Integrated photonics for trapped-ion quantum computing

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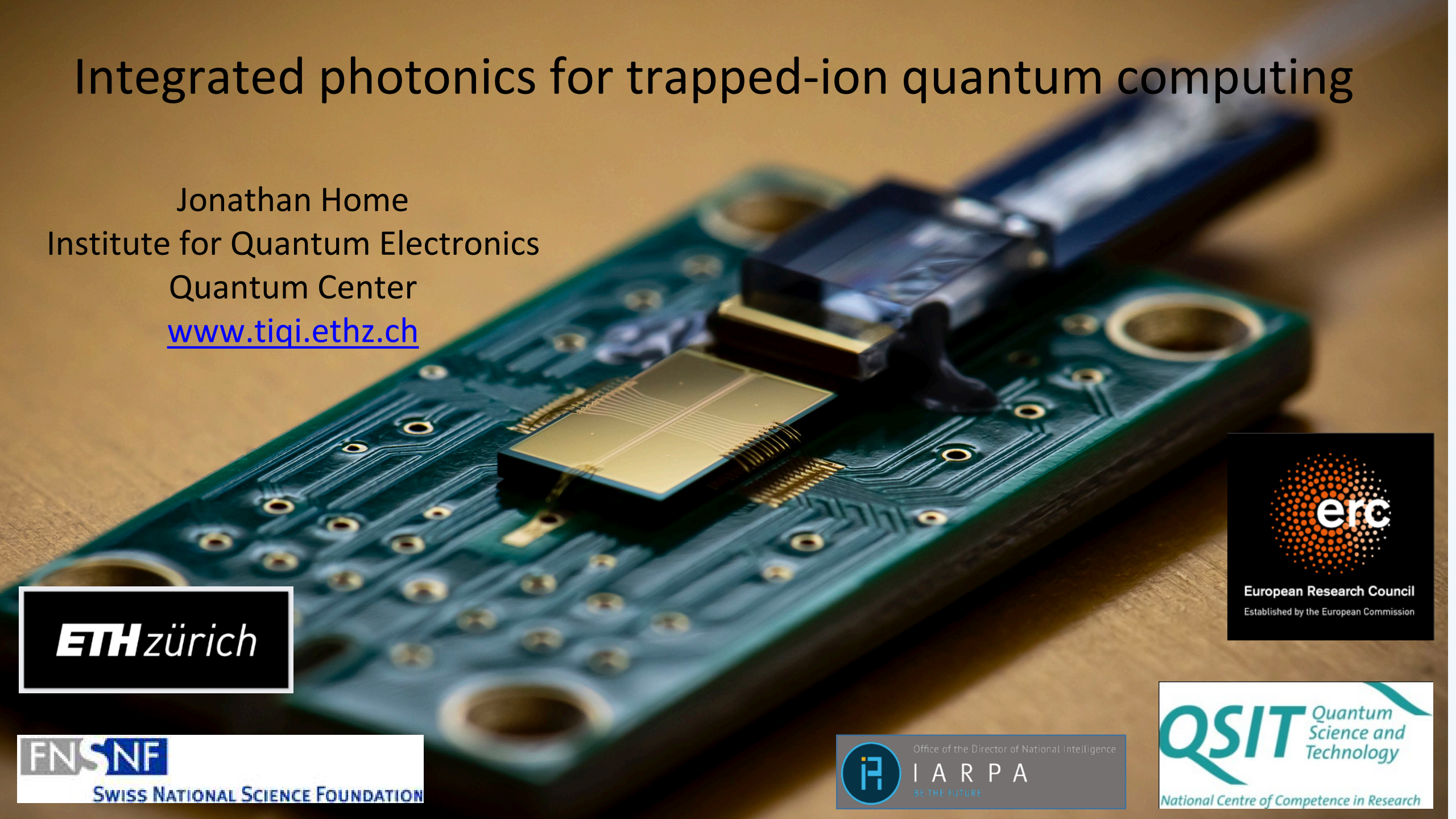

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QSIT Quantum Science and Technology
National Centre of Competence in Research

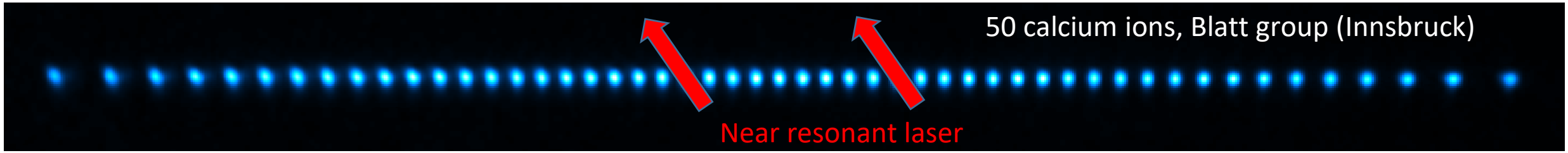
“Linear chain” Trapped-Ion Quantum Computing

Quantum computing:

- new paradigm taking advantage of structure of quantum mechanics (information is physical, the physics matters!)
- Promises speed up for a range of intractable computational problems
- Known use cases: chemistry, materials + cryptography

Trapped Ion Quantum computing:

Every atom provides a quantum bit. Ion chain is semi-rigid: all ions can be coupled



