NRC·CNRC

Quantum and Nanotechnologies Research Centre

Qubit Technologies

Building the Hardware of the Quantum Age

Dr Khaled Mnaymneh, PEng

National Research Council Canada
Conseil national de recherches Canada

Canada

Content

1) What is a qubit, and how they differ from classical bits

2) Challenges in building stable and scalable quantum systems

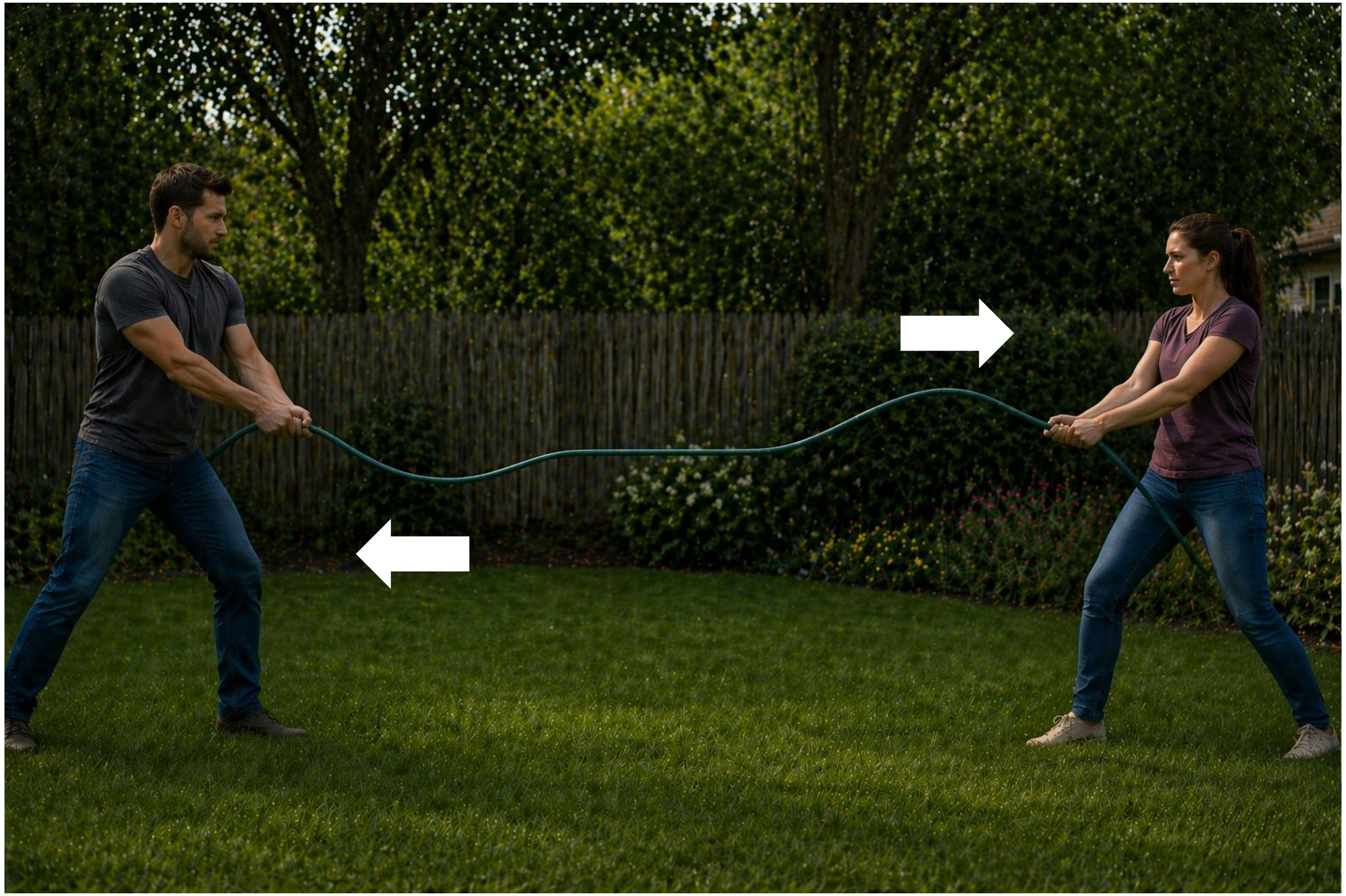
3) Qubit Modalities

4) Quantum Engineering – Support structures need for the Quantum Age

5) Quantum Business – Opportunities

Quantum Computing – What is a Qubit?

