Matter wave fluctuations and correlated atoms

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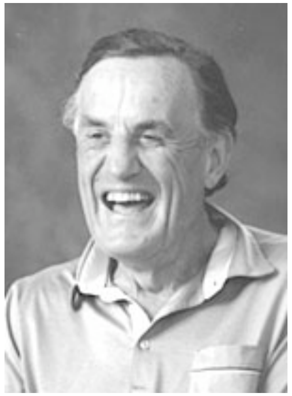
"Noise is the chief product and authenticating sign of civilization." Ambrose Bierce

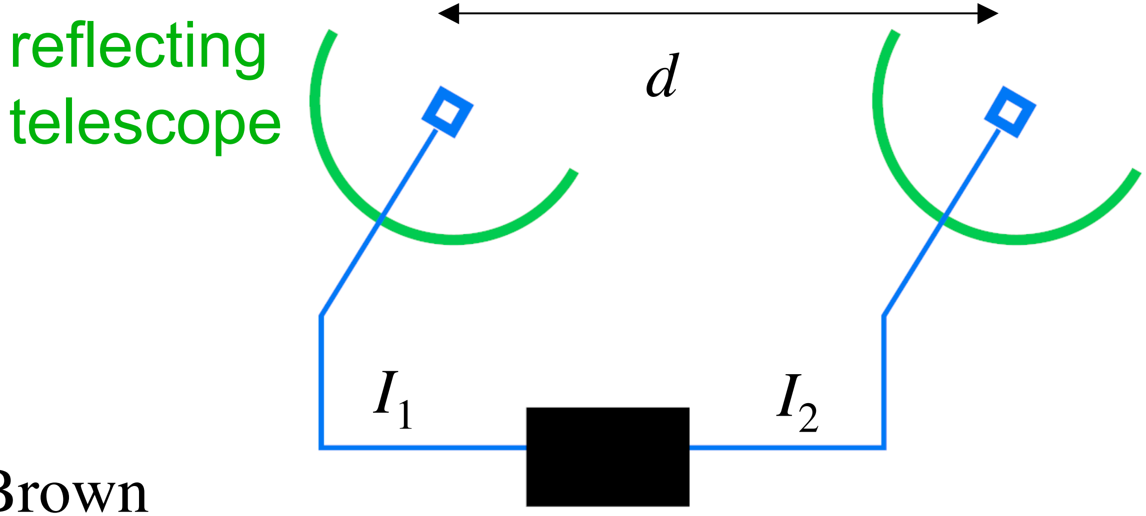
Outline

- The Hanbury Brown Twiss effect
  - Review of 50's Q-optics
  - Hanbury Brown Twiss effect for:
    - bosons
    - fermions
- Pair production

Intensity interferometry



Robert Hanbury Brown
1916-2002



correlator ($C \sim \langle I_1 I_2 \rangle$)

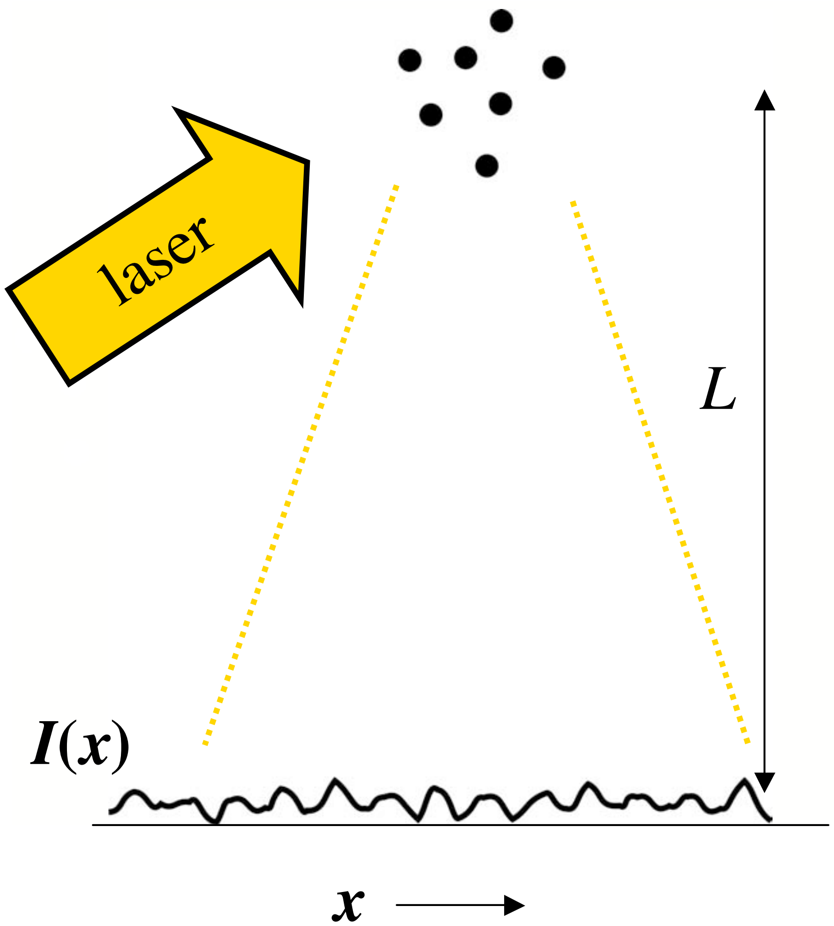
The noise in two optical (or radio) telescopes should be correlated for sufficiently small separations *d*. Reminiscent of Michelson's interferometer to measure stellar diameters, but less sensitive to vibrations or atmospheric fluctuation.

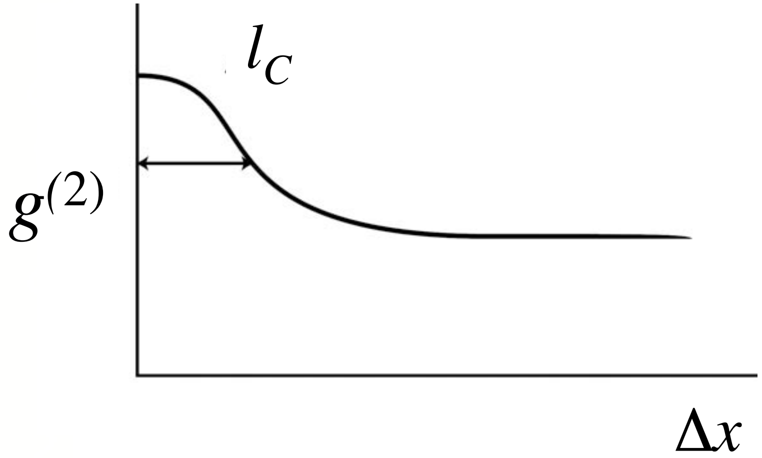
Simple, classical interpretation in terms of speckle.

