

Center for  
**Quantum Networks**  
*NSF Engineering Research Center*



# Quantum Entanglement— *No, It's Not FTL!*

**Stephen Fleming**

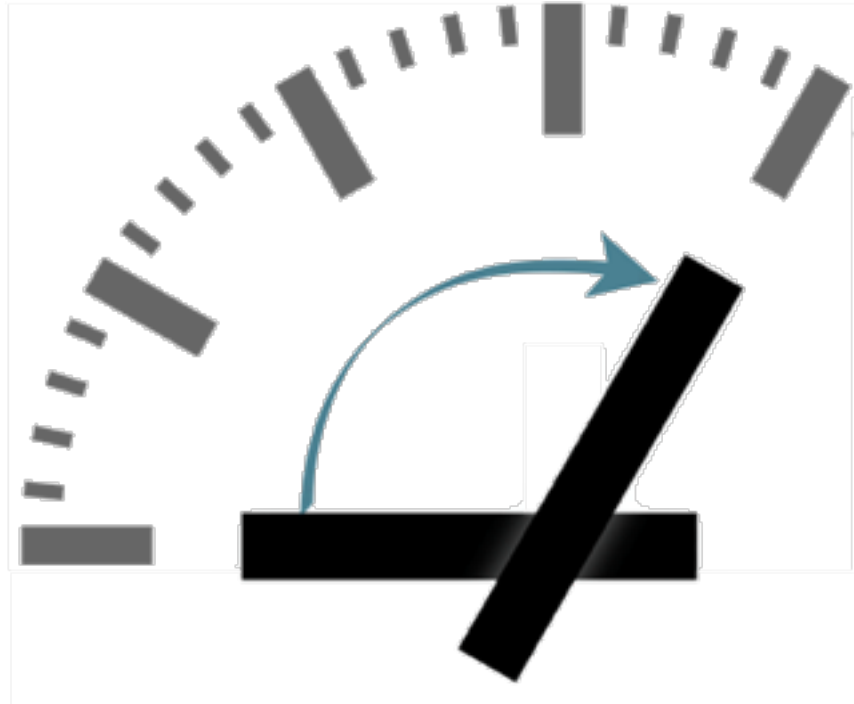
*Director of Strategic Partnerships and Innovation*

University of Arizona — [stephenfleming@arizona.edu](mailto:stephenfleming@arizona.edu)

Funded by the National Science Foundation and the Department of Energy under NSF cooperative agreement #1941583



# Agenda



Who Am I?

Einstein was Wrong!

Entanglement and Superposition

So What?

Example: Secure Quantum Communications

Sputnik Moment and Societal Impact

Industrial Value Chain

Chattanooga Quantum Network

Questions?

# Who Am I?

## 6 years in leadership at University of Arizona

*Corporate engagement, Arizona Space Business Roundtable, Center for Quantum Networks, and more...*

## 11 years as Vice President, Georgia Institute of Technology.

*Responsible for economic development, including commercialization, corporate engagement, manufacturing support, incubators, accelerators, ecosystem development, and more. Helped create and launch NSF I-Corps program.*



# What Did I Do Before?

## 10 years VC experience at General Partner level

*18 investments as lead investor*

*12 profitable exits (including 4 IPOs, one \$650M acquisition); 47% annualized cash-on-cash IRR*

## 15 years corporate operations

*AT&T Bell Labs*

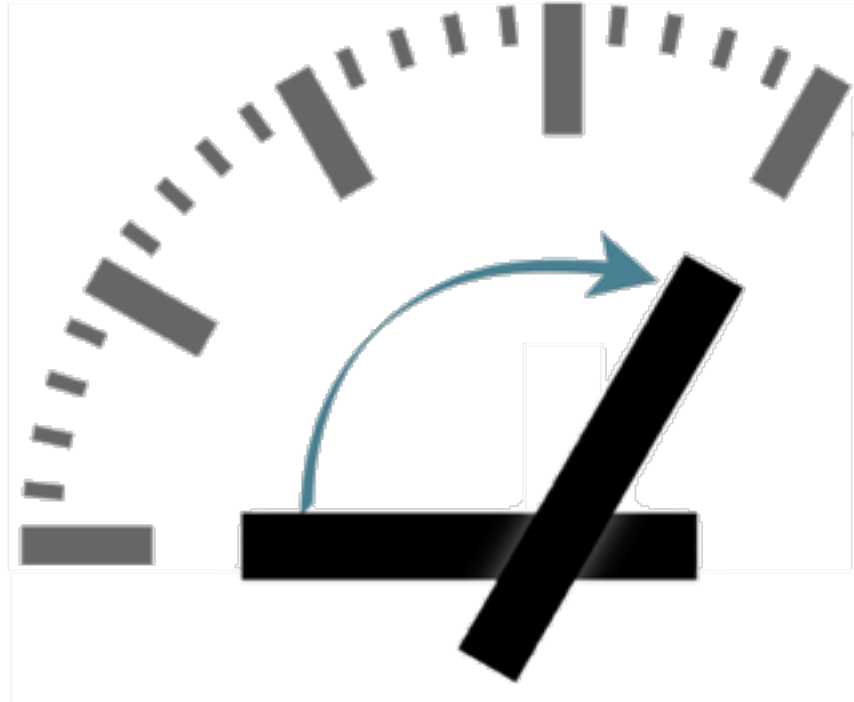
*Nortel Networks*

*LICOM (venture-backed telecom equipment startup)*

**BS, Optical Physics, Georgia Tech (*Highest Honors*)**



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Example: Secure Quantum Communications

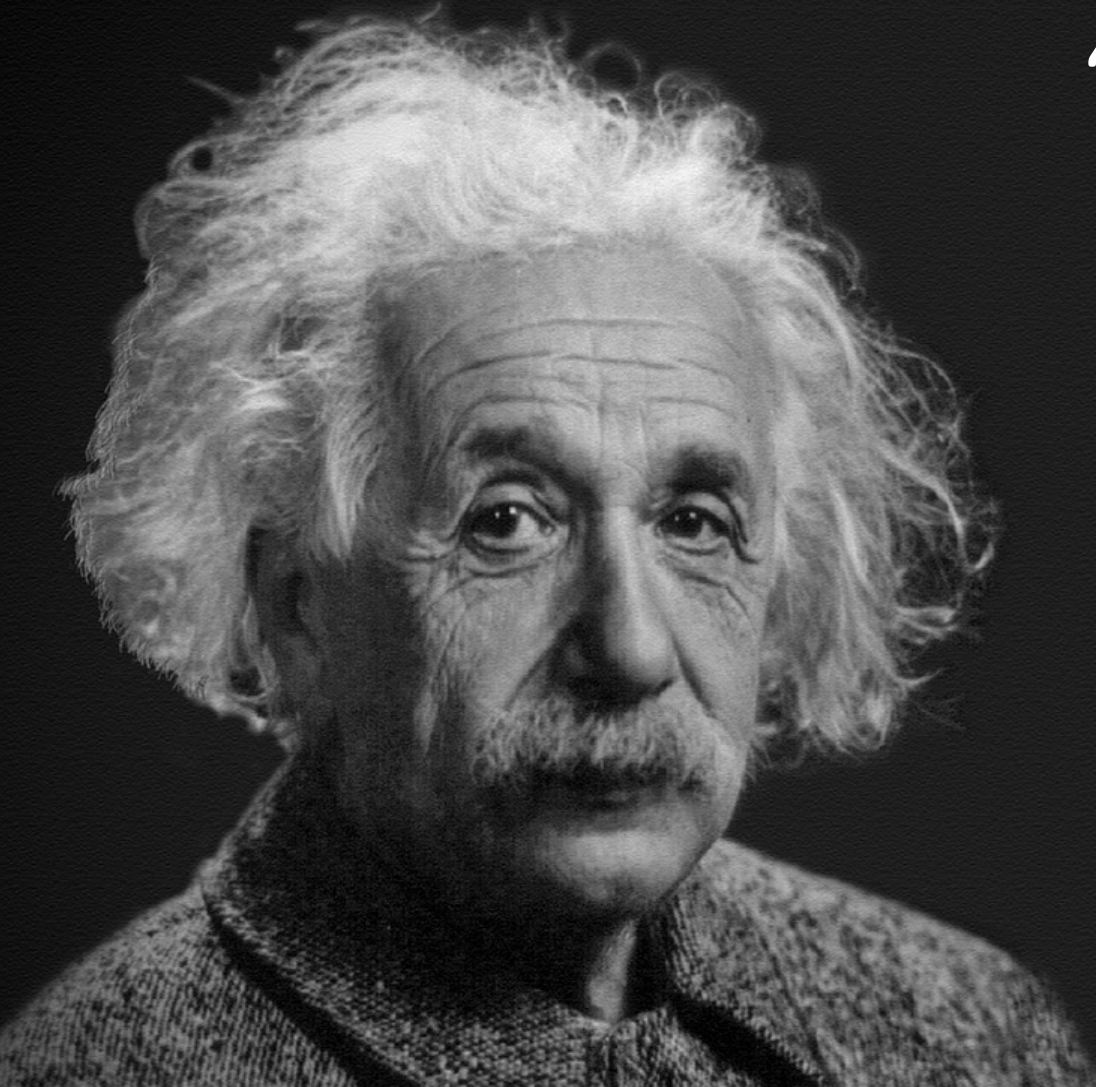
Sputnik Moment and Societal Impact

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# Einstein Was Wrong!



“I cannot seriously believe in [quantum entanglement] because the theory cannot be reconciled with the idea that physics should represent a reality in time and space, free from **spooky action at a distance**.”

—Letter to Max Born, 1947

# 2022 Nobel Prize in Physics



# 2022 Nobel Prize in Physics



Jointly awarded to Alain Aspect, John F. Clauser, and Anton Zeilinger for experiments with entangled photons, establishing the violation of Bell inequalities, and pioneering quantum information science.



