aCryComm: attojoule Cryogenic Communication

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Quantum Science and Technology seminar

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Quantum Technology Finland

European Commission

HORIZON 2020

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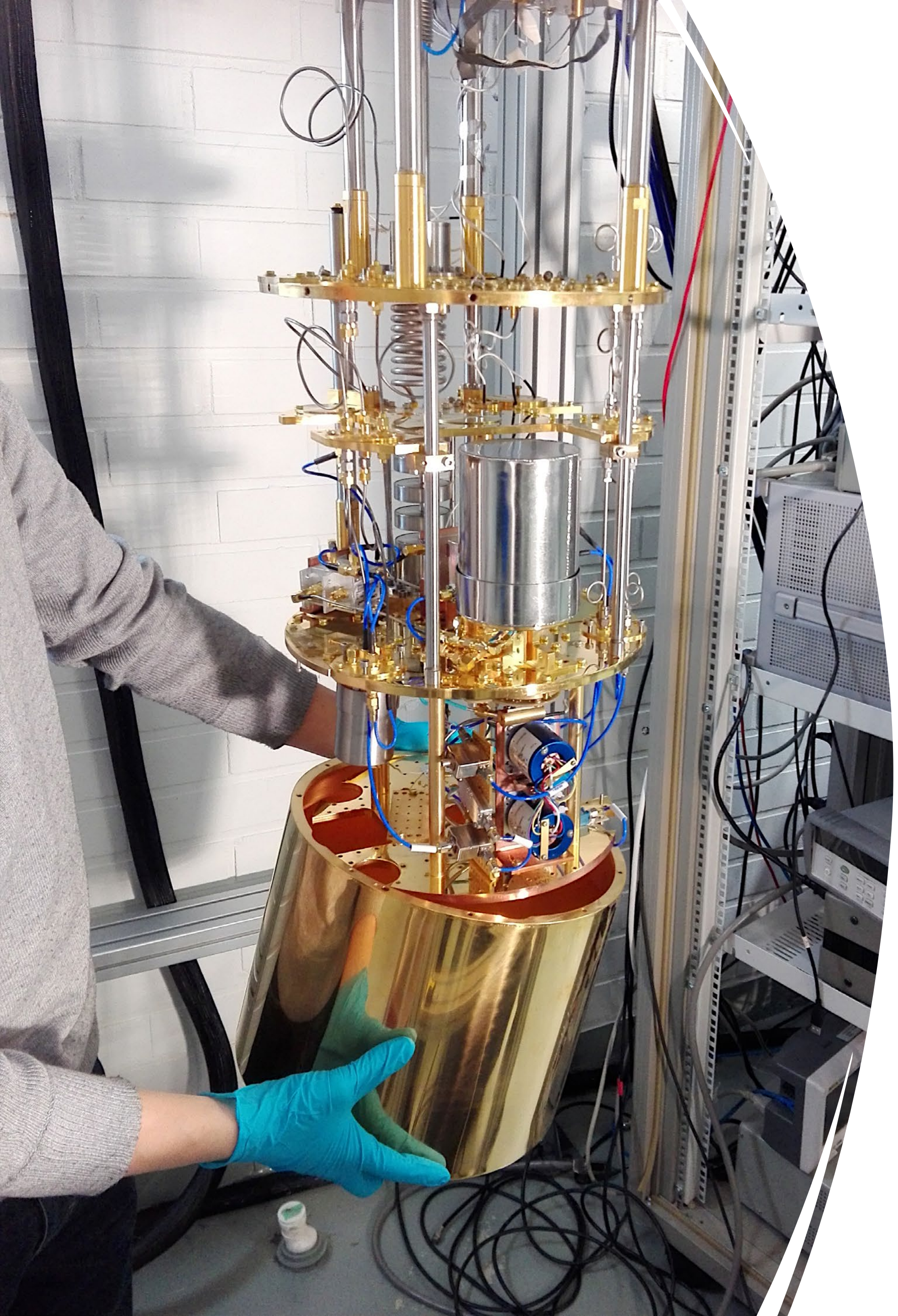
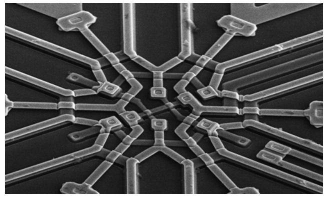


Outline

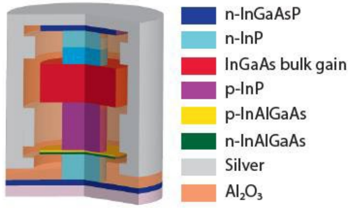
- aCryComm in a nutshell
- Our vision
- SFQ electronics
- Our proposed solutions
- Cryogenic OE conversion
- Cryogenic EO conversion
- Cryogenic packaging
- Conclusion

aCryComm in a nutshell

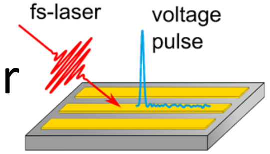
VTT
- Quantum technology team
- Silicon photonics team
- Electrical metrology group (MIKES)



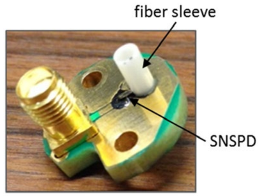
Tampere University Optoelectronic Research Centre, Prof. Mircea Guina



PTB Physikalisch Technische Bundesanstalt Braunschweig und Berlin Electricity division, Dr Mark Bieler

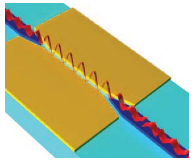


KTH VETENSKAP OCH KONST Quantum Nano Photonics group, Prof. Val Zwiller

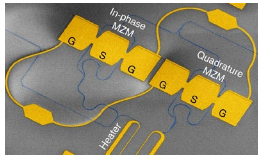


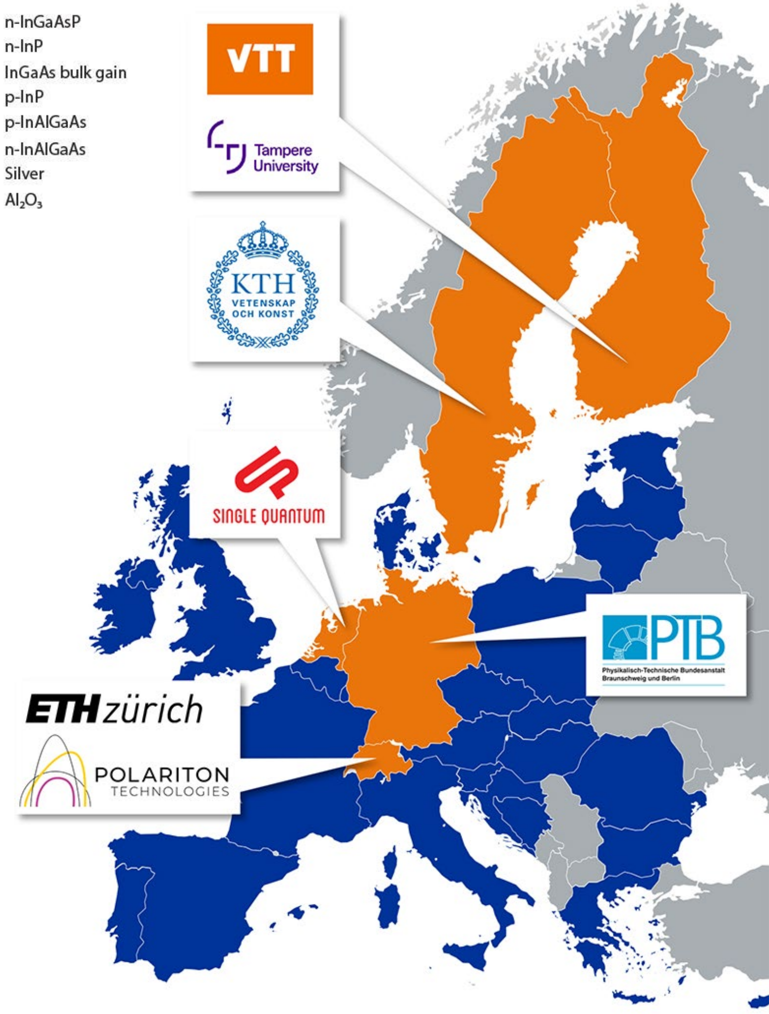
SINGLE QUANTUM SNSPDs , CEO Sander Dorenbos

ETH zürich Institute of Electromagnetic Fields, Prof. Juerg Leuthold



POLARITON TECHNOLOGIES Plasmonic modulators, CEO Claudia Hössbacher





Project duration: October 2020 - September 2023

EU contribution: € 3 016 372,50

www.aCryComm.eu

Our vision

Supercomputer today

- Air conditioned room ≈20°C, liquid cooling of processors;
- Up to 200 MW overall power consumption: need a dedicated power plant

Supercomputer in 5 years?

a Cry Comm

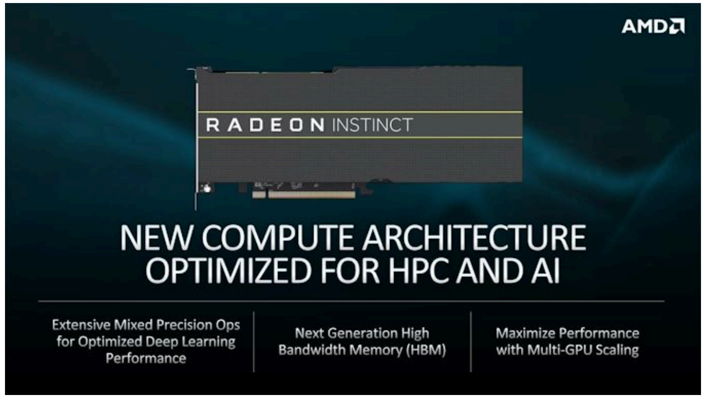
Introduce superconducting classical co-processor units
high speed + energy efficiency

Supercomputer in 10 years?

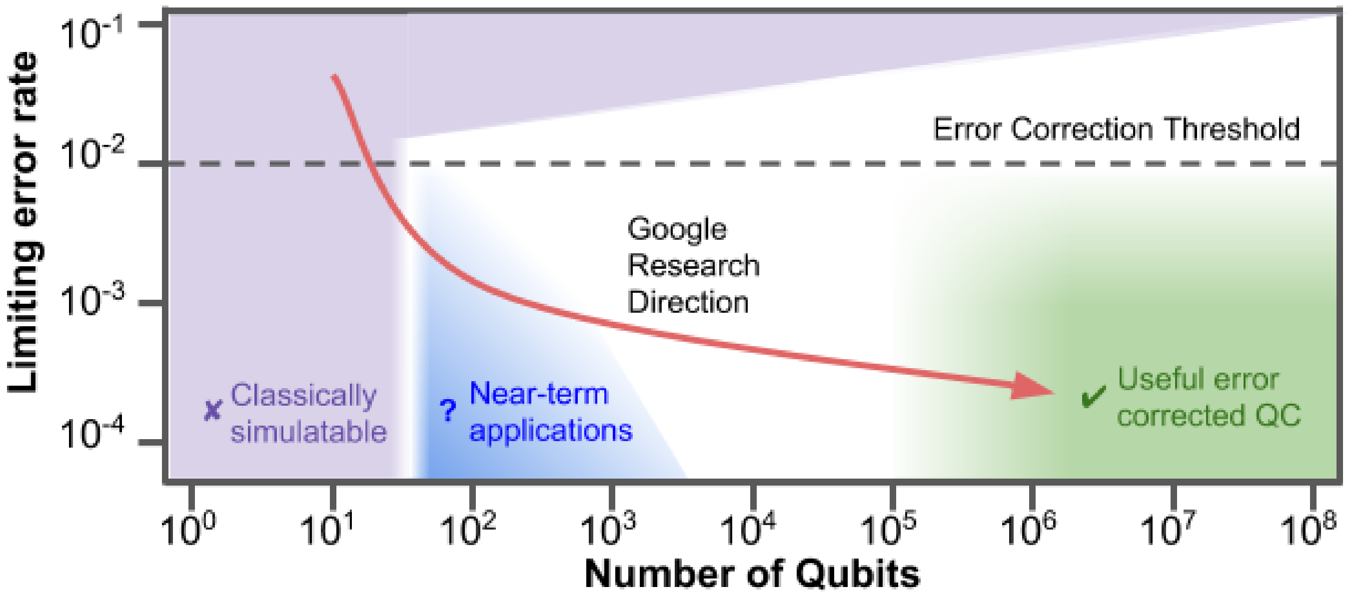
Introduce superconducting <u>quantum</u> co-processor units to exploit quantum advantage

Case 1: HPC power consumption

- Graphics Processing Units (GPUs) play a key role in modern High Performance Computers (HPC) thanks to their superior handling of matrix and vector operations
- GPUs have helped improving the overall efficiency compared to CPU-only architectures
- Still, GPUs play a major role in power consumption of modern HPC architectures



Case 2: Scaling-up quantum computers



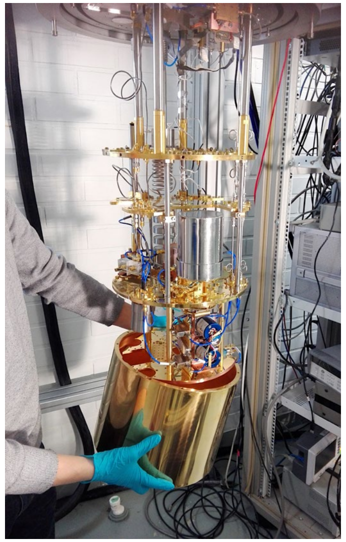
(source: Google https://ai.googleblog.com/2018/03/a-preview-of-bristlecone-googles-new.html)

The operating environment and control systems need a quantum leap, too!

