A review of different proposals to set up a polarization-entangled-photons bright source

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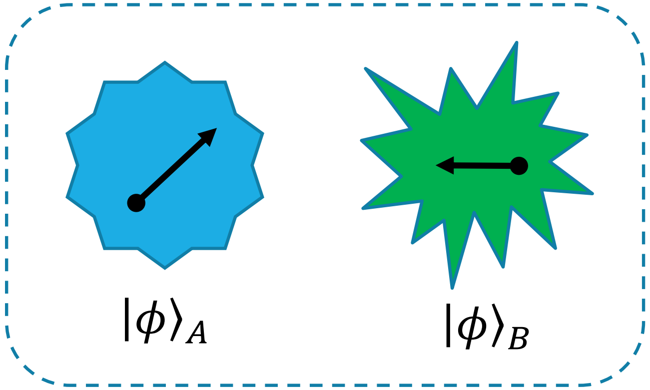
Outline

- Entangled states and measurements
- The first proofs of the quantum mechanics weirdness
- Non-linear processes as sources of pairs of photons
- BBO vs PPKTP – Bulk vs Periodically poled crystals
- Summary

Entangled State

"Entanglement" is a word that presents the concept of nonlocal quantum correlations between two or more quantum-mechanical systems.



$$|\psi\rangle_{AB} \neq |\phi\rangle_A \otimes |\phi\rangle_B$$

$$\hat{\rho}_{AB} \neq \hat{\rho}_A \otimes \hat{\rho}_B$$

Bell states

2-qubit maximally entangled pure states

$$|\Phi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|00\rangle \pm |11\rangle),$$
$$|\Psi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|01\rangle \pm |10\rangle),$$

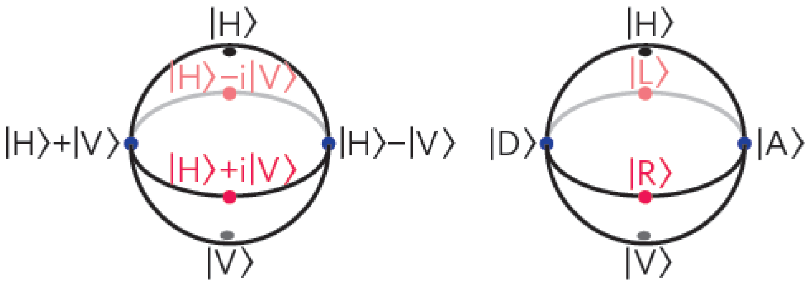
Werner states

$$\rho = \frac{1-a}{2}(|00\rangle + |11\rangle)(\langle 00| + \langle 11|) + \frac{a}{4}I$$

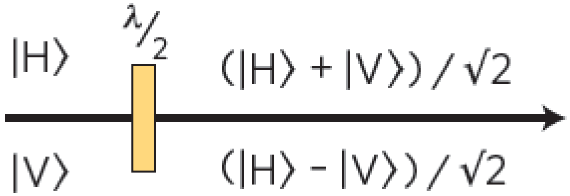
Types of photon qubit encoding

Any two orthogonal modes of light provide a way of constructing a two-level quantum system that can serve as a qubit.

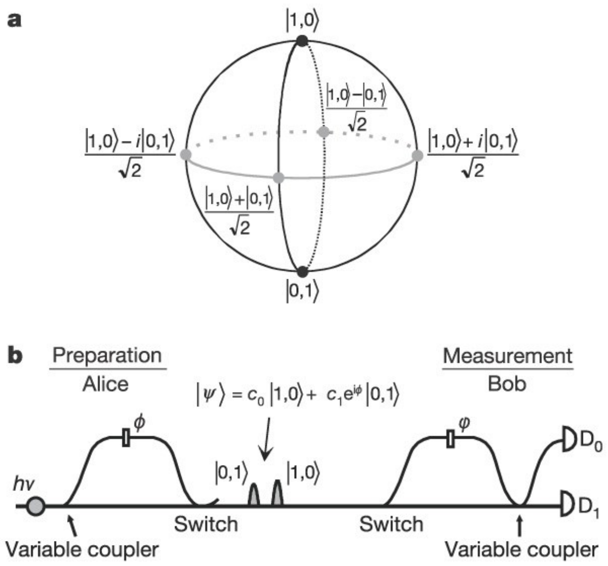
Polarization qubit



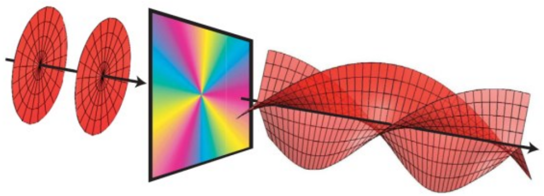
Hadamard gate



Time-bin qubit

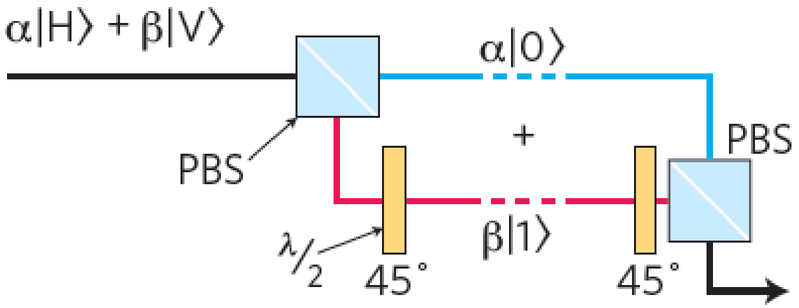


[J. l. O'brien, et. al. Nature Photonics **3**, 687 (2009)]
[Nature 421, 509-513(2003)]
[Quantum computation and quantum information. M. Nielsen and I. Chuang]

