Detection of quantum state of photons

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INFN Workshop on Future Detectors

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UNIVERSITÀ DI TRENTO

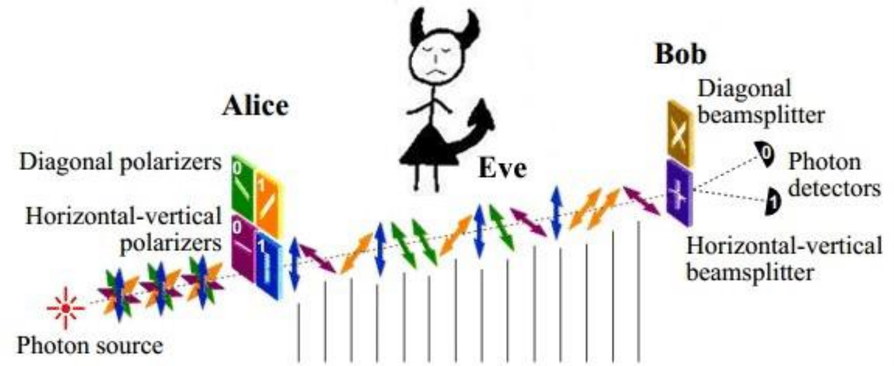
TIFPA Trento Institute for Fundamental Physics and Applications

Overview

- Detection of photons for quantum applications
- Semiconductor based photons
- Superconducting single photon detectors
- Homodyne detection
- Improving resolution with quantum state of light

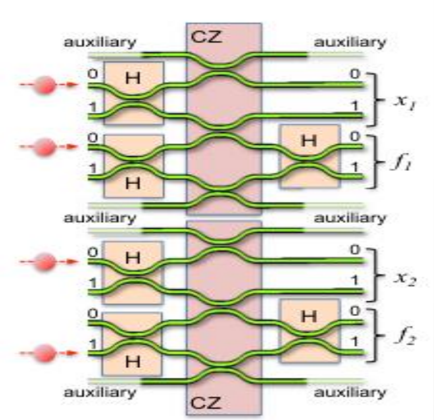
What do we use photons for?

Quantum communication



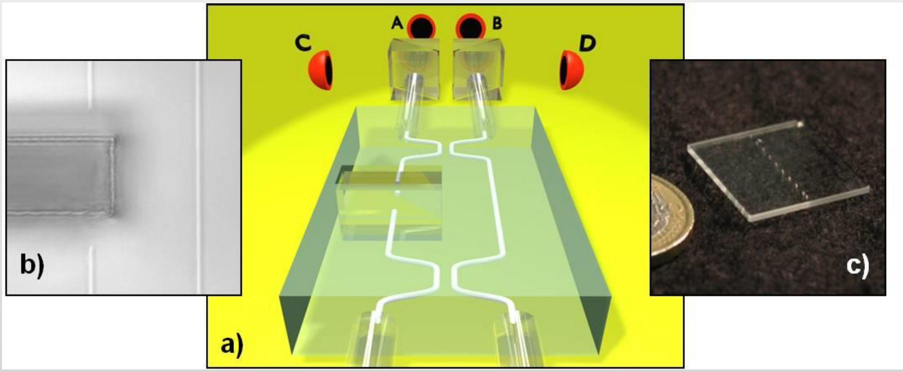
https://www.researchgate.net/figure/The-Principle-of-QC-According-to-the-BB84-Protocol_fig6_305768369

Quantum computation



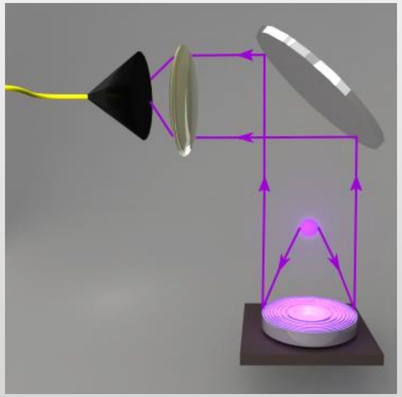
A. Politi, et al, *Science* **325**, 1221, (2009).

Quantum metrology



Crespi et al, Applied Physics Letters 100, 233704 (2012)

Atomic read-out

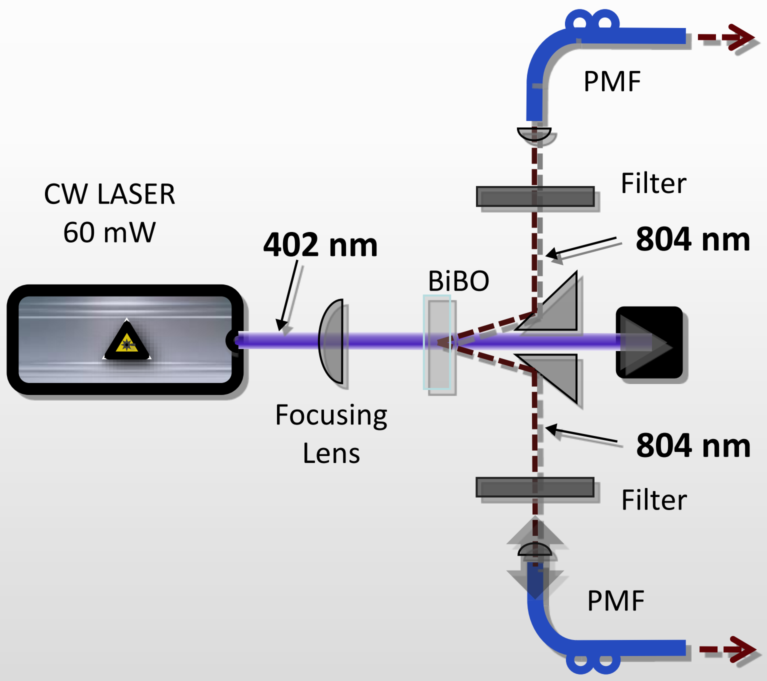


Ghadimi et al, npj Quantum Information 3, 4 (2017)