The state-of-art cryostat (Bluefors Oy) with control RF cabling (220 coaxial cables).

Cooling and cryogenics

larger fridges, closed-cycle solutions are available



major leap

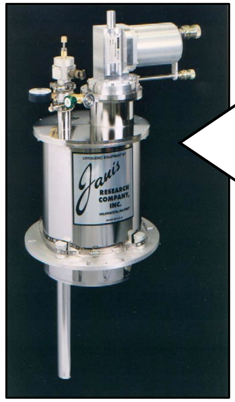
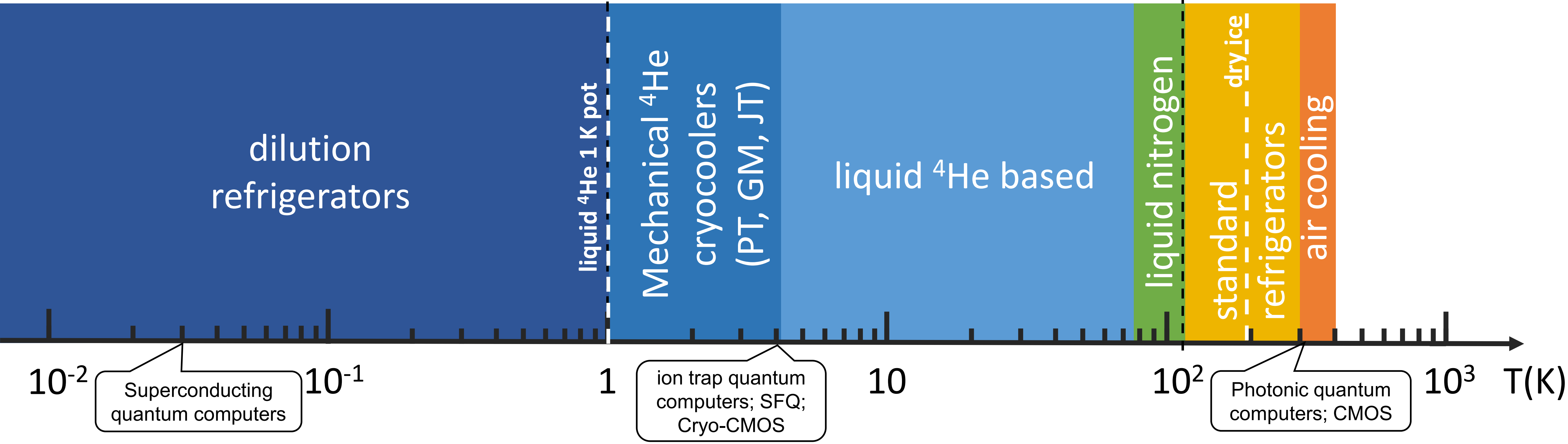


table-top, closed-cycle solutions are available

cryogenic | non-cryogenic*

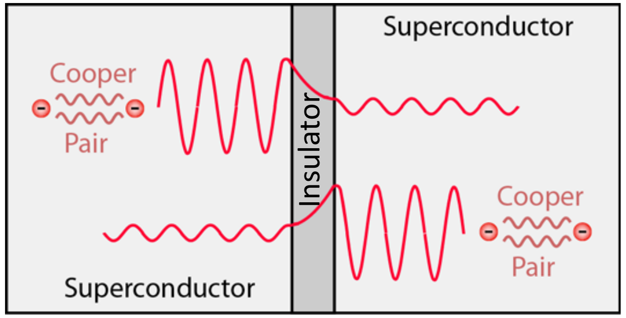
*13th IIR International Congress of Refrigeration, 1971



SFQ electronics

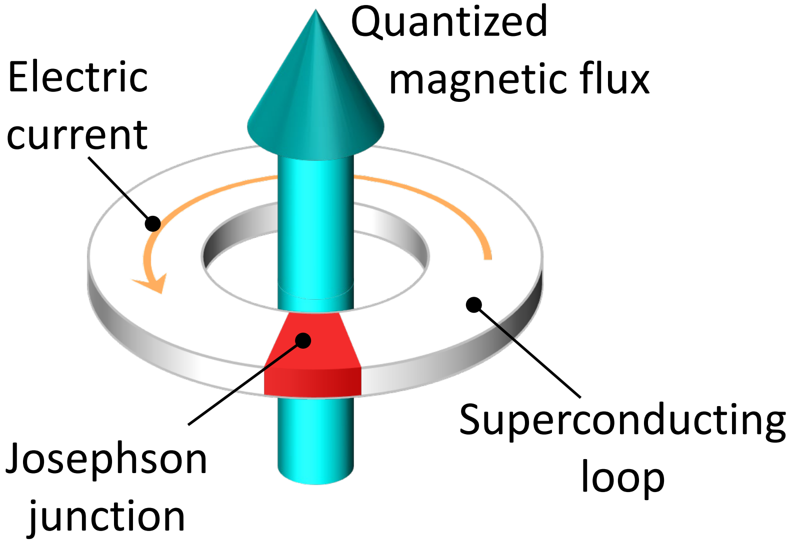
Superconducting electronics

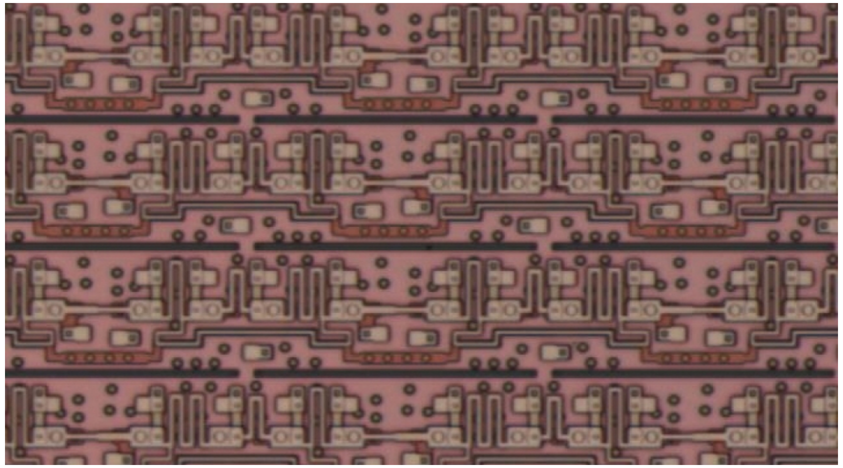
Josephson junction



hyperphysics.phy-astr.gsu.edu

Basic building block



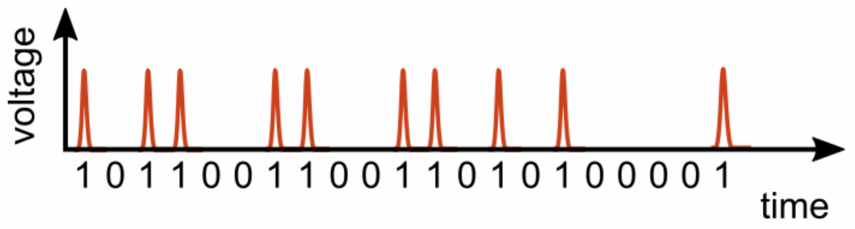


LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Up to ≈ 1M Josephson Junctions thanks to multi-metal-layer fabrication processes

Basic Facts

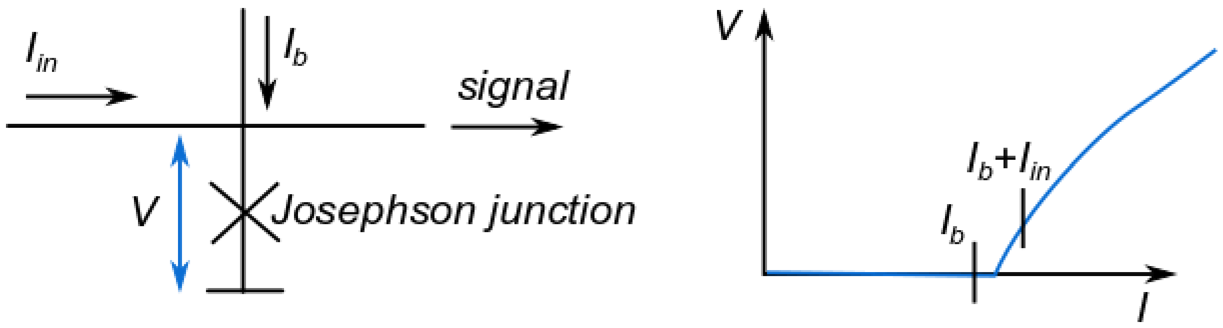
- SFQ stand for "Single flux quantum"
- Can be used to fabricate similar circuits as classical logic
- Based on driving pulses in Josephson junction logical circuit

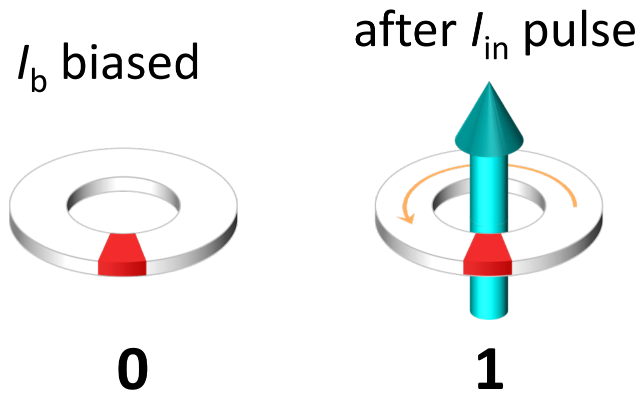


- Figures of Merit:
  - Parameters depend on the parameters of Josephson junctions
  - Voltages usually **few millivolts**
  - Current from few **micro to milli amperes**
  - Frequencies from **tens to hundreds of gigahertzs**
  - Power consumption depends on design, ultimately limited by the Josephson junctions (typically small **fractions of attoJoules** per junction per pulse)

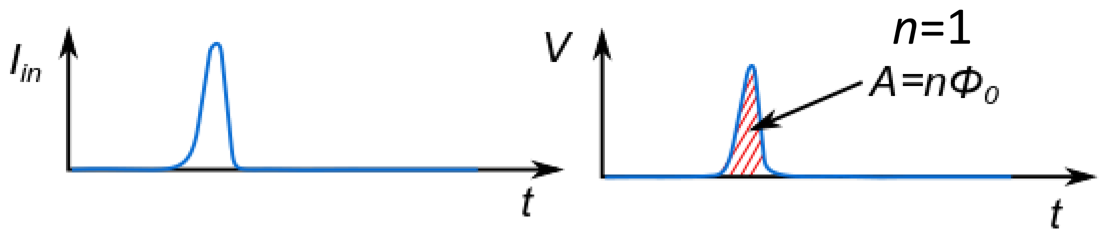
Basic Principles

- In SFQ the Josephson junctions are biased **near their critical current**
  - When additional current I_{in} is applied the junction will **switch** to normal state and voltage will be present



