The Hanbury Brown Twiss effect for matter waves

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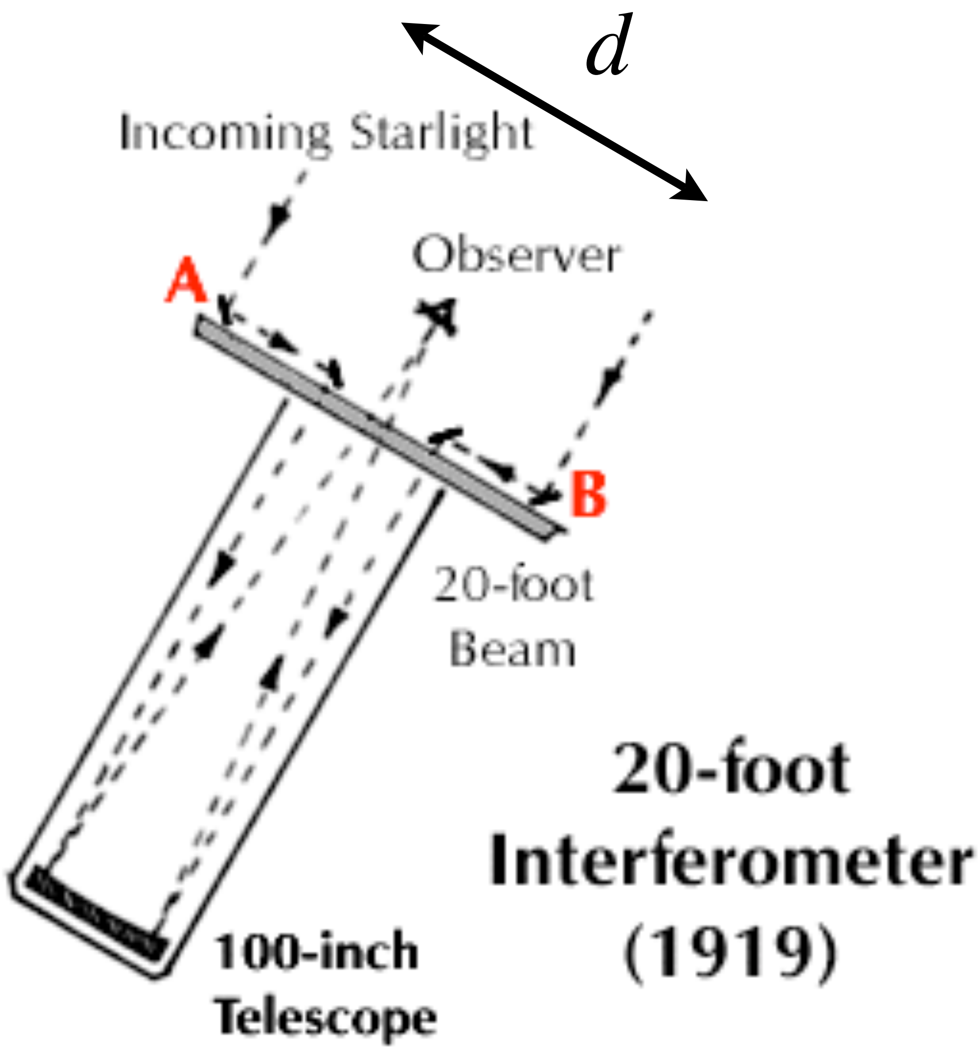
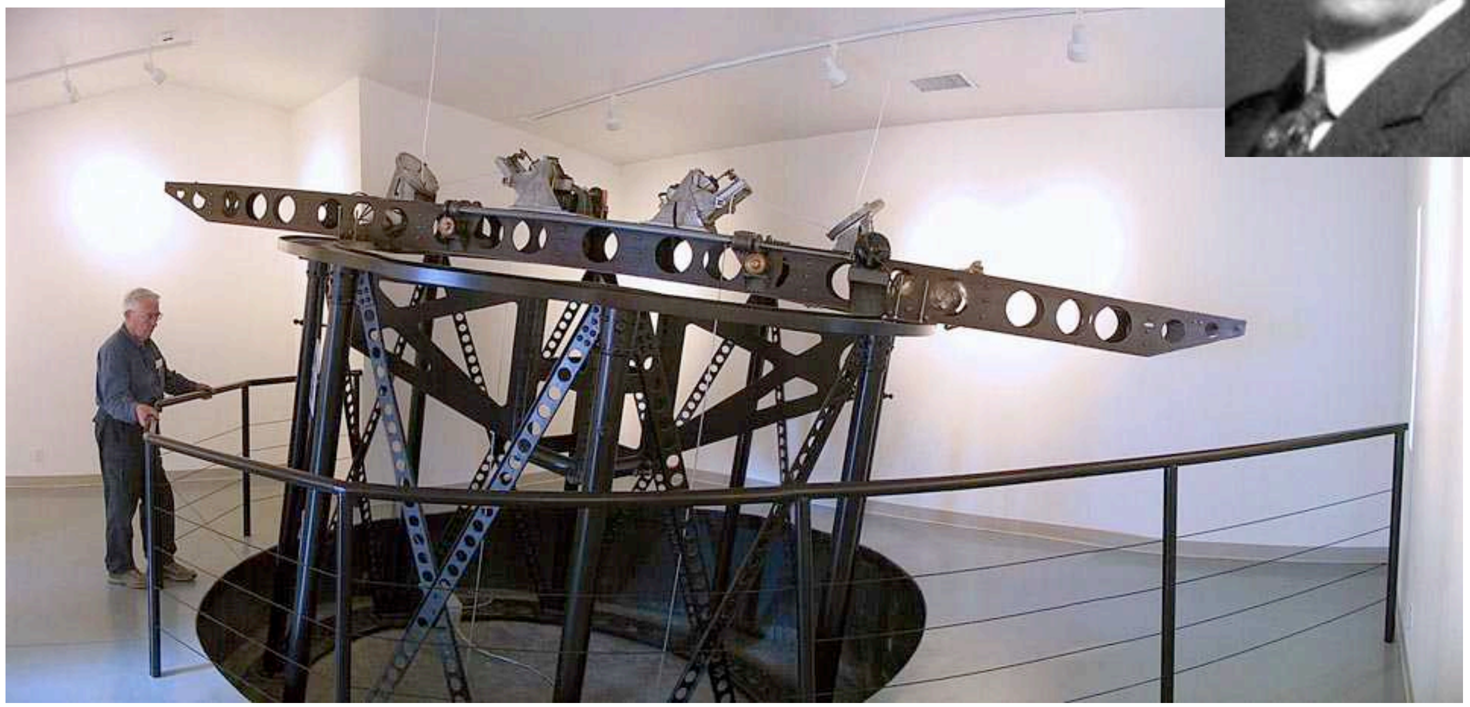
Workshop on HBT interferometry
12 may 2014

Outline: Hanbury Brown Twiss effect ...

1. ... in optics and astronomy
2. ... with matter waves
3. ... and “superradiance”

Michelson stellar interferometer



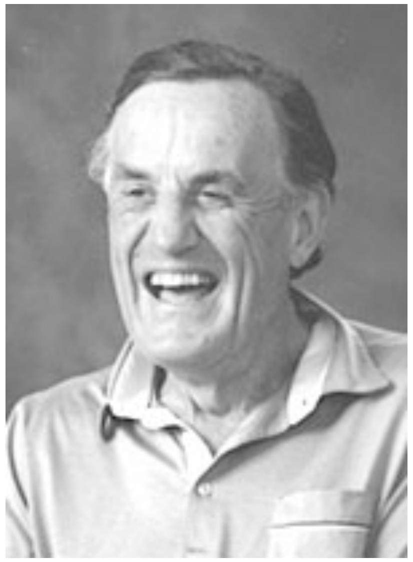


$\theta < \lambda/d \quad \rightarrow \quad$ *fringes*

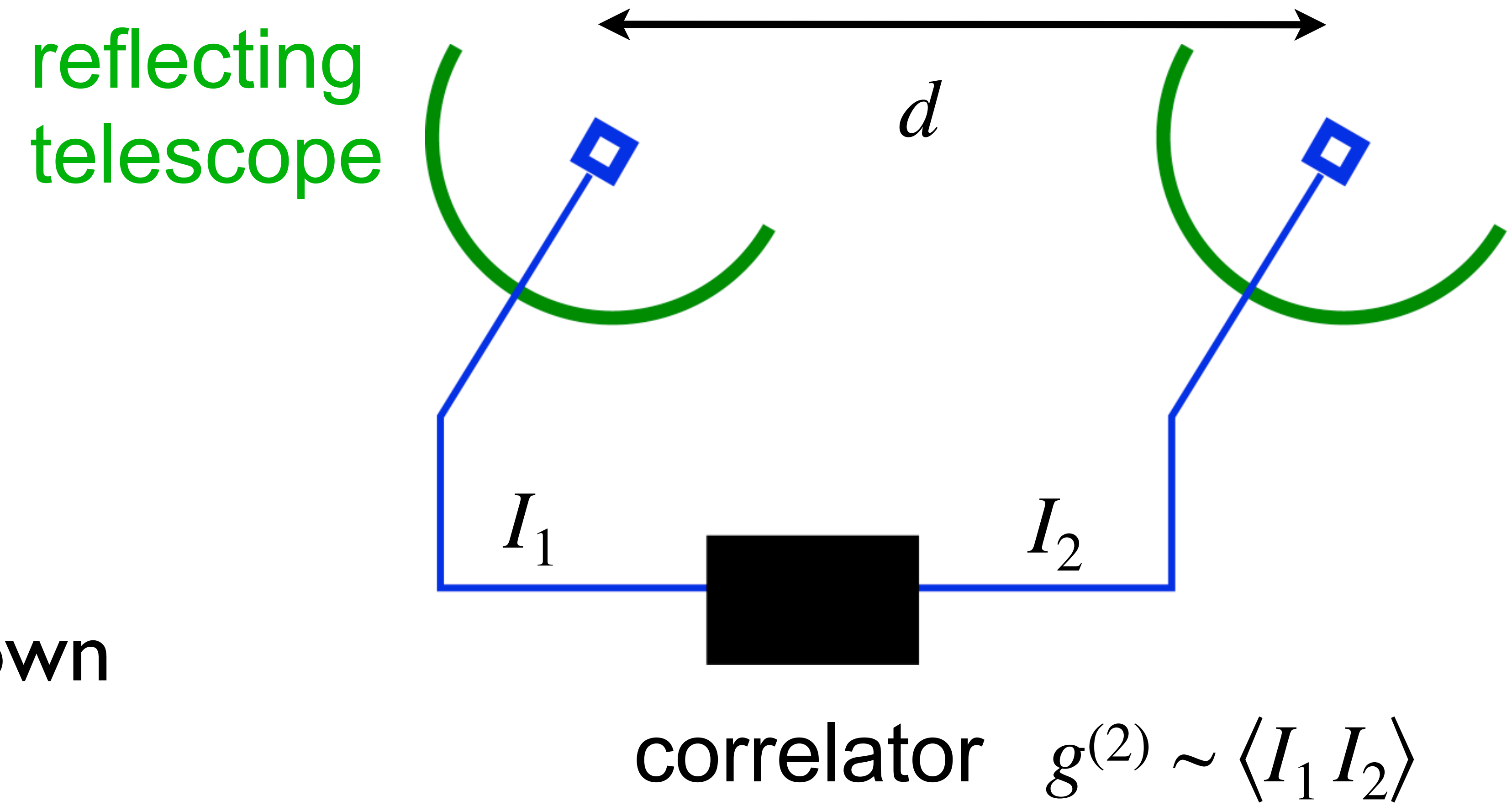
$d \sim 6\text{m} \quad \rightarrow \quad \theta_{\text{min}} \sim 10^{-7}$

Michelson measured the angular diameters of 6 (big) stars.