Generation of photons

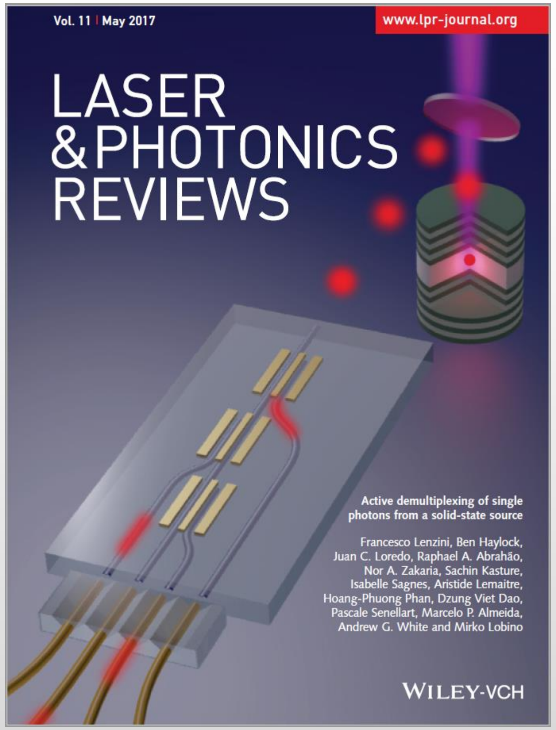
- Probabilistic sources

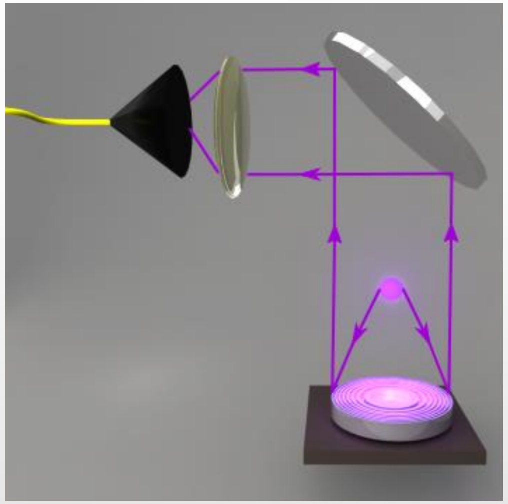
Parametric down conversion



- Deterministic sources

Quantum emitters





Ghadimi et al, npj Quantum Information 3, 4 (2017)

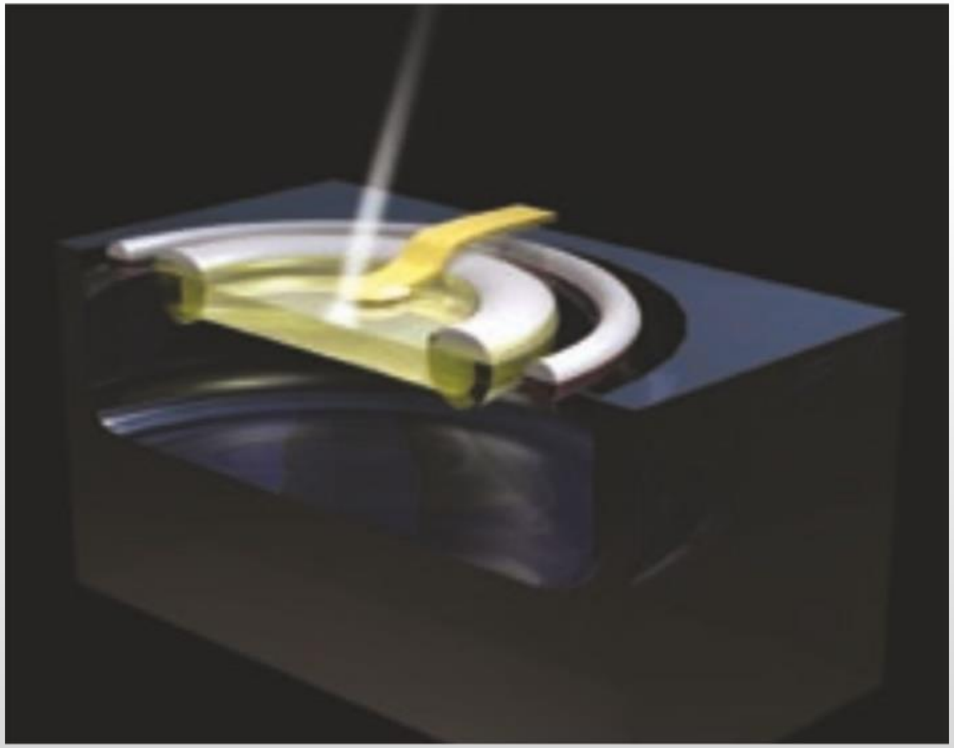
Silicon Single photon detectors (Si-SPD)

