BACK TO BASICS: Time-tagging single photons

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The analysis of time correlations between photons is the essence of quantum information processing protocols (communication, metrology and computing) presented in this special issue. These correlation measures are derived from fundamental quantum optical techniques formalised by R. Glauber in 1963 [Phys. Rev. 130, 2529] which enable the properties of electromagnetic fields to be measured, *i.e.* their fluctuations and signatures to be detected in a noisy signal. More generally, those fluctuations are the result of high order interferences and are, in certain cases, directly linked to the "traditional" coherence of the optical fields.

An analysis of the time correlations between two modes, 1 and 2, of the electromagnetic field takes the mathematical form of a normalised function such as

$$g^{(2)}_{1,2}(\tau)=\frac{\langle I_1(t)I_2(t+\tau)\rangle}{\langle I_1(t)\rangle\langle I_2(t)\rangle}=\frac{\langle :N_1(t)N_2(t+\tau):\rangle}{\langle N_1(t)\rangle\langle N_2(t)\rangle},$$

which enables to determine the degree of correlation of the fluctuations of the optical intensities $I(t)$ of the two modes, observed at two instants separated by a duration τ. It should be noted that, from a quantum standpoint, we can also express this magnitude using the numbers of photons $N_i(t)$ in a mode i. An easy interpretation of $g^{(2)}_{1,2}(0)$ can be obtained in a simple experiment, as illustrated in *Figure 1*. It consists in comparing the number of photons detected in each mode for each instant. If the time distribution of the photons in each mode is completely random and independent, then there is no correlation, which corresponds to a degree of correlation equal to 1. Conversely, if the time distributions of the photons are correlated, *i.e.* there is a photon simultaneously in each mode, then

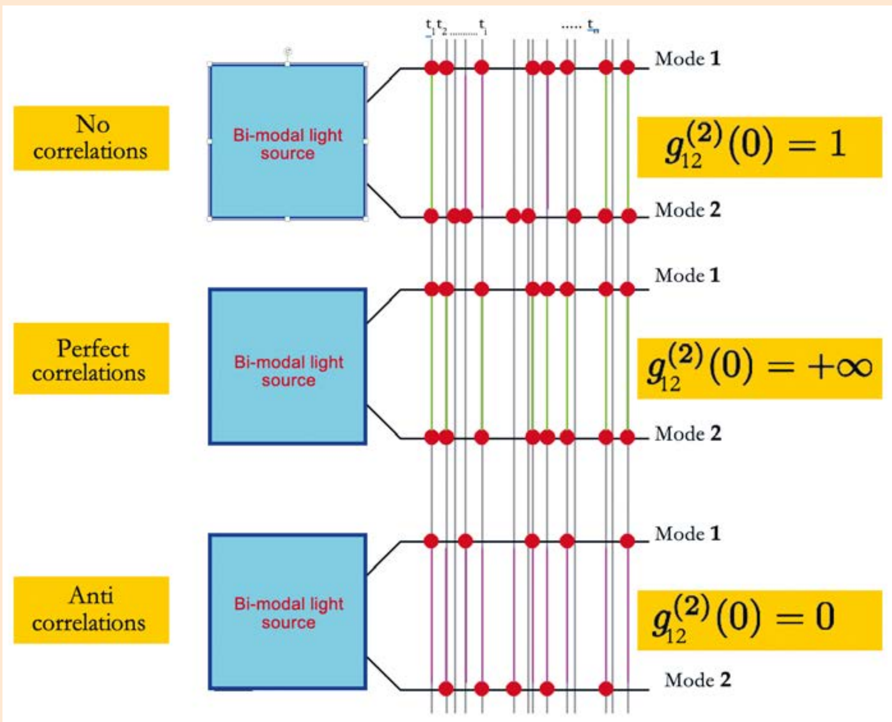

Figure 1. Analysis of correlations of the number of photons between two modes. The **correlations** (presence of a photon in each mode at instant *t*) are identified by a *green trace*, whereas the anticorrelations (presence of a photon only in one mode or the other) are identified by a purple trace. The aim in this case is to measure the correlations in the fluctuations of the light intensity between modes 1 and 2 over time. At the photon scale this corresponds to the conditional probability that a photon is present in mode 2, bearing in mind that a photon is present in mode 1. We have represented 3 (pedagogical) cases corresponding respectively to a photon pair source (perfect correlations), a coherent laser (complete lack of correlations) and a single photon source (perfect anticorrelations).

