Effet Hanbury Brown and Twiss, effet Hong-Ou-Mandel: des photons aux atomes

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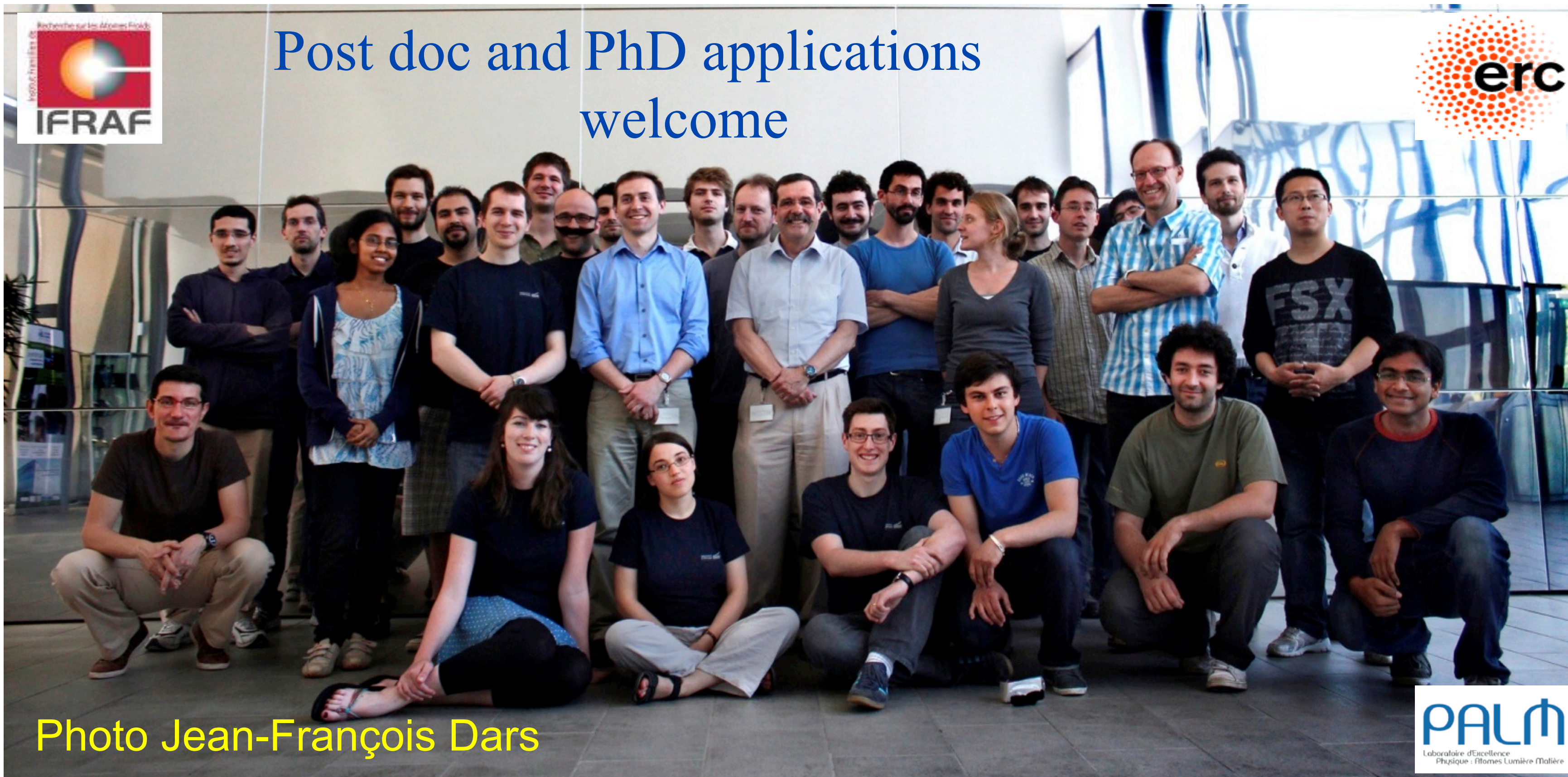
Groupe d'Optique Atomique du

Laboratoire Charles Fabry de l'Institut d'Optique



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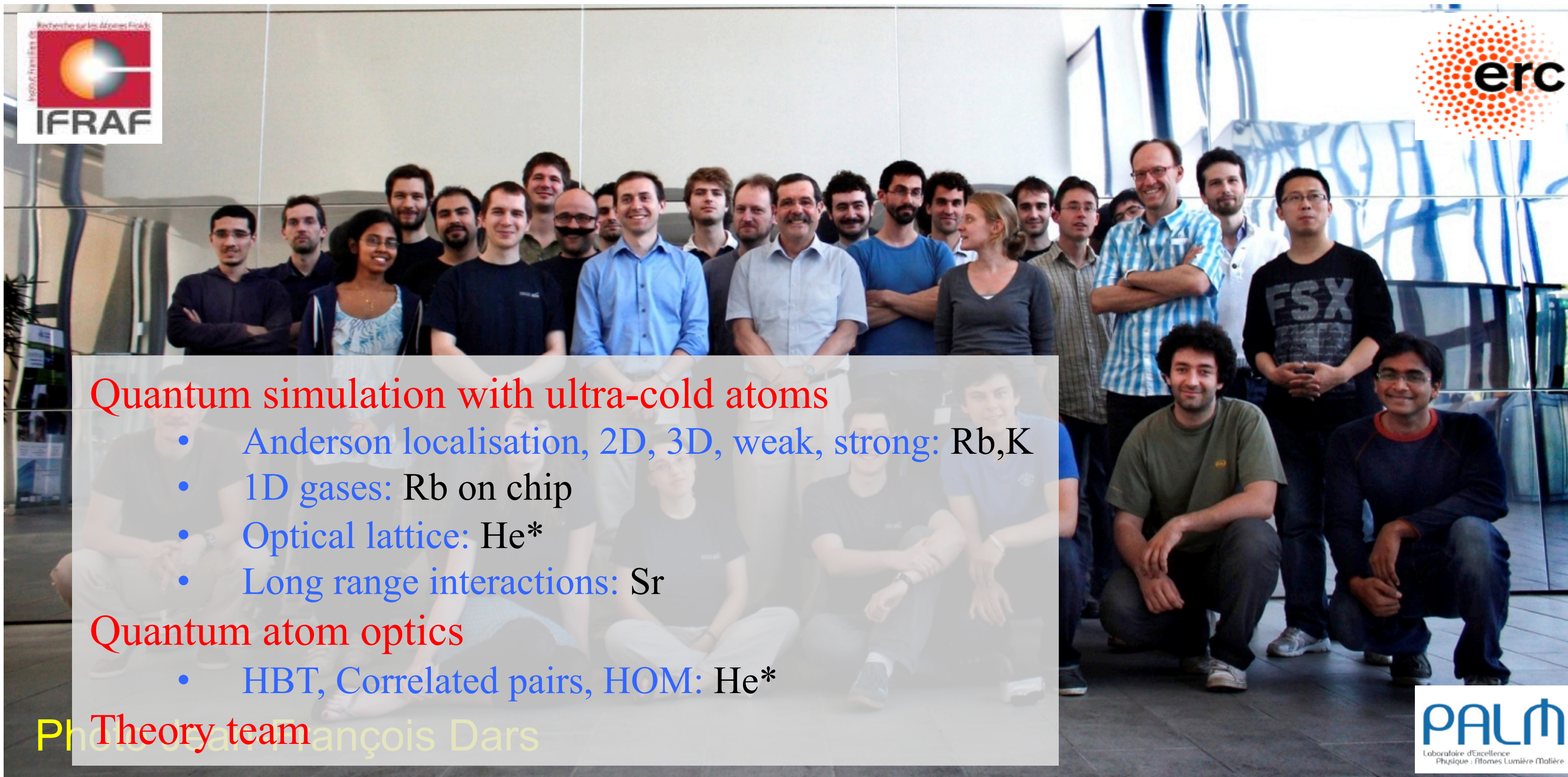


Quantum simulation with ultra-cold atoms

- Anderson localisation, 2D, 3D, weak, strong: Rb,K
- 1D gases: Rb on chip
- Optical lattice: He*
- Long range interactions: Sr

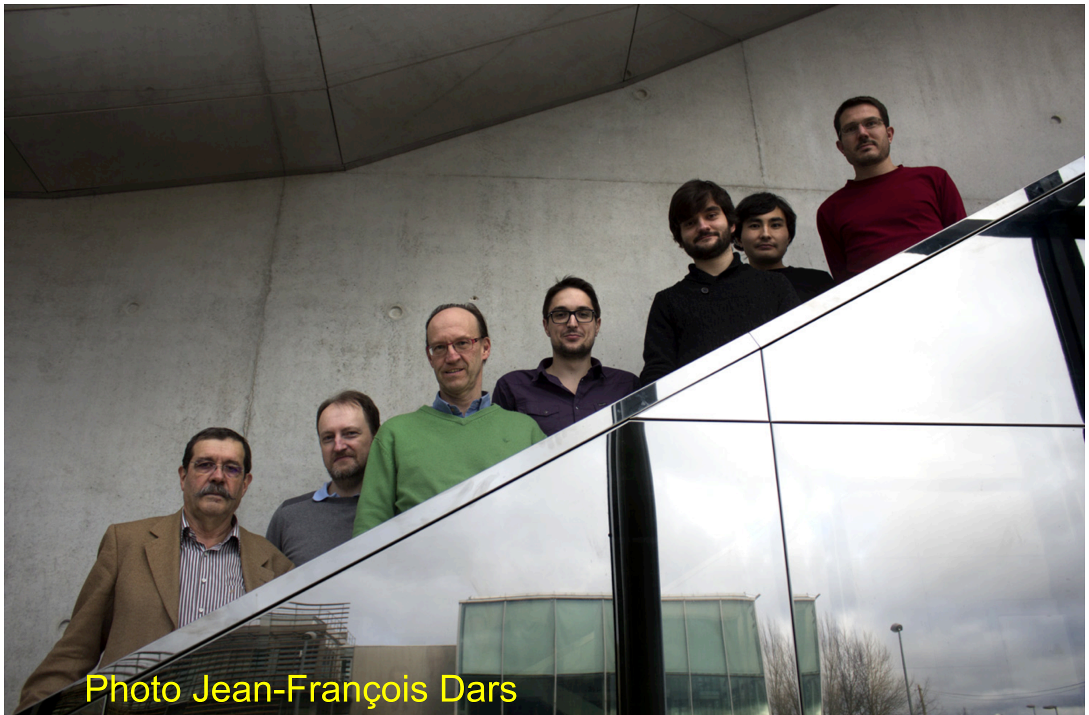
Quantum atom optics

- HBT, Correlated pairs, HOM: He*

Theory team

Photo Jean-François Dars

The He* Team



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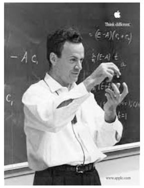
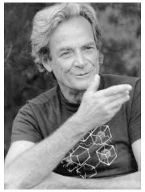
The HBT and HOM effects: from photons to atoms

1. Two “quantum mysteries”
2. The HBT effect with photons
3. Quantum Atom Optics with He*: HBT
4. The HOM effect with photons
5. HOM effect with atoms
6. Outlook





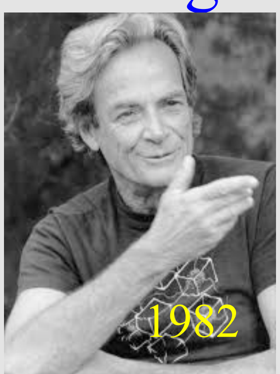
Two great "quantum mysteries"

Wave-particle duality: single particle interference

- A particle (an electron) also behaves as a wave
- A wave (light) can also behave as a particle (single photon effects)

Classical concepts, in ordinary space-time

Entanglement: interference between two-particles amplitudes



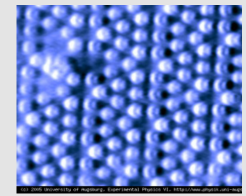
- Photon description of Hanbury Brown-Twiss effect
- Hong-Ou-Mandel effect
- Bell's inequalities violation

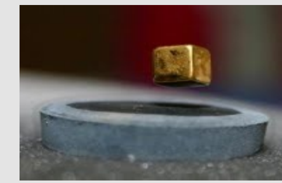
Interference in Hilbert space. No classical model in ordinary space-time

The first quantum revolution?

A revolutionary concept: Wave particle duality

- Understanding the structure of matter, its properties, its interaction with light
  - Electrical, mechanical properties

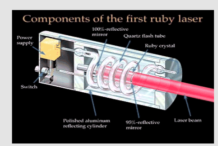


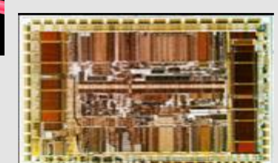


- Understanding "exotic properties"
  - Superfluidity, supraconductivity, Bose Einstein Condensate

Revolutionary applications

- Inventing new devices
  - Laser, transistor, integrated circuits
- Information and communication society





As revolutionary as the invention of heat engine (change society)

Not only conceptual, also technological

The second quantum revolution

Two concepts at the root of a new quantum revolution

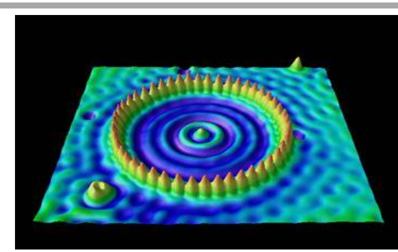
Entanglement

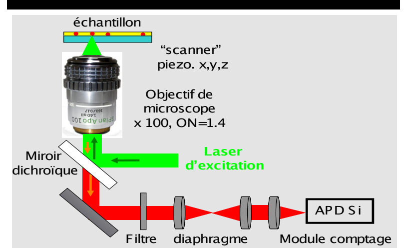
- A revolutionary concept, as guessed by Einstein and Bohr, strikingly demonstrated by Bell, put to use by Feynman et al.
- Drastically different from concepts underlying the first quantum revolution (wave particle duality).

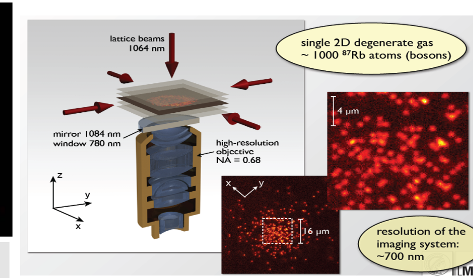
Individual quantum objects

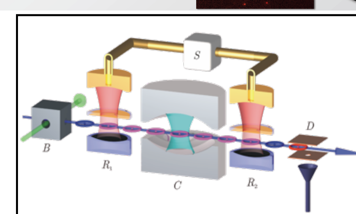
- experimental control
- theoretical description (quantum Monte-Carlo)

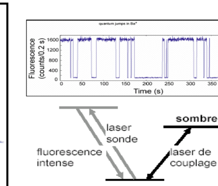
Examples: electrons, atoms, ions, single photons, photons pairs











The HBT and HOM effects: from photons to atoms

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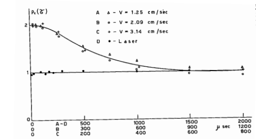

Fig. 1. Conditional probability $p_C(\tau)$ of a second count occurring at a time τ after a first has occurred at time $\tau = 0$.

