Quantum correlated sampling machines

Jake Bulmer
QLOC seminar
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People

Jake Bulmer (PhD student)

Stefano Paesani (postdoc)

Anthony Laing (boss)

QET Labs

University of BRISTOL

Zixin Huang

(Quantum comms theory collaborators)

Cosmo Lupo

SHEFFIELD QUANTUM CENTRE

The University Of Sheffield.

Who am I?

from Eaglescliffe (boring suburb of 10,000 people)

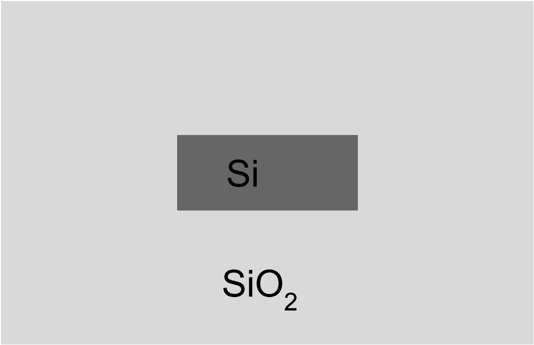
Who am I?

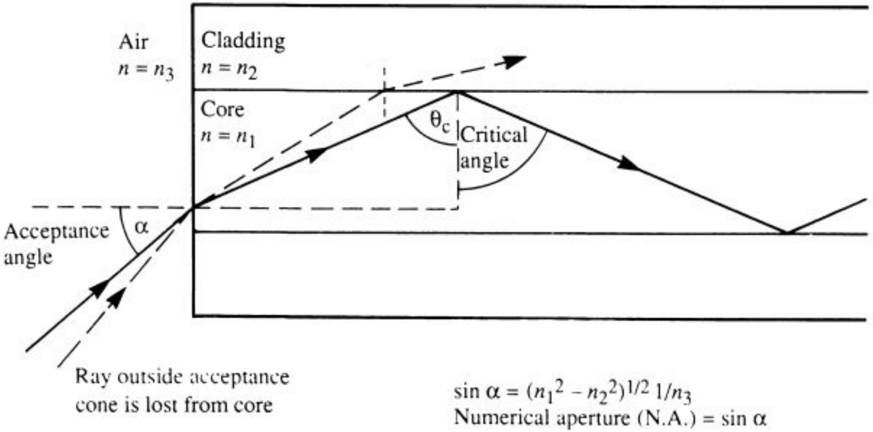
- Master's - Imperial College London
  - Supervised by P. Shadbolt + T. Rudolph
- PsiQuantum
  - LOQC theory/architectures
- PhD pt. 1 - University of Oxford
  - Ian Walmsley's group
  - Superconducting photon detectors (TES)
  - … and some theory side projects
- PhD pt. 2 - University of Bristol
  - Anthony Laing's group
  - Silicon quantum photonics
  - … and some theory side projects

In this talk

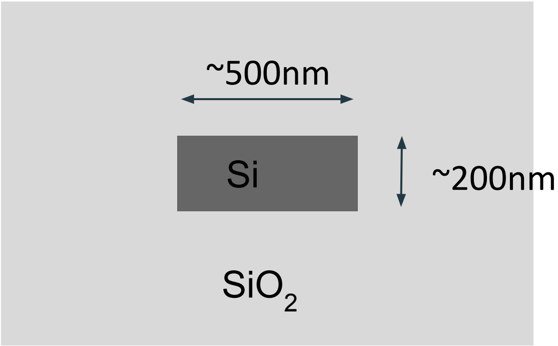
- Silicon quantum photonics toolkit
- Scattershot Boson sampling
- Quantum correlated sampling machines
- Quantum PIN verification?

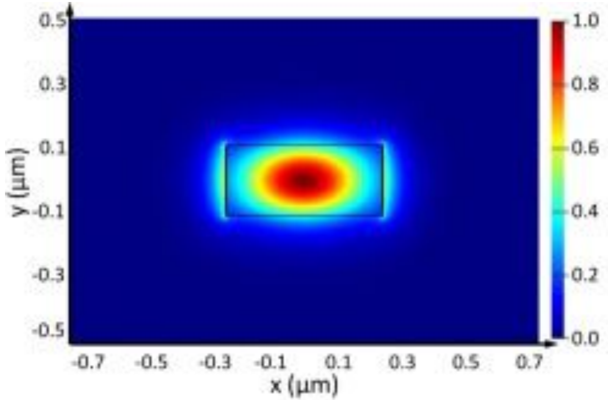
Waveguides


Si
SiO2

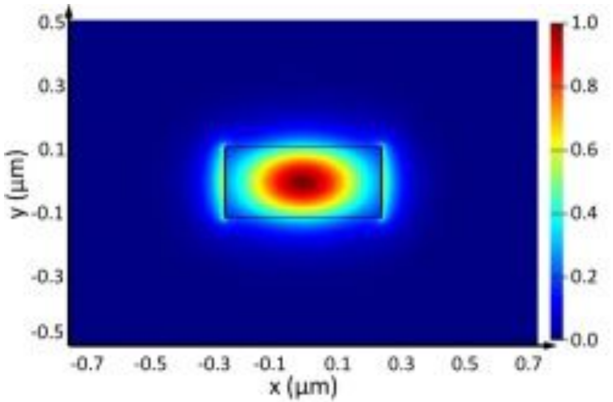

Air
n = n3
Cladding
n = n2
Core
n = n1
θc
Critical
angle
Acceptance
angle
α
Ray outside acceptance
cone is lost from core
sin α = (n1^2 − n2^2)^1/2 1/n3
Numerical aperture (N.A.) = sin α

Waveguides

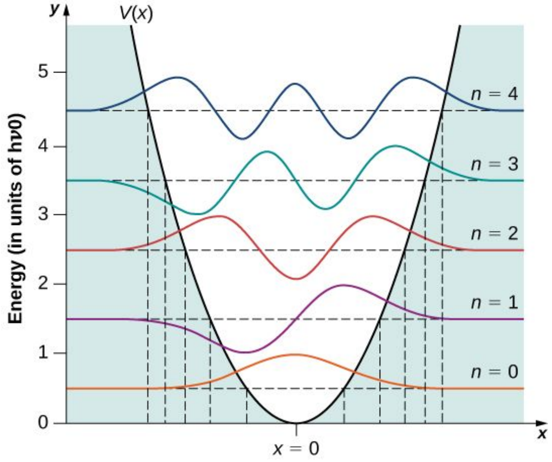

~500nm
Si
~200nm
SiO_2


0.5
0.3
0.1
-0.1
-0.3
-0.5
y (µm)
-0.7
-0.5
-0.3
-0.1
0.1
0.3
0.5
0.7
x (µm)
1.0
0.8
0.6
0.4
0.2
0.0

