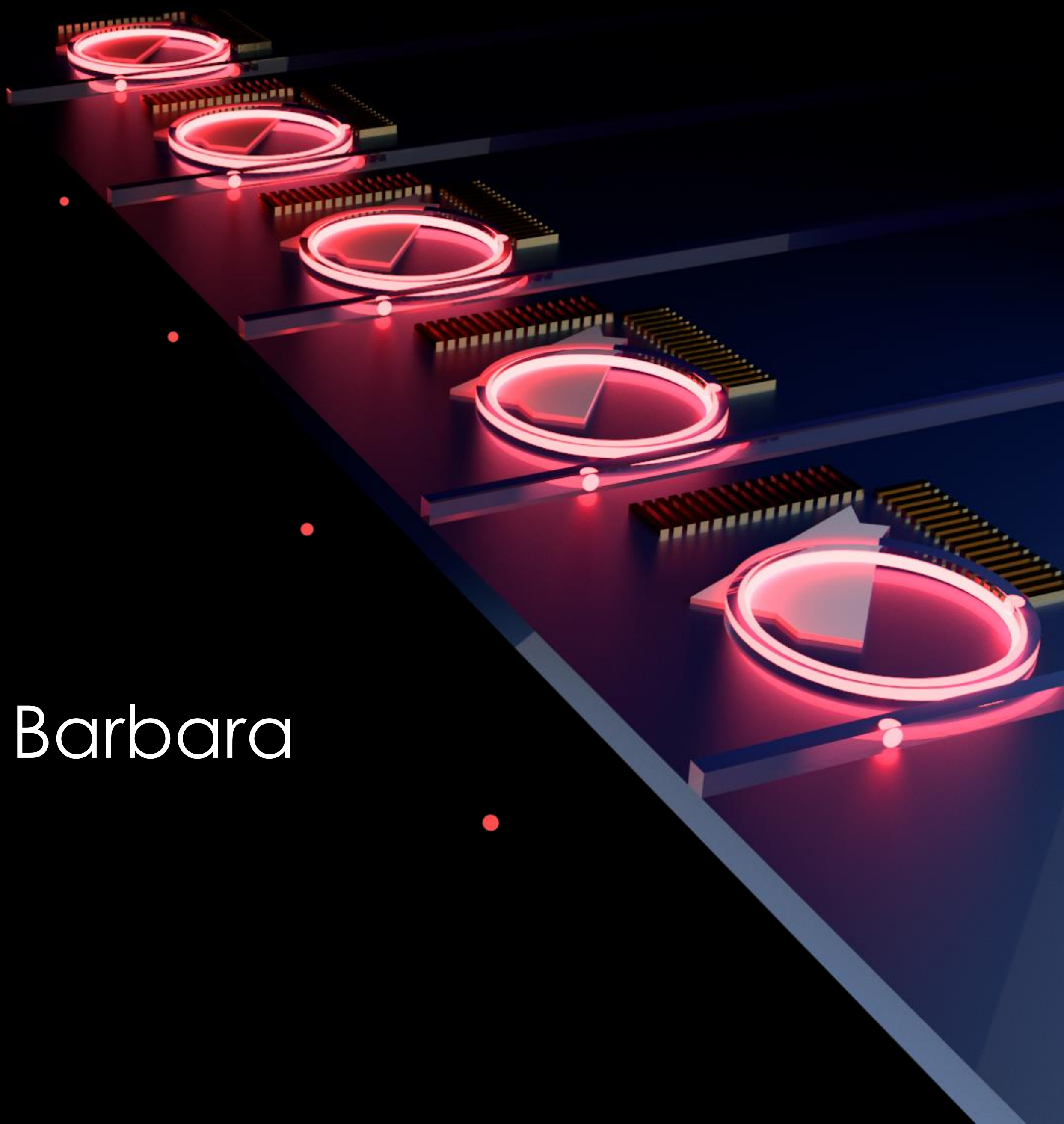
Progress in Quantum Computing, Communications, & Sensing with Integrated Photonics



Galan Moody

University of California Santa Barbara

Optica Webinar

December 4, 2023

PHYSICAL QUBIT ROADMAP FOR QUANTUM COMPUTER – HISTORY AND FUTURE

Source: Quantum Technologies report, Yole Développement, 2021

Graph below shows physical qubit roadmap (Note: for a quantum computer, 50 logical qubits minimum are required → it means 50 000 physical qubits)

Note! # of qubits isn't the best metric, but is just one metric of progress

[1] (Institute for Quantum Computing, Perimeter Institute for Theoretical Physics, MIT)
[2] (Los Alamos National lab)
[3] (TU Munich)
[4] (Oxford University, IBM, UC Berkeley, Stanford, MIT)

YOLE Intelligence

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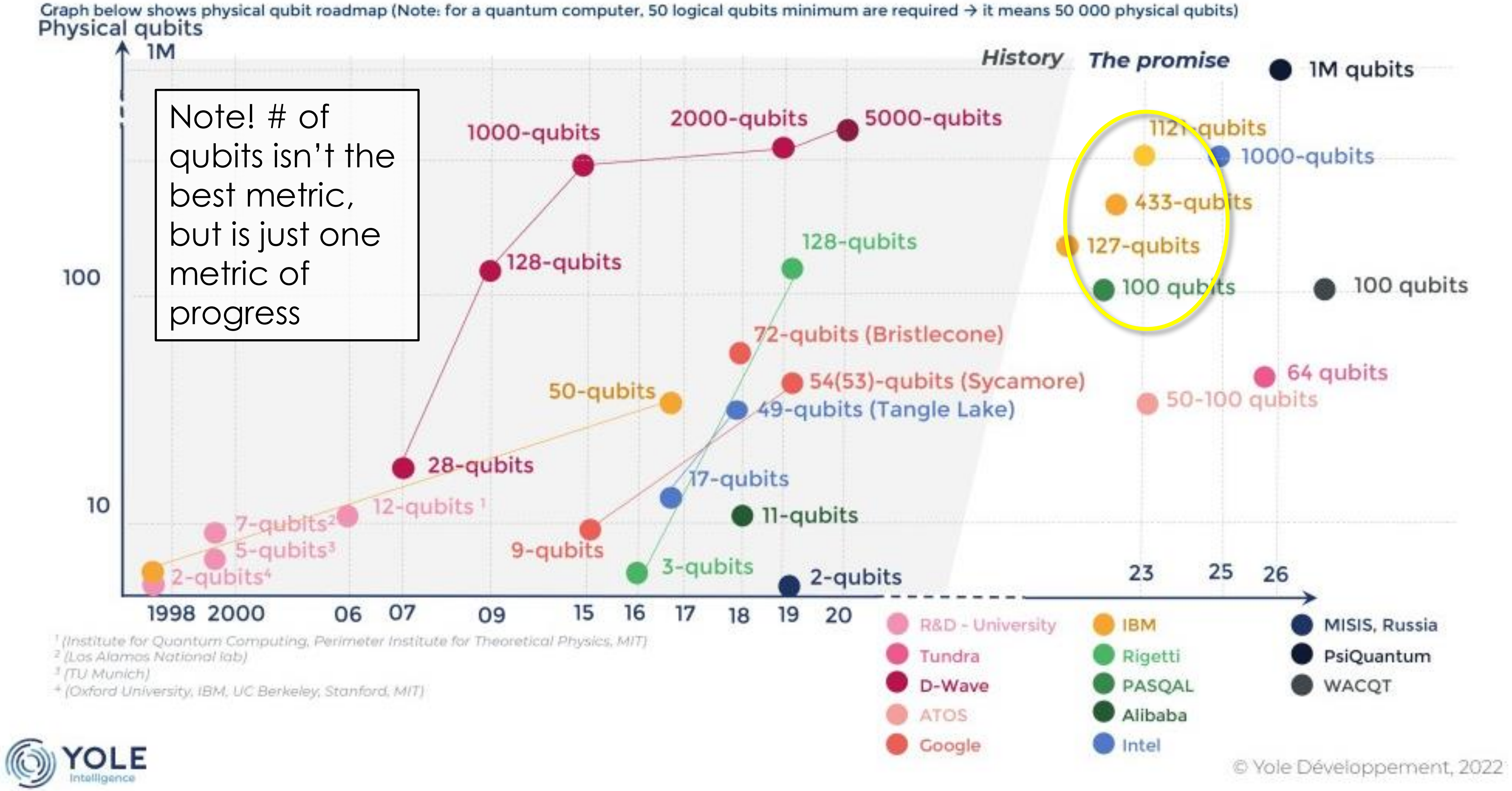

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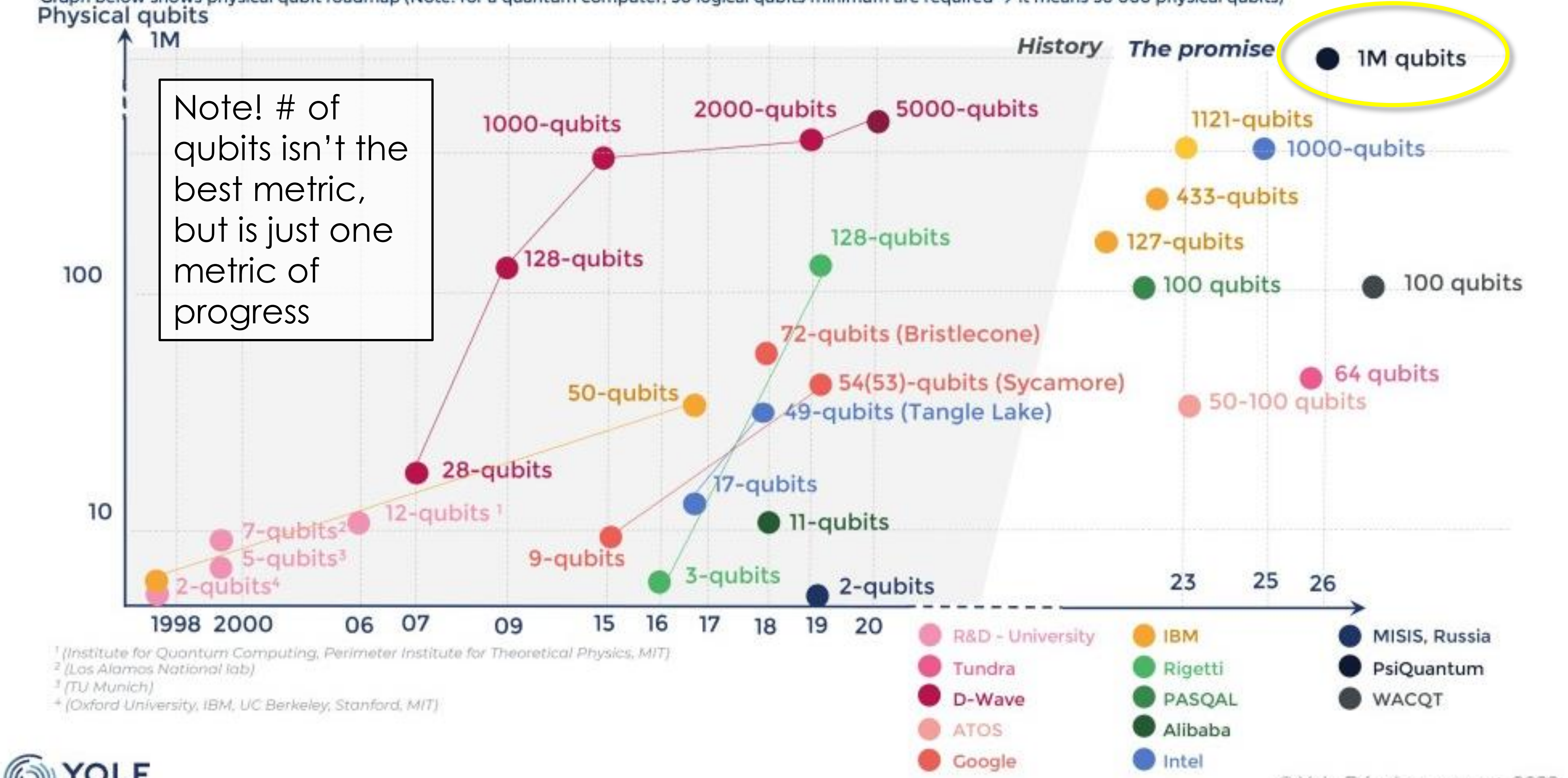

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YOLE Intelligence

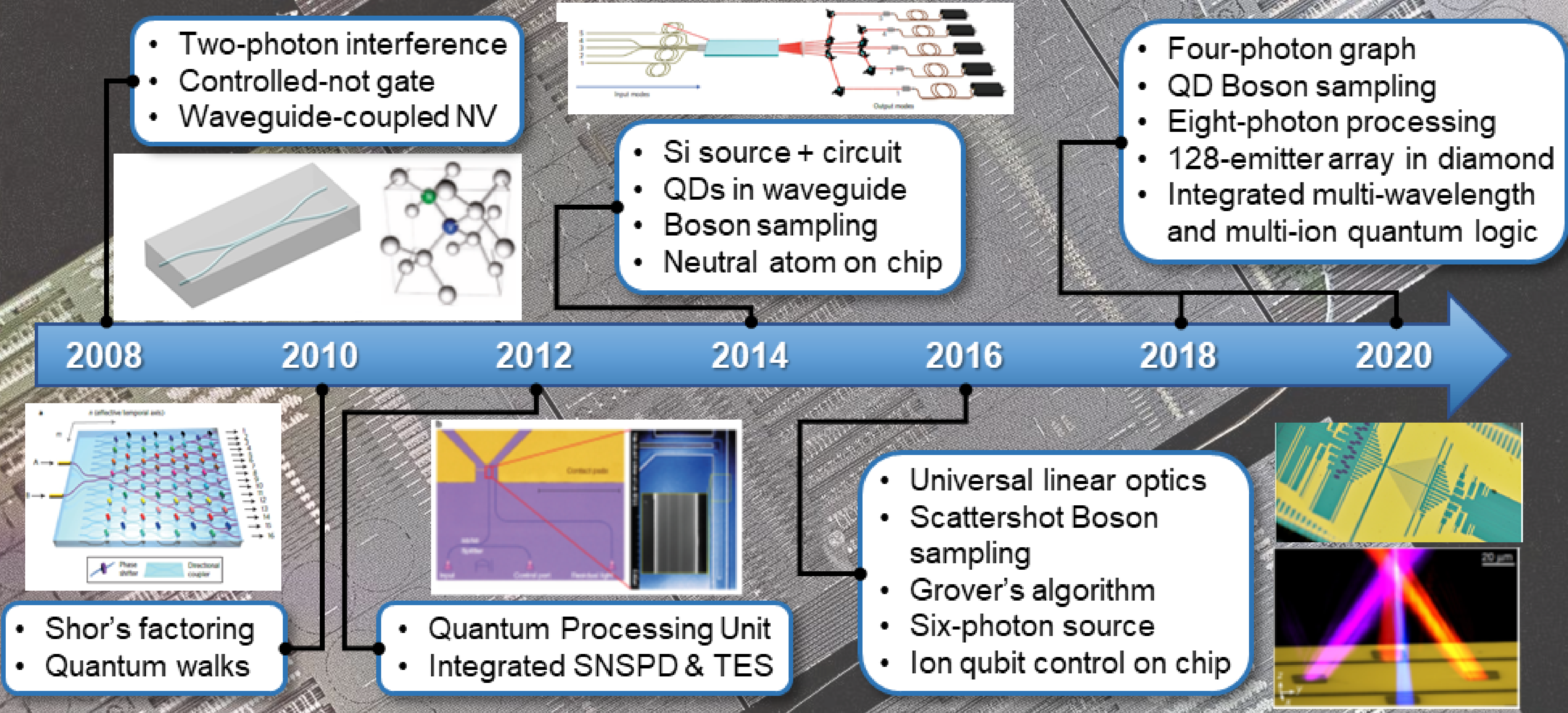
ROADMAP

OPEN ACCESS

RECEIVED
9 February 2021

2022 Roadmap on integrated quantum photonics

Galan Moody[1,*], Volker J Sorger[2], Daniel J Blumenthal[1], Paul W Juodawlkis[3], William Loh[3], Cheryl Sorace-Agaskar[3], Alex E Jones[4], Krishna C Balram[4], Jonathan C F Matthews[4], Anthony Laing[4],



- Two-photon interference
- Controlled-not gate
- Waveguide-coupled NV

- Shor's factoring
- Quantum walks

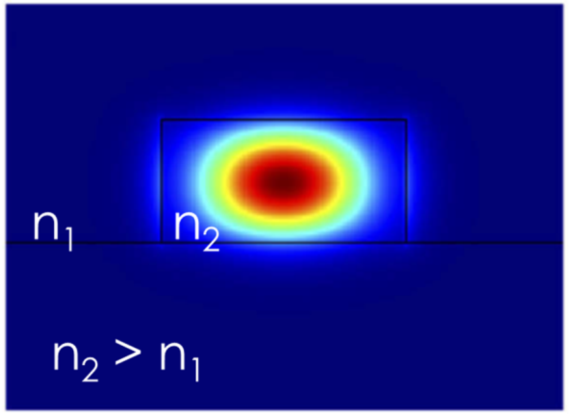
- Quantum Processing Unit
- Integrated SNSPD & TES

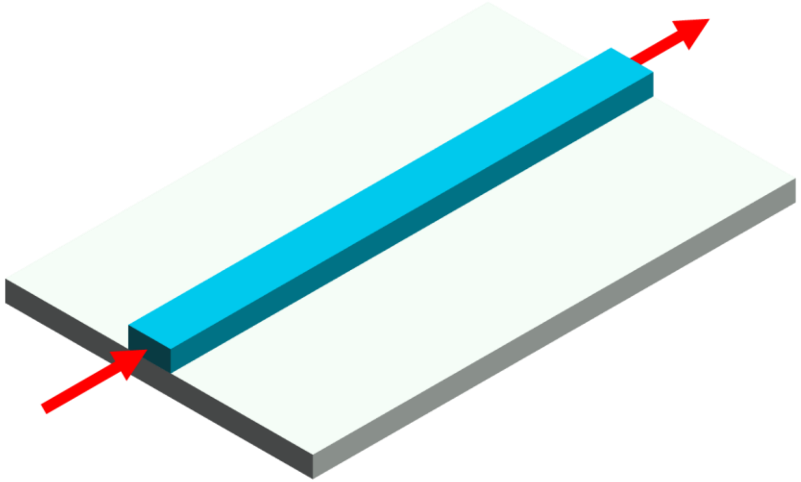
- Si source + circuit
- QDs in waveguide
- Boson sampling
- Neutral atom on chip

