ICSSUR 2009, Olomouc, Czech Republic, 21-25 June 2009

Some topics in Quantum Imaging

Theory :

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Experiment:

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QUANTUM IMAGING

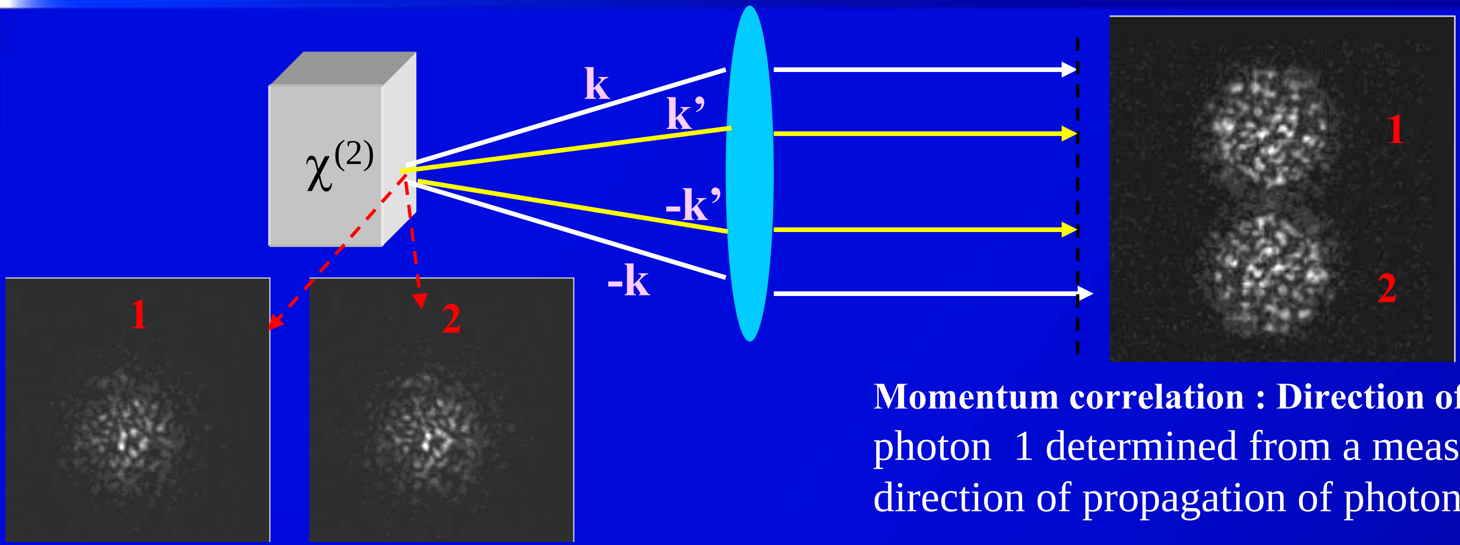
This field exploits the quantum nature of light and the natural parallelism of optical signals to devise novel technique for optical imaging and for parallel information processing at the quantum level.

Gatti, Brambilla, Lugiato, Quantum Imaging, Progress in Optics, Vol. 51, p.251, 2008

MENU

- “Ghost” Imaging
  (not necessarily quantum)
- Detection of a “weak” object
  in the quantum regime

Position-momentum entanglement of twin photons



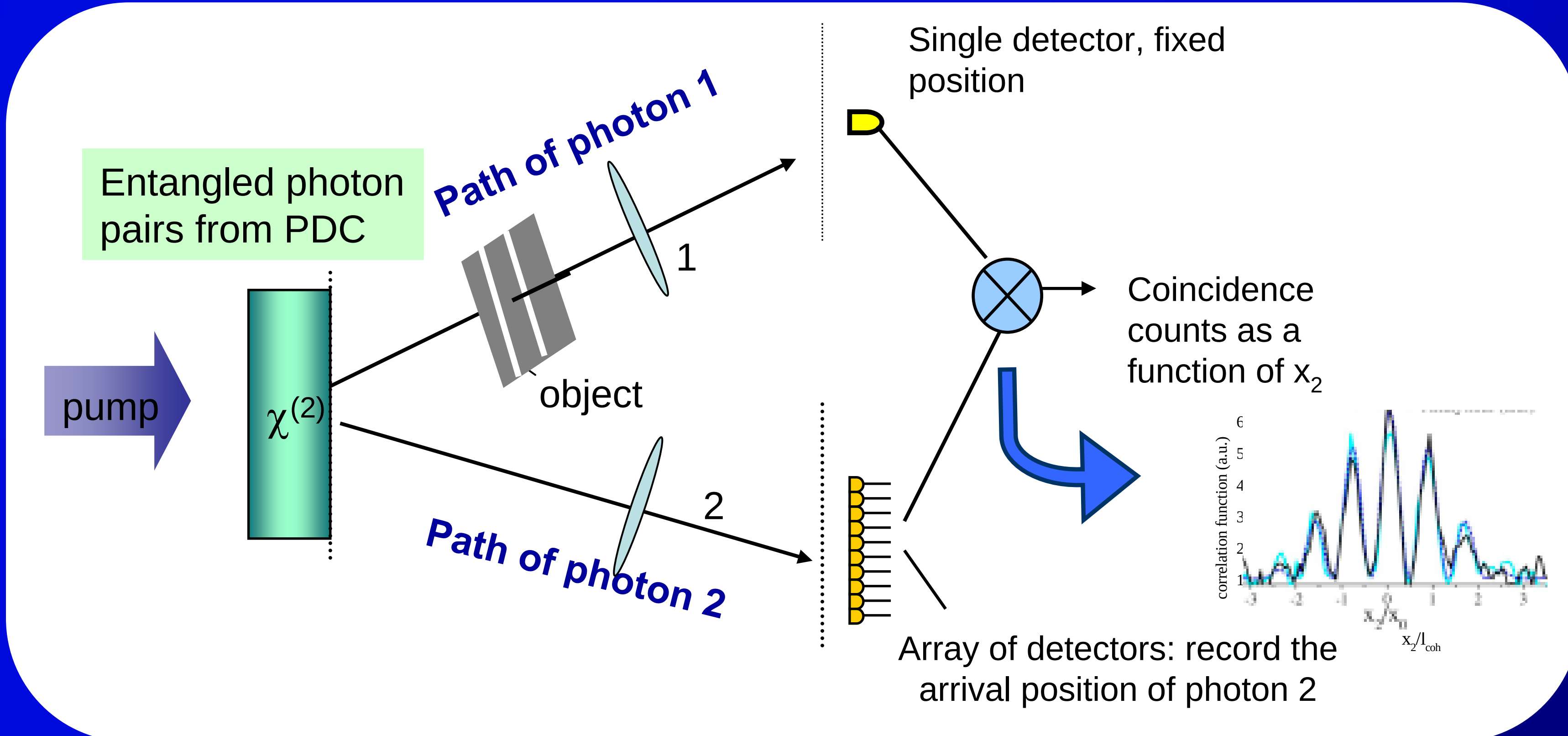
Momentum correlation : Direction of propagation of photon 1 determined from a measurement of the direction of propagation of photon 2

Position correlation: Position x of photon 1 determined from a measurement of the position of the photon 2

