Introduction

Andrei Nomerotski, Czech TU & FIU

Outline

- Principles of QM and logic behind it
- Examples of quantum sources of photons and their advantages
  - Quantum microscopes & ghost imaging
- Examples of quantum interference effects
  - HOM & HBT effects
- Measurements of photons in Quantum

Quantum Mechanics

Two miracles:

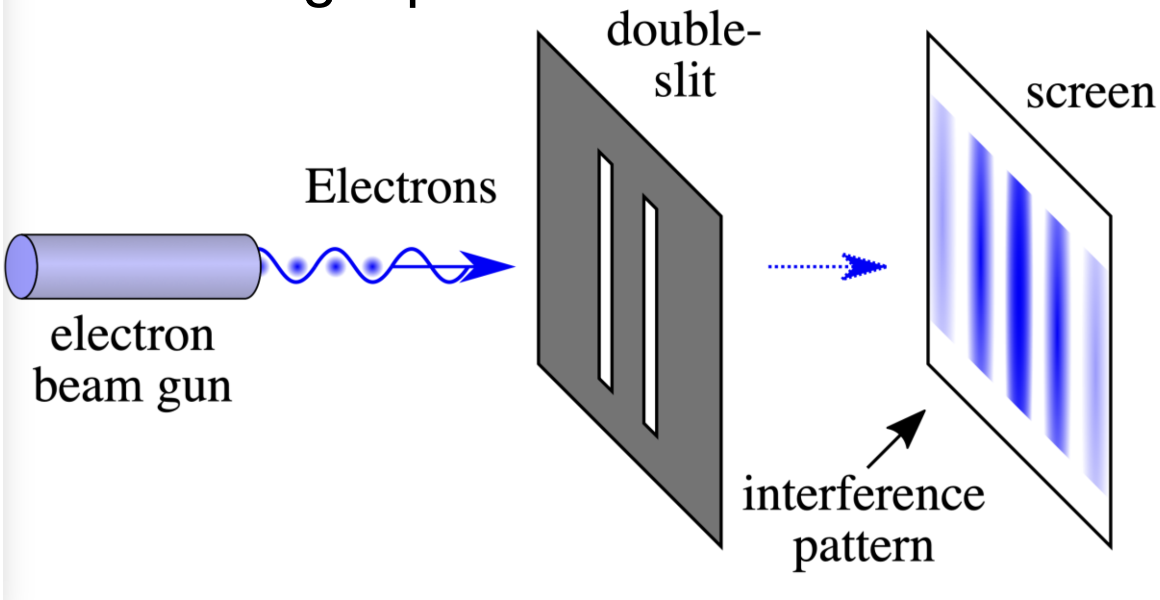
1) wave-particle duality

2) entanglement

They both are dictated by experiment, this is the way the Nature works. They can be reconciled with everything else.

1) Wave - Particle Duality

Applicable to single particles



From Wikipedia

Experiment tells us that particles are similar to waves,
even if you shoot them slowly, one by one

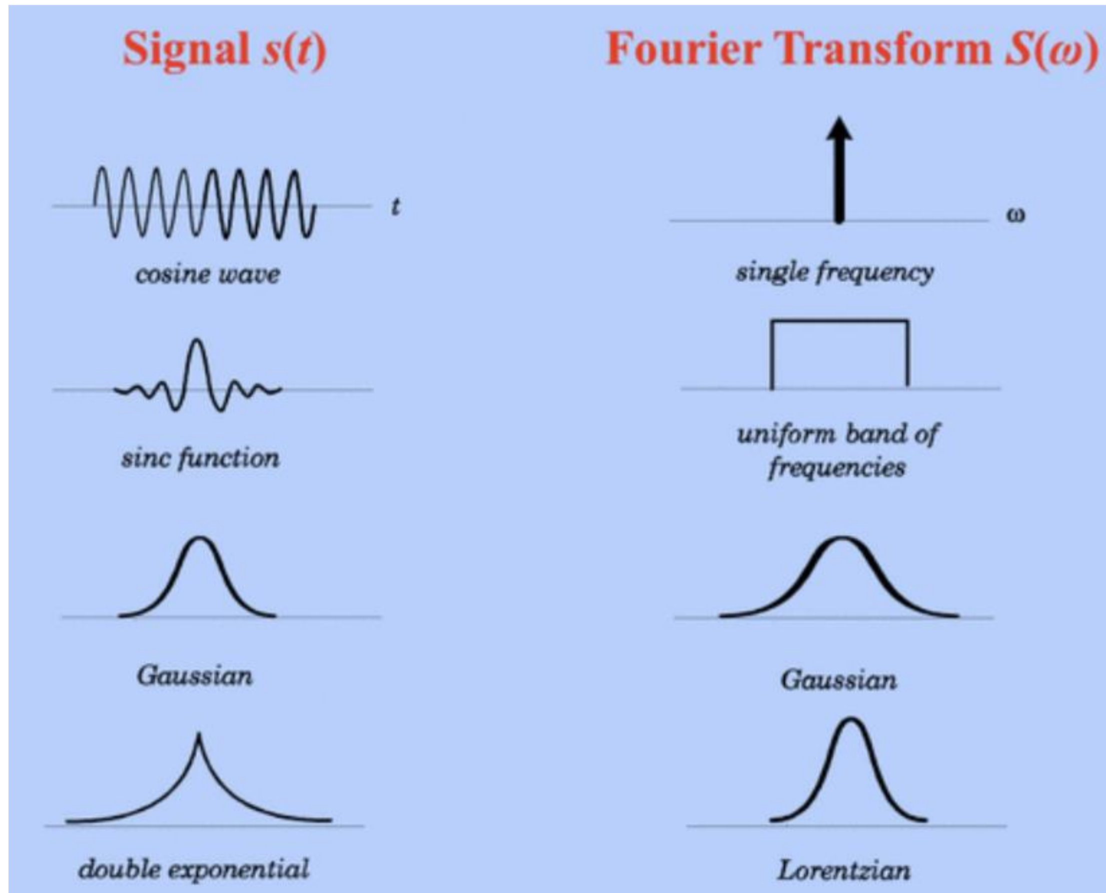
Superposition principle: add amplitudes (of wave function)

Heisenberg Uncertainty Principle

Similar to Fourier transform limit: infinite sine correspond to a single frequency but finite wave duration will correspond to finite bandwidth

$$\Delta w \Delta t \geq \frac{1}{2},$$

$$\Delta E \Delta t \geq \frac{\hbar}{2},$$



From Wikipedia

Indistinguishability

Cannot label particles and keep track since don't know where they are (because of Heisenberg Uncertainty Principle!)

Particles are indistinguishable

Exchange of two indistinguishable particles does not change the system but can change sign of wave function. It can be symmetric or anti-symmetric.

This leads to **two types of symmetries: Bose-Einstein & Fermi-Dirac.**

2) Entanglement

For two particles with interaction: they can strongly correlate in multiple observables: position, energy, time, polarization etc

“know about each other”, “spooky action” + other murky terminology.

it just means that they are correlated more than allowed classically

In certain situations this is called **‘quantum advantage’**

2) Entanglement

For two particles with interaction: they can strongly correlate in multiple observables: position, energy, time, polarization etc

↘

Has non-locality implications → hidden variables (which would allow each particle to have full information about the system)

↙

Bell’s inequalities allowed to prove there are no hidden variables. Experimental verification lead to Nobel in 2022 (Aspect, Zeilinger, Clauser)

When should we worry about Quantum?

Planck constant sets the scale in Heisenberg Uncertainty Principle

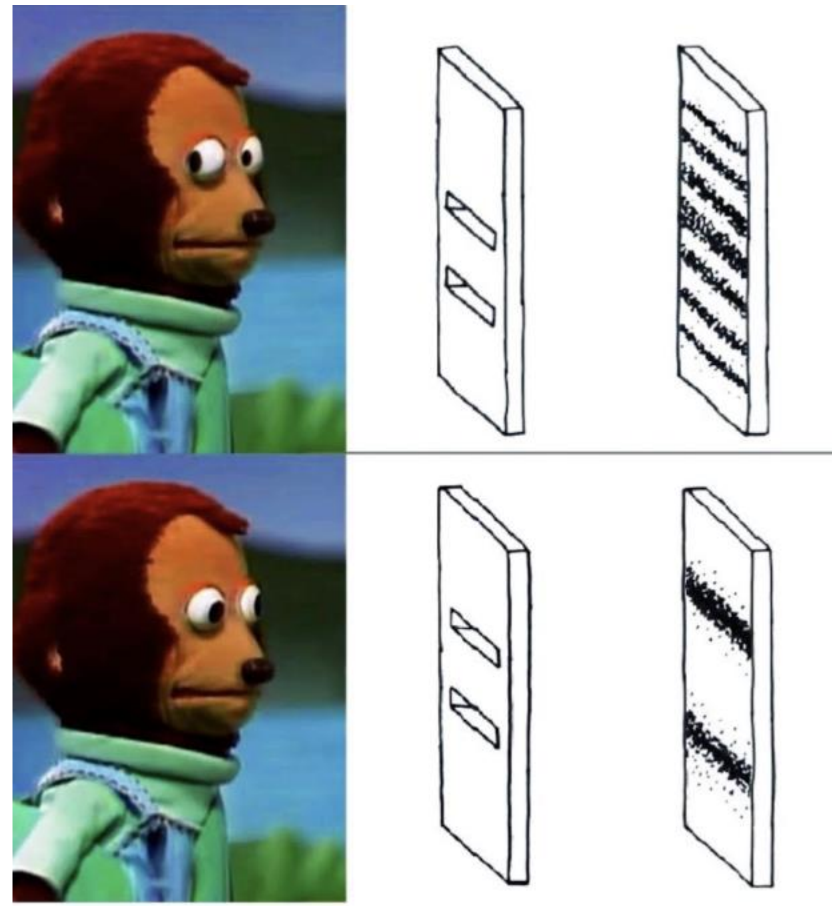
- Probing small distances requires large momentum transfer
- Production of new particles requires energy but does not violate energy conservation law

Quantum physics agrees with its classical limit if large '*action*' is assumed

Role of measurement

measuring instruments are classic

measurement ‘collapses’ wave function - good theoretical (and philosophical) topic all the way to many-worlds interpretation (Deutsch et al) and theory of consciousness (Penrose et al)