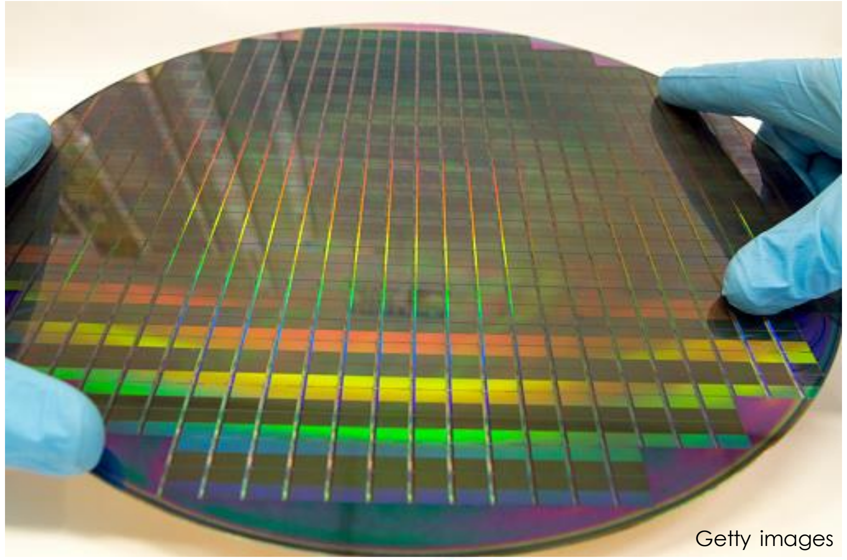
- Universal linear optics
- Scattershot Boson sampling
- Grover's algorithm
- Six-photon source
- Ion qubit control on chip

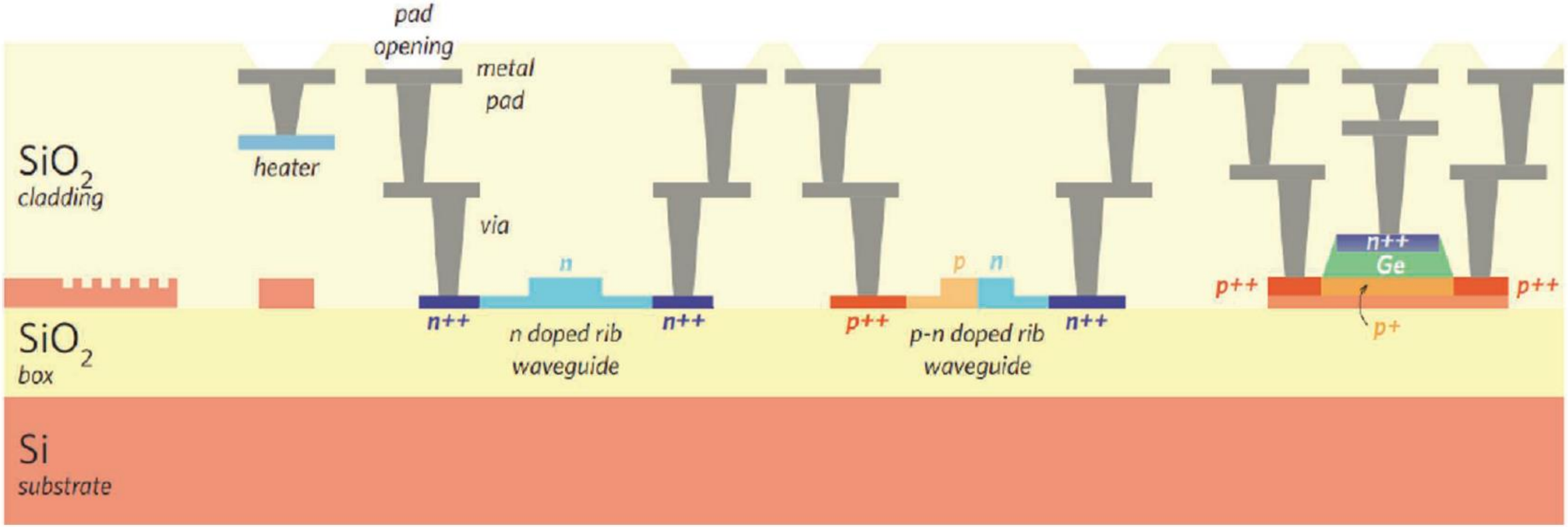
- Four-photon graph
- QD Boson sampling
- Eight-photon processing
- 128-emitter array in diamond
- Integrated multi-wavelength and multi-ion quantum logic

Leveraging the Mature CMOS Process for Silicon Photonics

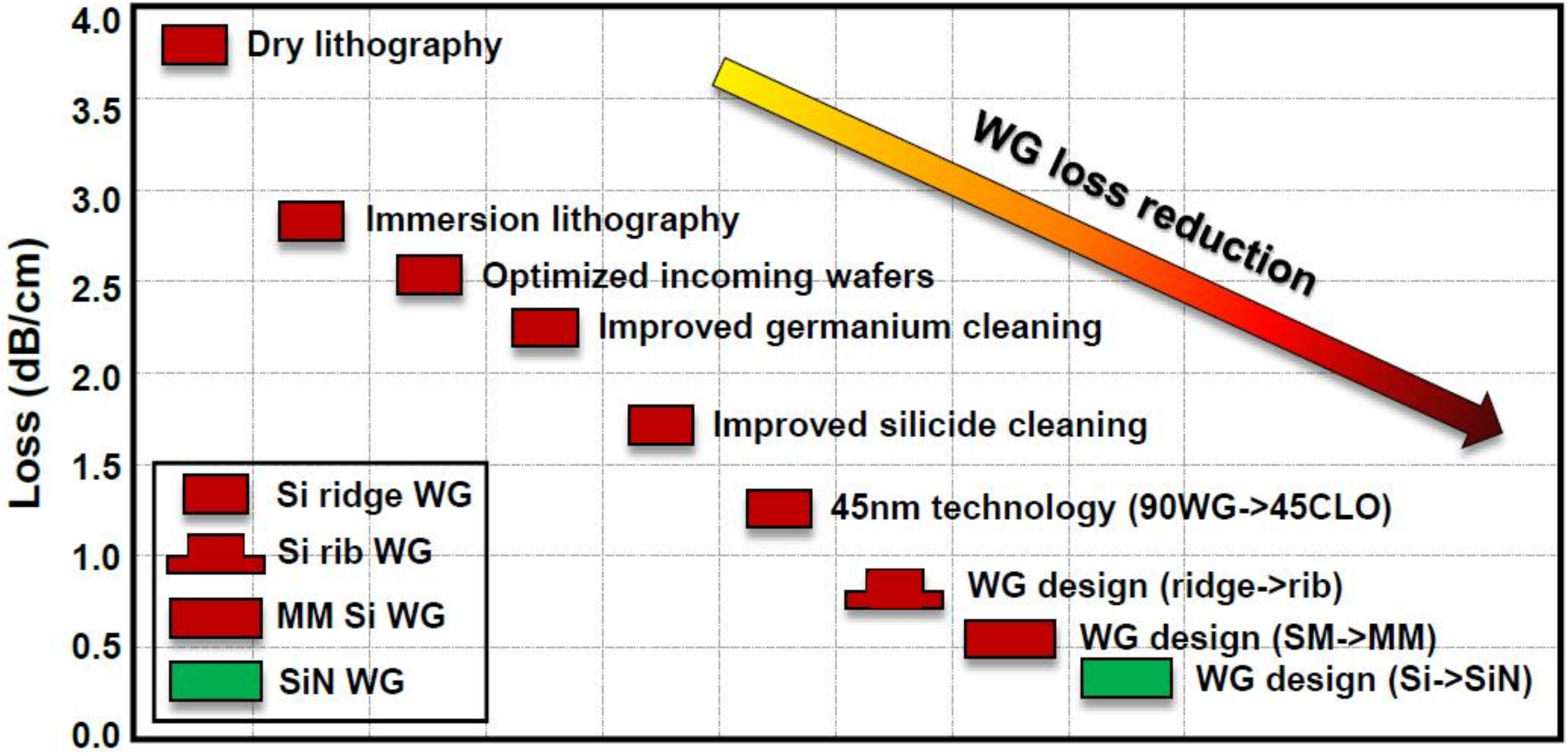




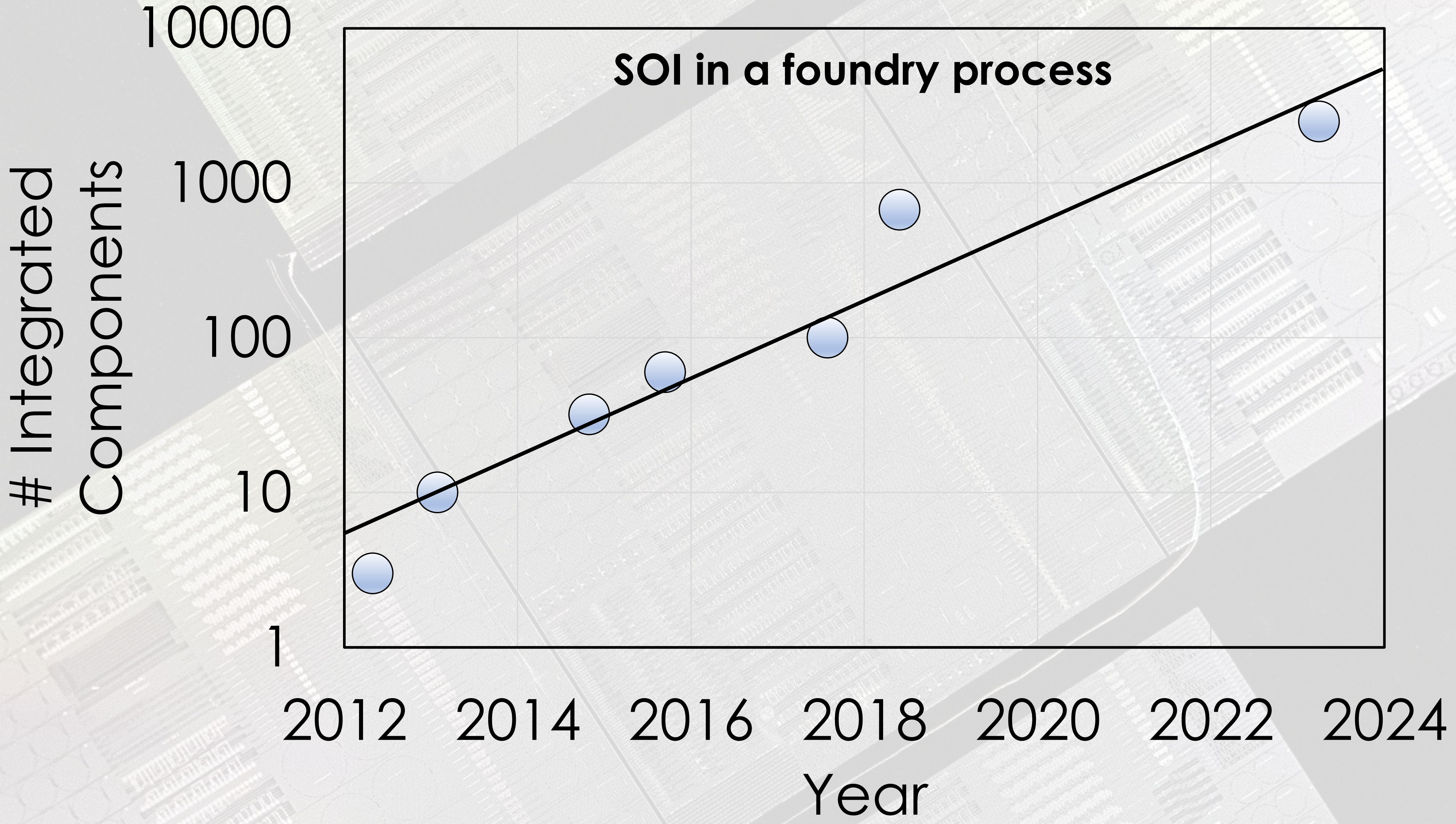


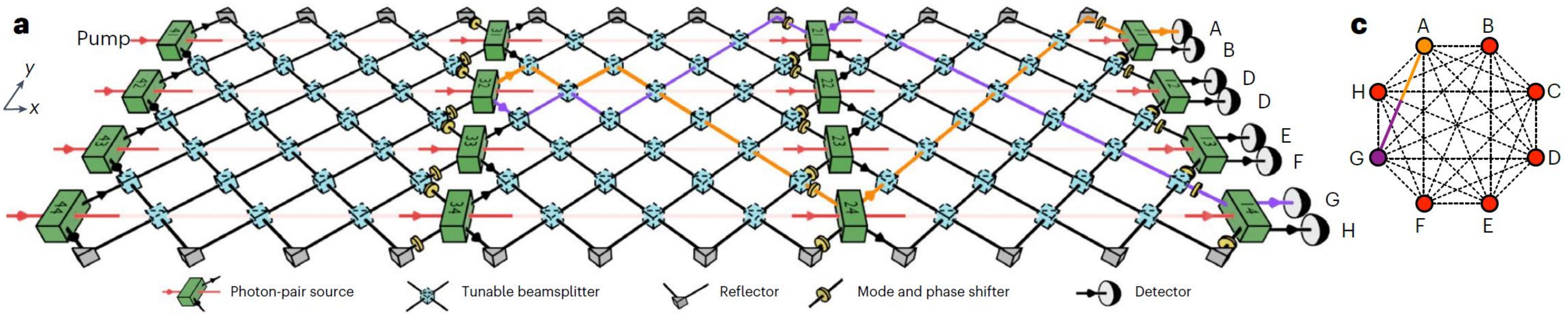


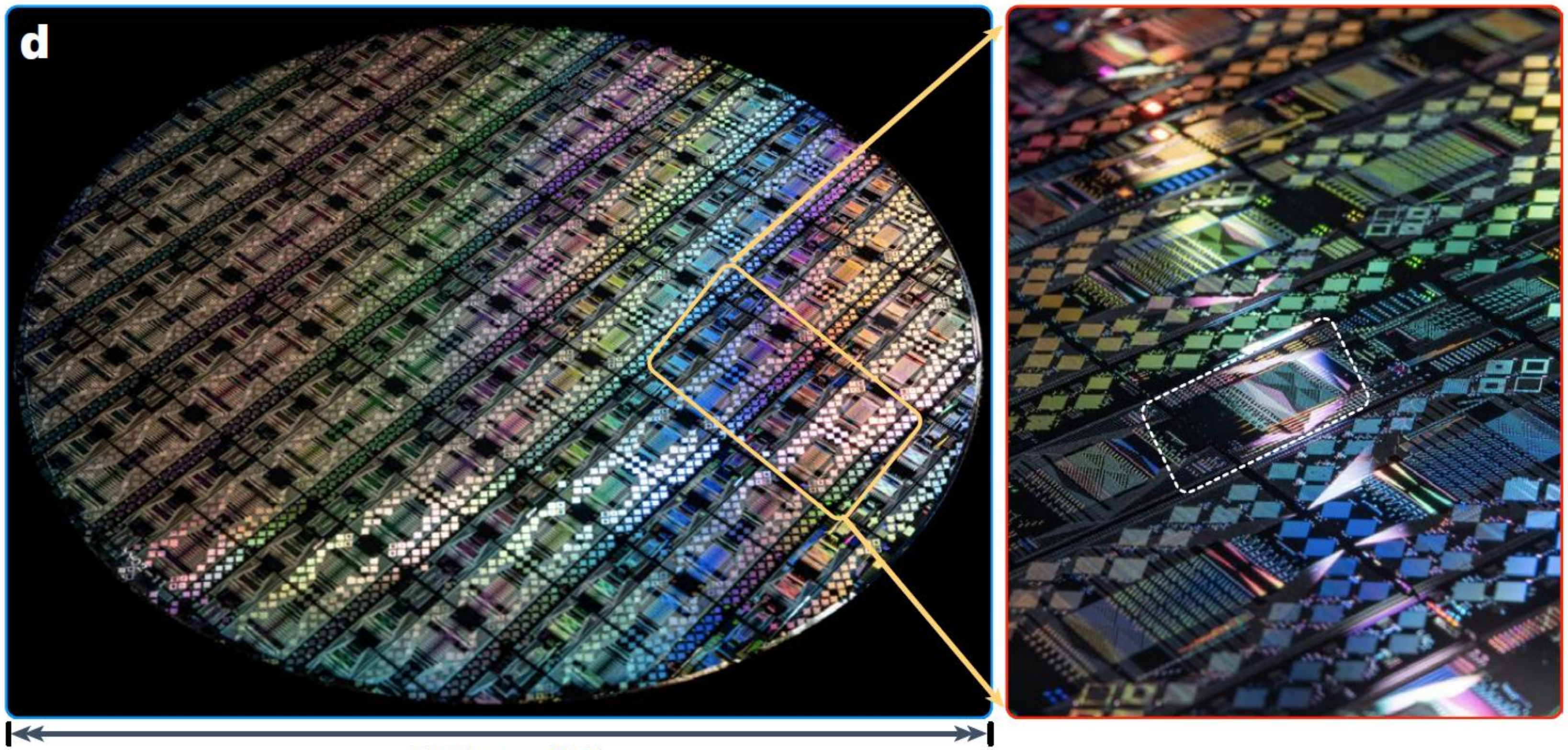
Co-Packaging Microelectronics and Photonics at GF



Global Foundries, FiO/LS Conference (2020)


SOI in a foundry process
Integrated Components
10000
1000
100
10
1
2012
2014
2016
2018
2020
2022
2024
Year



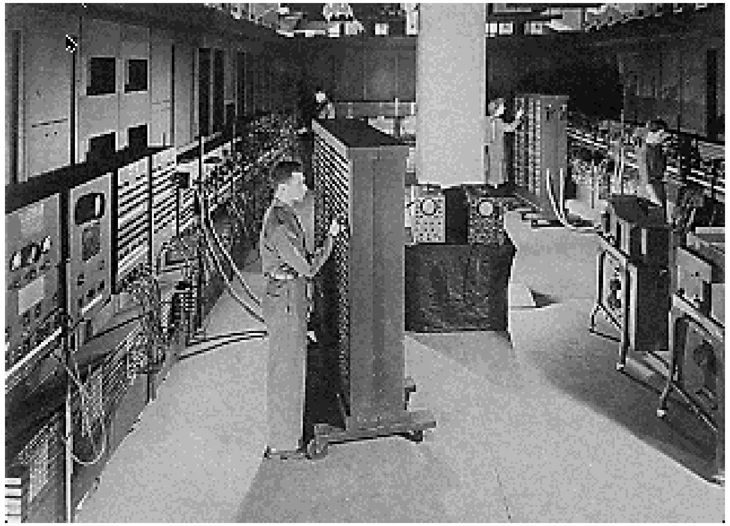


Generate up to 4-photon, 3-dimensional quantum states on chip with tunable PICs and off-chip lasers and detectors

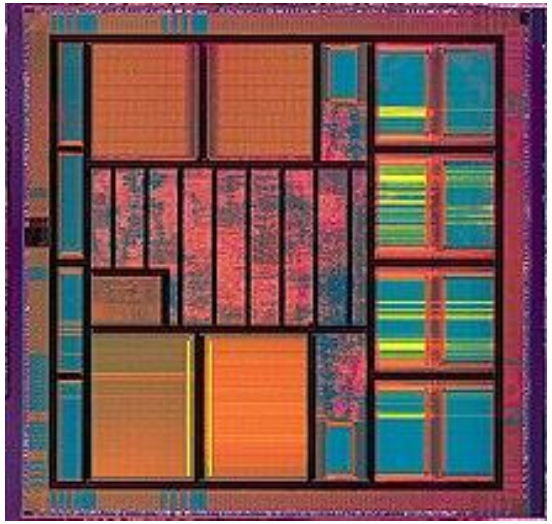
Bristol/PsiQuantum/PKU, Nature Photonics (2023)

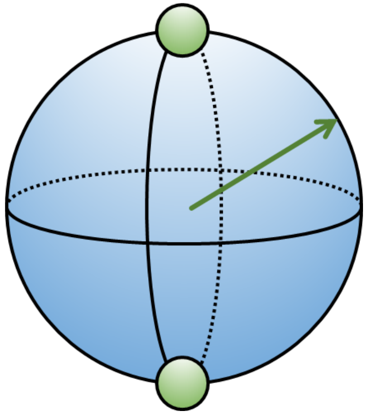
How do we go from a few qubits to a useful quantum system?