Simultaneous presence of correlation in both position and momentum of the two photons
→ Entangled (nonseparable) state, similar to the original EPR (Einstein-Podolsky Rosen , 1935) state

Exp. test: Howell, Bennink, Bentley and Boyd, PRL 92 210403, 2004; Bennink, Bentley, Boyd, Howell, PRL 92 033601 (2004) ; D'Angelo Kim Kulik Shih PRL 92, 233601 (2004)

Imaging with spatially entangled photons



The image emerges from the coincidence counts, as a function of the arrival position of photon 2, that never sees the object→ "Ghost Image" [Pittman, Shih , Strekalov and Sergienko, PRA 52, (R)3429 (1995)]

By simply changing the optical set-up in the path of photon 2→"Ghost Diffraction" [Ribeiro, Padua, Machado da Silva, Barbosa, PRA. 49, 4176, (1994); Strekalov, Sergienko, Klyshko and Shih, PRL 74, 3600 (1995)]

The ability to produce both the ghost image and the ghost diffraction pattern was initially attributed to the entanglement of the state (simultaneous presence of position and momentum correlation)

However, long debate about the need of entanglement for Ghost Imaging…

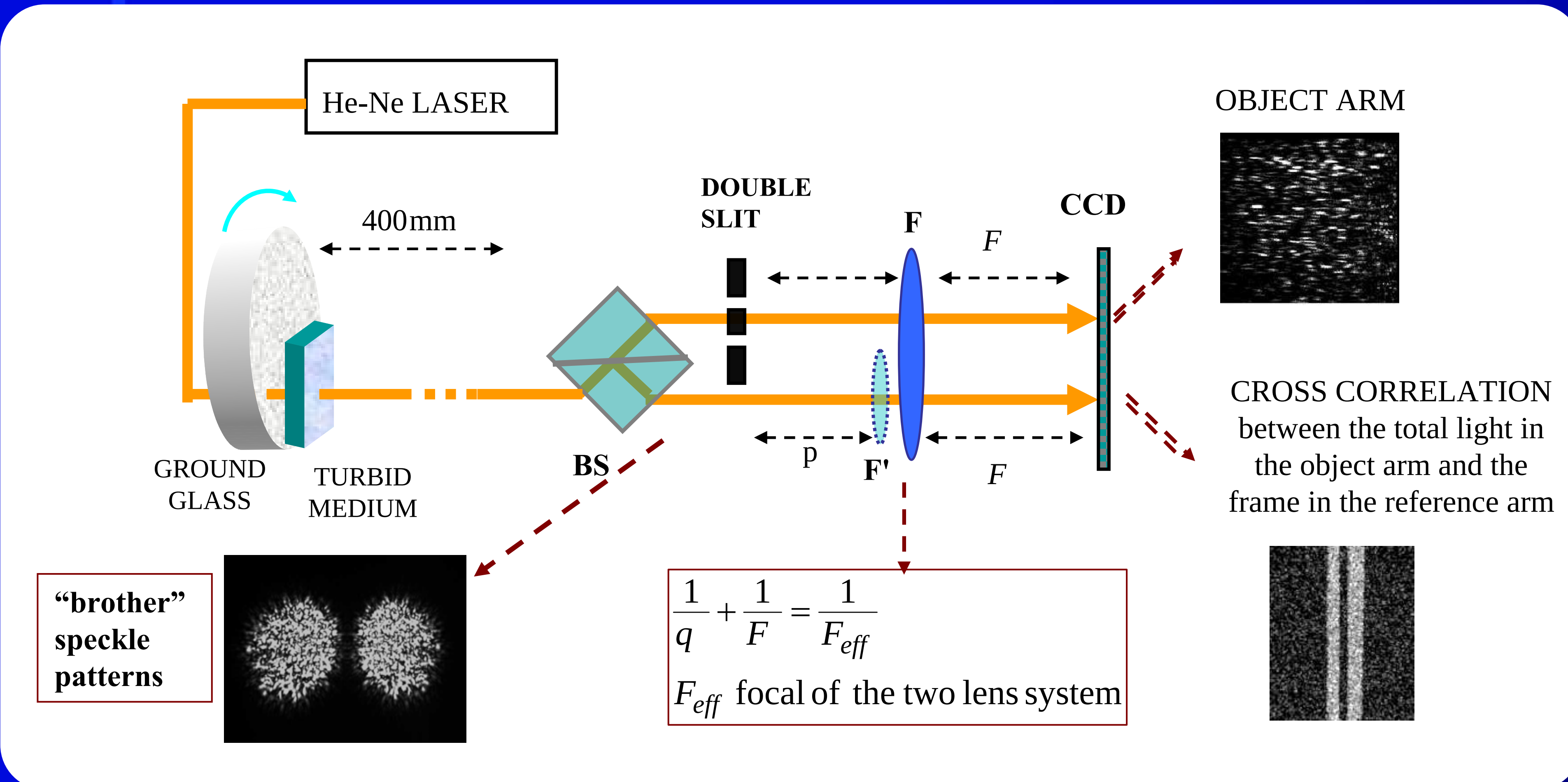
An essential literature:

- Abouraddy, Saleh, Sergienko, Teich, Phys. Rev. Lett. 87, 123602 (2001)
- Bennink, Bentley, Boyd, Phys. Rev. Lett. 89, 113601 (2002)
- Gatti, Brambilla, Lugiato, Phys. Rev. Lett. 90, 133603 (2003)
- Gatti, Brambilla, Lugiato, quant-ph/0307187 (2003) → Phys. Rev. Lett. 93, 093602 (2004); Phys. Rev. A 70, 013802 (2004)
- Bennink, Bentley, Boyd, Howell, Phys. Rev. Lett. 92, 033601 (2004)
- Cheng, Han, Phys. Rev. Lett. 92, 093903 (2004)
- Valencia, Scarcelli, D'Angelo, Shih, Phys. Rev. Lett. 94, 063601 (2005)
- Wang, Cao, Phys. Rev. A 70, 041801R (2004)
- Cai, Zhu, Opt. Lett. 29, 2716 (2004)
- Ferri, Magatti, Gatti, Bache, Brambilla, Lugiato, Phys. Rev. Lett. 94, 183602 (2005)

Etc. etc. etc.

