Title: From Bell's inequalities to CHSH : from a Gedanken Experiment to the possibility of real experiments

Date: Jul 20, 2006 09:15 AM

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Abstract:

Institut d'Optique

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

Perimeter Institute, July 20th, 2006

In honour of Abner Shimony

The atomic Hanbury Brown and Twiss effect: another example of quantum weirdness

Alain Aspect, Groupe d'Optique Atomique
Laboratoire Charles Fabry de l'Institut d'Optique
http://www.atomoptic.fr

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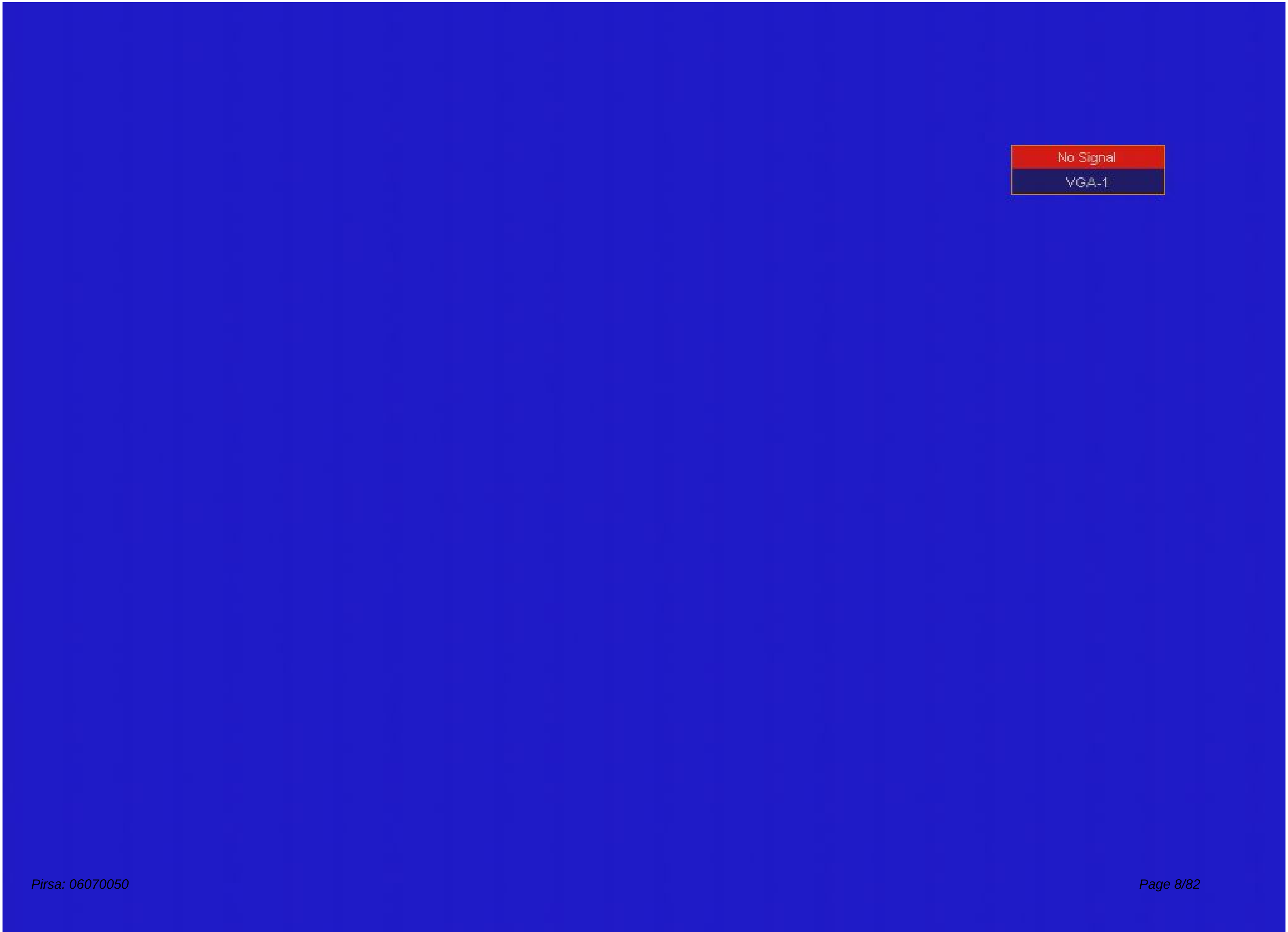
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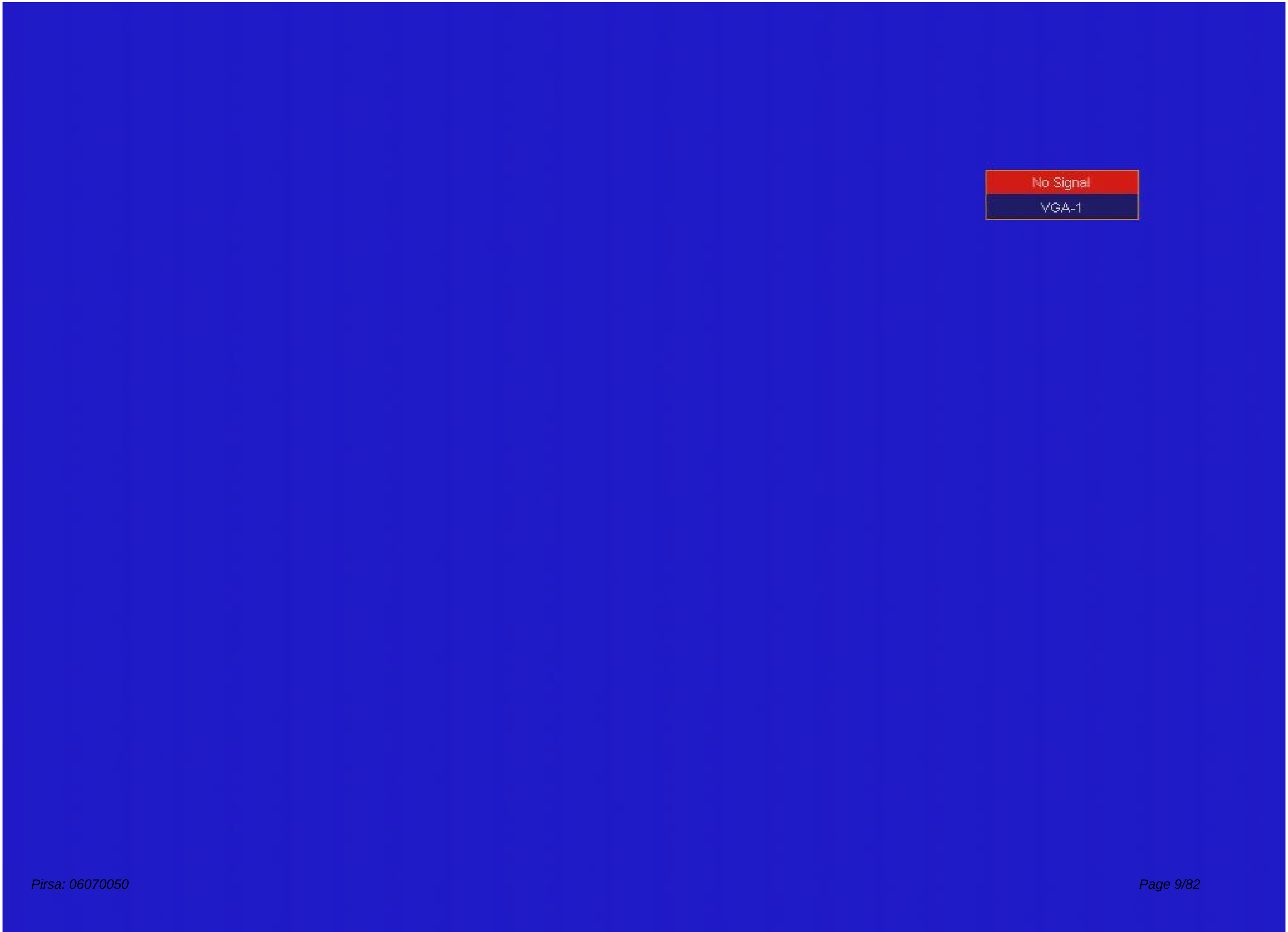
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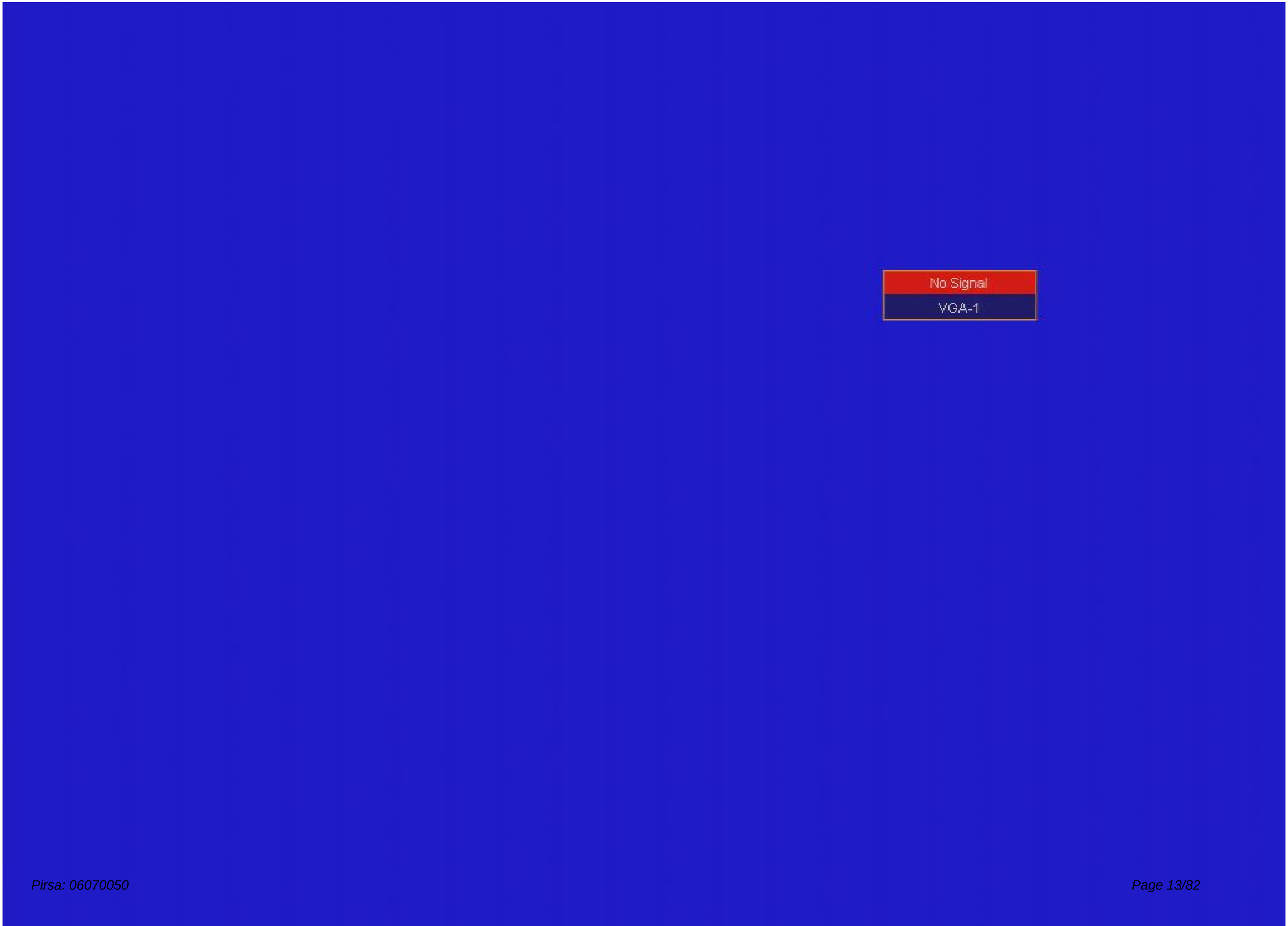
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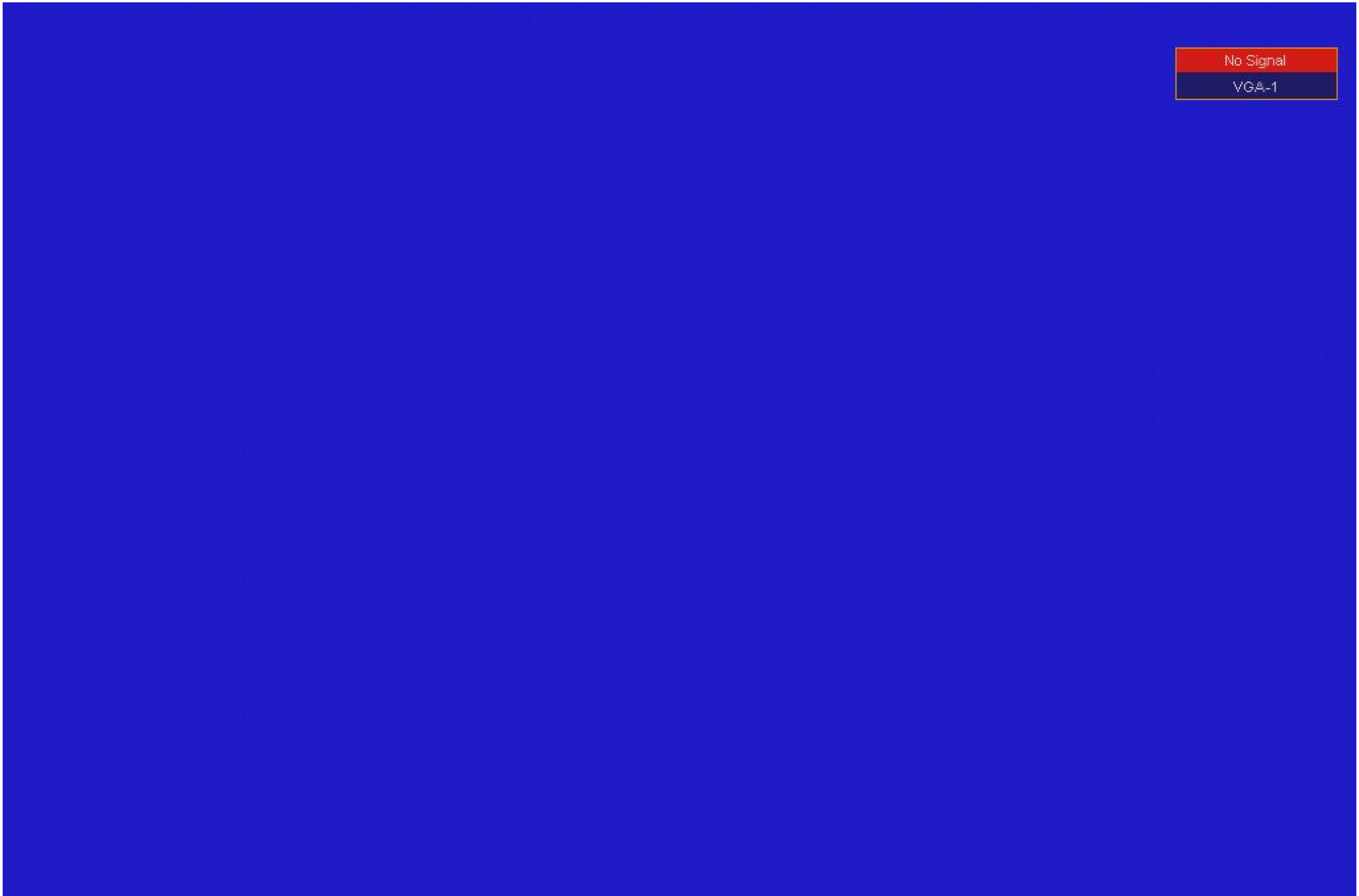
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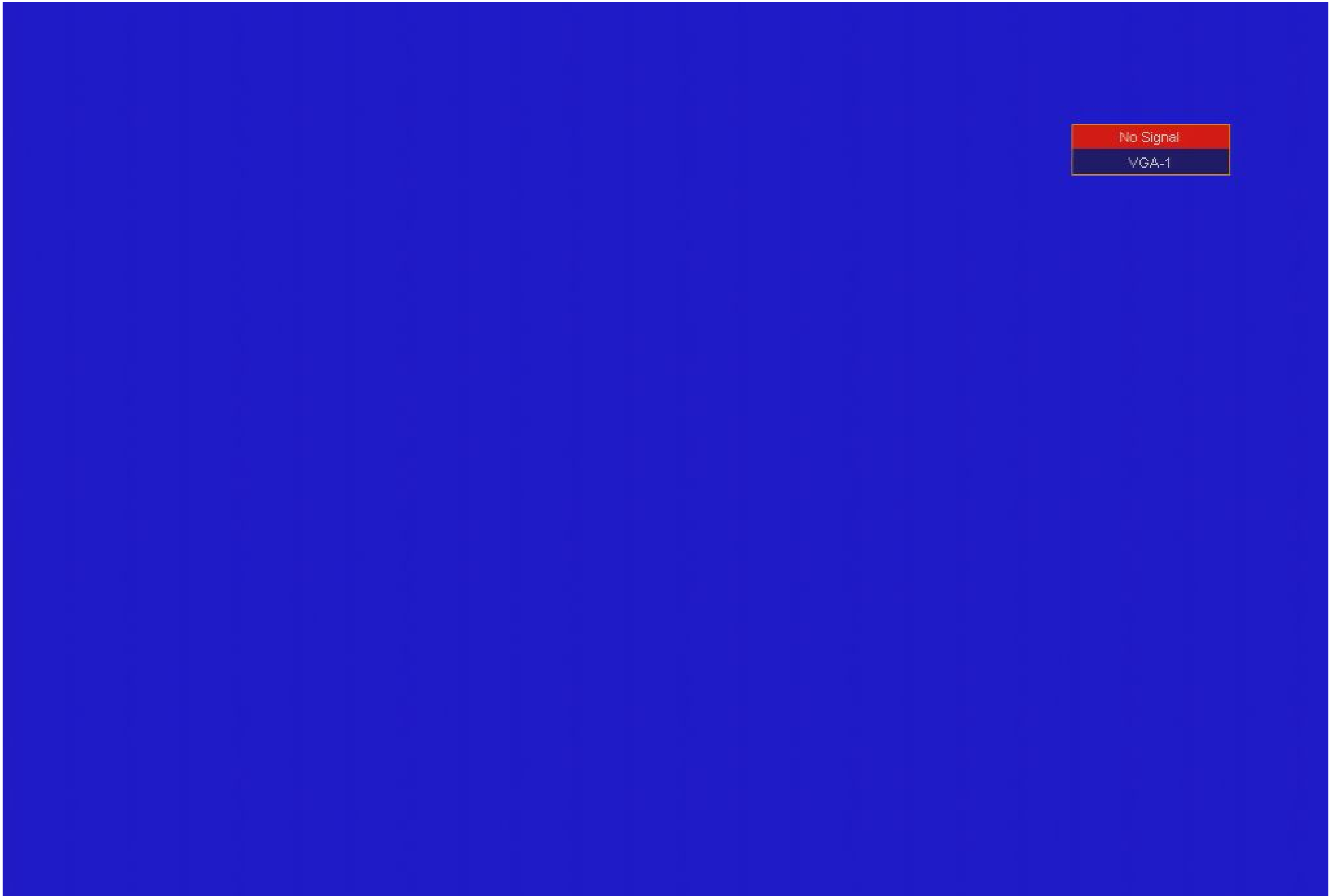
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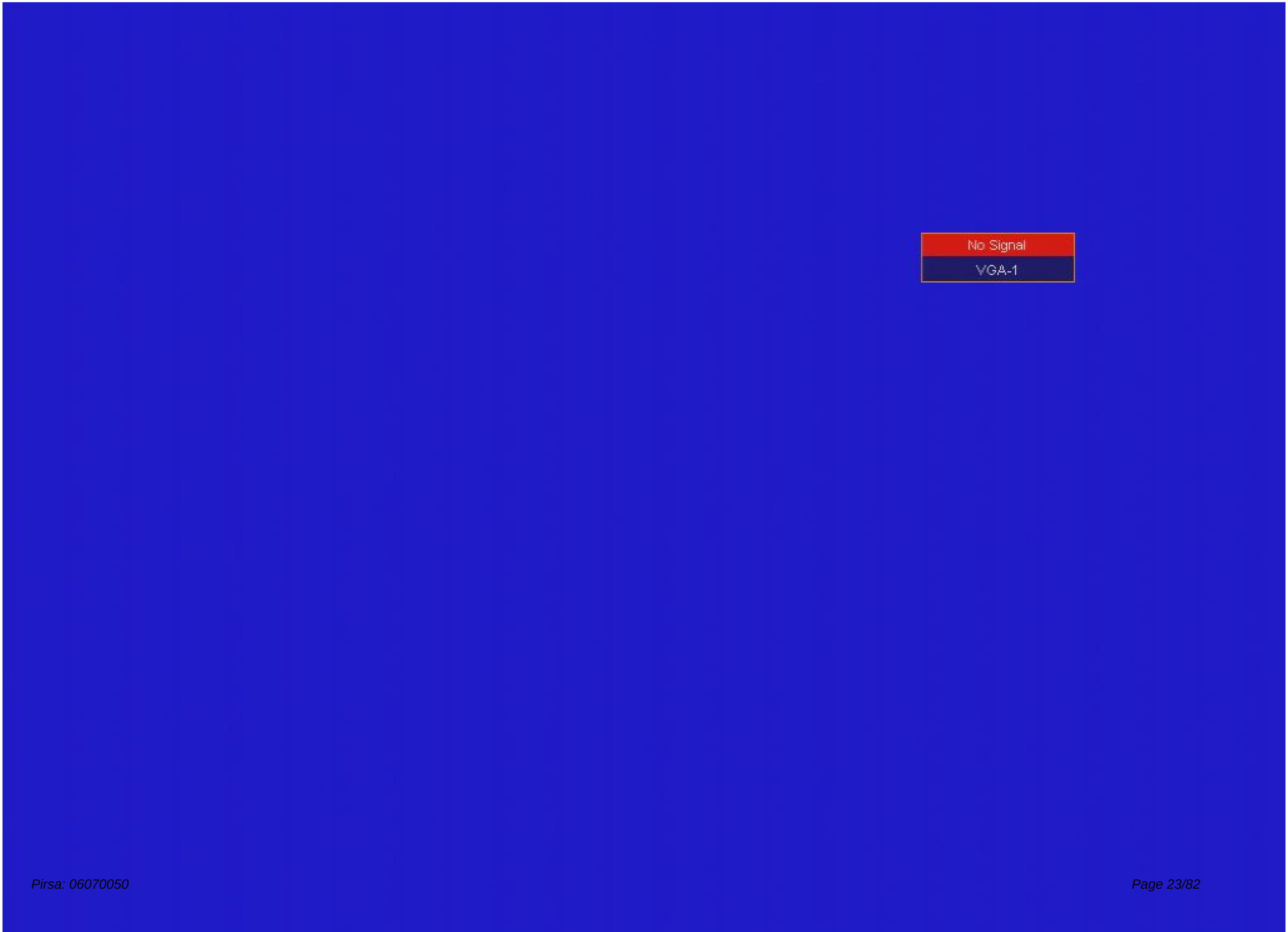
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Atomic Hanbury Brown and Twiss effect with He*: a step in quantum atom optics

