QUIX QUANTUM

Scalable Quantum Computing based on market-leading photonics technology

Dr. Caterina Taballione

EPIC - Industrial Quantum Photonics Technology
October 12th , 2023

OUR MISSION

Build Europe’s quantum computer.

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Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical.

Richard P. Feynman

The Nobel Prize in Physics 1965

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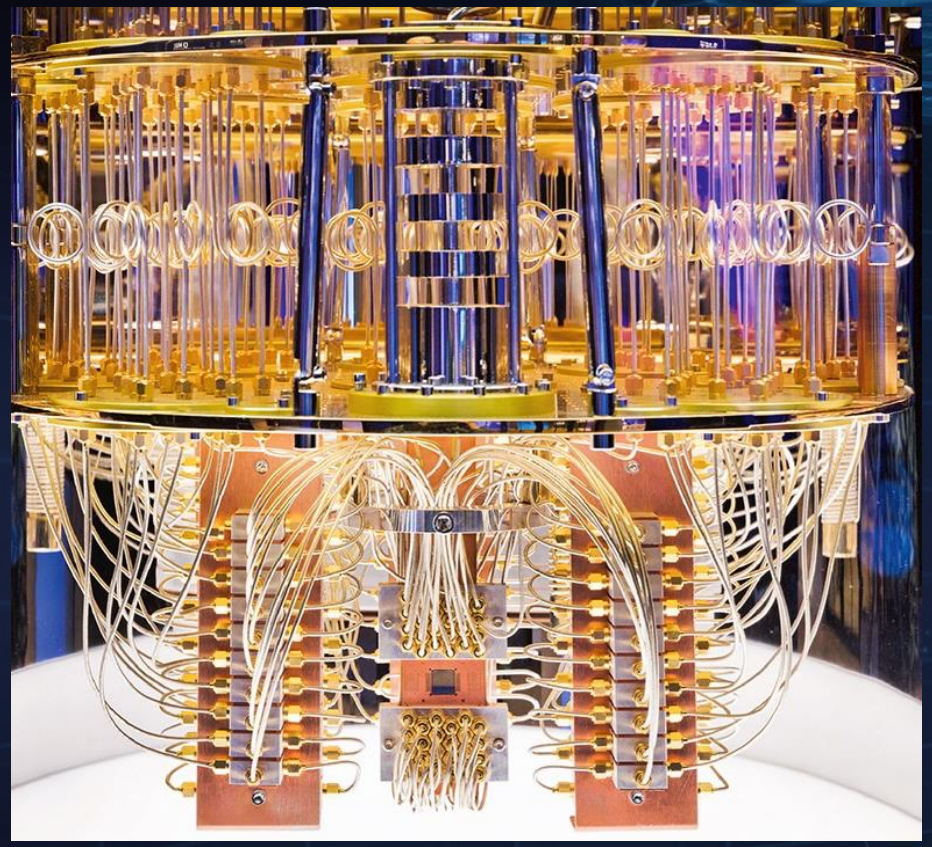
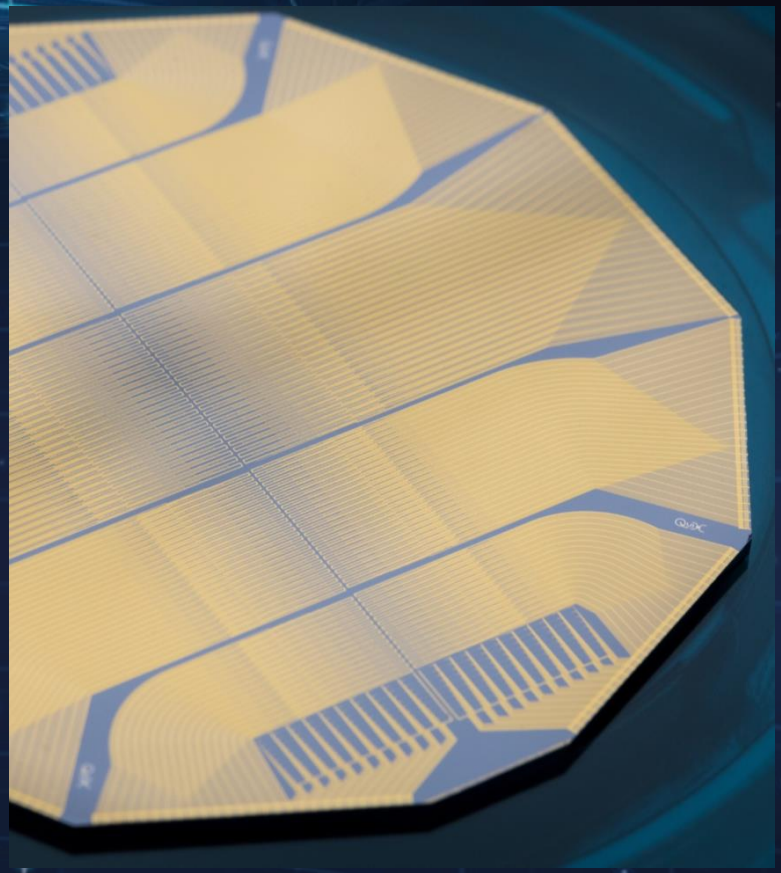
Gate-Based Quantum Computing



Measurement-Based Quantum Computing



Lot of technical knowhow needed to preserve the coherence of the qubits and do error correction!

One way quantum computing is very resource efficient, establishing the cluster state is challenging.

Source: IBM

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Photonics has unique advantages for universal quantum computing

Scalable

Modularity (coupling of processors) enables high scalability

Mature basis

- Leverage on existing telecoms technology
- Works at room temperature
- Strong industry buy-in

Affordable

- Cost-effective infrastructure
- Economies of scale

Forgiving

- Fault tolerant
- High stability - decoherence not an issue

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Photonics outperform existing quantum technologies

		Photonics	Superconductors	Ion Traps	Quantum Dots	Cold Atoms
Qubit Quality	Gate fidelity	**99.9%**	**99.9%**	**99.9%**	**99%**	**99%**
	Lifetime Qubit	∞	1 ms	50s	1 to 10 s	100 ns
Main Specifications	Temperature	Room temperature	Near OK	NA	Near OK	NA
	Integration	All-to-All	Nearest Neighbors	All-to-All	Nearest Neighbors	Nearest Neighbors
	Scalability	Horizontal	Horizontal	NA	NA	Horizontal
	Notable players	XANADU, PsiQuantum, ORCA, QUIX QUANTUM	IBM, IQM, Google	IONQ, Honeywell	Silicon Quantum Computing, intel	PASQAL, ColdQuanta

