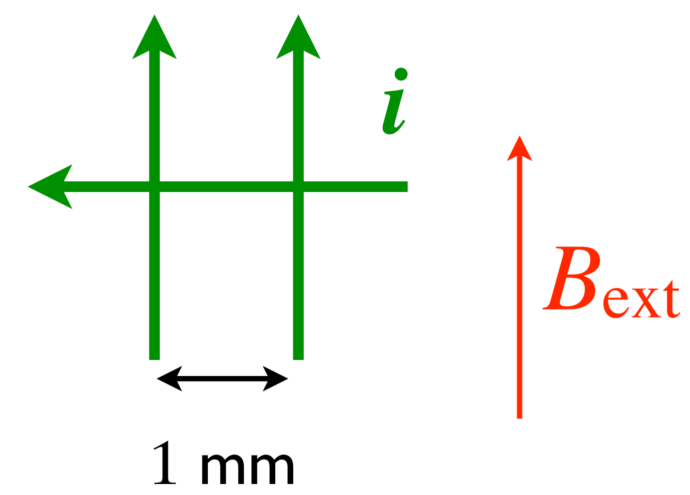


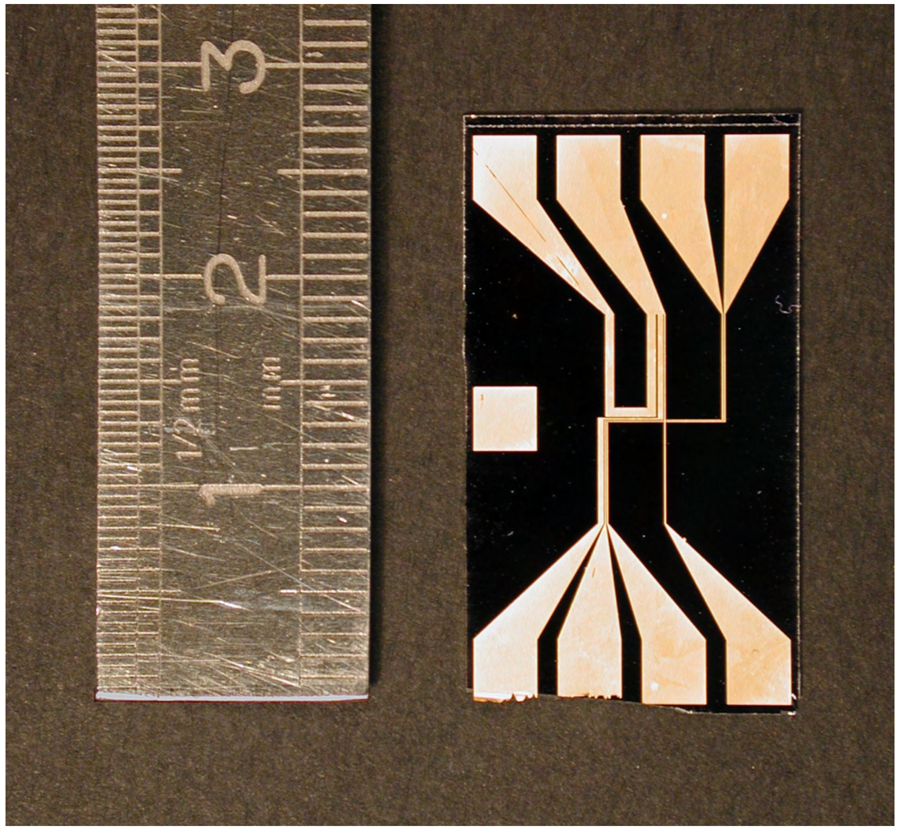
JILA
PRL 94, 110401 (2005)

