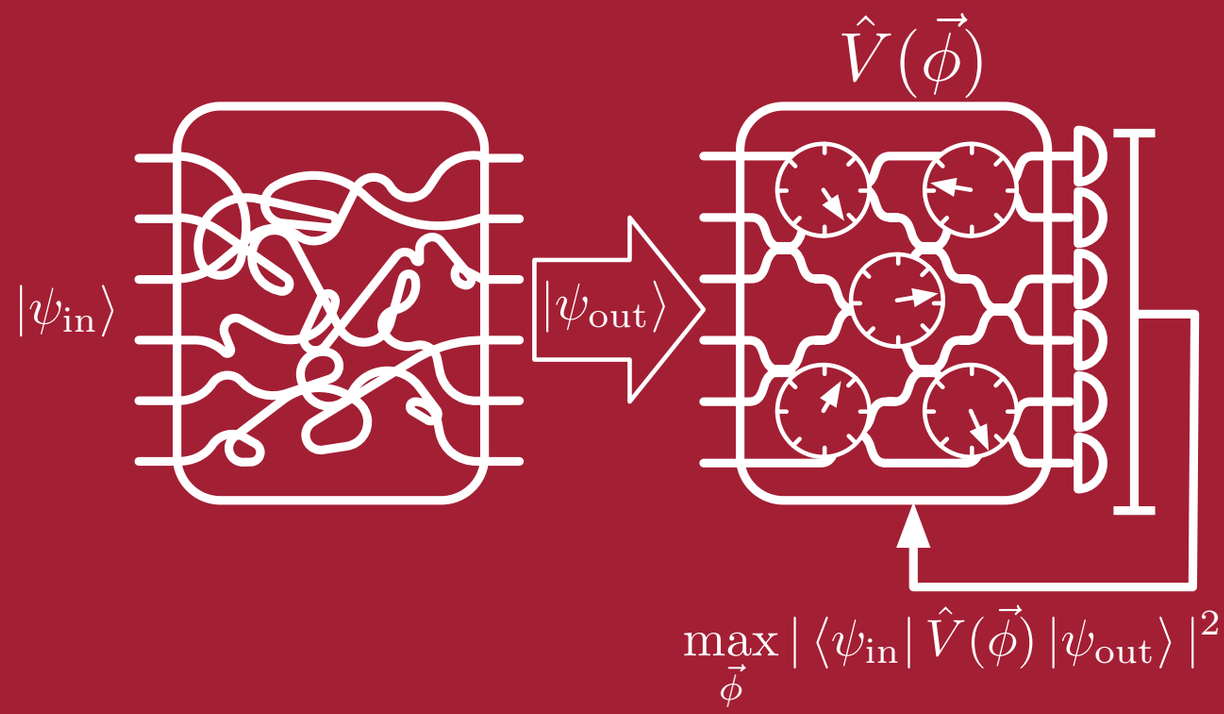
KØBENHAVNS
UNIVERSITET

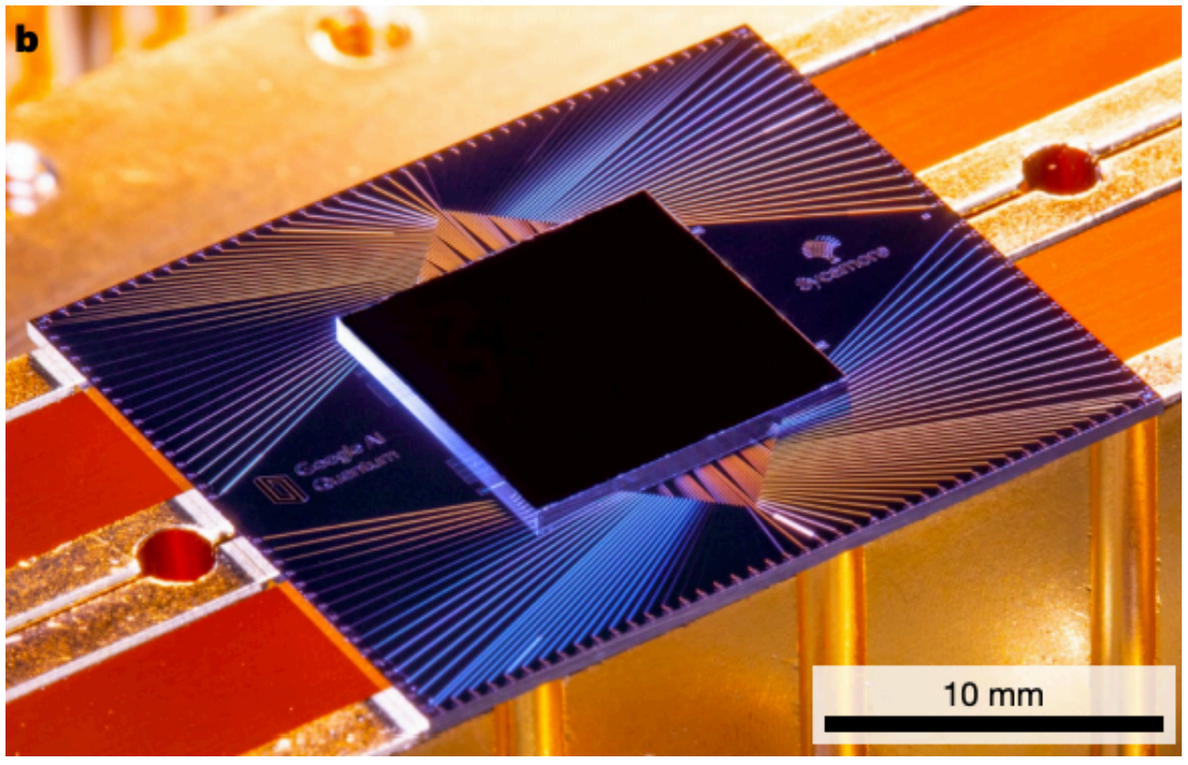
Quantum Photonic Processors to Accelerate Machine Learning

Jacques Carolan, NBI
@JacquesCarolan



Photonics for Quantum 2

Quantum is Mainstream!



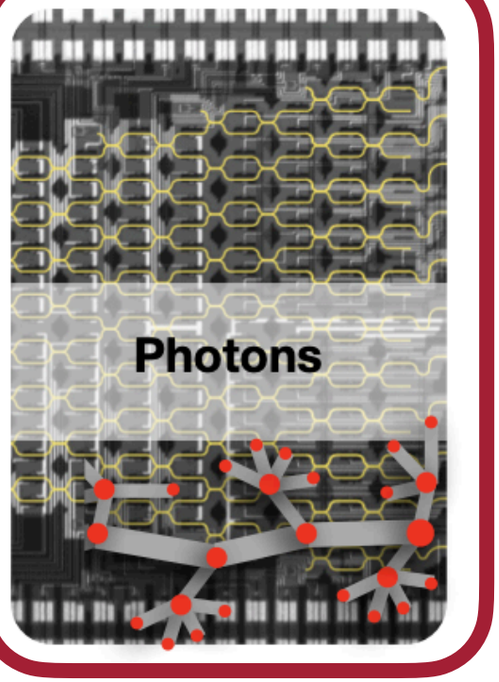
F. Arute et al., *Nature* **574,** 505–510 (2019)

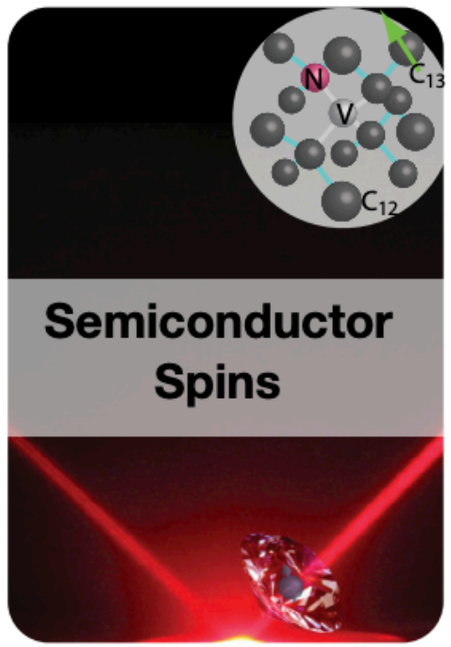
The New York Times

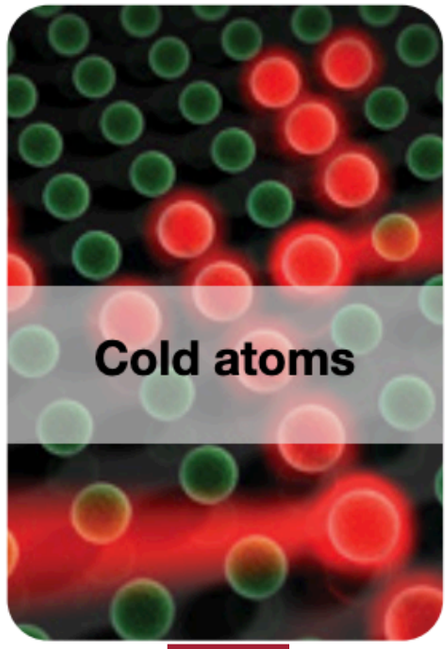
Google AI

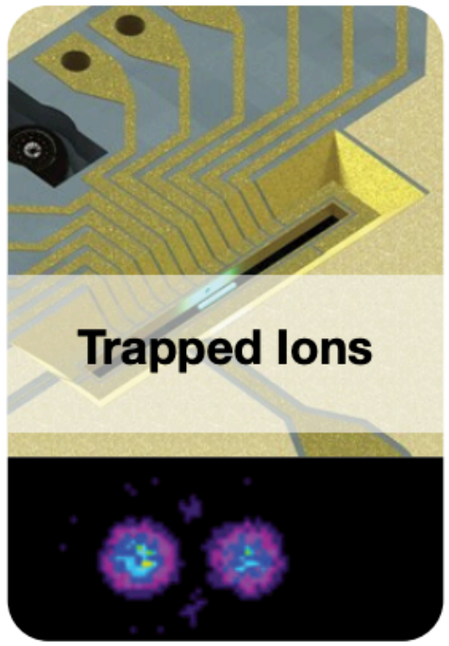
Google Claims a Quantum Breakthrough That Could Change Computing

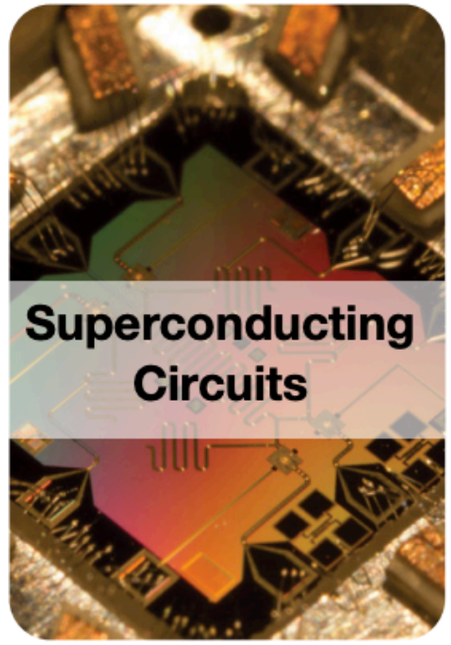
Qubit Technology





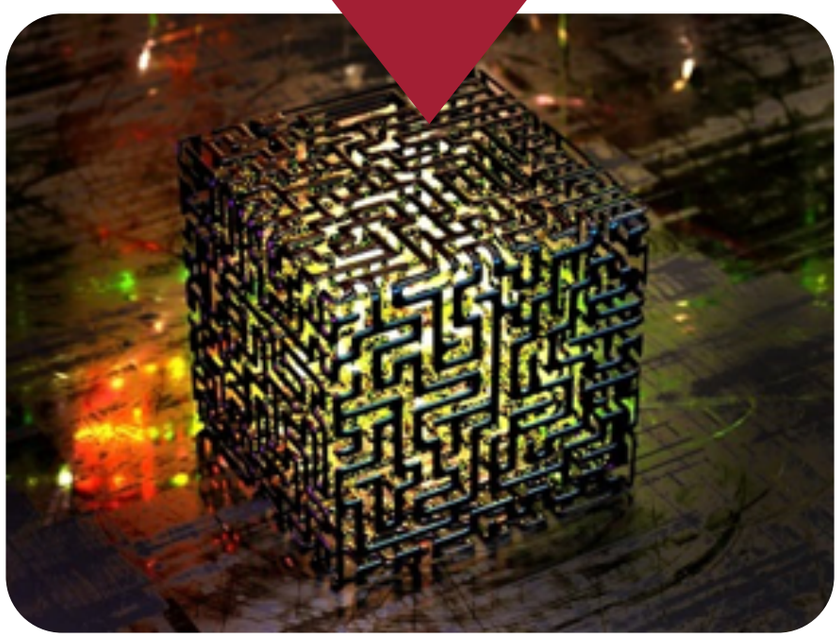






??

>$500M



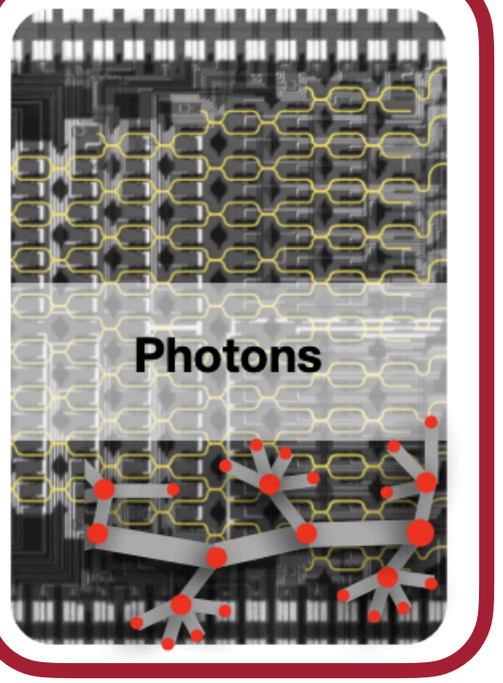
Universal Quantum Computer

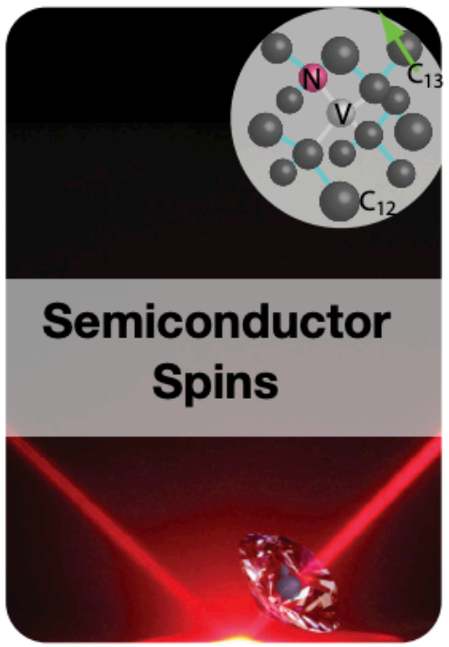
Open Questions

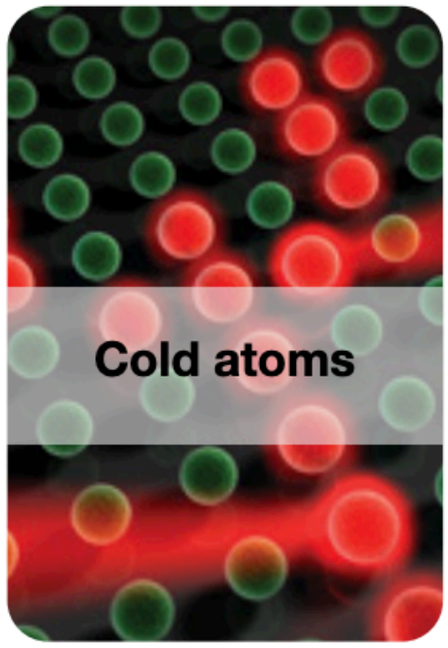
Material science?
Device design?
Architectures?
Engineering at scale?
Interconnects?
Errors?
Useful algorithms?