World’s best photonic quantum computing technology

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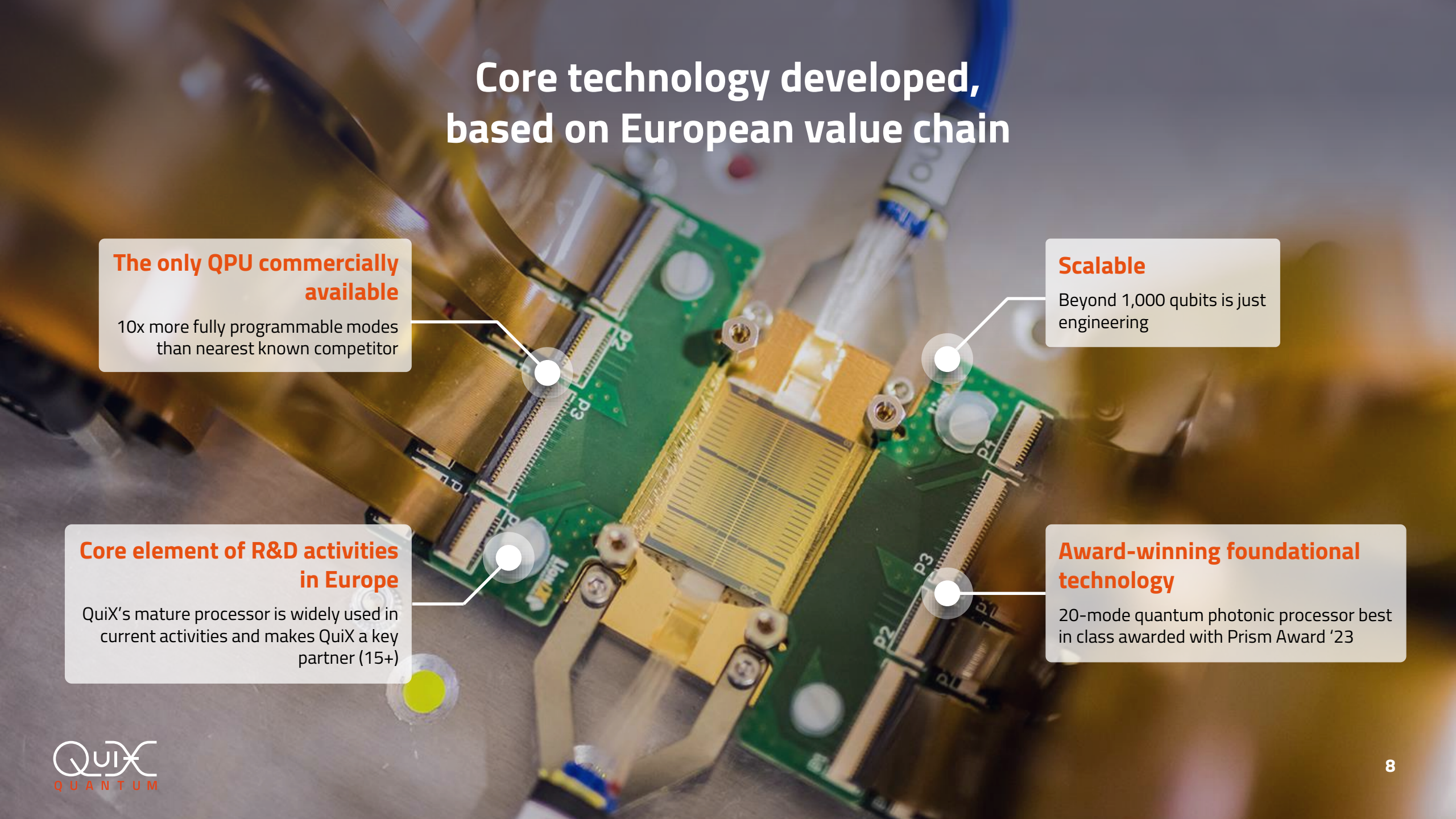
Core technology developed, based on European value chain



The only QPU commercially available

10x more fully programmable modes than nearest known competitor

Scalable

Beyond 1,000 qubits is just engineering

Core element of R&D activities in Europe

QuiX's mature processor is widely used in current activities and makes QuiX a key partner (15+)

Award-winning foundational technology

20-mode quantum photonic processor best in class awarded with Prism Award '23

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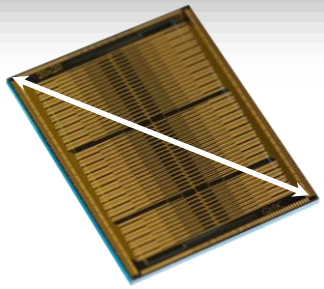
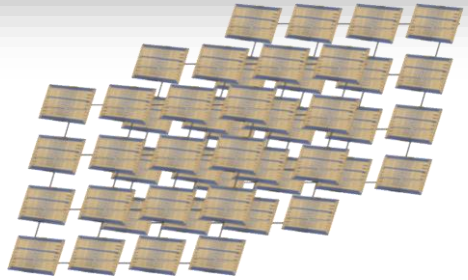
Useful Quantum Computers require 100+ logical Qubits. Quantum computing at scale requires modularity.

- limited qubit count
- physical-technical boundaries



Useful universal quantum computers need over 100+ logical qubits

- orders of magnitude more scalability
- Interconnecting neighboring processors



LIMITATIONS

- Increasing yield requirements with increased size
- Density of the electric supply lines
- Fiber coupling of many waveguides simultaneously reduces coupling efficiency

Flying Qubits offer enhanced error correction

MODULARITY

- Reduces fabrication requirements
- Allows for rapid scalability and large cluster states
- Ensures upgradeability
- Allows to cool the detector modules only

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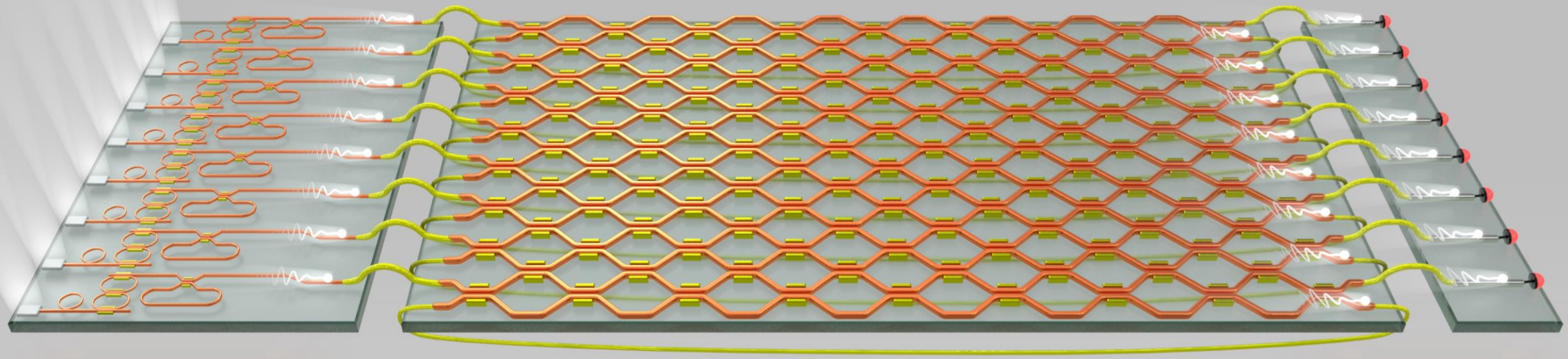
Design of a photonic quantum computer (MBQC)



Squeezed light generators

OR

Quantum Dots
(Single photons)

OR

Down conversion
(Single photons)

Processor

Feedback loops

Detectors SNSPD

AND

Photo diodes

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Deutsches Zentrum
für Luft- und Raumfahrt
German Aerospace Center

First universal photonic quantum computer in Europe sold to DLR

QuiX is the industry partner of the German Aerospace Center

- 4-year project of the DLR Quantum Computing Initiative (2022-2026)
- Co-development of use-cases
- Develop first-ever commercial sale of a photonics-based universal quantum computer

Post-quantum Cryptography

Quantum Machine Learning

Planning optimization for satellite operations

Simulation of chemical redox reactions

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First quantum computing hardware delivered on schedule

- Processor
- Power Supply, Control
- Photon Source & Delay
- Detectors

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Building partnerships for rapid market access-case study QMware

Qmware and QuiX Quantum set up a hybrid data center in Enschede

- Framework agreement signed
- Data Center for hybrid QC (commercial computer = quantum computer) will be located on site in Enschede
- QMware customer will have cloud access to the HPC/QCU unit