Speckle interpretation

$$g^{(2)}(\Delta x) = \langle I(x)\, I(x+\Delta x)\rangle \,/\, \langle I\rangle^2$$

$$\langle I(x)^2\rangle > \langle I(x)\rangle^2$$



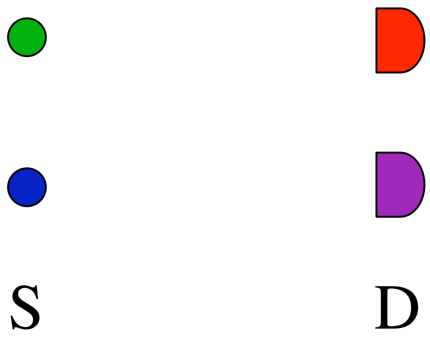


$$l_C = L\lambda/s$$

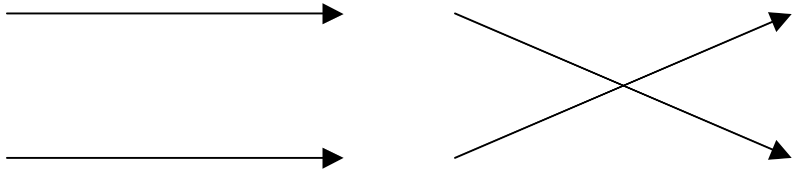
$$g^{(2)}(\Delta x) = 1 \text{ for large } \Delta x$$
$$= 2 \text{ for } \Delta x = 0$$

photon interpretation (Fano 1960)

<u>two particle</u> interference: two sources two detectors



two possibilities:



$a = \langle S_1 | D_1 \rangle \langle S_2 | D_2 \rangle \quad b = \langle S_1 | D_2 \rangle \langle S_2 | D_1 \rangle$

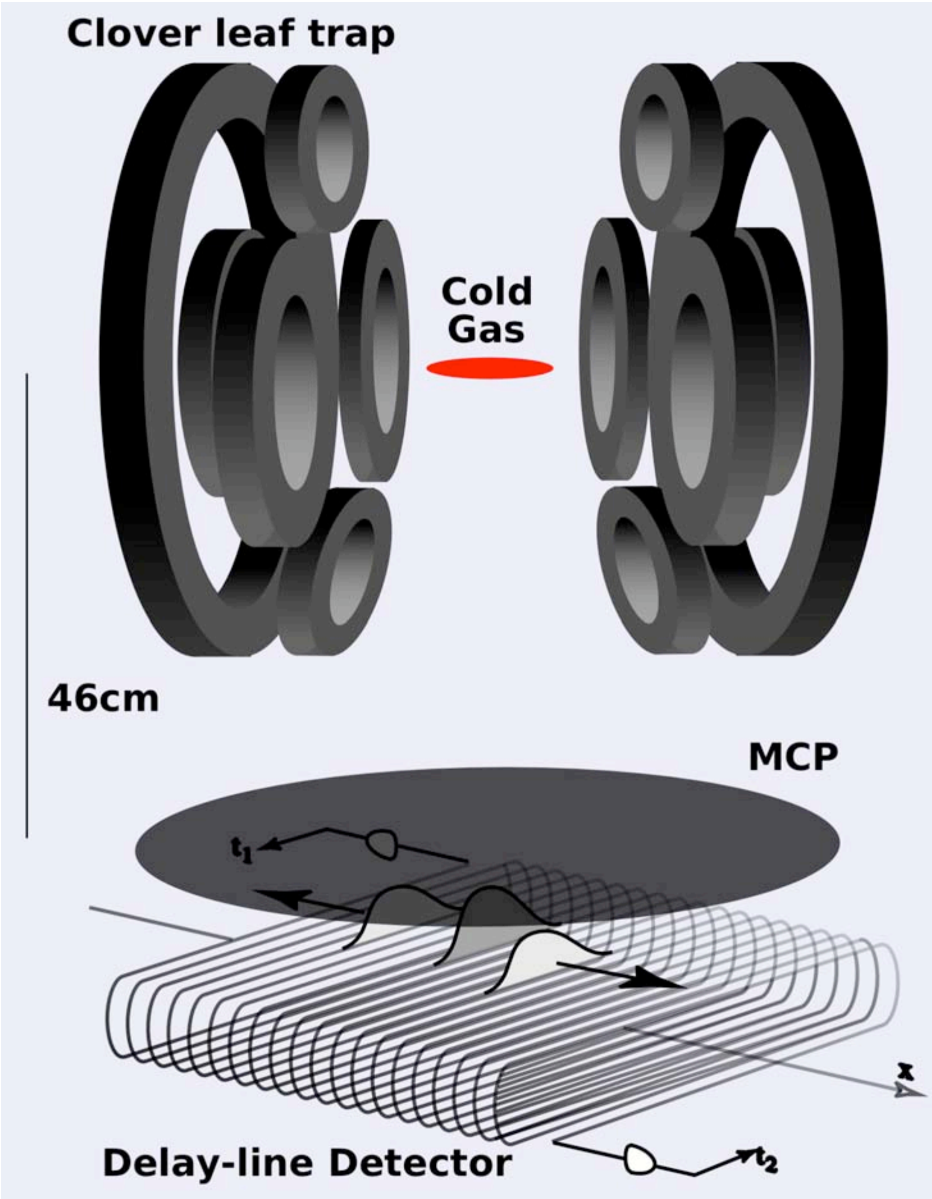
Indistinguishable possbilities, amplitudes add

$$|a + b|^2 = |a|^2 + |b|^2 + 2ab \cos \delta\phi$$

interference survives average over an extended source if source size and detector separation are small: $\delta S \delta D < L\lambda$.

Classical interpretation has a subtle QM analog with 2 particle states.

