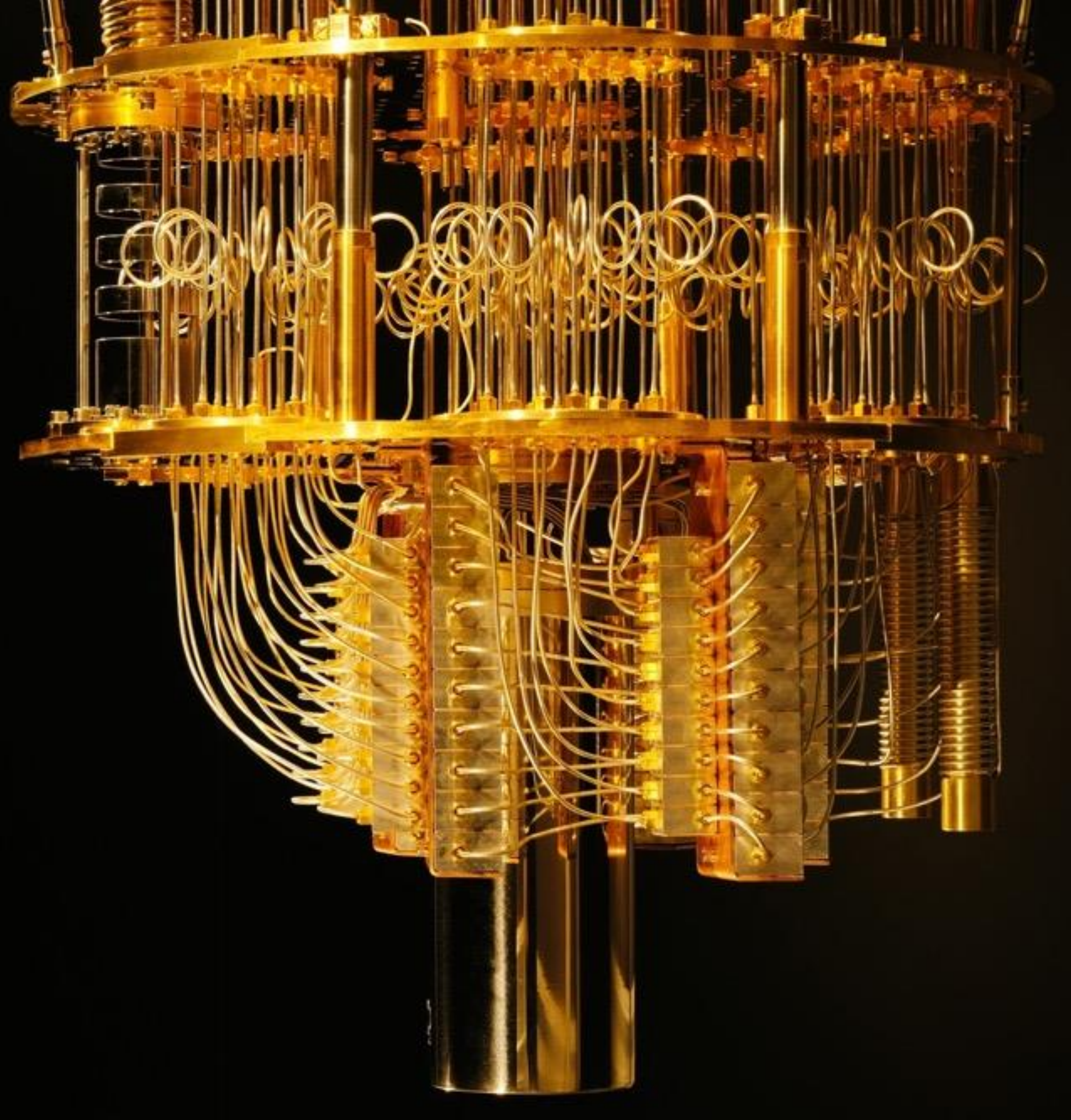
Future Quantum Technologies

Jerry Chow

Senior Manager, Quantum System Technology

IBM Q



"I think I can safely say that nobody understands quantum mechanics."

Richard Feynman

The Character of Physical Law (MIT Press: Cambridge, Massachusetts, 1995).

A physical system in a **perfectly definite state** can still behave **randomly**

Uncertainty principle, $\Delta x \, \Delta p \sim h$

Two systems that are **too far apart** to influence each other can nevertheless behave in ways that, though **individually random**, are somehow **strongly correlated**.

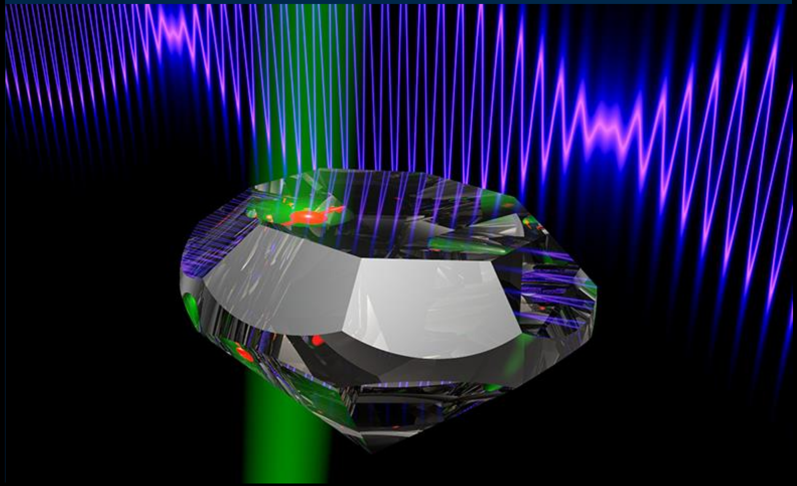
Entanglement, "spooky" action at a distance

Quantum Technologies are about working out how to effectively make use these two **principles**

New quantum technologies will reshape the way we do sensing, communication, and computing in the 21st century

Quantum Metrology

Dramatically improving the resolution and imaging of the world around and within us



Quantum Communication

Protecting the information and data we share from hackers and eavesdroppers

Quantum Computing

Reimagining information processing and the machines that do it

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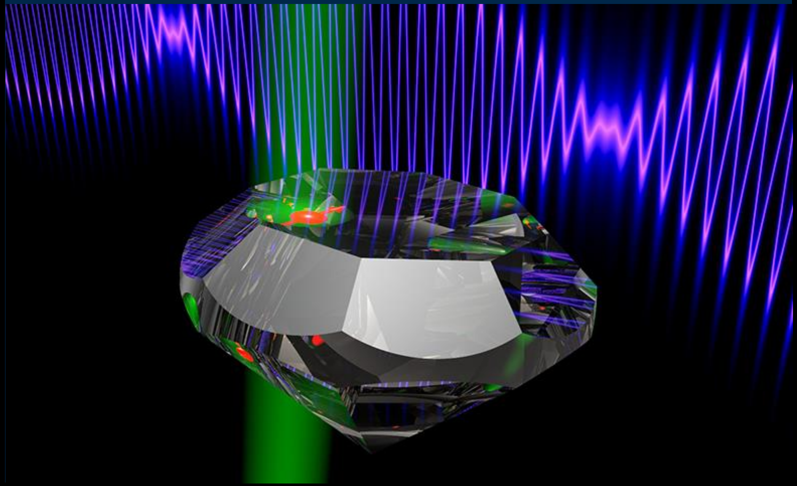

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Types of Quantum Computers

Color Key:
Applications
Properties
Computational Power

Universal quantum computers

Annealer

Analog Quantum Simulator

Adiabatic Quantum Computer

Improvement path

NISQ
Noisy Intermediate Scale Quantum Computer

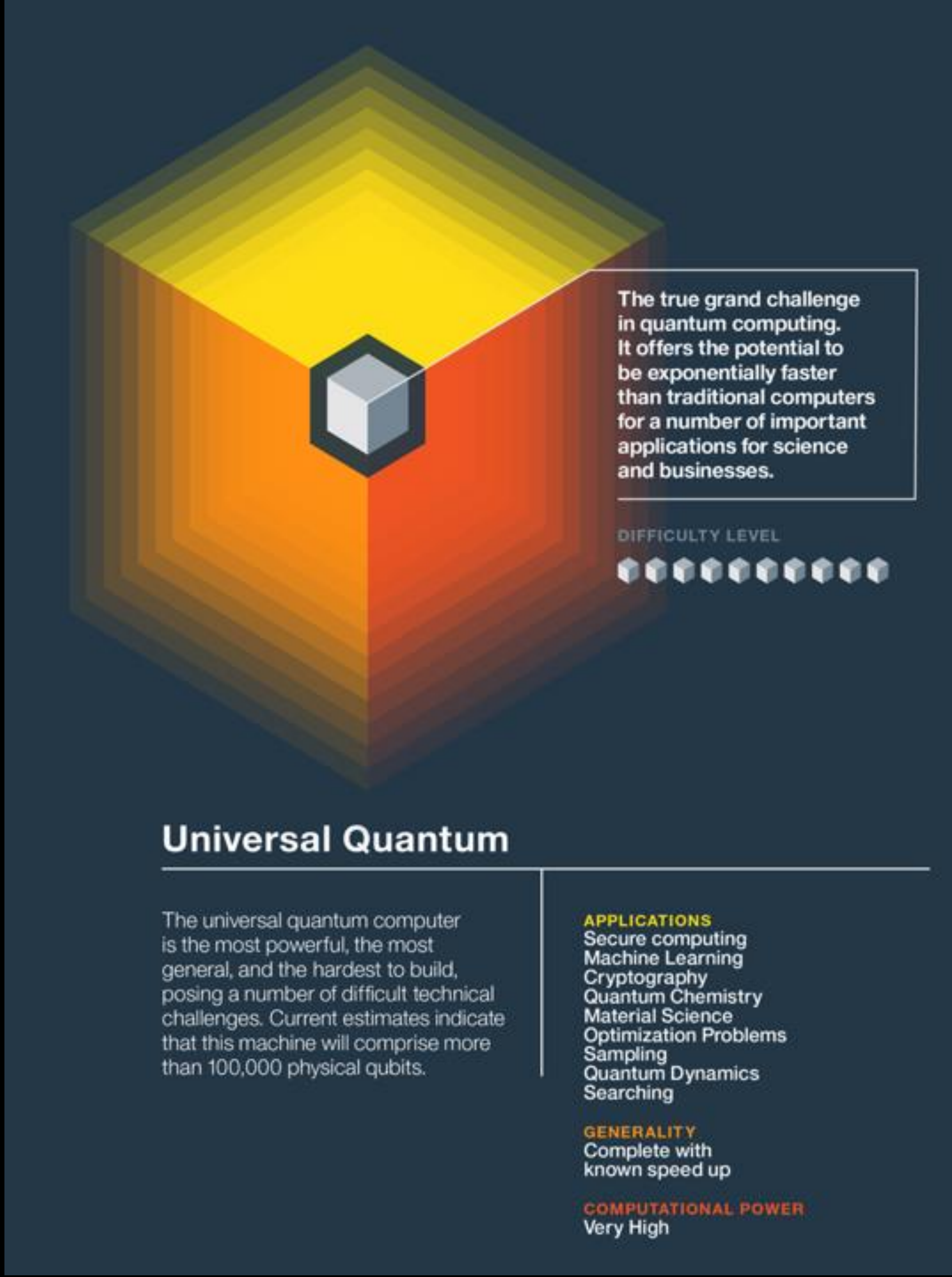
Fault Tolerant Quantum Computer

Hitachi 20K spin CMOS annealer
IEEE JSSC v51, 303 (2016)

Graphics: Carl De Torres for IBM Research

“Holy Grail” of quantum research is a fault-tolerant, universal quantum computer.

This is *the goal*, but it is still in the distant future, if it is possible.