AQT IONQ

Modularity in Trapped-ion quantum computing

110 calcium ions

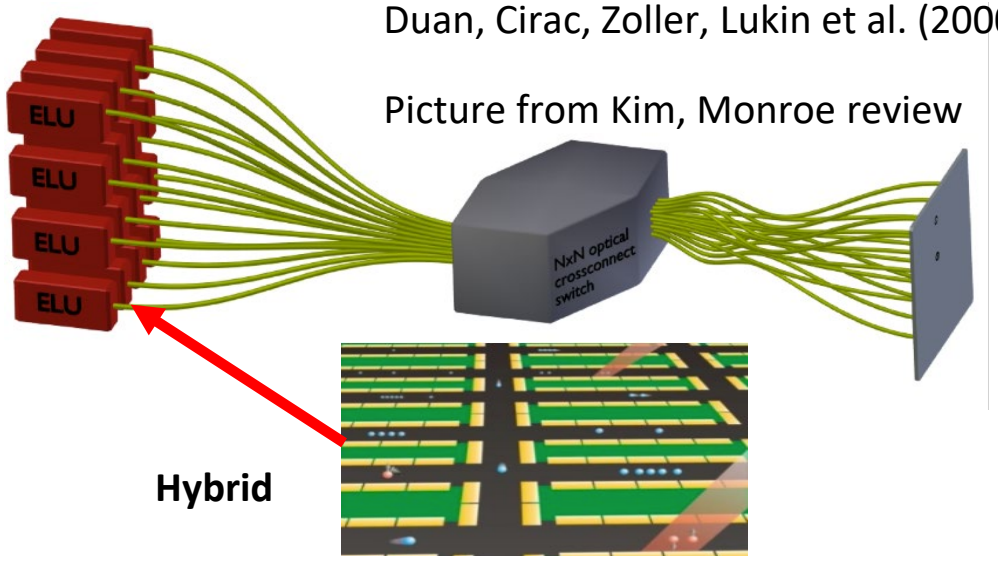
Marcus Reiher (ETHZ Chemistry) - “1000 ***perfect logical qubits*** is where you want to be”
- requires >> 10,000 qubits (ions): not possible in a linear chain

Quantum CCD: split + shuttle
Wineland et al. 2000,
NIST, ETH, Quantinuum, ZuriQ

Photonic links:
probabilistic remote entanglement

Duan, Cirac, Zoller, Lukin et al. (2000)