- A photodiode operating in the Geiger mode
- Not good for infrared (λ>1000 nm) because of the energy gap of Si (E_{gap}= 1.12 eV)
- Afterpulse (100 ns to 500 ns)
- Detection efficiency 65% (@600 nm)
- around 20 dark counts per second
- It does not resolve the number of photons

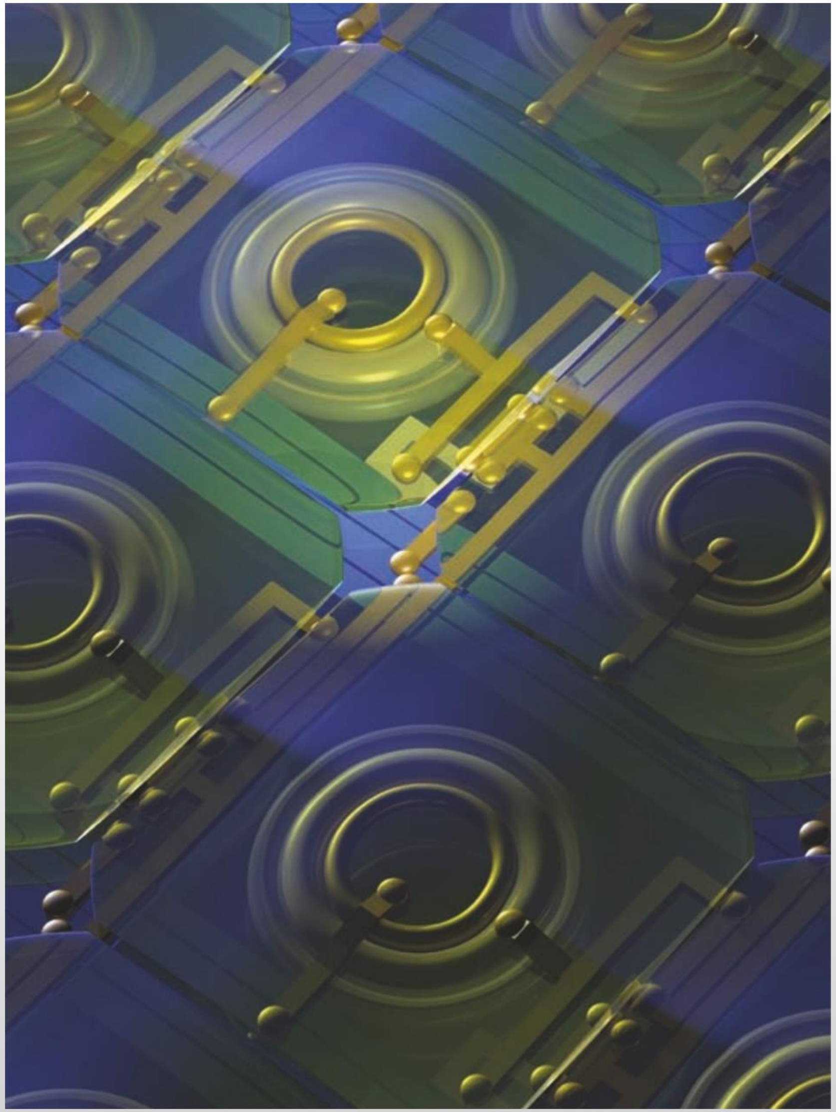
https://www.excelitas.com/product-category/single-photon-counting-modules

Array of single photon detectors (Si)

- They can be fabricate in arrays
- Integrated with fast time stamping electronics



Images are a courtesy of Prof. Charbon, EPFL

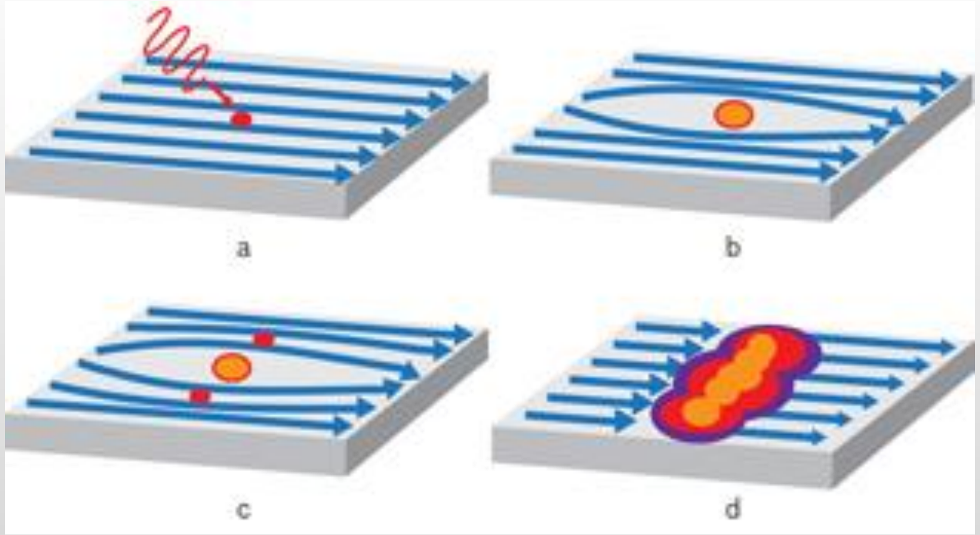


InGaAs Single photon detectors (InGaAs-SPD)