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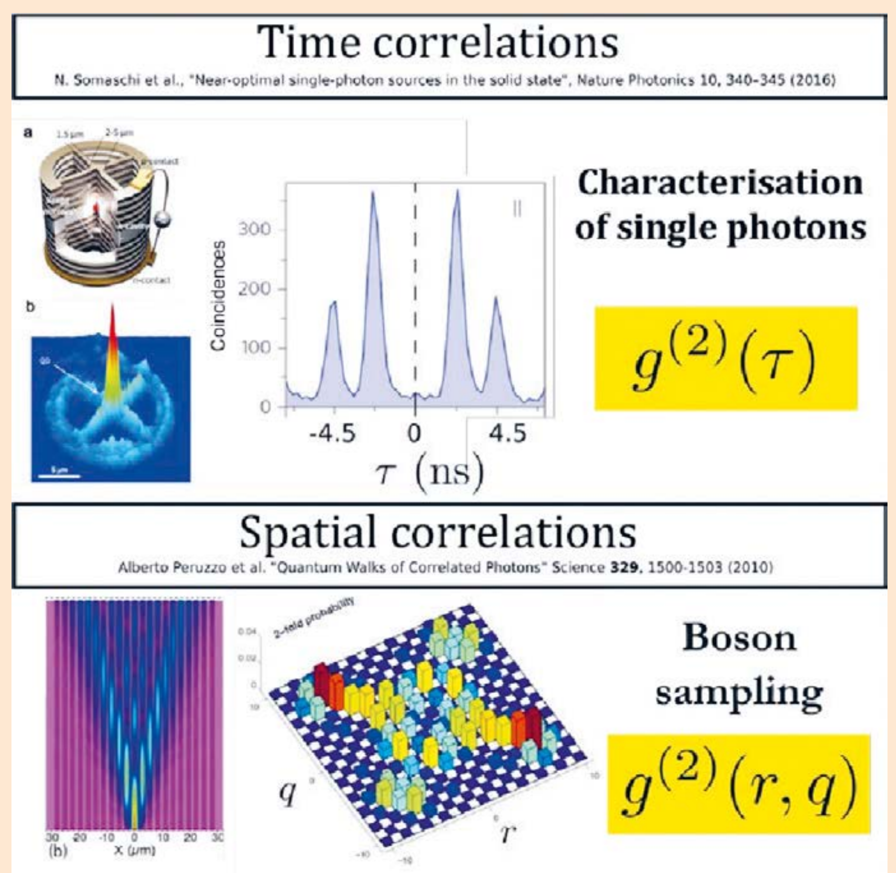

Figure 2. Two applications in quantum optics for the measurement of photon correlations. In the case of time correlations the aim is to characterise a single photon source based on a quantum dot [2] operating in the pulsed regime. In this case, it is the absence of a correlation peak at $\tau = 0$ which is significant. It reflects the fact that two photons are never produced simultaneously by the source. Conversely, the presence of correlation peaks at $\tau \neq 0$ is interpreted as the probabilities that a second single photon will be emitted in the next or previous pulses. Typically, it is the ratio of the two peaks (central to lateral) which enables the quality of a single photon source to be determined. In the spatial case, we introduce boson sampling, which consists in calculating the spatial correlations of a pair of photons at the output of a network of coupled waveguides of dimension $k \times k$ in which the coupling between the guides enables the action of beamsplitters to be simulated [3]. In this case correlated detection of photons is essential, since it enables the pairs of photons which actually travelled together (i.e. in the form of a two-photon wave packet) to be distinguished from those which travelled independently of one another (in the form of two single-photon wave packets). In fact the spatial signature at the output of the network in the two cases differs greatly, due to two-photon interference, which has no conventional equivalent.

function $g^{(2)}_{1,2}(0)$ takes a value higher than 1, which directly reflects the degree of the correlations. Finally, if the time distribution is such that there are perfect anticorrelations between the two modes, then $g^{(2)}_{1,2}(0) = 0$, showing there is only a single photon among the two modes.