Atom chips with wires

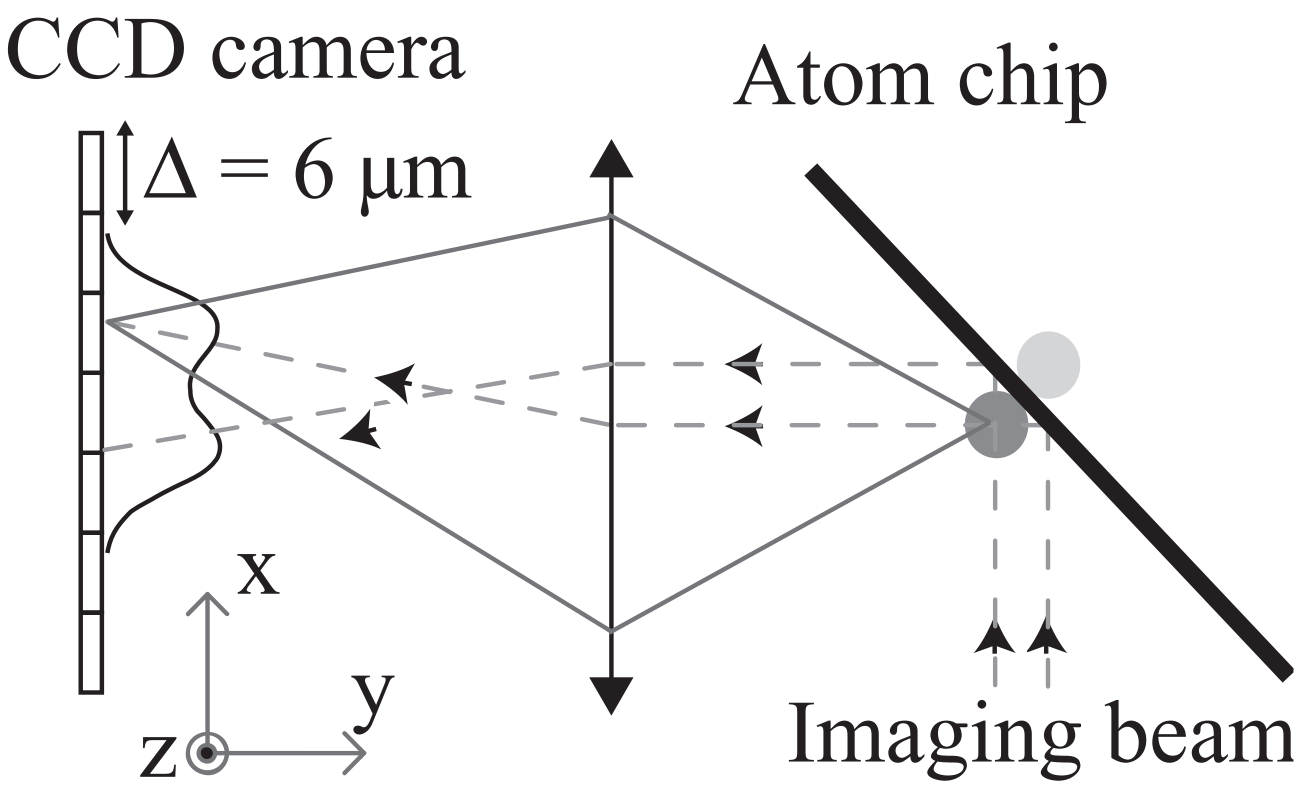
- An “H” and an external bias make a Ioffe-Pritchard trap
- Compact, insensitive to vibrations
- Naturally very elongated
  - $\omega_\perp/2\pi = 3$ kHz
  - $\omega_\| /2\pi = 7$ Hz
- Evaporation nearly freezes out the transverse motion - quasi 1D

