Entanglement

"About your cat, Mr. Schrödinger—I have good news and bad news."

Virginia O. Lorenz, Paul Kwiat, Brad Christensen

PHYS403 Spring 2021

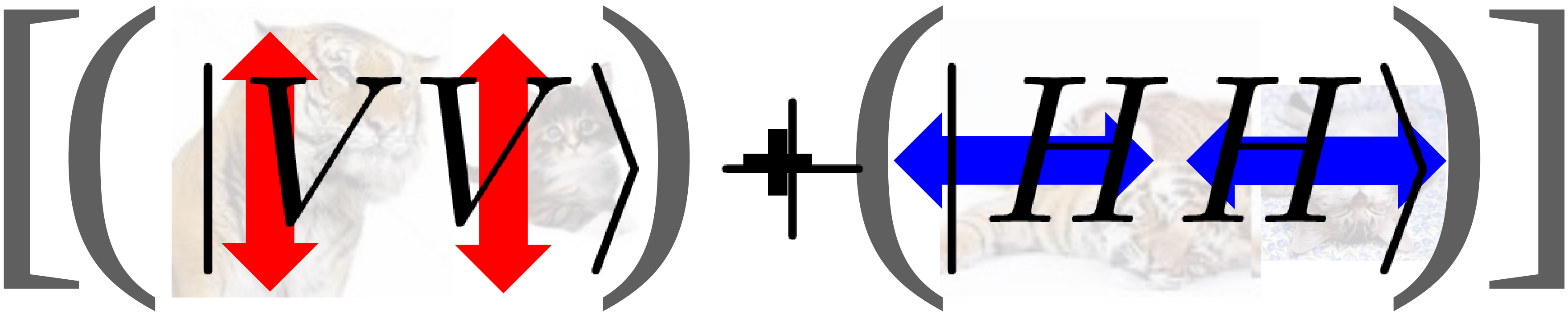
Entanglement

- A quantum object can be in a superposition of two states
- The cat is a quantum object
- Make a cat a quantum object
- It can be awake and asleep
- If we check, it will be in only one of the states

- If we have two objects, we can entangle the states such that knowing about one object affects the other

Entanglement

- An Entangled State:



- If I measure one object, it will end up in just one state, causing the other object to also be in just one state

- E.g. photons whose polarizations are entangled: $|\updownarrow\updownarrow\rangle + |\leftrightarrow\leftrightarrow\rangle$

$$|VV\rangle + |HH\rangle$$

Properties of Entanglement

at least

"It takes ^ two to tangle."
J. Eberly, 2015

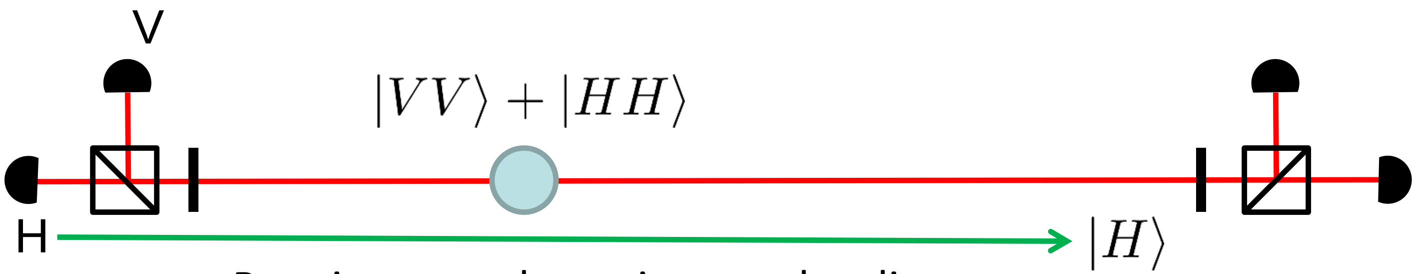
$$\psi_{pair} \propto |HH\rangle + |VV\rangle$$ Entangled

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

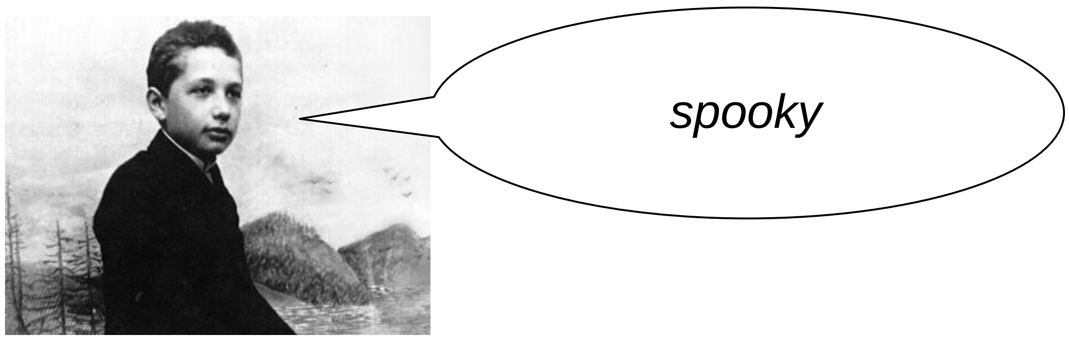
$$\psi_{12} = \psi_1 \psi_2 \propto |HH\rangle + |VV\rangle + |HV\rangle + |VH\rangle$$ Not Entangled

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).

1964: Bell's theorem

- Bell's theorem shows Quantum Mechanics gives different statistical predictions than any local realistic model
  - Certain inequalities are violated if non-local correlations exist, tested by measuring statistical correlations between spatially separated entangled systems

"If [a hidden variable theory] is local it will not agree with quantum mechanics, and if it agrees with quantum mechanics it will not be local."
– John Bell, 1975

J.S. Bell, Physics **1**, 195-200 (1964)

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,‡]

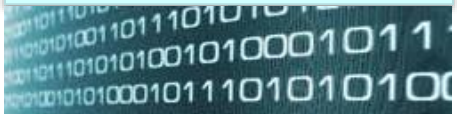
[1]*National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305, USA*
[2]*Institute for Quantum Computing and Department of Physics and Astronomy, University of Waterloo, 200 University Avenue West, Waterloo, Ontario, Canada, N2L 3G1*
[3]*Department of Physics, University of 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)

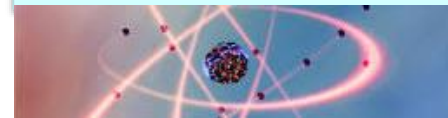
We present a loophole-free violation of local realism using entangled photon pairs. We ensure that all relevant events in our Bell test are spacelike separated by placing the parties far enough apart and by using fast random number generators and high-speed polarization measurements. A high-quality polarization-entangled 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

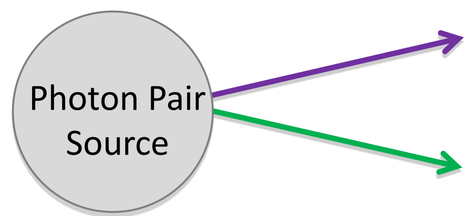
- Quantum Computing
- Quantum Communication
- Simulation of Quantum Systems
- Quantum Sensing

"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
…

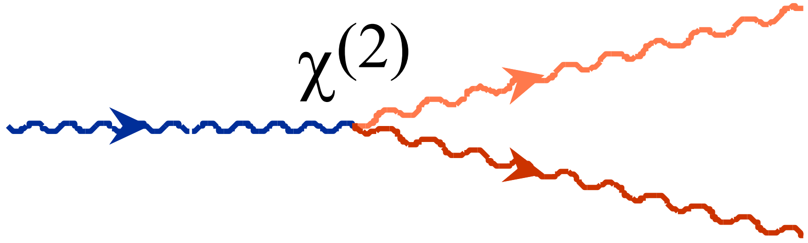
Spontaneous parametric down-conversion (SPDC)