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**Entanglement and Superposition**

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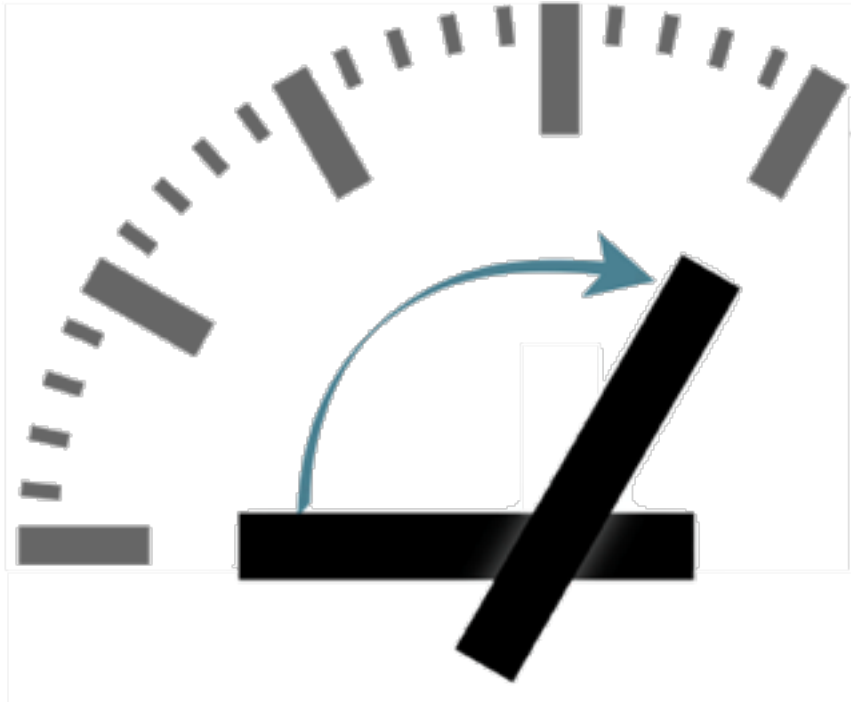
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# Quantum Entanglement

- A set of two (or more) particles where there is 100% correlation between momentum, spin, polarization, or other properties.
  - The properties of each particle are **indefinite** until measured.
  - The act of measuring one determines the probabilities of observing particular results when measuring the other, **even when separated by a distance.**

# Quantum Superposition



- Superposition does ***not*** mean “both states at the same time.”
- Superposition does ***not*** mean “or.”
- *Quantum systems don't behave like classical systems. Intuition and common sense don't work here.*



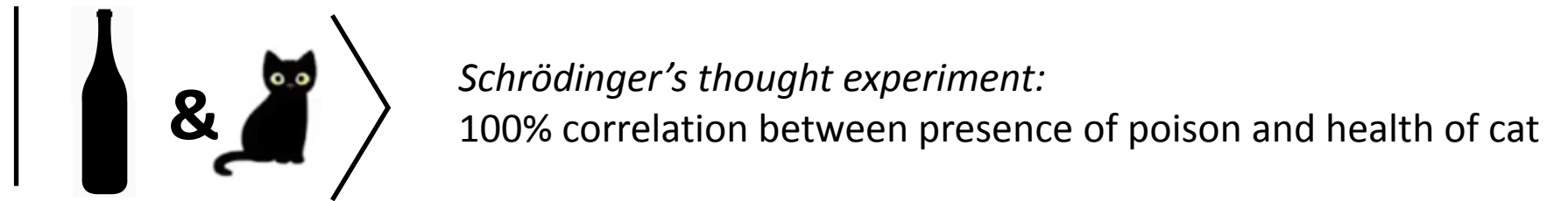
# Superposition and Entanglement



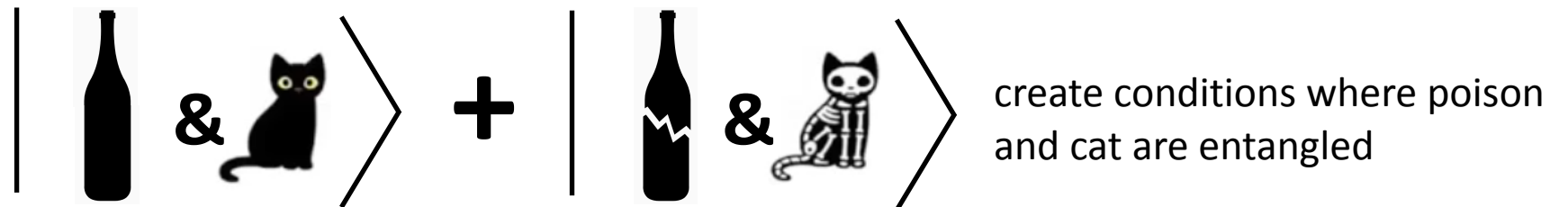
## Superposition:



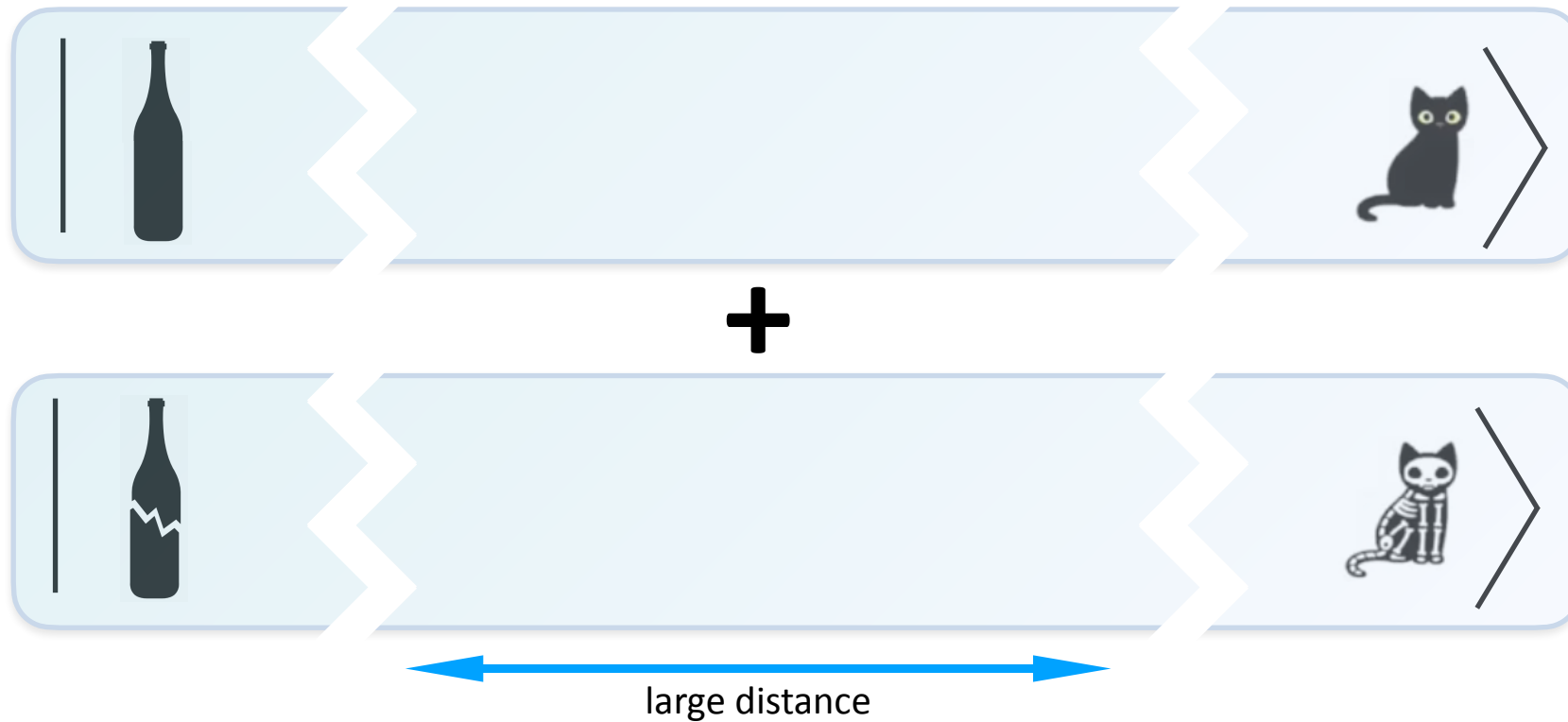
## Composite State:



## Entanglement:

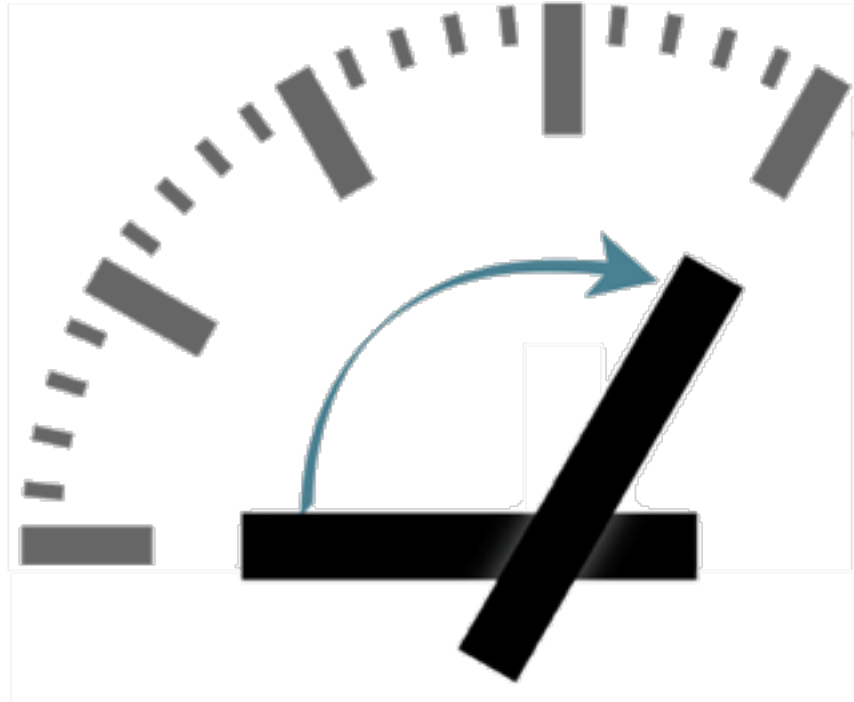


# Non-Local Entanglement



**Correlation does not imply causation!**

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# It's Not This...



# So What?



The **first quantum revolution** was based on behavior of materials made up of many atoms, and brought us:

- computers
- the Internet
- lasers
- medical imaging
- atomic clocks and GPS



# So What?

The **first quantum revolution** was based on behavior of materials made up of many atoms, and brought us:

- computers
- the Internet
- lasers
- medical imaging
- atomic clocks and GPS

The **second quantum revolution** will be based on behavior of individual atoms and photons with entanglement between them.

