QUANDELA

Single-photon based Quantum Computing:

a compact NISQ platform within reach

EPIC Quantum Summit 2022
Glasgow – September 2022

55 people dedicated to Quantum Computing

QUANDELA

More than 35 PhDs and engineers in algorithms, semiconductors, optical technologies and computer science

Offices, laboratories, clean-room facility in

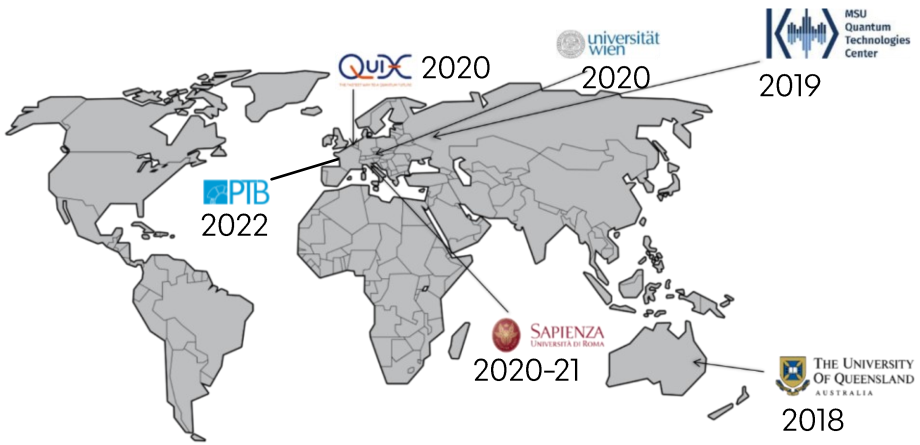
(FR) PARIS, MASSY, PALAISEAU
(DE) MUNICH
(SP) BARCELONA
(IT) ROMA

Commercialization activity driven by the needs of the scientific community

Since 2018 we commercialize reliable
- single photon source devices
- opto-electronics modules

to enable the emerging of q-technologies

Clients:

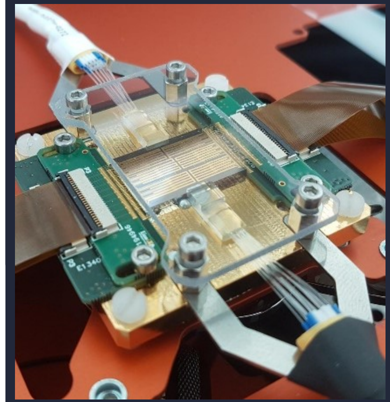


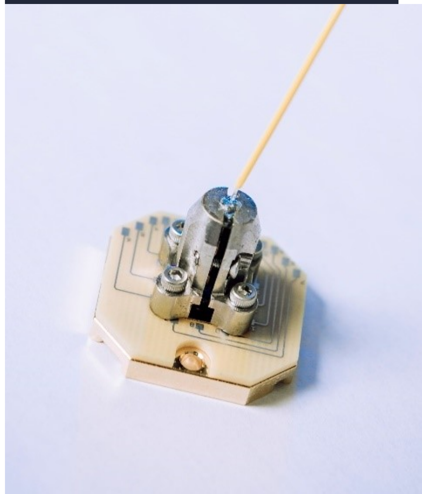
We build
the first full-stack optical QC

Upgradability offered by modularity

Scalability by the use of optical fibers and semi-conductors (1)

Low energy consumption with optimised and integrated cryostats and compatibility with any environment





MosaiQ

End-users	Cloud access or on-premise
Front end	Python Libs, REST API, Visual/Graphical interface, Integration with existing platforms
Compiler	Logical Qubits <> Photon encoding

Assembler

Calibration, Machine Language

Hardware Modules

Electronics, FPGA, Voltage Sequence

Perceval Optical QC Simulator

(< 20 qubits)

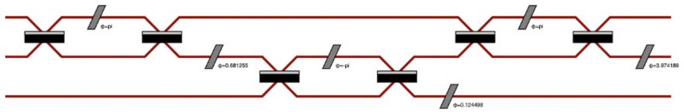
Semiconductors

(sources, photonics integrated chips, detectors,...)

1. Main computer
2. Lasers & Electronics
3. Photonic Integrated on Chip (PIC)
4. Qbit-controller module
5. Photonic Qubit Demultiplexer (DMX)
6. Cryogenically cooled qubit generator

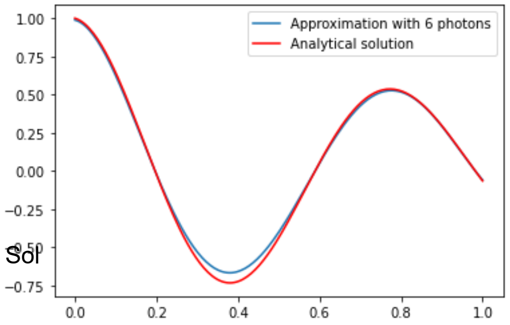
Perceval, Open-source programming framework for Quantum Photonics

