Silicon photonic quantum computing

Syrus Ziai
many colleagues & collaborators

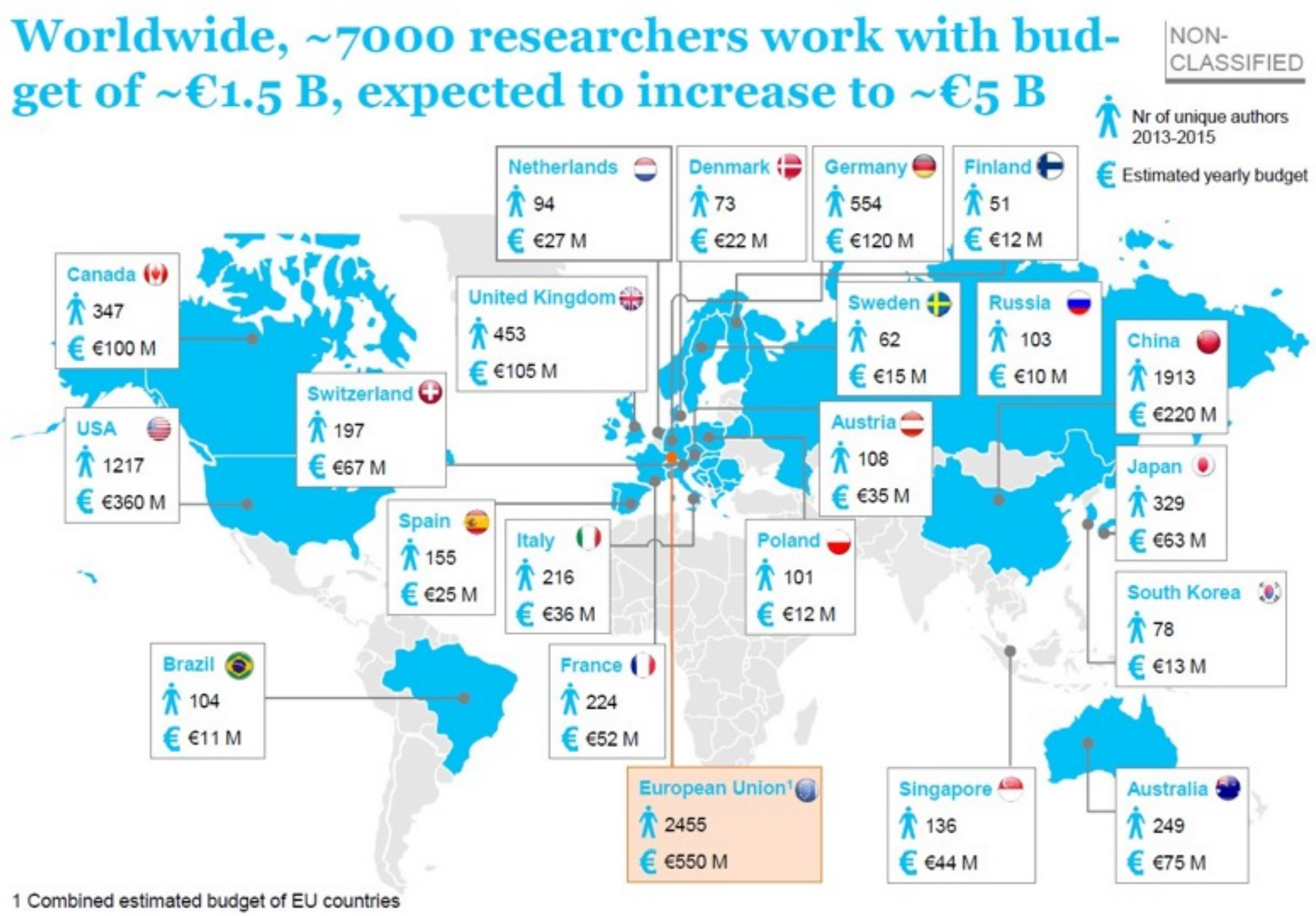
Cadence Photonics Summit
November 7, 2018

PsiQuantum Corporation

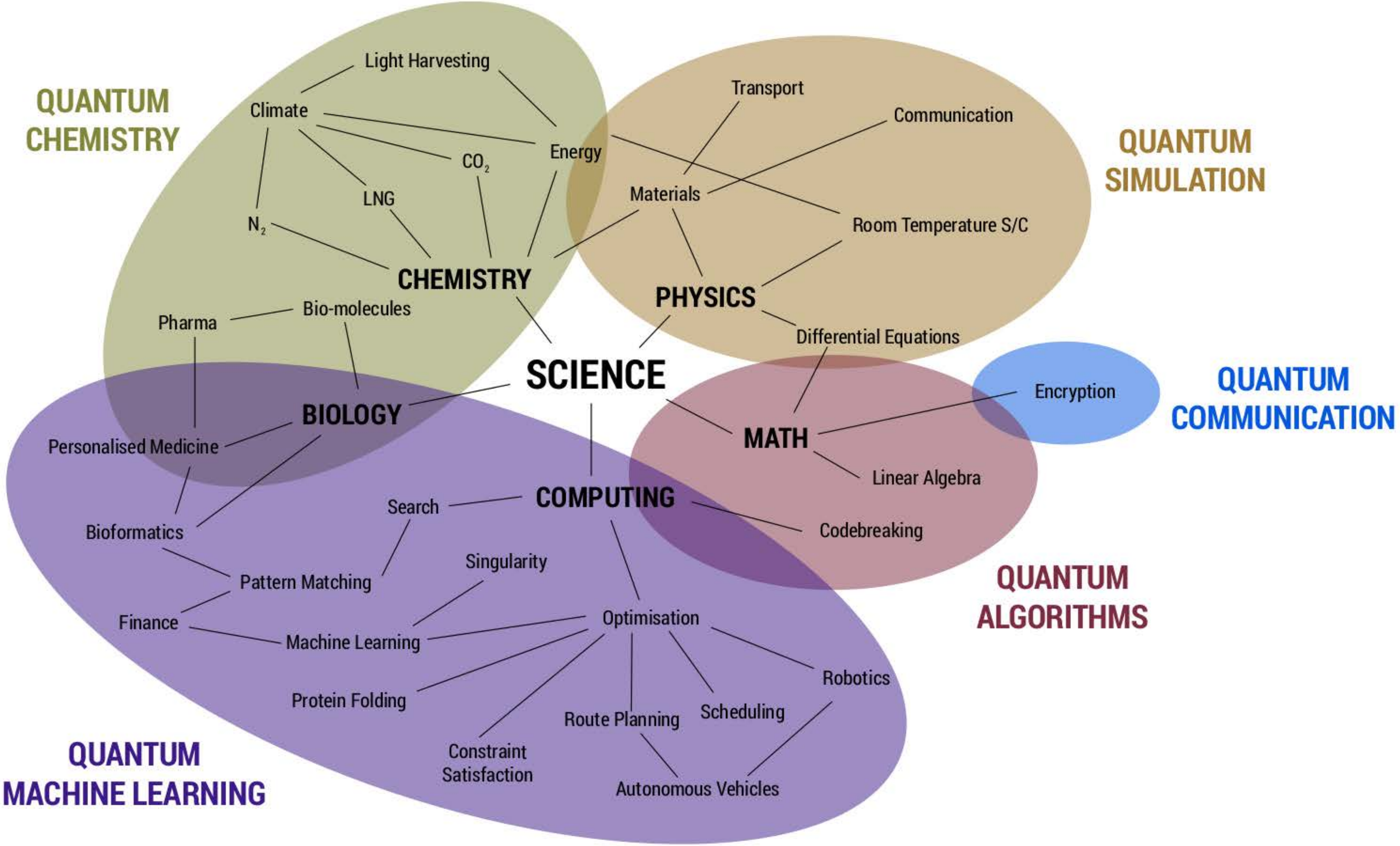
Quantum computing

Worldwide Quantum Activity

Dozens of startups, universities, governments.



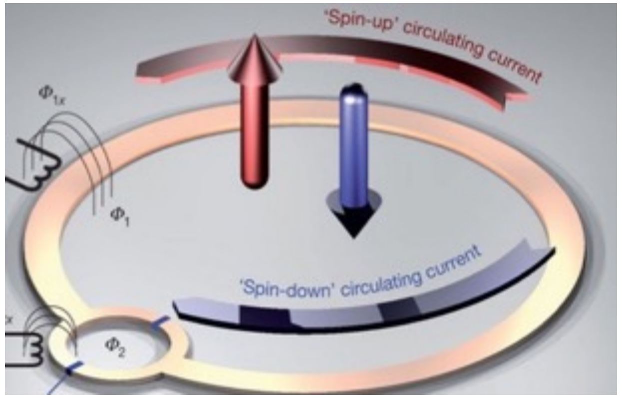
Source : Quantum Europe 2016


QUANTUM CHEMISTRY
QUANTUM SIMULATION
QUANTUM COMMUNICATION
QUANTUM ALGORITHMS
QUANTUM MACHINE LEARNING
Light Harvesting
Climate
Energy
CO_2
LNG
N_2
Transport
Communication
Materials
Room Temperature S/C
CHEMISTRY
PHYSICS
Pharma
Bio-molecules
Differential Equations
SCIENCE
Encryption
BIOLOGY
MATH
Personalised Medicine
Linear Algebra
Search
COMPUTING
Bioformatics
Codebreaking
Singularity
Pattern Matching
Finance
Optimisation
Machine Learning
Robotics
Protein Folding
Route Planning
Scheduling
Constraint Satisfaction
Autonomous Vehicles