Theoretical and experimental evidence of high resolution ghost image and ghost diffraction with classically correlated beams from a pseudo-thermal source

Gatti, Brambilla, Bache, Lugiato, PRL **93**, 093602 (2004), Phys. Rev. A **70**, 013802 (2004);
Ferri, Magatti, Gatti, Bache, Brambilla, Lugiato, PRL 94, 183602 (2005)



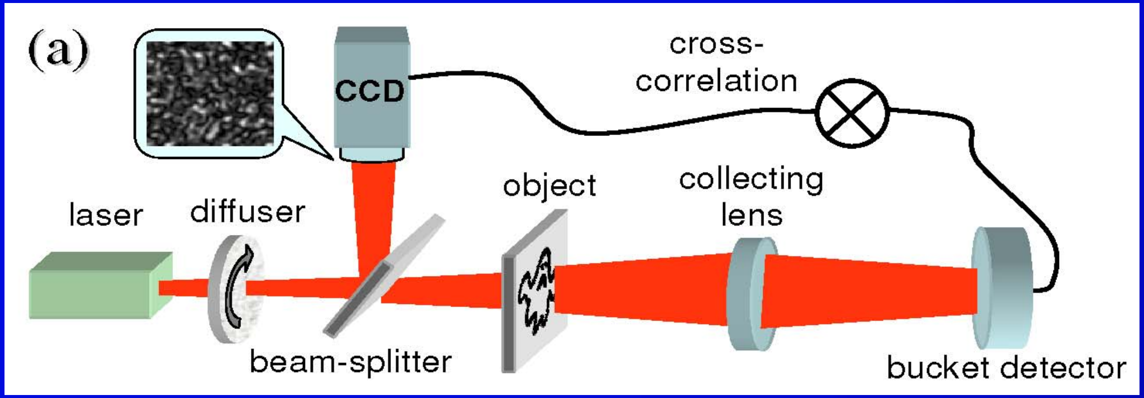
Further debate: can two-photon correlation of thermal light be considered as correlation of intensity fluctuations?

(Scarcelli, Berardi, Shih, PRL 96, 063602, 2006)

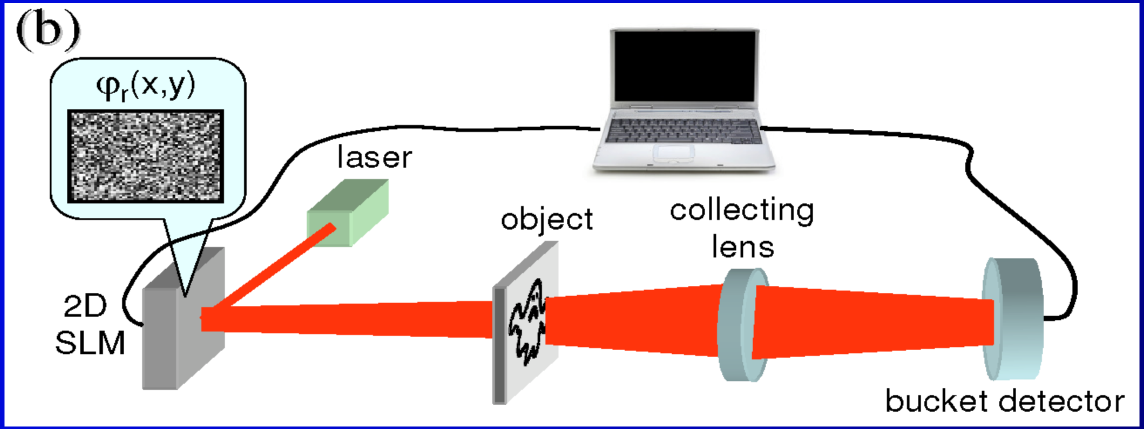
See

- Gatti, Bondani, Lugiato, Paris and Fabre, PRL 98, 39301 (2007)
- Erkmen, Shapiro, PRA 77, 043809 (2008)

STANDARD THERMAL GHOST IMAGING



COMPUTATIONAL GHOST IMAGING



Shapiro, Phys. Rev A 78, 061802(R) (2008)
Bromberg, Katz, Silberberg, arXiv:0812.2633v2 (2008)

Towards applications: 2 opportunities

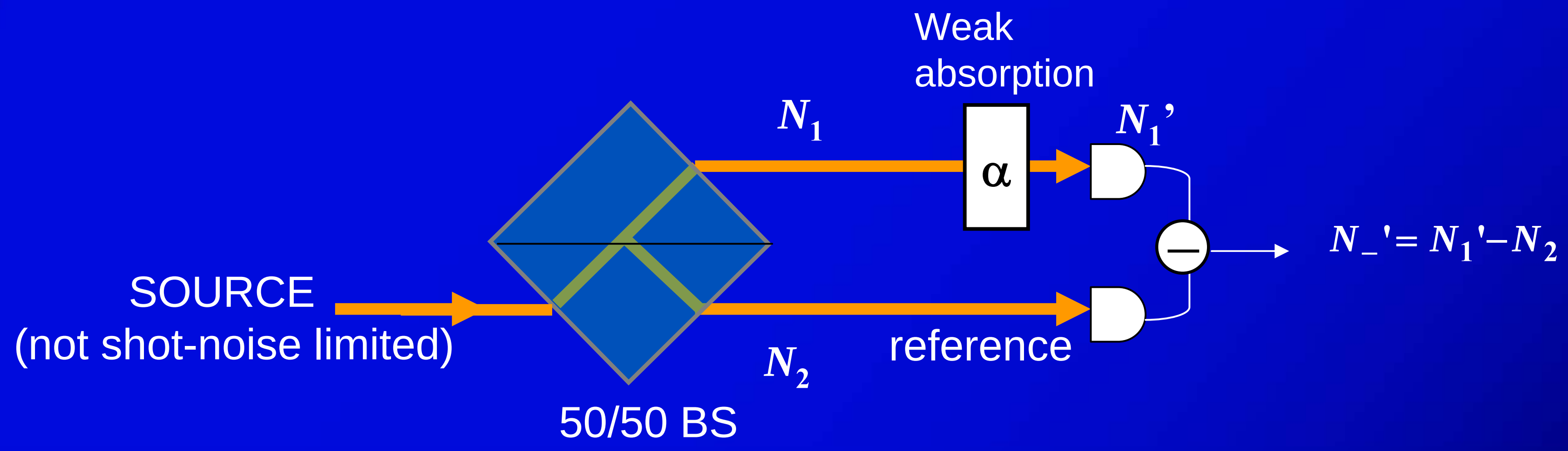
<u>ENTANGLED BEAMS</u>

Possibility of accessing the quantum regime

<u>PSEUDO-THERMAL BEAMS</u>

Inexpensive, easy to use

Detection of a weak absorption (e.g. a spectroscopic signal): typically a differential measurement is used



The signal is retrieved from $\langle N\_' \rangle = \alpha \langle N_2 \rangle$

The source beam may have some excess noise, but the signal-to-noise ratio

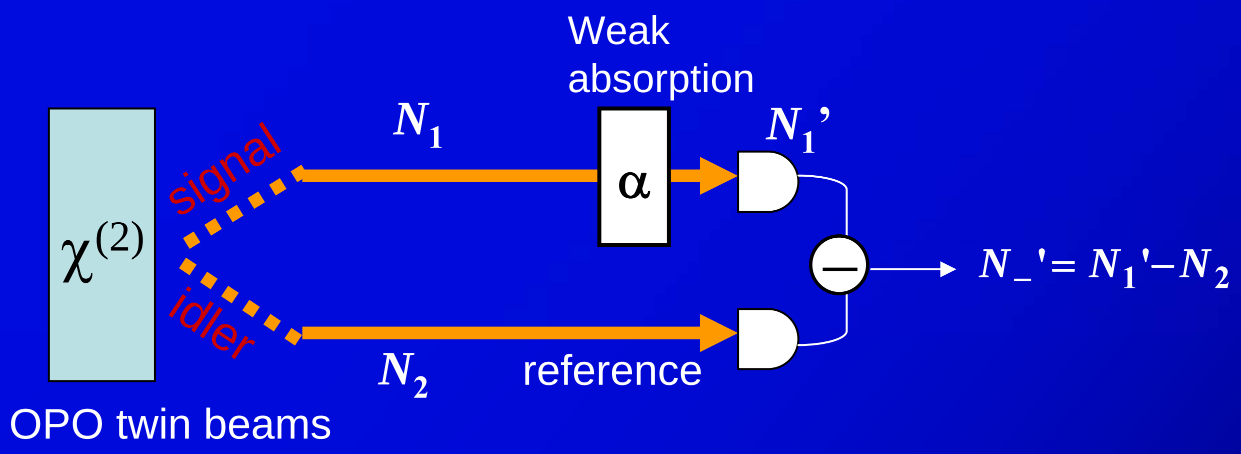
$$SNR \equiv \frac{\langle N\_' \rangle}{\sqrt{\langle \delta N'^2_- \rangle}} \approx SNR_{SQL} = \alpha \sqrt{\frac{\langle N_1 \rangle}{2}} \quad \text{for small } \alpha$$

