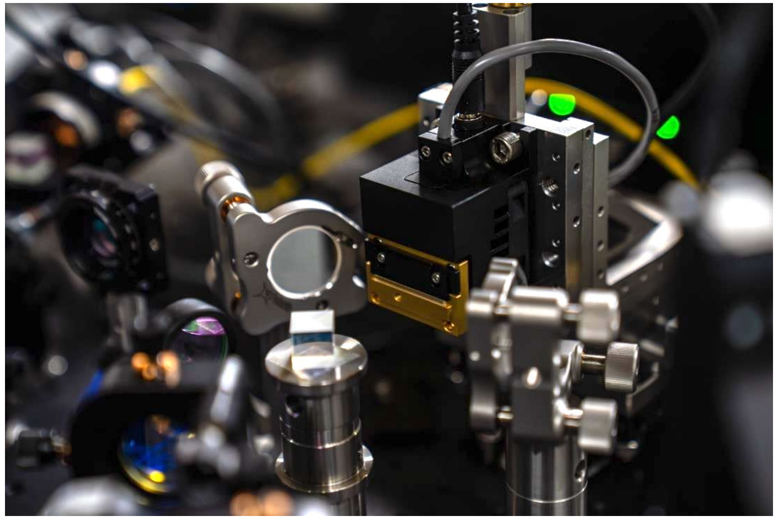
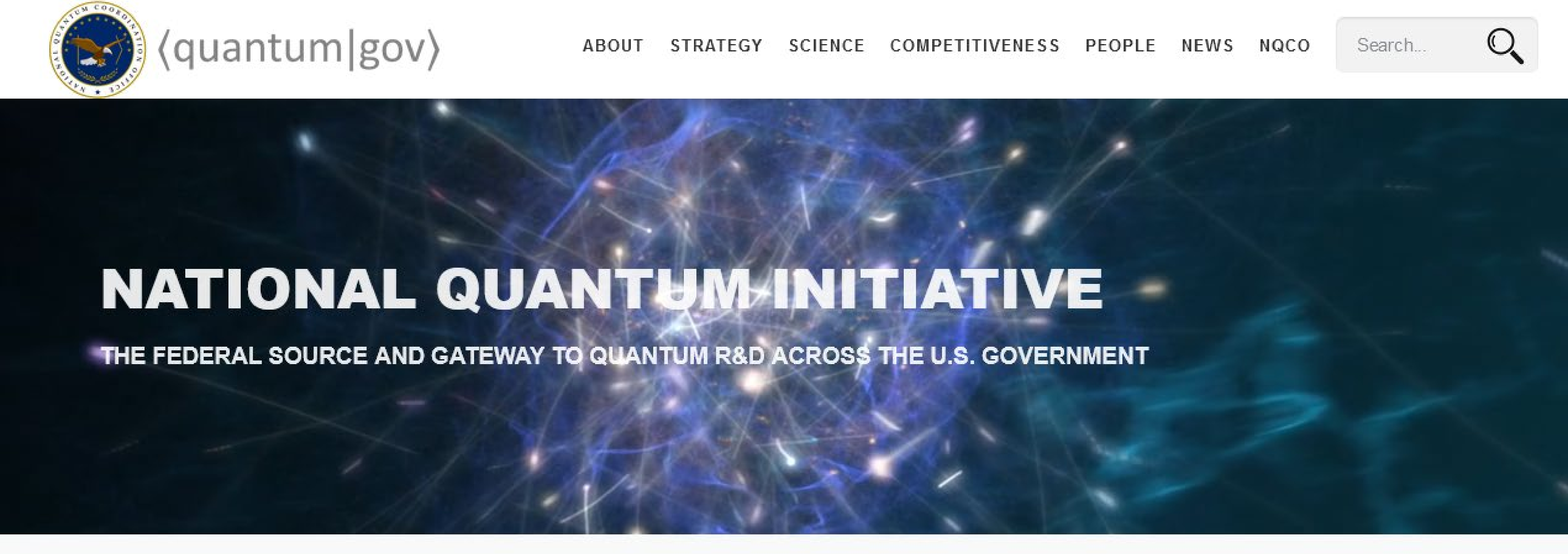
QUANTUM TECH IS IN YOUR PUBLIC LIBRARY



Gina Lorenz
University of Illinois Urbana-Champaign
PHYS403, 11/5/24

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

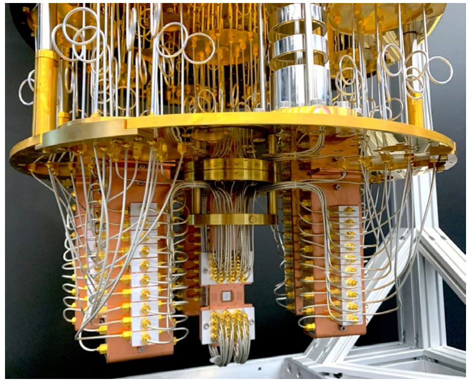


- The National Quantum Initiative Act was signed into law on December 21, 2018. The law gives the United States a plan for advancing quantum technology.

- This act has spurred a tsunami of funding for quantum research and industry, much of it centered around “Quantum 2.0” technology.

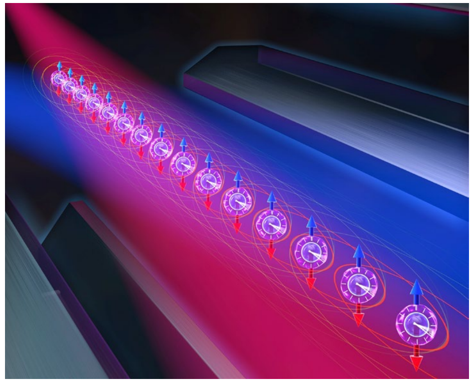
WHAT IS QUANTUM 2.0?

Quantum 1.0: semiconductor junctions, transistors, lasers, etc.
Quantum 2.0 tech uses phenomena like **superposition** and **entanglement** for



Quantum Computers

- break encryption
- perform calculations impossible for regular computers
- simulate quantum systems for e.g. drug discovery



Quantum Sensors

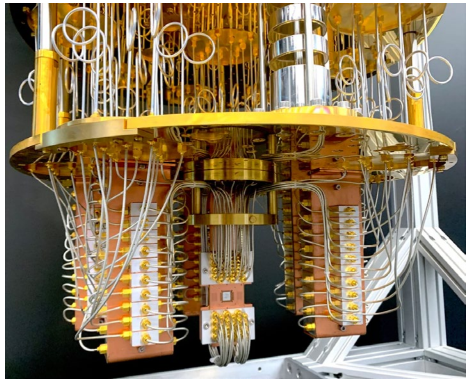
- synchronize clocks better → better GPS
- improve sensitivity of probes in medicine, transportation, and fundamental science

Quantum Networks

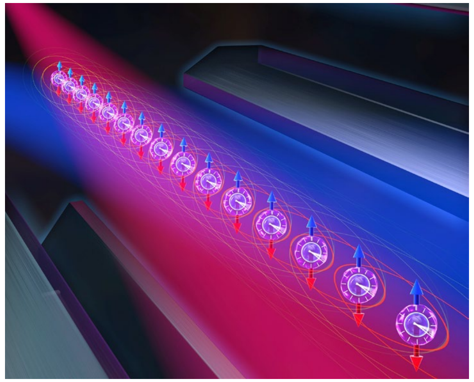
- connect quantum computers in a “quantum internet”
- communicate securely
- improve astronomical observation


1234567
NOKIA
NOKIA
BlackBerry
space
T · ·Mobile·

HANDS-ON QUANTUM 2.0



quantum cloud computing:
over a dozen companies



entanglement-based sensors
still in the lab

quantum networks: a few in the
world, but not publicly accessible

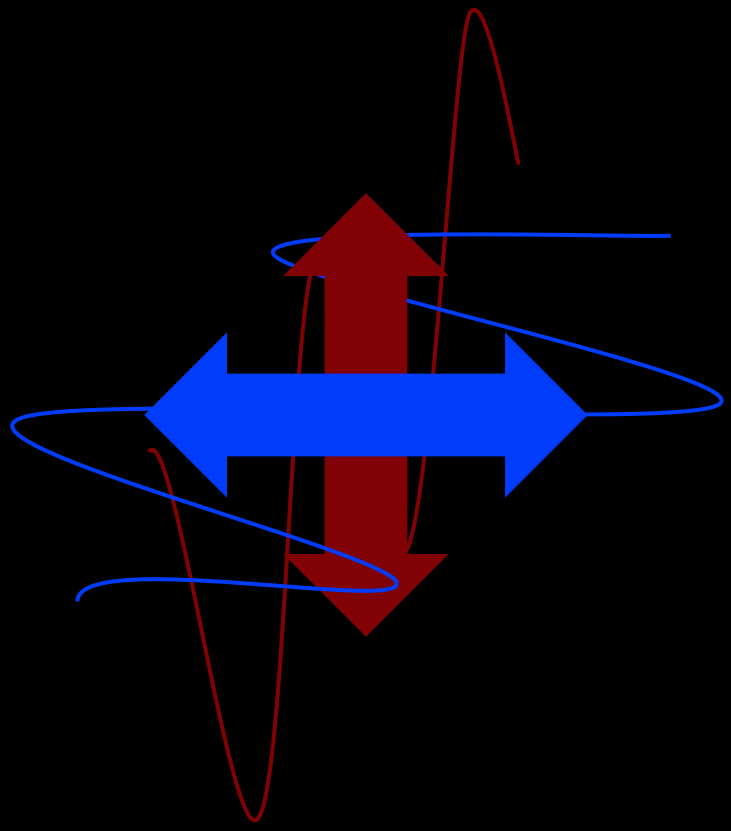
In the history of quantum entanglement, **quantum light** was and remains one of the most “accessible” hands-on quantum 2.0 technologies.

To see why this is, let’s dive right in…

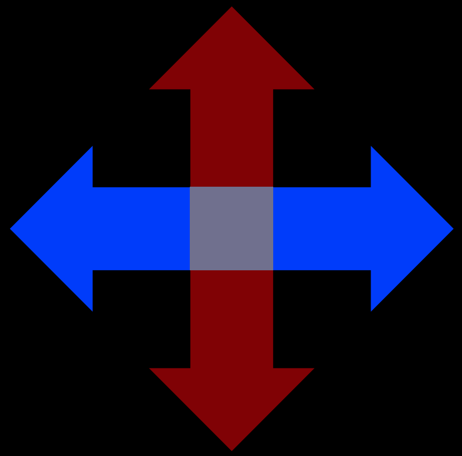
Quantum

The smallest quantity of light is a photon.
Quantum science describes how photons and other quantum particles behave.

Superposition



Superposition

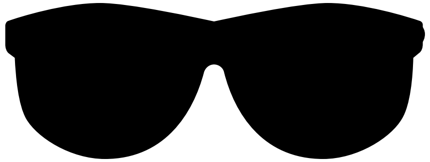


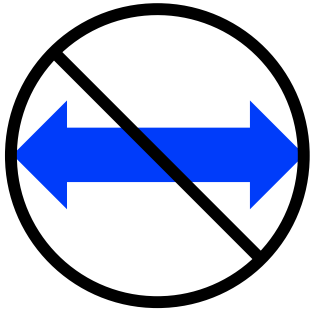
Measurement

Polarizers only let through photons that wave a certain direction.

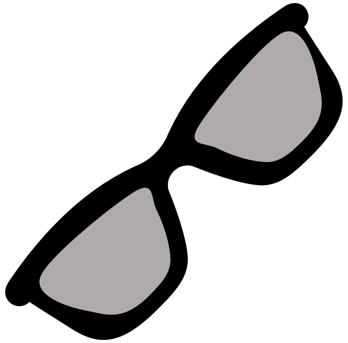
Polarizing sunglasses

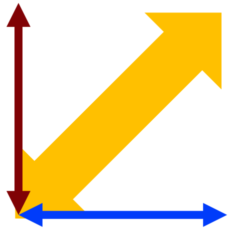
Imagine looking at a horizontally polarized screen.
At first the glasses block all the photons.
The polarizers block photons waving horizontally.



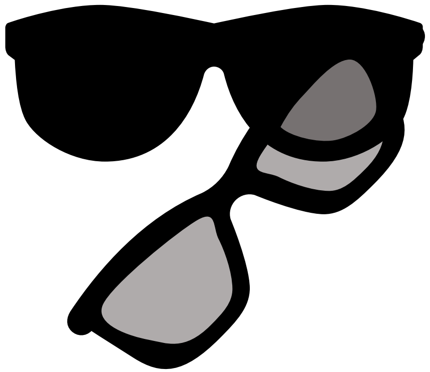


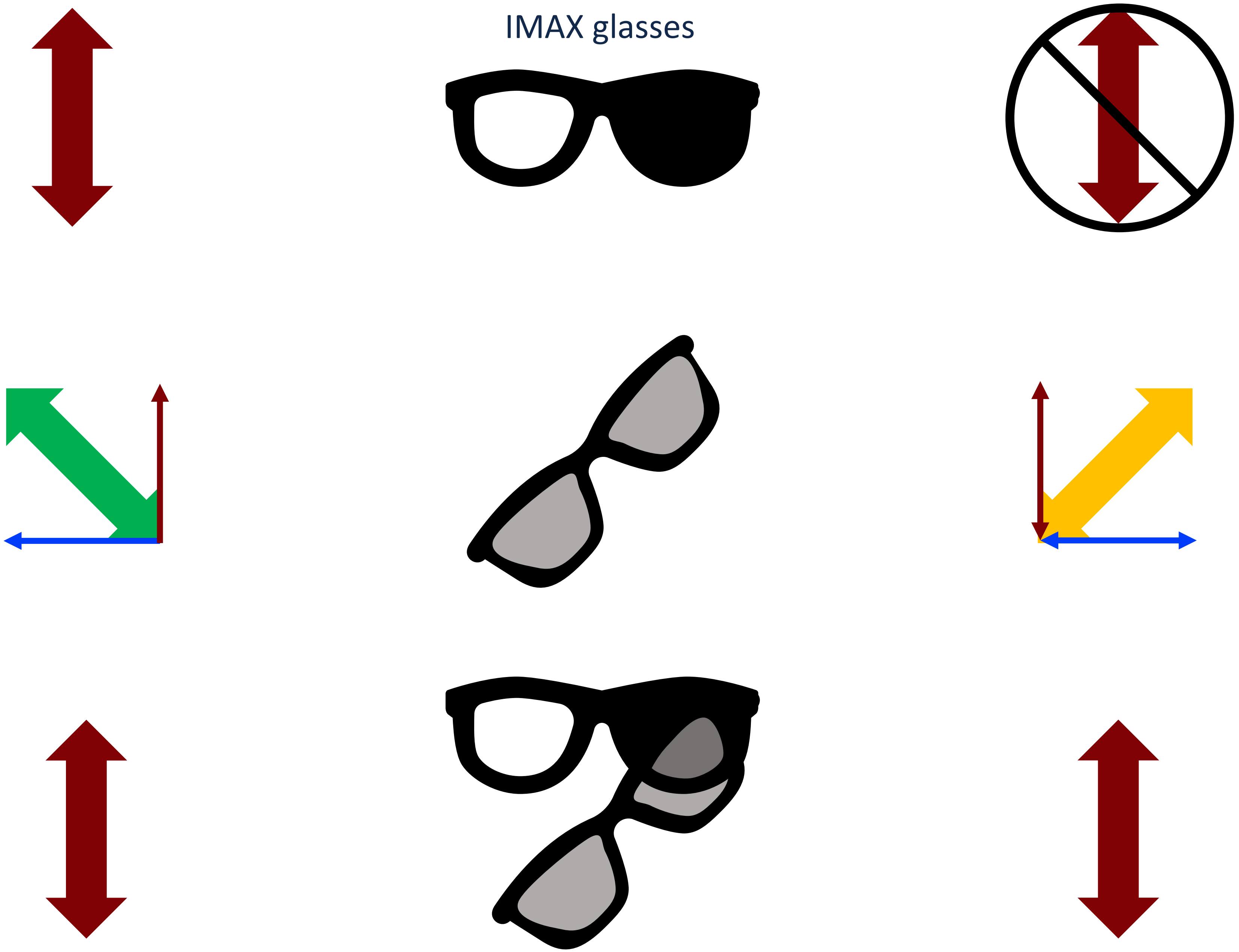
If you tilt your head, some get through.
The photons that get through are in a superposition of waving vertically and horizontally.





When you put the two together, now some horizontally polarized photons get through. That's because the photons' polarizations *changed* into a superposition after the diagonal polarizer.

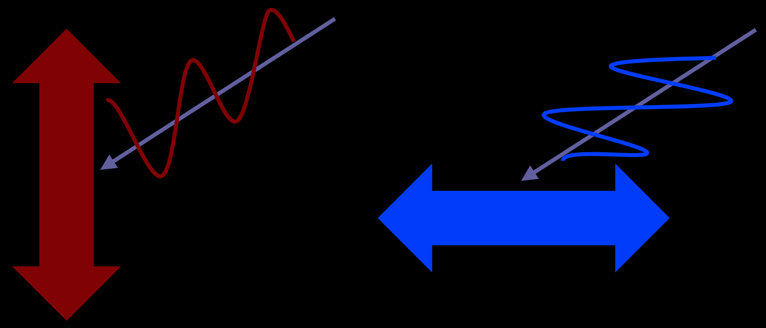




Note: some IMAX glasses use circular polarization and this won't work

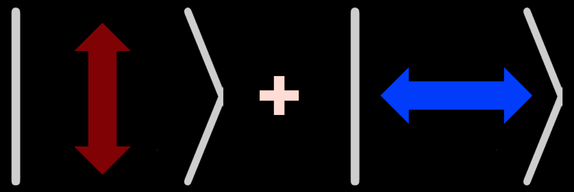
Superposition

Photons can be polarized



Photons can be in a superposition of two **p**ossibilities

possibility



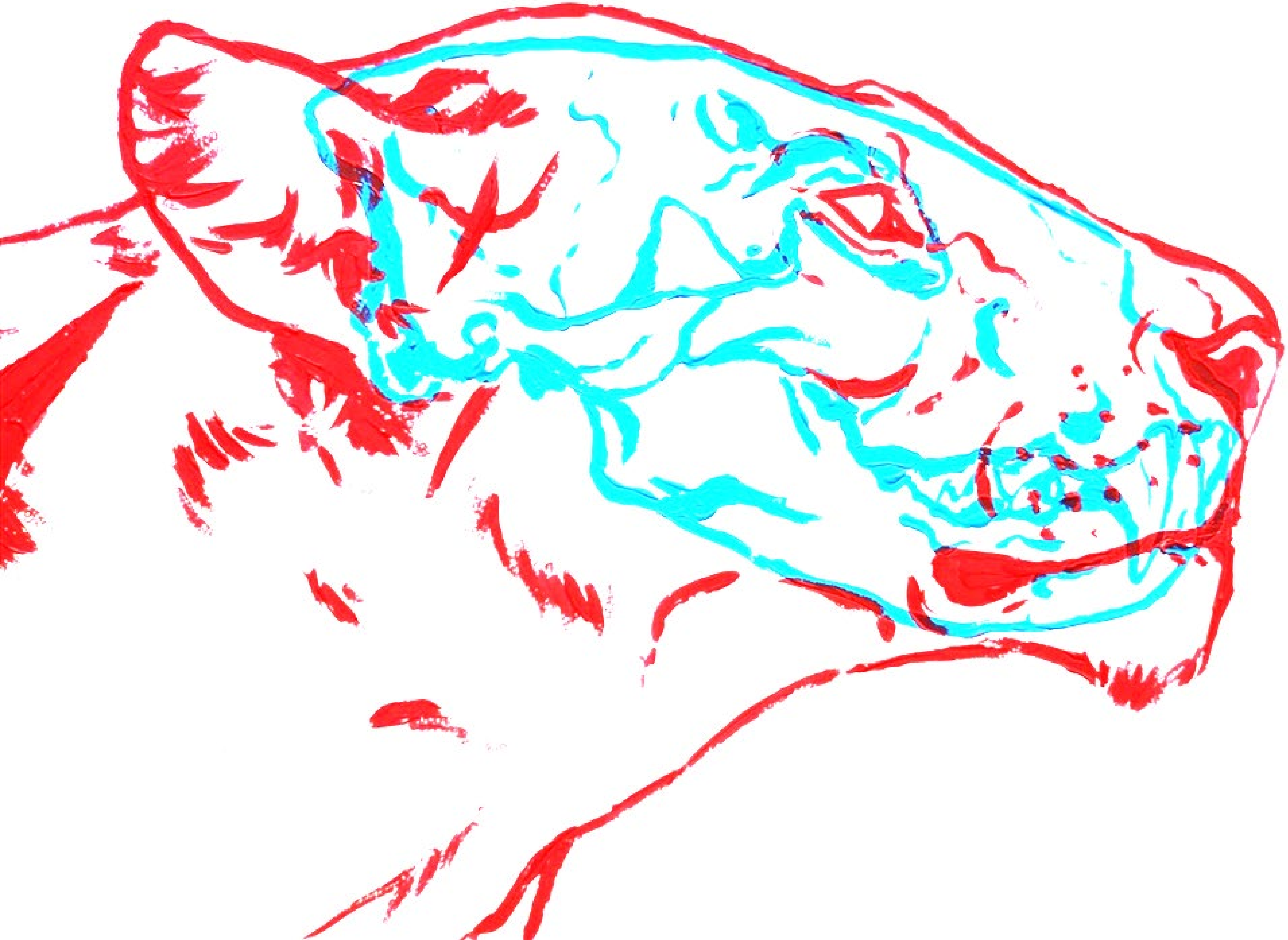
We write a superposition using symbols called “kets” (last part of “bracket”)

Quantum science challenges commonly held beliefs

Belief: “Objects have definite states before measurement.”