Waveguides

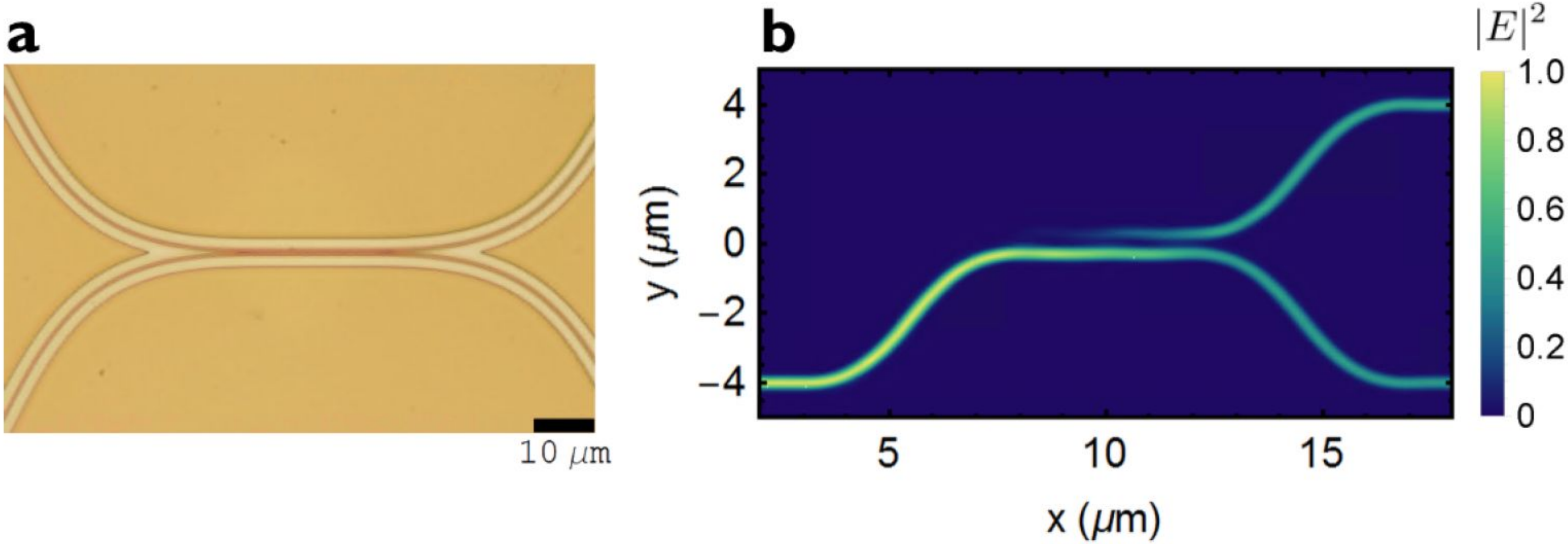


$$\otimes$$



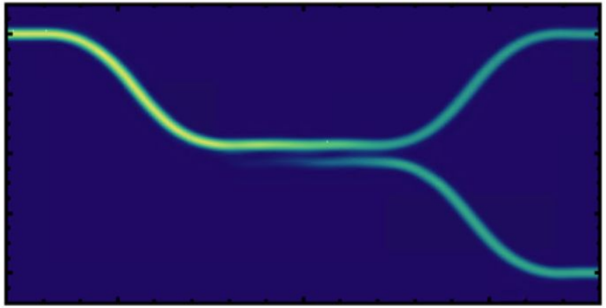
$$[a, a^\dagger] = 1$$

Couplers



Couplers

$$a_1^\dagger \Rightarrow$$



$$\Rightarrow \left(a_1^\dagger + a_2^\dagger \right) / \sqrt{2}$$

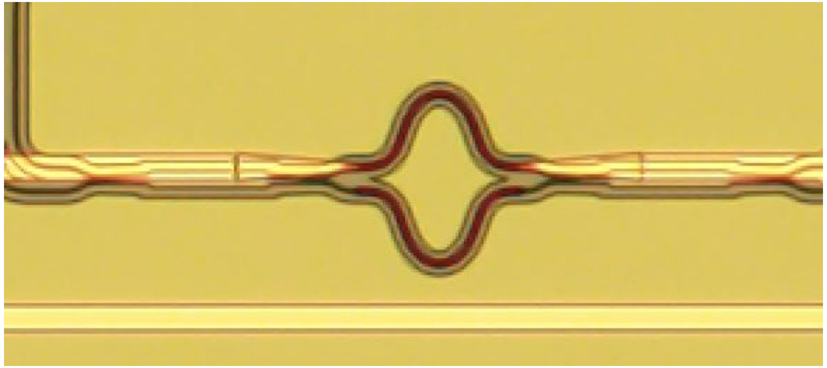
Couplers

$$a_2^\dagger \rightarrow \frac{1}{\sqrt{2}}\left(a_1^\dagger + a_2^\dagger\right)$$

$$H = c a_1^\dagger a_2 + c^* a_1 a_2^\dagger$$

Phase shifters

$$\frac{dn}{dT} = 1.86 \times 10^{-4} K^{-1}$$

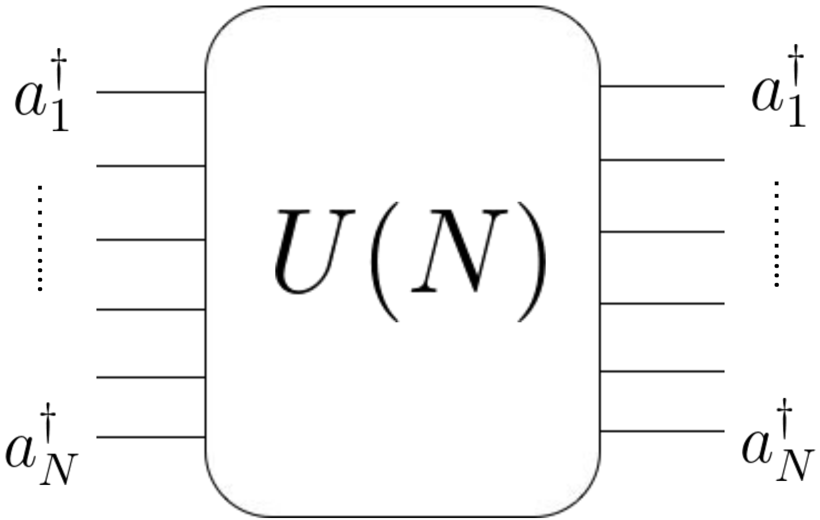


Thermo-optic effect

- Programmable :D
- Convenient :D
- Precise :D
- Slow :(
  (Typically kHz)