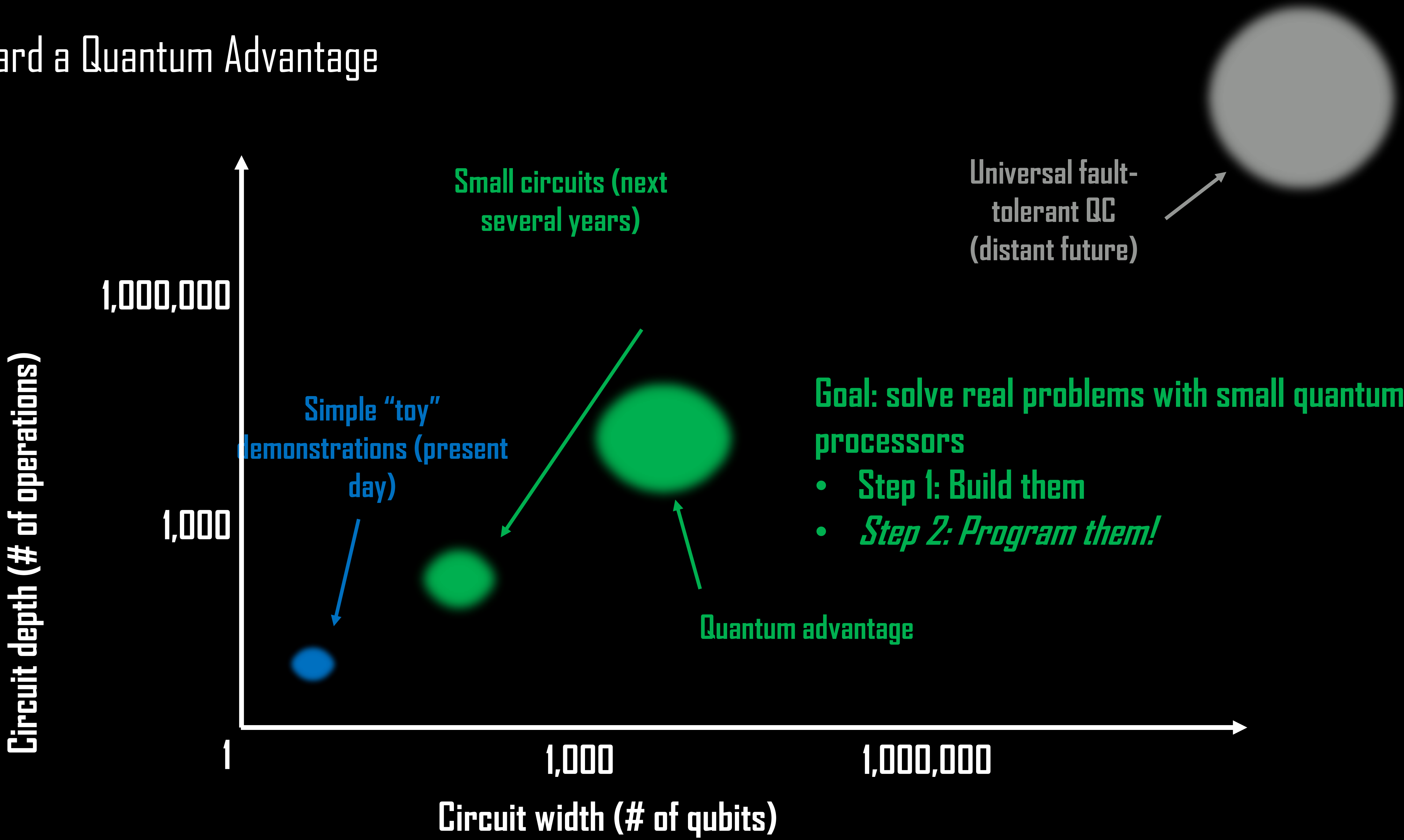


We are in the NISQ era of QC

- **N**oisy **I**ntermediate **S**cale **Q**uantum [1]
- Short algorithms limited by errors
- Heuristic applications with possible, but not (yet) provable advantage

[1] Quantum Computing in the NISQ era and beyond
John Preskill Quantum 2, 79 (2018)

Toward a Quantum Advantage

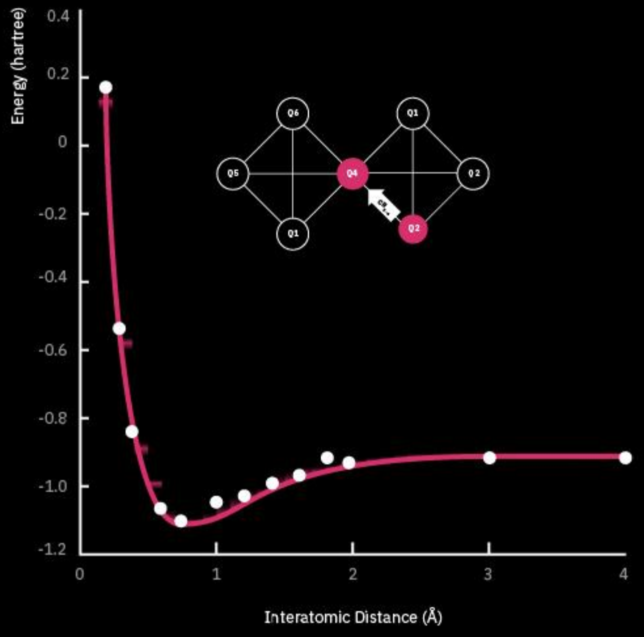


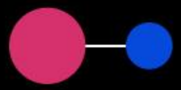
Goal: solve real problems with small quantum processors

- Step 1: Build them
- *Step 2: Program them!*

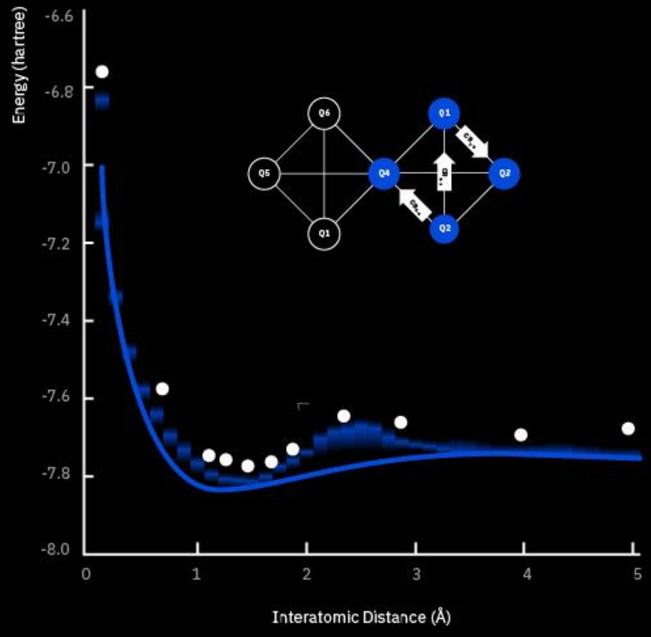
Chemistry with a quantum computer

Hydrogen (H_2): 2 Qubits

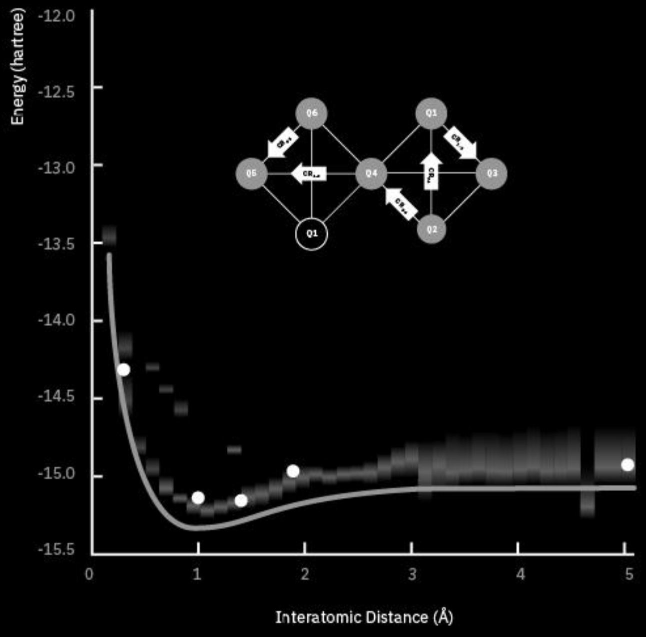




Lithium Hybride (LiH): 4 Qubits



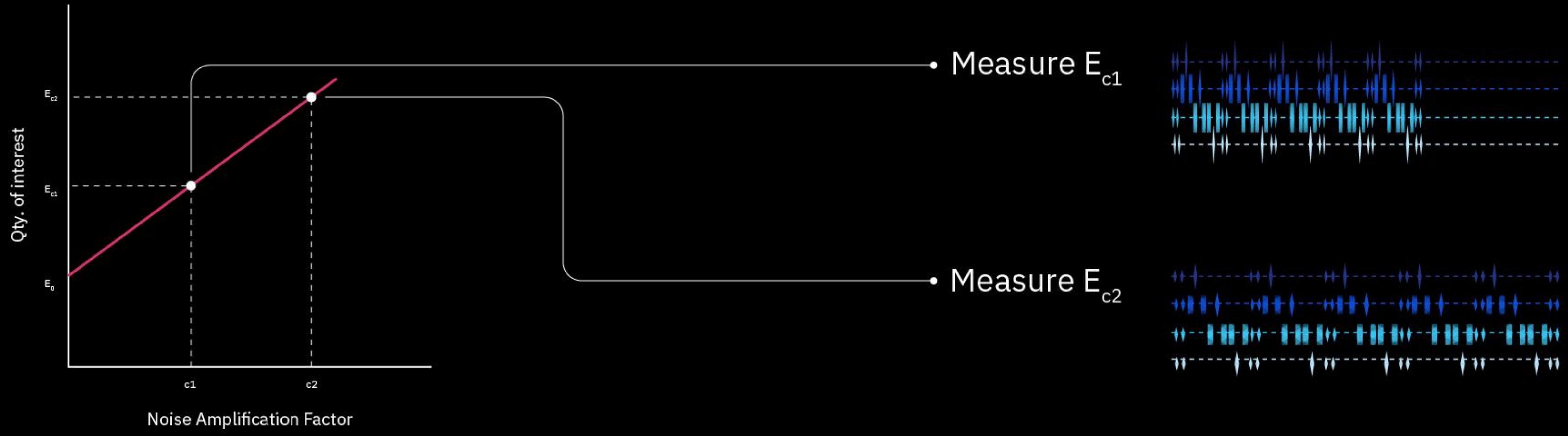
Beryllium hydride (BeH_2): 8 6 Qubits



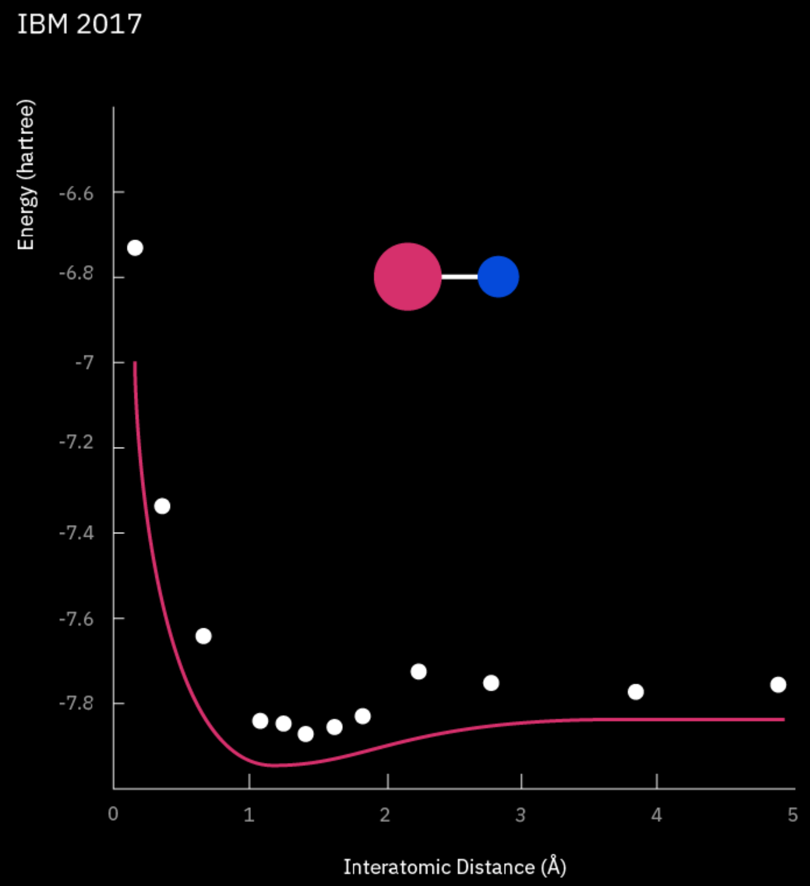
Nature
September 2017

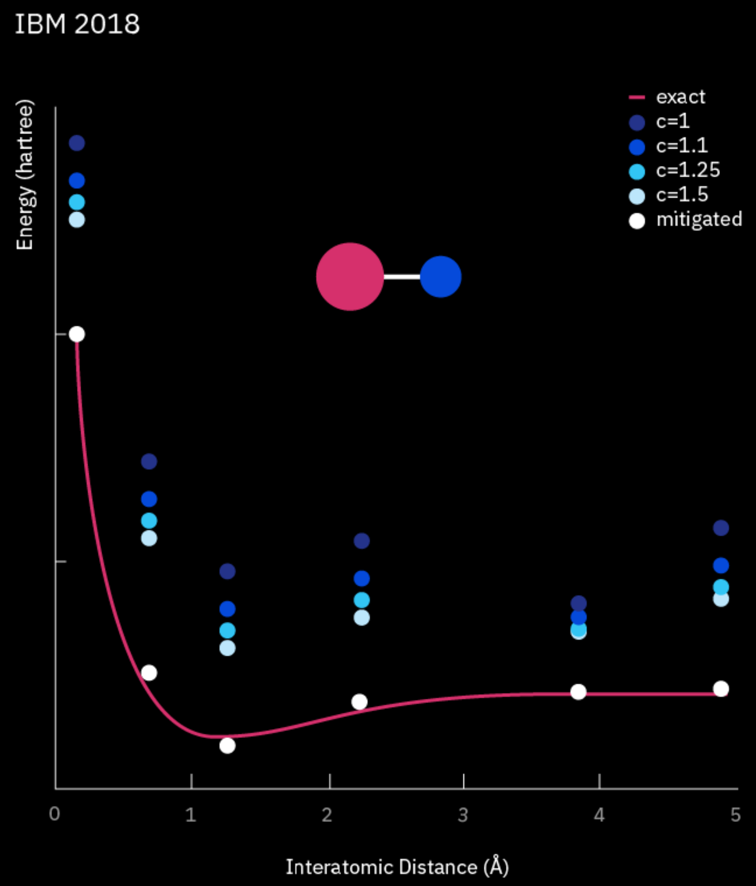
Finding the right answer in the presence of noise: Error mitigation