ENIAC
(1946)

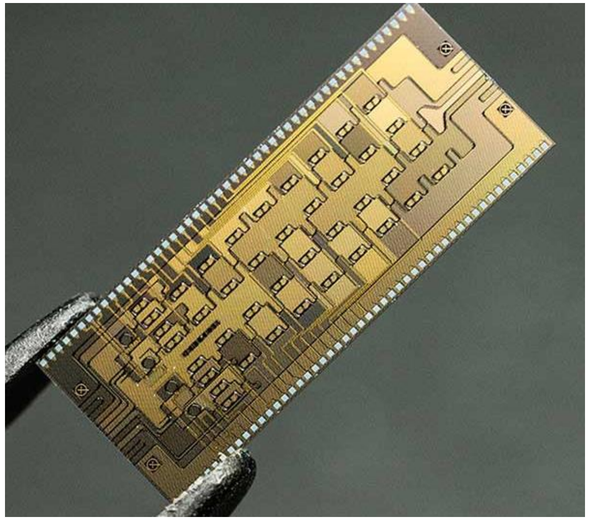


VLSI
(1980s)



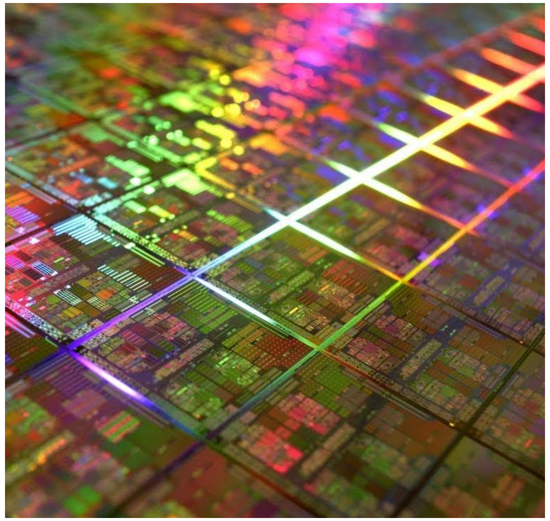


Quantum
Advantage
(2020s)

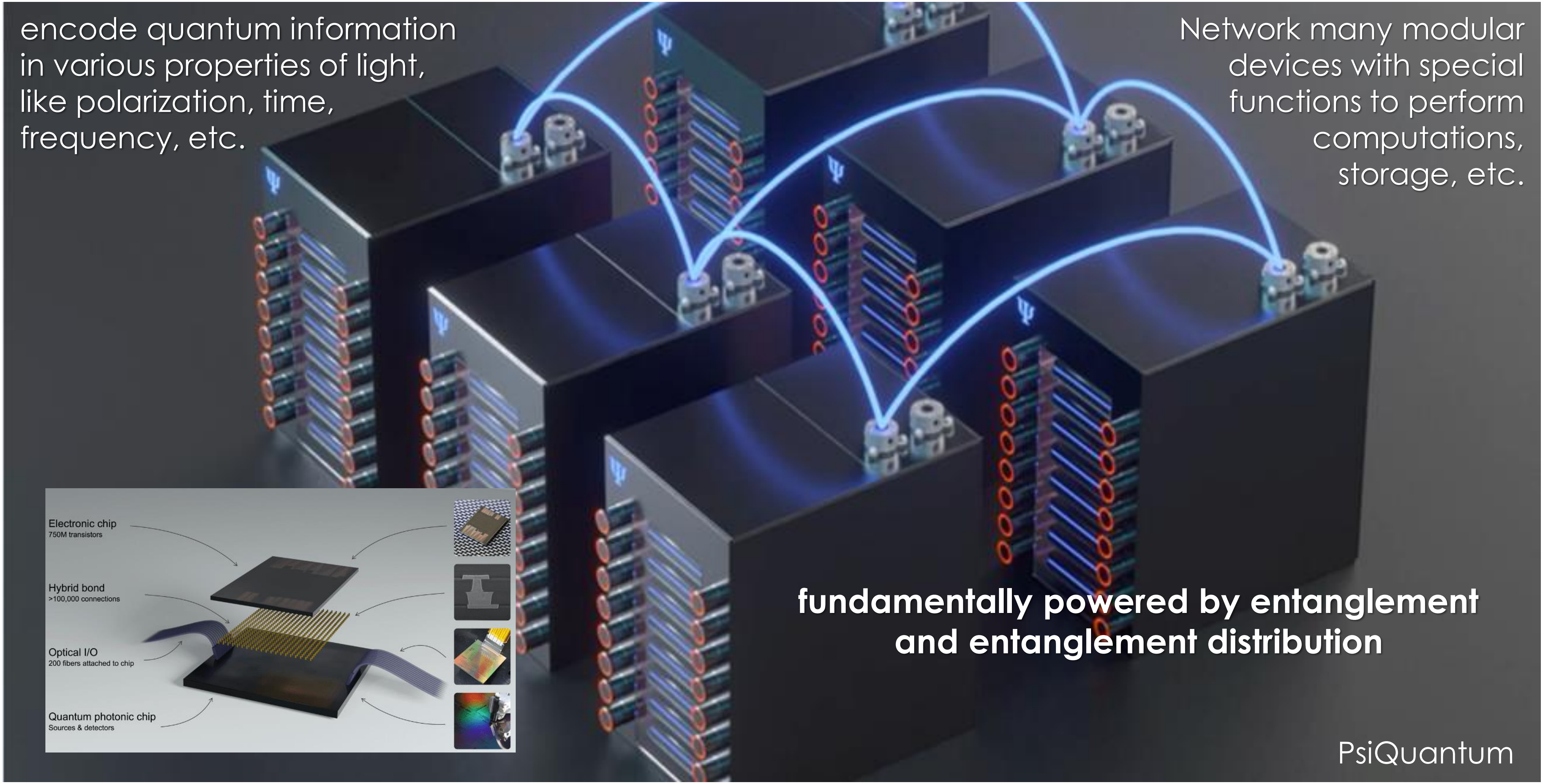


xanadu

Useful QC
(?)



Quantum Computers → Quantum Data Centers



encode quantum information in various properties of light, like polarization, time, frequency, etc.

Network many modular devices with special functions to perform computations, storage, etc.

fundamentally powered by entanglement and entanglement distribution

PsiQuantum

- Introduction to Optical Qubits
- How We Generate Optical Qubits with Integrated Photonics
- Some Near-Term Applications: QKD, Entanglement Distribution, Quantum Sensing
- Outlook

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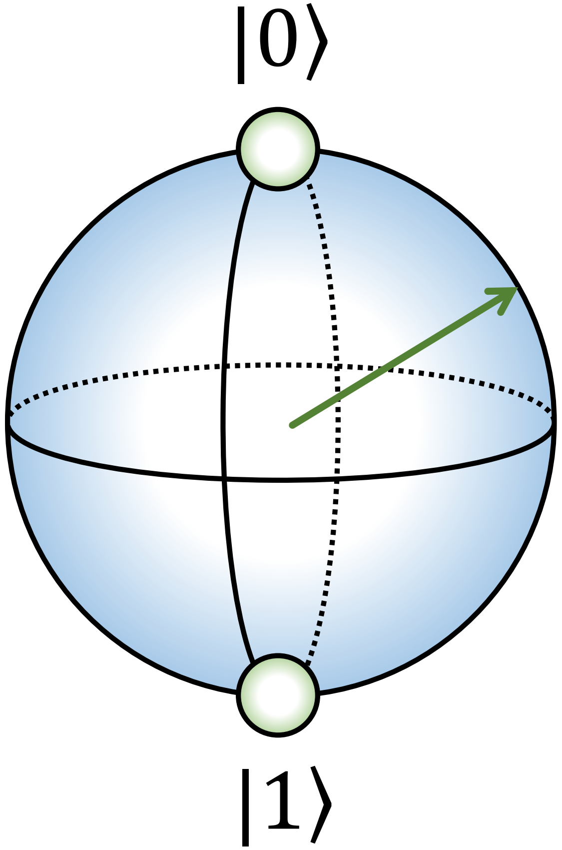
Bits vs. Qubits

Classical Bit

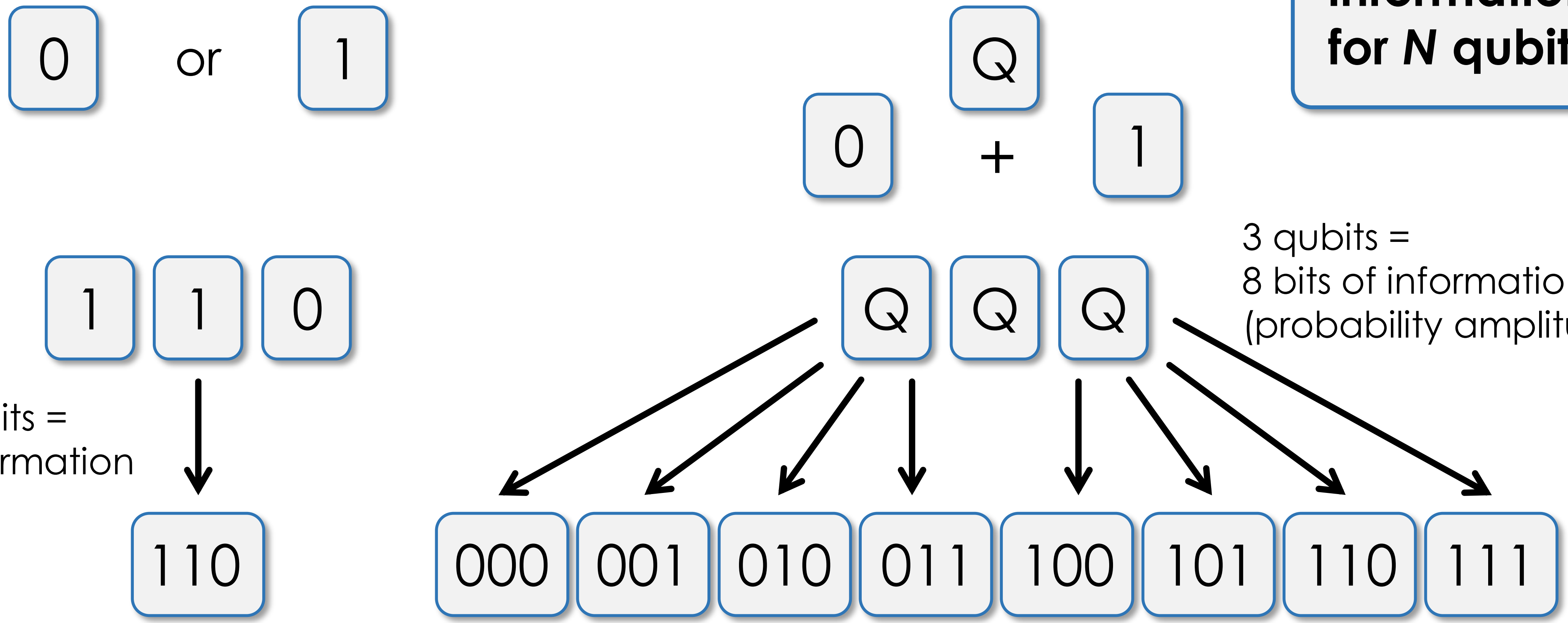
Qubit



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

3 Bits vs. 3 Qubits

2^N bits of information for *N* qubits



Classical

0 or 1

1 1 0

3 classical bits =
3 bits of information

110

Quantum

Q

0 + 1

Q Q Q

3 qubits =
8 bits of information
(probability amplitudes)

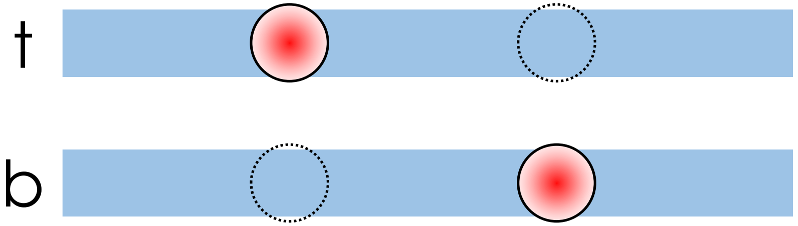
000 001 010 011 100 101 110 111

Photonic Qubits

the photon itself is not a qubit, but there are many ways to encode a qubit with a photon

- ***Path qubit***

  one photon across two modes



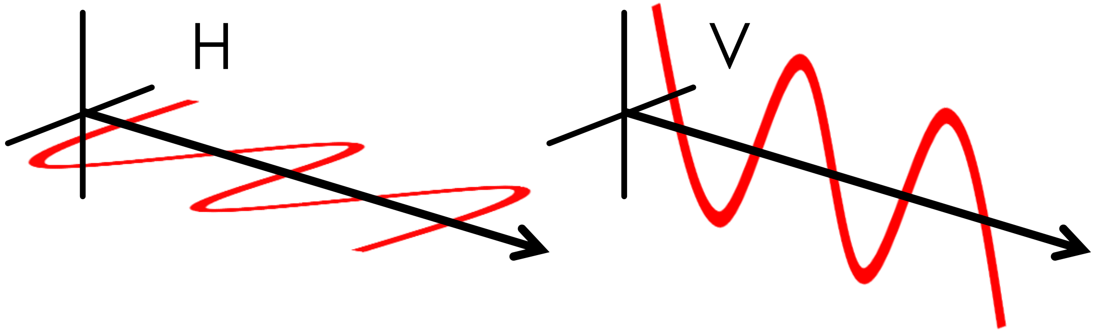
$|0\rangle = |1_t 0_b\rangle$

$|1\rangle = |0_t 1_b\rangle$

$$|\psi_{qubit}\rangle = \alpha|t\rangle + \beta e^{i\phi}|b\rangle$$

- ***Polarization qubit***

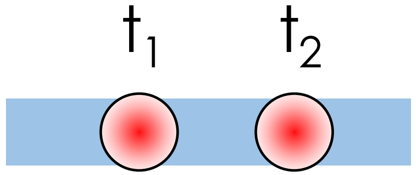
  orientation of electric field



$$|\psi_{qubit}\rangle = \alpha|H\rangle + \beta e^{i\phi}|V\rangle$$

- ***Time-bin qubit***

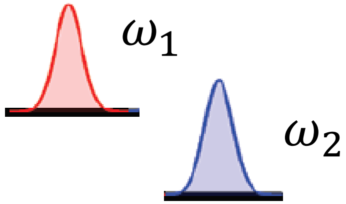
  one photon across two time windows



$$|\psi_{qubit}\rangle = \alpha|t_1\rangle + \beta e^{i\phi}|t_2\rangle$$

- ***Frequency-bin qubit***

  one photon across two frequency modes



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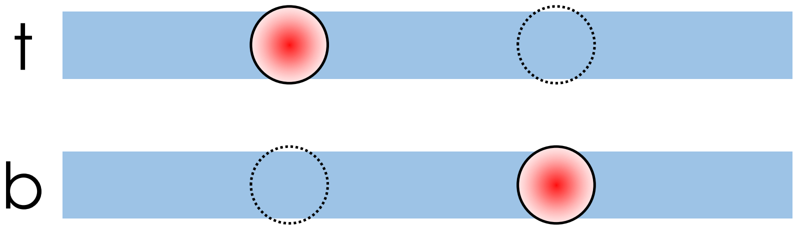

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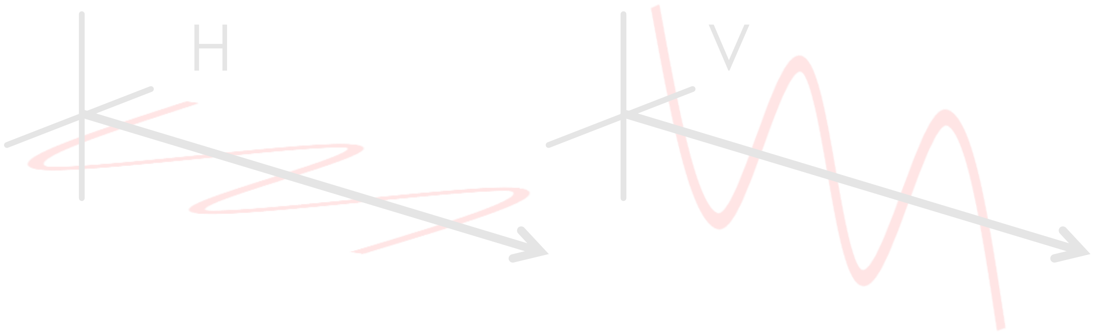

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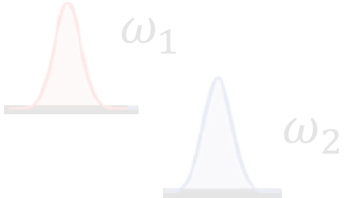

