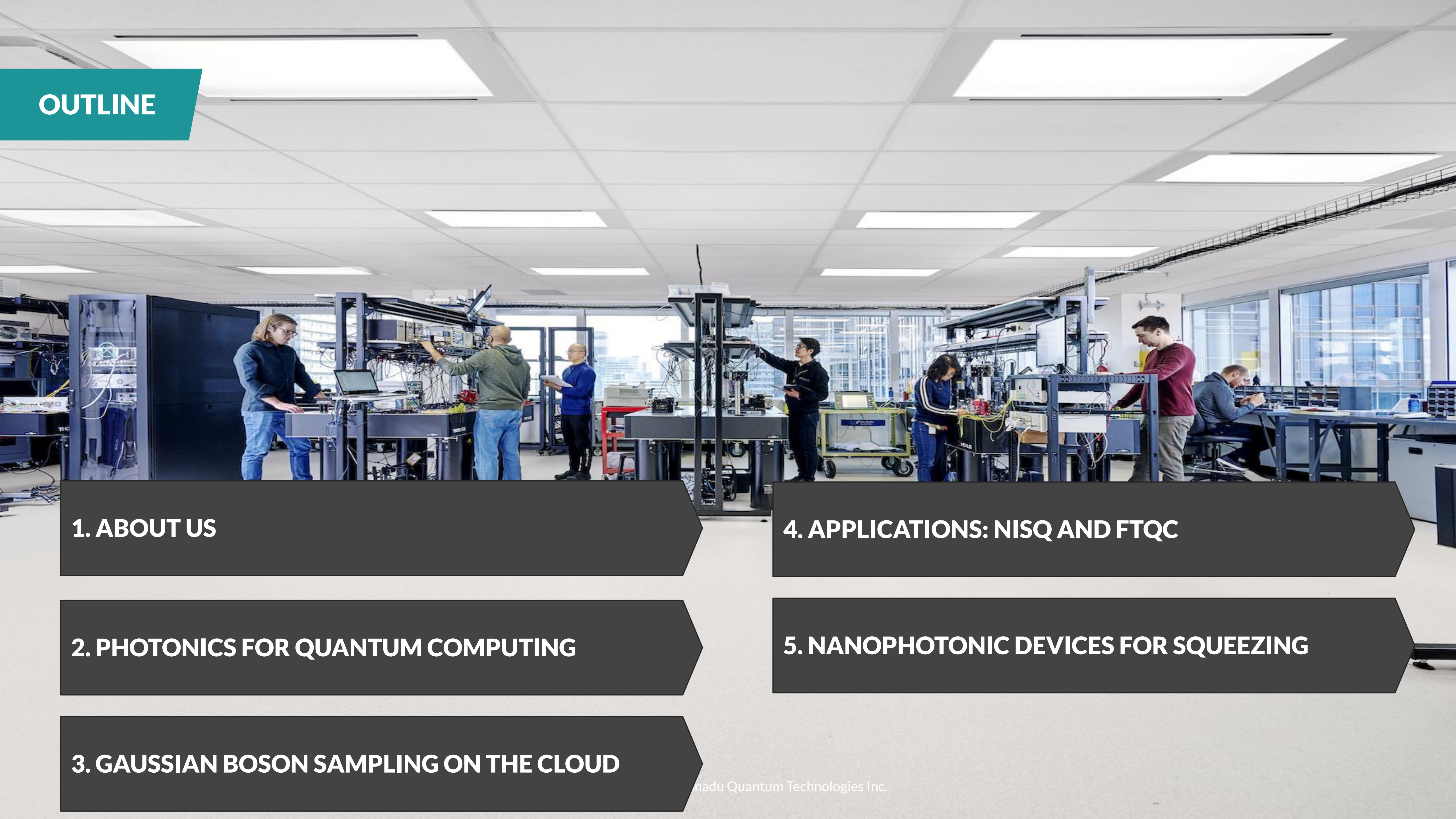
XANADU

Scaling photonic quantum computers

ZACHARY VERNON

University of Pavia Colloquium

29 April 2021



OUTLINE

1. ABOUT US
2. PHOTONICS FOR QUANTUM COMPUTING
3. GAUSSIAN BOSON SAMPLING ON THE CLOUD
4. APPLICATIONS: NISQ AND FTQC
5. NANOPHOTONIC DEVICES FOR SQUEEZING

ABOUT XANADU

CEO

Christian Weedbrook, PhD

HARDWARE

Zachary Vernon, PhD

SOFTWARE

Nathan Killoran, PhD

ARCHITECTURE

Ish Dhand, PhD

PRODUCT

Rafal Janik, MSc

Founded in 2016 | HQ in Toronto | 70+ people | 40+ PhDs | 15+ nationalities

Advisors:

Founded in **2016**	Funding: $45M	Office & Hardware Lab in Toronto

PHOTONICS FOR QUANTUM COMPUTING: MATTER VS LIGHT-BASED QUBITS

What makes a qubit?

DiVincenzo criteria, 2000:

The Physical Implementation of Quantum Computation

DAVID P. DIVINCENZO

IBM T. J. Watson Research Center, Yorktown Heights, NY 10598 USA

Fortschr. Phys.4892000) 9-11,
771-783

Requirements

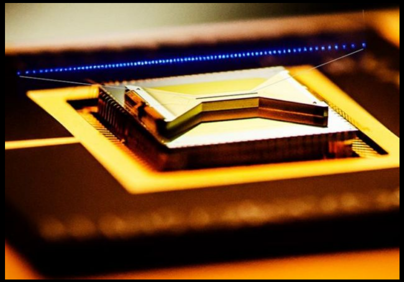
1. A scalable physical system with well characterized qubit
2. The ability to initialize the state of the qubits to a simple fiducial state
3. Long relevant decoherence times
4. A "universal" set of quantum gates
5. A qubit-specific measurement capability

Desiderata

1. The ability to interconvert stationary and flying qubits
2. The ability to faithfully transmit flying qubits between specified locations

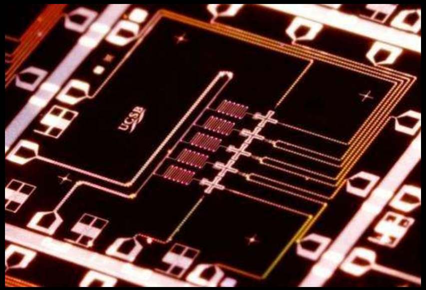
PHOTONICS FOR QUANTUM COMPUTING: MATTER VS LIGHT-BASED QUBITS

Trapped ions



Source: Physics World

Superconducting electronics



Source: Phys.org

At the time (c. 2000), matter-based qubits were generally assumed to be the only option

Blocker: Lack of single-photon level nonlinearity

<u>Requirements</u>

1. A scalable physical system with well characterized qubit
2. The ability to initialize the state of the qubits to a simple fiducial state
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Desiderata

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PHOTONICS FOR QUANTUM COMPUTING: MATTER VS LIGHT-BASED QUBITS

"KLM" protocol for photonic quantum computing, 2001:

Published: 04 January 2001

A scheme for efficient quantum computation with linear optics

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

Nature volume 409, pages 46–52(2001)

Showed that photonic QC was, in principle, possible without exotic photon-photon interactions.

Tradeoff: Lack of deterministic operation, leading to huge component counts.

PROS AND CONS OF PHOTONICS

	Photonics	Superconducting	Trapped ions
Operating environment	Mostly room temperature, no vacuum	Cryostat @ 10mK	Vacuum chamber, laser cooling to nK
Chip integration	Compatible with standard CMOS fabs	Specialized research/university fabs	Cannot be fully chip integrated
Prospects for scaling	Modularity via telecom fiber-optic interconnects	No suitable interconnect yet demonstrated	Optical interconnect using UV/visible photonic elements
Maturity of industry for components	Benefits from optical telecom industry components	Small market for superconducting electronics in other applications	Very little market for components outside scientific research
Bandwidth/clock speeds	Ultrahigh bandwidth: GHz possible	kHz reset rates, gates can be reasonably fast	Slow reset times and gate speeds

PROS AND CONS OF PHOTONICS

	Photonics	Superconducting	Trapped ions
Platform simplicity	Difficult to do everything in one material platform, need heterogeneous integration/multi-chip architecture	Qubits, gates, measurements done in same layer, control and readout done with RF pulses	Complicated laser control (many UV/visible beams required)
Component counts	Large due to non-deterministic elements	Moderate, but wiring inside cryostat is a serious challenge (cryoCMOS required?)	Low, also due to high fidelities allowing possibly lower overheads for fault tolerance