standard quantum limit, coherent source

⇨ **The differential scheme suppresses the excess noise in the incoming beam, but is affected by the shot-noise in N_2-N_1**

Detection of a weak absorption

A classical differential scheme suppresses the excess noise in the incoming beam, but is limited by the partition noise (=shot-noise) in N_2-N_1



The shot-noise can be beaten by replacing the classical copies with quantum copies: twin-beams with sub-shot noise intensity correlation

⇨ signal-to-noise ratio is improved with respect to the standard quantum limit

$$SNR_{twin-beams} \approx SNR_{SQL} \frac{1}{\sqrt{\sigma}} \quad \text{for small } \alpha$$

Signal-idler degree of correlation

$$\sigma = \frac{\langle \delta N_-^2 \rangle}{\langle N_1 + N_2 \rangle} \begin{cases} = 1 & \text{splitted beams} \\ < 1 & \text{sub-shot noise twin-beams} \end{cases}$$

Improvement of the SNR when detecting a weak spectroscopic signal with **single-mode** twin beams generated by an OPO**:**

- Souto Ribeiro, Schwob, Maitre, Fabre, Opt. Lett. **22**, 1893 (1997)
- Jiangrui Gao et al., Opt.Lett. **23**, 870 (1998)

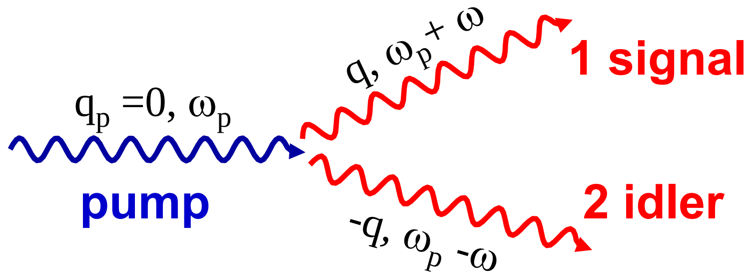
Question: can we use the same technique to detect the spatial distribution of an absorption coefficient $\alpha(x)$, i.e. the image of a weak object ?

- **No** if the twin beams are single mode.
- **Yes**, if we use multi-mode twin beams, as those generated by single-pass parametric down-conversion (PDC)

⇨ we need pixel-to-pixel sub-shot-noise correlation between the signal and idler cross-section, i.e. **quantum correlation in the spatial domain**.

Quantum Spatial correlation in the far-field of PDC

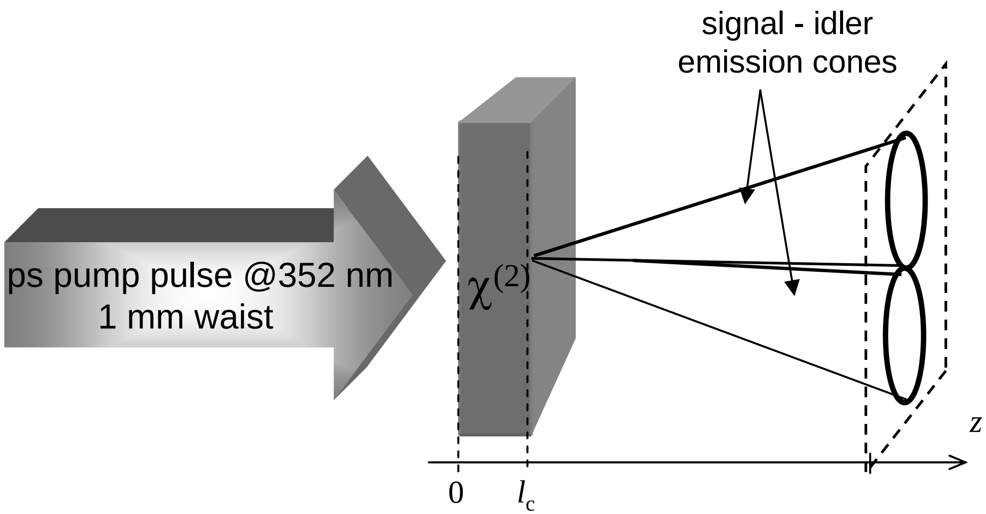
Brambilla, Gatti, Bache, Lugiato, Phys Rev A **69**, 023802 (2004)



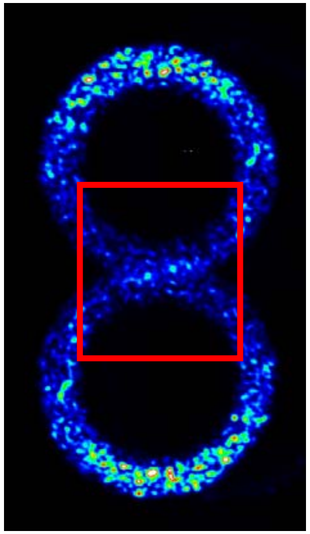
Microscopic process: momentum conservation creates correlation in the directions of propagation of twin photons

Detection of Quantum Spatial Correlation in high-gain PDC

Experiment performed at Como Lab. (Jedrkiewicz, Jiang, Di Trapani)