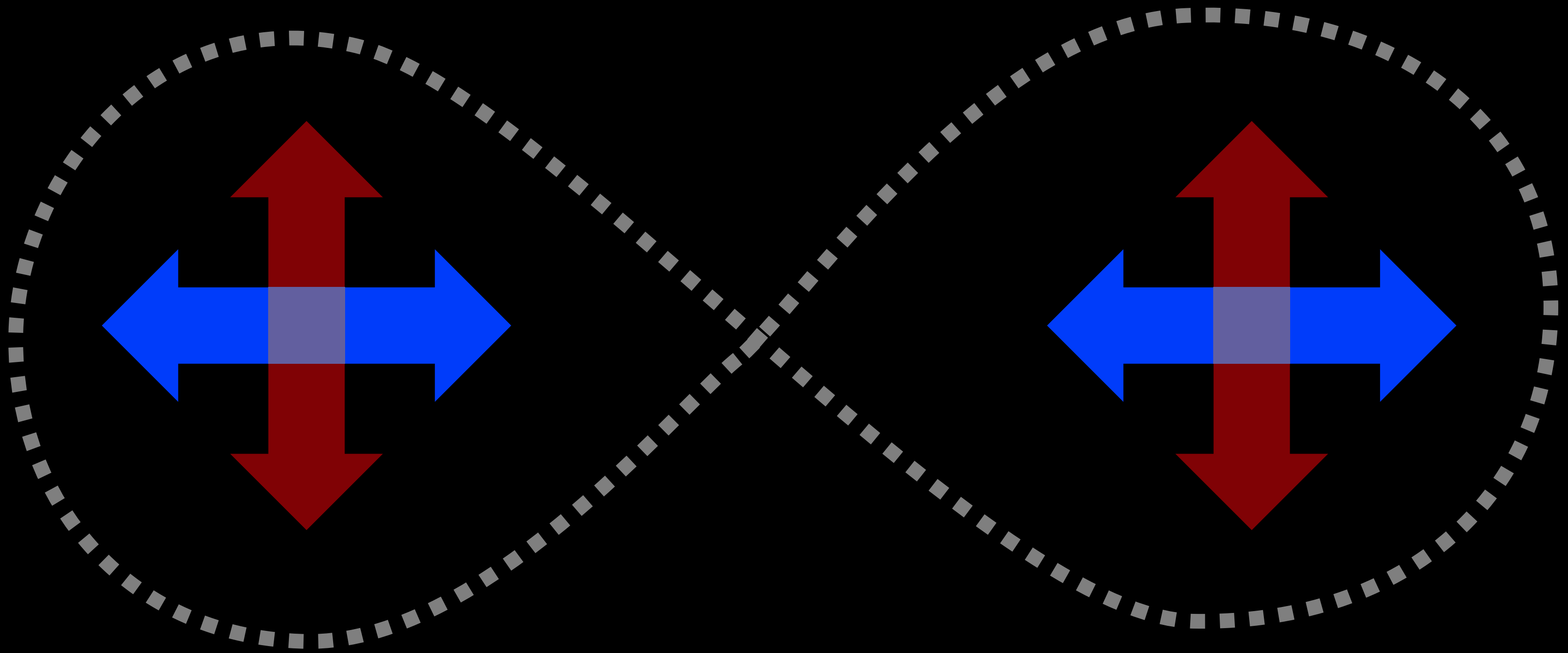
Superposition implies quantum particles may not.

Then is there an objective **reality** before measurement?

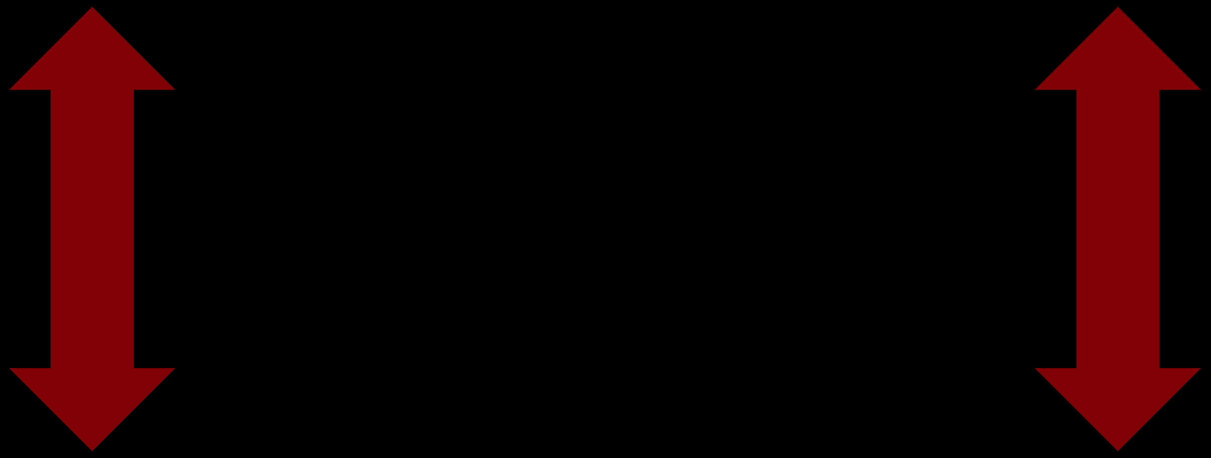


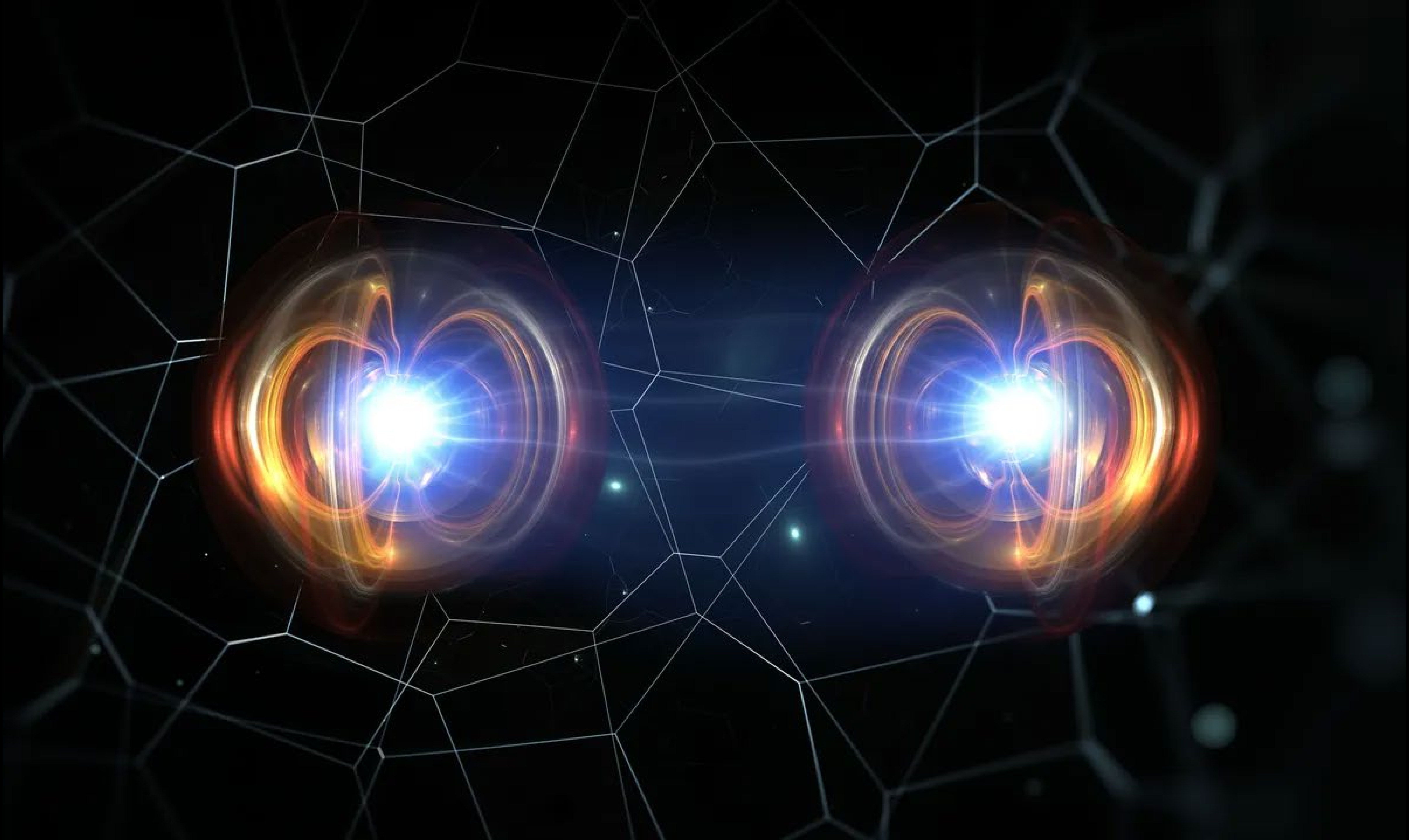
Entanglement

Entanglement



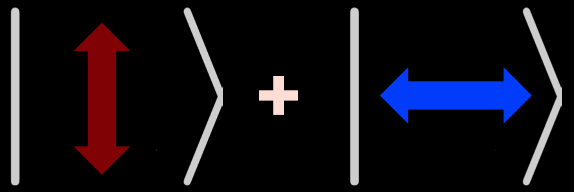
Measurement



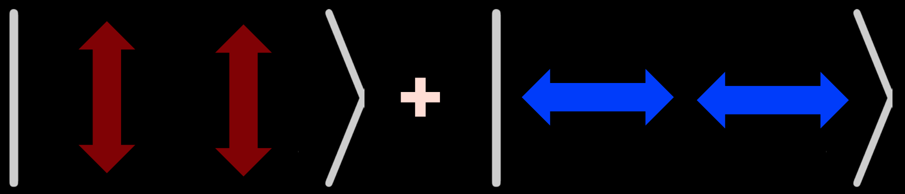


Polarization Entanglement

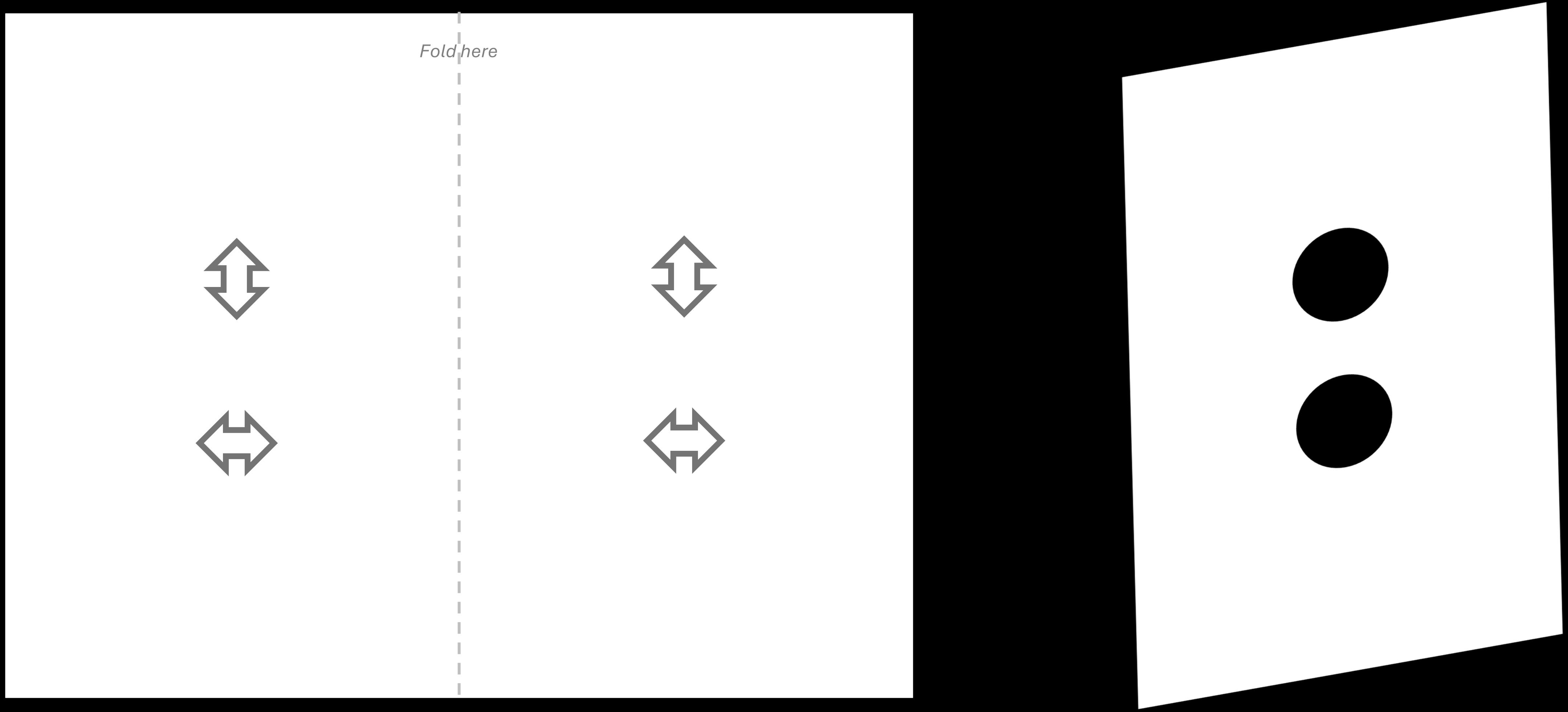
- Photons can be in a **superposition** of two polarizations



- 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 behave as if they were one object no matter the distance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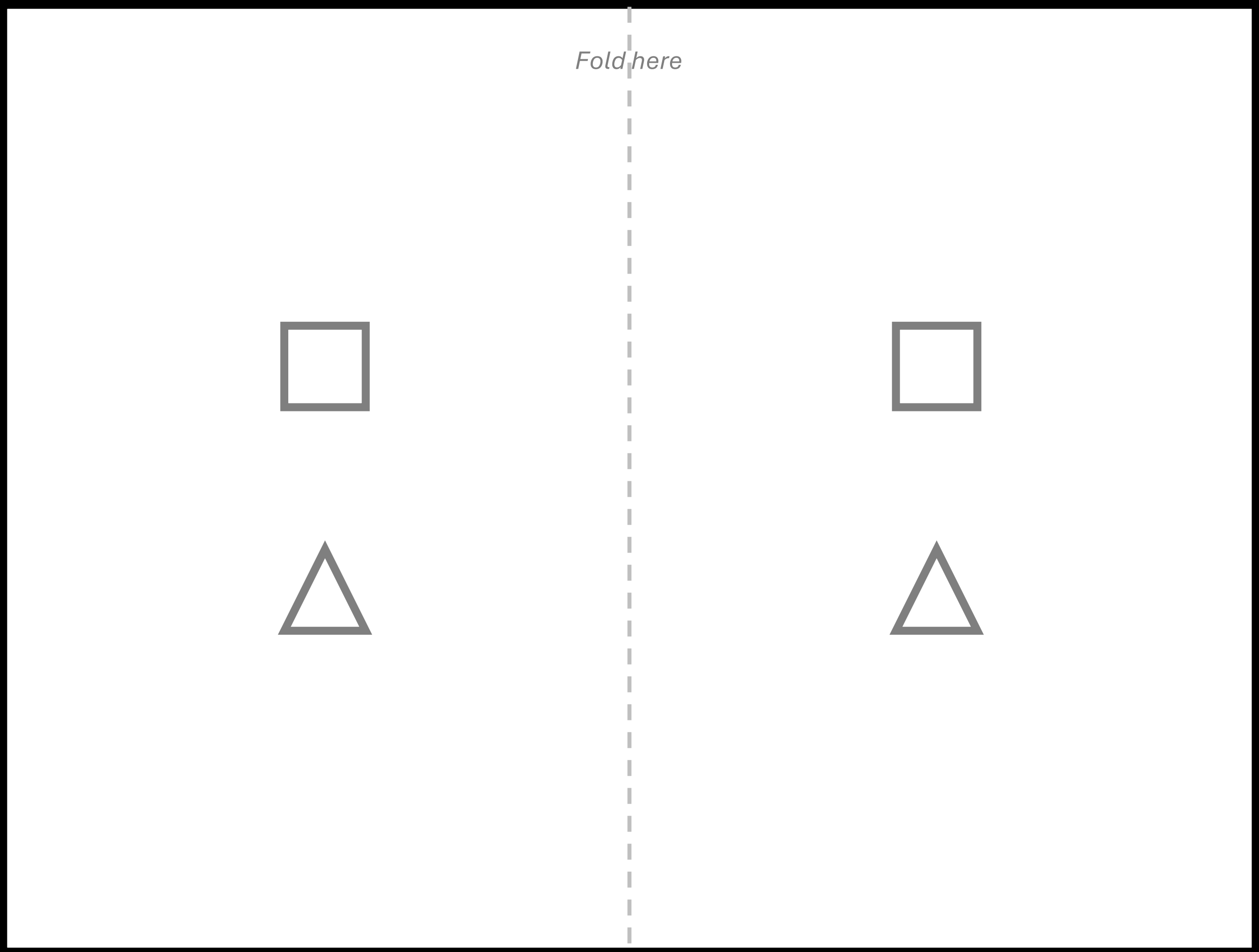
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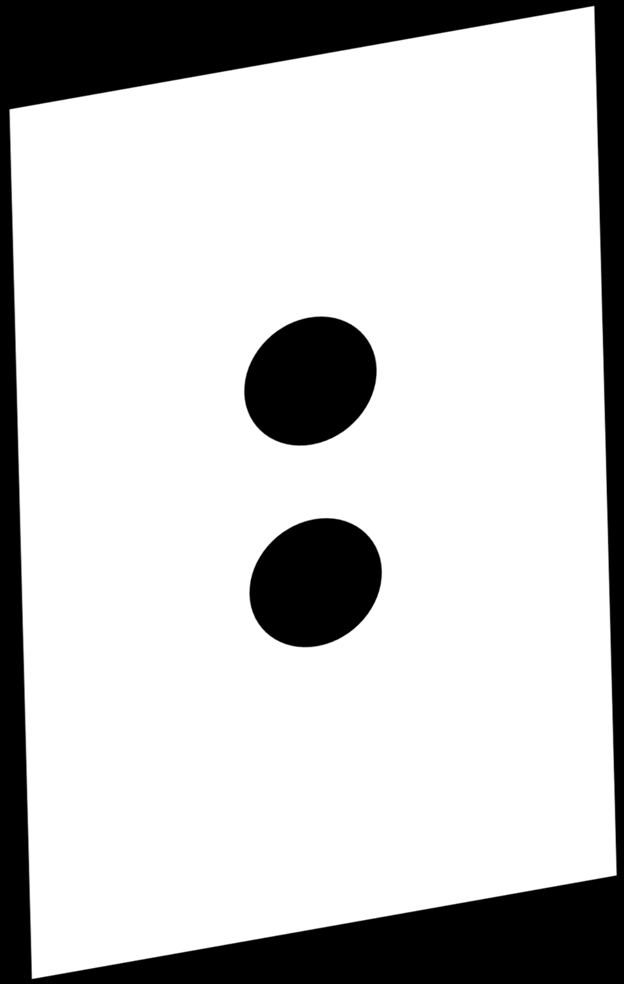

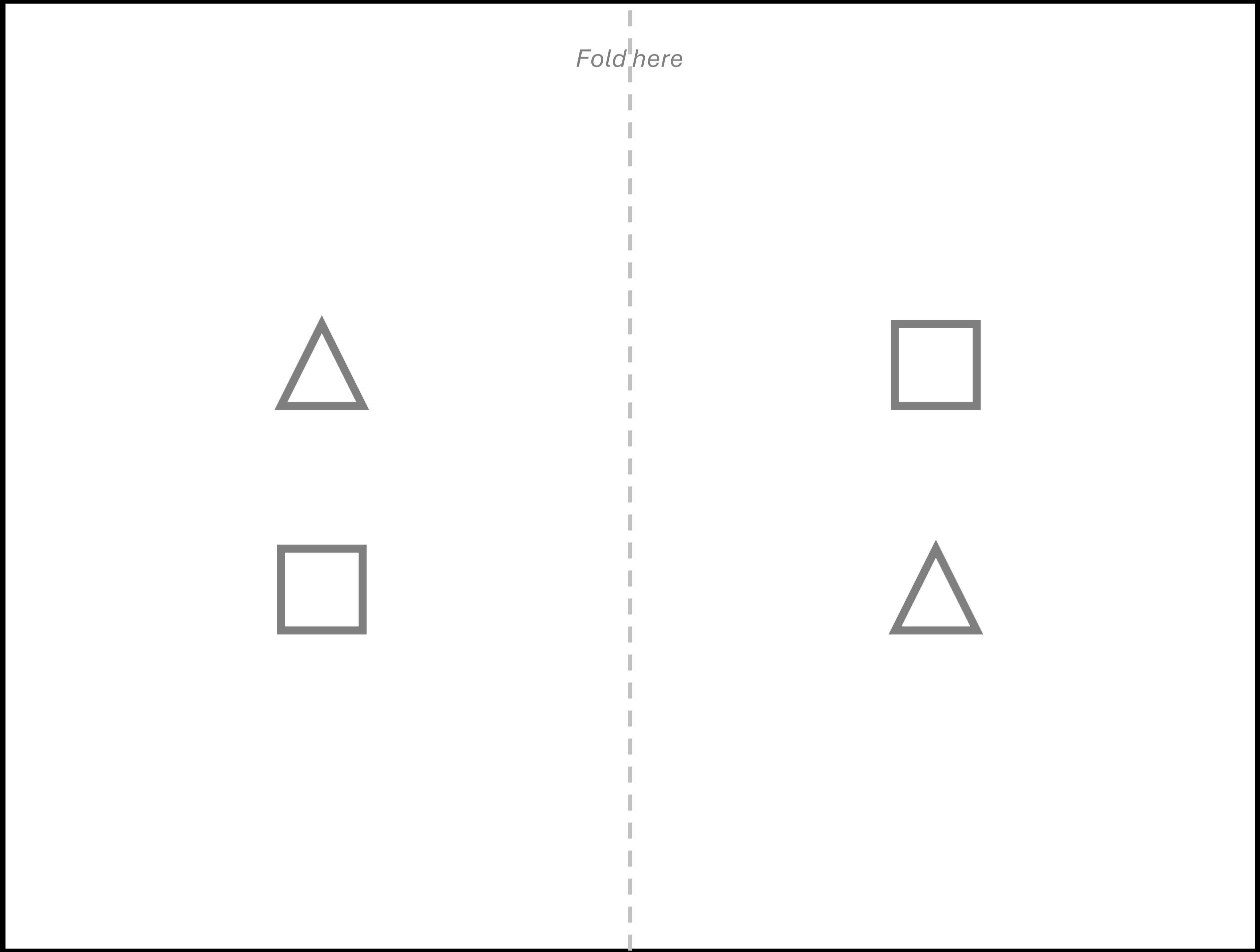
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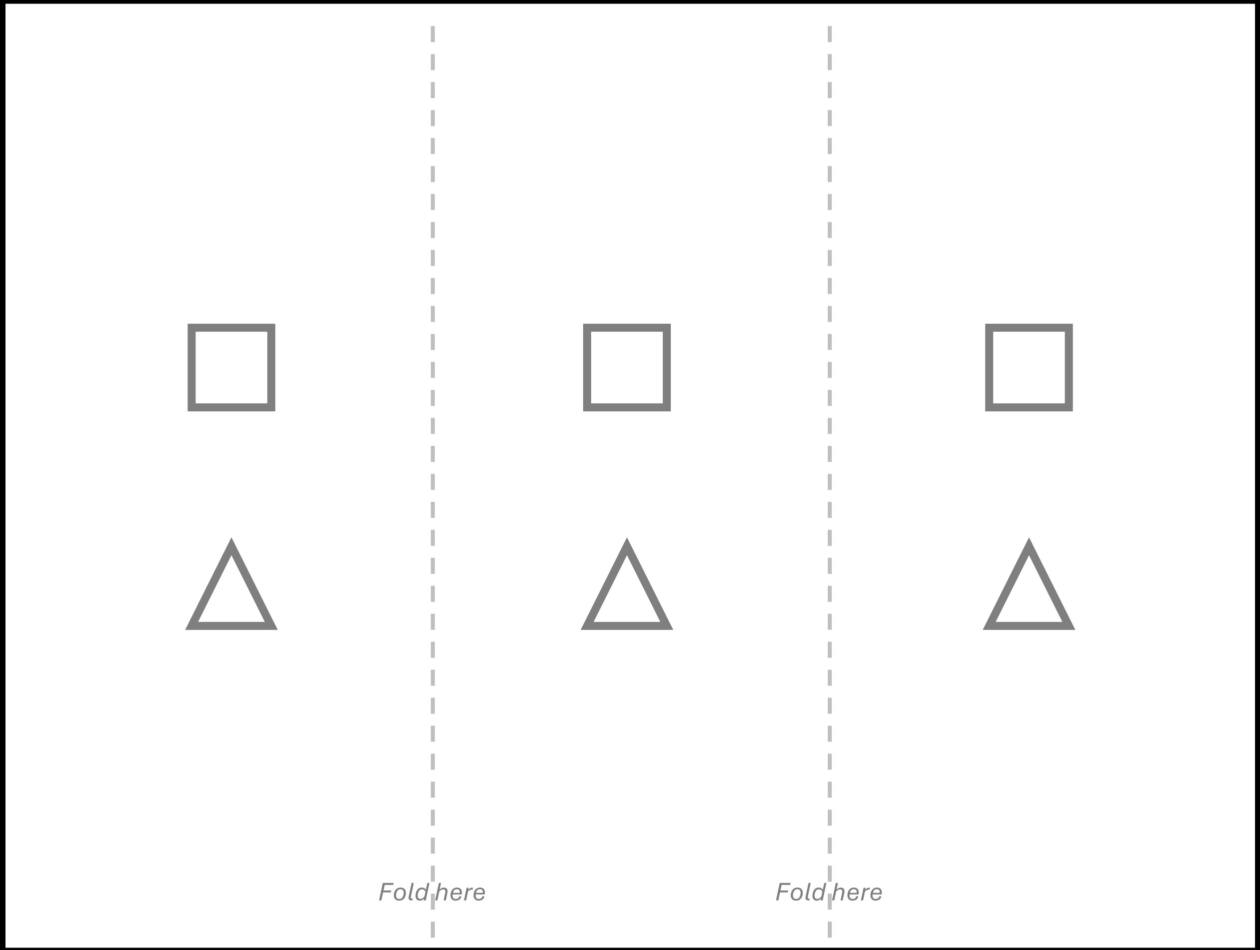
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Quantum Analogies

"Every analogy is limited, otherwise it would be the real thing and not an analogy."

