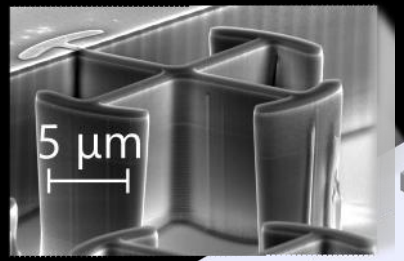
Recent progresses in photonic quantum computing

Pascale Senellart

Center for Nanoscience and Nanotechnology
CNRS – University Paris Saclay

CSO @ Quandela

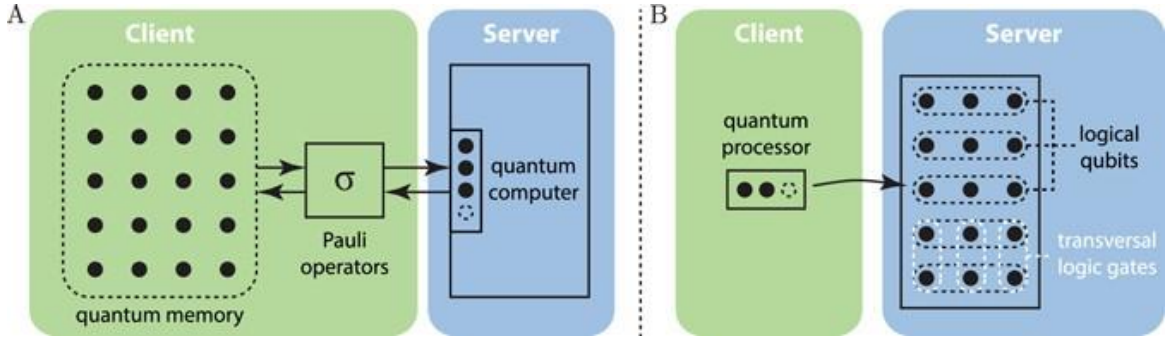


Optical quantum computing

Science 370, 1460 (2020)

Beyond photonic quantum computing

Delegated, secure, distrbuted quantum computing



npj Quantum Information 3, 23 (2017)

Quantum networks

China's quantum satellite achieves 'spooky action' at record distance

By Gabriel Popkin | Jun. 15, 2017 , 2:00 PM

Different flavors of quantum light

Discrete variables

photons

Continous variables

onde

Different flavors of quantum light

Discrete variables

photons

Continous variables

onde

QUANDELA

PsiQuantum

XANADU

Different flavors of quantum light

Discrete variables

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Continous variables

onde

QUANDELA

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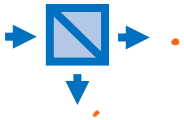
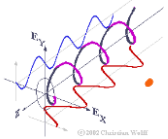
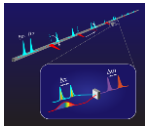
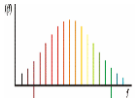
Many degree of freedom to encode – hyper encoding

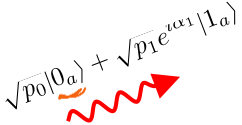
- ✓ Path
- ✓ Polarization
- ✓ OAM
- ✓ Time
- ✓ Energy
- ✓ Photon number







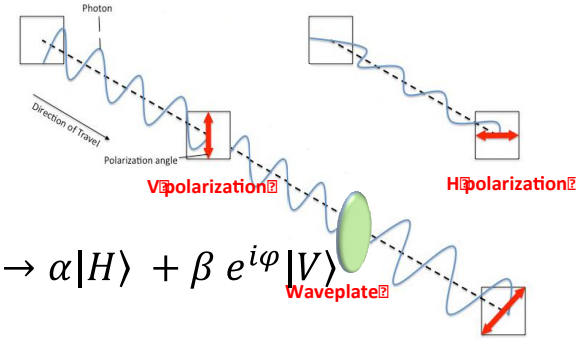




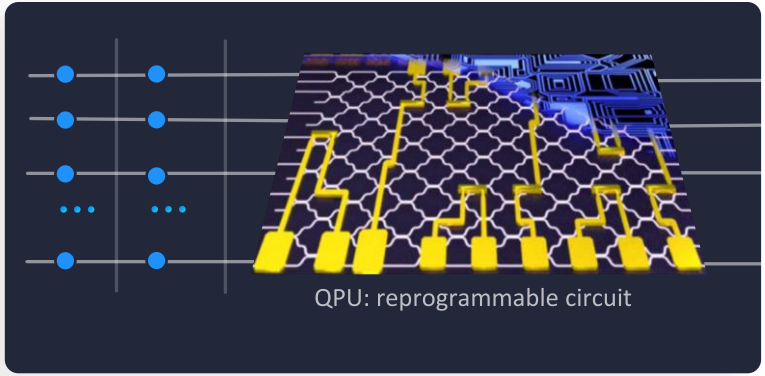
Photonic quantum computing

Strength:

- No decoherence
- Easy single qubit gates



$$|H\rangle \rightarrow \alpha|H\rangle + \beta\, e^{i\varphi}|V\rangle$$



- Moderated cryogenic resources
- Integration, modularity
- Distributed, delegated computation

Photonic quantum computing

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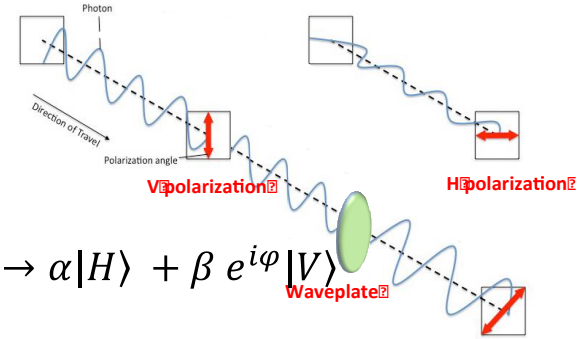

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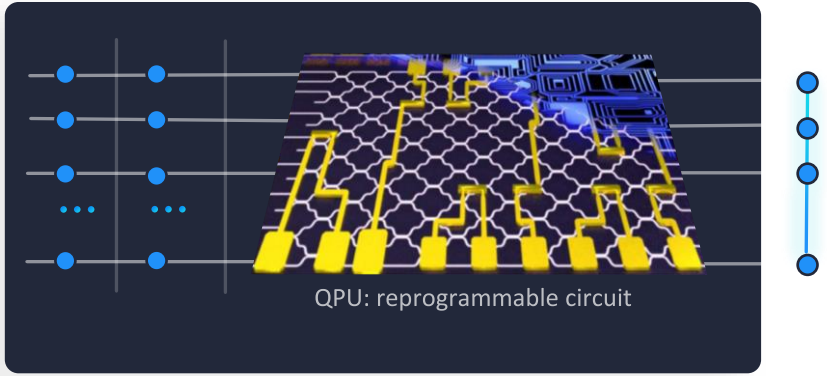


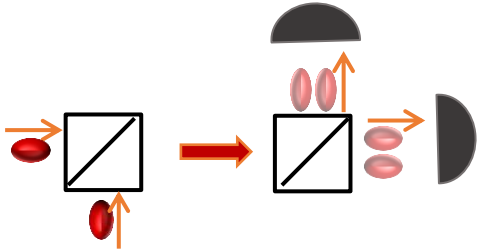
Challenges:

- Efficient single photon sources
- Losses
- 2 qubits gates

⇔ multiphoton entanglement

Photonic quantum computing roadmap

NISQ: linear computation



A scheme for efficient quantum computation with linear optics

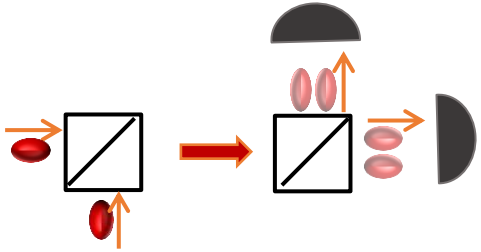
E. Knill*, R. Laflamme* & G. J. Milburn†

* Los Alamos National Laboratory, MS B265, Los Alamos, New Mexico 87545, USA
† Centre for Quantum Computer Technology, University of Queensland, St. Lucia, Australia

$$|1\rangle_1 |1\rangle_2 \xrightarrow{U_{BS}} \frac{1}{\sqrt{2}} (|2\rangle_3 |0\rangle_4 - |0\rangle_3 |2\rangle_4)$$

Photonic quantum computing roadmap

NISQ: linear computation



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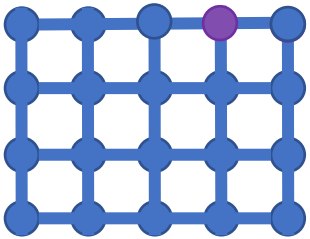
Large scale and fault tolerance : measurement based QC



R. Raussendorf, D.E. Browne, H.J. Briegel
Phys. Rev. A 68, 022312 (2003)

Photonic quantum computing roadmap

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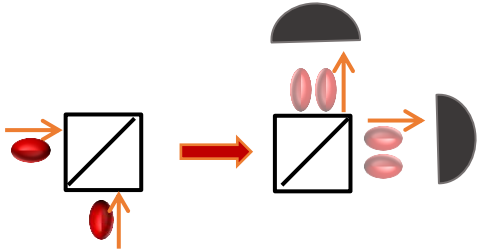

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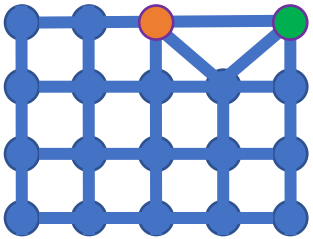

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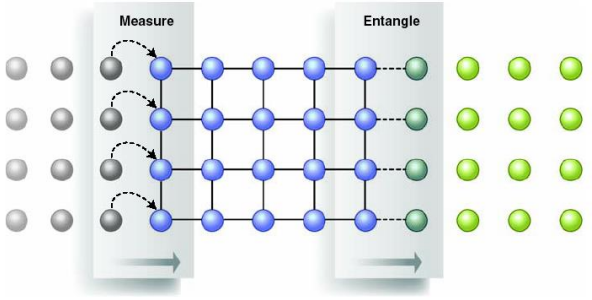
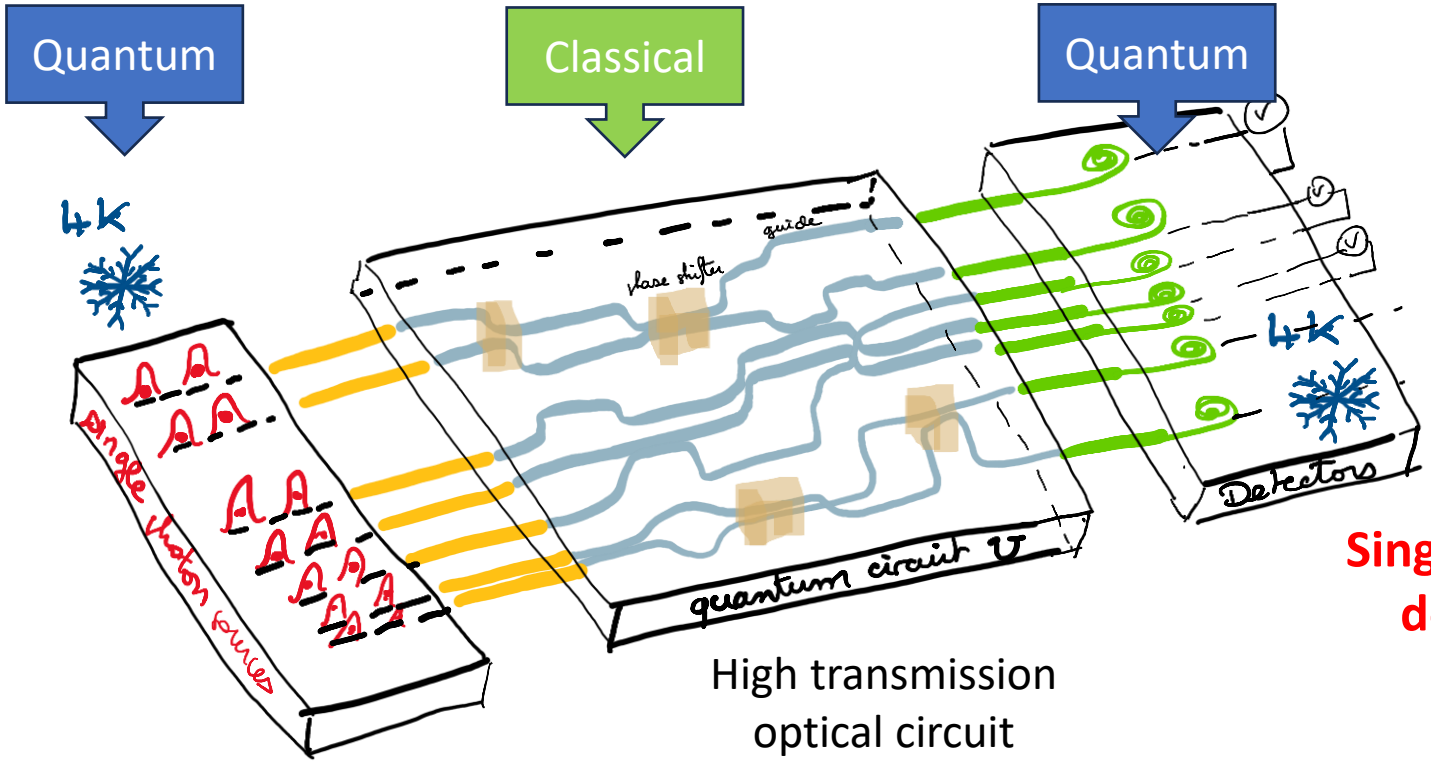


