Image Formation Using Quantum-Entangled Photons

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Presented at IQEC, May16-20, 2004.

Research in Quantum Imaging

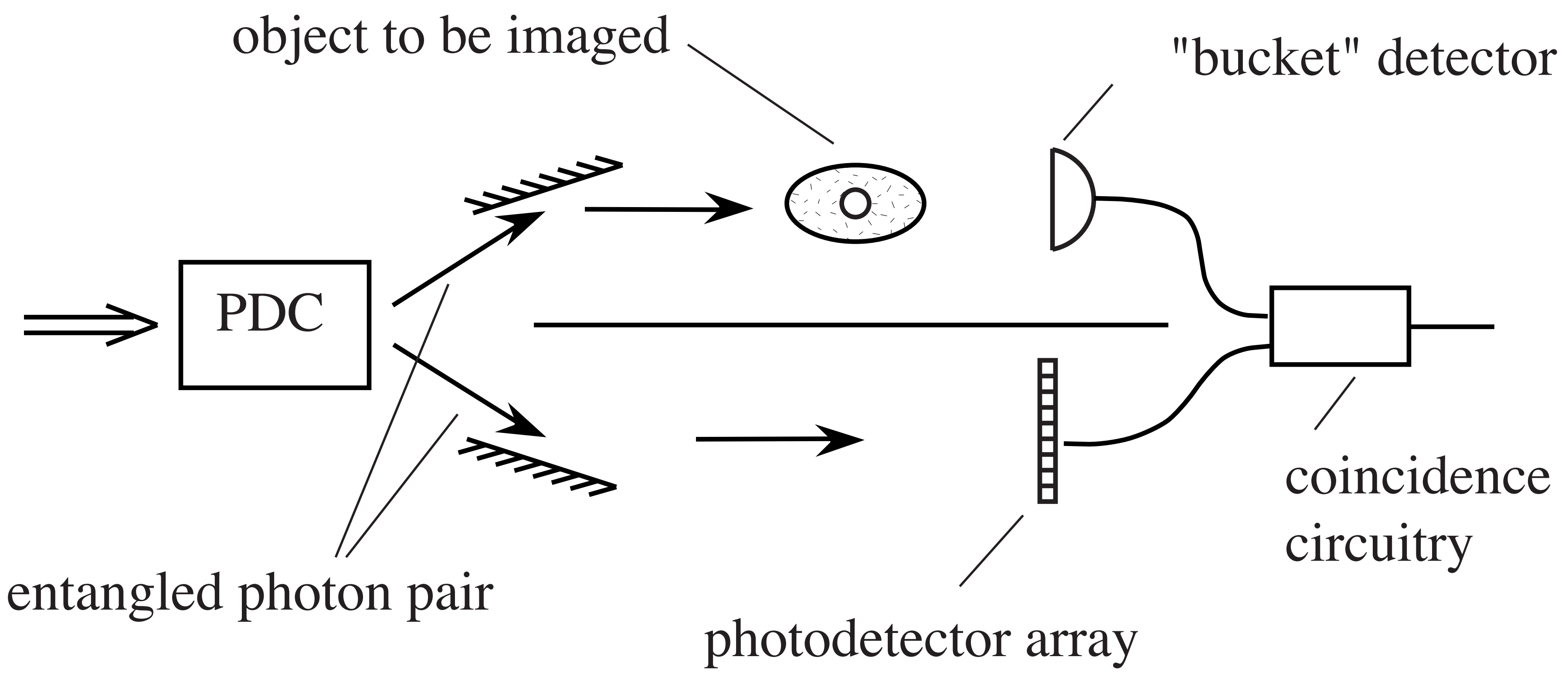
Can images be formed with higher resolution or higher sensitivity through use of quantum states of light?

Can one “beat” the Rayleigh resolution limit?

Quantum states of light: squeezed states, twin beams, entangled states, etc.

Founders: Barbosa, Kylshko, Kolobov, Kumar, Lugiato, Monken, Saleh, Sergienko, Shih, Teich.

