Huntingdon and Broad Top Mountain RR

Hanbury Brown and Twiss effect for bosons and fermions

Chris Westbrook
Laboratoire Charles Fabry, Palaiseau

DPP - fermions 2019, Lille
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Outline

1. HB&T for light (stars & history)
2. HB&T for particles (atoms)
3. The Hong Ou Mandel effect

Fluctuations:
"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.

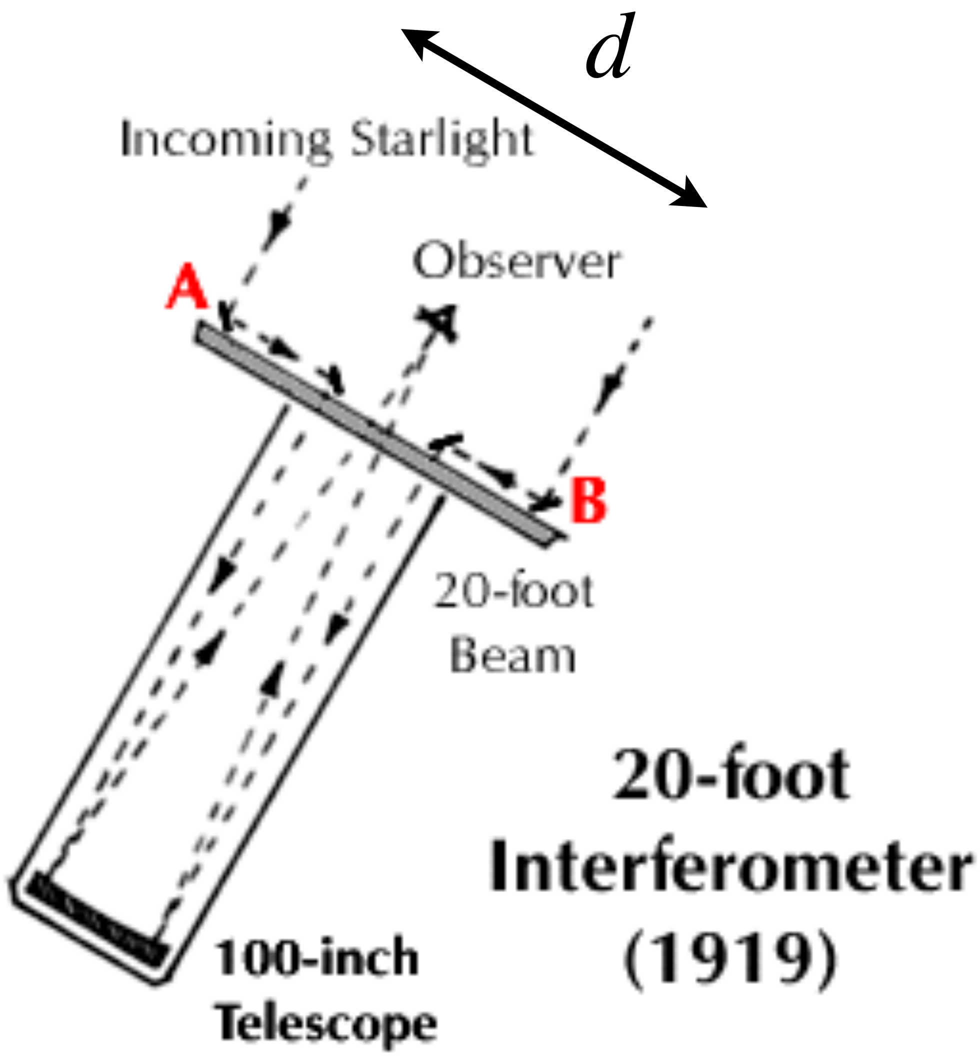
$\langle N \rangle$ "... if the molecules were independent"

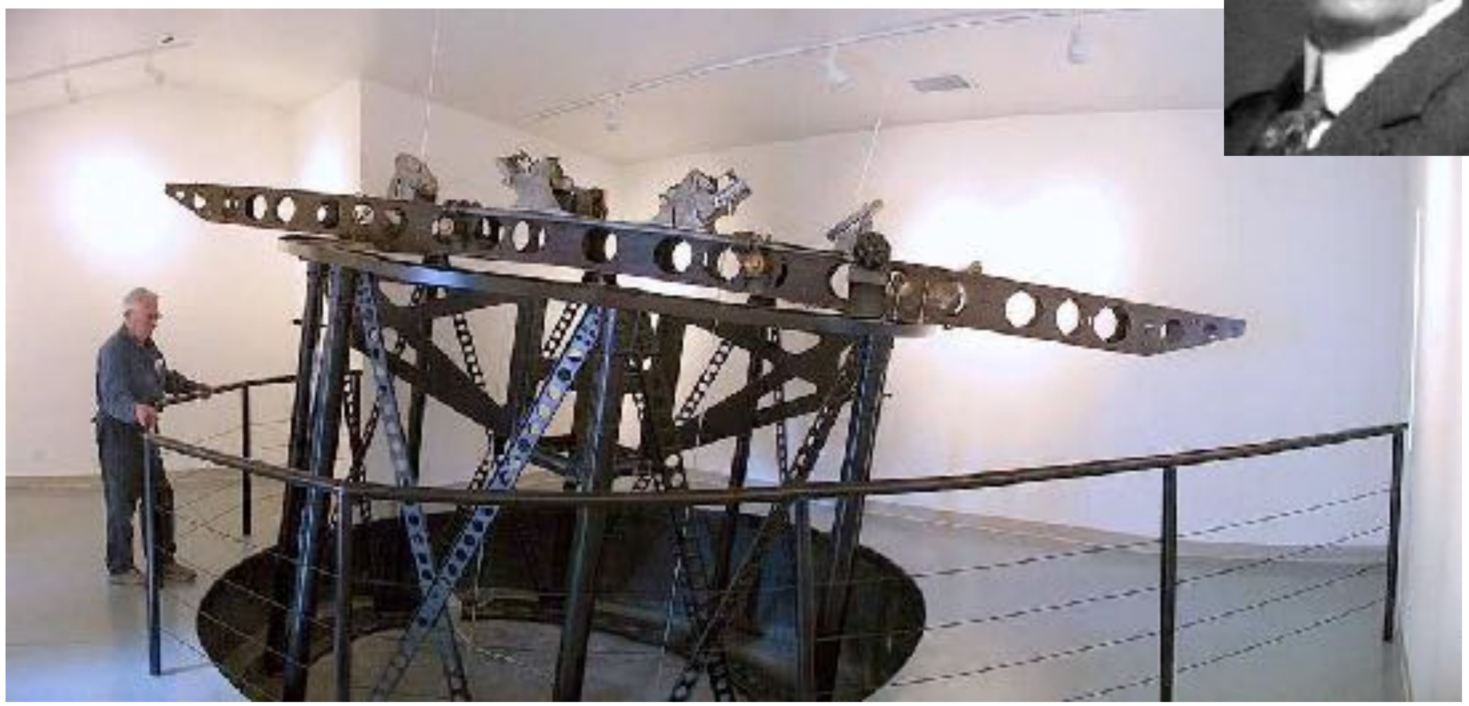
$\langle N \rangle^2$ "... interference fluctuations" *interferenzschwankungen*

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

eine gegenseitige Beeinflussung der Moleküle von vorläufig ganz rätselhafter Art

Michelson: stellar interferometer



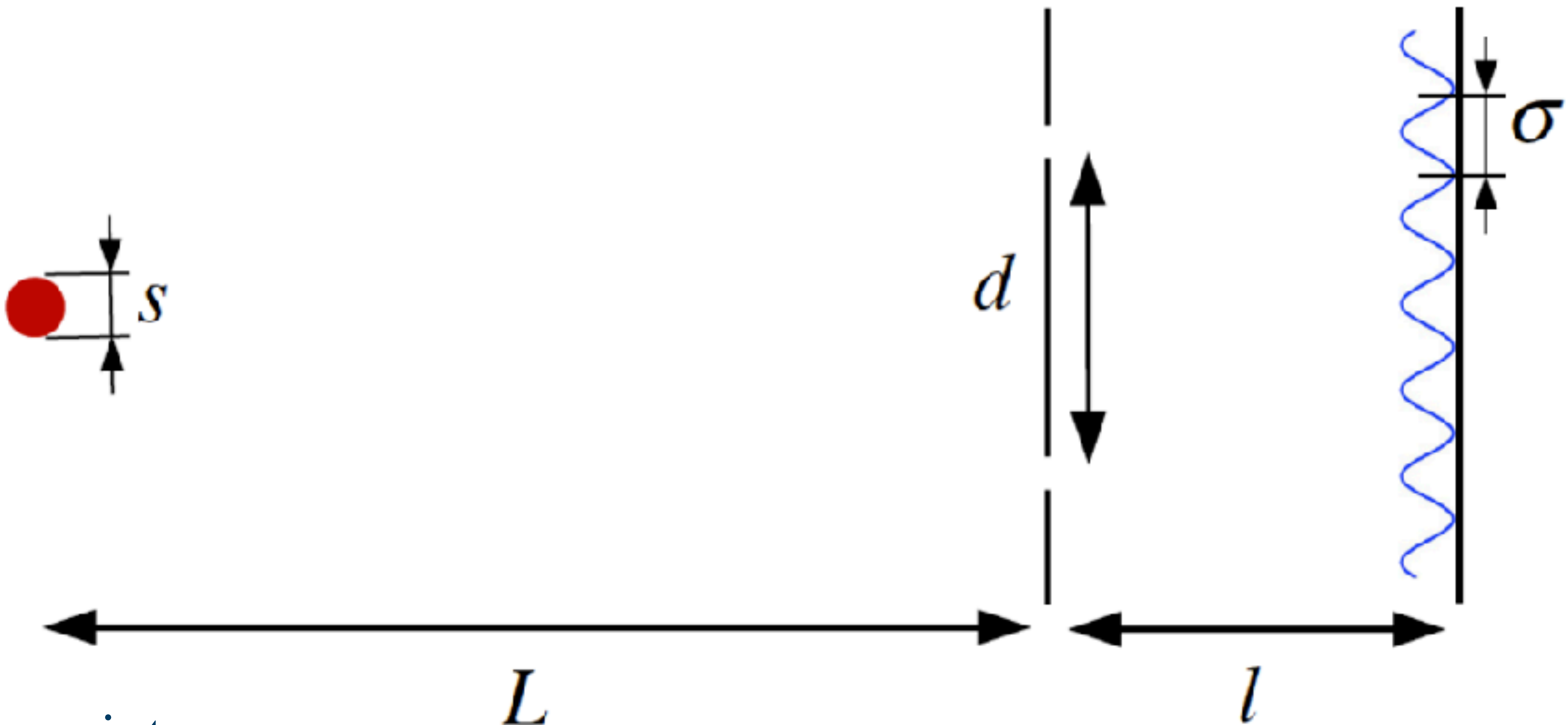


Fringe contrast indicates the spatial coherence of the source.
When d is too big, fringes disappear:

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

Michelson measured the angular diameters of 6 stars.

Principle of stellar interferometry



For point source

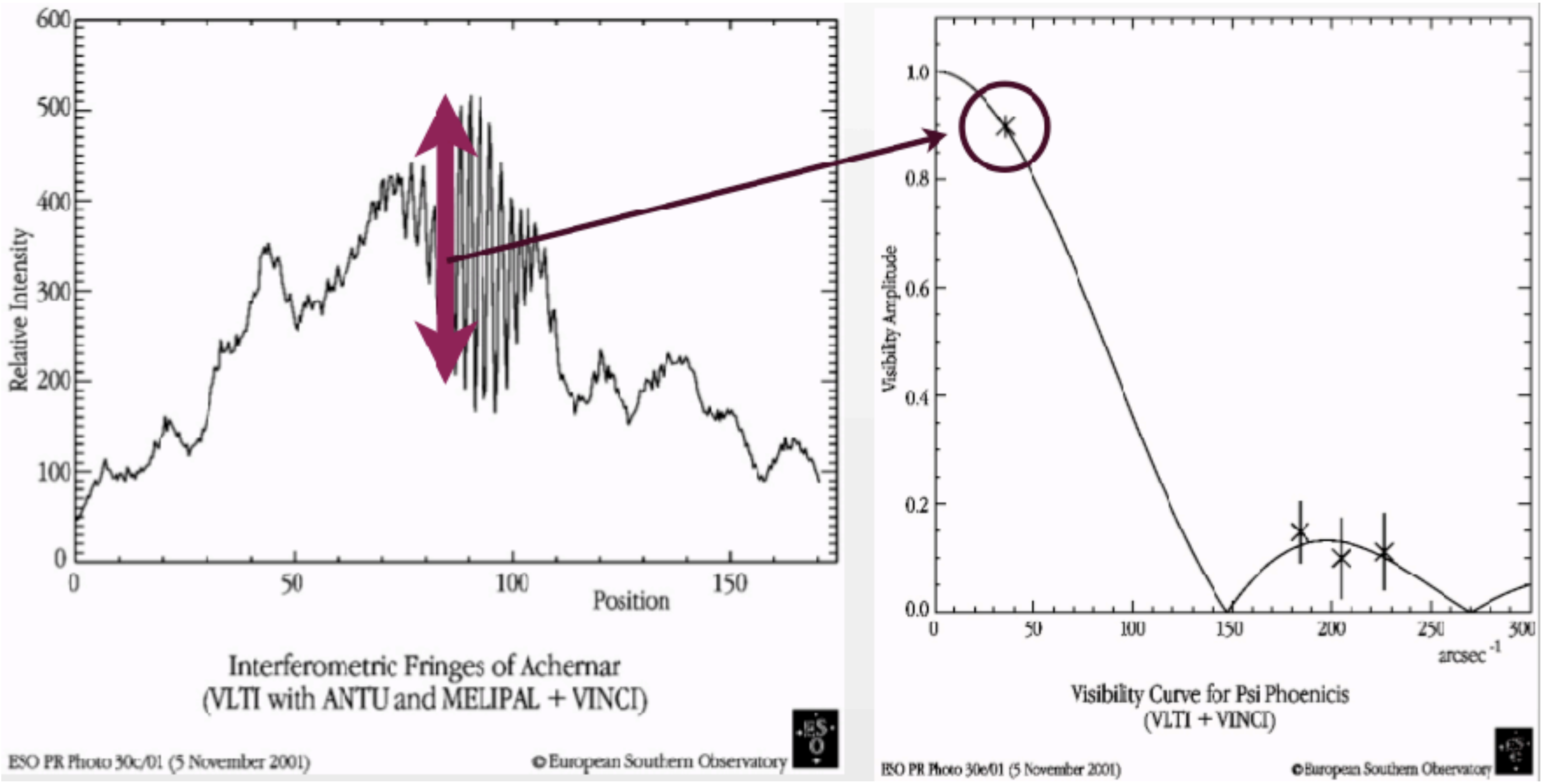
$\sigma = l\,\lambda/d$

displace source by $\theta \rightarrow$ fringe shift $\delta = l\,\theta$

$\theta_{max} = s/L \sim \lambda/d$

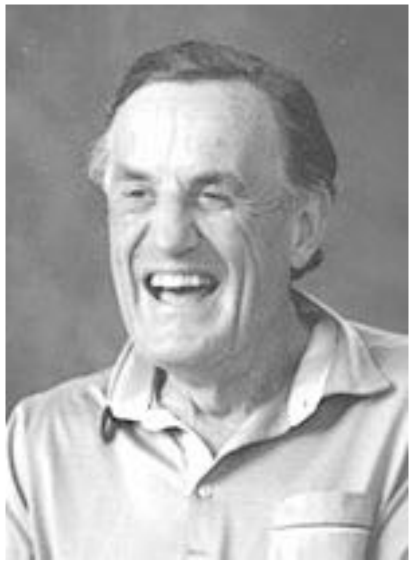
If the source is not monochromatic, fewer fringes

