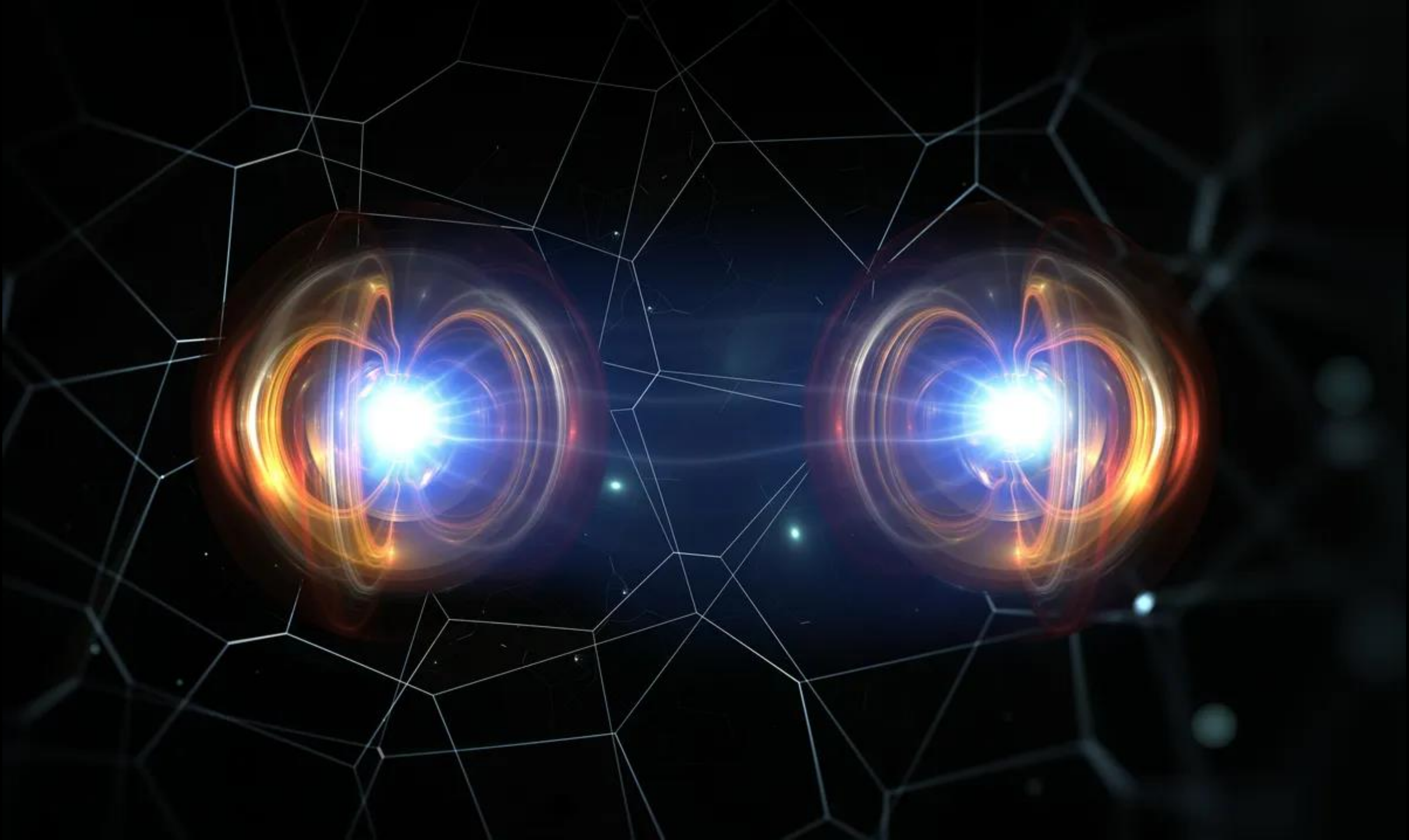
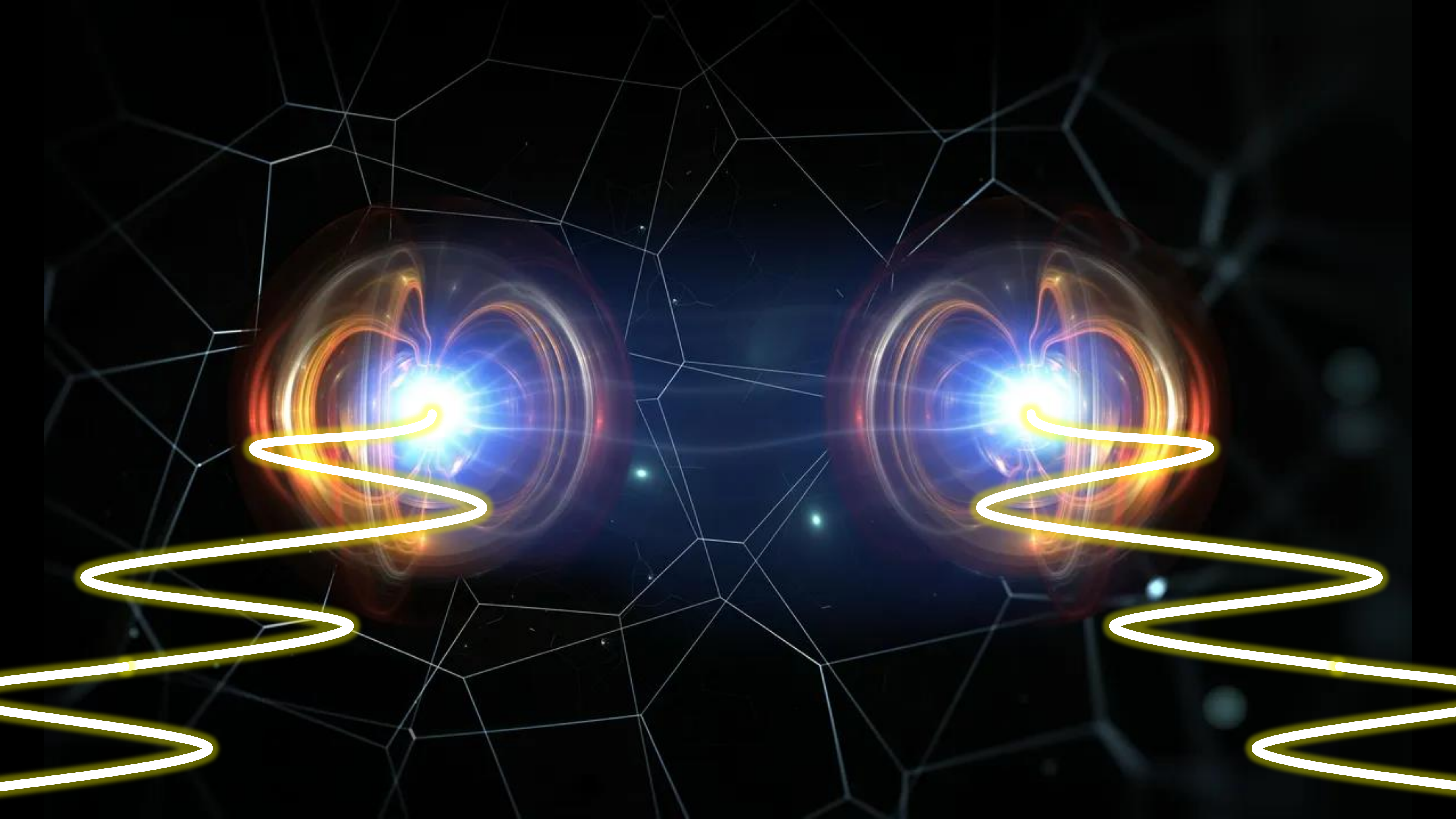
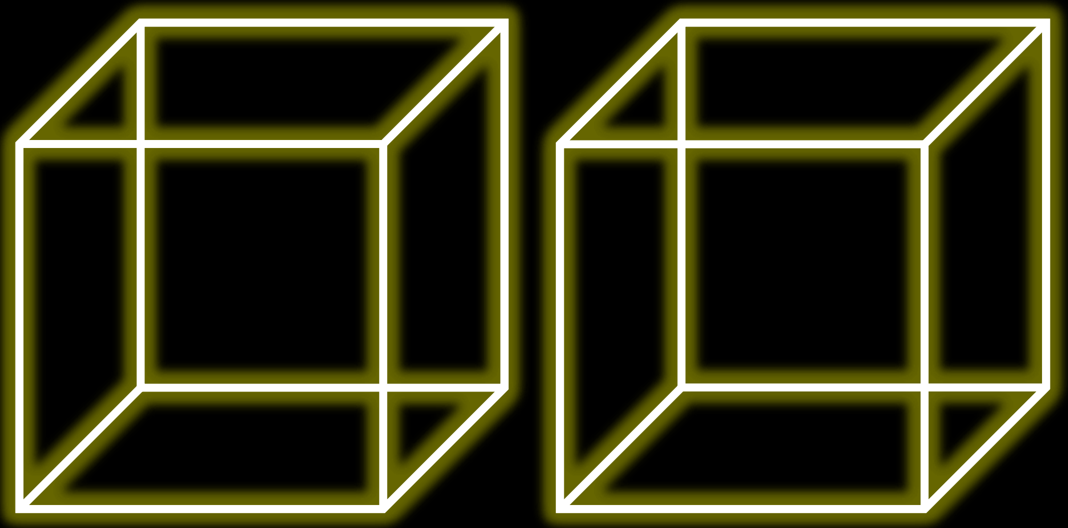
Entanglement

Virginia (Gina) Lorenz
University of Illinois Urbana-Champaign

March 18, 2023

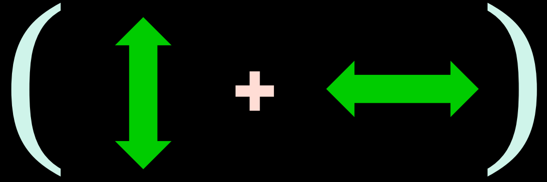


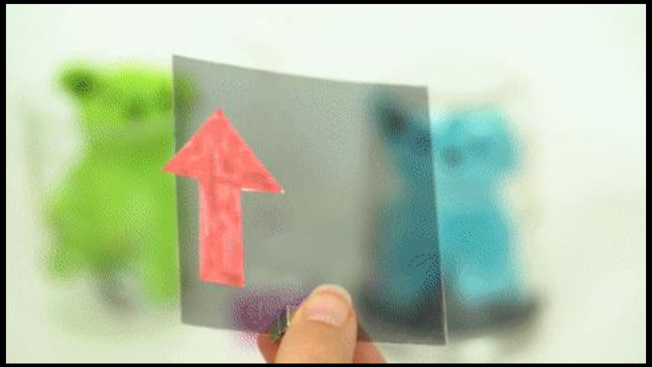




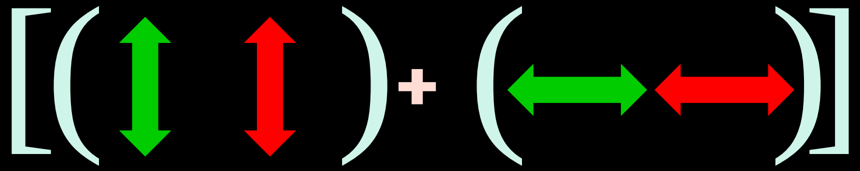
Polarization Entanglement

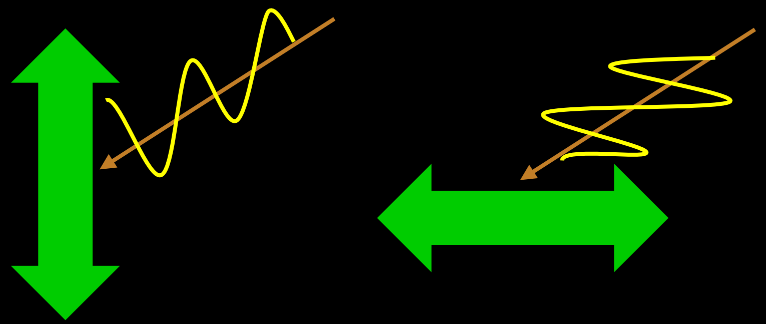
- Photons can be in a superposition of two polarizations





- 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 (but information about which state they end up in cannot travel faster than the speed of light)

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

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

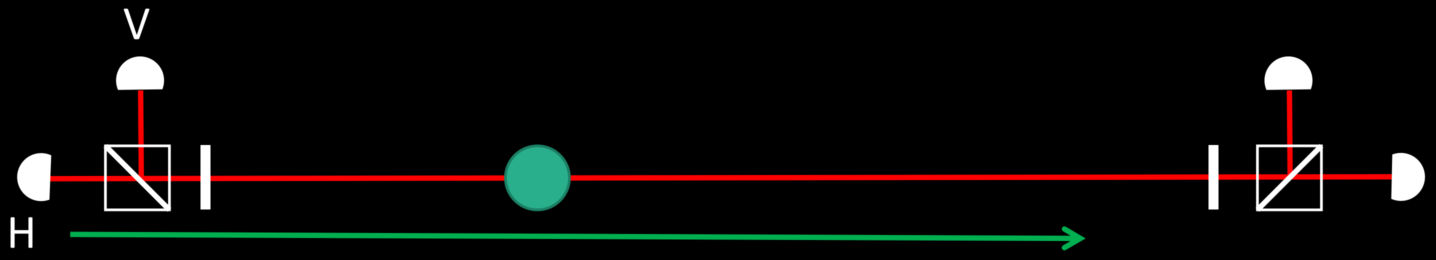
$$\psi_2 \propto |H\rangle + |V\rangle$$

$$\psi_{12} = \psi_1 \psi_2 \propto |HH\rangle + |VV\rangle + |HV\rangle + |VH\rangle$$ 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



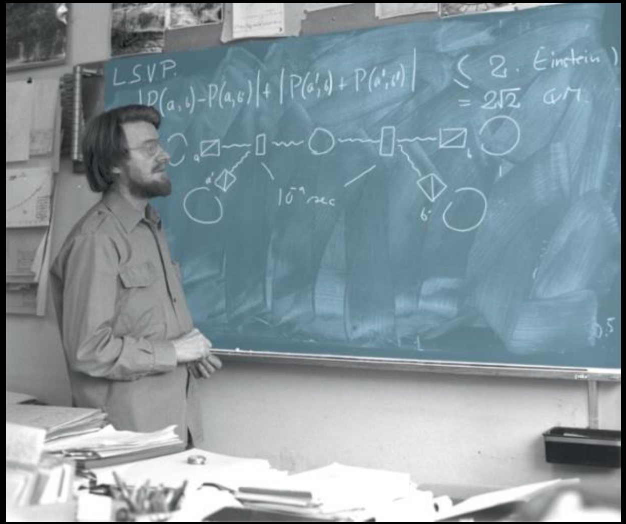
Requires speeds > c, i.e. non-locality

EPR: Action at a distance (non-locality) is spooky.