- David Bohm

Editors' Suggestion

Probing the Connection between Entangled Particles and Wormholes in General Relativity

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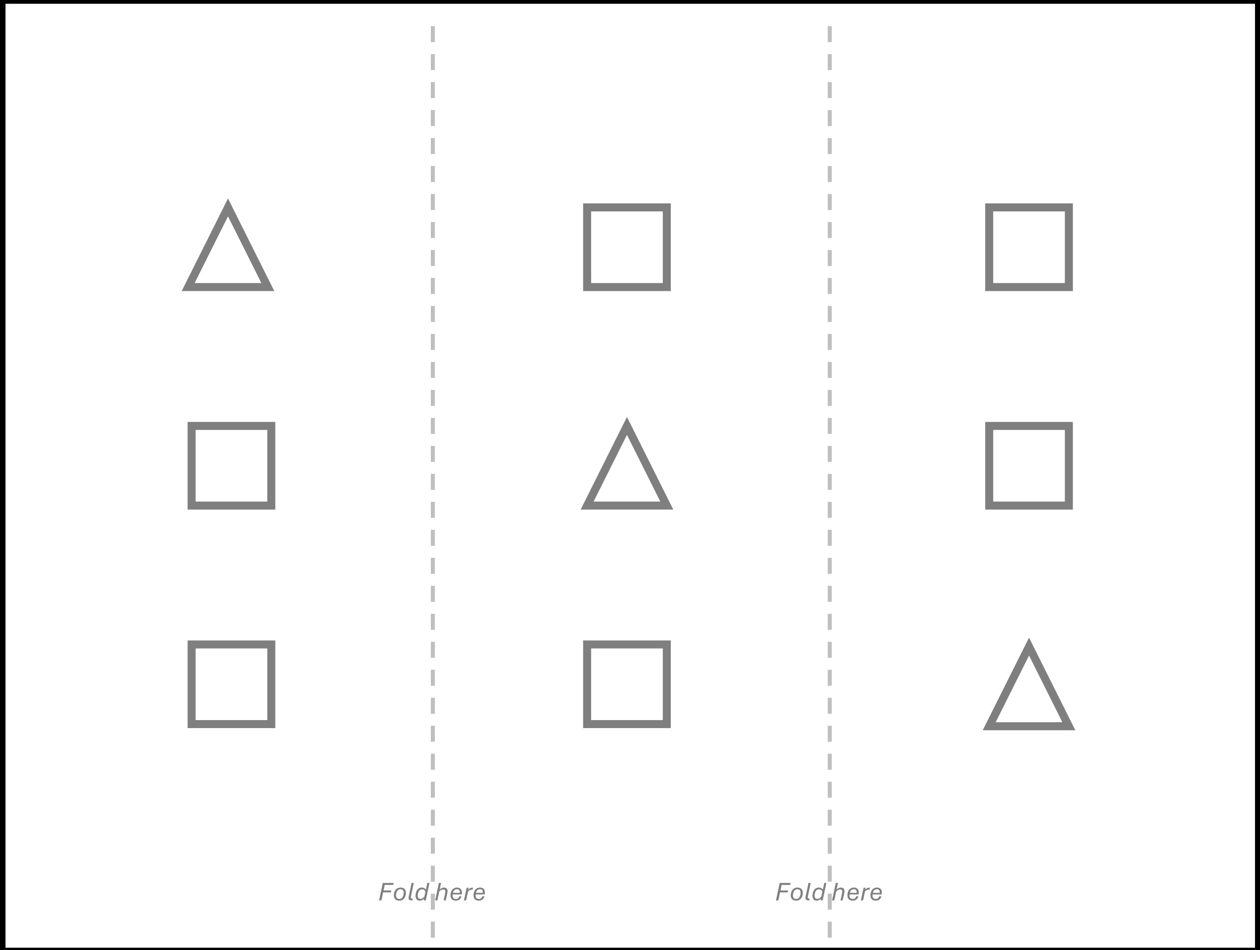
Department of Physics, College of the Holy Cross, Worcester, Massachusetts 01610, USA

(Received 4 January 2023; accepted 26 July 2023; published 5 September 2023)

Maldacena and Susskind conjectured that two entangled particles, which can be thought of as forming an Einstein-Podolsky-Rosen (EPR) pair, are connected by a nontraversable wormhole or Einstein-Rosen (ER) bridge. They named their conjecture ER = EPR. We present a concrete quantitative model for ER = EPR, in which two spin-1/2 particles in a singlet state are connected by a nontraversable wormhole in asymptotically flat general relativity. In our model, the fermions are described by the charged Dirac equation minimally coupled to gravity. This system has static wormhole solutions. We use these solutions as initial data and numerically evolve them forward in time. Our simulations show that black holes form, which are connected by the wormhole and which render the wormhole nontraversable. We also find that the wormhole throat shrinks, which places the particles in close proximity to one another and suggests an explanation for how the wormhole facilitates the nonlocal communication required by entanglement.

DOI: 10.1103/PhysRevLett.131.101001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Make your own entangled states!

- Fold the paper according to the number of particles you want entangled
- Open the paper and draw dashes on the creases you created
- Add symbols for the different possible states of each particle
  - Choose which order the symbols are written according to what state you want
  - Keep the symbols vertically aligned with other particles' symbols
- Flip the paper over and draw filled-in circles over where the symbols are on the other side
- Give it to someone else for them to make a measurement!
- How would you write your entangled state using kets?

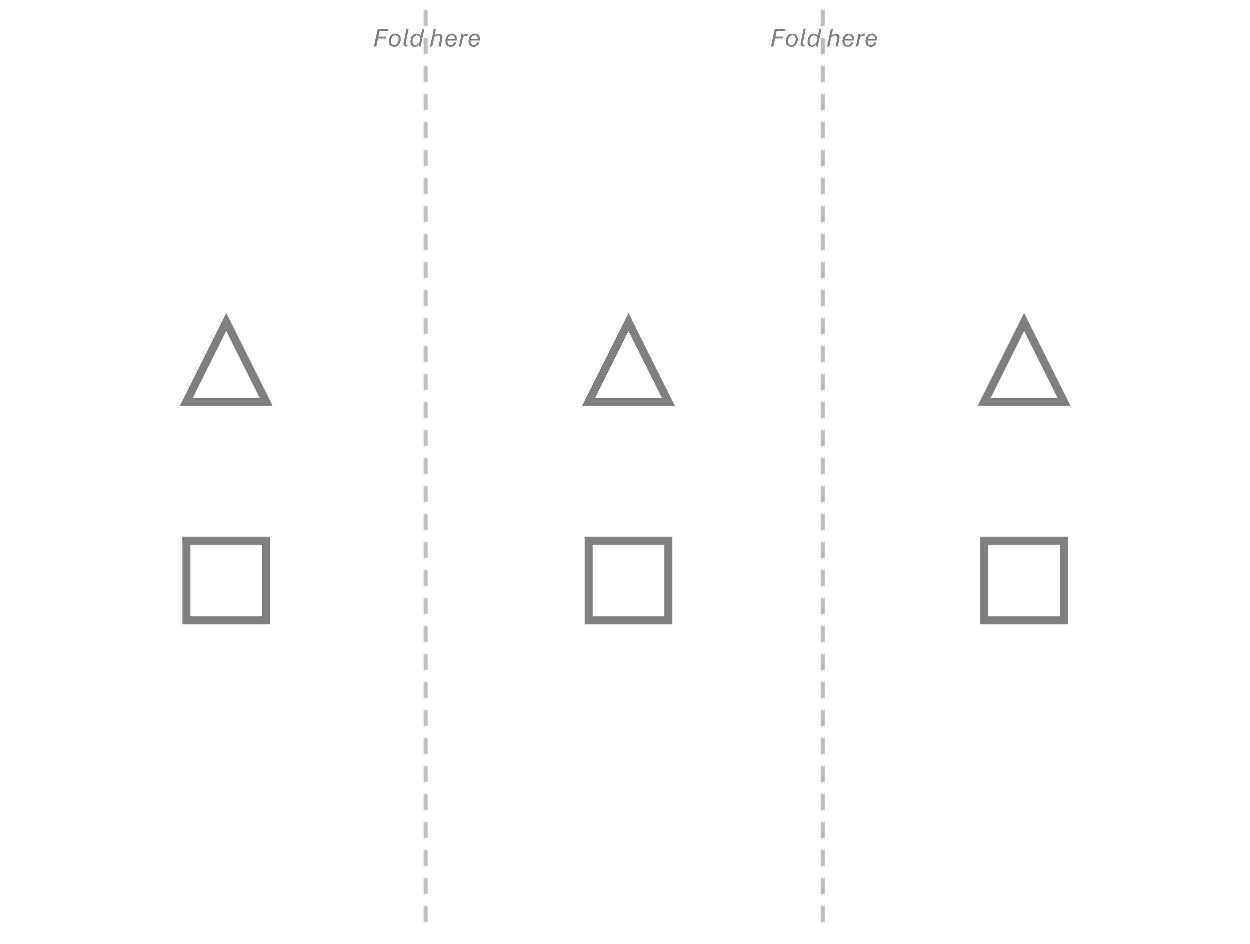
Write the entangled state using kets

- Draw a vertical line to start the ket

- Add the first symbol of each particle to the ket

- Close the ket

- Draw a plus sign to add kets for the other possible state combinations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So what is the real quantum understanding?

Unlike most other science concepts, at the root we do not have an intuitive understanding of quantum phenomena.

Quantum interpretations are used to provide a sense of intuition. They are not yet proven.

Quantum analogies are based on quantum interpretations.

Why is this not entanglement?

- 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.
- Great fox! 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)

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

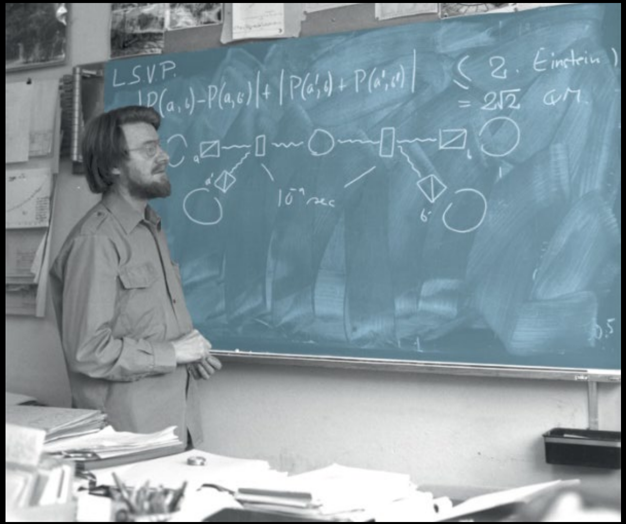
Quantum mechanics challenges two commonly held beliefs:

1. "Objects have definite states before measurement." Superposition implies quantum particles 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).

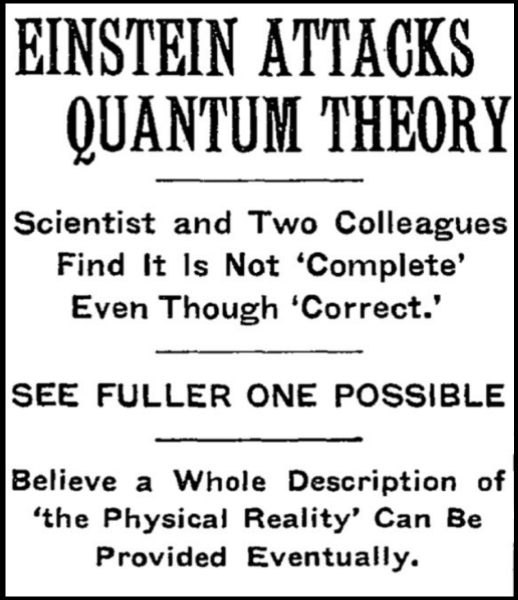


1930's

1960's

1970's to present

2022

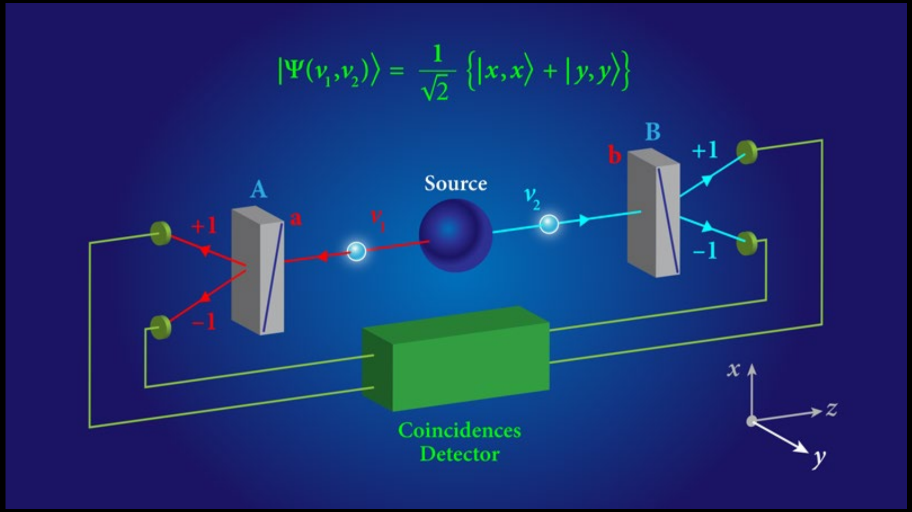


EINSTEIN ATTACKS QUANTUM THEORY

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

SEE FULLER ONE POSSIBLE

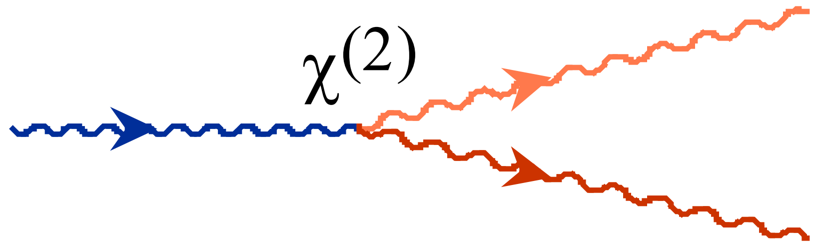
Believe a Whole Description of 'the Physical Reality' Can Be Provided Eventually.



Such experiments are now regularly incorporated in undergraduate laboratories

We can create photons in pairs

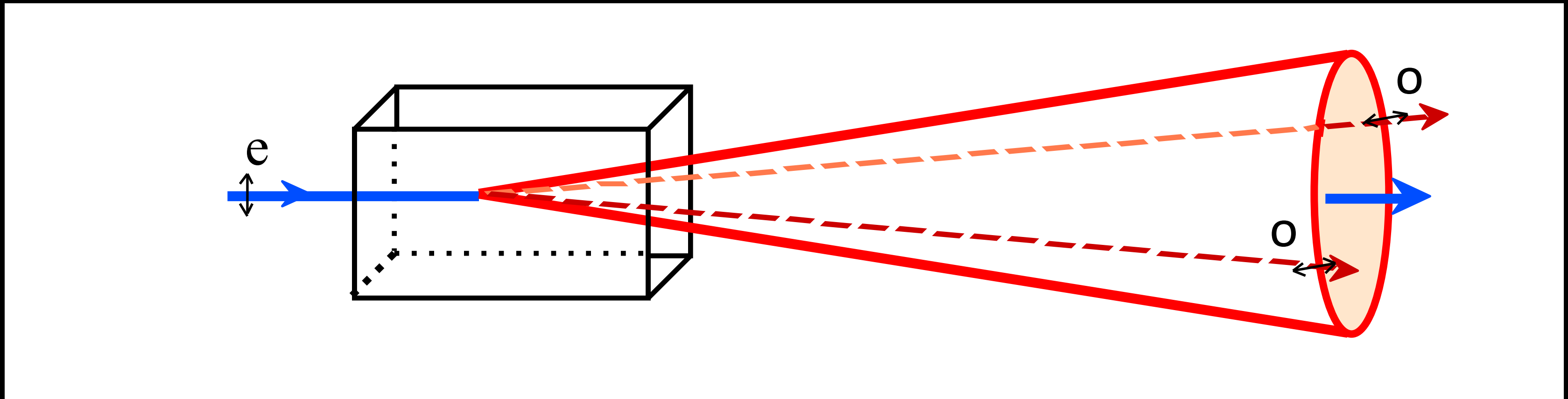
In 1970, the theory for spontaneous parametric down-conversion showed we can create photons in pairs



$\omega_p = \omega_s + \omega_i$ Energy conservation

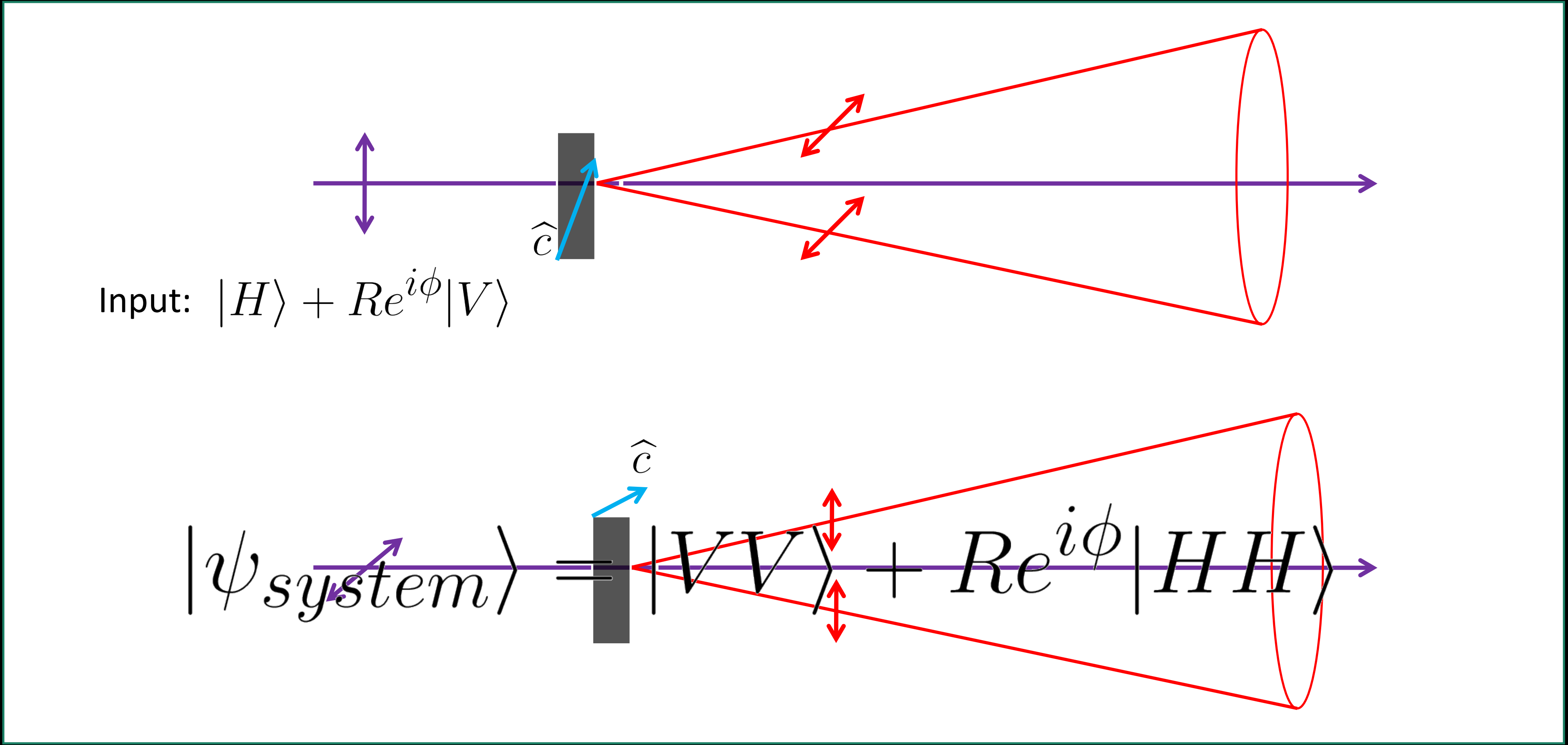
$\vec{\kappa}_p = \vec{\kappa}_s + \vec{\kappa}_i$ Momentum conservation

