Entanglement

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

arnoldzwicky.org

Virginia O. Lorenz, Paul Kwiat, Brad Christensen

PHYS403

Entanglement

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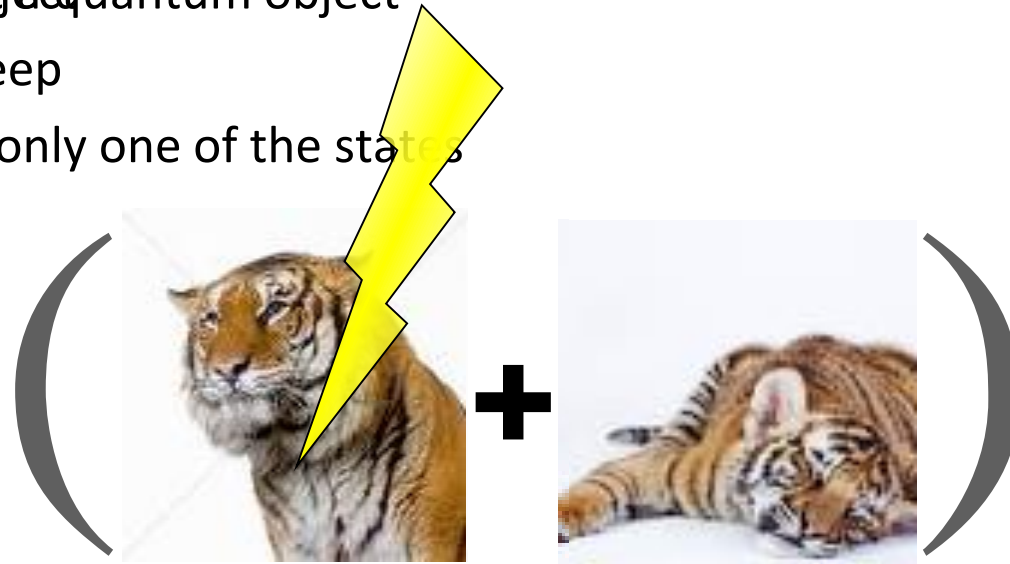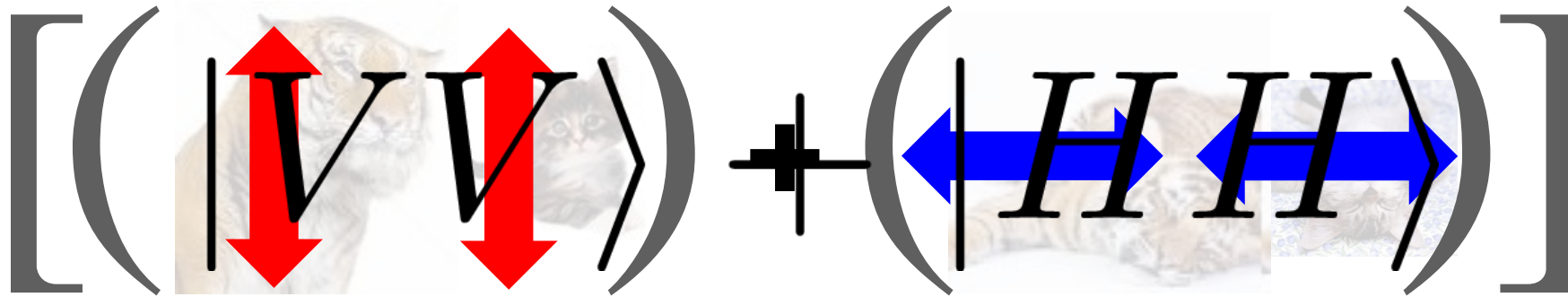

- If we have two objects, we can entangle the states such that knowing about one object affects the other

Entanglement

- An Entangled State:

$$\left[\left(|VV\rangle \right) + \left(|HH\rangle \right) \right]$$

- 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: $|\uparrow\uparrow\rangle + |\leftrightarrow\leftrightarrow\rangle$

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

Properties of Entanglement

at least

"It takes ^ two to tangle."

J. Eberly, 2015

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

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

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

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

V

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

H → $|H\rangle$

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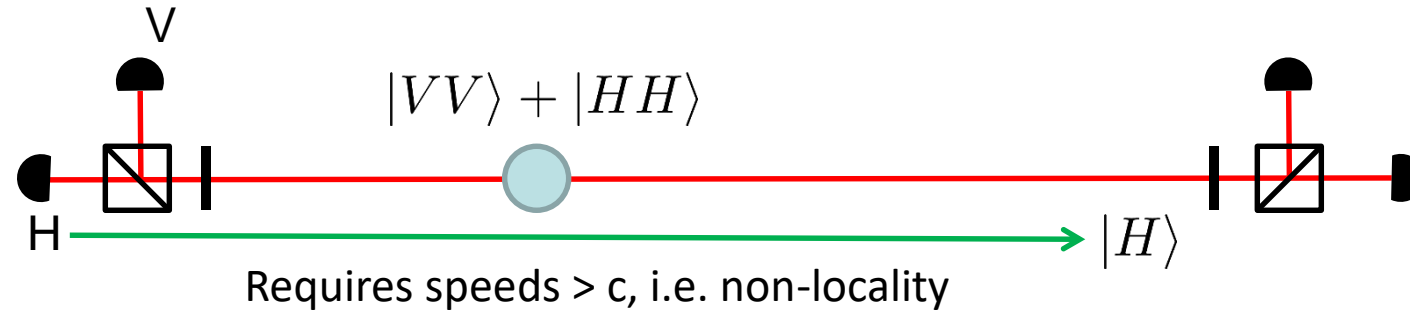
spooky

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)

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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Gaithersburg, Maryland 20899, USA
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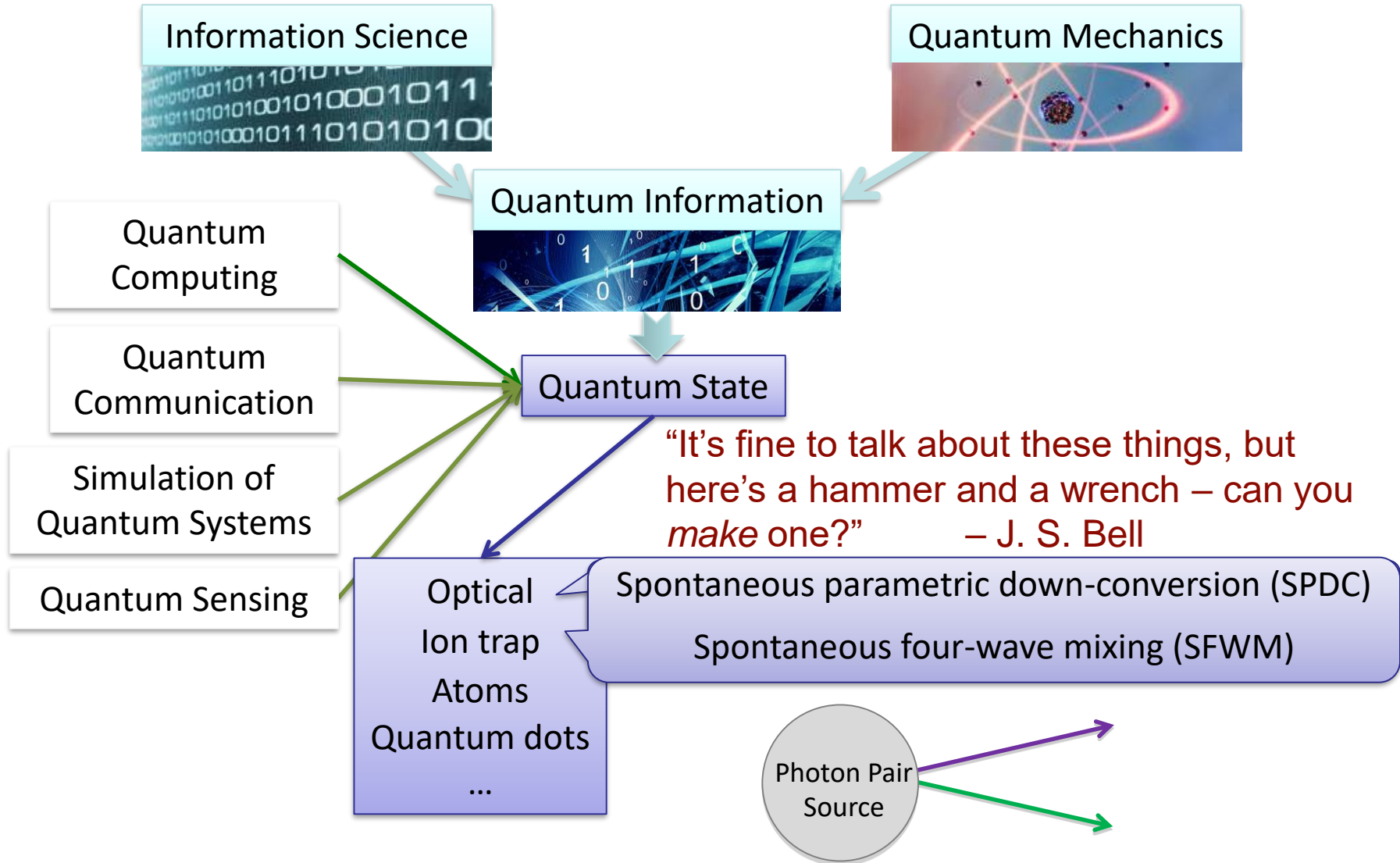[10]*Quantum Information Science Program, Canadian Institute for Advanced Research, Toronto, Ontario, Canada*
(Received 10 November 2015; published 16 December 2015)