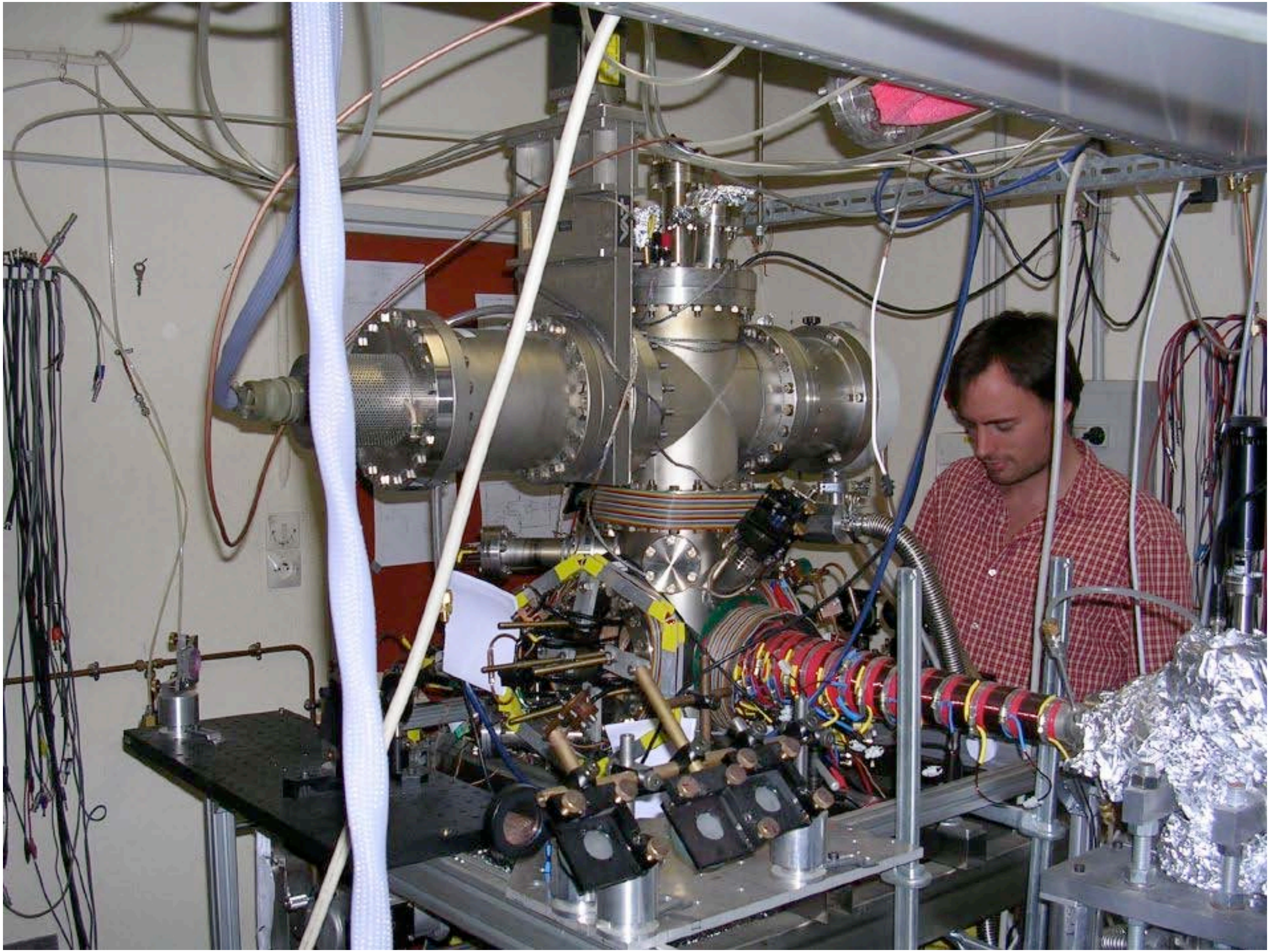
Experimental realization



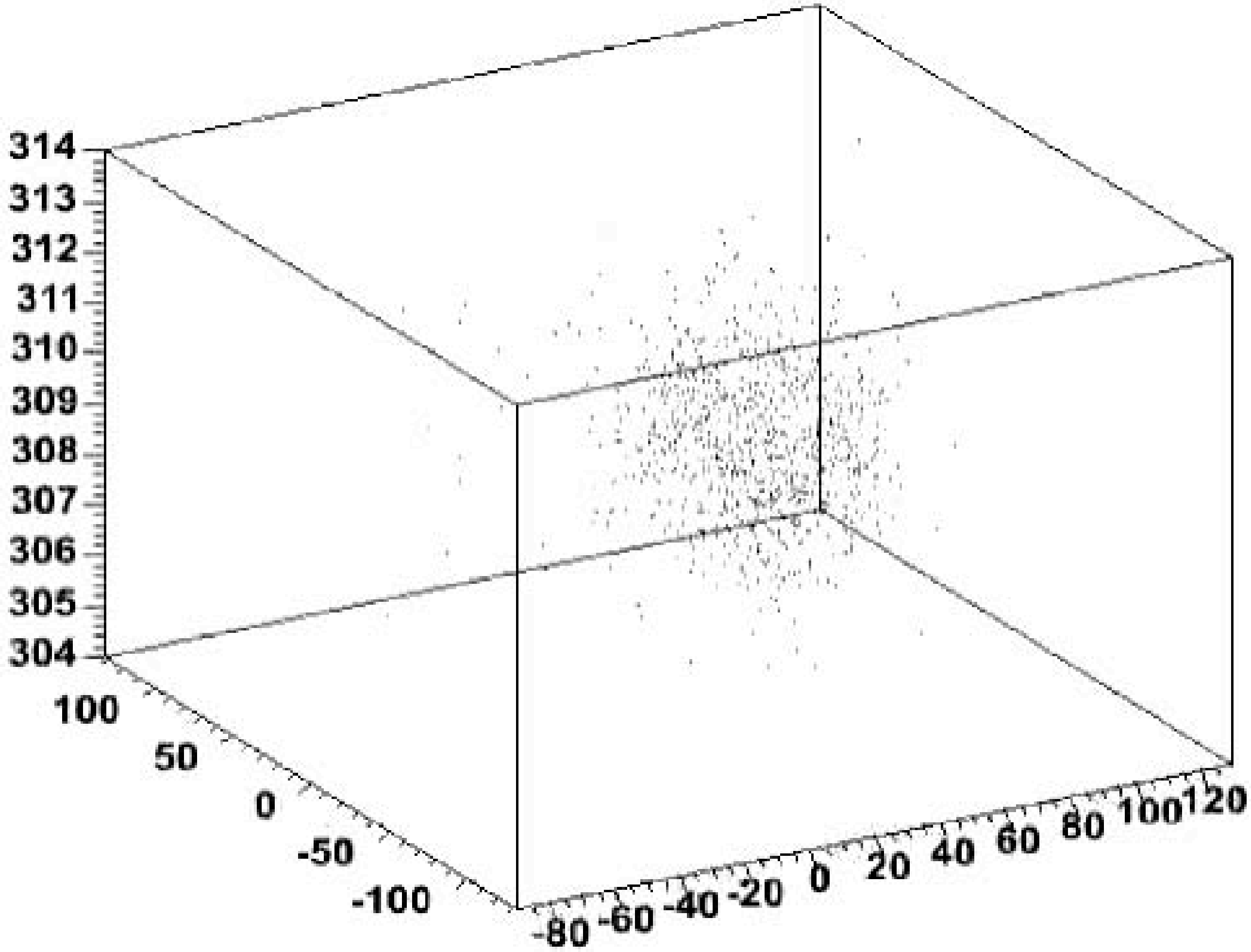
- Production of BEC or cold thermal cloud of He 2^3S_1
- Detection of metastable atoms by μ-channel plate. (He 2^3S_1 has ~ 20 eV).
- Excellent time (vertical) resolution (1 ns).
- Delay-line anode gives in plane resolution (500 μm). 5×10^4 detectors in //.
- Max. data rate ~