We can choose an orientation so that the photons have identical polarizations:

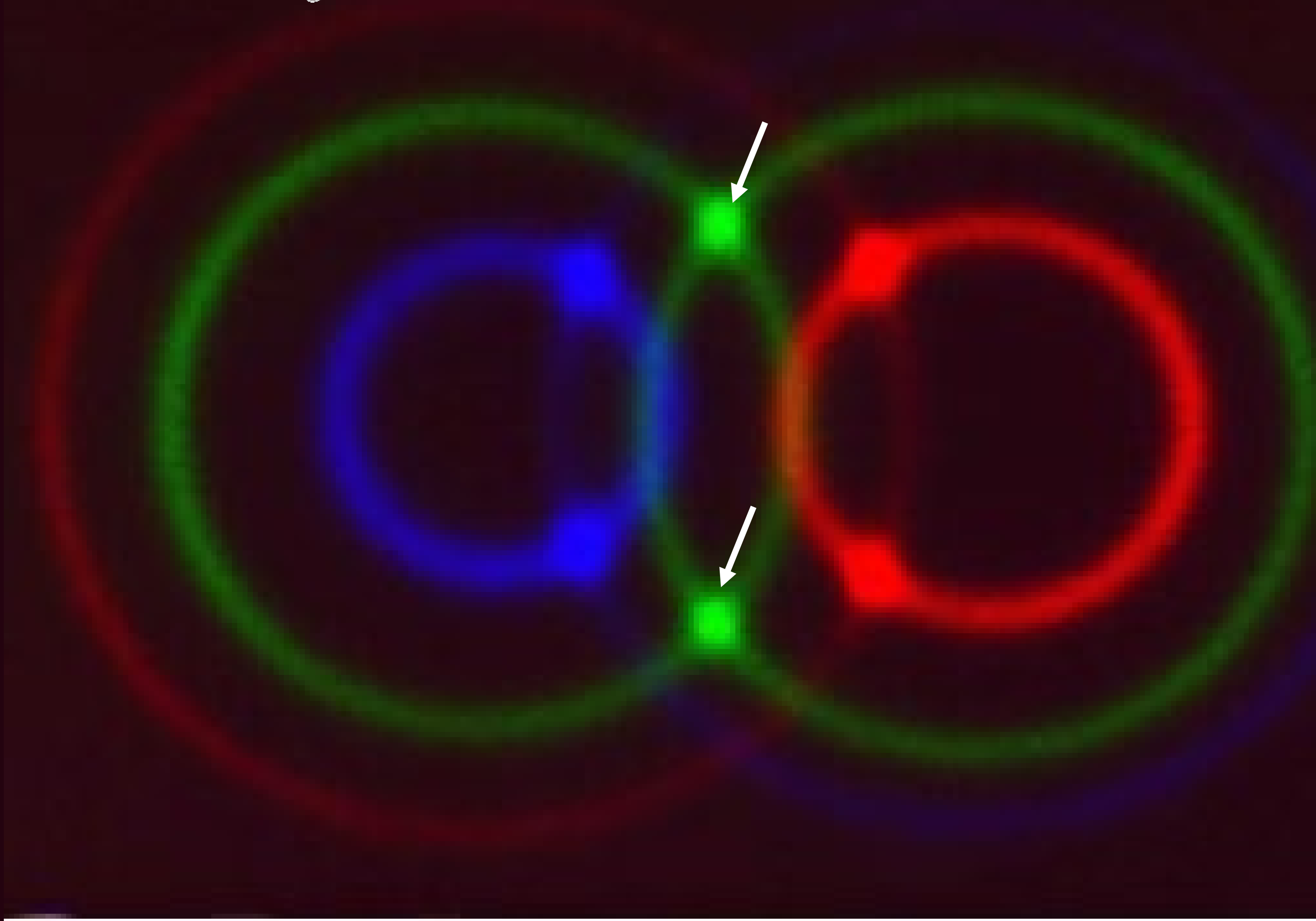


Burnham & Weinberg, PRL **25**, 84 (1970).

Using two crystals, we can create polarization-entangled photon pairs



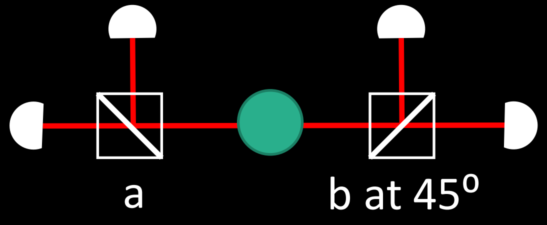
$$|\psi_{system}\rangle = |VV\rangle + Re^{i\phi}|HH\rangle$$

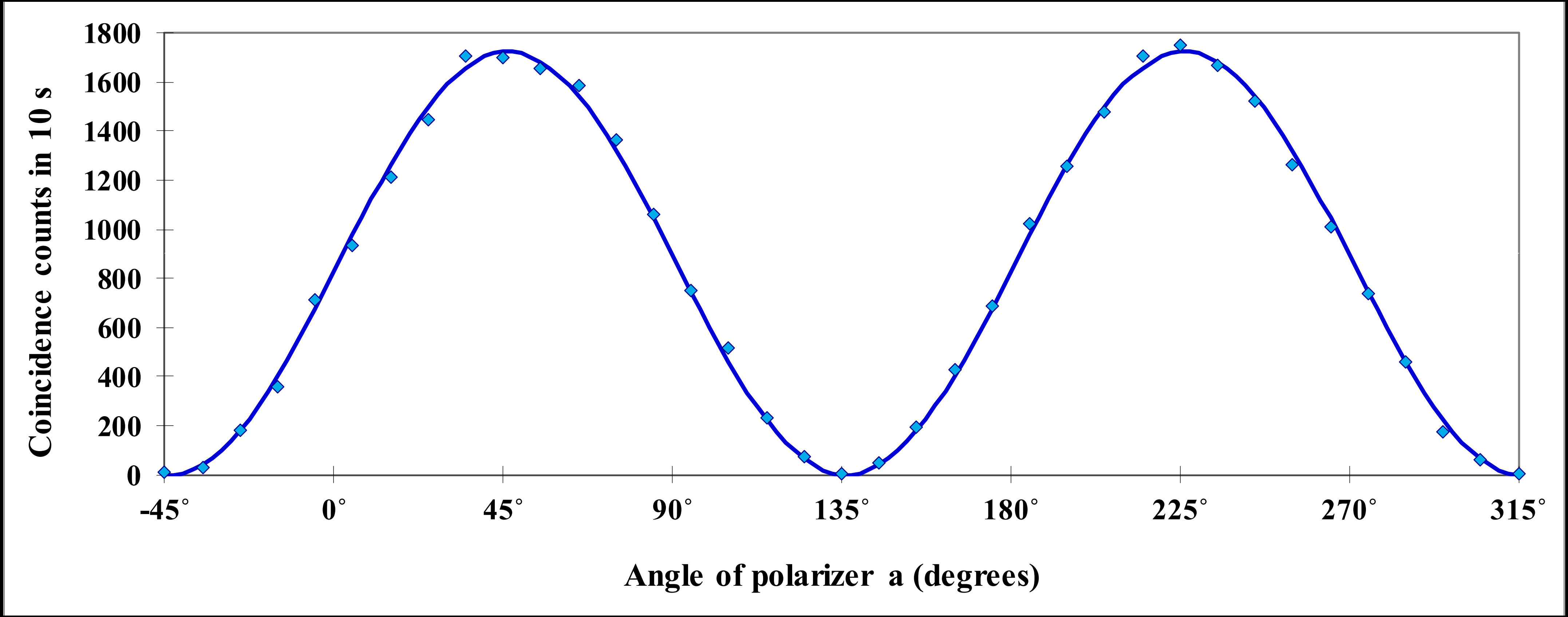


Paul Kwiat

Phys. Rev. Lett. 75, 4337 (1995).

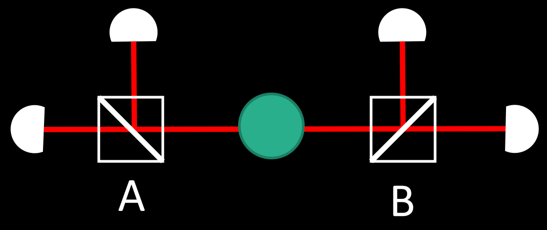
Measuring the photons with polarizers shows near-perfect quantum correlation





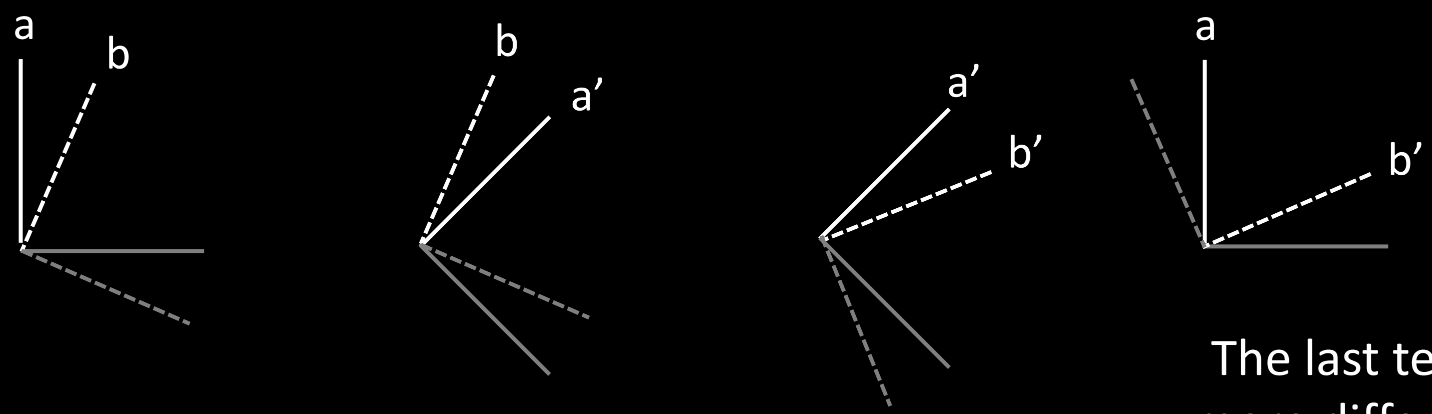
Bell's theorem tests for entanglement

- 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



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

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



The last term ~ likelihood more different than similar

With entanglement, the correlations are stronger, resulting in a larger value

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,‡]

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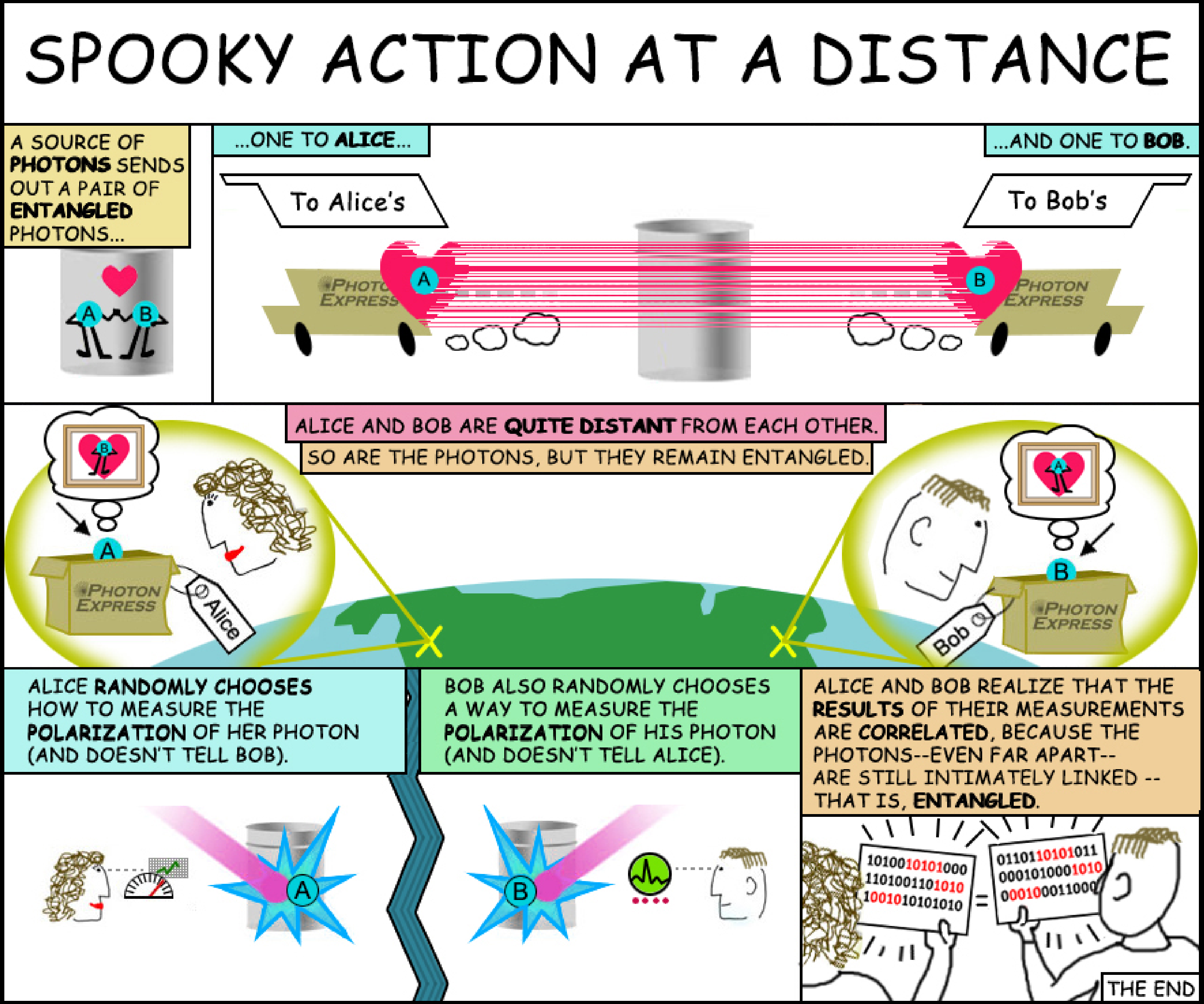
[10]*Quantum Information Science Program, Canadian Institute for Advanced Research, Toronto, Ontario, Canada*

(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.

Does this mean we can communicate faster than light?

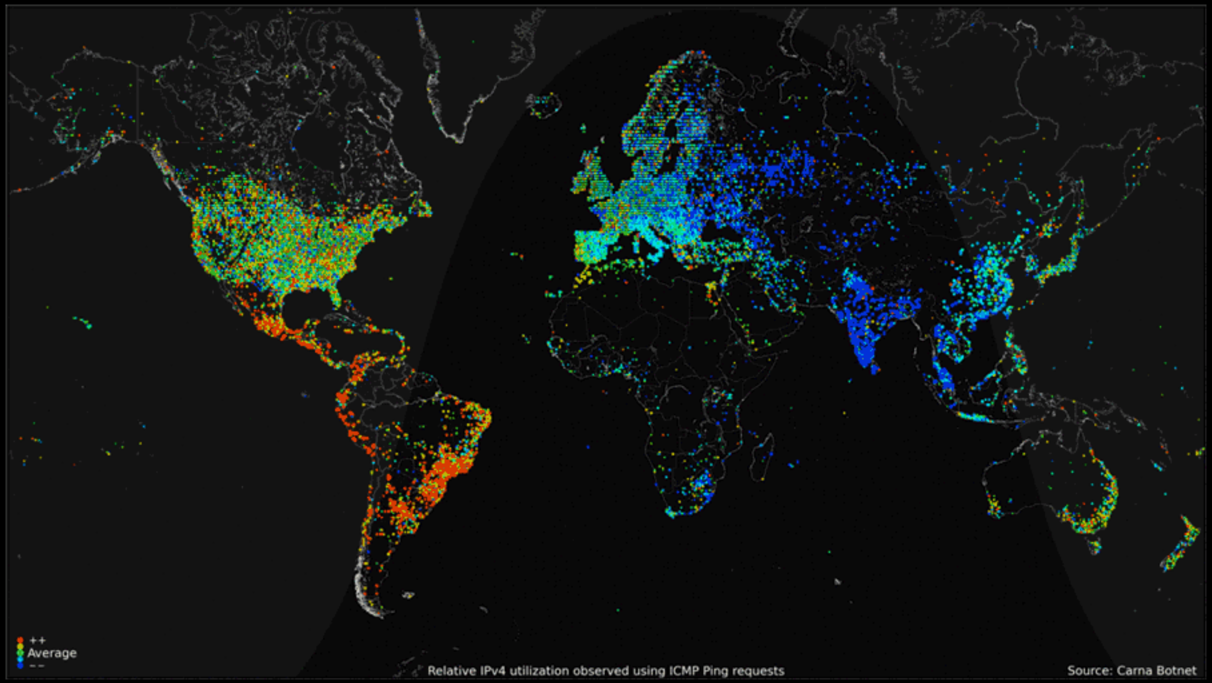
- Because the state the photons end up in is random, knowing that you share the same state cannot be used to communicate – although it can be used as a resource called “shared randomness”



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
- There are a handful of few-node and many (~40) node quantum networks in the world.

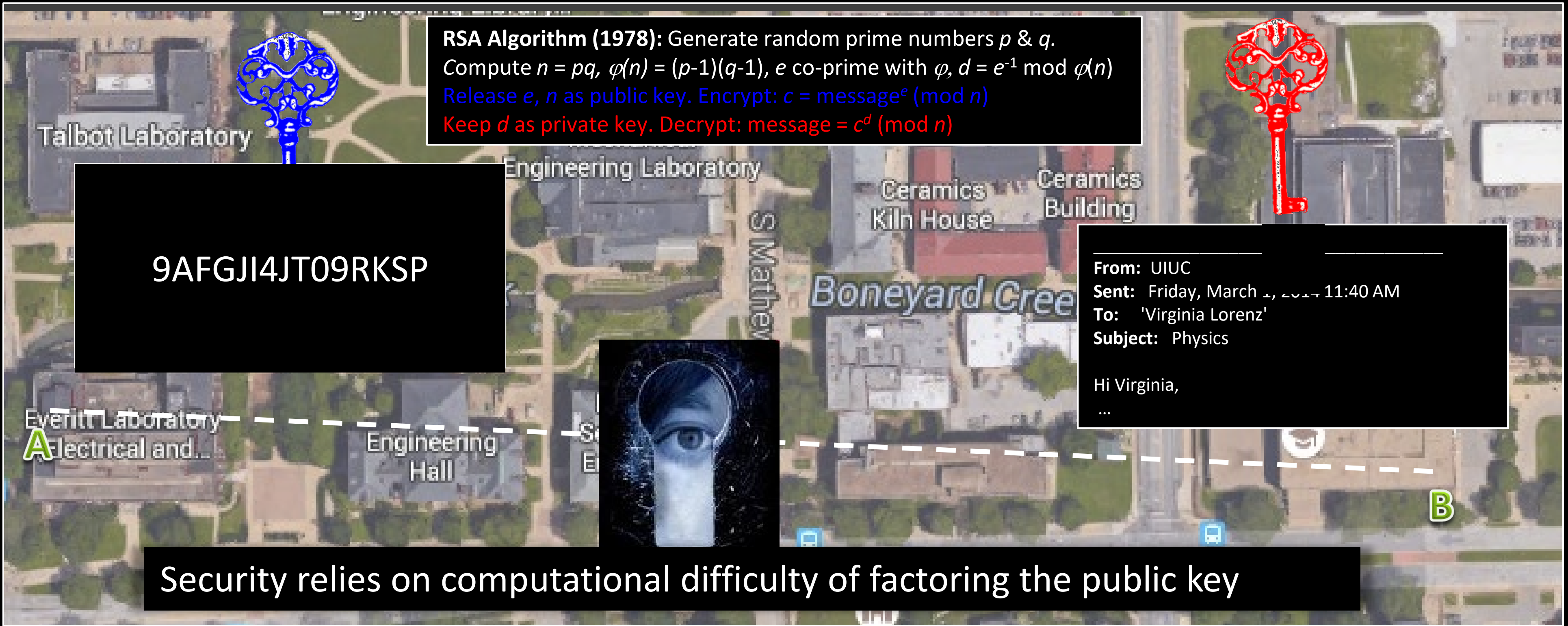


Why are entangled states important?

- Responsible for quantum measurements and decoherence
- Central to demonstrations of quantum nonlocality (e.g., Bell's inequality)
- **Quantum computation** – intermediate states are all complex entangled states
- **Quantum cryptography** – separated particles' correlations allow sharing of secret random key
- **Quantum teleportation** – transmit unknown quantum state without sending the state itself

Classical Cryptography

http://en.wikipedia.org



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

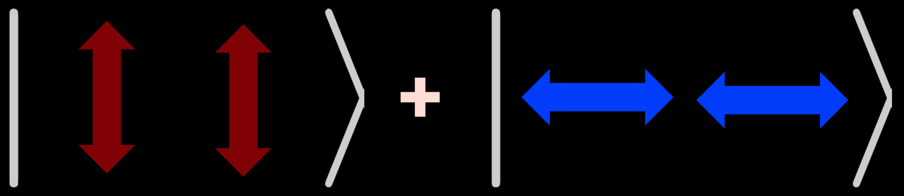
From: UIUC
Sent: Friday, March [redacted] 11:40 AM
To: 'Virginia Lorenz'
Subject: Physics

Hi Virginia,

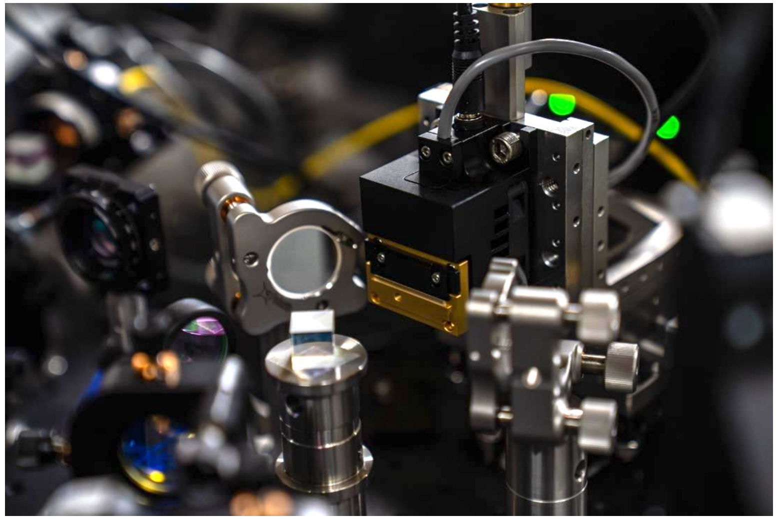
...