Ghost (Coincidence) Imaging



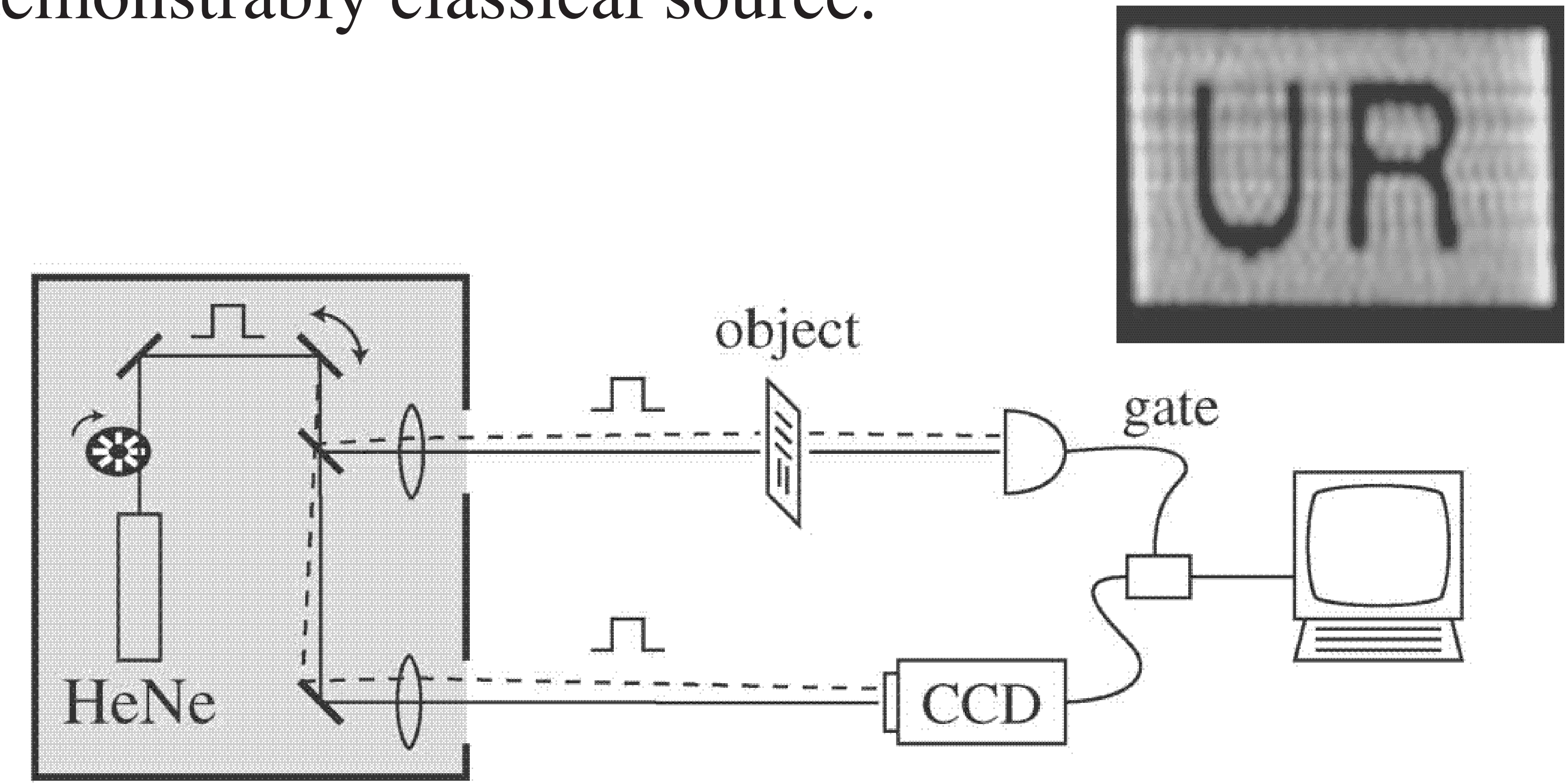
Obvious applicability to remote sensing!

- Is this a purely quantum mechanical process?

  Strekalov et al., Phys. Rev. Lett. **74**, 3600 (1995).
  Pittman et al., Phys. Rev. A **52** R3429 (1995).
  Abouraddy et al., Phys. Rev. Lett. **87**, 123602 (2001).

