Entanglement

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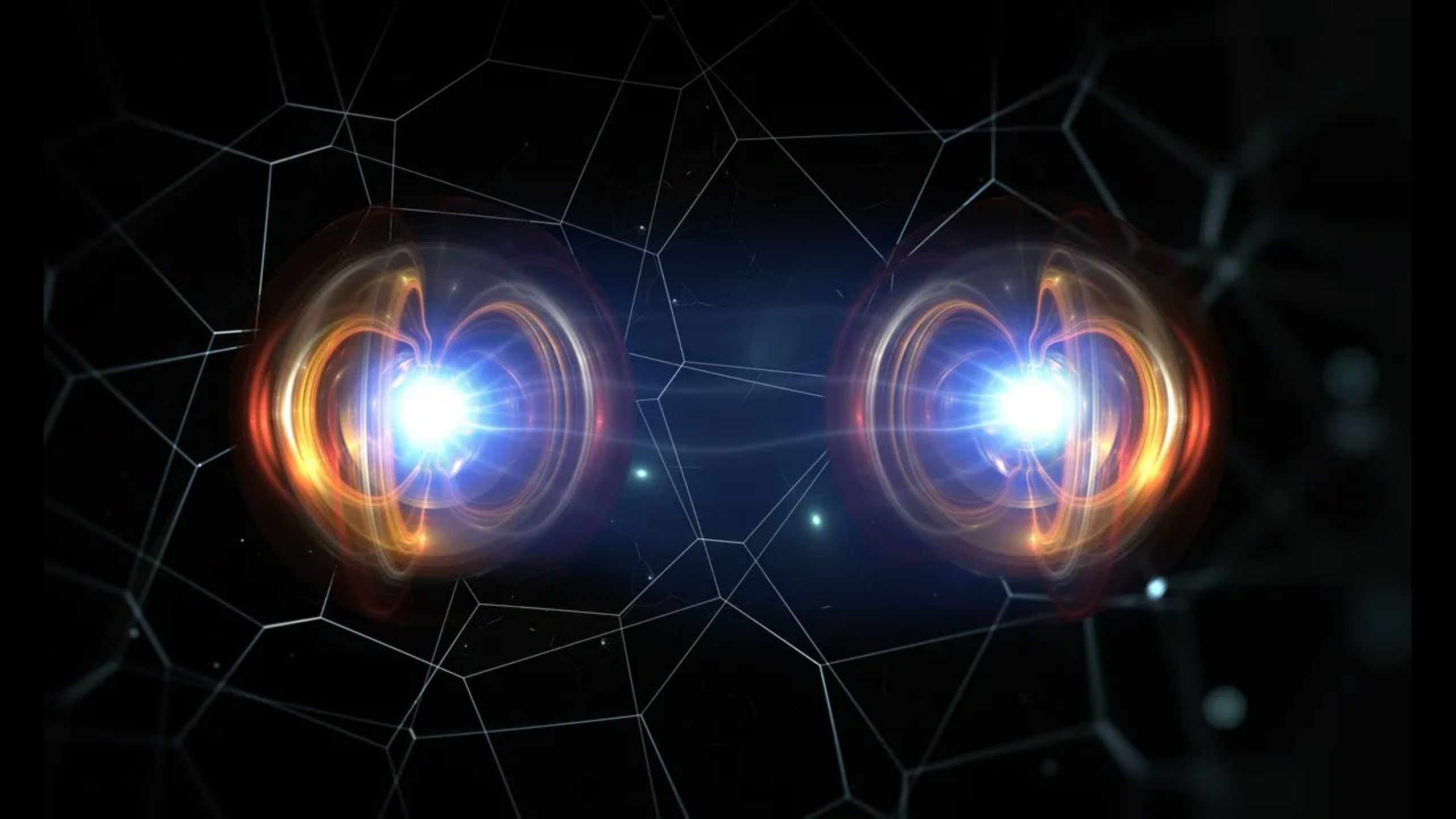
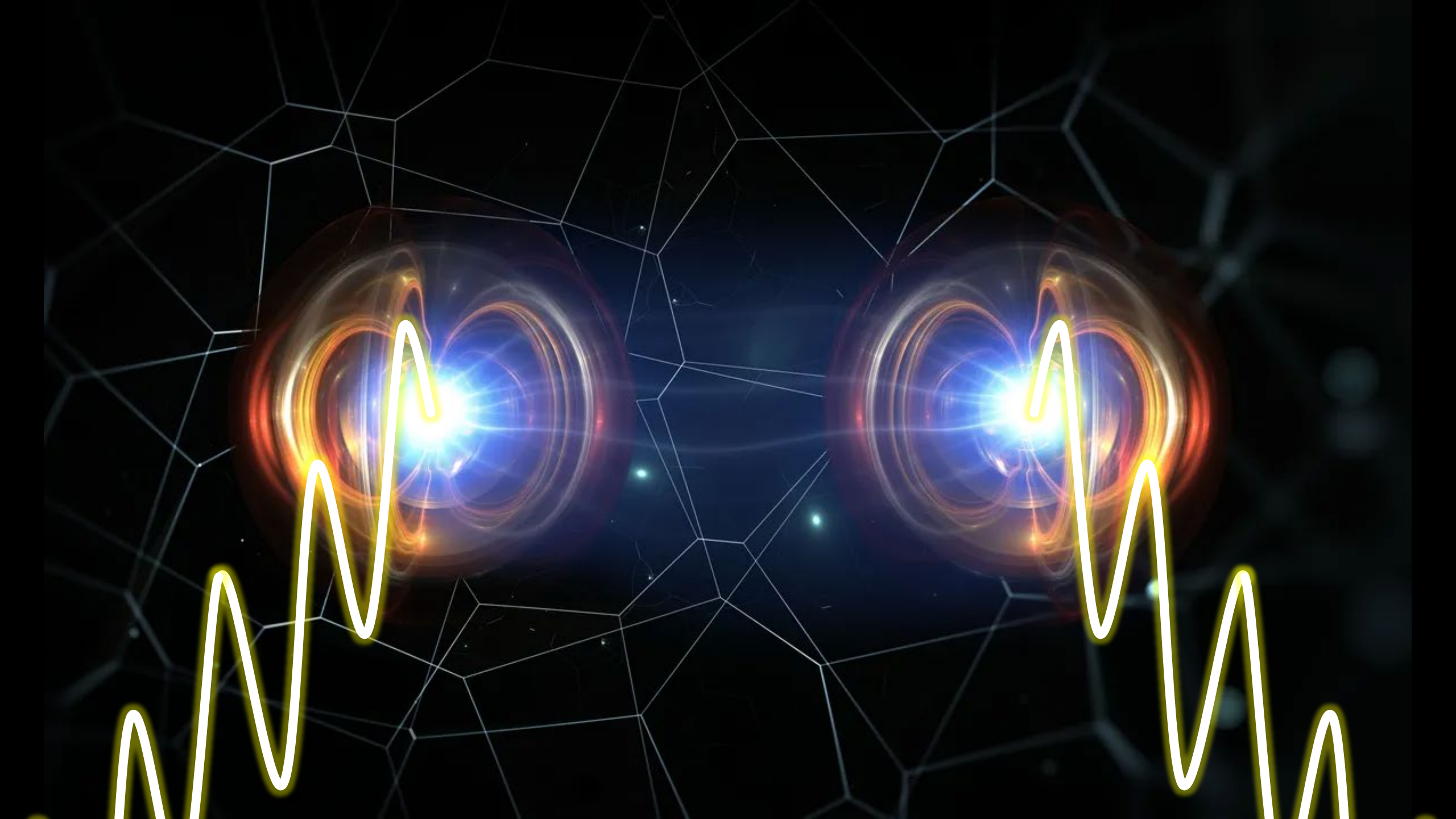
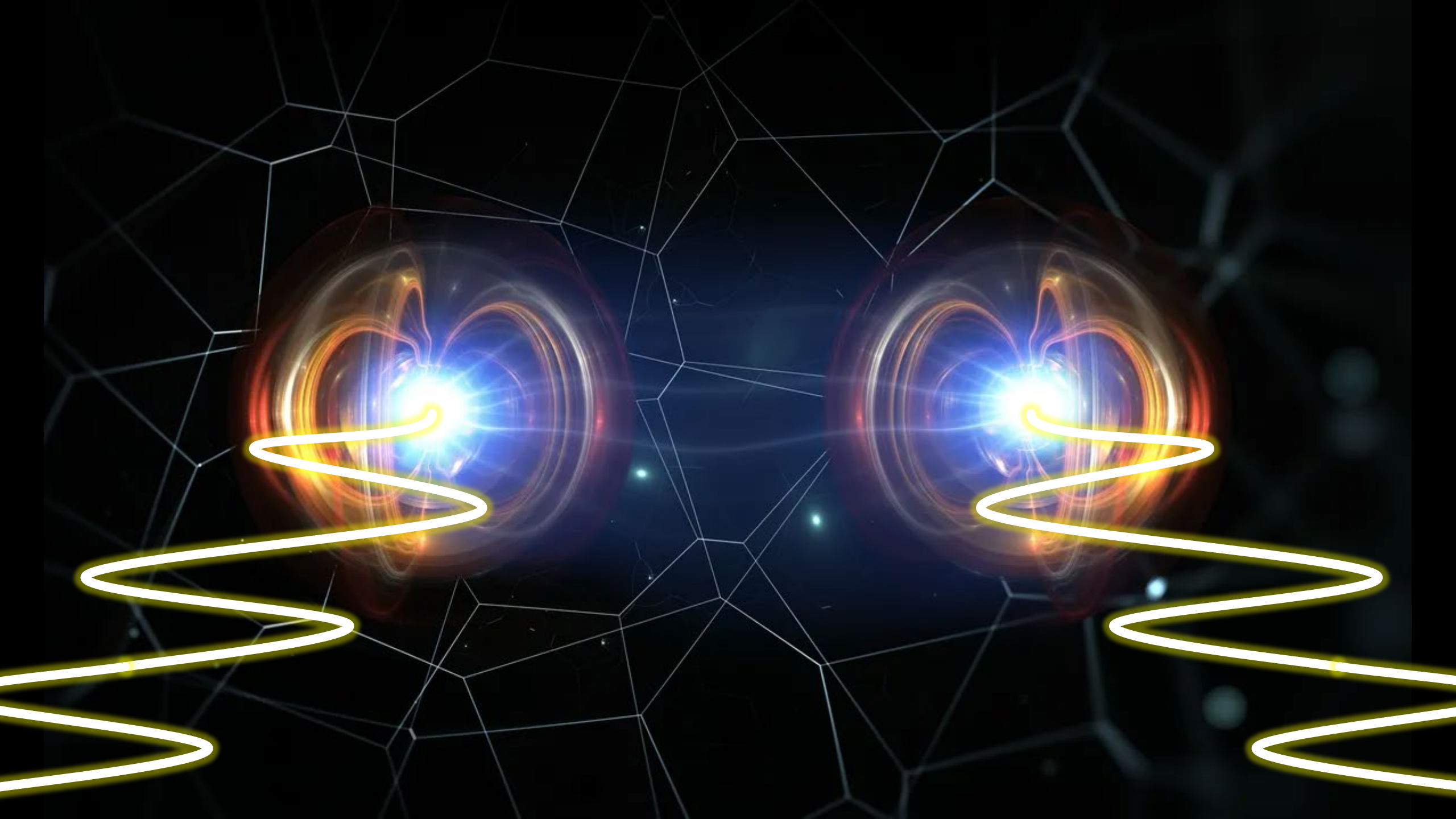
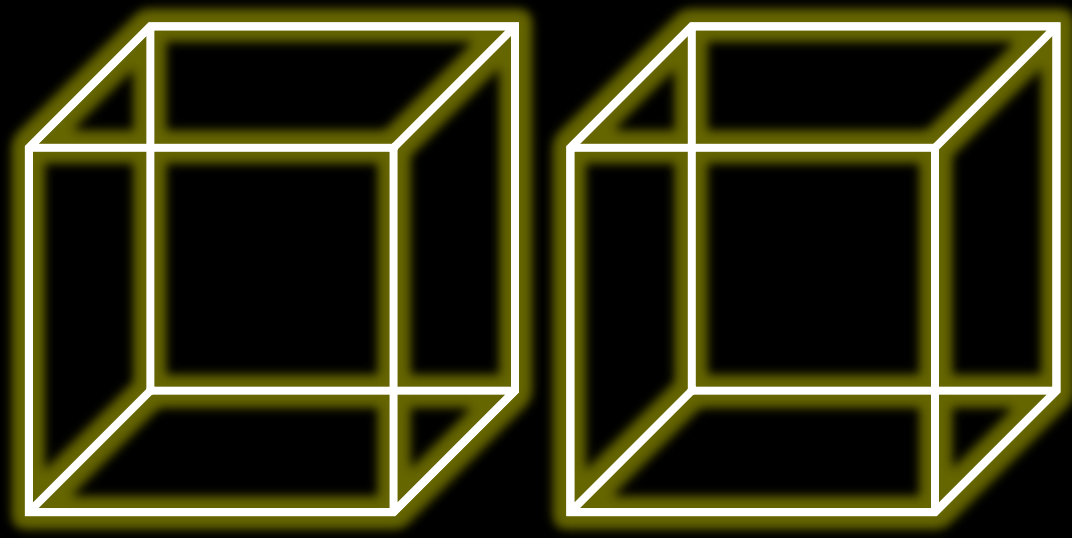
July 2, 2024

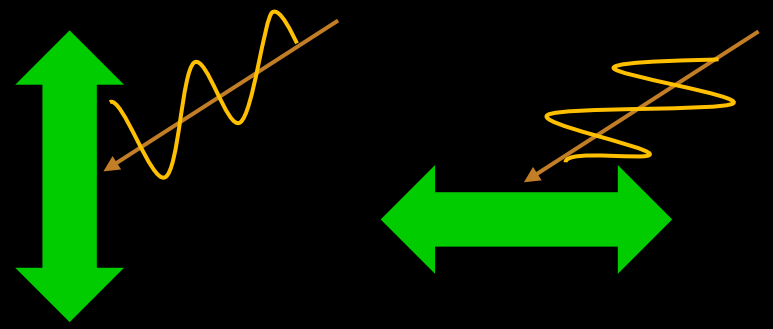




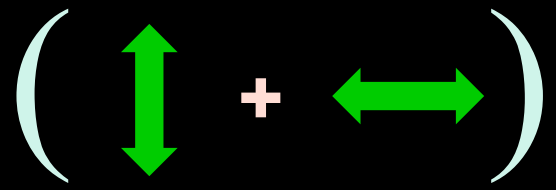




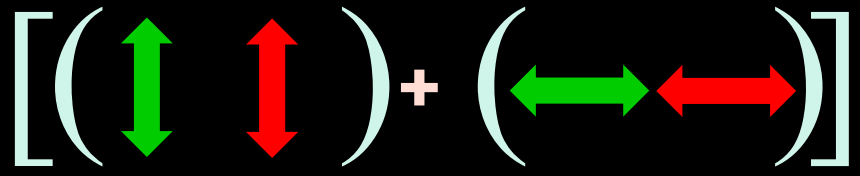
Polarization Entanglement



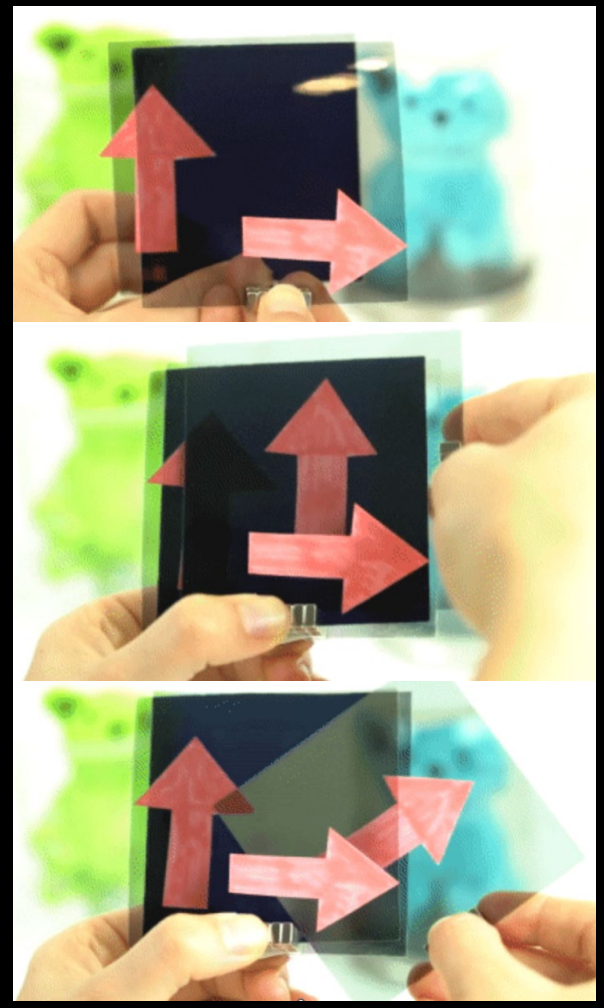
- Photons can be in a superposition of two polarizations



- Two photons can be **entangled** such that when one of them is measured, they always end up being the same polarization



- This property allows them to instantaneously “affect” each other no matter the distance



Properties of Entanglement

at least
∨
"It takes two to tangle."
J. Eberly, 2015

$$\psi_{pair} \propto |HH\rangle + |VV\rangle$$ Entangled

1935: Entanglement is
"*the* characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought"
—E. Schrödinger

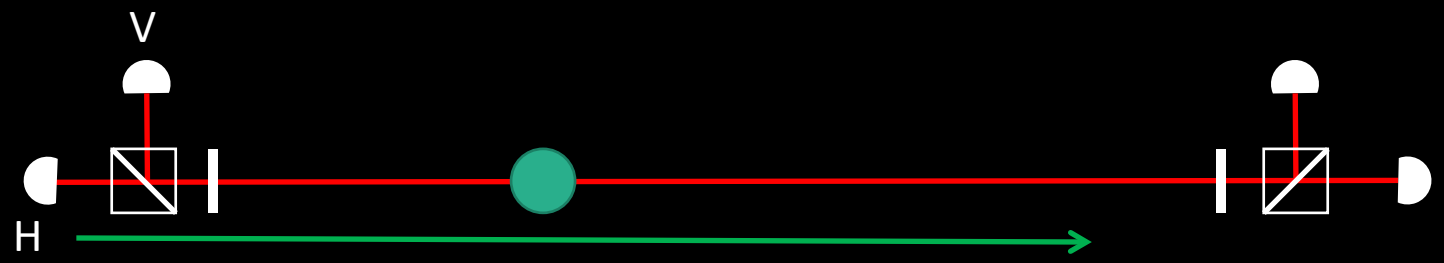
$$\psi_1 \propto |H\rangle + |V\rangle$$

$$\psi_2 \propto |H\rangle + |V\rangle$$

$$\psi_{12} = \psi_1\psi_2 \propto |HH\rangle + |VV\rangle + |HV\rangle + |VH\rangle$$ Not Entangled

In an **entangled** state, neither particle has definite properties alone.
$\Rightarrow$ All the information is stored in the *joint* properties.