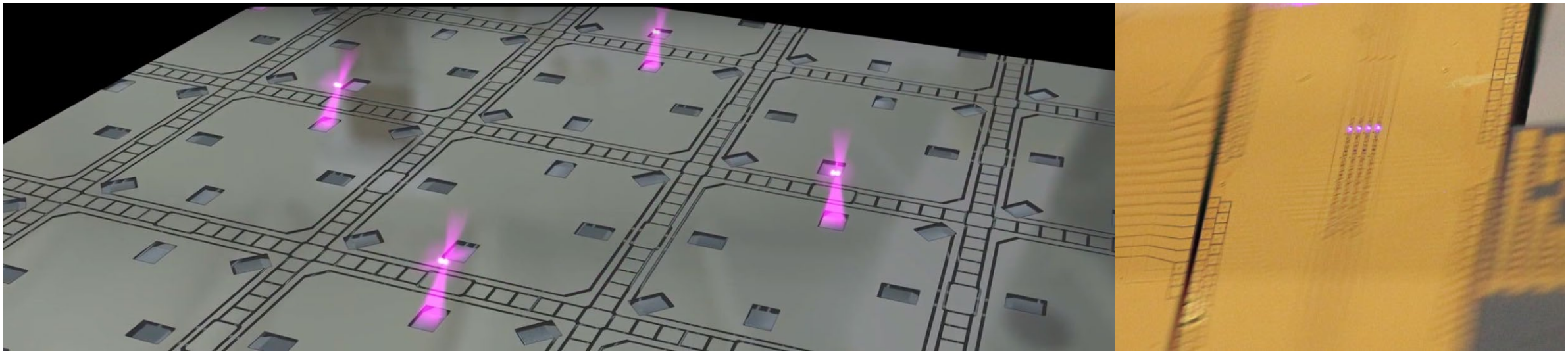
Picture from Kim, Monroe review



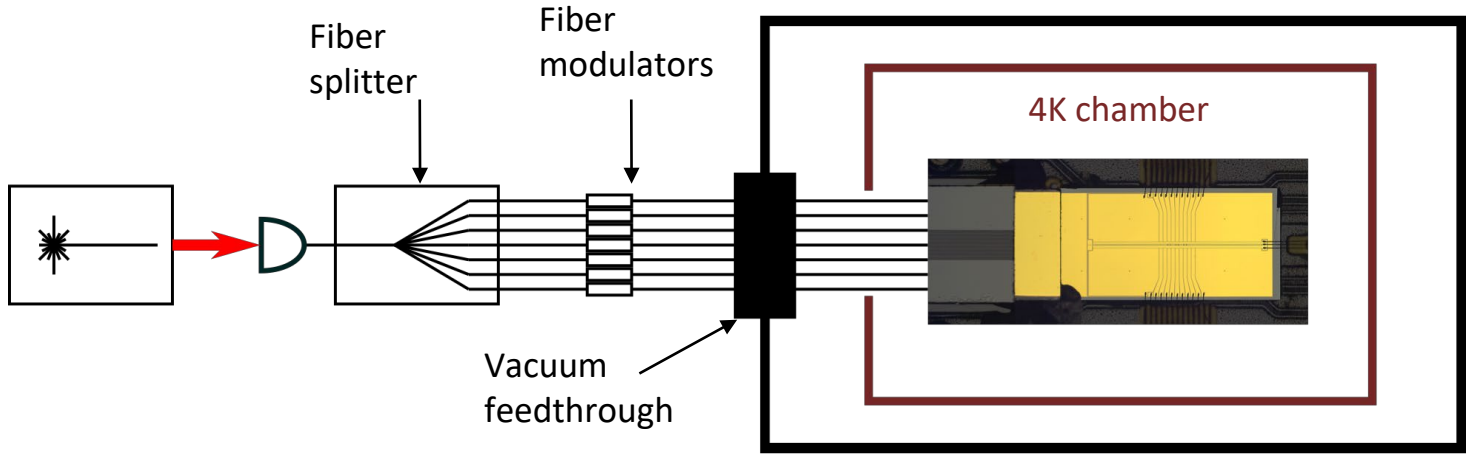
Hybrid

Modularized approaches need modularized control + delivery (light + electonics)

Optical wiring of the quantum computer



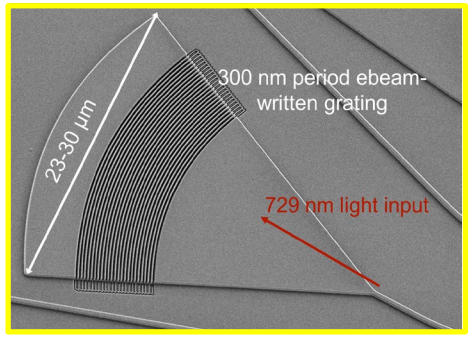
Aim: a "optically wired" ion trap processor using integrated optics

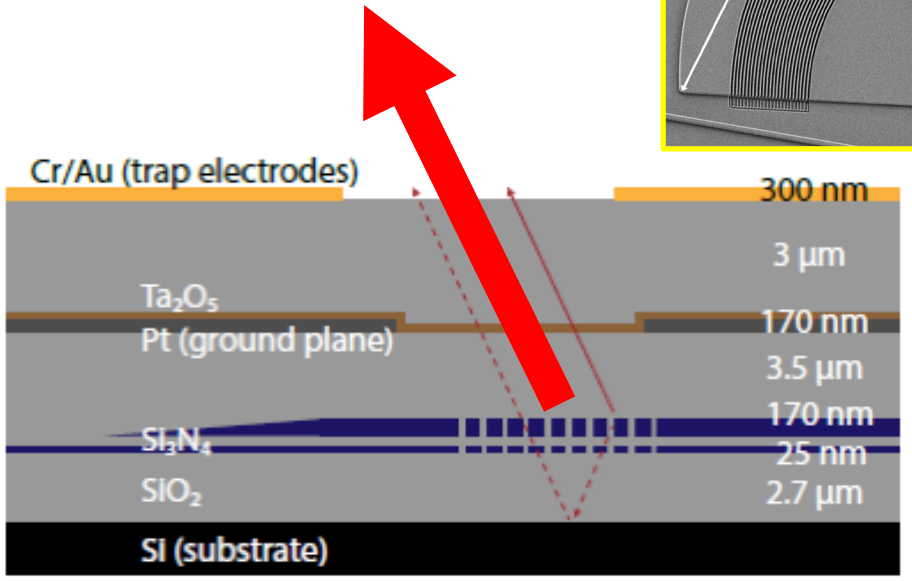


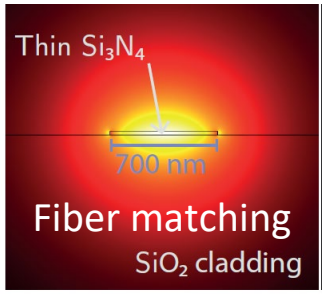
- MIT + Lincoln labs: K. Mehta et al. Nature Nano 11 1066 (2016), Challenge: 33 dB loss from input to ion
- R. J. Niffenegger *et al*, Nature 586, 538 (2020): Delivery of near-UV and visible light to ions but also high loss