From Meta

Particle Physics

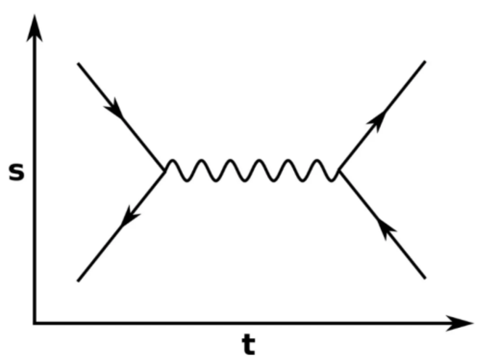
Deals with elementary particles which are small or even point-like

Needs to be reconciled with **relativity** since typically in Particle Physics **energy >> mass**

Quantum Field Theory approaches :

creation and annihilation operators (→ quantized field excitations → particles) or

path integrals (→ Feynman diagrams)



Recent LHC results -

all way back to entanglement

The ATLAS Collaboration, Observation of quantum entanglement with top quarks at the ATLAS detector. *Nature* **633**, 542–547 (2024)

The CMS Collaboration, Observation of quantum entanglement in top quark pair production in proton–proton collisions at 13 TeV, *Rep. Prog. Phys.* **87** 117801 (2024)

Quantum Computing

Employs entanglement implemented as qubits to do calculations

Qubit is superposition of two bit values: 0 & 1 $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$

Requires special algorithms

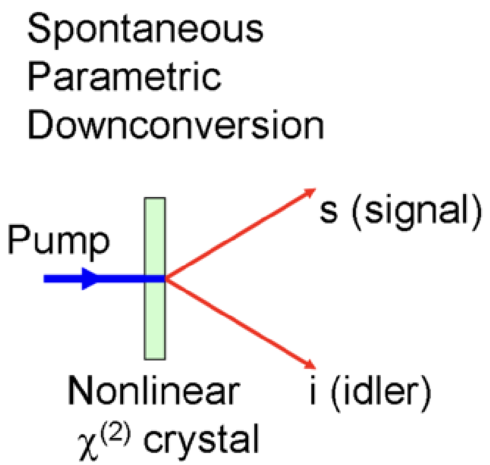
Lots of progress in qubit technology: multiple candidates using superconductivity, atomic physics, condensed matter physics etc

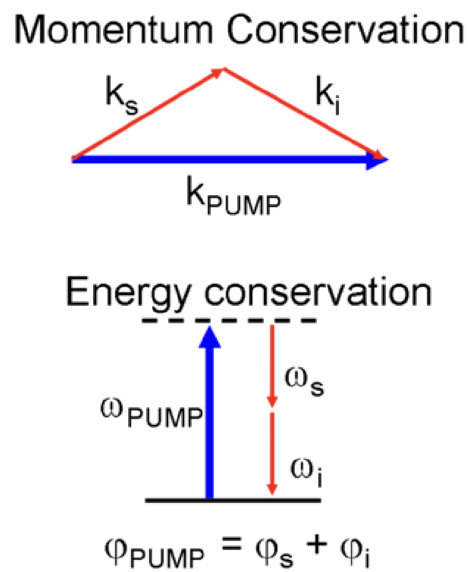
Quantum sensing

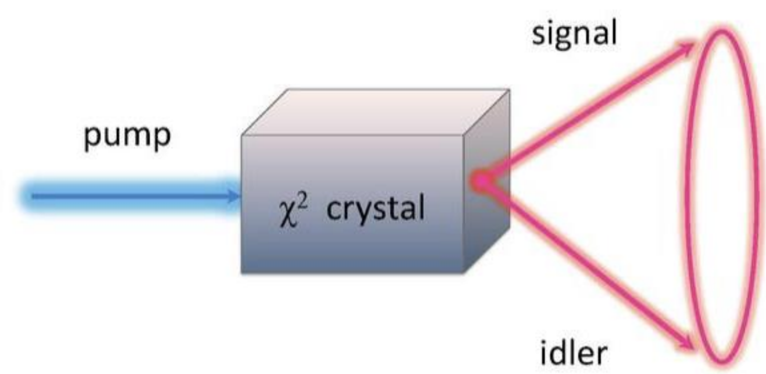
Entanglement for improving measurements - in application to microscopy, telescopy, metrology etc

Most of cases employs **OPTICAL PHOTONS**

Quantum photon sources - spontaneous parametric down-conversion (SPDC) sources





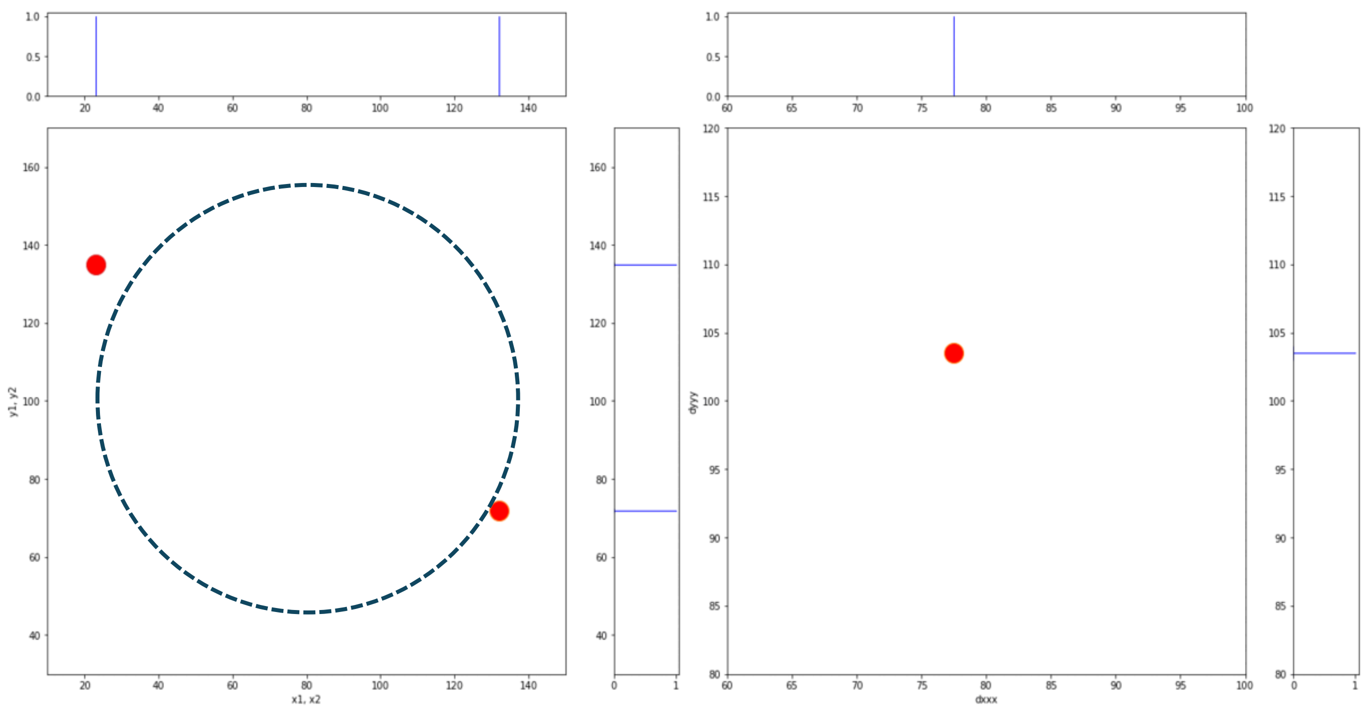


From Wikipedia

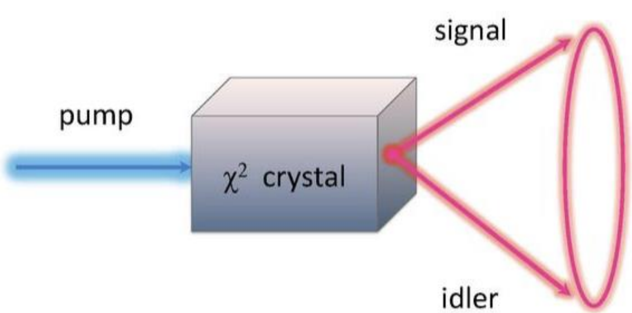
Produce two photons correlated (sometimes entangled) in

1. Time
2. Position
3. Energy

Quantum pair photon source

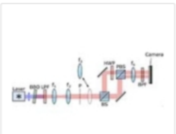


two photons are correlated in position



Recorded with single photon sensitive fast camera Tpx3Cam

Optics Letters Vol. 48, Issue 13, pp. 3439-3442 (2023) • https://doi.org/10.1364/OL.487182



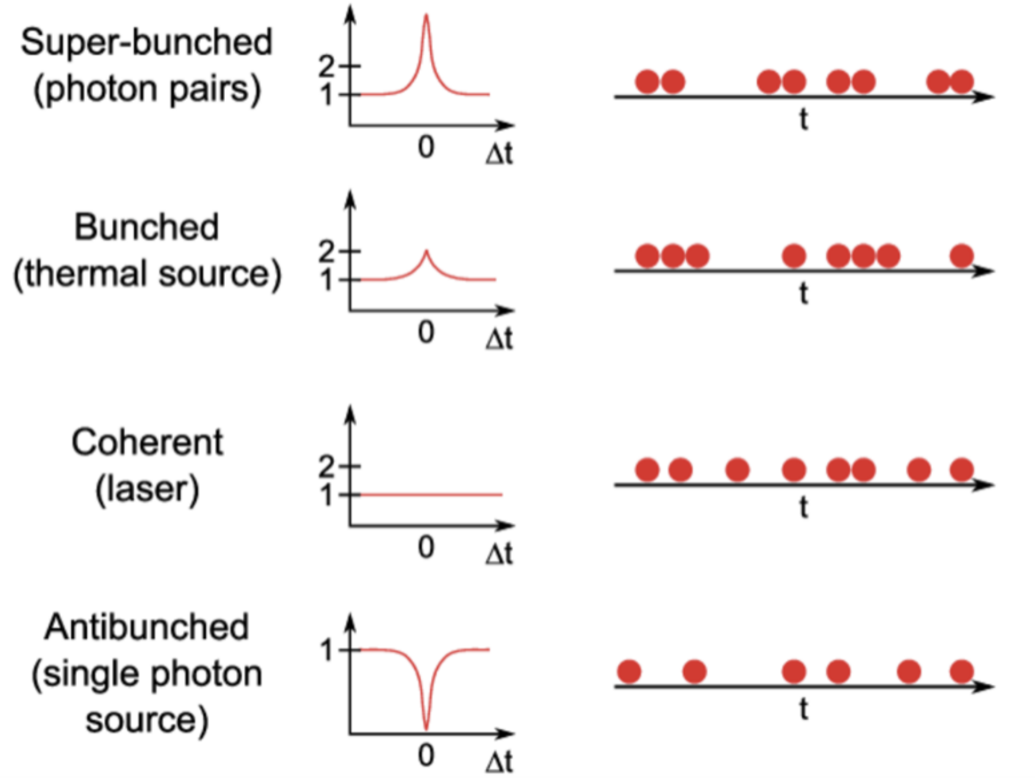
Quantifying high-dimensional spatial entanglement with a single-photon-sensitive time-stamping camera