Hanbury Brown: intensity interferometry

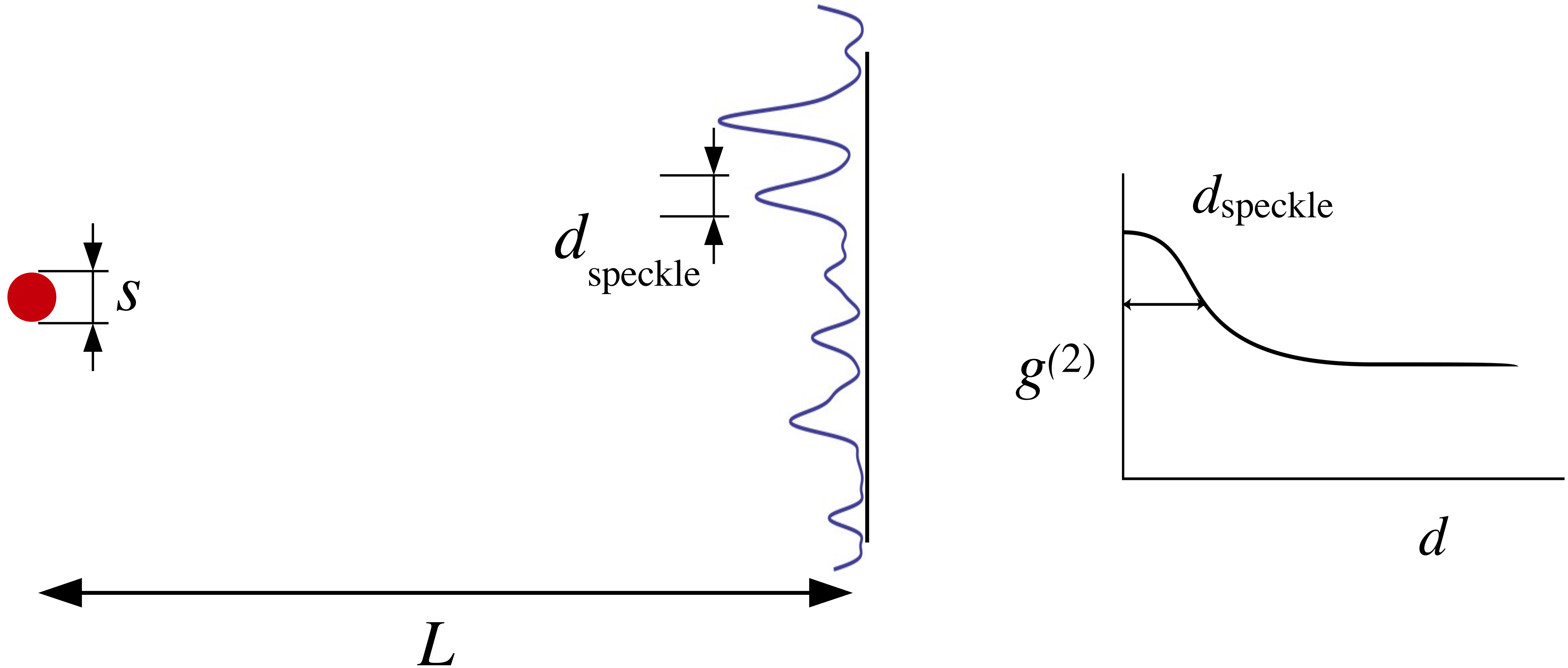


Robert Hanbury Brown
1916 - 2001



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.
But what was interfering?

HBT stellar interferometer principle



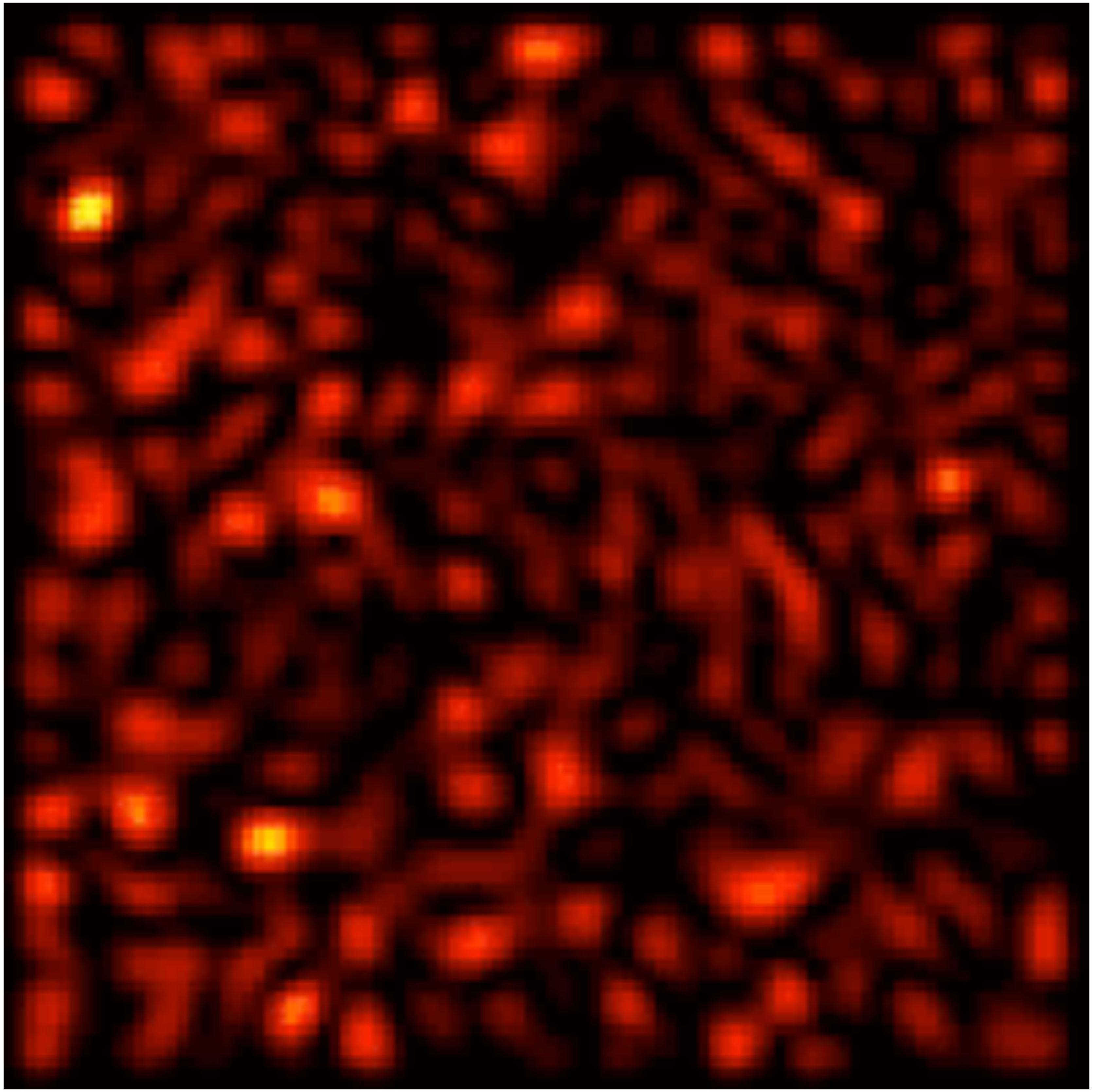
Starlight produces rapidly fluctuating speckle on the earth. The size of the speckle is:

$$d_{\text{speckle}} \sim \lambda L/s \sim \lambda/\theta$$

Intensity fluctuations within one speckle are correlated so that

$$\langle I_1\, I_1 \rangle \;\geq\; \langle I_1 \rangle \quad \langle I_2 \rangle$$

Visualisation de speckle



Stellar interferometer in Australia 1960's

Hanbury Brown's group measured diameters of 32 (bright) stars

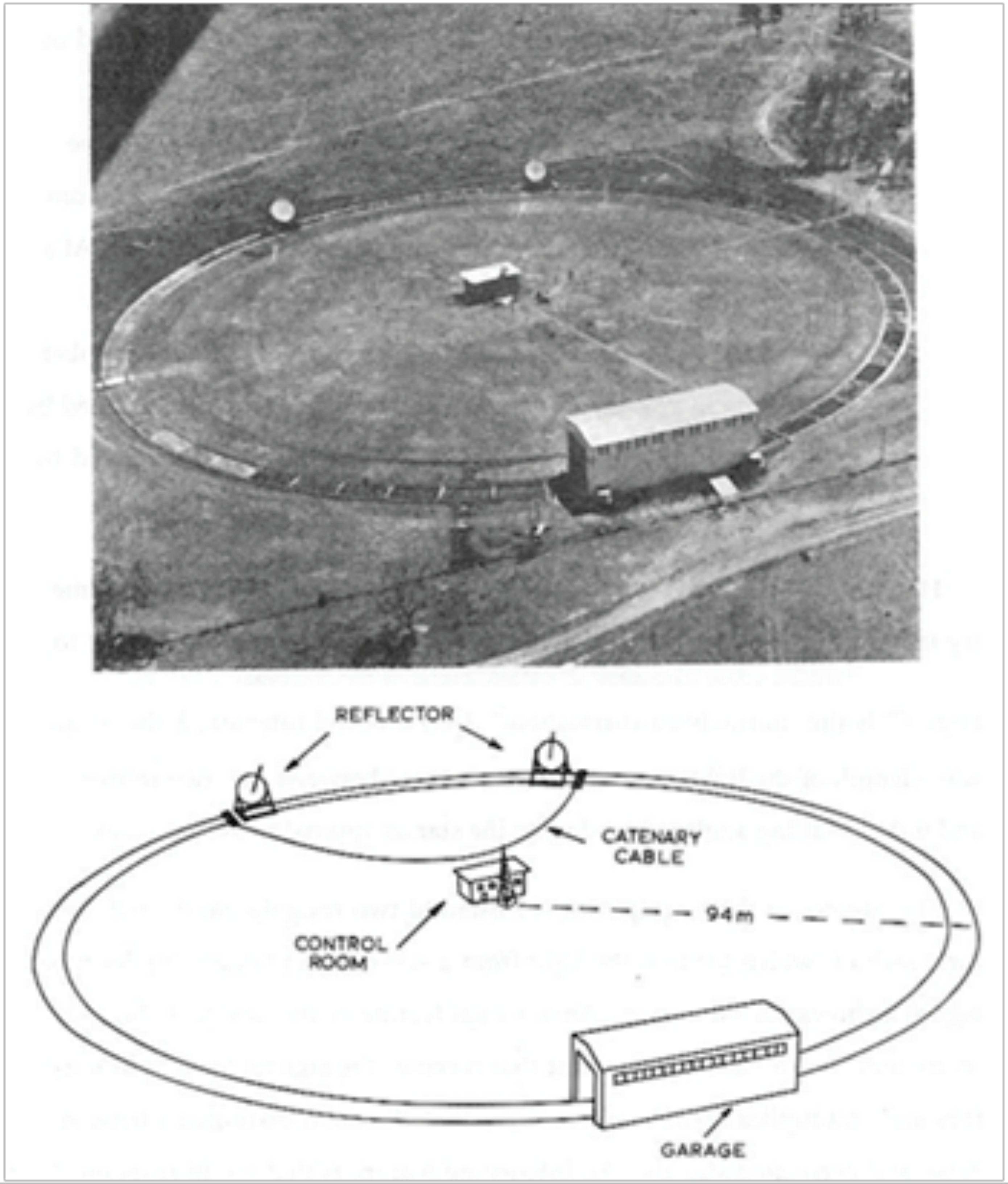
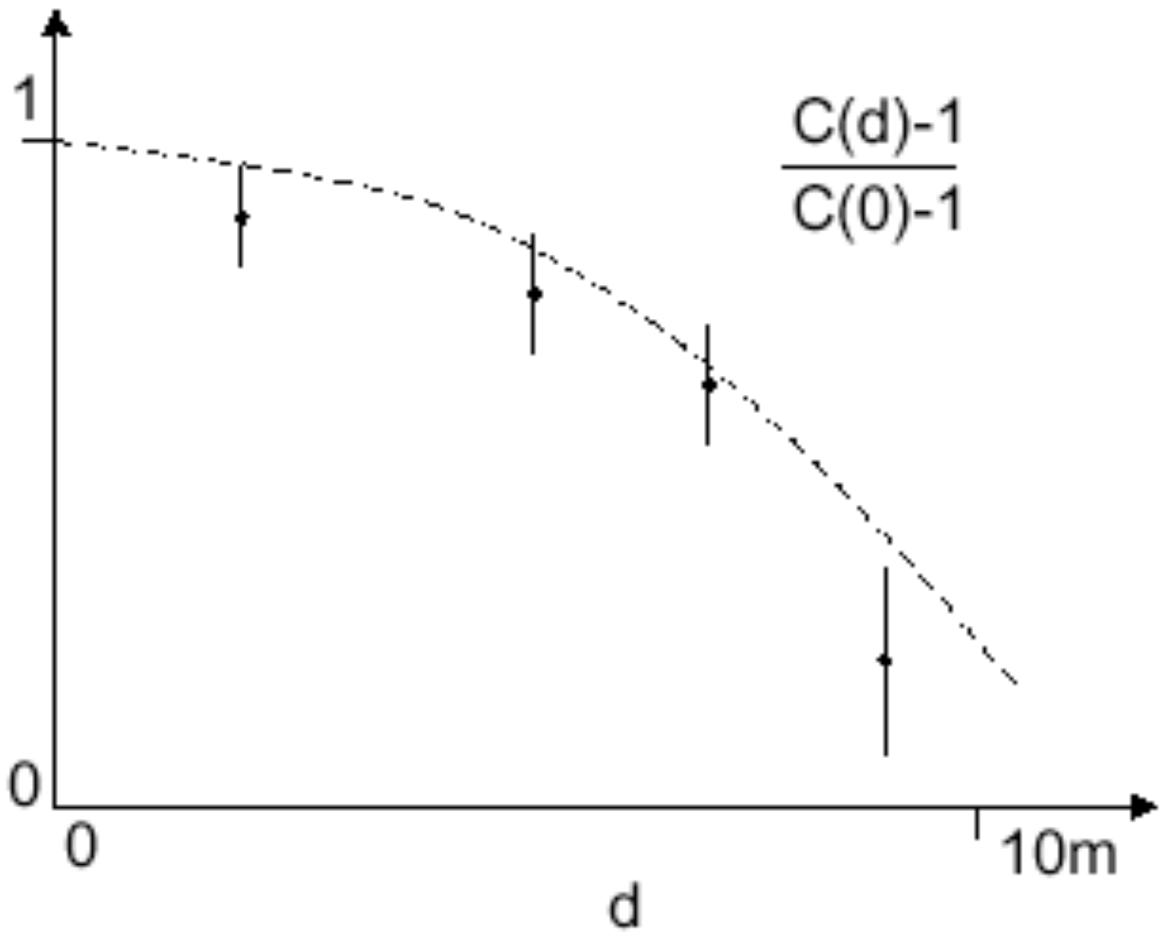