- **the qubit …**

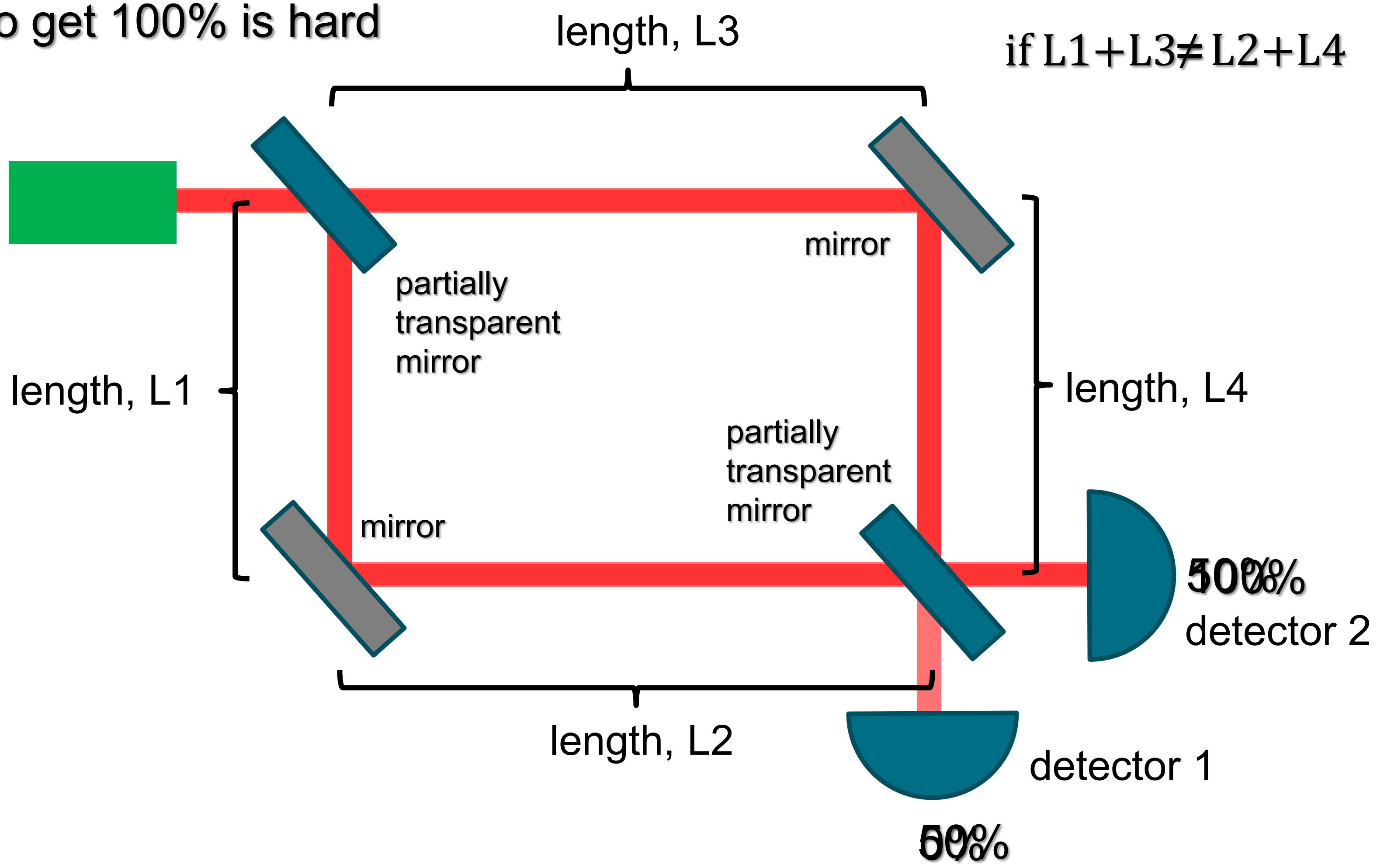


readout

Review – Many Worlds … Quantum Parallelism

- Mach-Zehender Interferometer
- alignment to get 100% is hard

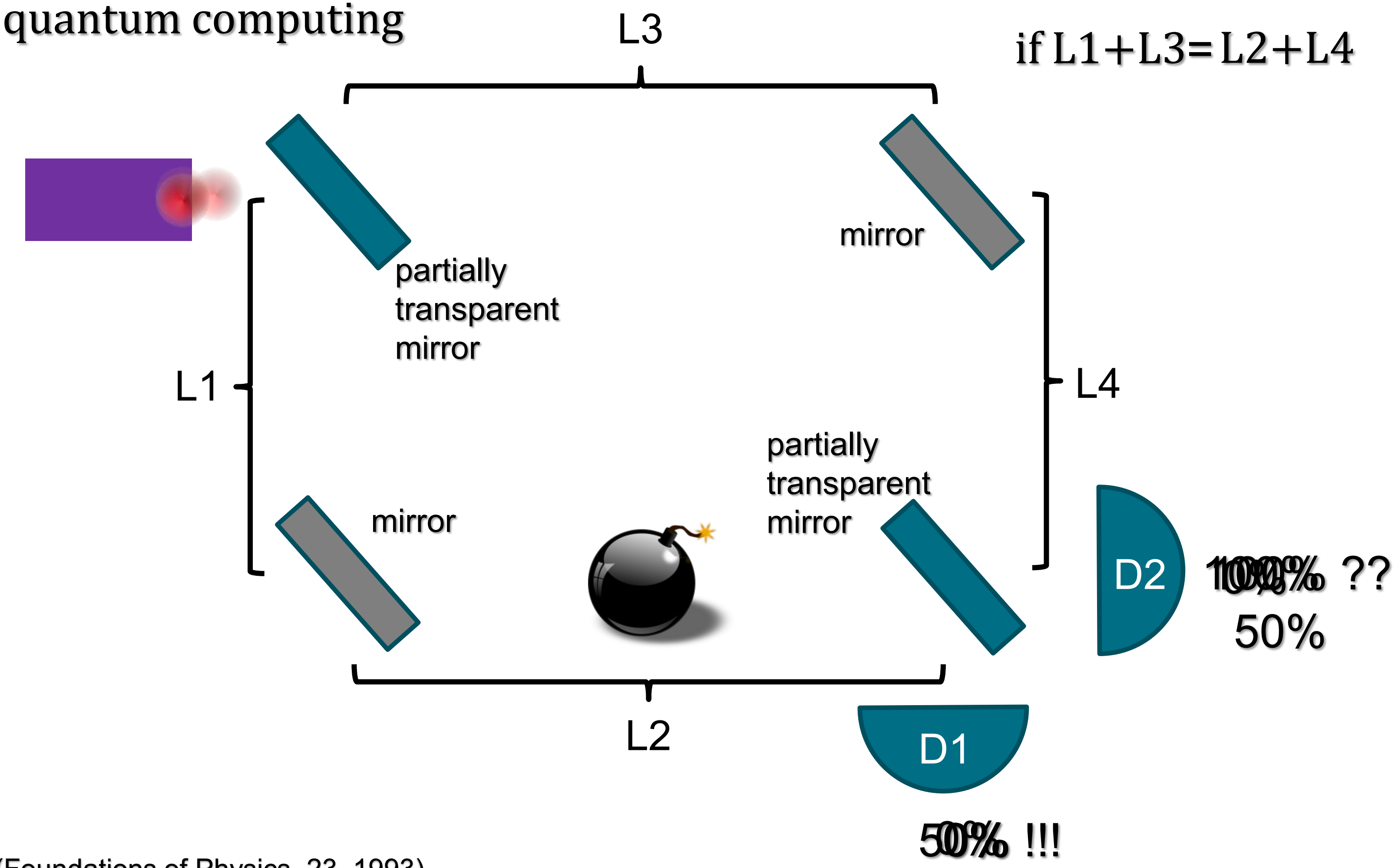
if L1+L3≠L2+L4



Review – Many Worlds … Quantum Parallelism

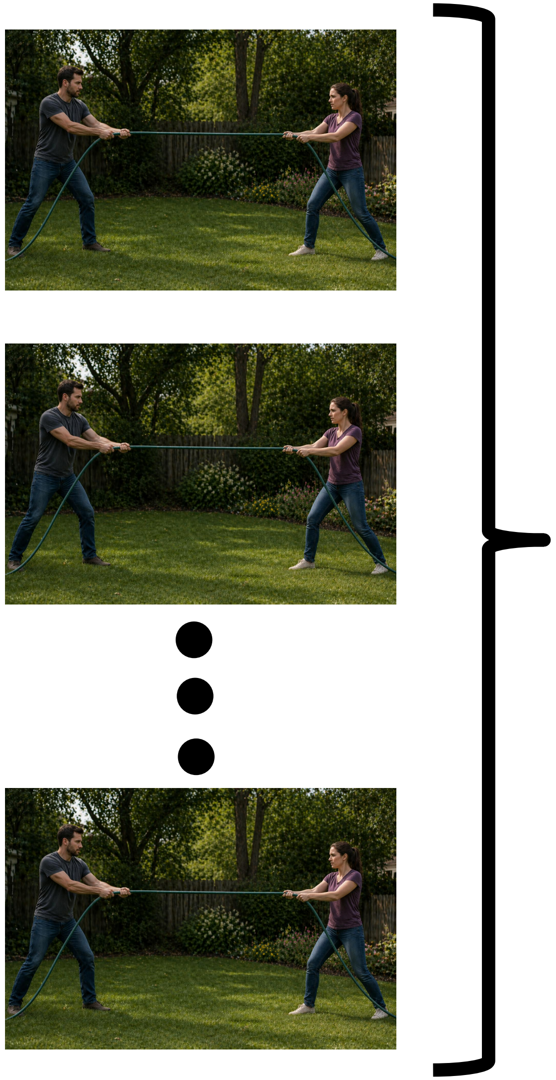
- real access to “what ifs” [counterfactual realities]
- essence of quantum computing

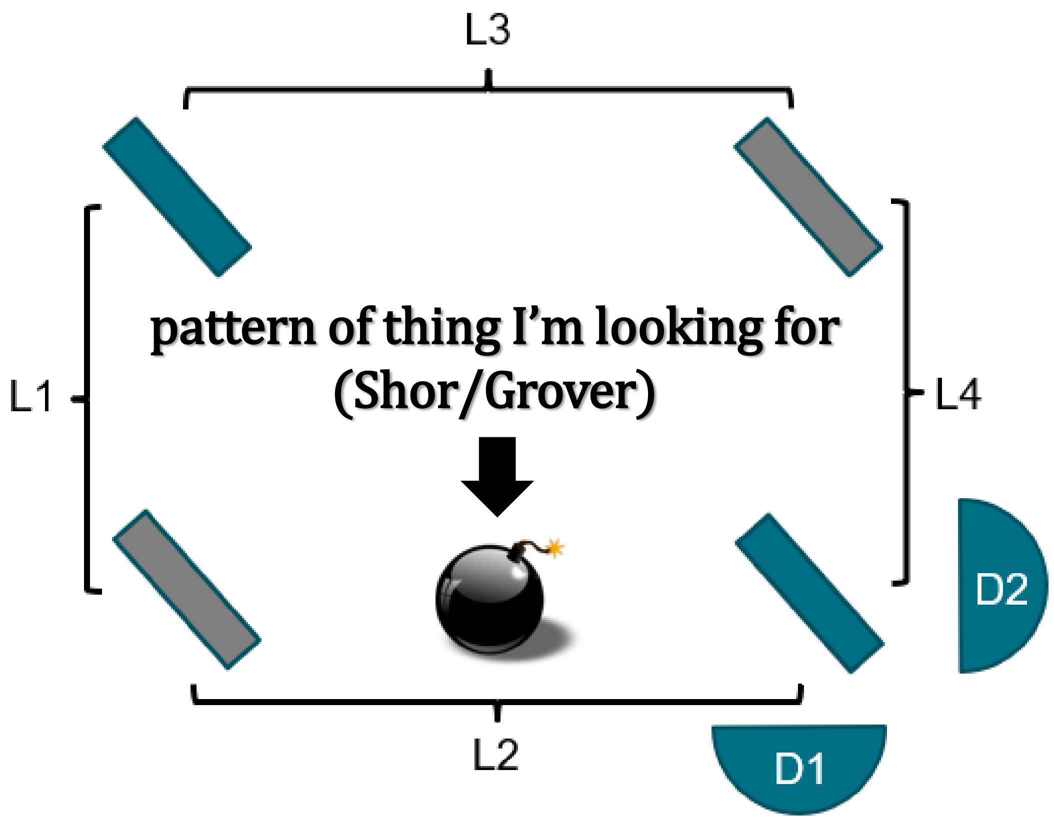
if L1+L3=L2+L4



Elitzur-Vaidman Bomb Tester (Foundations of Physics, 23, 1993)

Review – Many Worlds … Quantum Parallelism



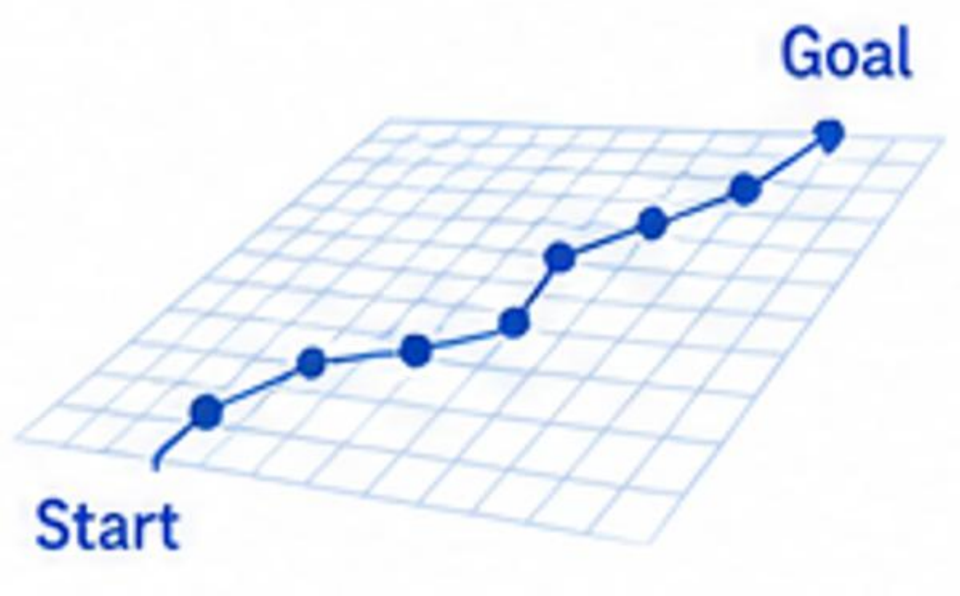


right answer in 10 days
(instead of 10^{80} days)

