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Emergent quantum technology and applications

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Quantum Truisms

- Quantum technologies *can potentially* be better than classical

- Quantum Computing & Software longest time horizon

- Quantum Sensing & Encryption here now

- Quantum states are fragile

- Expertise and suppliers are few

Quantum Computing – Entangled “Qubits”

- Qubit = “Quantum Bit” = atom with two states, or photon with two modes
- Entangled qubits allow for massively parallel computing
- Fundamental Problem: Environment quickly destroys entanglement
- Secondary Problem: Expertise and supplies

Quantum Algorithms - using a quantum computer

- Only a handful of quantum algorithms proven to enhance computing
- Requires programmers who understand quantum
- In the future, could enhance pharmaceutical development, etc.

Quantum Sensing – ultrasensitive measurements

- Quantum states are fragile
- Quantum sensing leverages quantum sensitivity to environmental perturbations
- Opposite situation for quantum computing, where need to isolate from the environment

Quantum Encryption – Unbreakable (in theory)

- Quantum Key Distribution (QKD) – relies on non-cloning of quantum wave functions
- Shares random numbers between parties
- Random numbers for One-Time Pad (OTP) encryption protocol (unbreakable)

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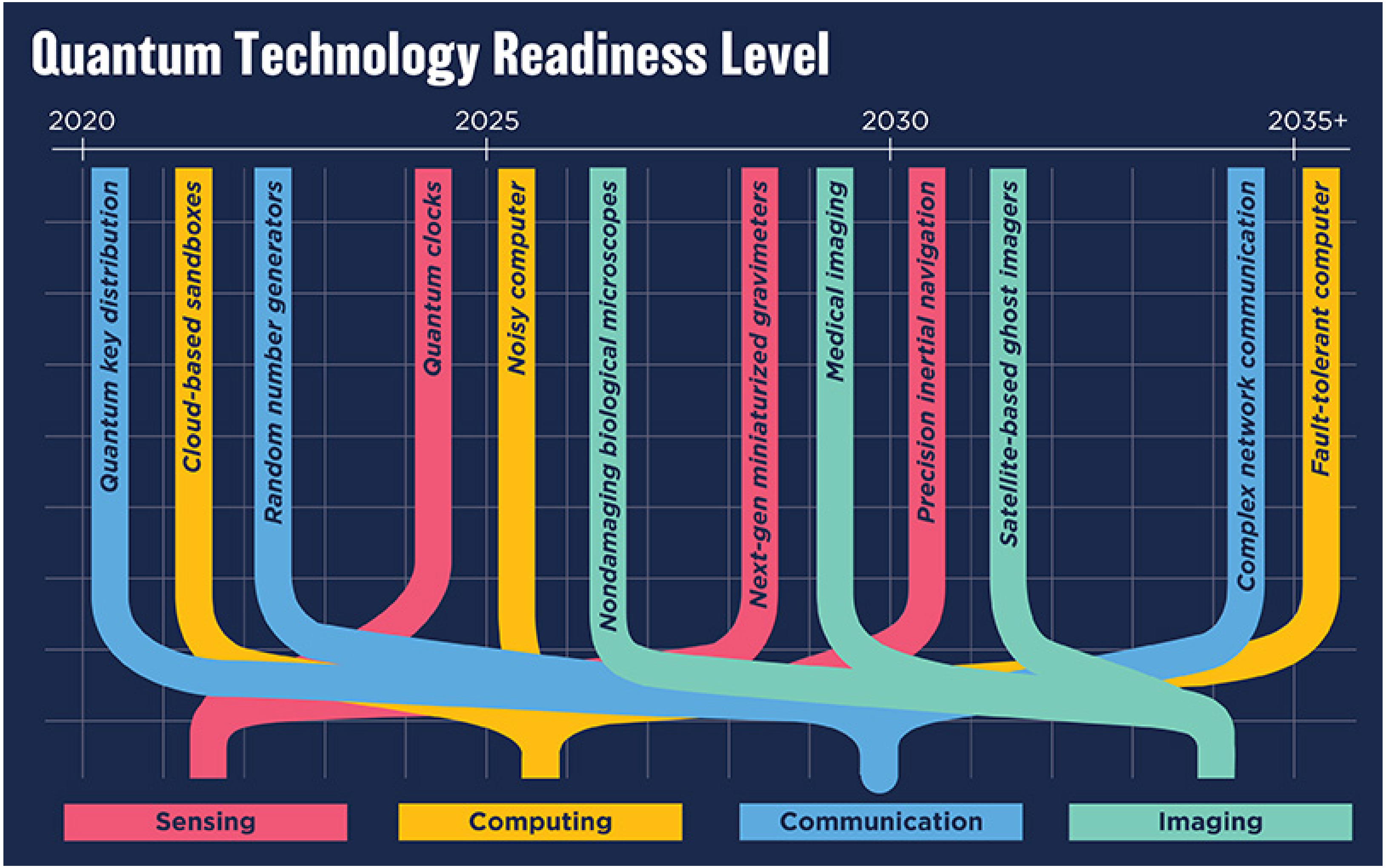


Basic Quantum Theory (“spooky physics”)

Put a “state” into a “ket”: |vertical polarization> = $|V\rangle$

Now make a “superposition” of pure states: $|\psi\rangle = c_V|V\rangle + c_H|H\rangle$

This wave function is in both the horizontal and vertical states, until measured

Now consider <u>two</u> “entangled” particles (photons): $|\psi\rangle = c_1|HV\rangle + c_2|VH\rangle$

There is no way to factor out vertical or horizontal states

Quantum computers seek to leverage the entanglement of many particles

"Qubit" versus "Bit"

A classical computer uses "bits", which are <u>either</u> a "zero" (0 Volts) or a "one" (5 Volts)

In quantum, we have the "qubit", which is <u>both</u> a "zero" <u>and</u> a "one" $|\psi\rangle = |0\rangle + |1\rangle$