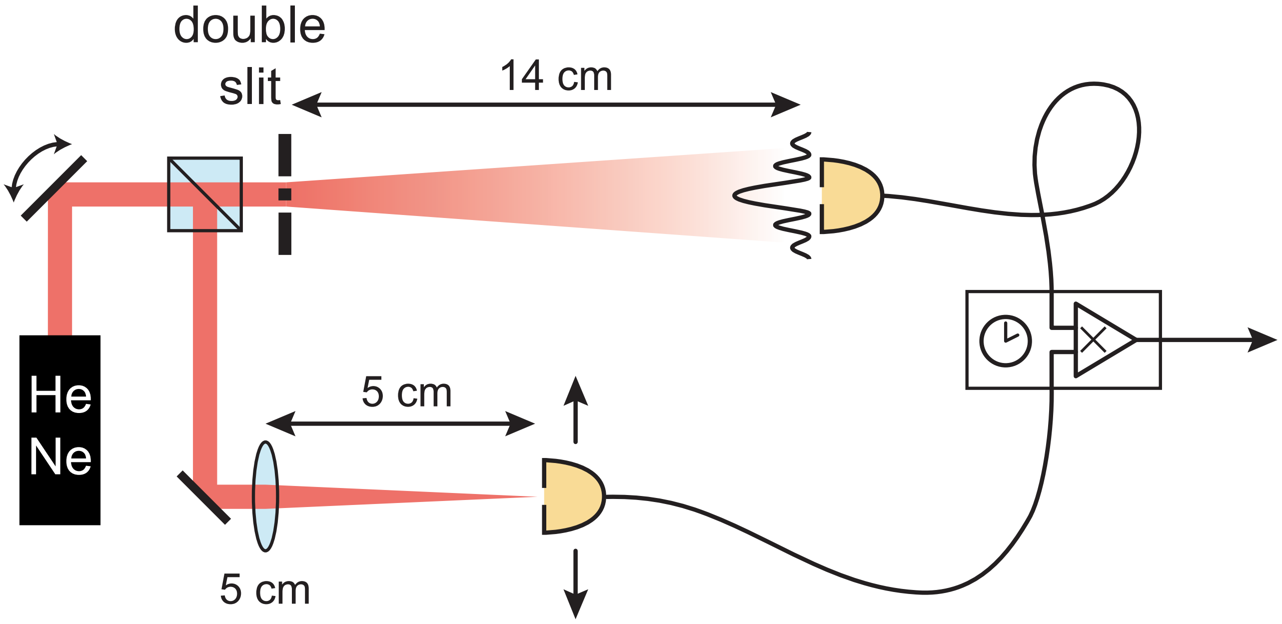
Classical Coincidence Imaging

We have performed coincidence imaging with a demonstrably classical source.

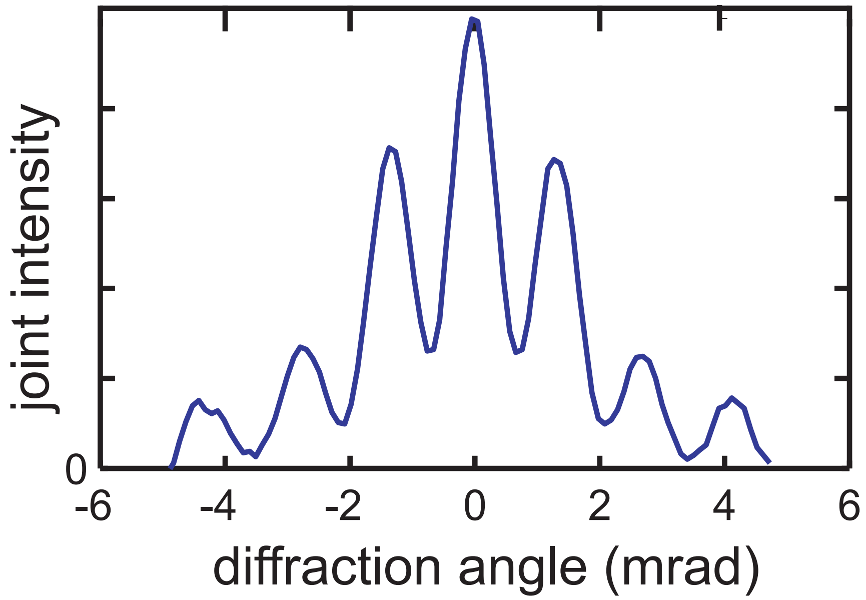


Bennink, Bentley, and Boyd, Phys. Rev. Lett. **89** 113601 (2002).

Ghost Diffraction with a Classically Correlated Source



Even diffraction effects are observable with classical coincidence imaging.



Further Development

VOLUME 90, NUMBER 13 PHYSICAL REVIEW LETTERS week ending 4 APRIL 2003

Entangled Imaging and Wave-Particle Duality: From the Microscopic to the Macroscopic Realm

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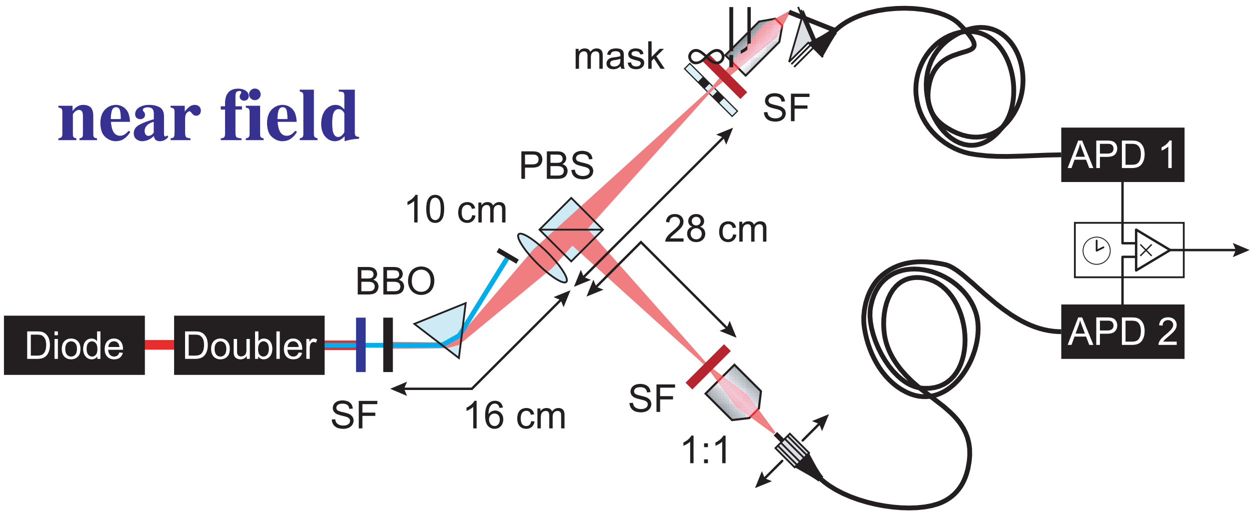
(Received 11 October 2002; published 3 April 2003)