Security relies on computational difficulty of factoring the public key

Quantum Key Distribution



Security is guaranteed by the laws of quantum physics



PUBLIC QUANTUM NETWORK

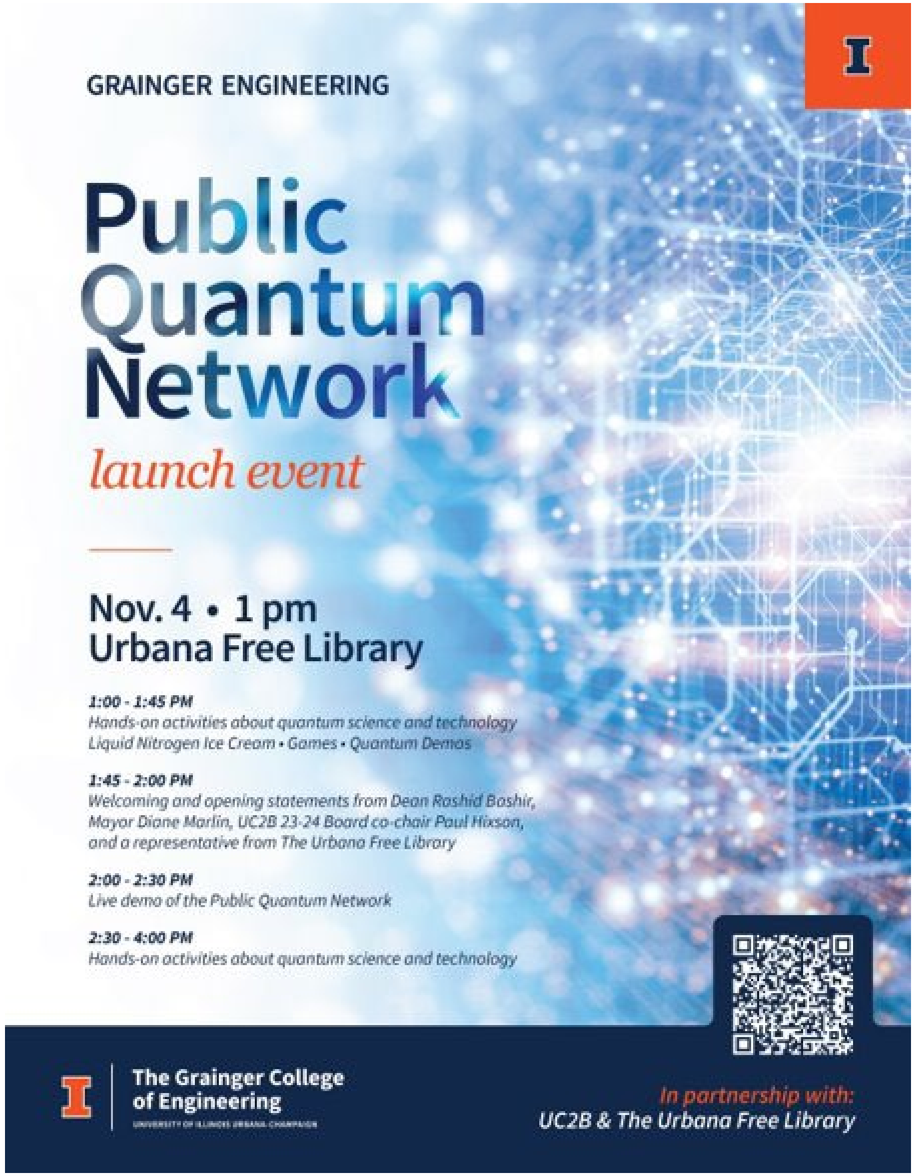
THE IDEA

Enable the public to make measurements on a real quantum network that transmits entangled photons, for

- Extensive public engagement
  - Hands-on public participation in quantum technologies
  - Quantum curricula (K-12 & community college)

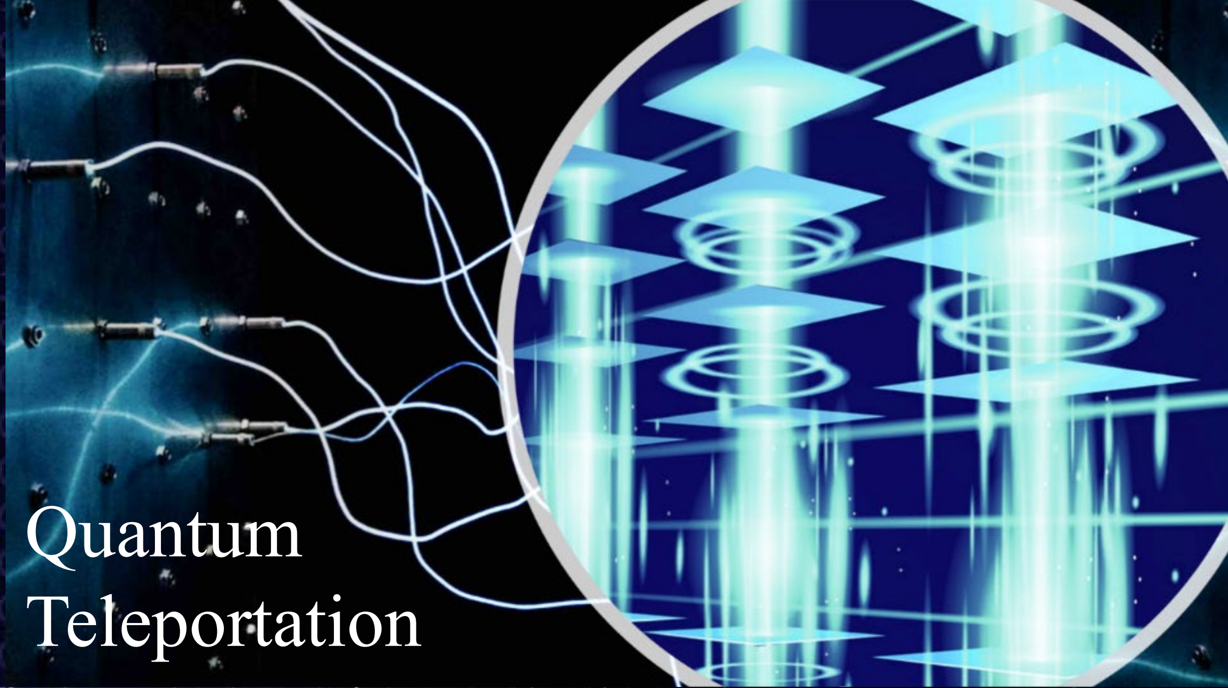
- Fundamental research
  - State-of-the-art quantum protocols
  - Fundamental tests at scale

- Quantum technology innovation
  - Involvement of industry partners



NOKIA
NOKIA
BlackBerry
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 the
public

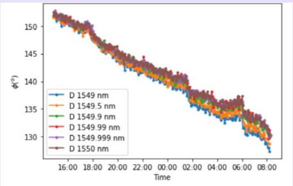
TIMELINE

Idea

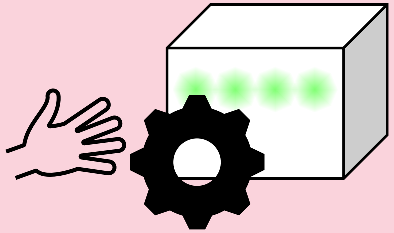
Spring 2022

Fall 2022

Fiber link characterization



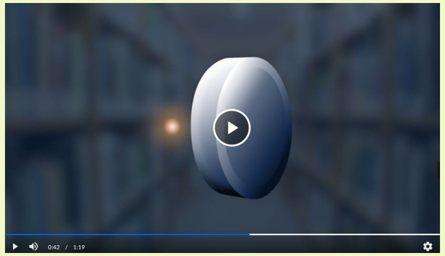
Source and public interface development



Spring 2023

Summer 2023

Preparations for public launch event



Launch Event

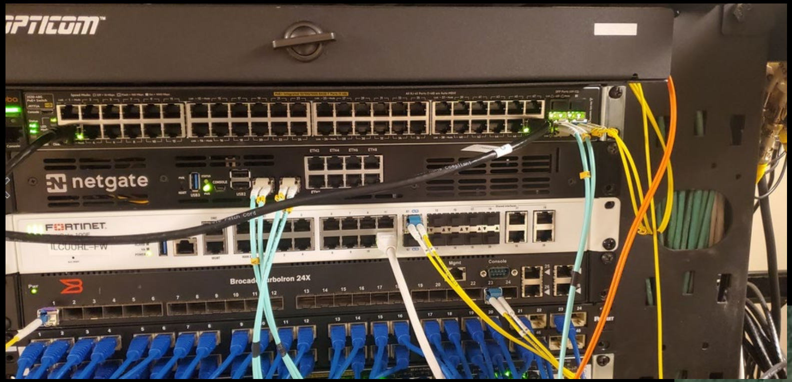
PUBLIC QUANTUM NETWORK

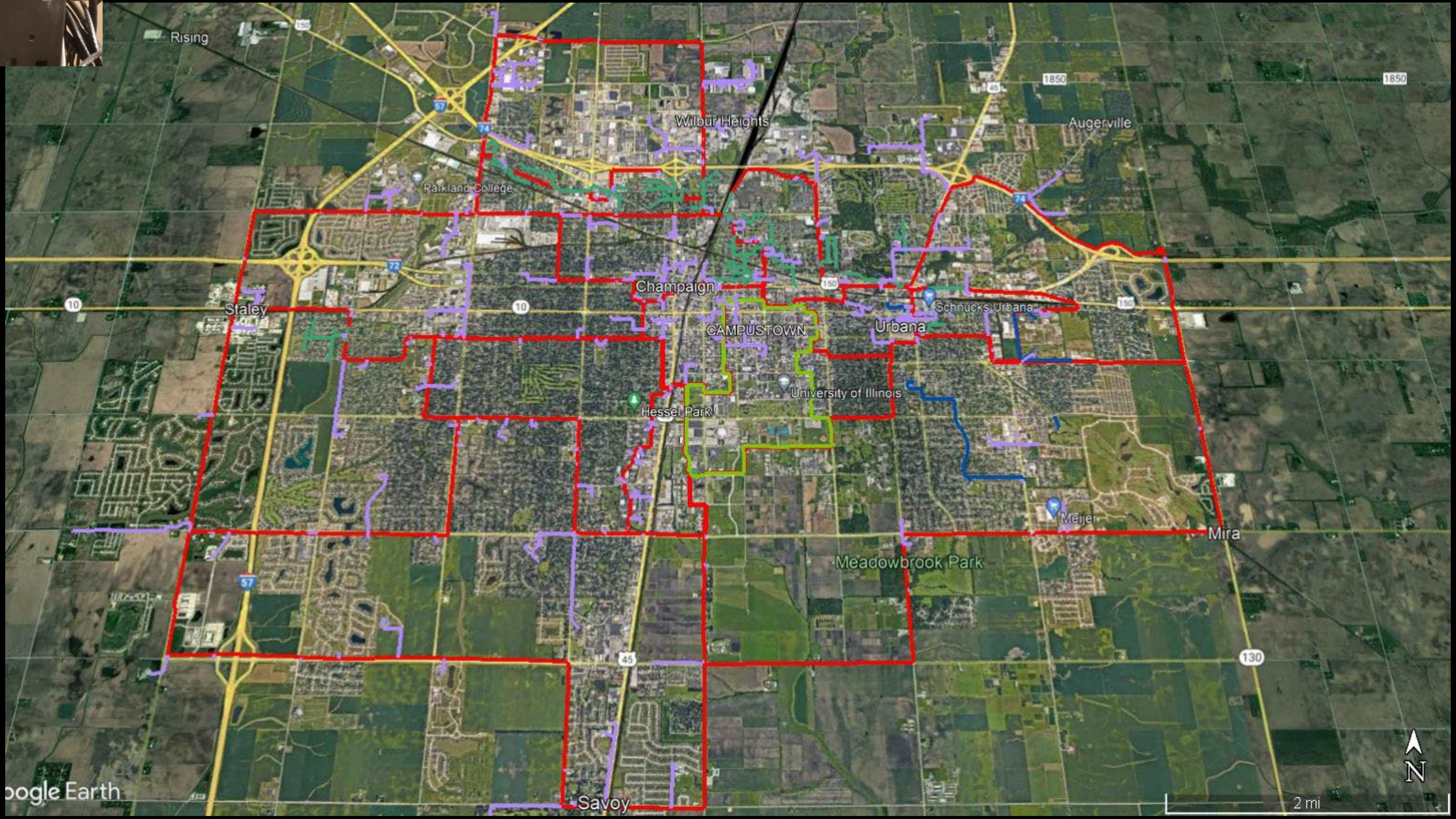
Fall 2023

Summer 2024

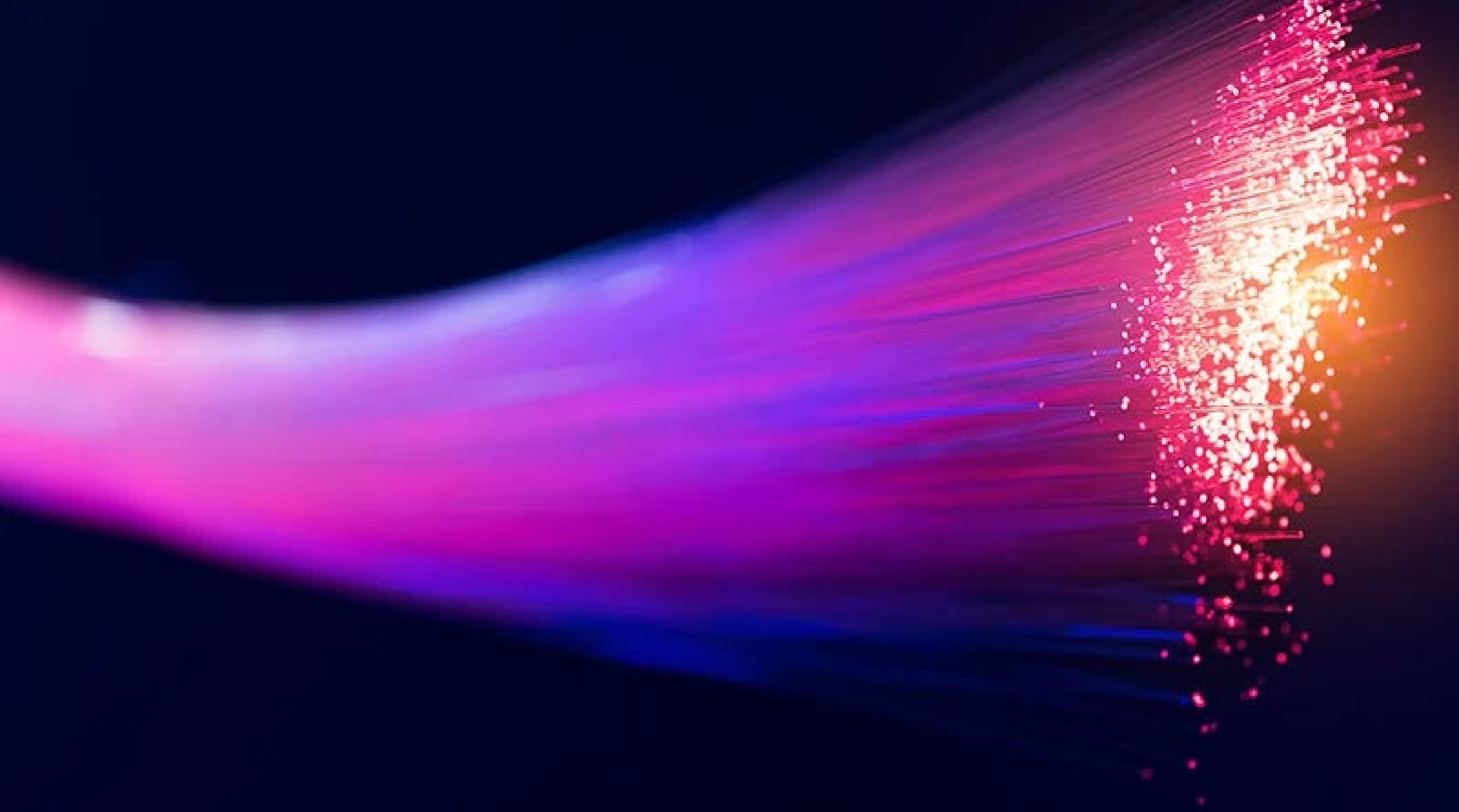
Full measurement automation

THE LINK


netgate
FURTINET


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

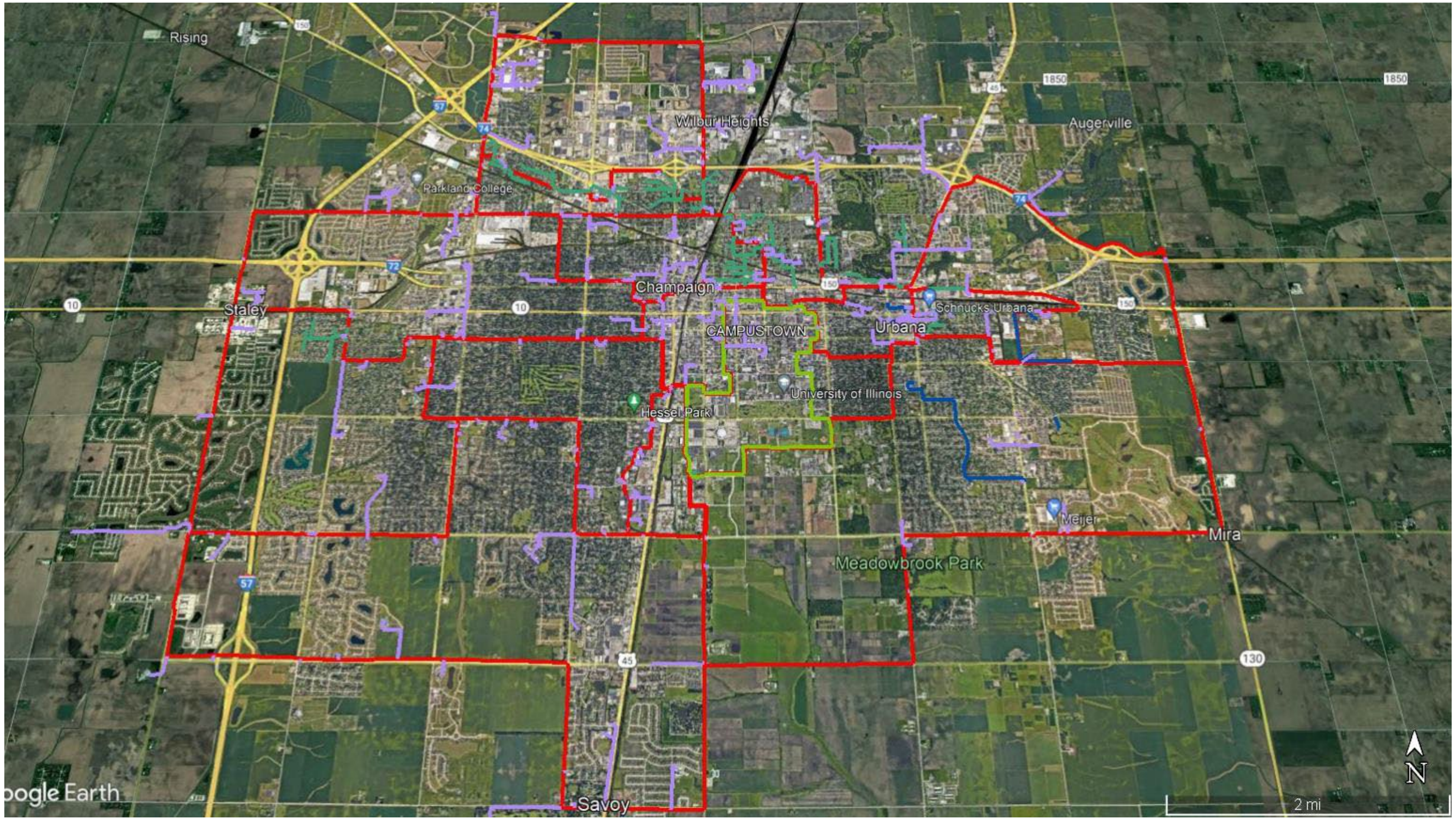
FIBER OPTIC CABLE



URBANA-CHAMPAIGN BIG BROADBAND

UC2B

- Broadband network to underserved communities created from funding via 2009 American Recovery and Reinvestment Act
- UIUC-city partnership
- Public quantum network was in-line with vision for community access
- Generously providing fiber links and service

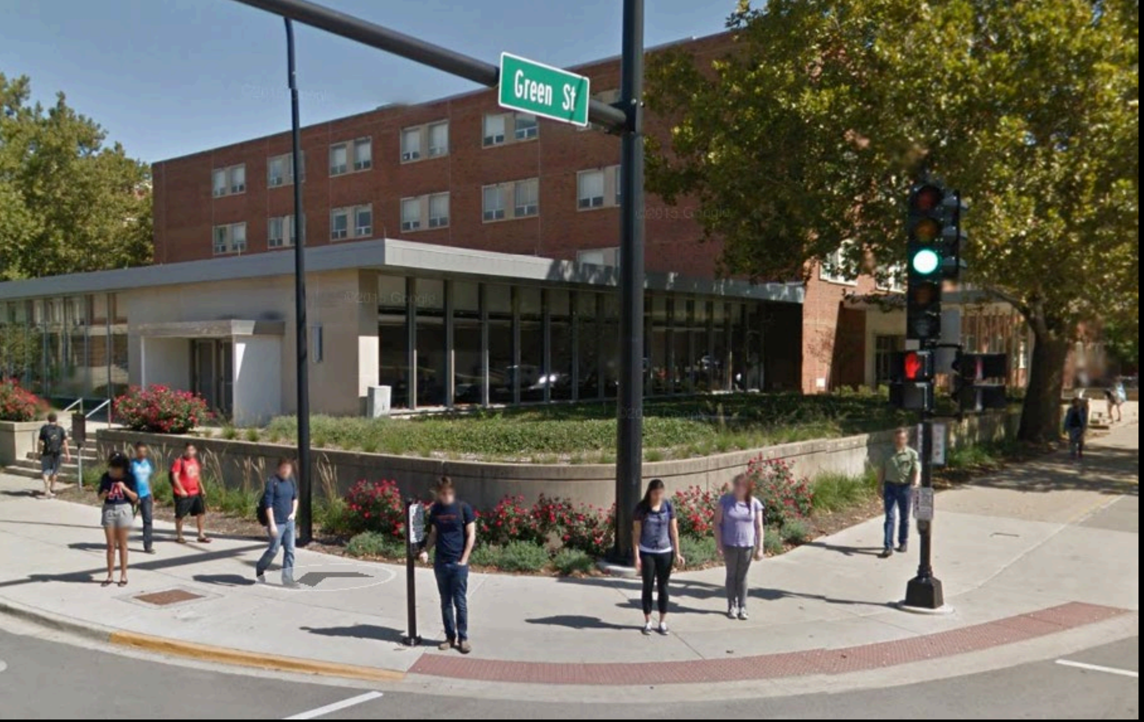


THE URBANA FREE LIBRARY

THE URBANA FREE LIBRARY

- Founded in 1874
- Provides free internet service
- Runs STEM workshops for kids

