Unlocking the Quantum Frontier: Harnessing the Power of Entanglement for Cutting-Edge Quantum Technology

Lorenzo Pavesi
Director
Quantum Science and Technology in Trento

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  → leverages on human resources and state of the art infrastructures of the partners

- Q@TN promotes
  - basic & applied research,
  - technological transfer & innovation,
  - education & training
- Q@TN is rooted in Trentino with a European outlook

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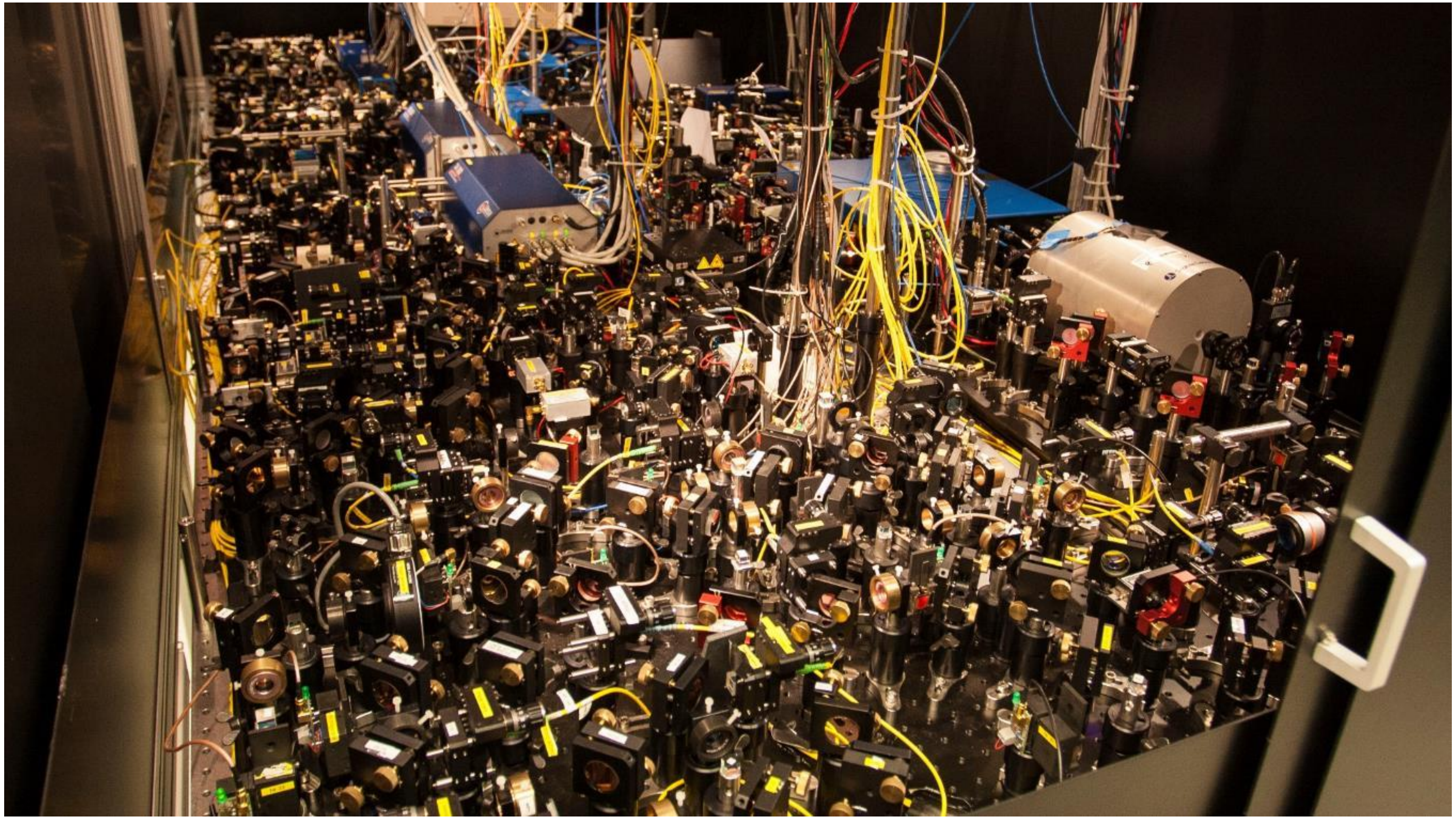
Outline

- Building blocks (contextuality, nonlocality)
- Applications of entangled photon sources
- Applications of single photon entanglement
- Few considerations

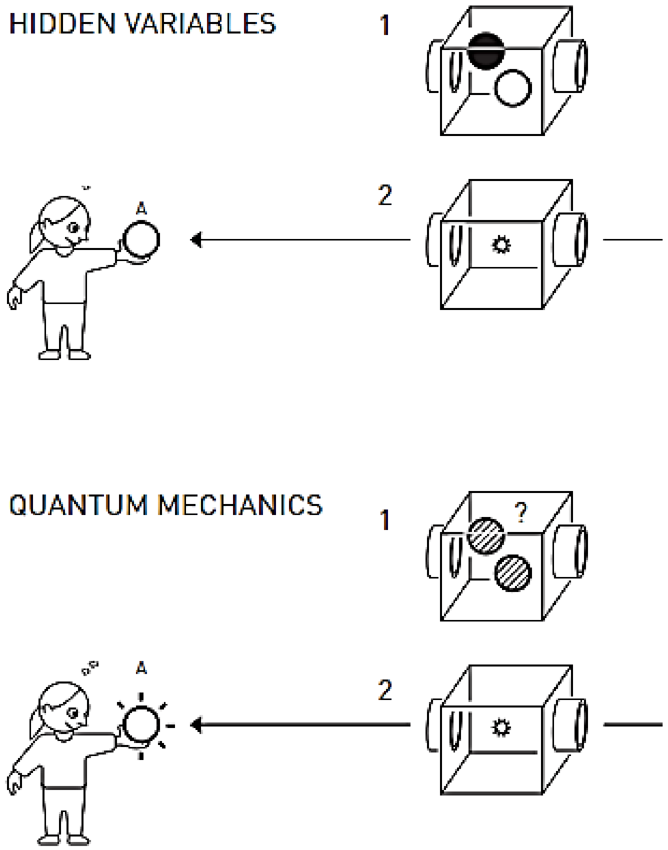
1. Building block: Integrated photonics



2. Building block: contextuality and nonlocality

Does colour exist when no one is watching?

Quantum mechanics' entangled pairs can be compared to a machine that throws out balls of opposite colours in opposite directions. When Bob catches a ball and sees that it is black, he immediately knows that Alice has caught a white one. In a theory that uses hidden variables, the balls had always contained hidden information about what colour to show. However, quantum mechanics says that the balls were grey until someone looked at them, when one randomly turned white and the other black. Bell inequalities show that there are experiments that can differentiate between these cases. Such experiments have proven that quantum mechanics' description is correct.



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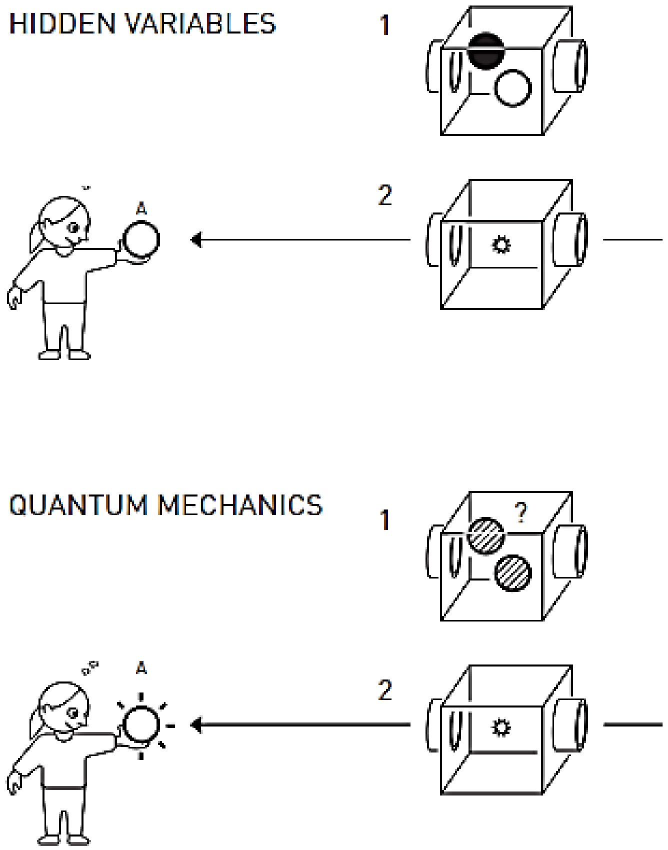

- Quantum **contextuality** is a feature of the phenomenology of quantum mechanics whereby measurements of quantum observables cannot simply be thought of as revealing pre-existing values.
- More formally the measurement result (assumed pre-existing) of a quantum observable is dependent upon which other commuting observables are within the same measurement set.

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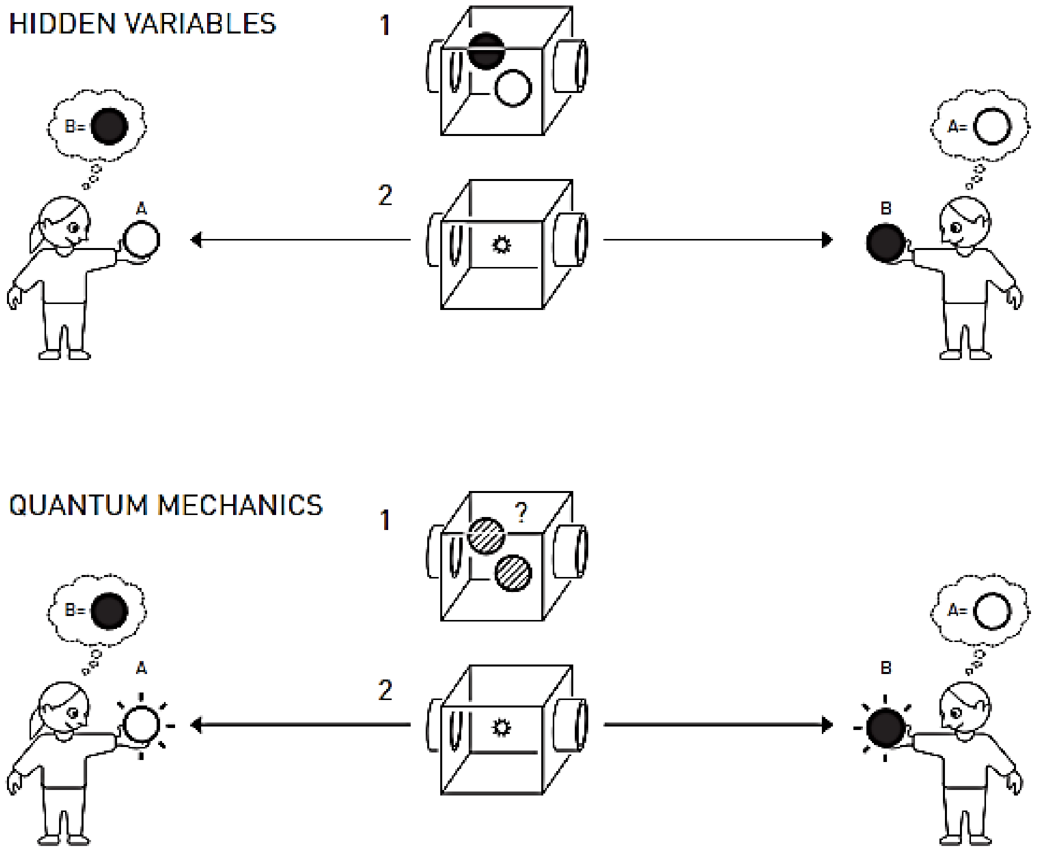

©Johan Jarnestad/The Royal Swedish Academy of Sciences

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©wikipedia

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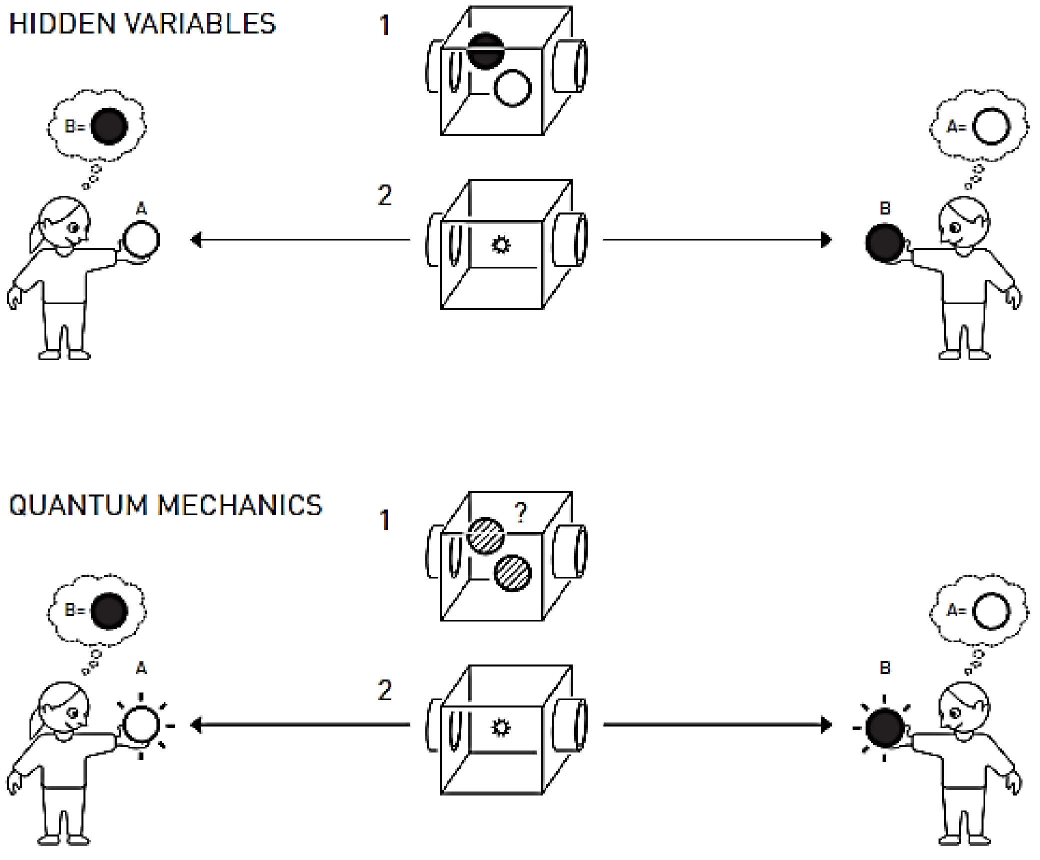

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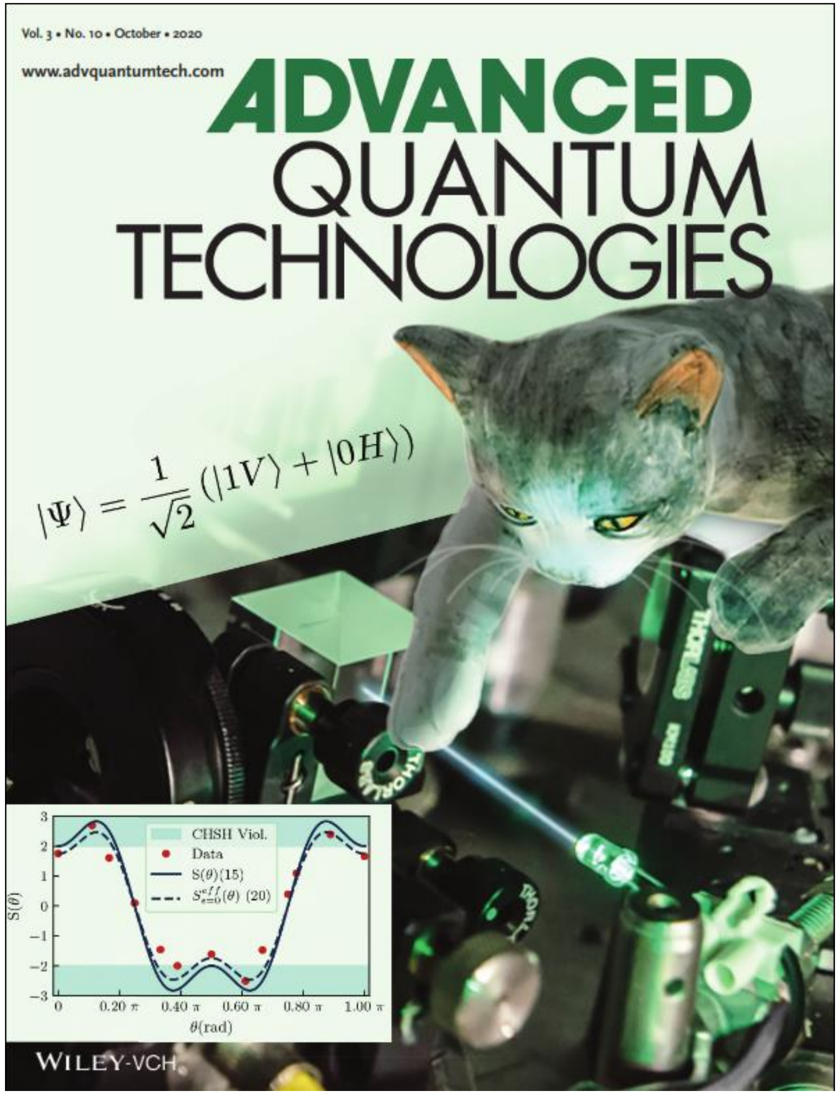
- More formally the measurement result (assumed pre-existing) of a quantum observable is dependent upon which other commuting observables are within the same measurement set.
- **Nonlocality** may be viewed as a special case of the more general phenomenon of contextuality, in which measurement contexts contain measurements that are distributed over spacelike separated regions. This follows from Fine's theorem.

©wikipedia

3. Building block: Entanglement



"I would not call entanglement 'one,'
but rather 'the' trait of quantum mechanics,"
Schrödinger in 1935.

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|1V\rangle + |0H\rangle\right)$$

3. Building block: Entanglement

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|1V\rangle + |0H\rangle\right)$$

One photon

Intraparticle entanglement

Two photons

Interparticle entanglement

3. Building block: Entanglement

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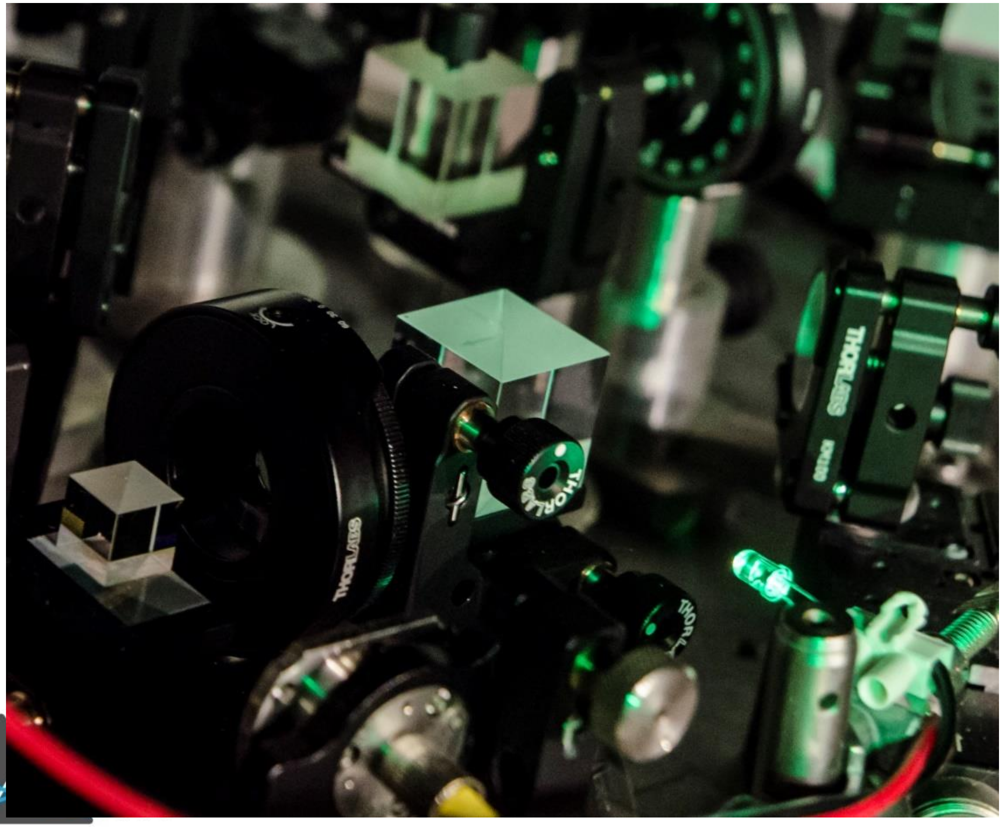
One photon