  50 000 atoms/10 ms

  20 Bytes/atom - 100 MB/s



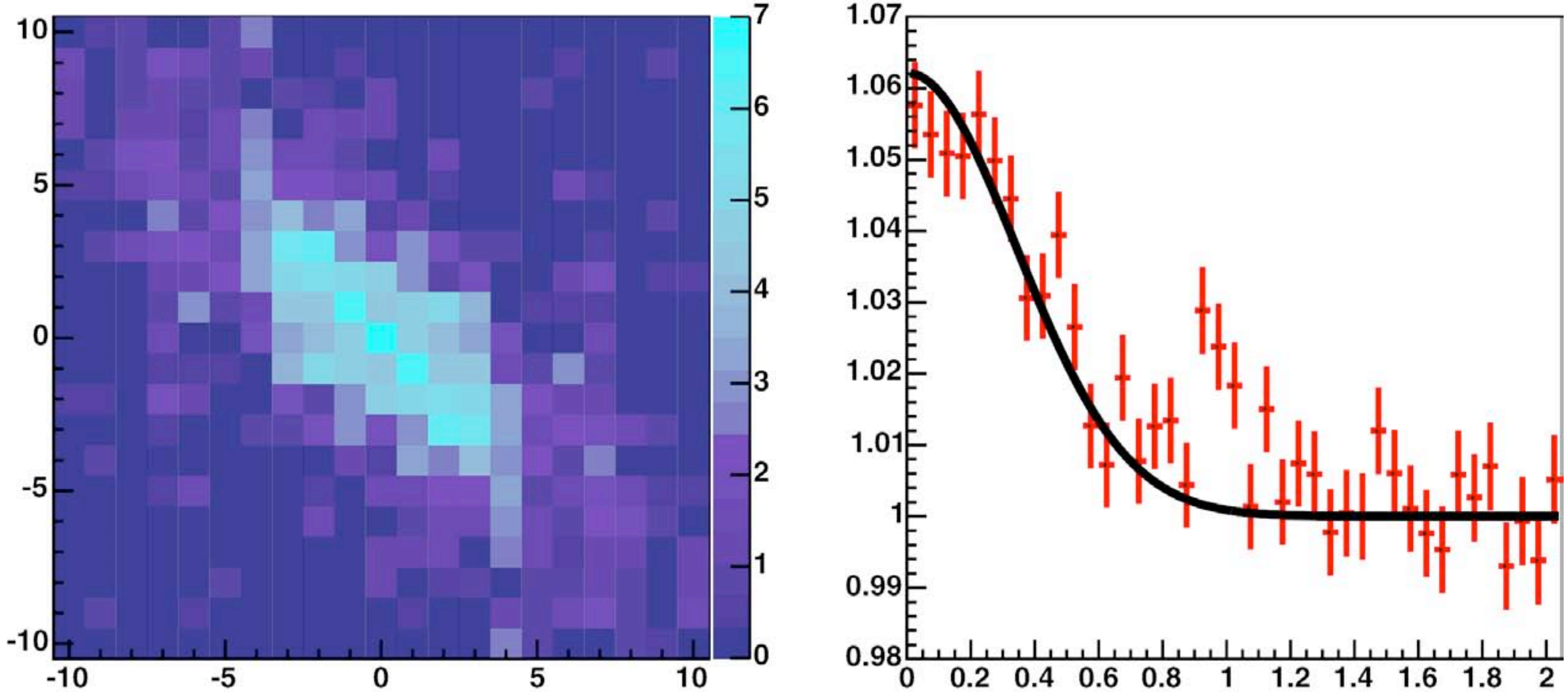
BEC in 3D



single particle distribution $n(r)$

normalized correlation $g^{(2)}$

$\langle n(\mathbf{r})\, n(\mathbf{r}+\boldsymbol{\rho})\rangle$ $\langle n(t)\, n(t+\tau)\rangle$



x - *y* plane

1 pix = 0.2 mm

τ (ms)

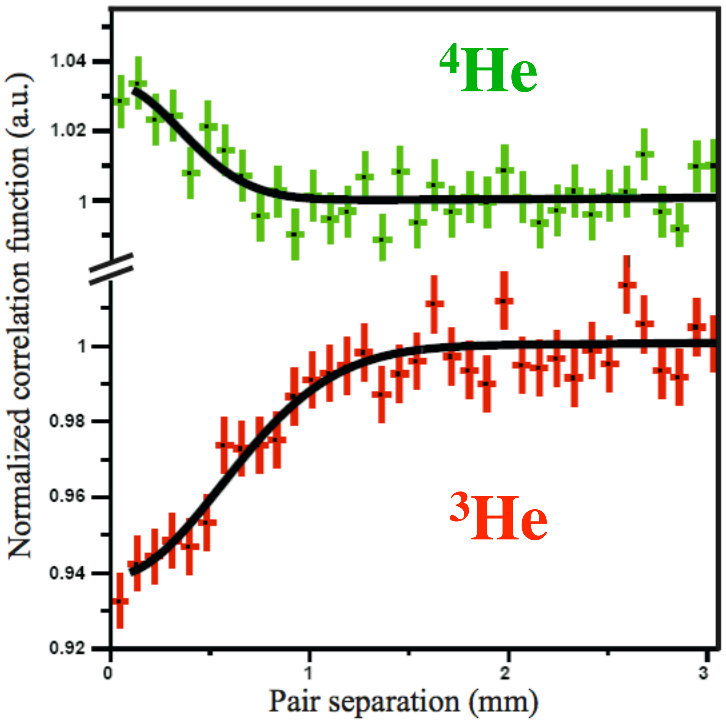
(1 ms ~ 3 mm)

using a histogram of pair separations

anisotropy is due to elliptical shape of trap

6% excess means that we observed ~16 phase space cells ($d/l_{C,x}$)