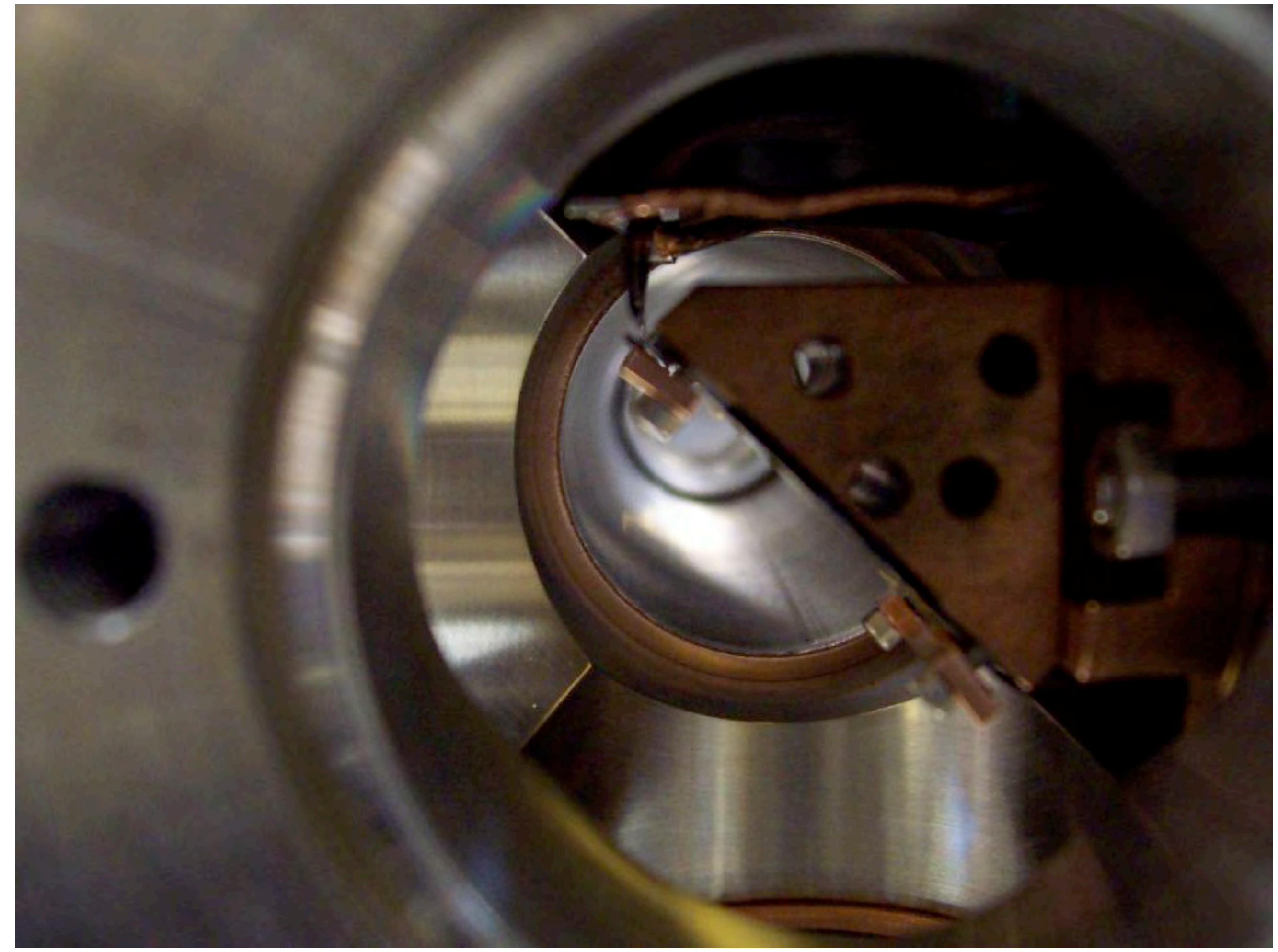
  $k_B T \sim \hbar\omega_\perp \approx 150$ nK





Imaging setup





Pixel size 6 μm, resolution ~ 10 μm. Transverse profile of trap is not resolved

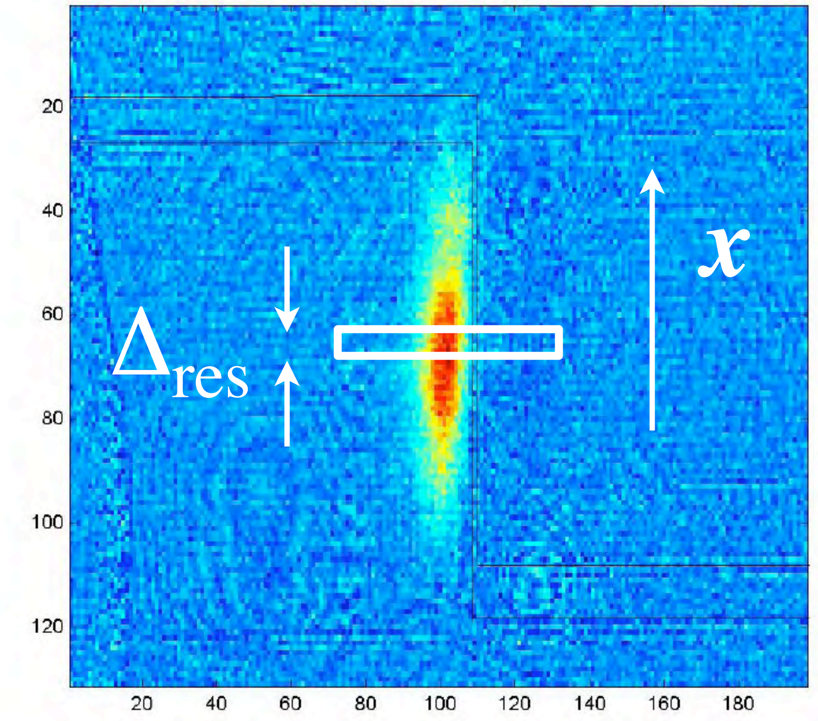
measuring density

$N_{\text{total}} \sim$ 5000

T = 200 nK

"typical" image (10^3 photons/pixel)

