Quantum Plasmonics
Revisiting quantum optics with surface plasmons

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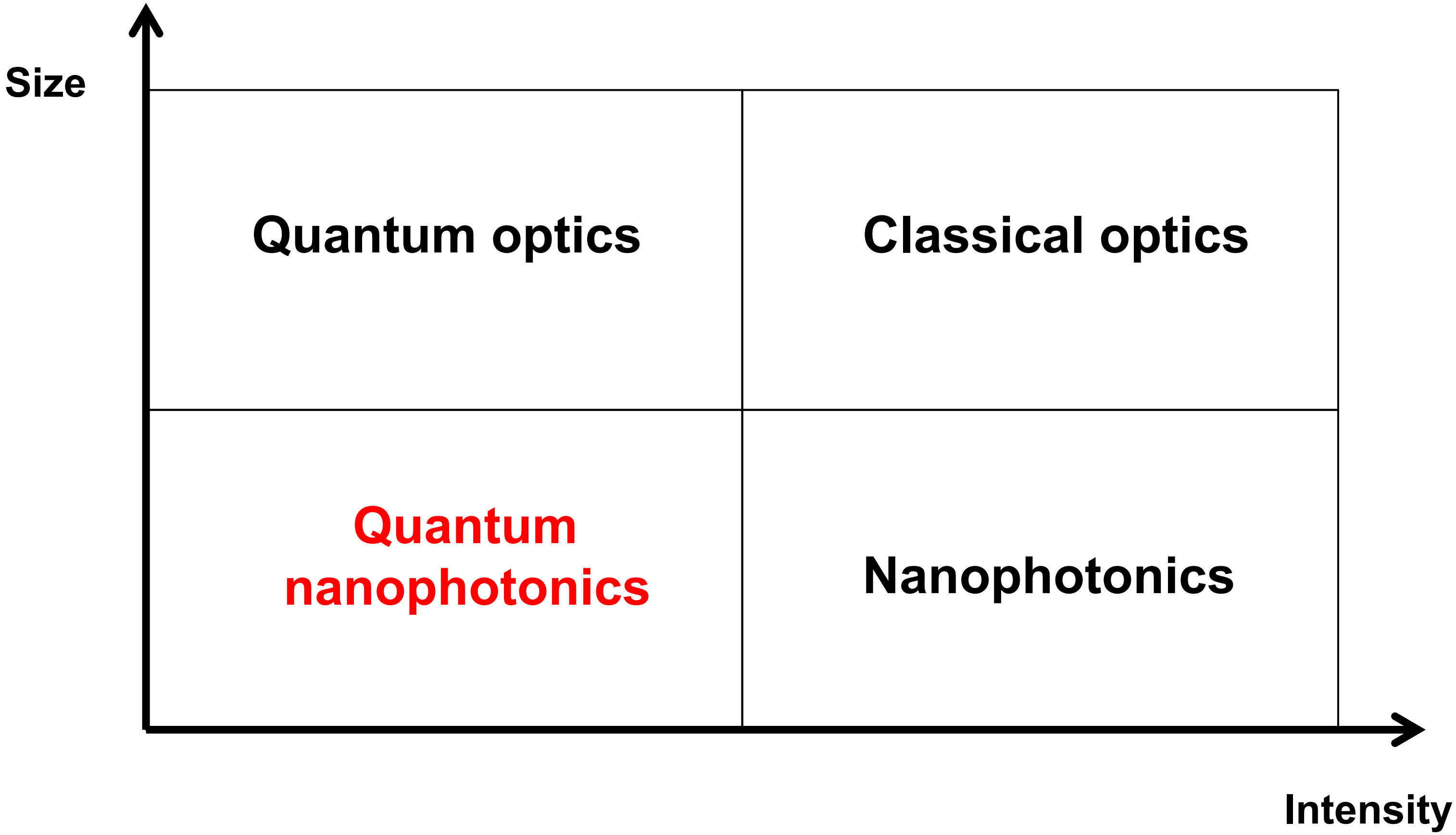
This work has been supported by the Agence Nationale de la Recherche, RTRA Triangle de la Physique, NanoK, Labex NanoSaclay, Institut Universitaire de France, SAFRAN-IOGS chair on Ultimate Photonics.

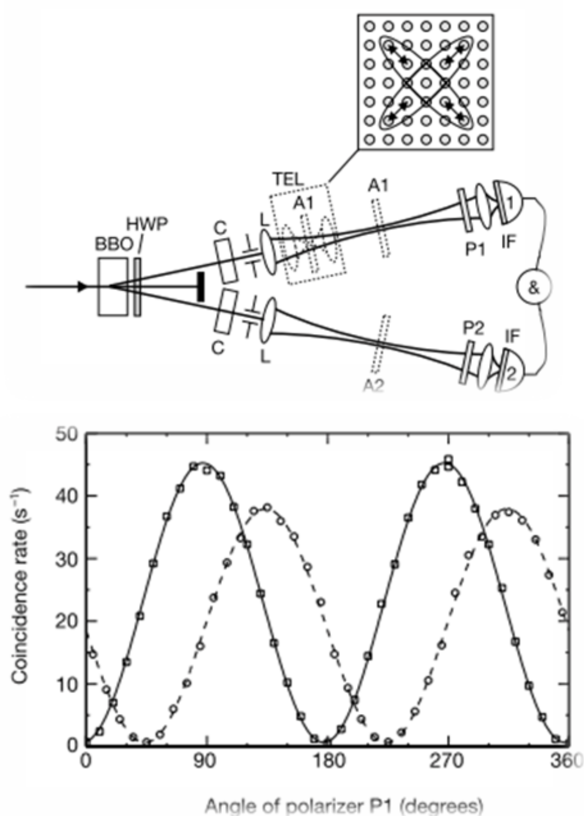
Outline



1. **Wave-particle duality with surface plasmons**
2. **Hong Ou Mandel experiment**
3. **Hybrid entanglement photon-plasmon**

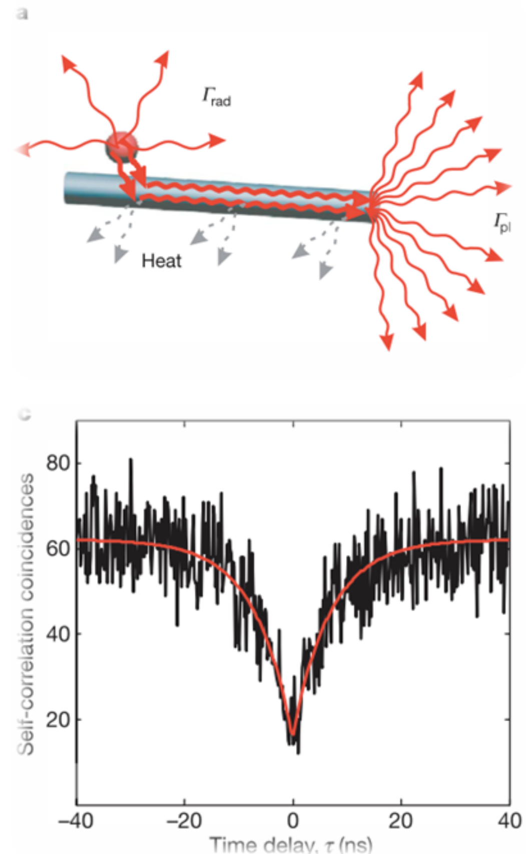
Previous results in quantum plasmonics

Entanglement preservation



E. Altewischer et al., Nature 418, 304–306 (2002).

Single plasmons



V. Akimov et al., Nature 450, 402–406 (2007).

Single photon source

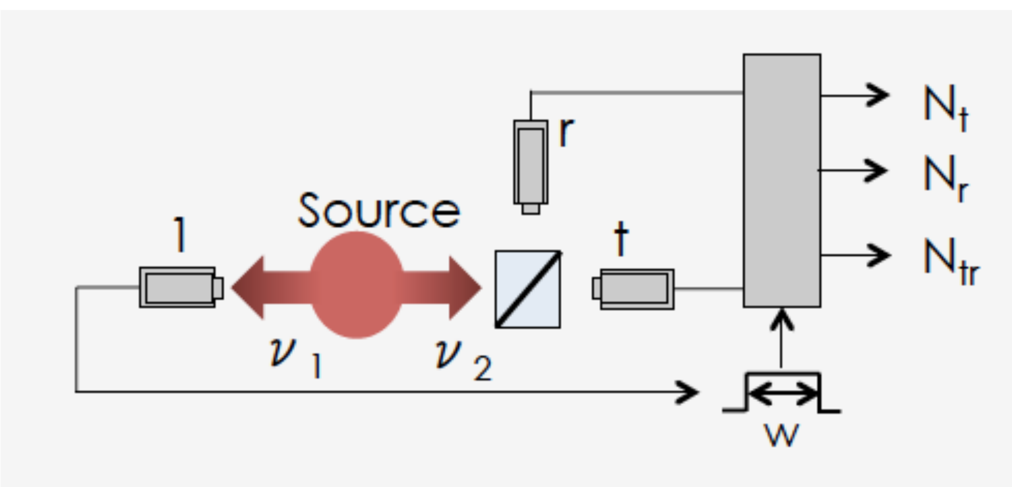
EUROPHYSICS LETTERS 15 February 1986

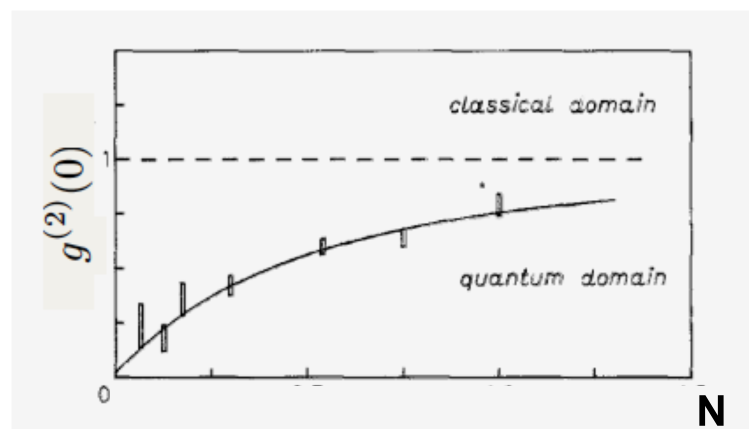
Europhys. Lett., 1 (4), pp. 173-179 (1986)