Until we measure it

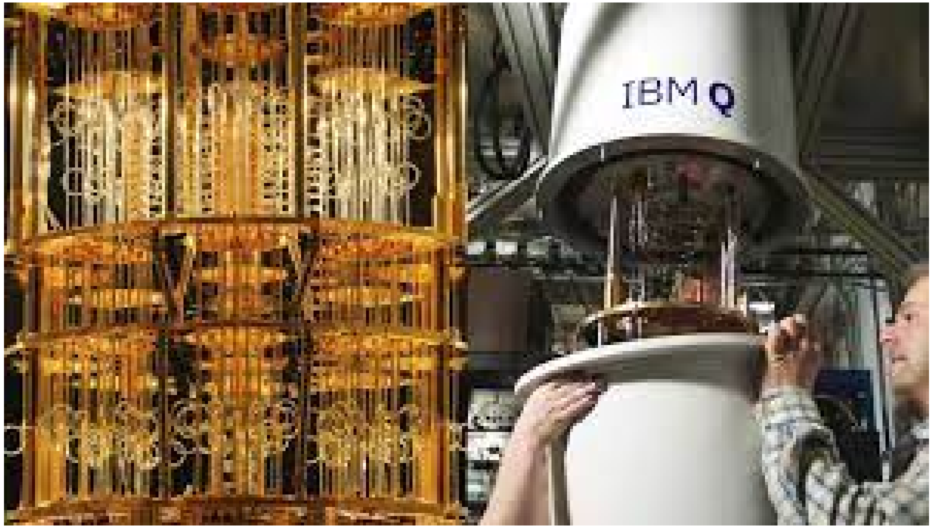
We can entangle two (or more) qubits: $|\psi\rangle = |10\rangle + |01\rangle$

This is the idea of a quantum computer

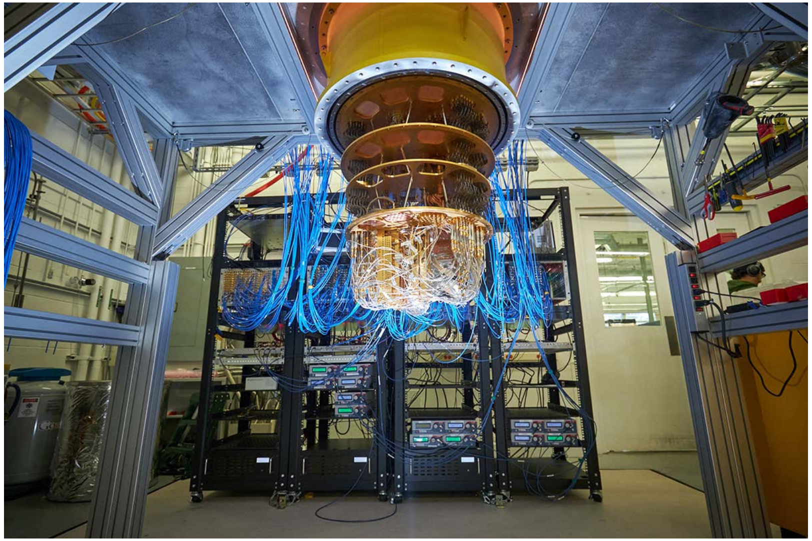
<u>Quantum Advantage Example: Li-3</u>

To simulate the electron wave function for Lithium (N=3 electrons) using a computational grid divided into 3*m* regions requires a classical computer able to store 2^{3mN} amplitudes. To achieve a precision of 10% requires m=3, so <u>2^{27} bytes needed (500 petabytes!)</u>. *A quantum computer needs just 27 entangled qubits.*

Quantum Computing



IBM



Google

<u>Different Approaches:</u>

- Superconducting qubits (pics)
- Trapped Ions
- Quantum dots
- Photons
- Others

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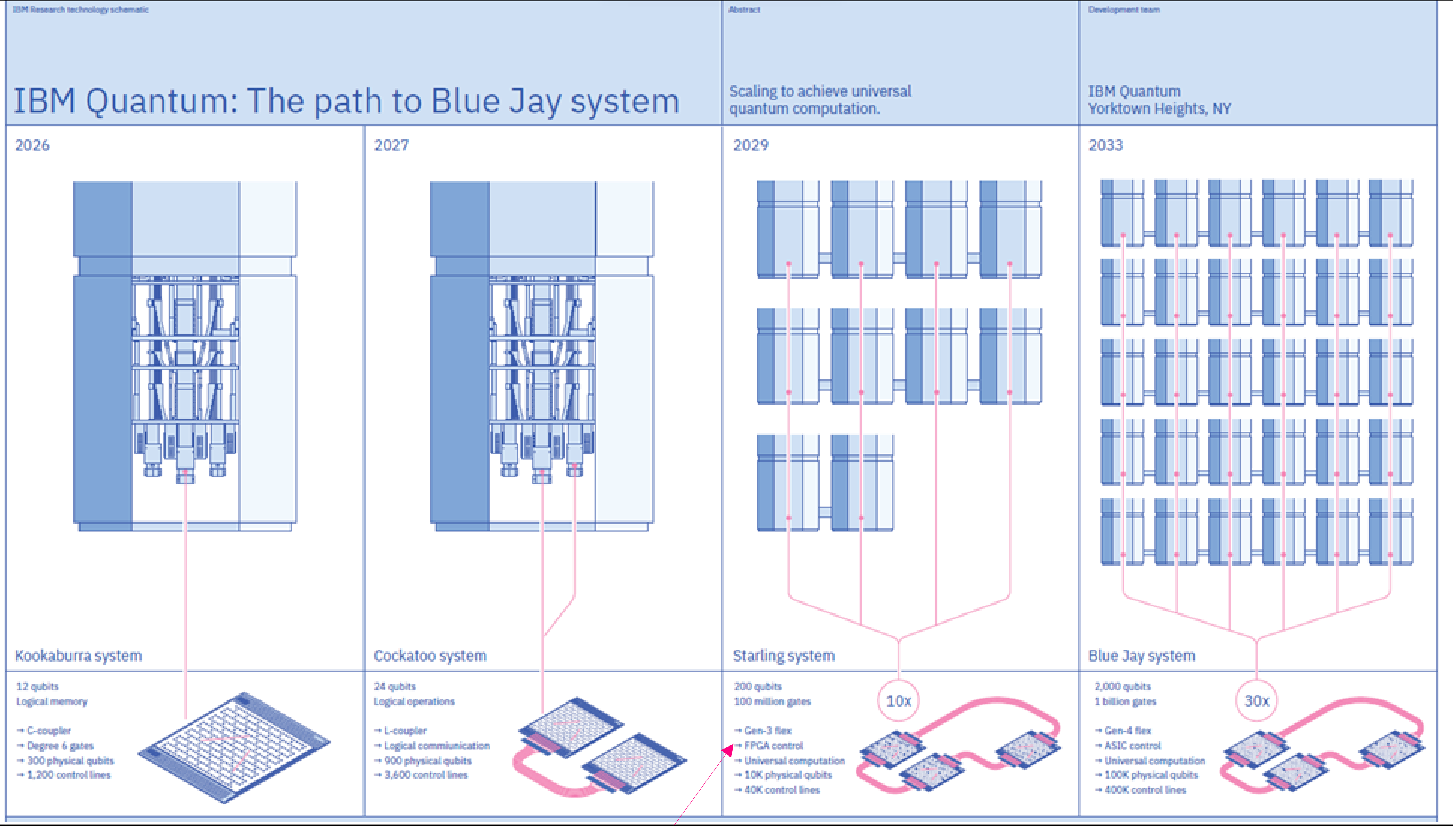


