Huntingdon and Broad Top Mountain RR

The Hanbury Brown and Twiss effect: from stars to cold atoms

Chris Westbrook
Institute Optique, Palaiseau

Toronto, 18 November 2010

Outline

1. HB&T for light (stars & history)
2. HB&T for particles (atoms)

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

Einstein, Sitz. Ber. Preuss. Ak., 1925, p. 18

Number fluctuations in an ideal quantum gas

$$\delta N^2 = \langle N^2 \rangle - \langle N \rangle^2 = \langle N \rangle + \langle N \rangle^2 / z$$

$z = (\Delta p \Delta x / h)^3$ is the number of phase space cells in the volume.

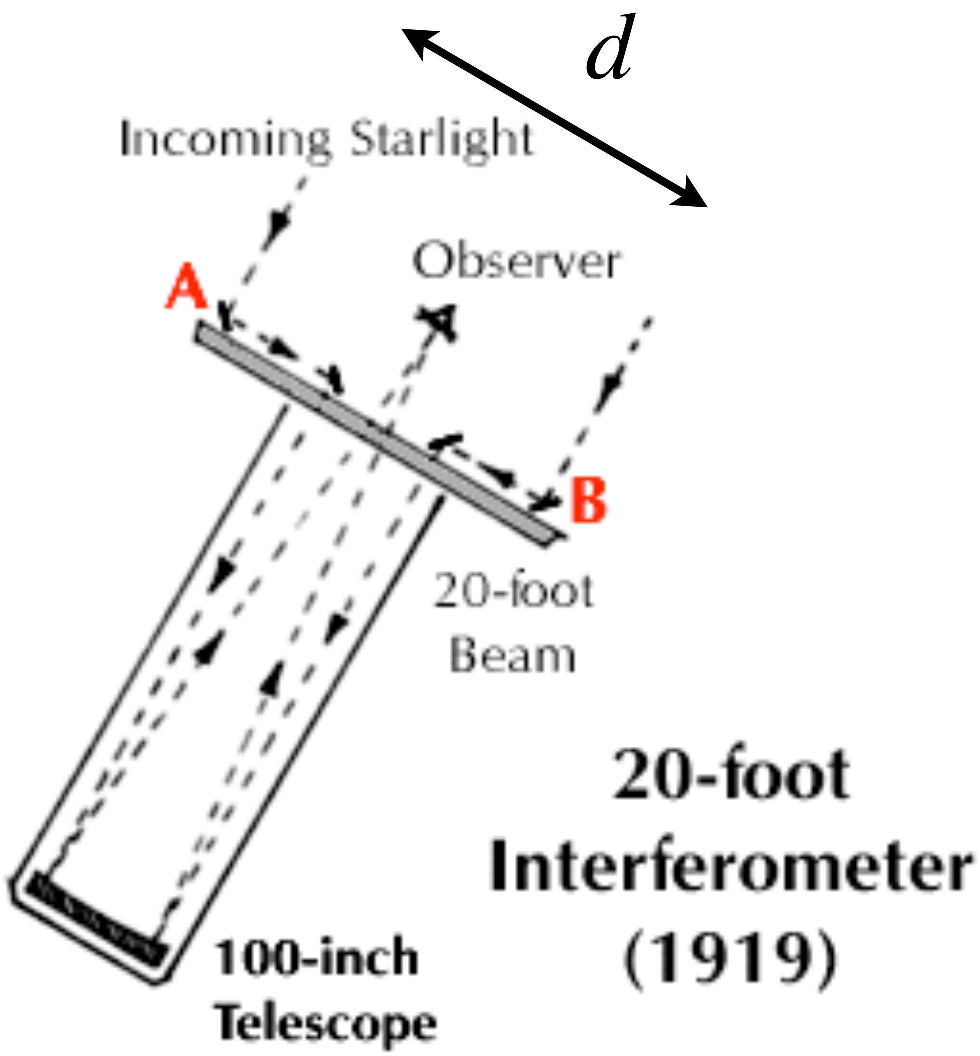
$\langle N \rangle$ "... if the molecules were independent"

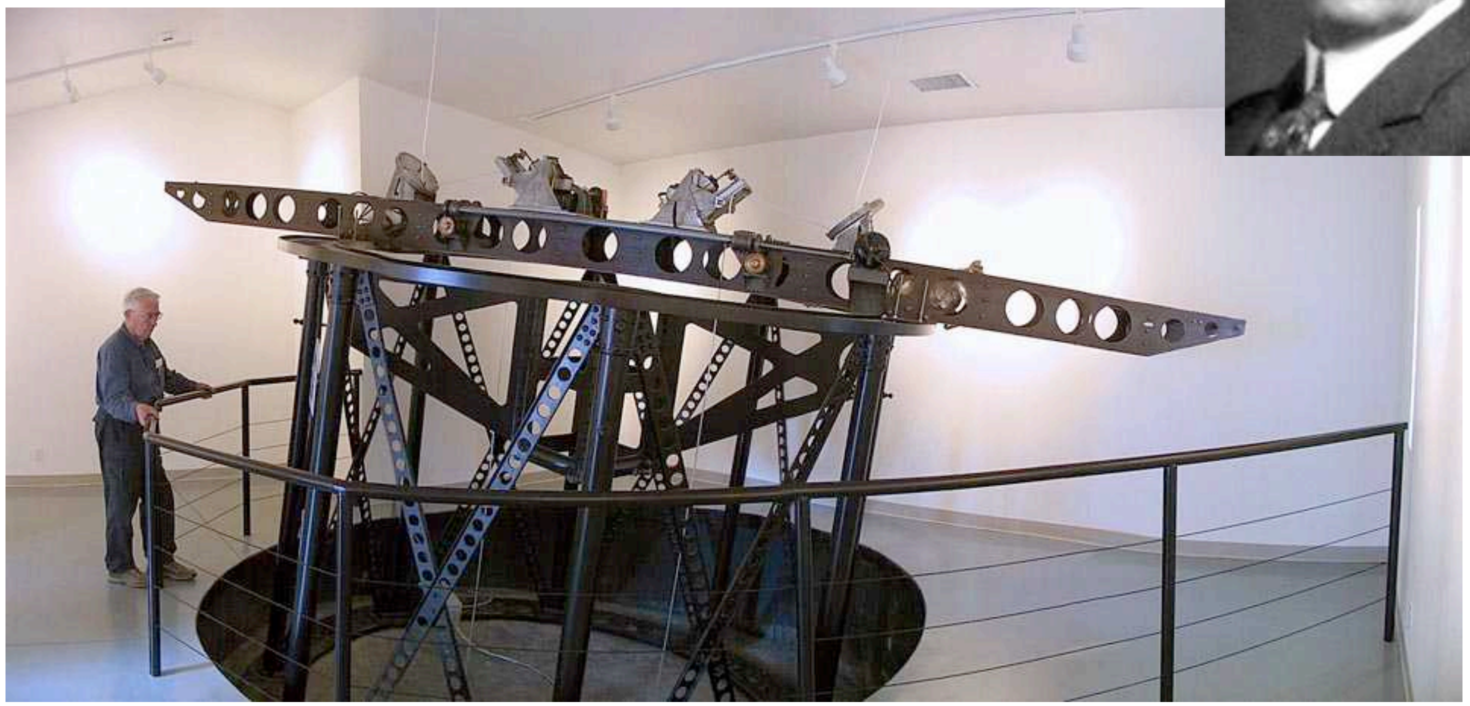
$\langle N \rangle^2$ "... interference fluctuations" *interferenzschwankungen*

"… a mutual influence between molecules of a currently altogether puzzling nature."

eine gegenseitige Beeinflussung der Moleküle von vorläufig ganz rätselhafter Art

Michelson: stellar interferometer



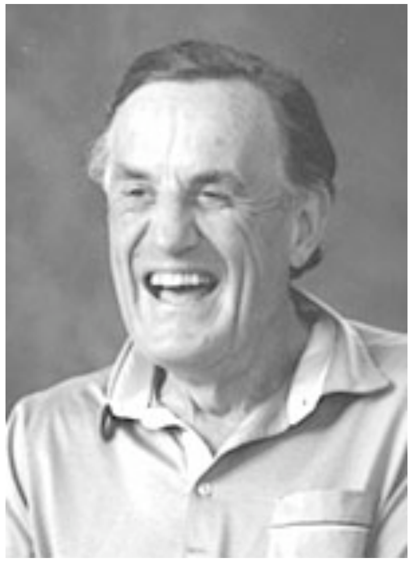


Fringe contrast indicates the spatial coherence of the source.
When d is too big, fringes disappear:

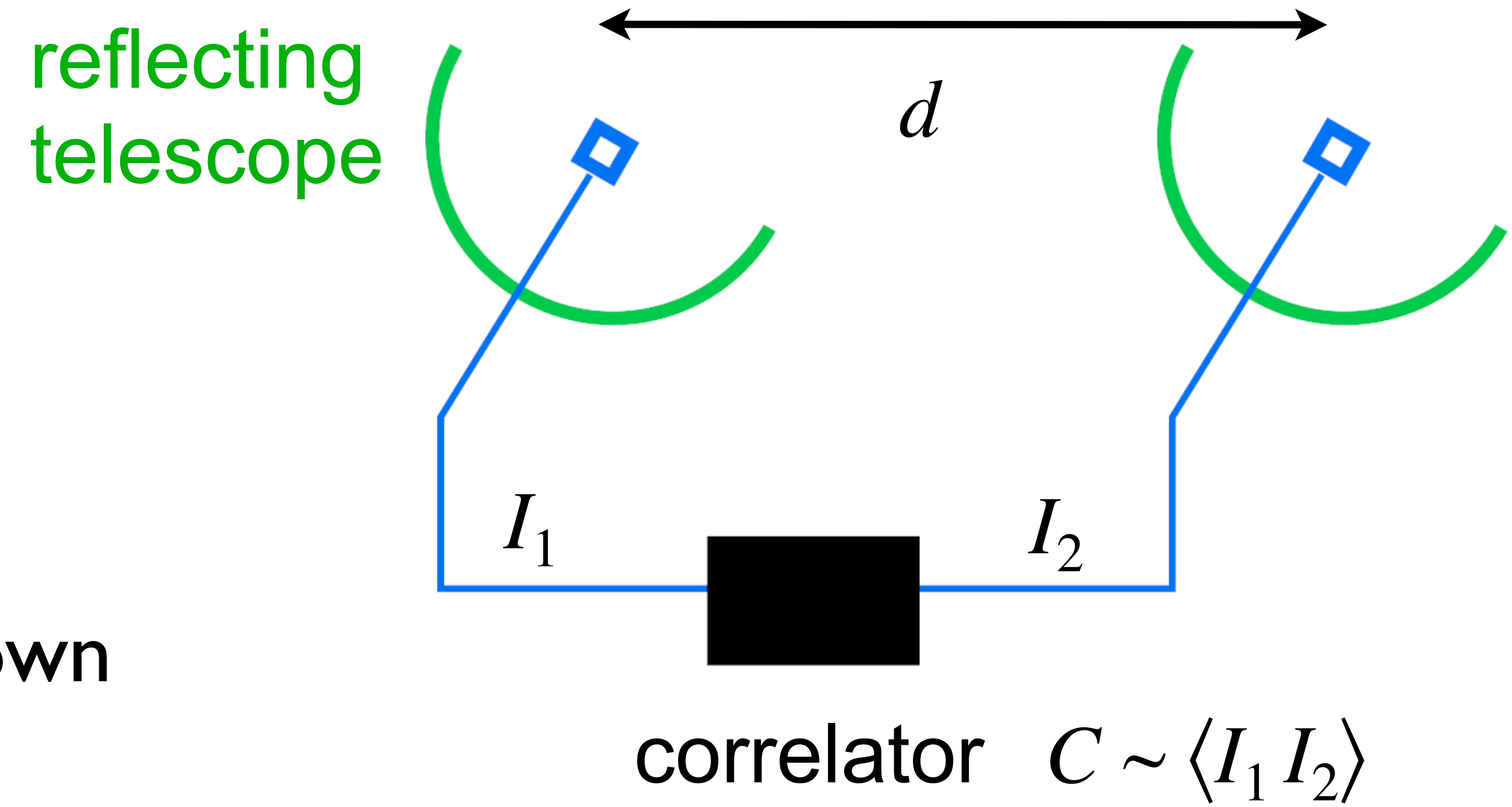
$$\theta \sim \lambda / d$$

Michelson measured the angular diameters of 6 stars.