*What will it bring?*

# What Will Quantum Technology Do?

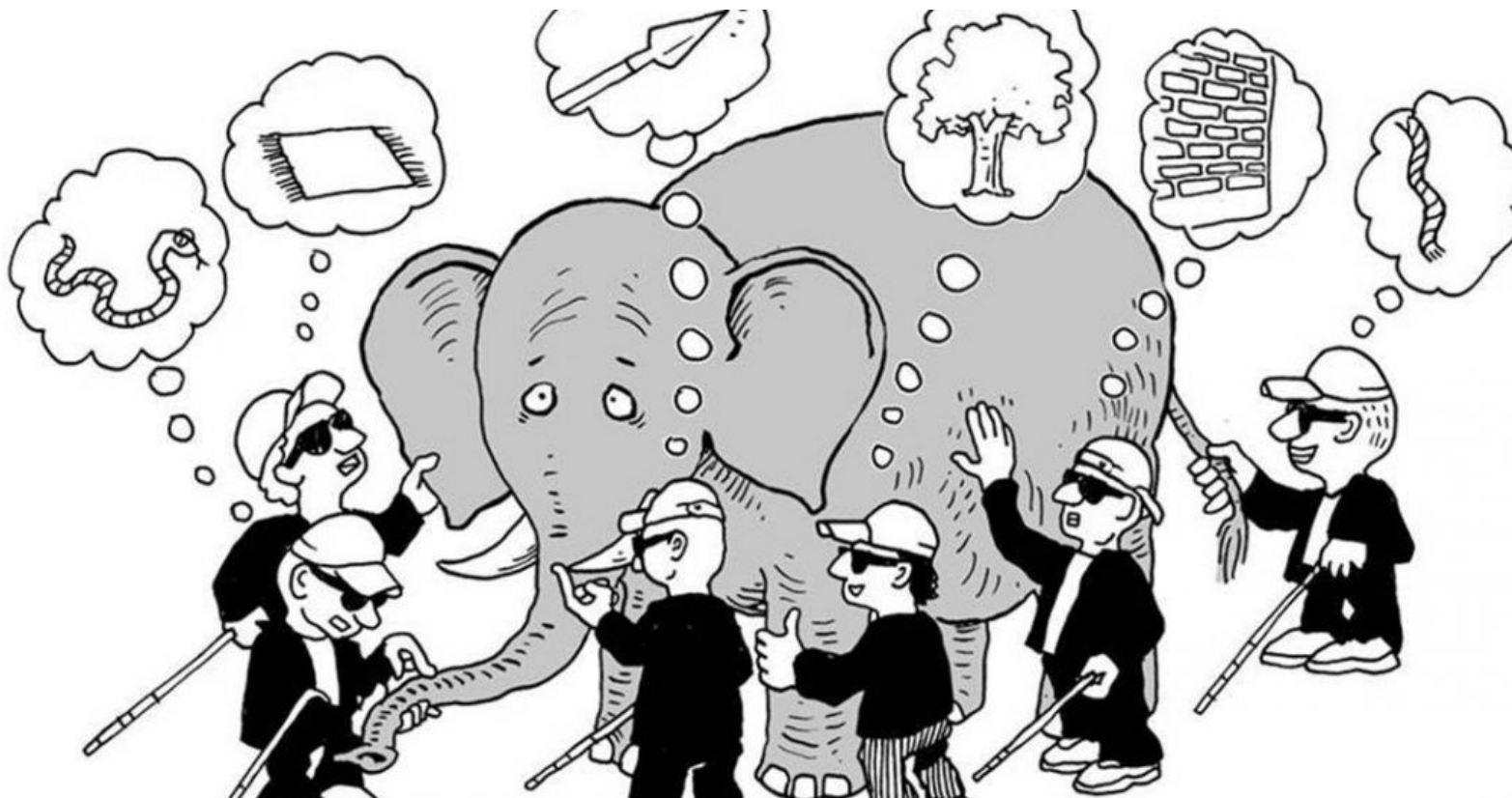


Fundamentally  
powerful  
**computing**

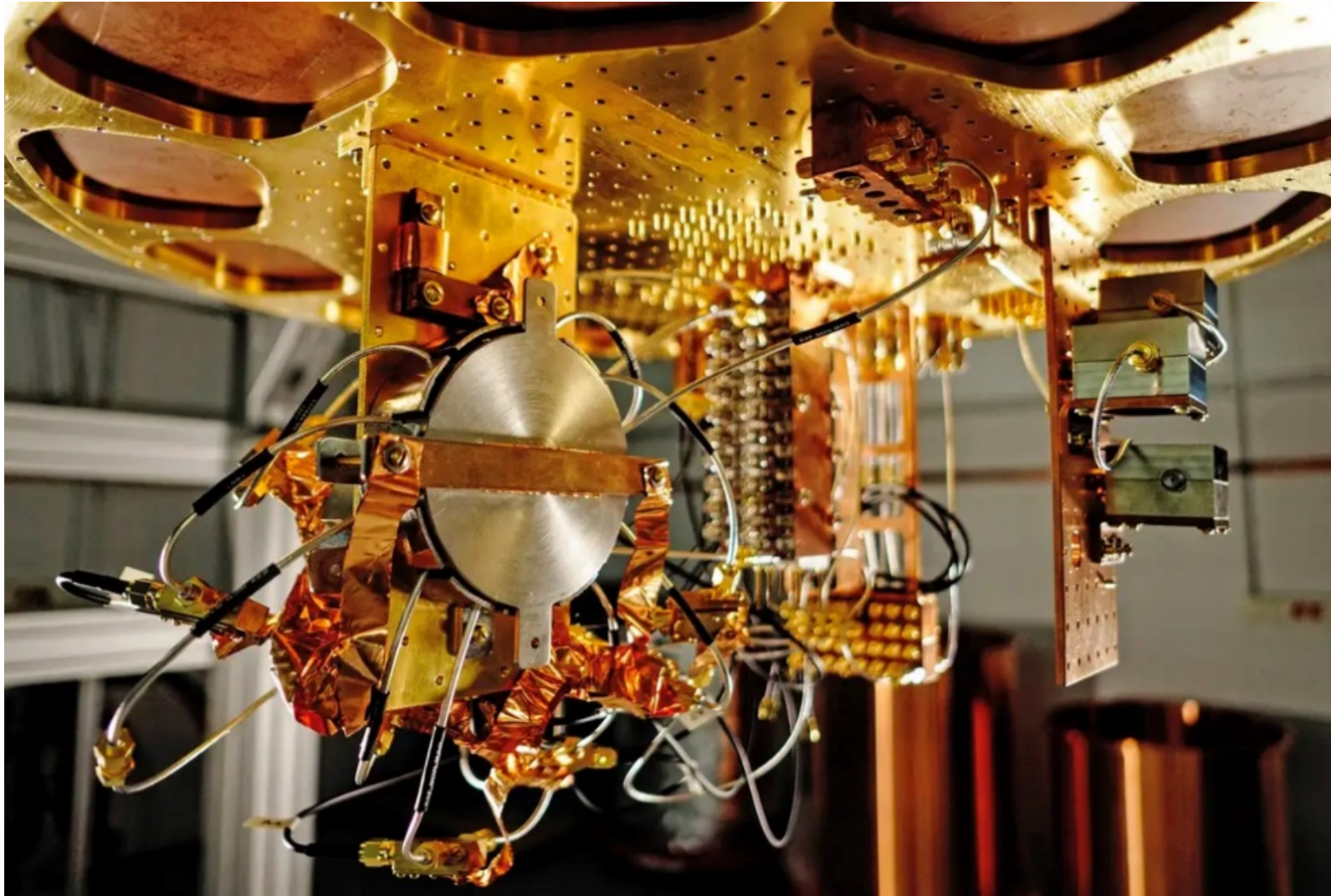
Provably-secure  
**communications**

High-  
resolution  
**sensing**

Quantum-  
enabled  
applications  
that we  
cannot  
**imagine**  
today!



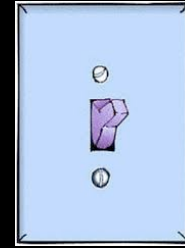
# Quantum Computing



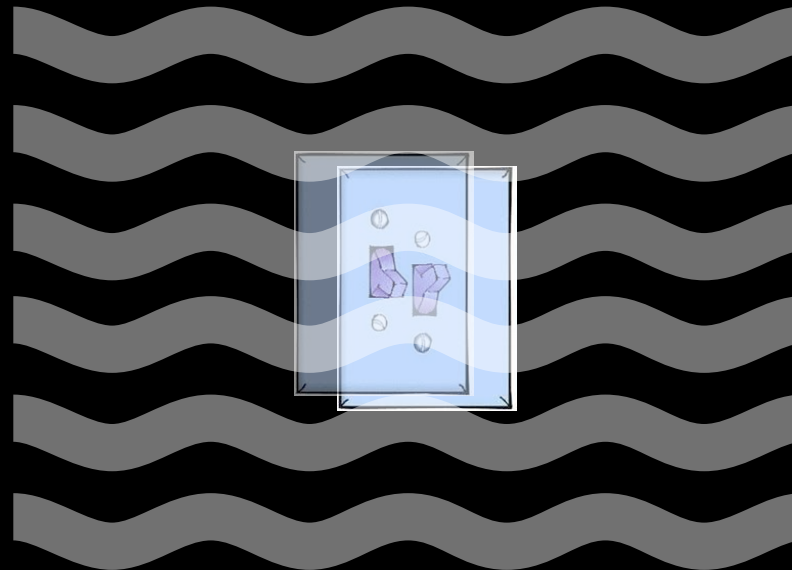
Optimization  
Designer molecules  
*(drugs, solar cells...)*  
Materials design  
Pattern recognition  
*(traffic patterns)*  
Machine learning  
Artificial intelligence  
Decryption