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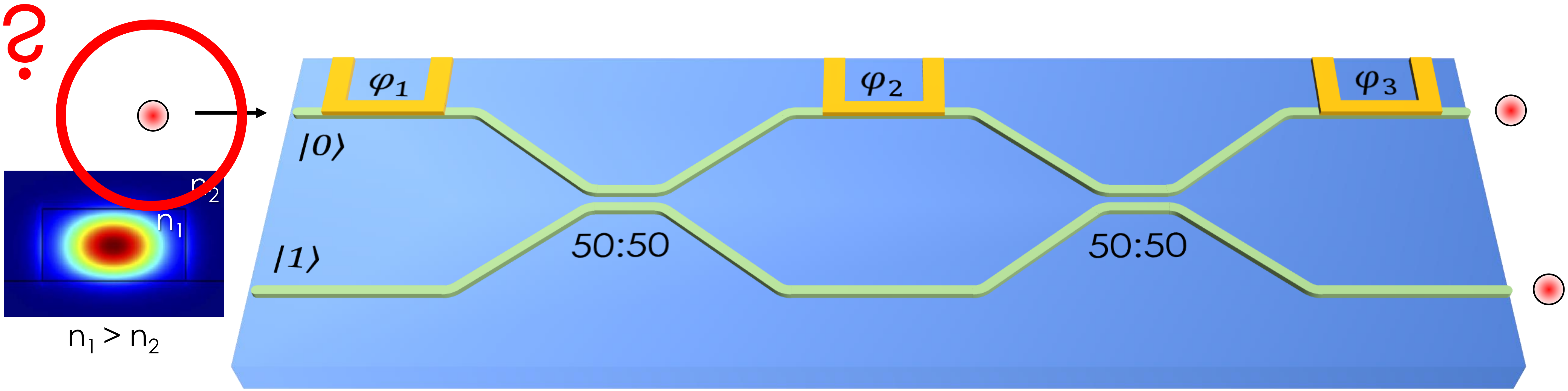
Integrated Photonic Path-Encoded Qubits



manufacturable technology

1,000’s components per chip with high reliability

high-fidelity operations

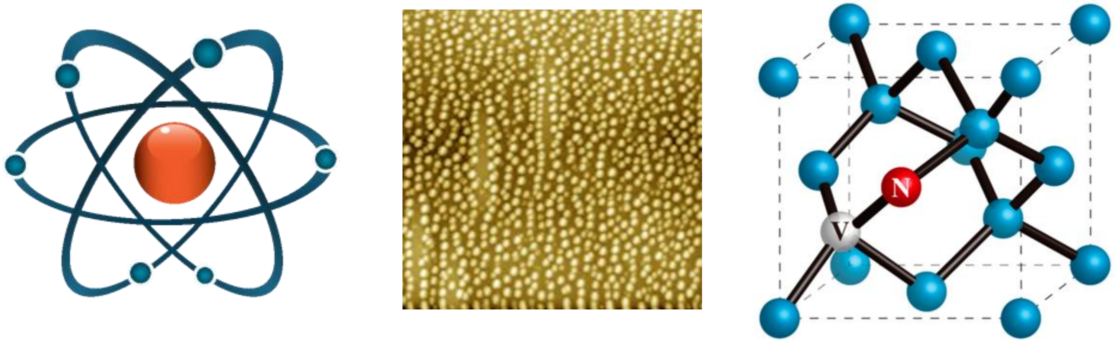
arbitrary single-qubit gates and entangling operations

loss-tolerant

ancilla qubits for heralded measurements and entanglement

Nonlinear Photonics for Quantum Light Generation

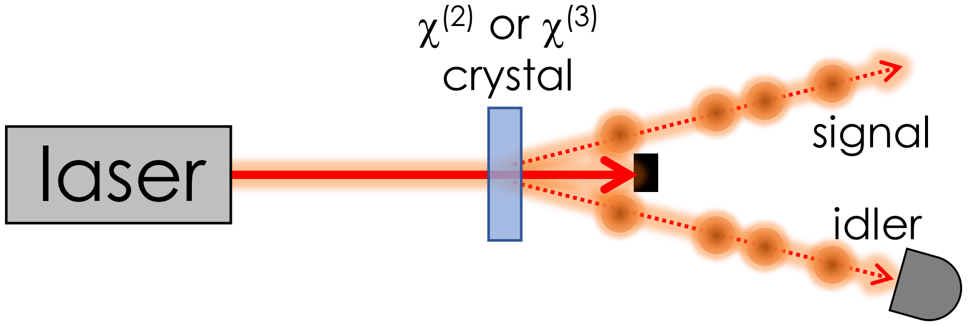
Single Photon Emitters
(Atoms, QDs)



Excite a two-level system, collect spontaneous fluorescence

- ✓ Emits one photon at a time (on-demand)
- ✓ Brightness decoupled from purity, indistinguishability
- ✗ Difficult to get high collection efficiency
- ✓ Apps that require one emitter (QKD)
- ✗ Apps that require more (computing)

Nonlinear Optics



- ✓ Pure, indistinguishable, heralded
- ✓ High rates (10^9 pairs s^{-1})
- ✓ Scalable: can make 1000’s of identical copies on a wafer
- ✗ Nonlinear optics:
  - o Pump harder to get more photons = higher chance of many pairs in a time window ☹

Moody, Chang, Steiner, Bowers, AVS Quantum Science **2**, 041702 (2020)

Comparison of Photonic Materials

Material	$\chi^{(2)}$ [pm/V]	$\chi^{(3)}$ [cm^2/W]	Refractive Index @ 1550 nm	Bandgap [nm]	Scalability [mm]
SOI	-	6.5×10^{-14}	~3.4	1100	300
SiNOI	-	2.5×10^{-15}	~2	238	300
LNOI	26	5.3×10^{-15}	~2.14	310	150
AlGaAsOI	180	2.6×10^{-13}	~3.4	625	200
GaNOI	9	1.2×10^{-14}	~2.3	365	-
InGaPOI	263	1.1×10^{-13}	~3.2	650	200
Ta_2O_5	-	6.2×10^{-15}	~2	320	100
AlN-OI	1	2.3×10^{-15}	~2	205	300
SiC-OI	12	1×10^{-14}	~2.7	383	100

See: Moody, Chang, Steiner, Bowers, AVS Quantum Science **2**, 041702 (2020)
Baboux, Moody, Ducci, Nonlinear integrated quantum photonics with AlGaAs, Optica **10**, 917-931 (2023)

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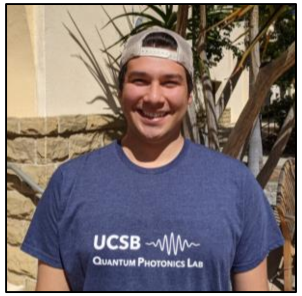
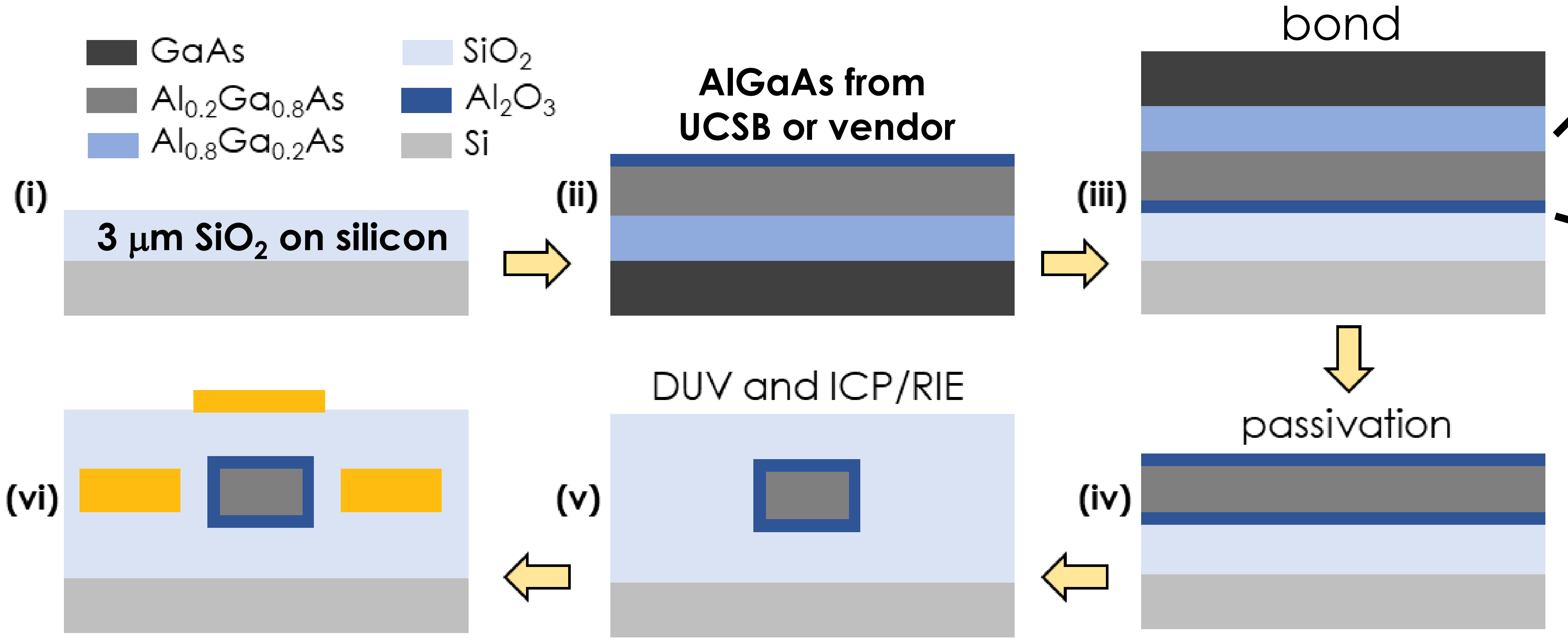
Compound Semiconductor-on-Insulator (CSOI)

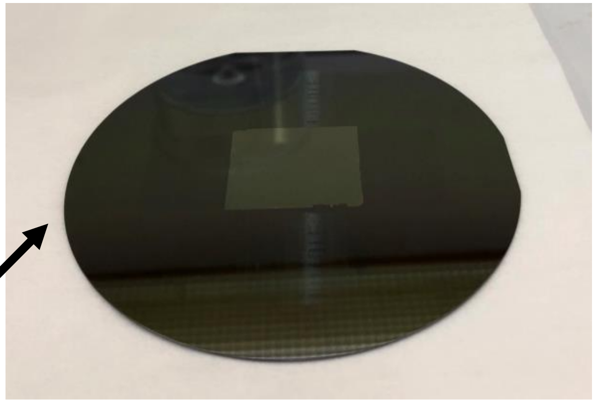

Lilli Thiel

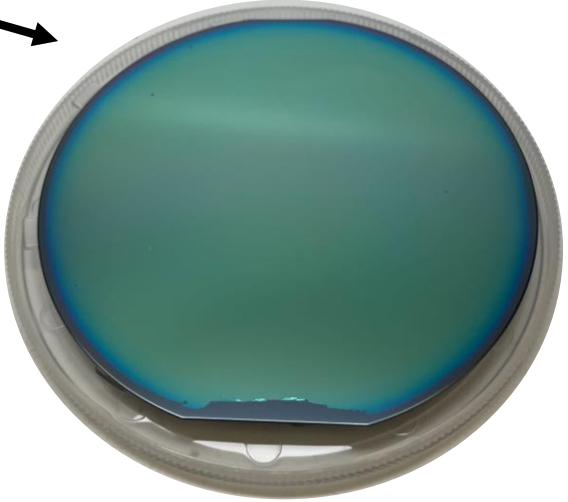

Nick Lewis


Josh Castro



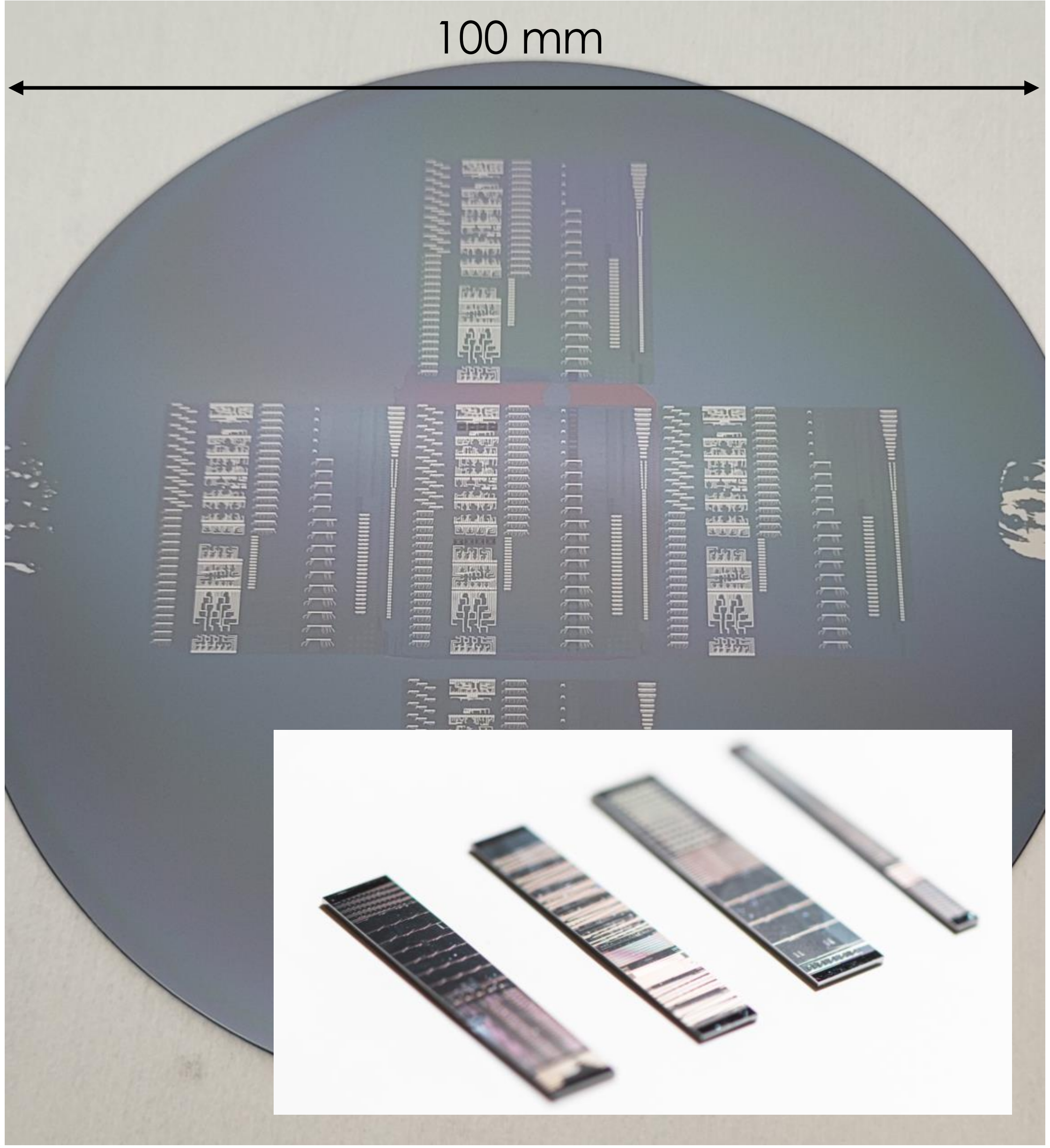
chip-scale

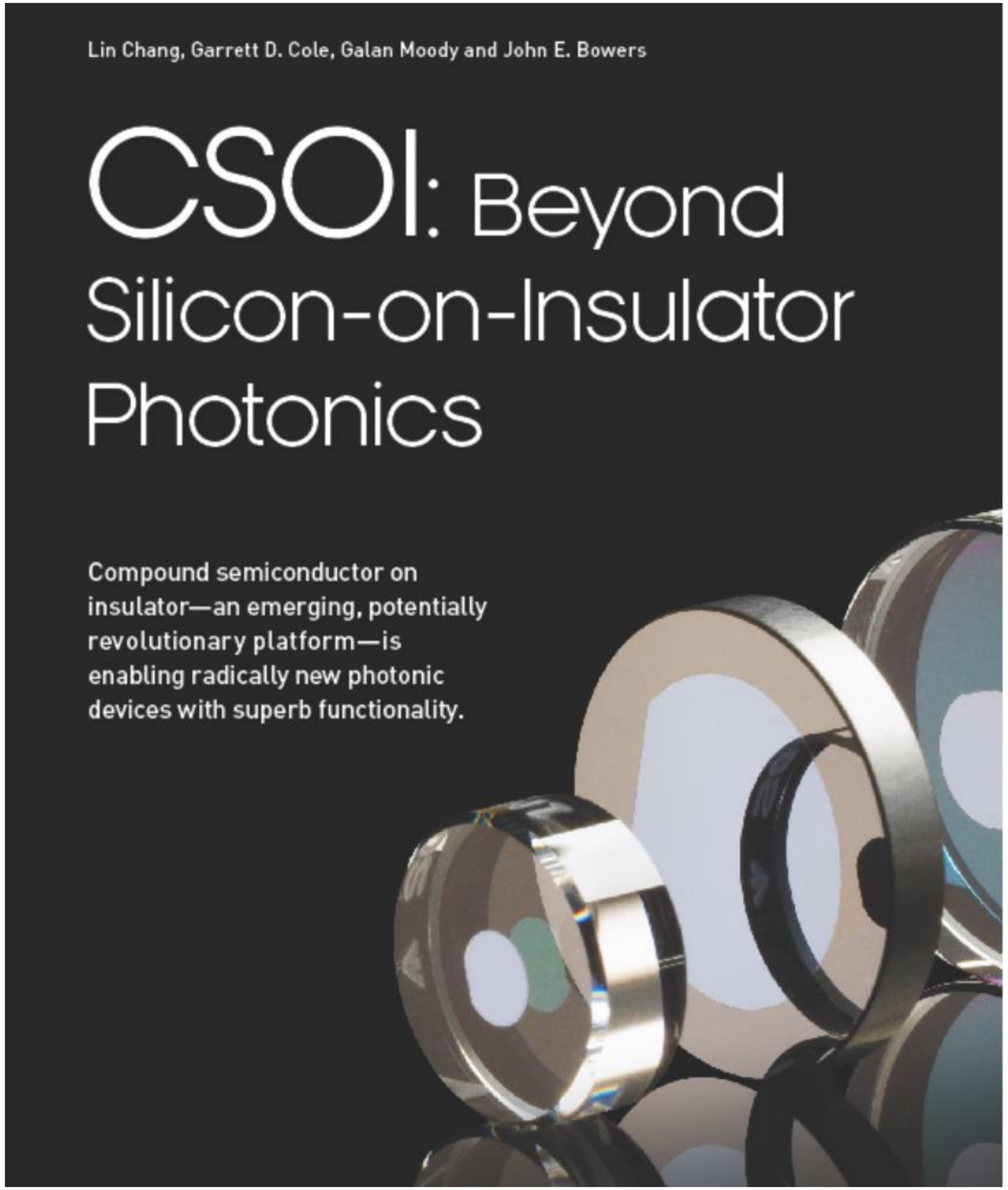




wafer-scale

Compound Semiconductor-on-Insulator (CSOI)



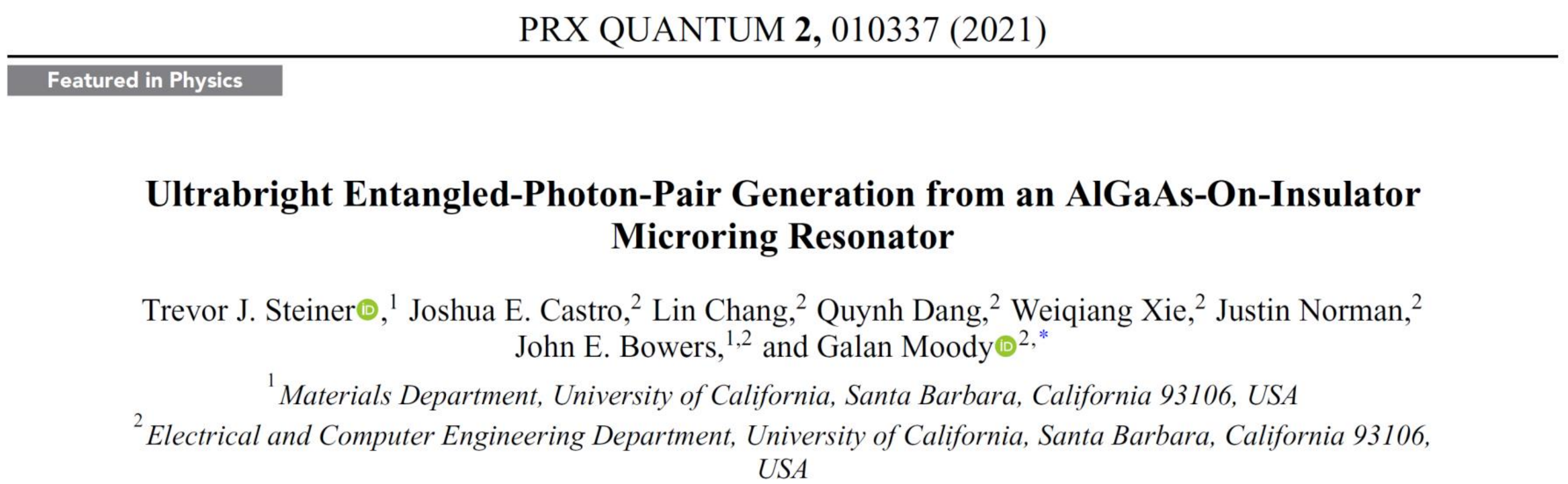


Lin Chang, Garrett D. Cole, Galan Moody and John E. Bowers

CSOI: Beyond Silicon-on-Insulator Photonics

Compound semiconductor on insulator—an emerging, potentially revolutionary platform—is enabling radically new photonic devices with superb functionality.