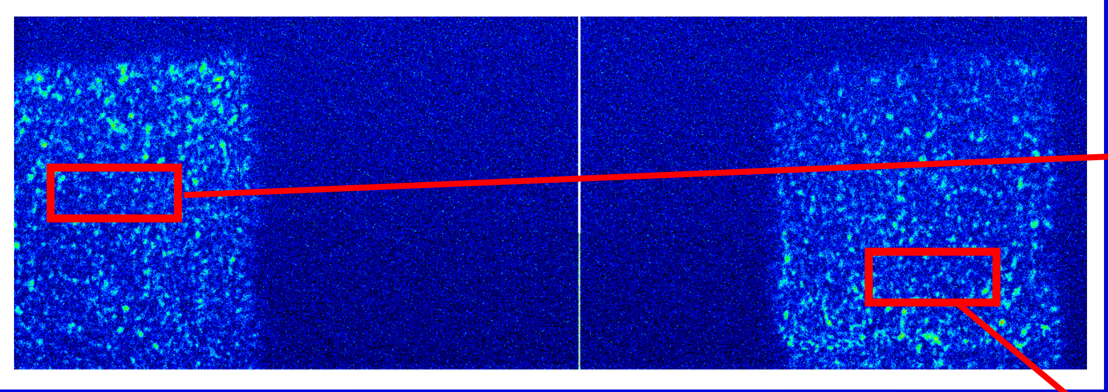
4 mm type II BBO crystal



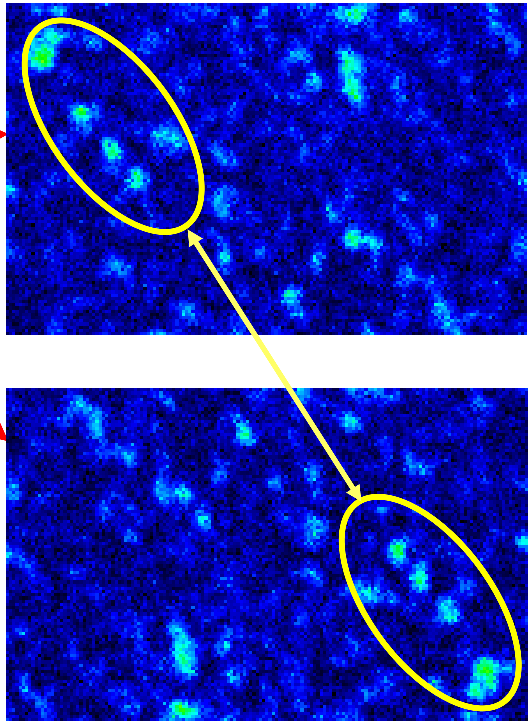
Far-field pattern @704 nm in a single shot

$x_{coh} \propto \lambda f / w_p$ coherence length

Signal and idler distributions on the high efficiency CCD



Zoomed signal @704 nm



Zoomed idler @704 nm

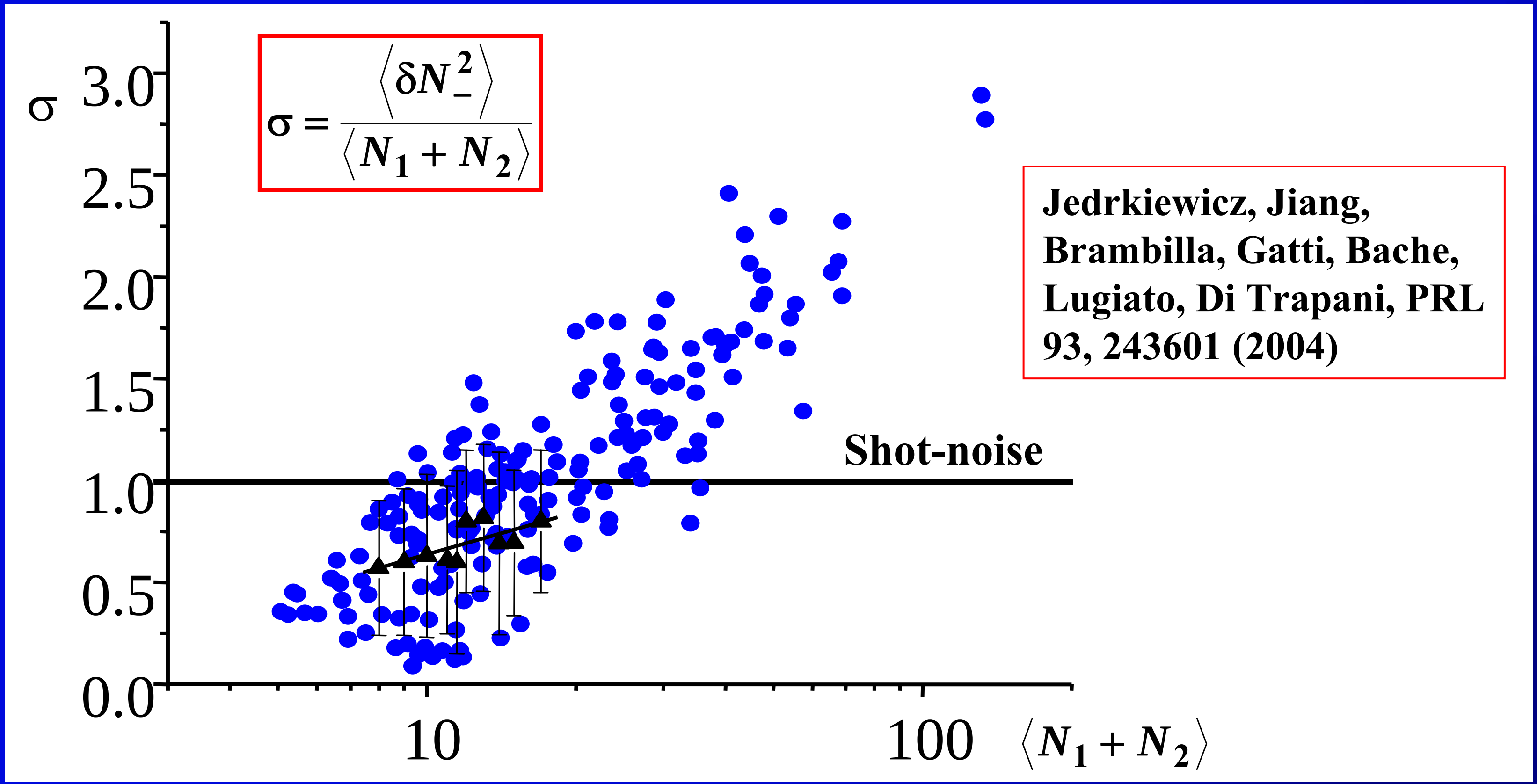
⇨ **evident spatial correlation between the two images**

- Degree of correlation: noise in the difference N_- of photocounts from symmetric signal-idler pixels

$$\sigma = \frac{\langle \delta N_-^2 \rangle}{\langle N_1 + N_2 \rangle}$$

- *CCD* noise variance is subtracted $\langle \delta N_-^2 \rangle = \langle \delta N_-^2 \rangle_{measured} - \langle \delta N_-^2 \rangle_{background}$

Experimental evidence of sub-shot noise spatial correlation



⇨ Twin beam effect over several phase conjugate signal/idler modes. Can be used to enhance the sensitivity of imaging.

Problem: rapid deterioration of signal-idler correlation with increasing gain. Quantum correlation only at relatively low photon number (<20 ph/pixel): the CCD noise $\langle \delta N_-^2 \rangle_{background} \approx 90$ ph/pixel would be detrimental for high-sensitivity measurements.