Spontaneous four-wave mixing (SFWM)



1970: Spontaneous Parametric Down-Conversion

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



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

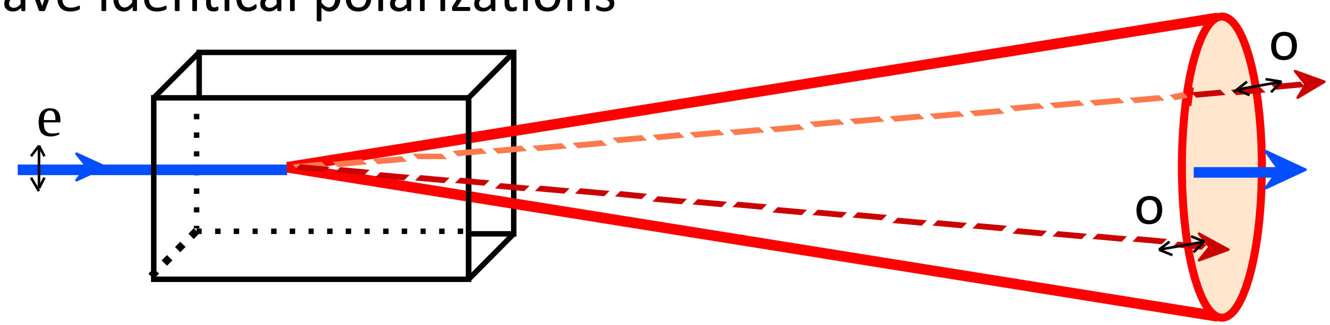
$$\vec{\kappa}_p = \vec{\kappa}_s + \vec{\kappa}_i \; \dagger$$

*Energy conservation → energy entanglement

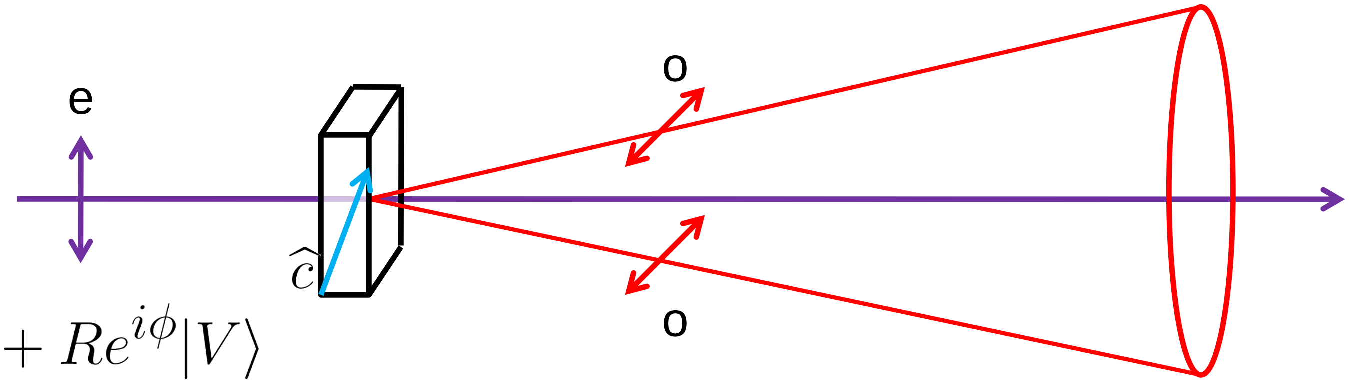
†Momentum conservation → momentum entanglement