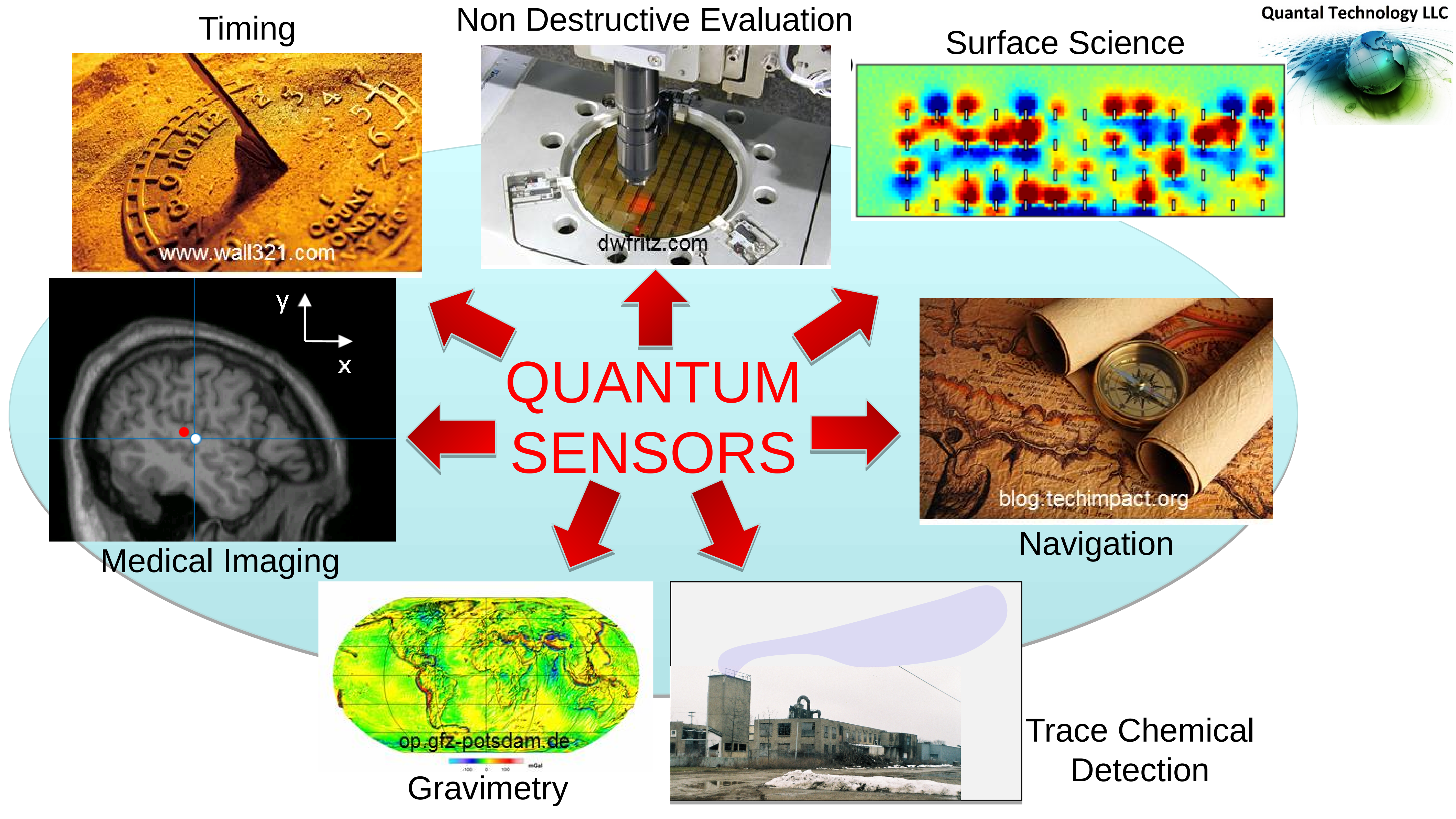
“FPGA control”

Quantum Algorithms

Quantum computers are useless without quantum algorithms (software):

- Currently requires expert knowledge in quantum mechanics and applications
- Only a handful of algorithms have been developed that would make a QC better than a classical computer
  - Shor’s Algorithm (breaks public-key encryption)
  - Grover’s Algorithm (sort a large database faster)