Hanbury Brown: intensity interferometry

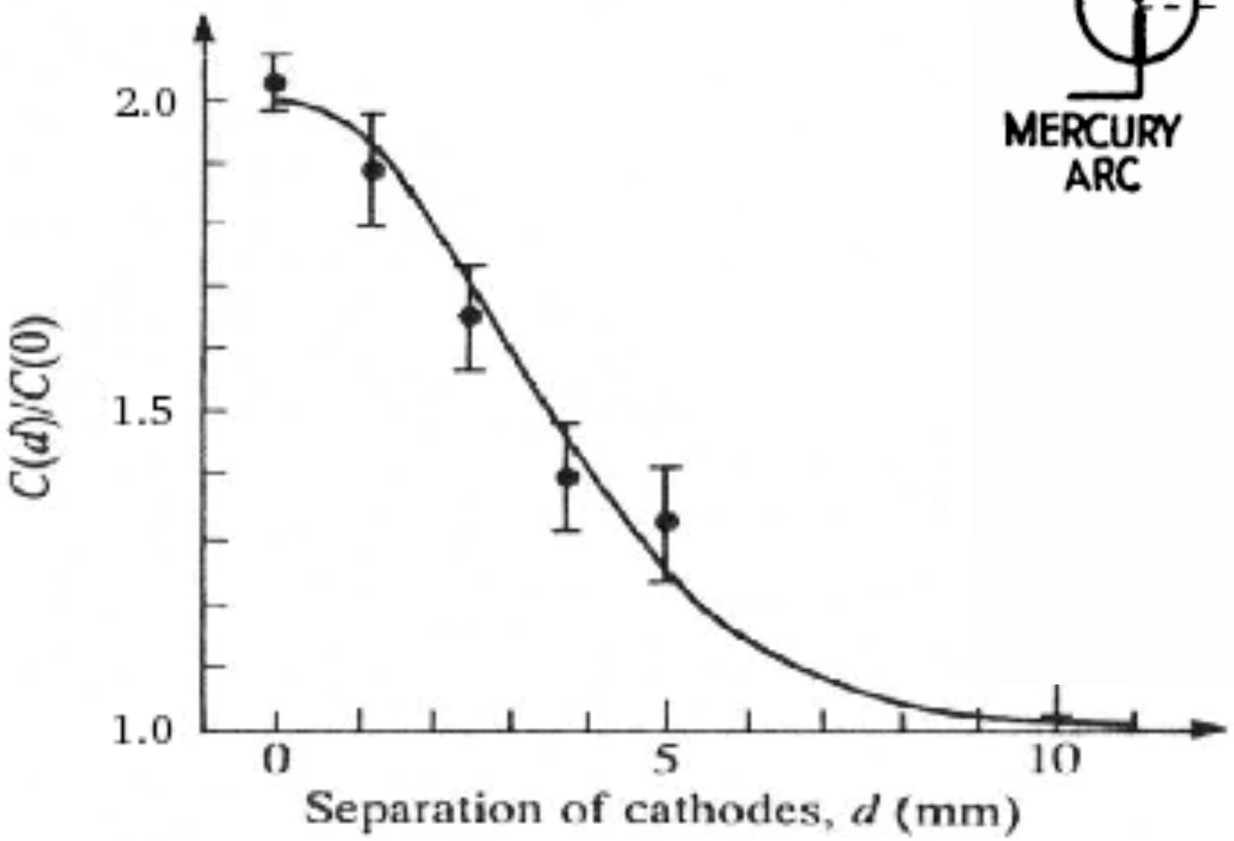


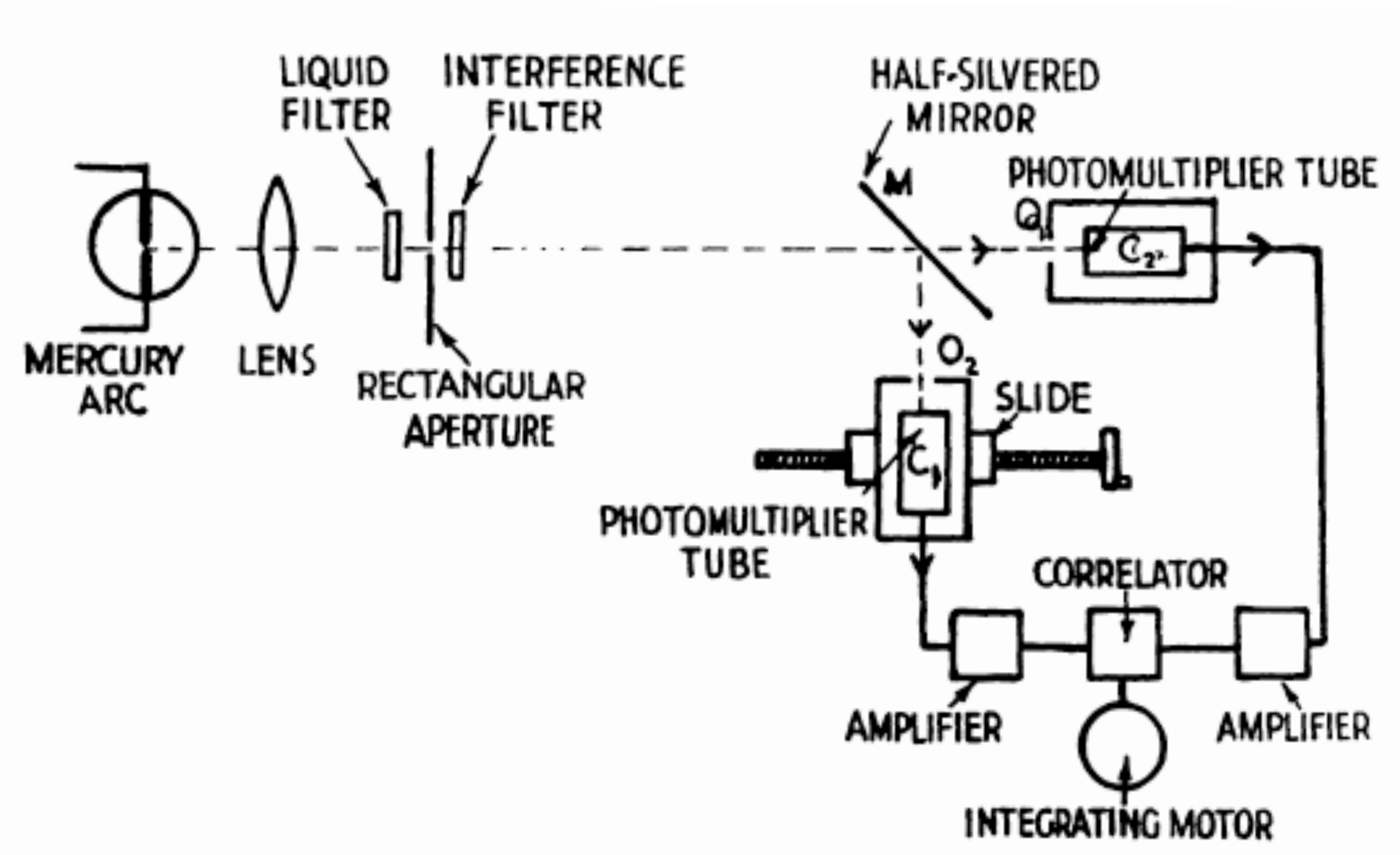
Robert Hanbury Brown
1916 - 2001



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.

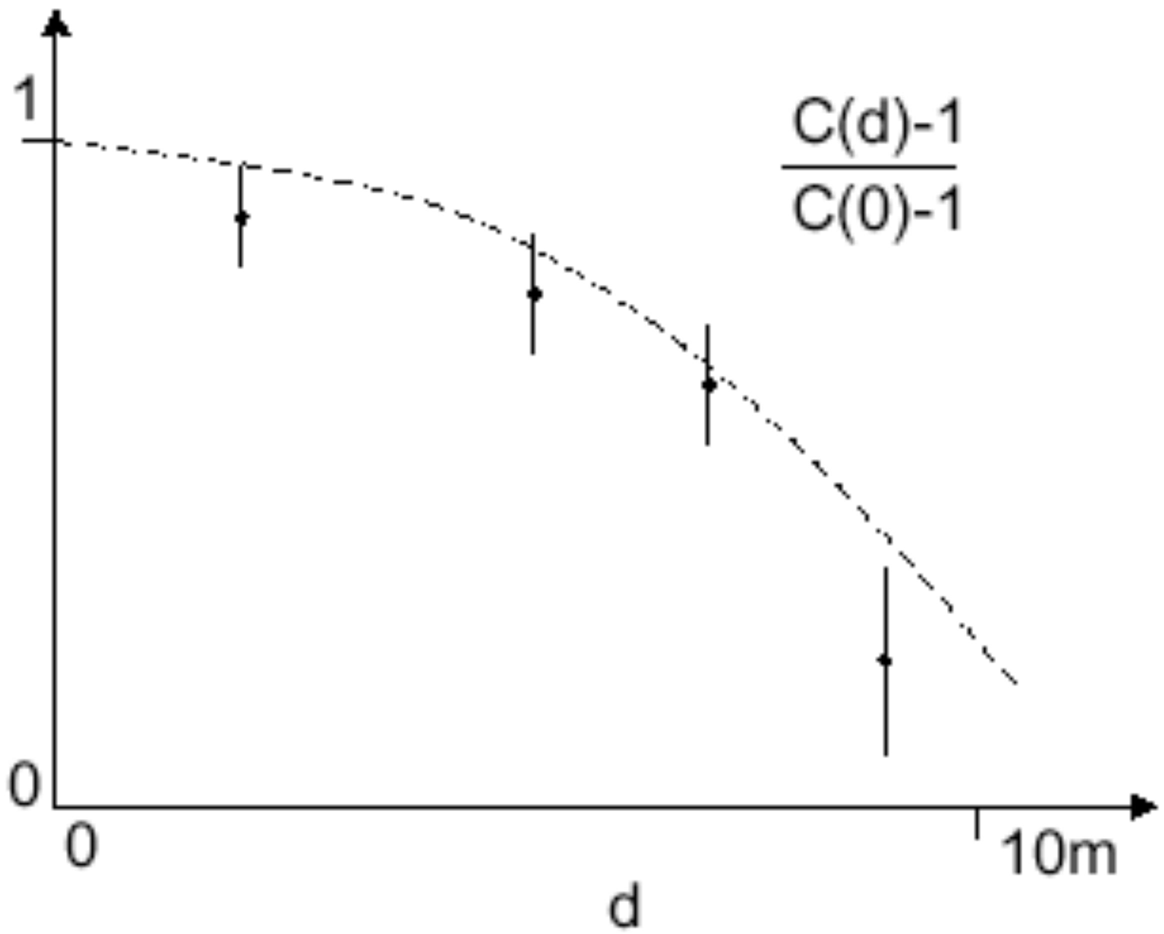
The Hanbury Brown Twiss experiment (Nature, 1956)





"The experiment shows beyond question that the photons in the two coherent beams of light are correlated and that this correlation is preserved in the process of photoelectric emission."

Measurement of a stellar diameter (1957)



Sirius

$\theta = 3\times10^{-8}$ radians

Independent photons from different points on a star "stick together" - photon bunching

Stellar interferometer in Australia 1960's

Hanbury Brown's group measured diameters of 32 stars

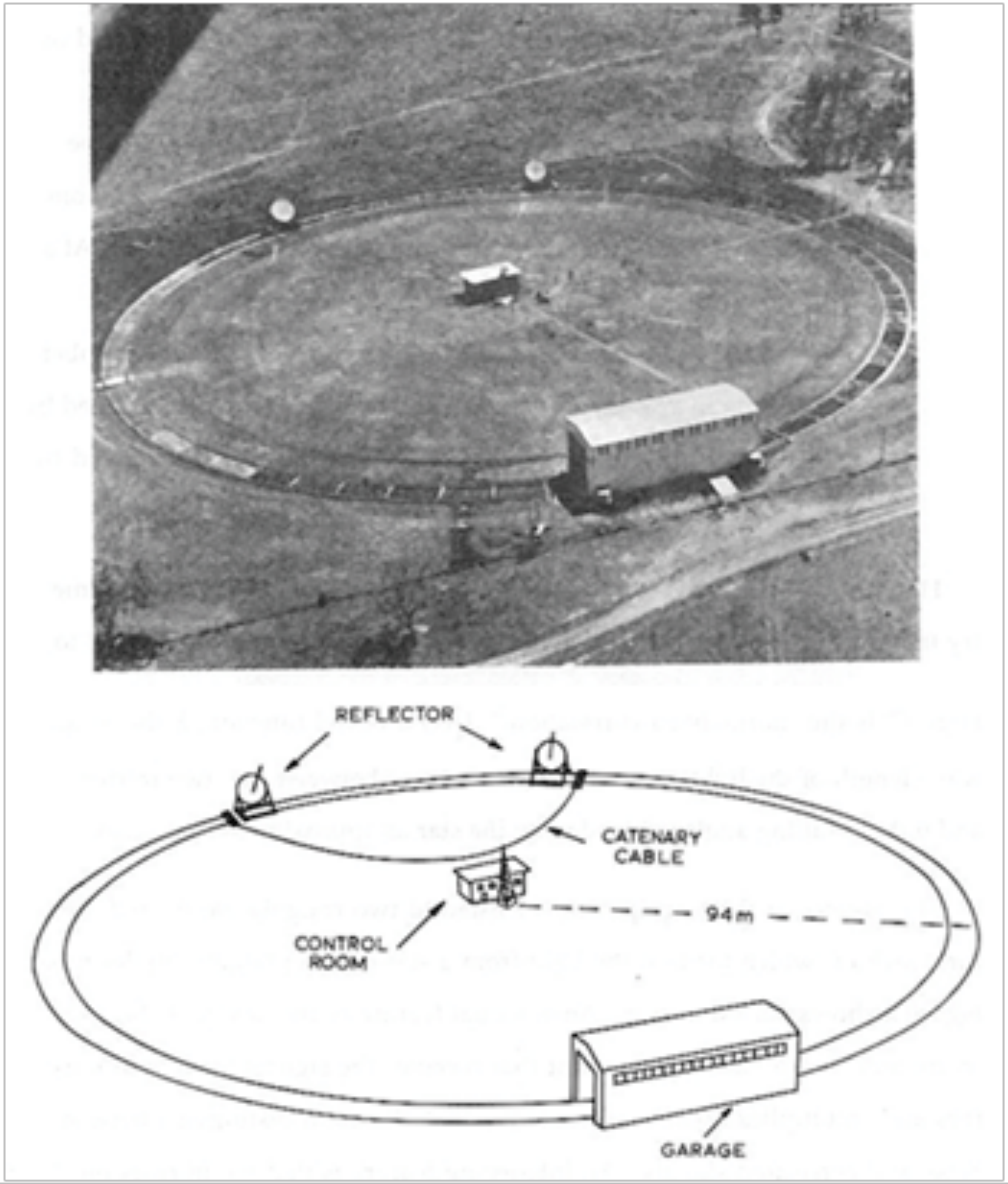
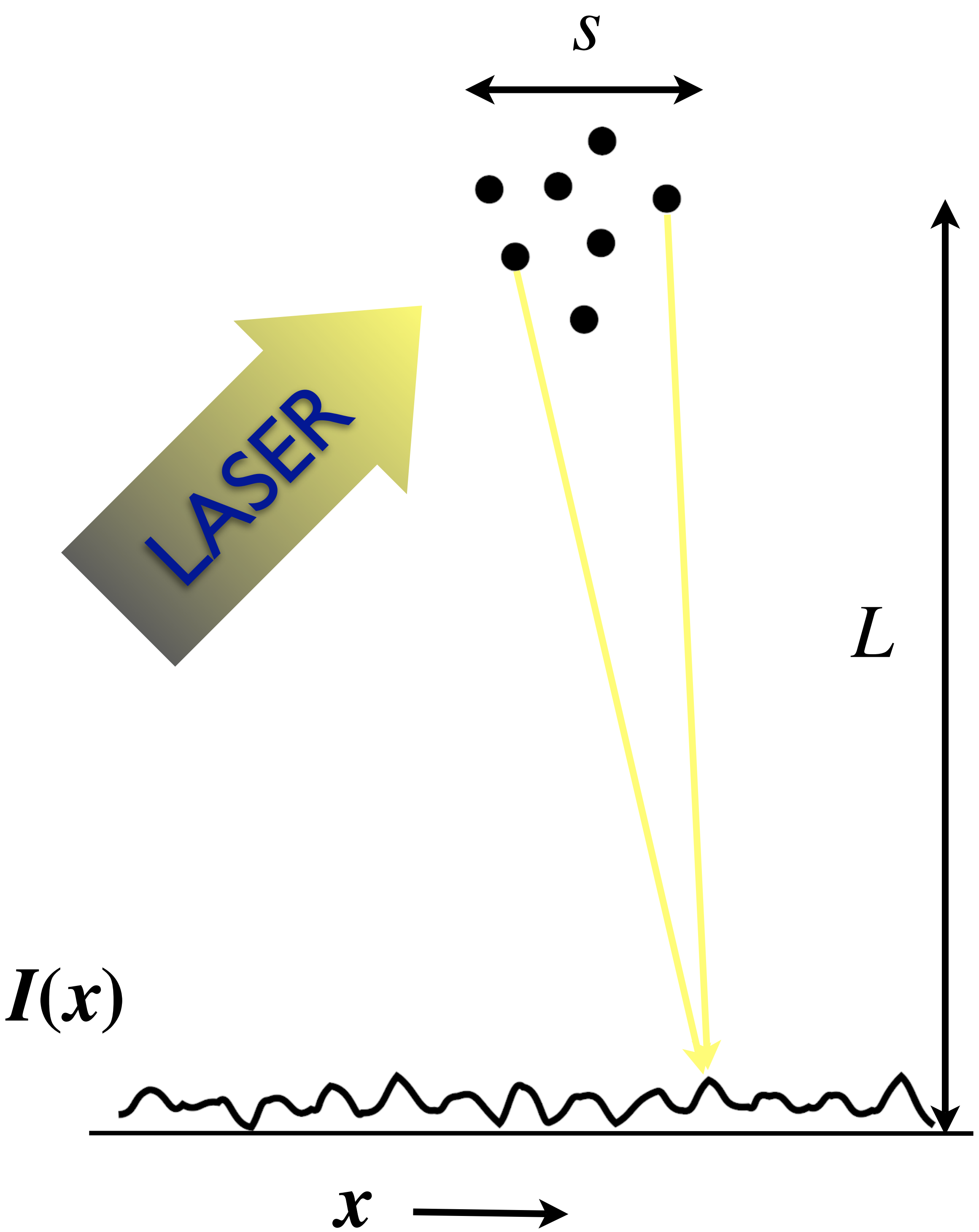


Figure 1. Aerial photo and illustration of the original HBT apparatus. They have been extracted from Ref.[1].