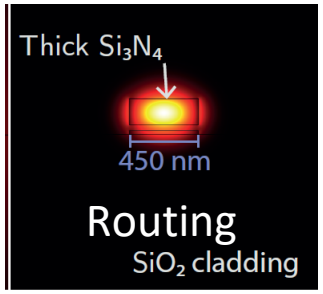
On-chip delivery of light

Light to ion
50 micron above surface

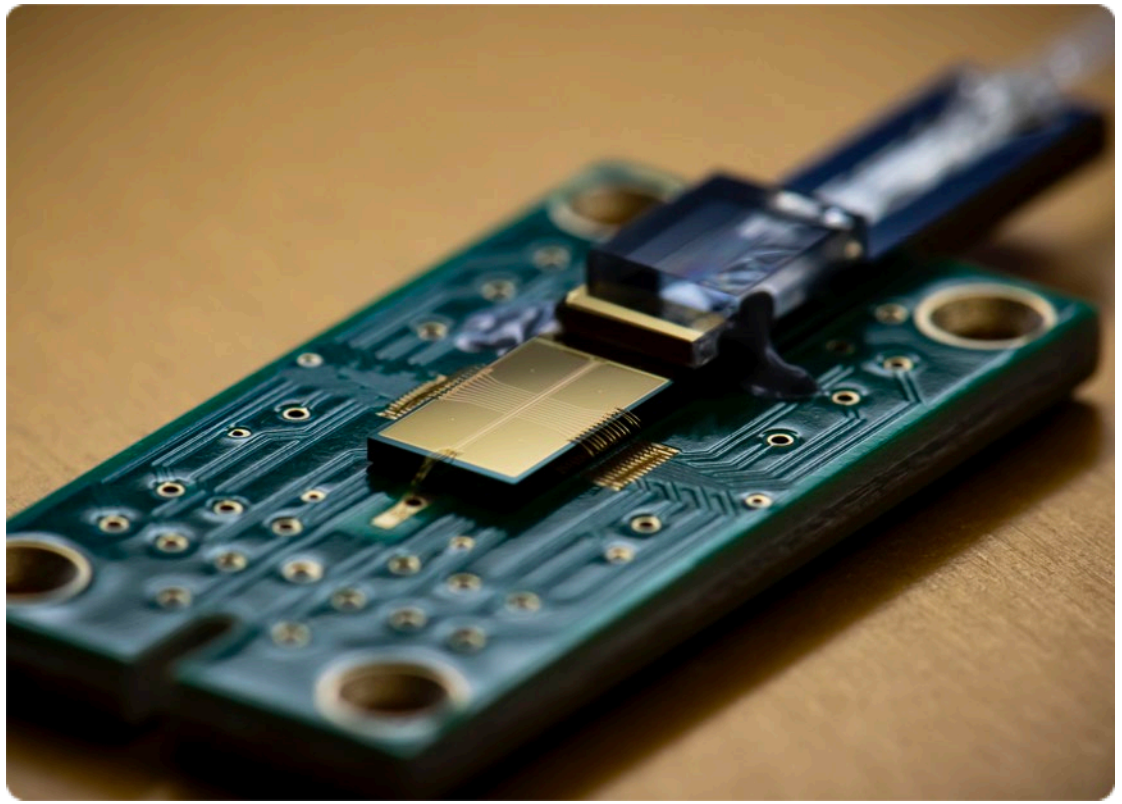








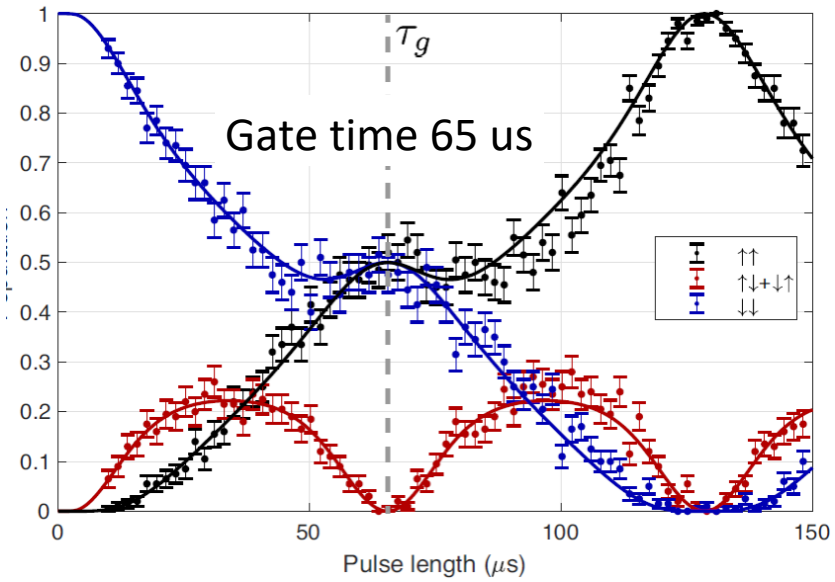
K. Mehta et al. Nature 586, 7830 (2020)



1.5 dB level fibre-chip coupling loss at 300 K and 7K

ETH chip 7: Multi-qubit gates using integrated photonics

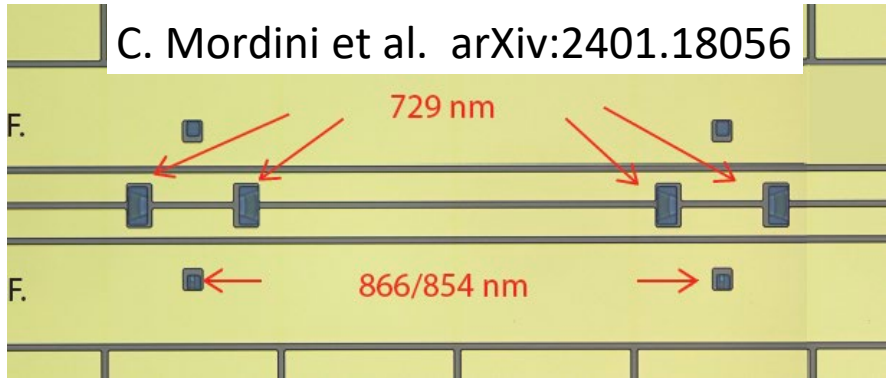
2-qubit gates + entanglement



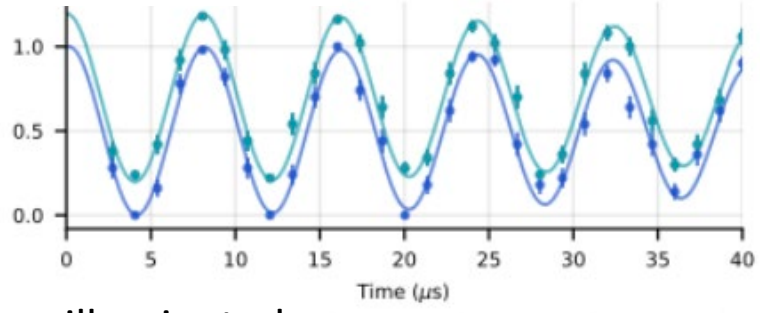
K. Mehta et al. Nature 586, 7830 (2020)