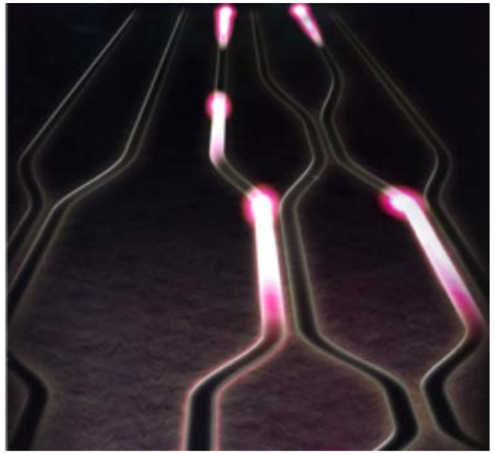
How to build a QC : qubits

Qubits

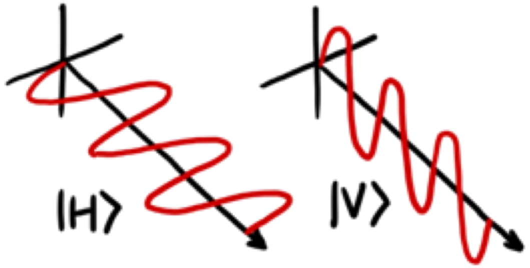
Super-conducting



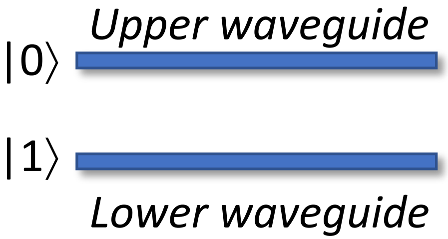
Photons



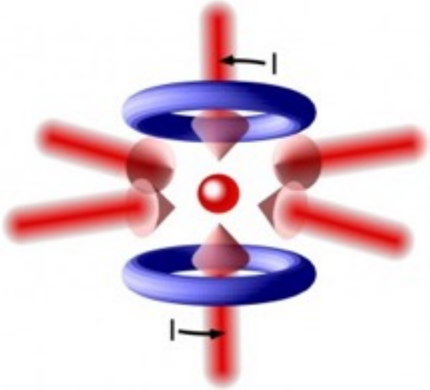
Polarization Encoding



Path Encoding



Ions



Motivation for photonic qubit

Low noise

Does not require mK temperatures

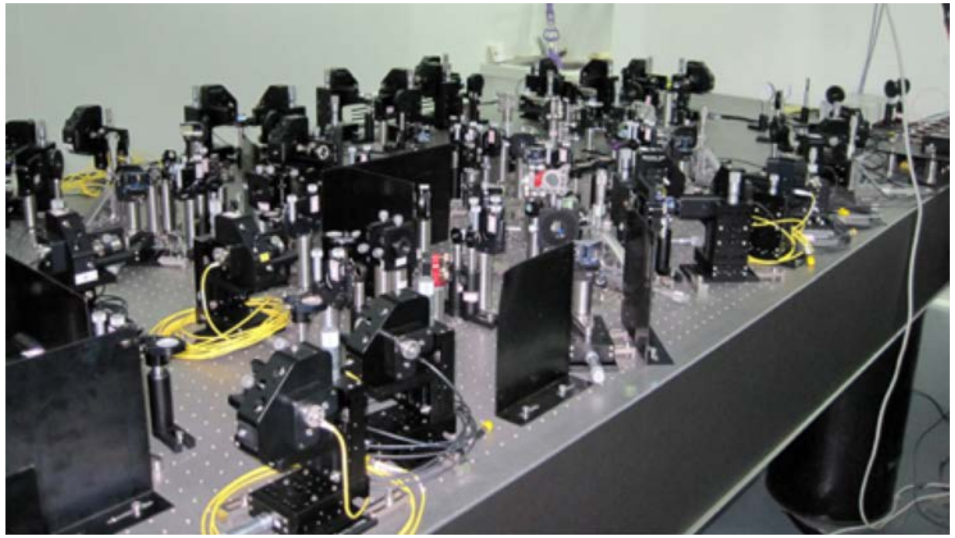
No atomic-scale fabrication

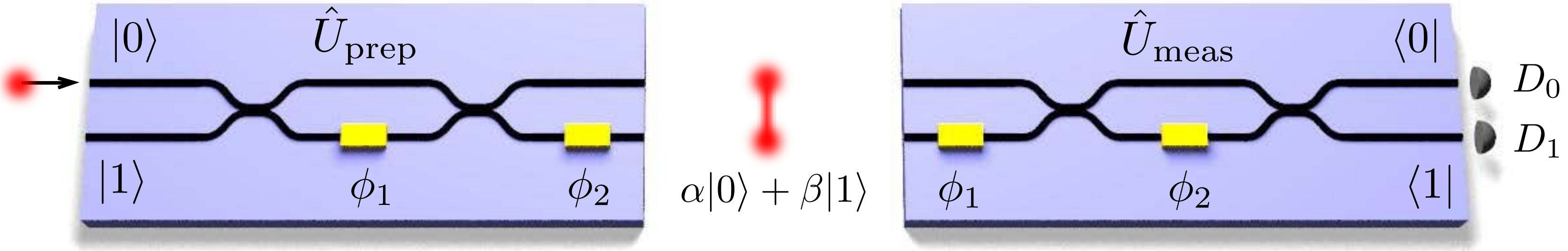
CMOS compatible

Inherent quantum I/O

No quantum cross-talk

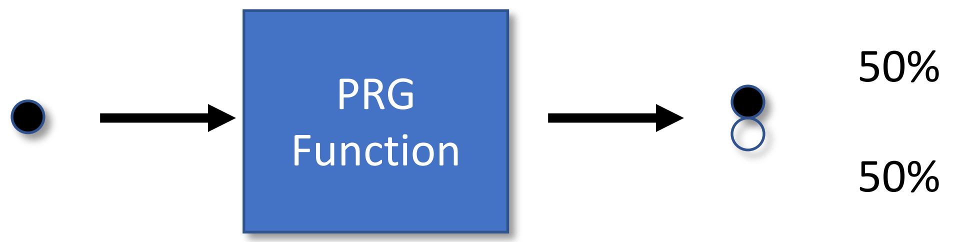
Manufacturable



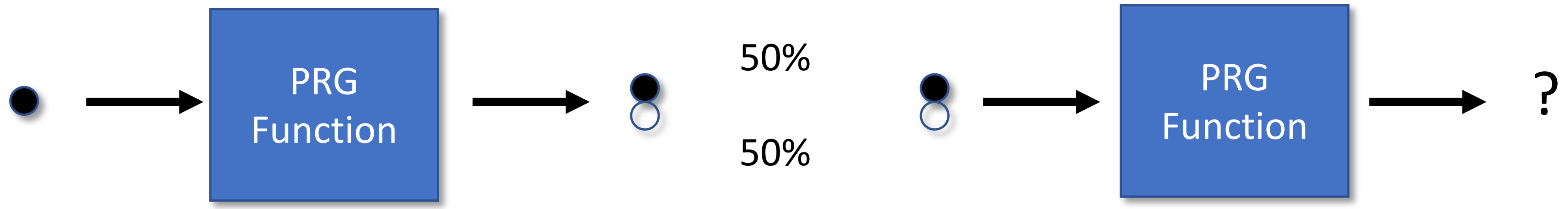


Superposition

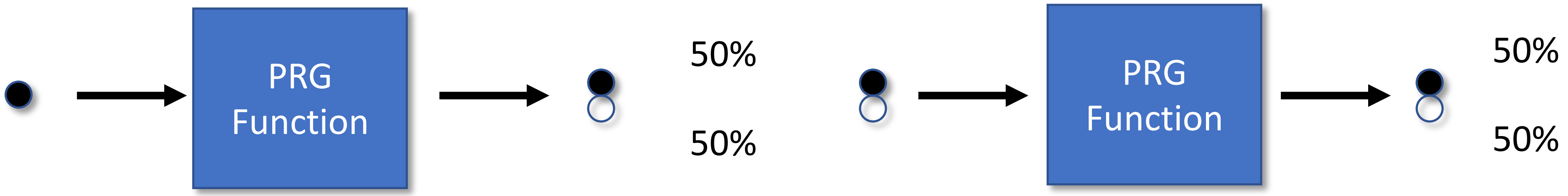
Classical Function



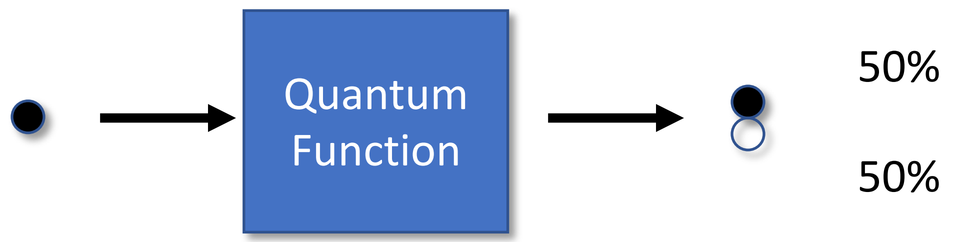
Classical Function



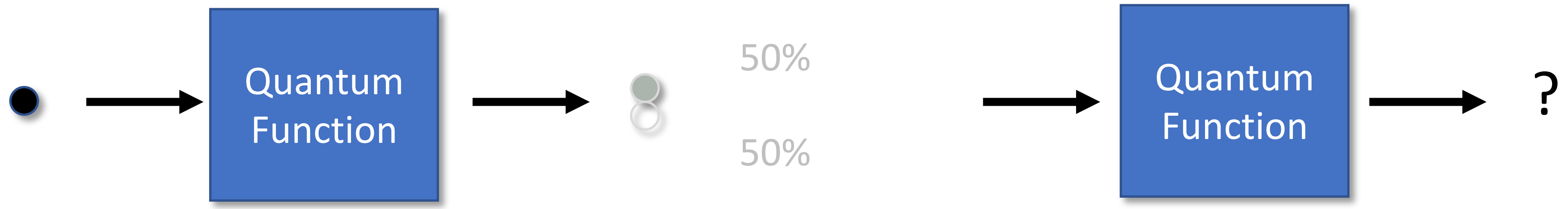
Classical Function



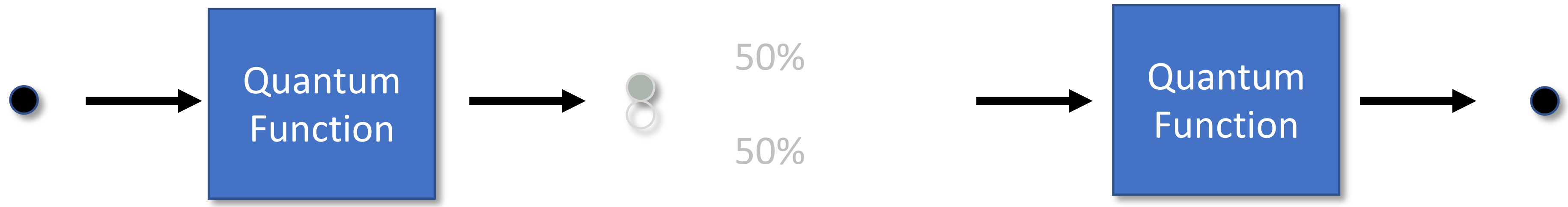
Quantum Function



Quantum Function

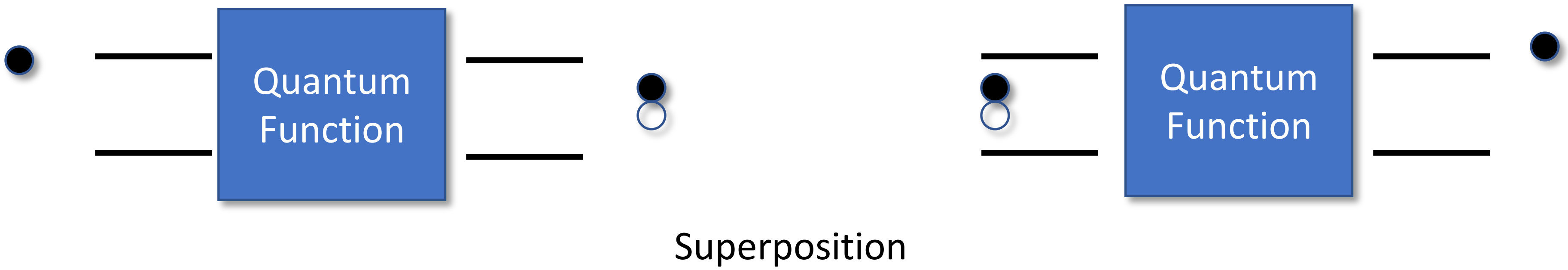


Quantum Function

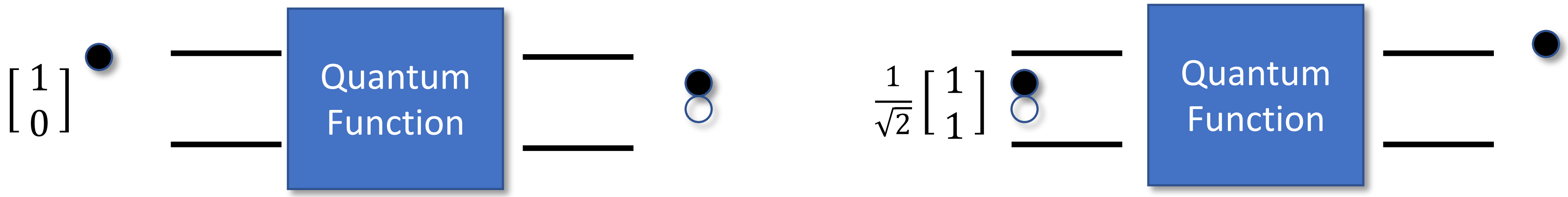


Quantum Optics Function

Quantum Optics Function



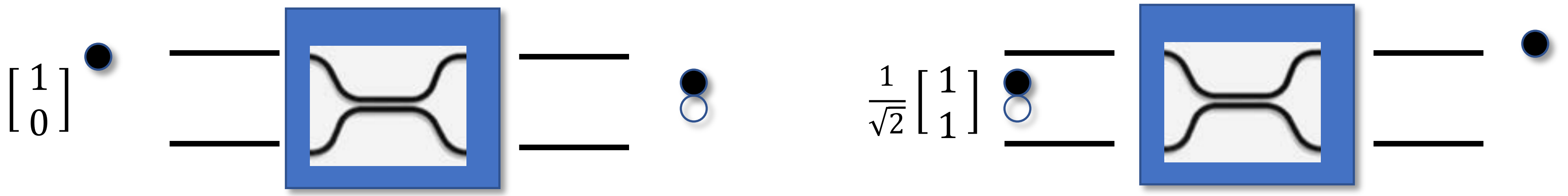
Quantum Optics Function



Superposition

$|0\rangle$ $\quad \frac{1}{\sqrt{2}} (|0\rangle + |1\rangle)$ $\quad |0\rangle$

Quantum Optics Function



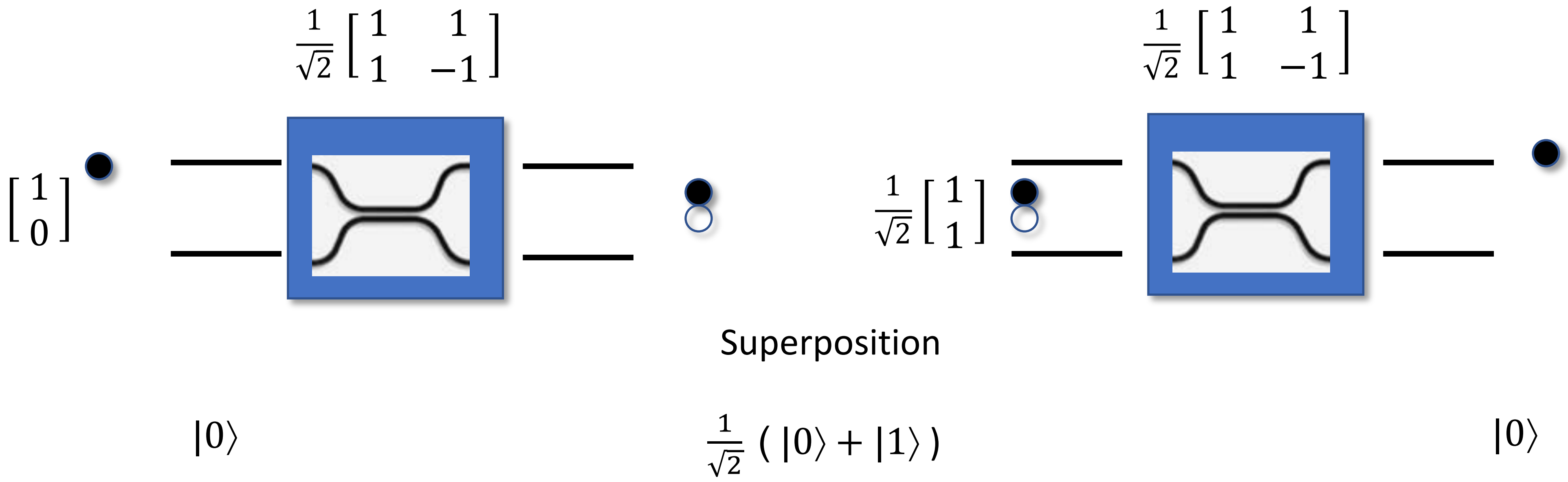
Superposition

$|0\rangle$

$\frac{1}{\sqrt{2}} (|0\rangle + |1\rangle)$

$|0\rangle$

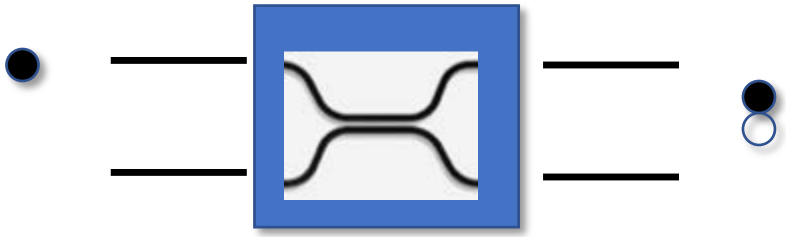
Quantum Optics Function



Quantum Optics Function

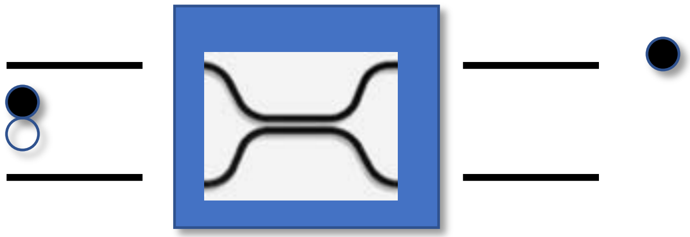
$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$

$\begin{bmatrix}1\\0\end{bmatrix}$



$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$

$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$



Superposition

$|0\rangle$

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

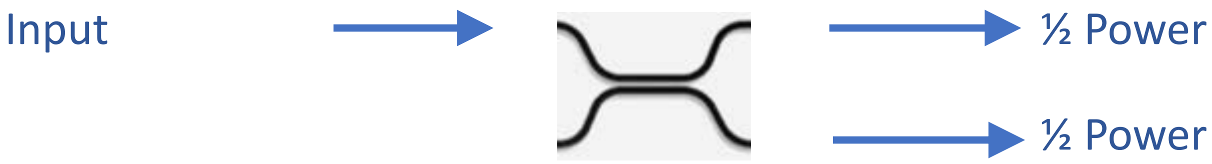
$|0\rangle$

$$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}\begin{bmatrix}1\\0\end{bmatrix} = \frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$$

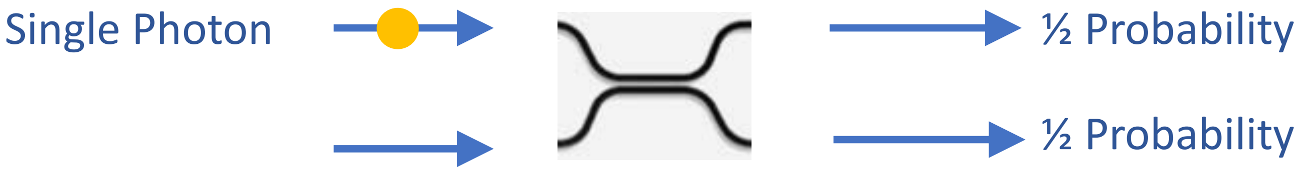
$$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}\ \frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix} = \begin{bmatrix}1\\0\end{bmatrix}$$