# Bits and Qubits

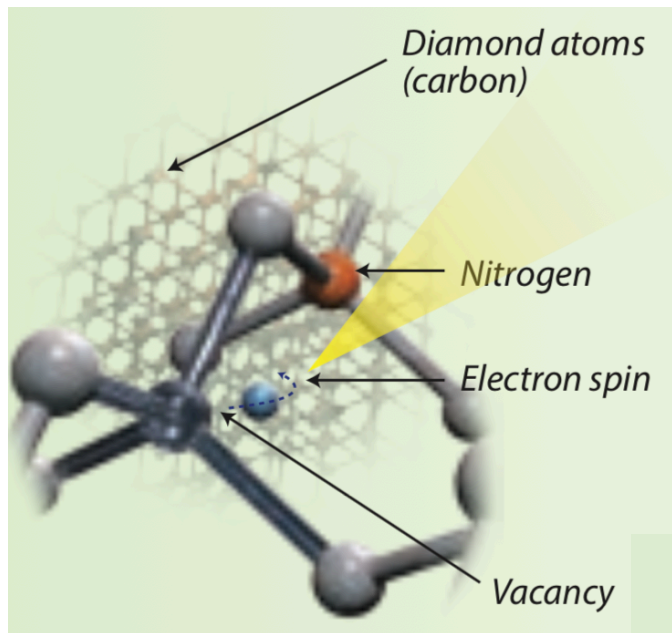
Bit



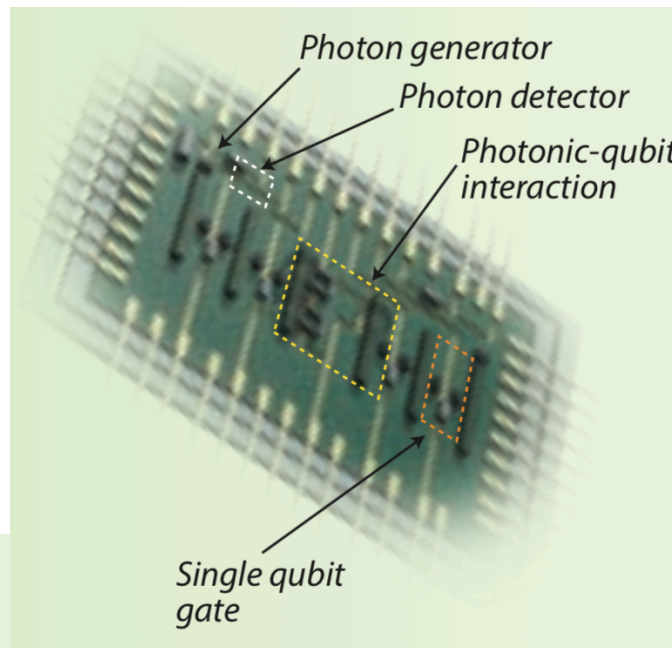
Qubit



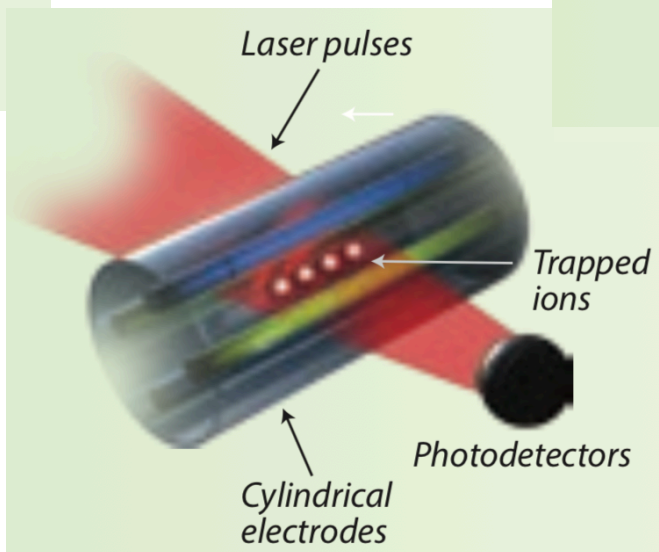
# Manipulating Qubits



Electron spins  
in diamond  
vacancies

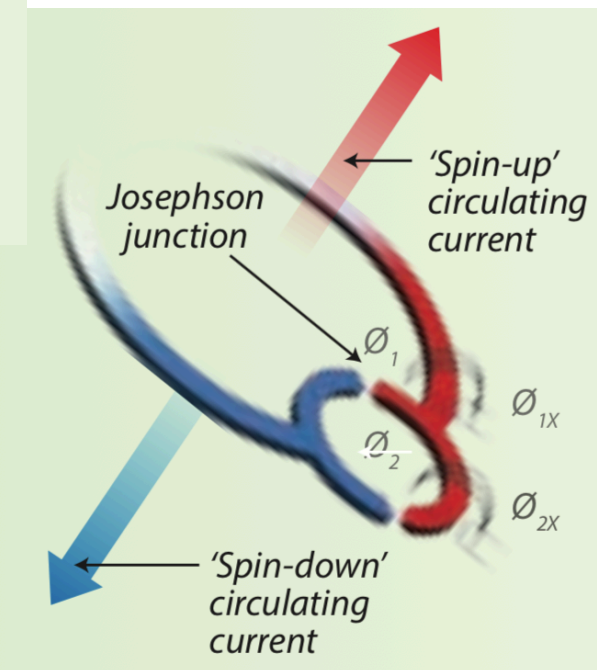


Photonic circuits



Trapped ions or  
neutral atoms

Superconducting  
circuits



# Manipulating Qubits



*No-cloning theorem:*

- You can't make a copy of a quantum state without destroying the state of the original object.
- Actions that we take for granted with classical bits (memory, storage, display) **are very complex** for qubits.

# No-Cloning Theorem



*Star Trek* photos courtesy of CBS and Paramount Pictures.

# Qubits are Fragile!

Quantum states of electrons and photons are extremely sensitive to external perturbations

- **Bad** — decoherence destroys quantum computation

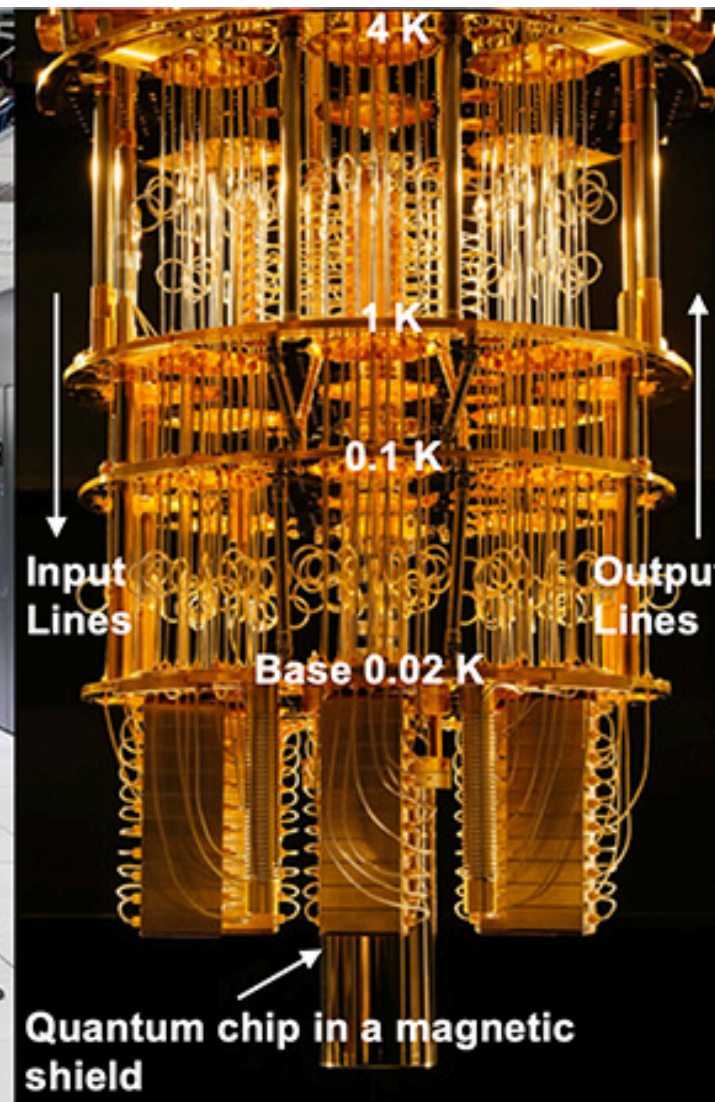




# Sub-Kelvin Operations

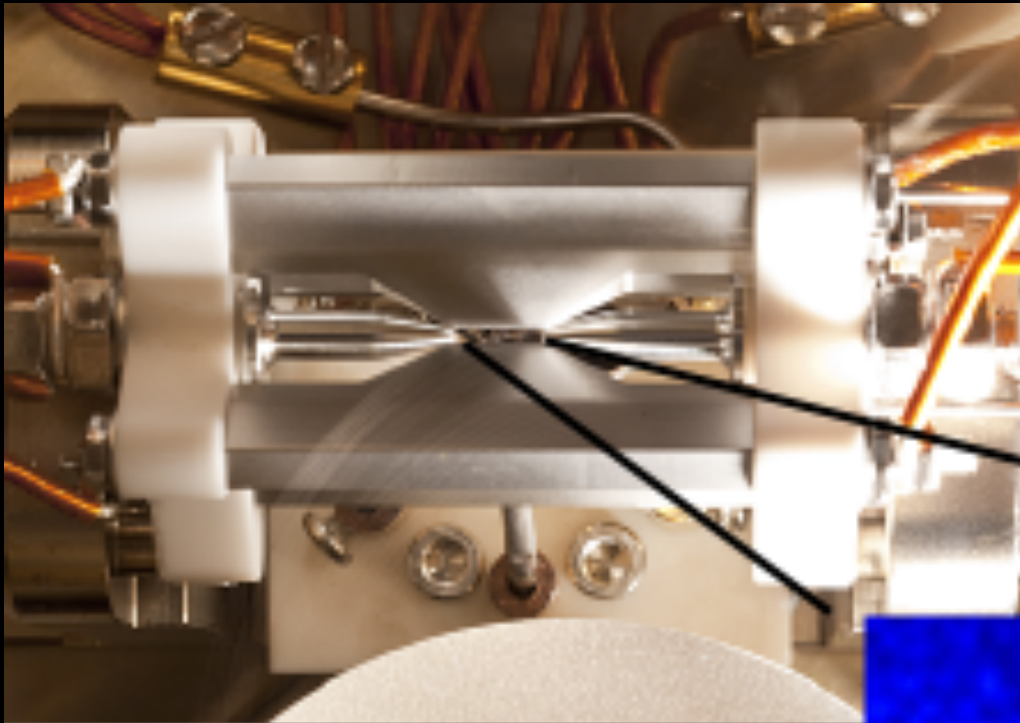


**Dilution fridge setup: outside view**

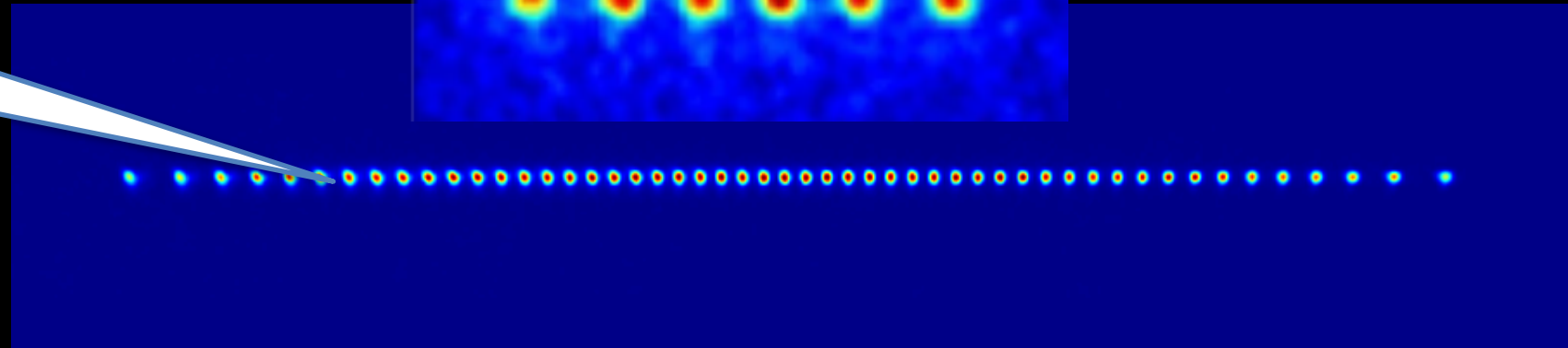
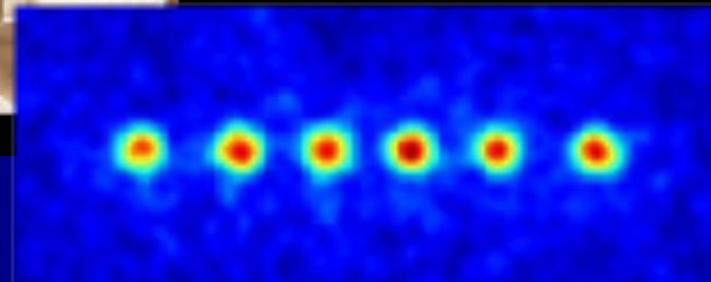
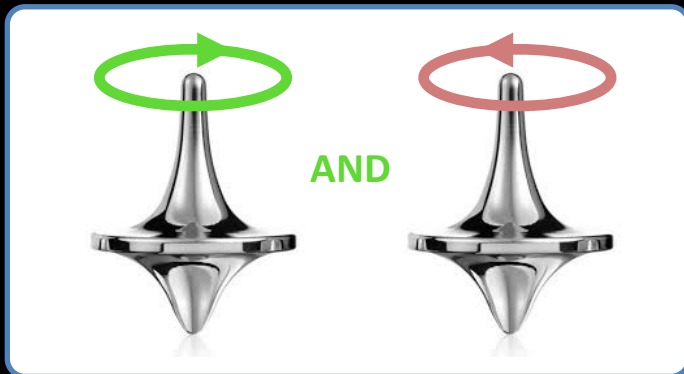