AlGaAsOI for Quantum Light Generation



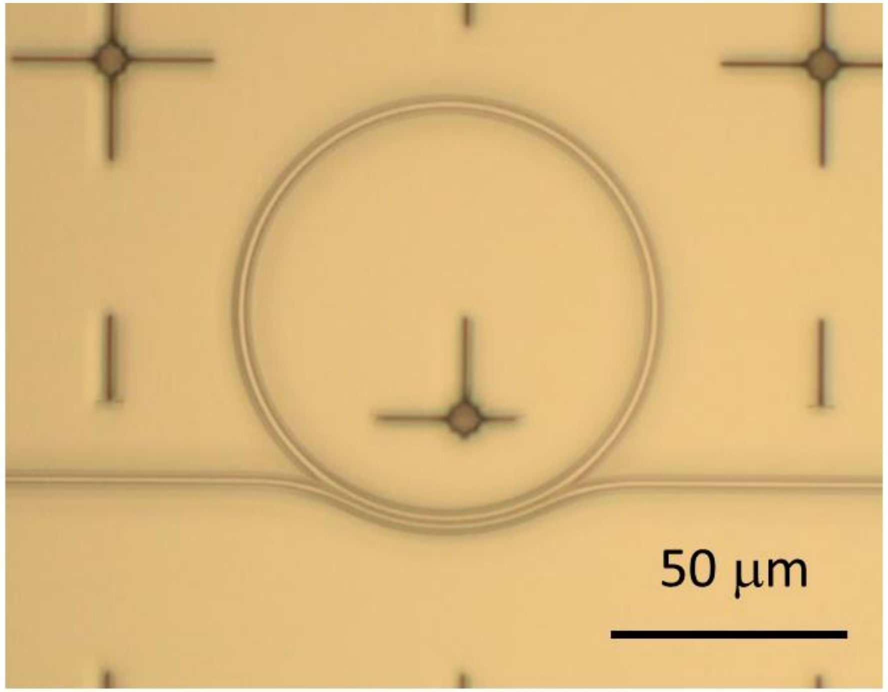
PRX QUANTUM **2,** 010337 (2021)

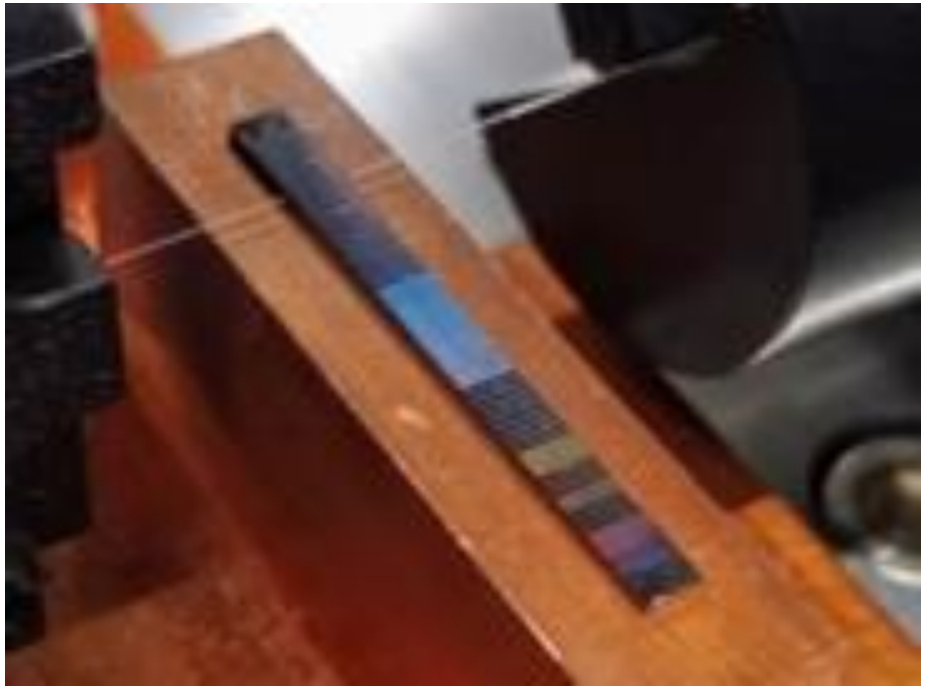
Featured in Physics

Ultrabright Entangled-Photon-Pair Generation from an AlGaAs-On-Insulator Microring Resonator

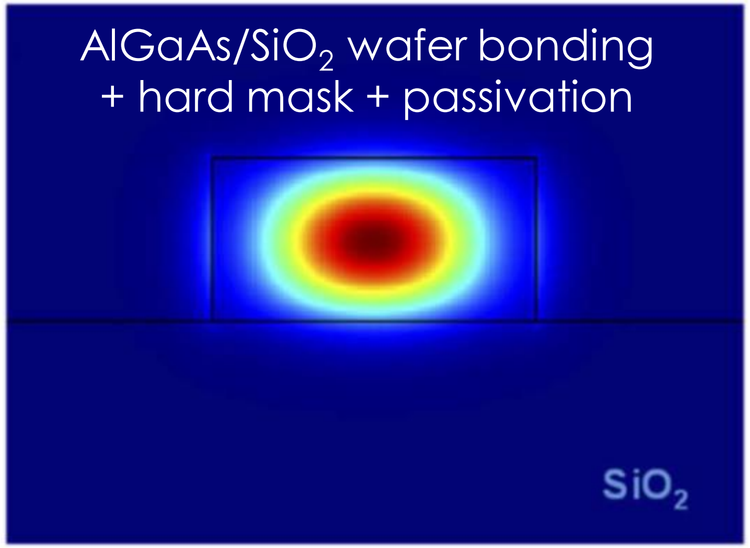
Trevor J. Steiner,[1] Joshua E. Castro,[2] Lin Chang,[2] Quynh Dang,[2] Weiqiang Xie,[2] Justin Norman,[2]
John E. Bowers,[1,2] and Galan Moody[2,*]

[1] *Materials Department, University of California, Santa Barbara, California 93106, USA*
[2] *Electrical and Computer Engineering Department, University of California, Santa Barbara, California 93106, USA*

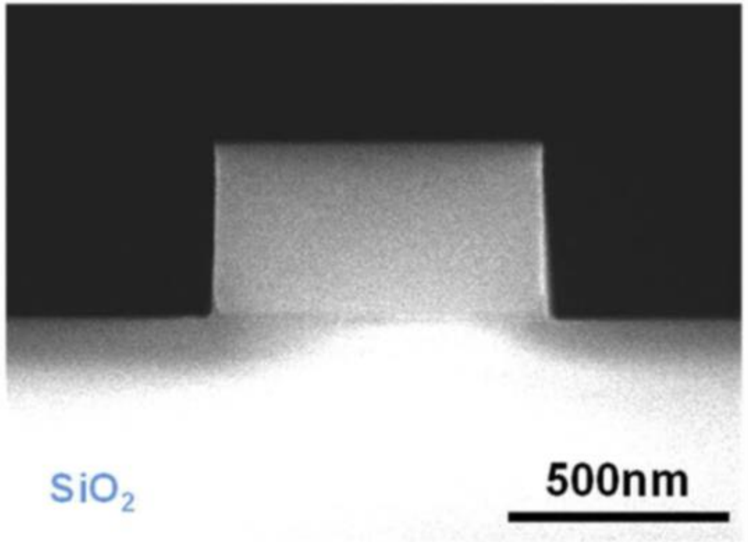


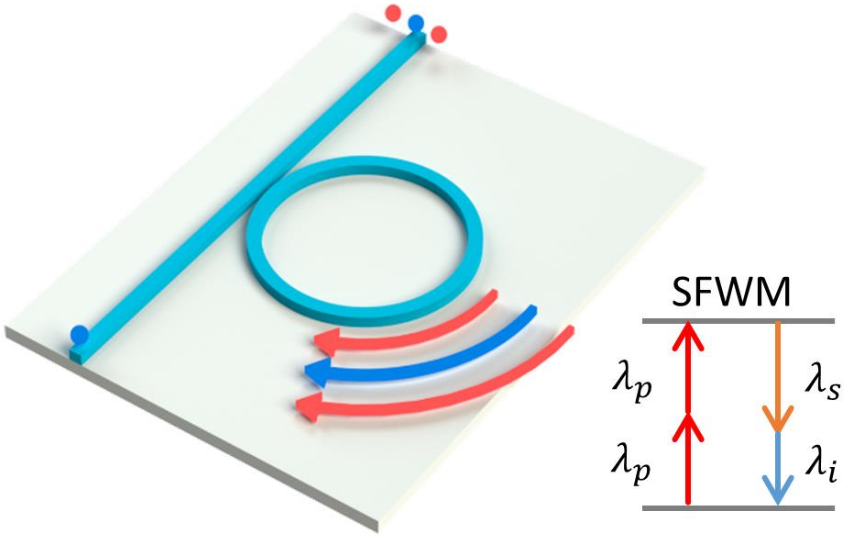


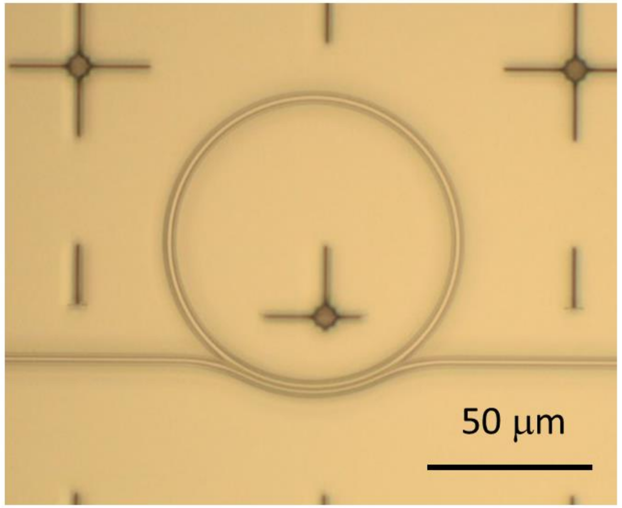
AlGaAs-on-Insulator Microrings for Entangled-Pair Generation



AlGaAs/SiO_2 wafer bonding + hard mask + passivation

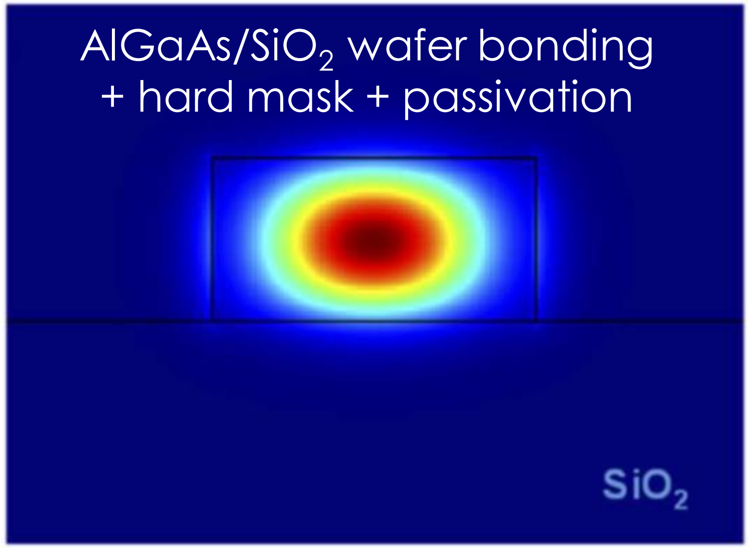






- **SFWM:** Two pump photons are annihilated to create a signal and idler photon
- Conservation of energy and momentum dictates wavelengths
- Signal/idler are entangled in time and energy, i.e. two photons that are correlated in time and in frequency
- Process occurs randomly in time (with a CW pump), with resonant enhancement from microring cavity

AlGaAs-on-Insulator Microrings for Entangled-Pair Generation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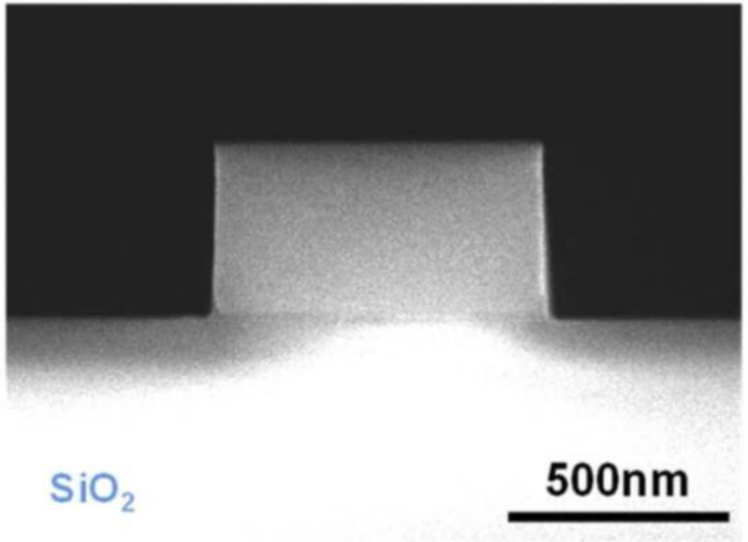
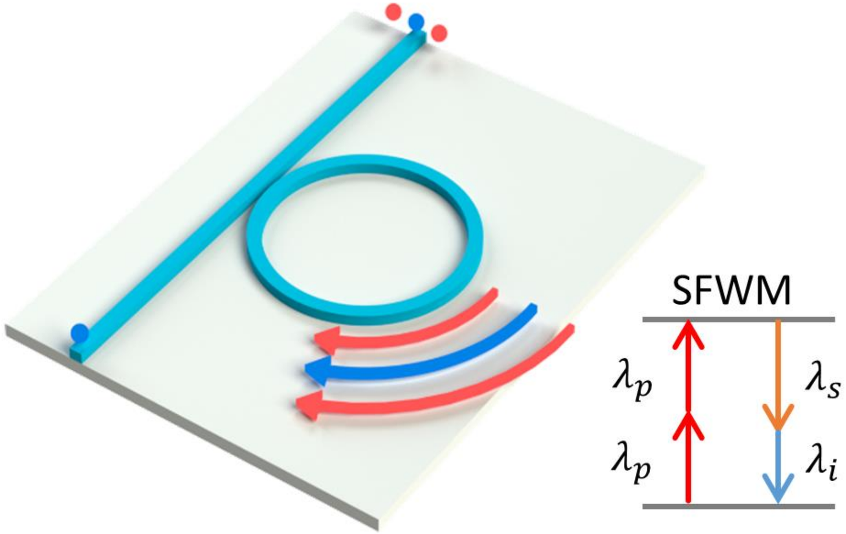
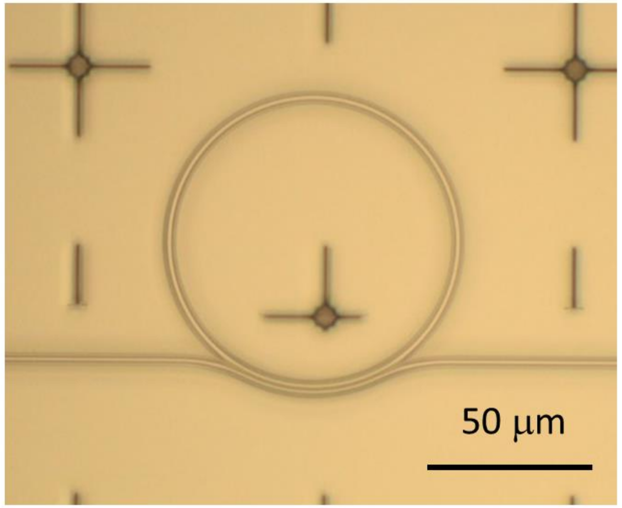
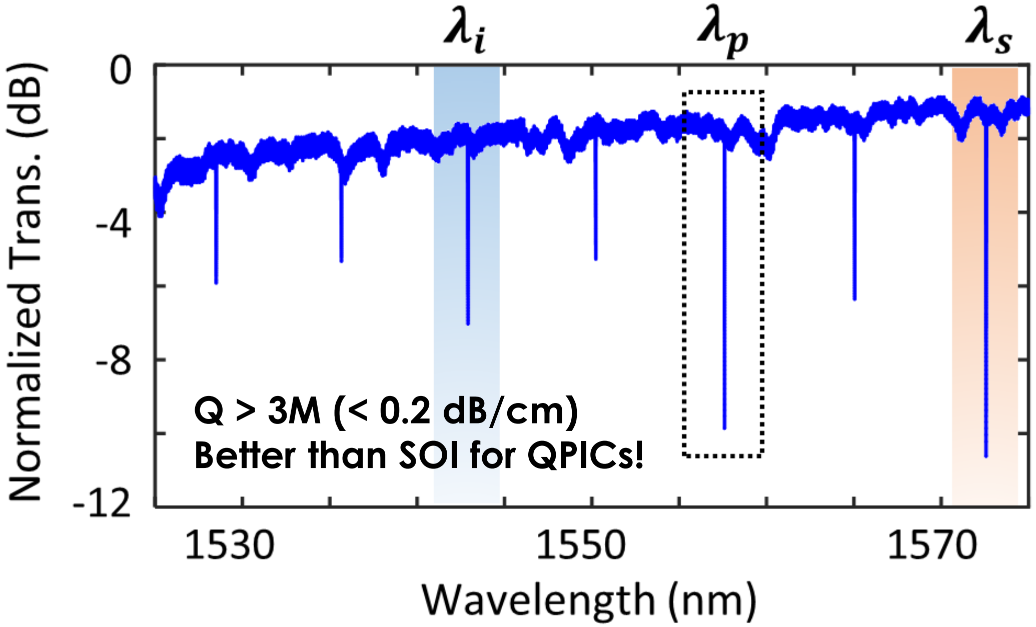