Company	Quantum Software Development Kit (QSDK)	Language	License
Microsoft	Microsoft Quantum Development Kit	Q#	MIT
Google	Cirq	Python	Apache 2
IBM	Qiskit	Python	Apache 2
Rigetti	Forest	Python	Apache 2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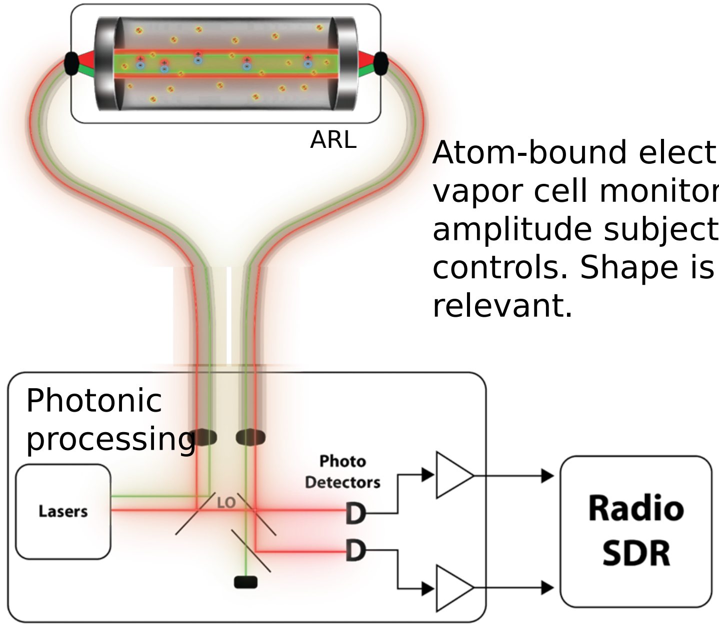
Quantum "Antenna" or Aperture Established circa 2010



Atom-bound electrons in a vapor cell monitor RF amplitude subject to laser controls. Shape is not relevant.

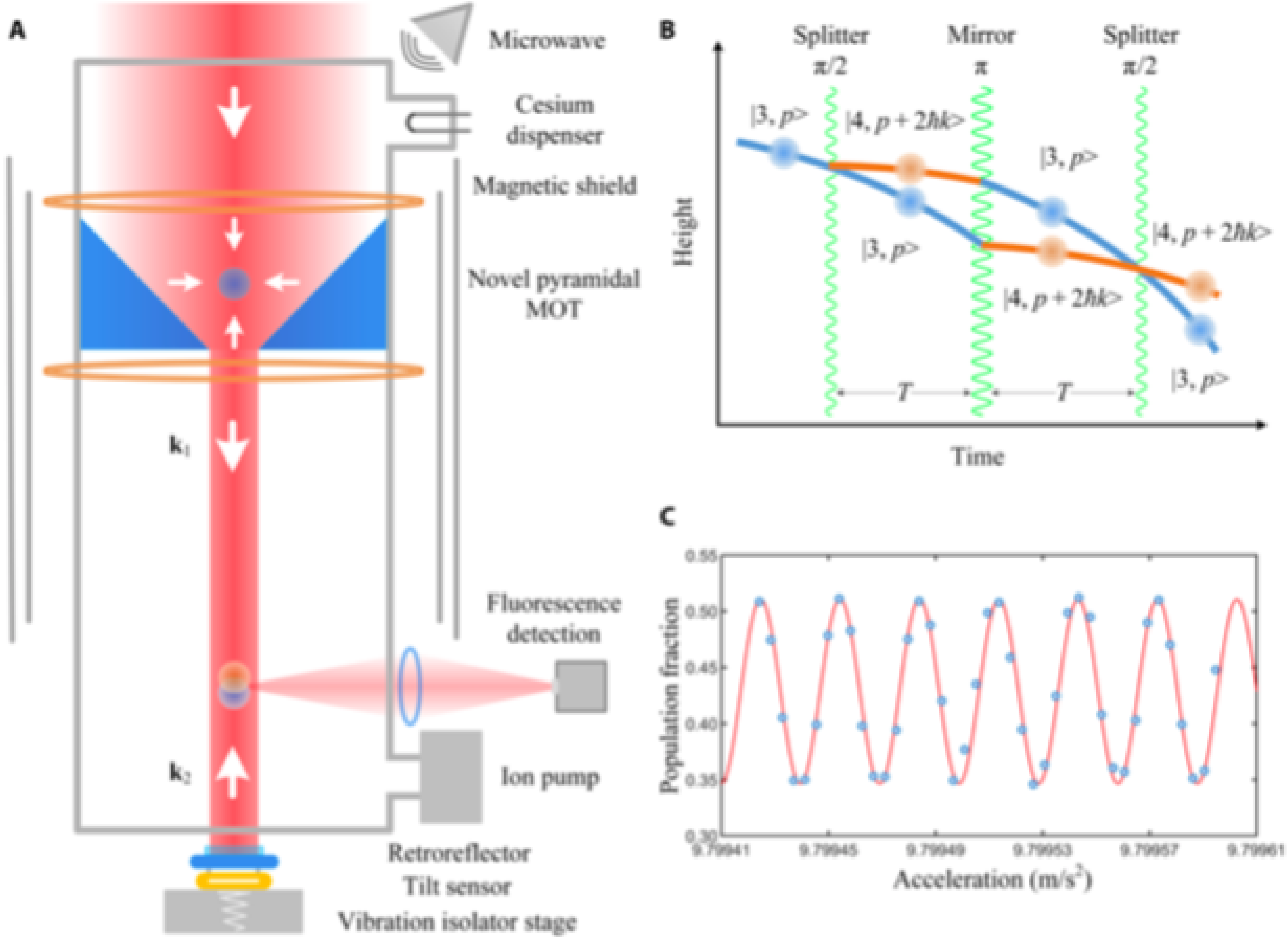
Receive only without inherent "gain"

DARPA Envisioned Program End State

Different Physics and Different Limits = Large Opportunity

DARPA *Quantum Apertures* Program

Atom Interferometry ("Quantum Gravity Sensor")