Amplify strength of noise (Rescale dynamics of state preparation)
Re-measure quantity of interest
Extrapolate to zero-noise value



Error mitigation for quantum chemistry

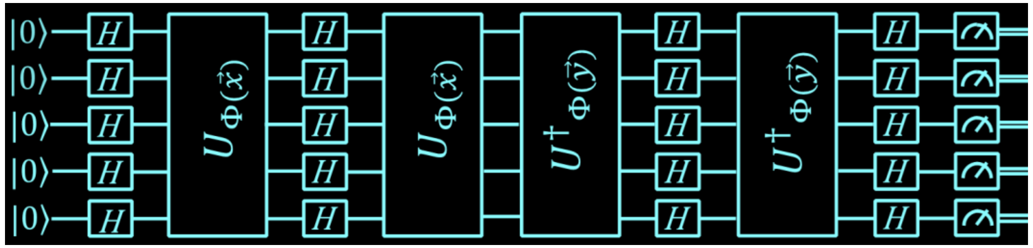


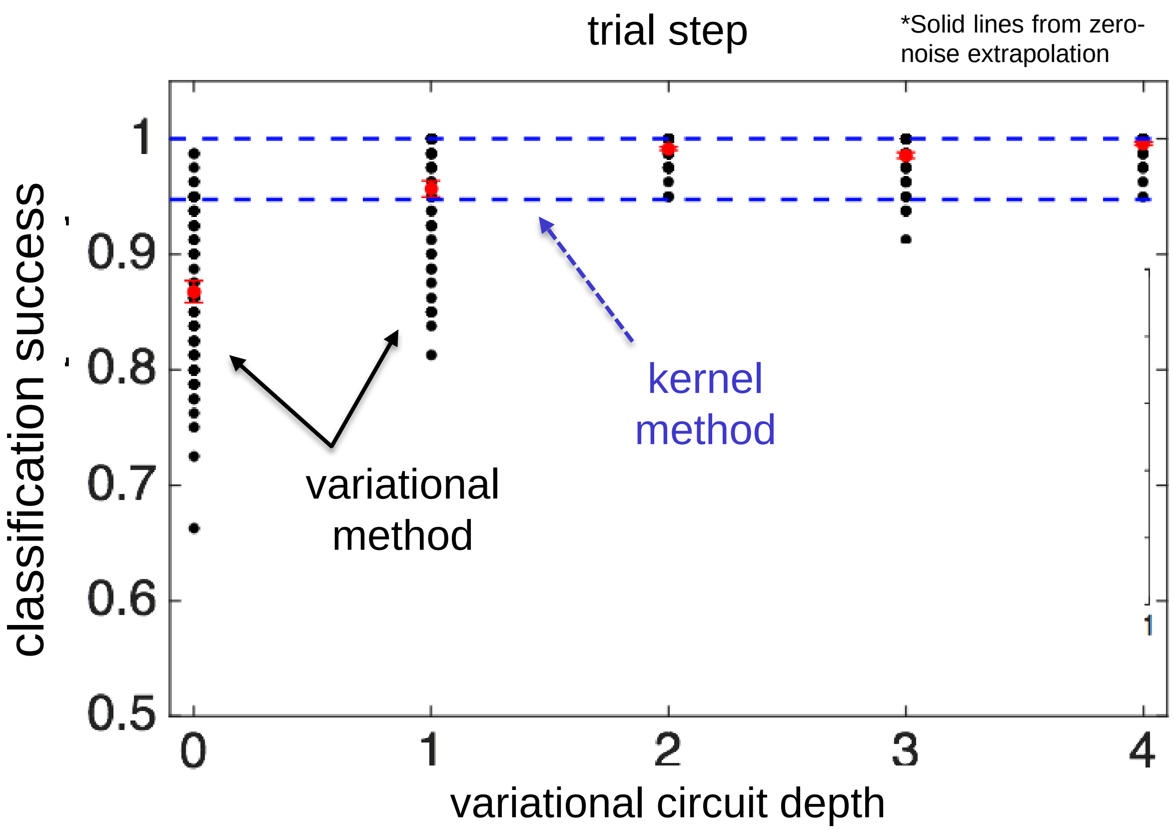


Extending the computational reach of a noisy superconducting quantum processor, arxiv: 1805.04492

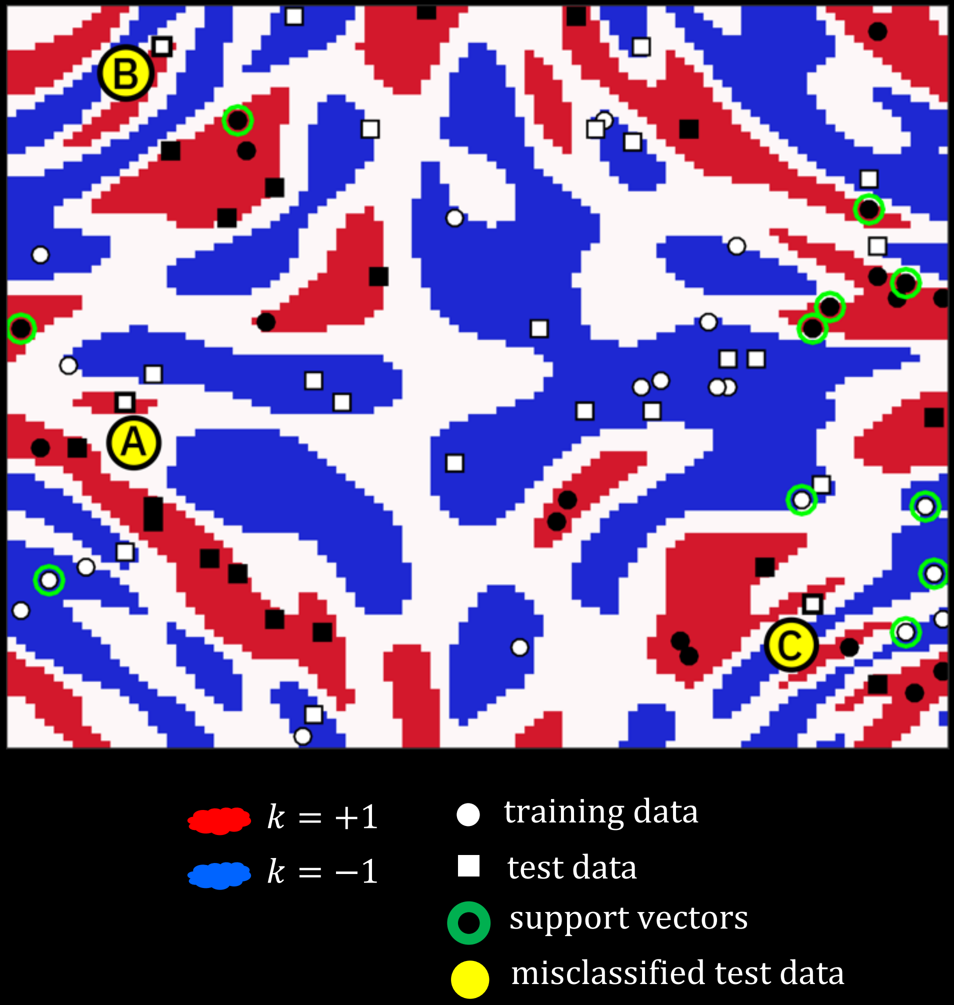
Supervised Learning with a Quantum Kernel Estimator

Apply feature map and its inverse





Example training and test set for the Kernel method:



Supervised learning with quantum enhanced feature spaces, Nature 2019

What can we do with shallow circuits ?

depth

depth-2 | $O(1)$ | $O(\log n)$

depth-2

Efficient classical simulation

$O(1)$

Hybrid algorithms:

approximate Optimization

Quantum kernel estimator

VQE for chemistry

quantum error correction demos

$O(\log n)$

Shor's factoring

Clifford circuits

Variational tensor networks (MERA)

Toy models of black holes ?

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Graphics: Carl De Torres for IBM Research

Analog Quantum Simulation

- **Idea:** Build a controllable (somewhat) quantum system and vary its parameters to mimic the properties of another system

- **Payoff**: Simulate chemistry, material properties that are intractable with classical computers

- **Challenge:** noise in your system has to be similar enough to noise in real system. How similar?

- **Challenge:** how to prepare ground state, extract information

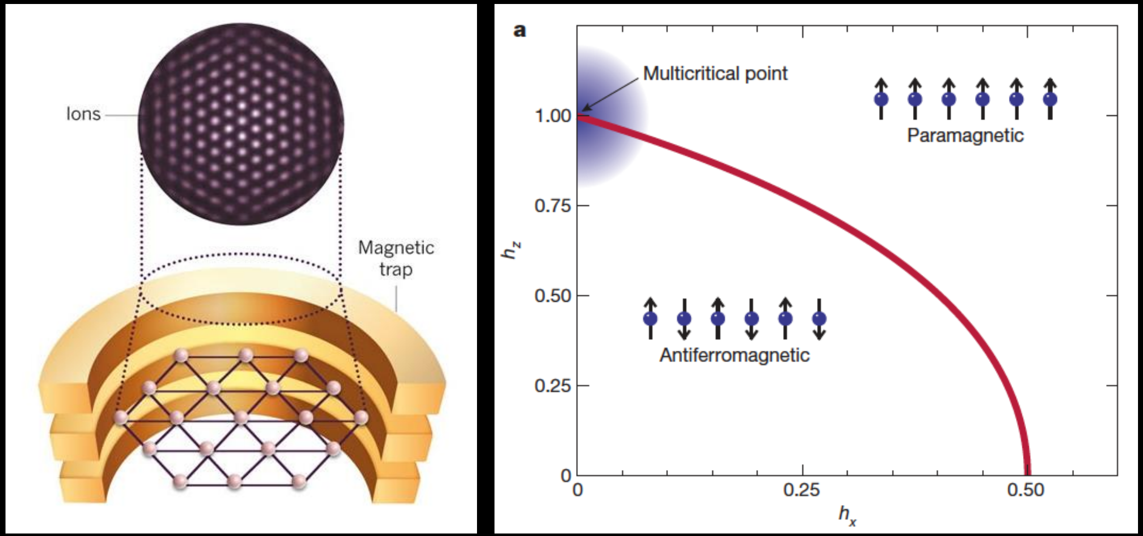
1901 Wright Brothers' wind tunnel.
By matching dimensionless parameters in scale-models we get reliable predictions of behavior.

Similarly, by matching ratios of Interaction strengths in controllable quantum Circuits can we studyexotic materials?