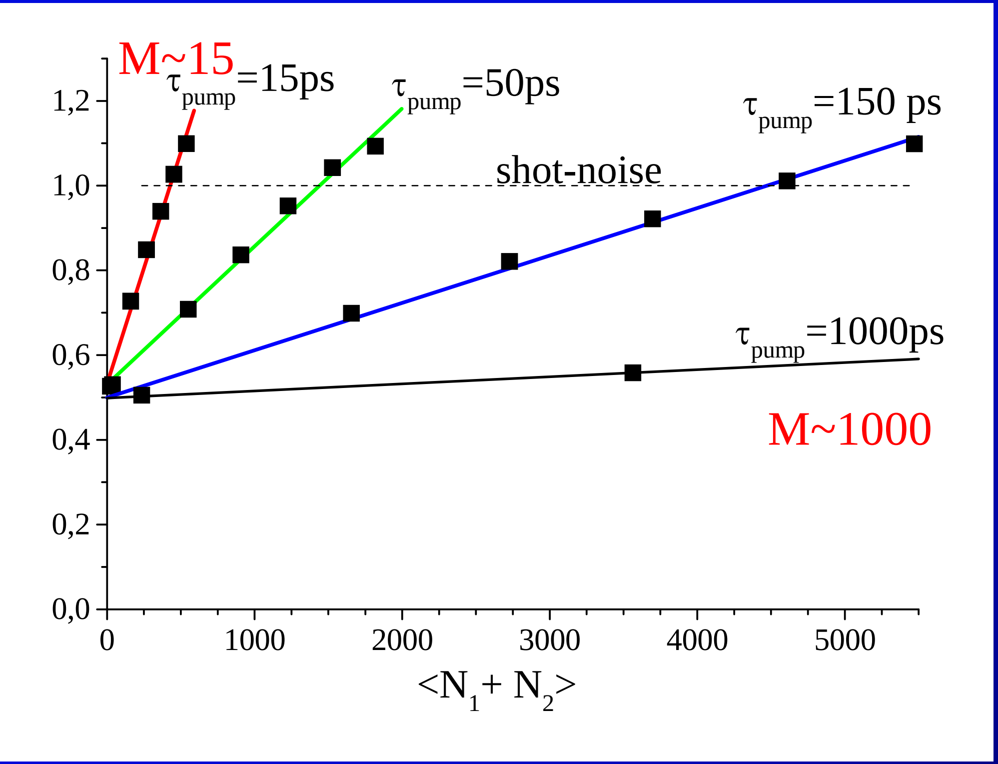
Proposed solution: decrease the excess noise

(Brambilla, Caspani, Jedrkiewicz, Lugiato, Gatti, Phys. Rev. A 69, 053807, 2008)

Regime of low-gain - long pulse duration. The degeneracy factor $M \propto \tau_{pump} / \tau_{coh}$ increases with pulse duration ⇨signal and idler statistics become Poissonian-like

Numerics: degree of correlation σ as a function of the gain (photon number), X_{shift} fixed = 4 μm

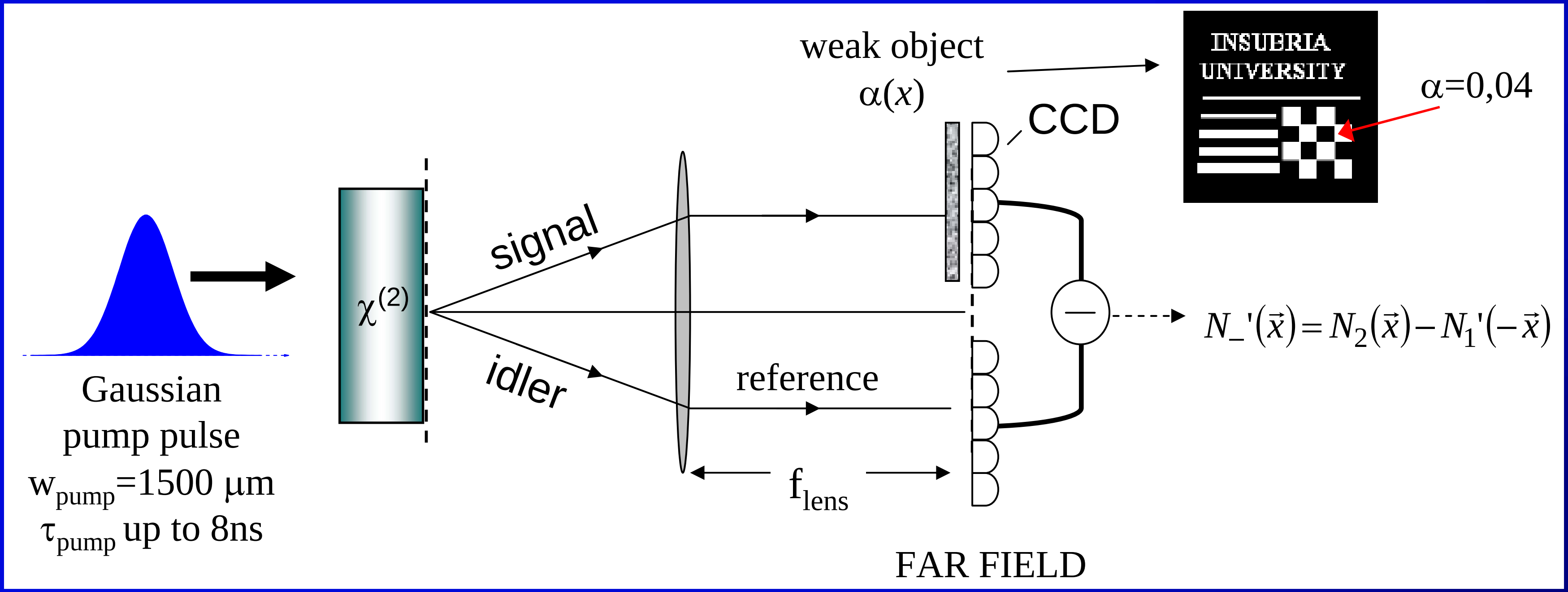
$$\sigma = \frac{\langle \delta N_-^2 \rangle}{\langle N_1 + N_2 \rangle}$$



$$\text{slopes} \propto \frac{1}{M} \approx \frac{\tau_{coh}}{\tau_{pump}}$$

Correlation is more robust for long pump pulses, low excess noise ⇨ sub-shot noise correlation at higher photon number