THE CASE FOR PHOTONICS

FASTER DEVELOPMENT

Much faster prototyping cycles due to room temperature QPUs

+

UNIQUE ENCODING

Different NISQ applications and more ways to implement error correction

+

LOWER COST

Can borrow many tools from optical telecom industry

+

SCALABLE & MODULAR

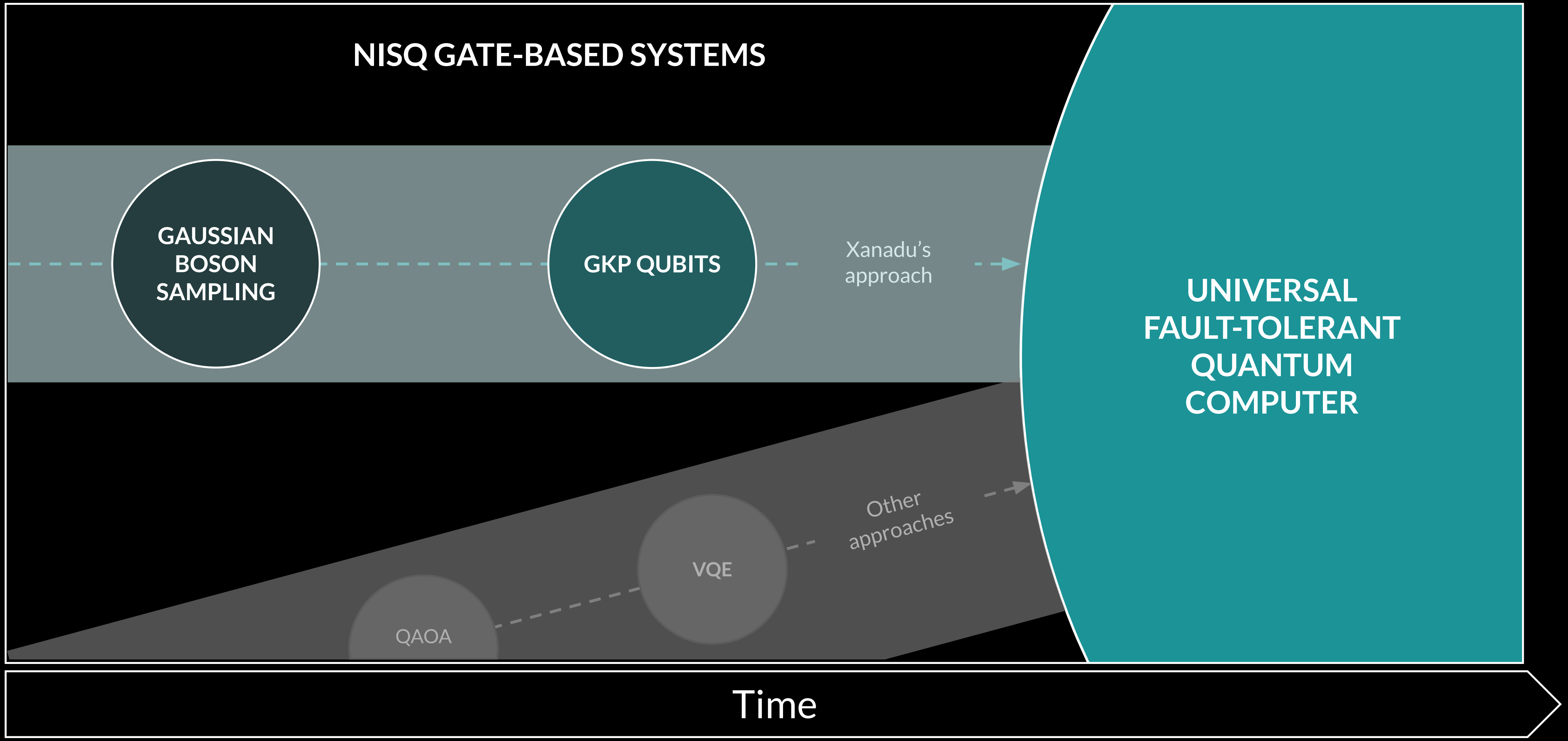
Fiber interconnects distribute qubits across many chips

+

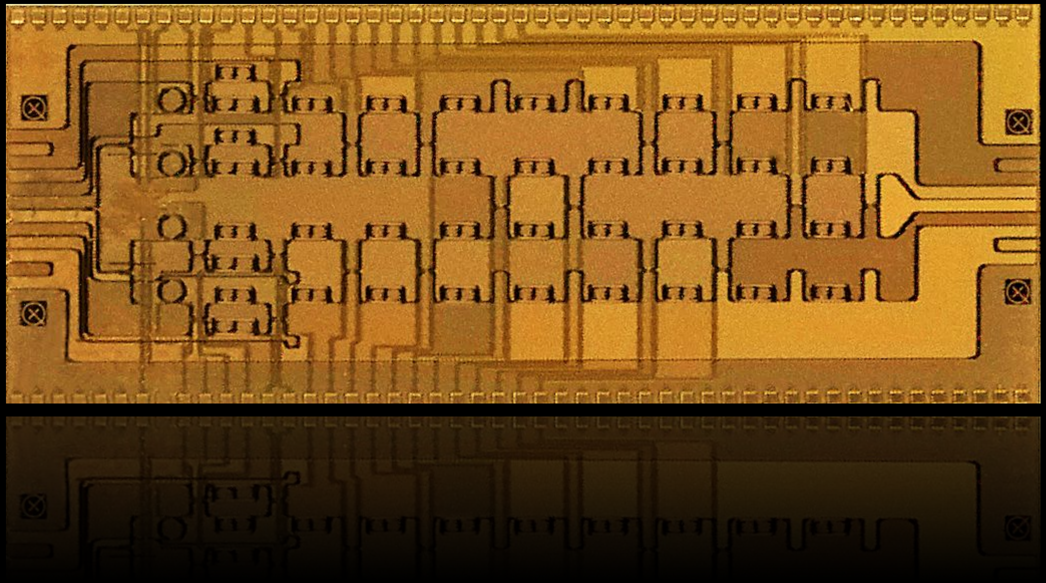
NETWORK COMPATIBLE

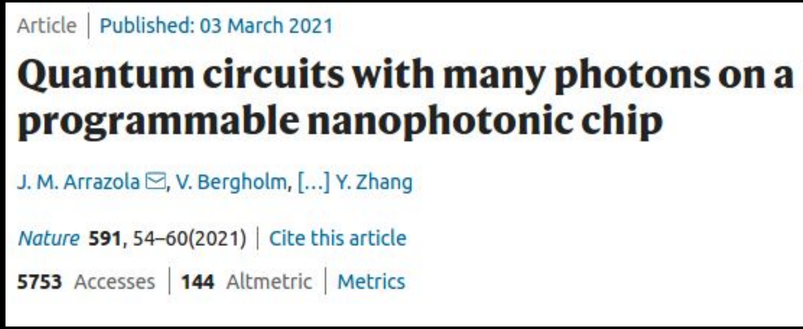
Natural interface with future quantum internet

XANADU'S ROADMAP TO UNIVERSAL QUANTUM COMPUTING



PHOTONIC QUANTUM COMPUTING ON THE CLOUD




Article | Published: 03 March 2021

Quantum circuits with many photons on a programmable nanophotonic chip

J. M. Arrazola, V. Bergholm, [...] Y. Zhang

Nature **591**, 54–60(2021) | Cite this article

5753 Accesses | **144** Altmetric | Metrics

GAUSSIAN BOSON SAMPLING

The formula

Squeezed states
(single temporal mode)