Quantum interference and 2-qubits gates

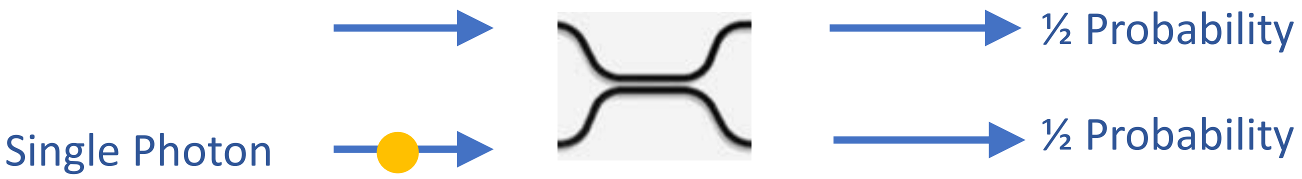
Beam Splitter and Classical Photons



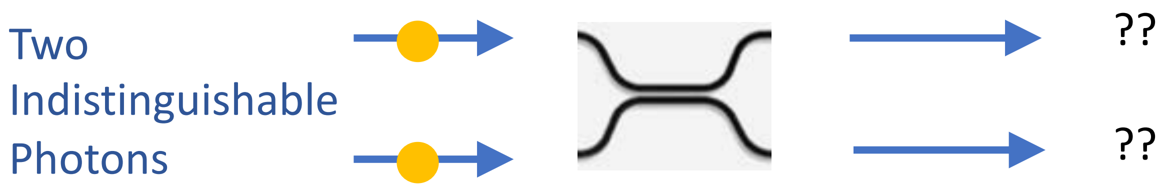
Single photon interference



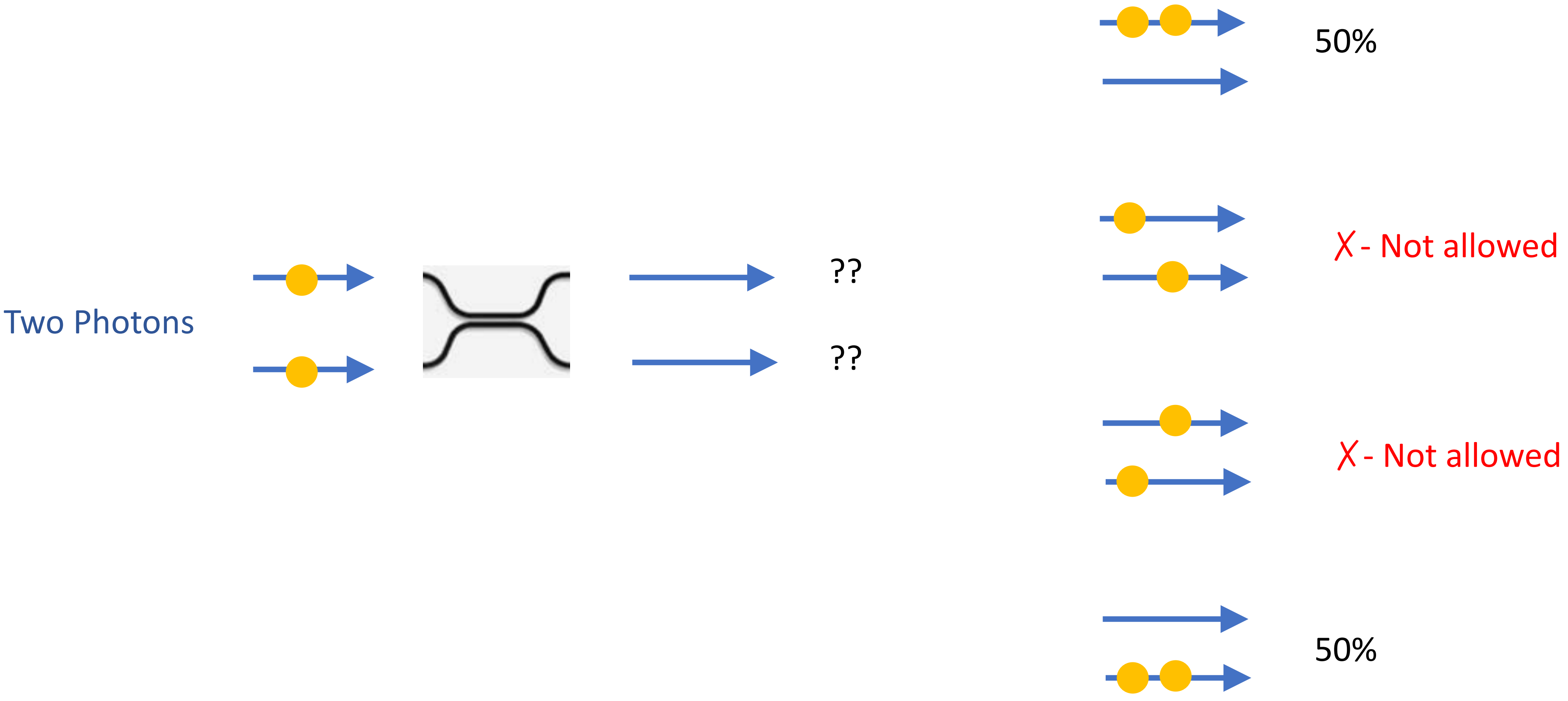
Single photon interference



Single photon interference



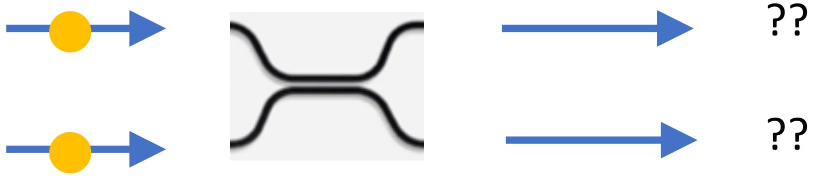
Single photon interference

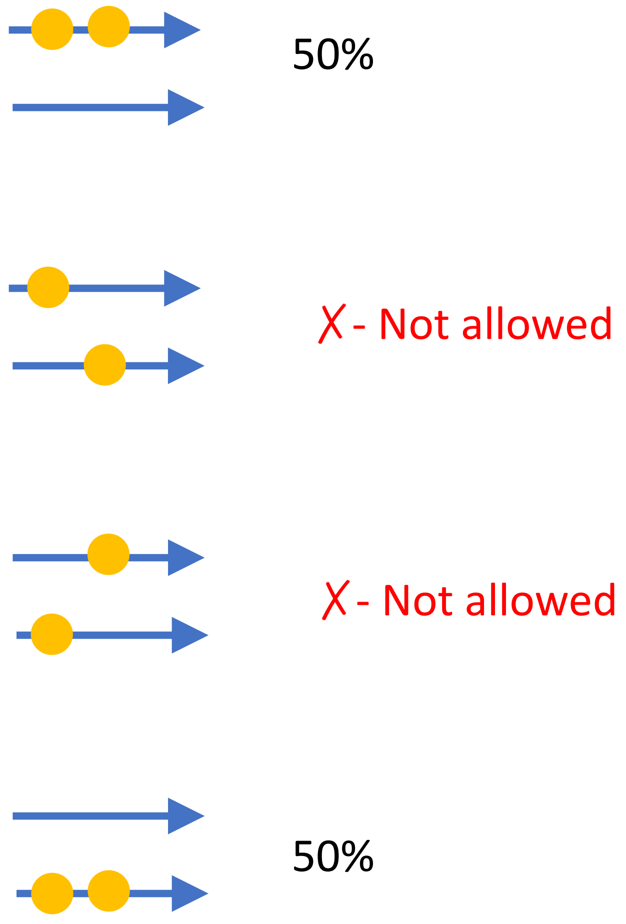


Interference between two *indistinguishable* photons only allows for above two possible outcomes

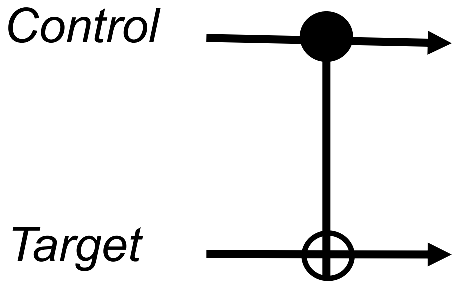
Single photon interference

Two Photons





Basis for building qubit interactions



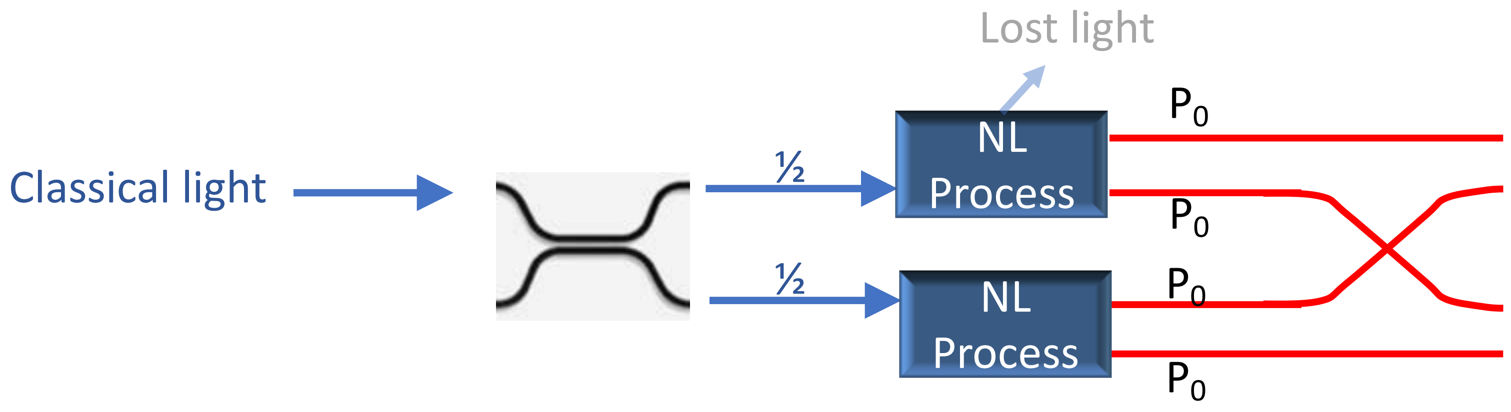
C-NOT Logic circuit

IN		OUT	
C	T	C’	T’
$|0\rangle$	$|0\rangle$	$|0\rangle$	$|0\rangle$
$|0\rangle$	$|1\rangle$	$|0\rangle$	$|1\rangle$
$|1\rangle$	$|0\rangle$	$|1\rangle$	$|1\rangle$
$|1\rangle$	$|1\rangle$	$|1\rangle$	$|0\rangle$

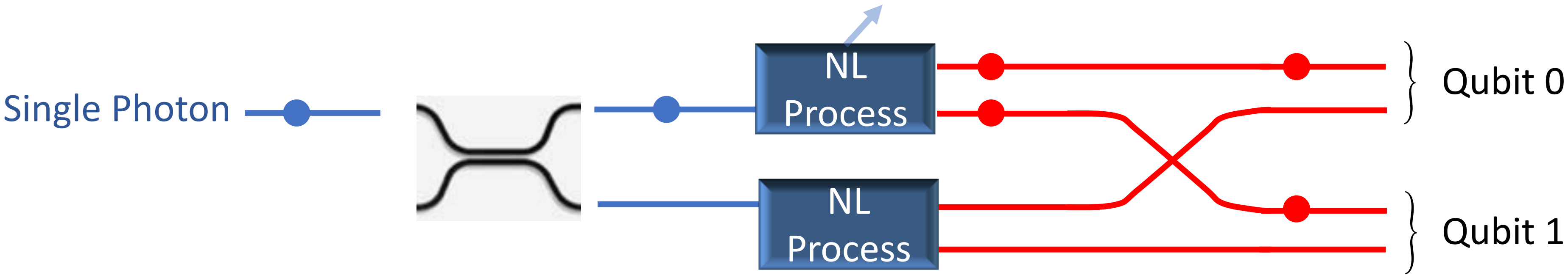
Interference between two *indistinguishable* photons only allows for above two possible outcomes