FRONT-END INTERFACE

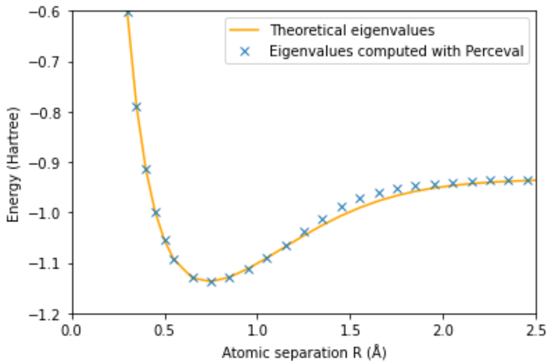


Shor's and Grover's Algorithms on a photonic processor

Up to 15 (20) photons on a laptop (supercomputer)



Solving Differential Equations



Simulation of Variational Quantum Eigensolvers

Compatible with IBM Q Qiskit

Partnership with OVHcloud

300+ downloads per month
1600+ downloads since March 2022

- **Fast evolution**: 5 majors releases in 5 months
- **Simple to use**, both for physicists and for computer scientists
- **Does not constrain** the user **to any framework-specific** conventions that are theoretically equivalent
- Provides **state-of-the-art optimized algorithms**
- Optimized simulation backends (sampling, strong simulation, matrix product state)
- Provides companion tools, like a unitary matrix toolkit, LateX or HTML rendering of algorithms
- Support **multiple encodings**: dual rail, polarization, qudit, time and hybrid encodings

Simulation (Amplitude Estimation)	Optimization (Variational Algorithms, Quantum Semi-Definite Programming)	Quantum Machine Learning (HHL, Quantum Super-Vector Machine)
✔ Option Pricing Portfolio Risk	✔ Portfolio Optimization, Diversifications, Issuance	✔ Financial forecasting Credit Scoring Fraud Detection and Money-laundering

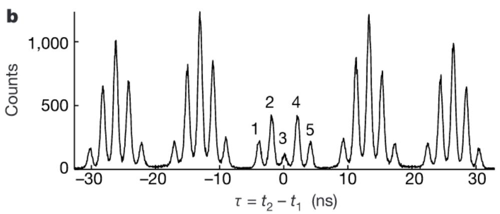
Heurtel et al., Perceval: A Software Platform for Discrete Variable Photonic Quantum Computing, arXiv (2022)

Collaborative & Open Source

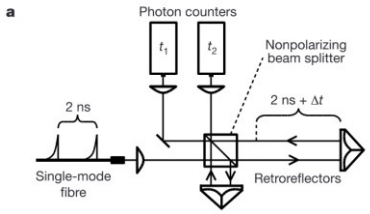
Example of simple codes

Simulation of experiments

Experimental Results



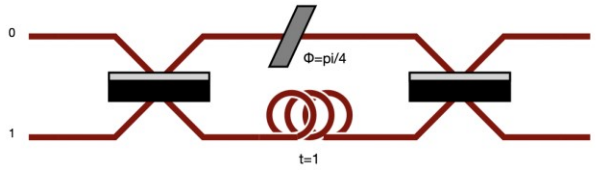
Experimental Set-up



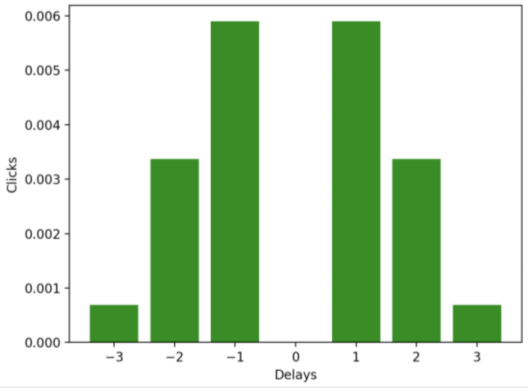
Perceval Implementation

```
c = pcvl.Circuit(2) // comp.SimpleBS() // comp.PS(np.pi/4) // (1, comp.TD(1)) // comp.SimpleBS()
```

```
pcvl.pdisplay(c)
```