Hybrid Quantum Computing

Quantum Machine Learning

Quantum Photonics technology challanges

Low loss

Transmission of photonic chips is impoved constantly. Coupling loss gives still the major contribution

Fast and low loss Phase shifters

Integration of different materials (piezo-electric, electro-optics or others)

Beam sources

- Currently there are competing approaches
- Single Photons vs. Squeezed light

Control electronics & Detectors

- Multiple manufacturers
- Good progress through continuous engineering

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Low loss phase shifters and fast phase shifters

Thermal	Piezo-electric	Electro-optic	Others
Au on SiN	$Pb[Zr_xTi_{1-x}]O_3$	$BaTiO_3$	Polaritons
	$LiNbO_3$	$LiNbO_3$	Liqud crystalls
	AlN	InP	Magneto-optical
	AlScN	SiC	

complicated control system

Requirements:

- Voltages < 5 V
- Switching times > 100 MHz
- Power consumption: < 100 mW
- Lowest losses per unit cell

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Supply and Value Chain Development

Building the leading eco-system in Europe

QuiX focus

Looking for new/additional partners

Thank you for the great cooperation, QuiX ecosystem

Supply Chain and Co-Development

MESA+ INSTITUTE · LioniX INTERNATIONAL · phix · Pixel Photonics · QBLOX

Software development

QuSoft Research Center for Quantum Software · kvantify

Hardware integrators

QUANDELA

Platforms and Data-Centers

QM ware · E4 COMPUTER ENGINEERING

Eco Systems

PhotonDelta Gateway to Integrated Photonics · Quantum Delta NL · QCi · oost nl · European Innovation Council · European Commission Horizon 2020 European Union funding for Research & Innovation

Pilot customers (Extract)

DLR Deutsches Zentrum für Luft- und Raumfahrt German Aerospace Center · Universität Stuttgart · UNIVERSITÄT PADERBORN

Industry Networks

UIC European Quantum Industry Consortium — 100 industry partners

EPIC European Photonics Industry Consortium — 800 photonic companies

IVAM. — 200 companies for microtechnology

IQBN — 80 quantum companies

QPhot innovation network — 20 quantum photonic companies

Academic partners

UNIVERSITY OF TWENTE. · RWTH AACHEN UNIVERSITY · Tyndall National Institute Institiúid Náisiúnta · Fraunhofer

> 100 partners in more than 10 EU funded projects

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Thank you!

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Appendix

Product Portfolio

	Processors	SP Quantum Computers	Universal Quantum Computers
Solutions for	R&D, quantum computing	Optimization, simulation	All industry sectors
Customers	Researchers, QC companies	Healthcare, finance, logistics	Full industry
Cloud access	No	Yes	Yes

- QuiX Quantum sells hardware and also cloud access as a service.
- QuiX Quantum sells OEM processors as well as full Quantum Computing systems.

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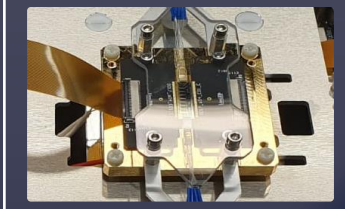
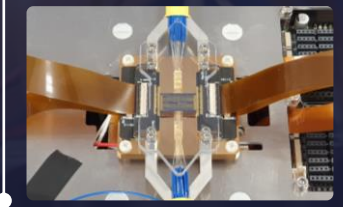
Proven product development

Product Development

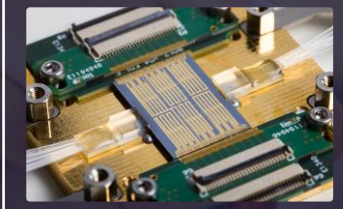
2019
4x4-mode processor



2019
8x8[1] -mode processor

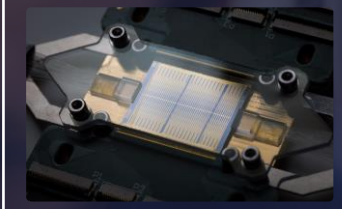


2020
12x12[2] - mode processor

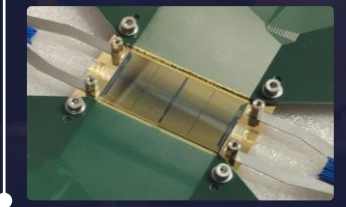


2021
16x16 -mode processor

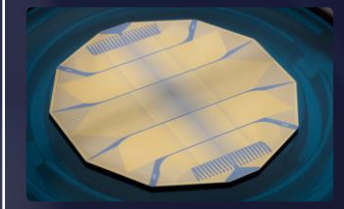
2022
20x20 - mode processor



2022
32x32[3] - mode processor



2023
50x50 - mode processor



In **4** years from **16** to **2500** tunable and fully operational interferometers including thermal and electrical error correction

[1] Taballione, Caterina, et al. "8× 8 reconfigurable quantum photonic processor based on silicon nitride waveguides." Optics express 27.19 (2019): 26842-26857.
[2] Taballione, Caterina, et al. "A universal fully reconfigurable 12-mode quantum photonic processor." Materials for Quantum Technology 1.3 (2021): 035002.
[3] Taballione, Caterina, et al. "20-mode universal quantum photonic processor." arXiv preprint arXiv:2203.01801 (2022).

Support from a well-developed photonics ecosystem

MESA+ INSTITUTE

Provide and maintain infrastructure

- 1250 m2 cleanroom (ISO 5 / ISO 7)
- 1000 m2 specialized analysis equipment

Capital efficiency

LioniX INTERNATIONAL

Manufacture TriPleX chips, process design kit (PDK)

- 2 decades of experiance with SiN photonics
- TriPleX exclusively licensed to QuiX Quantum