Intraparticle entanglement



Two photons

Interparticle entanglement

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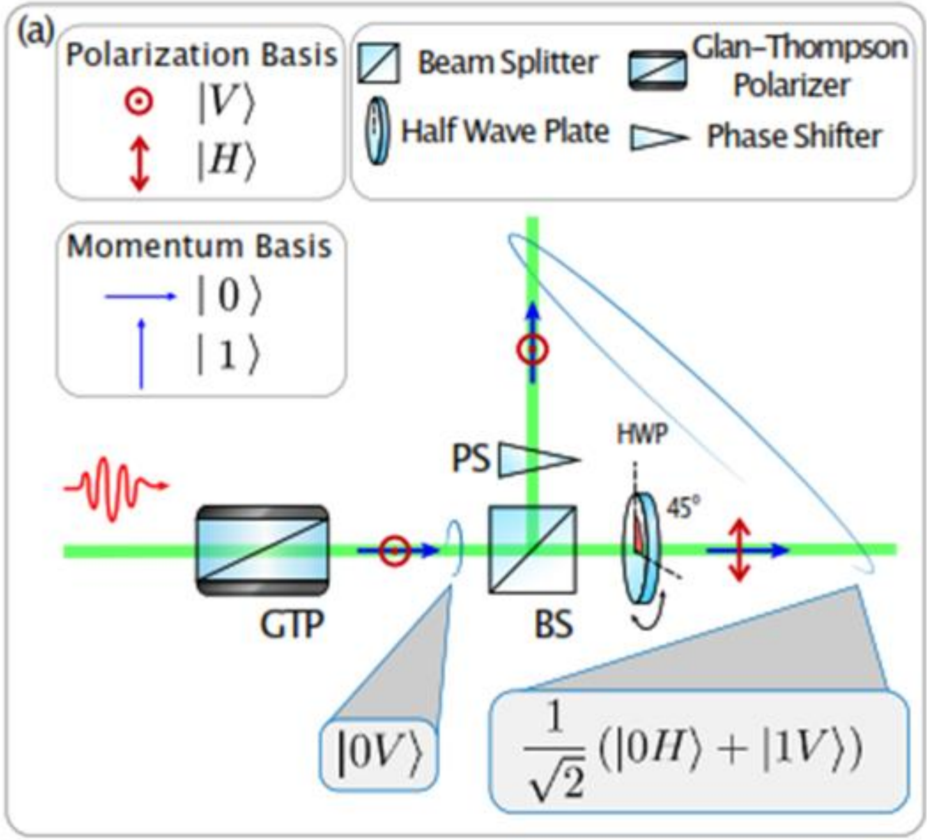

Two photons

Interparticle entanglement

M. Pasini, N. Leone, S. Mazzucchi, V. Moretti, D. Pastorello, L. Pavesi Physical Review A102, 063708 (2020)

3. Building block: entanglement

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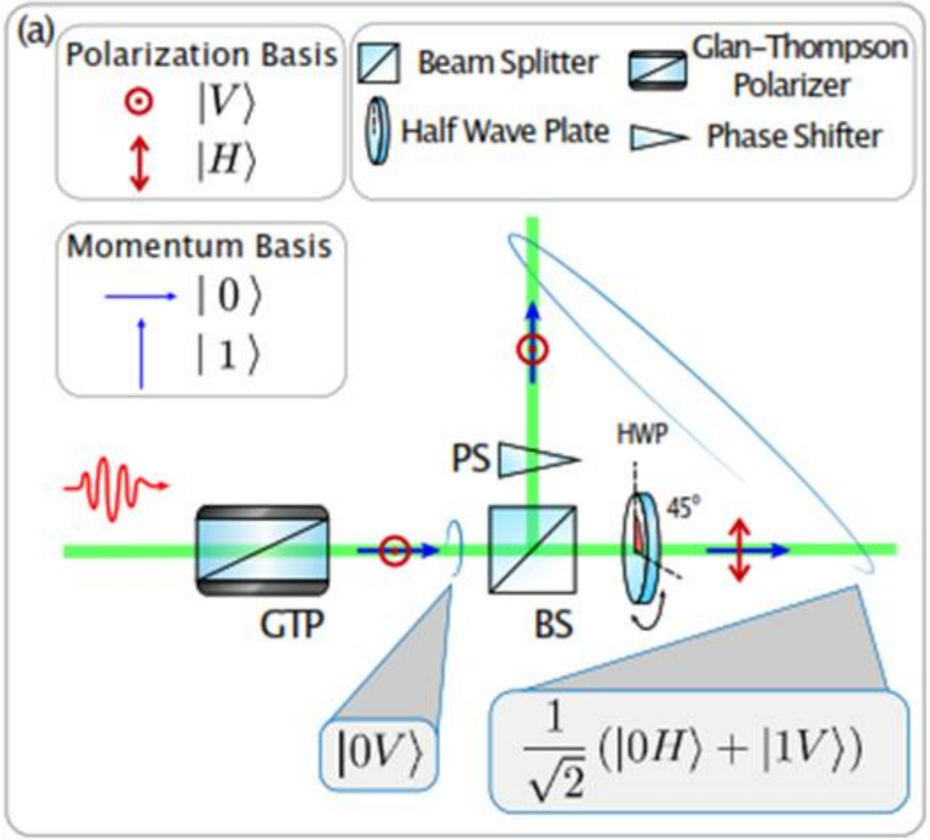
One photon

Intraparticle entanglement



Two photons

Interparticle entanglement

- Nonlinear optics (SFWM)

3. Building block: entanglement

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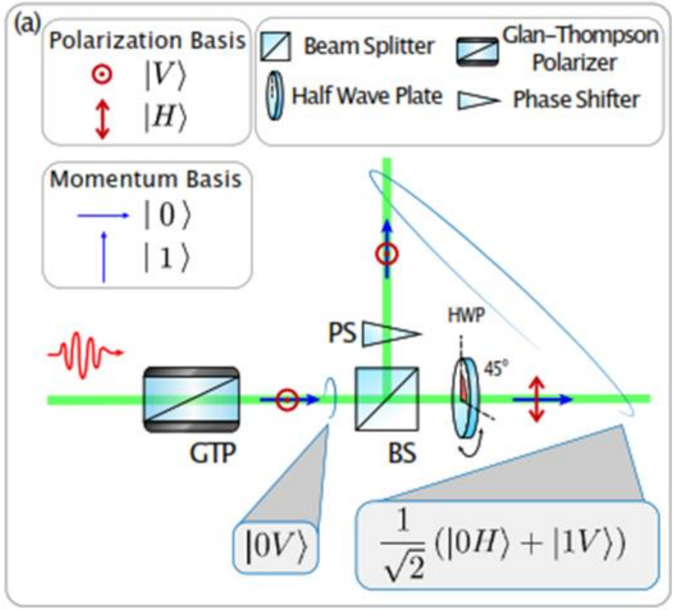
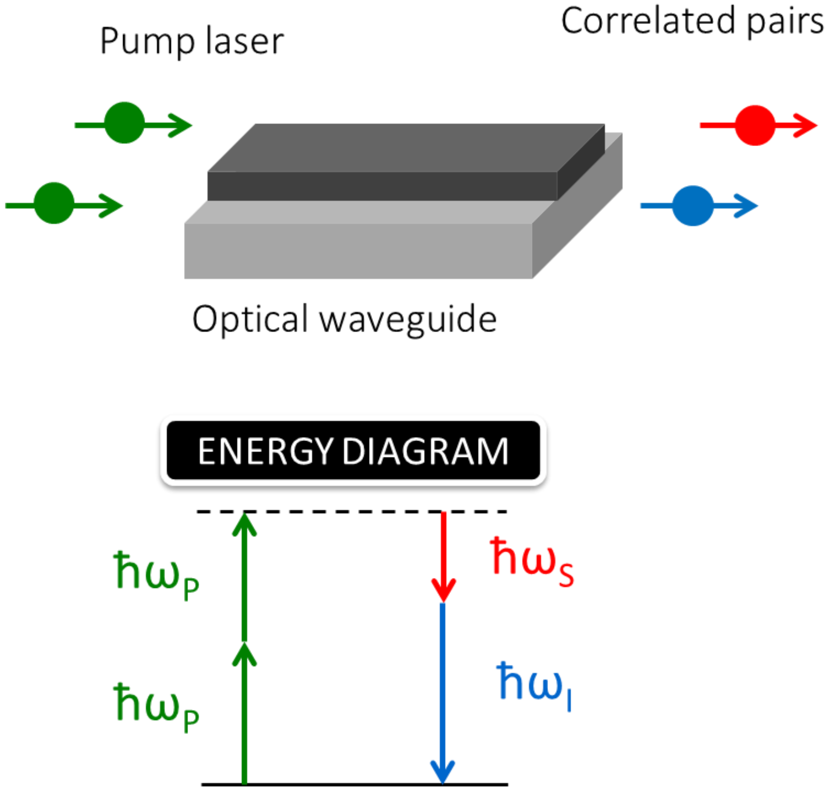
One photon

Intraparticle entanglement



Two photons

Interparticle entanglement



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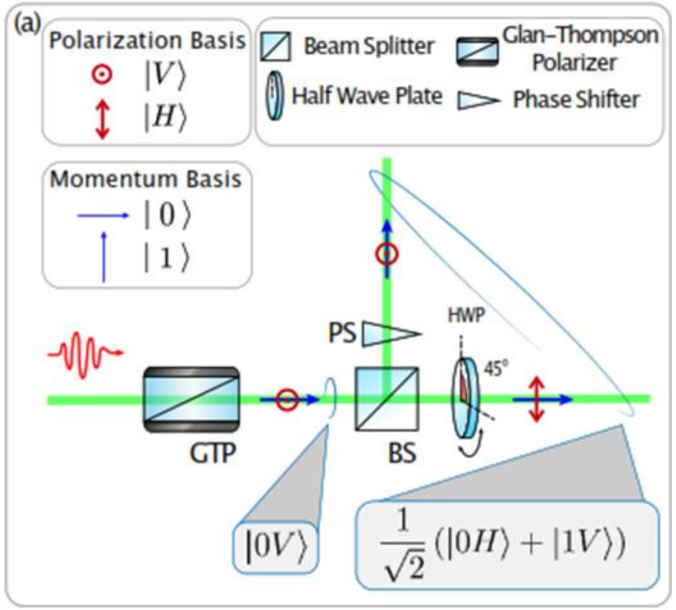
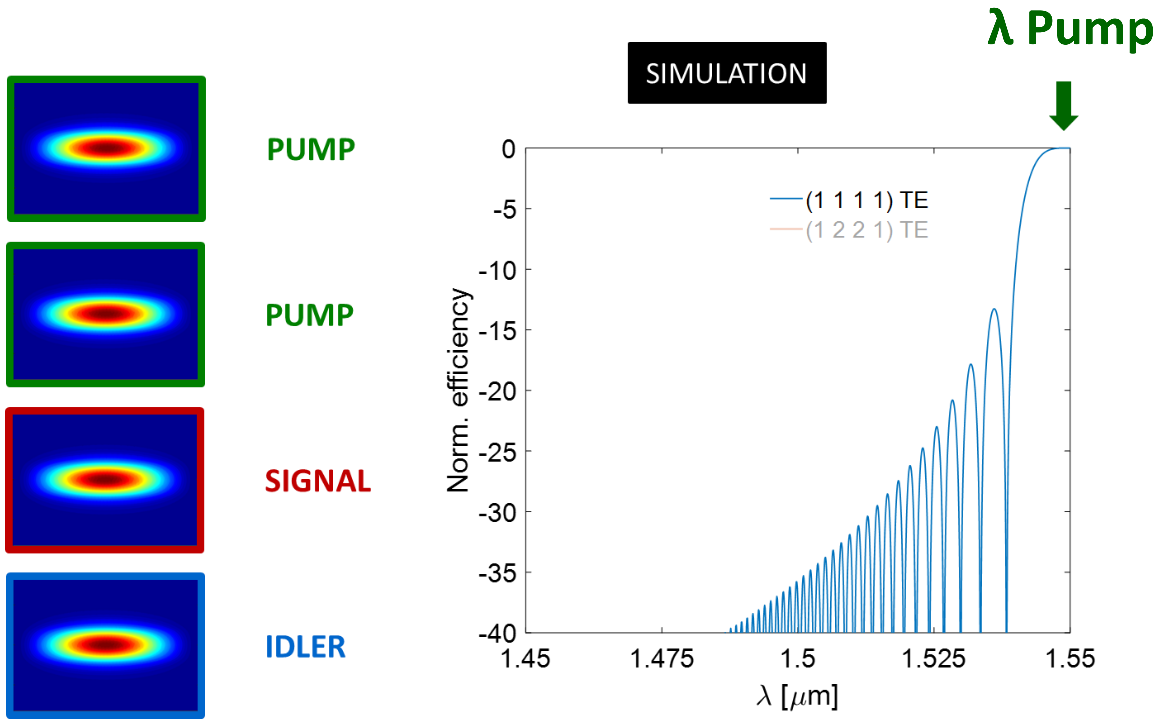


Two photons

Interparticle entanglement



Intramodal SFWM

UNIVERSITÀ DI TRENTO

Stefano Signorini, et al "Intermodal Four Wave Mixing in Silicon waveguides", Photonics Research **6**, 805-814 (2018).

NanoScience Laboratory

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One photon

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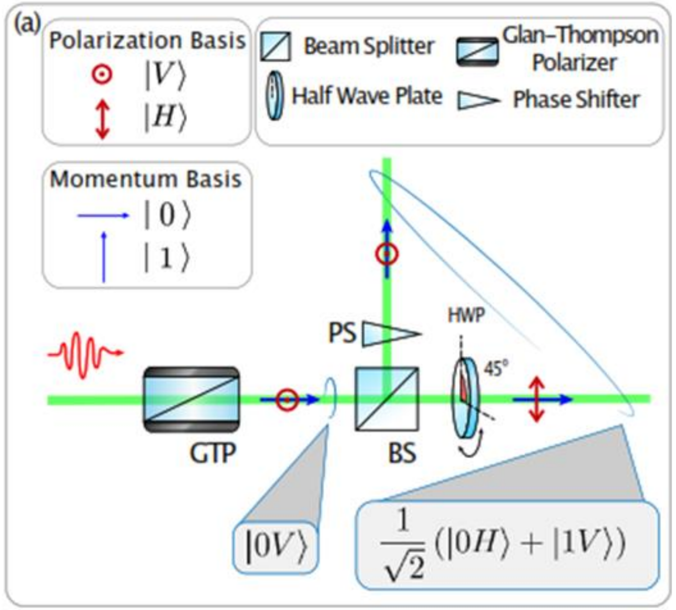

Two photons

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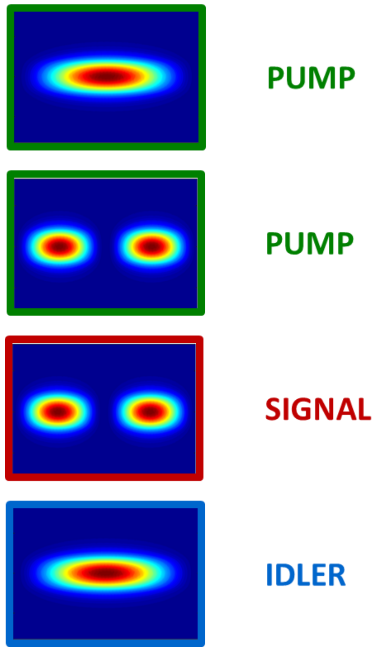
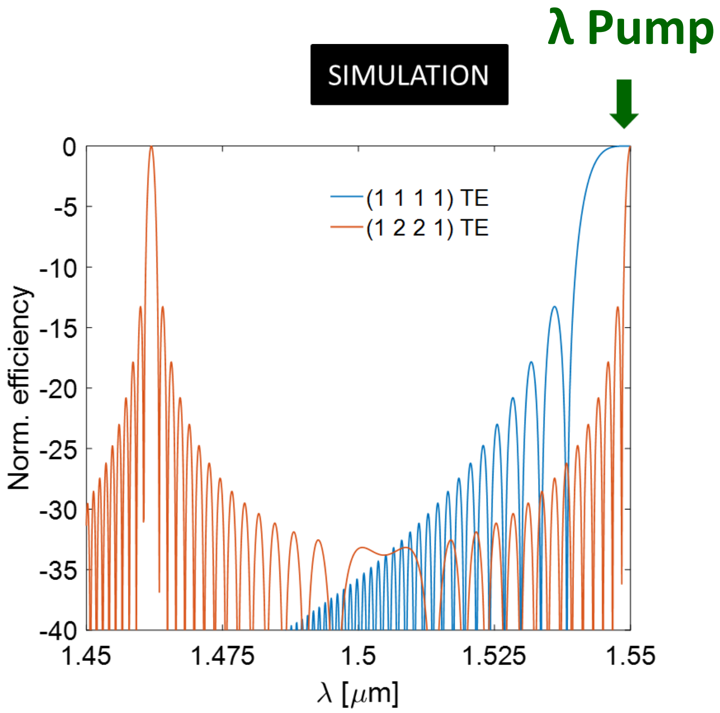




Intermodal SFWM

Parametric photon-pair source

The emitted state reads

$$|\psi\rangle = \xi_0|zero\ photon\rangle + \xi_1|\mathbf{1}\ photon\rangle_s|\mathbf{1}\ photon\rangle_i + \xi_2|\mathbf{2}\ photons\rangle_s|\mathbf{2}\ photons\rangle_i + \cdots$$

where $|\xi_0|^2$ is the probability of zero photons, $|\xi_1|^2$ is the probability of **two correlated photons**, etc.

Examples: spontaneous Four-Wave-Mixing (sFWM) in $\chi^{(3)}$-materials.

PRO: they are **easy to integrate** on a chip.
CONS: they are **probabilistic sources** ($|\xi_1|^2 \ll 1$ and $|\xi_0|^2 < |\xi_1|^2 < |\xi_2|^2 < \cdots$).

Joint Spectral Amplitude and Joint Spectral Intensity

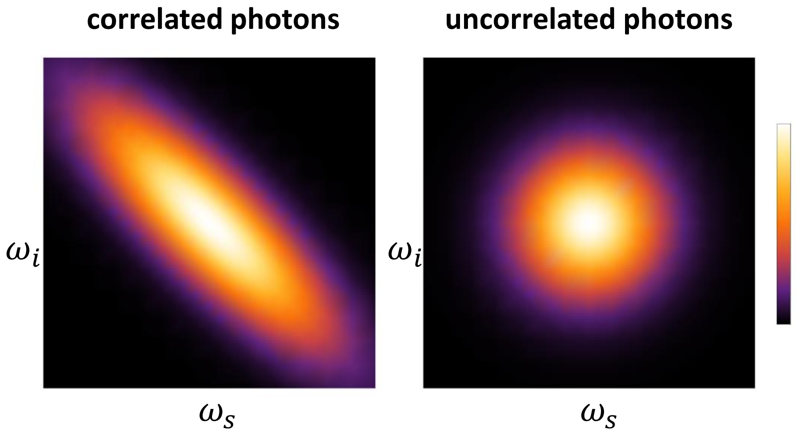
Neglecting the zero-photon and the multi-photon states, the **two-photon state** for sFWM can be written as

$$|\psi\rangle \sim \iint d\omega_s d\omega_i \,\mathrm{JSA}(\omega_s\,,\omega_i)\,\underbrace{|\mathbf{1}(\omega_s)\rangle}_{\text{Signal}}\,\underbrace{|\mathbf{1}(\omega_i)\rangle}_{\text{Idler}}\,.$$

JSA quantifies the probability amplitude to generate the first photon in the state $|\mathbf{1}(\omega_s)\rangle$ and the second photon in the state $|\mathbf{1}(\omega_i)\rangle$.

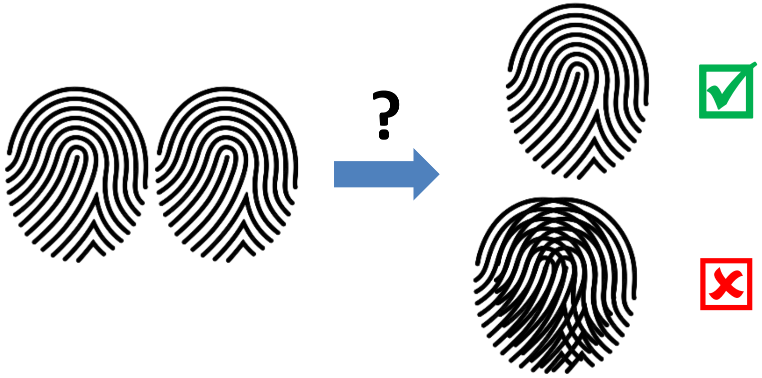
The squared modulus, called JSI, gives the probability:

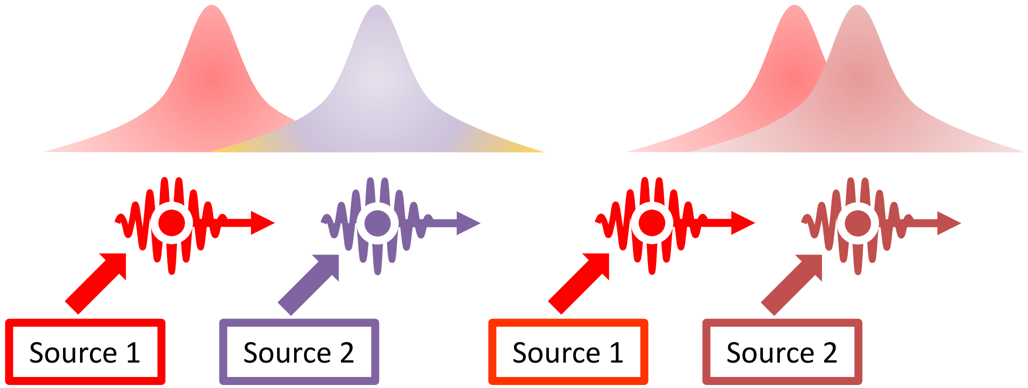
$$\mathrm{JSI} = |\mathrm{JSA}(\omega_s\,,\omega_i)|^2.$$



Indistiguishability of photon sources

Contrary to P, the notion of indistinguishability is **extrinsic**, since it arises from the comparison of two or more sources.