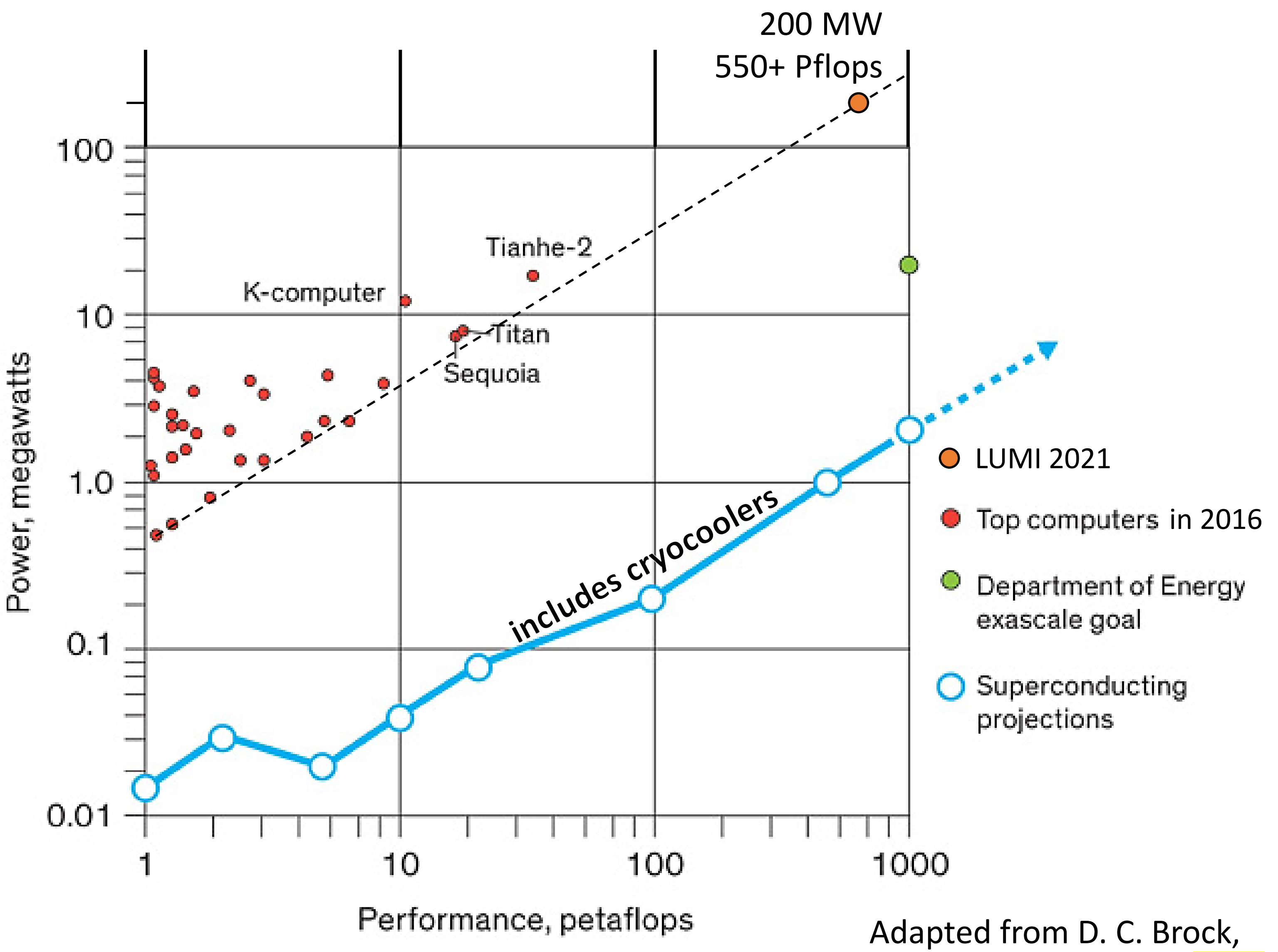


- SFQ is driven with **pulses**
  - Due to quantum effects the area under voltage pulse will be a multiple of flux quantum $A \propto \Phi_0 = h/2e$



Power consumption

- In the USA, Japan and China there are efforts to build exascale superconducting supercomputers
- Projections indicate **2 orders of magnitude** improvement on energy efficiency compared to CMOS, when including also the cryocoolers.

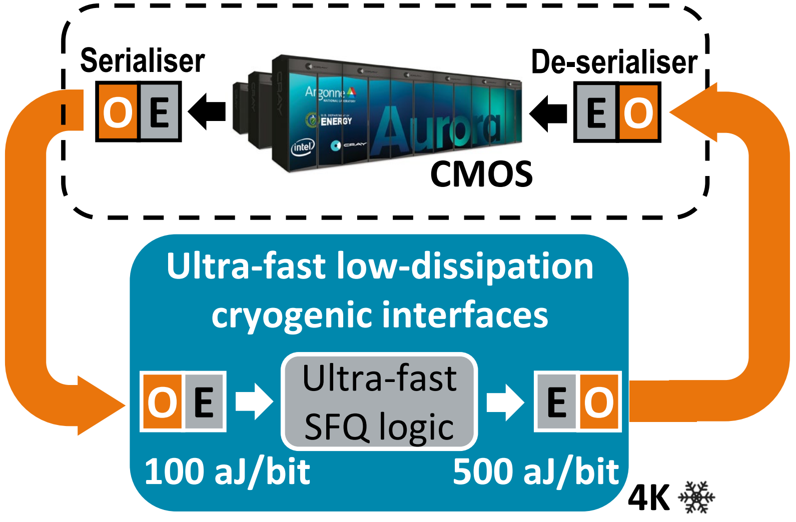


Adapted from D. C. Brock, IEEE Spectrum **53**, 54 (2016)

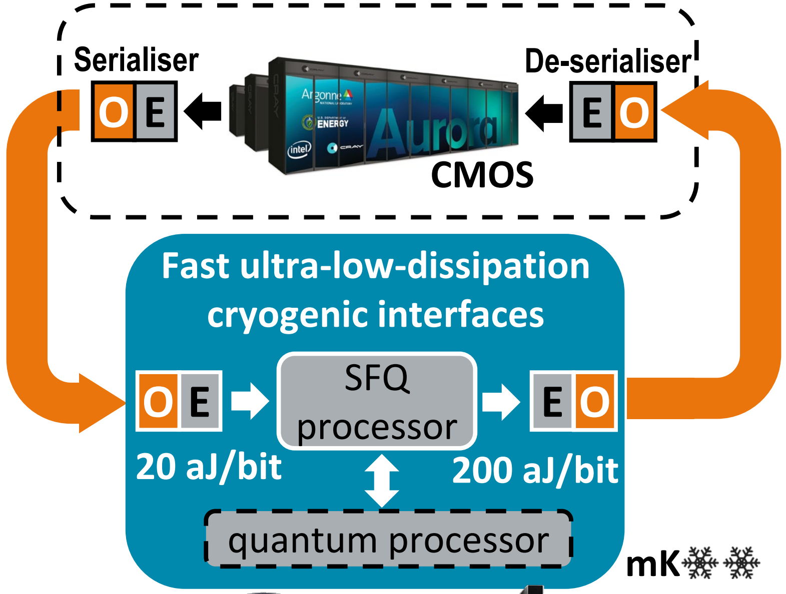
Our proposed solutions

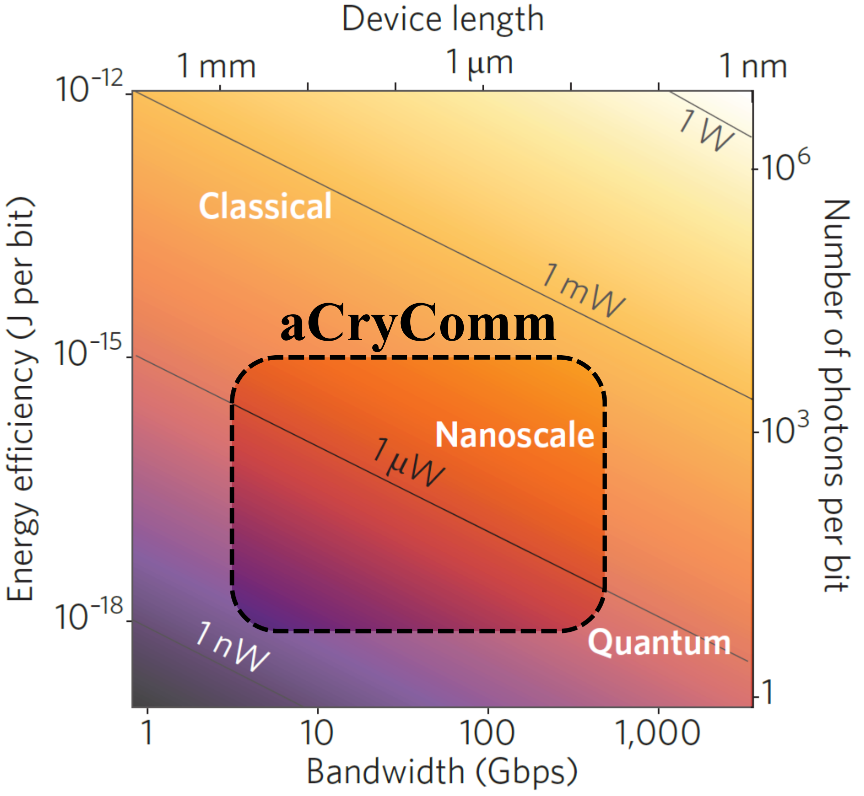
Long term targets

Target 1: Computing beyond CMOS
Fast SFQ co-processors for HPC



Target 2: Quantum computing
CMOS HPC for quantum error correction



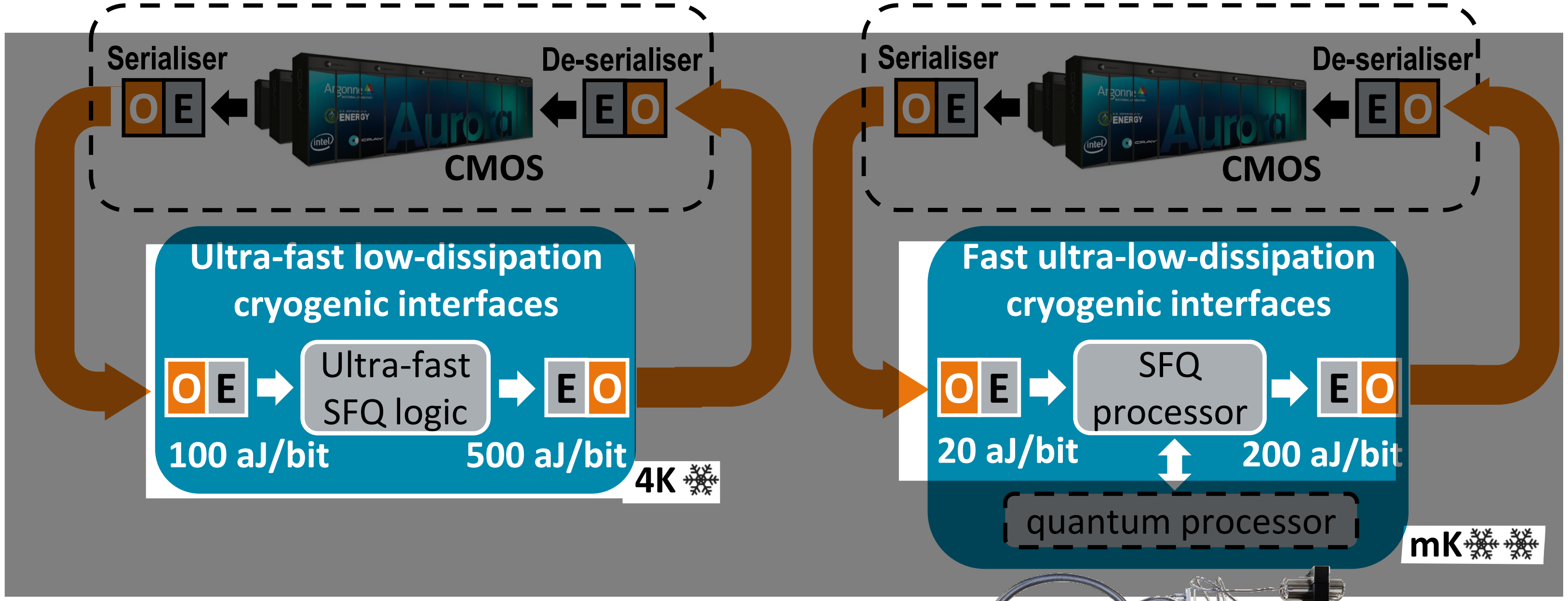


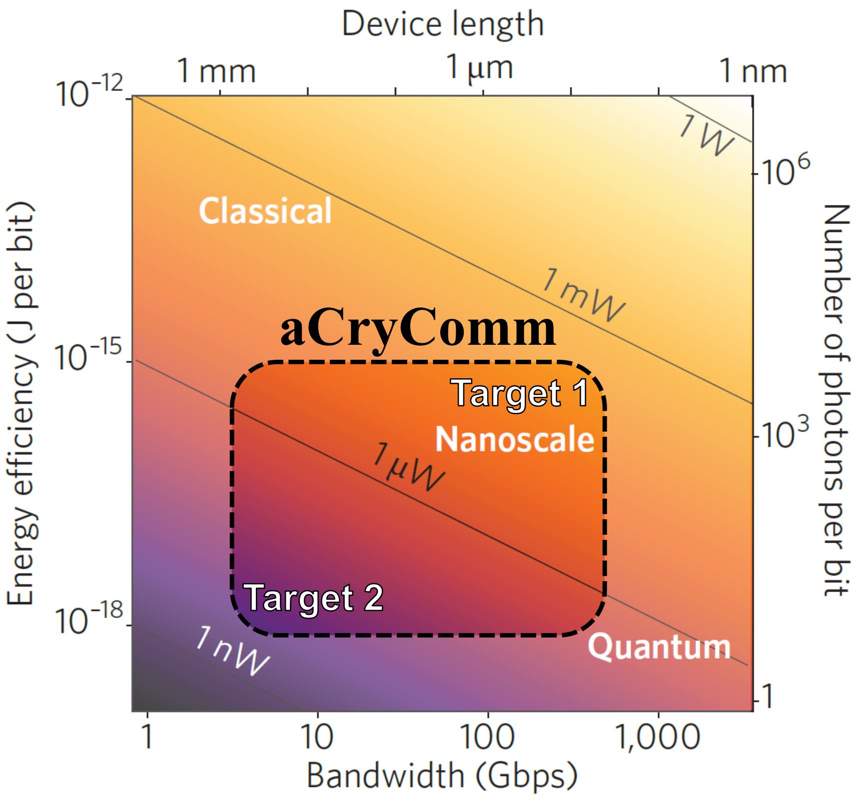
V. J. Sorger, *Nat. Nanotechnol.* **10**, 14 (2015)