Entanglement

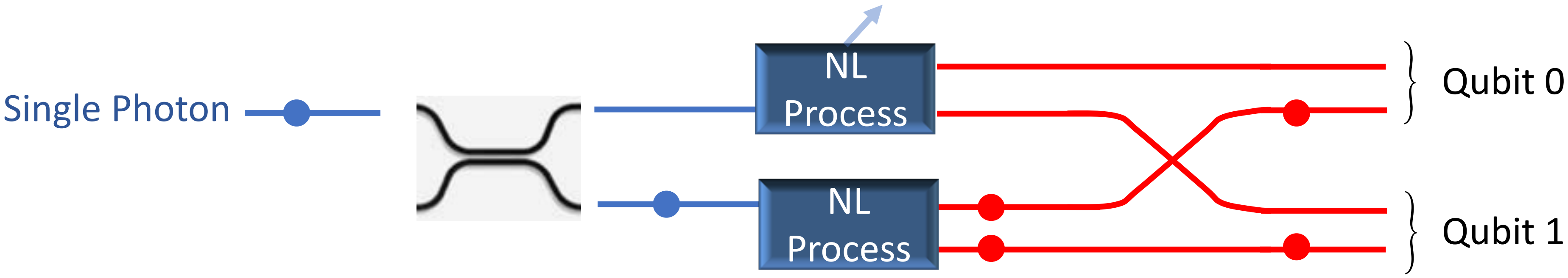
Classical Light



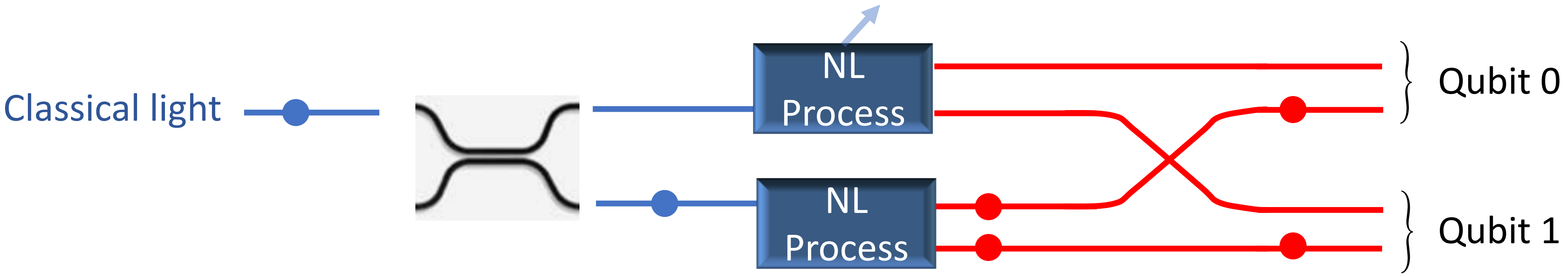
Single Photons

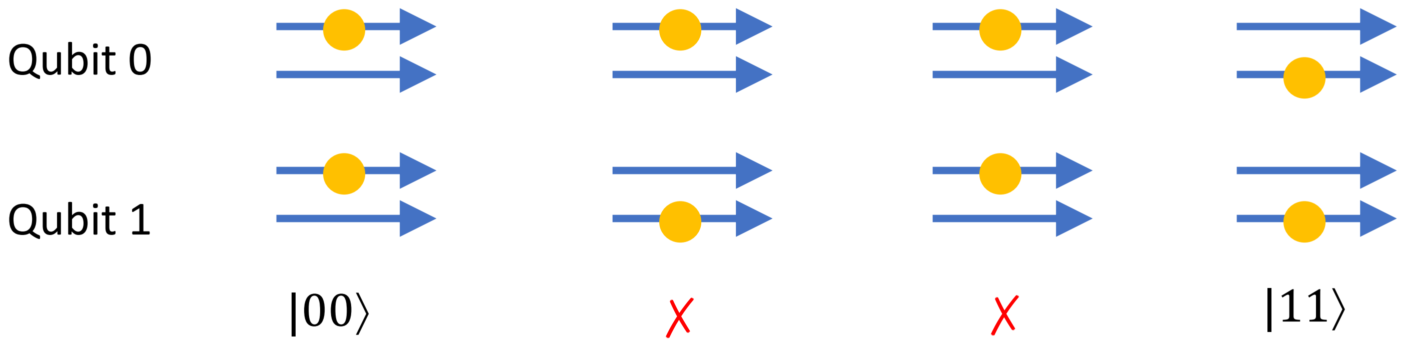


Single Photons

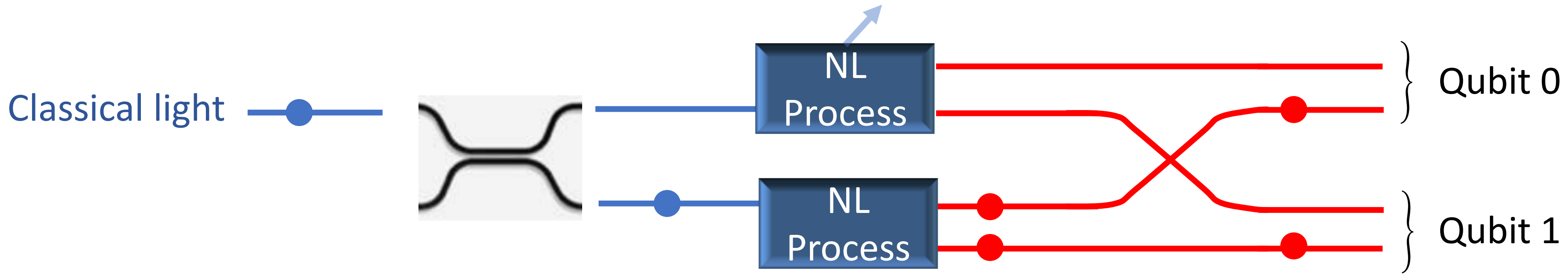


Single Photons

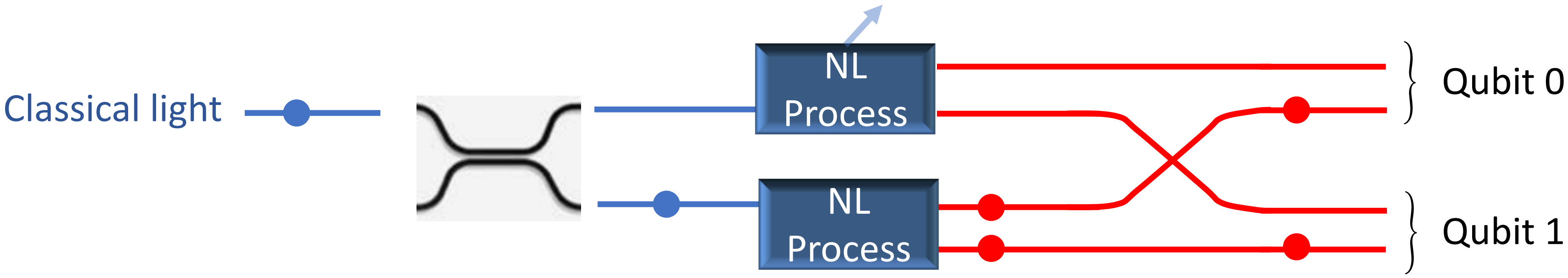


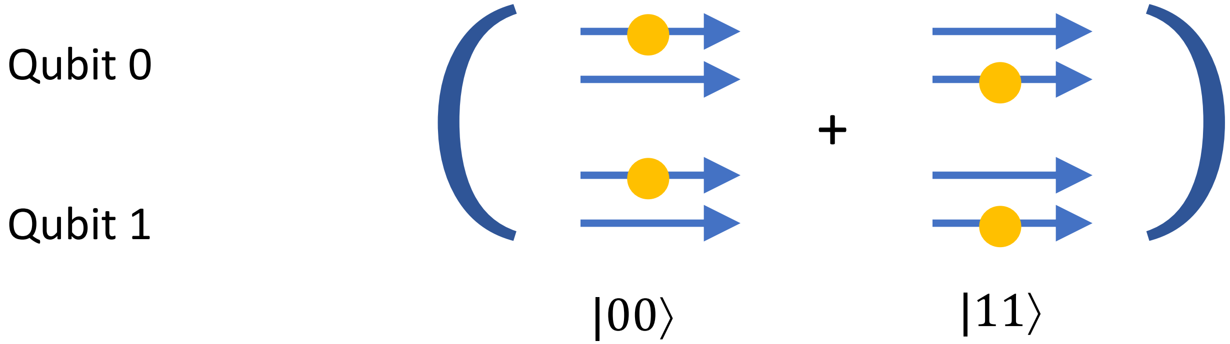


Single Photons



Single Photons



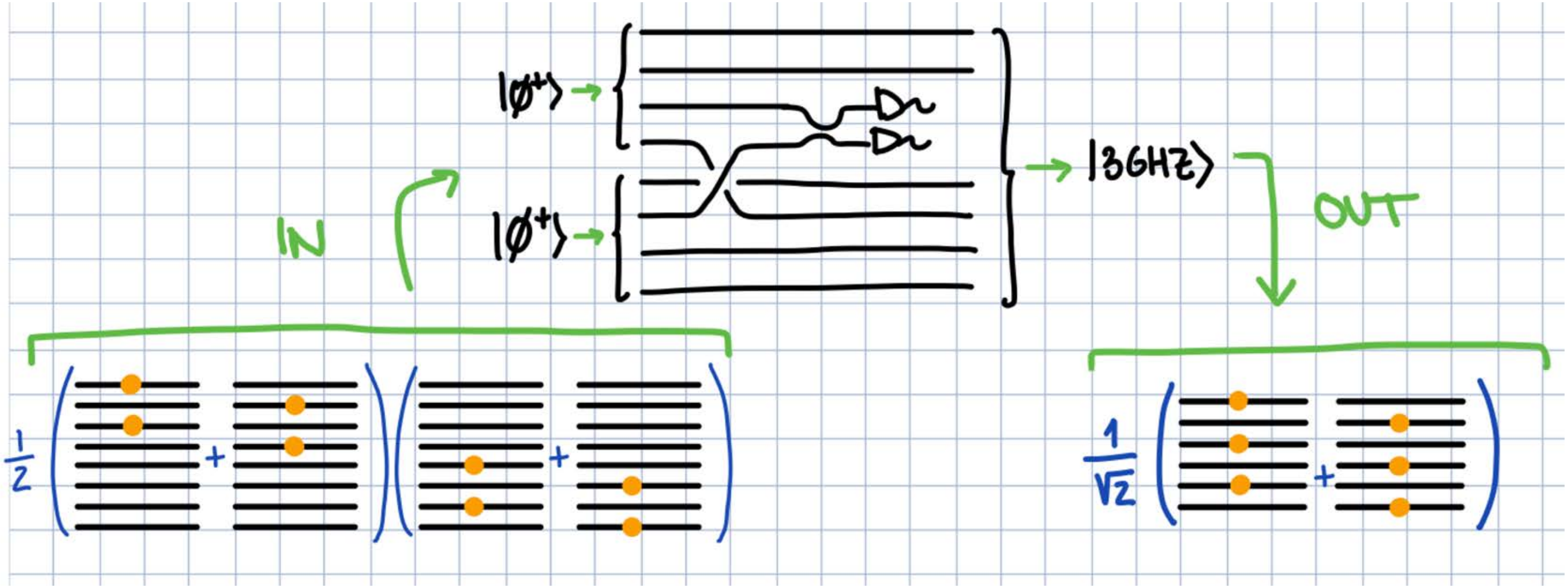


$\frac{1}{\sqrt{2}}\left(|00\rangle + |11\rangle \right)$

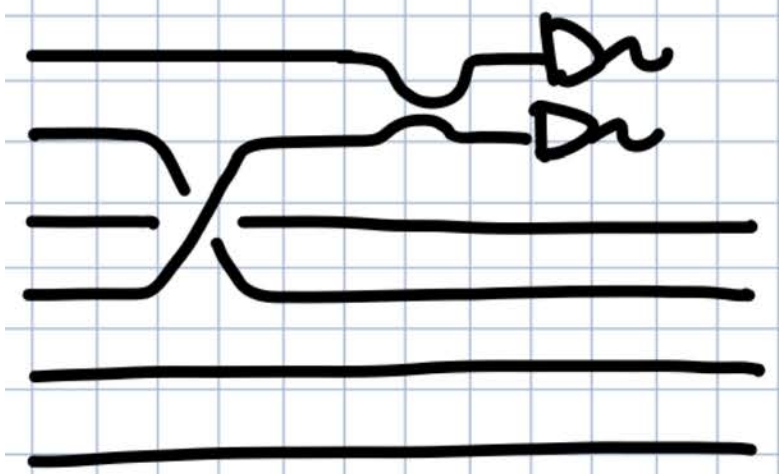
Entangled State

More complex entangled states

Generating 3-photon entangled states from a pair of 2-photon entangled states



Entanglement Circuit



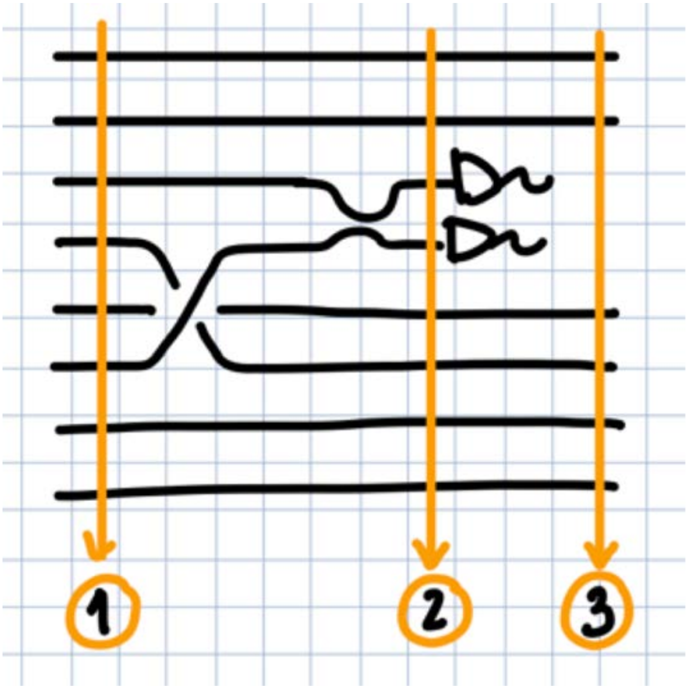
SUCCESS

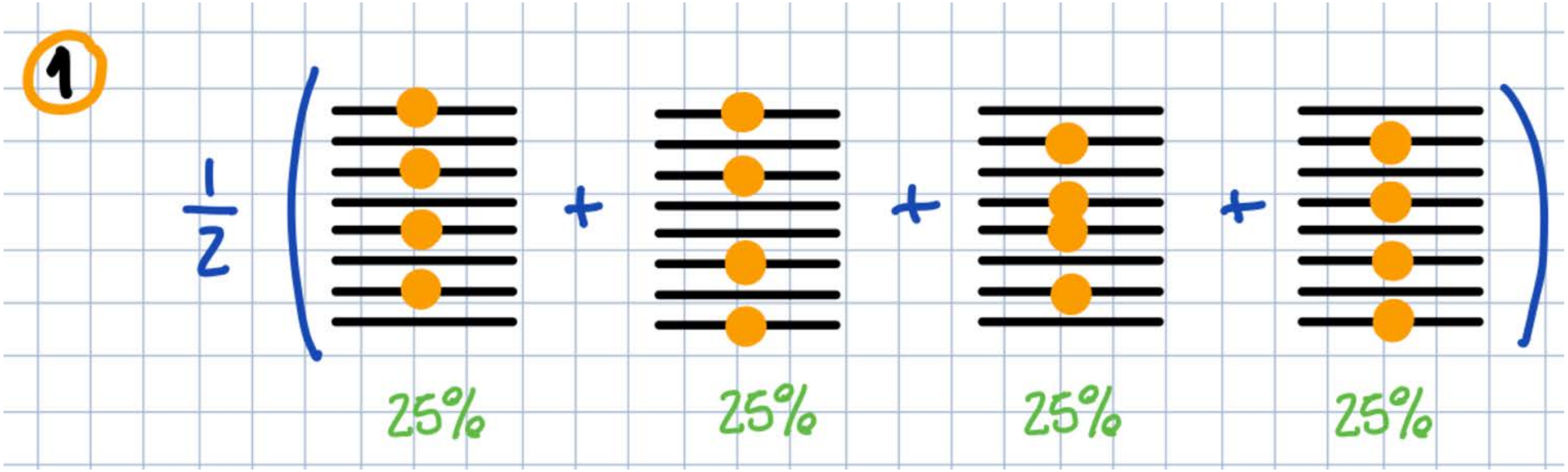
Detecting 1γ in either detector

FAILURE

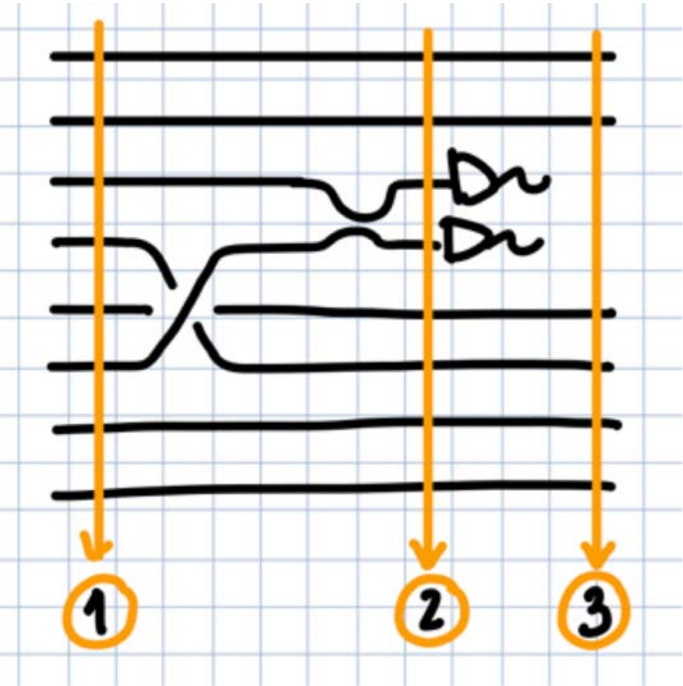
Detecting 0γ or 2γ accross the two detectors