Type-I phase-matching

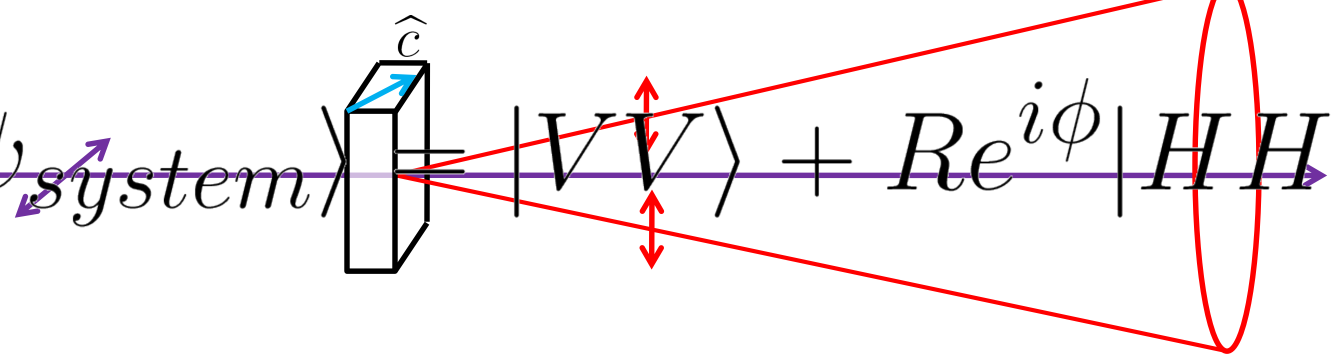
Photons have identical polarizations



Polarization Entanglement

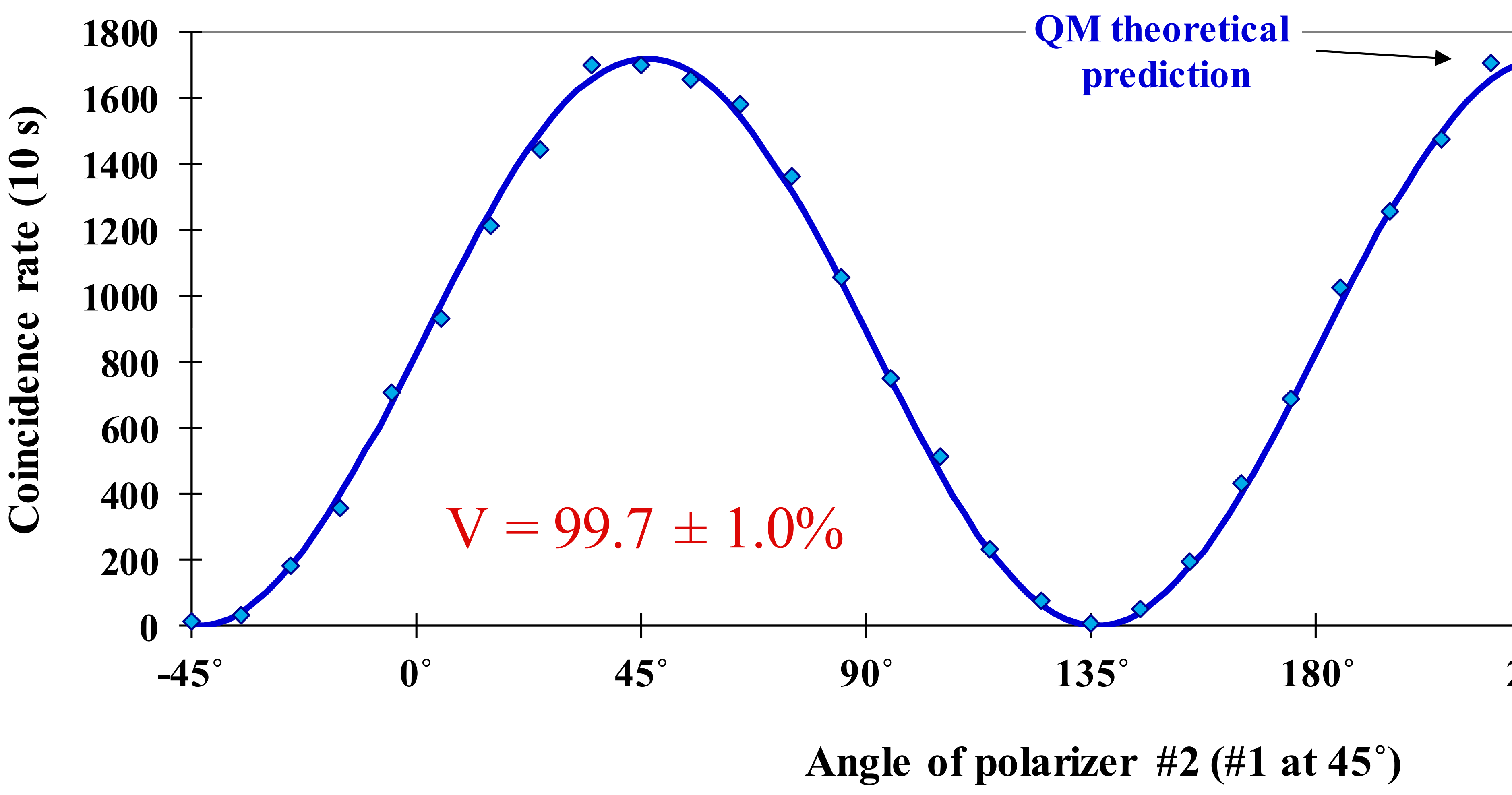


Input: $|H\rangle + Re^{i\phi}|V\rangle$

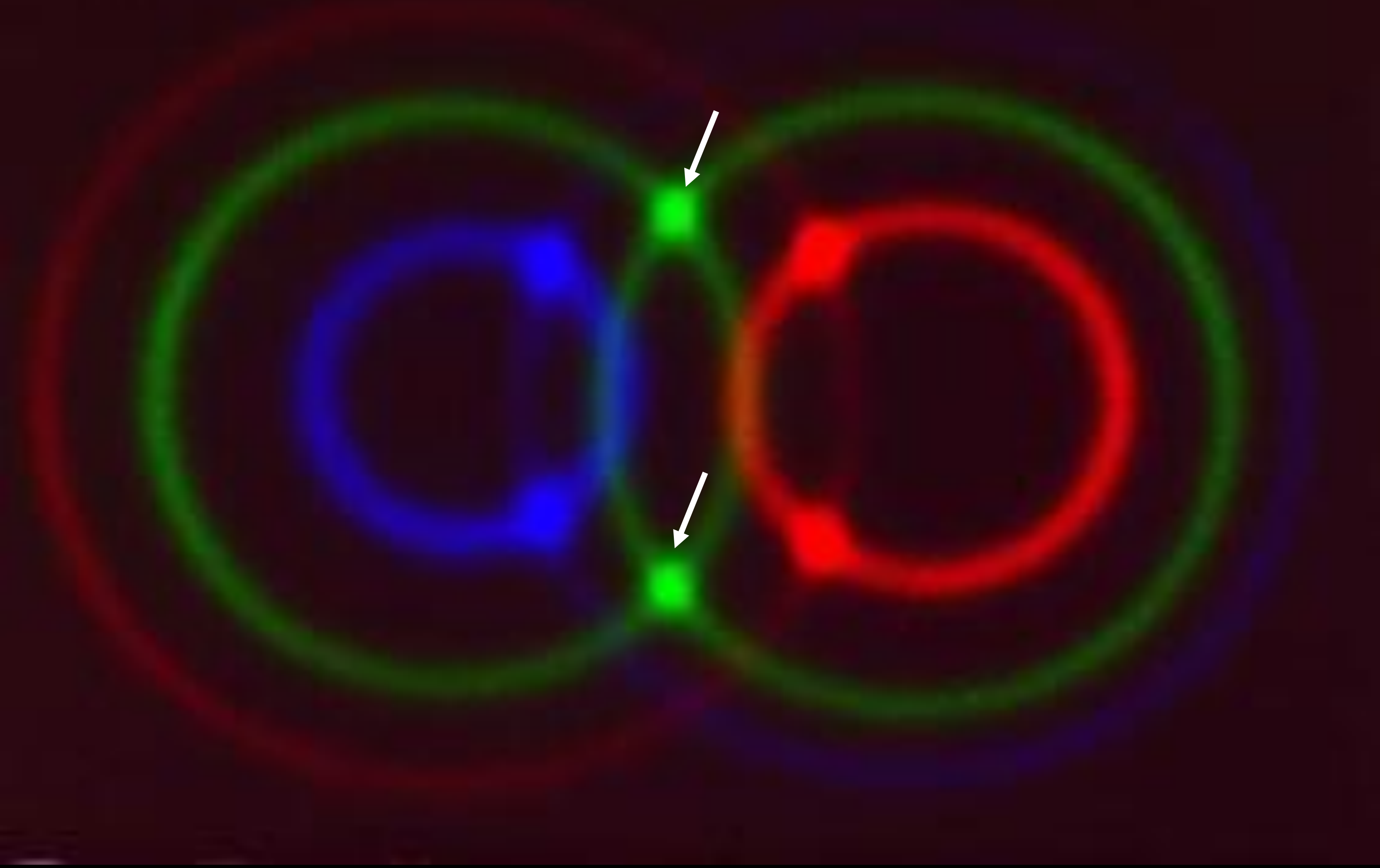


$$|\psi_{system}\rangle = |VV\rangle + Re^{i\phi}|HH\rangle$$

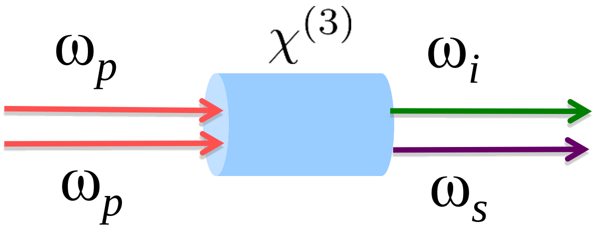
Proof of Quantum Correlations