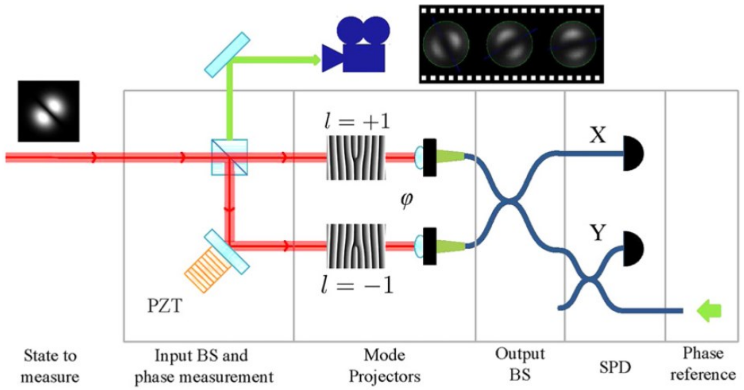


Types of photon qubit encoding

Dual-rail (Path) qubit



OAM qubit



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[Nature 421, 509-513(2003)]
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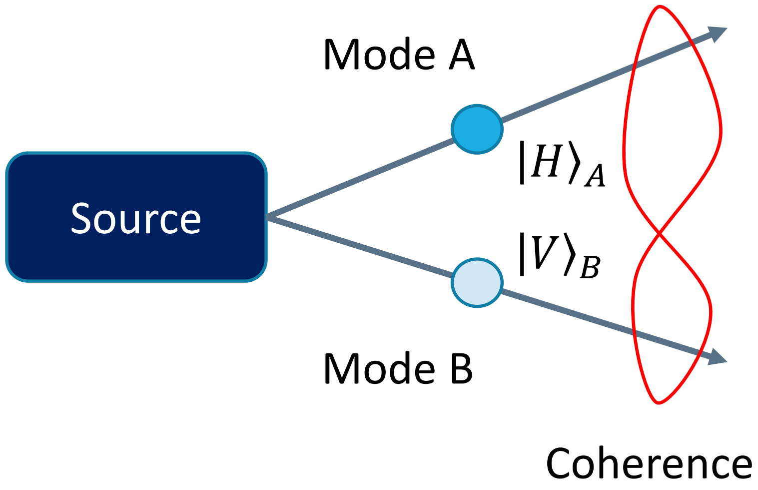
A. Yao and M. J. Padgett. Advances in Optics and Photonics **3**, 161–204 (2011)]
[A. Nicolas et. al. New J. Phys. 17 (2015) 033037]

Entangled State

Modes + Coherence → Entanglement



Polarization-entangled Bell states

$$|\Phi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|\mathrm{HH}\rangle \pm |\mathrm{VV}\rangle),$$

$$|\Psi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|\mathrm{HV}\rangle \pm |\mathrm{VH}\rangle).$$

Observation of Entanglement

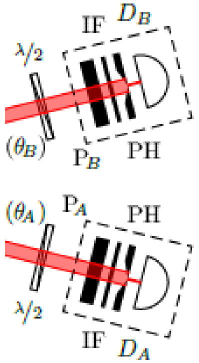
Polarization correlation measurement

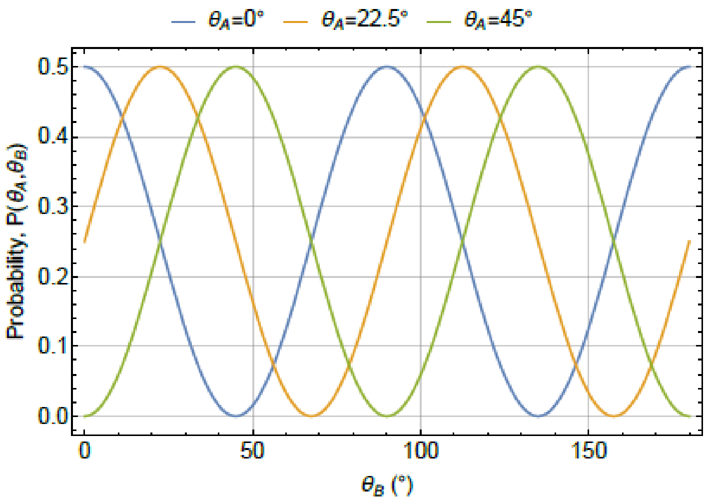
Violation of Bell's inequality

Bell theorem (1964)

CHSH theory (1969)

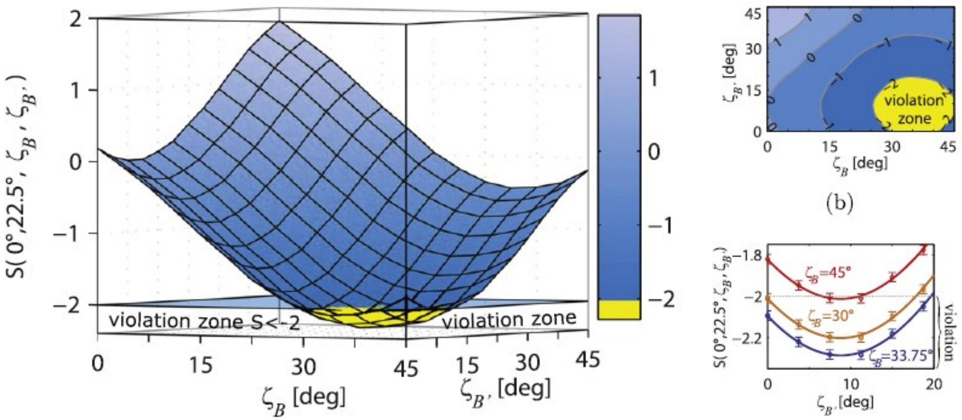
$|\psi^-\rangle$





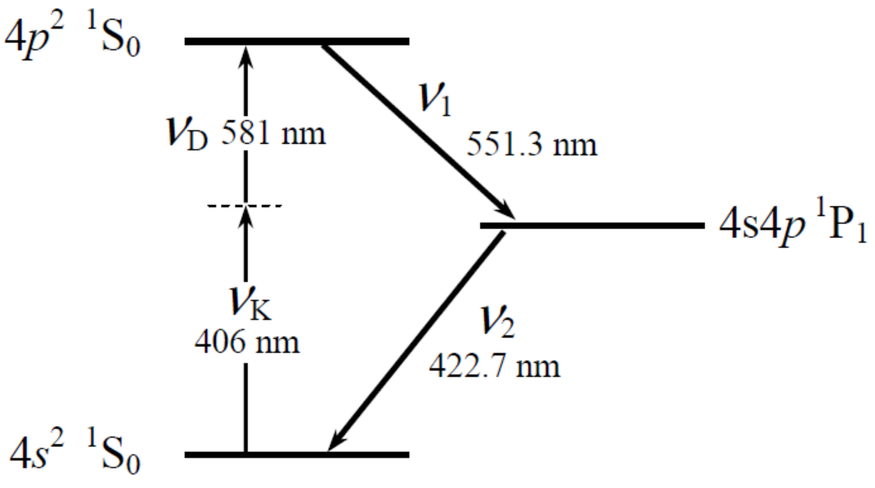
$$S = |E(\theta_A, \theta_B) - E(\theta_A, \theta'_B) + E(\theta'_A, \theta_B) + E(\theta'_A, \theta'_B)| \leq 2,$$

$$E(\theta_A, \theta_B) = \frac{C(\theta_A, \theta_B) + C(\theta_A^\perp, \theta_B^\perp) - C(\theta_A^\perp, \theta_B) - C(\theta_A, \theta_B^\perp)}{C(\theta_A, \theta_B) + C(\theta_A^\perp, \theta_B^\perp) + C(\theta_A^\perp, \theta_B) + C(\theta_A, \theta_B^\perp)}$$