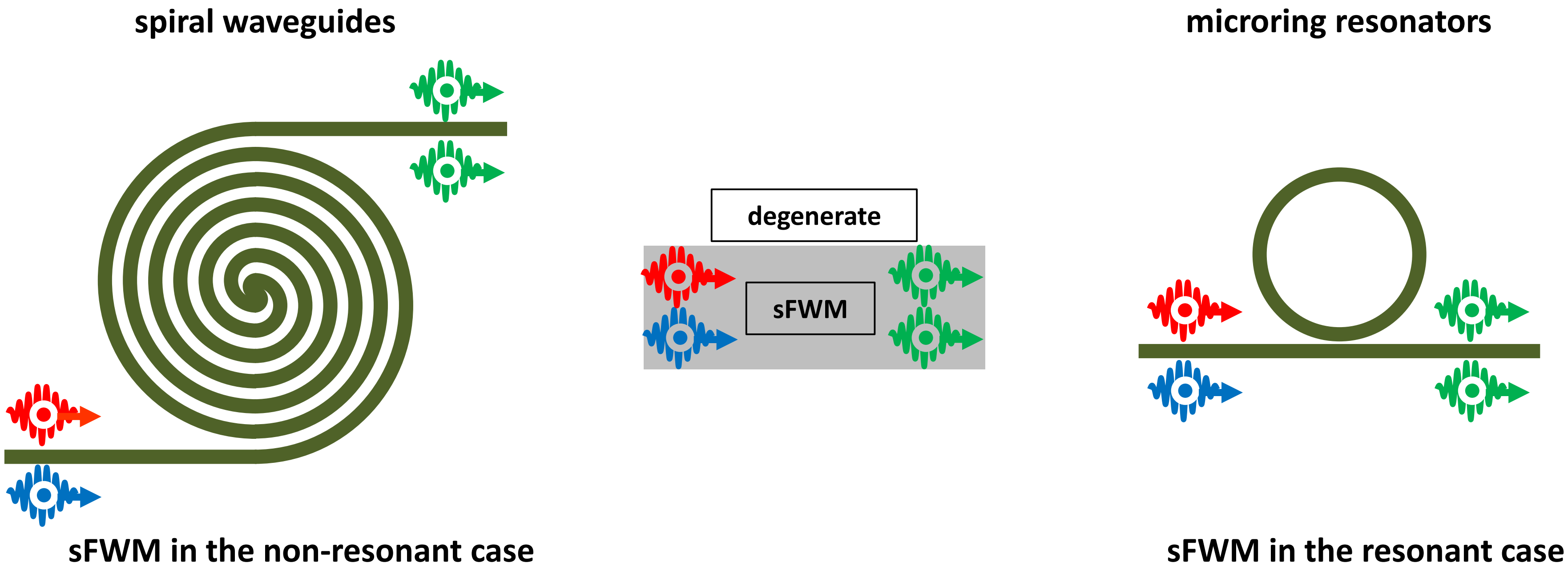
Any quantum algorithm relies on this property.

How can we **experimentally** access it?

Hong-Ou-Mandel effect!

Comparison of two different photon-pair sources

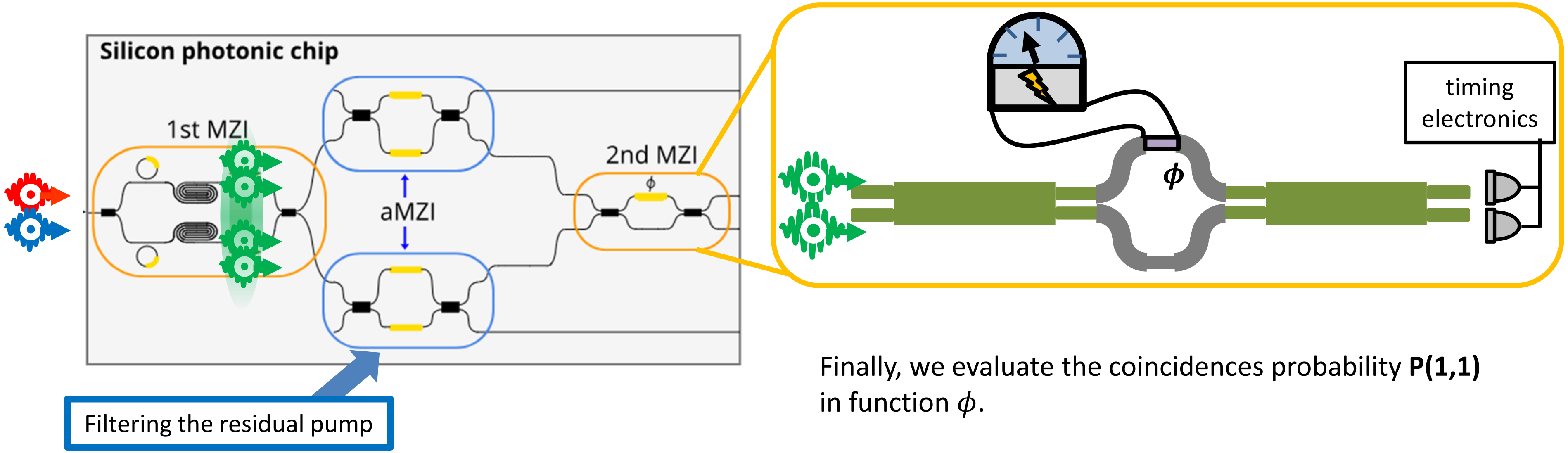
We quantified the indistinguishability between two photon-pair sources using **on-chip Hong-Ou-Mandel interference** making a direct comparison between two different kinds of sources:



Photonic circuit to measure HOM interference

Inside the 1st MZI, it is possible to tune the microring resonators resonances and choose the source typology, either two **microring resonators** or two **spiral waveguides**.

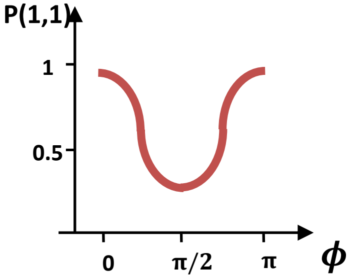
Then, the generated photons are led to the 2nd MZI, where we vary the relative phase of the two arms.



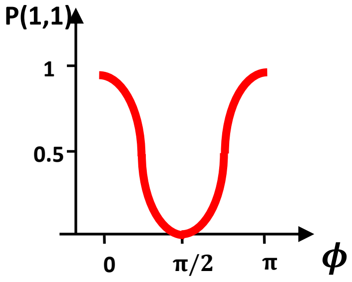
Finally, we evaluate the coincidences probability **P(1,1)** in function ϕ.

Hong-Ou-Mandel effect in integrated photonics

The MZI is a tunable beam-splitter, thus we achieve an interference pattern for **P(1,1)** .



Partially distinguishable



Not distinguishable

The depth of the interference fringe of **P(1,1)** is quantified by the visibility (V):

$$V = \frac{\max_{\phi} \text{coincidences} - \min_{\phi} \text{coincidences}}{\max_{\phi} \text{coincidences}}$$

The **visibility of the fringe pattern** (V) is related to the two **sources' JSA overlap**, which gives a quantitative estimation of the indistinguishability of the two sources:

visibility ➡ **sources' JSA overlap**

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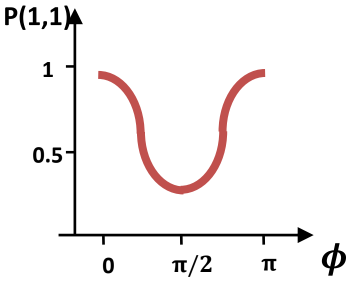

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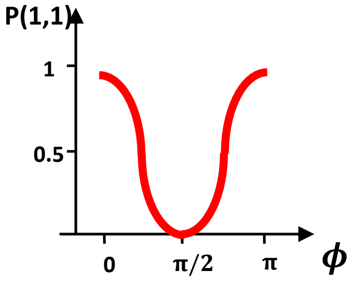

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visibility $\rightarrow$ **sources' JSA overlap**

Results

	extimated JSA overlap	simulated purity	…
microring resonators	89% ☒	90% ☑	…
spiral waveguides	98% ☑	81% ☒	…

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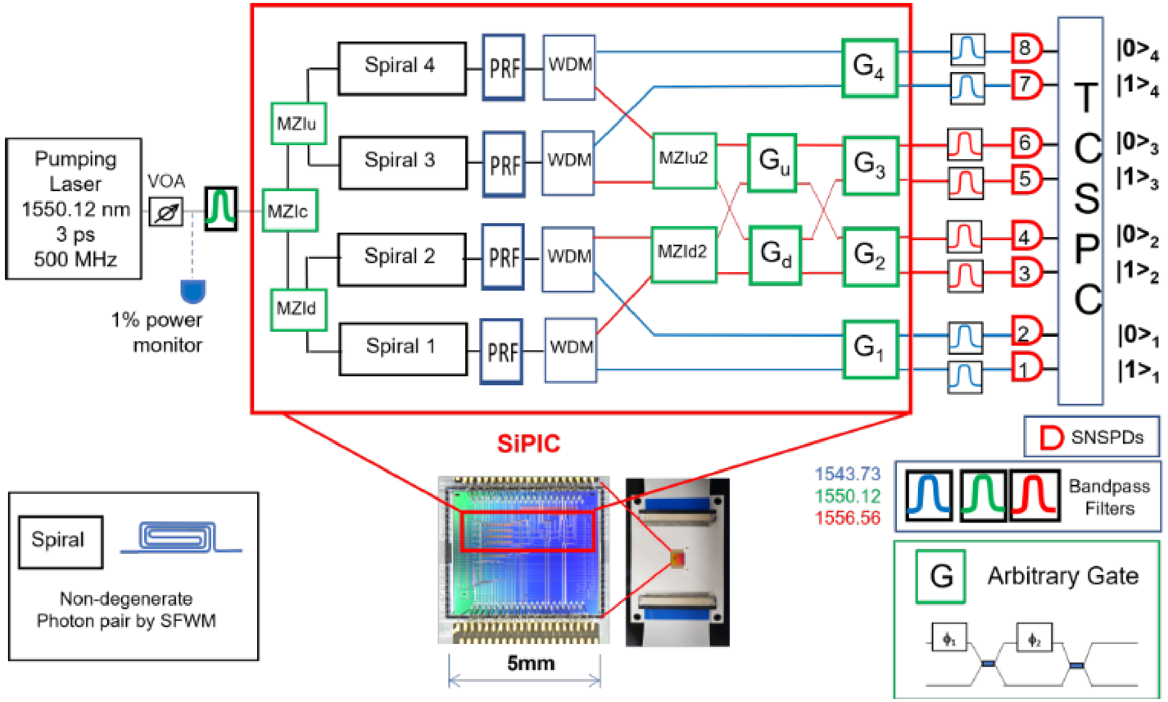

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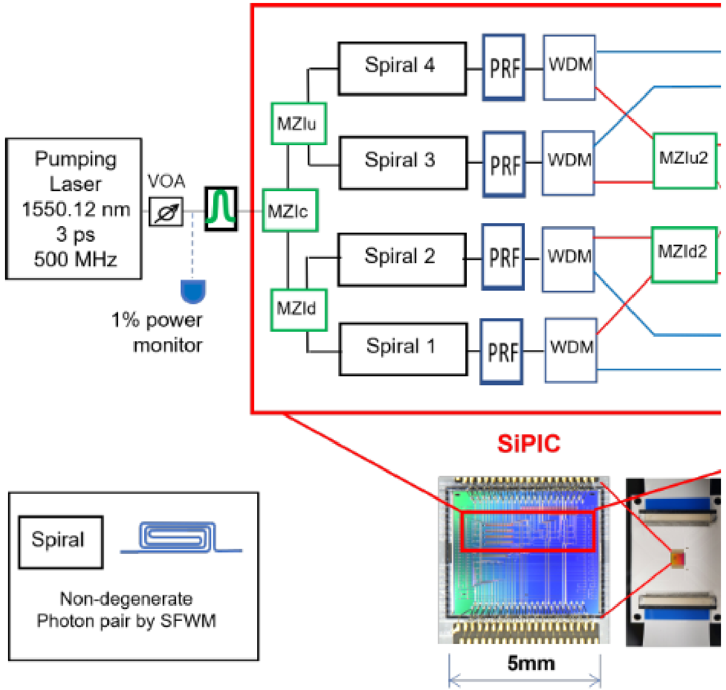


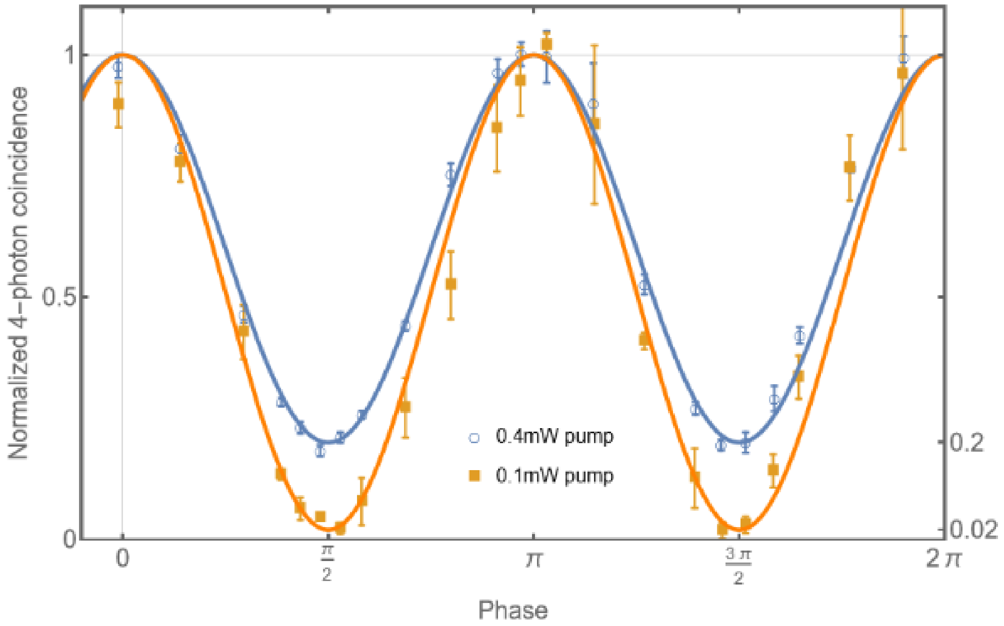
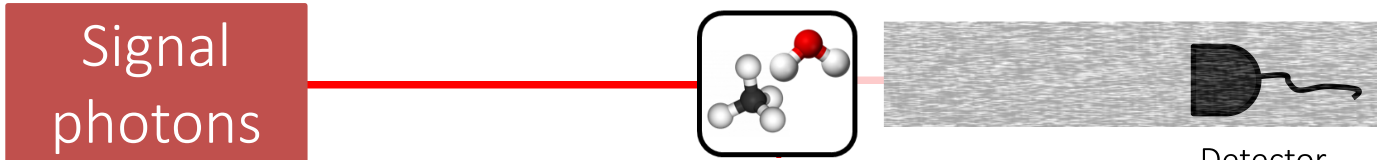


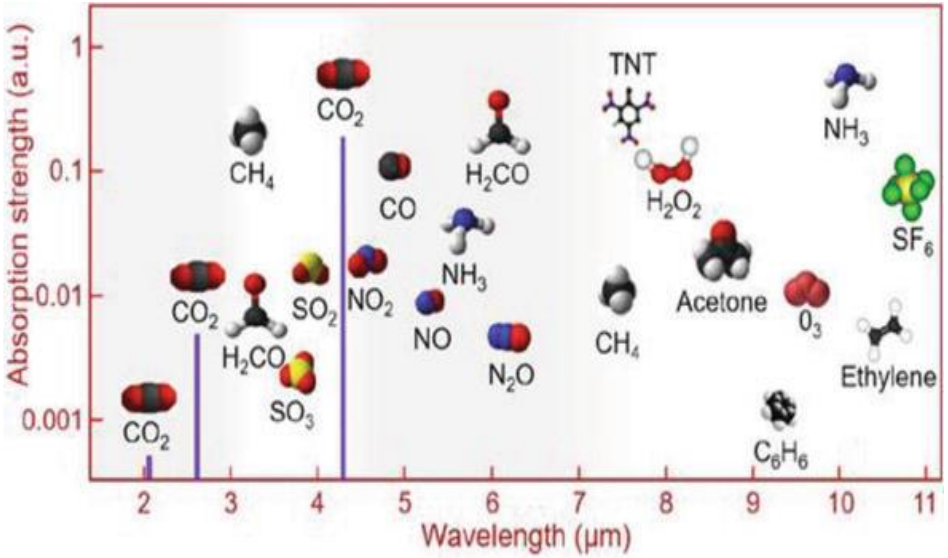
Fig. 4. HOM interference measured by 4-photon coincidence for the average pumping powers 0.1 and 0.4 mW per spiral, respectively. The measured visibility is 98% for the 0.1 mW pumping.

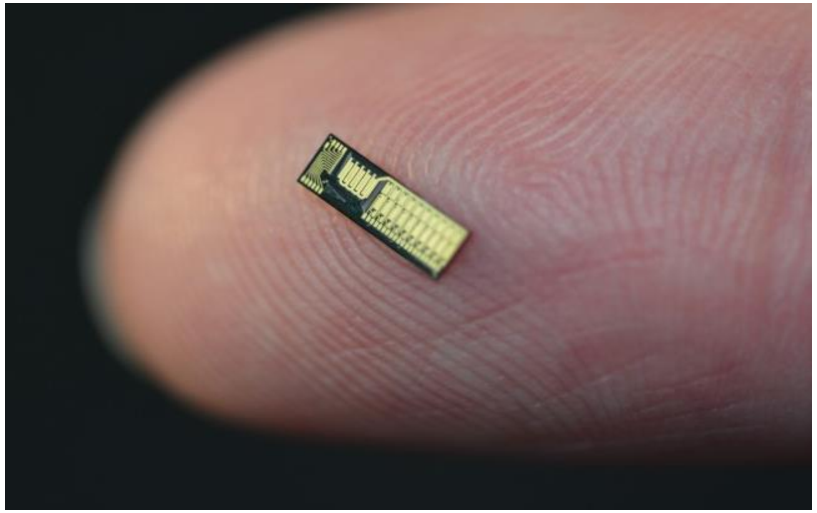
MIR sensing via Ghost Spectroscopy

Absorption Spectroscopy

High environmental noise (SNR ~ 0)

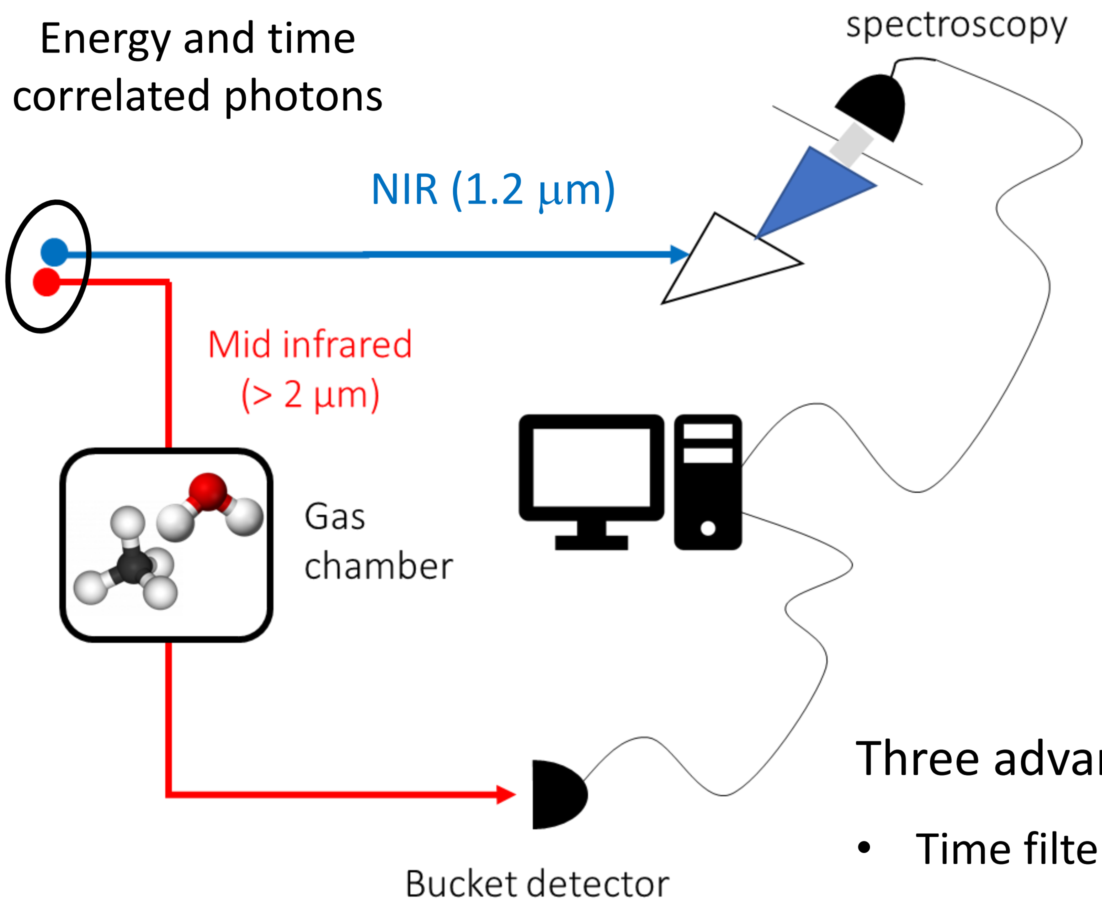


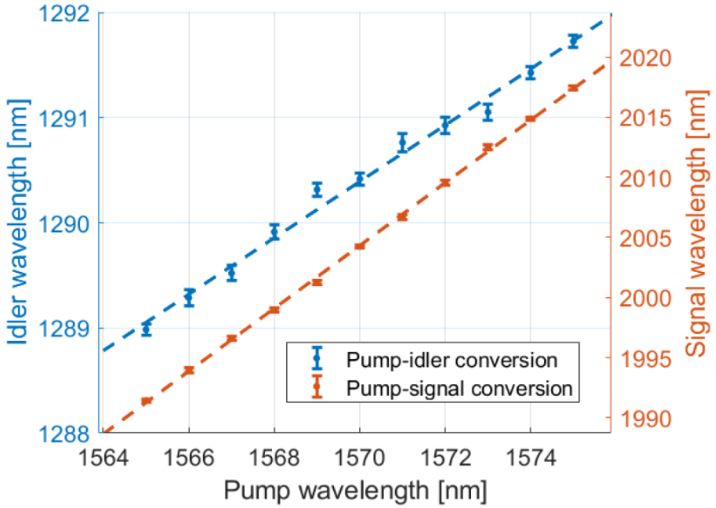




Matteo Sanna, et al" Advanced Quantum Technologies 2300159 (2023).