- The H. B. & T. experiment with light: a landmark in quantum (photon) optics
- The HB&T effect with massive particles
- Ultra cold He* with a space and time resolved single atom detector: a complete atomic HB&T experiment
- Towards an ideal CHSH test with entangled He* atoms?

The HB&T experiment

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

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

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

Measure of the correlation function of the light intensity:

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

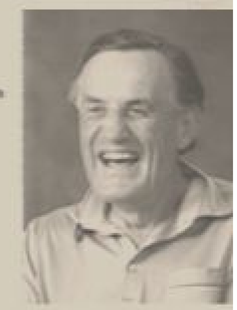
NATURE January 7, 1956 VOL. 177

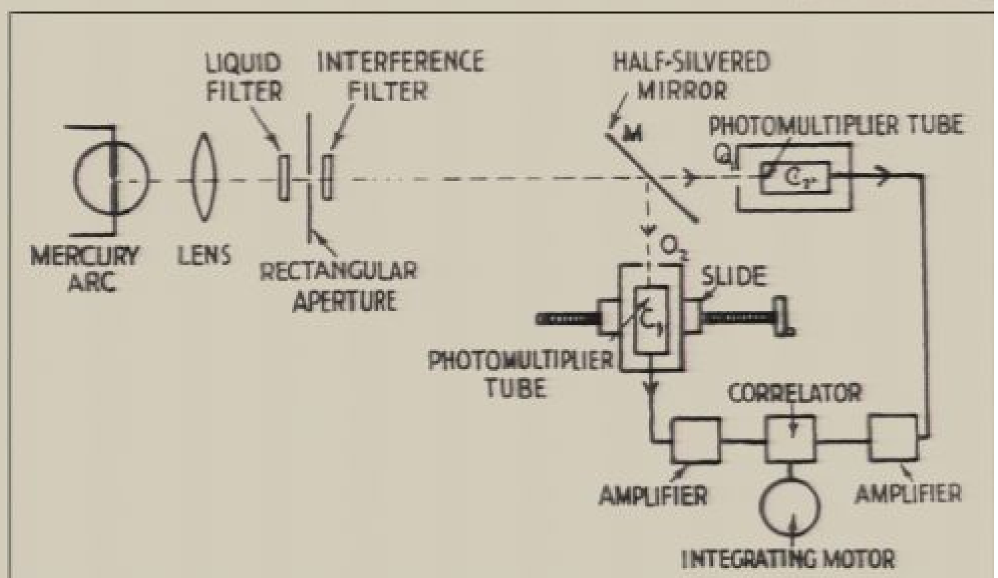
CORRELATION BETWEEN PHOTONS IN TWO COHERENT BEAMS OF LIGHT

By R. HANBURY BROWN
University of Manchester, Jodrell Bank Experimental Station

AND

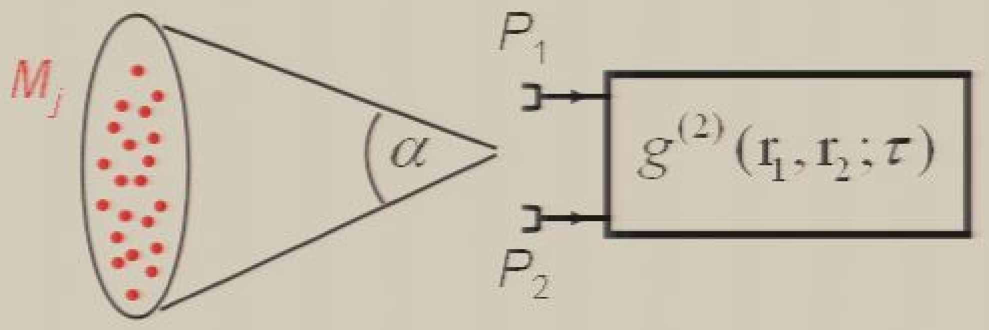
R. Q. TWISS
Services Electronics Research Laboratory, Baldock



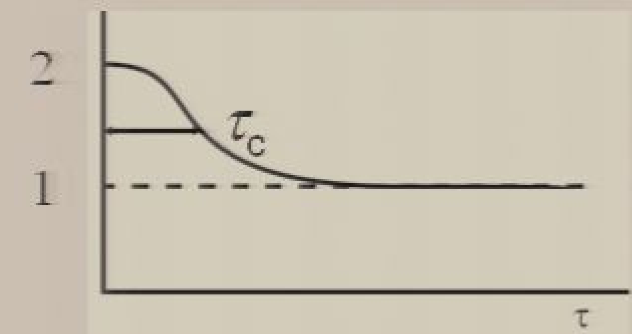


The HB&T effect

Light from incoherent source: time and space correlations



$$g^{(2)}(r_1 = r_2; \tau) > 1$$



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

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

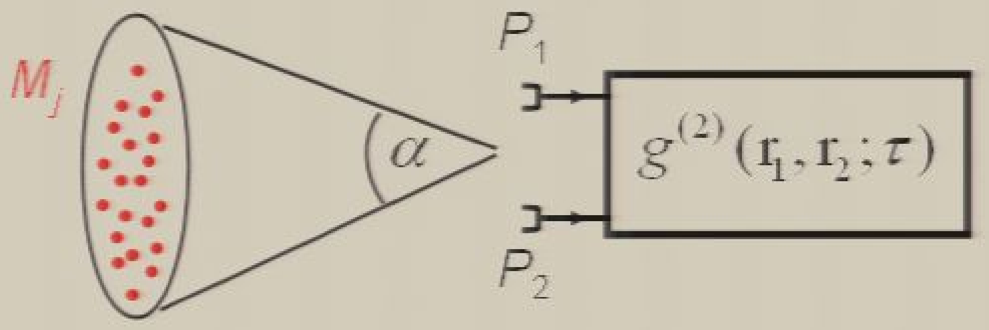
A measurement of $g^{(2)} - 1$ *vs.* τ and $\mathbf{r}_1 - \mathbf{r}_2$ yields the coherence volume