HB&T: correlations in light intensity

Measurement of the correlation function of the photocurrents at two different points and times

$$g^{(2)}(\mathrm{r}_1,\mathrm{r}_2;\tau)=\frac{\langle i(\mathrm{r}_1,t)\,i(\mathrm{r}_2,t+\tau)\rangle}{\langle i(\mathrm{r}_1,t)\rangle\langle i(\mathrm{r}_2,t)\rangle}$$

Semi-classical model of photodetection (classical em field, quantized detector):

Measurement of the correlation function of light intensity:

$$i(\mathrm{r},t)\ \propto\ I(\mathrm{r},t)=\left|\mathrm{E}(\mathrm{r},t)\right|^2$$

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CORRELATION BETWEEN PHOTONS IN TWO COHERENT BEAMS OF LIGHT

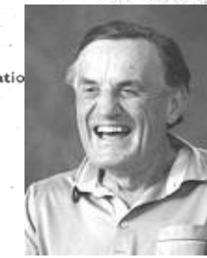
By R. HANBURY BROWN

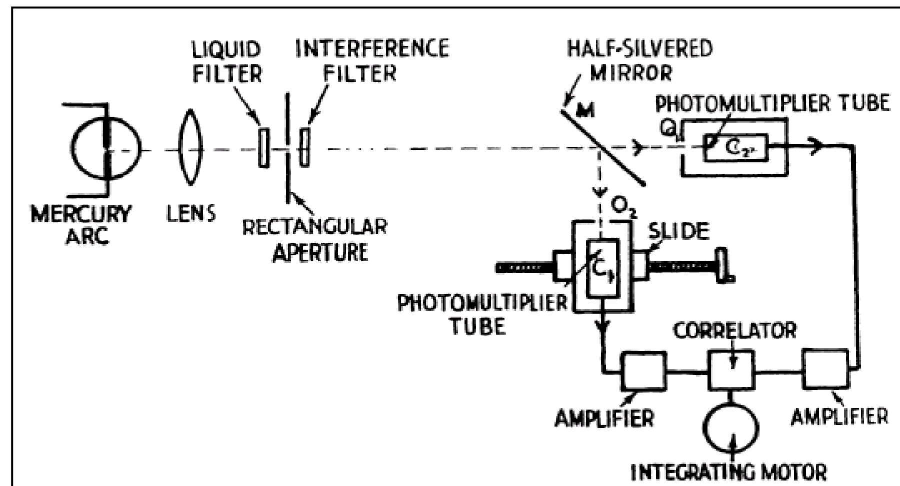
University of Manchester, Jodrell Bank Experimental Statio

AND

R. Q. TWISS

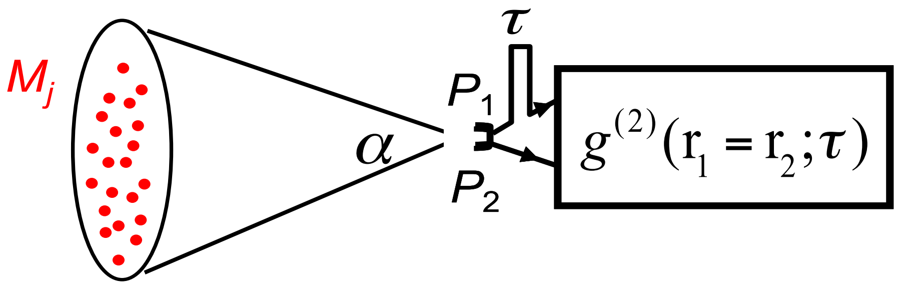
Services Electronics Research Laboratory, Baldock

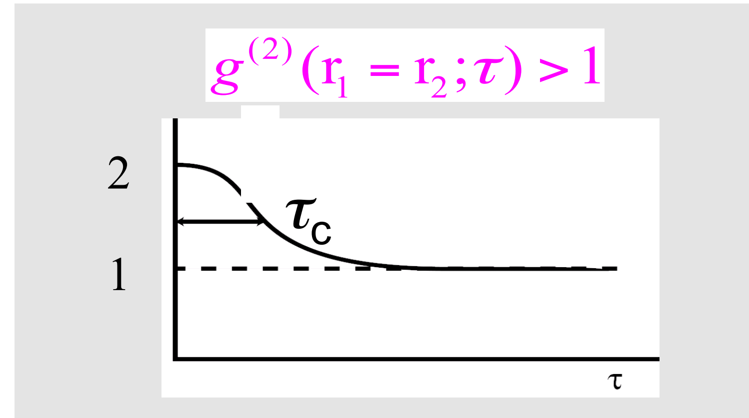




HB&T: correlations in light intensity

Light from incoherent source: time and space correlations



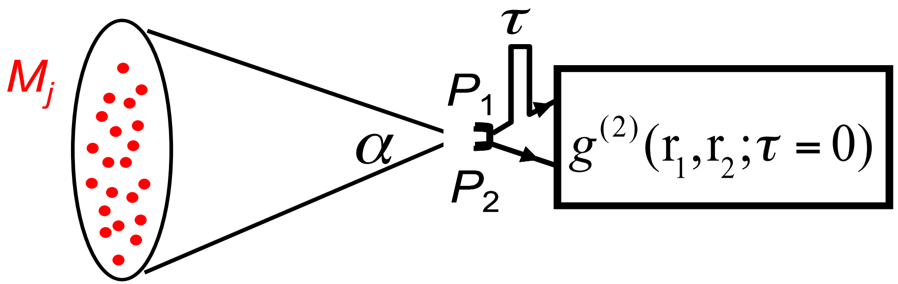


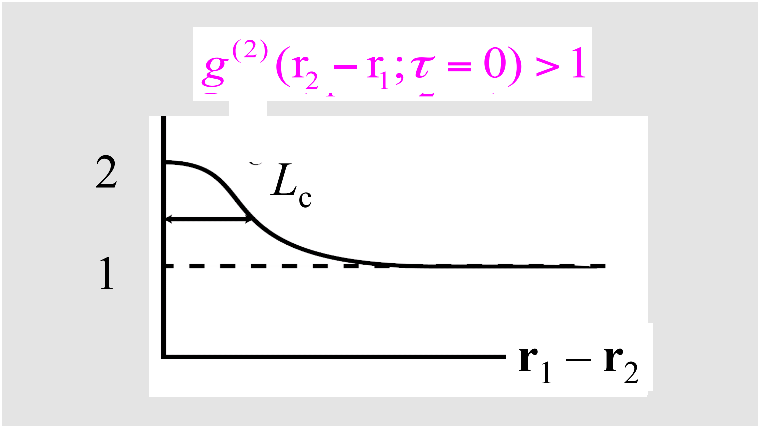
- time coherence

$$\tau_c \approx 1/\Delta\omega$$

HB&T: correlations in light intensity

Light from incoherent source: time and space correlations





$$g^{(2)}(r_1 = r_2; \tau = 0) = 2$$

$$g^{(2)}(r_1 - r_2 \gg L_c; \tau \gg \tau_c) = 1$$

A measurement of $g^{(2)} - 1$ *vs.* τ and $\mathbf{r}_1 - \mathbf{r}_2$ yields the coherence volume

- time coherence

$$\tau_c \approx 1/\Delta\omega$$

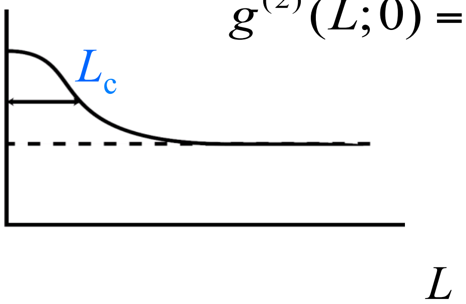
- space coherence

$$L_c \approx \lambda/\alpha$$

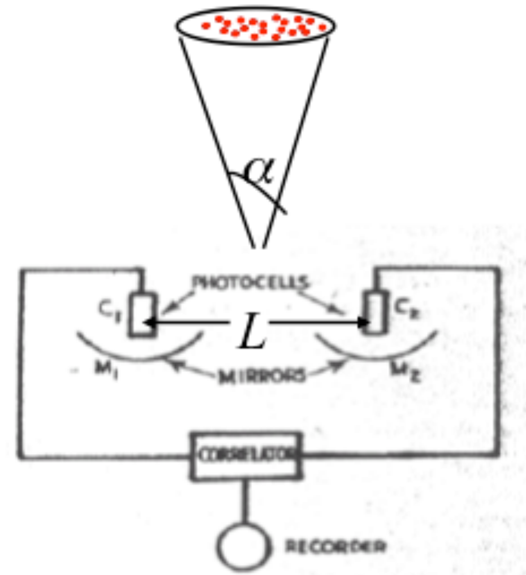
The HB&T stellar interferometer: astronomy tool

Measure of the coherence area $\Rightarrow$ angular diameter of a star

$$g^{(2)}(L;0)=\frac{\langle i(\mathrm{r}_1,t)\,i(\mathrm{r}_1+L,t+\tau)\rangle}{\langle i(\mathrm{r}_1,t)\rangle\langle i(\mathrm{r}_2,t)\rangle}\;\Rightarrow L_C$$



$$\boxed{\alpha=\frac{\lambda}{L_C}}$$



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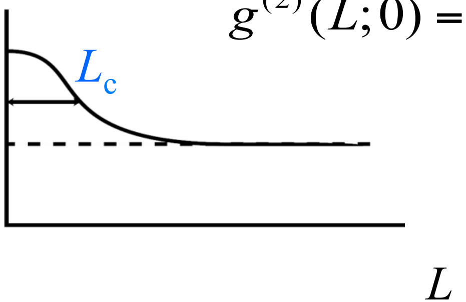
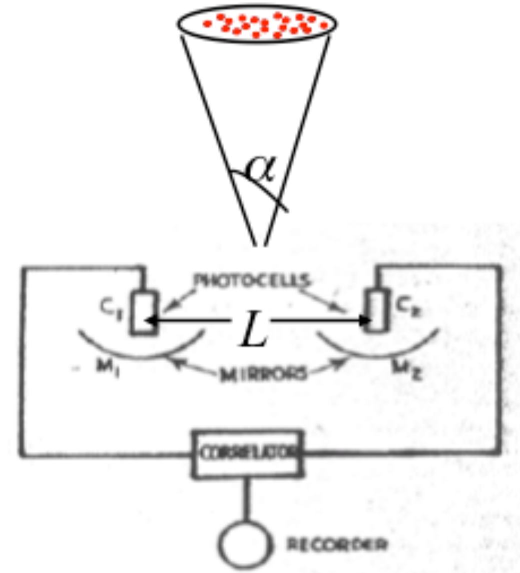


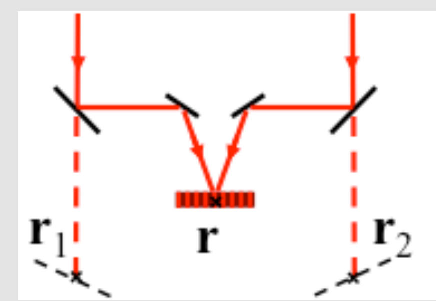
$$\Rightarrow \quad \boxed{\alpha = \frac{\lambda}{L_C}}$$



Equivalent to the Michelson stellar interferometer ?

Visibility of fringes

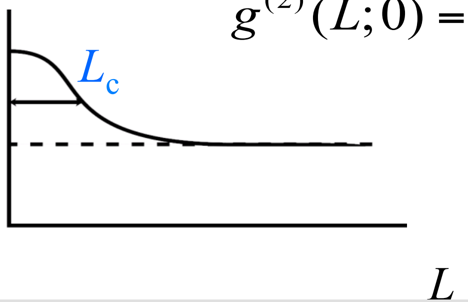
$$g^{(1)}(\mathrm{r}_1,\mathrm{r}_2;\tau) = \frac{\langle \mathrm{E}(\mathrm{r}_1,t)\,\mathrm{E}(\mathrm{r}_2,t+\tau)\rangle}{\langle |\mathrm{E}(\mathrm{r}_1,t)|^2\rangle^{1/2}\langle |\mathrm{E}(\mathrm{r}_2,t+\tau)|^2\rangle^{1/2}}$$



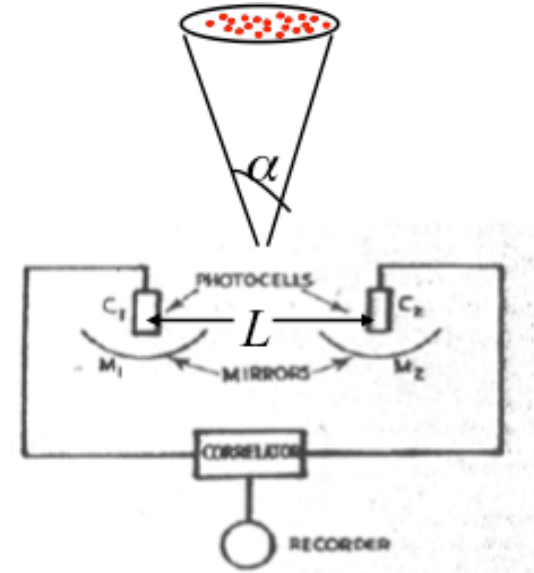
The HB&T stellar interferometer: astronomy tool

Measure of the coherence area $\Rightarrow$ angular diameter of a star

$$g^{(2)}(L;0)=\frac{\langle i(\mathrm{r}_1,t)\,i(\mathrm{r}_1+L,t+\tau)\rangle}{\langle i(\mathrm{r}_1,t)\rangle\langle i(\mathrm{r}_2,t)\rangle}\quad\Rightarrow L_\mathrm{C}$$



$$\boxed{\alpha=\frac{\lambda}{L_\mathrm{C}}}$$



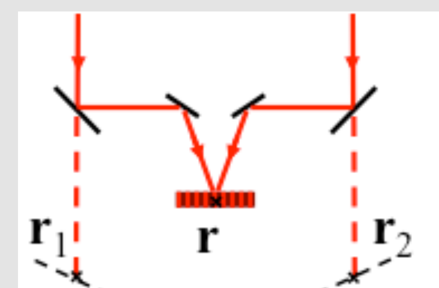
Not the same correlation function: $g^{(2)}$ vs $g^{(1)}$

HB&T insensitive to atmospheric fluctuations!

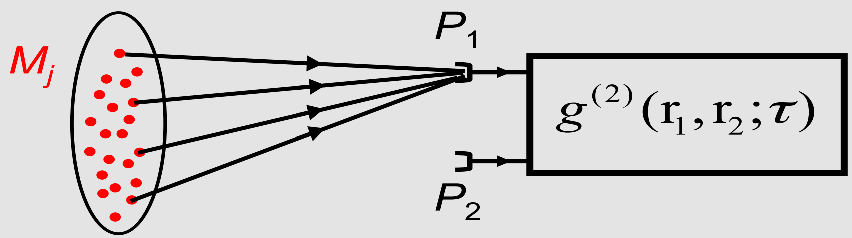
Equivalent to the Michelson stellar interferometer ?

Visibility of fringes

$$g^{(1)}(\mathrm{r}_1,\mathrm{r}_2;\tau)=\frac{\langle \mathrm{E}(\mathrm{r}_1,t)\,\mathrm{E}(\mathrm{r}_2,t+\tau)\rangle}{\langle|\mathrm{E}(\mathrm{r}_1,t)|^2\rangle^{1/2}\langle|\mathrm{E}(\mathrm{r}_2,t+\tau)|^2\rangle^{1/2}}$$



HBT and Michelson stellar interferometers yield the same quantity



Many independent random emitters:
complex electric field = sum of many independent random variables

$$E(P,t) = \sum_j a_j \exp\left\{\phi_j + \frac{\omega_j}{c} M_j P - \omega_j t\right\}$$

Central limit theorem
$\Rightarrow$ Gaussian random process

$$\Longrightarrow \quad g^{(2)}(r_1, r_2; \tau) = 1 + \left|g^{(1)}(r_1, r_2; \tau)\right|^2$$

$$g^{(1)}(r_1, r_2; \tau) = \frac{\left\langle E^*(r_1, t) E(r_2, t+\tau)\right\rangle}{\left\langle \left|E(r_1, t)\right|^2 \right\rangle^{1/2} \left\langle \left|E(r_2, t+t)\right|^2 \right\rangle^{1/2}}$$

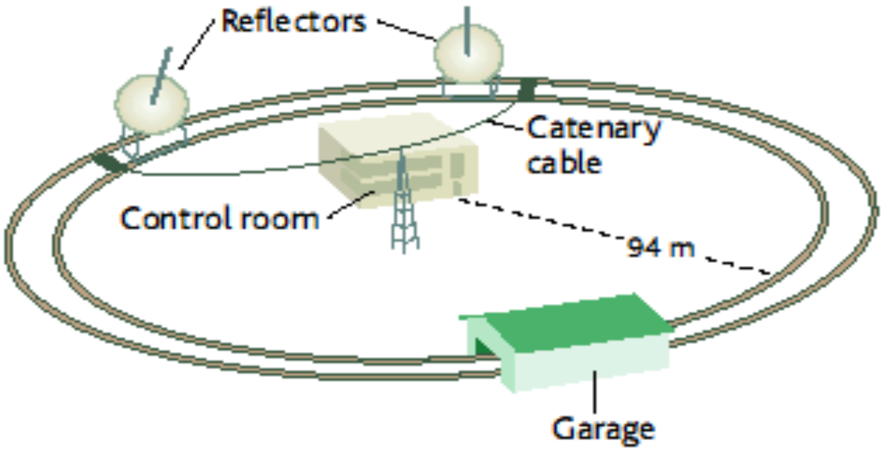
Michelson Stellar Interferometer

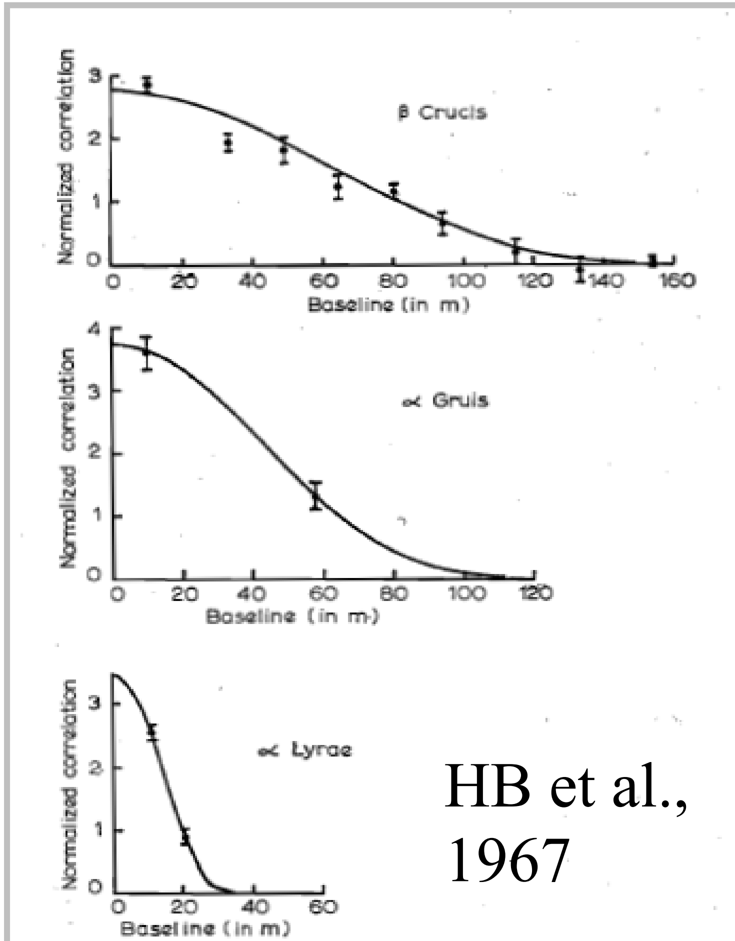
Same width:
$\Rightarrow$ star size

$$g^{(2)}(r_1, r_2; \tau) = \frac{\left\langle i(r_1, t)\, i(r_2, t+\tau)\right\rangle}{\left\langle i(r_1, t)\right\rangle \left\langle i(r_2, t)\right\rangle} = \frac{\left\langle E^*(r_1, t) E(r_1, t) E^*(r_2, t+\tau) E(r_2, t+\tau)\right\rangle}{\left\langle \left|E(r_1, t)\right|^2 \right\rangle \left\langle \left|E(r_2, t+\tau)\right|^2 \right\rangle}$$

HBT Stellar Interferometer

The HB&T stellar interferometer: it works!