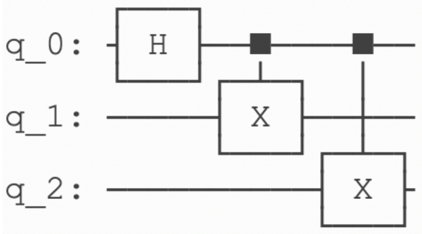


Perceval Simulation

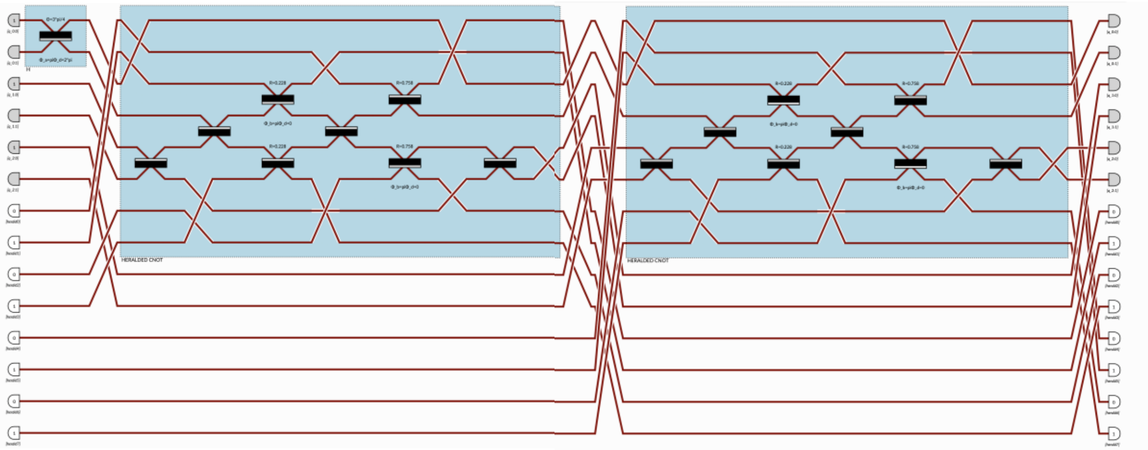


Conversion of Gate-based circuits

Qiskit

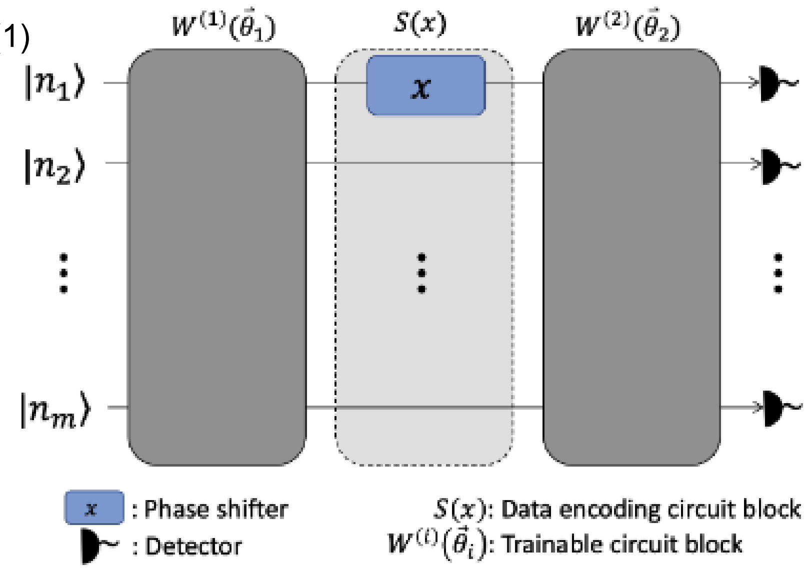



```
qiskit_converter = QiskitConverter(phys)
quantum_processor = qiskit_converter.convert(circuit, heralded=True)
pcvl.pdisplay(quantum_processor, recursive=True)
```



Exploration of useful applications with Perceval

- Trainable circuit[1]



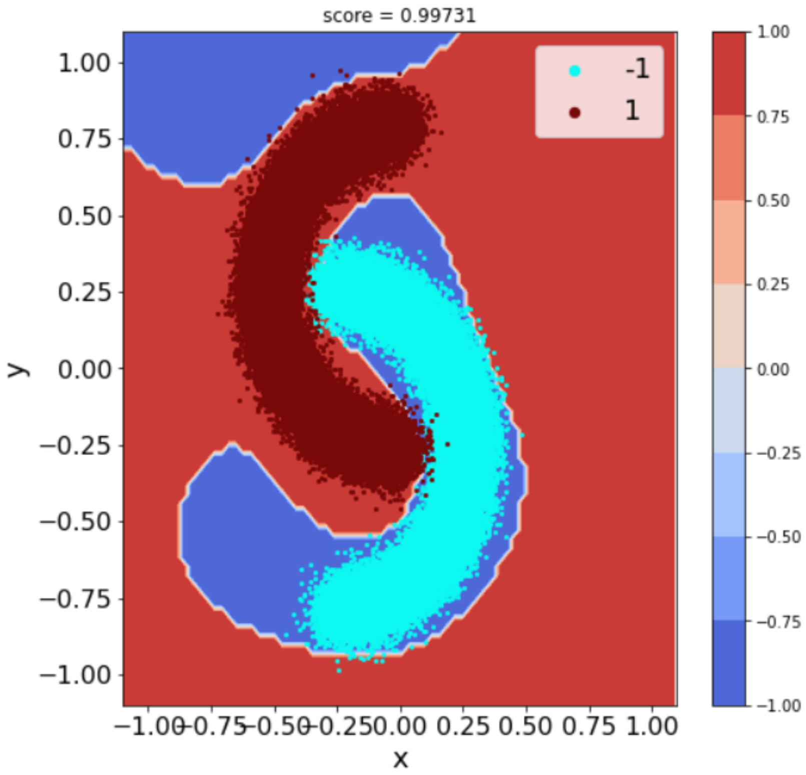
- Machine Learning model:

$$f^{(n)}(\boldsymbol{x}, \boldsymbol{\theta}, \boldsymbol{\lambda}) = \langle \mathbf{n}^i | U^\dagger(\boldsymbol{x}, \boldsymbol{\theta}) Meas(\boldsymbol{\lambda}) U(\boldsymbol{x}, \boldsymbol{\theta}) | \mathbf{n}^i \rangle$$

- Classification: sign of the model $f^{(n)}(-, \boldsymbol{\theta}, \boldsymbol{\lambda})$

Possible improvement to learn faster or from less data

Example: clustering



Simulation with 10 photons

(1) Gan et al. "Fock State-enhanced Expressivity of Quantum Machine Learning Models", arXiv:2107.05224

Exploration of useful applications with Perceval

- Same trainable circuit than clustering able to solve PDEs as it amounts to Fourier expand a discretised solution of the PDE.