NISQ Architecture

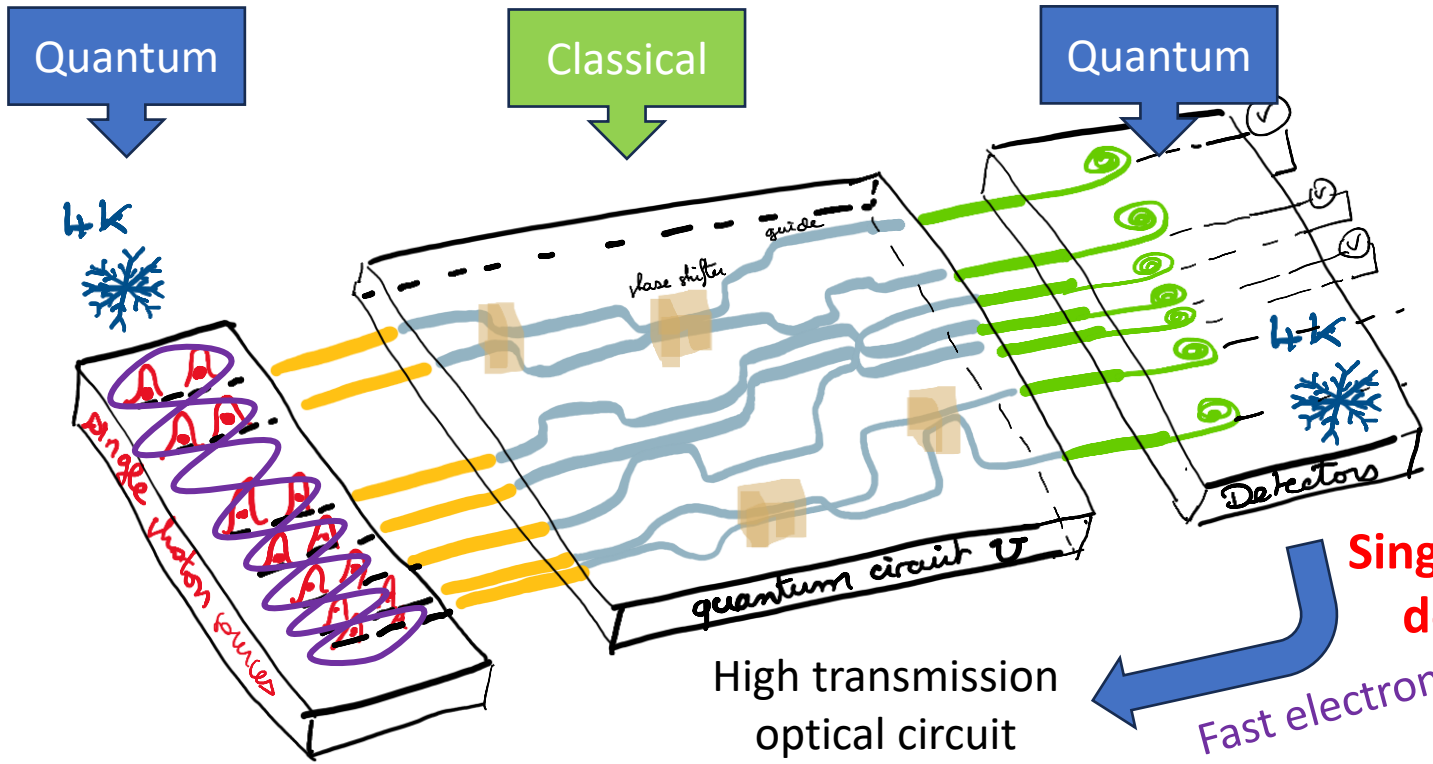


Single photon sources

High transmission optical circuit

Single photon detectors

Fault Tolerant Architecture



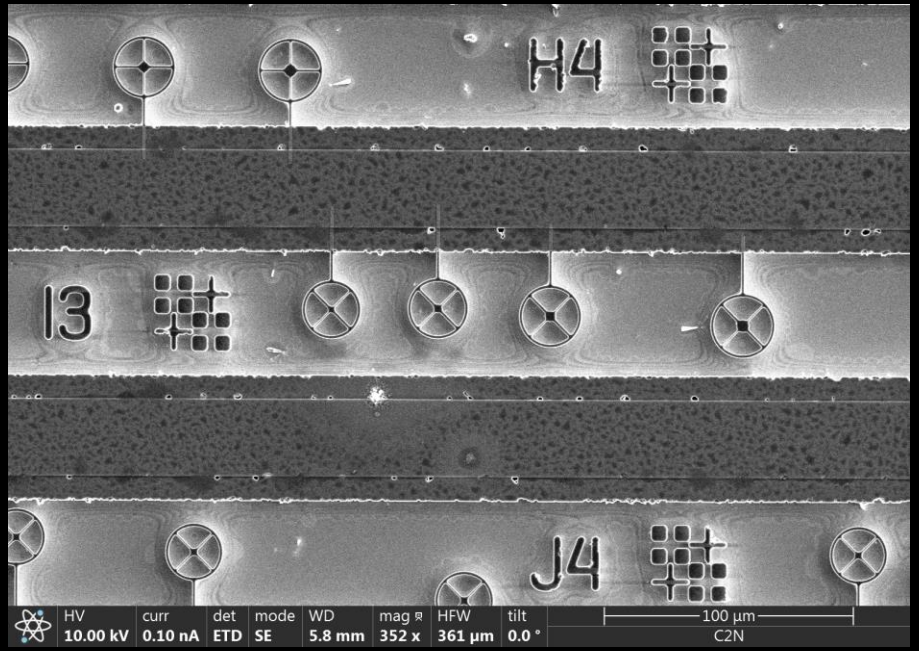
Entangled photon sources

High transmission optical circuit

Fast reconfiguration

Single photon detectors

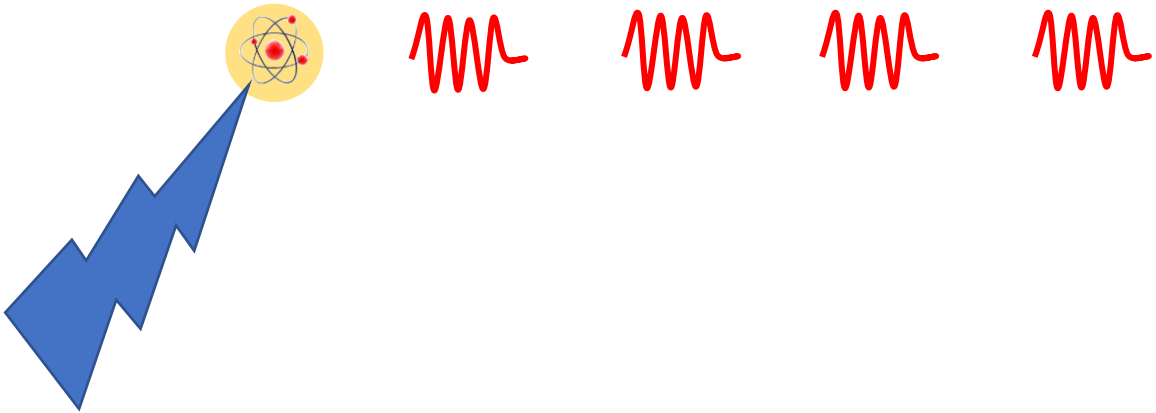
Fast electronics



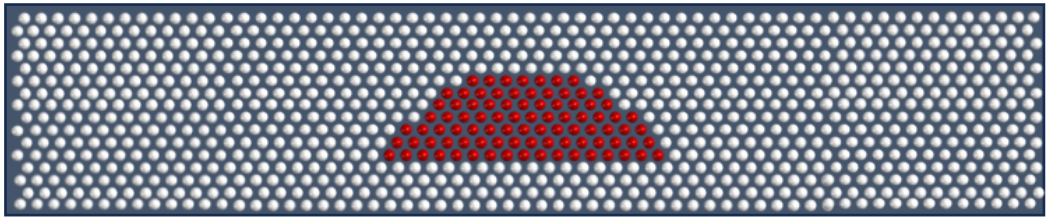
Efficient semiconductor
Single-photon sources