Speed, technological superiority

phix

Packaging the QuiX processor

- Automated packaging technology solutions for thermal and electrical contacting

Scalability, reproducibility

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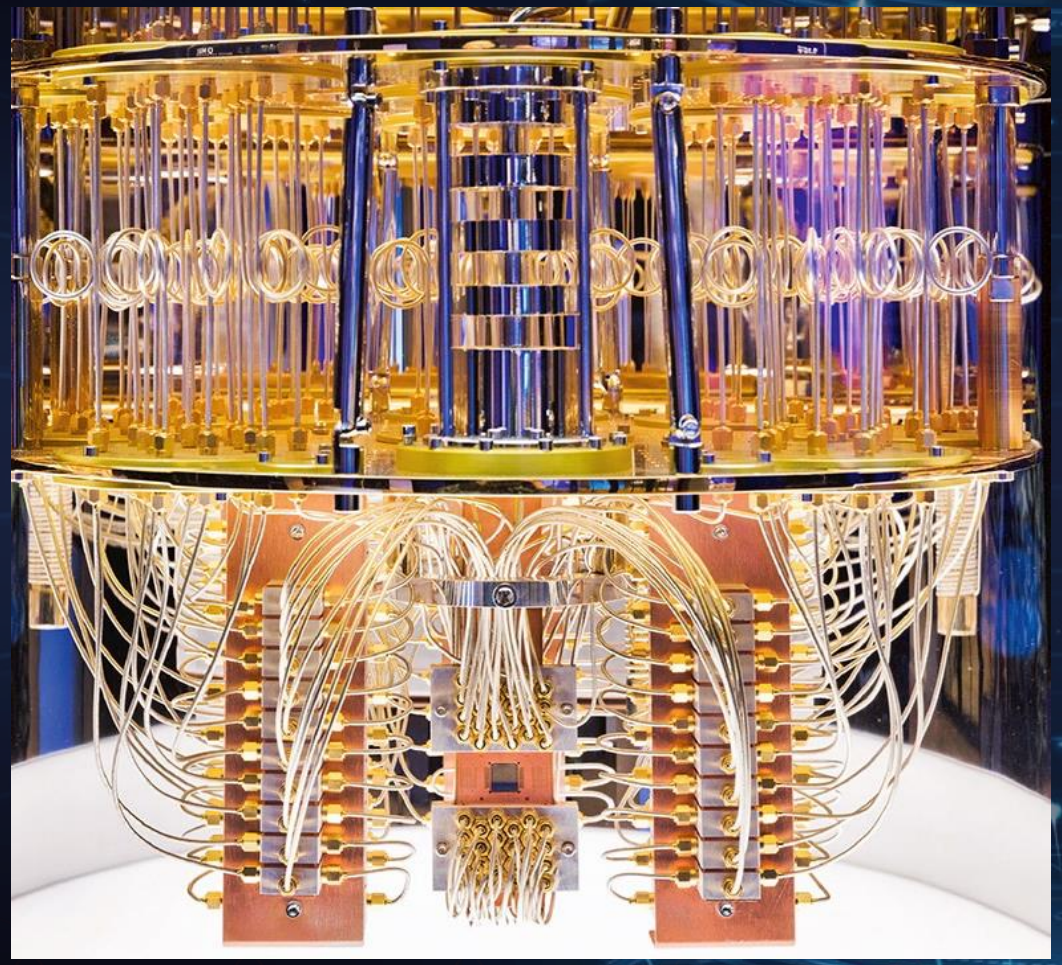
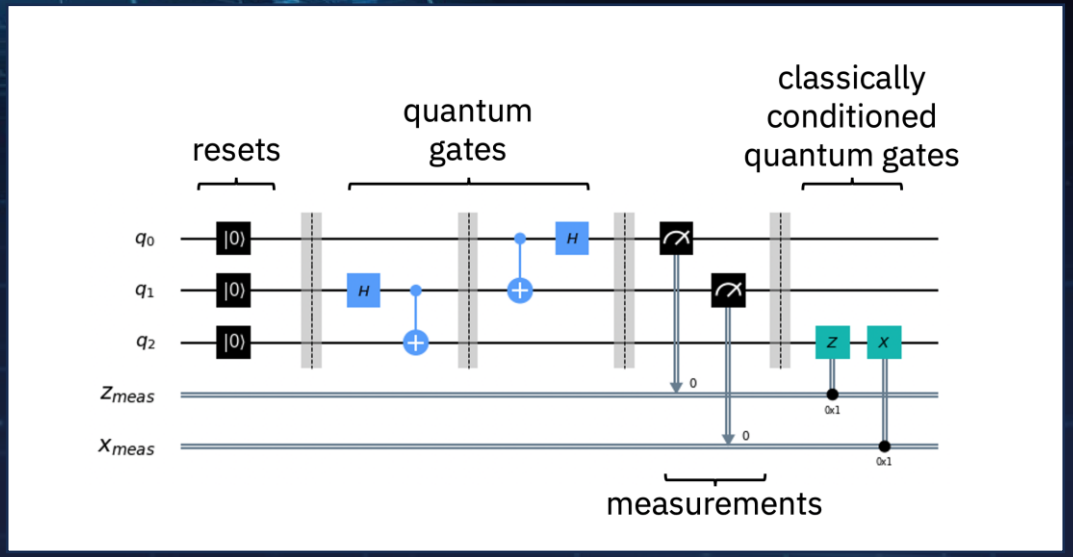
4.0 K
23 %
800 M
4.0 K
23 %
800 M
4.0 K
23 %
800 M
4.0 K
23 %
800 M

Gate-Based Quantum Computing



Source: IBM



Source: Qiskit documentation

Quantum computing in three steps!

1. Input Qubits
2. Apply gates
3. Perform measurements

Lot of technical knowhow needed to preserve the coherence of the qubits and do error correction!

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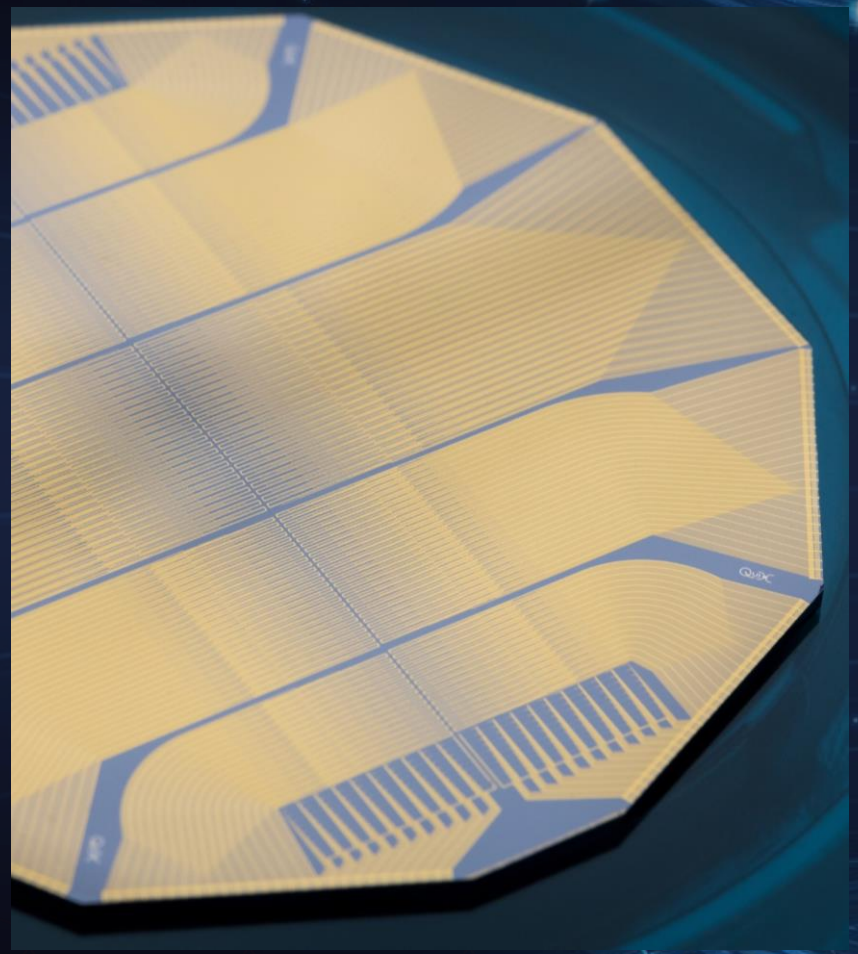
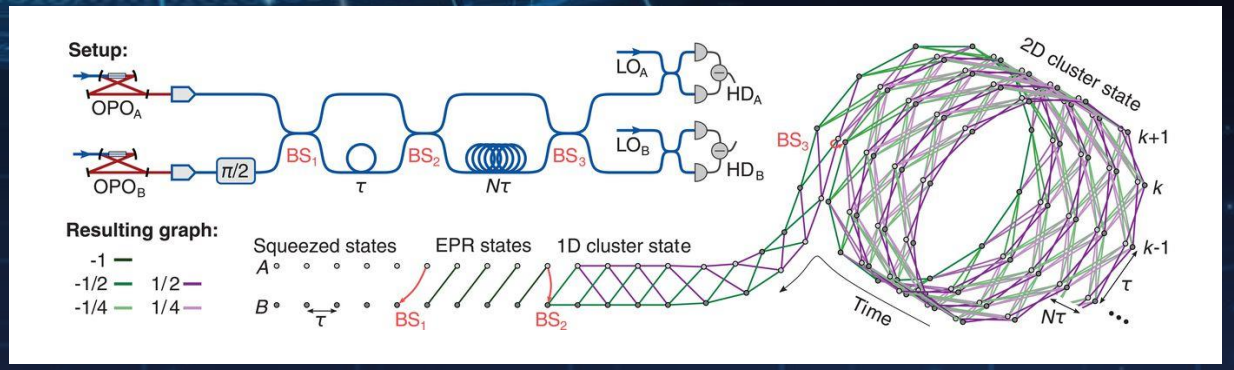
Measurement-Based Quantum Computing





Mikkel V. Larsen et al. „Deterministic generation of a two-dimensional cluster state.*Science***366**,369 372(2019). DOI:10.1126/science.aay4354

Workings of measurement based quantum computing:

1. Create a large entangled network of (photonic) qubits
2. Apply only single-qubit gates
3. Measure the qubits in selected basis
4. Depending on measurement outcome change basis and measure another qubit.