Baptiste Courme, Chloé Vernière, Peter Svihra, Sylvain Gigan, Andrei Nomerotski, and Hugo Defienne

Quantum light sources

Different types of sources

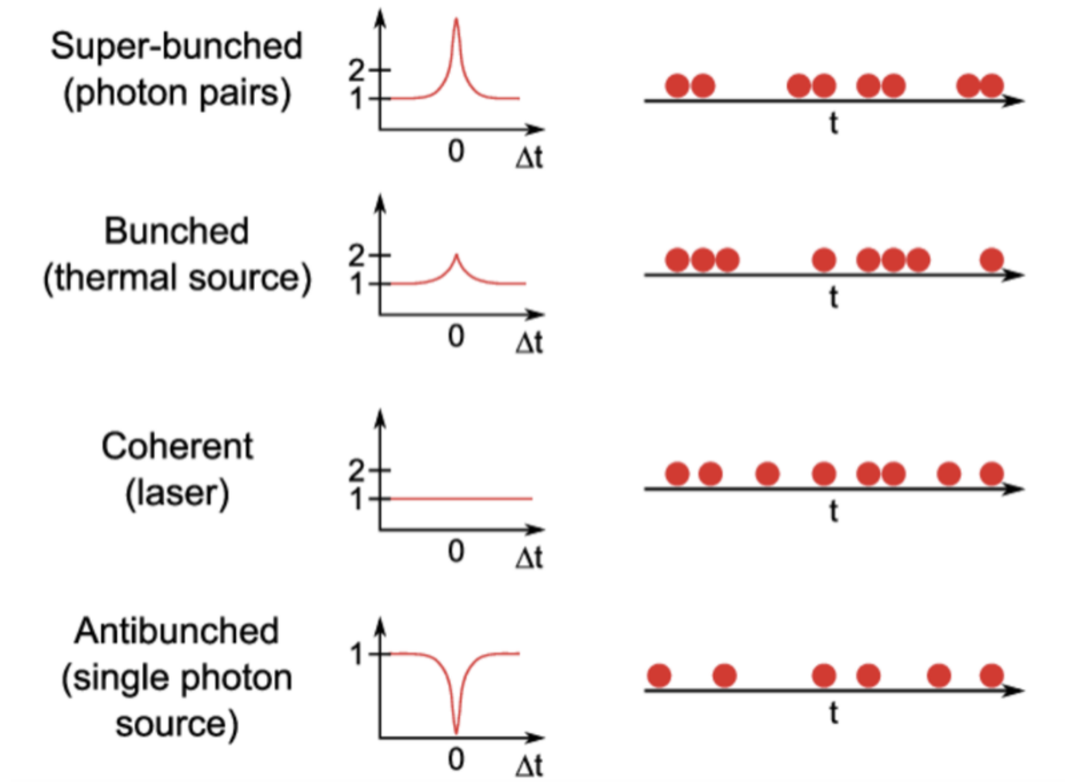
Pair photon sources
Thermal sources
Lasers (coherent sources)
Single photon sources

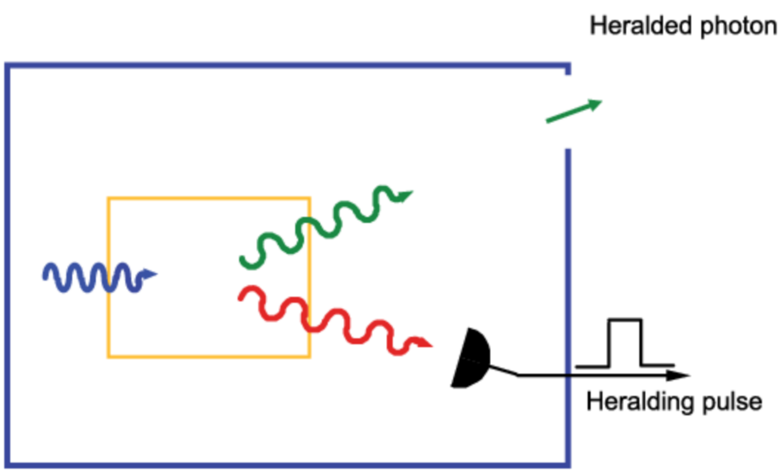


Roy Glauber (Nobel 2005) developed quantum description of single photon detection and of their correlations, based on coherent states (introduced by Schrodinger)

Single photon sources

Thermal photons are bunched so it's impossible to achieve single photon regime even for very small rates of thermal photons

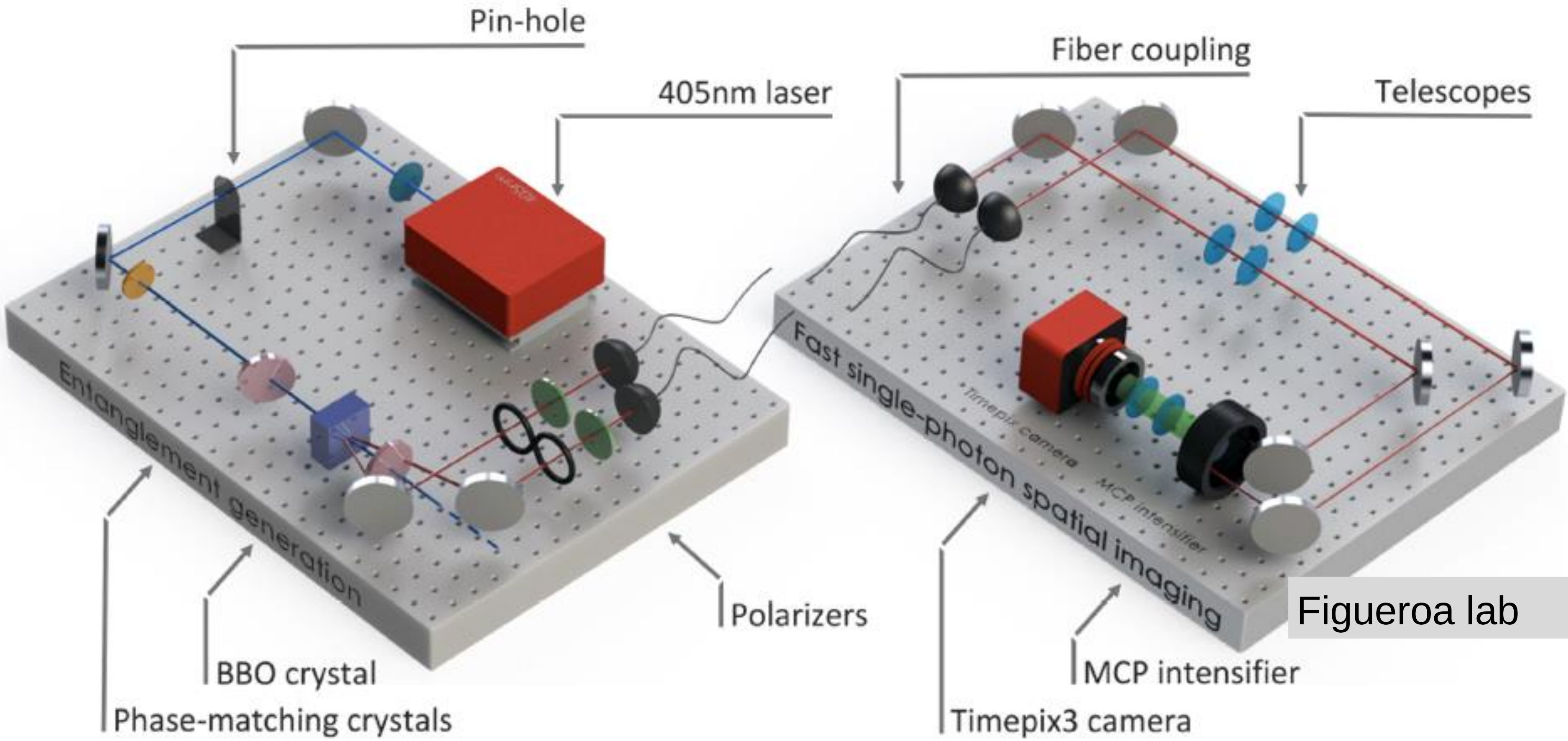




Credit S.Castelletto, R.Scholten

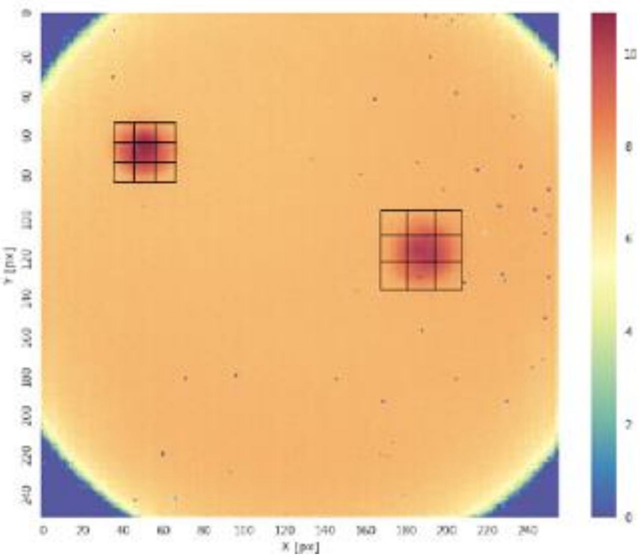
Use one photon in pair source to 'herald' single photon