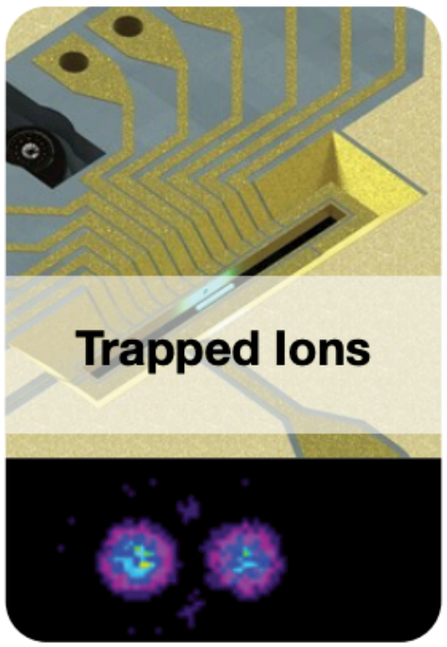
D. Englund & S. Lloyd, “Future Directions of Quantum Information Processing”

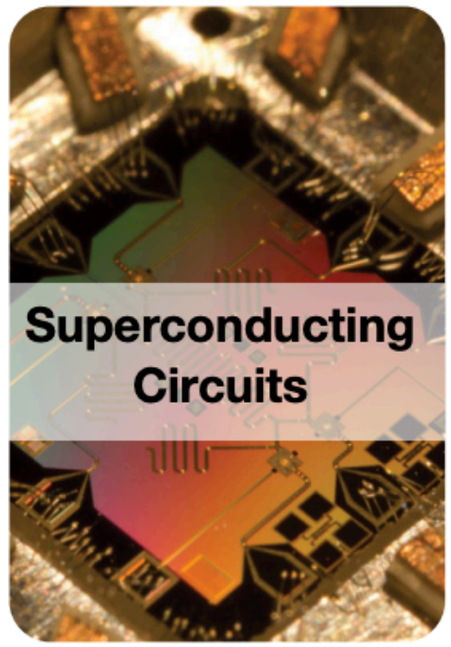
Qubit Technology











1) Quantum Interconnects

~mm = atomic quantum computers

~m = quantum clusters

~km = quantum internet

2) Integrated Photonics Foundries

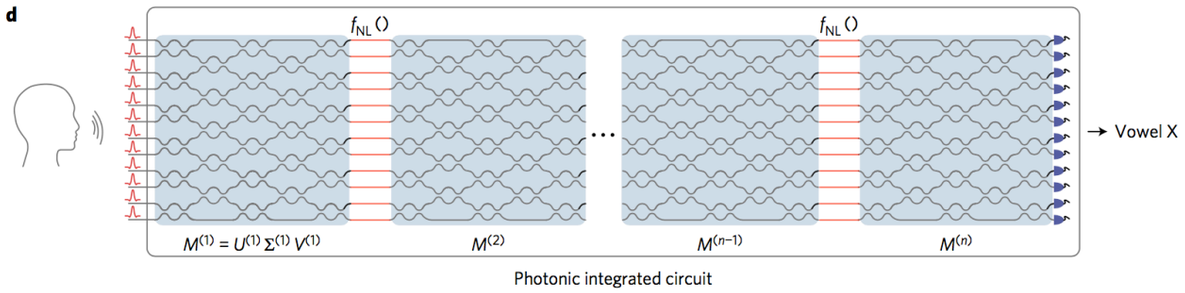
→ driven by classical comms.