MIR sensing via Ghost Spectroscopy

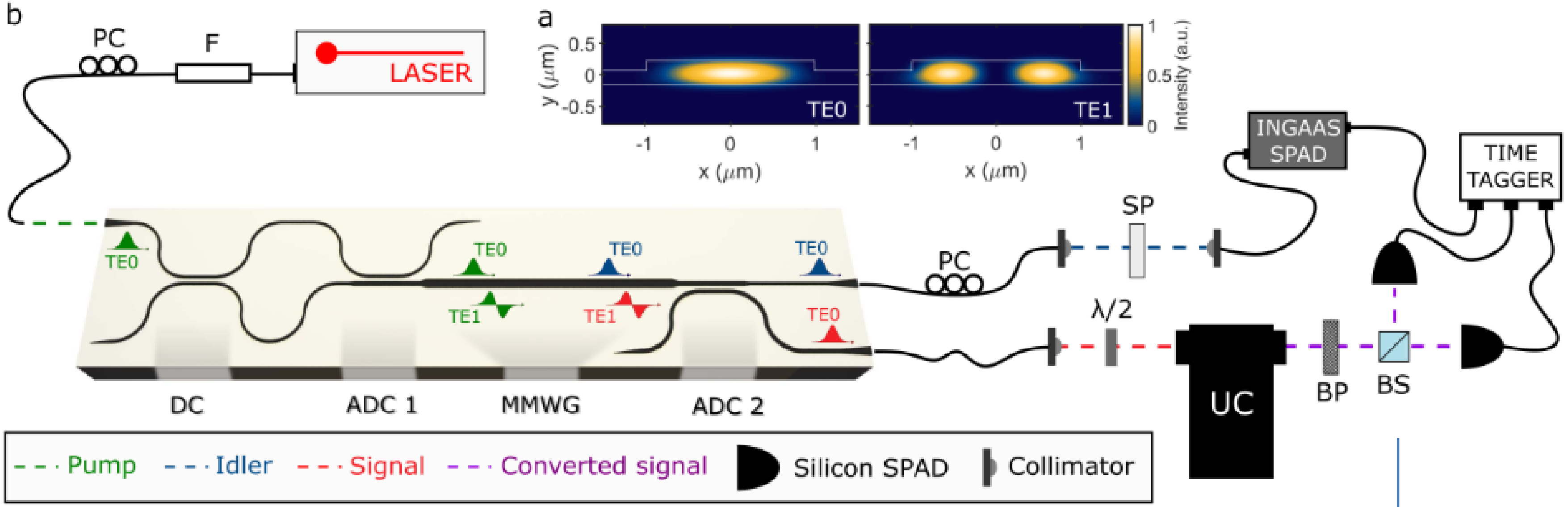


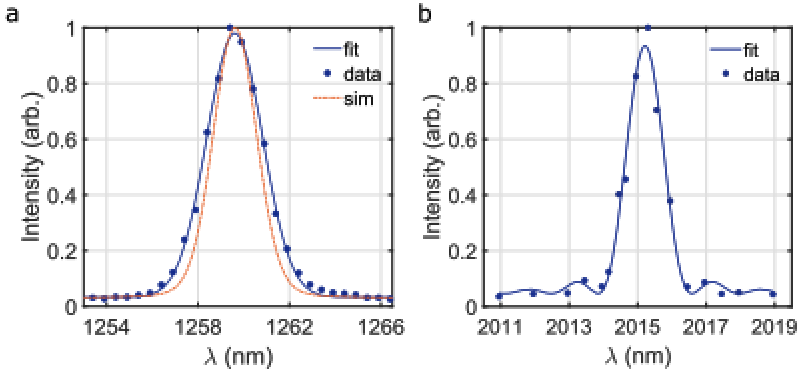


Three advantages:

- Time filtering (correlation)
- Ghost information translation (entanglement)
- Large spectral shift between the twin photons

MIR sensing via Ghost Spectroscopy



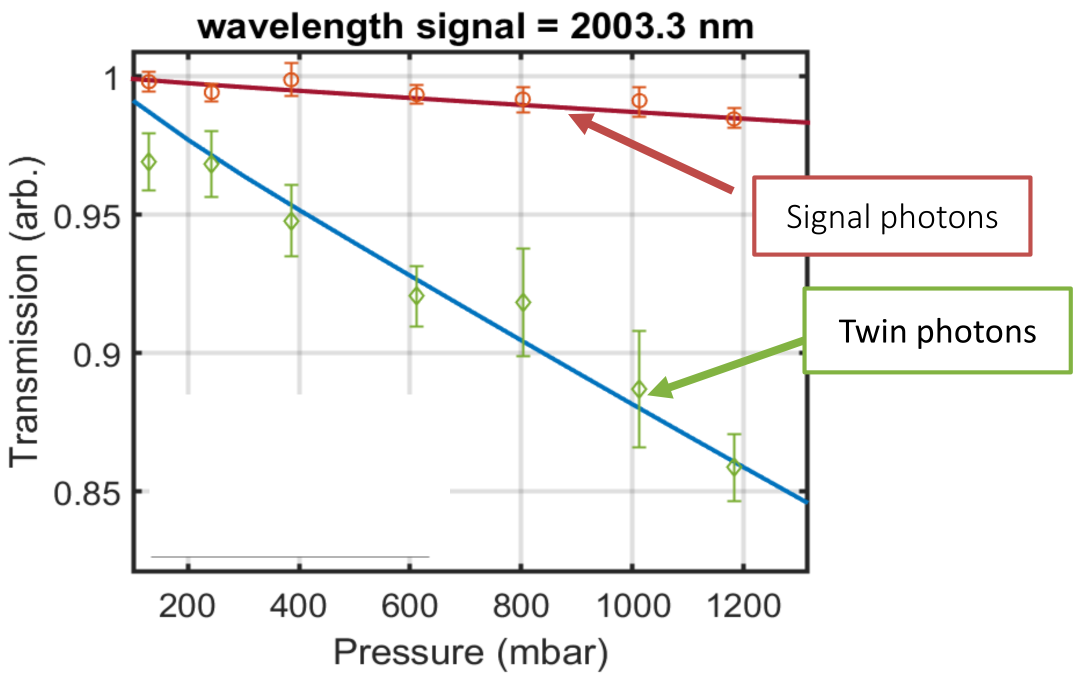


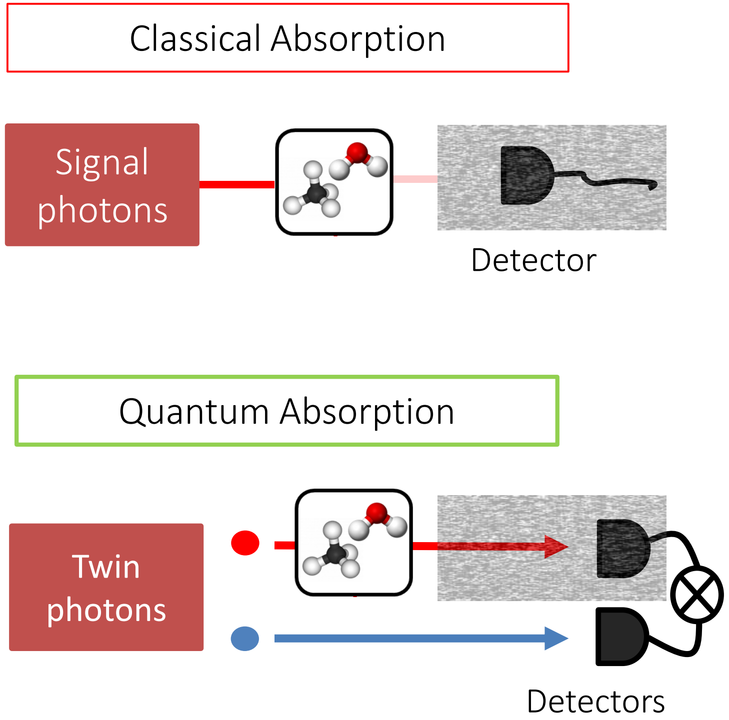
Second order coincidence

$g^{(2)}(\Delta t)$

MIR sensing via Ghost Spectroscopy

High environmental noise (SNR = 0.04)



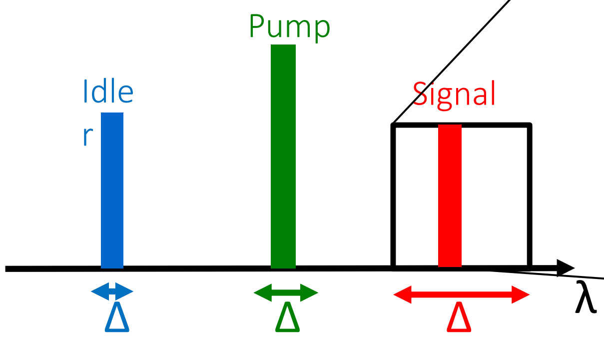


Time filtering

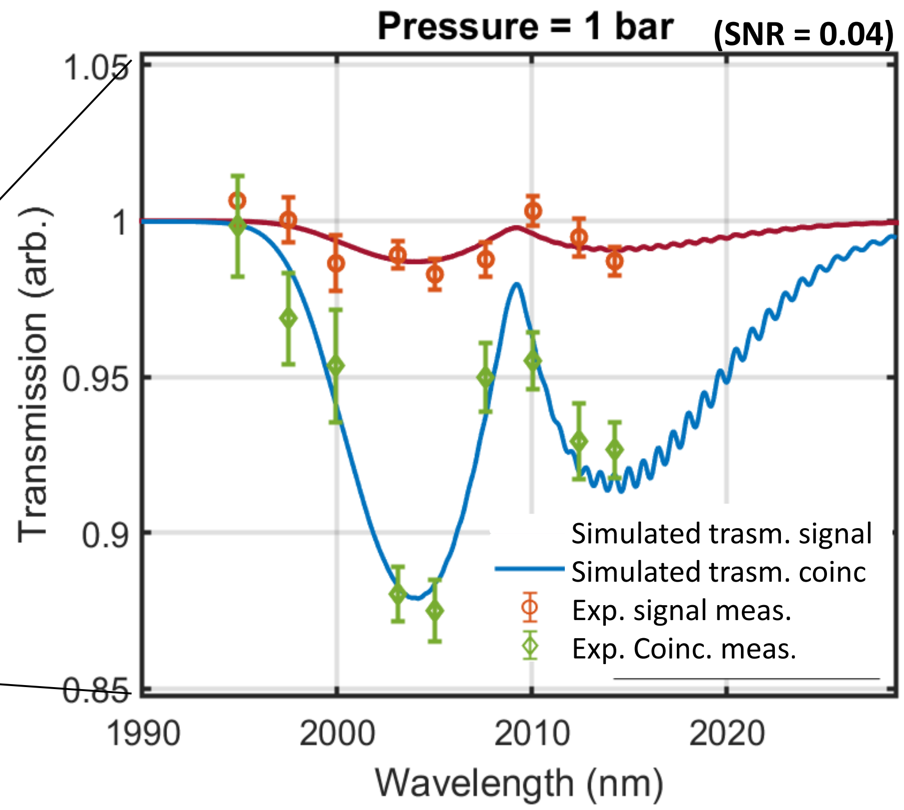
MIR sensing via Ghost Spectroscopy

High environmental noise (SNR = 0.04)

- Spectrum of CO_2
- Pressure variation measurement

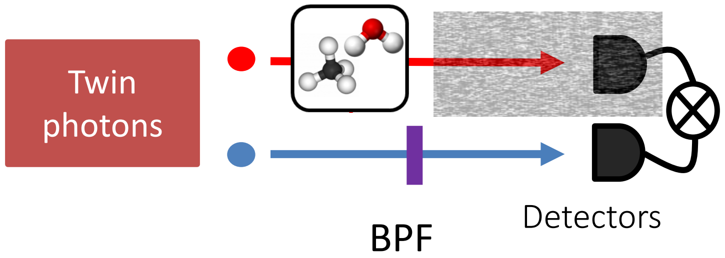


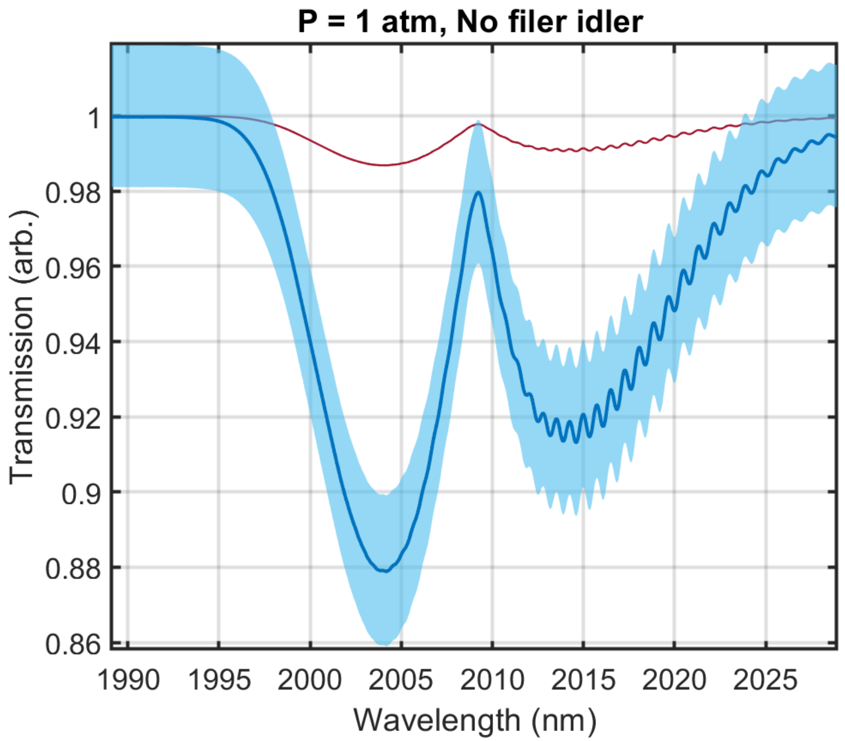
$$2\hbar\omega_P = \hbar\omega_S + \hbar\omega_I$$