Multi-zone operations

C. Mordini et al. arXiv:2401.18056

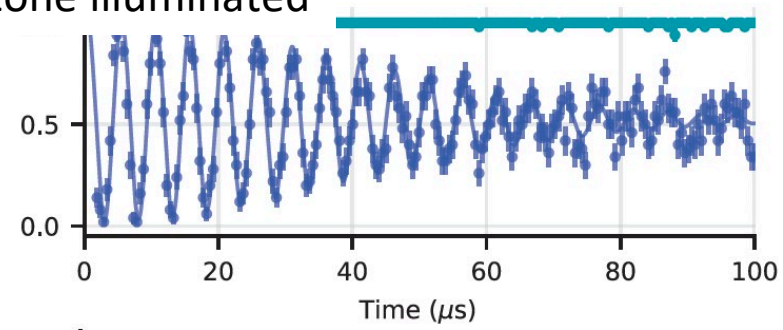


Both zones illuminated



$\Omega_1/\Omega_2 = 0.992(6)$

One zone illuminated

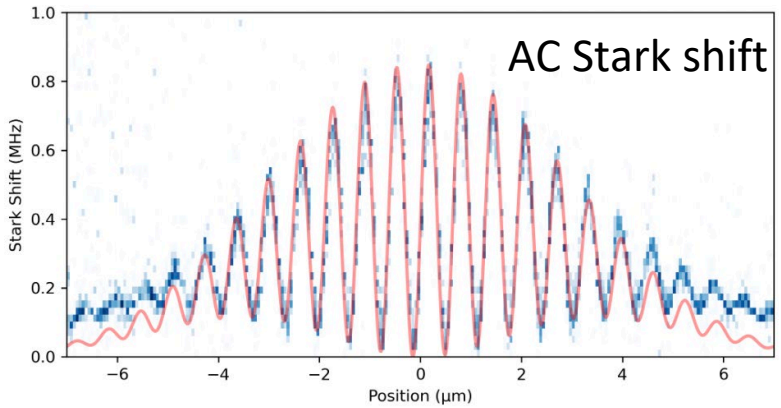


$\Omega_1/\Omega_2 = 0.0014$

Opportunities in beam design

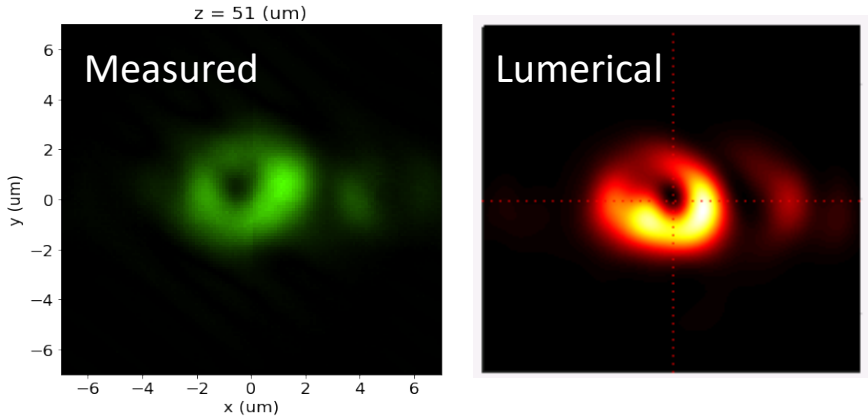
Idea: K. Mehta et al. SPIE OPTO (2019), expts: A. Ricci et al. Phys. Rev. Lett. **130**, 133201 (2023)

Phase stable standing wave formed on-chip
(Propagates away from surface)



Diffraction limited 1.5 micron spots
Beck et al arXiv:2306.09220 (2023)