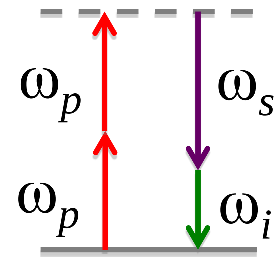


$$|\psi_{system}\rangle = |VV\rangle + Re^{i\phi}|HH\rangle$$



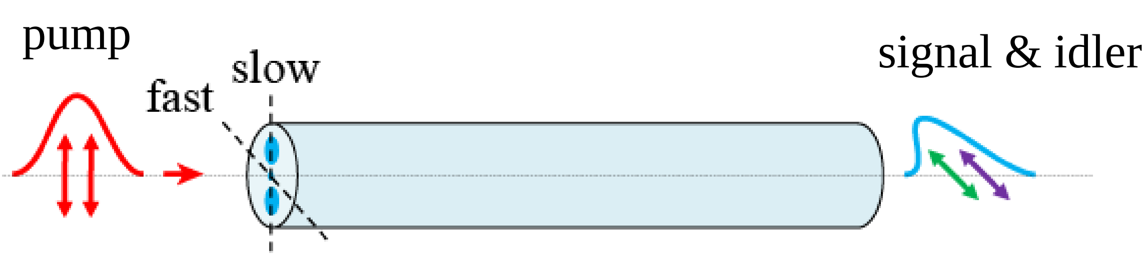
Spontaneous four-wave mixing





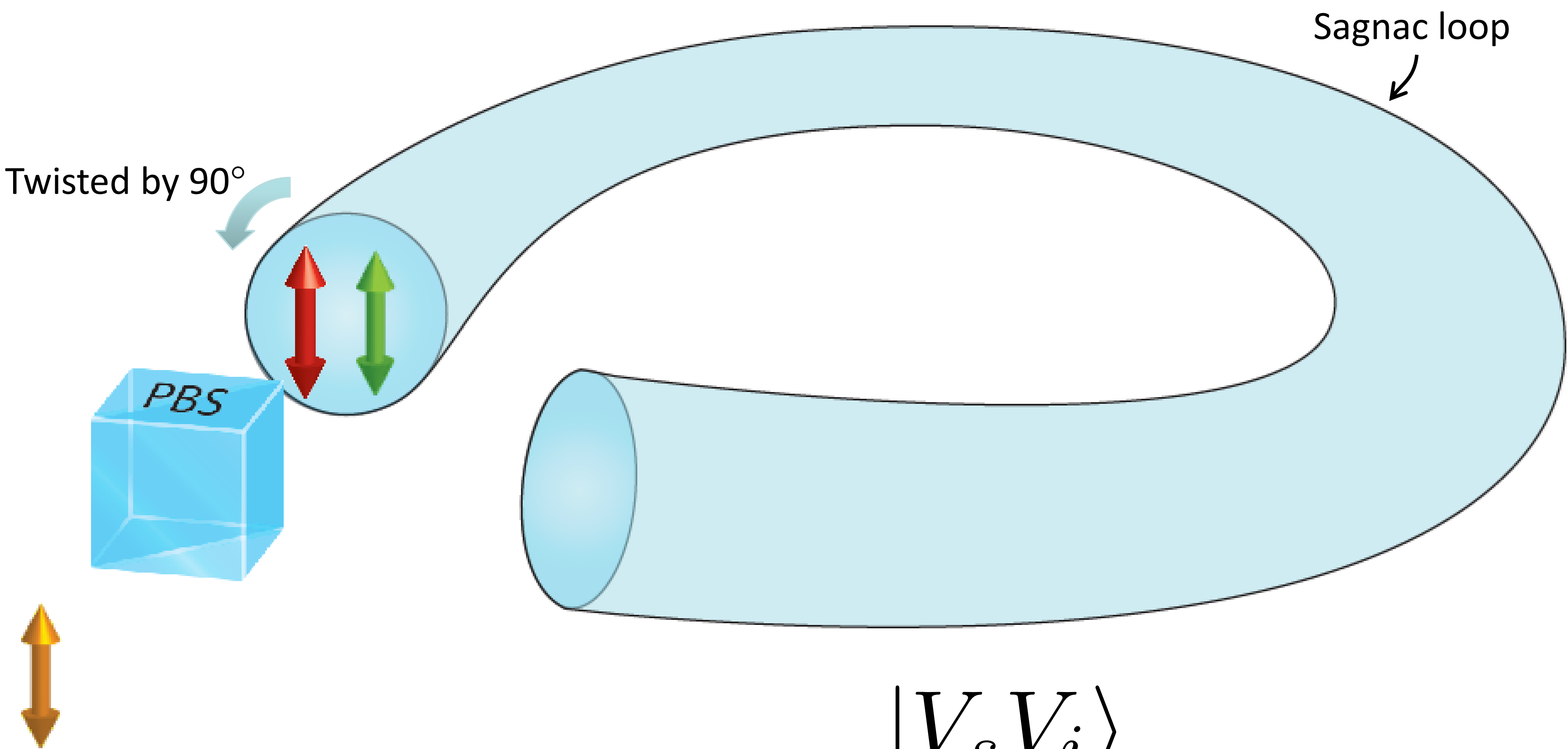
Conservation of energy

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



  – *Birefringent* phase-matching: $\Delta k = 2k(\omega_p) - k(\omega_s) - k(\omega_i) + 2\Delta n \frac{\omega_p}{c} = 0$