From single paths to many histories

- interference AMPLIFIES good histories and cancels bad ones

classical computation

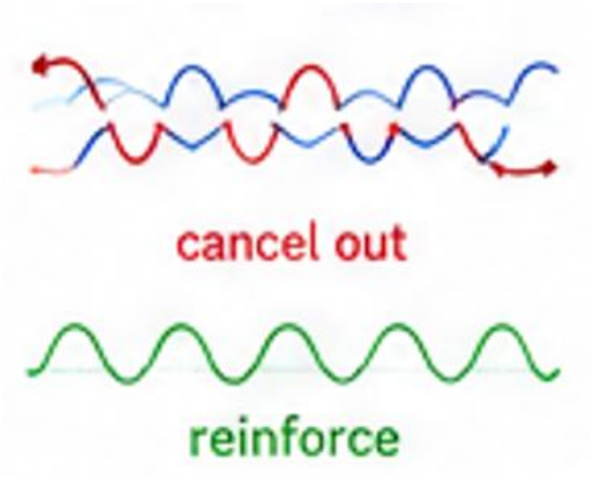


quantum computation

From single paths to many histories

- we do not read out histories; we get ONE measurement
- power comes from **engineering interference** so that only useful histories survive
- this is why in quantum, software and hardware are “tied at the hip”, unlike classical computation

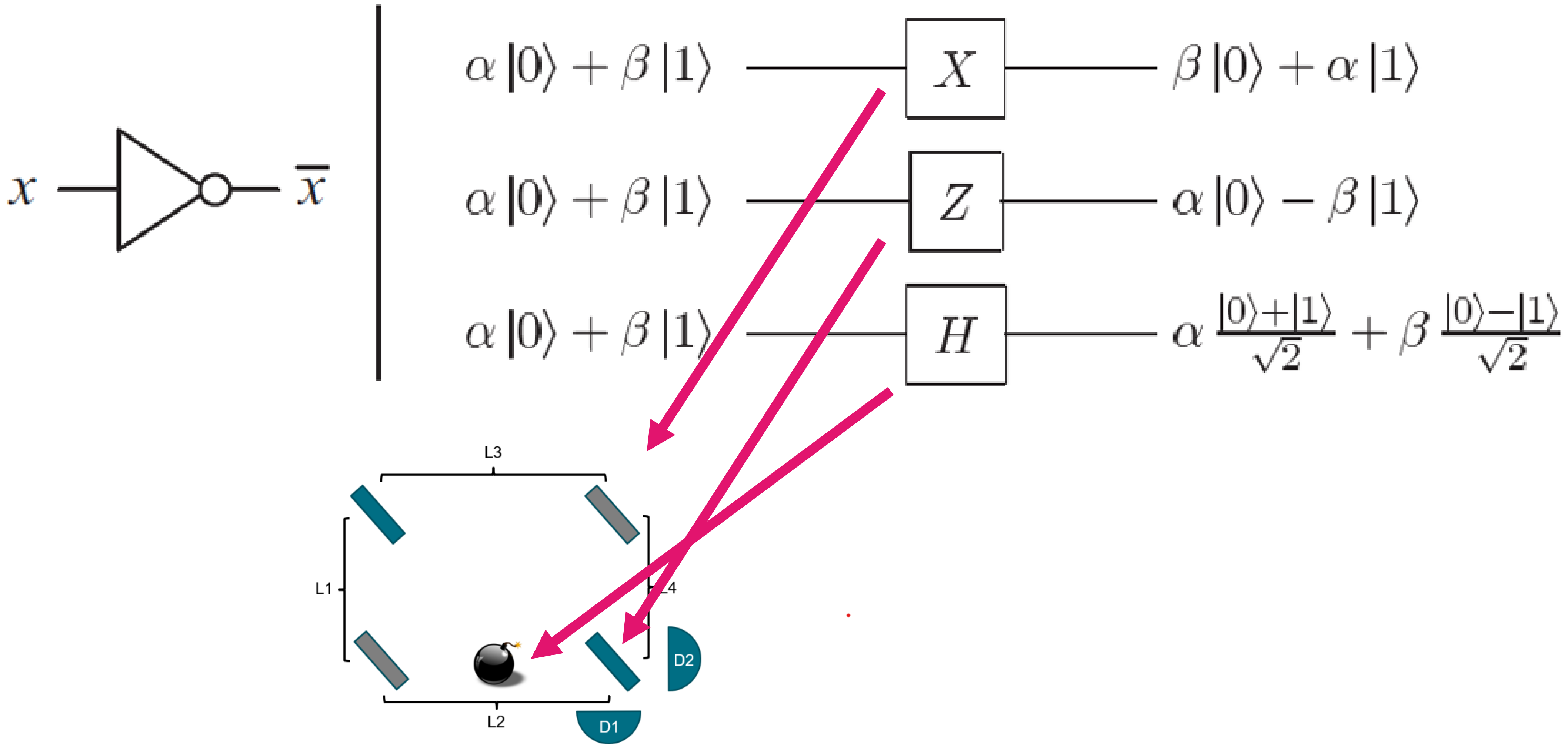
- many possible histories
- computation explores many trajectories



- phase cause destructive and constructive interference

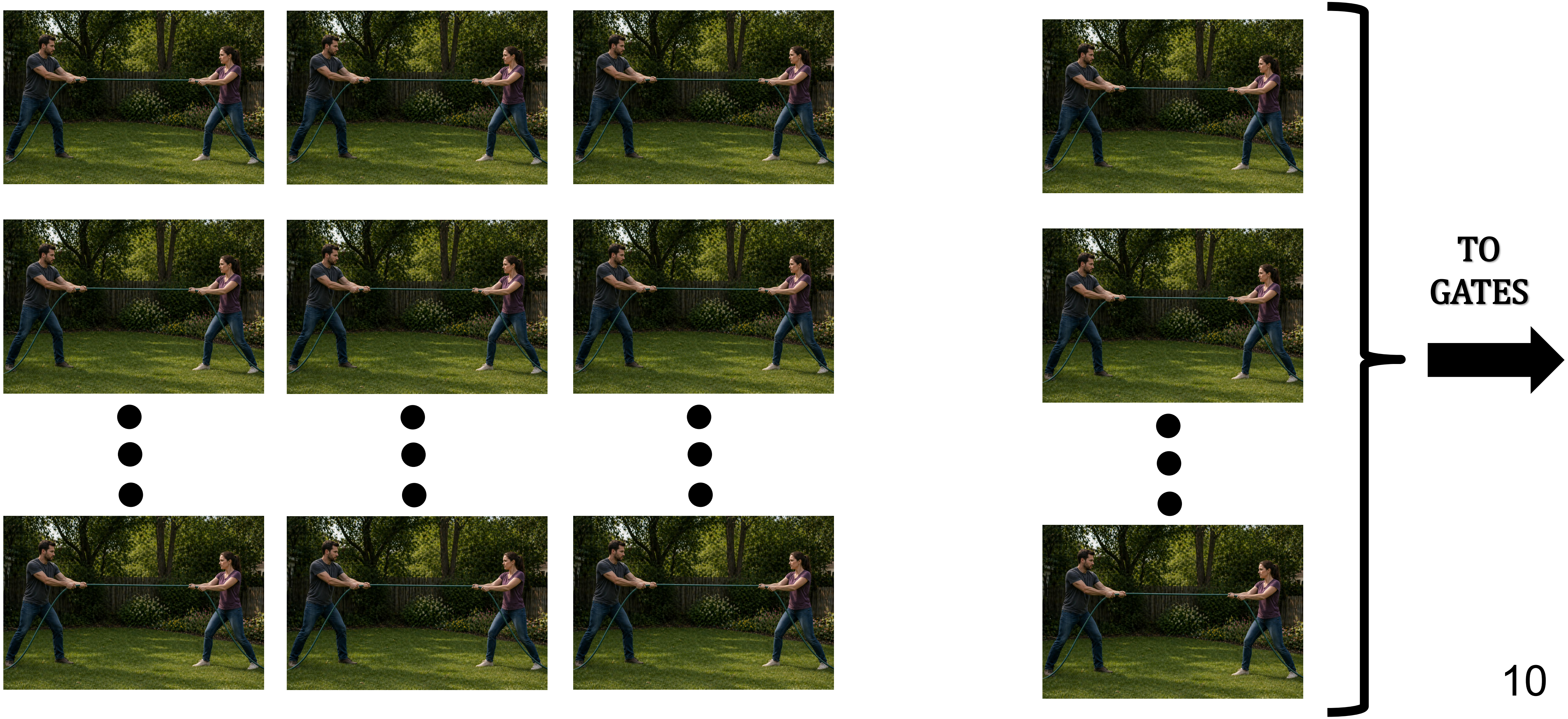
- probability concentrates on right answers