Is Quantum Mechanics wrong?

Maybe correlations are due to some local element of reality ("local hidden variable" model)?

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

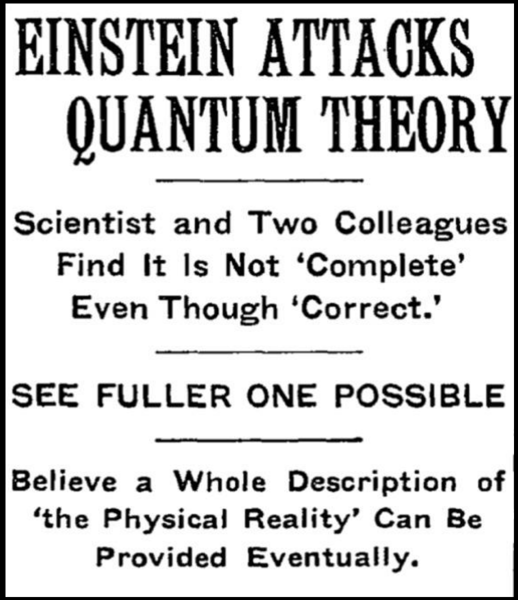


1930's

1960's

1970's to present

2022

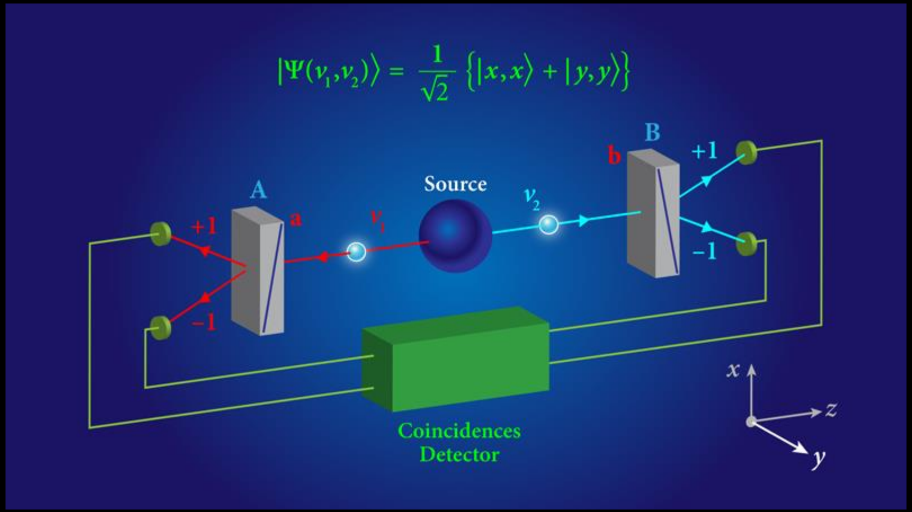


EINSTEIN ATTACKS QUANTUM THEORY

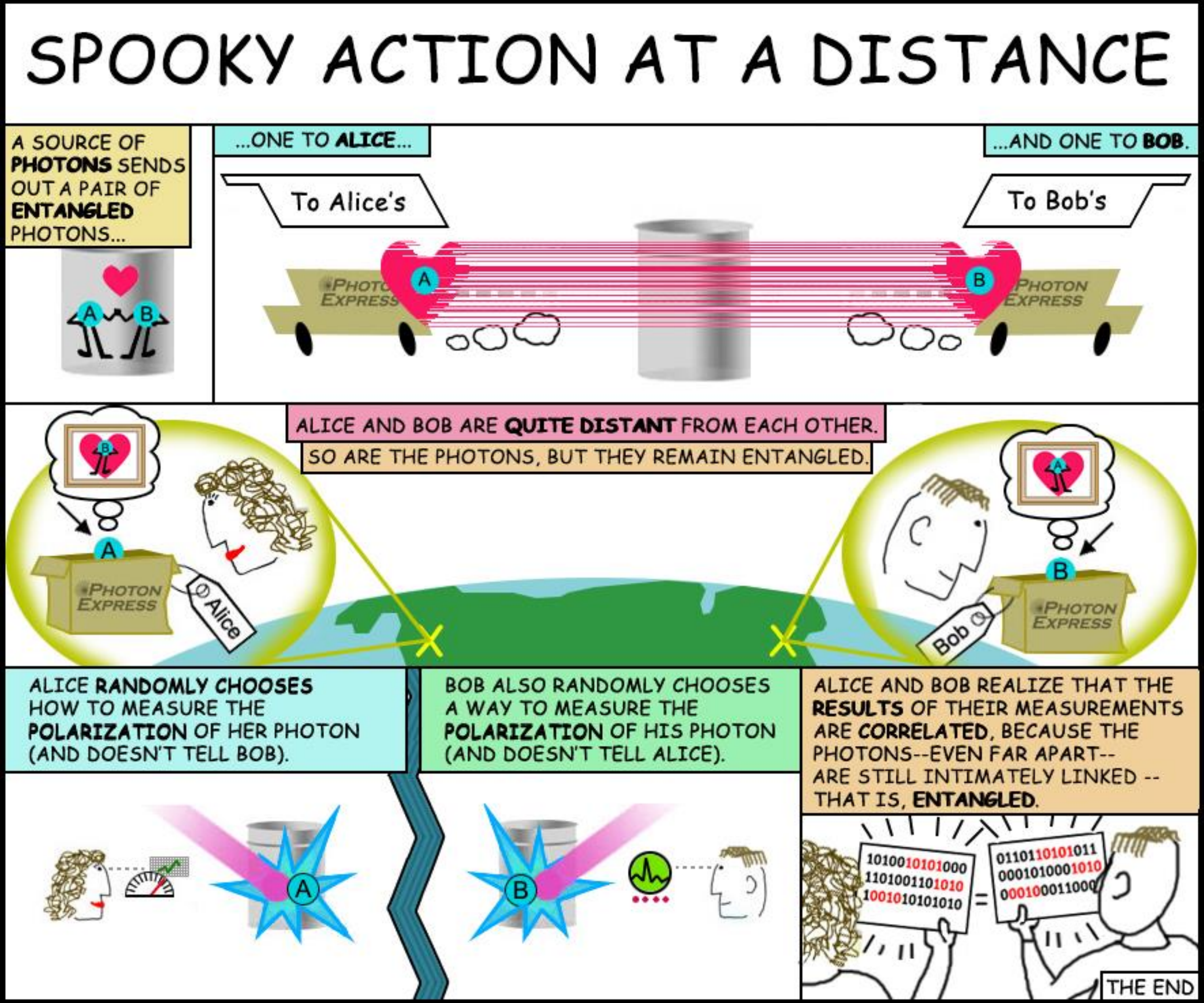
Scientist and Two Colleagues Find It Is Not 'Complete' Even Though 'Correct.'

SEE FULLER ONE POSSIBLE

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



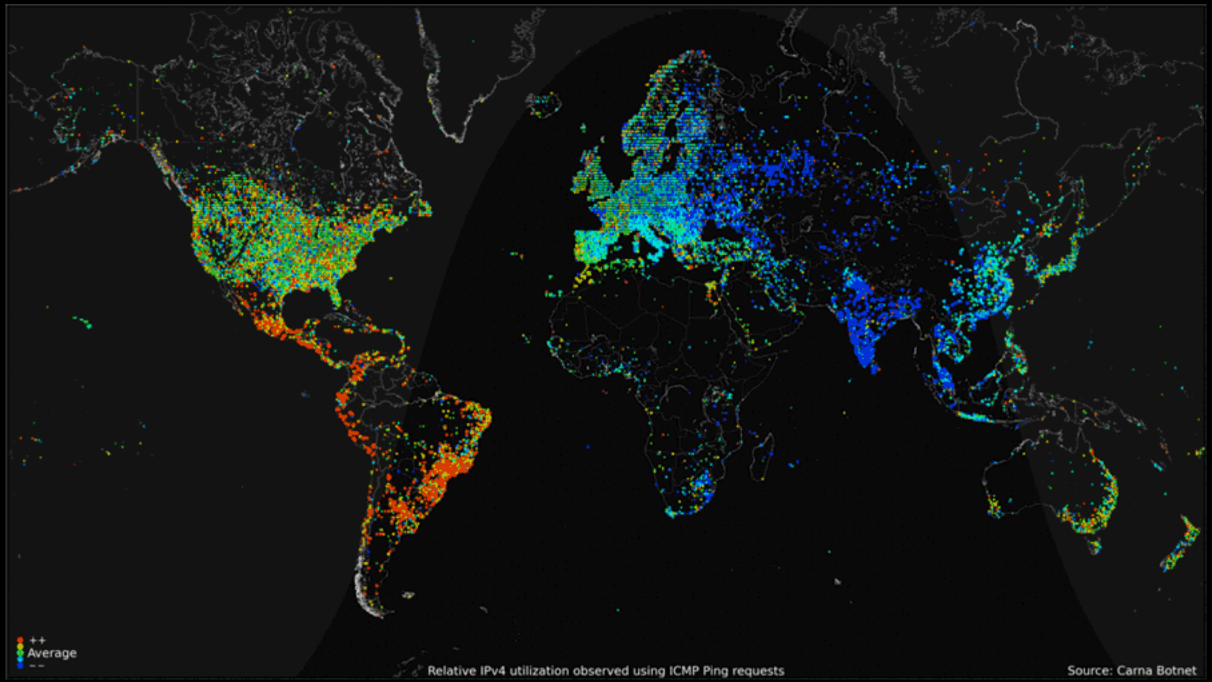
Entangled photons allow new applications



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



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 different color socks inside.
- They are sent to distant locations.
- The recipients open the boxes at the same time. Wow! They always find different 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 other color.

- 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)

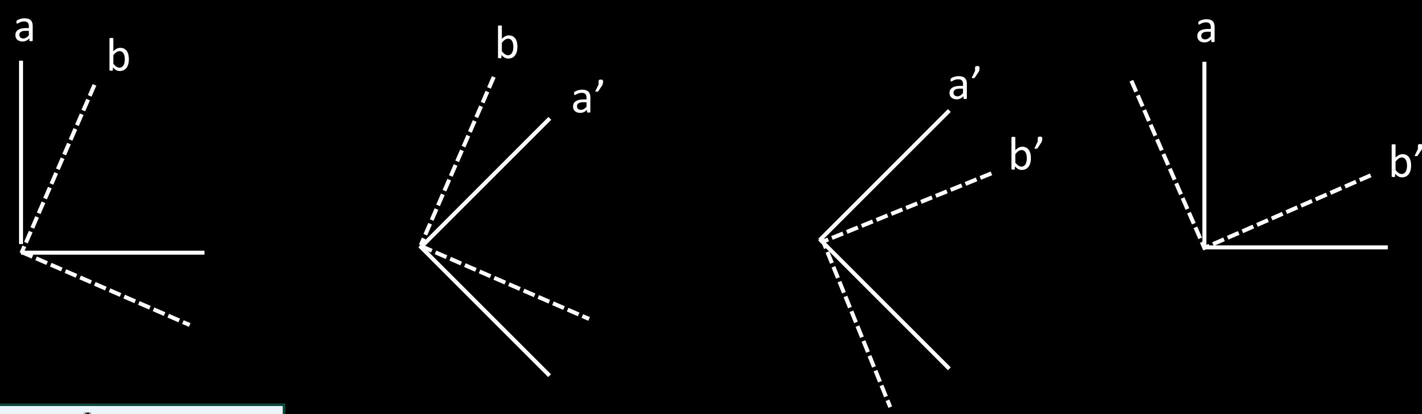
- How do we test for this?

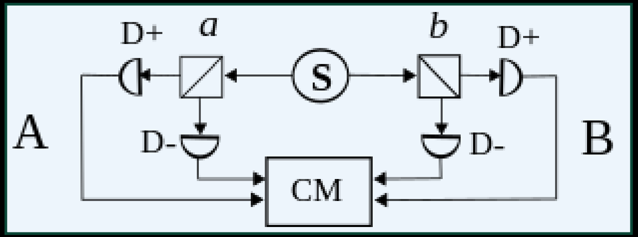
1964: Bell's theorem

- 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





- If the states were "set ahead of time", the photons would always give the same results for a given setting.

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

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

Strong Loophole-Free Test of Local Realism*

Lynden K. Shalm,[1,†] Evan Meyer-Scott,[2] Bradley G. Christensen,[3] Peter Bierhorst,[1] Michael A. Wayne,[3,4] Martin J. Stevens,[1] Thomas Gerrits,[1] Scott Glancy,[1] Deny R. Hamel,[5] Michael S. Allman,[1] Kevin J. Coakley,[1] Shellee D. Dyer,[1] Carson Hodge,[1] Adriana E. Lita,[1] Varun B. Verma,[1] Camilla Lambrocco,[1] Edward Tortorici,[1] Alan L. Migdall,[4,6] Yanbao Zhang,[2] Daniel R. Kumor,[3] William H. Farr,[7] Francesco Marsili,[7] Matthew D. Shaw,[7] Jeffrey A. Stern,[7] Carlos Abellán,[8] Waldimar Amaya,[8] Valerio Pruneri,[8,9] Thomas Jennewein,[2,10] Morgan W. Mitchell,[8,9] Paul G. Kwiat,[3] Joshua C. Bienfang,[4,6] Richard P. Mirin,[1] Emanuel Knill,[1] and Sae Woo Nam[1,‡]

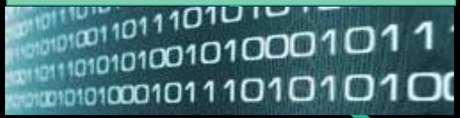
[1]*National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305, USA*
[2]*Institute for Quantum Computing and Department of Physics and Astronomy, University of Waterloo, 200 University Avenue West, Waterloo, Ontario, Canada, N2L 3G1*
[3]*Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA*
[4]*National Institute of Standards and Technology, 100 Bureau Drive, Gaithersburg, Maryland 20899, USA*
[5]*Département de Physique et d'Astronomie, Université de Moncton, Moncton, New Brunswick E1A 3E9, Canada*
[6]*Joint Quantum Institute, National Institute of Standards and Technology and University of Maryland, 100 Bureau Drive, Gaithersburg, Maryland 20899, USA*
[7]*Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA*
[8]*ICFO-Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels (Barcelona), Spain*
[9]*ICREA-Institució Catalana de Recerca i Estudis Avançats, 08015 Barcelona, Spain*
[10]*Quantum Information Science Program, Canadian Institute for Advanced Research, Toronto, Ontario, Canada*

(Received 10 November 2015; published 16 December 2015)

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.