- Other (approx. similar) approach: variationnally minimise (potential) energy(2)

discretised PDE

$$E_p = \frac{1}{2}\mathbf{v}^{\mathrm{T}}\mathrm{H}\mathbf{v} - \mathbf{v}^{\mathrm{T}}\mathbf{f} \qquad \text{with} \qquad H = K + gC^{T}C$$

boundary conditions

  - Encoding:

$$\vec{v} \to r|\psi(\boldsymbol{\theta})\rangle, \quad \vec{u} \to r_{opt}|\psi(\boldsymbol{\theta_{opt}})\rangle \quad \text{and} \quad \vec{f} \to |f\rangle$$

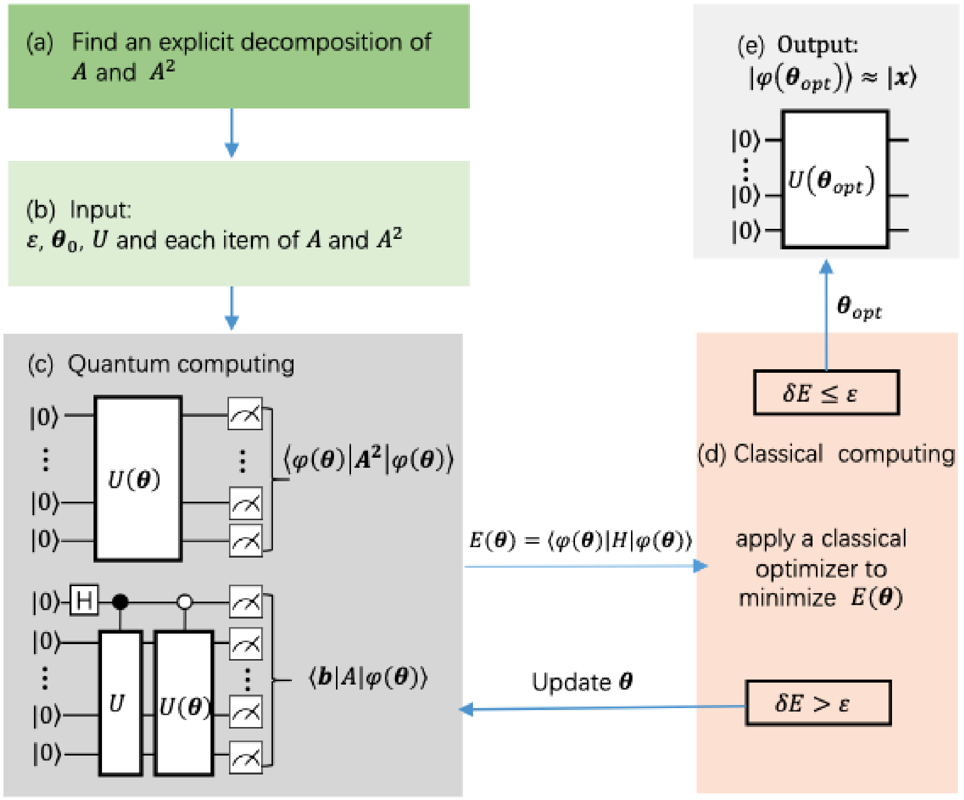
$$E_p = \langle f,\psi(\boldsymbol{\theta})|r^2 I_1 \otimes H - rX \otimes I^{\otimes n}|f,\psi(\boldsymbol{\theta})\rangle$$

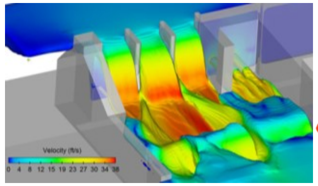
where $|f,\psi(\theta)\rangle = (|0\rangle|f\rangle + |1\rangle|\psi\rangle)/\sqrt{2}$

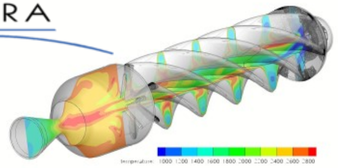
  - Minimisation problem:

$$\min_{\mathrm{r}},_{\theta} E_p(r,\theta)$$

- We use Perceval to convert the Hermitian matrix into a photonic encoding.

