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JULIANE PRICE

Vocalist & Multi-Instrumentalist

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DR. MICHAEL J. HAYDUK

Deputy Director

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COL. TIMOTHY LAWRENCE

Retired

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Rome, NY

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PROF. DAVID REILLY

Professor

University of Sydney

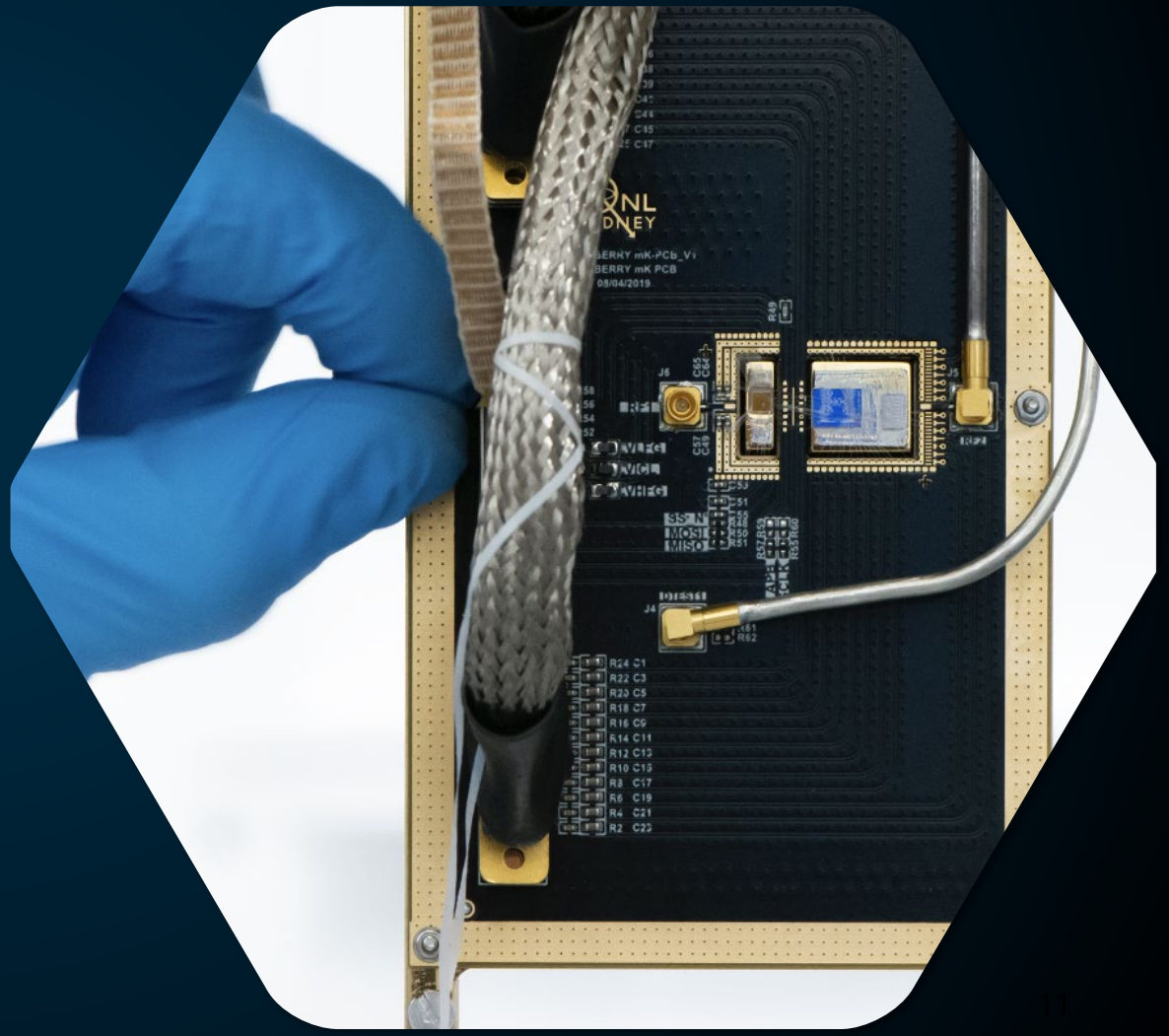
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Scaling the Control Interface of a Quantum Computer

David Reilly





THE UNIVERSITY OF SYDNEY



THE UNIVERSITY OF SYDNEY

Students Graduated

John Hornibrook

Alice Mahoney

Xanthe Croot

Sebastian Pauka

Marie Clare Jarrett

Steven Waddy

Ewa Rej

James Colless

Brendan Harlech-Jones

Sam Bartee

Abdallah El Kass

David Waddington

Thomas Boele

Professional Staff

Kushal Das

Yuanyang Yang

Jonathan Knoblaunch

Deshan Govender

Andrew Kelly

Brendan Altus

Alex Sharp

Torsten Gaebel

EQUS
Australian Research Council Centre of Excellence for Engineered Quantum Systems

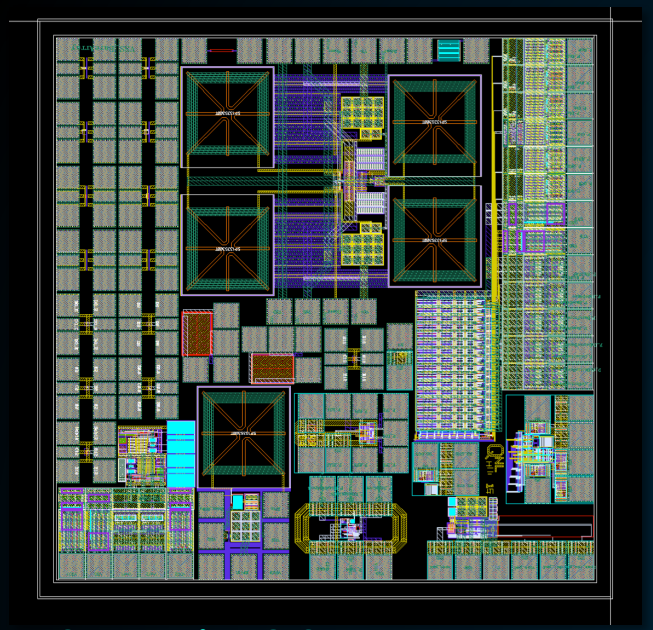
NSW GOVERNMENT

Australian Government
Australian Research Council

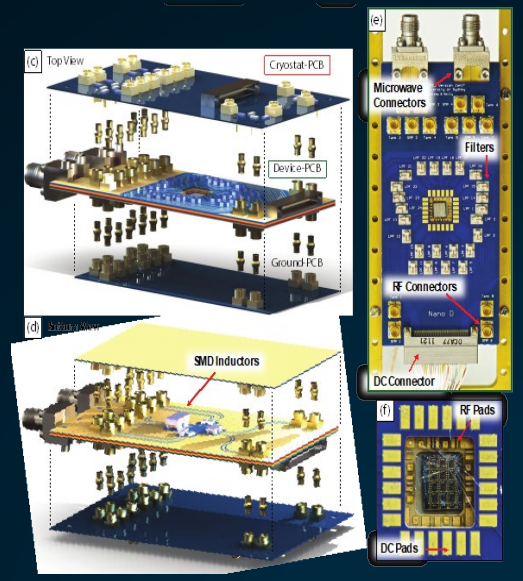
IARPA

Laboratory for Physical Sciences
LPS

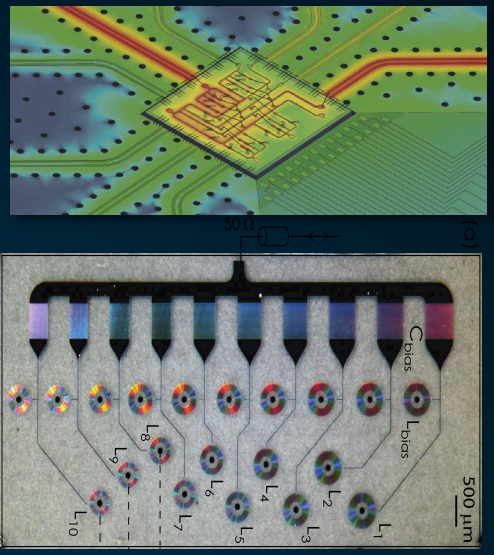
Microsoft



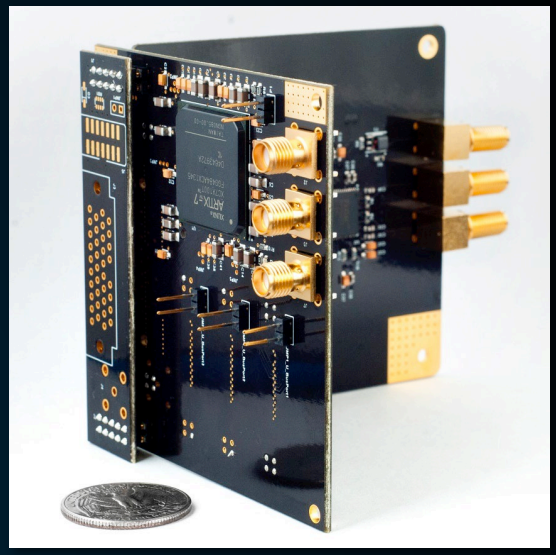
Cryogenic ASICs



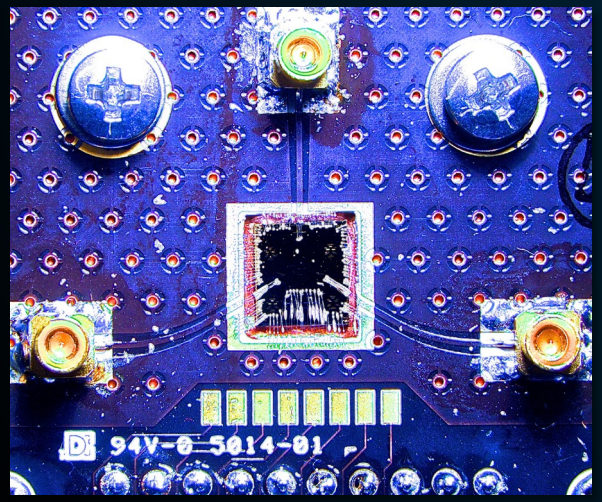
Packaging & Interconnects



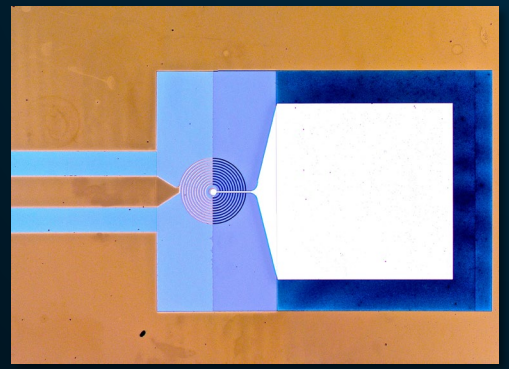
Multiplexing



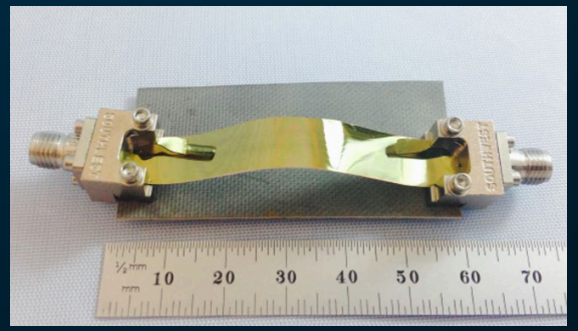
Cryo-FPGA



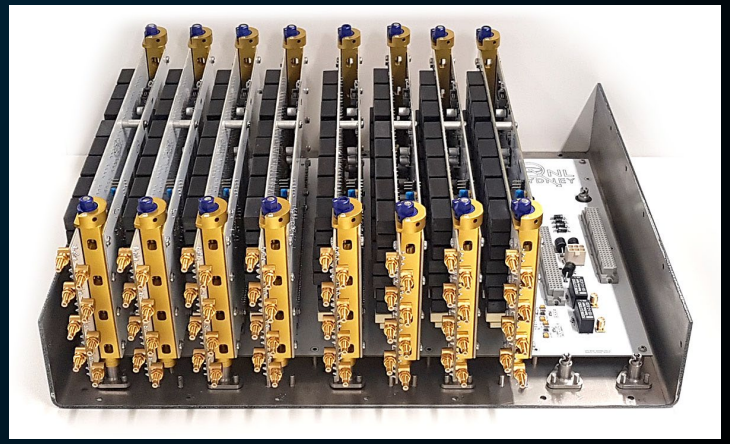
On-chip Circulators



Integrated Parametric Amplifiers



Superconducting flex Cables



Custom Electronics

THE UNIVERSITY OF SYDNEY

Job Interview Q1

"Would you trade qubit fidelity for the number of control wires per qubit? Why / why not"

A1: No. Lower fidelity means more physical qubits which brings more wires.

A2: Yes. More wires bring more noise and heat and lower fidelity.

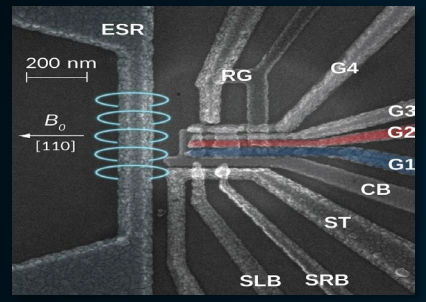
A3: It depends. How many wires and what fidelities are we talking?

A4: I think I'm in the wrong meeting. Sorry… what are we controlling?

The Tyranny of Numbers

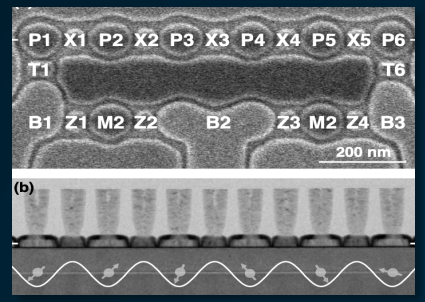
Single Spin Qubits
(5 wires per qubit)

Dzurak (2022)



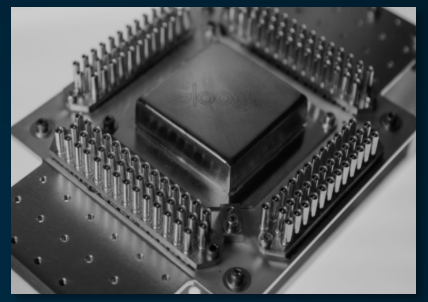
E-O Spin Qubits
(10 wires per qubit)

HRL (2022)



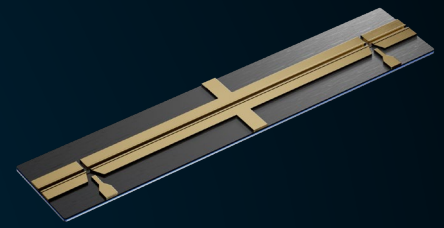
Superconducting Qubits
(200 wires for 54 qubits)

Google (2020)



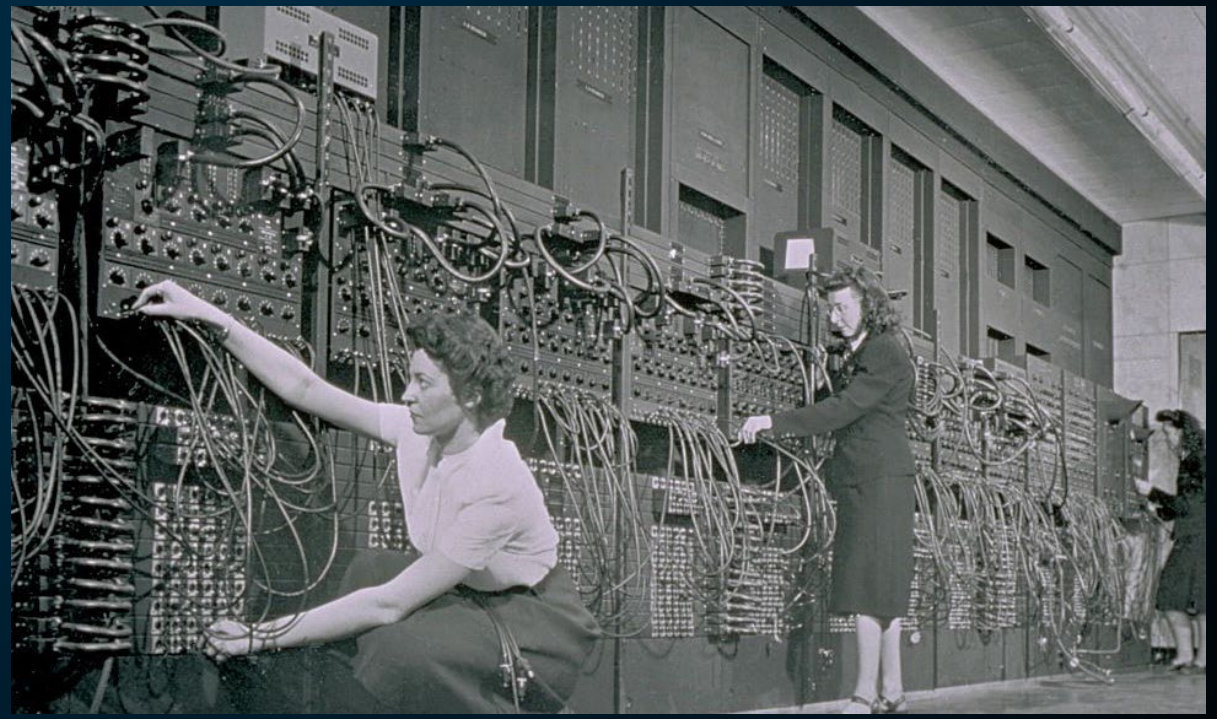
Majorana Qubits
(20 wires per qubit)

Microsoft (2022)

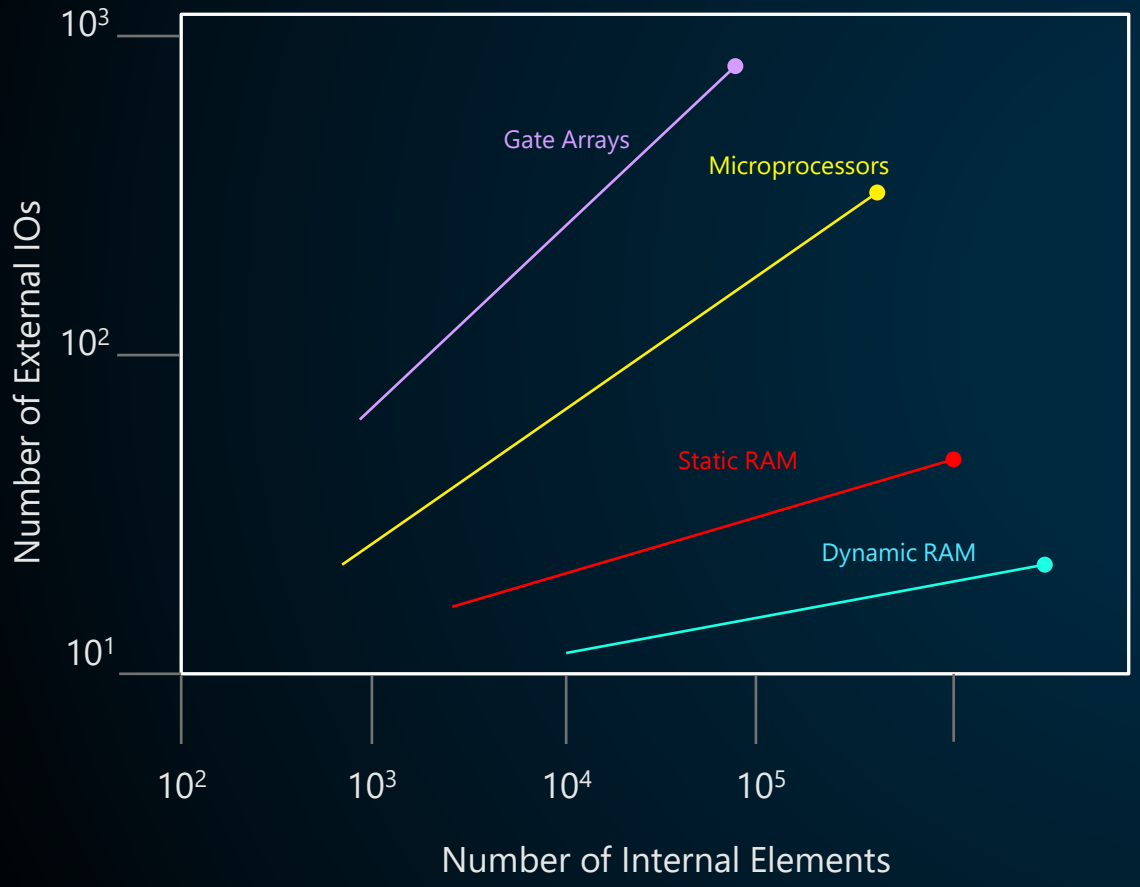


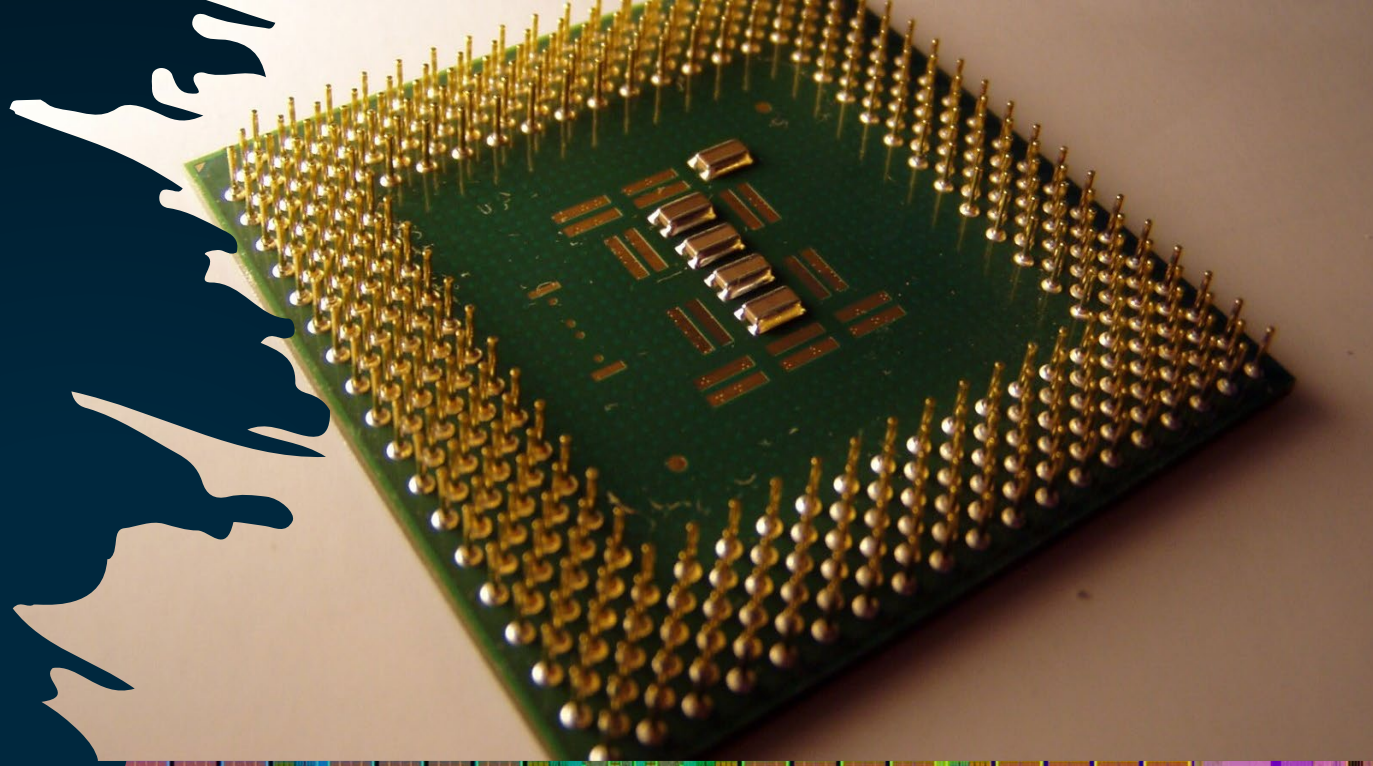
For some time now, electronic man has known how 'in principle' …however, Such systems, because of their complex digital nature, require hundreds, thousands, and ***sometimes tens of thousands*** *of electron devices.*

— Jack Morton 1958.



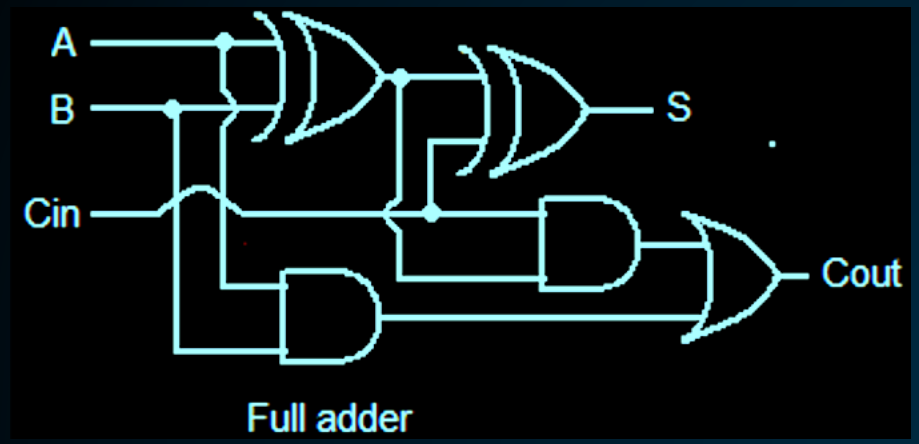
Rent's Rule (1960):







Abstraction and Internal fan-out



(Classical) logic gates directly drive other logic gates

- *`No-cloning' theorem prevents fan-in and fan-out of quantum information*
- *Multiplexing is essential for efficient use of IO resources*

A single quantum cannot be cloned

W. K. Wootters*

Center for Theoretical Physics, The University of Texas at Austin, Austin, Texas 78712, USA

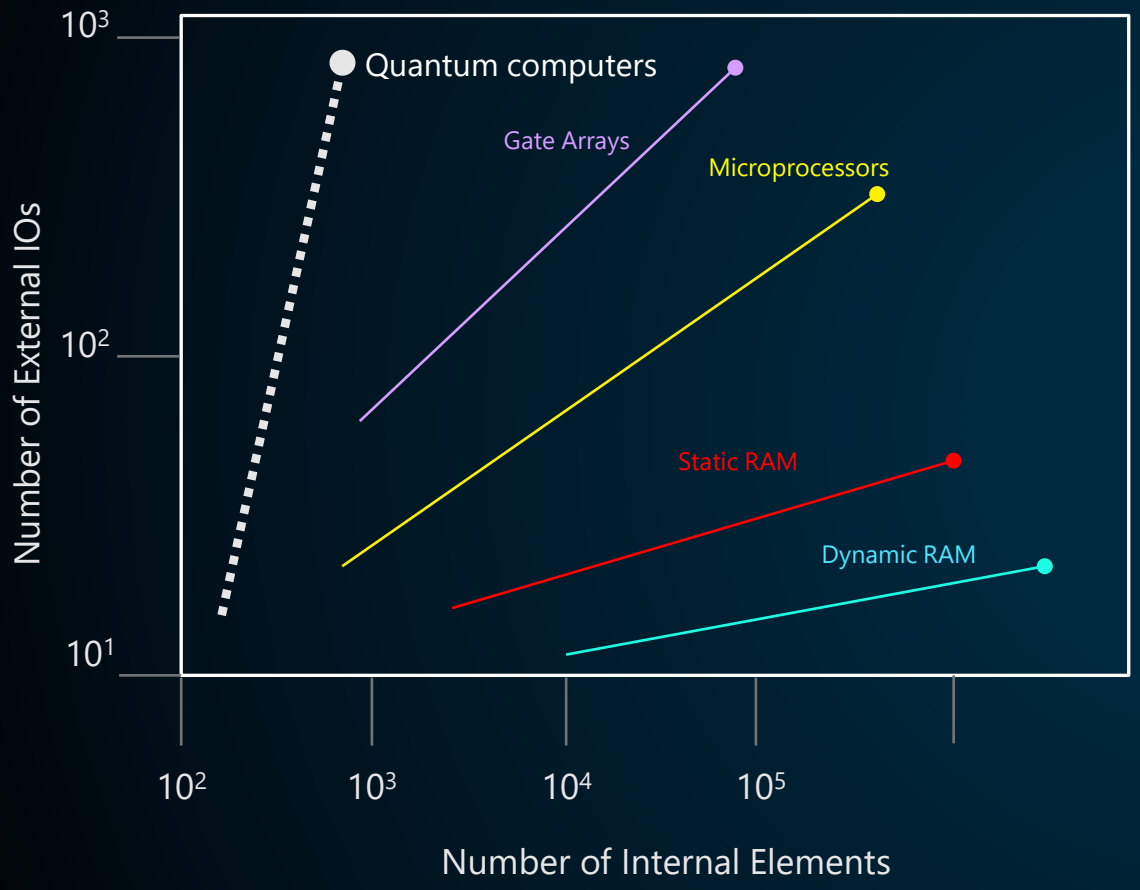
W. H. Zurek

Theoretical Astrophysics 130–33, California Institute of Technology, Pasadena, California 91125, USA

If a photon of definite polarization encounters an excited atom, there is typically some nonvanishing probability that the atom will emit a second photon by stimulated emission. Such a photon is guaranteed to have the same polarization as the original photon. But is it possible by this or any other process to amplify a quantum state, that is, to produce several copies of a quantum system (the polarized photon in the present case) each having the same state as the original? If it were, the amplifying process could be used to ascertain the exact state of a quantum system: in the case of a photon, one could determine its polarization by first producing a beam of identically polarized copies and then measuring the Stokes parameters[1]. We show here that the linearity of quantum mechanics forbids such replication and that this conclusion holds for all quantum systems.

(Nature, 1982)

Rent's Rule for Quantum Processors



…. And to make matters worse, temperature must be < 0.1 kelvin

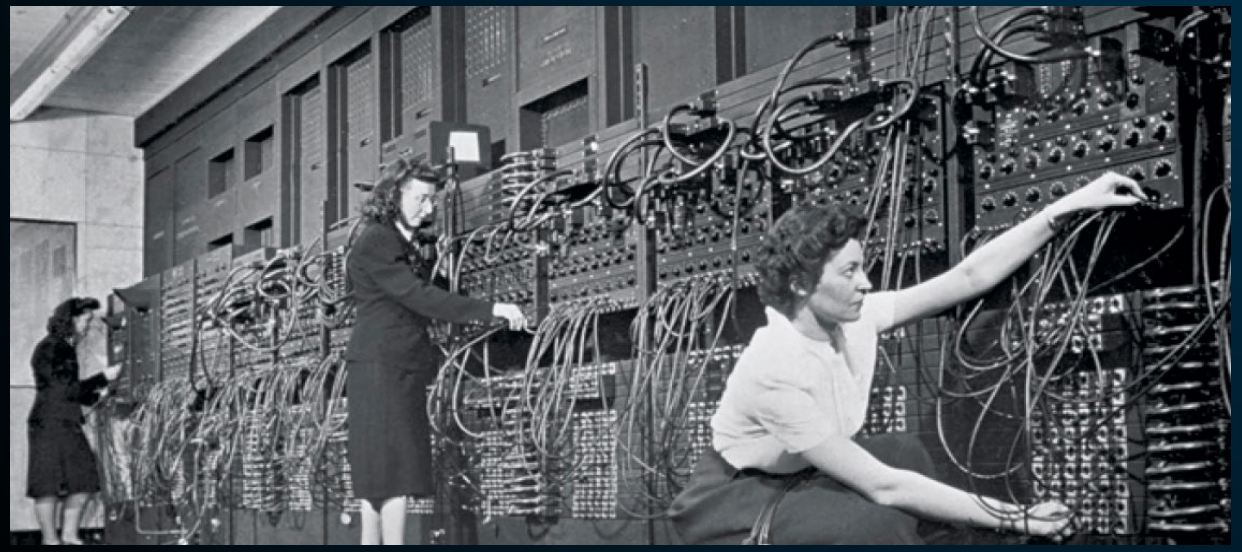


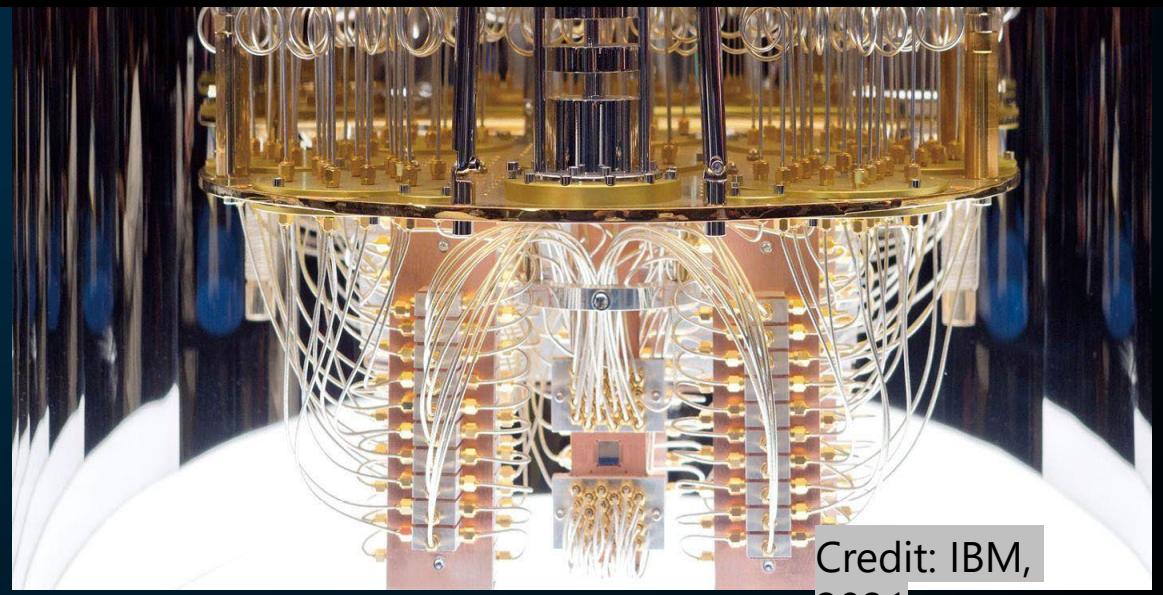
Credit: Google, 2019

Tyranny of numbers is a fundamental barrier to scale: TODAY



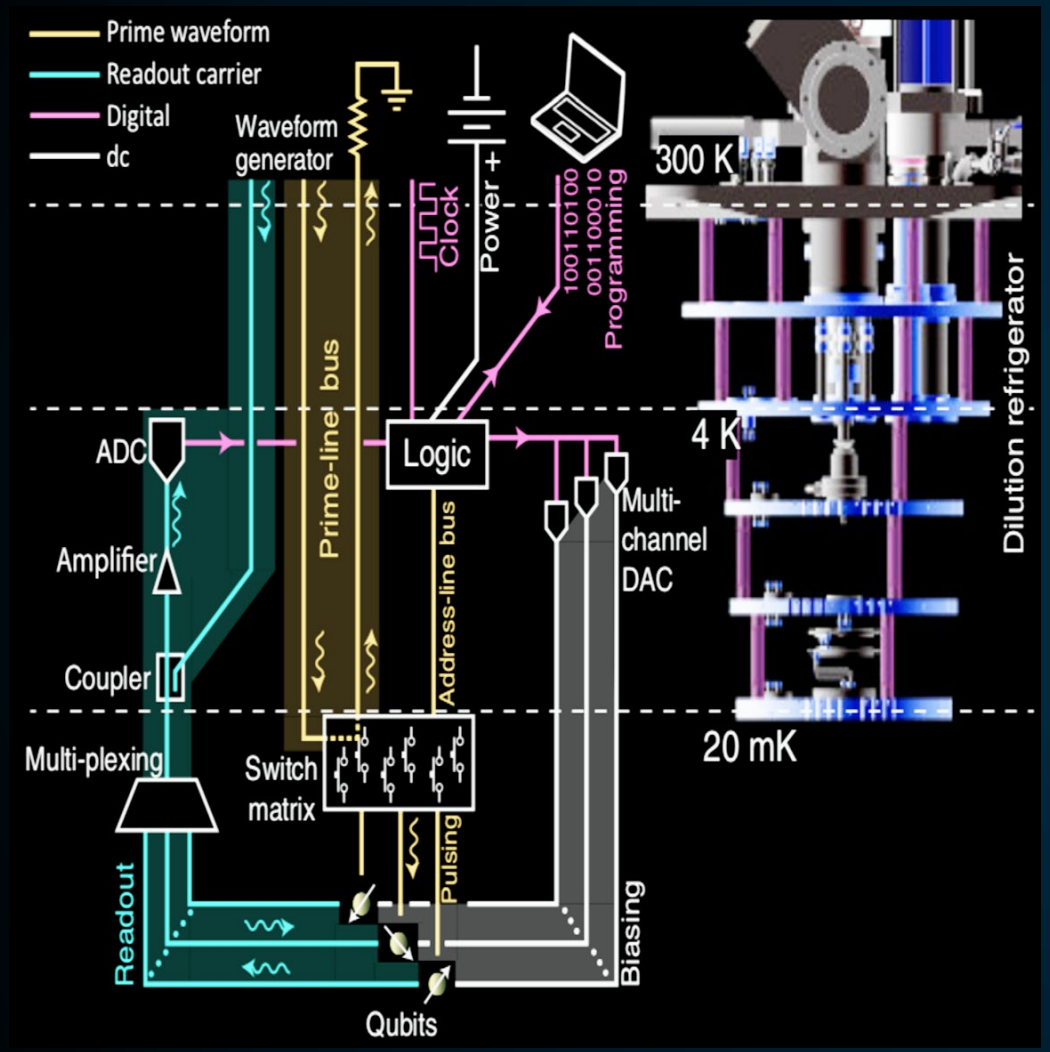
SWaP constraints are today the limiting barrier to scaling quantum computing



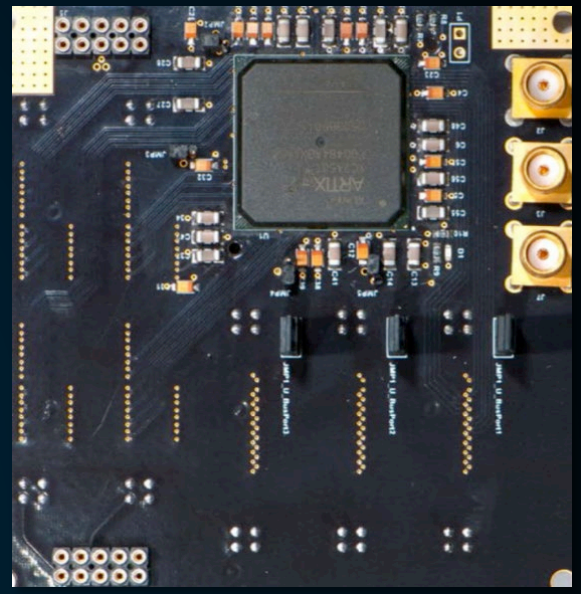


Credit: IBM, 2021

4 kelvin Control?



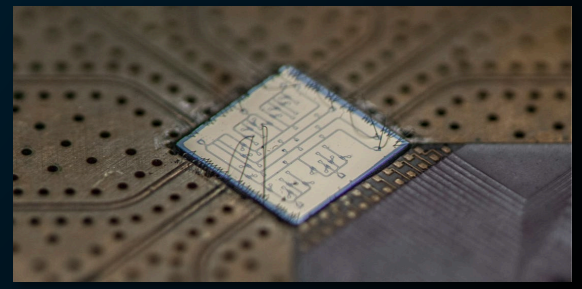
4 K FPGA



Internal cables



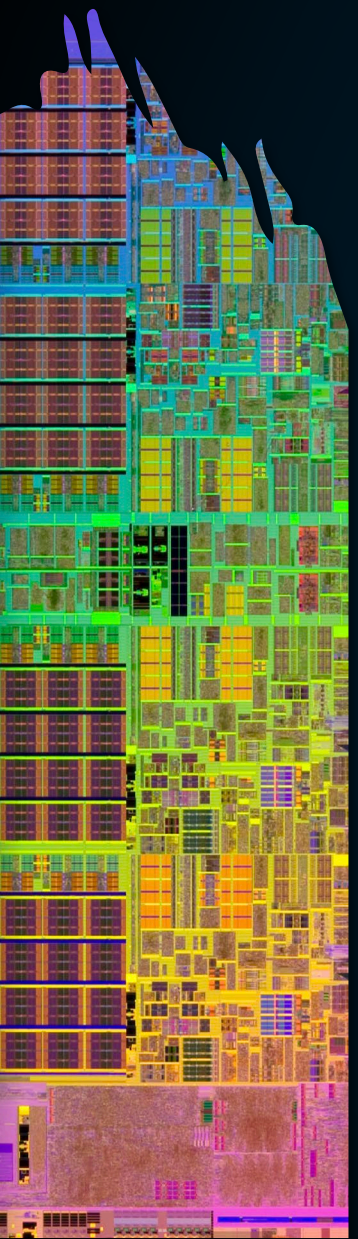
0.1 K Device



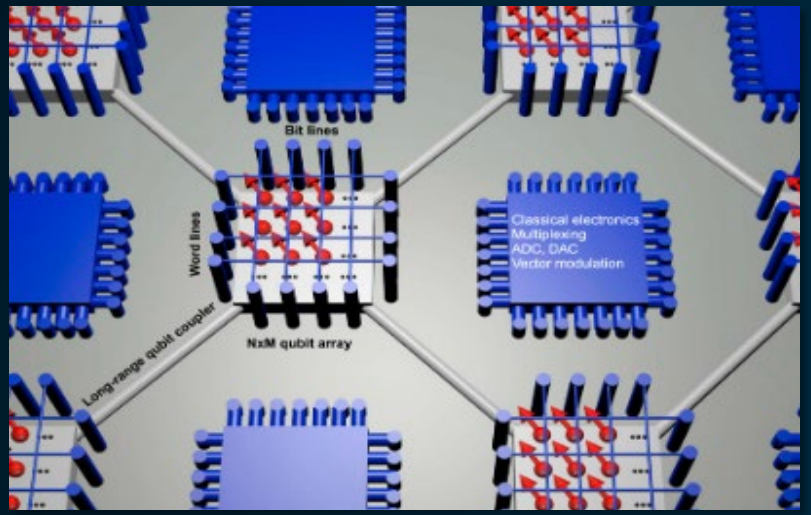
Cryogenic Control Architecture for Large-Scale Quantum Computing, J. M. Hornibrook, J. I. Colless, ...DJR, Phys. Rev. Appl. (2015).

An FPGA-based instrumentation platform for use at deep cryogenic temperatures, I. Conway Lamb, J. I. Colless...DJR, Rev. Sci. Inst. (2016).

Monolithic Integration “SOC”?

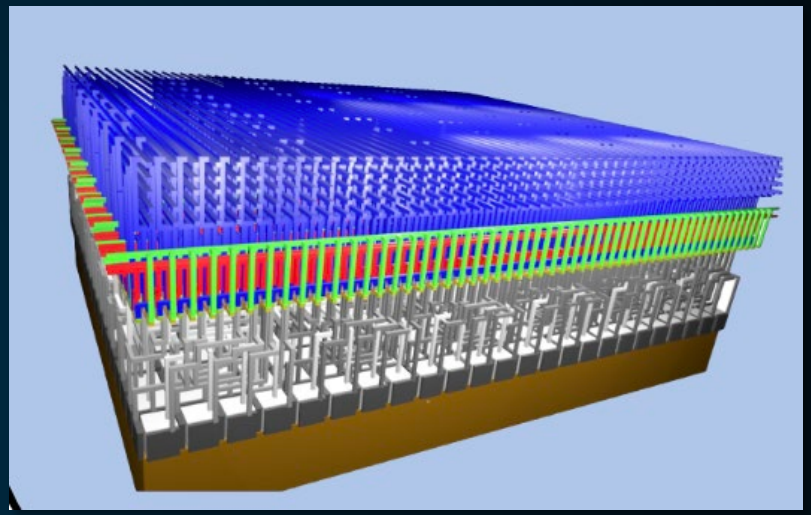


Modular 2D Integration



Vandersypen, et al., (2017).

Full 3D Integration

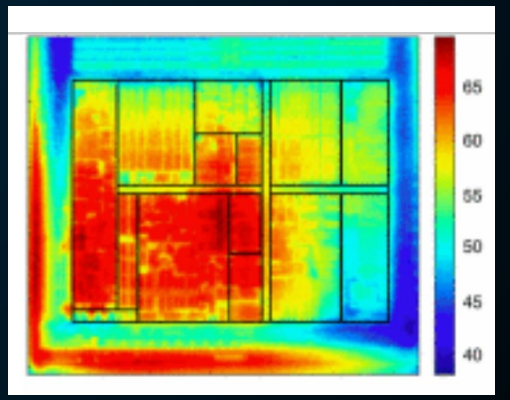


Veldhorst, et al., (2017).

Major Challenges:

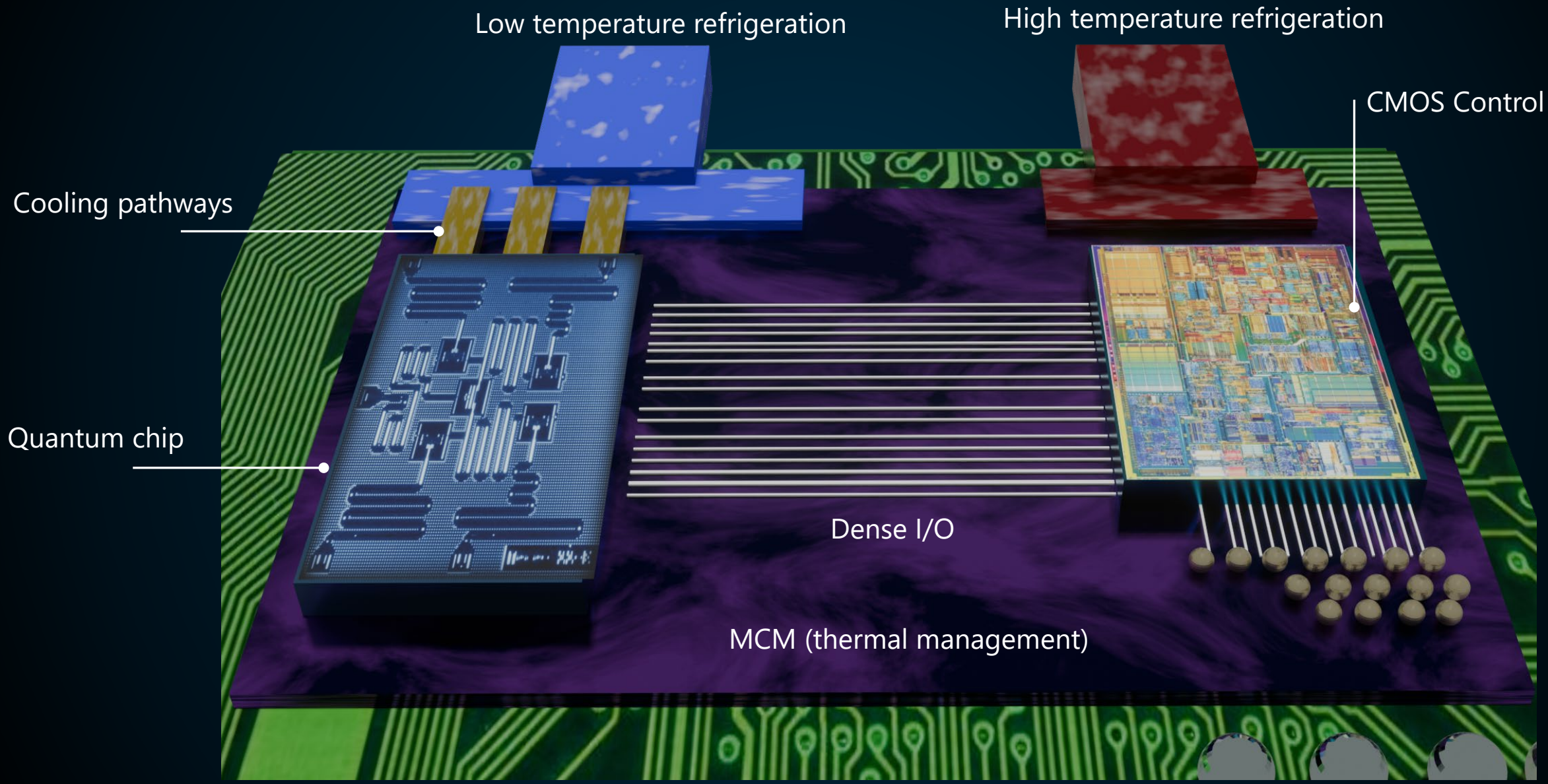
- Power density (control circuits nanometers away from qubits)
- EM Crosstalk
- Qubit – control footprint mismatch
- Materials and Fabrication mismatch

Measuring power and temperature from real processors

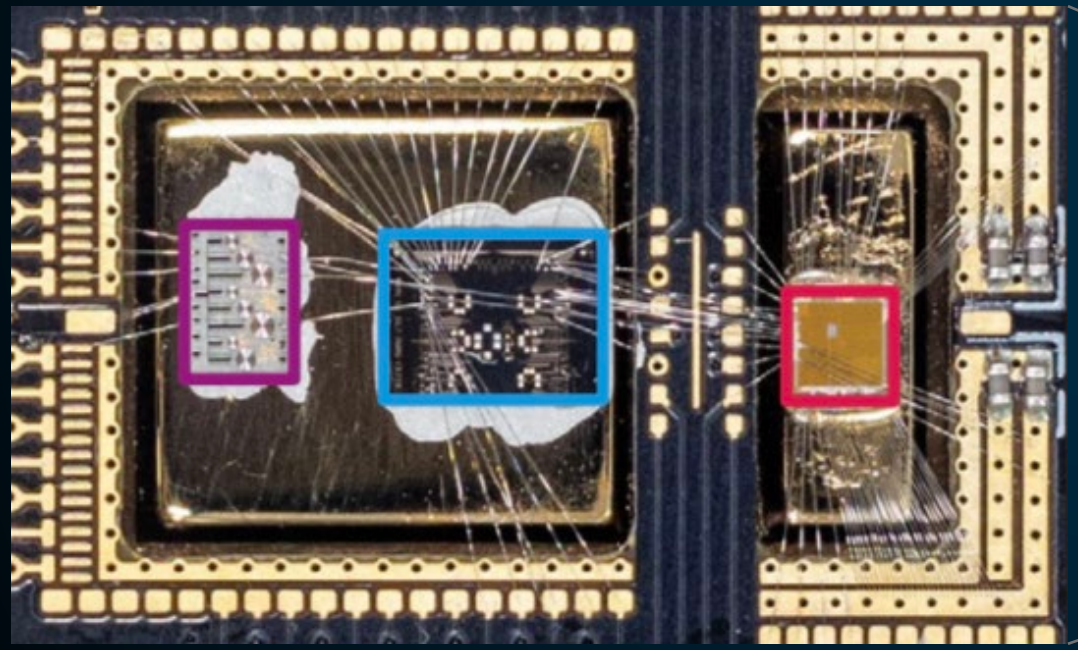


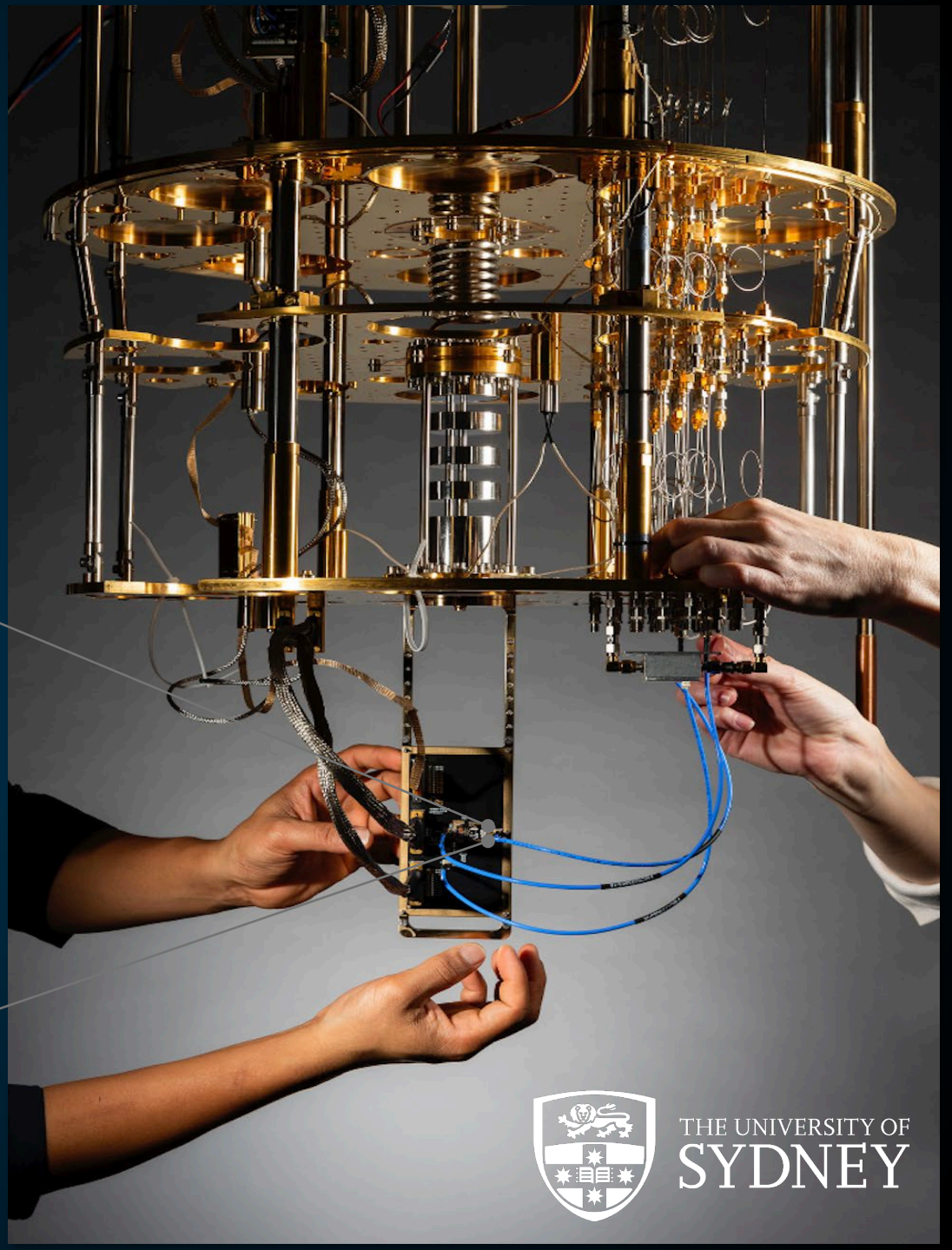
Mesa-Martinez et al., (2008)

`Chiplet-style' Heterogeneous Integration at milli-kelvin



Mixed-Signal Chiplet CMOS at 100 mK



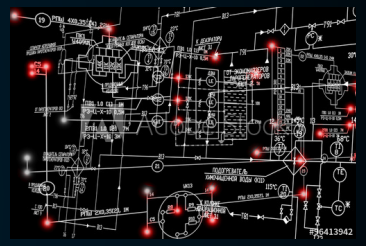


Approaches to Engineering Cryo-CMOS below 1 kelvin

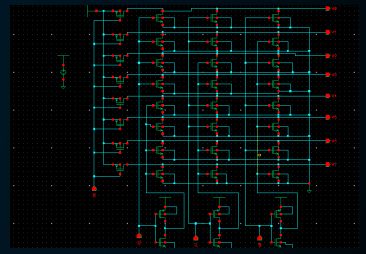
1. Cool commercially available electronics and hope for the best!



2. Carefully design circuits to avoid adverse effects of cooling



3. Develop cryo-PDK and design accordingly

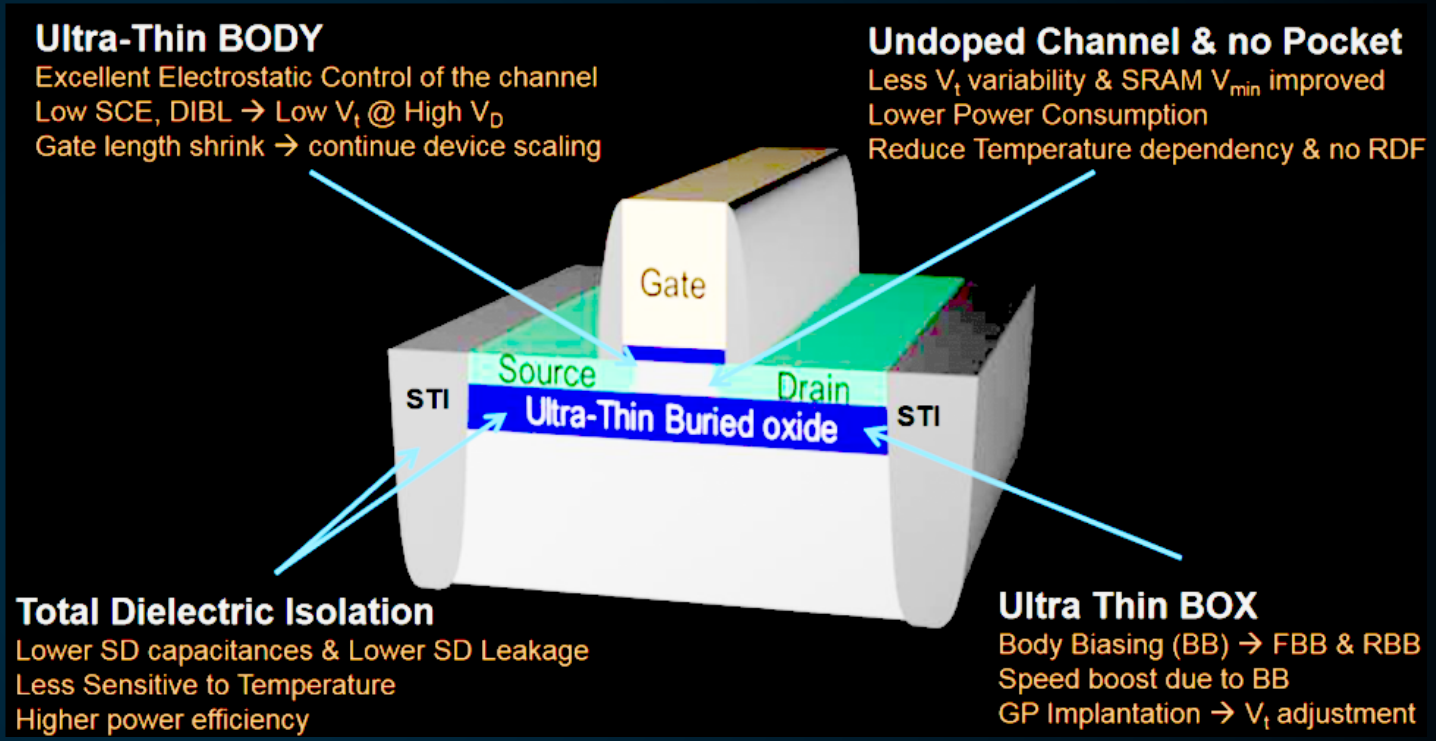


4. Adjust foundry parameters

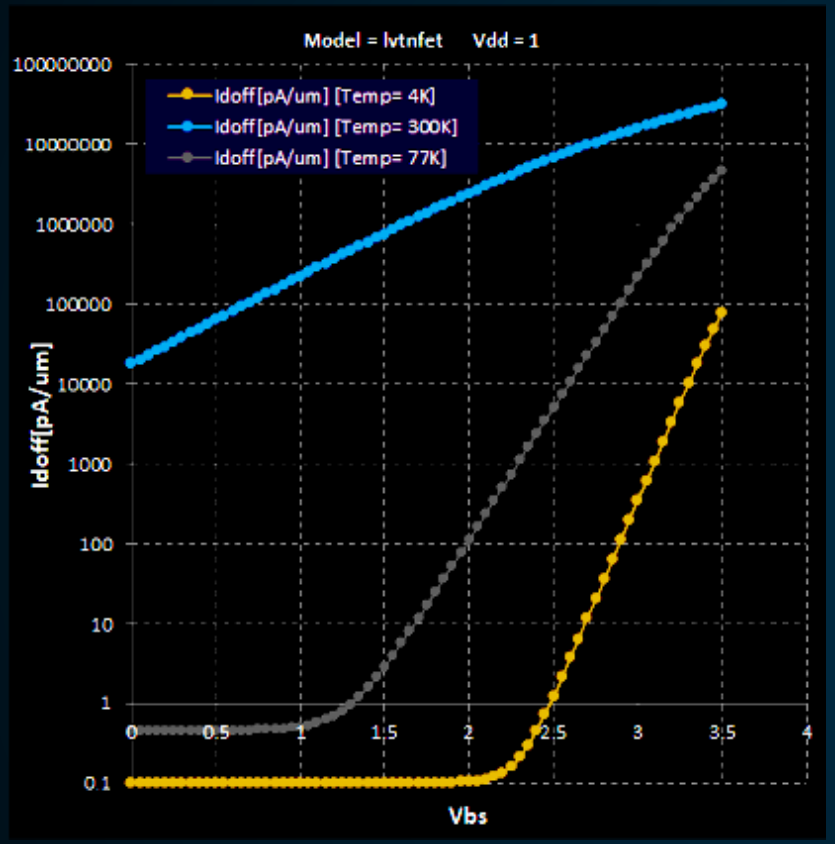


Why Fully-depleted Silicon on Insulator (FDSOI) for Cryo?