[D A Guzmán, L J Uribe, A Valencia, F J Rodríguez and L Quiroga. Eur. J. Phys. **36**, 055039 (2015)]

First Generation Experiments



$4p^2\ ^1S_0 \rightarrow 4s4p\,^1P_1 \rightarrow 4s^2\ ^1S_0$

- In the Berkeley experiment (1972), Clauser and Freedman built a source using calcium atoms.

- Since the signal was weak, and spurious cascades occurred, it took more than 200 hours of measurement for a significant result.

- In the Aspect's experiment (1975) the source was optimized to obtain a coincidence rate of $\sim 10^2\ s^{-1}$, several orders of magnitude larger than in the first experiments. The measurements took just ~4 hour under these conditions.

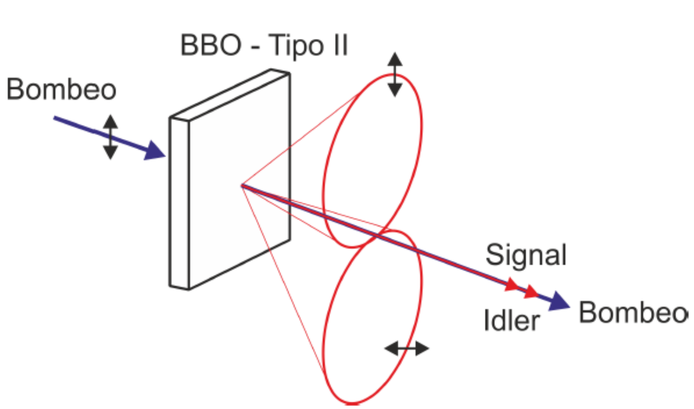
- They violated the Bell's inequality by 40 standard deviations!

["Quantum [Un]speakables – From Bell to Quantum information", R. A. Bertlmann and A. Zeilinger, Springer (2002).]

Parametric Down-Conversion (SPDC) Age

Biphoton Source

Crystal with $\chi^{(2)}$ optical nonlinearity



(a)SPDC Colineal (b)SPDC No-colineal

$$H = \hbar g(\hat{a}_1^\dagger \hat{a}_2^\dagger \hat{a}_0 + \hat{a}_0^\dagger \hat{a}_2 \hat{a}_1),$$

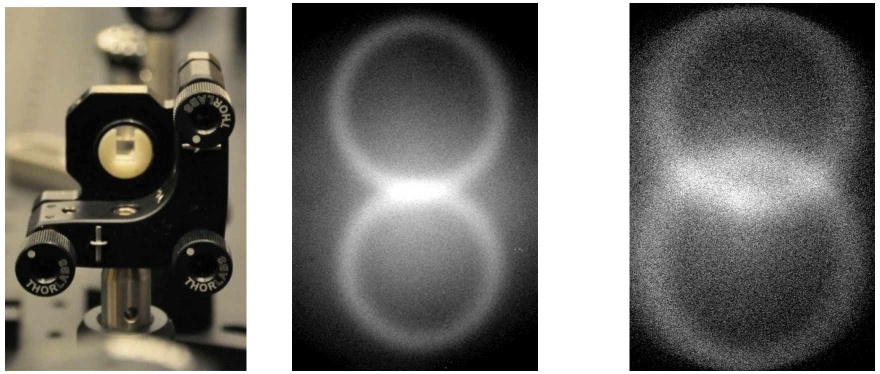
Energy conservation

$$\omega_s + \omega_i = \omega_p$$

Momentum conservation

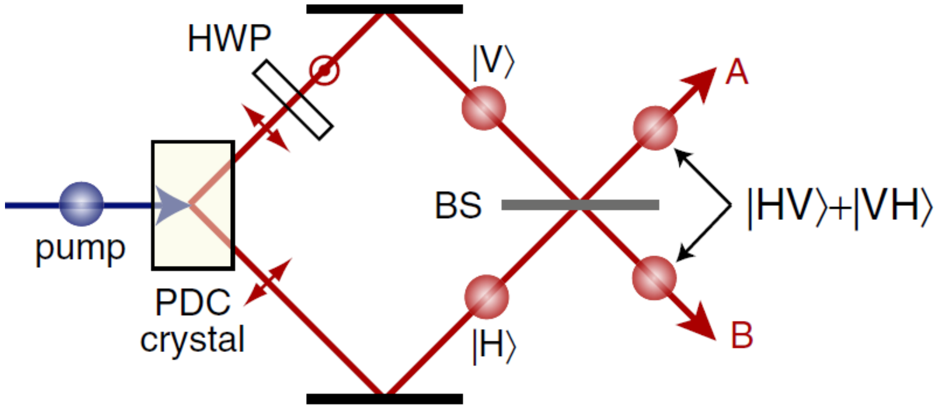
$$\vec{k}_s + \vec{k}_i = \vec{k}_p$$

Phase-matching conditions



The parametric fluorescence has been observed since the 1960s!

SPCD age



PDC crystals: Deuterated potassium dihydrogen phosphate (DKDP) or **Monopotassium phosphate (KDP)** single crystals widely used in non-linear optics as the second, third and fourth harmonic generators for Nd:YAG and Nd:YLF lasers.