$$a^\dagger \rightarrow \exp(i\phi) a^\dagger$$

Programmable unitaries

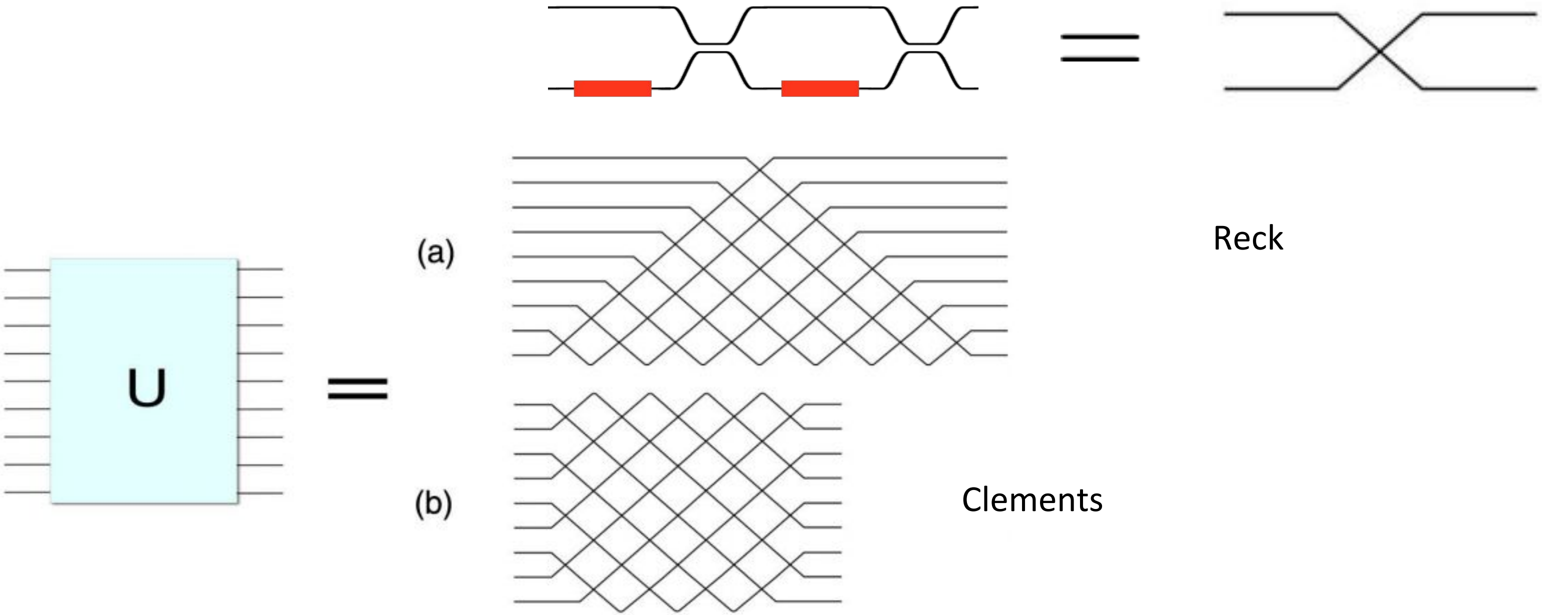


$$a_i^\dagger \to \sum_j U_{ij} a_j^\dagger$$

Programmable unitaries

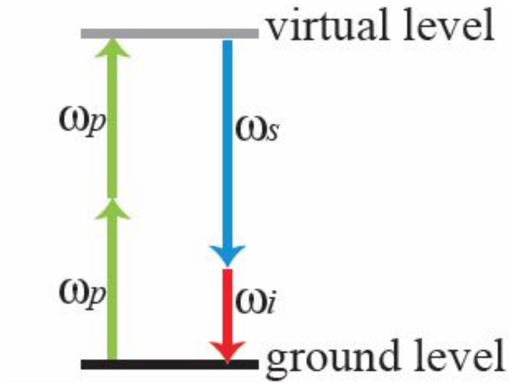
$$U(2) =$$

Programmable unitaries



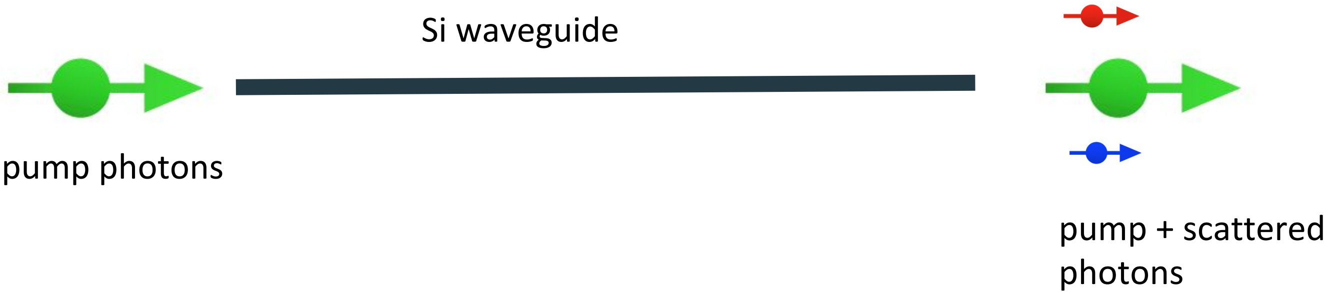
How do we make the photons?

$$\frac{\boldsymbol{P}}{\epsilon_0} = \chi^{(1)}\boldsymbol{E} + \cancel{\chi^{(2)}\boldsymbol{E}\boldsymbol{E}} + \chi^{(3)}\boldsymbol{E}\boldsymbol{E}\boldsymbol{E} + \cdots$$



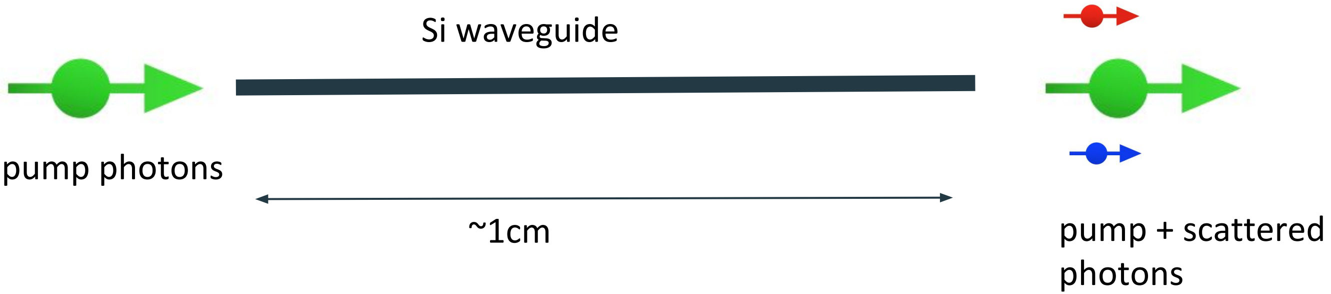
Spontaneous four wave mixing (SFWM)

How do we make photons?

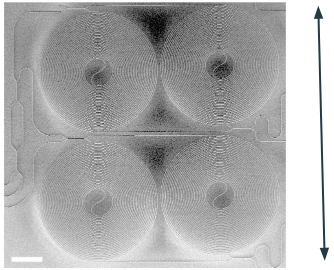


$$H = \xi a_r^\dagger a_b^\dagger - \xi^* a_r a_b$$

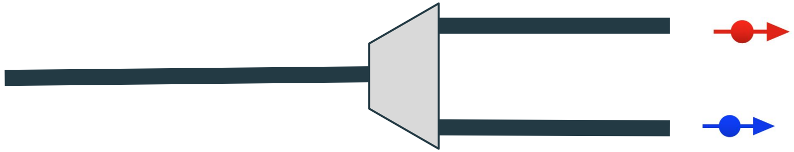
How do we make photons?



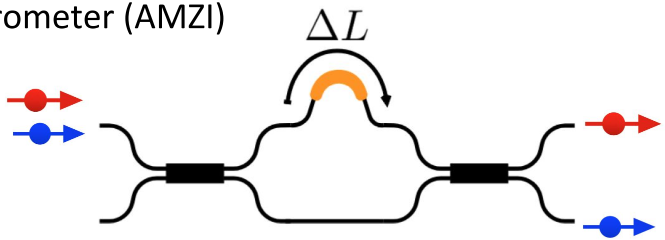
spirals!



Frequency demultiplexing



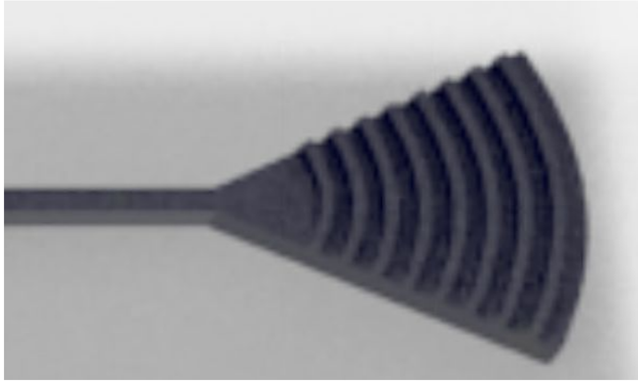
Asymmetric Mach-Zehnder interferometer (AMZI)

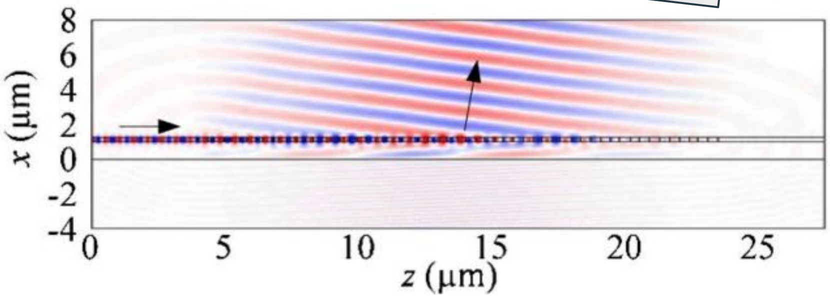


$$\Delta L = \begin{matrix} 100\lambda_r \\ 100.5\lambda_b \end{matrix}$$

Getting light on/off the chip

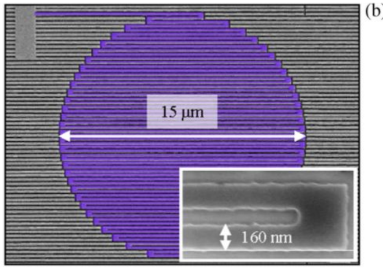
Grating couplers





Off-chip tools

Pulsed laser



Superconducting nanowire
single photon detectors (0.8K)

Fiber optic filters

Fast detector readout
electronics

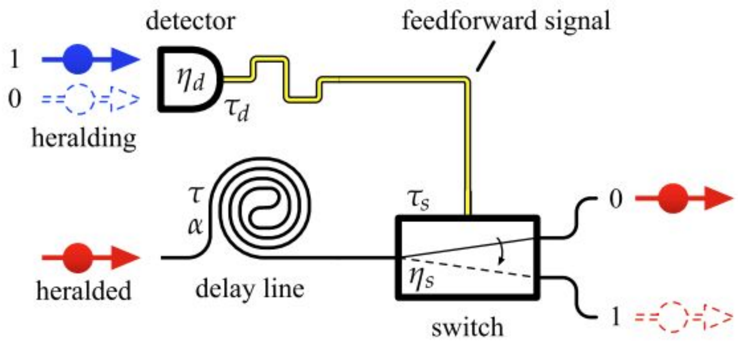
Heater control electronics

In this talk

- Silicon quantum photonics toolkit ✓
- Scattershot Boson sampling
- Quantum correlated sampling machines
- Quantum PIN verification?