$\Delta_{\text{res}} \sim$ 6 μm, $l_c \sim$ 150 nm



$$\langle N(x)^2\rangle - \langle N(x)\rangle^2 = (1/z)\,\langle N(x)\rangle^2 + \langle N(x)\rangle$$

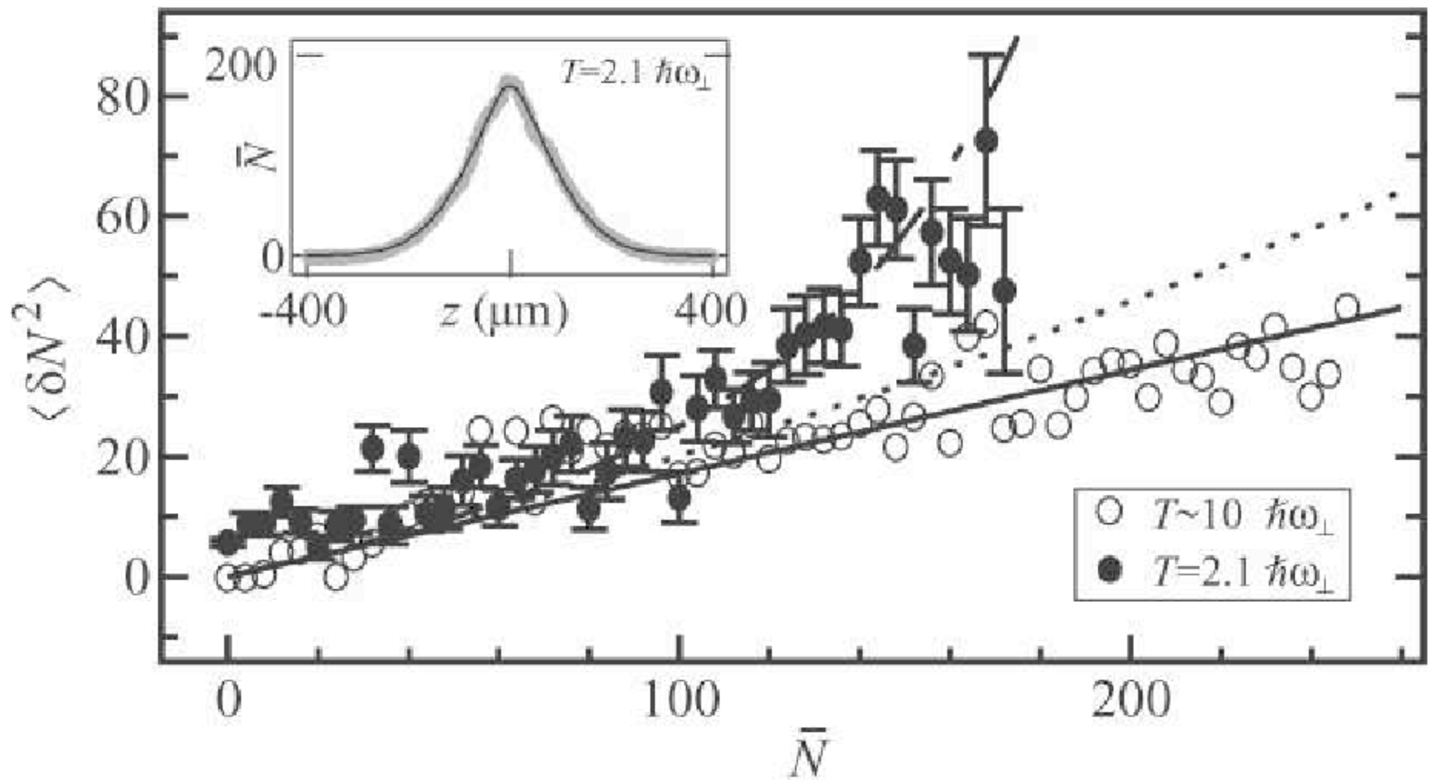
N atoms in a pixel

atom shot noise

Average over 300 shots. Subtract photon shot noise - little technical noise. Chips provide high vibration stability.