Generaly speaking, the degree of correlation is expressed as a function of space and time such as $g^{(2)}(x,t)$. In practice this function is often reduced to a single variable, depending on the considered experiment. As illustrated in *Figure 2*, the "time" configuration is, for example, used to characterise single photon sources, for which we are looking for anticorrelations at $\tau = 0$ [2]. Indeed, in the case of an ideal source, one should never observe two photon at the same *time*, such that the autocorrelation function $g^{(2)}(0)$ has a value lower than 1 (ideally 0). Spatial correlations, for their part, are exploited in quantum computation, *i.e. boson sampling* for instance, which is a very difficult task for a conventional computer [3]. The aim is to analyse the spatial distribution of a pair of photons at the output of a $k \times k$-dimension

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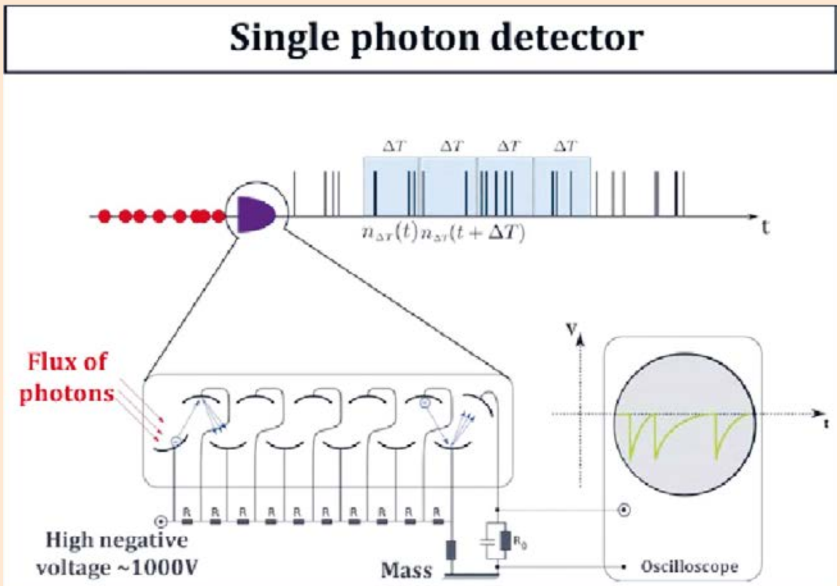

Figure 3. Principle of a photomultiplier. Incident photons produce, by cascade, electrical pulses whose time distribution reflects that of the incident photons. In practice a photon gives rise to a photoelectron which is not sufficient to obtain a signal which can be measured directly. However, after few tens of bounces the amplification is such that the quantity of electrons is high enough to allow each photoelectron to be registered. One million electrons form, indeed, an electrical charge $Q = 10^{-13}$ C, the electrostatic action of which, although low, is perfectly measurable. Arriving all together at a single instant, they temporarily charge readout capacitance C_L positioned where the last electrode was. For instance, a capacitance of 10 pF can lead to voltages of the order of $Q/C \sim 10$ mV, ~ 10 mV, which are easily observable, and can be counted with an oscilloscope. The user can then extract a magnitude $n(t)$ which corresponds to a number of photons detected over a time unit ΔT.

network of half-silvered mirrors (each mirror reflects or transmits a photon with a probability of 50%). In this case, we are interested directly in spatial correlations (i.e. the joint probability that a photon exits the network through port r and, while the other photon leaves simultaneously through port q), through correlation function $g^{(2)}_{r,q}(0) = g^{(2)}(r,q)$.

These few examples enable us to put the issues of correlated photon detection in context, but pose several questions: how can a single photon be detected? To what type of signal does the detection of a photon correspond? What are the important characteristics which define a good "photon counter"? Which experimental methods enable the detection of a photon to be "time-tagged" accurately?