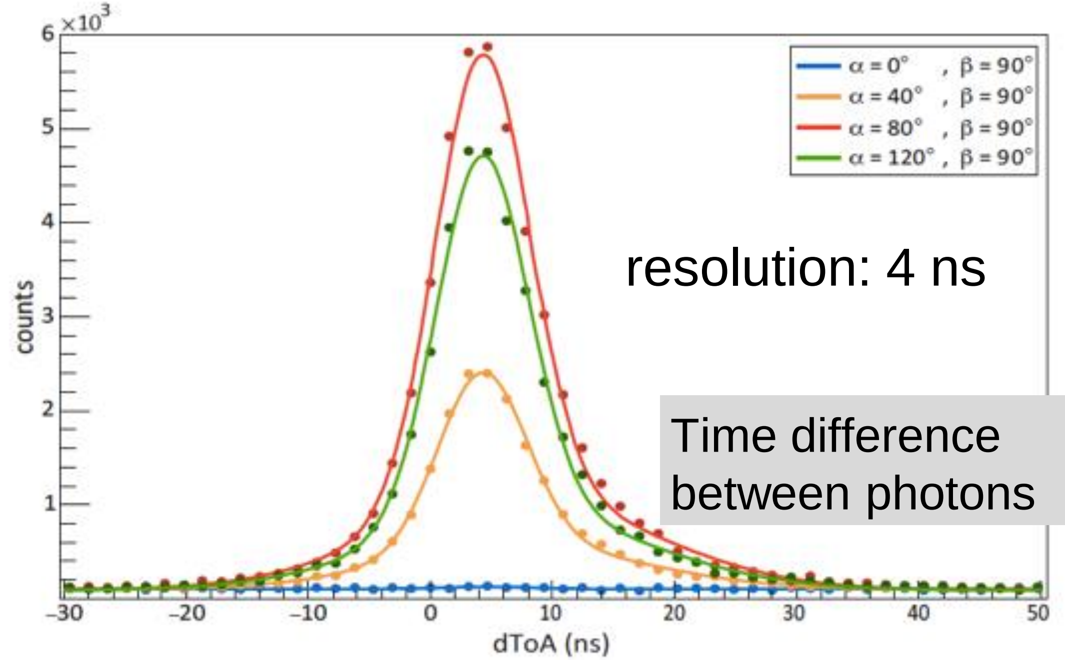
Measuring Entanglement



Figueroa lab

qubit: use H, V photon polarization states $$|\phi^{\pm}\rangle = \frac{(|HH\rangle \pm |VV\rangle)}{\sqrt{2}}$$



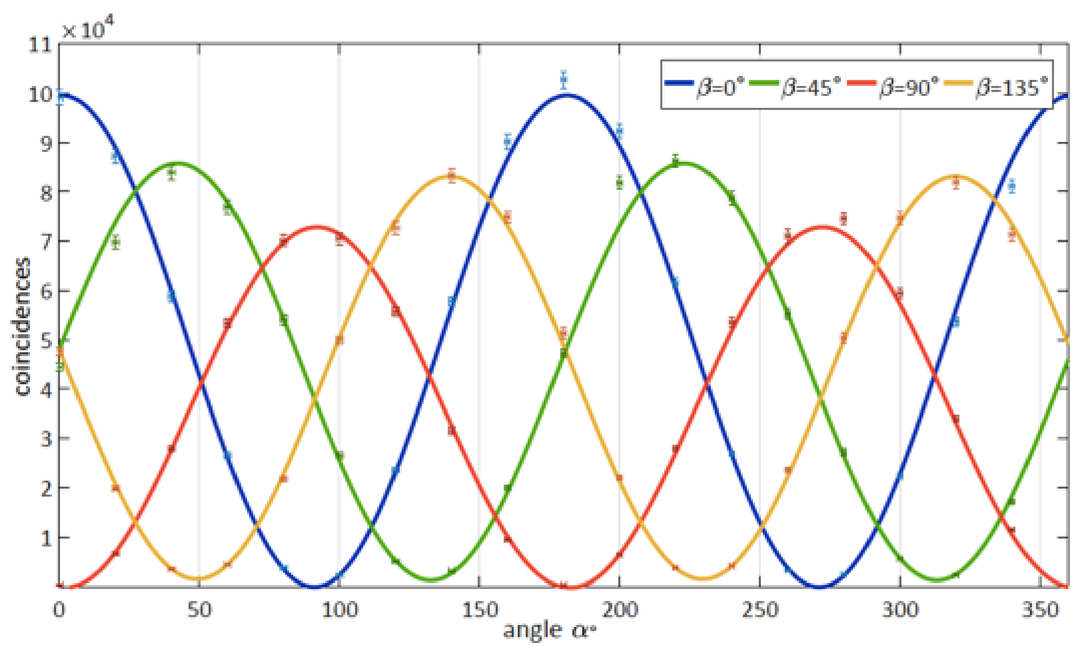


- Find coincidences, plot as function of two polarizations
- Figure of merit: S-value
  - If > 2: photons are entangled
  - max value: $2\sqrt{2} = 2.82$

Clauser-Horne-Shimony-Holt (CHSH) inequality

- Measurement:

S-value = 2.72±0.02



Fast camera spatial characterization of photonic polarization entanglement

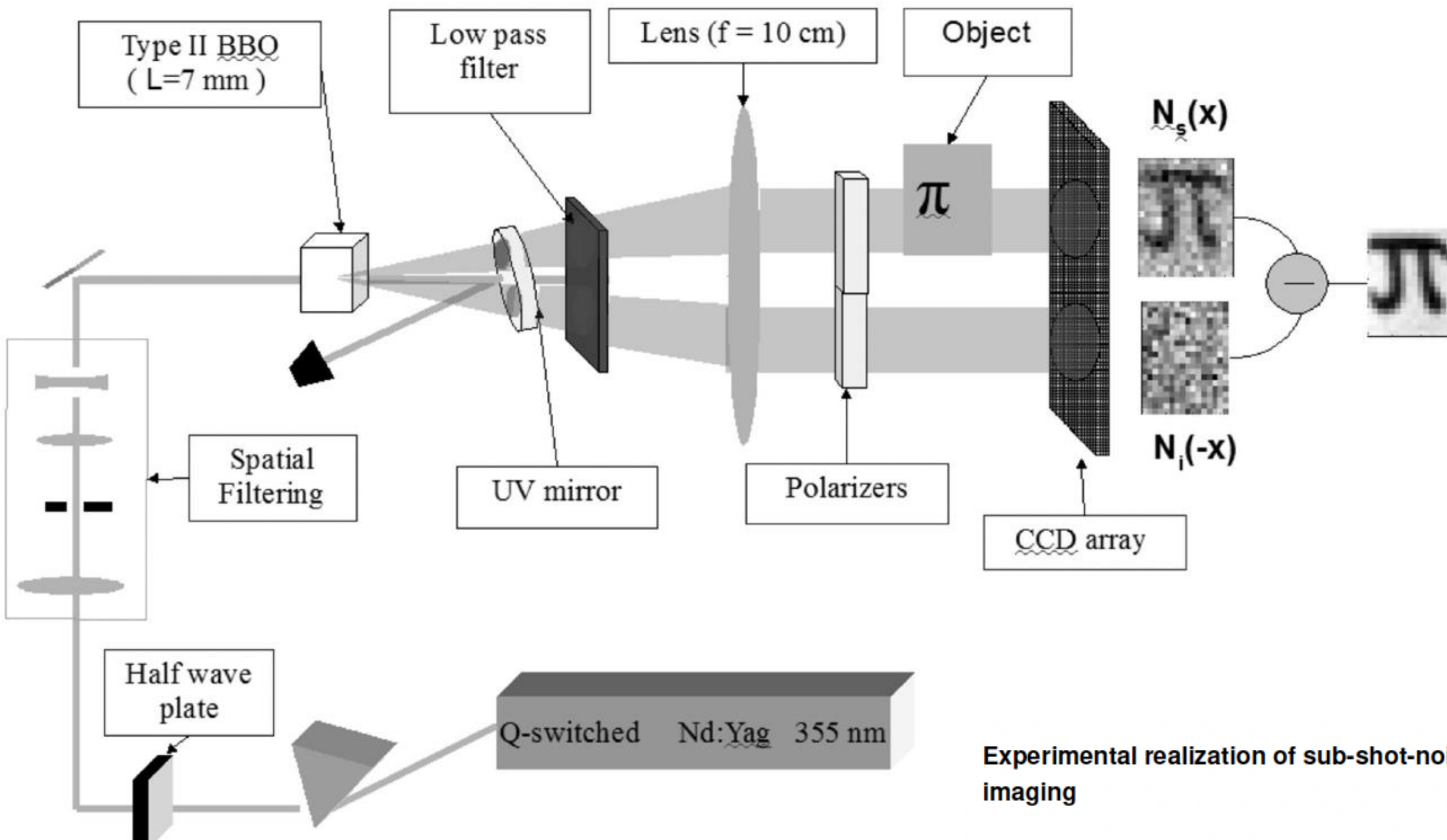
Christopher Ianzano, Peter Svihra, Mael Flament, Andrew Hardy, Guodong Cui, Andrei Nomerotski & Eden Figueroa

Scientific Reports **10**, Article number: 6181 (2020) | Cite this article

Advantages of quantum sources

Use one beam of the pair as a probe while the other acts as a reference for the shot noise