Experimental Evidence for a Photon Anticorrelation Effect on a Beam Splitter: A New Light on Single-Photon Interferences.

P. GRANGIER, G. ROGER and A. ASPECT (*)

Institut d'Optique Théorique et Appliquée, B.P. 43 - F 91406 *Orsay, France*

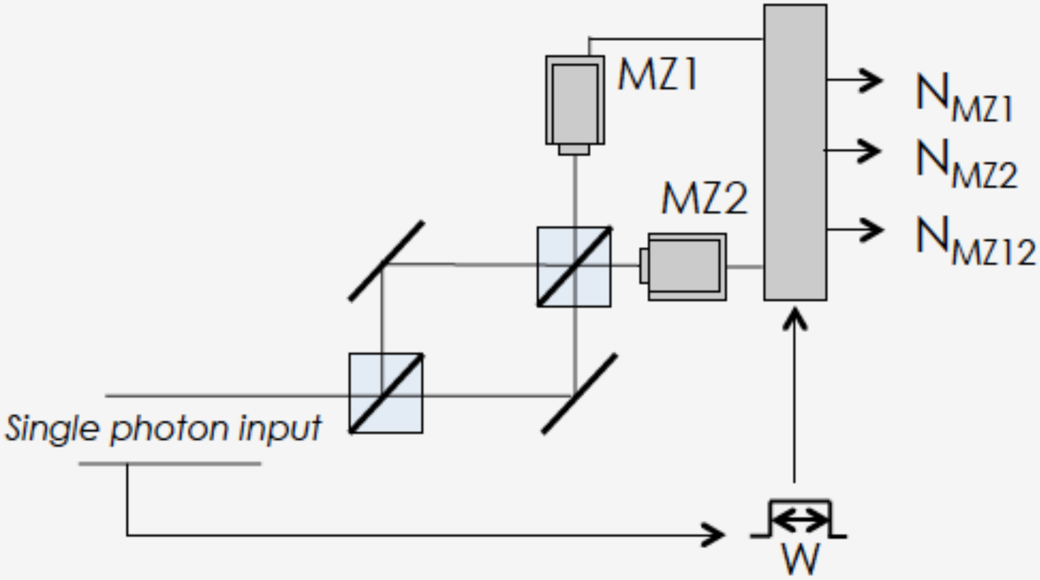


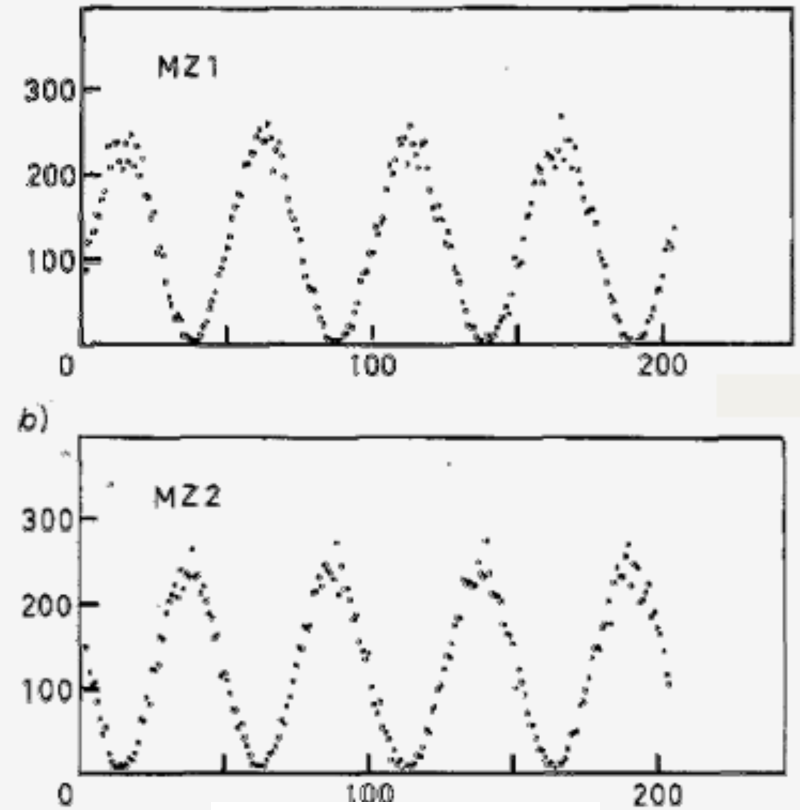


$$g^{(2)}(0) = \frac{P(1_t 1_r)}{P(1_t)P(1_r)}$$

Single photon interferences

- Experimental setup

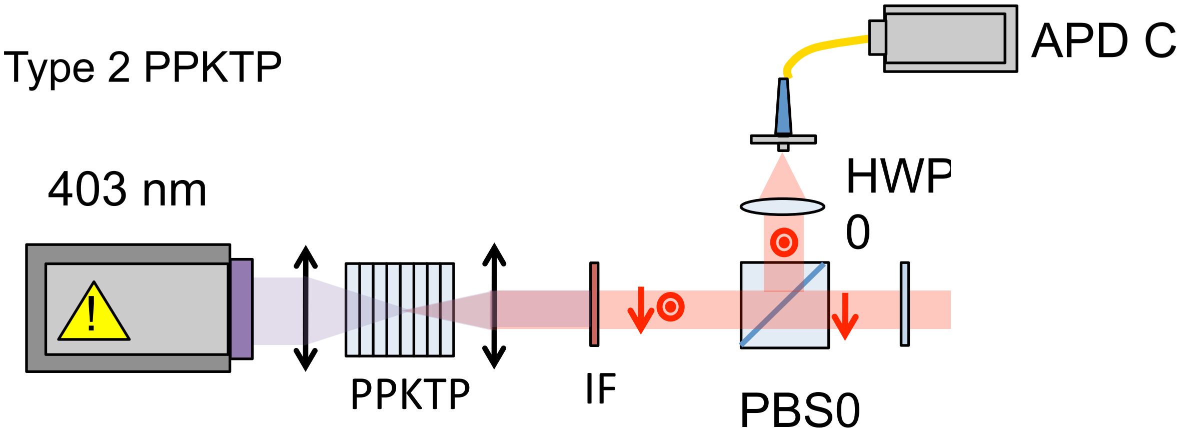