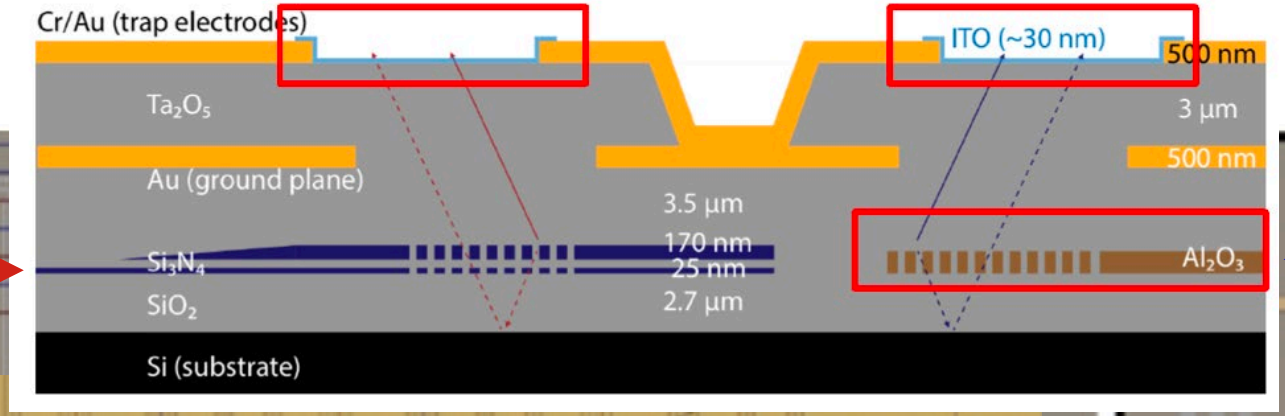
Laguerre-Gaussian beams

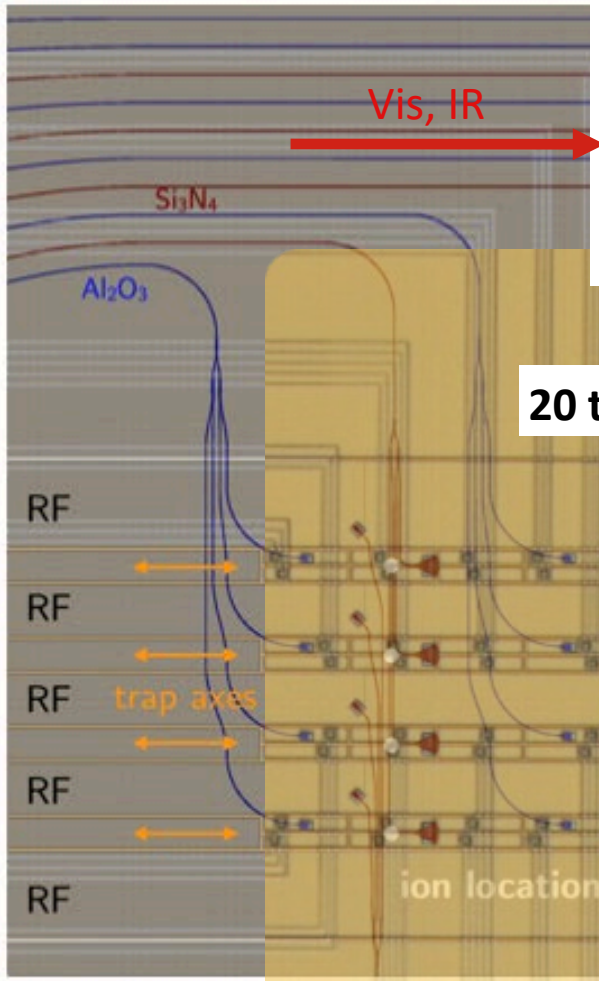


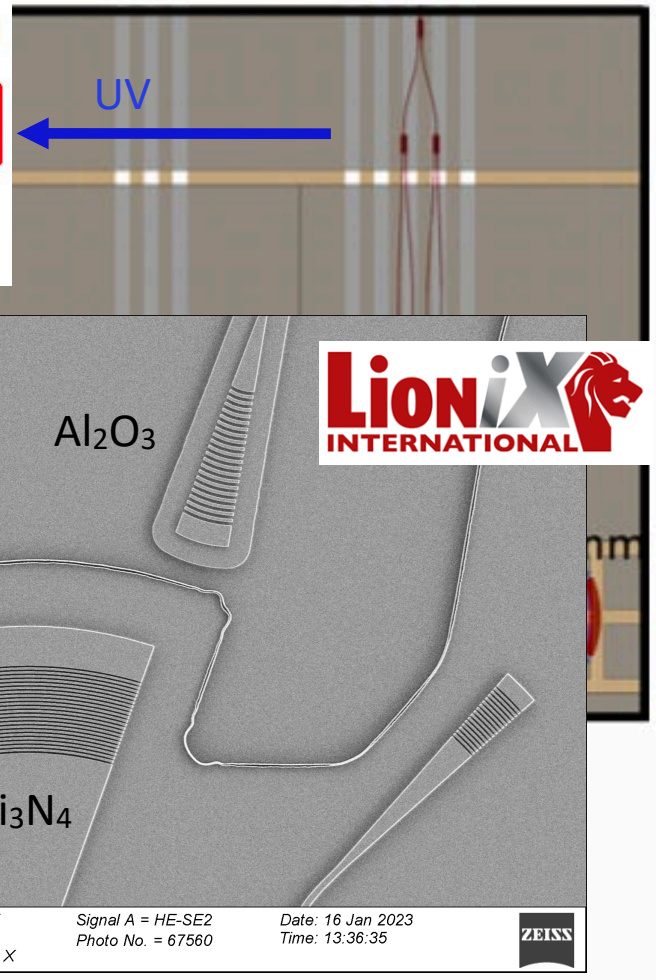
Interfering focused beam arrays

Next: multi-colour integration and scaling

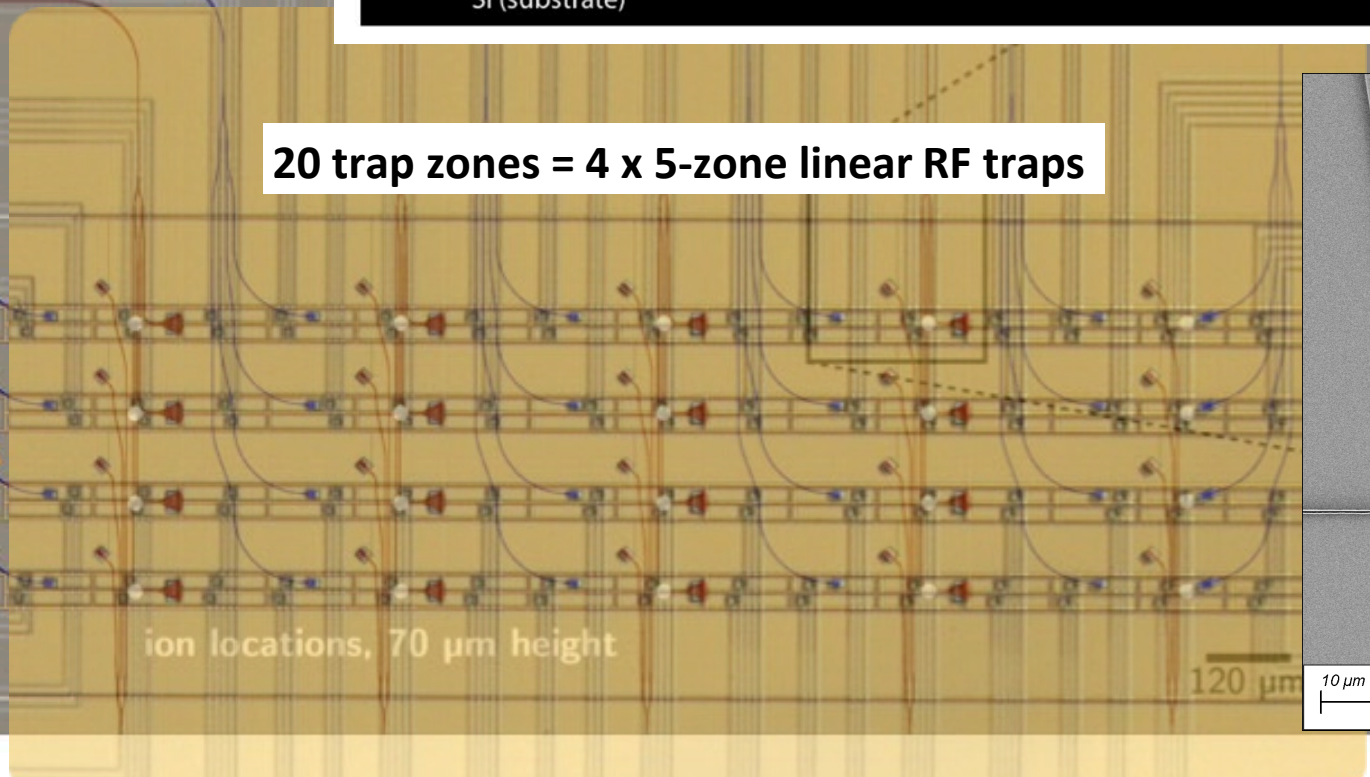
Designs: Gillenhaal Beck, Karan Mehta, Grating design: arXiv:2306.09220 (2023)