What difference is there between a detector with several photons and a single photon detector?

Let us suppose that we have an ideal source of single photons at 980 nm which emit photons on demand at a rate of 1 MHz: this corresponds to a

What detectors in practice? Conventional and less conventional single photon detectors

These are detectors operating along the principle of the photomultiplier, *i.e.* sensitive to single photons and capable of sending a conventional signal enabling the individual arrival times of these photons to be "tagged". In practice experimentalists now have access to detectors associated to a very high gain based on reverse-polarised semiconductor diodes operated near their breakdown voltage (the reverse voltage at which the diode switch to conducting states). The principle of amplification occurs as follows: the arrival of a photon gives rise to an electron-hole pair which is accelerated to the edges of the junction, and triggers an avalanche by switching the diode to the conducting state. An avalanche of electrons can then be measured at the terminals of a simple resistor. Recently, a new technology based on superconductor materials has appeared. The operating concept is related to the operation of a bolometer which is extremely sensitive to the heating of the material when a single photon is absorbed. An optical fibre delivers light to the surface of a superconducting stripe (of resistance zero to approximately 2 K), in which a direct current of several nA is flowing. The quantity of energy provided by a photon ($2\ 10^{-19}$ J) is sufficient to locally switch the material to be resistant to the passage of the current. The increased potential difference at the stripe's terminals enables the arrival of a single photon to be "seen".
Currently, the activity of research and development into superconductor detectors is progressing in leaps and bounds.

The performance of the laboratory devices shows efficiency close to 95%, time jitters of the order of 10 ps, and maximum counting rates of 100 MHz for dark counts rates of less than 10^{-9} ns. No single detector combines all these qualities for the time being, but the community has observed performance improvement of single photon detectors of a factor of 100 over 10 years. Anecdotally the human eye could act as a photon counter. It is commonly accepted that a trained eye well accustomed to darkness is sensitive to a flux of 100 photons per second, but recent experiments show that it is, in fact, capable of resolving a single photon [5]. However, the eye must be used only with a very relative confidence, since reliability (not efficiency, which excludes the probability of believing that one has seen a photon when there was nothing) is only very slightly higher than 50% for "counting" photons.
From another angle, all detectors presented up till now are inexorably associated with absorption of the photon: measuring the photon often means losing the photon! Prolific research activity is being devoted to implementing quantum measuring techniques which are non-destructive of single photons. These measurements generally rely on an atomic interferometry assembly, and exploit the light-material interaction to cause small phase variations in the core of the interferometer. The difficulty of this technique lies in the ability to resolve these small phase jumps when a photon passes [6].