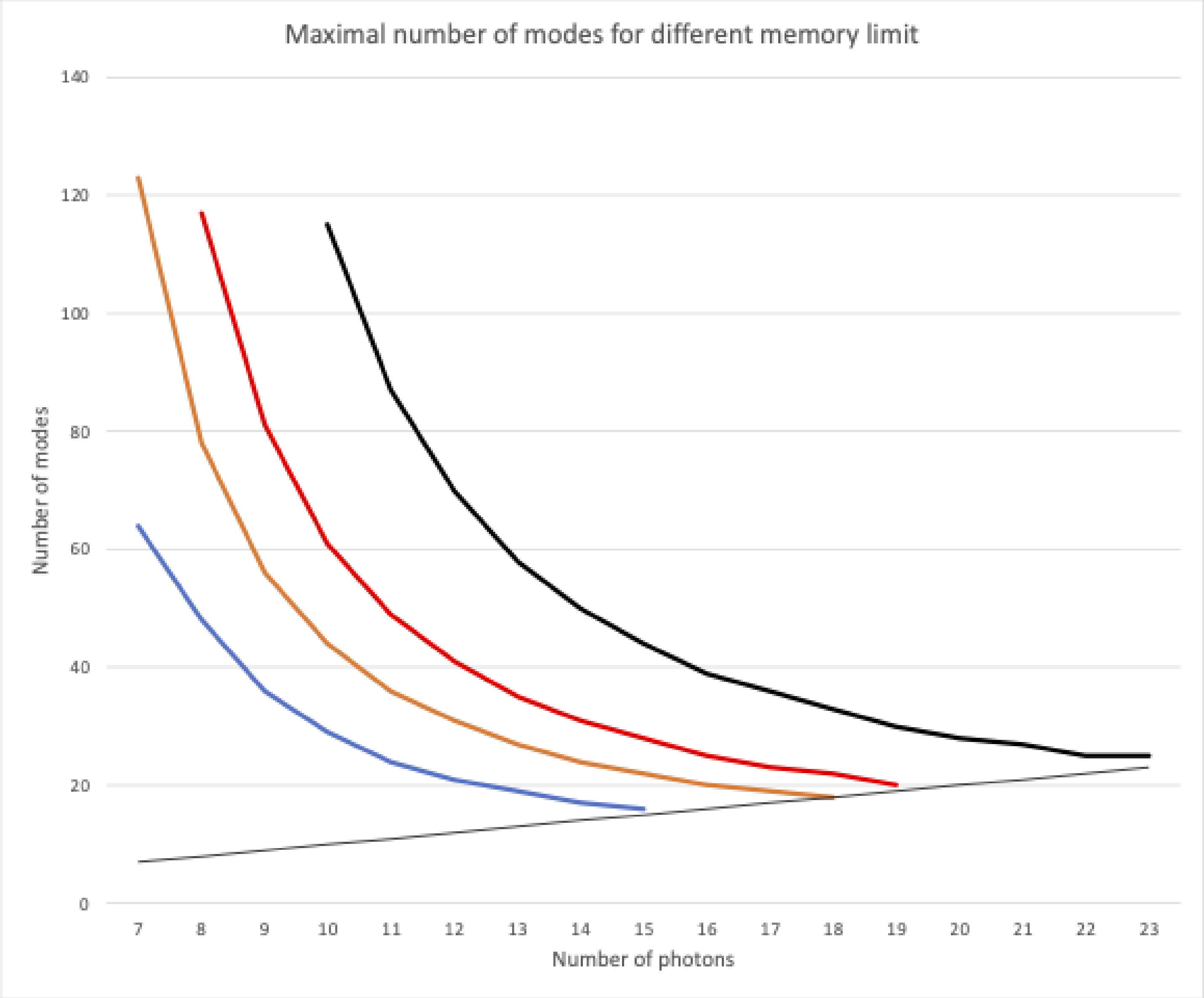






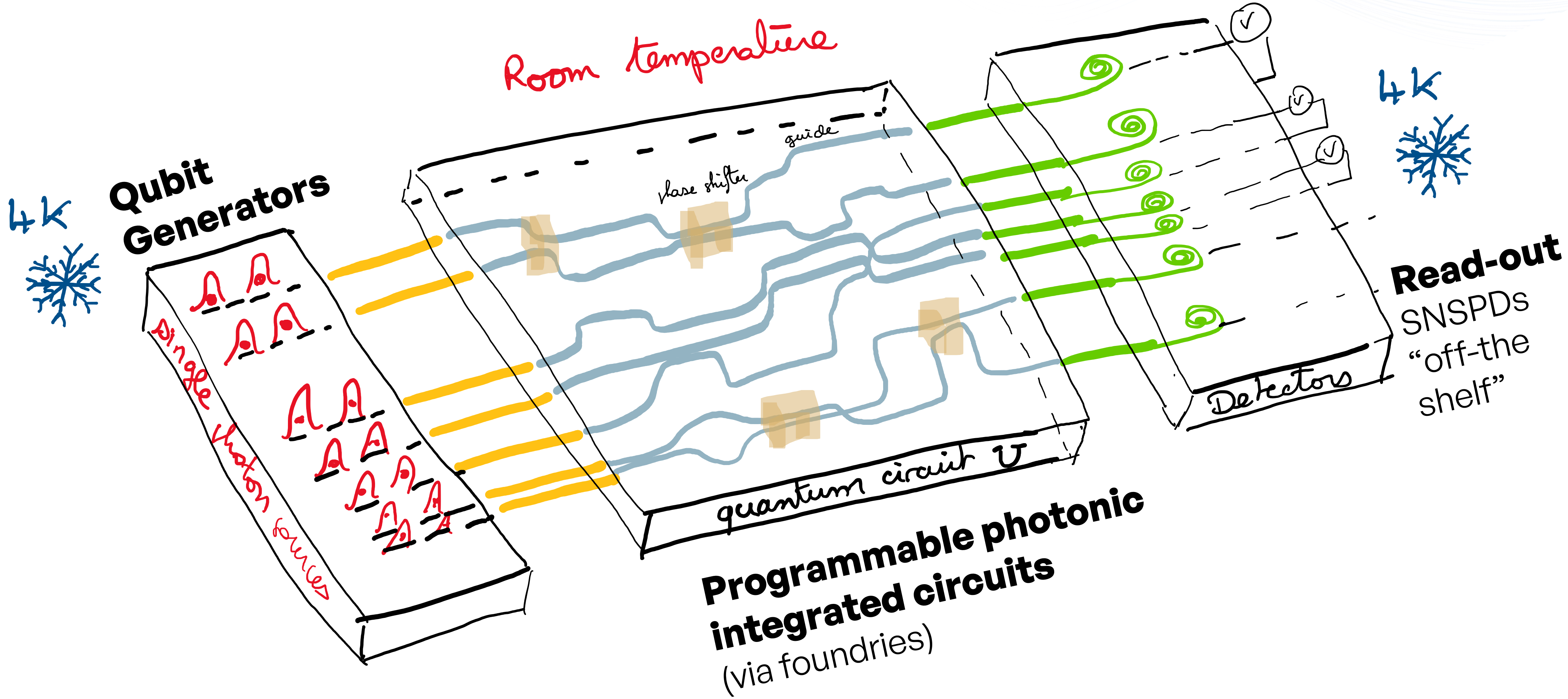
(2) Liu et al. "Variational Quantum algorithm for Poisson equation", arXiv:2012.07014 (2020)