(Source: Wikipedia.org)

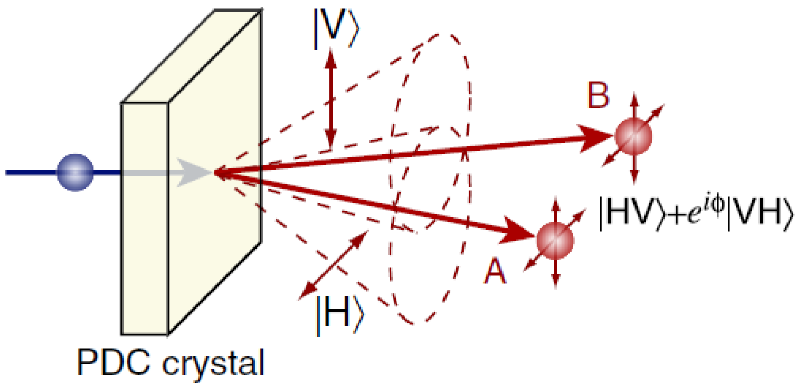
- Ou/Mandel Experiment (1988). The violation of Bell's inequality is as large as 6 standard deviations. The maximum coincidence rate measured was 25 coin/min. Non pump power was provided.
- Shih/Alley experiment (1988). In this case the violation of the inequality occurs by 3 standard deviations. 150 coin/run. Non power information was provided.

This technique involves the so-called postselection procedure, with a success probability of 1/2 and thus it is inappropriate for applications such as the loophole-free Bell's inequality test.

[Z. Y. Ou and L. Mandel. Phys. Rev. Lett. **61**, 50 (1988)]
[Y. H. Shih and C. O. Alley. Phys. Rev. Lett. **61**, 2921 (1988)]

[P. G. Kwiat, K. Mattle, H. Weinfurter, A. Zeilinger, A. V. Sergienko, and Y. Shih. Phys. Rev. Lett. 75, 4337 (1995)]

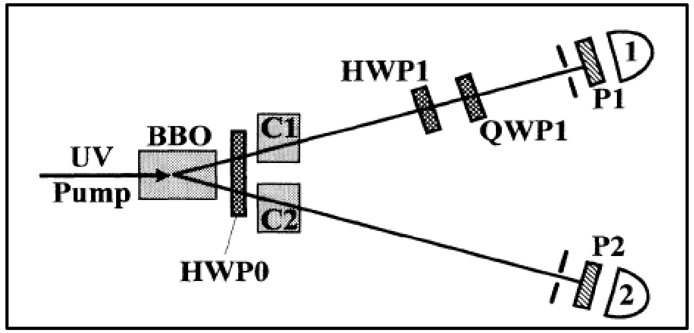
SPCD age – BBO Crystal

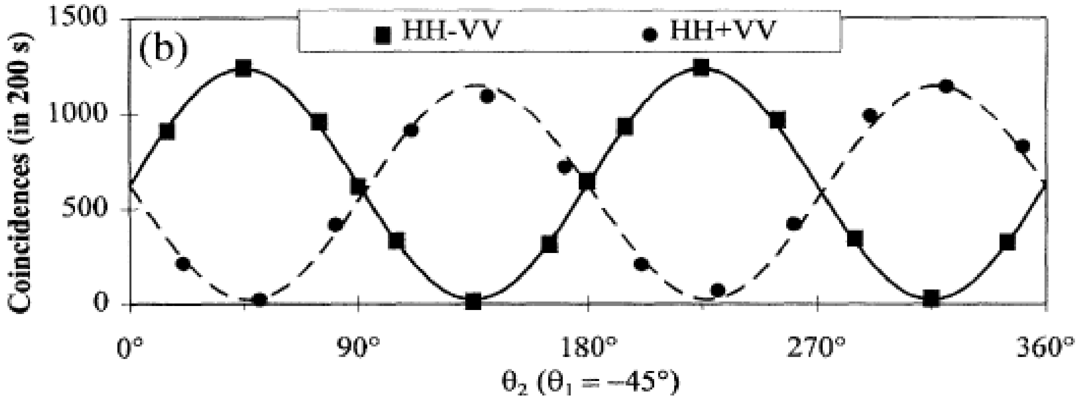


Kwiat et. al. (1995). They demonstrated a violation of Bell's inequality by over 100 standard deviations in less than 5 min!

Coincidence rates greater than 1500 s^{-1}. With an estimated flux of pairs of 10 pairs/s·mW.

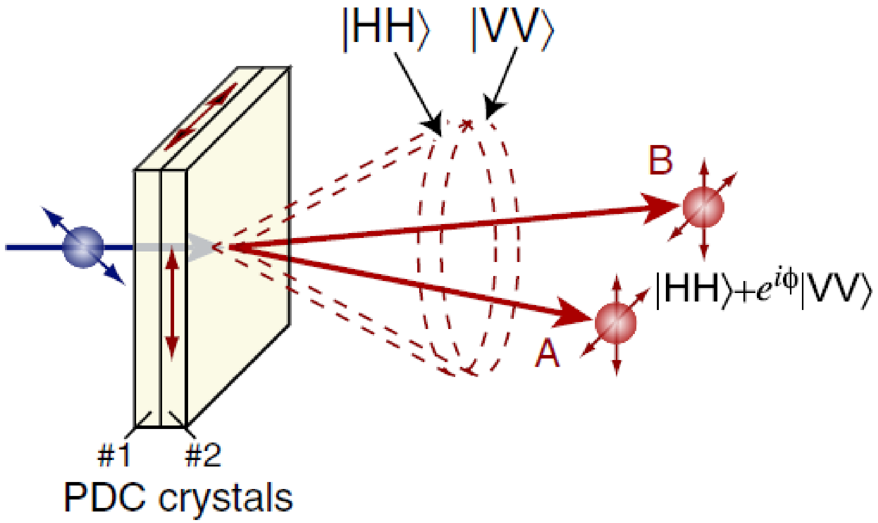
PDC Crystal: Beta-barium borate (BBO) – Type II noncollinear phase-matching





Coincidence fringe polarization correlations, 95% visibility

SPCD age – BBO Crystal



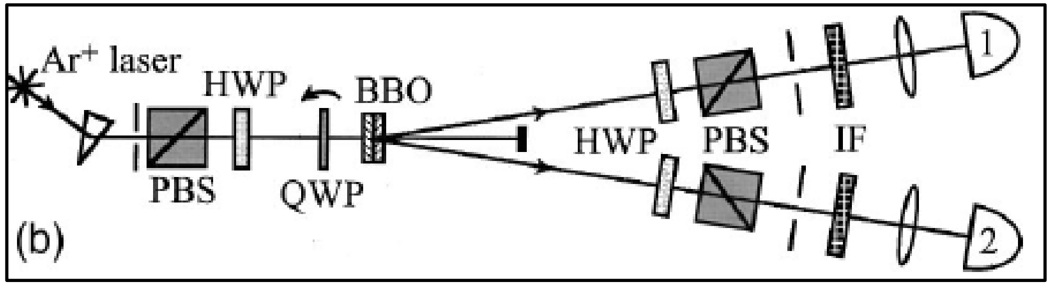
PDC Crystal: Two crossed BBO – Type I, noncollinear phase-matching

Kwiat et. al. (1999). The necessary statistics for the 242-σ violation were obtained in only 2 min!