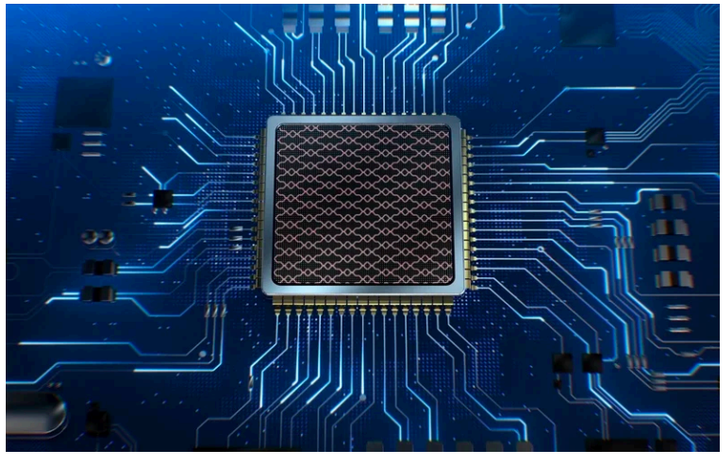
3) Classical Applications

→ low power computing

→ signals processing

→ imaging

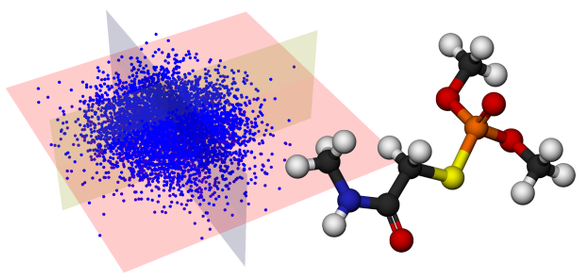




Y. Shen, N. Harris et al., *Nat. Photon.* (2017)

D. Englund & S. Lloyd, “Future Directions of Quantum Information Processing”

Overview

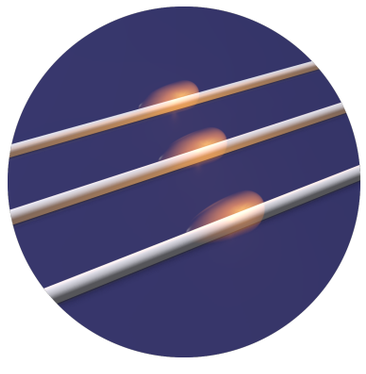


Applications

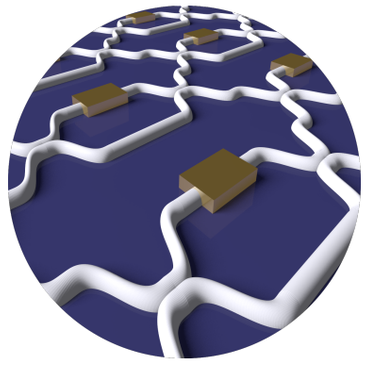
3. Quantum & AI

2. Systems Engineering Challenges

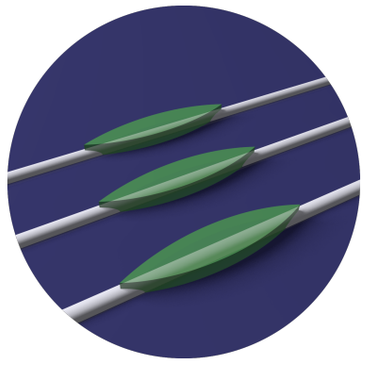
1. Key Building Blocks



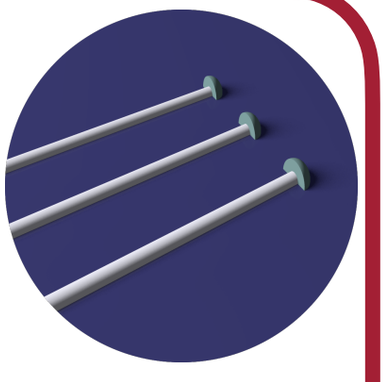
Nonclassical
states of light



Reconfigurable
optical circuitry

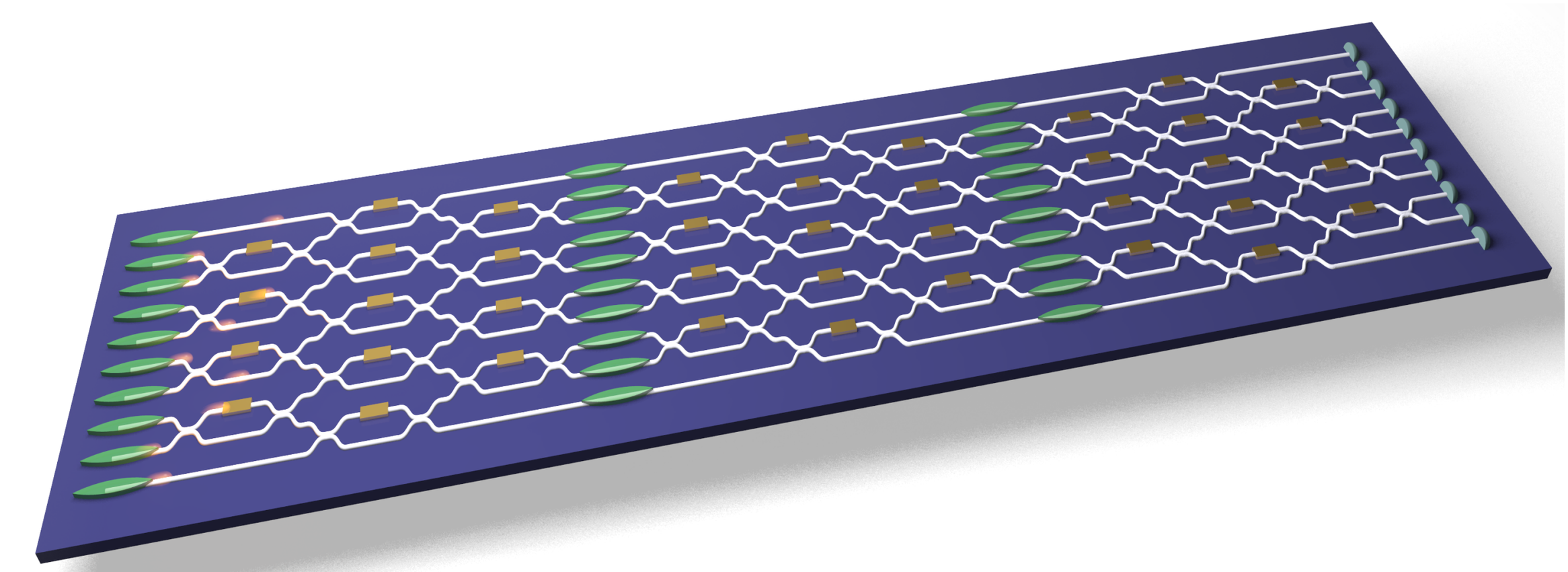


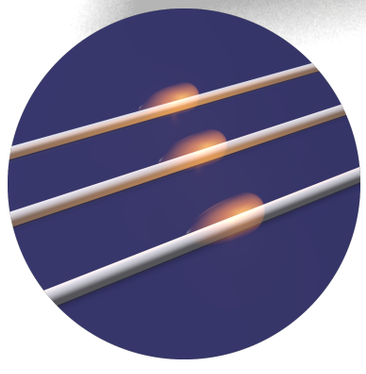
Nonlinear
light-matter interaction



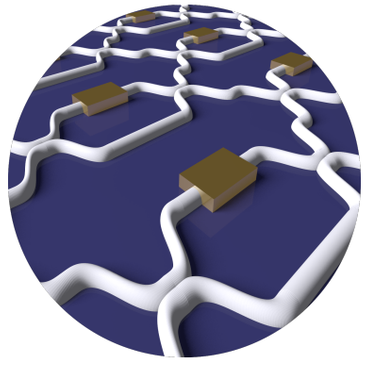
Single photon
readout

Quantum Photonic Processor

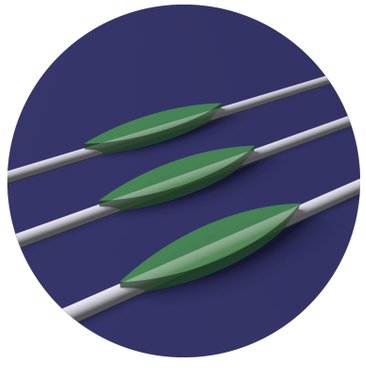




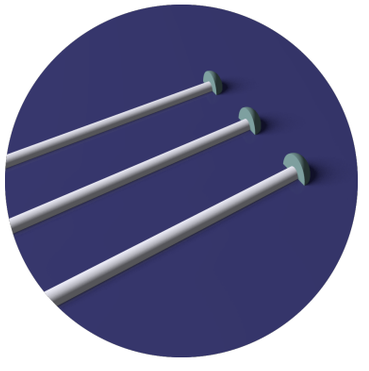
Nonclassical
states of light



Reconfigurable
optical circuitry

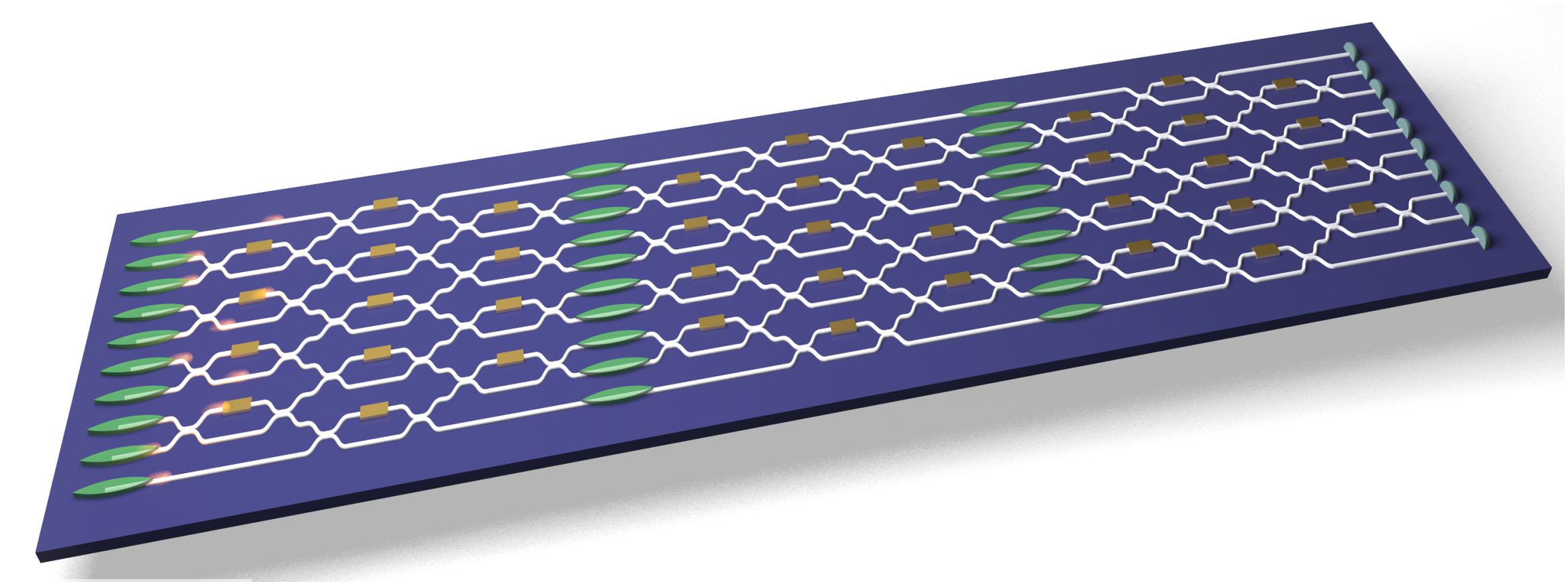


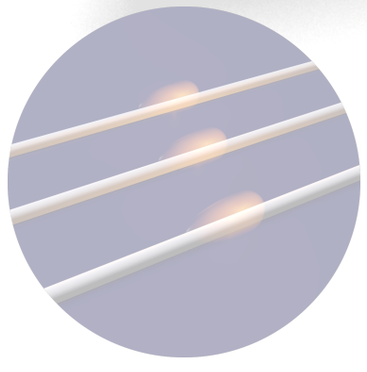
Nonlinear
light-matter interaction



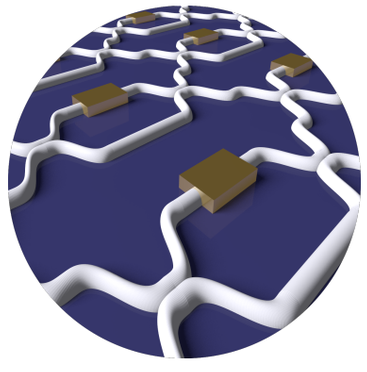
Single photon
readout

Quantum Photonic Processor

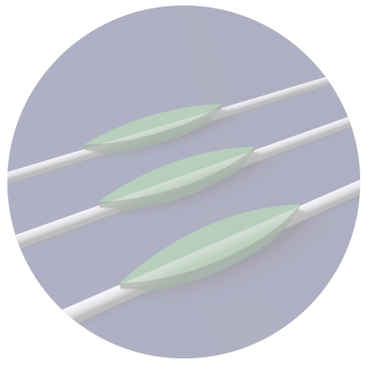




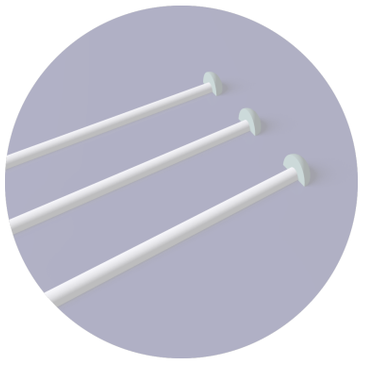
Nonclassical
states of light



Reconfigurable
optical circuitry



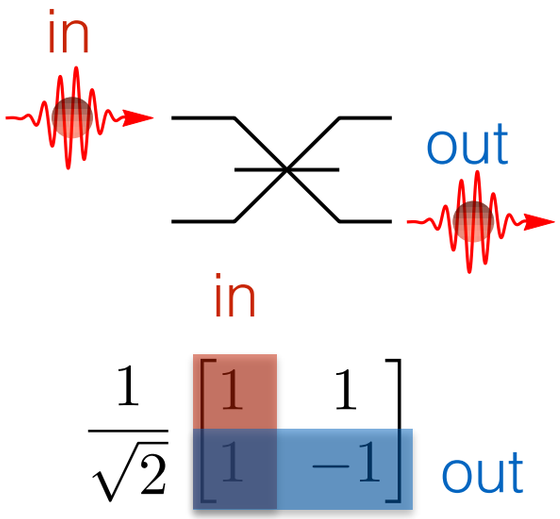
Nonlinear
light-matter interaction



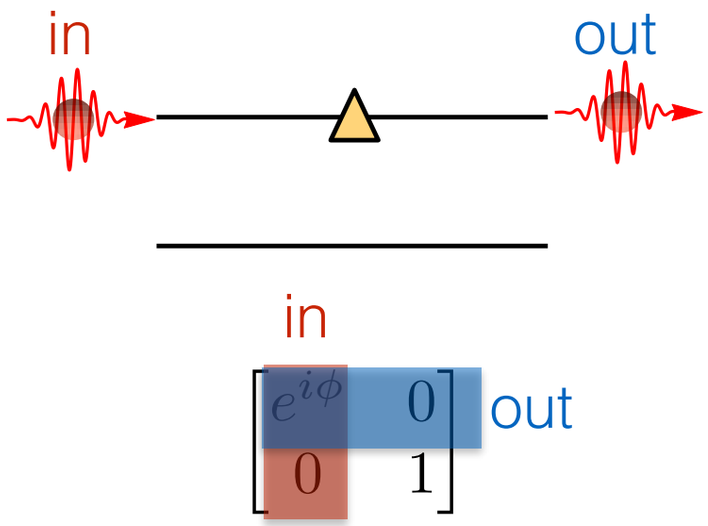
Single photon
readout

Building Blocks

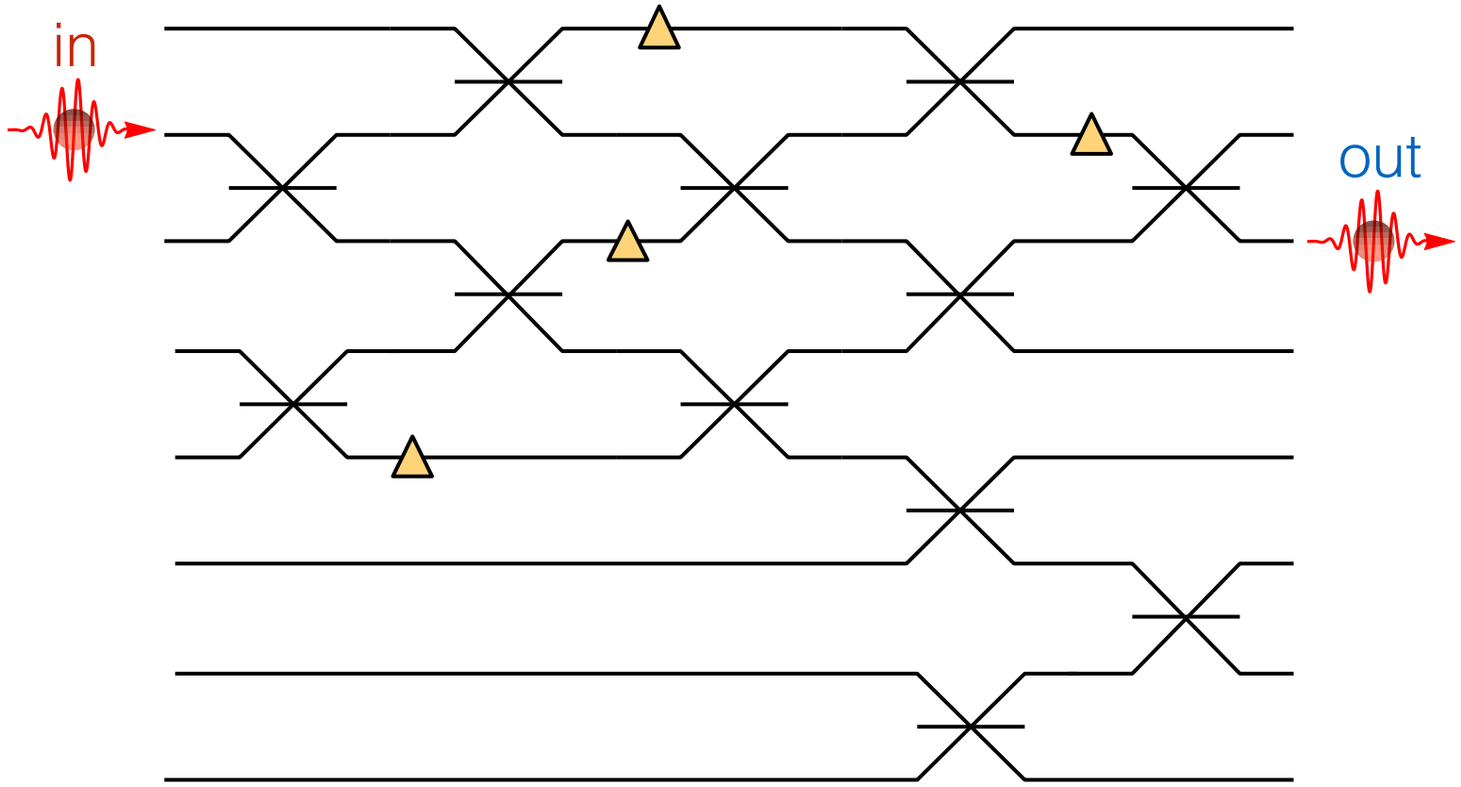
Beamsplitters

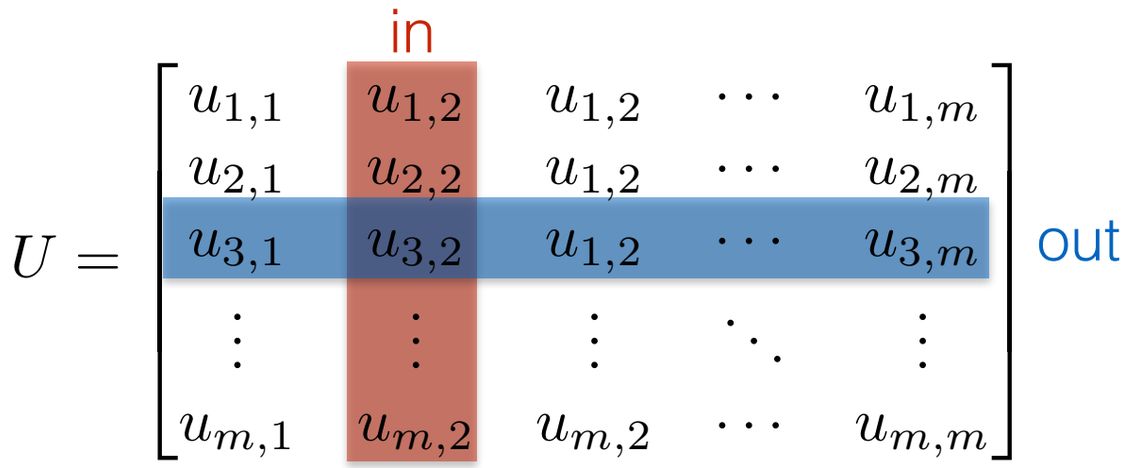


Phase shifters

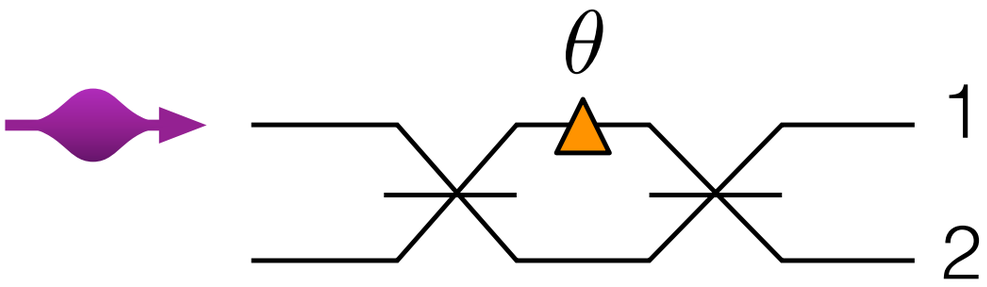


Large circuits

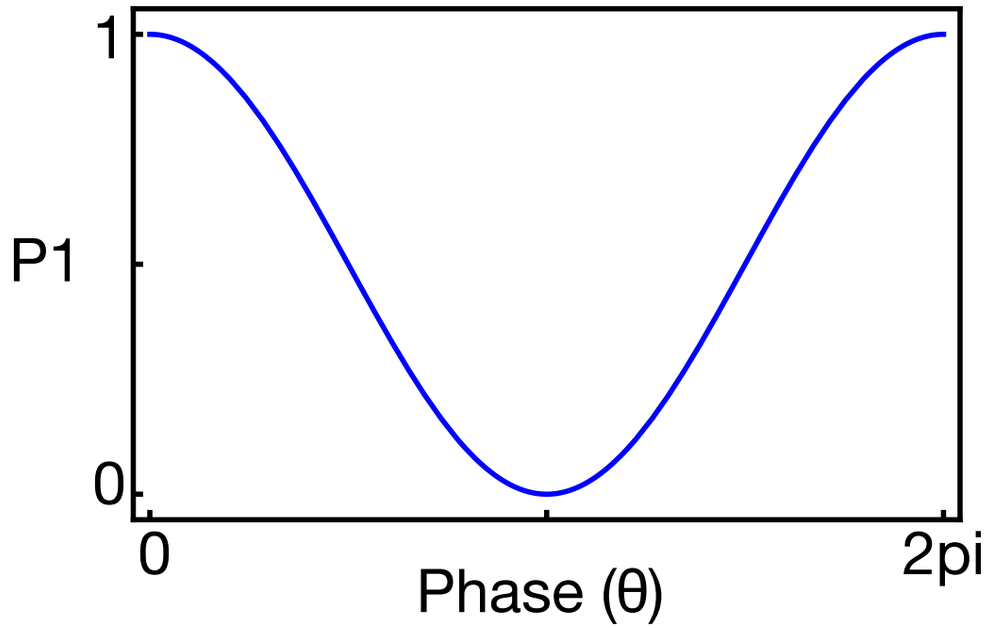




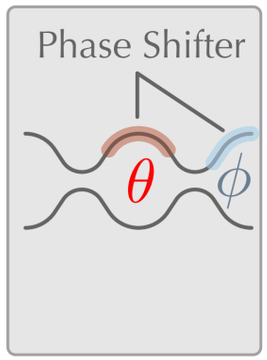
Programmable Photonics

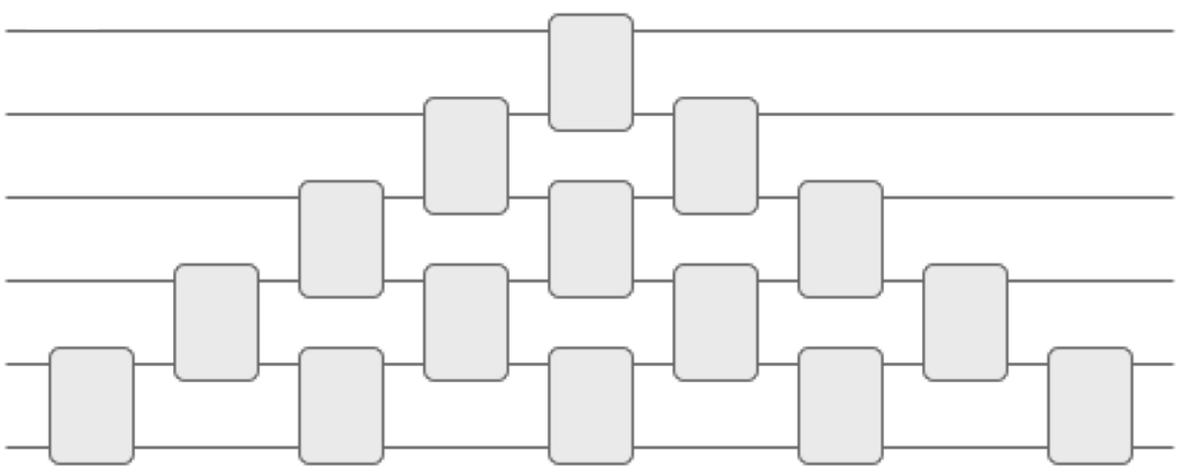


Mach-Zehnder Interferometer

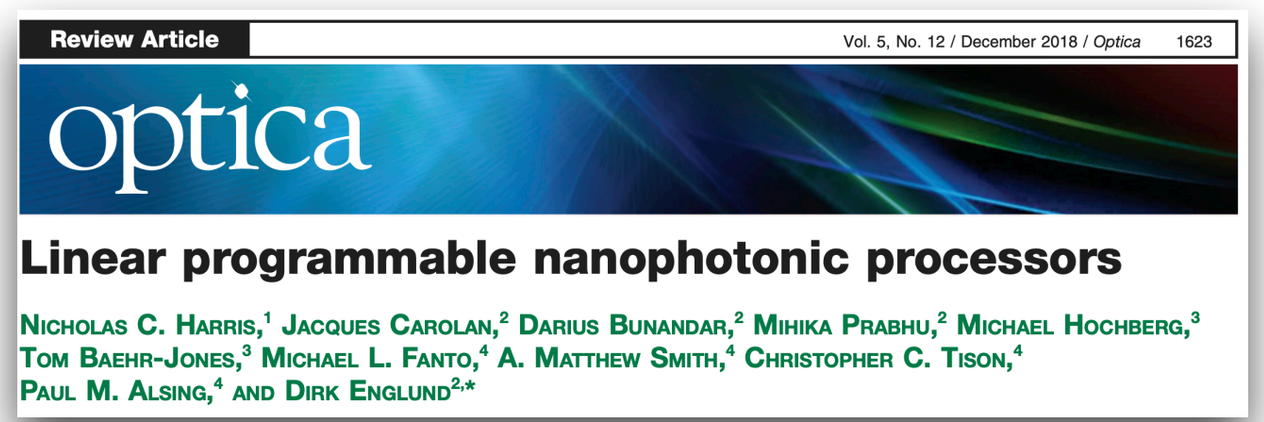


Arbitrary N x N unitary can be constructed out of N^2 SU(2) MZIs





M. Reck et al., *PRL* (1994)



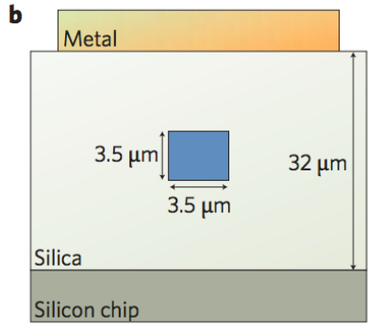
Review: N. Harris, J. Carolan et al., *Optica* 5, 12 (2018).

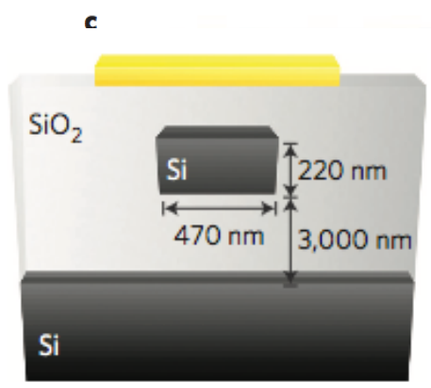
Integrated Photonics

Waveguide devices

Si, SiN, SiO2, LN, AlN

A. Politi et al., *Science*, 320, 646 (2008).
A. Politi et al., *Science*, 325, 1221 (2009).
J. W. Silverstone et al., *Nat. Photon.* 8, 104 (2014).