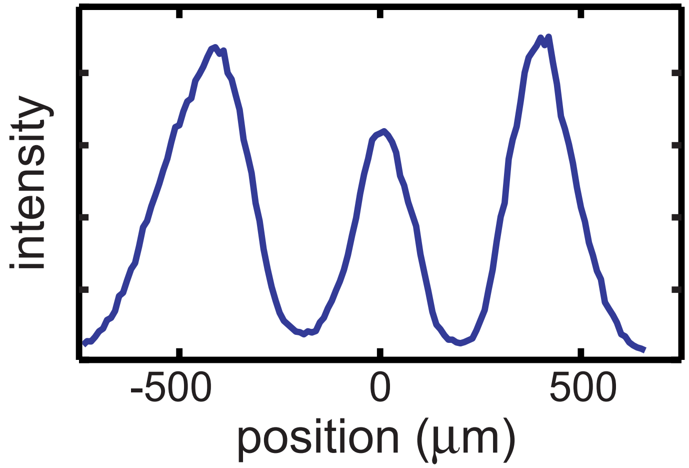
We formulate a theory fo~~r entan~~gled imaging, which includes also the case of a large number of photons in the two entangled beams. We show that the results for imaging and for the wave-particle duality features, which have been demonstrated in the microscopic case, persist in the macroscopic domain. We show that the quantum character of the imaging phenomena is guaranteed by the simultaneous spatial entanglement in the near and in the far field.

DOI: 10.1103/PhysRevLett.90.133603 PACS numbers: 42.50.Dv, 03.65.Ud

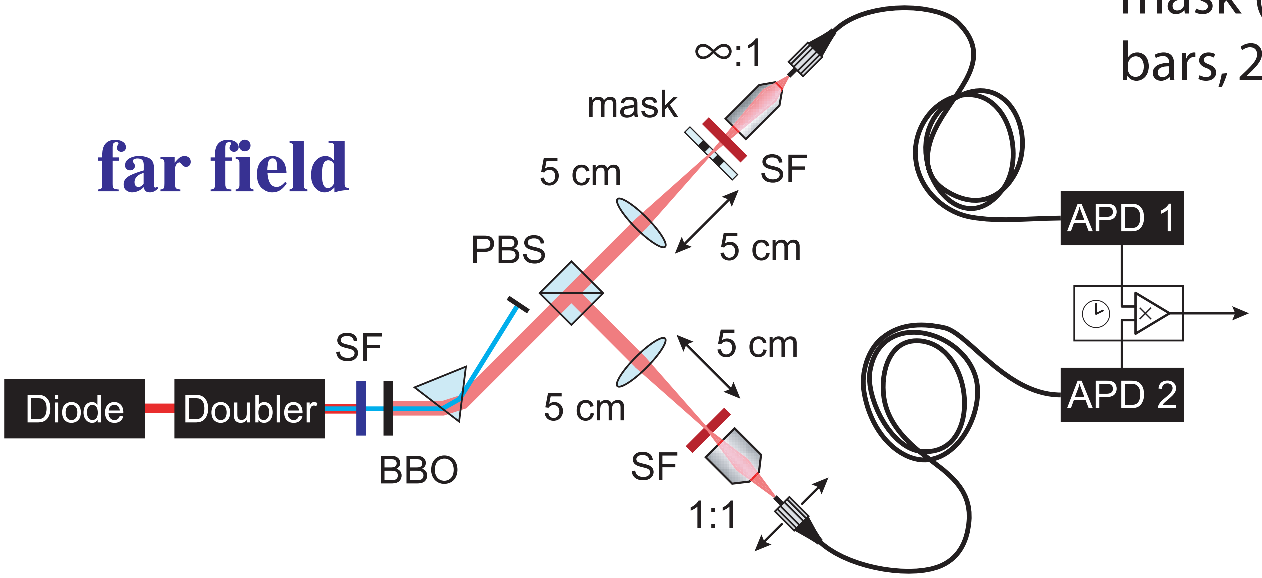
Near- and Far-Field Imaging Using Quantum Entanglement