1935: Einstein, Podolsky, Rosen (EPR) Paradox



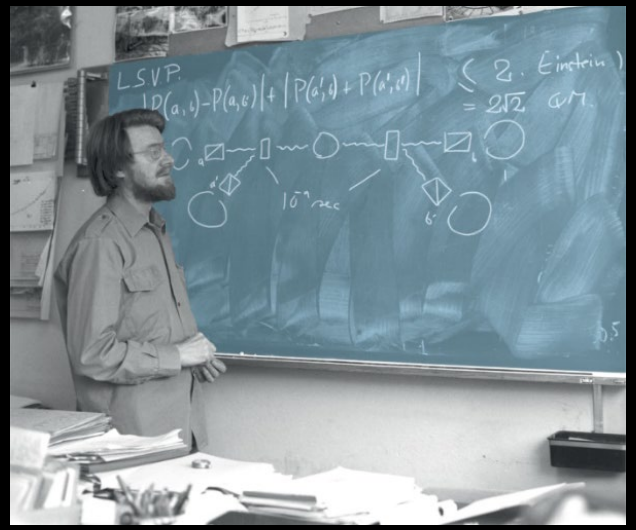
Requires speeds > c, i.e. non-locality

Quantum mechanics challenges two commonly held beliefs:

1. "Objects have definite states before measurement." Superposition implies they do not. (Then is there an objective **reality** before measurement?)
2. "Physical changes can only be caused locally." Entanglement implies **nonlocal** correlations exist. (Does this allow faster-than-light communication? No, because results are random.)

EPR: Maybe correlations are due to some local element of reality that we haven't detected yet ("local hidden variables")?

A. Einstein, B. Podolsky, and N. Rosen, Phys. Rev. **47**, 777 (1935).



1930's

1960's

1970's to present

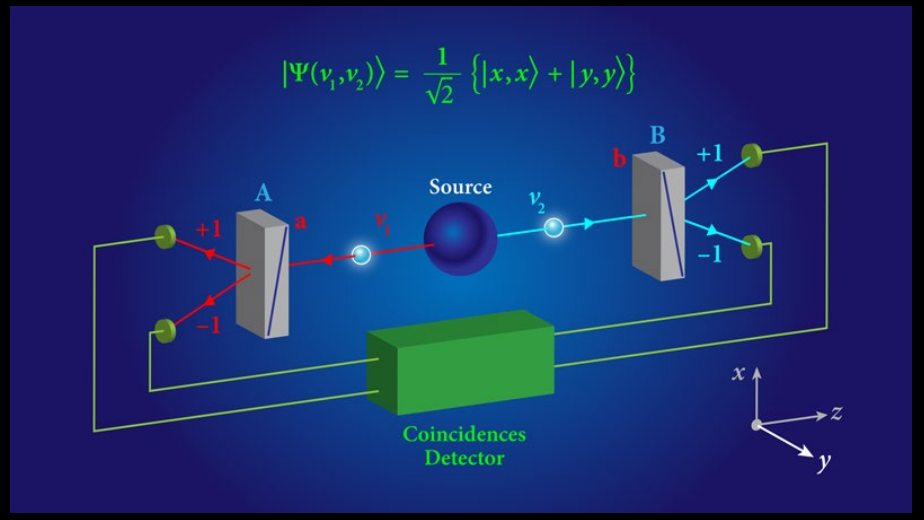
2022

EINSTEIN ATTACKS QUANTUM THEORY

Scientist and Two Colleagues Find It Is Not 'Complete' Even Though 'Correct.'

SEE FULLER ONE POSSIBLE

Believe a Whole Description of 'the Physical Reality' Can Be Provided Eventually.



What's the difference with classical correlations?

- Consider socks in a box
- There are two boxes of socks. The socks can be red or green.
- Which color they are is determined randomly by a machine, but the two boxes always have the same color sockses.
- The sox are sent to distant locations, like Timbuktu and Wananifee.
- The recipients open the boxes simultaneously.
- Wow! They always find the same color sox in the box!

With photons

- We don’t know what color the photons are, not because it’s hidden, but because the photons are in a superposition of colors
- Their color won’t be determined until the recipient sees the color.
- At the instant the color is measured, the color of the other photon becomes the same.

- So the key differences are:
  - The colors are not predetermined (violating realism)
  - Measuring the color of one instantaneously sets the color of the other (violating locality)

But but but…

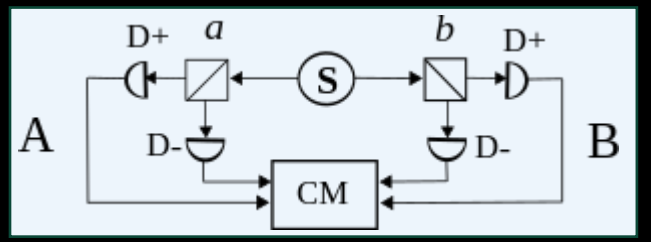
- But energy is always conserved, right?
  - Yes! The creation of photons obeys energy conservation, so if a photon is created in a superposition of different energies, the energy difference is compensated for through the creation process (e.g. atomic momentum)

- But does this mean we can communicate faster than light?
  - Since the photons choose a color randomly, knowing that you share the same color photon cannot be used to communicate – although it can be used as a resource called “shared randomness”, like the valentine example.

- How do we *test* for entanglement?

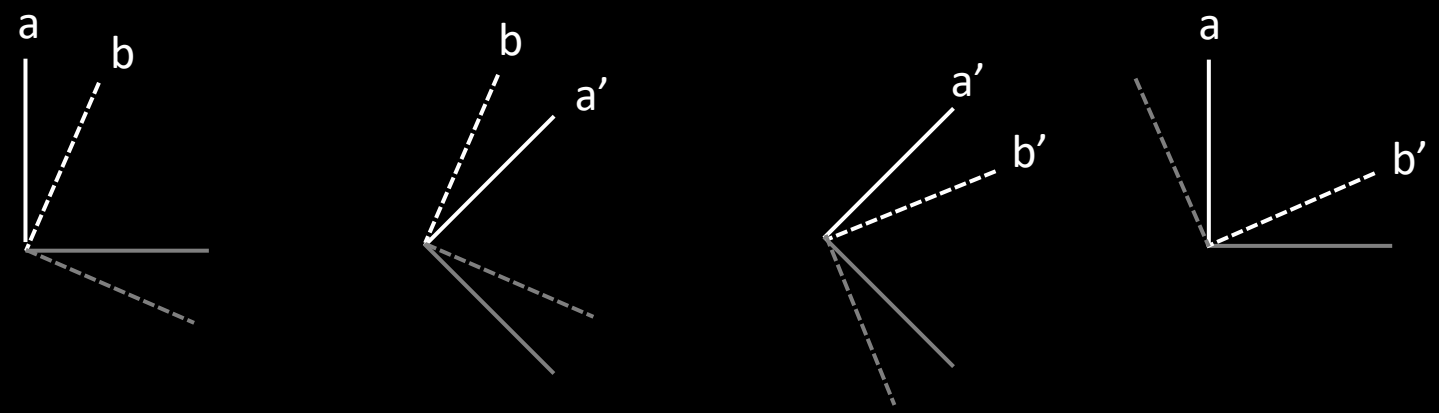
1964: Bell's theorem

- Bell's theorem gives an inequality that would hold if local realism were true
  - The measurements are taken over many entangled pairs and thus are statistical
  - The angles are chosen to maximize violation of the inequality



$$[\ E(a,b) + E(a',b) + E(a',b') - E(a,b')\ ] \leq \mathbf{2}$$

First 3 terms ~ likelihood the results are more similar than different



J.S. Bell, Physics **1**, 195-200 (1964)
J.F. Clauser, M.A. Horne, A. Shimony, R.A. Holt, PRL 23, 880-884 (1969)

PRL 115, 250402 (2015) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 18 DECEMBER 2015

Strong Loophole-Free Test of Local Realism*

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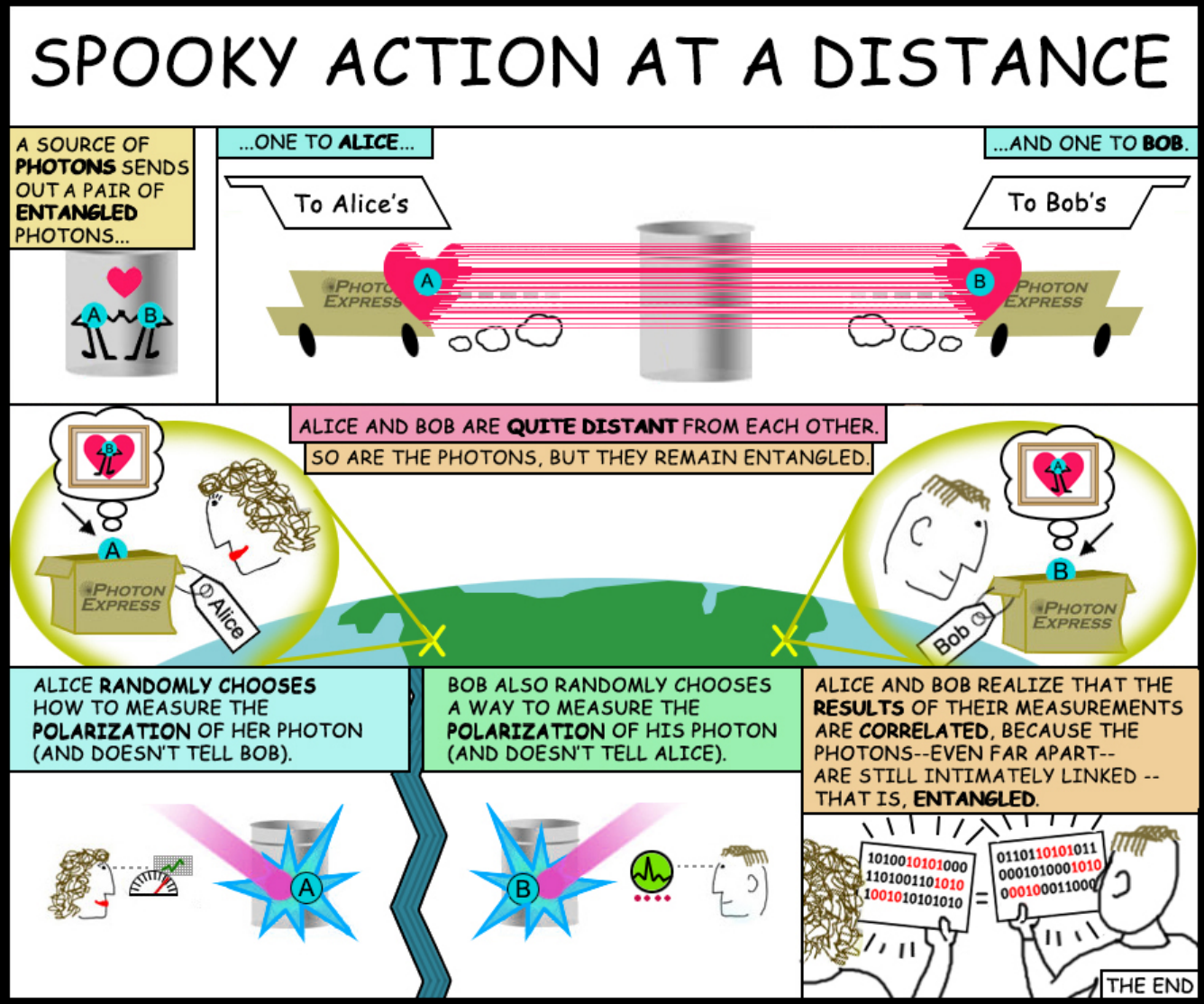
We present a loophole-free violation of local realism using entangled photon pairs. We ensure that all relevant events in our Bell test are spacelike separated by placing the parties far enough apart and by using fast random number generators and high-speed polarization measurements. A high-quality polarization-entangled source of photons, combined with high-efficiency, low-noise, single-photon detectors, allows us to make measurements without requiring any fair-sampling assumptions. Using a hypothesis test, we compute p values as small as 5.9×10^{-9} for our Bell violation while maintaining the spacelike separation of our events. We estimate the degree to which a local realistic system could predict our measurement choices. Accounting for this predictability, our smallest adjusted p value is 2.3×10^{-7}. We therefore reject the hypothesis that local realism governs our experiment.

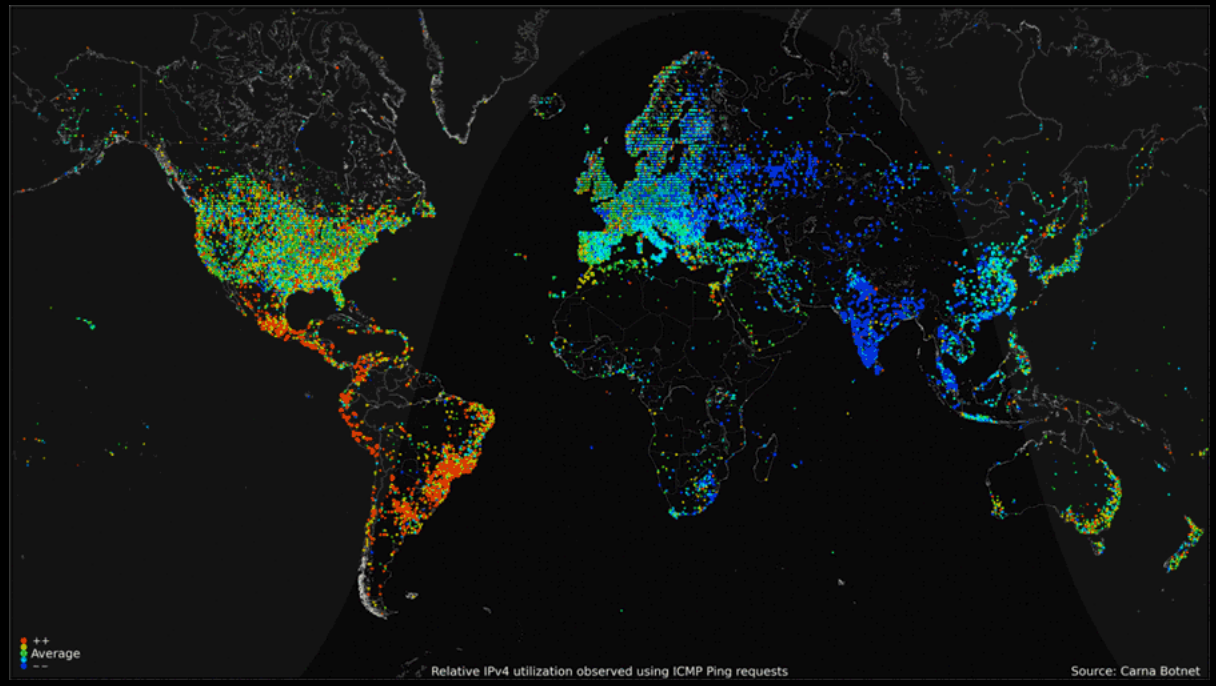
Entangled photons allow new applications



https://www.jpl.nasa.gov/news/news.php?feature=5210

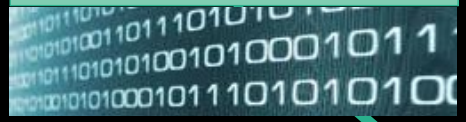
Quantum networks: a new type of internet

- Genuinely secure communication through detection of eavesdropping
- Connections with real-world quantum computers (once they are ready)
  - Fundamentally new ways of solving computational problems
- Improved sensing of astronomical objects
- Unforeseen applications of the technology