Fringes from a real star

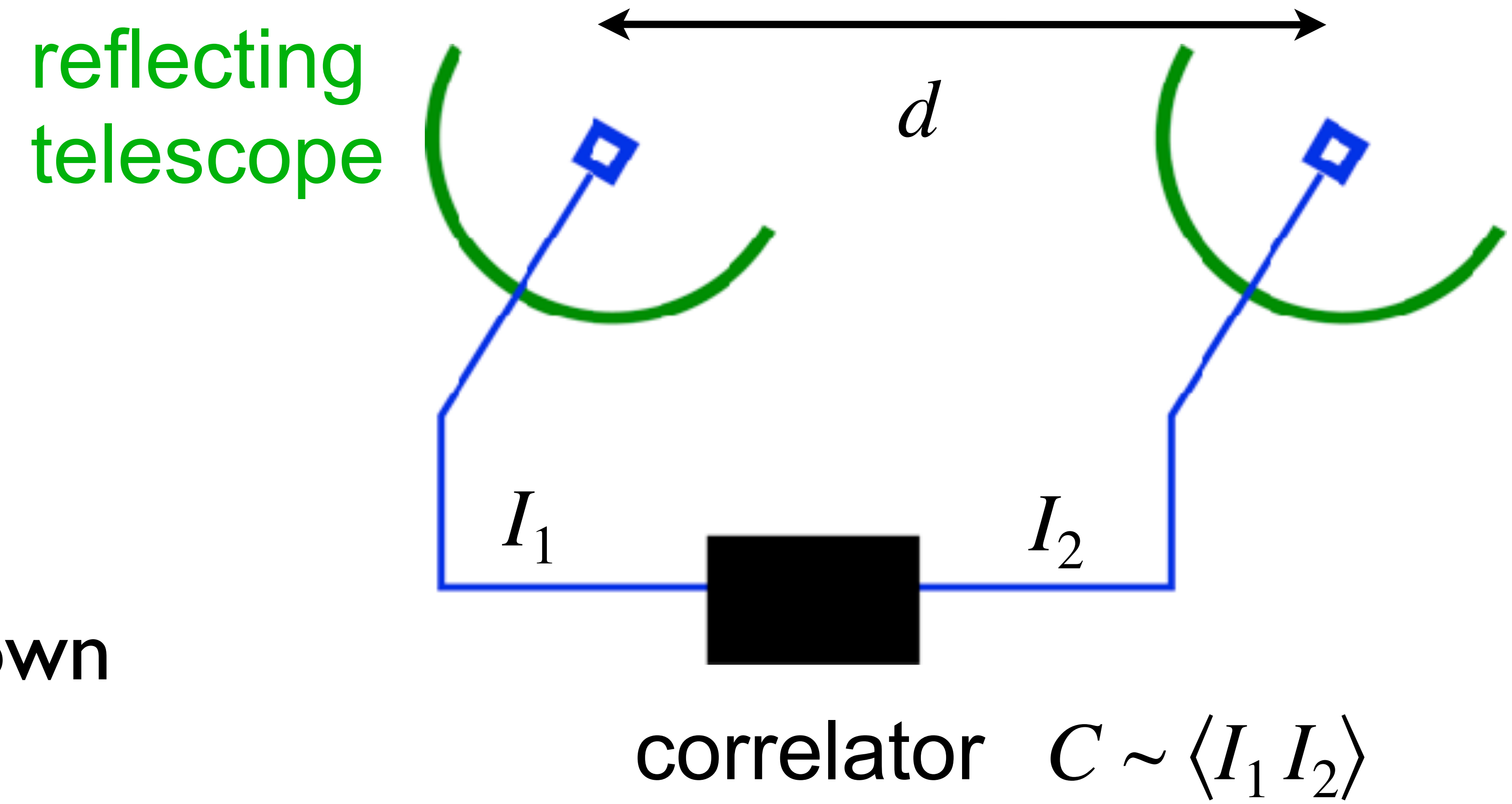


from the European Southern Observatory

Hanbury Brown: intensity interferometry

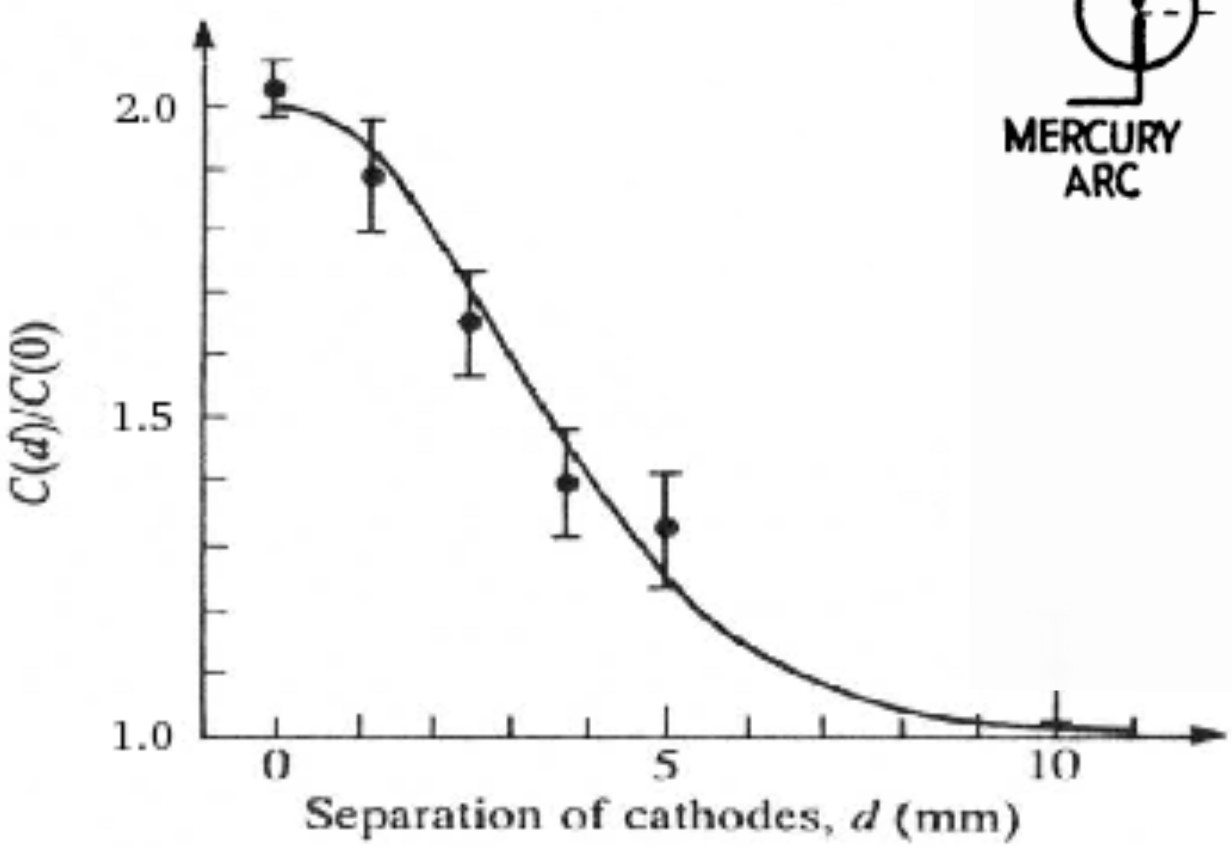


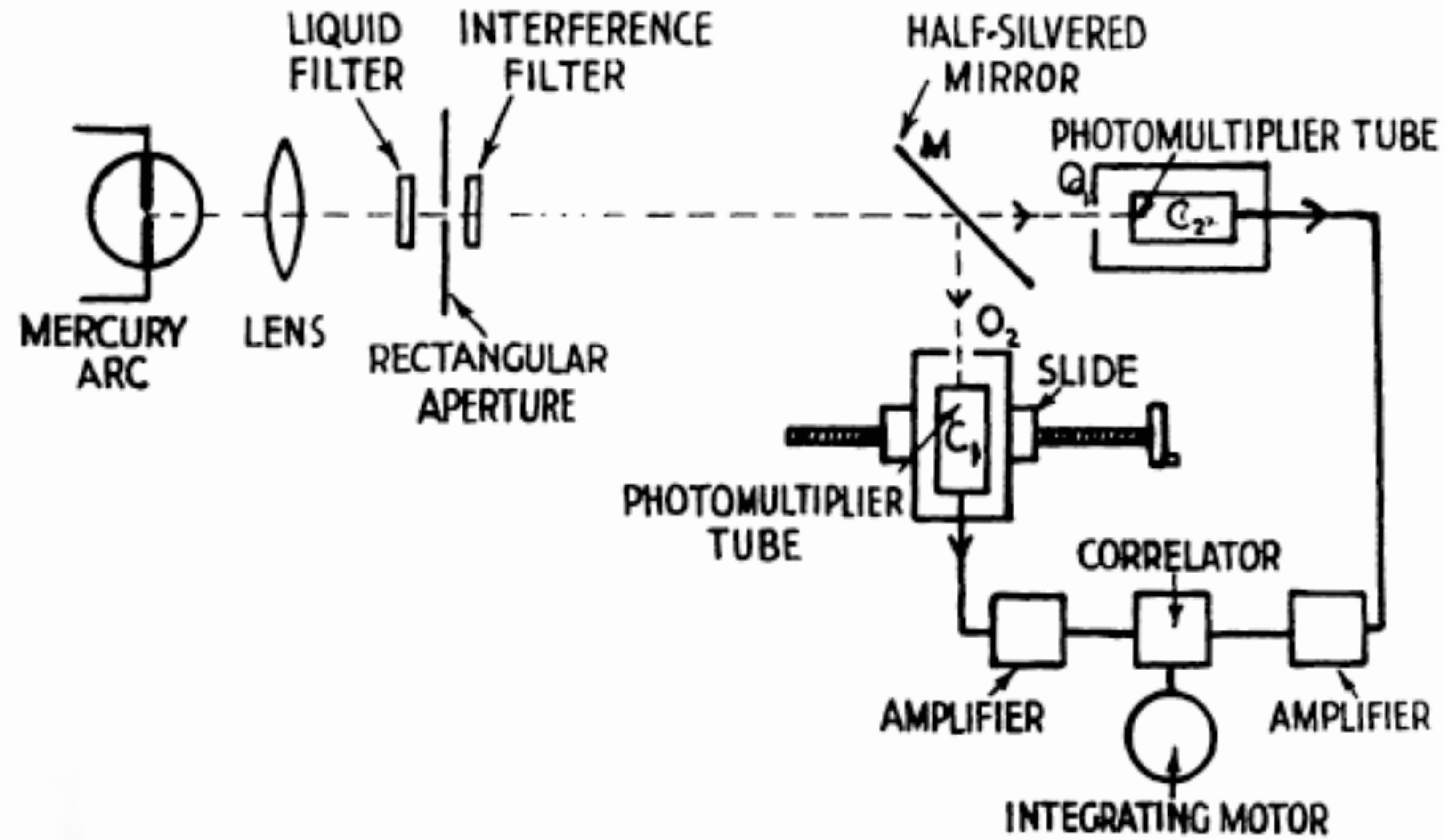
Robert Hanbury Brown
1916 - 2001



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.

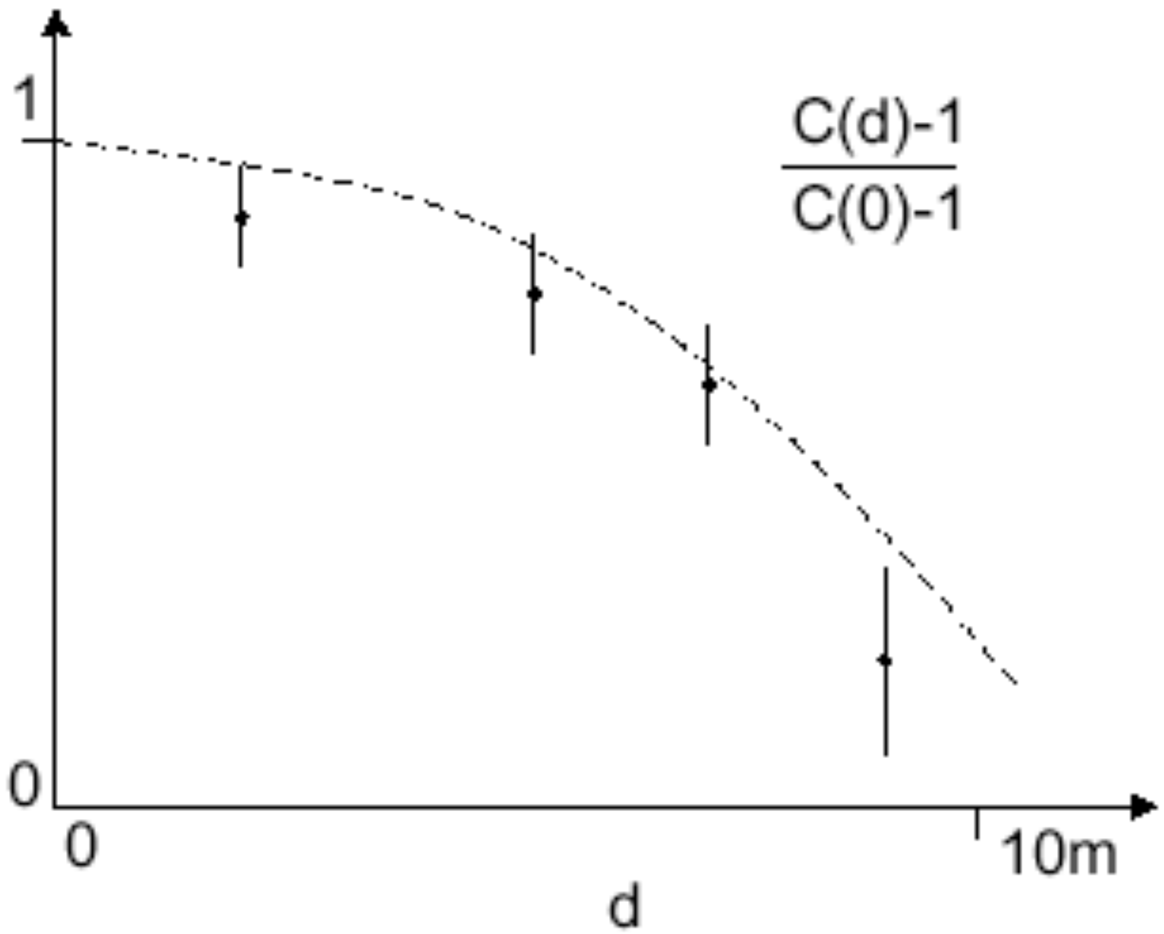
The Hanbury Brown Twiss experiment (Nature, 1956)