The installation at Narrabri (Australia): it works!

HB et al., 1967

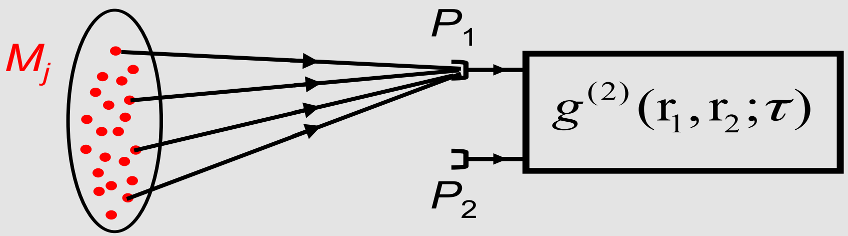
HBT intensity correlations: classical or quantum?

HBT correlations were predicted, observed, and used to measure star angular diameters, 50 years ago. Why bother?

The question of their interpretation provoked a debate that prompted the emergence of modern quantum optics!

Classical or quantum?

Classical wave explanation for HB&T correlations (1): Gaussian intensity fluctuations in incoherent light



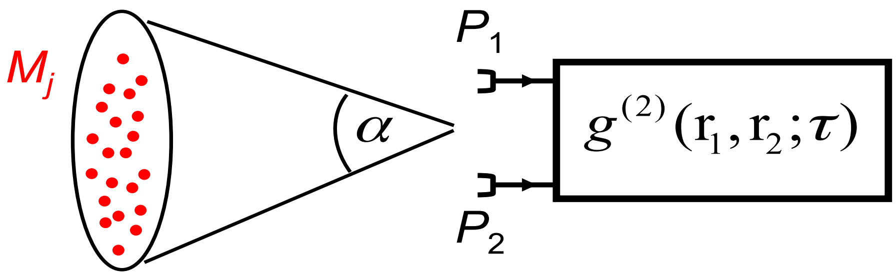
Many independent random emitters: complex electric field fluctuates

$$\left\langle I(t)^2 \right\rangle \geq \left\langle I(t) \right\rangle^2 \Leftrightarrow g^{(2)}(\mathbf{r}_1, \mathbf{r}_1; 0) \geq 1$$

Gaussian random process $\Rightarrow$ $g^{(2)}(\mathrm{r}_1, \mathrm{r}_2; \tau) = 1 + \left| g^{(1)}(\mathrm{r}_1, \mathrm{r}_2; \tau) \right|^2$

For an incoherent source, intensity fluctuations (second order coherence function) are related to first order coherence function

Classical wave explanation for HB&T correlations (2): optical speckle in light from an incoherent source



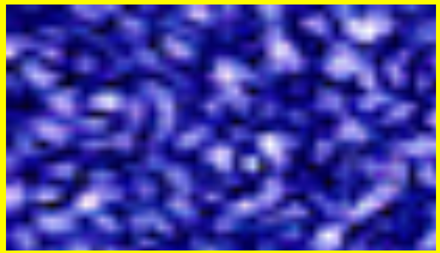
Many independent random emitters: complex electric field = sum of many independent random variables

$$\mathrm{E}(P,t) = \sum_j a_j \exp\left\{\phi_j + \frac{\omega_j}{c} M_j P - \omega_j t\right\}$$

Gaussian random process $\Rightarrow$ $g^{(2)}(\mathrm{r}_1, \mathrm{r}_2; \tau) = 1 + \left|g^{(1)}(\mathrm{r}_1, \mathrm{r}_2; \tau)\right|^2$

Intensity pattern (speckle) in the observation plane:

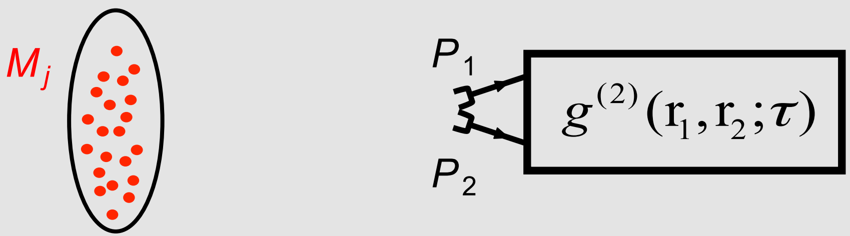
- Correlation radius $L_c \approx \lambda / \alpha$
- Changes after $\tau_c \approx 1 / \Delta\omega$



The HB&T effect with photons: a hot debate

Strong negative reactions to the HB&T proposal (1955)

In term of photon counting



joint detection probability

$$g^{(2)}(\mathrm{r}_1, \mathrm{r}_2; \tau) = \frac{\langle \pi(\mathrm{r}_1, \mathrm{r}_2; t, t+\tau) \rangle}{\langle \pi(\mathrm{r}_1, t) \rangle \langle \pi(\mathrm{r}_2, t) \rangle}$$

single detection probabilities

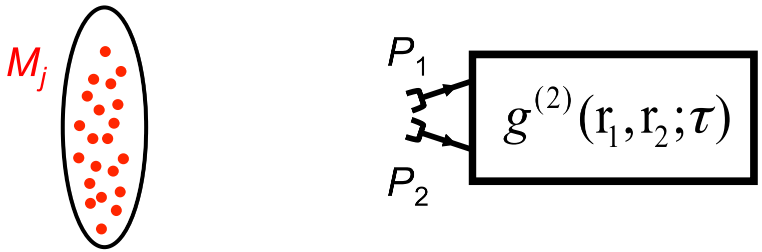
For independent detection events $g^{(2)} = 1$

$g^{(2)}(0) = 2 \quad \Rightarrow$ probability to find two photons at the same place larger than the product of simple probabilities: bunching

How might independent particles be bunched ?

The HB&T effect with photons: a hot debate

Strong negative reactions to the HB&T proposal (1955)



$g^{(2)}(0) > 1 \quad \Rightarrow$ photon bunching

How might photons emitted from distant points in an incoherent source not be statistically independent?

HB&T answers

- Experimental demonstration!

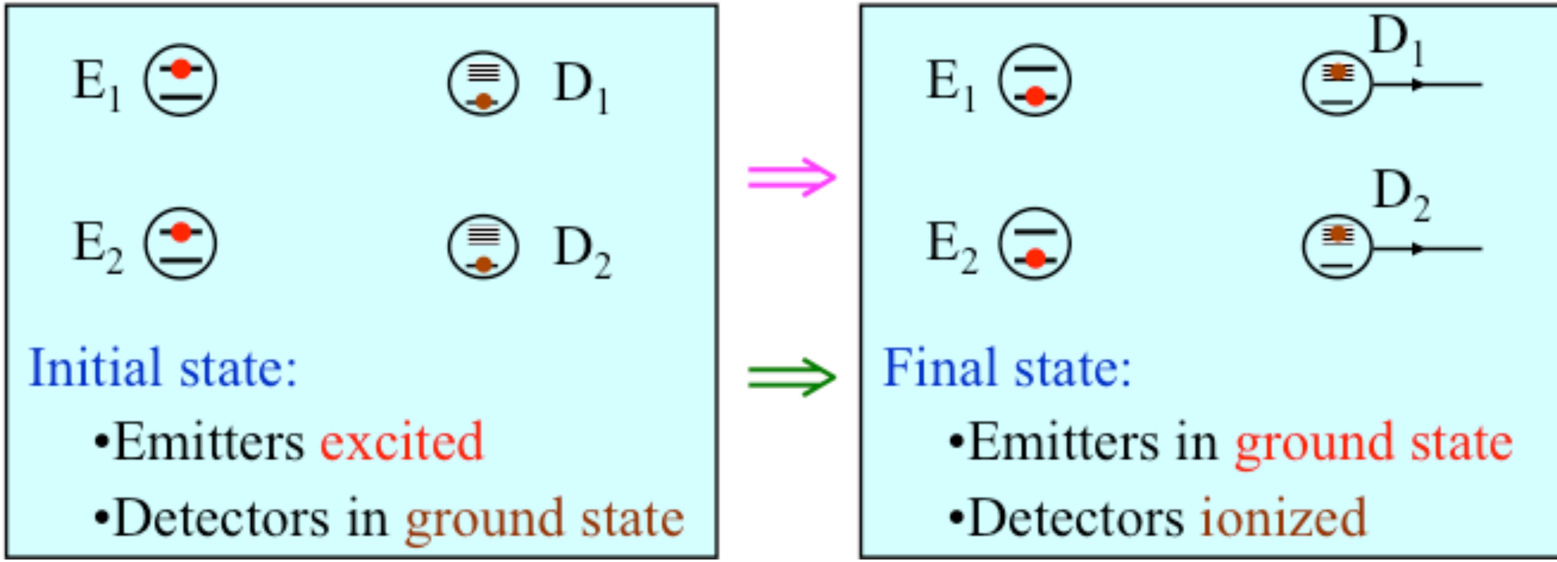
- Light is both wave and particles.

$$g^{(2)}(r_1, r_2; \tau) = 1 + \left| g^{(1)}(r_1, r_2; \tau) \right|^2$$

  - Uncorrelated detections easily understood as independent particles (shot noise)
  - Correlations (excess noise) due to beat notes of random waves

    cf. Einstein's discussion of wave particle duality in Salzburg (1909), about black body radiation fluctuations

The HB&T effect with photons: Fano-Glauber quantum interpretation



Two paths to go from THE initial state to THE final state

Amplitudes of the two process interfere $\Rightarrow$ $\pi(\mathrm{r}_1, \mathrm{r}_2, t) \neq \pi(\mathrm{r}_1, t) \cdot \pi(\mathrm{r}_2, t)$

Incoherent addition of many interferences: factor of 2 (Gaussian process)

The HB&T effect with particles: a non trivial quantum effect

Two paths to go from one initial state to one final state: quantum interference of two-photon amplitudes

Two photon interference effect: quantum weirdness “of the second kind”

- happens in configuration space, not in real space
- related to entanglement (violation of Bell inequalities), HOM, etc…

Lack of statistical independence (bunching) although no “real” interaction

cf. Bose-Einstein Condensation (letter from Einstein to Schrödinger, 1924)

Intensity correlations in laser light? yet more hot discussions!

1960: invention of the laser (Maiman, Ruby laser)

- 1961: Mandel & Wolf: HB&T bunching effect should be easy to observe with a laser: many photons per mode
- 1963: Glauber: laser light should NOT be bunched: $\rightarrow$ quantum theory of coherence
- 1965: Armstrong: experiment with single mode AsGa laser: no bunching well above threshold; bunching below threshold
- 1966: Arecchi: similar with He Ne laser: plot of $g^{(2)}(\tau)$

Intensity correlations in laser light? yet more hot discussions!

1960: invention laser)

•1961: Mandel ect should be easy to observe with ode

•1963: Glauber bunched:

→ quantum the

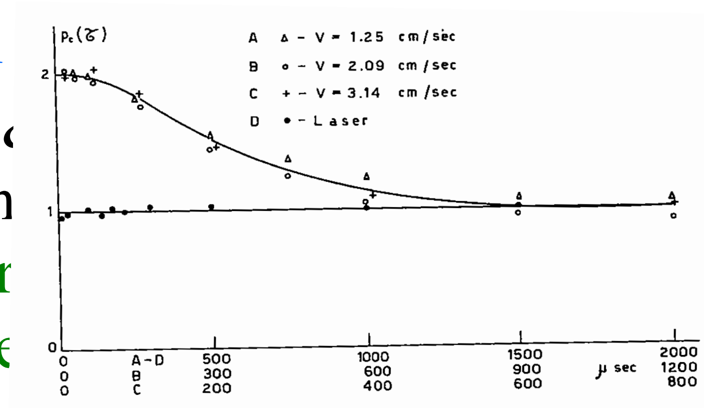


Fig. 1. Conditional probability $p_C(\tau)$ of a second count occurring at a time τ after a first has occurred at time $\tau = 0$.

•1965: Armstr mode AsGa laser: no bunching well above threshold; bunching below threshold

•1966: Arecchi: similar with He Ne laser: plot of $g^{(2)}(\tau)$

Simple classical model for laser light:
$$E = E_0 \exp\{-i\omega t + \phi_0\} + e_n \qquad |e_n| = |E_0|$$

Quantum description identical by use of Glauber-Sudarshan P representation (coherent states)

The Hanbury Brown and Twiss effect: a landmark in quantum optics

- Easy to understand if light is described as an electromagnetic wave
- Subtle quantum effect if light is described as made of photons

Intriguing quantum effect for particles*

Hanbury Brown and Twiss effect with atoms?

* See G. Baym, Acta Physica Polonica (1998) for HBT with high energy particles

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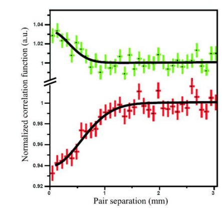
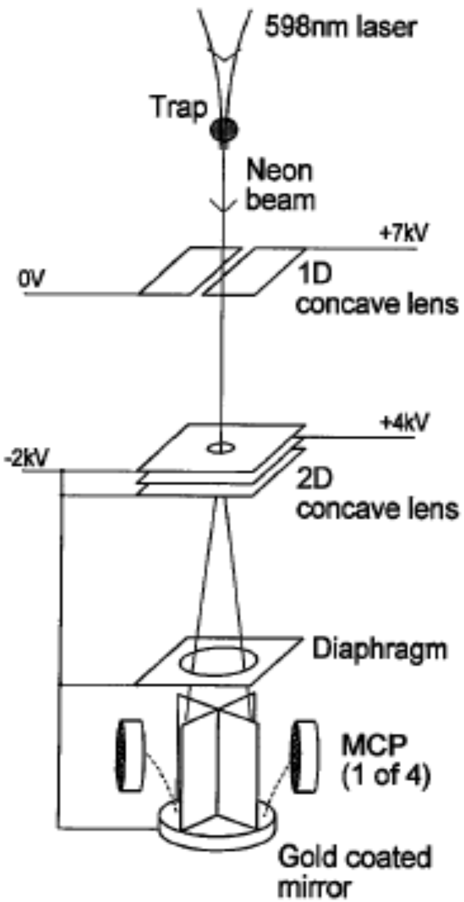


The HB&T effect with atoms: Yasuda and Shimizu, 1996

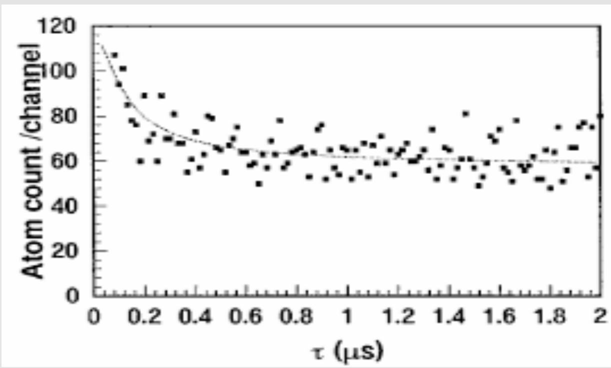


- Cold neon atoms in a MOT (100 μK) continuously pumped into an untrapped (falling) metastable state
  - ➢ Single atom detection (metastable atom)
  - ➢ Narrow source (<100μm): coherence volume as large as detector viewed through diverging lens: no reduction of the visibility of the bump

Effect clearly seen

•Bump disappears when detector size $\gg L_C$

•Coherence time as predicted: $h/\Delta E \approx 0.2\,\mu s$



Totally analogous to HB&T: continuous atomic beam

Atomic density correlation ("noise correlation"): a new tool to investigate quantum gases

3 atoms collision rate enhancement in a thermal gas, compared to a BEC

- Factor of 6 ($\langle n^3(\mathrm{r})\rangle = 3!\langle n(\mathrm{r})\rangle^3$) observed (JILA, 1997) as predicted by Kagan, Svistunov, Shlyapnikov, JETP lett (1985)

Interaction energy of a sample of cold atoms

- $\langle n^2(\mathrm{r})\rangle = 2\langle n(\mathrm{r})\rangle^2$ for a thermal gas (MIT, 1997)
- $\langle n^2(\mathrm{r})\rangle = \langle n(\mathrm{r})\rangle^2$ for a quasicondensate (Institut d'Optique, 2003)

Noise correlation in absorption images of a sample of cold atoms (as proposed by Altmann, Demler and Lukin, 2004)