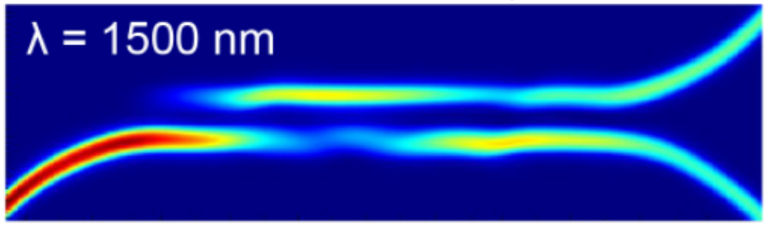




Passive Control

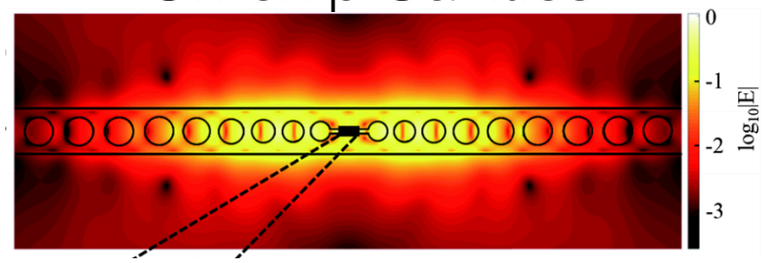
WG crossings
Grating couplers
Edge couples
Microring resonators

Directional Couplers



Lu, *Op. Ex* (2015)

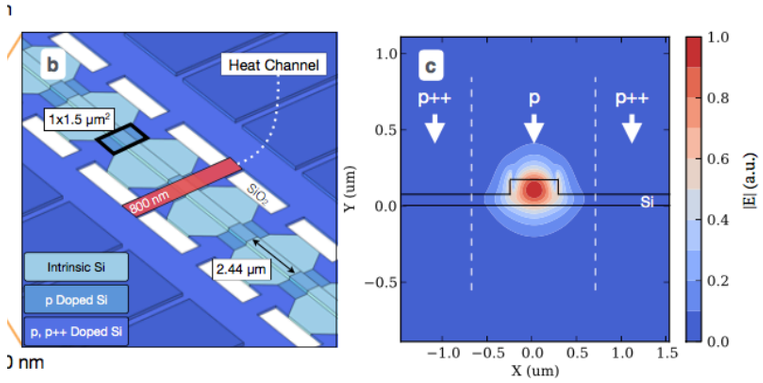
On-chip Cavities



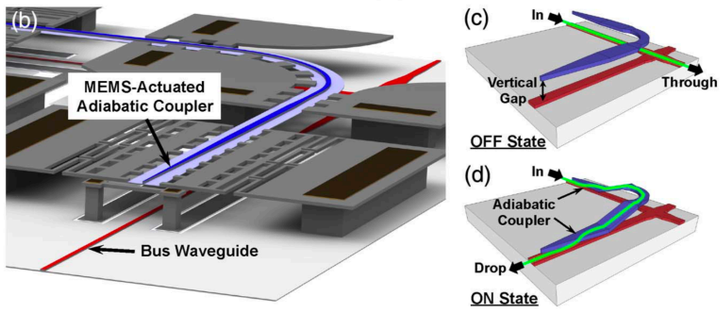
Choi, Heuck, Englund *PRL* (2017)

Active control

Thermal (KHz)
MEMS (MHz)
Electro-optic (GHz)



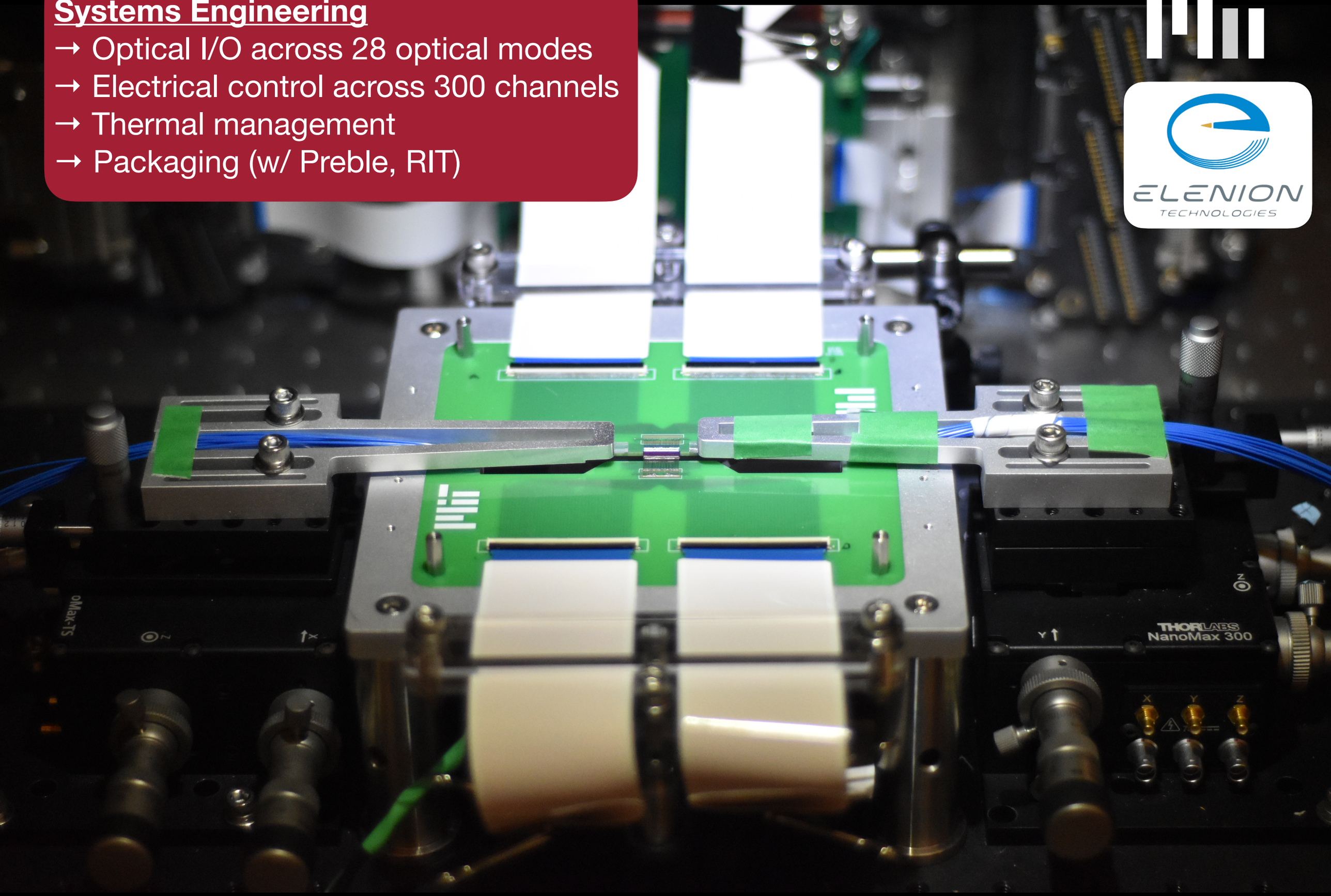
N. C. Harris et al., *Opt. Exp.* 22, 10487 (2014).



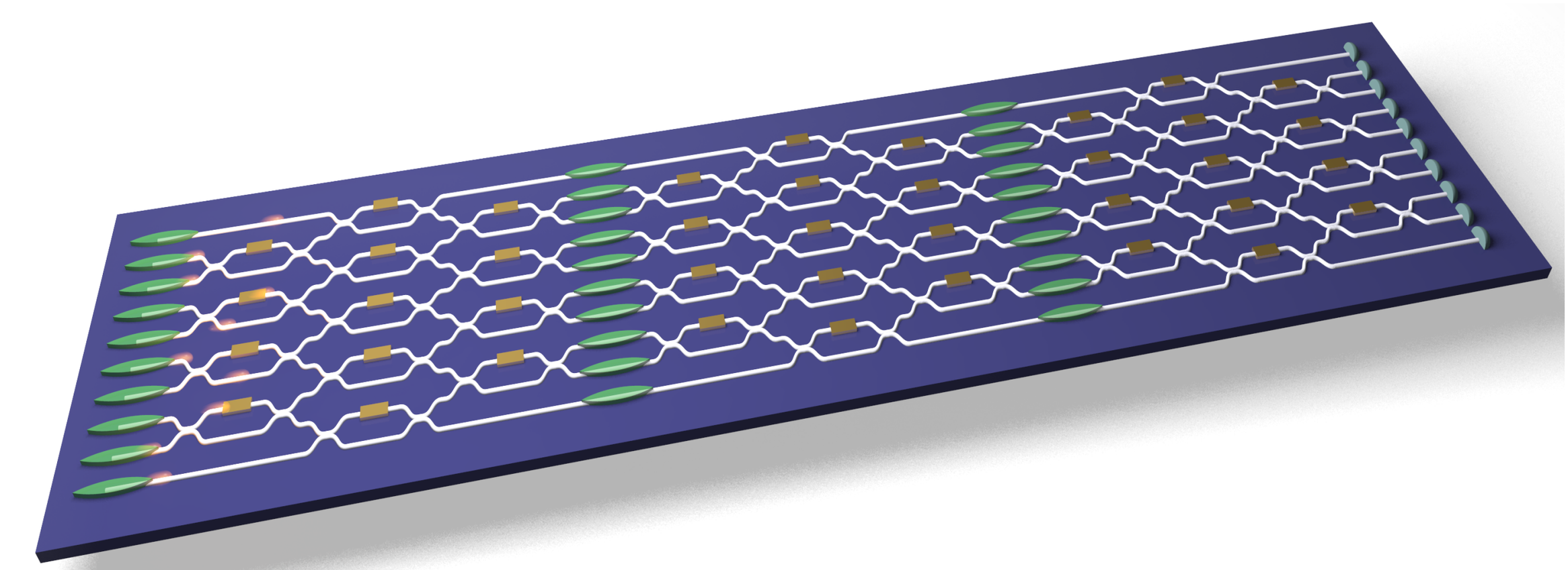
T. J. Seok et al., *Optica* **3**, 64 (2016).

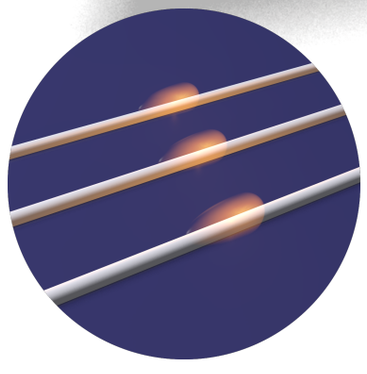
Systems Engineering

→ Optical I/O across 28 optical modes
→ Electrical control across 300 channels
→ Thermal management
→ Packaging (w/ Preble, RIT)

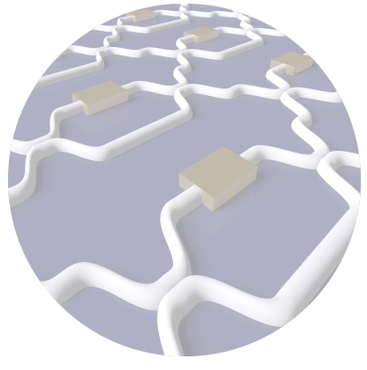


Quantum Photonic Processor

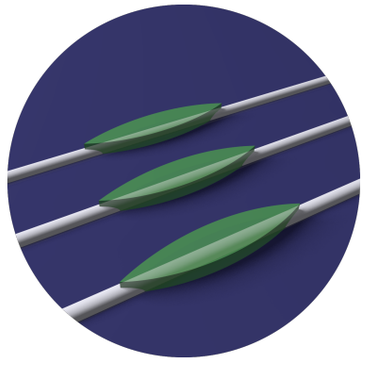




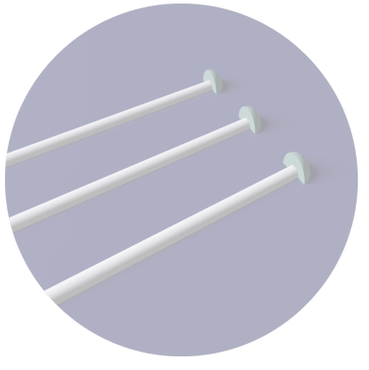
Nonclassical
states of light



Reconfigurable
optical circuitry



Nonlinear
light-matter interaction

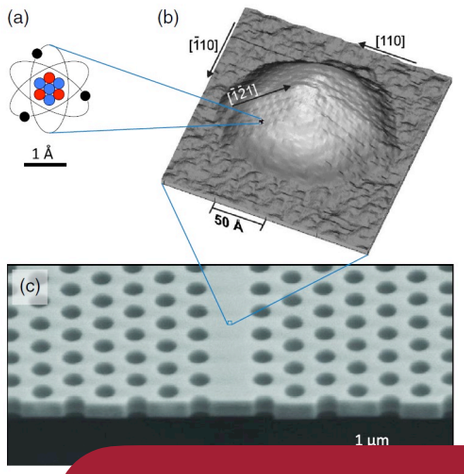


Single photon
readout

III/V Semiconductor QDs

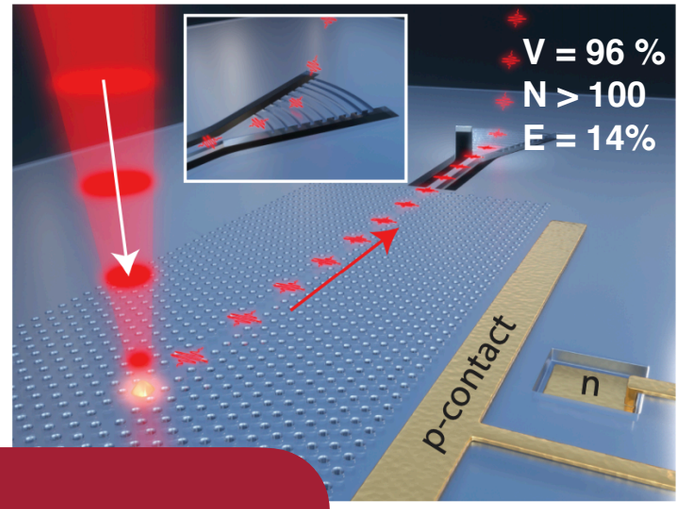
Artificial Atoms

KØBENHAVNS UNIVERSITET



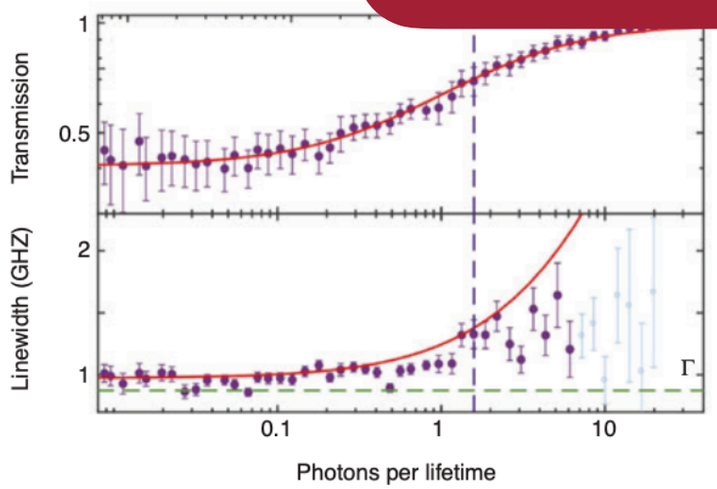
P. Lodahl et al., *Rev* *003.08919v1* (2020)

Efficient Single Photon Sources

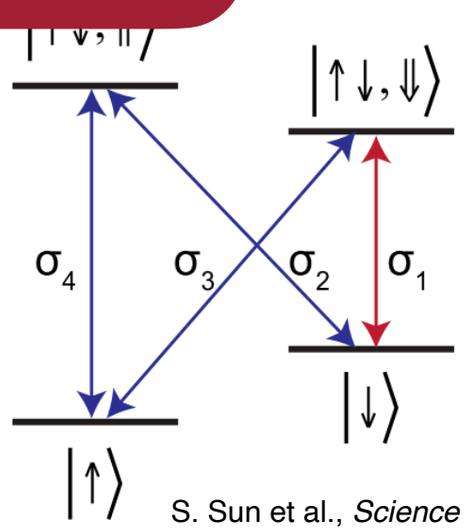


→ Spatial variation
→ Spectral variation
→ Compatibility with foundry PICs

Single Photon Switc



H. Thyrrestrup et al., *Nano. Lett.* (2018)



S. Sun et al., *Science* (2018)

Hybrid Integration

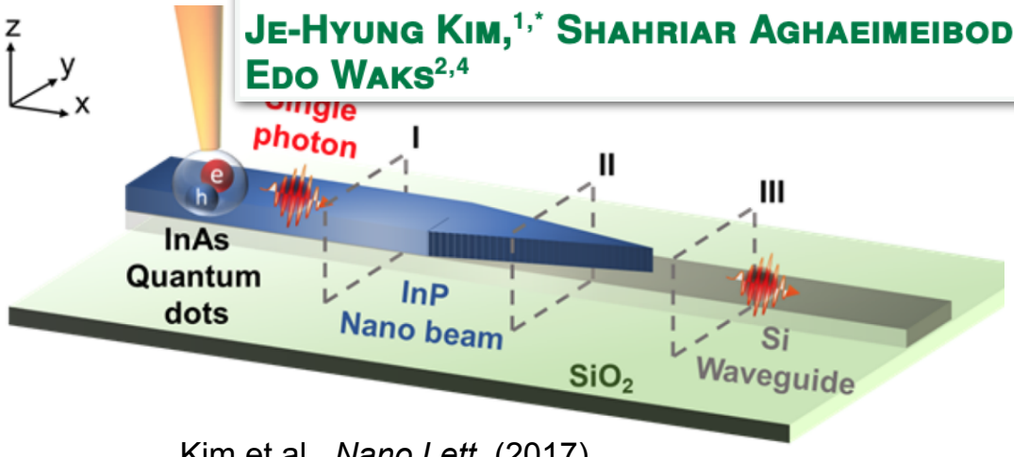
Review Vol. 7, No. 4 / April 2020 / Optica 291

optica

Hybrid integration methods for on-chip quantum photonics

JE-HYUNG KIM,[1,*] SHAHRIAR AGHAEIMEIBODI,[2] JACQUES CAROLAN,[3] DIRK ENGLUND,[3] AND EDO WAKS[2,4]