Limits of Simulation



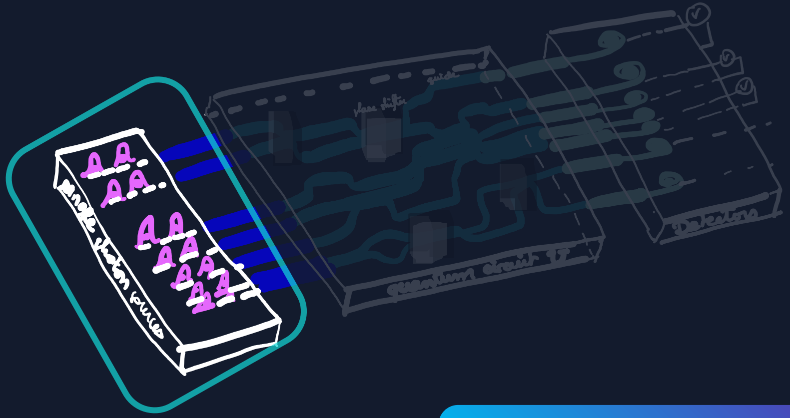
8Gb
256Gb
4Tb
1Pb

Hardware architecture

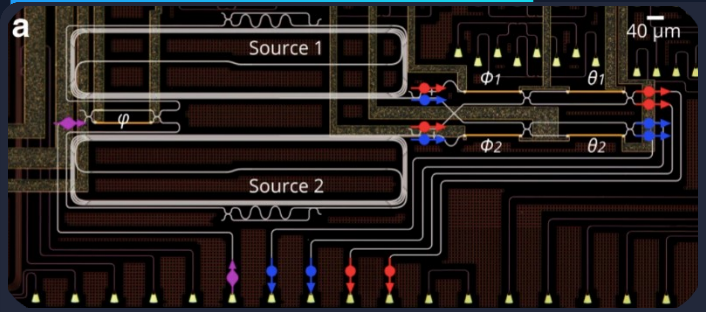


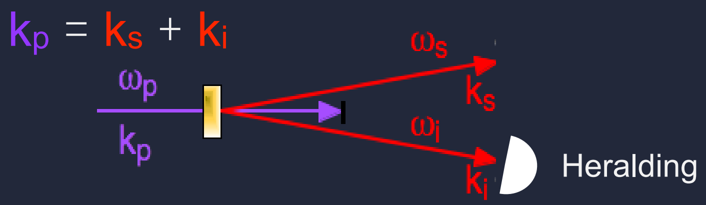
*Feedforward not shown

Single-photon sources : two approaches



PROBABILISTIC SOURCE



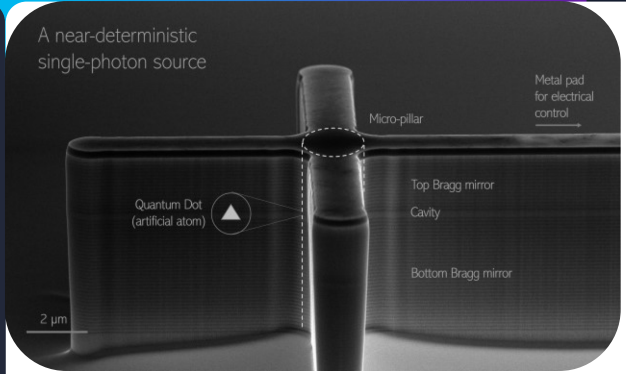


Probabilistic processes
(4wave-mix or SPDC)