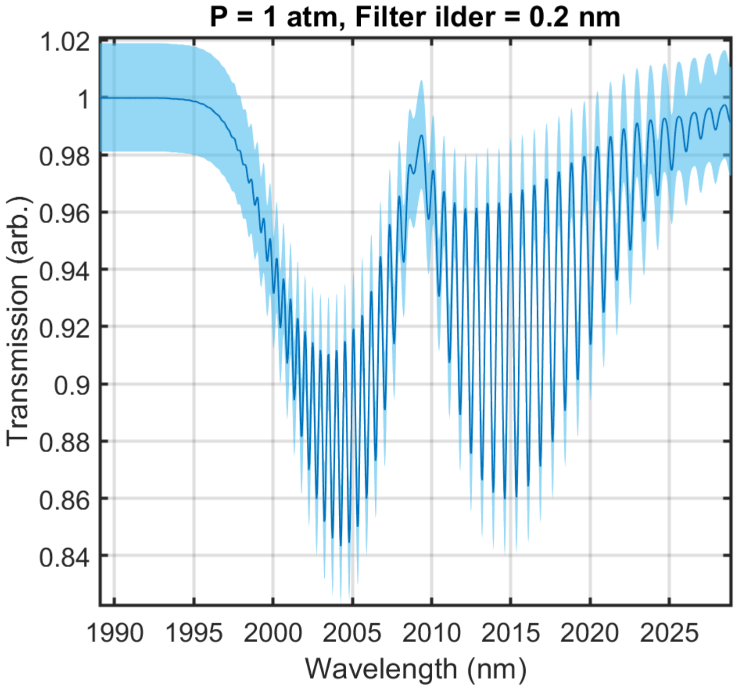


Time filtering

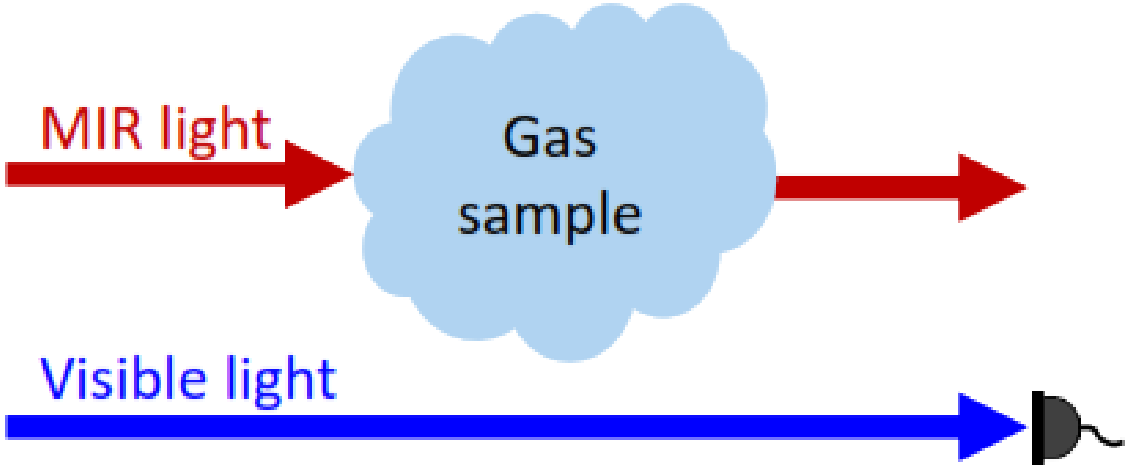
MIR sensing via Ghost Spectroscopy



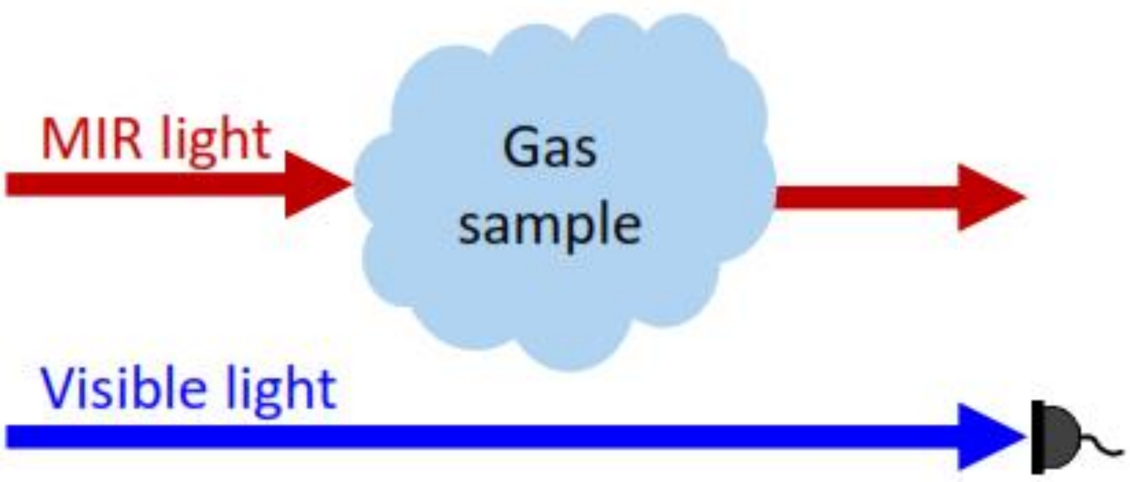


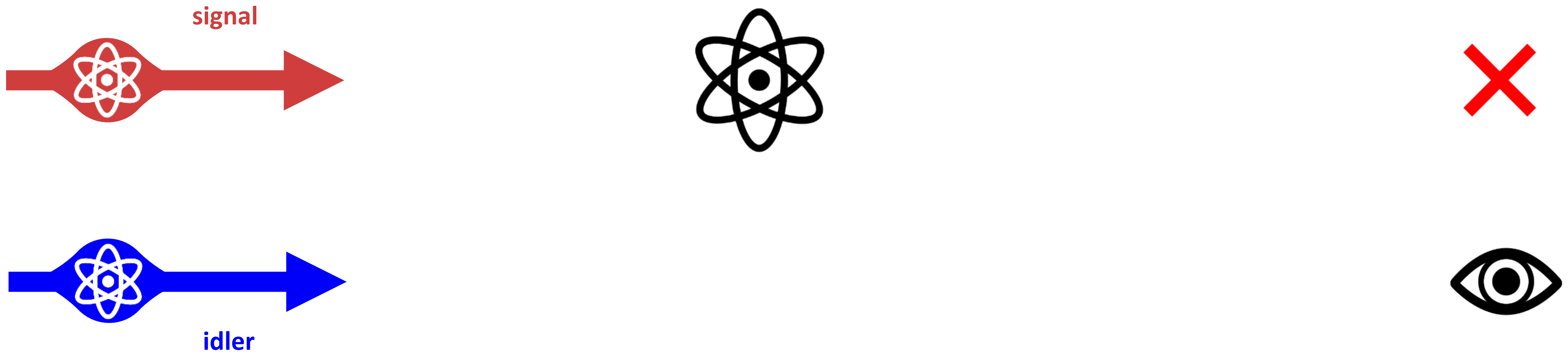


- Ghost information translation

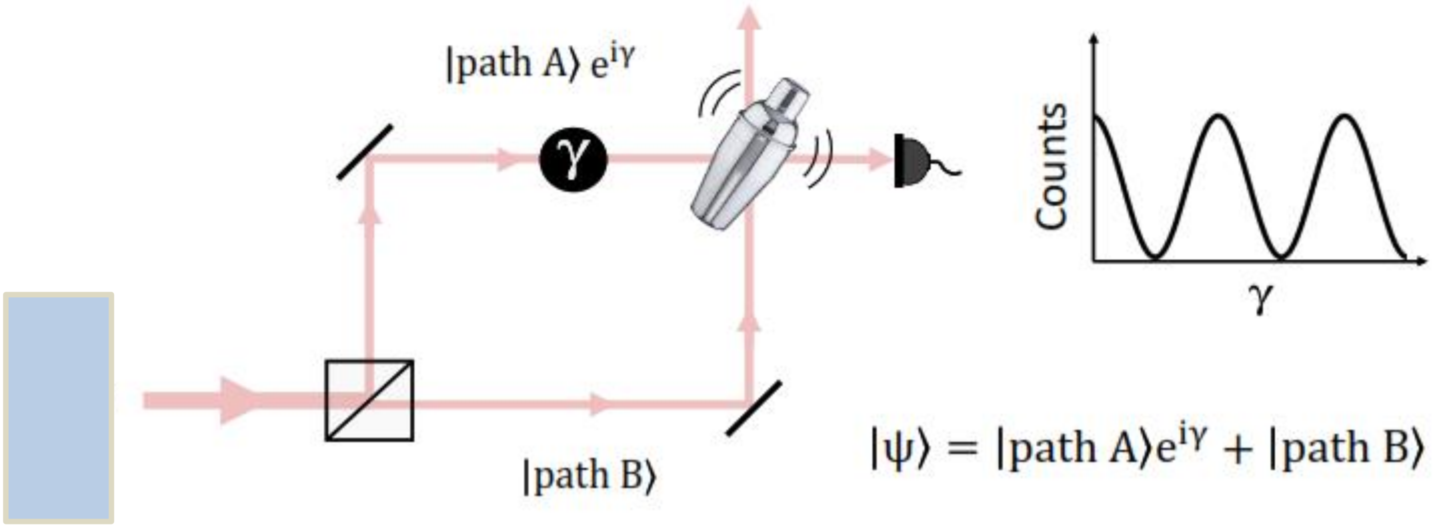

MIR light
Gas
sample
Visible light

Undetected photon spectroscopy



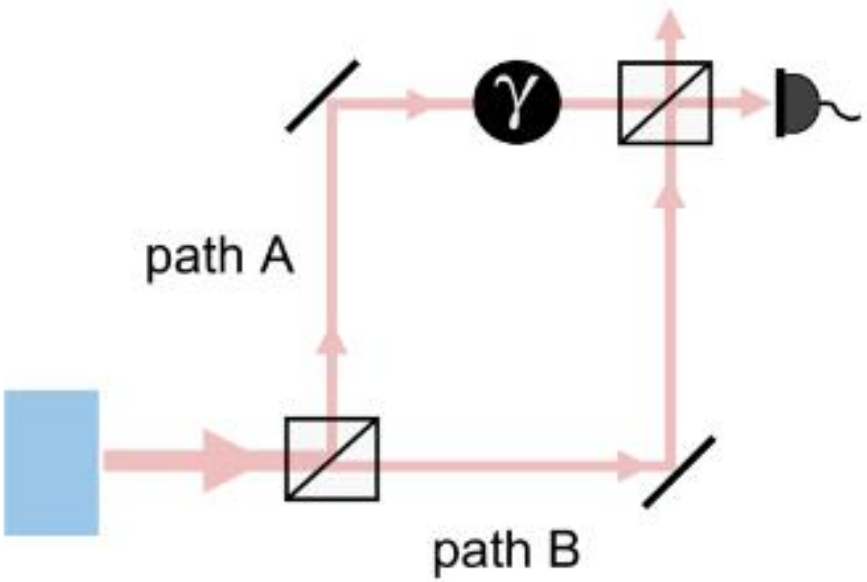

signal
idler

Quantum Mach-Zehnder Interferometer



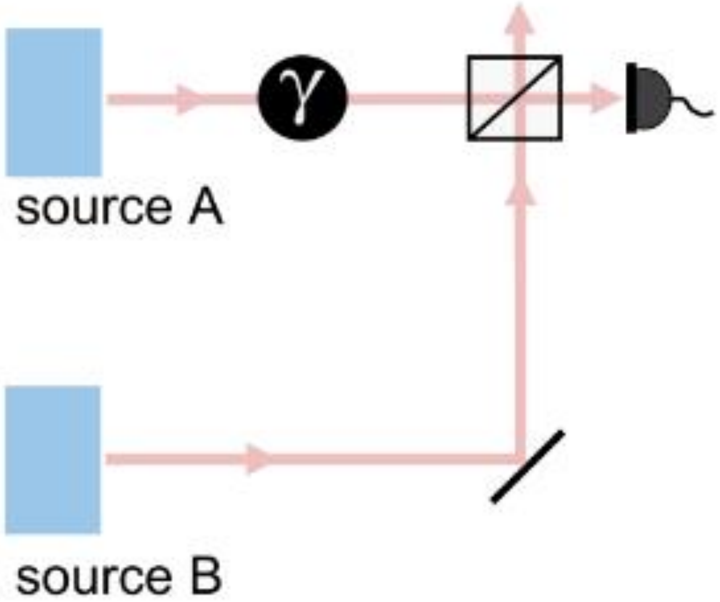
$$|\psi\rangle = |\text{path A}\rangle e^{i\gamma} + |\text{path B}\rangle$$

Which path?



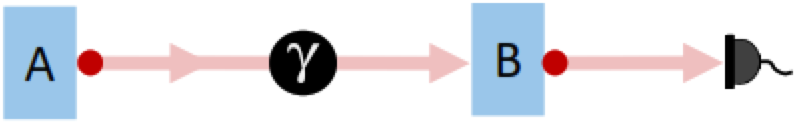
$$|\psi\rangle = |\text{path A}\rangle e^{i\gamma} + |\text{path B}\rangle$$

Which source?



$$|\psi\rangle = |\text{source A}\rangle e^{i\gamma} + |\text{source B}\rangle$$

Path superposition



$$|\psi\rangle = |\text{source A}\rangle e^{i\gamma} + |\text{source B}\rangle$$

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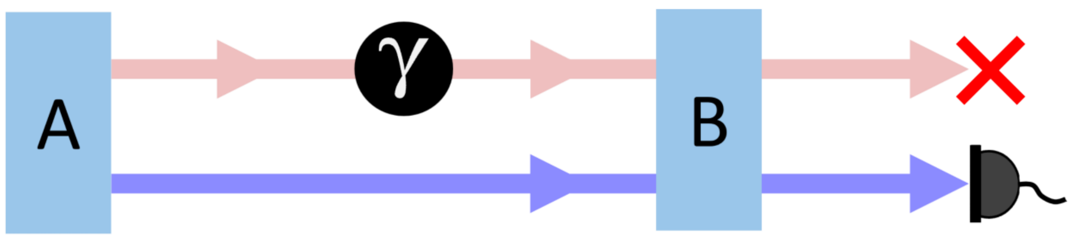
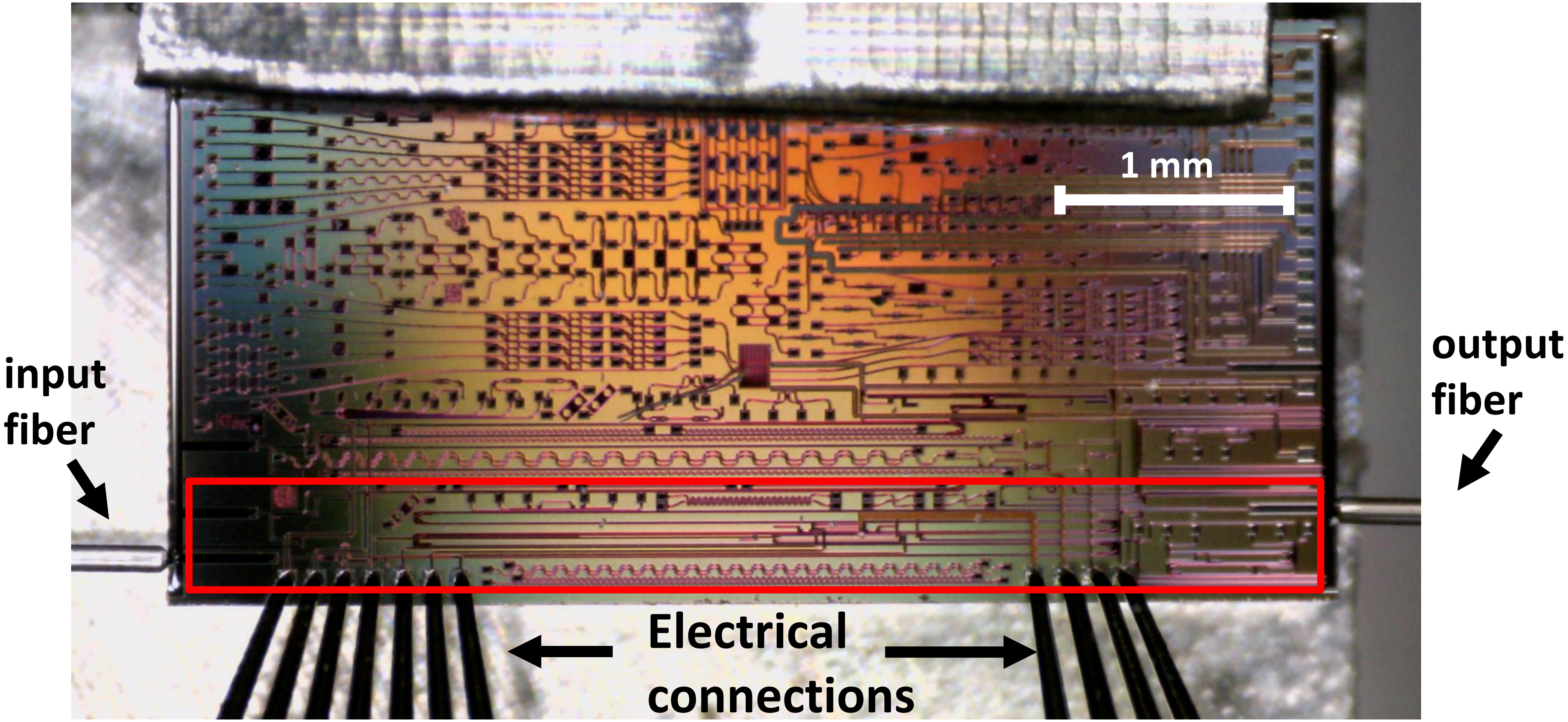


$$|\psi\rangle = |A\rangle|A\rangle e^{i\gamma} + |B\rangle|B\rangle$$

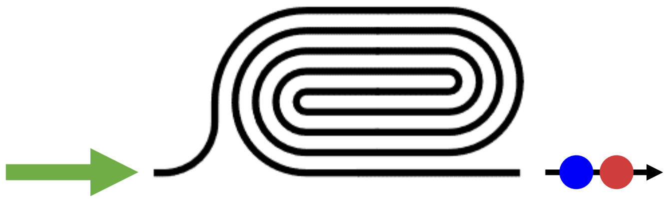


input
fiber
output
fiber
1 mm
Electrical
connections

pump:1.57 µm

signal: 2.00 µm

idler: 1.29 µm



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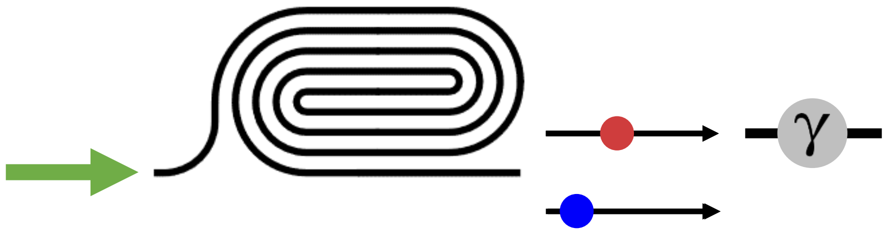

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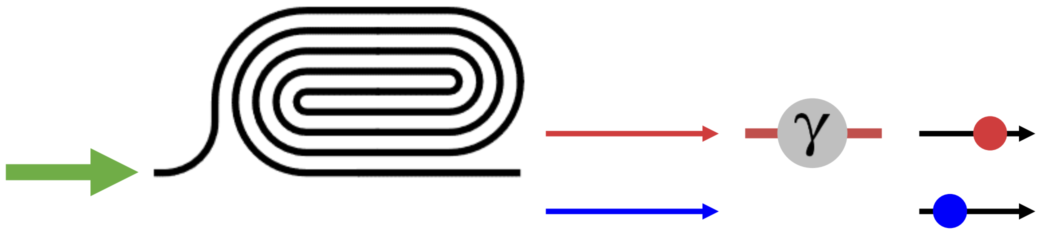

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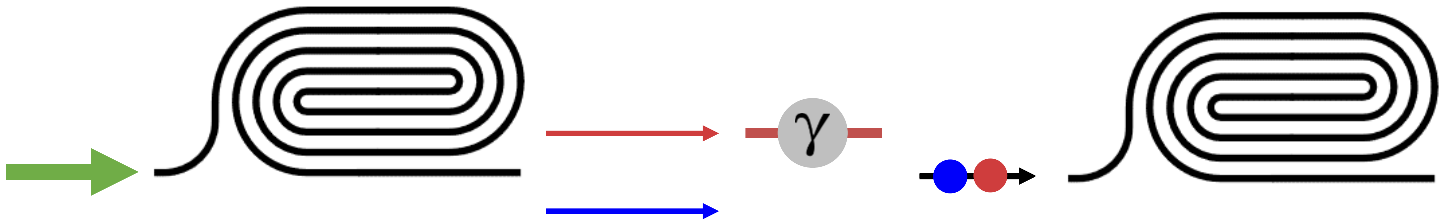

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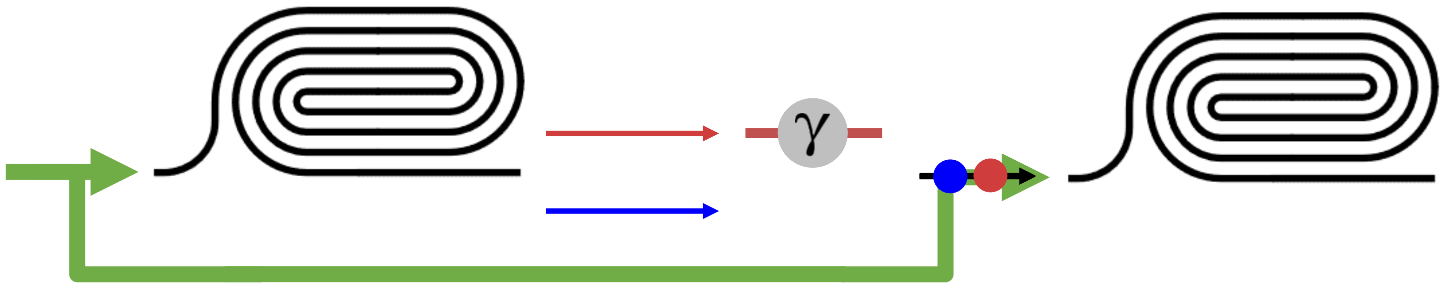

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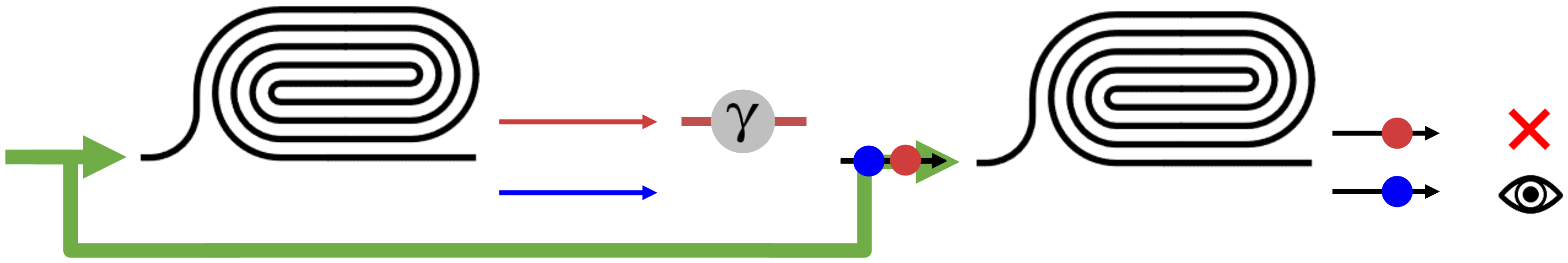
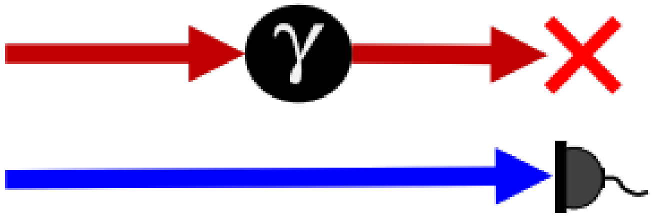
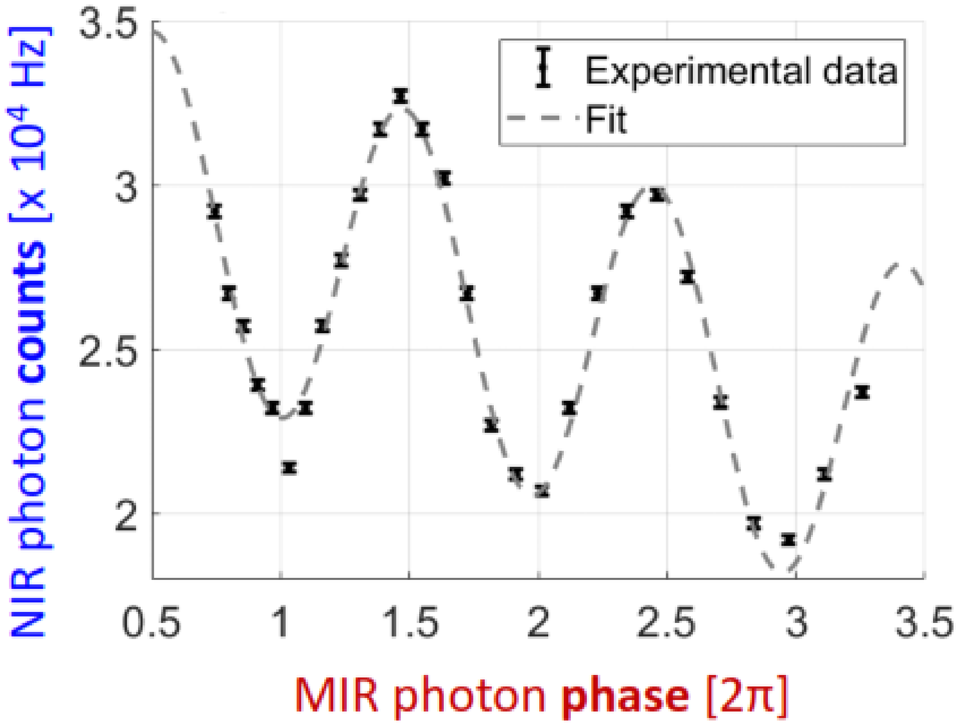


Results

- MIR photon: 2 µm
- NIR photon: 1.29 µm





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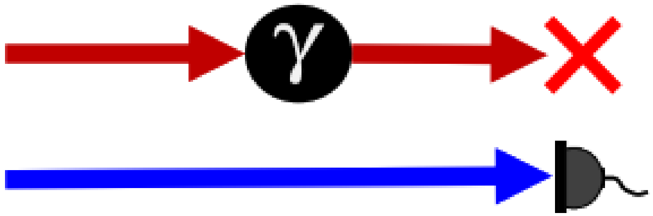
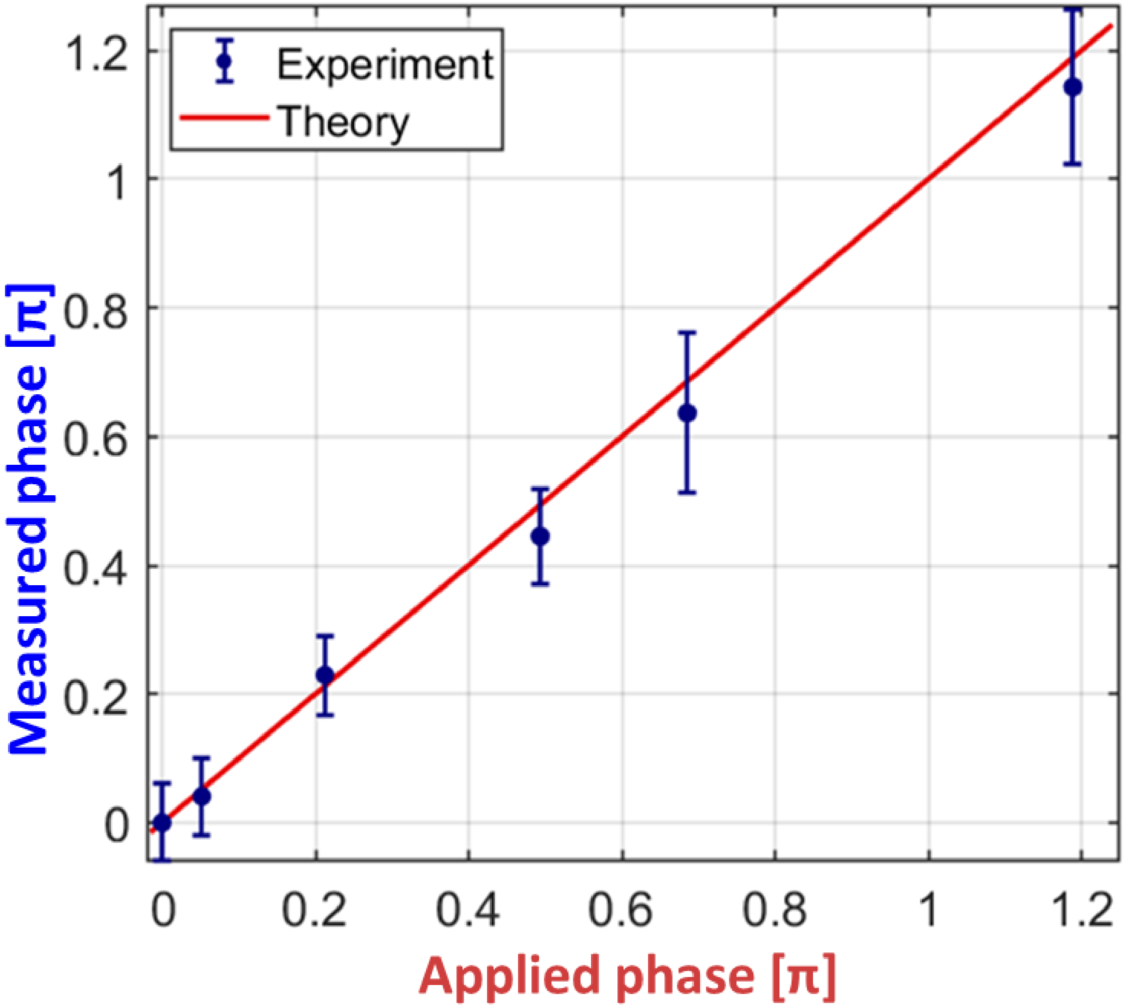