"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

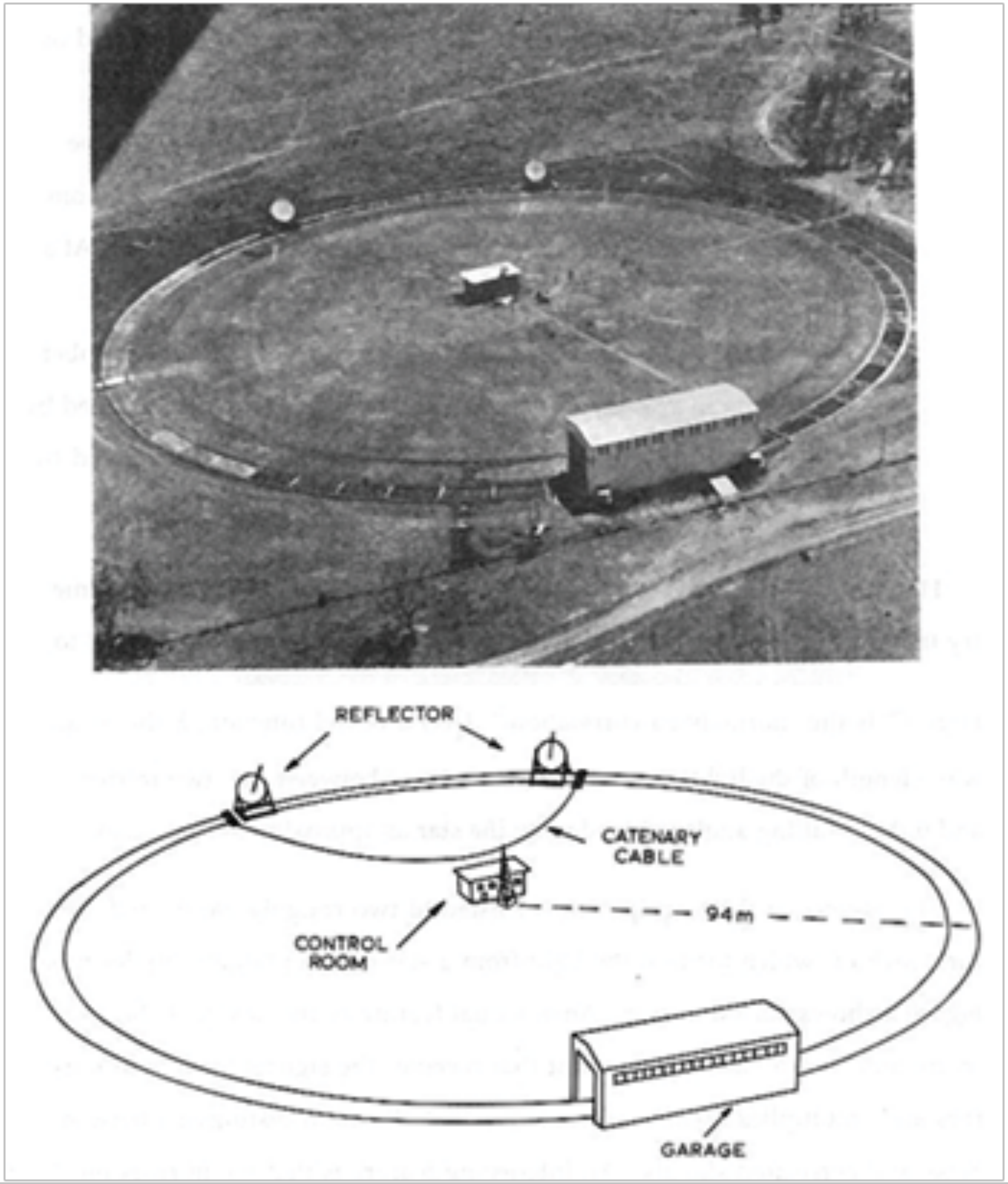
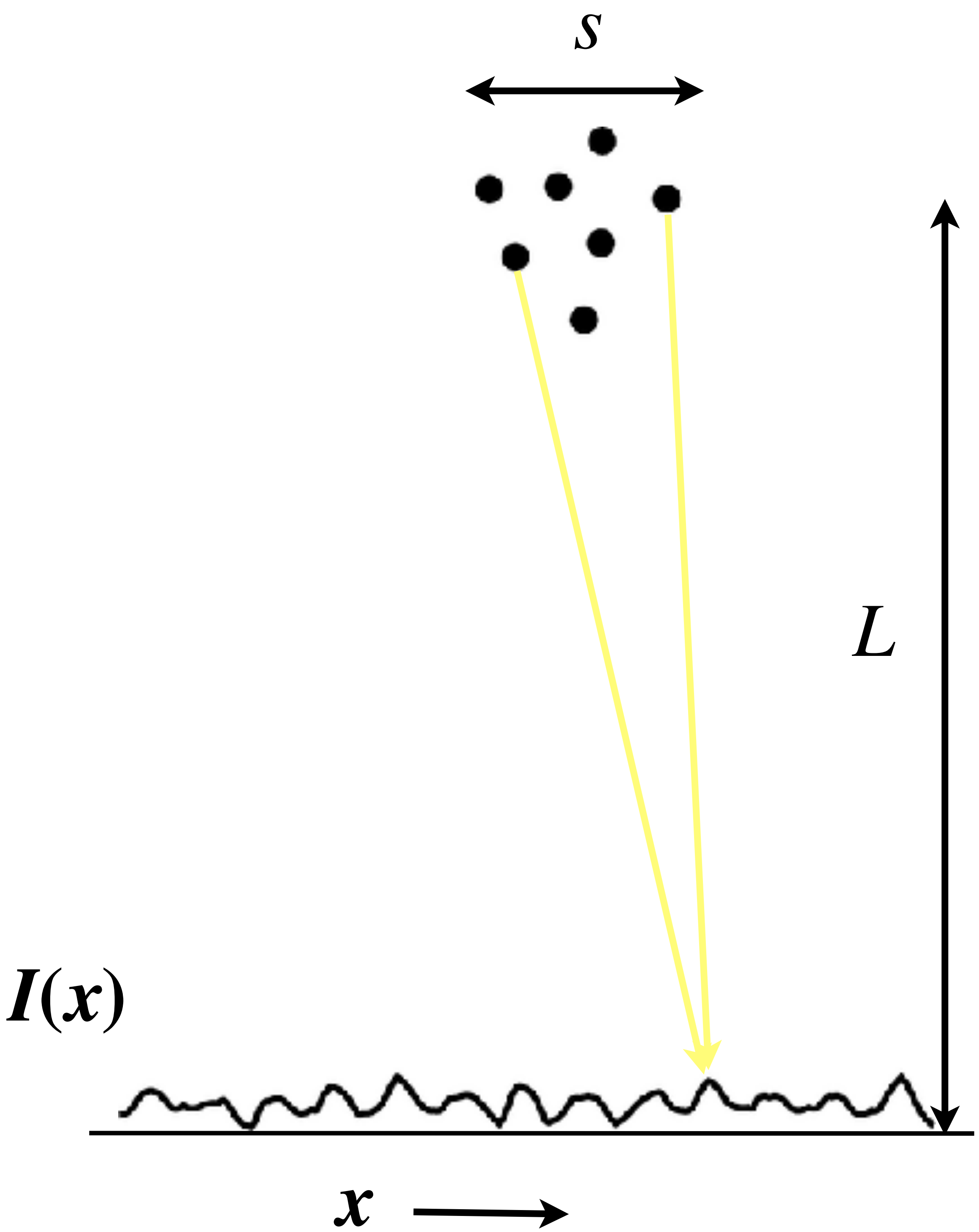


Figure 1. Aerial photo and illustration of the original HBT apparatus. They have been extracted from Ref.[1].

(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 $\Delta x \rightarrow$ uncorrelated:

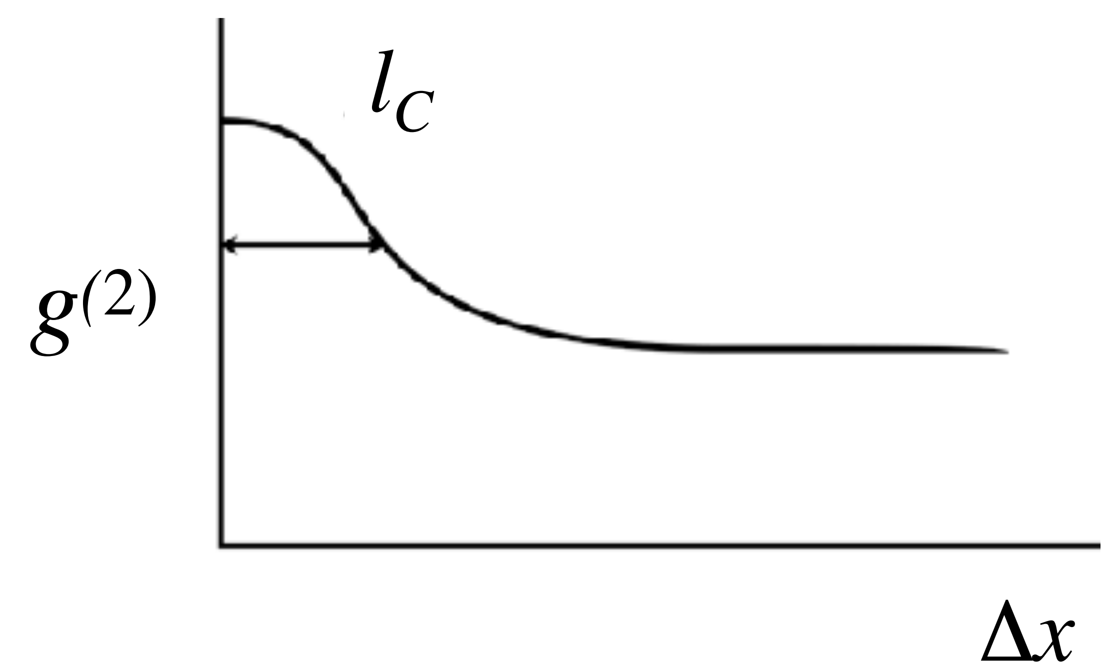
$$\langle I_1\, I_2\rangle = \langle I_1\rangle\langle I_2\rangle$$

$\Delta x = 0$:

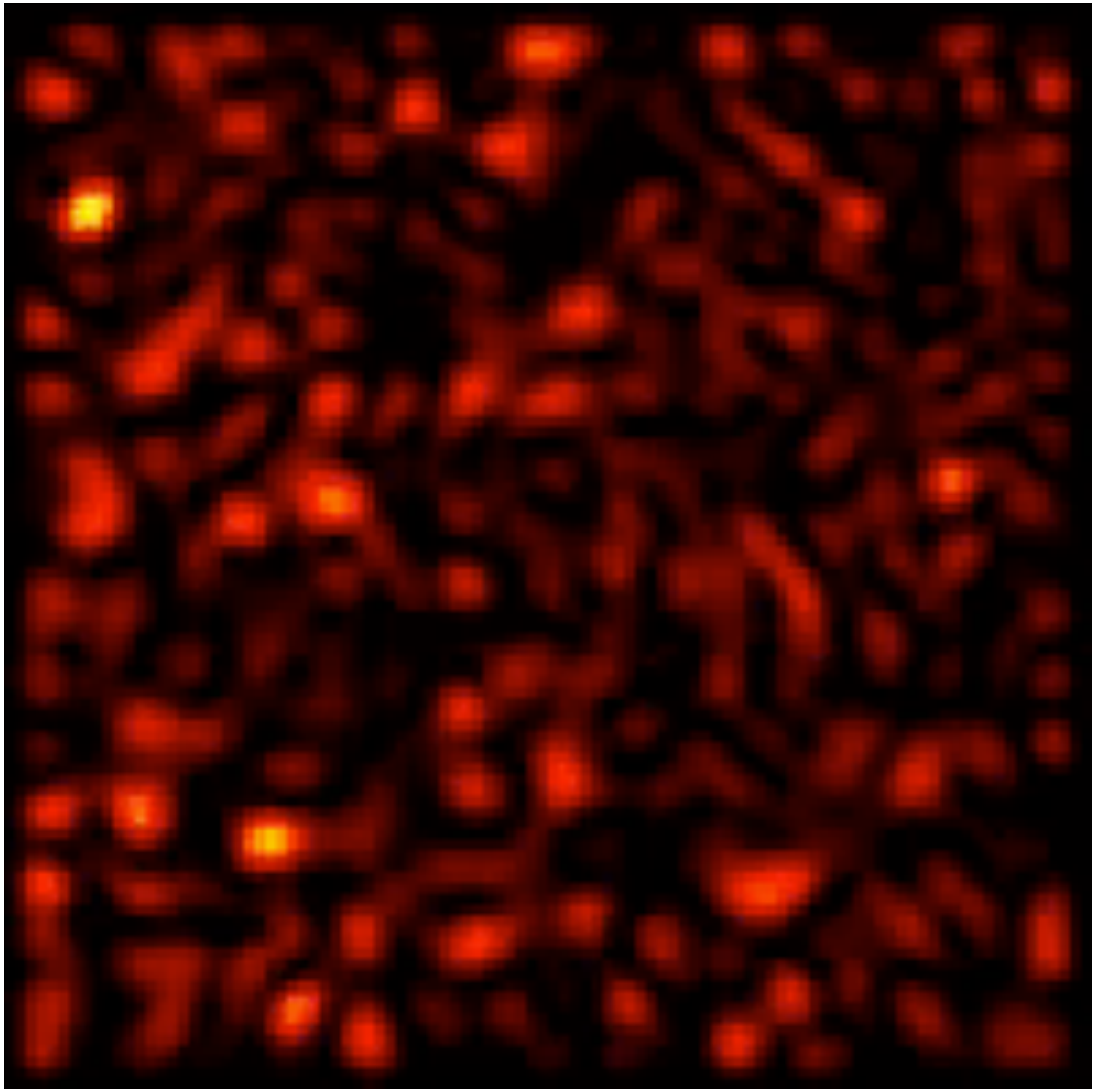
$$\langle I^2\rangle > \langle I\rangle^2$$

thermal source (Einstein):

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



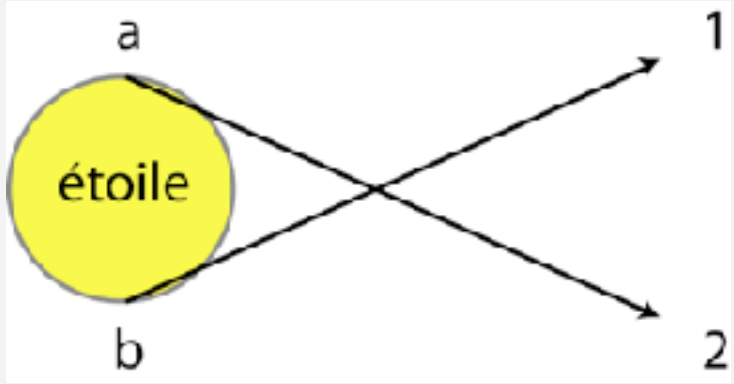
Time dependent speckle



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:

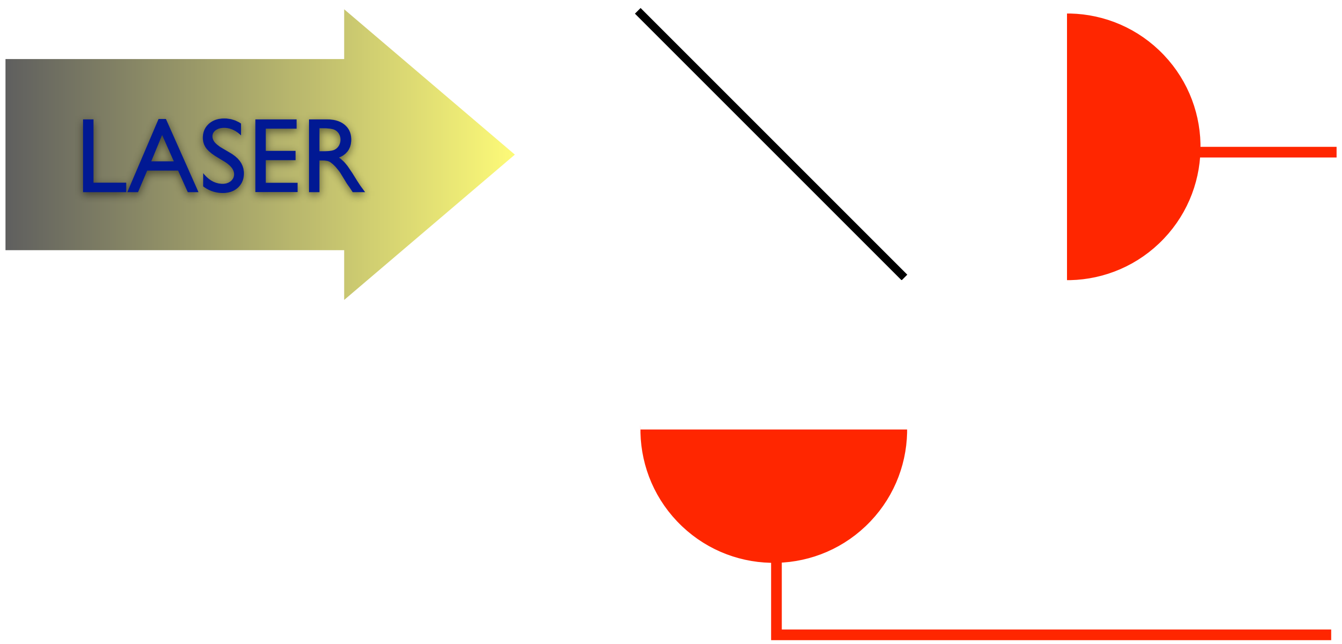
$$P = |\langle 1|a\rangle\langle 2|b\rangle \pm \langle 1|b\rangle\langle 2|a\rangle|^2$$

+ 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 large-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."

Temporel correlations in a laser: measurement

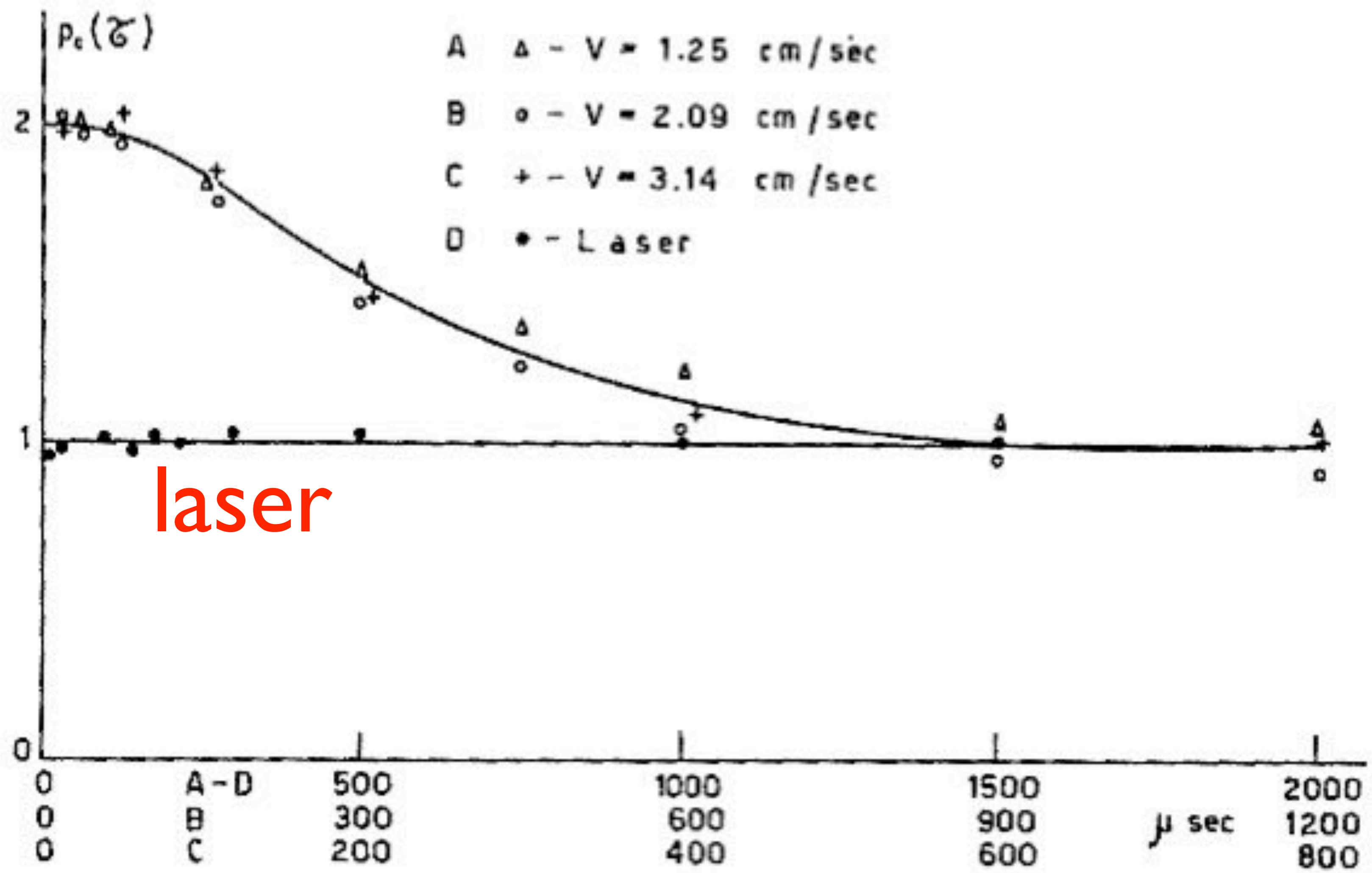


Fig. 1. Conditional probability $p_C(\tau)$ of a second count occurring at a time τ after a first has occurred at time $\tau = 0$.

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
Les Houches, 1965
Quantum Electronics
p. 65-185

$$
\begin{aligned}
\hat{E} &= \hat{E}^{+} + \hat{E}^{-} \\
\hat{E}^{+} &= \sum_{\omega} \sqrt{\frac{\hbar\omega}{2\epsilon_0 V}} e^{-i\omega t} \hat{a}_{\omega} \\
\langle I(t) I(t') \rangle &= \langle \hat{E}^{-}(t)\hat{E}^{+}(t)\hat{E}^{-}(t')\hat{E}^{+}(t') \rangle \\
&= \underbrace{\langle \hat{E}^{-}(t)\hat{E}^{-}(t')\hat{E}^{+}(t')\hat{E}^{+}(t) \rangle}_{\text{joint, 2 photon detection prob.}} + \delta(t-t')\underbrace{\langle \hat{E}^{-}(t)\hat{E}^{+}(t) \rangle}_{\text{shot noise}}
\end{aligned}
$$

for thermal bosons:

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

Einstein formula recovered
For a laser there is only one mode: no interference.
For fermions, use anti-commutation: minus sign.

Summary of (temporal) coherence

Stationary processes

$$g^{(1)}(\tau) = \frac{\langle E(t)\, E^{+}(t+\tau)\rangle}{\langle E(t)\, E^{+}(t)\rangle} = \frac{\tilde{\rho}_1(\tau)}{\rho_1(0)}$$

Interference contrast

$$g^{(2)}(\tau) = \frac{\langle E(t+\tau)\, E(t)\, E^{+}(t)\, E^{+}(t+\tau)\rangle}{\langle E(t)\, E^{+}(t)\rangle \langle E(t)\, E^{+}(t)\rangle} = \frac{\rho_2(0,\tau)}{\rho_1(0)\, \rho_1(\tau)}$$

Gaussian processes

$$g^{(2)}(\tau) = 1 + \left|g^{(1)}(\tau)\right|^2$$

Not true for a laser nor for "non-classical" light sources

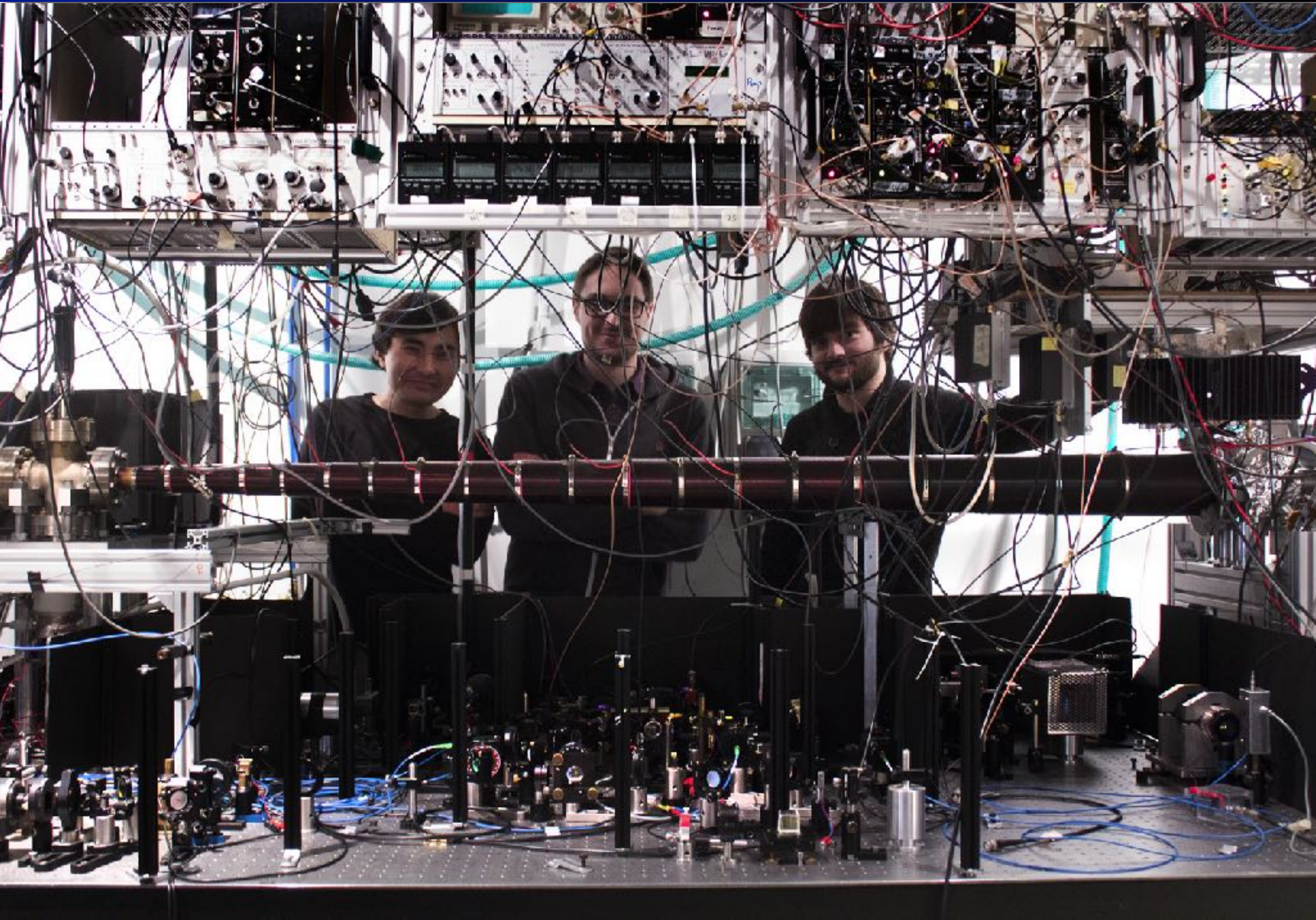
Before HBT and lasers, $g^{(2)}$ was ignored

Experiments with (cold atoms)

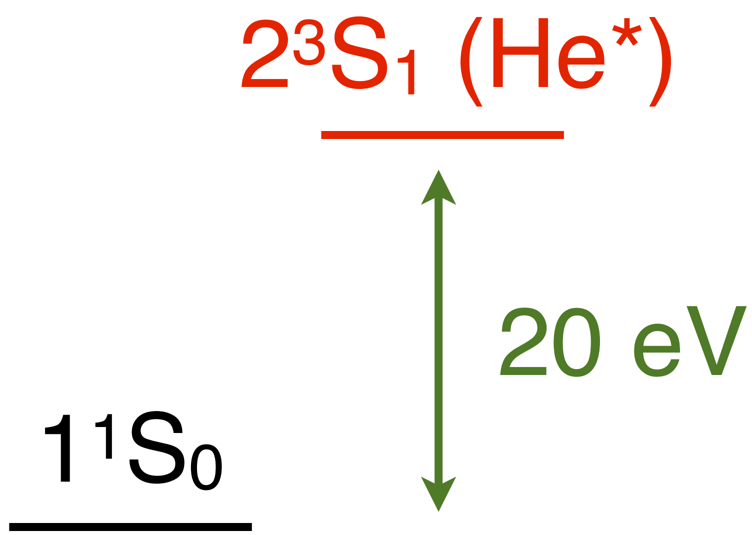
Why?