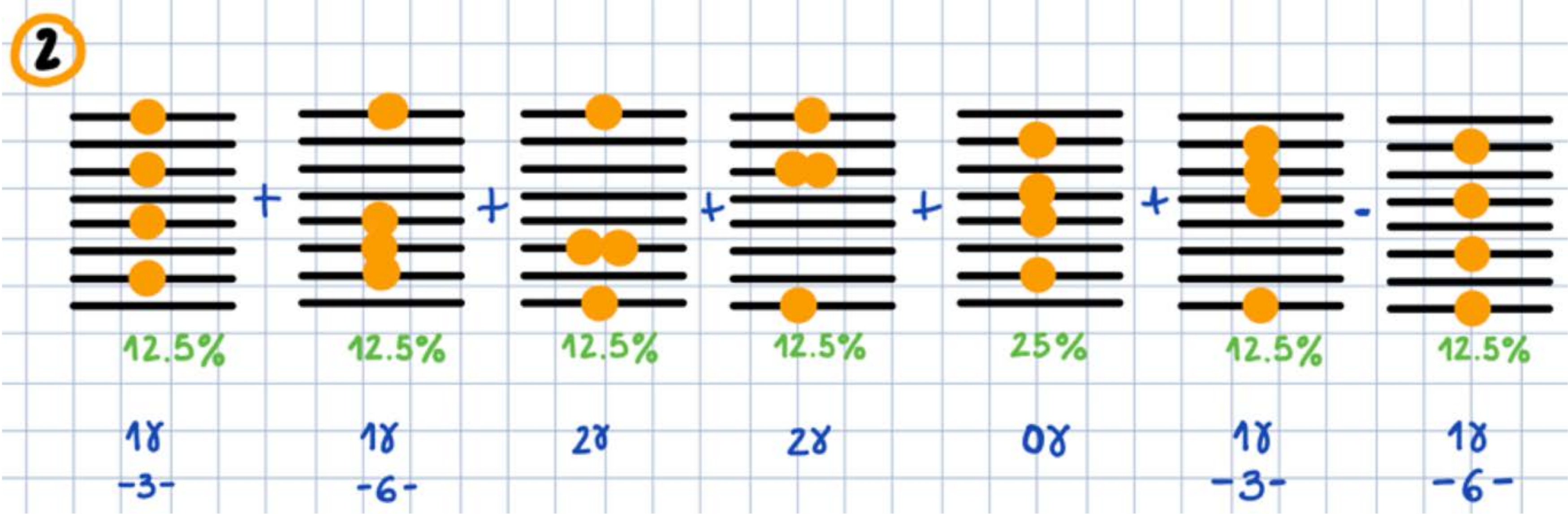
Step 1



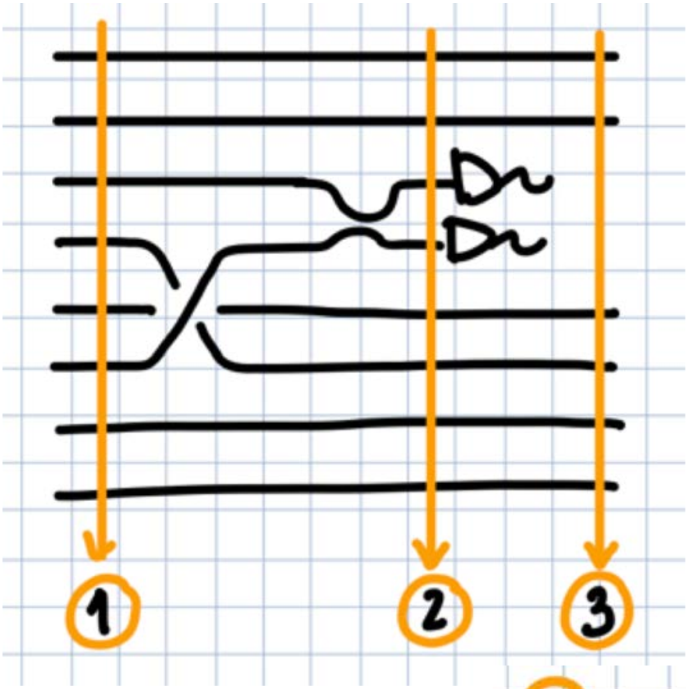


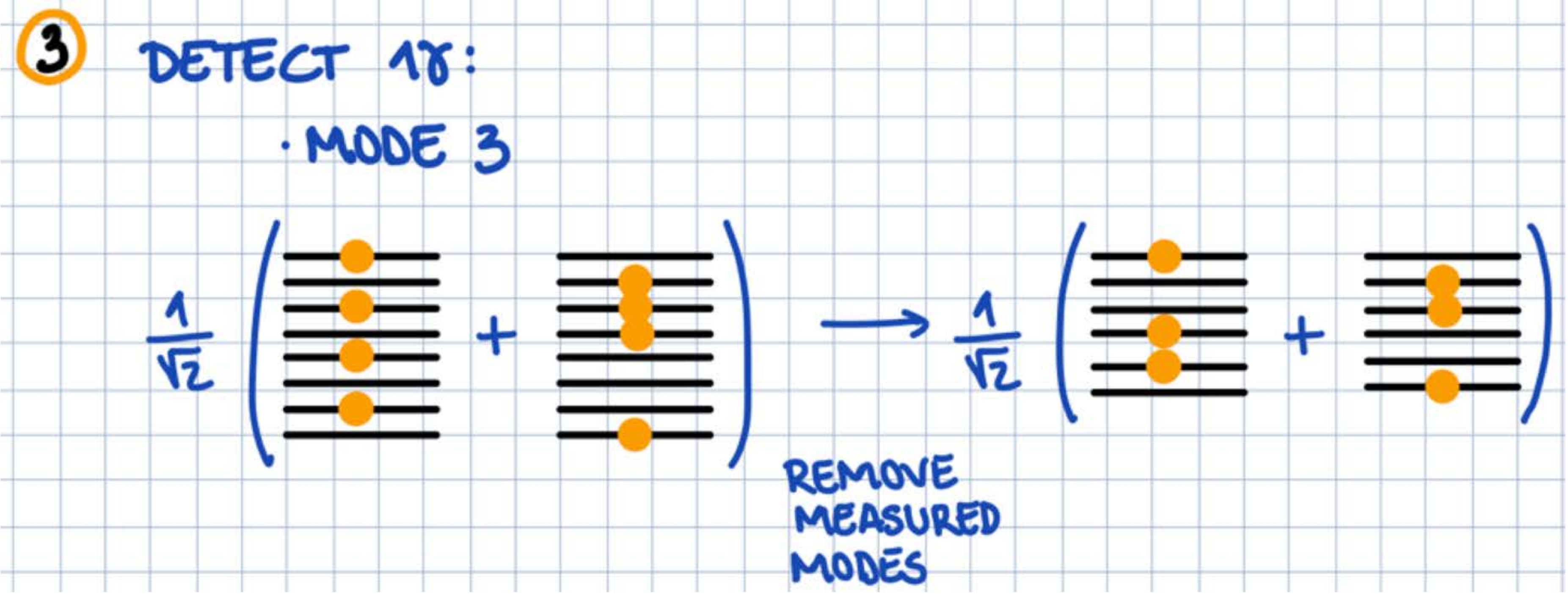
Step 2



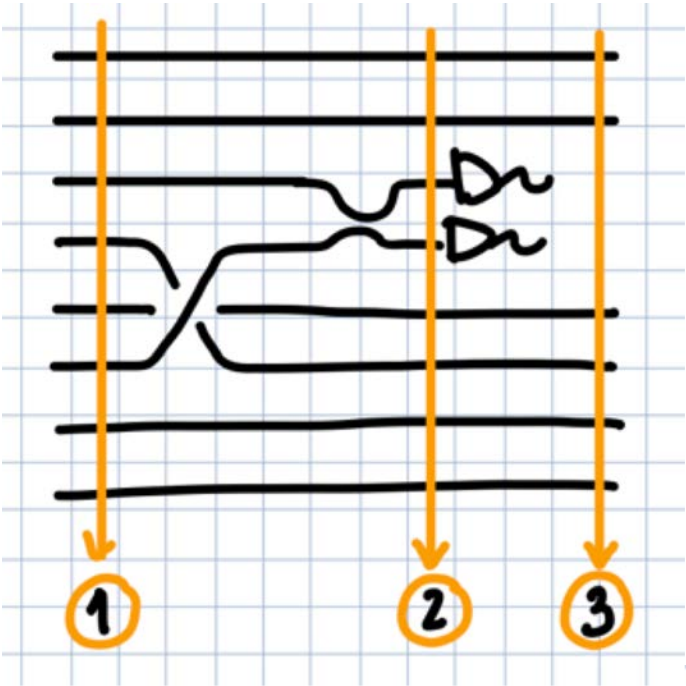


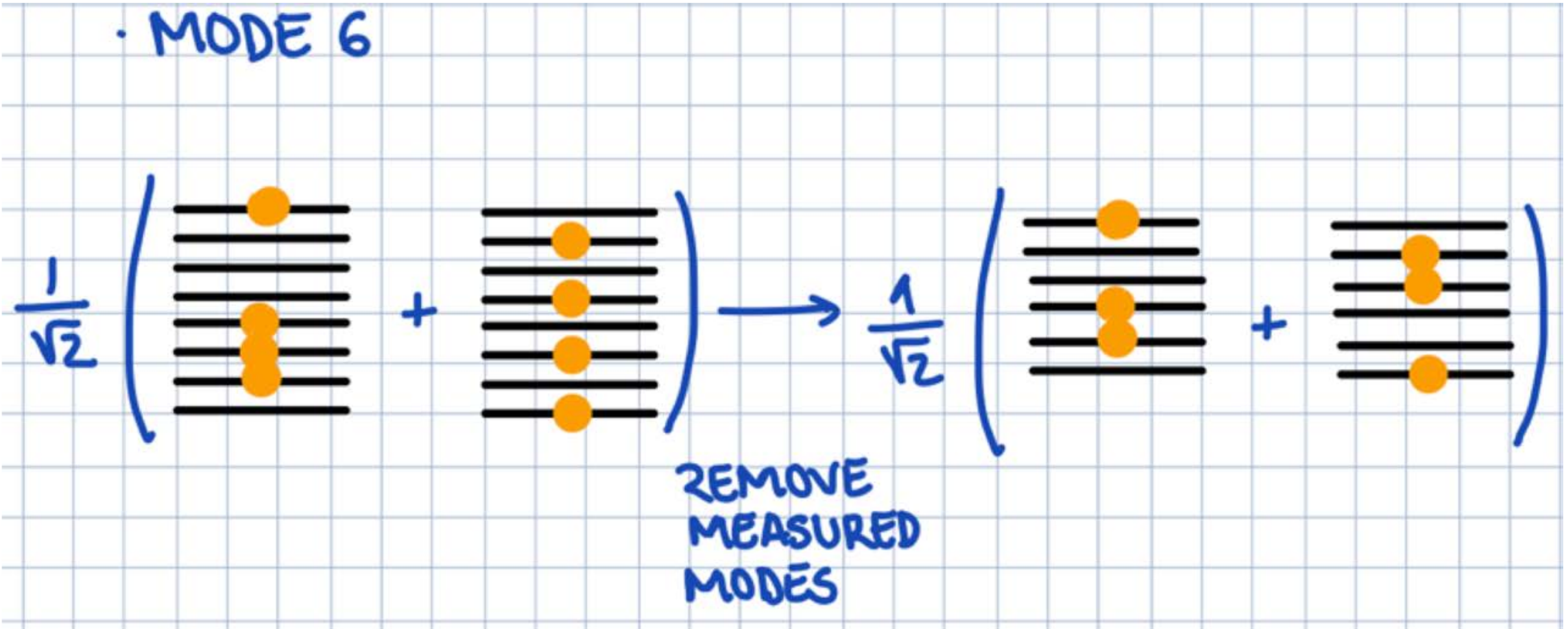
Step 3a


1
2
3

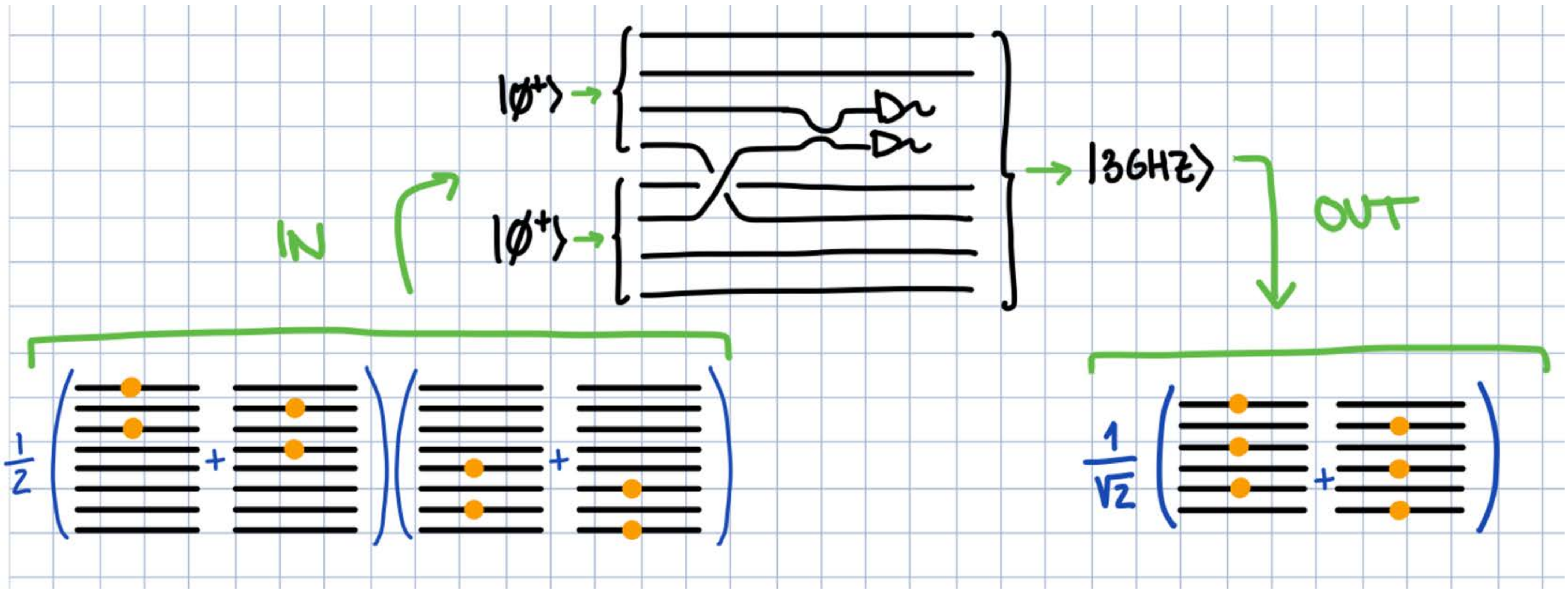

3
DETECT 1γ:
· MODE 3
$\frac{1}{\sqrt{2}}$
+
$\frac{1}{\sqrt{2}}$
+
REMOVE MEASURED MODES

Step 3b



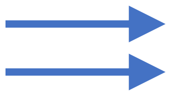


Generating 3-photon entangled states from a pair of 2-photon entangled states

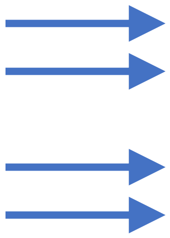


Memory representation

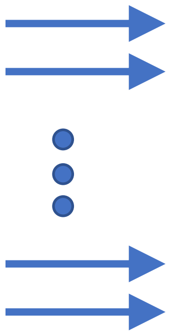
Quantum State Representation



$|0\rangle + |1\rangle$



$(|0\rangle + |1\rangle)\,(|0\rangle + |1\rangle) = (\,|00\rangle + |01\rangle + |10\rangle + |11\rangle\,)$



$(\,|0\rangle + |1\rangle\,)^N$

N=30 : ~1G
N=50 : ~1P
N=100 : >>WW production of memory
N=300 : More than the particles in the universe

Requirements for building a QC

Requirements

1. A scalable physical system with well characterized qubits
2. The ability to initialize the state of the qubits to a simple fiducial state, such as $|000...\rangle$
3. Long relevant decoherence times, much longer than the gate operation time
4. A “universal” set of quantum gates
5. A qubit-specific measurement capability

1. Qubits
2. Set qubits
5. Read qubits
4. Gates
3. Persistence

DiVincenzo, D. P. & Loss, D. Quantum information is physical. Superlatt. Micro. 23, 419–432 (1998)
DP DiVincenzo Fortschritte der Physik 48, 120 (2000)

Compelling system requirements

1. Integration with classical electronics
2. Scalable system*
3. Manufacturable
4. Supports quantum error correction

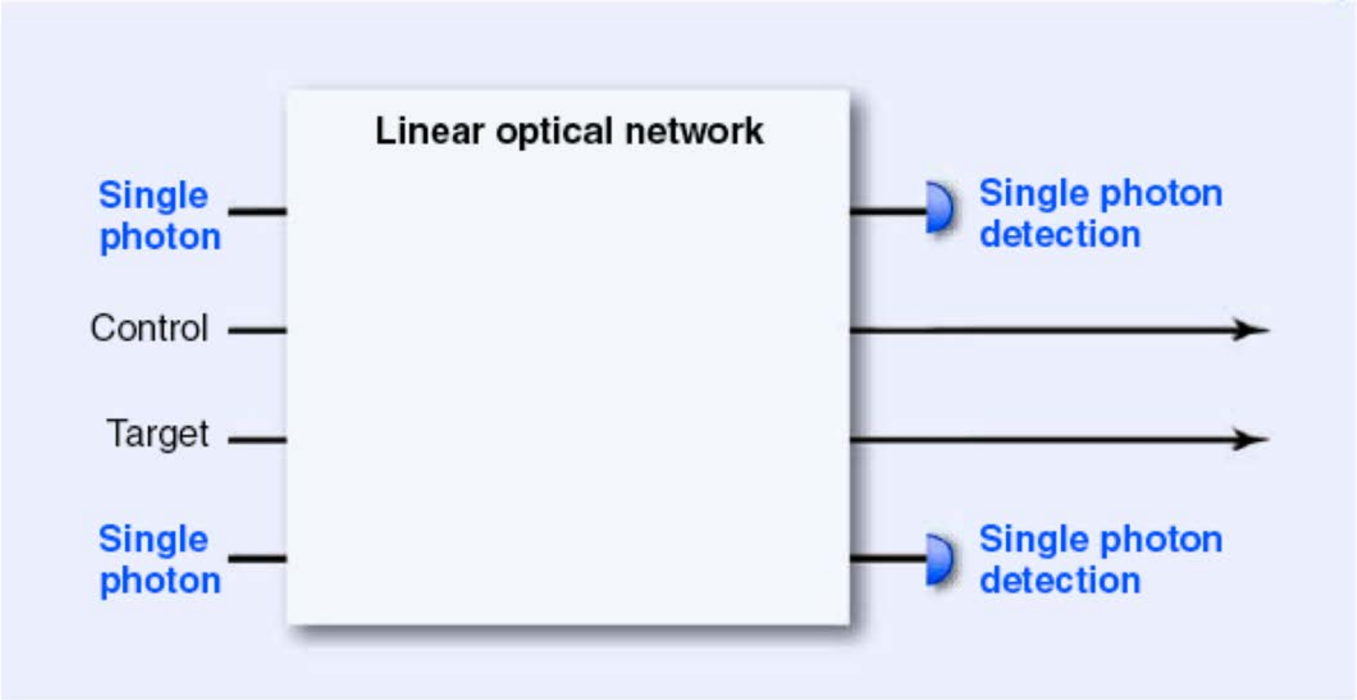
Compelling system requirements

1. Integration with classical electronics
2. Scalable system* to 1,000,000 qubits
3. Manufacturable
4. Supports quantum error correction

Quantum computation with photons

Knill, Laflamme and Milburn *Nature* **409**, 46 (2001)

Quantum computation with photons



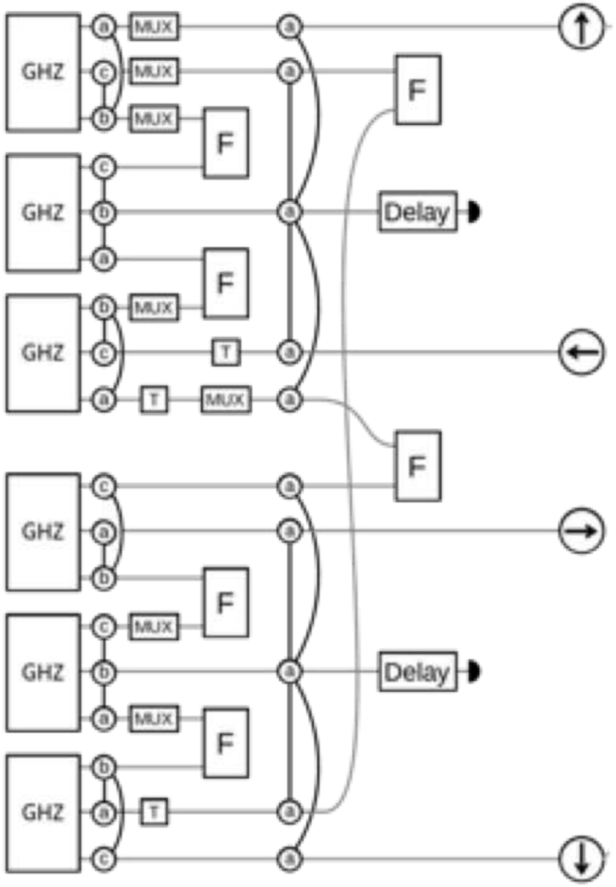
Theoretical solution: Measurement induced non-linearity, with ancillas

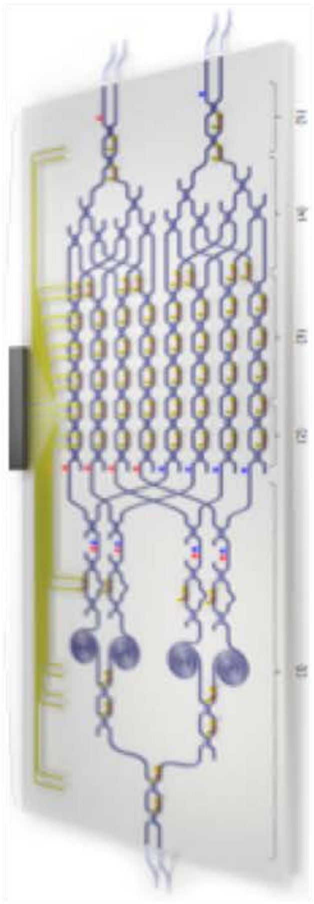
Quantum computing possible with:

- Single photon sources
- Single photon detectors
- Linear optical elements (beamsplitter, phaseshifter)

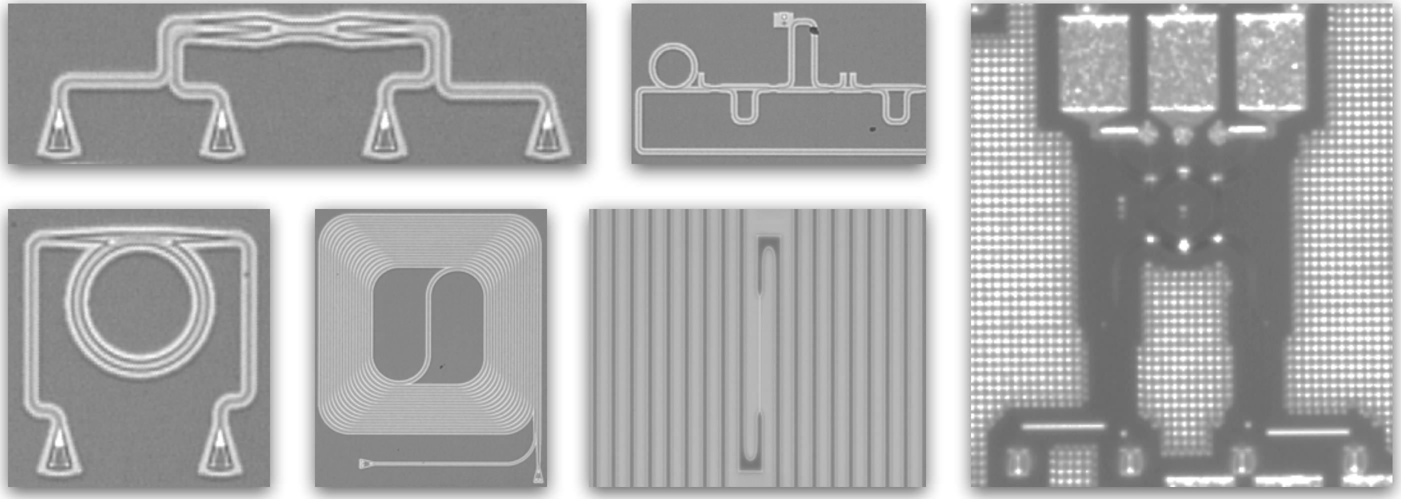
Knill, Laflamme and Milburn *Nature* **409**, 46 (2001)

Linear optical quantum computing architecture





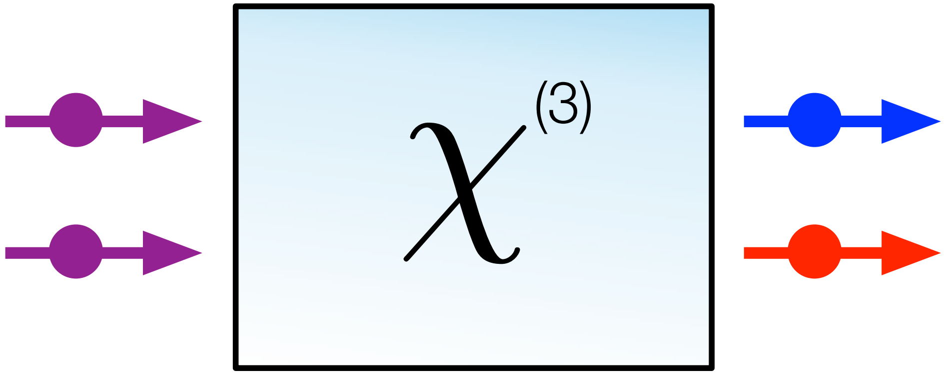
Existing Silicon Photonics Components



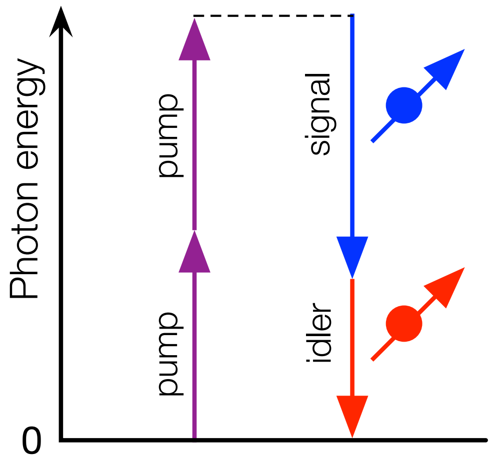
- Waveguides
- Delay lines
- Beamsplitters
- Phase shifters
- Switching
- Detectors
- Sources
- Filters

Single Photon Sources and Detectors

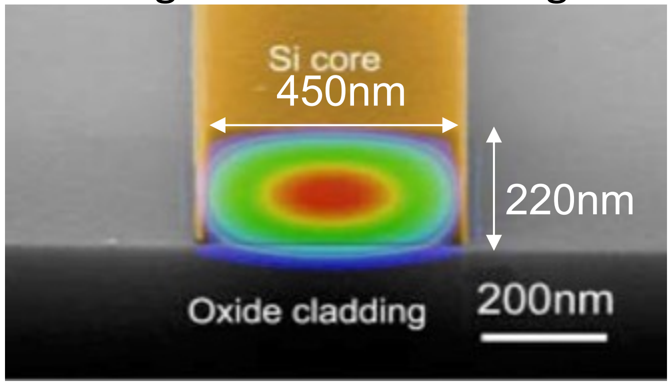
Photon generation in Si waveguide



- High $\chi^{(3)}$ nonlinearity ~ x100 > SiO_2
- Low Raman noise

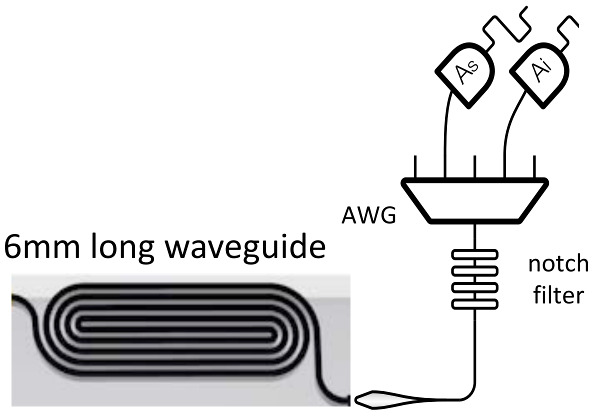


Ultra-high confinement of light:



1mW waveguide power gives ~1MW/cm^2 power density

Photon generation in Si waveguide



- Correlated photon pairs
- λ_p = 1547nm
- 6mm long waveguide
- 100's KHz generation rate
- mW's input power

Pump intensity

Waveguide length

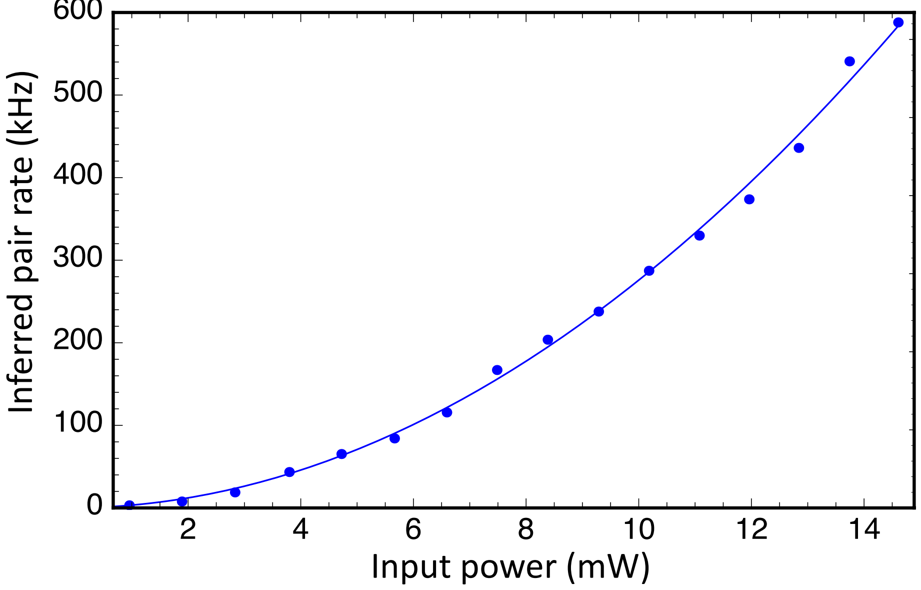
$$\text{pair rate} = \frac{I^2 L^2 \gamma^2}{4} \frac{1}{\pi} \Delta t \Delta \Omega$$

Effective non-linearity

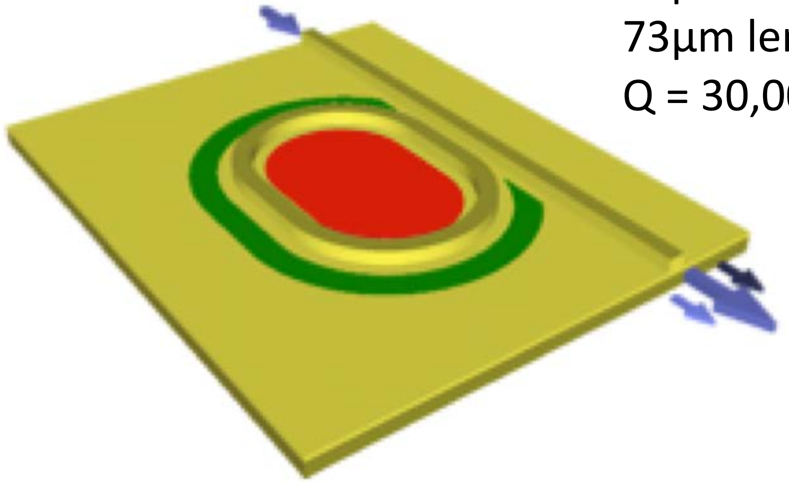
Integration time

Filter bandwidth

Photon pair generation rate

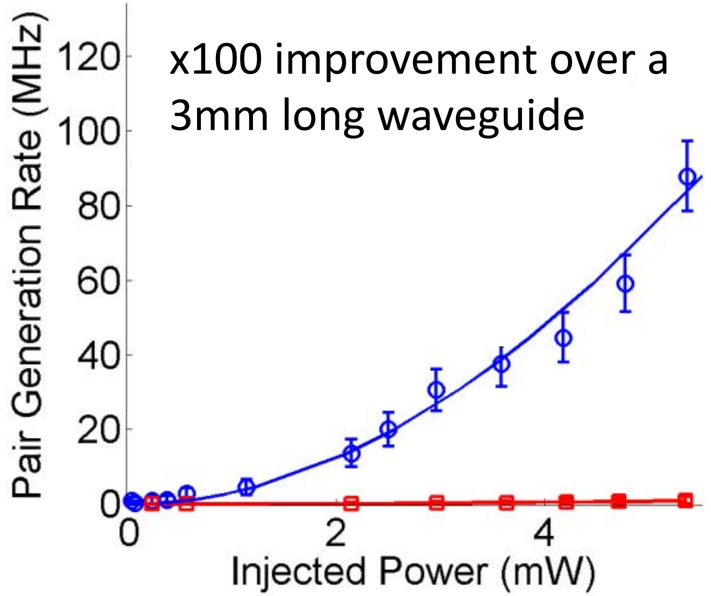


Enhancing photon generation

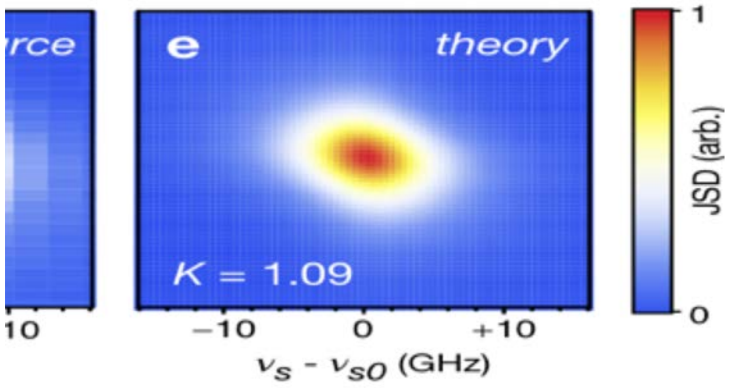


10μm radius ring
73μm length
Q = 30,000

On-chip pair generation rate

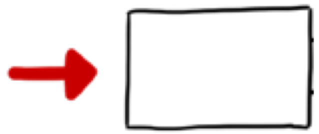


- Enhanced efficiency due to resonance effect: $$E_{ring} = \frac{it}{1-re^{ikL}} E_{in}$$
- Photon pairs are spectrally shaped
  - Improved brightness
  - Control over JSA
- > x100 improvement in efficiency

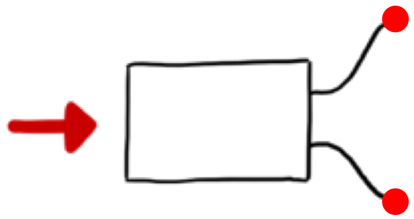


Engin, et al Opt. Express **21**, 27826 (2013)