The last 50 years: Quantum Information

Information Science



Quantum Mechanics

Quantum Information

Quantum Computing

Quantum Communication

Simulation of Quantum Systems

Quantum Sensing

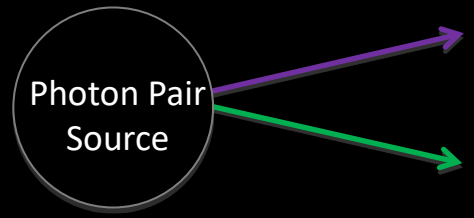
Quantum State

"It's fine to talk about these things, but here's a hammer and a wrench – can you *make* one?" – J. S. Bell

Optical
Ion trap
Atoms
Quantum dots
…

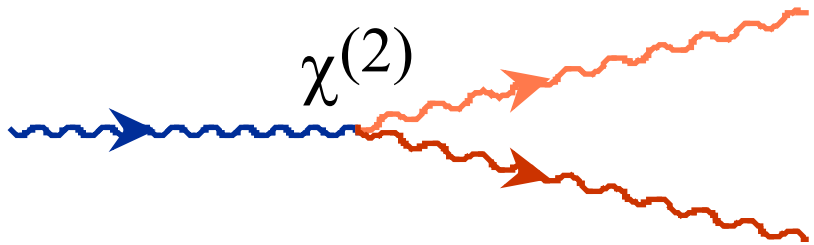
Spontaneous parametric down-conversion (SPDC)

Spontaneous four-wave mixing (SFWM)



1970: Spontaneous Parametric Down-Conversion

- Burnham & Weinberg, PRL **25**, 84 (1970):



$$\omega_p = \omega_s + \omega_i \ ^*$$

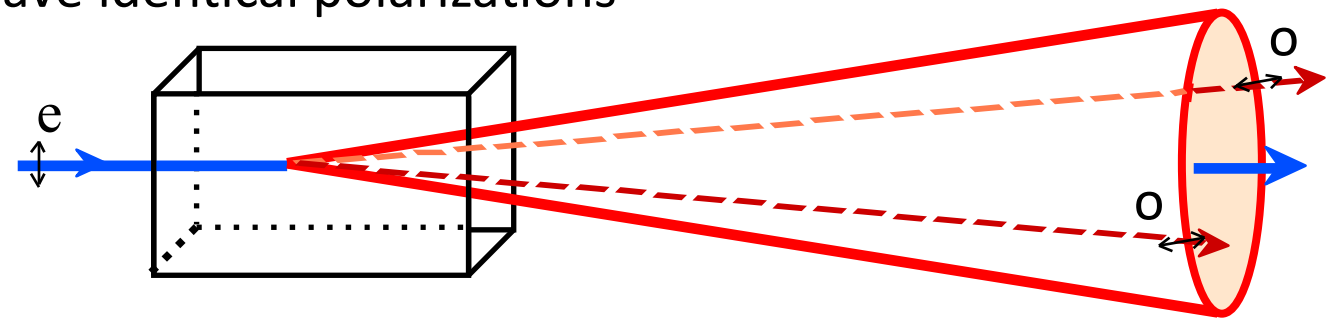
$$\vec{\kappa}_p = \vec{\kappa}_s + \vec{\kappa}_i \ ^\dagger$$

*Energy conservation → energy entanglement

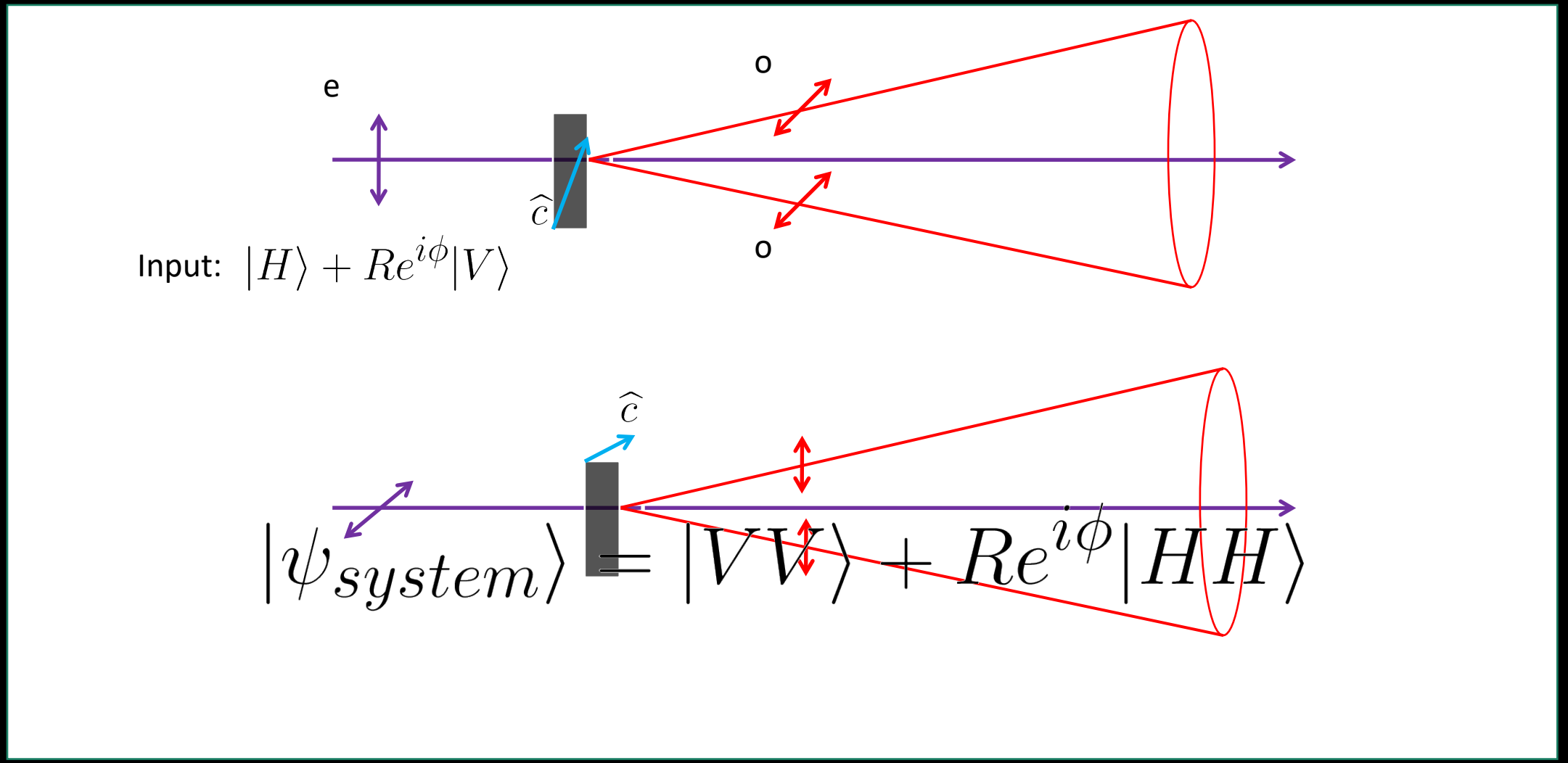
†Momentum conservation → momentum entanglement

Type-I phase-matching

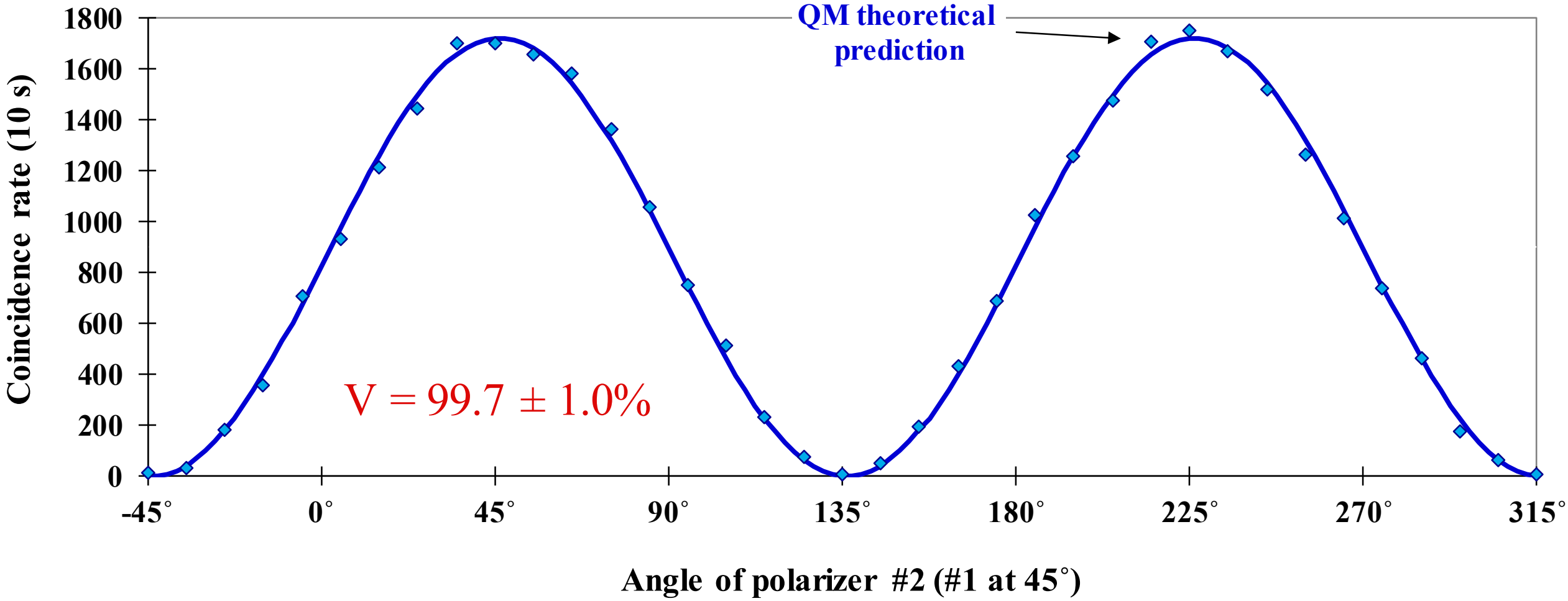
Photons have identical polarizations



Polarization Entanglement

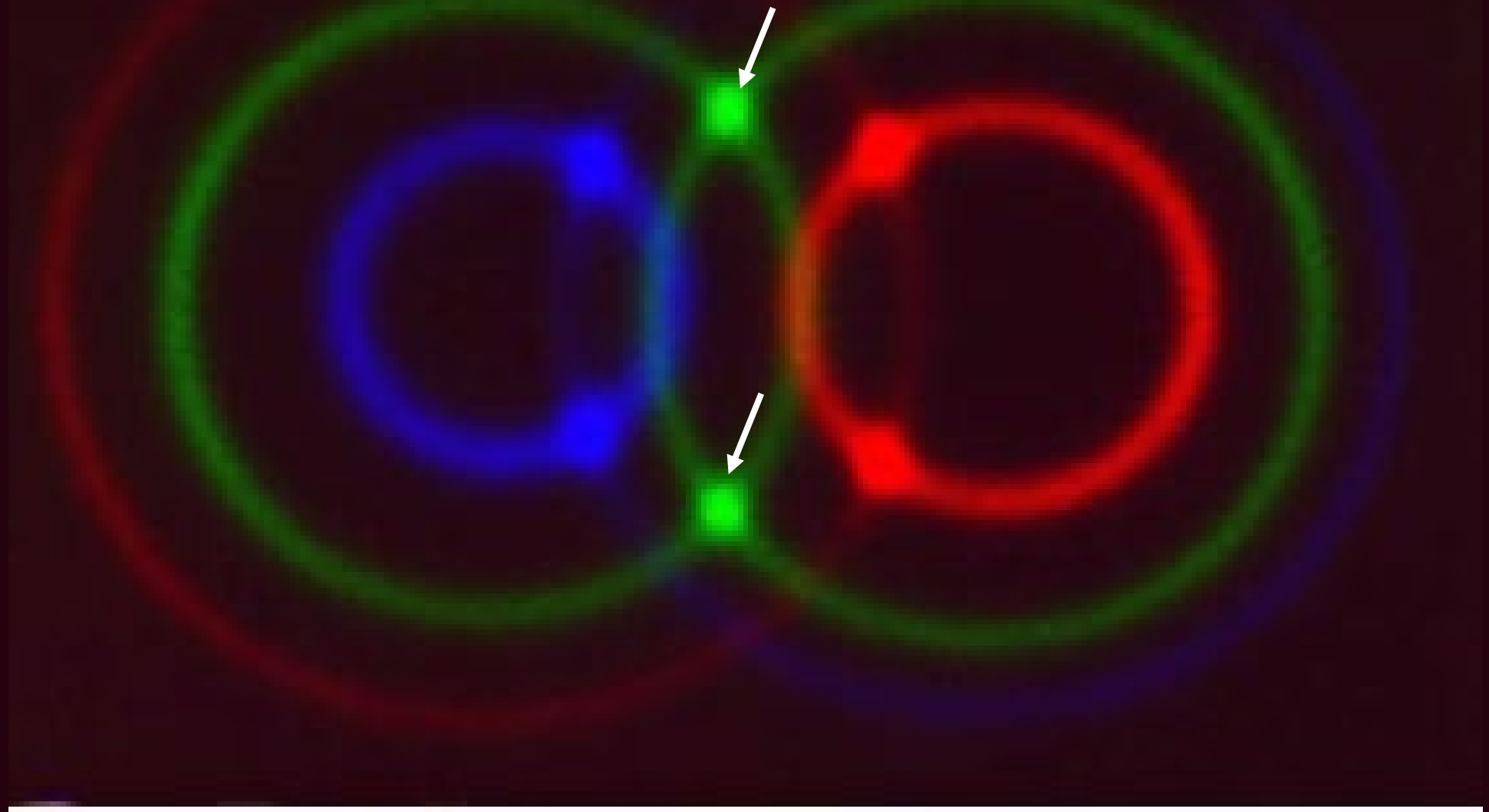


Proof of Quantum Correlations

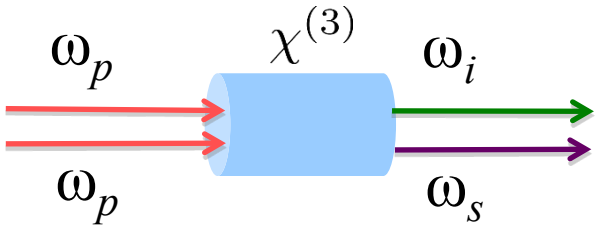


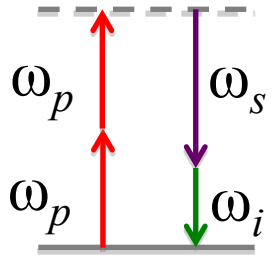
Near-perfect quantum behavior

$$|\psi_{system}\rangle = |VV\rangle + Re^{i\phi}|HH\rangle$$



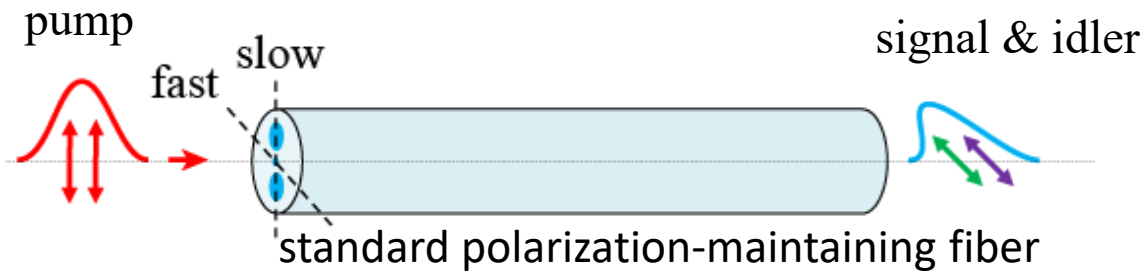
Spontaneous four-wave mixing





Conservation of energy

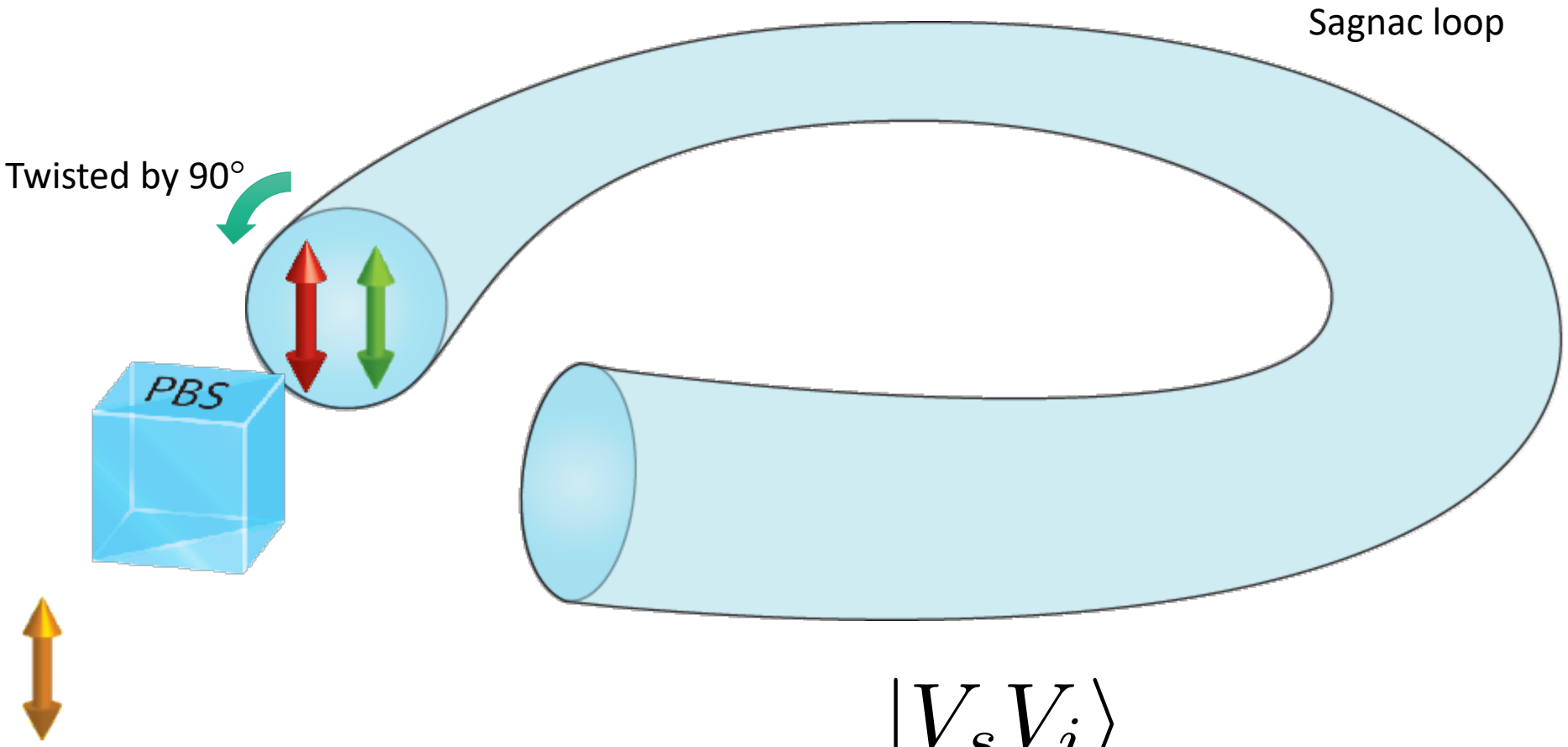
- Spontaneous four-wave mixing in polarization-maintaining optical fiber:



$$\Delta k = 2k(\omega_p) - k(\omega_s) - k(\omega_i) + 2\Delta n \frac{\omega_p}{c} = 0$$