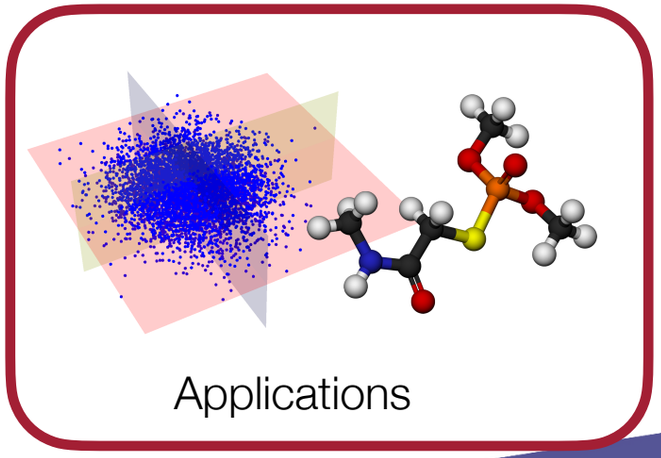
anco)



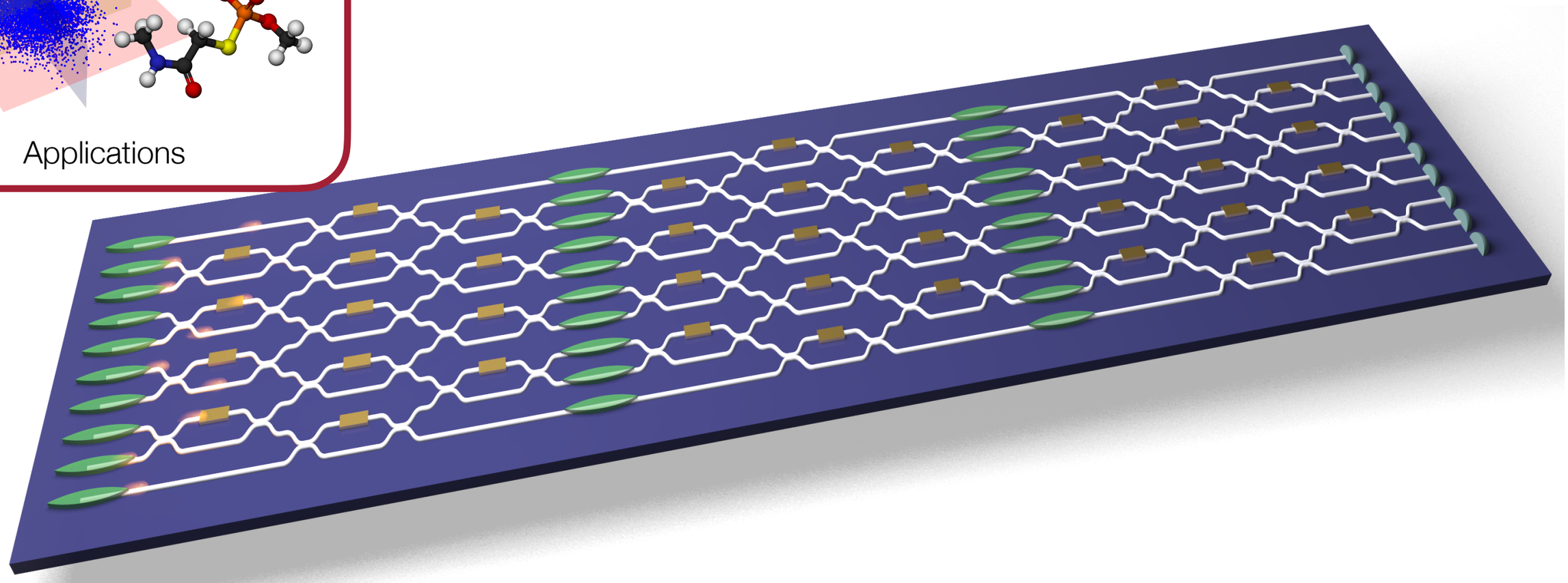
Kim et al., *Nano Lett.* (2017)

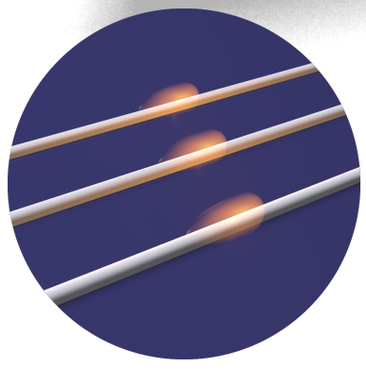
→ **Pre-select** QDs (frequency, bandwidth)
→ Use **PIC for control** (strain, Stark)
→ **Wafer-wafer bonding**

Quantum Photonic Processor

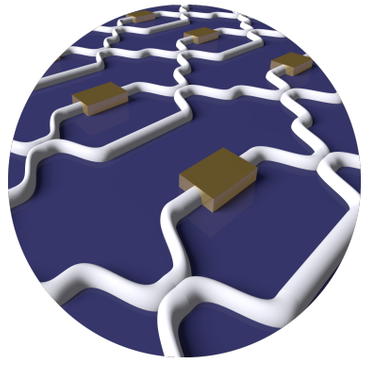


Applications

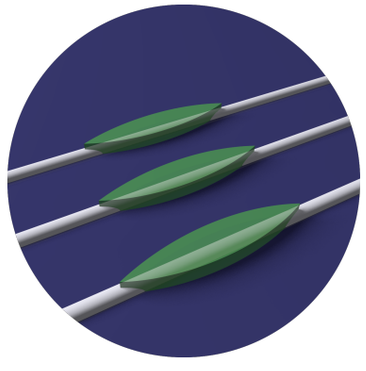




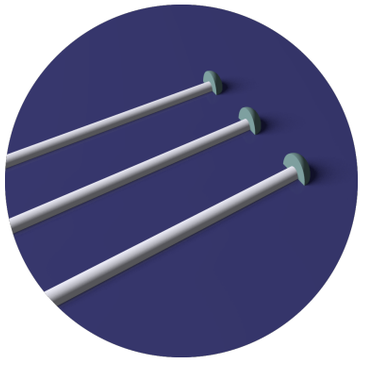
Nonclassical
states of light



Reconfigurable
optical circuitry



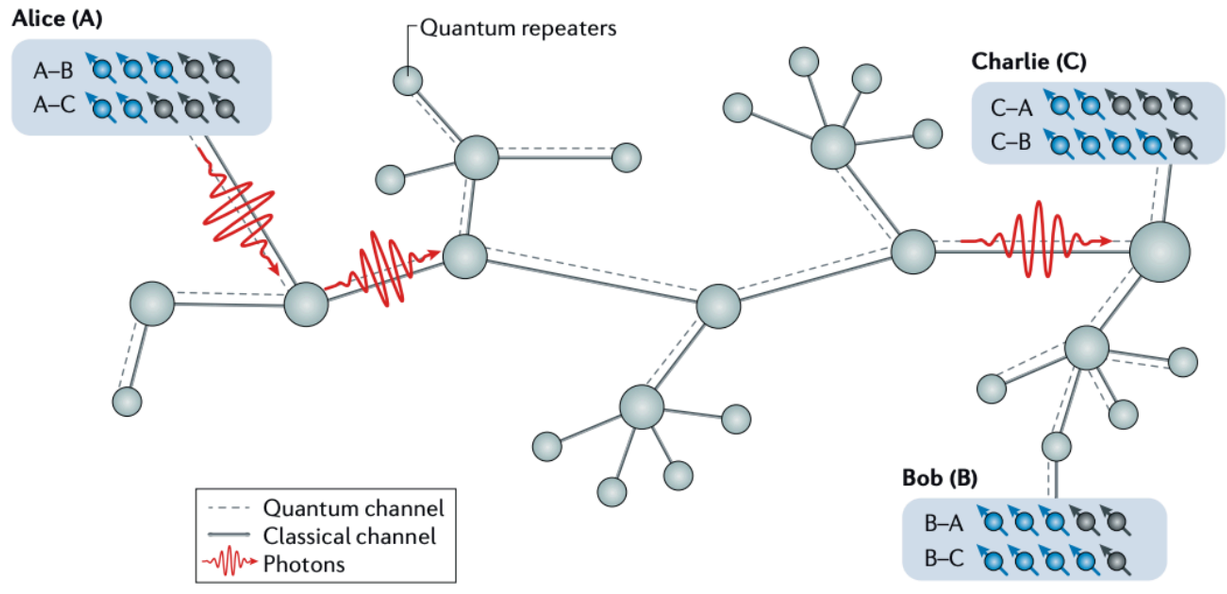
Nonlinear
light-matter interaction



Single photon
readout

Loss Correction

- Primary error mechanism is **loss**
- Encode a single qubit of information across multiple photons s.t.
  if the error occurs information can still be recovered!
- **One-way quantum repeaters** do this without measurement or quantum memories



Codeword[1]

$$|0\rangle_L \equiv (|40\rangle_{12} + |04\rangle_{12})/\sqrt{2}$$
$$|1\rangle_L \equiv |22\rangle_{12},$$

System

$$\hat{S}|30\rangle_{12} = (|40\rangle_{12} + |04\rangle_{12})/\sqrt{2}$$
$$\hat{S}|03\rangle_{12} = (|40\rangle_{12} + |04\rangle_{12})/\sqrt{2}$$
$$\hat{S}|12\rangle_{12} = |22\rangle_{12}$$
$$\hat{S}|21\rangle_{12} = |22\rangle_{12}.$$

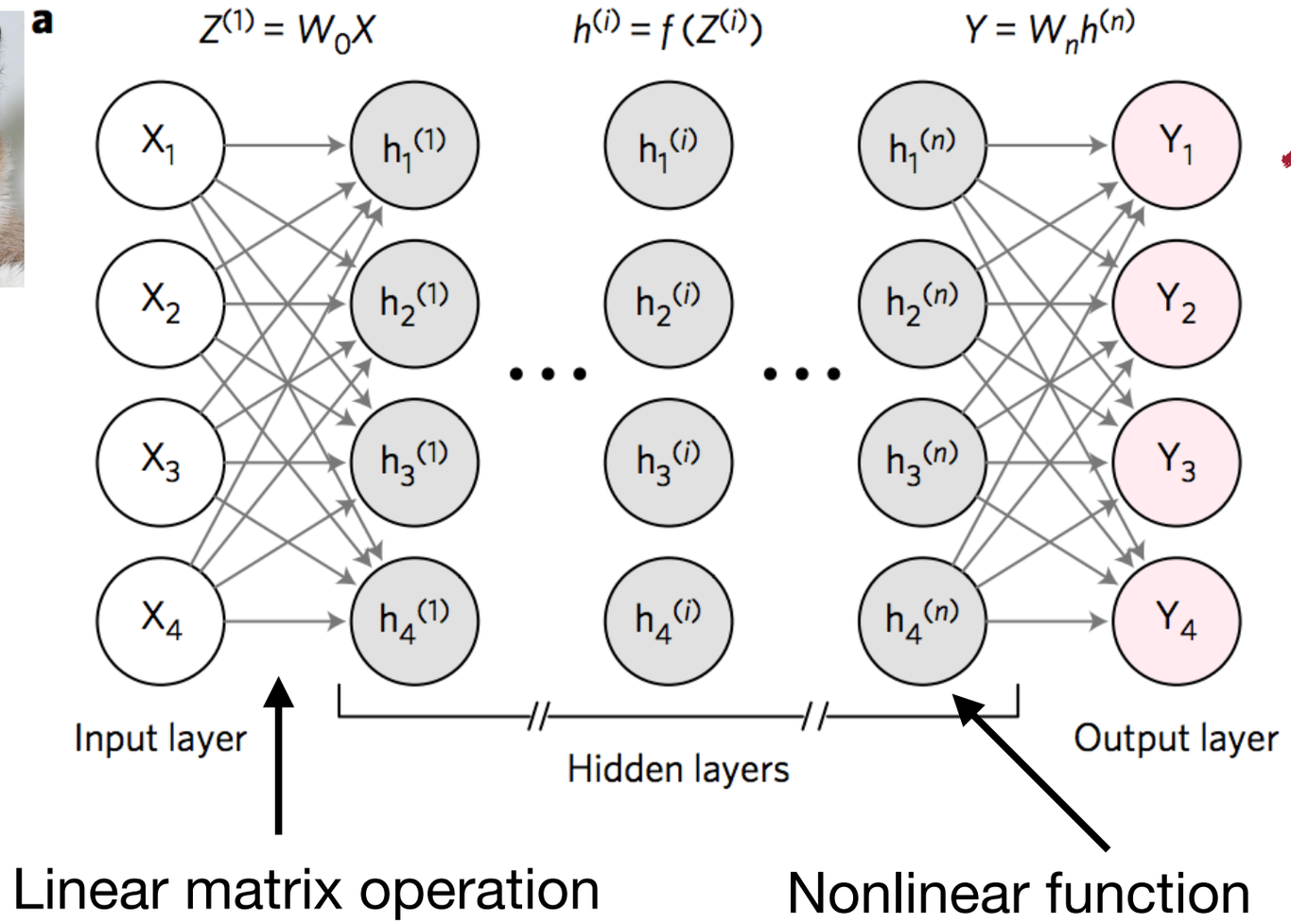
"we do not yet understand how to determine if a given Hamiltonian can be implemented (or approximated to a satisfactory degree) by arranging a reasonable number of optical components"

F. M. Miatto et al., Quantum 2, 75 (2018)

[1]Chuang et al. PRA **56**, 1114 (1997)

Neural Networks

$|30\rangle$



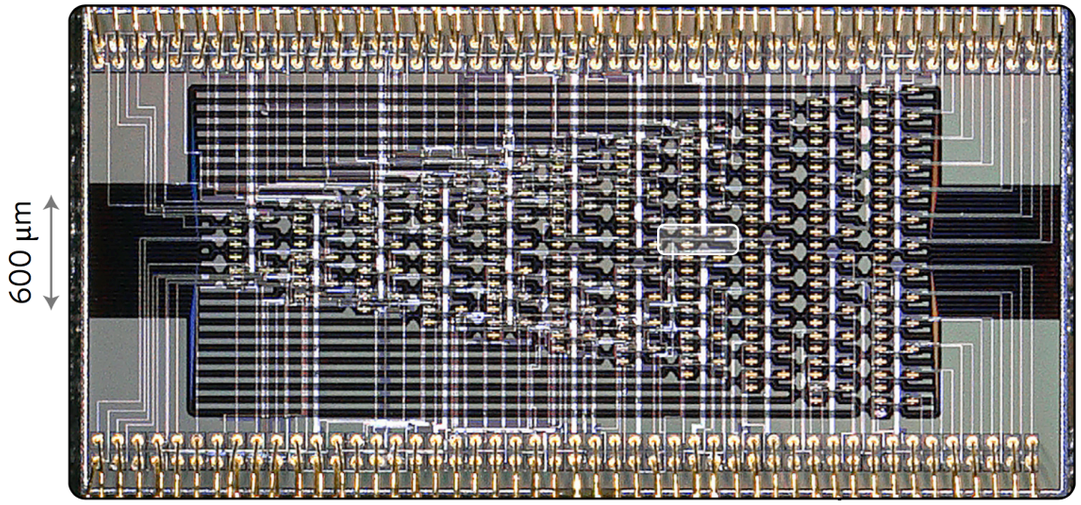
~~'CAT'~~

$(|40\rangle + |04\rangle)/\sqrt{2}$

Y. LeCun, Y. Bengio, and G. Hinton, Nature **521**, 436 (2015).

Optical Neural Networks

→ Matrix Multiplication
→ High bandwidth (100 GHz photodiodes)
→ Low power (quasi-static phase control)



15).
2017).
(2018).

nature photonics

ARTICLES

PUBLISHED ONLINE: 12 JUNE 2017 | DOI: 10.1038/NPHOTON.2017.93

Deep learning with coherent nanophotonic circuits

Yichen Shen[1*†], Nicholas C. Harris[1*†], Scott Skirlo[1], Mihika Prabhu[1], Tom Baehr-Jones[2], Michael Hochberg[2], Xin Sun[3], Shijie Zhao[4], Hugo Larochelle[5], Dirk Englund[1] and Marin Soljačić[1]

LIGHTMATTER

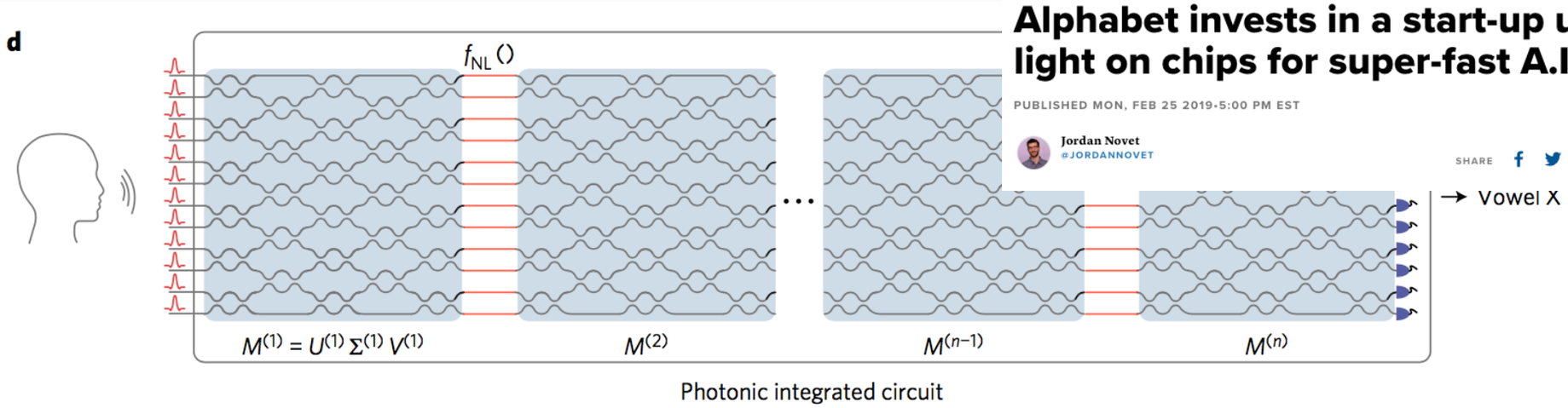
Alphabet invests in a start-up using beams of light on chips for super-fast A.I.