Emission efficiency **bounded to few %, with high qubit purity.**

Require efficient detectors and fast switching

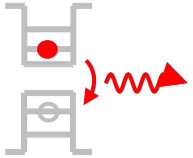
DETERMINISTIC SOURCE



Deterministic process

Emission efficiency up **to 50 % with high qubit purity**

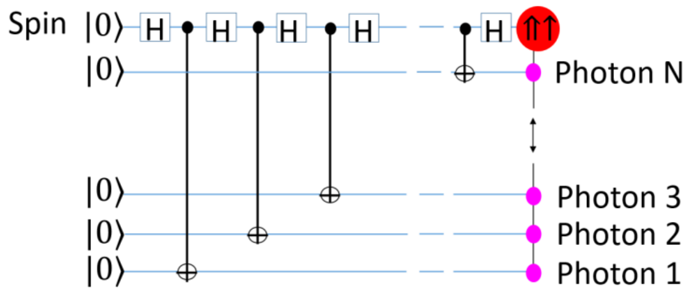
source footprint ~ few µm²



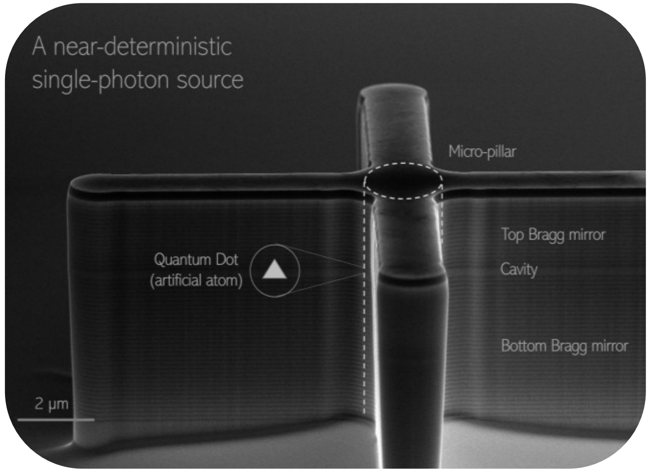
Theoretical max Brightness > 95%
Threshold for Universal QC: ~ 80%*

* Assuming 95%-efficient detectors and 90%-transmittivity circuits

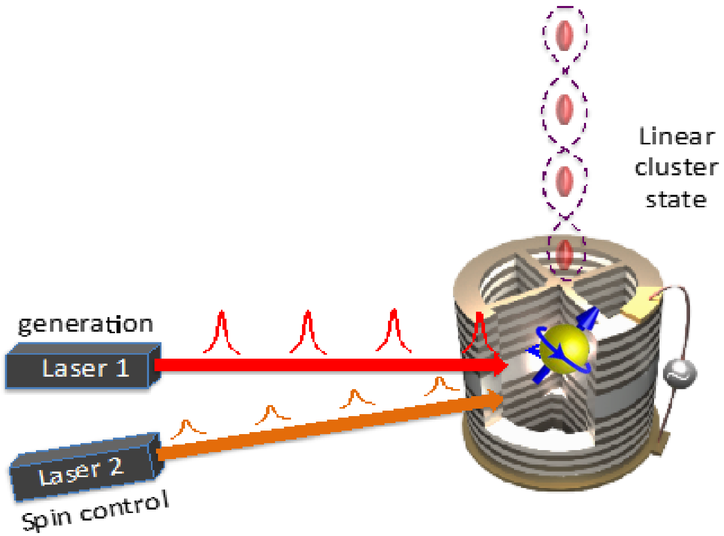
Generation of optical linear cluster states



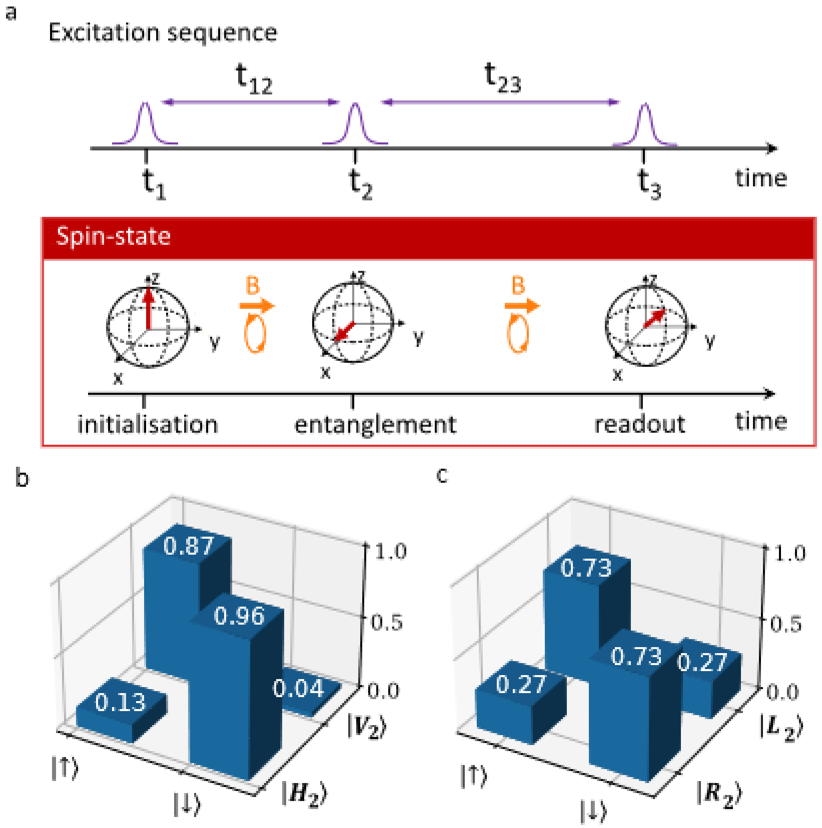
Linder, Rudolph, PRL, 103, 113602 (2009)