- time coherence

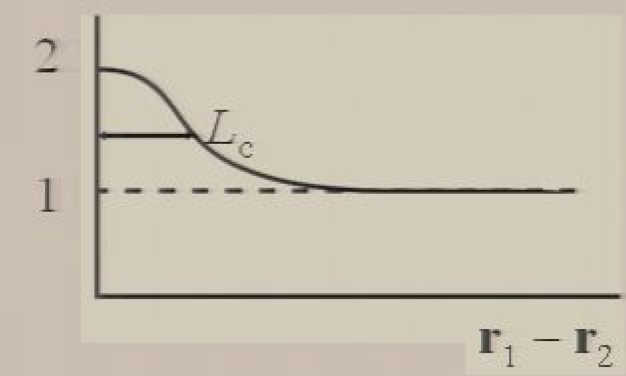
$$\tau_c \approx 1/\Delta\omega$$

The HB&T effect

Light from incoherent source: time and space correlations



$g^{(2)}(r_2 - r_1; \tau = 0) > 1$



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- time coherence

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

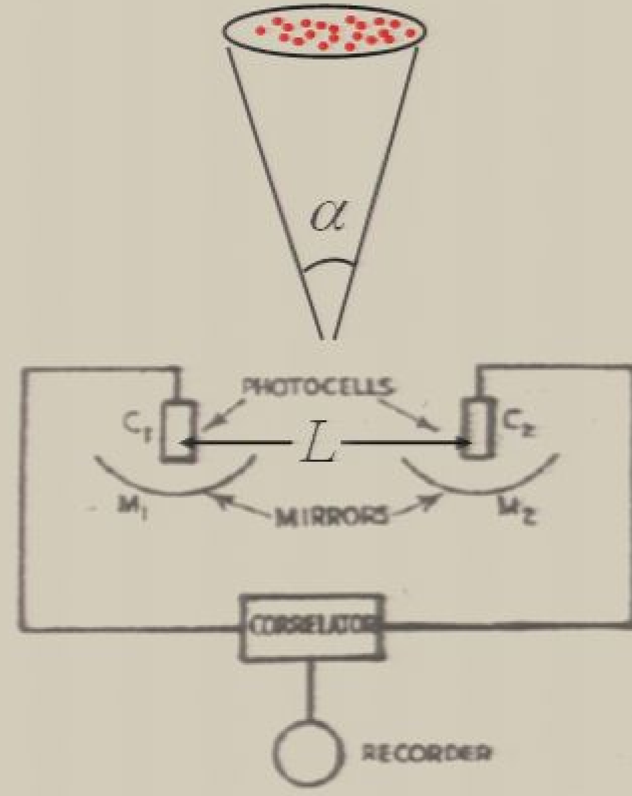
- space coherence

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

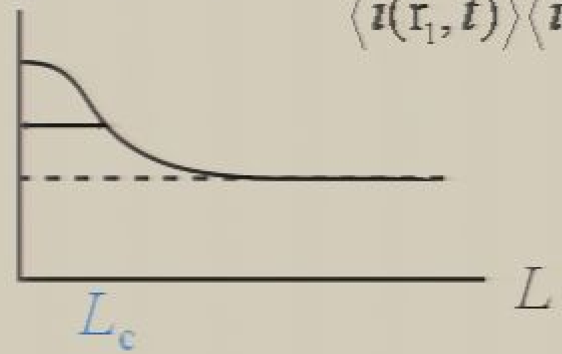
The HB&T stellar interferometer

Measure of the coherence area

$\Rightarrow$ angular diameter of a star



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

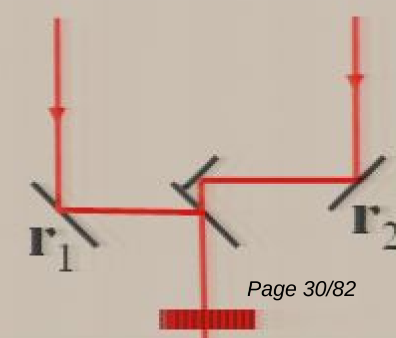


$$\alpha = \frac{\lambda}{L_\mathrm{C}}$$

Equivalent to the Michelson stellar interferometer ?

Visibility of fringes

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



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Measure of the coherence area

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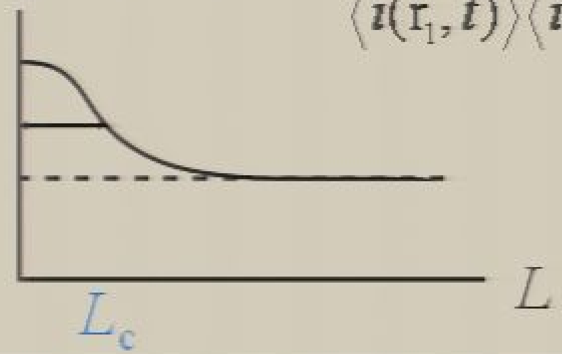
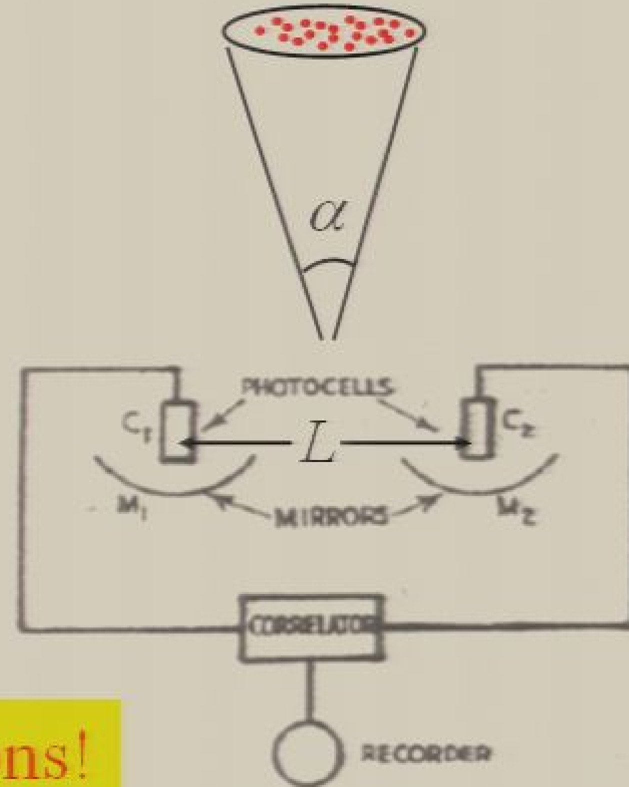
$$g^{(2)}(L;0)=\frac{\langle i(\mathbf{r}_1,t)\,i(\mathbf{r}_1+L,t+\tau)\rangle}{\langle i(\mathbf{r}_1,t)\rangle\langle i(\mathbf{r}_2,t)\rangle} \Rightarrow L_C$$



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

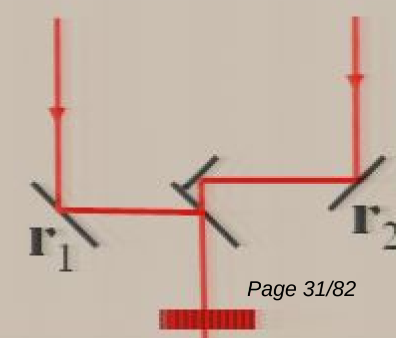


HB&T insensitive to atmospheric fluctuations!

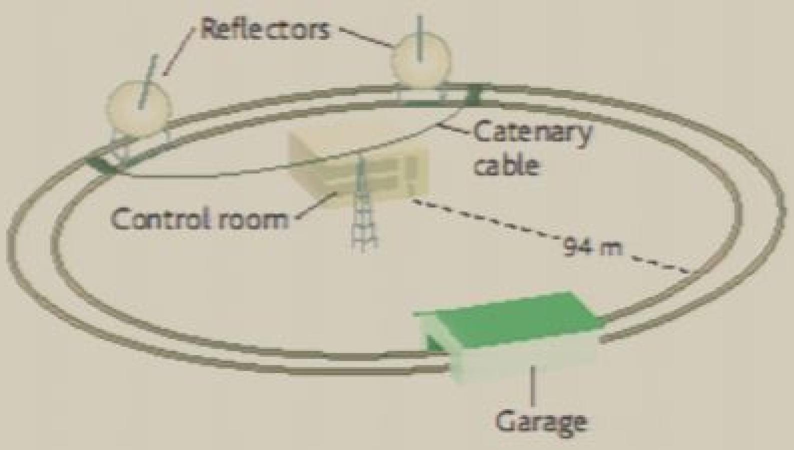
Equivalent to the Michelson stellar interferometer ?

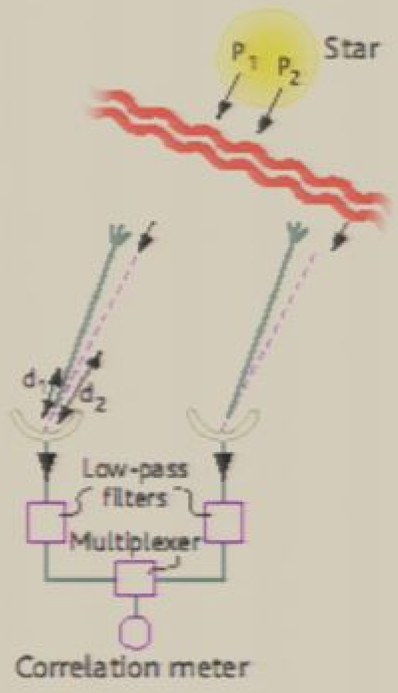
Visibility of fringes

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



The HB&T stellar interferometer





NATURE November 10, 195

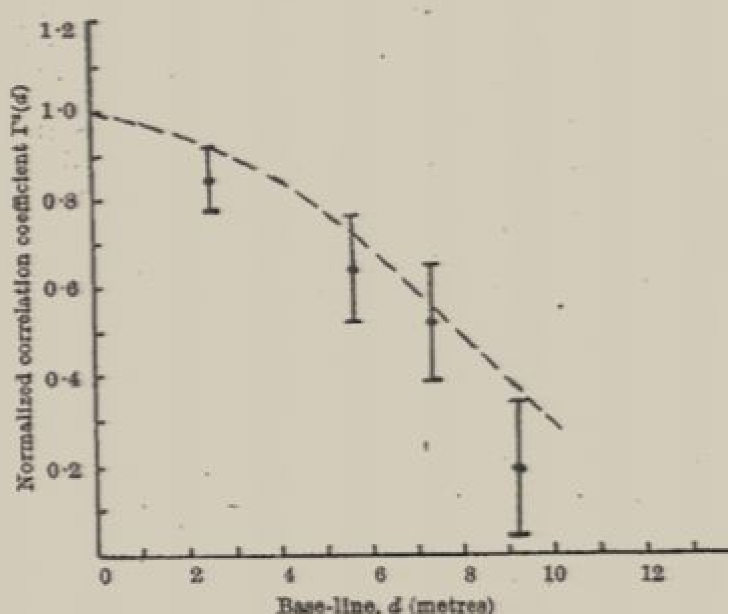


Fig. 2. Comparison between the values of the normalized cor relation coefficient Γ²(d) observed from Sirius and the theoretica values for a star of angular diameter 0·0068″. The errors show are the probable errors of the observations

A TEST OF A NEW TYPE OF STELLAR INTERFEROMETER ON SIRIUS

By R. HANBURY BROWN

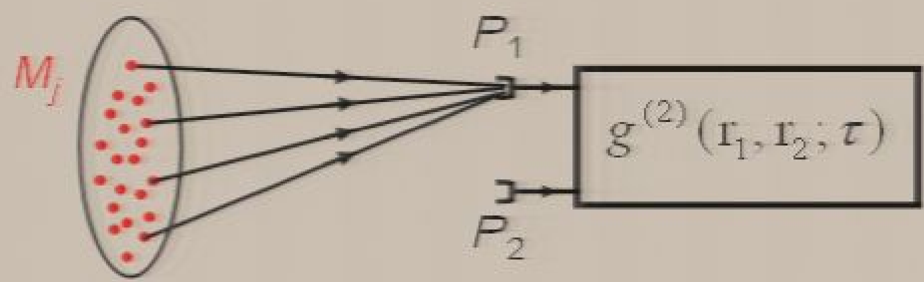
Jodrell Bank Experimental Station, University of Manchester

AND

Dr. R. Q. TWISS

Services Electronics Research Laboratory, Baldock

Classical wave explanation for HB&T correlations (1)



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

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

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

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

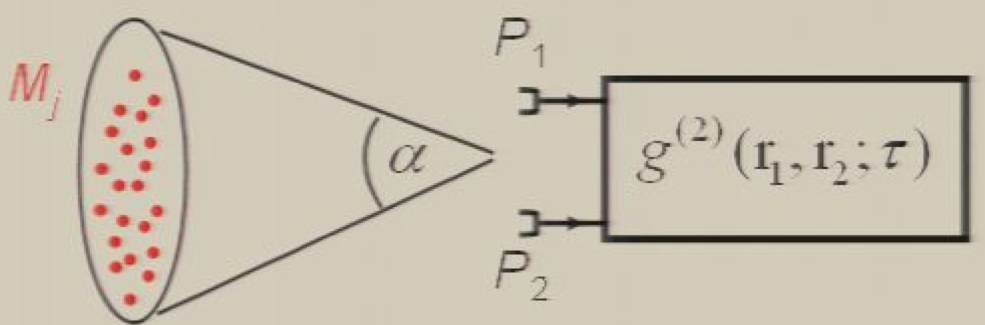
$$g^{(1)}(\mathrm{r}_1, \mathrm{r}_2; \tau) = \frac{\langle \mathcal{E}^*(\mathrm{r}_1, t) \mathcal{E}(\mathrm{r}_2, t+\tau) \rangle}{\langle |\mathcal{E}(\mathrm{r}_1, t)|^2 \rangle^{1/2} \langle |\mathcal{E}(\mathrm{r}_2, t+t)|^2 \rangle^{1/2}}$$

Stochastic process

$\langle\rangle$ = statistical (ensemble) average

(= time average if stationary and ergodic

Classical wave explanation for HB&T correlations (1')



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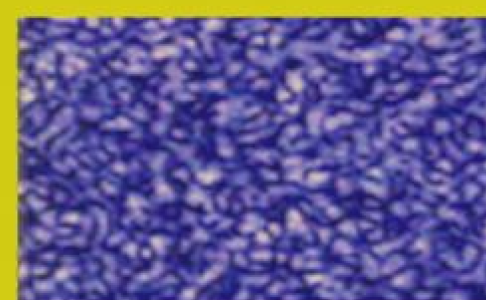
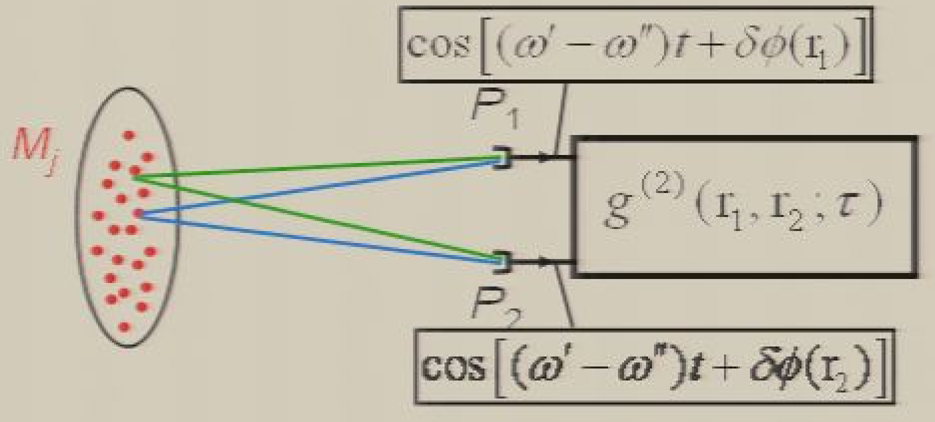
Gaussian random process $\Rightarrow$ $g^{(2)}(\mathbf{r}_1, \mathbf{r}_2; \tau) = 1 + \left|g^{(1)}(\mathbf{r}_1, \mathbf{r}_2; \tau)\right|^2$

Speckle in the observation plane:

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



Classical wave explanation for HB&T correlations (2)