Complex atomic and ion lattice simulations

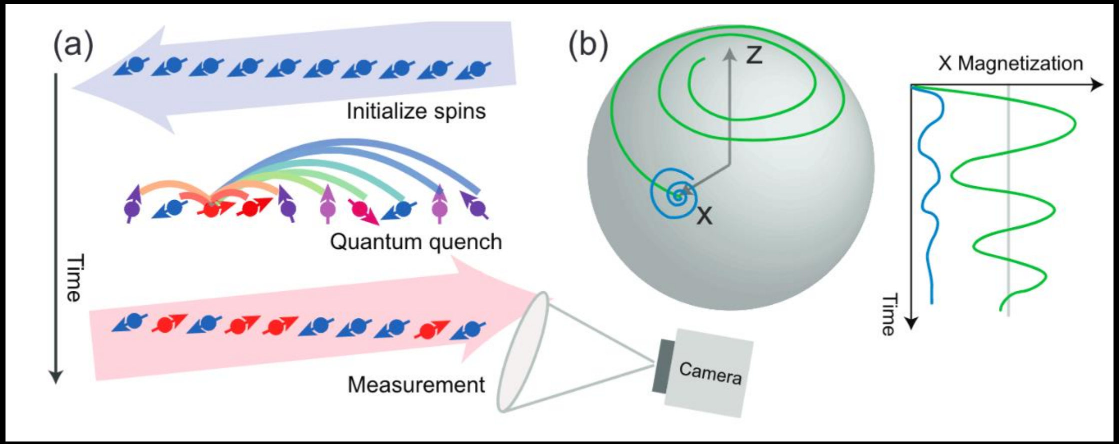
Rb atoms simulate magnetic phase transition

Simon et.al., Nature, v. 472, pp. 307 (2011)



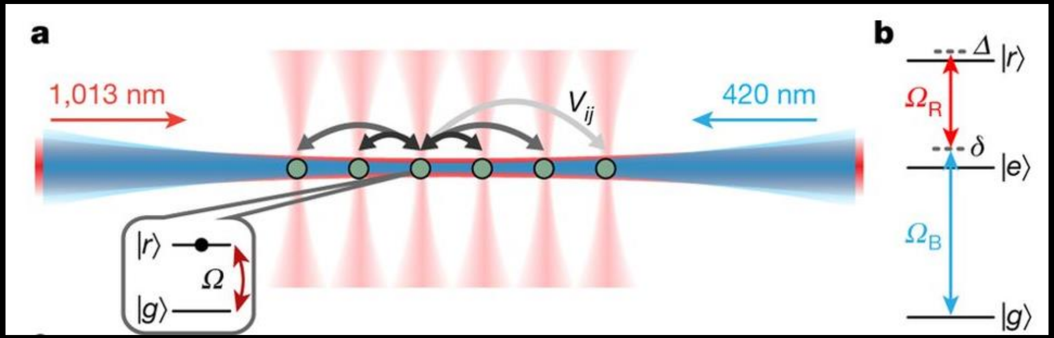
Many body dynamical phase transition on 53 ions

Zhang et.al., Nature, v. 551, pp. 601 (2017)



Many body-dynamics on a 51 atom simulator

Nature v. **472**, pp. 307 (2017)



Potentially a lot to learn about condensed matter physics and new materials via this direct route!

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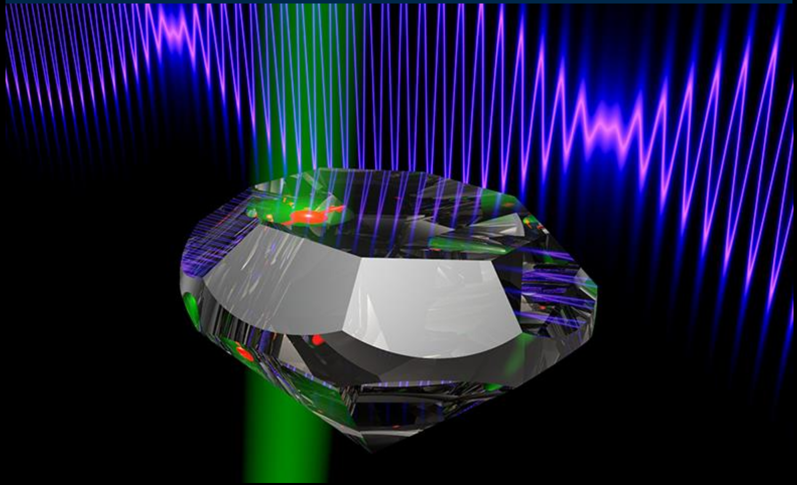

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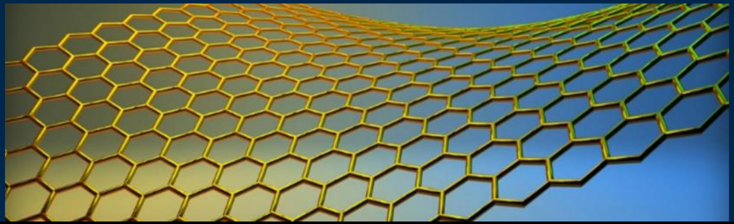
Novel Quantum Materials

Quantum technology enablement through materials that behave quantumly



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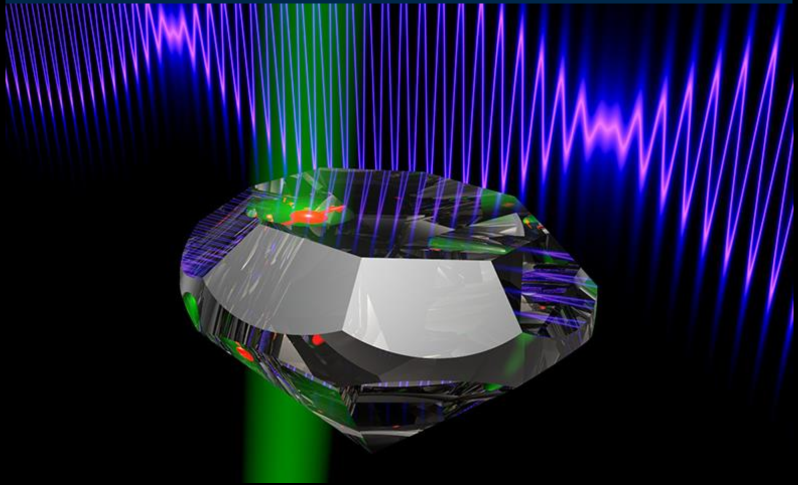

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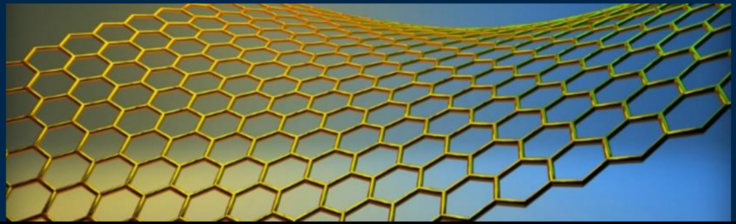

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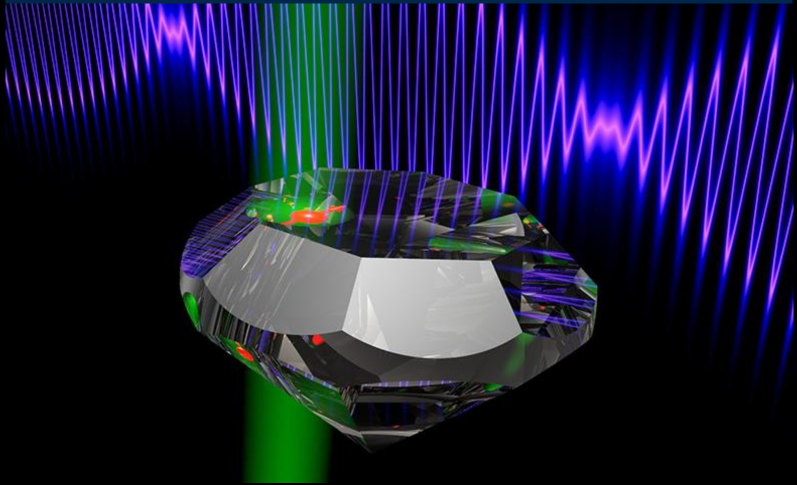

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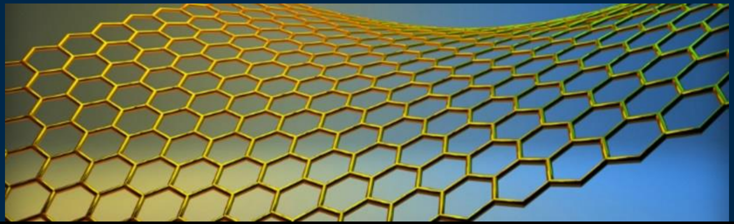
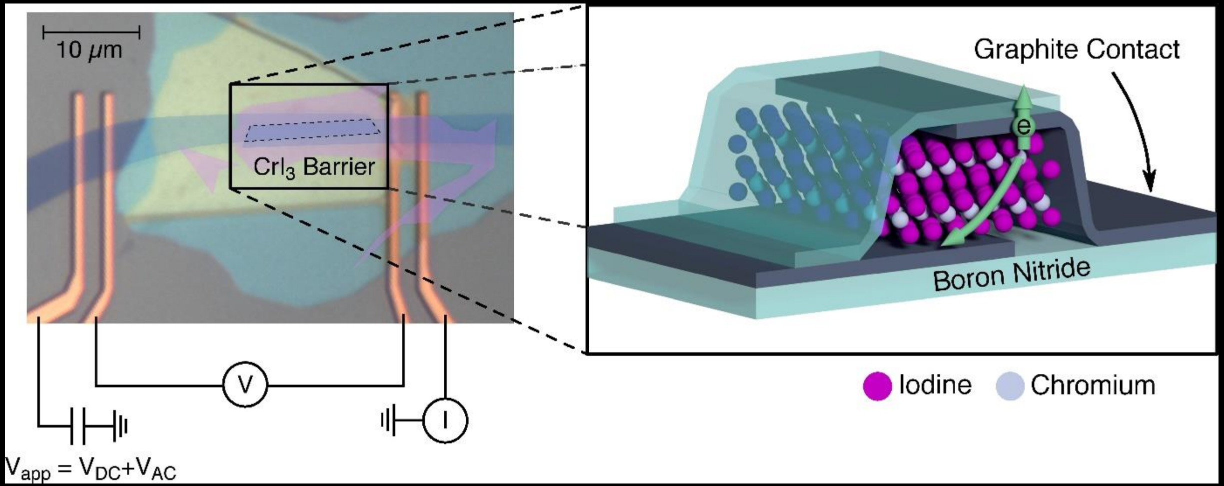
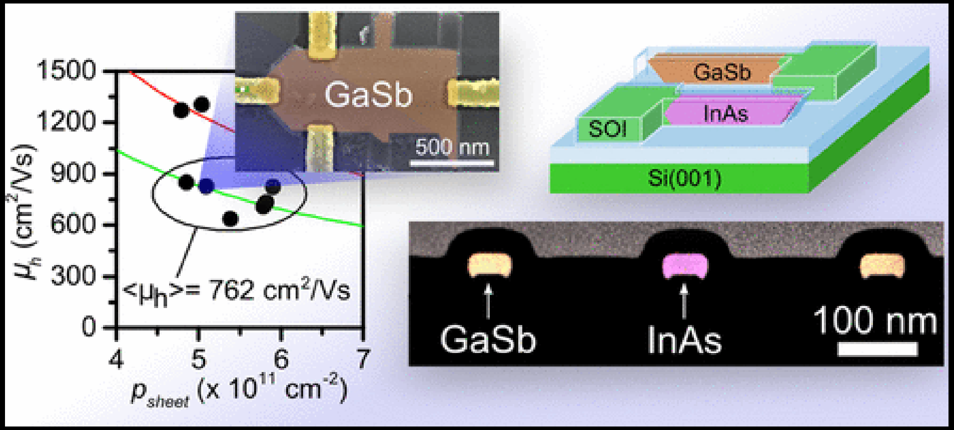


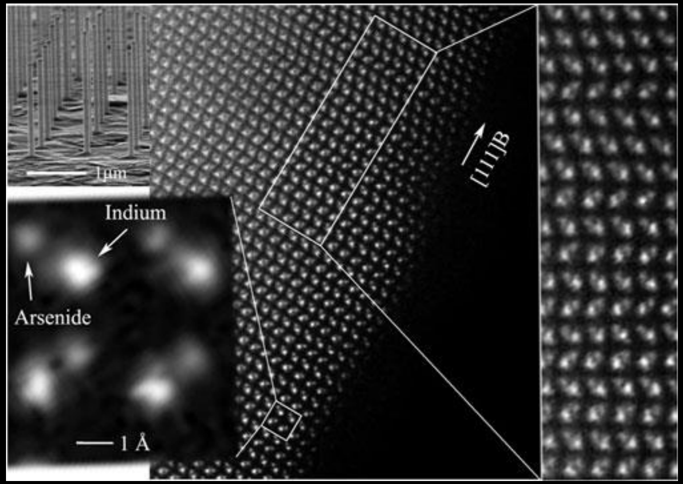
Examples of quantum materials



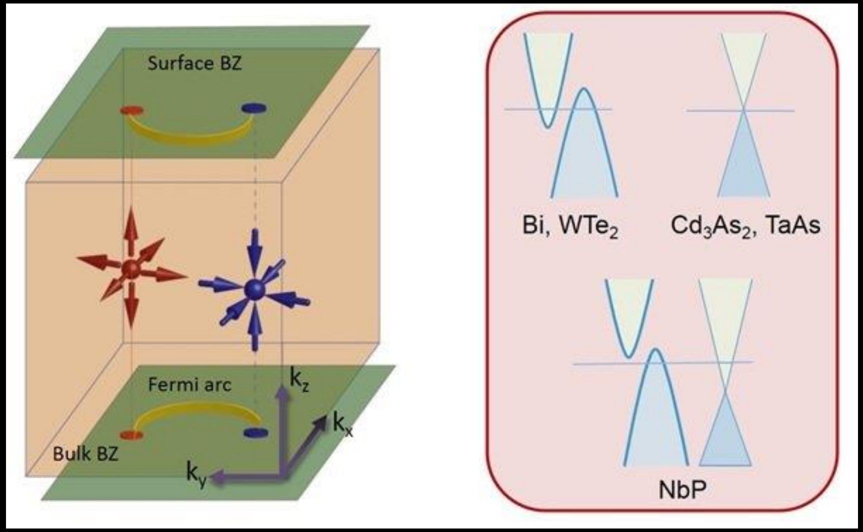
Bilayer graphe
Source: Jarillo-Herrero Group