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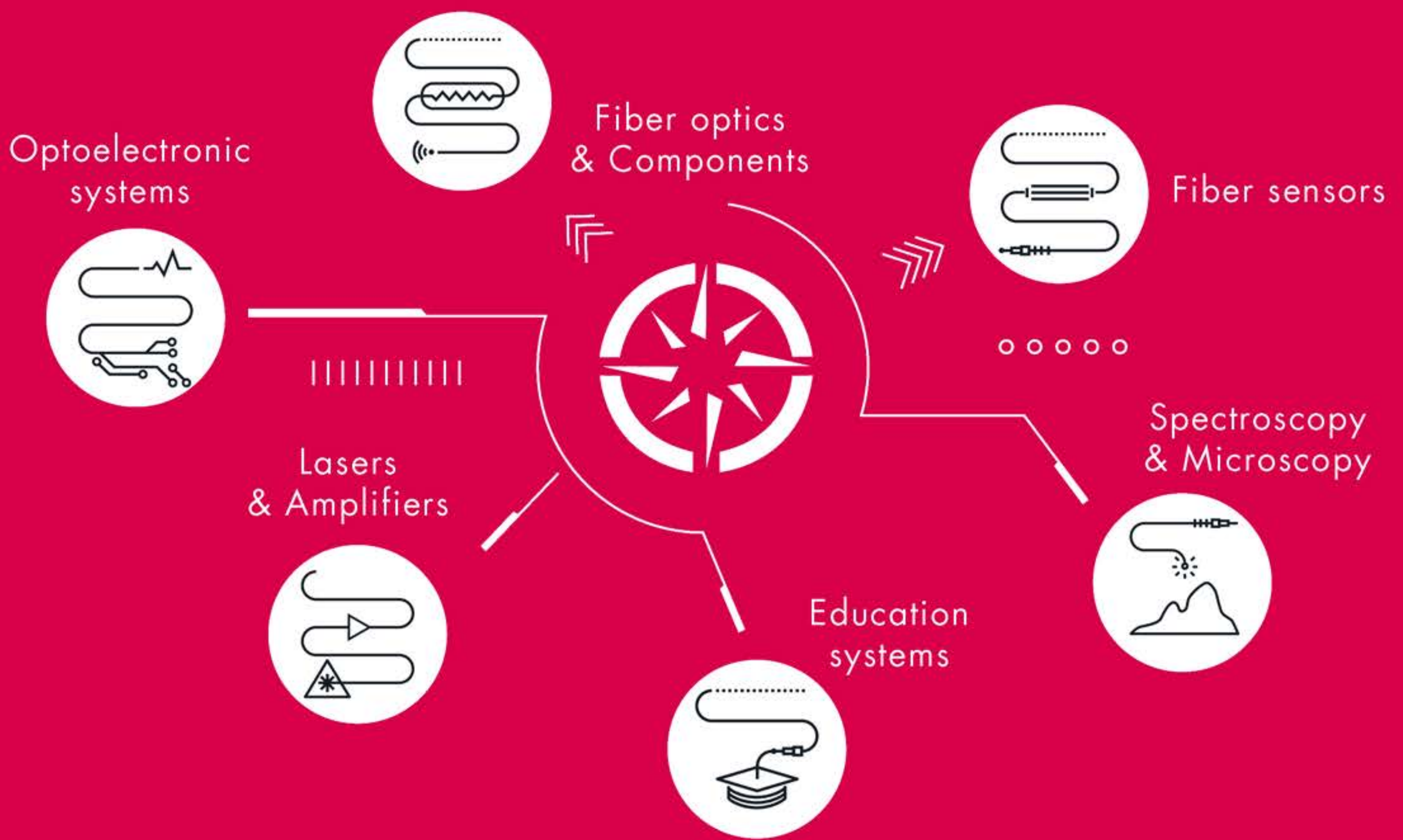

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light power of 2 10^{-13} W. Although it is true that a conventional detector – assuming that each incident photon releases one electron by photoelectric effect – can easily "accumulate" over time few hundreds of photoelectrons to obtain a charge which can be measured at the terminals of a capacitance, its low gain means that it is not capable of detecting a single photon. The appropriate solution is that of a photomultiplier tube as pedagogically represented in *Figure 3*. Few tens of electrodes subjected to increasing potentials are enclosed in a vacuum tube. The first, at the lowest potential, is a photocathode which, upon the absorption of a photon, emits a photoelectron. This electron is accelerated to the second electrode, and strikes it with a kinetic energy enabling several electrons to be extracted from the metal. When released, these new electrons are subsequently accelerated towards the next electrode, where they again extract several electrons each. The number of electrons is thus gradually increased, and a charge *Q* received by the last electrode is rapidly amplified by a factor of 10^6. This gain is sufficiently large to enable individual detection of the initial photoelectron at the terminals of a capacitance *C*. The phenomenon can be observed simply using an oscilloscope in the form of short pulses of amplitude $V_0 = Q/C$. The user therefore receives electric pulses which he can "count" over the time interval of his choice ΔT. This number can be averaged and expressed in Hz in certain circumstances, but the information contained in the instant of arrival of the photon would be lost [4].

The difference between "photon detectors" capable of measuring light fluxes of several hundreds of photons and true "photon counters", capable of resolving the arrival time of a photon, is substantial. These are two completely different devices which do not supply the same signal, and which must not be confused. Quantum technologies require the photons to be detected one-by-one.