near field

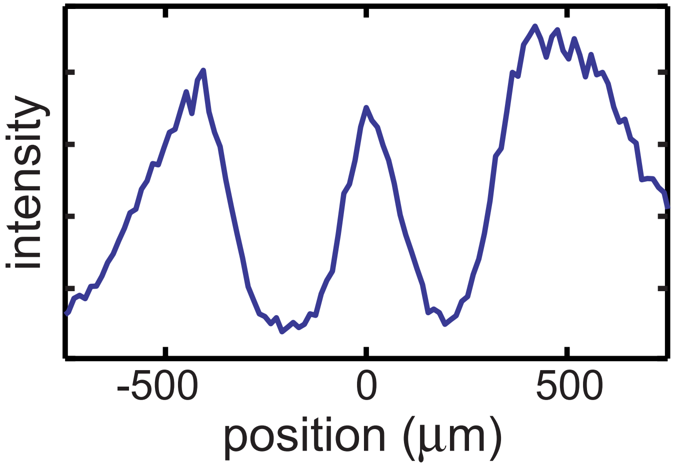




far field



mask (object) is two opaque bars, 200 μm wide

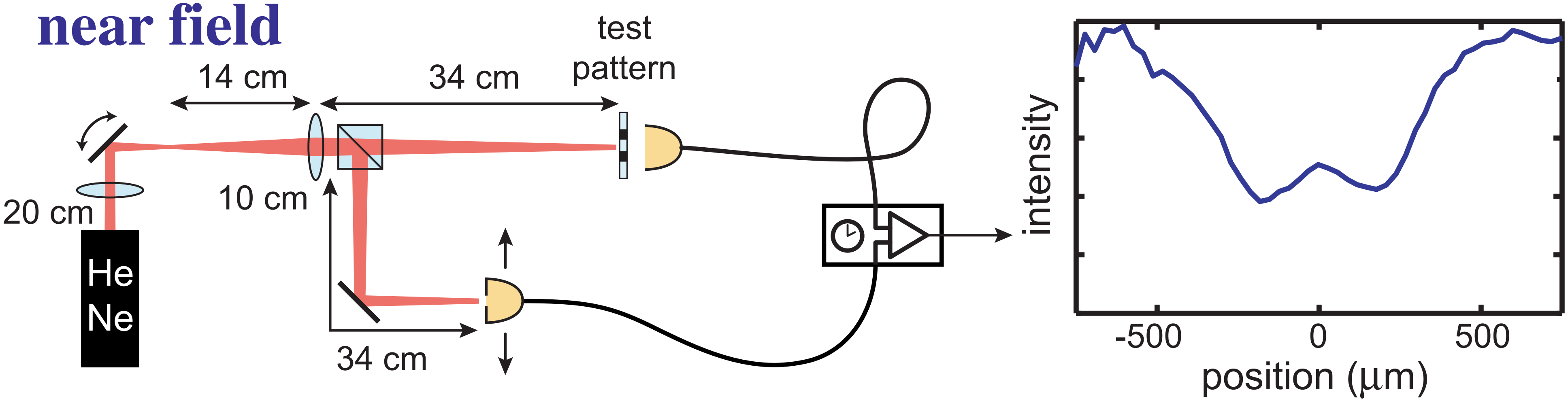


Good imaging observed in both the near and far fields!

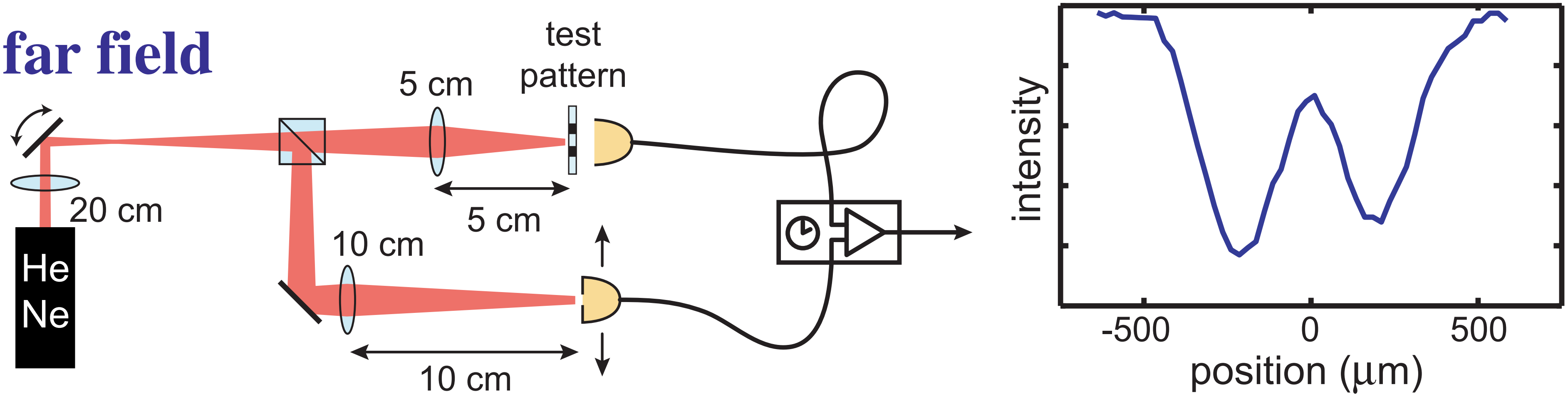
Bennink, Bentley, Boyd, and Howell, Phys. Rev. Lett., 92, 033601, 2004.