  - *Birefringent* phase-matching:

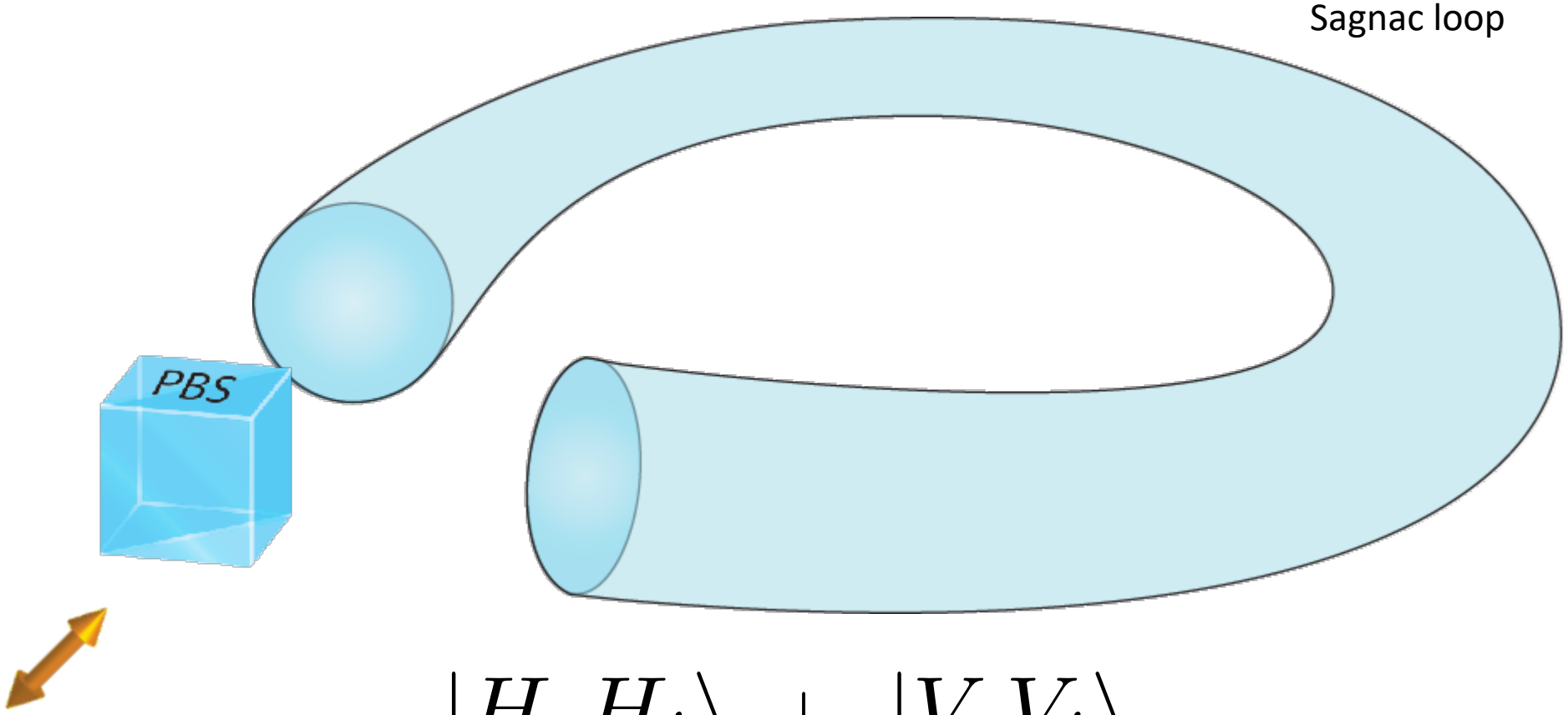
Generation of polarization entanglement



$$|V_s V_i\rangle$$

Pump travels on slow axis. Signal and idler travel on fast axis.
One end of the fiber is twisted by 90° relative to the other end.

Generation of polarization entanglement

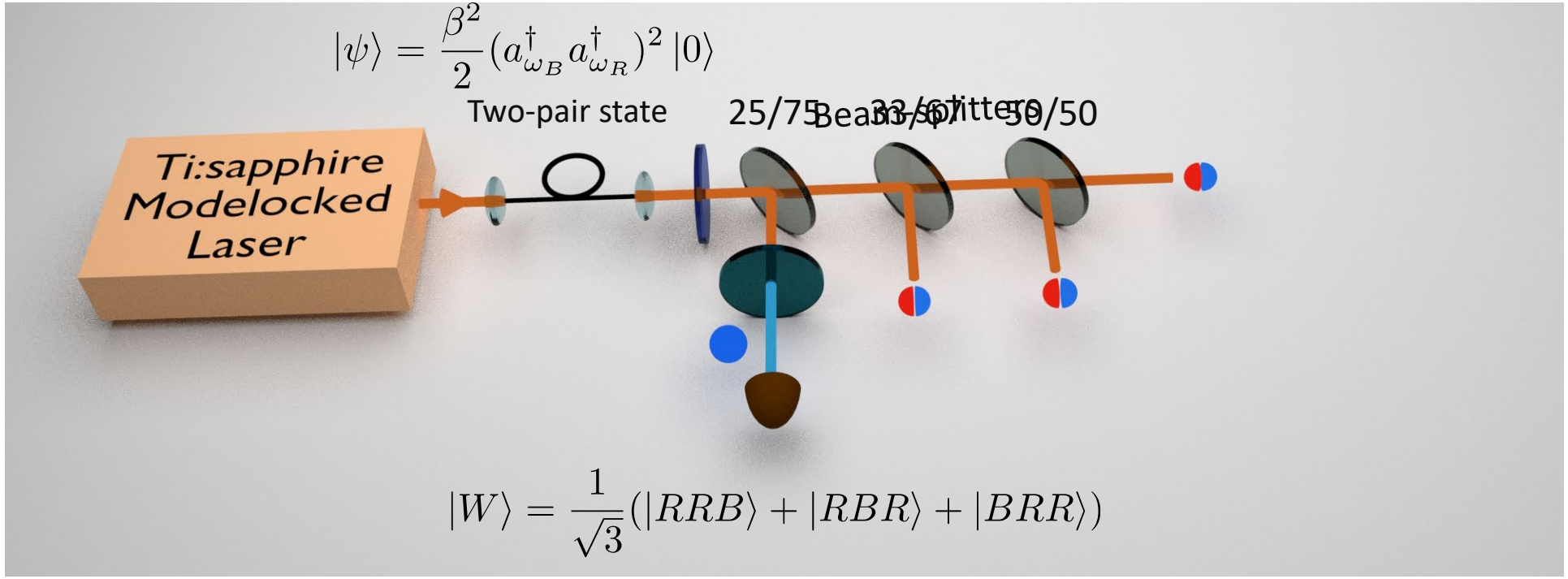


$$|H_s H_i\rangle + |V_s V_i\rangle$$

Pump travels on slow axis. Signal and idler travel on fast axis.
One end of the fiber is twisted by 90° relative to the other end.

Three-photon discrete-energy-entangled W-state

$$|W\rangle = \frac{1}{\sqrt{3}}\left(|RRB\rangle + |RBR\rangle + |BRR\rangle\right)$$



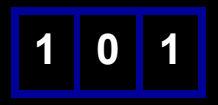
- Test non-locality of quantum mechanics
- Quantum communication protocols
- Robust against loss & decoherence

Why are entangled states important?

- Responsible for quantum measurements and decoherence
- Central to demonstrations of quantum nonlocality (e.g., Bell's inequalities, GHZ, Hardy, etc.)
- **Quantum cryptography** – separated particles' correlations allow sharing of secret random key
- **Quantum teleportation** – transmit unknown quantum state via 2 classical bits + EPR pair
- **Quantum computation** – intermediate states are all complex entangled states

Entanglement, and the scaling that results, is the key to the power of quantum computing

- Classically, information is stored in a bit register:
  - A 3-bit register can store **one** number, from 0-7



- Quantum Mechanically, a register of 3 qubits can store all of these numbers in superposition:

$$|000\rangle+|001\rangle+|010\rangle+|011\rangle+|100\rangle+|101\rangle+|110\rangle+|111\rangle$$

Result:

- Classical: one N-bit number
- Quantum: 2^N (all possible) N-bit numbers
  - N.B. A 300-qubit register can simultaneously store more combinations than there are particles in the universe.
- Acting on the qubits simultaneously affects all the numbers:

$$\left(|0\rangle+|1\rangle+...|7\rangle\right)\otimes|f(x)\rangle\Rightarrow|0\rangle|f(0)\rangle+|1\rangle|f(1)\rangle+...|7\rangle|f(7)\rangle$$

- Some important problems benefit from this entanglement, enabling solutions of otherwise insoluble problems.

Quantum Logic

Controlled-Not Gate:

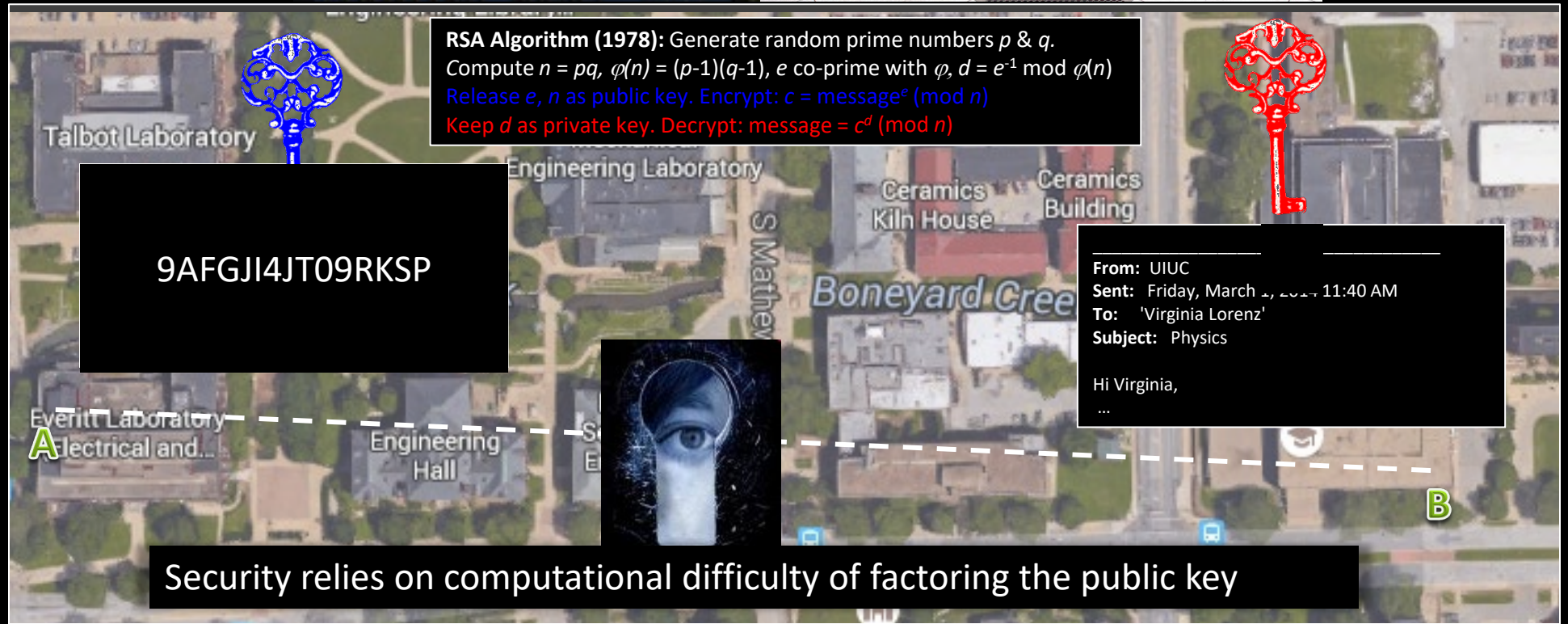
$$|0\rangle_c|0\rangle_t \rightarrow |0\rangle_c|0\rangle_t$$
$$|0\rangle_c|1\rangle_t \rightarrow |0\rangle_c|1\rangle_t$$
$$|1\rangle_c|0\rangle_t \rightarrow |1\rangle_c|1\rangle_t$$
$$|1\rangle_c|1\rangle_t \rightarrow |1\rangle_c|0\rangle_t$$

$$\left(|0\rangle_c + |1\rangle_c\right)|0\rangle_t \xrightarrow{CNOT} |0\rangle_c|0\rangle_t + |1\rangle_c|1\rangle_t$$

2-Qubit interactions lead to entangled states.

Classical Cryptography

RSA Algorithm (1978): Generate random prime numbers p & q.
Compute $n = pq$, $\varphi(n) = (p-1)(q-1)$, e co-prime with φ, $d = e^{-1} \bmod \varphi(n)$
Release e, n as public key. Encrypt: $c = \text{message}^e \pmod n$
Keep d as private key. Decrypt: $\text{message} = c^d \pmod n$



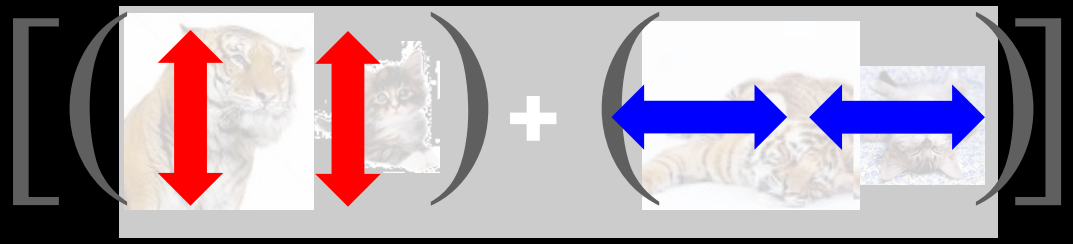
9AFGJI4JT09RKSP

From: UIUC
Sent: Friday, March 1, 2013 11:40 AM
To: 'Virginia Lorenz'
Subject: Physics

Hi Virginia,
…

Security relies on computational difficulty of factoring the public key

Quantum Key Distribution

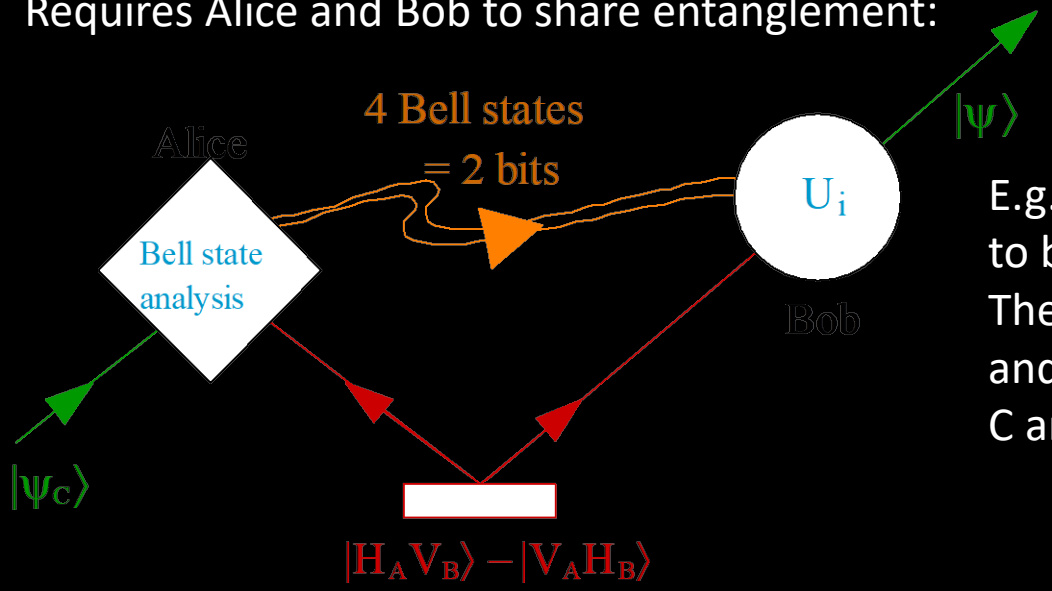


Security is guaranteed by the laws of quantum physics

Quantum Teleportation

Bennett et al., PRL **70**, 1895 (1993)

The basic idea: transfer the (infinite) amount of information in a qubit from Alice to Bob without sending the qubit itself.
Requires Alice and Bob to share entanglement:



E.g. Alice measures photons C and A to be in a singlet state.
Then since C and A are perpendicular, and since A and B are perpendicular, C and B must be identical!