Intraparticle Entanglement

Intraparticle Entanglement

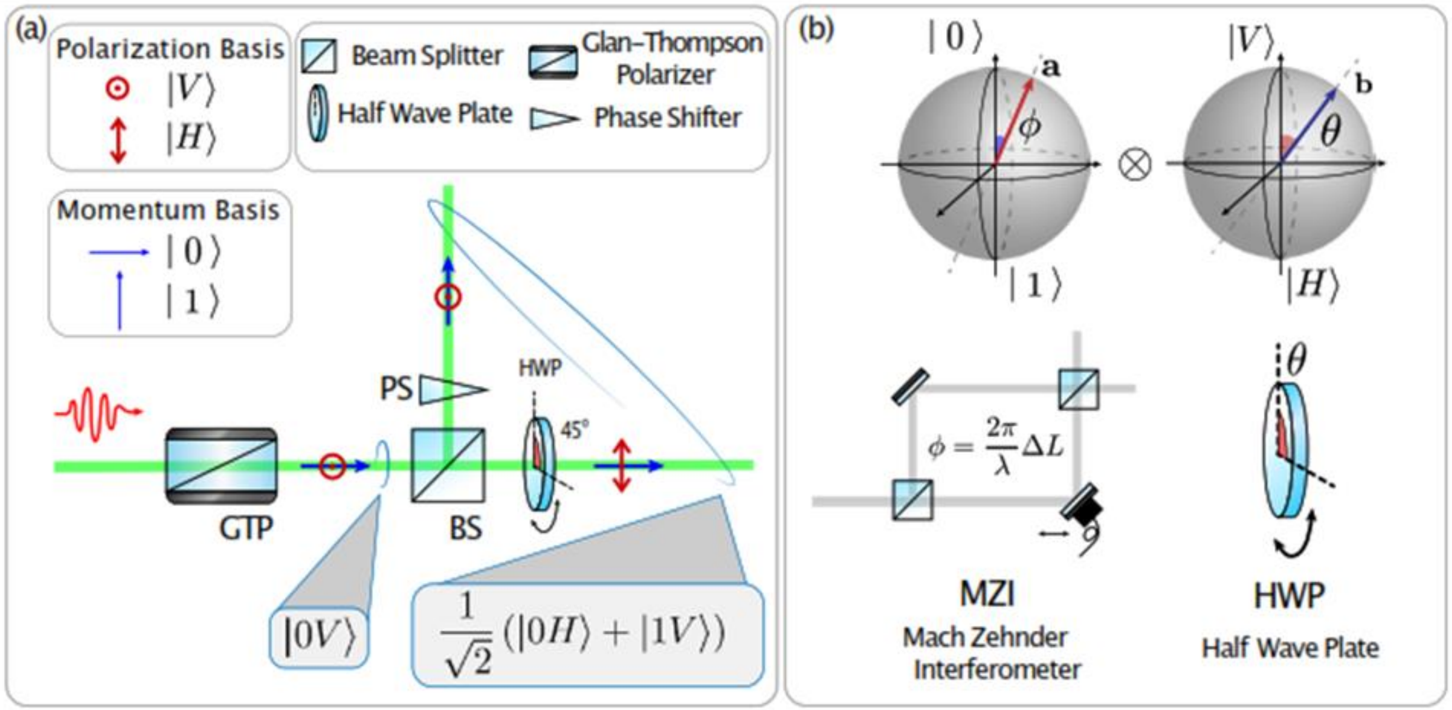
ORANGE

One photon with TWO internal degrees of freedom entangled

Attenuated light

Example:

PATH (MOMENTUM) AND POLARIZATION



Bell test on the CHSH inequality

M. Pasini, N. Leone, S. Mazzucchi, V. Moretti, D. Pastorello, L. Pavesi Physical Review A102, 063708 (2020)

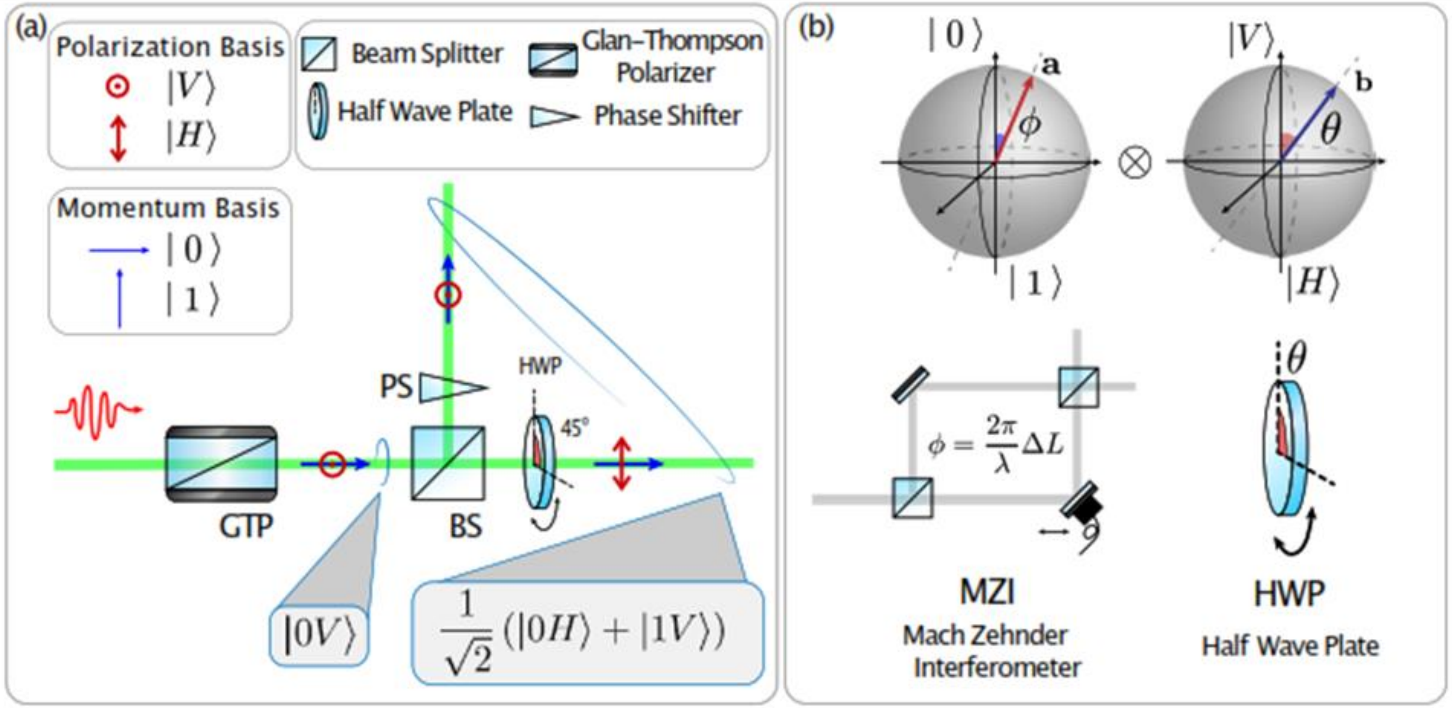
Intraparticle Entanglement

Attenuated light

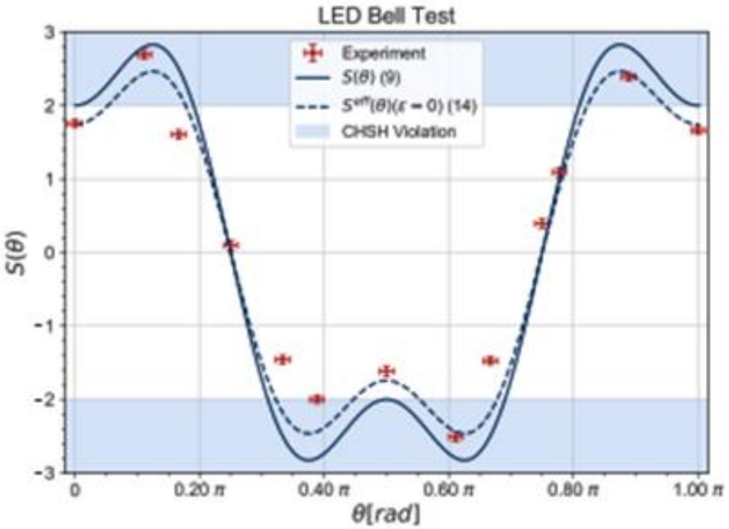
One photon with TWO internal degrees of freedom entangled

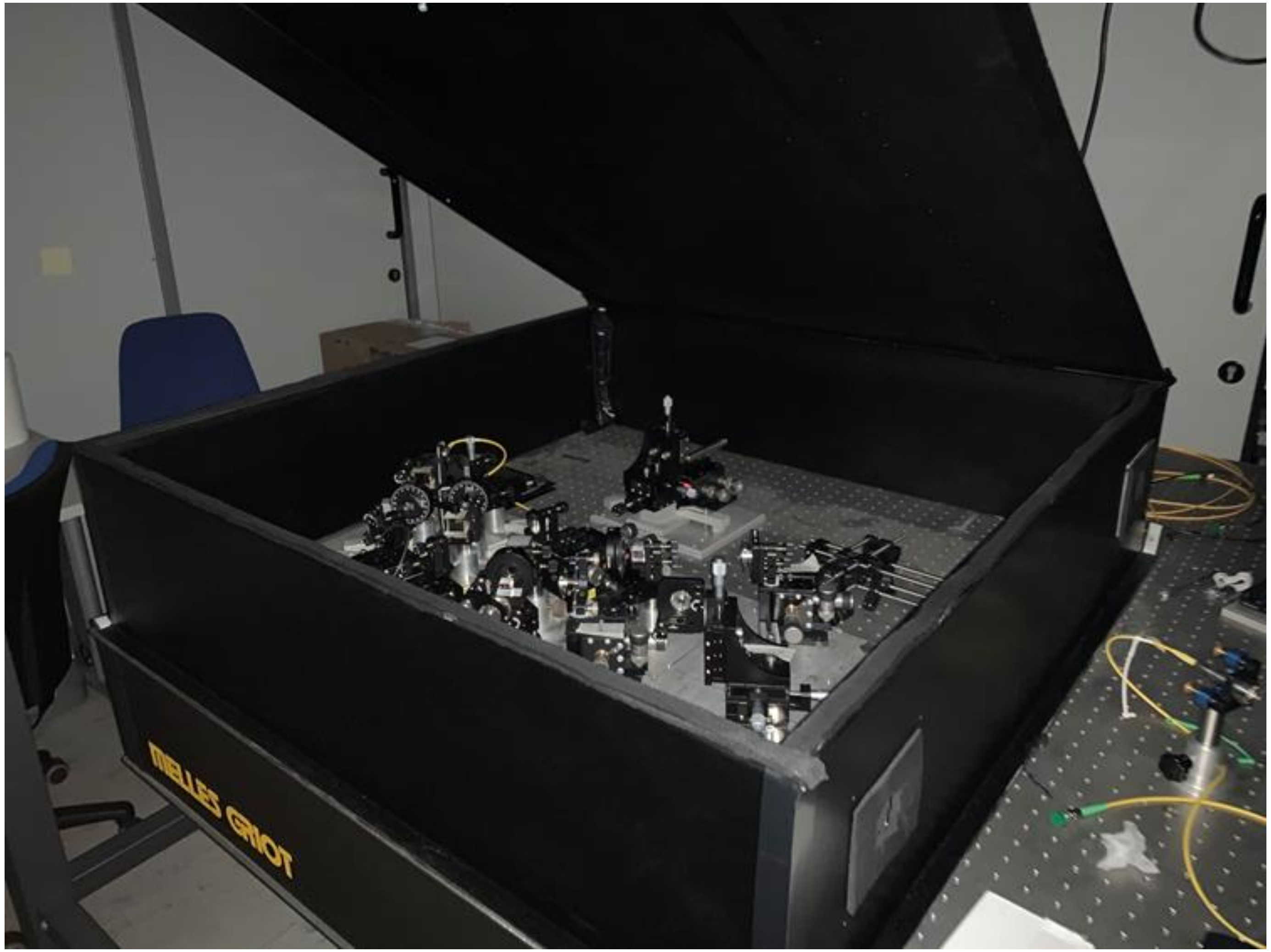
Example:

PATH (MOMENTUM) AND POLARIZATION



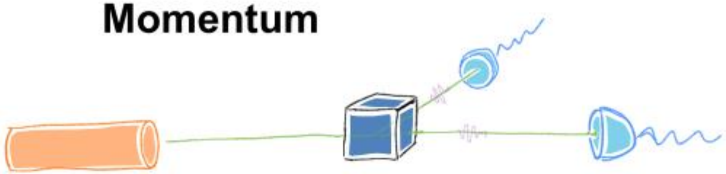
Bell test on the CHSH inequality

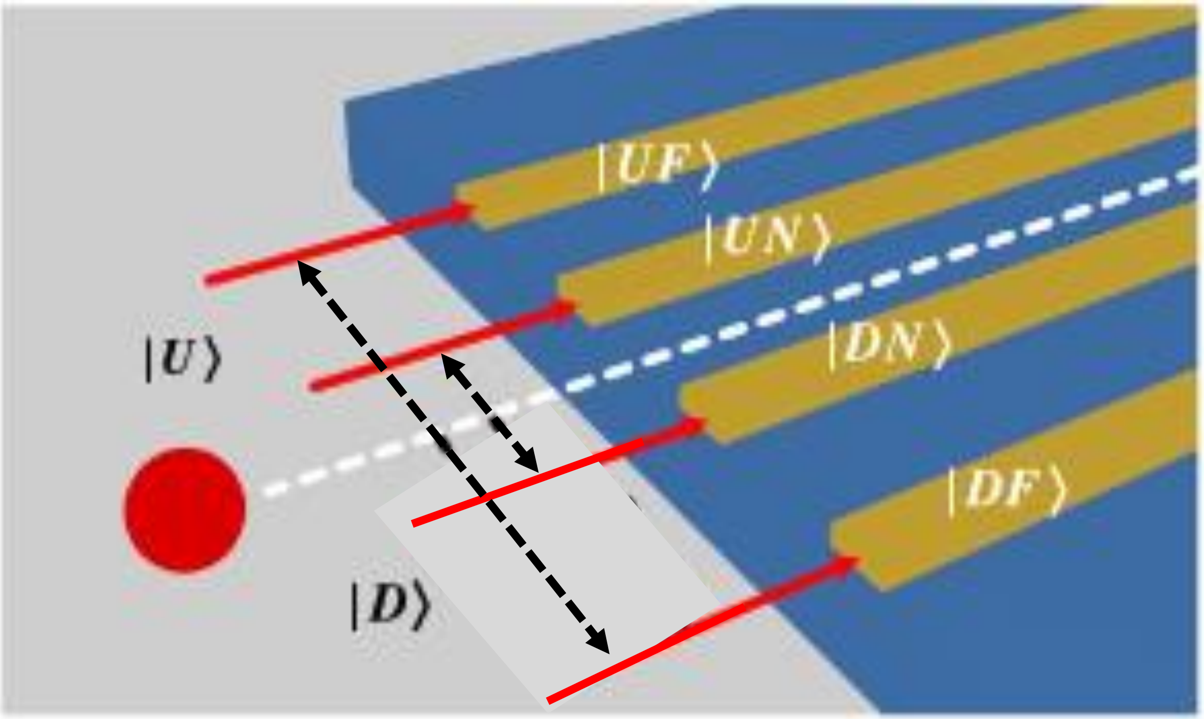



MELLES GRIOT

Qubit encoding: path encoding

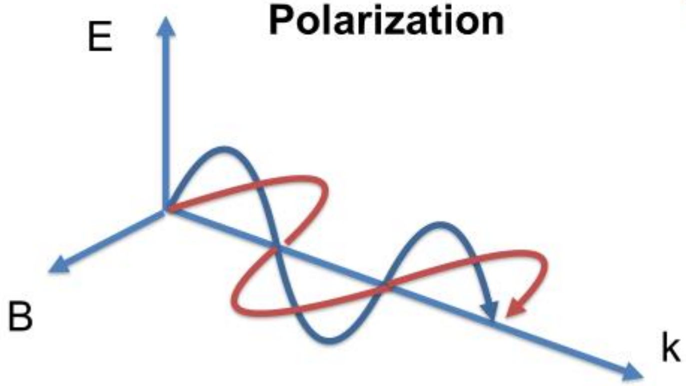
Momentum

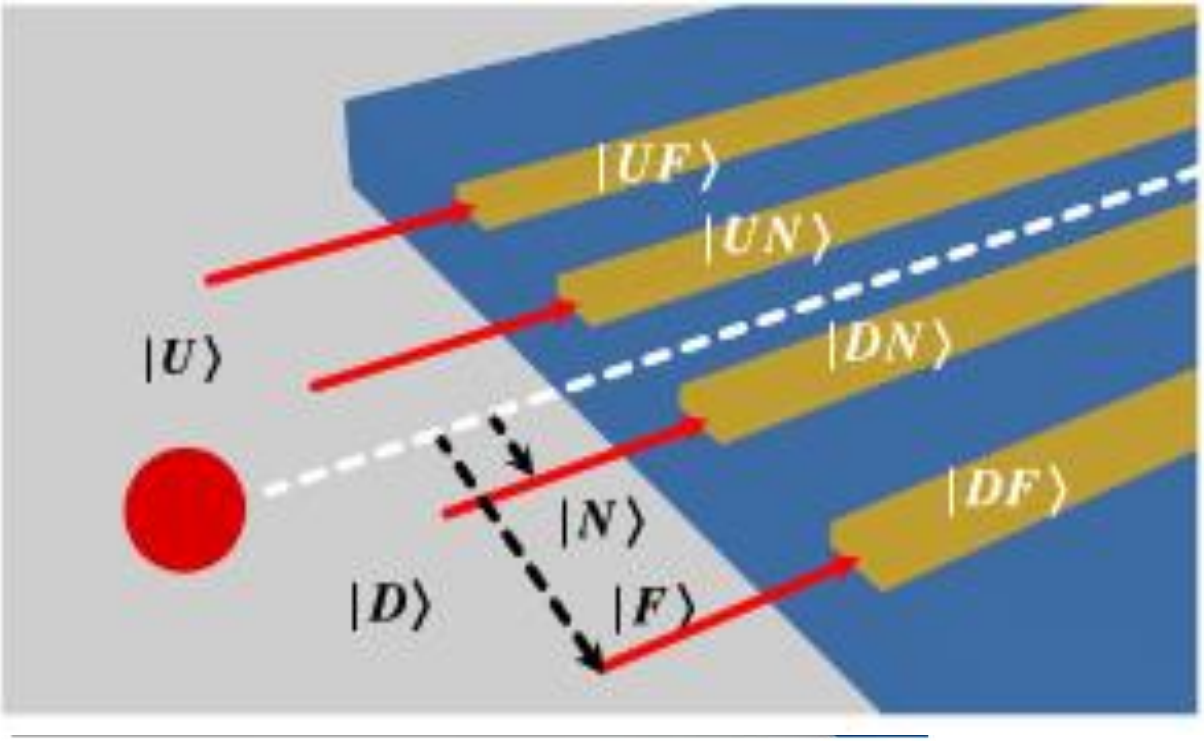




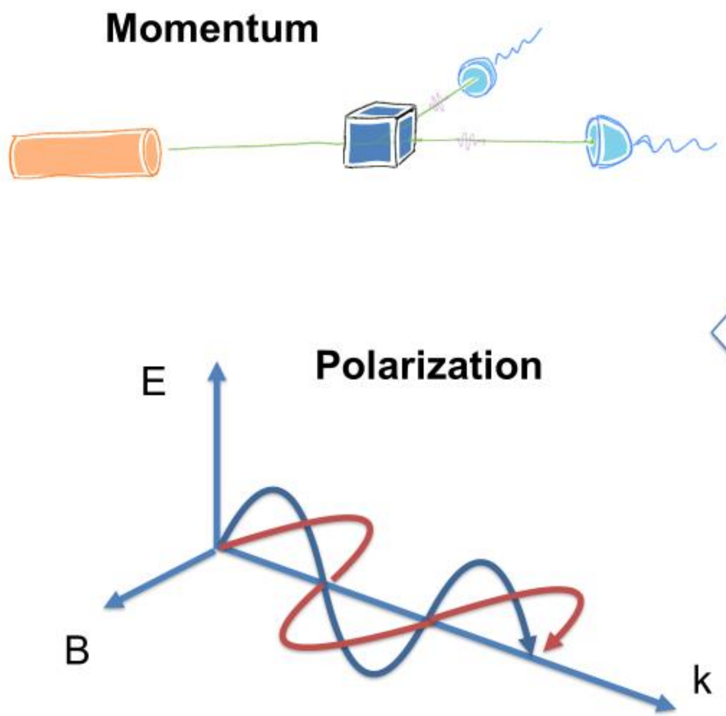
Nicolò Leone, et al, Photon. Res. 11, 1484 (2023)