$(1/z) \sim (h\nu_\perp/k_B T)^2\,(l_c/\Delta_{\text{res}}) \sim 0.01$ mainly resolution but if $N \sim$ 100, excess noise = shot noise

Density fluctuations on a chip



number of atoms/6 μm pixel

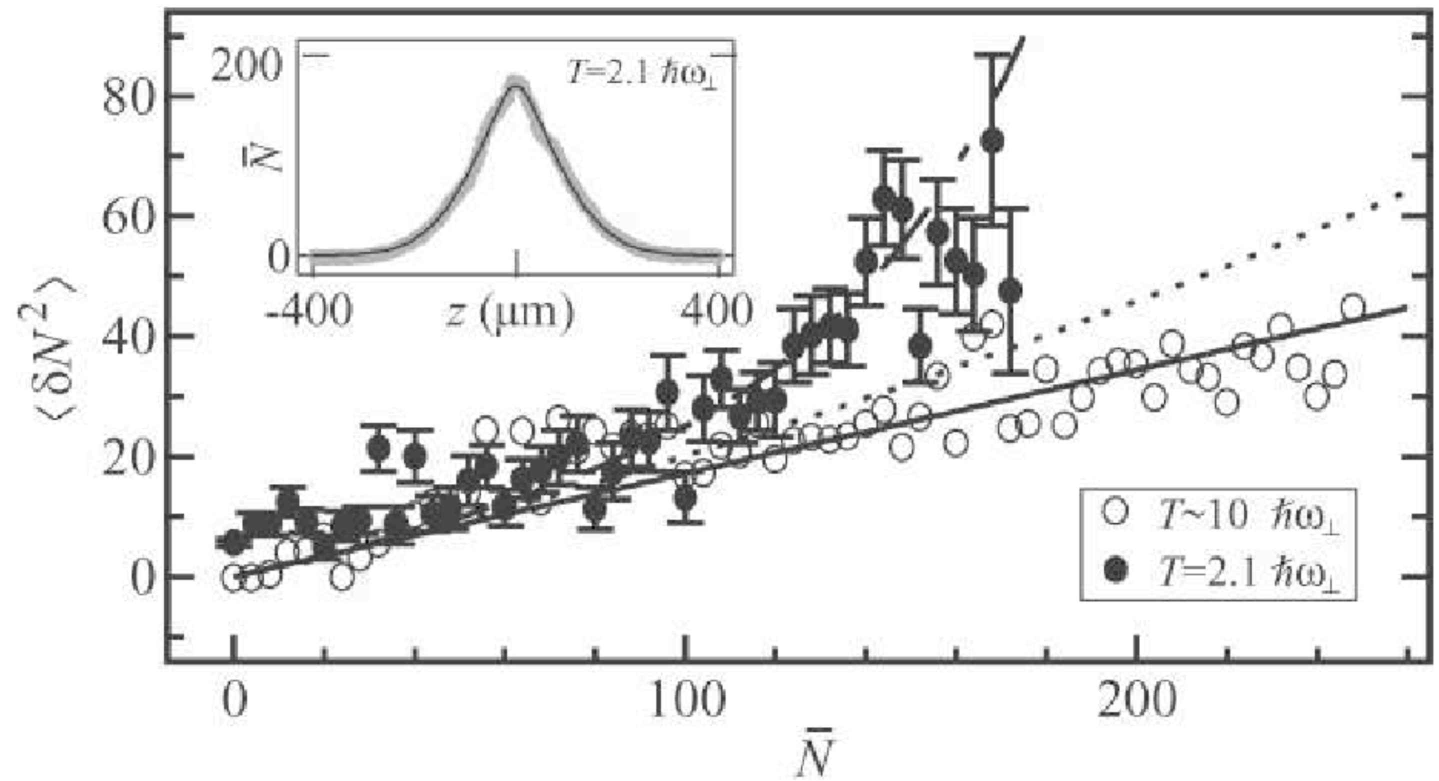
$T \sim 10\ h\nu_{\mathrm{perp}}$ (1.2 μK): excess noise is negligible due to averaging