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.

But information is not transmitted > c

- Even though nonlocal correlations are instantaneous, information cannot be gained faster than the speed of light

- The person at the receiving end does not know what the state is until they either measure it or the sender tells them what state it is using communication < c.

The last 50 years: Quantum Information

Information Science

Quantum Mechanics

Quantum Information

Quantum Computing

Quantum Communication

Simulation of Quantum Systems

Quantum Sensing

Quantum State

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

Optical
Ion trap
Atoms
Quantum dots
…

Spontaneous parametric down-conversion (SPDC)

Spontaneous four-wave mixing (SFWM)

Photon Pair Source

1970: Spontaneous Parametric Down-Conversion

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

$$\chi^{(2)}$$

$$\omega_p = \omega_s + \omega_i \quad *$$
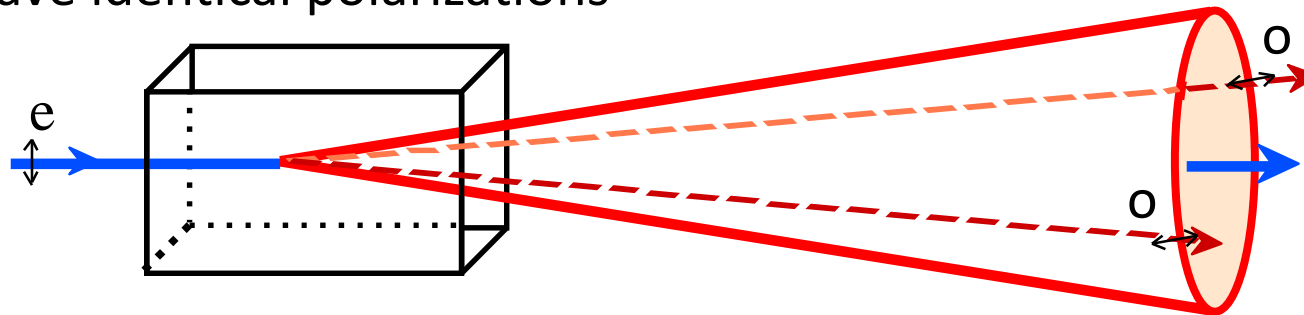
$$\vec{\kappa}_p = \vec{\kappa}_s + \vec{\kappa}_i \quad \dagger$$
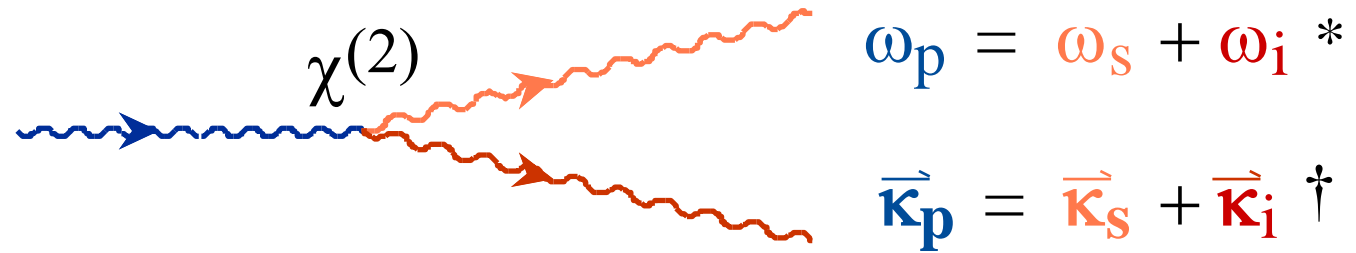
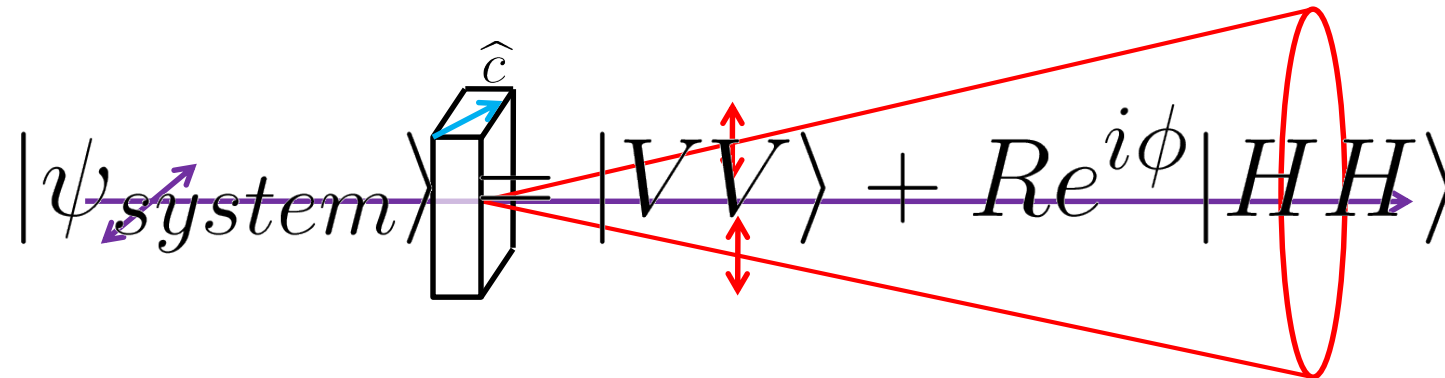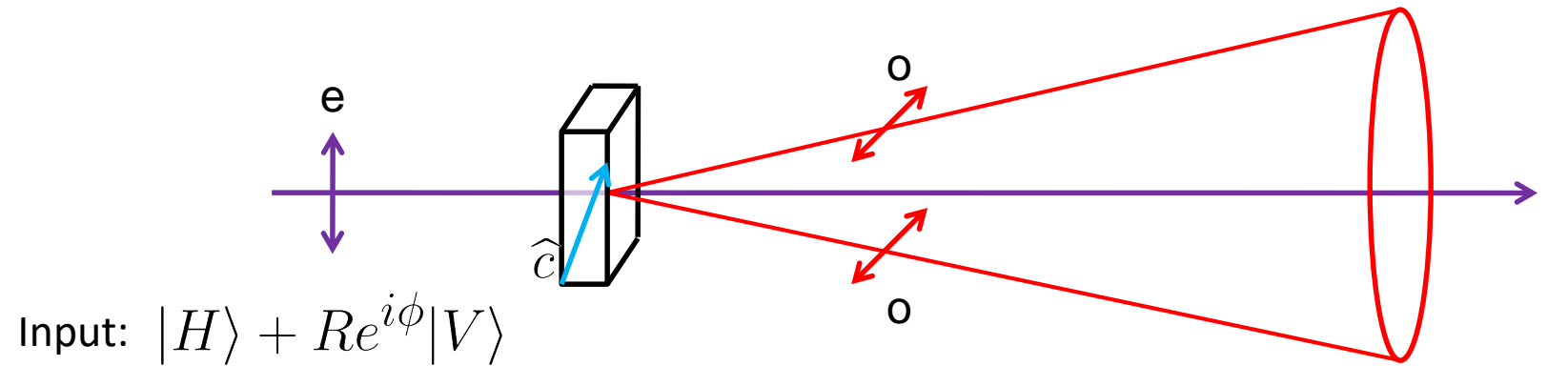*Energy conservation → energy entanglement