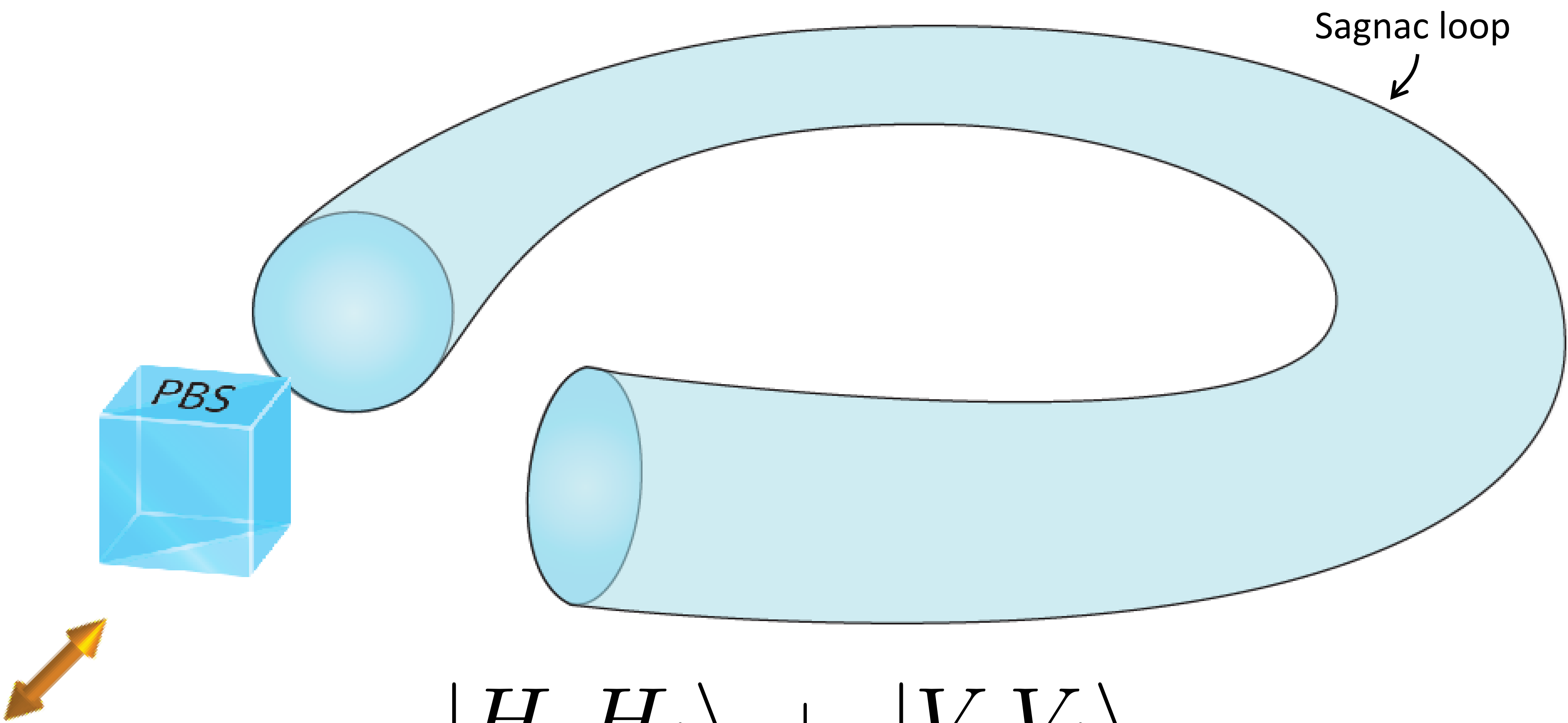
Generation of polarization entanglement



$$|V_s V_i\rangle$$

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



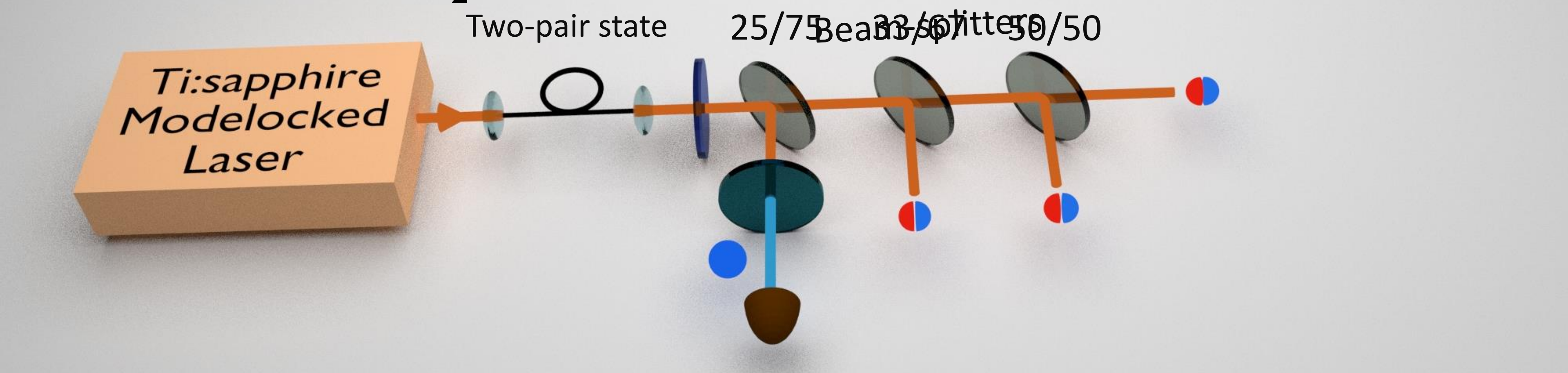
$$|H_s H_i\rangle + |V_s V_i\rangle$$

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

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

$$|\psi\rangle = \frac{\beta^2}{2}\left(a^{\dagger}_{\omega_B} a^{\dagger}_{\omega_R}\right)^2 |0\rangle$$



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

- 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

1	0	1

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

$$|000\rangle+|001\rangle+|010\rangle+|011\rangle+|100\rangle+|101\rangle+|110\rangle+|111\rangle = |0\rangle+|1\rangle+\ldots|7\rangle$$

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:

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

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

Quantum Logic

Controlled-Not Gate:

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

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

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

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

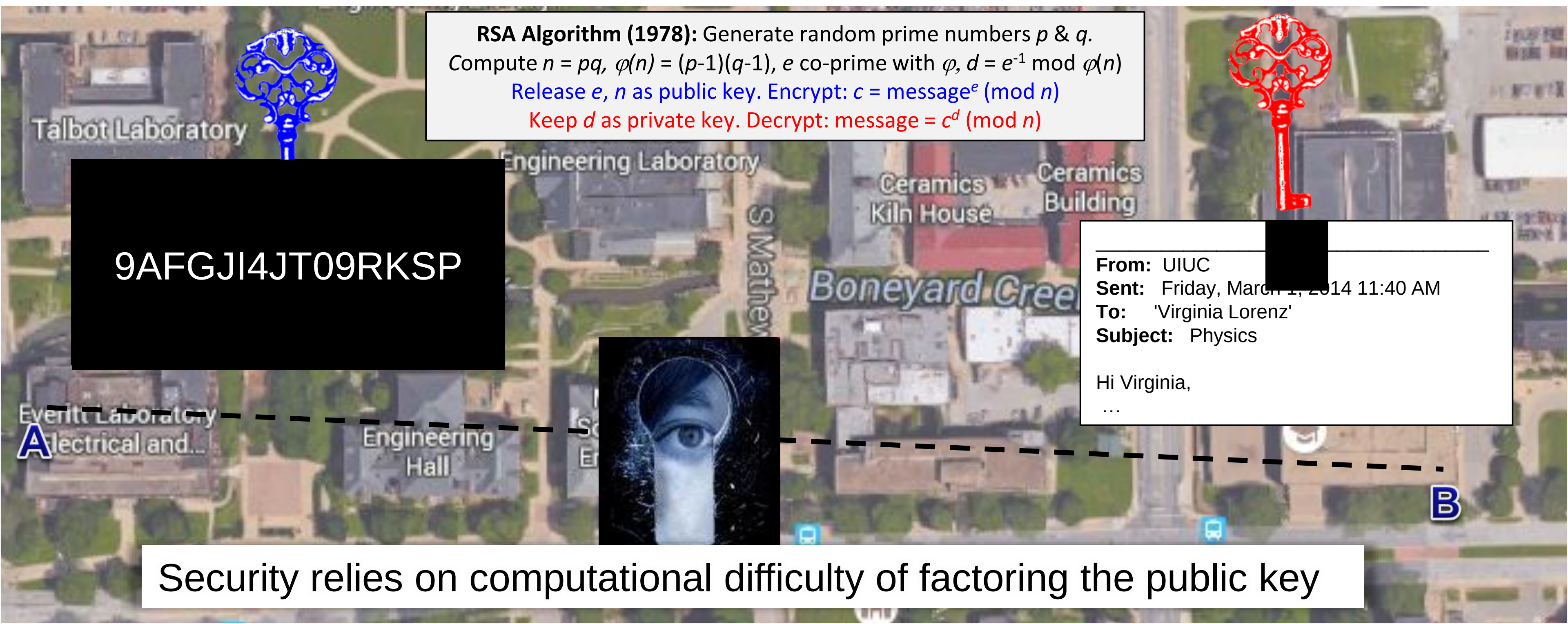
$$\left(|0\rangle_c + |1\rangle_c\right)|0\rangle_t \xrightarrow{CNOT} |0\rangle_c|0\rangle_t + |1\rangle_c|1\rangle_t$$

2-Qubit interactions lead to entangled states.

Classical Cryptography

USA TODAY:

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



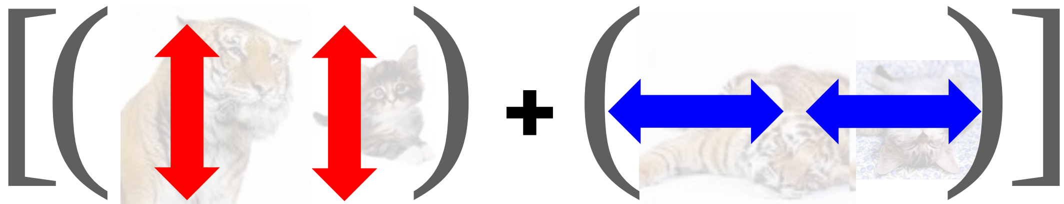
9AFGJI4JT09RKSP

From: UIUC
Sent: Friday, Marc[redacted]014 11:40 AM
To: 'Virginia Lorenz'
Subject: Physics