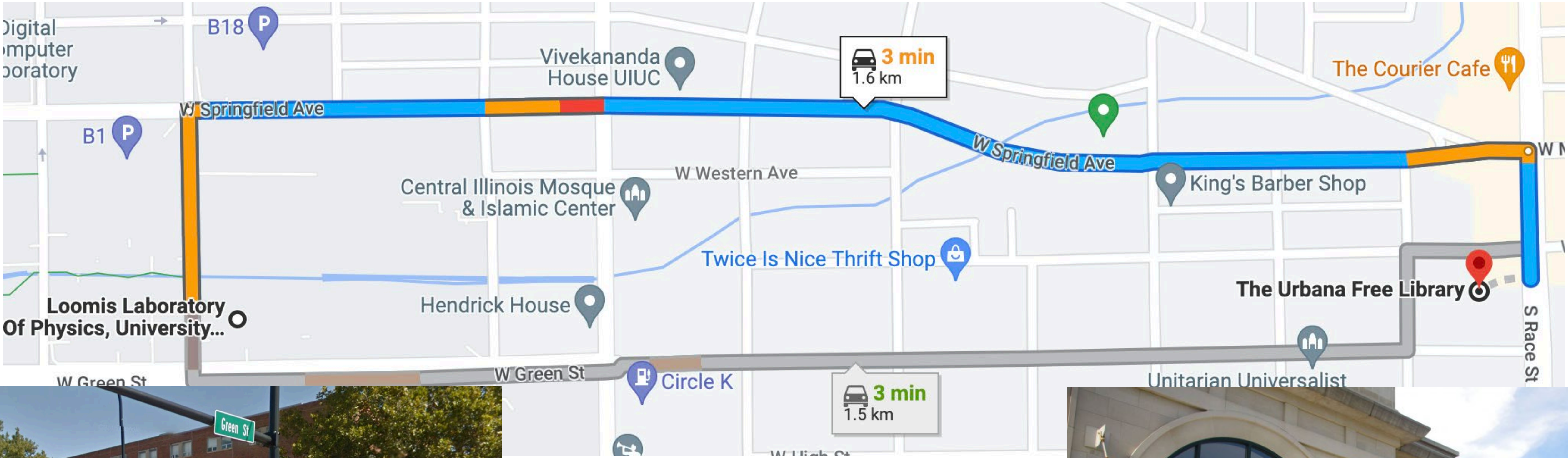
teen open lab
est. 2013


Green St


THE URBANA FREE LIBRARY

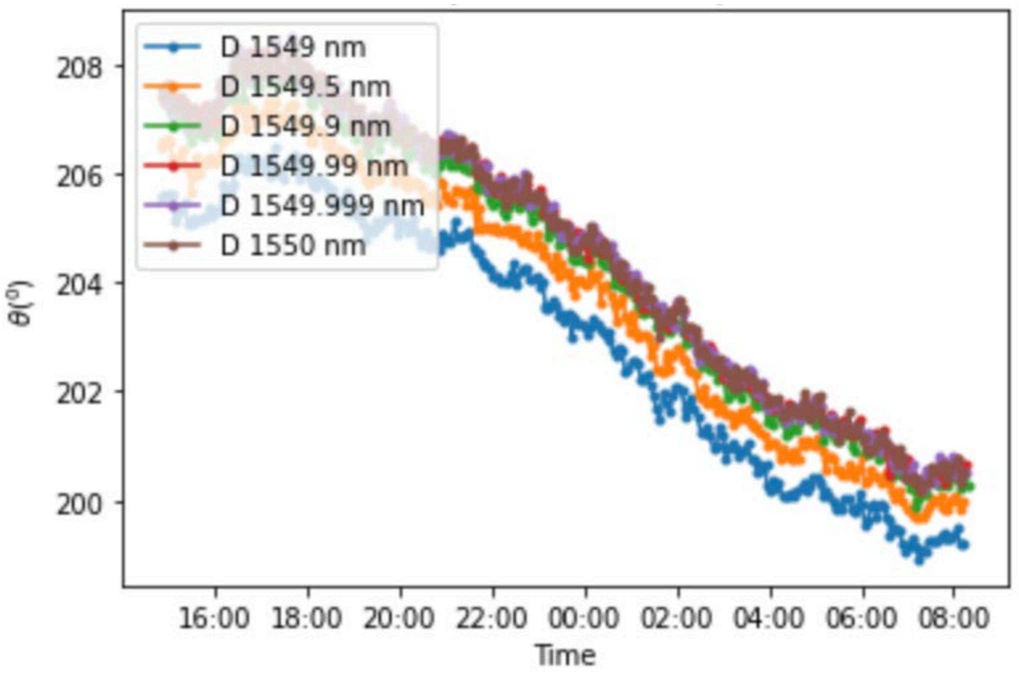

Loomis Laboratory Of Physics, University...
The Urbana Free Library

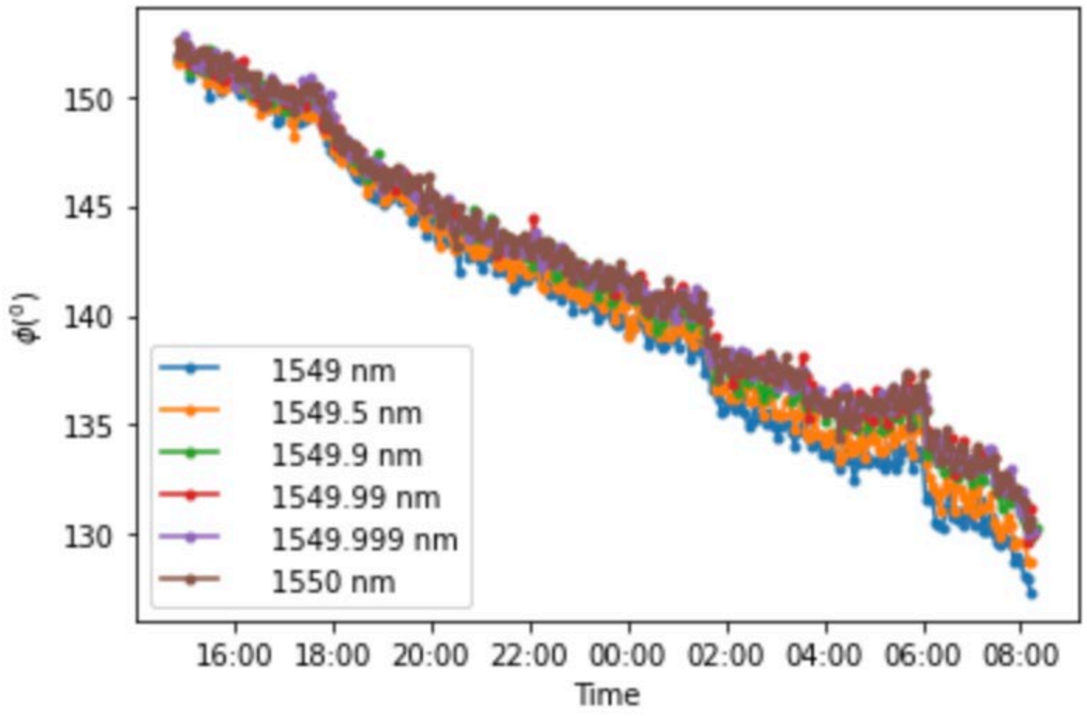
LINK SPECIFICATIONS



- Fiber Loop from UIUC → library → UIUC
- 24.3-km roundtrip fiber
- ~10-dB loss at 1550 nm
- ~1,500 cps dark counts

POLARIZATION STABILITY

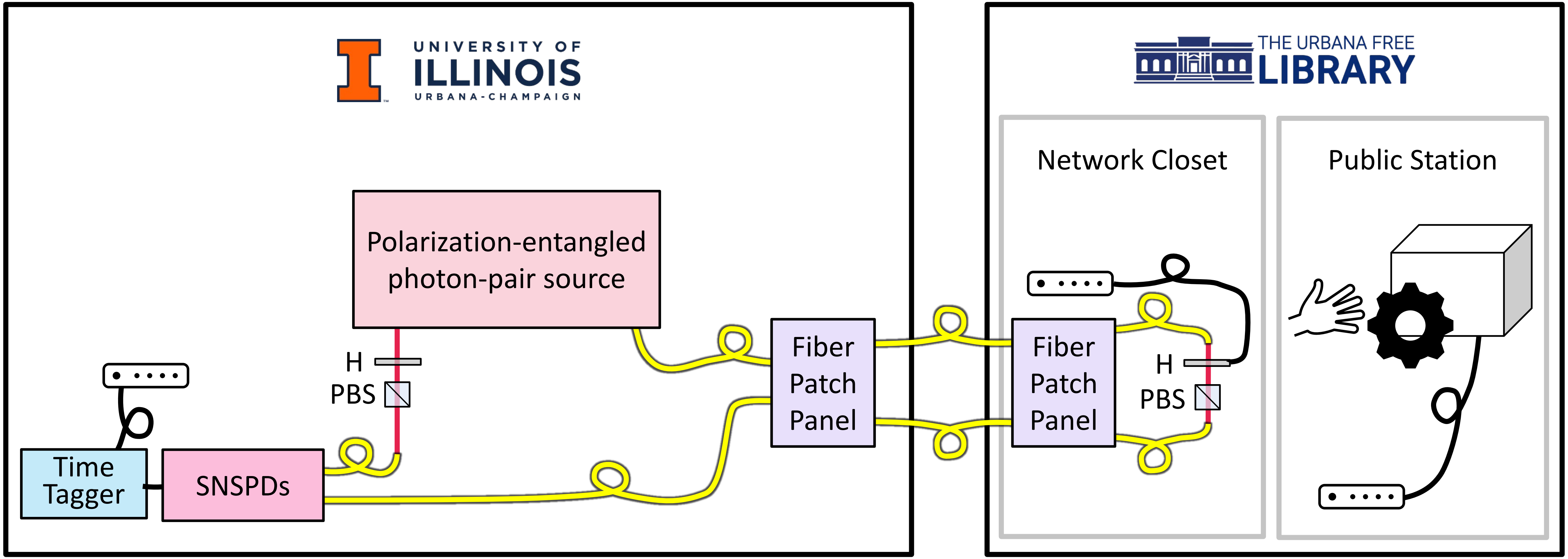




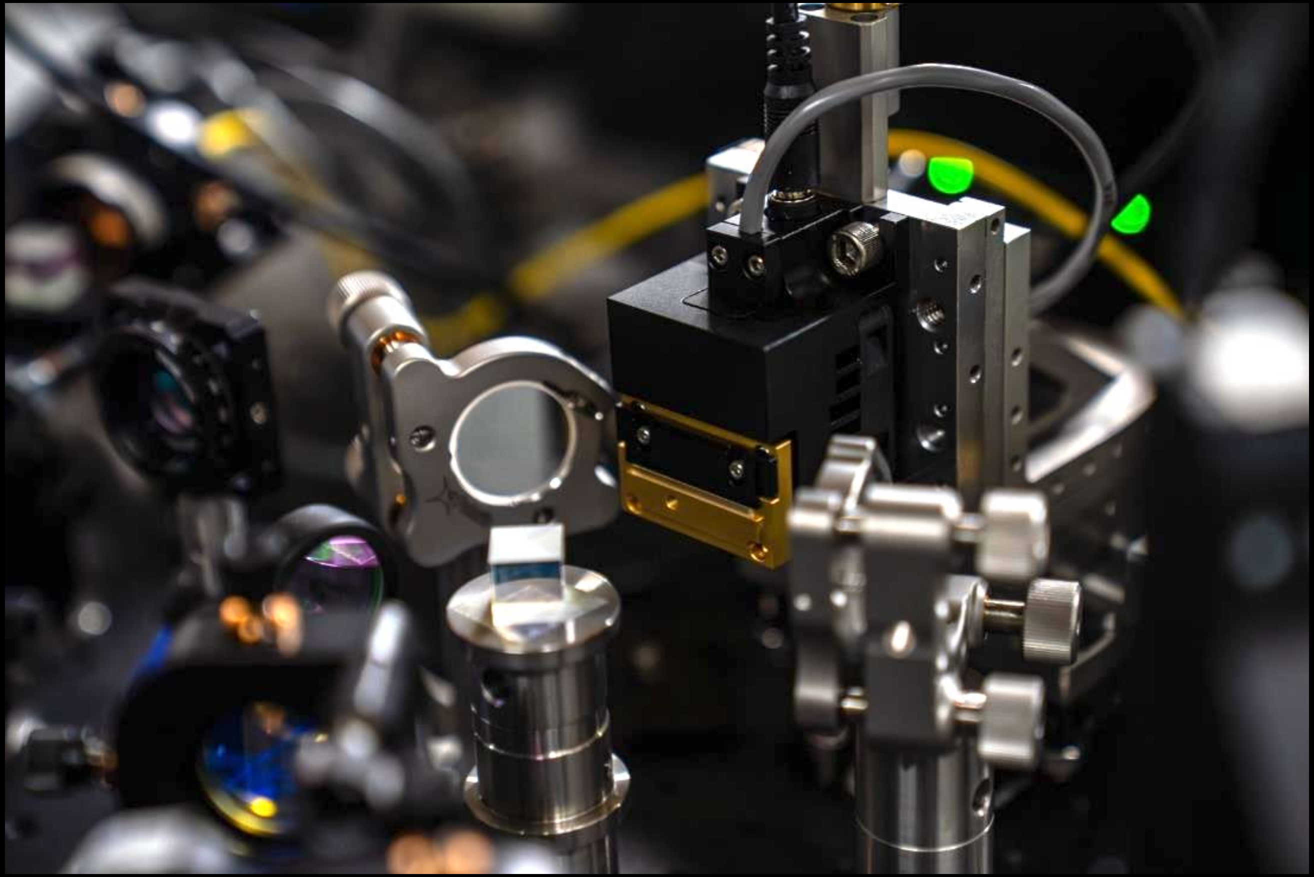
- Polarization rotated 10-20 degrees in 16 hours
- Depolarization is minimal
- Since measurements take just a few minutes, manual compensation enough to start

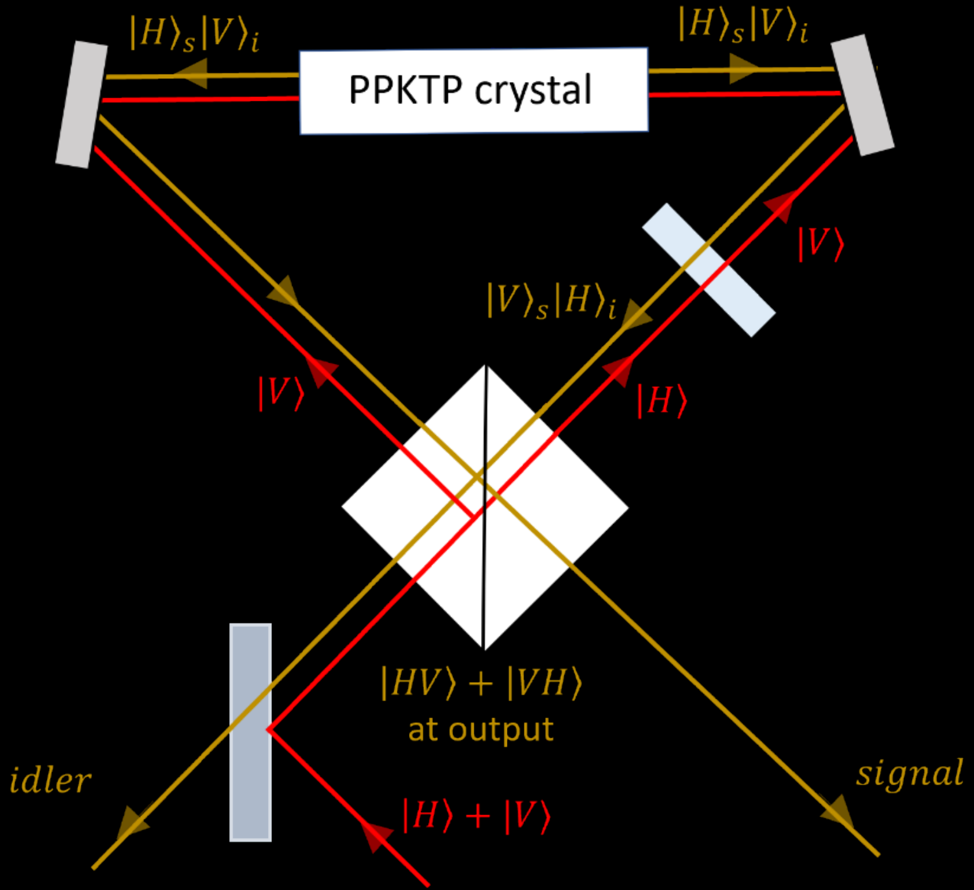
THE VISION

Send one photon from each pair of polarization-entangled photons in a loop to the library, where users can perform a Bell test (CHSH inequality)