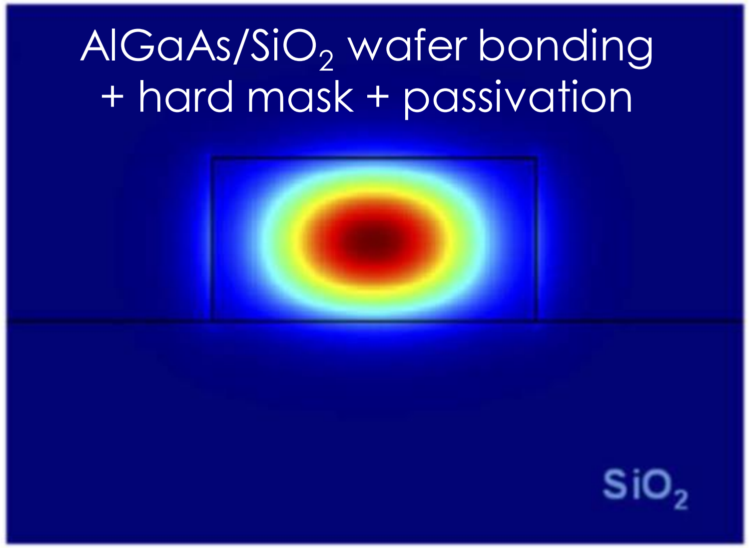


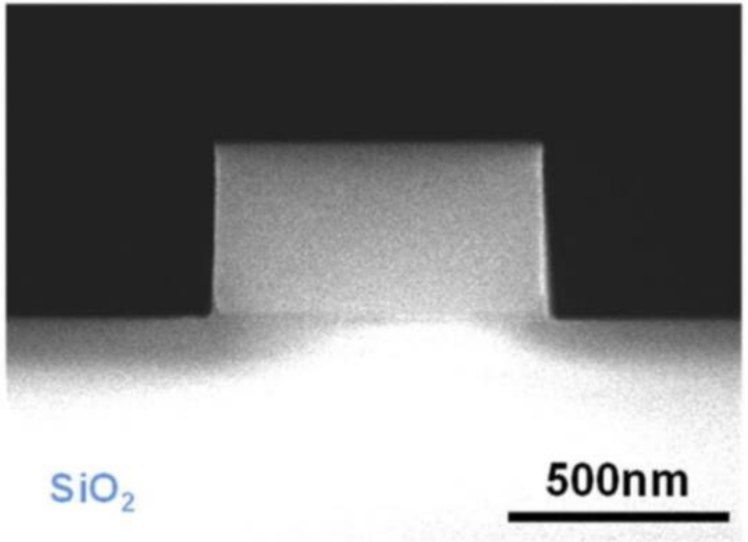


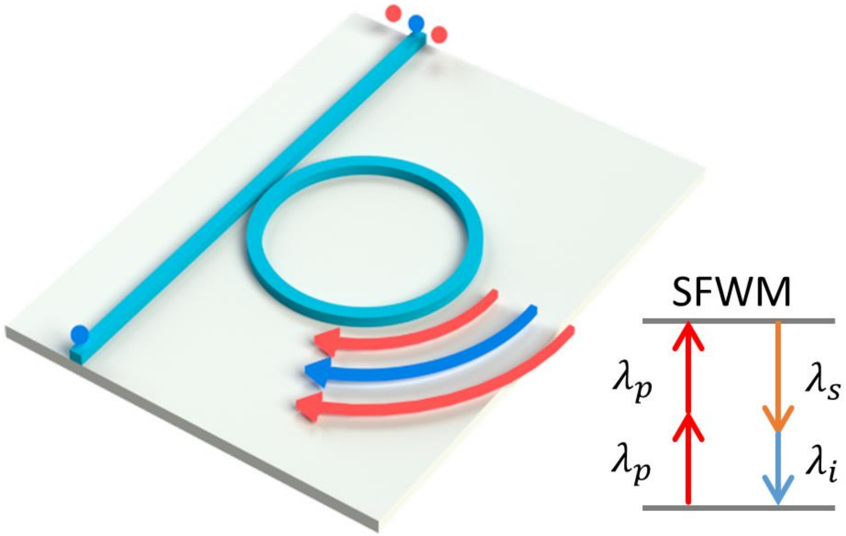


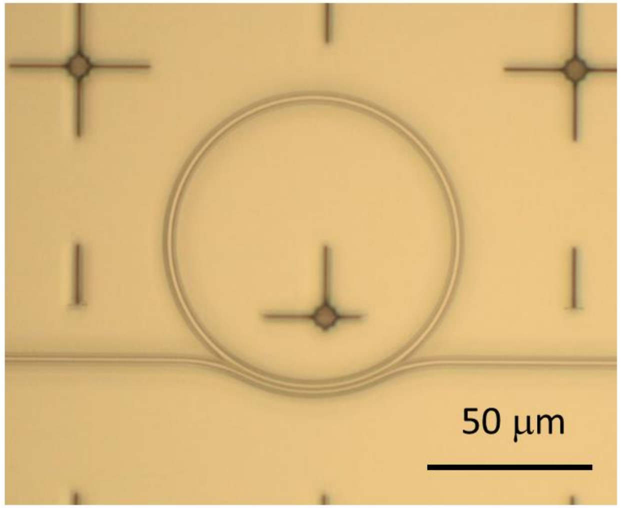
Q > 3M (< 0.2 dB/cm)
Better than SOI for QPICs!

AlGaAs-on-Insulator Microrings for Entangled-Pair Generation


AlGaAs/SiO_2 wafer bonding
+ hard mask + passivation







Entangled Pair Generation Rate

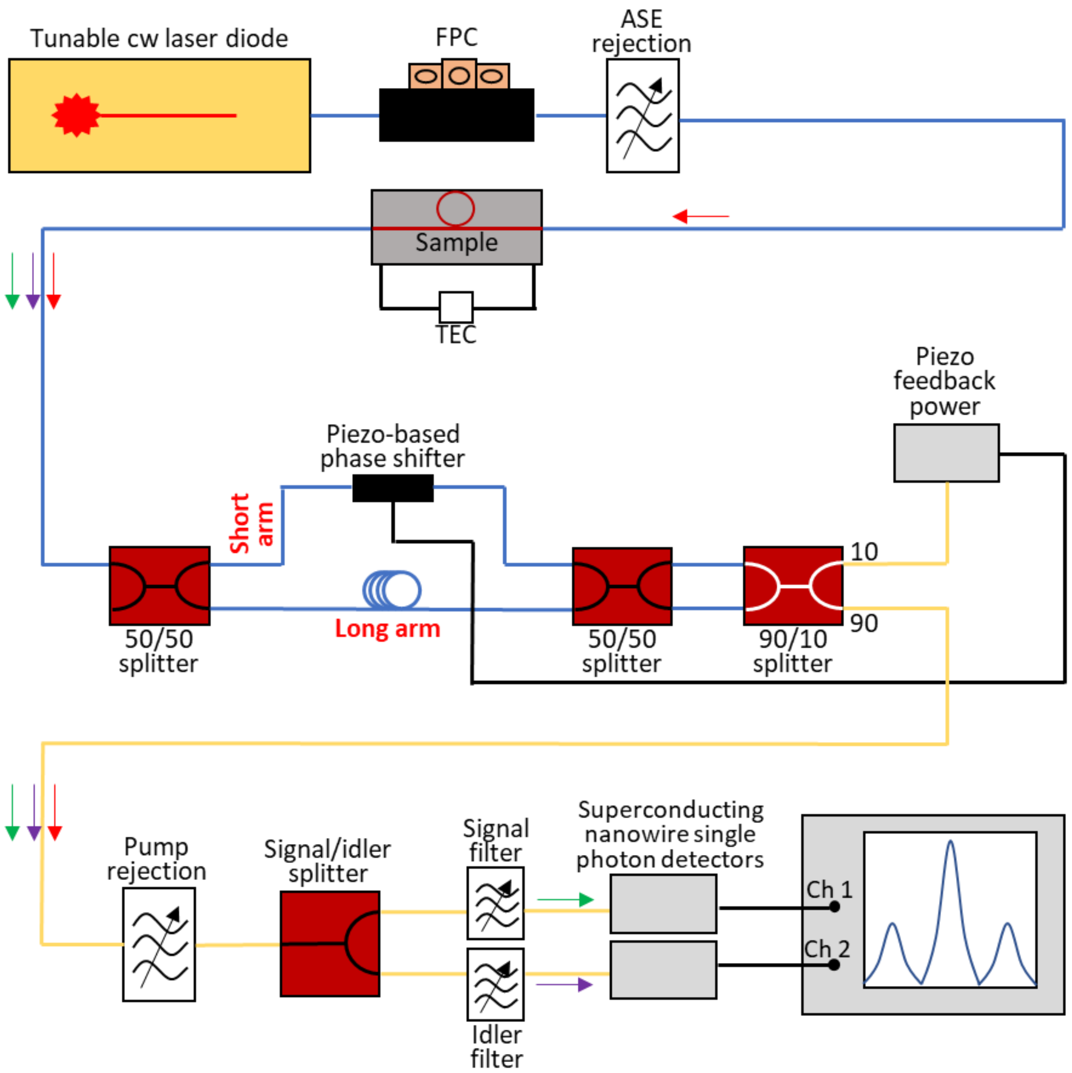
$$\propto \gamma^2 Q^3 R^{-2}$$

nonlinearity/
confinement

low loss

maintain high Q
@ small R

Measuring Entangled Photons



Tunable cw laser diode

FPC

ASE rejection

Sample

TEC

Piezo feedback power

Piezo-based phase shifter

Short arm

Long arm

50/50 splitter

50/50 splitter

90/10 splitter

10

90

Pump rejection

Signal/idler splitter

Signal filter

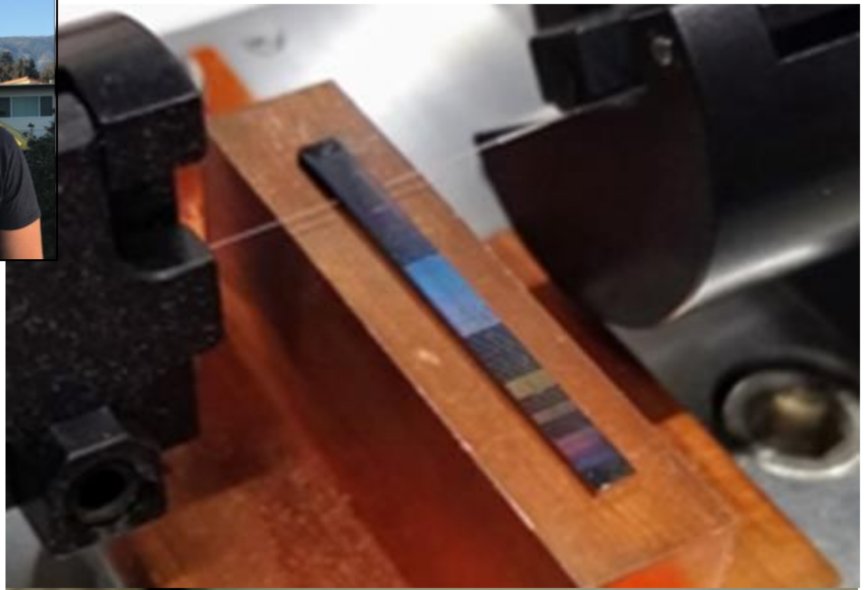
Idler filter

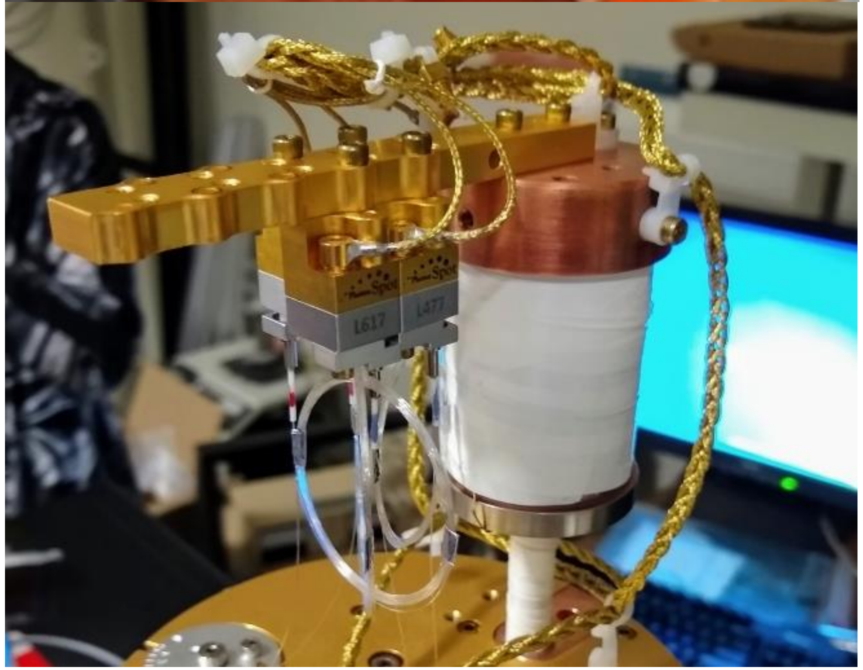
Superconducting nanowire single photon detectors