One way quantum computing is very resource efficient, establishing the cluster state is challenging.

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Core IP is scalable platform for future development requirements

Future Development Layers on TriPleX©

1+
Patent pending

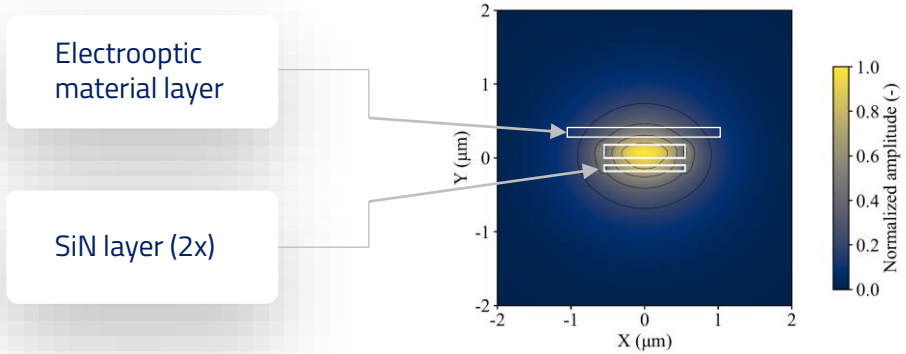
- Fast multiplexers and switches are required for efficient and powerful quantum computing
- TriPleX™ Silicon Nitride has low loss but no ability of fast electro-optic oder piezo-optic modulation. Another sandwich layer, deposited locally where fast modulation is required, enables optimized properties:
  - Switching voltages < 5 V
  - Switching times > 100 MHz
  - Power consumption < 100 mW
  - Lowest losses per unit cell

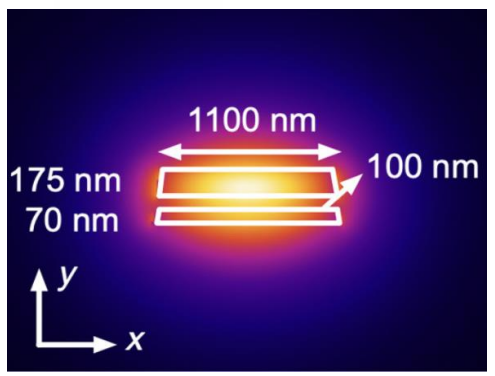
Core IP Platform TriPleX© Silicon Nitride

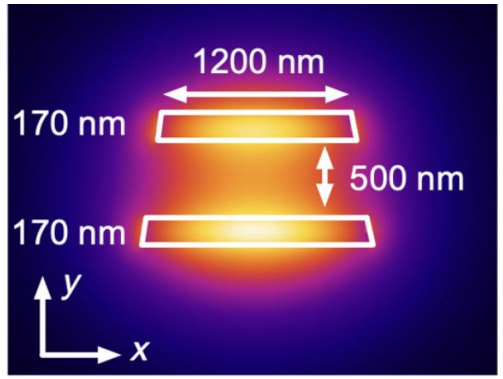
37+
Patent families

- TriPleX™ Silicon Nitride: a low loss waveguide technology for single mode laser light in 405-2350 nm wavelength range
- Low loss – down to 0.001dB per cm
- Control of signal combination/splitting, intensity, phase, mode size, polarization and input-output geometries
- Library of passive and active building blocks
- Stable over wide temperature range
- Optimized interface to fiber or free space configurations

Electronmagnetic field in SiN, SiO_2 Sandwich







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Silicon Nitride is an essential platform for quantum computing

- TriPleX™ Silicon Nitride: a low loss waveguide technology for single mode laser light in 405-2350 nm wavelength range
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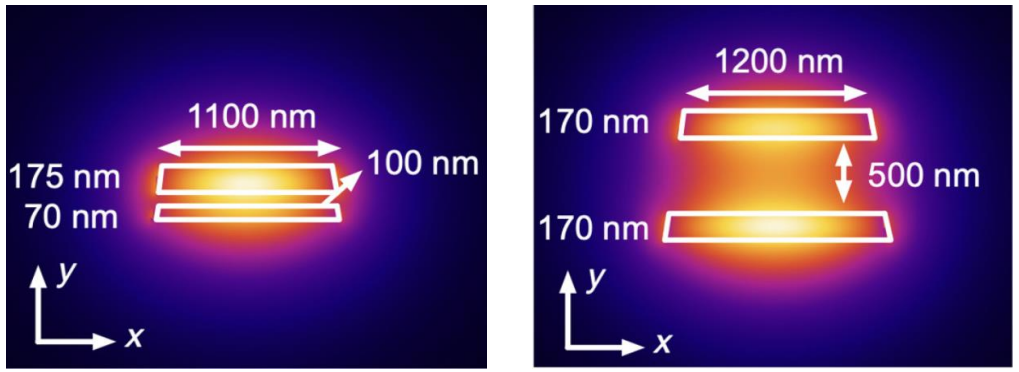