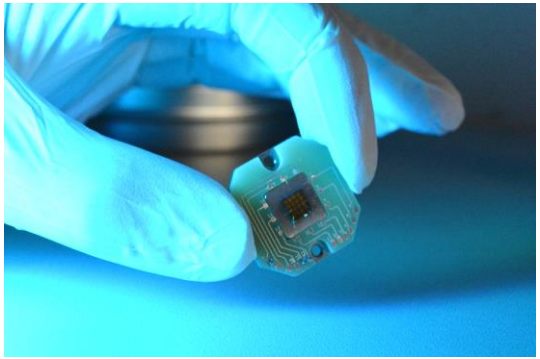
Single photon source

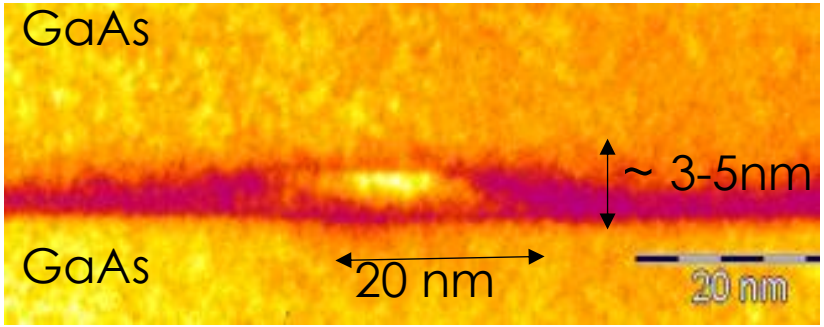
Atom – single photon emitter



Artificial semiconductor atom

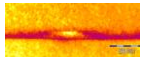




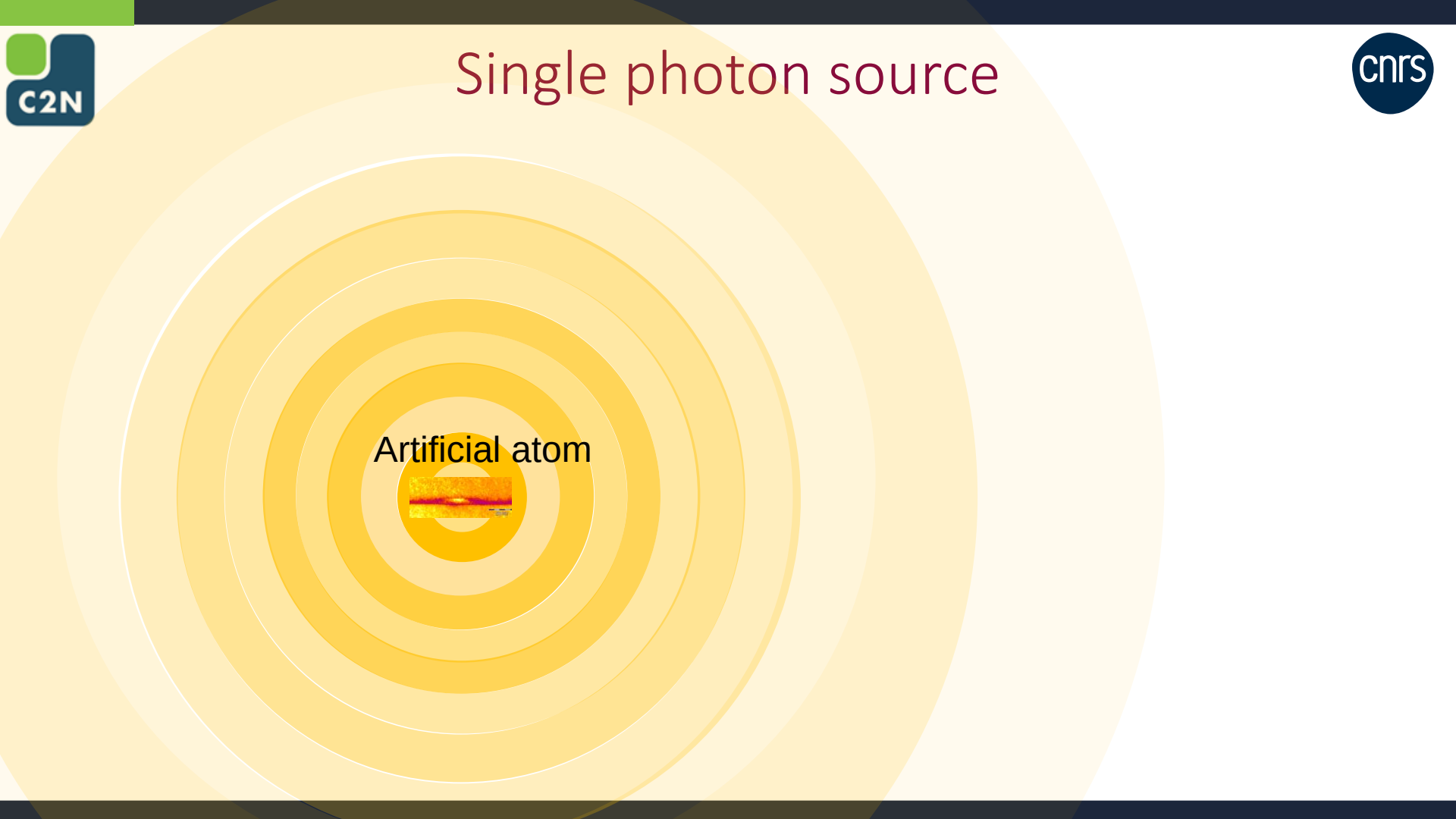


Single photon source

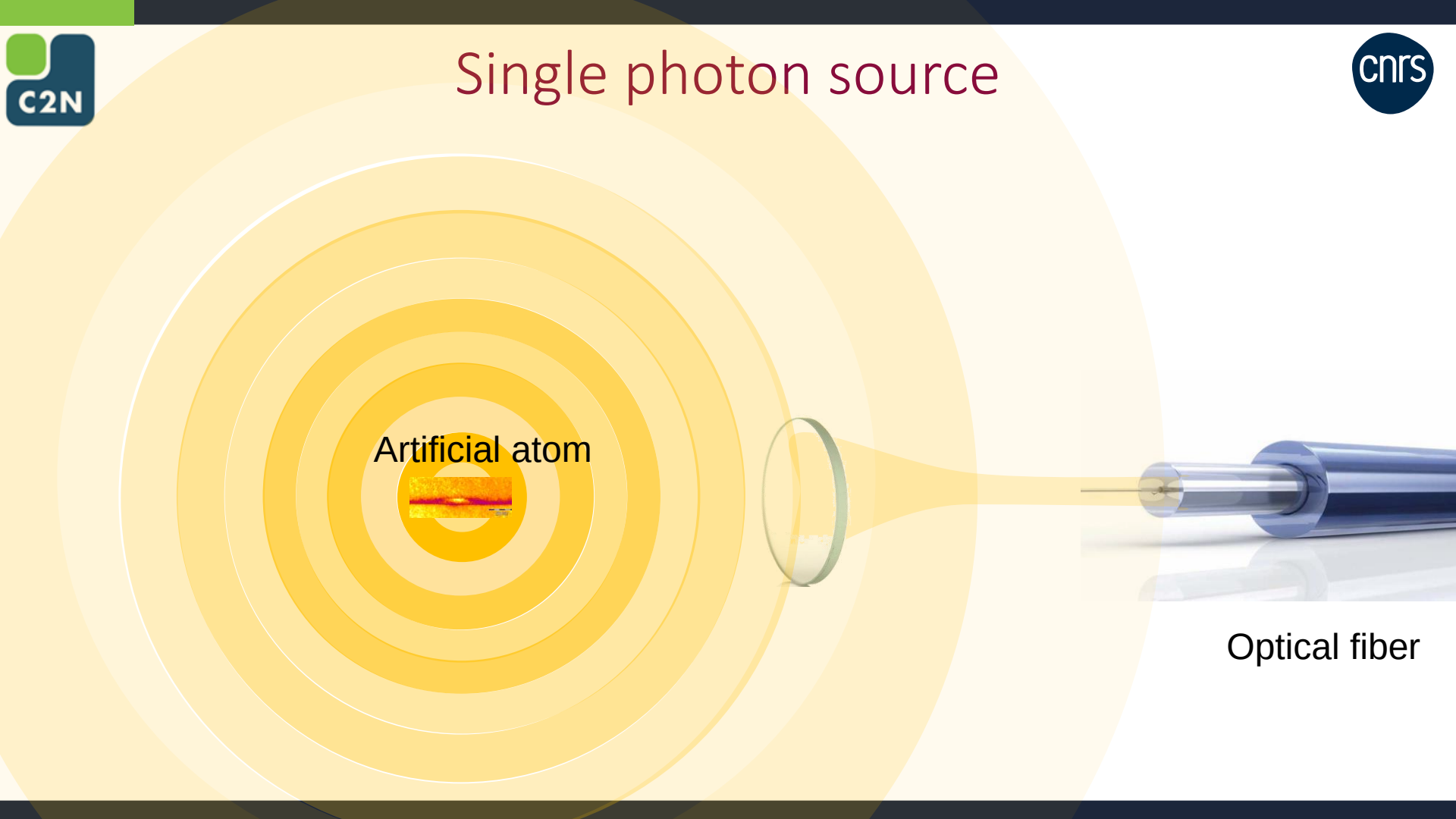
Artificial atom



Single photon source

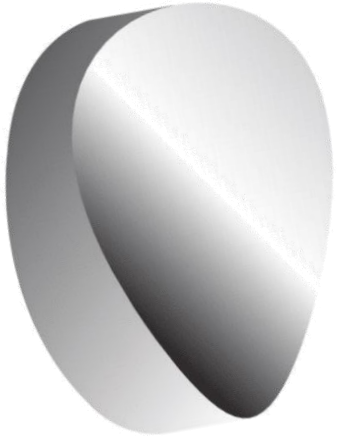


Single photon source

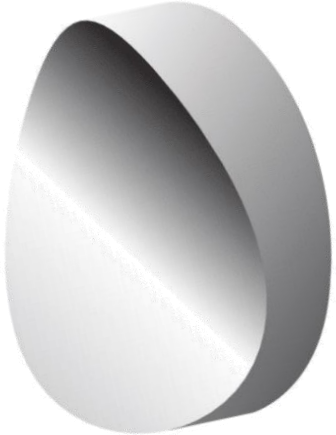


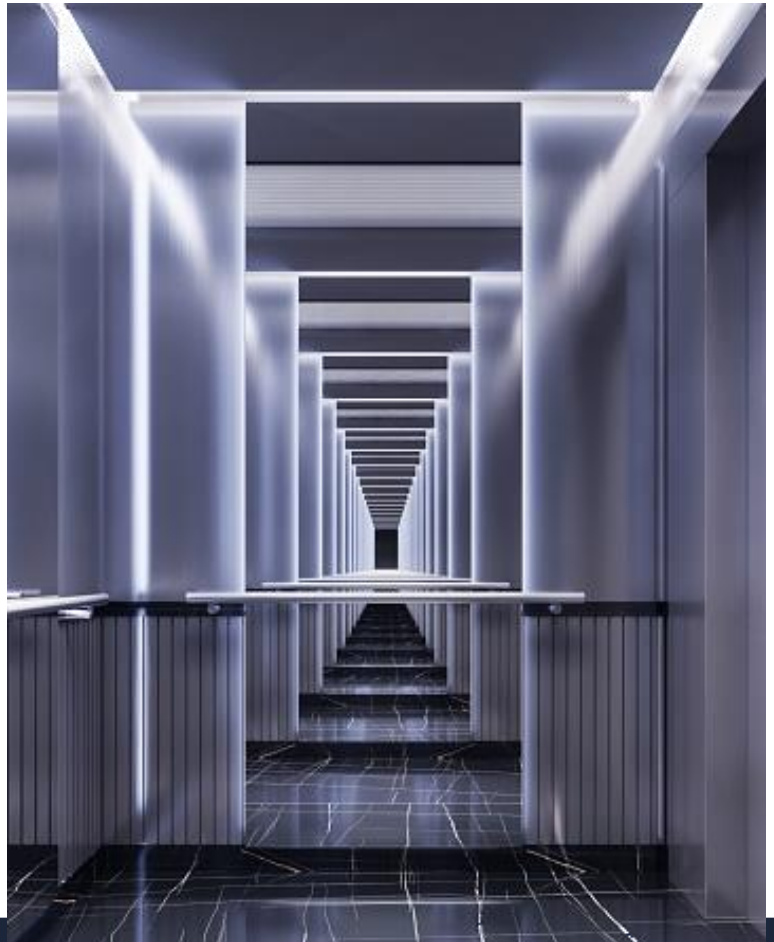
Single photon source

mirror



mirror





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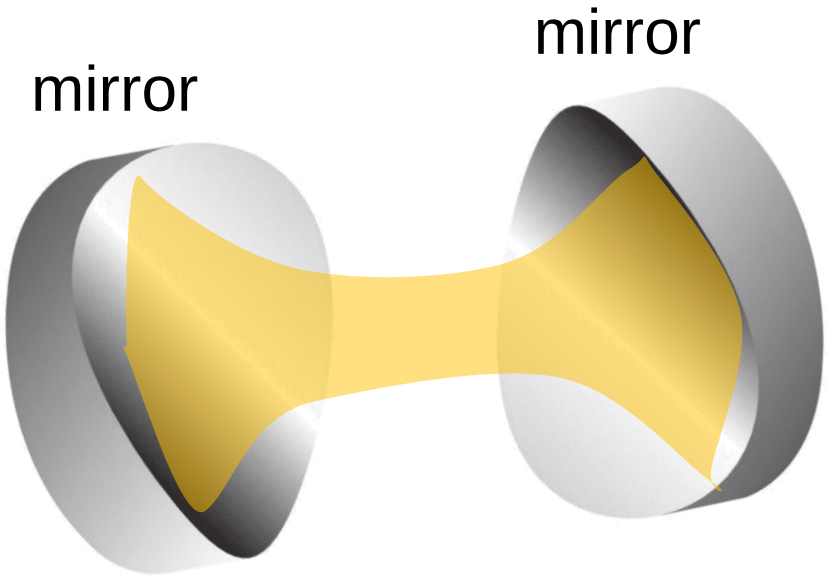

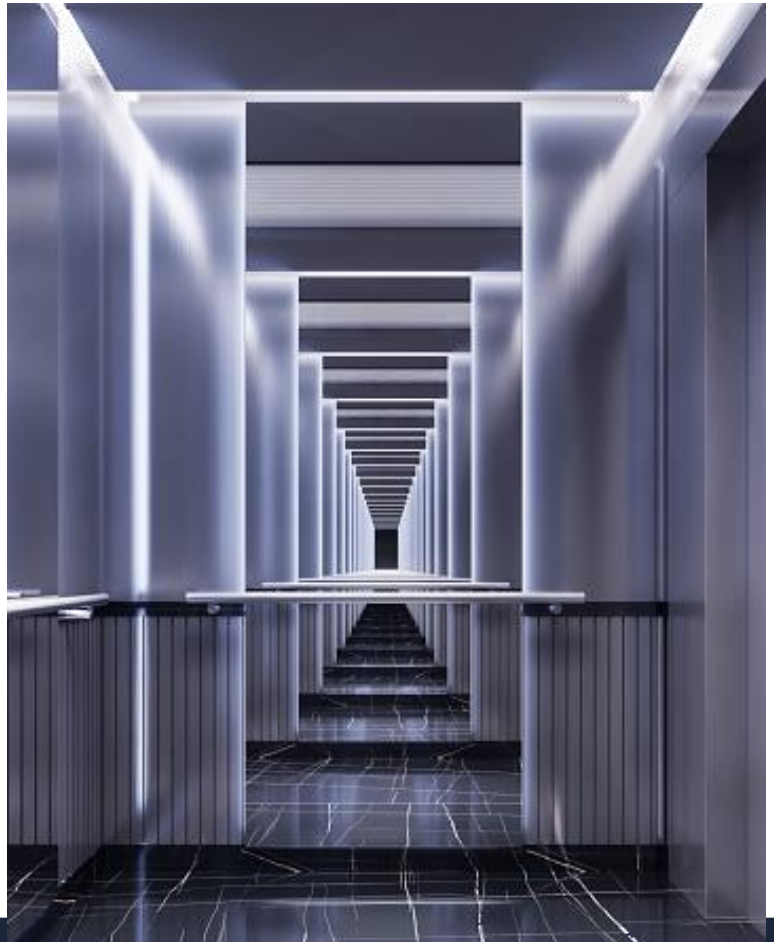

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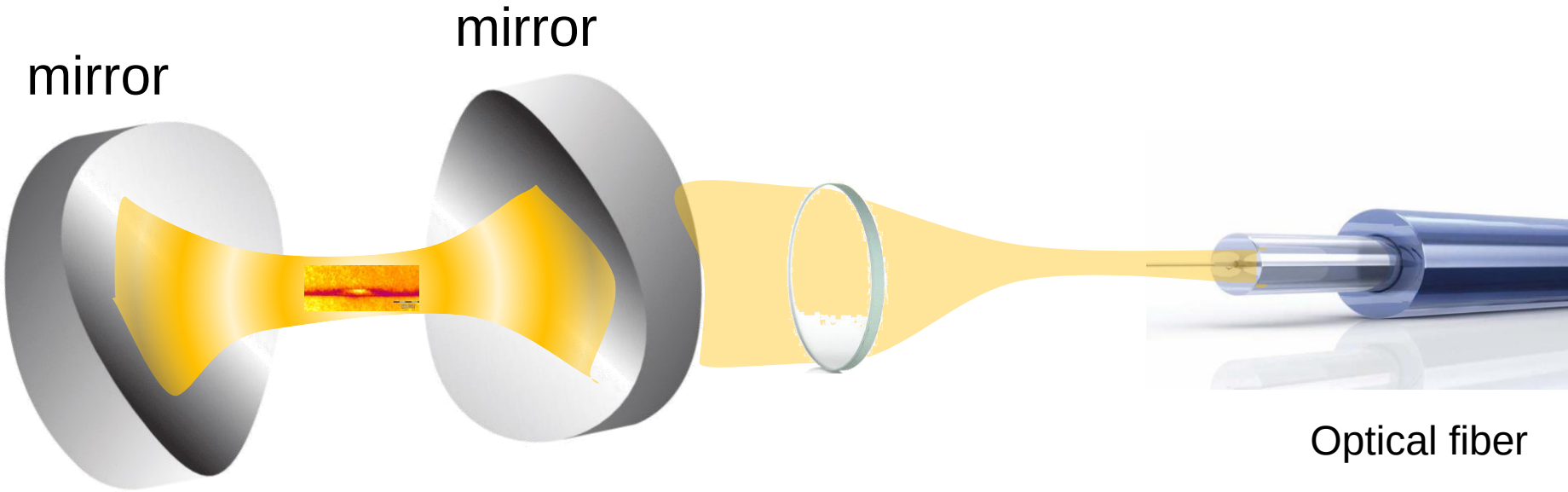
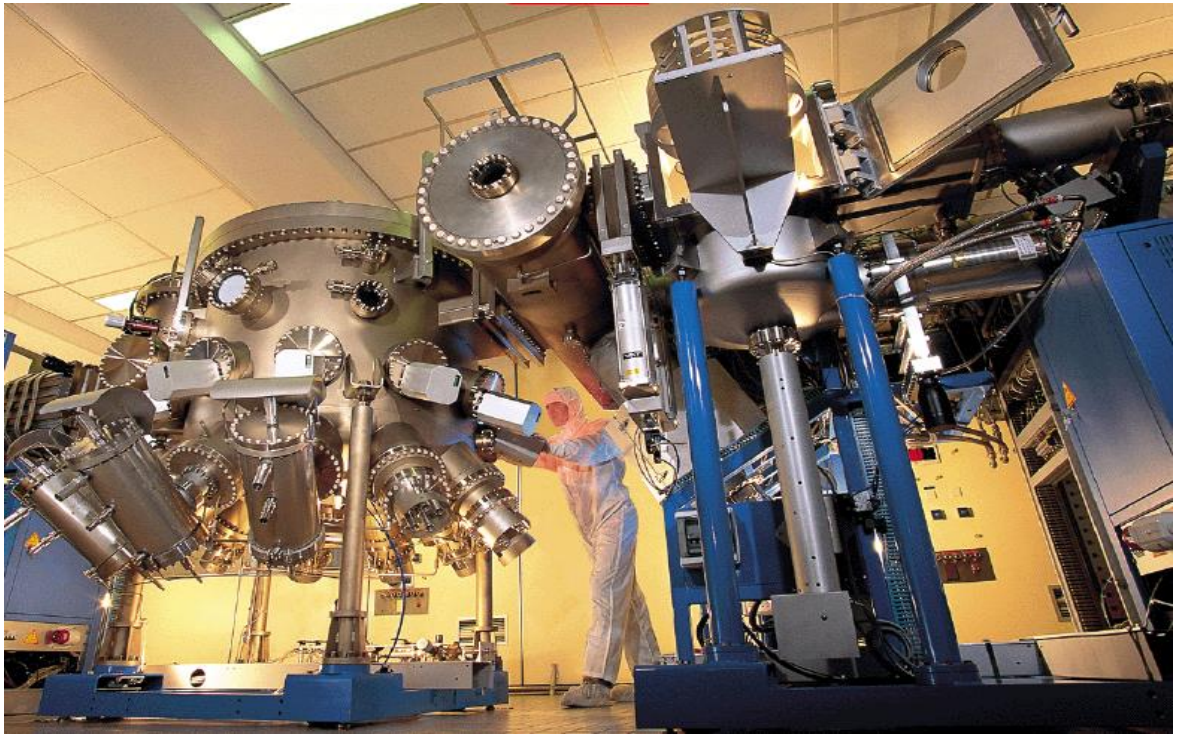
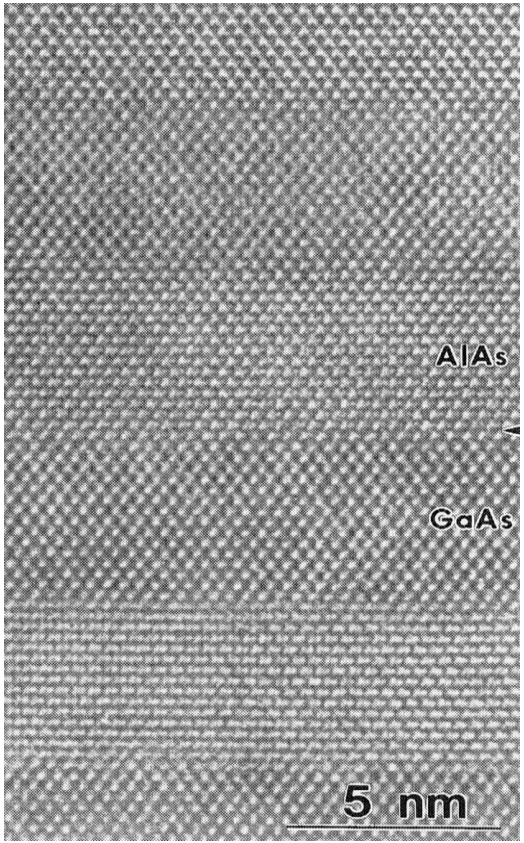
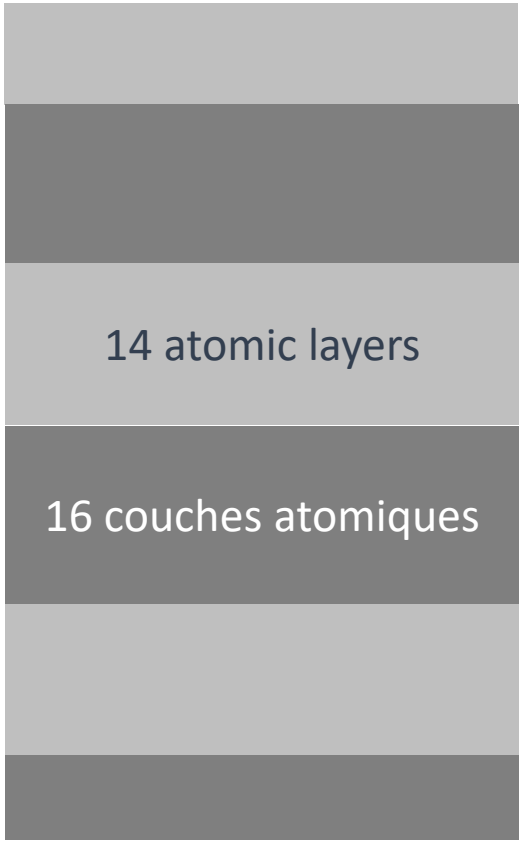