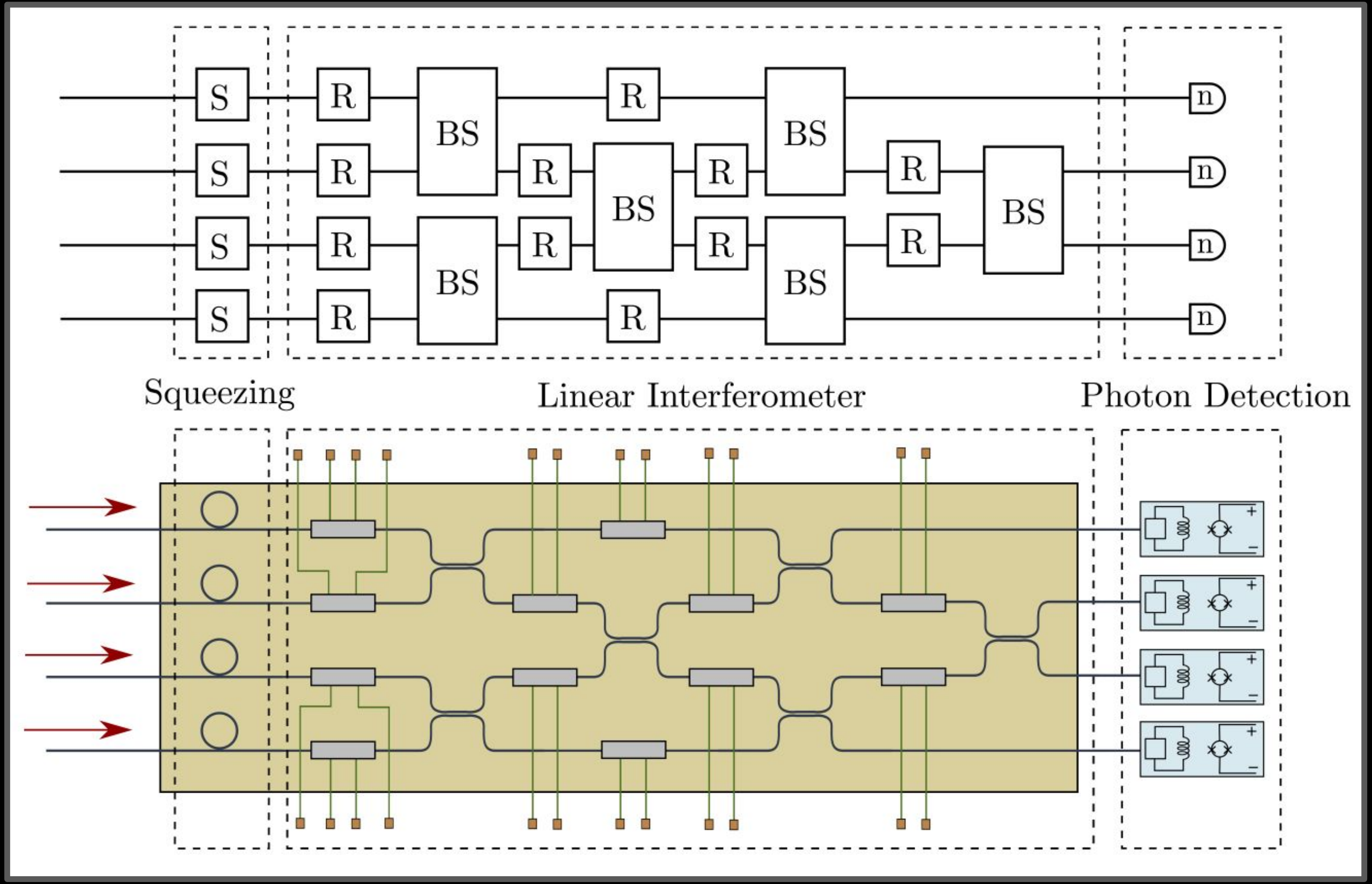
+

Linear optics
(programmable, phase stable)

+

Photon counting
(photon number resolving)

=



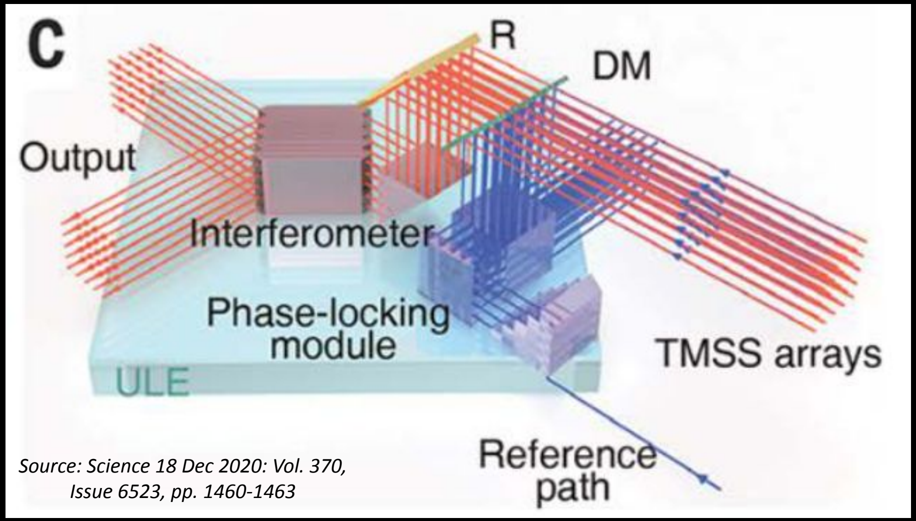
Source: "Applications of near-term photonic quantum computers: Software and algorithms", T.R. Bromley et al., Quantum Science and Technology (2020)

GAUSSIAN BOSON SAMPLING

中国科学技术大学
University of Science and Technology of China

Quantum computational advantage using photons

Han-Sen Zhong[1,2*], Hui Wang[1,2*], Yu-Hao Deng[1,2*], Ming-Cheng Chen[1,2*], Li-Chao Peng[1,2], Yi-Han Luo[1,2], Jian Qin[1,2], Dian Wu[1,2], Xing Ding[1,2], Yi Hu[1,2], Peng Hu[3], Xiao-Yan Yang[3], Wei-Jun Zhang[3], Hao Li[3], Yuxuan Li[4], Xiao Jiang[1,2], Lin Gan[4], Guangwen Yang[4], Lixing You[3], Zhen Wang[3], Li Li[1,2], Nai-Le Liu[1,2], Chao-Yang Lu[1,2], Jian-Wei Pan[1,2†]



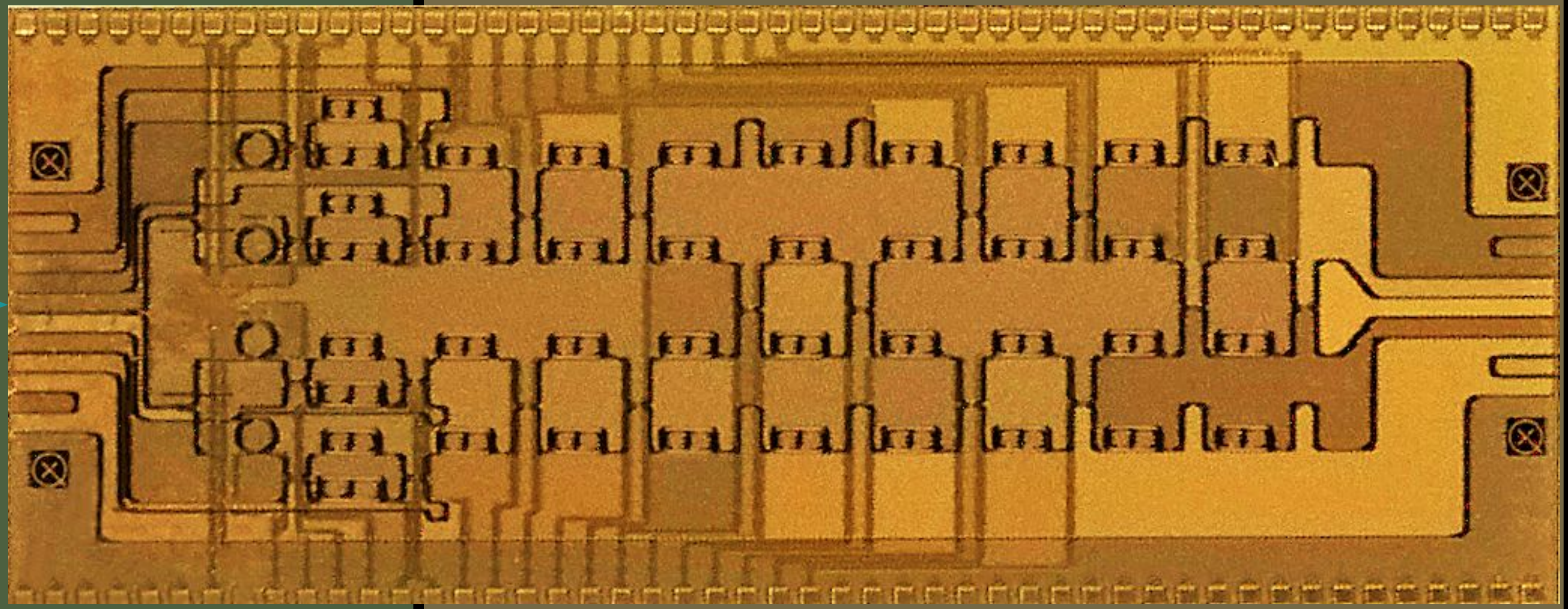
Source: Science 18 Dec 2020: Vol. 370, Issue 6523, pp. 1460-1463

Source: “Applications of near-term photonic quantum computers: Software and algorithms”, T.R. Bromley et al., Quantum Science and Technology (2020)