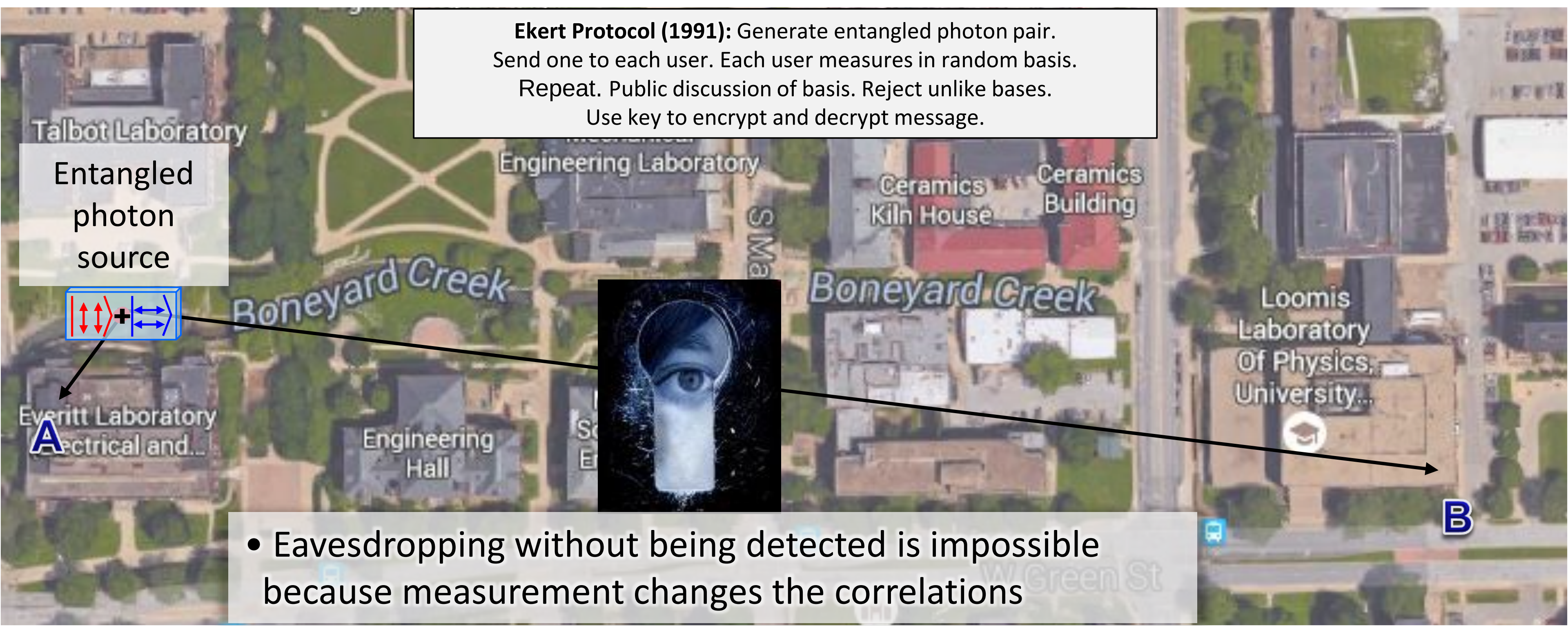
Hi Virginia,
…

Security relies on computational difficulty of factoring the public key

Quantum Key Distribution



Security is guaranteed by the laws of quantum physics!



Ekert Protocol (1991): Generate entangled photon pair. Send one to each user. Each user measures in random basis. Repeat. Public discussion of basis. Reject unlike bases. Use key to encrypt and decrypt message.

Entangled photon source

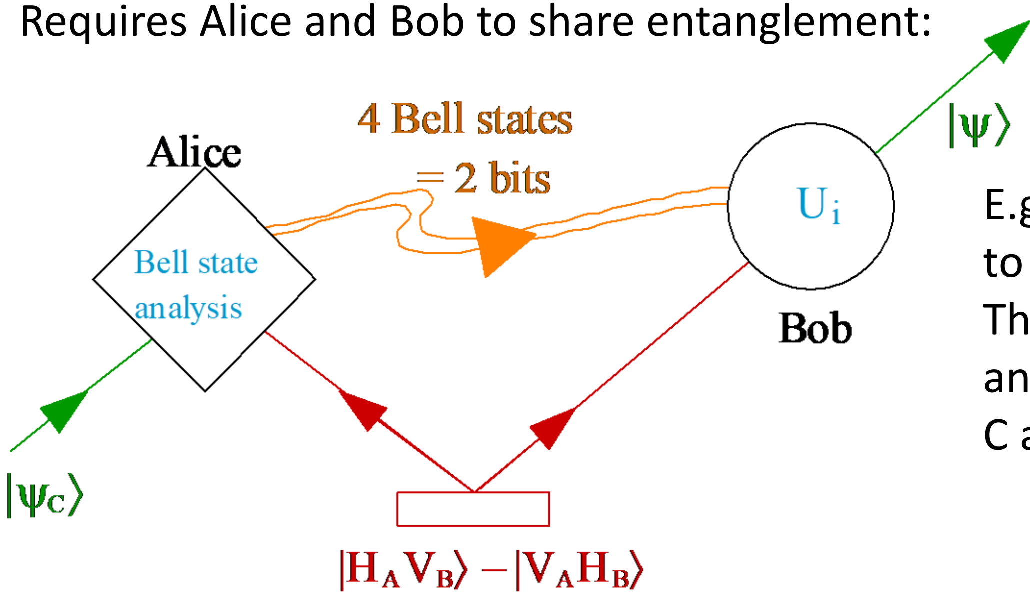
- Eavesdropping without being detected is impossible because measurement changes the correlations

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!

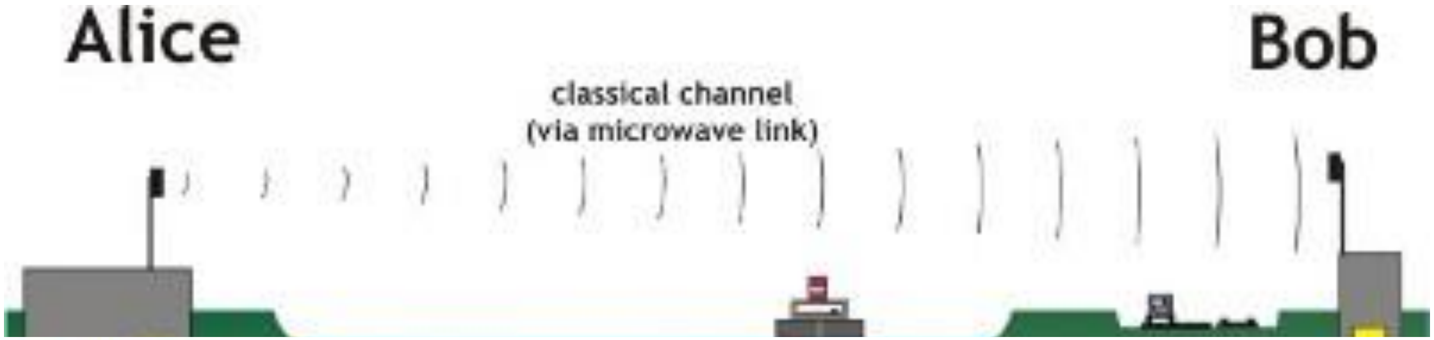
Remarks:

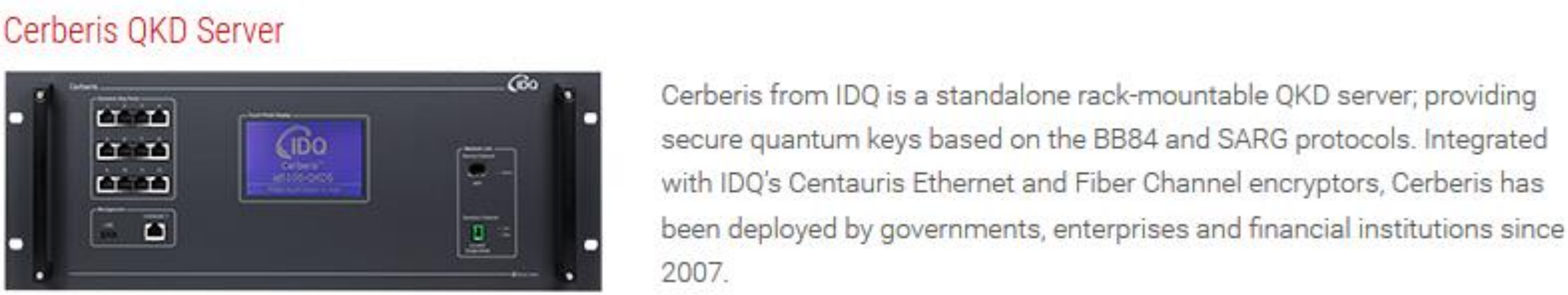
- The original state is gone.
- Neither Alice nor Bob know what it was.
- Requires classical communication – no superluminal signaling.
- Bell state analysis is hard.