Near- and Far-Field Imaging With a Classical Source

near field



far field



- Good imaging can be obtained only in near field **or** far field.
- Detailed analysis shows that in the quantum case the space-bandwidth exceeded the classical limit by a factor of ten.

Uncertainty Product: Classical Versus Quantum

- The image resolution can be quantified by the width of the point spread function.

- For images obtained with our classical source, we find that the uncertainty product is given by

$$(\Delta x_2)_{x_1}{}^2 \, (\Delta k_2)_{k_1}{}^2 = 2.2 \pm 0.2$$

which in agreement with theory is larger than unity.

- For images obtained with entangled photons, we find that the uncertainty product is given by

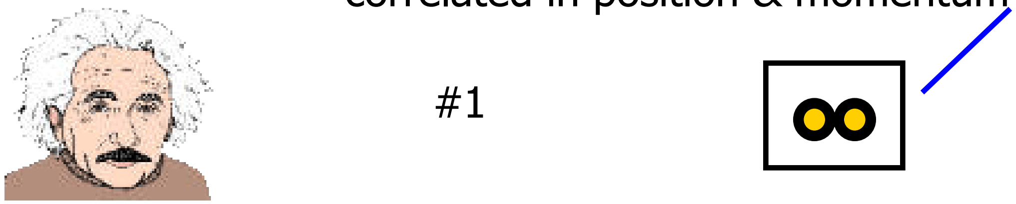
$$(\Delta x_2)_{x_1}{}^2 \, (\Delta k_2)_{k_1}{}^2 = 0.01 \pm 0.03$$

which is 100 times smaller than the limiting value of unity.

- Thus, nonclassical behavior has been observed.

The EPR Paradox

In 1935, Einstein, Podolsky, and Rosen argued that quantum mechanics must be "incomplete."



entangled particles, perfectly correlated in position & momentum

#1

#2

measure x or p

- measure x_1 ⇒ know x_2 with certainty ($\Delta x_2 = 0$)
- measure p_1 ⇒ know p_2 with certainty ($\Delta p_2 = 0$)
- measurement of particle 1 cannot affect particle 2 (?!)

$$\Rightarrow \quad \Delta x_2 = 0 \text{ and } \Delta p_2 = 0 \text{ simultaneously (?!)}$$

in conflict with $$\Delta x_2 \Delta p_2 \geq \frac{1}{2}\hbar$$

Quantum Imaging and the EPR Effect

- The quantum signature of ghost imaging is simultaneous correlations in both x and k
- EPR thought that simultaneous correlations in both x and p contradicted Heisenberg's uncertainty principle

The criterion for quantum features in coincidence imaging,

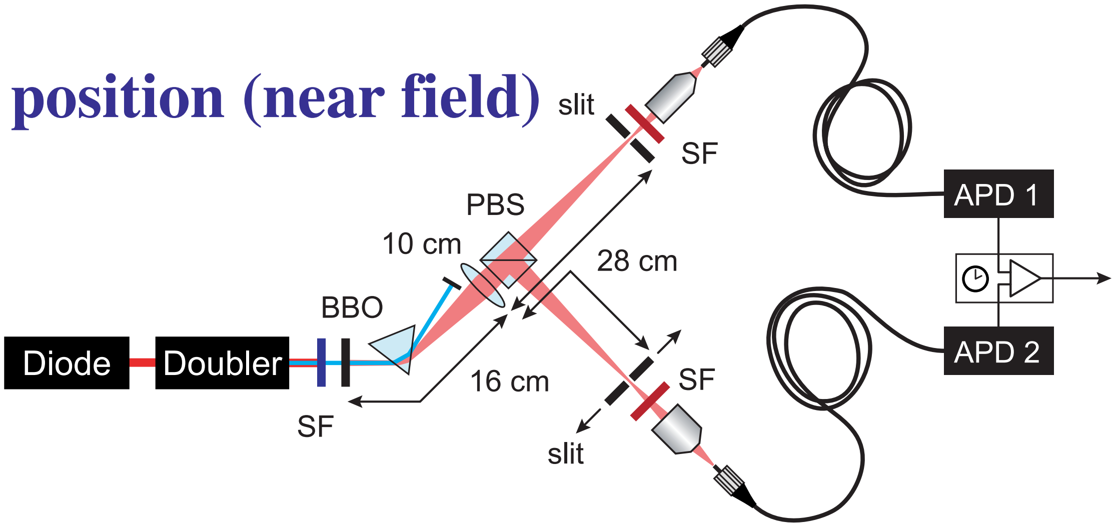
$$\left((\Delta x_2)_{x_1}\right)^2\left((\Delta k_2)_{k_1}\right)^2 \leq 1$$