(Classical) speckle interpretation



$l_C = L\lambda/s$

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

large Δx → uncorrelated:

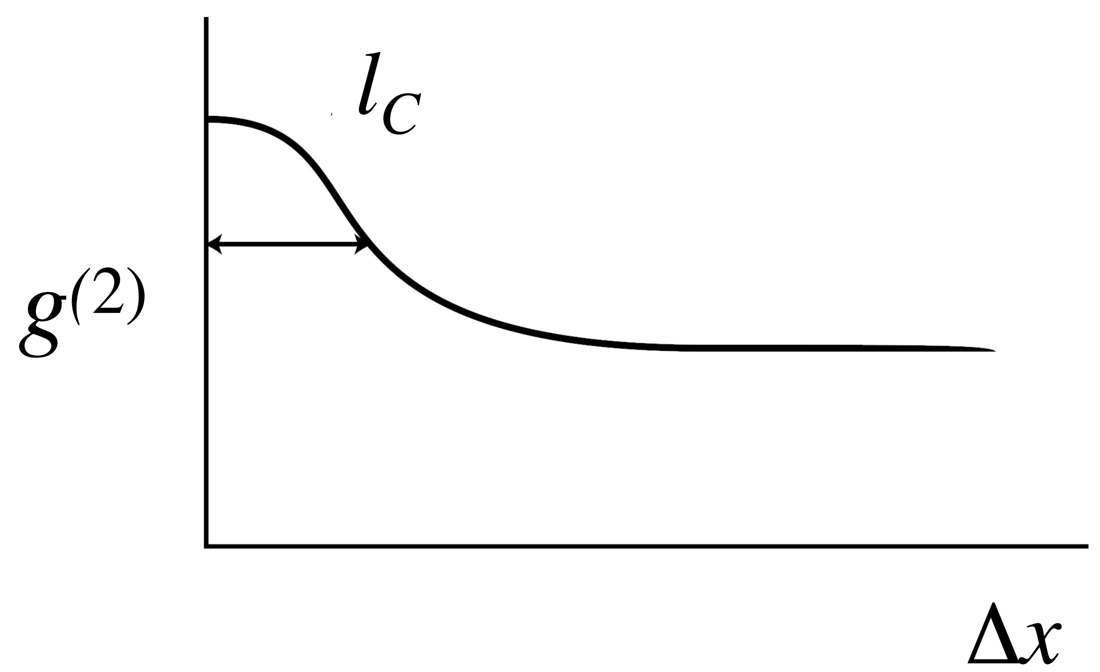
$$\langle I_1\, I_2\rangle = \langle I_1\rangle\langle I_2\rangle$$

$\Delta x = 0$:

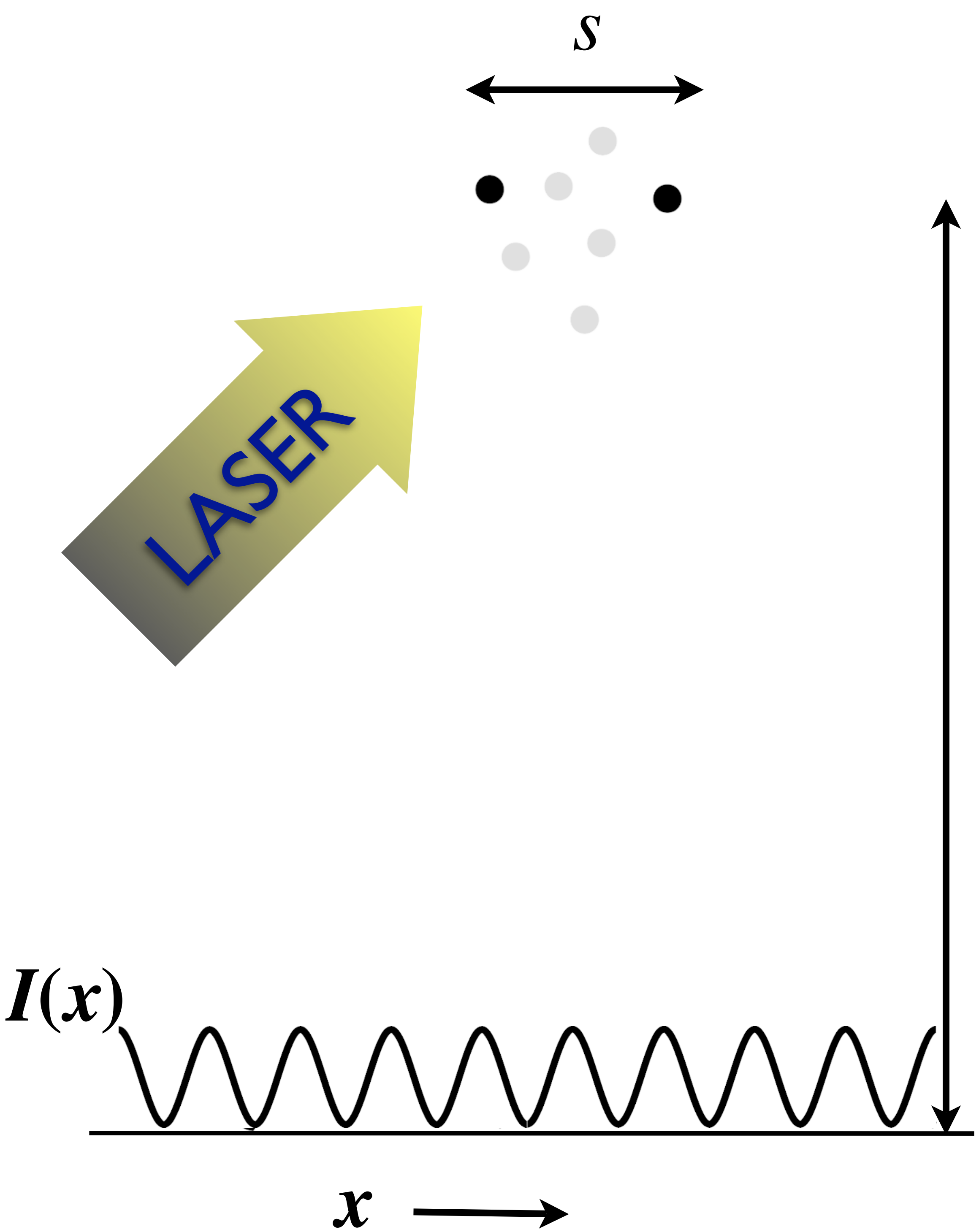
$$\langle I^2\rangle > \langle I\rangle^2$$

thermal source (Einstein):

$$\langle I^2\rangle = 2\,\langle I\rangle^2$$



Speckle correlation length

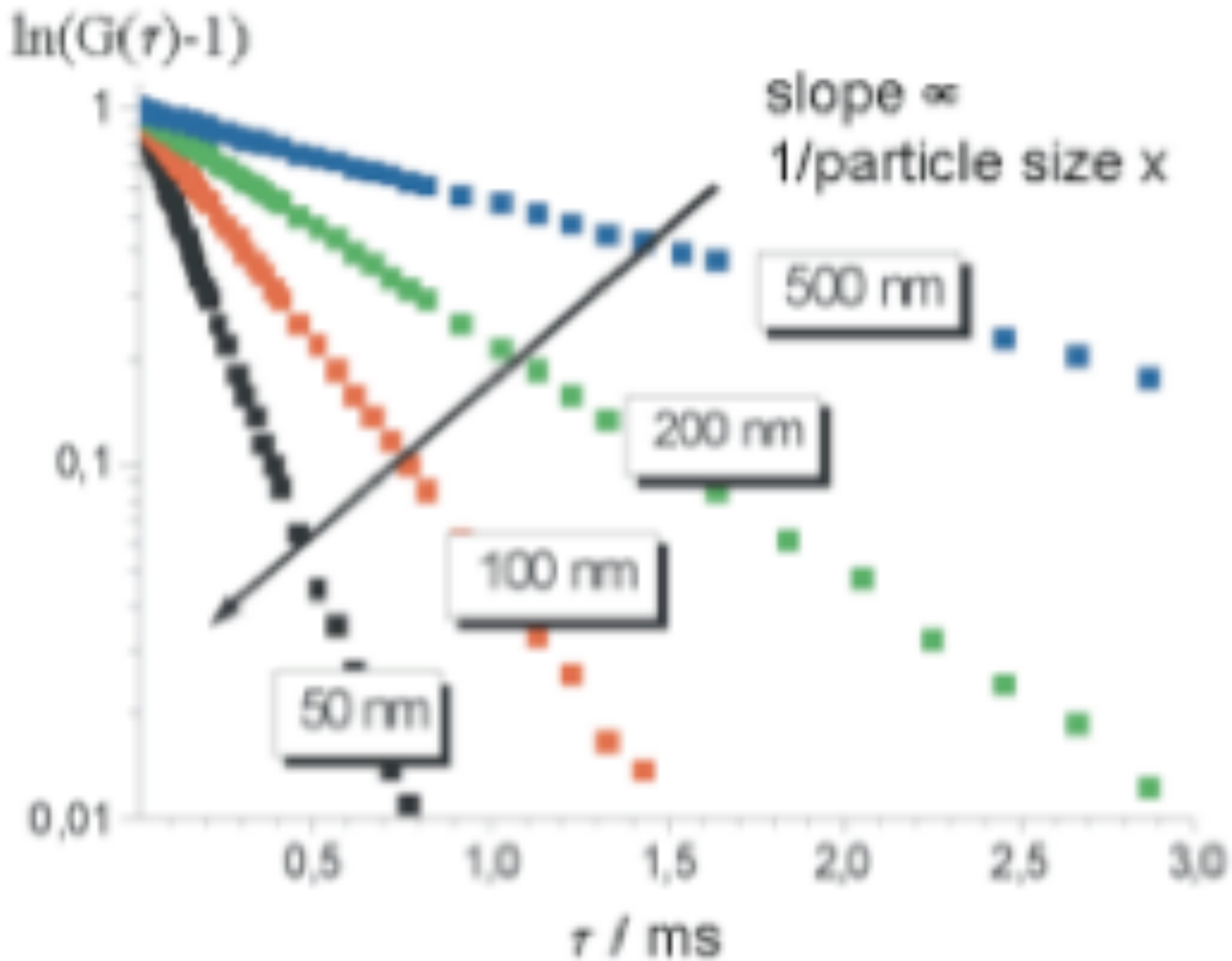


Young's fringe spacing for two sources with separation s:

$$l = L\lambda/s$$

Add up many source pairs. l is the smallest length scale on which intensity can vary.

Cosmetics industry: particle size measurements



particles in a viscous liquid (water)

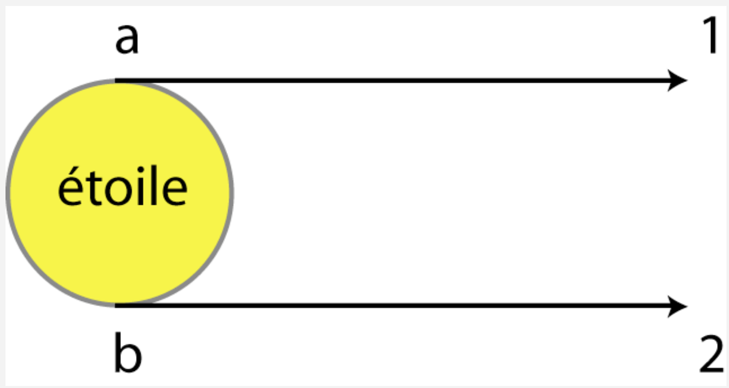
Diffusion coefficient is related to viscosity and particle size

$$g^{(2)} \sim \exp[-\, t/\tau_C], \quad (\lambda/2\pi)^2 = D\, \tau_C$$

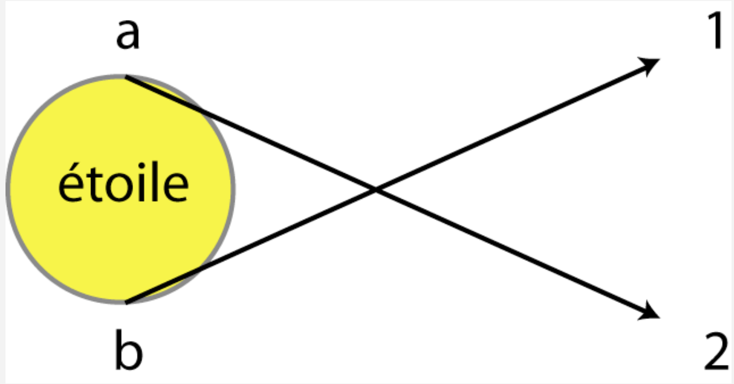
corresponding bandwidth: 100 Hz

Photon interpretation (Fano, Am. J. Phys. 1961)

Two “paths”



Amplitude: $\langle 1|a\rangle\langle 2|b\rangle$



Amplitude: $\langle 1|b\rangle\langle 2|a\rangle$

Interference:

$$P = |\langle 1|a\rangle\langle 2|b\rangle \pm \langle 1|b\rangle\langle 2|a\rangle|^2$$

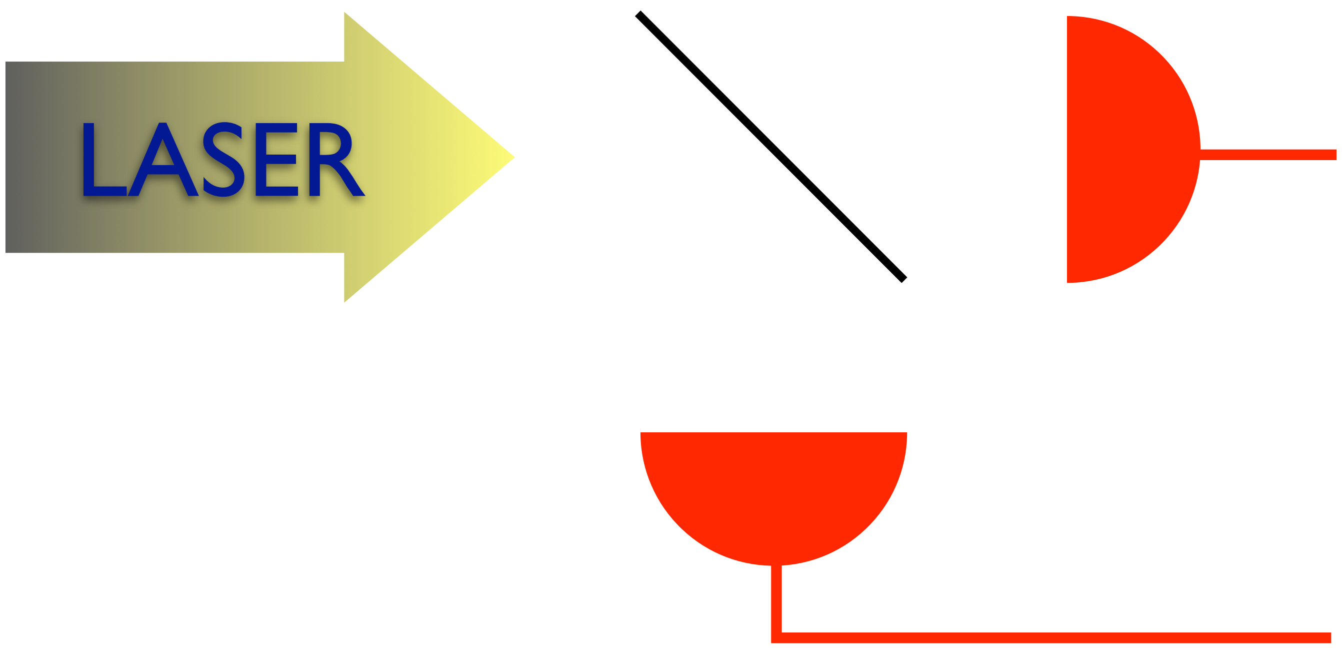
+ for bosons, − for fermions.

After summing over extended source, interference term survives if

$$ds \,/\, \lambda L \ll 1$$

A simple classical effect corresponds to a subtle quantum one: photons are not independent.

What about a laser?



Coherence length is very long.
Strong correlations?
Some said "yes"

Glauber, PRL 10, 84 (1963)

"The fact that photon correlations are enhanced by narrowing the spectral bandwidth has led to a prediction of lange-scale correlations to be observed in the beam of an optical maser. We shall indicate that this prediction is misleading and follows from an inappropriate model of the maser beam."