- Correlations in a quasicondensate (Ertmer, Hannover 2003)
- Correlations in the atom density fluctuations of cold atomic samples
  - Atoms released from a Mott phase (I Bloch, Mainz, 2005)
  - Molecules dissociation (D Jin et al., Boulder, 2005)
  - Fluctuations on an atom chip (J. Estève et al., Institut d'Optique, 2005)
  - … (Inguscio, …)

Atomic density correlation ("noise correlation"): a new tool to investigate quantum gases

3 atoms collision rate enhancement in a thermal gas, compared to a BEC

- Factor of 6 ($\left\langle n^3(\mathrm{r})\right\rangle = 3!\left\langle n(\mathrm{r})\right\rangle^3$) observed (JILA, 1997) as predicted by Kagan, Svistunov, Shlyapnikov, JETP lett (1985)

Interaction energy of a sample of cold atoms

- $\left\langle n^2(\mathrm{r})\right\rangle = 2\left\langle n(\mathrm{r})\right\rangle^2$ for a thermal gas (MIT, 1997)
- $\left\langle n^2(\mathrm{r})\right\rangle = \left\langle n(\mathrm{r})\right\rangle^2$ for a quasicondensate (Institut d'Optique, 2003)

Noise correlation in absorption images of a sample of cold atoms (as proposed by Altmann, Demler and Lukin, 2004)

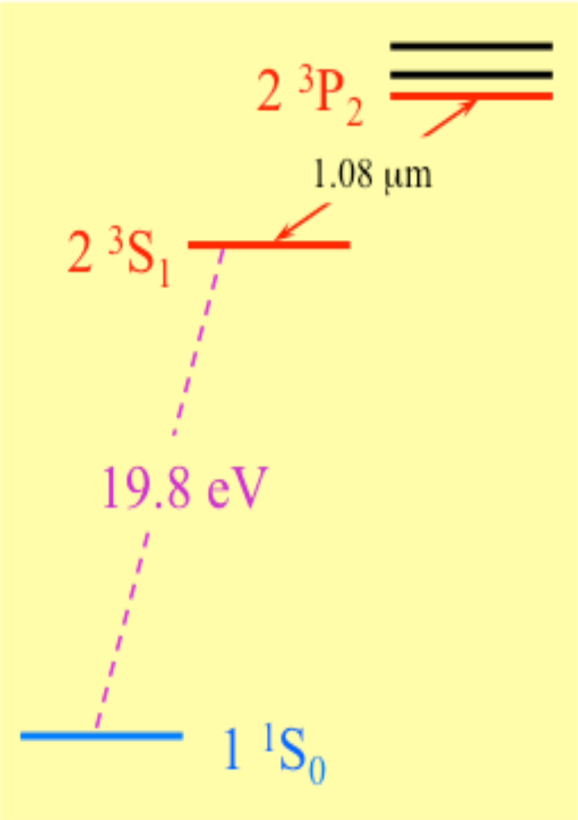
Measurements of atomic density averaged over small volumes

What about individual atoms correlation function measurements?

Metastable Helium 2 $^3S_1$
A tool for Quantum Atom Optics

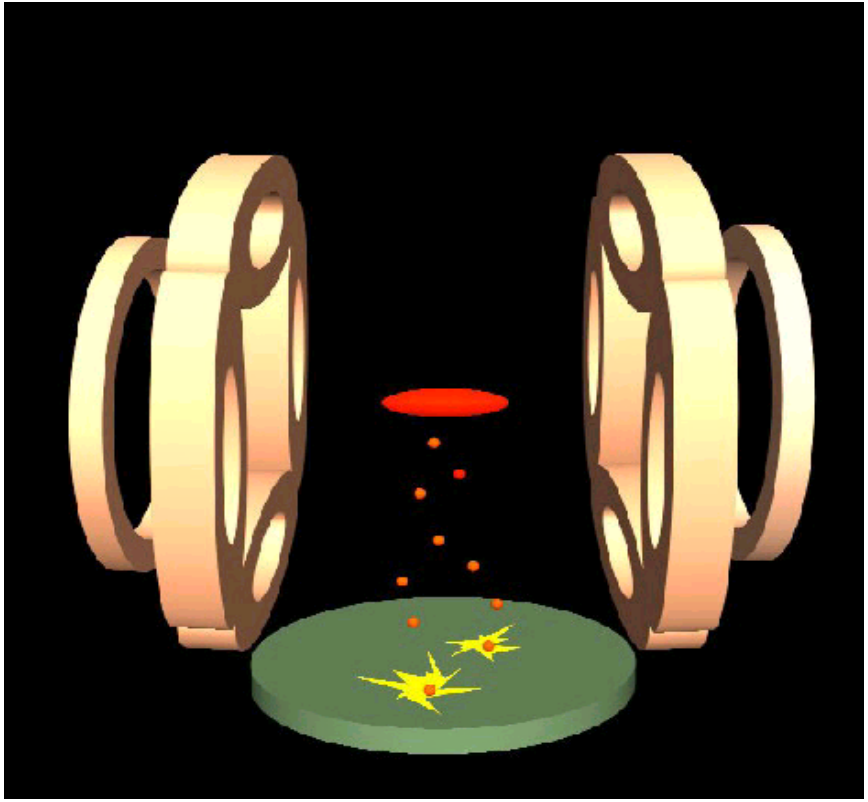
- Triplet (↑↑) 2 $^3S_1$ cannot *radiatively* decay to singlet (↑↓) 1 $^1S_0$ (lifetime 9000 s)
- Laser manipulation on closed transition 2 $^3S_1 \rightarrow$ 2 $^3P_2$ at 1.08 μm (lifetime 100 ns)

- Large electronic energy stored in He*
  - ⇒ ionization of any collider
  - ⇒ extraction of electron from metal: single atom detection with Micro Channel Plate detector



Similar techniques in Canberra, Amsterdam, ENS, Stony Brook, Vienna

He* laser cooling and trapping, and MCP detection: unique tools



Clover leaf trap

@ 240 A : B_0 : 0.3 to 200 G ;

B' = 90 G / cm ; B''= 200 G / cm^2

$\omega_z / 2\pi = 50$ Hz ; $\omega_\perp / 2\pi = 1800$ Hz

He* on the Micro Channel Plate:

⇒ an electron is extracted

⇒ multiplication

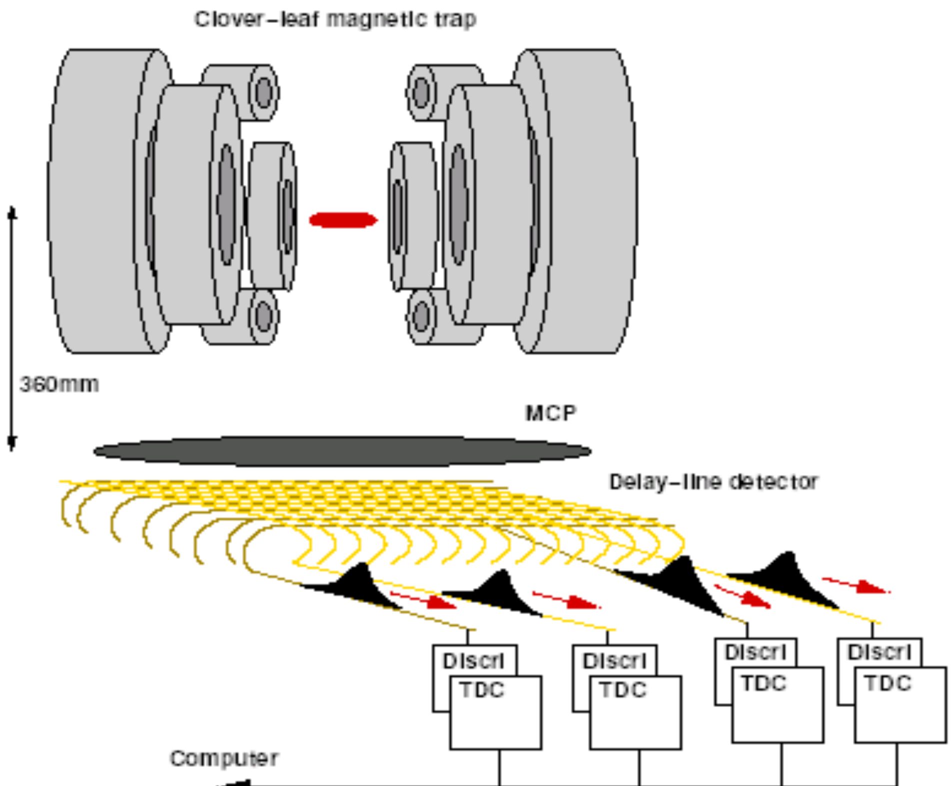
⇒ observable pulse

Single atom detection of He*

Analogue of single photon counting development, in the early 50's

Tools crucial to the discovery of He* BEC (2000)

Position and time resolved detector: a tool for atom correlation experiments

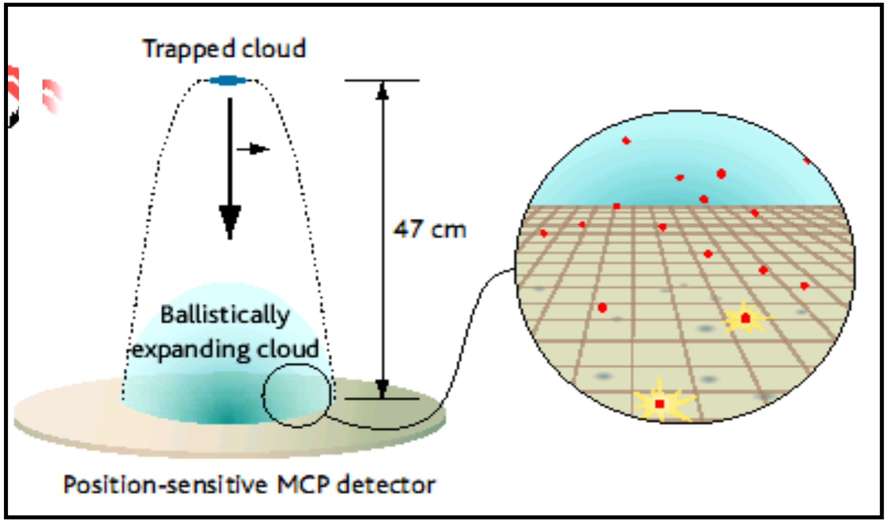


Delay lines + Time to digital converters: detection events localized in time and position

- Time resolution in the ns range ☺
- Dead time : 30 ns ☺
- Local flux limited by MCP saturation ☹
- Position resolution (limited by TDC): 200 μm ☹

10^5 single atom detectors working in parallel ! ☺ ☺ ☺ ☺ ☺ ☺

Atom atom correlations in the atom cloud



$$\left(i_1, t_1\right), \ldots \left(i_n, t_n\right), \ldots$$

- Cool the trapped sample to a chosen temperature (above BEC transition)
- Release onto the detector
- Monitor and record each detection event n:
  - ✓Pixel number i_n (coordinates x, y)
  - ✓Time of detection t_n (coordinate z)

$\left\{\left(i_1, t_1\right), \ldots \left(i_n, t_n\right), \ldots\right\}$ = a record of the atom positions in a single cloud

Repeat many times (accumulate records) at same temperature

Pulsed experiment: 3 dimensions are equivalent $\neq$ Shimizu experiment

$g^{(2)}$ for a thermal sample (above T_{BEC}) of ^{4}He*

- For a given record (ensemble of detection events for a given released sample), evaluate probability of a pair of atoms separated by Δx, Δy, Δz.

$$\rightarrow [\pi^{(2)}(\Delta x, \Delta y, \Delta z)]_i$$

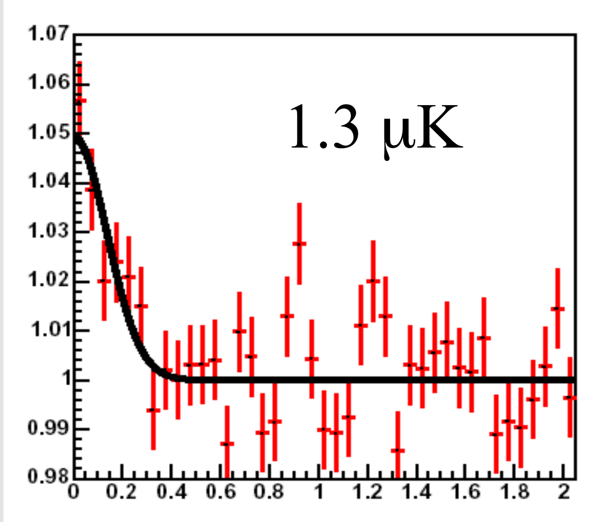
- Average over many records (at same temperature)

- Normalize by the autocorrelation of average (over all records)

$$\rightarrow \quad g^{(2)}(\Delta x, \Delta y, \Delta z)$$

$\Rightarrow$ HBT bump around $\Delta x = \Delta y = \Delta z = 0$

$$g^{(2)}(\Delta x = \Delta y = 0; \Delta z)$$



Bump visibility = 5 x 10^{-2}

Agreement with prediction (resolution)

$g^{(2)}$ for a thermal sample (above T_{BEC}) of ^{4}He*

- For a given record (ensemble of detection events for a given released sample), evaluate probability of a pair of atoms separated by Δx, Δy, Δz.

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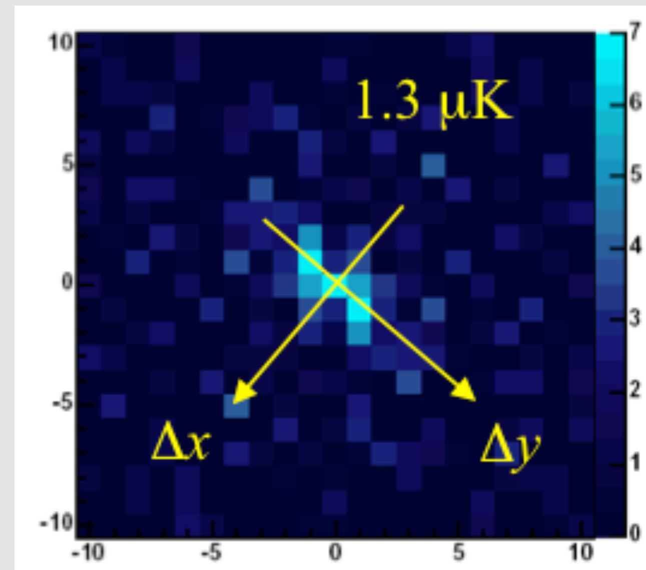
  $\rightarrow \quad g^{(2)}(\Delta x, \Delta y, \Delta z)$

$\Rightarrow$ HBT bump around $\Delta x = \Delta y = \Delta z = 0$

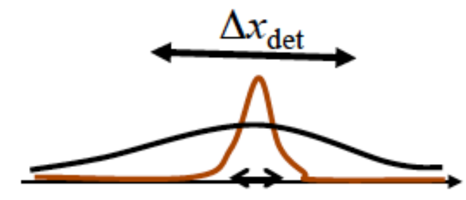
$g^{(2)}(\Delta x; \Delta y; \Delta z = 0)$



Extends along y (narrow dimension of the source)

The detector resolution issue

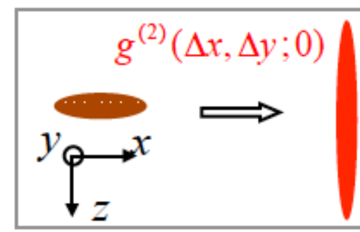
If the detector resolution Δx_{det} is larger than the HBT bump width L_{cx} $\quad L_{cx} \simeq \dfrac{\hbar}{2M\Delta x_{\mathrm{source}}} t_{\mathrm{fall}}$



then the height of the HB&T bump is reduced: $g^{(2)} - 1 \simeq \dfrac{L_C}{\Delta x_{\mathrm{det}}} < 1$