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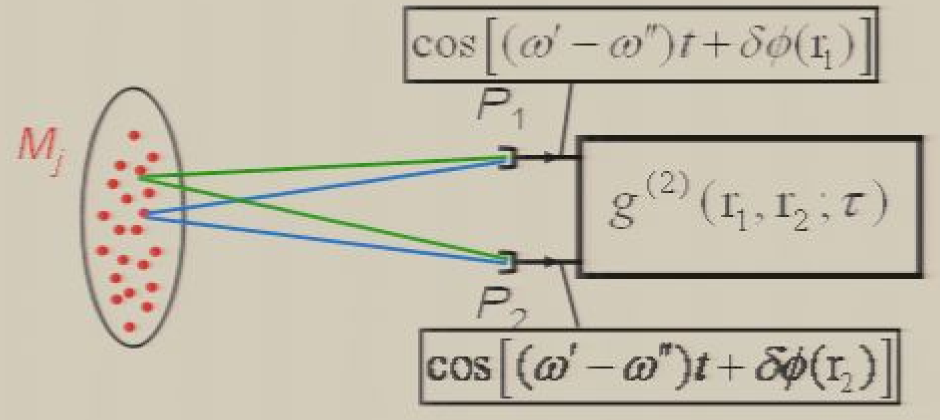
Noise excess, due to beat notes between various spectral components from various emitters, is correlated in coherence volume $\left|\delta\phi(\mathrm{r}_1) - \delta\phi(\mathrm{r}_2)\right| < \pi/2$

Classical wave explanation for HB&T correlations (2)



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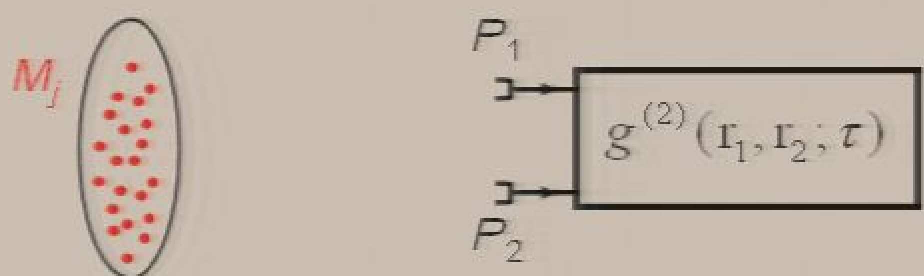
Simple explanation for insensitivity to atmospheric turbulence:

- path fluctuations small compared to "effective wavelength" $\lambda = c/(\omega'-\omega'')$ of beat note
- but large at the scale of optical wavelength: Michelson fringes move

The HB&T effect with photons: a hot debate

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

In term of photons



joint detection probability

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

single detection probabilities

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

$g^{(2)}(0) = 2 \Rightarrow$ 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

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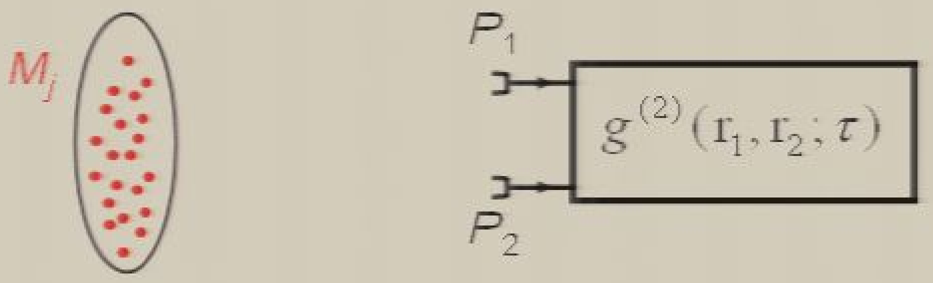

How might photons emitted from distant points in an incoherent source (possibly a star) not be statistically independent ?

HB&T answer

- Experimental demonstration!
- Light is both wave and particles.
  - ➢ Uncorrelated detections easily understood as independent particles (shot noise)
  - ➢ Correlations (excess noise) due to beat notes of random waves

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

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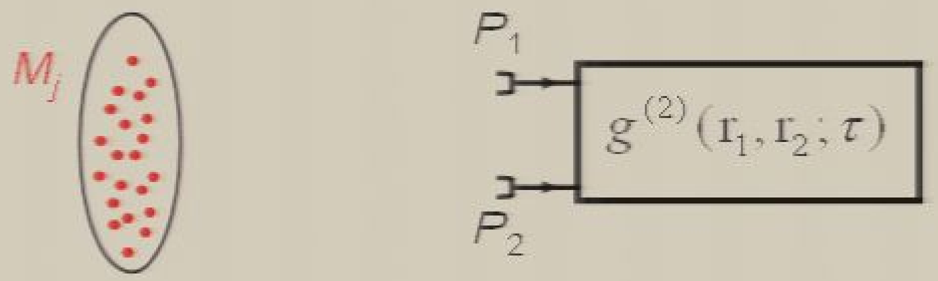

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cf. Einstein's discussion of wave particle duality in Salzburg (1909), about black body radiation fluctuations

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

Two photon emitters, two detectors

Initial state:

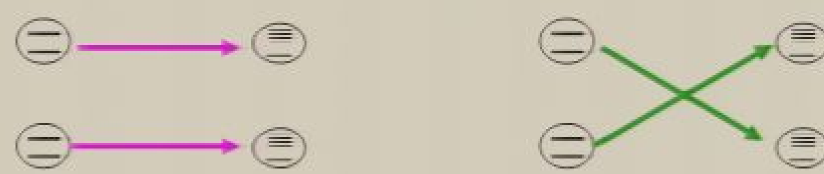
- Emitters excited
- Detectors in ground state

⇒

Final state:

- Emitters in ground state
- Detectors ionized

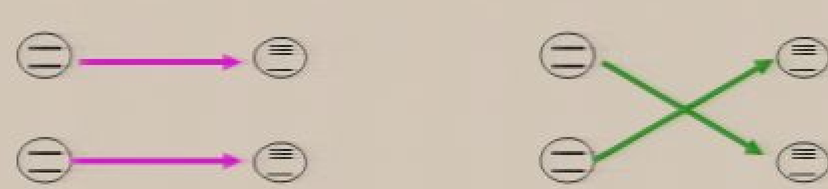
Two paths to go from THE initial state to THE final state



Amplitudes of the two process interfere ⇒ factor 2

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



Two photon interference effect: quantum weirdness

- happens in configuration space, not in real space
- A precursor of entanglement, HOM, etc…

Lack of statistical independence (bunching) although no "real" interaction

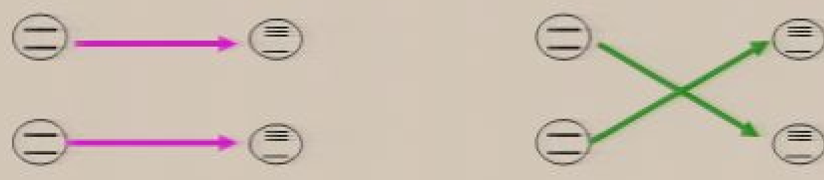
cf Bose-Einstein Condensation (letter from Einstein to Schrödinger, 1924)

… but a trivial effect for a radio (waves) engineer or a physicist working in classical optics (speckle)

$$\left\langle I(t)^2 \right\rangle \geq \left\langle I(t) \right\rangle^2$$

The HB&T effect with fermions: a fully quantum effect

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

- happens in configuration space, not in real space
- A precursor of entanglement etc…

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

Intensity correlation with laser light: more confusion

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: quantum theory of coherence : no bunching for laser light (quasi classical state of a single mode) $g^{(2)}(\mathbf{r}_2 - \mathbf{r}_1; t_2 - t_1) = 1$
- 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 correlation with laser light:

1960:

•1961:
to obs

•1963
laser li

•1965:
laser:
below

•1966

PHOTON CORRELATIONS*

Phys Rev Lett 1963

Roy J. Glauber
Lyman Laboratory, Harvard University, Cambridge, Massachusetts
(Received 27 December 1962)

In 1956 Hanbury Brown and Twiss[1] reported that the photons of a light beam of narrow spectral width have a tendency to arrive in correlated pairs. We have developed general quantum me-

tons counted in an incoherent beam. The fact that photon correlations are enhanced by narrowing the spectral bandwidth has led to a prediction[2] 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.

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Intensity correlation with laser light: more confusion

VOLUME 14, NUMBER 3 PHYSICAL REVIEW LETTERS 18 JANUARY 1965

INTENSITY FLUCTUATIONS IN A GaAs LASER

J. A. Armstrong and Archibald W. Smith
IBM Watson Research Center, Yorktown Heights, New York
(Received 19 November 1964)

the laser begins to oscillate. Below threshold the mode emits random noise like a narrow-band black-body source; above threshold its noise is characteristic of a quieted, amplitude-stabilized oscillator. Our measurements of the

1960

- 1961
to ob
- 1963
laser
- 1965
laser:
below threshold

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

Simple classical model for laser light:

$$\mathcal{E} = E_0 \exp\{-i\omega t + \phi_0\} + e_n \qquad |e_n| \ll |E_0| \quad \Longrightarrow \quad I(t) = |\mathcal{E}|^2 = |E_0|^2 = \text{cst}$$

$$\langle I(t)^2 \rangle = \langle I(t) \rangle^2$$

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- 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 $g^{(2)}(\tau)$

Simple classical model for laser light:

$$\mathcal{E}=E_0\exp\{-i\omega t+\phi_0\}+e_n \qquad |e_n|\ll|E_0| \Longrightarrow \qquad I(t)=|\mathcal{E}|^2=|E_0|^2=\text{cst}$$

$$\langle I(t)^2\rangle=\langle I(t)\rangle^2$$

Intensity correlation with laser light:

1960: invention of

•1961: Mandel & \
to observe with a l

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laser light (quasi c

•1965: Armstrong
laser: no bunchin
below threshold

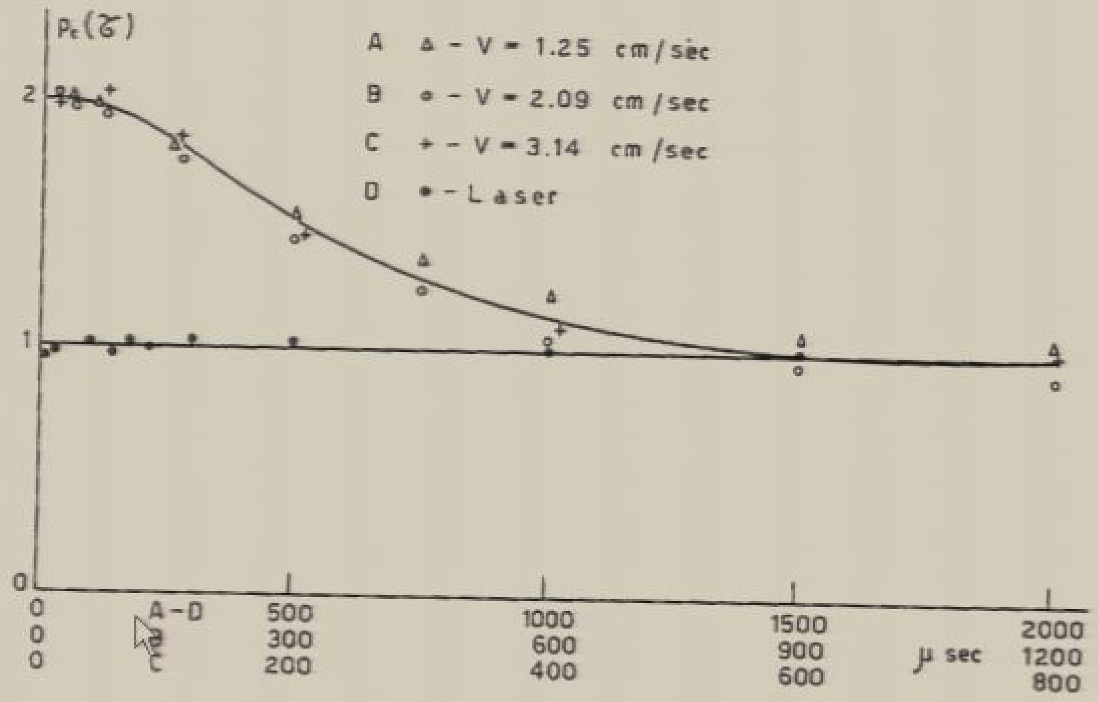

Fig. 1. Conditional probability $p_C(\tau)$ of a second count occurring at a time τ after a first has occurred at time $\tau = 0$.

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$t_1) = 1$

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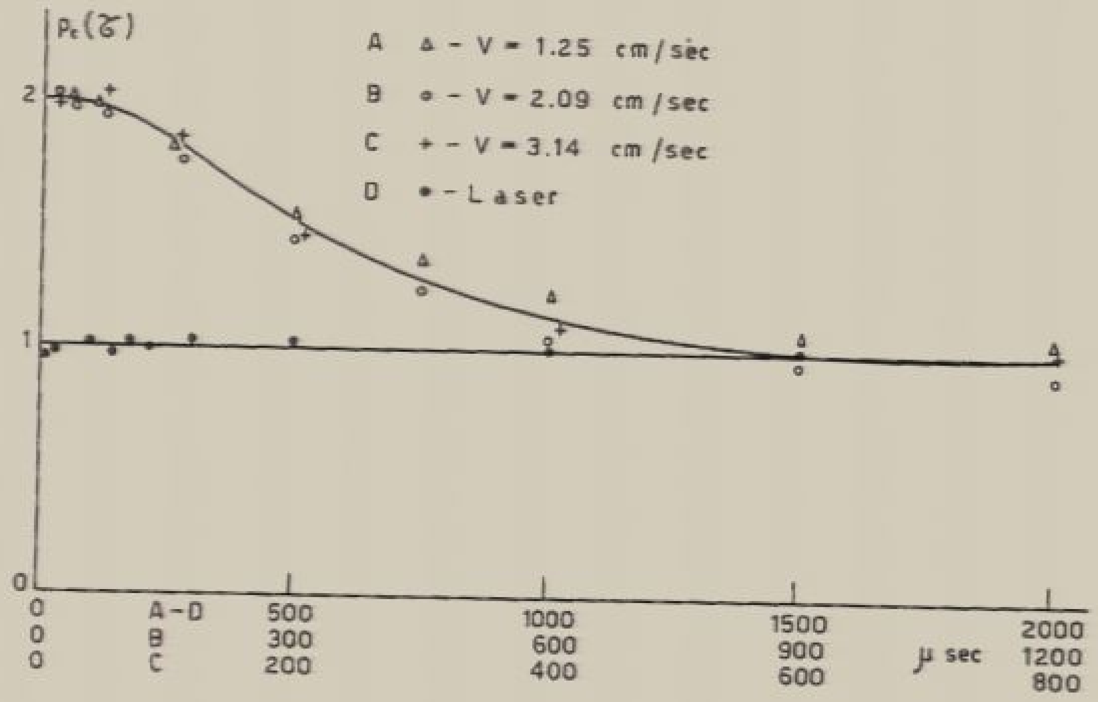