- Advances in quantum optics, awareness of quantum and classical coherence theory
- Possibility to study bosons and fermions
- With our without interactions (non-linearities)
- Cold atoms and BEC's provide long coherence times
- Distinction between temporal and spatial coherence is blurred

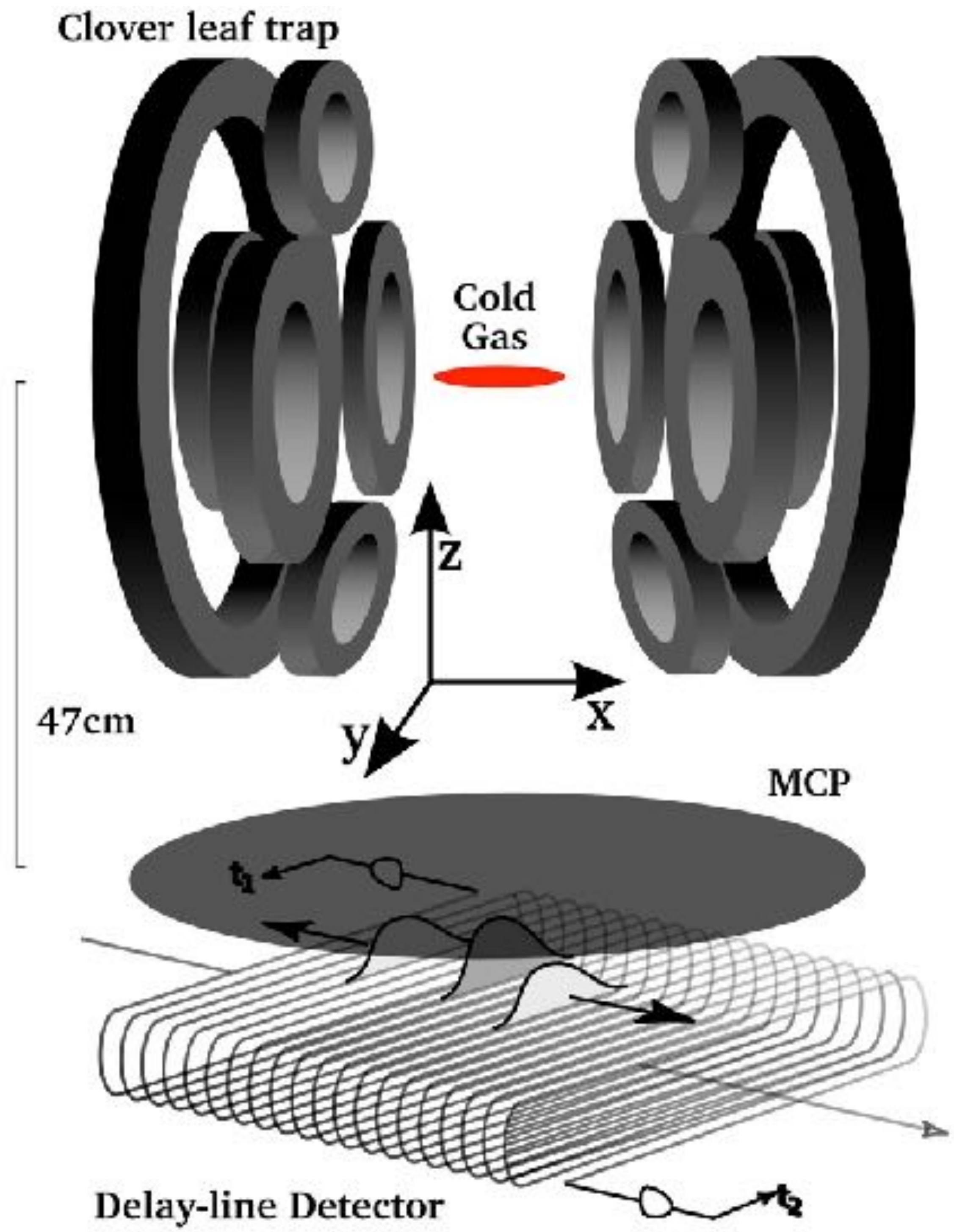
Experiments with atoms



Metastable helium and 3D detection



- detection by μ-channel plate (He* has 20 eV)
- single atom detection 25% quantum efficiency
- ~ 200 μm horizonta res. 10^5 detectors in //
- ~ 20 μm vertical res.
- ~ 200 ns deadtime

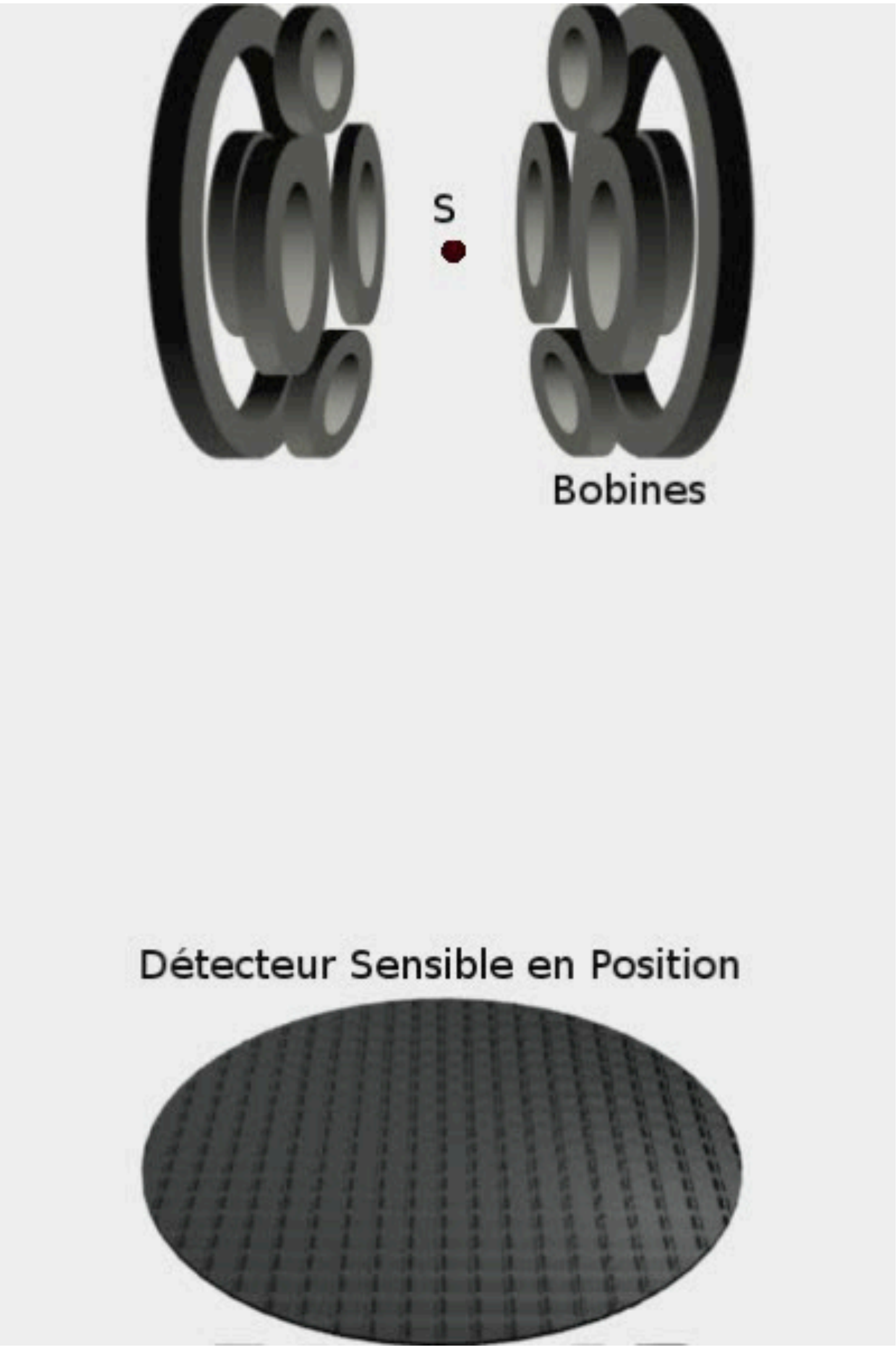


A “time of flight” observation

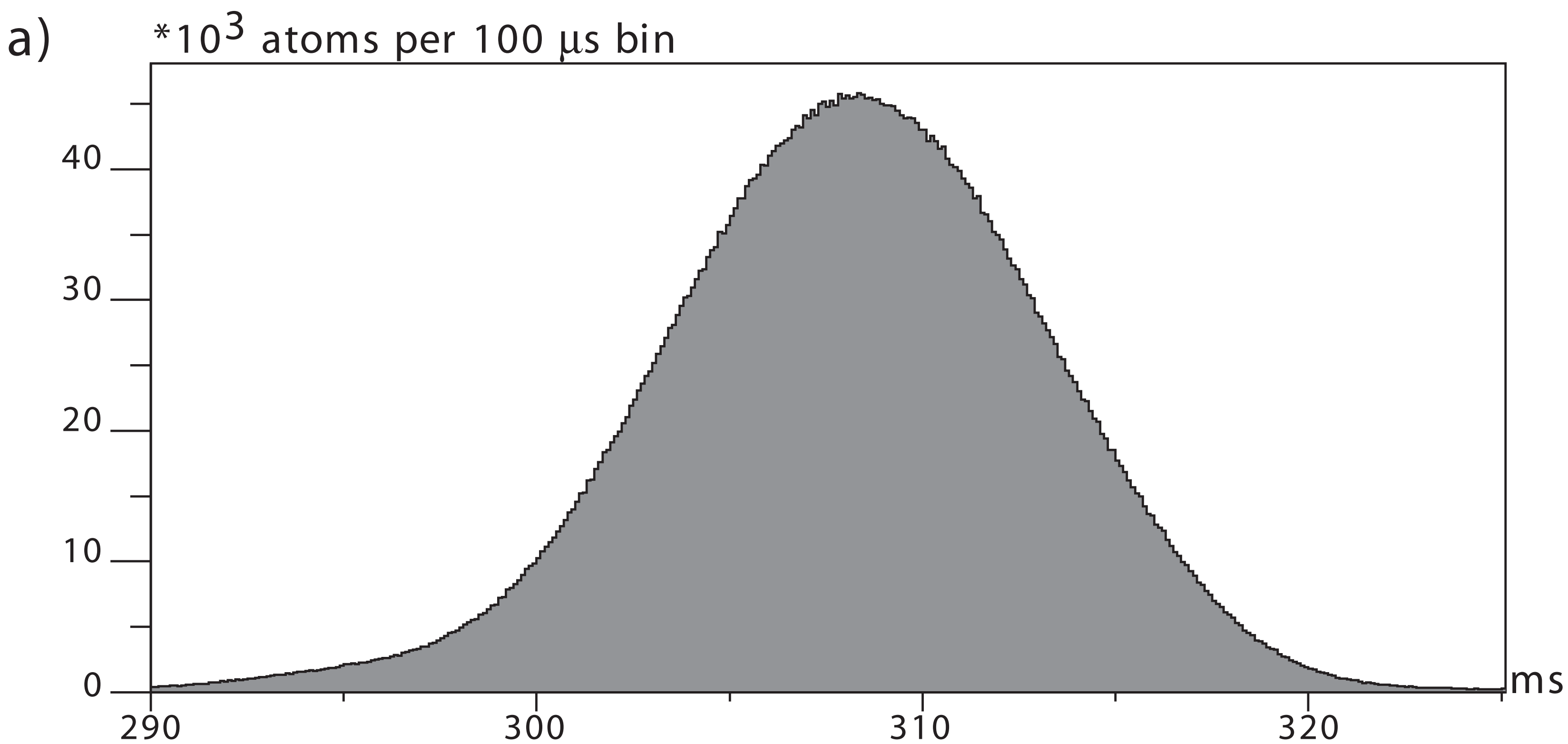
trap

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

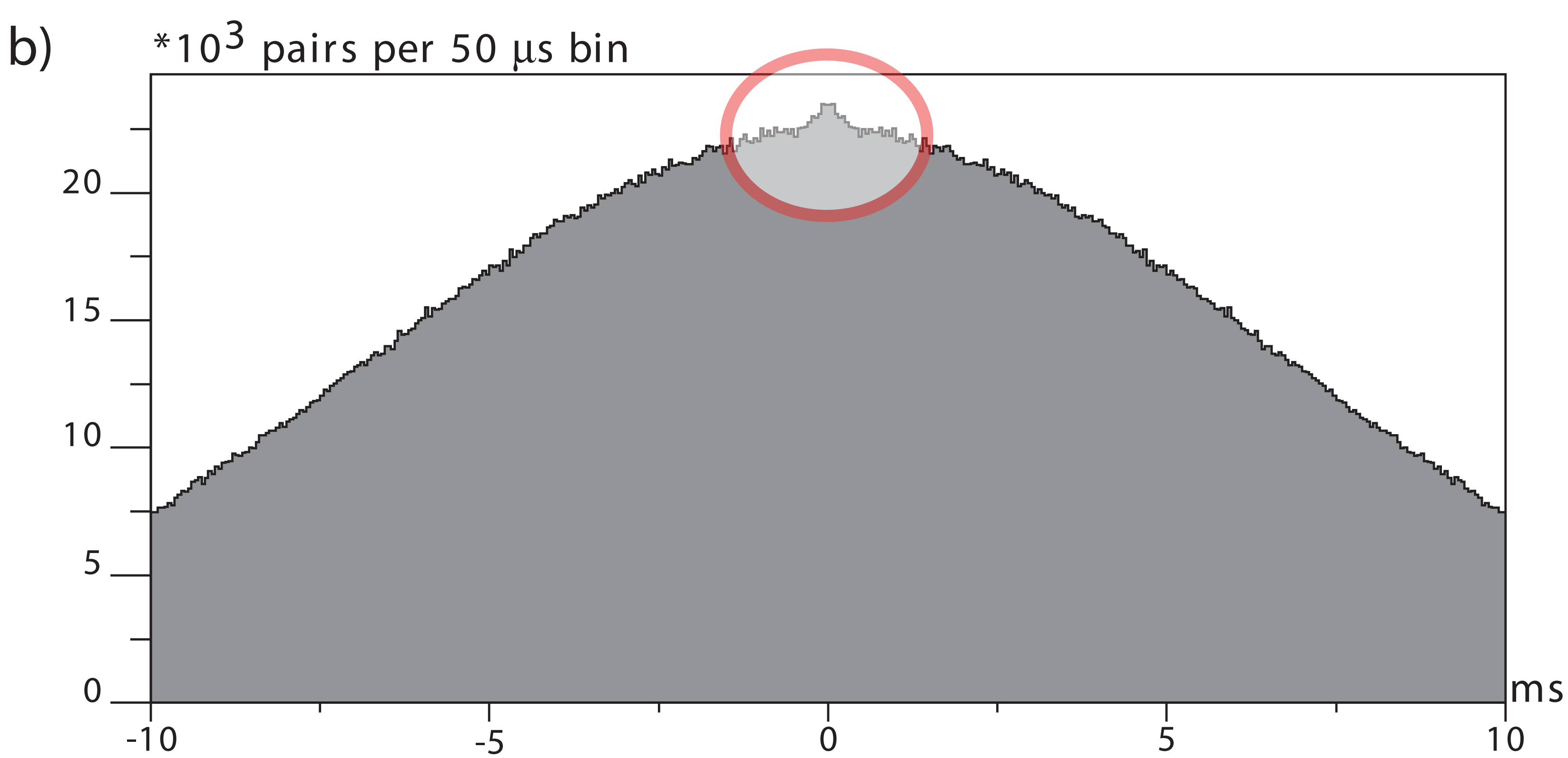
detector



Atoms dropped onto detector

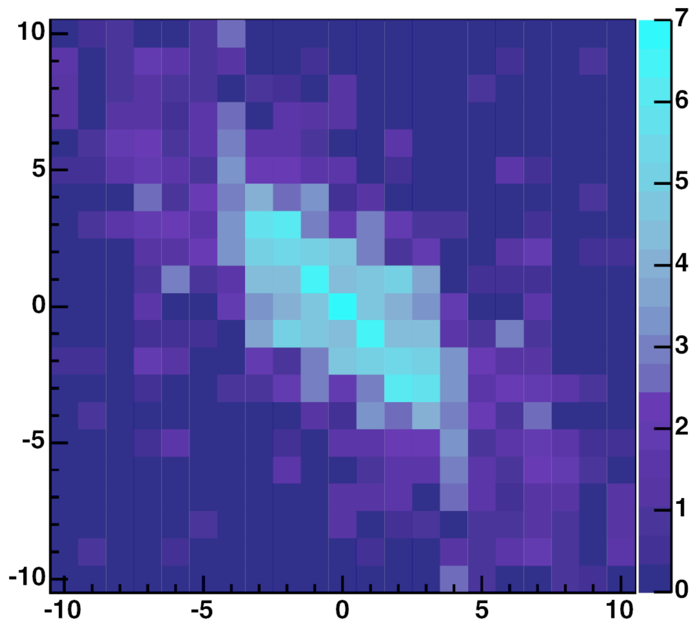


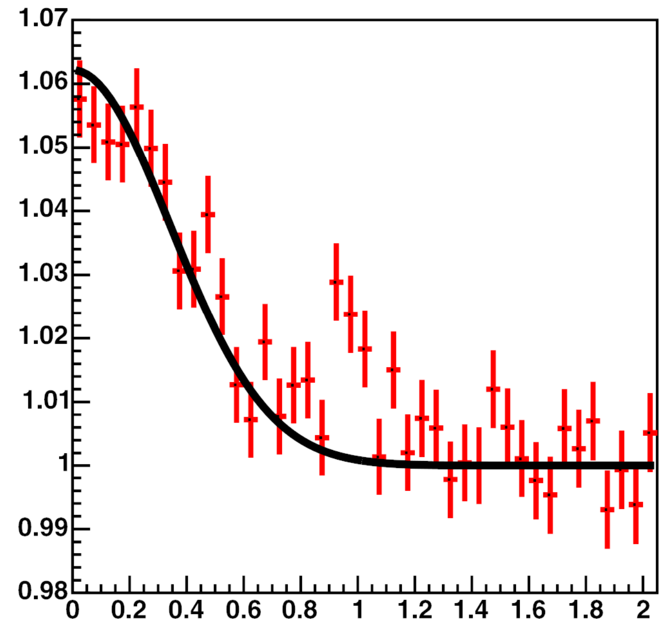
$n(p_z)$
arrival time distribution integrated over detector, summed ~1000 times