At 1 μK,

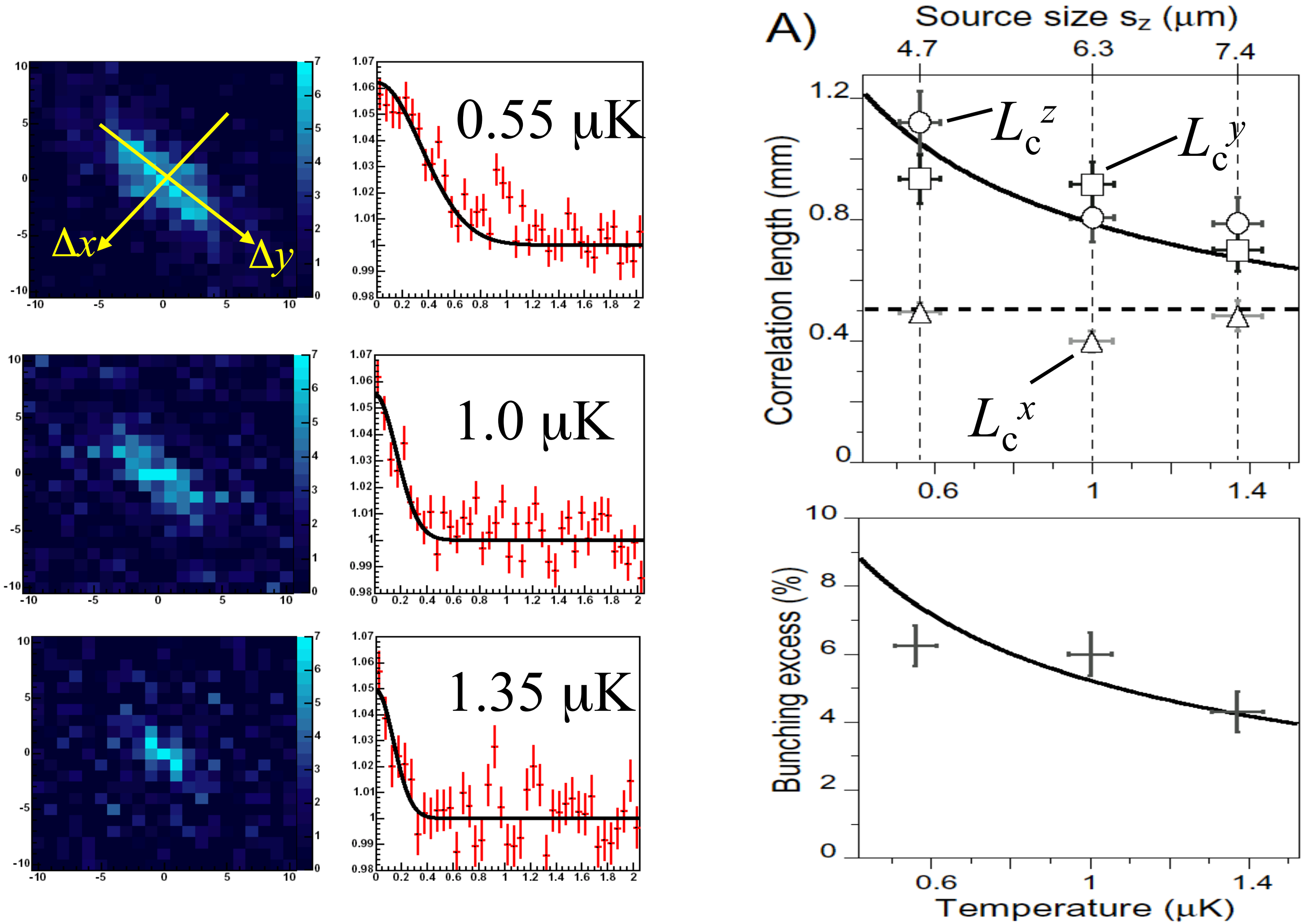
- $\Delta y_{\mathrm{source}} \approx 4\ \mu\mathrm{m} \Rightarrow L_{cy} = 500\ \mu\mathrm{m}$ ☺
- $\Delta x_{\mathrm{source}} \approx 150\ \mu\mathrm{m} \Rightarrow L_{cy} = 13\ \mu\mathrm{m}$ ☹



Resolution (200 μm) sufficient along y but insufficient along x. Expected reduction factor of 15

NB: vertical resolution is more than sufficient: $\Delta z_{\mathrm{det}} \approx V\,\Delta t \approx 1\ \mathrm{nm}$ ☺

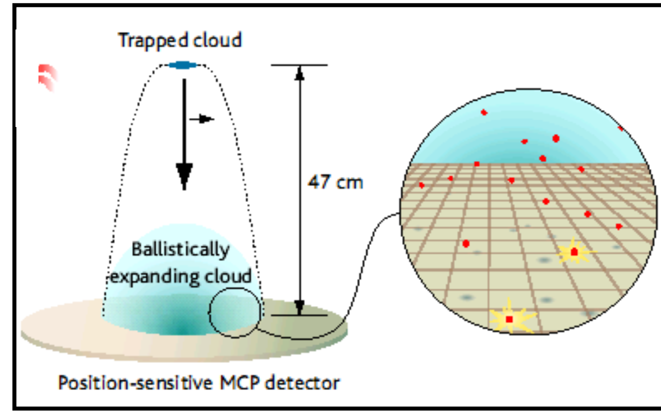
Role of source size (^{4}He* thermal sample)

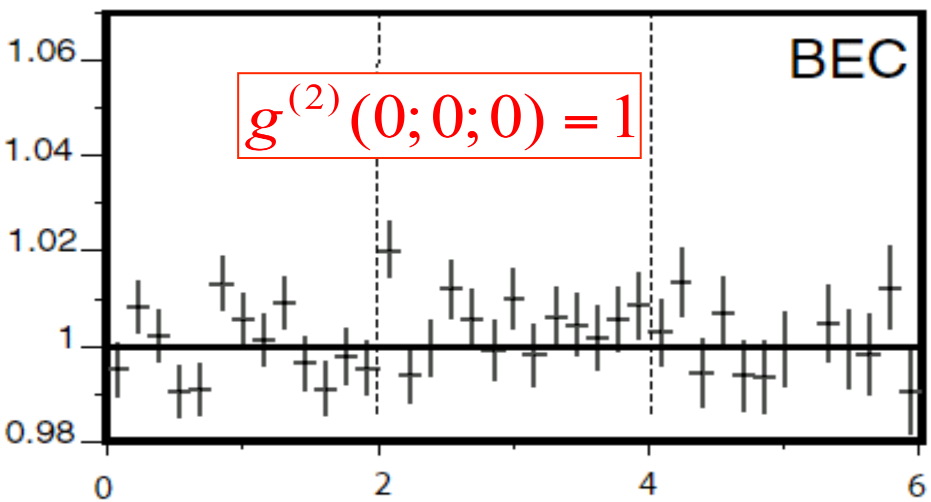


Temperature controls the size of the source (harmonic trap)

$g^{(2)}$ for a $^4He^*$ BEC ($T < T_c$)

Experiment more difficult:
atoms fall on a small area
on the detector
$\Rightarrow$ problems of saturation





No bunching: analogous to laser light

(see also Öttl et *al.*; PRL 95,090404)

Atoms are as fun as photons?

They can be more!

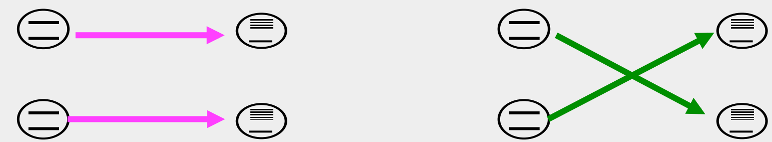
In contrast to photons, atoms can come not only as bosons (most frequently), but also as fermions, *e.g.* ^{3}He, ^{6}Li, ^{40}K...

Possibility to look for pure effects of quantum statistics

- No perturbation by a strong "ordinary" interaction (Coulomb repulsion of electrons)
- Comparison of two isotopes of the same element (^{3}He *vs* ^{4}He).

The HB&T effect with fermions: antibunching

Two paths to go from one initial state to one final state: quantum interference



Amplitudes added with opposite signs: antibunching

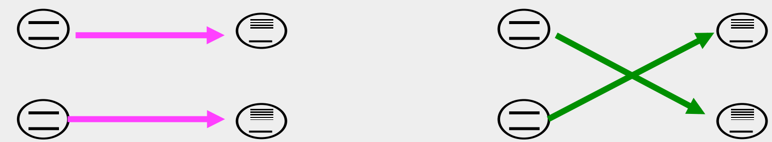
Two particles interference effect: quantum weirdness, lack of statistical independence although no real interaction

… no classical interpretation

$$\langle n(t)^2 \rangle < \langle n(t) \rangle^2$$ impossible for classical densities

The HB&T effect with fermions: antibunching

Two paths to go from one initial state to one final state: quantum interference



Amplitudes added with opposite signs: antibunching

Two particles interference effect: quantum weirdness, lack of statistical independence although no real interaction

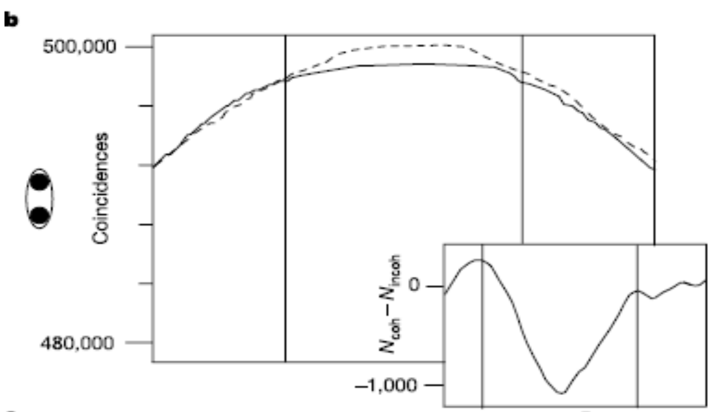
… no classical interpretation

$\langle n(t)^2 \rangle < \langle n(t) \rangle^2$ impossible for classical densities

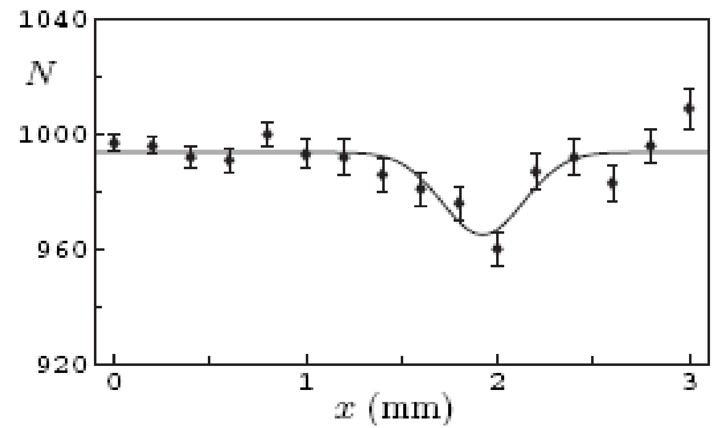
Not to be confused with antibunching for a single particle (boson or fermion): a single particle cannot be detected simultaneously at two places

Evidence of fermionic HB&T antibunching

Electrons in solids or in a beam:
M. Henny et al., (1999); W. D. Oliver et al.(1999);
H. Kiesel et al. (2002).

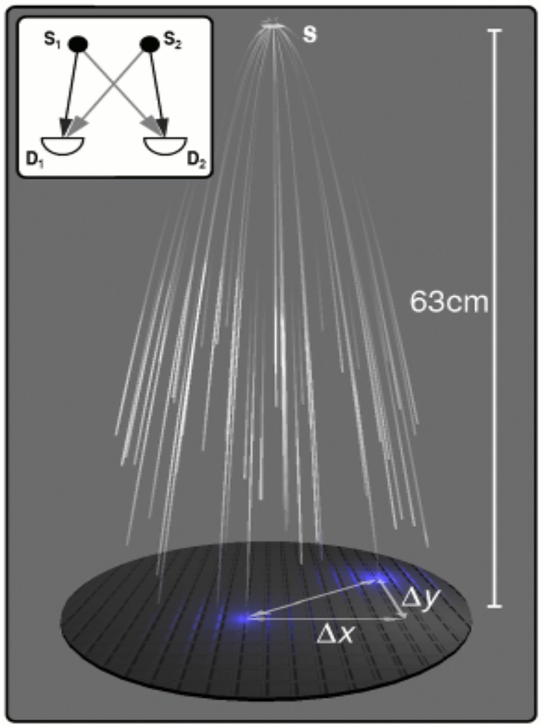


Neutrons in a beam:
Iannuzi et al. (2006)



Heroic experiments, tiny signals !

HB&T with $^3He^*$ and $^4He^*$ an almost ideal fermion vs boson comparison



Neutral atoms: interactions negligible

Samples of $^3He^*$ and $^4He^*$ at same temperature (0.5 μK, sympathetic cooling) in the trap :

⇒ same size (same trapping potential)

⇒ Coherence volume scales as the atomic masses (de Broglie wavelengths)

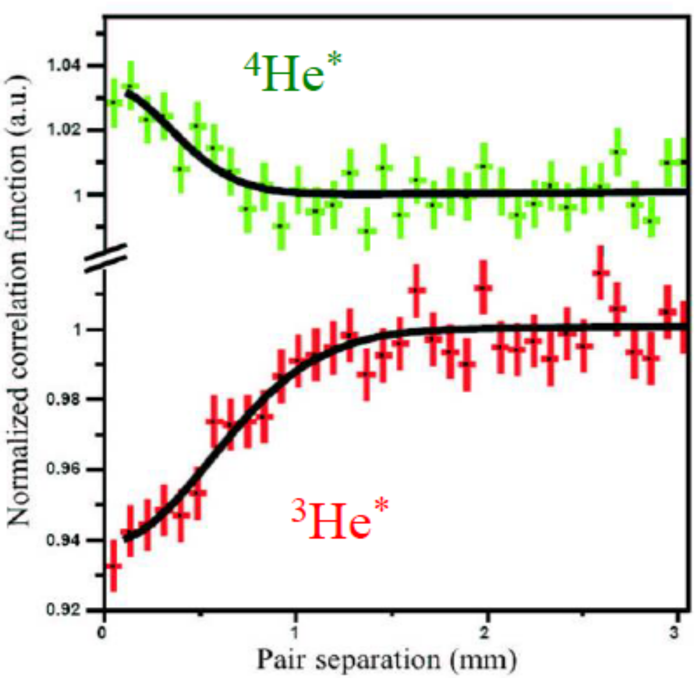
⇒ ratio of 4 / 3 expected for the HB&T widths

Collaboration with VU Amsterdam (W Vassen et al.)

HB&T with ^{3}He* and ^{4}He*
an almost ideal fermion vs boson comparison

Jeltes et al. Nature 445, 402–405 (2007) (Institut d'Optique-VU)

Collaboration with VU Amsterdam (W Vassen et al.)



Direct comparison:

- same apparatus
- same temperature

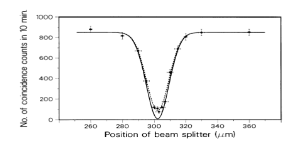
Ratio of about 4 / 3 found for HB&T signals widths (mass ratio, ie de Broglie wavelengths ratio)

Pure quantum statistics effect

Fermion anticorrelation also seen in Mainz : Rom et al. Nature 444, 733–736 (2006)

The HBT and HOM effects: from photons to atoms

1. Two “quantum mysteries”
2. The HBT effect with photons
3. Quantum Atom Optics with He*: HBT
4. The HOM effect with photons
5. HOM effect with atoms
6. Outlook



The Hong-Ou-Mandel effect (photons)

Measurement of Subpicosecond Time Intervals between Two Photons by Interference

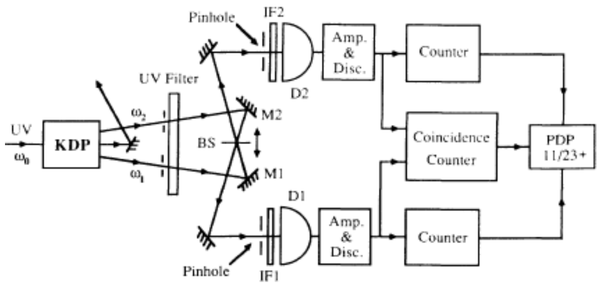
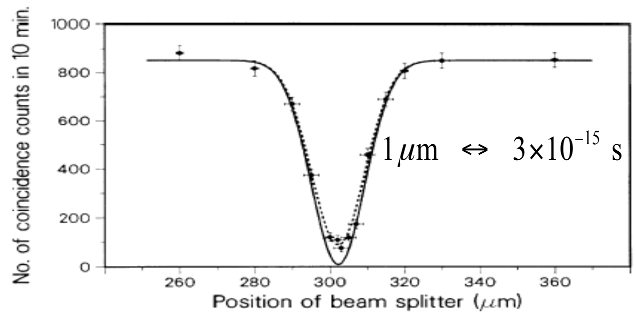
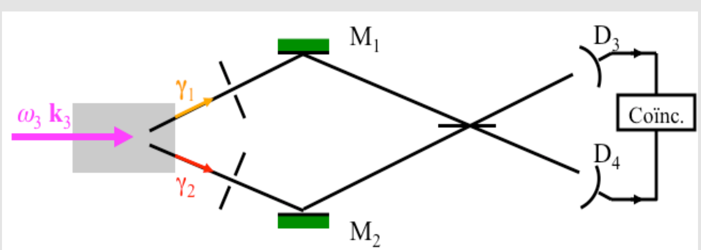


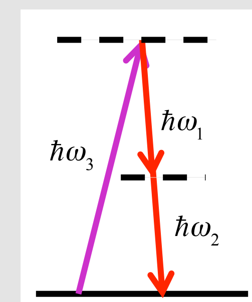
FIG. 1. Outline of the experimental setup.