GaSb 2DEG
Source: IBM ZRL



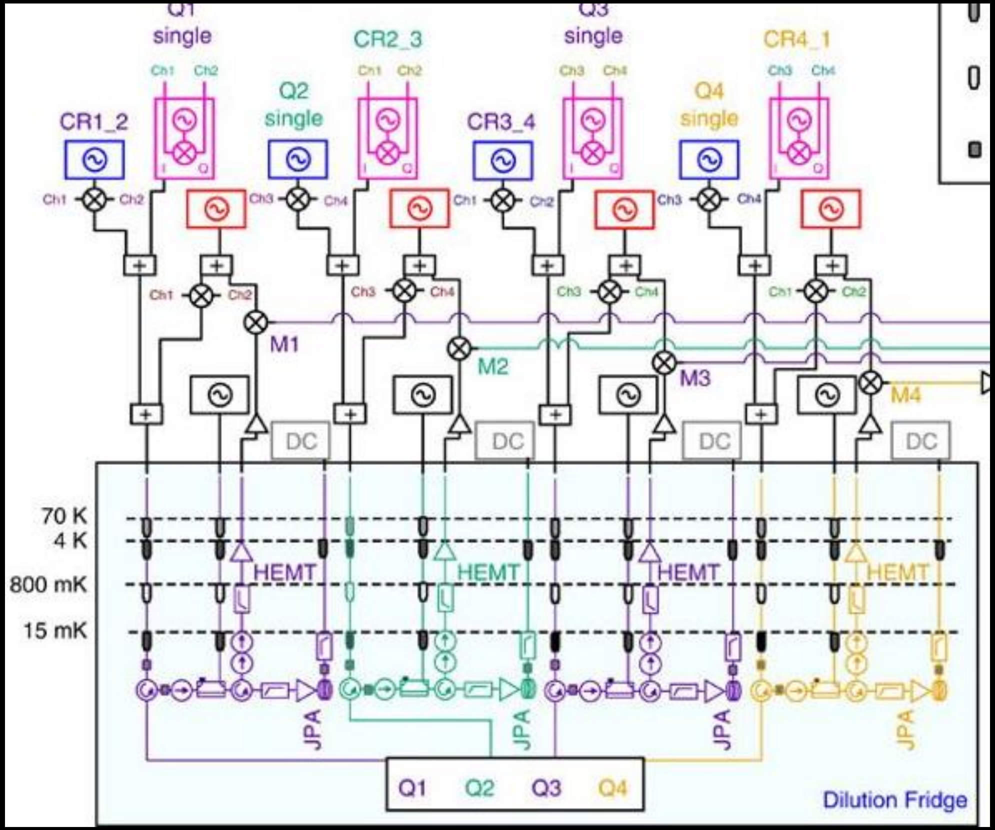
InAs nanowires
Source: Qdev, Center for Quantum Devices, C. Marcus



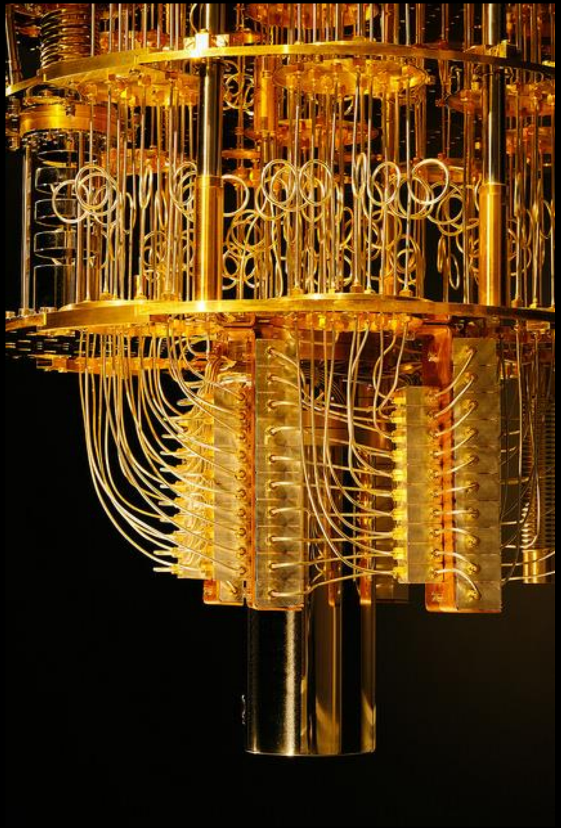
Topological semimetals,
Weyl. semimetals
Source: MPI, Muenich

How can quantum materials impact quantum computing?

Schematic for just controlling 4 qubits



Corcoles et al, Nature Comms. 6 (2015)



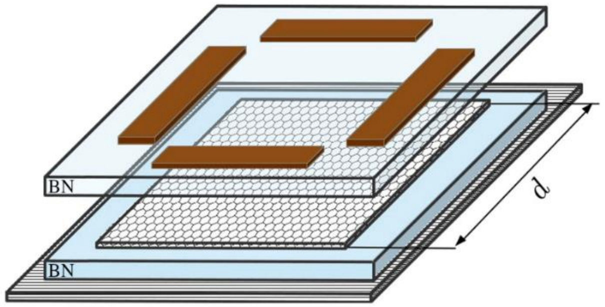
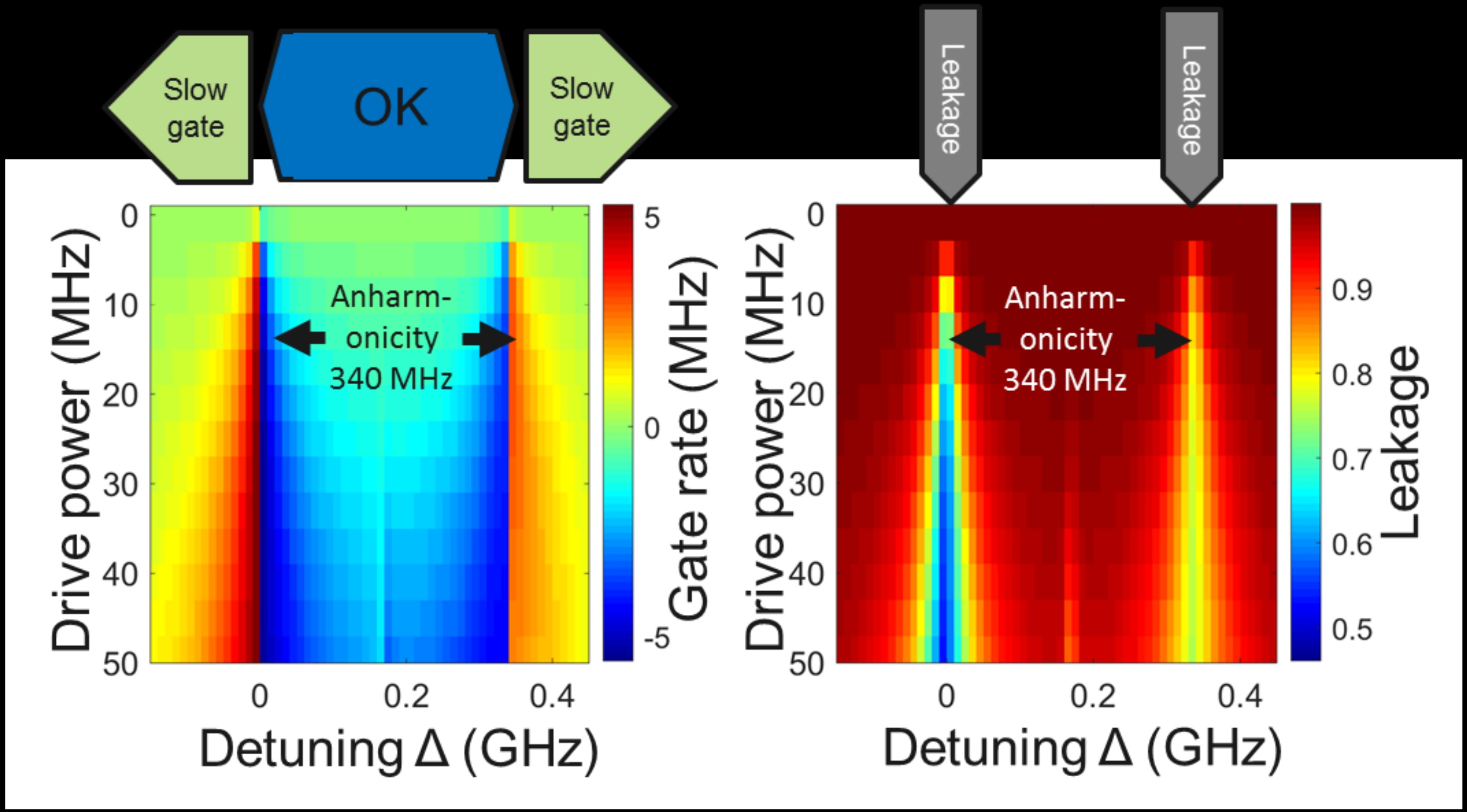


FIG. 15. An exploded view of a sandwich structure, based on the capabilities recently reported in Ref. [62]. A graphene flake is encapsulated between two layers of insulating boron nitride (BN). Four edge electrodes grown above the structure as shown could serve as the four capacitive contacts of the two-port gyrator.

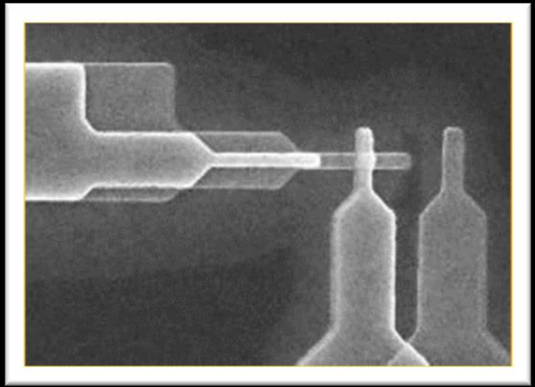
2DEG based isolators
Viola and DiVincenzo (2014)

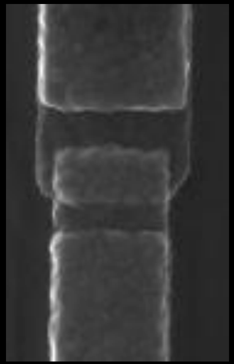
How can quantum materials impact quantum computing?

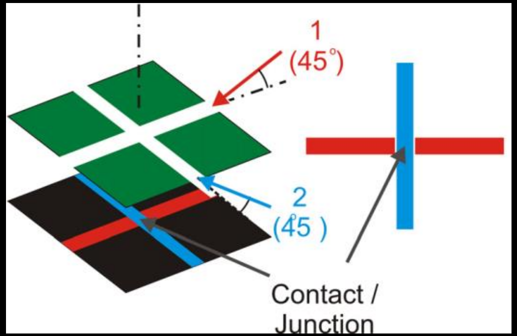
Cross-resonance gate frequency operation window



When extending beyond just two qubits, there are 7 distinct collision types to avoid