Ch 1

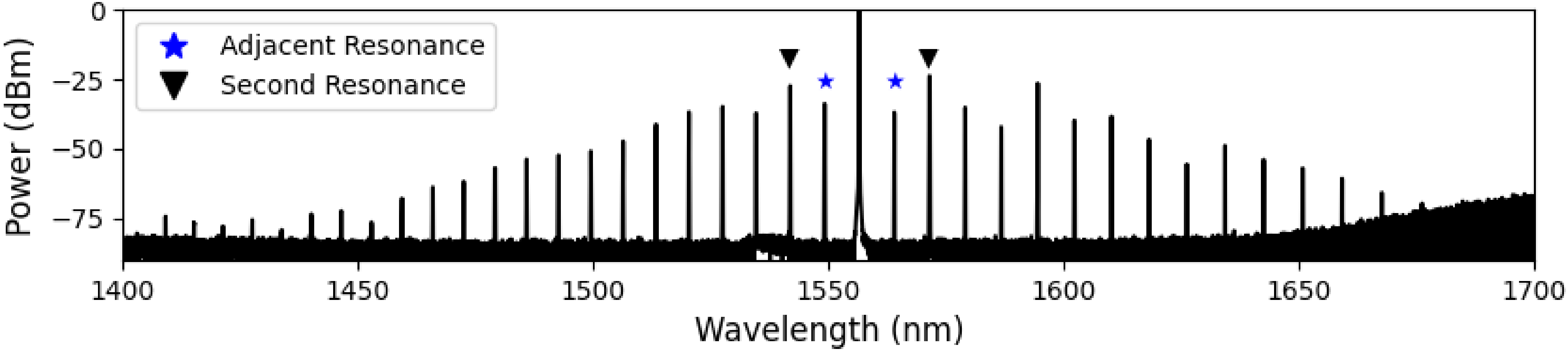
Ch 2

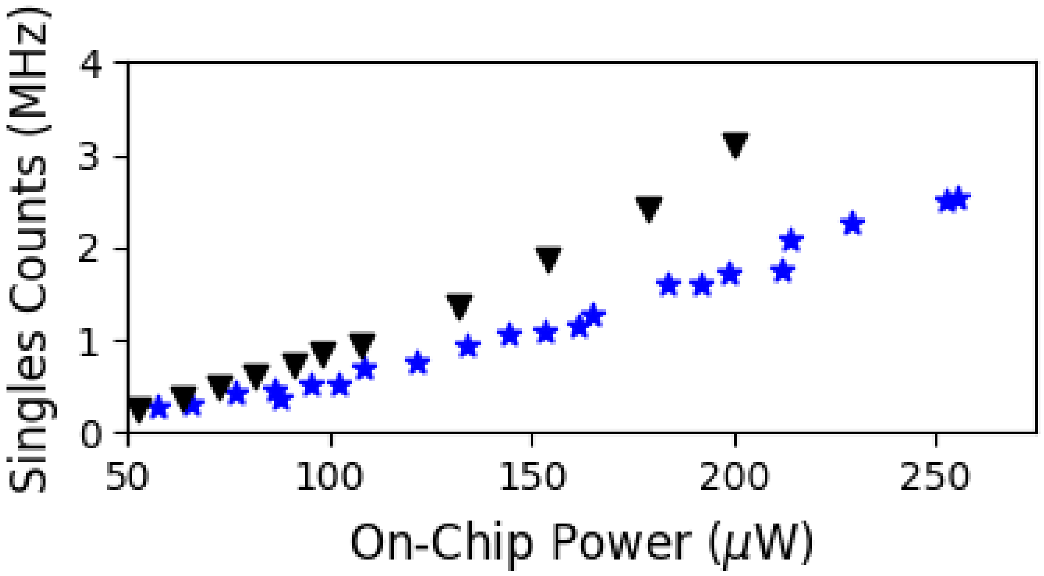
Trevor Steiner

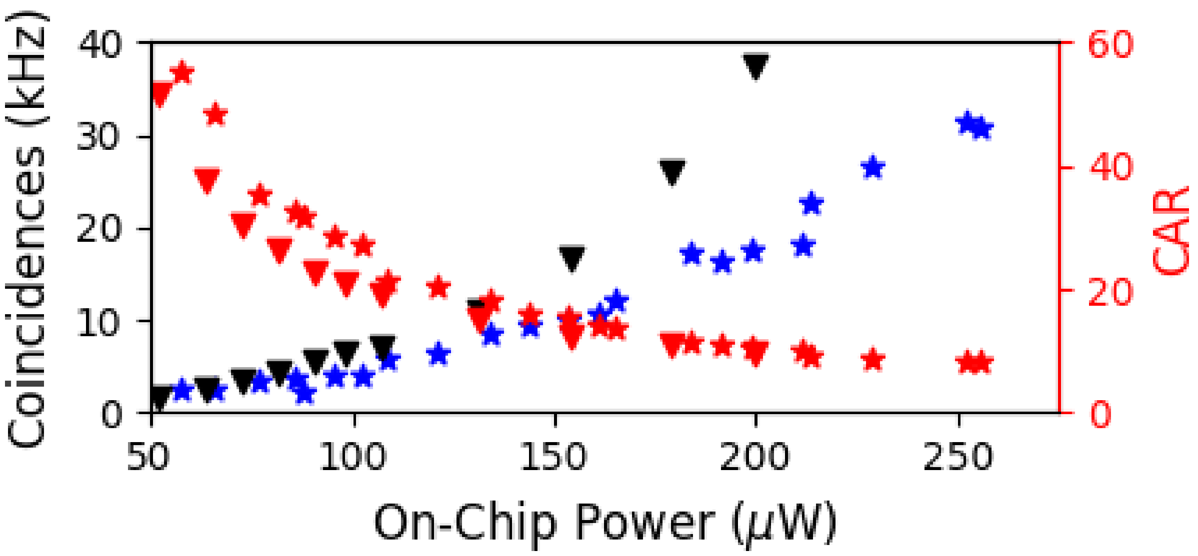




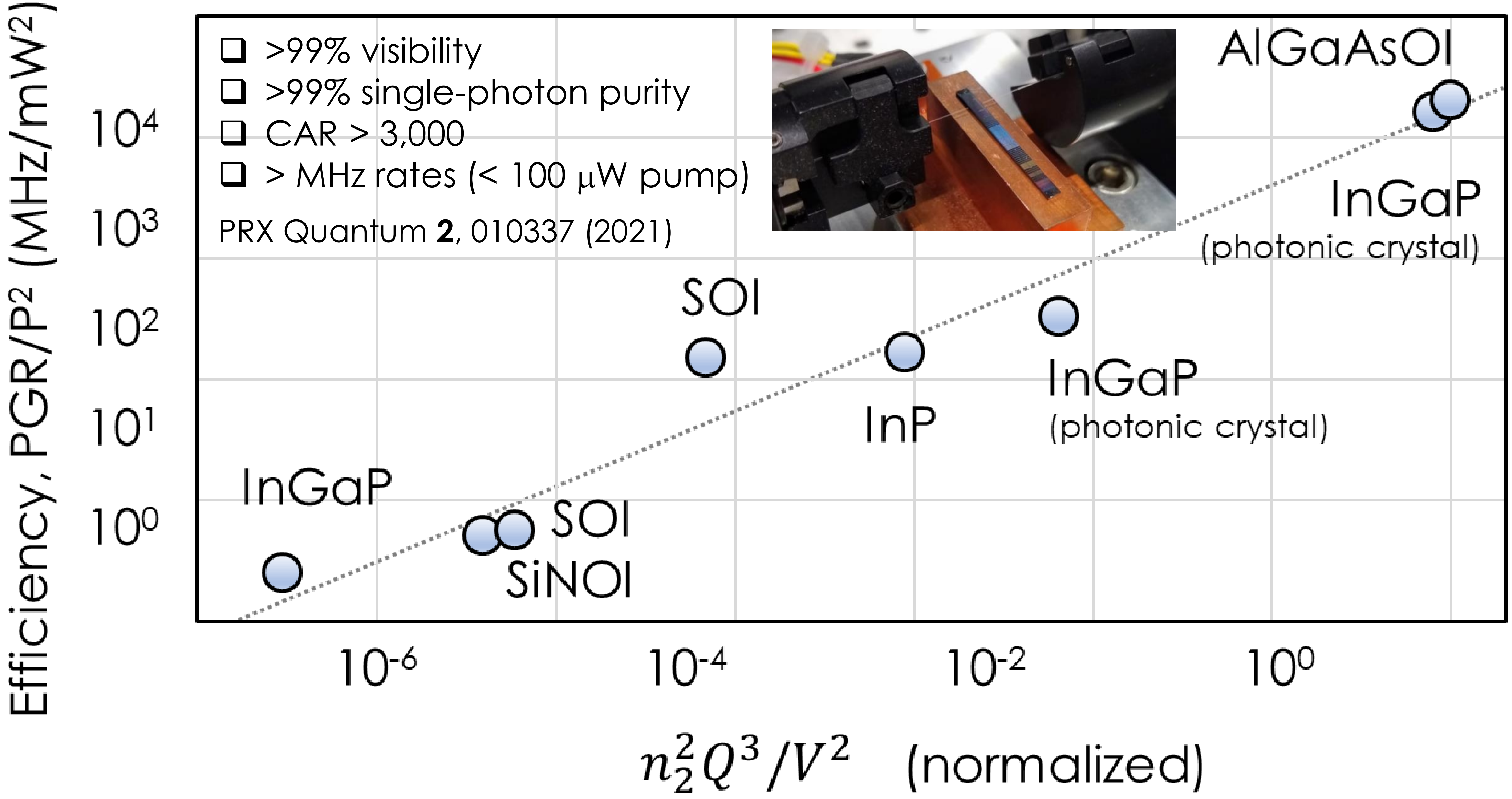
Broadband Continuous Entanglement







Ultra-Efficient Entangled-Photon Pair Generation

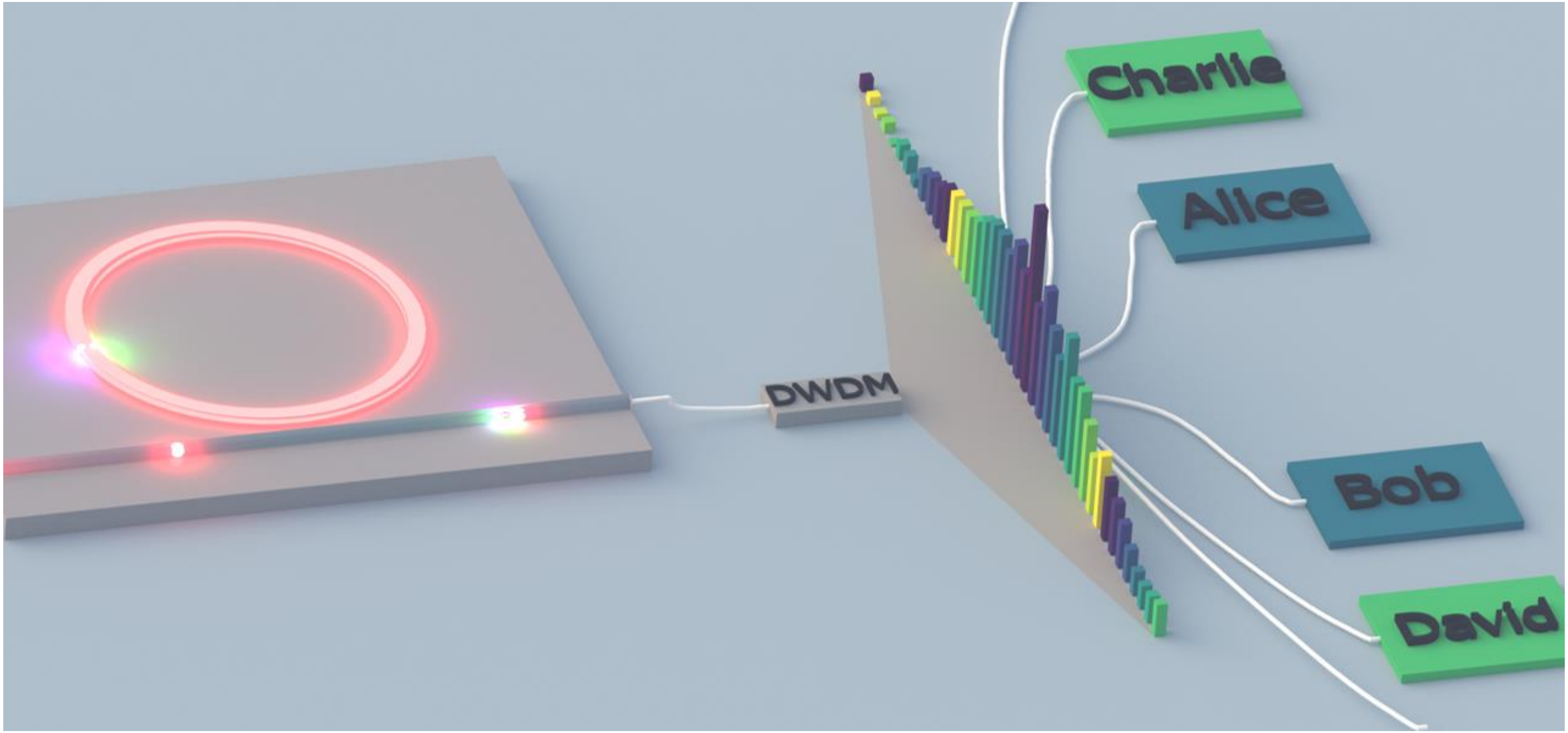


- ☐ >99% visibility
- ☐ >99% single-photon purity
- ☐ CAR > 3,000
- ☐ > MHz rates (< 100 μW pump)

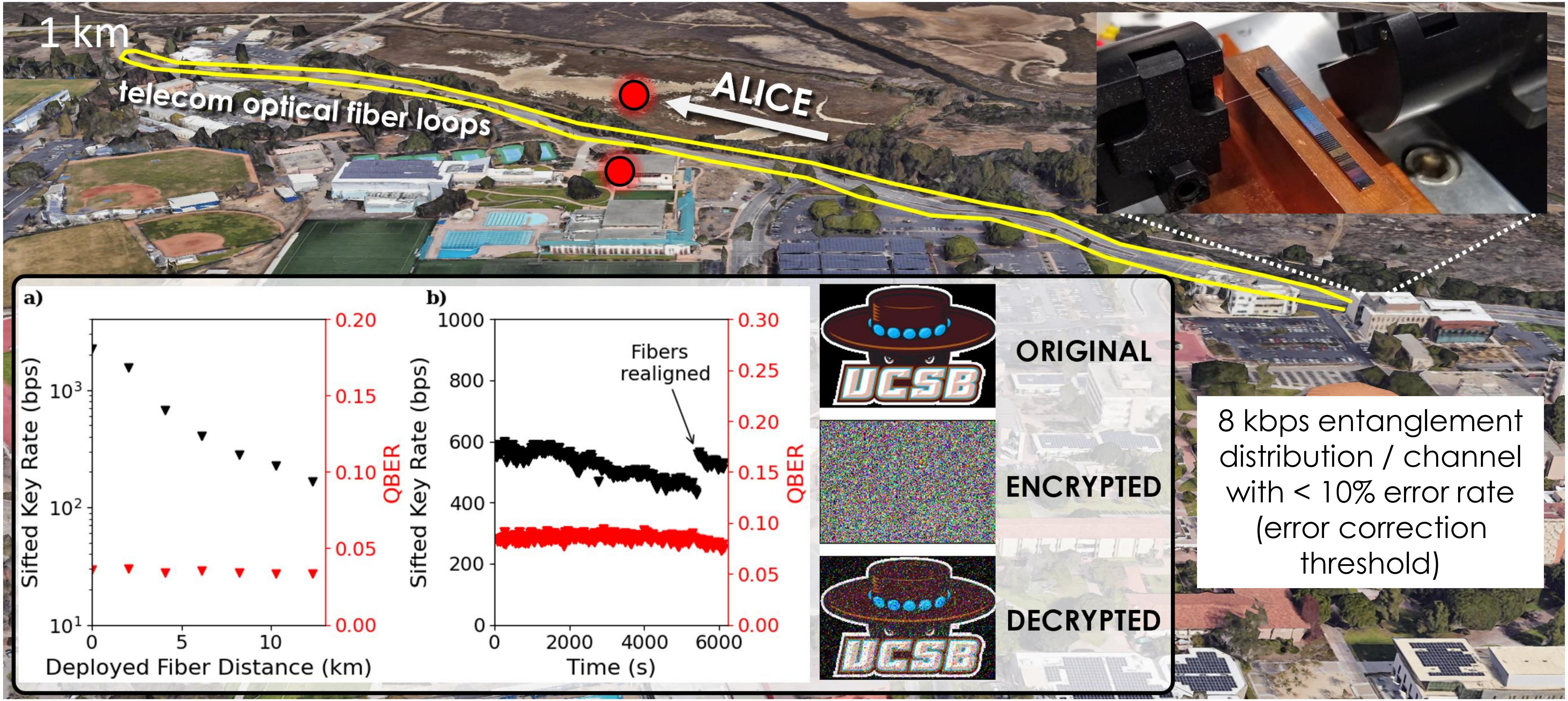
PRX Quantum **2**, 010337 (2021)

- Introduction to Optical Qubits
- How We Generate Optical Qubits with Integrated Photonics
- **Some Near-Term Applications: QKD, Entanglement Distribution, Quantum Sensing**
- **Outlook**

Application 1: Entanglement-Based Quantum Key Distribution



Application 1: Entanglement-Based Quantum Key Distribution



8 kbps entanglement distribution / channel with < 10% error rate (error correction threshold)

Steiner, Castro, Shen, Bowers, Moody, *in press*, also at arXiv:2310.14112 (2023).

Application 2: On-Chip Manipulation and Control

AlGaAsOI Component Library:

☐ Tunable MZIs for programmable circuits

☐ Qubit demultiplexers

☐ Optimized tunable rings for maximal entangled pair rates

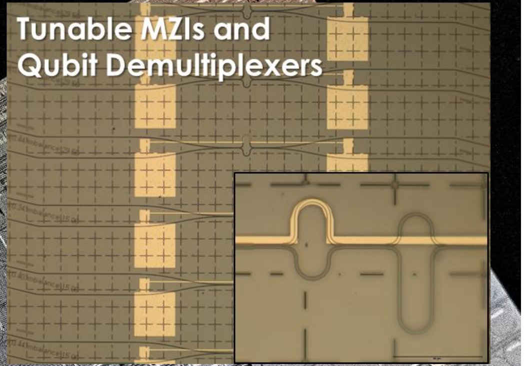
☐ Waveguide crossers

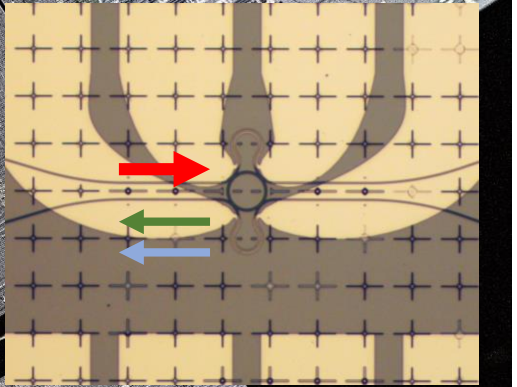
Castro *et al.*, APL Photonics 7, 096103 (2022)

☐ Low-jitter, low-dark-count, high-efficiency SNSPDs

☐ Waveguide-integrated SNSPDs

Nature Photonics 14, 250 (2020)
APL 115, 081105 (2019)
APL 111, 141101 (2017)





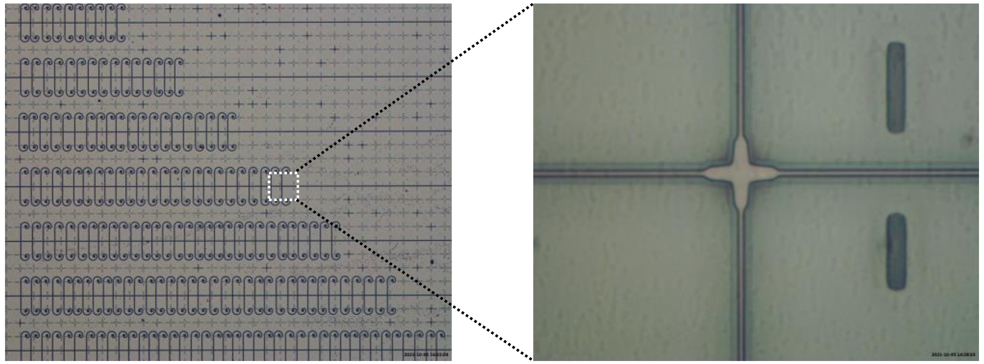
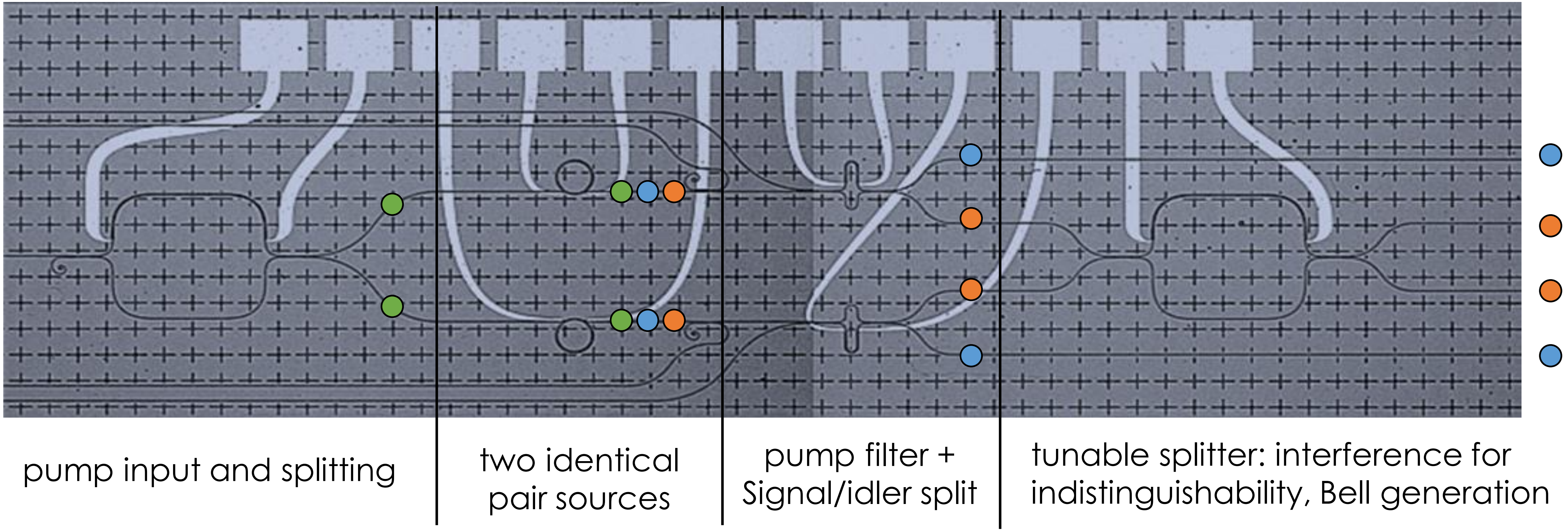


TABLE I. Table comparing the AlGaAsOI platform with SOI and Si_3N_4 designed for integrated quantum photonics.