Quantum Gravimetry

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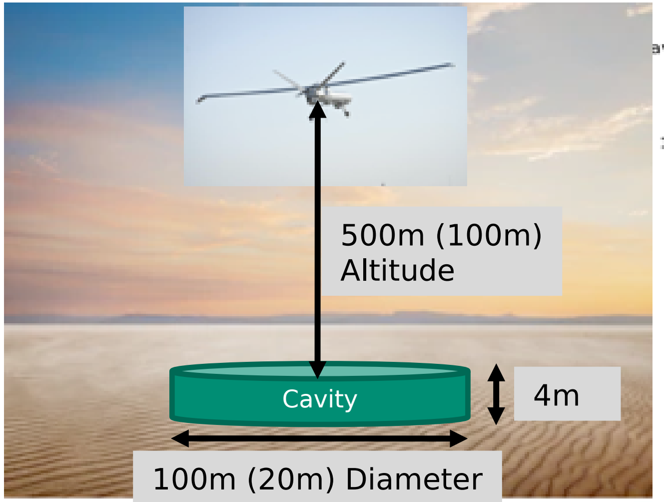
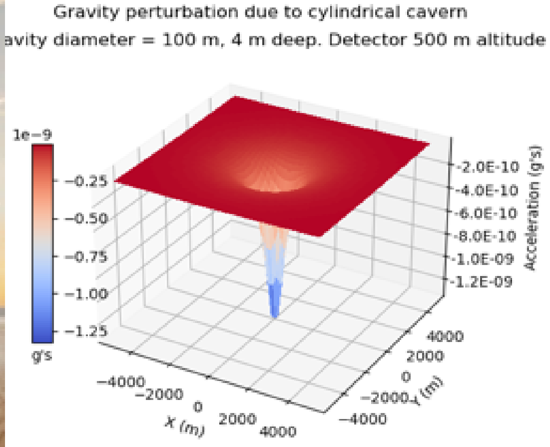
Detect Underground Structures

- Gravimetric signatures are always present as mass cannot be shielded
- Gravimetric methods based on atom interferometry may offer a solution for rapid, sensitive detection of buried structures





Muquans Instrument

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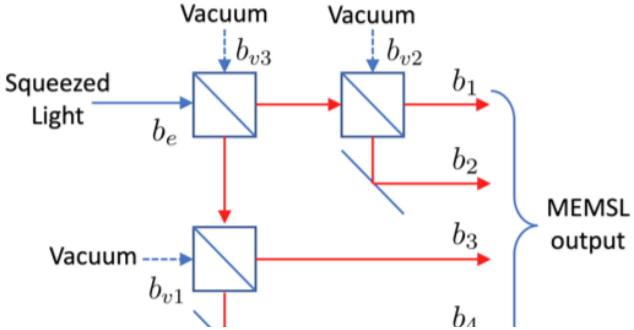
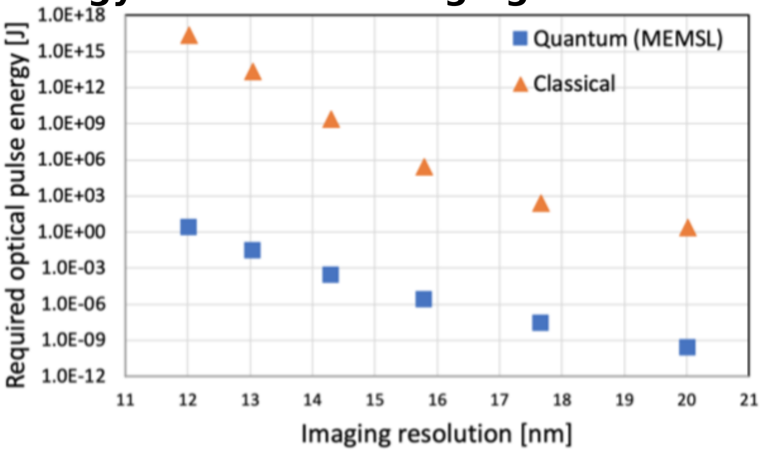
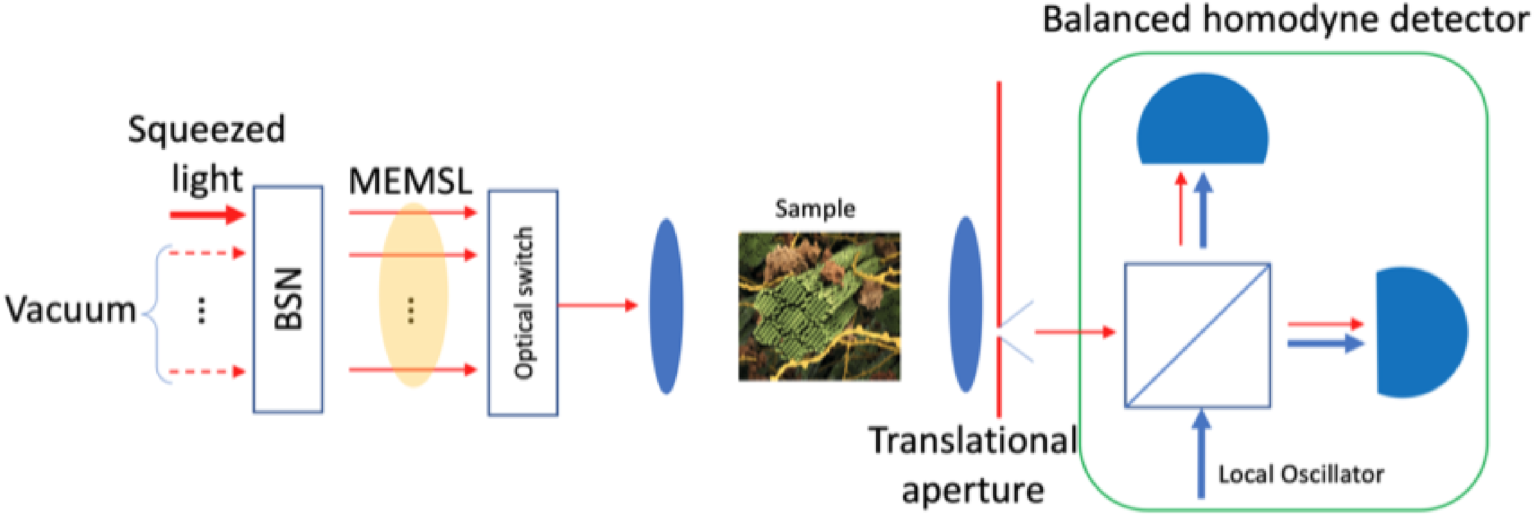
Quantum Imaging using Massively Entangled Multimode Squeezed Light (MEMSL)