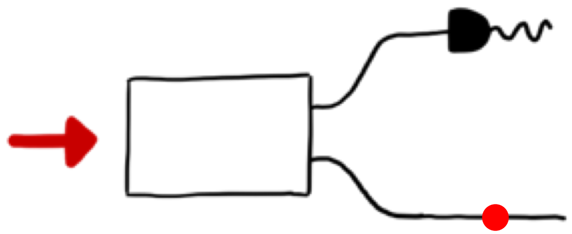
Multiplexed single photon source



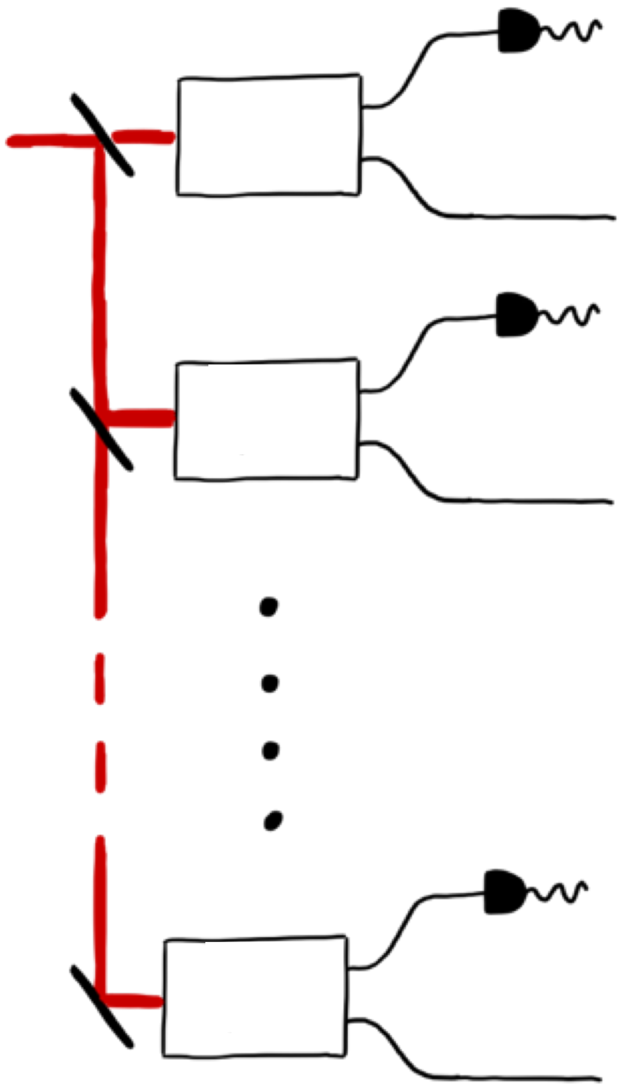
Multiplexed single photon source



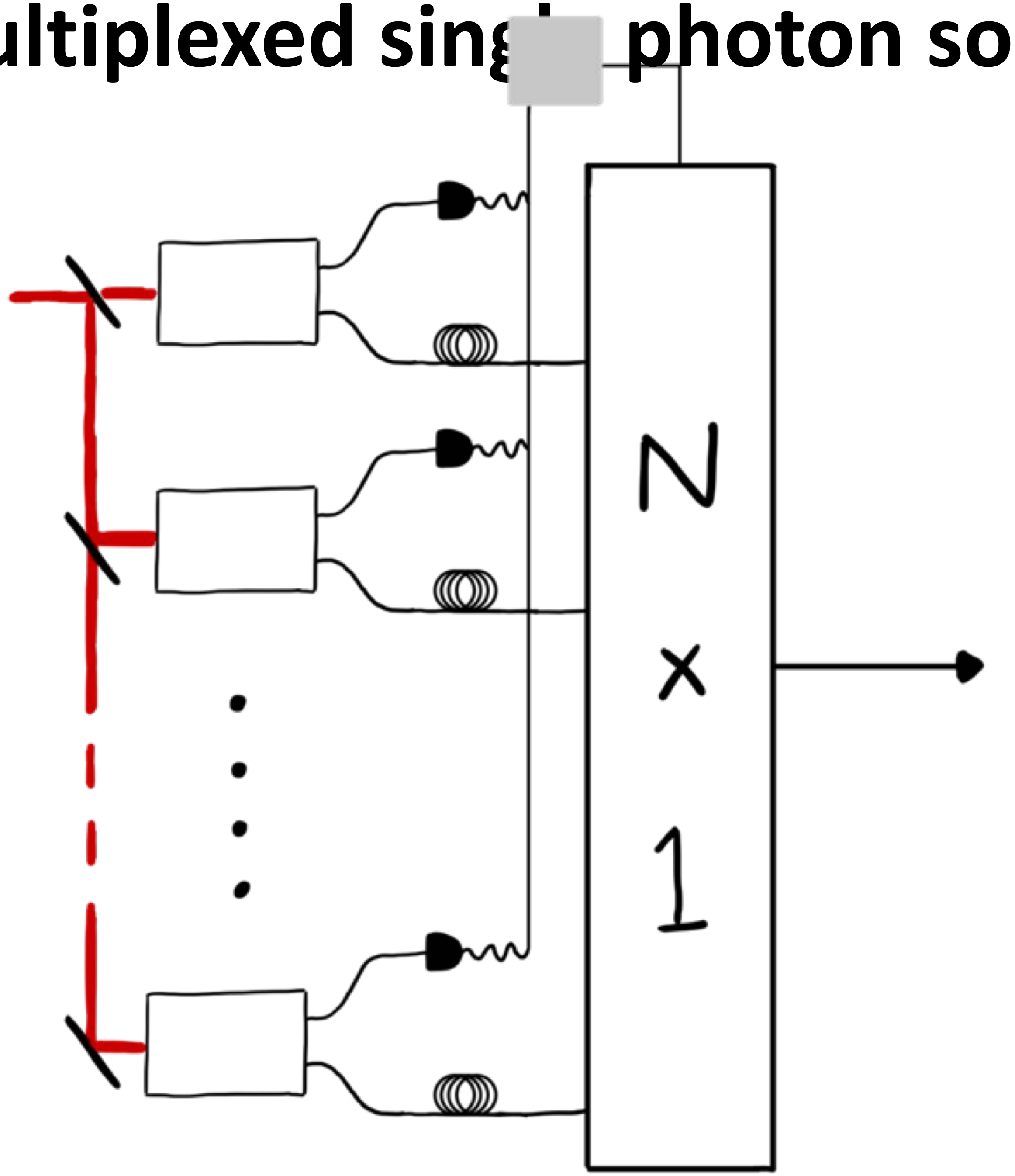
Multiplexed single photon source



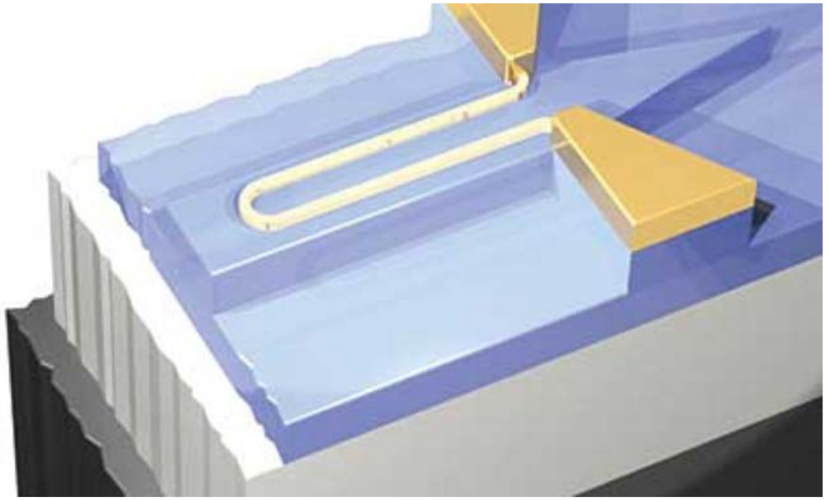
Multiplexed single photon source



Multiplexed sing[illegible] photon source



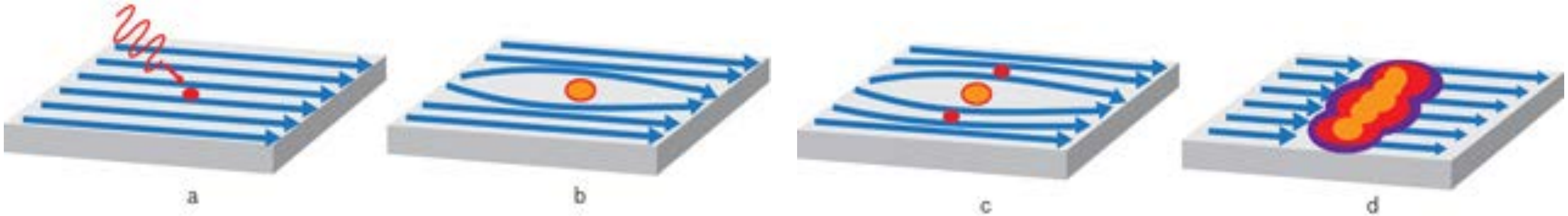
Single photon detection



Superconducting Nanowire Single Photon Detector (SNSPD)

- > 95% single photon detection
- Timing jitter ~10 ps
- Dead time ~1 ns (GHz rate operation)
- Dark (noise) <1 Hz
- Single photon sensitivity
- Operating temperature ~4K
- Many Material systems: NbN, WSi, MoSi

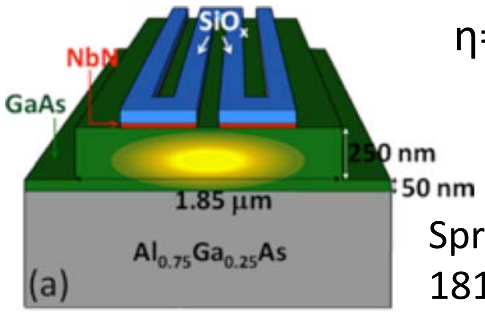
- Thin film of superconducting material (amorphous and polycrystalline) -- Deposited via standard semiconductor deposition techniques
- Nano-wire widths sub-100nm



Gol'tsman et al, Applied Physics Letters, 79:705 707, 2001

Single photon detections

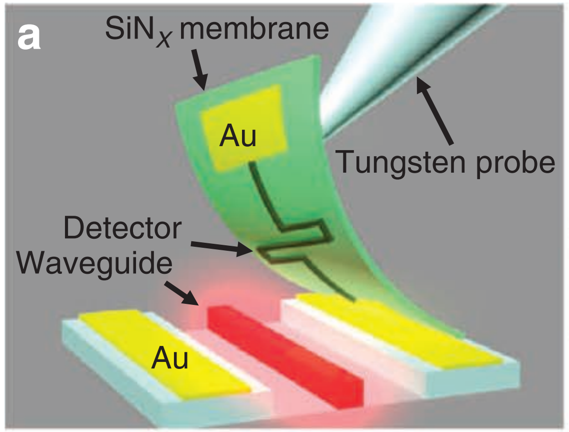
GaAs waveguide superconducting detector



η=20%

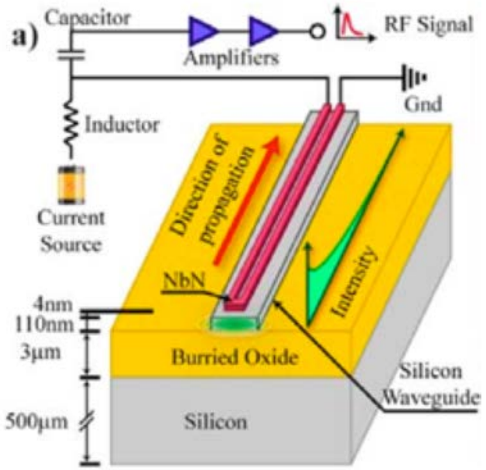
Sprengers et al , Appl. Phys. Lett. **99**, 181110 (2011)

Flip-chip integration



Najafi, et al Nat Comms **6**, 5873 (2015).

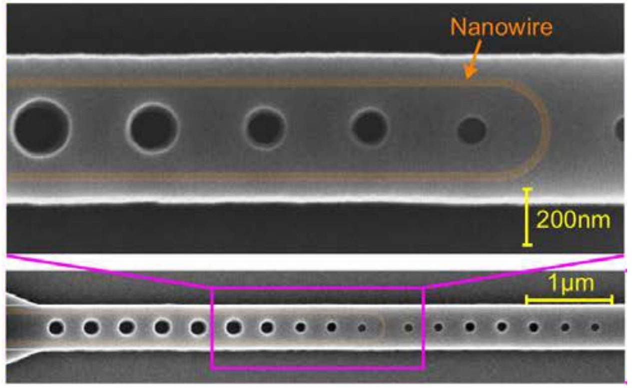
Silicon waveguide superconducting detector



η=91%

Pernice et al Nat Comms **3**, 1325 (2012)

Cavity enhanced

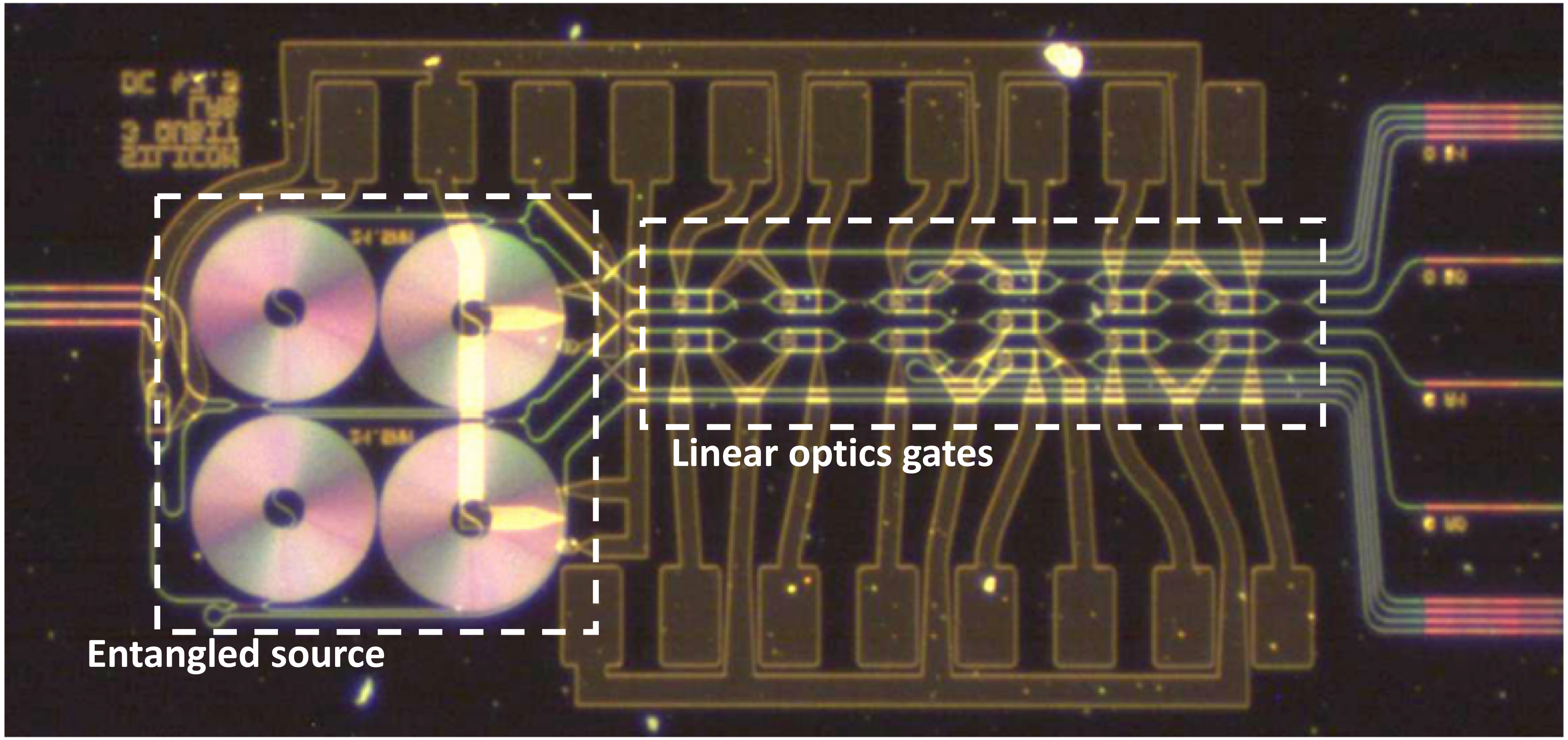


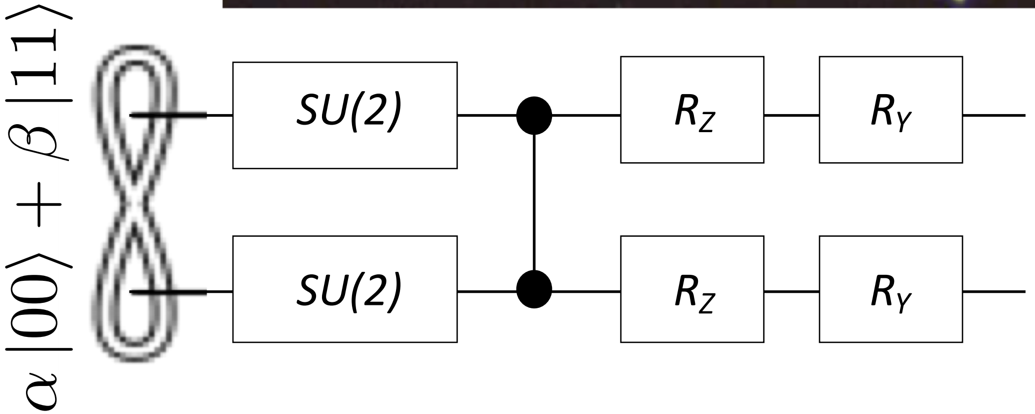
NbTiN
η=96%
0.1Hz dark counts
53ps jitter
7ns reset time

Akhlaghiet al, Nat Comms **6**, 8233 (2015).