$\sqrt{N}$



Experimental realization of sub-shot-noise quantum imaging

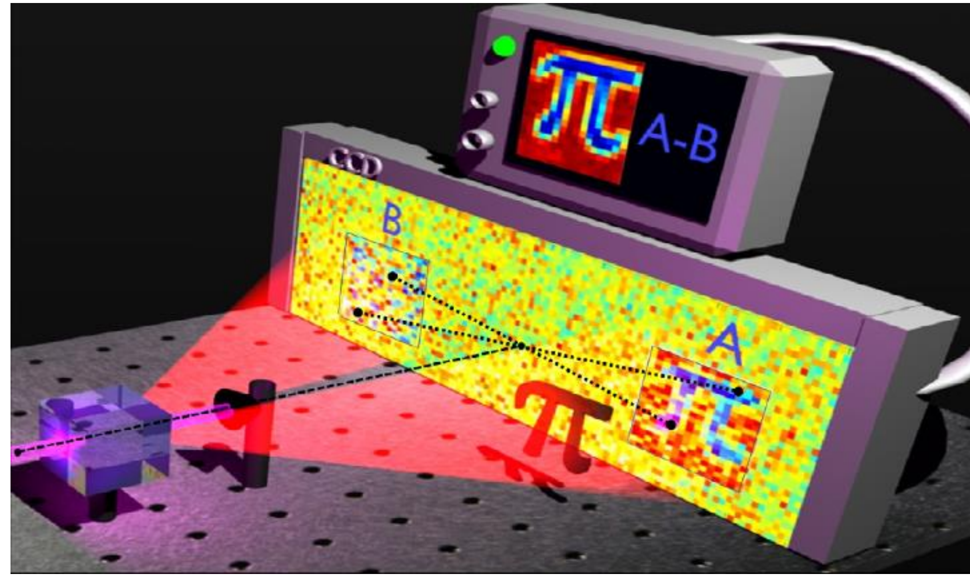
G. Brida, M. Genovese, I. Ruo Berchera*

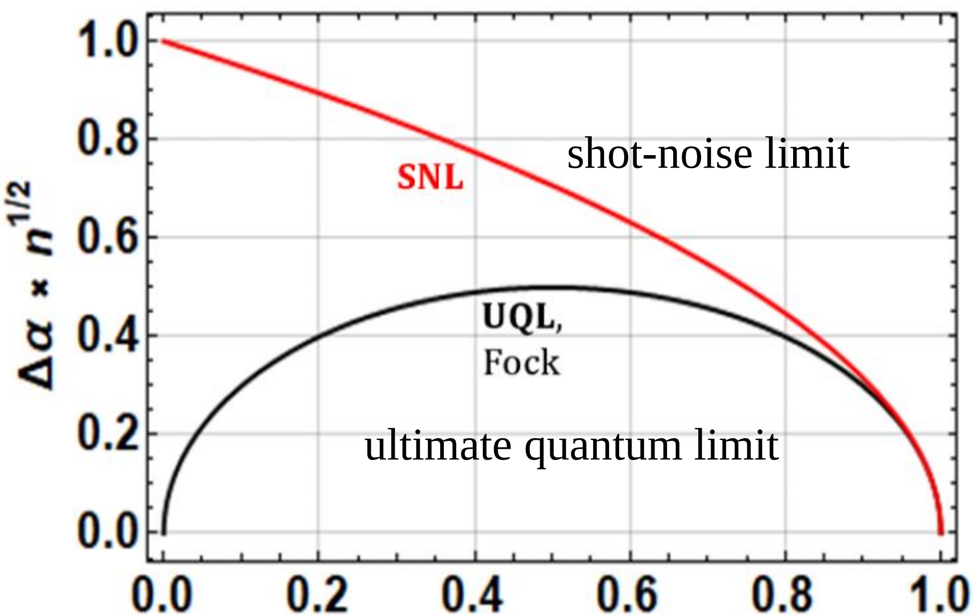
Sub-shot noise quantum imaging

Differential measurement scheme for loss coefficient α

Shot noise is the same for two beams and cancels in subtraction assuming same detection efficiency and zero losses

Example of ‘quantum advantage’





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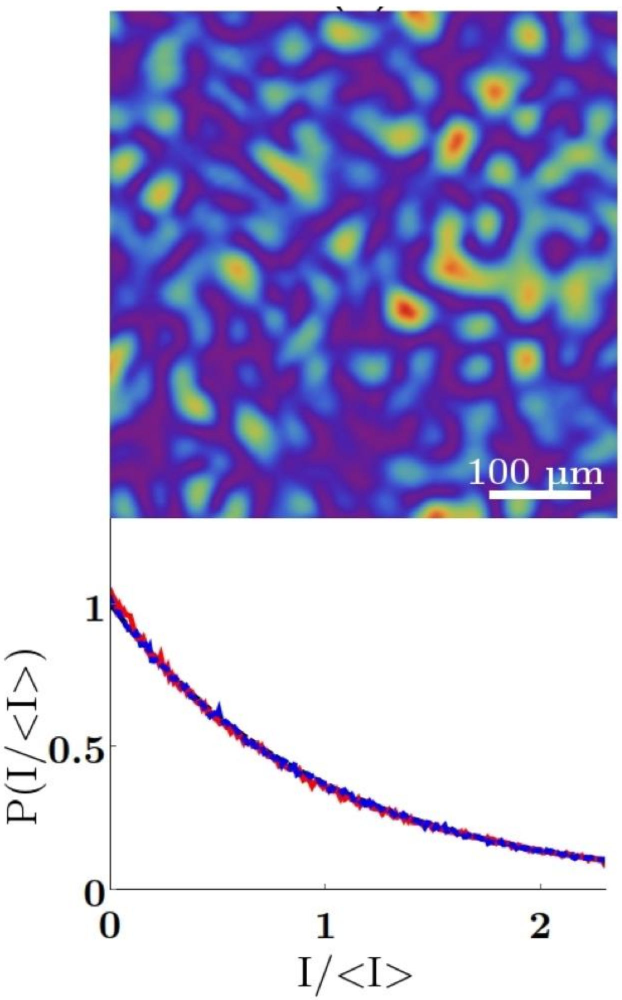
Metrologia 56 (2019) 024001 (22pp)
https://doi.org/10.1088/1681-7575/aaf7b2

Quantum imaging with sub-Poissonian light: challenges and perspectives in optical metrology

I Ruo Berchera and I P Degiovanni

INRIM, Strada delle Cacce 91, I-10135 Torino, Italy

Thermal photons



Rayleigh speckle pattern

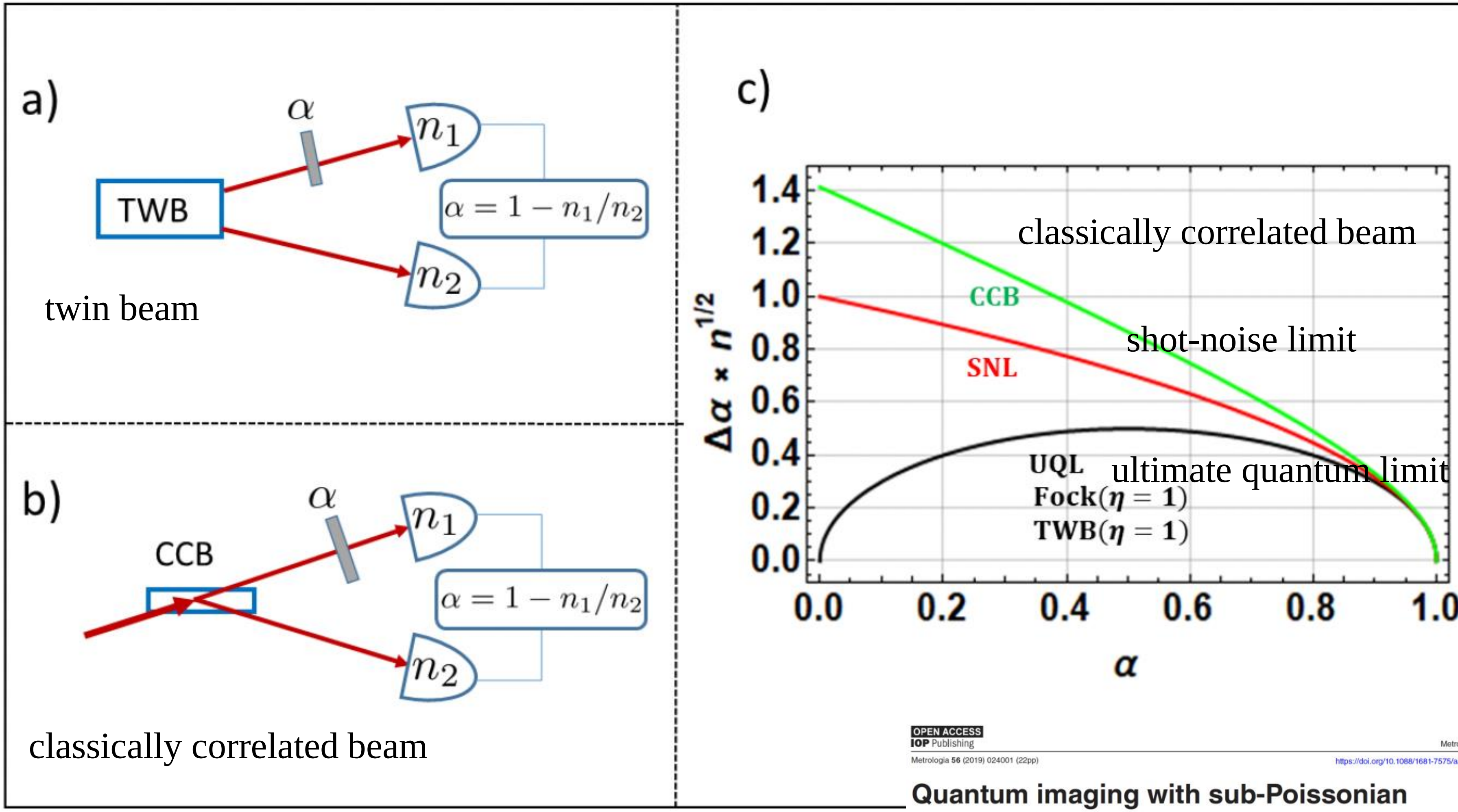
Scattering on small particles << λ

Results in ‘classical’ correlations similar to quantum correlations but weaker

Also temporal correlations

Of course, sources of thermal photons are much more powerful than quantum sources

Quantum advantage in imaging



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Quantum imaging with sub-Poissonian light: challenges and perspectives in optical metrology

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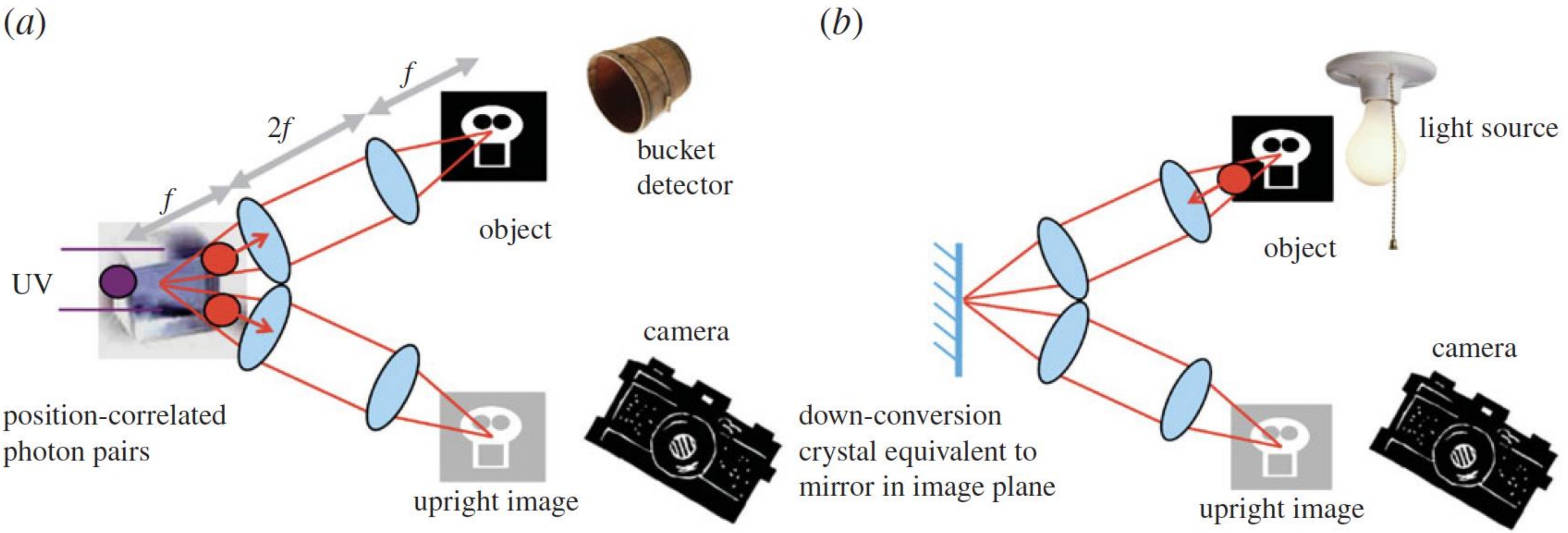
Important caveat!
classical photon sources (so far) are
much more powerful then quantum sources