†Momentum conservation → momentum entanglement

Type-I phase-matching

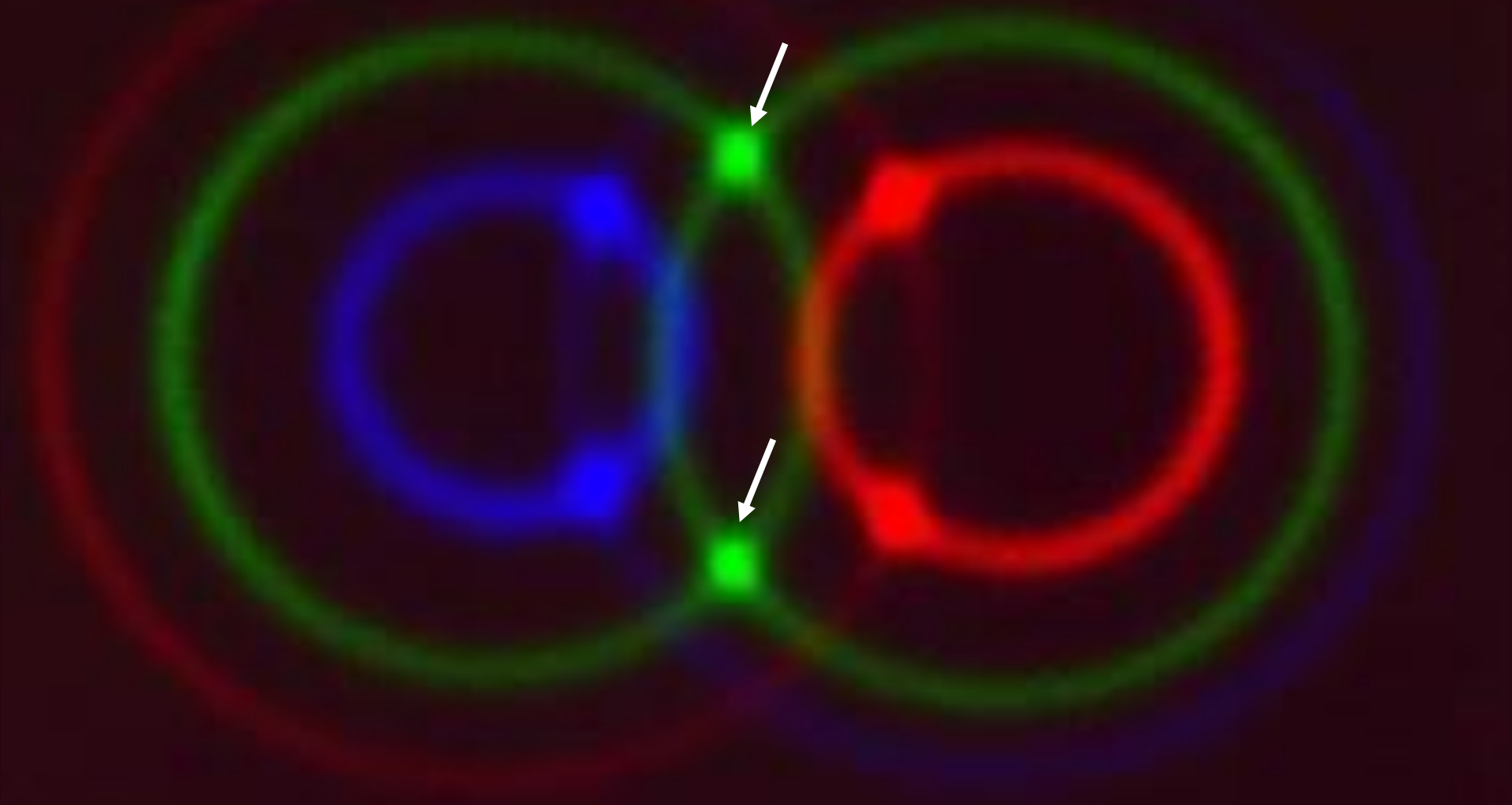Photons have identical polarizations

e

o

o

Polarization Entanglement

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

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

Proof of Quantum Correlations

Coincidence rate (10 s) vs. Angle of polarizer #2 (#1 at 45°)