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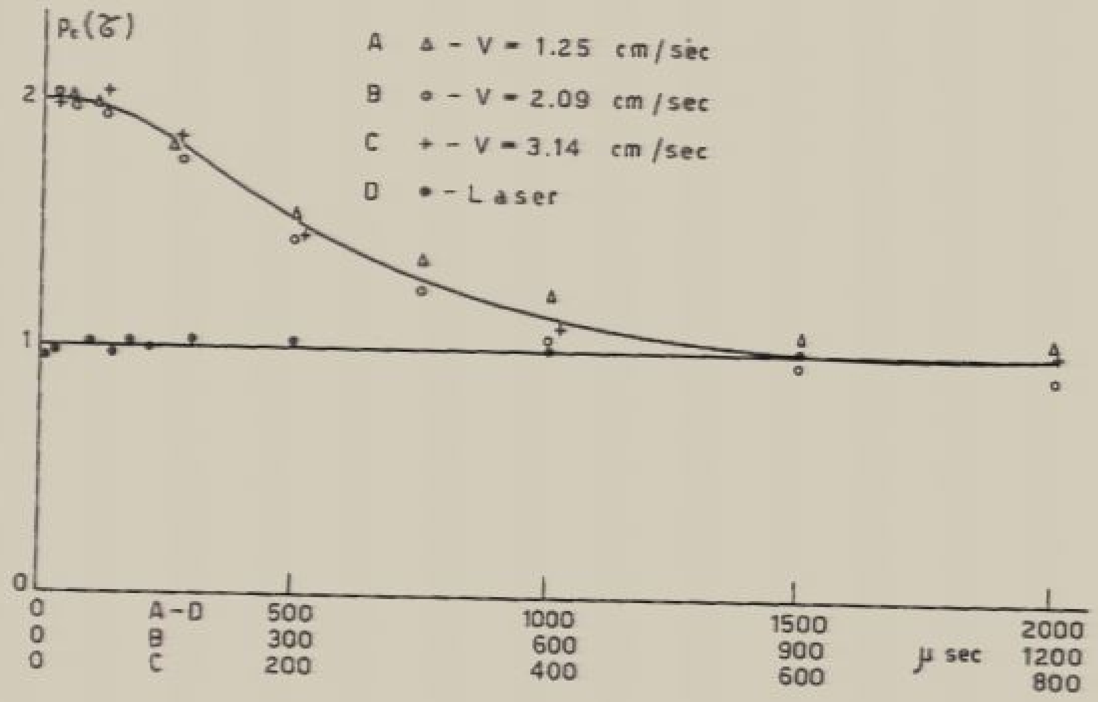

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Intensity correlation with laser light: more confusion

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

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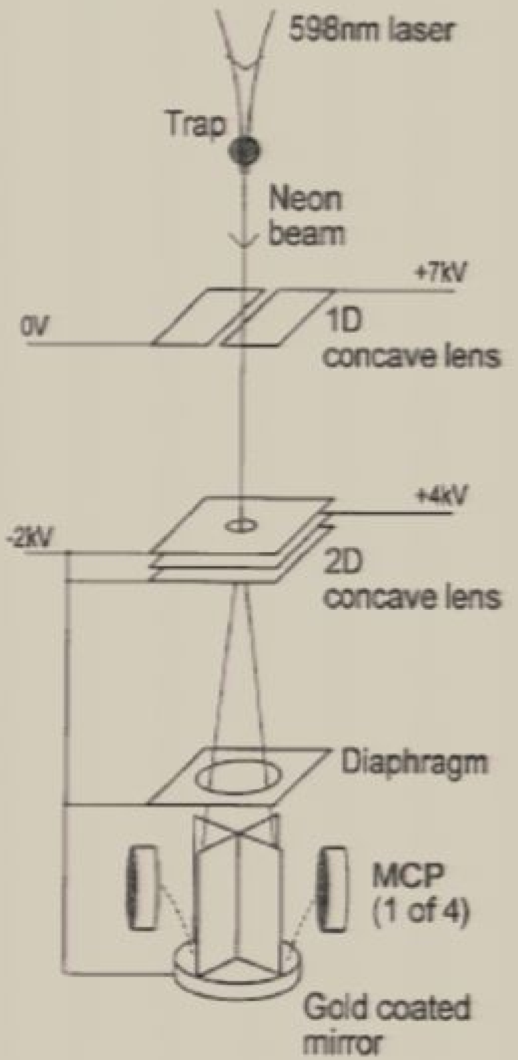
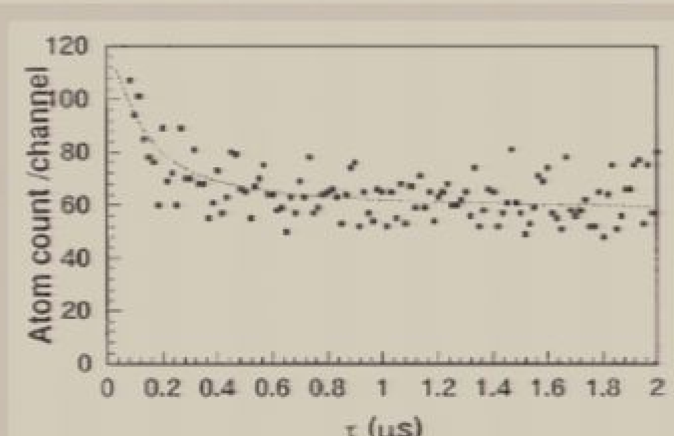
The HB&T effect with atoms: Yasuda and Shimizu, 1996



- Cold neon atoms in a MOT (100 μK) continuously pumped into a non trapped (falling) metastable
  - 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 $>> L_C$
- Coherence time as predicted: $\hbar / \Delta E \approx 0.2\,\mu s$



A wonderful experiment. No complete study of $g^{(2)}(\mathbf{r}_1, \mathbf{r}_2; \tau)$

HB&T type effects with particles

Atomic density correlations for bosonic atoms

- $g^{(3)}(0) = 3!$ (JILA, 1997): 3 body collisions in a thermal cloud, in contrast to a BEC (Kagan, Svistunov, Shlyapnikov, JETP lett 1985)
- $g^{(2)}(0) = 2$ (MIT, 1997): Interaction energy of a thermal gas
- Correlations in a quasicondensate (Hannover 2003)
- Correlations in the atom density fluctuations in cold atomic samples
  - ➢Atoms released from a Mott phase (Mainz, 2005)
  - ➢Molecules dissociation (D Jin et al., Boulder, 2005)
  - ➢Atomic density fluctuations in a thermal gas on an atom chip (Orsay, 2005)

Also observed in nuclear and particle physics

G. Baym, Acta Phys. Pol. B 29, 1839 (1998).

HB&T effect with fermionic particles

Fermionic antibunching observed with electrons

2D electron gas in a semi-conductor

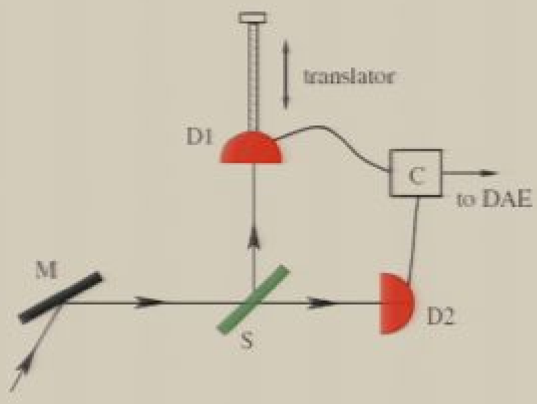
M. Henny et al., (1999); W. D. Oliver et al.(1999);

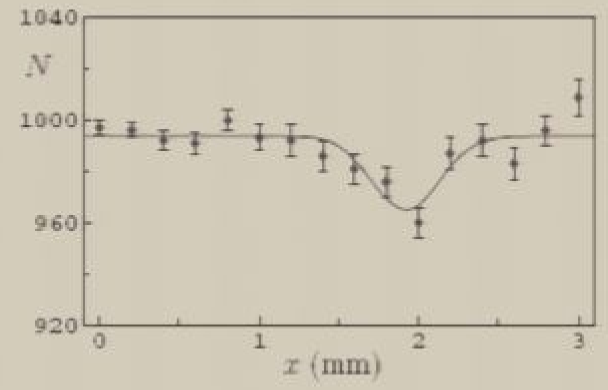
Low density electron beam

H. Kiesel et al. (2002)

Fermionic antibunching observed with neutrons

Iannuzzi et al.(2005).





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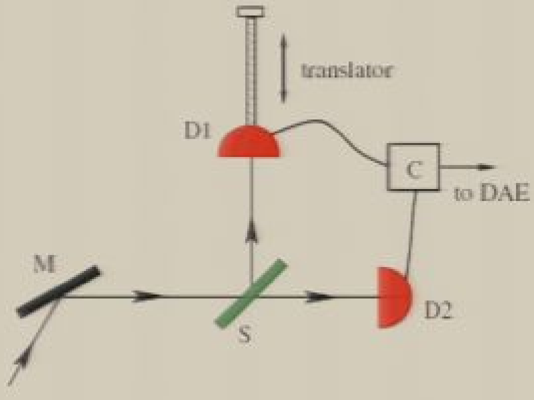

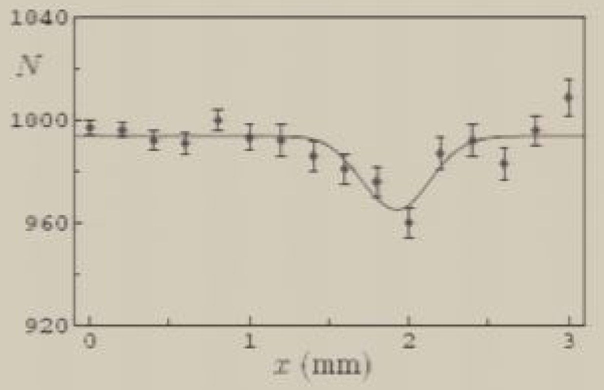

Fermionic atoms?

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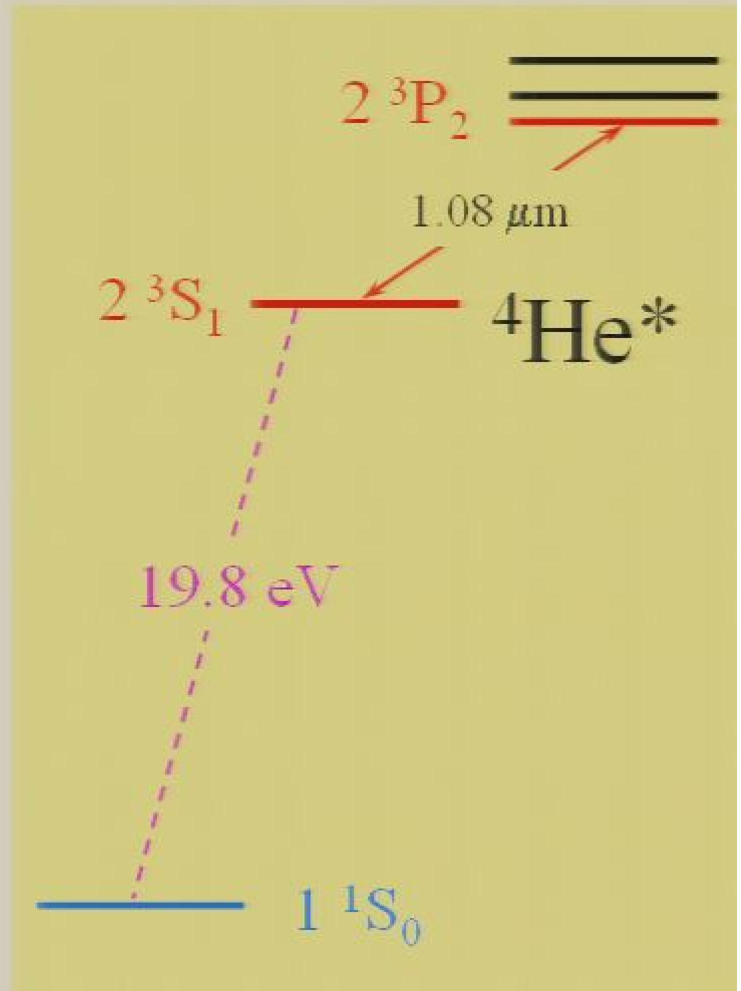
Metastable bosonic Helium $^4He^*$

- 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 colliding atoms or molecules
  - ⇒ extraction of electron from metal: single atom detection with Micro Channel Plate detector



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He* trap and MCP detection

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

(1200 Hz)

He* on the Micro Channel Plate detector:

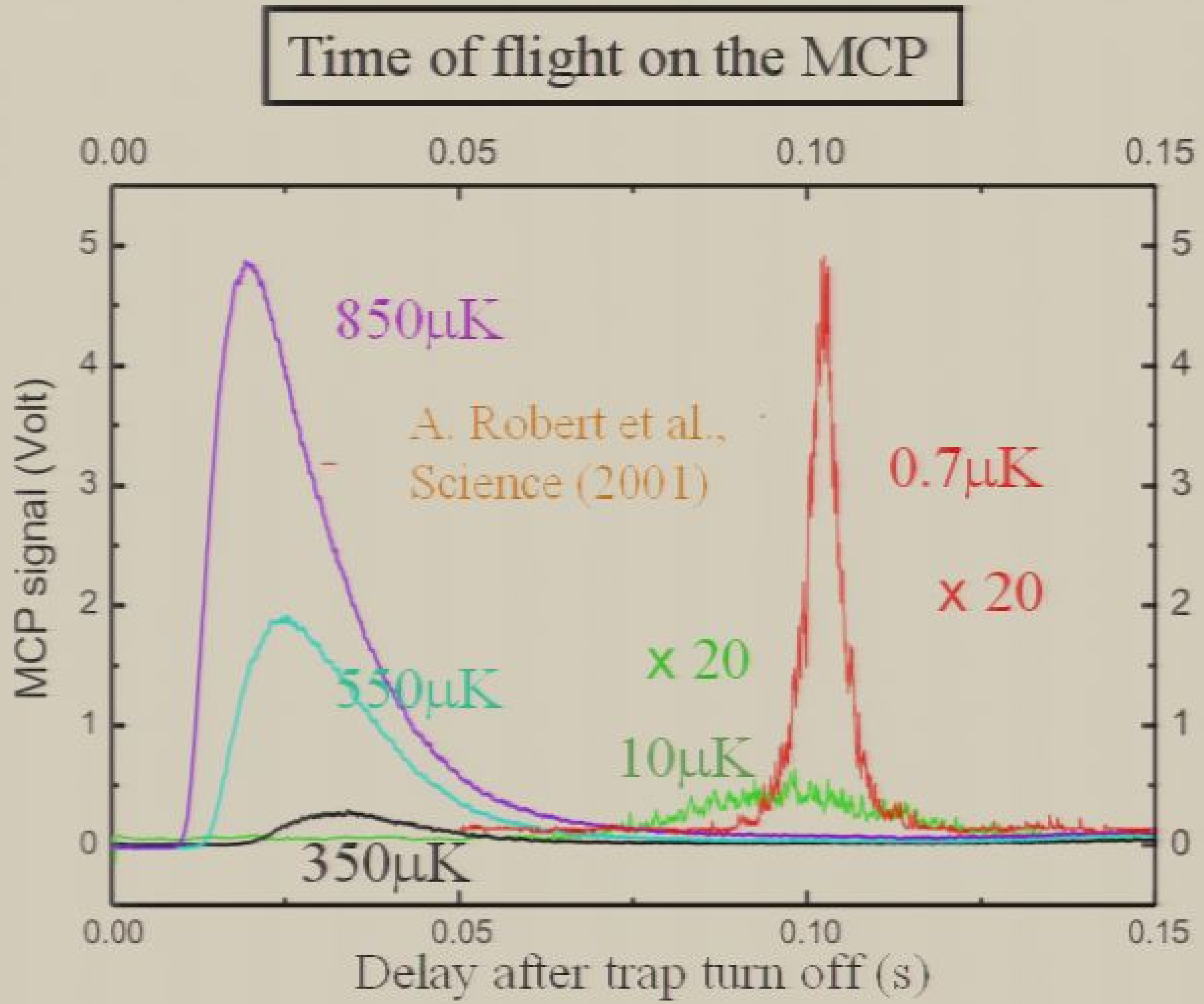
⇒ an electron is extracted

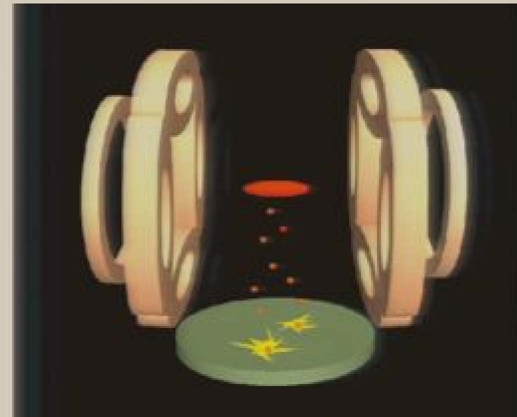
⇒ multiplication

⇒ observable pulse

Single atom detection of He*

Evaporative Cooling $^4He^*$ to BEC

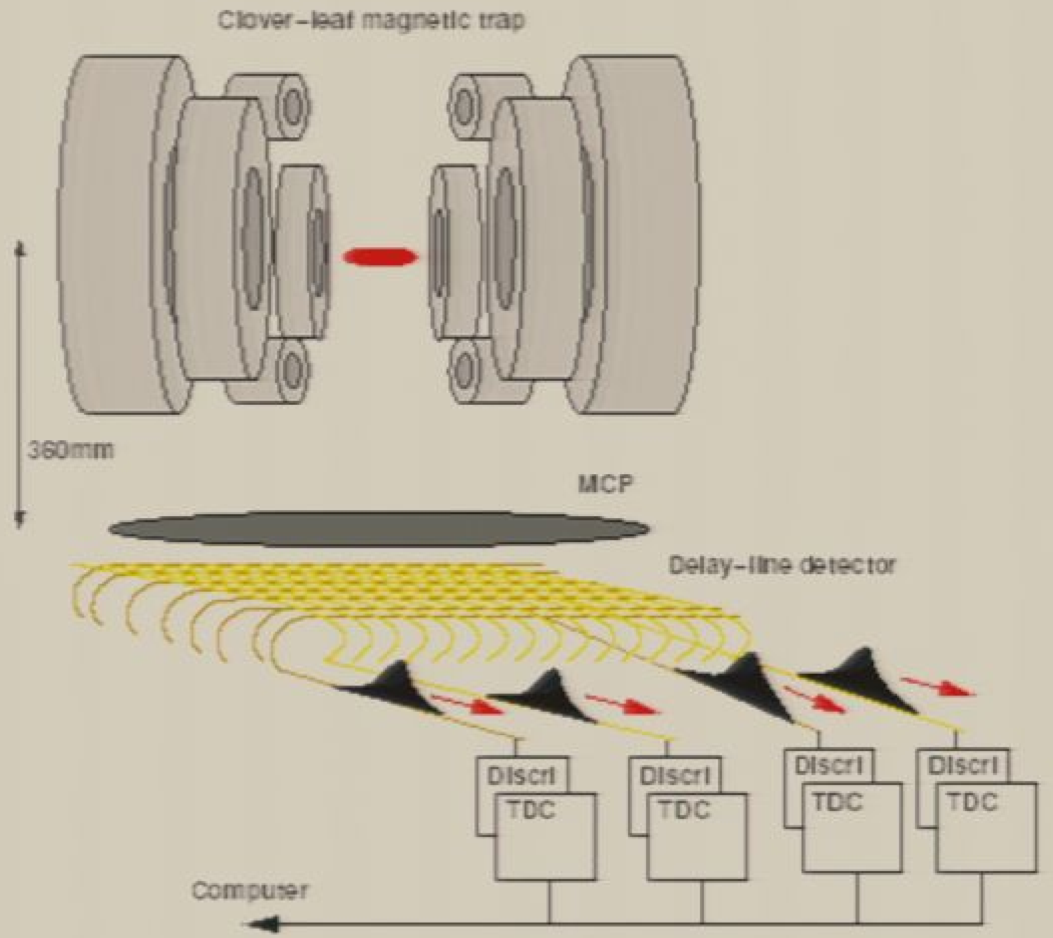




- RF ramped down from 130 MHz to ~ 1 MHz in 70 s (exponential 17 s)
  $\Rightarrow$ less atoms, colder
- Small enough temp. (about 2µK): all atoms fall on the detector, better detectivity
- At 0.7µK: narrow peak, BEC

Ultra cold sample above or below BEC critical temperature

A position and time resolved detector



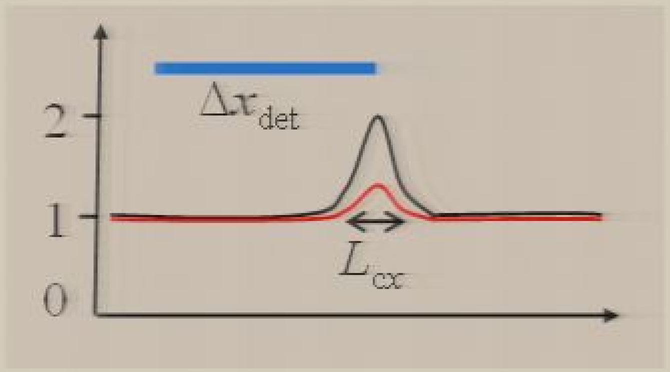
Delay lines + Time to digital converters: detection events localized in time and position

- Time resolution better than 1 ns ☺
- Dead time : 30 ns ☺
- Local flux limited by MCP saturation ☹
- Position resolution (limited by TDC): 200 μm ☹

10^4 detectors working in parallel ! ☺ ☺ ☺ ☺ ☺ ☺

The detector resolution issue

If the detector size Δx_{det} is larger than the HBT bump width L_{cx} then the height of the HB&T bump is reduced by $L_{cx} / \Delta x_{det}$

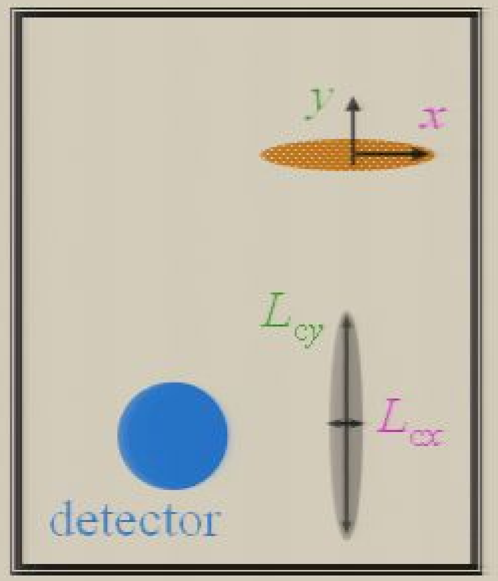


At 1 μK

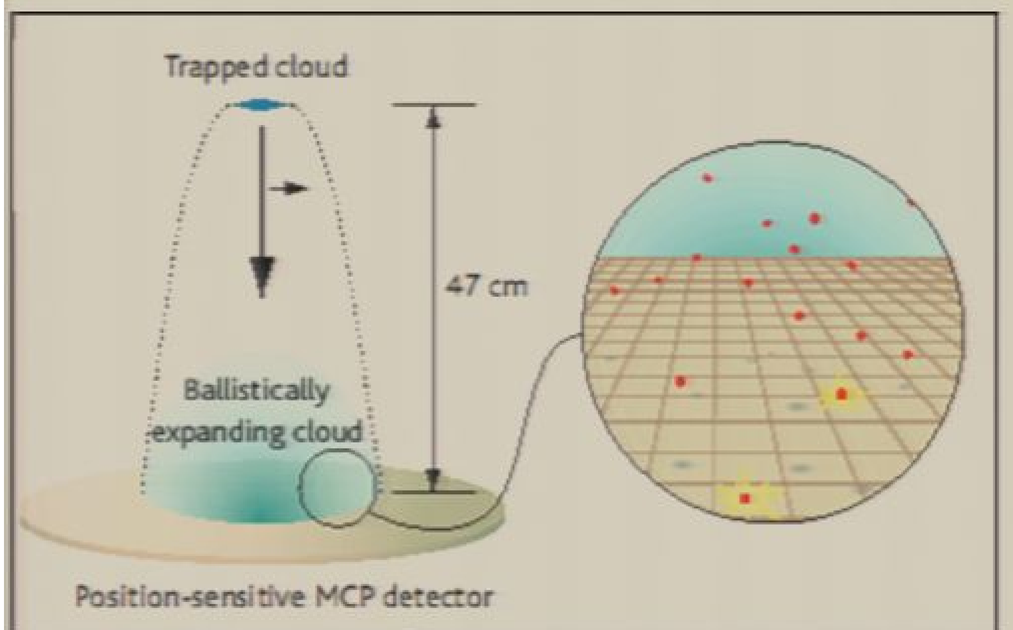
- $\Delta y_{source} \approx 4\ \mu m$ (1800 Hz) $\Rightarrow L_{cy} \approx 500\ \mu m$
- $\Delta x_{source} \approx 150\ \mu m$ (50 Hz) $\Rightarrow L_{cx} \approx 13\ \mu m$

Resolution (200 μm) sufficient along y ☺
but insufficient along x ☹

Expected reduction factor of 15



Experimental procedure



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

- 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

$\{(i_1, t_1), \ldots (i_n, t_n), \ldots\}$ = a record

Related to a single cold atom sample

Repeat many times (accumulate records) at same temperature

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

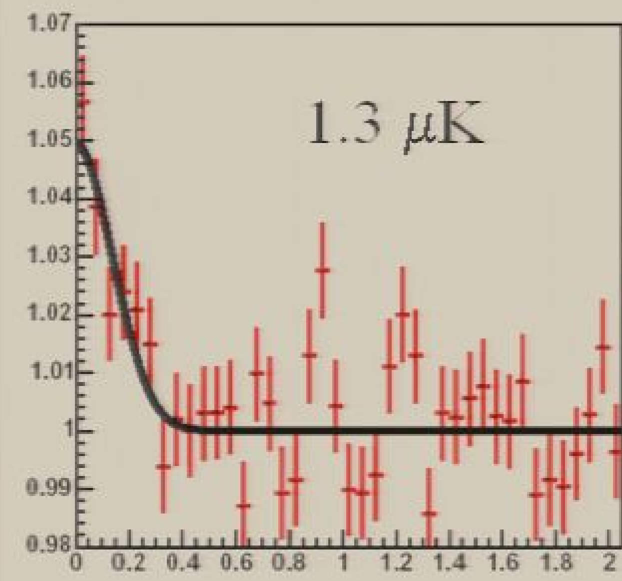
z axis (time) correlation function: $^4He^*$ thermal sample above T_c

- For a given record (ensemble of detection events for a given released sample), evaluate two-time joint detections probability separately for each pixel j

  $\rightarrow [\pi^{(2)}(\tau)]_j$
- Average over all pixels of the same record and over all records (at same temperature)
- Normalize by the autocorrelation of average (over all pixels and all records) time of flight

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

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



Bump visibility = 5×10^{-2}

Agreement with prediction (resolution)

x,y correlation function (^{4}He* thermal sample)

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For a given record (ensemble of detections for a given released sample), look for time correlation of each pixel j with neighbours k

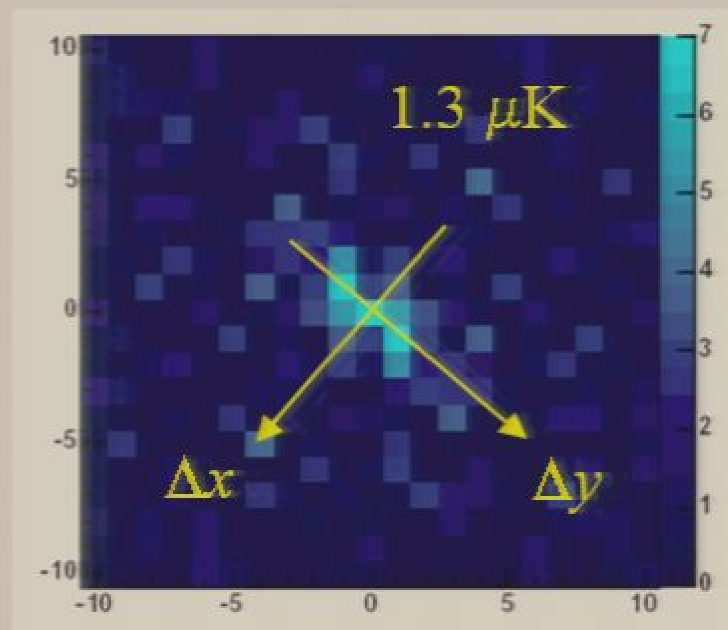
$$\rightarrow [\pi^{(2)}(\tau)]_{jk}$$

Process

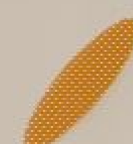
- Average over all pixel pairs with same separation, and over all records at same temperature
- Normalize

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

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



Extends along y (narrow dimension of the source)