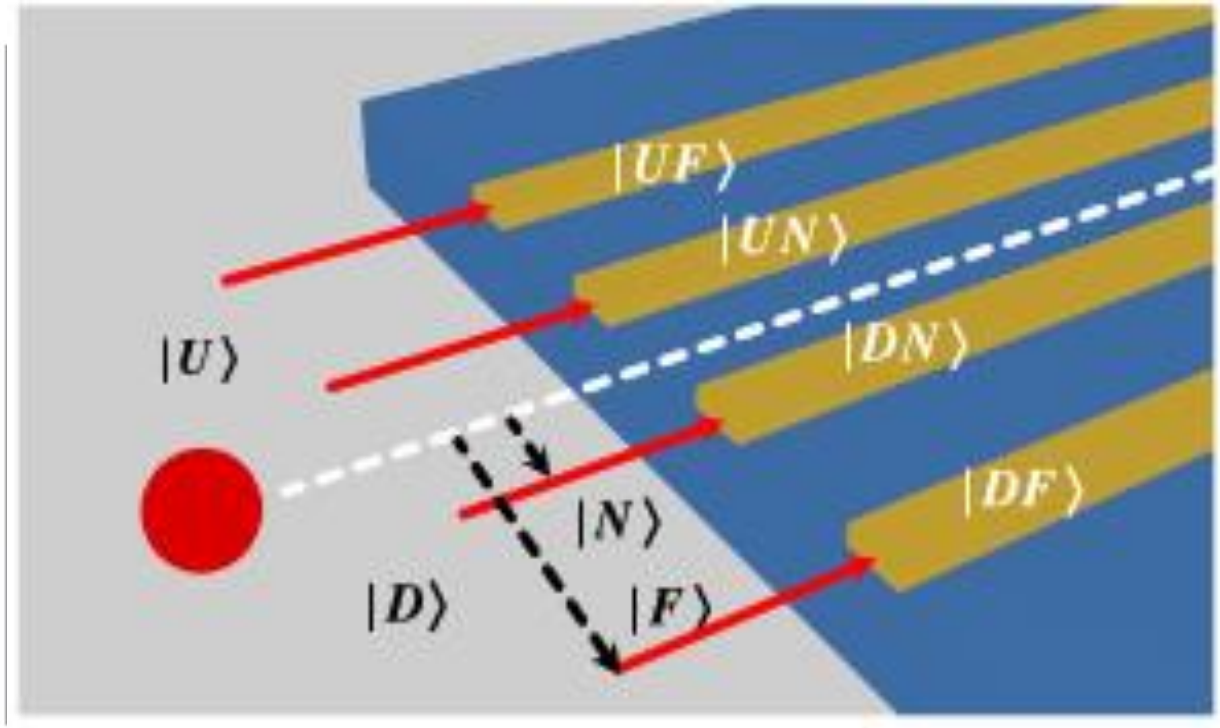
Qubit encoding: path encoding



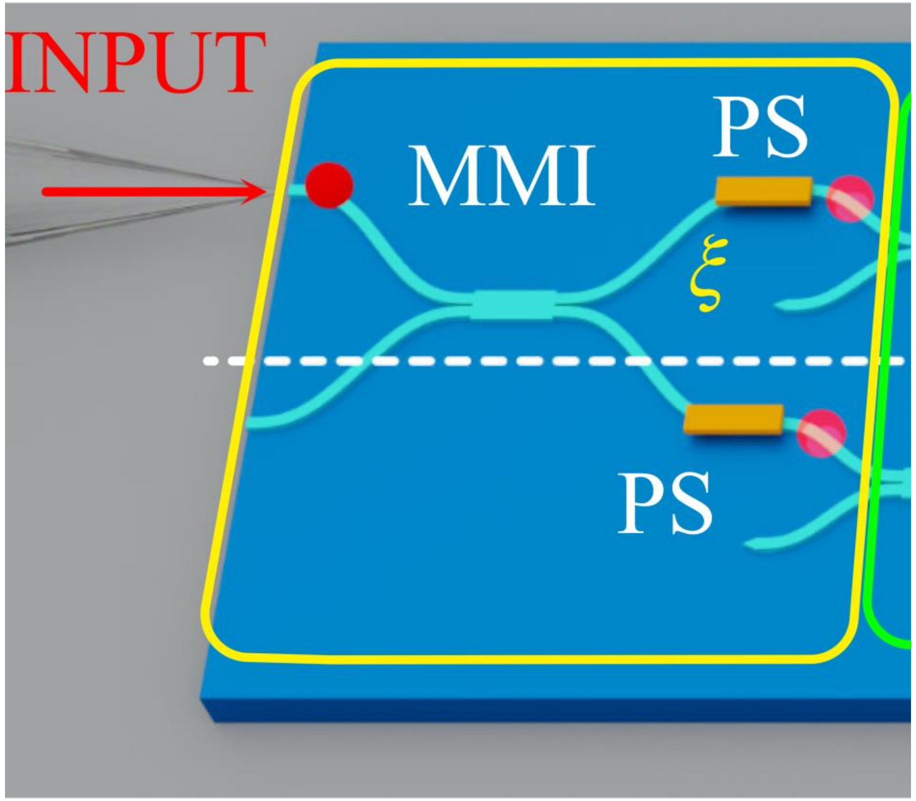


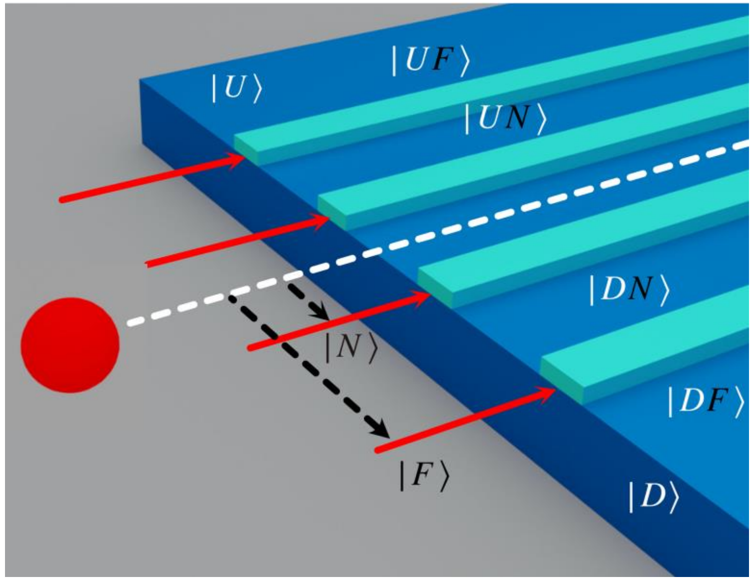
Qubit encoding: path encoding





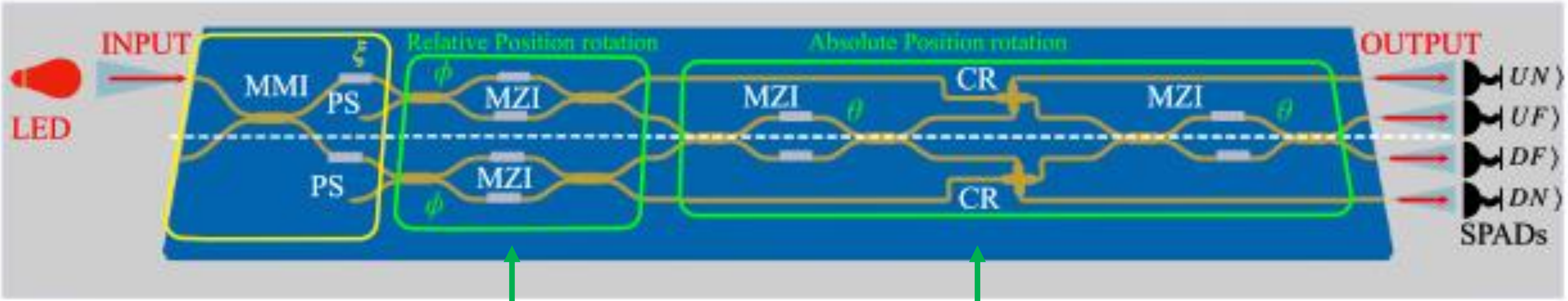
Chip structure: generation





Target state: $$|\phi^+\rangle = \frac{1}{\sqrt{2}}(|UF\rangle + |DN\rangle)$$

Chip structure

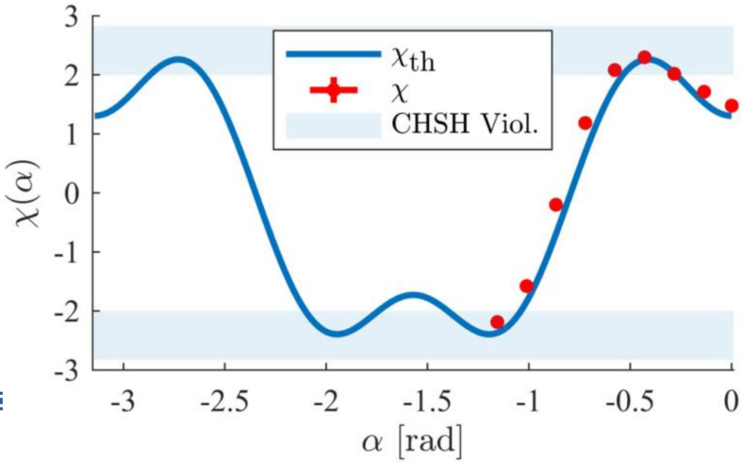


Relative position

Absolute position

Commercial red LED
$\lambda_p \simeq 730nm$
$\Delta\lambda$=10 nm

1) Linear optical elements
2) Not interested in the time of arrival of the photons



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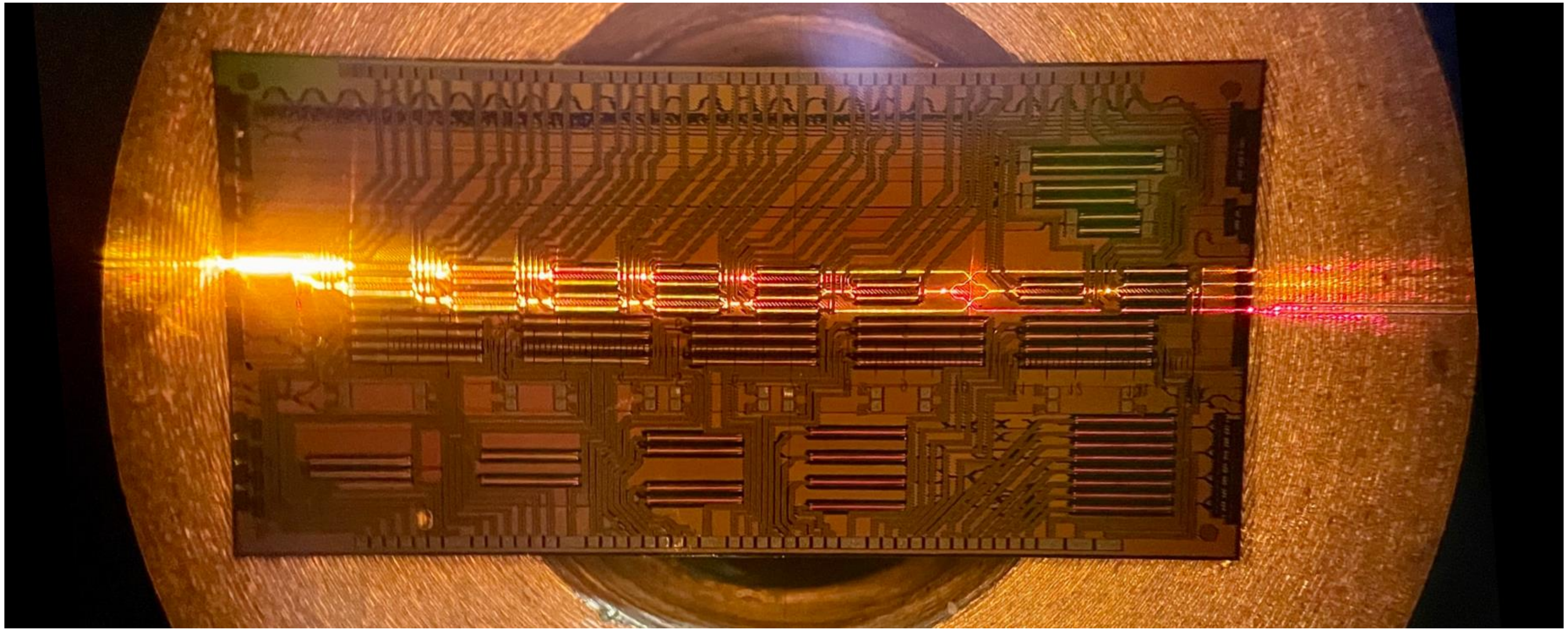
Nicolò Leone, et al, Photon. Res. 11, 1484 (2023)



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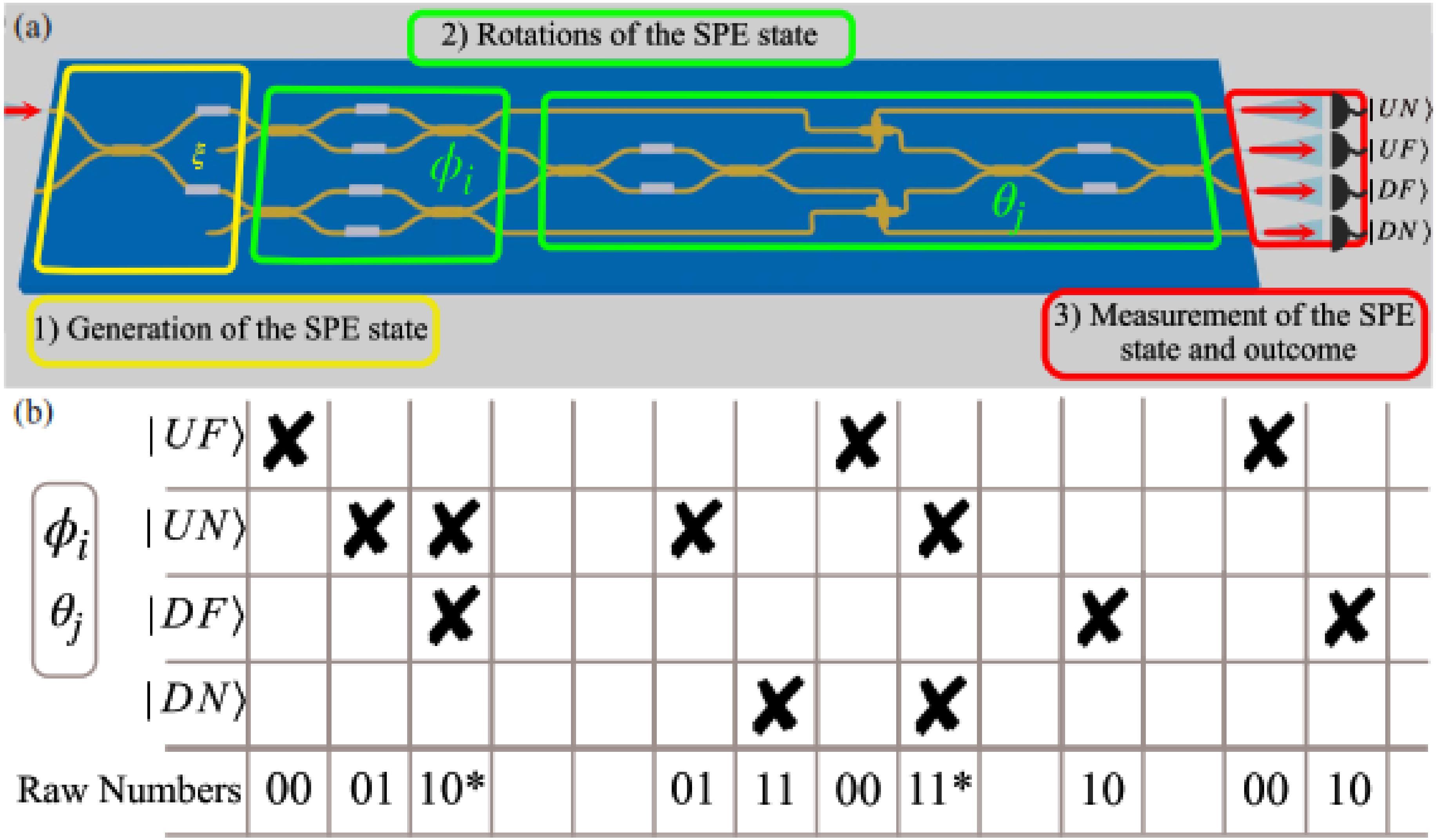
Quantum Random Number Generation



Nicolò Leone, et al, Photon. Res. 11, 1484 (2023)

Startup initiative

Single-**P**hoton **E**ntanglement for **Q**uantum **K**ey distribution

Few considerations

Quantum Supremacy

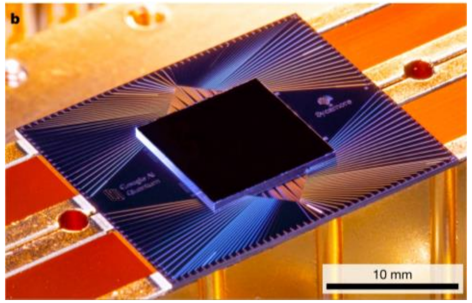
2000-2019

Quantum Advantage

2020-2022

Quantum Utility

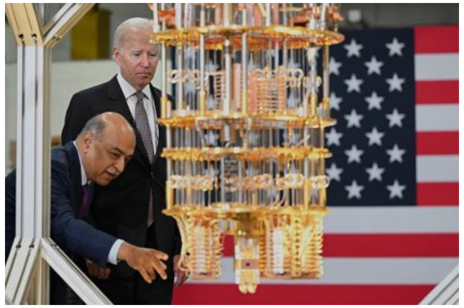
2023 -



The Sycamore chip

Arute, F., Arya, K., Babbush, R. et al. Quantum supremacy using a programmable superconducting processor. Nature 574, 505–510 (2019)

Han-Sen Zhong et al. ,Quantum computational advantage using photons.Science370,1460-1463(2020).



Kim, Y., Eddins, A., Anand, S. *et al.* Evidence for the utility of quantum computing before fault tolerance. *Nature* **618**, 500–505 (2023).

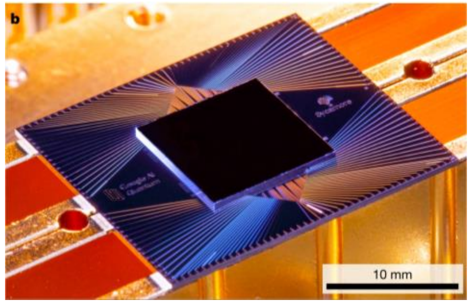
Few considerations

TPU
CPU
GPU
QPU

Quantum Supremacy
2000-2019

Quantum Advantage
2020-2022

Quantum Utility
2023 -



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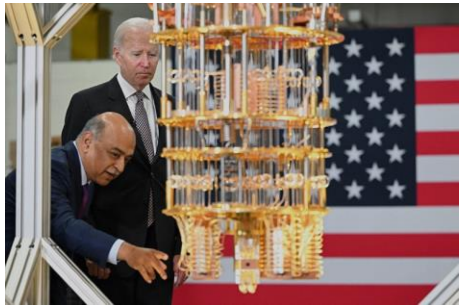

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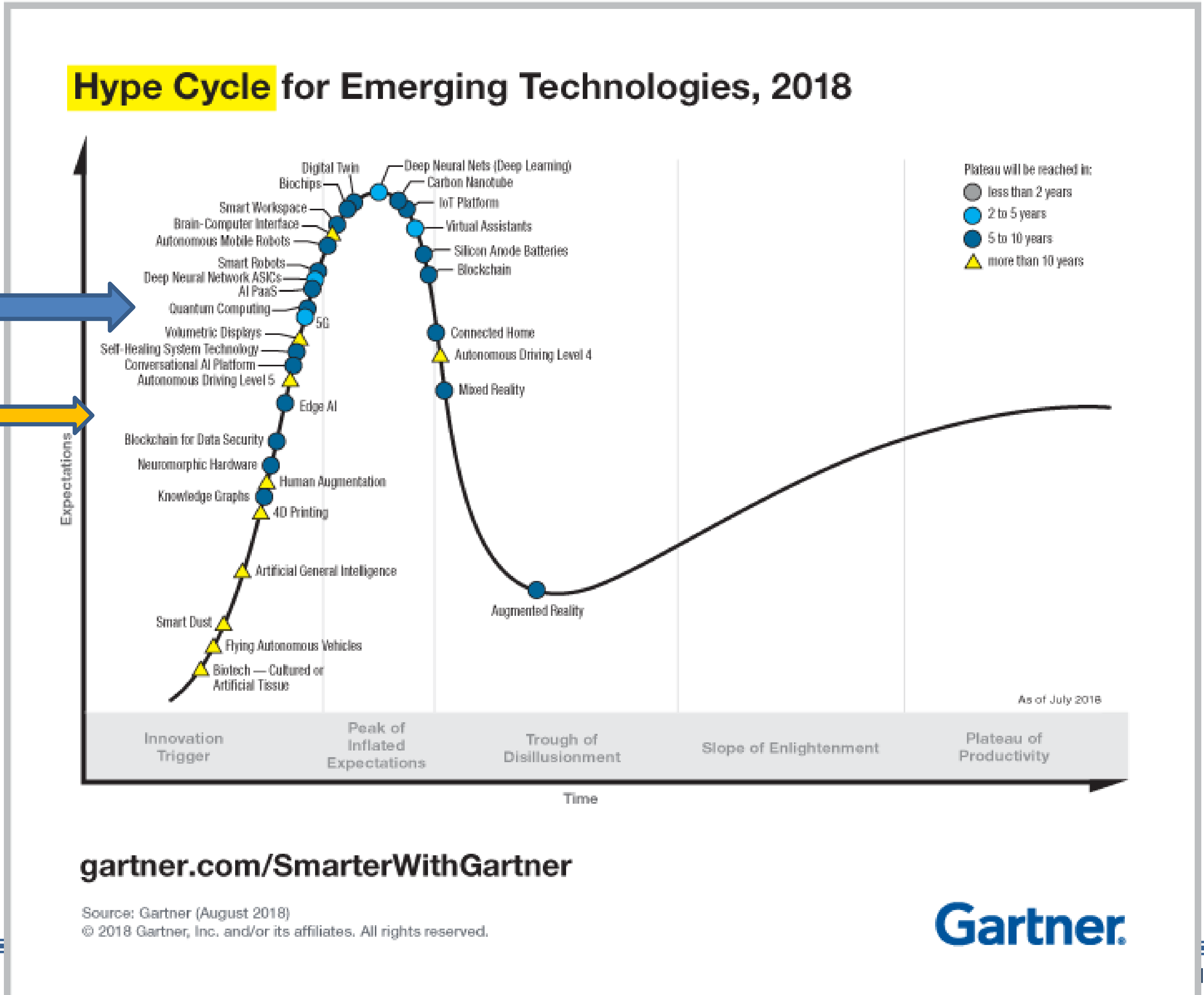
The Gartner Hype Cycle for Emerging Technologies 2018