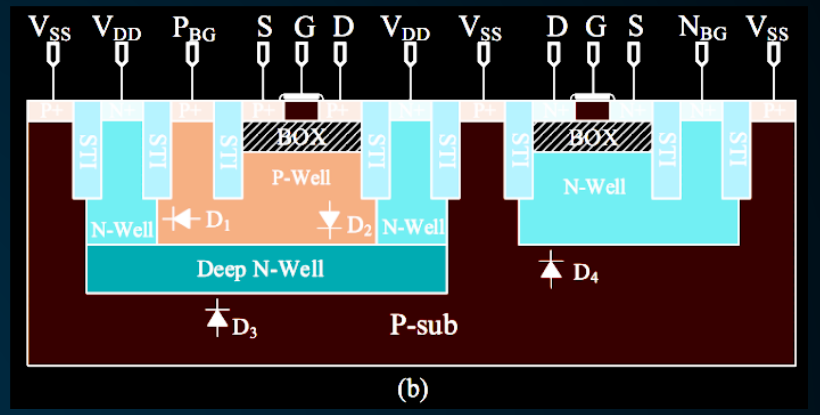
- Fully depleted -> lower power
- VT tunable via body-bias (4 terminal transistors)
- Ultra-low leakage
- Low parasitics
- No dopants – tighter V_T distribution



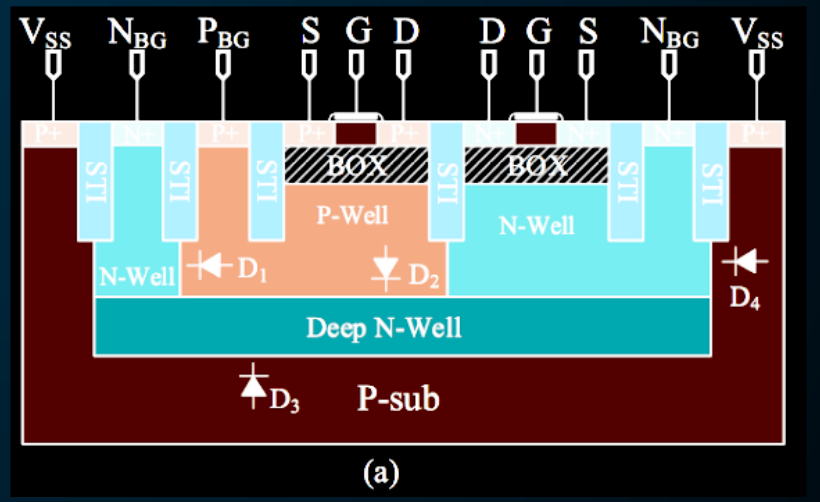
Configuring Circuit-blocks with Different Body-Bias



Body-bias enables V_T compensation



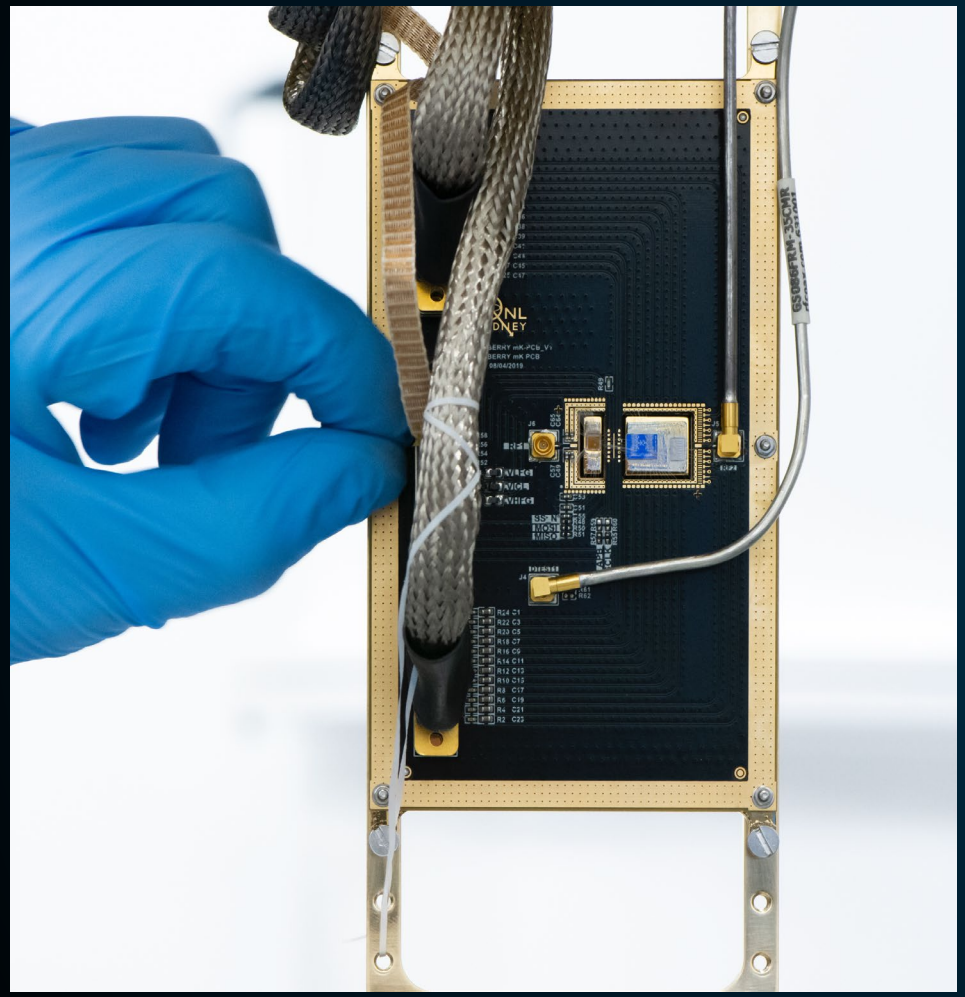
Analog: (Independent Body-bias)

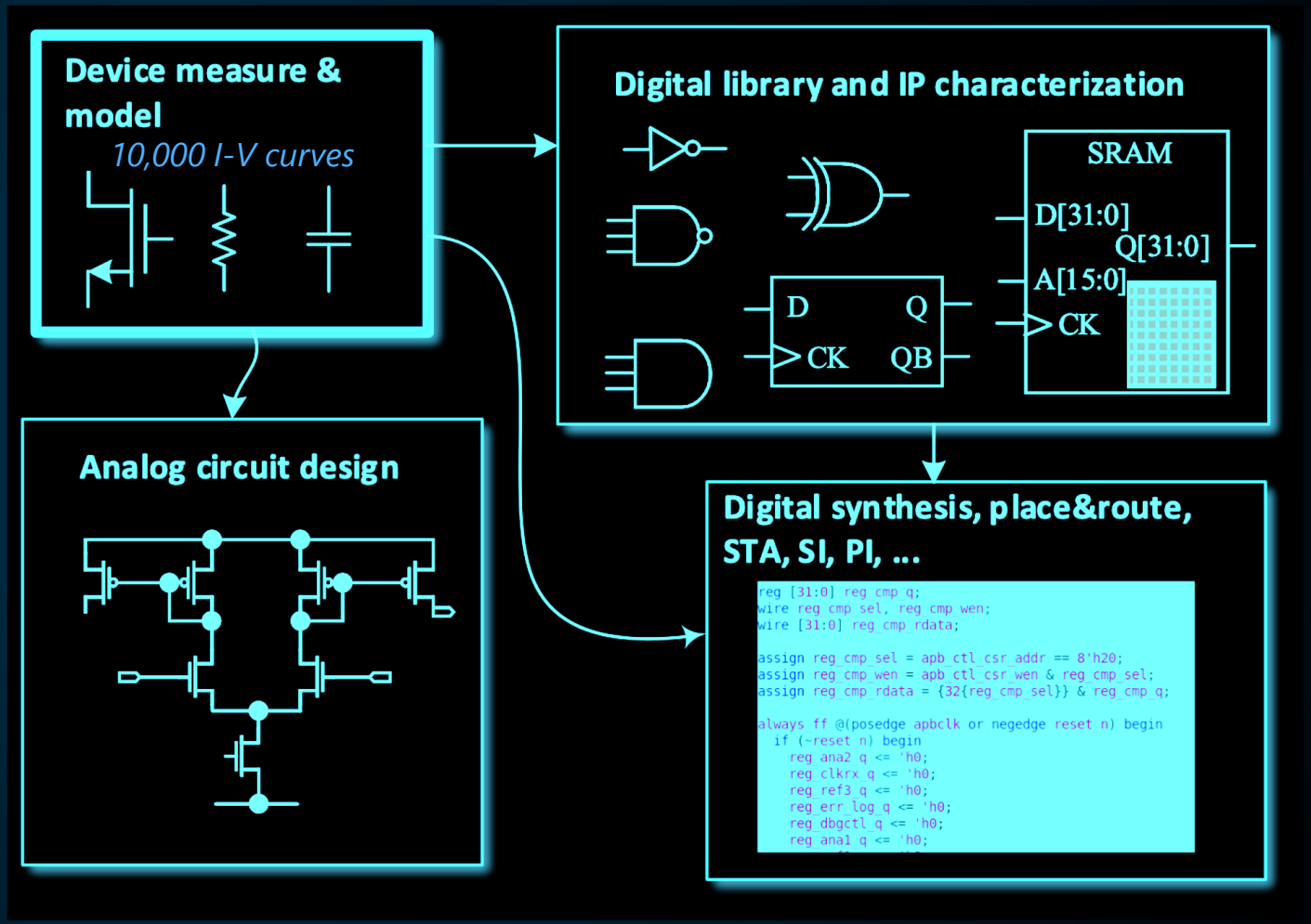


Digital: (Common Body-bias for higher density)

A multi - year challenge:

If control system must be proximal to qubits, complex CMOS circuits must operate in milli-kelvin temperature domain

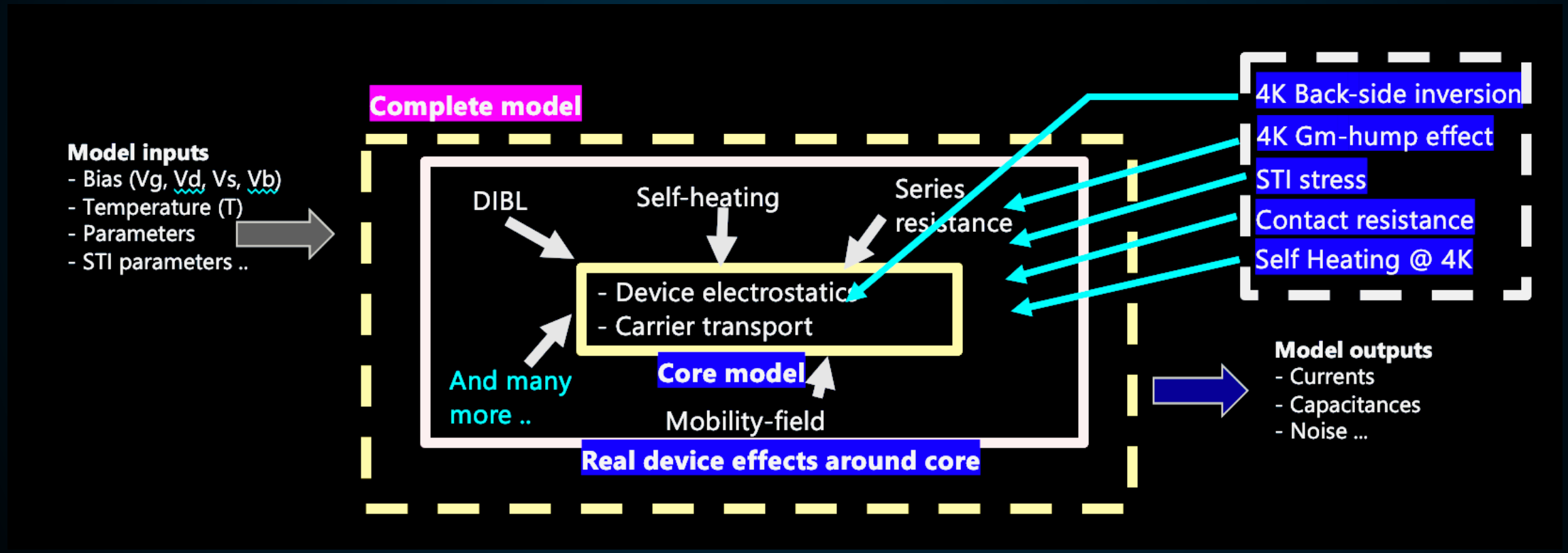




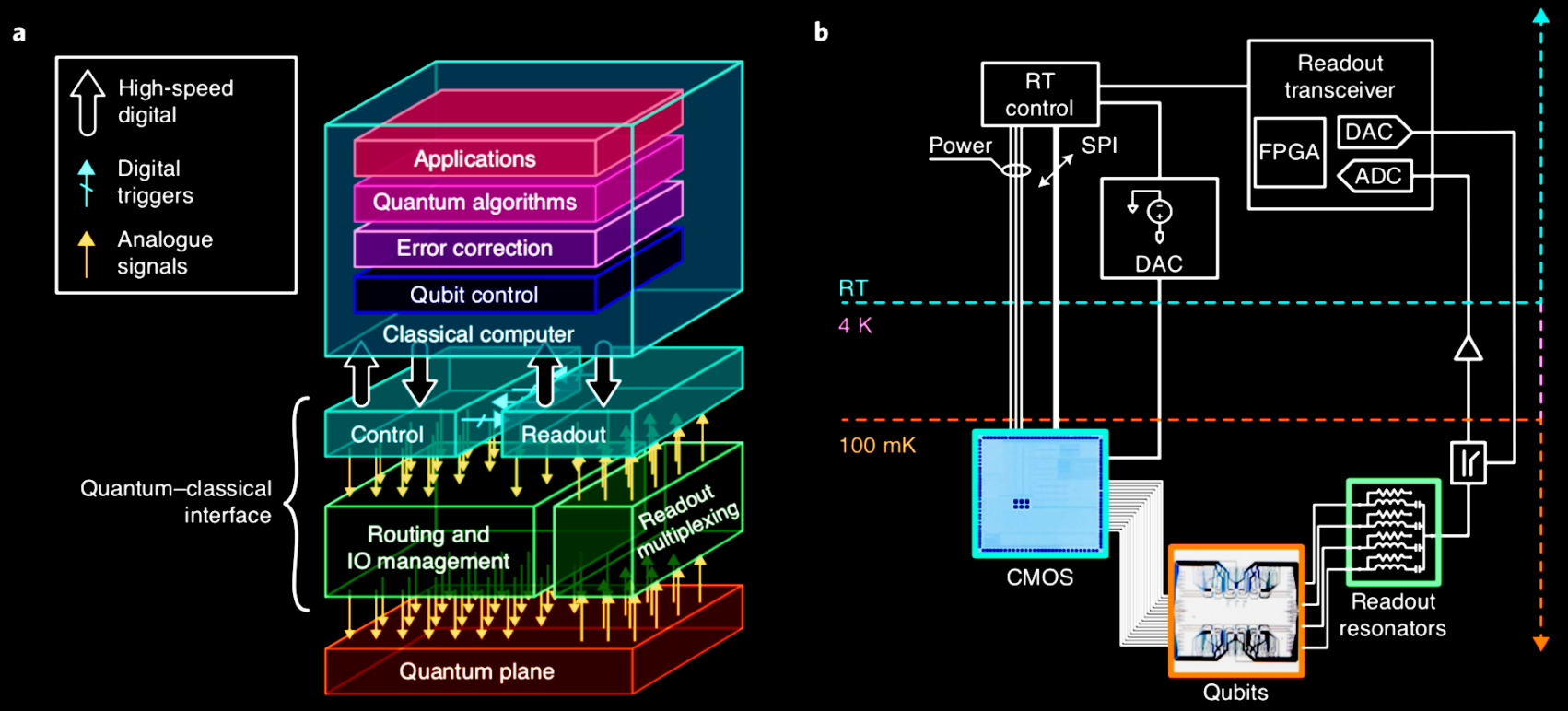
Process design kit (PDK) development requires extensive characterization of cryogenic device performance

Cryo-PDK needs to include parameters not captured by factory models

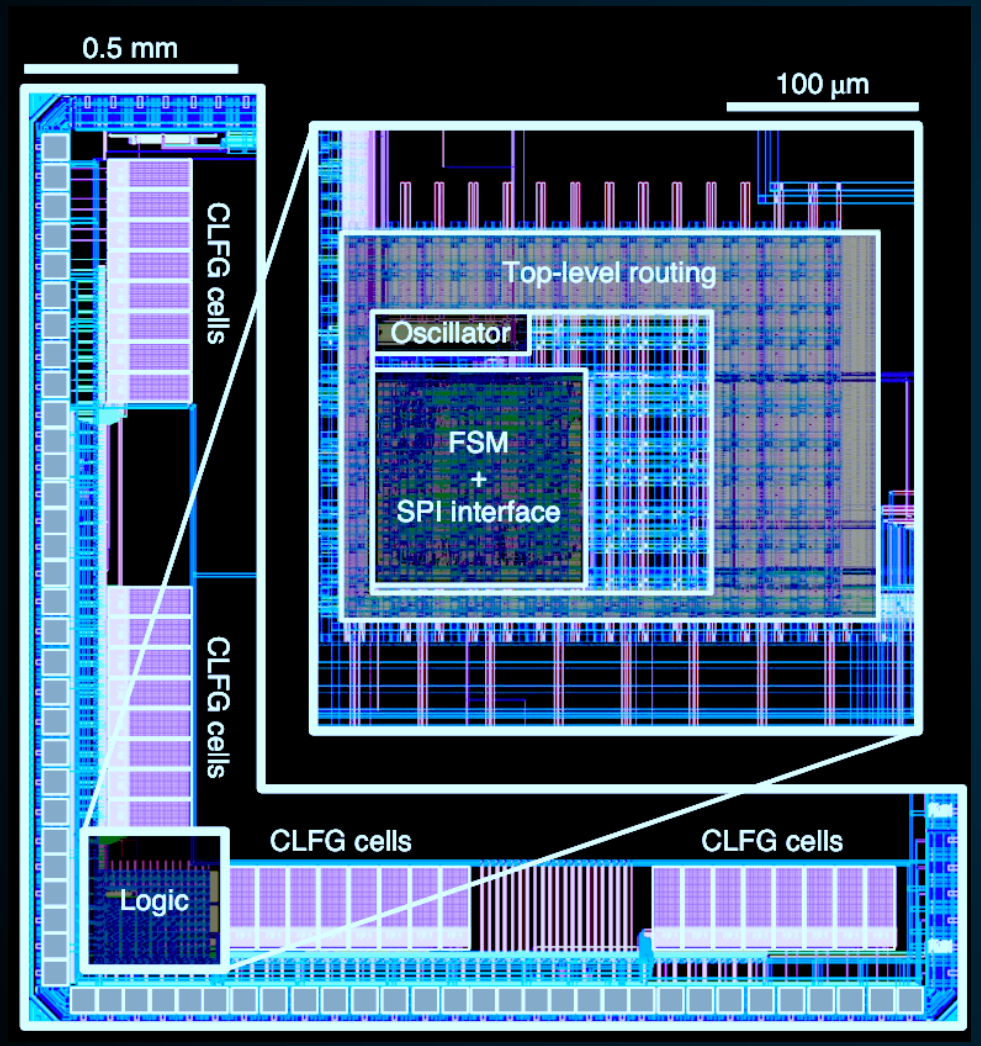
- New models are critical in debugging and tuning performance of Cryo-CMOS



Pauka *et al.*, Nature Electronics, (2021)



Mixed Signal Cryo-CMOS at 100 mK



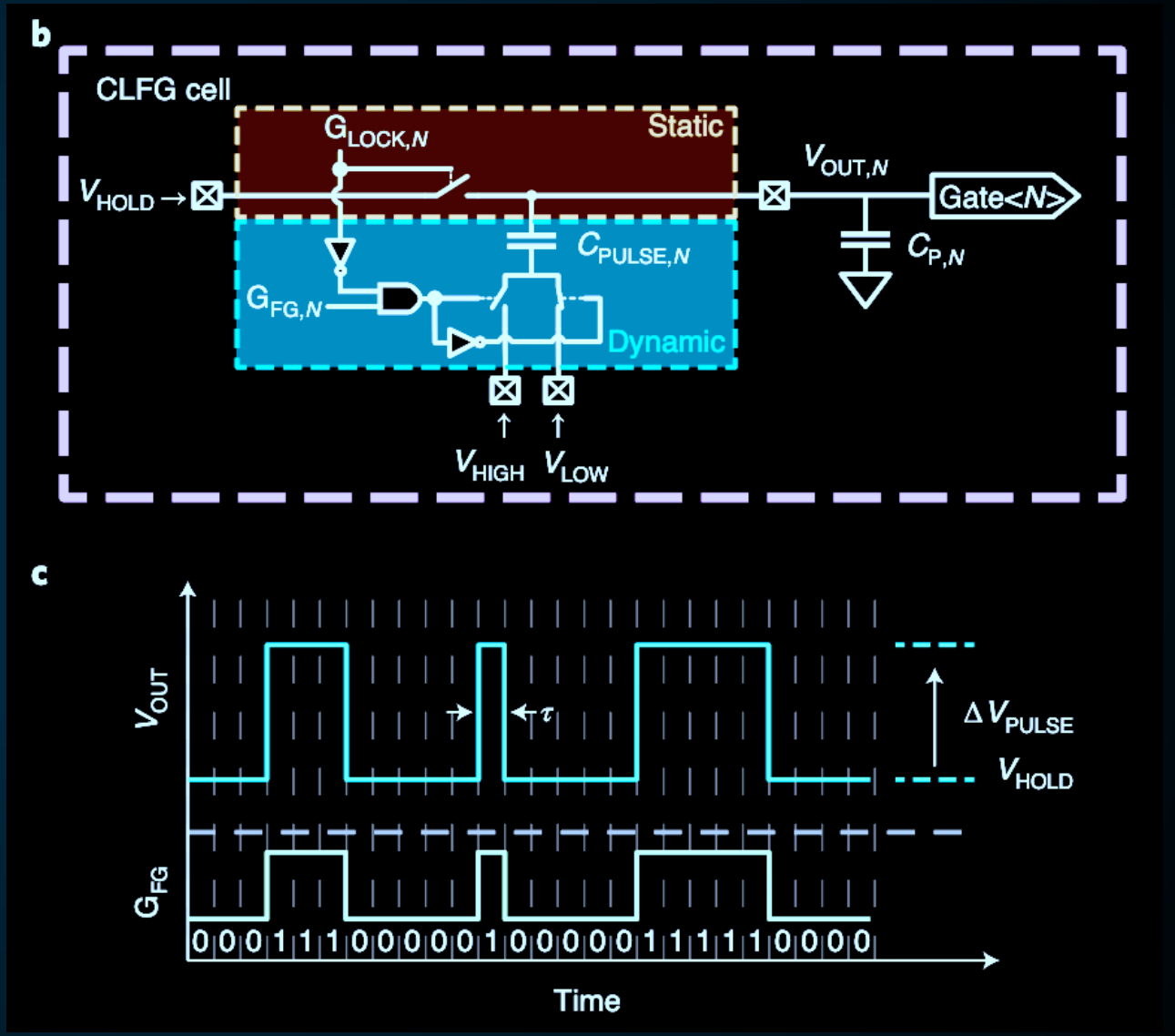
Digital blocks that are programed via instructions from room temperature:

- SPI Interface
- Finite state machines
- Waveform memory
- Internal configurable oscillator

- Array of analog output cells that generate volt-scale dc biases and rf pulses

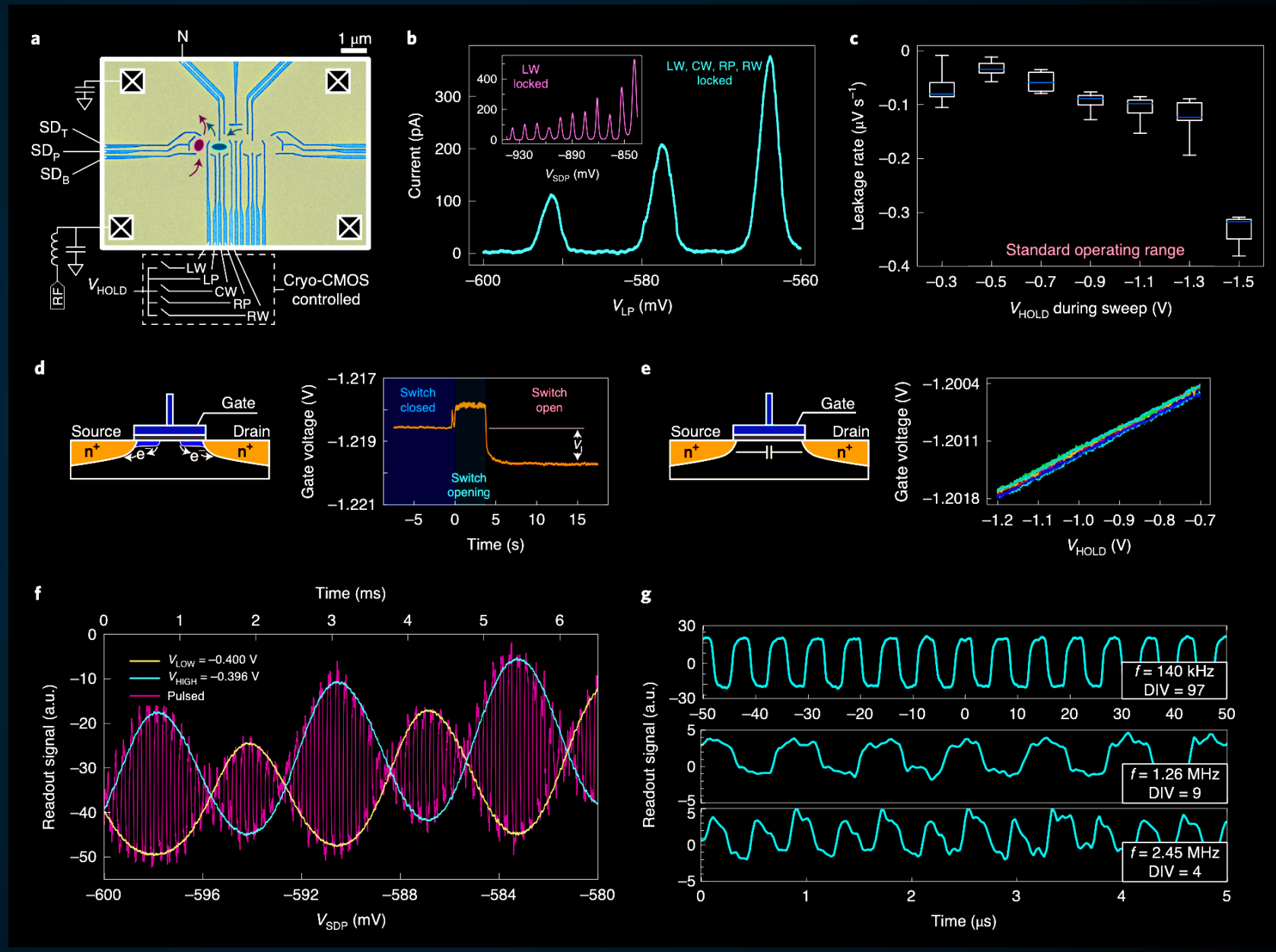
Mixed Signal Cryo-CMOS at 100 mK

- Exploit ultra-low transistor leakage at cryo-temperature to `lock' dc bias voltages on capacitors.
- Exploit capacitance of interconnect to hold charge.
- Create fast voltage pulses by transfer of charge between small capacitors.
- No cables – operates in the high impedance domain.

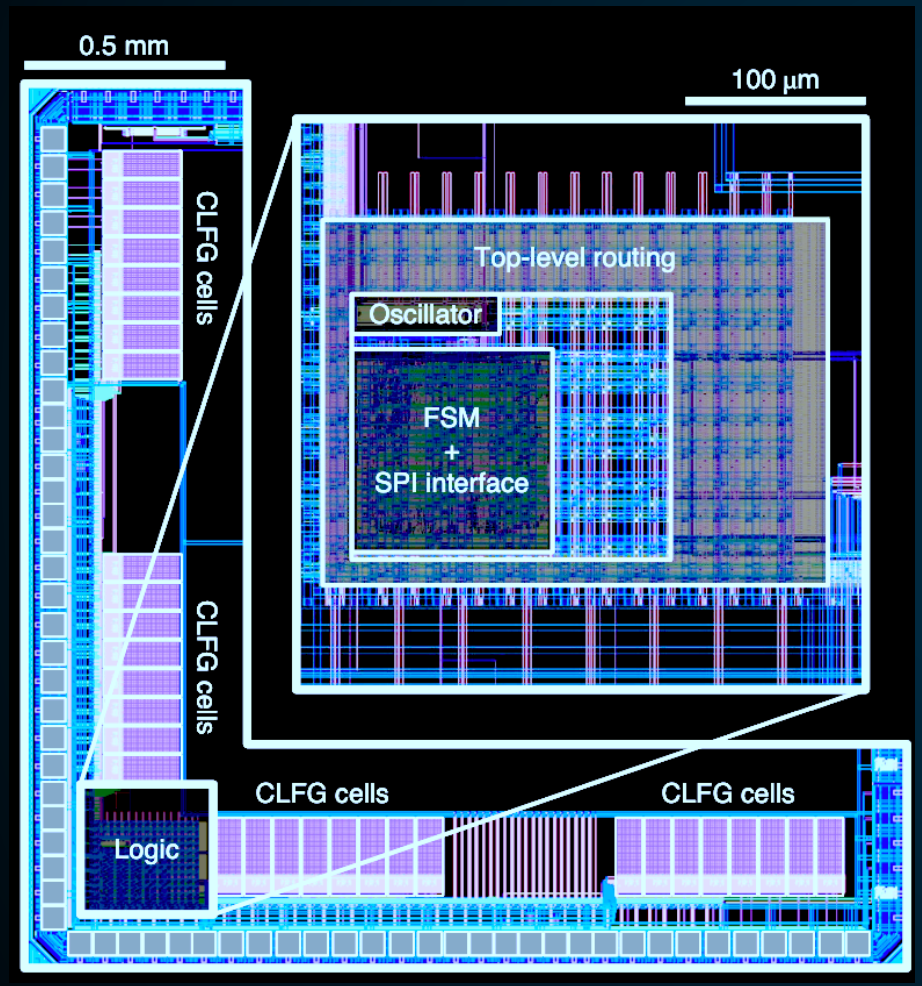


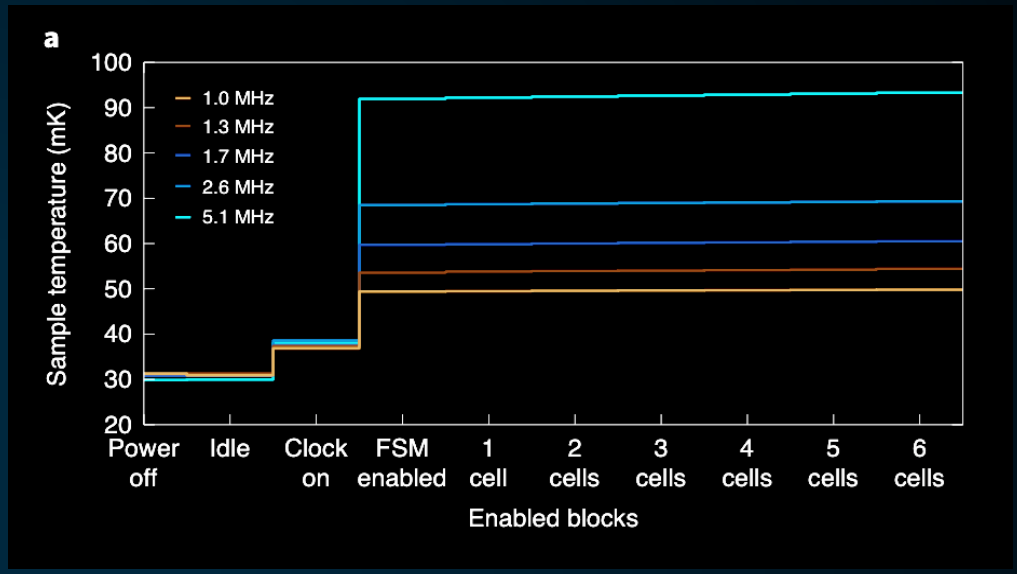
Mixed Signal Cryo-CMOS at 100 mK controlling quantum devices

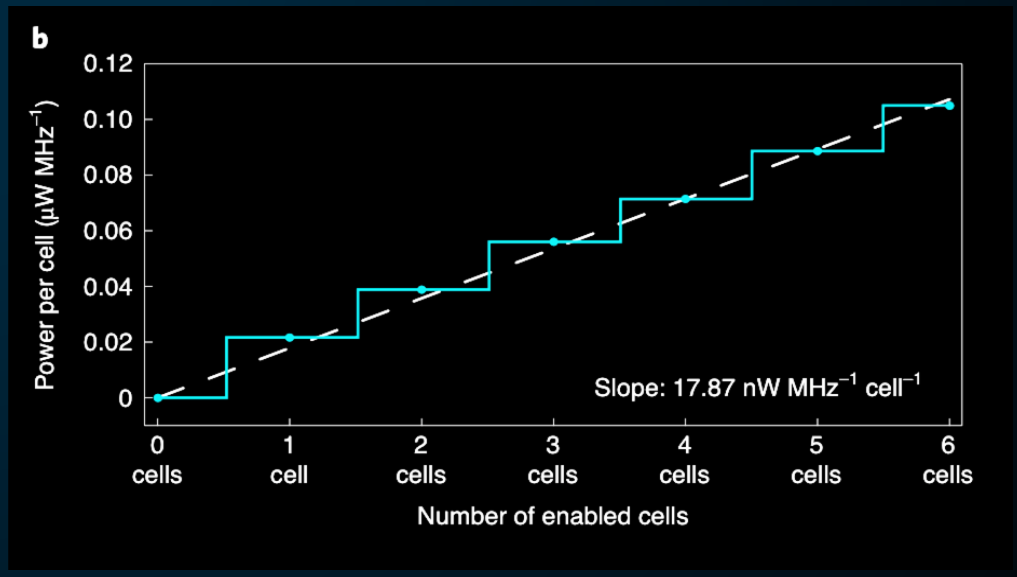
- Bias to define quantum dots provided by CMOS.
- rf-charge sensing used to characterize high bandwidth response.



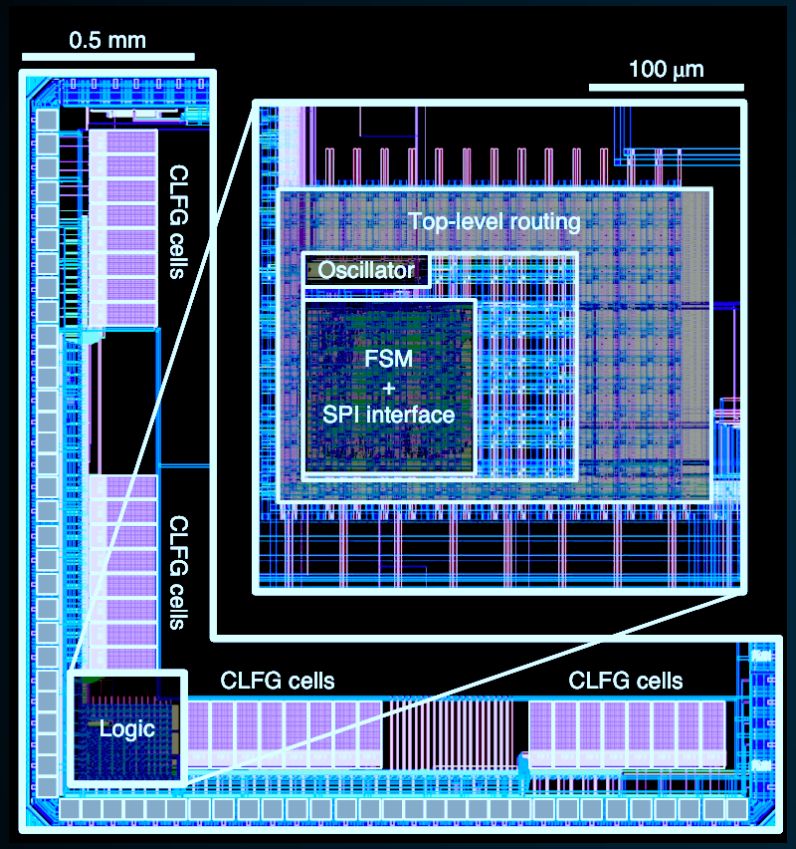
Mixed signal Cryo-CMOS at 100 mK: Power density

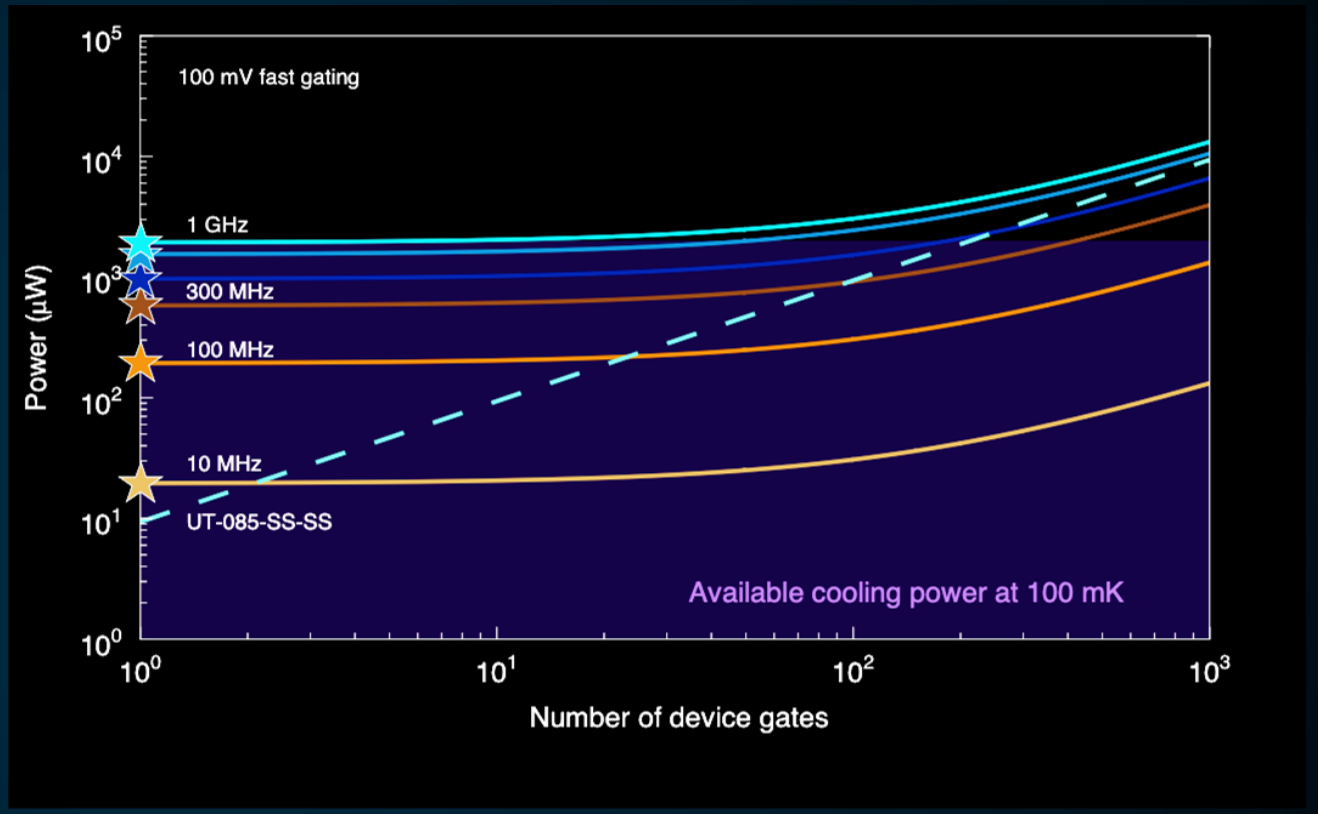






Extrapolation to a scaled machine





- Extrapolating, data suggests 1 million independent, **100 mV** MHz pulses can be delivered within cooling power of dilution fridge.

Further Opportunities: Floating-Gate Approaches

Enabling Technologies

IEEE Transactions on Quantum Engineering

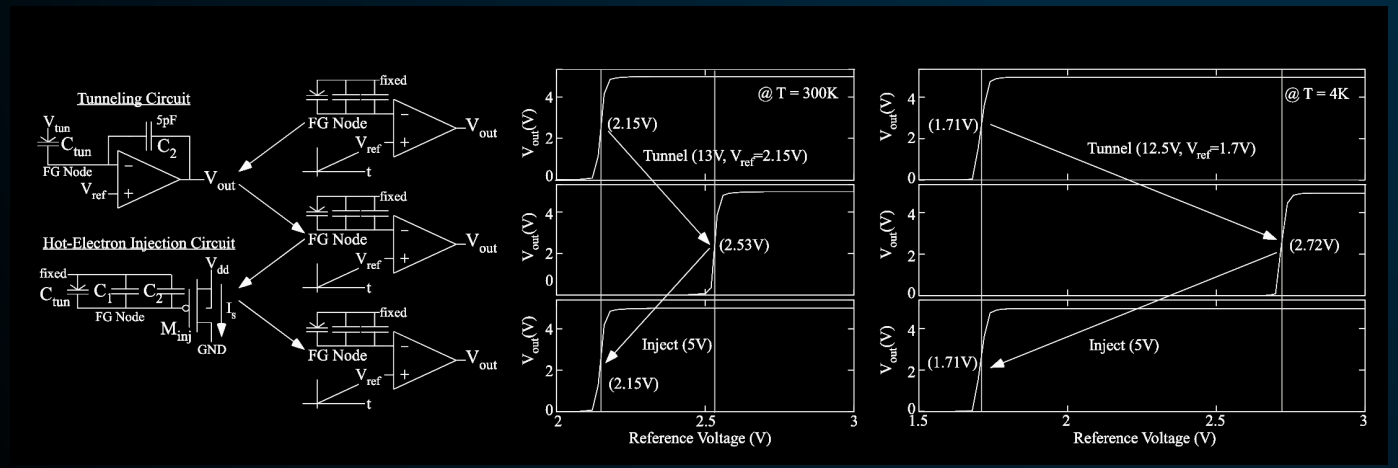
Received November 12, 2020; revised February 8, 2021 and February 26, 2021; accepted March 5, 2021; date of publication March 23, 2021; date of current version May 4, 2021.

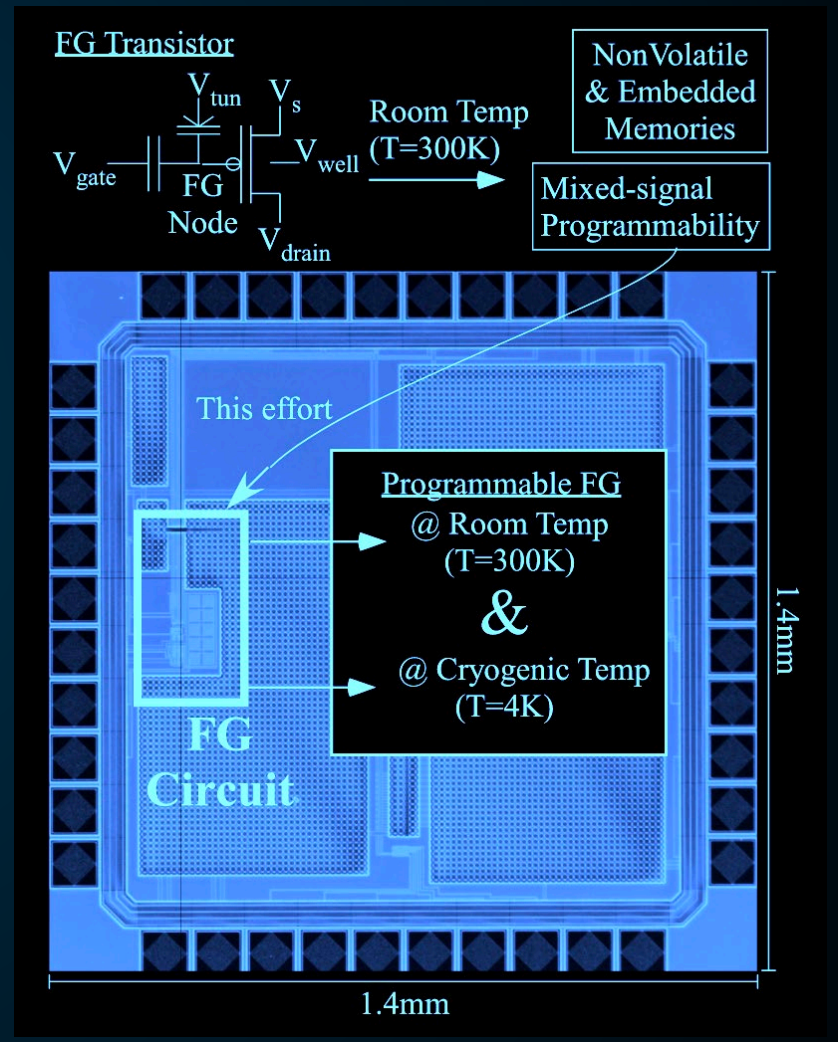
Digital Object Identifier 10.1109/TQE.2021.3067996

Cryogenic Floating-Gate CMOS Circuits for Quantum Control

JENNIFER HASLER[1], NEIL DICK[3], KUSHAL DAS[3], BRIAN DEGNAN[2], ALIREZA MOINI[3], AND DAVID REILLY [3] (Member, IEEE)

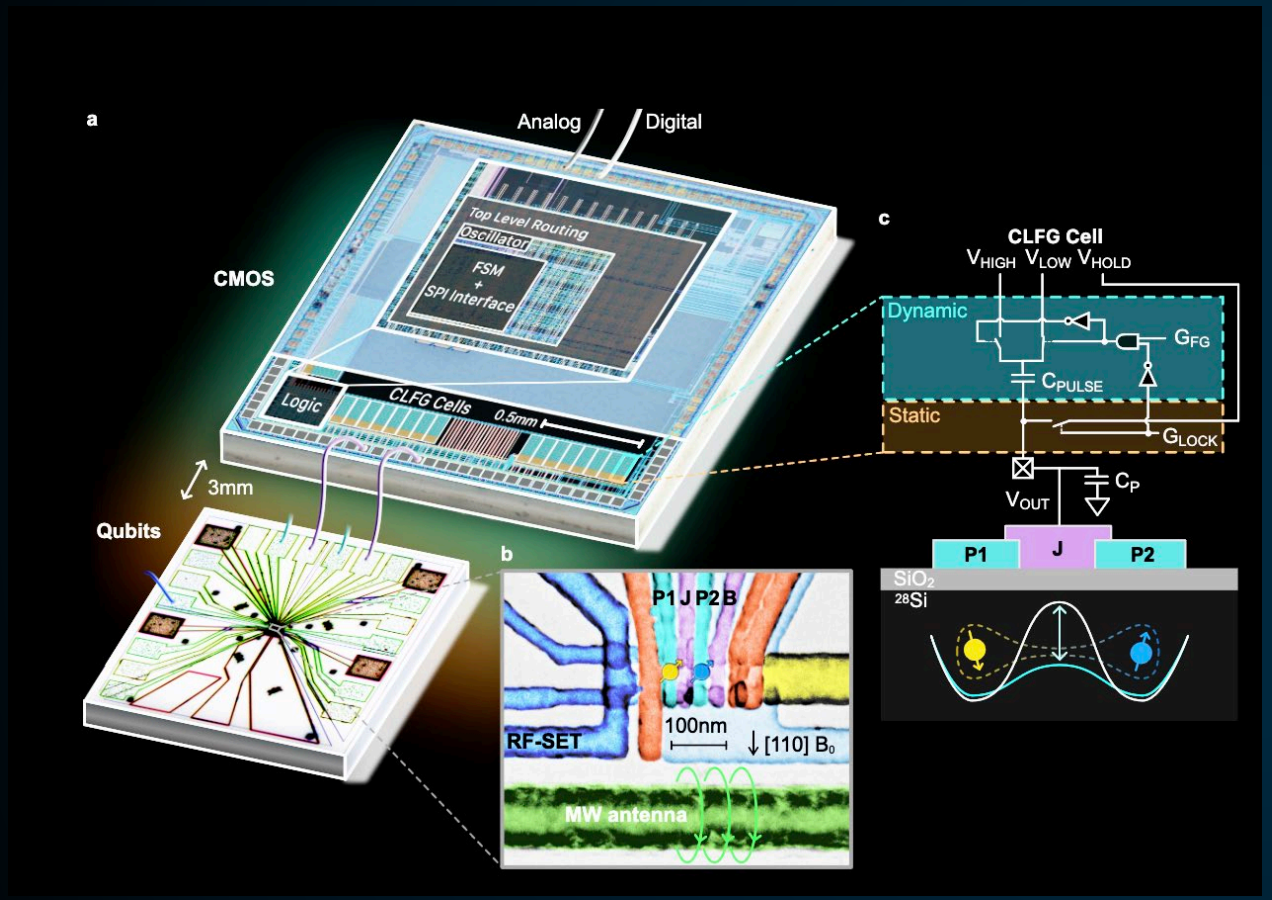
[1] School of Electrical, and Computer Engineering (ECE), Georgia Institute of Technology, Atlanta, GA 30332 USA
[2] White River Technologies, Newton, MA 02464 USA
[3] Microsoft Quantum Sydney, The University of Sydney, NSW 2006, Australia

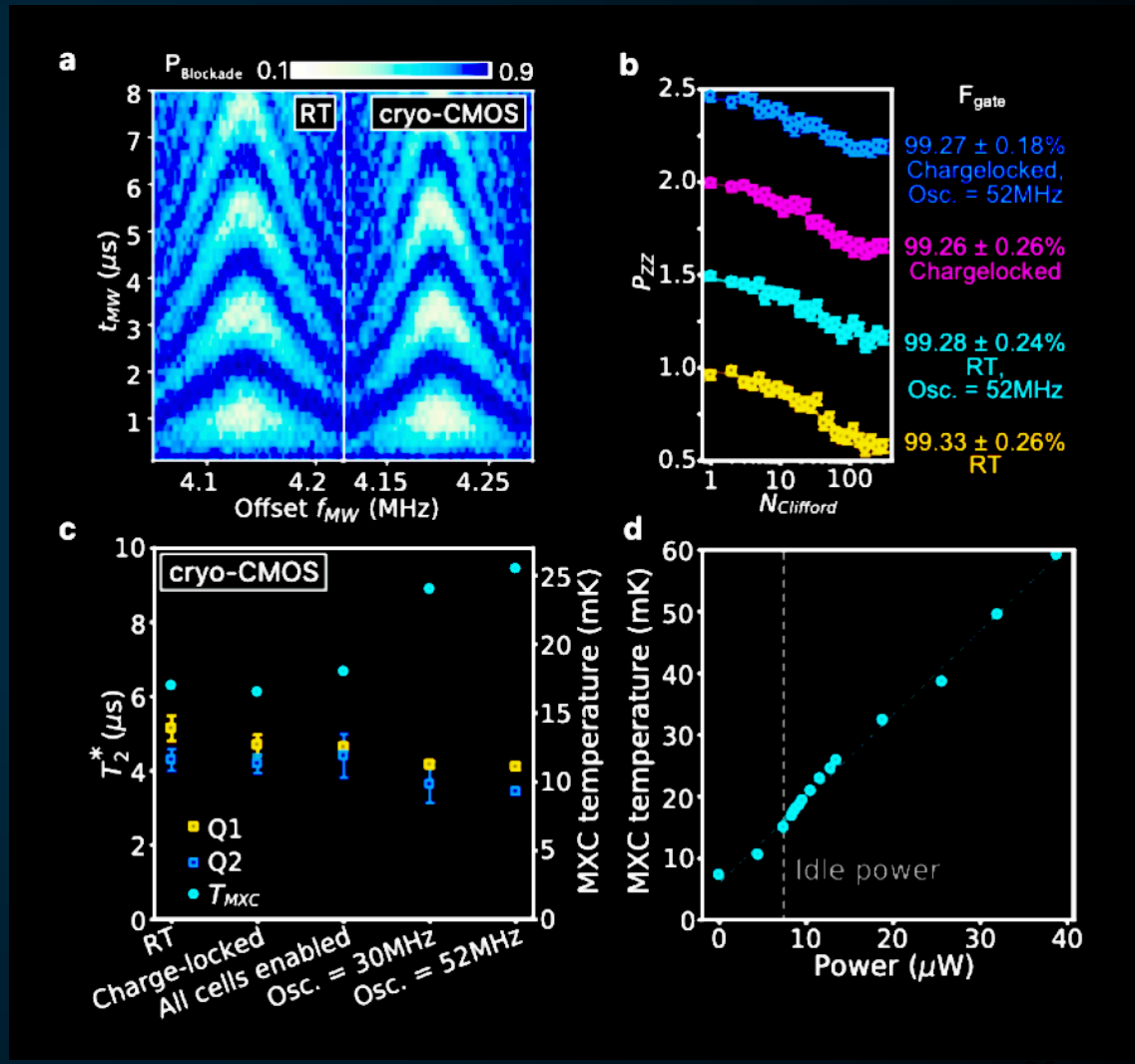




Spin Qubits with Scalable milli-kelvin CMOS Control

Single Qubit Control



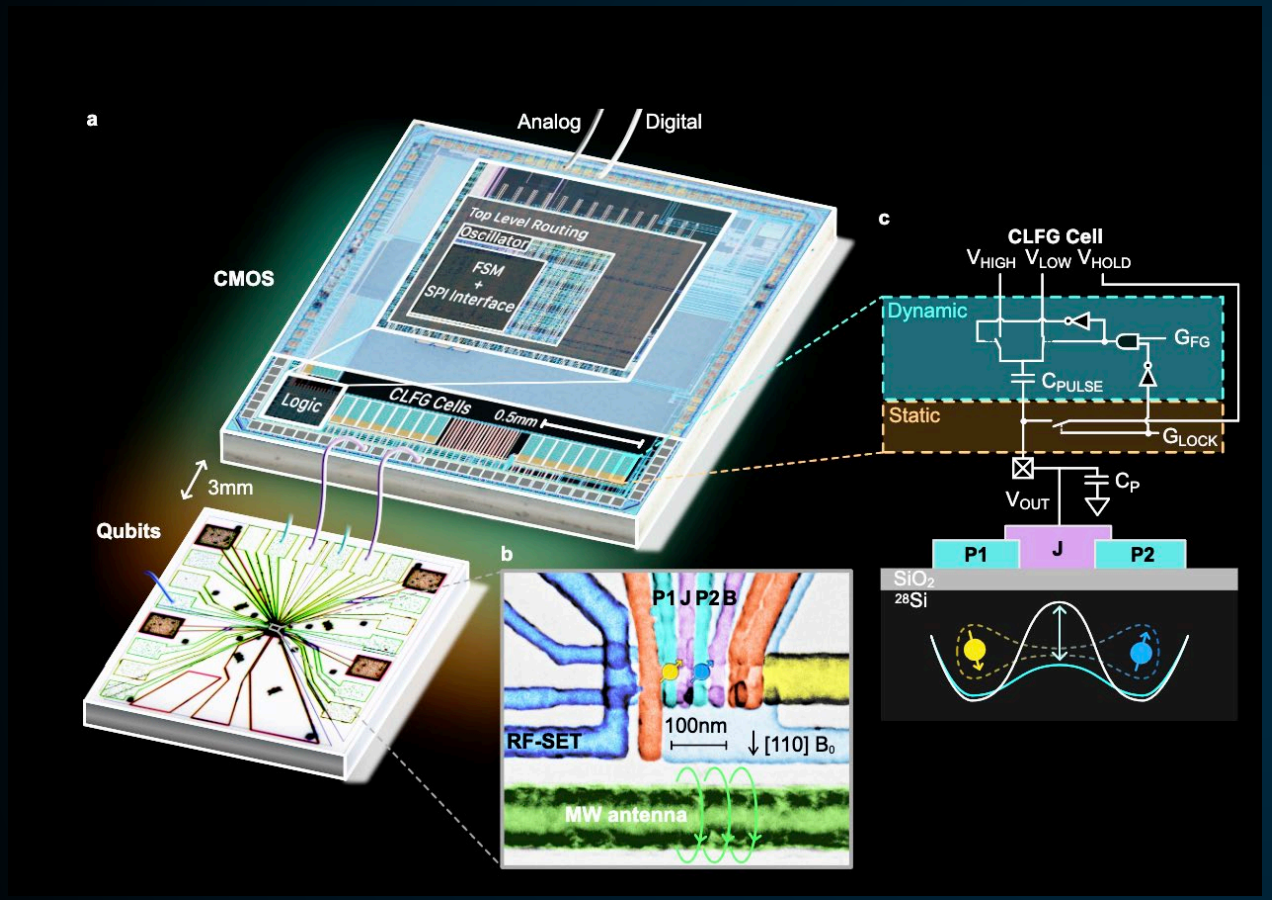


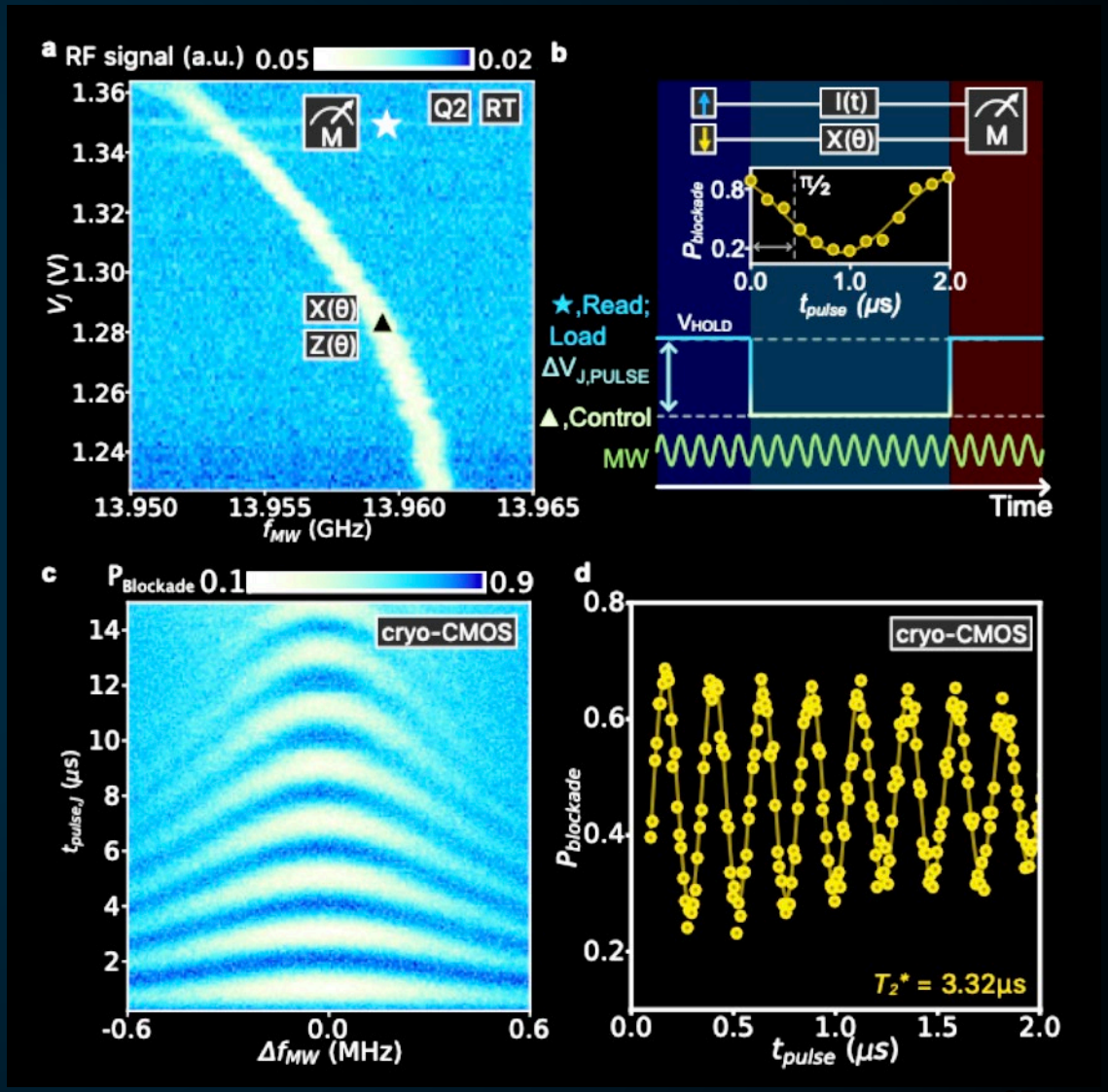
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Spin Qubits with Scalable milli-kelvin CMOS Control

Global Field Control



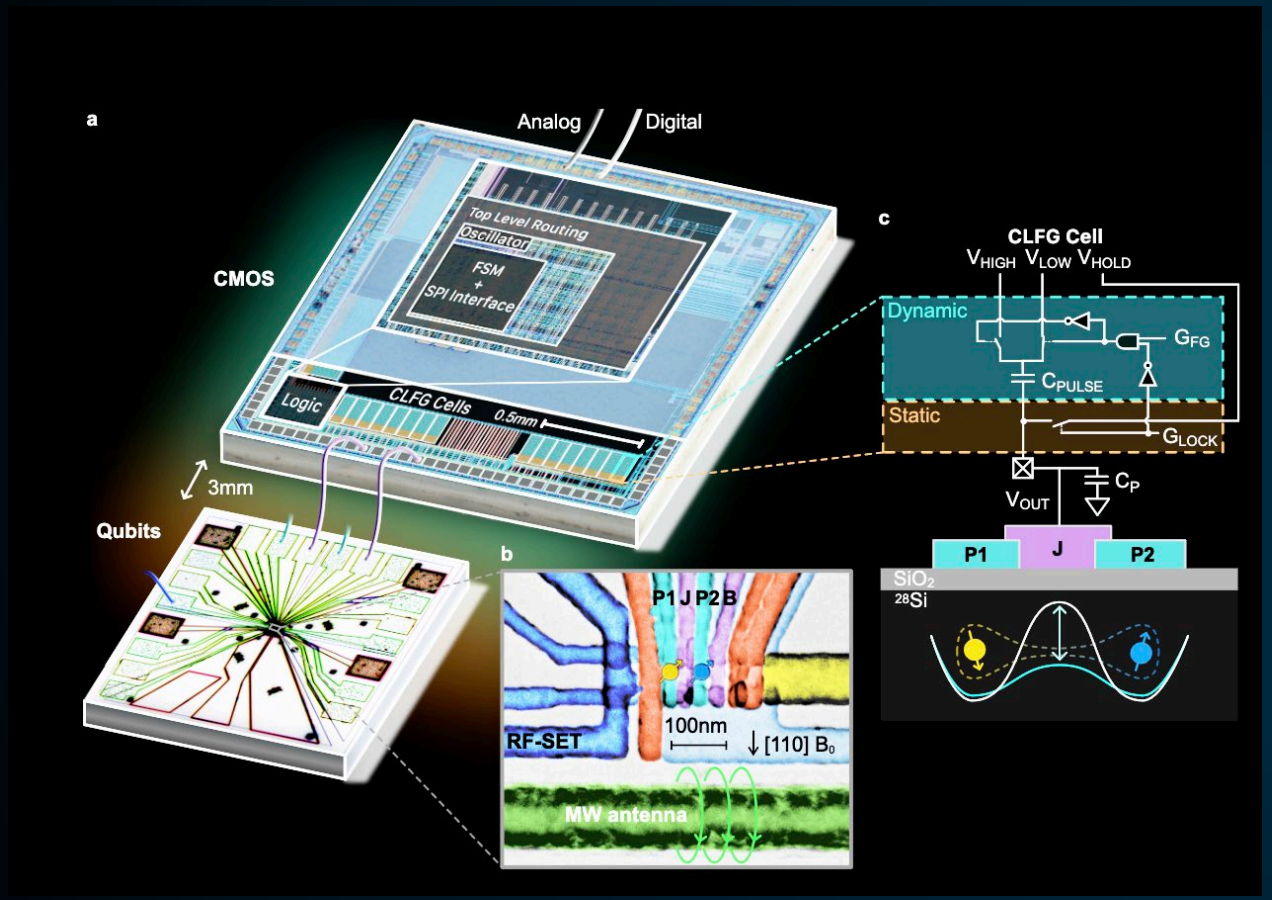


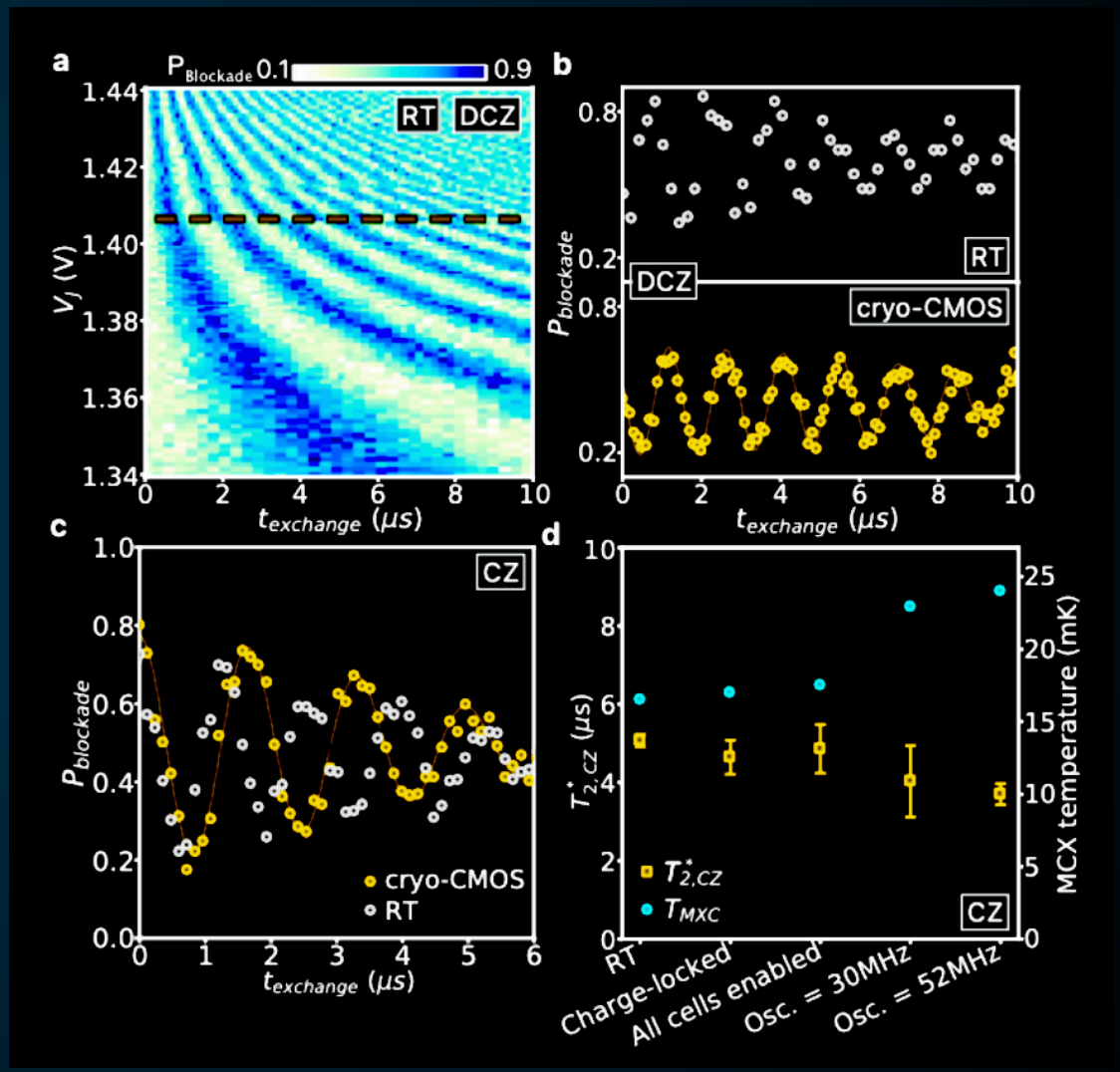
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Spin Qubits with Scalable milli-kelvin CMOS Control

Two-Qubit Control





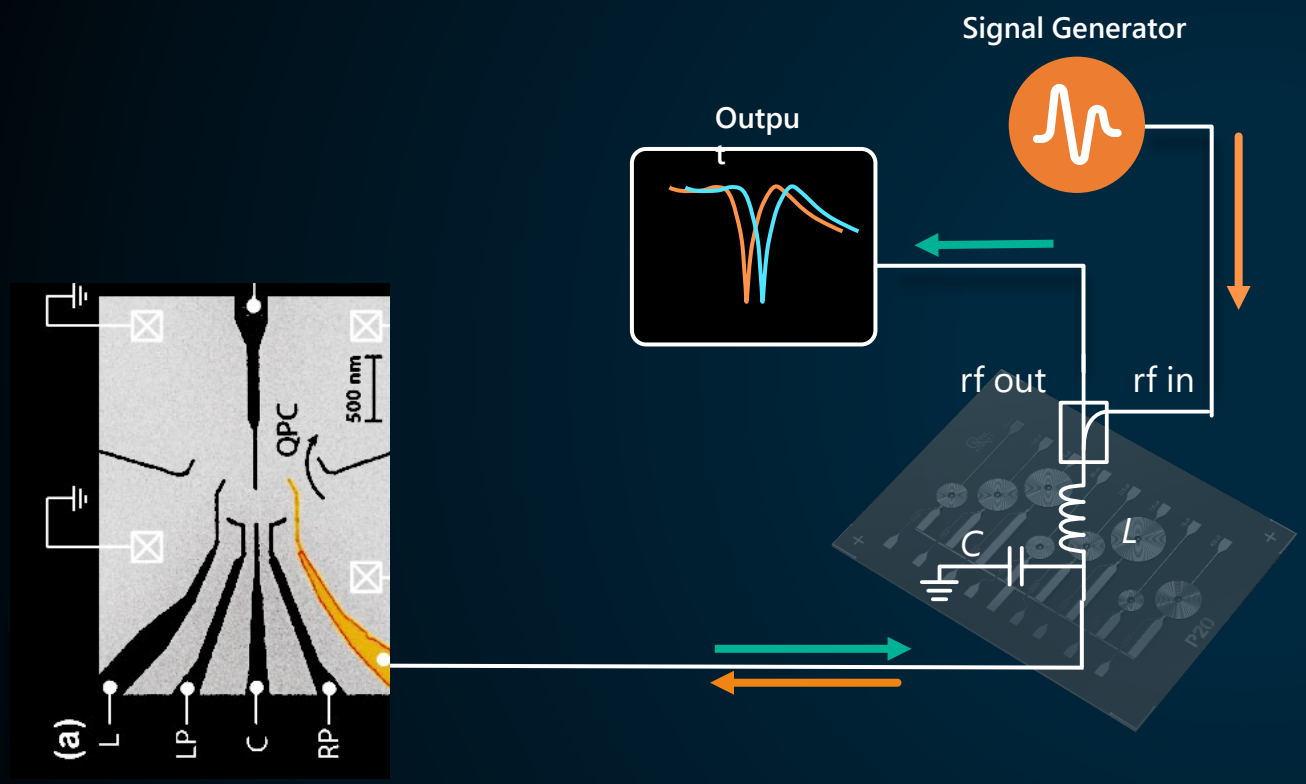
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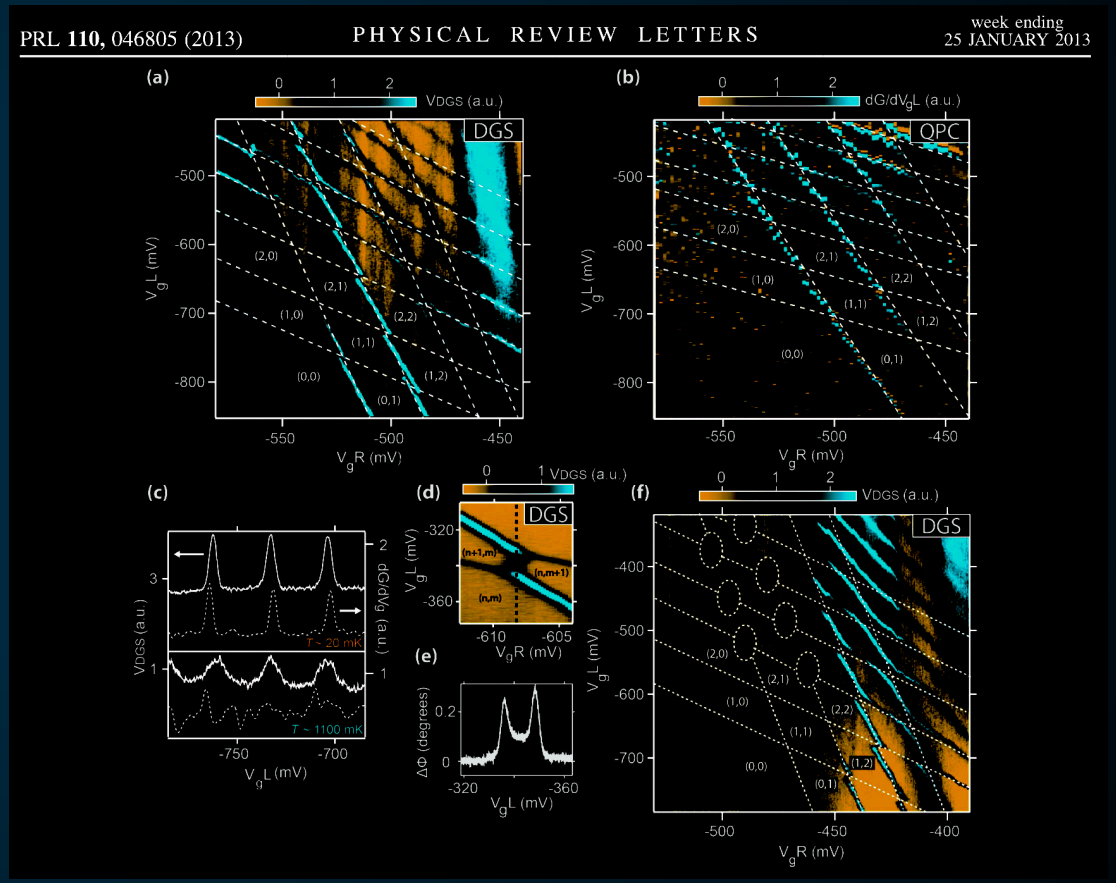
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Readout at Scale



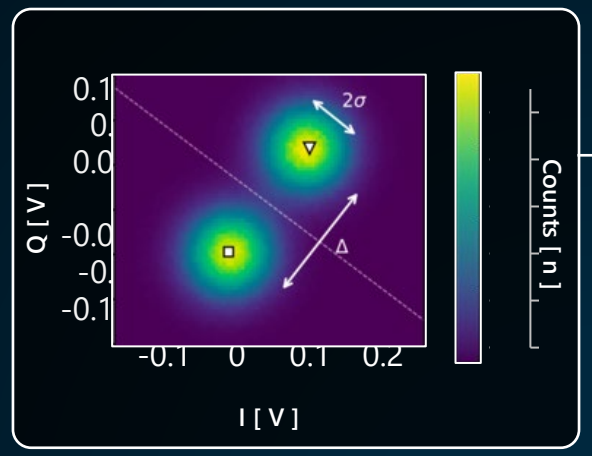
Qubit Measurement: Dispersive Gate Sensing





Dispersive Readout of a Few-Electron Double Quantum Dot with Fast rf Gate Sensors
J. I. Colless, A. C. Mahoney, J. M. Hornibrook, A. C. Doherty, H. Lu, A. C. Gossard, and D. J. Reilly, PRL 110, 046805 (2013).