Correlations in a laser: measurement

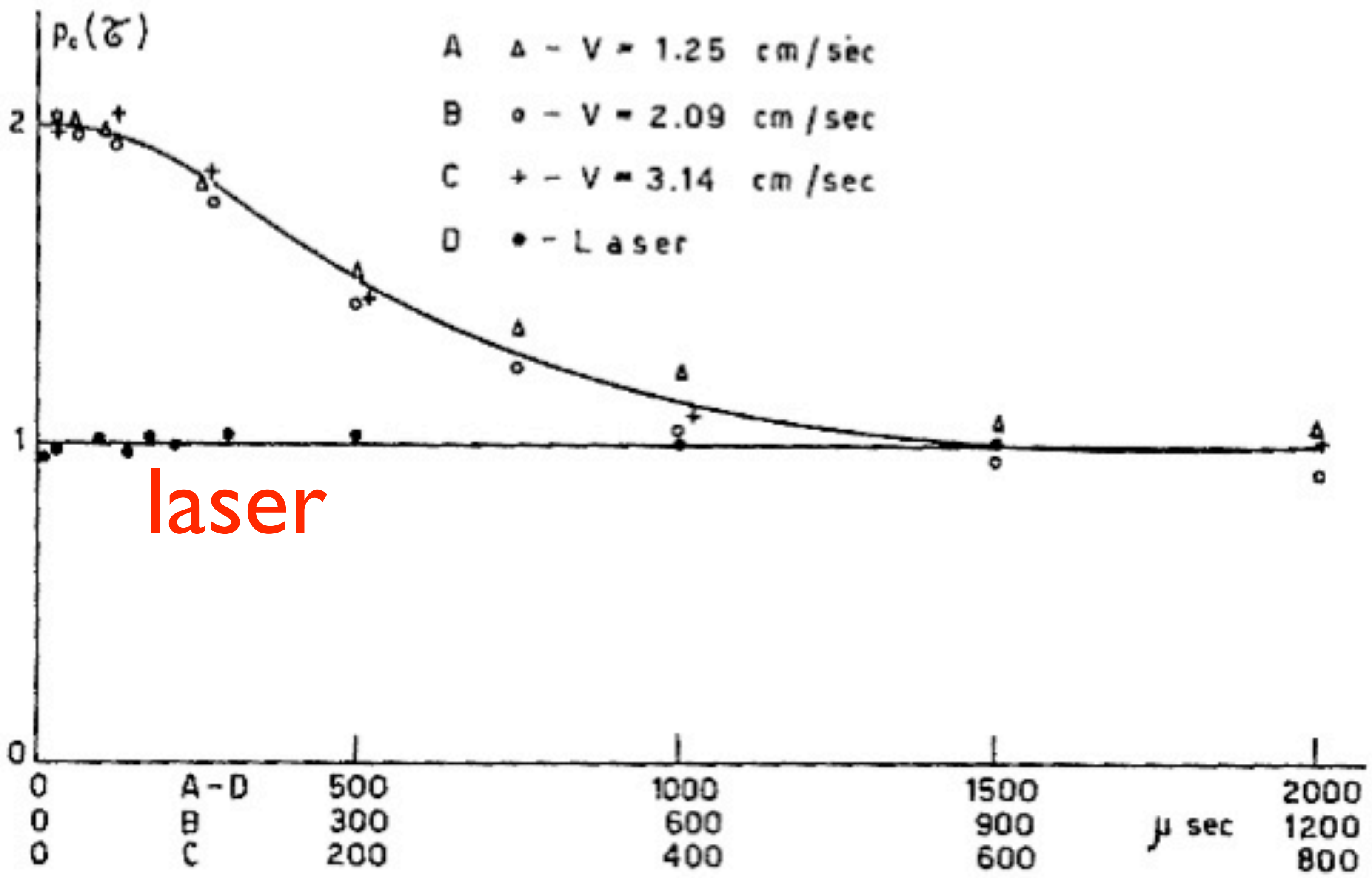


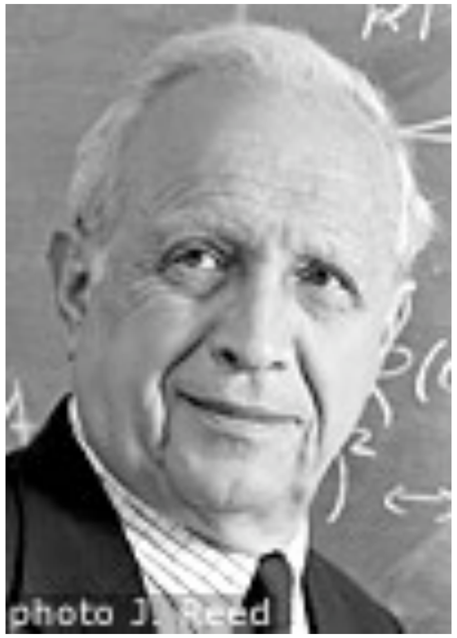
Fig. 1. Conditional probability $p_C(\tau)$ of a second count occurring at a time τ after a first has occurred at time $\tau = 0$.

Arecchi, Gatti, Sona, Phys. Lett. 1966
Temporal fluctations are only due to shot noise.

$$g^{(2)}(\tau) = 1$$

Photon interpretation using quantized fields 1963

Roy Glauber
Nobel prize
2005



$$\hat{E} = \hat{E}^+ + \hat{E}^-$$

$$\hat{E}^+ = \sum_\omega \sqrt{\frac{\hbar\omega}{2\epsilon_0 V}} e^{-i\omega t}\hat{a}_\omega$$

$$\langle I(t)I(t')\rangle = \langle \hat{E}^-(t)\hat{E}^+(t)\hat{E}^-(t')\hat{E}^+(t')\rangle$$

$$= \langle \hat{E}^-(t)\hat{E}^-(t')\hat{E}^+(t')\hat{E}^+(t)\rangle + \delta(t-t')\langle \hat{E}^-(t)\hat{E}^+(t)\rangle$$

joint, 2 photon detection prob. — shot noise

and

$$\langle \hat{a}_i^\dagger \hat{a}_j^\dagger \hat{a}_k \hat{a}_l\rangle = \langle \hat{a}_i^\dagger \hat{a}_i\rangle\langle \hat{a}_k^\dagger \hat{a}_k\rangle(\delta_{i,k}\delta_{j,l} + \delta_{i,l}\delta_{j,k})$$

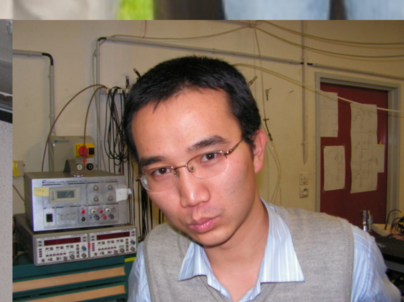
Einstein formula recovered
for a laser there is only one mode: no interference
for fermions, use anticommutation: minus sign

Atoms: the quantum atom optics group

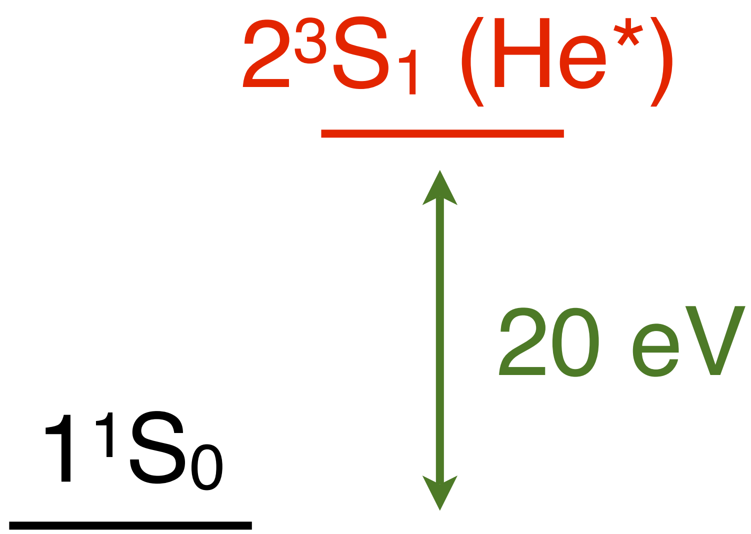
Rodolphe Hoppeler
Jose Gomes
Martijn Schellekens
Aurélien Perrin
Valentina Krachmalnicoff
Jean-Christophe Jaskula
Marie Bonneau
Josselin Ruaudel

Hong Chang
Vanessa Leung
Guthrie Partridge

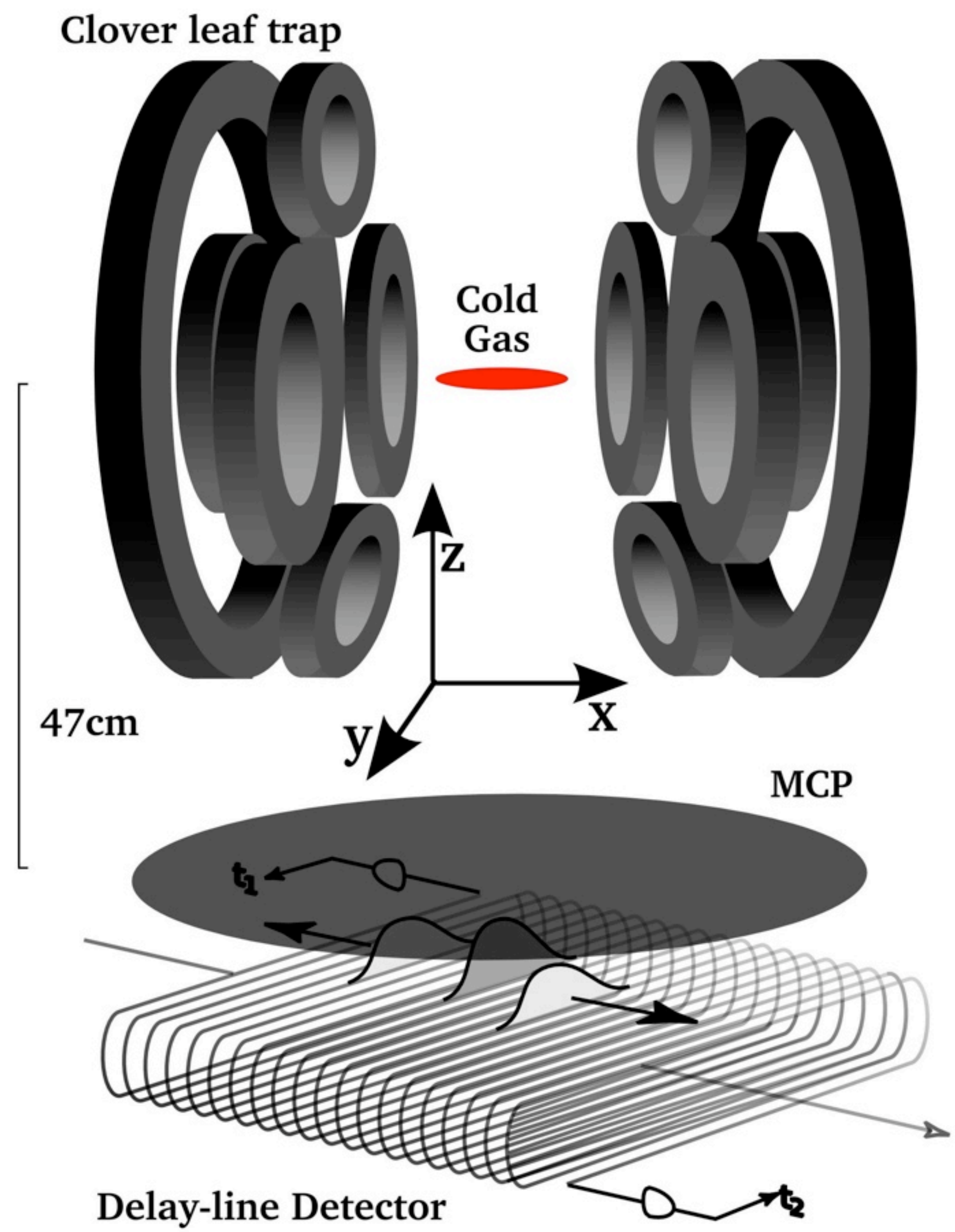
Denis Boiron
Alain Aspect
CIW



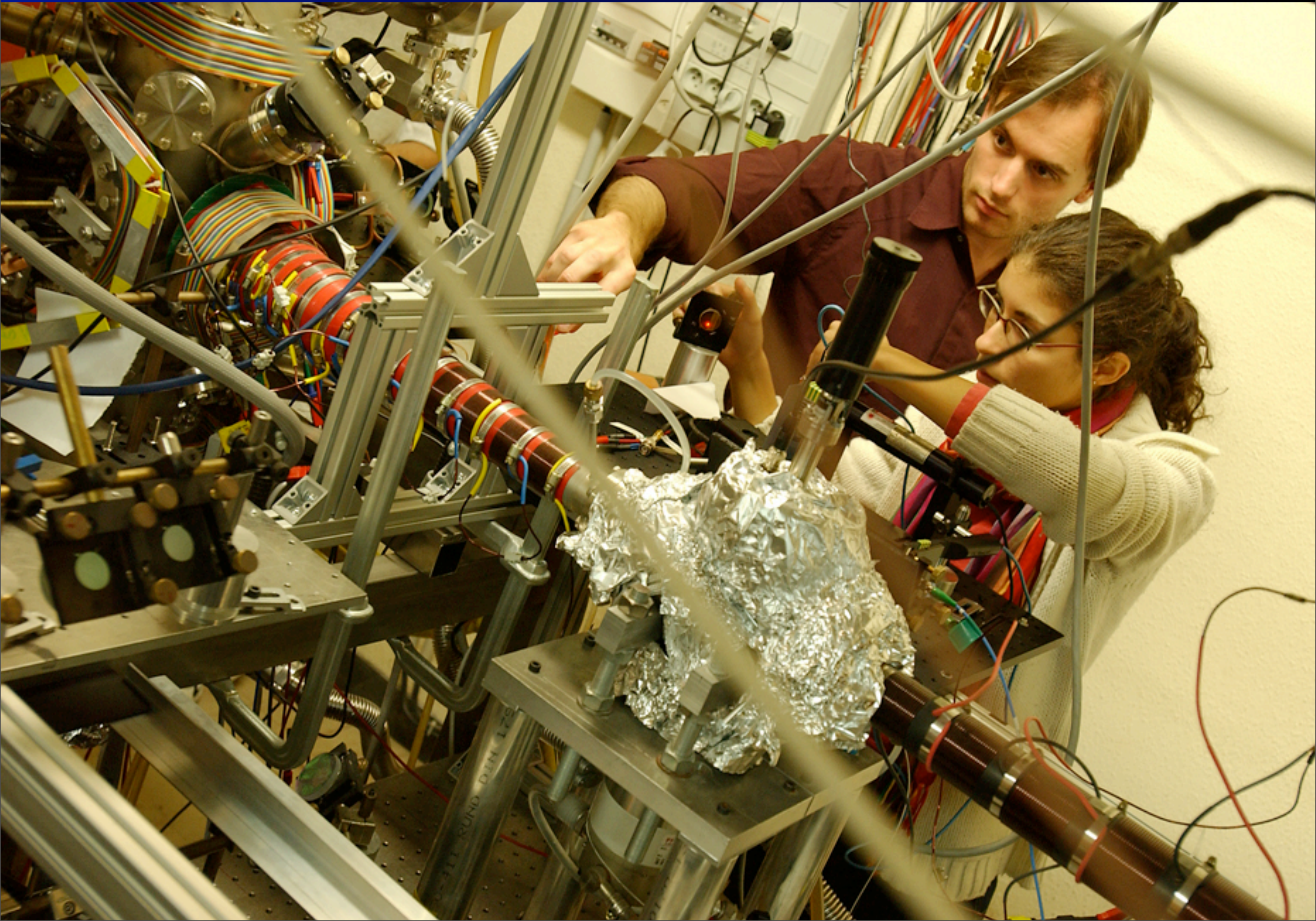
Metastable helium and 3D detection



- detection by μ-channel plate (He* has 20 eV)
- excellent time (vertical) resolution
- single atom detection 10% quantum eff.
- ~ 500 μm horiz. res. 5×10^4 detectors in //
- ~ 200 ns deadtime