SCIENCE ADVANCES, 7 Oct 2022, Vol 8, Issue 40 DOI: 10.1126/sciadv.abq2196

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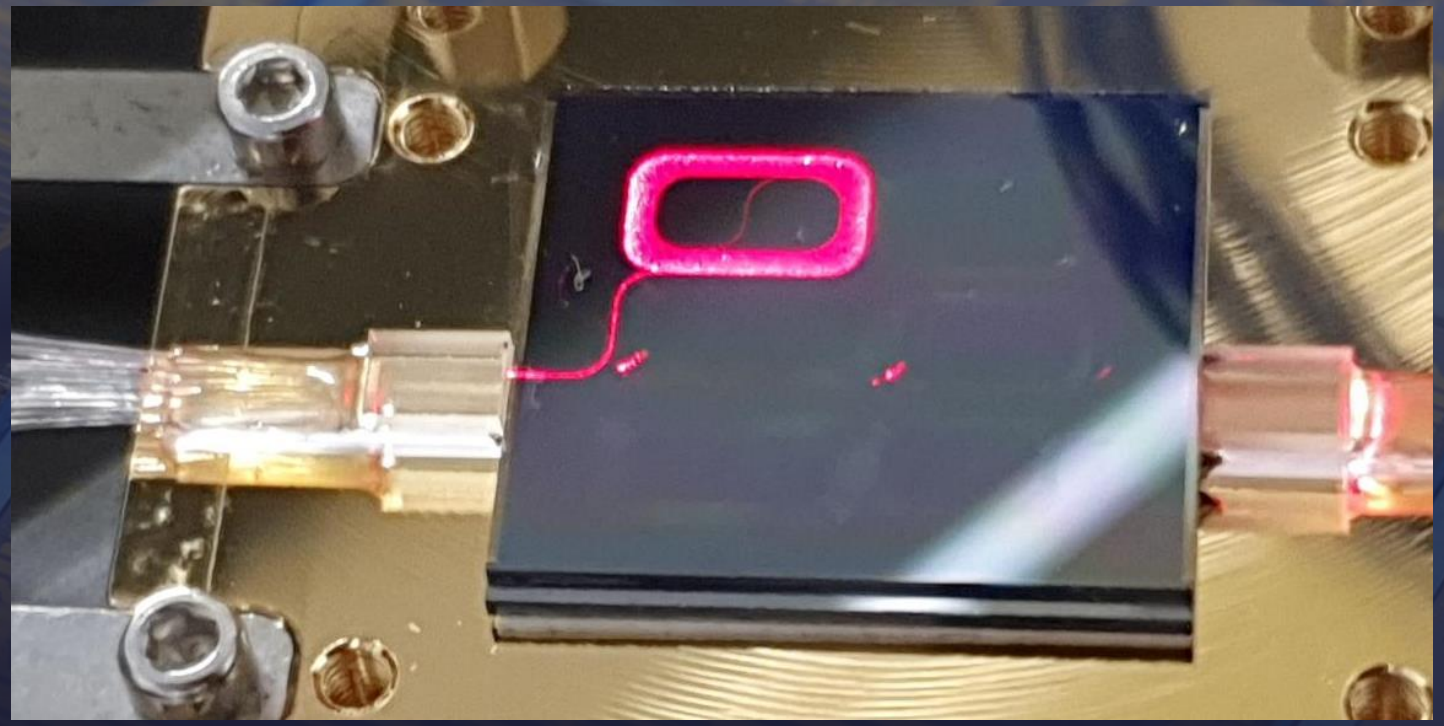
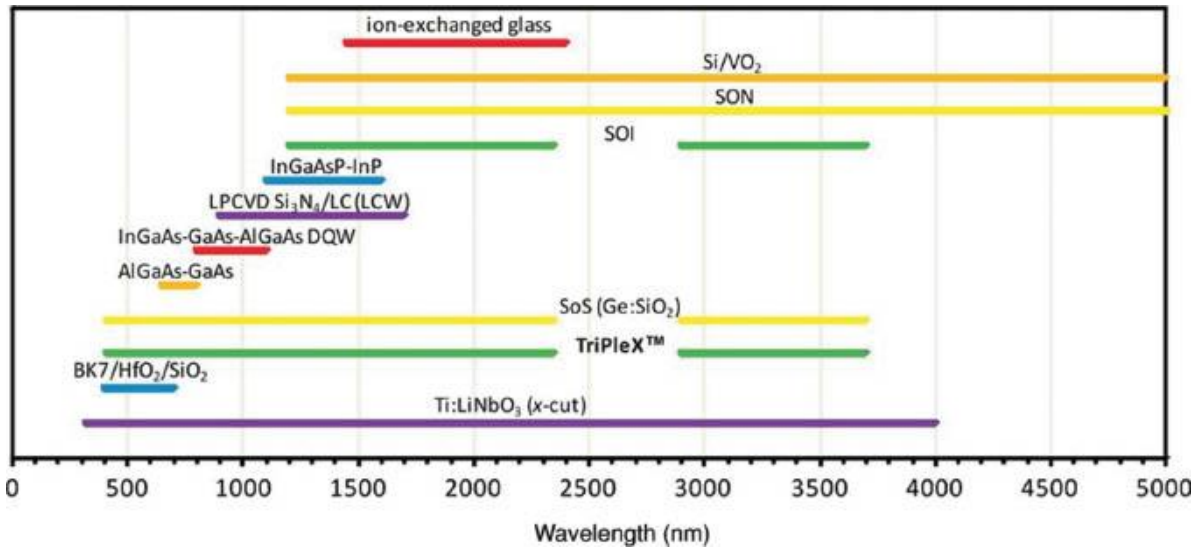
spiral waveguides with attenuation of 0.3 dB/m measured in Lab



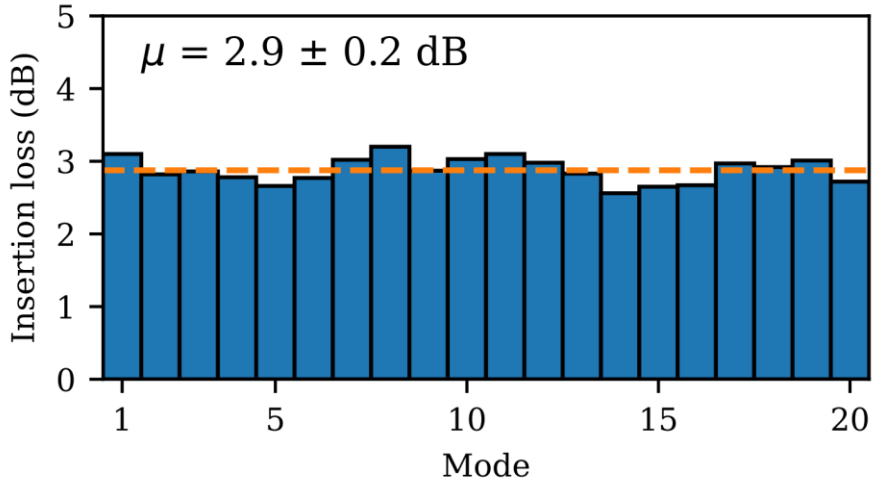
Insertion Loss < 3dB
Transparency at 9xx and 15xx