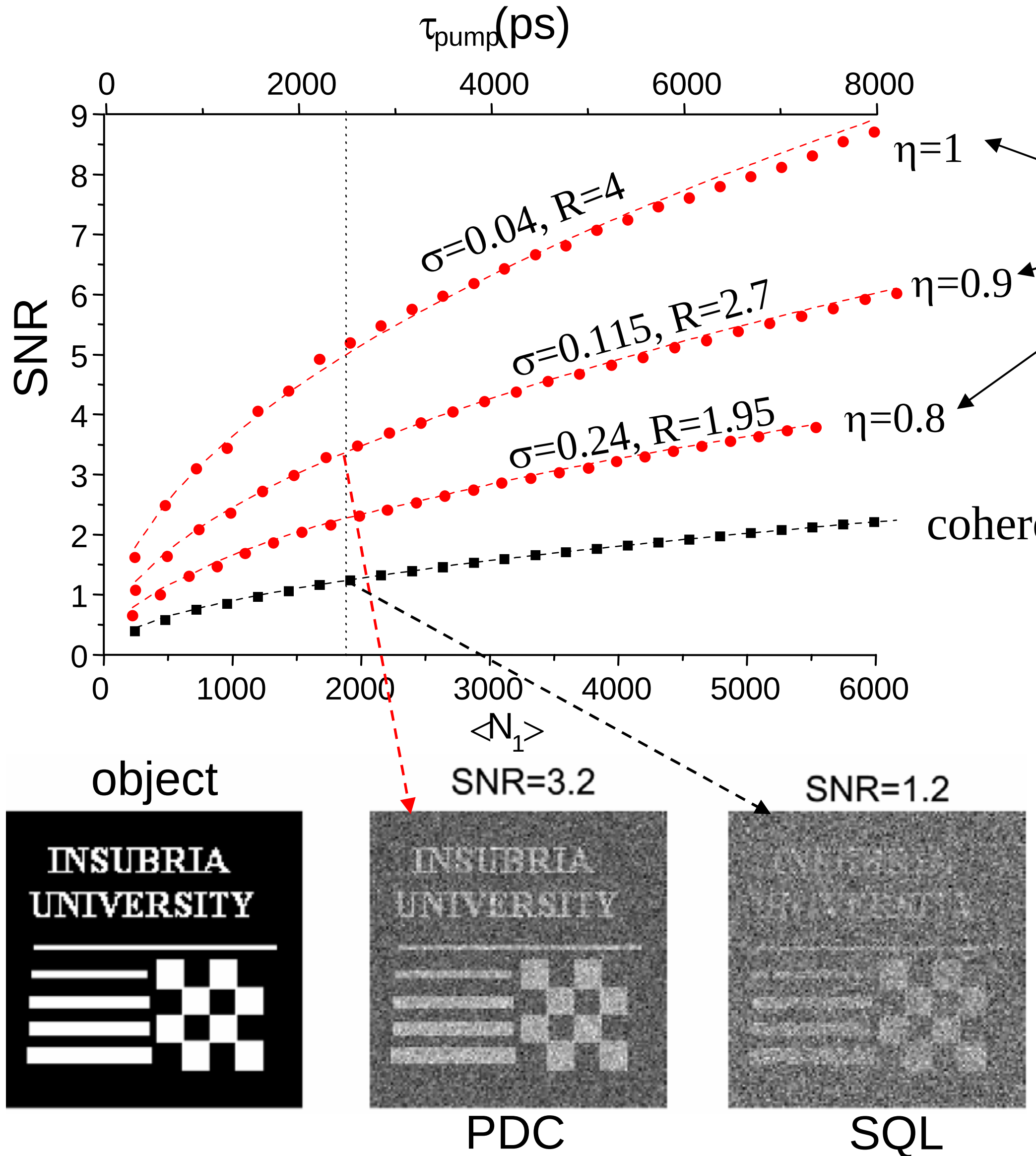
Numerical simulation of the detection of a weak object $\alpha(x)$



Relevant quantities evaluated from the simulations:

σ	degree of spatial correlation (without object)
SNR_σ	signal-to-noise ratio
$R = \dfrac{SNR_\sigma}{SNR_{SQL}}$	improvement of SNR with respect to SQL

Signal-to-noise ratio as a function of photon number (pump pulse duration)



$$\eta = 0.9$$

$$\tau_{pump} = 2500\text{ps}$$

$$\langle N_1 \rangle = 2000\text{ph./pixel}$$

$$\alpha_{obj} = 0.04$$

PRL **102**, 213602 (2009) PHYSICAL REVIEW LETTERS week ending 29 MAY 2009

Measurement of Sub-Shot-Noise Spatial Correlations without Background Subtraction

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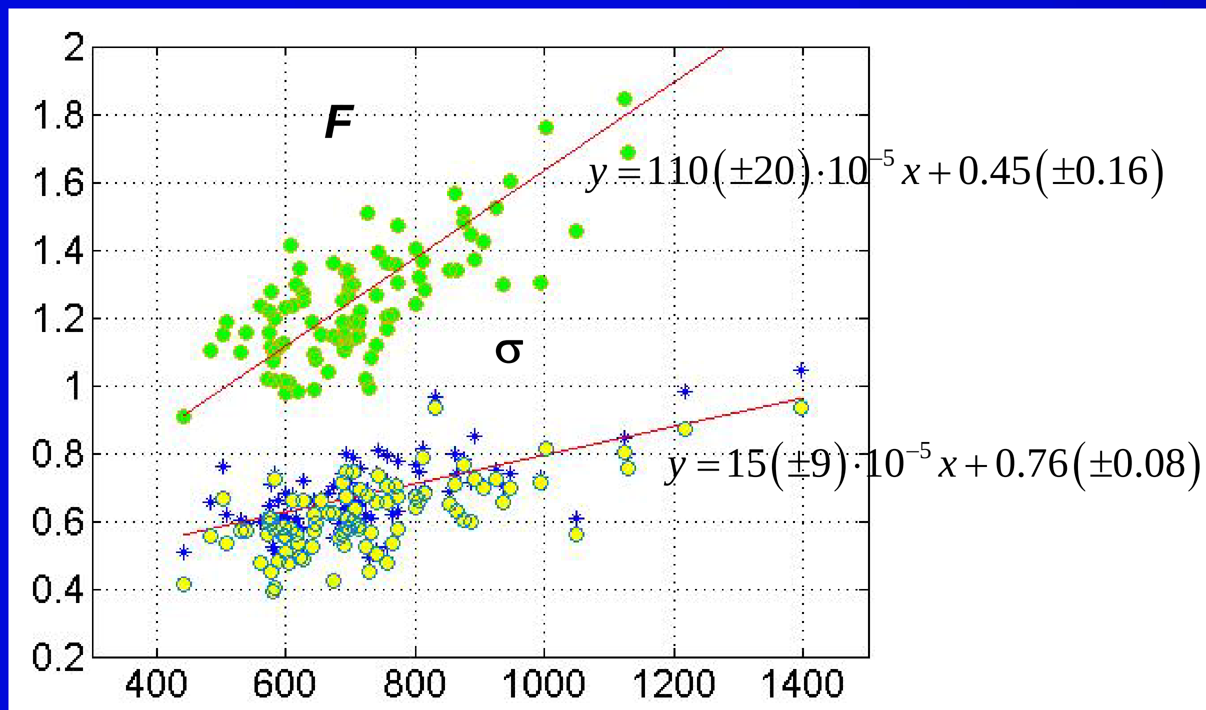
(Received 8 October 2008; published 28 May 2009)

In this Letter we present the measurement of sub-shot-noise spatial correlations without any subtraction of background, a result paving the way to realize sub-shot-noise imaging of weak objects.