Maximum SNR



Readout

Transmit

293 K

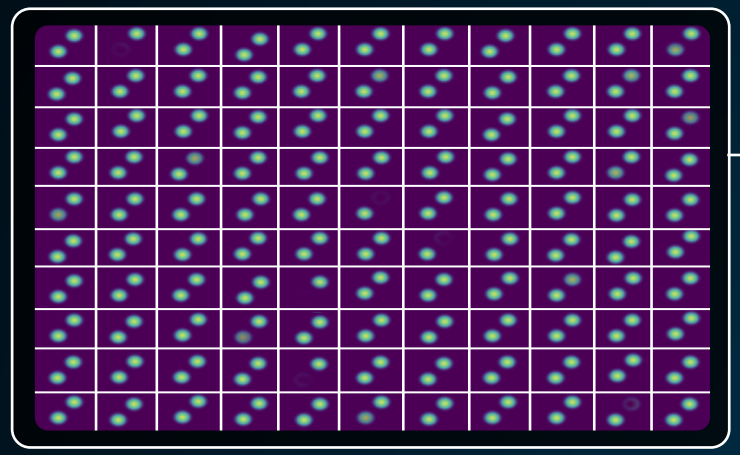
D/A Converter

Cryo-amplifier

Quantum Plane
Resonators, and Qubits

100 mK

Scalable readout: *A deluge of data*



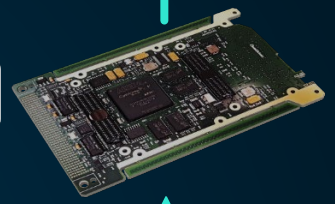
Reado

Transm

293 K

4 K

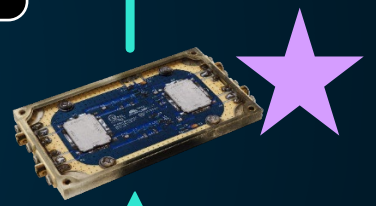
D/A Converter



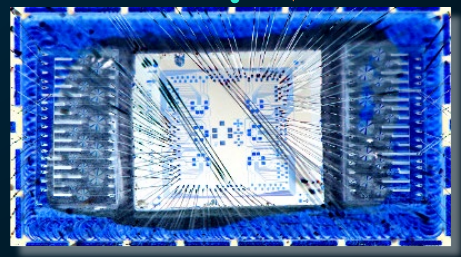
multiplex measurements from many channels

RF

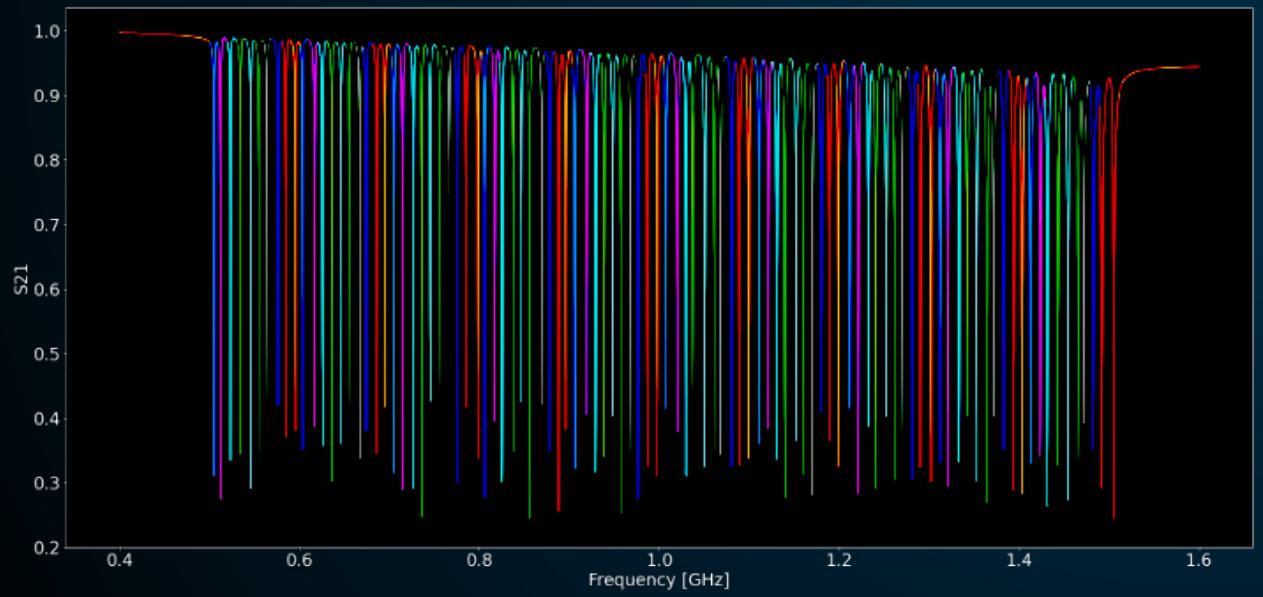
Cryo-amplifier



Input power compression?



100 mK



An rf Quantum Capacitance Parametric Amplifier

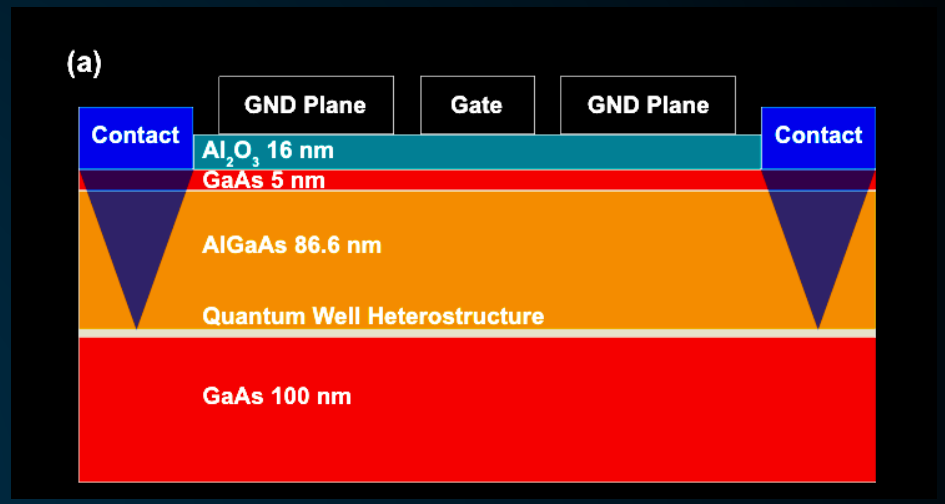
A. El Kass,[1,2] C. T. Jin,[2] J. D. Watson,[3] G. C. Gardner,[3] S. Fallahi,[3] M. J. Manfra,[3,4] and D. J. Reilly[†5,1]

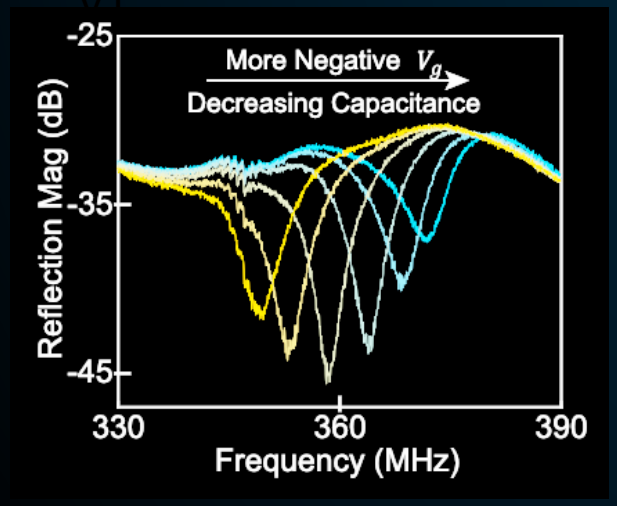
[1] *ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, The University of Sydney, Sydney, NSW 2006, Australia*
[2] *School of Electrical and Information Engineering, The University of Sydney, Sydney, NSW 2006, Australia*
[3] *Microsoft Quantum Lab West Lafayette, West Lafayette, Indiana, USA*
[4] *Department of Physics and Astronomy, Purdue University, West Lafayette, Indiana, USA*
[5] *Microsoft Quantum Lab Sydney, The University of Sydney, Sydney, NSW 2006, Australia*

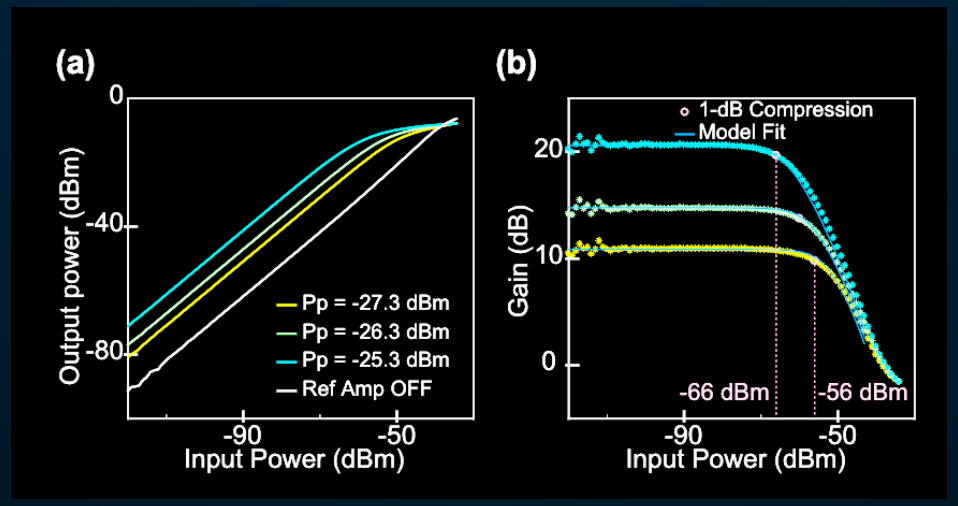
(Dated: April 27, 2023)

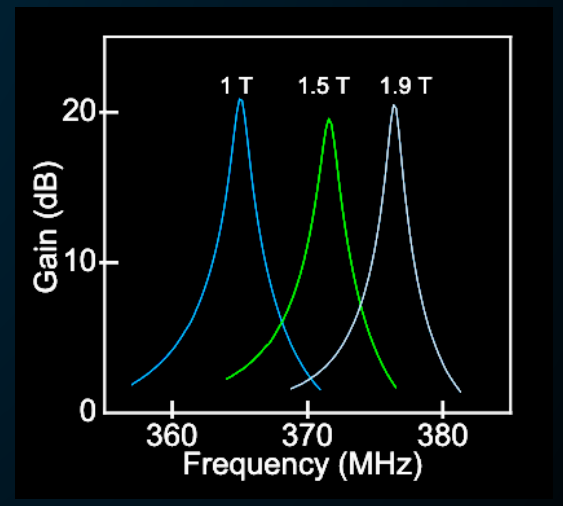
We demonstrate a radio-frequency parametric amplifier that exploits the gate-tunable quantum capacitance of an ultra-high mobility two dimensional electron gas (2DEG) in a GaAs heterostructure at cryogenic temperatures. The prototype narrow-band amplifier exhibits a gain > 20 dB up to an input power of -66 dBm (1-dB compression), and a noise temperature $T_N \sim 1.3$ K at ~ 370 MHz. In contrast to superconducting amplifiers, the quantum capacitance parametric amplifier (QCPA) is operable at tesla-scale magnetic fields and temperatures ranging from milli-kelvin to a few kelvin. These attributes, together with its low power (microwatt) operation when compared to conventional transistor amplifiers, suggest the QCPA may find utility in enabling on-chip integrated readout circuits for semiconductor qubits or in the context of space transceivers and radio astronomy instruments.

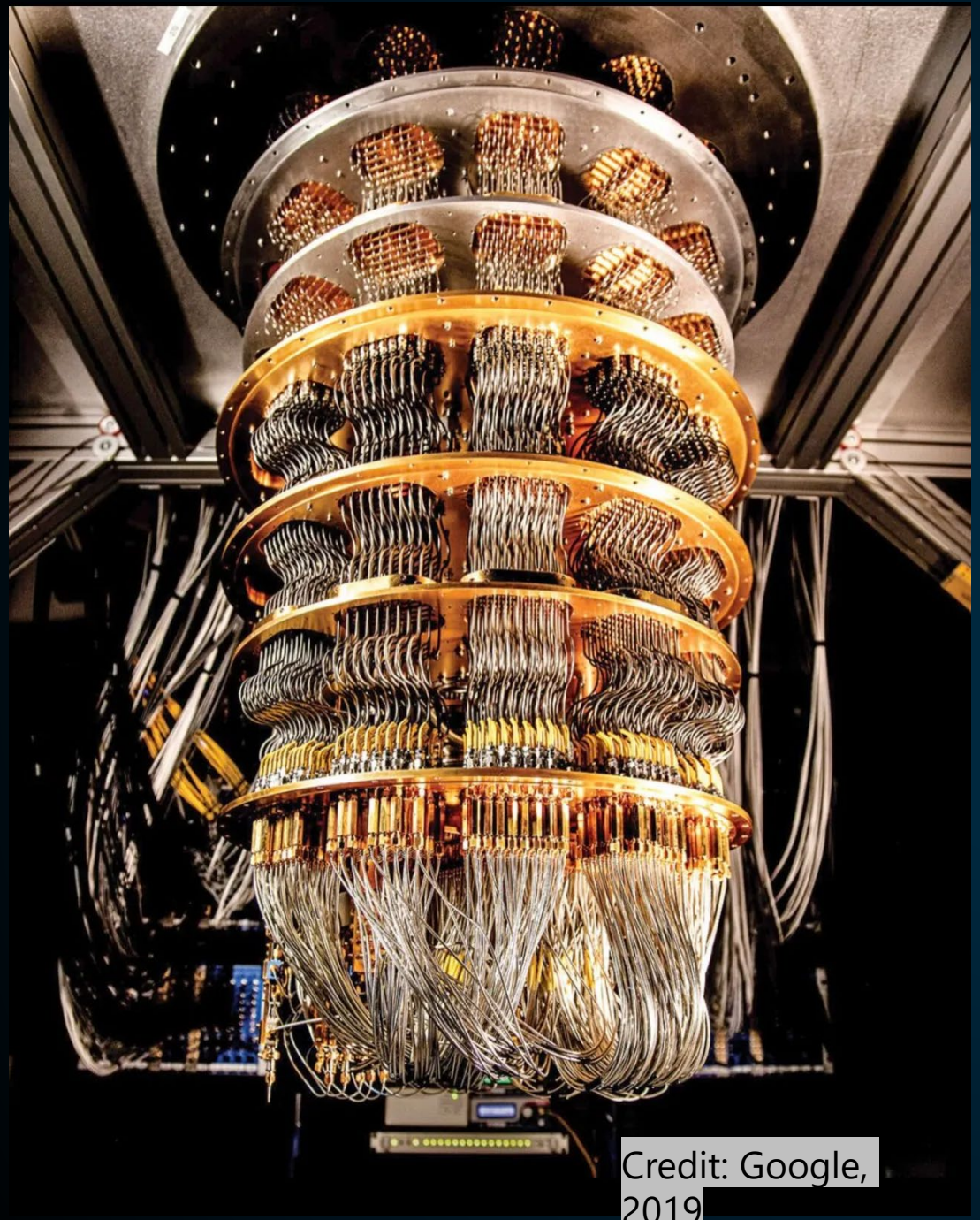
arXiv:2304.13227
v1











Credit: Google, 2019

Article

Quantum supremacy using a programmable superconducting processor

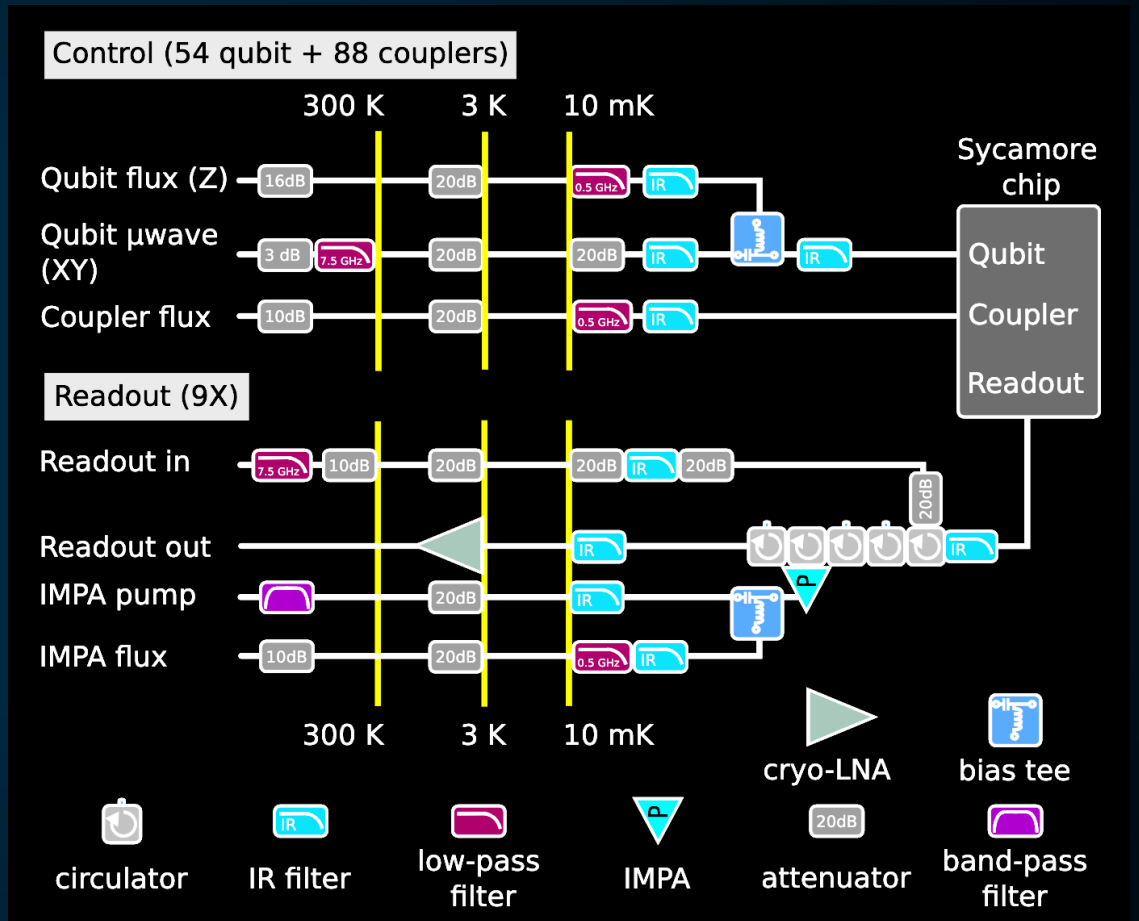
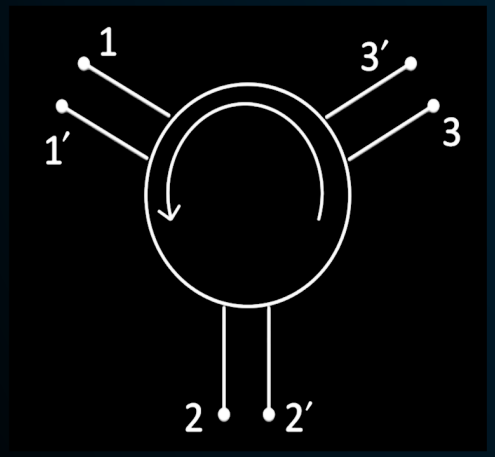
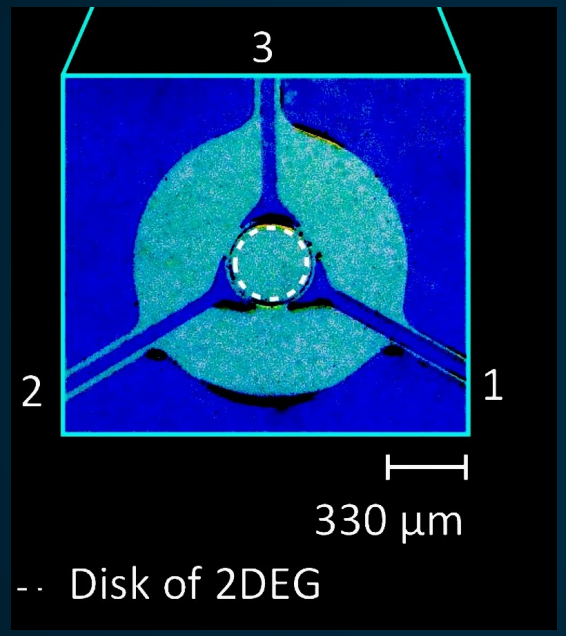


FIG. S3. **Cryogenic wiring.** Control and readout signals are carried to and from the Sycamore chip with a set of cables, filters, attenuators, and amplifiers.

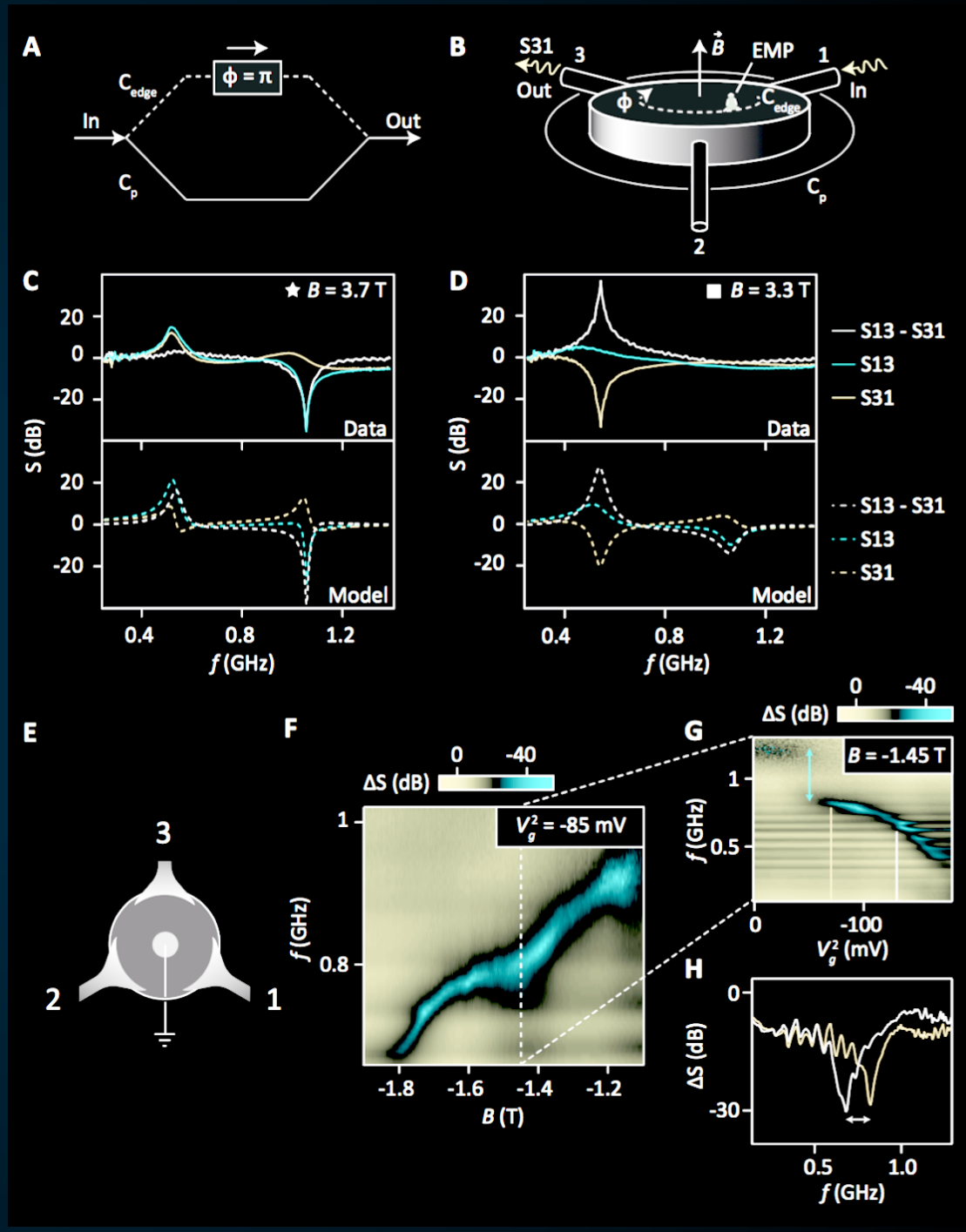
Compact Non-reciprocal Elements







On-Chip Microwave Quantum Hall Circulator, A. C. Mahoney *et al.*, PRX (2017).

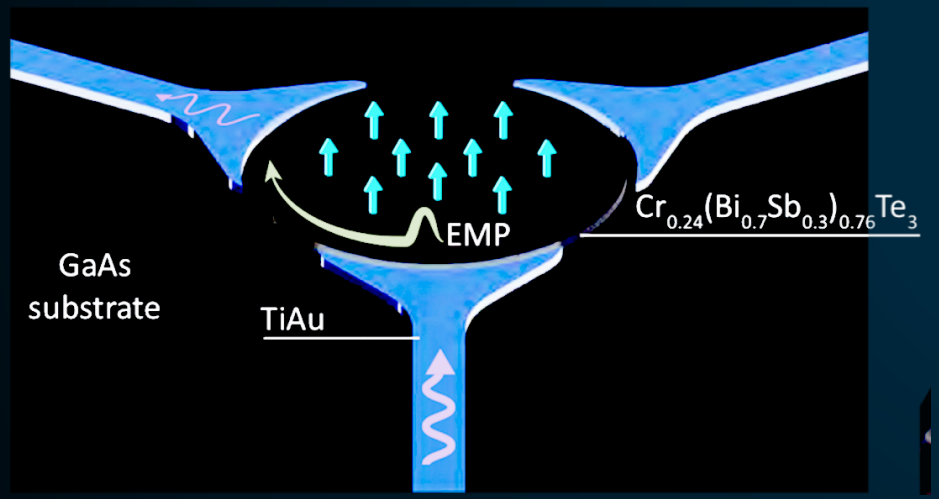


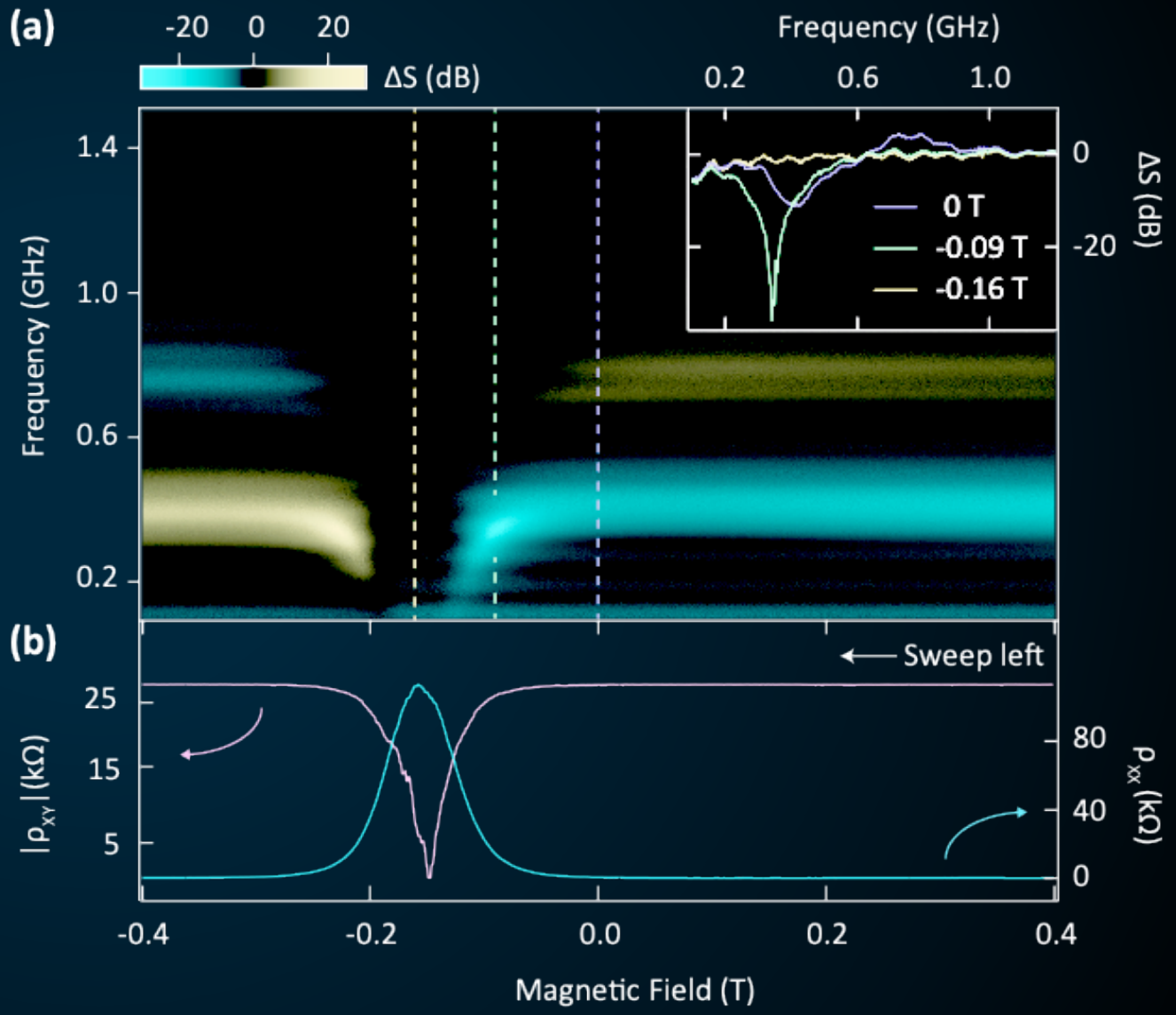
ARTICLE

DOI: 10.1038/s41467-017-01984-5 OPEN

Zero-field edge plasmons in a magnetic topological insulator

Alice C. Mahoney[1], James I. Colless[1,6], Lucas Peeters[2], Sebastian J. Pauka[1], Eli J. Fox[2,3], Xufeng Kou[4,7], Lei Pan[4], Kang L. Wang[4], David Goldhaber-Gordon[2,3] & David J. Reilly[1,5]





Enhanced SNR Via Correlated Digital Readout

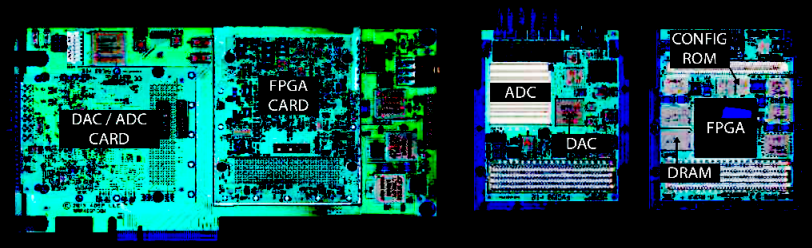
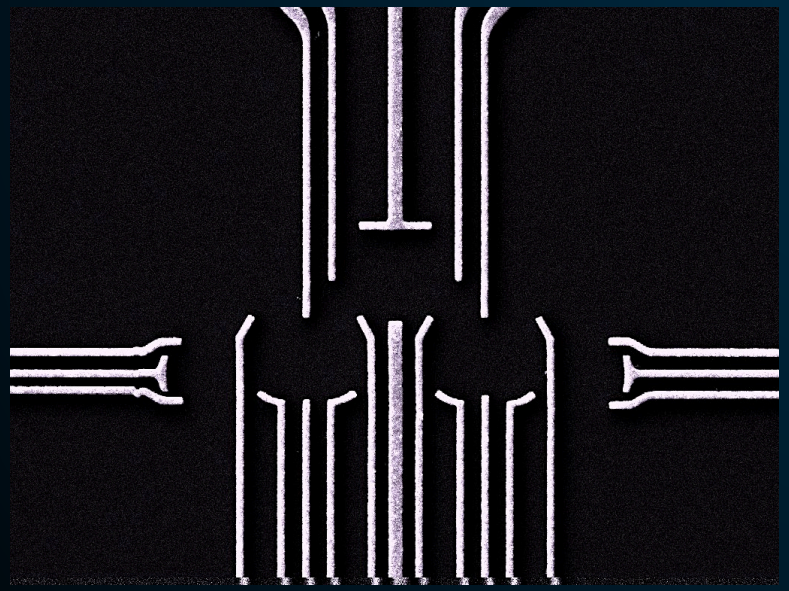
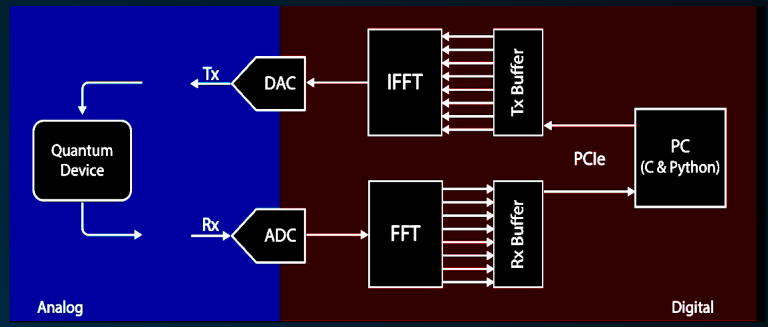
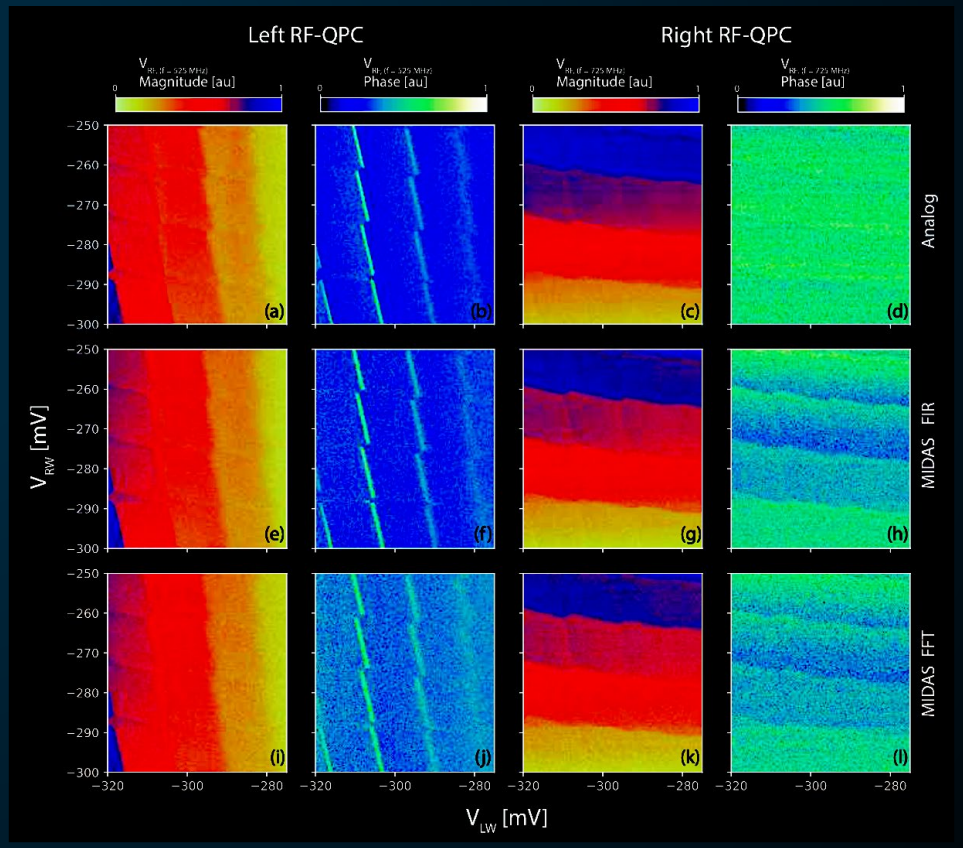


Fig. 3.1: MIDAS Hardware:
4DSP FPGA card (PC720) with ADC / DAC mezzanine card (FMC160).
FPGA: Xilinx Kintex-7 FPGA (XC7K410T) with 406,720 Logic cells.
ADC: Texas Instruments ADC12D1800, 12-Bit, 3.6 GSPS interleaved (running at 1.8 GSPS non-interleaved).
DAC: Analog Devices AD9129, 14-Bit, 5.6 GSPS (running at 1.8 GSPS).

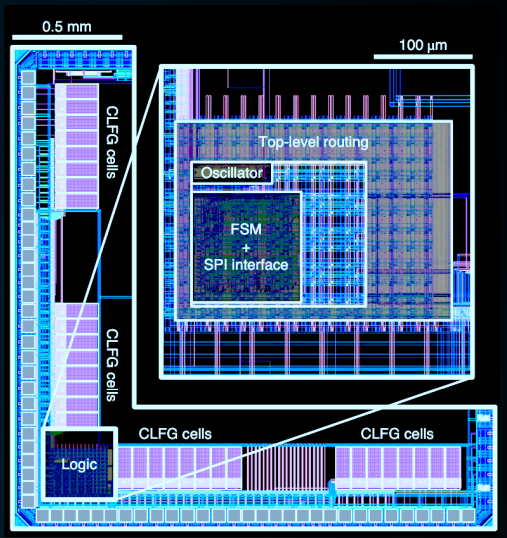


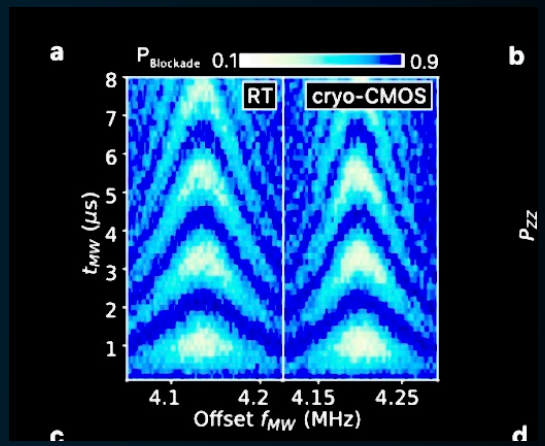


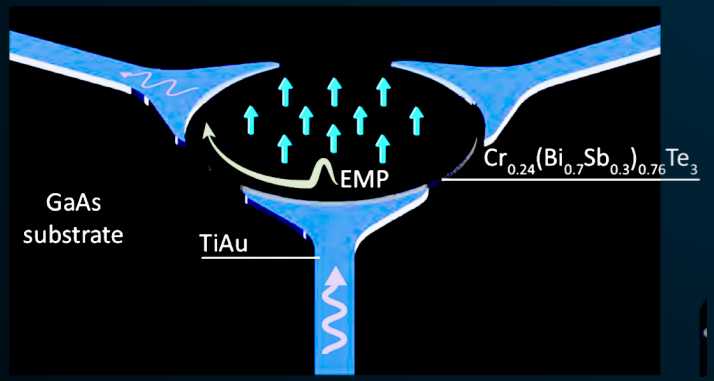


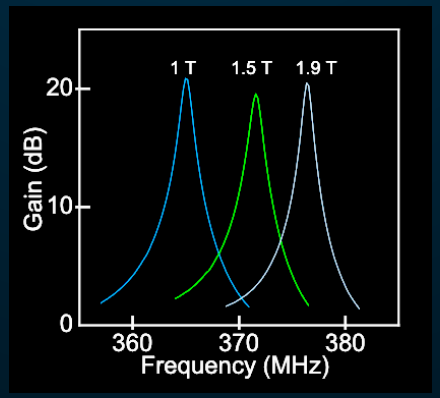
Summary

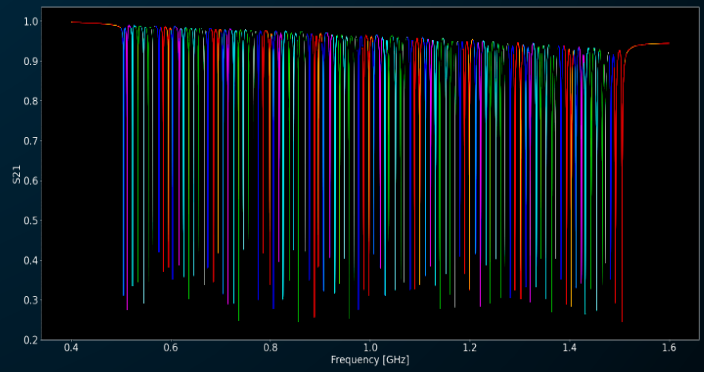
- Milli-kelvin CMOS appears viable for taming the IO density of a scaled-up quantum system.
- Heterogeneous integration and thermal management are new directions for scaling quantum systems.
- There are new opportunities to improve SWaP specifications of the readout chain in a scaled quantum machine.













THE UNIVERSITY OF SYDNEY

Students Graduated

John Hornibrook

Alice Mahoney

Xanthe Croot

Sebastian Pauka

Marie Clare Jarrett

Steven Waddy

Ewa Rej

James Colless

Brendan Harlech-Jones

Sam Bartee

Abdallah El Kass

David Waddington

Thomas Boele

Professional Staff

Kushal Das

Yuanyang Yang

Jonathan Knoblaunch

Deshan Govender

Andrew Kelly

Brendan Altus

Alex Sharp

Torsten Gaebel

EQUS
Australian Research Council Centre of Excellence for Engineered Quantum Systems

NSW GOVERNMENT

Australian Government
Australian Research Council

IARPA

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WORKSHOP
25-27 JUNE 2024
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DR. ANDERSON BERALDO DeARAUJO

Quantum-Intelligence Mathematician

University of Campinas

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Q4I

6TH ANNUAL Q4I WORKSHOP | JUNE 25-27 | ROME, NY







Synalgebraic Simulation of Quantum Circuits

Anderson Beraldo DeAraujo

University of Campinas (IMECC, Brazil)
University of Minho (CMAT, Portugal)

This material is based upon work supported by the Air Force Office of Scientific Research,
under award number FA9550-24-1-0003, but the opinions expressed are responsibility of its author.

Overview

Aim: To develop a classical simulator of large-scale quantum circuits for applications of quantum AI to cryptology.

Approach: Creation of a new mathematical framework called *synalgebra* that represents quantum gates and measurements with rules and schemas.

Outcome: Knowledge about quantum Fourier networks based on Shor's algorithm and SAT solvers designed to attack the RSA cryptosystem.

This material is based upon work supported

Quantum Computing Postulates Interpreted

1) States are unit vectors in complex Hilbert spaces. They are abstract moving coins.

$$a|0\rangle + b|1\rangle = a\begin{bmatrix}1\\0\end{bmatrix} + b\begin{bmatrix}0\\1\end{bmatrix}$$

2) Evolutions are invertible distance preserving linear operators over complex Hilbert spaces. They are general rotations.

$$X = \begin{bmatrix}0 & 1\\1 & 0\end{bmatrix} \qquad X(a|0\rangle + b|1\rangle) = aX|0\rangle + bX|1\rangle = a|1\rangle + b|0\rangle$$

3) Measurements are projectors that probabilistically yield their eigenvectors. They are registrations in your sensors.

$$|1\rangle\langle 1| = \begin{bmatrix}0 & 0\\0 & 1\end{bmatrix} \qquad |1\rangle\langle 1|(\frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle) \equiv |1\rangle \text{ with probability } 0.5$$

4) States, evolutions and measurements are composable by tensors. They are pointwise parallel processes.

$$|0\rangle \otimes |1\rangle = \begin{matrix}0\\1\\0\\0\end{matrix} \qquad X \otimes X = \begin{matrix}0&0&0&1\\0&0&1&0\\0&1&0&0\\1&0&0&0\end{matrix} \qquad X \otimes X(|0\rangle|1\rangle) = X|0\rangle \otimes X|1\rangle$$

This material is based upon work supported

Quantum Software Challenges

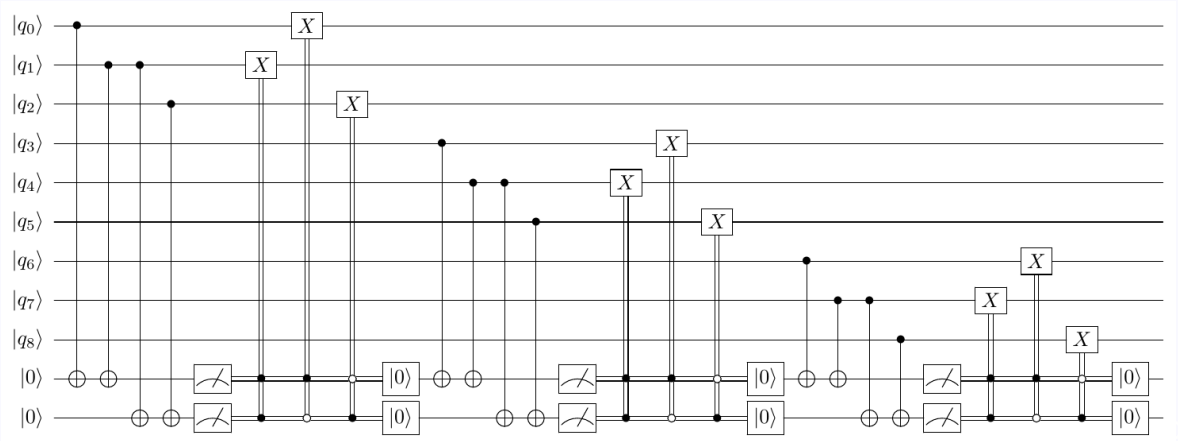
1) We need tools to synthesize, verify and compile quantum circuits in large-scale and with noise.

2) Best simulators are based on tensor networks; they can't reach to thousands of qubits and their results are hard to interpret.

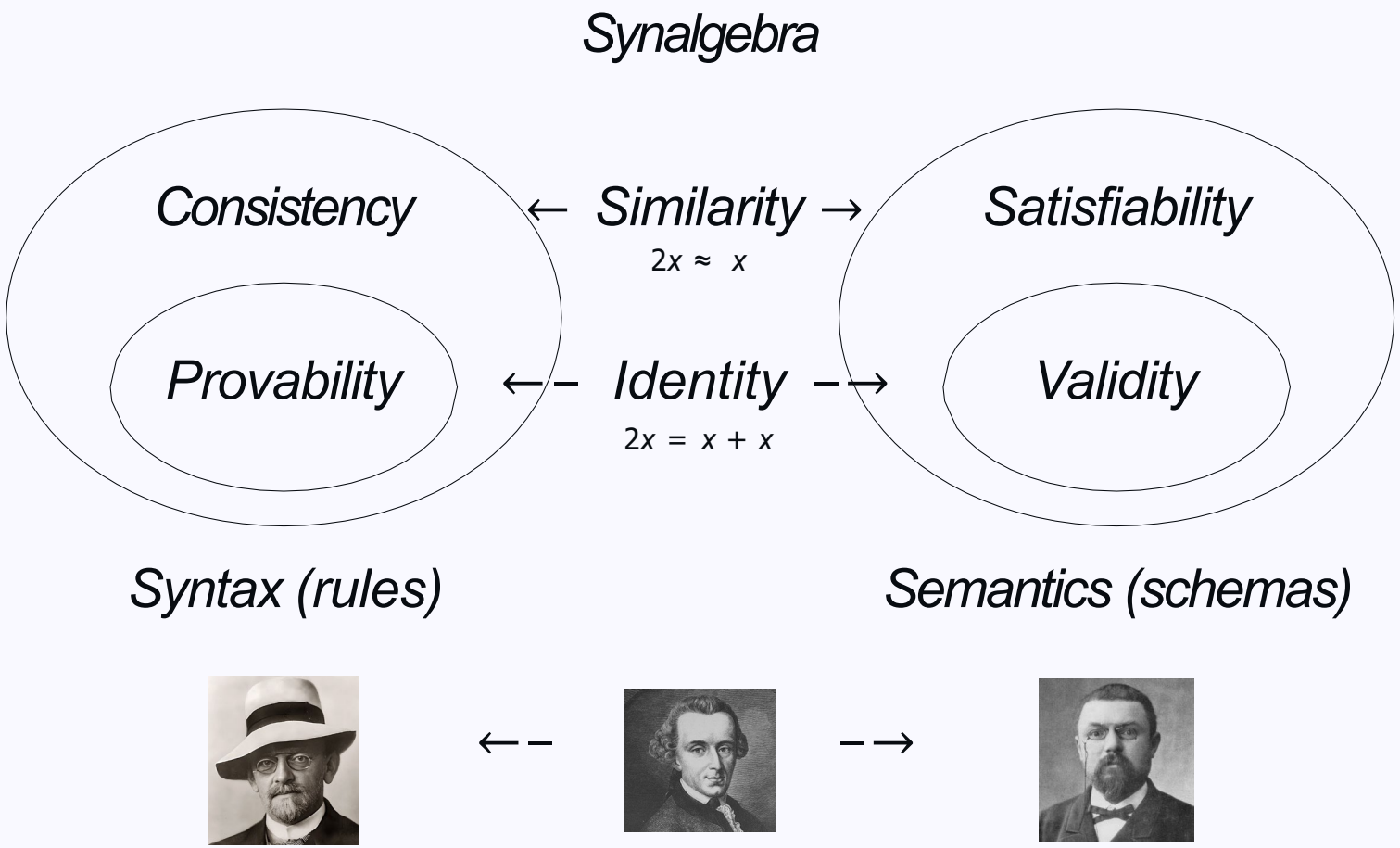
3) New idea: How do we know whether this equations is true

$$\underbrace{X \otimes \cdots \otimes X}_{1000\ times} |0\rangle \cdots |0\rangle = \underbrace{|1\rangle \cdots |1\rangle}_{1000\ times}?$$

We don't do 2^{1000} operations! We perform *quantum reasoning*.



Idea: Equality (=) is identity ($\doteq$) and similarity ($\approx$)



"Mathematics is a game played according to certain rules with meaningless marks on paper." (Hilbert)

"Mathematics is the art of giving the same name to different things." (Poincar´e)

This material is based upon work supported

Syntactical intuition

Global:

$$\frac{f : n \to m \vdash g : n \to m \quad g : n \to m \vdash f : n \to m}{\vdash f \equiv g} \equiv_R$$

$$\frac{\vdash f : n \to m \quad g : n \to m \vdash}{f \equiv g \vdash} \equiv_L \qquad \frac{\vdash g : n \to m \quad f : n \to m \vdash}{f \equiv g \vdash} \equiv_L$$

Substitute $\doteq$ for $\equiv$ if the leaves of the proof are *axioms* in the form

$$f : n \to m \vdash f : n \to m$$

Substitute $\approx$ for $\equiv$ in case the leaves of the proof are *postulates* like

$$f : n \to m \vdash \qquad \text{or} \qquad \vdash f : n \to m$$

Local:

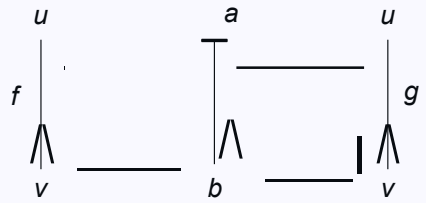
$$\frac{|1\rangle : 1 \to 2 \vdash}{X \circ |0\rangle : 1 \to 2 \vdash} X_{L_0} \qquad \frac{\vdash |1\rangle : 1 \to 2}{\vdash X \circ |0\rangle : 1 \to 2} X_{R_0}$$

This material is based upon work supported

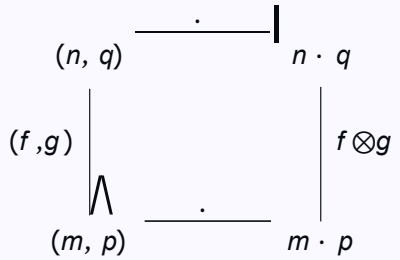
Semantic intuition

Global:

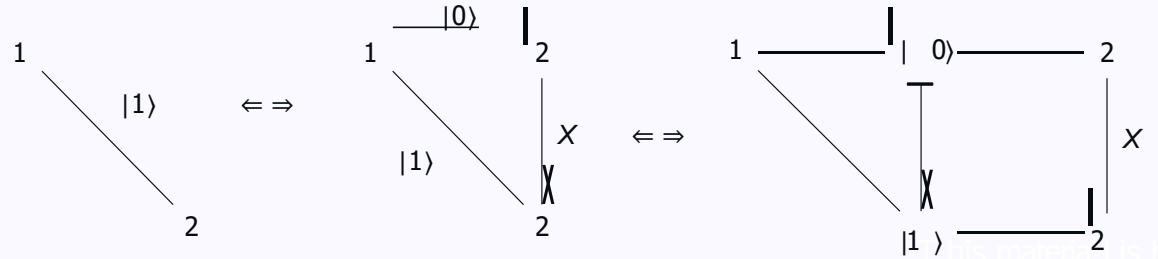
$f \doteq g$ or $f \approx g$ according it holds for all or for some, respectively:



There are schemas for linear operators:



Local:



This material is based upon work supported

Related works

1. MacLane (1971), *Categories for the Working Mathematician*.
2. Lambek (1972): Deduction calculus for multicategories.
3. Szabo (1978): *Algebra of Proofs*.
4. Lambek & Scott (1986): *Introduction to Higher Categorical Logic*.
5. Freyd & Scedrov (1990): Axioms with partial logic for categories.
6. Shulman (2016): Sequent calculus for categories using type theory.
7. Benzmuller & Scott (2020): Free-logic axiomatization of categories.

None provides a theory of equalities as identities and similarities:

Identities preserve the information about the action of gates without using matrices.

Similarities specify useful approximations of the measurements with statistical sampling.

This material is based upon work supported

Example of measurement (one direction)

Similarity:

$$P_{\frac{\sqrt{1}}{3}|0\rangle+\frac{2}{\sqrt{6}}|1\rangle}(|1\rangle) = 2/3 \Leftrightarrow |1\rangle\langle 1| \circ \left(\sqrt{\frac{1}{3}}|0\rangle + \sqrt{\frac{2}{6}}|1\rangle\right) \approx |1\rangle^{2/3}$$

Proof:

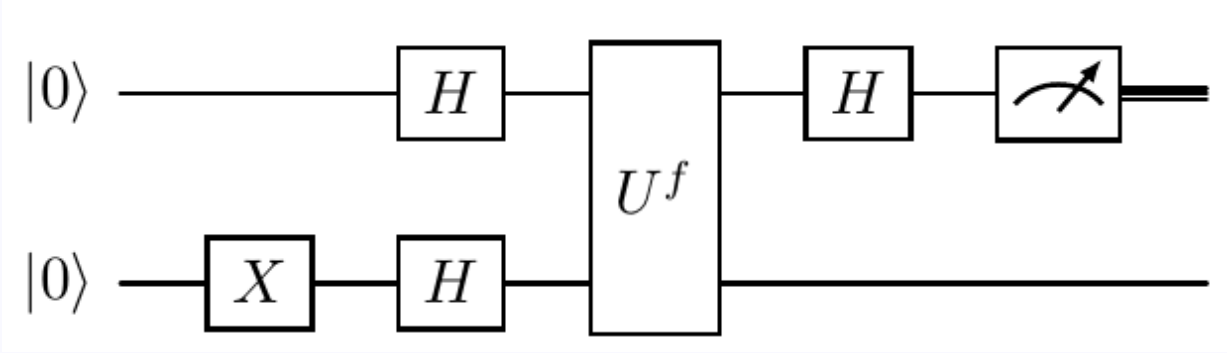
$$\dfrac{\dfrac{\dfrac{}{|1\rangle\langle 1| \vdash_0}\,P_L}{\frac{\sqrt{1}}{3}|0\rangle;|1\rangle\langle 1| \vdash_0}\,M_L \qquad \dfrac{\dfrac{\dfrac{}{|1\rangle^{\frac{2}{3}} \vdash_0 |1\rangle^{\frac{2}{3}}}\,A}{\sqrt{\frac{2}{3}}|1\rangle^{\frac{2}{3}} \vdash_0 |1\rangle^{\frac{2}{3}}}\,F_L}{\mathcal{D}\,|1\rangle^{\frac{\sqrt{6}}{2}} \vdash \frac{\sqrt{2}}{6} \cdot \frac{2}{\sqrt{6}} * |1\rangle^{\frac{2}{3}}}\,S_L}{\frac{\sqrt{2}}{6}|1\rangle;|1\rangle\langle 1| \vdash_0 |1\rangle^{\frac{2}{3}}}\,B_L}{\frac{\sqrt{1}}{3}|0\rangle + \frac{\sqrt{2}}{6}|1\rangle;|1\rangle\langle 1| \vdash_0 |1\rangle^{\frac{2}{3}}}\,+_L$$

$$\dfrac{\frac{\sqrt{1}}{3}|0\rangle + \frac{\sqrt{2}}{6}|1\rangle;|1\rangle\langle 1| \vdash_0 |1\rangle^{\frac{2}{3}}}{|1\rangle\langle 1| \circ \left(\frac{\sqrt{1}}{3}|0\rangle + \frac{\sqrt{2}}{6}|1\rangle\right) \vdash_0 |1\rangle^{\frac{2}{3}}}\,\circ_L$$

This material is based upon work supported

Deutsch's algorithm

Given a function $f : \{0, 1\} \to \{0, 1\}$, is f constant or not?



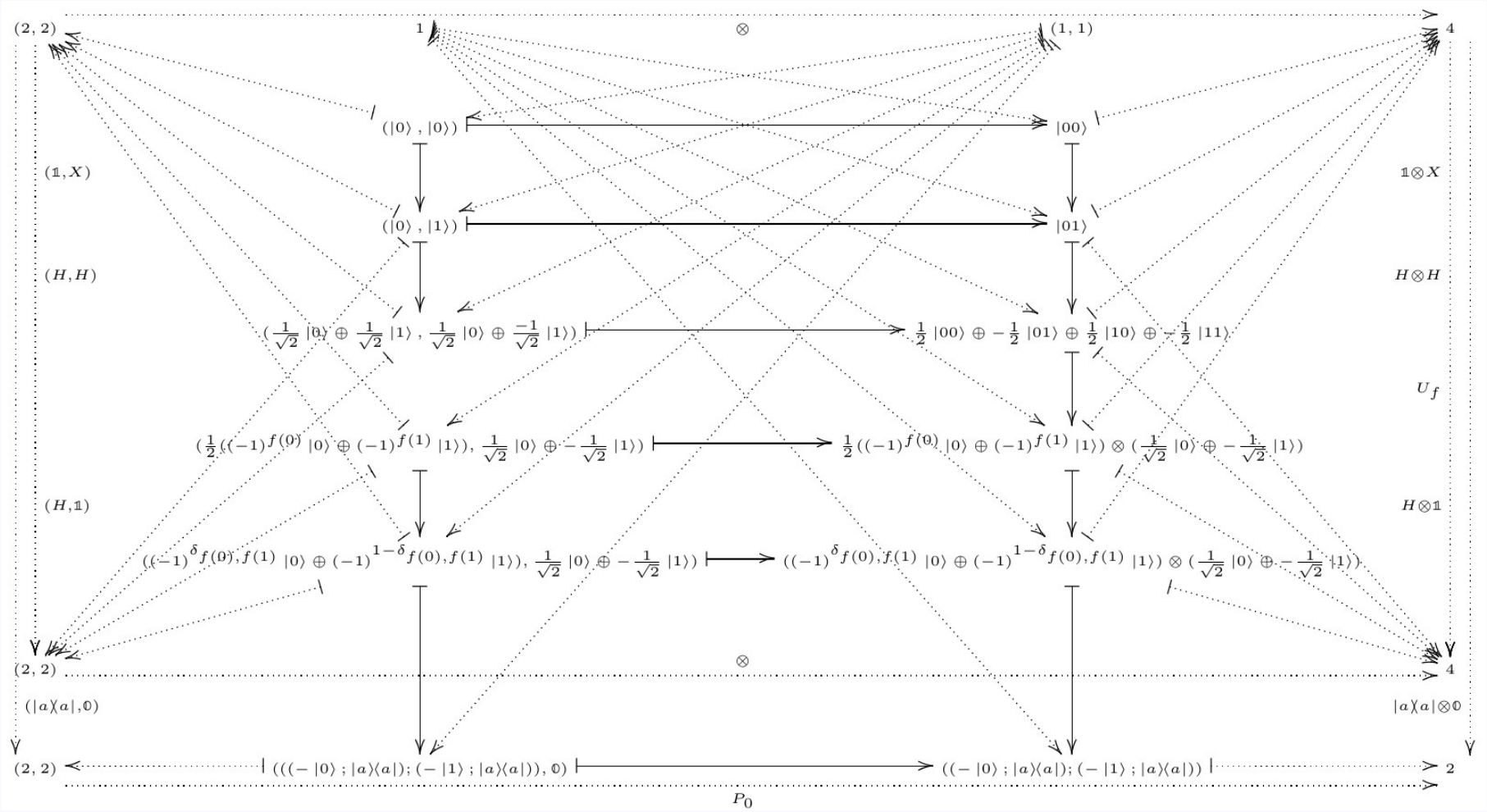
Circuit

$$(|a\rangle\langle a| \otimes 0) \circ (H \otimes 1) \circ U_f \circ (H \otimes H) \circ (1 \otimes X) \circ |0\rangle \otimes |0\rangle$$

Formula

This material is based upon work supported

Deutsch's schema



This material is based upon work supported

What can go wrong?

Potential limitations:

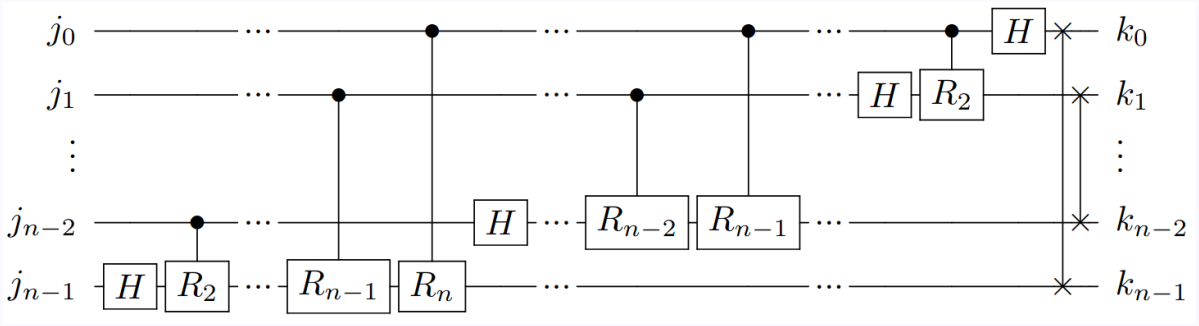
1. The complexity of quantum algorithms may demand resources practically inviable.
2. Statistical significance about the output probability distributions may require too much samples.

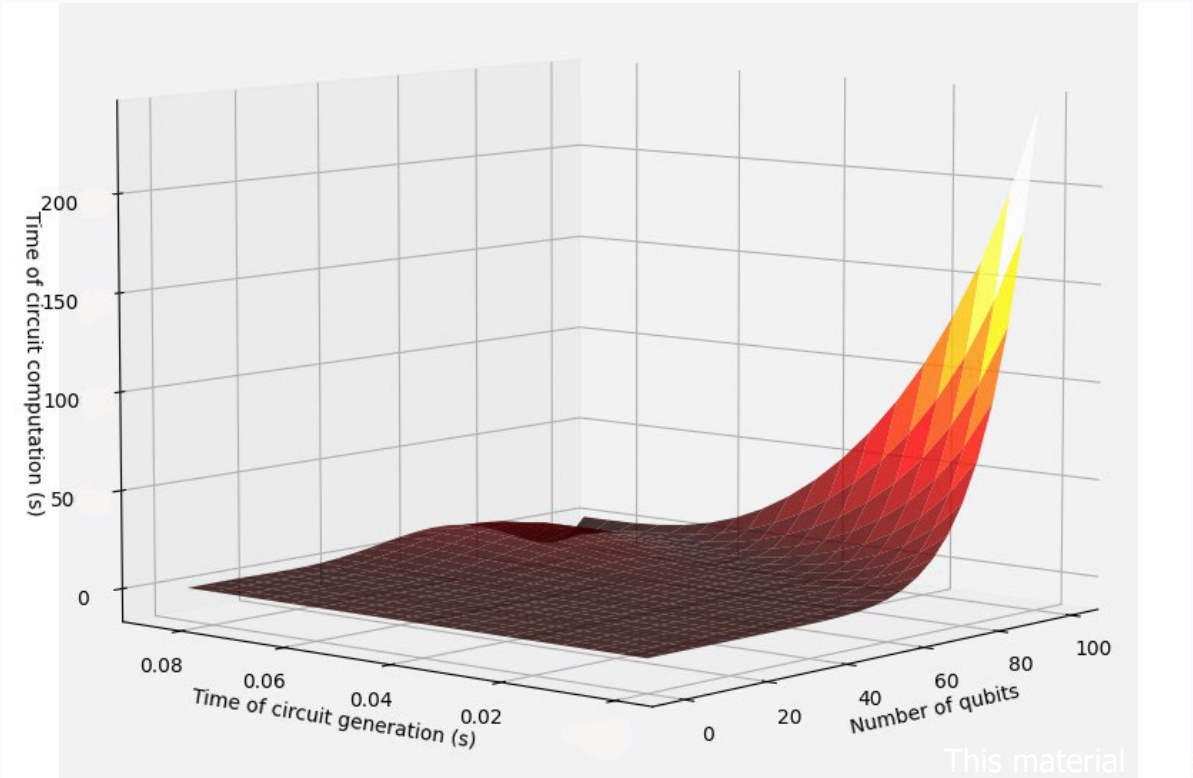
Practical Strategies:

1. Quantum patterns: Rules based on Clifford group and SATs.
2. Quantum edges: Experimental design modeled with machine learning.