Semiconductor single photon sources

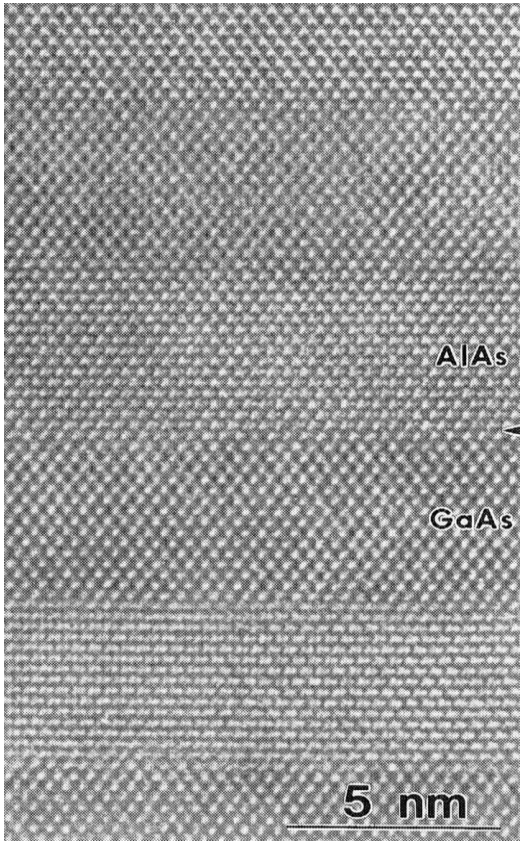


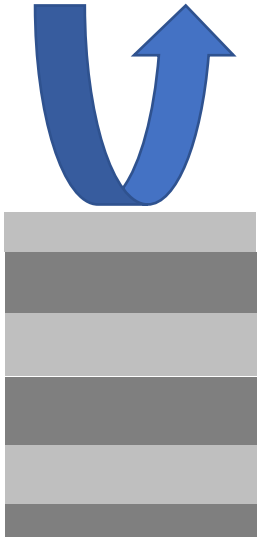
Semiconductor mirrors



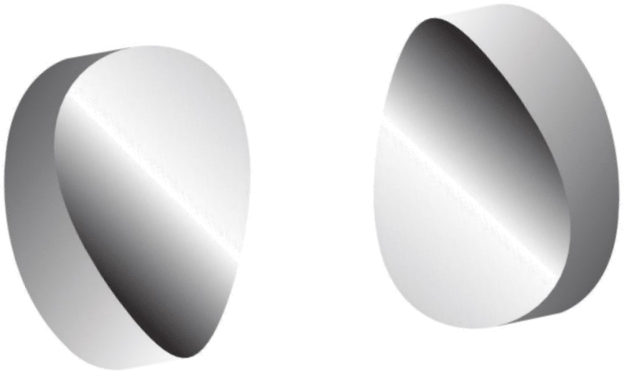


Semiconductor optical cavity

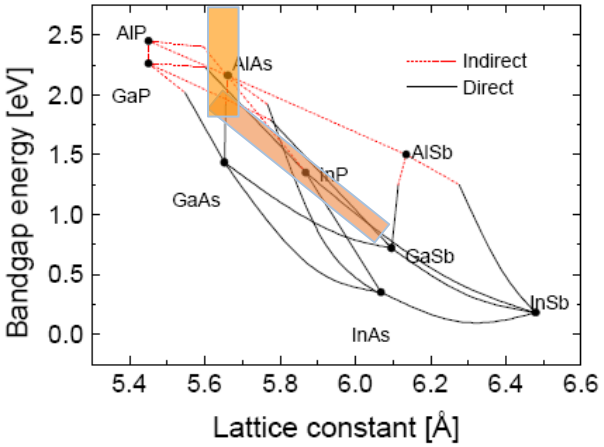


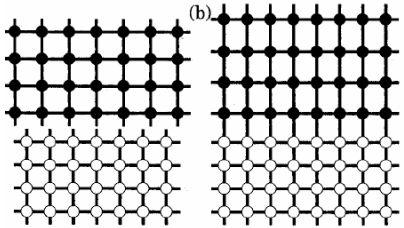


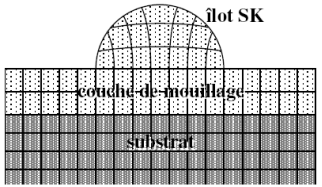
mirror

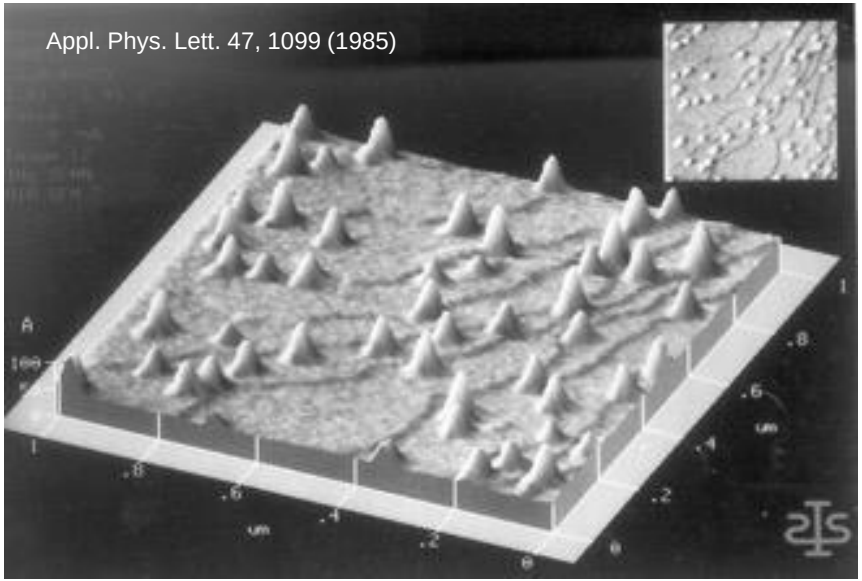


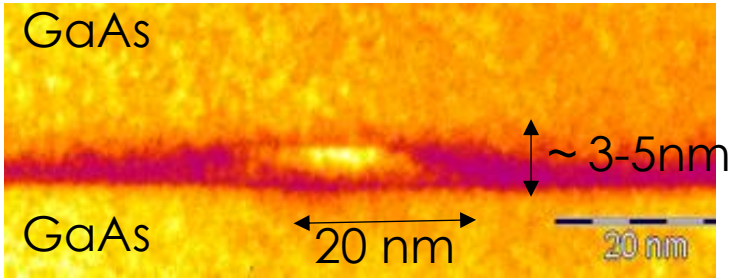
Artificial atom – semiconductor quantum dot