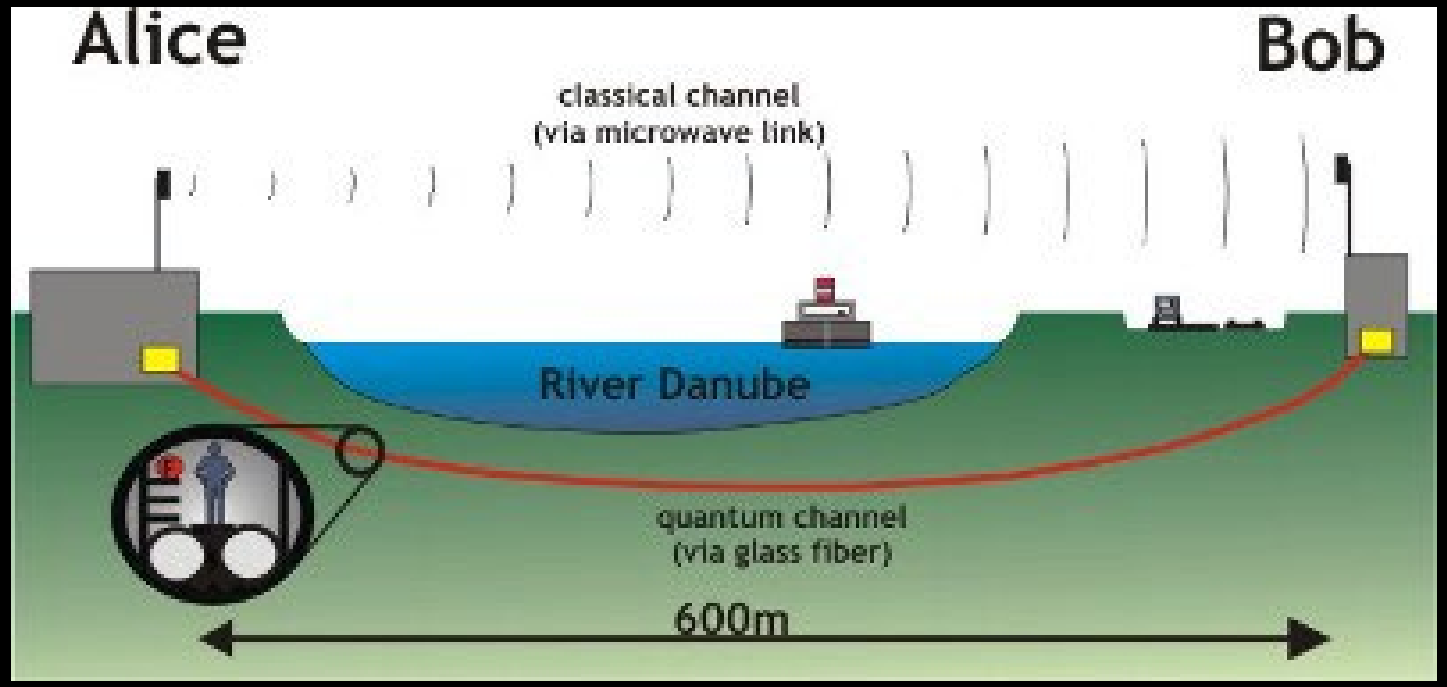
Remarks:

- The original state is gone.
- Neither Alice nor Bob know what it was.
- Requires classical communication – no superluminal signaling.
- Bell state analysis is hard.

Experimental Teleportation

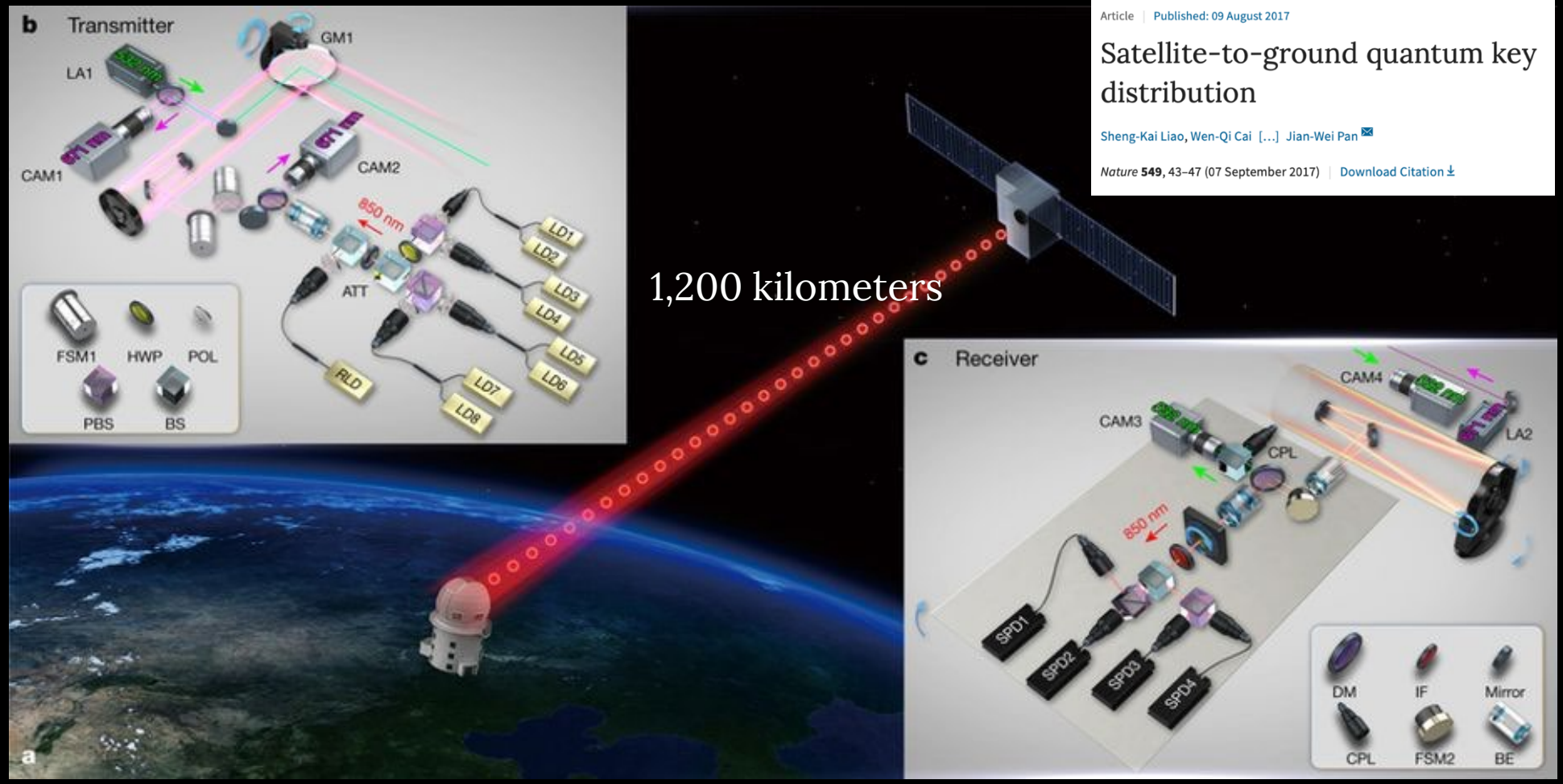
1997: **First demonstration** [Bouwmeester *et al*., Nature **390**, 575 (1997)]

2004: **Quantum teleportation across the Danube** [Ursin *et al*., Nature **430**, 849 (2004)]



- Now demonstrated teleportation of entanglement, other degrees of freedom, continuous variables, energy states of ions, 2-qubits …

Satellite-to-ground QKD



nature
International journal of science

Article | Published: 09 August 2017

Satellite-to-ground quantum key distribution

Sheng-Kai Liao, Wen-Qi Cai [...] Jian-Wei Pan

Nature **549**, 43–47 (07 September 2017) | Download Citation

Research & innovation

Innovation

Emerging Technologies

Brain Research

Future & Emerging Technologies

FET Open

FET Proactive

FET Flagships

Projects Portfolio

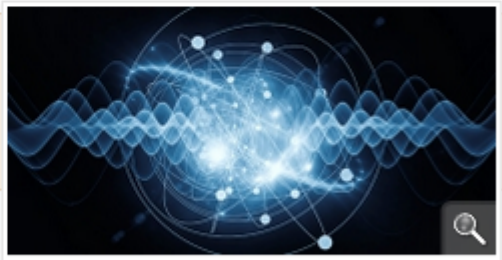
European Open Science Cloud

Digital Infrastructures

European Commission will launch €1 billion quantum technologies flagship

Published on 17/05/2016

Günther H. Oettinger, Commissioner for the Digital Economy and Society outlined the Commission's plan to launch a €1 billion flagship initiative on quantum technology.



Speaking at the Quantum Europe Conference organised by The Dutch presidency of the EU, the European Commission and the QuTech center in Delft, the Commissioner outlined his objective to reinforce European scientific leadership and excellence in quantum research and in quantum technologies.

Share

MIDWEST COLLABORATION, LED BY IQUIST, AWARDED $25 MILLION QUANTUM INFORMATION INSTITUTE

7/21/2020 9:53:05 AM Michelle Huls Rice for Grainger Engineering

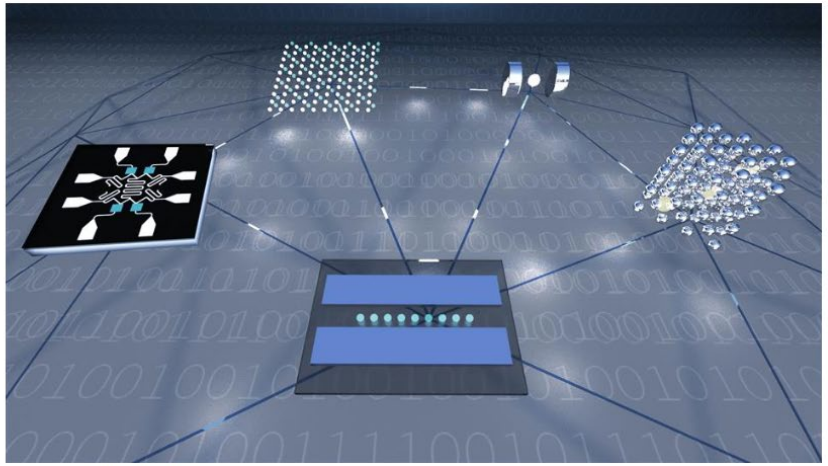


Image by Emily Edwards, IQUIST

The Grainger College of Engineering's Illinois Quantum Information Science and Technology Center (IQUIST) will launch a National Science Foundation Quantum Leap Challenge Institute for Hybrid Quantum Architectures and Networks (HQAN). The collaborative institute spans three Midwest research powerhouses, all of which are members of the Chicago Quantum Exchange: The University of Illinois, University of Chicago, and the University of Wisconsin. HQAN also includes partnerships with industry and government labs.

Established with a $25 million, five-year NSF award, the HQAN institute will be one of only three Quantum Leap Challenge Institutes in the country. Quantum Leap Challenge Institutes will bring together multidisciplinary researchers and diverse partners to advance scientific, technological, and workforce development goals.

NEW CENTER AWARDED $12.6M BY DOE

Jul 13, 2020

A team from the University of Illinois at Urbana-Champaign's Grainger College of Engineering was awarded an Energy Frontier Research Center by the Department of Energy (EFRC).

The new center is highly-collaborative spanning three institutions, with additional team members and leadership from University of Illinois-Chicago and the SLAC National Accelerator Laboratory. On campus, the program draws together experts in quantum information science, physics and materials science from the Illinois Quantum Information Science and Technology Center (IQUIST), from the Physics Department, Materials Science and Engineering, and the Materials Research Laboratory.

Department of Energy

U.S. Department of Energy Unveils Blueprint for the Quantum Internet at 'Launch to the Future: Quantum Internet' Event

JULY 23, 2020

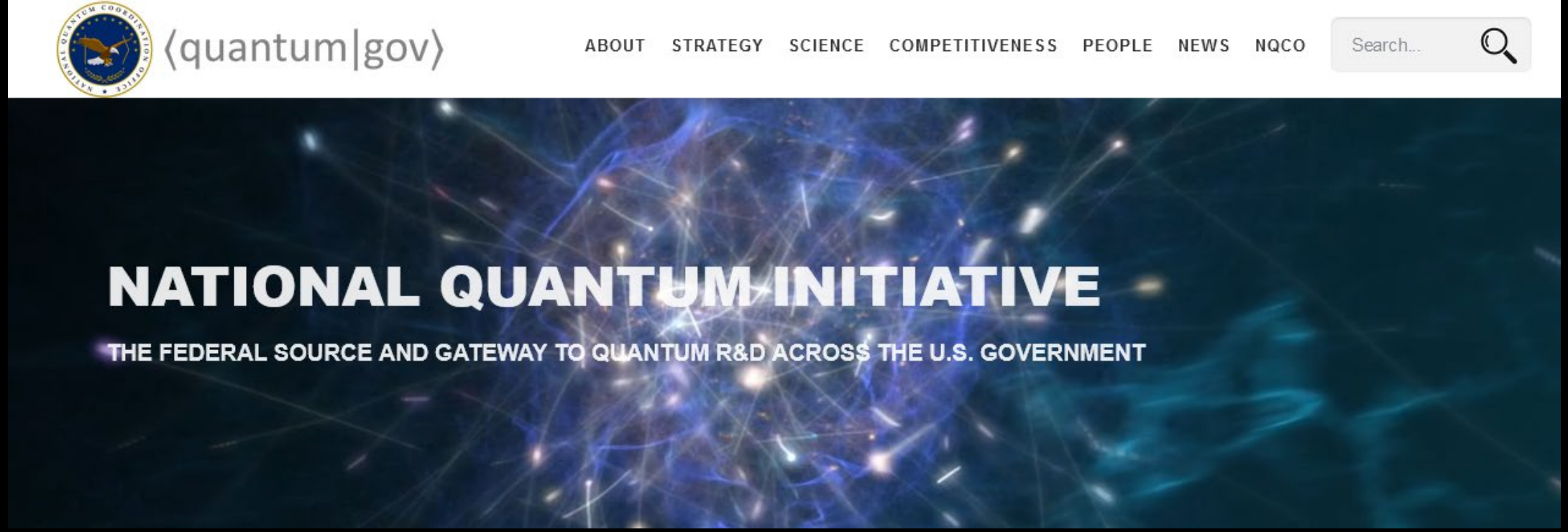
Nationwide Effort to Build Quantum Networks and Usher in New Era of Communications

CHICAGO, IL – In a press conference today at the University of Chicago, the U.S. Department of Energy (DOE) unveiled a report that lays out a blueprint strategy for the development of a national quantum internet, bringing the United States to the forefront of the global quantum race and ushering in a new era of communications. This report provides a pathway to ensure the development of the National Quantum Initiative Act, which was signed into law by President Trump in December of 2018.

Around the world, consensus is building that a system to communicate using quantum mechanics represents one of the most important technological frontiers of the 21st century. Scientists now believe that the construction of a prototype will be within reach over the next decade.

In February of this year, DOE National Laboratories, universities, and industry met in New York City to develop the blueprint strategy of a national quantum internet, laying out the essential research to be accomplished, describing the engineering and design barriers, and setting near-term goals.

"The Department of Energy is proud to play an instrumental role in the development of the national quantum internet," said U.S. Secretary of Energy Dan Brouillette. "By constructing this new and



- The National Quantum Initiative Act was signed into law on December 21, 2018. The law gives the United States a plan for advancing quantum technology, particularly quantum computing.

- This act has spurred a tsunami of funding for quantum research and industry.