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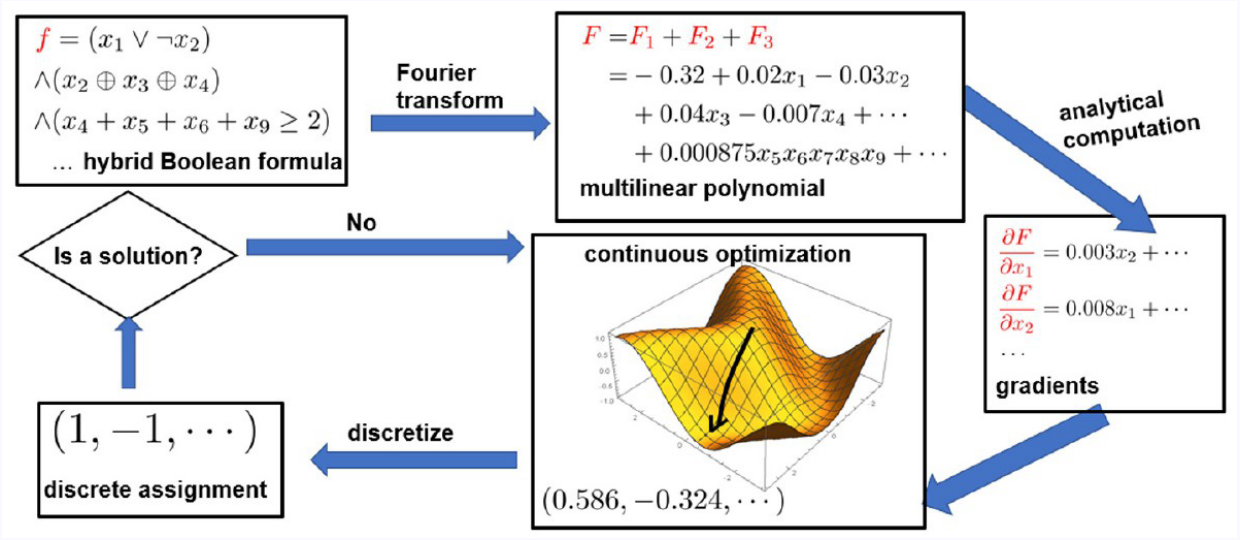
Quantum Fourier Transform in the library Synal (Rust)

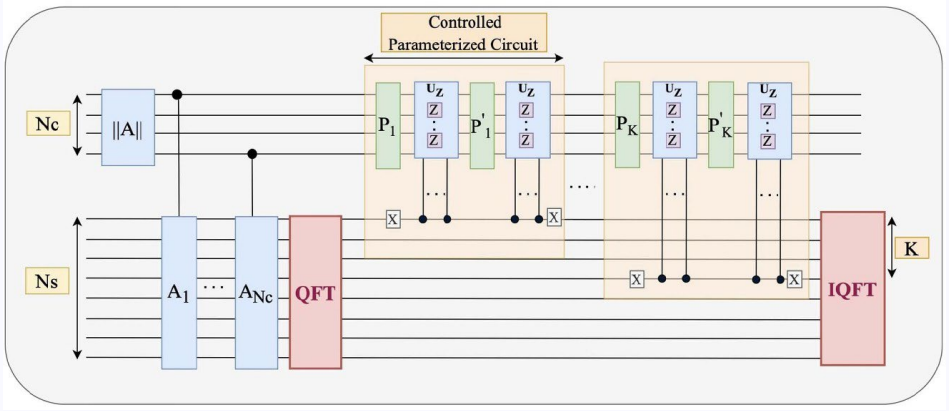




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Quantum Fourier Networks + SAT Solver in Synal (VHDL)





Taking insights from Shor's algorithm attack to the RSA cryptosystem.

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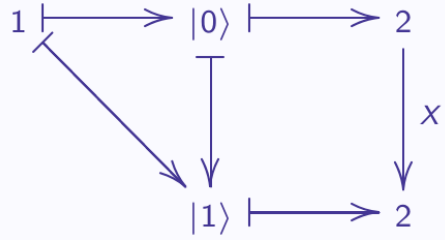
What if we succeed?

1. Powerfull tool for quantum softwares in large-scale and with noise.
2. Math framework to explore identities and similarities in applications.
3. Understanding the threats of quantum AI for cryptosystems.

$$\dfrac{\dfrac{}{|1\rangle : 1 \to 2 \vdash |1\rangle : 1 \to 2}}{X \circ |0\rangle : 1 \to 2 \vdash |1\rangle : 1 \to 2} \qquad \dfrac{\dfrac{}{|1\rangle : 1 \to 2 \vdash |1\rangle : 1 \to 2}}{|1\rangle : 1 \to 2 \vdash X \circ |0\rangle : 1 \to 2}$$

$$\vdash X \circ |0\rangle \doteq |1\rangle$$

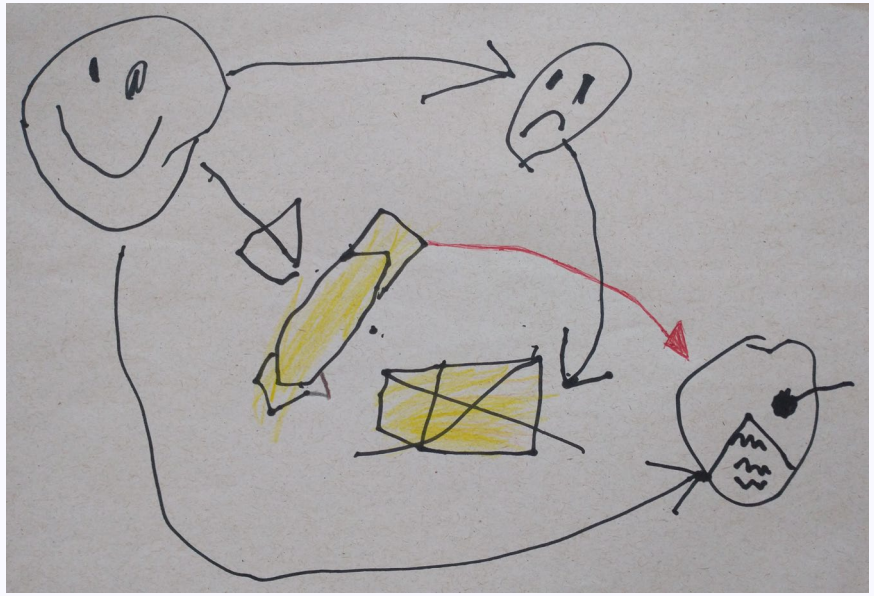
$\rightleftharpoons$



This material is based upon work supported

Thanks to

Kathy-Anne Soderberg, Laura Wessing, Shannon Ray (AFRL/RI)
James Lyke, Roger Greenwood (AFOSR/SOARD), Kyle Gustafson (ONRG) Luis Pinto, José Carlos Espirito Santo (UMinho)
Marcelo Terra Cunha, Rafael Rabelo (Unicamp) Viviane e Antoni Beraldo DeAraujo



Thank you!

This material is based upon work supported


6TH ANNUAL
QUANTUM FOR INTERNATIONAL
WORKSHOP
25-27 JUNE 2024
ROME, NEW YORK
Q4I
INNOVARE ADVANCEMENT CENTER
AFRL
GRIFFISS INSTITUTE

INNOVARE ADVANCEMENT CENTER

AFRL

GRIFFISS INSTITUTE



DR. KAZI RAJIBUL ISLAM

Associate Professor

University of Waterloo

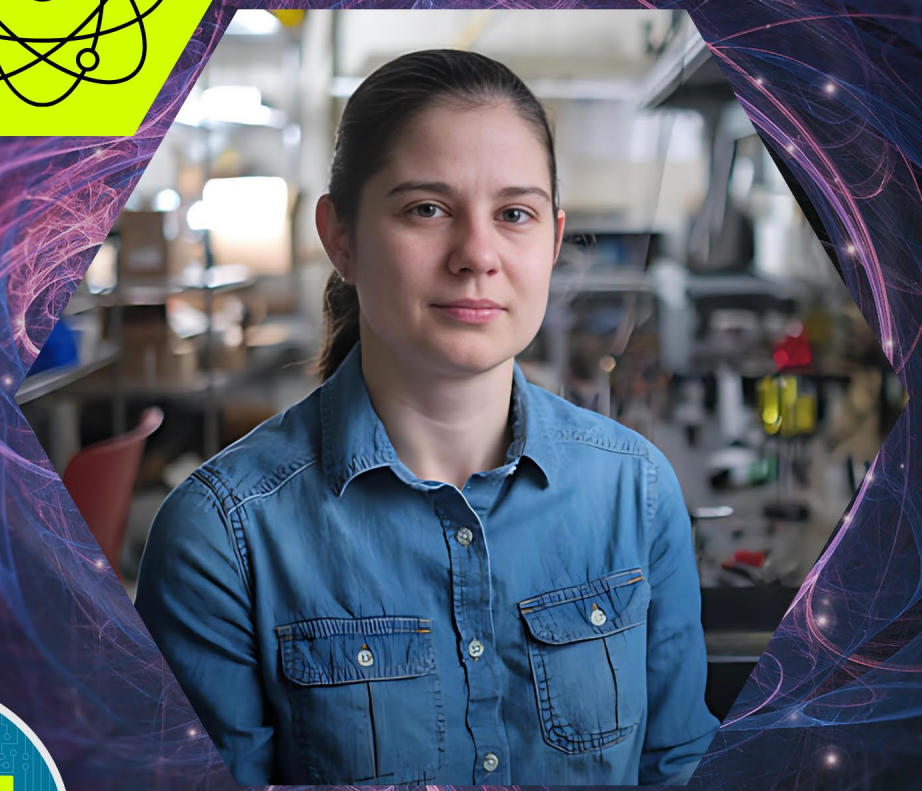
Q4I

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INNOVARE ADVANCEMENT CENTER

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GRIFFISS INSTITUTE



DR. CRYSTAL SENKO

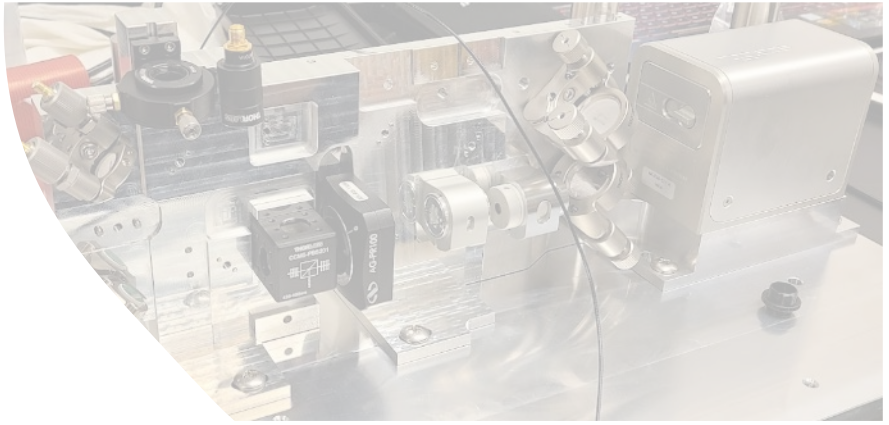
Associate Professor
University of Waterloo

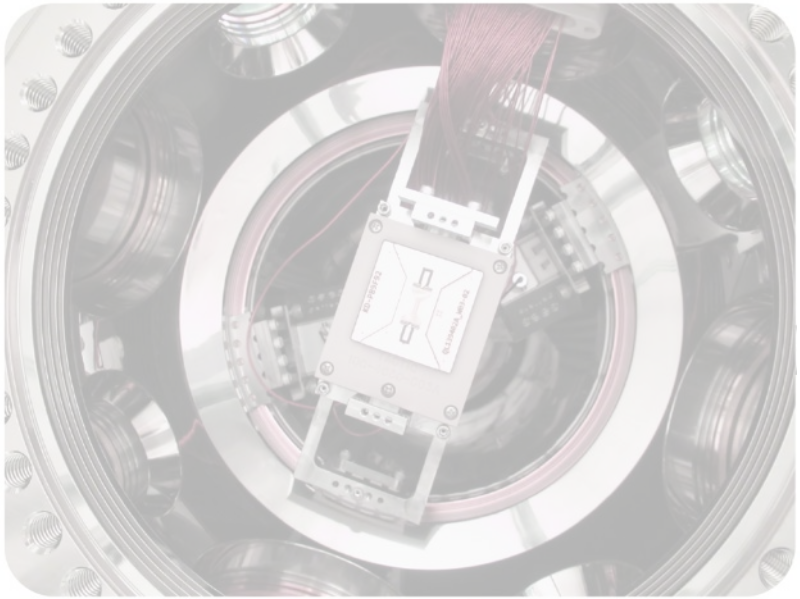
Q4I

6TH ANNUAL Q4I WORKSHOP | JUNE 25-27 | ROME, NY

Institute for Quantum Computing

Overview of trapped ion quantum computing at Waterloo





Quantum for International (Q4I) workshop
Crystal Senko
June 26, 2024

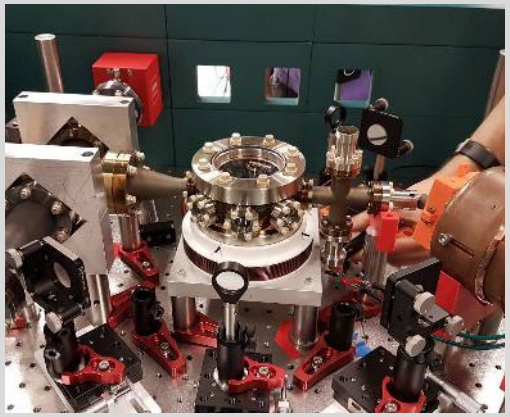
UNIVERSITY OF WATERLOO | IQC Institute for Quantum Computing

INSTITUTE FOR QUANTUM COMPUTING

- Internationally recognized as a top quantum institute worldwide for over 20 years
- $675M+ private-public partnership
- 400+ research community including theorists, experimentalists, students, postdoctoral fellows and technical staff
- State-of-the-art technology, laboratory, clean room and fabrication facilities
- 1,000+ research collaborations globally
- 45% of faculty commercializing their expertise



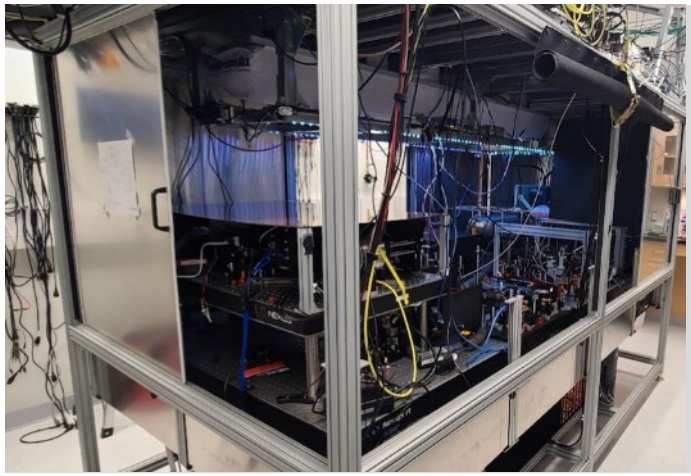
Our quantum processors



Ba^+ ion-based process development

(1 very large qudit)

Operational



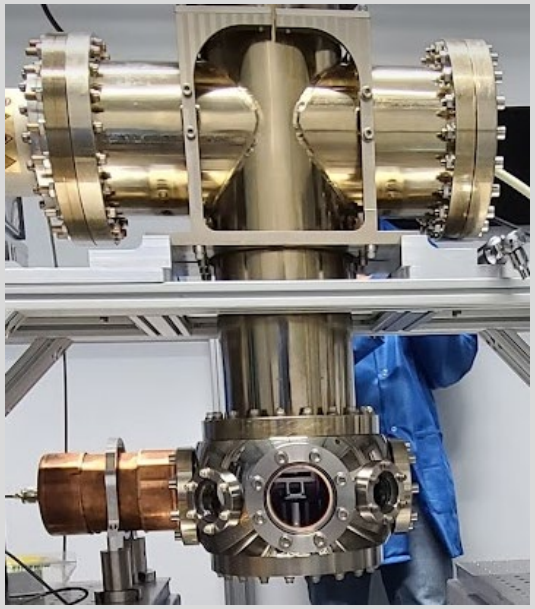
Yb^+ ion-based quantum simulator

(< 10 qubits)

Operational



Prof. Senko

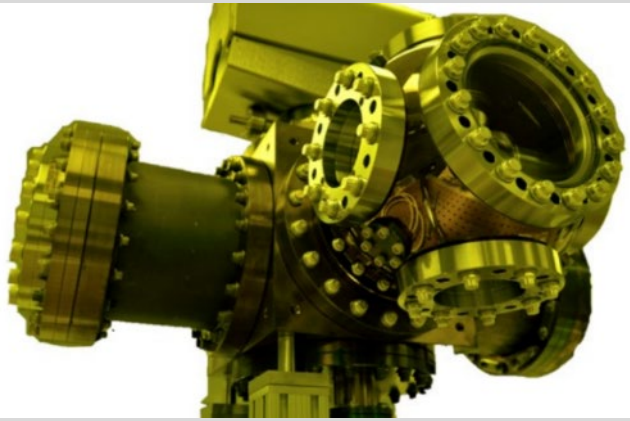


QuantumION

Ba^+ in surface trap (Sandia Nat'l Lab)

(16 qubits)

final stages of construction



Yb^+ ion-based quantum processor for long ion chains

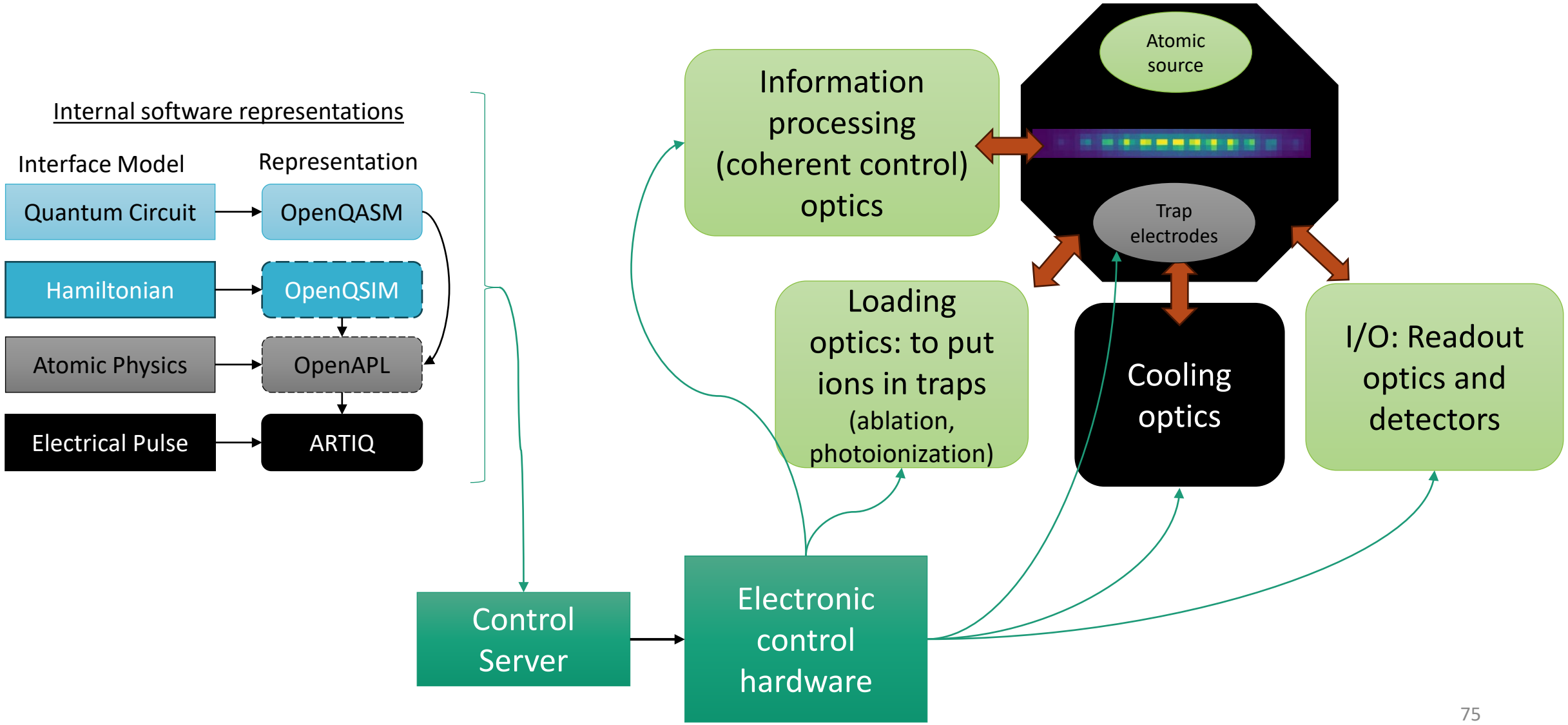
(> 30 qubits)

final stages of construction



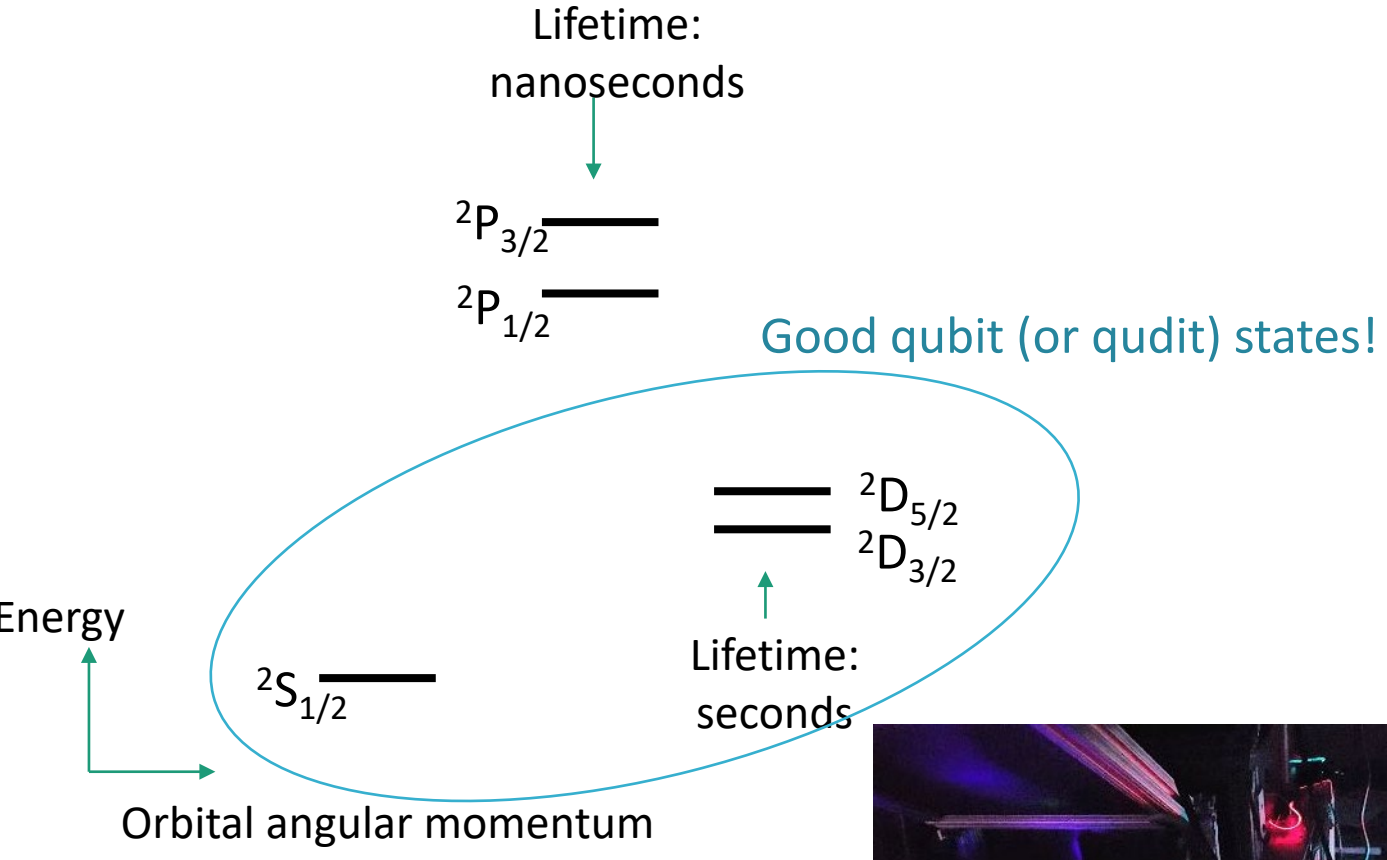
Prof. Islam

Toward full-stack open access quantum computing

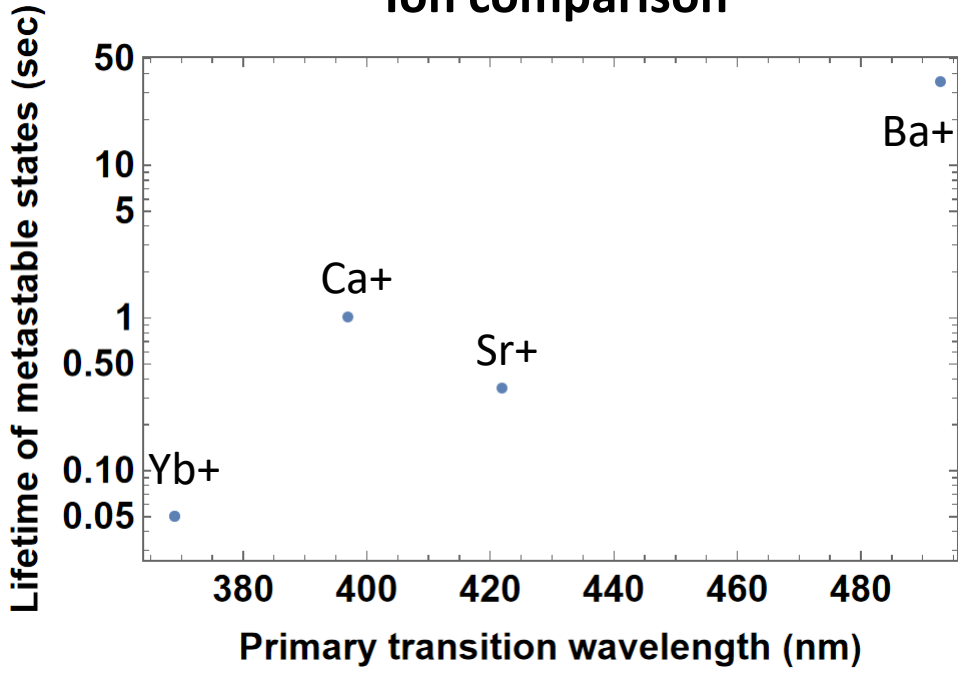


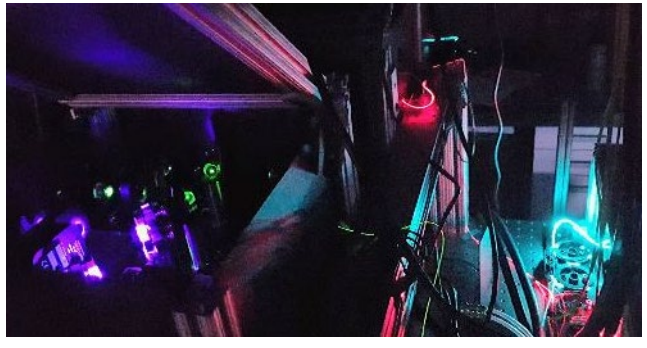
Aside: Motivating Ba+

Generic ion energy structure

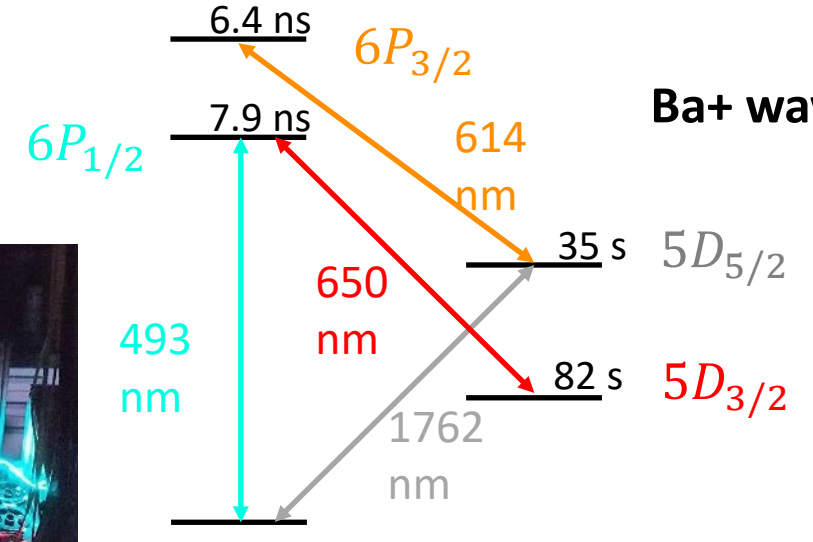


Ion comparison

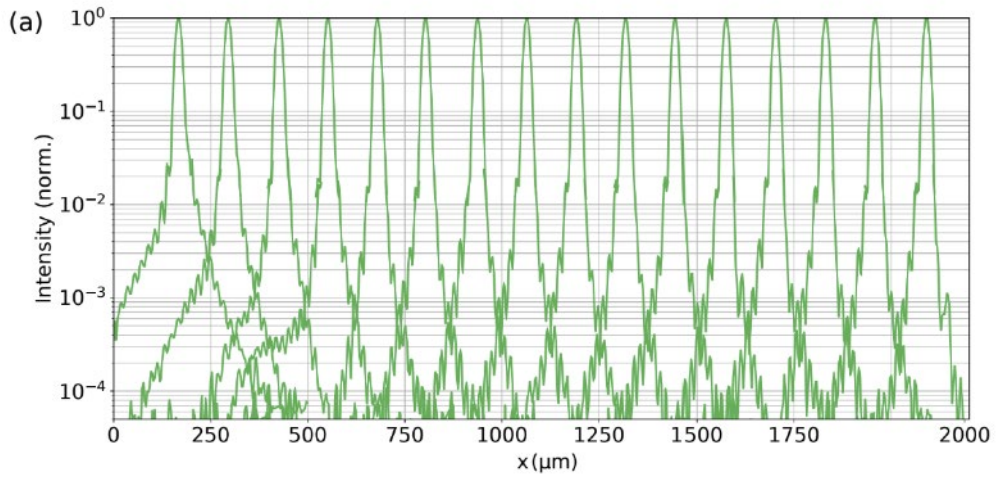




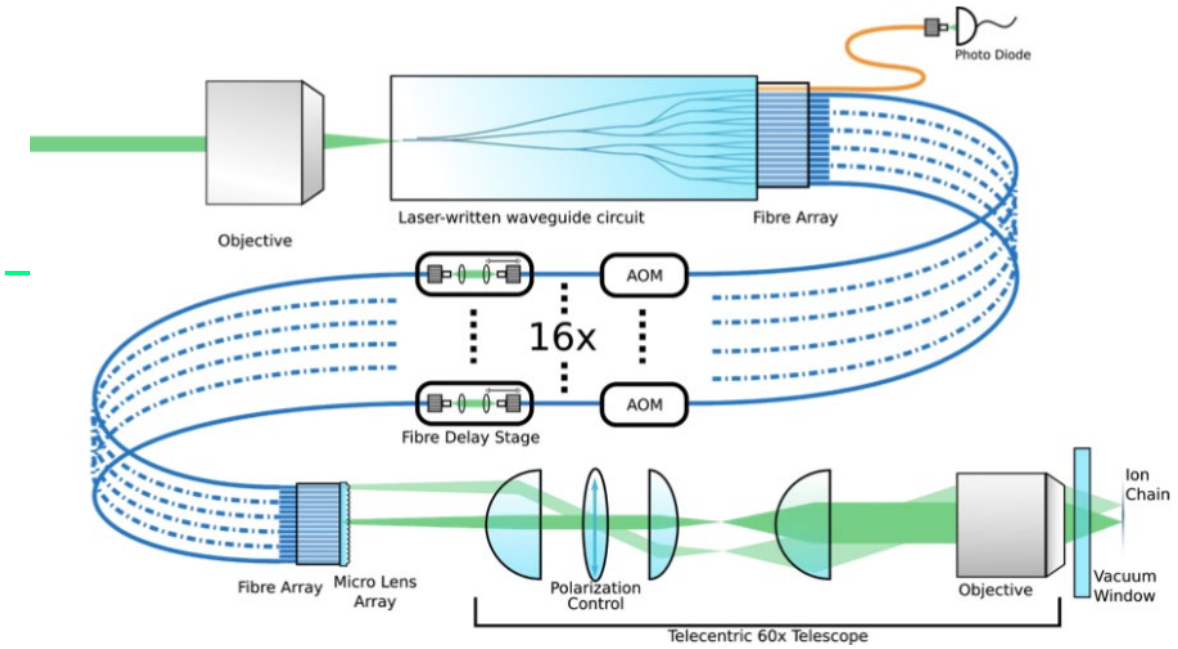
Ba+ wavelengths

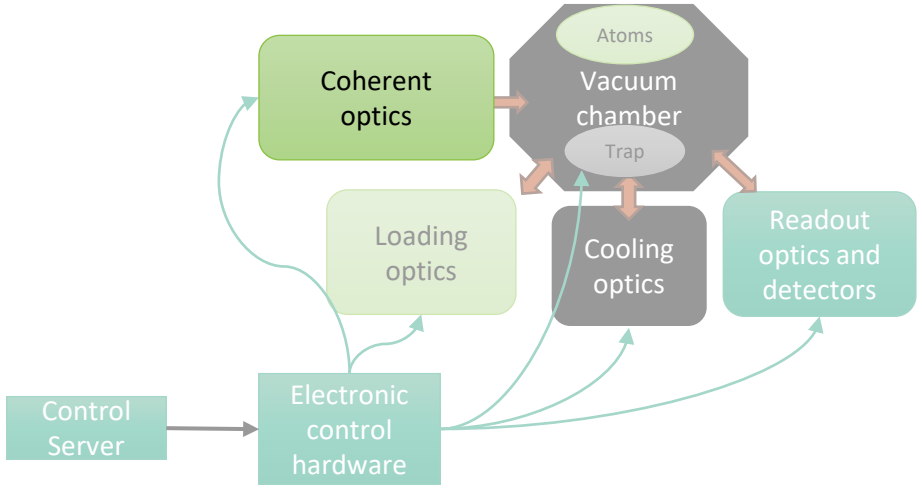


Required new optical hardware for individual qubit control



Individual addressing system with 1e-4 optical crosstalk at 4 microns!
(Crosstalk ~= error on qubit operations)





532 nm wavelength for coherent control

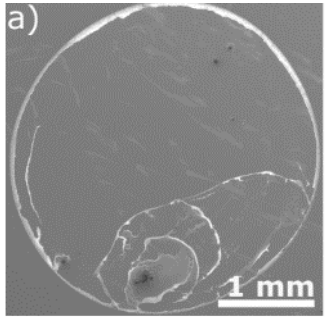
Use laser-written waveguides, microlens arrays, fiber-coupled modulators to achieve independent intensity/frequency/phase control

A. Binai-Motlagh…. CS, R. Islam,
Quantum Science and Technology 8 045012 (2023)

Require better atomic sources

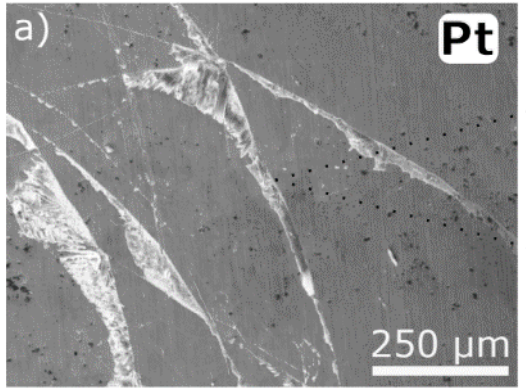
Ba-133+ is radioactive: ~5 microgram limit!
Ion sources usually use many milligrams!

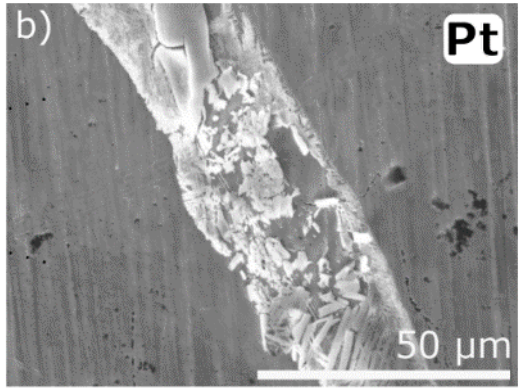
- Hard to obtain except as BaCl salt in solution (that's ok- can use laser ablation)
- Deposition causes 'coffee ring' inhomogeneities

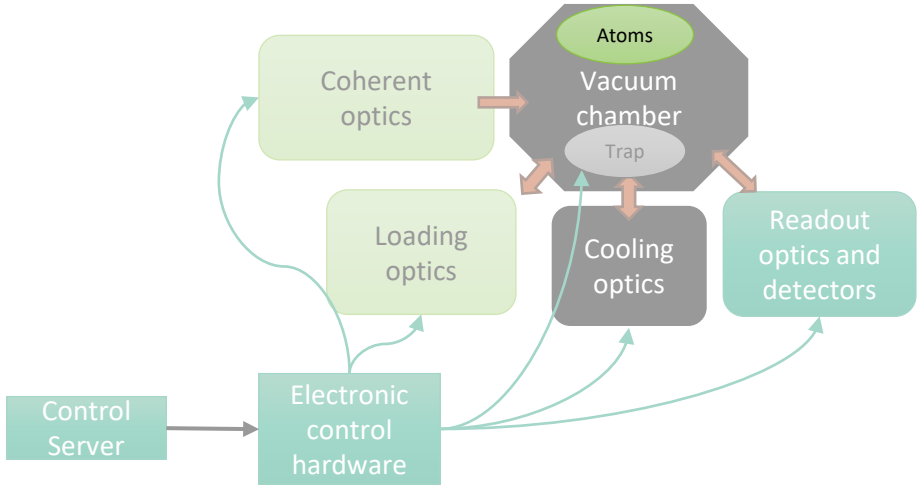


Laser ablation (nanosecond pulses, milliJoule energy) only known technique to extract atoms from microgram sources

- Salt flakes off substrates easily







N. Greenberg, A. Jozani, C. Epstein, X. Tan, R. Islam, CS, Rev. Sci. Instruments 95, 045117 (2024)

Fabrication process with appropriate heat treatments increases microgram-scale Ba source lifetime by 20-40x

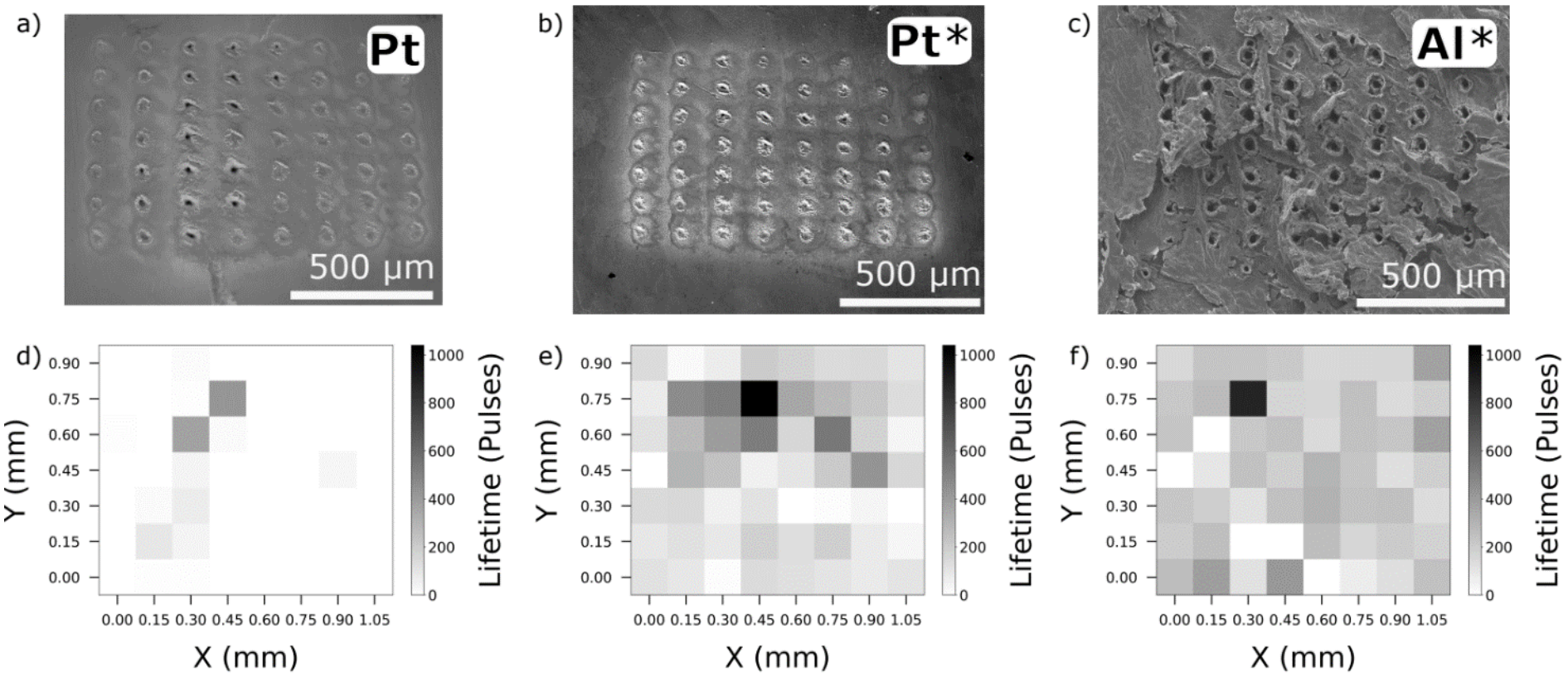
No heat treatment:
Inhomogeneity, not much Ba

Melting BaCl gives best results

Melting the substrate is fine too

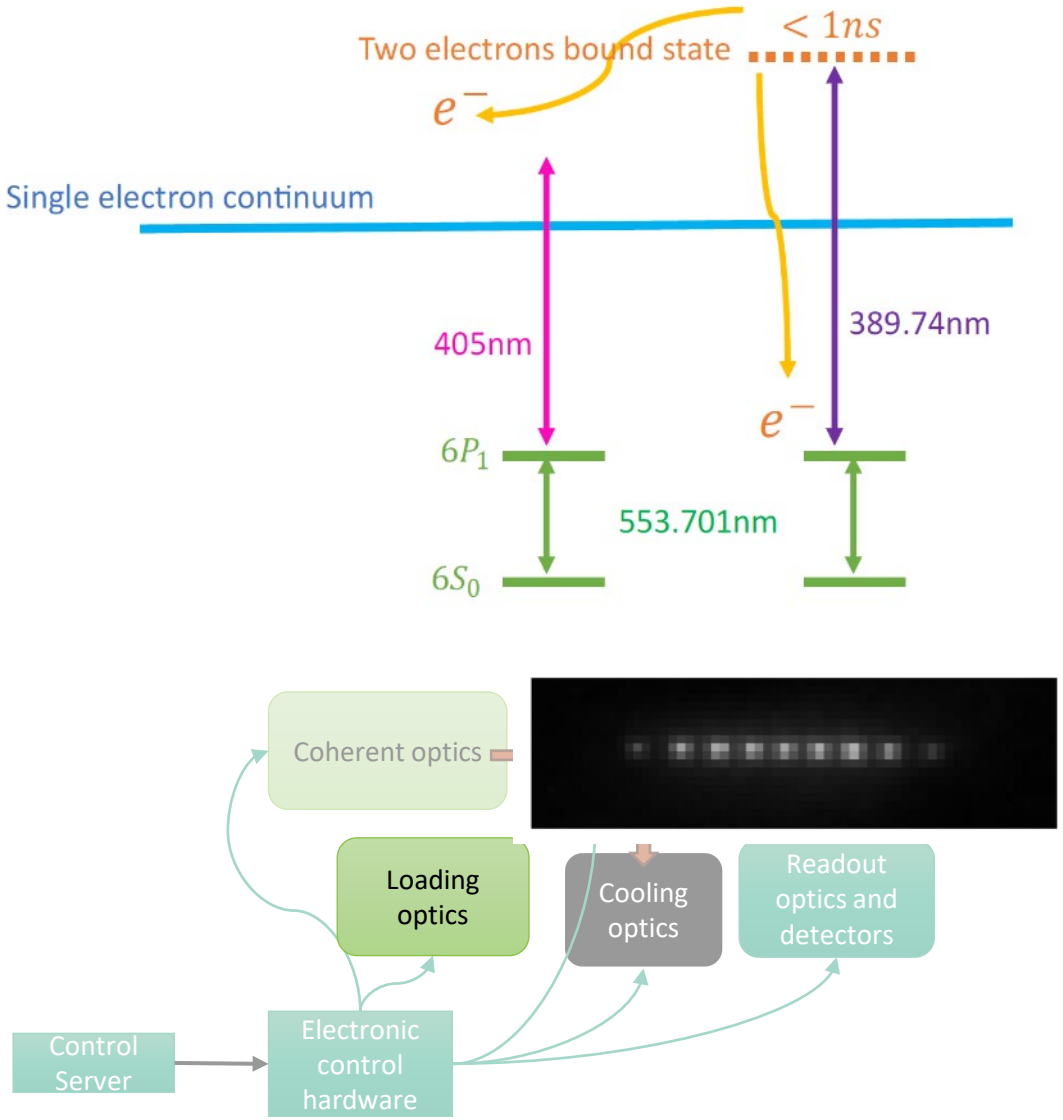
SEM images

Neutral Ba production
(per ablated spot)

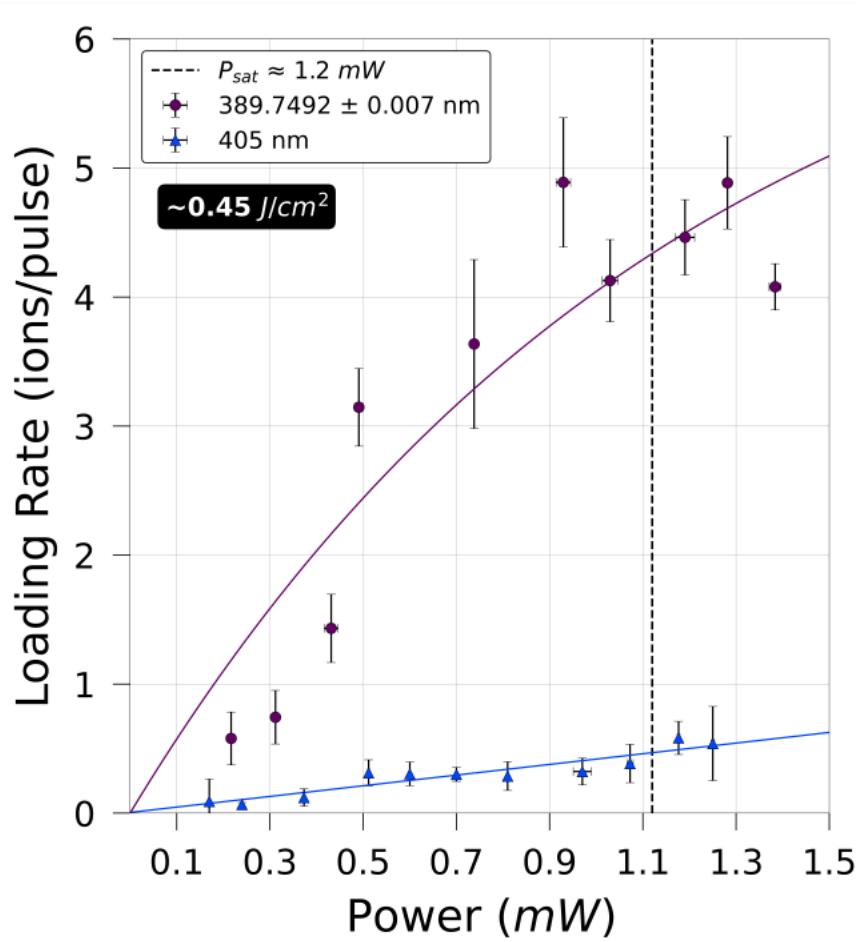


N. Greenberg, A. Jozani, C. Epstein, X. Tan, R. Islam, CS, Rev. Sci. Instruments 95, 045117 (2024)

Improved ionization for loading ions



Autoionizing resonance improves loading rates 7.5x compared to our previous method



N. Greenberg, B. White, P. Low, CS, Quantum Science and Technology 9, 035023 (2024)

Putting together the control stack

Classical computing infrastructure:
New collaboration on “full stack” control



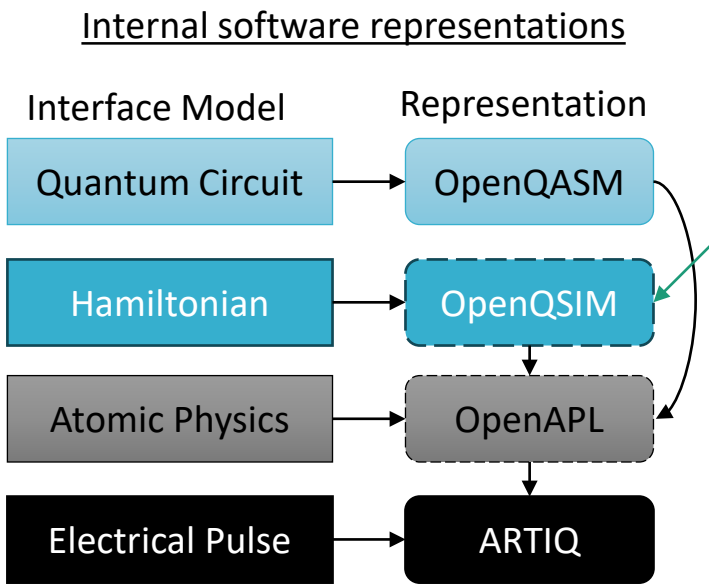
Prof. Senko



Prof. Islam

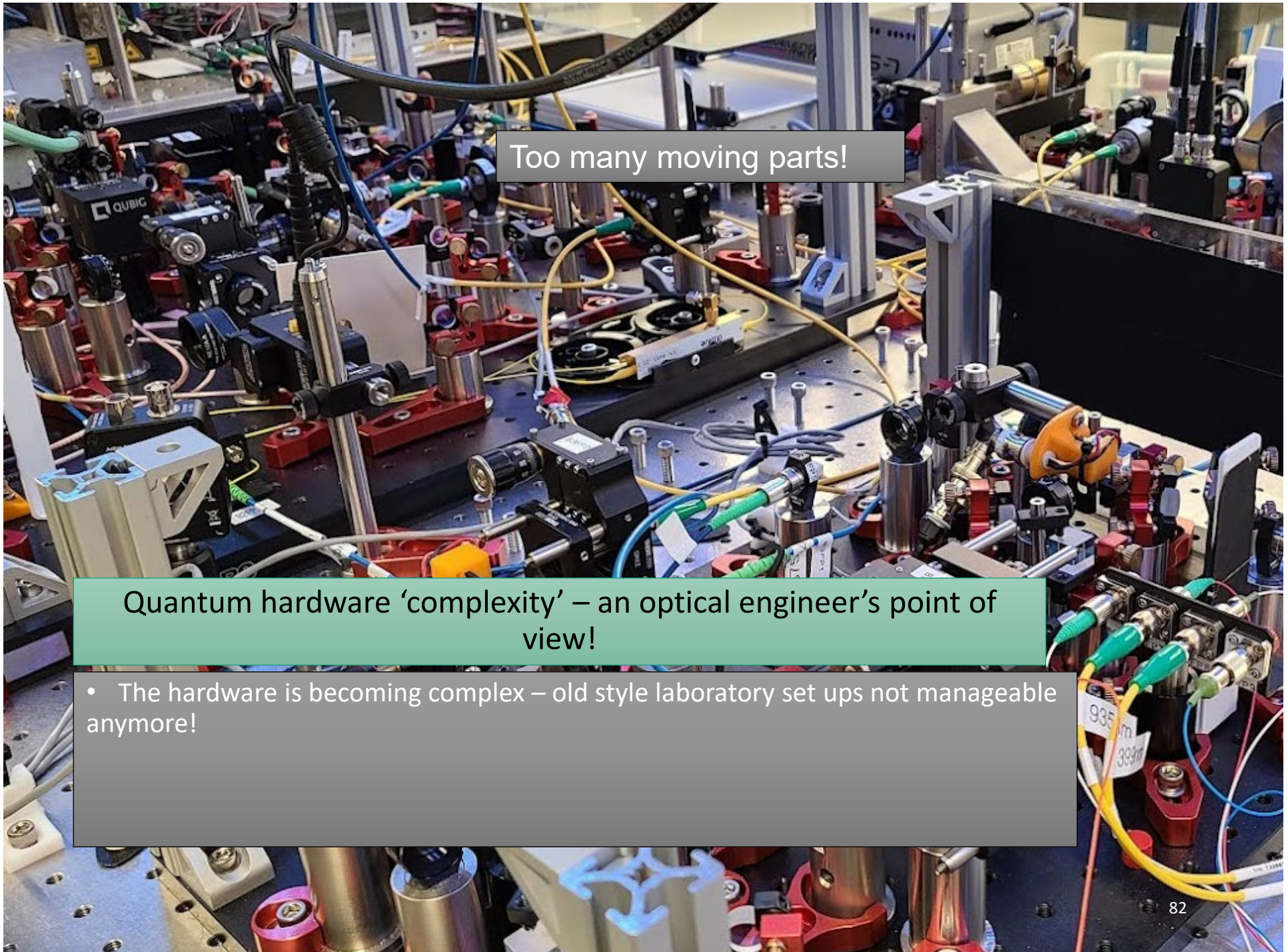


Prof. Roger Melko
Canada Research Chair in
Computational Many-Body Physics

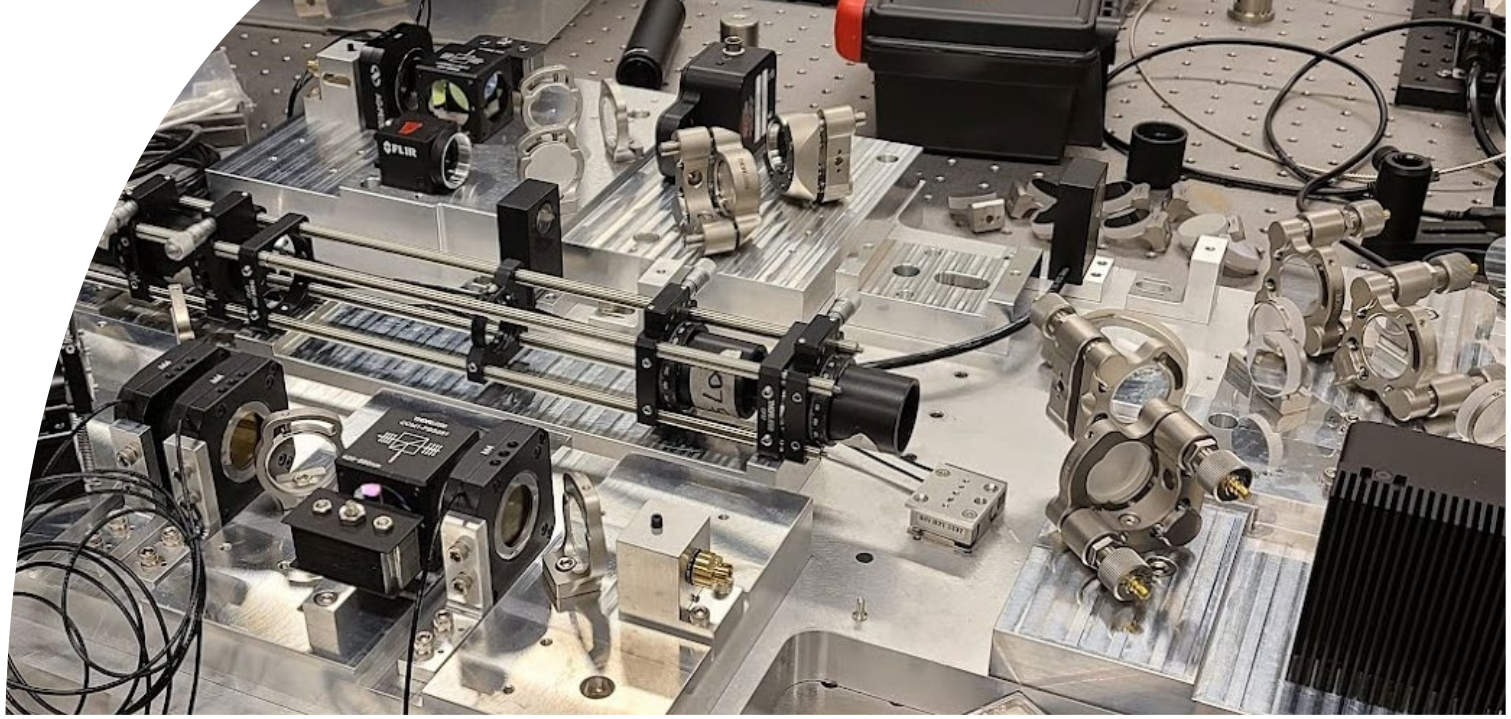


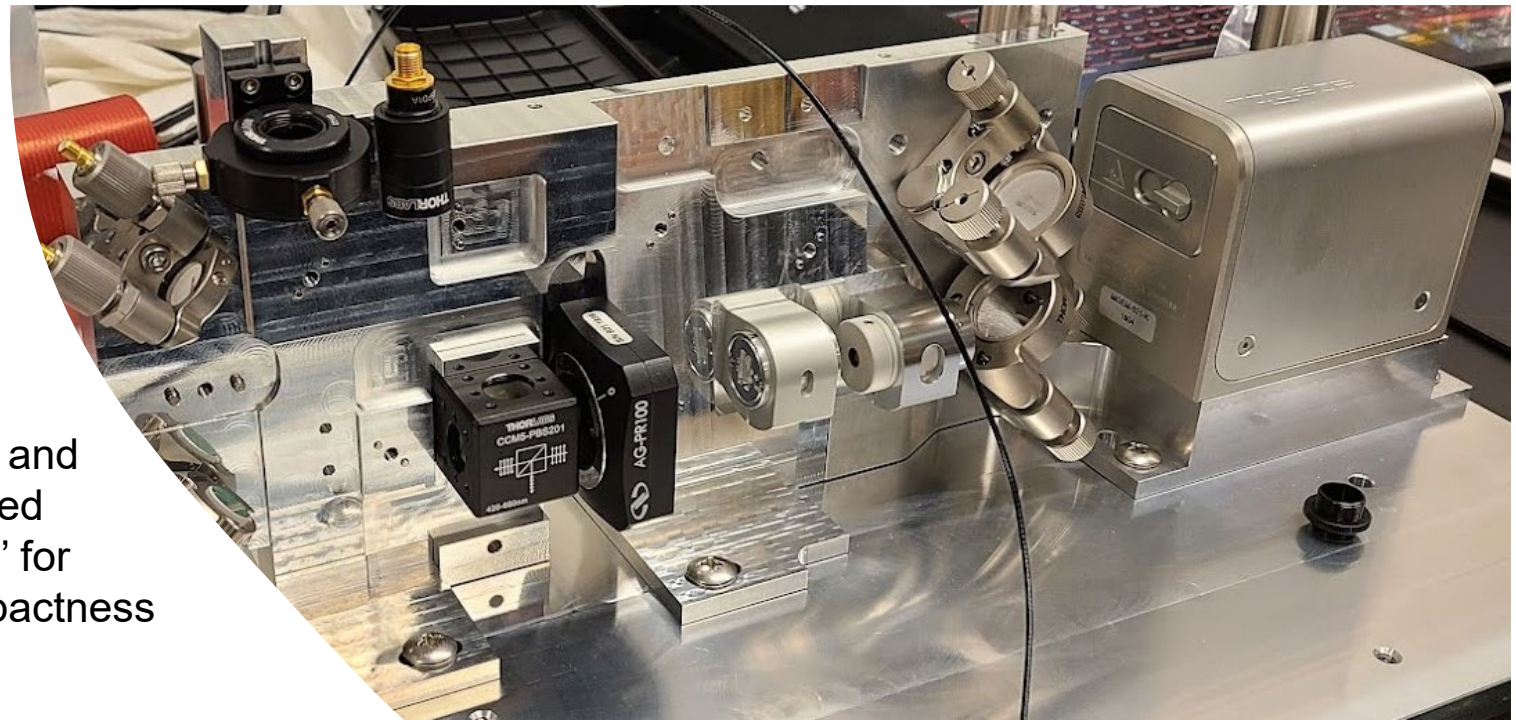
Current focus: Consistent language/API to specify “analog” quantum simulations

Ising model, XY model, Heisenberg model, qudit/higher-spin models… (all now demonstrated!)


Too many moving parts!
Quantum hardware ‘complexity’ – an optical engineer’s point of view!
• The hardware is becoming complex – old style laboratory set ups not manageable anymore!

Systems engineering approach





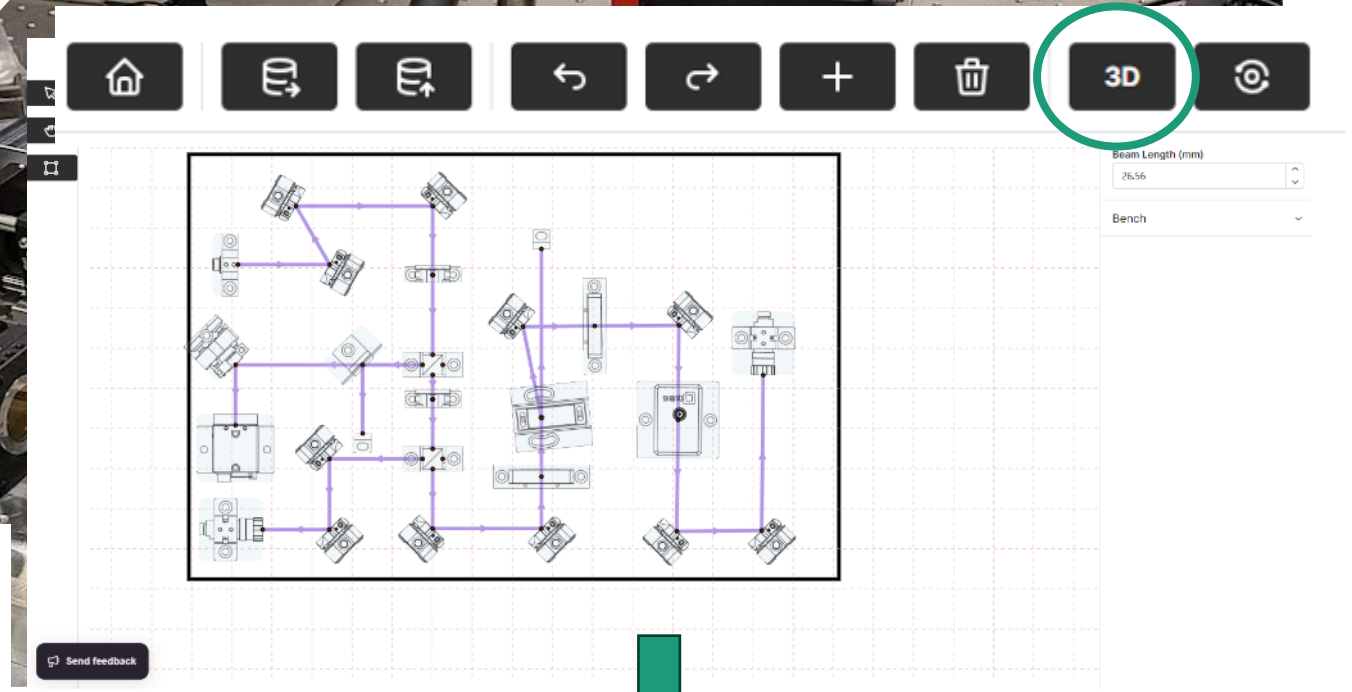
CAD optimization and Custom CNC-milled optics ‘pegboards’ for stability and compactness

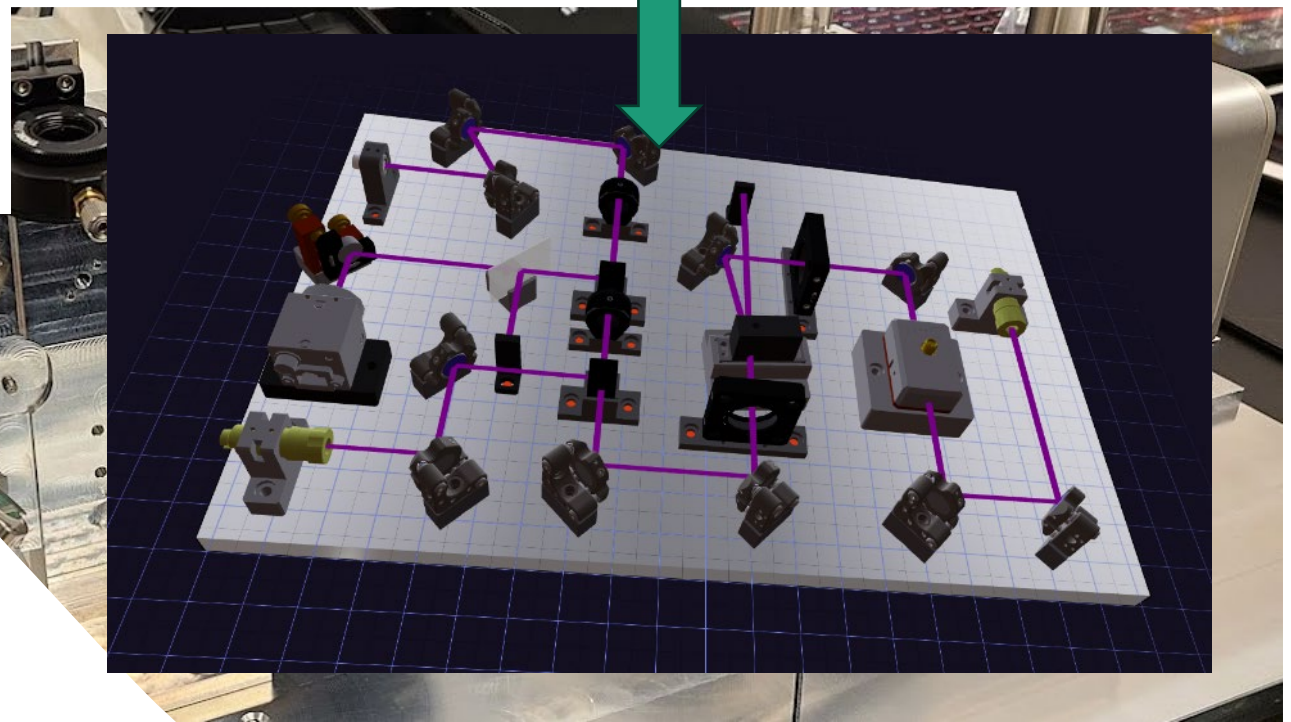
Systems engineering approach

Spin-off company from Prof. Islam's group:

LightFlow

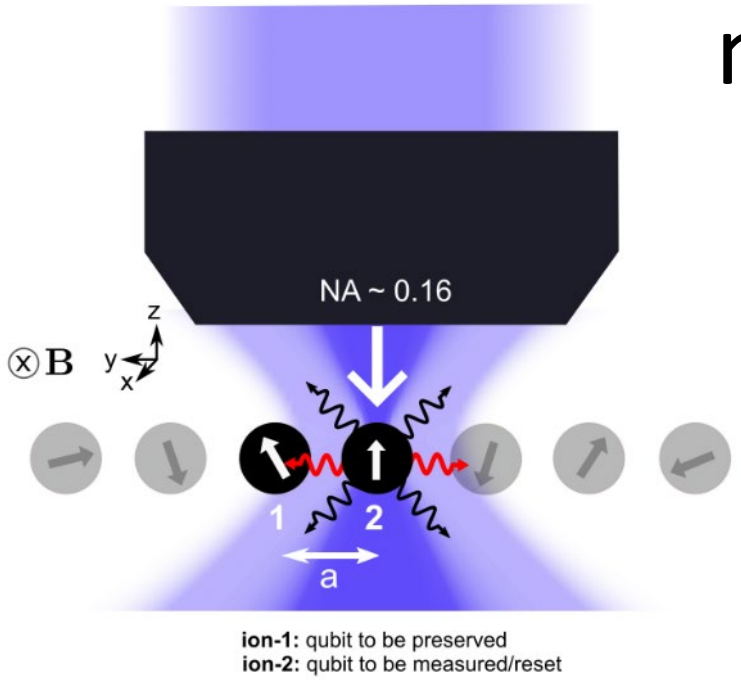
Optimal design flow for optical circuits
lightflow-optics.com

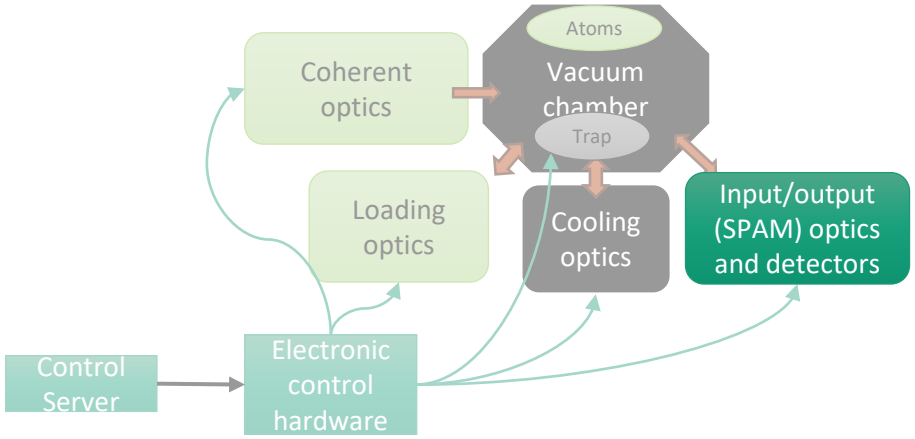




CAD optimization and Custom CNC-milled optics 'pegboards' for stability and compactness

Preserving a qubit during state-destroying operations on an adjacent qubit at a few micrometers distance





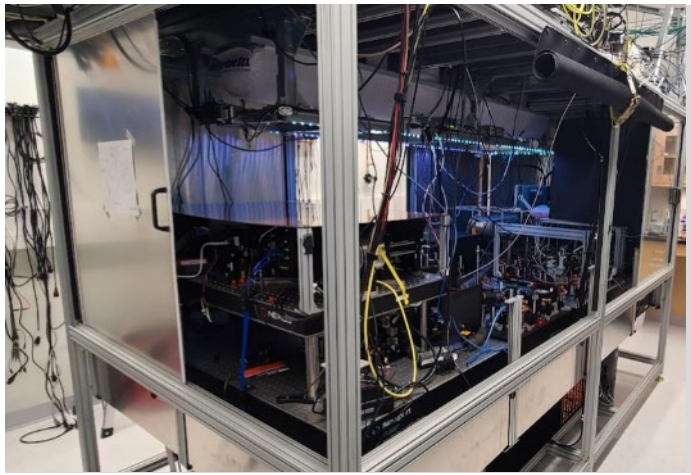
Holographic control with spatial light modulators enables precision control
Sensitive ion detection technique allows calibration of optical wavefront errors

- 1e-3: probability of accidentally measuring qubit 1 while resetting qubit 2
- 4e-3: probability of accidentally measuring qubit 1 while measuring qubit 2 for 11 microseconds

S. Motlakunta, N. Kotibhaskar, C.-Y. Shih, A. Vogliano, D. Mclaren, L. Hahn, J. Zhu, R. Habluetzel, R. Islam, arXiv:2306.03075
(in press, Nat. Comm.)