Qubit vs Bit

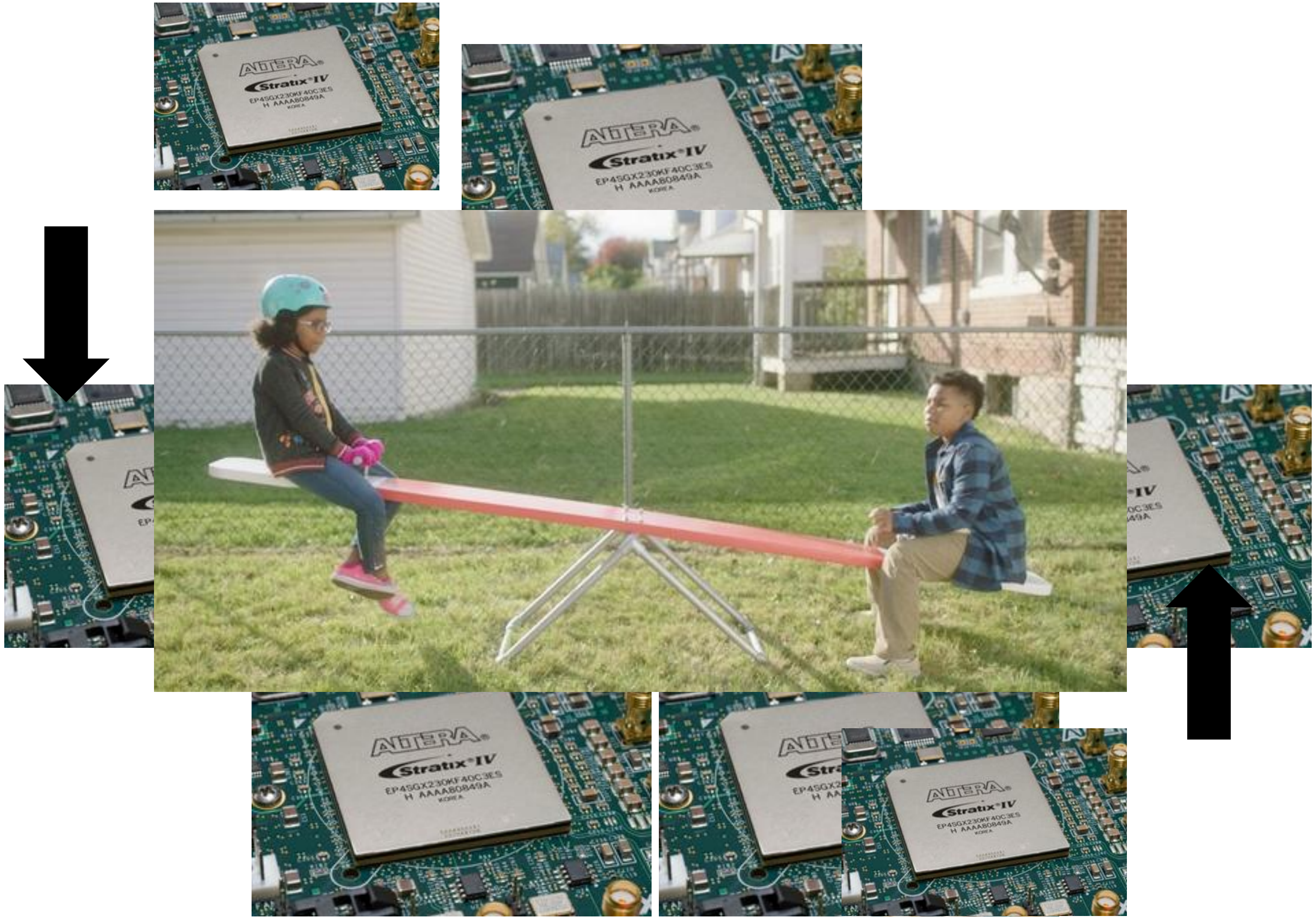


x
$\overline{x}$
$\alpha|0\rangle + \beta|1\rangle$
X
$\beta|0\rangle + \alpha|1\rangle$
$\alpha|0\rangle + \beta|1\rangle$
Z
$\alpha|0\rangle - \beta|1\rangle$
$\alpha|0\rangle + \beta|1\rangle$
H
$\alpha\frac{|0\rangle+|1\rangle}{\sqrt{2}} + \beta\frac{|0\rangle-|1\rangle}{\sqrt{2}}$
L3
L1
L4
L2
D2
D1

Error Correction / Fault Tolerance

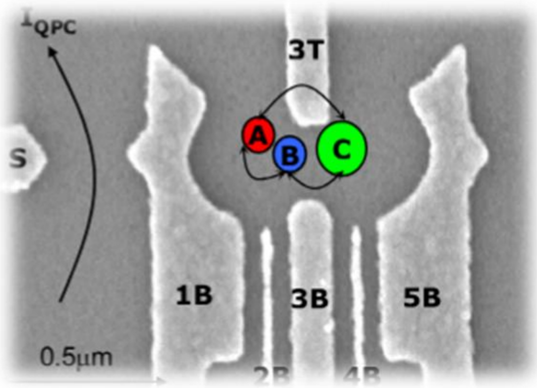


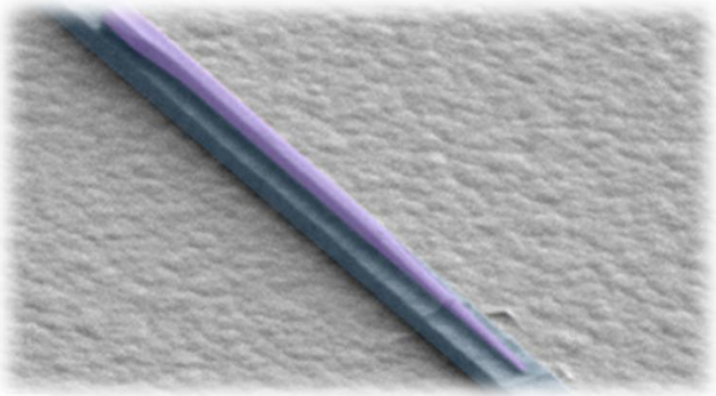
Classical Electronics to the Rescue!



Qubit Modalities

NRC's Spin Qubit

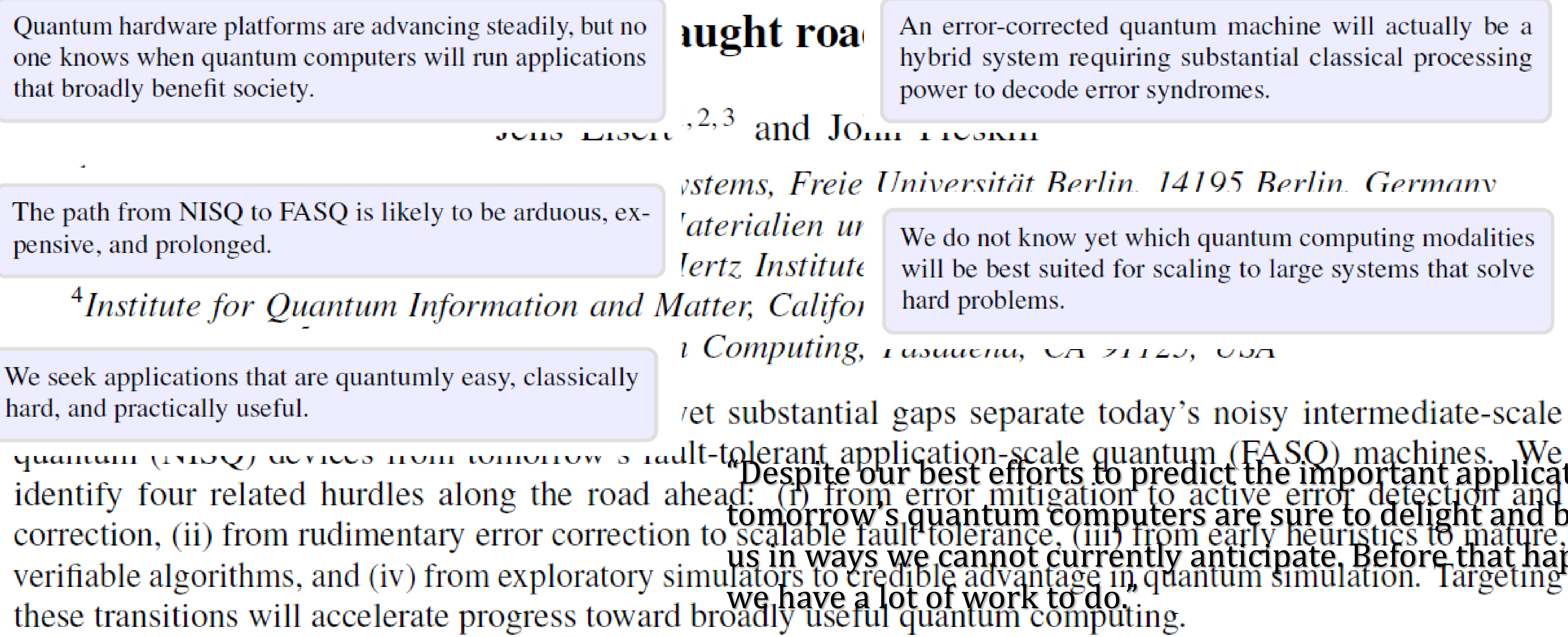




NRC's Photon Qubit

Studenikin, et al. Coherence Characteristics of a GaAs Single Heavy-Hole Spin Qubit Using a Modified Single-Shot Latching Readout Technique. *Nanomaterials*, *13*, 950, 2023
Mnaymneh, et al. On-Chip Integration of Single Photon Sources via Evanescent Coupling of Tapered Nanowires to SiN Waveguides. Adv. Quantum Technol., 3: 1900021, 2020

Challenges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4 Institute for Quantum Information and Matter, Califo...

...Computing, ...

...yet substantial gaps separate today's noisy intermediate-scale quantum (NISQ) devices from tomorrow's fault-tolerant application-scale quantum (FASQ) machines. We identify four related hurdles along the road ahead: (i) from error mitigation to active error detection and correction, (ii) from rudimentary error correction to scalable fault tolerance, (iii) from early heuristics to mature, verifiable algorithms, and (iv) from exploratory simulators to credible advantage in quantum simulation. Targeting these transitions will accelerate progress toward broadly useful quantum computing.