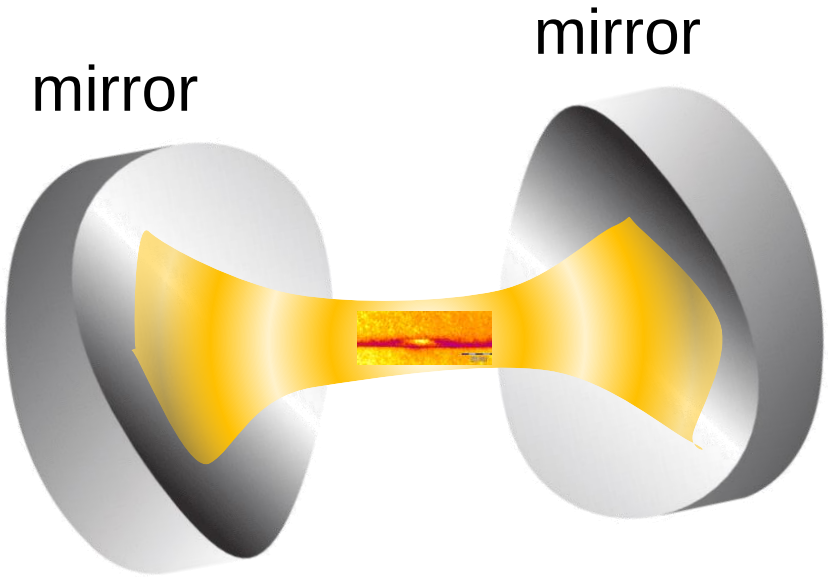




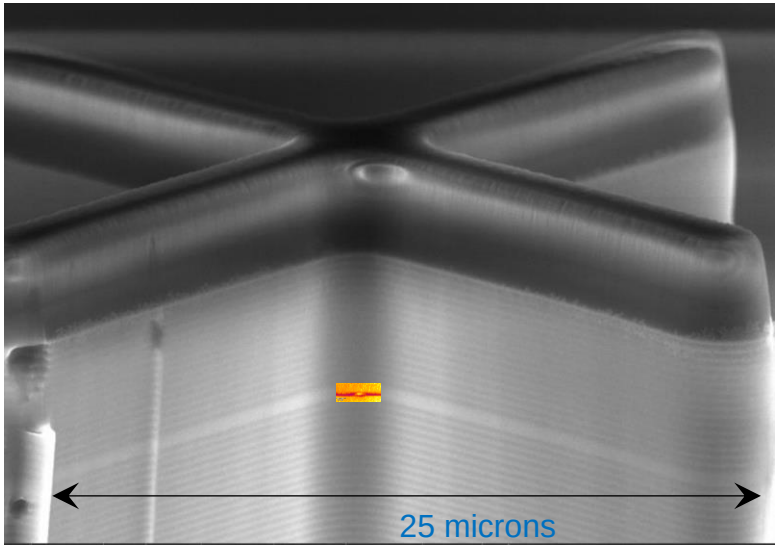




Semiconductor single-photon source



Our cavity cavité



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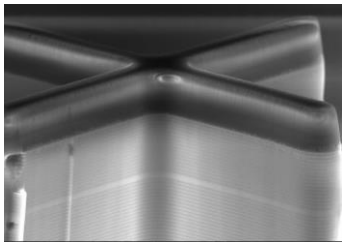
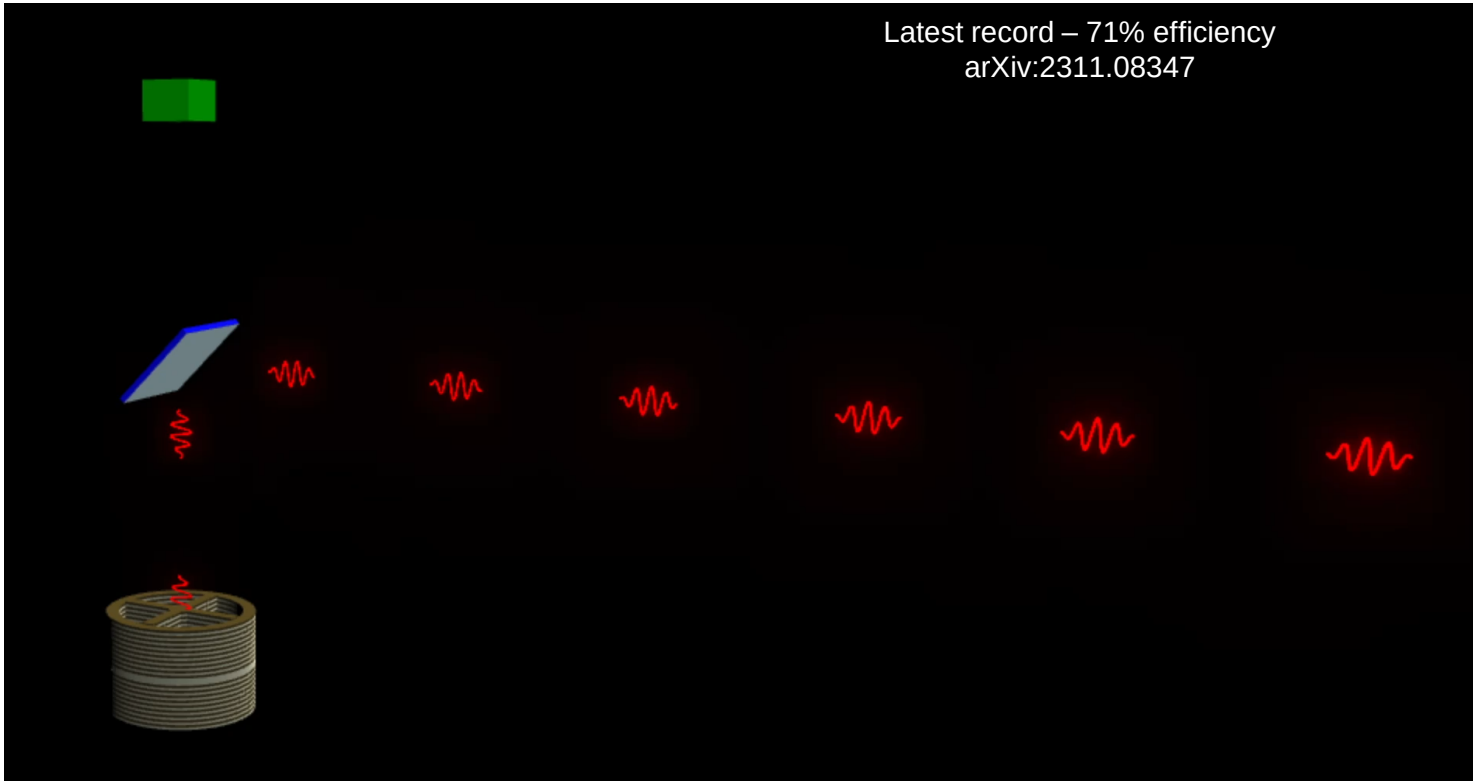
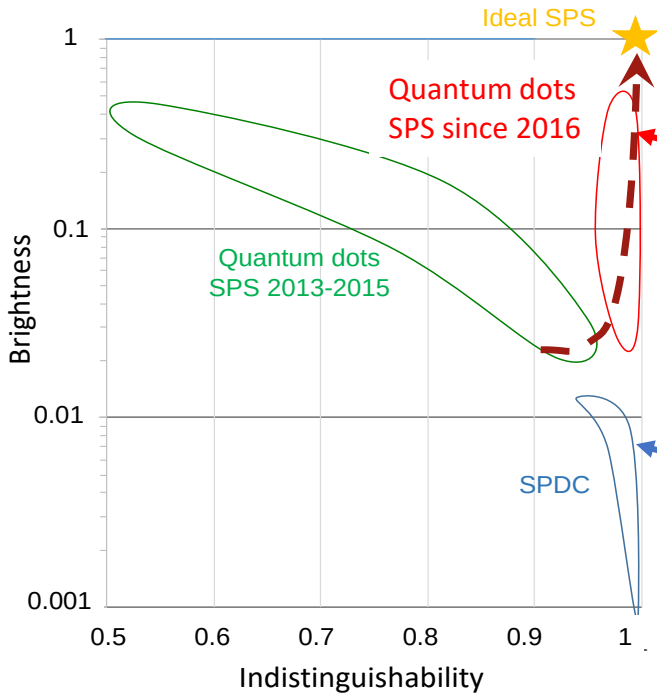


25 µm



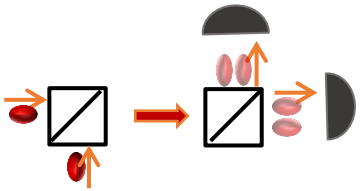
Quantum dot based of single photon sources

Latest record – 71% brightness in fibre
arXiv:2311.08347



QUANDELA

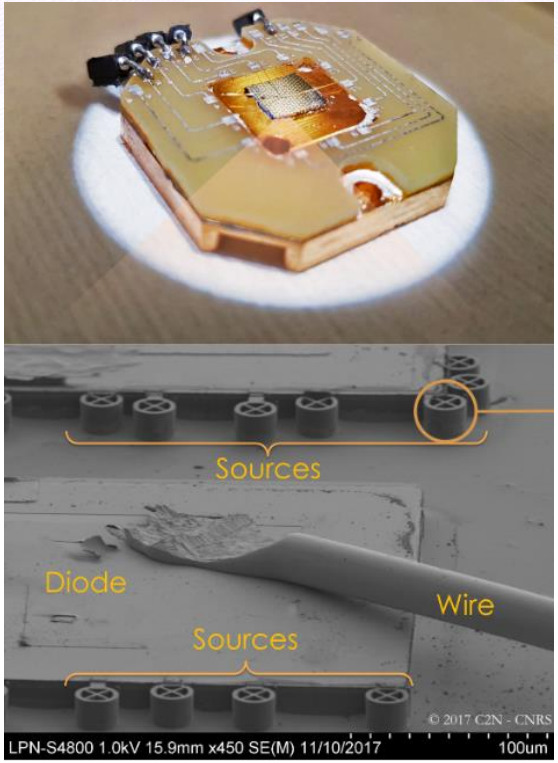
PsiQuantum

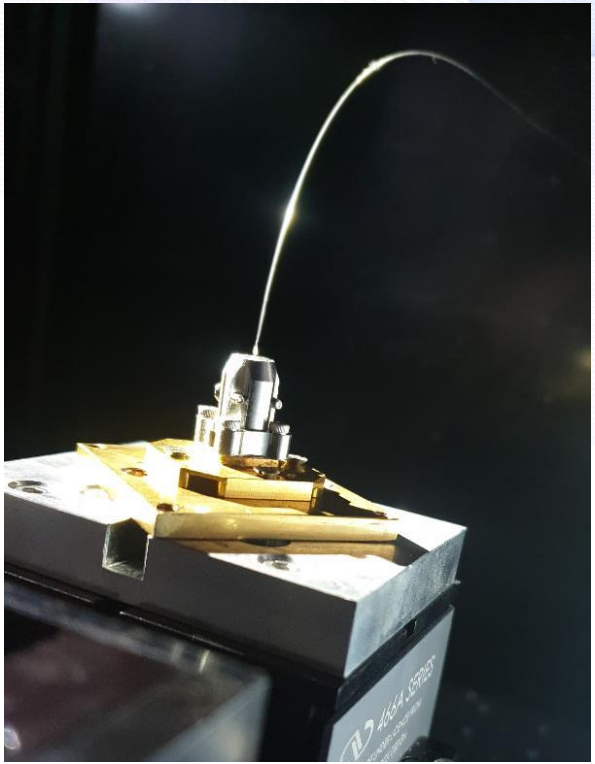


Senellart , Solomon and White,
Nature Nanotechnology Review (2017)