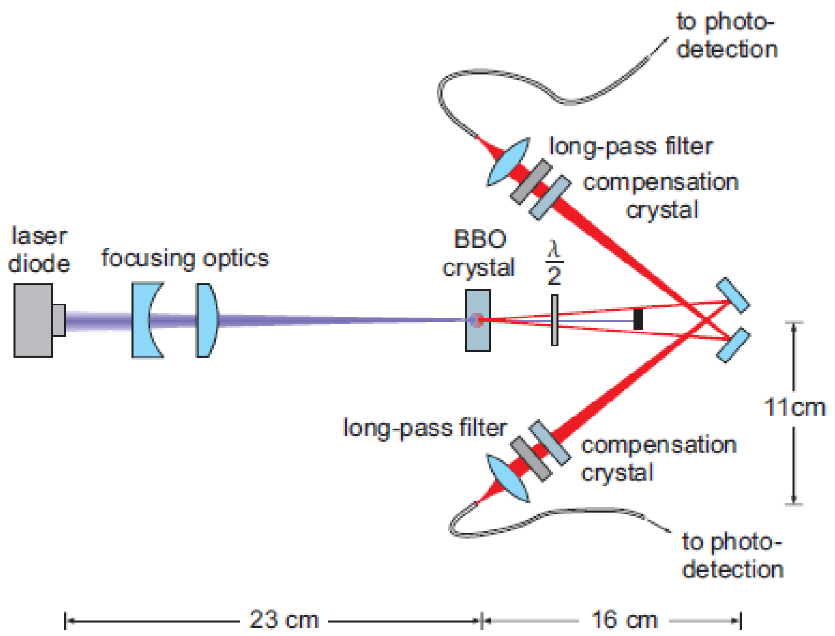
Coincidence rates of 21000 s^{-1}. With an estimated flux of pairs of 140 pairs/s·mW in a 5-nm bandwidth.

Coincidence fringes with a visibility of 99.6%.

Collection efficiency: ~10% (the probability of collecting one photon *conditioned* on collecting the other)



SPCD age – BBO Crystal



An stricter optimization coupling was performed: The pump waist, crystal length, emission angle and collection modes were engineered for the operation wavelength.

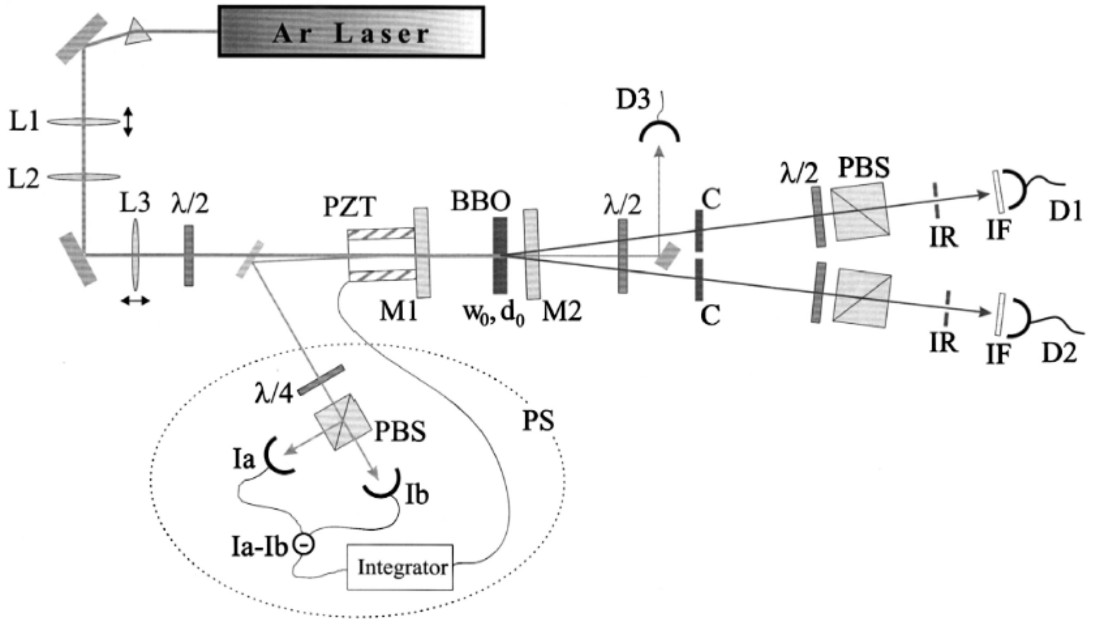
The flux of pairs was 220 pairs/s·mW in a 6-nm bandwidth. (No interference filters were used)

Coincidence fringes with a visibility of 98%.