The last 50 years: Quantum Information

Information Science



Quantum Mechanics

Quantum Information

Quantum State

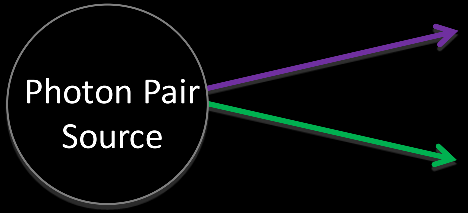
- Quantum Computing
- Quantum Communication
- Simulation of Quantum Systems
- Quantum Sensing

“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
- …

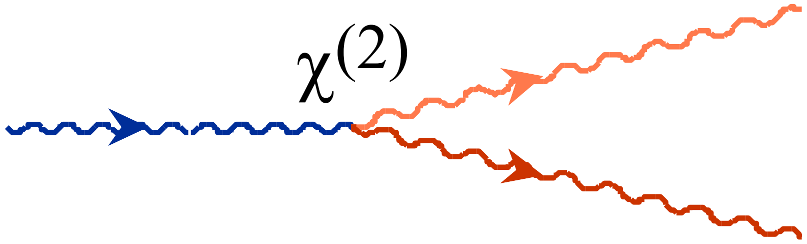
Spontaneous parametric down-conversion (SPDC)

Spontaneous four-wave mixing (SFWM)



1970: Spontaneous Parametric Down-Conversion

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



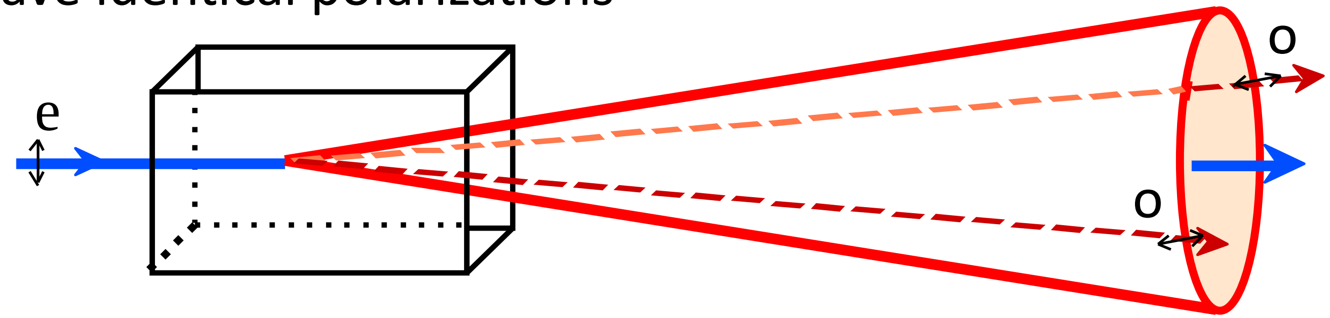
$$\omega_p = \omega_s + \omega_i \; *$$

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

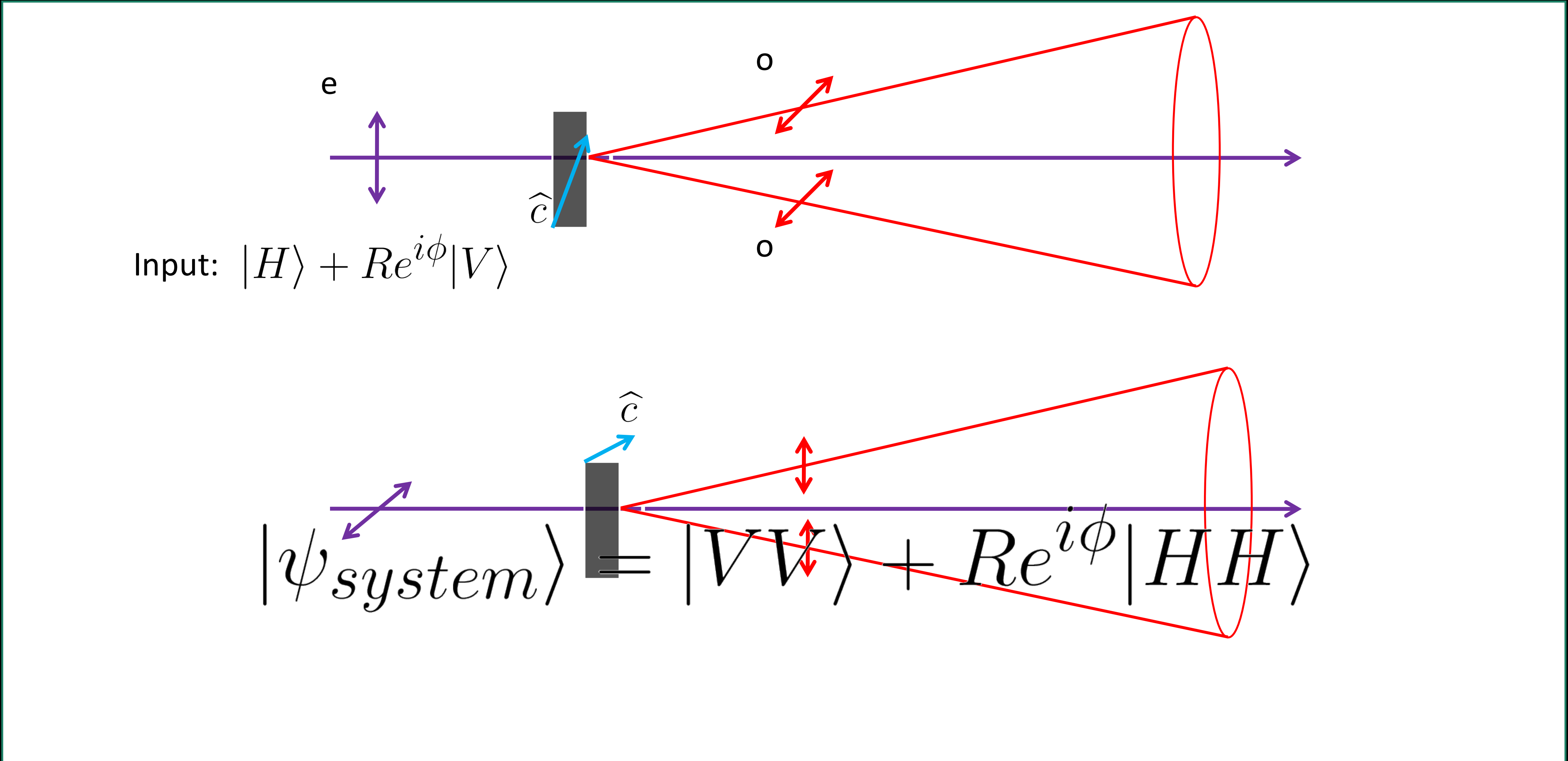
*Energy conservation → energy entanglement
†Momentum conservation → momentum entanglement

Type-I phase-matching

Photons have identical polarizations



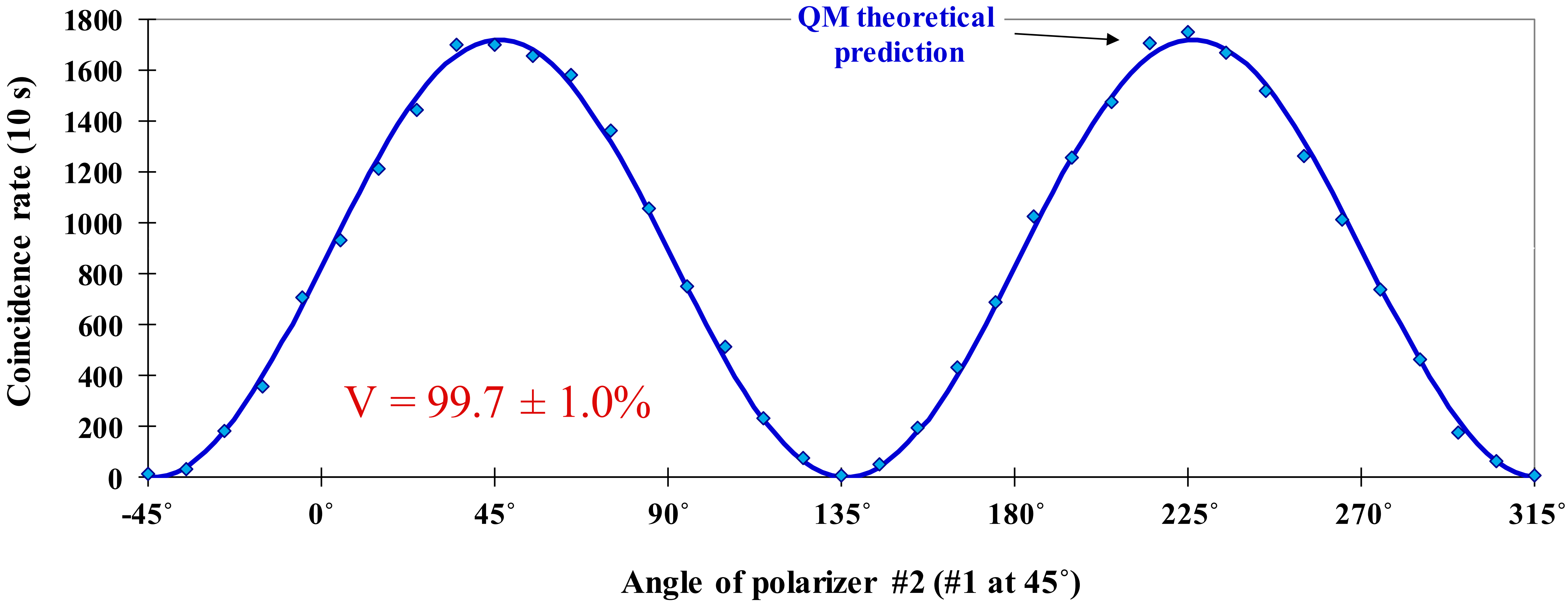
Polarization Entanglement



Input: $|H\rangle + Re^{i\phi}|V\rangle$

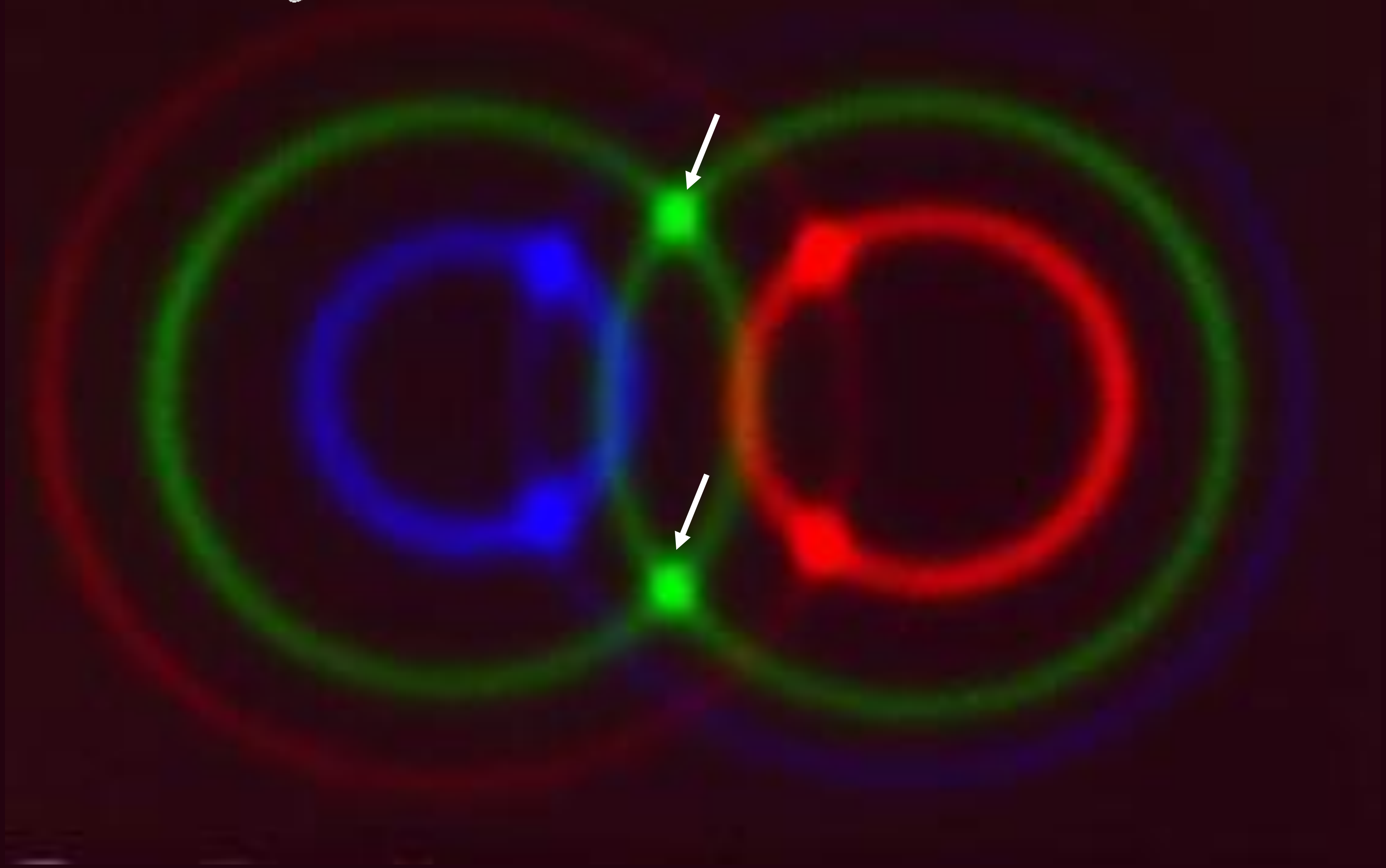
$$|\psi_{system}\rangle = |VV\rangle + Re^{i\phi}|HH\rangle$$