**Dilution fridge setup: inside view**

# e.g. Trapped-Ion Quantum Computing



- A line of 50 individual atoms (ions) trapped in vacuum
- 1,125,000,000,000,000 states represented simultaneously



# Qubits are Fragile!



Quantum states of electrons and photons are extremely sensitive to external perturbations

- **Bad** — decoherence destroys quantum computation
- **Good** — quantum sensors can detect weak signals

# Quantum Sensing



Magnetic fields  
Gravitational fields  
Quantum-enhanced radar  
Biomedical imaging  
Materials engineering  
Accelerometers  
GPS-free navigation  
Superresolution imaging  
Quantum spectrometry



# *e.g.* Quantum Brain Scanner

**THE ENGINEER**

**Nottingham University scientists receive IOP award for wearable brain scanner**

News | ⌚ 1 min read

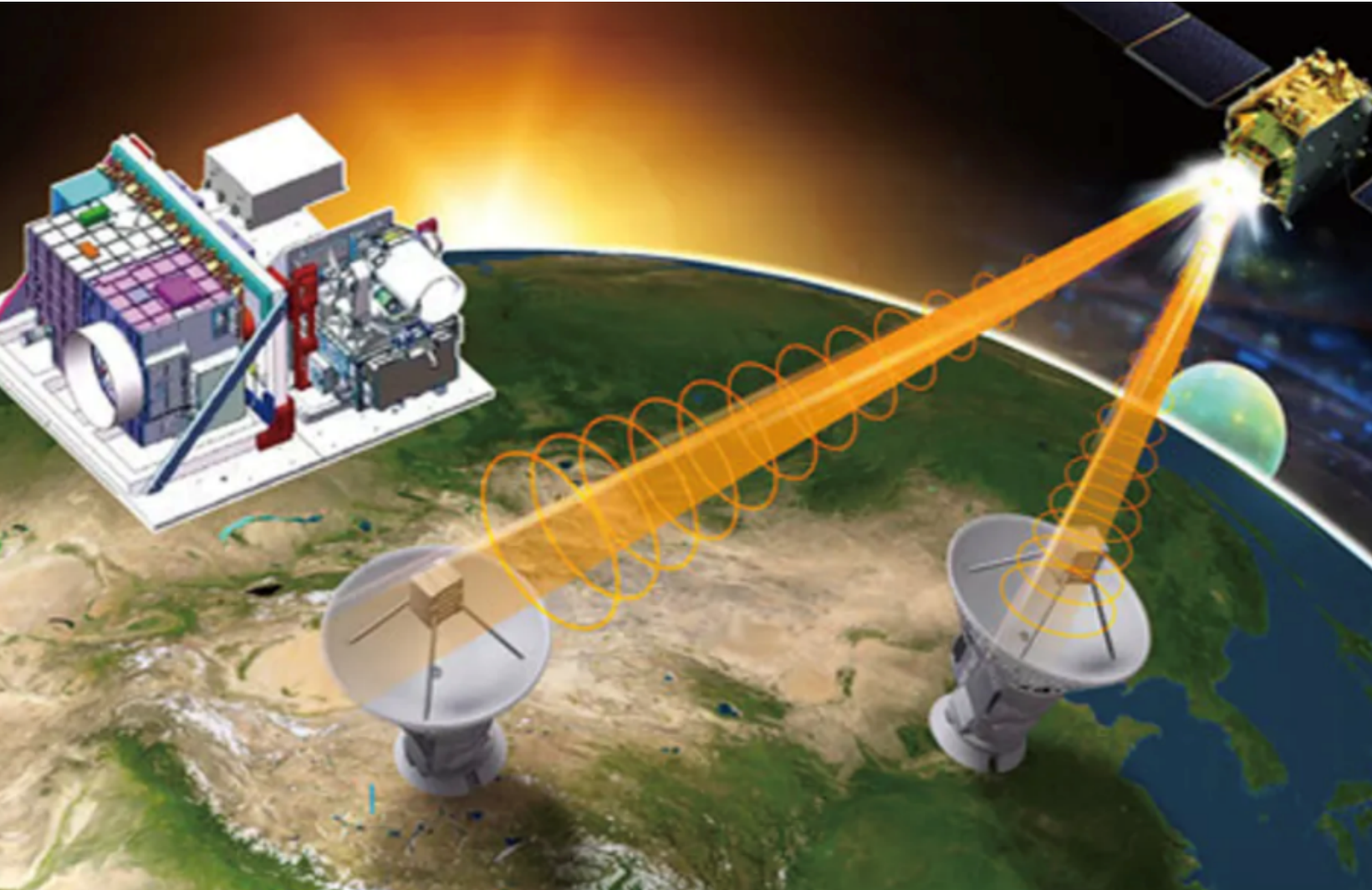
Nottingham University scientists have been recognised for their work to transform brain imaging with the development of a new kind of wearable brain scanner.

28 Oct 2022



Award winning OPM-MEG - Nottingham University

# Quantum Networking



Secure data encryption  
Remote quantum  
computing  
Distributed quantum  
computing  
Distributed sensing  
Multiparty entangled  
protocols

# The Quantum Internet

Fault-tolerant quantum memories are used to build quantum repeaters and switches for high-fidelity high-rate quantum communications over thousands of kilometers.