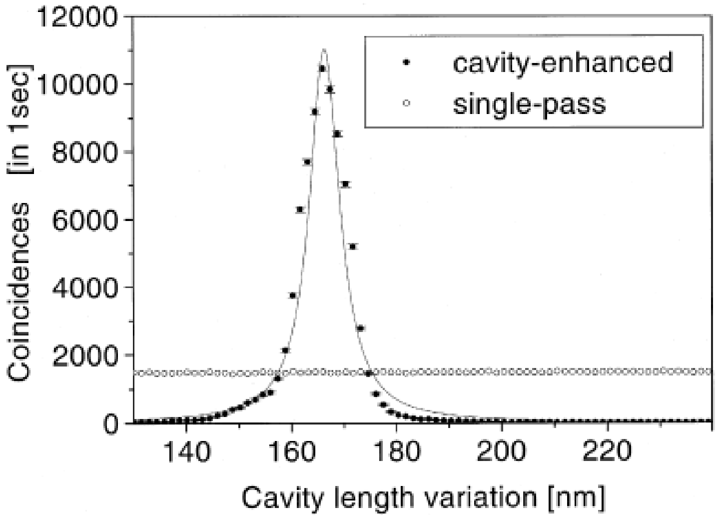
Collection efficiency: ~19%

[Ch. Kurtsiefer, M. Oberparleiter, and H. Weinfurter Phys. Rev. A **64**, 023802 (2001).
F. A. Bovino, P. Varisco, A. M. Colla, G. Castagnoli, G. Di Giuseppe, and A. V. Sergienko, Opt. Commun. **227**, 343–348 (2003).
P. Trojek, Ch. Schmid, M. Bourennane, H. Weinfurter, and Ch. Kurtsiefer. Opt. Express **12**, 276-281 (2004)]

SPCD age – BBO Crystal



The crystal is placed in a linear cavity

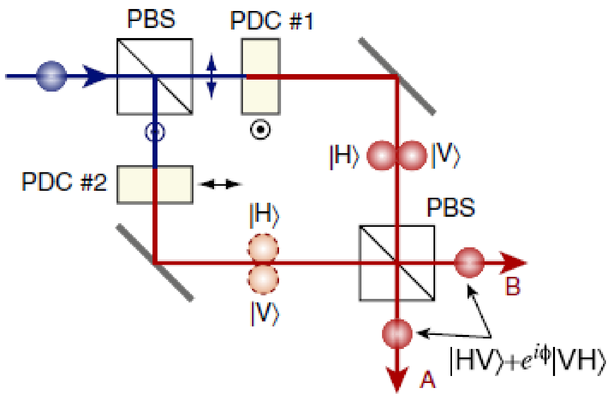


The flux of pairs was 105 pairs/s·mW, cavity-enhanced

Coincidence fringes with a visibility of 92%.

[M. Oberparleiter, H. Weinfurter. Optics Communications **183,** 133 (2000)]

SPCD age – BBO Crystal



This setup is made because of a problem in the compensation when a pulse laser is used as pump.

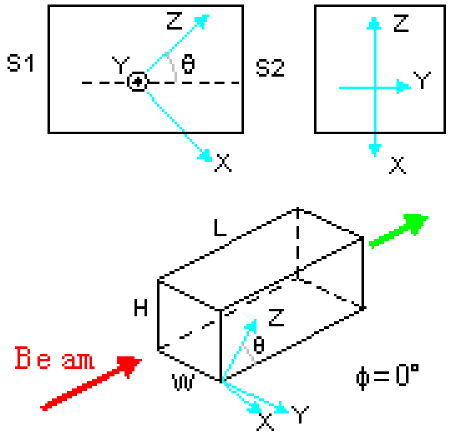
Was part of the first proposal of a loophole-free Bell inequality experiment.

[P. G. Kwiat, P. H. Eberhard, A. M. Steinberg, and R. Y. Chiao. Phys. Rev. A **49**, 3209 (1994)]
Y.-H Kim, S. P. Kulik, and Y. S. Phys. Rev. A, **62**, 011802(R) (2000)

SPCD age

Bulk materials

BaB_2O_4 (BBO)
$KTiPO_3$ (KTP)
$RbTiPO_4$
$LiNbPO_3$ (LN)
$LiTaO_3$ (LT)

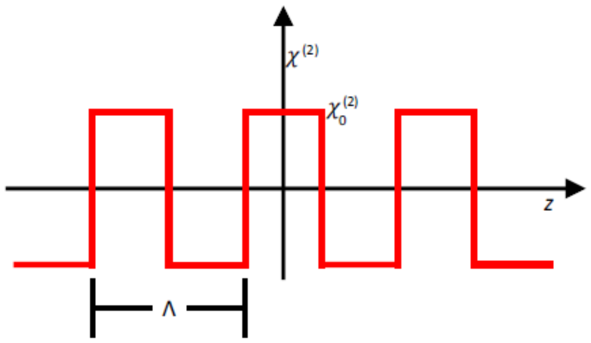


- A wide variety of nonlinear crystals are used for SPDC in a given range of frequencies. All these materials must be birefringent.
- The phase-matching conditions are fulfilled by using temperature and angle tuning.
- Limitations:
  - Some materials with high optical nonlinearities are not birefringent, or have insufficient birefringence, particularly at shorter wavelengths
  - Because the direction of propagation in the crystal is dictated by the phase-matching, it is usually not along one of the crystallographic axes. This leads to spatial walk-off, which limits the length of crystals that can be used.

SPCD age

Periodically poled materials

Ferromagnetic families		
	$KTiPO_3$ (KTP)	PPKTP
	$RbTiPO_4$ (RTP)	PPRTP
	$LiNbPO_3$ (LN)	PPLN
	$LiTaO_3$ (LT)	PPLT



Effective nonlinear coefficient

The quasi-phasematching condition:

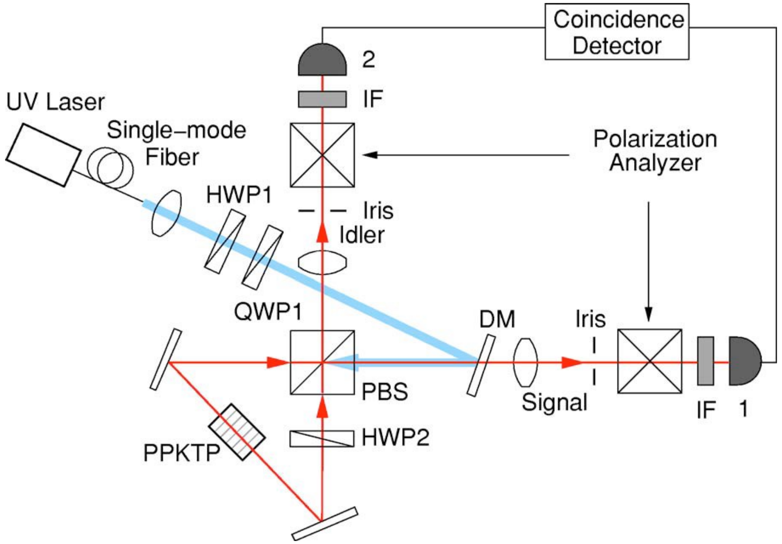
$$\boxed{k_p = k_s + k_i + \frac{2\pi}{\Lambda}}$$

The angle tuning is not needed any more!