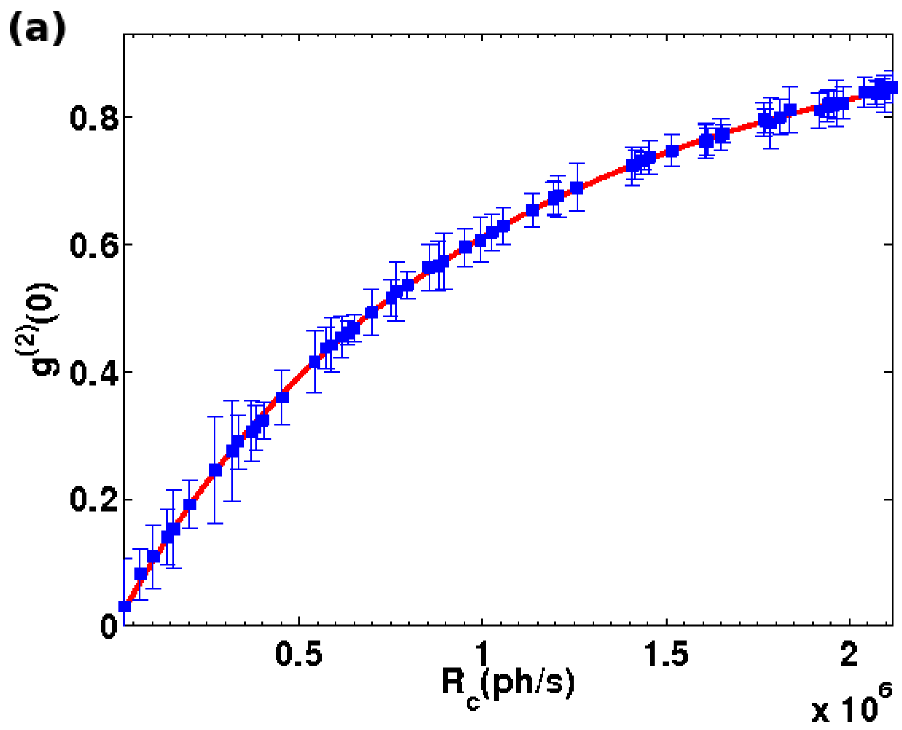
Path difference

Single photon source

Parametric downconversion



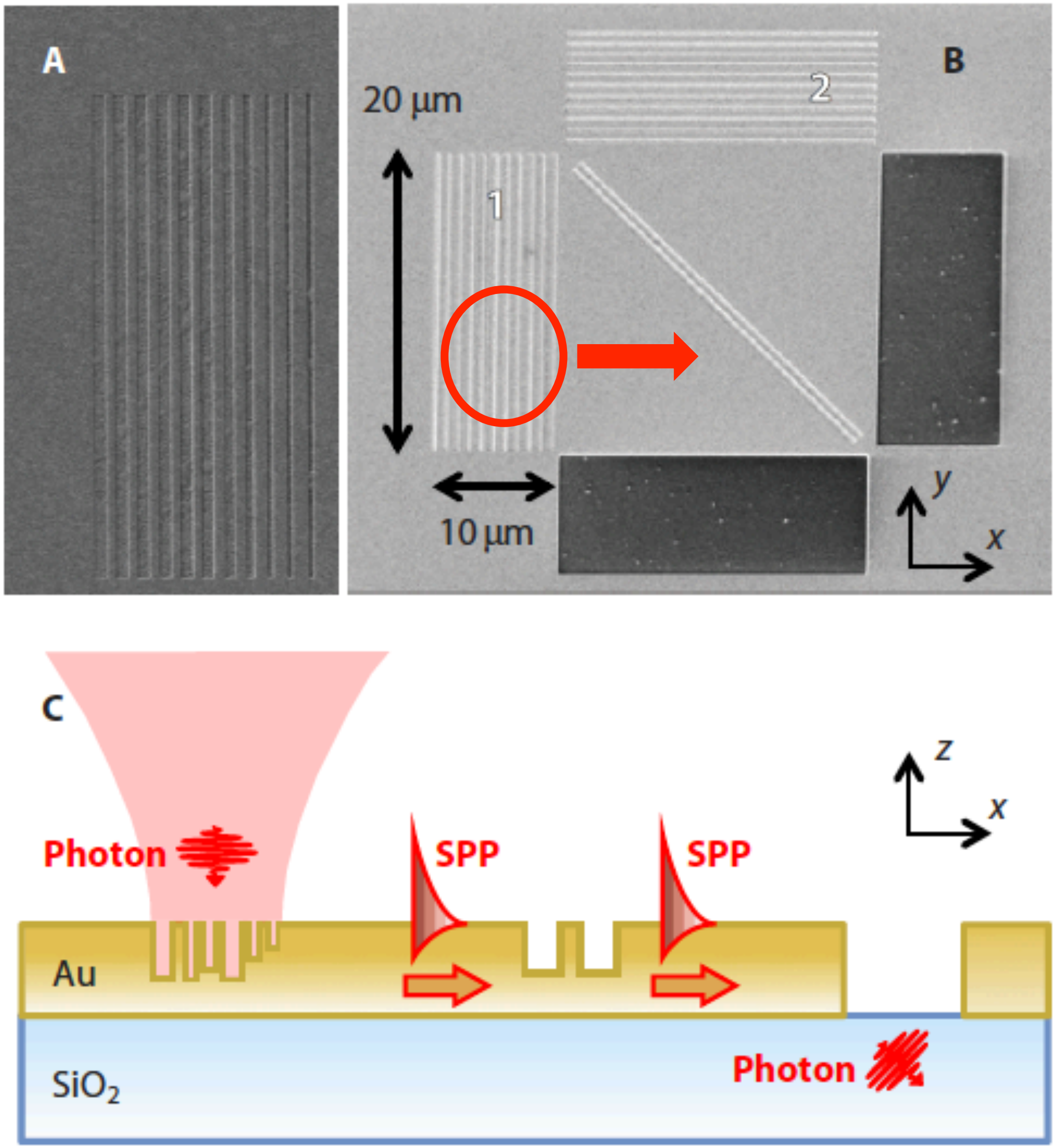
Degree of second order coherence



$$g^{(2)}(0) = \frac{P(1_t 1_r)}{P(1_t)P(1_r)}$$

Photon-SPP conversion

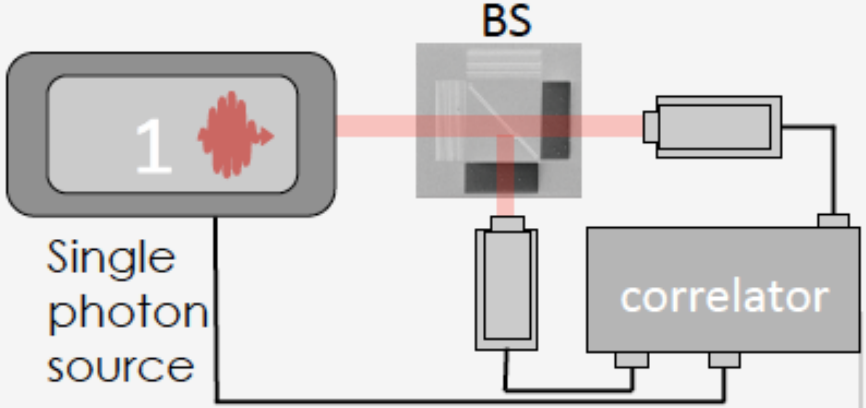
Fabrication: E Devaux
Characterization: A Baron
Design: P. Lalanne



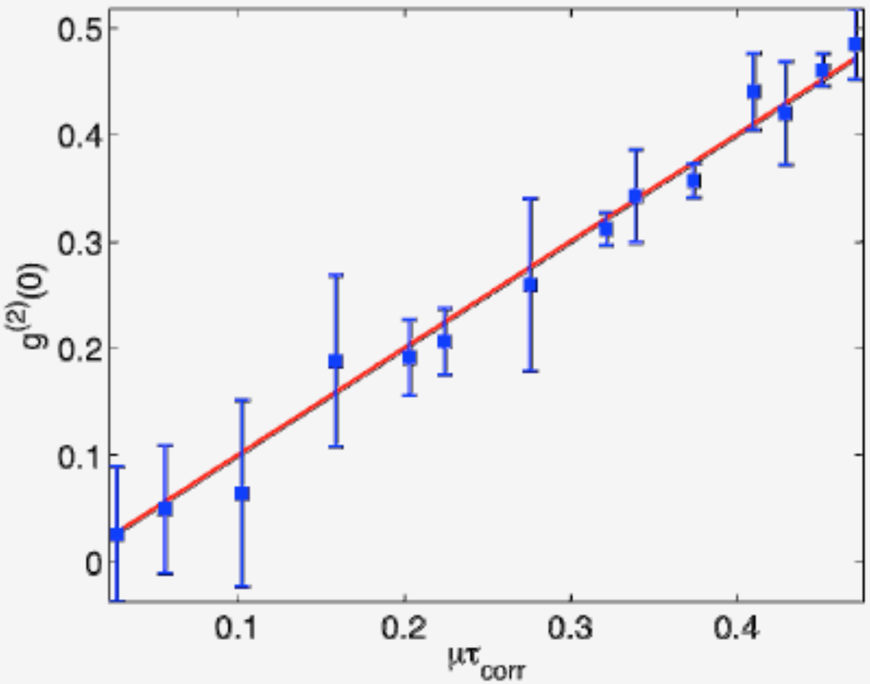
Dheur et al Sci. Adv. ***2****, e1501574 (2016)*

Single SPP source

- HBT experiment :