Quantum Si Photonics Systems

2 qubit processor

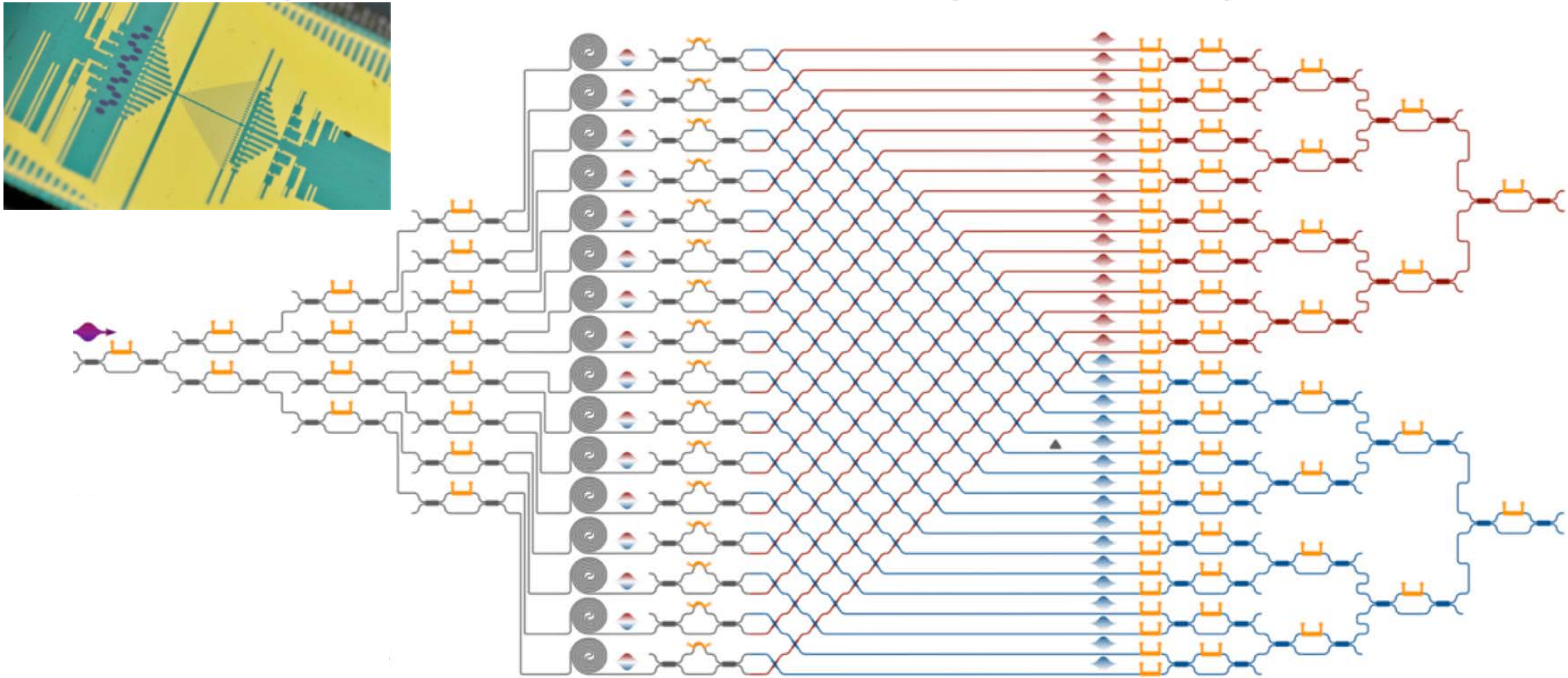




- 4 sources + entangling gate
- 16 controllable elements
- Arbitrary 2-qubit preparation and measurement

Santagati et al. (2017). Silicon photonic processor of two-qubit entangling quantum logic. Journal of Optics, 19(11), 114006

High dimensional entanglement generation



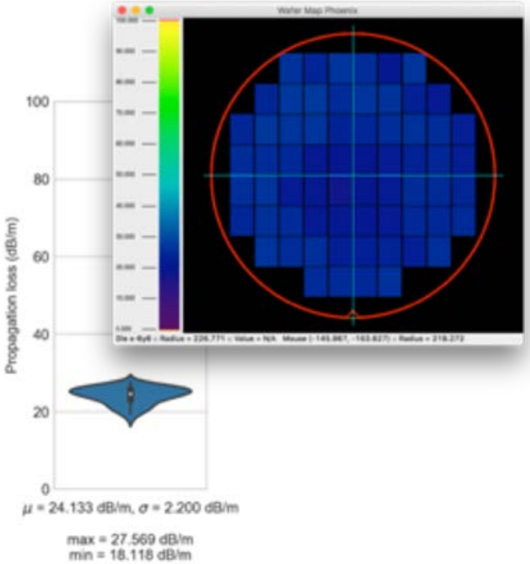
- 16 sources, 48 grating couplers, 182 MMIs, 256 crossers
- ≈ 600 optical components
- Generation and analysis of 16 dimensional entangled quantum state

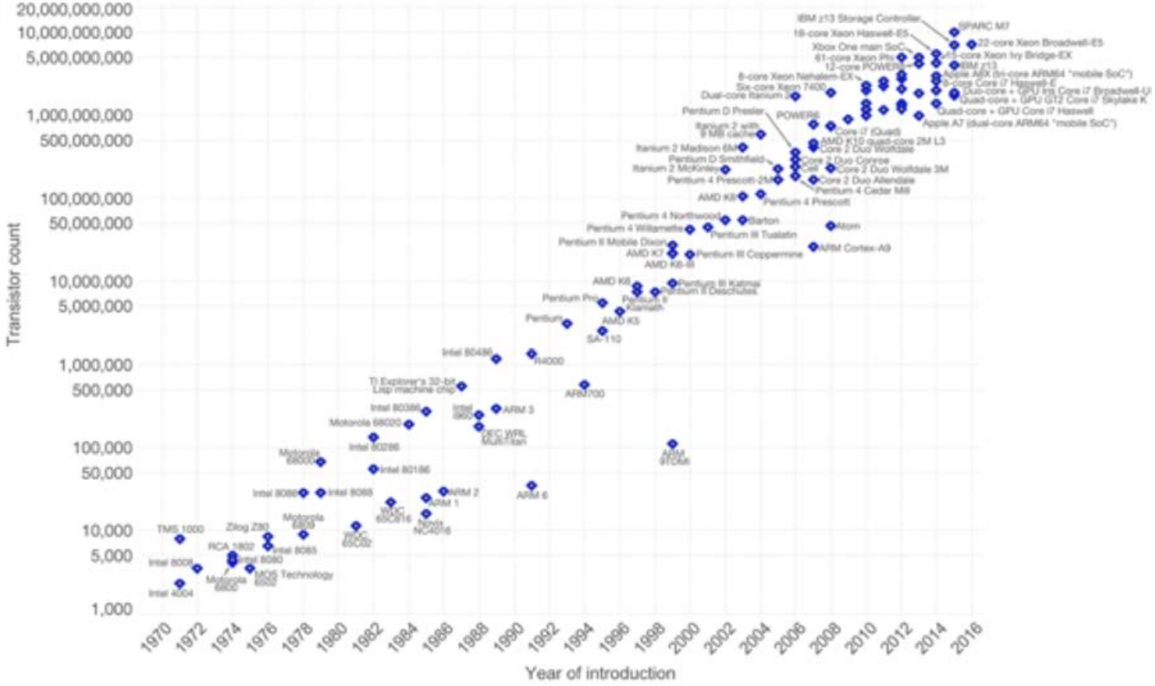
DTU

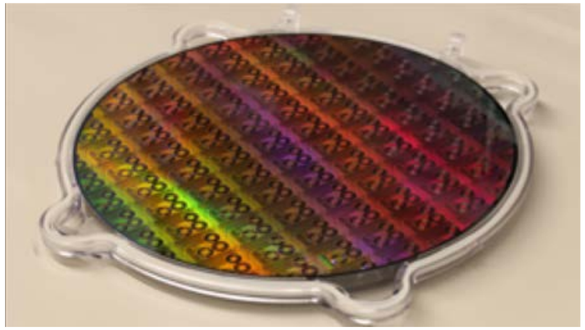
Wang et al., Science, 2018

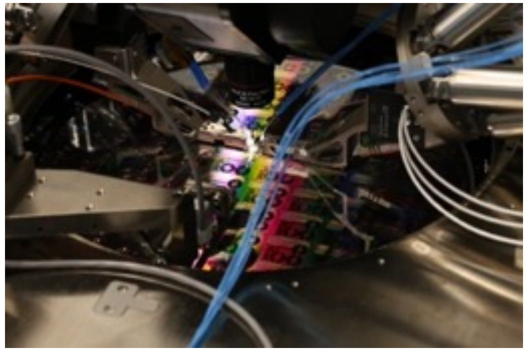
Silicon Photonics
State of the industry

Si Photonics Industry

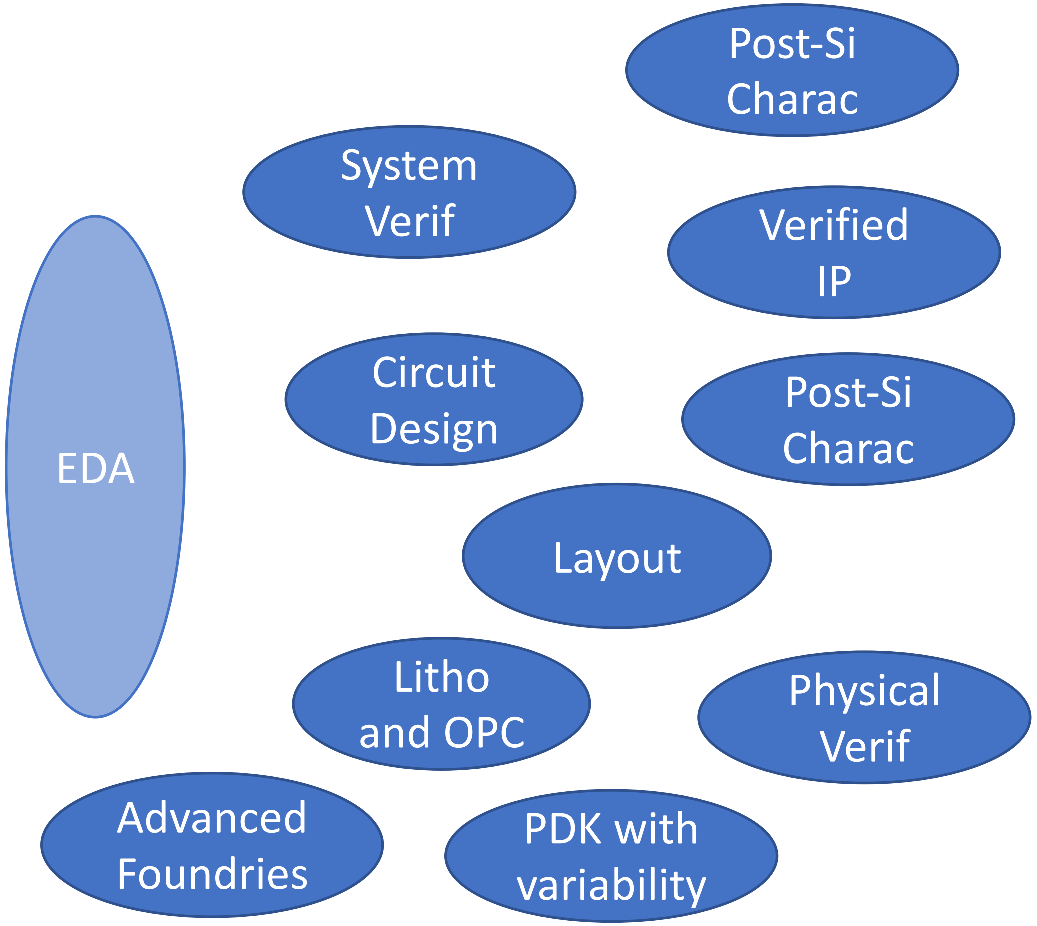


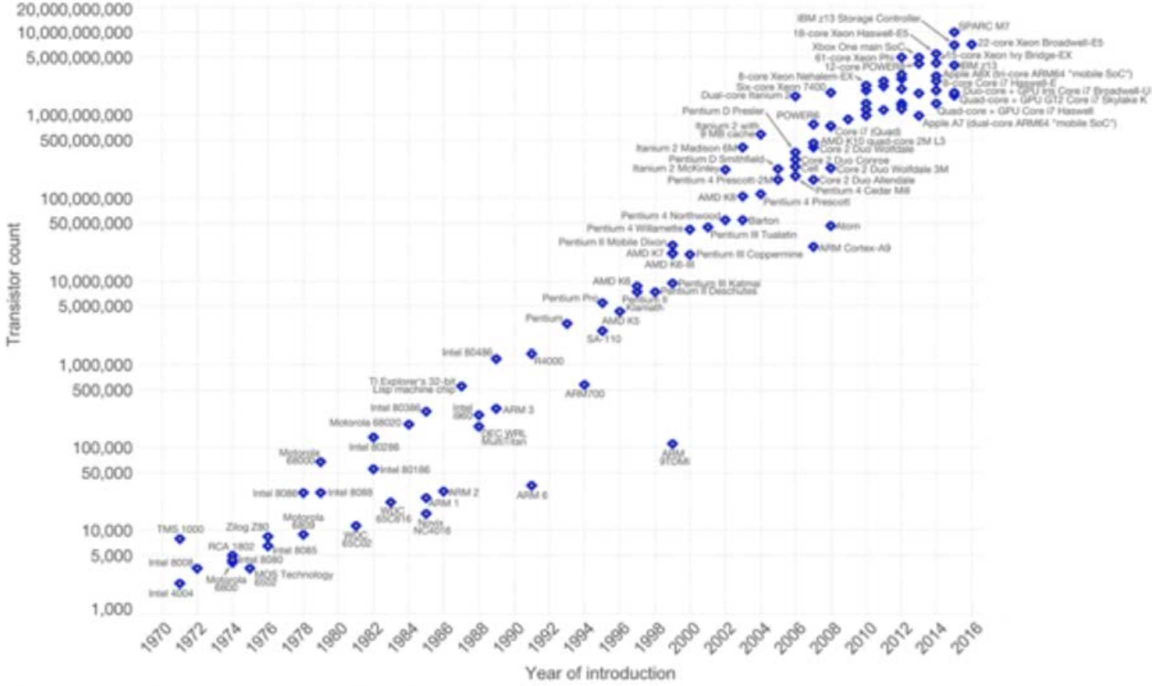




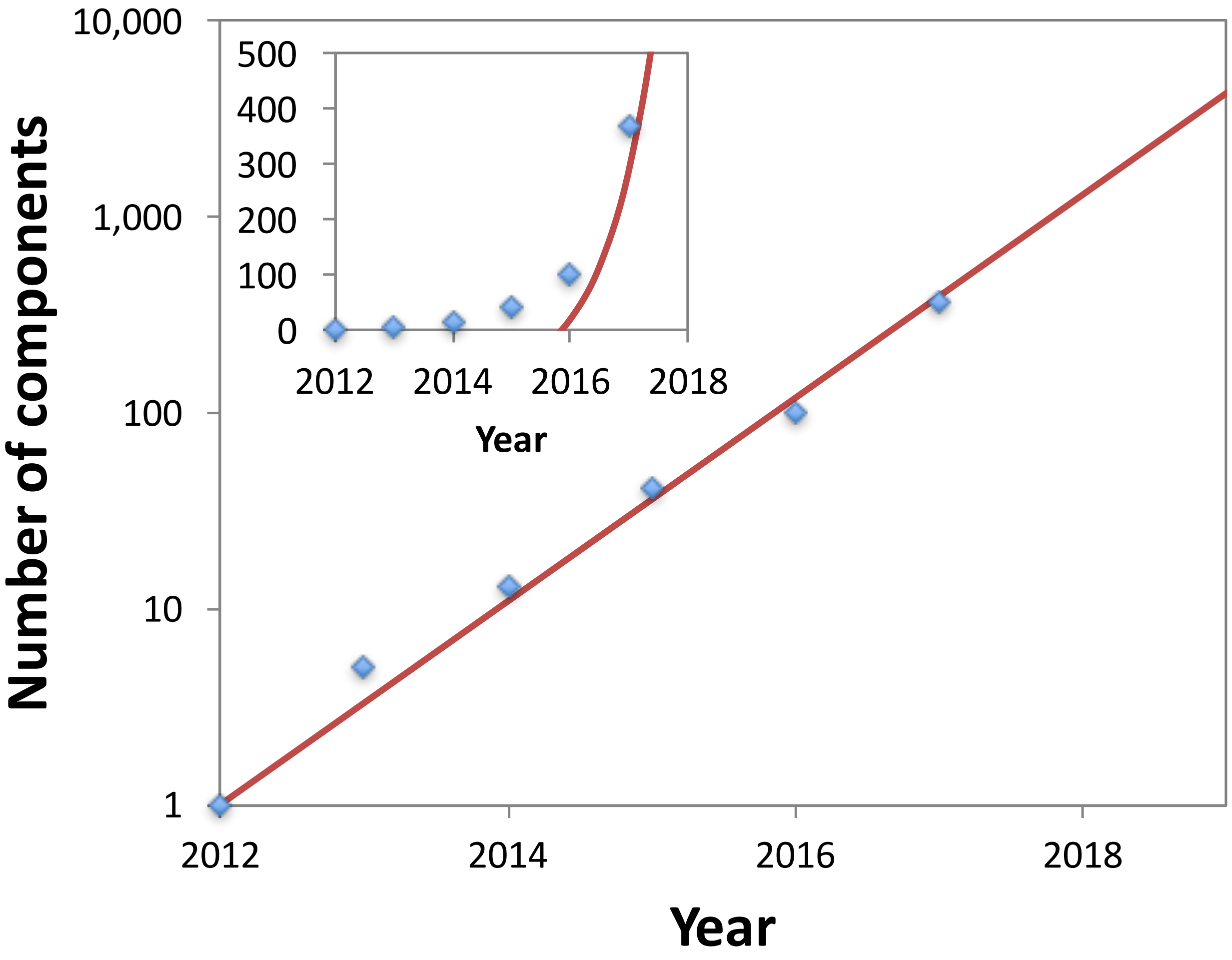


Si Photonics Industry





Quantum photonics Moore's Law



Summary of PSIQuantum

- Mission to build the worlds first useful silicon photonic quantum computer
- Founded by foremost experts in the fields (quantum computing and silicon photonics)
- Assembled world class team, investors, advisors
- Based in Palo Alto, California

The right materials
(silicon)
+
Technological advancements
(fewer, simpler components required)
+
The right people
(the world leaders)
+
Approach
(low noise silicon photonics)

“There are a **million** ways to make **one qubit**…
…But only **one** way to make a **million qubits**”

Stu Aaron, COO

PsiQuantum