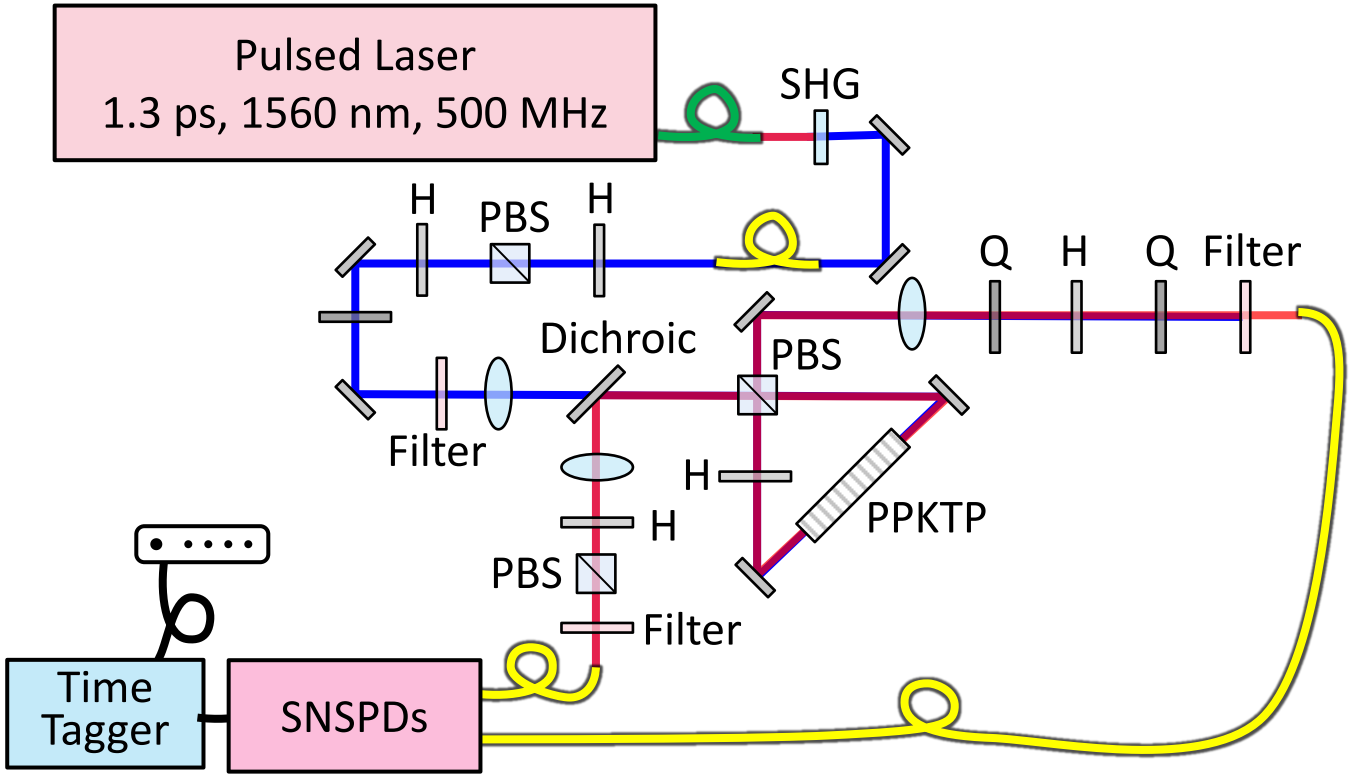


THE ENTANGLEMENT SOURCE

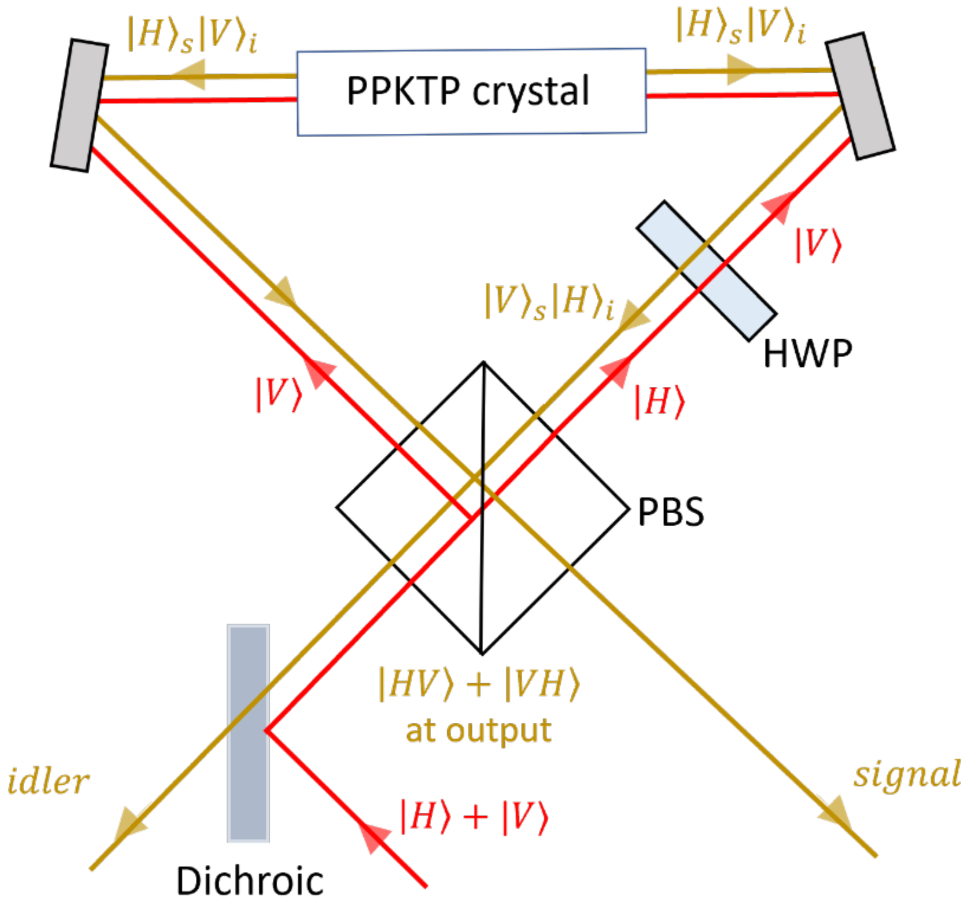




SPDC SOURCE



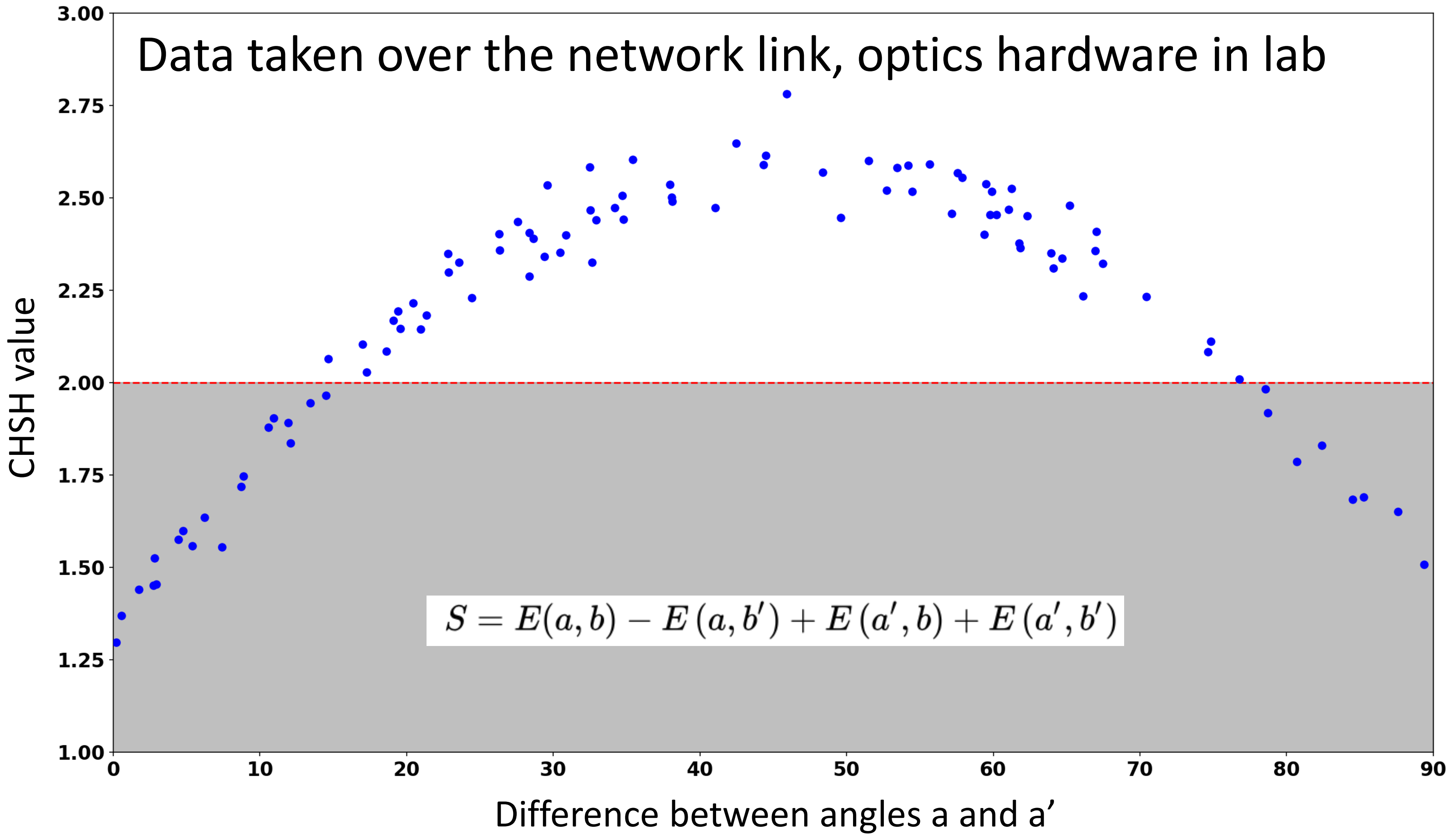
Pulsed Laser
1.3 ps, 1560 nm, 500 MHz
SHG
H
PBS
H
Q
H
Q
Filter
Dichroic
PBS
Filter
H
H
PPKTP
PBS
Filter
Time Tagger
SNSPDs



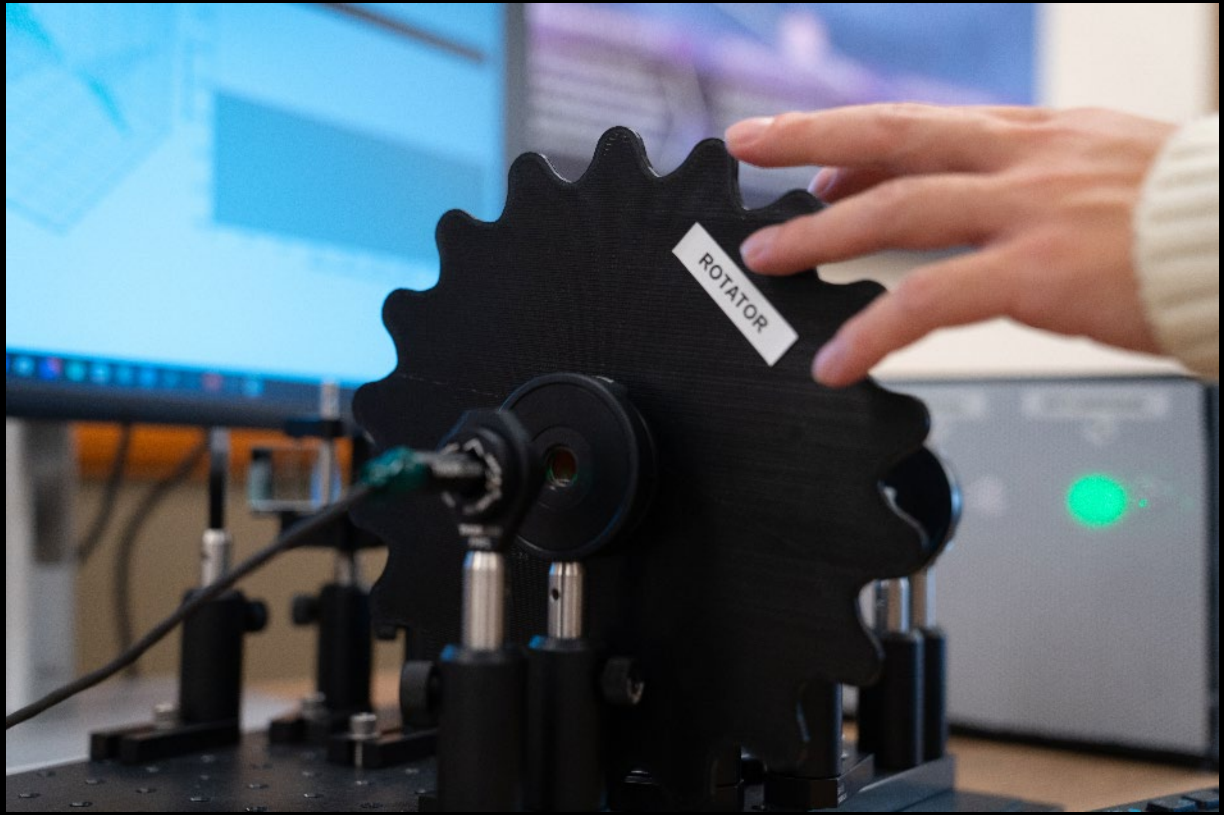
$|H\rangle_s|V\rangle_i$
PPKTP crystal
$|H\rangle_s|V\rangle_i$
$|V\rangle$
$|V\rangle_s|H\rangle_i$
HWP
$|V\rangle$
$|H\rangle$
PBS
$|HV\rangle + |VH\rangle$
at output
idler
signal
$|H\rangle + |V\rangle$
Dichroic

CHSH VS ANGLE DIFFERENCE

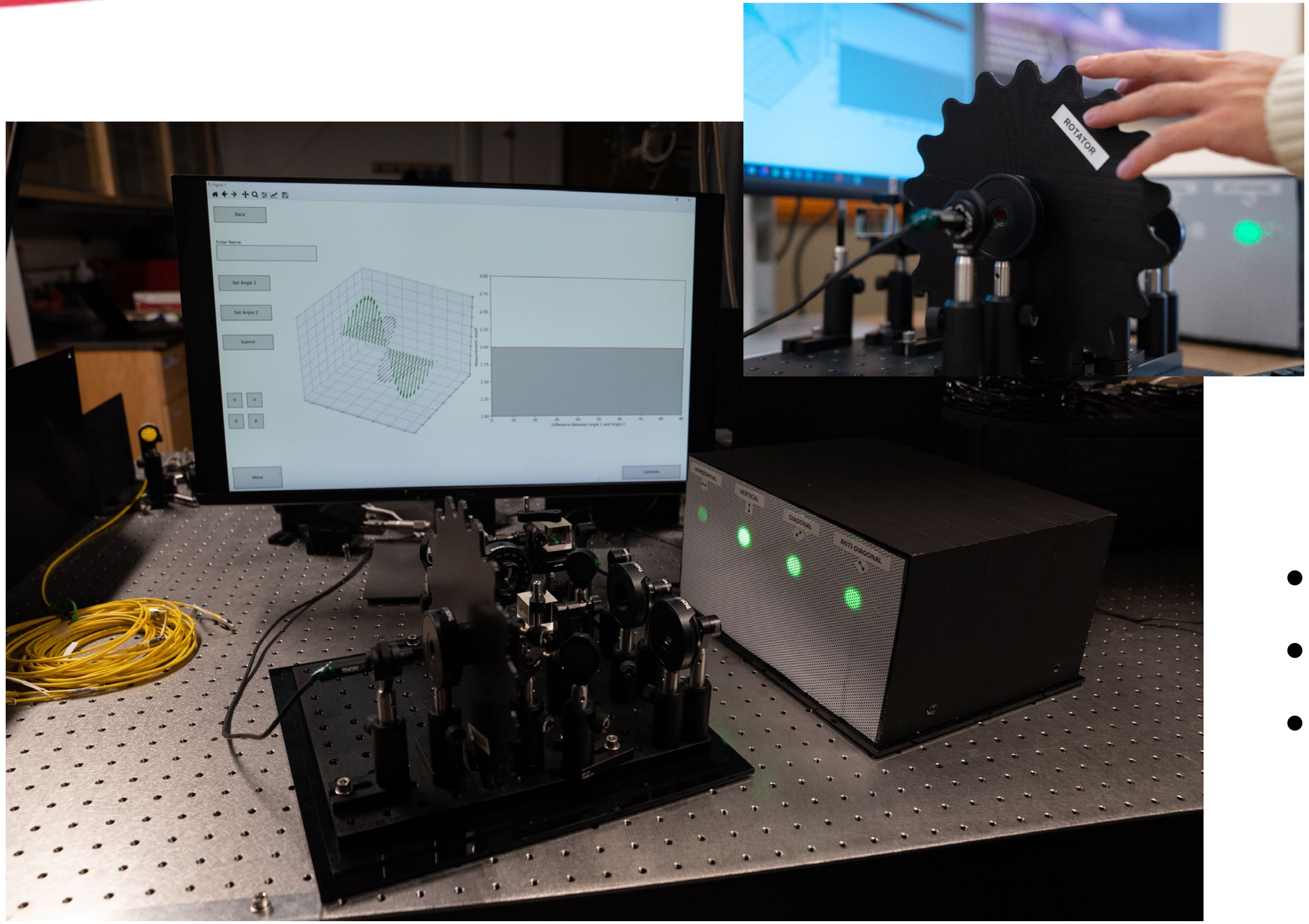
- Analytical fit function can provide CHSH results to users while automation is still under construction

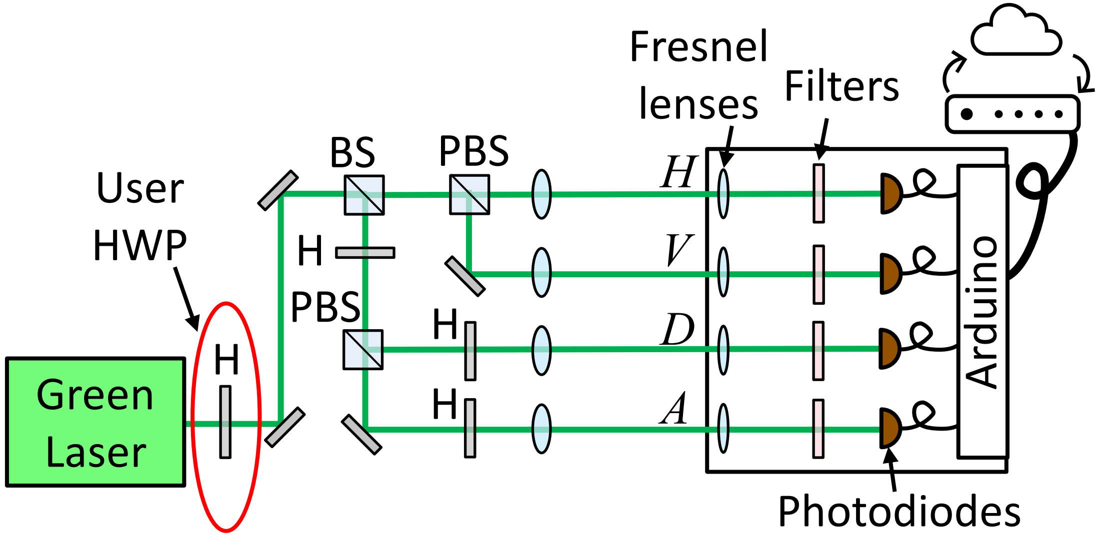


THE PUBLIC INTERFACE



MEASUREMENT SETUP

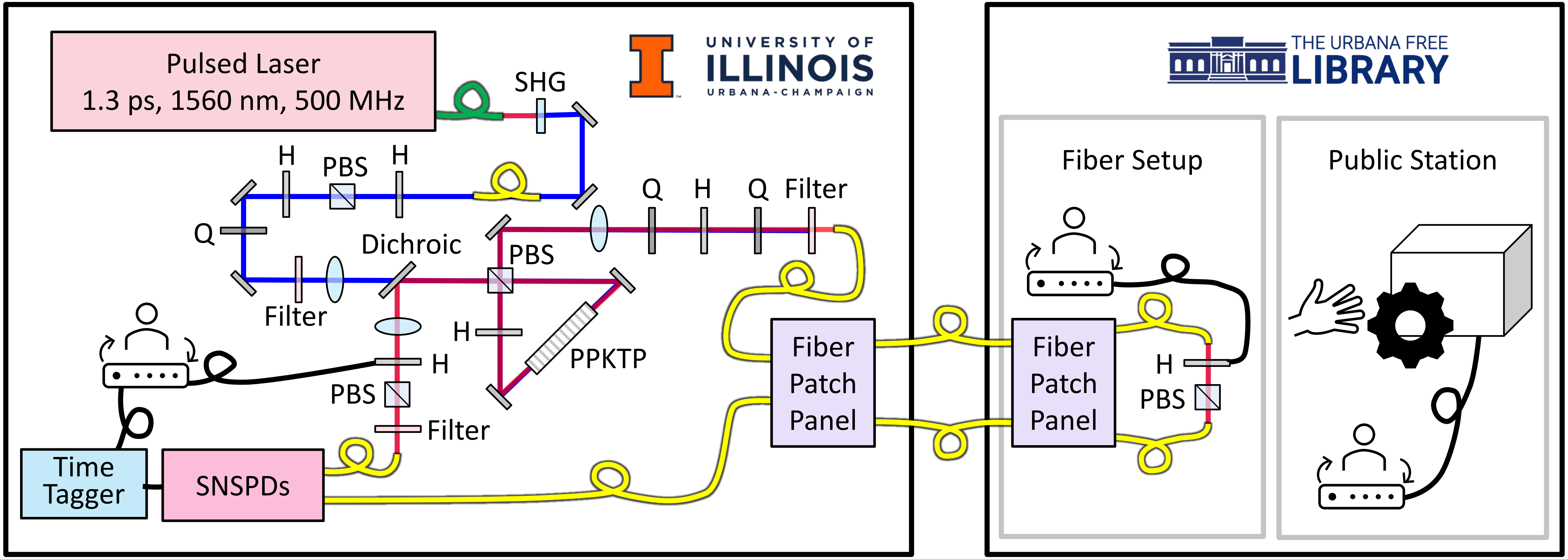




- 4 outputs: H, V, D, A
- Rotatable HWP to select using the lights
- User enters 2 CHSH angles for library node; the other 2 are calculated to maximize CHSH value


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

THE QUANTUM NETWORK V.1



Measurements facilitated by communication amongst researchers

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

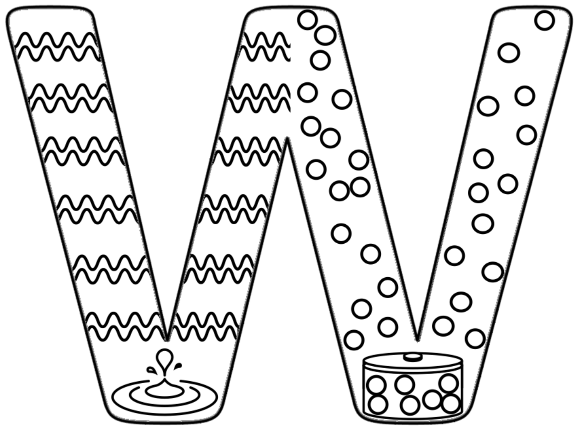
UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN


PUBLIC
QUANTUM
NETWORK


GRAINGER
ENGINEERING

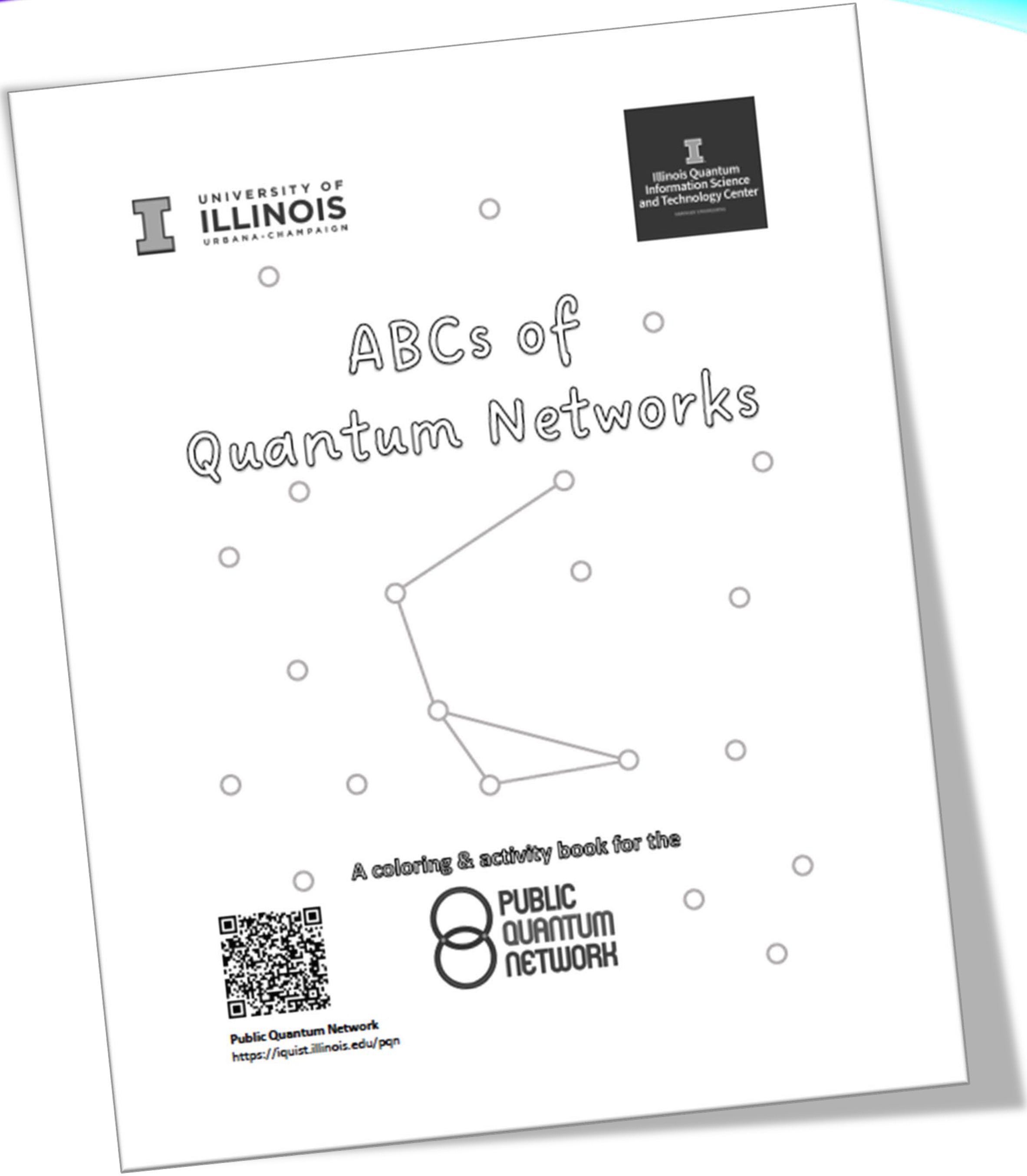
Print out a coloring book!