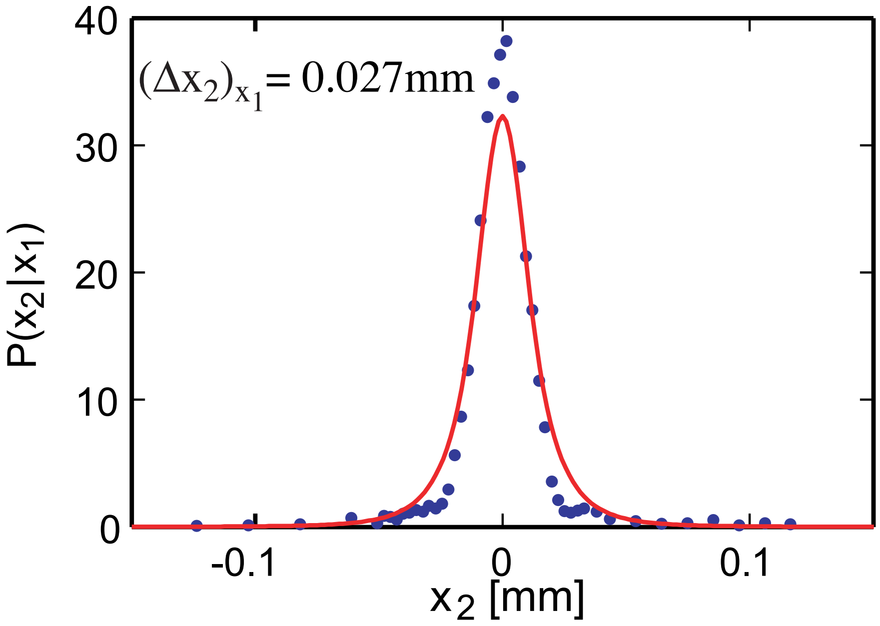
is equivalent to that for violating the EPR hypothesis.

- With entangled photons, one can perfom the original EPR experiment (not Bell's). EPR were considering continuous variables (momentum and position) not the spin variable.

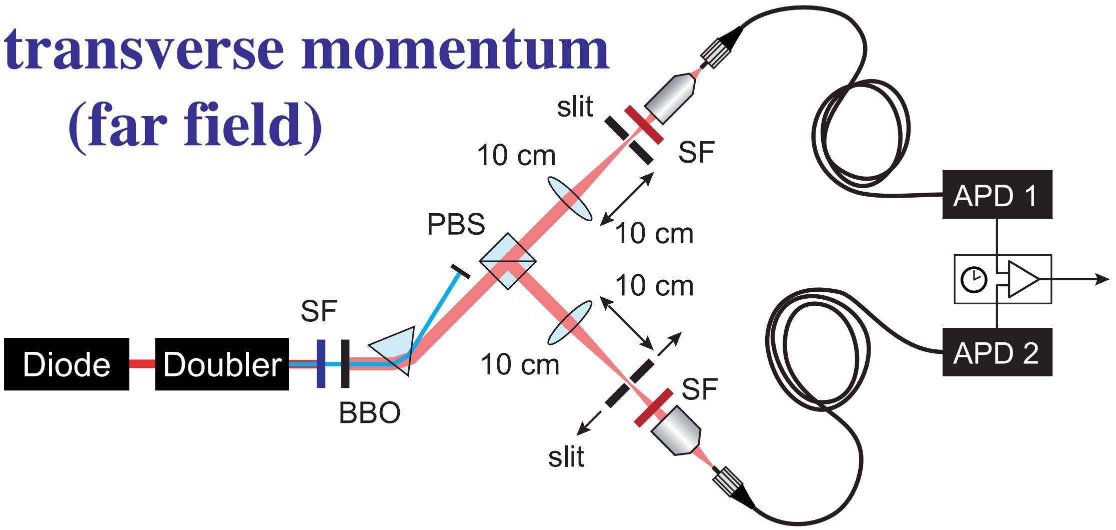
Position-Momentum Realization of the EPR Paradox

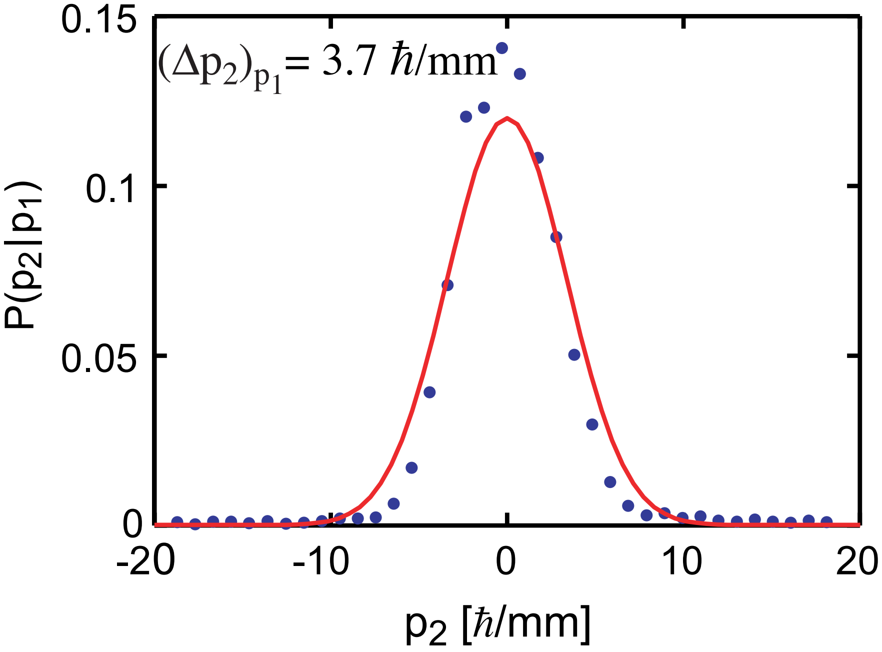
position (near field)