Generation of a MEMSL source using a Beam Splitter Network



Calculated required optical pulse energy vs. desired imaging resolution





Quantum “Ghost” imaging

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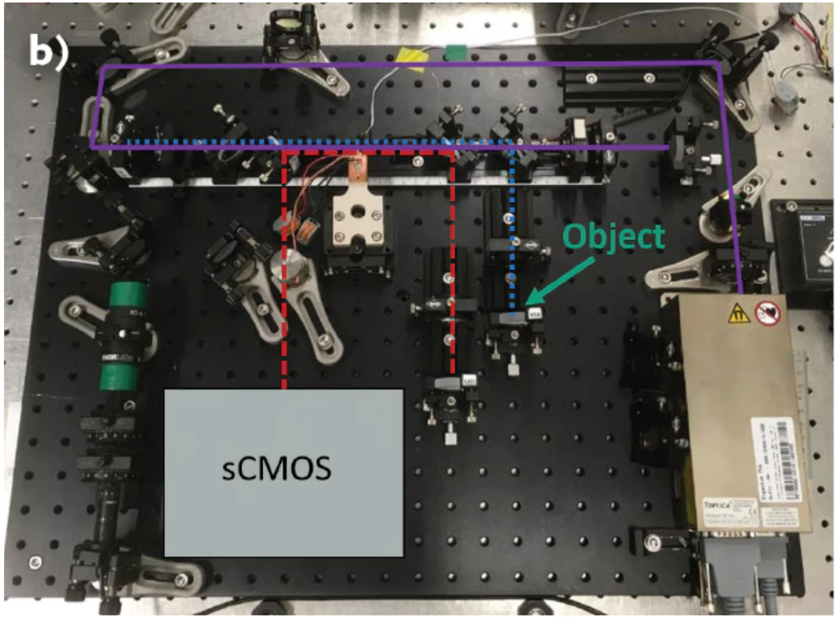
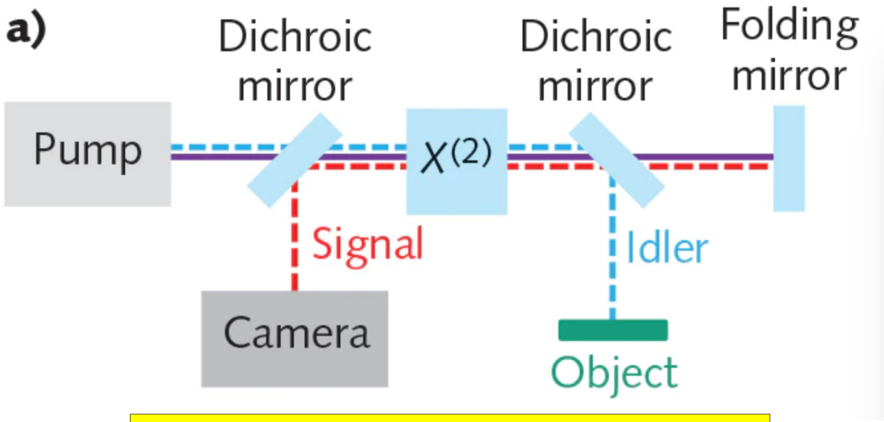


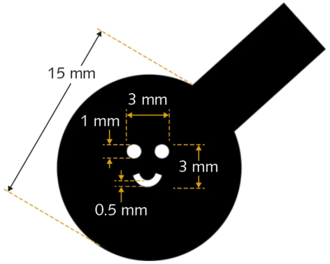


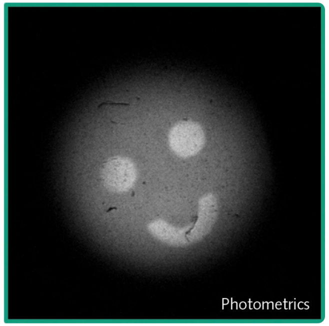
Entangled photon source

Quantum imaging with undetected photons

Gabriela Barreto Lemos, Victoria Borish, Garrett D. Cole, Sven Ramelow, Radek Lapkiewicz & Anton Zeilinger

Nature **512**, 409–412(2014) | Cite this article





Target

Image of target
in other spectral region

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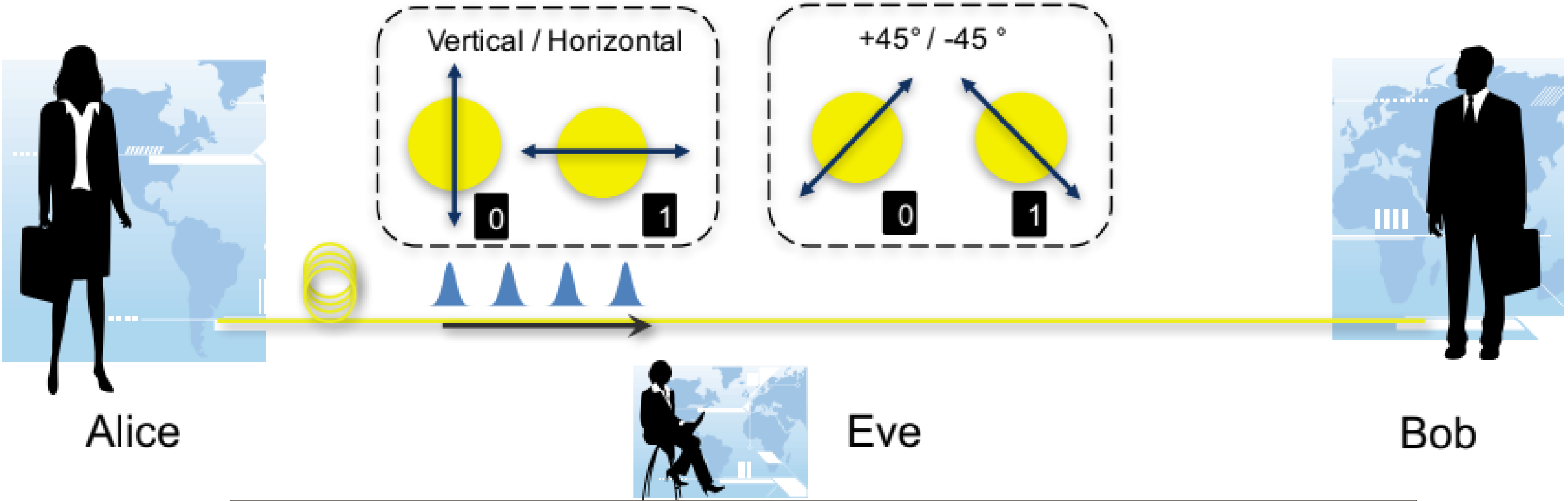
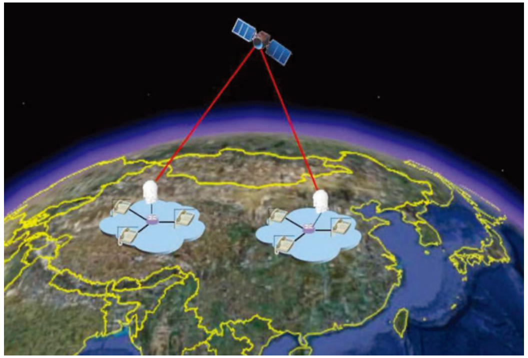
Quantum Key Distribution (QKD) – “Quantum Encryption”