Comparison of bosons and fermions: atom bunching and antibunching



Jeltes et al. Nature 445, 402 (2007)

Collaboration with VU Amsterdam. Similar conditions.

Correlation length l_C:

$$l_C = \frac{\hbar t}{ms} \qquad (\delta x \delta p \sim \hbar)$$

Depth varies as l_C/d where d is resolution.

Anti-bunching has no simple, "classical" interpretation. Does it?

Almost everything about the data can be understood in terms of a non interacting gas.

Other experiments

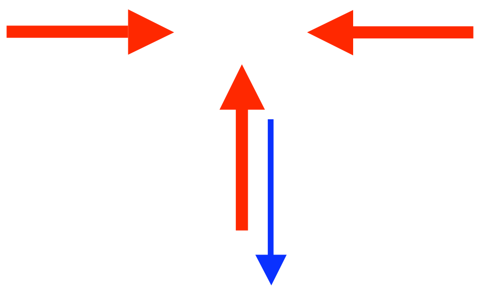
- Yasuda and Shimizu for Ne* (1996)
- Fölling et al. (Mainz): $g^{(2)}(x)$ peaks at $x = (hk/m)t$ for a Mott insulator in an optical lattice after expansion (2005). Rom et al. same for fermions (2006)
- Öttl et al. (Zürich), temporal correlation in atom laser (2005)
- Burt et al. (JILA) $g^{(3)}_{T>TC}(0) = 6\, g^{(3)}_{BEC}$ (1997) and other collision experiments which are sensitive to the correlation function at short distances.
- On an atom chip (Orsay, 2006)
- Greiner et al. (JILA) $g^{(2)}(x) > 1$ et after dissociation of molecules (2005).
- With electrons (1999, 2002) neutrons (2006)(anti-bunching)
- In accelerators with π, K …

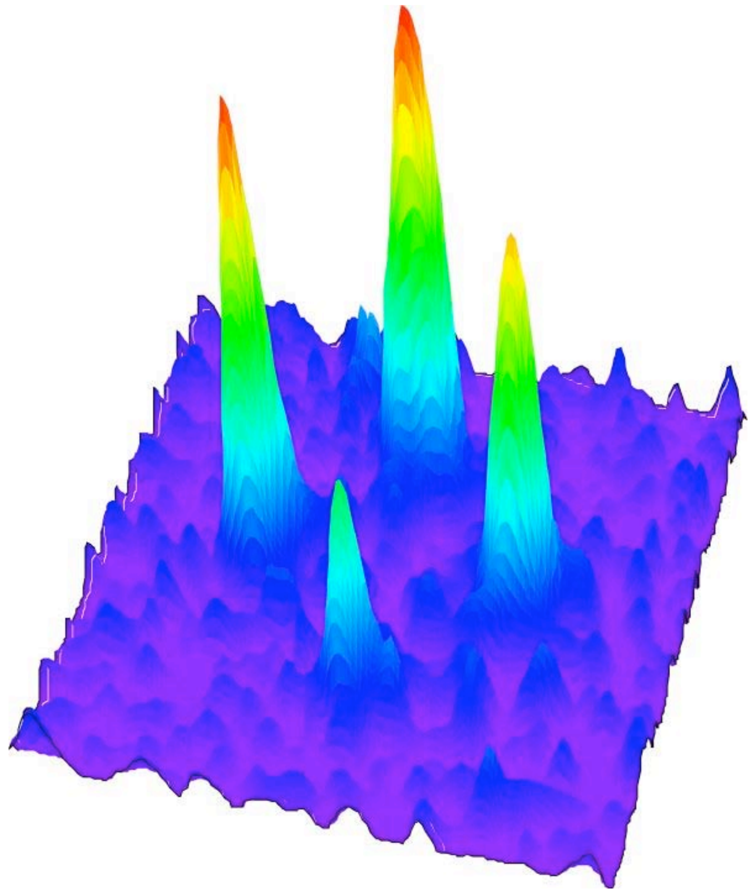
making correlated atom pairs

Four wave mixing

NIST: Science 398, 218 (1999)

MIT: cond-mat/0203286 (2002)





Data from NIST 1999

Atoms (photons) created in entangled pairs

Duan et al. PRL 85, 3987 (2000)

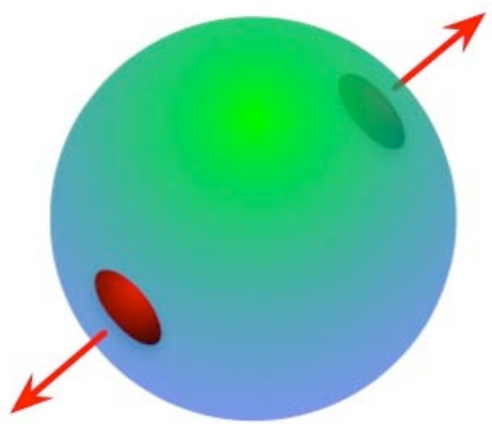
Pu et al. PRL 85, 3991 (2000)