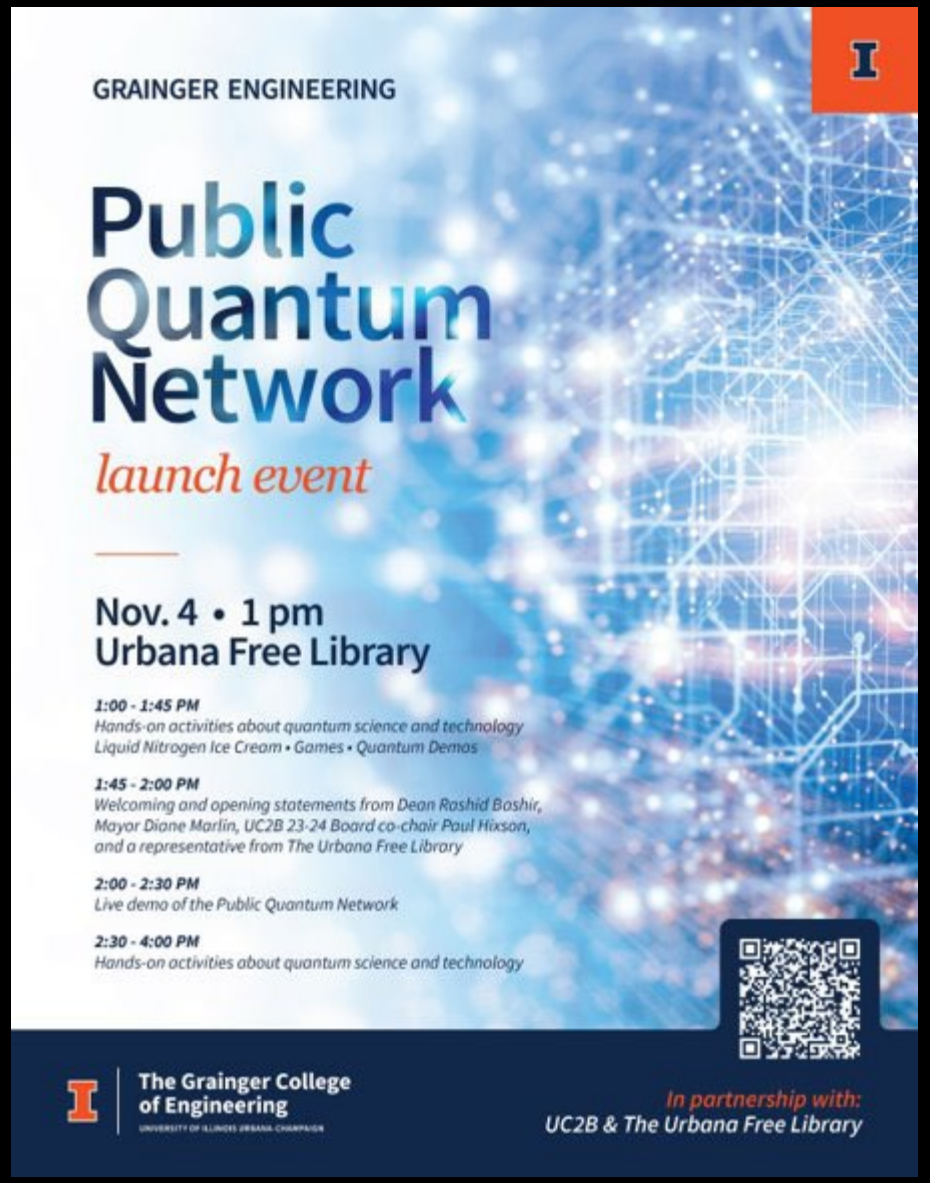
- Illinois positioned itself well and has become a global leader in quantum technology.
  - University research teams span the range of quantum technologies
  - Captured 4/10 National Quantum Centers for research (=$280M)
  - Chicago Quantum Exchange nucleated academic and industry partnerships
  - Quantum technology industry is strong and continues to grow in Illinois

What is the Public Quantum Network (PQN)?

PQN will transmit entangled photons through existing fiber, connecting UIUC quantum optics labs with public institutions throughout Urbana-Champaign.

This creates a publicly accessible network for

- Extensive public engagement: public participation in quantum technologies, quantum curricula in underserved communities (8th grade through community college)
- Fundamental research: state-of-the-art quantum protocols and tests at scale
- Quantum technology innovation: deep involvement of industry partners



Public Quantum Network Launch Event

Saturday, November 4, 1:00 - 4:00 p.m.
The Urbana Free Library | For all ages.

Celebrate the launch of the first publicly accessible quantum network in the nation!

Where everyone can
play with quantum particles.
Come explore with us!

Quantum activities for all ages

Liquid nitrogen ice cream

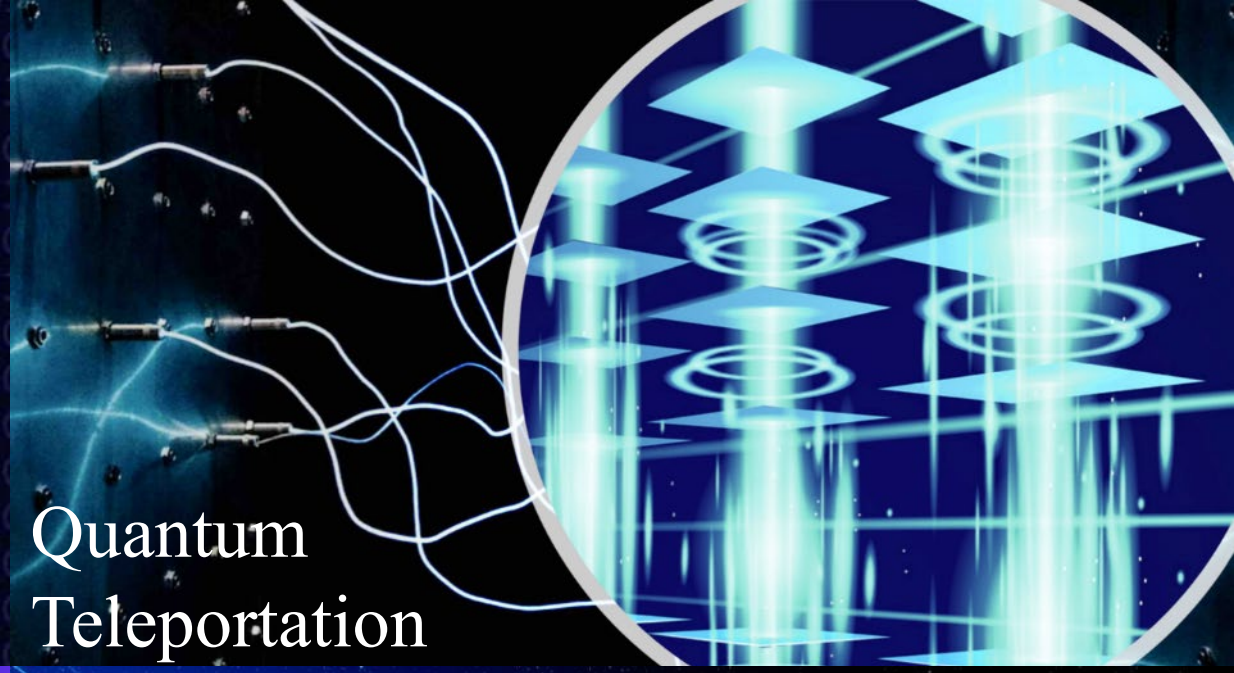
THE URBANA FREE LIBRARY

UC2B Urbana-Champaign Big Broadband

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

NOKIA
NOKIA
BlackBerry
space
T-Mobile

Quantum Secure Communication



Quantum Teleportation

The Quantum Internet

Fault-tolerant quantum memories are used to build repeaters and switches for high-fidelity high-rate quantum communications over 1000s of km

Secure Communications

Quantum Multi-User Applications

Sensing,Timing, GPS

Networked Quantum Computing

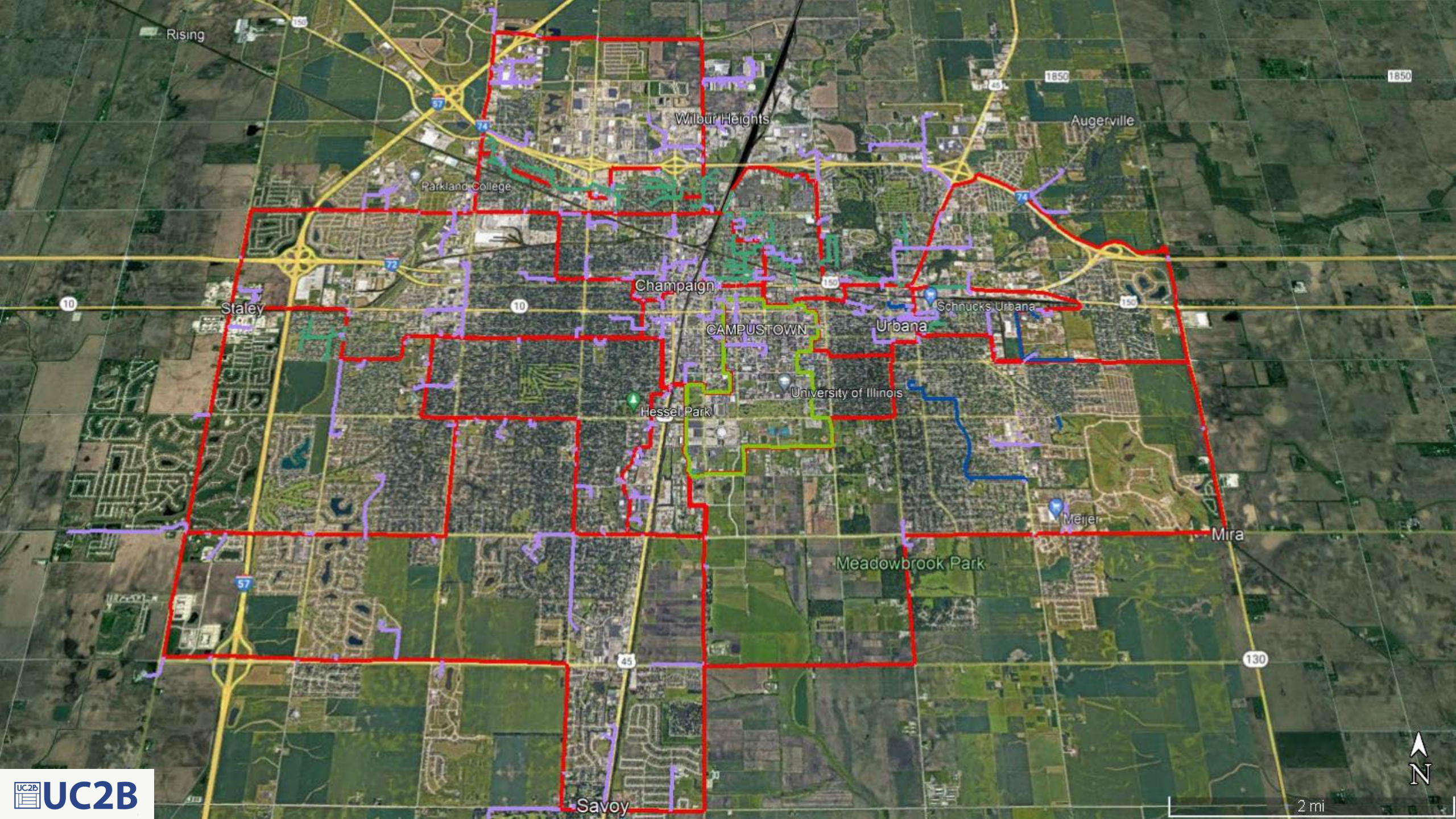
QUANTUM REPEATER (QR)

QUANTUM SWITCH (QS)

QUANTUM COMPUTER (QC)

USER

Unforeseen applications from people like you


Rising
Wilbur Heights
Augerville
Parkland College
Champaign
Staley
CAMPUSTOWN
Urbana
Schnucks Urbana
University of Illinois
Hessel Park
Meijer
Mira
Meadowbrook Park
Savoy
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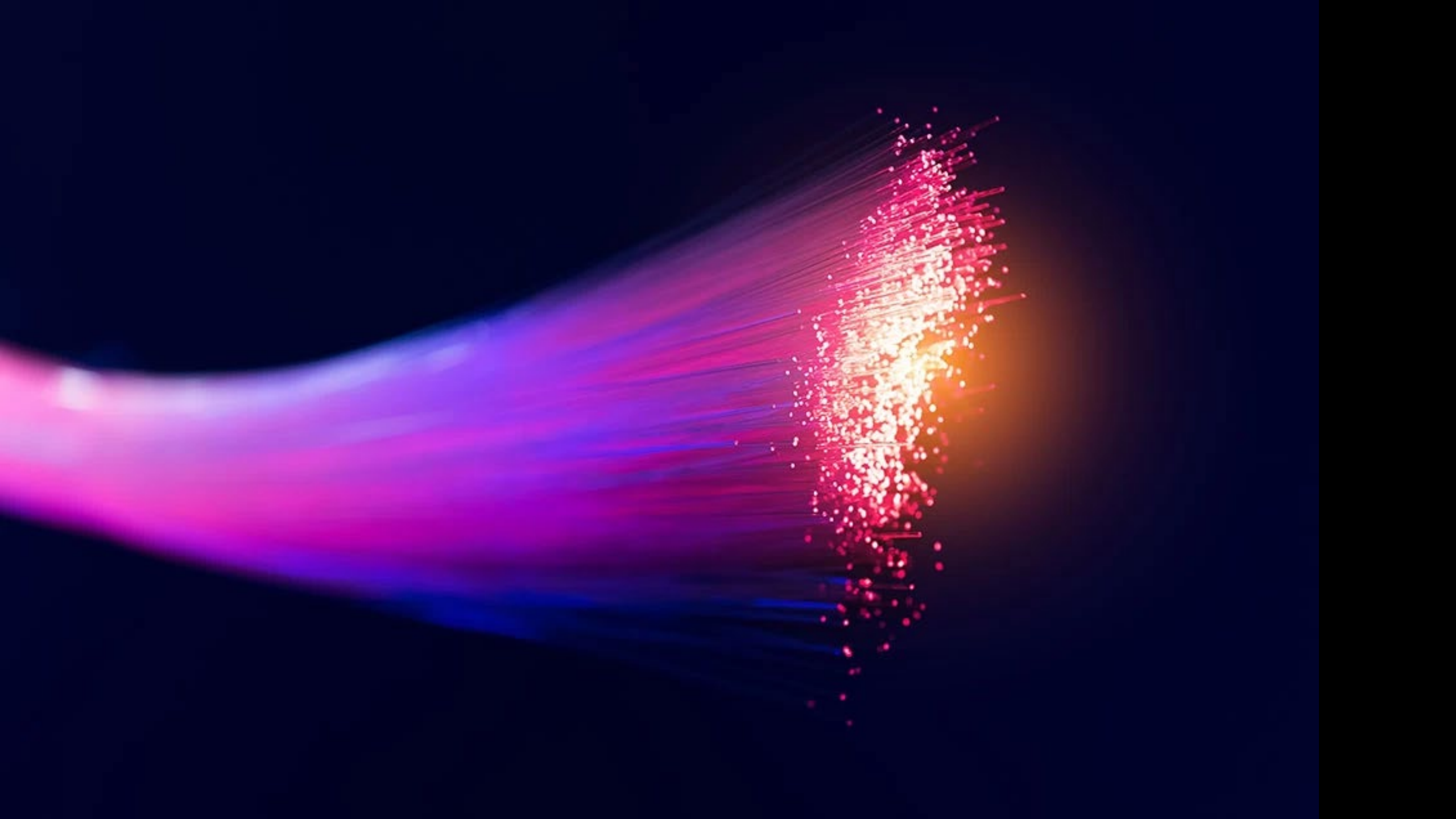
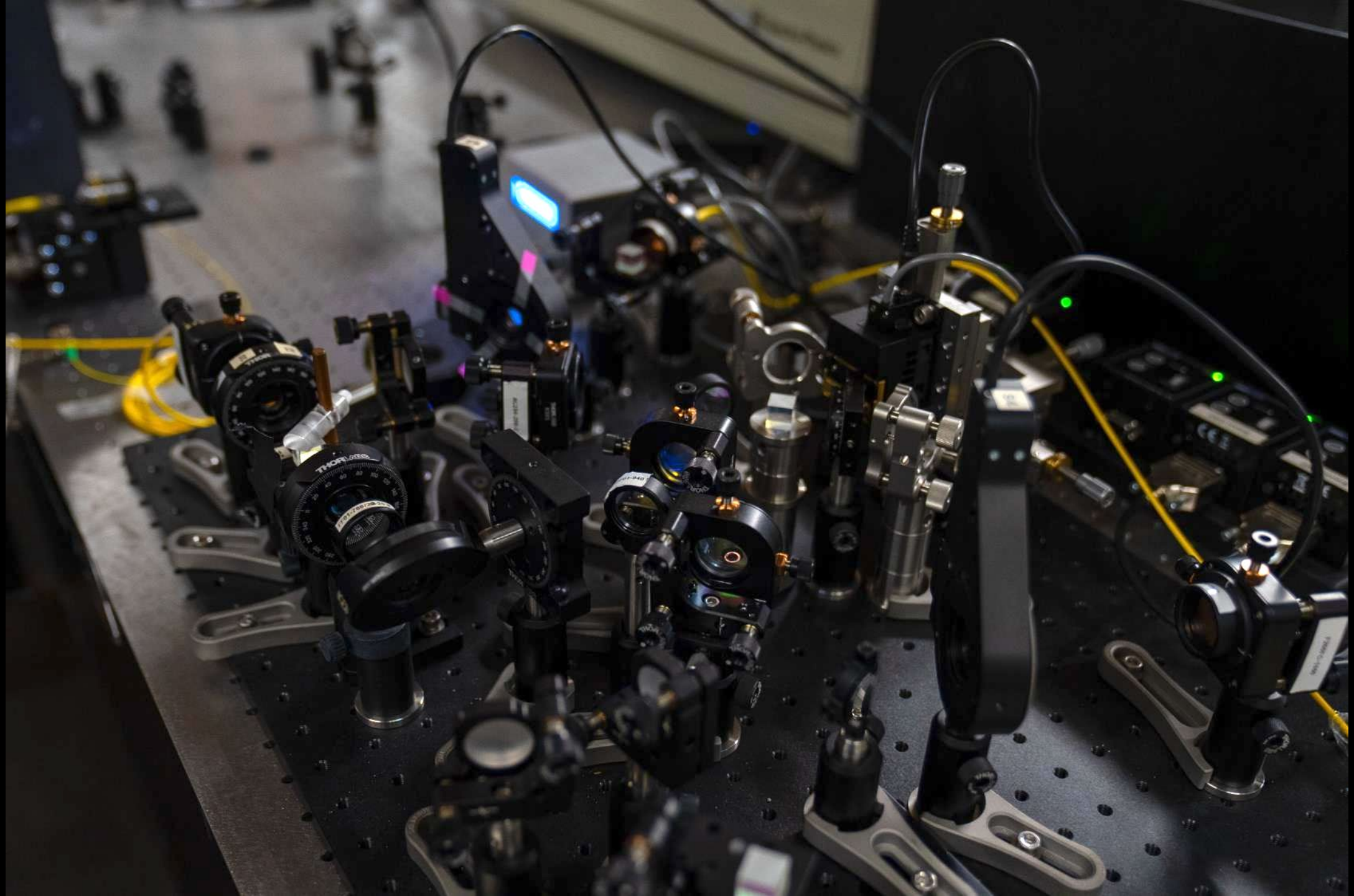