$G^{(2)}(p-p')$
number of pairs within a small volume ($500 \times 500 \times 150\ \mu m^3$)

Normalized correlation functions

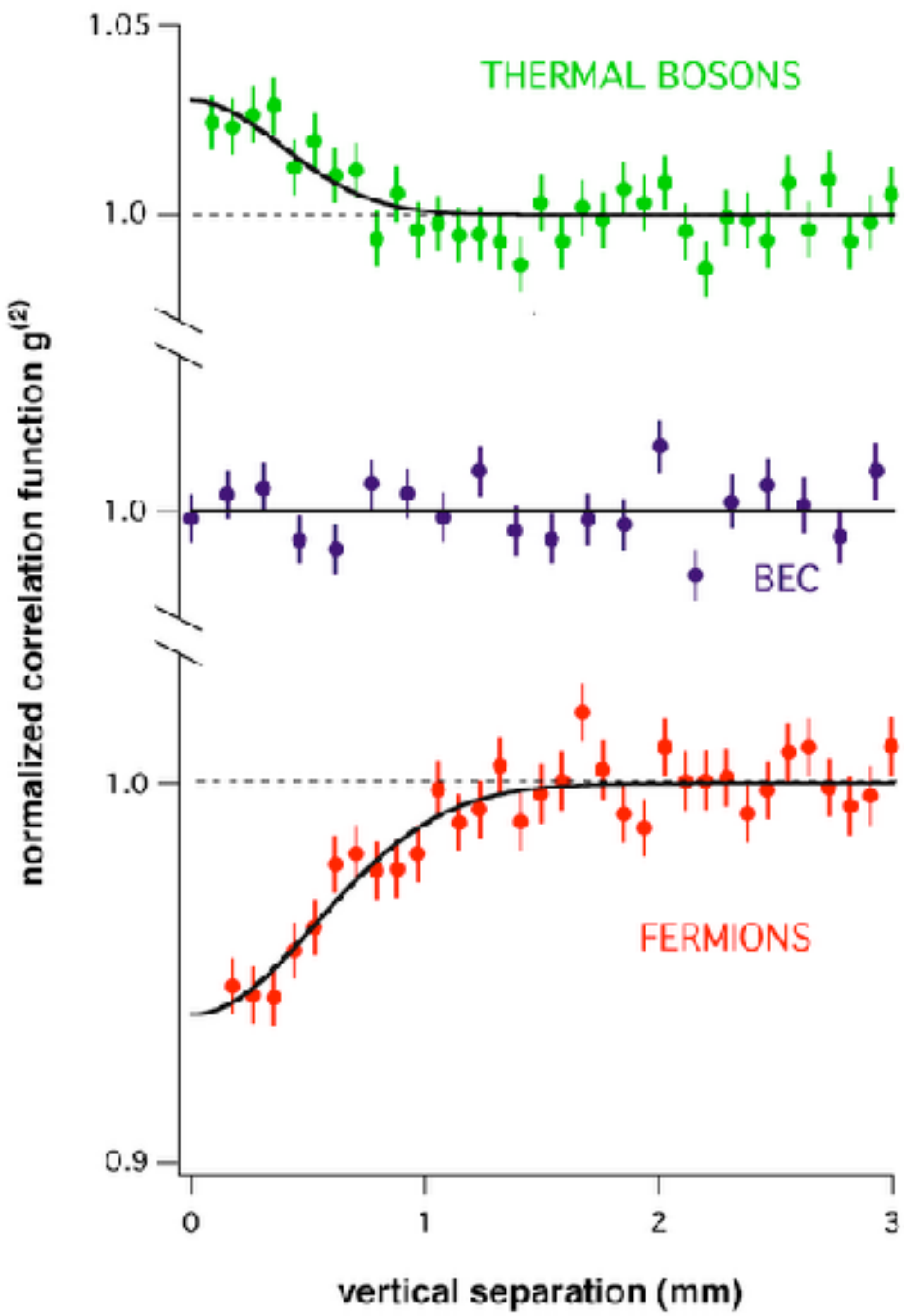




in detector plane

vertical

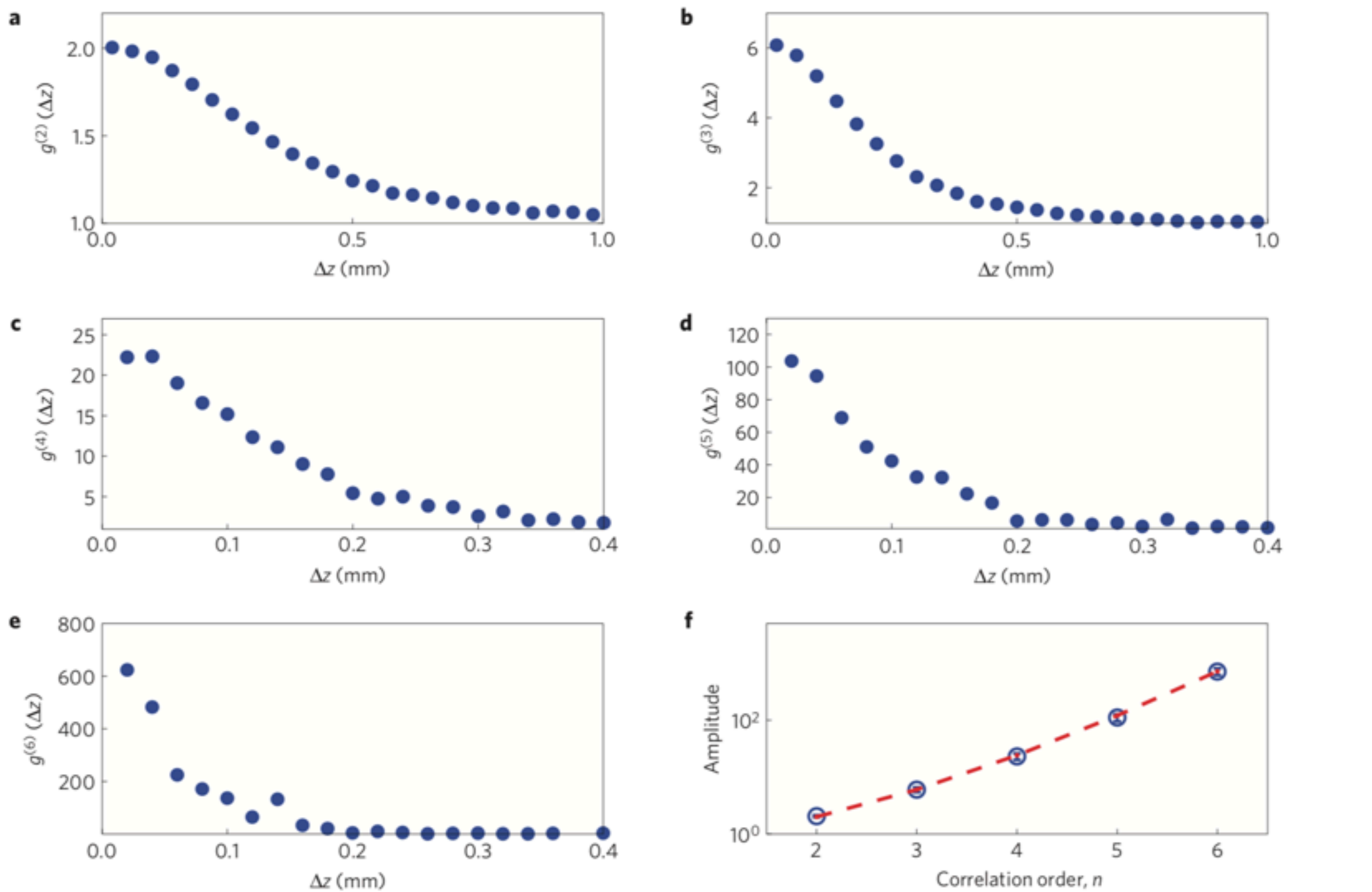
$g^{(2)}(p-p')$ of a thermal bose gas



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

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

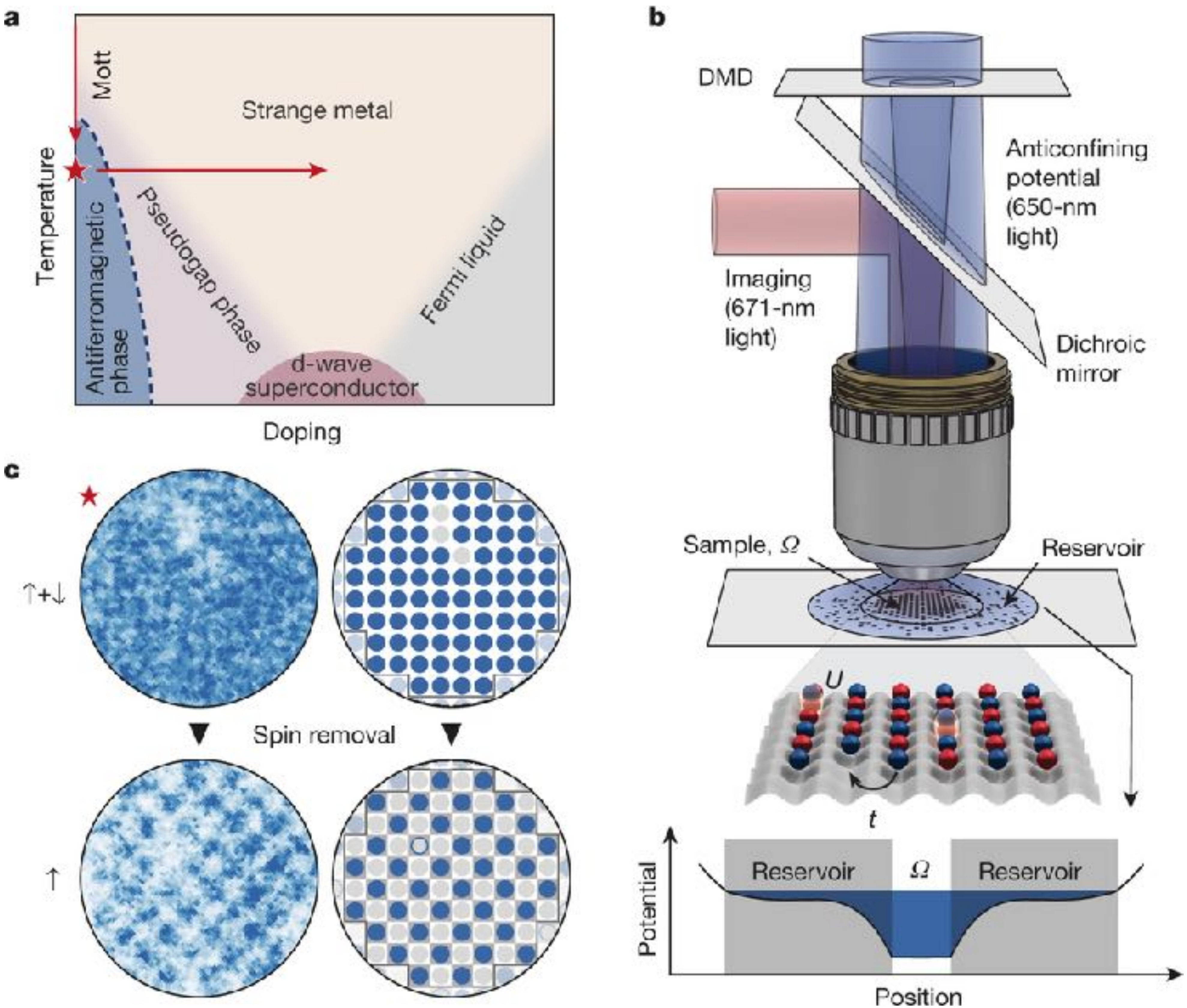
Higher order (bosons)



$$A_n \sim n!$$

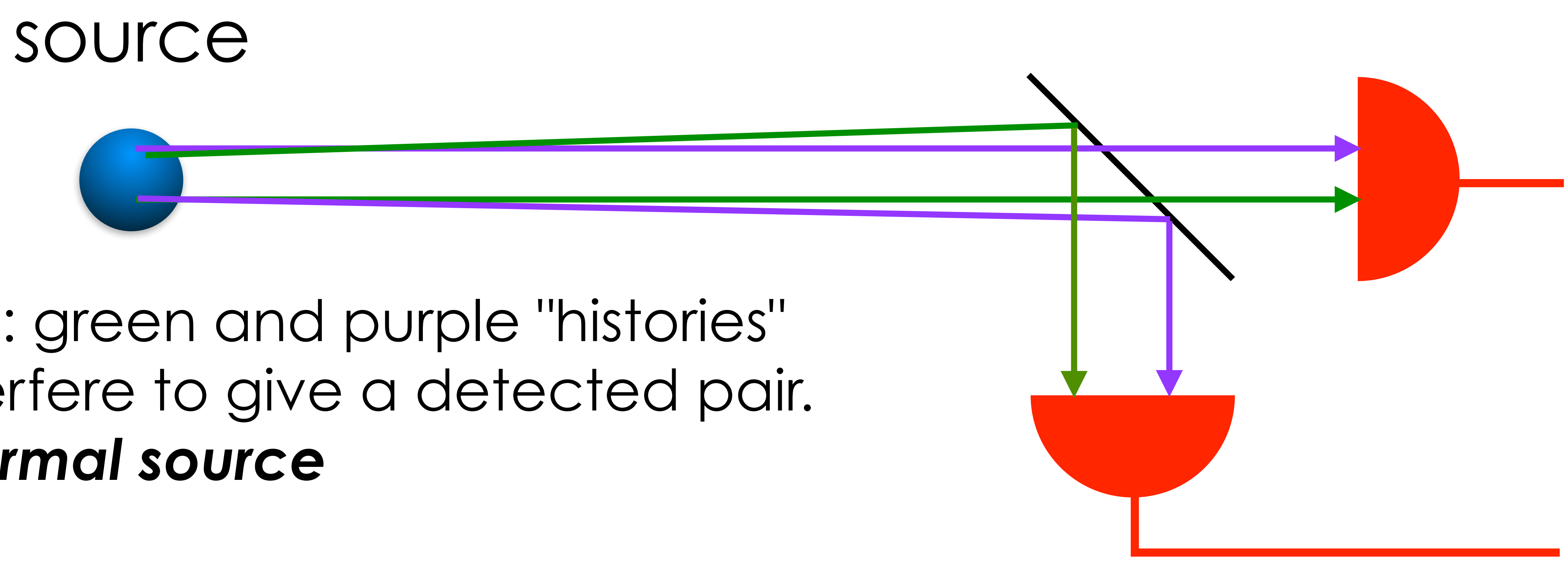
Dall et al. Nature Phys. 2013, DOI: 10.1038/NPHYS2632