Also UQ and Otago

Pair production

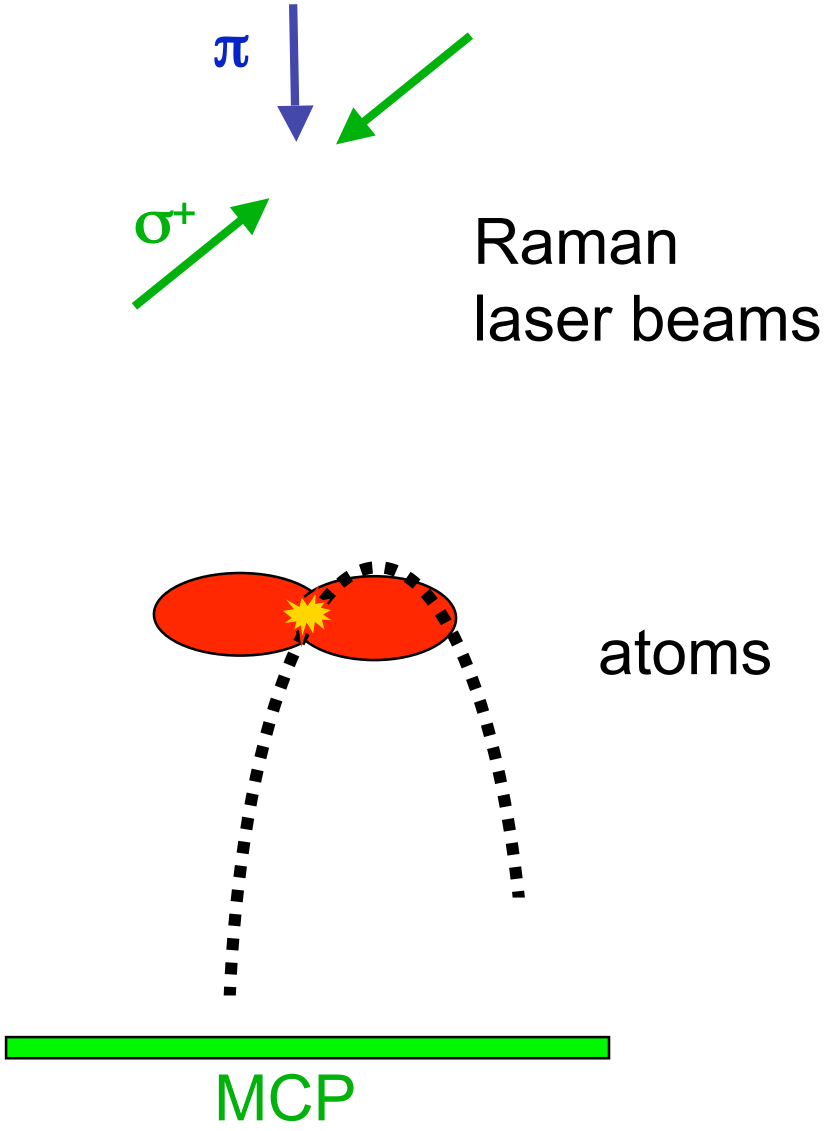
Instead of using 3 input beams, we use only 2 and allow the 3rd and 4th beams to arise spontaneously much like optical parametric fluorescence.

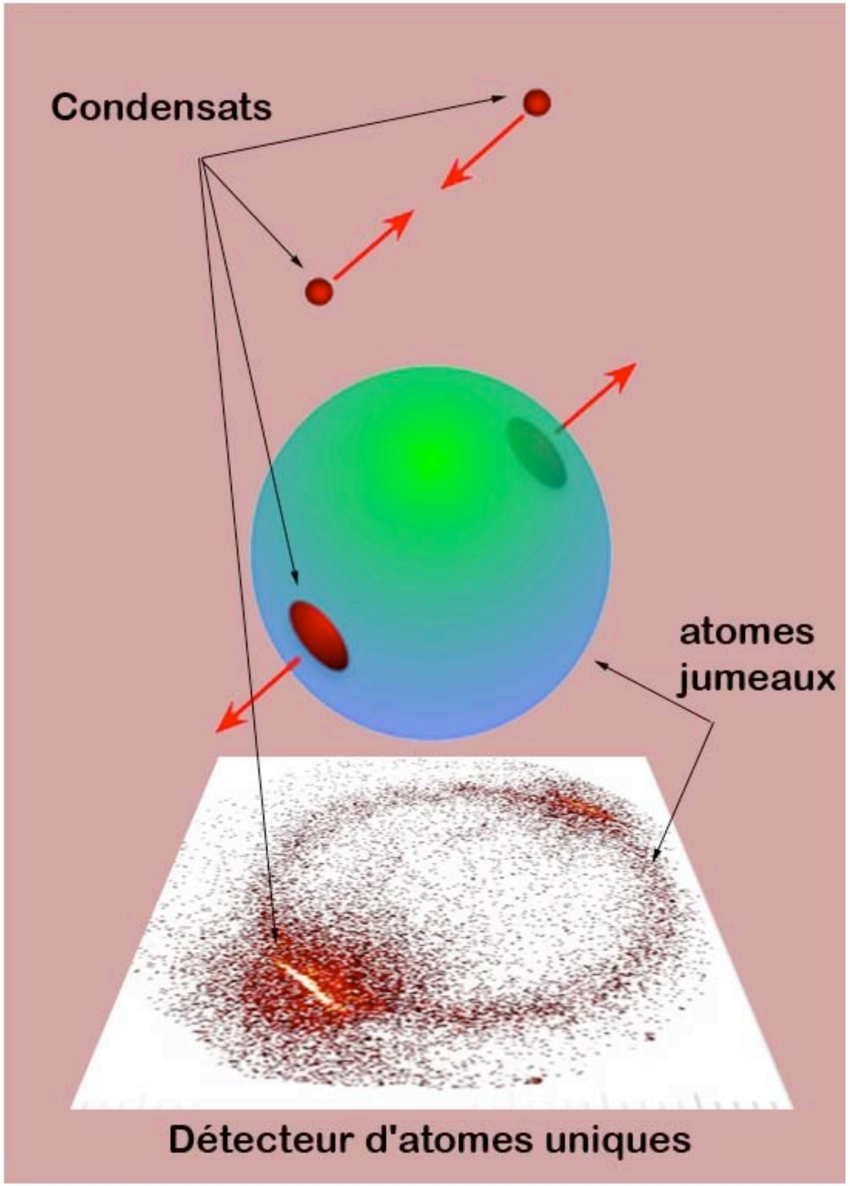
2 colliding condensates
(Thanks P. Lett, P. Drummond)