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)]





http://www.idquantique.com/quantum-safe-crypto/

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

Satellite-to-ground QKD

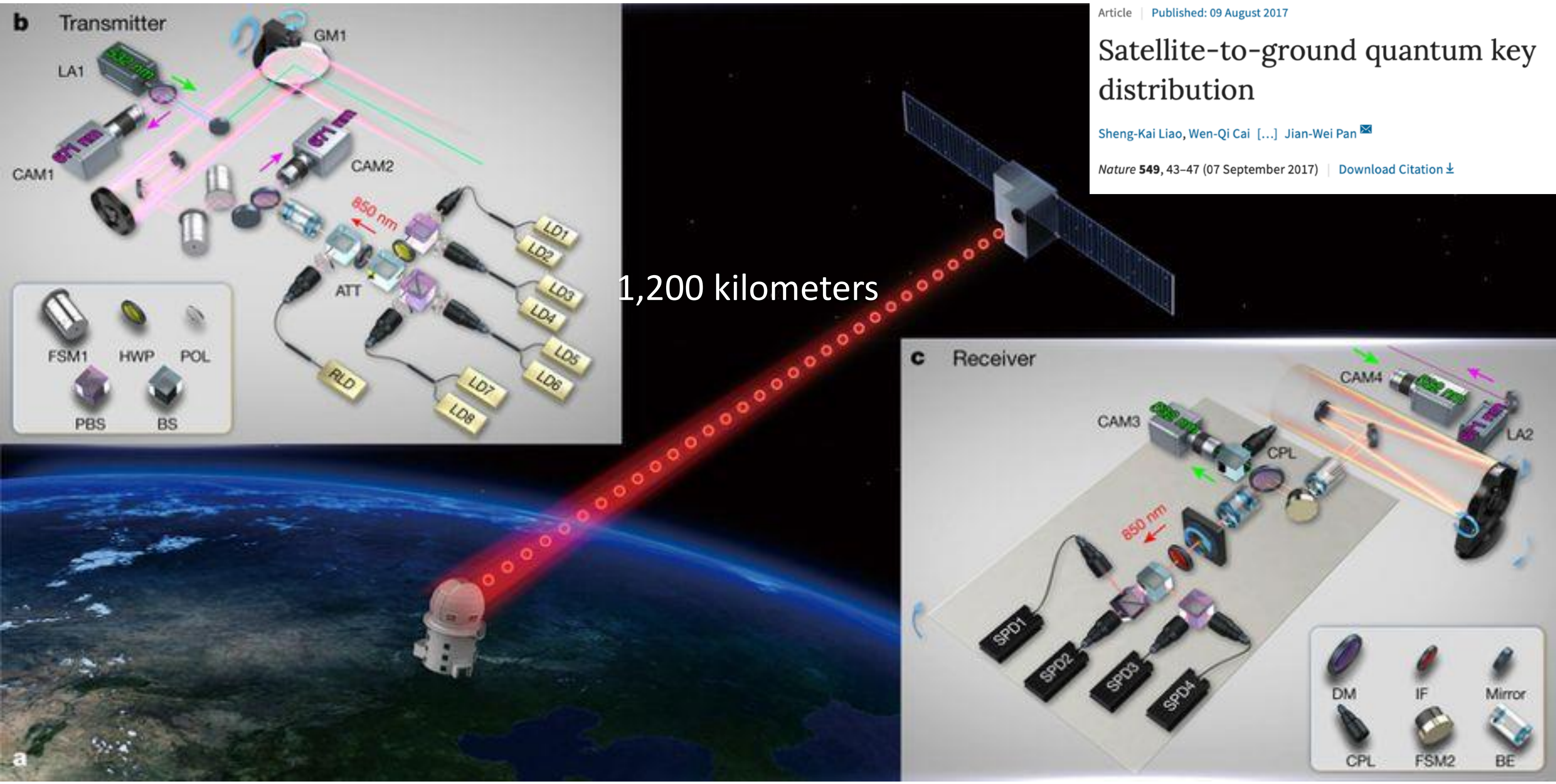
nature
International journal of science

Article | Published: 09 August 2017

Satellite-to-ground quantum key distribution

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

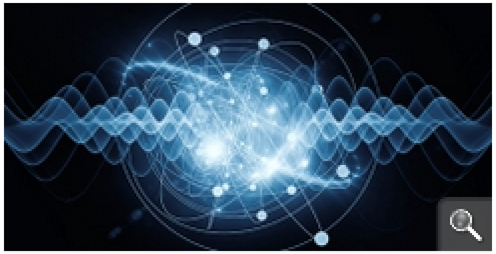
Nature **549**, 43–47 (07 September 2017) | Download Citation



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

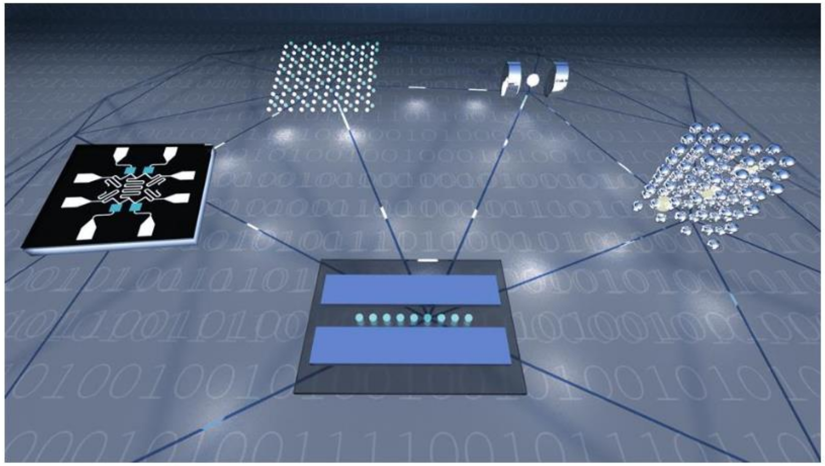


Image by Emily Edwards, IQUIST

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.

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.