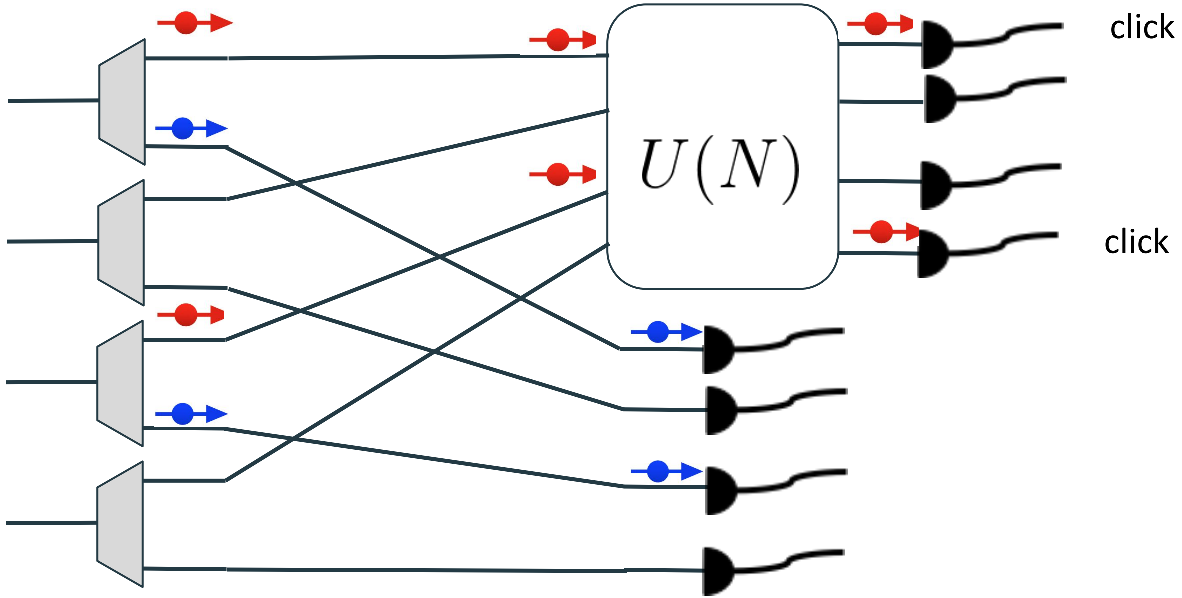
What we cannot do with this toolkit (today)

- Scalable universal quantum computing requires *feedforward*
- Slow switches mean no feedforward



What can we use this for?

Scattershot Boson sampling



Scattershot Boson sampling

$$p(\mathrm{output}|\mathrm{input}) = |\mathrm{Perm}(U_{out,in})|^2$$

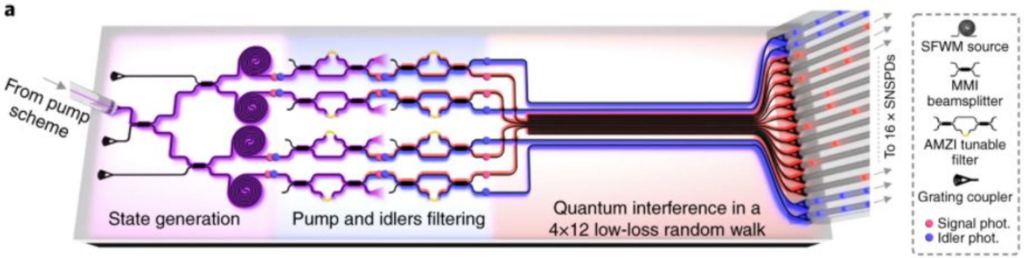
#P (exponential time)

Quantum advantage?

Quantum advantage? We are trying...

Generation and sampling of quantum states of light in a silicon chip

Stefano Paesani[1,6], Yunhong Ding[2,3,6*], Raffaele Santagati[1], Levon Chakhmakhchyan[1], Caterina Vigliar[1], Karsten Rottwitt[2,3], Leif K. Oxenløwe[2,3], Jianwei Wang[1,4,5*], Mark G. Thompson[1*] and Anthony Laing[1*]



4 photon pairs

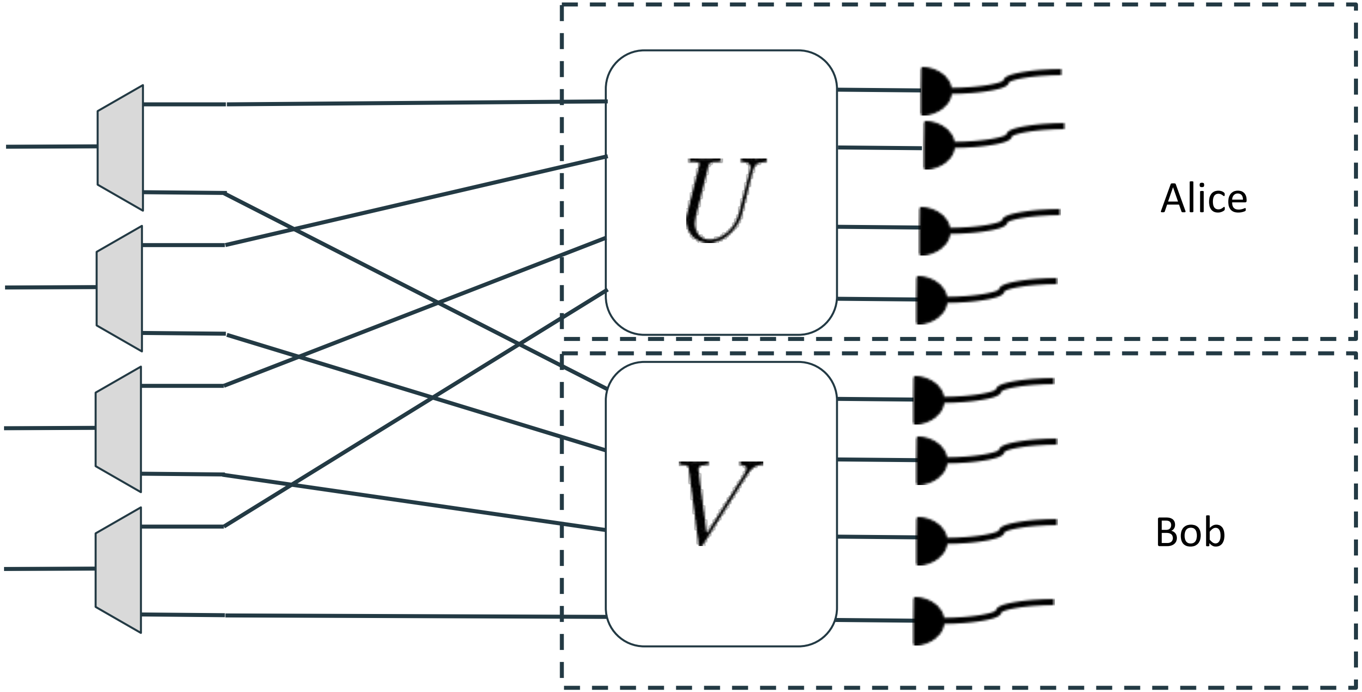
10+ pairs in next version?*

*tbc

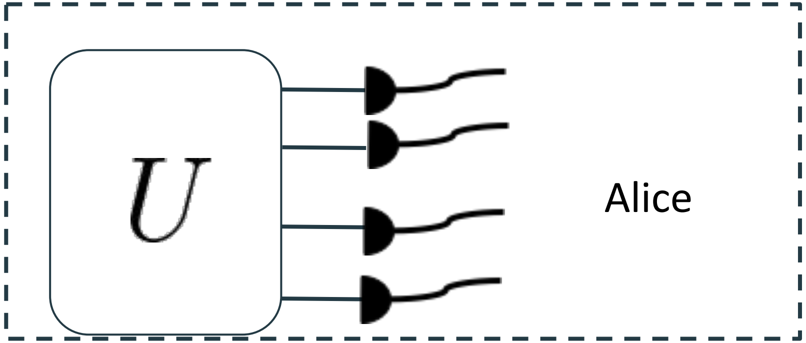
Challenges

- Verification
  - Efficiently verifying that your data is due to quantum interference
- Applications
  - Is it useful for anything other than showing a quantum advantage?