Secure because can detect Eavesdropper ”Eve”, who disrupts the quantum state



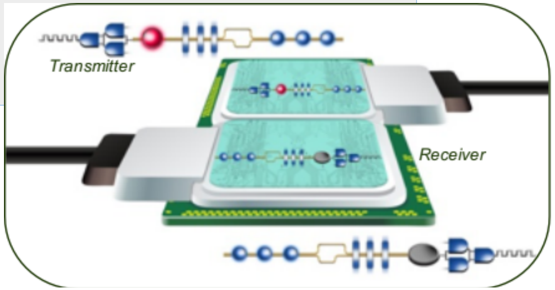
China’s Micius satellite sets distance record for quantum entanglement in space

Part of ambitious Chinese program: Quantum Experiments at Space Scale (QUESS; Chinese: 量子科学实验卫星)

QKD requires hardware unlike Public Keys, but significant software processing needed

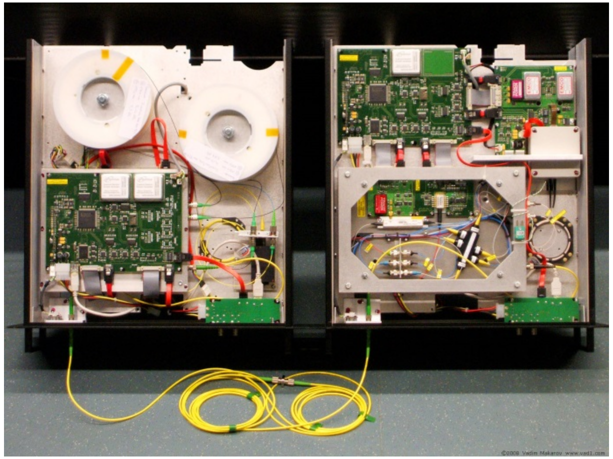
Unlike current data encryptions standards, which are software-based (e.g. RSA, AES, SHA), QKD relies on hardware:

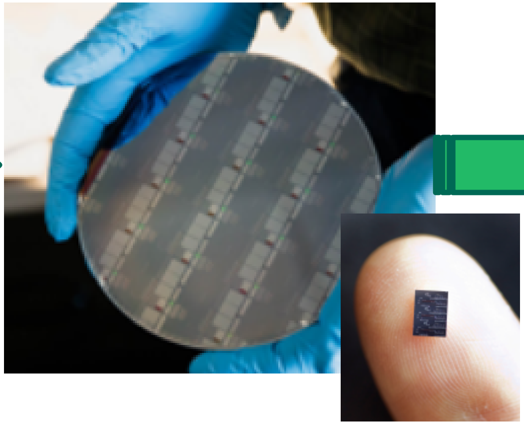
- Lasers (single photon or traditional laser)
- Detectors (single photon or homodyne)
- Fiber optics
- High-speed modulators

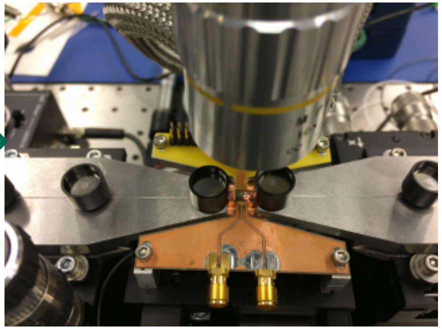


Trend is to put all components on a photonic chip

ID Quantique Clavis QKD System (Swiss)