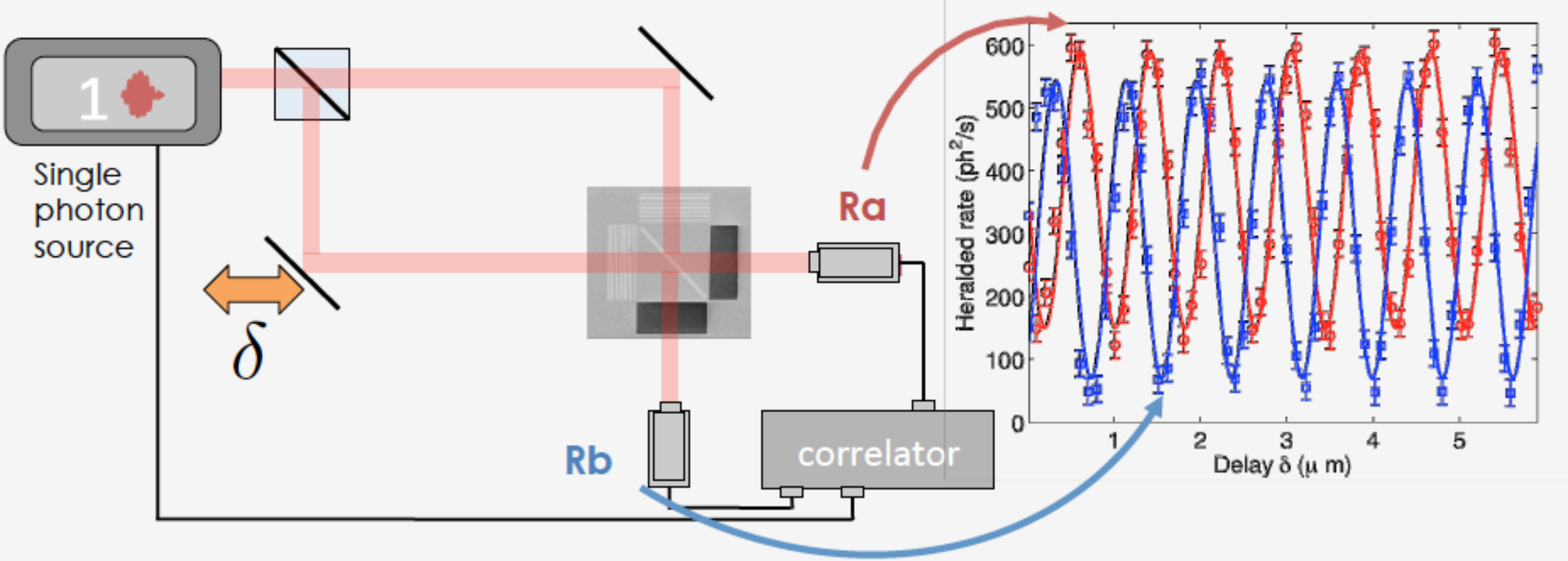


- Characterization: $g^2(0)$=3% !!!



Dheur et al Sci. Adv. ***2****, e1501574 (2016)*

Single SPP interference

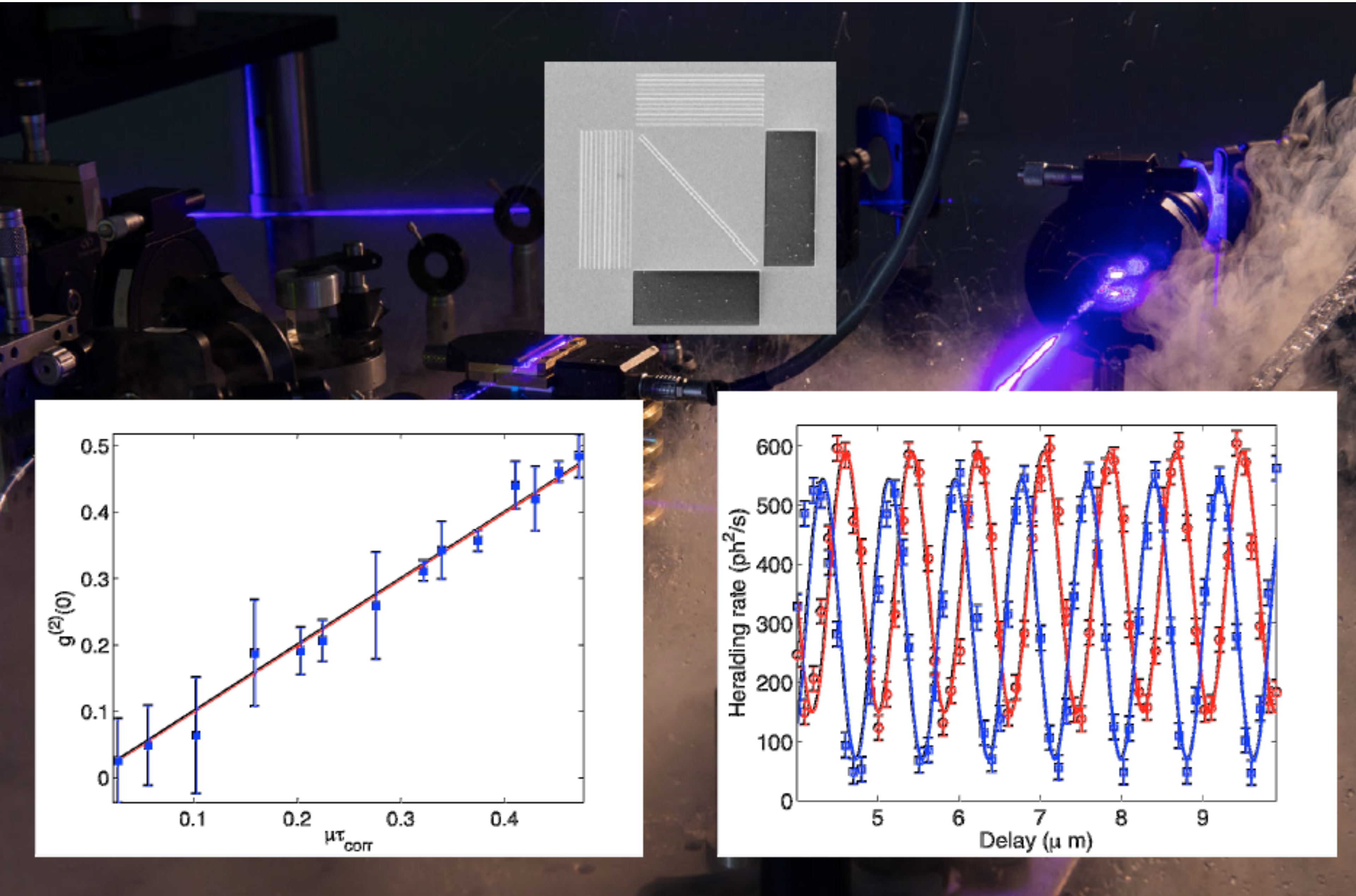


- Single SPP interferences !!!

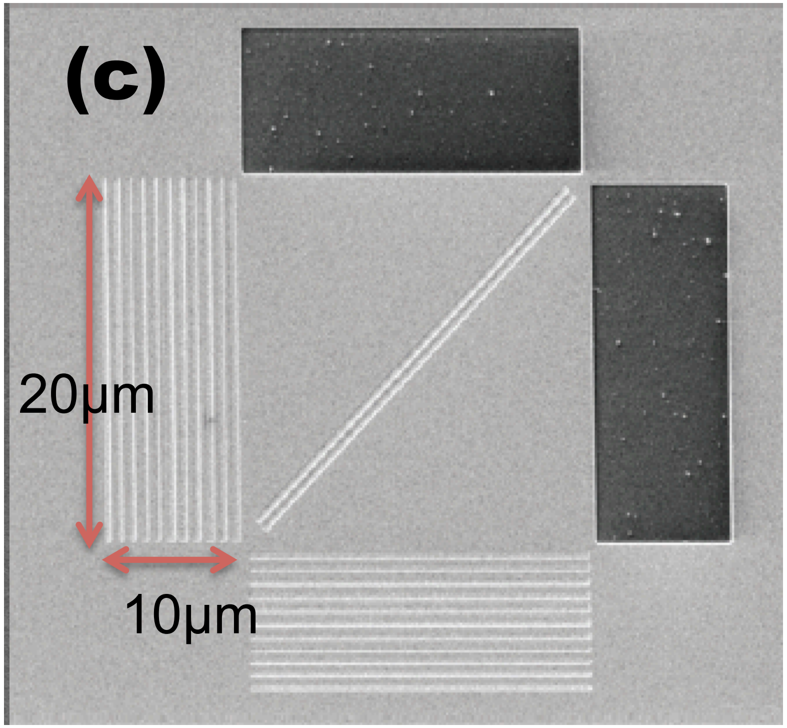
- Remarks
  - Lossy BS -> $\Phi_r - \Phi_t \neq pi/2$
  - Asymetric offsets : asymmetric setup
  - Absorption depends on the path difference !!!