PUBLISHED MON, FEB 25 2019·5:00 PM EST

Jordan Novet
@JORDANNOVET

SHARE

LIGHTELLIGENCE



Quantum Optical Neural Networks

ARTICLE OPEN

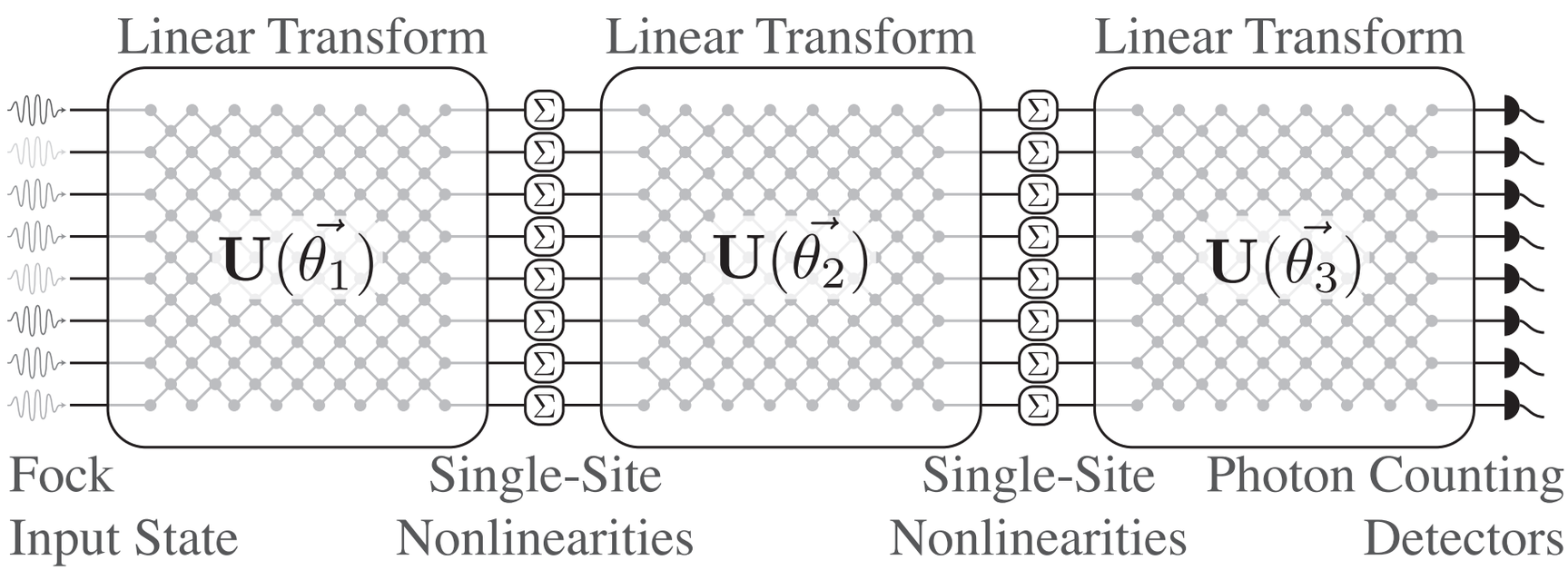
npj | Quantum Information

Quantum optical neural networks

Gregory R. Steinbrecher[1], Jonathan P. Olson[2], Dirk Englund[1] and Jacques Carolan[1]

(b) A Quantum Optical Neural Network

$$\Sigma(\phi) = \sum_{n=0}^{\infty} e^{in(n-1)\phi/2} |n\rangle \langle n|$$

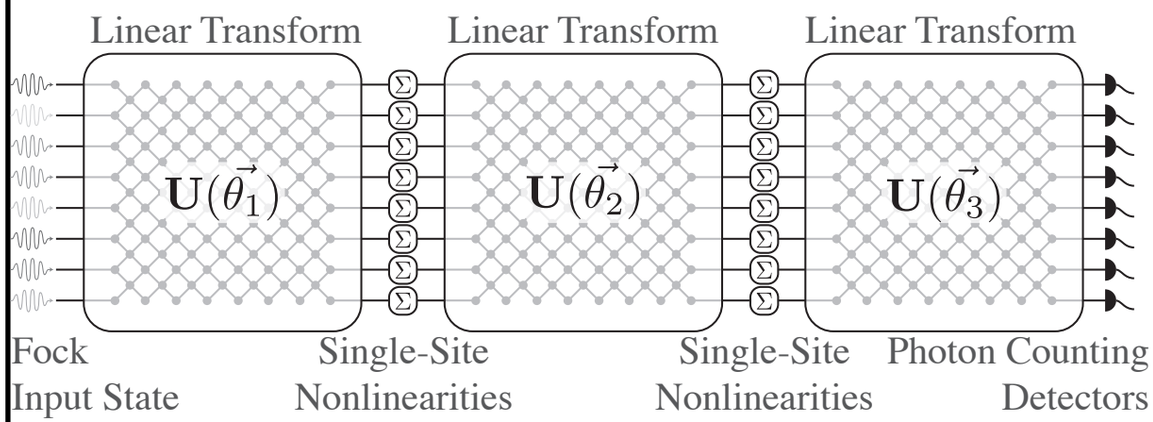


Greg Steinbrecher

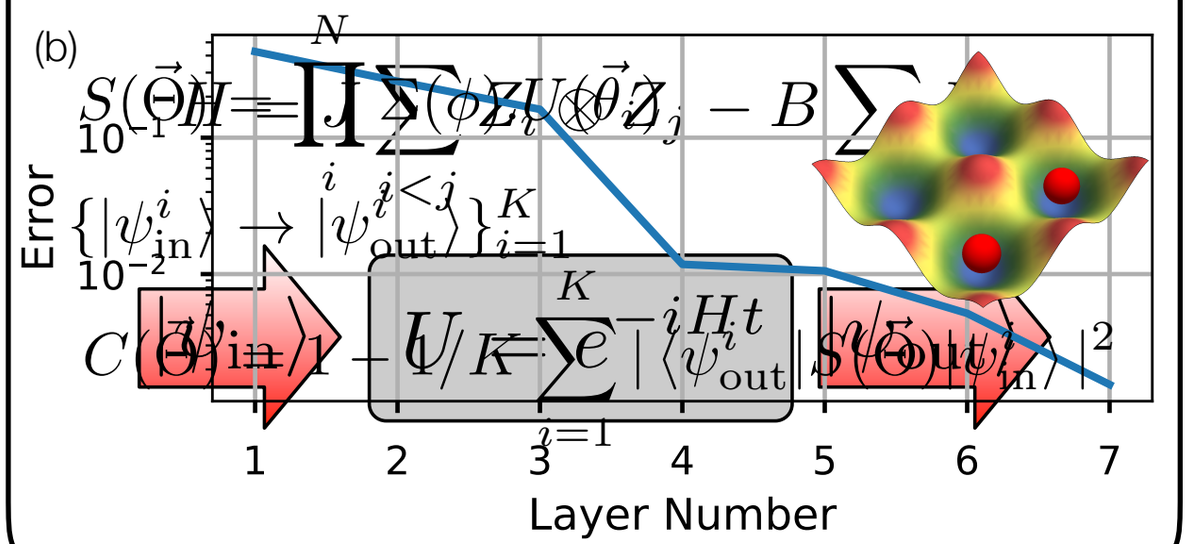
G. Steinbrecher, J. Olson, D. Englund, J. Carolan *npj QI* **5**, 60 (2019)

Applications

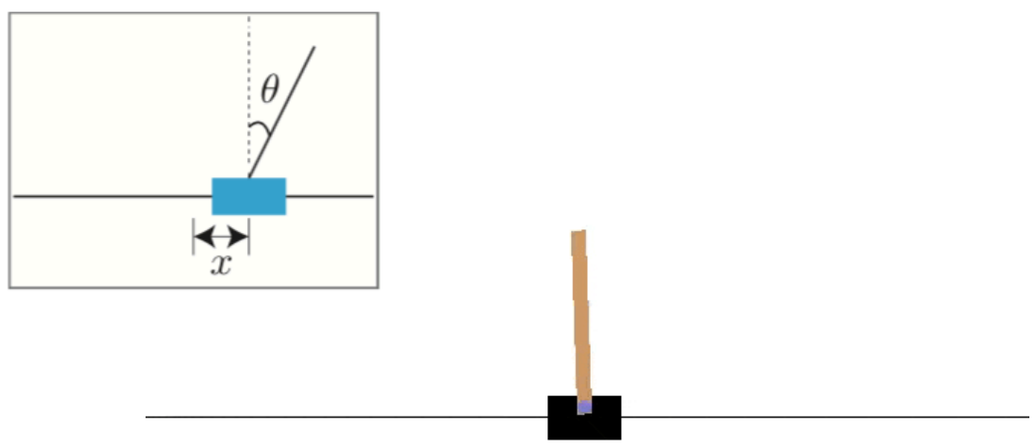
Training



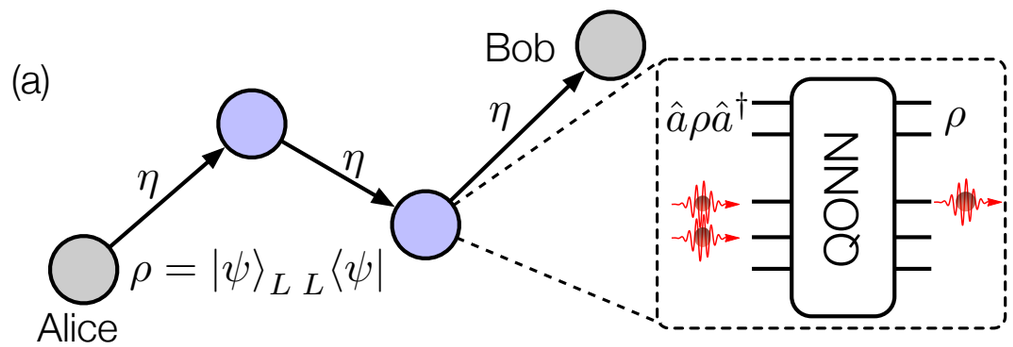
Black Box Quantum Simulation



Reinforcement Learning



One Way Quantum Repeater!



G. Steinbrecher, J. Olson, D. Englund, J. Carolan *npj QI* **5**, 60 (2019)

NISQ

- **N**oisy **I**ntermediate **S**cale **Q**uantum (NISQ) processors[1]:
  - Shallow depth
  - Small [O(100)] qubits
  - Error above threshold

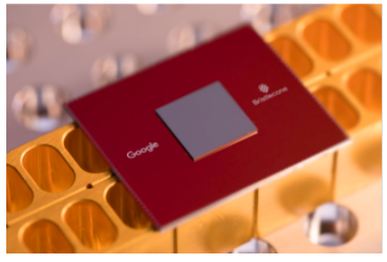
- **Quantum Advantage:**
  - Random Circuit Sampling
    Bouland et al., Nat. Phys. (2018)
  - IQP sampling
    Bremner et al,. Quantum (2016)
  - Boson Sampling
    Aaronson & Arkhipov (2014)

- **Near-term quantum algorithms:**
  - QAOA (Max Cut)
    Farhi et al., arXiv:1411.4028
  - Variational Quantum Eigensolver
    Peruzzo et al, Nat. Comms (2014)
  - Quantum Autoencoder
    Romero et al., QST (2017)

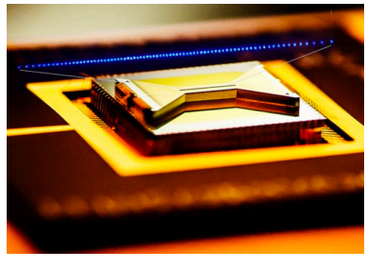
[1] J. Preskill, Quantum 2, 79 (2018)

When you see the ratio of physical to logical qubits for fault tolerant quantum computation

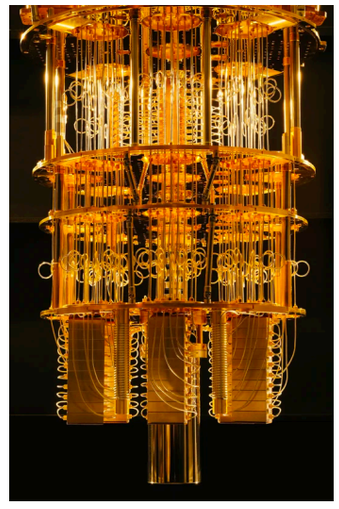
[1] Quantum Computing Memes for QMA-complete Teens, Proceedings of the Royal Society of Quality Memes, Vol 5., 2018.