Senellart & Thomas
Nature Nanotechnology 16 (4), 367-368 (20

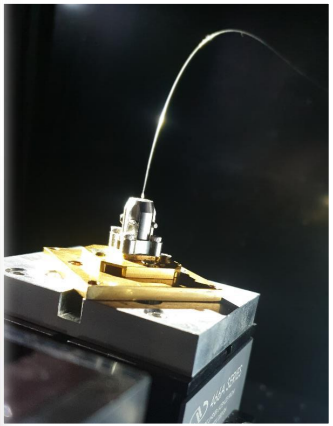
Quandela single photon sources

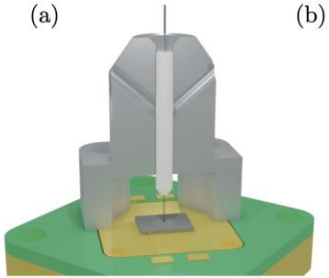


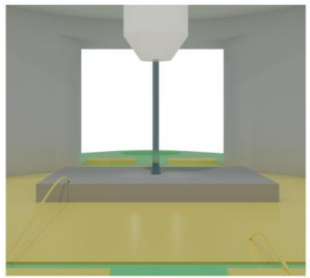


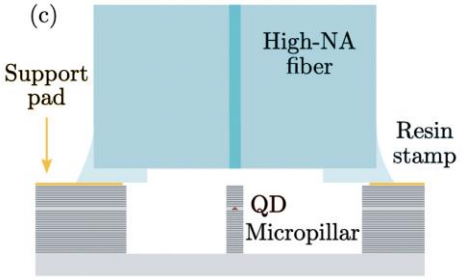
Stand alone single photon source

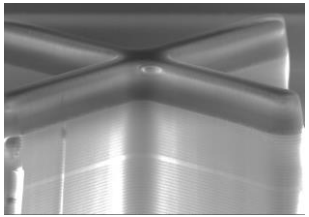
since 2017







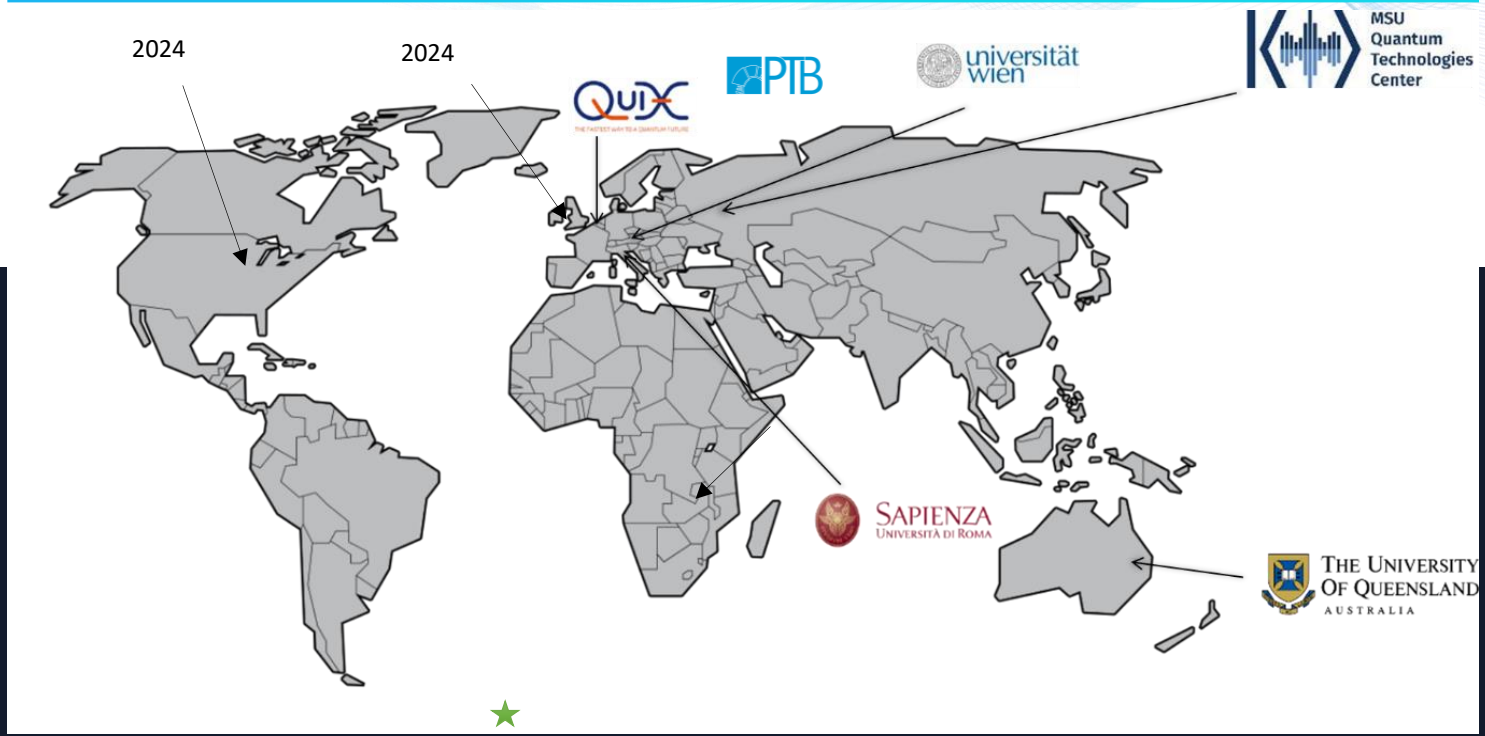




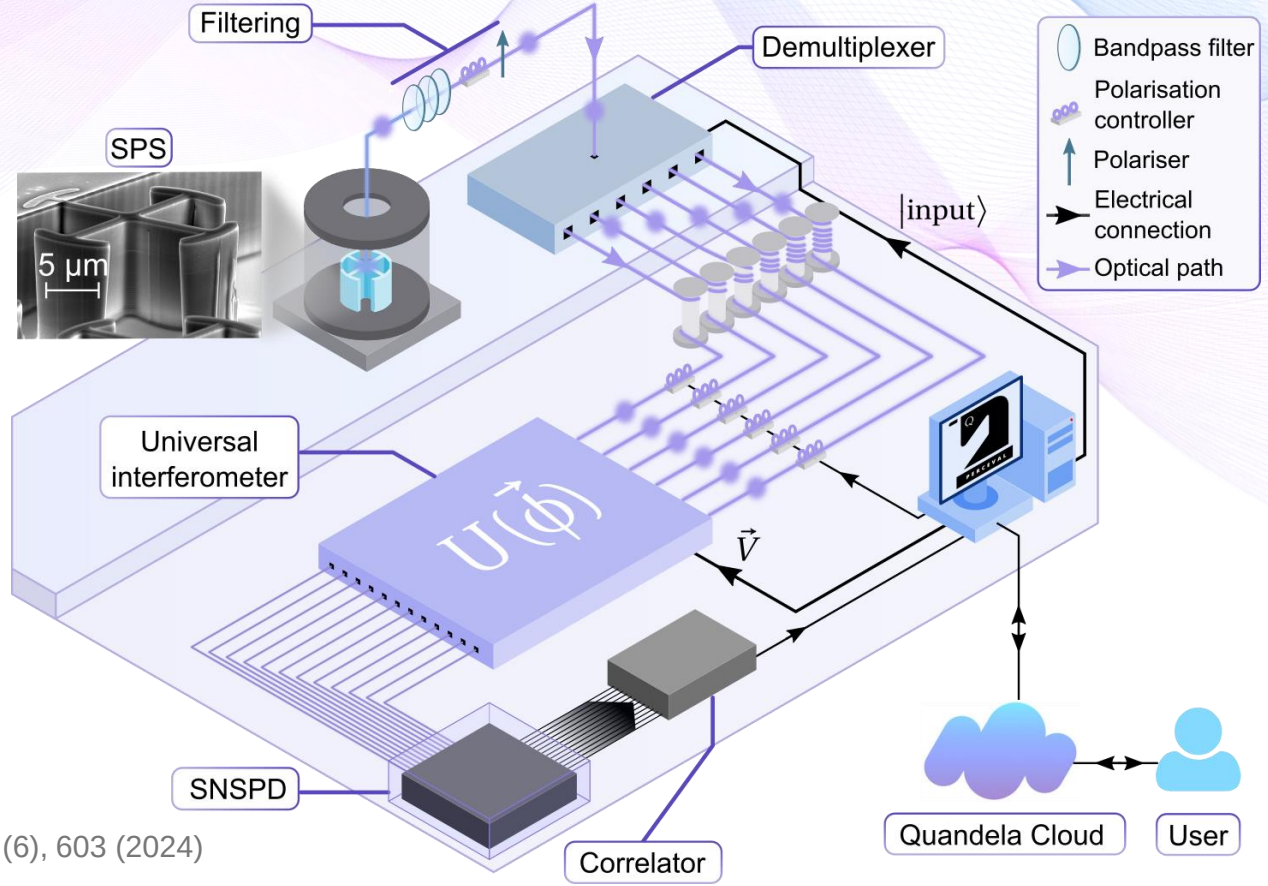
Margaria et al. :2410.07760

Quandela single photon sources

Clients

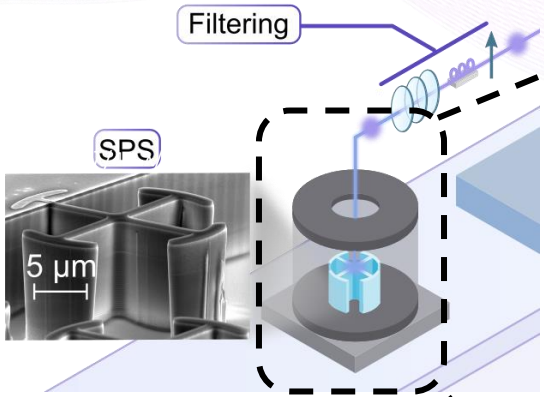


Quandela NISQ quantum computer



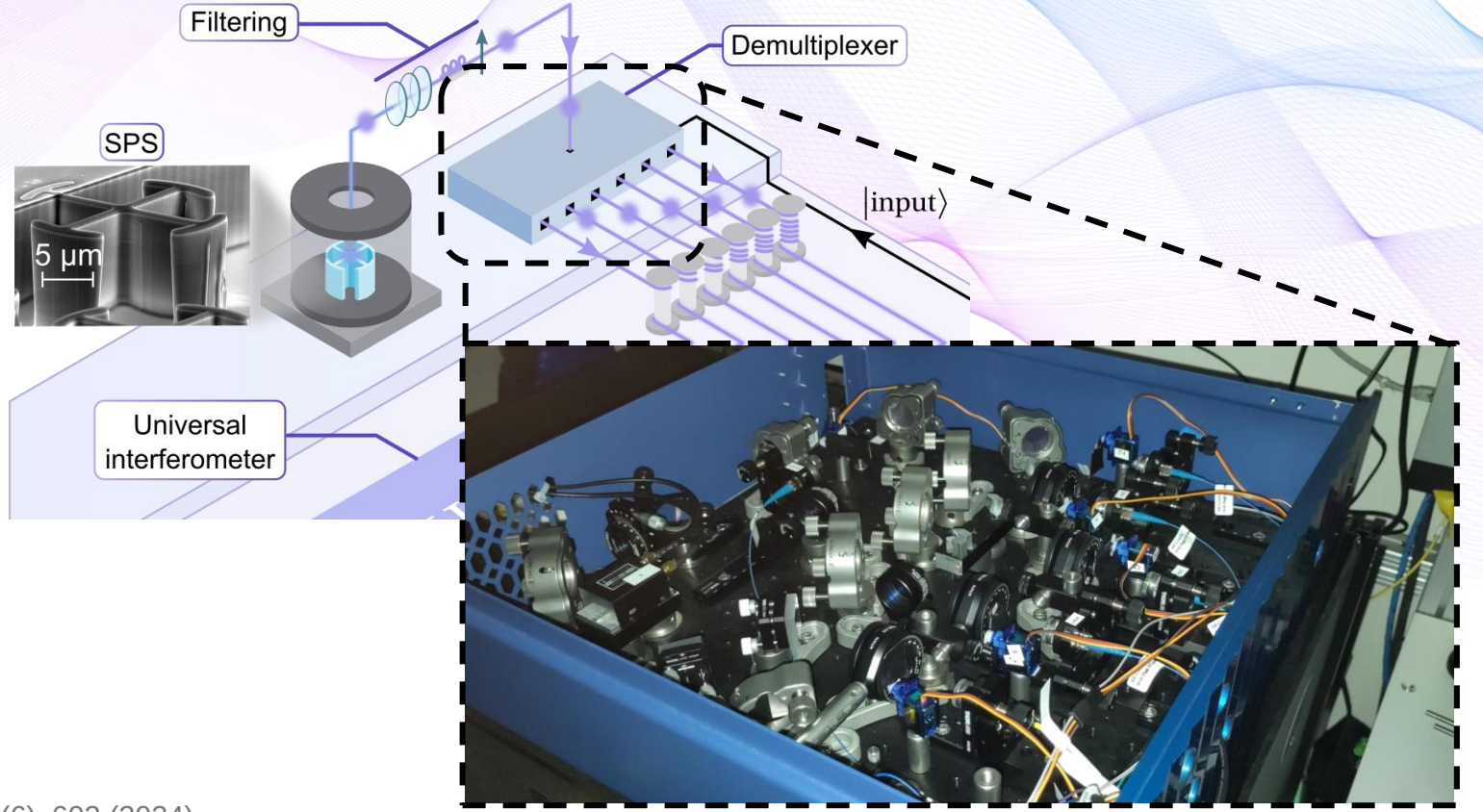
Nature Photonics 18 (6), 603 (2024)

Quandela NISQ quantum computer



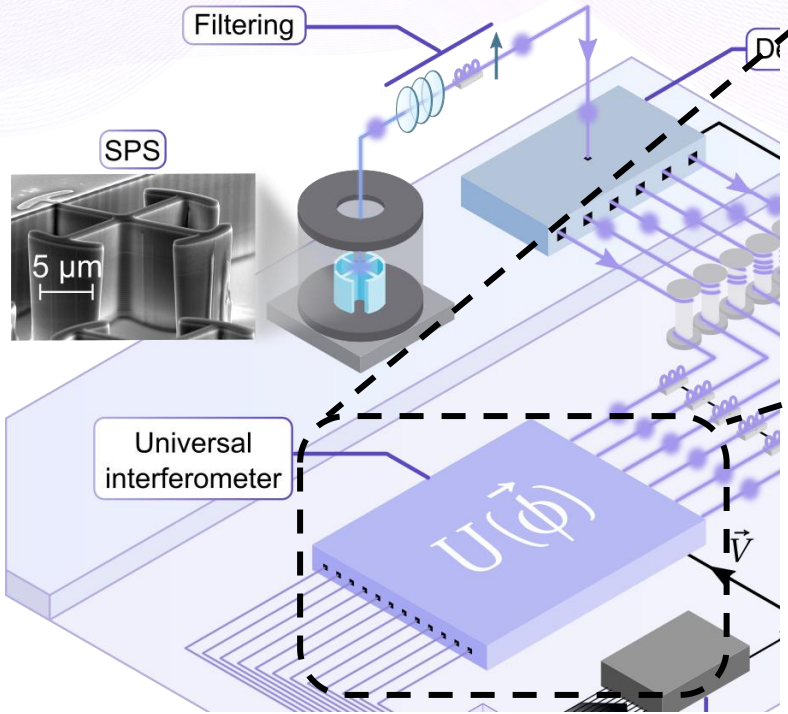
Nature Photonics 18 (6), 603 (2024)

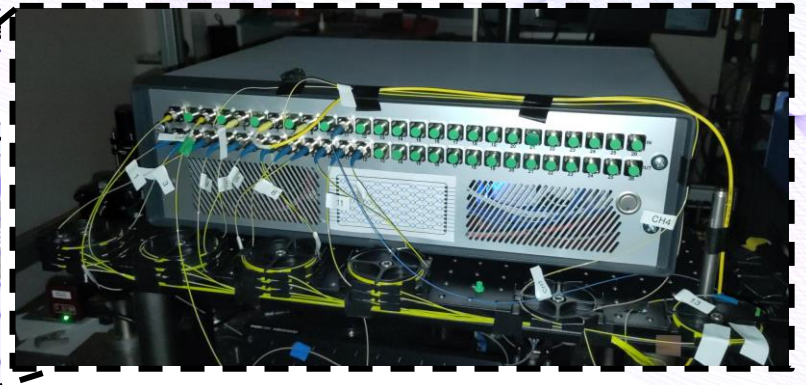
Quandela NISQ quantum computer : virtual tour

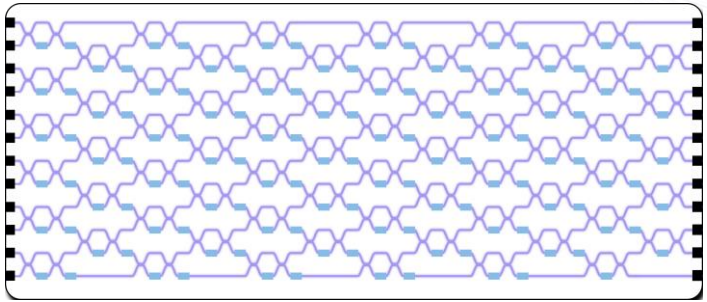


Nature Photonics 18 (6), 603 (2024)

Quandela NISQ quantum computer : virtual tour







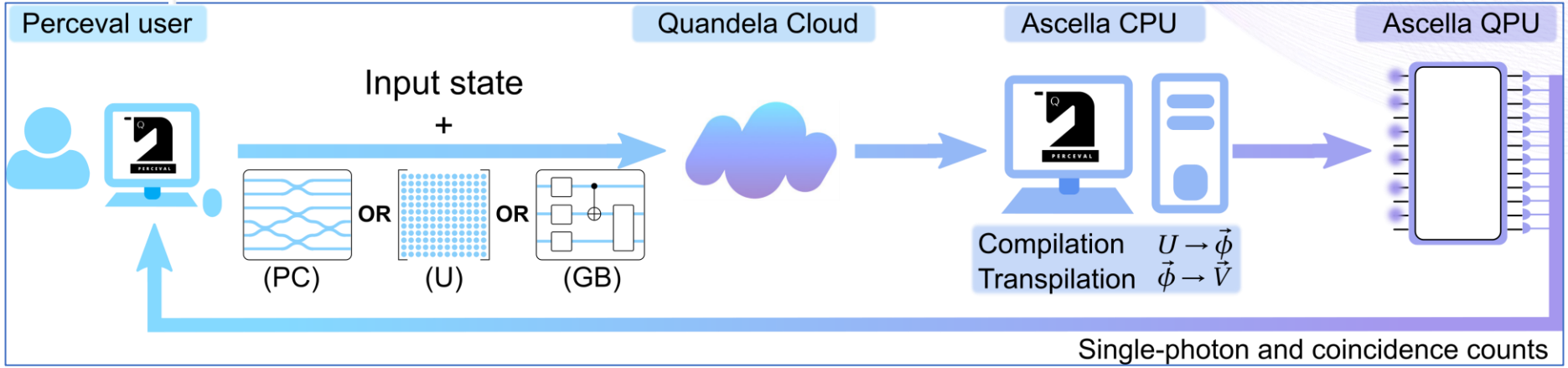
Nature Photonics 18 (6), 603 (2024)