Dheur et al Sci. Adv. ***2****, e1501574 (2016)*

Interferences with single plasmons



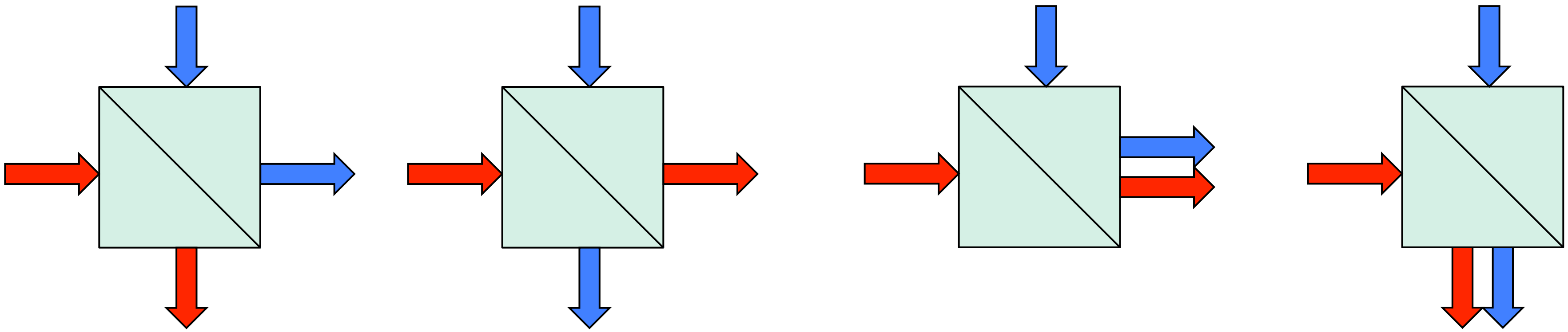
Hong Ou Mandel experiment: Coalescence of two photons



B. Vest et al., Science ***356****, 1373 (2017)*

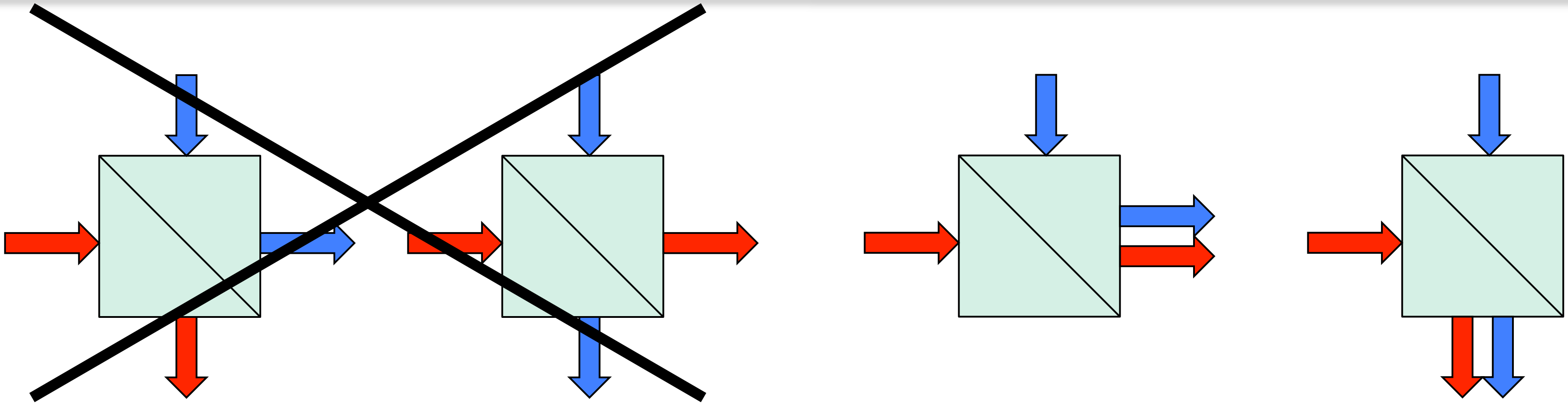
The HOM experiment

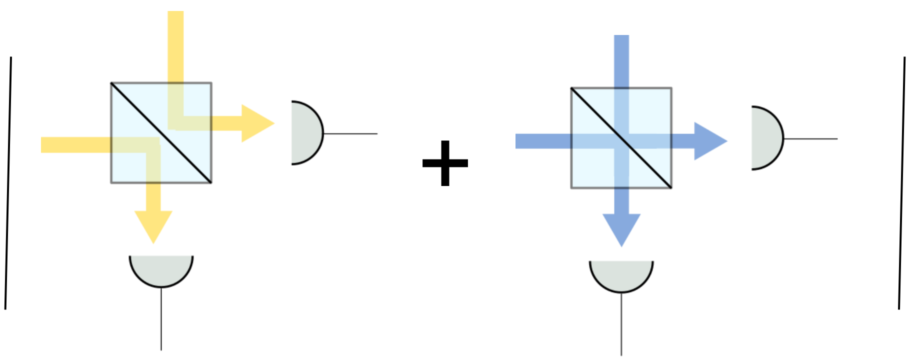
Hong, Ou, Mandel, PRL 59 (18) (1987)



The HOM experiment

Hong, Ou, Mandel, PRL 59 (18) (1987)





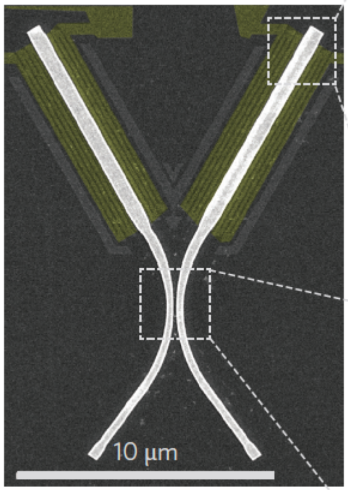
^{2} **= 0 !**

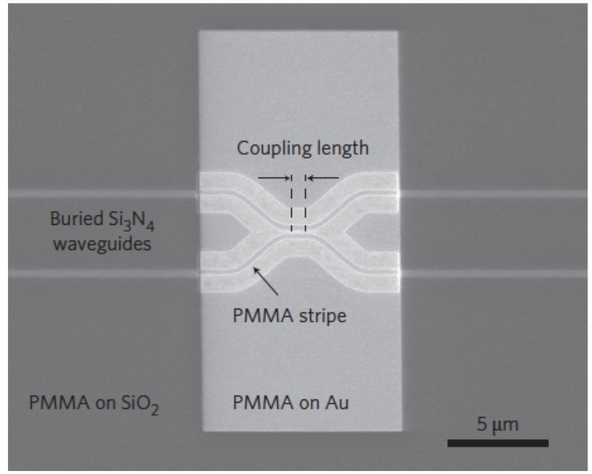
Destructive interference of indistinguishable quantum paths