Photo

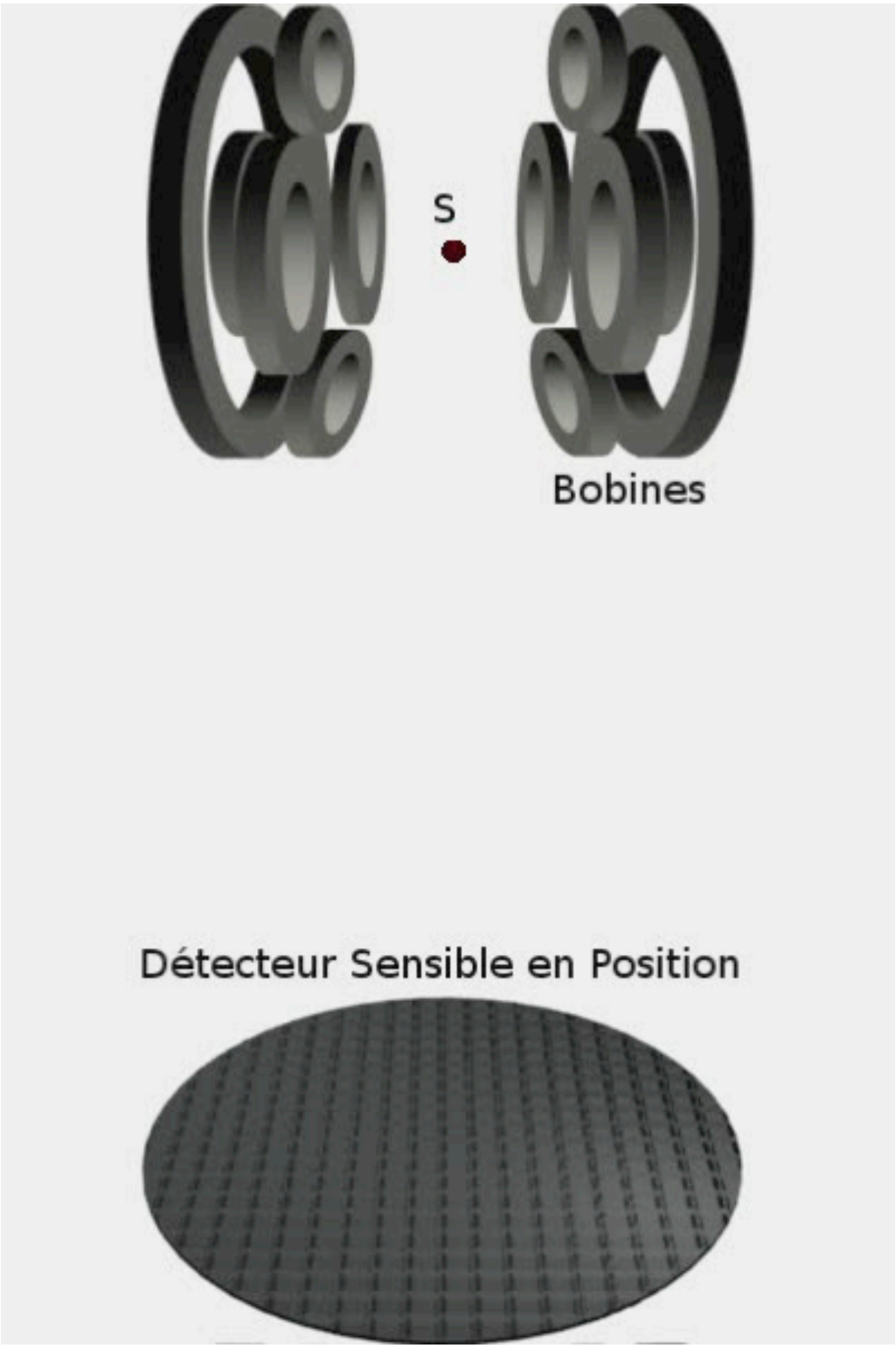


A "time of flight" observation

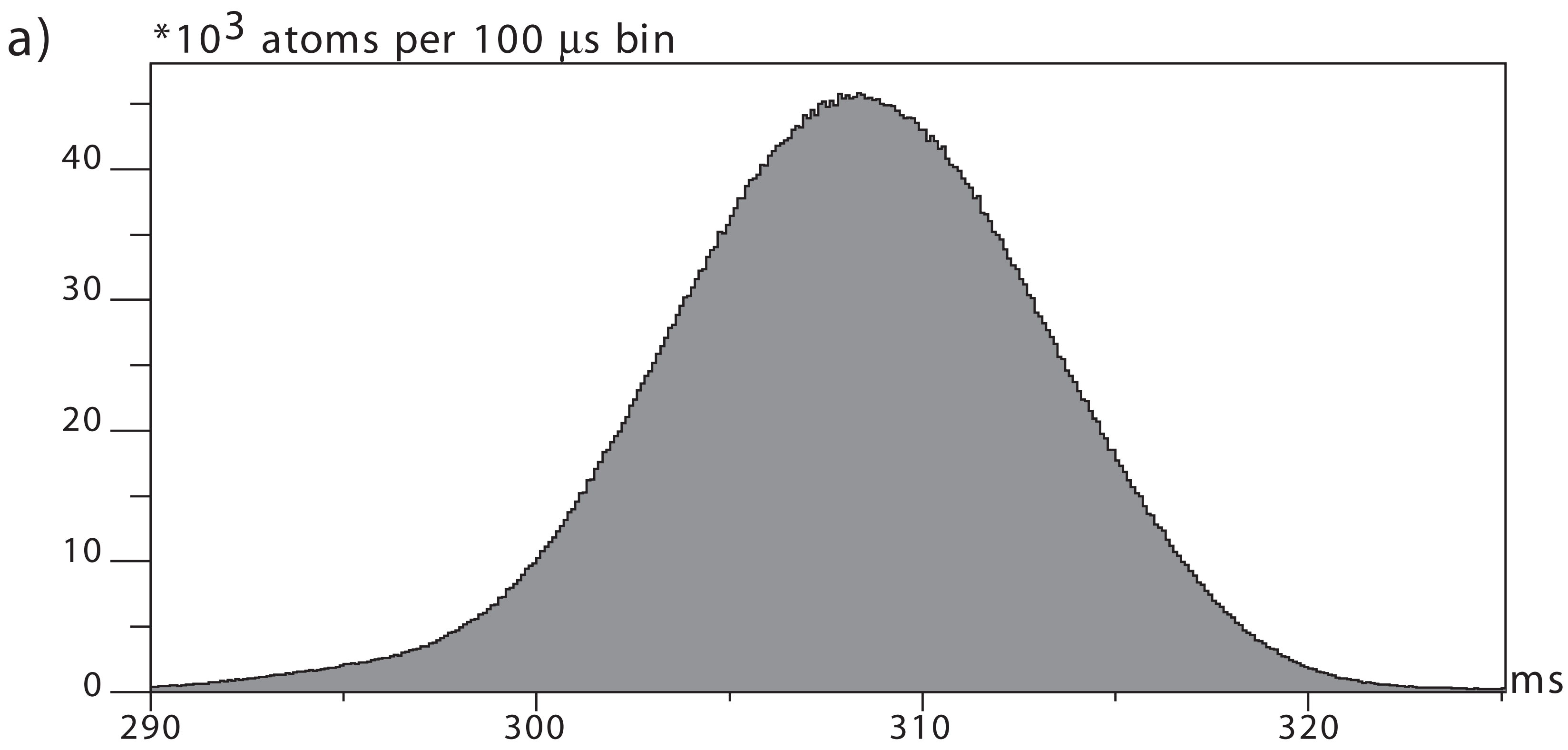
trap

typically 10^5 atoms
time of flight ~ 300 ms
width of TOF ~ 10 ms
we record x,y,t for every detected atom

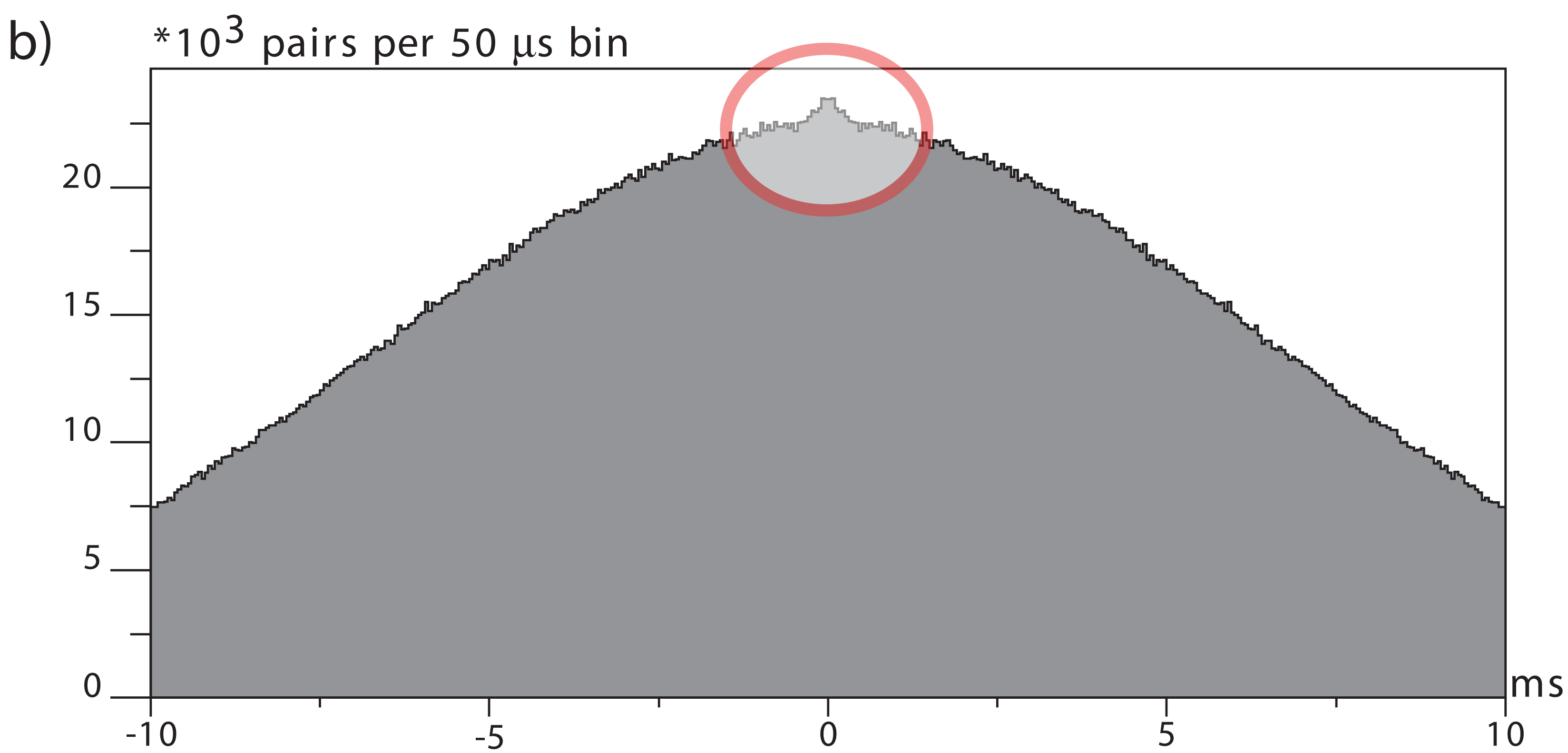
detector



Atoms dropped onto detector

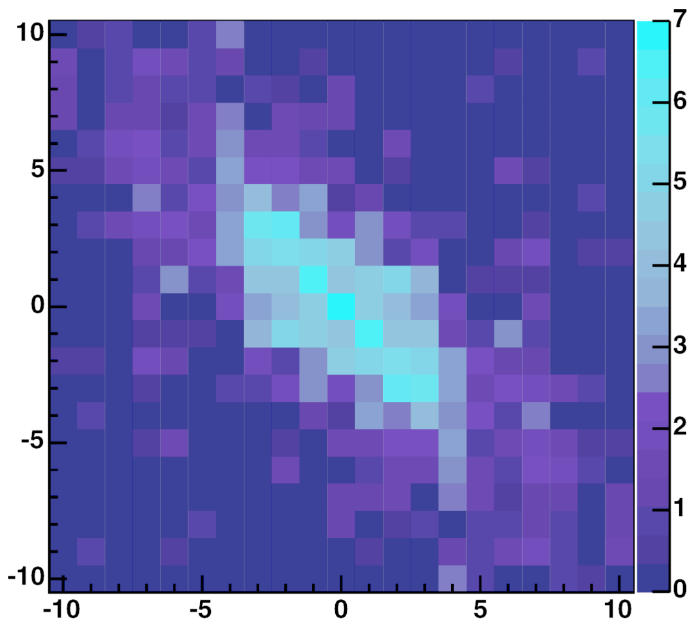


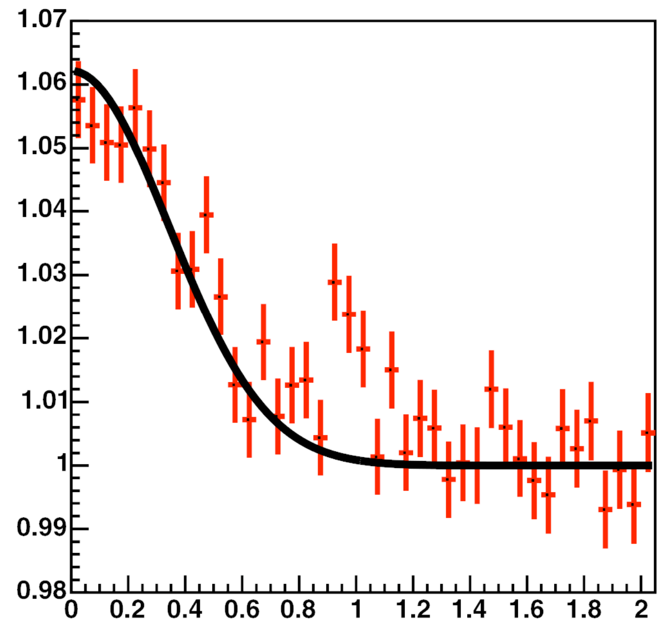
$n(p_z)$
arrival time distribution integrated over detector, summed ~1000 times



$G^{(2)}(p-p')$
number of pairs within a small volume ($500\times500\times150\ \mu m^3$)