Advantages:

- The collinear or noncollinear configuration can be achieved just changing the period of the pole.
- We can have the beams traveling along one of the crystal's crystallographic axes. This eliminates the problems caused by spatial walk-off. The use of much longer crystals is allowed, which leads to an increased signal.
- We can chose the wavelength of the signal and idler by changing the crystal temperature.

SPCD age - PPKTP



$$|\Psi\rangle \propto (|H_s\rangle_1 |V_i\rangle_2 + e^{i\phi}\beta |V_s\rangle_1 |H_i\rangle_2)$$

PPKTP Crystal: 10-mm-long (crystallographic *X* axis), 2-mm-wide (*Y* axis), 1-mm-thick (*Z* axis) with a grating period of 10.0 μm for frequency-degenerate type-II quasi-phasematched collinear parametric down-conversion.

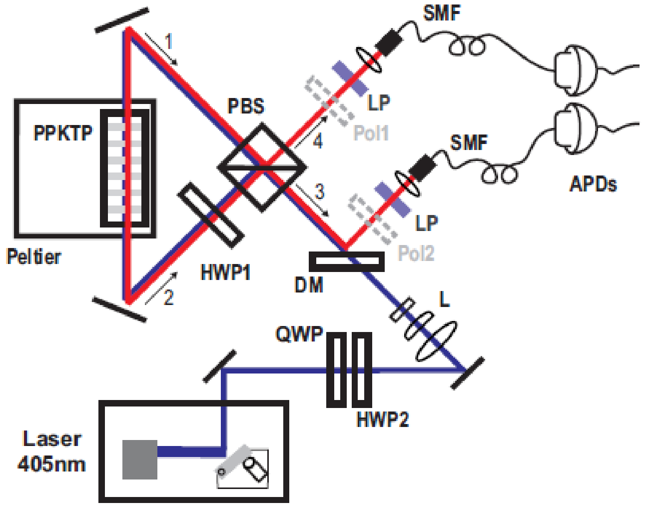
The spectral brightness ~5000 pairs/(s·mW·nm)

With a violation of the classical limit by more than 500 standard deviations!

Coincidence fringes with a visibility of 96.8%.

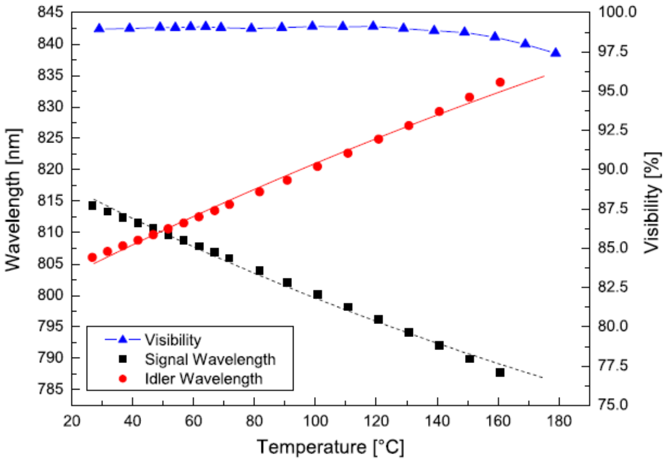
[T. Kim, M. Fiorentino, and F. N. C. Wong. Physical Review A **73**, 012316 (2006)]

SPCD age - PPKTP



This improvement was achieved by use of a long crystal, careful selection of focusing parameters and single-mode fiber coupling.

The visibility of coincidence fringes was 99.5% and the fidelity with the maximally entangle state $|\psi^{-}\rangle$ was 0.99.



It is a wavelength-tunable, fiber-coupled source of polarization-entangled photons.

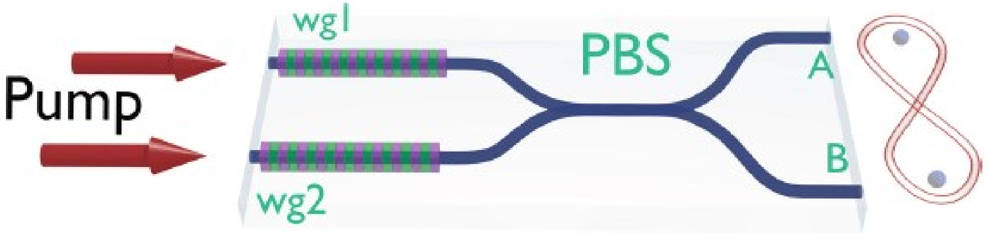
A spectral brightness of 273000 pairs $(\mathrm{s} \cdot \mathrm{mW} \cdot \mathrm{nm})^{-1}$

[A. Fedrizzi, T. Herbst, A. Poppe, T. Jennewein and A. Zeilinger. Optics Express, 15, 15377 (2007)]

Other sources

Two-photon Raman scattering

Chip schemes

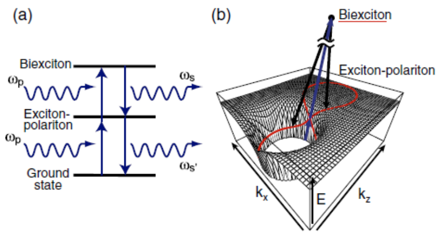


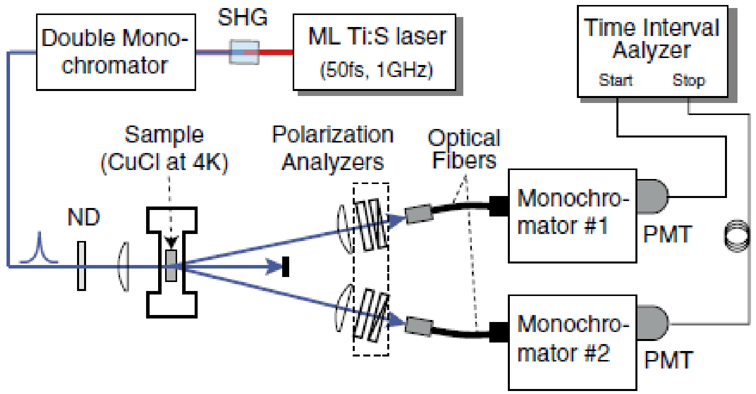
Spectral brightness of $\sim 5 \times 10^6$ pairs $(\mathrm{s} \cdot \mathrm{mW} \cdot \mathrm{nm})^{-1}$

A violation of Bell inequality of more than 14 standard deviations.