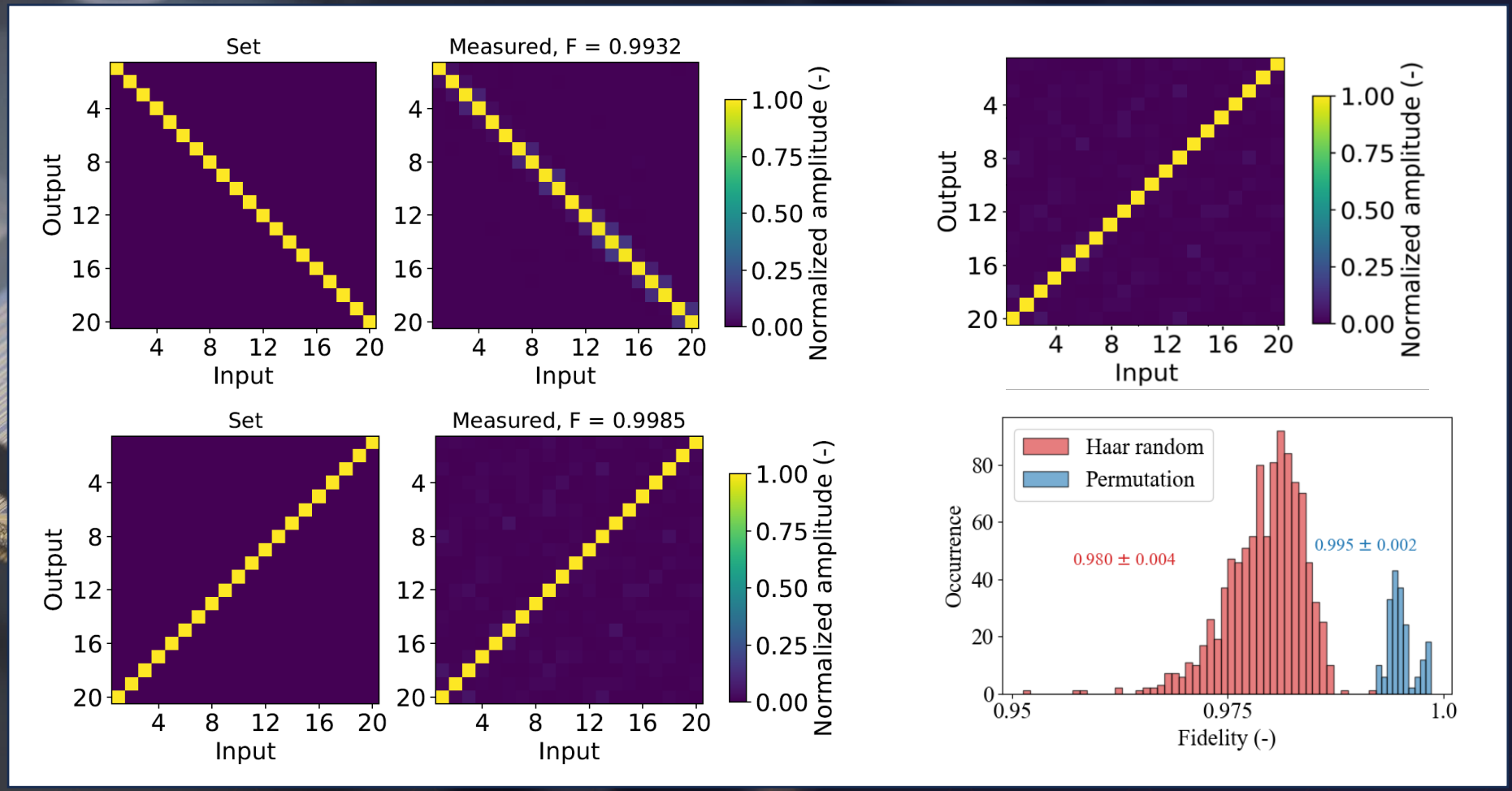
Product specifications:

Optical losses to ≤ 2.9 dB

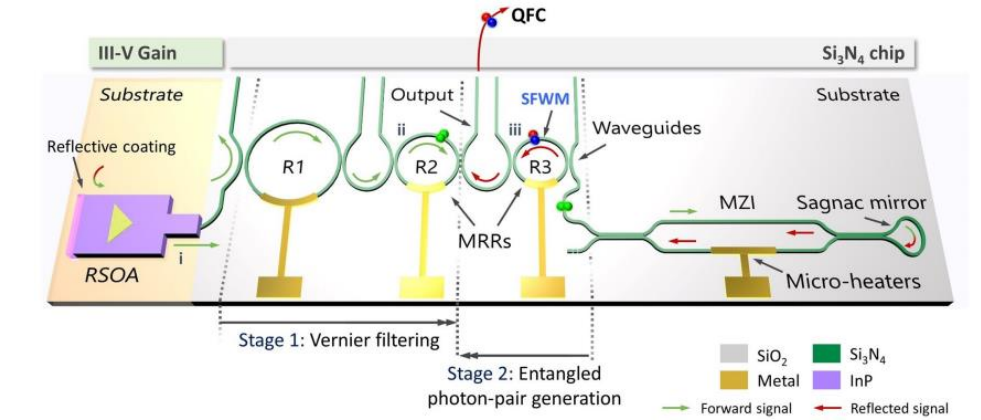
- Fiber-chip coupling: 0.7 dB/facet
- Propagation loss: 0.07 dB/cm