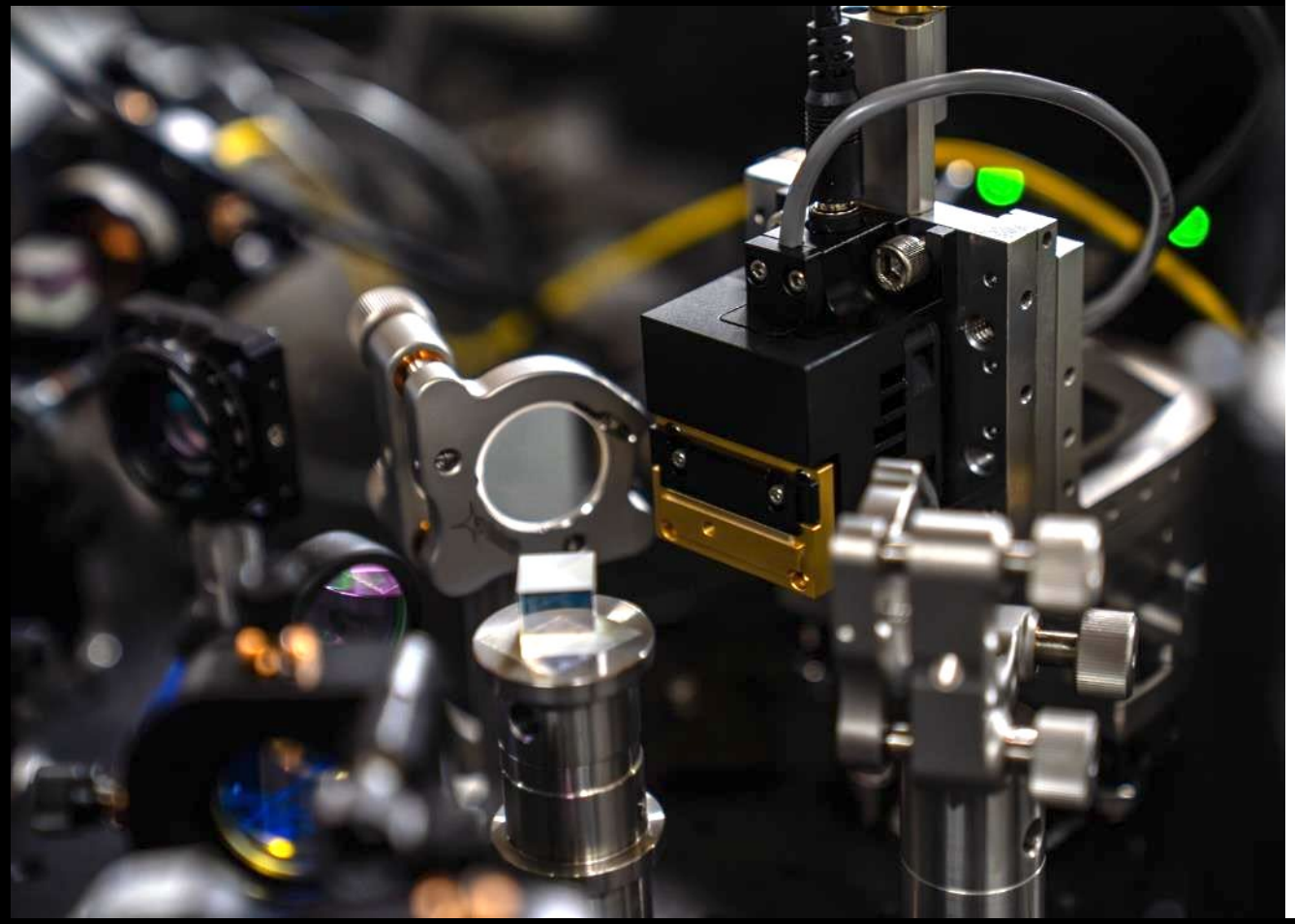
Green St

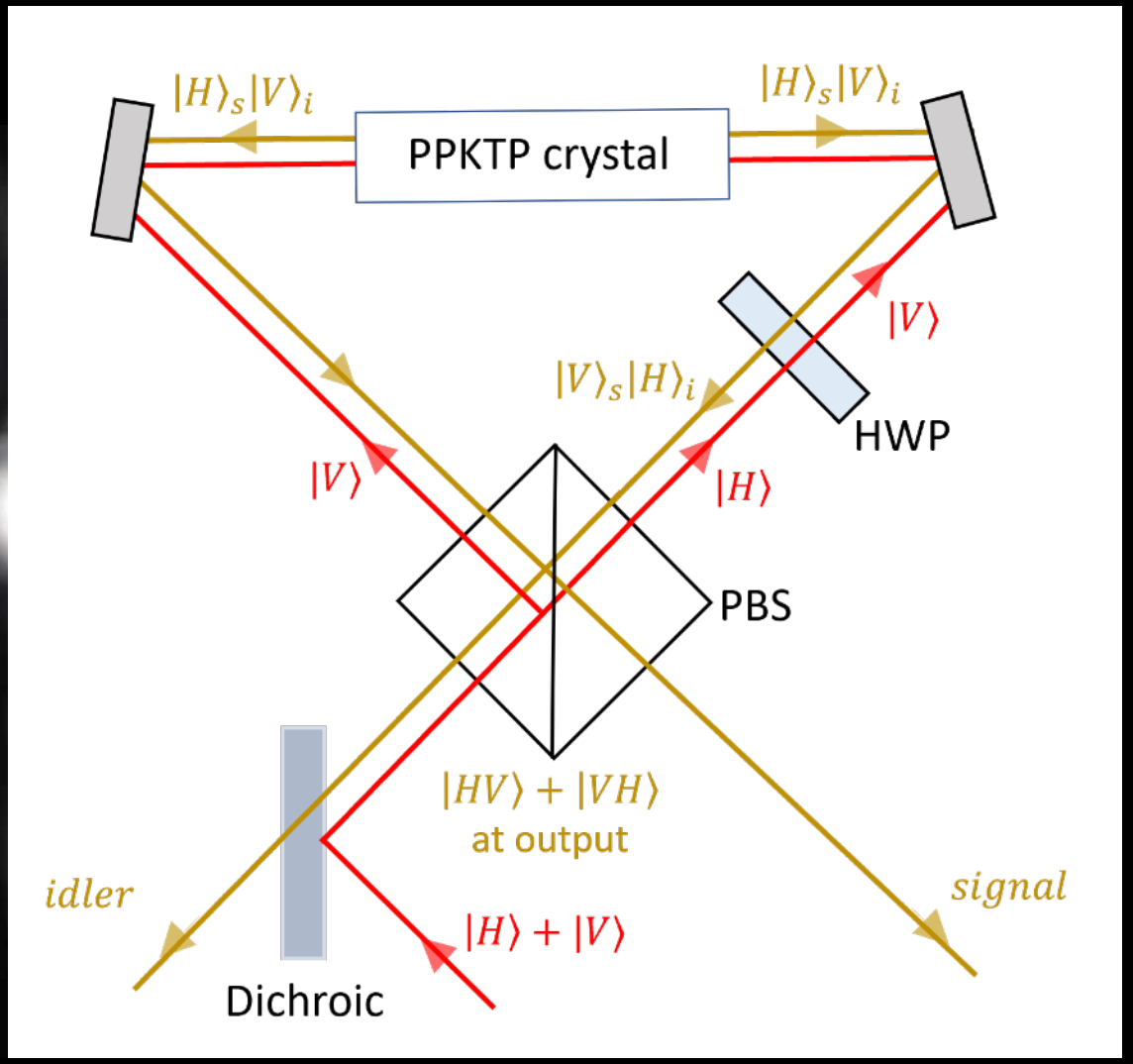
THE URBANA FREE LIBRARY

Loomis Laboratory Of Physics, University...
The Urbana Free Library

PUBLIC
QUANTUM
NETWORK
Where everyone can play with quantum particles. Come explore with us!
THE (INTER) NETWORK
The internet relies on a network of optical fiber, cellular towers, Wi-Fi, and cables. The optical fibers are long glass tunnels. Light travels through them carrying information (bits) to homes, libraries, schools, and more.
QUANTUM TRAVELERS
Photons are individual packets, or quanta, of light. We can make the quantum version of a bit out of a photon and send it through an optical fiber network.
JUST OUT OF SIGHT
Quantum mechanics is a theory that helps us understand how nature works when things get really tiny. Electrons, atoms, and photons are all examples of quantum particles.
QUANTUM PARTICLES FOLLOW QUANTUM RULES
1. A particle's properties are not always set to one value. They can exist in a mixture, or SUPERPOSITION, of many options all at once.
2. ENTANGLEMENT ties the properties of multiple particles together.
3. MEASUREMENT randomly chooses from the different possibile options for a property, destroying superposition and entanglement.
MAKING CONNECTIONS
Entanglement lets us connect quantum objects, like particles, across a network. In the future, controlling entanglement will enhance sensing, computing, and communications.
TEST FOR YOURSELF
In the 1960s, a scientist named John Bell learned how to test whether or not objects were entangled. In this exhibit, you can probe entanglement, just as Bell did, and play with a quantum network.
Superposition
Entanglement
Measurement


THORLABS




$|H\rangle_s|V\rangle_i$
$|H\rangle_s|V\rangle_i$
PPKTP crystal
$|V\rangle$
$|V\rangle_s|H\rangle_i$
HWP
$|V\rangle$
$|H\rangle$
PBS
$|HV\rangle + |VH\rangle$
at output
idler
signal
$|H\rangle + |V\rangle$
Dichroic

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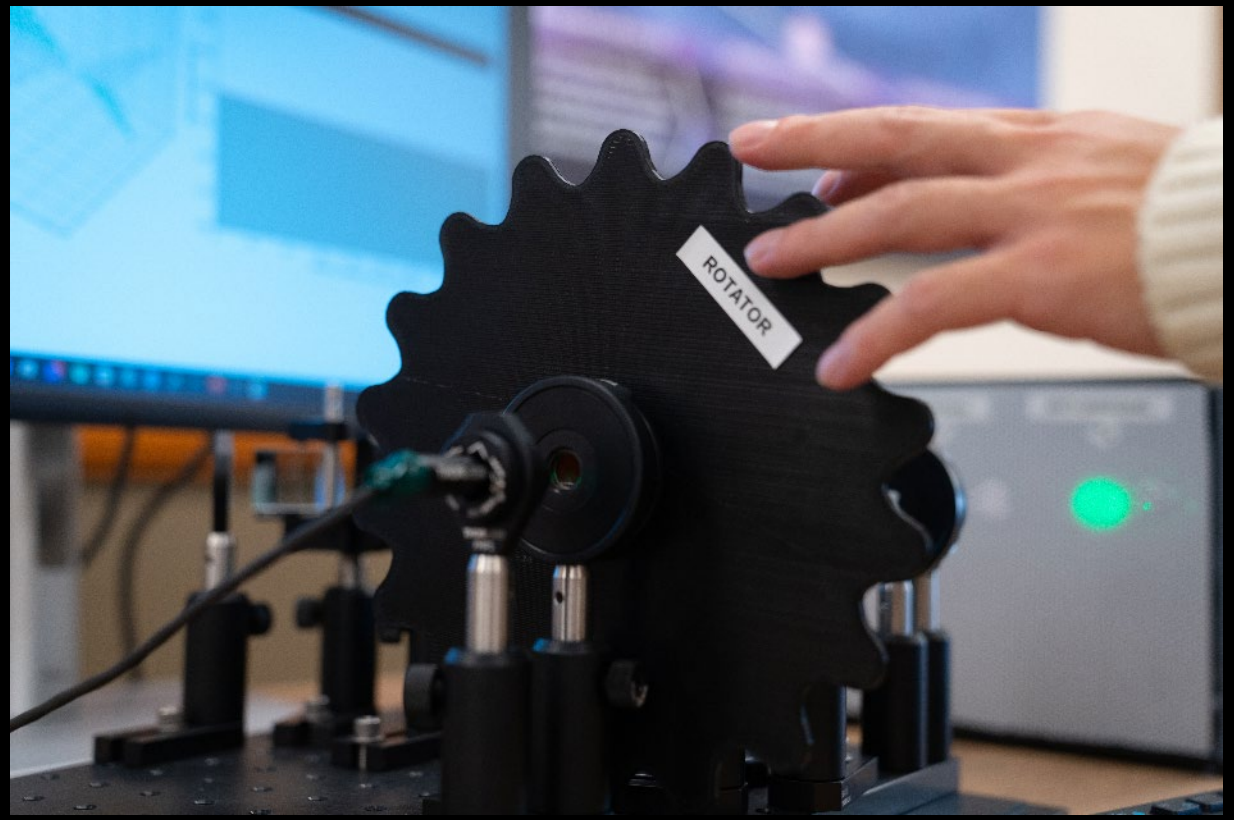
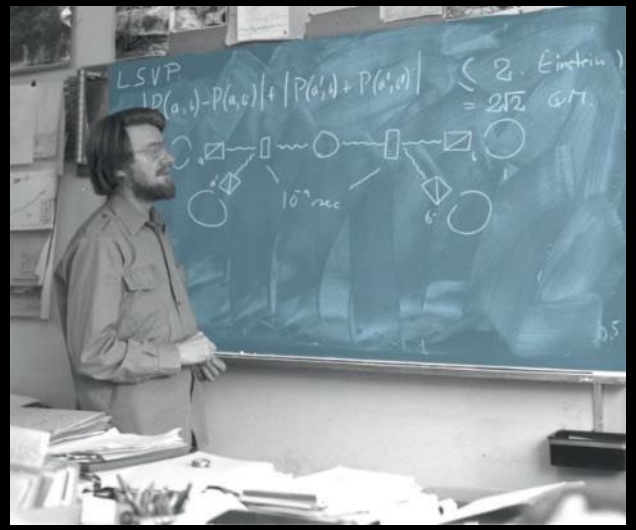

ROTATOR



1930's

1960's

1970's to present

2022

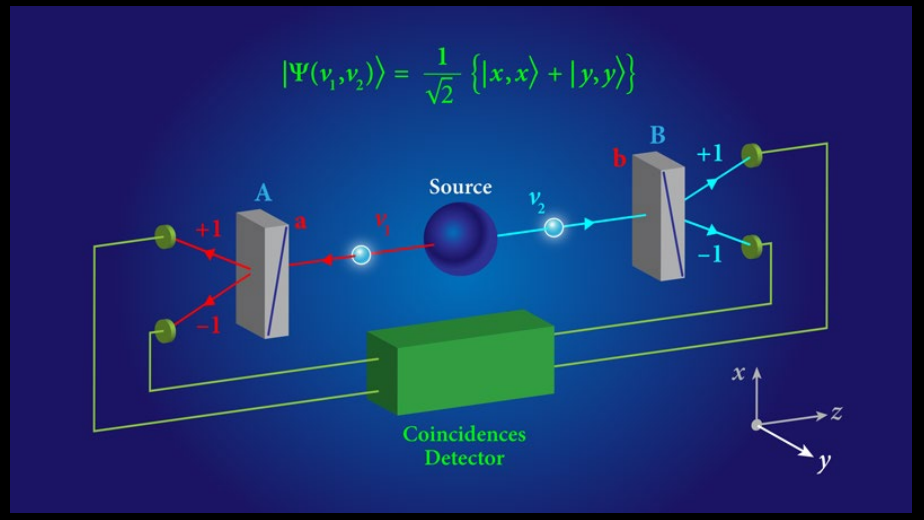
2023

EINSTEIN ATTACKS QUANTUM THEORY

Scientist and Two Colleagues Find It Is Not 'Complete' Even Though 'Correct.'