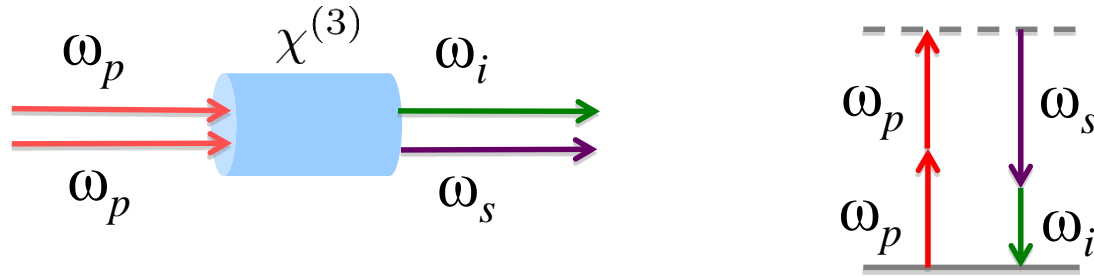QM theoretical prediction

V = 99.7 ± 1.0%
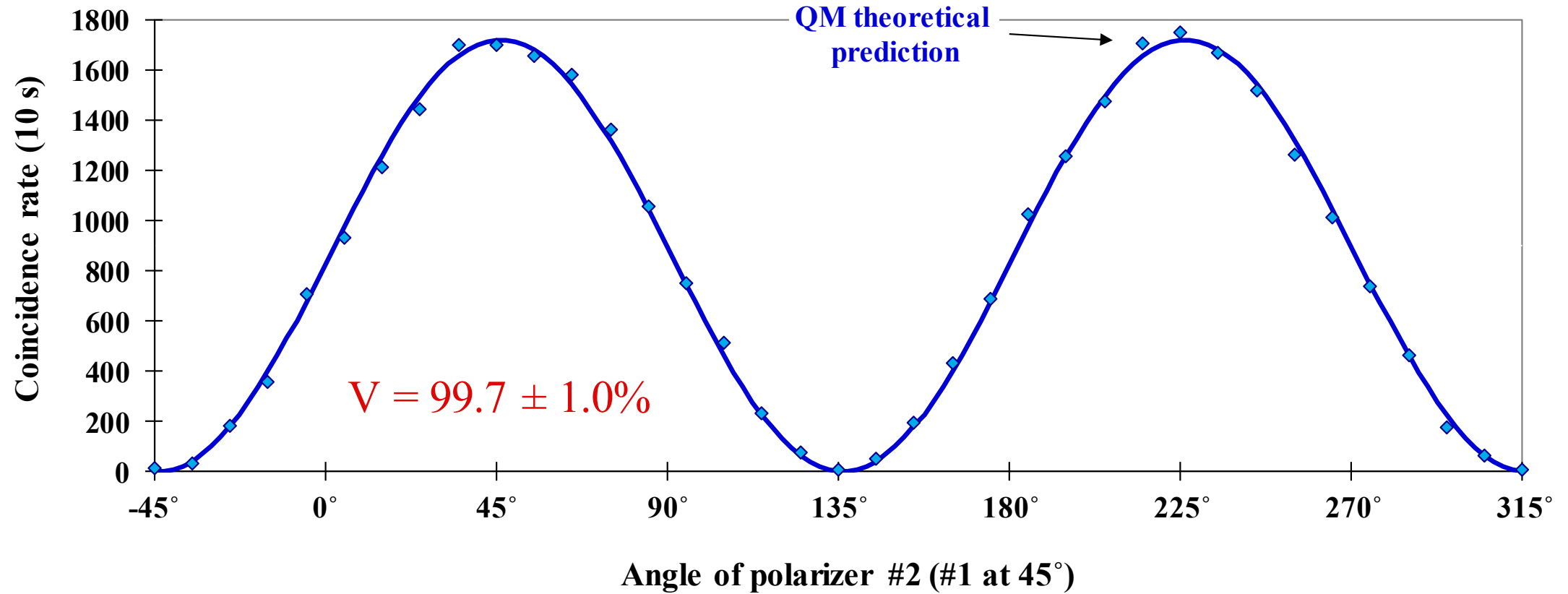
Near-perfect quantum behavior

$$|\psi_{system}\rangle = |VV\rangle + Re^{i\phi}|HH\rangle$$
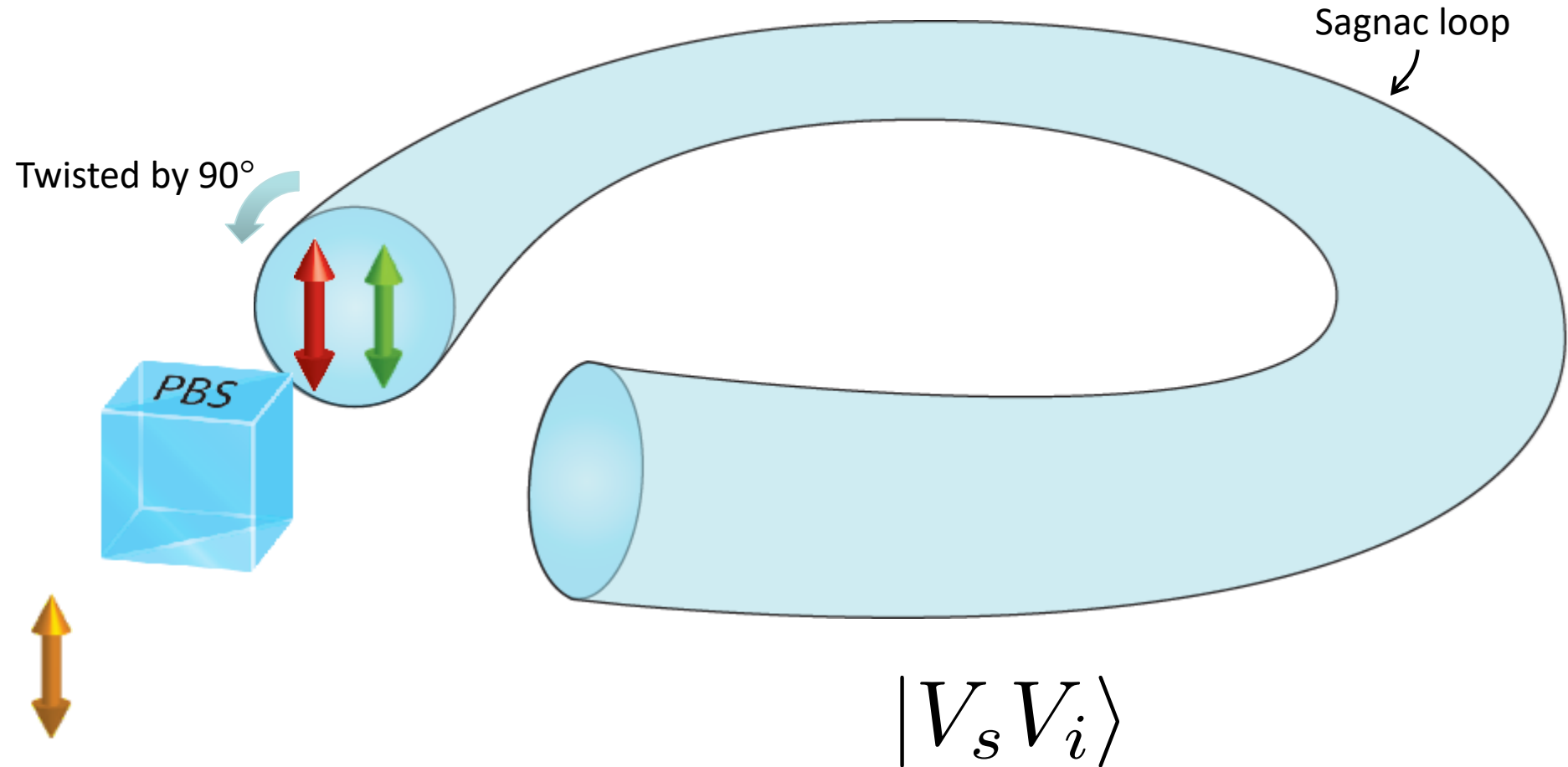
Spontaneous four-wave mixing

Conservation of energy

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

  – *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

Twisted by 90°

Sagnac loop

PBS

$$|V_s V_i\rangle$$

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.
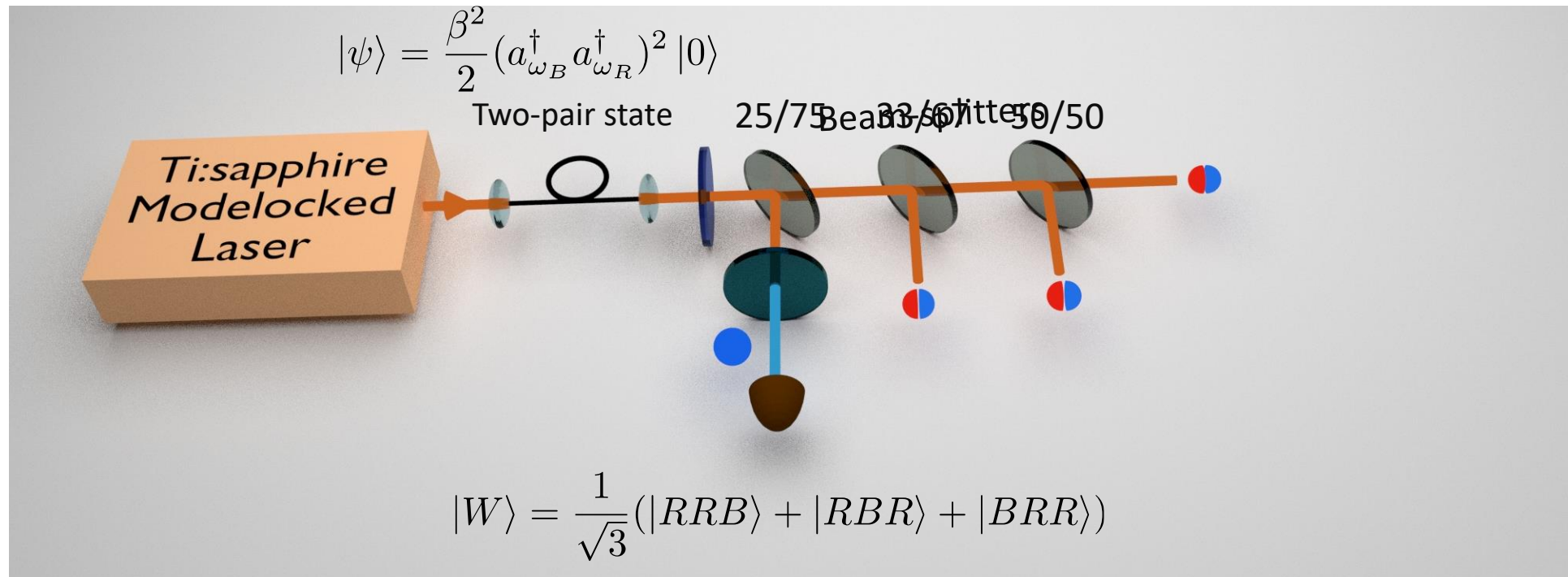
Generation of polarization entanglement