	AlGaAsOI (this work)	SOI	Si_3N_4
Inverse Taper Coupling Loss	2.9 dB	< 3 dB[35]	2 – 3 dB[60]
Waveguide Crossing Loss	0.23 dB	0.2 dB[45]	0.3 dB[46]
MZI Extinction Ratio	> 30 dB	> 30 dB[61]	> 40 dB[62]
MZI Bandwidth (> 10 dB ER)	200 nm Cross 90 nm Through	> 40 nm[57]	180 nm[62]
MZI Heater Efficiency	20 mW/π (10.2 nm FSR)	12 mW/π[56] (5.8 nm FSR)	200 mW/π[55] (NA)

Application 2: Tunable Two-Photon Entanglement

demonstrate indistinguishable sources, tunable entanglement for large resources of entanglement



pump input and splitting

two identical pair sources

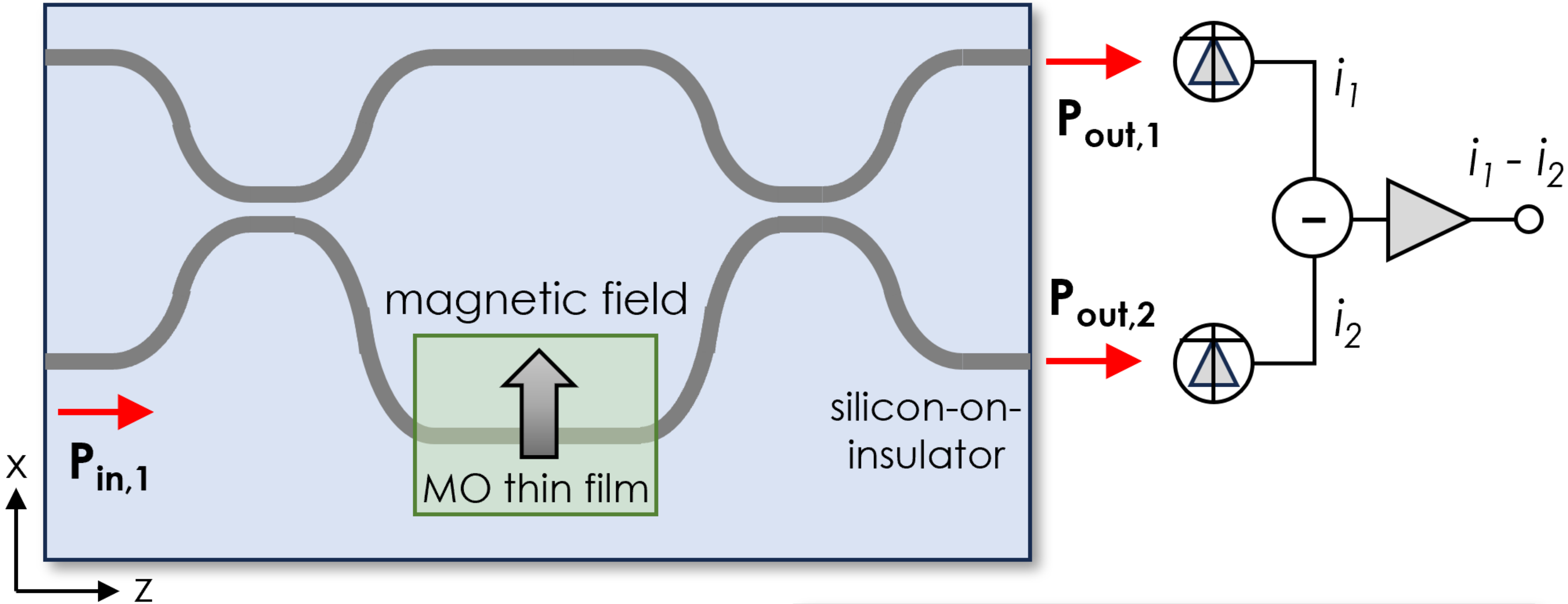
pump filter + Signal/idler split

tunable splitter: interference for indistinguishability, Bell generation

- ☐ 1 MHz detected rates with ~10 μW on-chip power
- ☐ Indistinguishability > 72%

- ☐ Reconfigure to produce two of four maximally entangled Bell states

Application 3: (Towards) Quantum Sensing

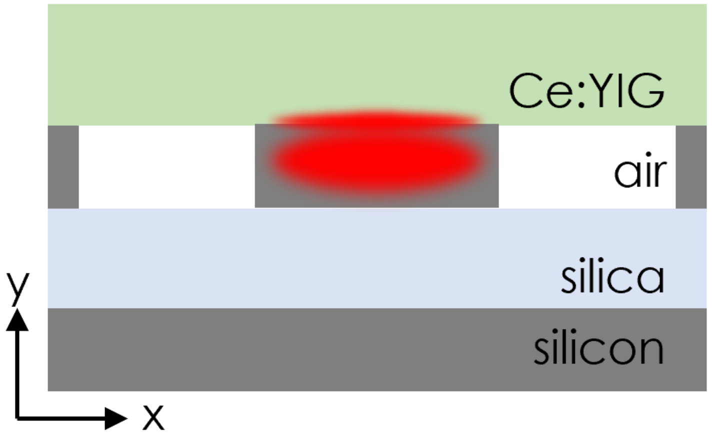


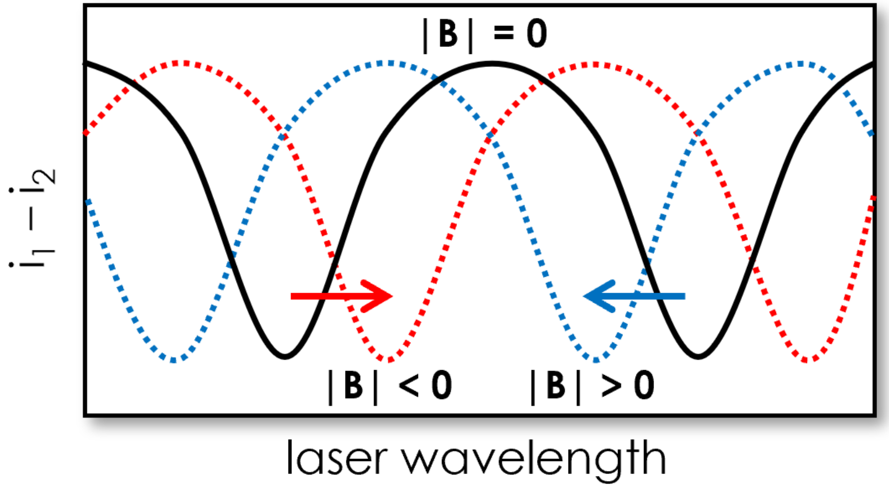

Paolo Pintus


Amalu Shimamura

PIC Magnetometer

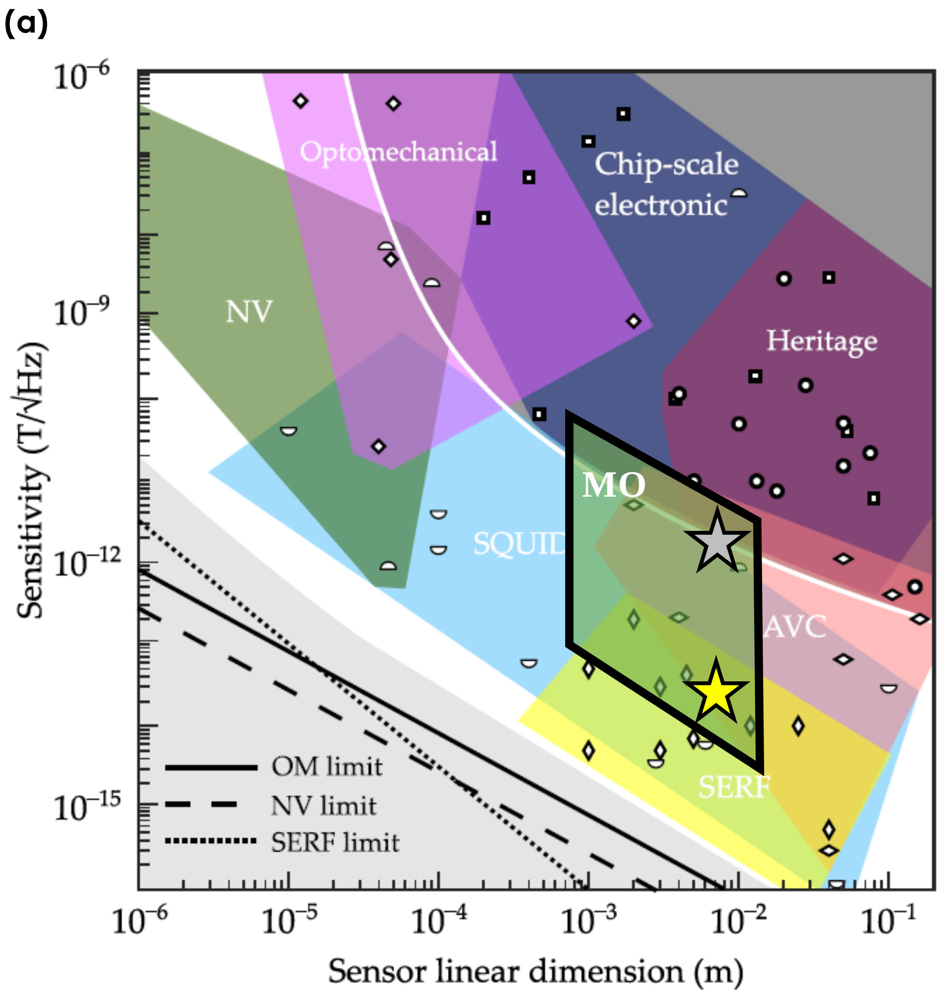
Integration of magneto-optic material above waveguide MZI (such as Ce:YIG)





Non-reciprocal phase shift + large MO effect leads to high sensitivity for magnetic field sensing

Application 3: (Towards) Quantum Sensing



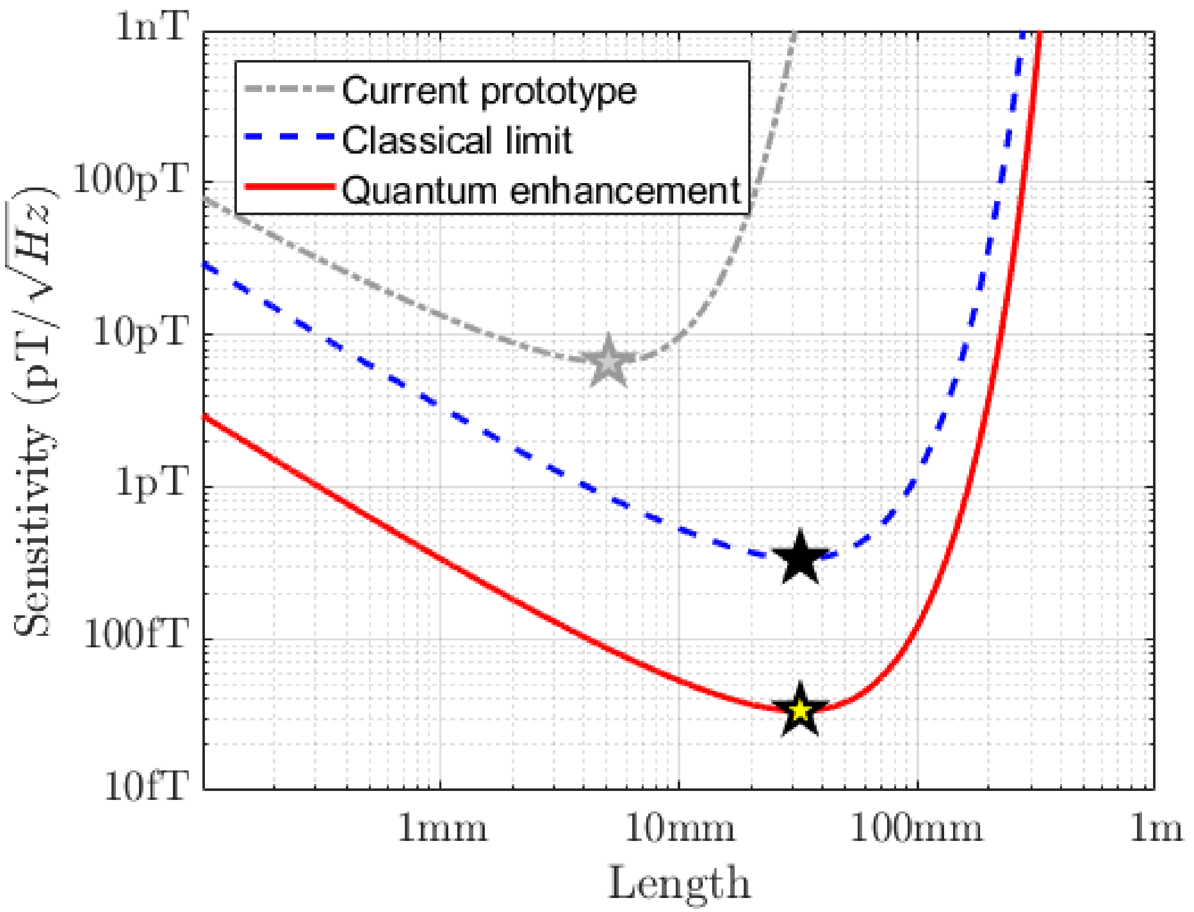
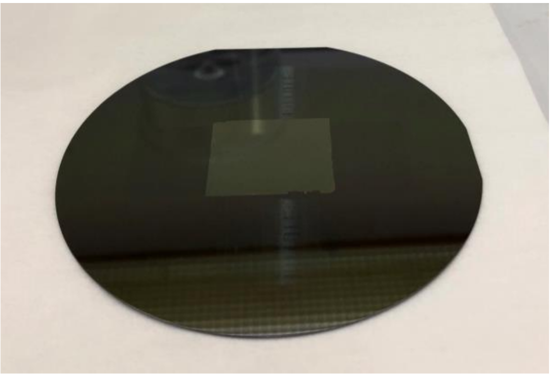


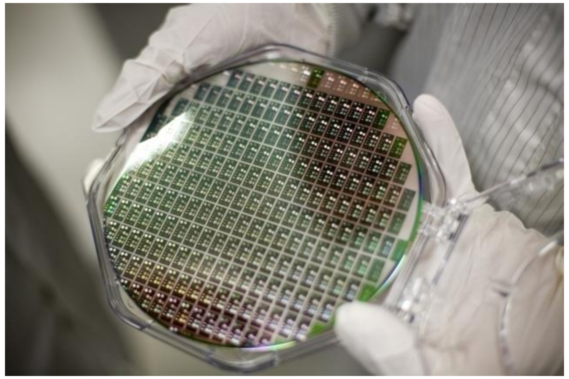
Image modified from
Bennett, James S., et al. "Precision magnetometers for aerospace applications: A review." Sensors 21.16 (2021): 5568.

Exciting Directions for the Next 5 Years

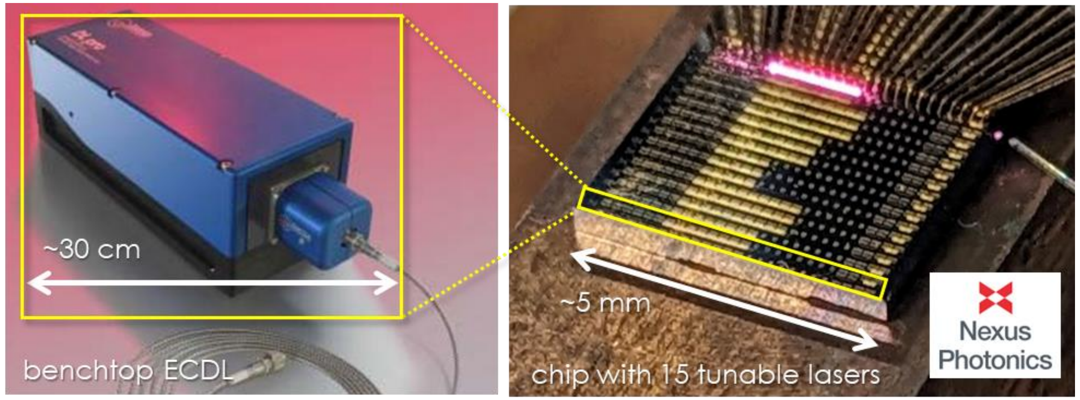
100 mm, UCSB



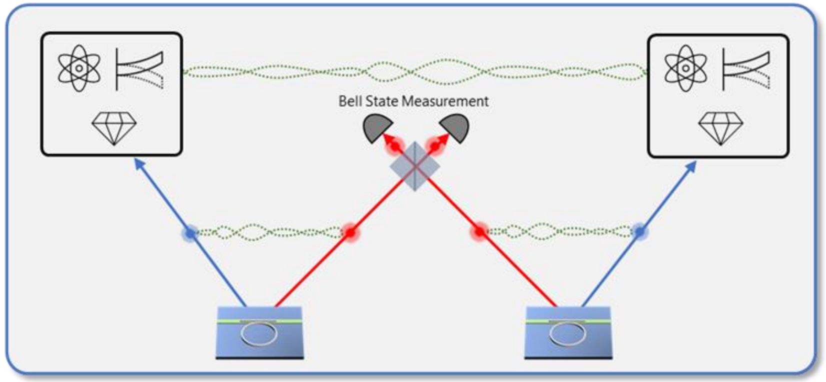
100-200 mm, foundry



- ☐ **Heterogeneous PICs, leverage SOI**
  - ☐ Nonlinear actives
  - ☐ SOI/SiNOI passives
  - ☐ Foundry manufacturing



- ☐ **Systems-on-chip**
  - ☐ Lasers + sources
  - ☐ Lasers + sources + frequency conversion
  - ☐ Lasers + sources + microelectronics



- ☐ **Near-Term Applications**
  - ☐ Quantum satellites for space-based networking and communications
  - ☐ Broadband entanglement generation & conversion
  - ☐ High-speed (GHz) programmable quantum photonic resource states

Not pictured: Yiming Pang, Amalu Shimamura

Thank You!

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collaborators

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Navin Lingaraju (JH APL)
Marco Liscidini (Pavia)
Daniele Bajoni (Pavia)
Andrew Weiner (Purdue)
Yifei Li (UMass Dartmouth)

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