- 12 x 12 fully reconfigurable universal interferometer

Quandela NISQ quantum computer : software stack

```python
def computation(params):
    global current_loss
    global computation_count
    "compute the loss function of a given differential equation in order for it to be optimized"
    computation_count += 1
    f_theta_0 = 0  # boundary condition
    coefs = lambda_random  # coefficients of the M observable
    # initial condition with the two universal interferometers and the phase shift in the middle
    U_1 = pcvl.Matrix.random_unitary(m, params[:2 * m ** 2])
    U_2 = pcvl.Matrix.random_unitary(m, params[2 * m ** 2:])
```

https://perceval.quandela.net/

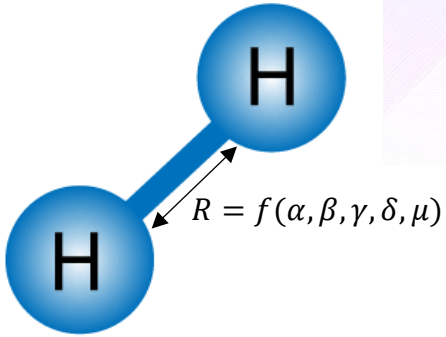


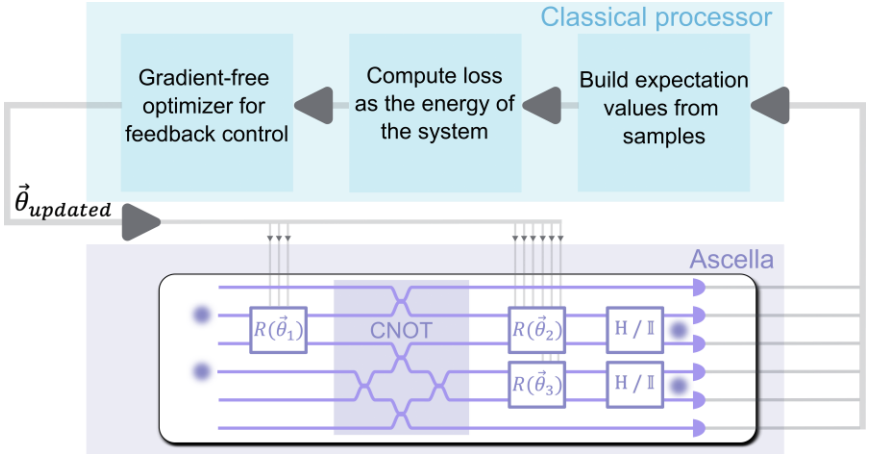
Quandela cloud quantum computer

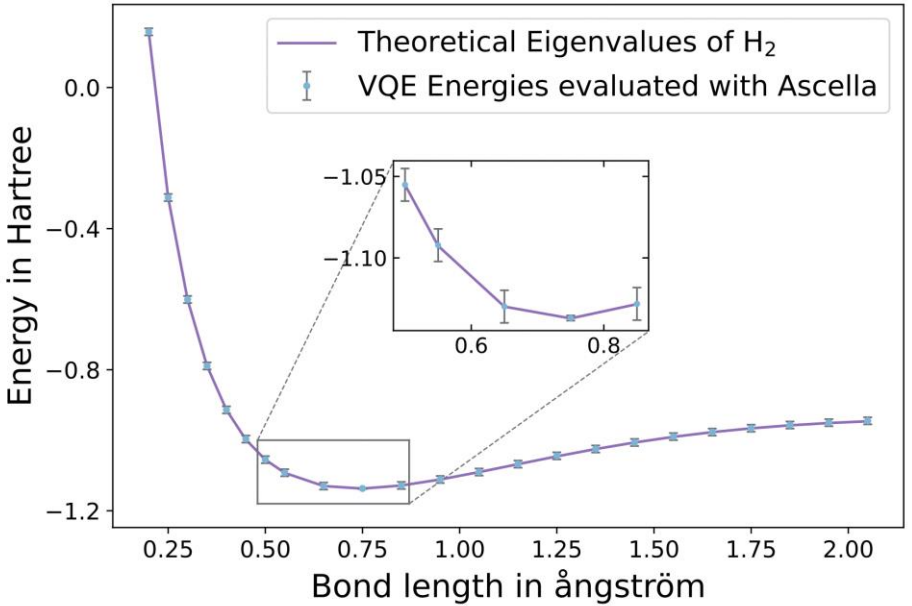
Nature Photonics 18 (6), 603 (2024)

Differential equation resolution

Basic quantum chemistry



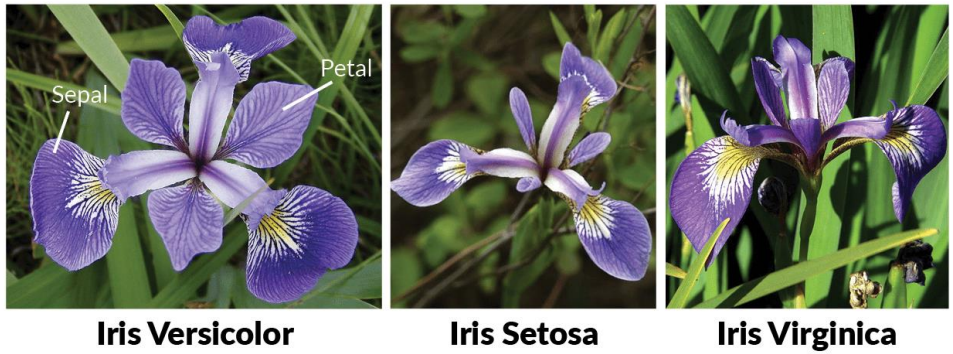


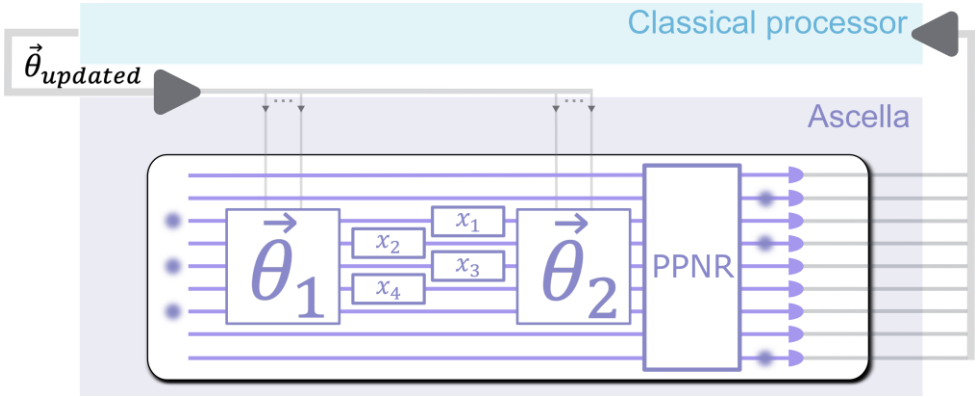


Nature Photonics 18 (6), 603 (2024)

Quantum machine learning

Test : iris images classification

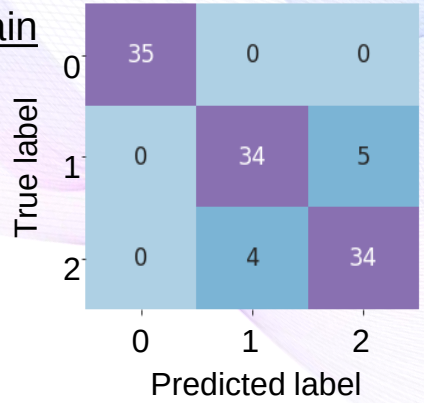




Nature Photonics 18 (6), 603 (2024)

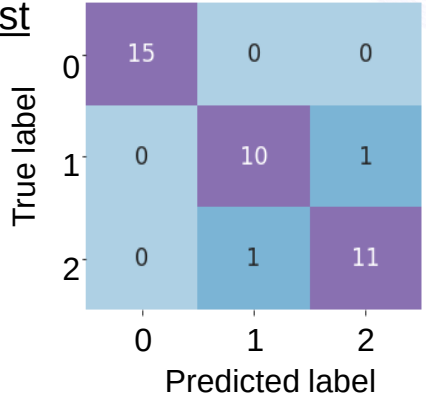
Confusion matrices

Train



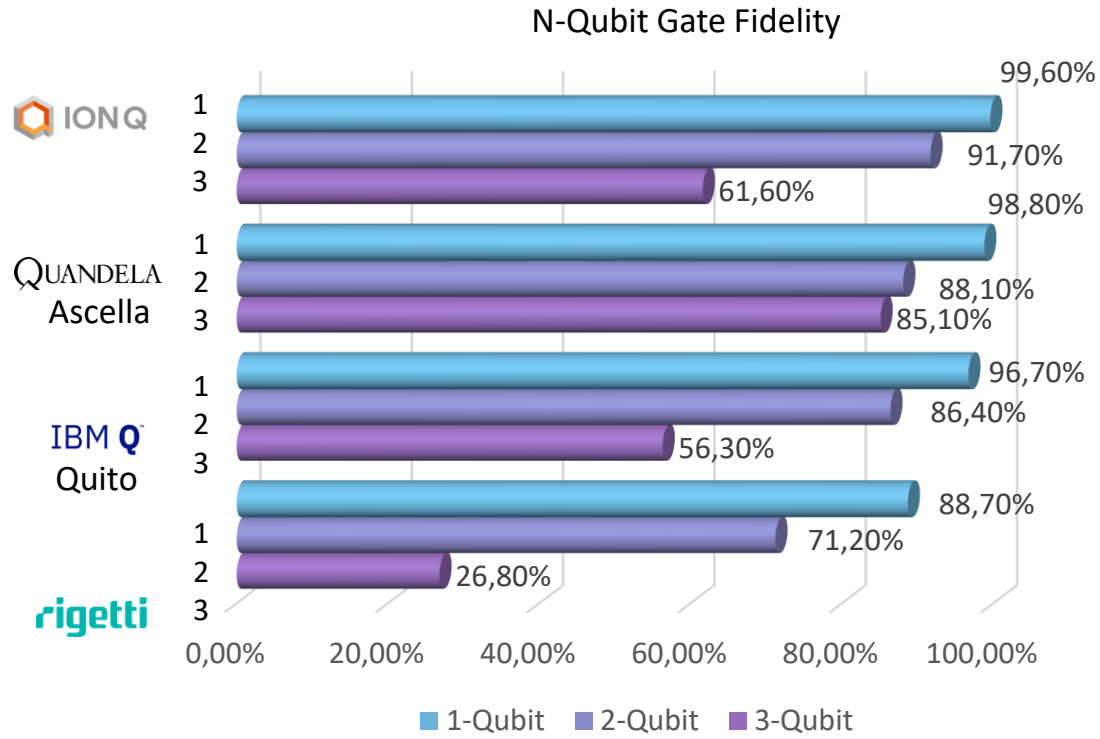
Accuracy = 92%

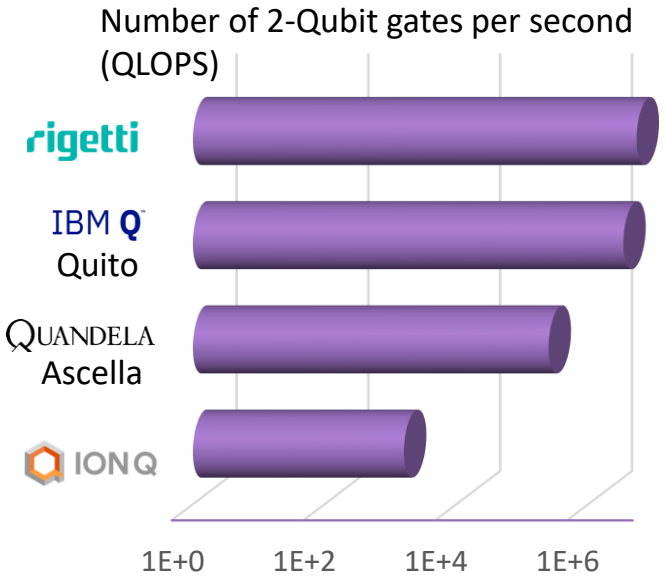
Test



Accuracy = 95%

Benchmarking with other online platforms (2023)





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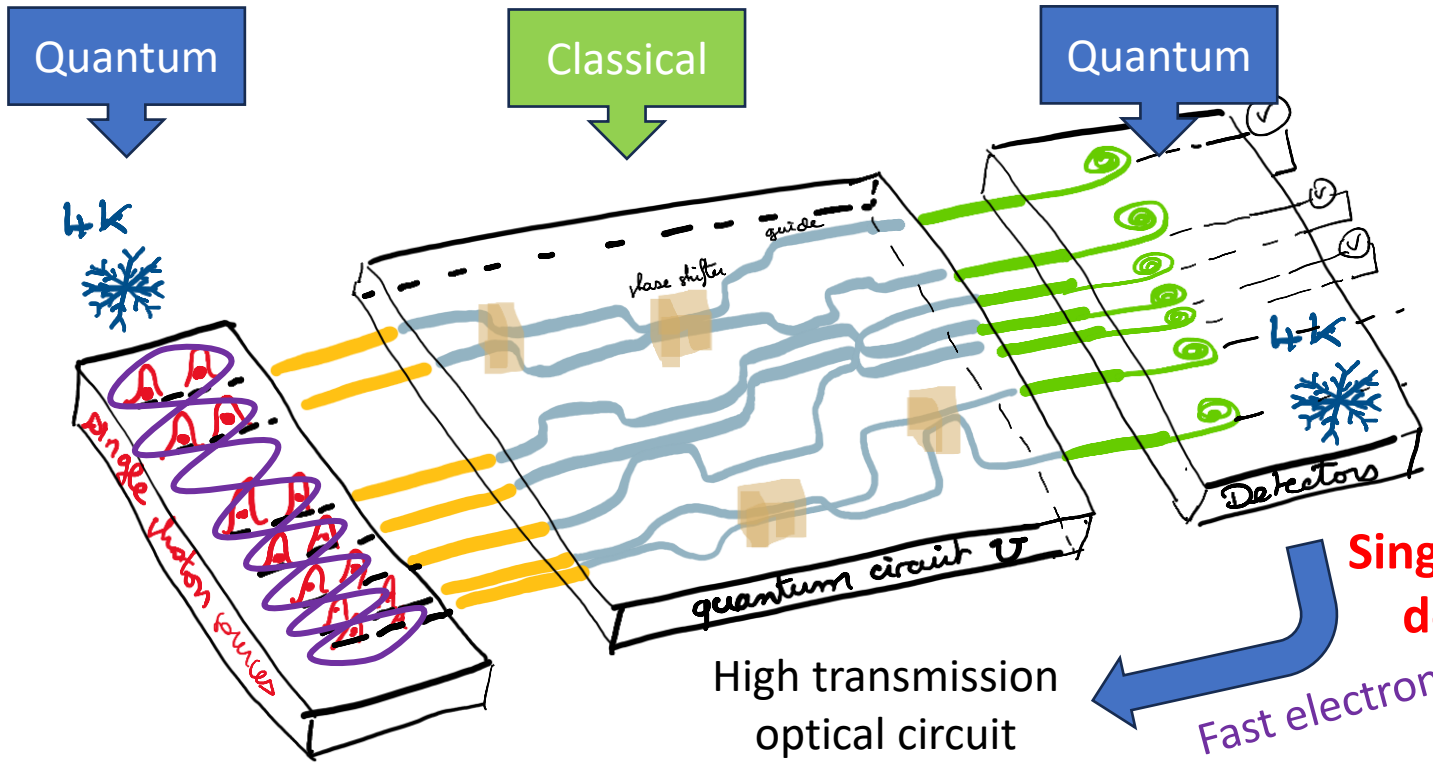
Fault Tolerant Architecture