Pilot program on user collaborations

- **Primary focus: quantum simulations in <10 qubit system**
- Dissipative cooling of a many-body system
- Floquet Hamiltonian engineering
- Efficient Hamiltonian tomography
- Dissipation driven phases of quantum matter …

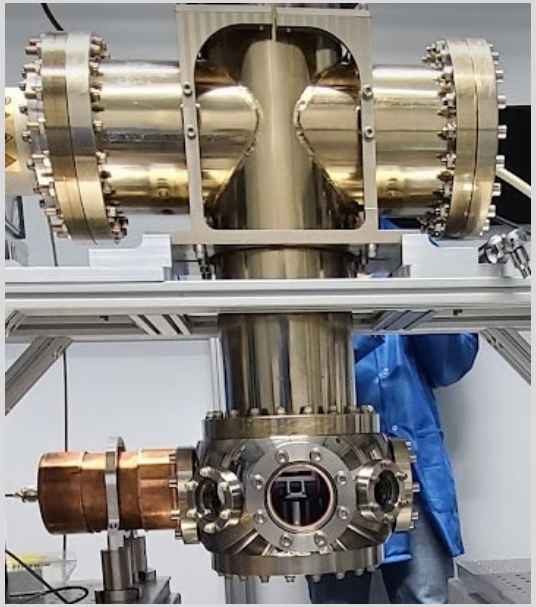


Yb^+ ion-based quantum simulator
(< 10 qubits)

Operational

- Long list of theory collaborators (from 5 countries) waiting to get access to ion simulators.

New machines for user collaborations coming soon

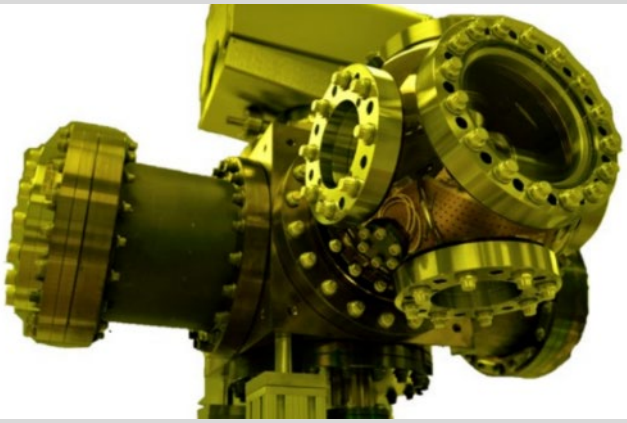


QuantumION

Ba^+ in surface trap (Sandia Nat'l Lab)

(16 qubits, arbitrary connectivity)

final stages of construction



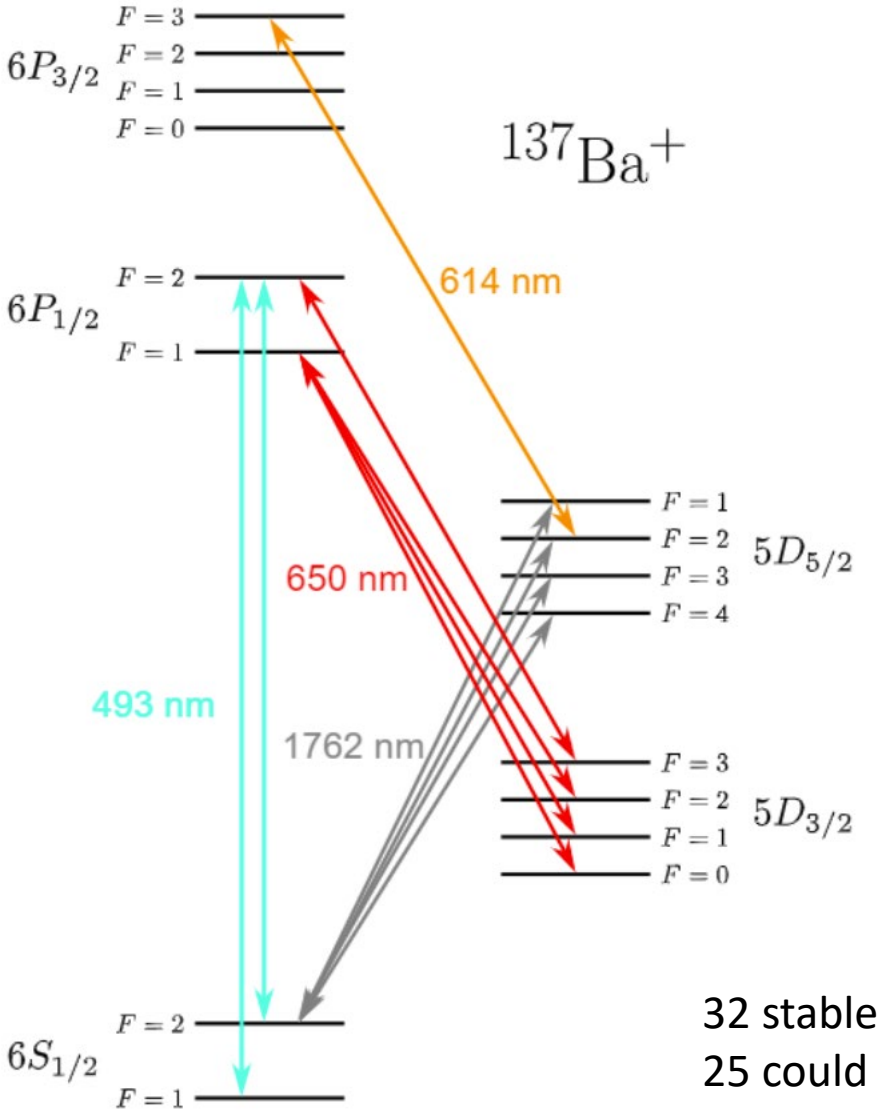
Yb^+ ion-based quantum processor for long ion chains

(> 30 qubits, mid circuit measurement and reset)

final stages of construction

Partnerships will include: viewers like you?!

Going beyond qubits



$$m_{\tilde{F}} = \quad -4 \quad -3 \quad -2 \quad -1 \quad 0 \quad 1 \quad 2 \quad 3 \quad 4$$

$$\tilde{F} = \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \end{array} \quad \begin{array}{ccccccccc} & & & — & — & — & & & \\ & & — & — & — & — & — & & \\ & — & — & — & — & — & — & — & \\ — & — & — & — & — & — & — & — & — \end{array} \quad 5D_{5/2}$$

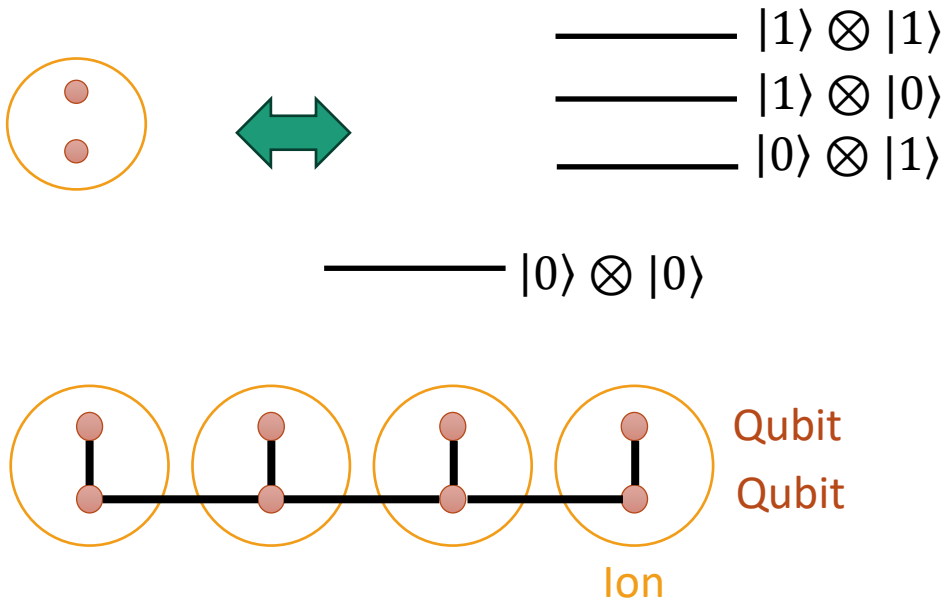
$$\tilde{F} = \begin{array}{c} 2 \\ 1 \end{array} \quad \begin{array}{ccccccccc} & — & — & — & — & — & & & \\ & & & — & — & — & & & \end{array} \quad 6S_{1/2}$$

32 stable and metastable states!!
25 could be distinguished in a single shot measurement!

Why use only two states?? (less complexity, less sensitivity to noise…)

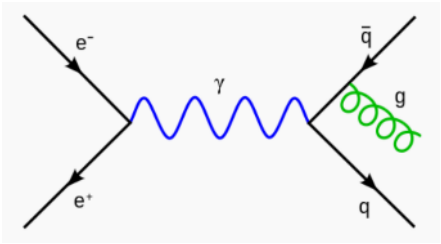
Would controlling multi-level qudits have practical benefit?

Data compression:
Add a laser, *double*
(or triple or quadruple) your qubit count??

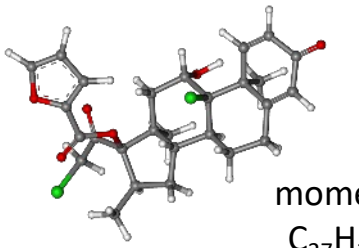


Simulating spins… or bosons

For lattice gauge theory



For quantum chemistry

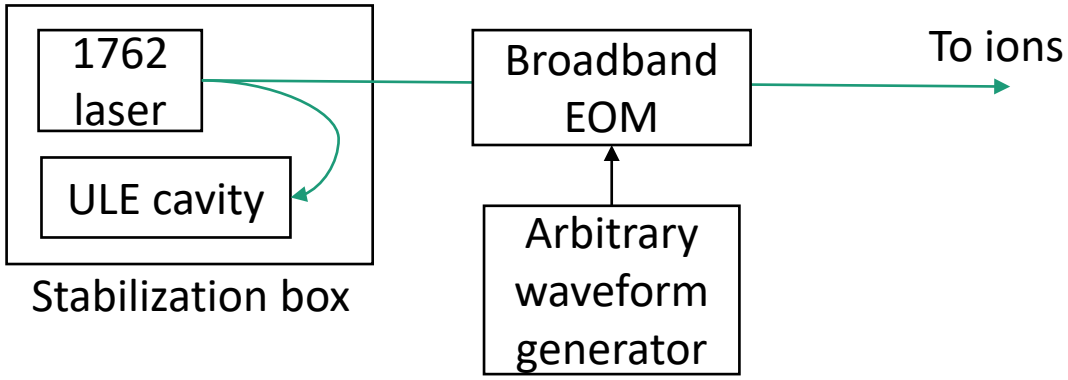


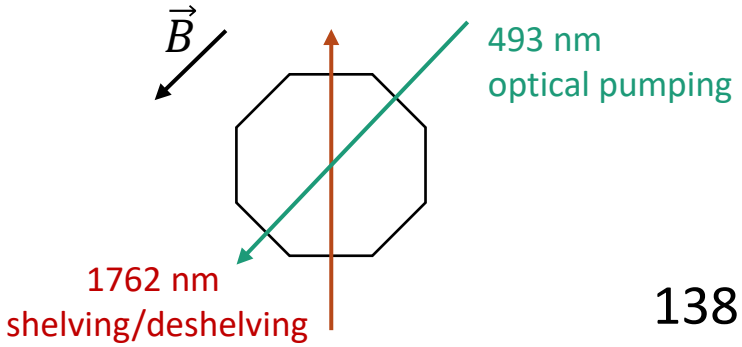
mometasone
$C_{27}H_{30}O_6Cl_2$

More efficient circuit compilation

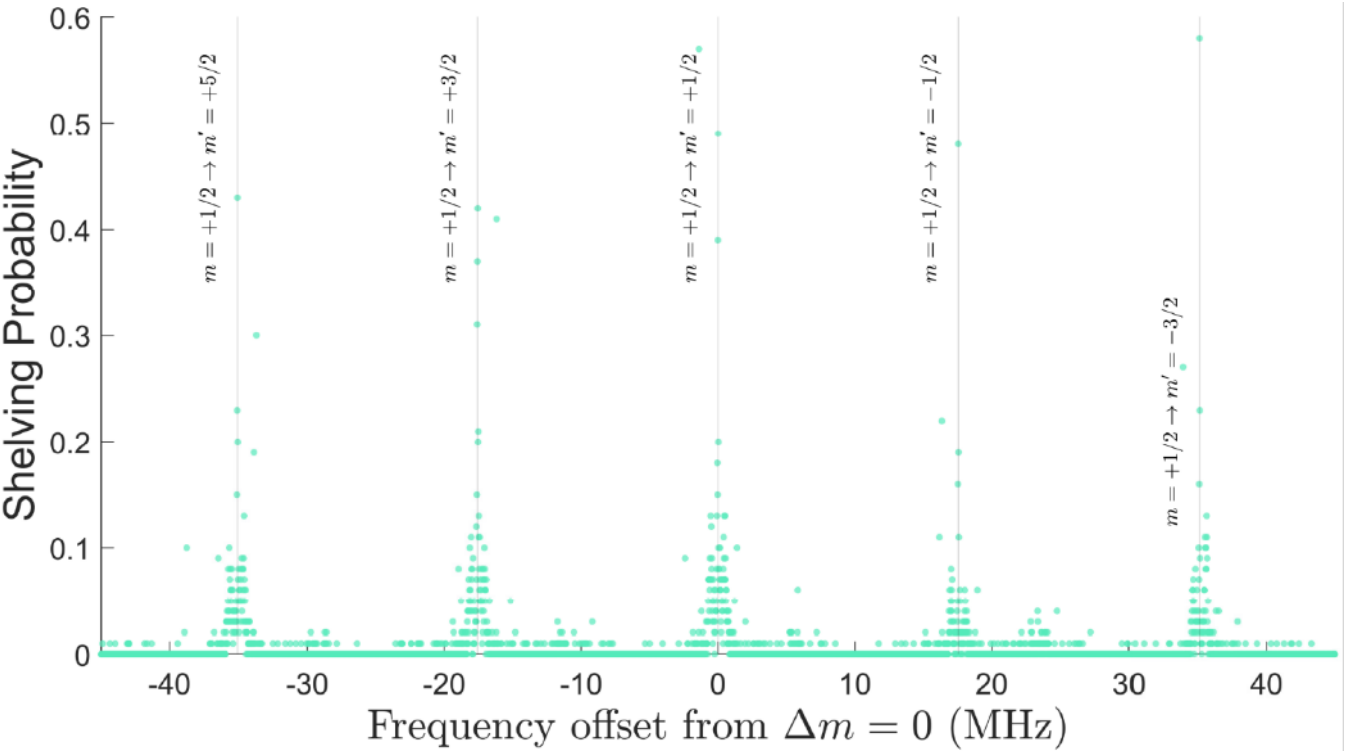
Potential benefits for QEC

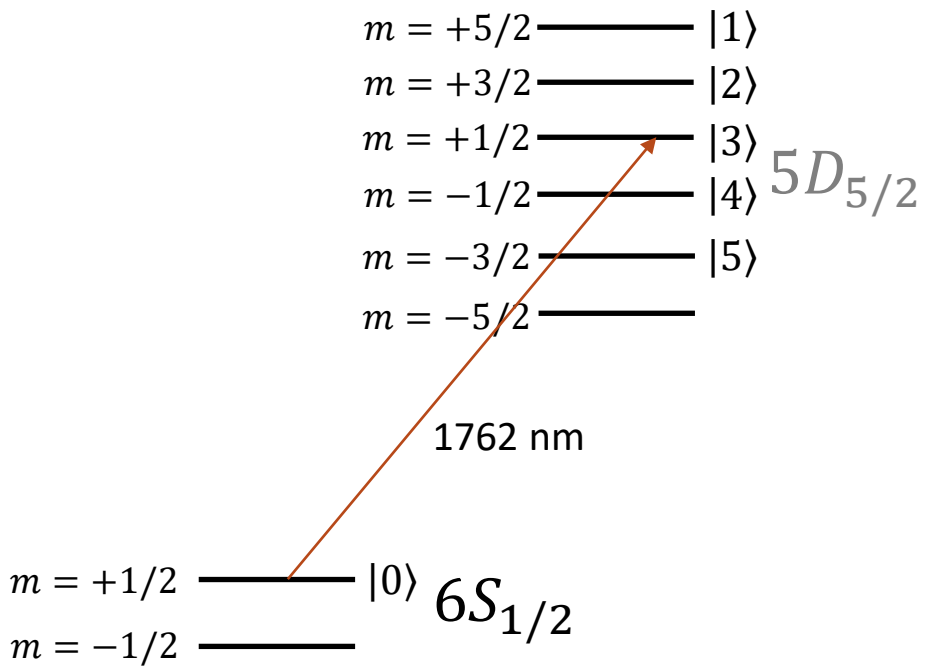
Optical qudit setup



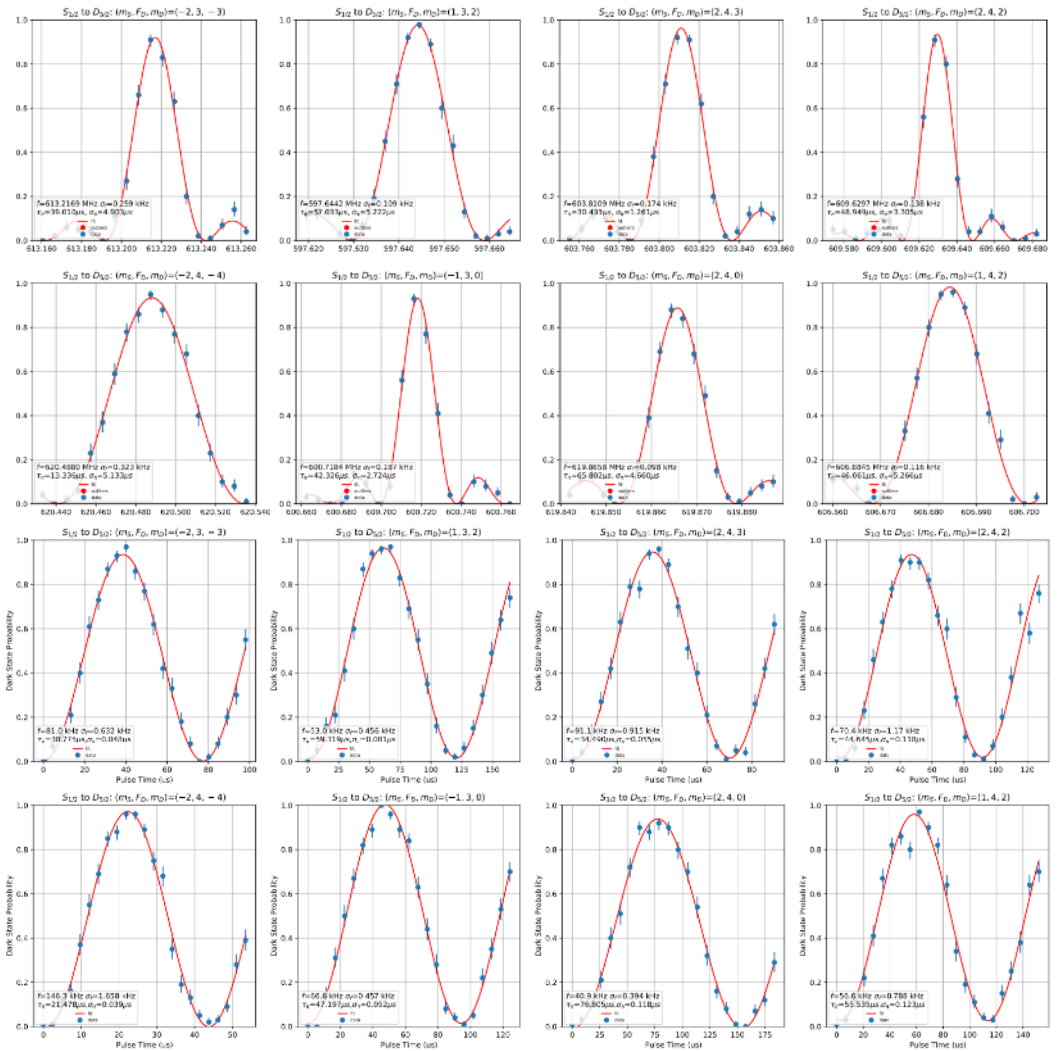


$^{138}Ba^{+}$



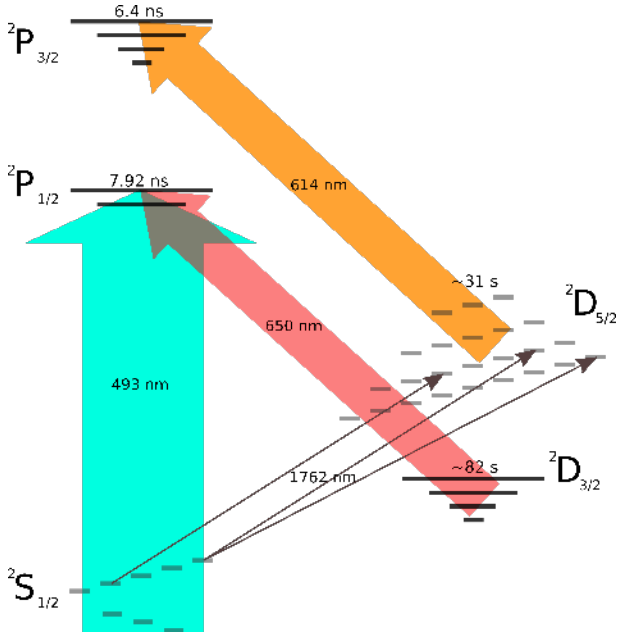


GETTING TO KNOW $^{137}Ba^{+}$

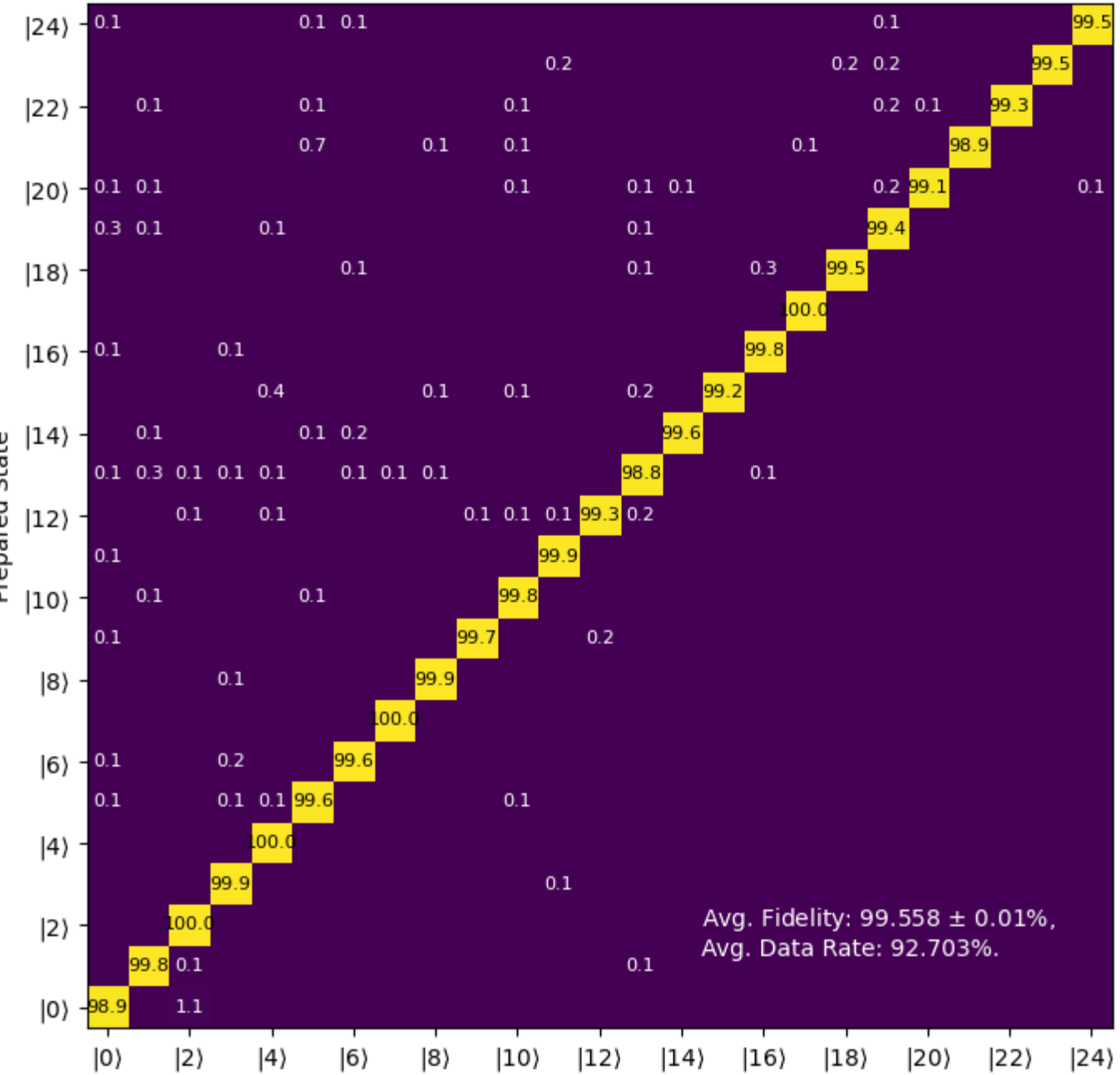


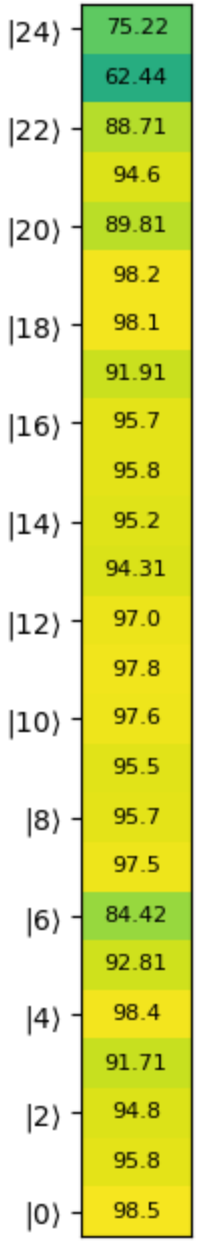
- Spectroscopy of 38 transitions of interest for initialising all states in $D_{5/2}$ and $S_{1/2}$ (out of 80 transitions total)

- Efficient calibration of all transition frequencies by checking just two reference transitions



Heralded SPAM for 25-level qudit (*preliminary data)*





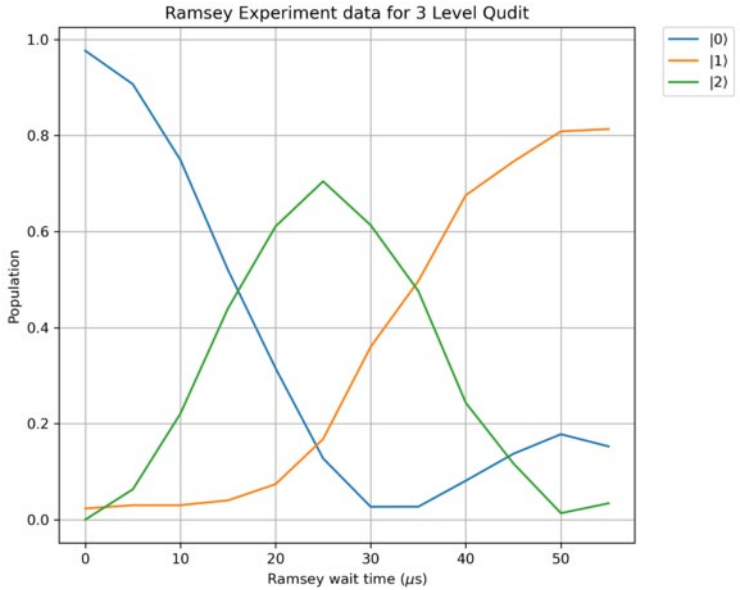
Left: probability of measuring state N after preparing state M

99.6% average success rate at measuring the state prepared (for successful runs)

7.3% of runs include a detectable error

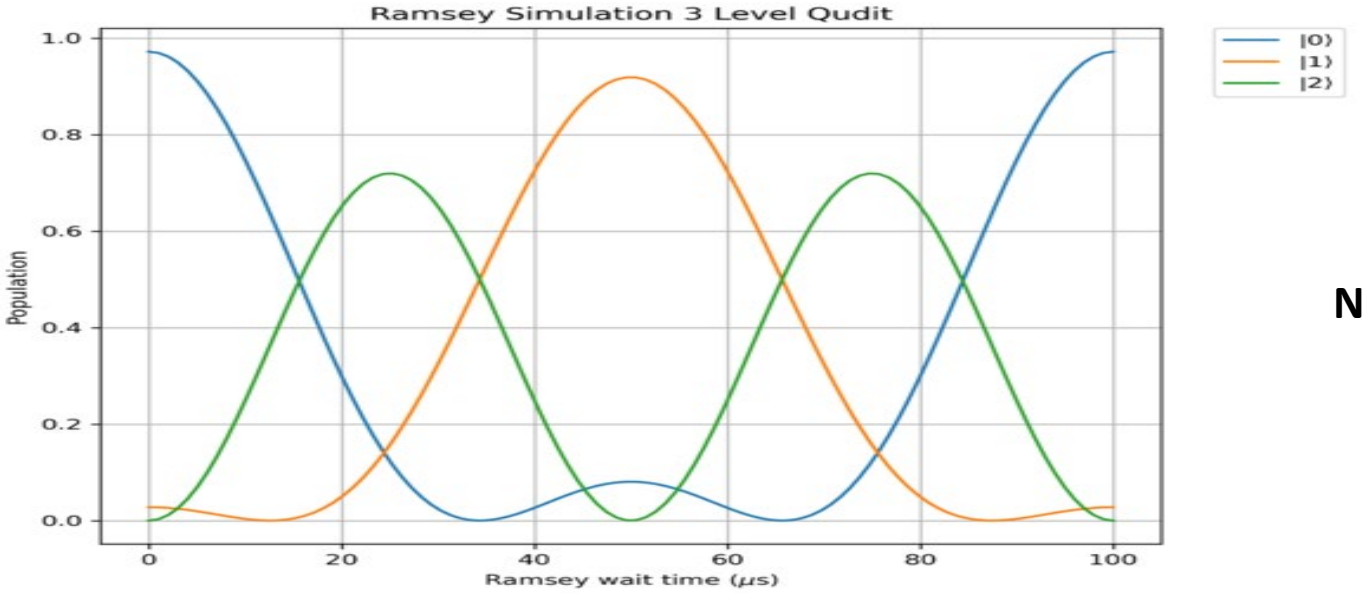
4 qubits = 16 states
0.999^4 = 0.996
→ Our result favorably compares with 99.9% qu**b**it SPAM!

Multi-level coherence *(preliminary)*



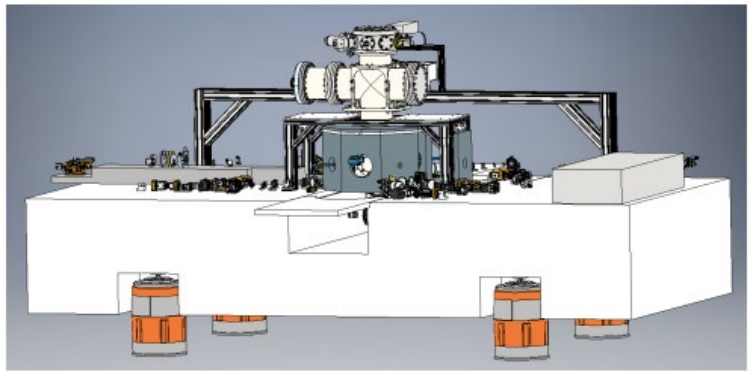
Experimental data: demonstrating coherence and phase control of 3 levels

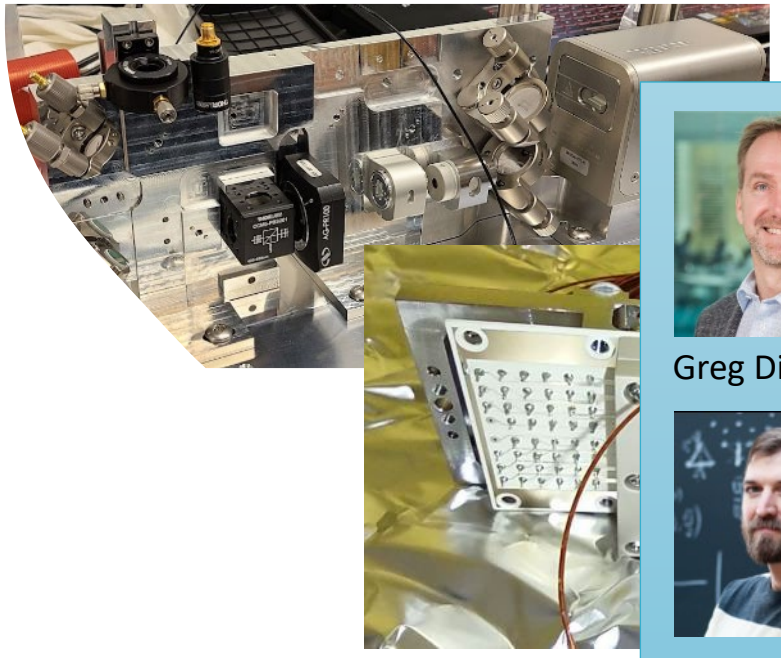
(first data set, collected <1 week ago)



Numeric simulation of our ‘generalized Ramsey’ sequence

Bottlenecks in hardware access: An impediment to innovation



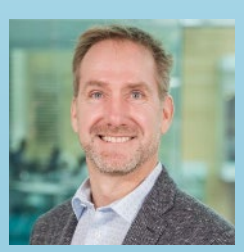


Limited access to quantum processors:

- Impedes benchmarking and algorithm development
- Low level “under the hood” controls highly restricted

Difficulty of replicating designs (PCB layouts, manufacturing drawings, bitstreams, source code, BOMs…):

- Increases barriers to entry on hardware research
- Impedes demonstrations of new architectures



Greg Dick, CEO



Prof. Rajibul Islam



Prof. Roger Melko



Prof. Crystal Senko

Open Quantum Design

openquantumdesign.org

Mission: Open source, full stack quantum processor designs

Thanks to:



Senko group

Current:
Ana Bershanskaa
Collin Epstein
Dr. Pei Jiang Low
Gaurav Tathed
Nico Zutt

Alums:
Matthew Day → Photonic
Elijah Durso-Sabina → Quantinuum
Virginia Frey → Keysight Technologies
Noah Greenberg → IonQ
Rich Rademacher → Q-CTRL, U. Sydney
Yvette de Sereville → Nord Quantique
Brendan Bramman White → IonQ



Islam group

Postdoc:

Dr. Yu-Ting Chen
Dr. Akbar Jozani
Dr. Sainath Motlakunta

PhD:

Nikhil Kotibhaskar
Yi Hong Teoh
Anthony Vogliano
Jingwen Zhu
Xinghe (Hawking) Tan
Lewis Hahn

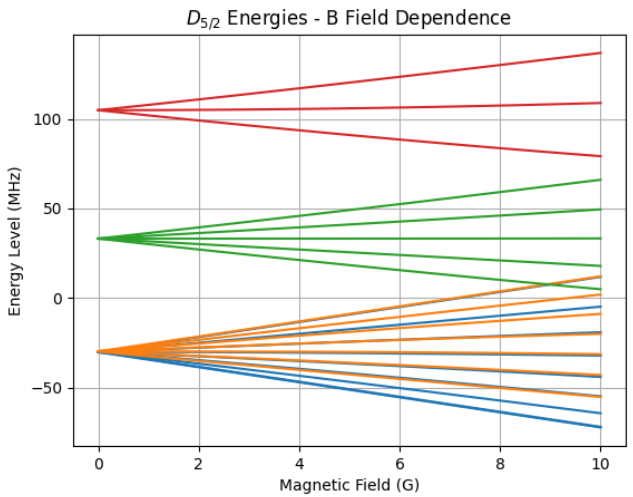
MSc: Ali Khatai, Akimasa Ihara, Shilpa Mahato, Fabien Lefebre
Research assistant: Sakshee Patil
Undergrad: Siddharth Chawla
Recent Alum: Chung-You Shih → Robinhood (software)
Roland Habluetzel → UK National Quantum Computing Centre
Fereshteh Rajabi → McMaster (Faculty)
Ali Binai-Motlagh → Columbia Univ (PhD)

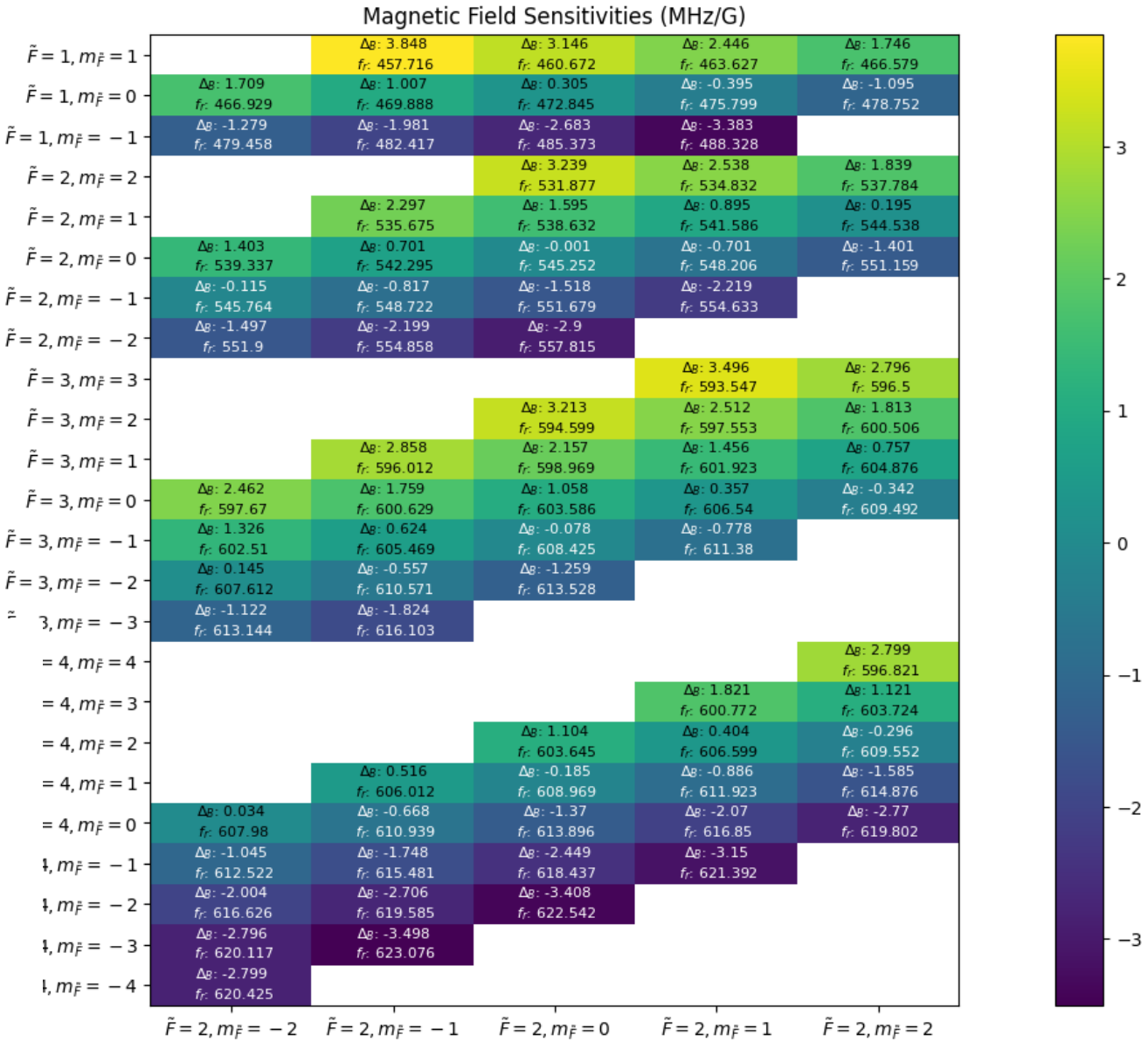
Now hiring on all projects from undergrad to postdoc levels!!

Canada Research Chairs
TQT Transformative Quantum Technologies
CANADA FIRST RESEARCH EXCELLENCE FUND
NSERC CRSNG
UNIVERSITY OF WATERLOO | IQC Institute for Quantum Computing
+ Ontario Early Researcher Award, NFRF

For Ba-137+: many many transitions

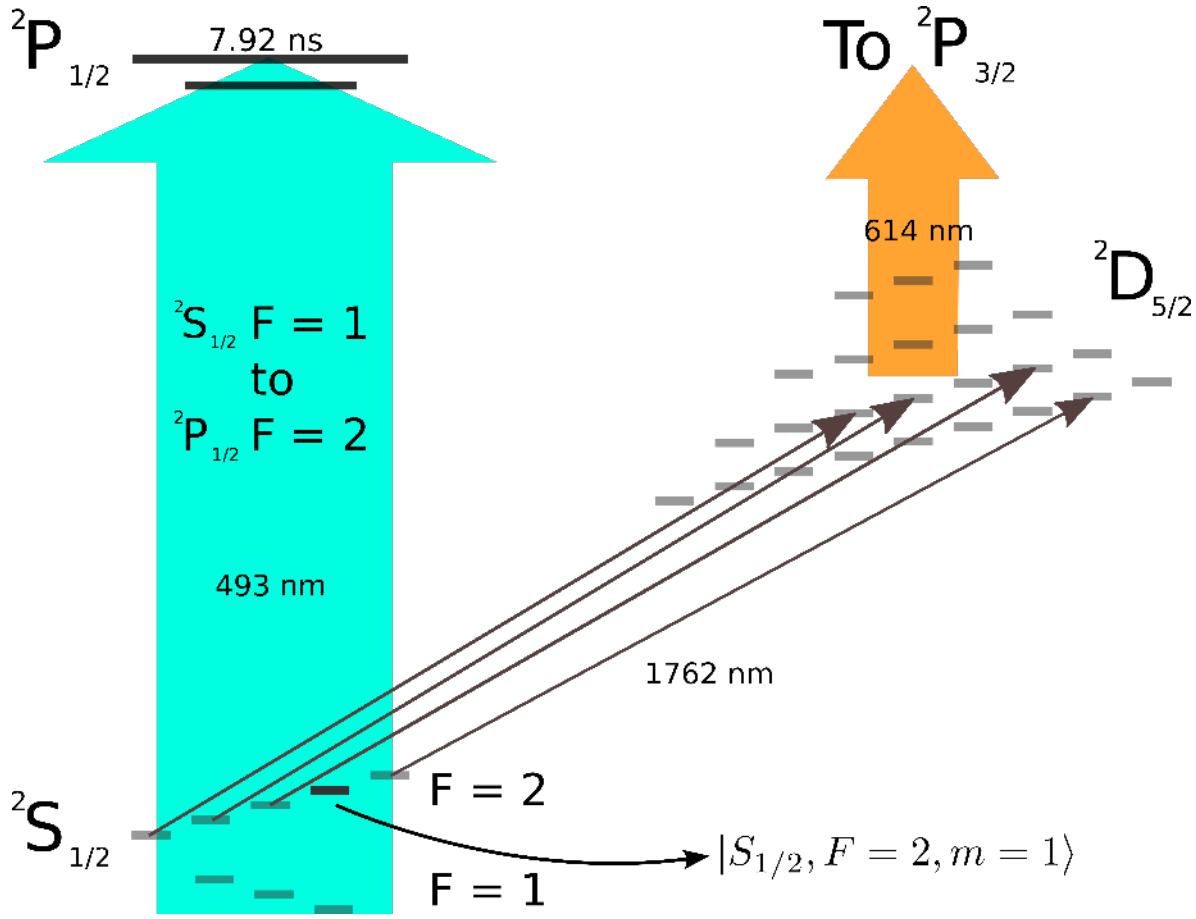
- Transitions have varying magnetic field sensitivities
- These variations lead to differences in the expected coherence times of each transition, as well as limits to shelving efficiency (and therefore SPAM results)
- Nonlinear Zeeman shifts → full spectral resolution





INITIALISATION IN $^2S_{1/2}$

1. **Flush** the $^2S_{1/2}, F = 1$ states with a short $(0.5\ \mu s)$ pulse.
2. **Shelve** 4/5 states in $^2S_{1/2}, F = 2$ with π −pulses $(\sim 250\ \mu s)$.
3. **Re-pump** population in $^2D_{5/2}$ to $^2S_{1/2}$ using $614\ nm$ laser $(1\ ms)$.
4. **Repeat** n times (depending on desired initialisation fidelity).

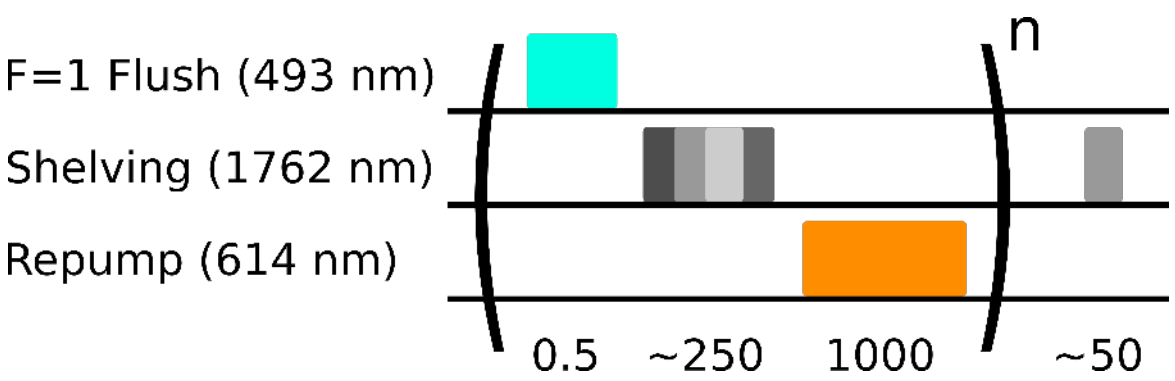


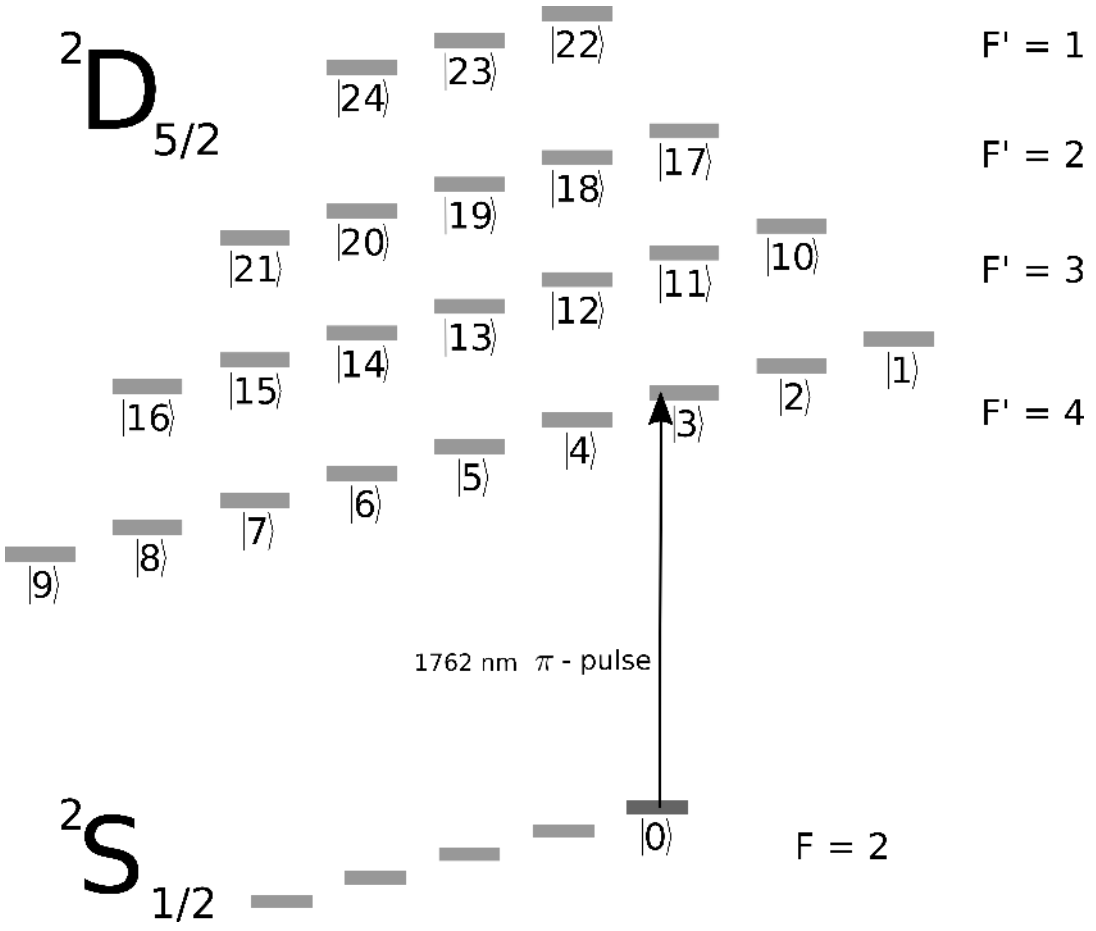
STATE PREP. AND MEASUREMENT – 25 LEVELS

Initialisation:

– Initialise some state in $^2S_{1/2}$ (eg. $m = 2$)

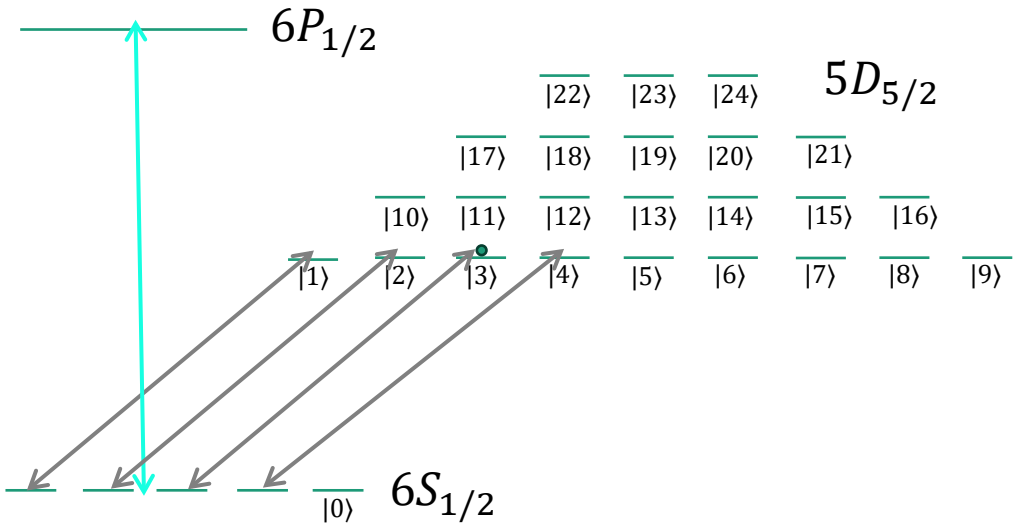
– Apply a π-pulse to shelve population in a desired initial state in $^2D_{5/2}$





STATE READOUT

- Qudit readout should distinguish each level in $5D_{5/2}$.
- Readout scheme:
  1. Start with Fluorescence:
     - Bright ion → $|0\rangle$
     - Dark ion → step 2
  2. De-shelve $|1\rangle$ to $6S_{1/2}$ level, then fluoresce:
     - Bright ion → $|1\rangle$
     - Dark ion → repeat step 2 for all $|n\rangle$ in $5D_{5/2}$
- In the readout table only first bright ion matters.



$\|0\rangle$	$\|1\rangle$	$\|2\rangle$	$\|3\rangle$	$\|4\rangle$	$\|5\rangle$	$\ldots\|n\rangle$
D	D	D	B	B	B	B

STATE PREP. AND MEASUREMENT – 25 LEVELS

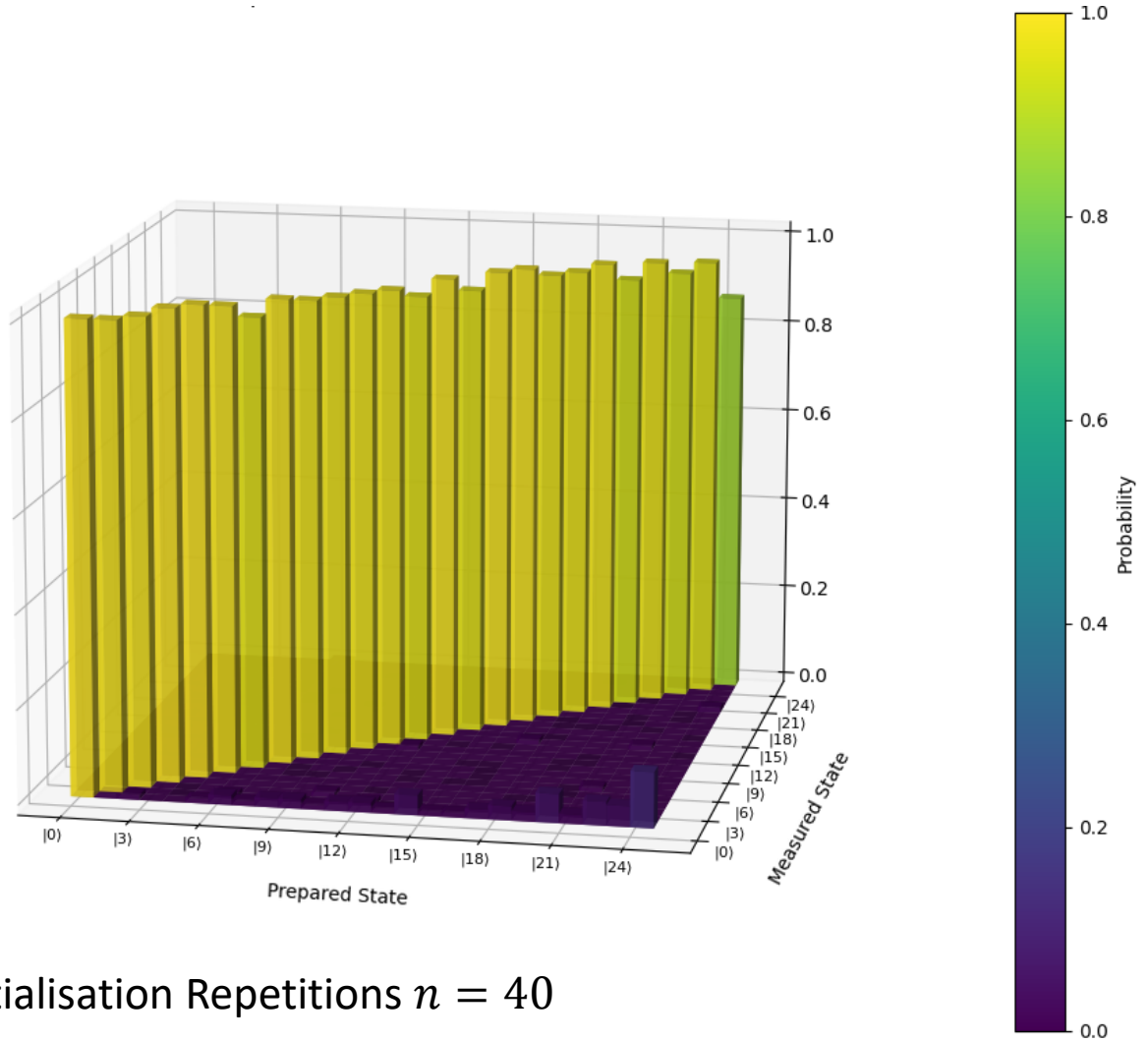
Average SPAM Fidelity: 97.28(8)%.

Main Error Sources Technical in Nature

– Magnetic field noise (affects weaker transitions)

– Frequency and π-time (mis)-calibration

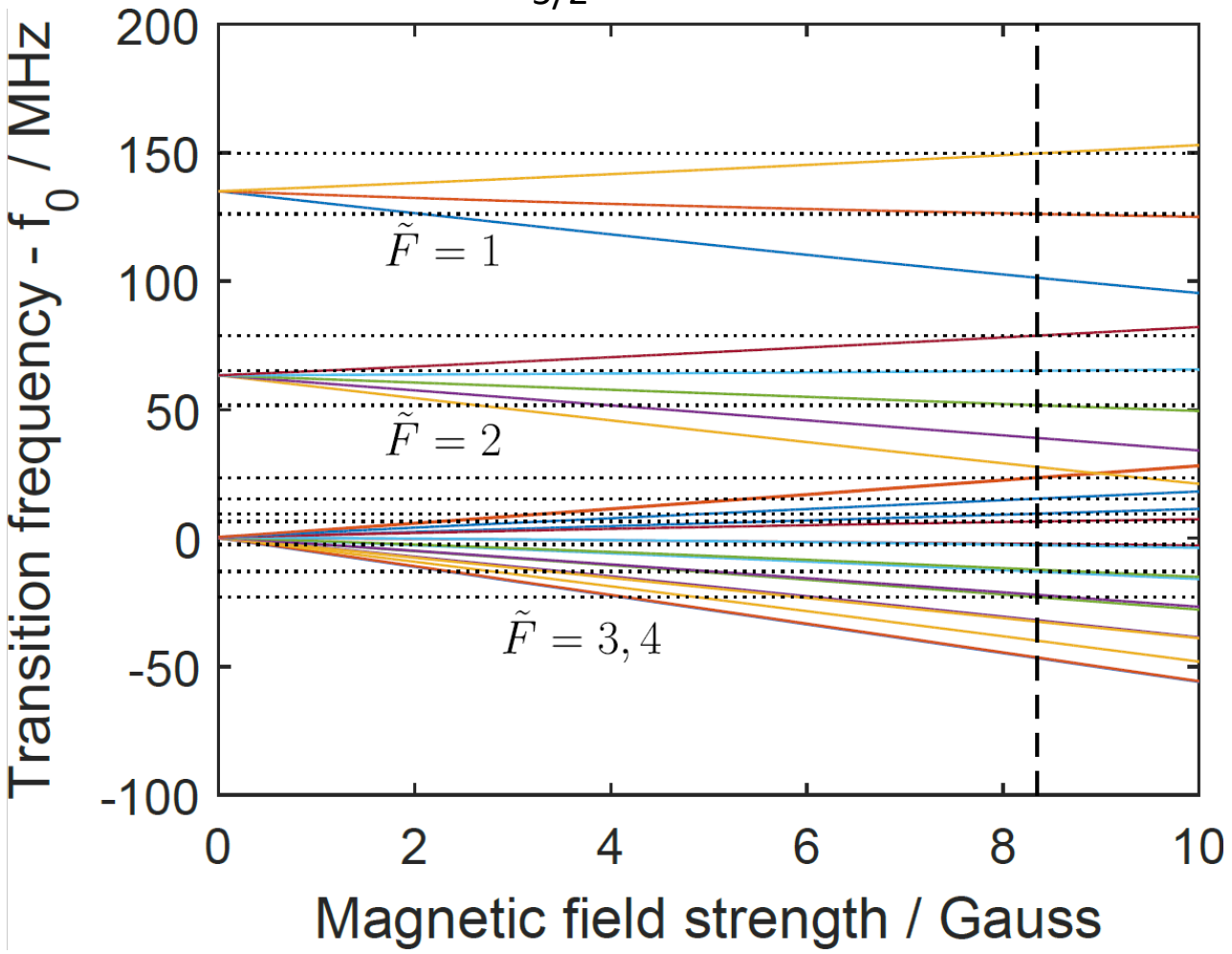
– Off-resonant or accidental driving of unwanted transitions (crowded spectrum of over 80 allowed transitions!)