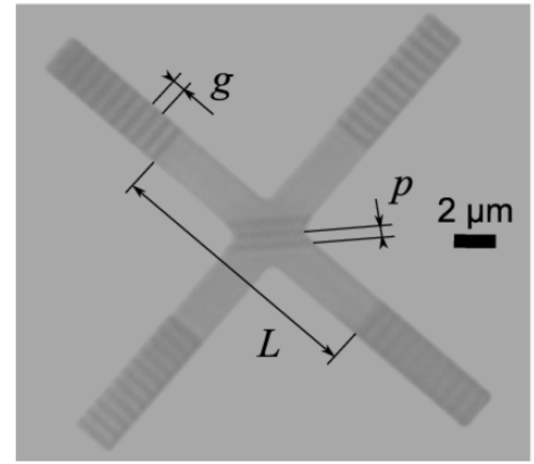
$$P(1_a, 1_b) = |t^2 + r^2|^2$$

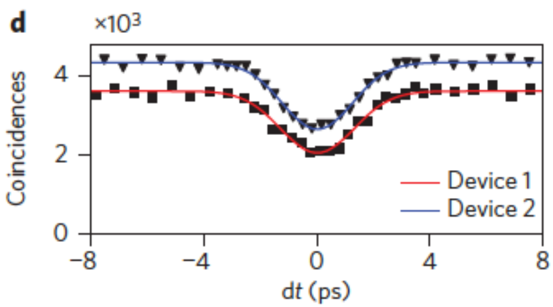
= 0 **(With r = +/- it)**

Plasmonic versions of the HOM experiment

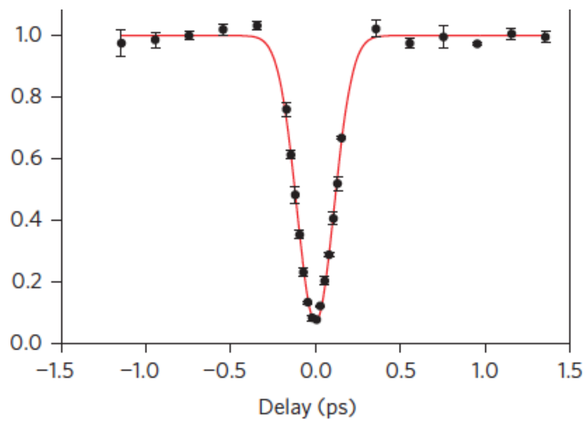




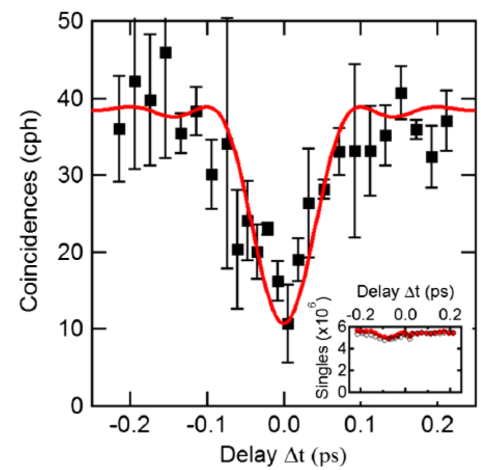




R. Heeres et al.,
Nat. Nano. 8, 719–722 (2013).



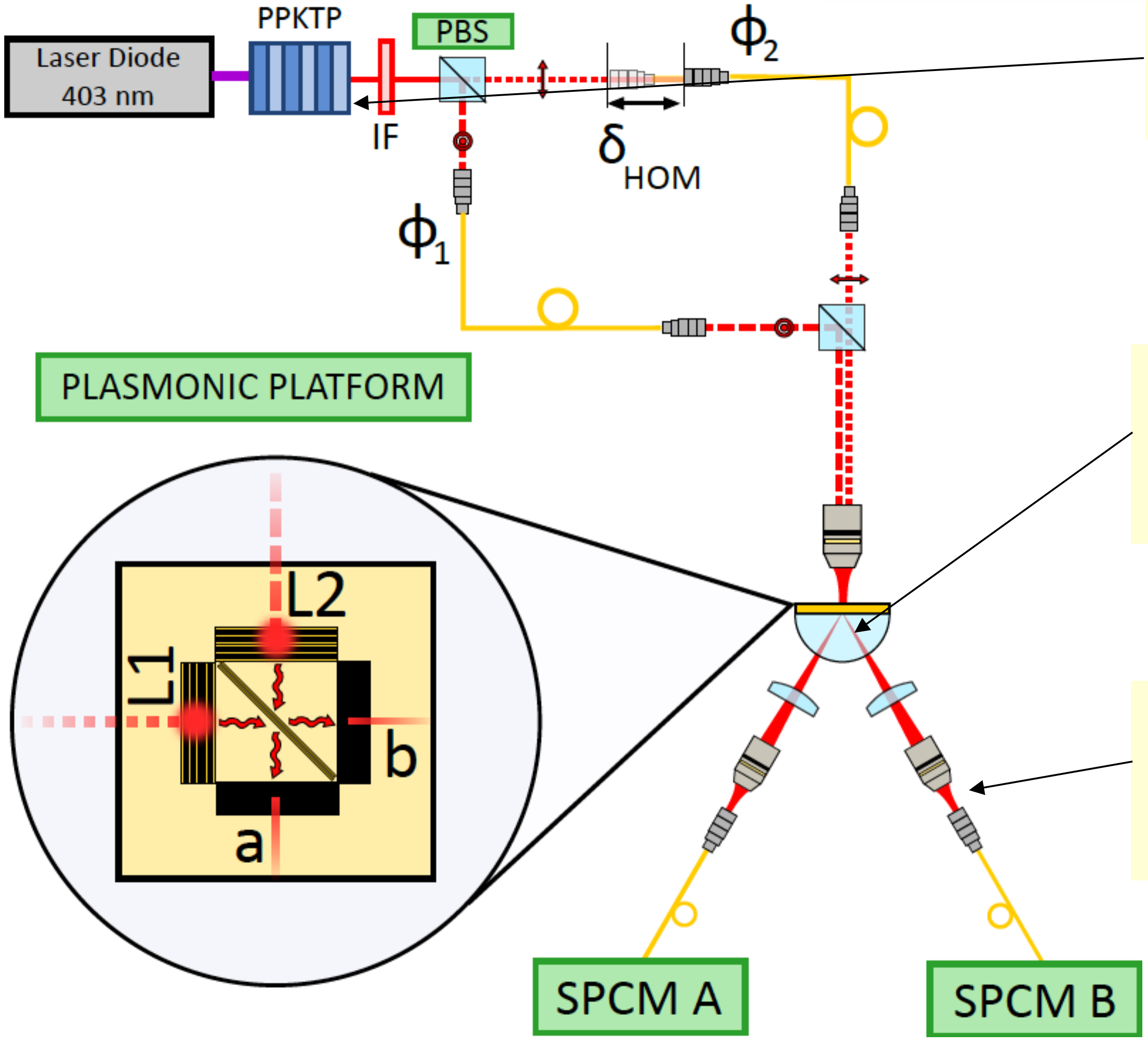
J. Fakonas et al.,
Nat. Phot. 8, 317–320 (2014).



Di Martino et al.,
Phys. Rev. Appl. 1, (2014).

- Bosonic behavior of plasmons is clearly confirmed (waveguides)

A plasmonic HOM experiment



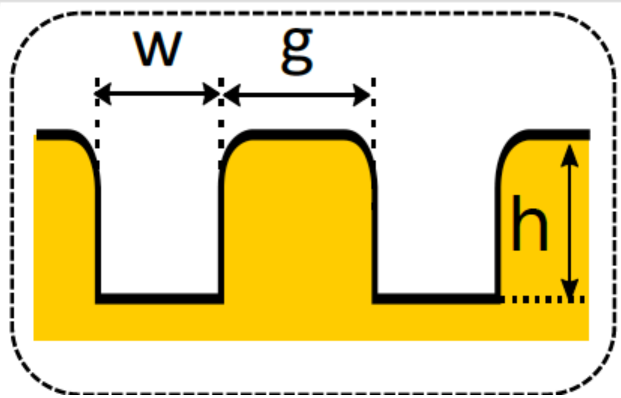
Generation of photon pairs @ 806 nm

Conversion into single SPPs with plasmonic launchers

Interference on the beam splitter, outcoupling and collection

B. Vest et al., Science ***356****, 1373 (2017)*

Two beam splitters



Design and fabrication of samples with different geometrical parameters

CASE OF A 25/25 BEAMSPLITTER

A) « Lossy lossless » beamsplitter

$$|t| = |r| = 1/2$$

$$t = \pm i r$$

w [nm]	180
g [nm]	140
h [nm]	120

B) Lossy anomalous beamsplitter

$$|t| = |r| = 1/2$$

$$t = \pm r$$

w [nm]	320
g [nm]	280
h [nm]	250

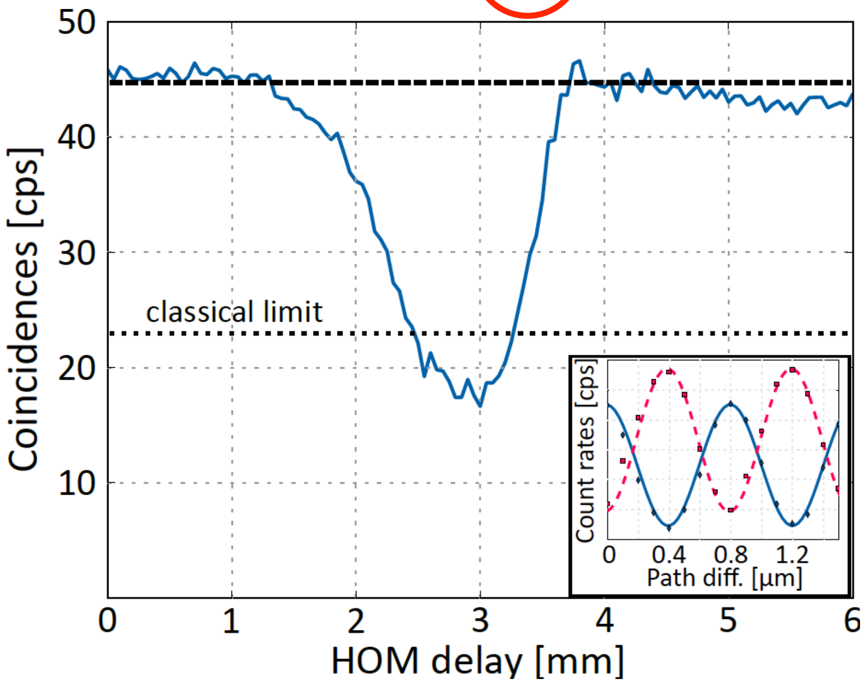
$$P(1_a, 1_b) = |t^2 + r^2|^2$$

From HOM dip to HOM peak

A) Lossy « lossless type » beamsplitter

$$|t| = |r| = 1/2$$

$$t = \pm i r$$



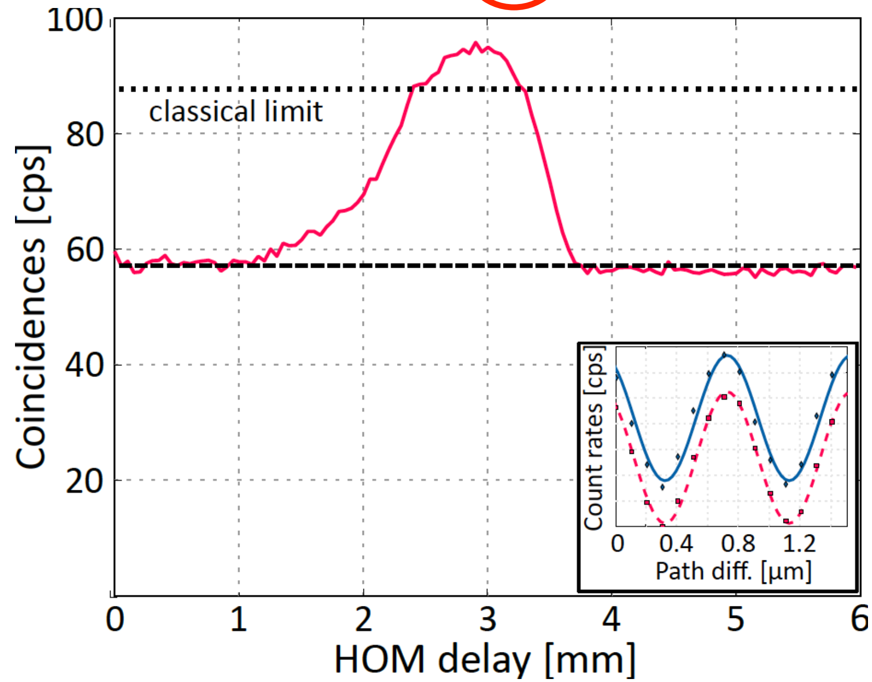
- Usual HOM dip with contrast above 60%
- Bosonic nature of SPPs
- Freely propagating, unguided particles