Normalized correlation functions

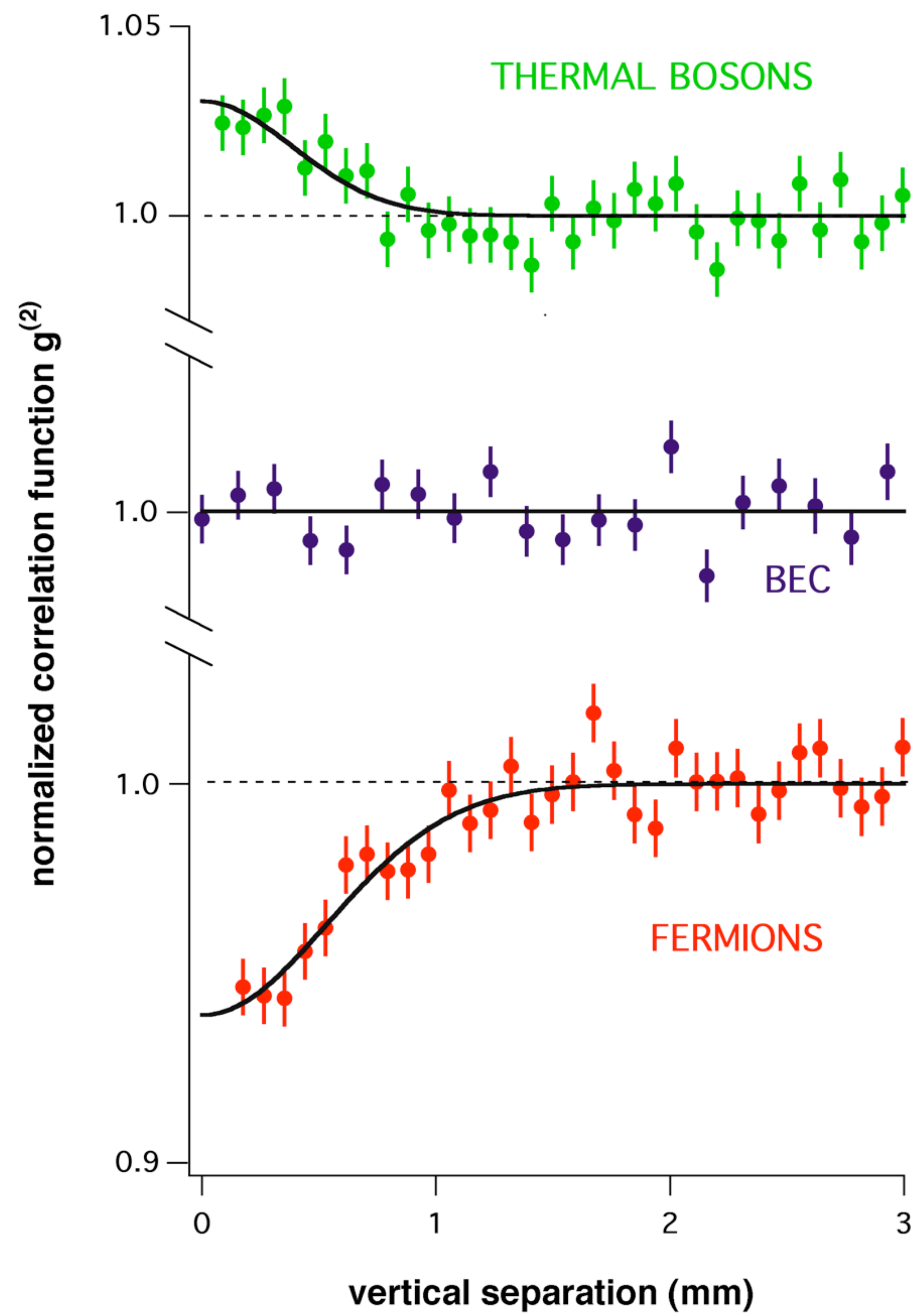




in detector plane

vertical

$g^{(2)}(p - p')$ of a thermal bose gas



comparison of a bose gas, a BEC and a fermi gas

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

Coherence length

In the trap:
(anisotropic in *p*)

$$l_{coh} \sim \lambda_{dB} \sim \frac{\hbar}{\Delta p}$$

$$p_{coh} = \hbar / s$$

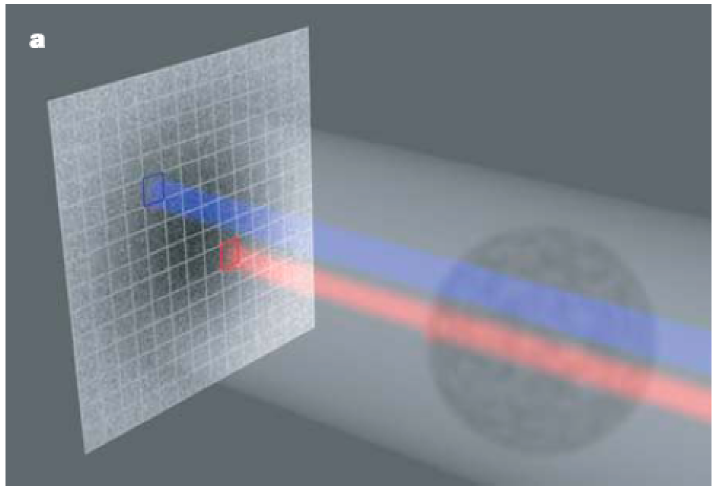
After expansion, measured positions correspond to momenta. After a time of flight *t*:

$$\rightarrow l_{coh} = \frac{\hbar t}{ms}$$

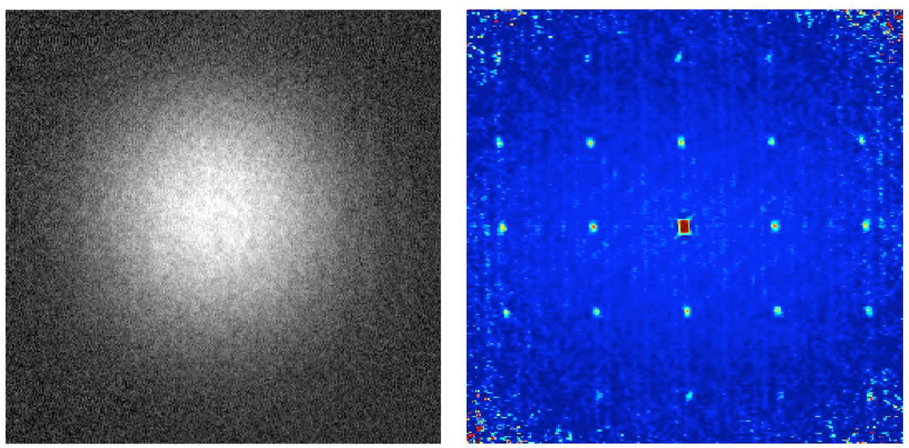
Analogy with optical speckle:

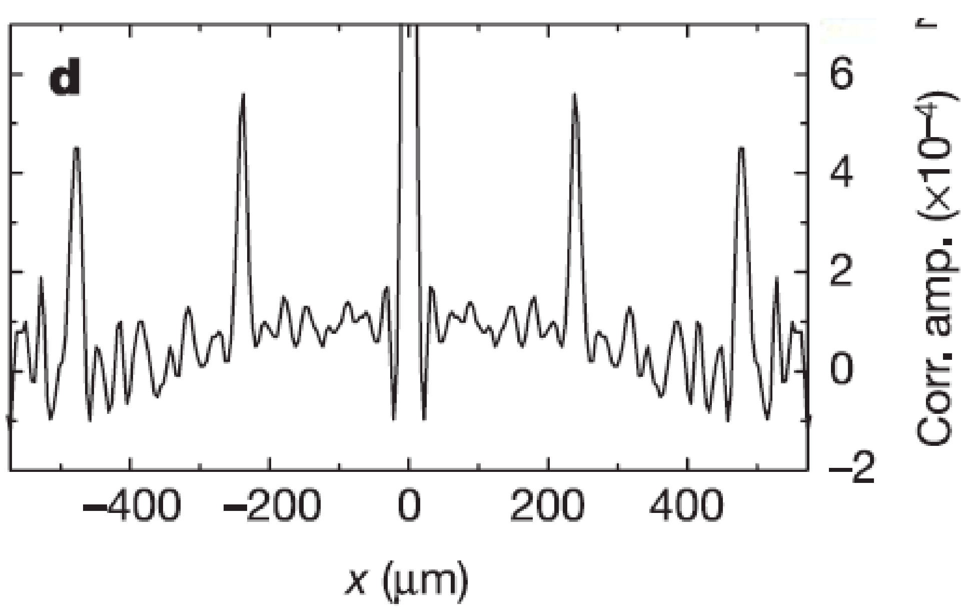
$$\frac{\hbar t}{ms} = \frac{\hbar}{mv} \frac{vt}{s} = \lambda \frac{L}{s}$$

Other Experiments

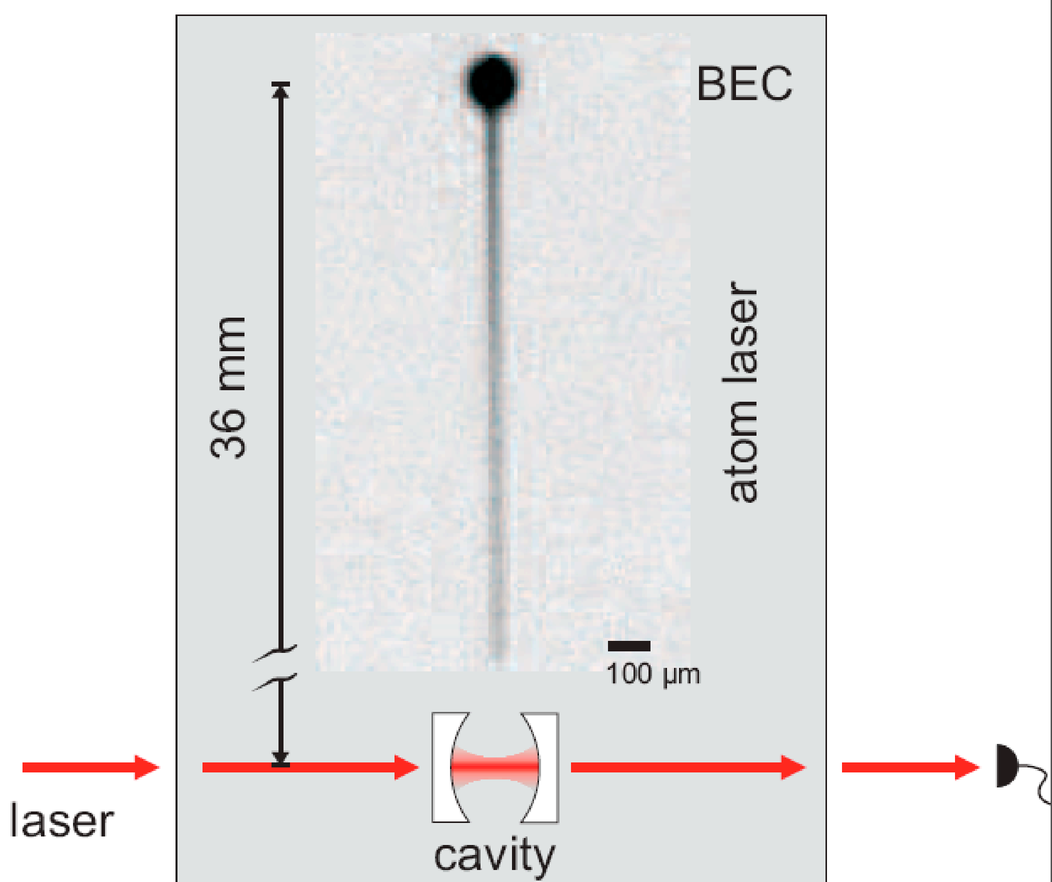


Optical lattice, Mott state, using absorption imaging. You see the FT of the density distribution (Mainz, NIST, LENS ...)





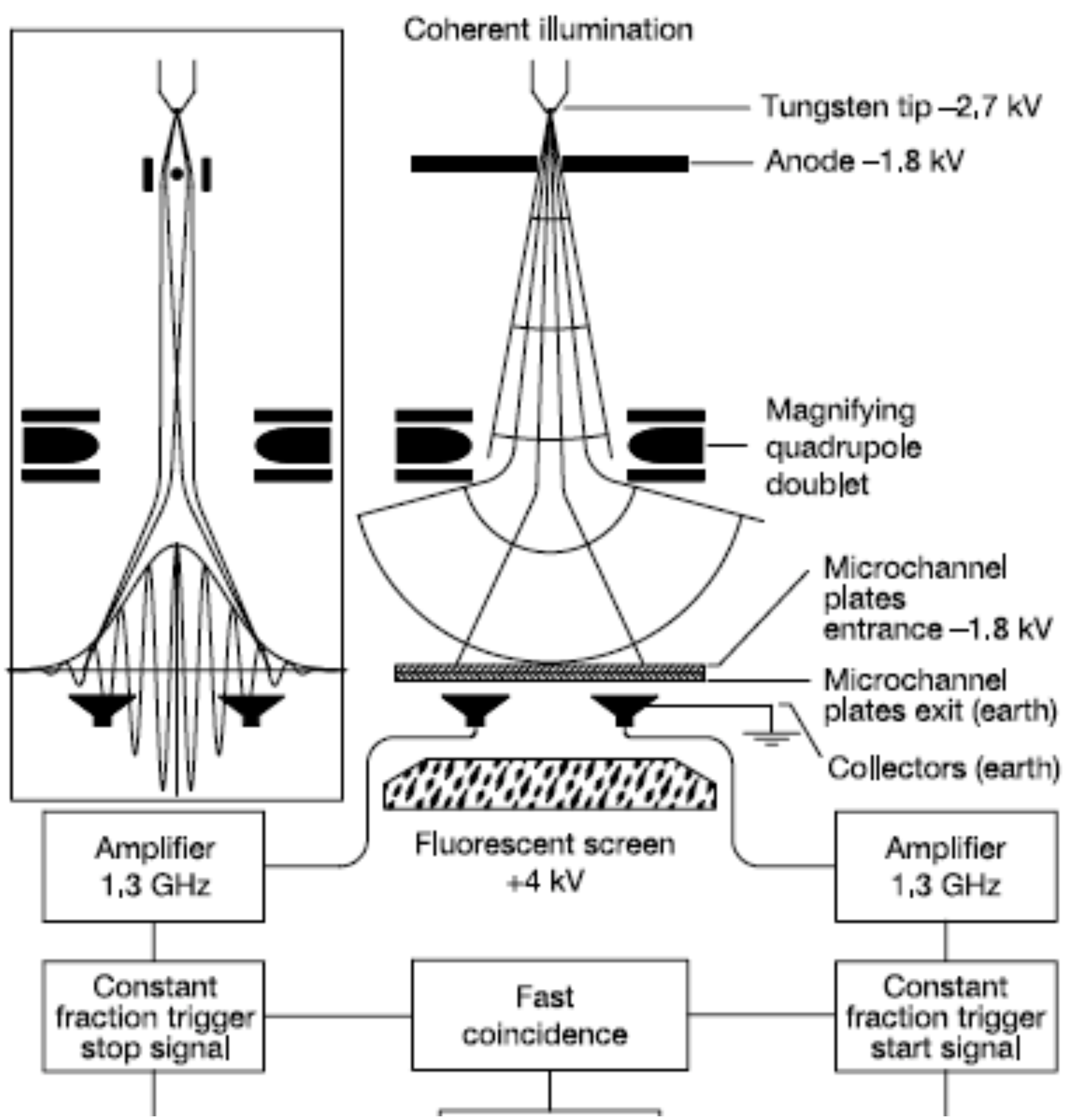
Fölling et al. *Nature* **434**, 481-484 (2005)