Proof of Quantum Correlations

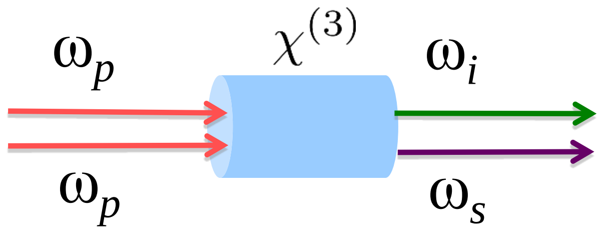


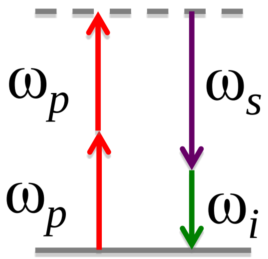
Near-perfect quantum behavior

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



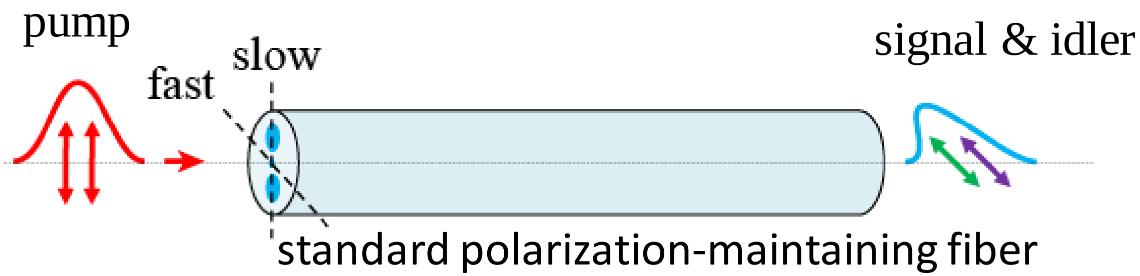
Spontaneous four-wave mixing





Conservation of energy

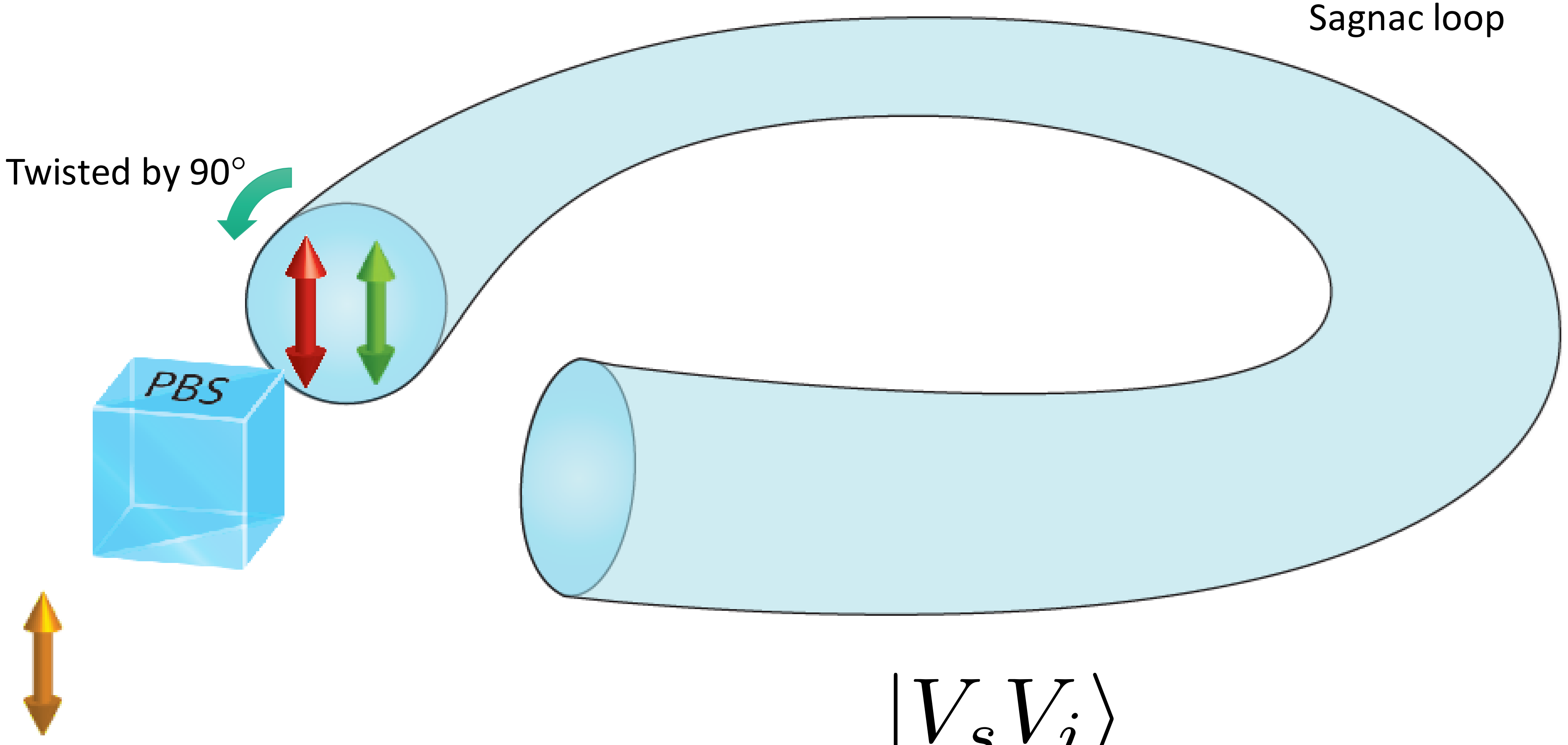
- Spontaneous four-wave mixing in polarization-maintaining optical fiber:



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

  - *Birefringent* phase-matching:

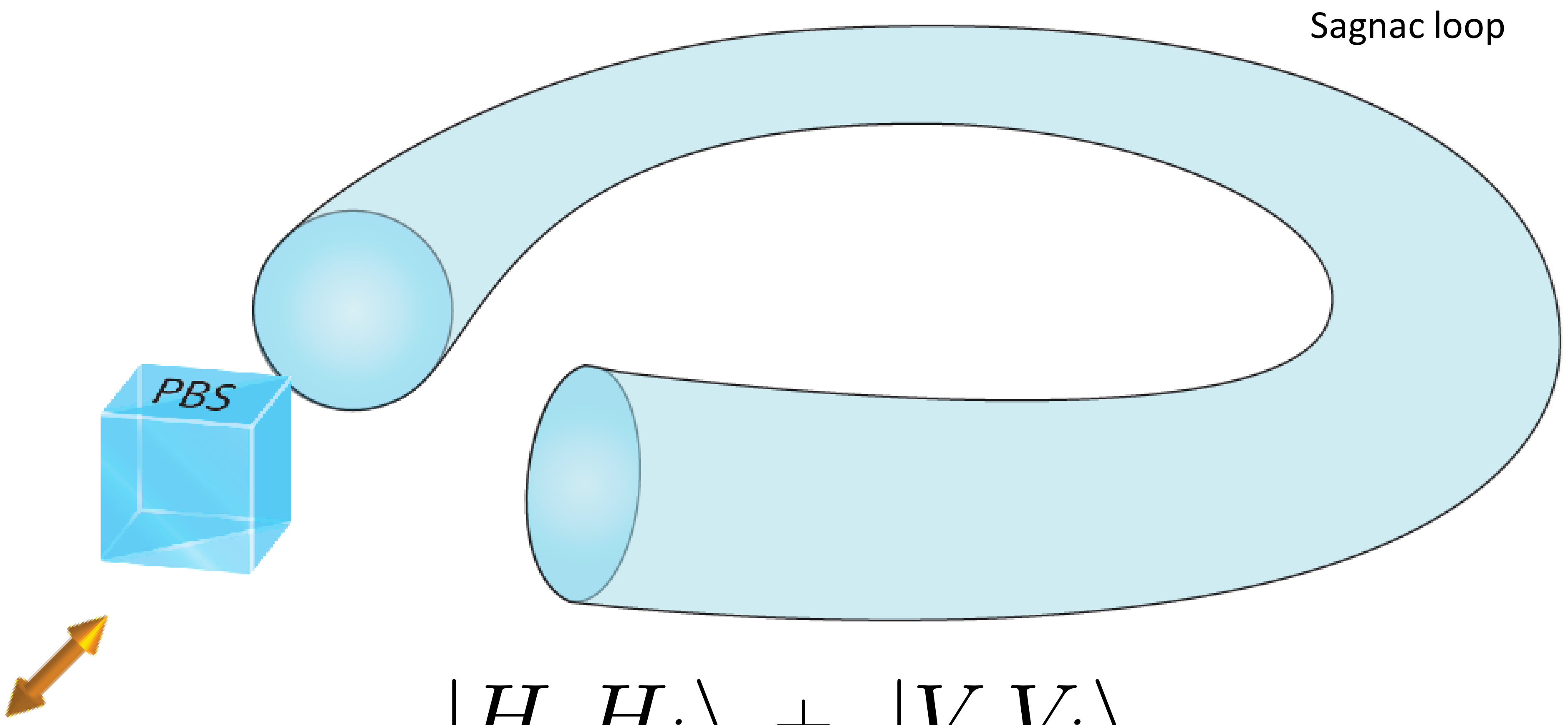
Generation of polarization entanglement



$$|V_s V_i\rangle$$

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

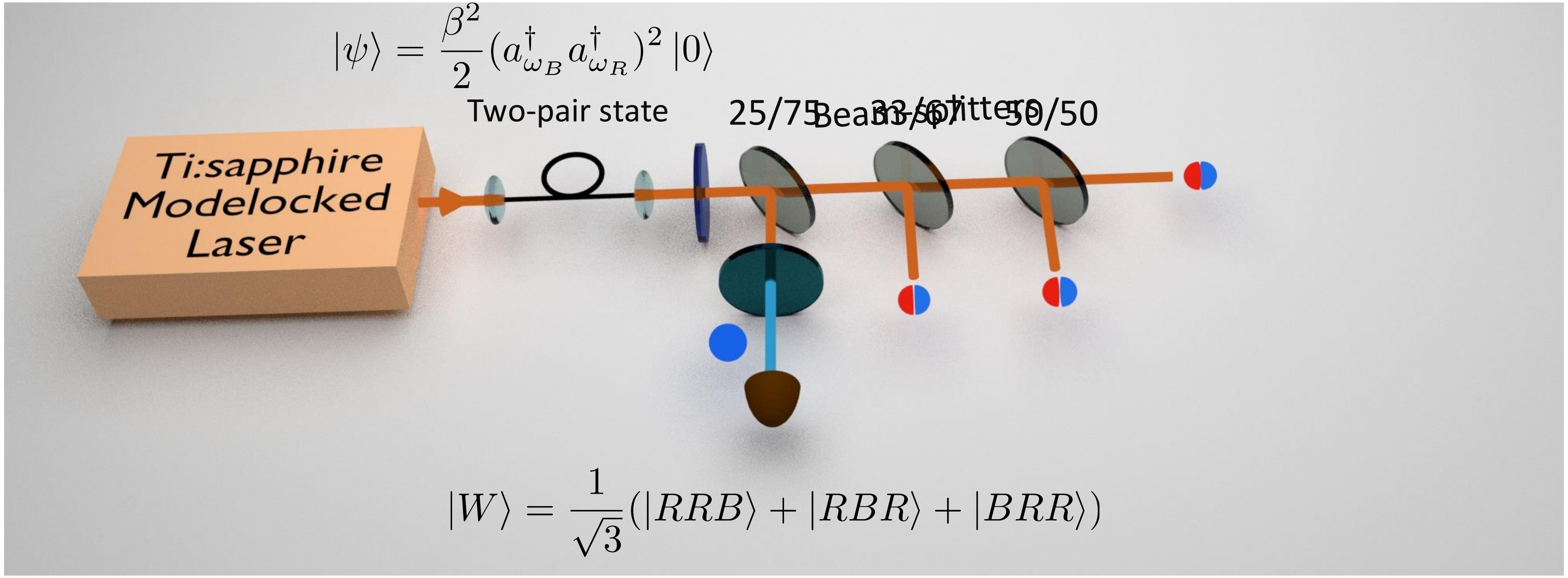


$$|H_s H_i\rangle + |V_s V_i\rangle$$

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: 1 0 1
  - 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:

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

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

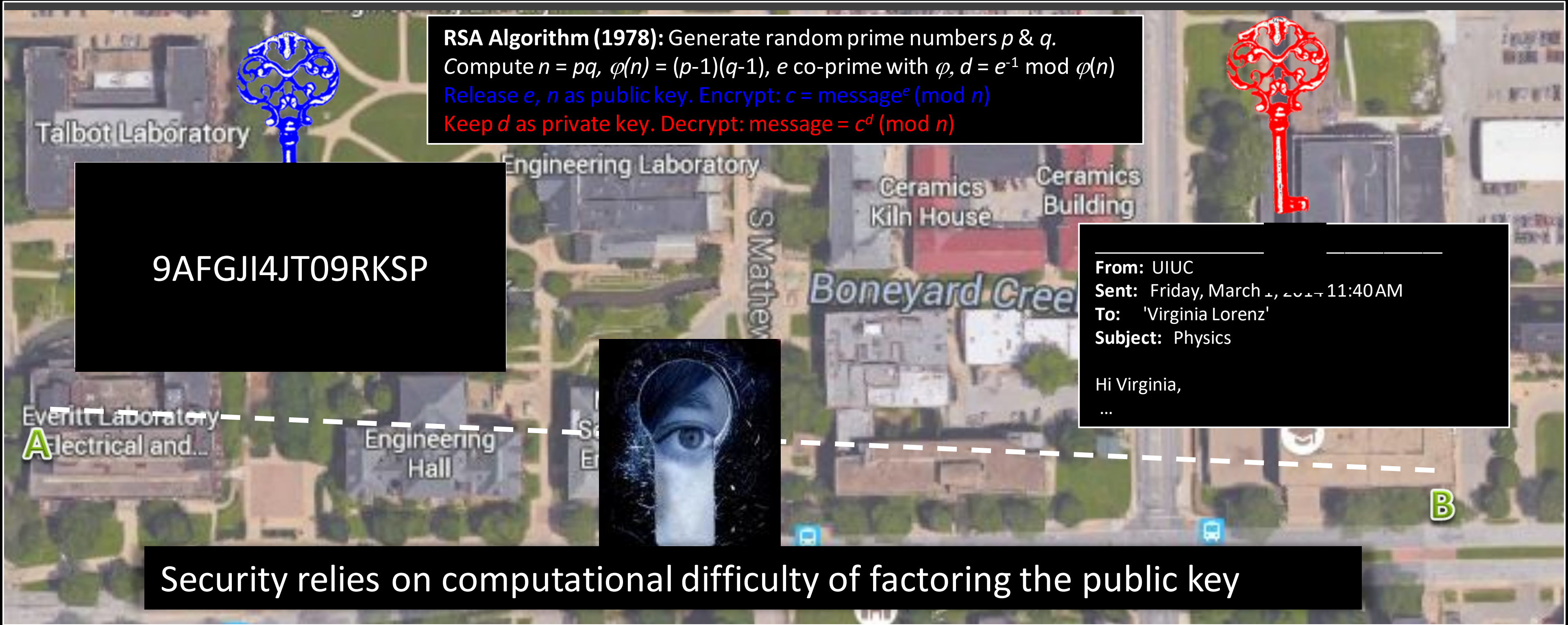
$$|1\rangle_c|0\rangle_t \rightarrow |1\rangle_c|1\rangle_t$$