aCryComm focus

Target 1: Computing beyond CMOS
Fast SFQ co-processors for HPC

Target 2: Quantum computing
CMOS HPC for quantum error correction



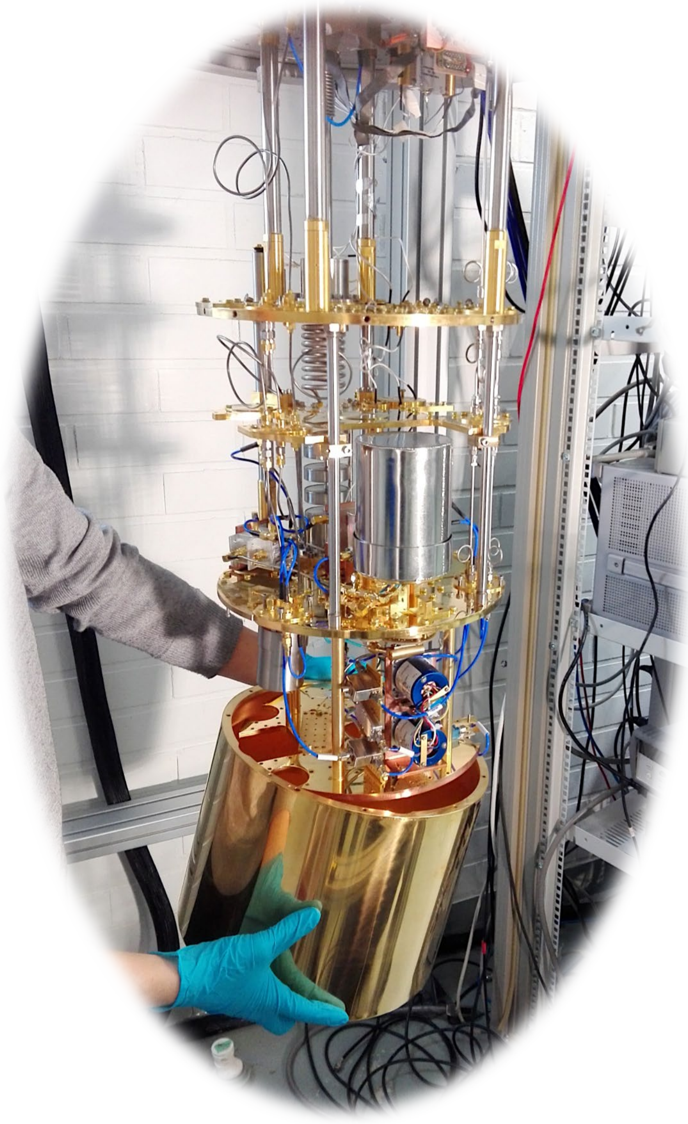


V. J. Sorger, *Nat. Nanotechnol.* **10**, 14 (2015)

Metrics

	Power consumption	Bandwidth/footprint
OE conversion @ 4 K	100 aJ/bit	1 Tbit/s/cm² (E.g. 100 Gbit/s speed, 10 mm² footprint)
EO conversion @ 4 K	500 aJ/bit	1 Tbit/s/cm² (E.g. 100 Gbit/s speed, 10 mm² footprint)
OE conversion @ 20 mK	20 aJ/bit	100 Gbit/s/cm² (E.g. 10 Gbit/s speed, 10 mm² footprint)
EO conversion @ 20 mK	200 aJ/bit	100 Gbit/s/cm² (E.g. 10 Gbit/s speed, 10 mm² footprint)

Challenges and opportunities



Challenges

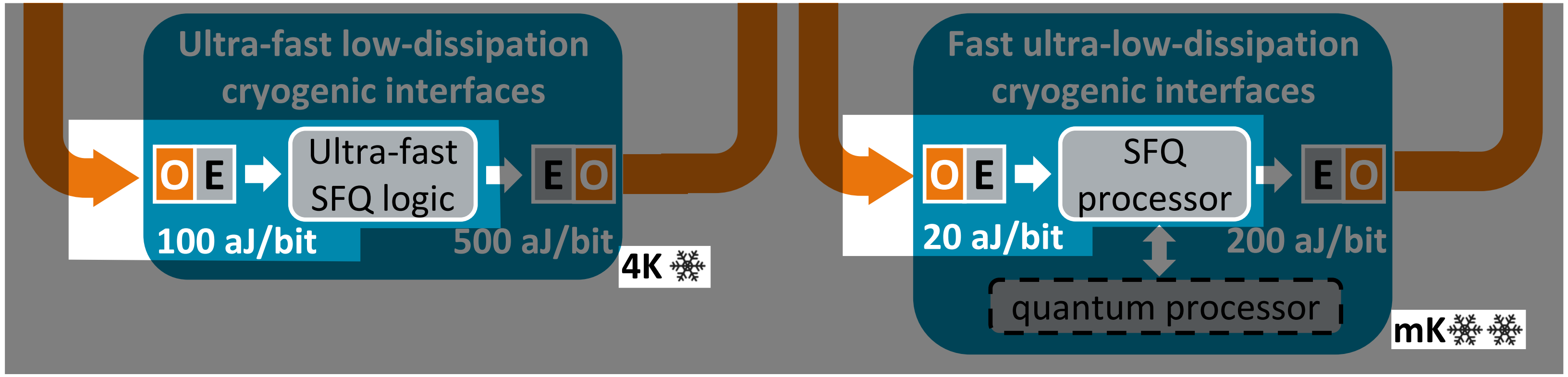
- **Mechanical** behaviour of material and their combinations
- **Nonlinear** optical coefficients can be smaller at cryo T
- Carrier **freeze-out** (dopings must be careful designed)
- **Cannot dissipate** much heat per bit, especially in the mK regime and especially at high bit rates
- SFQ logic has inherent **low-energy and low voltage**

Opportunities

- Can use **superconductors** also for photonics (e.g. SNSPDs)
- **Lower optical losses in metals**: perfect case for plasmonic devices, that don't require any dopant
- **Lower thermal noise**
  - cleaner driving signals
  - more efficient drive of light sources
  - can better exploit thresholds

Cryogenic
OE conversion

OE conversion

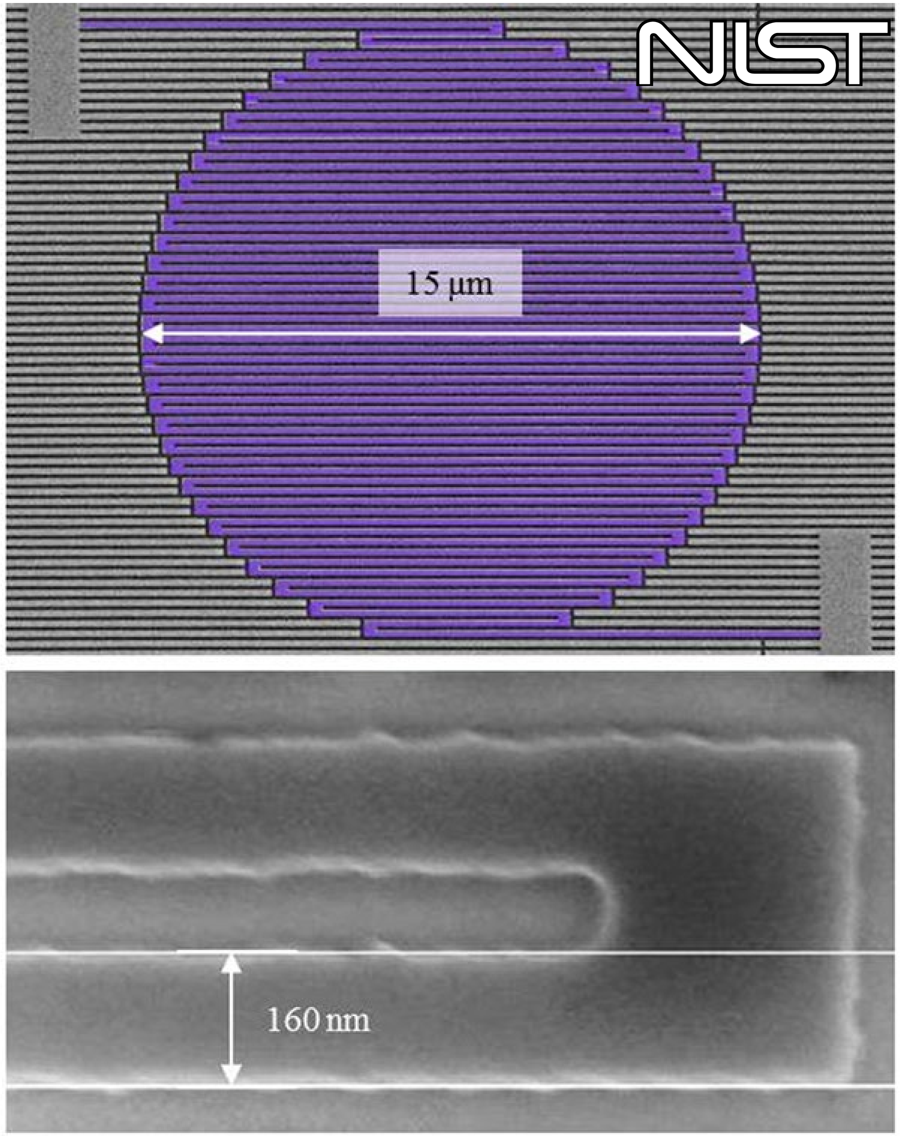


Need to develop converters of photonic signals into electrical signals, i.e. **photodetectors**

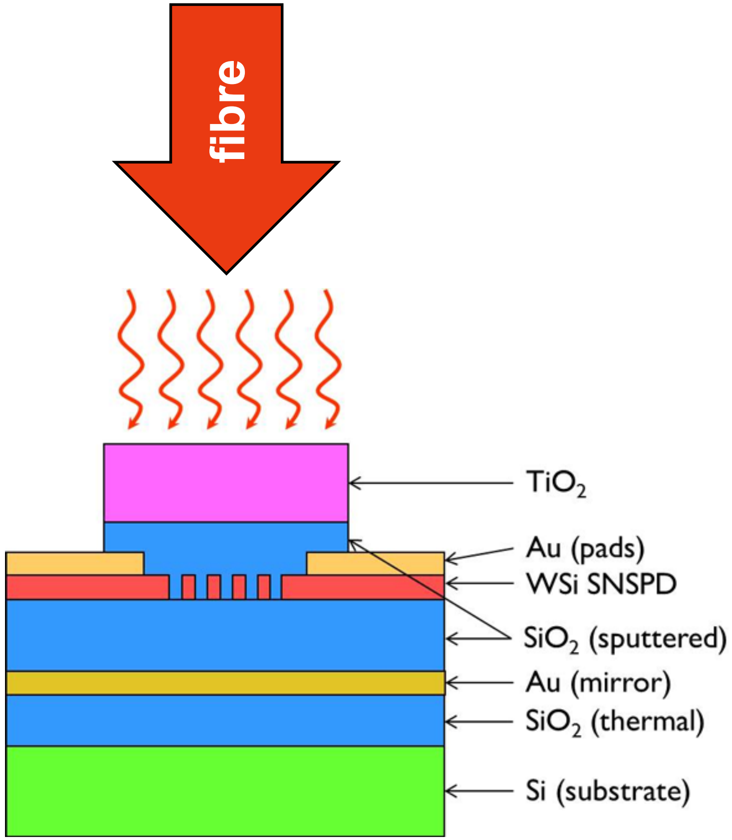
- for cryogenic operation
- energy efficient
- fast
- suitable to drive SFQ logic

SNSPD

Superconducting Nanowire Single Photon Detector



Marsili et al., *Nature Photon* **7,** 210 (2013)