Quantum correlated sampling machines

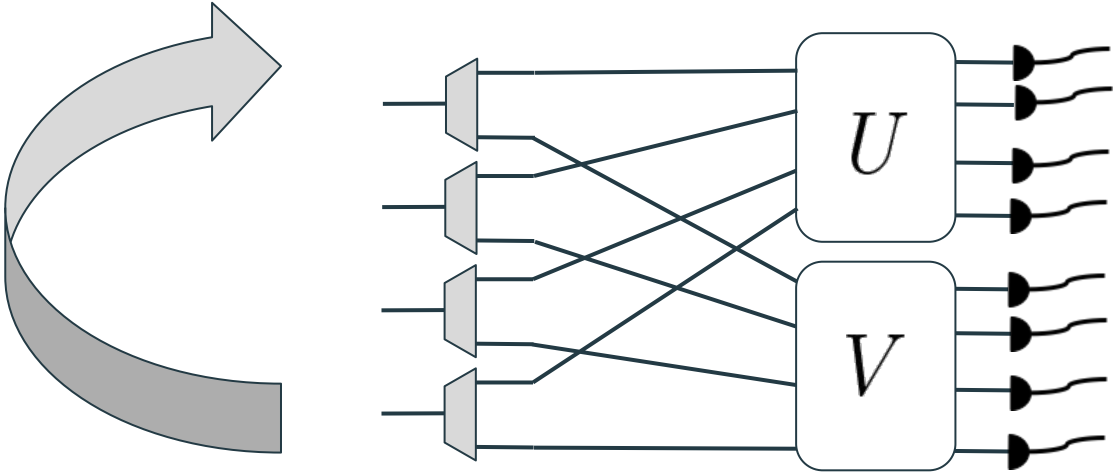


Quantum correlated sampling machines



$\rho =$ thermal state

Quantum correlated sampling machines



partial time reversal

Partial time reversal

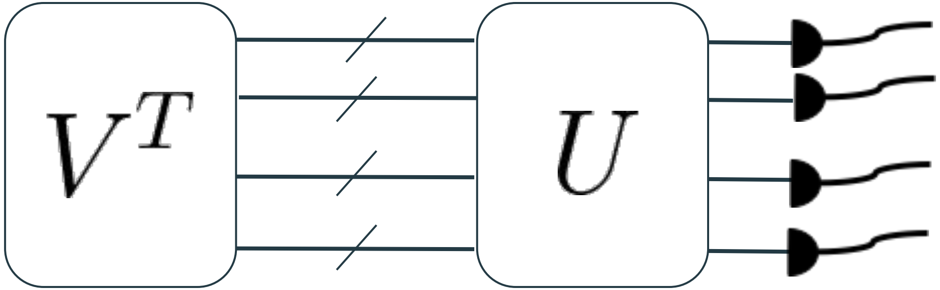
$$H_{squeezing} = \xi a_r^\dagger a_b^\dagger - \xi^* a_r a_b$$