Figure 1. Aerial photo and illustration of the original HBT apparatus. They have been extracted from Ref.[1].

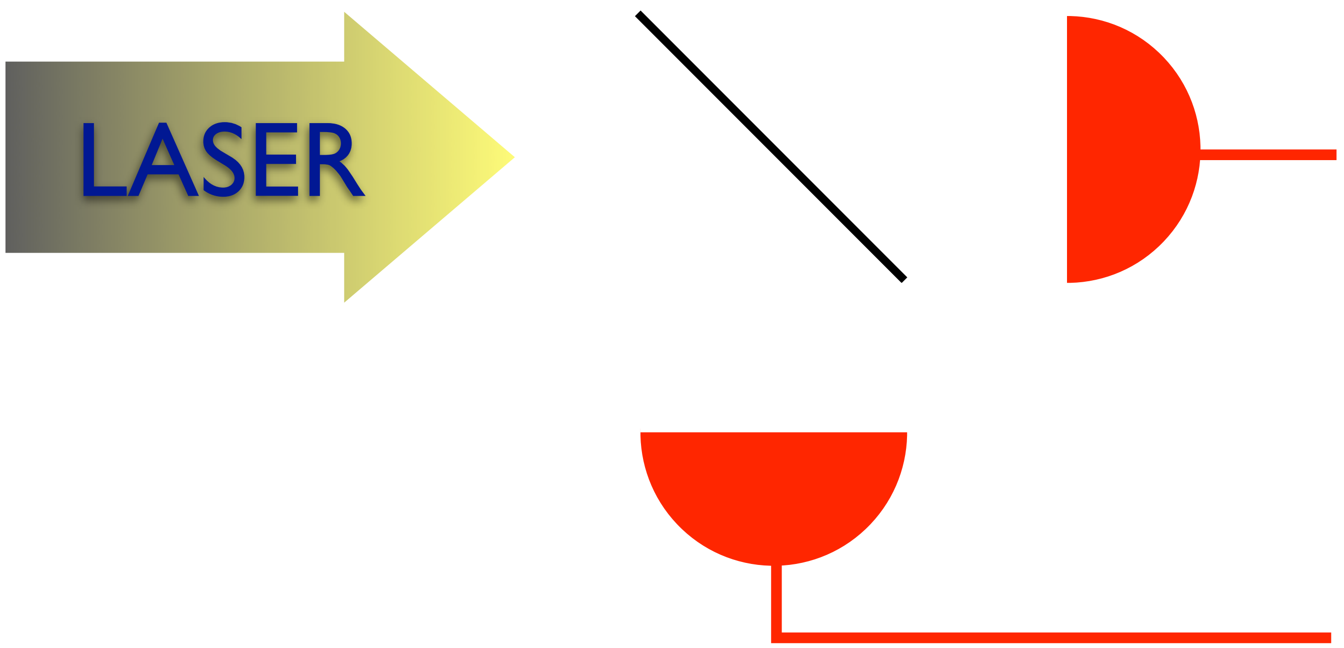
Measurement of a stellar diameter (1957)



$g^{(2)}-1$ for
Sirius
$\theta = 3\times10^{-8}$ radians

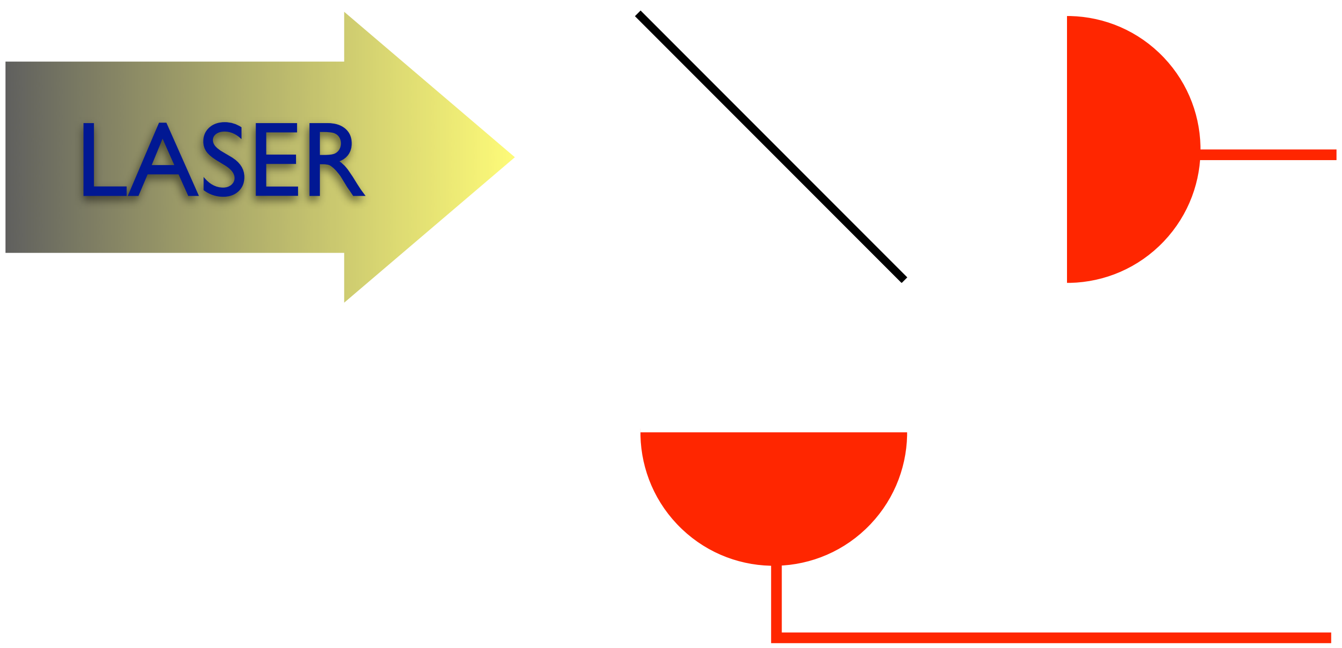
Independent photons from different points on a star "stick together"
- photon bunching

What about a laser?



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

What about a laser?



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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."