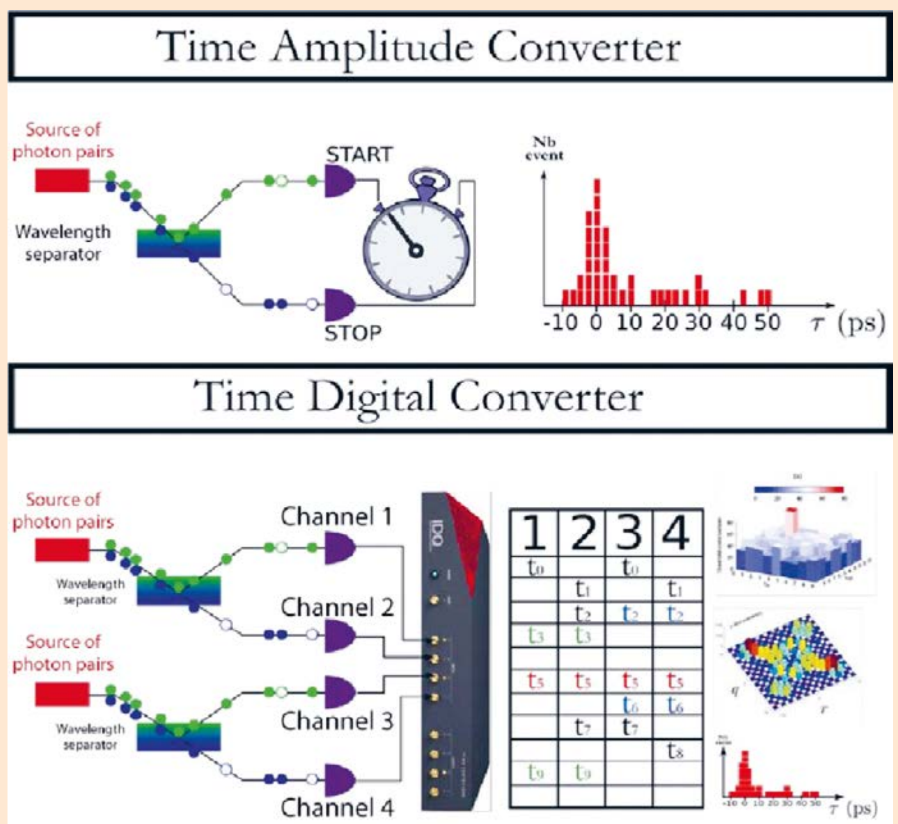

Figure 4. Principle of photon time-tagging. There are two ways of processing the data associated with the detection of single photons. The first consists in measuring time intervals between two events using a time-amplitude converter. The second is more sophisticated and more flexible since it consists in associating a label with precise time information with each detection.

Systems for dating electric signals

Surprinsingly, the first correlation devices were derived from research in particle physics, but did not enable an arrival time to be attributed to the photons. These were two-channel correlators (*time to amplitude converter*) which measured only the relative time which elapsed between two events received in each channel. In other words they were simple, but high-precision, chronometers, with a "start" channel and a "stop" channel, coupled to an analog-digital converter. This type of device then enabled bar charts to be produced showing the coincidences as a function of time τ separating the start and stop events such as the one shown in *figure 4*. It is easy to show that this diagram is directly related to time correlations function $g^{(2)}(\tau)$ presented at the beginning of the article. Their time resolution is now unequalled (~1 ps). However, the fact that they operate only using two channels limits any use in experiments using more than two photons.

Progress in the field of electronics has led to the appearance of high-precision dating systems (*time digital converters*). In this case it is simply an ultra-precise clock (between 10 and 100 ps) which enables a time label to be attributed to each detection, which is then kept in memory. Its strength lies in the number of accessible channels and in the richness of the possible post-processing analyses.