Quantum hardware platforms are advancing steadily, but no one knows when quantum computers will run applications that broadly benefit society.

An error-corrected quantum machine will actually be a hybrid system requiring substantial classical processing power to decode error syndromes.

The path from NISQ to FASQ is likely to be arduous, expensive, and prolonged.

We do not know yet which quantum computing modalities will be best suited for scaling to large systems that solve hard problems.

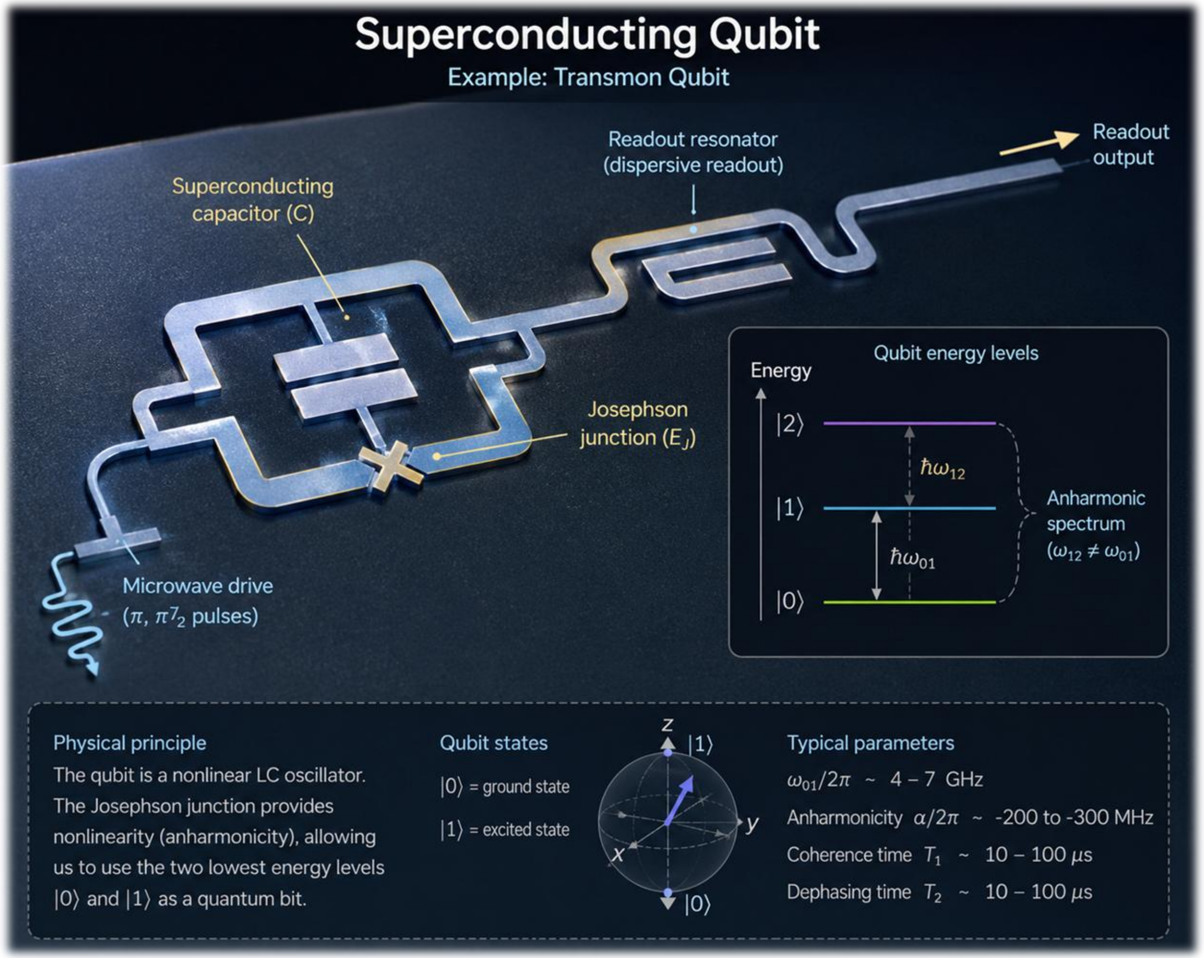
We seek applications that are quantumly easy, classically hard, and practically useful.

"Despite our best efforts to predict the important applications, tomorrow's quantum computers are sure to delight and benefit us in ways we cannot currently anticipate. Before that happens, we have a lot of work to do."

Qubit Modalities

We do not know yet which quantum computing modalities will be best suited for scaling to large systems that solve hard problems.

Platform: Superconducting - Transmons



ANYON

IBM

IQM

Google

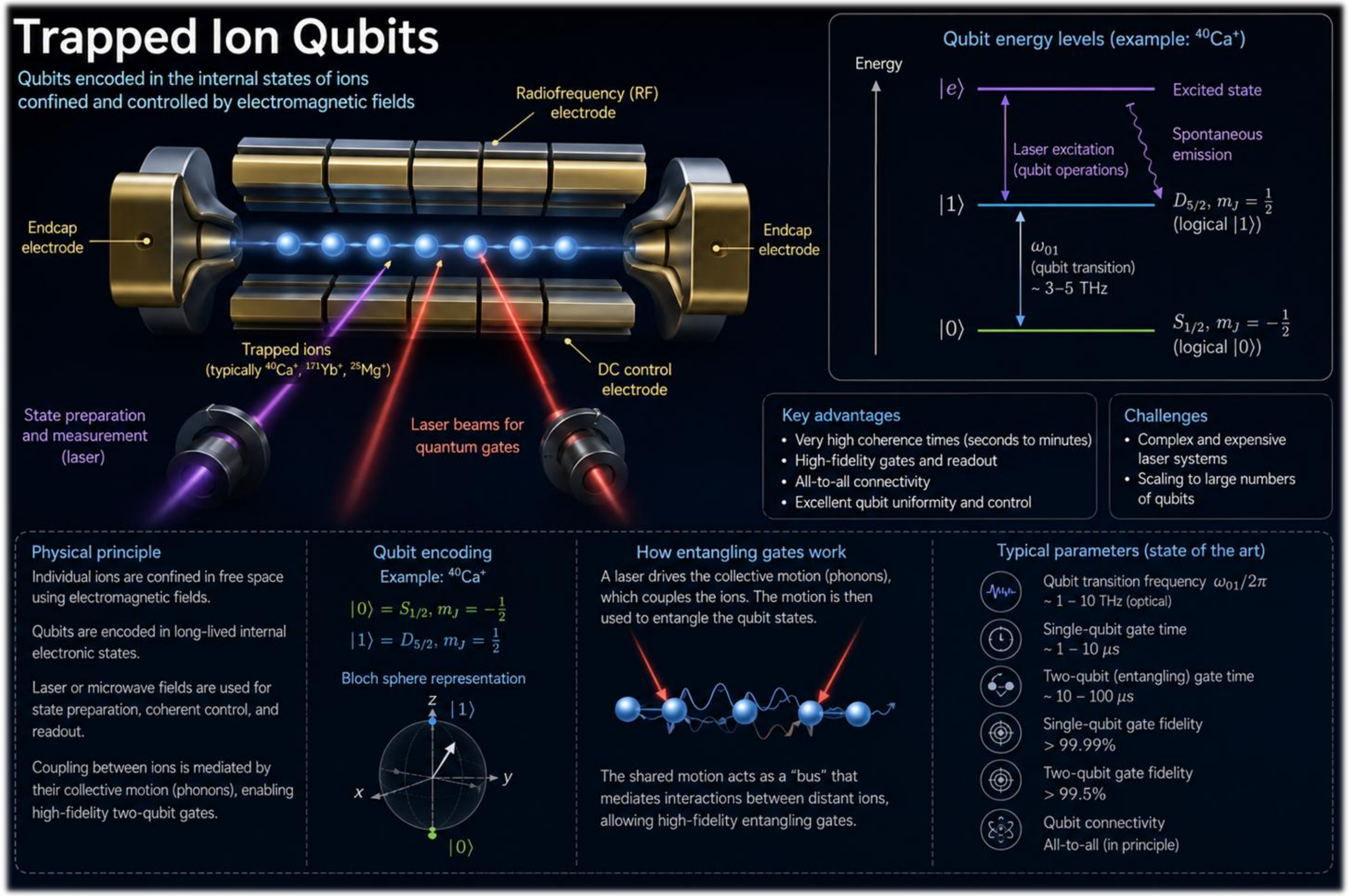
ATLANTIC QUANTUM

ALICE & BOB

Qubit Modalities

We do not know yet which quantum computing modalities will be best suited for scaling to large systems that solve hard problems.

Platform: Trapped Ion



IONQ
Quantum is now.