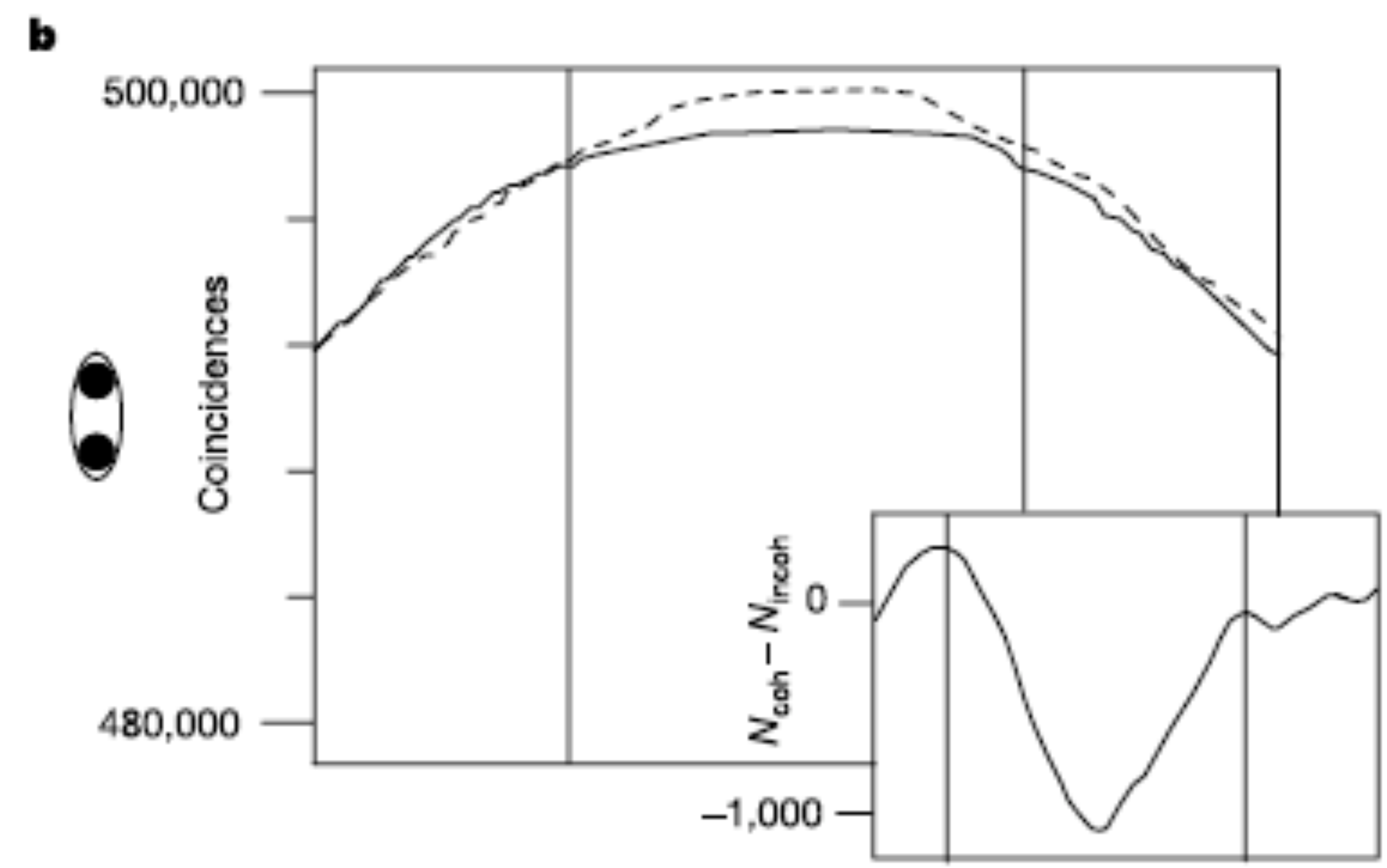


Zürich, atom laser, single atom detection with optics

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

Correlations with electrons





Dip ~ 10^{-4} mainly because of time resolution

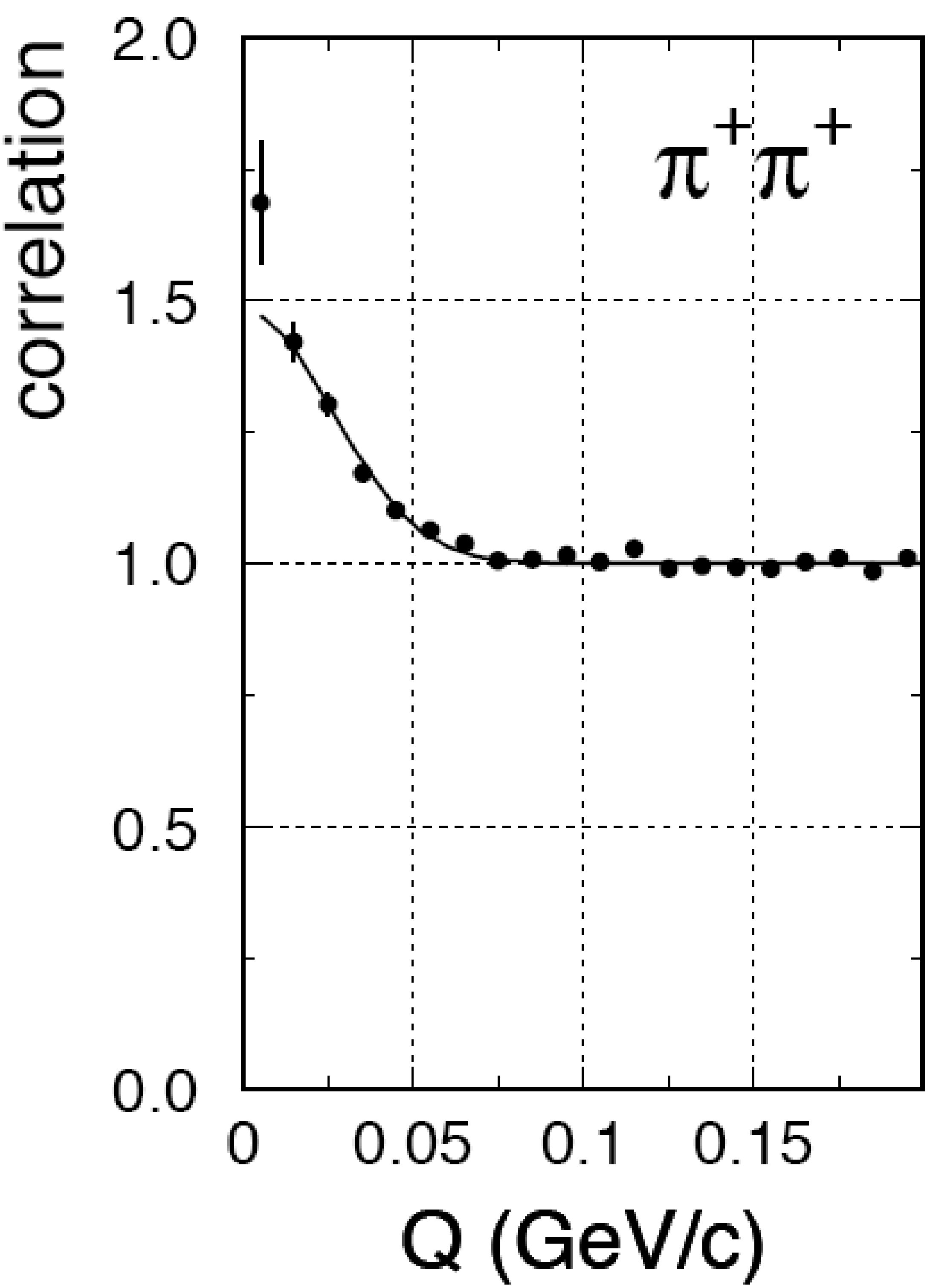
H. Kiesel, A. Renz, F. Hasselbach, Nature 418, 392 (2002).

Correlations in heavy ion collisions

Correlations between π's in Au + Au collisions at 10GeV/nucleon

Nucl. Phys. A610, 237 (1996)

Width is related to the size of the collision volume



Outlook: There are no ideal gases

ideal thermal gas: $g^{(2)}(p) \sim$ FourierTrns {source distribution}

ideal BEC : $g^{(2)} = 1$

Coulomb and strong interactions in high energy physics ...

Contact interactions in cold atoms (and optics):

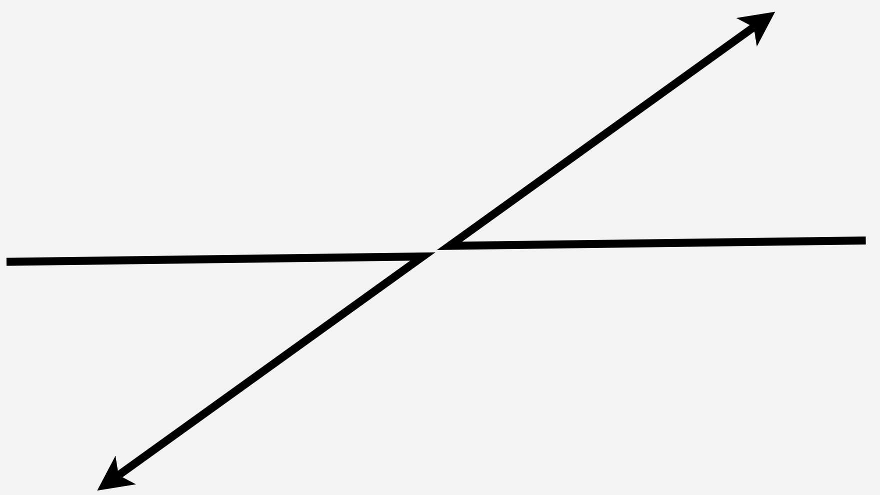
$$-\frac{\hbar^2}{m}\nabla^2\psi + g|\psi|^2\psi \qquad\qquad H = \chi\, \hat{a}_1\hat{a}_2\hat{a}_3^\dagger\hat{a}_4^\dagger + h.c.$$

Four wave mixing of matter waves:

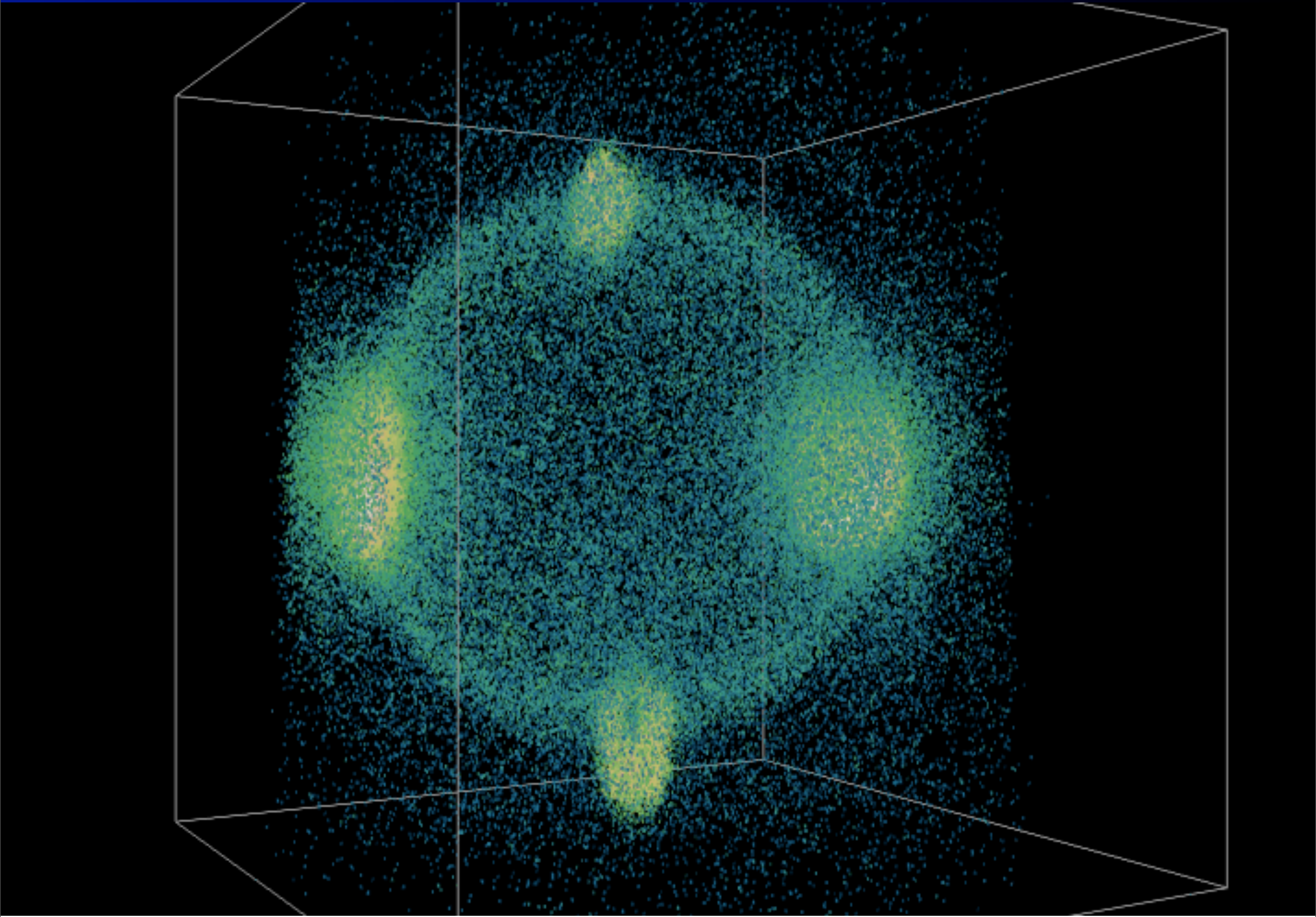
(Ist expt NIST 1999)