Quantum Ghost Imaging

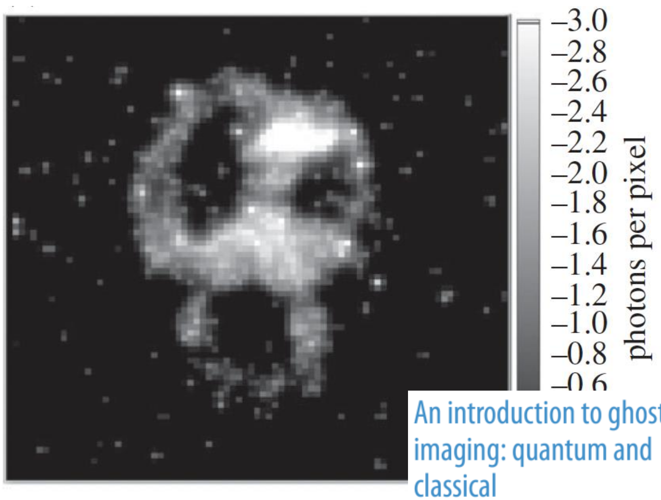
with quantum pair source



- Equivalent to images that could be produced by a classical imaging system
- Especially interesting are cases of non-degenerate photon energies:

  visible + IR

  optical + x-ray



An introduction to ghost imaging: quantum and classical

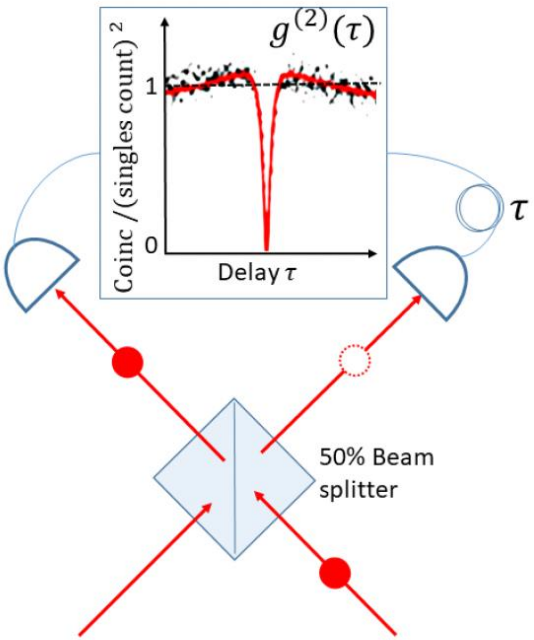
Miles J. Padgett[1] and Robert W. Boyd[1,2,3]

Quantum interference

to interfere photons must be indistinguishable: similar wavelength and time overlap

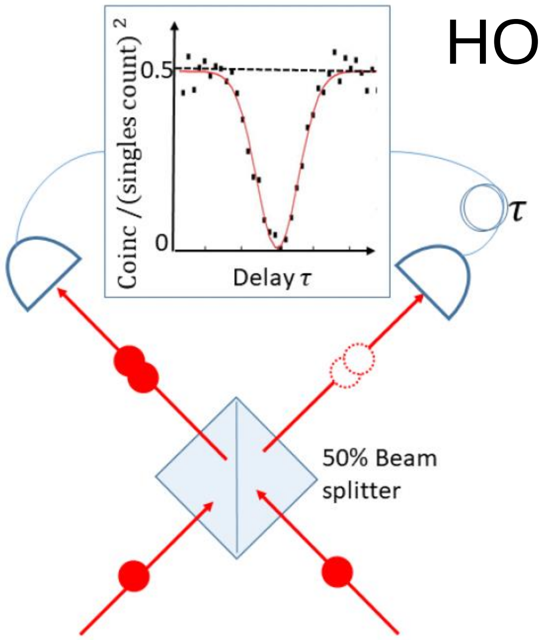
Simplest interferometer:

beam splitter = semi-transparent mirror



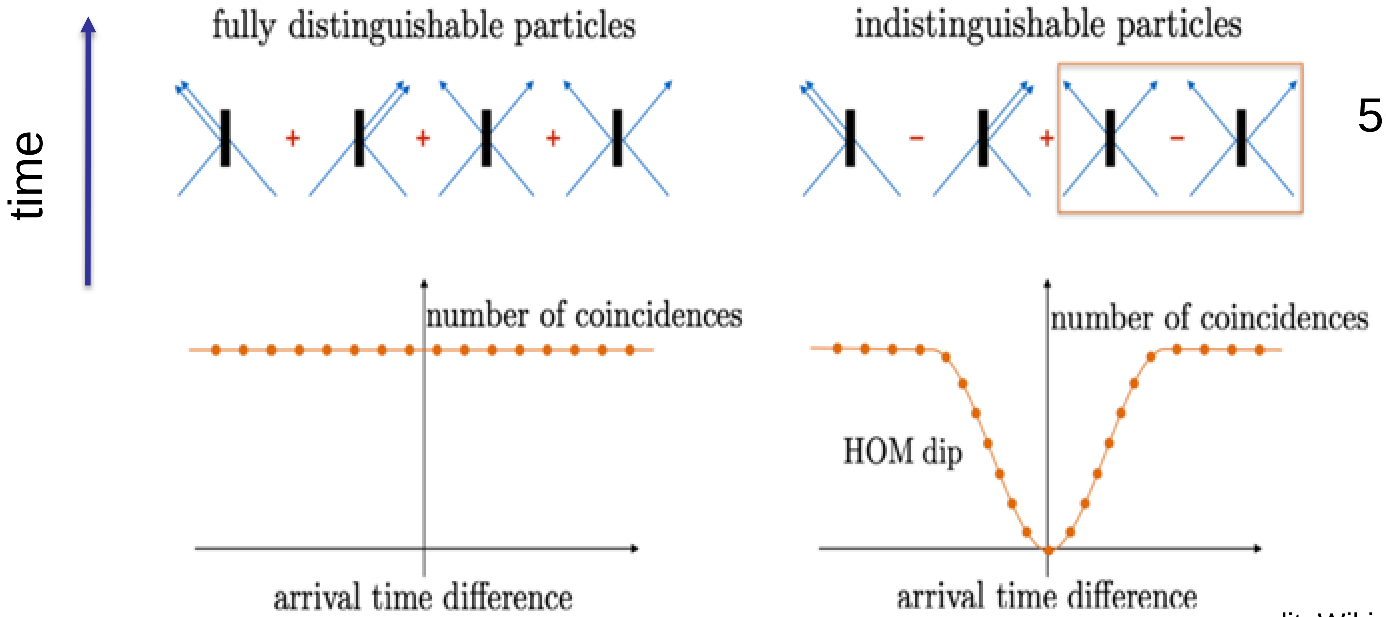
single photon source

HOM effect



photon pair source

Hong-Ou-Mandel effect

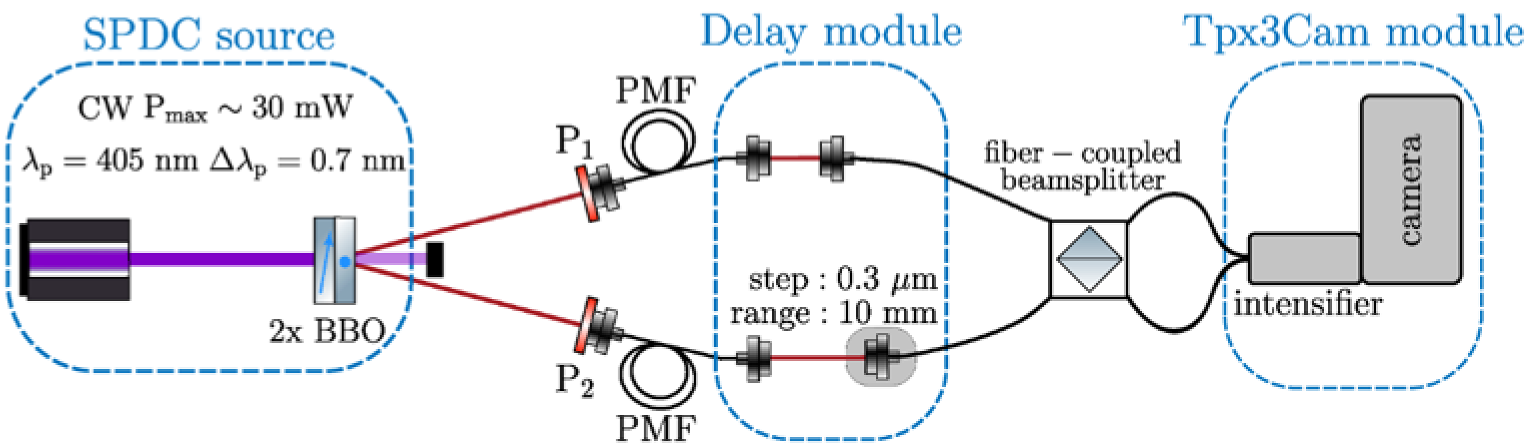


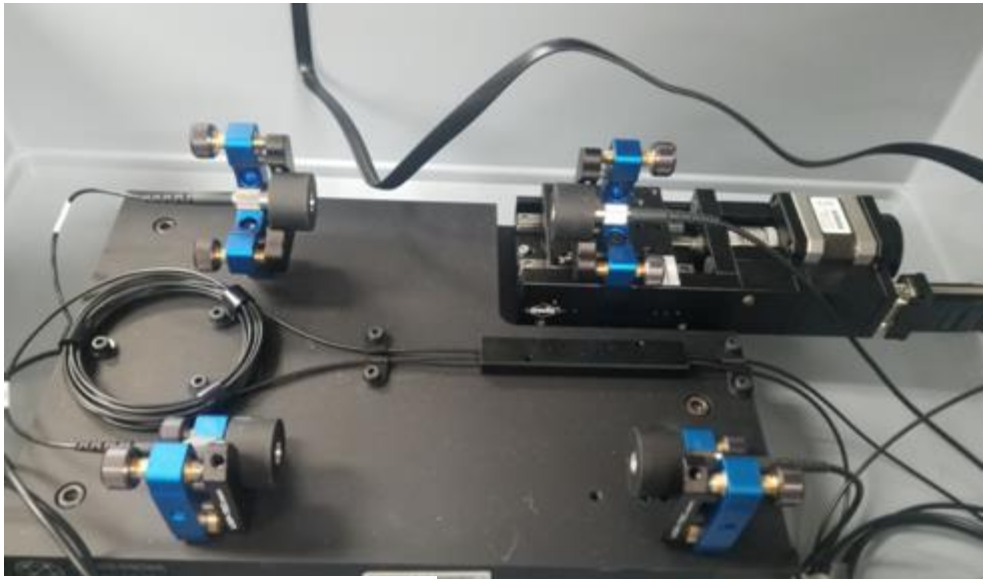
50/50 beam splitter

credit: Wikipedia HOM article

HOM dip for coincidences of two outputs

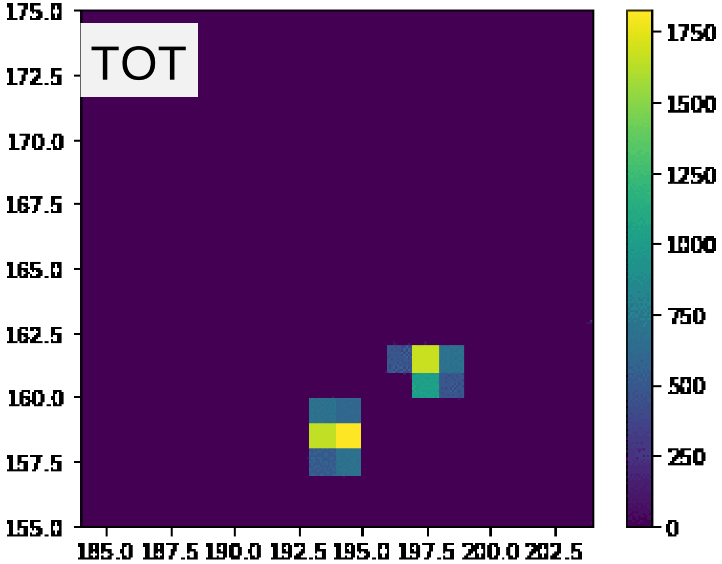
HOM Setup

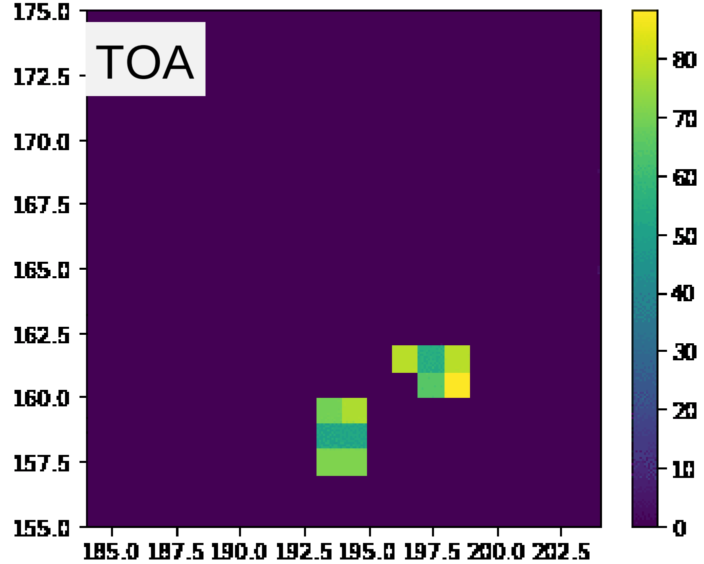


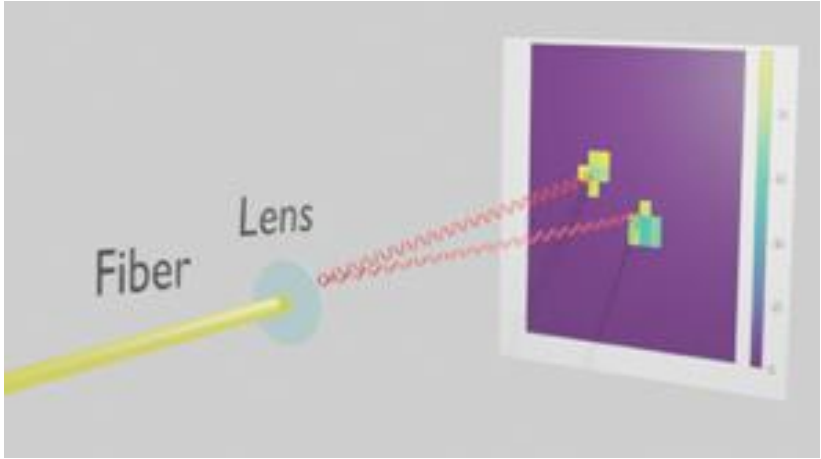


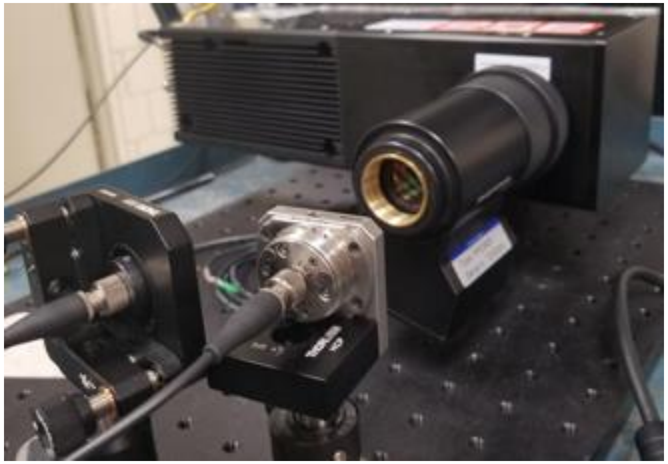
A. Nomerotski, M. Keach, P. Stankus, P. Svihra, and S. Vintskevich, "Counting of hong-ou-mandel bunched optical photons using a fast pixel camera," arXiv:2005.07982 (2020).

Examples of bunched HOM photons

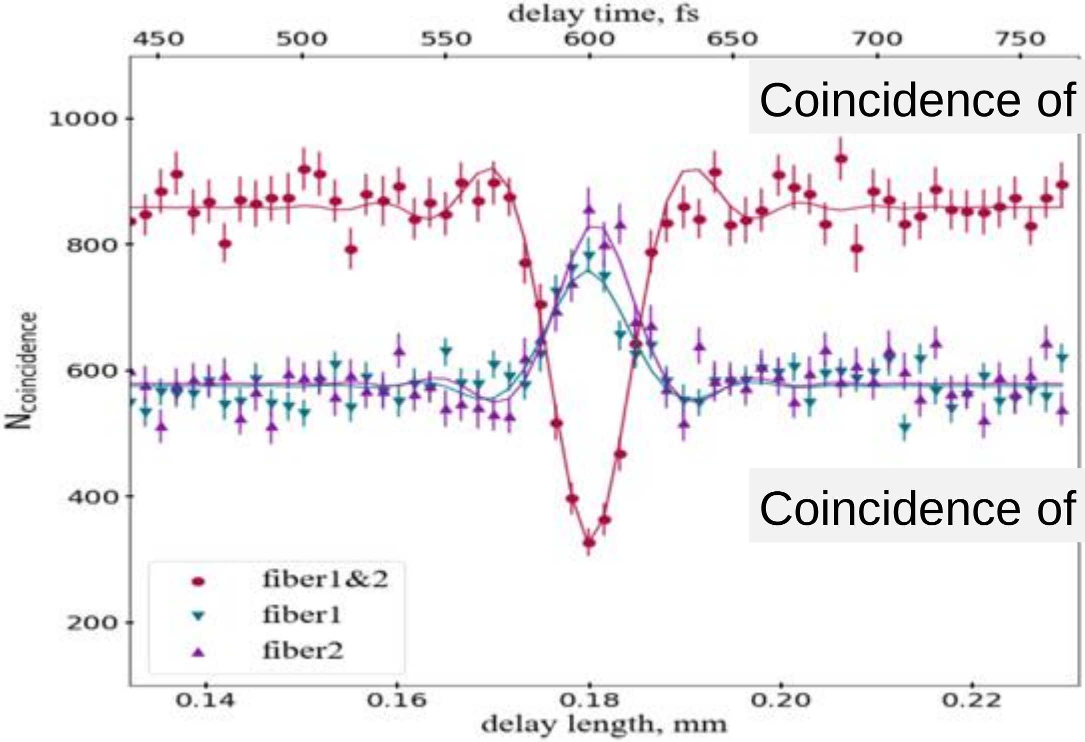








Hong-Ou-Mandel effect



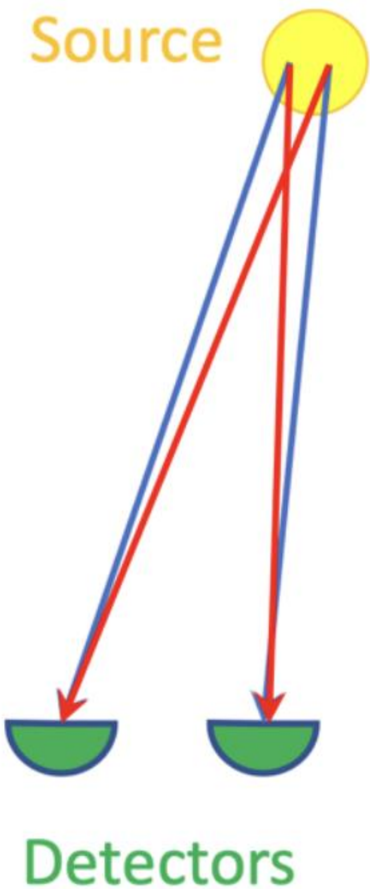
Coincidence of photons in two fibers

Coincidence of photons in single fibers

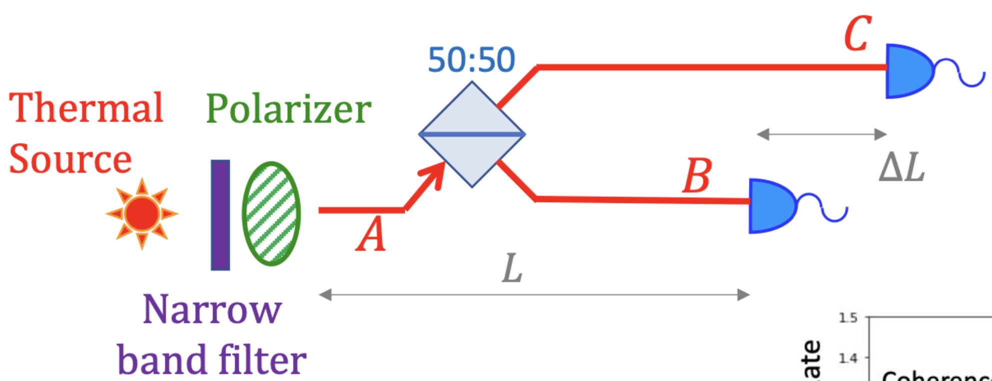
A. Nomerotski, M. Keach, P. Stankus, P. Svihra, and S. Vintskevich, “Counting of hong-ou-mandel bunched optical photons using a fast pixel camera,” arXiv:2005.07982 (2020).