QUANTINUUM

AQT

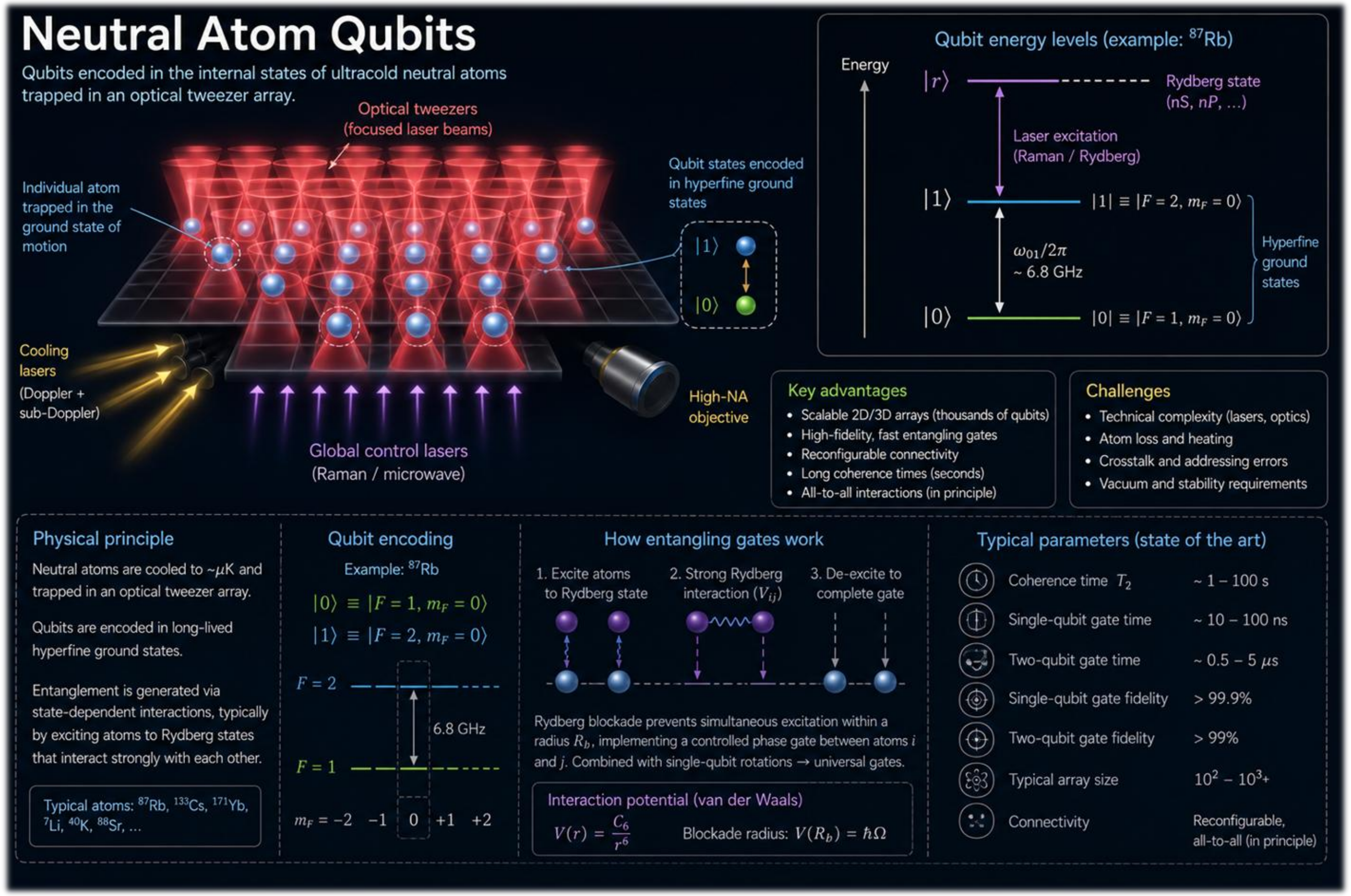
Universal Quantum

ZuriQ

Qubit Modalities

We do not know yet which quantum computing modalities will be best suited for scaling to large systems that solve hard problems.

Platform: Neutral Atom



Infleqtion

QuEra Putting Quantum to Work

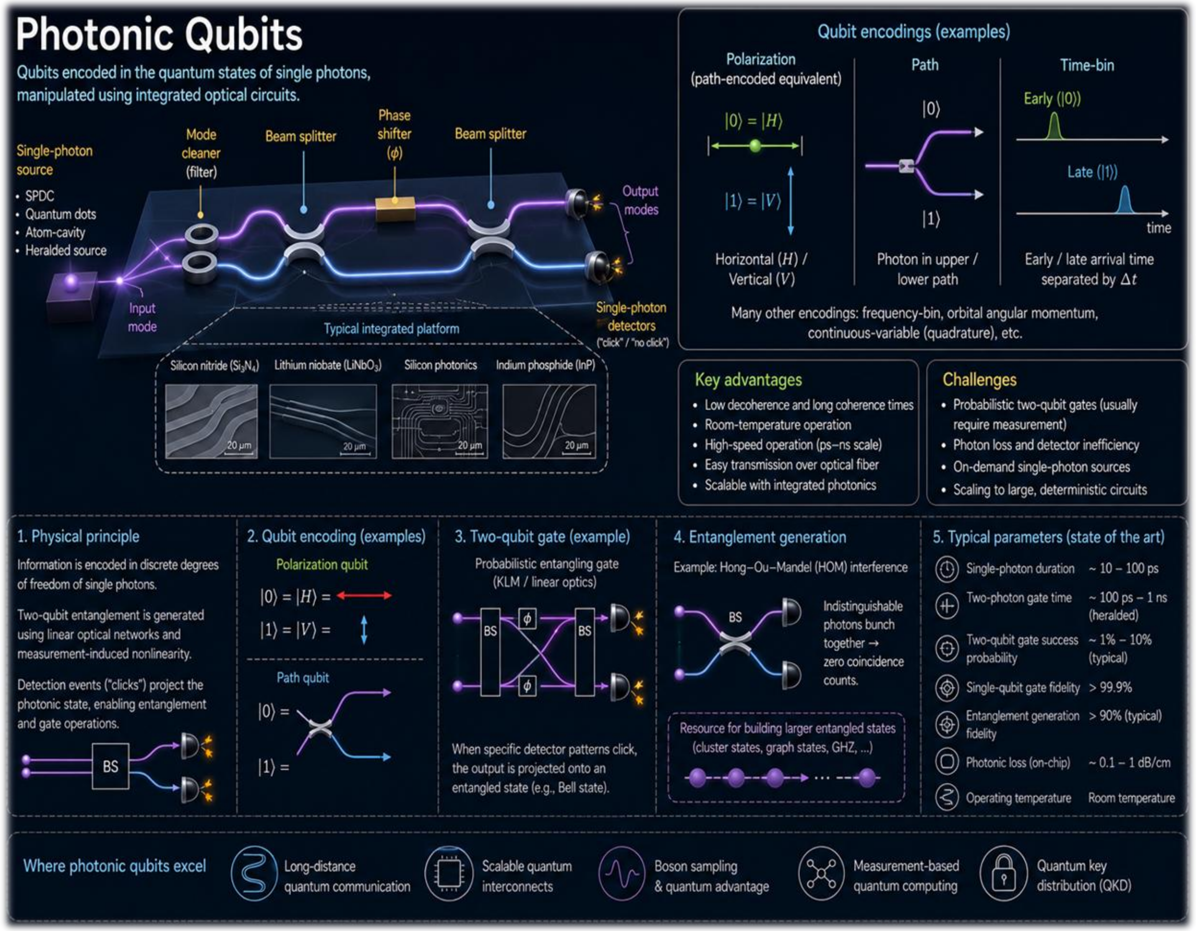
Pasqal

NanoQT Nanofiber Quantum Technologies

Qubit Modalities

We do not know yet which quantum computing modalities will be best suited for scaling to large systems that solve hard problems.