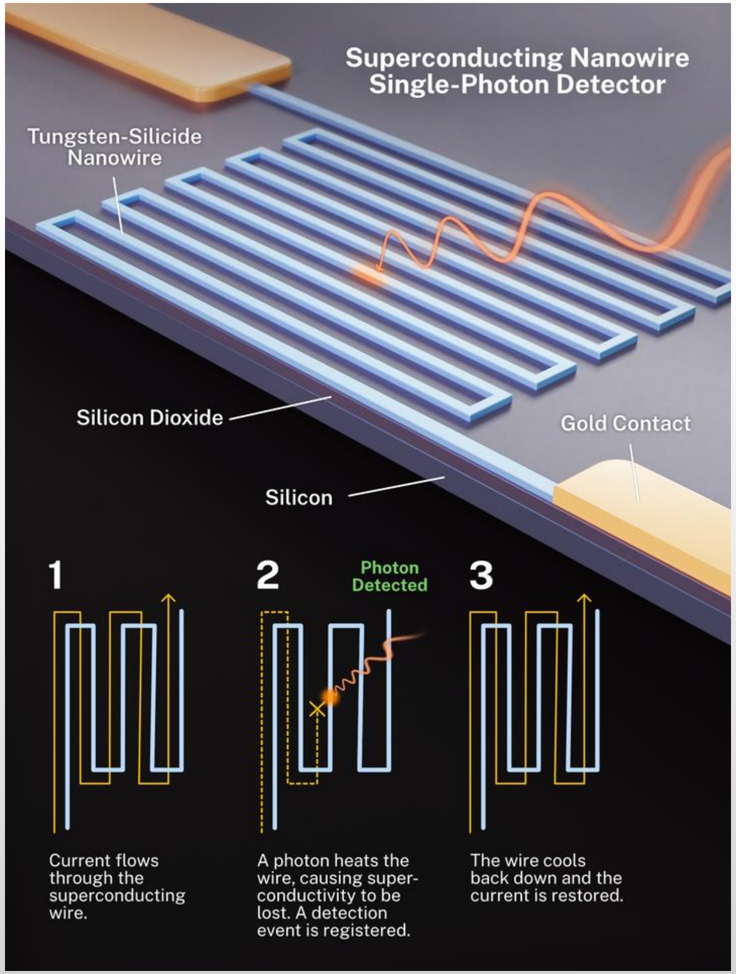
- Similar to Si-SPD but with general worst specs
- Good for infrared (λ>1000 nm)
- Higher afterpulse probability (1μs deadtime)
- Detection efficiency 25% (@1550 nm)
- around 800 dark counts per second at 10% efficiency
- It does not resolve the number of photons

Superconducting single photon detectors

- They represent the state of the art in single photon detection
- A superconducting nanowire is driven close to its critical current



https://archive.ll.mit.edu/publications/labnotes/nanowirephotondetector.html



https://www.nist.gov/image/superconducting-nanowire-single-photon-detector

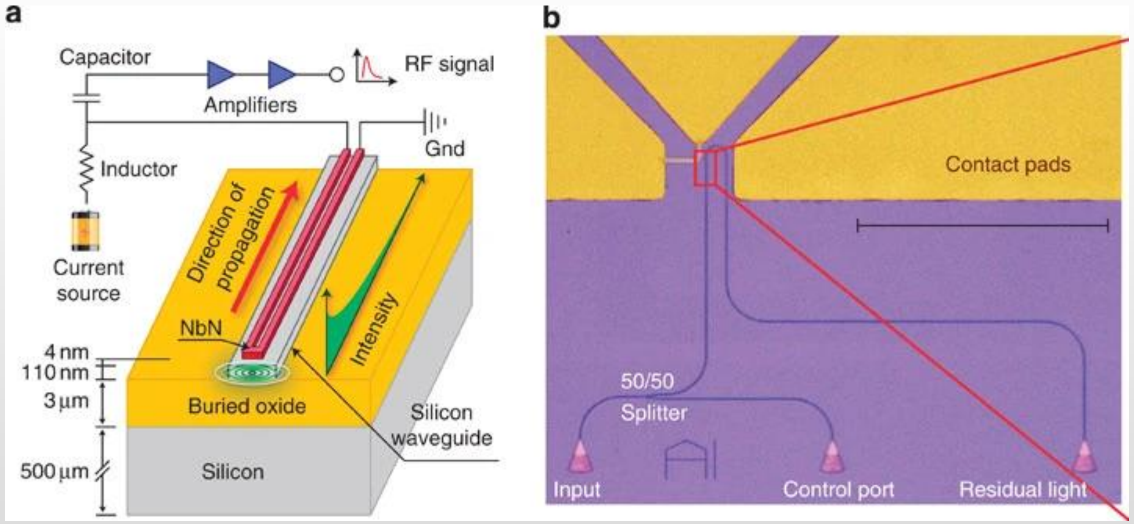
Superconducting single photon detectors

- Made of a superconducting nanowire (4-6 nm thickness and 500 nm width)
- Material: NbN, NbTiN and Wsi
- Efficiency >85% @1550nm, Low timing jitter: <15 ps, High count rate: >80 MHz, Low dark count rate: <10 Hz
- Detect photons up to 10 μm wavelength (APL Photonics 6, 056101, 2021)