Initialisation Repetitions $n = 40$

Work in a regime with highly nonlinear Zeeman shifts → good spectral resolution

$^{137}Ba^{+}$ $D_{5/2}$ energy sublevels



Hyperfine magnetic dipole component

$$\hat{H} = hA_d \vec{I} \cdot \vec{J}$$

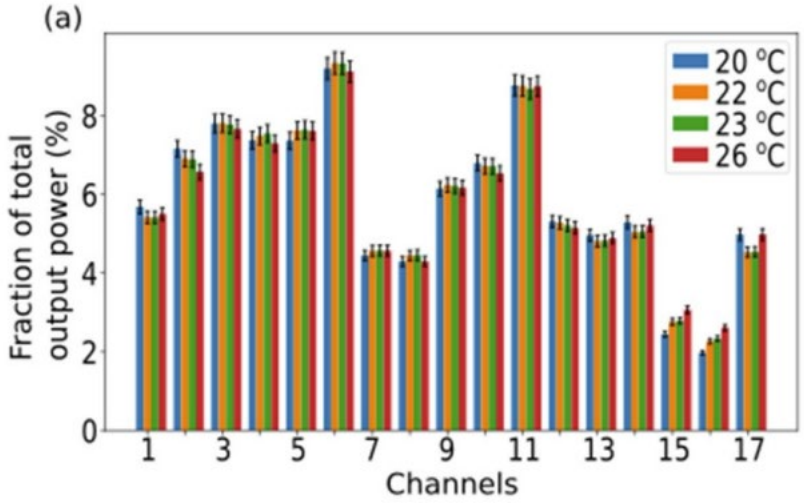
$$+hB_q \frac{3(\vec{I} \cdot \vec{J})^2 + \frac{3}{2}\vec{I} \cdot \vec{J} - I(I+1)J(J+1)}{2I(2I-1)J(2J-1)}$$

Hyperfine electric quadrupole component

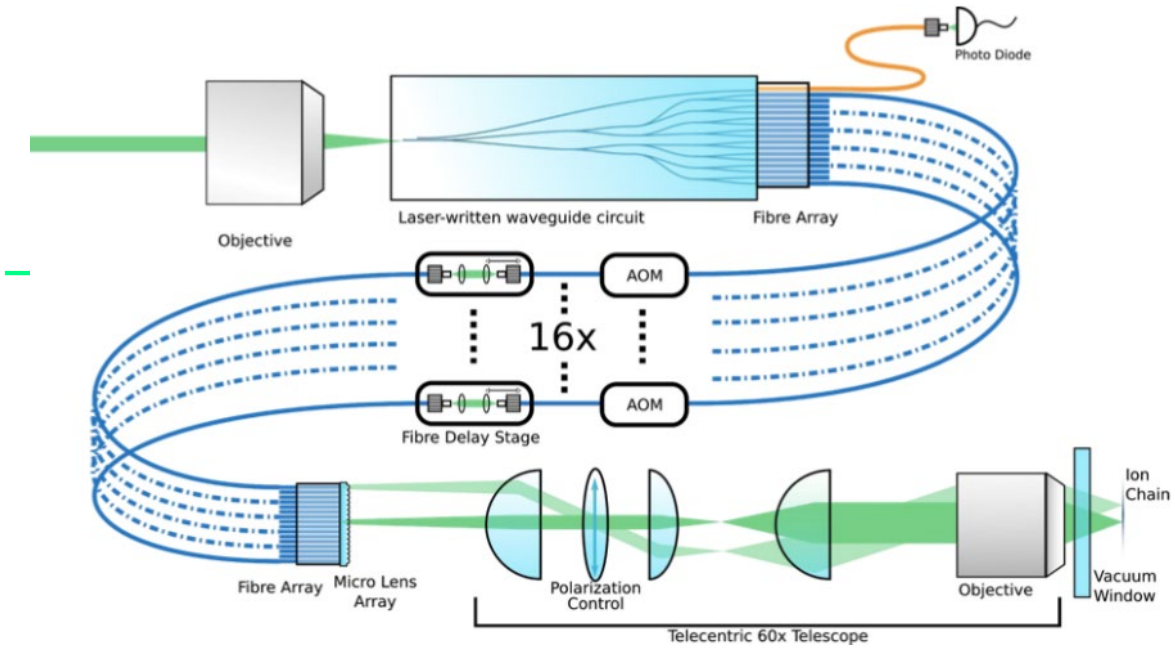
$$+B_{ext}\mu_B(g_J m_J + g_I m_I)$$

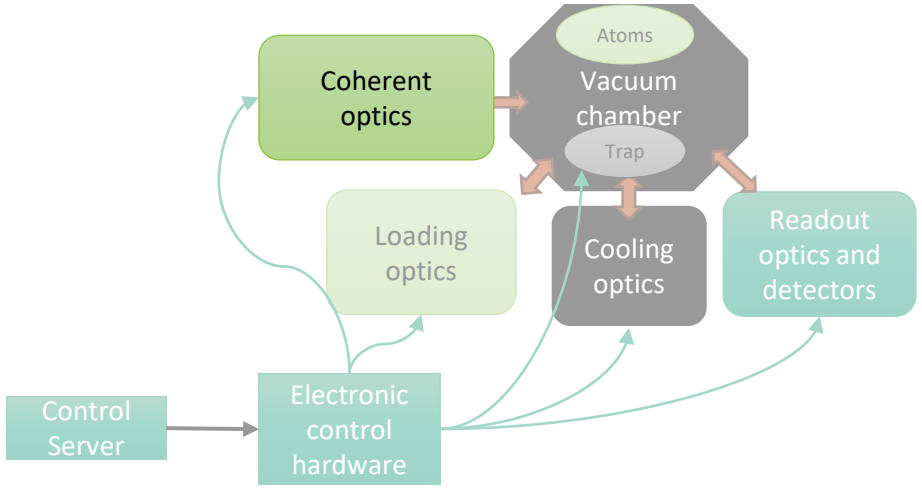
Zeeman shift in external magnetic field

Required new optical hardware for individual qubit control



Laser-written waveguide circuit splits optical power into 16 beams



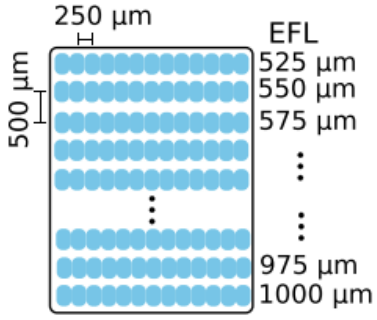


532 nm wavelength for coherent control

Use laser-written waveguides, microlens arrays, fiber-coupled modulators to achieve independent intensity/frequency/phase control

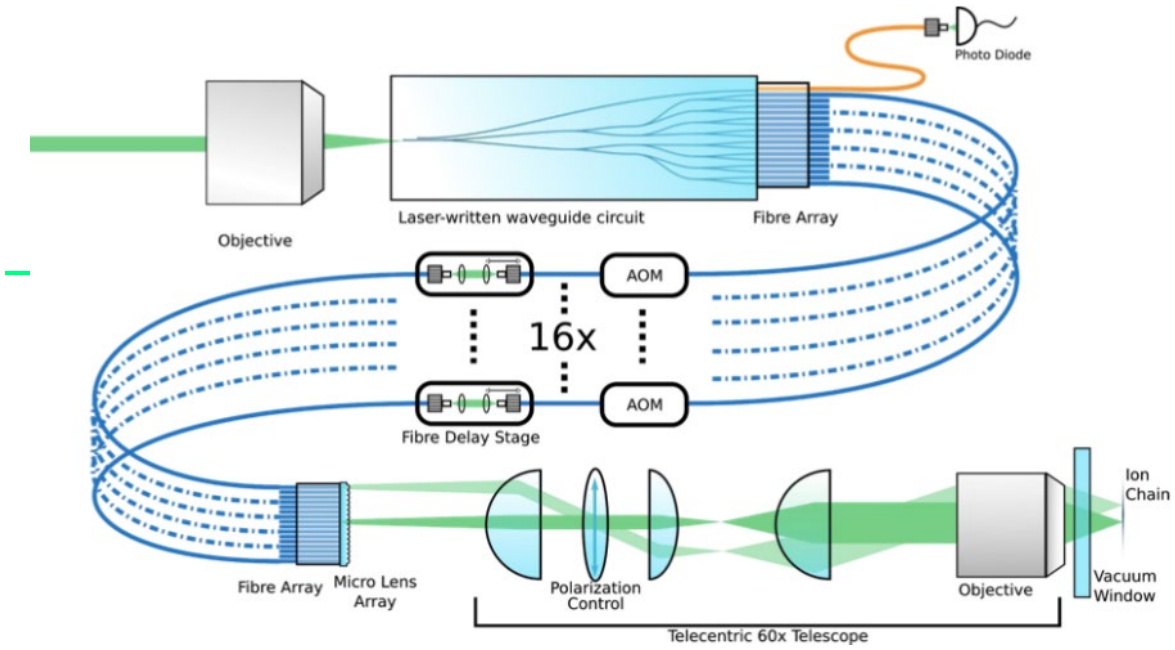
A. Binai-Motlagh…. CS, R. Islam,
Quantum Science and Technology 8 045012 (2023)

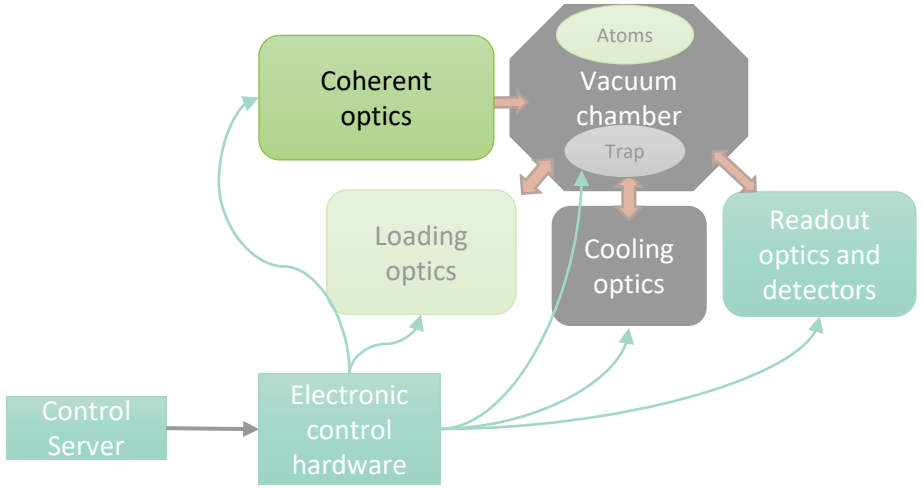
Required new optical hardware for individual qubit control



Microlens array part of the telescope mapping output beam width and pitch to ions

Only 1d array used… design multiple EFLs to correct for manufacturing imperfections





532 nm wavelength for coherent control

Use laser-written waveguides, microlens arrays, fiber-coupled modulators to achieve independent intensity/frequency/phase control

A. Binai-Motlagh…. CS, R. Islam,
Quantum Science and Technology 8 045012 (2023)


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PROF. FREDRICO BRITO

Senior Researcher

Technology Innovation Institute &

University of São Paulo

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Geometric Quantum Speed Limits in Open Quantum Systems

Frederico Brito





Q4i - 6th Annual Quantum for International Workshop. Rome-NY. 26/Jun/2024



Diego Paiva Pires (Universidade Federal do Maranhão - Brazil)



Eduardo R. deAzevedo (Universidade de São Paulo - Brazil)



Diogo O. Soares-Pinto (Universidade de São Paulo - Brazil)



Jefferson G. Filgueiras (Universidade Federal Fluminense - Brazil)

Agenda

- What?
- Why?
- How?
- Our findings

What?

By controlling the system-environment coupling, we experimentally evaluated geometric Quantum Speed Limits for paradigmatic metrics.

Key points:

- The open system quantum dynamic is due to a **structured environment**.
- **Markovian** and **non-Markovian** regimes could be exploited.
- We could derive analytical expressions for our figure of merit in terms of **expectation values of observables**.

Why?

QSL is related to the distinguishability of quantum states and a fundamental lower bound for the time evolution of quantum systems.

Key points:

The modern view relates QSL to **Information geometry**.

- Quantum Fisher information: $\delta^{\mathrm{QF}}(\rho,\sigma) = \arccos\sqrt{\mathcal{F}(\rho,\sigma)}$
- Wigner-Yanase skew Information: $\delta^{\mathrm{WY}}(\rho,\sigma) = \arccos\sqrt{\mathcal{A}(\rho,\sigma)}$

The origin of the QSL

What is the minimum τ so $\langle\psi(0)|\psi(\tau)\rangle$?

Two incompatible lower bounds are found: Which is the tightest?

- Mandelstam and Tamm (1945): $\tau_{MT} \geq (\pi\hbar/2)/\sqrt{\langle\Delta H^2\rangle}$
- Margolus and Levitin (1998): $\tau_{ML} \geq (\pi\hbar/2)/\langle H\rangle$

Solution: $\tau_{\min} \geq \max\{\tau_{MT}, \tau_{ML}\}$ Levitin-Toffoli (2009)

Today

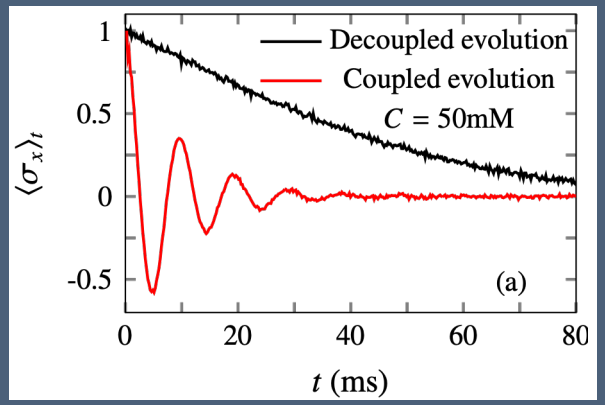
In addition to setting a lower bound on how fast the evolution can be (quantum computing), several works have found applications of QSL in quantum many-body systems, quantum thermodynamics, and non-equilibrium quantum dynamics.

How?

We performed NMR experiments by diluting the paramagnetic salt iron(III) acetylacetonate ($Fe(acac)_3$) to chloroform solutions ($CHCl_3$).

The chloroform encodes an interacting two-qubit system $(H = (\pi J/2)\sigma_Z^H \otimes \sigma_Z^C)$ using the ^{13}C and ^{1}H nuclei.

Using a decoupling technique, one can assess the single qubit evolution, characterizing their dissipative processes.

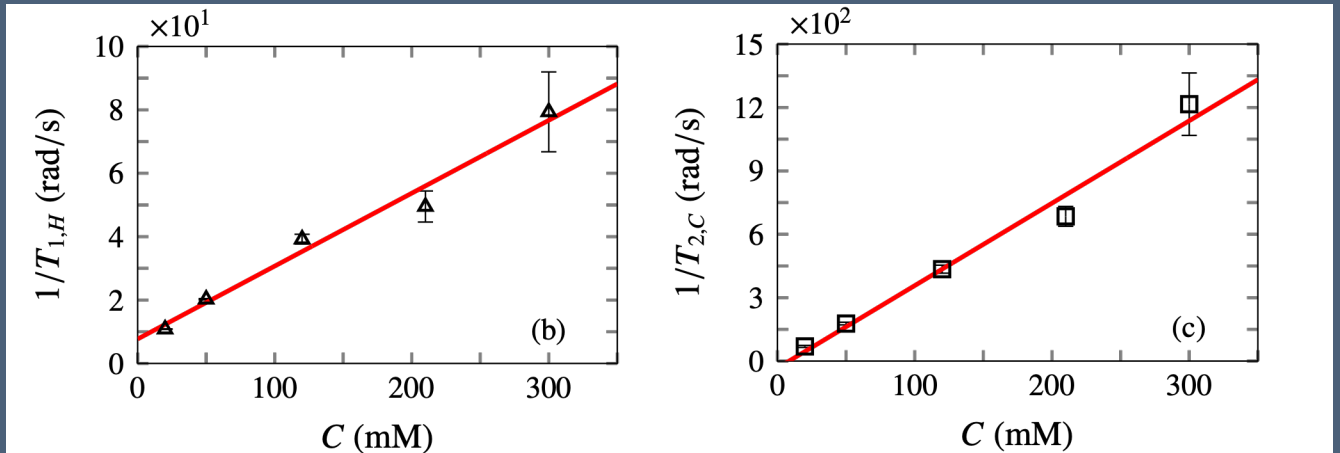


How?

Dissipative channels for single qubits:

Phase damping for ^{13}C and **bit-phase flip** for ^{1}H.

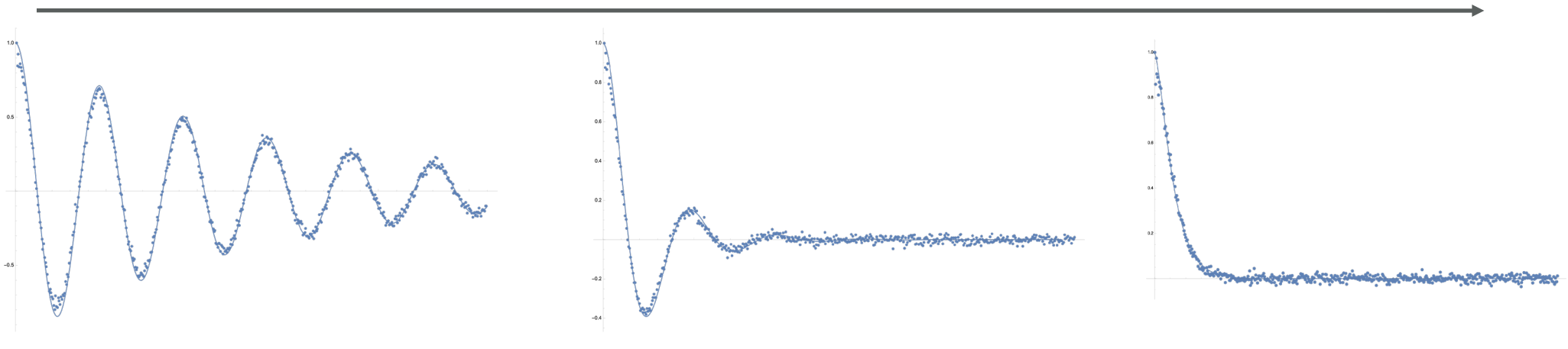
By increasing the paramagnetic salt concentration, one can control the qubit-environment coupling.



Our findings

The reduced ^{13}C dissipative dynamics due to the structured environment (paramagnetic salt + ^{1}H) can be determined analytically, giving $\langle \sigma_x \rangle_t = \xi(t) \langle \sigma_x \rangle_0$

$$\xi(t) = e^{-t/2T_{2,C}} e^{-t/4T_{1,H}} \left[\frac{t}{4T_{1,H}} \operatorname{sinc}\left(\frac{t}{4T_{1,H}} \sqrt{16\pi^2 J^2 T_{1,H}^2 - 1} \right) + \cos\left(\frac{t}{4T_{1,H}} \sqrt{16\pi^2 J^2 T_{1,H}^2 - 1} \right) \right]$$



Our findings

The path length of the state ρ_t can be written as:

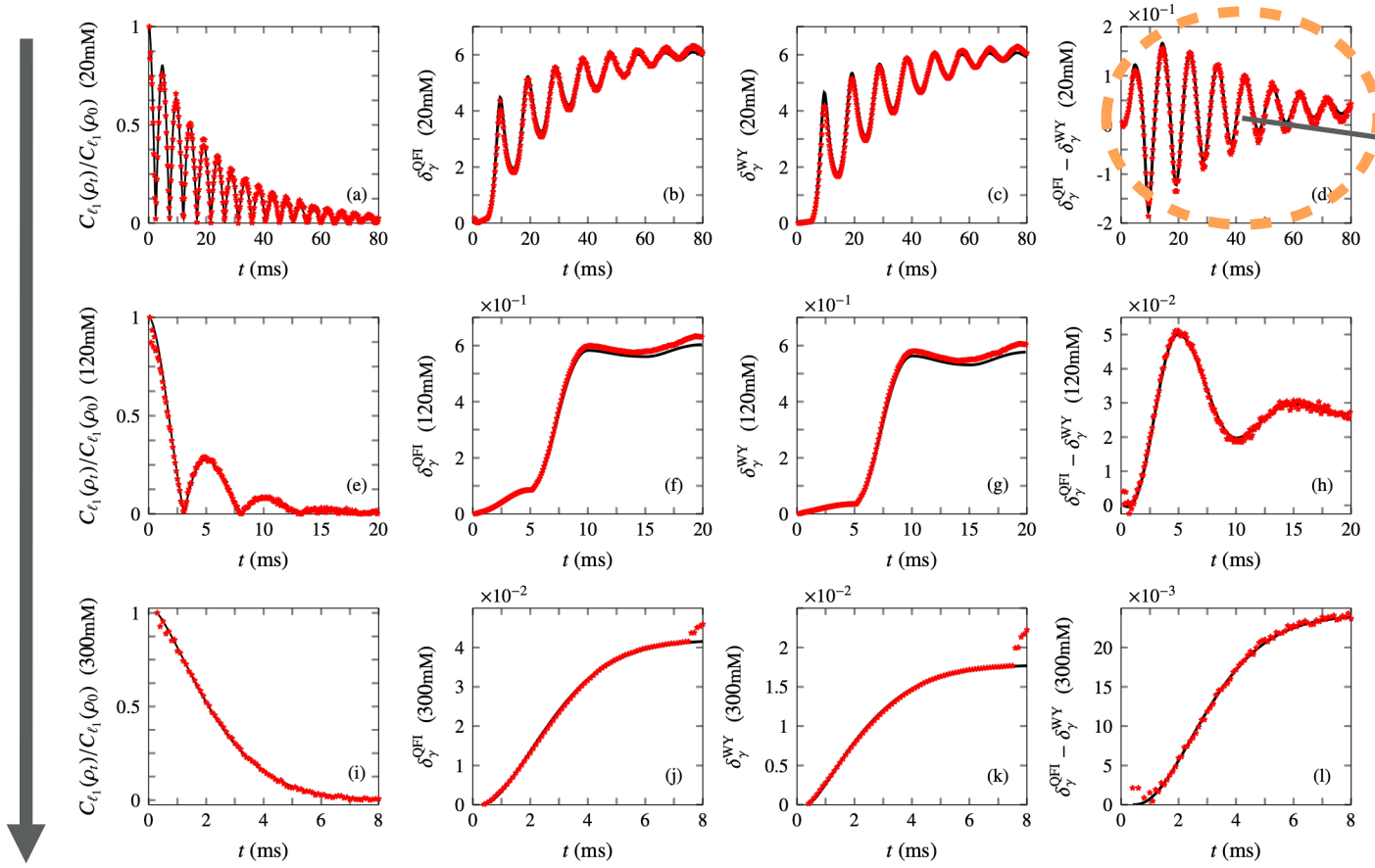
$$\ell_\gamma^f(\rho_0, \rho_\tau) = \frac{1}{2} \int_0^\tau dt \sqrt{h_t^f} \left| \frac{d\langle \sigma_x \rangle_t}{dt} \right| ,$$

$$h_t^{\mathrm{QFI}} := \frac{1 - \langle \sigma_z \rangle_0^2}{1 - \langle \sigma_x \rangle_t^2 - \langle \sigma_z \rangle_0^2}$$

$$h_t^{\mathrm{WY}} := \frac{\langle \sigma_x \rangle_t^2}{\left(\langle \sigma_x \rangle_t^2 + \langle \sigma_z \rangle_0^2 \right) \left(1 - \langle \sigma_x \rangle_t^2 - \langle \sigma_z \rangle_0^2 \right)} + \frac{2 \langle \sigma_z \rangle_0^2 \left(1 - \sqrt{1 - \langle \sigma_x \rangle_t^2 - \langle \sigma_z \rangle_0^2} \right)}{\left(\langle \sigma_x \rangle_t^2 + \langle \sigma_z \rangle_0^2 \right)^2}$$

Our findings

Relative deviations:



Crossovers Between FI and W Y Bounds

$$\delta_\gamma^f := \frac{\ell_\gamma^f(\rho_0,\rho_\tau) - \mathcal{L}^f(\rho_0,\rho_\tau)}{\mathcal{L}^f(\rho_0,\rho_\tau)}$$

Conclusions

As for our physical system, we found that the tightness of the QSL bound was related to the non-dissipative character of the system evolution, showing **crossovers** between the tightness of QFI and WY.

Such results suggest that neither QFI nor WY metrics can be seen as fundamental, even when considering the dynamics of the same open quantum system.

Commun Phys 7, 142 (2024)


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DR. AIMEE GUNTHER

Acting Program Director
Quantum Sensors Challenge Program
National Research Council Canada

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NRC·CNRC

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Quantum Technologies from Canada's National Laboratory

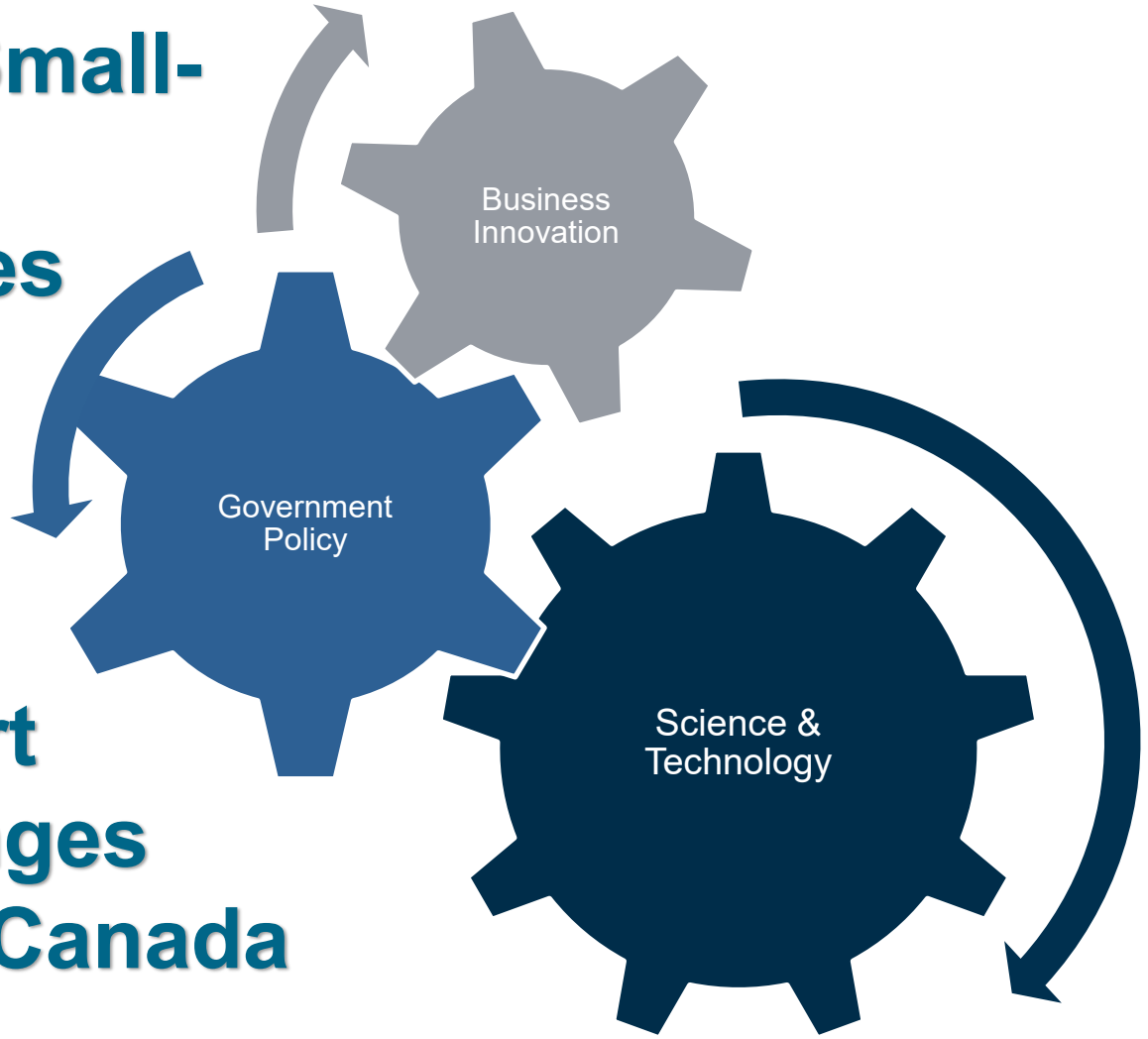
Dr. Aimee K. Gunther

Acting Director, Quantum Sensors Challege Program

Quantum 4 International, June 26, 2024

The National Research Council's Role Within Canada

Support Small-Medium Enterprises



Advance knowledge

Support challenges facing Canada

The Canadian Government has recently released quantum strategies

Federal and departmental quantum policies



National Quantum Strategy



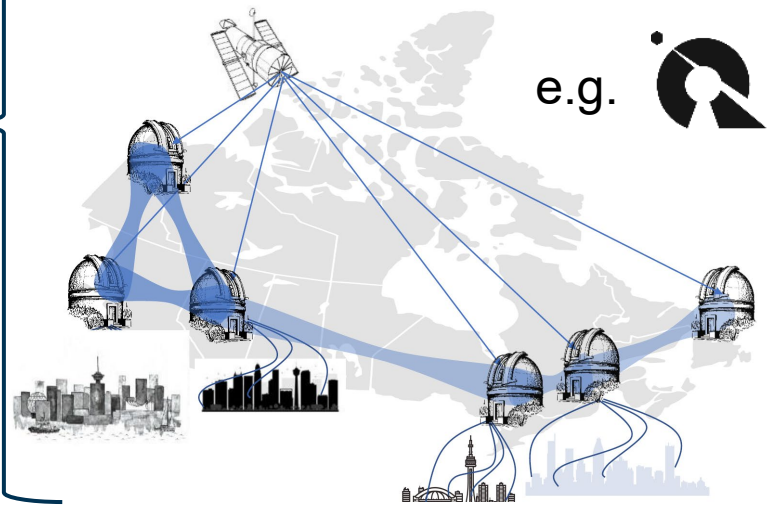
NRC Strategic Plan 2024-2029



DND Quantum Strategy and Implementation Plan

Canada's smallness is a feature

The Canadian quantum ecosystem is well-connected and drawn together via policy



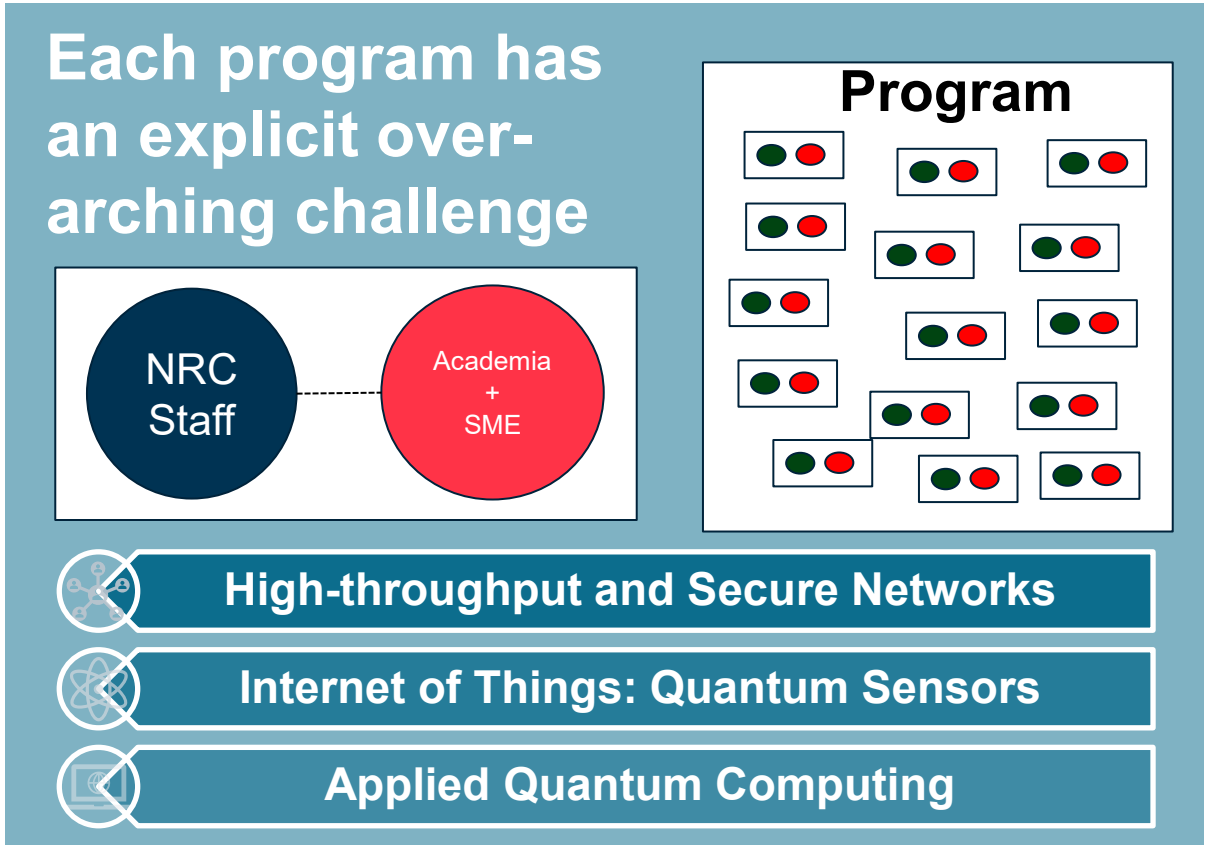
e.g. QEYS Sat

The NRC is a trusted partner in the ecosystem, committed to advancing quantum technologies

NRC Challenge programs: a key tool to work with the quantum ecosystem

NRC Challenge programs are an agile mechanism to enable R&D

- Funding and Collaborating on Quantum R&D
  - NSERC-NRC Joint call-for-proposal: “Advancing the industrial readiness of quantum sensing technologies”



NSERC CRSNG

National Research Council Canada

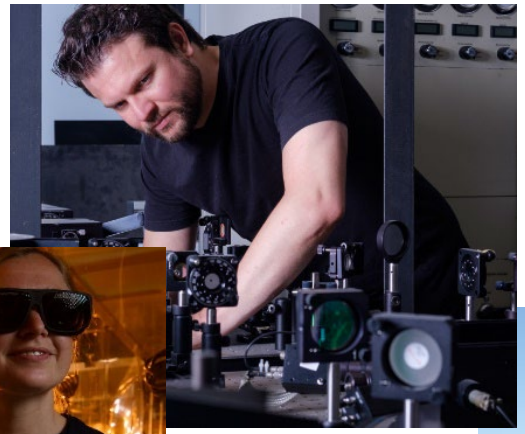
Conseil national de recherches Canada

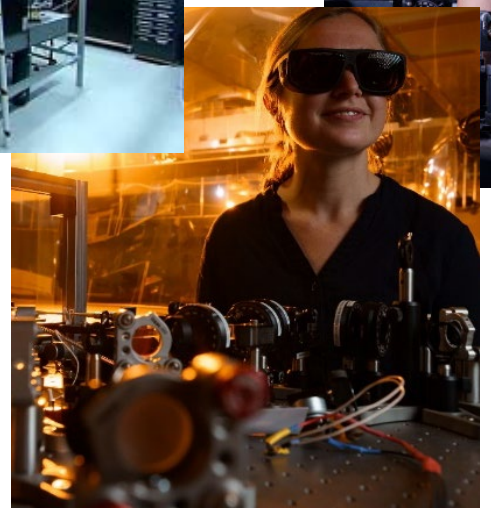
National Research Council of Canada: Conducting Research and Leveraging Innovation Programs

We work across the spectrum to *accelerate* the development of new quantum technologies that may be engineered and commercialized for priority application areas that benefit Canadians













Research & Build

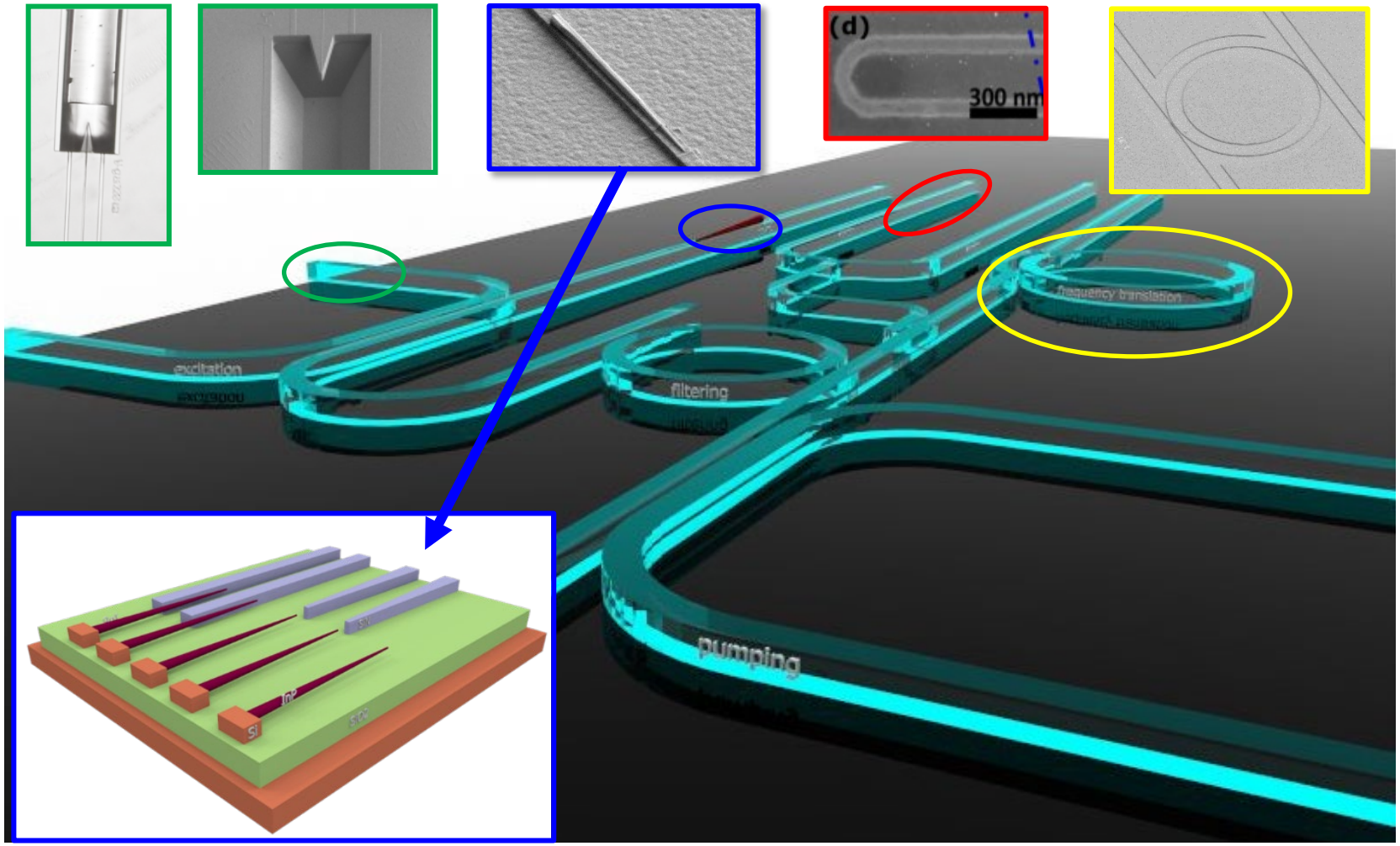
Understand & Improve

Integrate & Apply

Indistinguishable quantum dot photon sources

Over the last 20 years, NRC's researchers have been trailblazing the fabrication of quantum dots in tapered nanowires

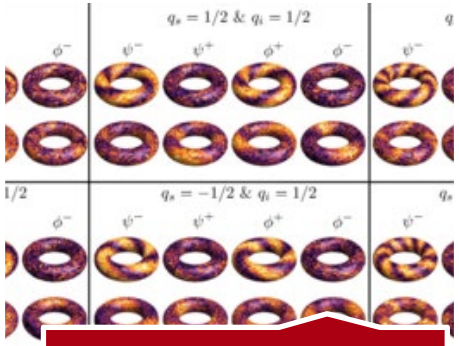
- QPICs: pick and place for on-chip frequency transduction, quantum interference, etc
- Photon rates now enhanced within a cavity



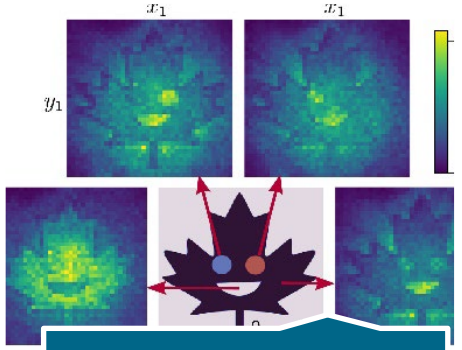
Quantum photonics for quantum technologies

NRC has a long heritage in atomic, molecular, and optical physics

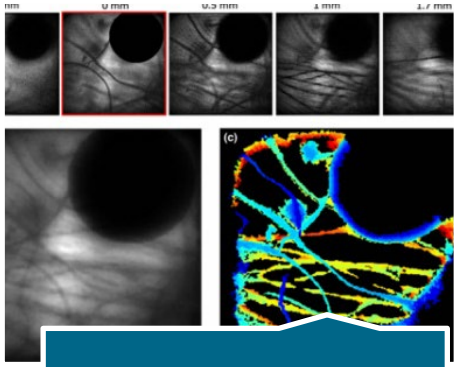
NRC's theorists and experimentalists now push the limits of quantum photonics for **fundamental science**, **quantum sensing**, **quantum computing**, and **quantum networking**



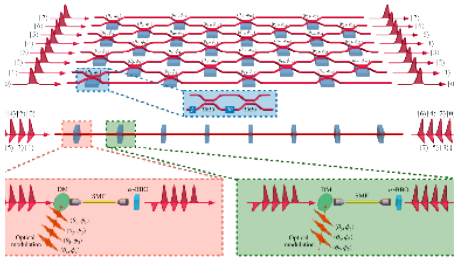
Spatial characterization of entangled photons



Quantum holography for imaging



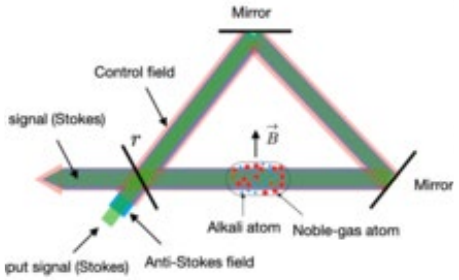
Quantum light-field microscopy



Ultrafast time-bin quantum processor



Fiber cavity quantum memory and frequency translation



Quantum repeater with hot alkali-noble gases

Success in Collaboration

Challenge Programs

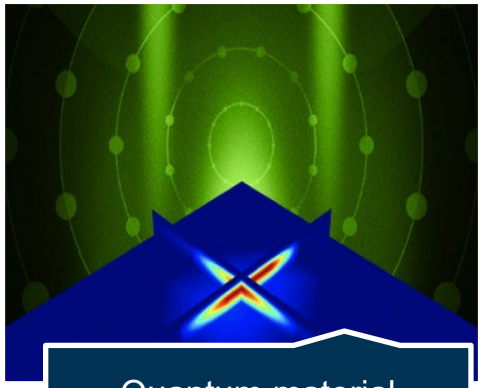
- Enable the Canadian and international quantum ecosystems to access the NRC and enrich the collaborations
- Advance the commercialization on quantum technology



Diamond-based quantum magnetometry

Quantum Bridge

Graph-state quantum sources



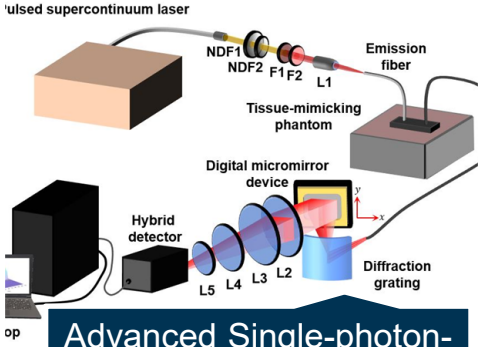
Quantum material simulation software



Quantum photonic measurement standards



Quantum dot coherent control



Advanced Single-photon-counting for reliable neuromonitoring

Exploring new strategies for quantum internetworking

Staying at the leading edge of quantum science by developing quantum internetworking technologies and systems that will revolutionize communications, sensing and computing

There is a need to address aspects of:

Scaling quantum information processors

Quantum devices and networking components work together while preserving the exchange of quantum information. These will form the building blocks for future, more powerful systems.

Accelerating commercialization and adoption of quantum *systems*

Quantum devices are engineered and embedded within existing systems to accelerate their adoption. Testbeds will be available to de-risk the interoperability of quantum components and inform standards.

Transmission of quantum information over long distances

Quantum information is preserved as quantum devices communicate with one another at a distance over existing telecom infrastructure to connect regional networks across Canada.

A New Quantum Challenge Program

Quantum InterNetworking

Objective: Connecting heterogeneous quantum devices at a distance.

Rationale

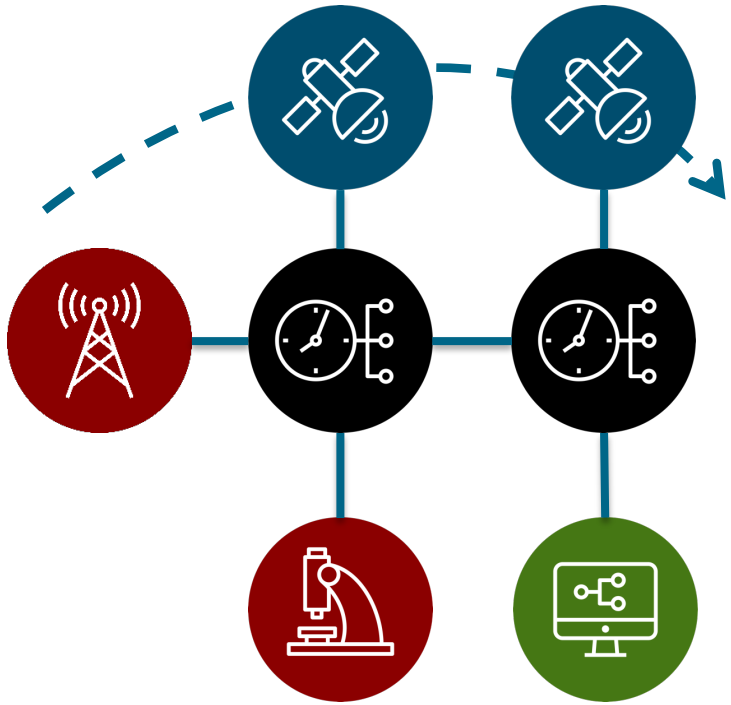
Leverage NRC's partnerships within the Canadian quantum ecosystem to drive an end-to-end, highly-integrated program of collaborative projects to build towards a common quantum networking land- and space-based demonstration goal.

Expected impacts

Incorporate the outcomes of the current tranche of National Quantum Strategy funding to engineer the next generation of quantum information processing.

Overlaps with:

- Continental Defence quantum R&D focus (DRDC's Quantum Implementation Plan) ($7.5M in Ops over 5 years for quantum networking?)
- National Quantum Strategy Quantum Communication Mission
- Defence Innovation Accelerator for the North Atlantic (DIANA) Secure Information Sharing and Quantum theme



Interconnecting:

Different quantum devices	Over Distance

NRC Mechanisms for Collaboration and Innovation

Challenge Programs

Grants and contributions to bring together academia, industry and government to attain critical mass to deliver technological breakthroughs

Collaboration Centres

Co-location of NRC researchers and infrastructure with academia to foster joint research and training opportunities for young scientists

Technical Services

Providing services and access to facilities to support business innovation. Include testing, prototyping, demonstrations, calibration and more

International Joint Projects

Collaboration to advance R&D, train new talent, leverage investments and facilitate knowledge exchange

Quantum at Canada's National Lab: Moving forward!

THANK YOU

Aimee Gunther • Aimee.Gunther@nrc-cnrc.gc.ca


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Quantum Optics Researcher

Quantum Interfaces Group

University of Innsbruck

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Entanglement of trapped-ion qubits separated by 230 m

Maria Galli

Quantum for International Workshop

universität innsbruck

June 26, 2024

Rome, NY

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Our basecamp: Innsbruck, Austria



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Implementing quantum technologies with diverse quantum platforms

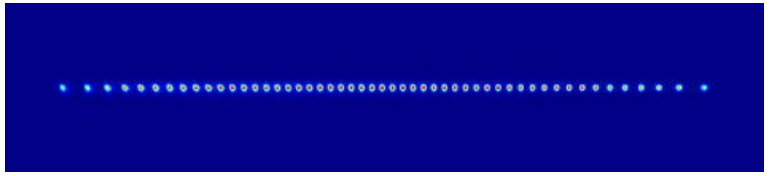
Quantum computation



IBM

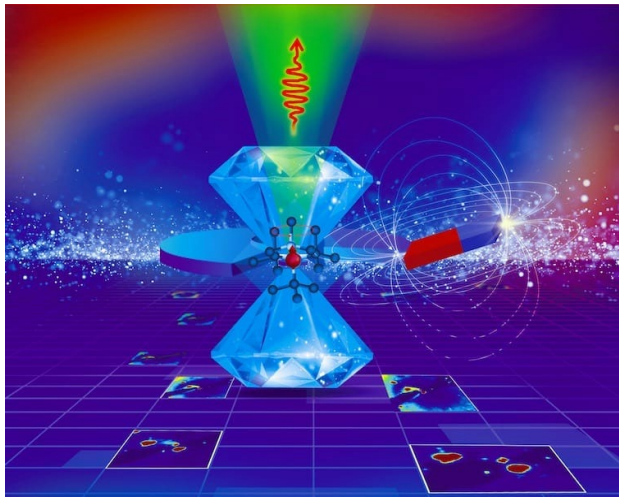
Superconducting qubits

Trapped ions



Quantum sensing

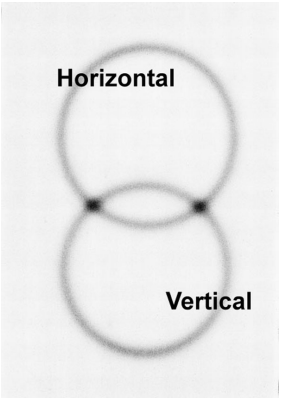
Nitrogen-vacancy (NV) centers



physicsworld

Quantum communication

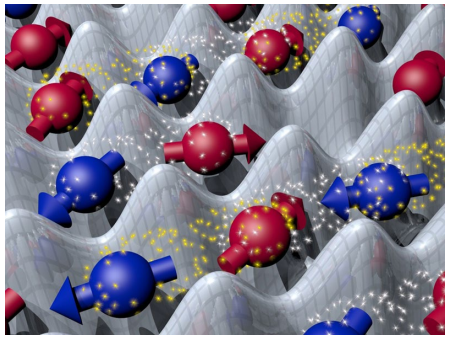
Photons



D. Bouwmeester et al., Nature **390**, 575 (1997)

Quantum simulation

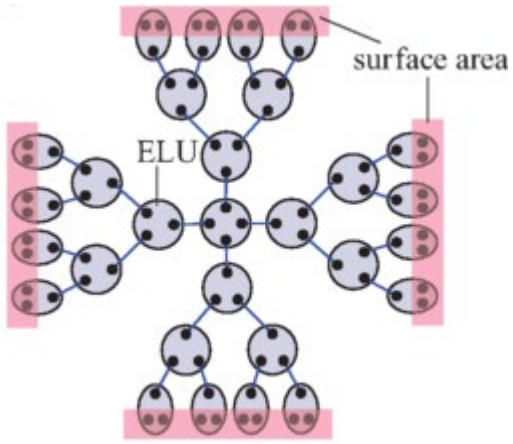
Neutral atoms



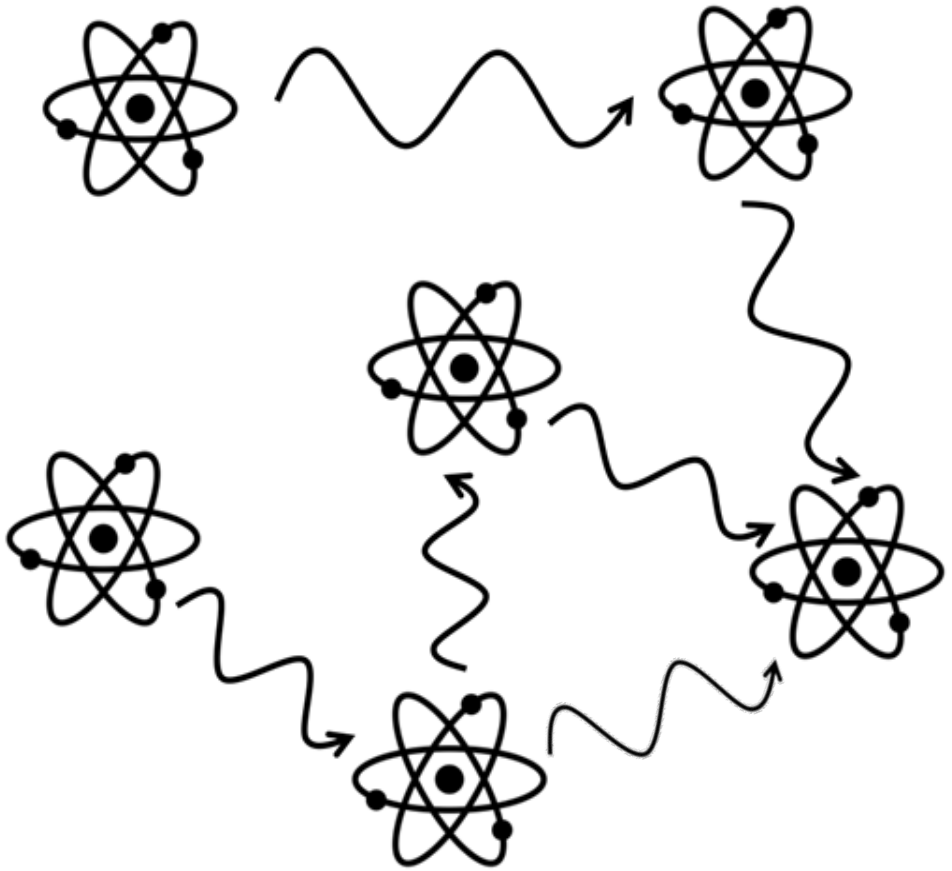
ETH

Quantum networks to enhance quantum technologies

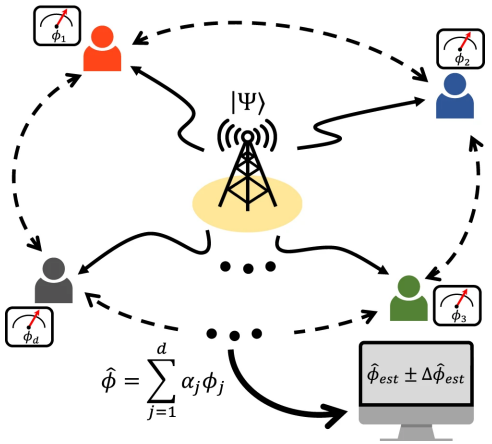
Quantum computation



C. Monroe et al., Phys. Rev. A **89**, 022317 (2014)

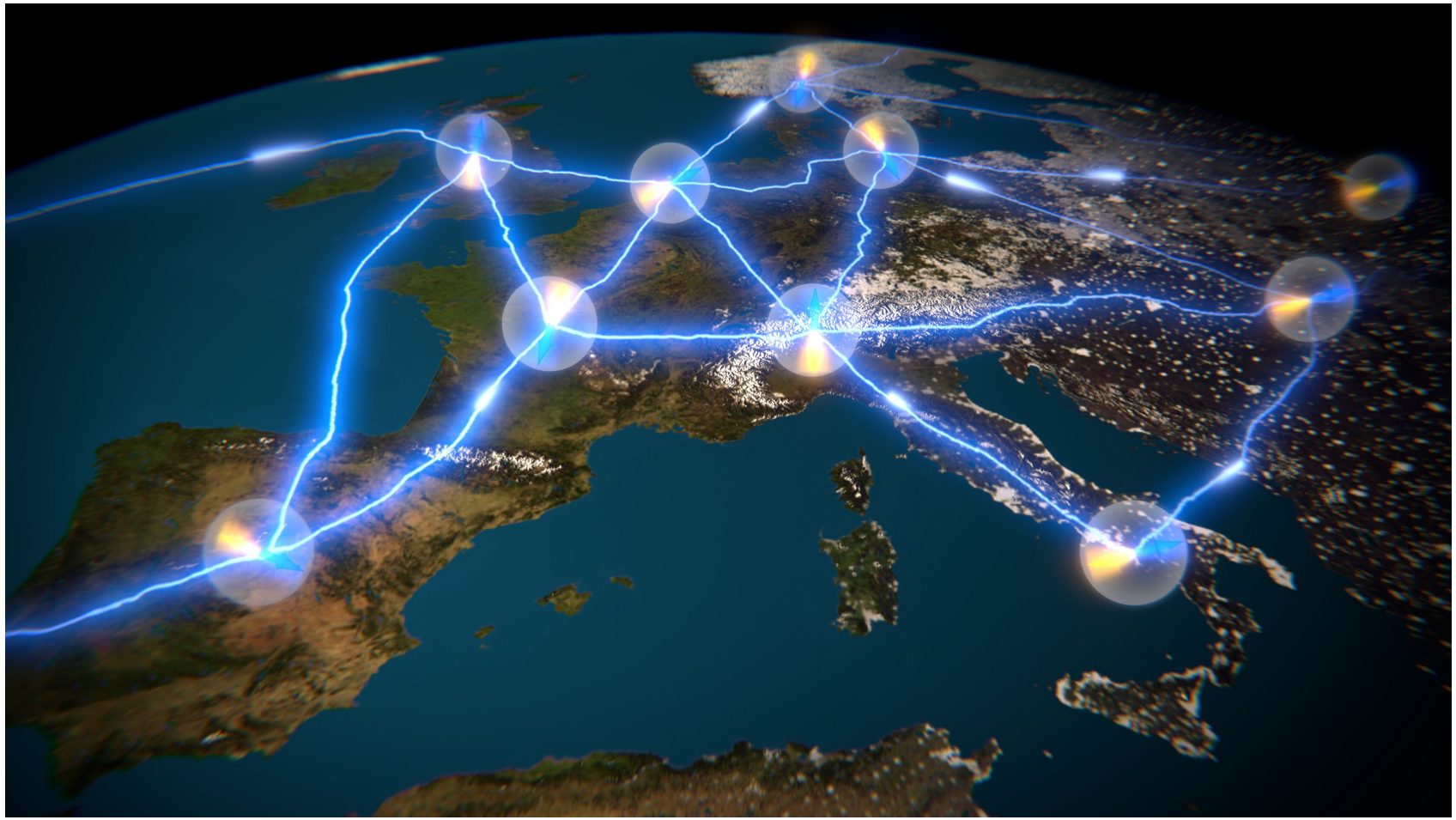


Quantum sensing



D.-H. Kim et al., Nature Comm. **15**, 266 (2024)

Our vision in Europe: a quantum internet

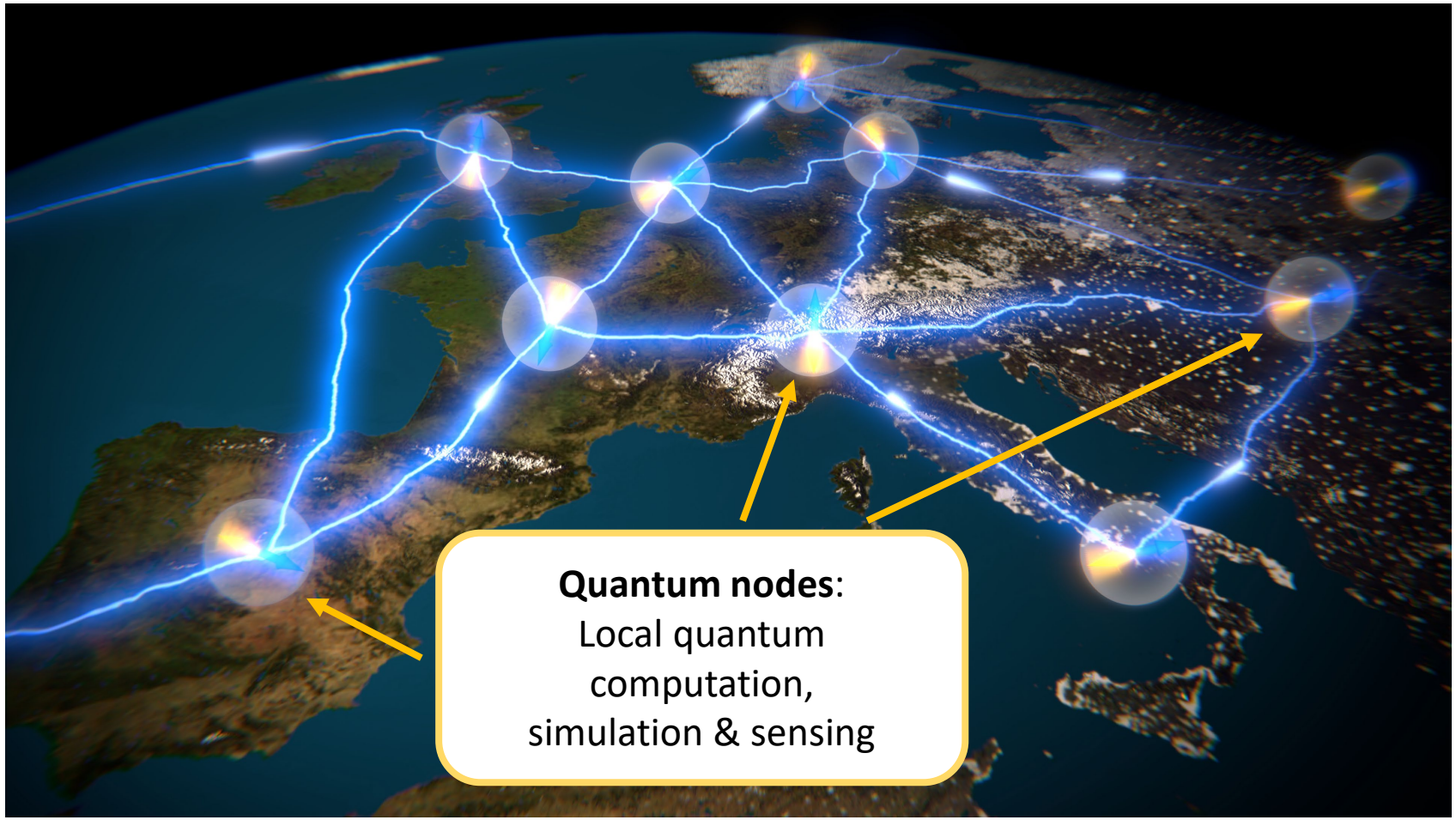


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QUANTUM FLAGSHIP

2018-2028

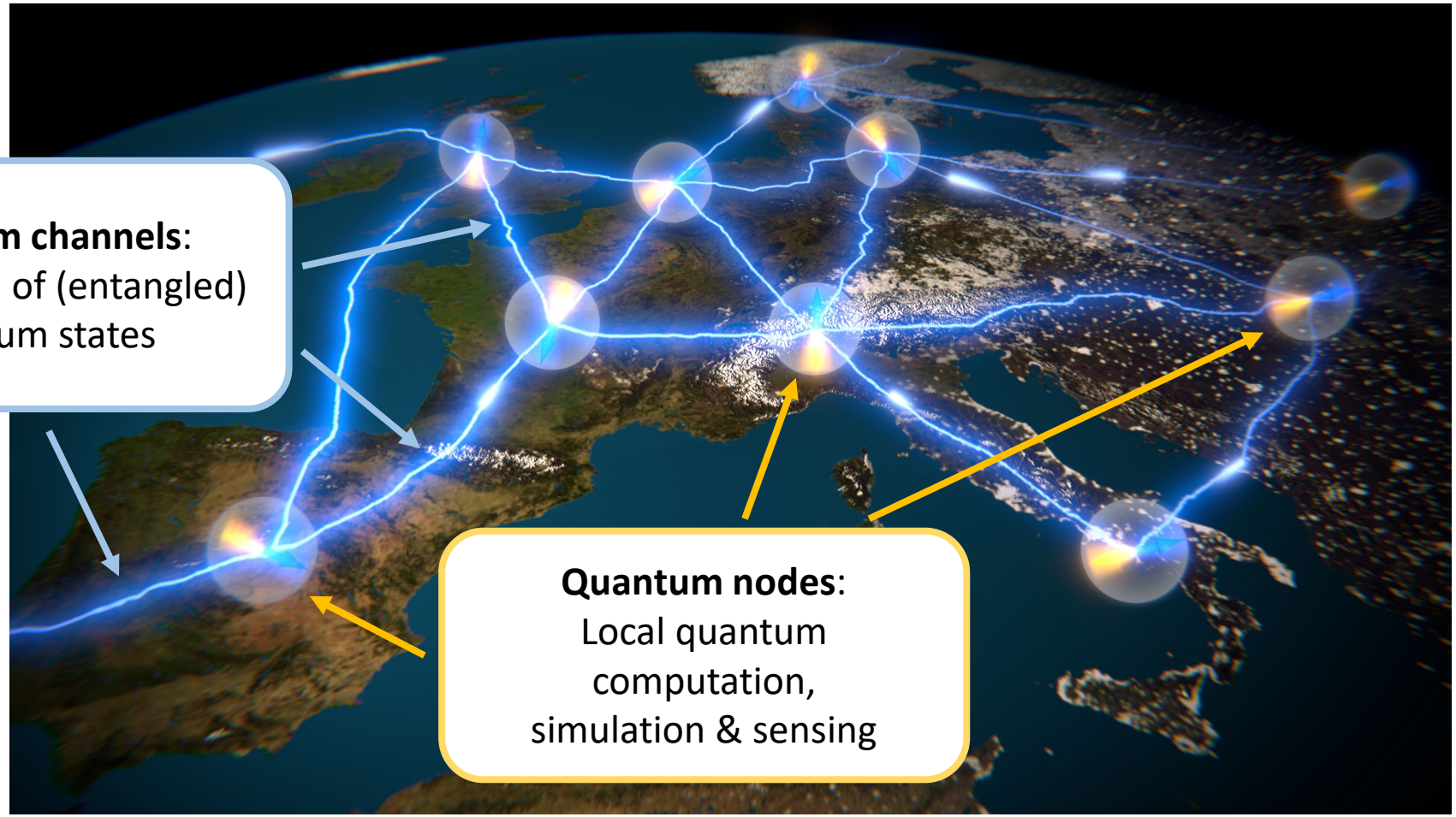
Our vision in Europe: a quantum internet



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Our vision in Europe: a quantum internet



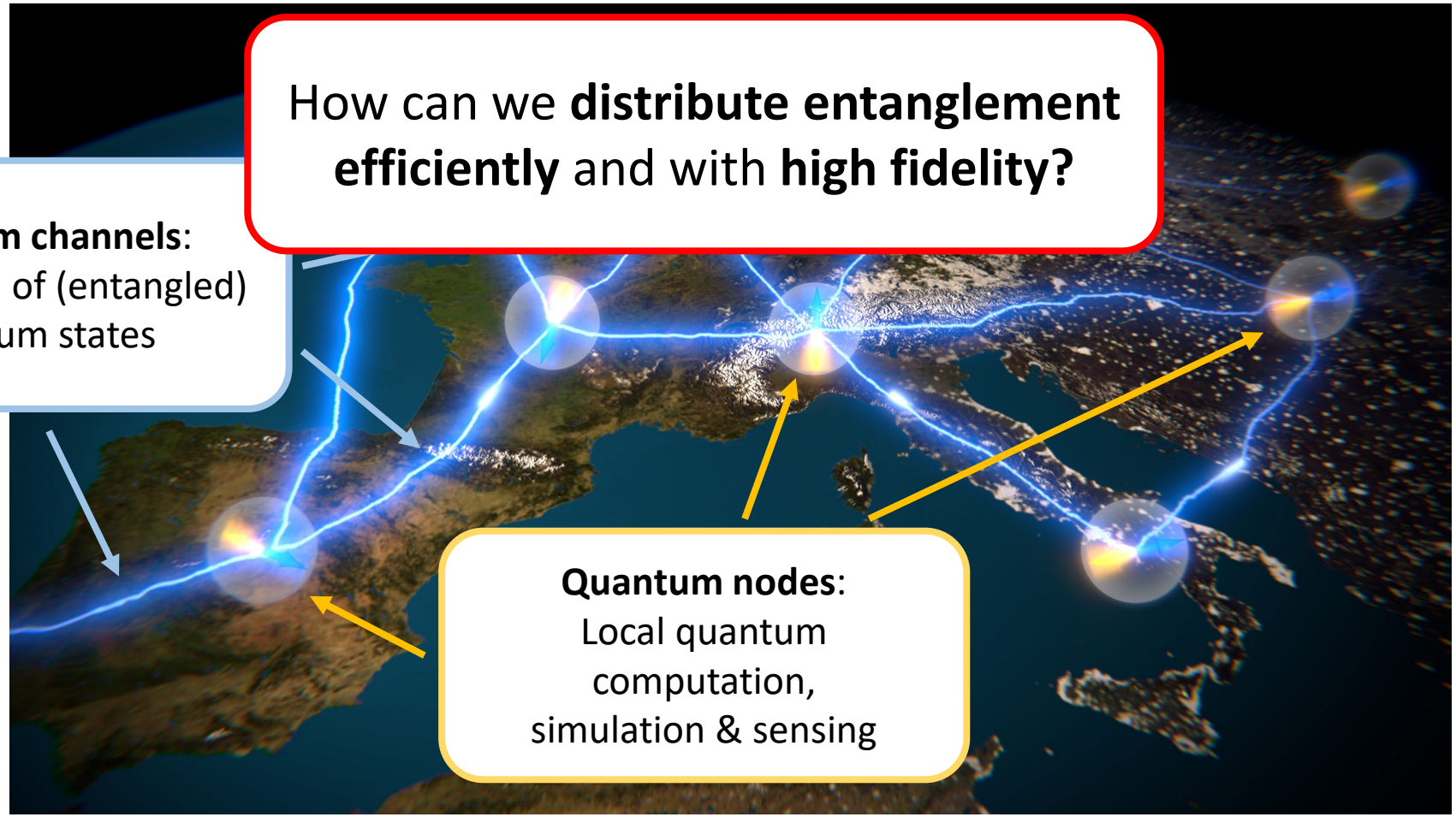
Quantum channels:
Distribution of (entangled) quantum states

Quantum nodes:
Local quantum computation, simulation & sensing

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2018-2028

Our vision in Europe: a quantum internet



How can we **distribute entanglement efficiently** and with **high fidelity?**

Quantum channels: Distribution of (entangled) quantum states

Quantum nodes: Local quantum computation, simulation & sensing

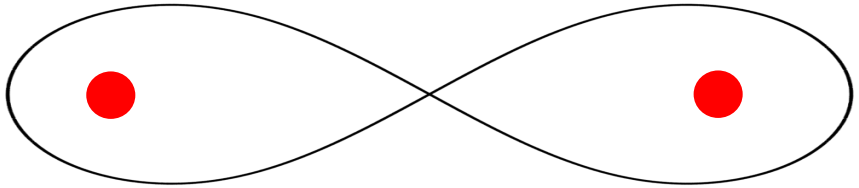
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2018-2028

Entanglement of remote qubits

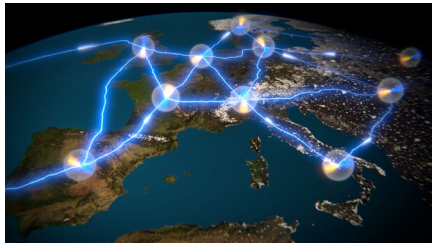
1. How to entangle remote qubits?