Platform: Photonics



XANADU

Photonic

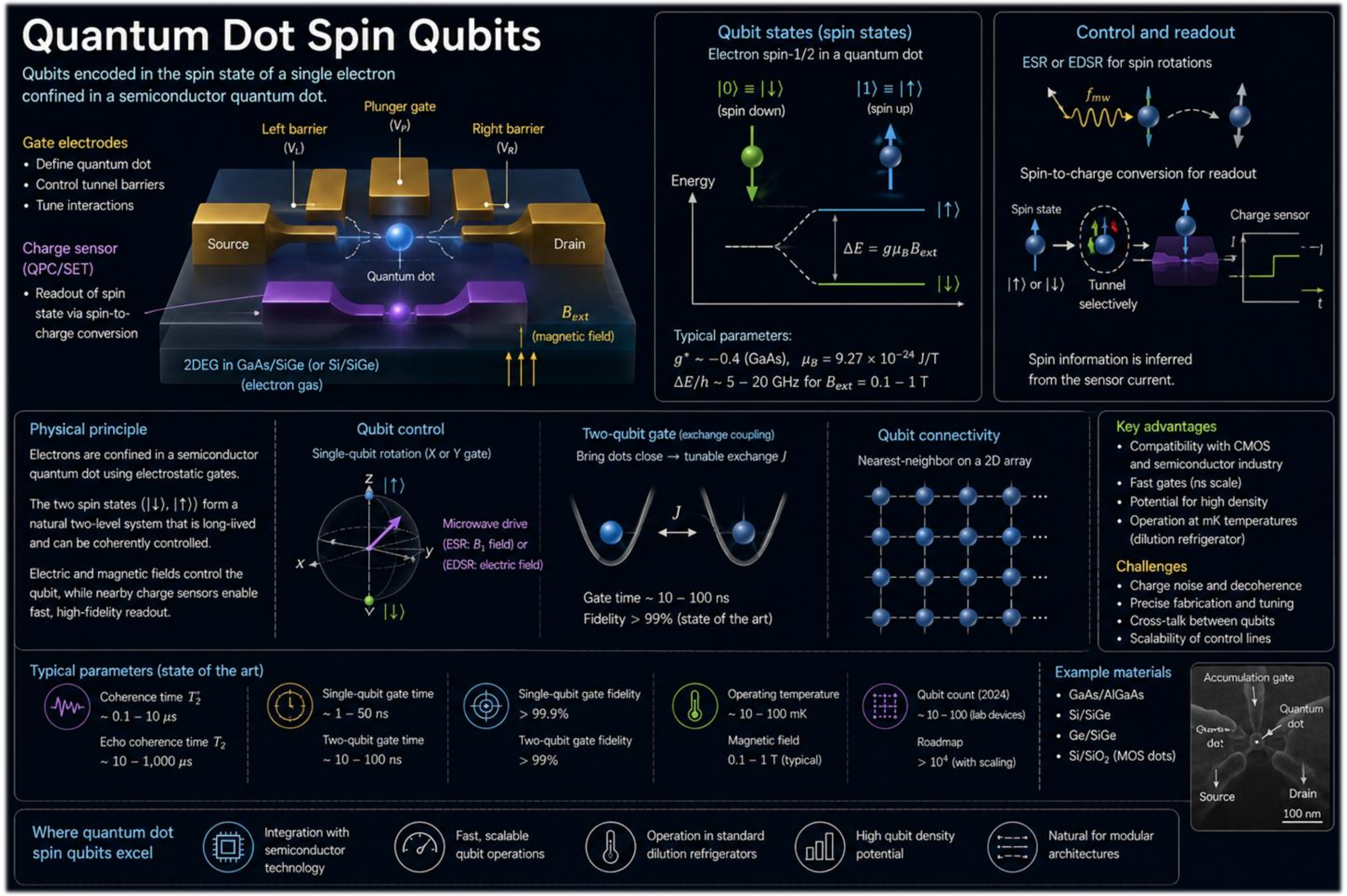
PsiQuantum

QUANDELA

Qubit Modalities

We do not know yet which quantum computing modalities will be best suited for scaling to large systems that solve hard problems.

Platform: Quantum Dots



intel

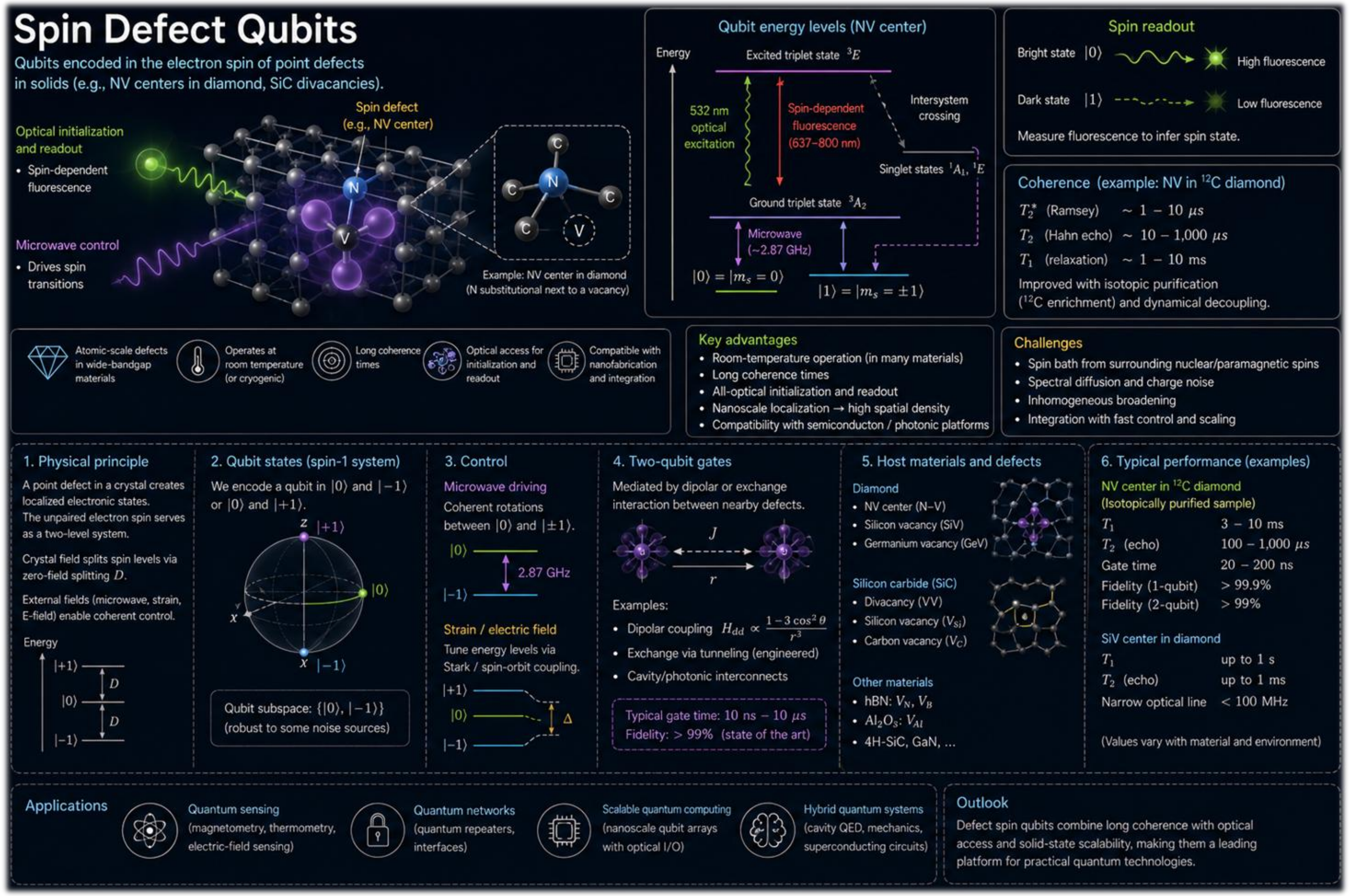
diraq

quobly

Qubit Modalities

We do not know yet which quantum computing modalities will be best suited for scaling to large systems that solve hard problems.

Platform: Spin defects



SBQuantum

Qnami

QUANTUM BRILLIANCE

SaxonQ

Challenges & Opportunities

REVIEW

vQR/ QI review

A QUANTUM WORLD

REVIEW

Challenges and opportunities for quantum information hardware

David D. Awschalom[1,2*], Hannes Bernien[1,3,4], Ronald Hanson[5,6], William D. Oliver[7,8,9], Jelena Vučković[10,11]

Platform	Quantum computing	Quantum simulation	Quantum networking	Quantum sensing
Superconducting	TRL 6-8 (scale 1 … 9)	TRL 6	TRL 3-4	TRL 3-5
Trapped ions	TRL 6-7	TRL 6-7	TRL 4-6	TRL 6-8
Neutral atoms	TRL 4-6	TRL 6-8	TRL 3-5	TRL 5-7
Photonics	TRL 4-6	TRL 4-6	TRL 6-9	TRL 5-7
Quantum dots	TRL 3-5	TRL 3-5	TRL 3-4	TRL 3-6
Spin defects	TRL 3-4	TRL 3-4	TRL 4-6	TRL 8-9

Silicon Nitride for Quantum Technologies

REVIEW

vQR/ QI review

A QUANTUM WORLD

REVIEW

Challenges and opportunities for quantum information hardware

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Prof. Connor Kupchak (Quantum Tech.) Carleton U

Dr. Abubaker Tareki (SiN Materials)