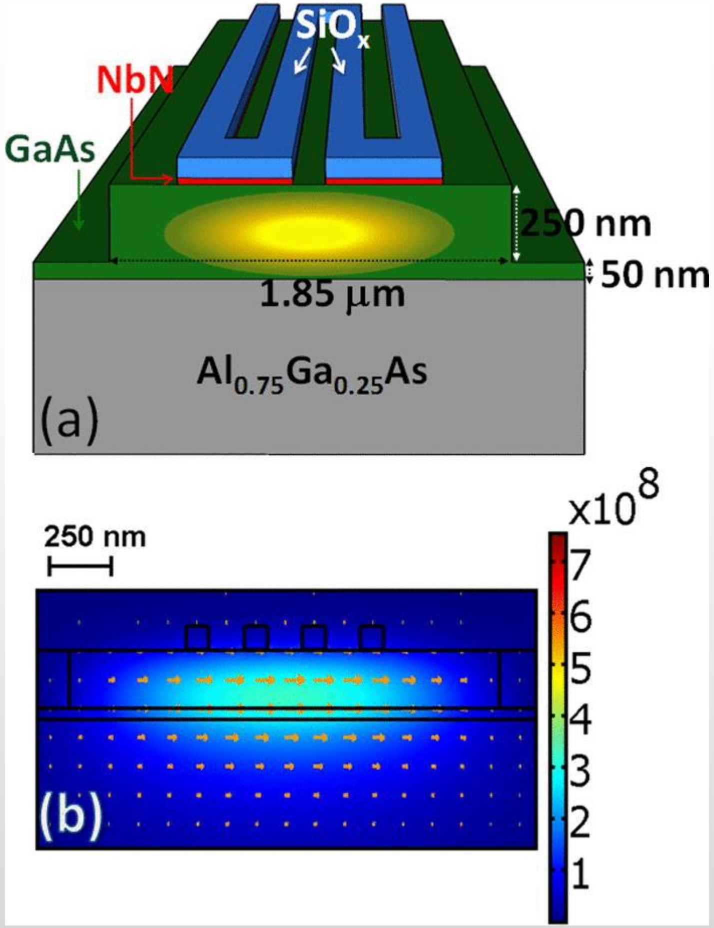
https://www.idquantique.com/quantum-sensing/products/id281-snspd-series/

Integrating the SNSPD with optical waveguides

- Best way to bring the efficiency close to 100%
- Photons are absorbed by evanescent coupling
- Longer interaction length



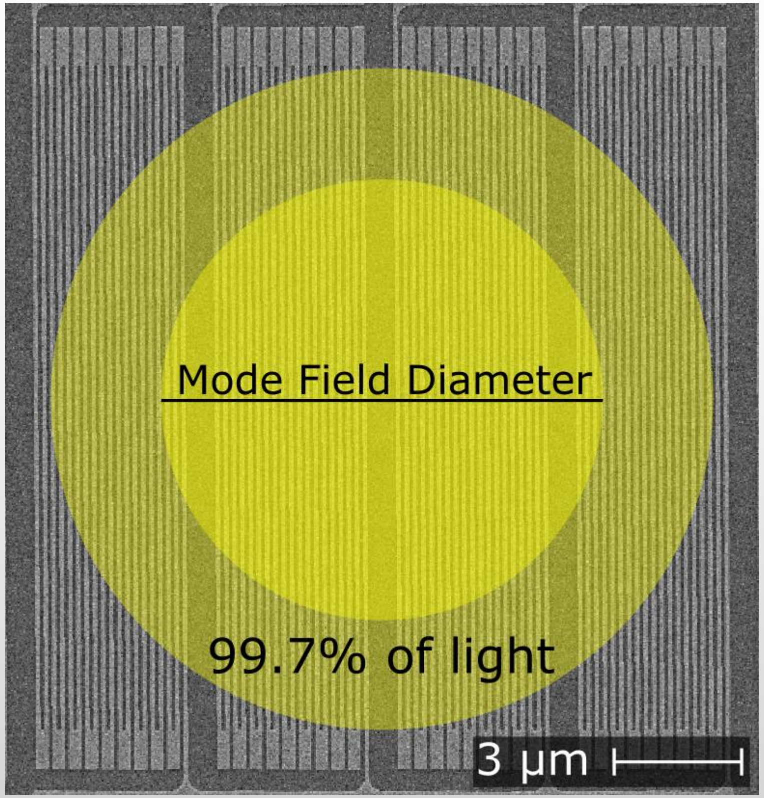
Pernice et al, Nature Comm. 3, 1325 (2012)