NANOPHOTONIC BUILDING BLOCKS

Input: Compiled program loaded to chip via DACs

Pulsed pump laser source

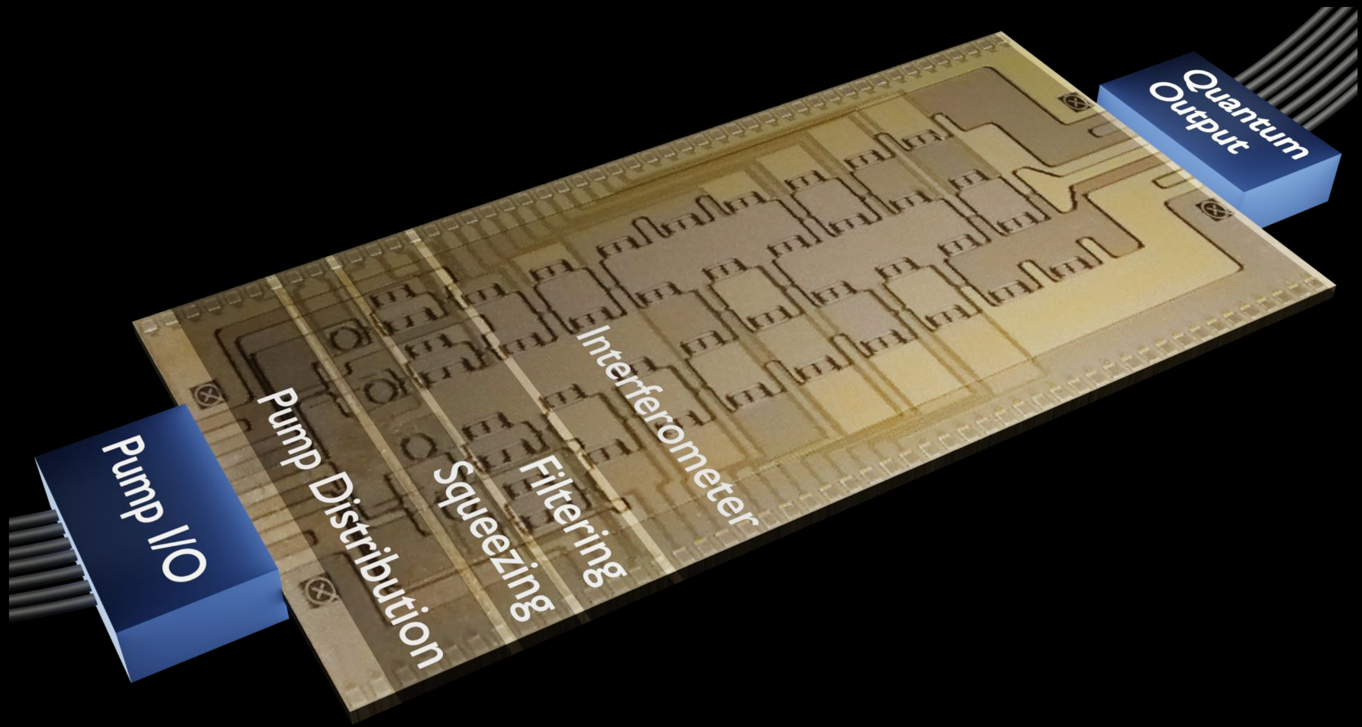


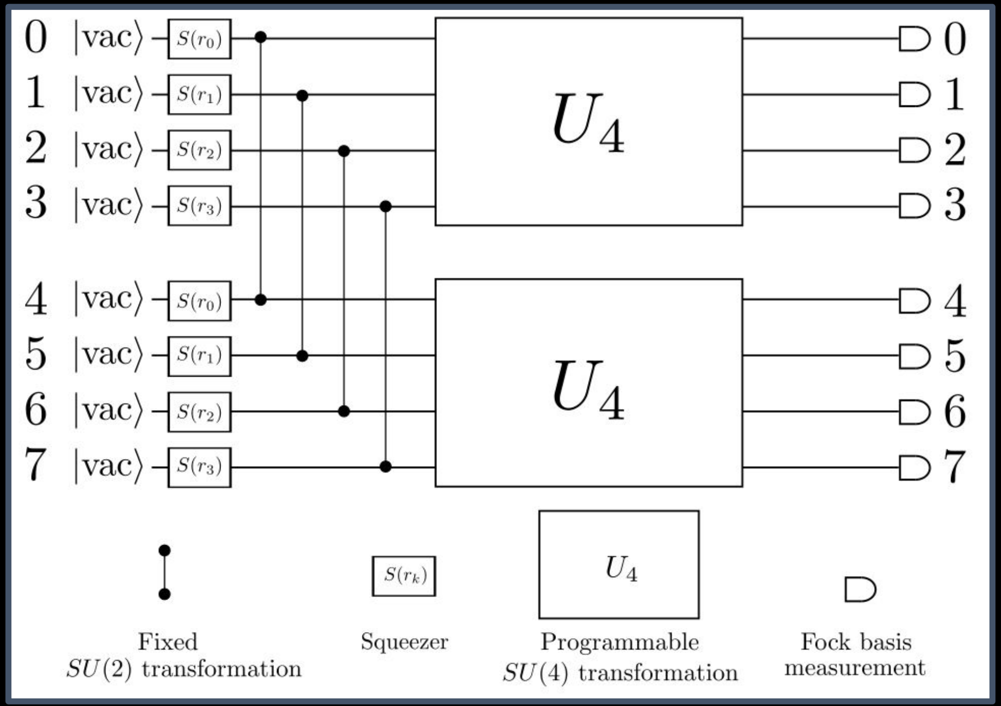
Squeezed light sources

Programmable interferometer
(Information encoding and quantum gate sequence)