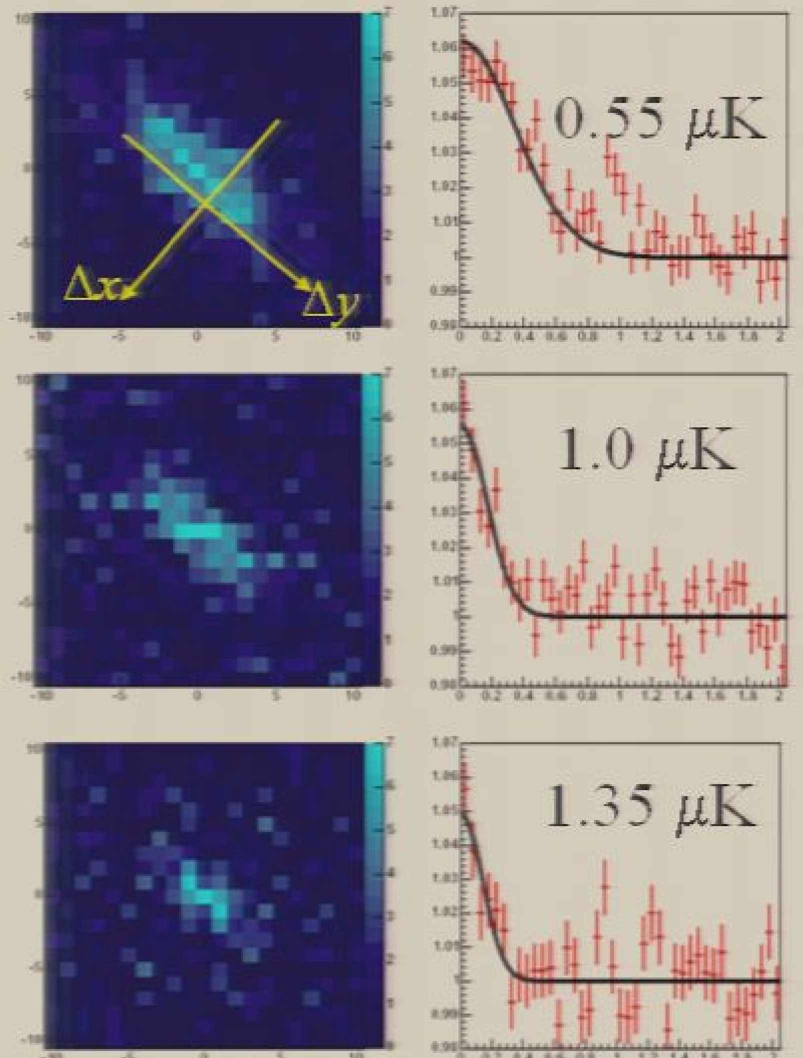


Hanbury Brown Twiss Effect for Ultracold Quantum Gases

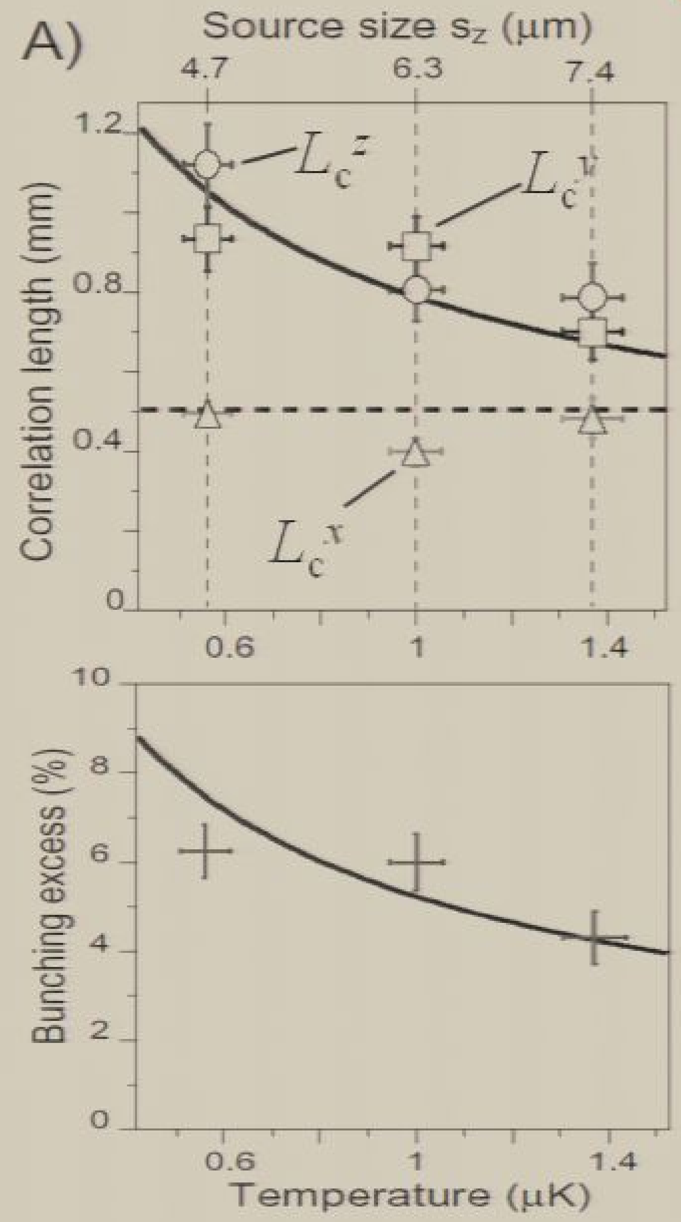
M. Schellekens,[1] R. Hoppeler,[1] A. Perrin,[1] J. Viana Gomes,[1,2] D. Boiron,[1] A. Aspect,[1] C. I. Westbrook[1*]

SCIENCE VOL 310 28 OCTOBER 2005

More results (^{4}He* thermal sample)



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

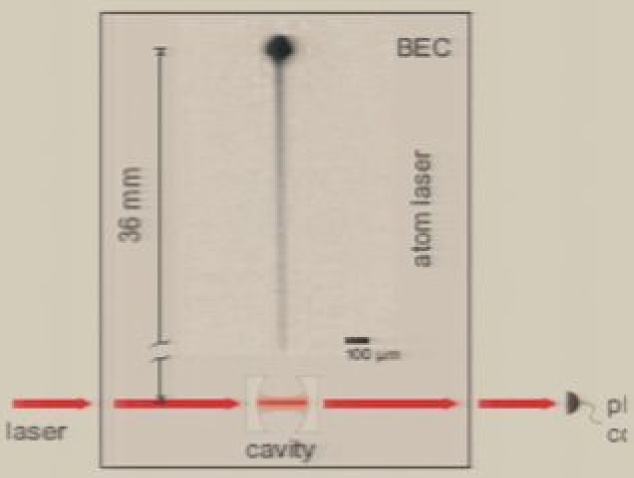


Temperature controls the size of the source (harmonic trap)

Case of a Bose Einstein Condensate: no bunching expected

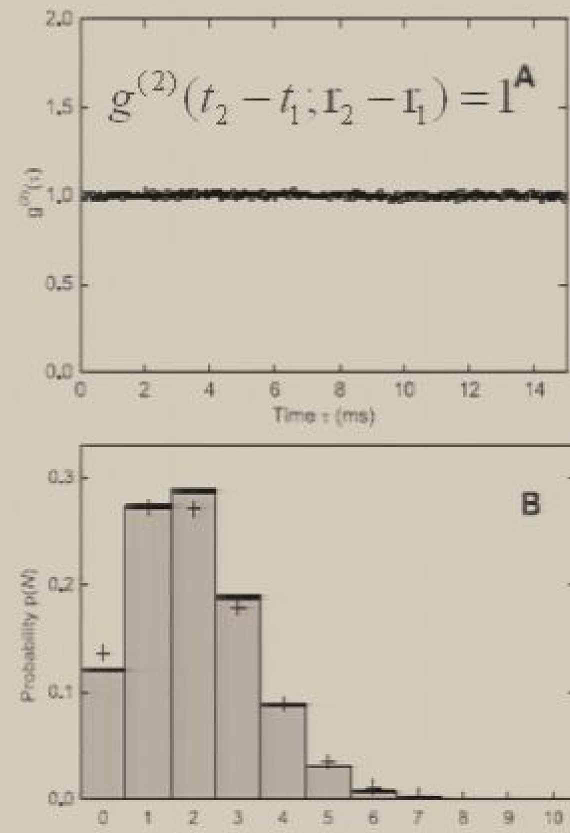
Analogy with a laser: all atoms in the same wave function, with a smooth density profile: no bunching

Observed in Zürich (^{87}Rb) with a time resolved detector
Öttl et *al.*; PRL 95,090404



Flat correlation function: uncorrelated detections

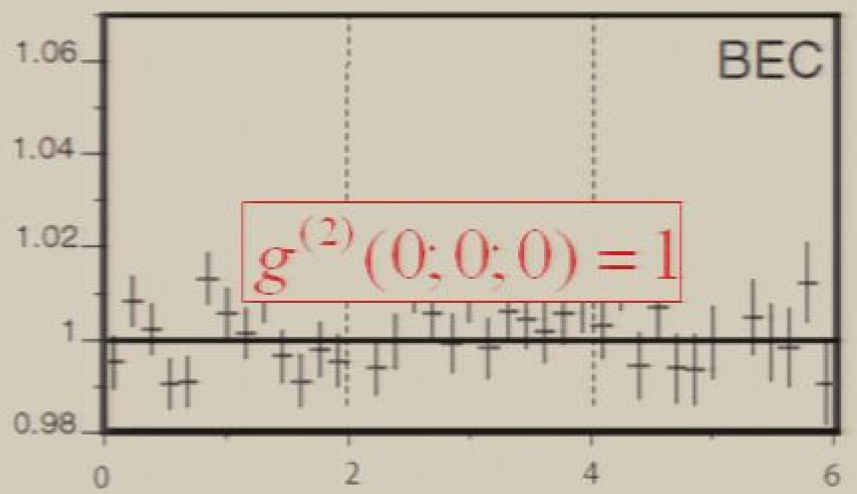
Poisson distribution of atom counts



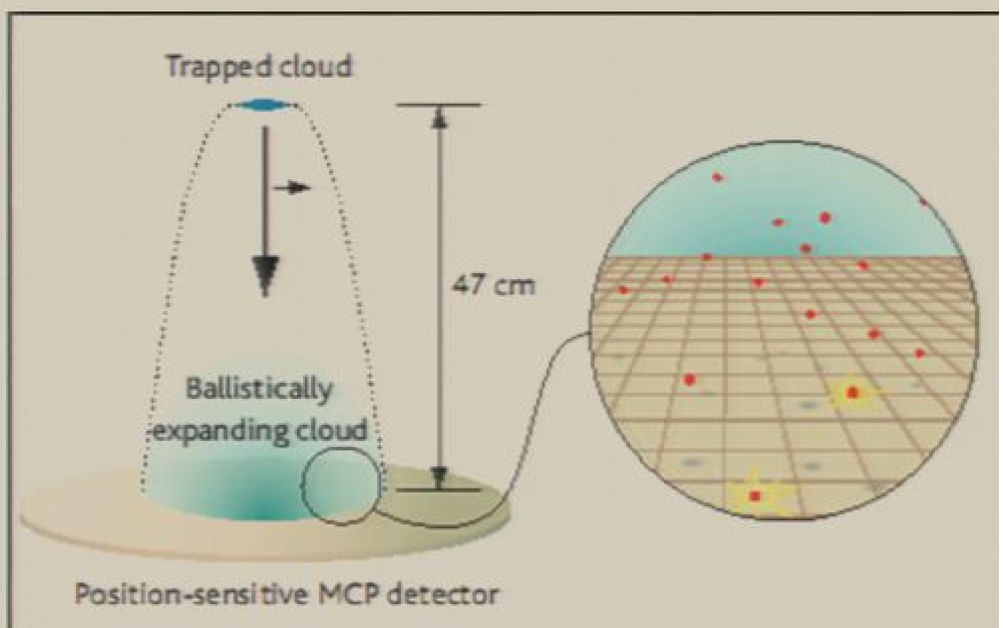
Atom-atom correlation function for a $^4He^*$ BEC ($T < T_c$)

Observed at Institut d'Optique with a time and space resolved detector

(Schellekens et al., Science 2005)



No bunching as expected: analogous to laser light



Experiment more difficult: atoms fall on a small area on the detector

$\Rightarrow$ problems of saturation

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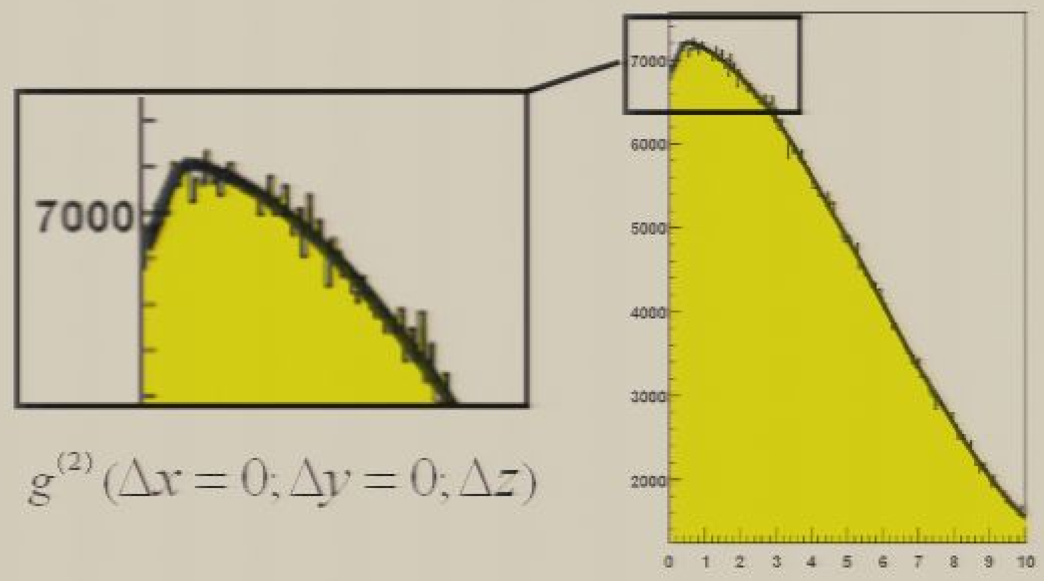
Hanbury Brown and Twiss experiment for ^{3}He* (fermionic atom)

Collaboration

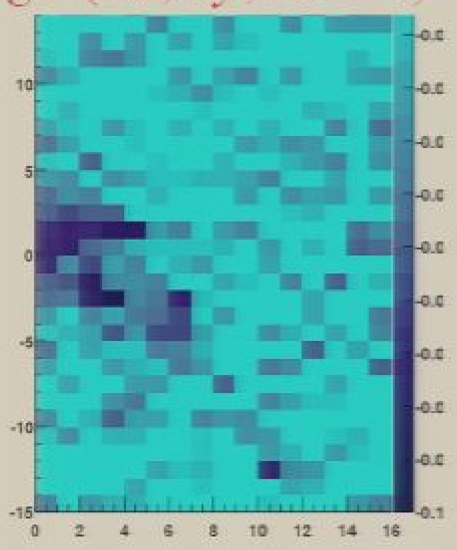
- Free University Amsterdam: cold (below T_F) ^{3}He*
- Institut d'Optique: time and space resolved detector; data analysis software

First results (july 14th, 2006): fermionic antibunching clearly seen ☺



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

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



Comparison with bosonic ^{4}He* (in the same apparatus) underway

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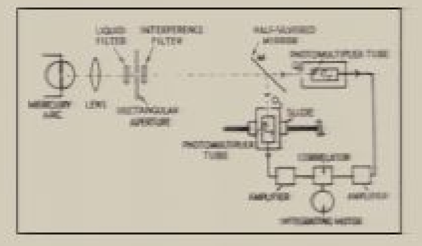
Single atom detection resolved in space and time: fascinating possibilities in quantum atom optics

Photon correlations (1950-): hard core of modern quantum optics $g^{(2)}(\mathbf{r}_1, t_1; \mathbf{r}_2, t_2)$



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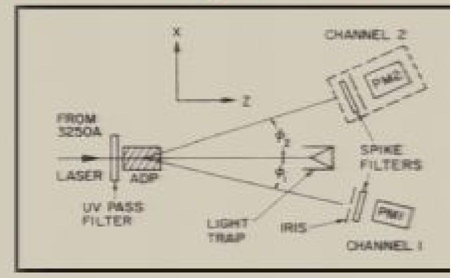

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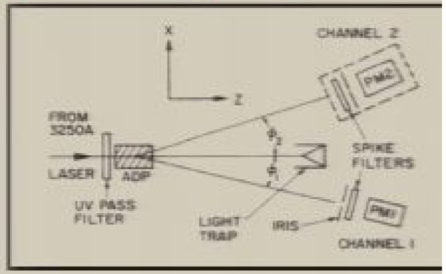