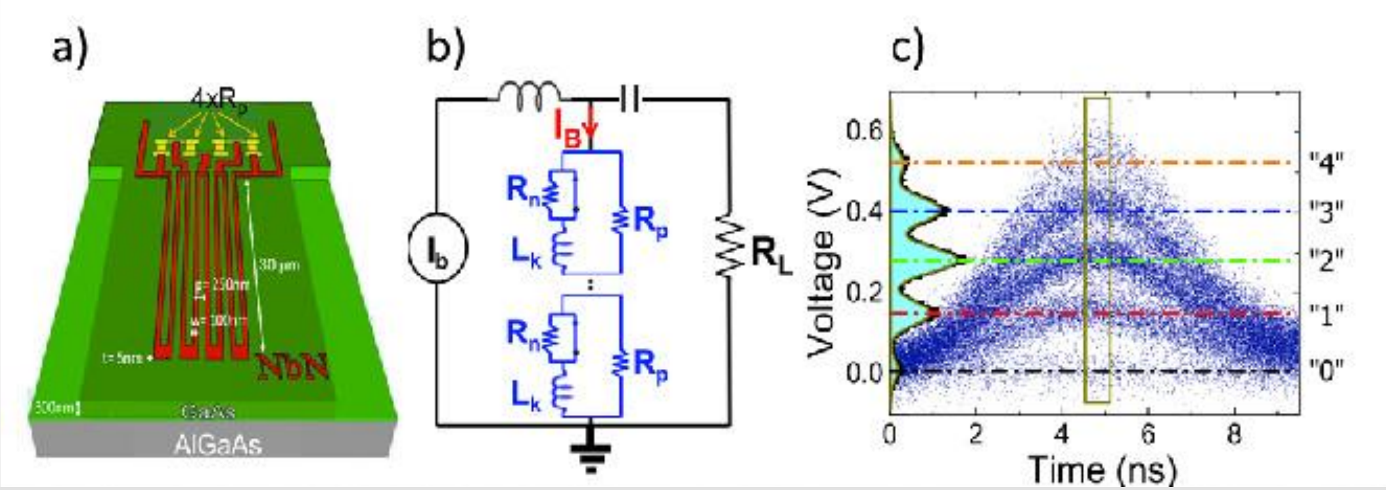
Sprengers et al, Appl. Phys. Lett. **99**, 181110 (2011)

Multiplexing of SNSPDs

- Multiple detectors can be integrated on a waveguide
- Probabilistic photon number resolving capability



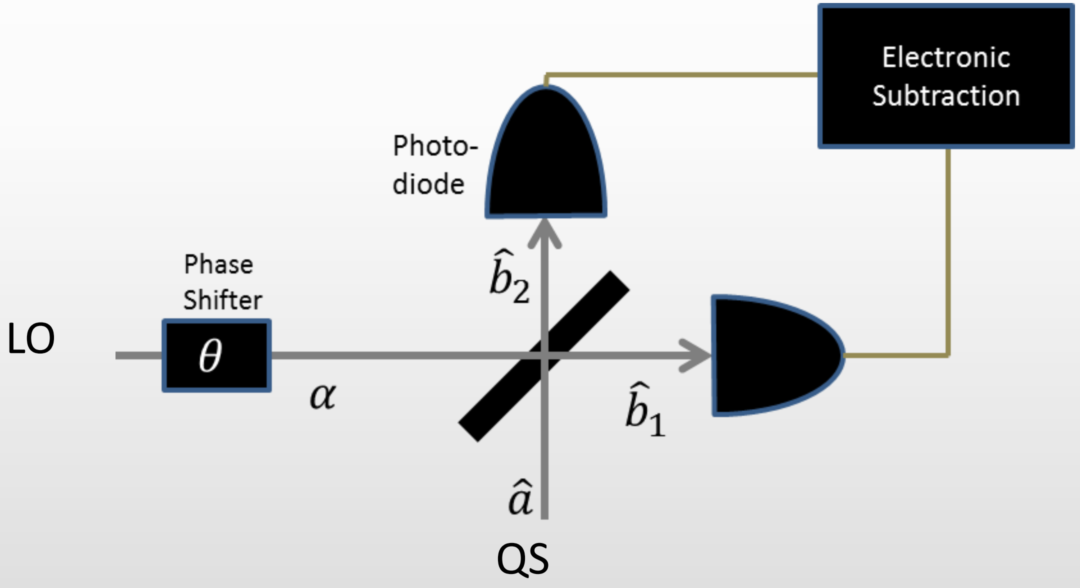
Stasi et al, Arxiv2207.14538

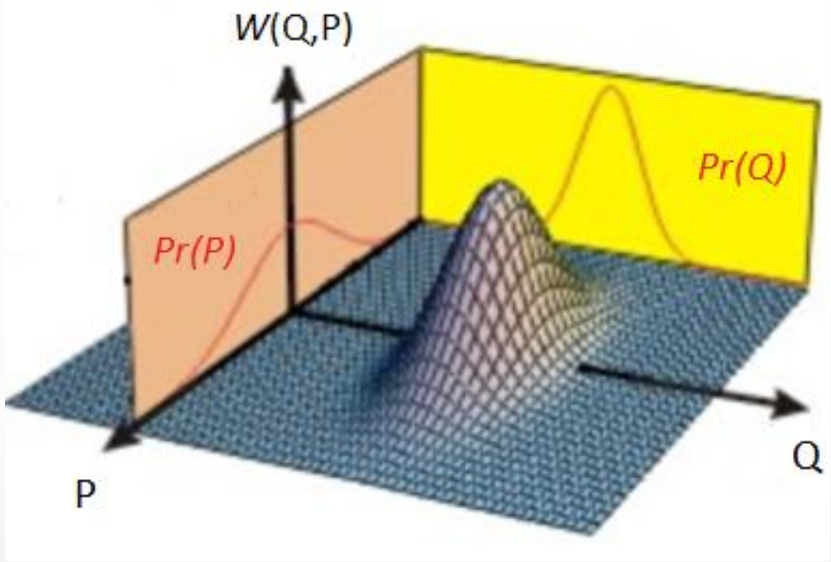


Sahin et al, Appl. Phys. Lett. **103**, 111116 (2013)

Homodyne detection

- Quantum Signal (QS) is mixed with a local oscillator (LO) on a balanced beam splitter
- Measures the difference in current produced by the two photodiodes.