DOI: 10.1103/PhysRevLett.102.213602 PACS numbers: 42.50.Ar, 42.50.Dv, 42.50.Lc, 03.65.Wj



- Large photon number per pixel
- No need for substraction of background

CONCLUSIONS

- Continuing interest in ghost imaging
- The quantum nature of light can really improve the SNR in the detection of faint objects
- There is a good progress towards the experimental realization of this concept (see Genovese’s talk Wednesday 9:00)

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Quantum properties of the optical field represent a resource of the utmost relevance for the development of quantum technologies, allowing unprecedented results in disciplines ranging from quantum information and metrology [1] to quantum imaging (for recent reviews see [2]). For applications in this latter field, a fundamental tool to be realized is the spatial correlation, at the level of quantum fluctuations, of two optical beams. An example is the high-sensitivity detection of weak objects proposed in [3], which exploits the intrinsic multimode quantum correlations of parametric down conversion (PDC) emission, a result that may have disruptive practical applications in biomedical imaging or whenever there is the need of illuminating an object with a low flux of photons [4]. This technique is based on the spatial correlation in the quantum noise of two conjugated branches of PDC emission [6–8]. The image of a weak absorbing object in one branch, previously hidden in the noise, can be restored by subtracting the strongly correlated spatial noise pattern measured in the other branch. In order to achieve a sensitivity superior to that available with classical techniques, one should be able to reach a sub-shot-noise (SSN) regime in spatial correlations even in the presence of the unavoidable background noise (electronic noise, scattered light) [3]. Nevertheless, up to now, such a result was not yet achieved. Indeed, previous demonstrations of the quantum nature [9,10] of the spatial correlation of PDC beams were realized only for low photon numbers. In that regime the background noise was dominant, so that a proof-of-principle demonstration of SSN correlation was possible only after correcting the results for the background noise (i.e., by subtracting the variance of the spatial pattern of the background, measured in the absence of PDC). Clearly, such a regime cannot be used for concrete imaging schemes, as the image distribution would remain hidden in the background noise. Similarly, a single-mode sub-shot-noise intensity correlation [11–16] cannot be used to retrieve high-sensitivity information on the spatial distribution of an object, since the quantum character of the correlation vanishes when one detects small portions of the beams instead of the whole beams. Thus, high-sensitivity imaging requires spatial quantum correlations (i.e., SSN intensity correlations between several portions of two twin beams) in a regime where the photon flux is high enough to make the background noise negligible. The purpose of the present Letter is to present this achievement: a clear observation of SSN spatial correlation, without any correction for the background noise, is presented and discussed, opening the concrete possibility of realizing imaging with a sensitivity beyond the standard quantum limit.

The strategy we shall follow to reach our goal is that indicated by [3]: the major limitation of the experiment [9] was the presence in each beam of a large excess noise with respect to coherent light, which made SSN correlation fragile with respect to unavoidable experimental imperfections (unbalances, errors in the determination of the symmetry center of the signal-idler distributions) and rapidly deteriorated the correlation for increasing gain. Such an excess noise can be lowered by working in a different regime, i.e., a pump pulse of duration much longer than the typical coherence time of PDC beams, which is on the order of picoseconds for a few millimeters crystal. As predicted in [3], a nanosecond pump pulse should enable the observation of SSN correlations at a much higher photon number. In our setup (Fig. 1) a type II beta-barium borate nonlinear crystal ($l = 7$ mm) is pumped by the third harmonic (355 nm) of a Q-switched Nd:Yag laser (with pulses of 5 ns, 10 Hz repetition rate, and a maximum

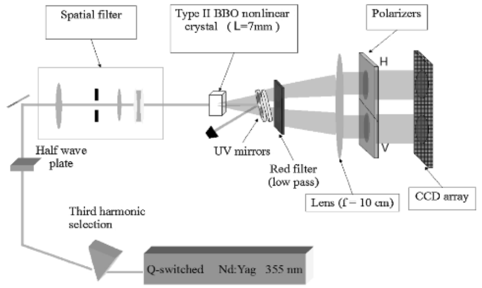
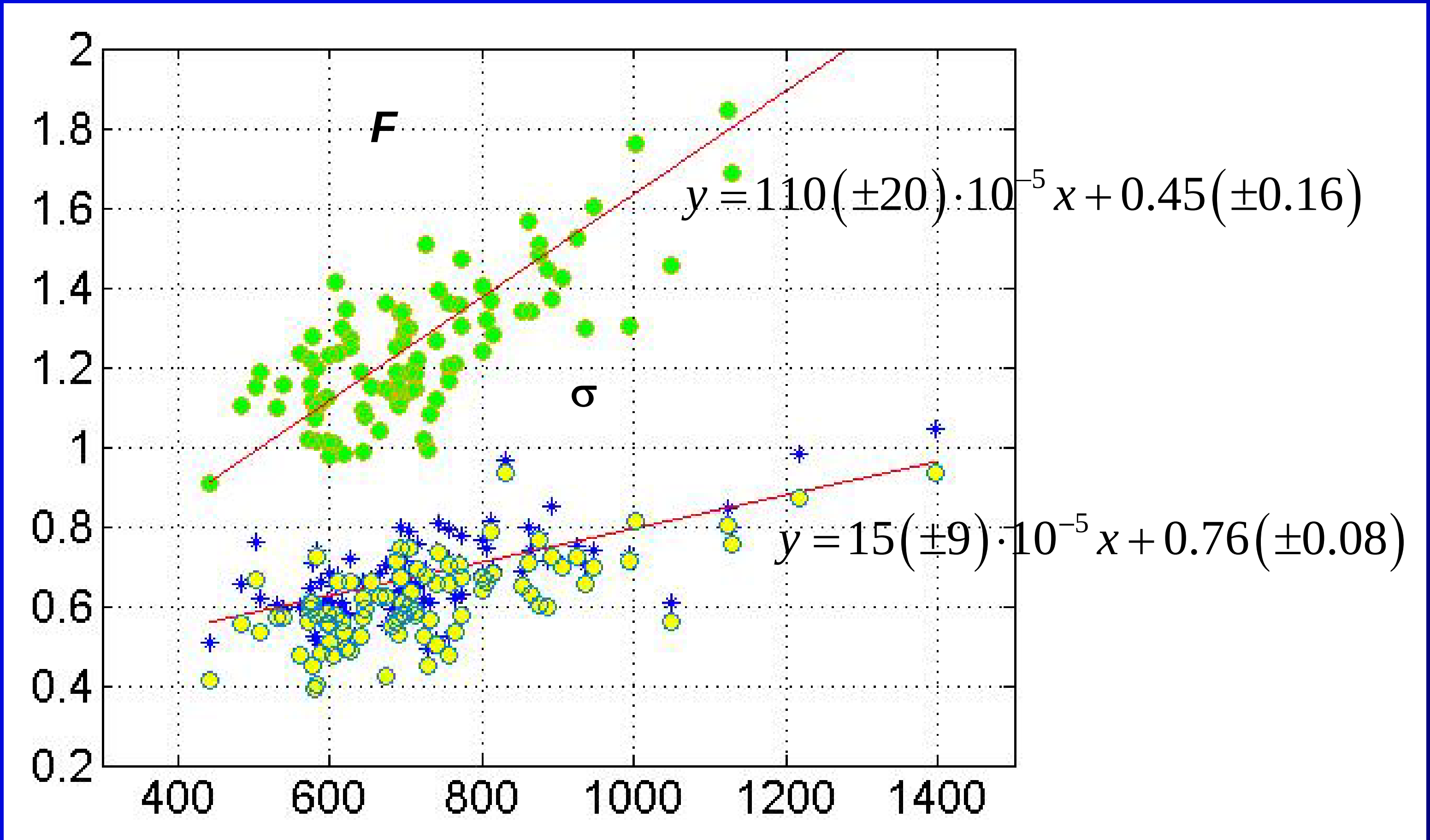


FIG. 1. Experimental setup. A triplicated Nd:Yag laser beam, after spatial filtering, produces type II PDC in a beta-barium borate crystal, which is then measured (after eliminating the UV beam) by a high-sensitivity CCD camera.



- Large photon number per pixel
- No need for substraction of background