20 trap zones = 4 x 5-zone linear RF traps

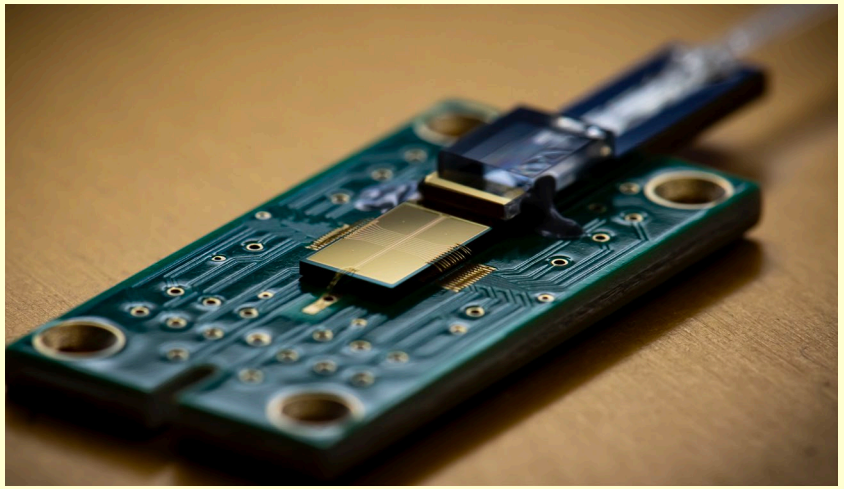


Summary

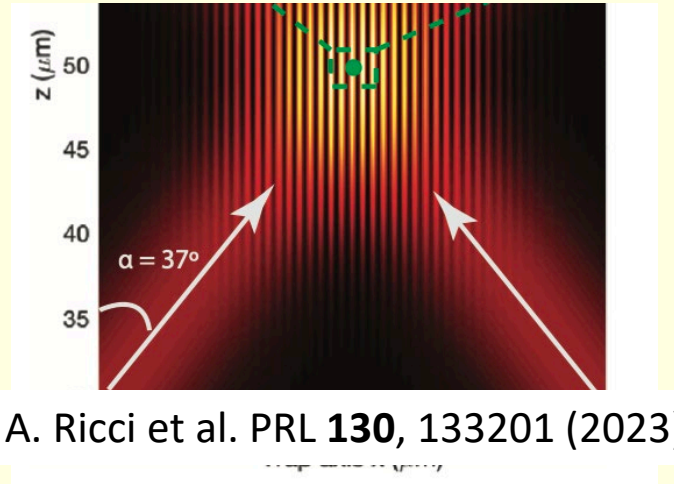
Integrated optics for quantum control

- High-fidelity multi-qubit gates

K. Mehta et al. Nature 586, 7830 (2020)
M. Malinowski, C. Zhang et al. PRL 128, 080503 (2022)
C. Mordini et al. arXiv:2401.18056 (2024)