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

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

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: $\text{message} = c^d \pmod{n}$

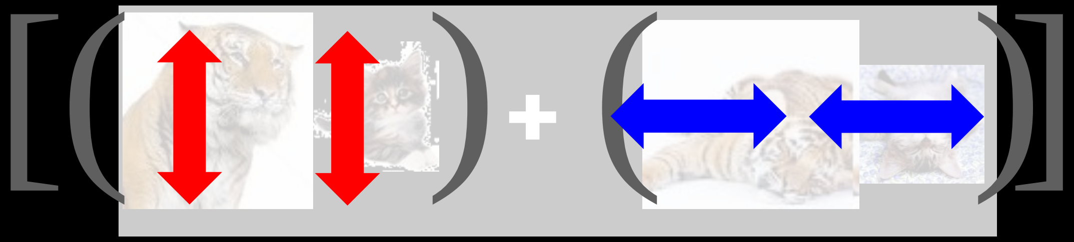
9AFGJI4JT09RKSP

From: UIUC
Sent: Friday, March [redacted] 11:40 AM
To: 'Virginia Lorenz'
Subject: Physics

Hi Virginia,
…

Security relies on computational difficulty of factoring the public key

Quantum Key Distribution



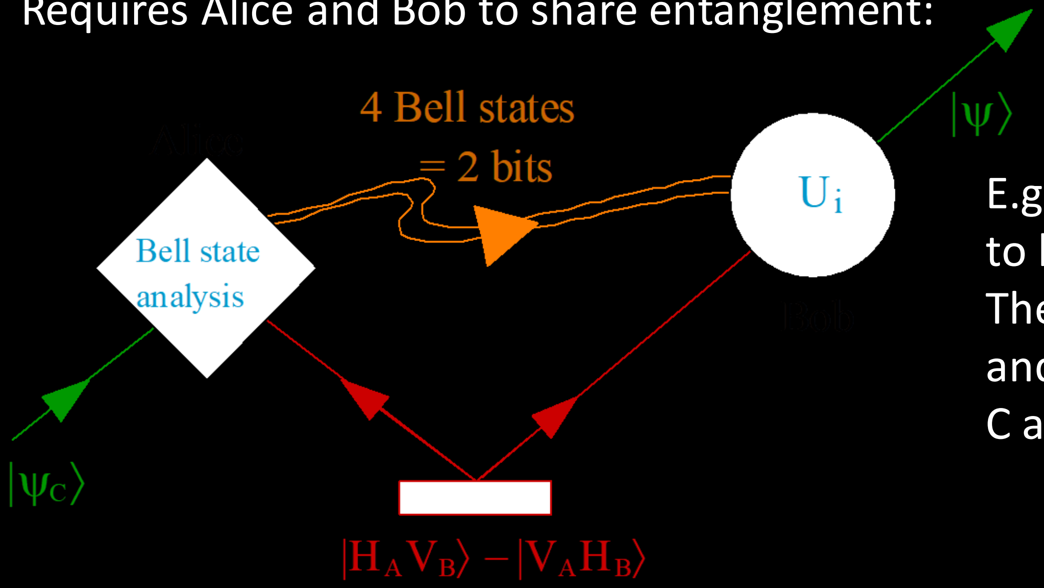
Security is guaranteed by the laws of quantum physics

- Eavesdropping without being detected is impossible because measurement changes the correlations

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!

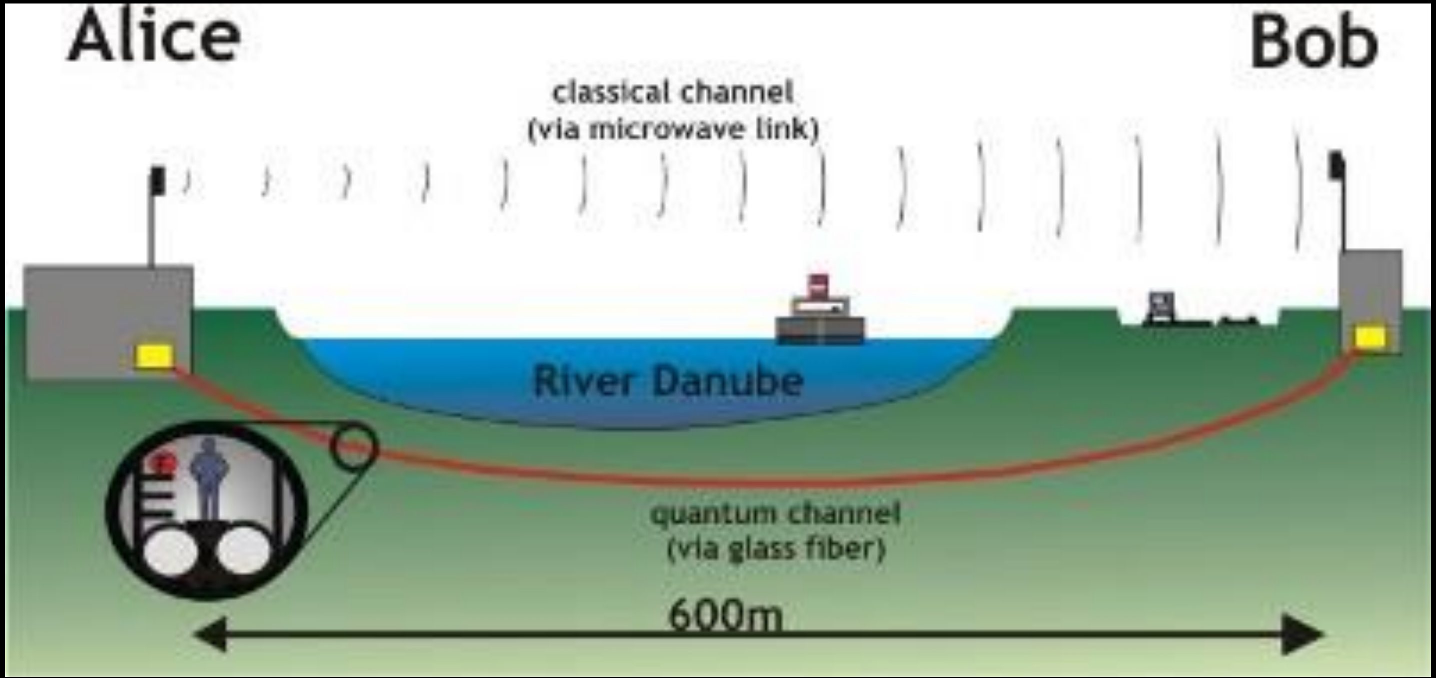
Remarks:

- 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

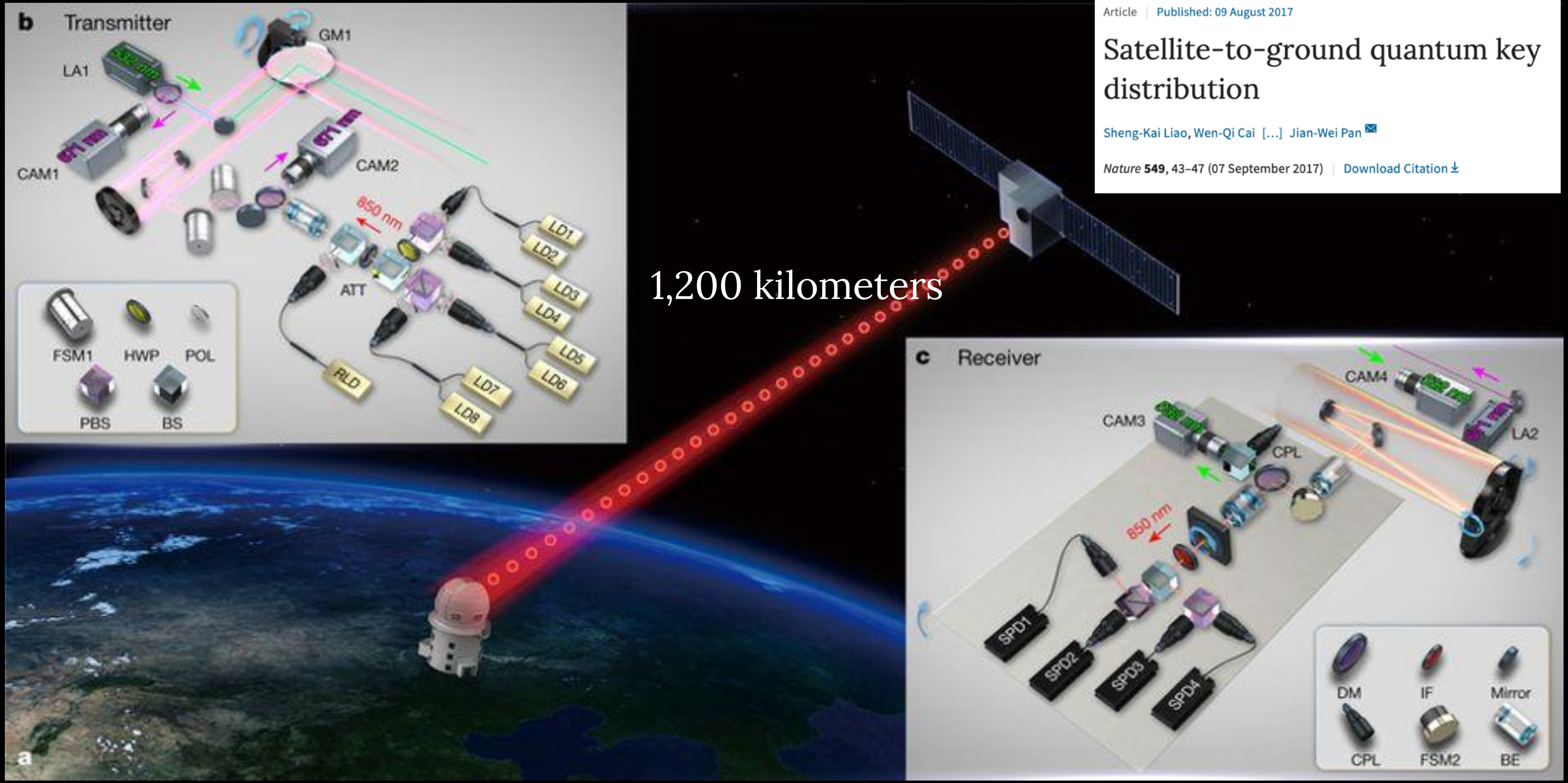
nature
International journal of science

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



DIGITAL SINGLE MARKET

Digital Economy & Society

Research & innovation

Innovation

Emerging Technologies

Brain Research

Future & Emerging Technologies

FET Open

FET Proactive

FET Flagships

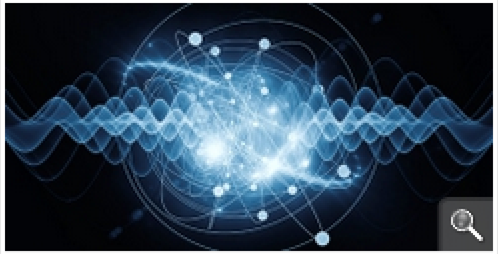
Projects Portfolio

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.

Share

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.

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

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

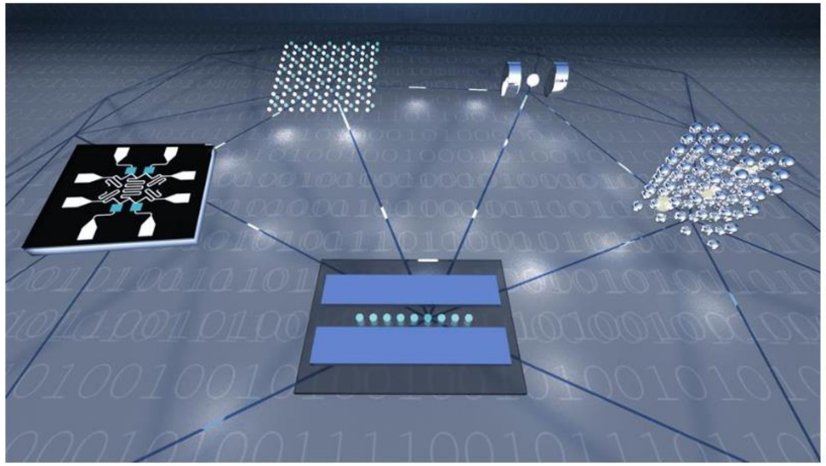


Image by Emily Edwards, IQUIST

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.

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

Quantum in the United States

- 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.