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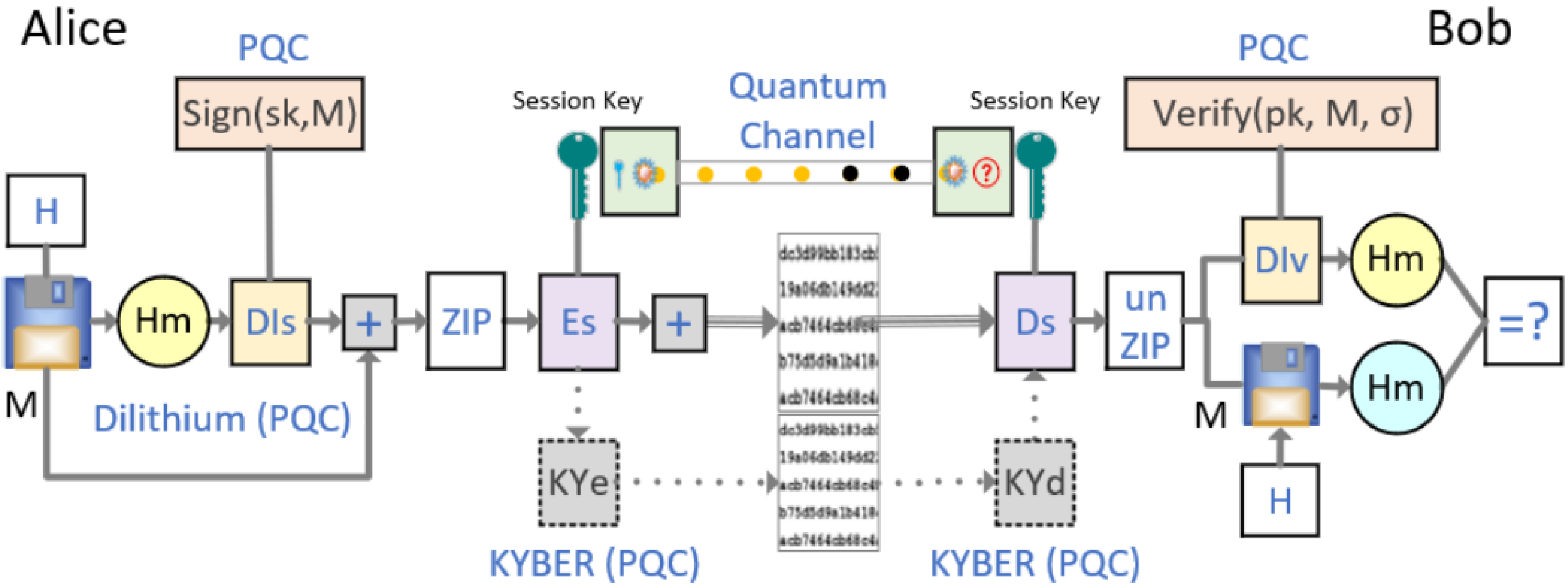
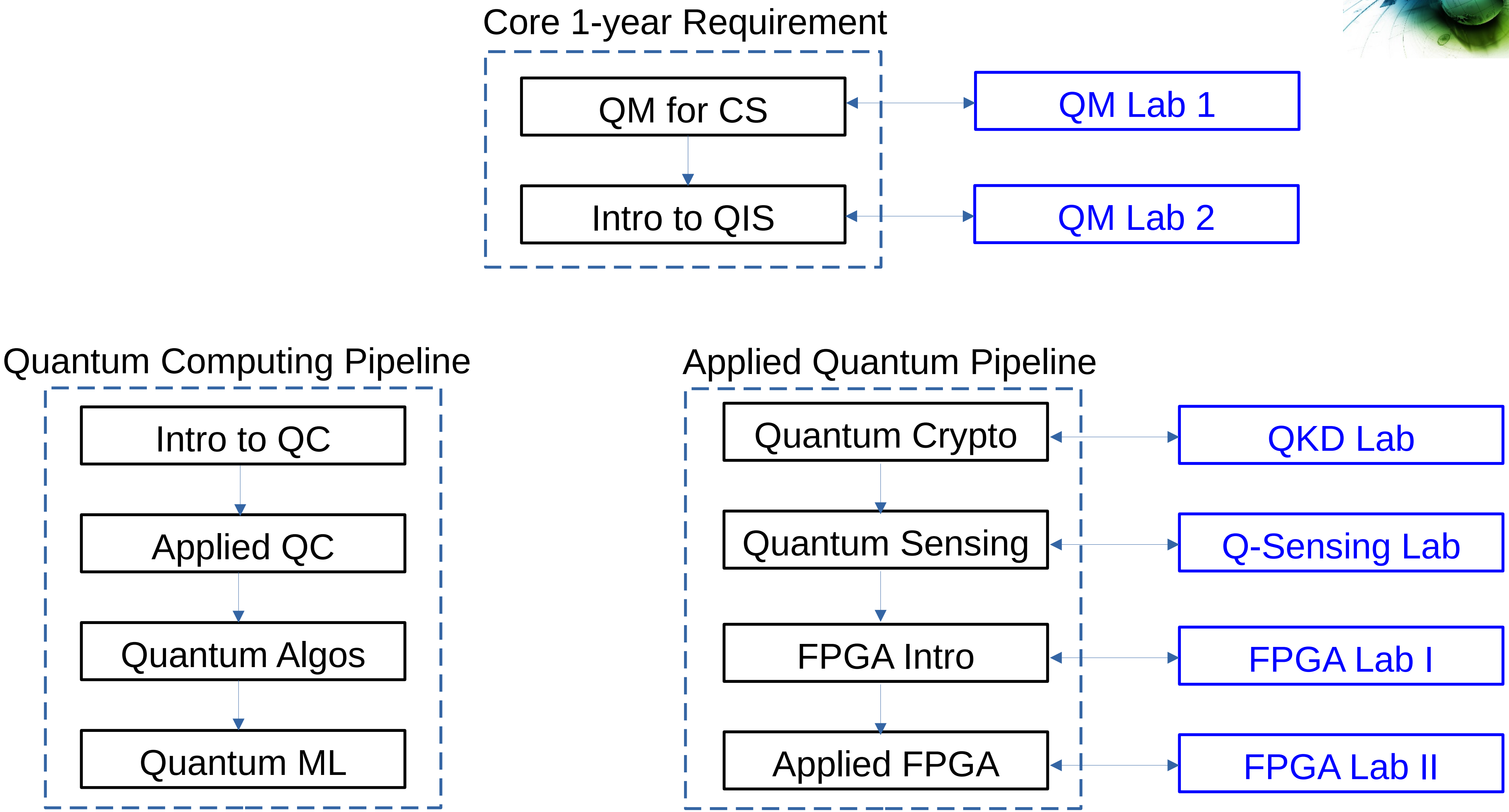
Quantum Good Privacy at Morgan State University



QGP Authentication Protocol Diagram. M: Message, H: Hash Functions (SHA 2/3), Hm: Hashed message, Dis/Div: Dilithius Sign/Verify (PQC), ZIP/unZIP: Compression/Decompression, Es/Ds: Symmetric Key Encryption/Decroption, KYe/KYd: KYBER Encryption/Decryption (PQC)

Quantum Courses Progression



Extras