-- correlated pair production

we have a correlation detector

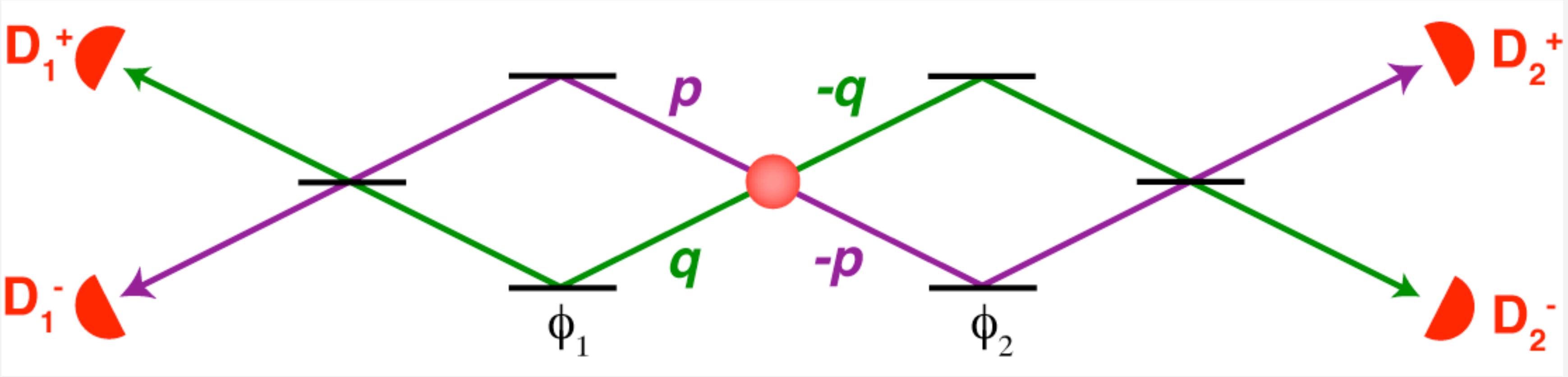


4 wave mixing

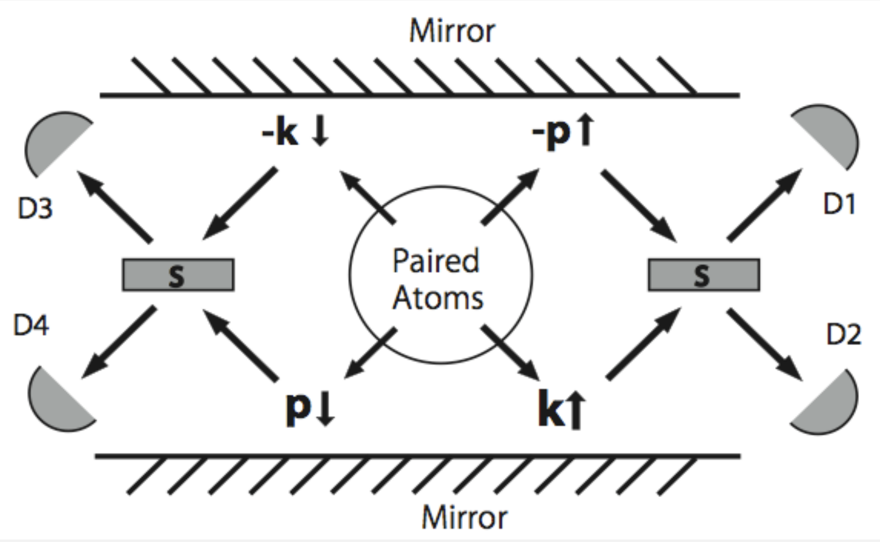


Prospects for correlation measurements

- Two particle interference experiments



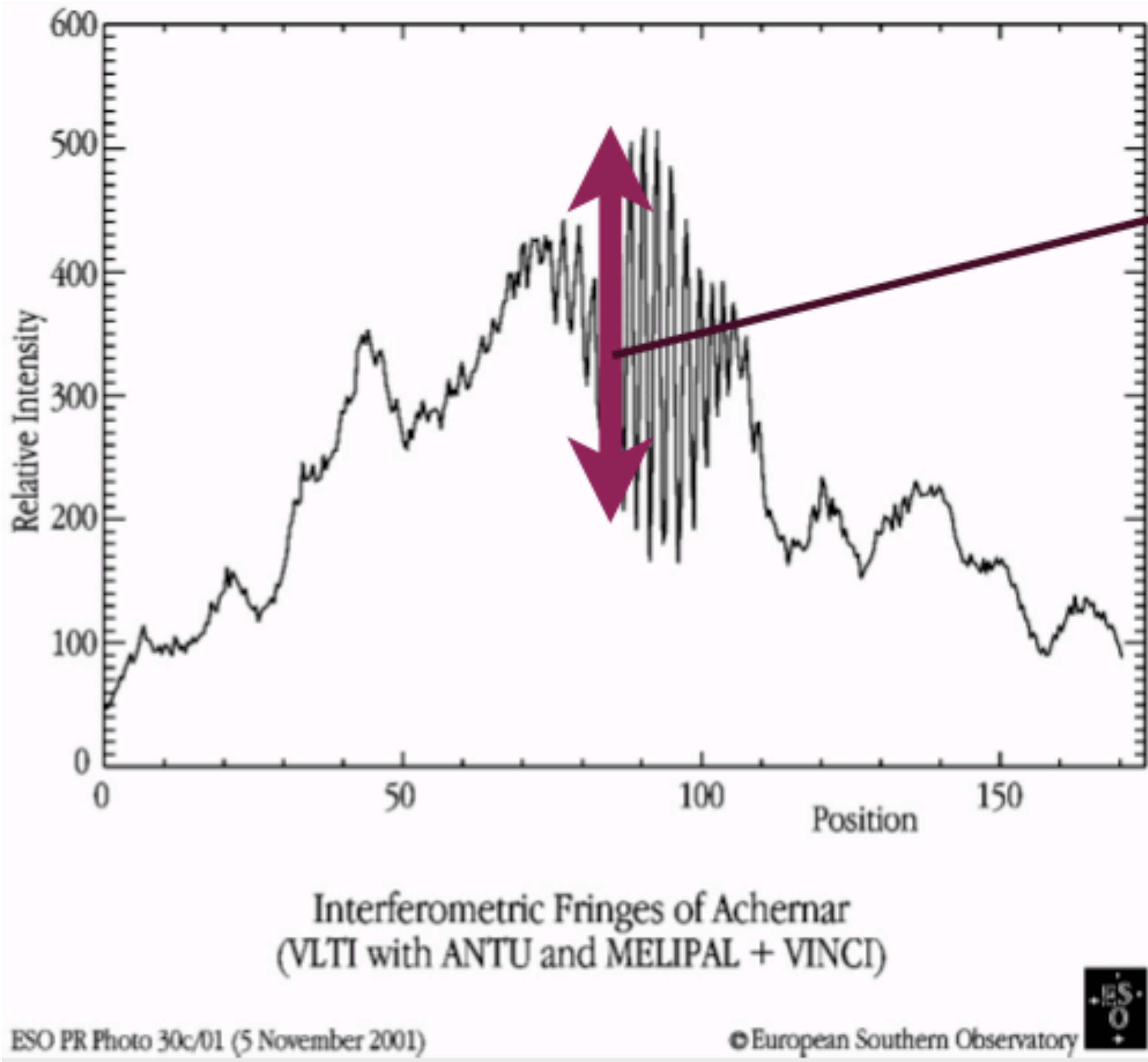
- Phase sensitive measurements of order parameters Kitagawa et al 1001.4358

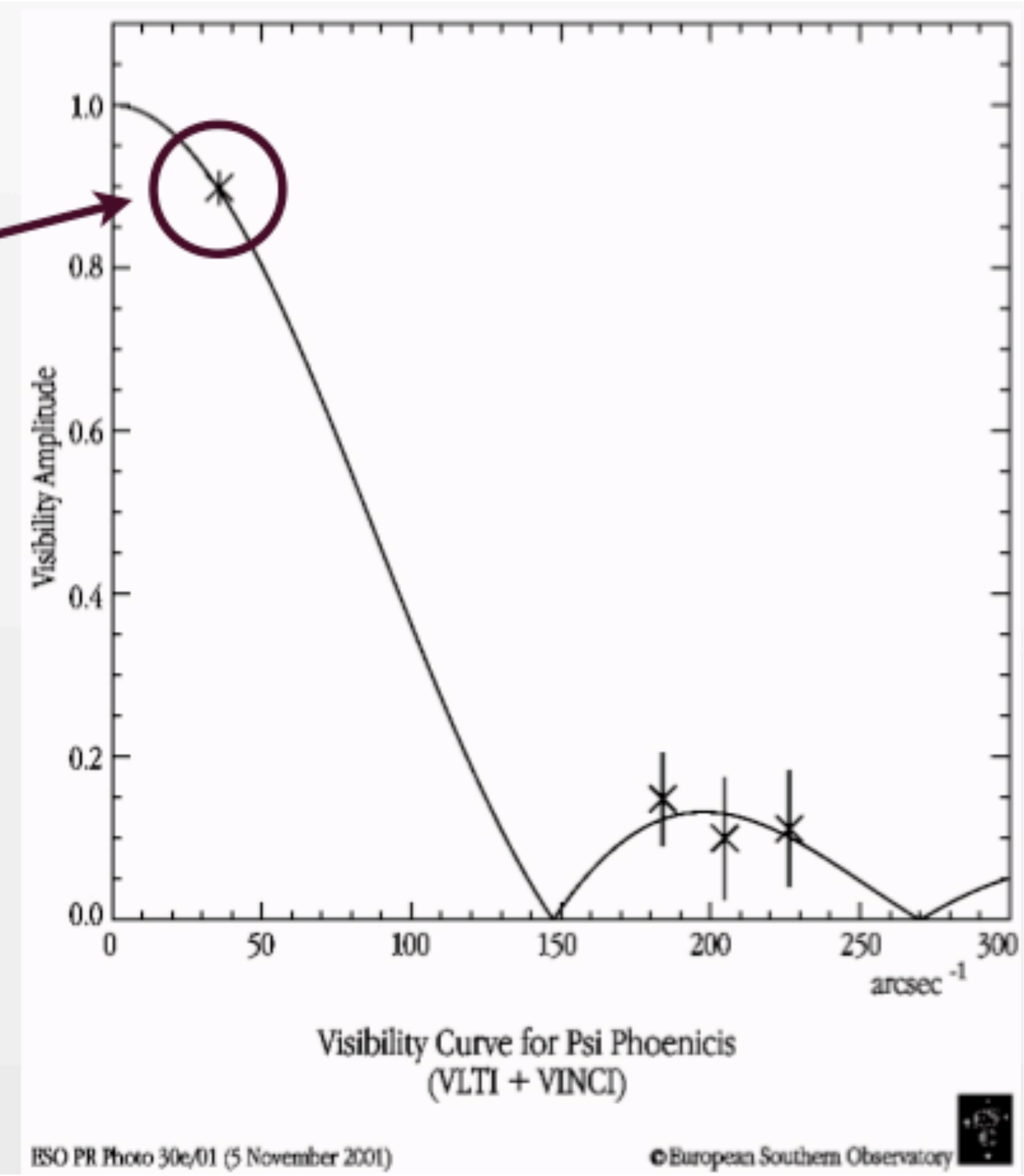


- Correlation measurements may be useful to detect Hawking radiation from sonic event horizons Carusotto et al. NJP 2008

Thanks

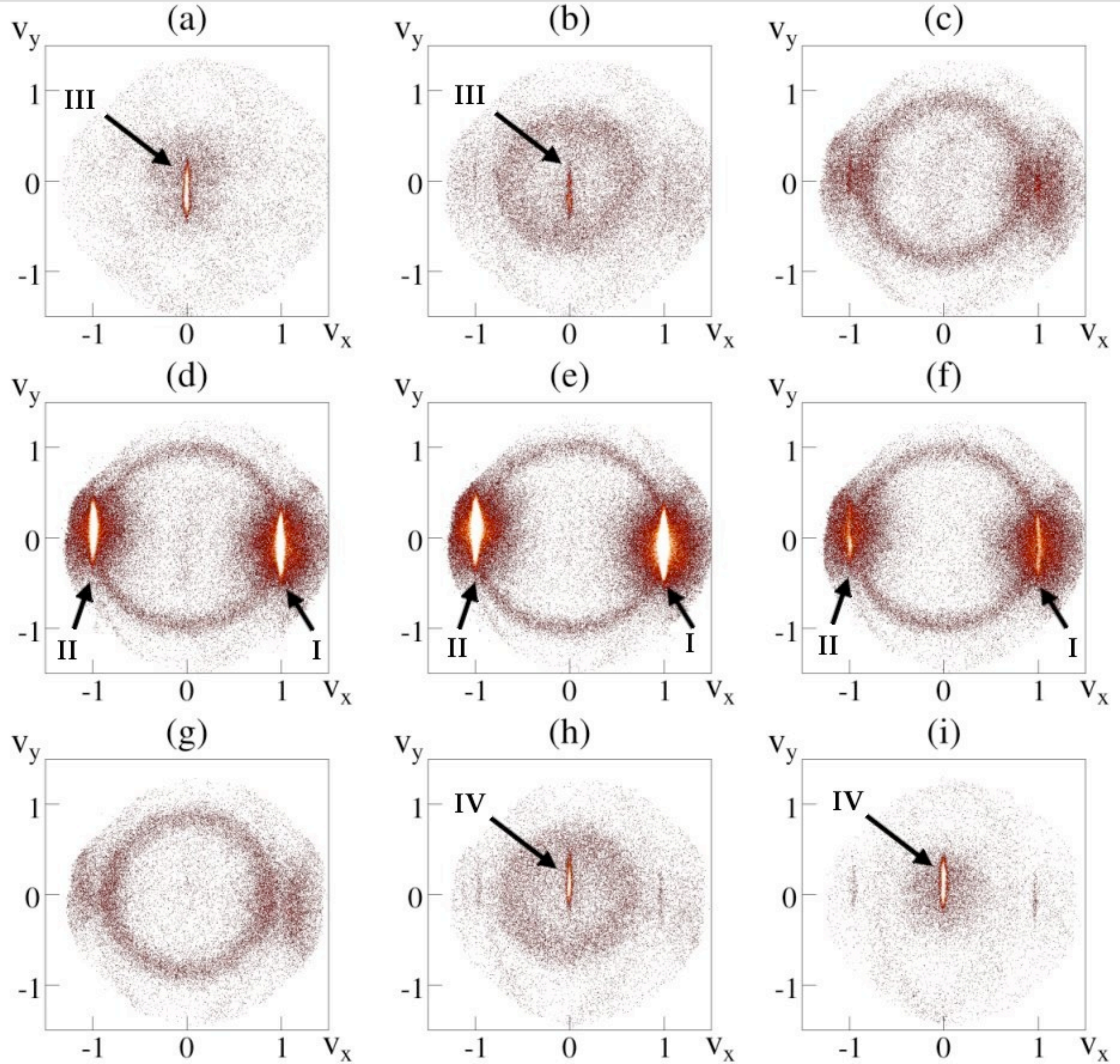
Fringes from a real star





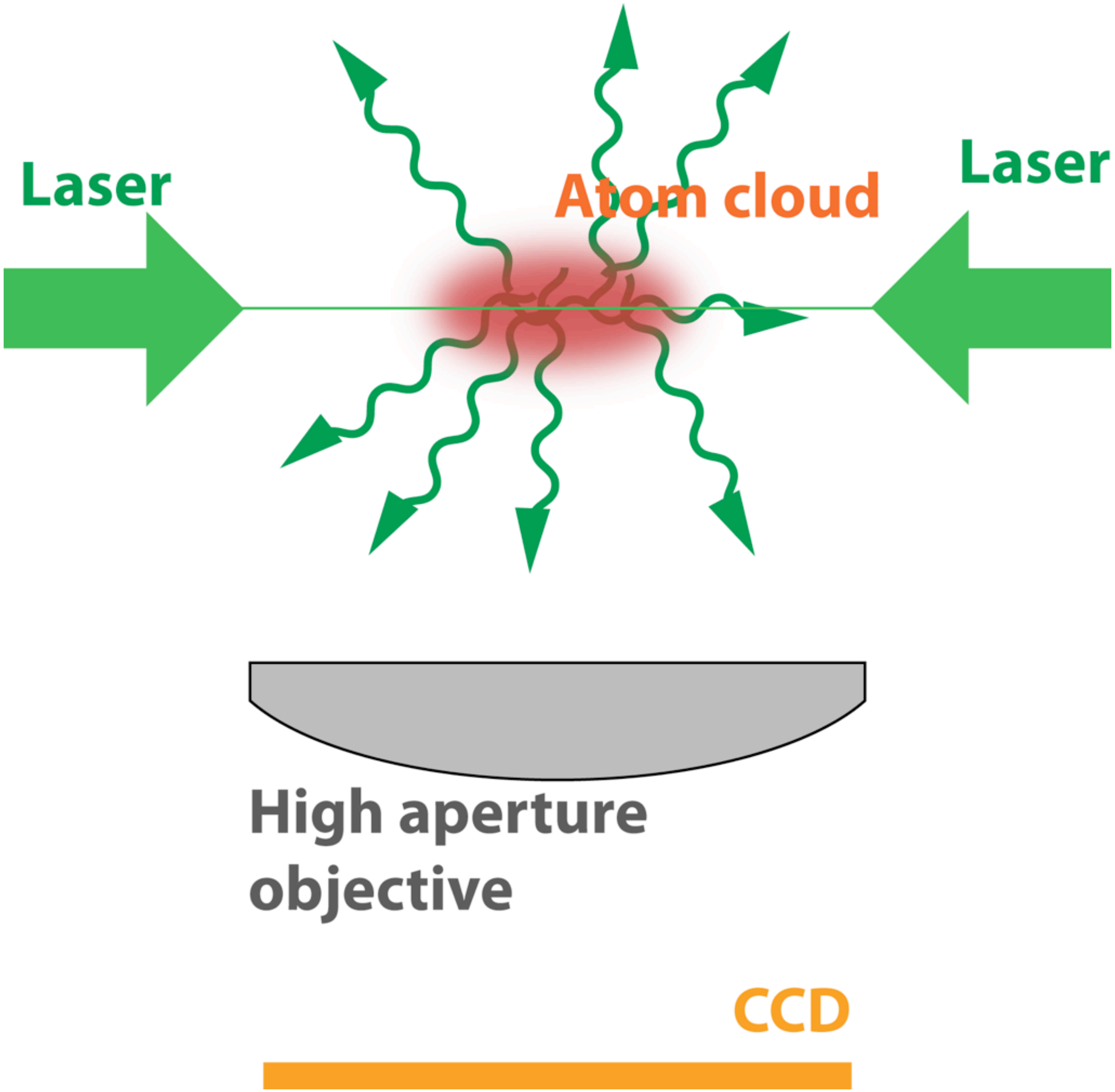
from the European Southern Observatory

4 wave mixing: slices



I, II and IV are the initial condensates. III is the condensate generated by 4 wave mixing

Position resolved fluorescence



An alternative method to detect atom correlations
T.U.Vienna
New J. Phys. 11(2009)103039

4 wave mixing