- $\delta N^2 \approx \langle N \rangle$

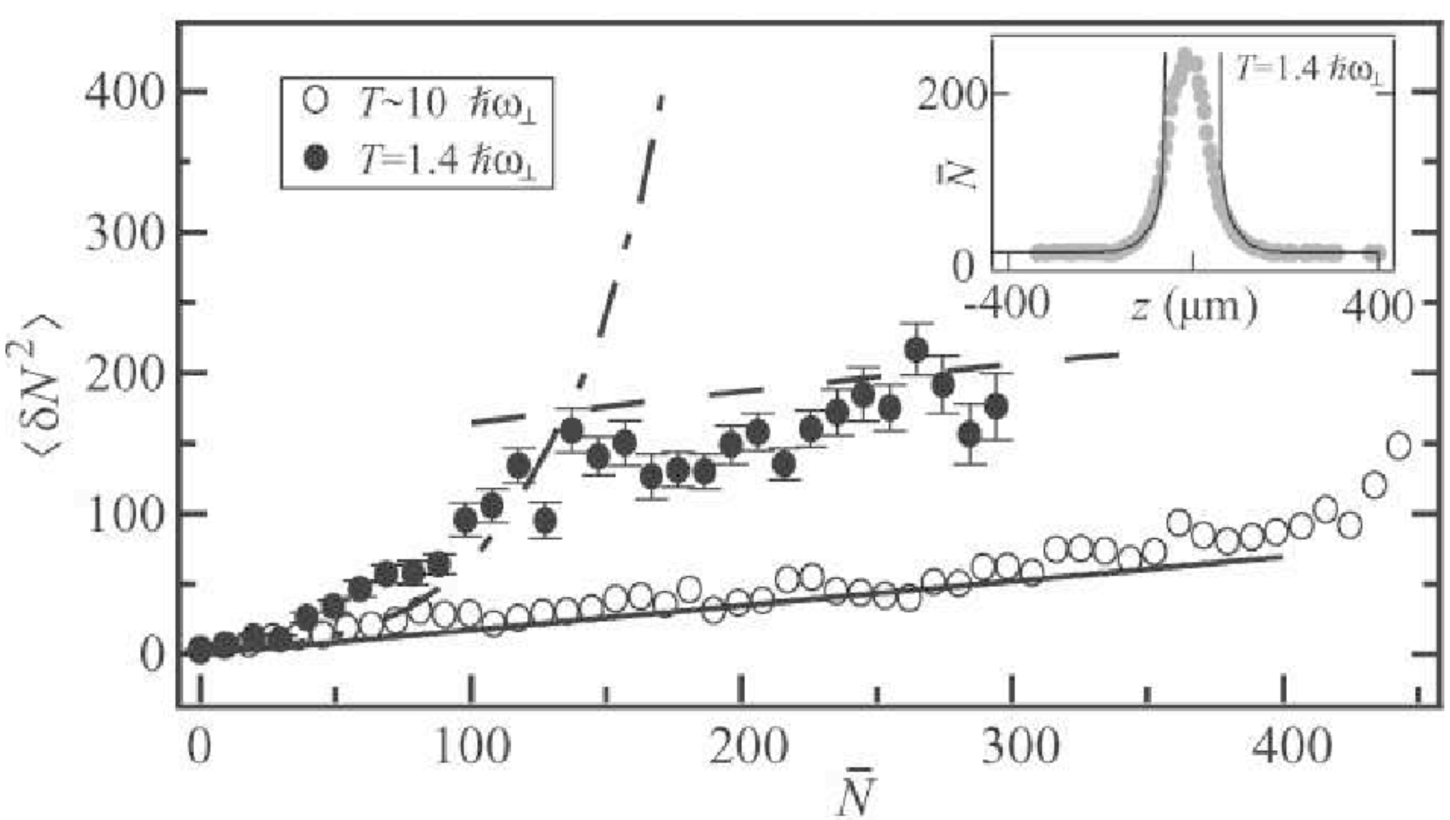
$T \sim 2\ h\nu_{\mathrm{perp}}$ (200 nK) ideal gas behavior:

- $\delta N^2 \approx \langle N \rangle^2$

Density fluctuations on a chip



$T \sim 10\ h\nu_{perp}$ (1.2 μK): excess noise is negligible
$T \sim 2\ h\nu_{\mathbf{perp}}$ (200 nK), low density ideal gas behavior.