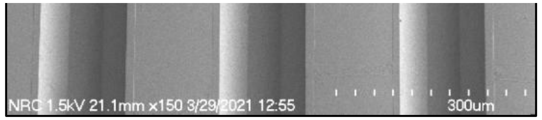
ADVANCED QUANTUM TECHNOLOGIES

Communication | Full Access

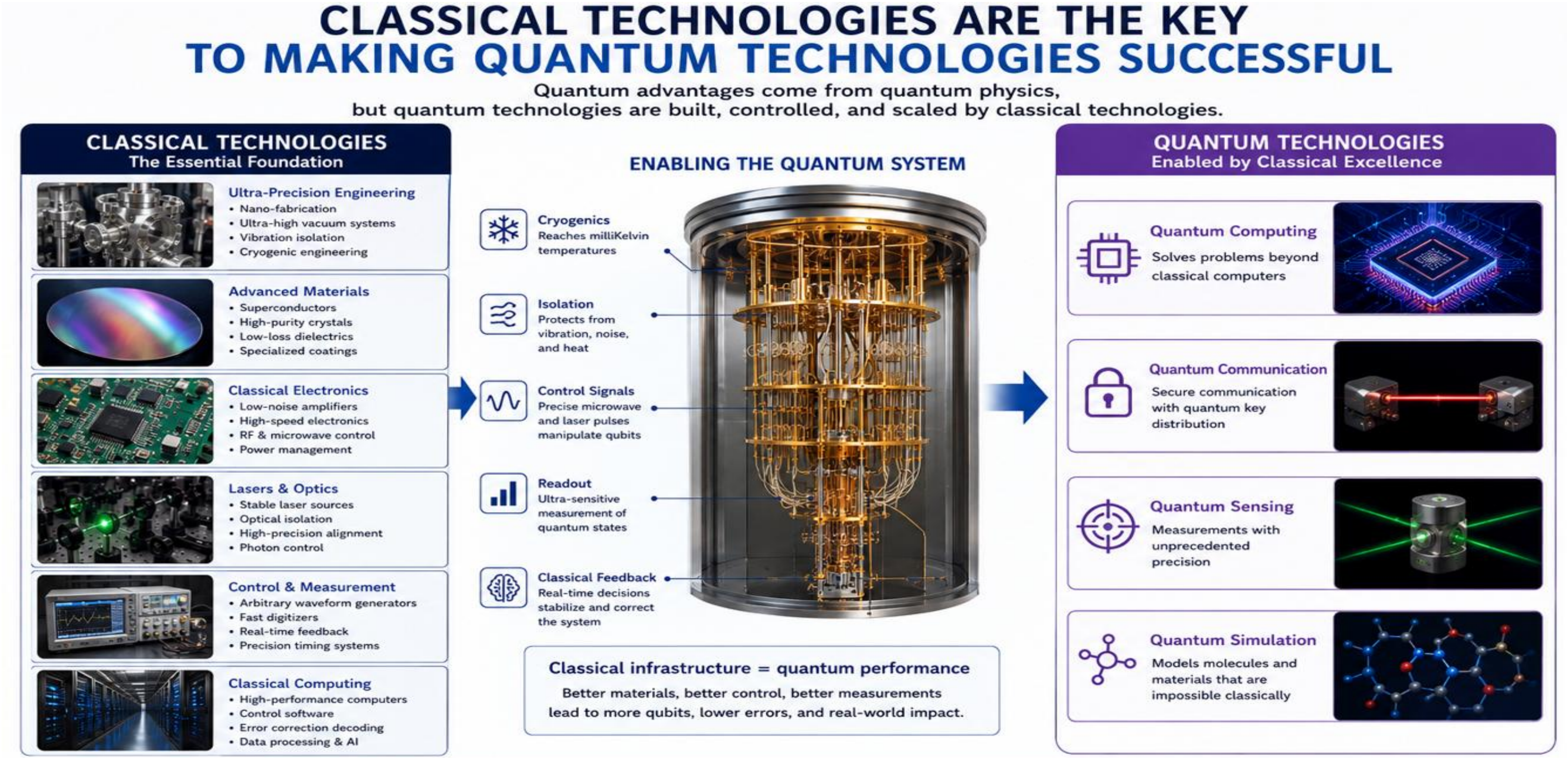
On-Chip Integration of Single Photon Sources via Evanescent

Photonics exemplifies the challenge: Silicon photonics fabricated in commercial foundries typically exhibits propagation loss of 0.25 to 1 dB/cm, and fiber-to-chip grating couplers available in their process design kits exhibit >3 dB of loss and are narrowband (*69*). Although lower propagation losses of decibels per meter have been reported in research-grade silicon nitride, lithium niobate, or silicon carbide photonics (*73, 79, 80*), these processes have not yet become widely available in a foundry environment. Moreover, state-of-the-art spatial light modulators have limited resolution and speed for scaling tweezer arrays (*81*), and solutions are needed at shorter wavelengths, with smaller pixel sizes and higher speed for trapping more atoms, reducing their separation, and controlling and moving atoms faster.

bulk losses < 0.1 dB/cm



Thanks to NRC's Quantum Sensing Program


CLASSICAL TECHNOLOGIES ARE THE KEY
TO MAKING QUANTUM TECHNOLOGIES SUCCESSFUL
Quantum advantages come from quantum physics,
but quantum technologies are built, controlled, and scaled by classical technologies.
CLASSICAL TECHNOLOGIES
The Essential Foundation
Ultra-Precision Engineering
• Nano-fabrication
• Ultra-high vacuum systems
• Vibration isolation
• Cryogenic engineering
Advanced Materials
• Superconductors
• High-purity crystals
• Low-loss dielectrics
• Specialized coatings
Classical Electronics
• Low-noise amplifiers
• High-speed electronics
• RF & microwave control
• Power management
Lasers & Optics
• Stable laser sources
• Optical isolation
• High-precision alignment
• Photon control
Control & Measurement
• Arbitrary waveform generators
• Fast digitizers
• Real-time feedback
• Precision timing systems
Classical Computing
• High-performance computers
• Control software
• Error correction decoding
• Data processing & AI
ENABLING THE QUANTUM SYSTEM
Cryogenics
Reaches milliKelvin temperatures
Isolation
Protects from vibration, noise, and heat
Control Signals
Precise microwave and laser pulses manipulate qubits
Readout
Ultra-sensitive measurement of quantum states
Classical Feedback
Real-time decisions stabilize and correct the system
Classical infrastructure = quantum performance
Better materials, better control, better measurements
lead to more qubits, lower errors, and real-world impact.
QUANTUM TECHNOLOGIES
Enabled by Classical Excellence
Quantum Computing
Solves problems beyond classical computers
Quantum Communication
Secure communication with quantum key distribution
Quantum Sensing
Measurements with unprecedented precision
Quantum Simulation
Models molecules and materials that are impossible classically

NRC’s supports the National Quantum Strategy

“Funding, de-risking and creating supportive policy frameworks for emerging technologies, convening and coordinating, procuring goods and services, and serving as a research partner.”

The NRC supports all Canadian strategies on quantum

National Metrology Institute Initiatives

nmiQ

Canadian Quantum Strategies

- NRC Quantum R&D Initiative ($9.0M)
- NRC Challenge Programs ($50.0M)

NRC funded initiatives

NRC Quantum + Portfolio

COLLABORATION R&D PROGRAMS

- Small teams and Ideation projects
- High-throughput and Secure Networks
- Quantum Sensors
- Applied Quantum Computing
- Quantum InterNetworking (NEW)

RESEARCH CENTRES

- Quantum & Nanotechnologies Research Centre
- Metrology Research Centre
- Digital Technologies

COLLABORATION CENTRE

- Joint Centre for Extreme Photonics

BUSINESS INNOVATION

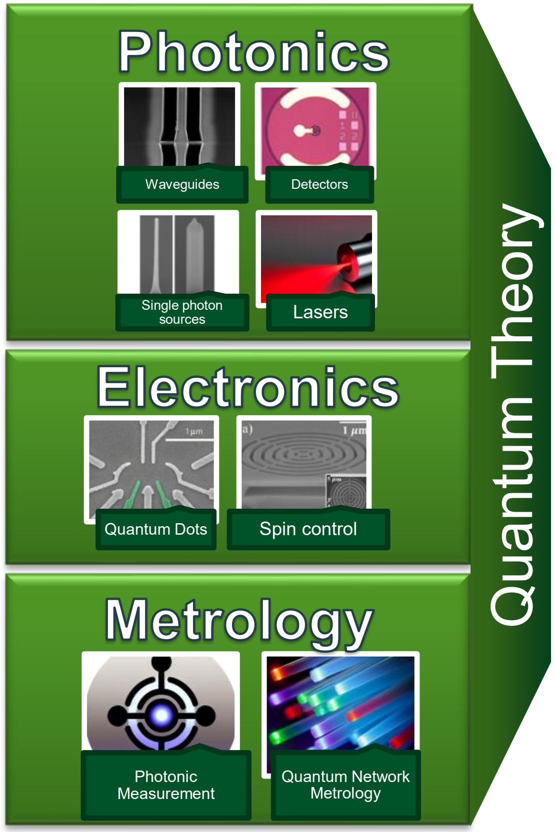
- Canadian Photonics Fabrication Centre
- Industrial Research Assistance Program

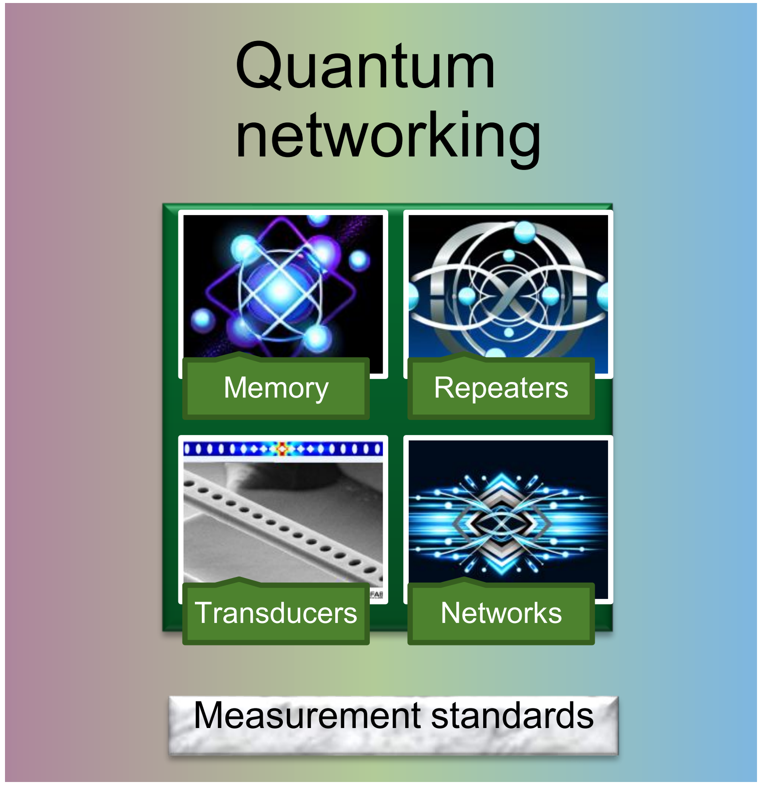
NRC QUANTUM
Bringing technical expertise to collaborations

NRC has a diversity of quantum expertise →

Essential ingredients for heterogeneous quantum networking

← **Canada has world-class quantum talent and expertise**





Quantum Industry

Quantum Valley Ideas Lab

Quantum Bridge

Nord Quantique

XANADU

photonic

DREAM PHOTONICS

SBQuantum

+ many more

Academic Hubs

Vancouver, Montréal, Sherbrooke, Calgary, Ottawa, Toronto, Edmonton, Waterloo

+ many more

Thank You!