Application to observation of energy-time entanglement of pairs of photons

In the case of quantum technologies based on photonic solutions, pairs of entangled photons are a widely exploited resource. These pairs are commonly generated by parametric

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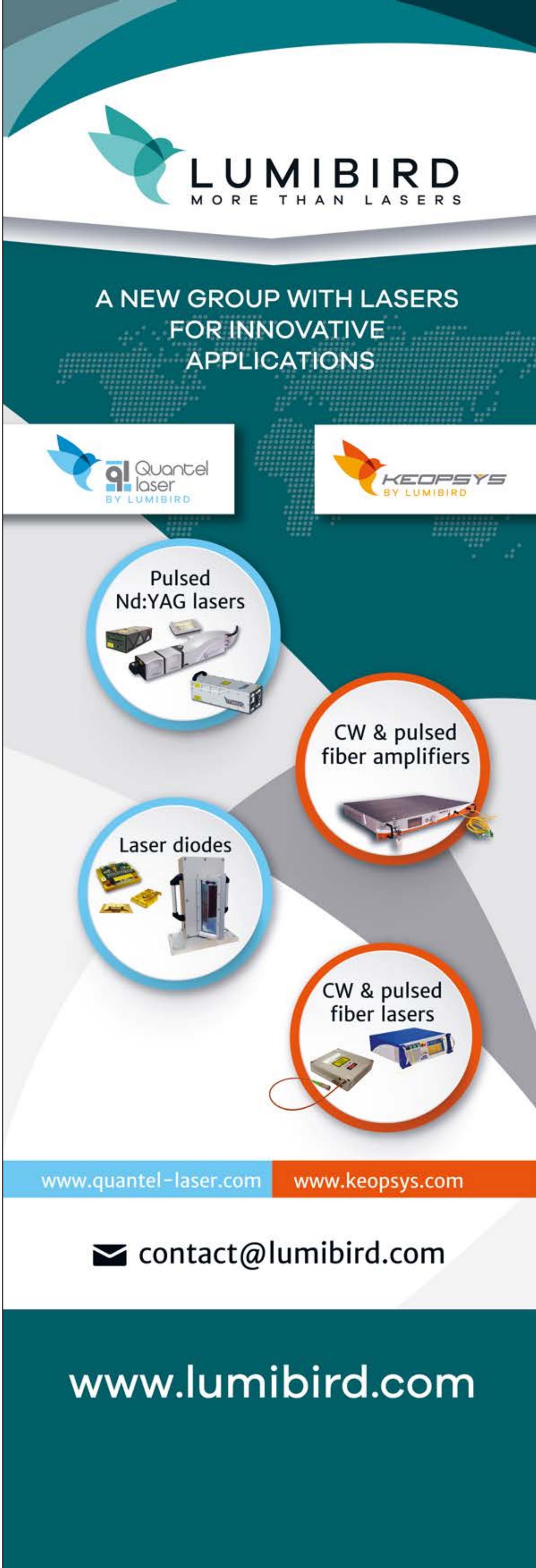