Fidelity and Programmability > 99 %

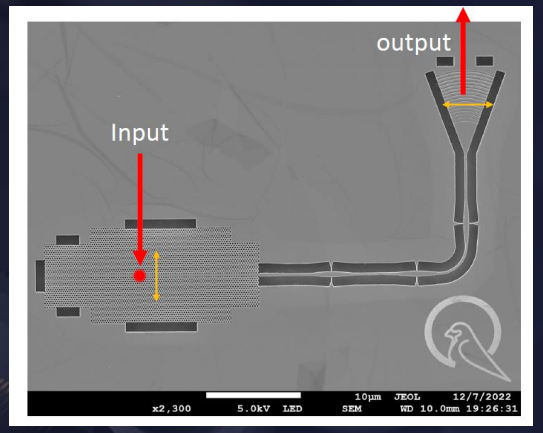


Beam sources: requirements



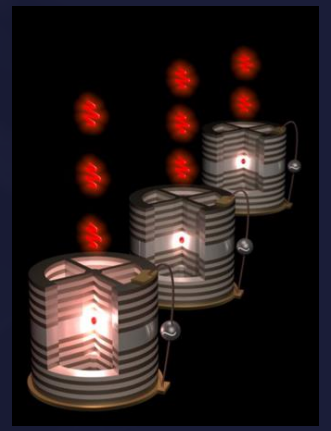
Mahmudlu et al., arXiv:2206.08715

Fully integrated photon source



Source: Sparrow Quantum

QD embedded in a photonic crystal



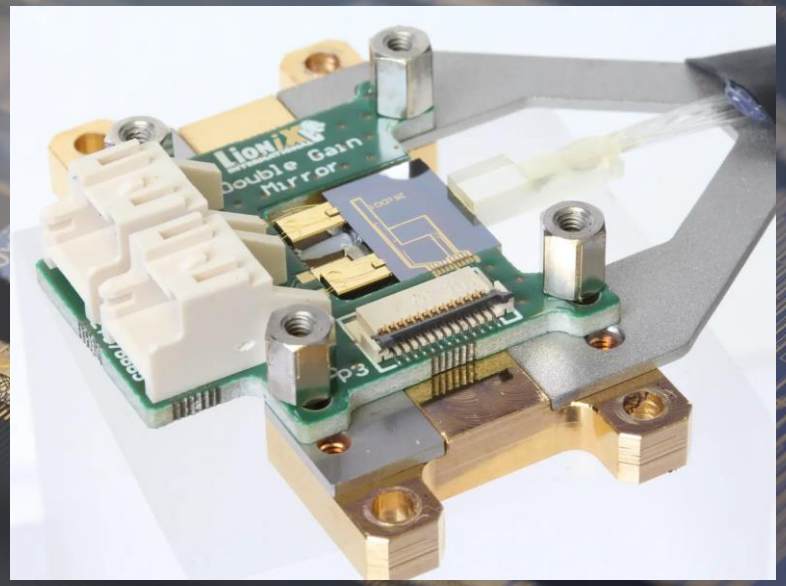
Source: Quandela

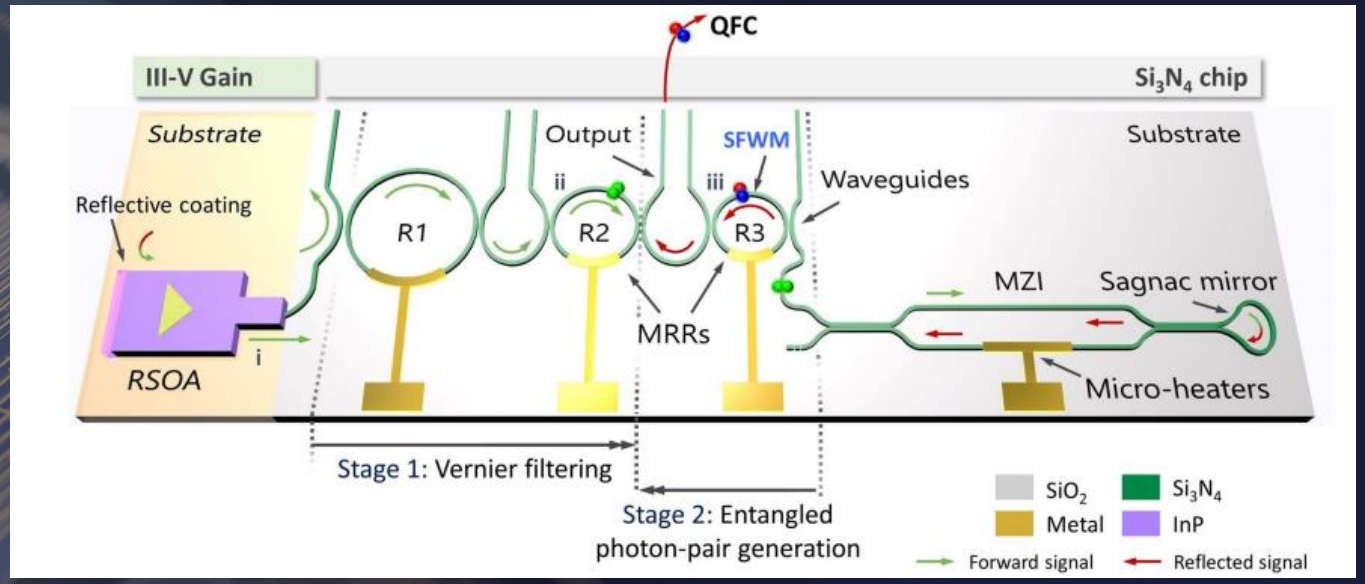
QD embedded in micropillar cavity

	GKP (CVDV)	Squeezed States (CV)	Single Photons (DV)
Minimal requirements	> 10 dB squeezing	> 15 dB of squeezing	> 90 % indistinguishability > 80 % brightness
Most promising	Optimal for error correction	Large scale cluster states demonstrated	Direct generation of linear cluster states possible
Most annoying	Probabalistic generation	Less efficient error correction schemes	Probabalistic clusterstate generation

Fully integrated, turn-key entangled photon source

Indistinguishability > 97%
Heralding efficiency > 80%





Mahmudlu et al., “Fully on-chip photonic turnkey quantum source for entangled qubit/qudit state generation“, arXiv:2206.08715

Quantum computing will make **the impossible** possible

Logistics

Route optimization

High Tech

AI & Machine Learning

Healthcare

Personalized medicines & incredibly fast drug discovery

Engineering

Simulate chemical and biological systems

Finance

Fraud detection & trading

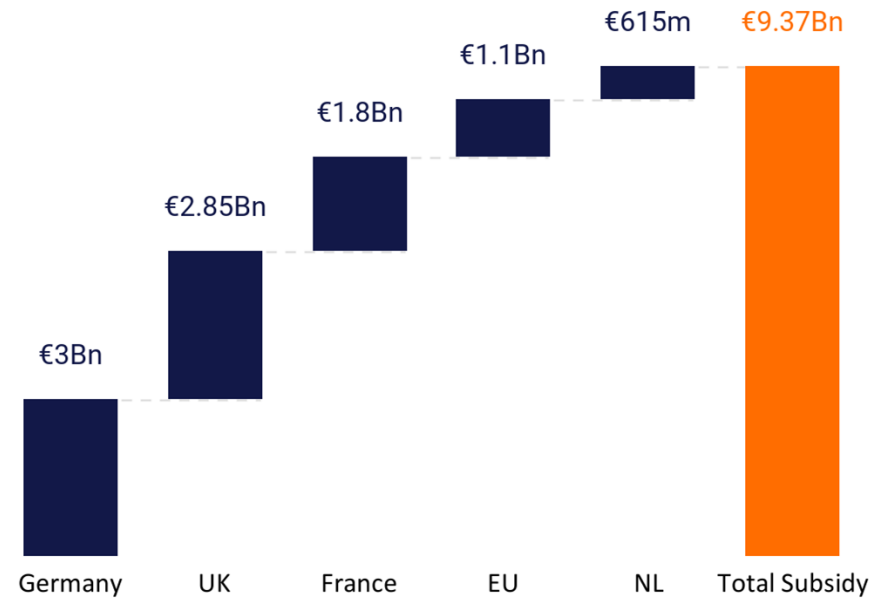
The QC Market will be large, but seems difficult to forecast

- Wildly different numbers are projected by market research companies
- But concensus is that after 2025 the market will be several B$ and after 2030 10's of B$

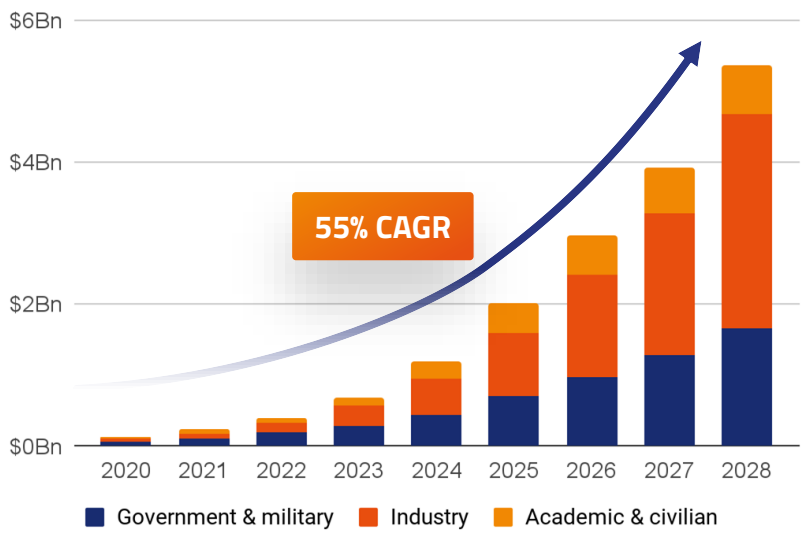
Publised by		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2040	CAGR	CAGR Period
2020	Fortune Business Insights		555	712							4,758					31%	2022-2029
2021	IDC	412							8,600							54%	2021-2027
2021	Brandessence Market Research	359							2,075							29%	2020-2027
2021	Quantum Insider						4,000					26,000				45%	2021-2030
2021	Quantum Insider – Low		300				3,500					18,000				39%	2025-2030
2021	Quantum Insider – High		1,300				10,000					65,000				45%	2025-2030
2021	Verified Market Research	252								1,797						30%	2021-2028
2022	Research and Markets		391					1,600								33%	2021-2026
2022	Market Research Future											18,160				34%	2022-2032
2022	Fortune Business Insights		486							3,181						31%	2021-2028
2023	Markets and Markets				866					4,375						38%	2023-2028
2023	Market Watch		236							1,988						35%	2022-2028
2023	Omdia			942										22,000		37%	2022-2032
2023	McKinsey - Low														9,000		
2023	McKinsey - High														93,000		
	Min	**252**	**236**	**712**	**866**	**0**	**3,500**	**1,600**	**2,075**	**1,797**	**4,758**	**18,000**	**0**	**22,000**	**9,000**		
	Max	**412**	**1,300**	**942**	**866**	**0**	**10,000**	**1,600**	**8,600**	**4,375**	**4,758**	**65,000**	**0**	**22,000**	**93,000**		

We are accessing a fast growing, billion euro market

Current subsidy market for next ~10 years



QC market for hardware and cloud services



Subsidy market: McKinsey Global Institute. 2023, April 24. Quantum technology sees record investments, progress on talent gap.
QC market size: Inside Quantum Technology, Quantum Network: A ten-year forecast and opportunity analysis. September 2020