Sagnac loop

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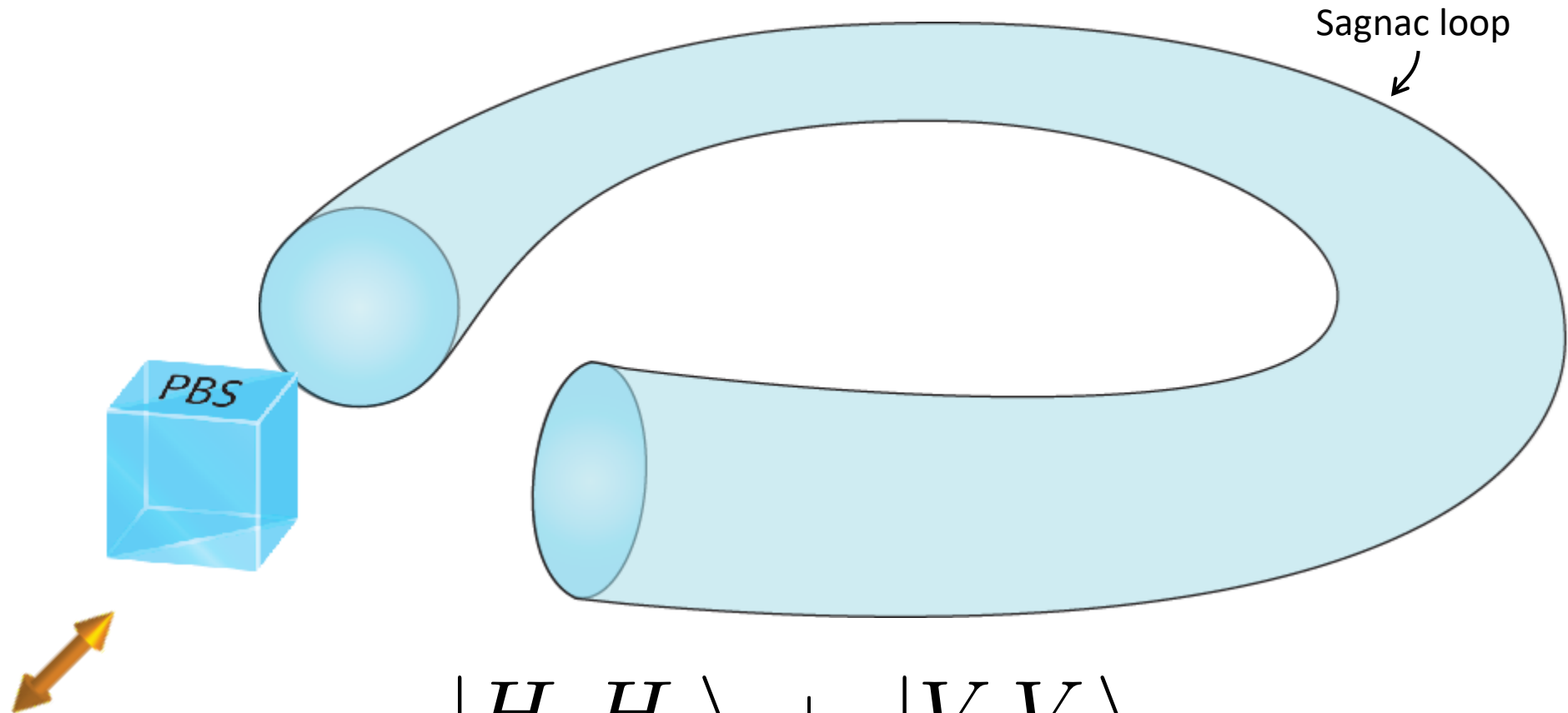
$$|H_s H_i\rangle \ + \ |V_s V_i\rangle$$

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

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

$$|\psi\rangle = \frac{\beta^2}{2} (a_{\omega_B}^\dagger a_{\omega_R}^\dagger)^2 |0\rangle$$

Two-pair state   25/75   Beamsplitter   33/67   50/50

Ti:sapphire
Modelocked
Laser

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

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

Other important metrics for photon-pair sources

- Are the photons always arriving in pairs? (degree of quantum correlation)

- Are you really only getting one heralded photon? (degree of single photon purity)

- Is the photon the same every time? (degree of quantum state purity)

- To test these, all you need is a beamsplitter and two detectors to measure the **second-order correlation function g$^{(2)}$**
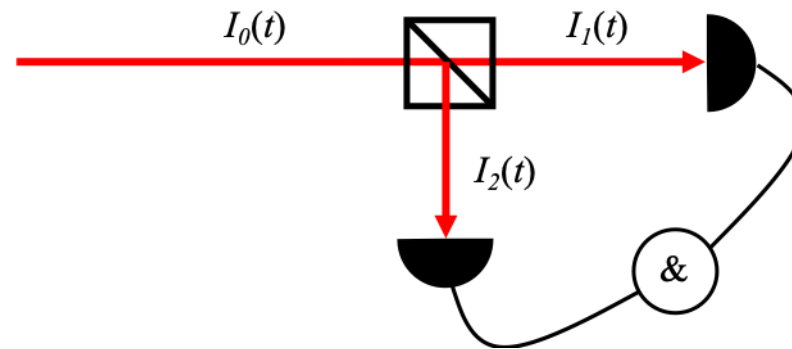
Why are entangled states important?

- 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:

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

- 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:

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

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

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

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

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

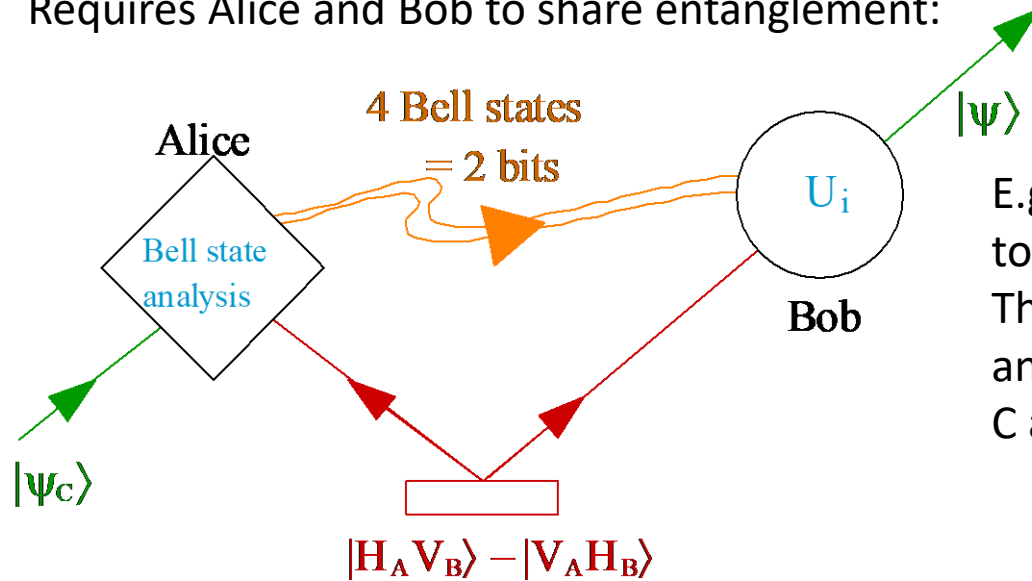2-Qubit interactions lead to entangled states.