C.K. Hong, Z.Y. Ou and L. Mandel, PRL **59**, 2044 (1987)



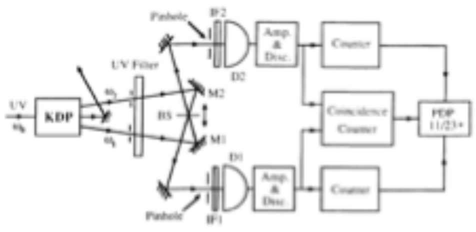
When the two photon wave packets exactly overlap: both photons emerge on the same side of the beam splitter (randomly)



Initial emphasis: Time correlation measured with fs accuracy

HOM: an intriguing quantum effect

Measurement of Subpicosecond Time Intervals between Two Photons by Interference



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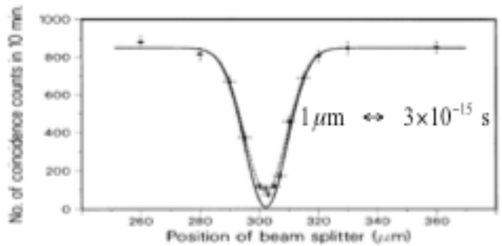
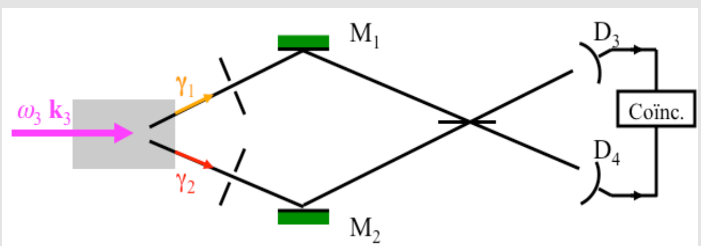
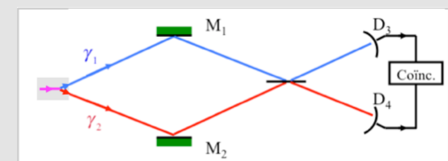


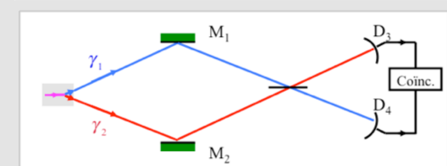
C.K. Hong, Z.Y. Ou and L. Mandel, PRL **59**, 2044 (1987)

See also: **Fourth order interference in parametric down conversion** J. Rarity and P.Tapster, Josa B 6, 1221 (1989)



Indistinguishable photons: same initial and final states, two paths: destructive interference between two photons amplitudes



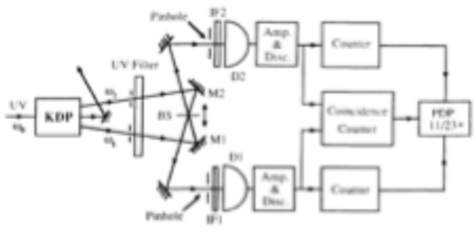


$$w^{(2)}(D_3;D_4)=\left\|\langle\gamma_1|D_3\rangle\langle\gamma_2|D_4\rangle+\langle\gamma_1|D_4\rangle\langle\gamma_2|D_3\rangle\right\|^2=0$$

A spectacular evidence of two photons interference

HOM: an intriguing quantum effect

Measurement of Subpicosecond Time Intervals between Two Photons by Interference



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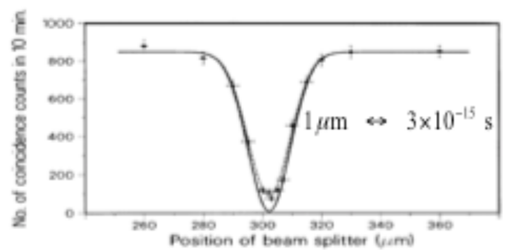

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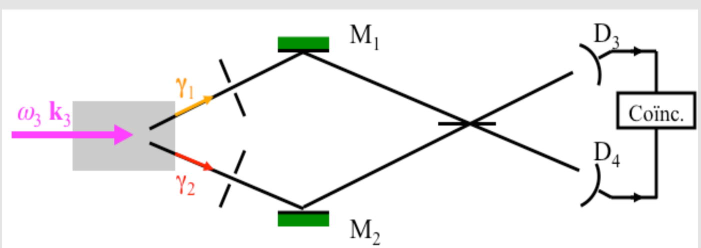

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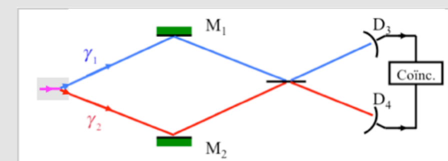
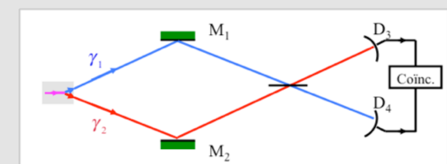


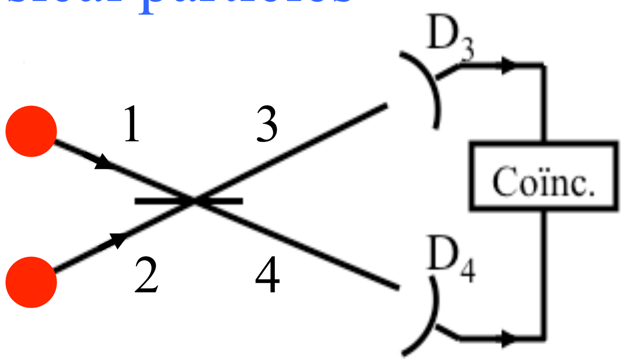


No classical description

- Classical particles
- Classical waves

HOM: no classical particles model

Classical particles



1 particle in input 1 and 1 particle in input 2

- Each particle has probability 1/2 to be transmitted, and 1/2 to be reflected
- They are independent

$$\mathcal{P}(2 \text{ particles in } 3) = 1/4$$

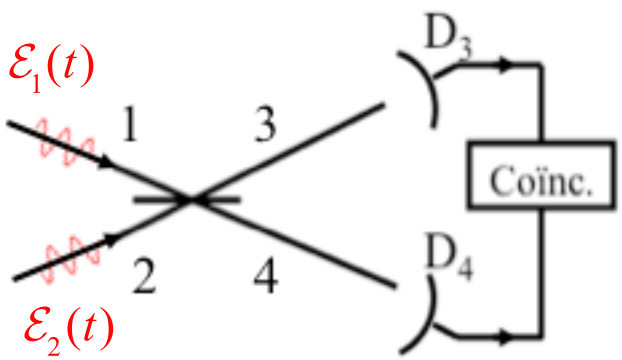
$$\mathcal{P}(2 \text{ particles in } 4) = 1/4$$

$$\mathcal{P}(1 \text{ particle in } 3 \text{ and } 1 \text{ particle in } 4) = 1/2$$

No HOM dip (no suppression of joint detection atD_3 and D_4)

HOM: no classical wave model

Classical waves: independent wave-packets



Rates of single detections (one set of wave packets)

$$w^{(1)}(\mathrm{D}_3) \propto I$$

$$w^{(1)}(\mathrm{D}_4) \propto I$$

Rate of joint detections $w^{(2)}(\mathrm{D}_3;\mathrm{D}_4) = w^{(1)}(\mathrm{D}_3) \cdot w^{(1)}(\mathrm{D}_4)$

Average over many pairs of wave-packets

Rates of single detections

$$\overline{w^{(1)}(\mathrm{D}_3)} \propto \overline{I}$$

$$\overline{w^{(1)}(\mathrm{D}_4)} \propto \overline{I}$$

Rate of joint detections

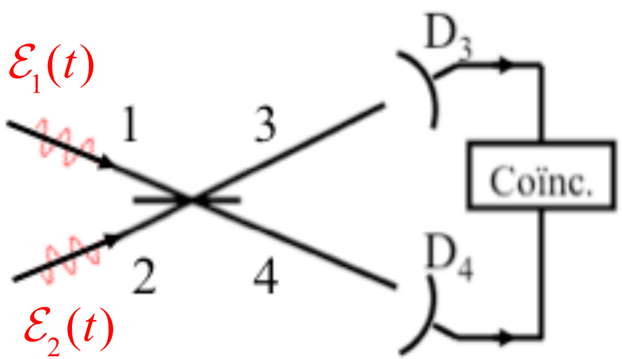
$$w^{(2)}(\mathrm{D}_3;\mathrm{D}_4) = \overline{w^{(1)}(\mathrm{D}_3) \cdot w^{(1)}(\mathrm{D}_4)}$$

$$= \overline{I^2} \geq \left(\overline{I}\right)^2 = \overline{w^{(1)}(\mathrm{D}_3)} \cdot \overline{w^{(1)}(\mathrm{D}_4)}$$

No dip

HOM: no classical wave model

Coherent classical waves (relative phase ϕ)



$$\mathcal{E}_1(t) = \mathcal{E}(t)$$

$$\mathcal{E}_2(t) = \mathcal{E}(t)\exp\{i\phi\}$$

Rates of single detections

$$w^{(1)}(\mathrm{D}_3) \propto 2\left|\mathcal{E}(t)\right|^2 \cos^2\phi$$

$$w^{(1)}(\mathrm{D}_4) \propto 2\left|\mathcal{E}(t)\right|^2 \sin^2\phi$$

Rate of joint detections $w^{(2)}(\mathrm{D}_3;\mathrm{D}_4) = w^{(1)}(\mathrm{D}_3)\cdot w^{(1)}(\mathrm{D}_4)$

$$= 4\left|\mathcal{E}(t)\right|^4 \cos^2\phi \sin^2\phi = \left|\mathcal{E}(t)\right|^4 \sin^2 2\phi$$

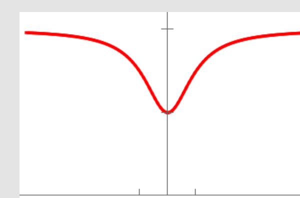
Average over ϕ (to mimick randomness)

Rate of single detections $w^{(1)}(\mathrm{D}_3) \propto \left|\mathcal{E}(t)\right|^2$; $w^{(1)}(\mathrm{D}_4) \propto \left|\mathcal{E}(t)\right|^2$

Rate of joint detections $w^{(2)}(\mathrm{D}_3;\mathrm{D}_4) \propto \left|\mathcal{E}(t)\right|^4 \overline{\sin^2 2\phi} = \frac{1}{2}\left|\mathcal{E}(t)\right|^4$

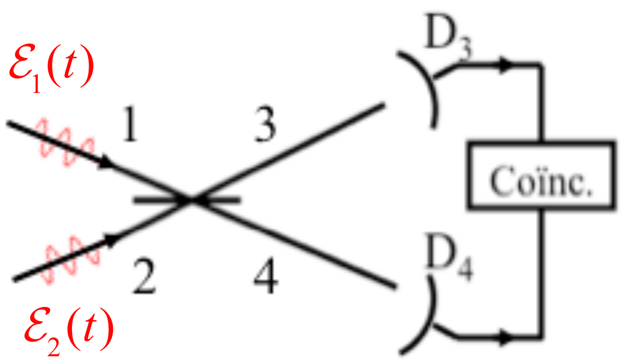
$$= \frac{1}{2} w^{(1)}(\mathrm{D}_3)\cdot w^{(1)}(\mathrm{D}_4)$$

Dip visibility 1/2



HOM: no classical wave model

Classical waves: wave-packets with mutual coherence



$$\mathcal{E}_1(t) = \mathcal{E}(t)$$
$$\mathcal{E}_2(t) = \mathcal{E}(t)\exp\{i\phi\}$$

Rates of single detections

$$w^{(1)}(\mathrm{D}_3) \propto 2\left|\mathcal{E}(t)\right|^2 \cos^2\phi$$
$$w^{(1)}(\mathrm{D}_4) \propto 2\left|\mathcal{E}(t)\right|^2 \sin^2\phi$$

Rate of joint detections $w^{(2)}(\mathrm{D}_3;\mathrm{D}_4) = w^{(1)}(\mathrm{D}_3)\cdot w^{(1)}(\mathrm{D}_4)$

$$= 4\left|\mathcal{E}(t)\right|^4 \cos^2\phi \sin^2\phi = \left|\mathcal{E}(t)\right|^4 \sin^2 2\phi$$

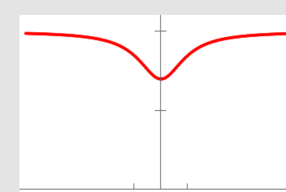
Average over ϕ and wave packets fluctuations

Rate of single detections $w^{(1)}(\mathrm{D}_3) \propto \overline{\left|\mathcal{E}(t)\right|^2}$; $w^{(1)}(\mathrm{D}_4) \propto \overline{\left|\mathcal{E}(t)\right|^2}$

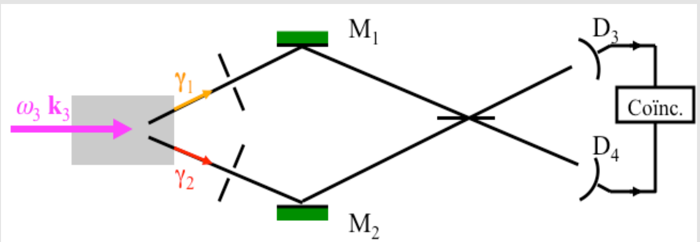
Rate of joint detections $w^{(2)}(\mathrm{D}_3;\mathrm{D}_4) \propto \frac{1}{2}\overline{\left|\mathcal{E}(t)\right|^4} \geq \frac{1}{2}\left(\overline{\left|\mathcal{E}(t)\right|^2}\right)^2$

$$\geq \frac{1}{2} w^{(1)}(\mathrm{D}_3)\cdot w^{(1)}(\mathrm{D}_4)$$

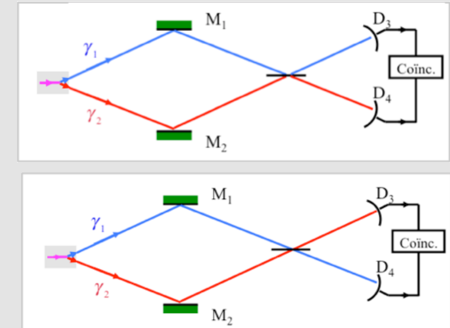
Dip visibility < 1/2

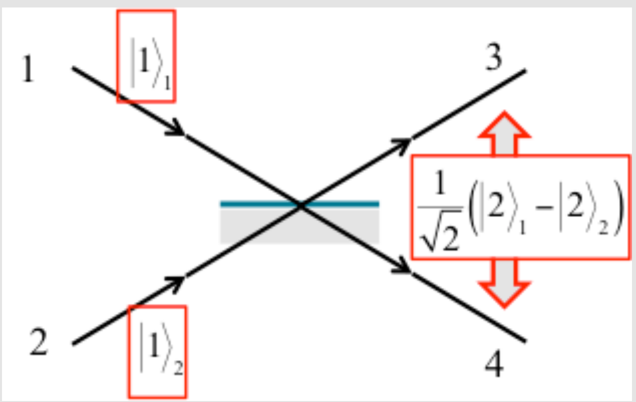


HOM : a mile-stone in Quantum Optics



Interference
between
two photons
amplitudes





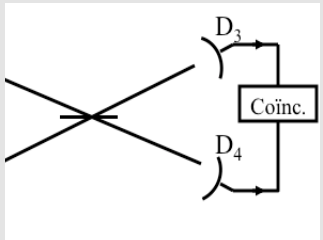
Two photons
entangled state
in the output space

The simplest
example of a
"quantum
mystery of the
second kind"

No classical description

- Classical particles: no dip
- Classical waves: dip not below 50%

HOM for photons from distinct sources



Interference
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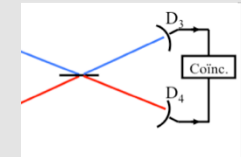
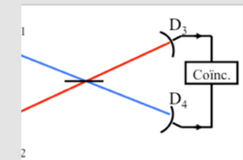
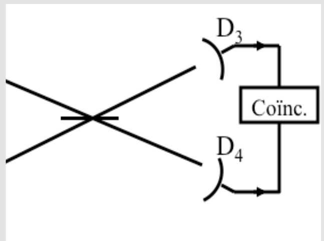




The two one-
photon modes
must be
indistinguishable

HOM for photons from distinct sources



Interference
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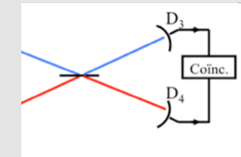
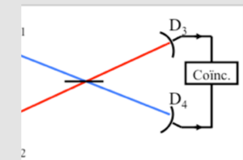
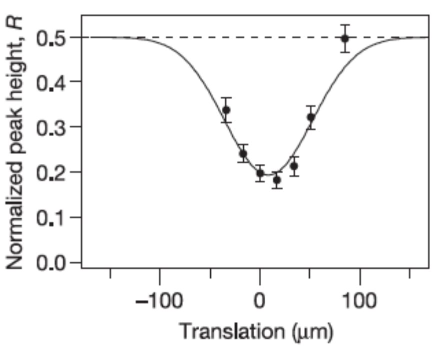


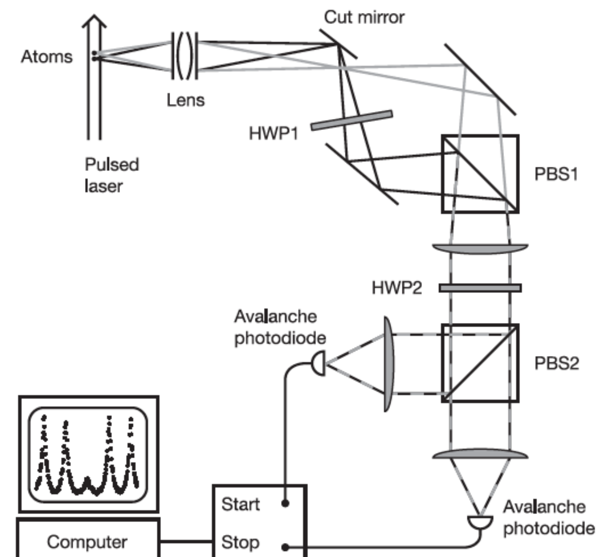


Quantum interference between two single photons emitted by independently trapped atoms

J. Beugnon[1], M. P. A. Jones[1], J. Dingjan[1], B. Darquié[1], G. Messin[1], A. Browaeys[1] & P. Grangier[1]



The two one-photon modes must be indistinguishable



The HBT and HOM effects: from photons to atoms

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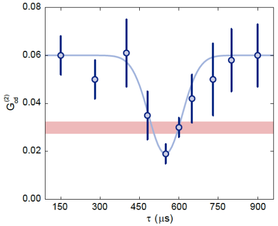
5. HOM effect with atoms
6. Outlook