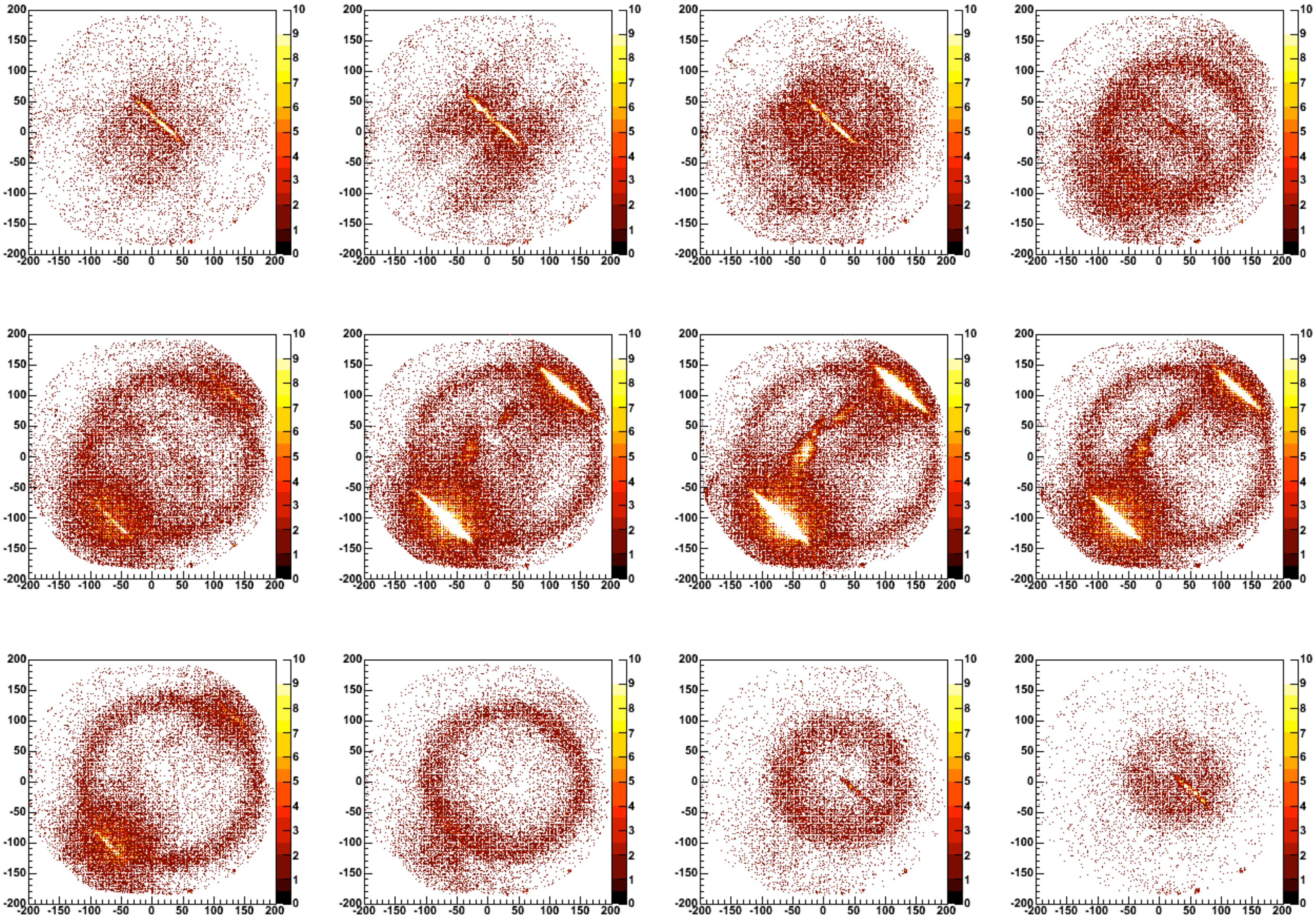
s-wave collision sphere
+ pancake shaped condensates
Otago, Amsterdam