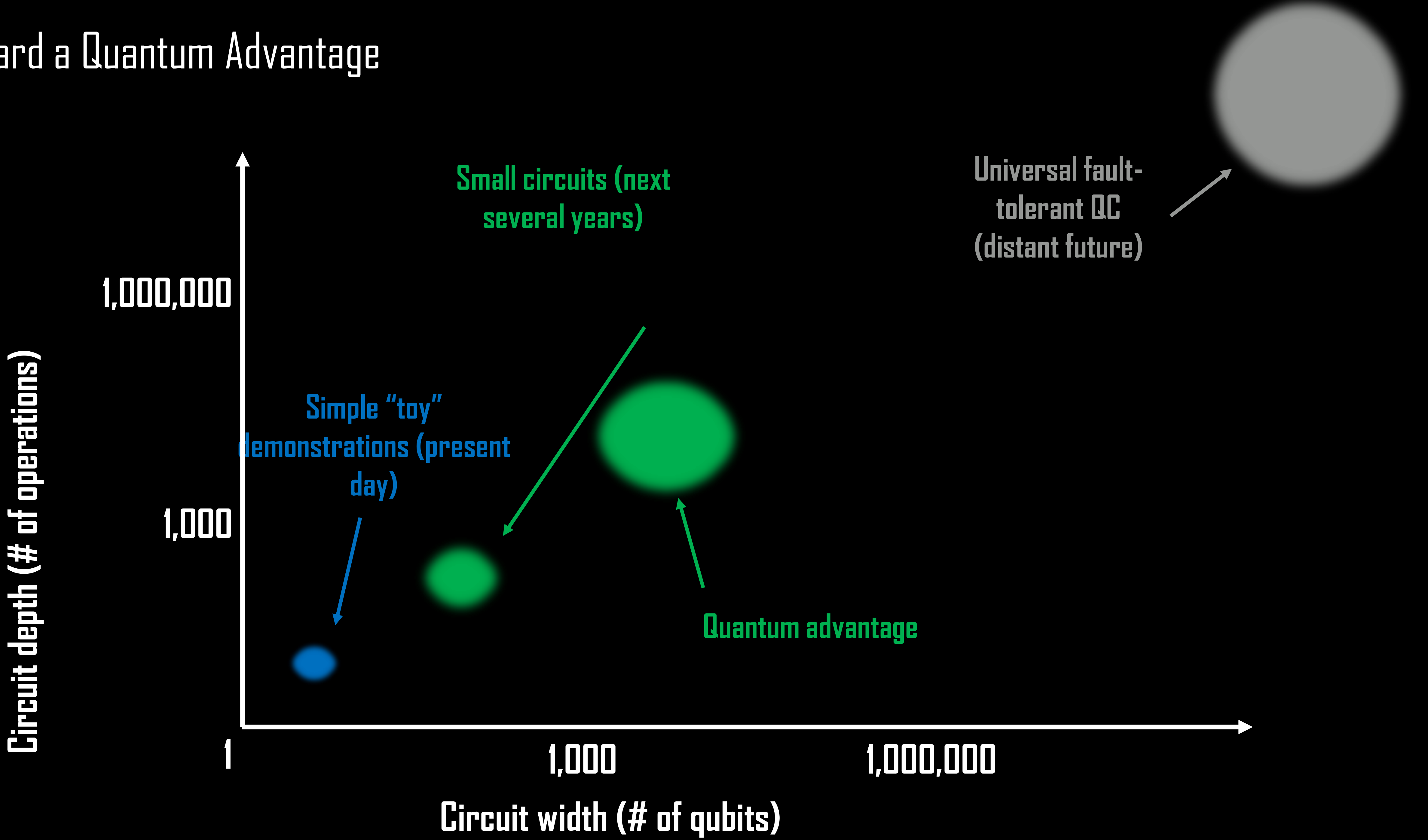




M. Costache et al., *JVSTB* 30, 04E105.
A. Potts et al., IEE Proc.-Science, Measurement and Technology 148, 225.

Junction Type	Area per Die (mm²)	Typical $\frac{\sigma_R}{R_{med}}$
Manhattan	2	5.9%
In-line Dolan	8	7.0%
In-line Dolan	8	2.9%
Multiple litho	3	8.8%
Dolan cross	48	4.9%
Manhattan	18	4.9%

Toward a Quantum Advantage



Shor's Algorithm – Requires Universal Fault-Tolerant QC

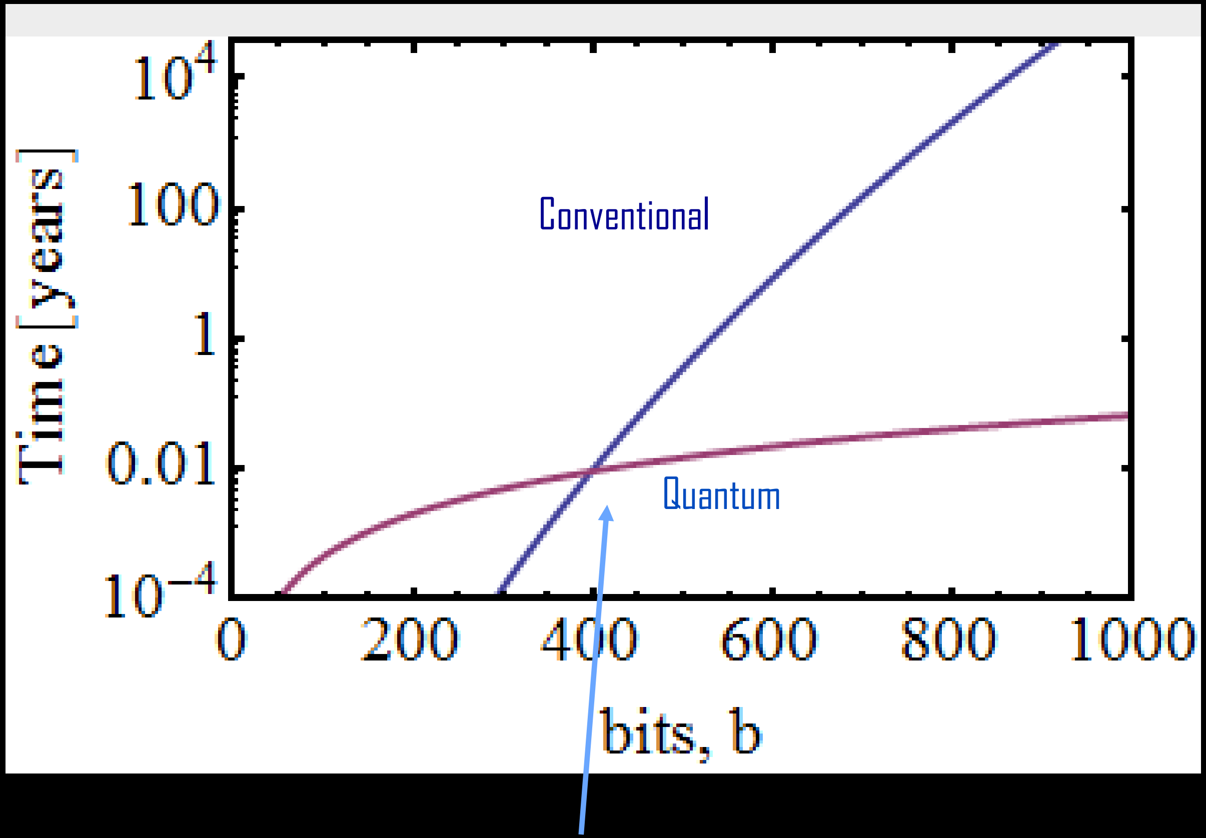
Factor a number into primes:

$$M = p * q$$

How long will it take ? (t)

Classical	Quantum
$t \sim \exp(O(n^{1/3} \log^{2/3} n))$	$t \sim O(n^3)$

P. W. Shor, "Polynomial-Time Algorithms for Prime Factorization and Discrete Logarithms on a Quantum Computer," SIAM Journal on Computing, no. 5, p. 1484.



>10^8 physical qubits required to reach cross-over...

Summary of Hardware Requirements for Problems

Problem	Type of Quantum Computer	# Qubits for advantage (est)[1,2]	Years to advantage (est)[2,3]
Quantum Chemistry	NISQ/Approximate QC	$10^2 \sim 10^3$	< 5 ?
Optimization (specific)	NISQ/Approximate QC	$10^2 \sim 10^3$	< 5 ?
Heuristic machine learning	NISQ/Approximate QC	$10^2 \sim 10^3$	< 5 ?
Shor's algorithm	Universal fault-tolerant QC	$> 10^8$	> 10~15 if possible
Big Linear Algebra Programs (FEM)	Universal fault-tolerant QC	$> 10^8$	> 10~15 if possible

Notes:

1- Not all qubits equal: different error rates or using them for different functions change above estimates

2- Still need a simple metric that relates quantum machine power to number of qubits, e.g. Quantum Volume

3- Making larger systems extremely difficult -> entirely different engineering problem to get to 10^8 vs intermediate getting to 10^3

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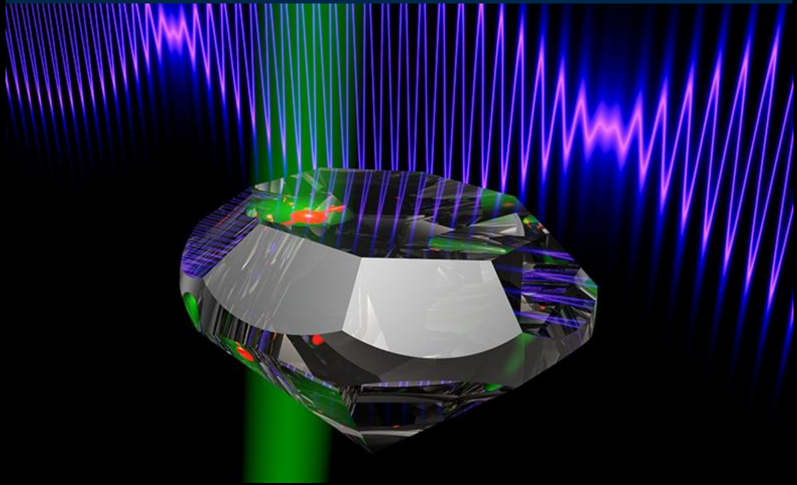

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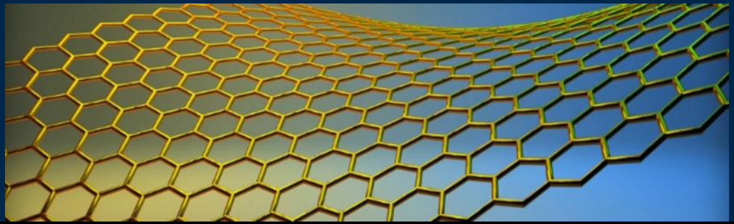
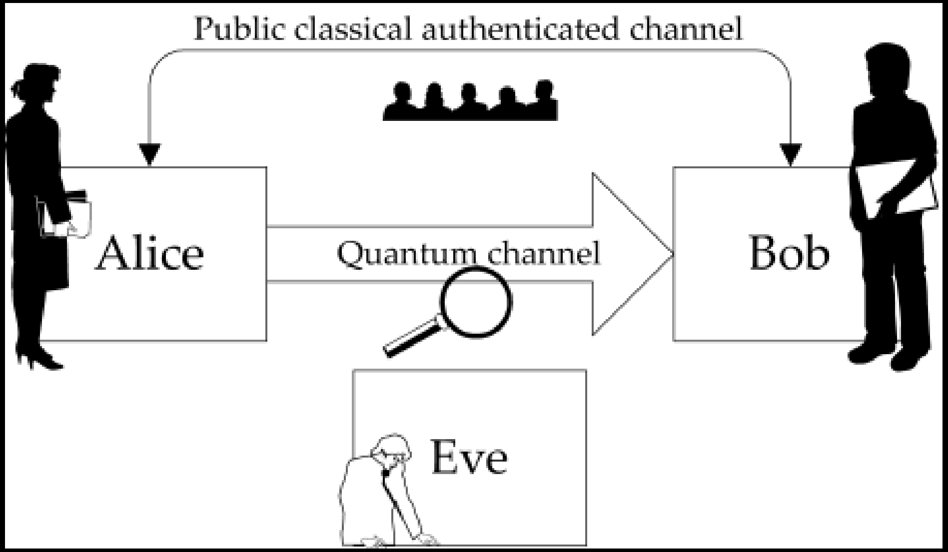


Quantum communication

Secure communication via Quantum Key Distribution, predicated not on computational difficulty of a task (like RSA is), but on laws of quantum mechanics, for example, collapse of a quantum measurement



1984 – Quantum cryptography born at IBM Research

Cannot measure quantum information without changing it.

Quantum no-cloning theorem:

Quantum information (pad) cannot be duplicated.