Secure communications



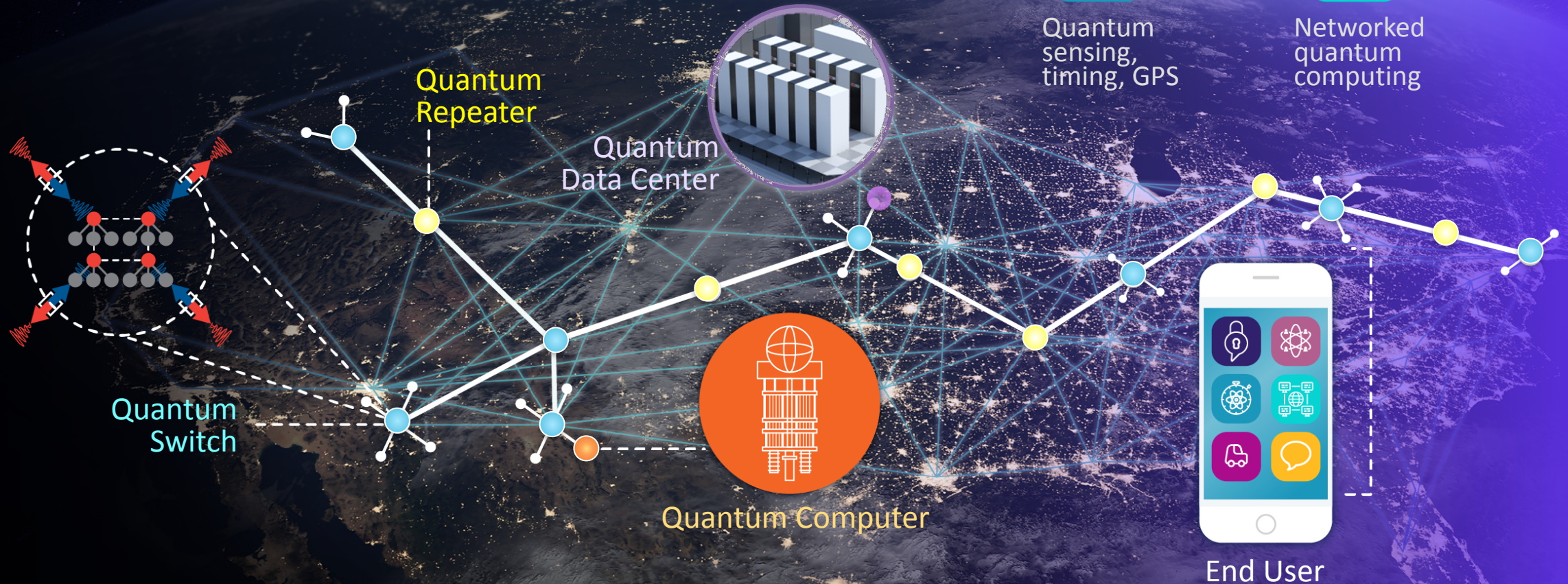
Multi-user quantum applications



Quantum sensing, timing, GPS



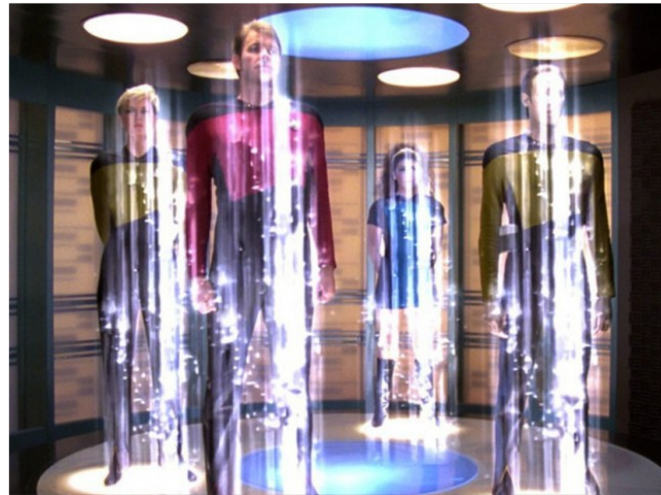
Networked quantum computing



# What Quantum Networks are Not!



Teleportation



*(Well, not of people)*

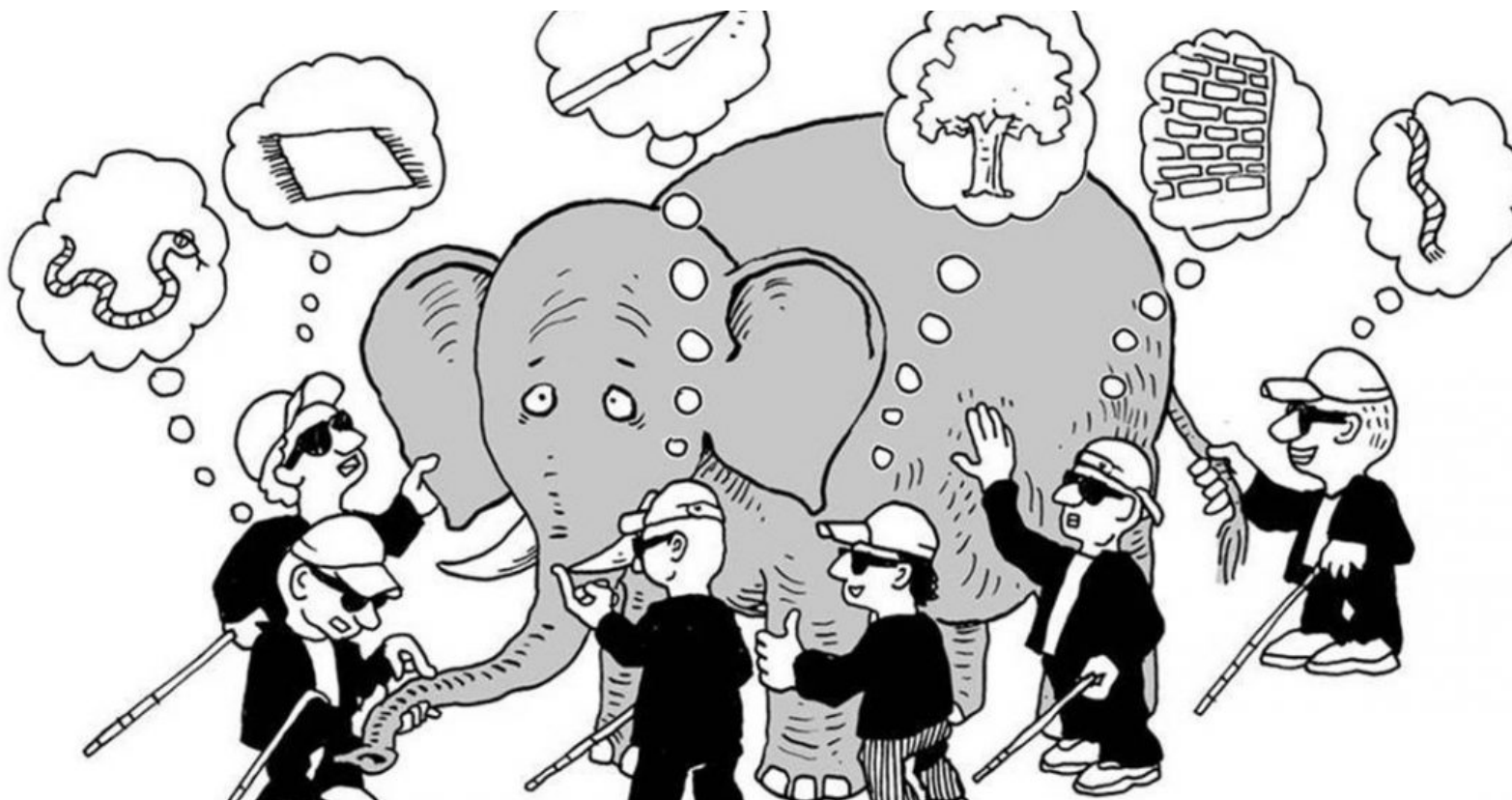
Faster Internet



Faster-Than-Light  
Communication

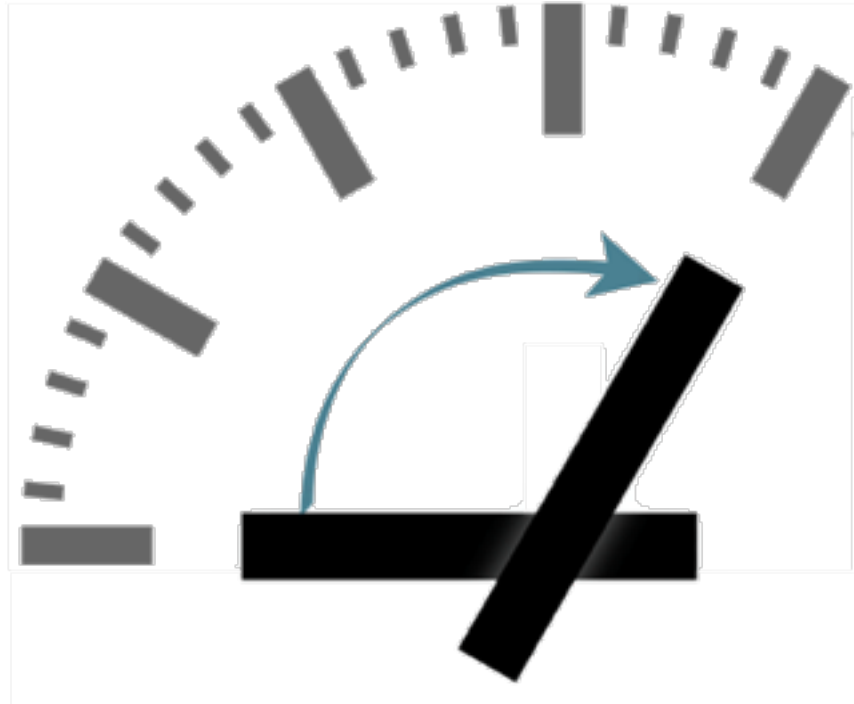


# What Will Quantum Technology Do?



Quantum-  
enabled  
applications  
that we  
cannot  
**imagine**  
today!

# Agenda



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Entanglement and Superposition

So What?

**Example: Secure Quantum Communications**

Sputnik Moment and Societal Impact

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Chattanooga Quantum Network

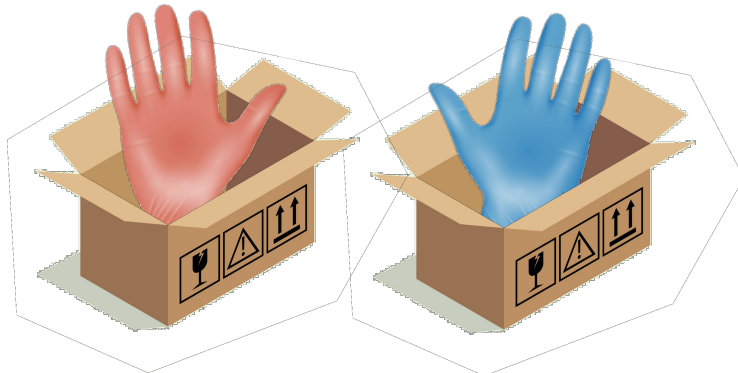
Questions?

# Secure Quantum Communications



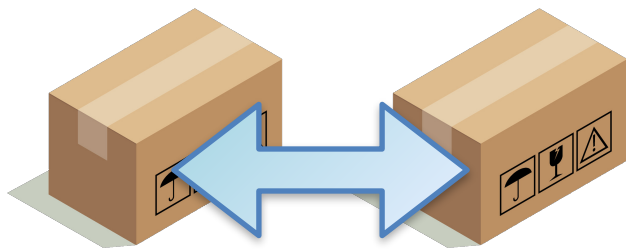
Alice has a pair of gloves.  
*Entanglement:* one L, one R.

# Secure Quantum Communications



Alice obtains two identical boxes,  
and places one glove in each.

# Secure Quantum Communications



Randomize the boxes so  
Alice does not know which  
glove is in which box.

# Secure Quantum Communications



Alice ships one of the boxes to Bob.

# Secure Quantum Communications



Alice opens her box and finds a blue glove.



# Secure Quantum Communications



Alice opens her box and finds a blue glove.

Alice knows with 100% certainty that Bob has a red glove.

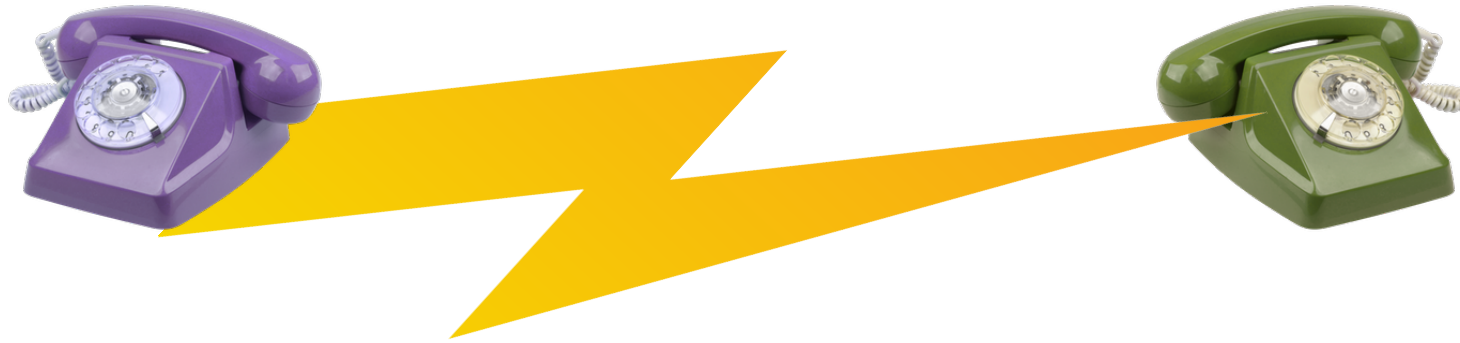
But opening her box did not suddenly “make” Bob’s glove turn red.



Bob doesn’t know what is in his closed box.



# Secure Quantum Communications

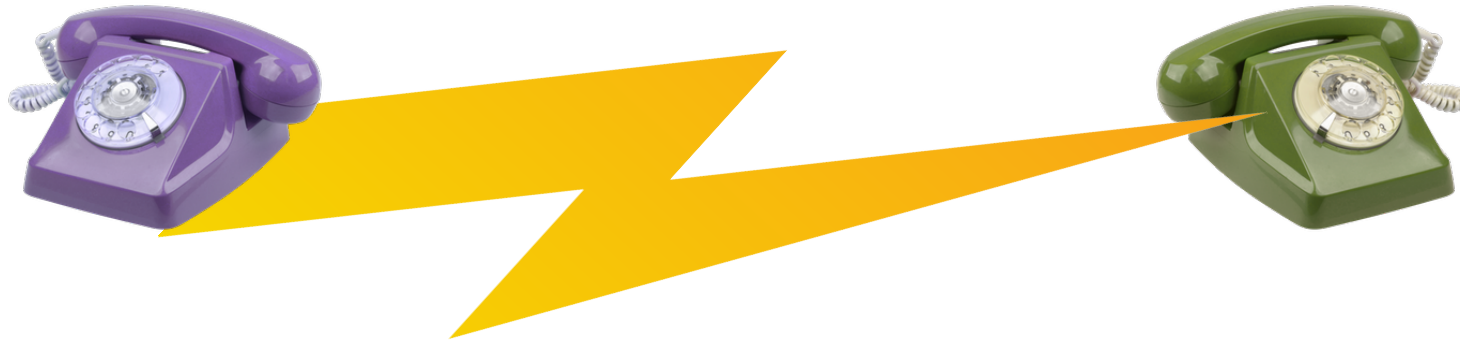


“Hi, Bob! It’s Alice. You have a red glove...”



Bob knows the contents of his box without opening it.

# Secure Quantum Communications



“Hi, Bob! It’s Alice. You have a red glove...”