B. Vest et al., Science ***356****, 1373 (2017)*

B) Lossy « anomalous » beamsplitter

$$|t| = |r| = 1/2$$

$$t = \pm r$$



- HOM peak with contrast above 65 %
- Boson anti-coalescence

INSTITUT d'OPTIQUE GRADUATE SCHOOL ParisTech

Quantum coherent absorption

Quantum non linear absorption of two bosons

Barnett et al., PRA 57(3) (1998)

$$t = \pm r$$

Two photons are absorbed or none.

$$P(1_a, 0_b) = 0 = P(0_a, 1_b)$$

$$P(0_a, 0_b) = \frac{1}{2}.$$

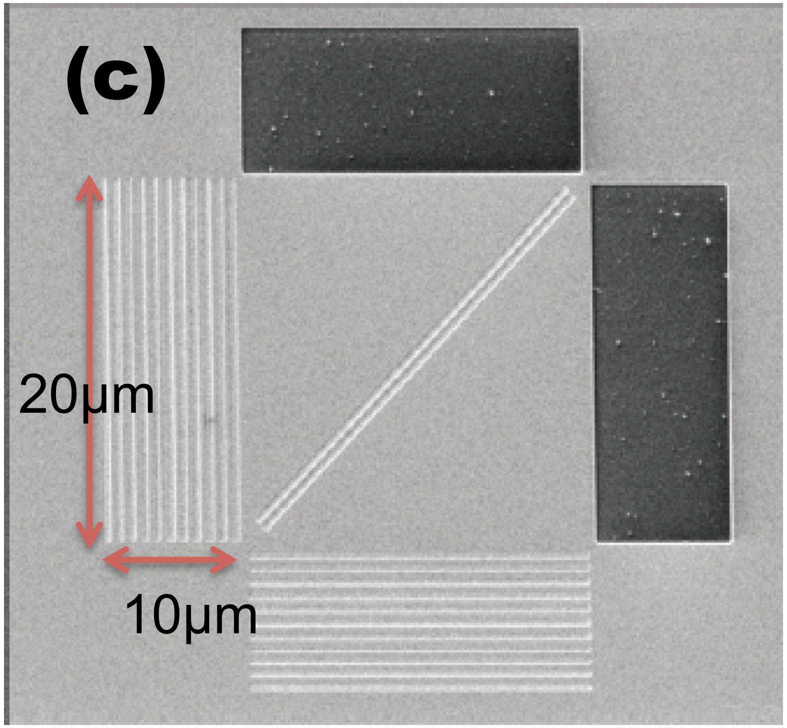
Quantum coherent absorption of two fermions

B. Vest et al., Science ***356****, 1373 (2017)*

$$t = \pm r$$

One and only one fermion is absorbed.

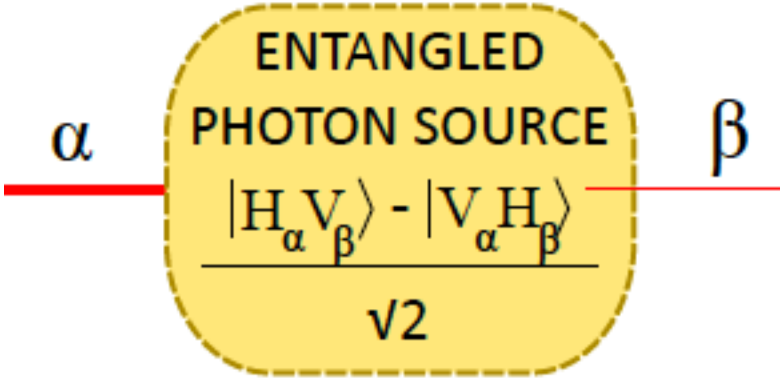
Remote control of a surface plasmon



Procedure:

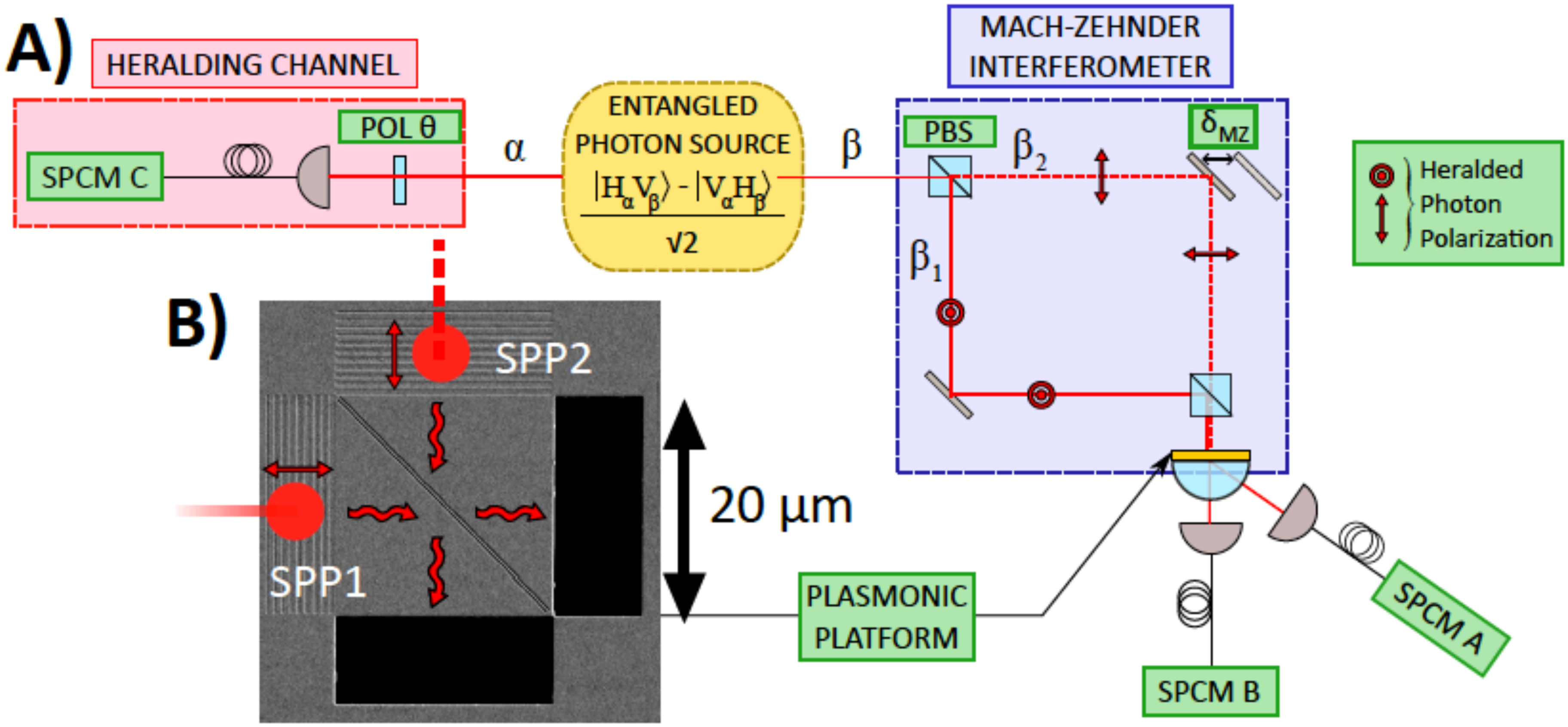
- generate a hybrid entanglement between a plasmon and a photon
- Perform a projective measurement on the photon

Source of entangled photons



$$|\psi_{\alpha\beta}\rangle = \frac{|H_\alpha; V_\beta\rangle - |V_\alpha; H_\beta\rangle}{\sqrt{2}}$$