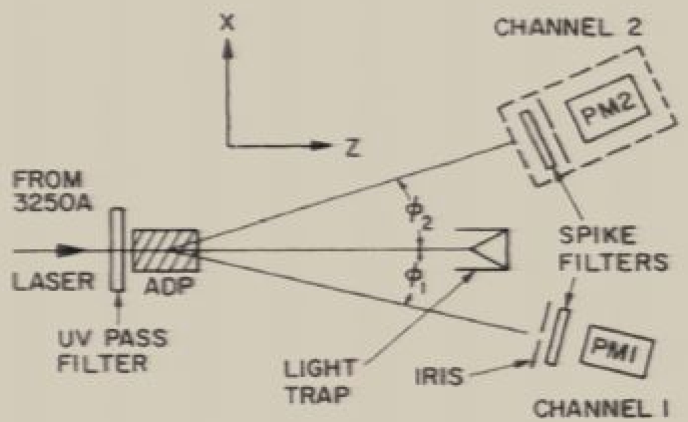

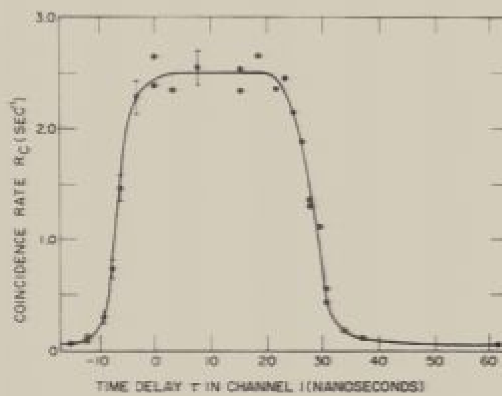

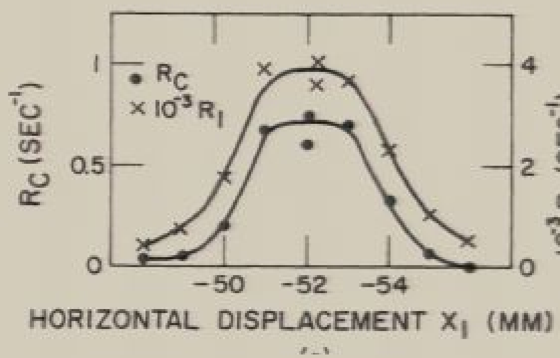

OBSERVATION OF SIMULTANEITY IN PARAMETRIC PRODUCTION OF OPTICAL PHOTON PAIRS

David C. Burnham and Donald L. Weinberg
National Aeronautics and Space Administration Electronics Research Center, Cambridge, Massachusetts 02142

(Received 12 May 1970)

PRL 25, 84 (1970)

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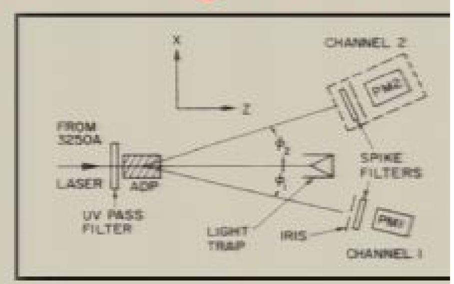

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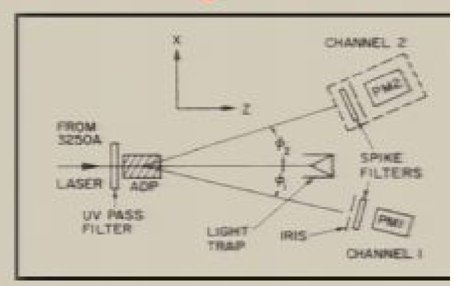
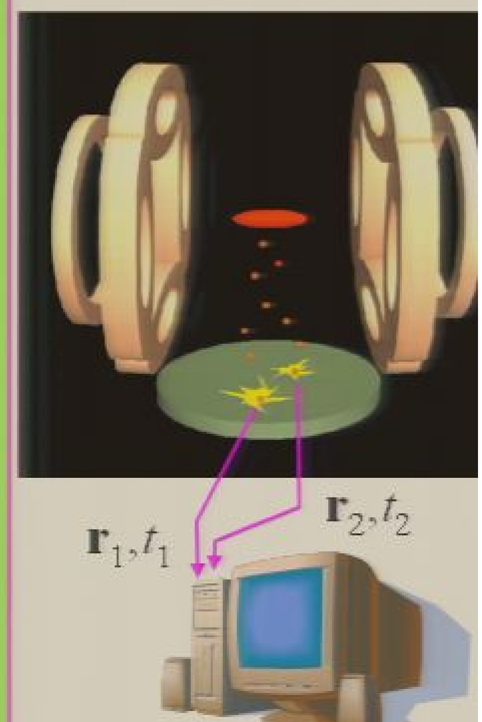
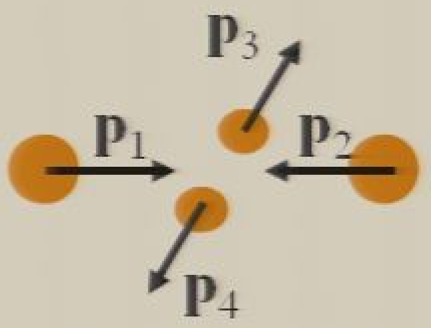


Single atom detection, resolved in time and space (2005-)

- Study of any correlation function of atomic field
  - Hanburry-Brown & Twiss type experiments
  - Fluctuations of atom laser around BEC transition
  - Detection of correlated atom pairs in 4-wave mixing
  - Entangled atomic pairs? Bell's inequalities violation? A ressource for quantum information?



Production of pairs in collision of atomic Bose-Einstein Condensates



$$1 + 2 \rightarrow 3 + 4$$

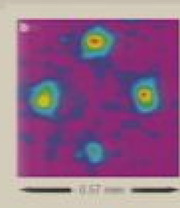
colliding BEC's — "daughter" BEC's

Analogous to 4 waves mixing ($\chi^{(3)}$ medium) in non linear optics

Energy-Momentum conservation (at individual atom level) $\Longrightarrow$ p_3 , p_4

Analogous to phase matching

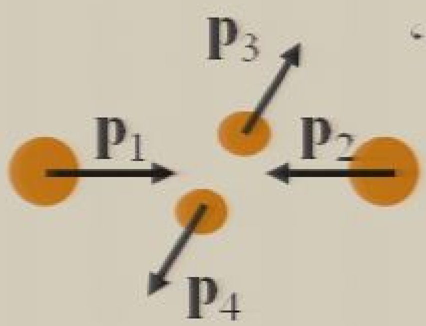
Observed in Gaithersburg, MIT



At low density, production of well separated pairs of correlated atoms ?

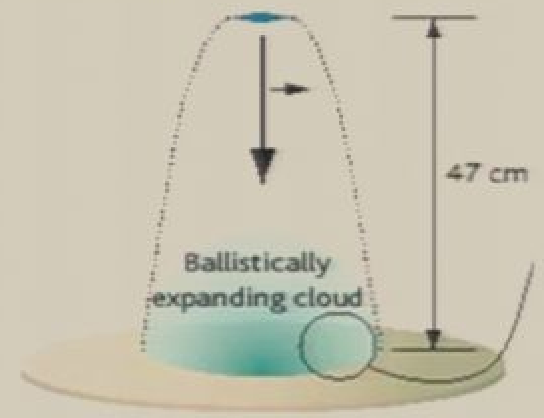
Analogous to production of pairs of correlated photons in parametric down conversion

Observation of correlated $^4He^*$ pairs



"degenerate" case $p_2 = -p_1$

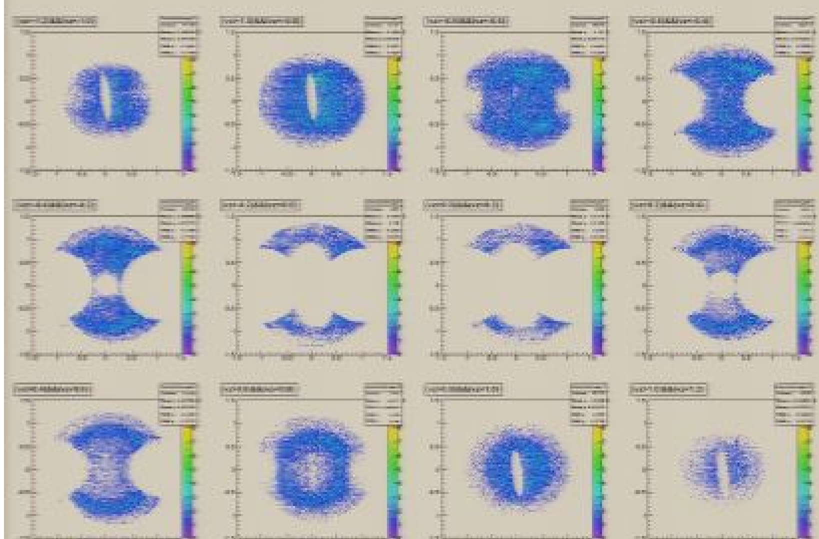
$$p_4 = -p_3$$
$$|p_3| = |p_4| = const$$



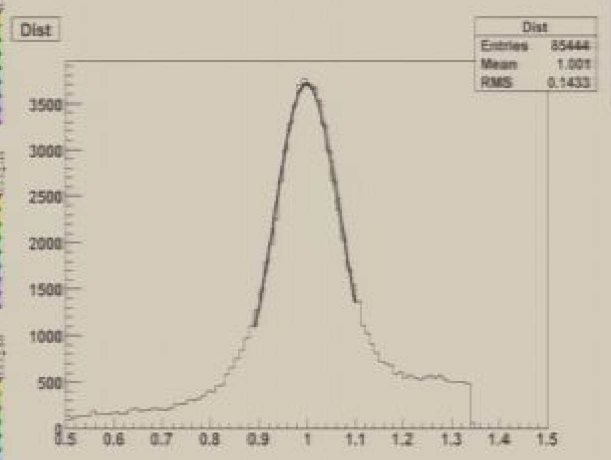
p reconstruction by elementary kinematics (free fall)

Momentum distribution of scattered atoms

Preliminary results



p distribution

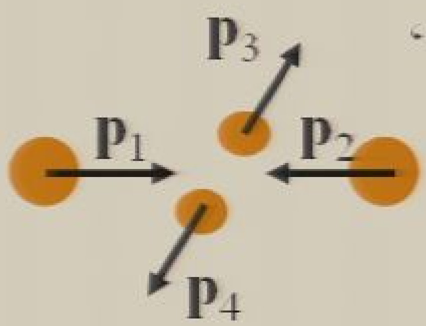


p distribution

Sphere in momentum space

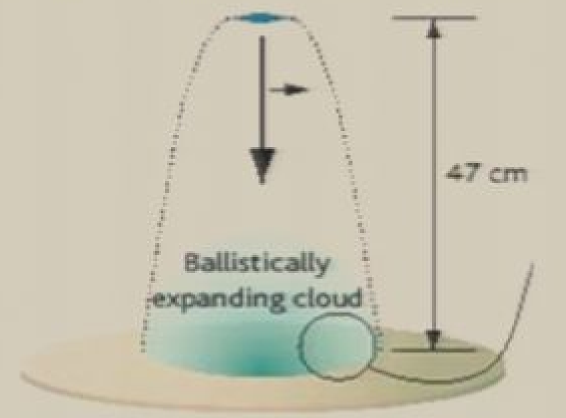
Observation of correlated $^4He^*$ pairs

Institut d'Optique



"degenerate" case $p_2 = -p_1$

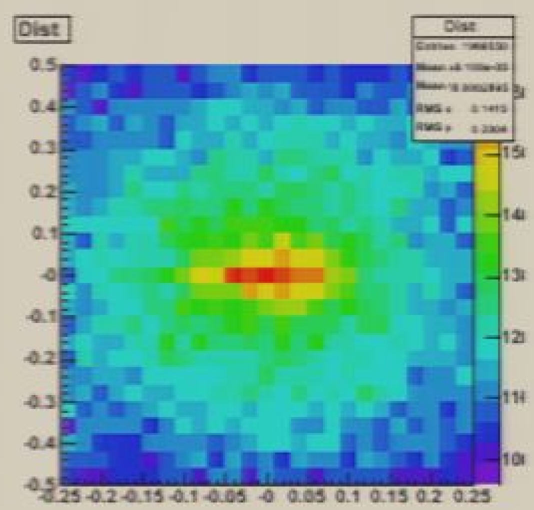
$$p_4 = -p_3$$
$$|p_3| = |p_4| = \text{const}$$



p reconstruction by elementary kinematics (free fall)

Momentum correlation in scattered atoms

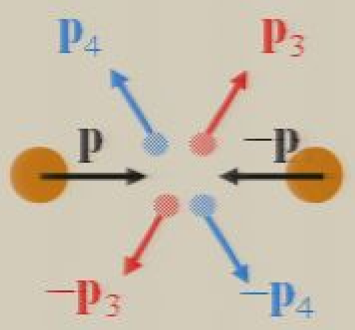
Preliminary results; elementary processing



Correlation of antipodes on momentum sphere

Atoms created by pairs of opposite momenta

Entanglement in correlated $^4He^*$ pairs?



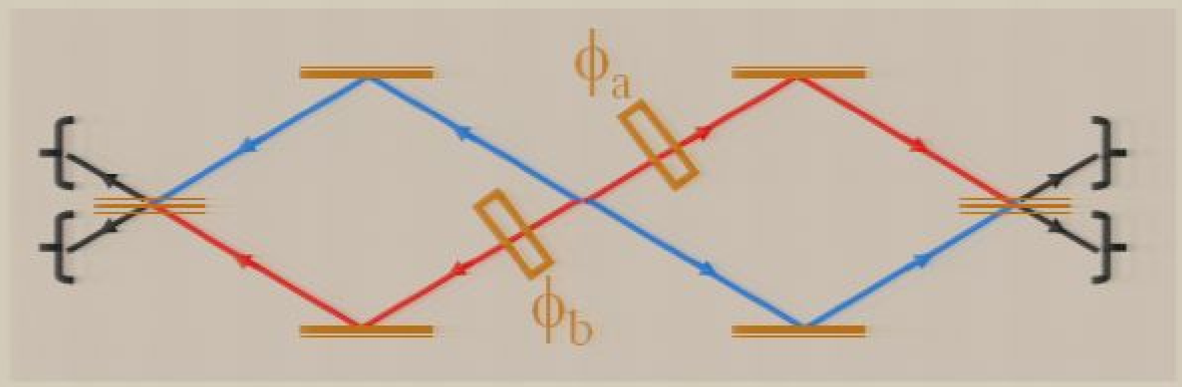
$$|\psi\rangle \propto |p_3, -p_3\rangle + |p_4, -p_4\rangle \ ???$$

A scheme within present technology: Bragg diffraction on laser standing waves : mirrors, beam splitters, phase shifters

⇒ 2 atoms interferometry

cf. M H, Abner S., AZ (1989)

Equivalent to EPRB scheme



BCHSH test possible ☺ . Next conference in honour of Abner ?

Groupe d'Optique Atomique du

Laboratoire Charles Fabry de l'Institut d'Optique

Graduate students and post docs welcome