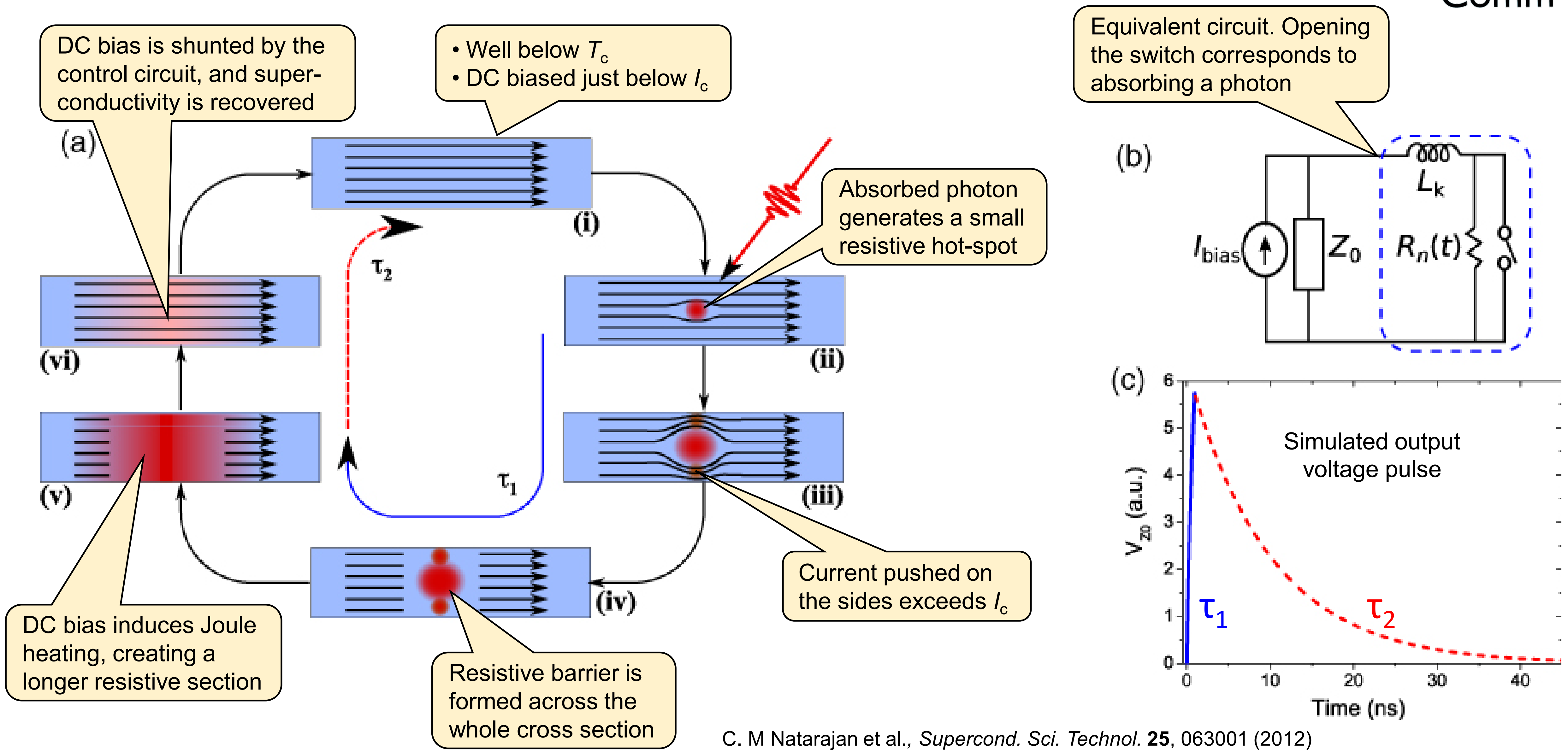


- 93% efficiency @1550 nm
- 140 ps time jitter
- 40 ns recovery time
- dark count rate: 1 KHz (fibre coupled)

Specifications

Optimization wavelength	800 nm	1550 nm
System detection efficiency	≥ 90%	≥ 85%
Dark count rate	≤ 10 Hz	≤ 300 Hz
Standard timing jitter	≤ 40 ps	≤ 50 ps
Optional low timing jitter	≤ 15 ps	≤ 25 ps
Dead time[1]	≤ 10 ns	≤ 30 ns
Maximum count rate[2]	≥ 80 MHz	≥ 50 MHz
Output pulse height	≥ 200 mV	≥ 200 mV
Number of channels	1-24	

SNSPD: working principle

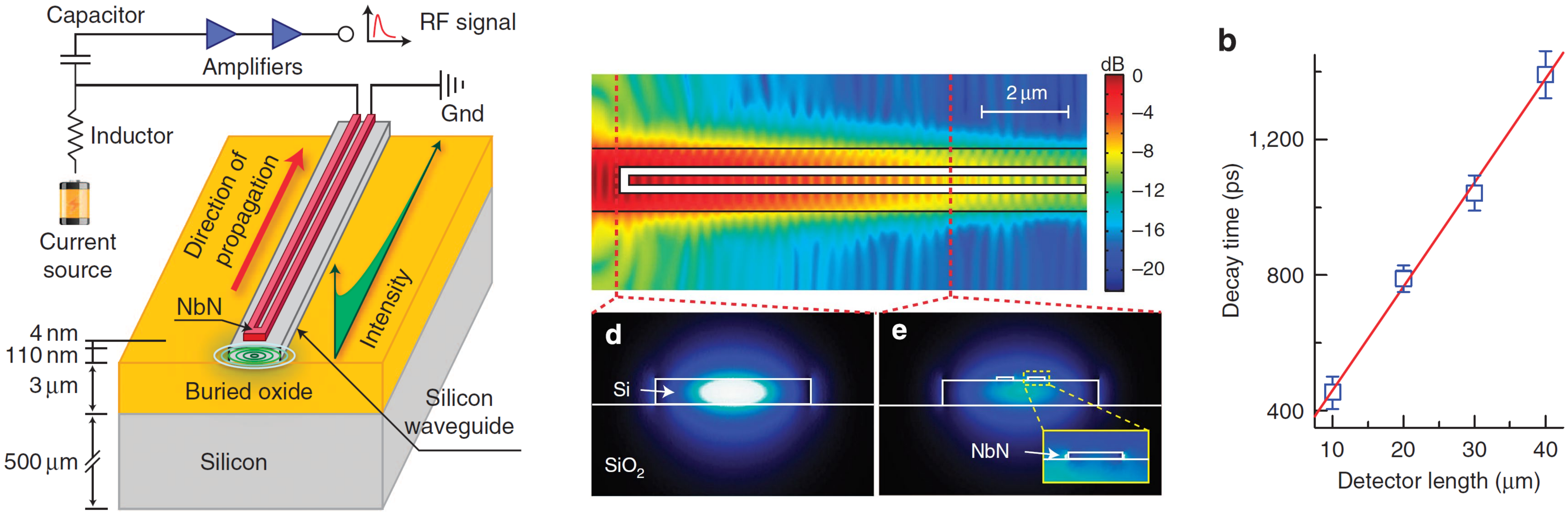


C. M Natarajan et al., *Supercond. Sci. Technol.* **25**, 063001 (2012)

Guided-wave SNSPD

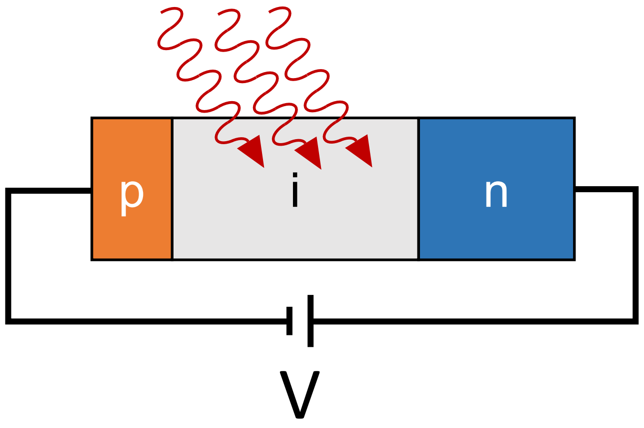
2 orders of magnitude shorter nanowire

- 91% internal efficiency at 1550 nm
- 18 ps time jitter (1 order of magnitude smaller)
- < 1 ns recovery time (up to 2 orders of magnitude smaller)
- As low as 50 Hz dark count rate achieved (1.5 orders of magnitude improvement)

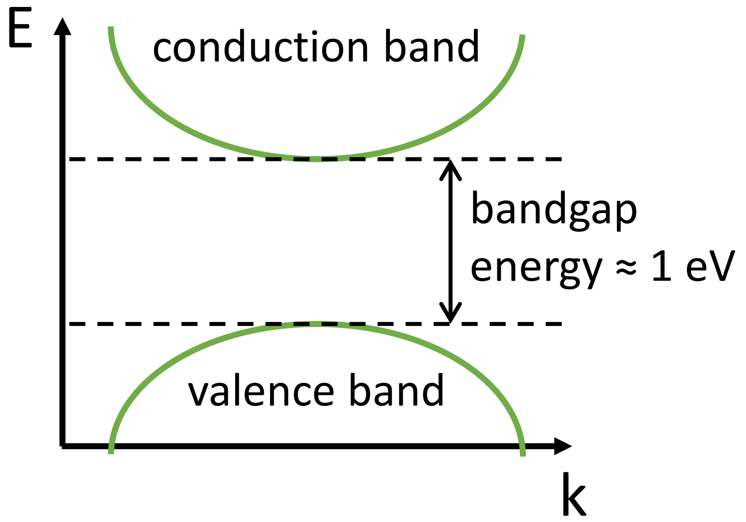


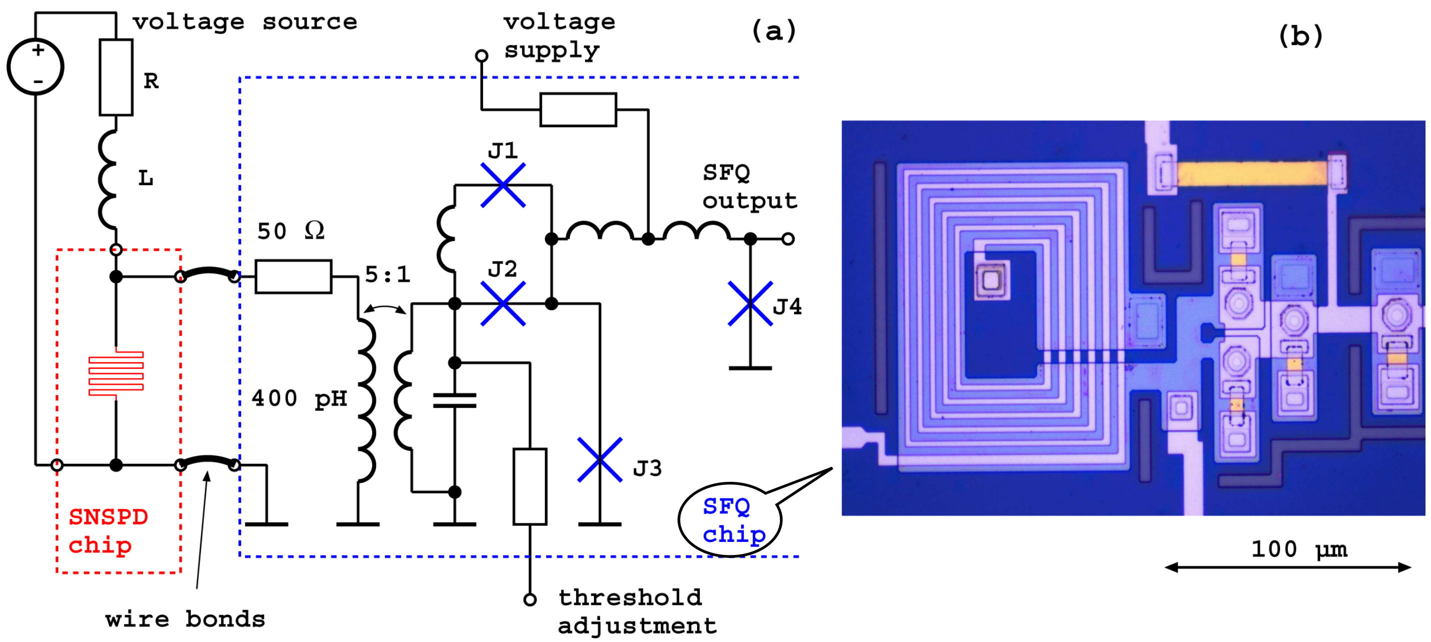
W. Pernice et al., *Nat Commun* **3,** 1325 (2012)

SNSPDs vs photodiodes



The generated voltage is in the order of 1 V



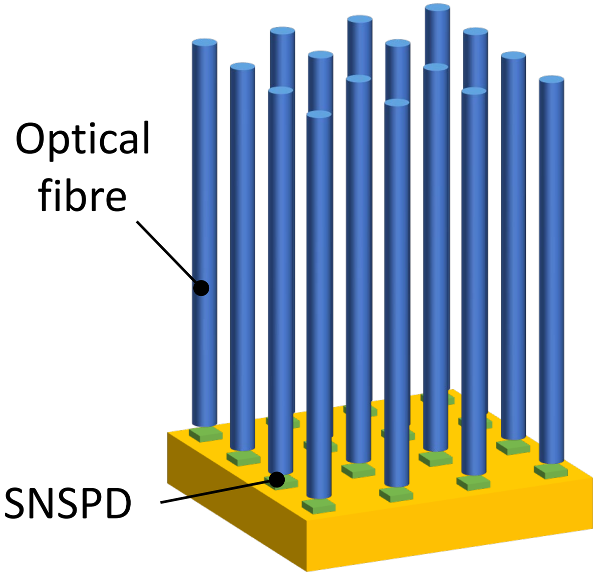


T, Ortlepp et al., Opt. Express **19**, 18593-18601 (2011)