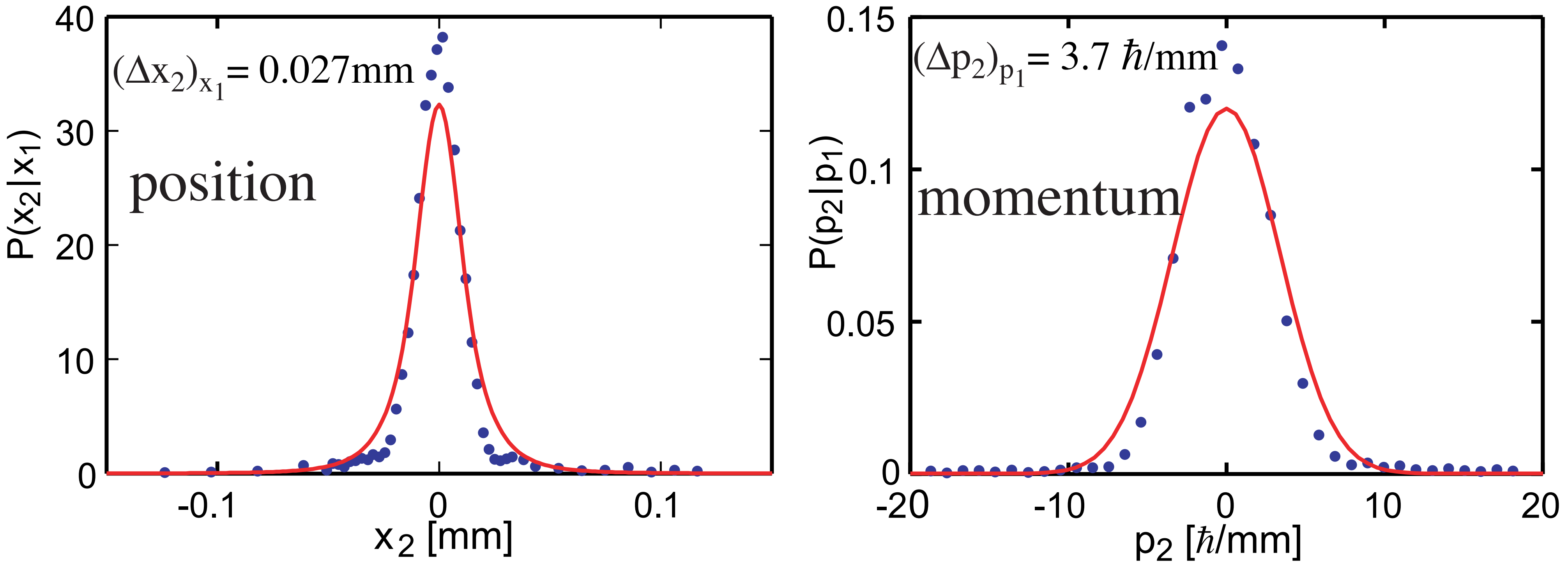
transverse momentum
(far field)





- We find that $(\Delta x_2)_{x_1} (\Delta p_2)_{p_1} = 0.1\hbar$

Discussion: Position-Momentum Realization of the EPR Paradox



- The spread in *p* is determined by the momentum uncertainty of the pump beam, which is limited by the pump spot size.
- The spread in *x* is determined by the angular bandwidth of the PDC process, which is limited by phase matching requirements.
- We find that $(\Delta x_2)_{x_1}{}^2\,(\Delta p_2)_{p_1}{}^2 = 0.01\hbar^2$, where according to EPR the product could be no smaller than unity.
- To appear in PRL

Advantages of x-p entanglement

Compared to other kinds of continuous entanglement (squeezed fields, macroscopic spin), twin-photon spatial entanglement has several advantages:

- easy to produce
- easy to measure
- not degraded by optical loss
- many possible states (100’s) for quantum info
    - pixel cryptography
    - image teleportation
    - ?

Summary

- Spatially entangled photons can be imaged in ways that classically correlated fields cannot
    - Near- and far-field coincidence imaging
- First single-experiment demonstration of position-momentum EPR
- Strong (100-fold) violation of continuous EPR criterion
- Suggests new possibilities in quantum information science involving continuous/large Hilbert spaces

Thank you for your attention!