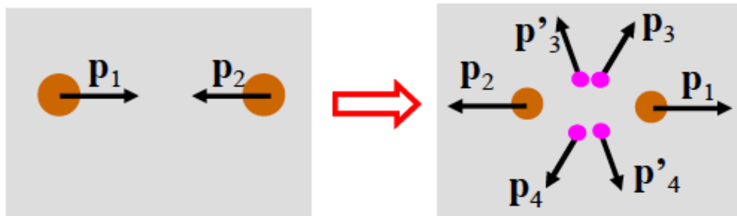


Production of atom pairs by spontaneous atomic 4-Wave Mixing

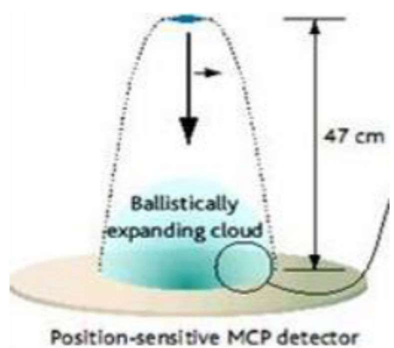
2 colliding BEC's

$\mathbf{p}_2 = -\mathbf{p}_1$

$p_1 = p_2$

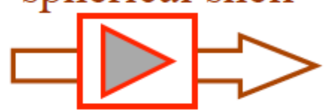


$p_4 = p_3 = p_1 = p_2$

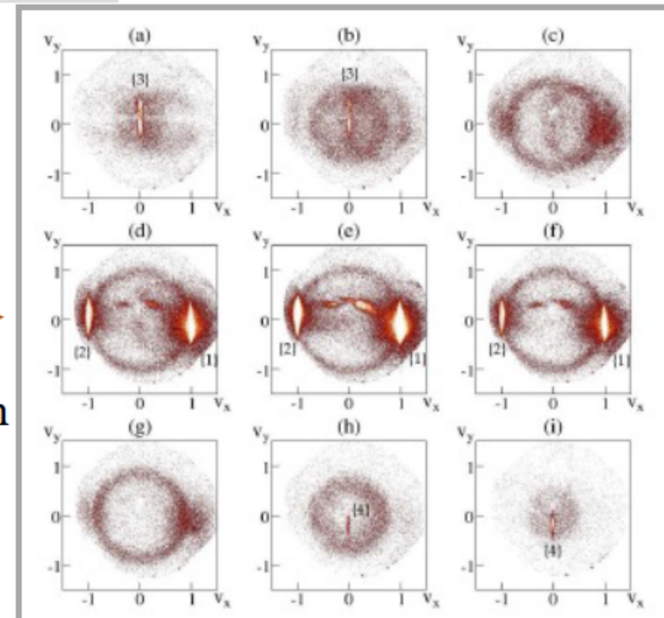


p reconstruction by elementary kinematics (free fall)

Observation of the full s-wave scattering spherical shell



s-wave collision halo (cf. MIT, Penn state, Amsterdam)



Do we really have atom pairs?

Production of atom pairs by spontaneous atomic 4-Wave Mixing

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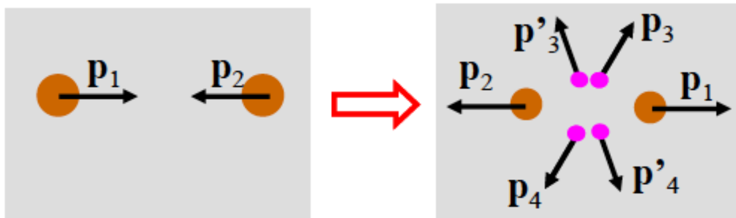

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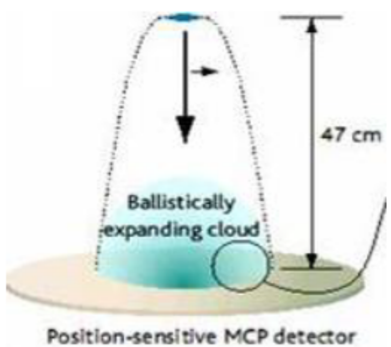

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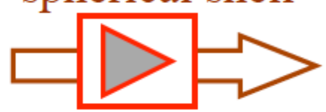

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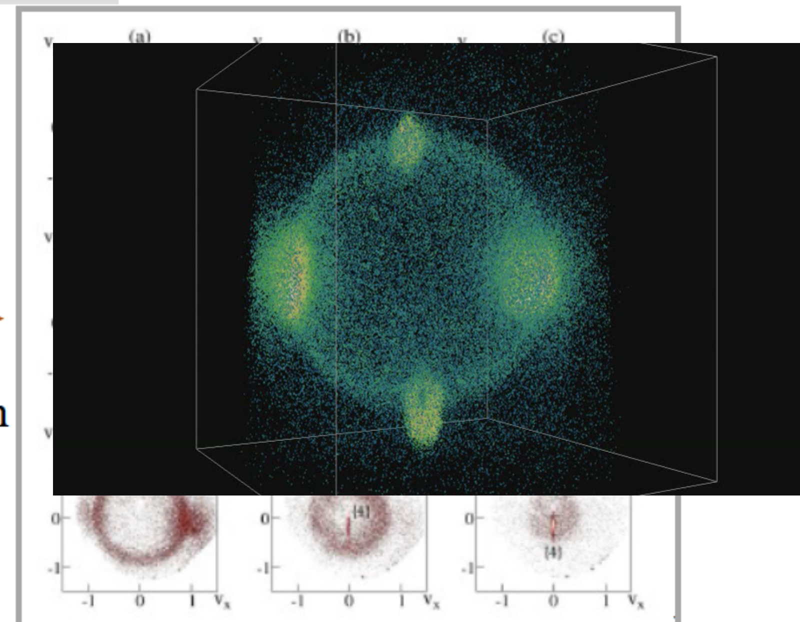
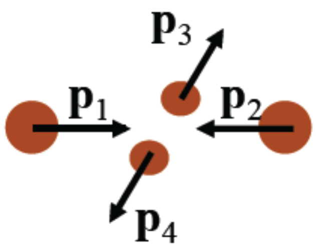


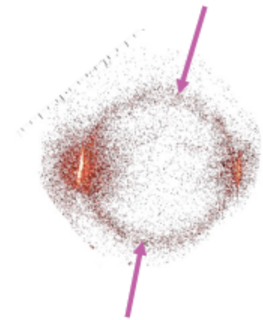
Do we really have atom pairs?

Pairs correlated in velocity



Colliding BEC's $p_2 = -p_1$

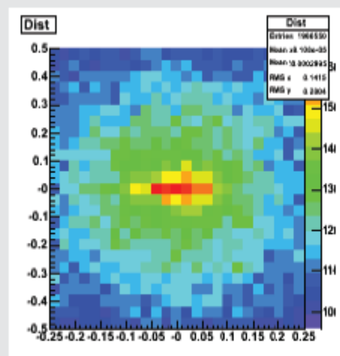
$$\boxed{\begin{aligned} p_4 &= -p_3 \\ |p_3| = |p_4| &= \text{const} \end{aligned}}$$

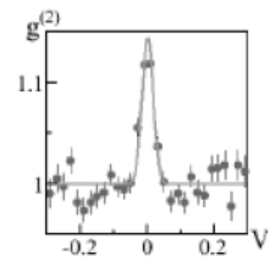


Momentum correlation in scattered atoms

Correlation of antipodes on momentum sphere

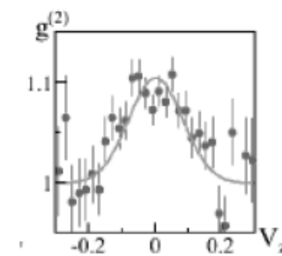
Atoms in pairs of opposite momenta





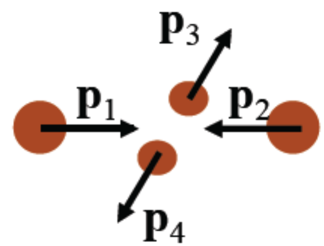
$g^{(2)}(V_{1P} + V_{2P})$

$g^{(2)}(V_{1\perp} + V_{2\perp})$



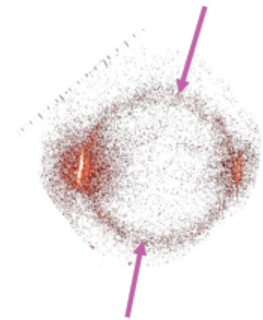
A. Perrin et al. PRL 2007

Pairs correlated in velocity



Colliding BEC's $\quad p_2 = -p_1$

$$\boxed{\begin{array}{c} p_4 = -p_3 \\ |p_3| = |p_4| = \text{const} \end{array}}$$



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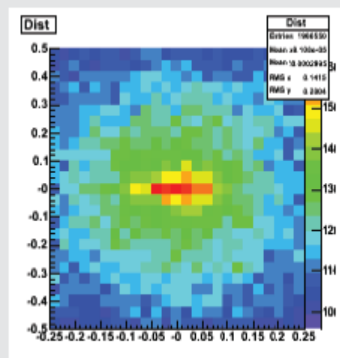

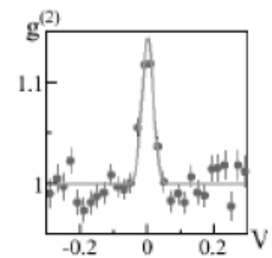

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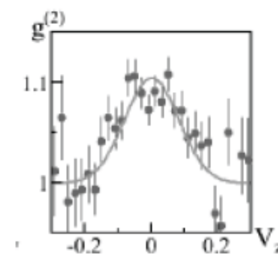
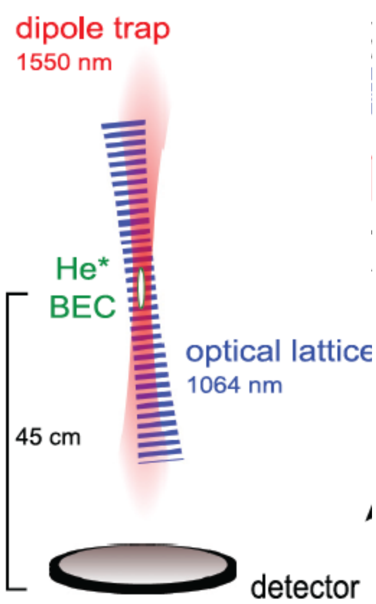


A. Perrin et al. PRL 2007

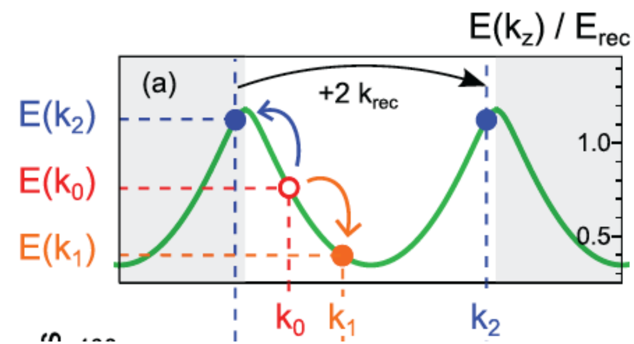
We have pairs, but emitted in all directions in space ☹

A phase matched source of atom pairs

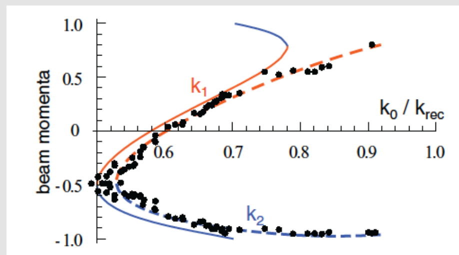
1D atomic 4-wave mixing with a superimposed moving optical lattice Proposed by Hilingsoe and Molmer as a phase matching condition (2005), demonstrated by Campbell et al (2006). See also B. Wu and Q. Niu (PRA 2001)



Non-trivial dispersion relation in lattice: one lattice velocity ➔ well defined velocities v_1 and v_2 for produced pair

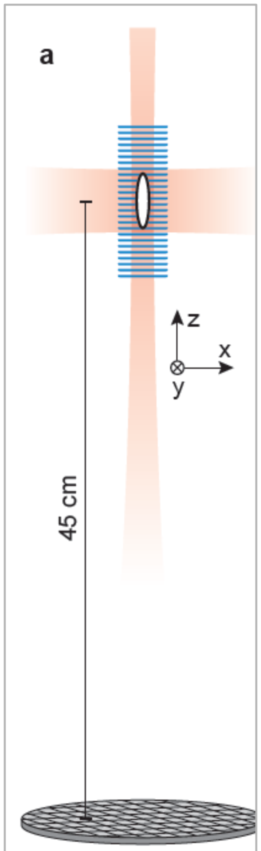


A tunable source of correlated atom pairs (correlations checked) : Bonneau et al., 2013

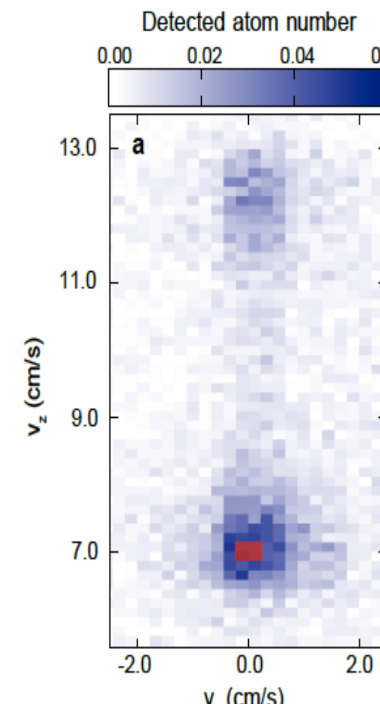


Production of atom pairs with well defined velocities, in a well defined direction

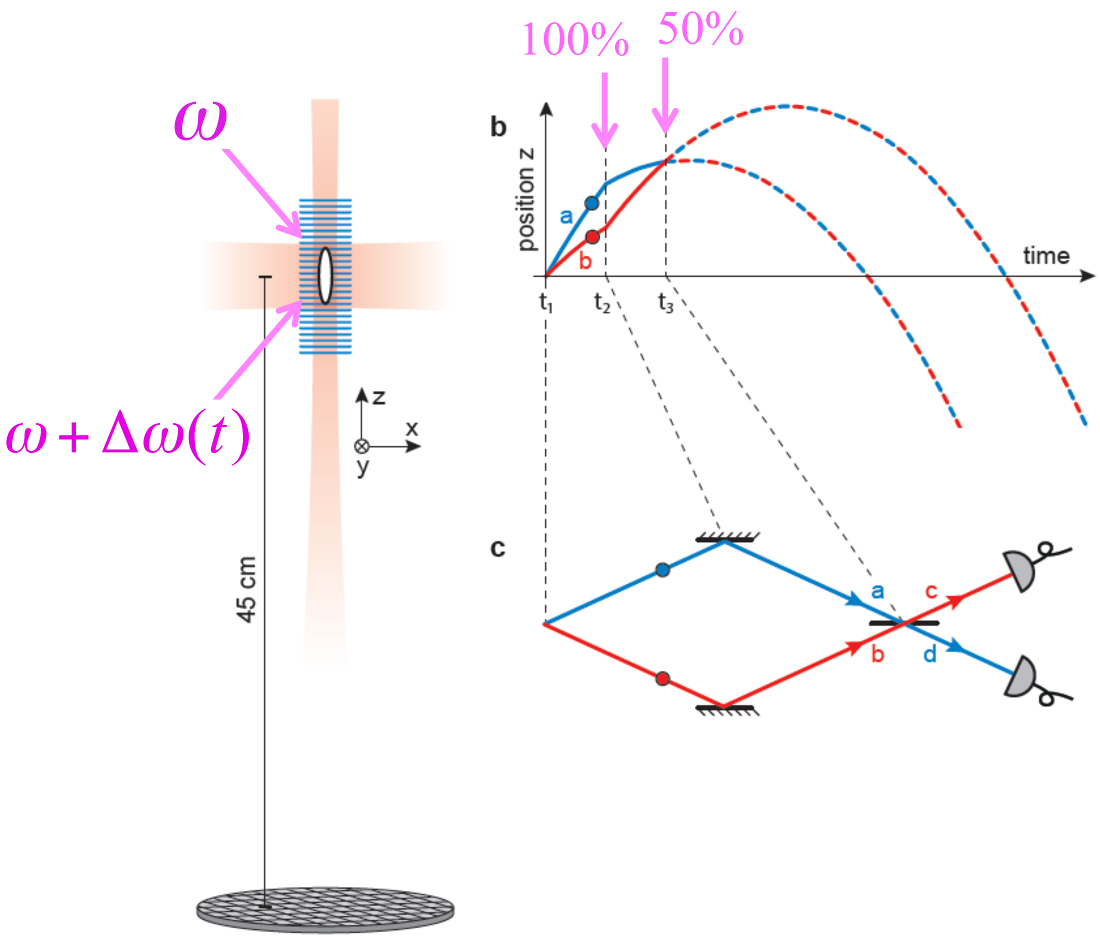
Improved phase matched source of He* atom pairs