Output: Programmable 8-mode entangled Gaussian state

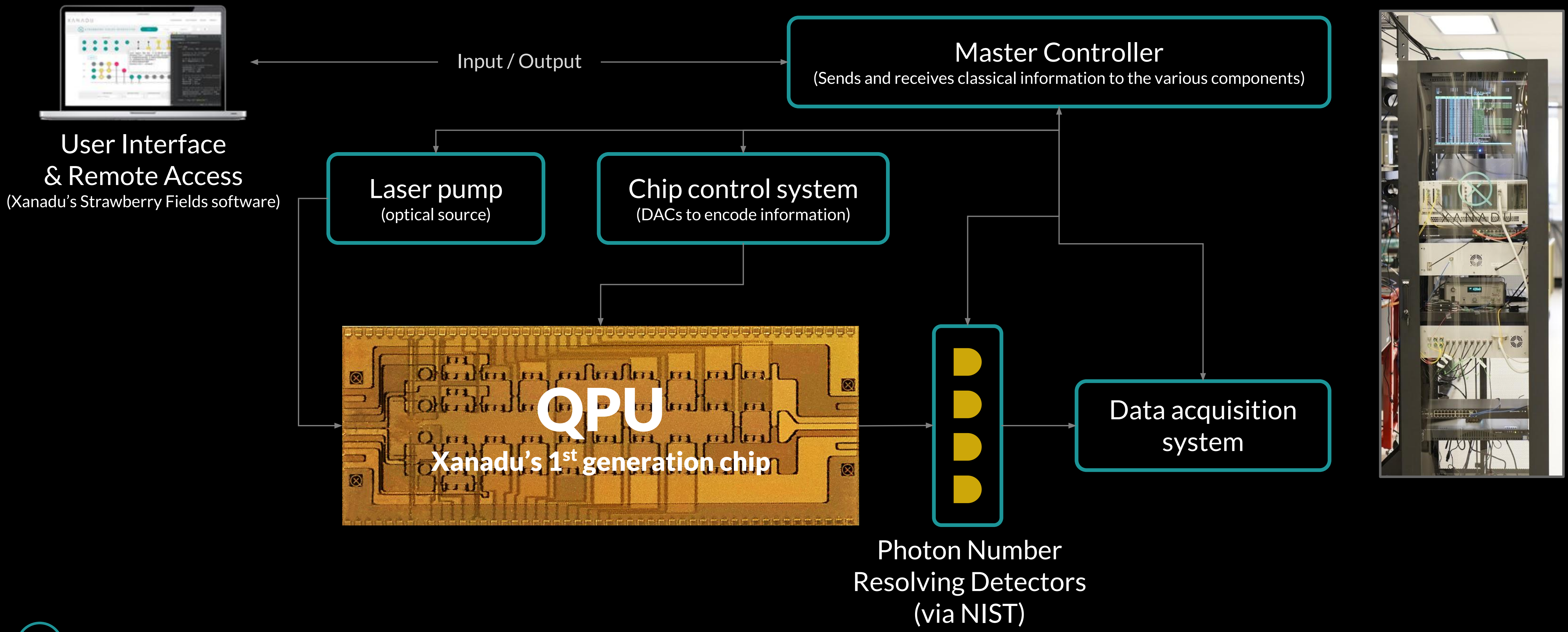
GAUSSIAN BOSON SAMPLING ON A CHIP



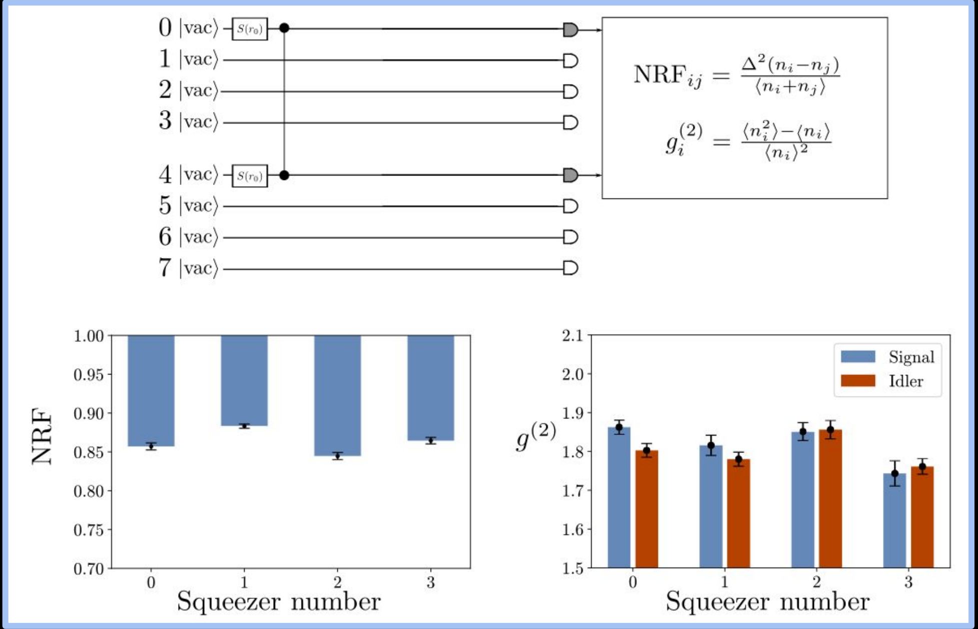


Equivalent quantum circuit

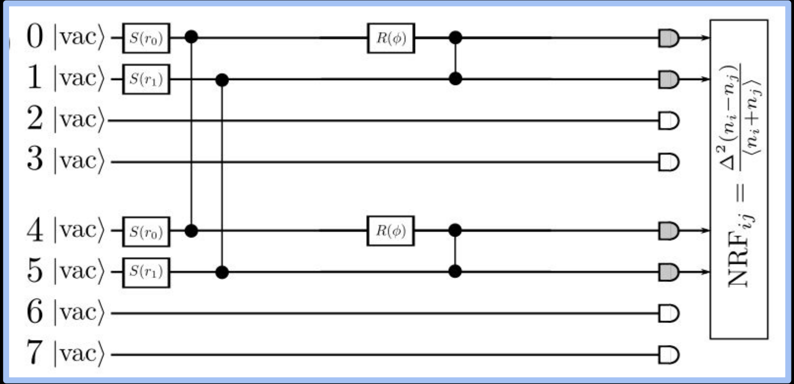
CONTROL SYSTEM (SIMPLIFIED)