illinois.edu

Quantum Teleportation

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:

4 Bell states
= 2 bits

Alice

Bell state analysis

U_i

$|\psi\rangle$

Bob

$|\psi_C\rangle$

$|H_A V_B\rangle - |V_A H_B\rangle$

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)]

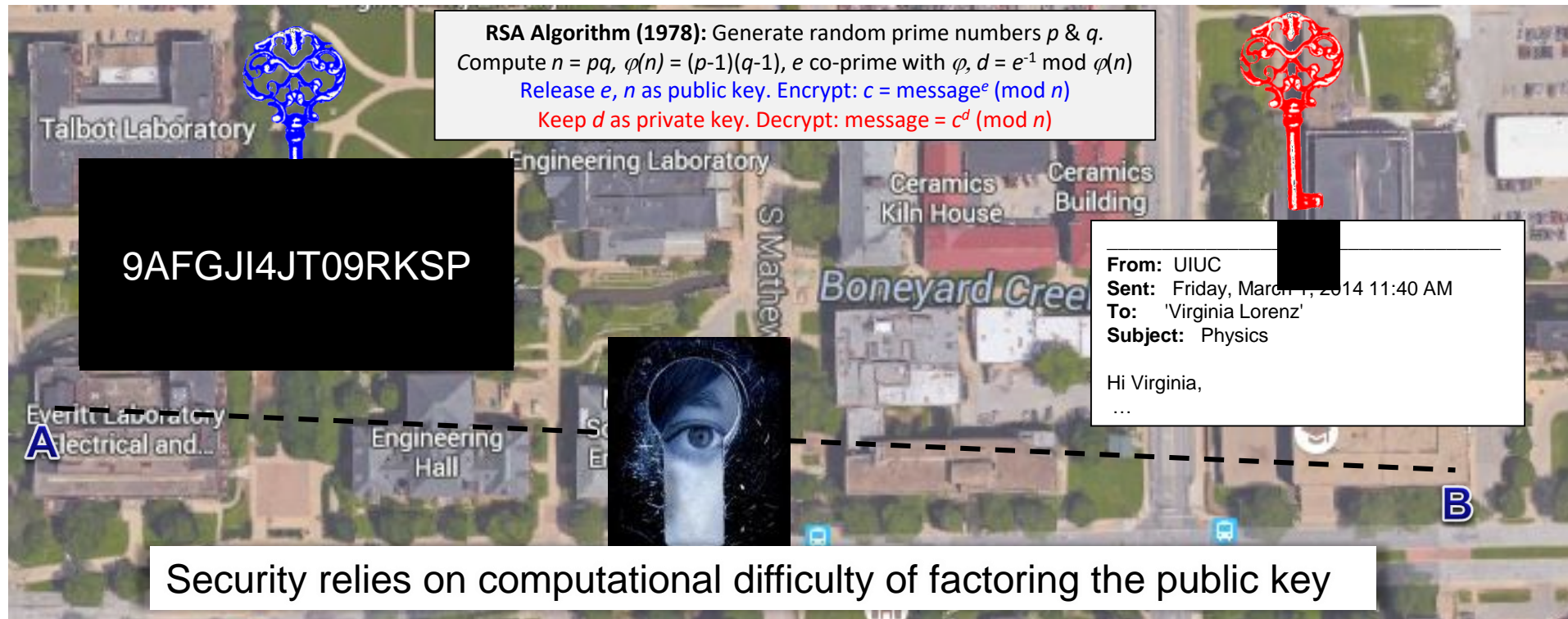2004: **Quantum teleportation across the Danube** [Ursin *et al.*, Nature **430**, 849 (2004)]

Alice

Bob

classical channel
(via microwave link)

Cerberis QKD Server

Cerberis from IDQ is a standalone rack-mountable QKD server; providing secure quantum keys based on the BB84 and SARG protocols. Integrated with IDQ's Centauris Ethernet and Fiber Channel encryptors, Cerberis has been deployed by governments, enterprises and financial institutions since 2007.

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

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

Classical Cryptography

USA TODAY:

NSA uses supercomputers to crack Web encryption, files show

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: $c = \text{message}^e \pmod n$
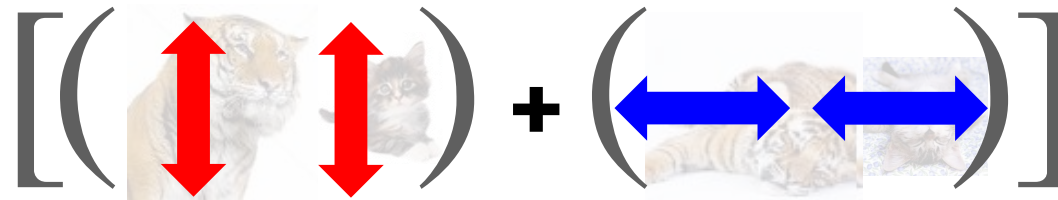Keep d as private key. Decrypt: $\text{message} = c^d \pmod n$

9AFGJI4JT09RKSP

From: UIUC
Sent: Friday, March 1, 2014 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

A

B

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

Quantum networks: a new type of internet

- Connections with real-world quantum computers
  - Fundamentally new ways of solving computational problems