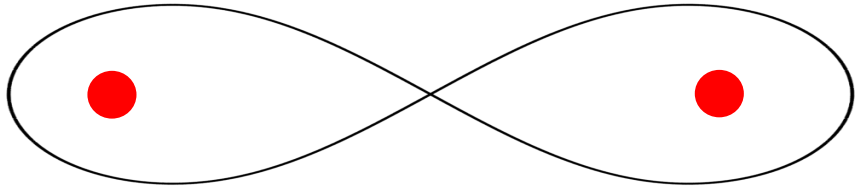


2. Our realization of remote-ion entanglement



3. Future experiments
   based on remote-ion entanglement





1. How to entangle remote qubits?

The entanglement swapping protocol

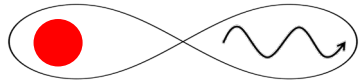
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Encoding quantum information

- Stationary qubit



Spin-polarization entanglement

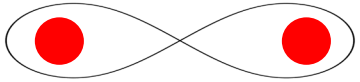


$$|\psi\rangle = |\uparrow H\rangle + |\downarrow V\rangle$$

- Flying qubit (photon)



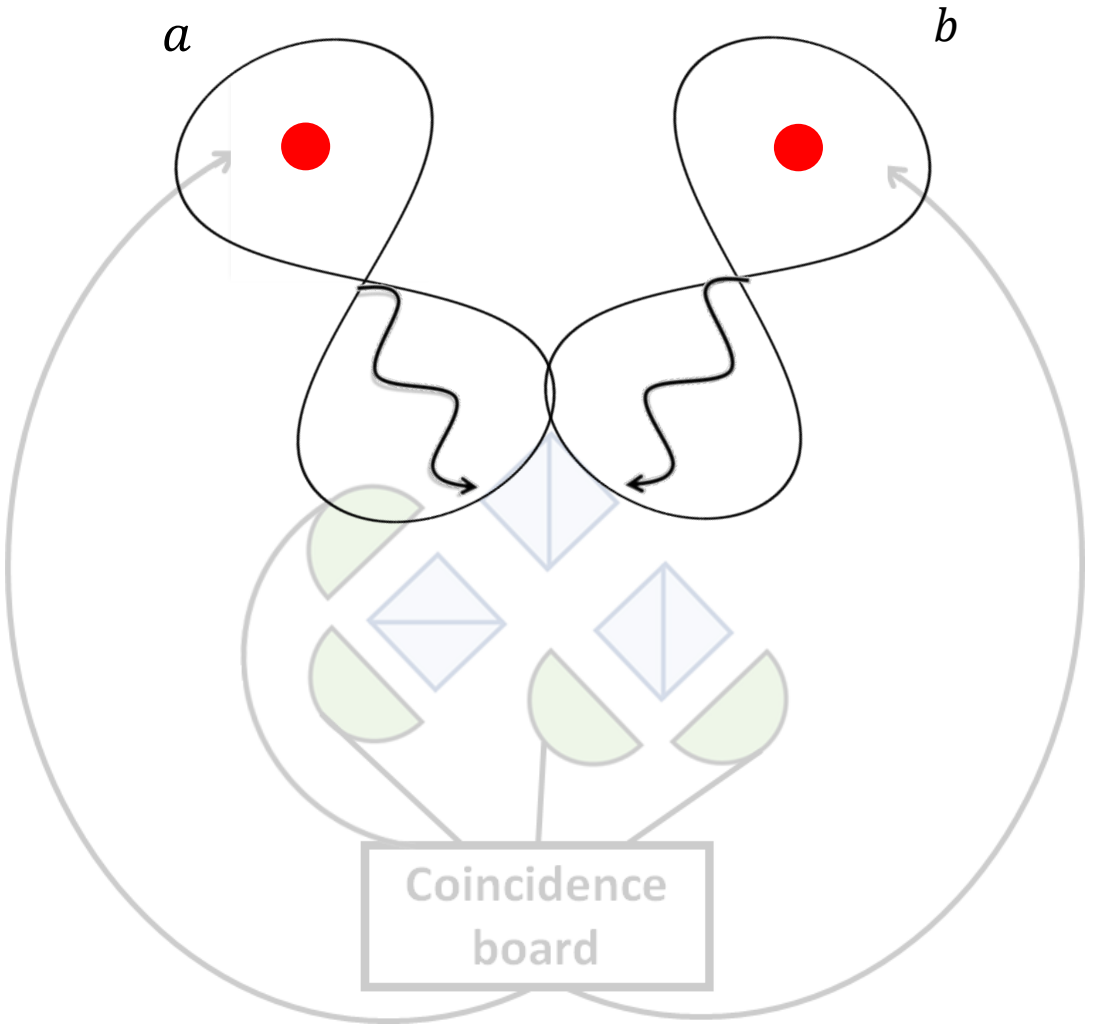
Spin-spin entanglement



$$|\psi\rangle = |\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle$$

How to entangle remote qubits?

1. Generation of **spin-polarization entanglement** pairs
2. Interference of spin-entangled photons
3. Photon detection

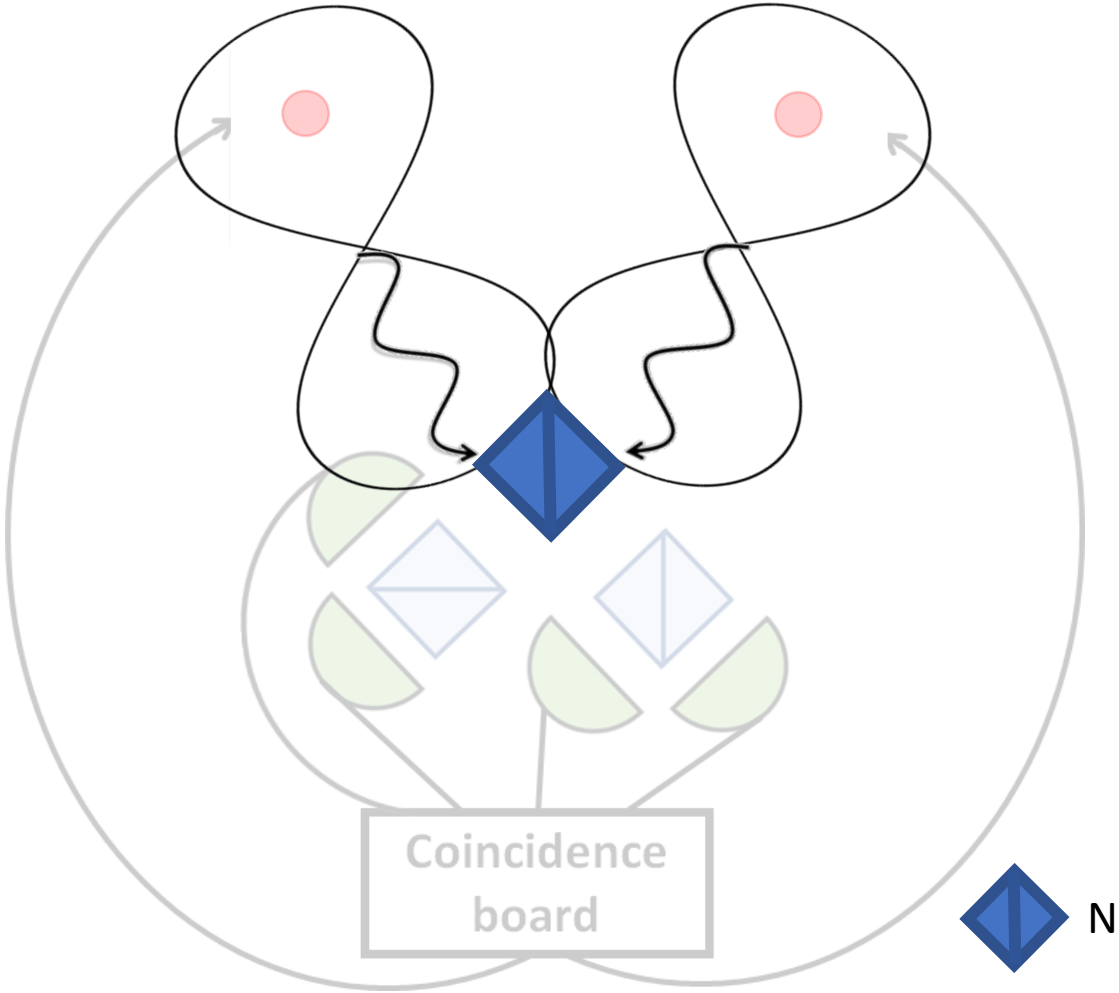


$$|\psi\rangle_{ab} = \left(|\uparrow \mathrm{H}\rangle_a + |\downarrow \mathrm{V}\rangle_a\right) \otimes \left(|\uparrow \mathrm{H}\rangle_b + |\mathrm{V} \downarrow\rangle_b\right)$$

How to entangle remote qubits?

1. Generation of spin-polarization entanglement pairs
2. **Interference** of spin-entangled **photons**
3. Photon detection

$$|\psi\rangle_{ab} = |H_a H_b \uparrow_a \uparrow_b\rangle + |H_a V_b \uparrow_a \downarrow_b\rangle + |V_a H_b \downarrow_a \uparrow_b\rangle + |V_a V_b \downarrow_a \downarrow_b\rangle$$

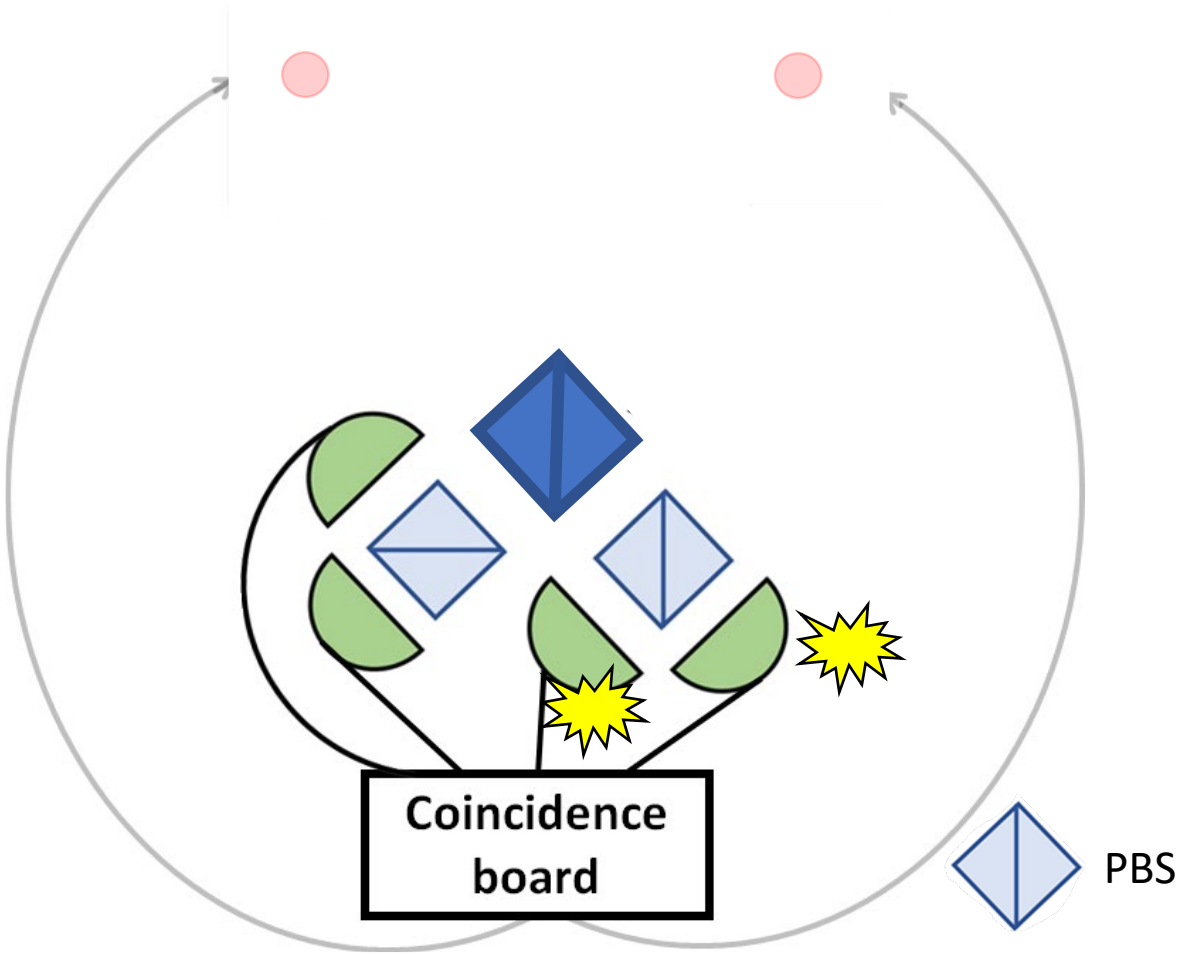


How to entangle remote qubits?

1. Generation of spin-polarization entanglement pairs
2. Interference of spin-entangled photons
3. **Photon detection**

$$|\psi\rangle_{ab} = \cancel{|H_a H_b \uparrow_a \uparrow_b\rangle} + |H_a V_b \uparrow_a \downarrow_b\rangle$$
$$+|V_a H_b \downarrow_a \uparrow_b\rangle + \cancel{|V_a V_b \downarrow_a \downarrow_b\rangle}$$

$$|\psi\rangle_{ab} = |\uparrow_a \downarrow_b\rangle + |\downarrow_a \uparrow_b\rangle$$



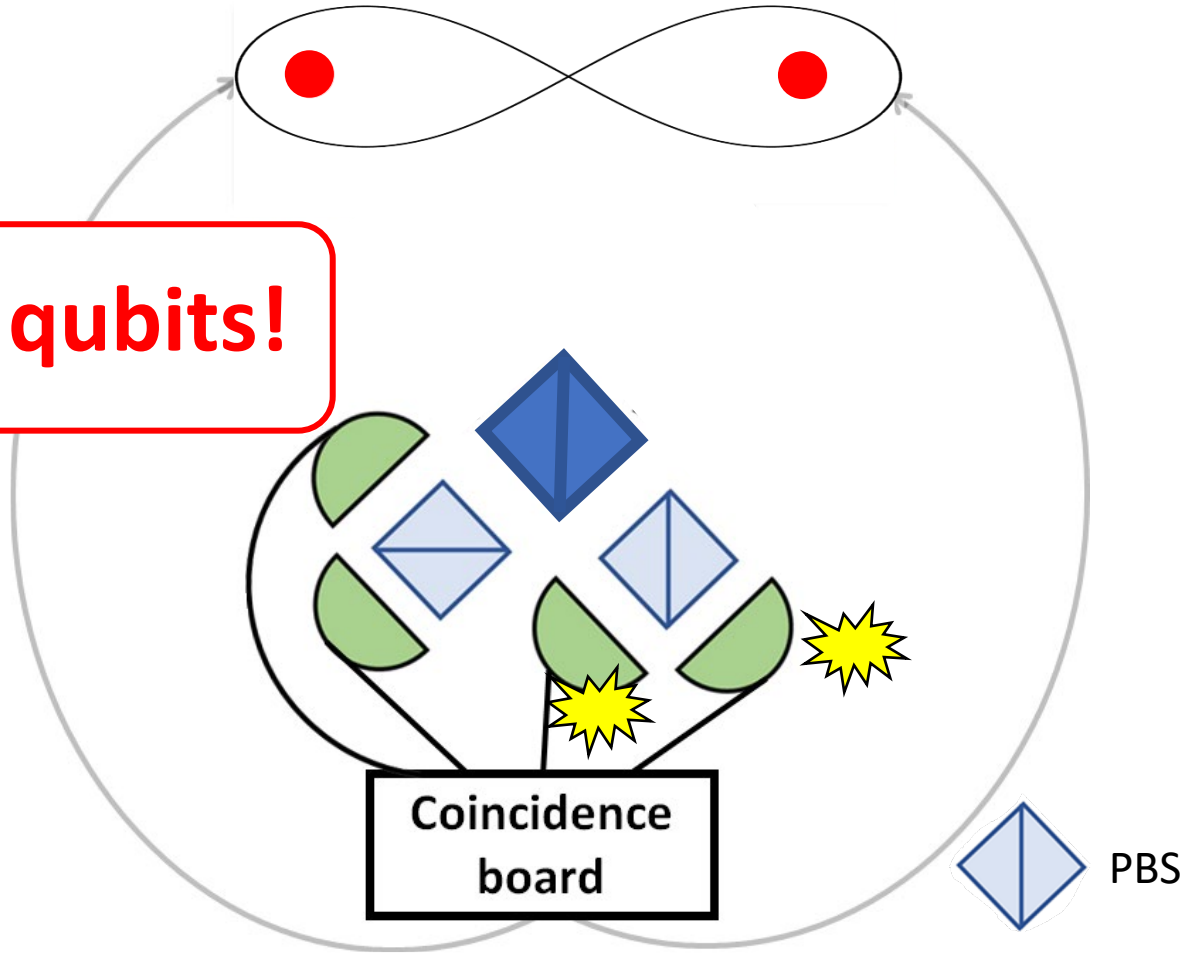
How to entangle remote qubits?

1. Generation of spin-polarization entanglement pairs
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Entangled qubits!

$$|\psi\rangle_{ab} = \cancel{|H_a H_b \uparrow_a \uparrow_b\rangle} + |H_a V_b \uparrow_a \downarrow_b\rangle + |V_a H_b \downarrow_a \uparrow_b\rangle + \cancel{|V_a V_b \downarrow_a \downarrow_b\rangle}$$

$$|\psi\rangle_{ab} = |\uparrow_a \downarrow_b\rangle + |\downarrow_a \uparrow_b\rangle$$



State-of-the-art remote entanglement

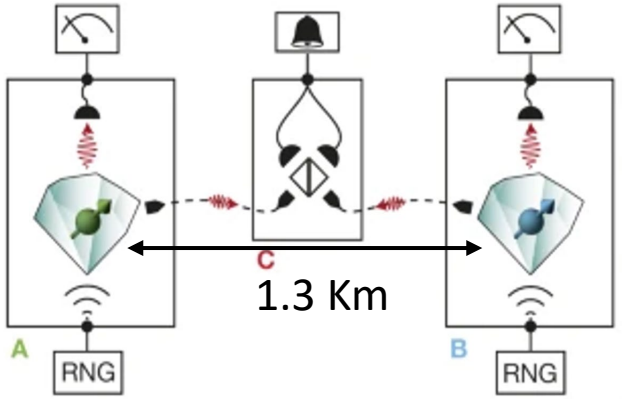
Platforms for quantum information processing:

- Ions
- NV centers
- Neutral atoms
- Quantum dots
- Superconducting qubits

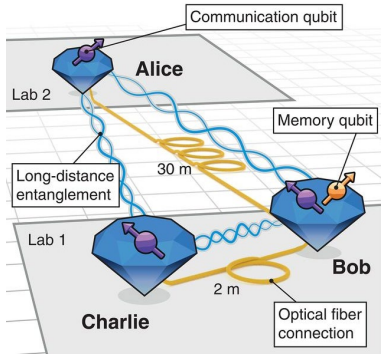
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B. Hensen et al., Nature **526,** 682-686 (2015)

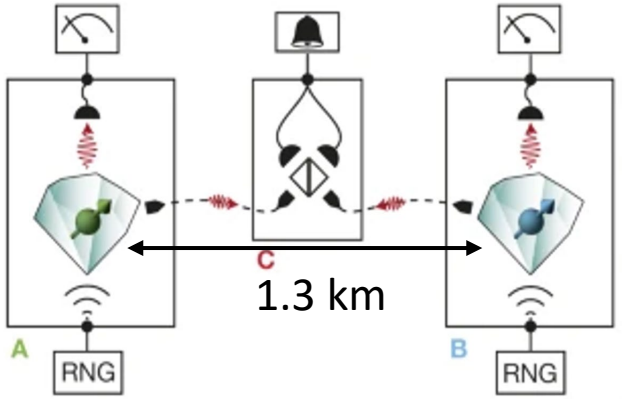


M. Pompili et al., Science **372,** 259–264 (2021)

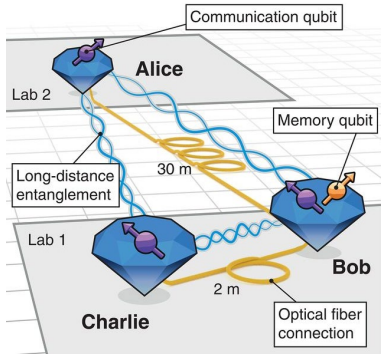
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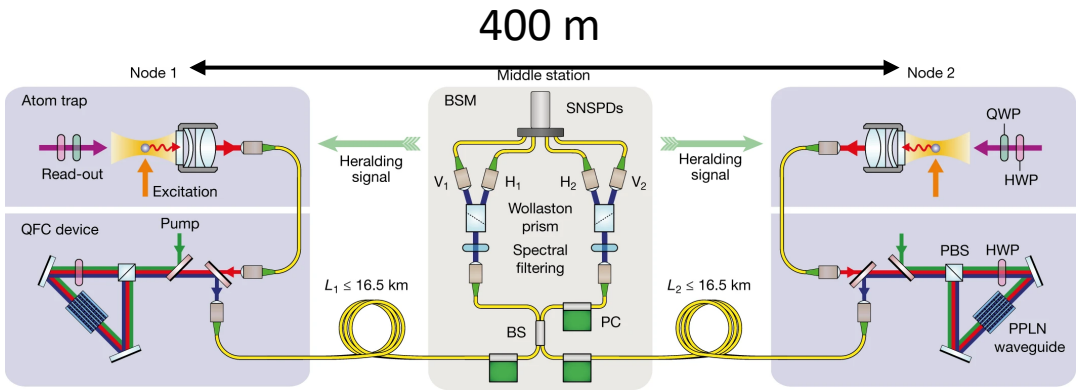
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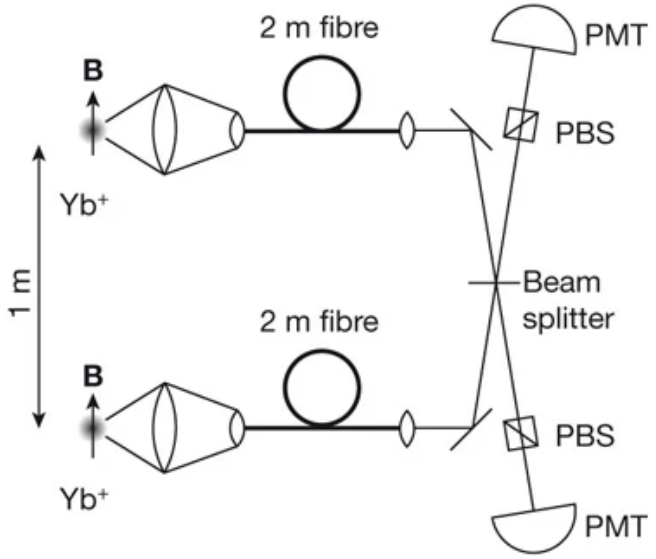


T. Van Leent et al., Nature **607,** 69–73 (2022)

33 km

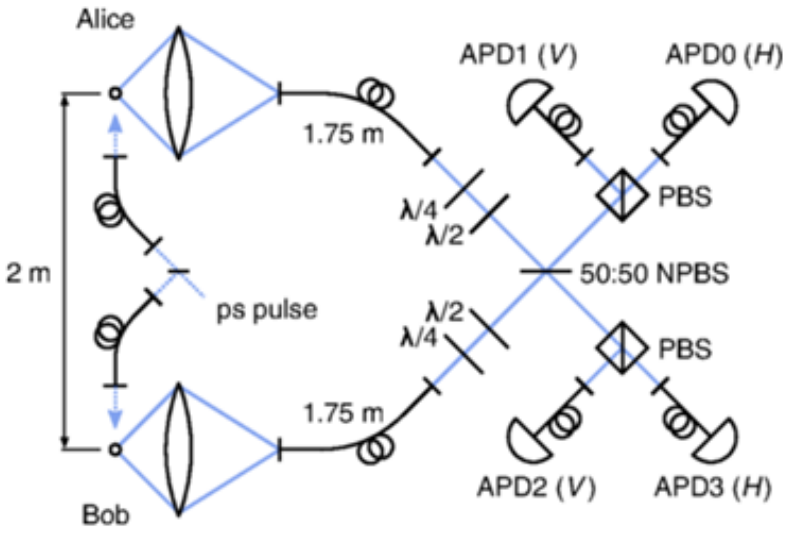
State-of-the-art remote-ion entanglement

Monroe's group @University of Michigan

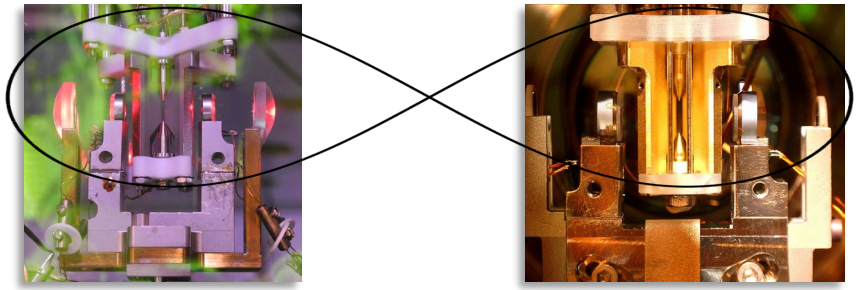


D. L. Moehring et al., Nature **449**, 68–71(2007)

Lucas's group @University of Oxford



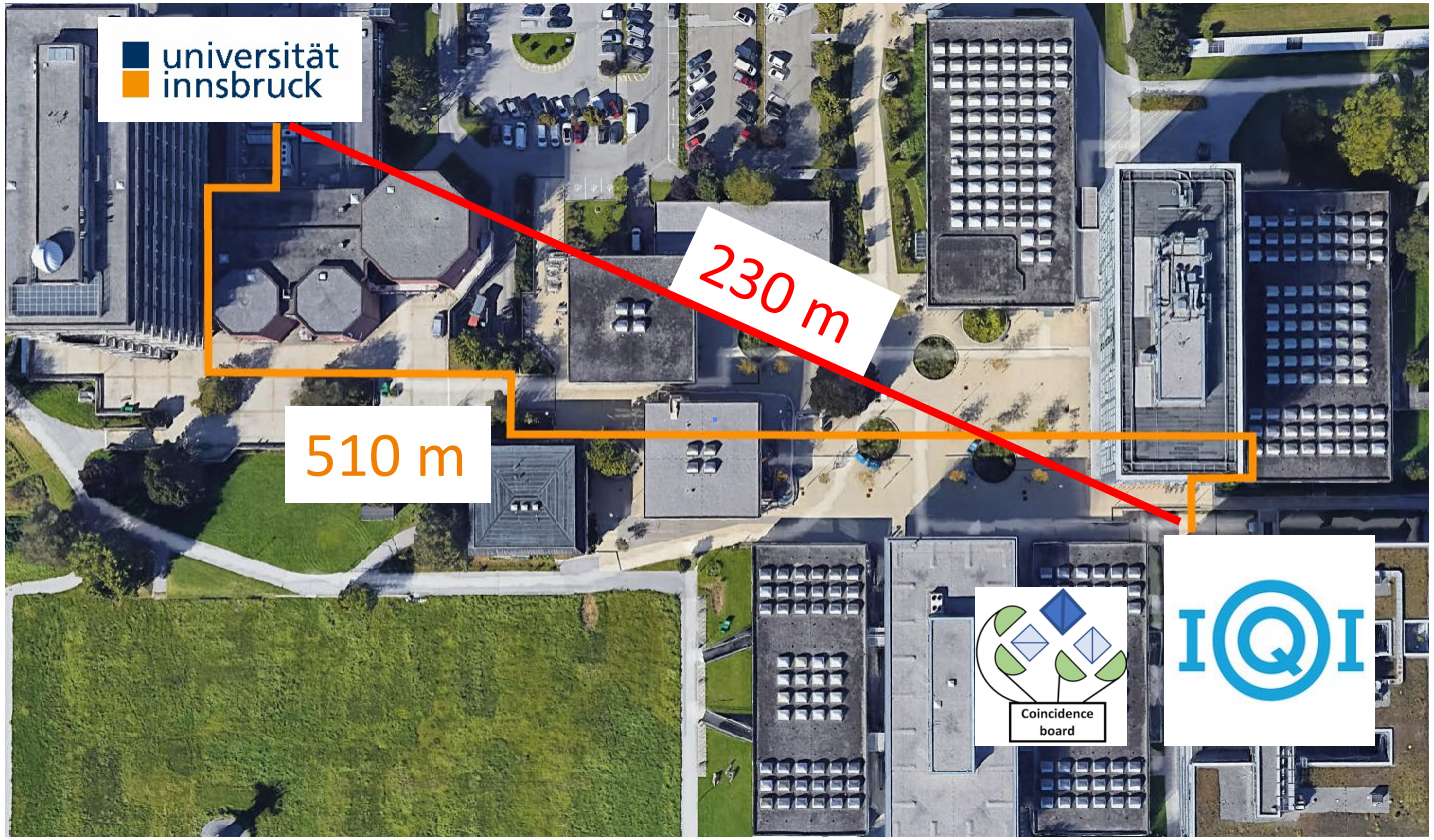
L. J. Stephenson et al., PRL **124**, 110501 (2020)



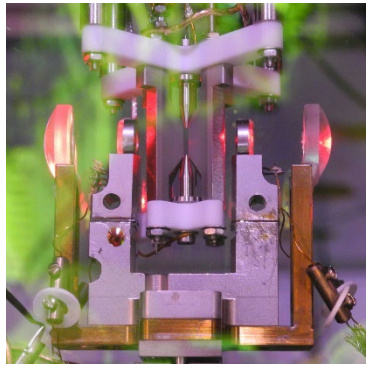
2. Our realization of remote entanglement

A realization based on trapped-ions coupled to cavities

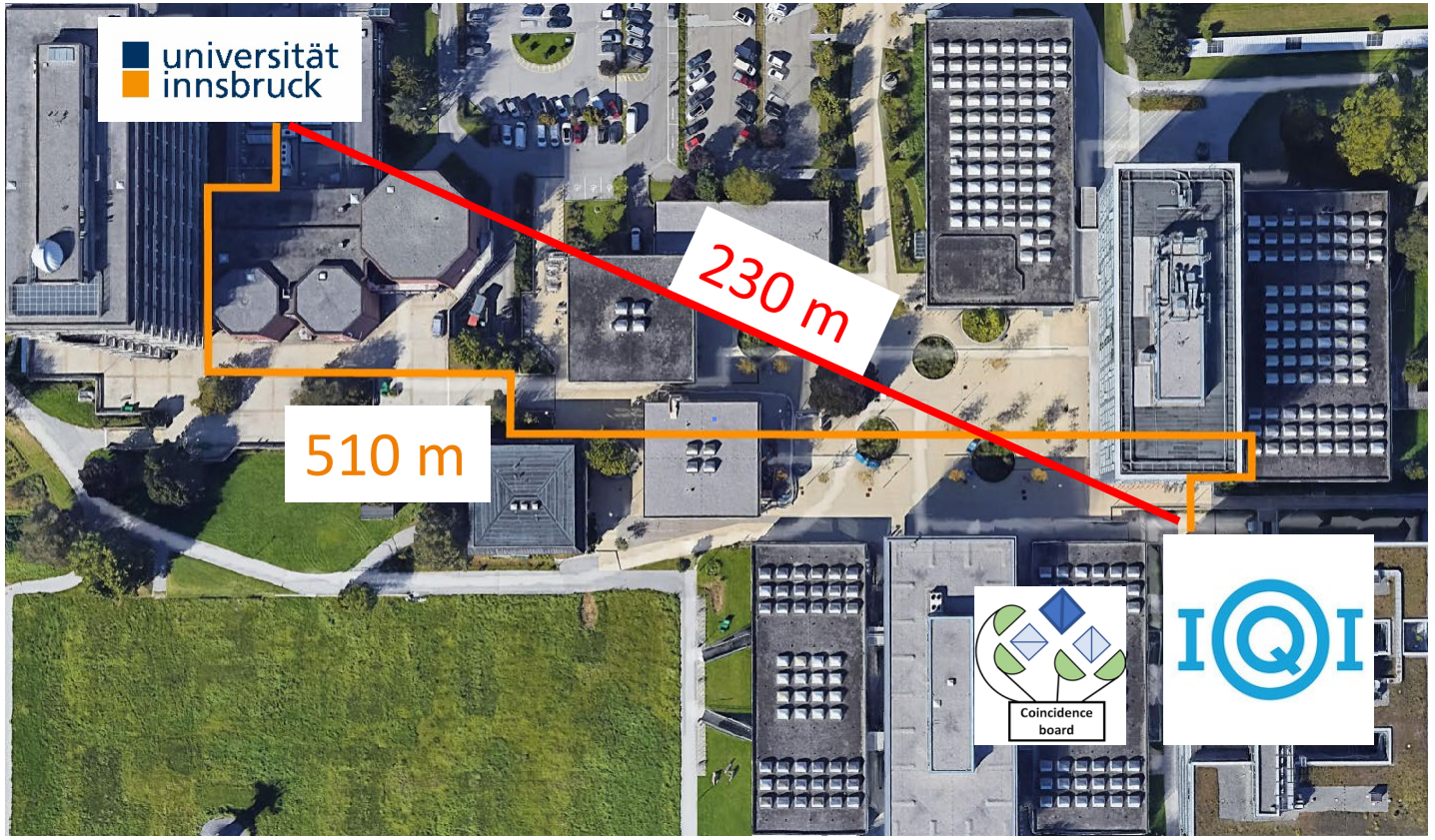
Our quantum network in Innsbruck



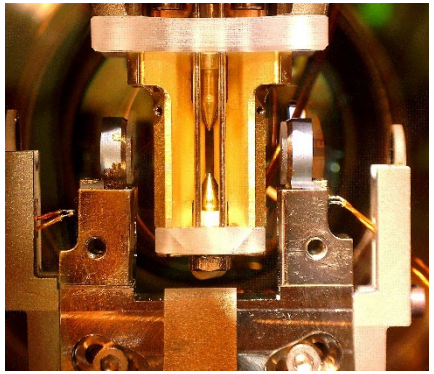
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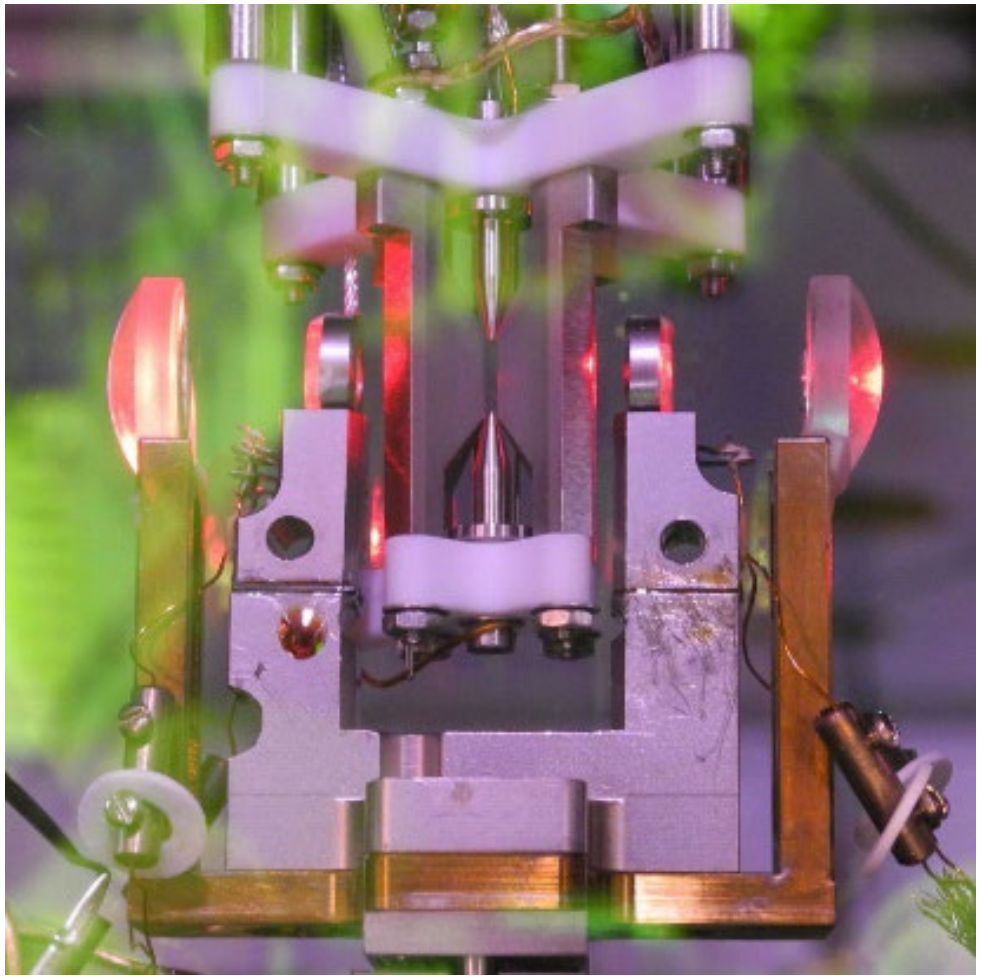
Tracy Northup's group



Ben Lanyon's group

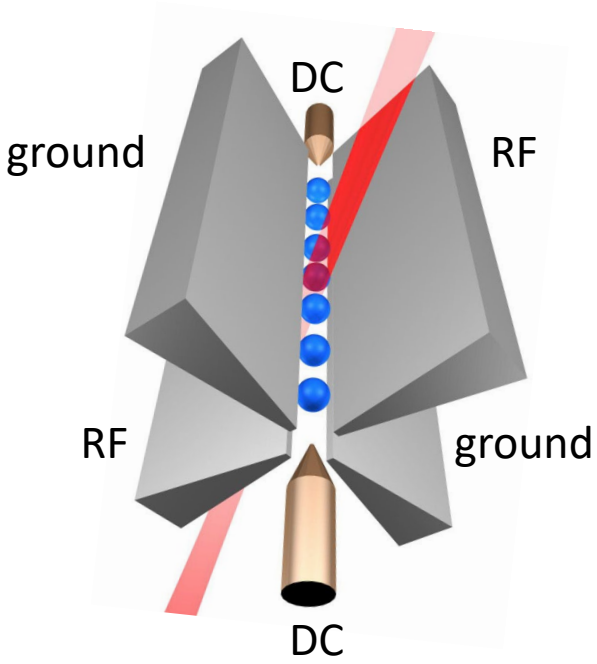


Quantum network node: an ion-cavity system

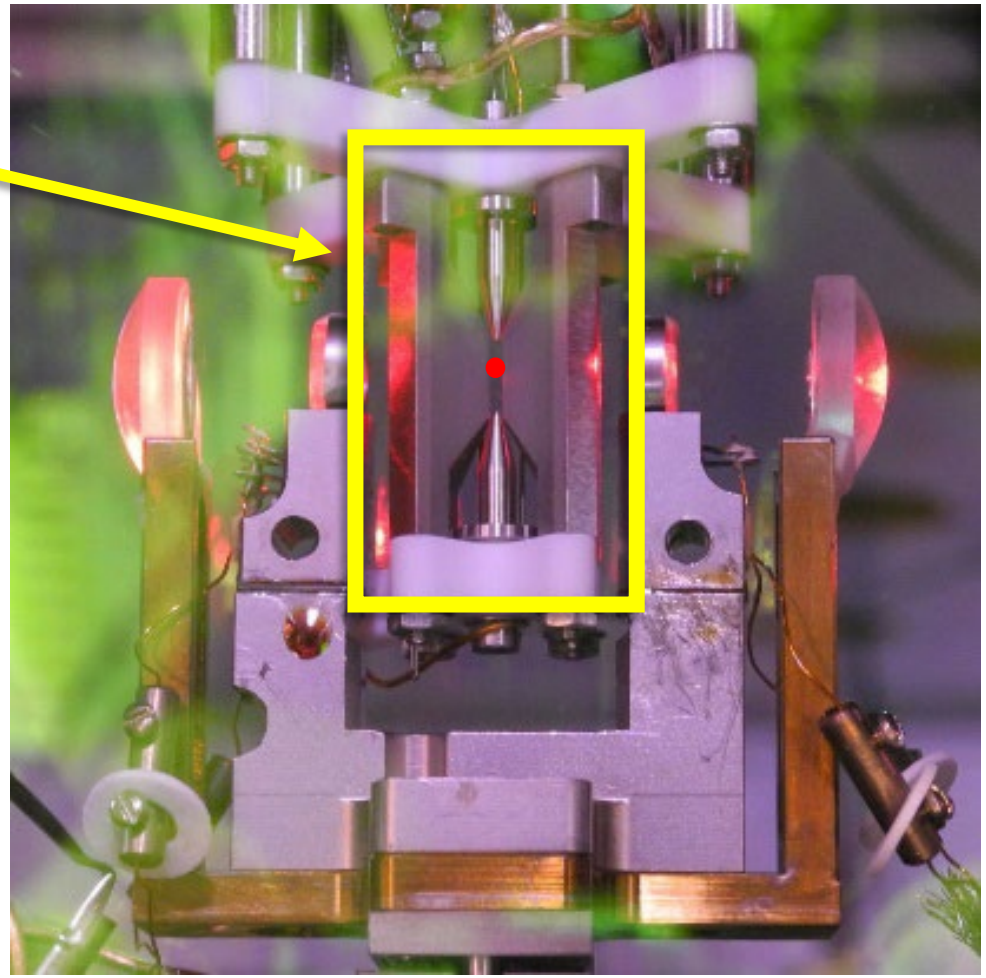


Quantum network node: an ion-cavity system

Ion trap

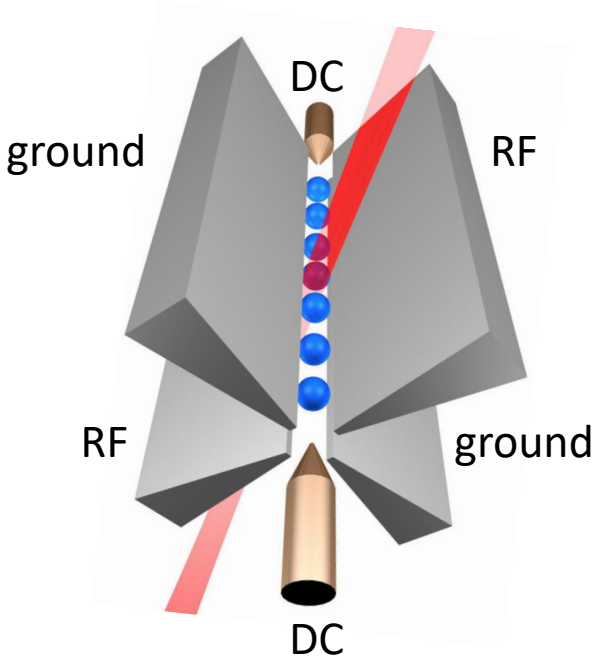


A.M. Eltony. et al., Quantum Inf Process 15, 5351–5383 (2016)

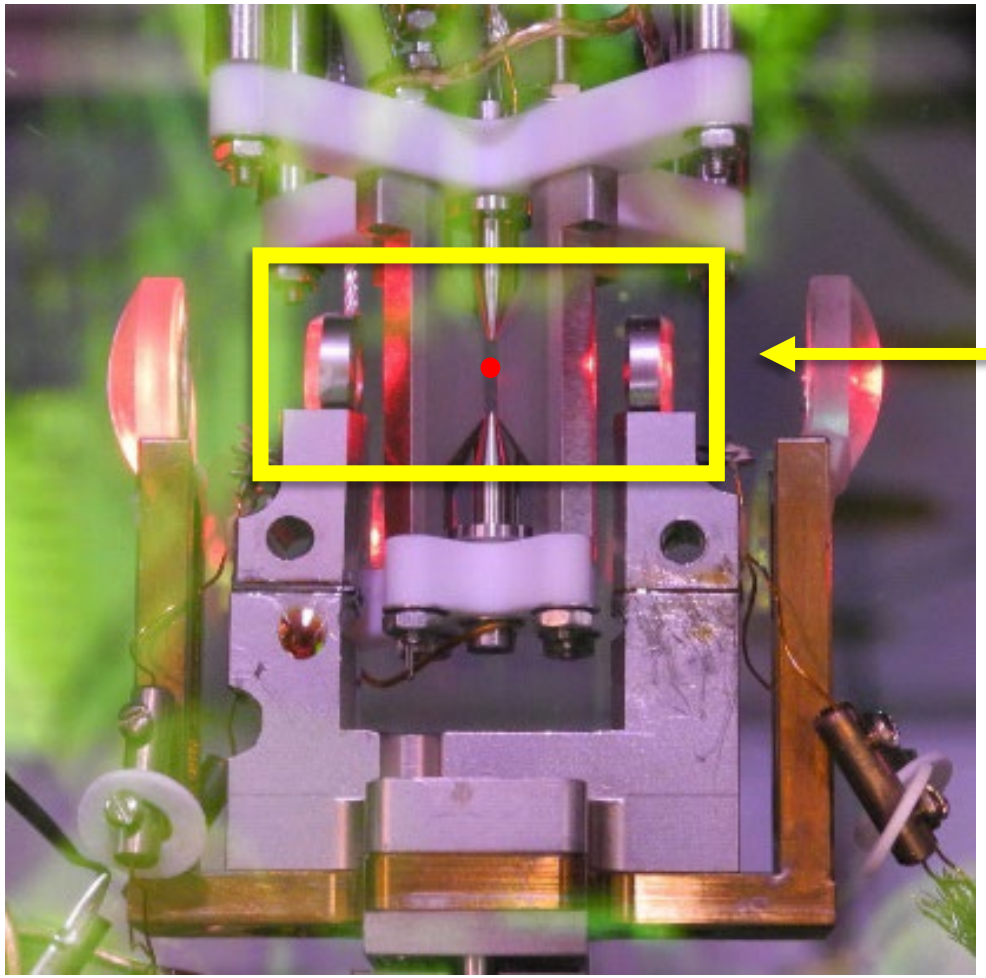


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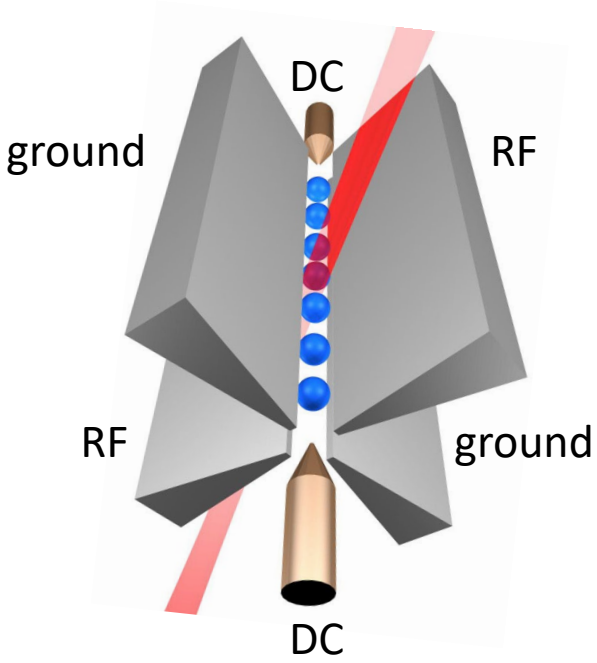
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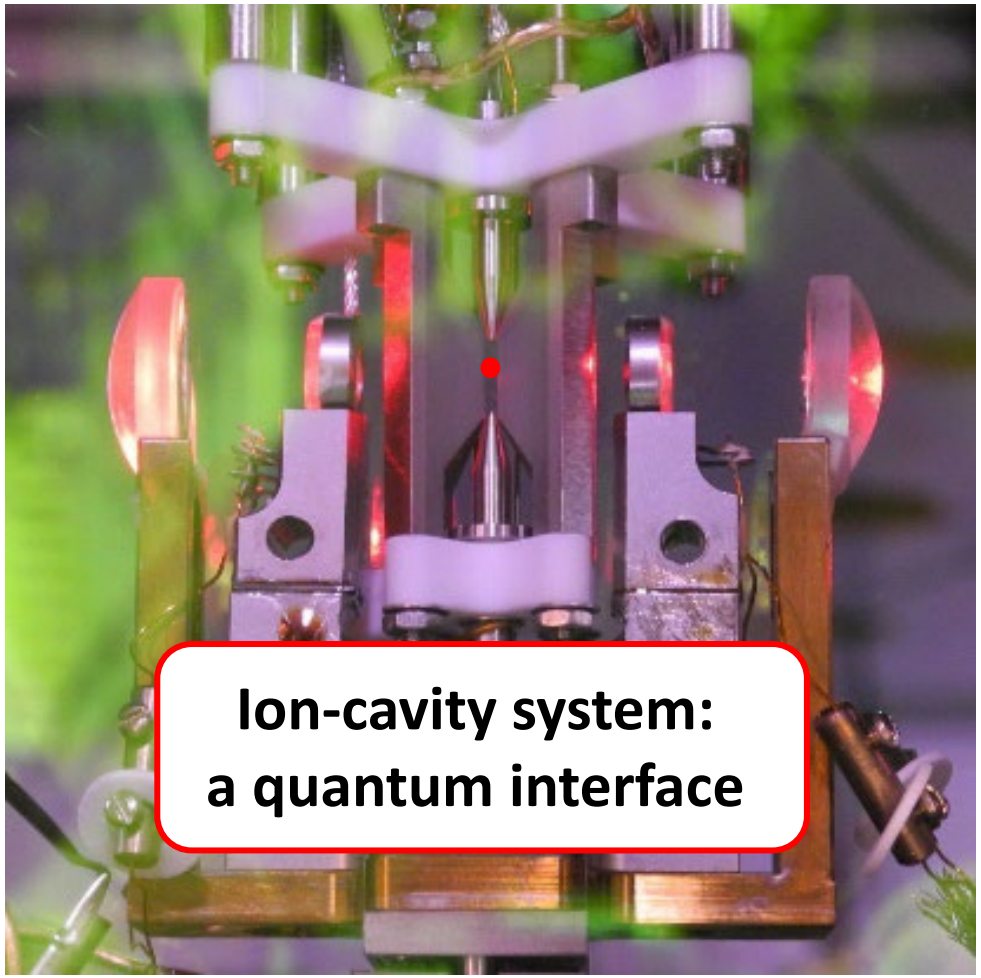
Optical cavity

Quantum network node: an ion-cavity system

Ion trap

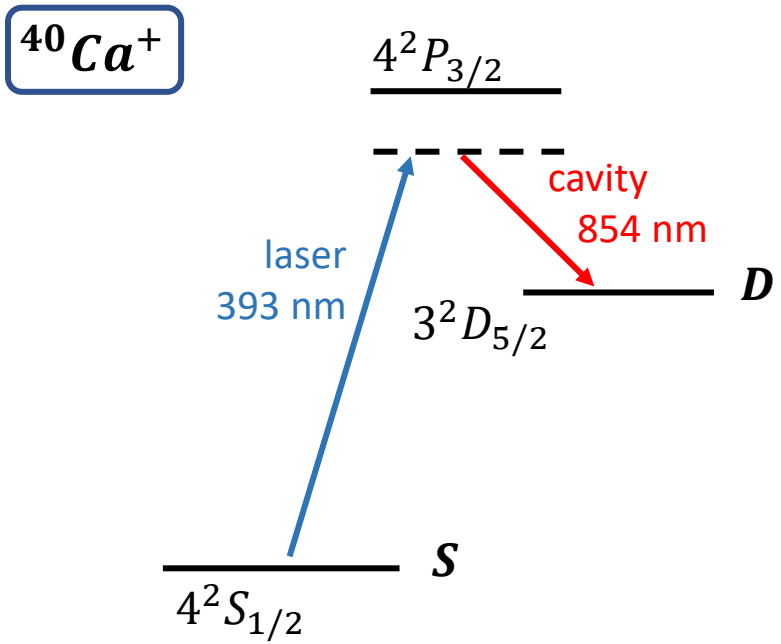


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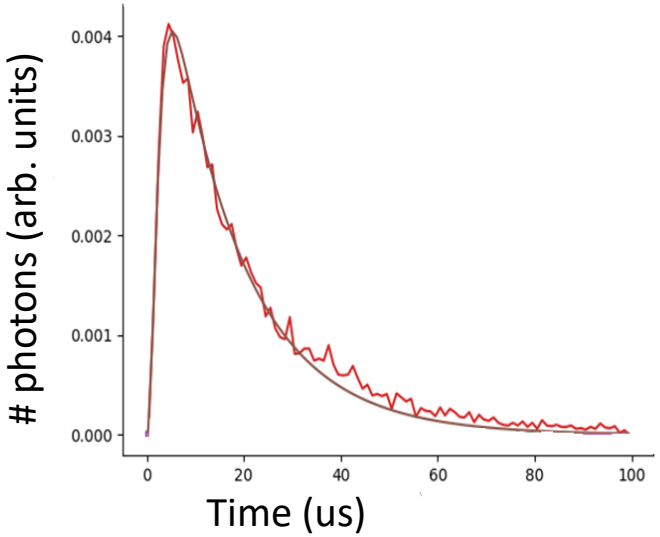


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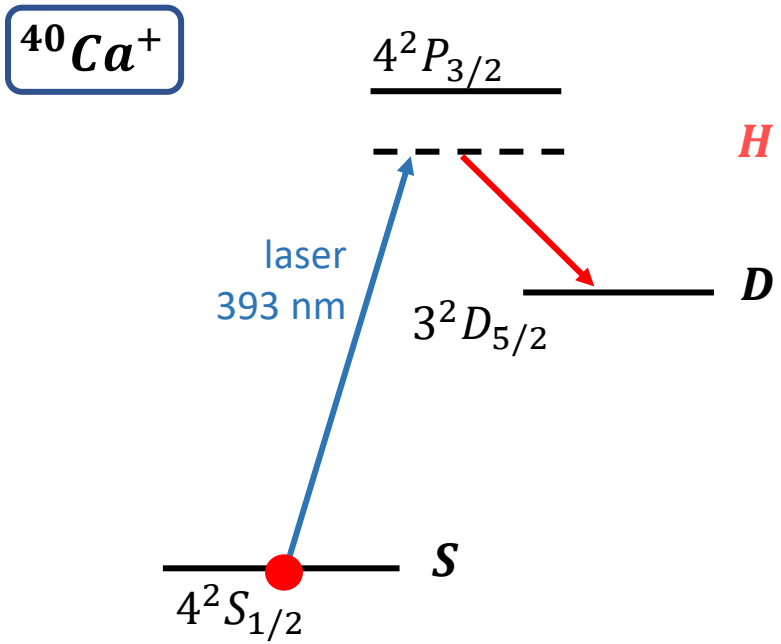
A Raman process generates single cavity photons



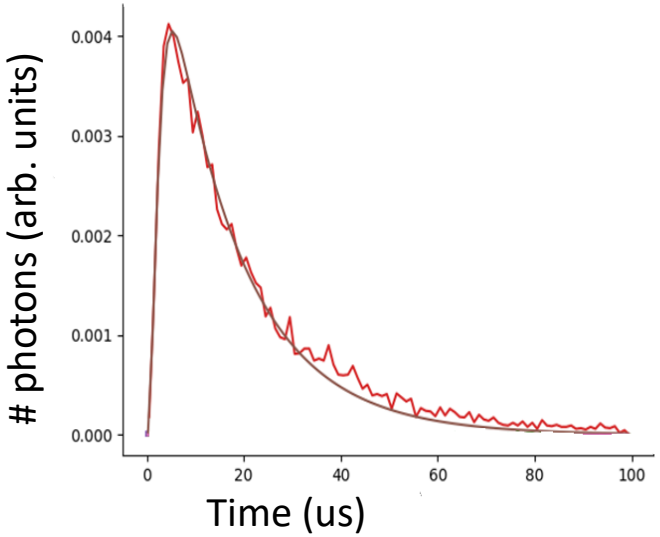
$$|\psi\rangle = |\mathrm{HD}\rangle$$



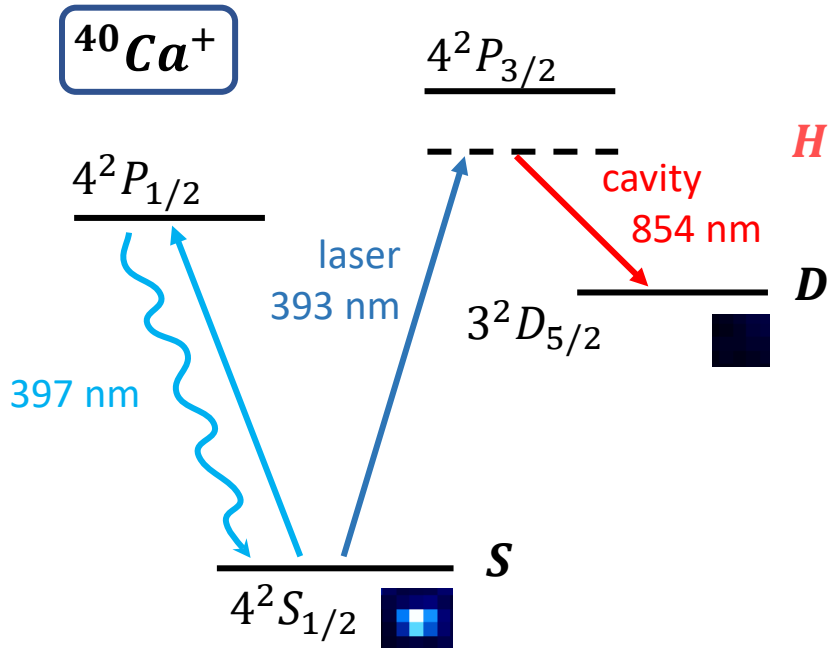
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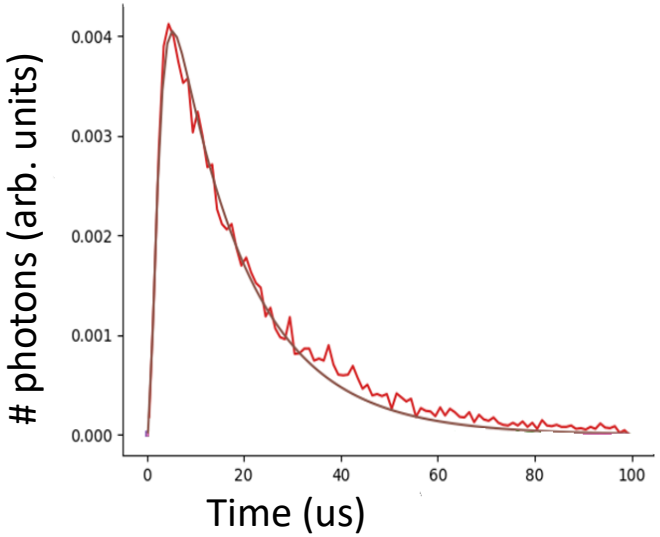
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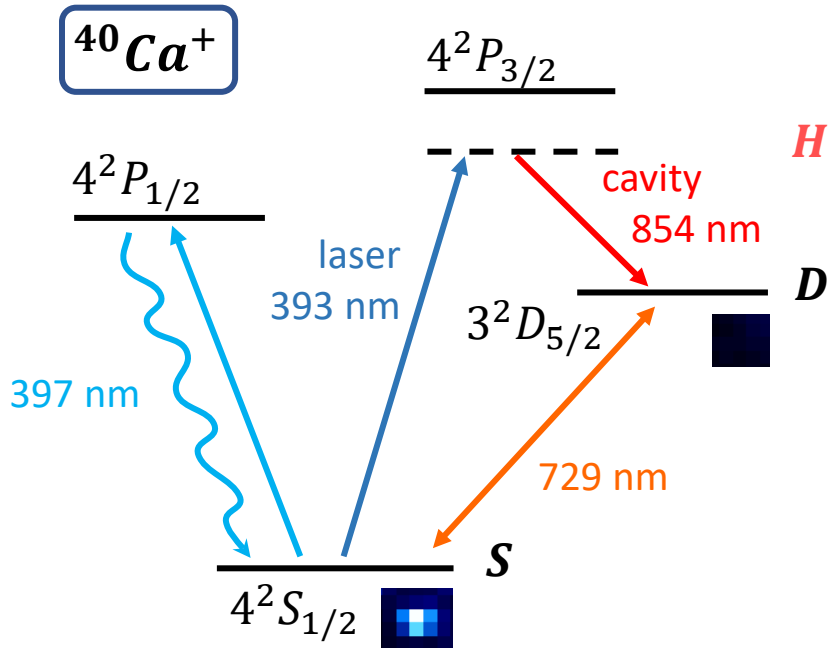
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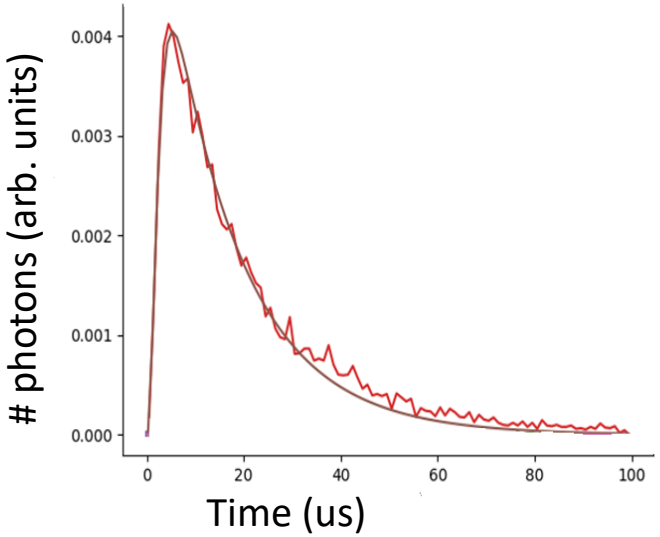
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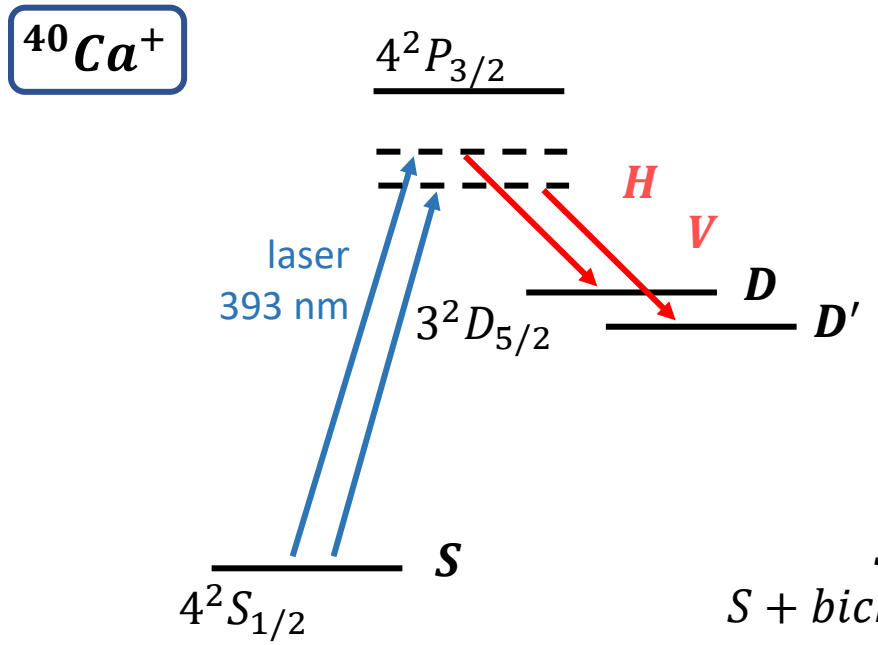
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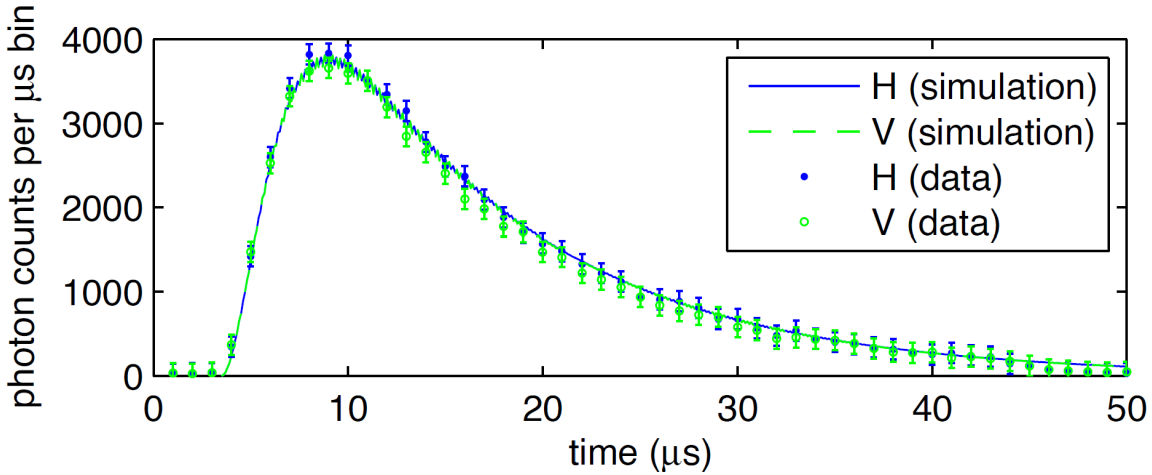


$$|\psi\rangle = |\mathrm{HD}\rangle$$



A *bichromatic* Raman process generates single cavity photons *entangled* with the ions





B. Brandstätter, Ph.D. thesis, University of Innsbruck (2013)

$$S + 393\ nm \rightarrow HD$$
$$S + 393'\ nm \rightarrow VD'$$
$$S + bichro\ 393\ nm \rightarrow HD + VD'$$

$$|\psi\rangle = |\mathrm{HD}\rangle + |\mathrm{VD'}\rangle$$

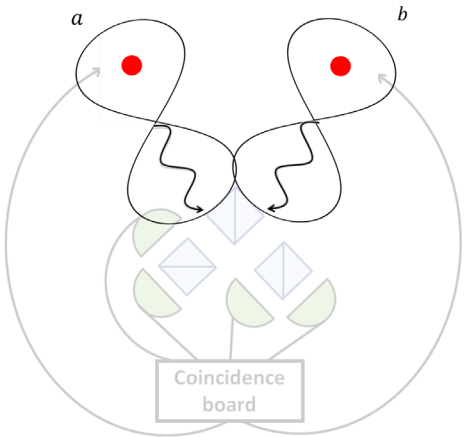
Assessing requirements for remote-qubit entanglement

Generation of spin-polarization entanglement

How to entangle remote qubits?

1. Generation of **spin-photon entanglement** pairs
2. Interference of spin-entangled photons
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$$|\psi\rangle_{ab} = (|\uparrow \mathrm{H}\rangle_a + |\downarrow \mathrm{V}\rangle_a) \otimes (|\uparrow \mathrm{H}\rangle_b + |\mathrm{V}\downarrow\rangle_b)$$



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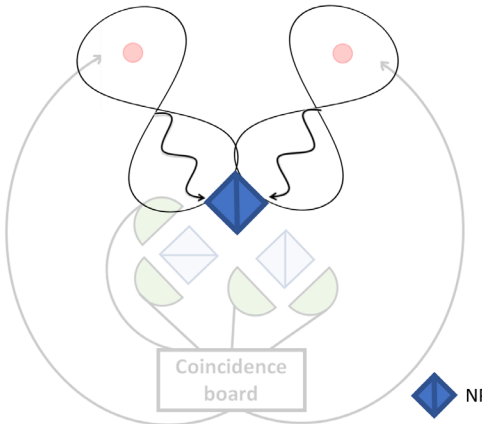
Entanglement between remote ions – Maria Galli 15

Indistinguishability of photons

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2. **Interference** of spin-entangled **photons**
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$$|\psi\rangle_{ab} = |\mathrm{H}_a\mathrm{H}_b\uparrow_a\uparrow_b\rangle + |\mathrm{H}_a\mathrm{V}_b\uparrow_a\downarrow_b\rangle + |\mathrm{V}_a\mathrm{H}_b\downarrow_a\uparrow_b\rangle + |\mathrm{V}_a\mathrm{V}_b\downarrow_a\downarrow_b\rangle$$



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Entanglement between remote ions – Maria Galli 16

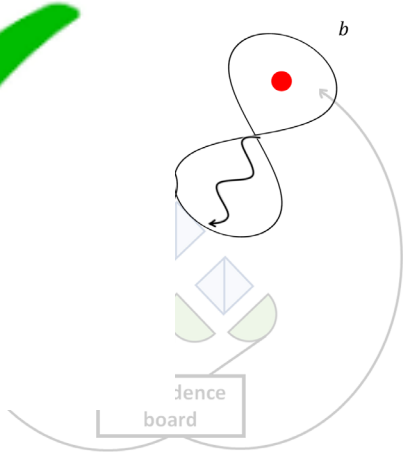
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Generation of spin-polarization entanglement

How to

1. Generati
   entangle
2. Interfere
   entangle
3. Photon d





$|\psi\rangle_{ab} = (|\uparrow \mathrm{H}\rangle_a +$

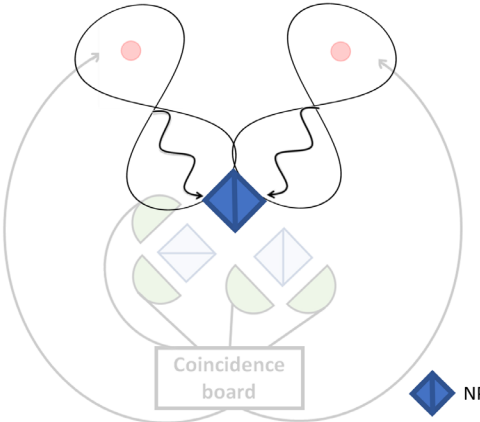
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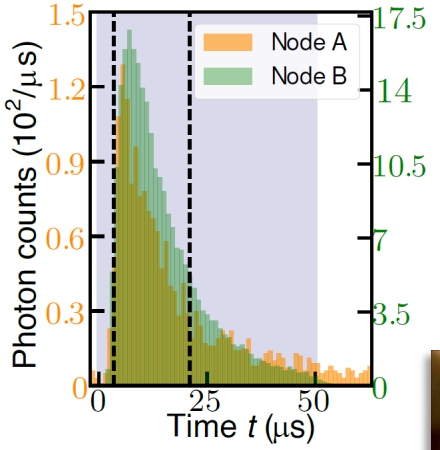
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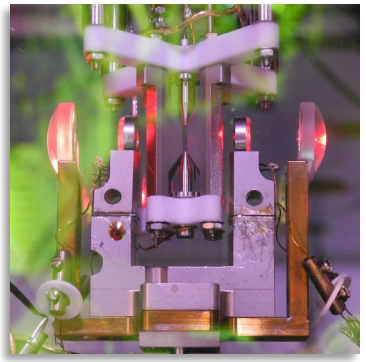
Making photons indistinguishable

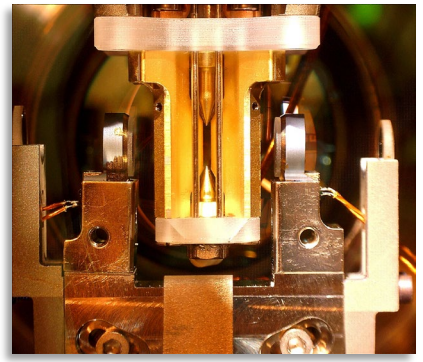
Between the labs:

- Time synchronization

  GPS clock signal, pulse sequences synch.