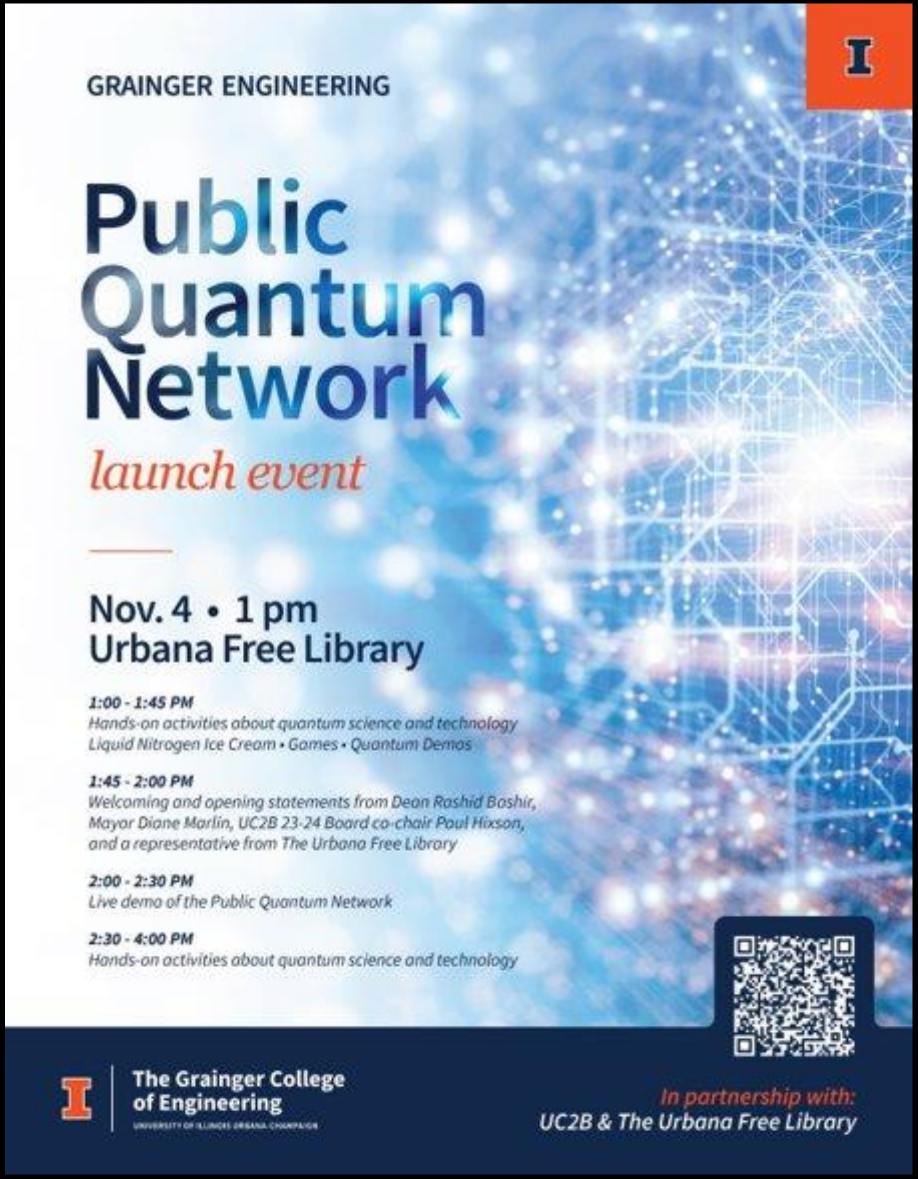
- Illinois positioned itself well and has become a global leader in quantum technology.
  - University research teams span the range of quantum technologies
  - Captured 4/10 National Quantum Centers for research (=$280M)
  - Chicago Quantum Exchange nucleated academic and industry partnerships
  - Quantum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


1234567
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BlackBerry
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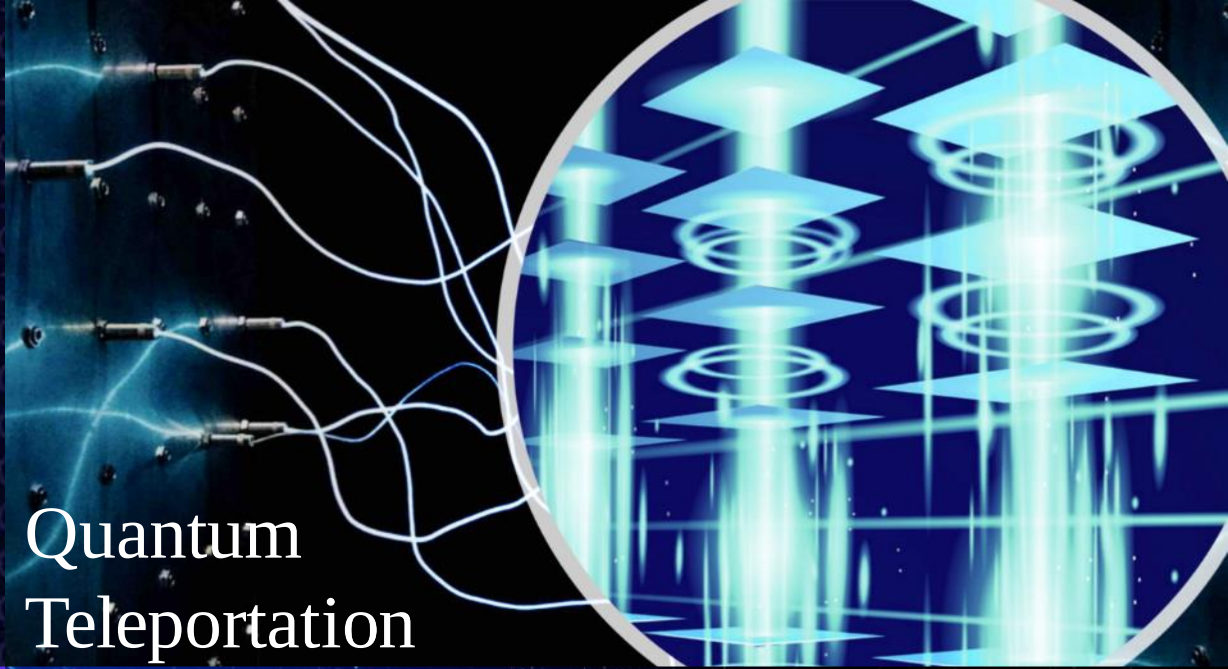
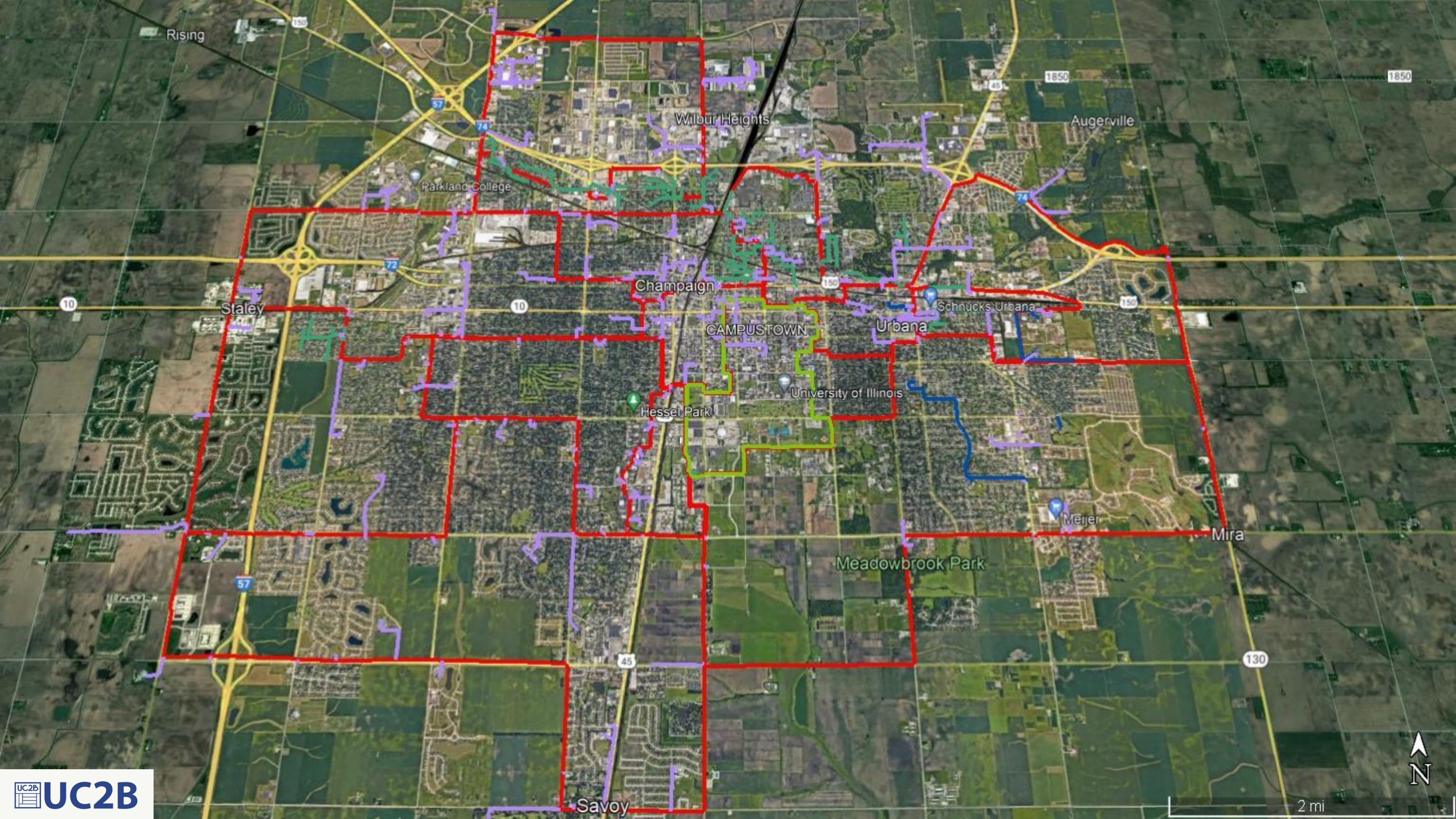
Quantum Secure
Communication


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
Staley
Champaign
CAMPUSTOWN
Urbana
Schnucks Urbana
University of Illinois
Hessel Park
Meijer
Mira
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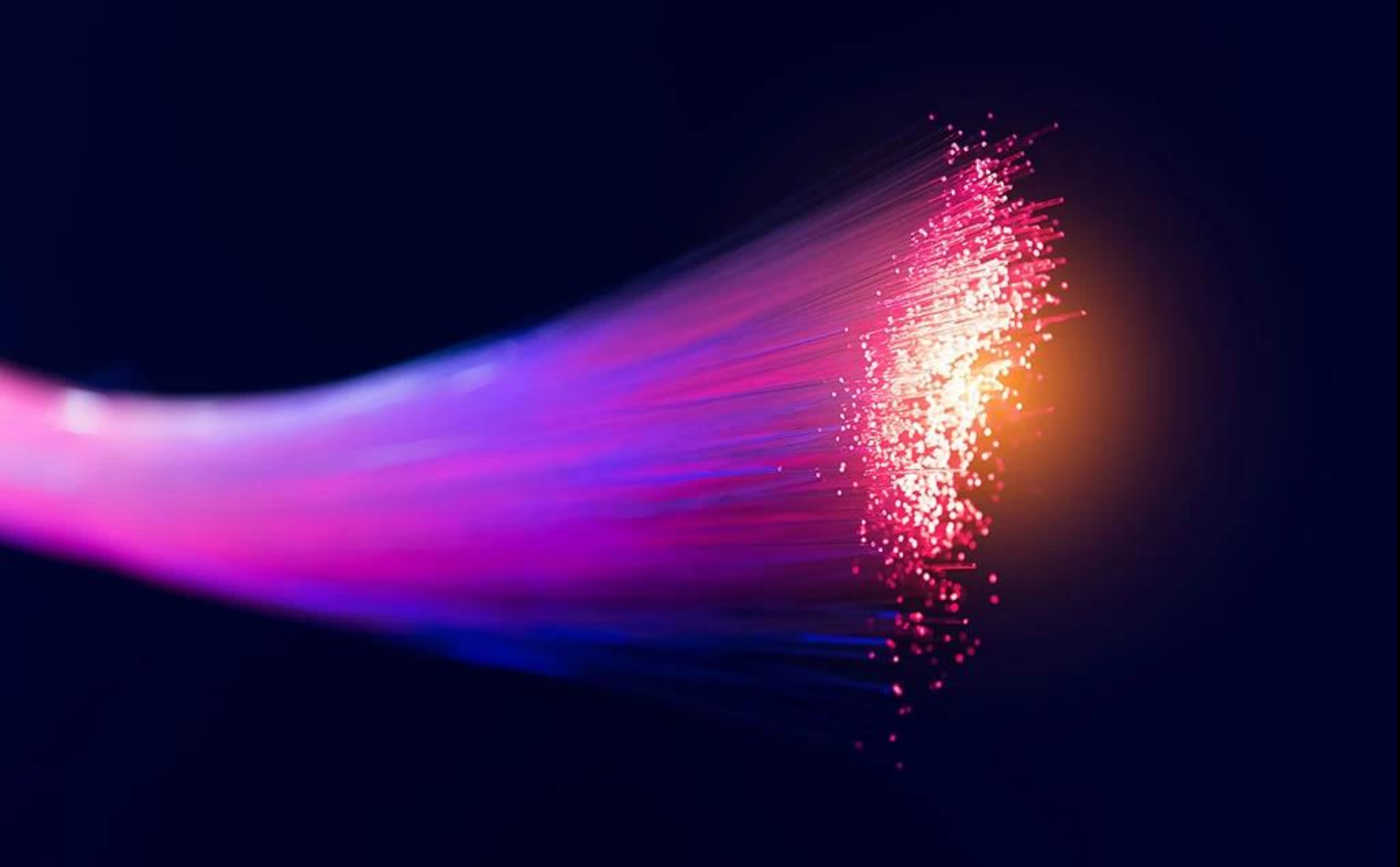