- Lattice perfectly aligned with the long direction of the BEC
- After pair production, atoms initially in m = 1 Zeeman sublevel transferred into m = 0 (field insensitive) by Raman transition
- Optical trap switched off: atoms fall freely; the atoms of the pairs separate from the atoms of the BEC
- Measurement of autocorrelation function in each beam: mostly one atom (2 atoms component < 25%)



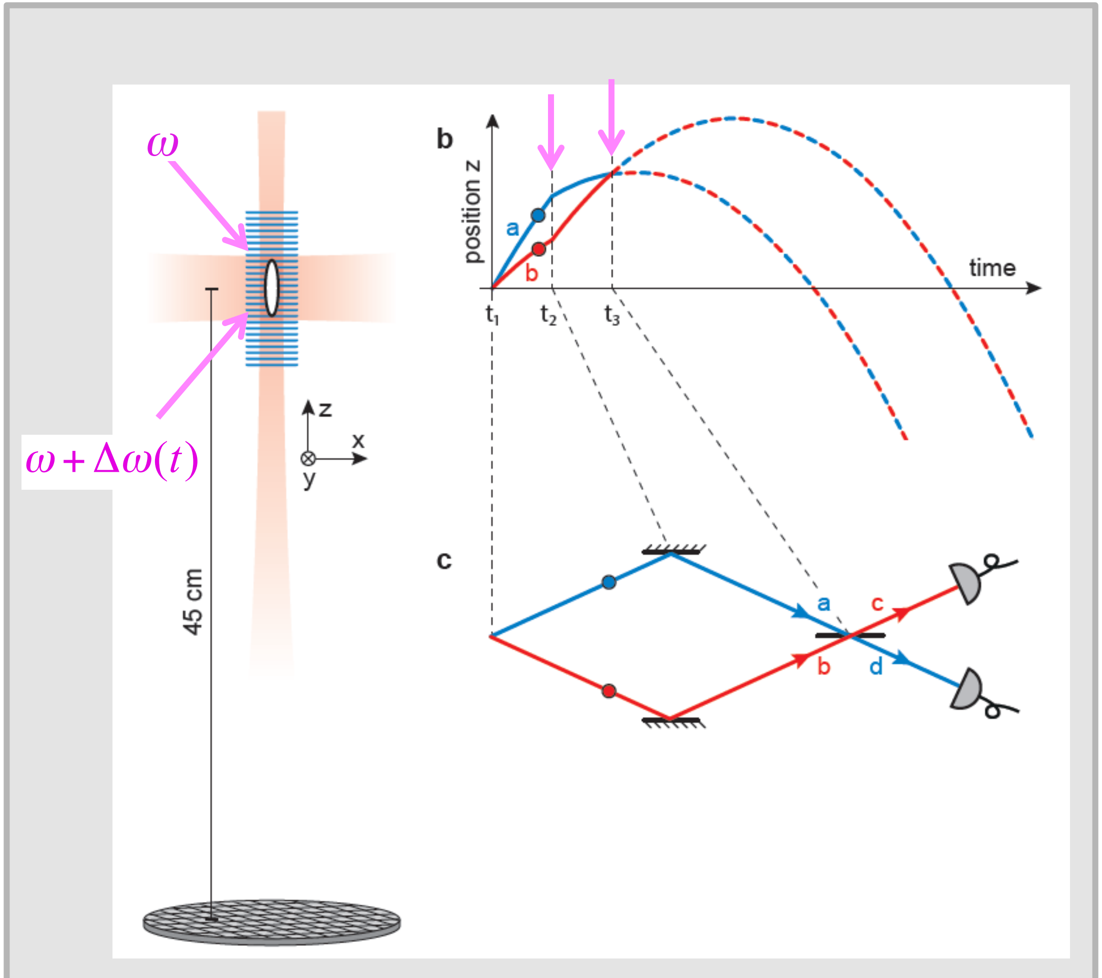
Mirrors and beam-splitter: Bragg reflection

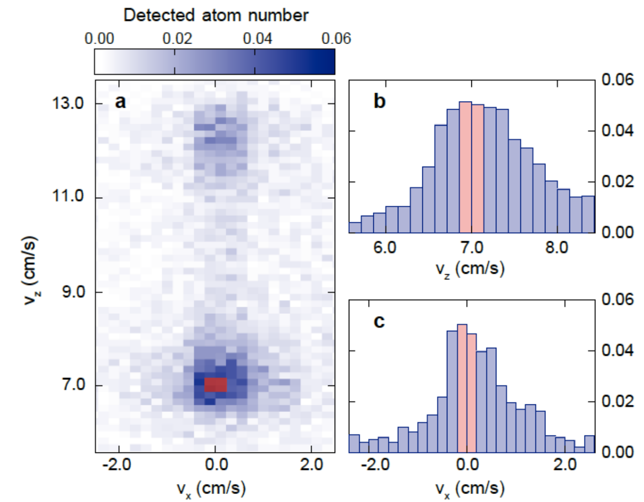


Initial atom velocities:
$v_a = 12$ cm/s ; $v_b = 7$ cm/s

Laser standing wave moving as the center of gravity of the two atoms: atoms move with opposite velocities (+/− 9.5 cm/s) in the optical lattice, whose period is adjusted (angle between the beams) to match this velocity: Bragg condition fulfilled; 100% reflection possible; 50% for a duration two times shorter : mirror, beam-splitter

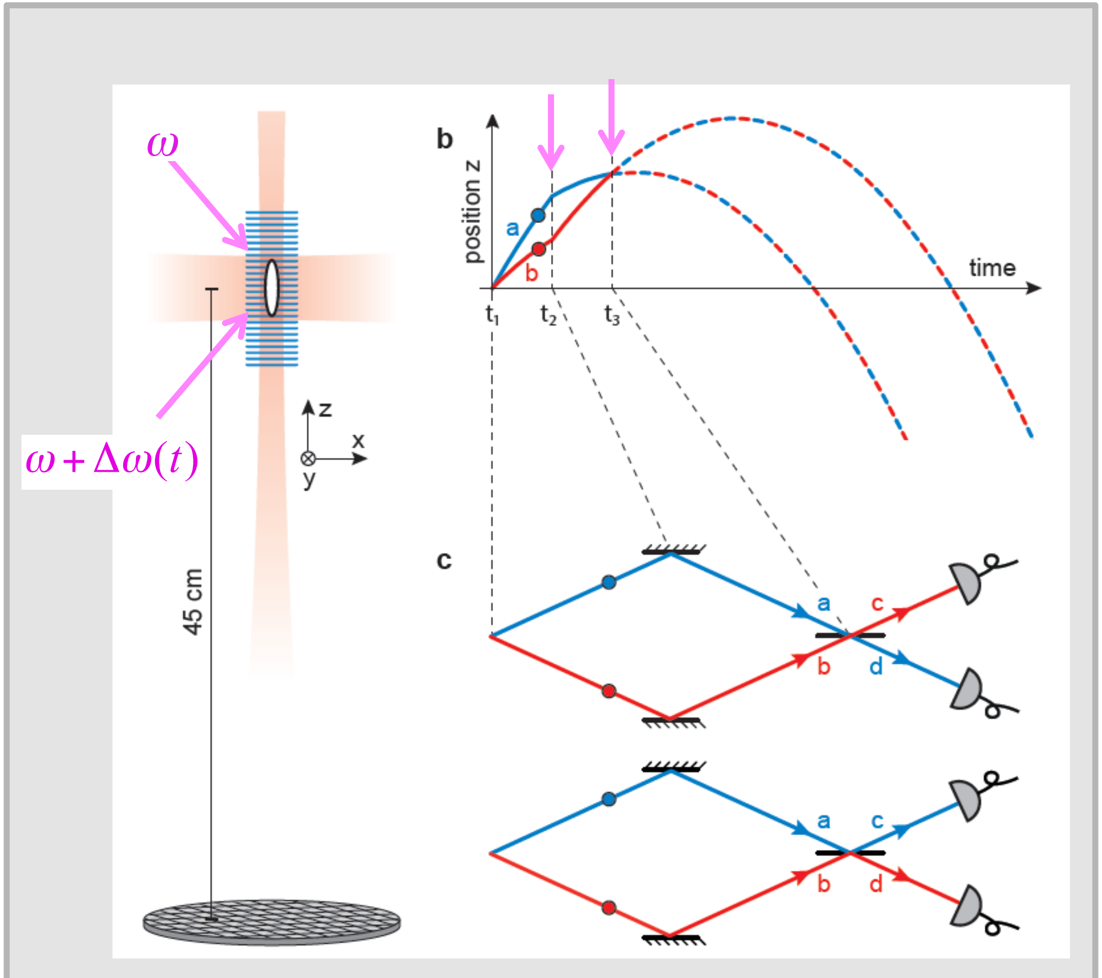
Conjugate modes filtering





We select for each beam small volumes in the velocity space exactly conjugate of each other in the beam-splitter: Indistinguishable modes

Indistinguishable process: HOM scheme



Two indistinguishable paths to go from an initial state (two atoms emitted) to a final state (two atoms detected), with indistinguishable atoms:

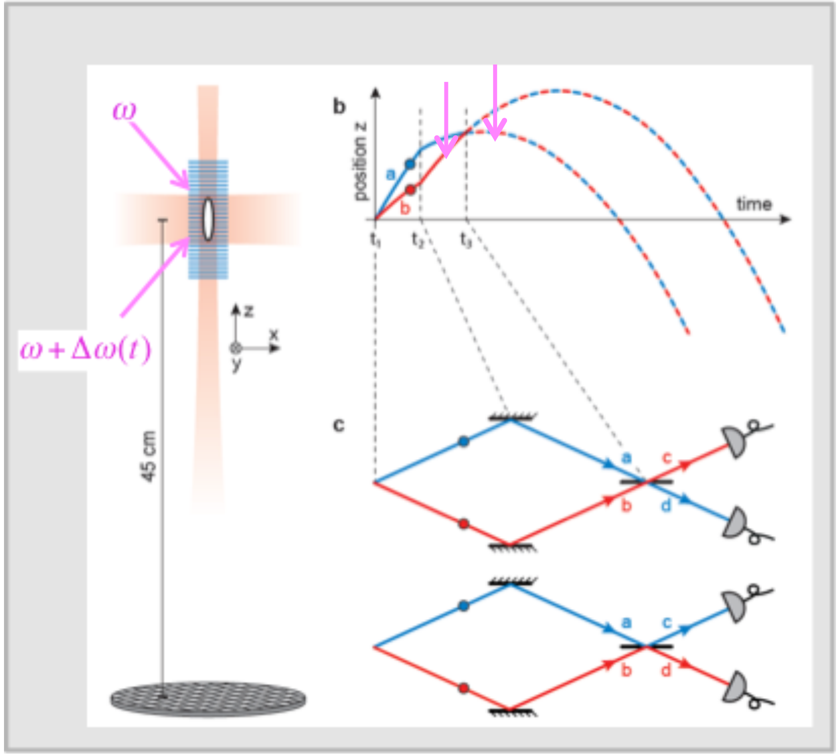
Interference of two atoms amplitudes

Opposite signs because of properties of beam splitter

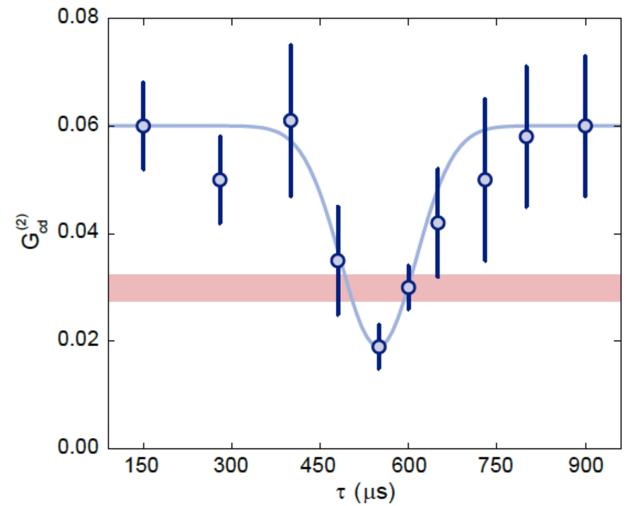
Destructive interference

Null probability to detect atoms on both detectors

Atomic HOM dip



The exact overlap between the modes is scanned by tuning the time of implementation of the beam-splitter



Visibility of the dip larger than 50%: cannot be explained by "ordinary" interferences between "classical" matter-waves: two atom interference effect, in the configuration space of tensor products of the two atoms: no image in ordinary space

The HBT and HOM effects: from photons to atoms

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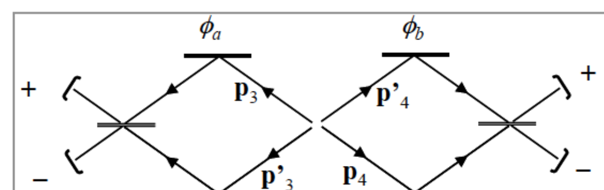
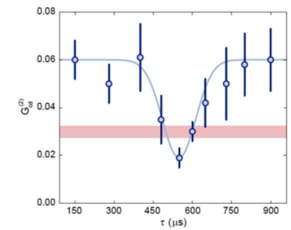


Summary and outlook

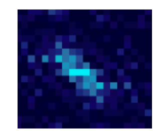
Unambiguous observation of the atomic HOM effect: interference of two-atom amplitudes, second quantum mystery

- Dip below 50% : no wave interpretation possible
- Non zero value of the dip: "slightly more" than one atom in each beam (direct evaluation on our data)

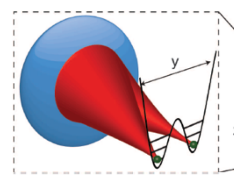


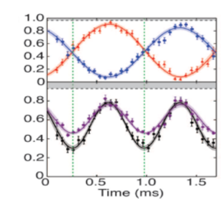
Other demonstrations of two atoms amplitudes interference:

- Atomic Hanbury Brown and Twiss effect (Palaiseau/Amsterdam, Canberra)



- Two-atom Rabi oscillation in tunnel-coupled optical tweezers (Boulder, C Regal, 2013)





- Condensed matter experiments (C Glattli, M Heiblum))

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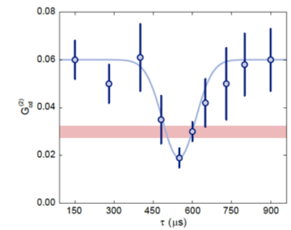

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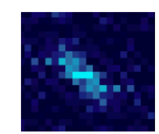

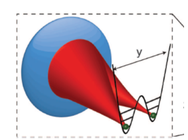

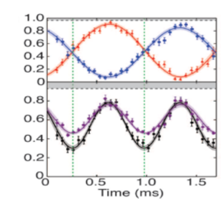

What next ? A yet stronger evidence of entanglement, Bell test

Quantum Optics milestones

Light

- Interference (Young, Fresnel)
- Single photons (1974,1985)
- Photon correlation: HBT (1955)
- $\chi^{(2)}$ photon pairs (1970's)
- Beyond SQL (squeezing, 1985)
- Bell inequalities tests: with radiative cascades (1972, 1982)
- HOM with $\chi^{(2)}$ pairs (1987)
- Bell inequalities tests with $\chi^{(2)}$ pairs (1989-1998-2015)

Atoms

- Interference (1990)
- Single atoms (2002)
- Atom correlations: HBT (2005)
- $\chi^{(3)}$ photon pairs (2007)
- Beyond SQL (squeezing, 2010)
- Bell inequalities tests with molecule dissociation ?
- HOM with $\chi^{(3)}$ pairs (2014)
- Bell inequalities tests with $\chi^{(3)}$ pairs ?

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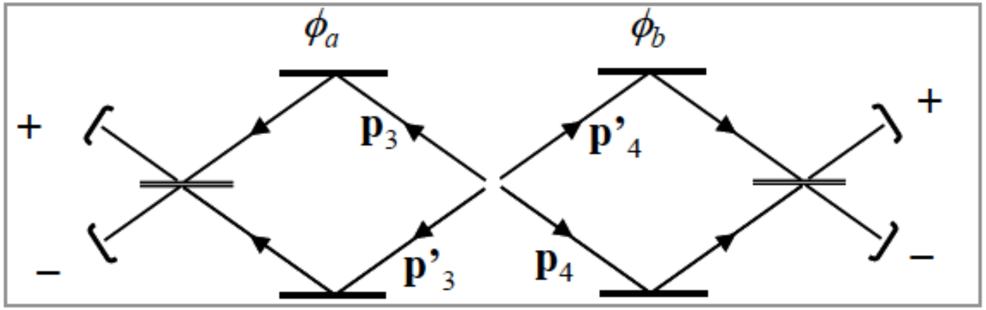
- Bell inequalities tests with molecule dissociation ?
- HOM with $\chi^{(3)}$ pairs (2014)
- Bell inequalities tests with $\chi^{(3)}$ pairs ?

A Bell inequalities test with entangled atom momenta

Our scheme (cf. Rarity - Tapster experiment with photons, 1990)

$$|\Psi\rangle = \sqrt{\frac{1}{2}}\left(|p_3, p_4\rangle + |p'_3, p'_4\rangle\right)$$



Test of Bell's inequalities
with mechanical observables of massive particles

Frontier between QM and gravity ?
(Decoherence due to quantum fluctuations?)

The HBT and HOM effects: from photons to atoms

1. Two “quantum mysteries”
2. The HBT effect with photons
3. Quantum Atom Optics with He*: HBT
4. The HOM effect with photons
5. HOM effect with atoms
6. Outlook