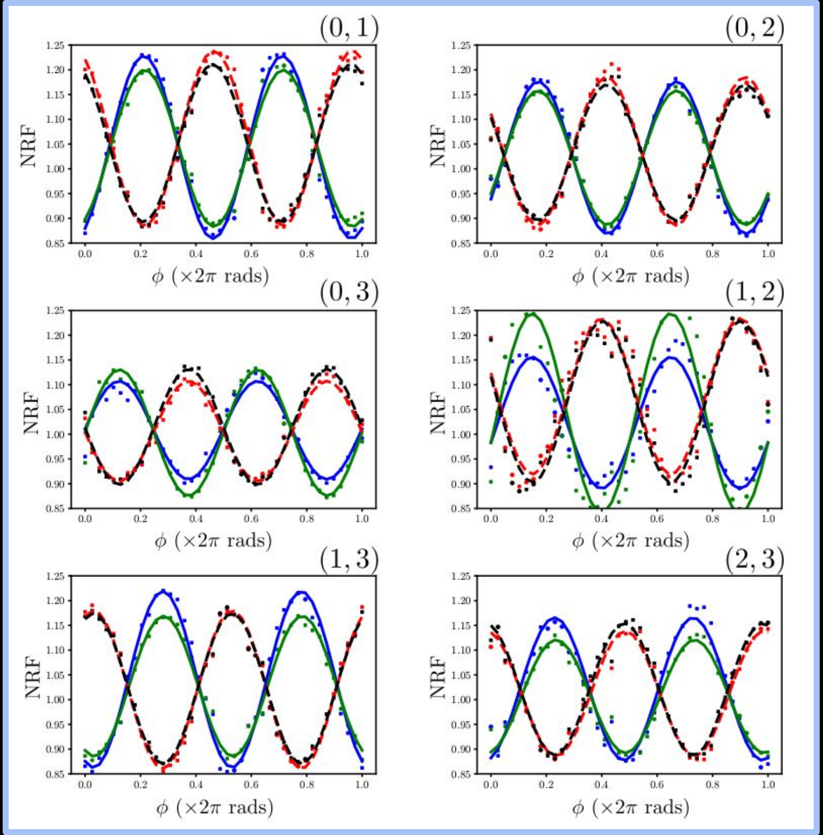


SQUEEZER PERFORMANCE



Single-squeezer statistics

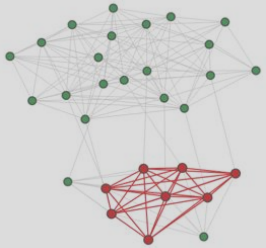




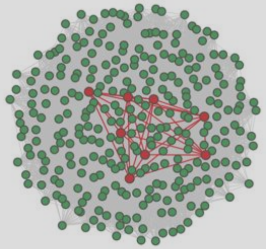
Two-squeezer interference

GAUSSIAN BOSON SAMPLING: NEAR-TERM APPLICATIONS

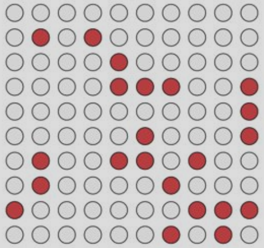
DENSE SUBGRAPH



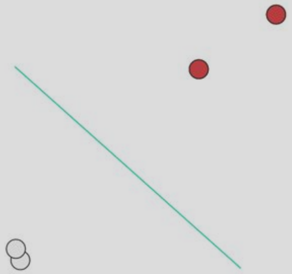
MAXIMUM CLIQUE



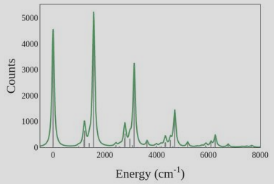
POINT PROCESS



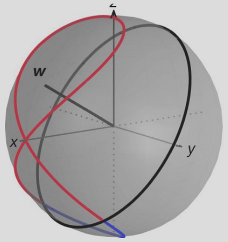
GRAPH SIMILARITY



VIBRONIC SPECTRA



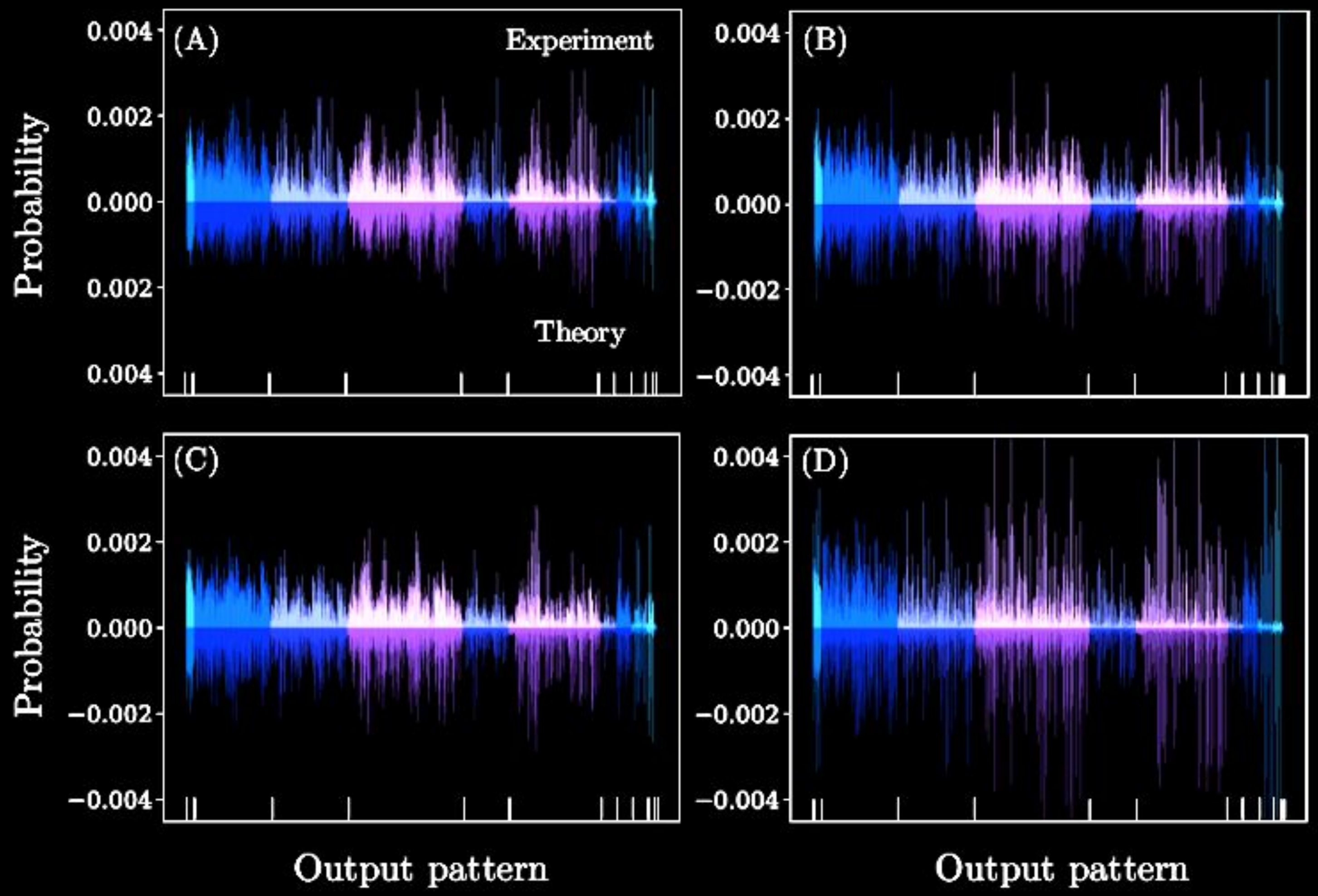
QUANTUM ENHANCED FEATURE



TUTORIALS AVAILABLE AT STRAWBERRYFIELDS.AI

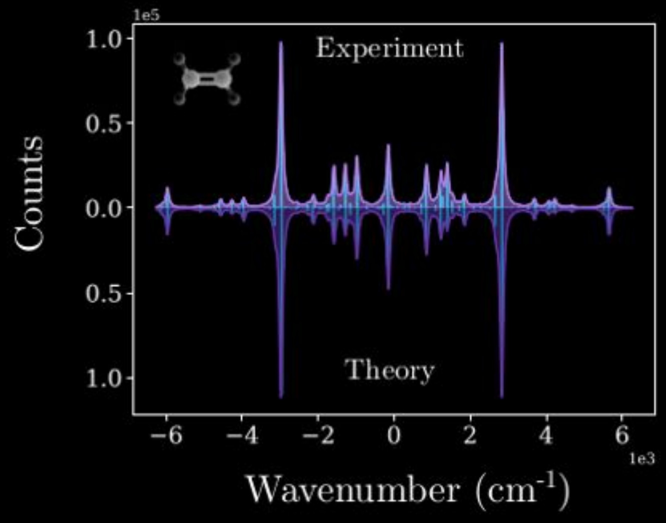
"Applications of near-term photonic quantum computers: Software and algorithms", T.R. Bromley et al., Quantum Science and Technology (2020)

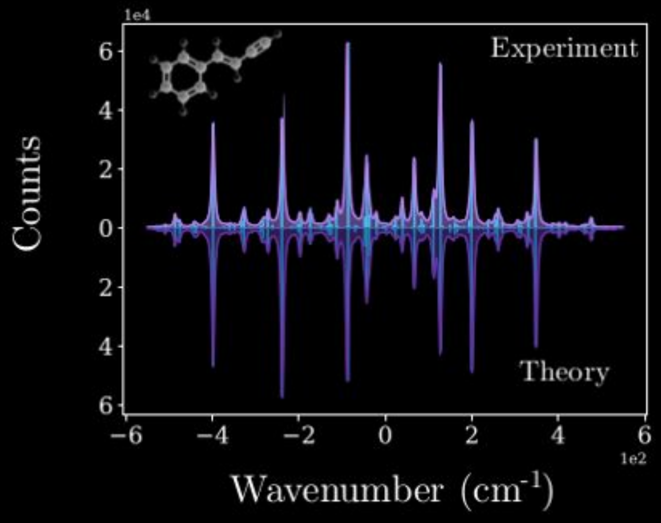
GAUSSIAN BOSON SAMPLING WITH RANDOM PARAMETERS



- Randomized benchmark for device performance
- Compare experimental and theoretical distributions
- Good quantitative and qualitative agreement between experiment and theory

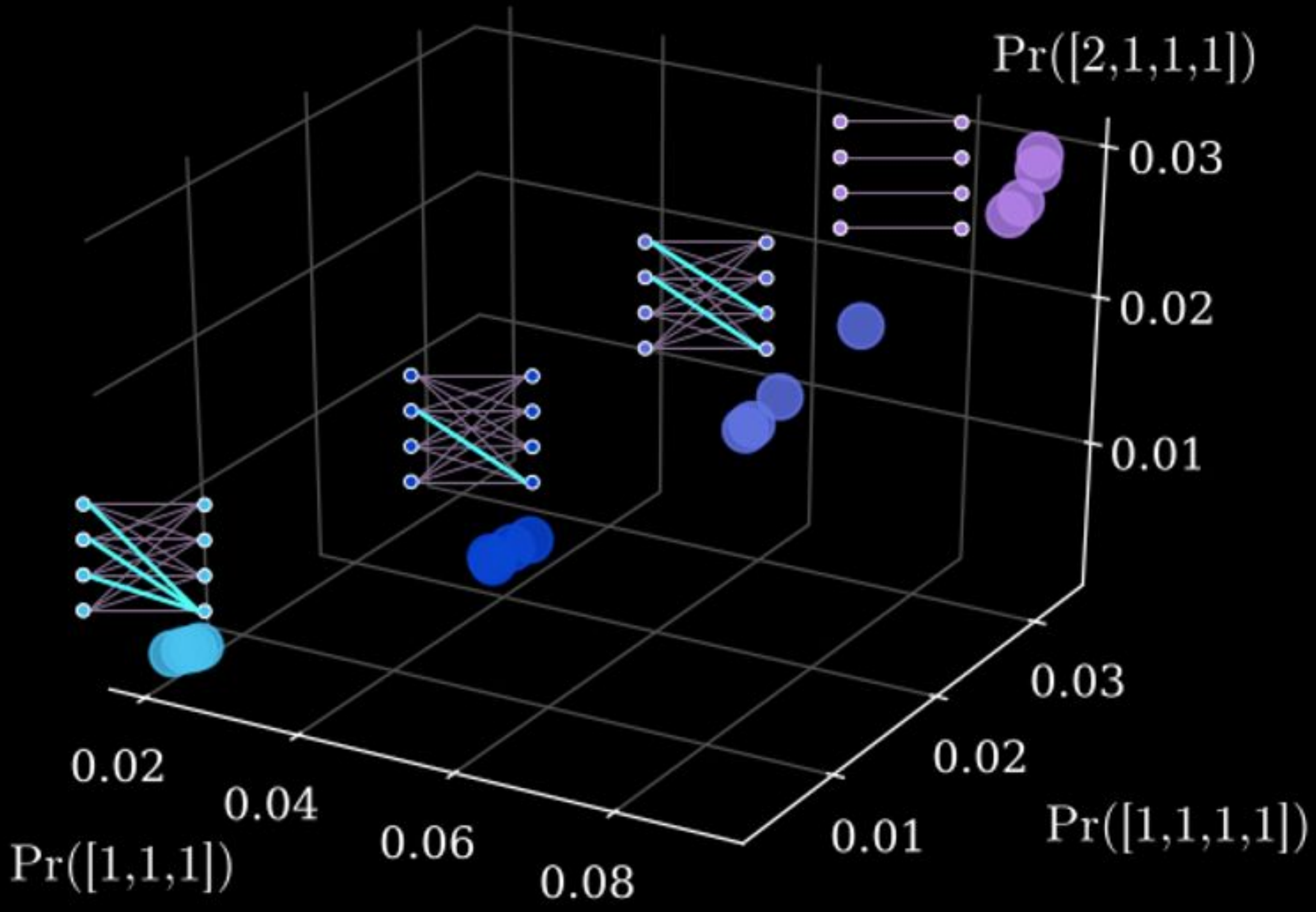
SIMULATION OF VIBRONIC SPECTRA





- Chemistry application unique to squeezing-based bosonic architecture
- Encode molecular structure directly in chip parameters