$$\Updownarrow \quad \text{time reverse blue photon}$$

$$\xi a_r^\dagger a_b - \xi^* a_r a_b^\dagger = H_{coupler}$$

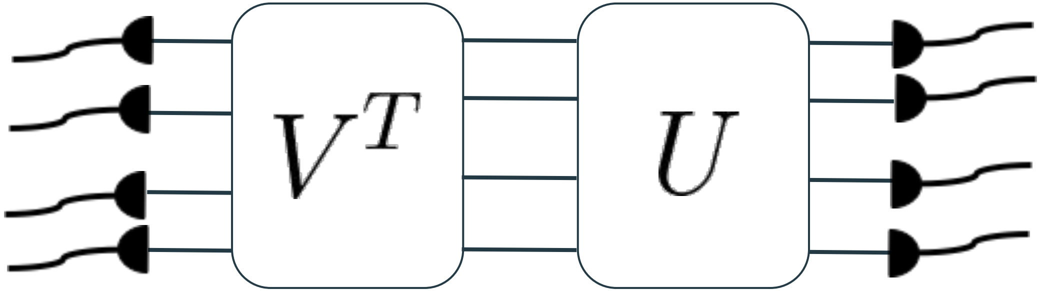
Partial time reversal

$$\xi a_r^\dagger a_b - \xi^* a_r a_b^\dagger = H_{coupler}$$

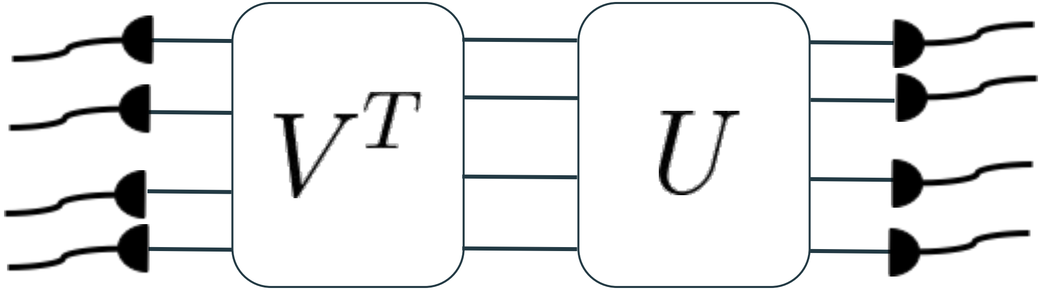


Partial time reversal

\+ post-selection

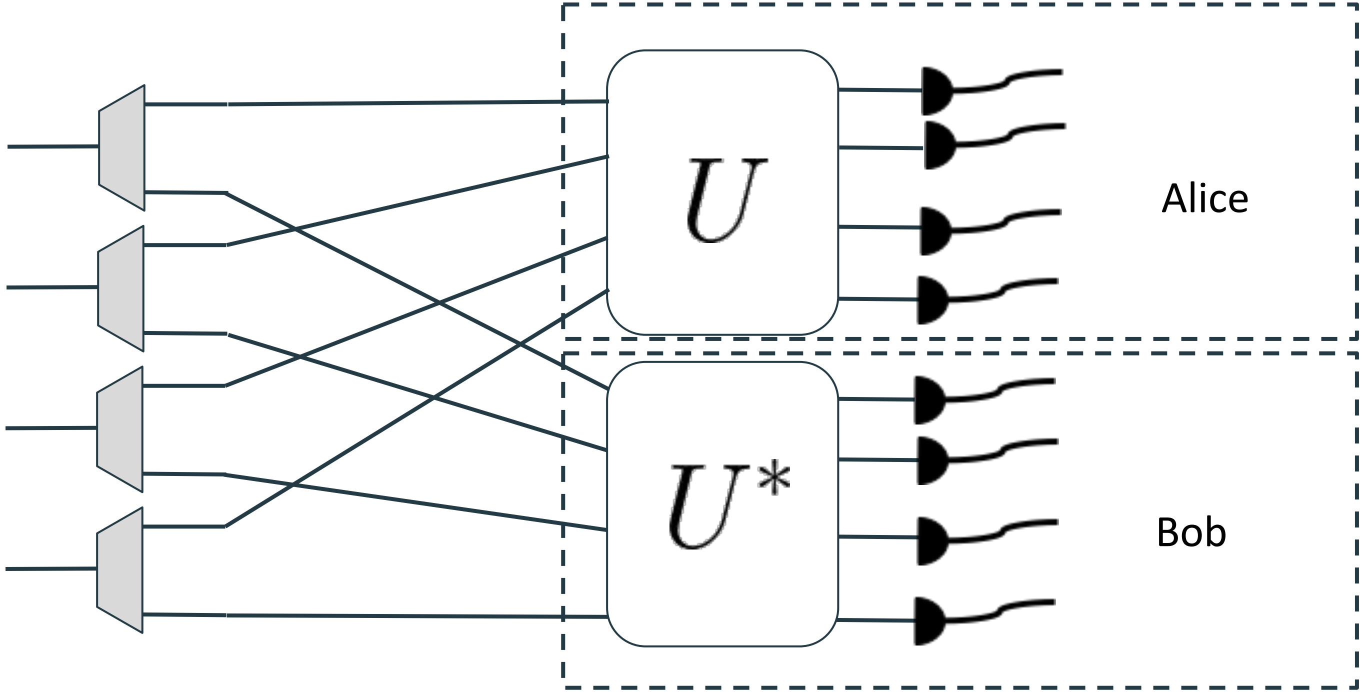


Partial time reversal

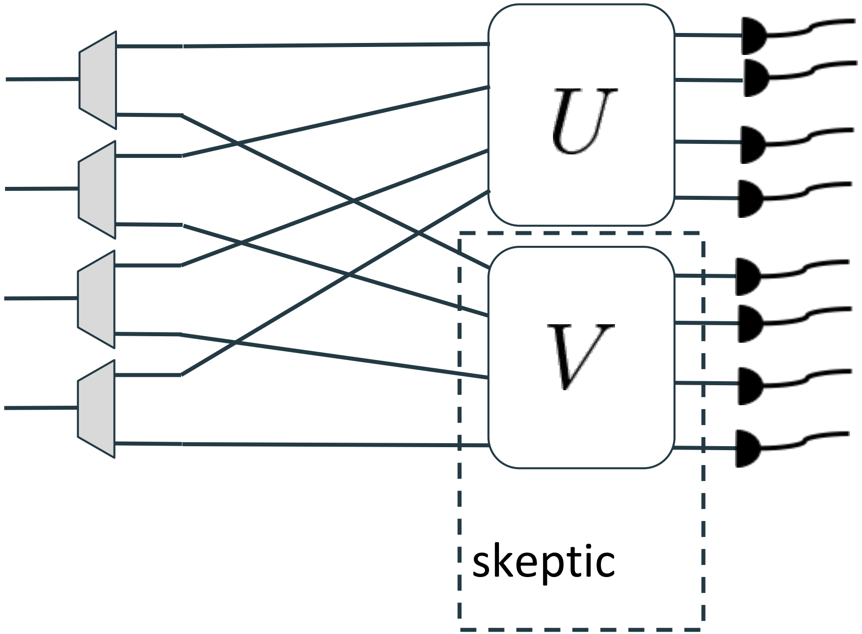


$$p(A,B) = \left|\mathrm{Perm}([V^T U]_{A,B})\right|^2$$

Quantum correlated sampling machines



Quantum correlated sampling machines



Verifying quantum advantage?

$$V = \mathbb{I}$$

$$\Updownarrow$$

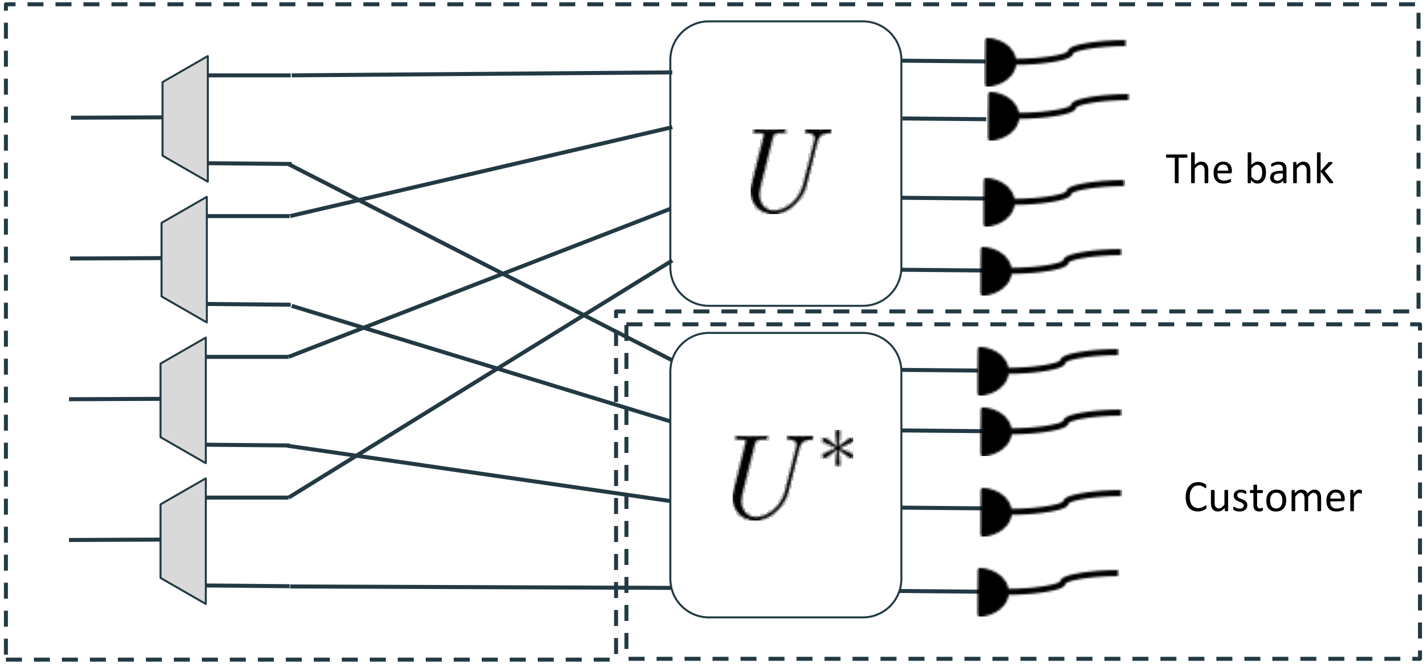
$$V = U^*$$

Quantum PIN verification?

The problem:

You shouldn’t
trust the ATM!

Quantum PIN verification?



Quantum PIN verification?

The alphabet:

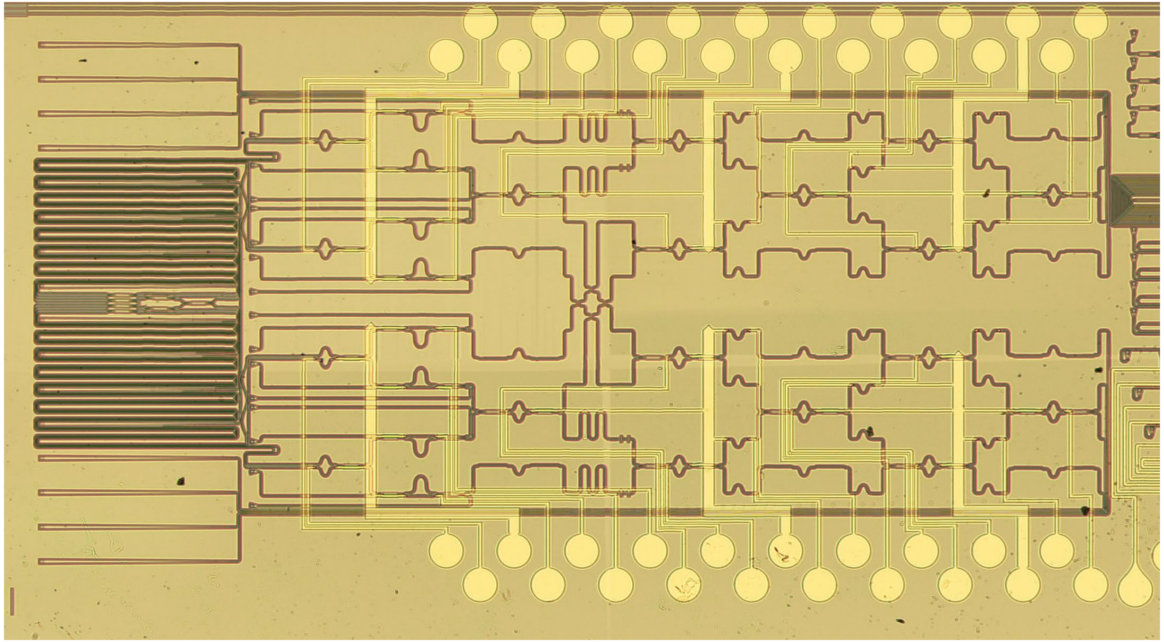
$$U_1, U_2, \ldots U_K$$

Chosen from Haar measure

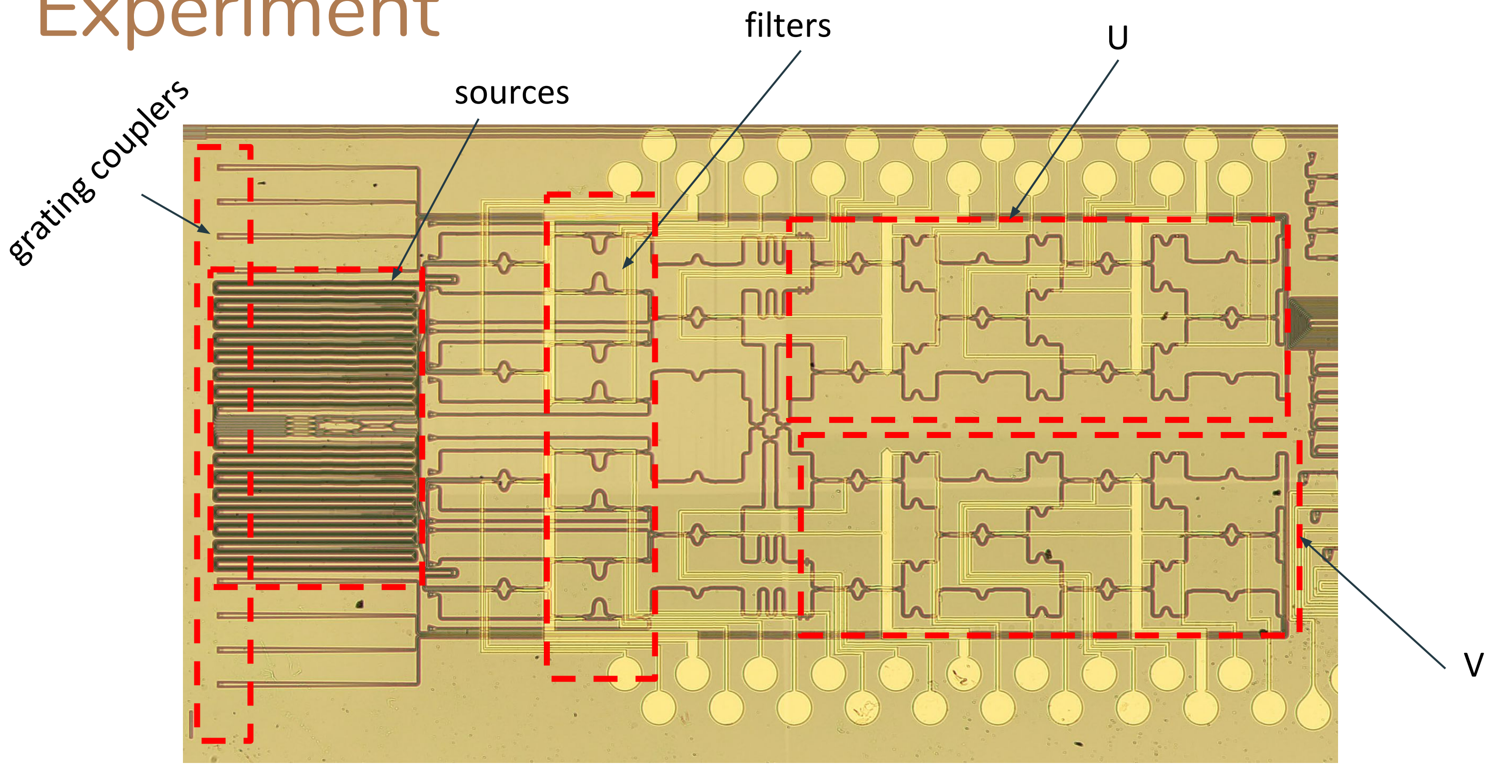
Quantum PIN verification?

	Bank is honest	Bank is dishonest
Customer is honest	Perfect correlation	Random correlation
Customer is dishonest	Random correlation	Random correlation