SEE FULLER ONE POSSIBLE

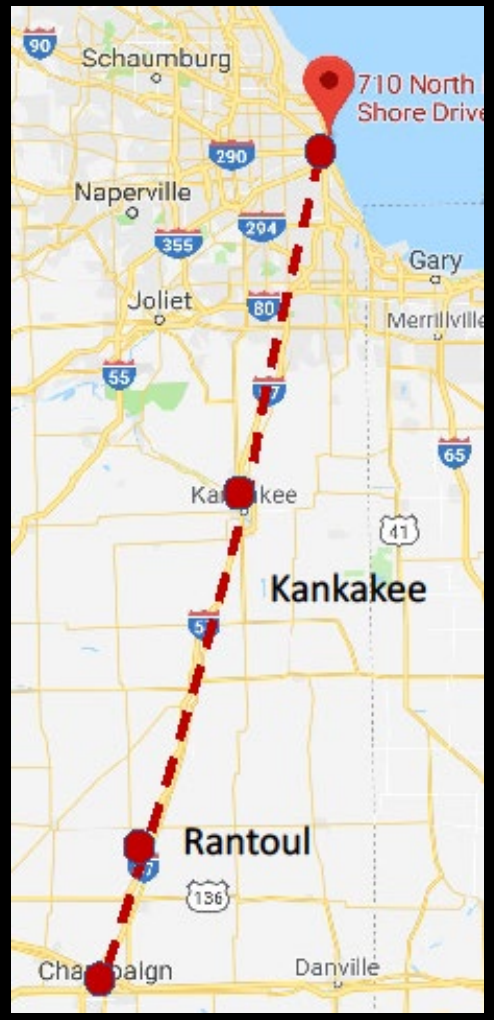
Believe a Whole Description of 'the Physical Reality' Can Be Provided Eventually.



PUBLIC QUANTUM NETWORK

What's next?

Links to Chicago: Kankakee Community College



Fermilab Visitor's Center

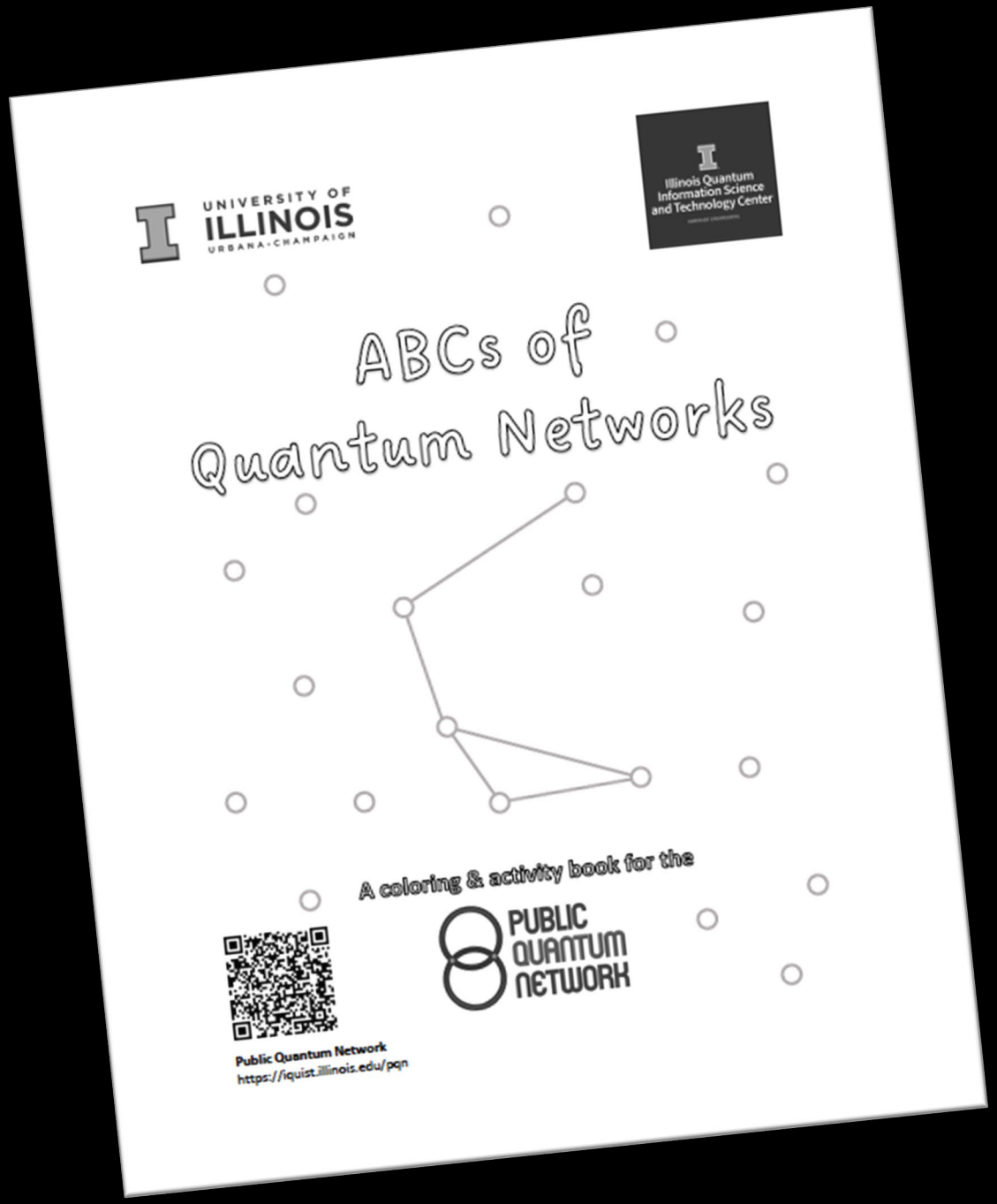
Locally: preparing for next node, ongoing outreach activities

Next spring: add a second measurement station at the Urbana Free Library to give people the power to share "quantum valentines"

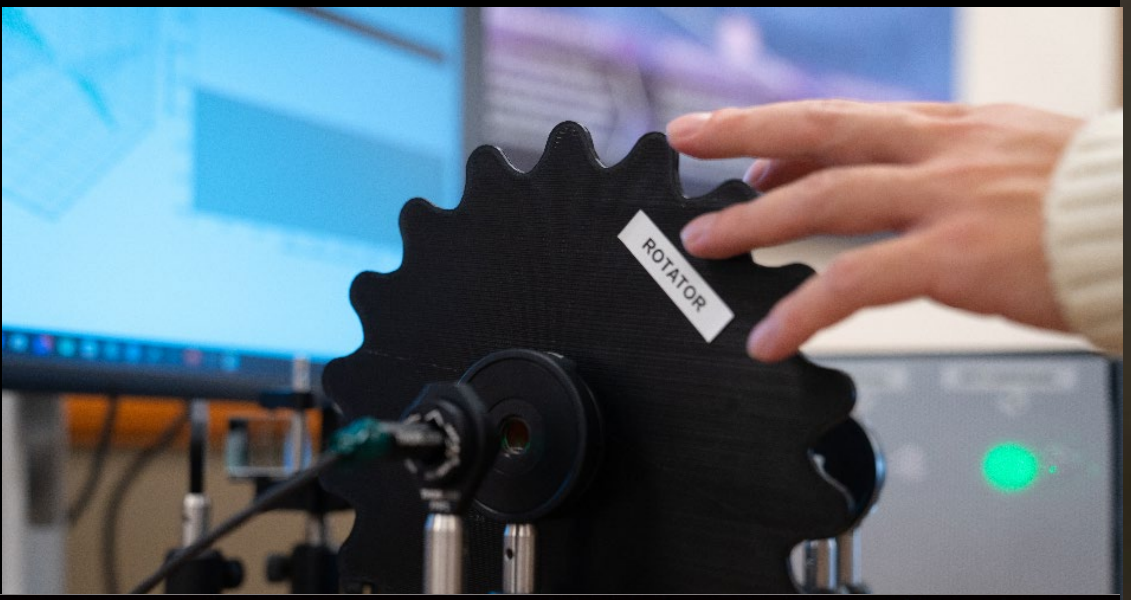
Next summer: work with TeachQuantum to build curricula with local high school teachers

Print out a coloring book!

iquist.Illinois.edu/outreach/pqn/coloring-book



Join us for a Quantum Adventure!



CASCADE: AN ARTS-SCIENCE CELEBRATION

LabEscape

NOW OPEN FOR MISSIONS AT OUR NEW LOCATION!

LabEscape Quantum Salvation Mission Center, Rm 1262 Digital Computing Lab

1304 W. Springfield Ave., Urbana, IL

Keshav Kapoor
UIUC

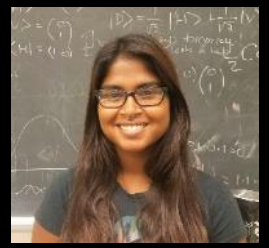
Yujie Zhang
UIUC

Jaehoon Choi
UIUC

Soroush Hosseini
UIUC

Benjamin Nussbaum
UIUC

Colin Lualdi
UIUC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UIUC

Brittany Karki
UIUC

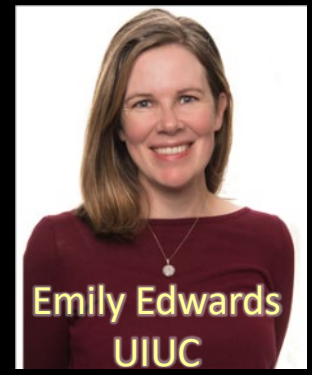
Kelsey Ortiz
UIUC

Chris Skaar
UIUC

Virginia Lorenz
UIUC

Paul Kwiat
UIUC

Rebecca Wiltfong
UIUC


Emily Edwards
UIUC

Tracy Smith
UC2B

Paul Hixson
UC2B

Leon Wilson
TUFL

Lauren Chambers
TUFL

Dawn Cassady
TUFL

Michael O'Boyle
UIUC

Kim Gudeman
UIUC

Canaan Daniels
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Angela Graham
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Brian Demarco
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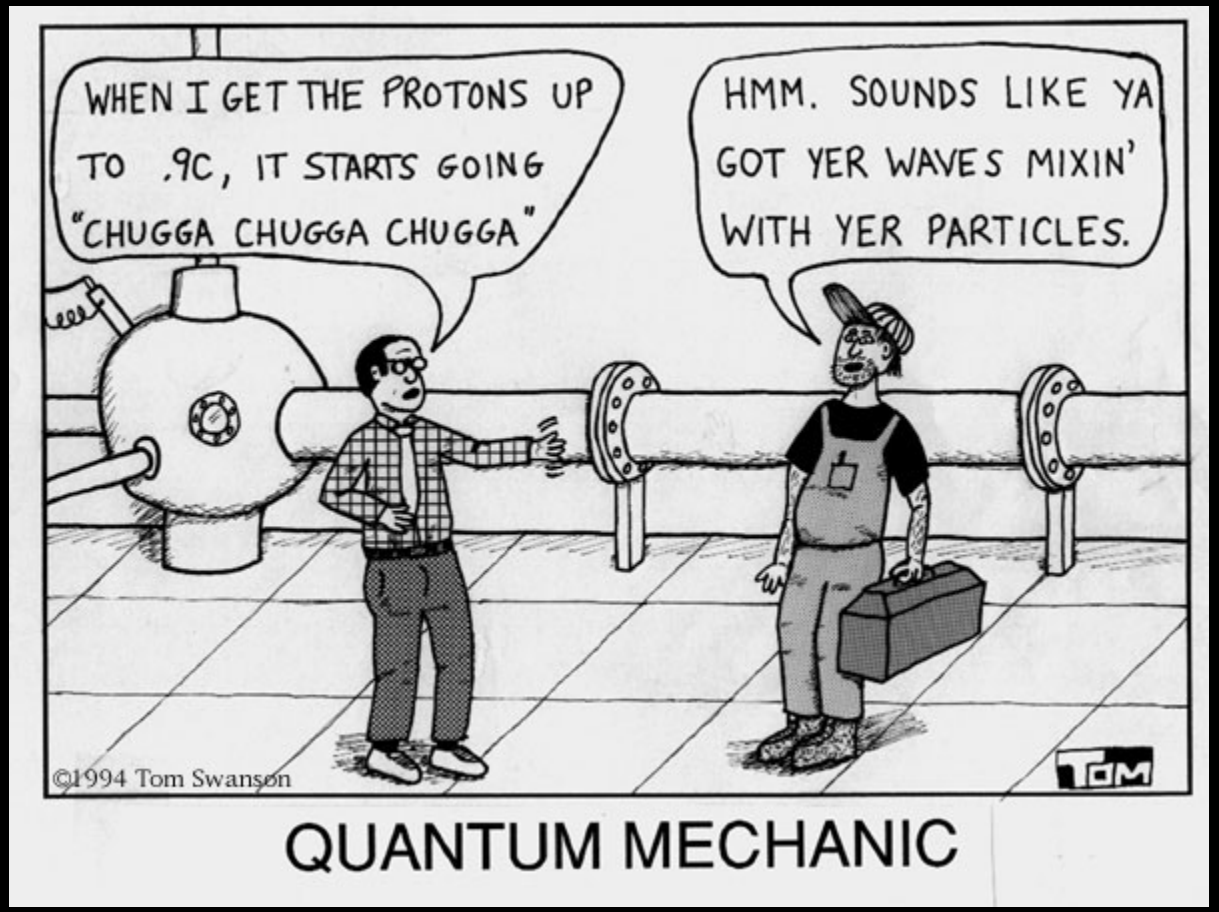
NSF

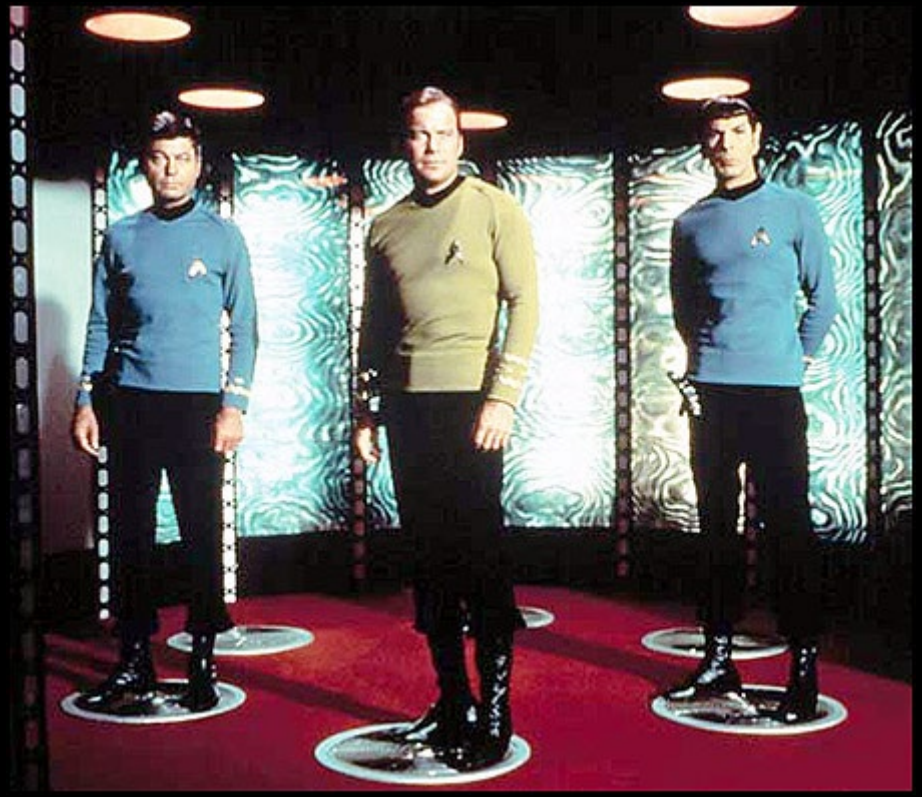
Conclusion

- Quantum entanglement breaks local realism
- Generating entangled photons & reconstructing their state is relatively easy, but engineering for applications is still a challenge
- Entanglement is not just “spooky”, it’s useful!



But there’s Quantum Teleportation, and then there’s

Quantum Teleportation



Anton Zeilinger

Yes, but there are two major differences. Firstly, we **transfer properties**, not matter. And secondly, until now we have had more success with light particles and occasionally with atoms, not with larger objects.

And even if it was possible, the problems involved would be huge. Firstly: for physical reasons, the original has to be **completely isolated** from its environment for the transfer to work. There has to be a total vacuum for it to work. And it is a well-known fact that this is **not particularly healthy** for human beings. Secondly, you would take all the properties from a person and transfer them onto another. This means producing a being who no longer has any hair colour, no eye colour, nix. A man without qualities! This is not only unethical – it's so crazy that it's impossible to imagine.

http://www.signandsight.com/features/614.html

Anton Zeilinger

The atoms in a human being are the equivalent to the information mass of about a **thousand billion billion billion bits**. Even with today's top technology, this means it would take about 30 billion years to transfer this mass of data. That's twice the age of the universe. So we'll need a number of major breakthroughs in technology first.

…

Who knows, perhaps in a thousand years we really will be able to **teleport a coffee cup**. But beware: even the tiniest interference can mean that the cup arrives without its handle. This method of transport would be far too dangerous for humans.

http://www.signandsight.com/features/614.html