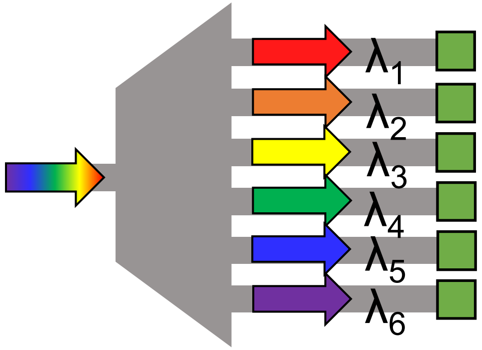
- SNSPDs have instead voltage and current levels comparable with those of SFQ circuits (mV, µA-mA)
- Indeed, efficient readout of SNSPDs with SFQ electronics have been demonstrated

High speed

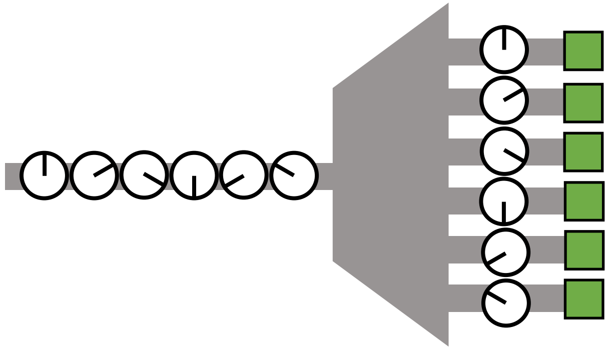
Space division multiplexing

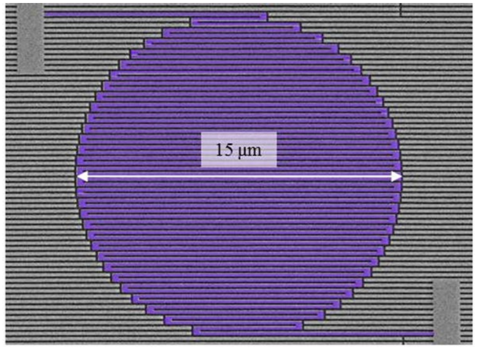


Wavelength division multiplexing

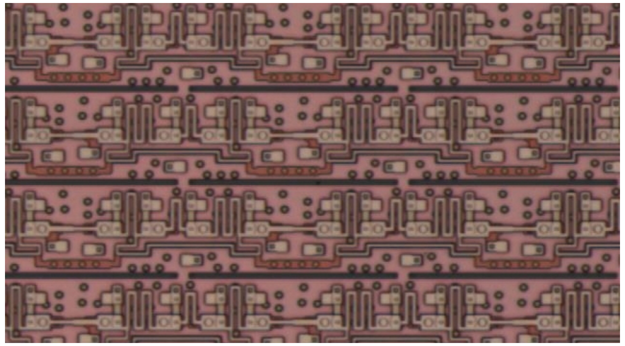


Time division multiplexing





SNSPD < 1 GHz



SFQ > 100 GHz

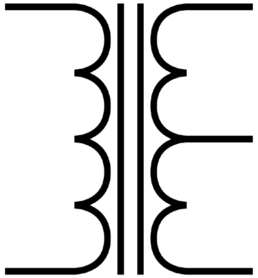
Alternative paths

Plasmonic detectors

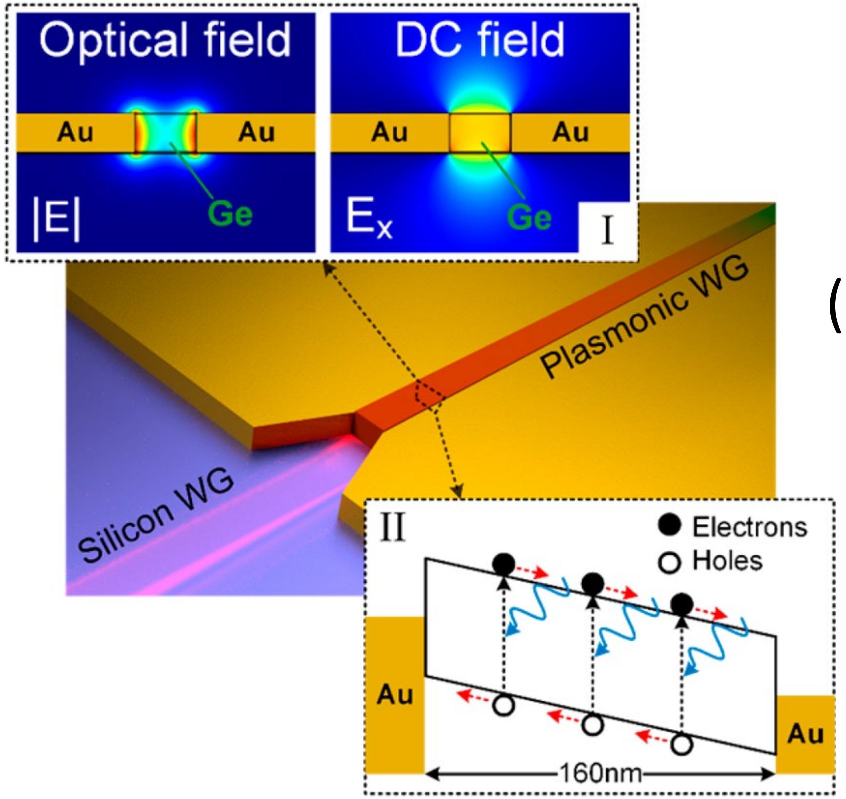
- Fast
- No doping
- Lower metal losses

BUT
Need voltage transformation
(it could affect the overall speed)

1 V → mV

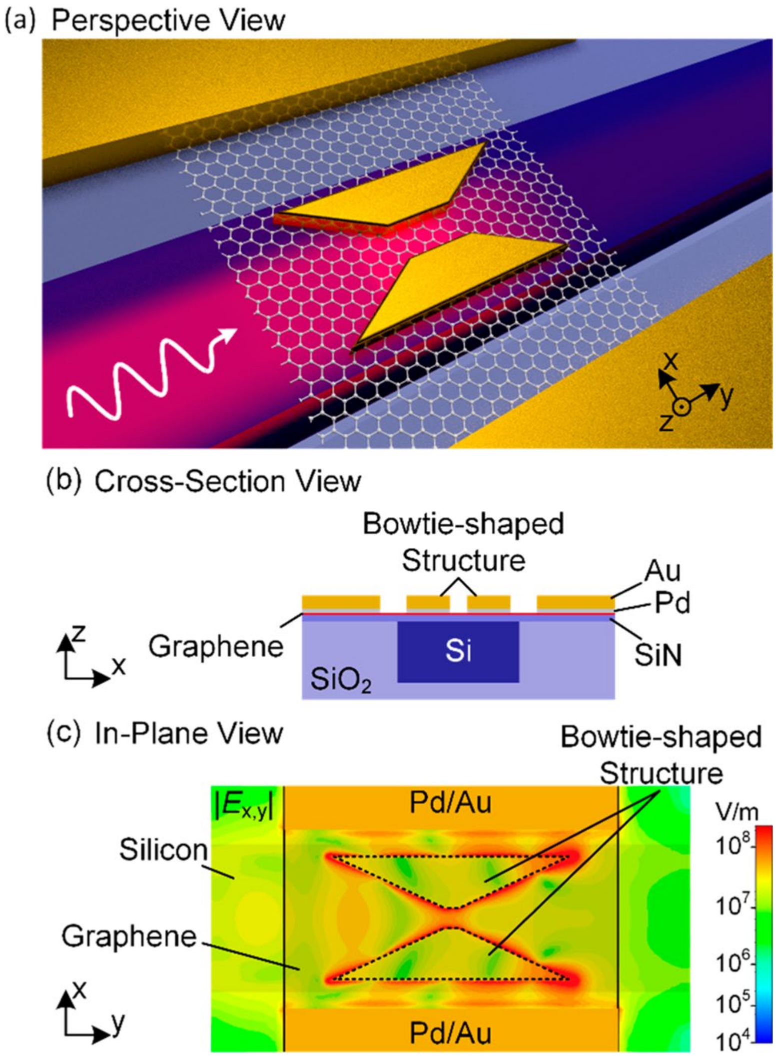


100 GHz



Y. Salamin, ACS Photonics **5**, 3291 (2018)

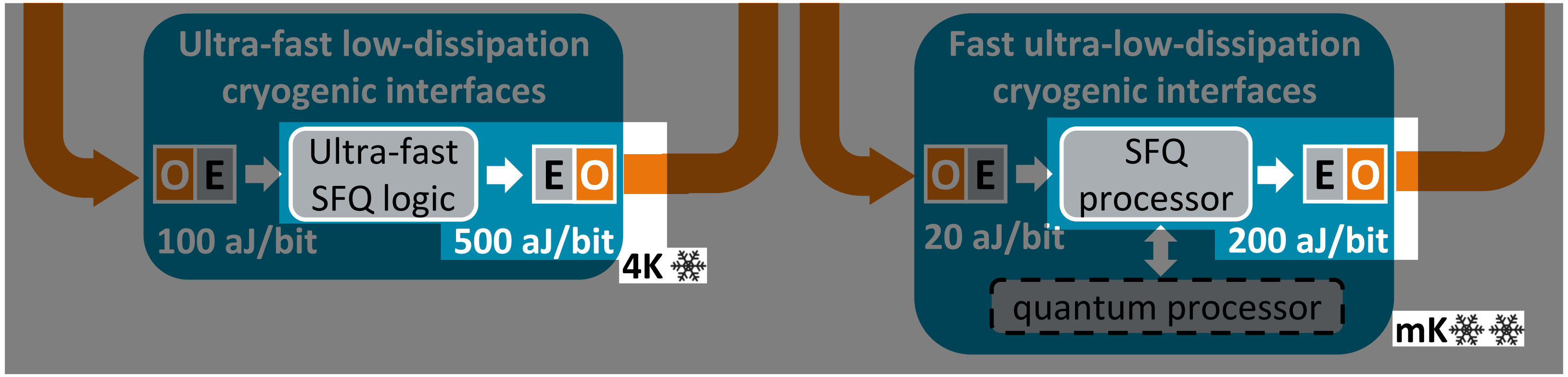
≈ 100 GHz



P. Ma, ACS Photonics **6**, 154 (2019)

Cryogenic
EO conversion

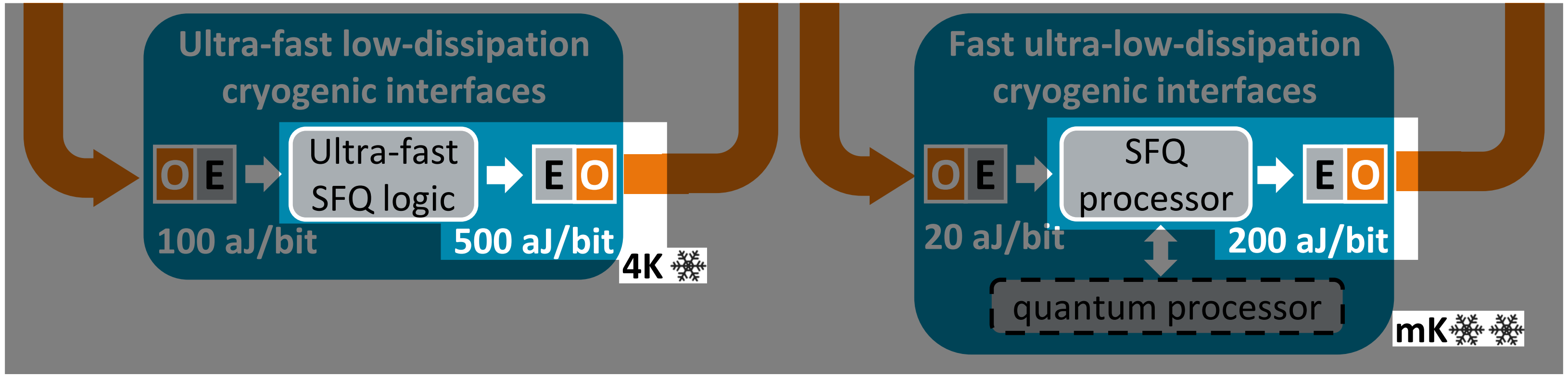
EO conversion



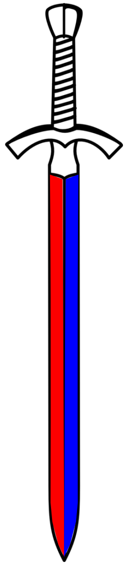
Need to develop converters of SFQ electrical signals to photonic signals, i.e. either optical **modulators** or directly modulated **light sources**

- for cryogenic operation
- energy efficient
- fast
- compatible with SFQ pulses

EO conversion



SFQ electronics is a double-edged sword



Positive side

- Low power consumption
- Low heat dissipation

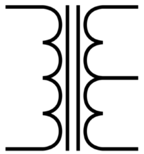
Negative side

Low power available
to drive EO converters
(e.g. electro-optical modulator)