- Improved sensing of astronomical objects

- Genuinely secure communication through detection of eavesdropping

https://www.science.org/doi/10.1126/sciadv.aba0959
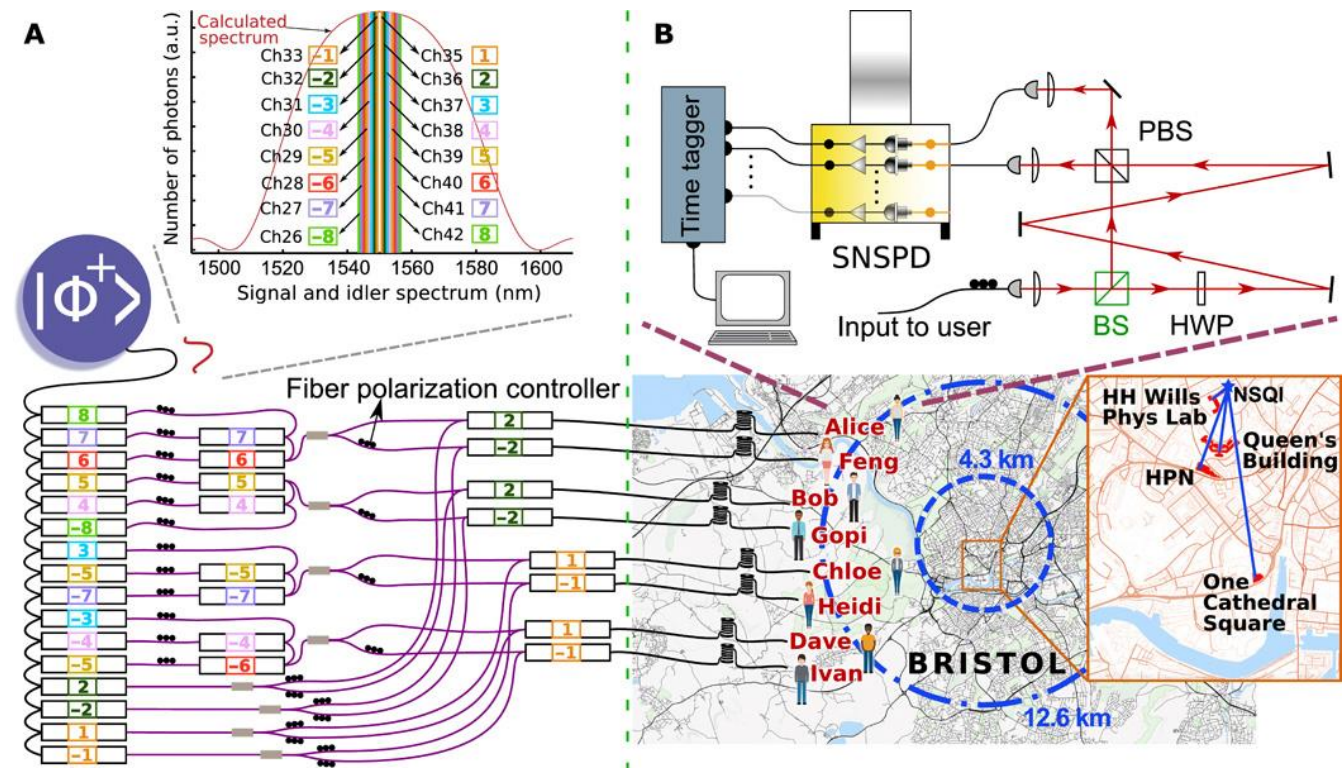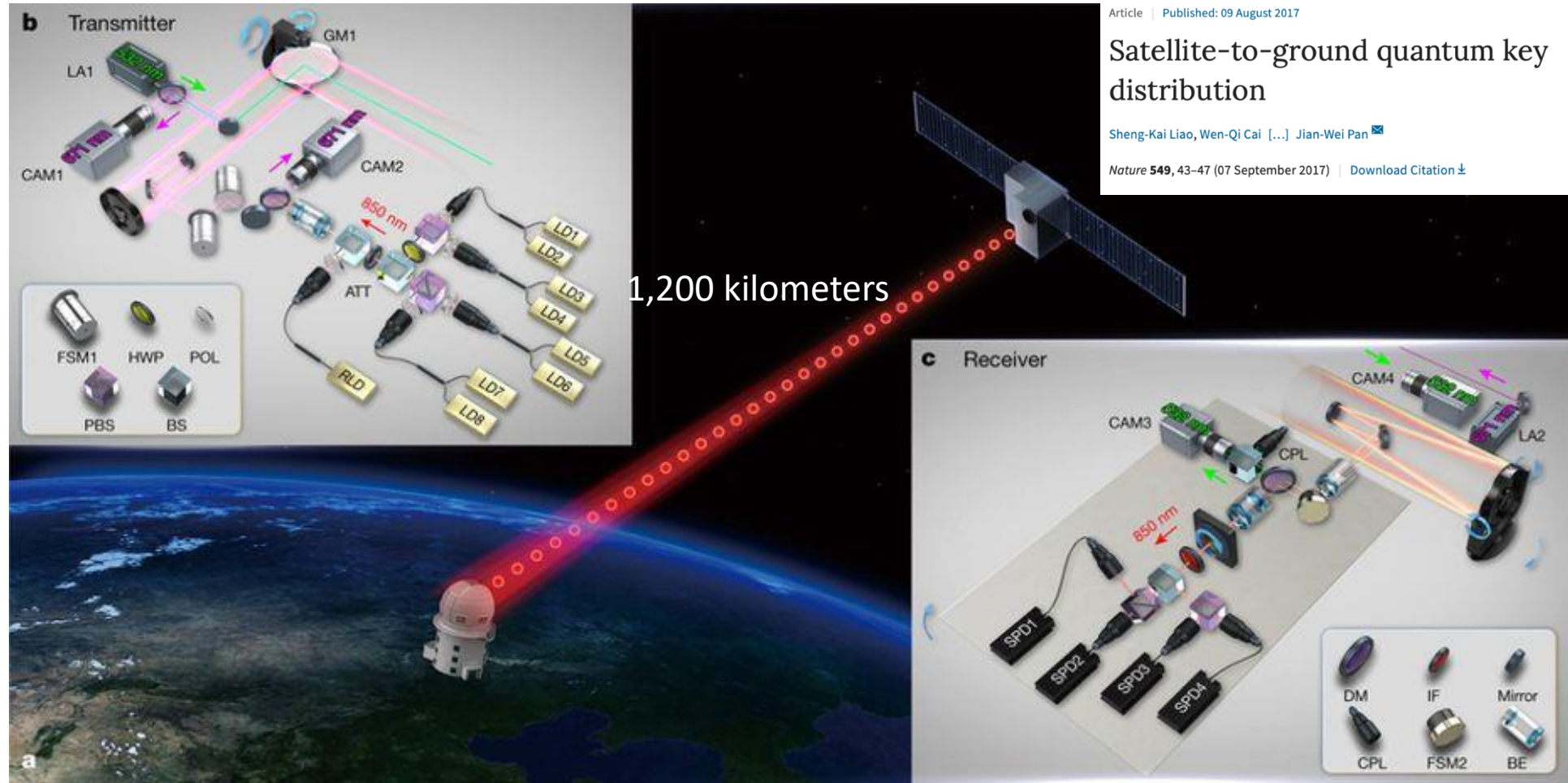
Satellite-to-ground QKD

1,200 kilometers

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 ⬇

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European Open Science Cloud

Digital Infrastructures

European Commission will launch €1 billion quantum technologies flagship

Published on 17/05/2016

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

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

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Grainger College of Engineering
Illinois Quantum Information Science and Technology Center

Home / News

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

📅 7/21/2020 9:53:05 AM   👤 Michelle Huls Rice for   f 🐦 in
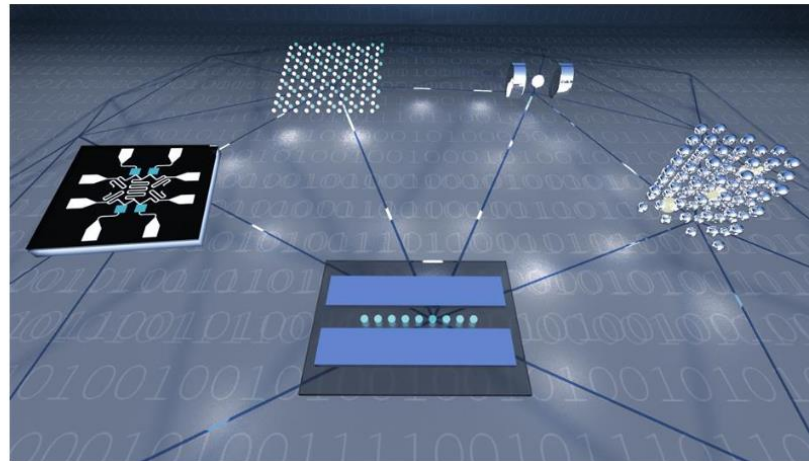Grainger Engineering