number of atoms/6 μm pixel

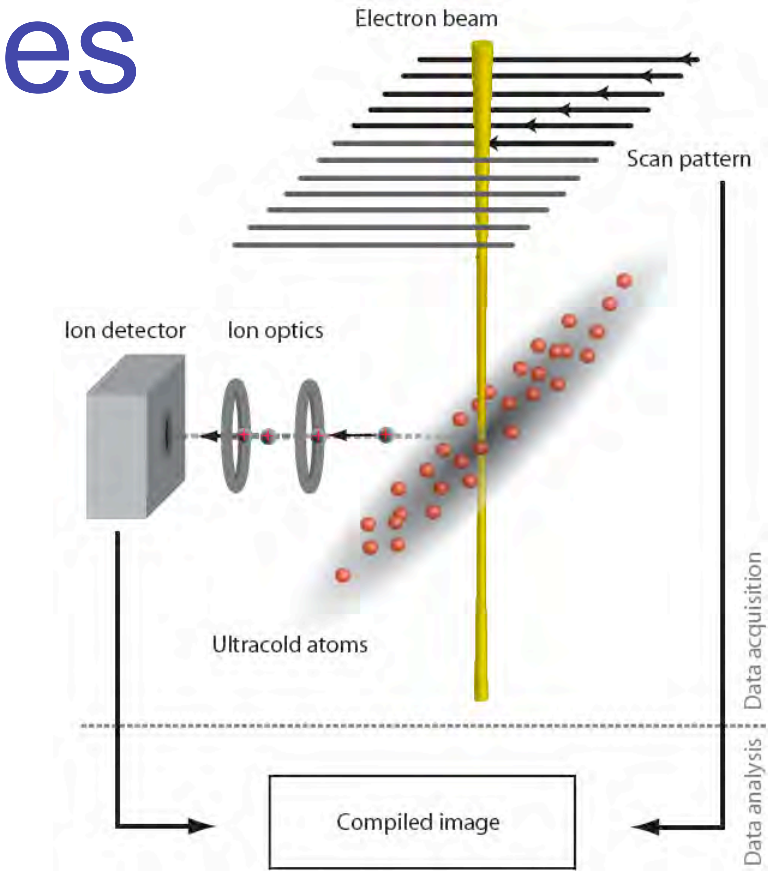
$T \sim 1.4\ h\nu_{\mathbf{perp}}$ high density: suppression of fluctuations by mutual repulsion. Crossover from a uncondensed gas to a quasi-condensate.

Estève et al. PRL 2006,
Theory: Petrov et al. PRL 85, 3745 (2000)

Newer techniques

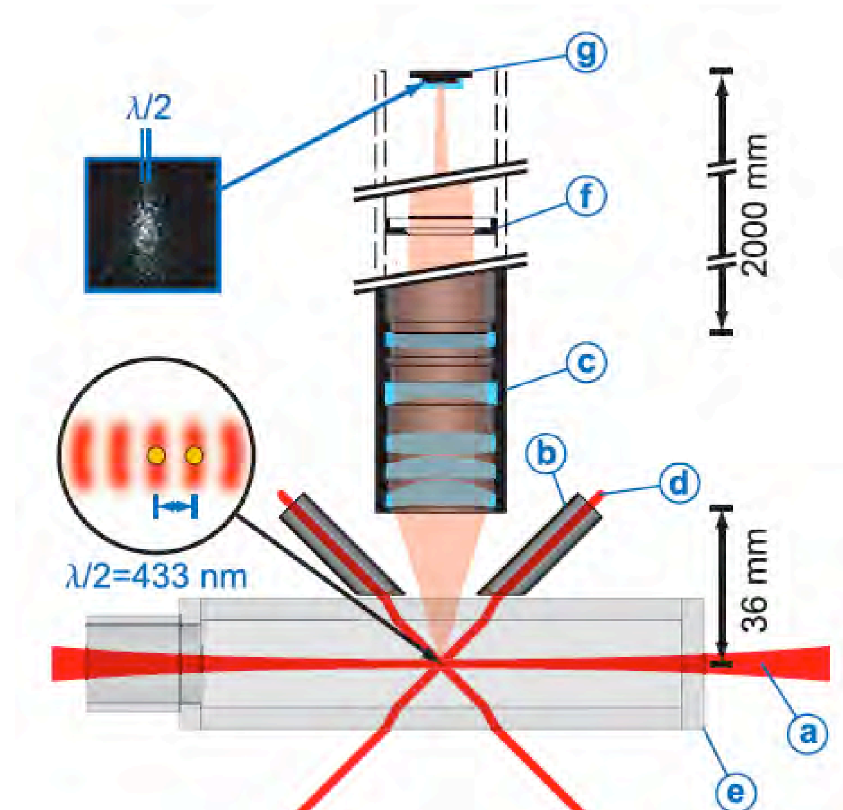
Use of electron μ-scope

High Resolution Imaging of Single Atoms in a Quantum Gas
Tatjana Gericke, Peter Wurtz, Daniel Reitz, Tim Langen, and Herwig Ott
Institut fur Physik, Johannes Gutenberg-Universitat, 55099 Mainz, Germany
arXiv:0804.4788



Use of direct, high resolution, optical imaging (one of many)