Google AI

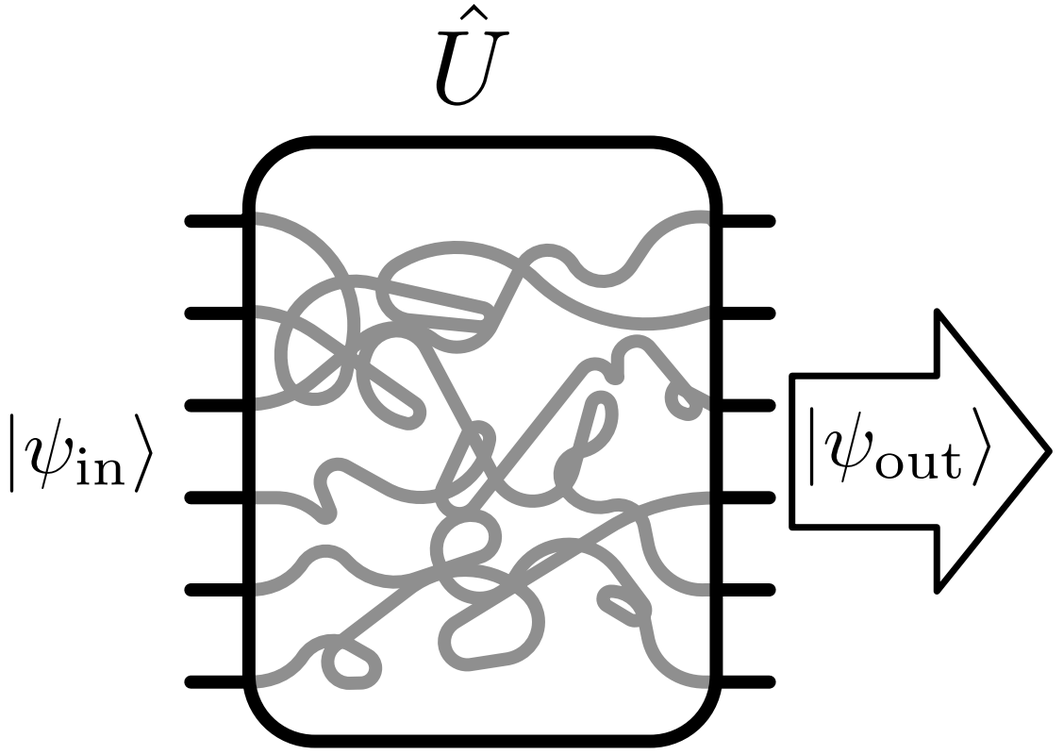


ION Q



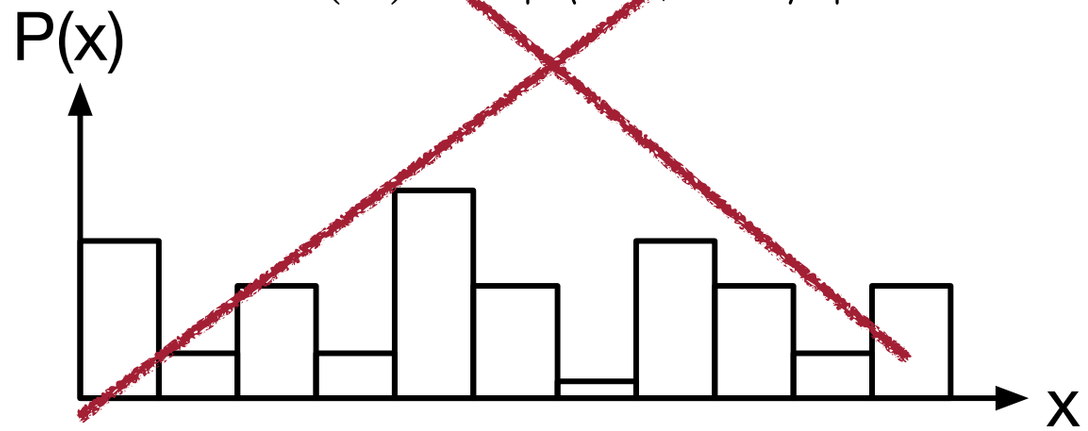
IBM Q™

Quantum Machine Learning



Given ψ_{in} + U, sample from P_U

$$P_U(x) = |\langle x|\psi_{\text{out}}\rangle|^2$$



Given ψ_{out}, what can we learn about U?

nature physics
ARTICLES
https://doi.org/10.1038/s41567-019-0747-6

Variational quantum unsampling on a quantum photonic processor

Jacques Carolan[1*], Masoud Mohseni[2], Jonathan P. Olson[3], Mihika Prabhu[1], Changchen Chen[1], Darius Bunandar[1], Murphy Yuezhen Niu[2], Nicholas C. Harris[4], Franco N. C. Wong[1], Michael Hochberg[5], Seth Lloyd[6] and Dirk Englund[1]

Dr. Masoud Moheseni

Google AI

Dr. Jonny Olson

ZAPATA

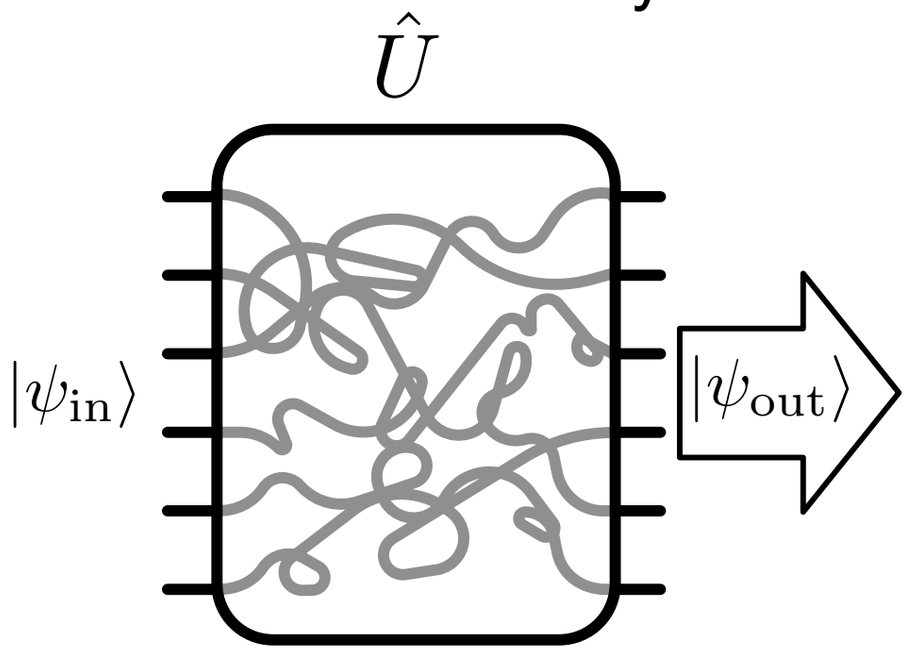
Prof. Seth Lloyd

MIT

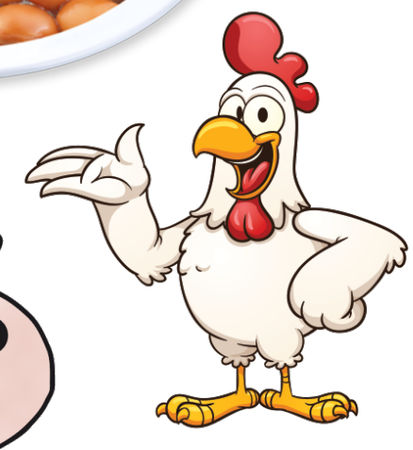
Variational Learning

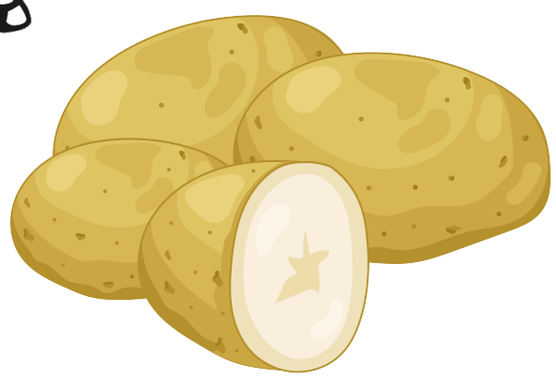
"Can we unravel the action of an unknown unitary on a known input state, to learn the inverse of the black box dynamics?!"

"Given knowledge of ψ_{in}, and access to ψ_{out}, learn an operation which efficiently returns ψ_{in}"

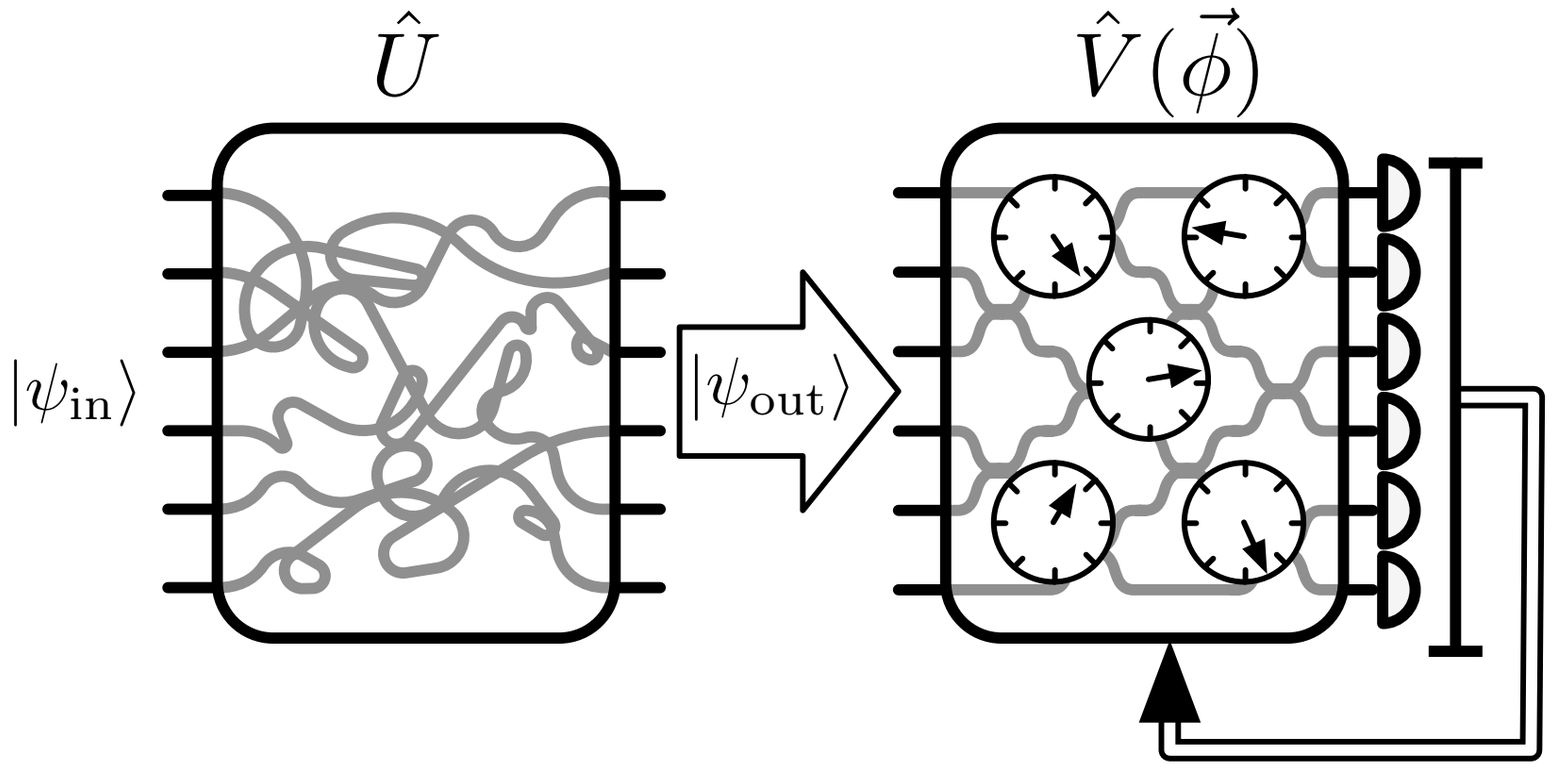


???





Variational Learning



$$\max_{\vec{\phi}} |\langle\psi_{\text{in}}|\hat{V}(\vec{\phi})|\psi_{\text{out}}\rangle|^2$$

$$L(\vec{\phi}) = 1 - |\langle\psi_{\text{in}}|\hat{V}(\vec{\phi})|\psi_{\text{out}}\rangle|^2$$

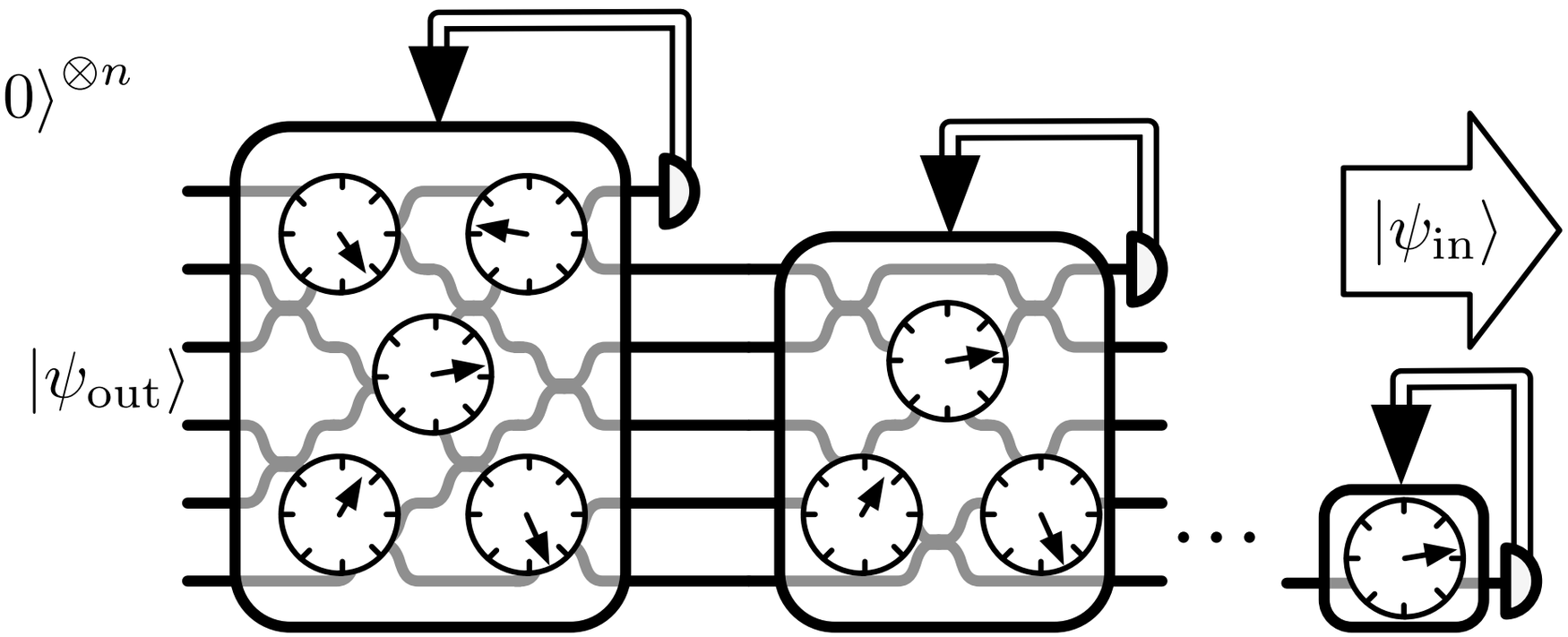
$$\min_{\vec{\phi}} L(\vec{\phi}) = 0$$

$$\rightarrow \hat{V}(\vec{\phi}) = \hat{U}^\dagger$$

1/D

Variational Quantum Unsampling

$$|\psi_{\text{in}}\rangle = |0\rangle^{\otimes n}$$



$$L_1(\vec{\phi}_n) = 1 - |\langle 0_1|\hat{V}_n(\vec{\phi}_n)|\psi_{\text{out}}\rangle|^2$$
$$L_2(\vec{\phi}_{n-1}) = 1 - |\langle 0_2|\hat{V}_{n-1}(\vec{\phi}_{n-1})|\psi_{\text{out}}\rangle|^2$$
$$\vdots$$
$$L_n(\vec{\phi}_1) = 1 - |\langle 0_n|\hat{V}_1(\vec{\phi}_1)|\psi_{\text{out}}\rangle|^2$$

$$L_i \approx \mathcal{O}(1)$$

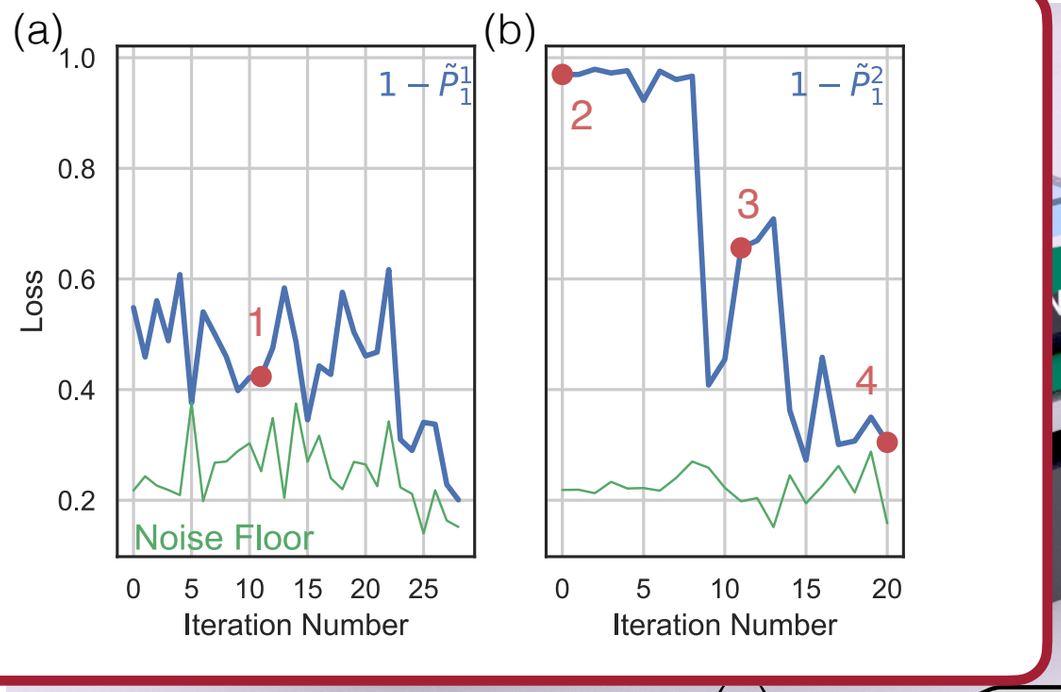
Verification:

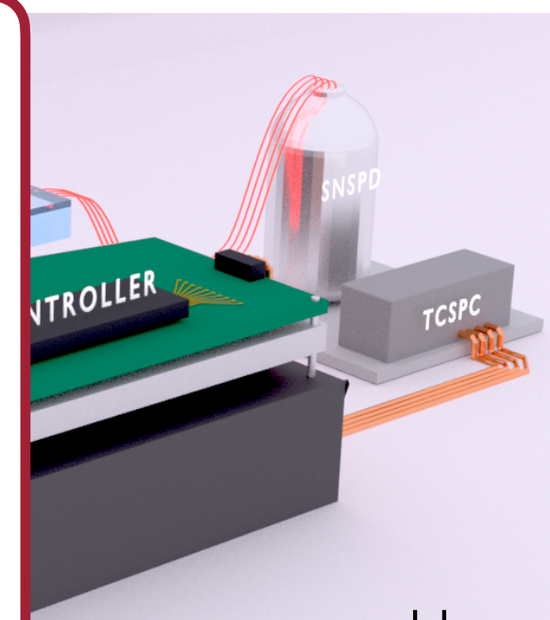
(1) Inspect V → $\hat{V}_{\text{sol}} = \prod_i^n \hat{V}_i$

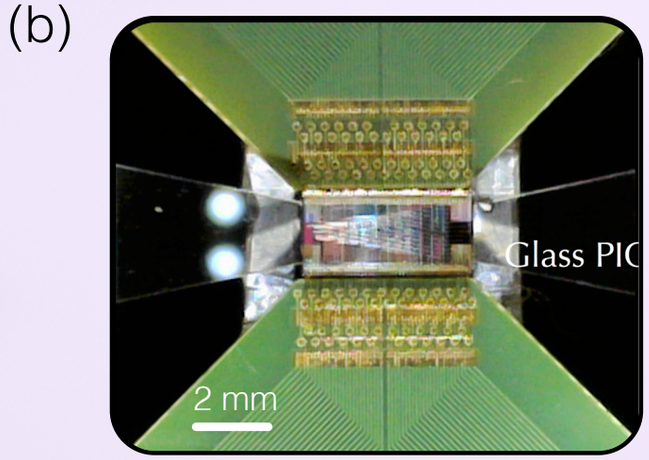
(2) Reduced tomography

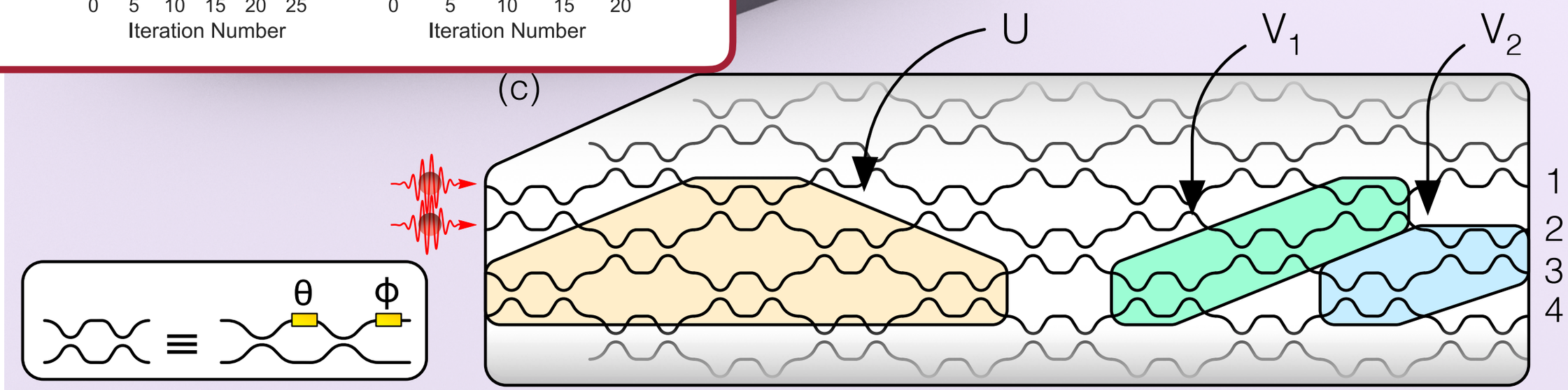
J. Carolan et al., *Nat. Phys.* (2020)

Experimental Boson Unsampling









Photon source

Pairs @ 1582 nm via SPDC
Custom PPKTP XaI[1]

Circuit

Si photonic PNP
176 tuneable phase shifters[2,3]

Mihika Prabhu

Darius Bunandar

Nick Harris

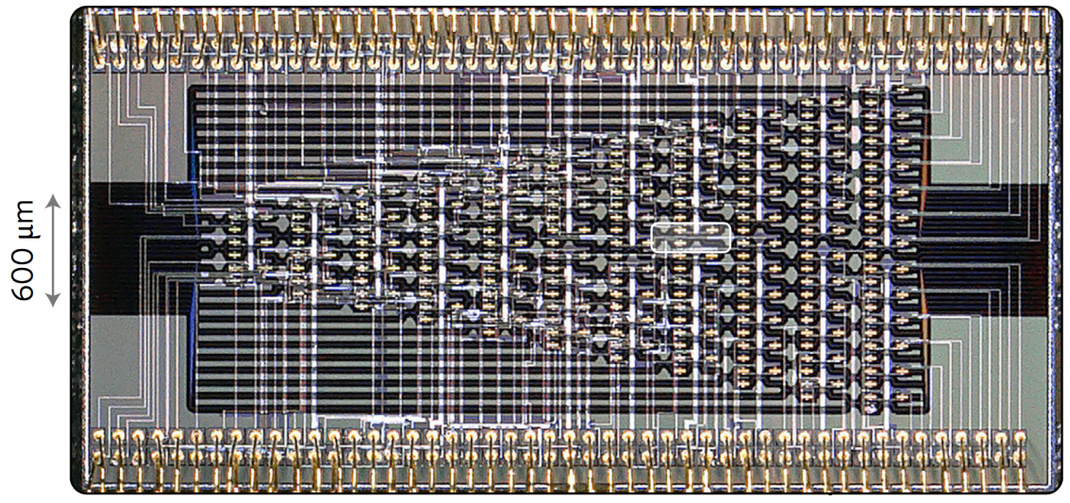
Franco Wong
Changchen Chen

[1]C. Chen et al., *Opt. Exp.* 25, 7300 (2017)

[2] N. C. Harris et al., *Nat. Photon.* 11, 447 (2017).
[3] N. C. Harris, J. Carolan et al., *Optica* 5, 12 (2018).

The Future…

The Future…



LIGHTMATTER

>$30M

LIGHTELLIGENCE

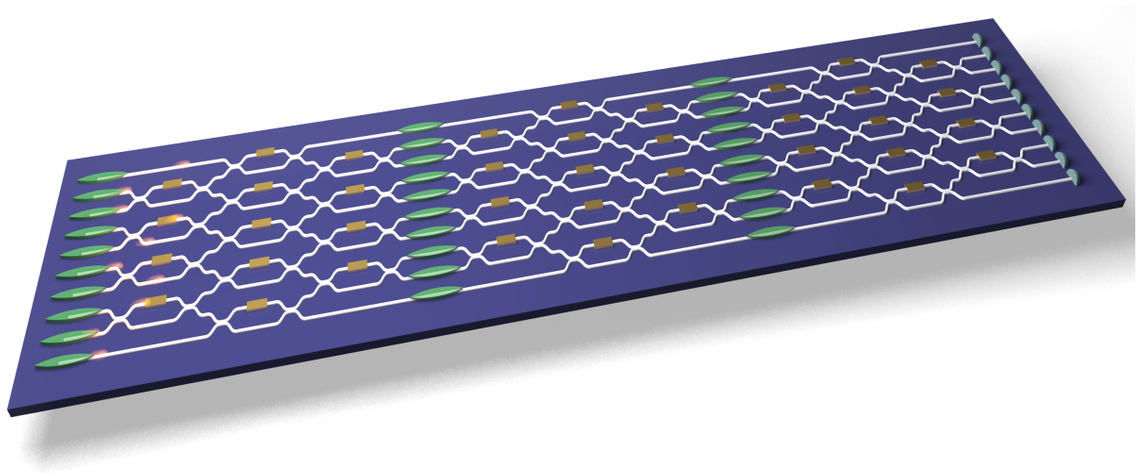
Optical Matrix Processors

Scaling to ~100 of optical modes

→ Optical Machine Learning

→ Optical FPGA for signal processing

→ New imaging modalities



Quantum Photonic Processors

10's of photons w/ nonlinearities

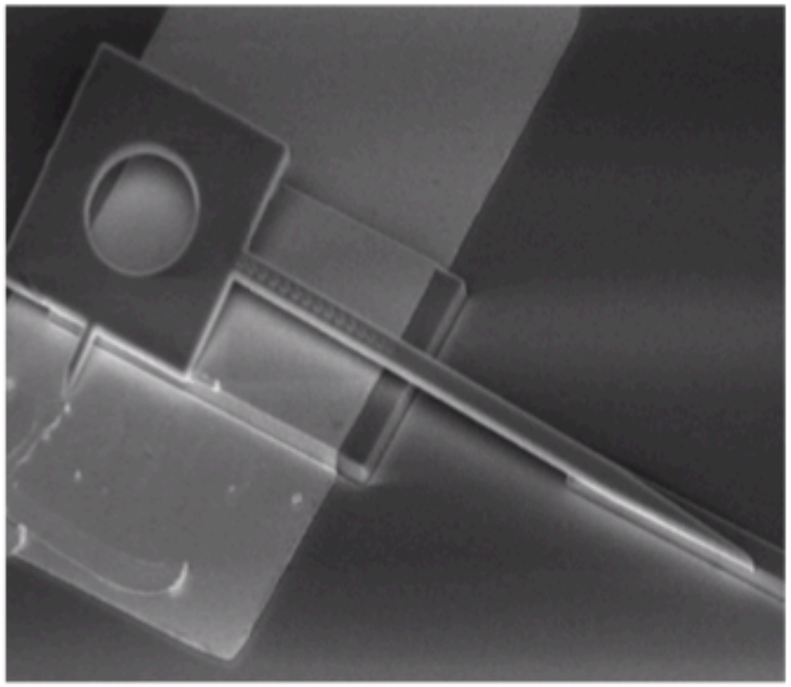
→ Practical molecular simulations

→ Quantum machine learning

→ New architectures: e.g. recurrent

QNN for time sequenced data analysis

The Future…



Hybrid Integration

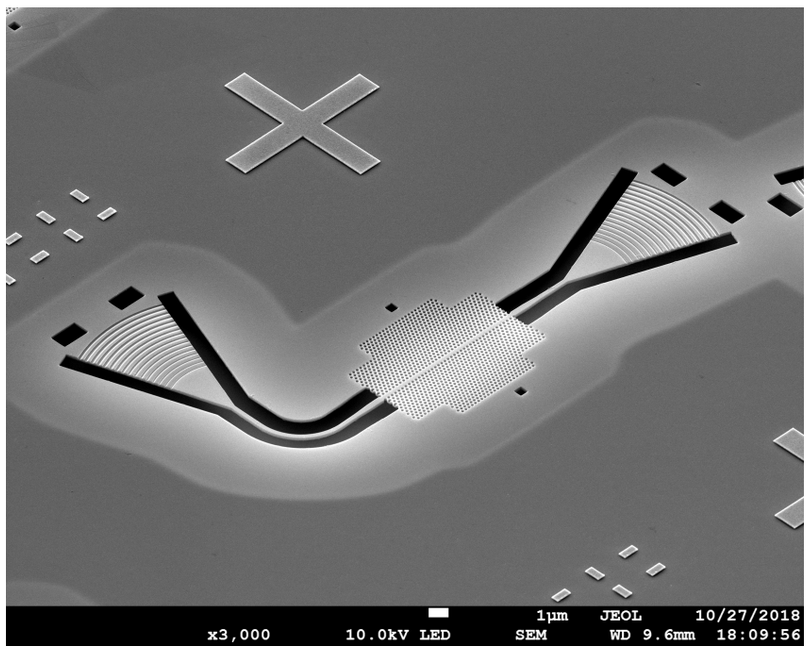
New materials

→ Phase change materials quasi-static

→ EO materials for cryogenic & low loss modulation (LN, BTO)

→ High Q/V chiplets for nonlinear optics

→ New emitters & quantum memories



Optical Nonlinearities

Ultra-high cooptivity QD-Cavity

→ Quantum repeaters

→ Forward error correction

→ Universal Quantum Computation

Acknowledgements

Academic

Prof. Dirk Englund

Prof. Seth Lloyd

Prof. Peter Lodahl

Industry

Quantum

Dr. Masoud Moheseni

Dr. Jonny Olson

Photonics

Dr. Michael Hochberg

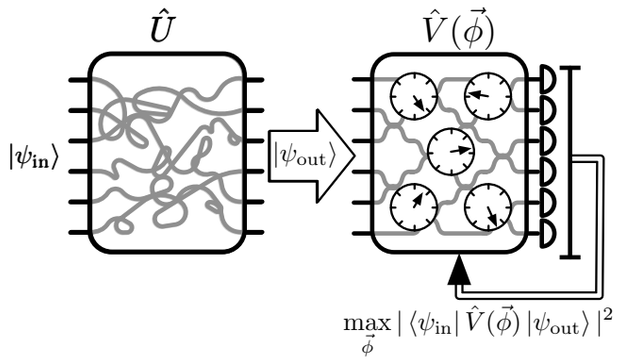
Dr. Nicholas Harris

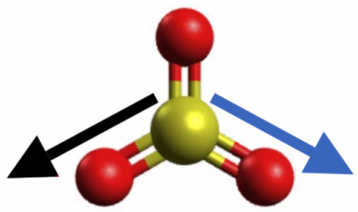
Thanks!

jacques.carolan@nbi.ku.dk
@JacquesCarolan

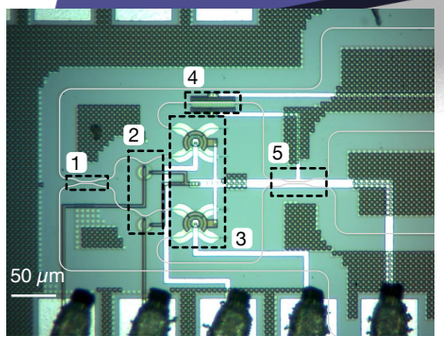
Thanks!

Applications



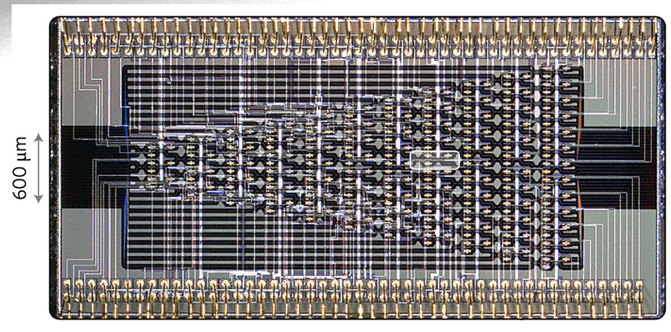


J. Carolan et al., *Nat. Phys.* (2020)
C. Sparrow et al., *Nature* 557, 660 (2018)
G. Steinbrecher et al., *npj QI* **5**, 60 (2019)



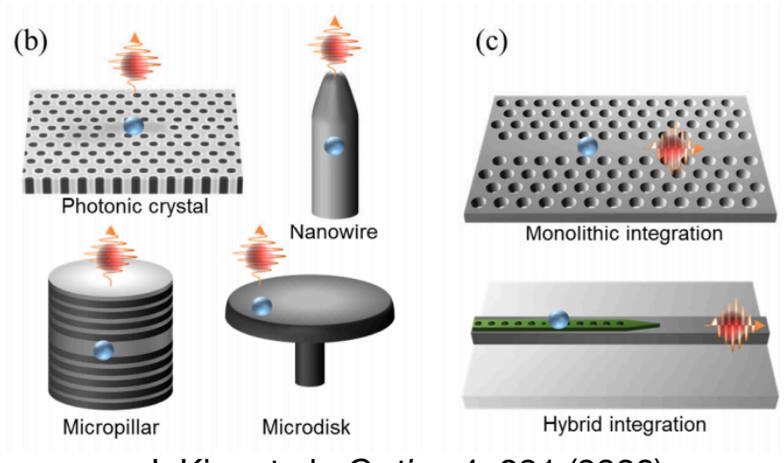
J. Carolan et al., *Optica*, 6, 335 (2019)

Nonclassical states of light



J. Carolan et al., *Science* 349, 711 (2015)
N. C. Harris, J. Carolan et al., *Optica* 5, 12 (2018)

Reconfigurable optical circuitry



J. Kim et al., *Optica* 4, 291 (2020)

Nonlinear light-matter interaction

Single photon readout

Thanks!

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@JacquesCarolan