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

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
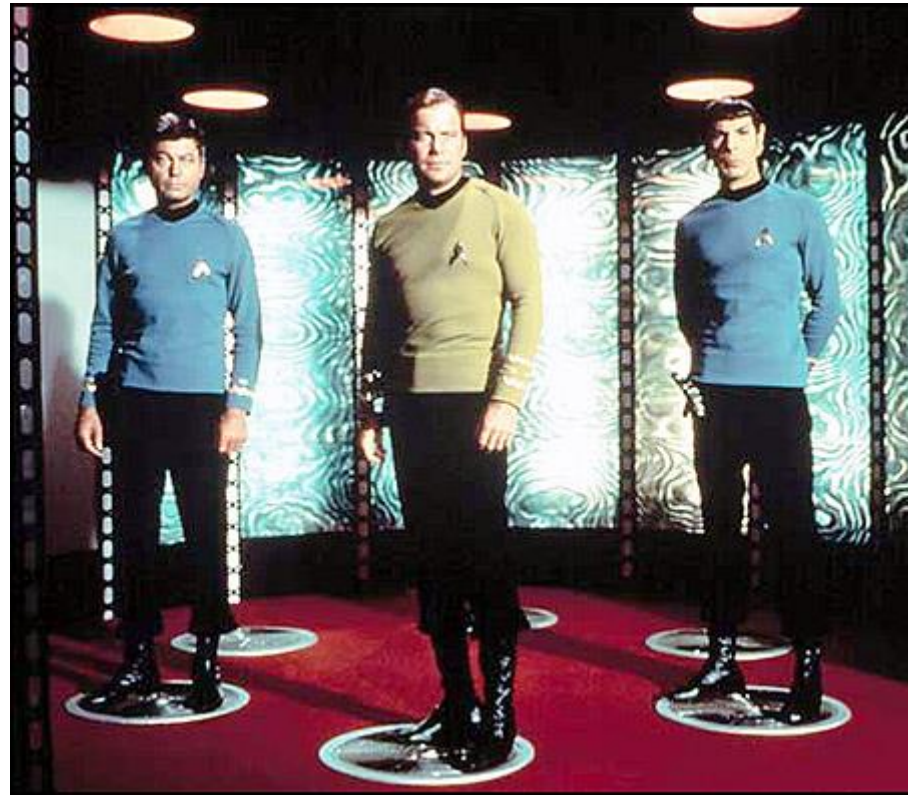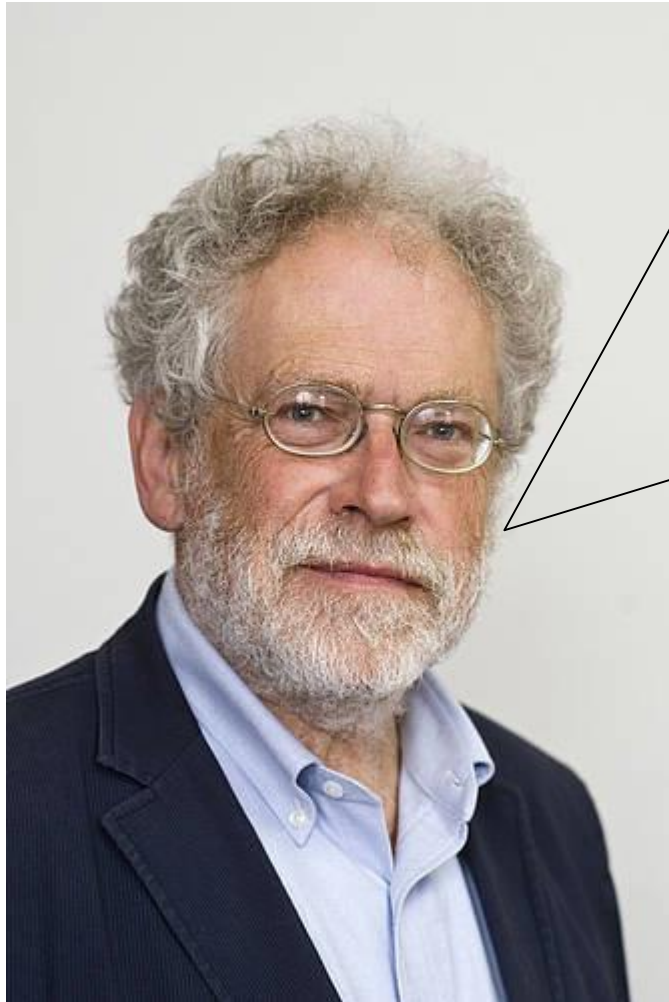
Conclusion

- Quantum entanglement breaks local realism

- Generating entangled photons & reconstructing their state is relatively easy, but engineering for applications is still a challenge

- Entanglement is not just spooky, it's useful!
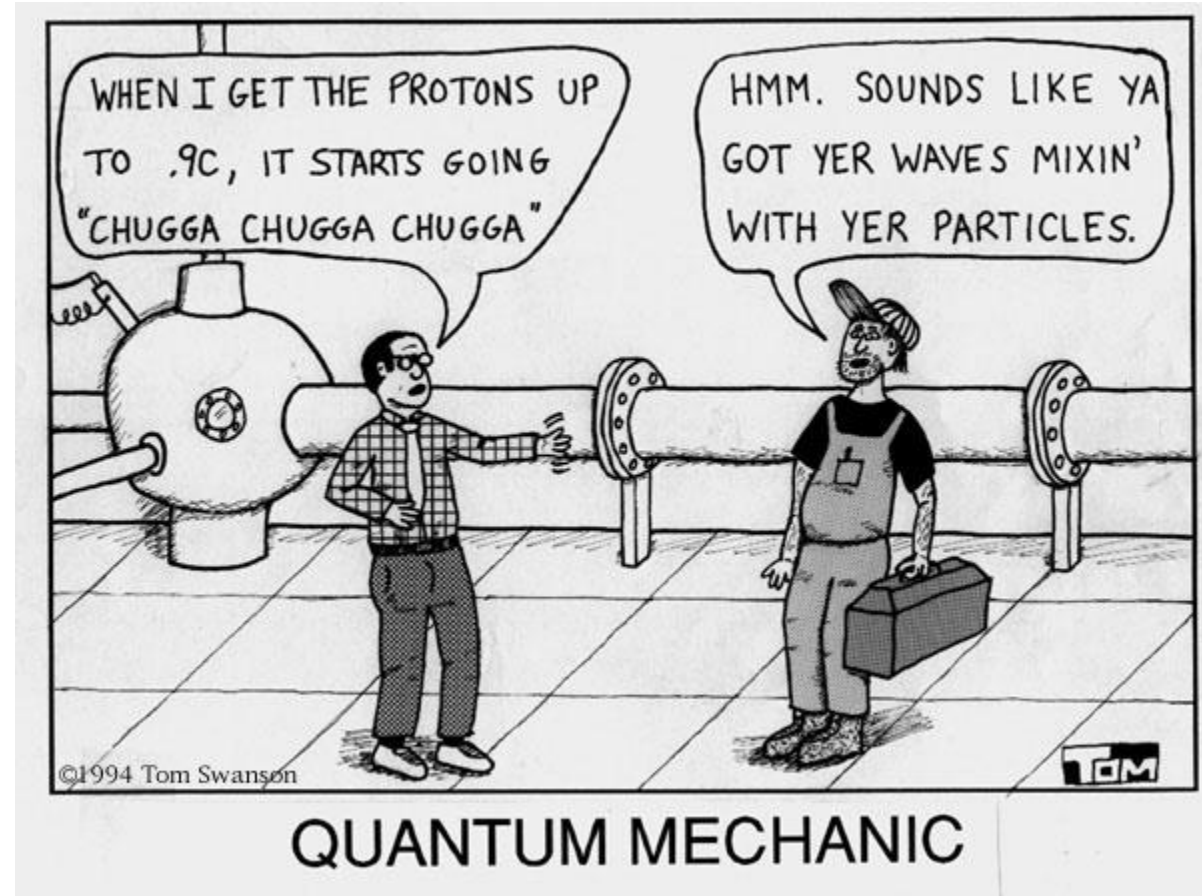
But there's Quantum Teleportation, and then there's

Quantum Teleportation

Anton Zeilinger

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

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

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

Anton Zeilinger

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

…

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

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