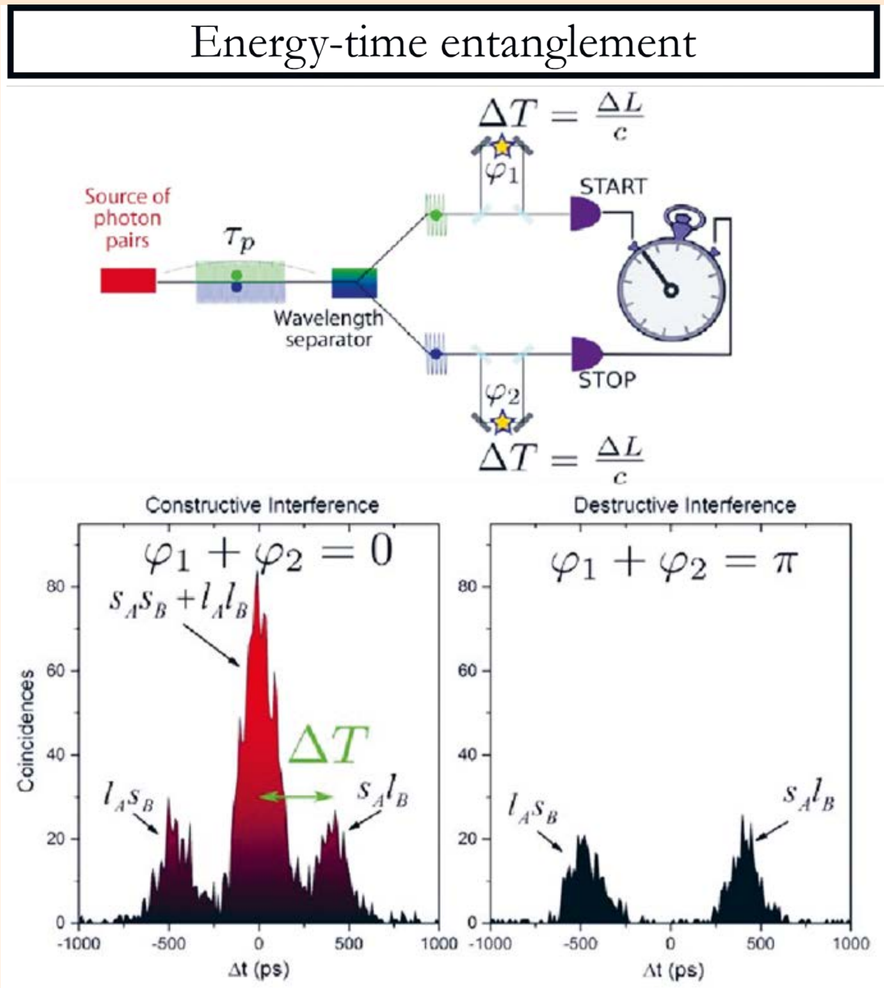

Figure 5. Measurement of energy-time correlations of pairs of entangled photons via an « Franson -type » interferometric setup. The key point of this device consists in observing the coherence of the pairs of photons via a phenomenon of interference, whilst avoiding observation of the single photon interferences. To accomplish this, the experimental conditions require highly unbalanced interferometers and a time tagging unit enabling the separation of the pair of photons contributions (central peak) from that of the two individual photons (lateral peaks). It is thus possible to observe interference patterns (not represented) which oscillate with the sum of the adjusted phases (φ_1 et φ_2) in the long arms of the interferometers. By imagining the interferometers separated by several tens of km, we can predict "the distance influence" of a choice of phase (φ_1 ou φ_2) on the result of the joint measurement. This is a manifestation of the quantum correlations non-locality.

down conversion of a pump photon into a pair of photons in a nonlinear crystal. This process respects the principle of energy conservation, which imposes strong correlations between the photons of a given pair. Bearing in mind that the paired photons are necessarily generated simultaneously, but that the instant of emission of a pair is coherently delocalised in according to the coherence time of the laser, one then speaks of *energy-time entanglement*. An experimental assembly enabling these correlations to be revealed has been proposed by J.D. Franson [7] and requires to observe photon pair interferences, strictly avoiding single photon interferences. To do so, two highly unbalanced Mach-Zehnder interferometers $\Delta T = \Delta L/c$, but which are identical to one another, are used as presented in *Figure 5*. After the interferometers, the state of a photon pair is written as the coherent superposition of 4 configurations:

$$|\psi\rangle = e^{i\varphi_2}|s_1 l_2\rangle + |s_1 s_2\rangle + e^{i(\varphi_1+\varphi_2)}|l_1 l_2\rangle + e^{i\varphi_1}|l_1 s_2\rangle$$

where s and l correspond respectively to the "short" or "long" paths followed by the photons of each mode (1 and 2) and 1, 2 are the phase shifts introduced in the long arms of both interferometers. The time correlation trace of such a state corresponds to three peaks, and it should be noted that the central peak is the result of the superposition of two indistinguishable paths $|s_1 s_2\rangle$ and $|l_1 l_2\rangle$ when coherence τ_p of the pair of photons (which is linked to that of the pump laser) is indeed higher than $\Delta L/c$. It is therefore possible to observe a phenomenon of (nonlocal) interference which takes the form of a disappearance of the central peak under certain conditions of the sum of phases $\varphi_1 + \varphi_2$. Only counting of time-correlated photons, *i.e.* using photon counters associated with a time correlations analysis device, enables this quantum phenomenon to be observed experimentally. ■

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