Correlations in a laser: measurement

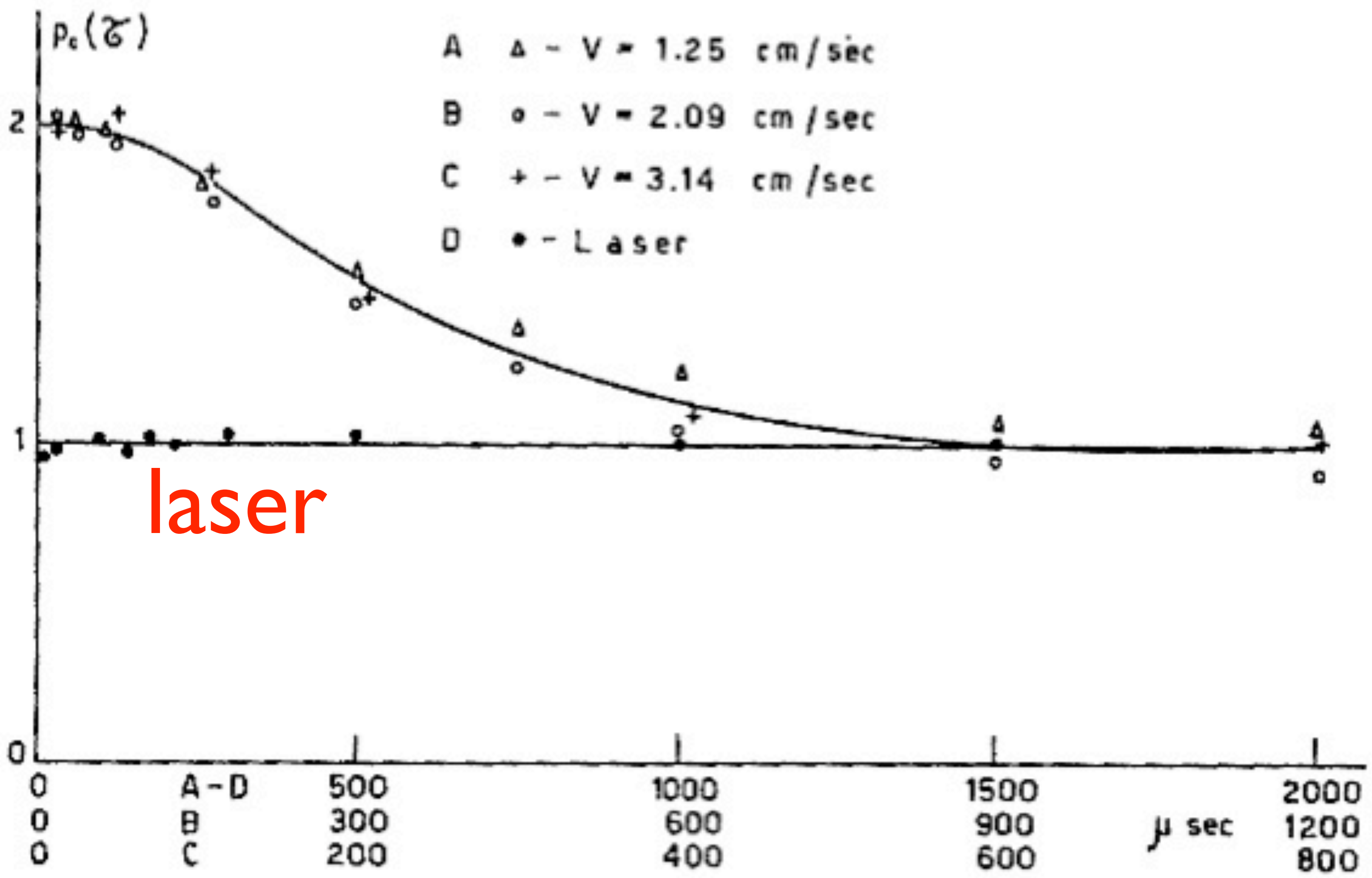
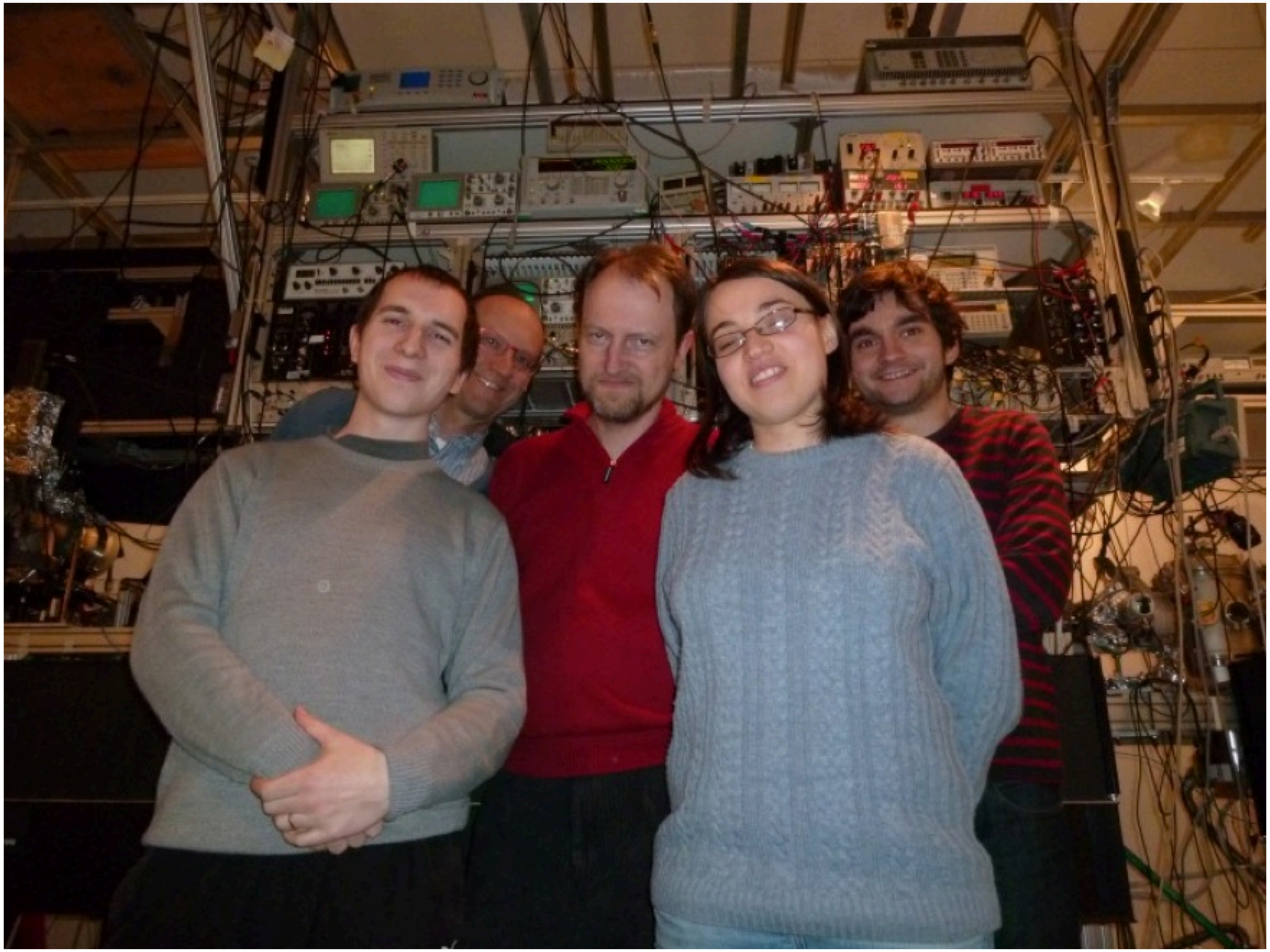


Fig. 1. Conditional probability $p_C(\tau)$ of a second count occurring at a time τ after a first has occurred at time $\tau = 0$.

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

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

HBT with atoms: the team



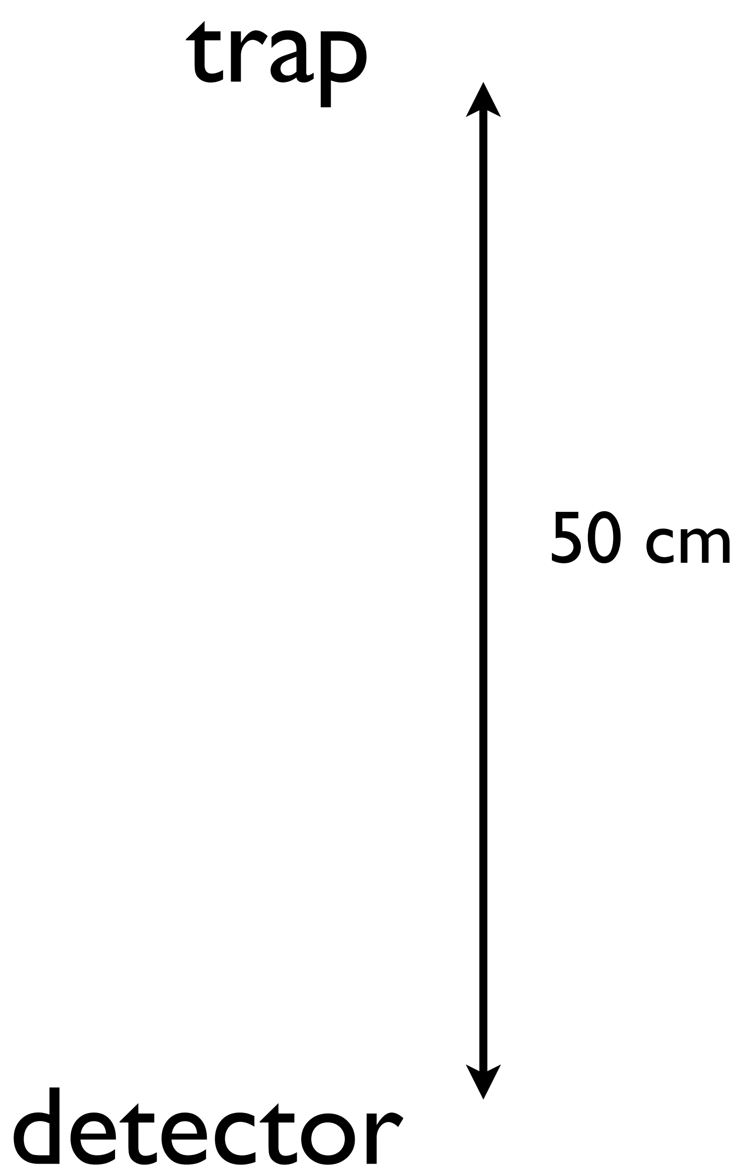
missing: Marc Cheneau, Almazbek Imanaliev

HBT with atoms: the idea

- Source: cloud of 10^5 metastable He atoms
- Time of flight ~ 300 ms parabolic trajectories
- Detector: μ-channel plate ~10^4 parallel detectors
- Record x,y,t for every detected atom
- Typical coherence length