Green St


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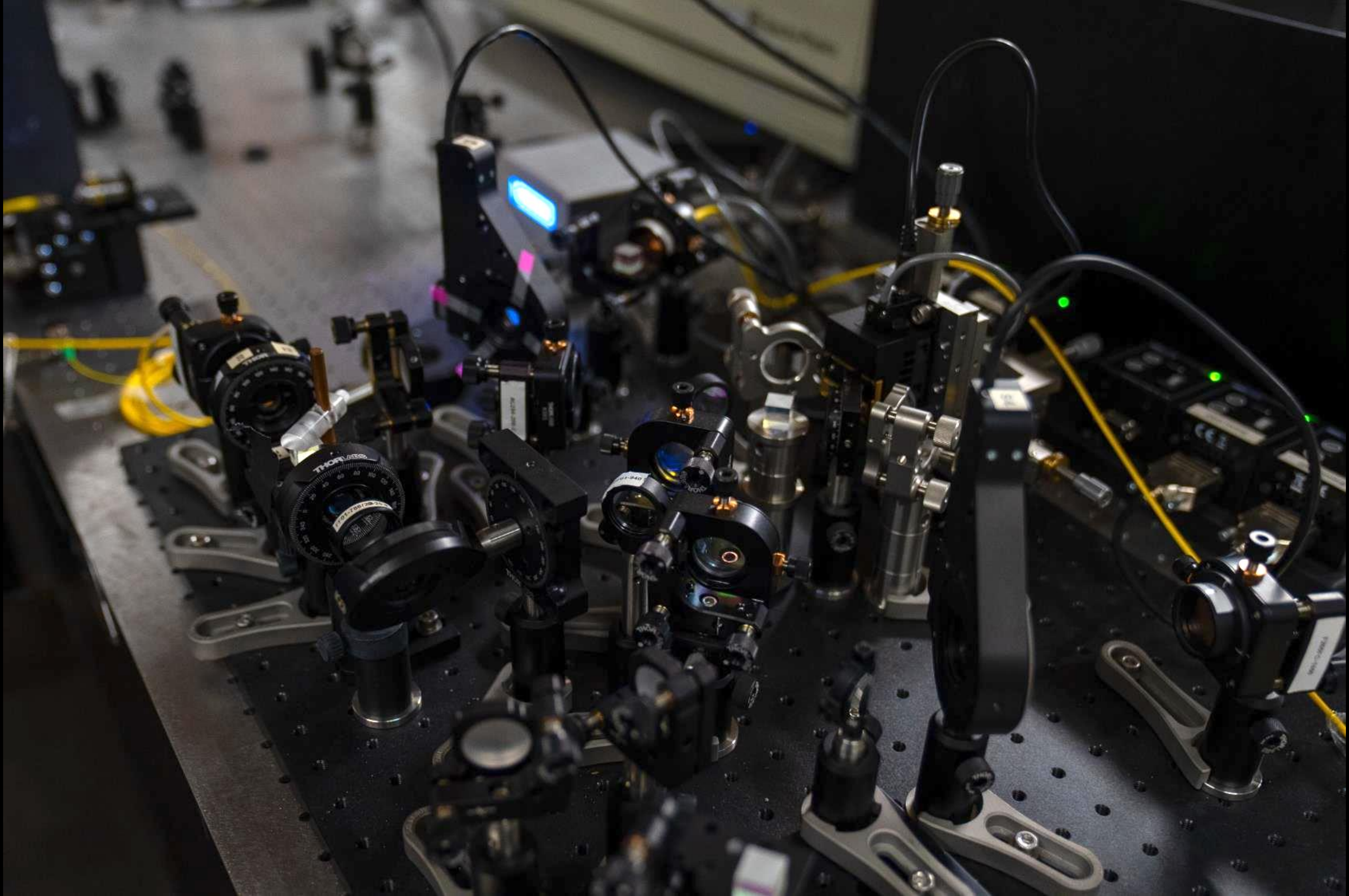
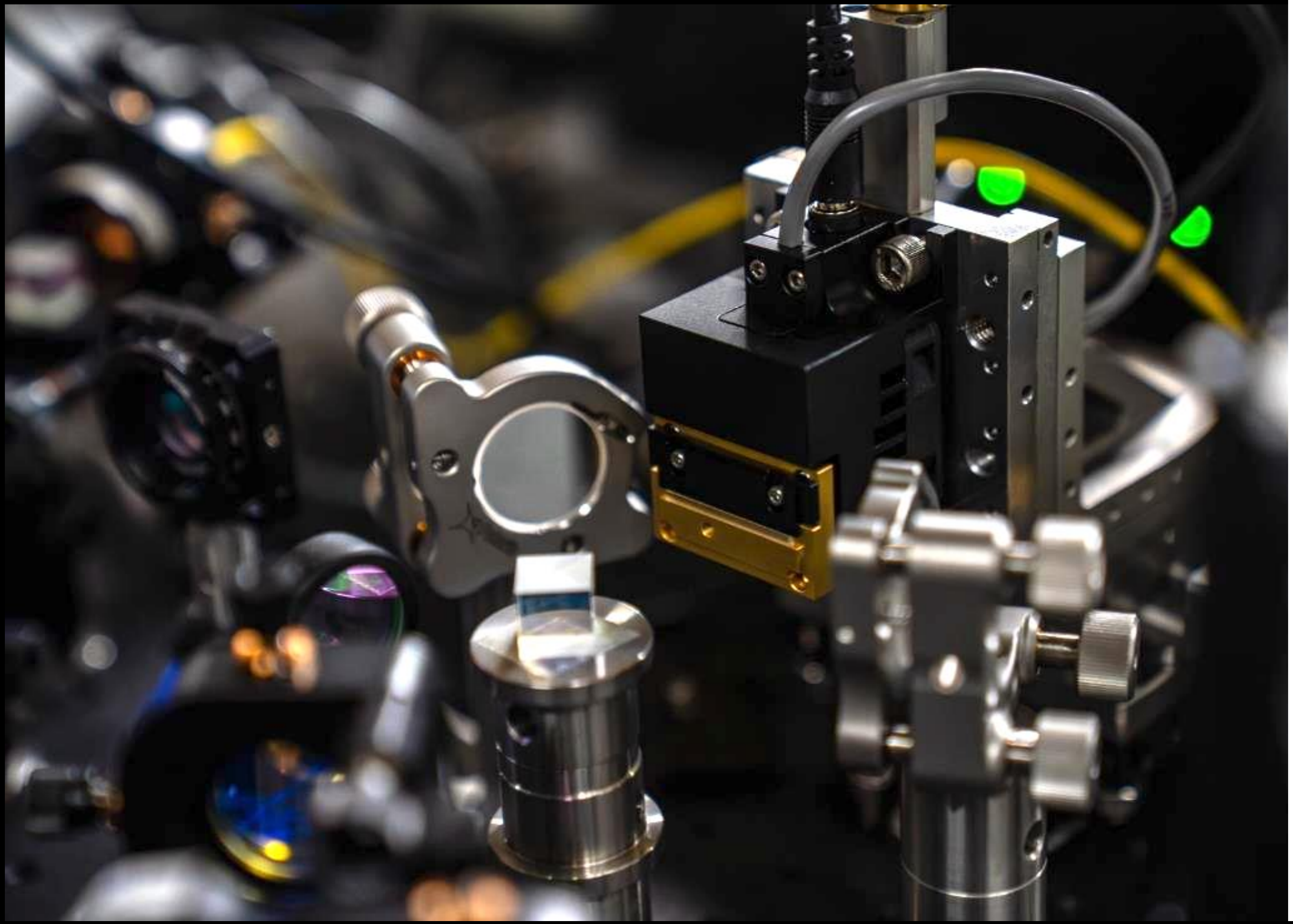
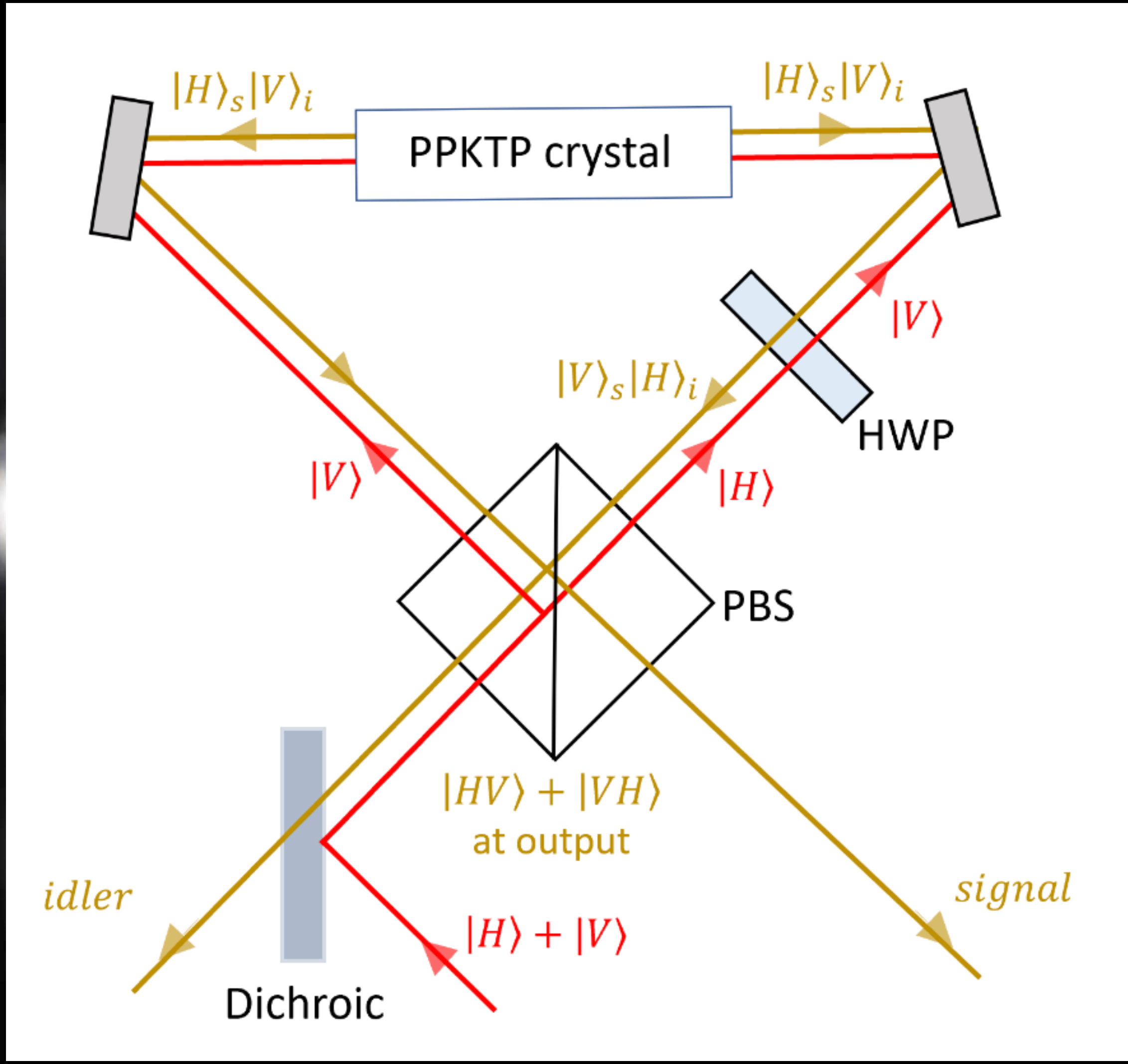
Loomis Laboratory Of Physics, University...
The Urbana Free Library


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.


THORLABS





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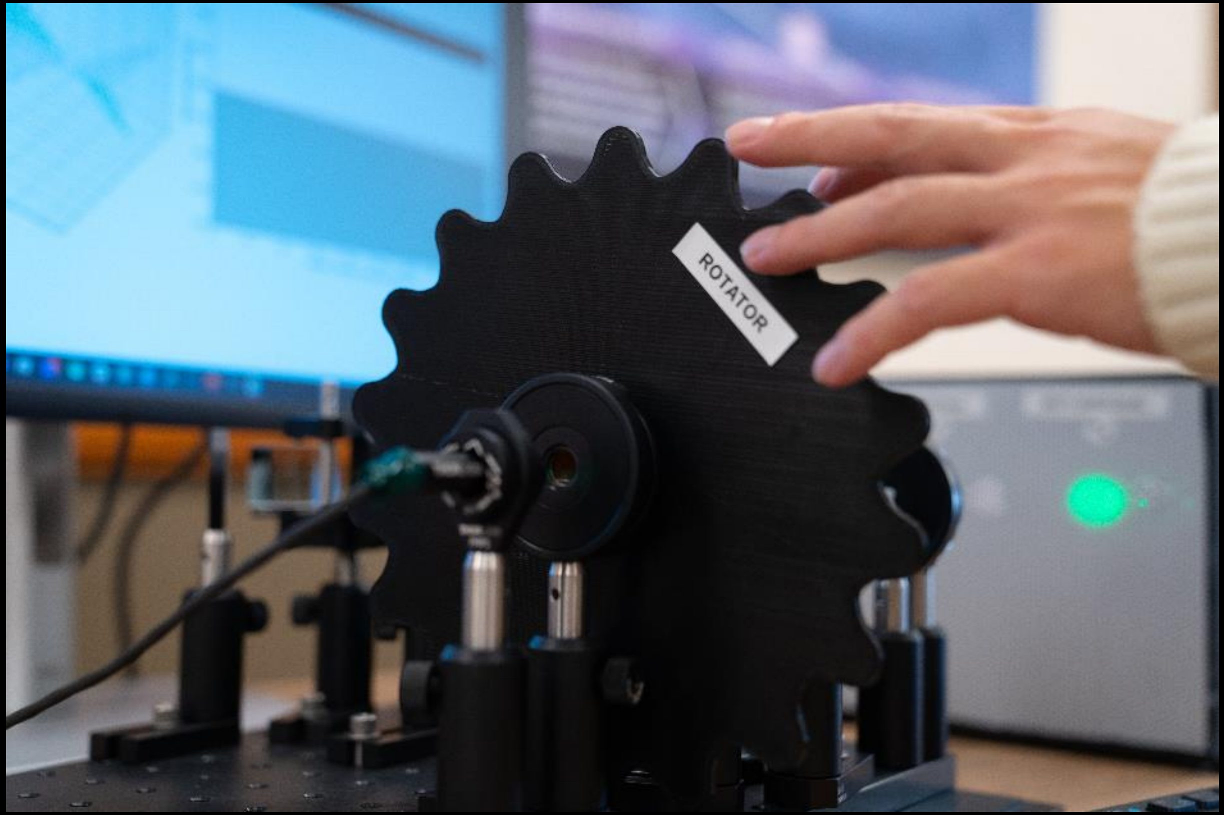
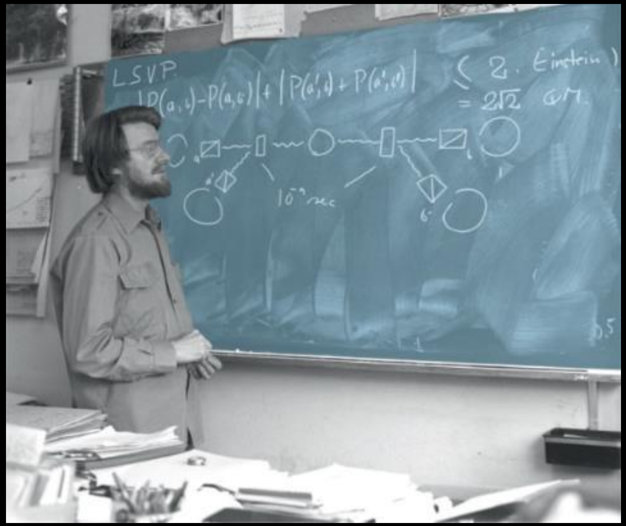