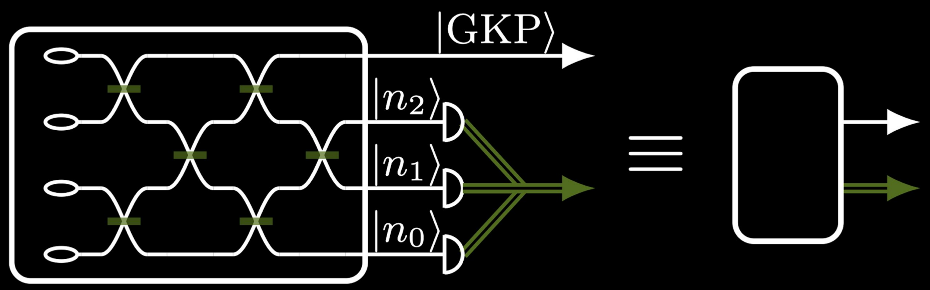
GRAPH SIMILARITY

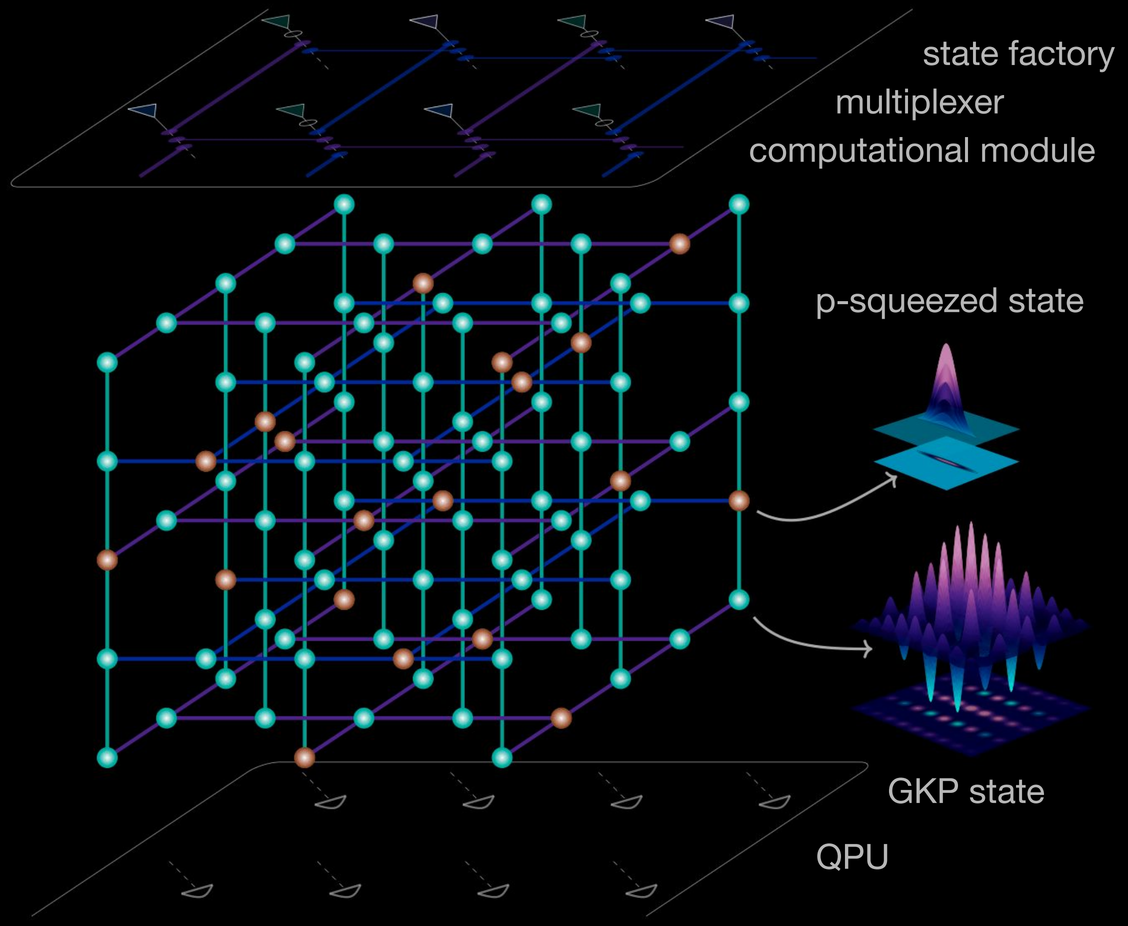


- Graph-structured data encoded into X8 chip
- Readout statistics classify different graphs
- Clustering shows X8 can distinguish different graph structures

GBS FOR FAULT TOLERANT QUANTUM COMPUTING

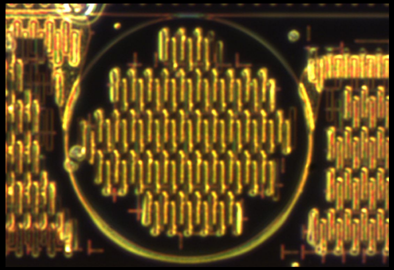
- Architecture relies on **GKP qubits**, enabling two layers of error correction
- X8 chips are the building blocks for synthesizing GKP qubits
- Squeezed states help deal with non-deterministic GKP sources

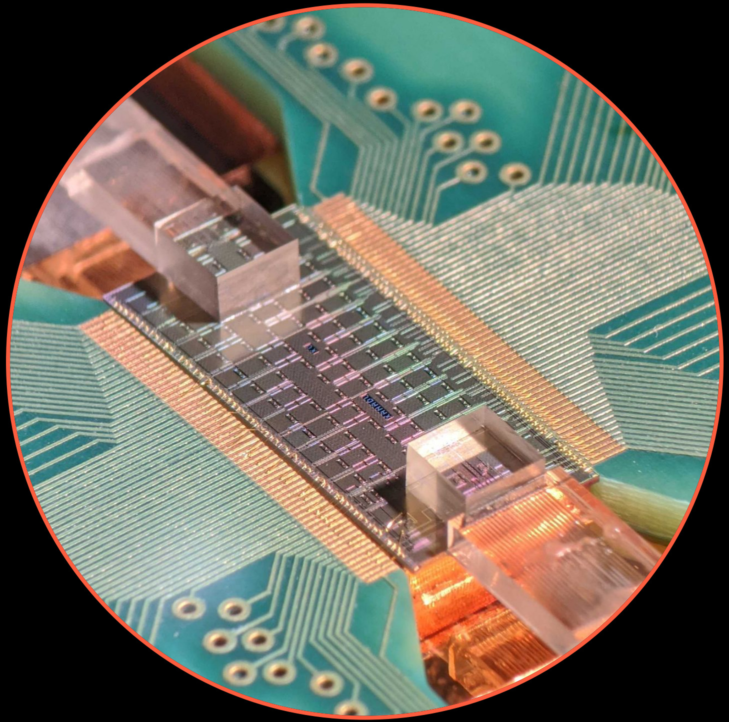


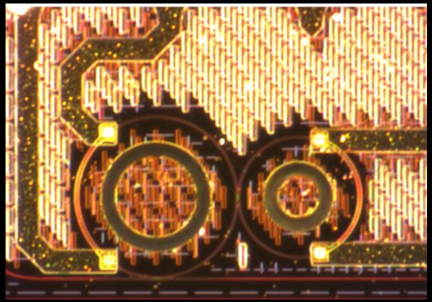


Blueprint for a Photonic Fault-Tolerant Quantum Computer
J. Eli Bourassa et al.
Quantum 5, 392 (2021)

NANOPHOTONIC SOURCES OF SQUEEZED LIGHT



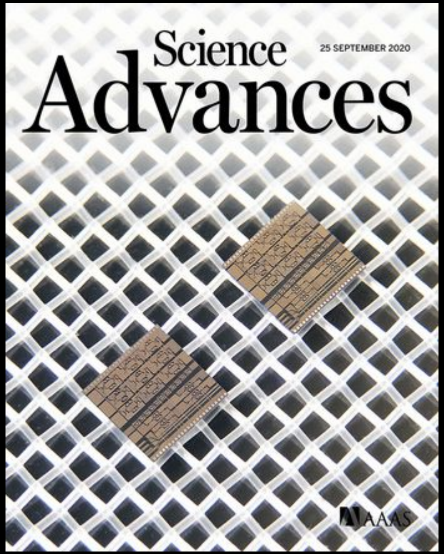


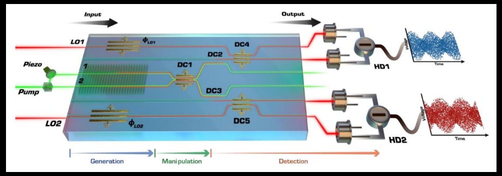


NANOPHOTONIC SQUEEZED LIGHT SOURCES

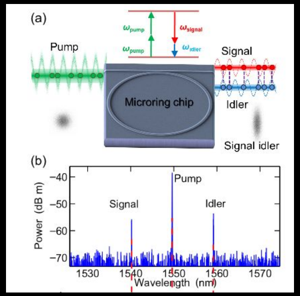
Wish list for integrated squeezing platform & device