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

~ 1 mm



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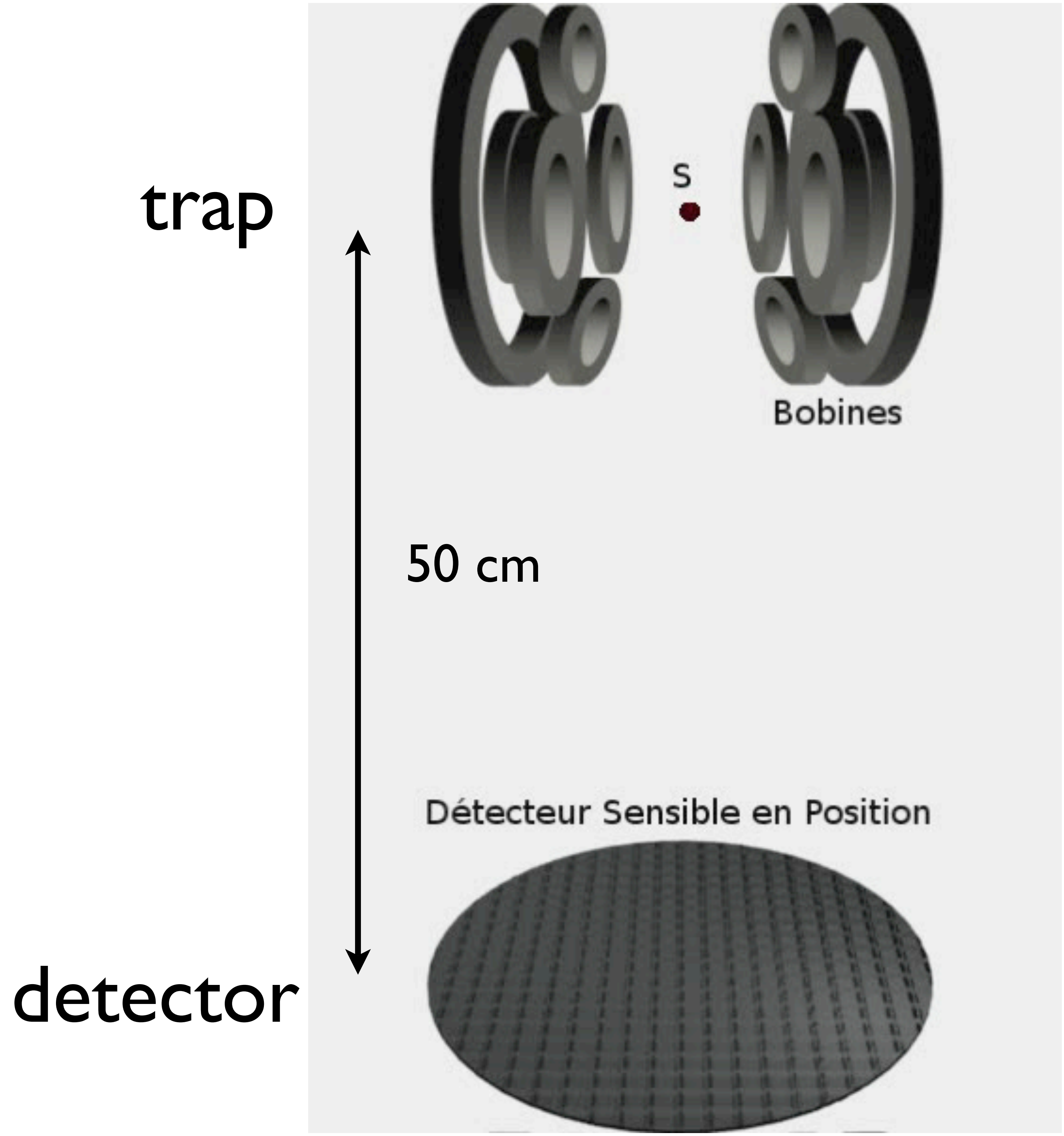
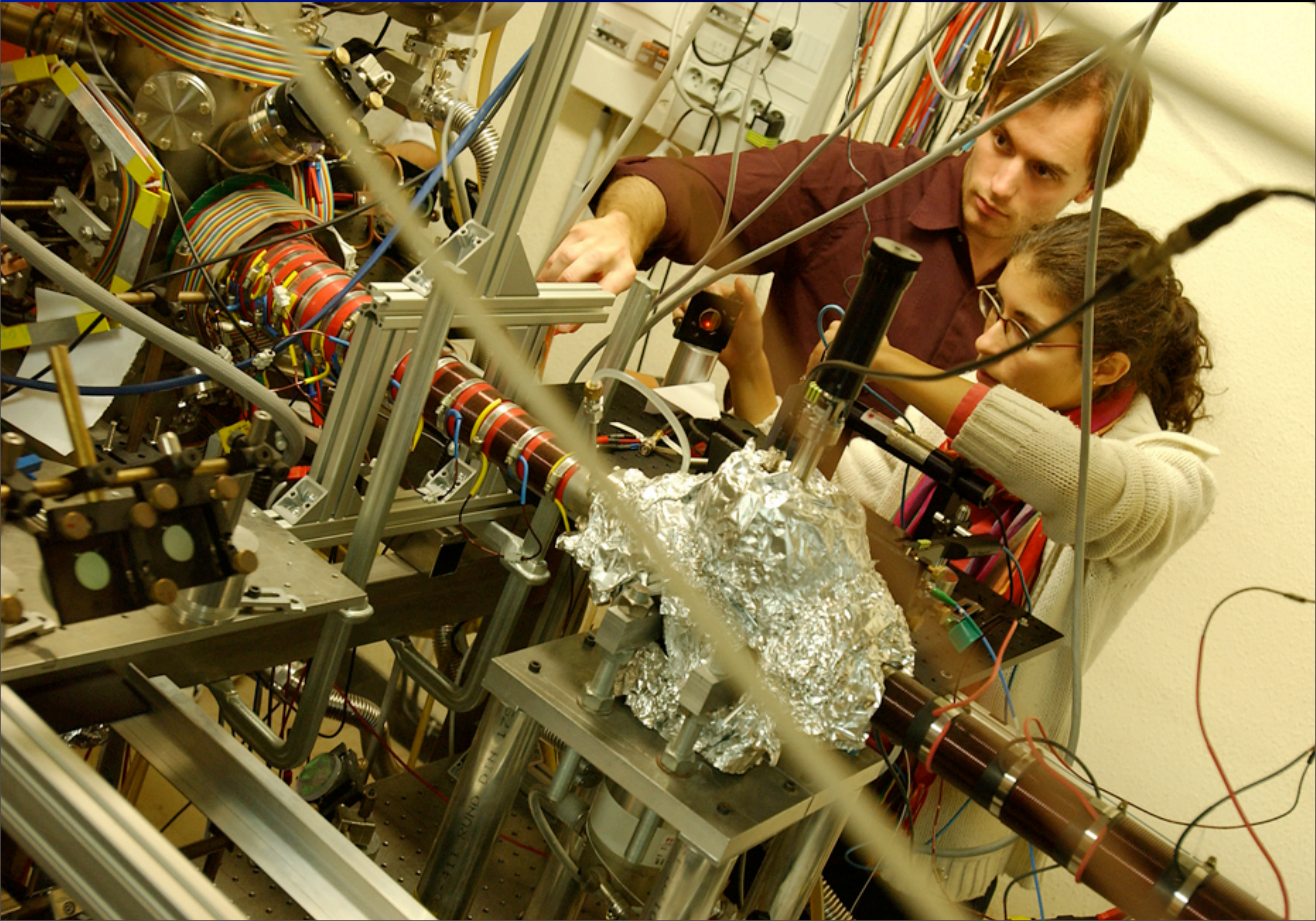
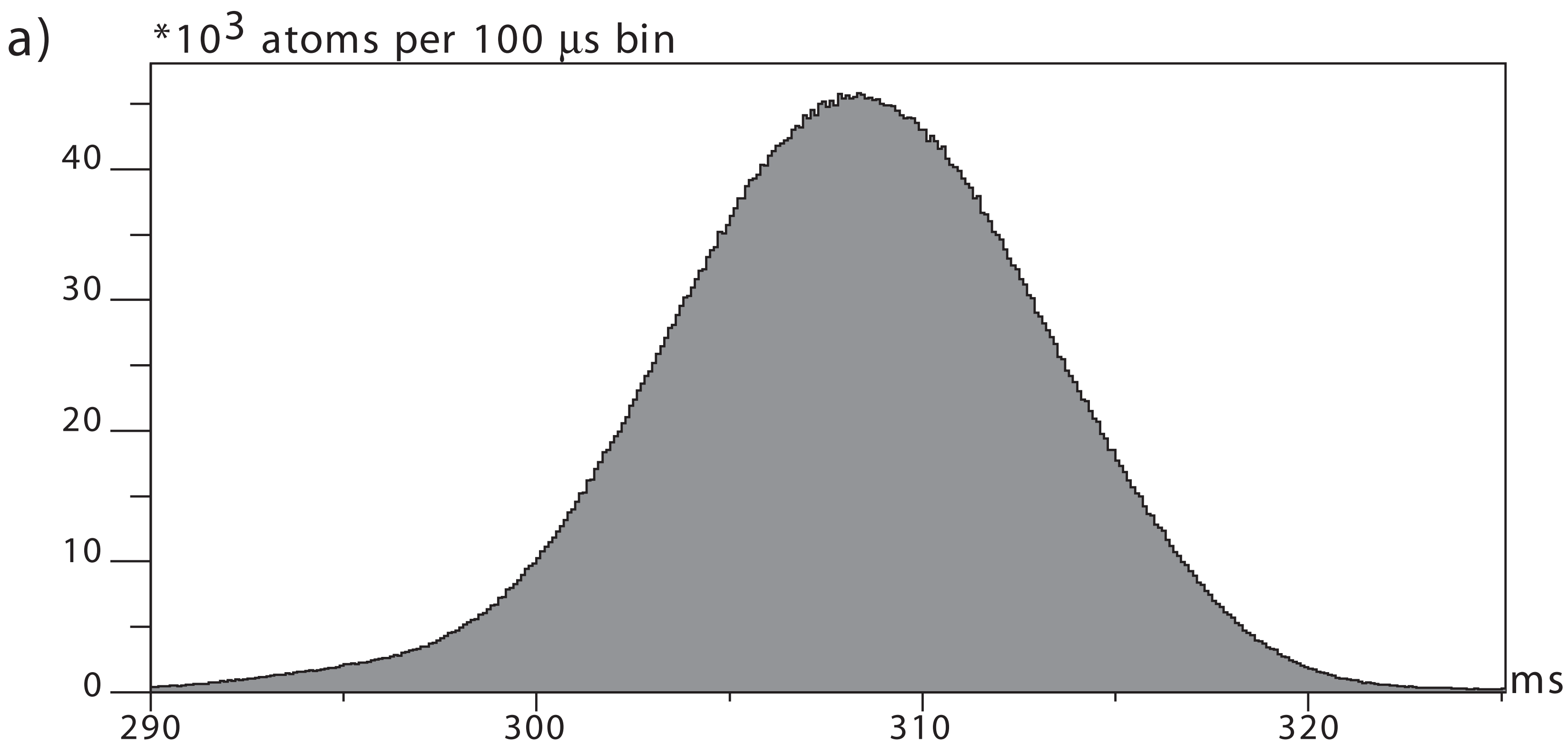