Pair production by spontaneous 4WM

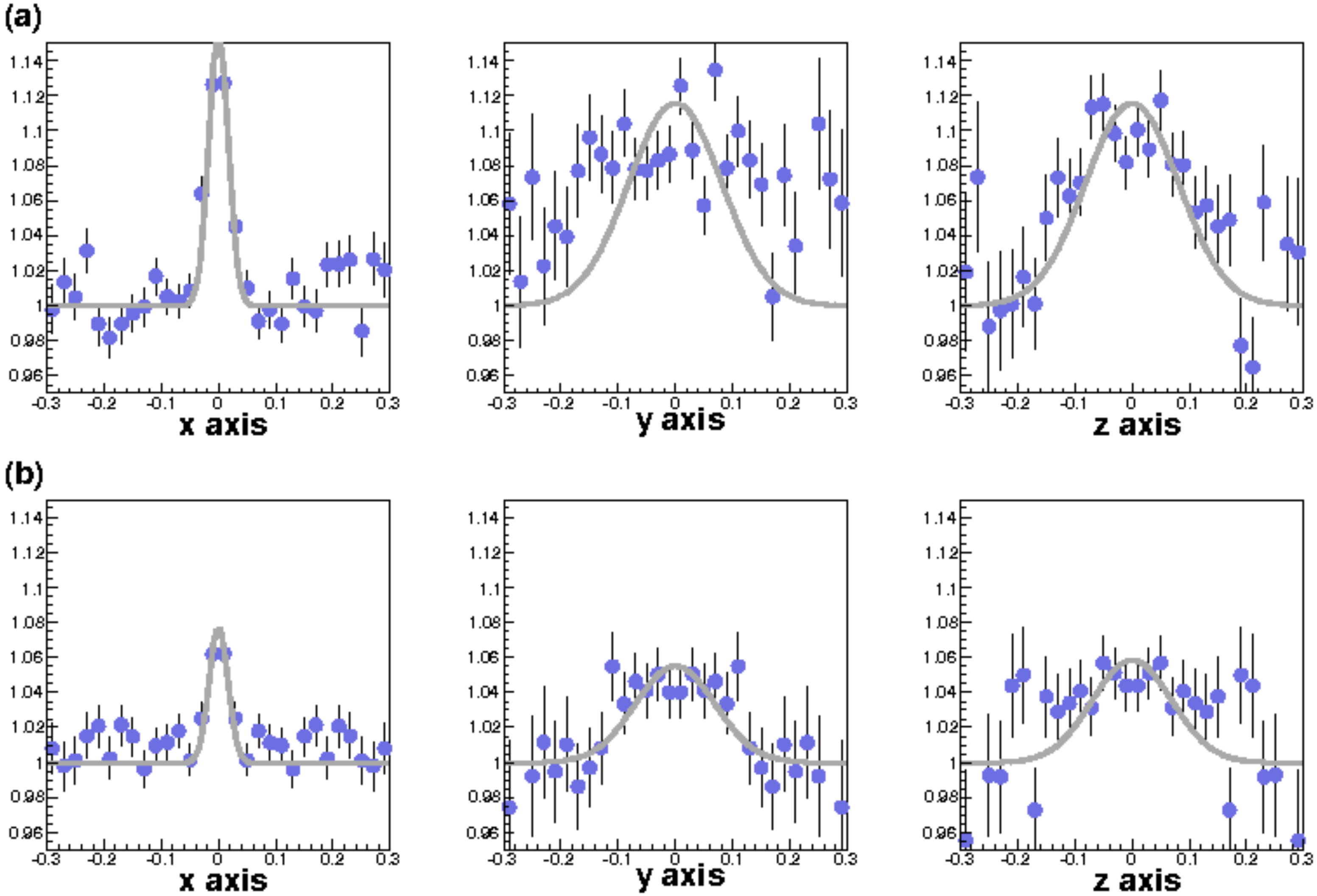




The s-wave sphere, in 2 ms slices



correlations at $\theta = \pi$ *and* $\theta = 0$



$\theta = \pi$

back to back

$\theta = 0$

collinear

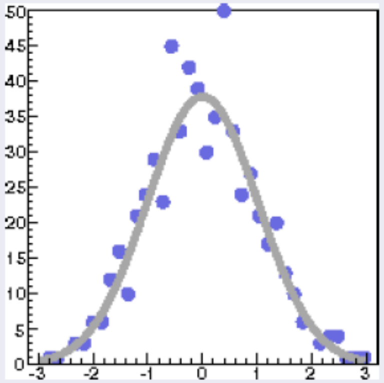
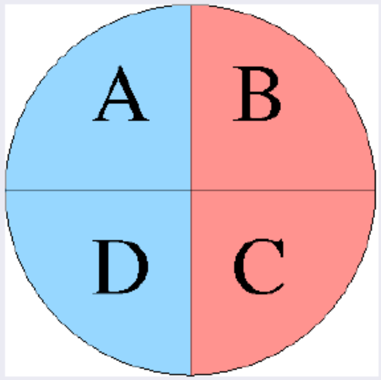
Perrin et al. arXiv:0704.3047v1

Simple analysis of peaks

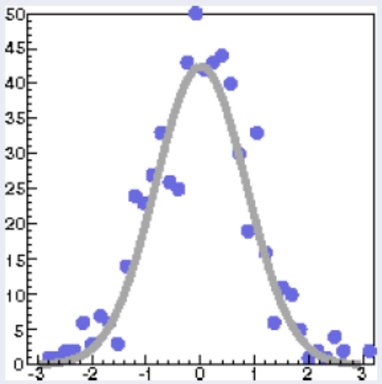
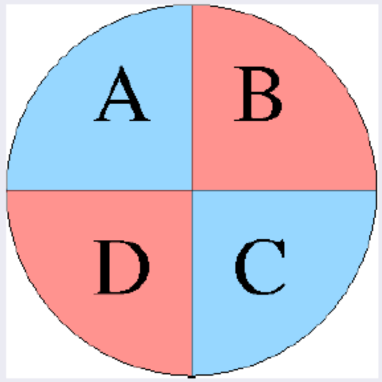
- Collinear ($\theta = 0$) peak is HBT effect
- Back to back peak has similar widths
- Widths (ave. over sphere):
  - $\delta v_{rad} \sim 0.1\, v_{rec}$ (v_{rec} is the radius of the sphere)
  - δv_{axial} unresolved $< 0.01\, v_{rec}$
- Relevant scales:
  - $\delta x \delta p \sim \hbar \rightarrow \delta v \sim \hbar/(mR_{TF}) \sim 0.1\, v_{rec}$, $0.004 v_{rec}$
  - $\sqrt{(\mu/m)} \sim 0.2\, v_{rec}$
- Peak heights ...
- More insight needed
- Can we produce occupation numbers > 1?

Sub-poissonian atom number difference

Divide sphere into slices and compare fluctuations number difference for sections with and without pairs. Normalize to $\sqrt{N}$, correct for shifts ...

$$\sigma_{B-C} = 1.012 \pm 0.035$$

$$\sigma_{B-D} = 0.834 \pm 0.029$$

Fluctuations over 1100 shots.
Consistent with QE $\eta \sim 25\%$
Is this obvious?

$$\sigma = \frac{\sqrt{N} \times \sqrt{(1-\eta)}}{\sqrt{N}}$$

The team

Orsay/Palaiseau

- Martijn Schellekens
- Aurélien Perrin
- Rodolphe Hoppeler
- Jose Gomes
- Valentina Krachmalnicoff
- Hong Chang
- Vanessa Leung
- Denis Boiron
- Alain Aspect
- CW

Amsterdam

- Tom Jeltes
- John McNamara
- Wim Hoogervorst
- Wim Vassen

Discussions with

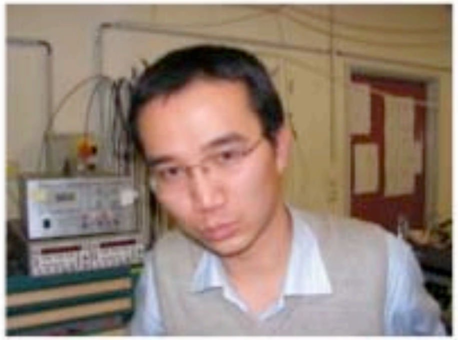
- K. Kheruntsyan
- K. Moelmer
- M. Trippenbach

PhD student
postoc
permanent

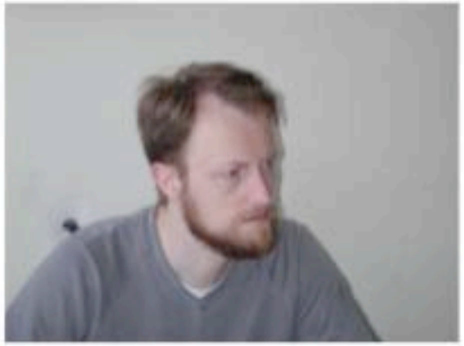
Faces

Aurélien

Martijn



Hong



Denis

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