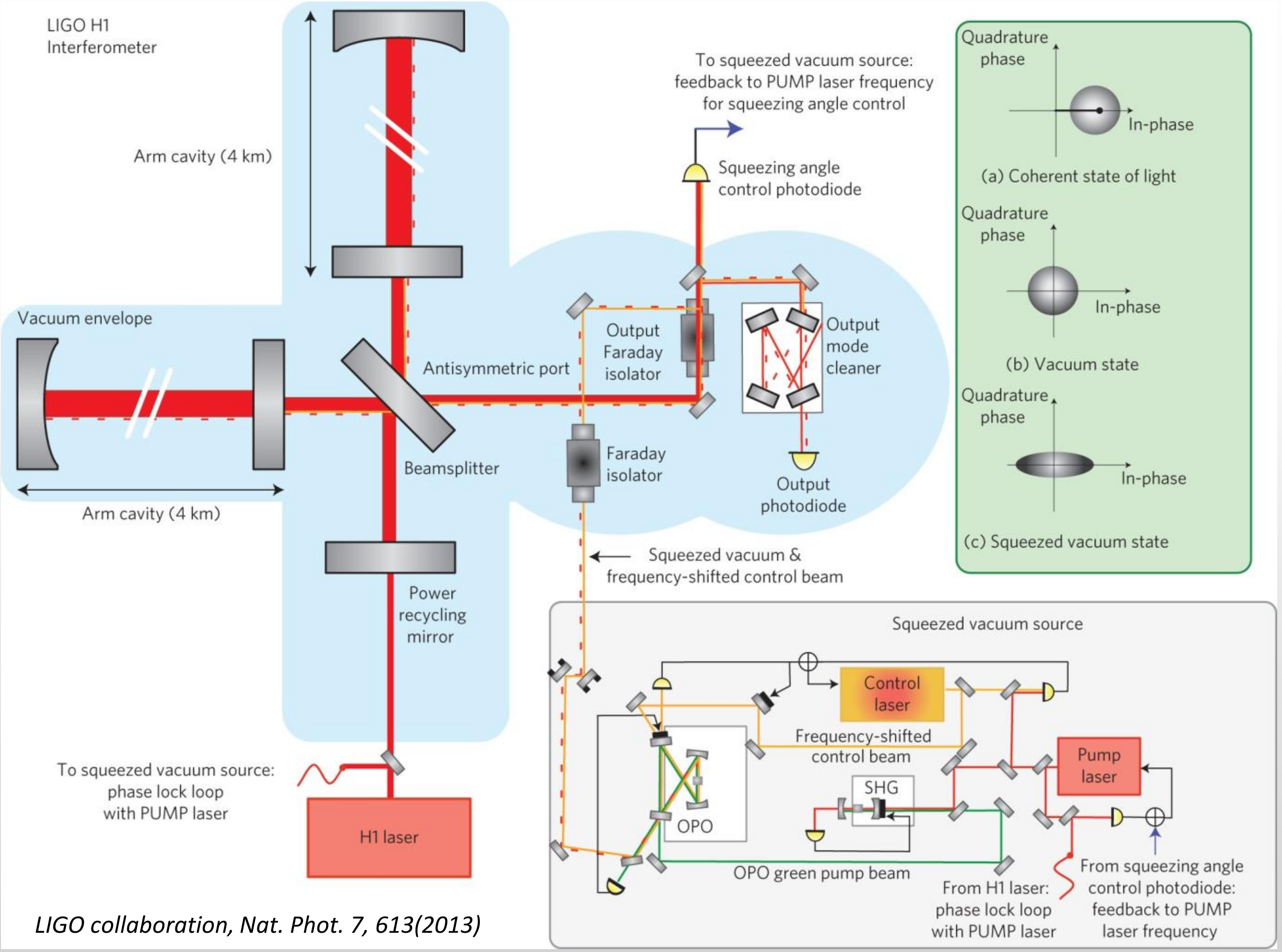


Image(altered) from: http://www.iqst.ca/quantech/wigner.php

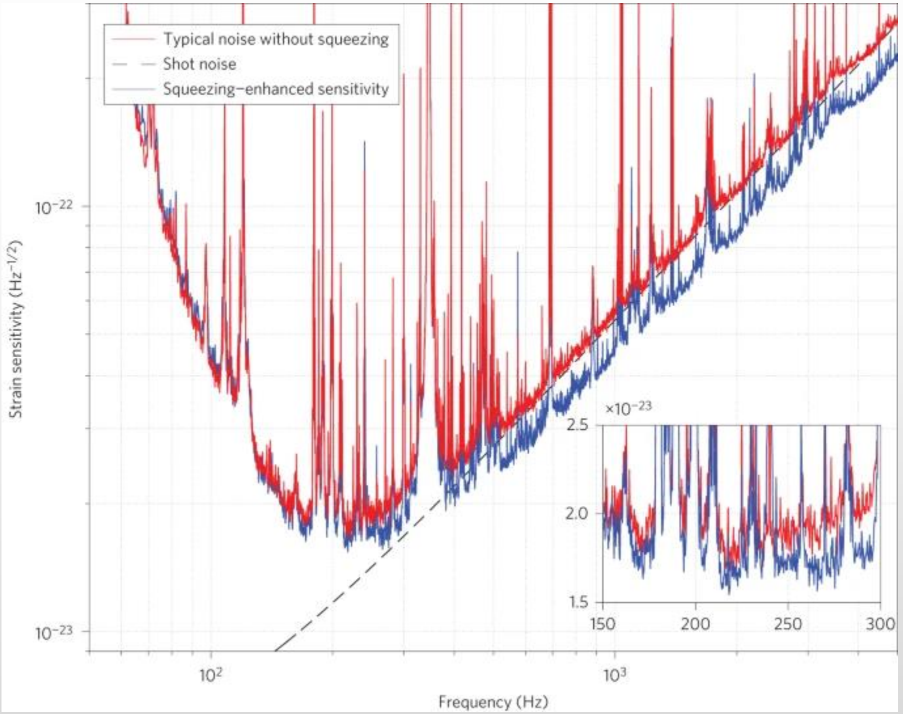
$$\hat{E} = \hat{Q}\cos(\omega t) + \hat{P}\sin(\omega t)$$

Quantum enhanced measurement

- Squeezed light used for enhancing the sensitivity of LIGO (up to 2.15 dB)



LIGO collaboration, Nat. Phot. 7, 613(2013)



A new INFN experiment: UNIDET

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FONDAZIONE BRUNO KESSLER

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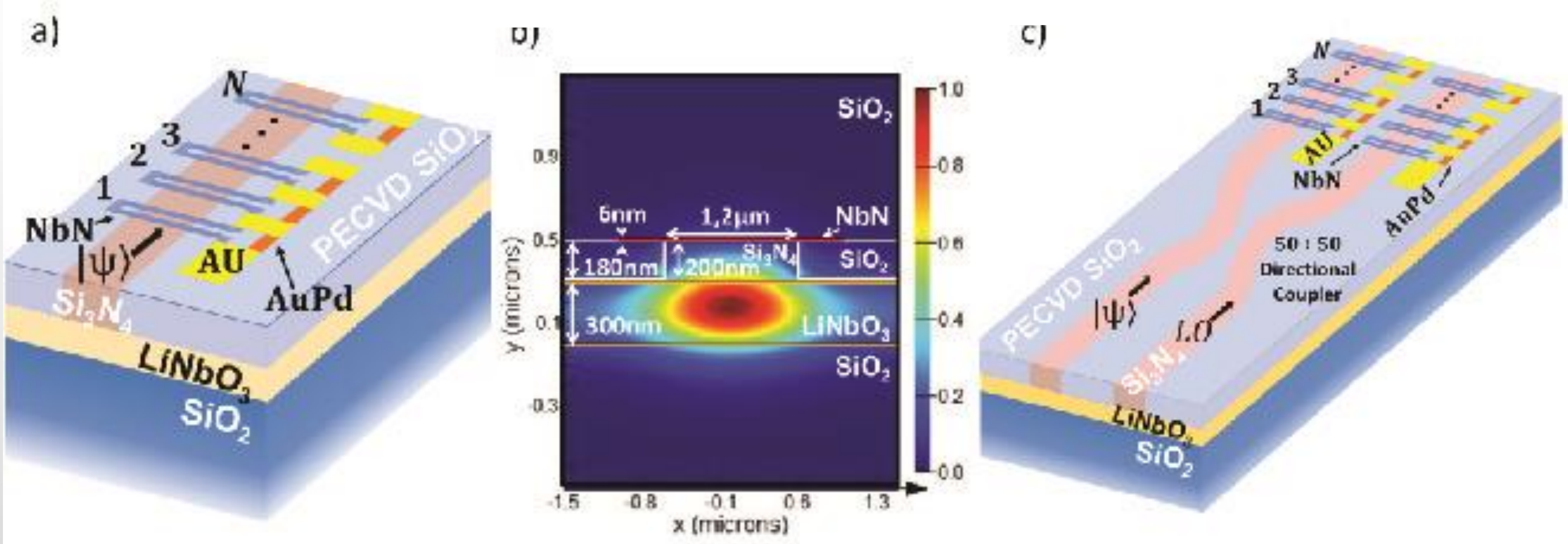

Figure 2 a) Schematic of the integrated PNR to develop in this project showing a series of N pixels composed by a NbN nanowire (80 nm width) and an AuPd on-chip parallel resistance (Rp=20 Ω value). b) Field intensity for the first TE mode propagating in the waveguide where the light absorption in each NbN nanowire element is at 3.4%. c) Schematic of the hybrid detector.

Conclusion

- Overview of the main detection strategies for quantum technology with photons
- Avalanche photodiodes
- Superconducting single photon detectors and photon number resolving detectors
- Homodyne detection and quantum enhanced measurement