Entangled photon sources

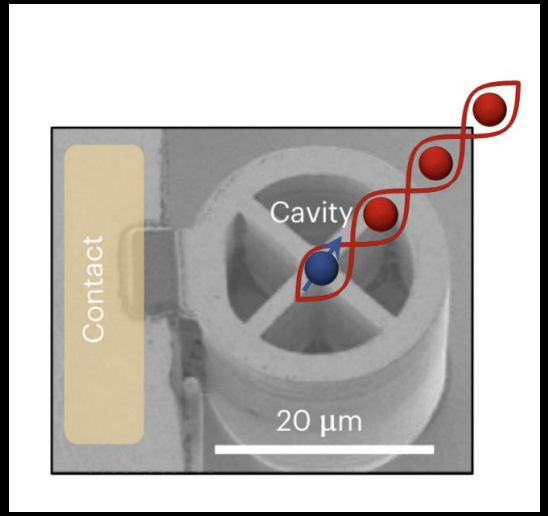
High transmission optical circuit

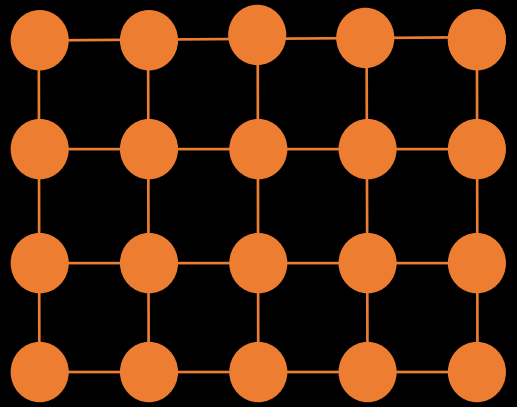
Fast reconfiguration

Single photon detectors

Fast electronics

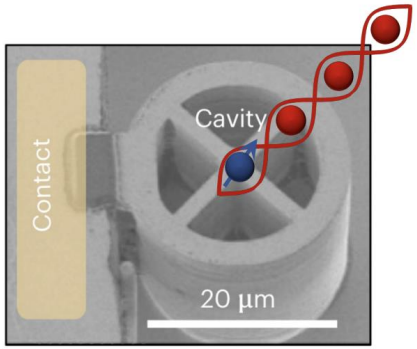
Deterministic generation of photonic graph states

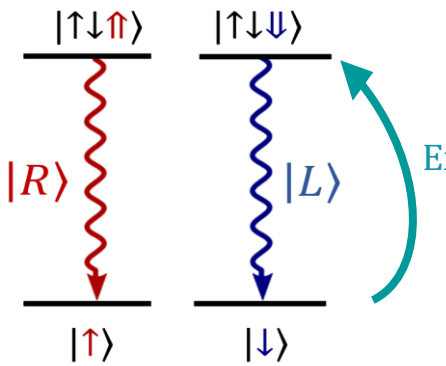




Coste et al. Nature Photonics (2023)
Huet et al. arXiv:2410.23518

Spin photon entanglement with a QD device





Spin-photon correlation

Entanglement protocol :

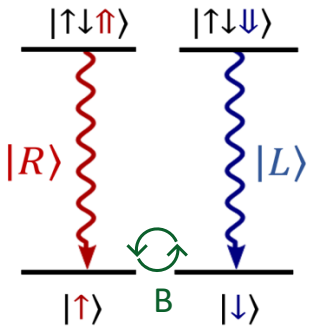
- **1.** Spin initialization

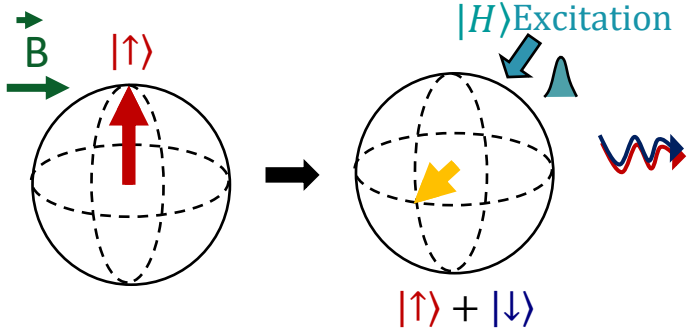
N. H. Lindner and T. Rudolph. Phys. Rev. Lett. ***103****, 113602 (2009)*

Spin photon entanglement with a QD device

Entanglement protocol :

➢ **2.** Spin precession
$\frac{\pi}{2}$ spin gate



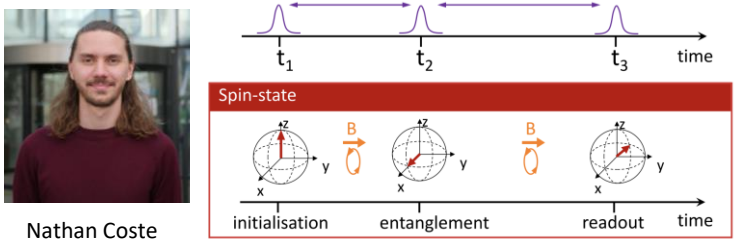


$\frac{\pi}{2}$ spin gate
+ Excitation

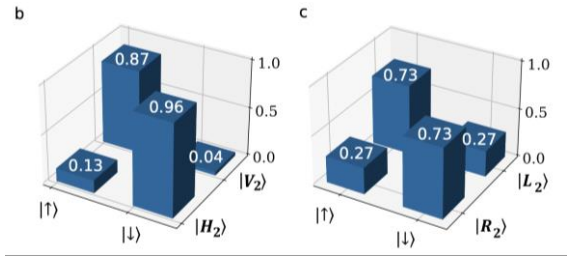
$|\uparrow\rangle|R\rangle + |\downarrow\rangle|L\rangle$ $\quad -i|\uparrow\rangle|R\rangle|V\rangle + |\downarrow\rangle|L\rangle|V\rangle$

Spin-photon entanglement

Spin-photon-photon entanglement

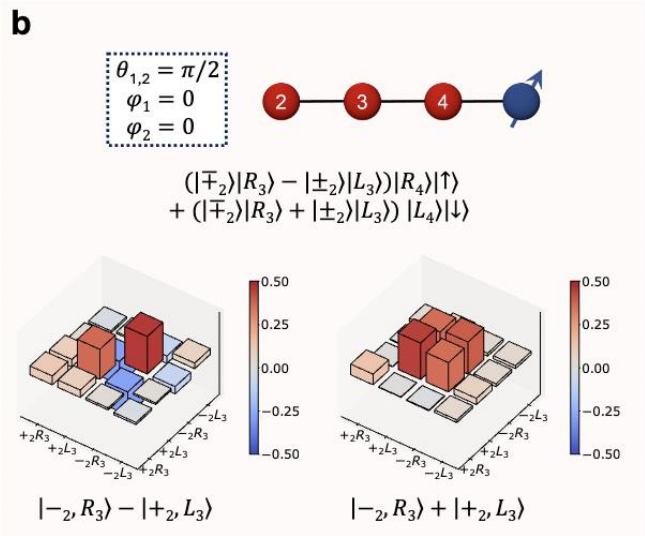


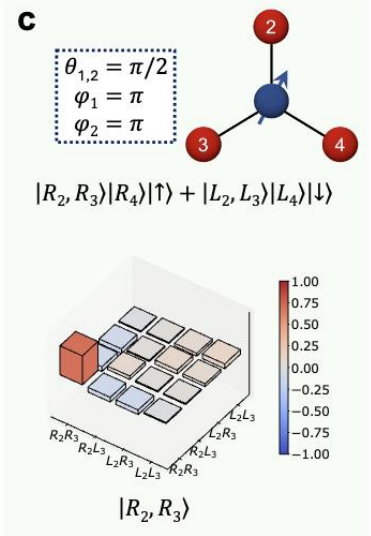
Nathan Coste

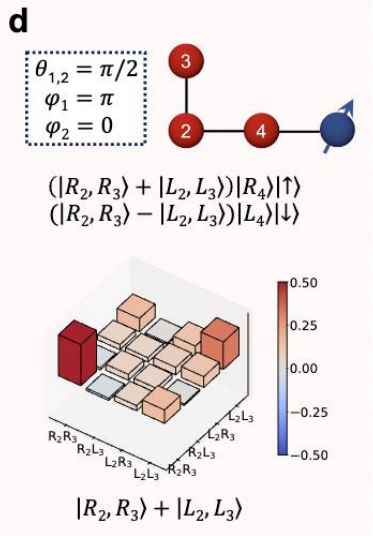


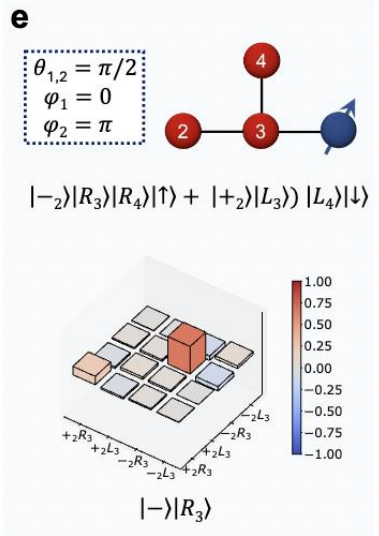
Coste et. al. Nat. Photon. **17**, 582–587 (2023)

Reconfigurable graph state generation





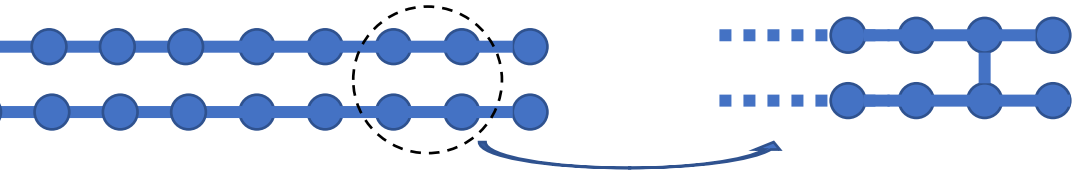




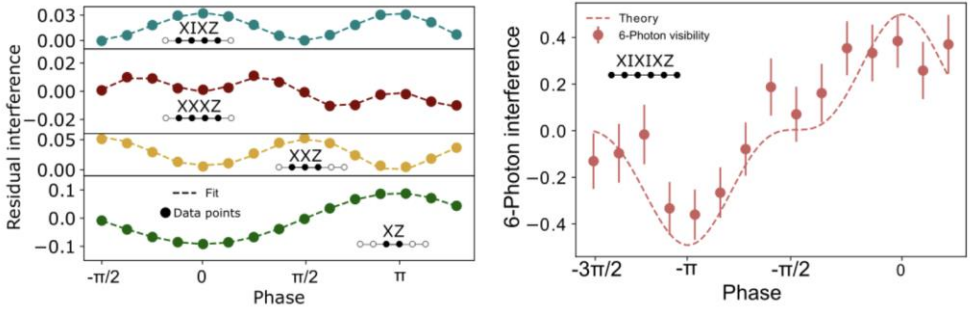
Huet et al. arXiv:2410.23518

Two approaches for 2D photonic graphe states

Fusion of linear clusters

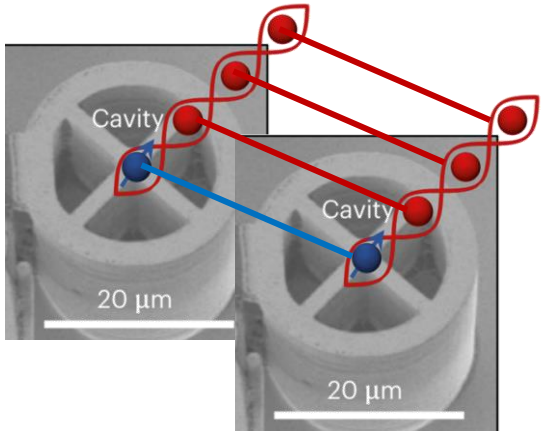


entangling gate



Guichard, Vidro et al – soon on arxiv

Remote spin entanglement



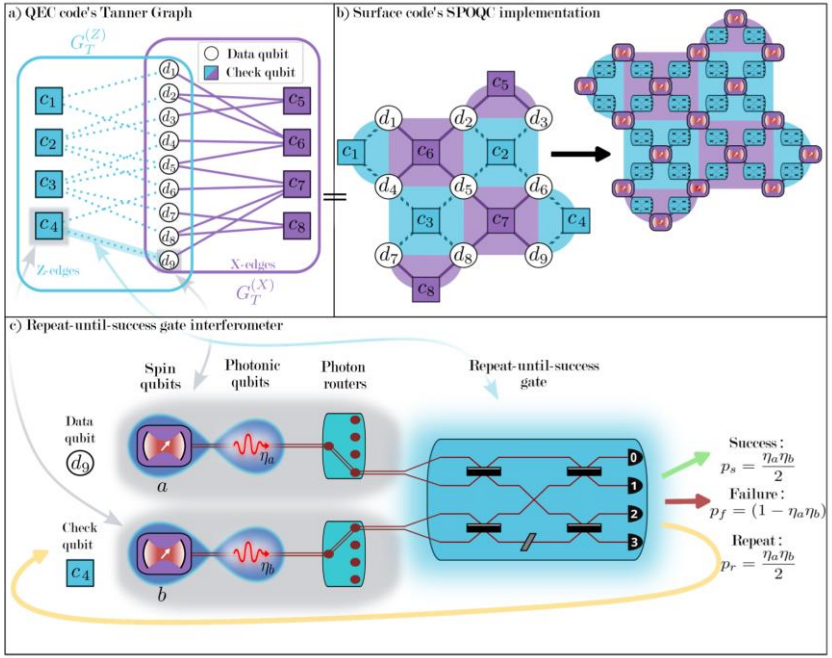
Scalable architecture - SPOQC

A Spin-Optical Quantum Computing Architecture

Grégoire de Gliniasty[1,2], Paul Hilaire[1], Pierre-Emmanuel Emeriau[1], Stephen C. Wein[1], Alexia Salavrakos[1], and Shane Mansfield[1]

[1]Quandela, 7 Rue Léonard de Vinci, 91300 Massy, France
[2]Sorbonne Université, CNRS, LIP6, F-75005 Paris, France

arXiv:2311.05605v3



- Any quantum error correcting code
- Maintains scalability for low-density parity check codes
- Exploits built-in non- local connectivity

CNRS team

Our Collaborations:

Fabio Sciarrino (Rome)
Roberto Osellame (Milan)
Hagai Eisenberg (Jerusalem)
Alexia Auffèves (Singapour)
Christoph Simon (Calgary)
Carlos Anton (Madrid)
Andrew White (Brisbane)

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Quandela teams– October 2023

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