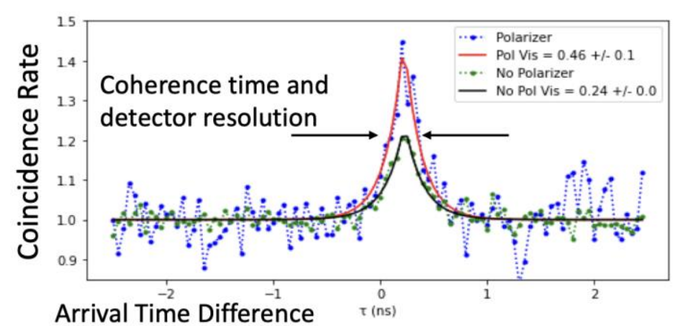
Hanbury Brown - Twiss effect

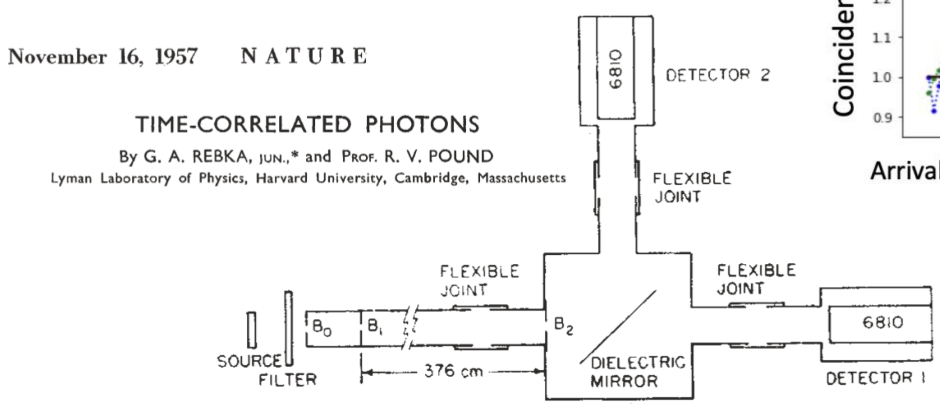
If points are close enough two options of photons paths are coherent = photon phases not so different and they interfere



Interference produces photon bunching or HBT effect






November 16, 1957 NATURE

TIME-CORRELATED PHOTONS

By G. A. REBKA, jun.,* and Prof. R. V. POUND

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts

visibility = S/B = 46%

Requirements to detectors

Will strongly depend on the task!

Single photon sensitivity

large amplification & low noise

High total detection efficiency

often use coincidences, rate ~ $(\text{efficiency})^2$

> 66 % to chase hidden variables loopholes in Bell inequalities

Timing resolution

mostly to improve S/B

~< 20 ps for two-photon interferometry

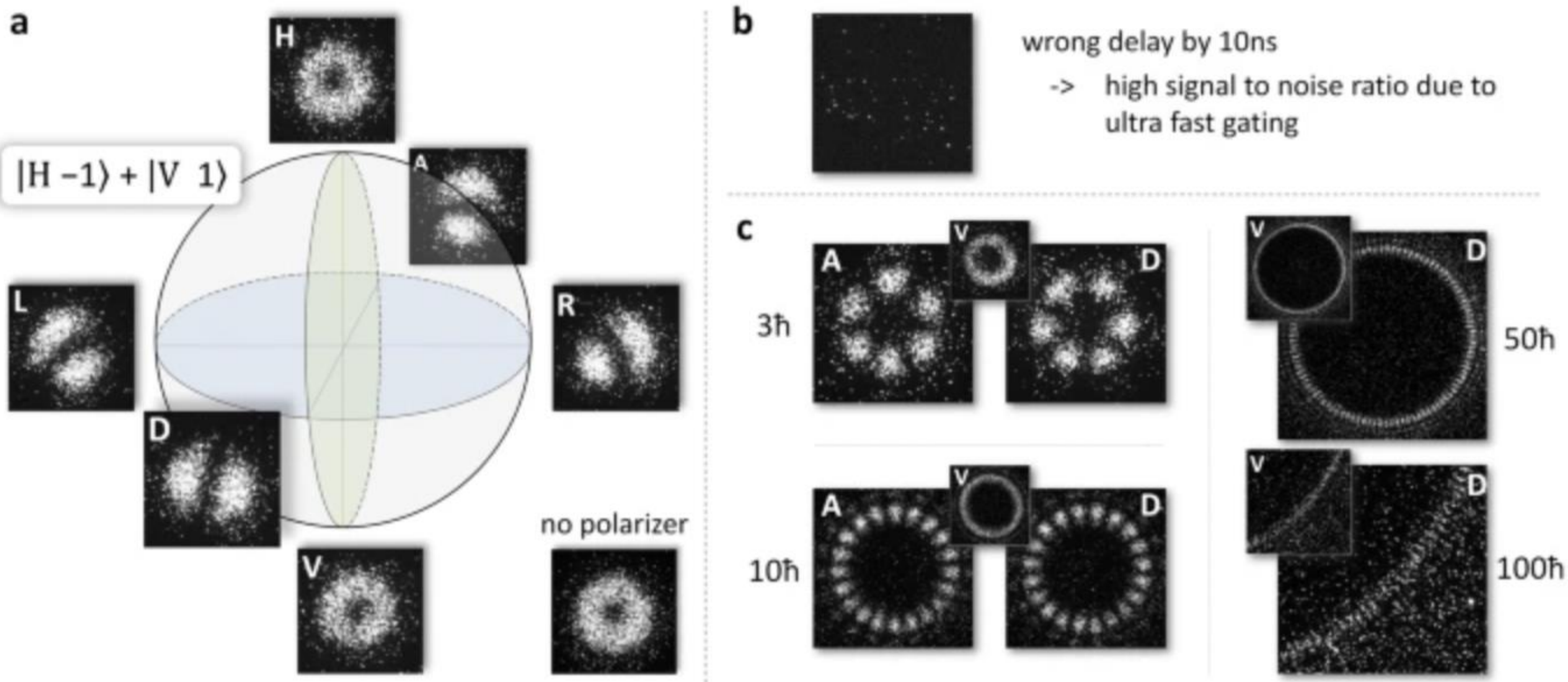
Imaging capabilities

for additional degrees of freedom and scalability

Other particles (x-rays, electrons, ions, neutrons, microwaves)?

Requirements to detectors: imaging

additional degrees of freedom in OAM: orbital angular momentum



Spatial structure of the optical (Laguerre-Gauss) modes of photons corresponding to projections of OAM m = [0, …, L]

Fickler, R., Krenn, M., Lapkiewicz, R. et al. Real-Time Imaging of Quantum Entanglement. Sci Rep 3, 1914 (2013)

Comparing detectors for HEP, astro, light sources and quantum?

Quantum:

Single photon detectors, visible + IR (telecom bands), fast FE, large data rates, imaging; qubits (many candidates, most superconducting)

HEP

Tracking and calorimetry; **ionizing particle and photon detectors in visible**; very fast FE, very large data rates, imaging (pixel detectors)

Astronomy

Low noise, slow FE, high sensitivity; **imaging in visible + IR**; large data rates (comparing to previous projects)

Light sources

X-rays, fast FE, large data rates, photon counting

HEP and Quantum

What Quantum can take from HEP for photon detection?

In HEP: detect particles collision per collision (= fast) then form observables for ‘events’ like transverse momentum, invariant mass etc.

This influenced modern x-ray detectors which detect x-rays as standalone objects, then count them in each pixel to produce an image (photon counting detectors).

Same ideas started to propagate in to quantum community - detect optical photons as objects, then correlate them spatially and/or spectrally pair by pair (= fast). Future: higher order correlations for more photons?

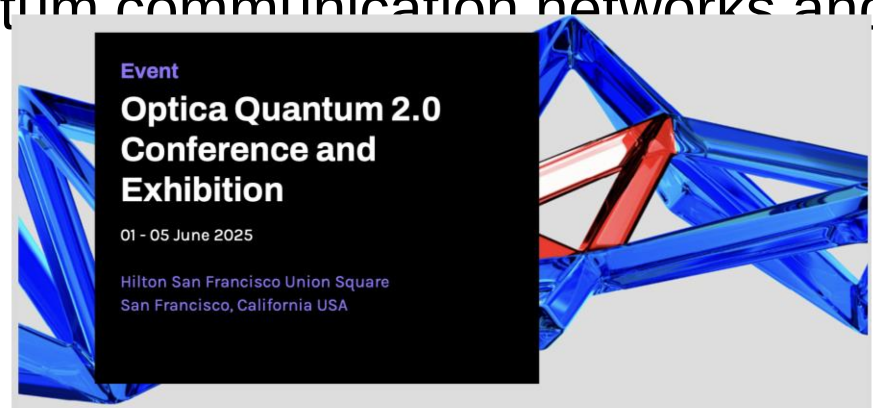
Quantum 2.0

This is about terminology

All in our life is quantum: transistors hence electronics, atoms, molecules, chemistry, biology etc.

However ‘*really exciting’* quantum topics now are called Quantum 2.0 - this is about quantum superposition and entanglement in systems.

Examples of such large quantum systems include quantum computers and simulators, quantum communication networks and arrays of quantum sensors.



Recap

Wave-particle duality leads to uncertainty principle, indistinguishability, symmetries

Entanglement leads to correlations beyond classical

Quantum advantage can be realized exploiting correlations in photon pair sources

Similarities in HEP and QIS instrumentation for photons

Disclaimer: I've cut corners and hidden several important things u

“The great advances in science usually result from new tools rather than from new doctrines”

Freeman Dyson (1923-2020)