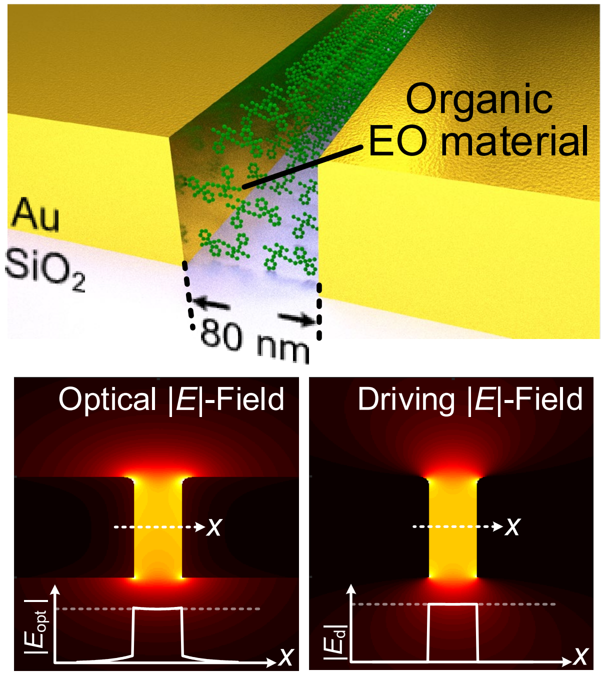
First approach: modulators

Pros
- No dopants
- Lower metal losses

Cons
- Pockels effect may be smaller
- Need voltage transformation and SFQ signal amplification

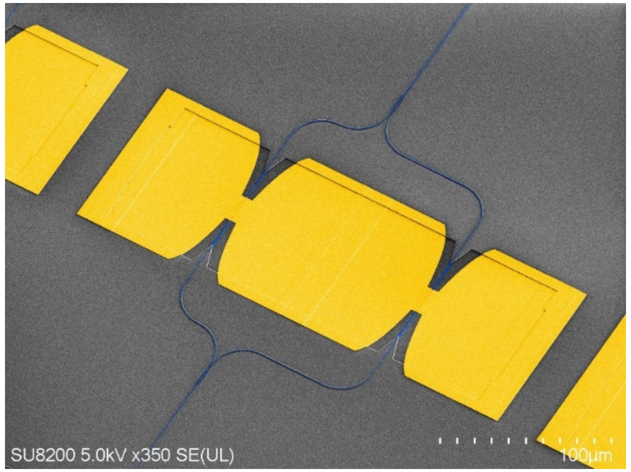


100 mV → mV



A. Melikyan, et al. *Nature Photonics* **8**, 229 (2014)
W. Heni, et al. *ACS Photonics* **4**, 1576 (2017)

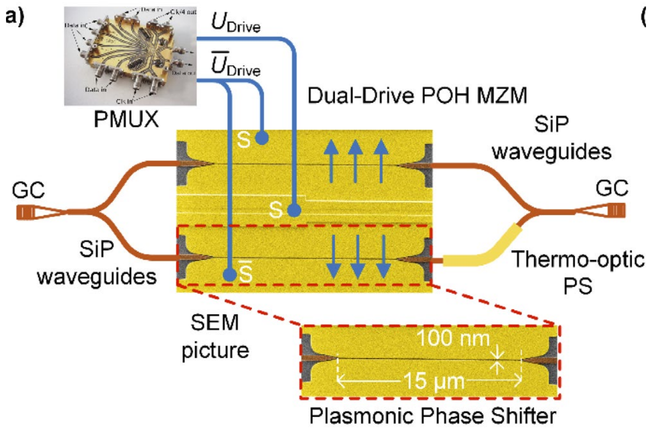
Fast



EO Bandwidth > 500 GHz

M. Burla, *et al.* APL Photonics **4**, 056106 (2019)

Low-voltage



120 GBd NRZ
with < 300 mV_{pp} driver

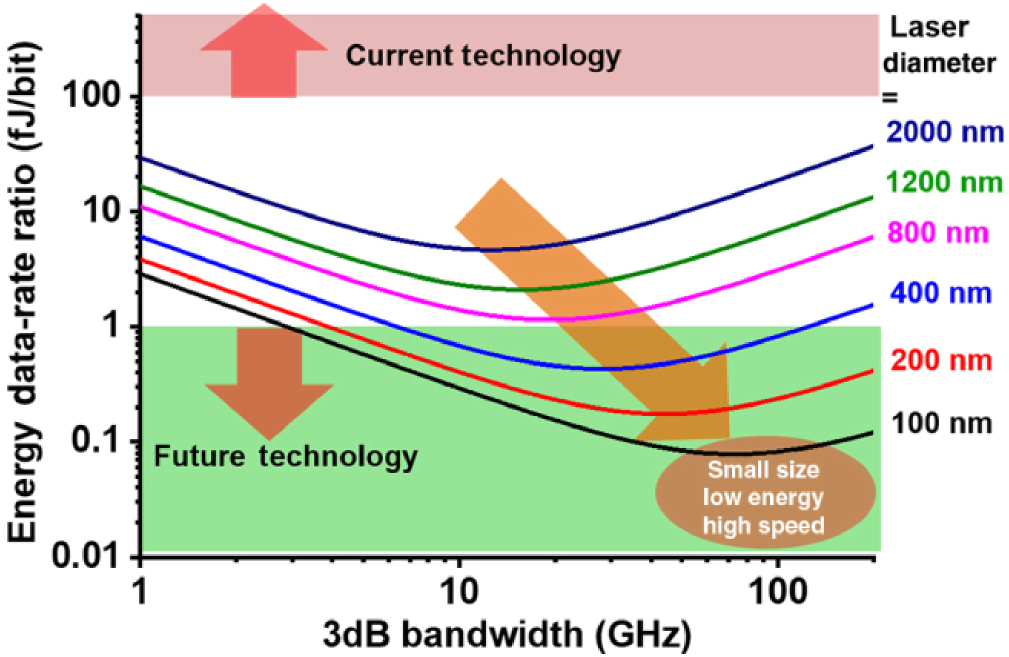
B. Baeuerle, *et al.* OFC19, M2F.3

Second approach: light sources

Directly modulated nanoscale light sources

Reduction of device dimensions

- ✓ Increase of modulation bandwidth
- ✓ Reduction J/bit
- ✓ Increase of spontaneous emission coupling factor
- ✓ Reduction of device footprint
- ❖ Increase of surface/volume
- ❖ Device processing challenges



C. Ning, *Advanced Photonics*, **1** 014002 (2019)

Major challenges

- Carrier freeze-out
- Low energy and voltage from SFQ pulses

Major opportunities

- Reduced thermal noise: can better exploit thresholds
- Lower metal losses

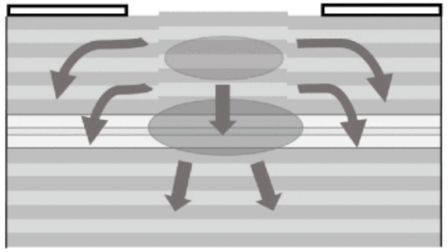
Second approach: light sources

Tampere University

Directly modulated nanoscale light sources

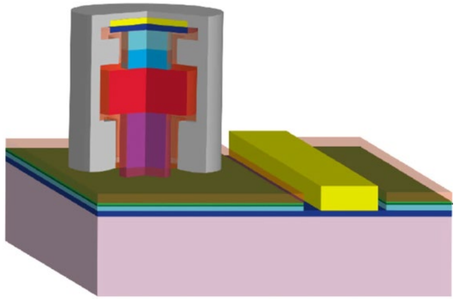
Three approaches:

1. Oxide-free small VCSELs designed for cryogenic operation



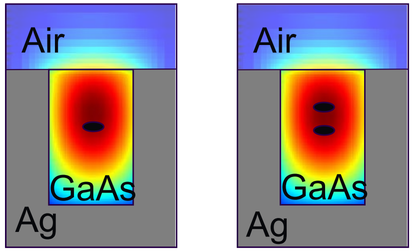
M. Bayat et al., *IEEE JQE*, **56**, 1 (2020)

2. Metal-clad semiconductor nanolaser diodes



C. Fang et al., Opt. Lett. **44**, 3669-3672 (2019)

3. Electrically driven single- or few-photon sources based on quantum dots in semiconductor-metal hybrid nanocavities



M. Versteegh et al., *Nat Commun* **5,** 5298 (2014)

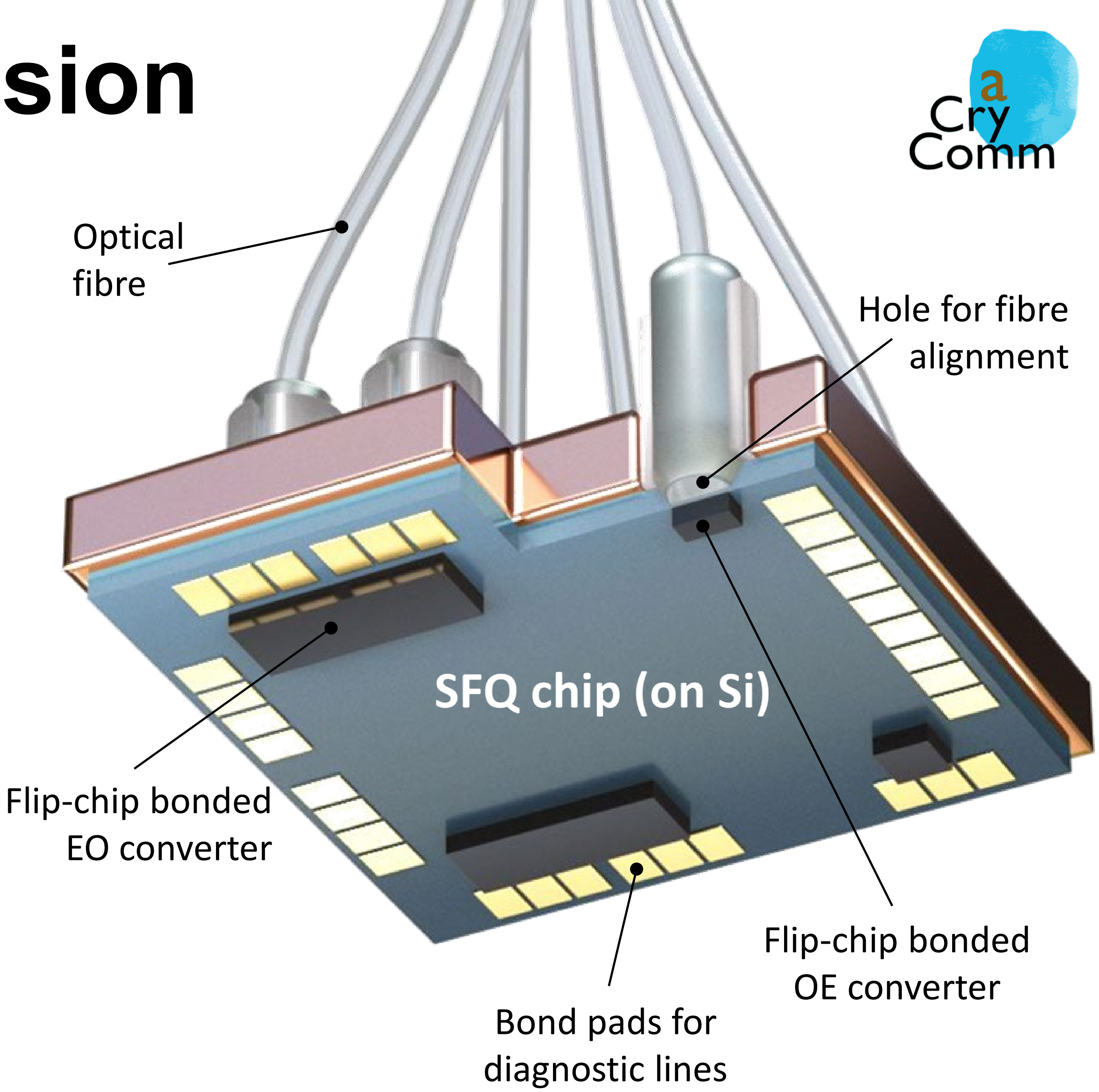
Cryogenic packaging

Vision

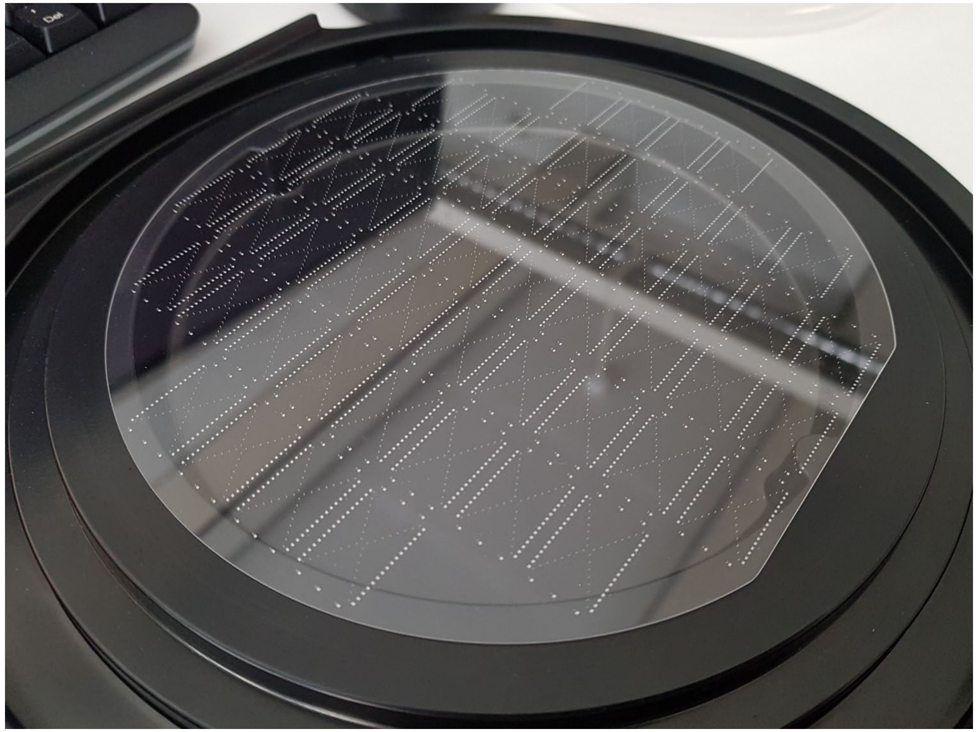
- SFQ silicon chip as **motherboard**
- Hybrid integration of different chips based on **flip-chip** bonding
- Optical fibres coupled through holes in the silicon substrate

aCryComm demonstrators (3 years)