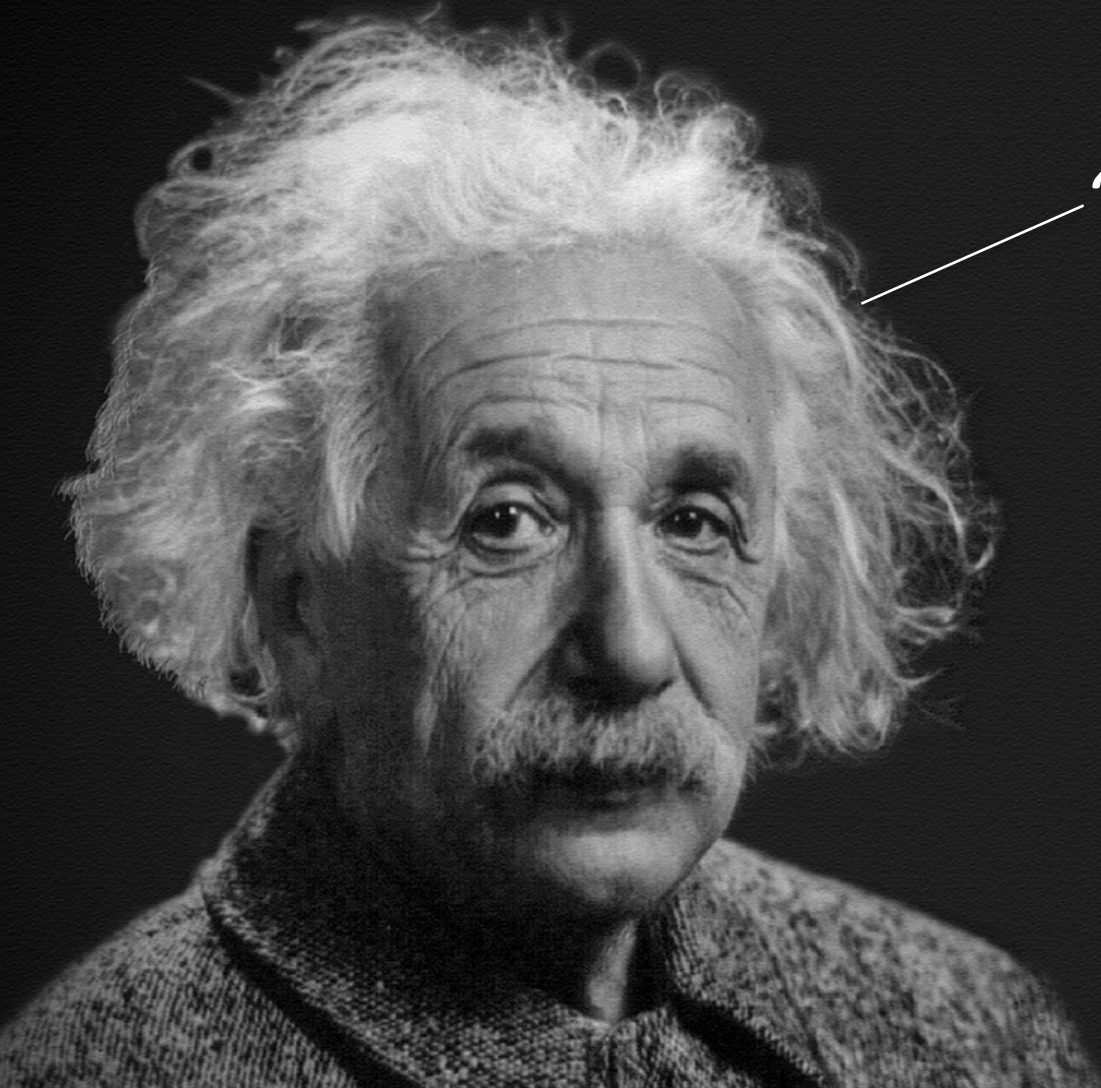


***Sadly, the phone call is limited to the speed of light...***



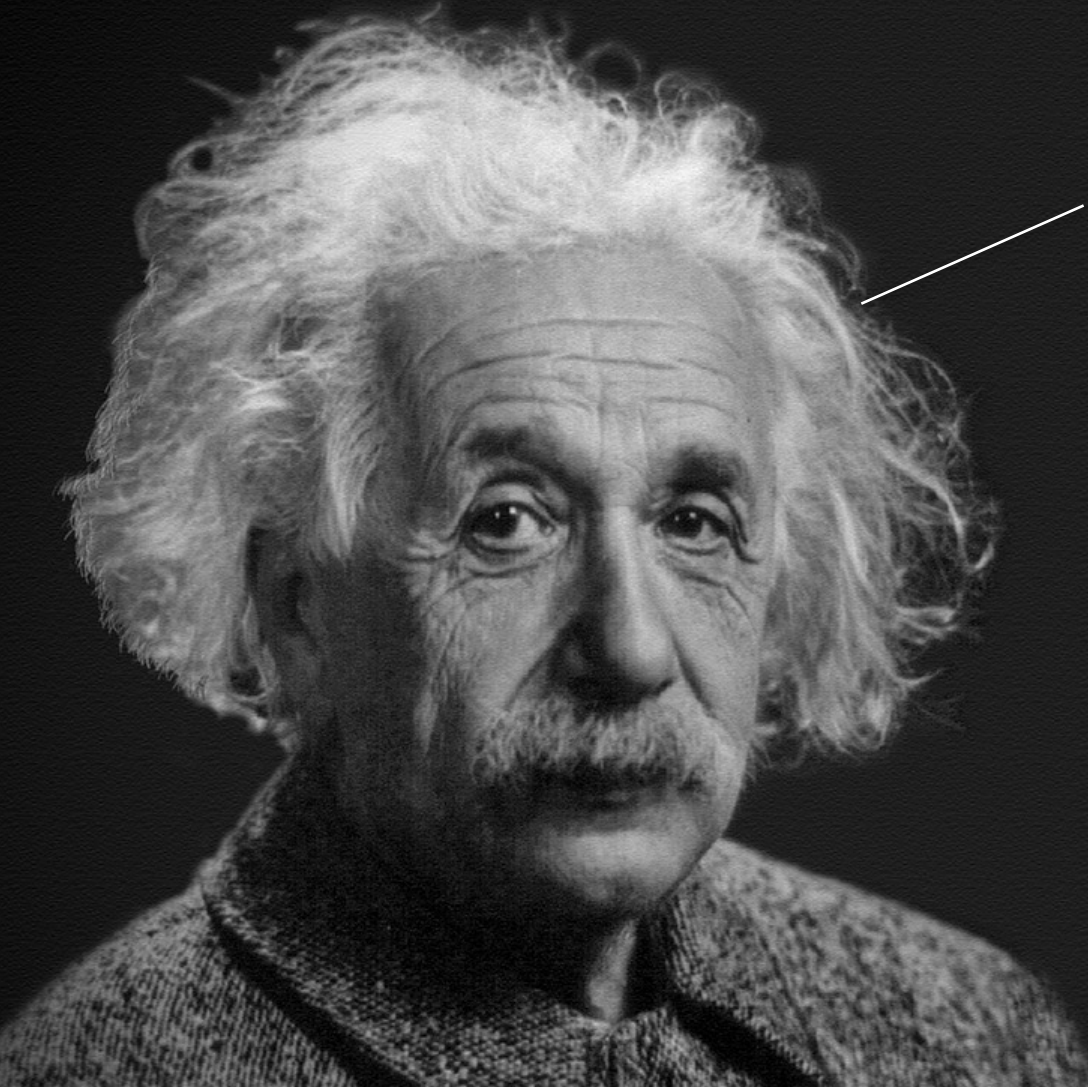
Bob knows the contents of his box without opening it.

# Einstein Was Right!



*“Told you so!”*

# Einstein Was Right!

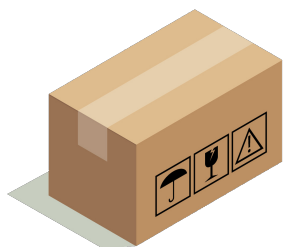
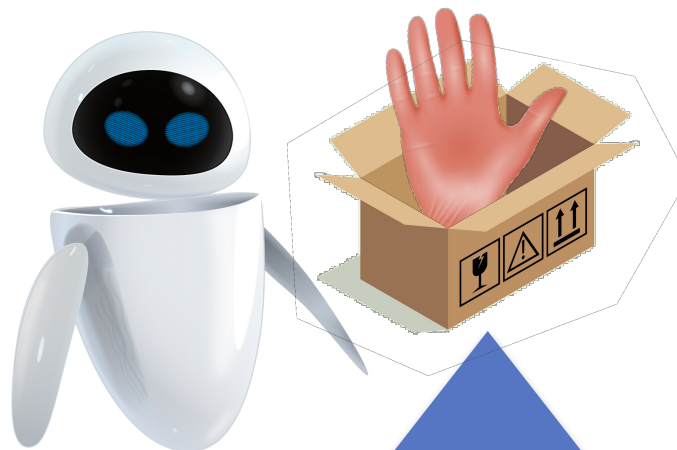


*"Told you so!"*



*"Dammit."*

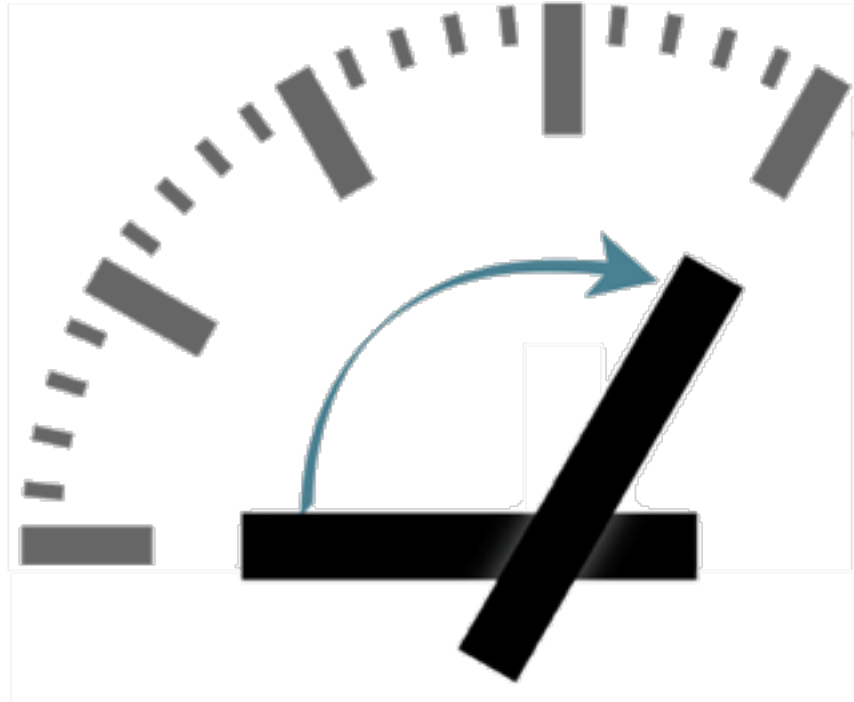
# Secure Quantum Communications



Eve intercepts Bob's box.

Bob knows instantly that his link to Alice has been compromised.