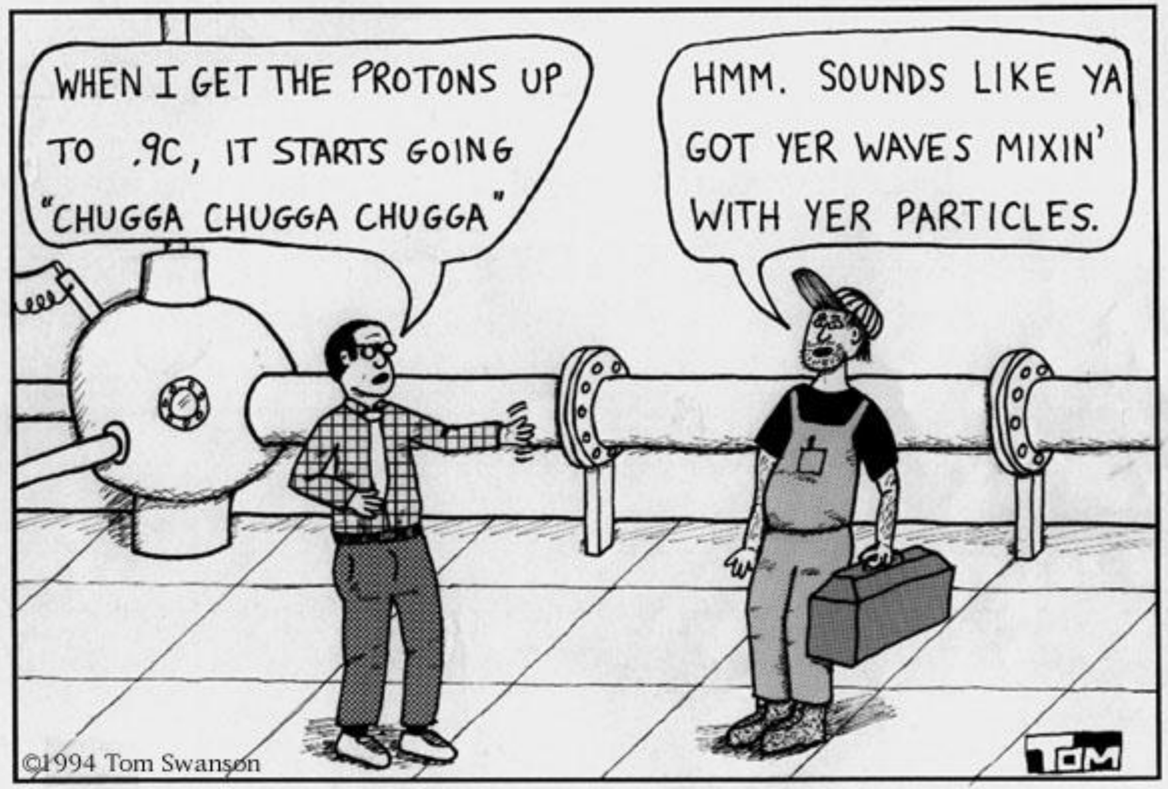
Around the world, consensus is building that a system to communicate using quantum mechanics represents one of the most important technological frontiers of the 21st century. Scientists now believe that the construction of a prototype will be within reach over the next decade.

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

Conclusion

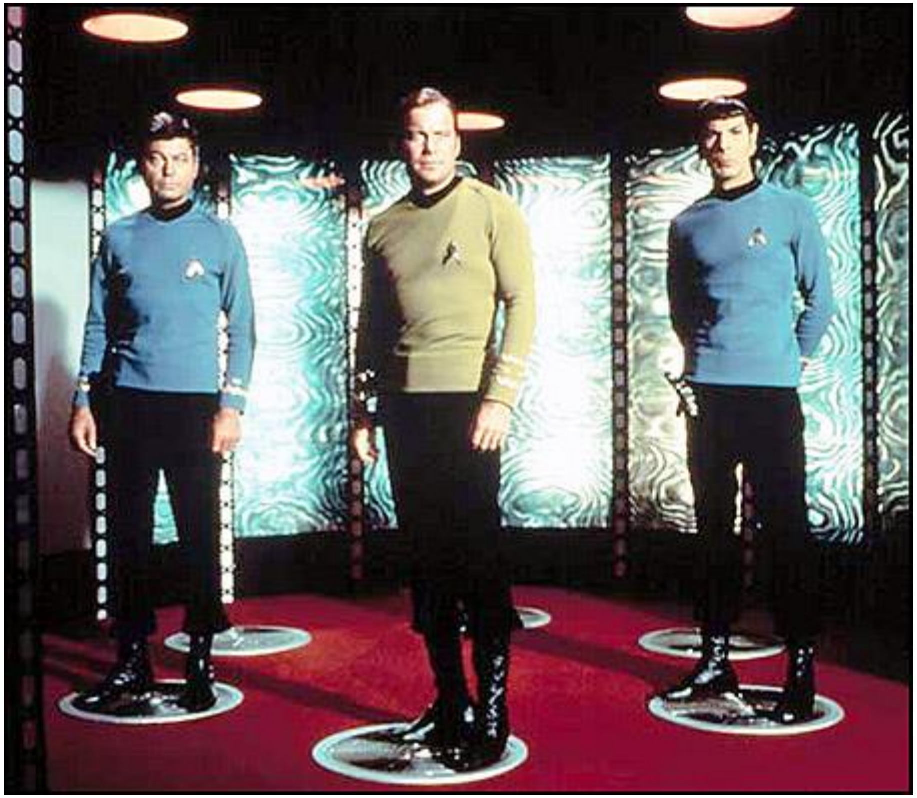
- Quantum entanglement breaks local realism
- Generating entangled photons & reconstructing their state is relatively easy, but engineering for applications is still a challenge
- Entanglement is not just spooky, it's useful!

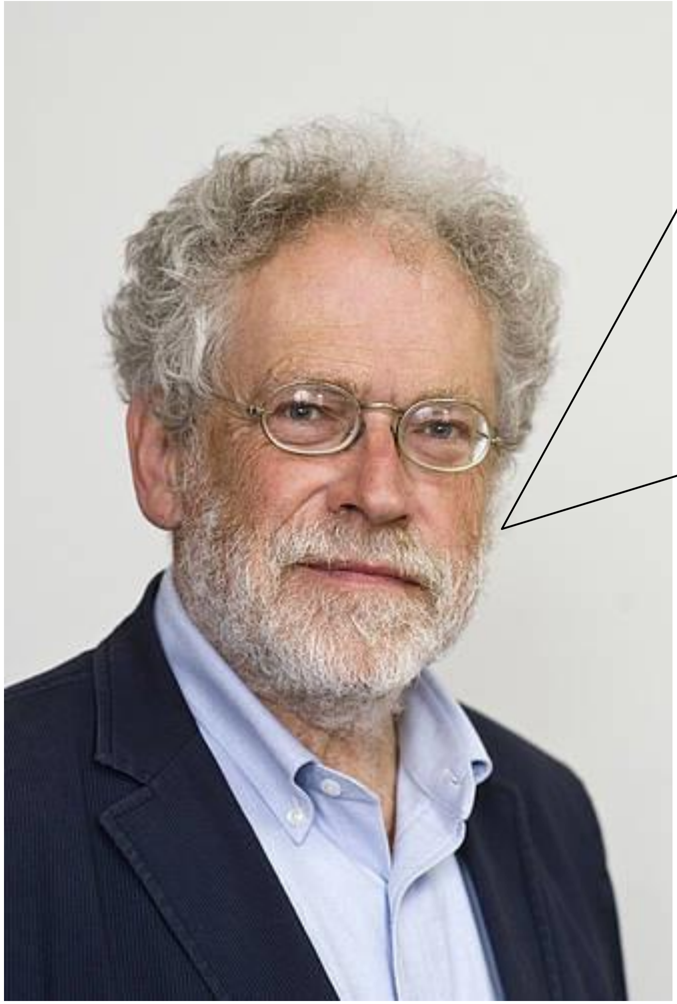


QUANTUM MECHANIC

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