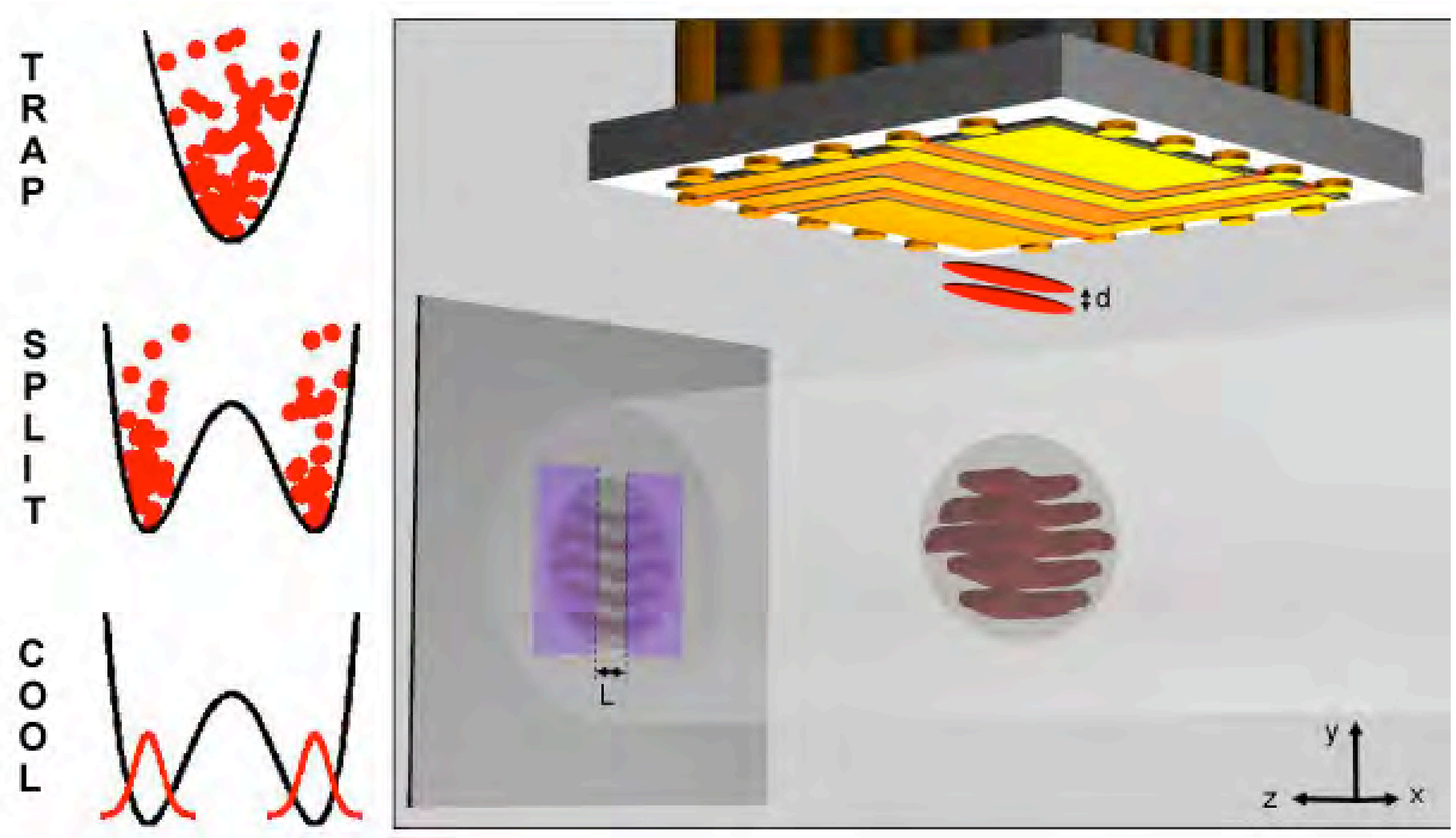
Direct observation of atom anti-bunching in an optical lattice by nearest-neighbor detection
M. Karski, L. Foerster, J. M. Choi, W. Alt, A. Widera, and D. Meschede
Institut fher Angewandte Physik der Universit¨at Bonn, Wegelerstrasse 8, 53115 Bonn, Germany
arXiv:0807.3894



other experiments II

Fringe contrast tells about correlations

Hofferberth et al. (TU Wien)
Nature Physics 4, 489 (2008)



Caution: mean contrast only gives $g^{(1)}$

To get $g^{(2)}$ you need the mean squared contrast

$$\langle |A_Q|^{2n} \rangle = \int_0^L \dots \int_0^L dz_1 \dots dz_n dz'_1 \dots dz'_n \; |\langle a^\dagger(z_1) \dots a^\dagger(z_n) a(z'_1) \dots a(z'_n) \rangle|^2$$

Polkovnikov, Altman, Demler
PNAS, 103, 6125-6129 (2006)

Thanks