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

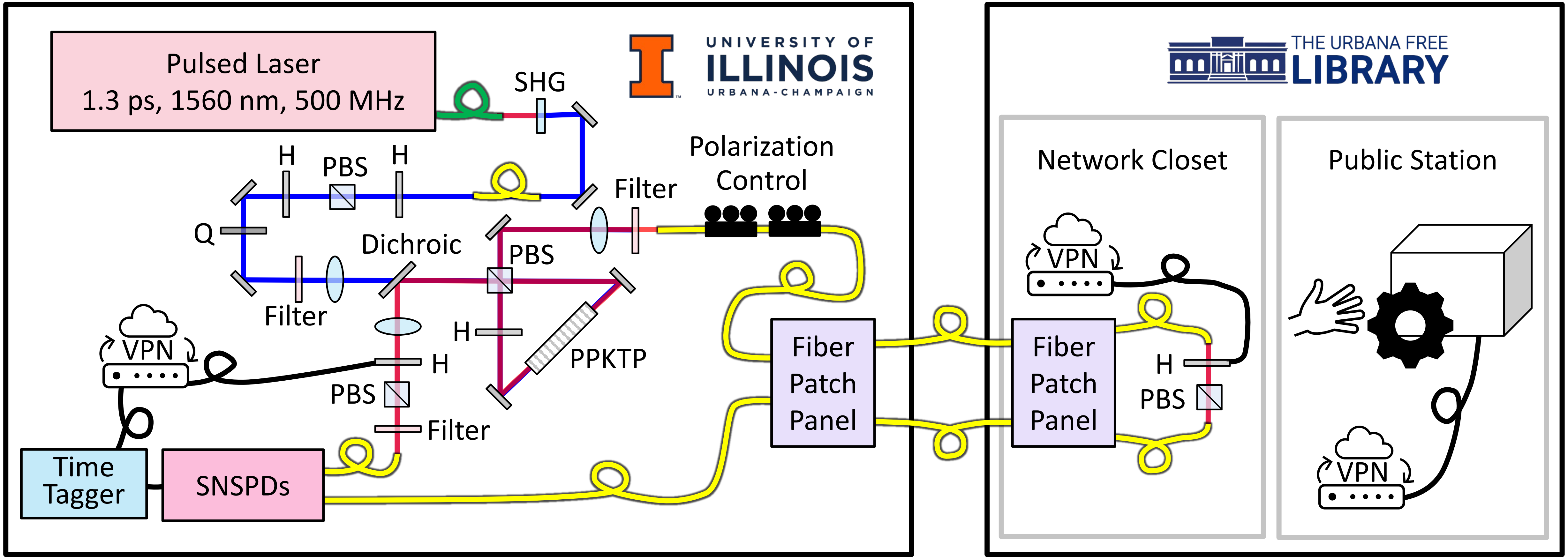


Wave-Particle Duality

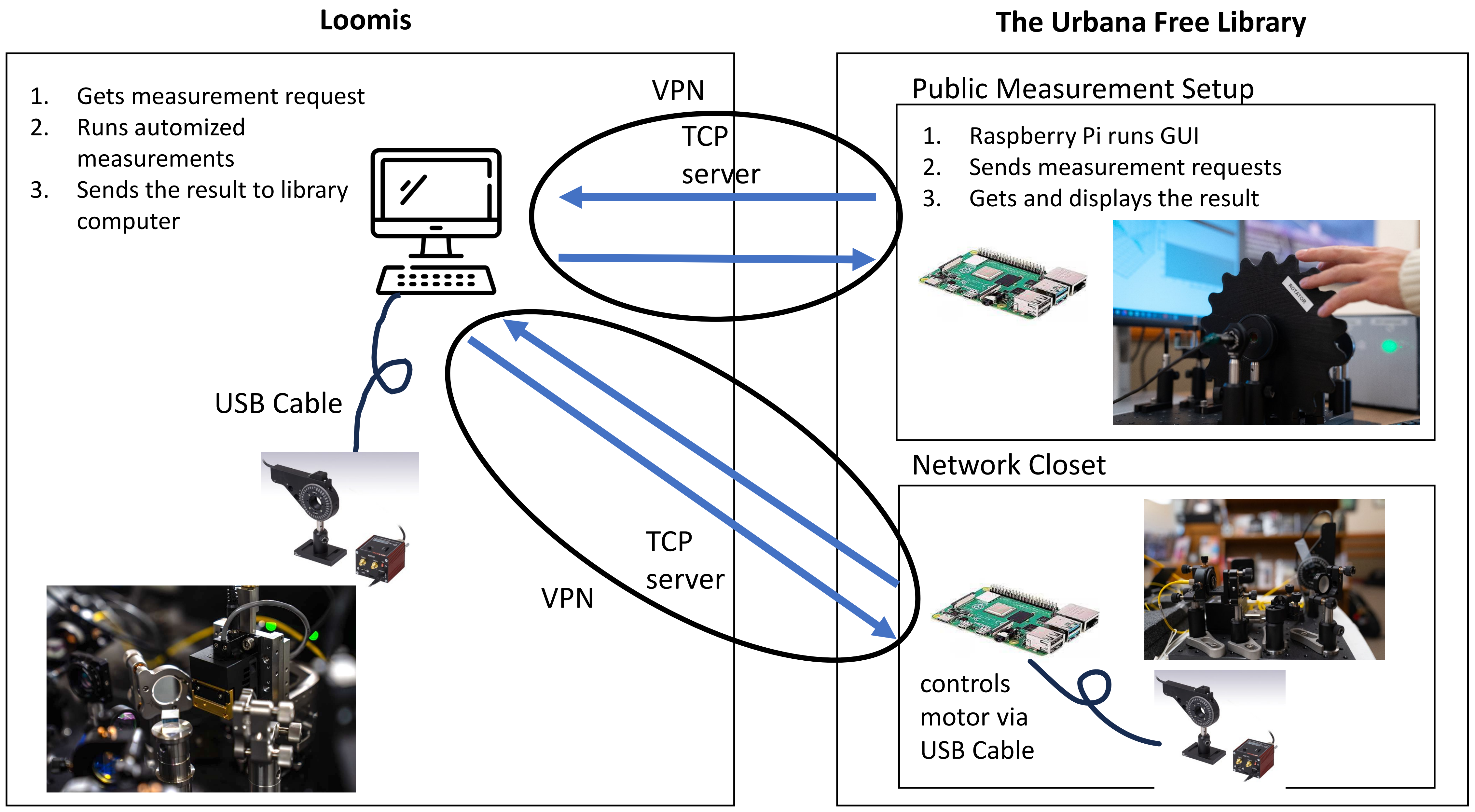
Do you ever feel sleepy and hungry at the same time? Quantum particles can be two things at the same time, too. They can act as both waves and particles.



THE QUANTUM NETWORK V.2



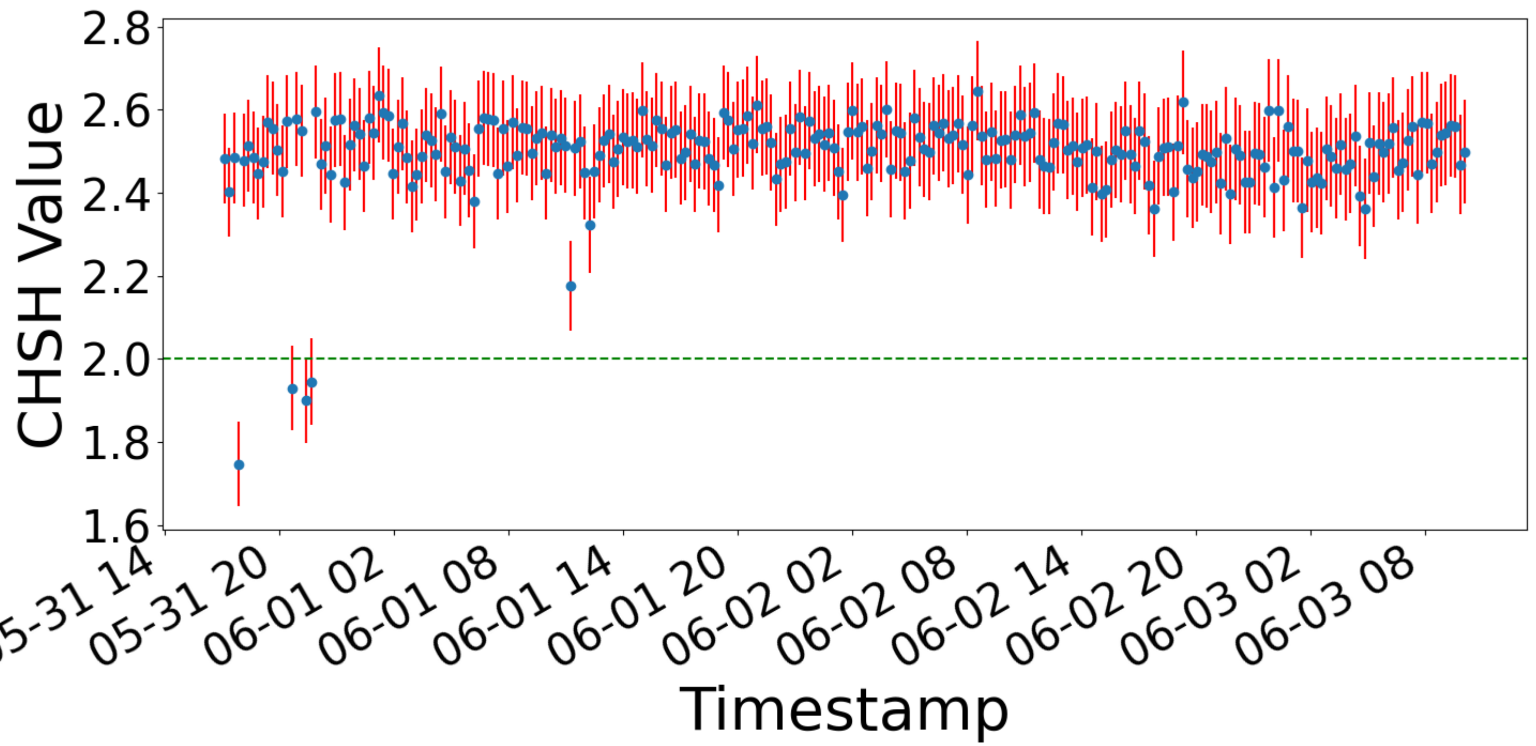
Fully automated measurements using VPN and TCP server; no active polarization control



Loomis
The Urbana Free Library
1. Gets measurement request
2. Runs automized measurements
3. Sends the result to library computer
VPN
TCP server
Public Measurement Setup
1. Raspberry Pi runs GUI
2. Sends measurement requests
3. Gets and displays the result
USB Cable
Network Closet
TCP server
VPN
controls motor via USB Cable

CHSH STABLE OVER 2 DAYS

- Fully automated CHSH measurements
- No active polarization compensation
- Most CHSH values stay above 2.4 for over 2 days
- Manually optimizing ~daily
- Next will implement active polarization compensation



WHAT'S NEXT?

Links to Chicago: Kankakee Community College

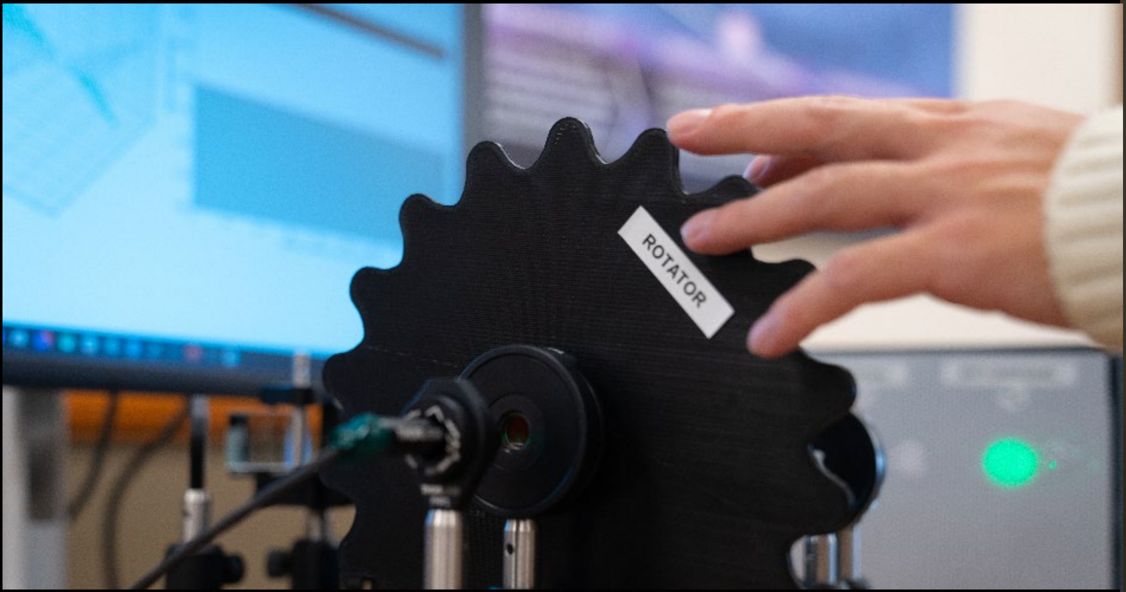
Fermilab Visitor's Center

Locally: preparing for next node, ongoing outreach activities

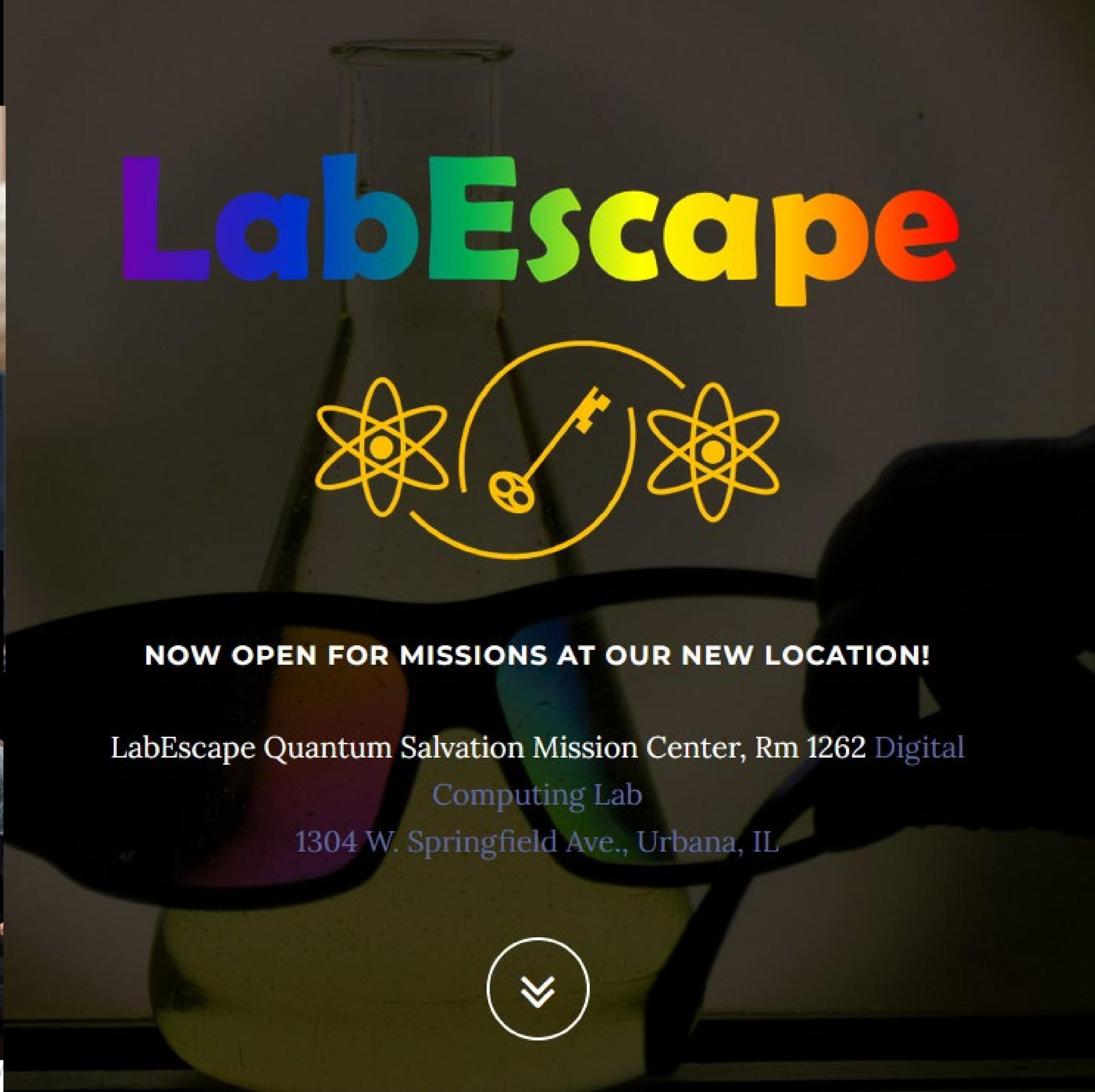
Next spring: add a second measurement station at the Urbana Free Library to give people the power to share "quantum valentines"

Next summer: build curricula with local high school teachers

Quantum outreach at UIUC



CASCADE: AN ARTS-SCIENCE CELEBRATION



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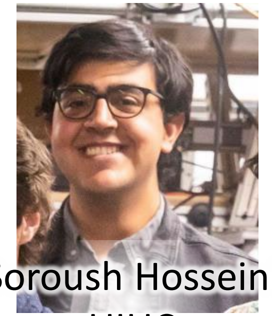
Soroush Hosseini
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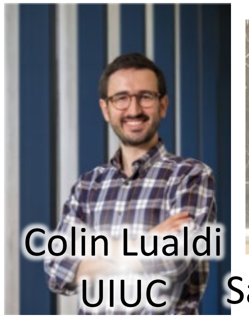
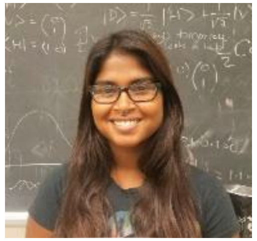
Benjamin Nussbaum
UIUC


Kriti Shetty
UIUC


Colin Lualdi
UIUC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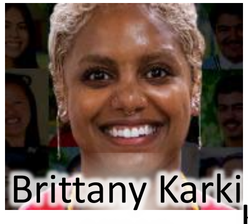
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Kelsey Ortiz
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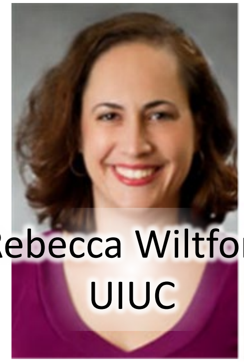
Chris Skaar
UIUC


Virginia Lorenz
UIUC


Paul Kwiat
UIUC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UIUC


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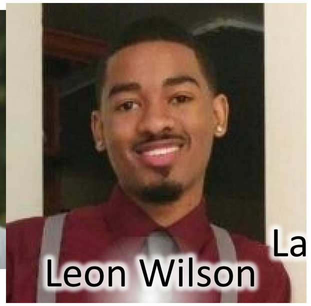
UC2B


Paul Hixson
UC2B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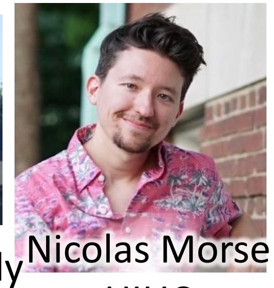
Lauren Chambers
TUFL


Dawn Cassady
TUFL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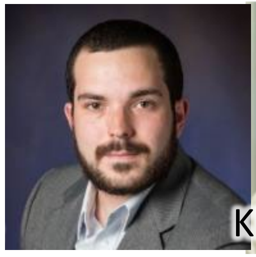
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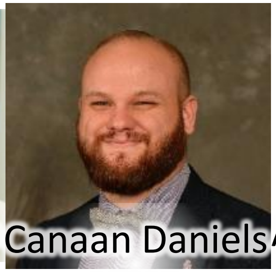
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Angela Graham
UIUC


Brian Demarco
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UC2B

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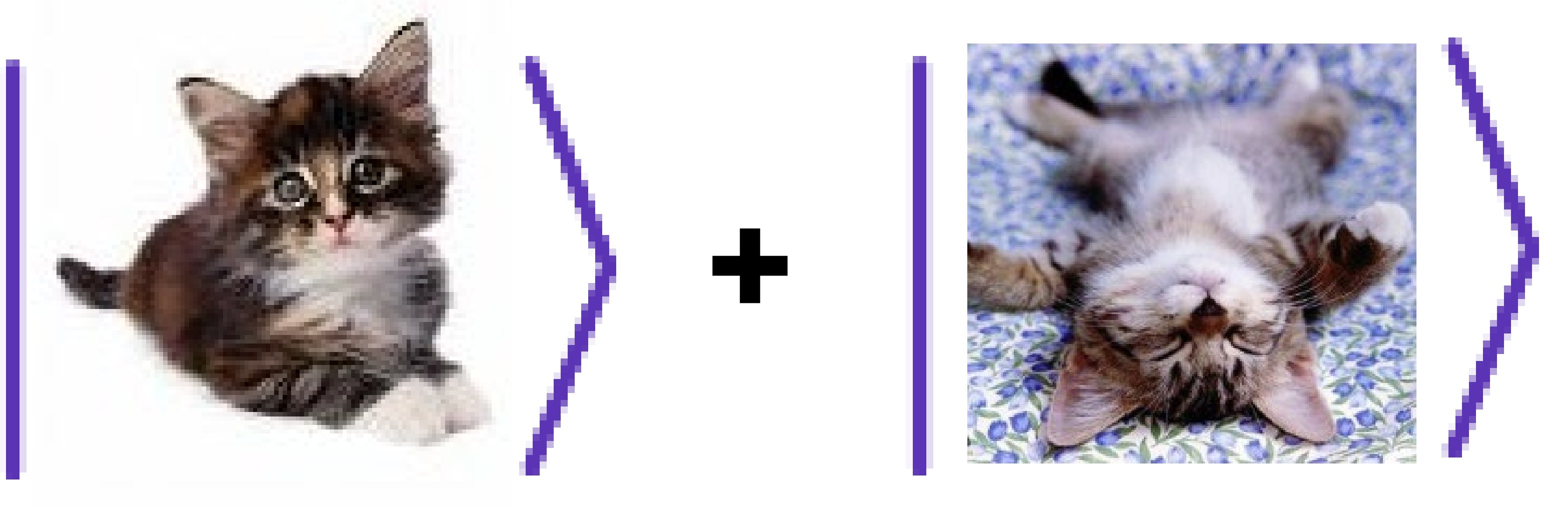
THANK YOU!



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