Current record link at 1200 km, Chinese satellite

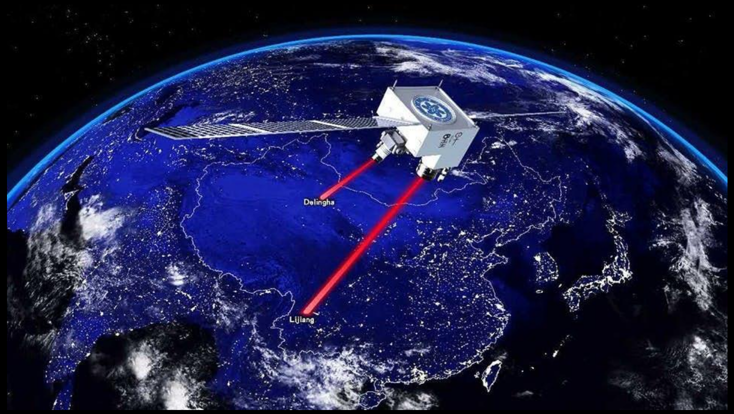
Breakthroughs needed for practical use

- Quantum repeaters
- Transduction

With these breakthroughs

- Quantum Internet
- Quantum Cloud Computing (like homomorphic encryption)

Current record link at 1200 km, Chinese satellite



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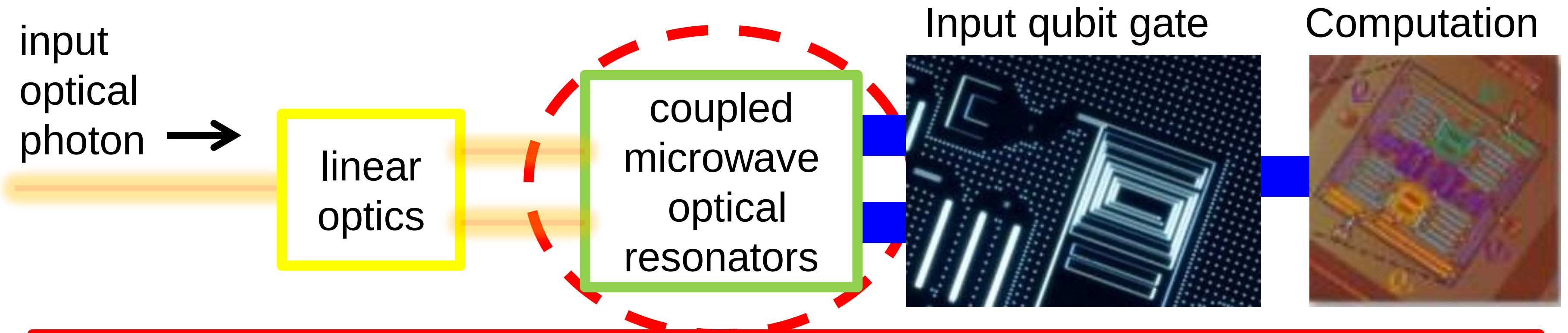
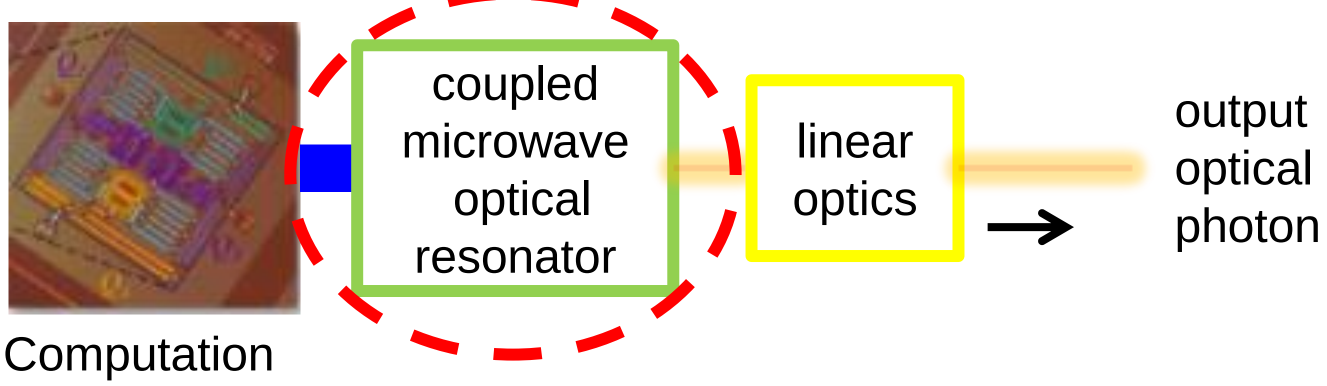
Microwave-optics transduction—electro-optic



Key challenges:

- Strong microwave-optical interaction
- High quality factor microwave resonator
- High quality factor optical resonator
- Qubit compatible scalable fabrication



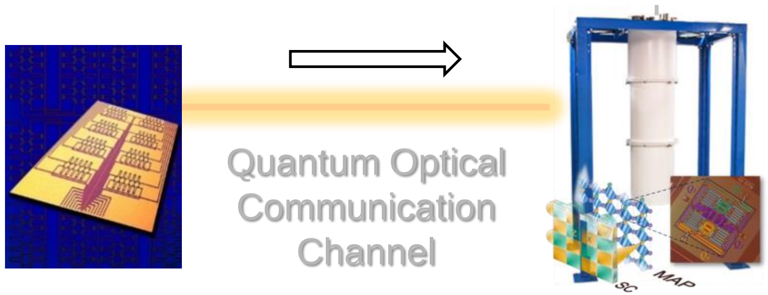
CQTS

The Laboratory for Physical Sciences

What new applications are enabled?

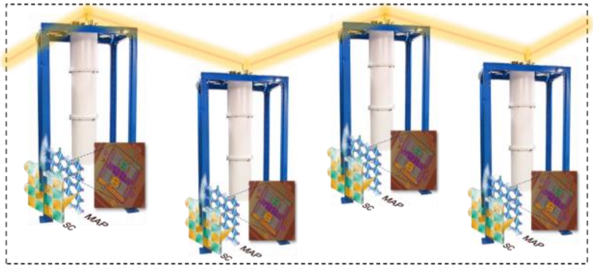
Cloud-based Blind Quantum Computing

- Provides a secure protocol between clients and a cloud quantum computing provider.

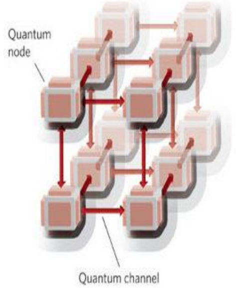


300 K   10 mK

Distributed Quantum Computing

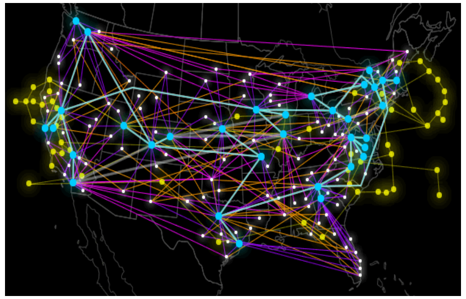


- Enable fast scale up of quantum computer



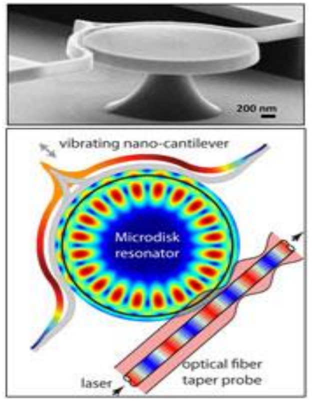
Quantum Communication

- Enables a long-distance secure communication method with a quantum repeater



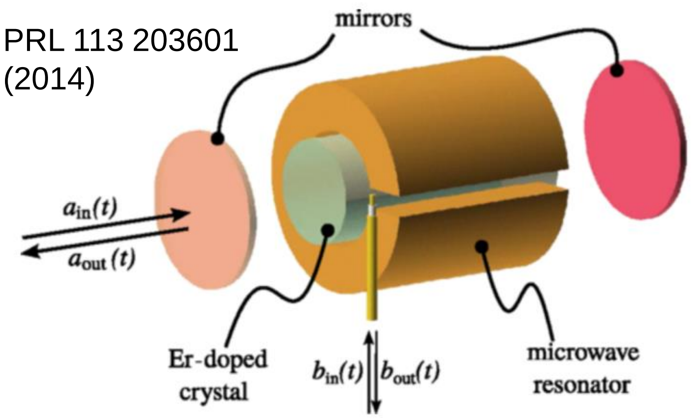
Quantum Sensors

- Enables ultra-low-noise sensing with distributed entanglement

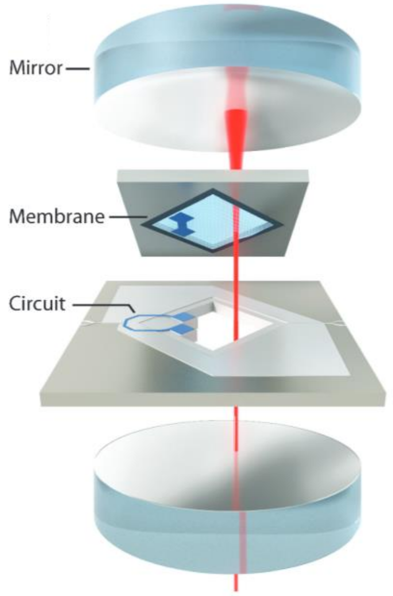


Quick overview of transduction mechanisms

PRL 113 203601
(2014)



Lambda-level systems



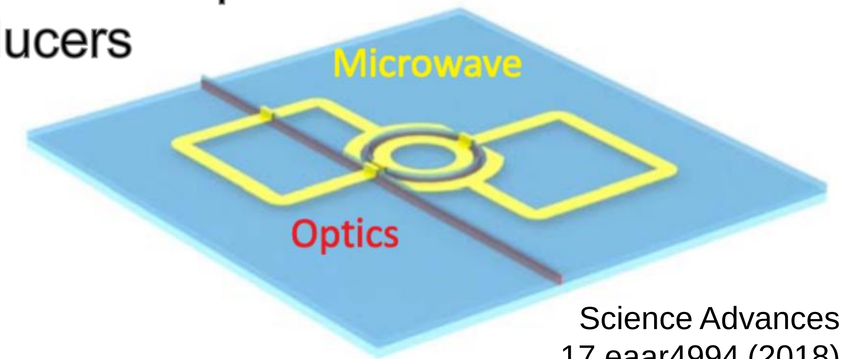
Electro-opto-
mechanical
transducers

(phonon-mediated)

Nature Physics 10
321-326 (2014)