- Frequency matching

  Match length of the optical cavities

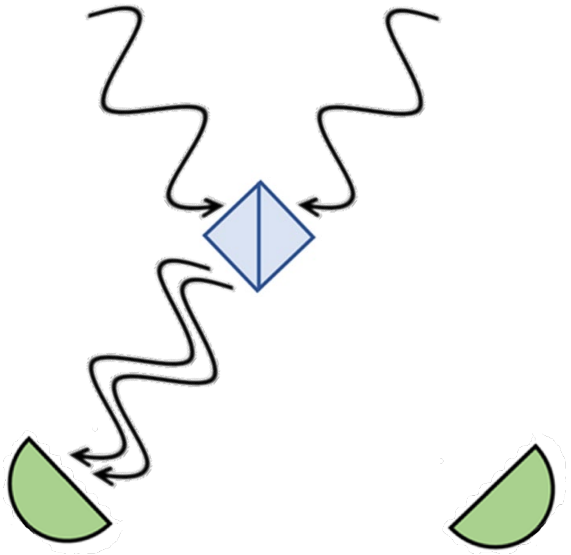
- Polarization stabilization

  Characterize and correct for polarization rotation

Assessing photon indistinguishability

The Hong-Ou-Mandel effect

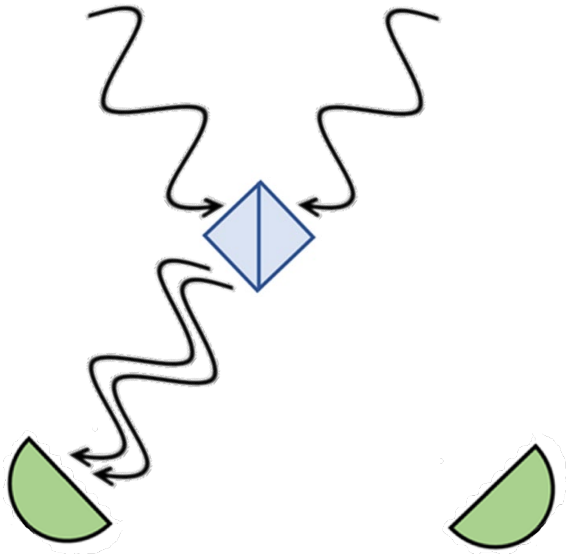
Indistinguishable photons leave the beam splitter at the same port.
No coincidences are observed.



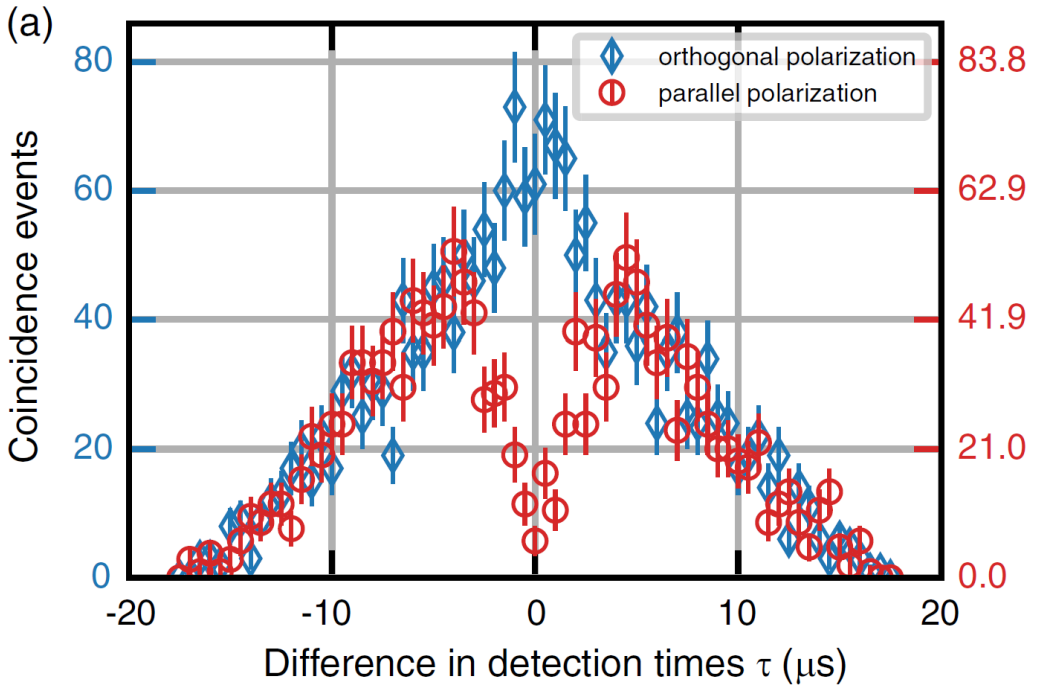
Assessing photon indistinguishability

The Hong-Ou-Mandel effect

Indistinguishable photons leave the beam splitter at the same port.
No coincidences are observed.



Our measurement



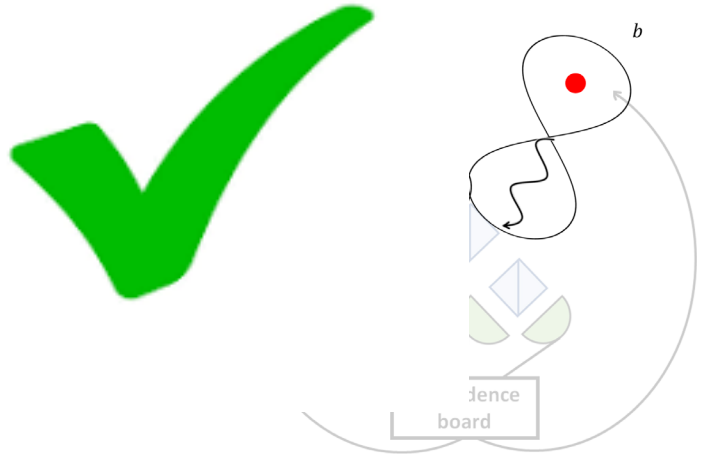
Assessing requirements for remote-qubit entanglement

Generation of spin-polarization entanglement

How to

1. Generati
   entangle
2. Interfere
   entangle
3. Photon c

$|\psi\rangle_{ab} = (|\uparrow\mathrm{H}\rangle_a +$



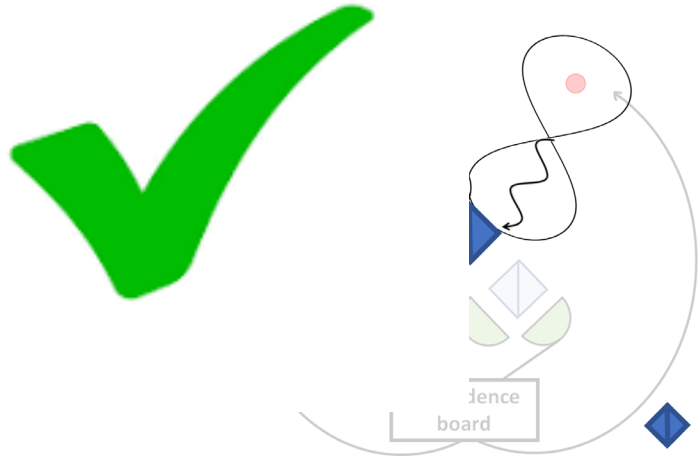
universität innsbruck

Indistinguishability of photons

How to

1. Generati
   entangle
2. **Interfere**
   entangle
3. Photon c

$|\psi\rangle_{ab} = |\mathrm{H}_a\mathrm{H}_b\uparrow_a\uparrow$
$+|\mathrm{V}_a\mathrm{H}_b\downarrow_a\uparrow$

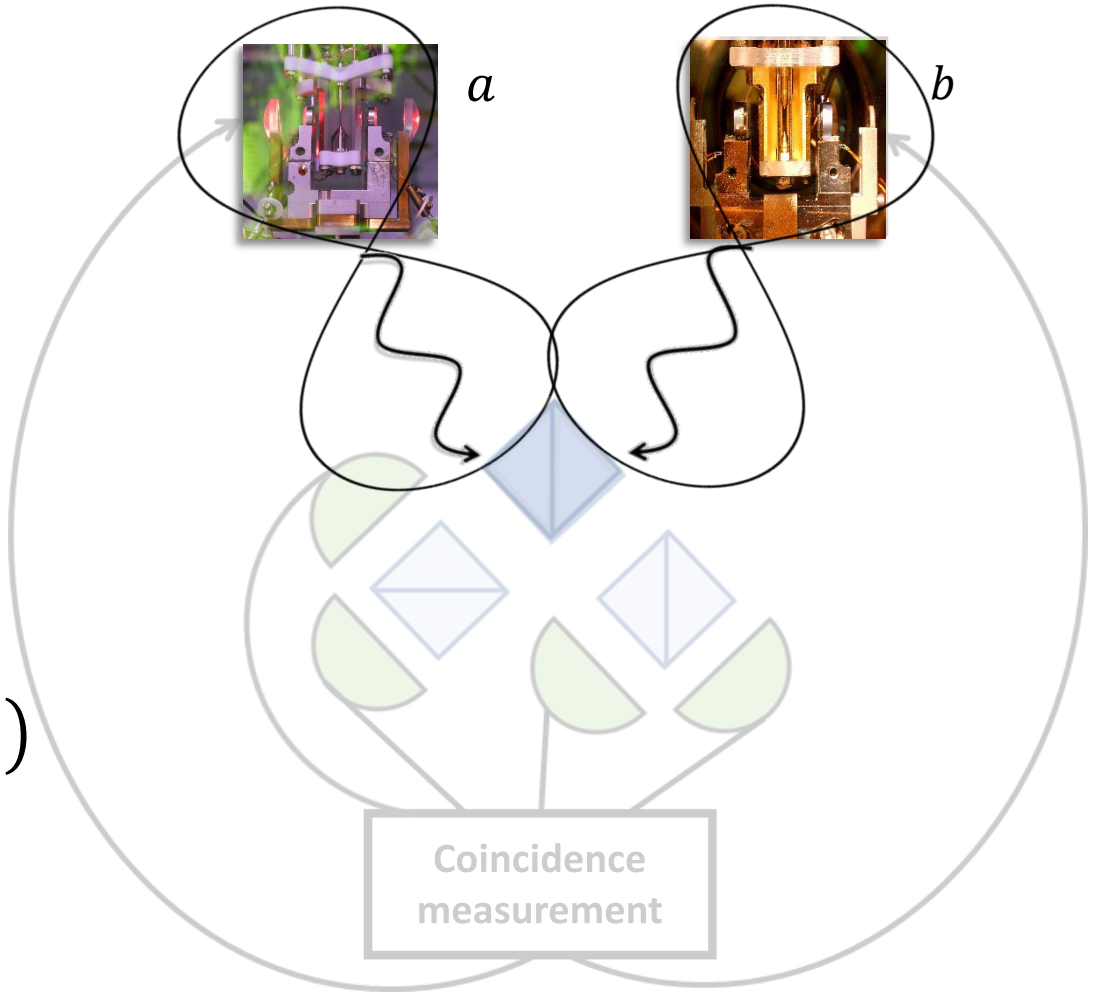


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Our realization of remote-ion entanglement

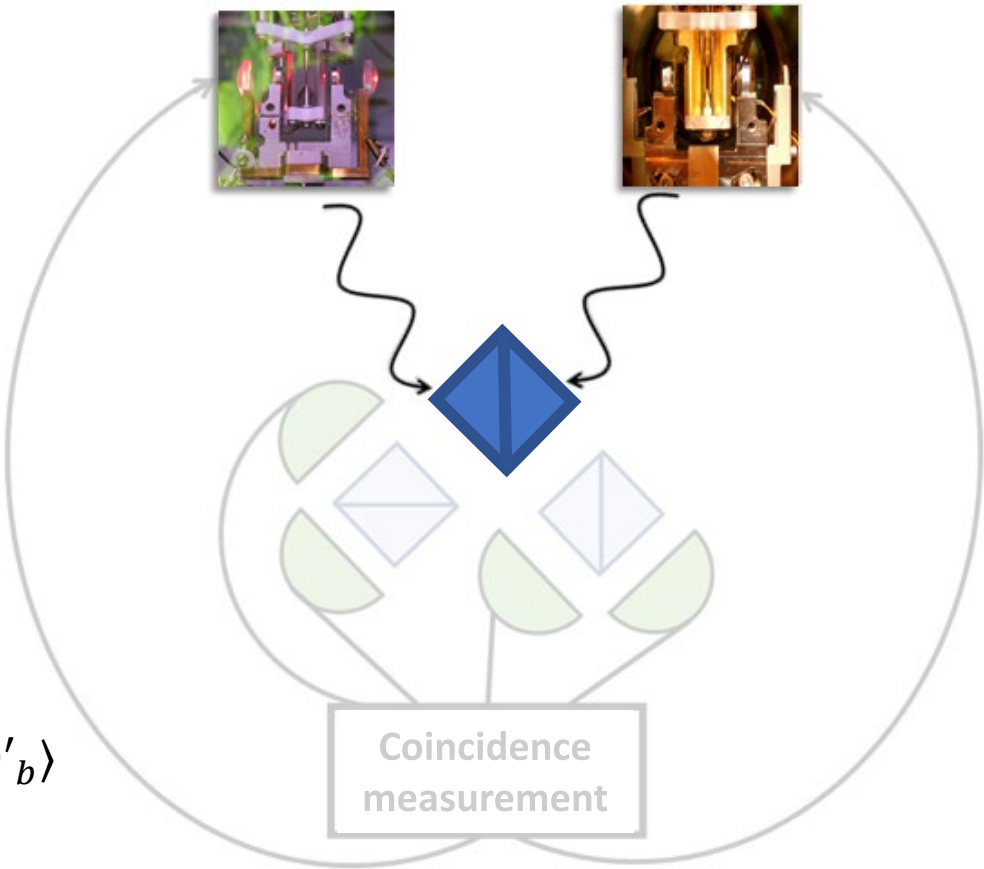
1. Generation of **ion-photon entanglement** pairs
2. Interference of ion-entangled photons
3. Photon detection
4. Ion state read-out

$$|\psi\rangle_{ab} = \left(|\mathrm{HD}\rangle_a + |\mathrm{VD'}\rangle_a\right) \otimes \left(|\mathrm{HD}\rangle_b + |\mathrm{VD'}\rangle_b\right)$$



Our realization of remote-ion entanglement

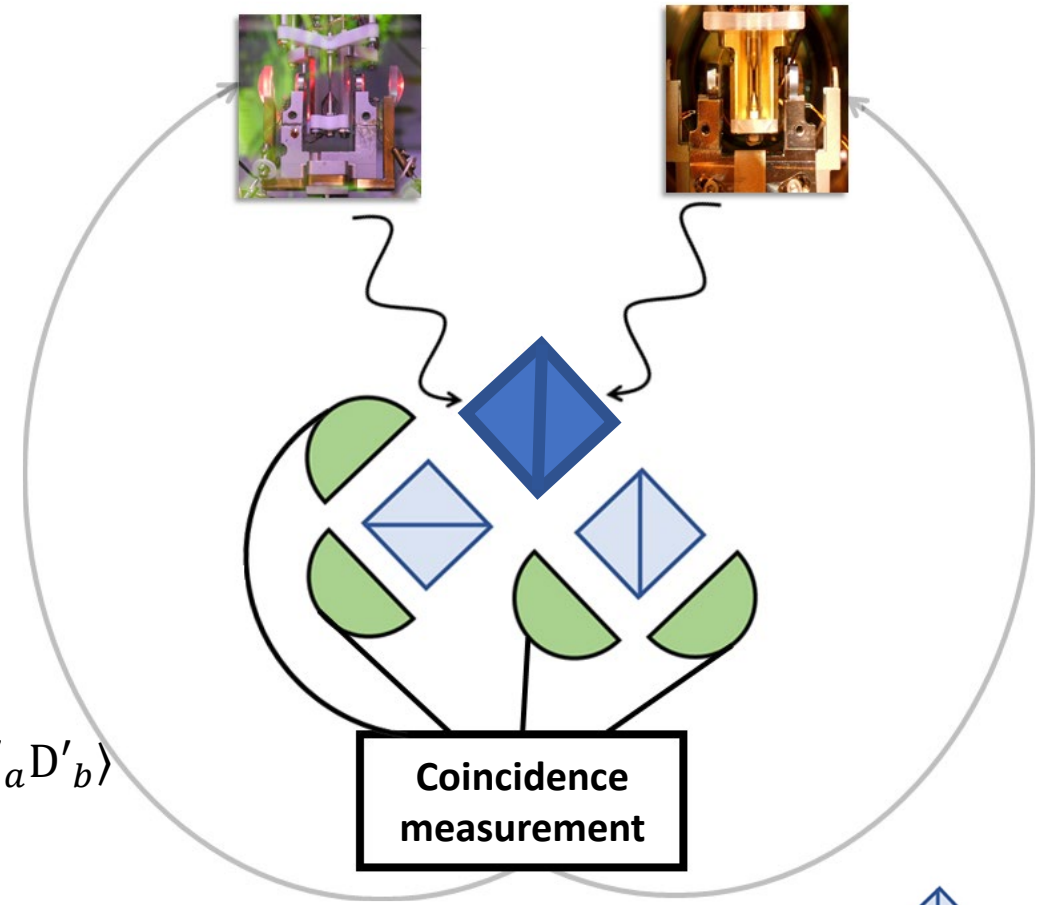
1. Generation of ion-photon entanglement pairs
2. **Interference** of ion-entangled **photons**
3. Photon detection
4. Ion state read-out



$$|\psi\rangle_{ab} = |\mathrm{H}_a\mathrm{H}_b\mathrm{D}_a\mathrm{D}_b\rangle + |\mathrm{H}_a\mathrm{V}_b\mathrm{D}_a\mathrm{D}'_b\rangle + |\mathrm{V}_a\mathrm{H}_b\mathrm{D}'_a\mathrm{D}_b\rangle + |\mathrm{V}_a\mathrm{V}_b\mathrm{D}'_a\mathrm{D}'_b\rangle$$

Our realization of remote-ion entanglement

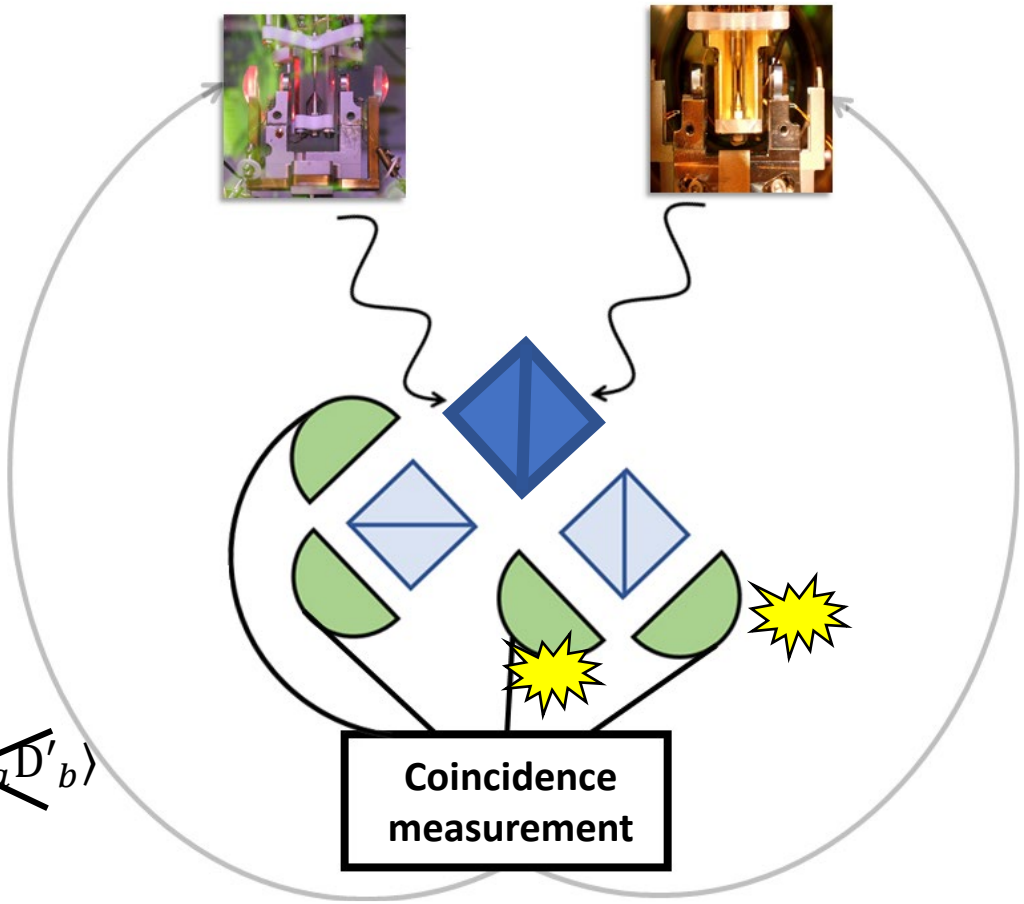
1. Generation of ion-photon entanglement pairs
2. Interference of ion-entangled photons
3. **Photon detection**
4. Ion state read-out



$$|\psi\rangle_{ab} = |\mathrm{H}_a\mathrm{H}_b\mathrm{D}_a\mathrm{D}_b\rangle + |\mathrm{H}_a\mathrm{V}_b\mathrm{D}_a\mathrm{D}'_b\rangle + |\mathrm{V}_a\mathrm{H}_b\mathrm{D}'_a\mathrm{D}_b\rangle + |\mathrm{V}_a\mathrm{V}_b\mathrm{D}'_a\mathrm{D}'_b\rangle$$

Our realization of remote-ion entanglement

1. Generation of ion-photon entanglement pairs
2. Interference of ion-entangled photons
3. **Photon detection**
4. Ion state read-out

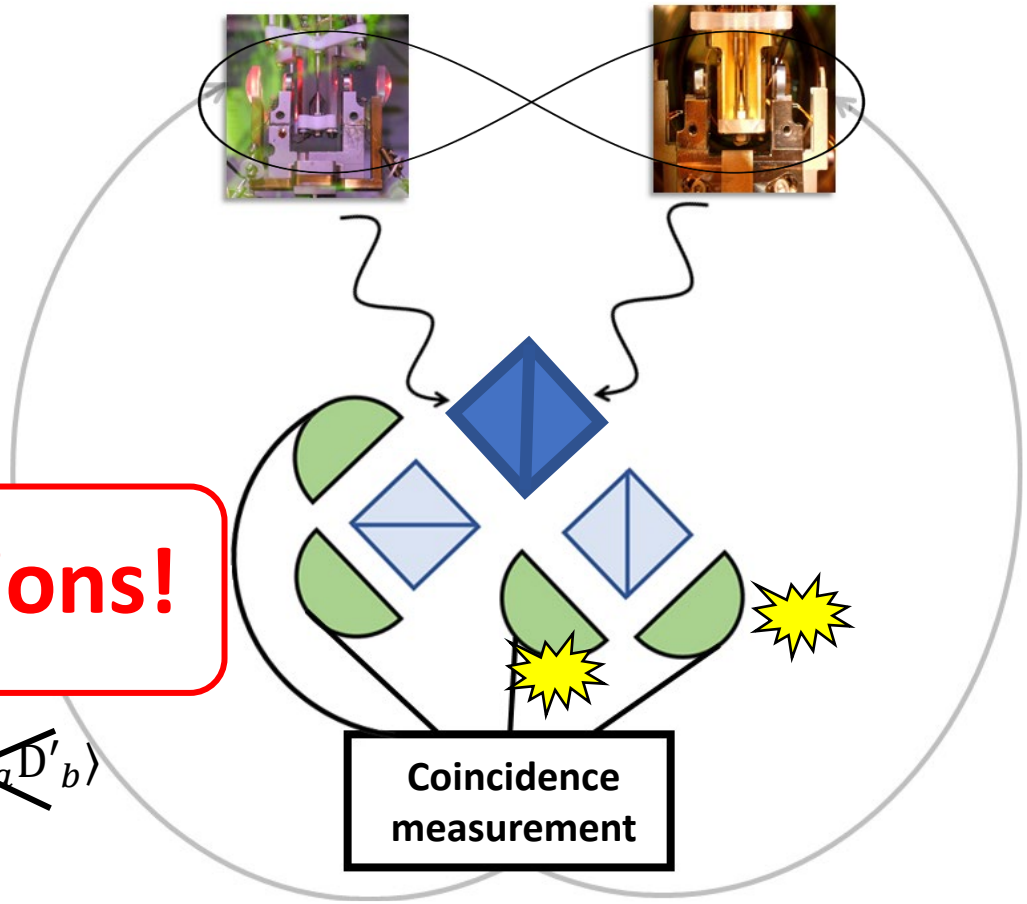


$$|\psi\rangle_{ab} = \cancel{|\mathrm{H}_a\mathrm{H}_b\mathrm{D}_a\mathrm{D}_b\rangle} + |\mathrm{H}_a\mathrm{V}_b\mathrm{D}_a\mathrm{D'}_b\rangle + |\mathrm{V}_a\mathrm{H}_b\mathrm{D'}_a\mathrm{D}_b\rangle + \cancel{|\mathrm{V}_a\mathrm{V}_b\mathrm{D'}_a\mathrm{D'}_b\rangle}$$

$$|\psi\rangle_{ab} = |\mathrm{D}_a\mathrm{D'}_b\rangle + |\mathrm{D'}_a\mathrm{D}_b\rangle$$

Our realization of remote-ion entanglement

1. Generation of ion-photon entanglement pairs
2. Interference of ion-entangled photons
3. **Photon detection**
4. Ion state read-out

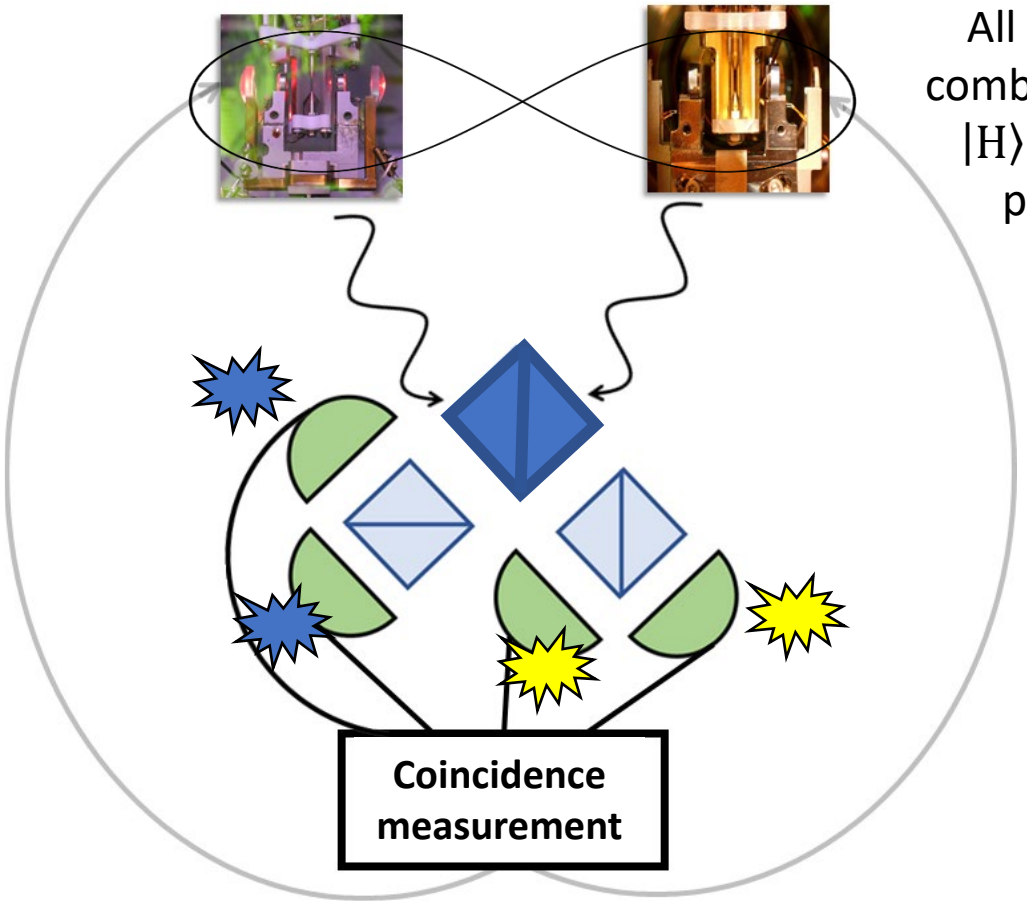


Entangled ions!

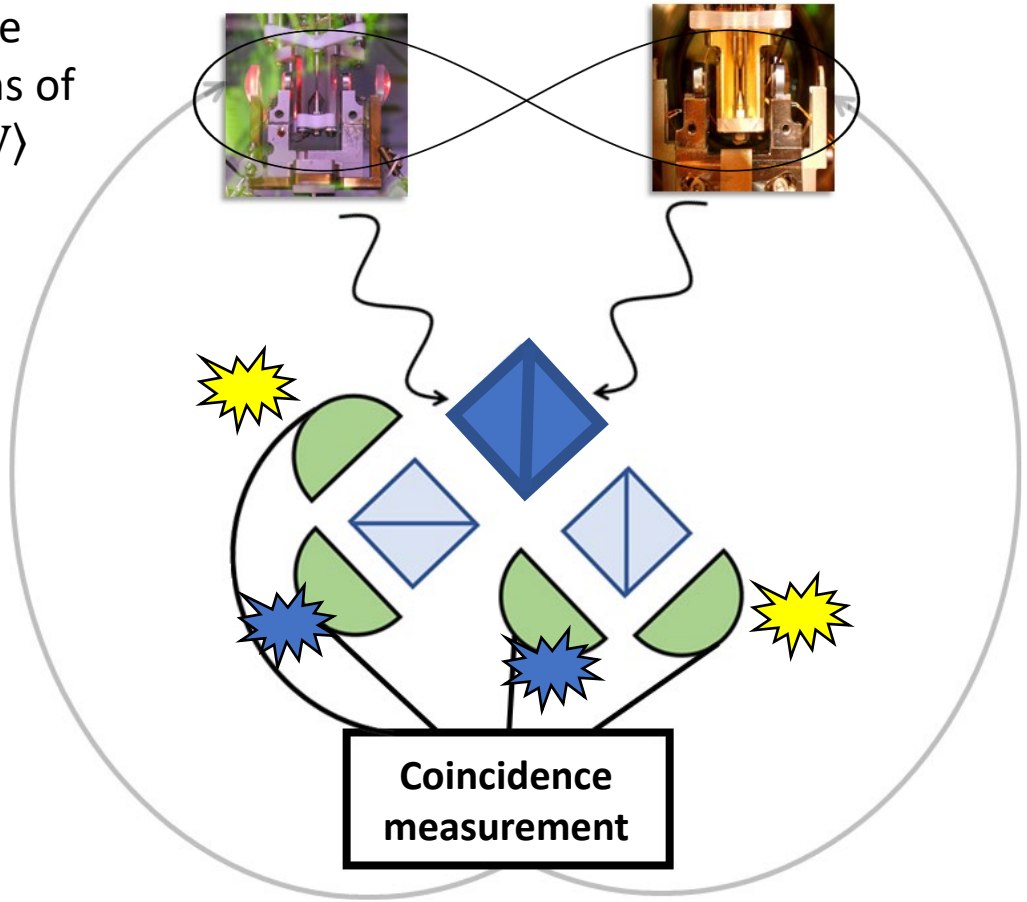
$$|\psi\rangle_{ab} = |\mathrm{H}_a\mathrm{H}_b\mathrm{D}_a\mathrm{D}_b\rangle + |\mathrm{H}_a\mathrm{V}_b\mathrm{D}_a\mathrm{D}'_b\rangle + |\mathrm{V}_a\mathrm{H}_b\mathrm{D}'_a\mathrm{D}_b\rangle + |\mathrm{V}_a\mathrm{V}_b\mathrm{D}'_a\mathrm{D}'_b\rangle$$

$$|\psi\rangle_{ab} = |\mathrm{D}_a\mathrm{D}'_b\rangle + |\mathrm{D}'_a\mathrm{D}_b\rangle$$

Photon detection possibilities



All possible combinations of $|H\rangle$ and $|V\rangle$ photons



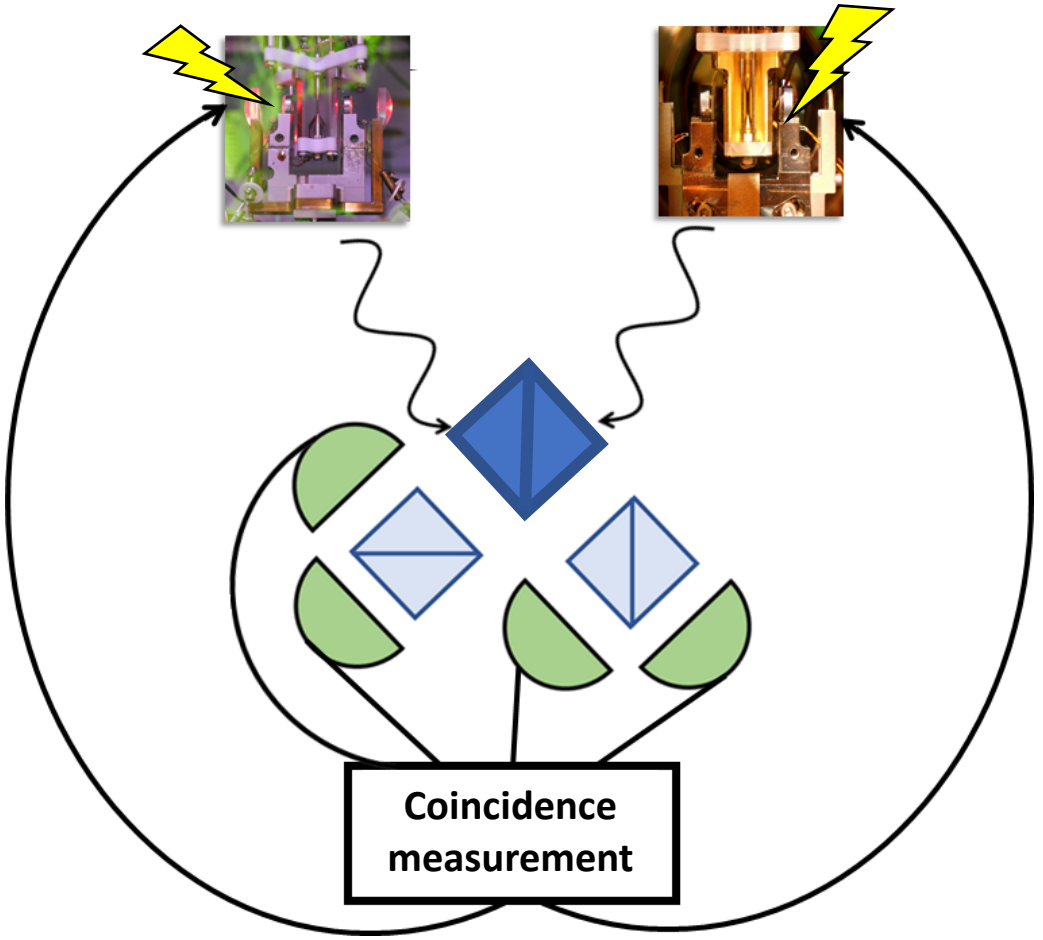
$$|\psi^+\rangle_{ab} = |D_a D'_b\rangle + |D'_a D_b\rangle$$

$$|\psi^-\rangle_{ab} = |D_a D'_b\rangle - |D'_a D_b\rangle$$

Our realization of remote-ion entanglement

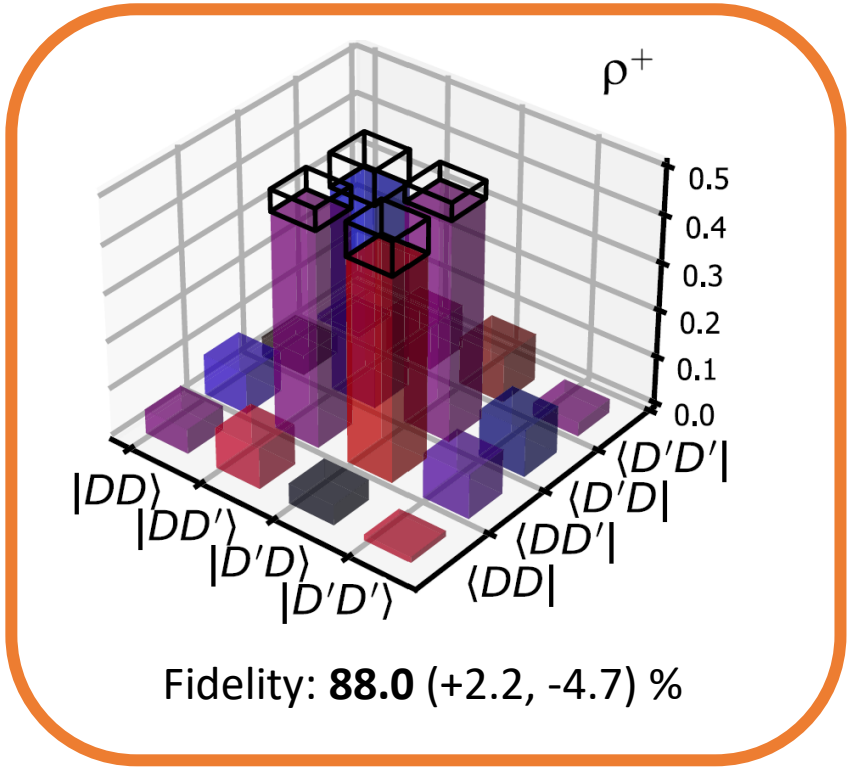
1. Generation of ion-photon entanglement pairs
2. Interference of ion-entangled photons
3. Photon detection
4. **Ion state read-out**

$$\left|\psi^{\pm}\right\rangle_{ab} = |\mathrm{D}_a \mathrm{D'}_b\rangle \pm |\mathrm{D'}_a \mathrm{D}_b\rangle$$

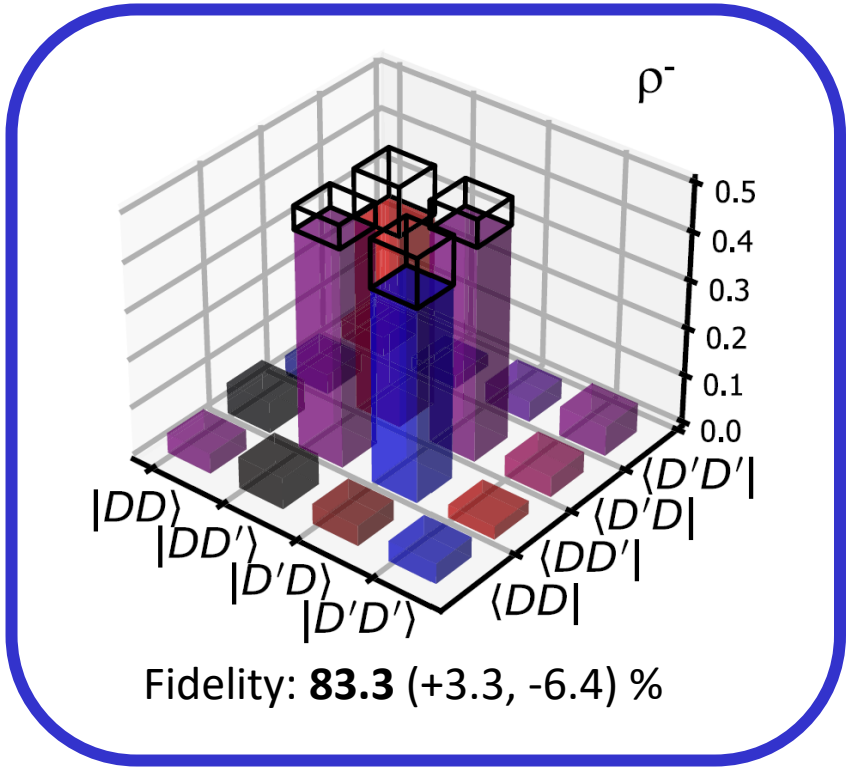


Entanglement of remote cavity-coupled ions

Full quantum state tomography ⟶ complete state reconstruction:



Fidelity: **88.0** (+2.2, -4.7) %



Fidelity: **83.3** (+3.3, -6.4) %

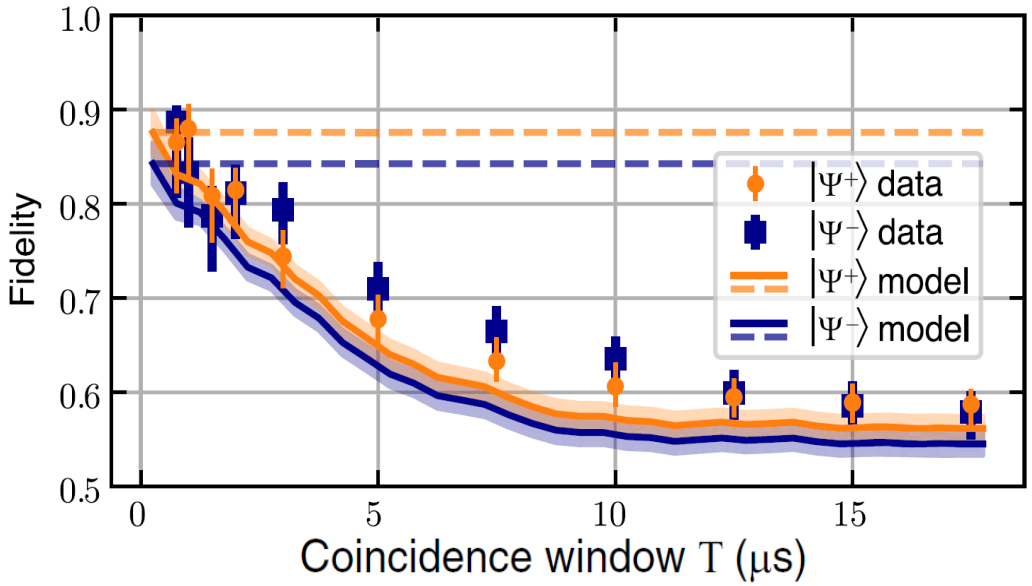
Phase



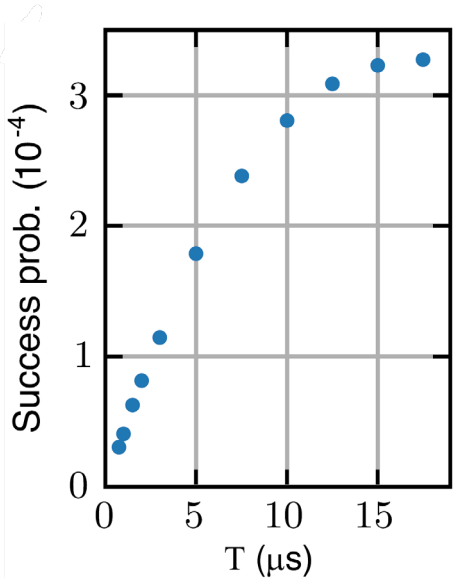
Target states: $\left|\psi^{\pm}\right\rangle_{ab} = \frac{1}{\sqrt{2}}(|\mathrm{D}_a\mathrm{D}'_b\rangle \pm |\mathrm{D}'_a\mathrm{D}_b\rangle)$

Krutyanskiy, Galli, et al.,
Phys. Rev. Lett. **130**, 050803 (2023)

Trade-off between fidelity and rate



Maximum time delay
Between the two
detected photons

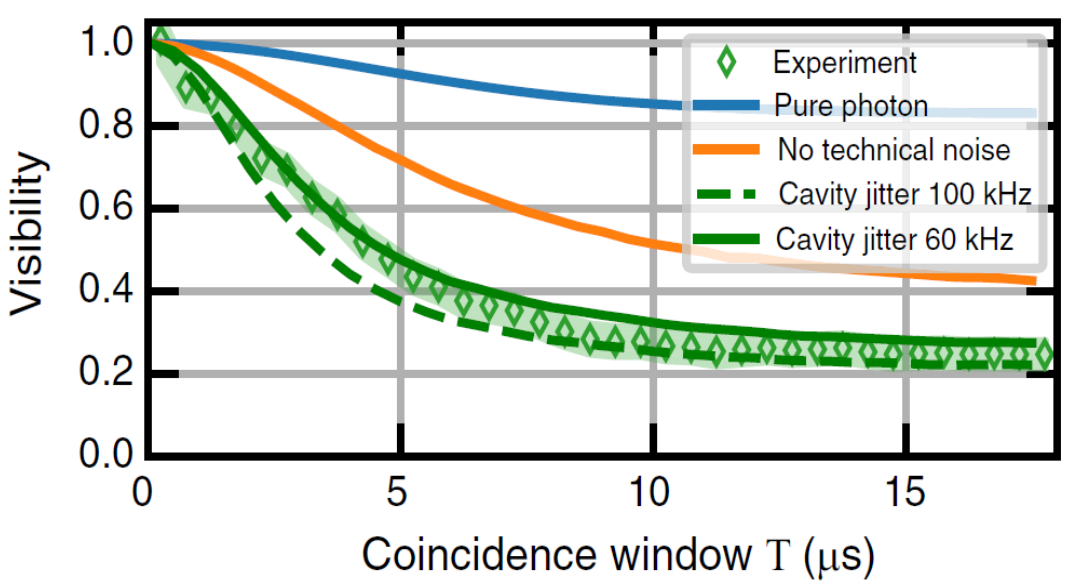


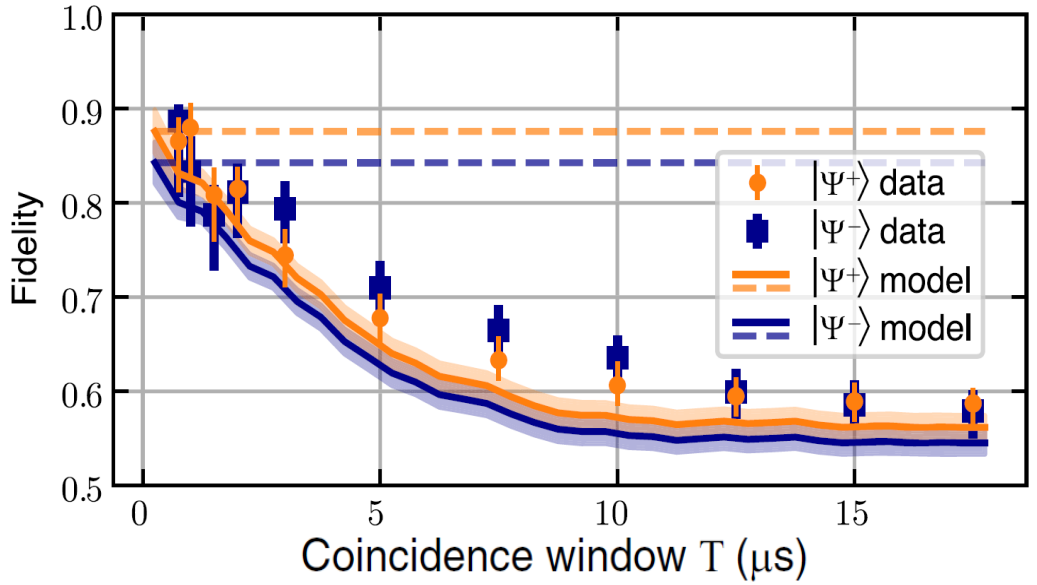
V. Krutyanskiy, M. Galli et al., Phys. Rev. Lett. **130**, 050803 (2023)

Coincidence window	1μs	17.5μs
Fidelity	0.880+0.022-0.047 0.83.3+0.033-0.064	0.587+0.017-0.021 0.580+0.020-0.029
Rate	0.058 Hz	0.49 Hz

How to improve entanglement fidelity

Photon distinguishability results in fidelity drop

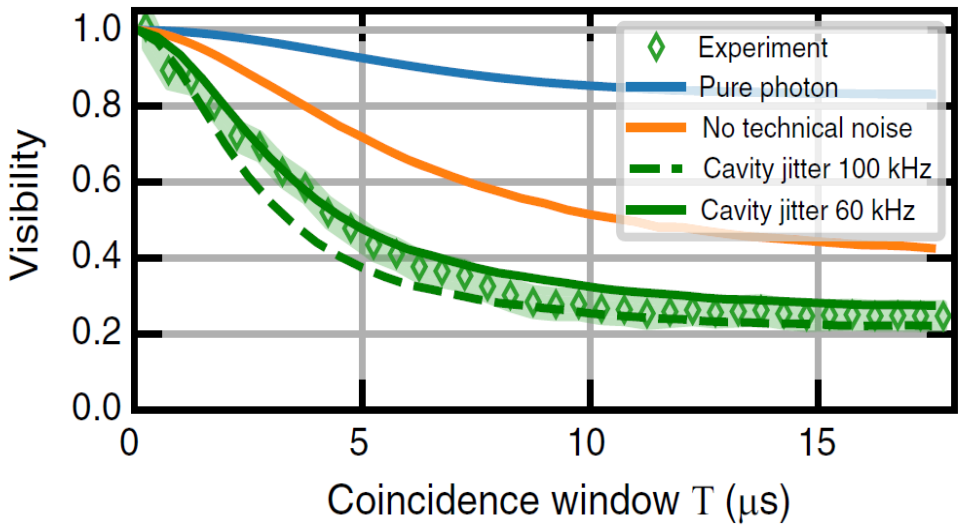




Krutyanskiy, Galli, et al.,
Phys. Rev. Lett. **130**, 050803 (2023)

How to improve entanglement fidelity

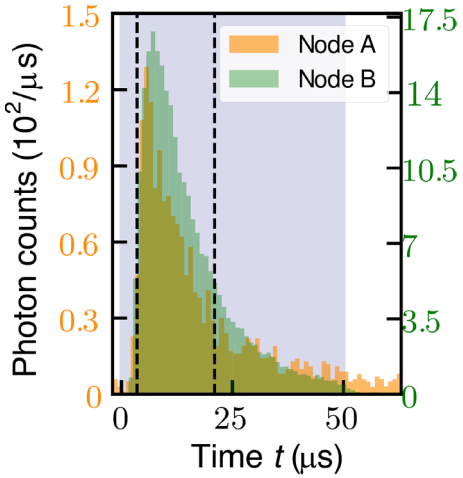
Limiting factors & possible improvements (1/3)



Krutyanskiy, Galli, et al.,
Phys. Rev. Lett. **130**, 050803 (2023)

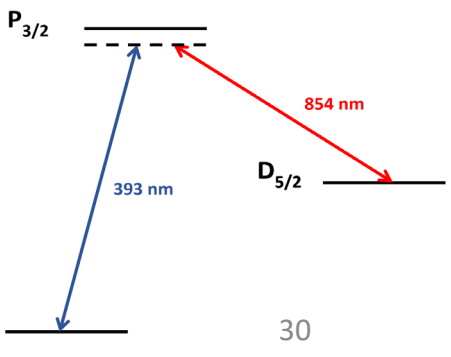
Cause for photon distinguishability

- In time:
  mismatch of photons temporal wavepackets



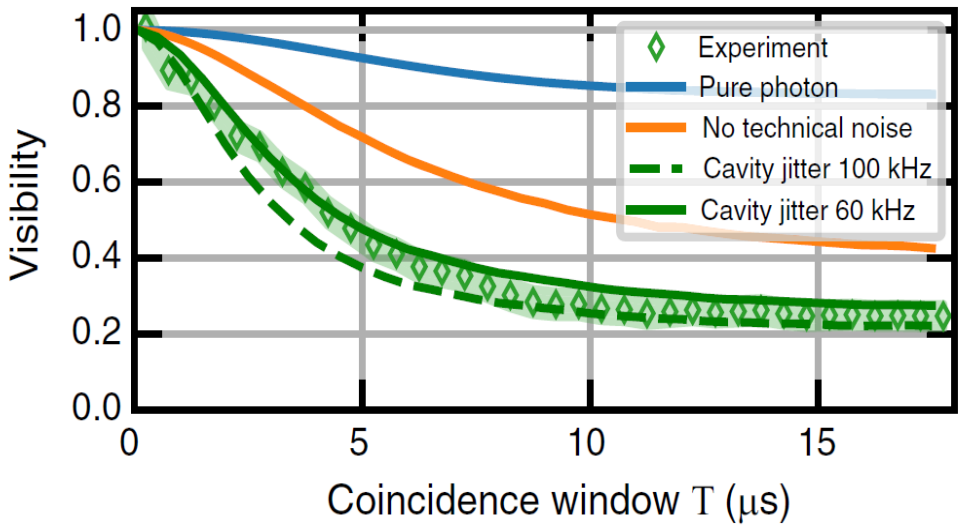
Possible solution

Shaping the drive laser pulse



How to improve entanglement fidelity

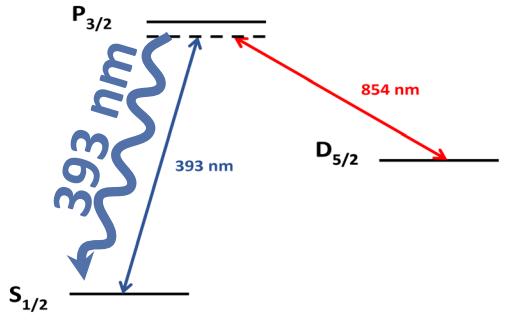
Limiting factors & possible improvements (2/3)



Krutyanskiy, Galli, et al.,
Phys. Rev. Lett. **130**, 050803 (2023)

Cause for photon distinguishability

- In time': spontaneous scattered photons provide which-path information



Meraner et al.,
PRA **102**, 052614 (2020)

Possible solution

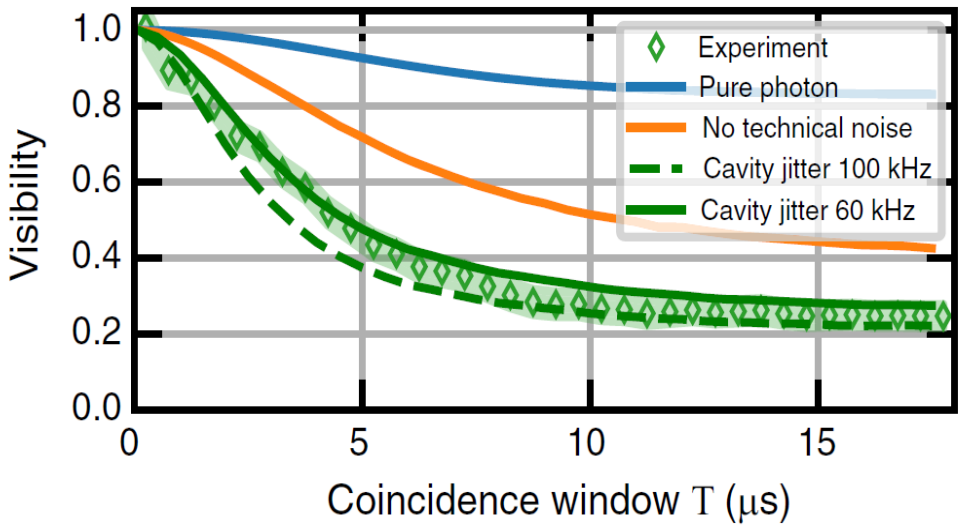
Increasing ion-cavity coupling

→ Superradiant states

→ Cavity with smaller mode volume

How to improve entanglement fidelity

Limiting factors & possible improvements (3/3)



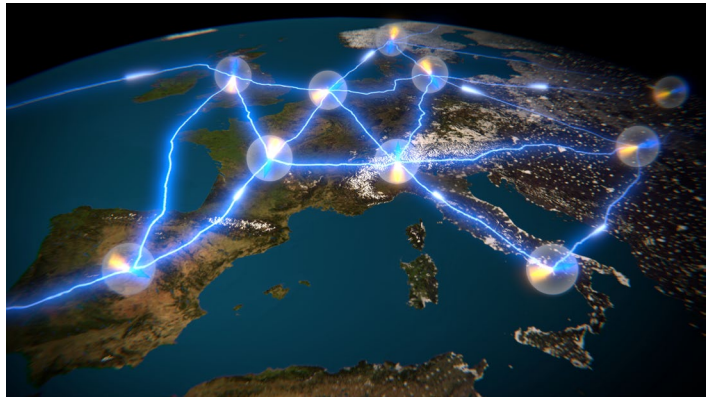
Krutyanskiy, Galli, et al.,
Phys. Rev. Lett. **130**, 050803 (2023)

Cause for photon distinguishability

- In frequency: not matching lengths of the cavities in two nodes

Possible solution

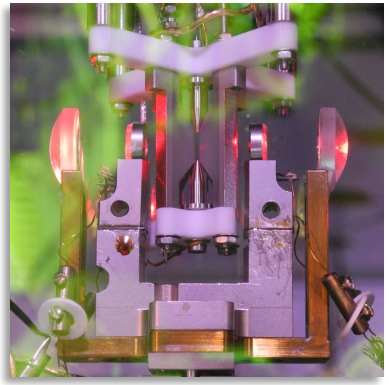
Fix technical noise of cavity jitter and cavity-locking-laser noise.



3. Future experiments

based on remote-ion entanglement

3.1 Entangling ions over 50 km

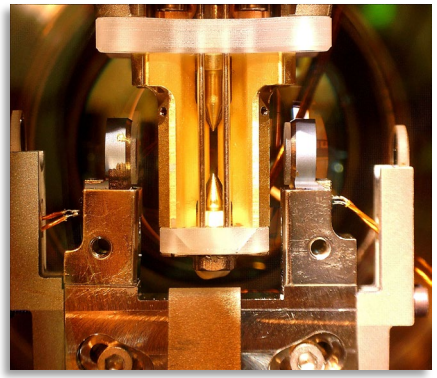


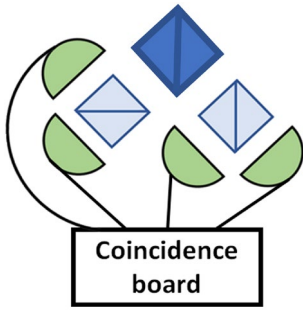
Quantum frequency conversion

25 km

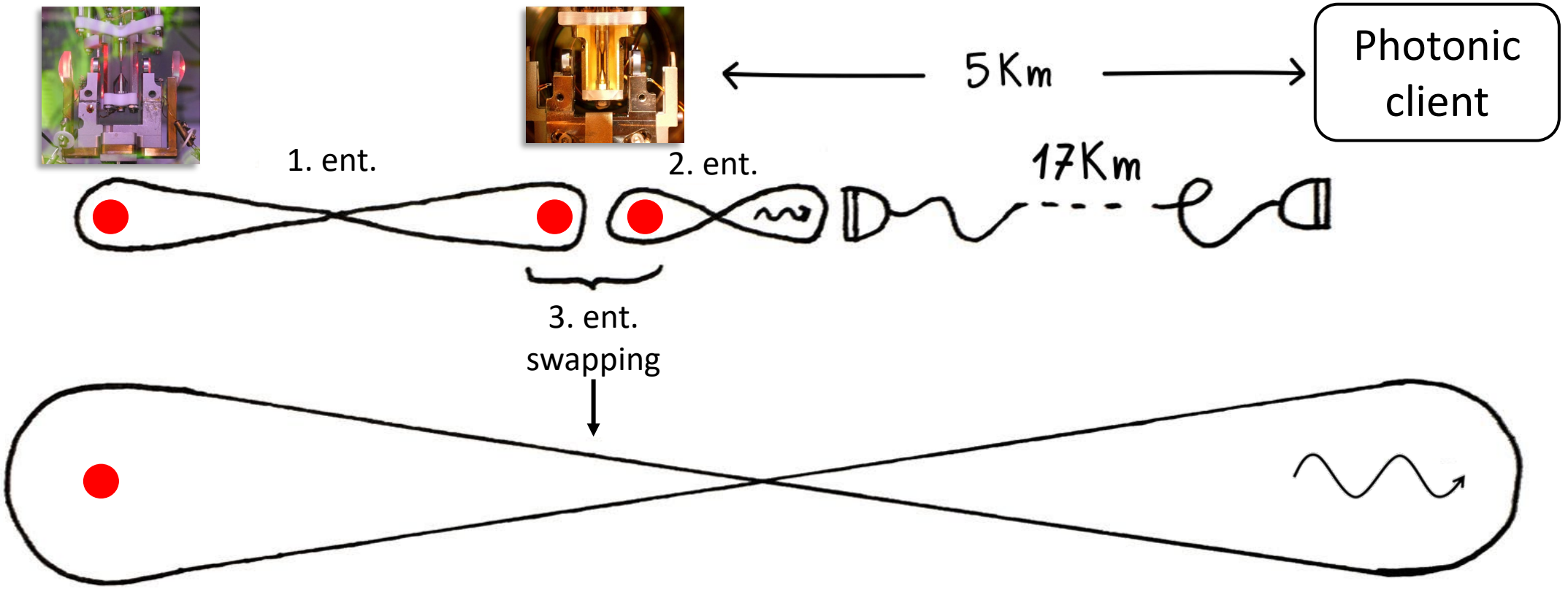
25 km

Quantum frequency conversion

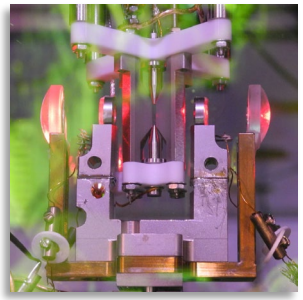


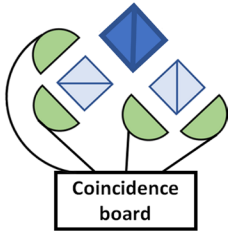


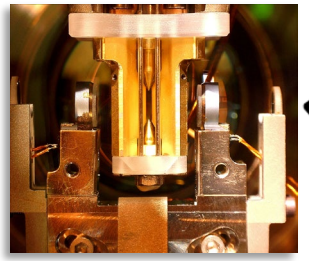
3.2 Demonstrating fundamental building blocks for quantum repeaters



3.3 Extending the network: more and diverse nodes

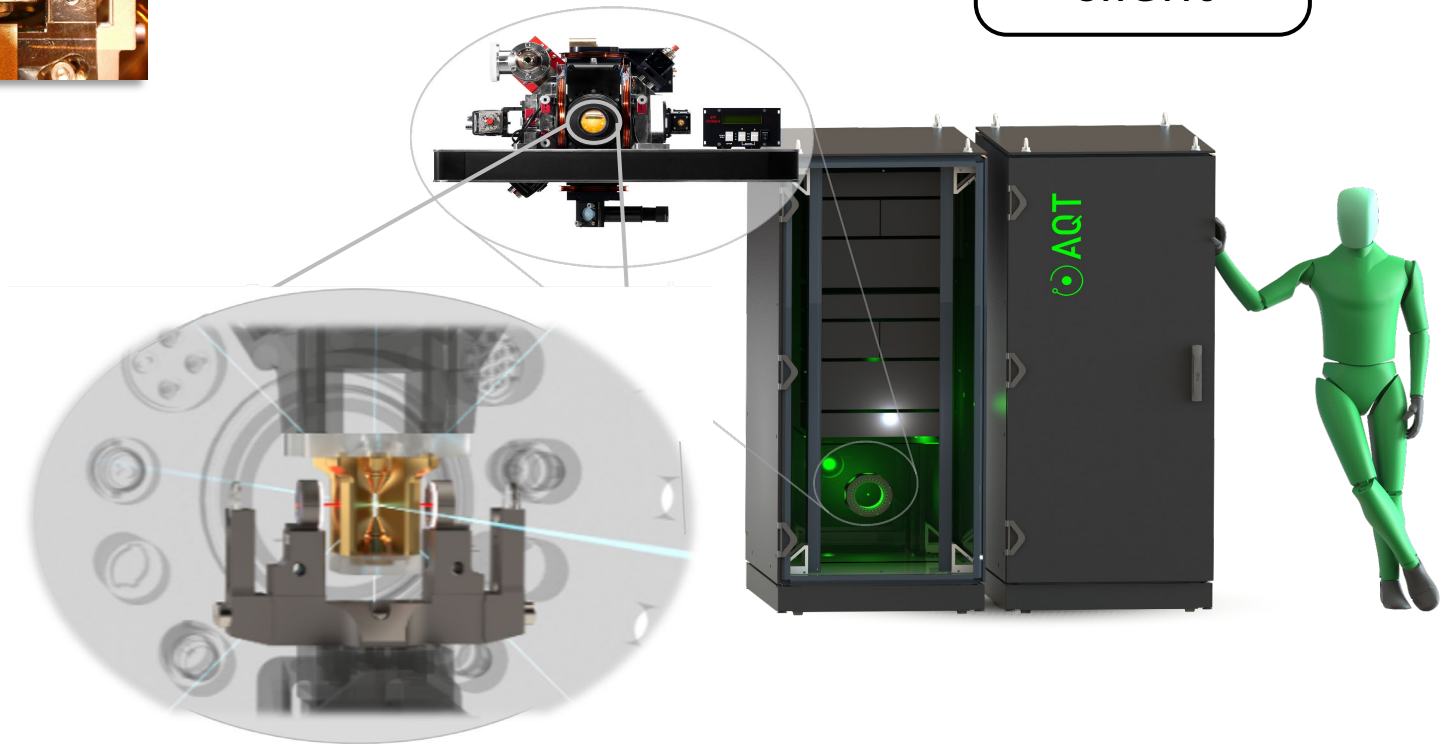




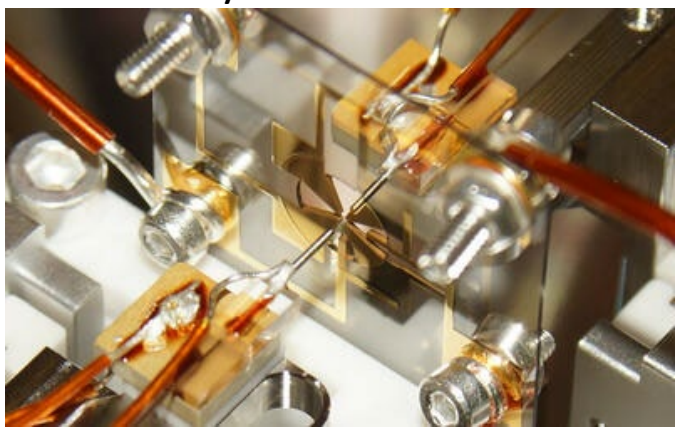


5 Km

Photonic client



Fiber cavity



The quantum network team in Innsbruck

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Senator (R-NY, 53rd District)

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JULIANE PRICE

Vocalist & Multi-Instrumentalist

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