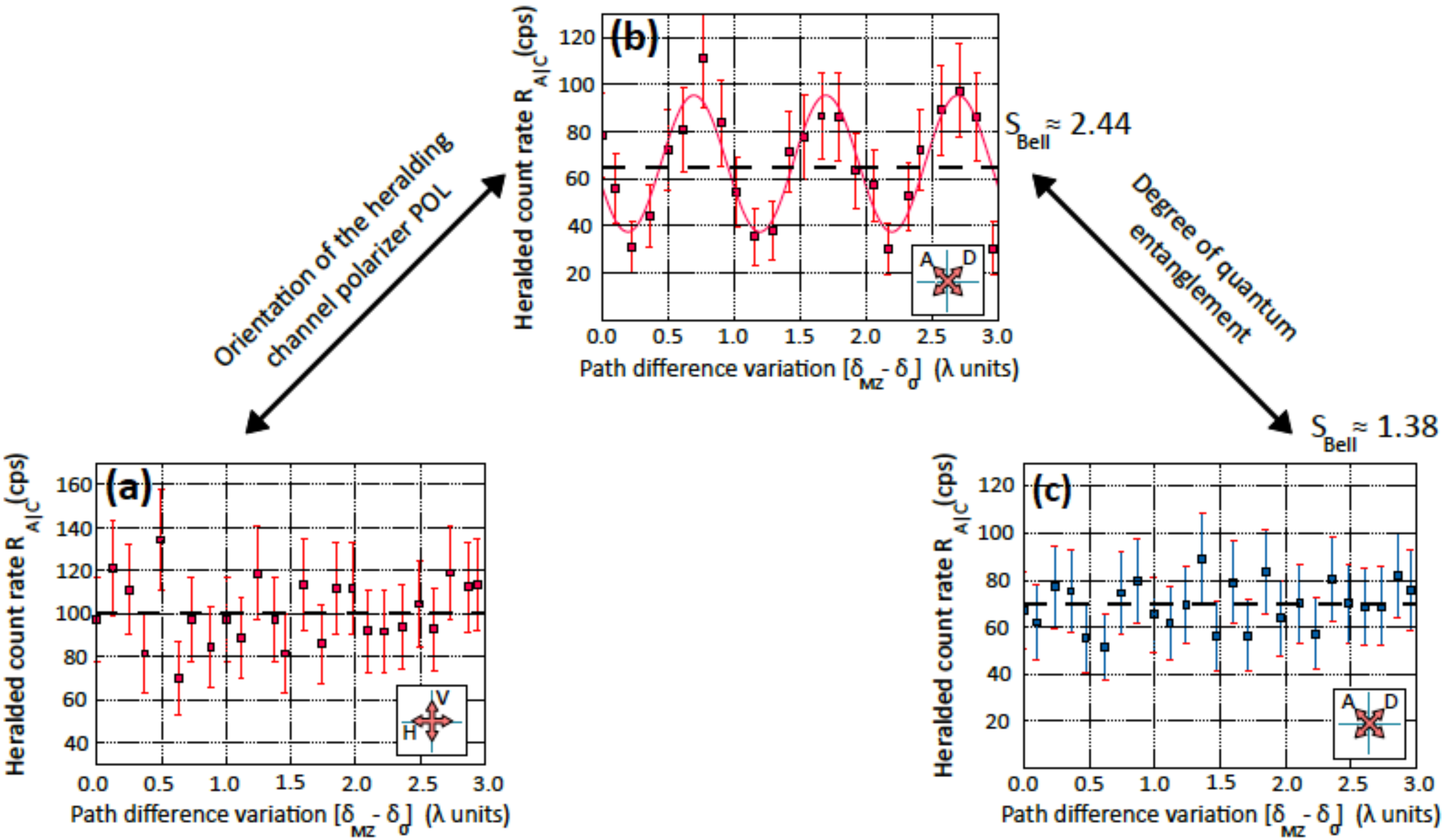
Polarization-path entanglement



$$|\psi_{\alpha\beta}\rangle = \frac{|H_\alpha; 1_{\beta_1}; 0_{\beta_2}\rangle - |V_\alpha; 0_{\beta_1}; 1_{\beta_2}\rangle}{\sqrt{2}}$$

$$|\psi'_{\alpha\beta}\rangle = \frac{|H_\alpha; 1_{\mathrm{SPP}_1}; 0_{\mathrm{SPP}_2}\rangle - |V_\alpha; 0_{\mathrm{SPP}_1}; 1_{\mathrm{SPP}_2}\rangle}{\sqrt{2}}$$

Observation of the MZI output

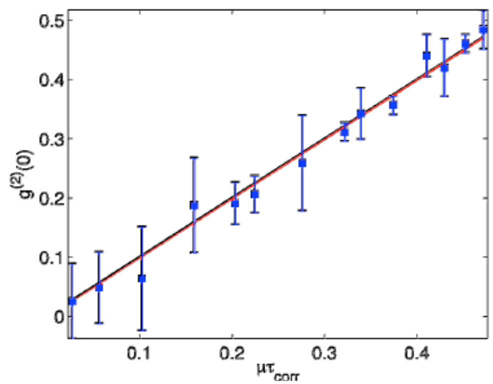


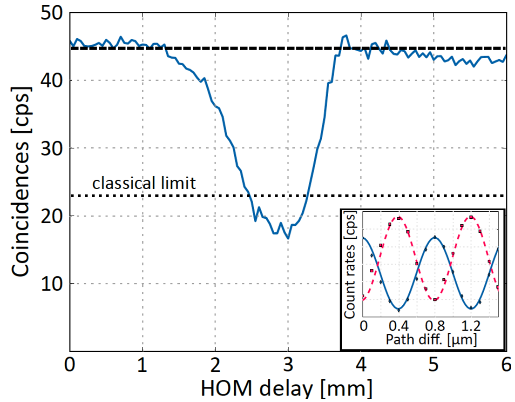
The plasmon state depends on the projective measurement performed on the photon:
It can be remotely controlled through its entanglement with the photon.

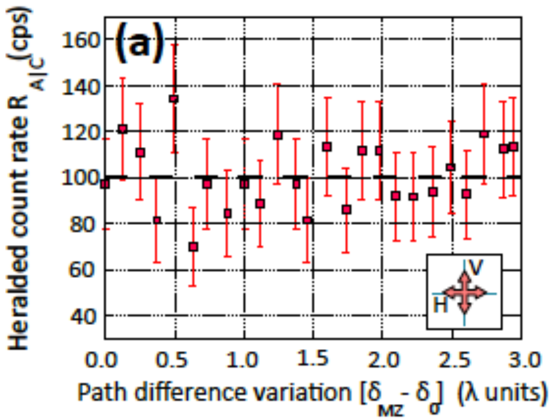
Fabrication: Eloise Devaux, Th. Ebbesen, ISIS Strasbourg
Design: P. Lalanne, C2N Bordeaux
Characterization: A. Baron, CPP, Bordeaux

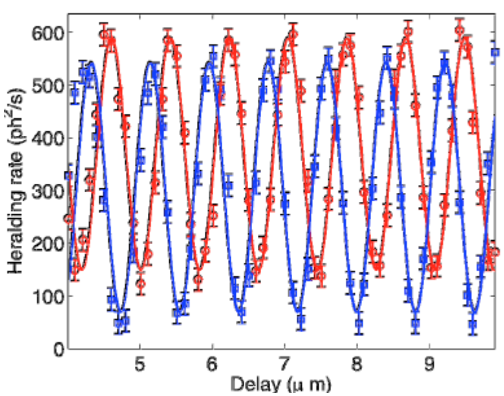
IOGS: MC Dheur, B. Vest, E. Rousseau, JP Hugonin, G. Messin, F. Marquier

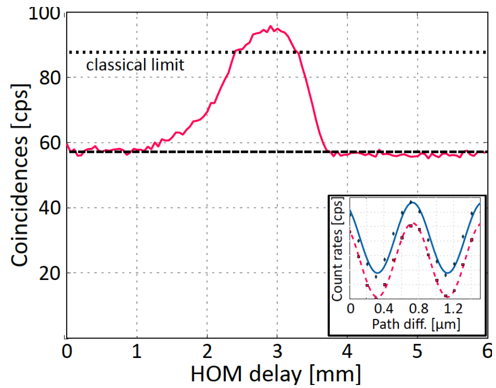
Summary

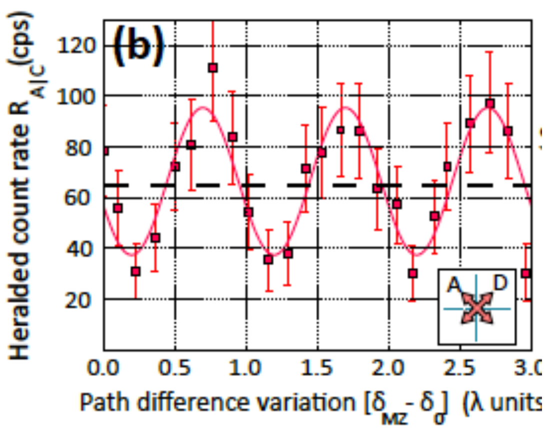

$g^{(2)}(0)$
$\mu\tau_{corr}$


Coincidences [cps]
classical limit
HOM delay [mm]
Count rates [cps]
Path diff. [µm]


(a)
Heralded count rate $R_{A|C}$(cps)
Path difference variation $[\delta_{MZ} - \delta_{\sigma}]$ (λ units)
V
H


Heralding rate (ph^2/s)
Delay (µ m)


Coincidences [cps]
classical limit
HOM delay [mm]
Count rates [cps]
Path diff. [µm]


(b)
Heralded count rate $R_{A|C}$(cps)
Path difference variation $[\delta_{MZ} - \delta_{\sigma}]$ (λ units
A
D