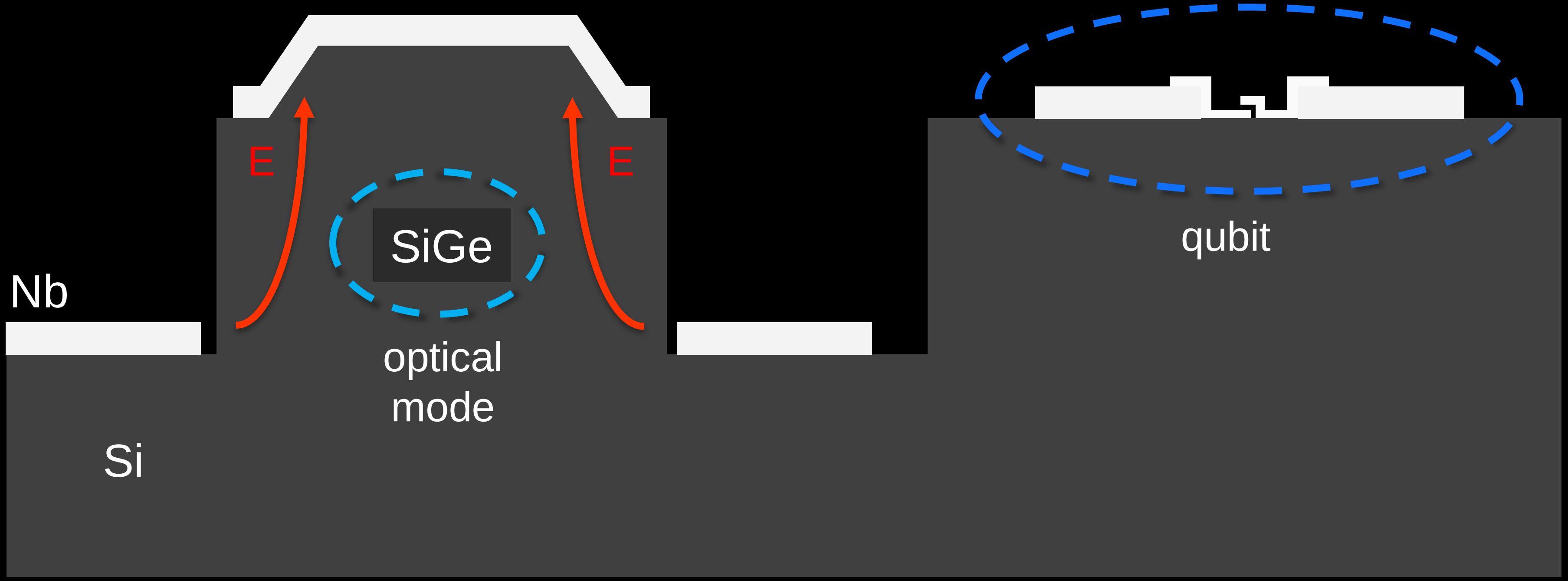
Magnon-mediated transducers

Direct electro-optic
transducers



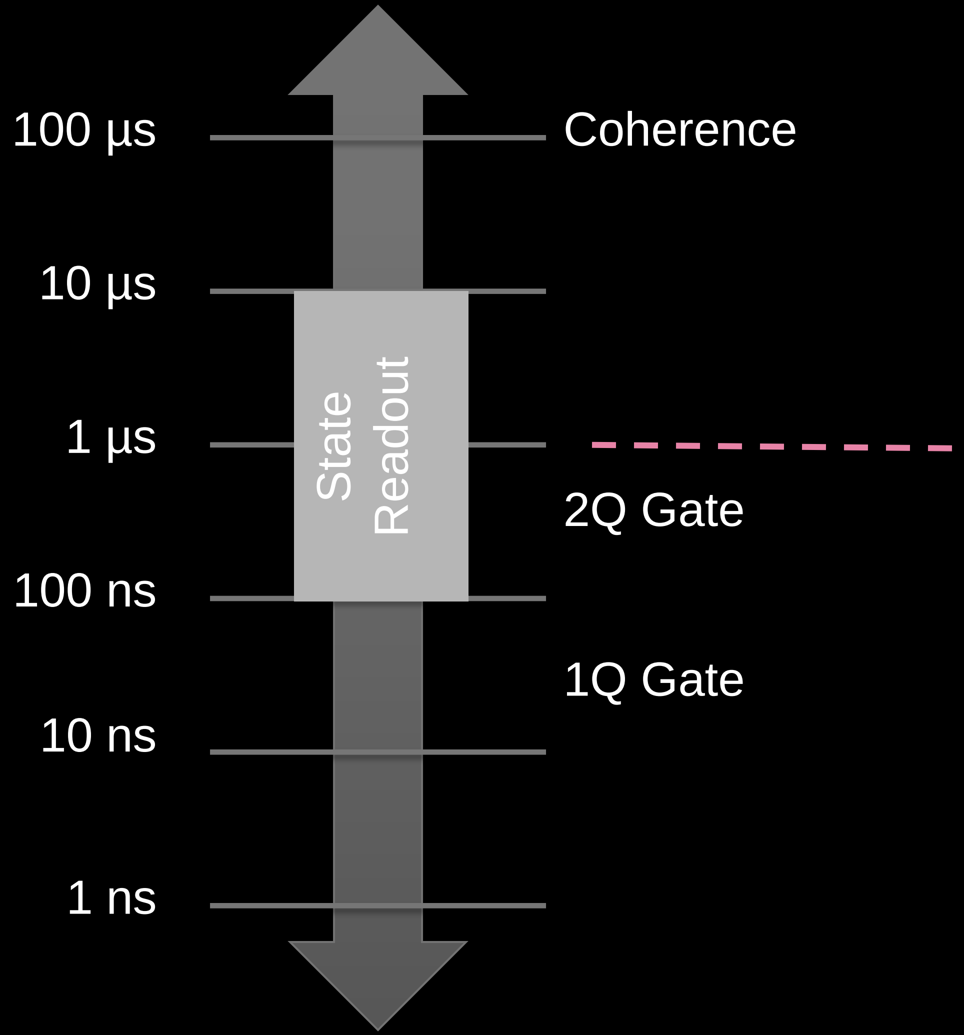
Science Advances
17 eaar4994 (2018)

Low loss transducer integration proposal



- Simple, integrated platform
- Monocrystalline semiconductors
- Low refractive index contrast

Required transduction time constant



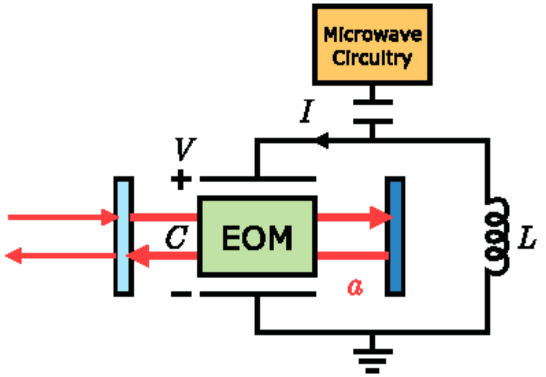
Target ~1 µs
i.e. ~1 MHz
transducer

Challenge:
Build ultra low loss
electro-optic devices

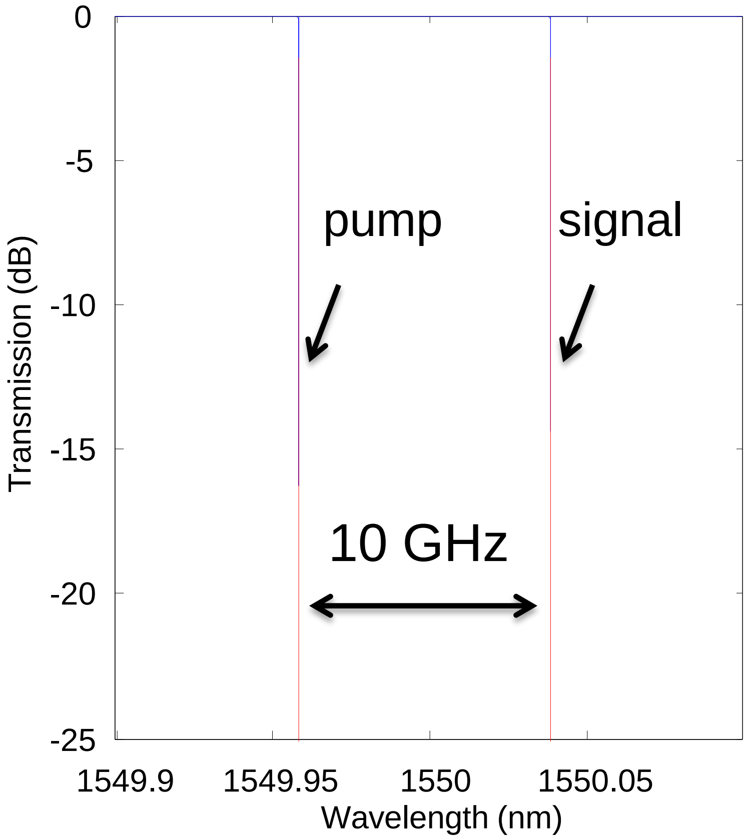
Coupling via three wave mixing

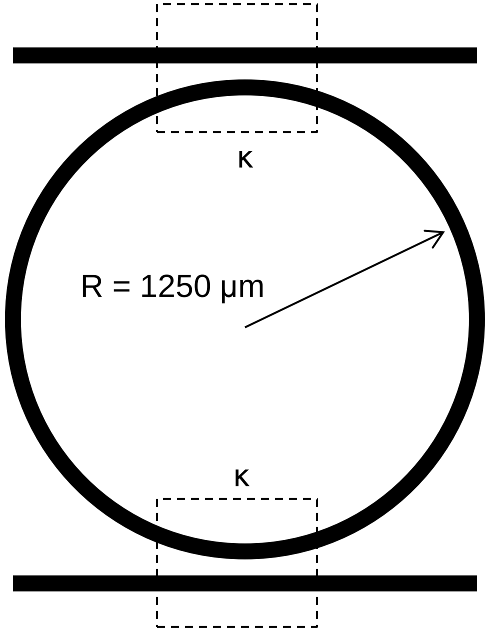
Change in a refractive index with an external electric field E_j

$$\Delta n = -\frac{1}{2} n^3 r_{ij} E_j$$



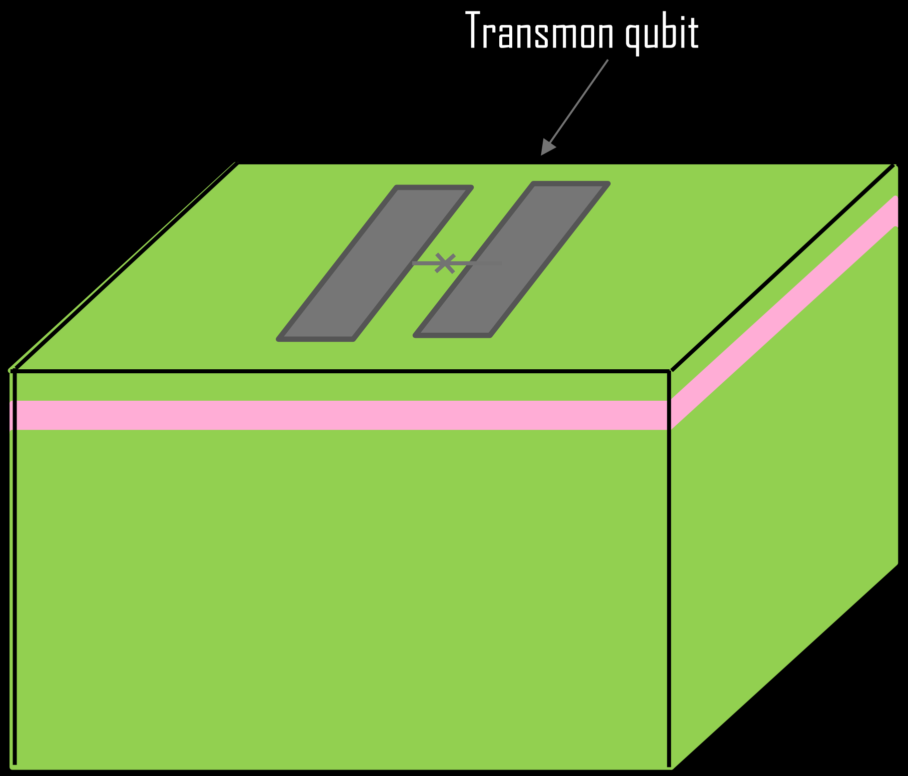
M. Tsang, PRA 81, 063837 (2010)





Three-wave mixing in mm-scale resonator

Device for studying SiGe loss



Epi Si 100 nm

SiGe 150 nm

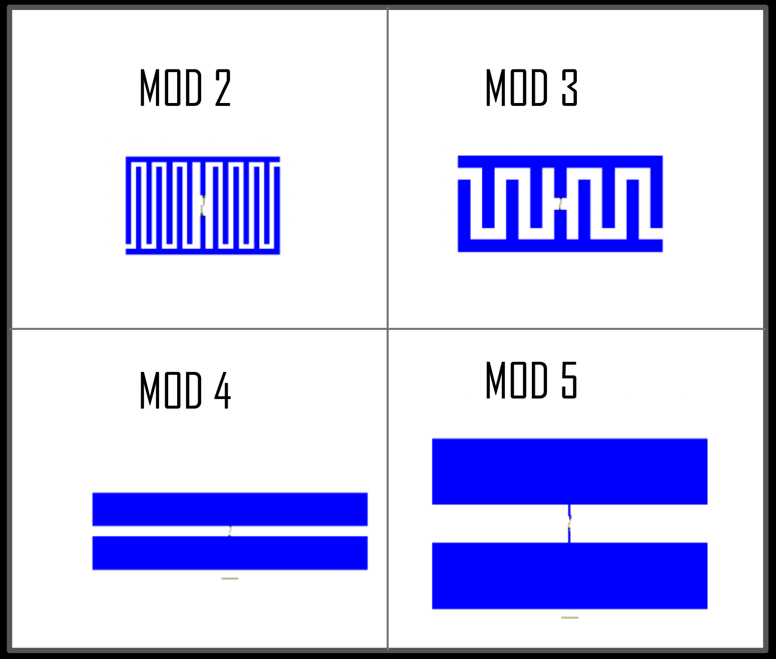
Si substrate

SiGe parameters:

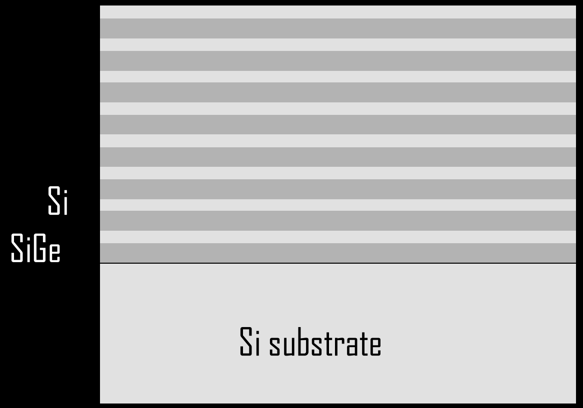
RTCVD grown with Ge mole fraction 15%

ε_{SiGe}=11.7 + 4.5x=12.4

Grown on intrinsic Si 200mm wafer



Multi-layer stack



In multi-layer stack in actual transducer device, here single layer SiGe

Core quantum science challenges for computation

Improved materials for devices	Scalable controls and readout	Integration of qubit networks	Validation and characterization	Codes and algorithms
Investigate surfaces	RF Controls	Microwave hygiene	How quantum?	Reduce the physical qubit overhead
Increase coherence	Cost perspective	Packaging and interconnects	Better metrics of performance	Error mitigation
Reduced junction variability and spreads	High density high fidelity readout	Scaling to N >> 1000	How well do N qubits work?	Dynamical decoupling for gate improvements
Alternative qubits	Integrated isolators and circulators	Low-loss microwave dielectric	Noise characterization & spectroscopy	Interesting problems for near term QC
Novel non-reciprocal effects	Integrated quantum amplification	Microwave-optical transduction	Calibration techniques with AI	
Electro-optic				

Core quantum science challenges for computation

Improved materials for devices

- Investigate surfaces
- Increase coherence
- Reduced junction variability and spreads
- Alternative qubits
- Novel non-reciprocal effects
- Electro-optic

Scalable controls and readout

- RF Controls
- Cost perspective
- High density high fidelity readout
- Integrated isolators and circulators
- Integrated quantum amplification

Integration of qubit networks

- Microwave hygiene
- Packaging and interconnects
- Scaling to N >> 1000
- Low-loss microwave dielectric
- Microwave-optical transduction

Validation and characterization

- How quantum?
- Better metrics of performance
- How well do N qubits work?
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Codes and algorithms

- Reduce the physical qubit overhead
- Error mitigation
- Dynamical decoupling for gate improvements
- Interesting problems for near term QC
- New codes

Longer time horizons