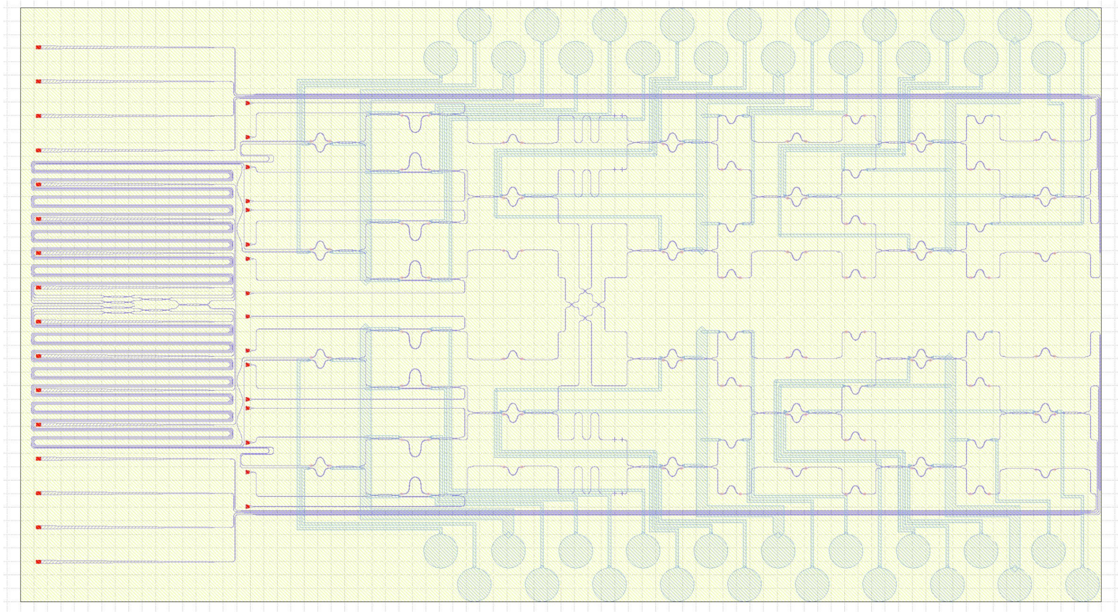
Experiment



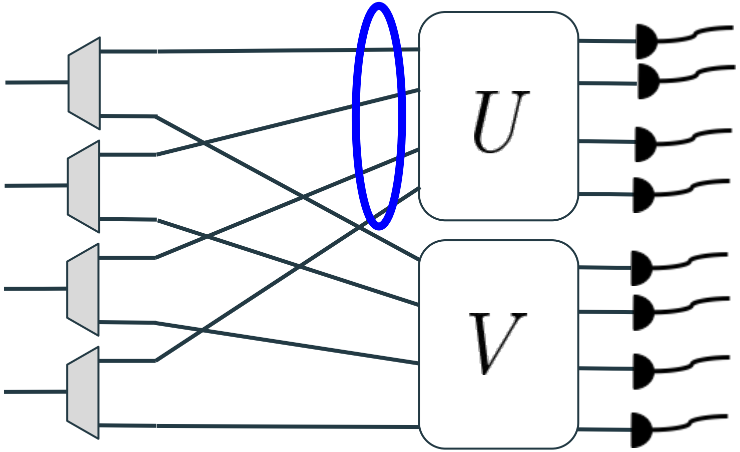
Experiment

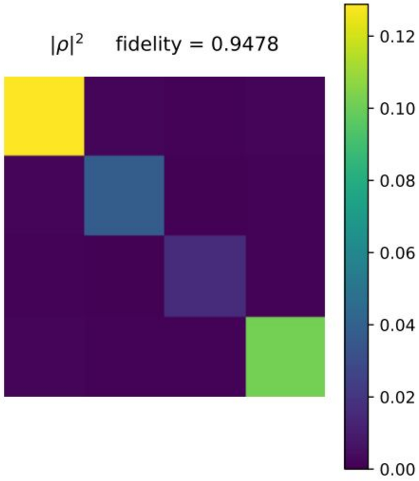


Experiment

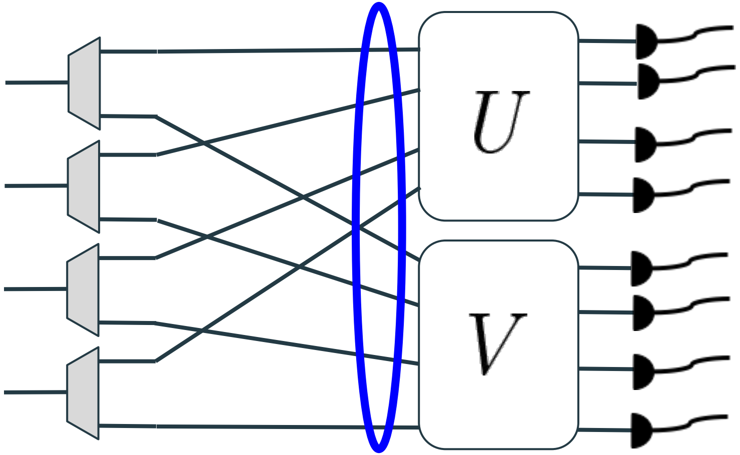


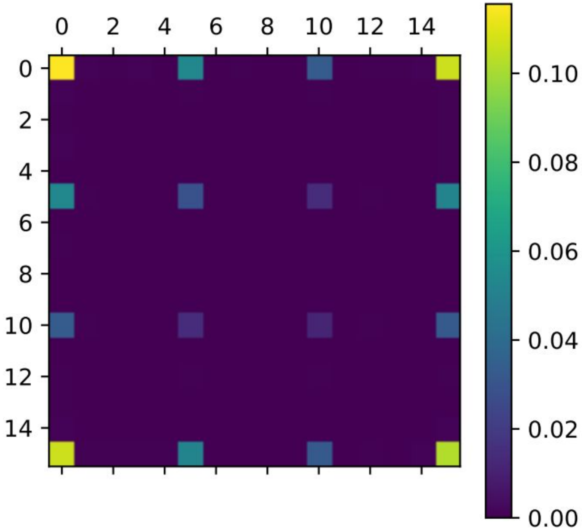
Experimental results: 1 photon tomography



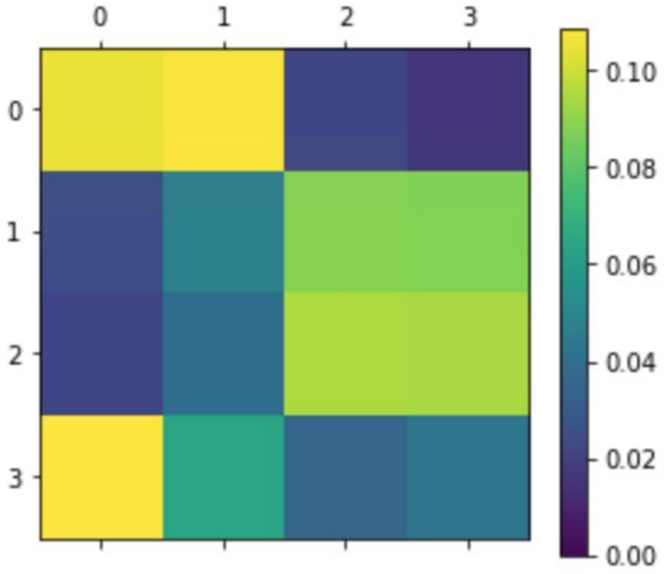


Experimental results: 2 photon tomography

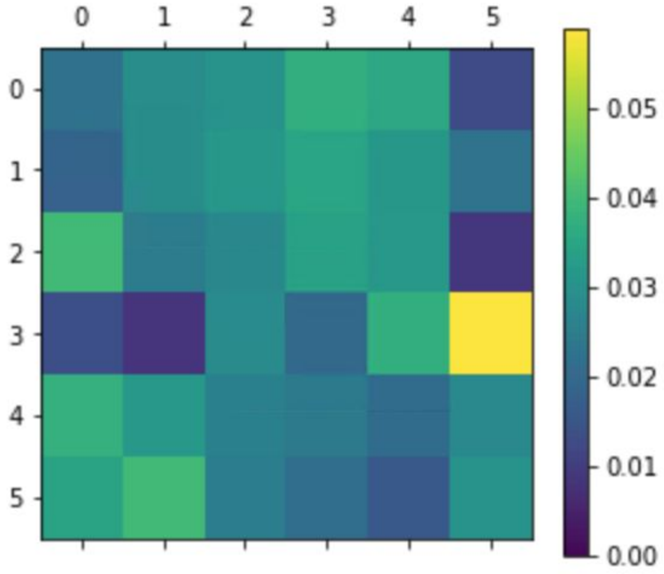




Experimental results: scattershot

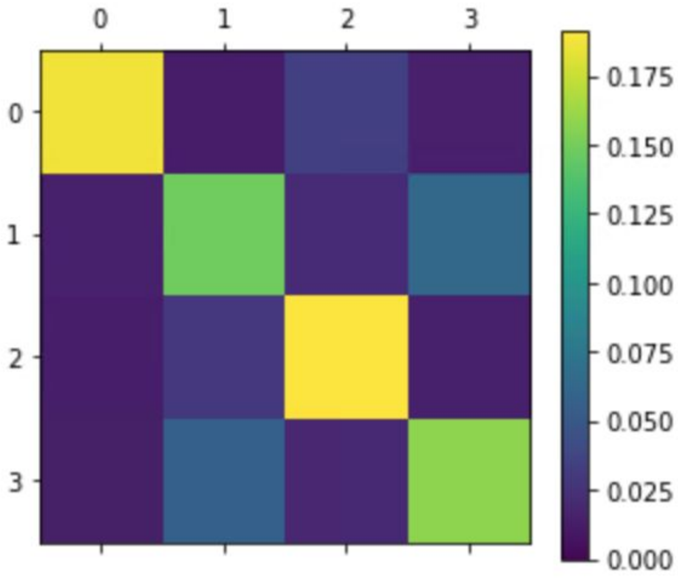


2 photon outcomes

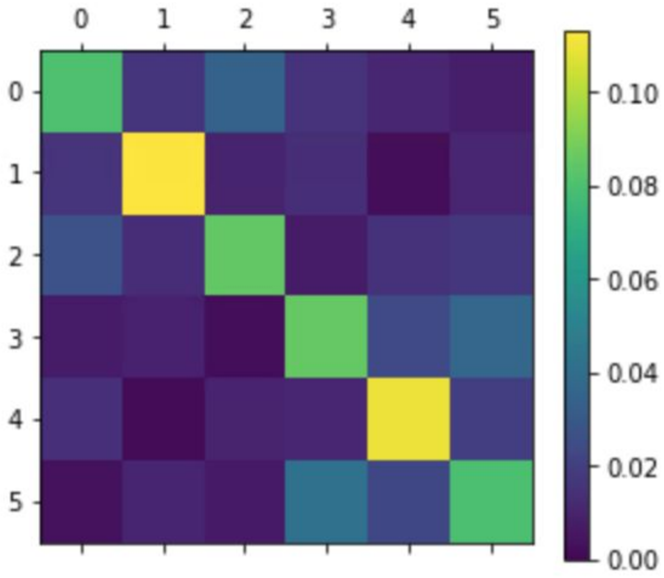


4 photon outcomes

Experimental results: perfect correlations



2 photon outcomes



4 photon outcomes

Thanks!

Questions?