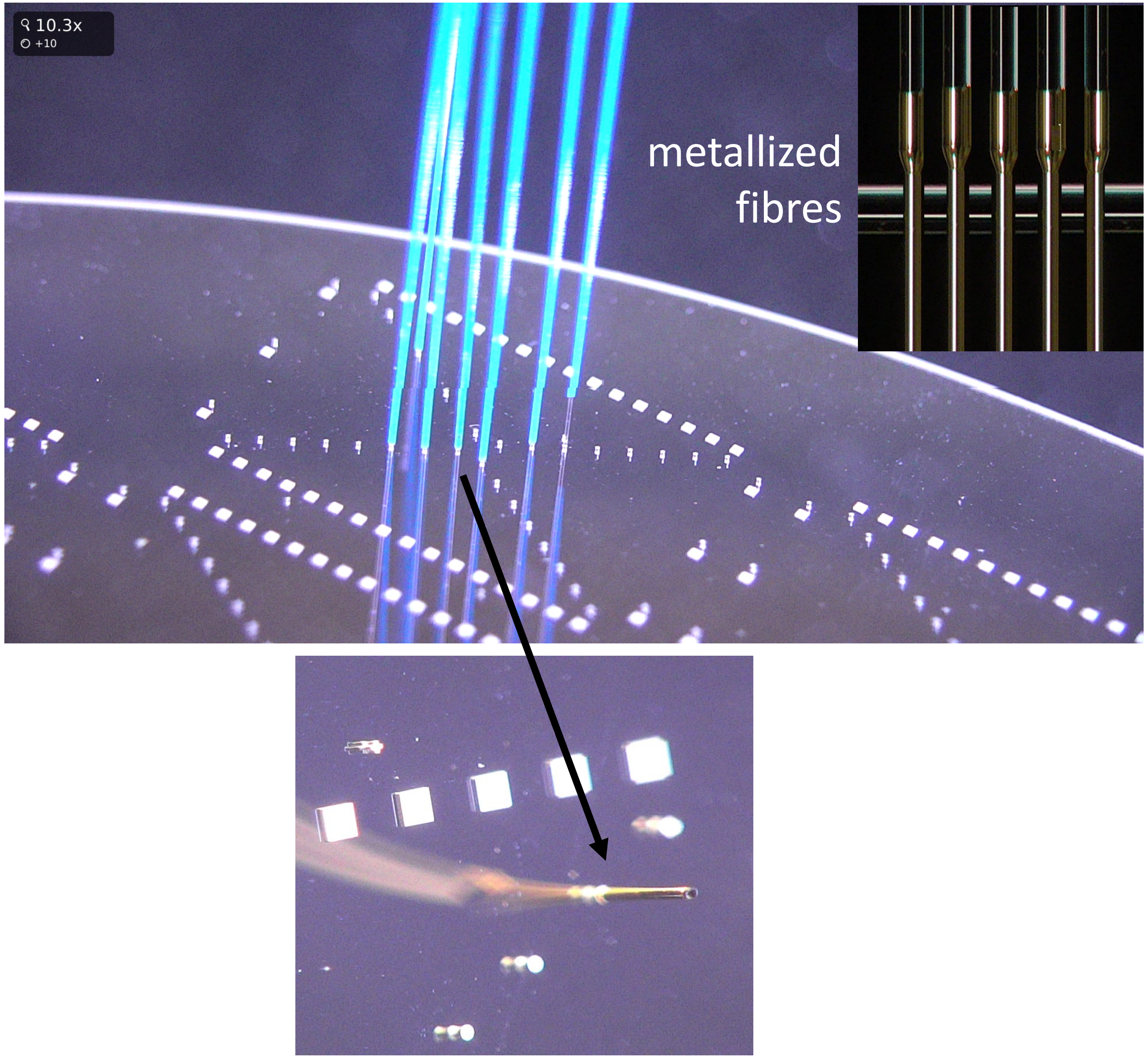
1. optical drive of SFQ at 4 K
2. optical drive of SFQ at 20 mK
3. SFQ output to optical fibre at 4 K
4. SFQ output to optical fibre at 20 mK



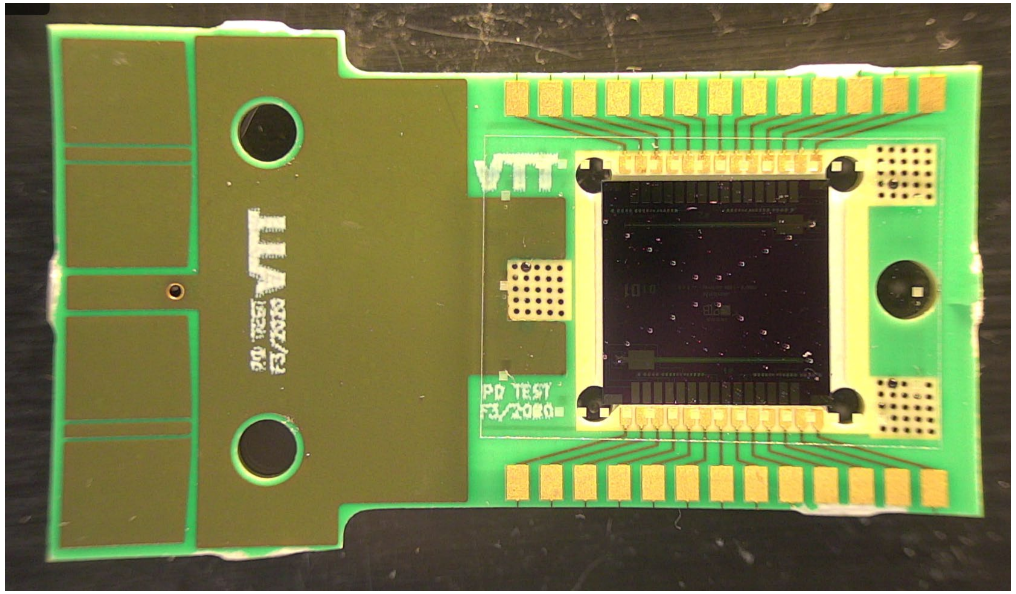
Progress

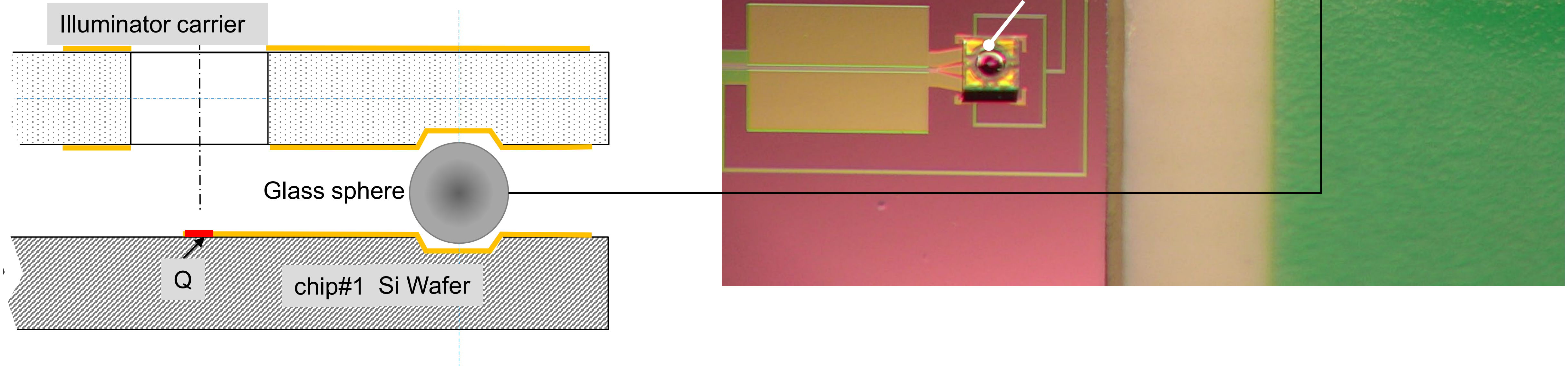


Glass wafer with “illuminator” chips
for multi-fibre assemblies



Progress


VTT
PD TEST
F3/2020


Illuminator carrier
Glass sphere
Q
chip#1 Si Wafer
71.4x
Laser on
Commercial PD

Conclusion

Conclusion

- We have presented our vision how to **upgrade supercomputers** based on **SFQ** superconducting electronics as
  - power efficient technology for GPUs
  - cryogenic classical electronics for superconducting qubits
- We have shown how such upgrade can be made possible thanks to **special optical interconnects**
- We have shown our **3-year plan** how to develop the required cryogenic optoelectronic building blocks, including their assembly
- We our pioneering the field of **cryogenic optoelectronics**, and we know we are not alone. We will be happy to collaborate and share visions with all other pioneers all around the world

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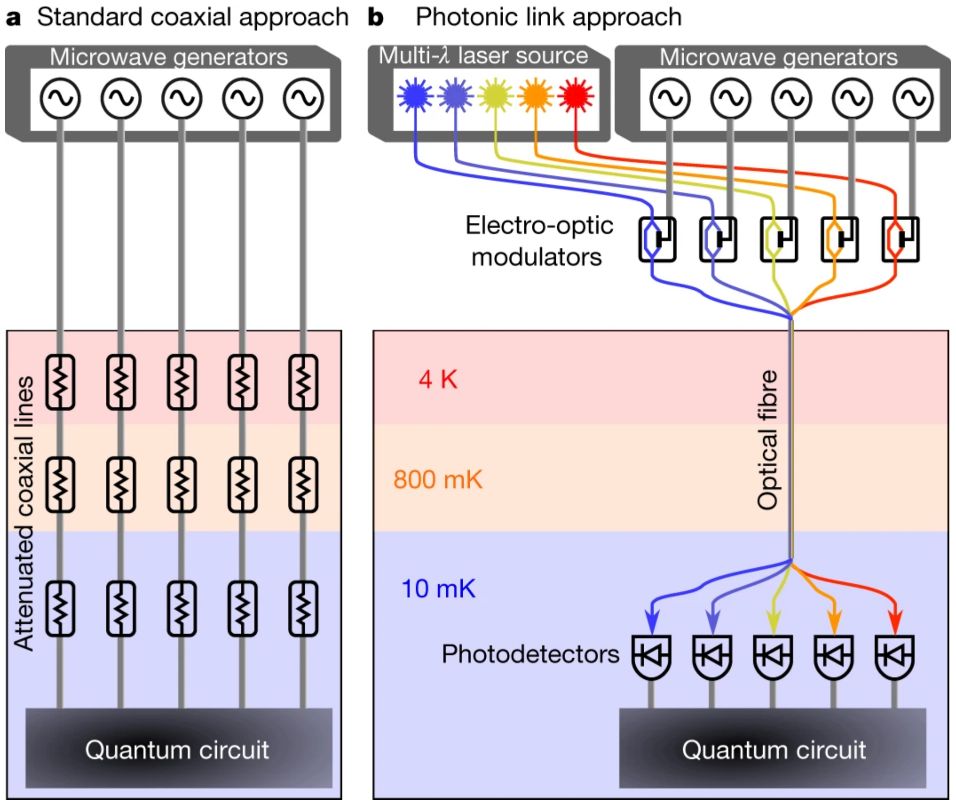

Demonstrated with commercial InGaAs telecom photodiodes

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