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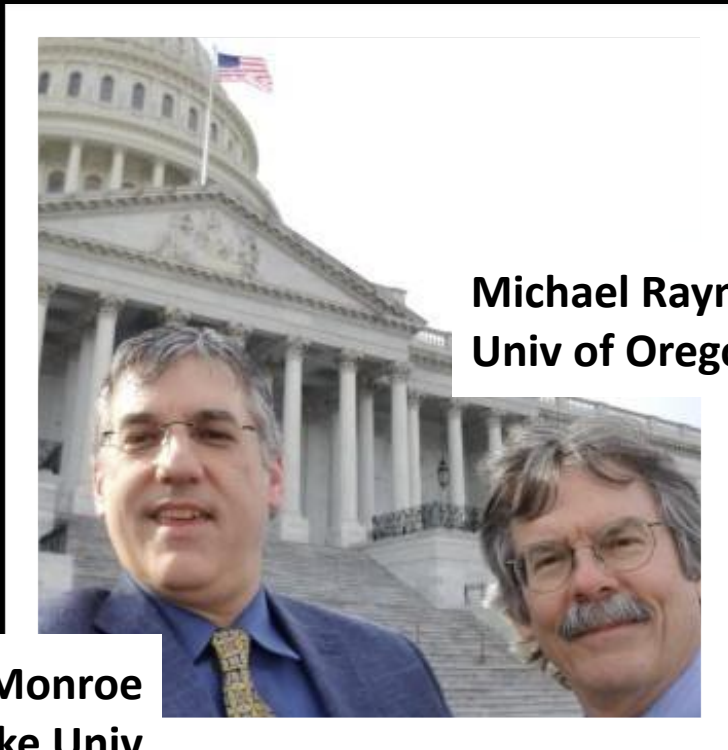
# 2017: “Sputnik Moment” for USA



“Trusted node” repeaters



16 June 2017



**Michael Raymer**  
Univ of Oregon

**Chris Monroe**  
Duke Univ

# One Hundred Fifteenth Congress of the United States of America

AT THE SECOND SESSION

*Begun and held at the City of Washington on Wednesday,  
the third day of January, two thousand and eighteen*

## An Act

To provide for a coordinated Federal program to accelerate quantum research and development for the economic and national security of the United States.

*Be it enacted by the Senate and House of Representatives of  
the United States of America in Congress assembled,*

### SECTION 1. SHORT TITLE; TABLE OF CONTENTS.

- (a) SHORT TITLE.—This Act may be cited as the “National Quantum Initiative Act”.
- (b) TABLE OF CONTENTS.—The table of contents of this Act is as follows:

- Sec. 1. Short title; table of contents.
- Sec. 2. Definitions.
- Sec. 3. Purposes.

TITLE I—NATIONAL QUANTUM INITIATIVE



# Key Societal Impacts

**Data  
Security and  
Privacy**



National Security

Personal Finance

Digital Transactions

Medical Records

**Pattern  
Search on  
Distributed  
Data**



Weather Forecasts

Self-Driving Cars

Personalized Medicine

Financial Modeling

**Getting  
Quantum  
Out of  
the Lab**



Democratized Access

Inter-Organization Collaboration

Shift “from the Mainframe to the PC”

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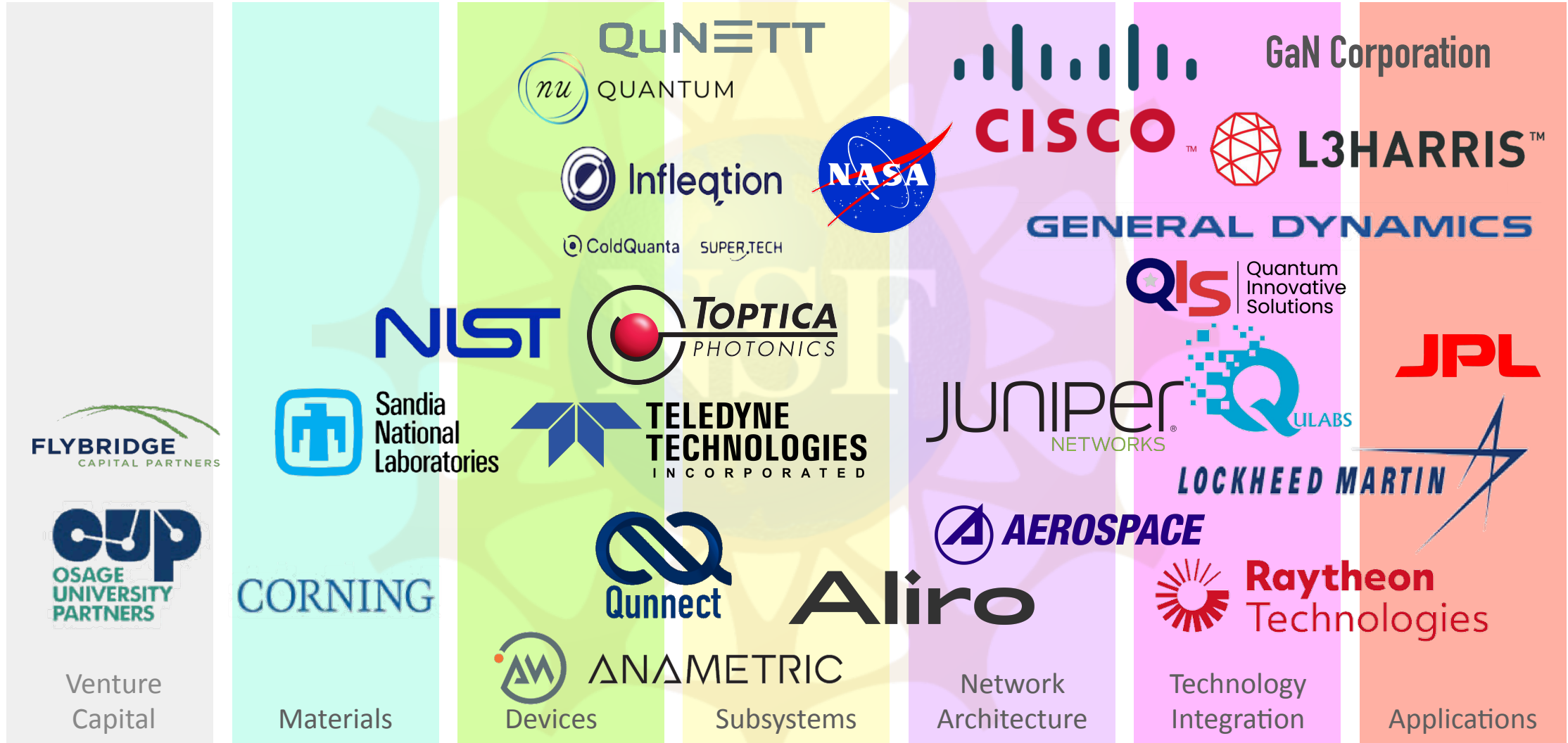
Sputnik Moment and Societal Impact

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# Partners in CQN Value Chain



Companies on this page have joined or committed to join the CQN IPP.

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# EPB Quantum Network



**GIG CITY GOES  
QUANTUM**

**Come Join Us!**

Celebrate World Quantum Day  
April 14 - May 31, 2023



**The First Commercial Quantum Network is here!**



# EPB Quantum Network



EPB Quantum Network powered by Qubitekk is America's first industry-led, commercially available quantum network designed for private companies as well as government and university researchers to run quantum equipment.



# EPB Quantum Network

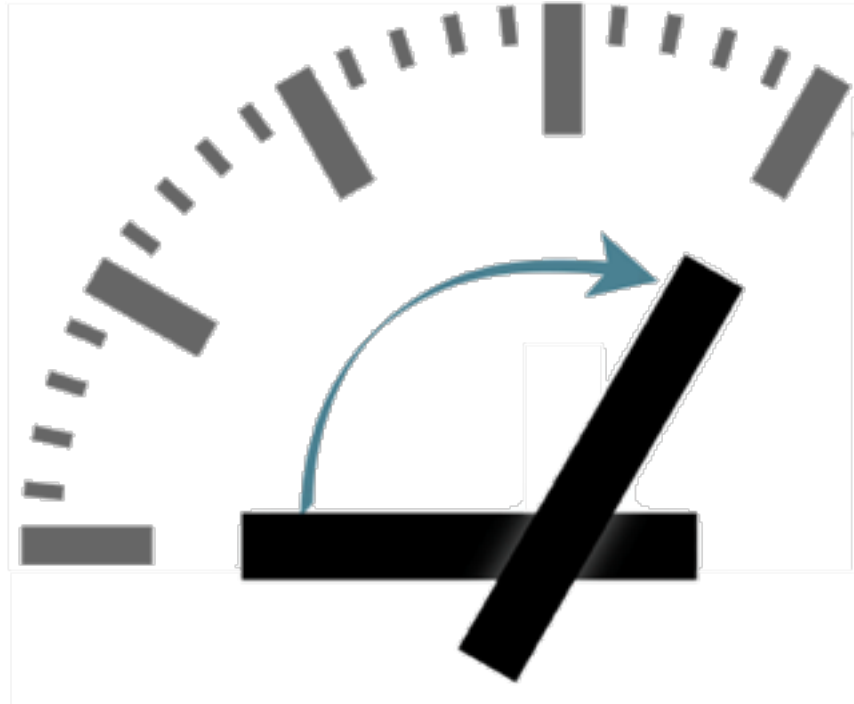


216 fibers  
Initial route: 2.4 km  
(Total: 500 fiber-km)

Nodes accessible to  
public, private, and  
academic users



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# Thank You!

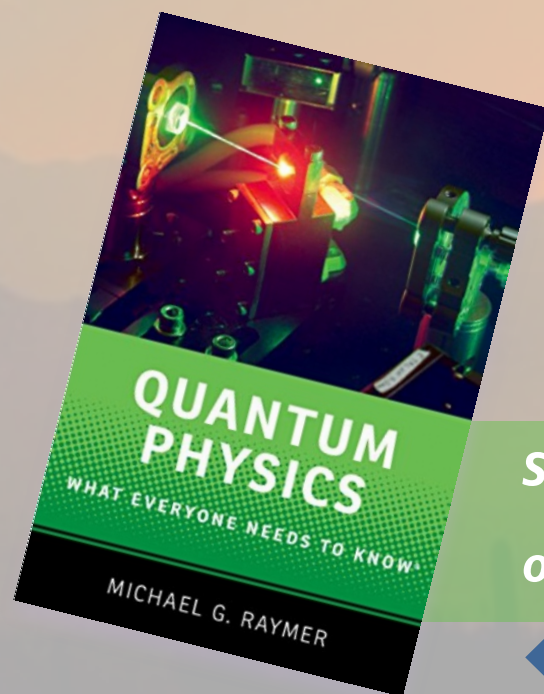
**Stephen Fleming**



stephenfleming@arizona.edu

Twitter @stephenfleming

**Download these slides:**  
files.boostphase.com



*Special thanks to Michael Raymer for much  
of the content included in this presentation.*

← Buy his book! <https://a.co/d/4ZWmnb>