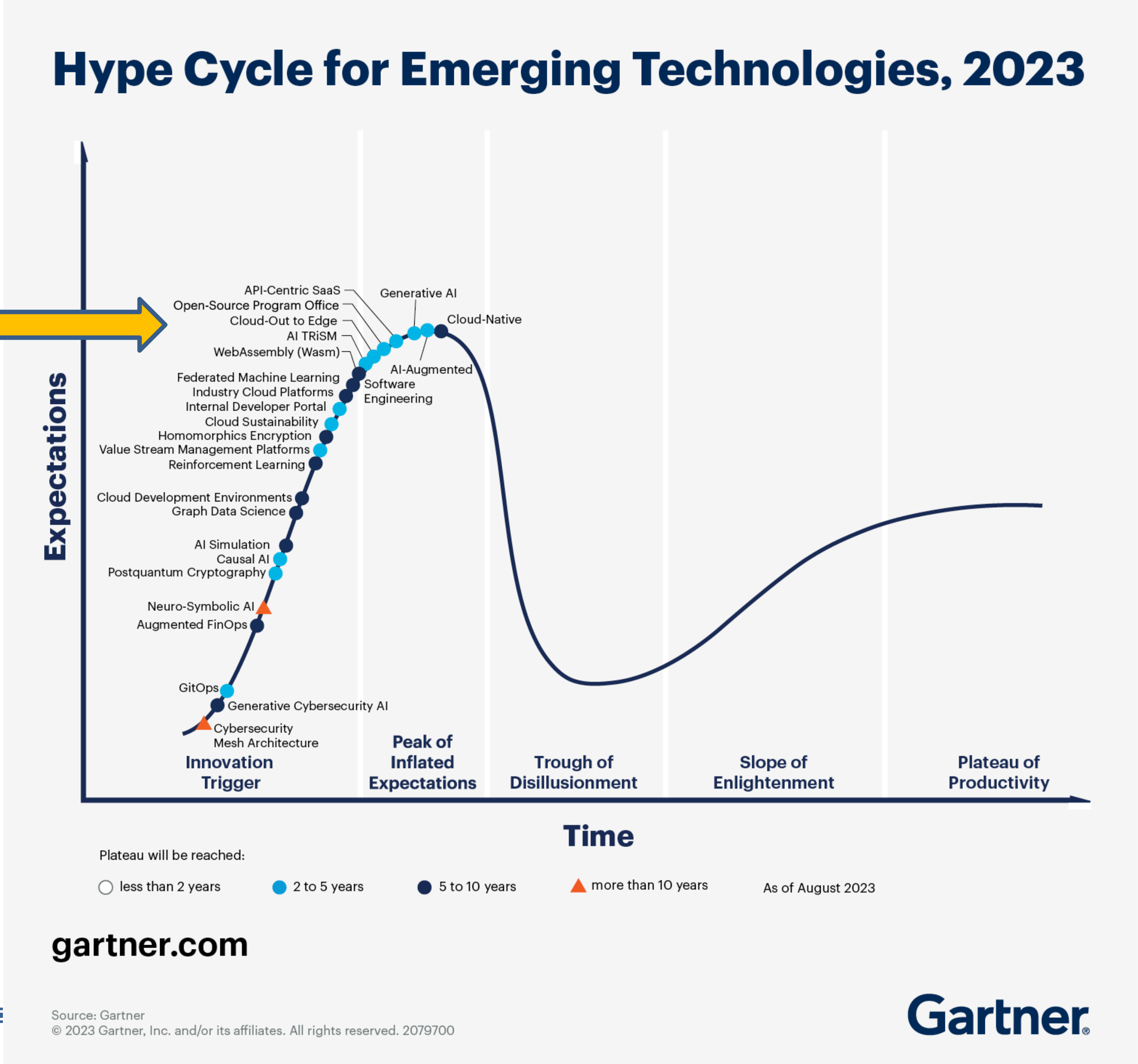
Quantum Computing

Edge AI



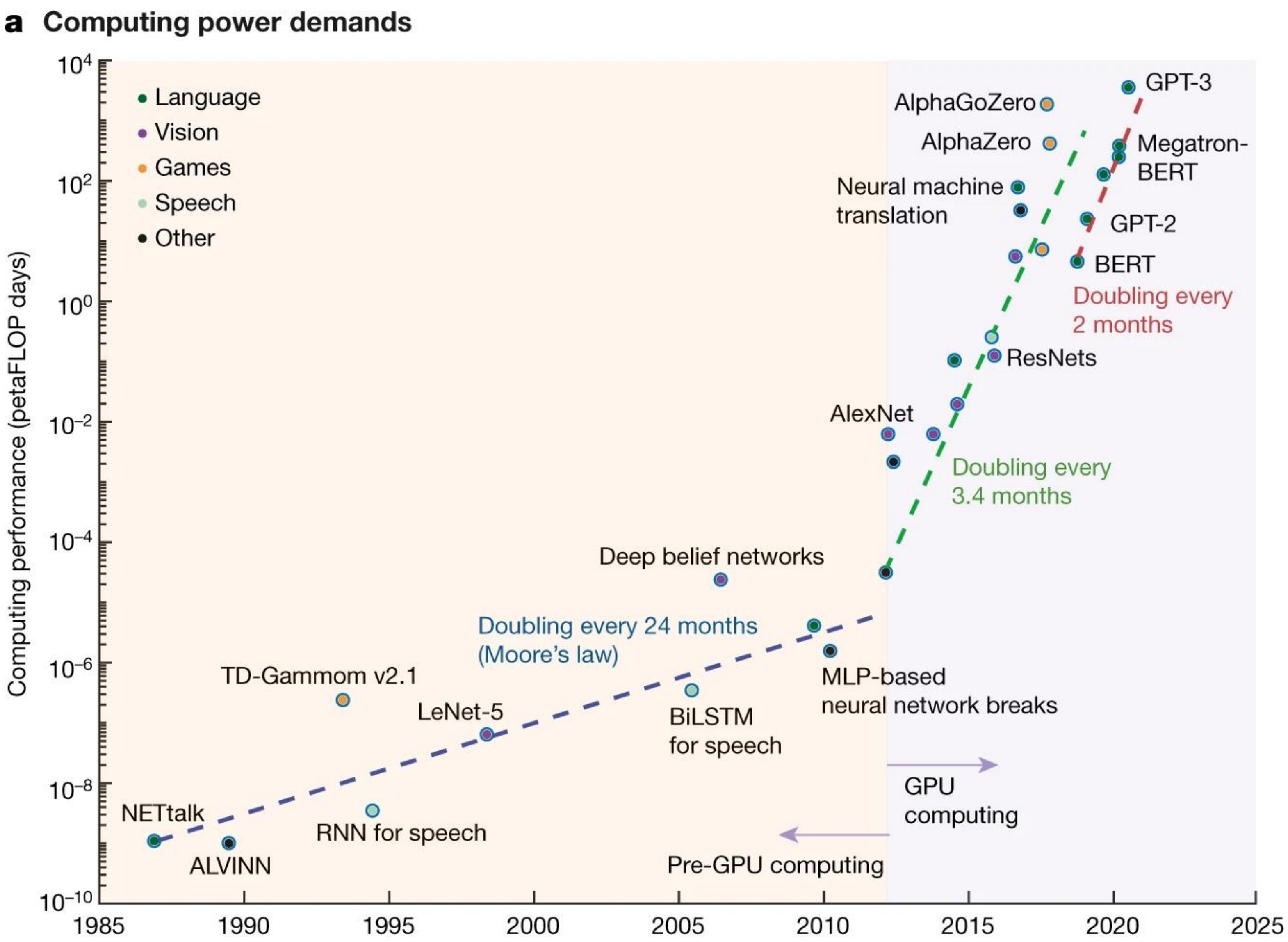
The Gartner Hype Cycle for Emerging Technologies 2023

Generative AI



Quantum Computing

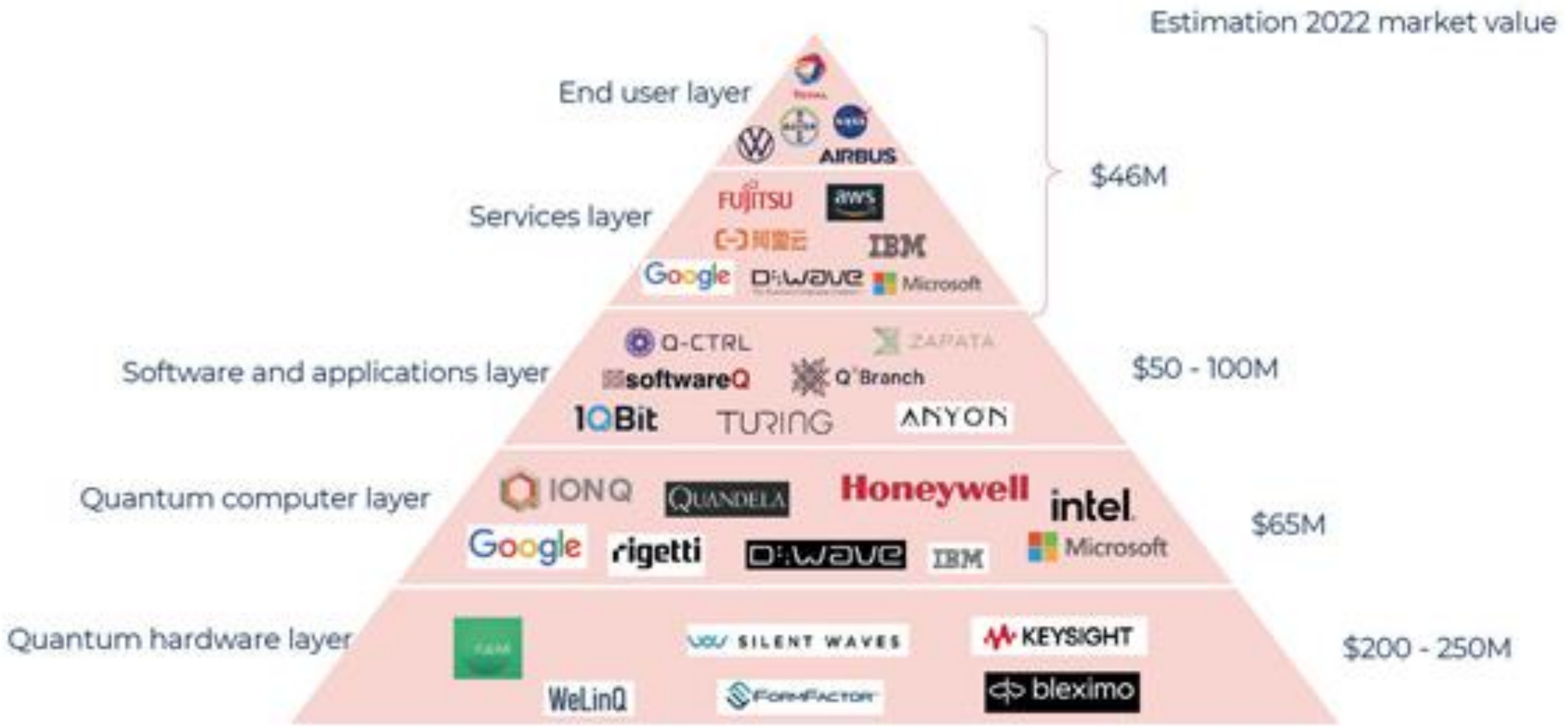
Evolution of AI due to hardware development



Mehonic, A., Kenyon, A.J. Brain-inspired computing needs a master plan. Nature 604, 255–260 (2022).

2023 QUANTUM TECHNOLOGIES SUPPLY CHAIN

Source: Quantum Technologies 2023 report, Yole Intelligence, 2023



Non exhaustive list of companies

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Quantum Sensing

Quantum sensing leverages the inherent instability of quantum states to detect minute changes in the physical world, including motion, electric, and magnetic fields that would otherwise be undetectable. By combining these properties with AI, quantum sensing applications can be developed for a broad range of industries, including healthcare, transportation, energy, sustainability, security, defense, and more.

Some of the areas where quantum sensors have demonstrated great impact include:

Biomagnetic Sensing

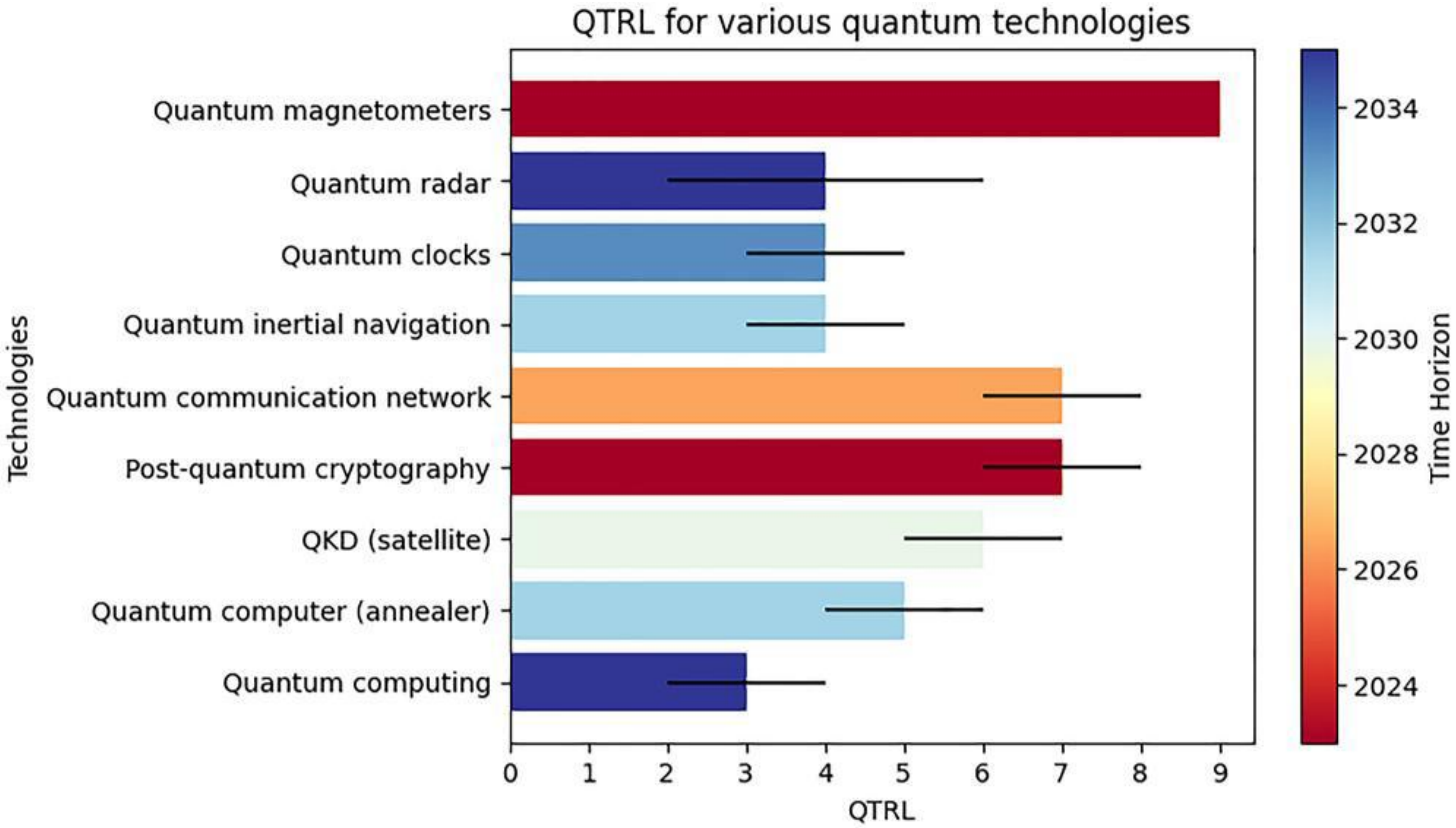
- Portable, non-invasive heart, brain, and organ scanning
- Continuous medical monitoring (e.g., wearable devices)
- Human/machine interfaces

Geophysical Sensing

- Geo-magnetic location for aerospace, nautical, autonomous and other vehicle navigation
- Underwater or underground detection, mapping and surveying
- Mineral exploration

Material Sensing

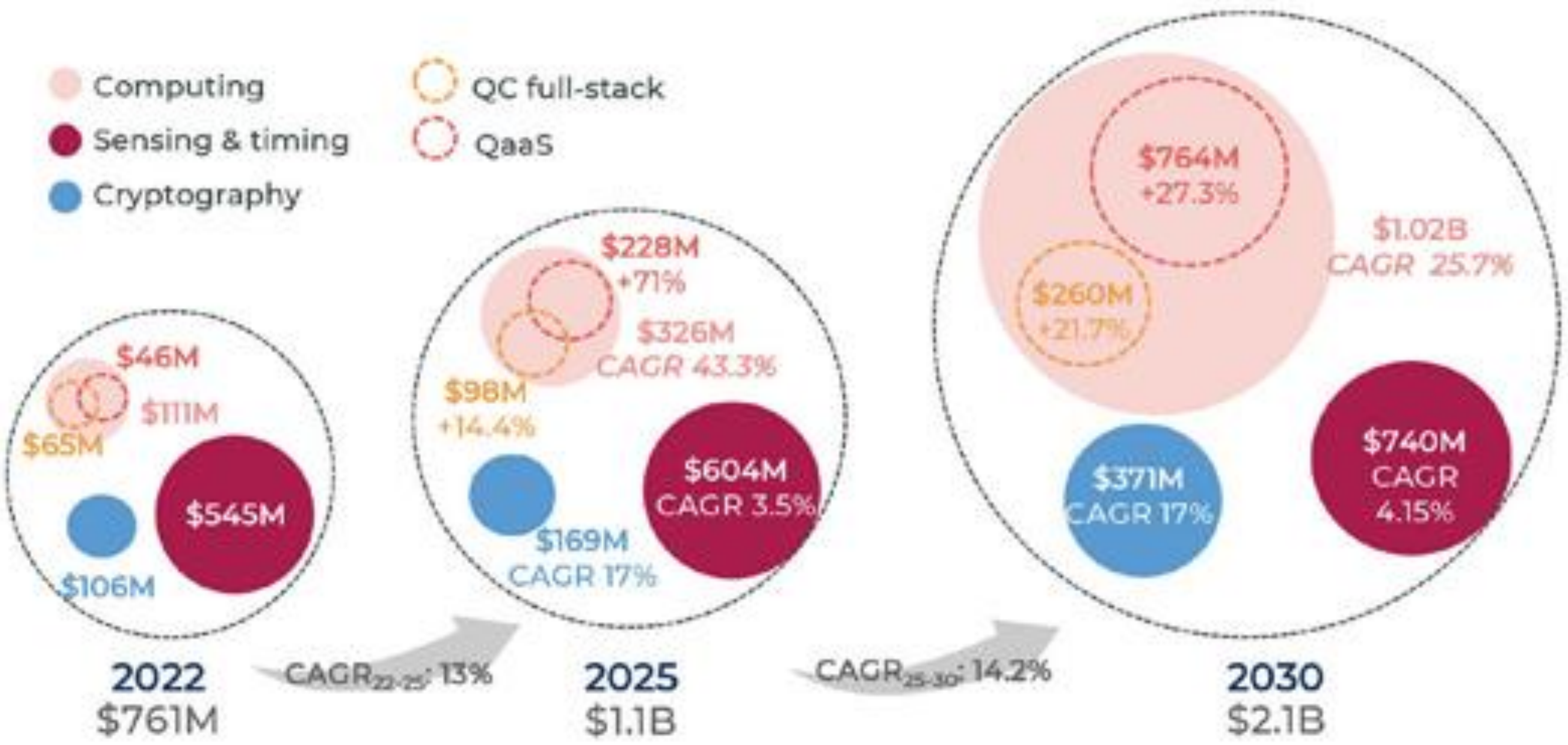
- Cybersecurity
- IT hardware diagnostics
- Nanoparticle and energy detection
- Environmental management



Purohit, A., et al.: Building a quantum-ready ecosystem. IET Quant. Comm. 1–18 (2023). https://doi.org/10.1049/qtc2.12072

2022-2030 QUANTUM TECHNOLOGIES MARKET FORECAST

Source: Quantum Technologies 2023 report, Yole Intelligence, 2023



Acknowledgments

And together with

- PRIN 2017 Photonic Extreme Learning Machine: from neuromorphic computing to universal optical interpolant, strain gauge sensor and cancer morphodynamic monitor
- PRIN 2022 Time REsolved multiparametric Sensing with opticAl Unstable REservoir
- PRIN 2022 Astrocytes gain molecular control over visual cortex plasticity and function
- PRIN 2022PNRR Targeting mitochondria to modulate neuron-astrocyte crosstalk and halt Alzheimer's Disease

BACKUP neuromorphic photonics and the brain

European Research Council
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