Emission of indistinguishable and entangled photons with a high brightness



Small mT magnetic field + compact cryostat

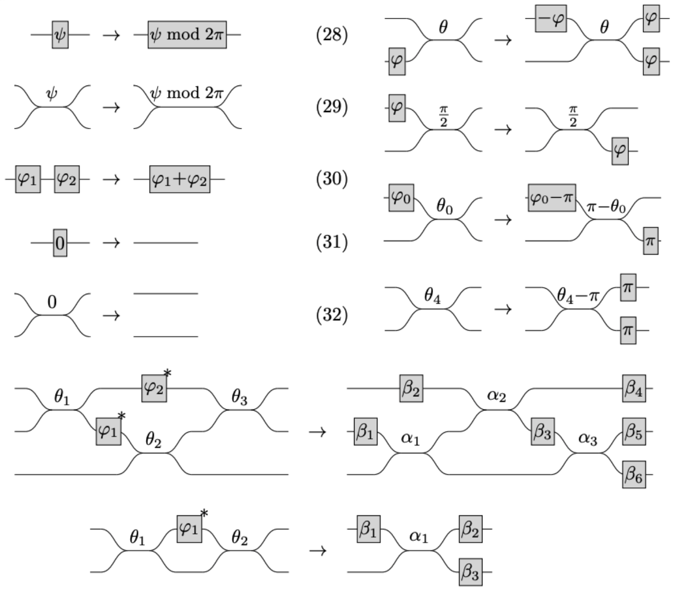


Coste at al.
High-rate entanglement between a semiconductor spin and indistinguishable photons
https://arxiv.org/abs/2207.09881

From
Algorithms to real Implementation, we are full stack!

MOSAIQ

LOv-Calculus



We developed the first graphical language for photonic processors

Clément et al., Lov-Calculus: a graphical language for linear optical quantum circuits (2022)

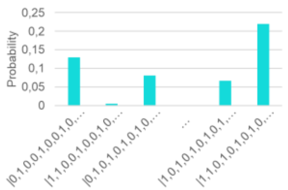
PERCEVAL

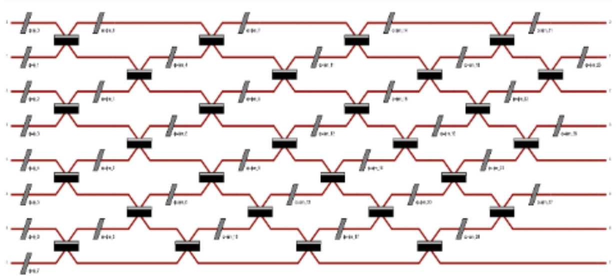
Open-source programming platform
https://perceval.quandela.net/

```
import perceval as pcvl
import perceval.lib.phys as phys

N=8
c = pcvl.Circuit.generic_interferometer(
    N,
    lambda idx: phys.BS() // (0, phys.PS(phi=pcvl.P("φm_%d" % idx))),
    depth=N,
    phase_shifter_fun_gen=lambda idx: phys.PS(phi=pcvl.P("φ_%d" % idx))
)

pcvl.pdisplay(c)
```





Heurtel et al., Perceval: A Software Platform for Discrete Variable Photonic Quantum Computing (2022)

Fabrication and integration of semiconductors

Optics and Electronic Modules

Cloud Servers and API applications

2-Qubit and 4-Qubit processors ready

6-Qubit under assembly

```python
import perceval as pcvl
import perceval.lib.symb as symb
import numpy as np

backend = pcvl.BackendFactory().get_backend('SLOS')

PhotonicCircuit = symb.Circuit(2)
PhotonicCircuit.add((0,1),symb.BS())
PhotonicCircuit.add(0,symb.PS(np.pi/4))
PhotonicCircuit.add((0,1),symb.BS())

pcvl.pdisplay(PhotonicCircuit)

simulator = backend(PhotonicCircuit.U)
ca = pcvl.CircuitAnalyser(simulator,\
                    [pcvl.BasicState([0,1])])

pcvl.pdisplay(ca)
```

14-16 Nov. 22'
Paris

(Sorbonne Université)

At the Crossroads of
Physics and Software!

LOQCathon

Powered by Quandela with a partnership of QICS (Quantum Information Center Sorbonne)

QUANDELA

Building the most advanced Photonic Quantum Computers in the world

Commercial traction from leading Supercomputing Centers

Integrating the best of European Technologies