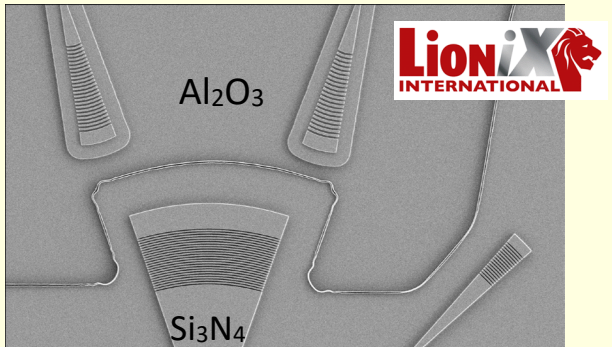


New optical fields



A. Ricci et al. PRL **130**, 133201 (2023)

Full optical integration + scaling

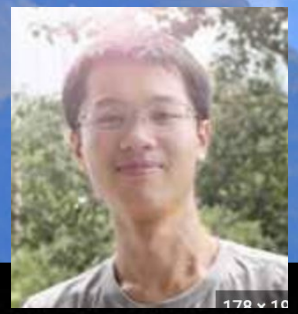


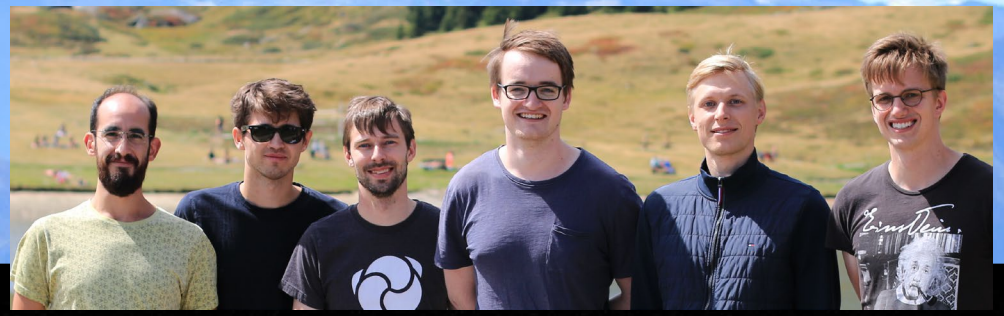
Beck et al arXiv:2306.09220 (2023)

Still much to do…

Integrated electronics,
Integrated detection
On chip modulation + multiplexing
(MHz bandwidths, >40 dB extinction)

Trapped Ion Quantum Information Group
ETH Zürich
www.tiqi.ethz.ch



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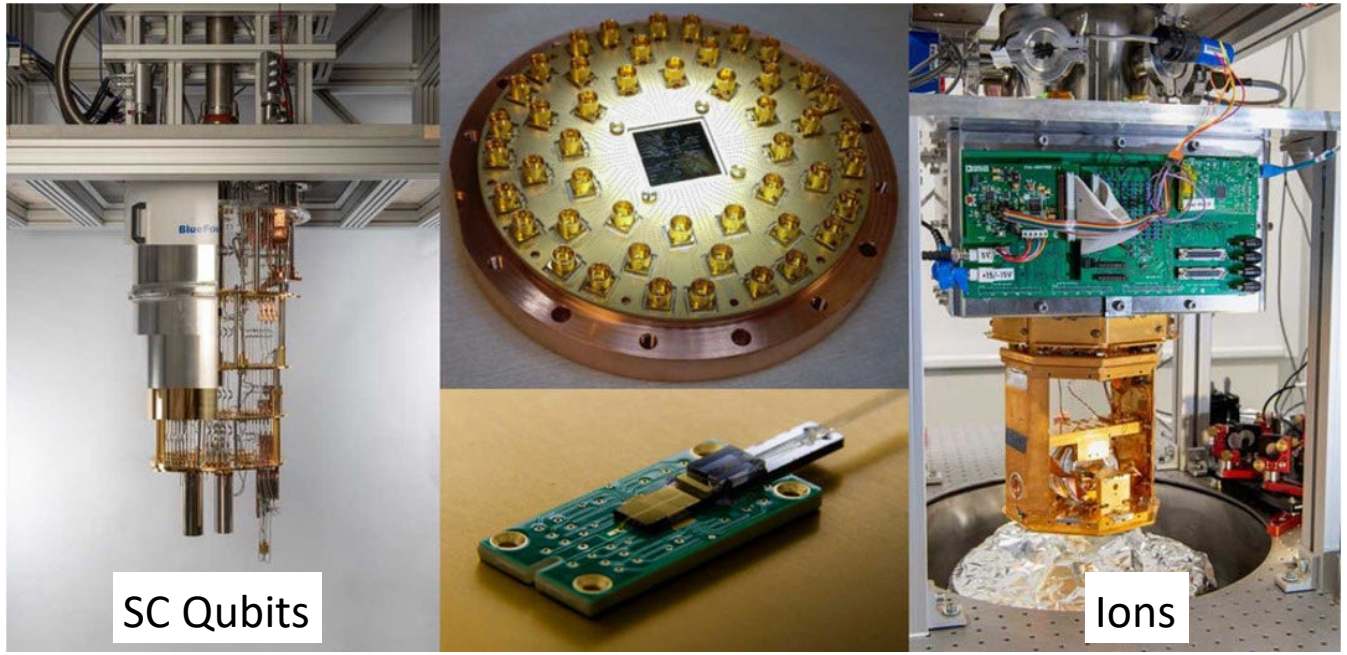

Prof. Andreas Wallraff

Prof. Jonathan Home

Ion trap group lead:
Cornelius Hempel

Labs occupied since 07.2021