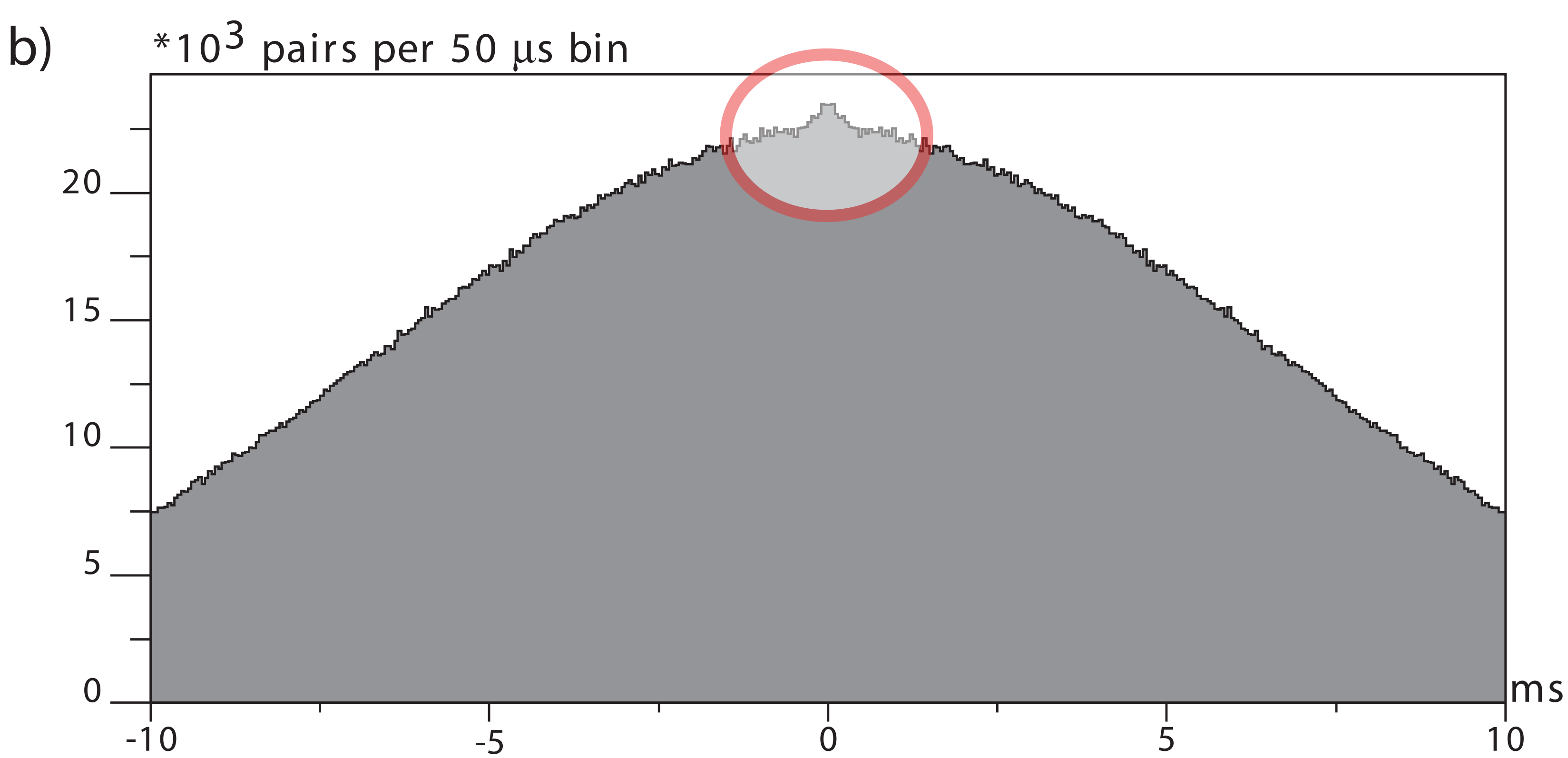
Photo



Atoms dropped onto detector

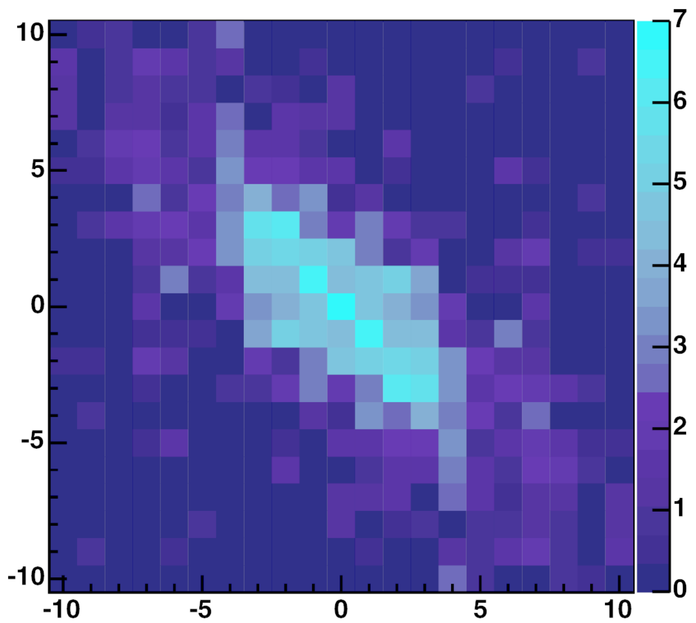


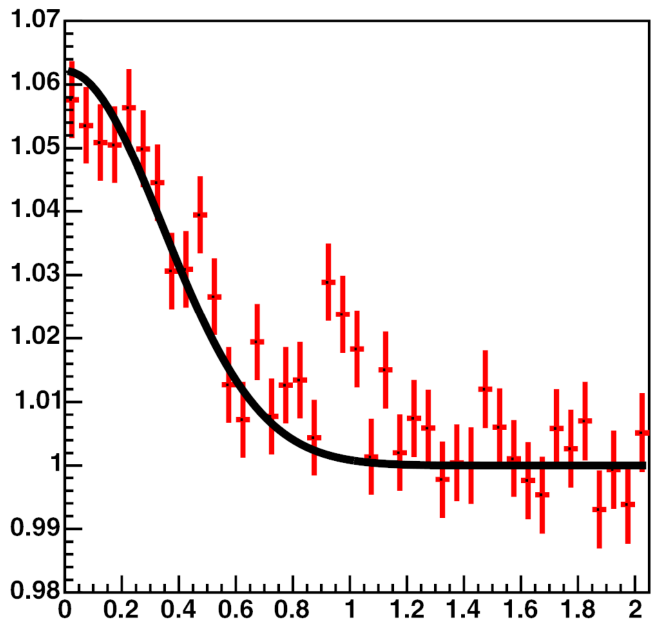
$n(p_z)$
arrival time distribution integrated over detector, summed ~1000 times



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

Normalized correlation functions

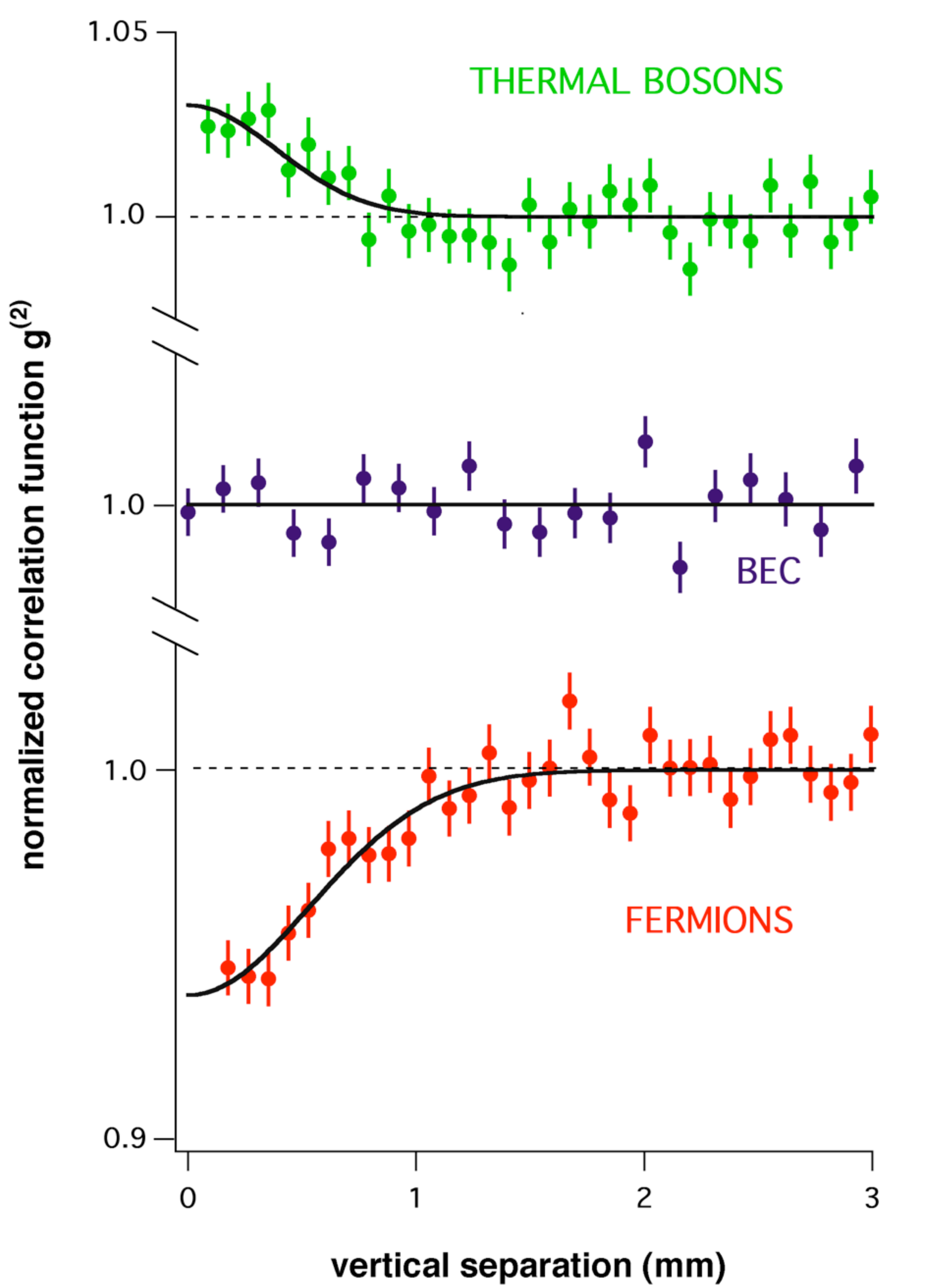




in detector plane

vertical

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



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)

Other matterwave HBT experiments

- optical lattices
- cold atom collisions
- heavy ion collisions
- free electrons
- electrons in metals
- ...

Higher order correlations

Dall et al., Nat. Phys. (2013)

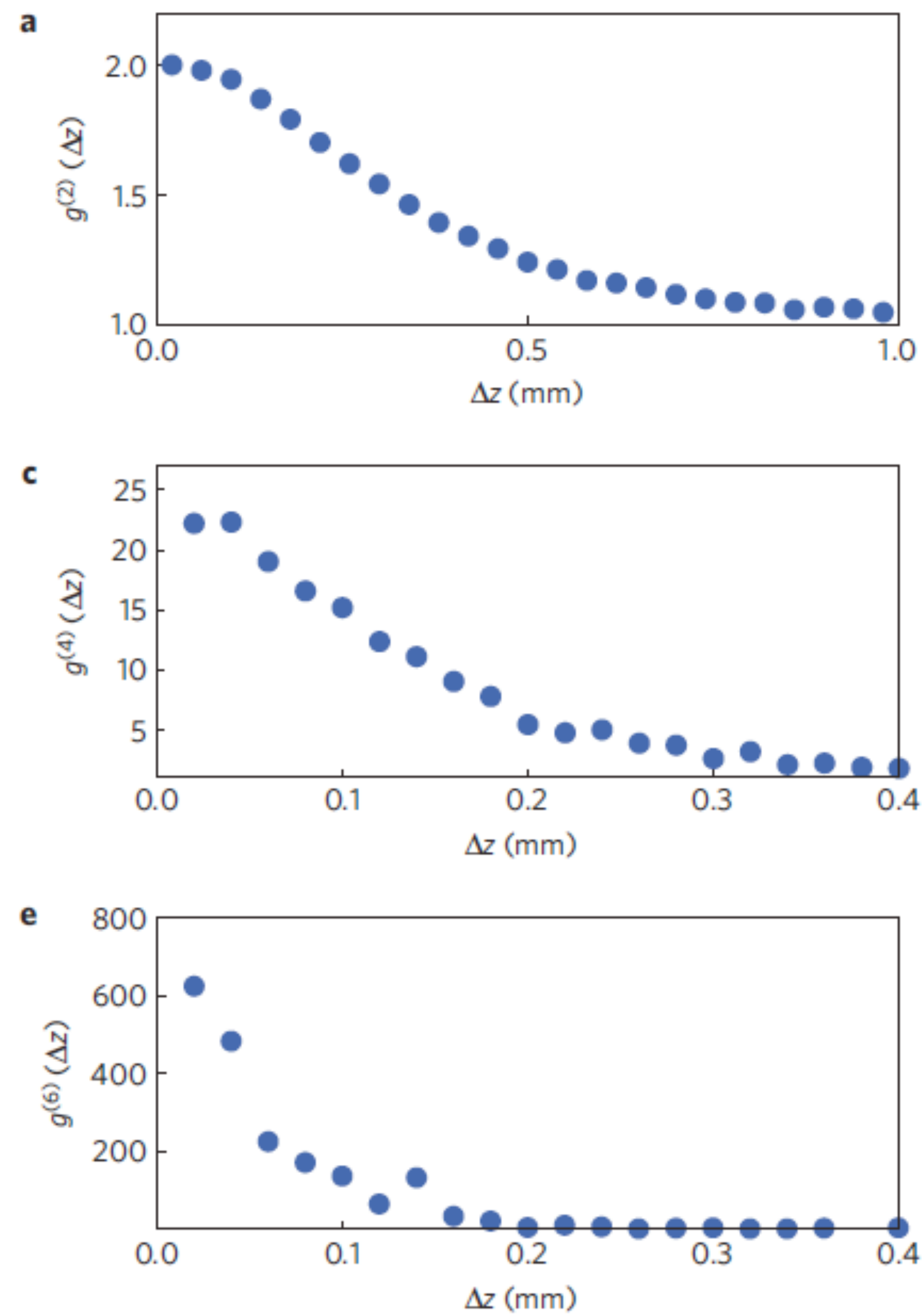
$A_n \sim n!$

$\sigma_n \sim \sigma_1 / \sqrt{n}$ (?)

$g^{(2)}$

$g^{(4)}$

$g^{(6)}$

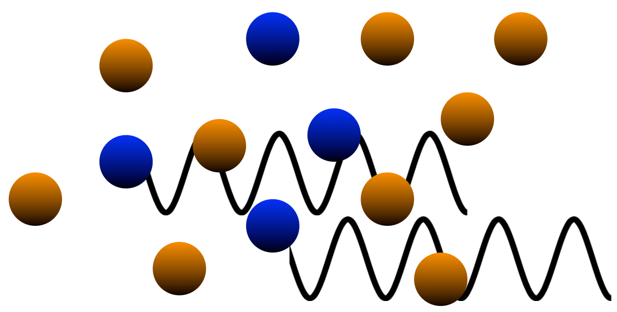


More complex: collective emission

Thermal radiation shows a HBT effect.
"Coherent" radiation does not.
What about superradiance?