	Low confinement PPLN	SiN OPOs above threshold	SiN microring below threshold
Nanophotonic system	X	✓	✓
Quadrature squeezing	✓	X	✓
Photon counting compatible	✓	X	✓
Single temporal mode	?	X	✓
No excess noise	✓	X	✓

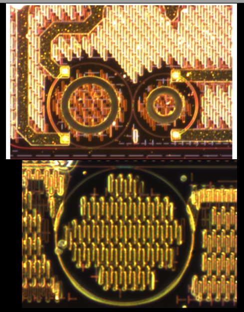




Lenzini *et al.*, Sci. Adv. 4, eaat9331 (2018)

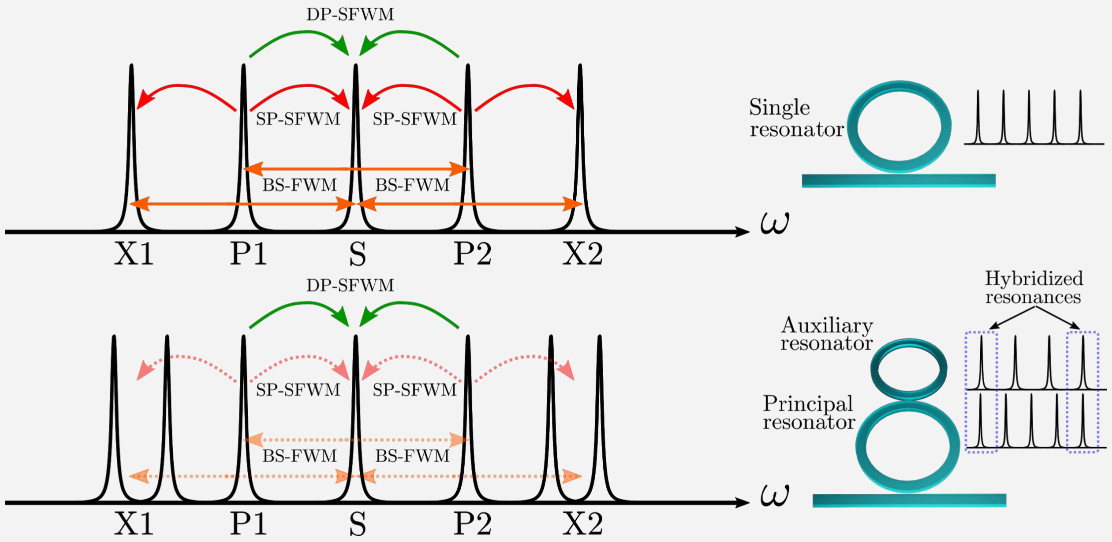


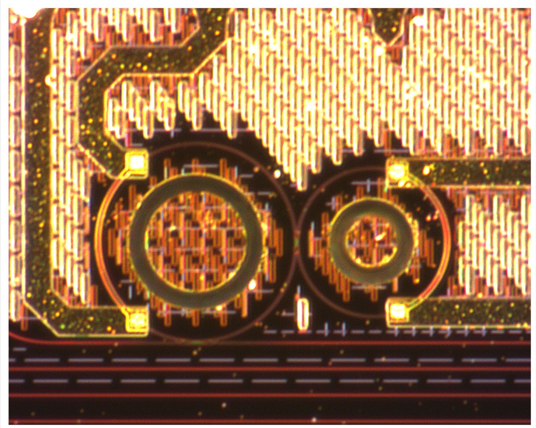
Dutt *et al.*, Phys. Rev. Applied 3, 044005 (2015)

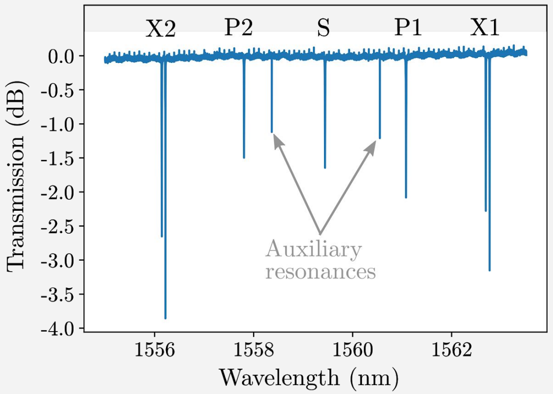


Vaidya *et al.*, Sci. Adv. eaba9186 (2020)
Zhang *et al.*, Nat. Comm. (2021)

NANOPHOTONIC MOLECULES FOR DEGENERATE SQUEEZING

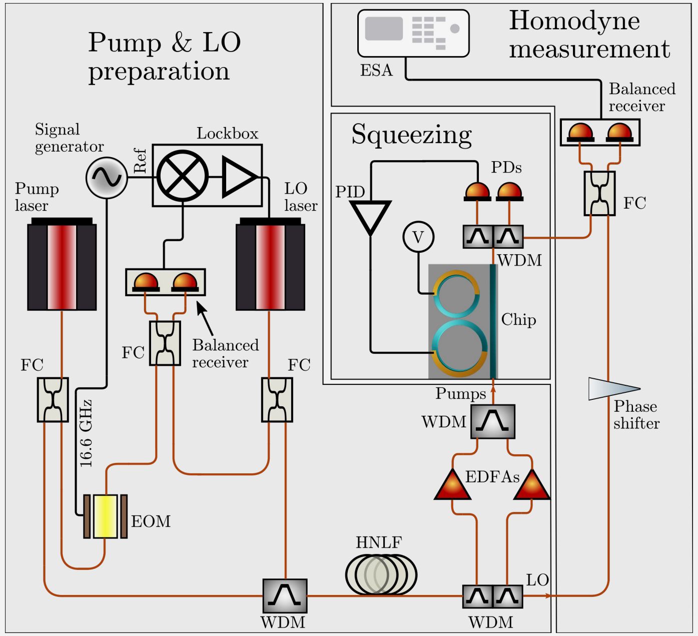




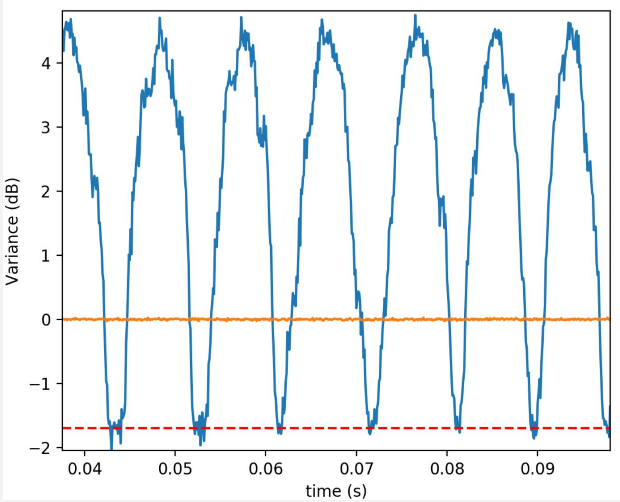


Zhang *et al.*, "Squeezed Light from a Nanophotonic Molecule"Nature Communications (2021)

NANOPHOTONIC MOLECULES FOR DEGENERATE SQUEEZING

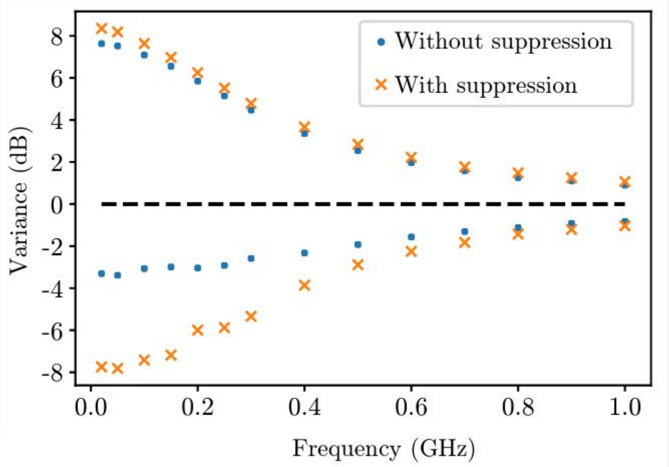


Similar setup to before, HNLF added to generate a tighter phase lock



Similar setup to before, HNLF added to generate a tighter phase lock

Record highest squeezing from a nanophotonic device!



Zhang *et al.*, "Squeezed Light from a Nanophotonic Molecule"Nature Communications (2021)

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