Telecom wavelength

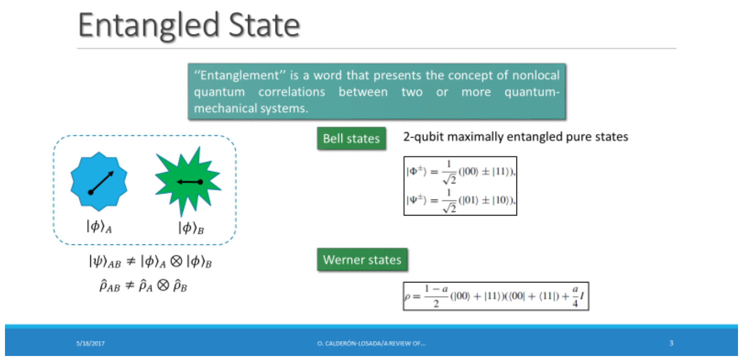
Biexciton-resonant hyper parametric scattering (RHPS).





L. Sansoni, K. H. Luo, C. Eigner, R. Ricken, V. Quiring, H. Herrmann & C. Silberhorn. npj Quantum Information **3**, 5 (2017)

Summary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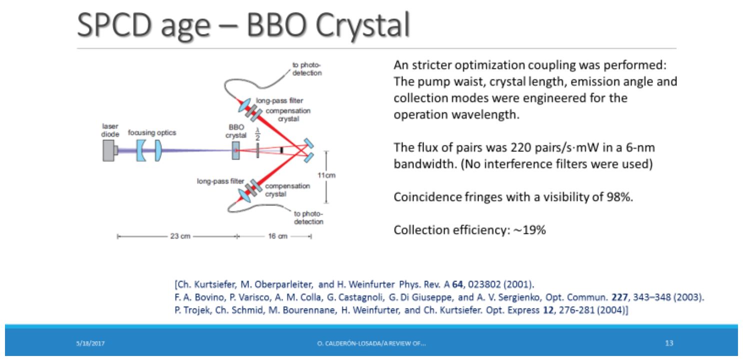
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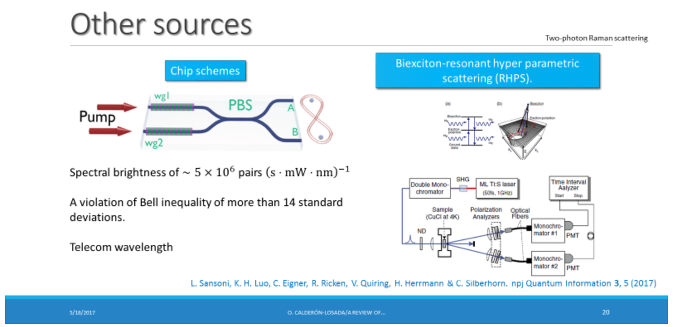
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Pump
PBS
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Telecom wavelength
L. Sansoni, K. H. Luo, C. Eigner, R. Ricken, V. Quiring, H. Herrmann & C. Silberhorn. npj Quantum Information 3, 5 (2017)
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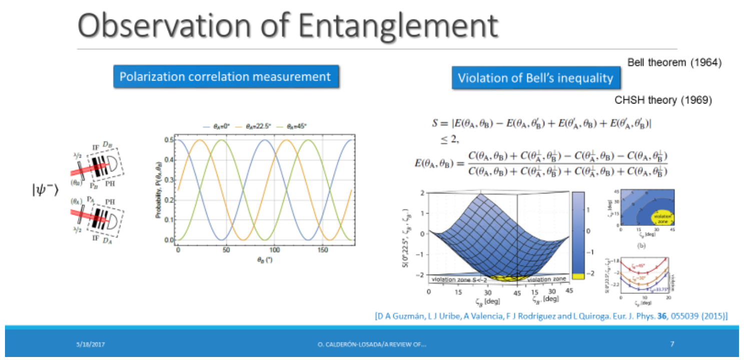
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$|\psi^-\rangle$
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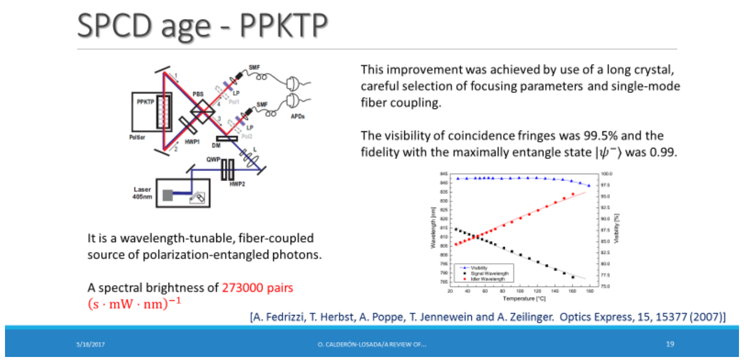
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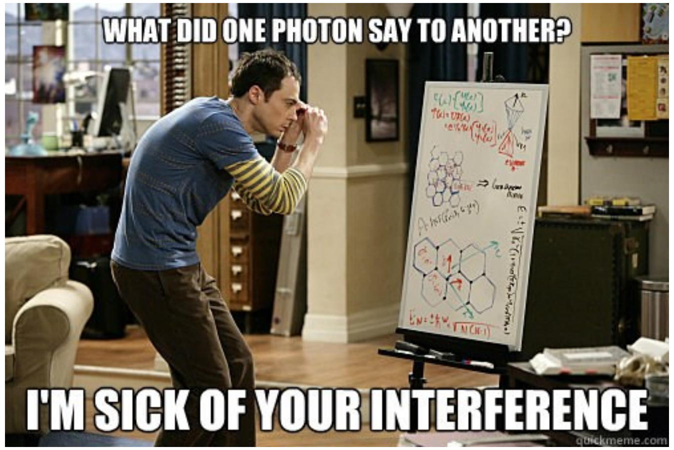

Thanks for your attention!

Any other question?