What *is* superradiance? Inouye et al. Science 285, 571 (1999)

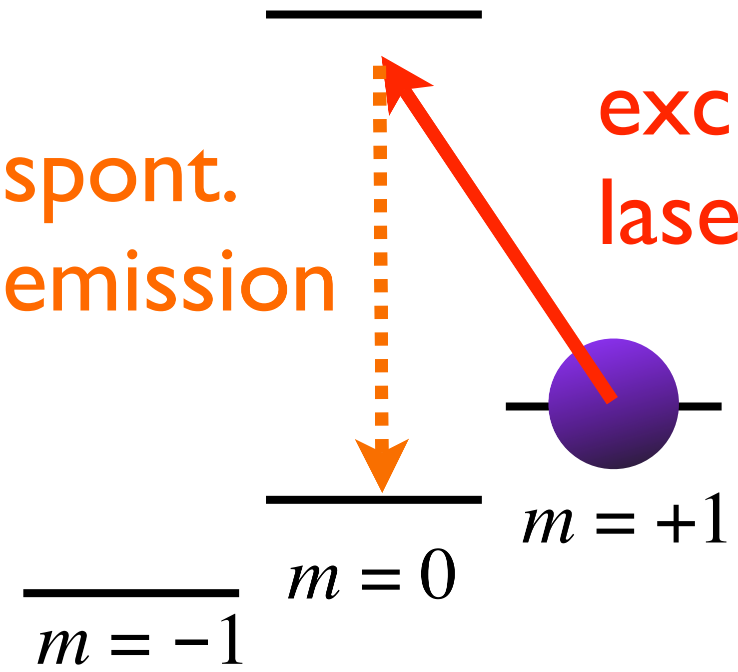
- Sufficient optical thickness that one spontaneous photon stimulates additional deexcitations, *i.e.* gain
- → Strong enhancement of emission rate



- excited atom
- ground state atom

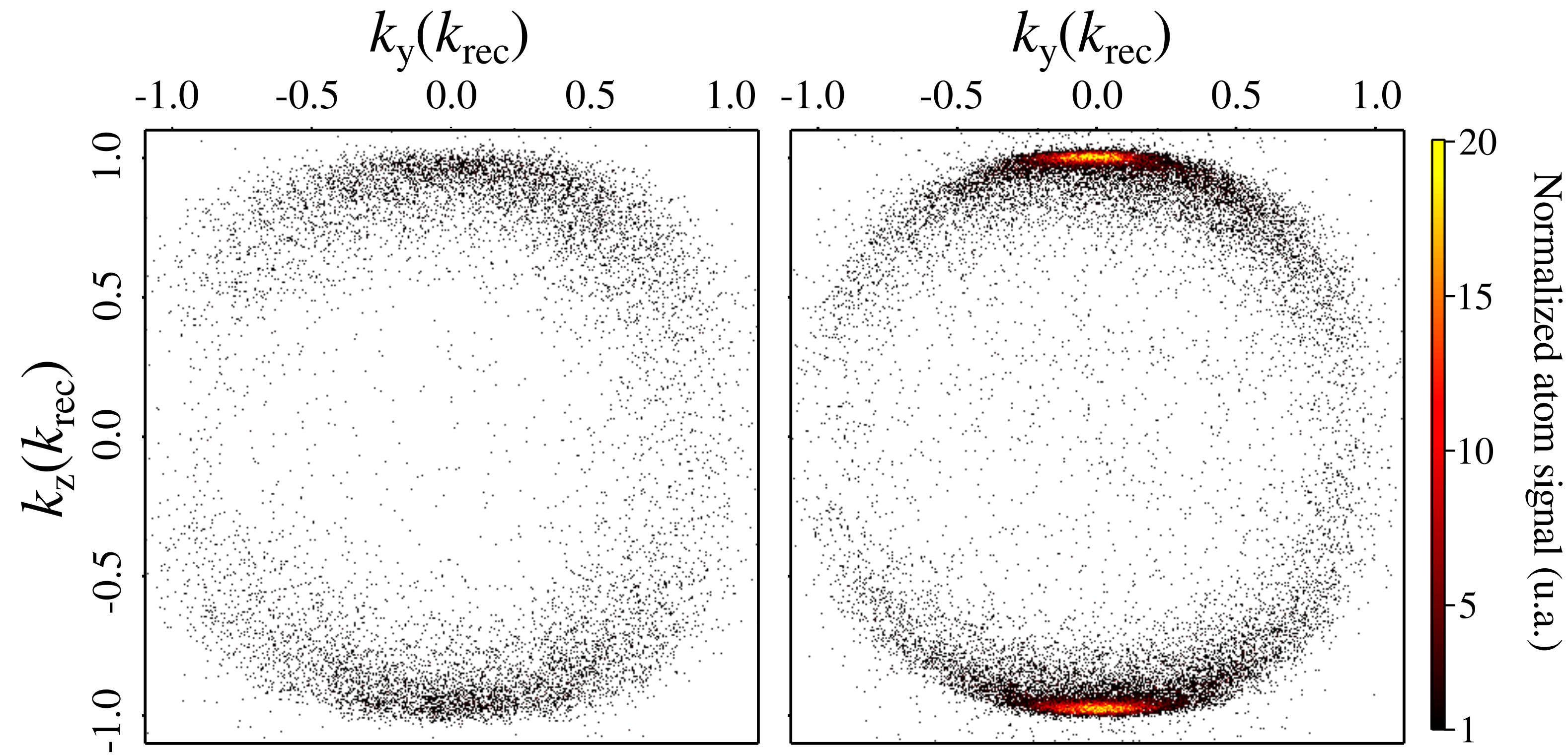
A "mirrorless laser"
amplified spontaneous emission, superfluorescence, ...
Thought to exist in astrophysical settings

Experiment



^4He: 2^3S_1 state

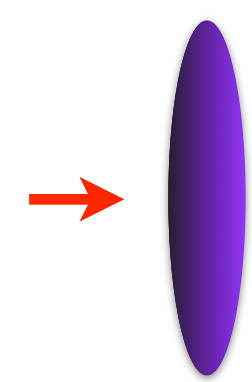
angular distribution of atom recoils



low density
$\sin^2 \theta$

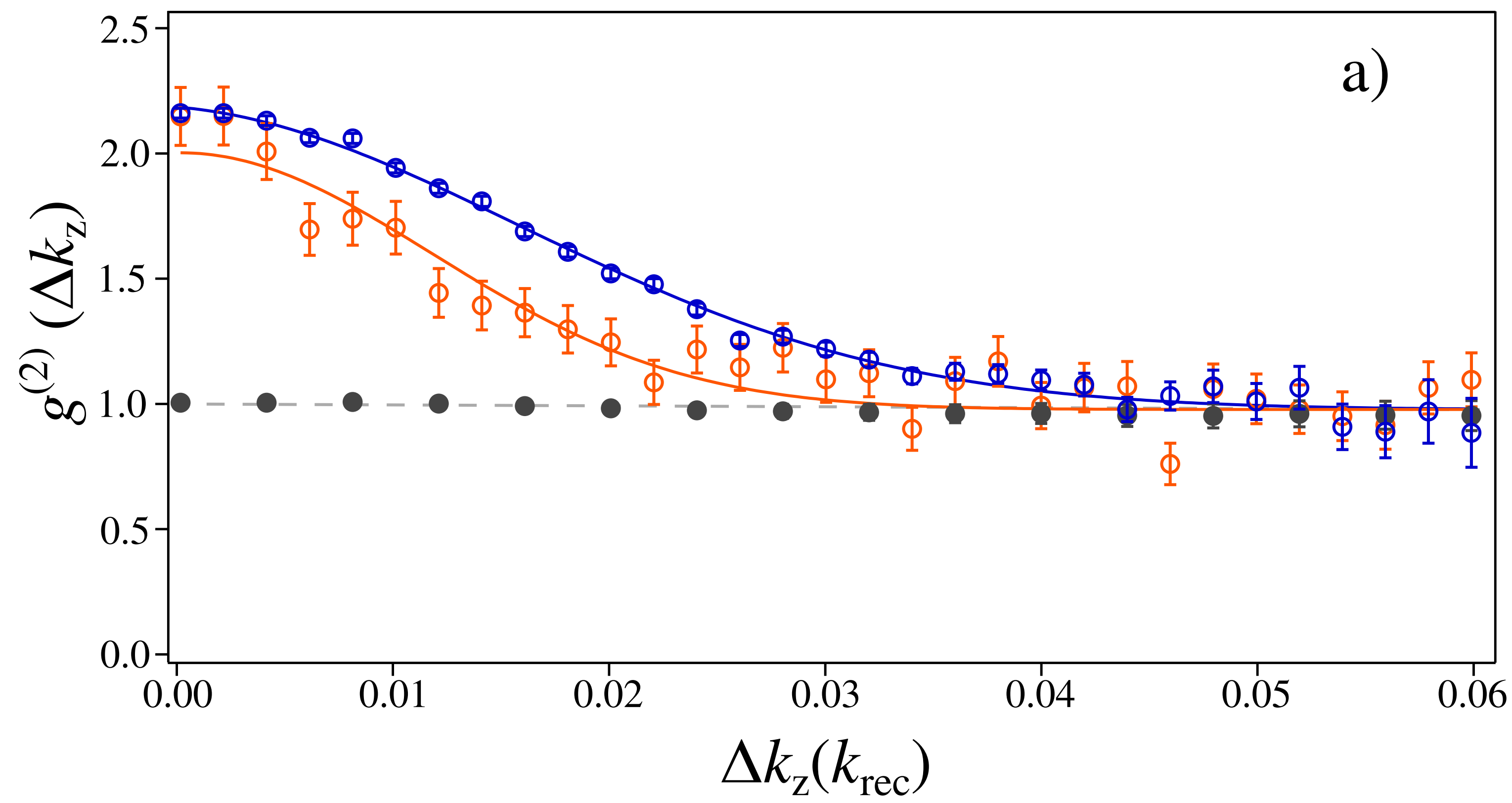
high density
10 × more
emission on top
and bottom

- observe recoiling atom (only in $m = 0$)
- anisotropic sample with variable optical density



Correlation functions, $g^{(2)}$

- blue: superradiant peak
- orange: all but the superradiant peak
- black: coherent seed beam