In situ imaging the quantum gas microscope



Mazurenko et al
Nature (2017).
DOI: 10.1038/nature22362

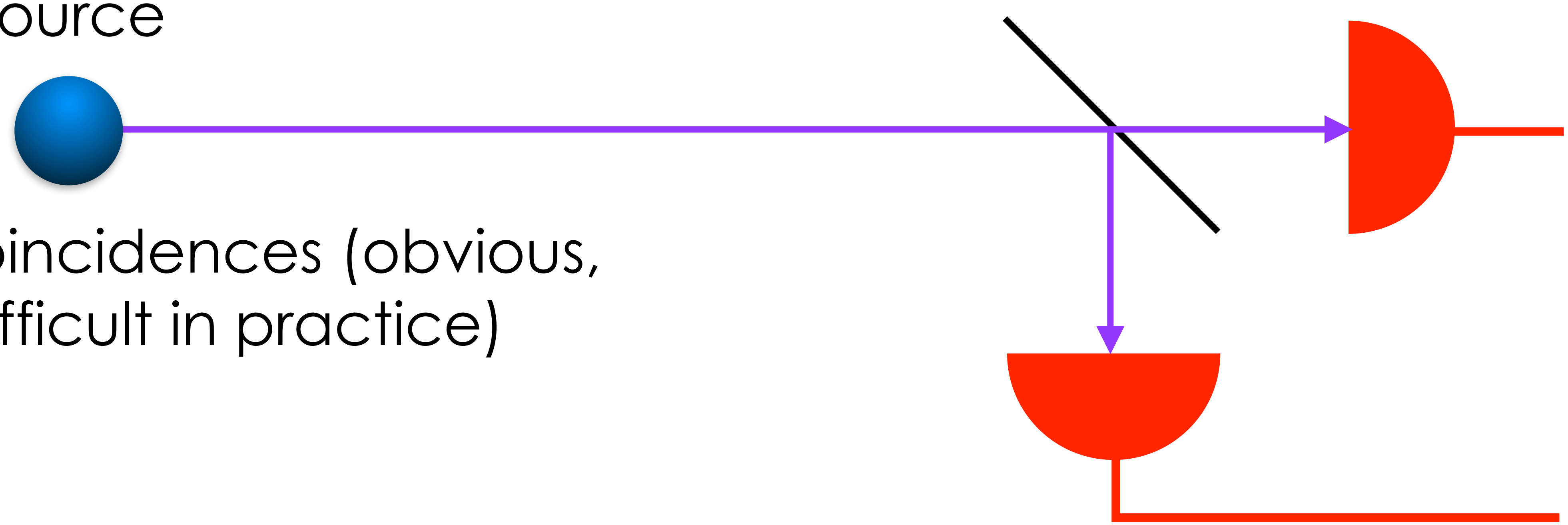
More general 2 particle interference



HBT: green and purple "histories" interfere to give a detected pair.
Thermal source

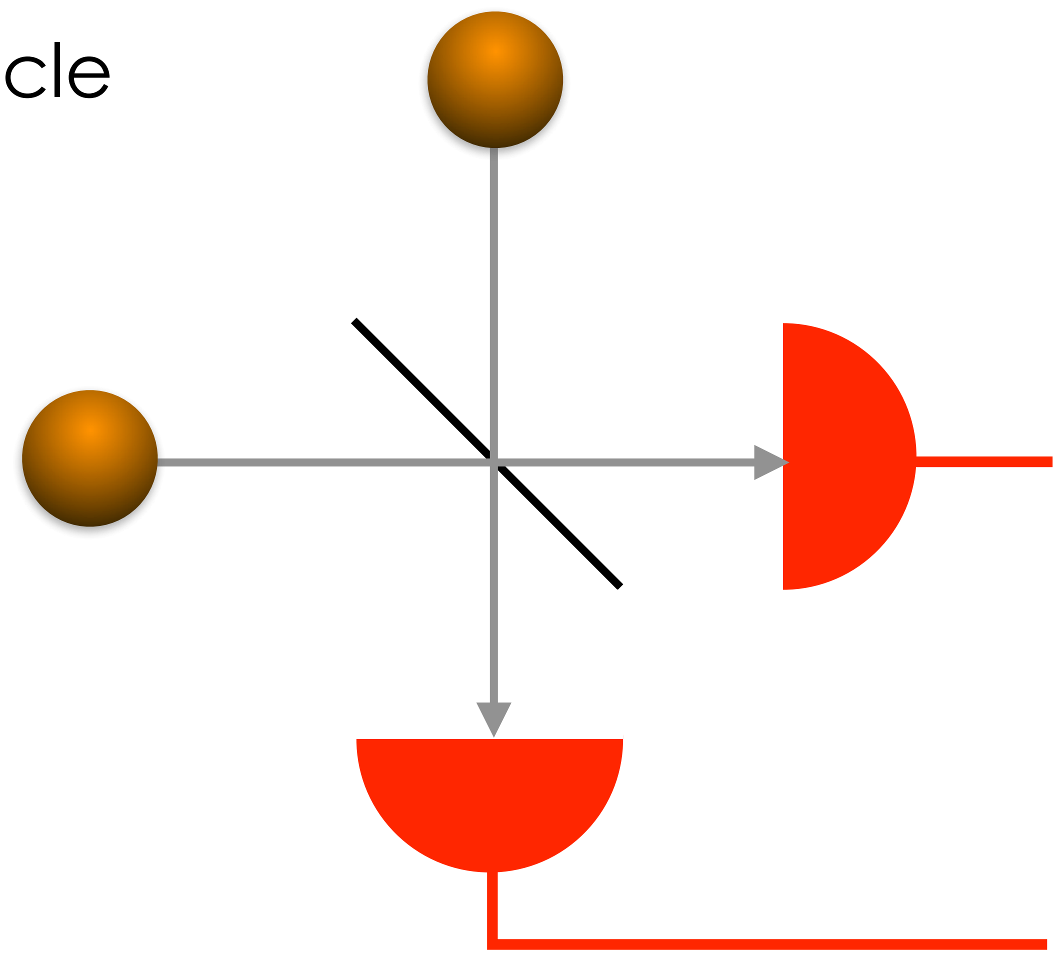
single particles

single particle
source



No coincidences (obvious,
but difficult in practice)

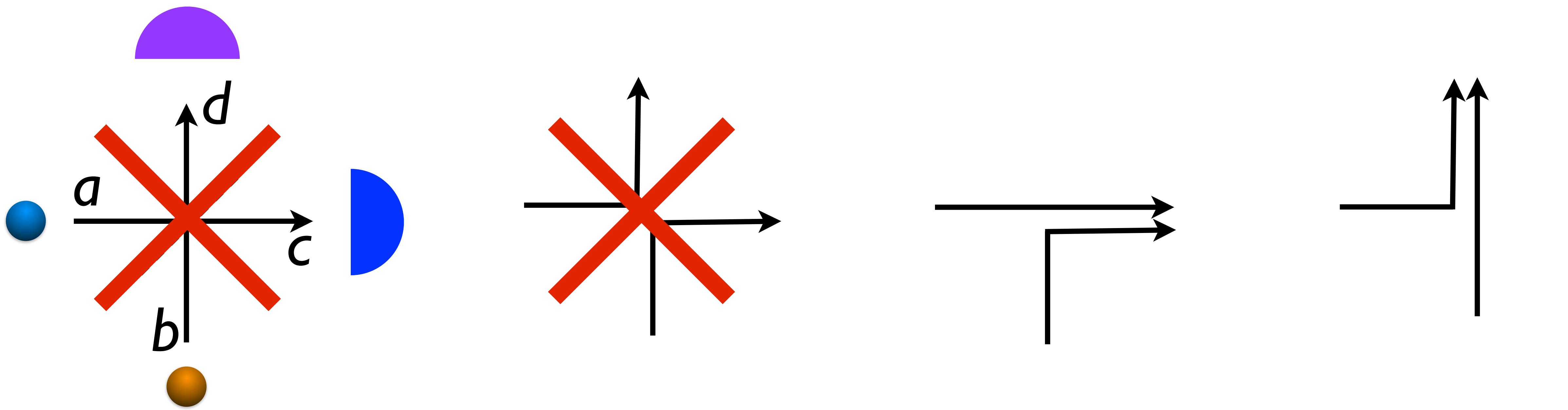
2 single particle
sources



Coincidence?

2 particles at a beam splitter

1 particle at each input → 4 possibilities:



both transmitted

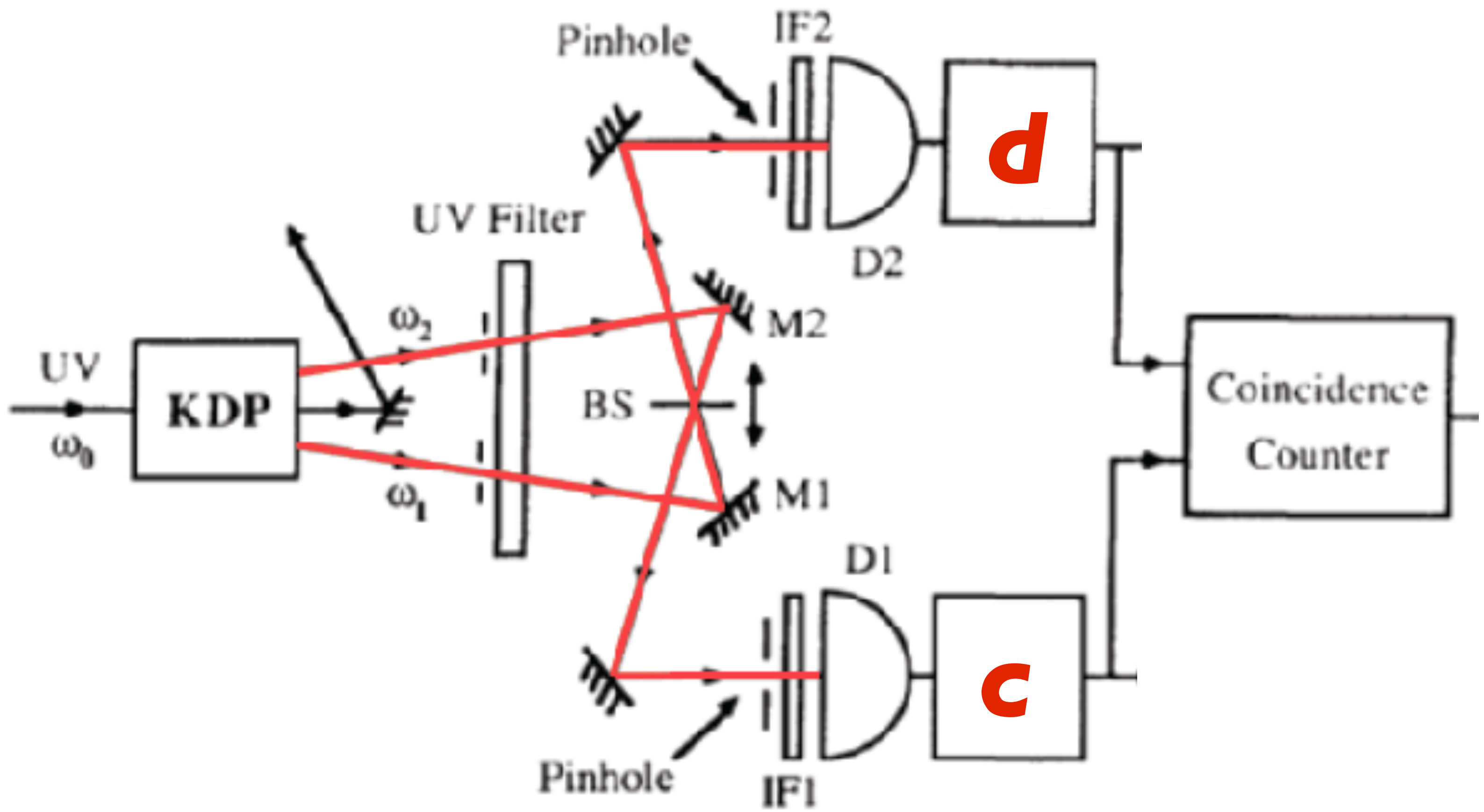
both reflected

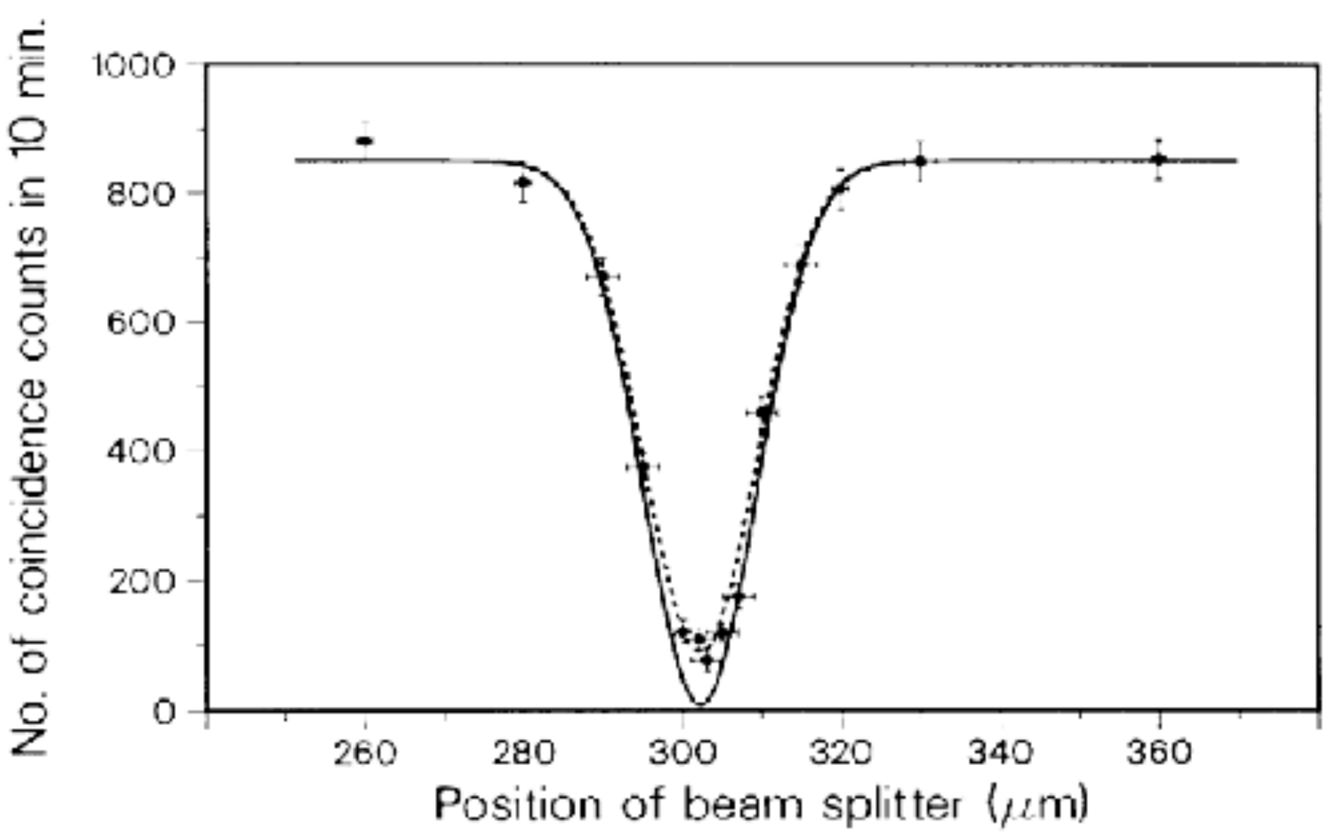
both in c

both in d

Hong Ou Mandel effect: only 2 possibilities

Hong, Ou and Mandel PRL 59, 2044 (1987)