ROTATOR



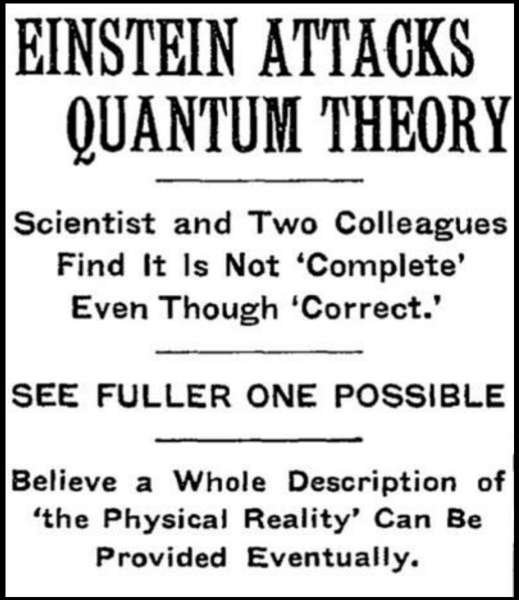
1930's

1960's

1970's to present

2022

2023

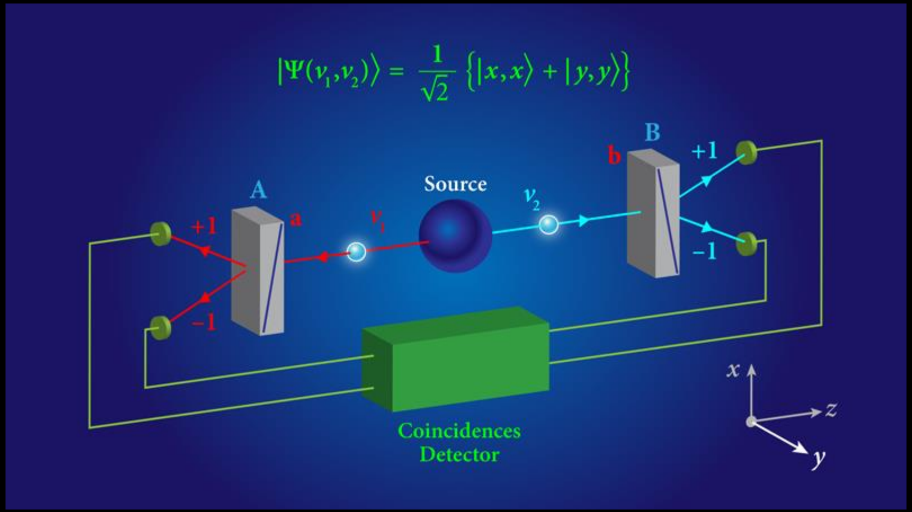


EINSTEIN ATTACKS QUANTUM THEORY

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

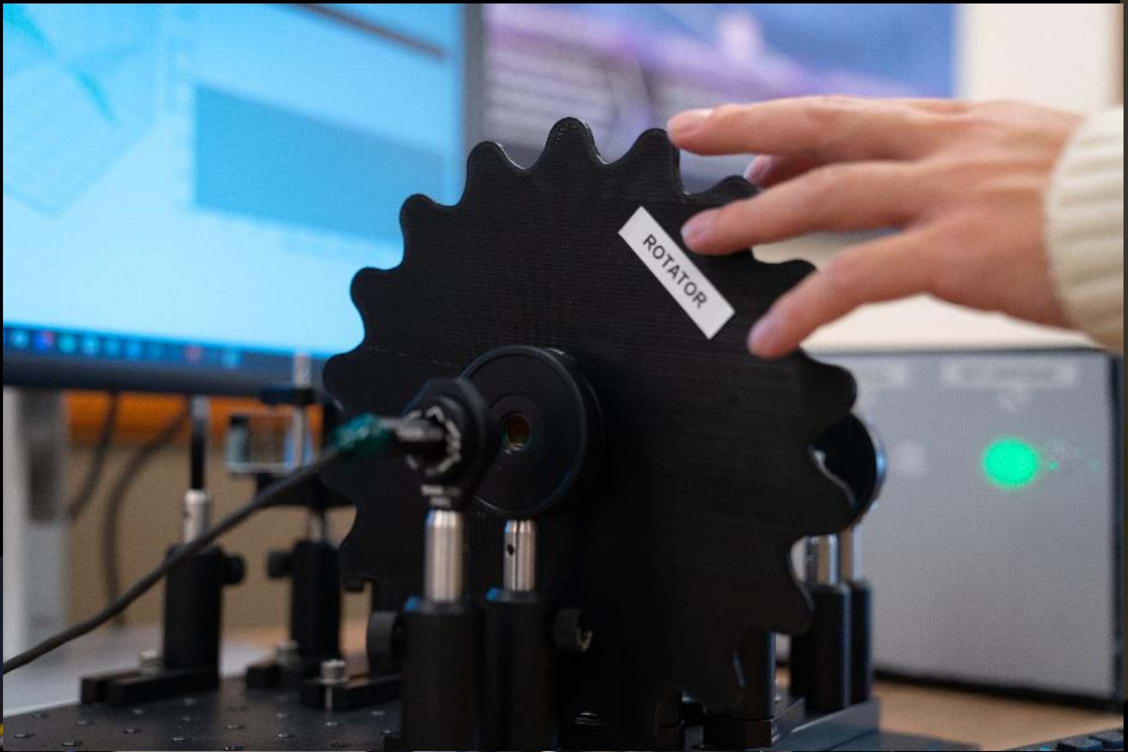
SEE FULLER ONE POSSIBLE

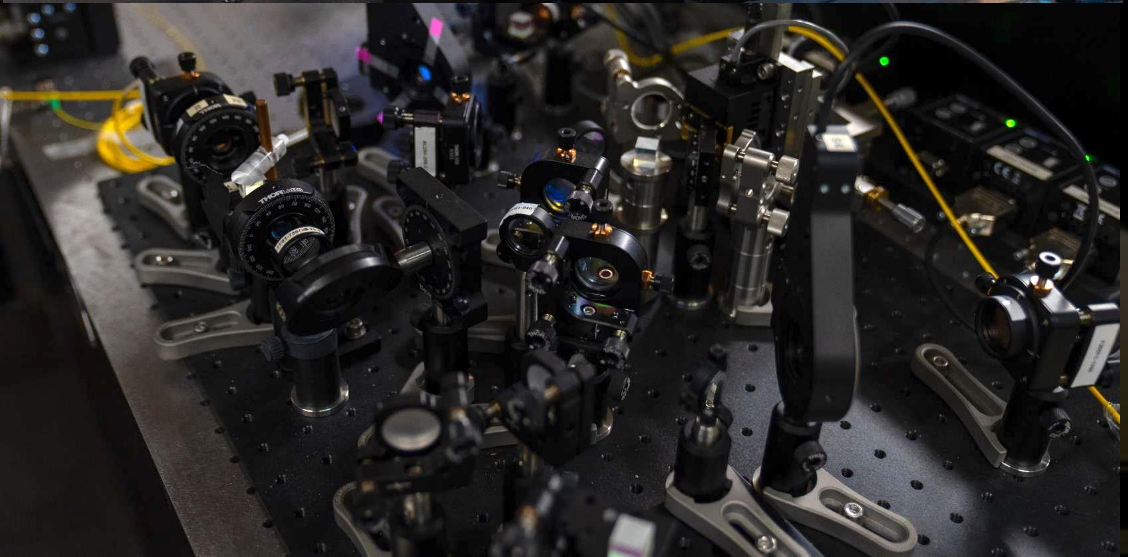
Believe a Whole Description of 'the Physical Reality' Can Be Provided Eventually.

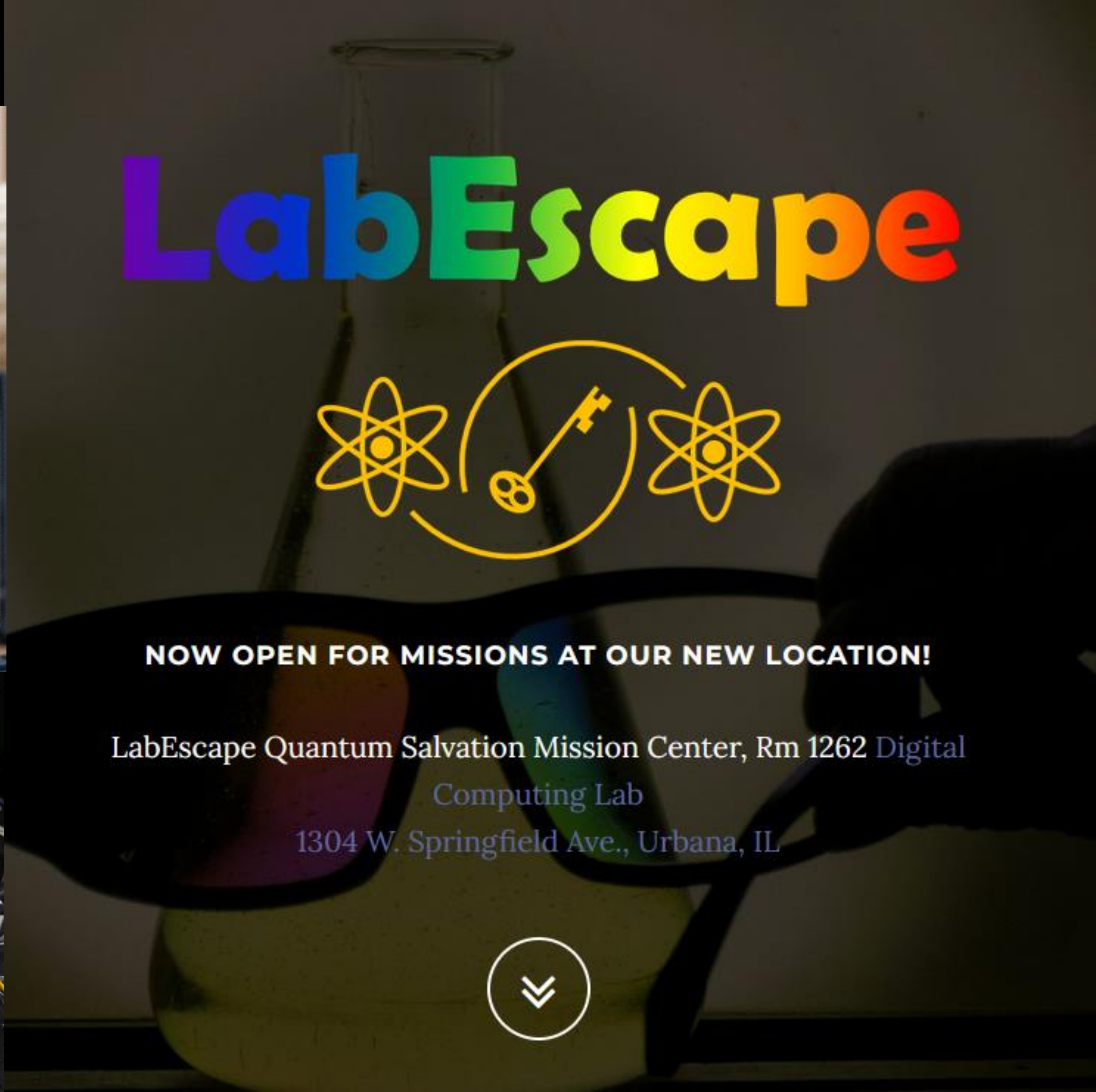


PUBLIC QUANTUM NETWORK

Join us for a Quantum Adventure!







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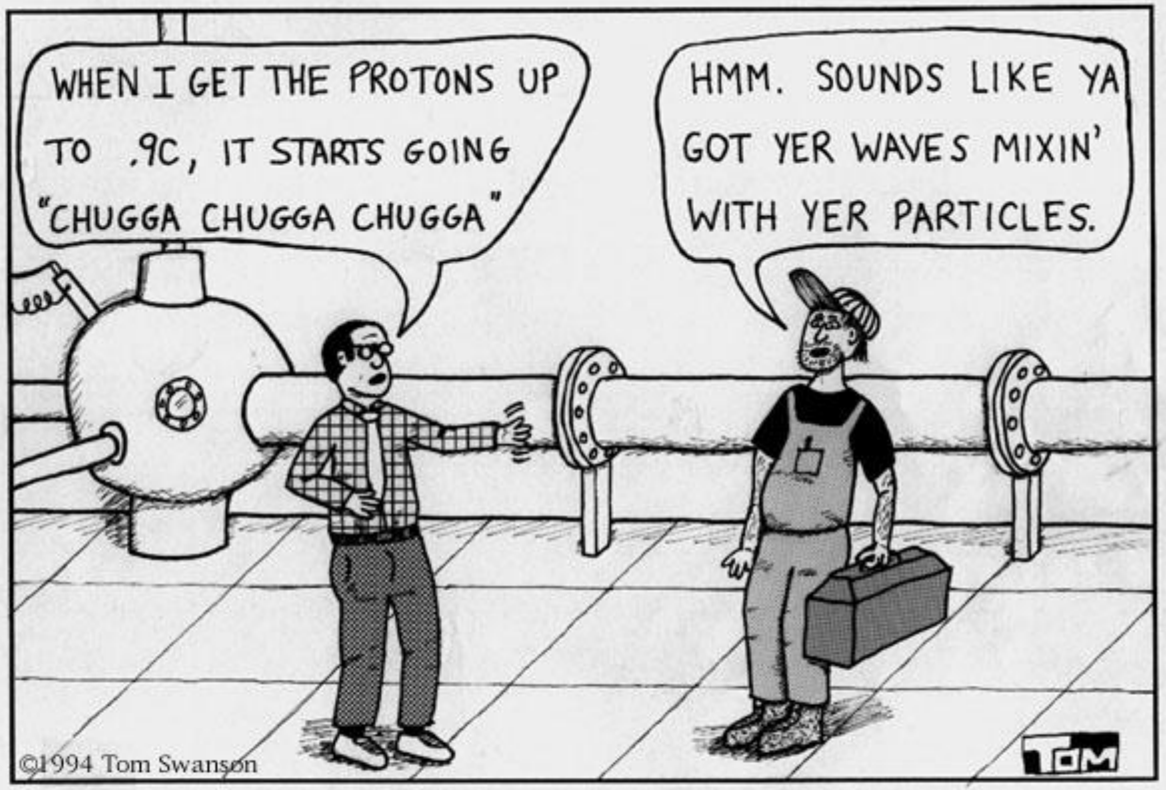
Conclusion

- 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!



QUANTUM MECHANIC