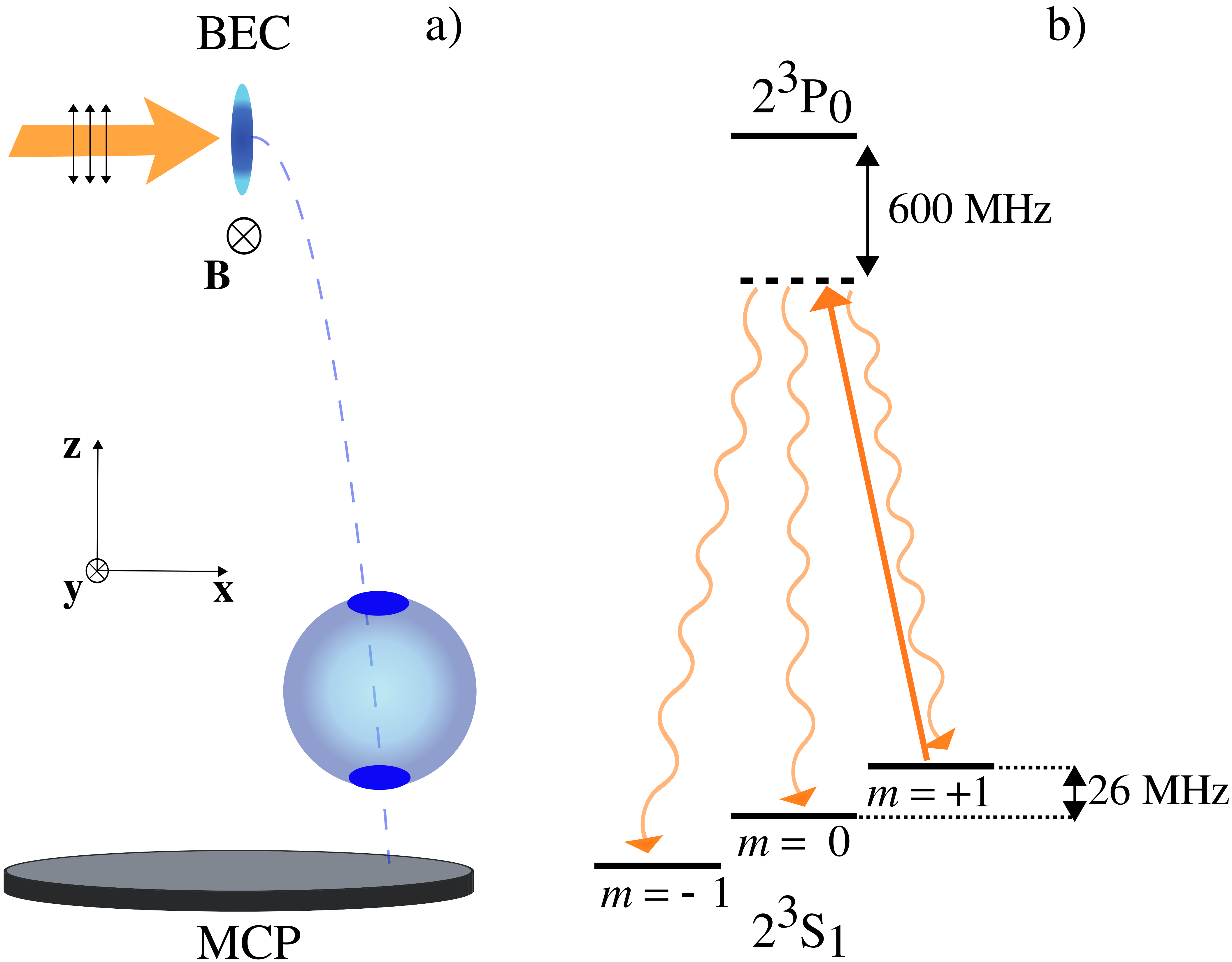


Superradiance appears to be thermal. What about other mirrorless emission phenomena such as random lasers?

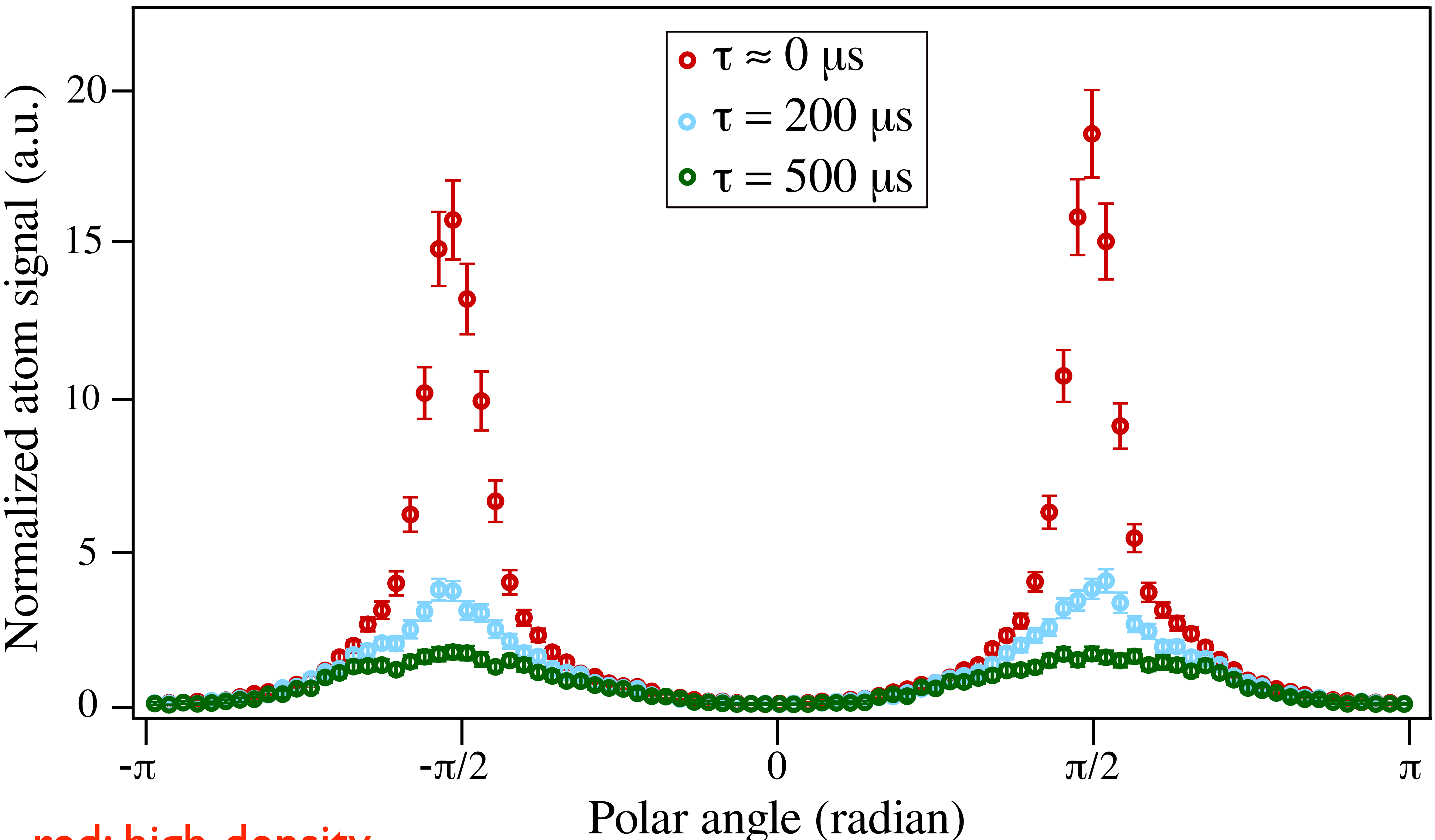
Lopes et al., arXiv:1312.6772 and poster

Thanks

Superradiance: setup



Superradiance: angular distribution



red: high density
blue: intermediate density
green: low density

Coherence length

In the trap:
(anisotropic in *p*)

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

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

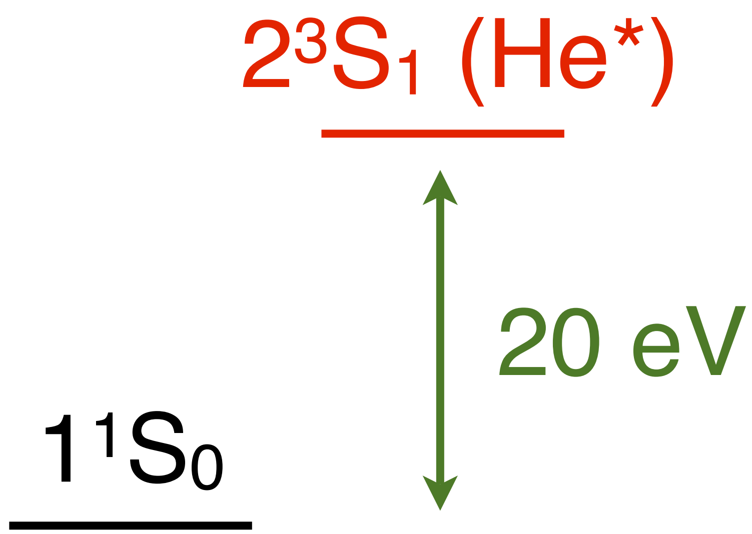
After expansion, measured positions correspond to momenta. After a time of flight *t*:

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

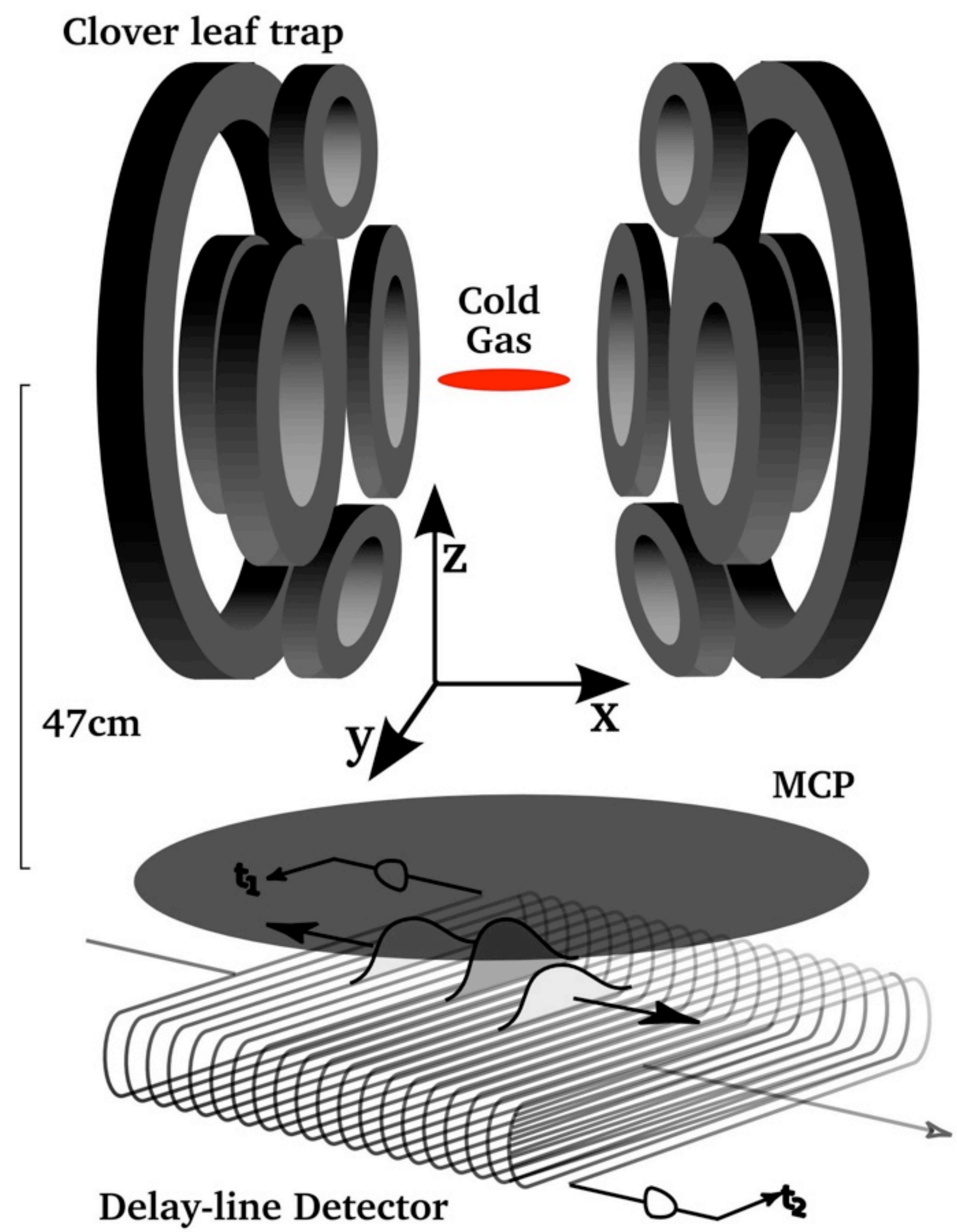
Analogy with optical speckle:

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

Metastable helium and 3D detection



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



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