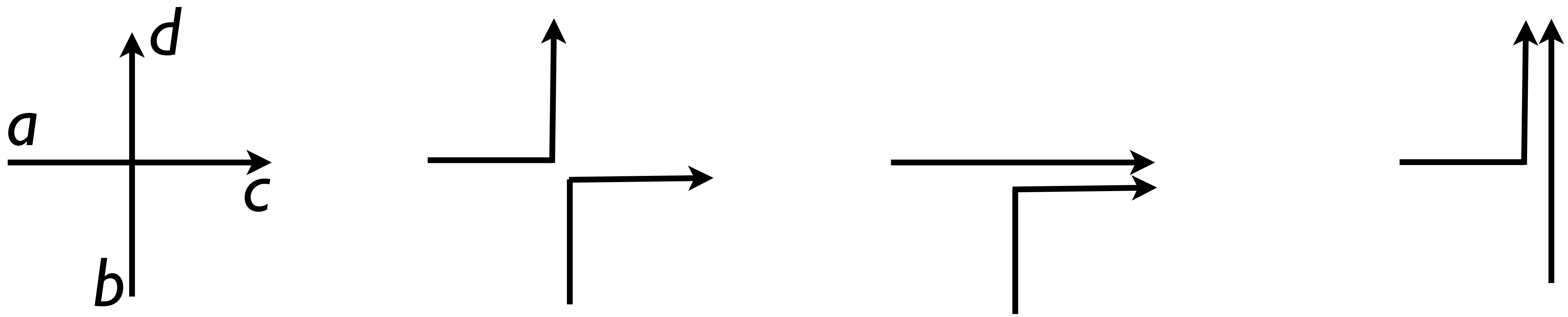


$$\langle n_c \rangle = \langle n_d \rangle \neq 0$$
$$\langle n_c n_d \rangle \approx 0$$

"HOM dip" as a function of the overlap between the two arms.

2 boson fields at a beam splitter

1 particle at each input → 4 QM amplitudes:



both transmitted

both reflected

$$|1,1\rangle_{a,b} = a^\dagger\, b^\dagger \big|0,0\big\rangle = \tfrac{1}{2}\left(c^\dagger + d^\dagger\right)\left(-c^\dagger + d^\dagger\right)\big|0,0\big\rangle$$

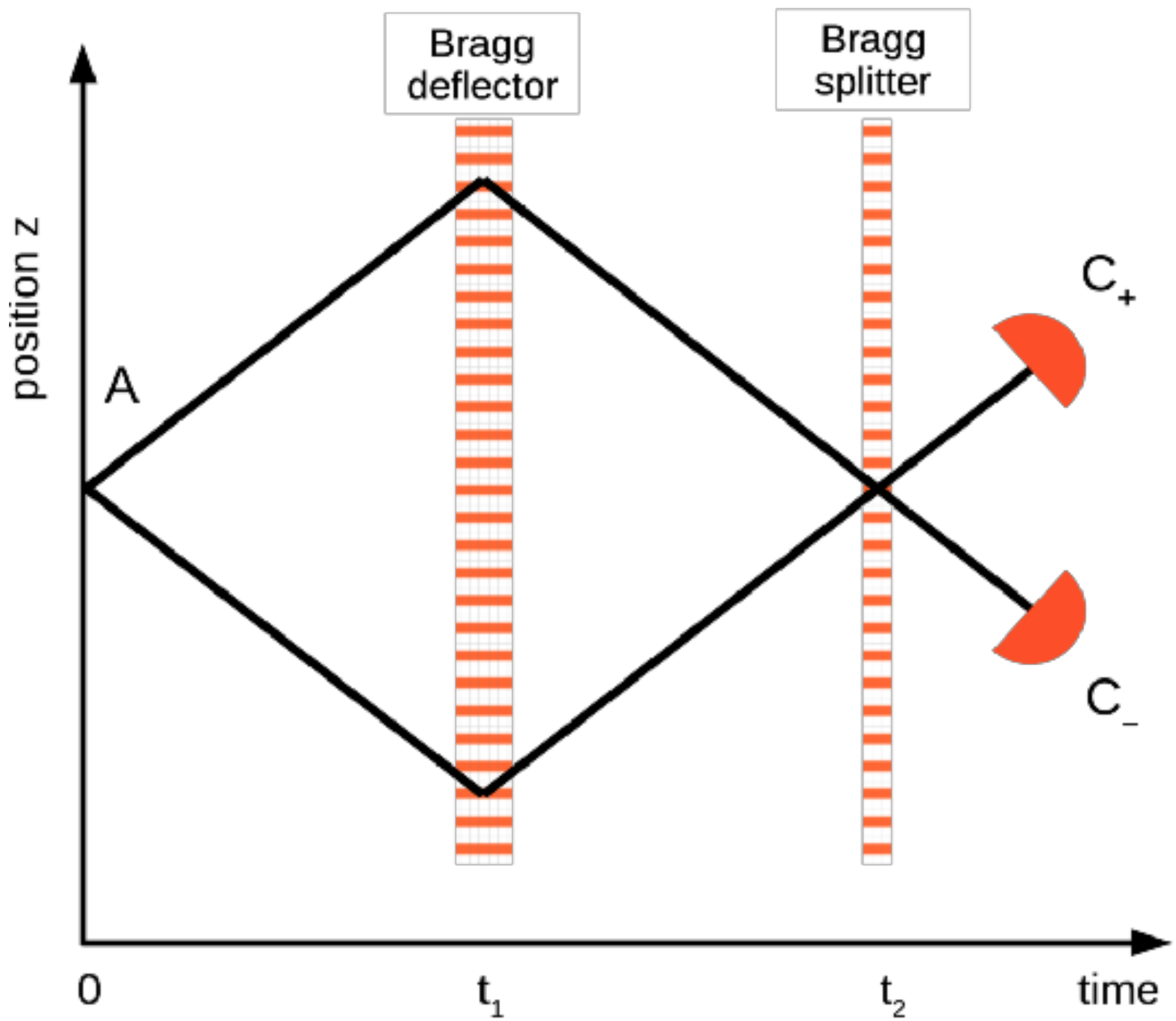
$$= \tfrac{1}{2}\left(-c^{\dagger 2} + d^{\dagger 2} + c^\dagger\, d^\dagger - d^\dagger\, c^\dagger\right)\big|0,0\big\rangle$$

$$= \frac{1}{\sqrt{2}}\left(\,-|2,0\rangle_{c,d} + |0,2\rangle_{c,d}\,\right)$$

$G^{(2)}_{cd} = \langle n_c n_d \rangle = 0$

independent of relative phase; no classical waves either

Experimental sequence

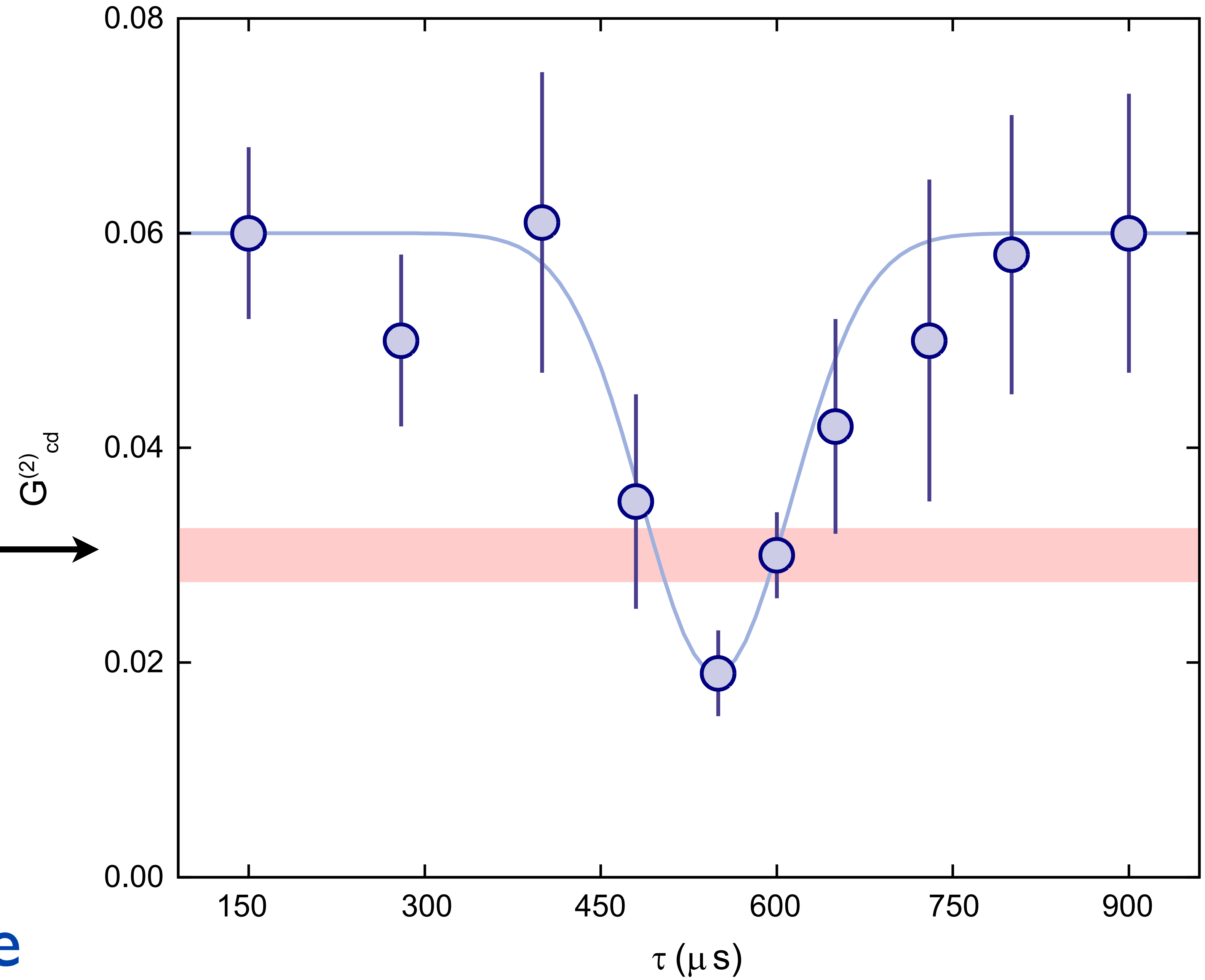


- beam splitter use Bragg diffraction
- $t = 0$ pair creation
- t_1 mirror exchanges k_a and k_b
  $t_1 = 500\ \mu s$
- t_2 beam splitter mixes 2 modes
- atoms fall to detector

HOM correlation

$G^{(2)}_{cd} = \langle n_c n_d \rangle$
0.06 coincidences per shot

50% contrast



~10 hrs for each point

lack of 100% contrast due to extra particles

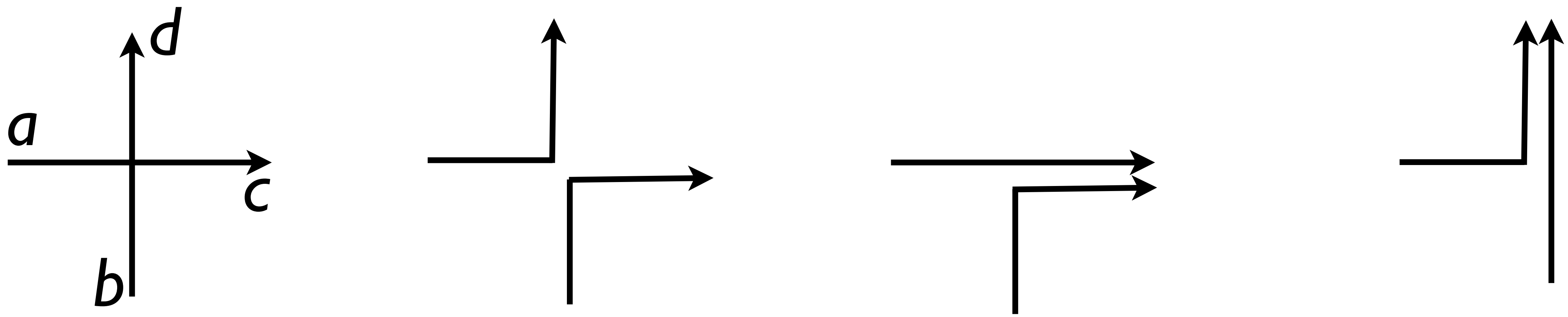
delay: $\tau = t_3 - t_2$

n.b. $t_2 - t_1 = 500\ \mu s$

Lopes et al., Nature 520, 66 (2015)

2 fermi fields at a beam splitter

1 particle at each input → 4 QM amplitudes:



both transmitted

both reflected

$$|\,1,1\rangle_{a,b} = a^\dagger\, b^\dagger \big|\, 0,0\big\rangle = \frac{1}{2}\left(c^\dagger + d^\dagger\right)\left(-c^\dagger + d^\dagger\right)\Big|\, 0,0\Big\rangle$$

$$= \frac{1}{2}\left(-c^{\dagger 2} + d^{\dagger 2} + c^\dagger\, d^\dagger - d^\dagger\, c^\dagger\right)\Big|\, 0,0\Big\rangle$$

$$= |\,1,1\rangle_{c,d}$$

the interference effect is absent (less dramatic)

Thanks