Entanglement

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

arnoldzwicky.org

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with adapted PHYS403 content from Paul Kwiat, Brad Christensen

PHYS403, July 26, 2017

Entanglement

- A quantum object can be in a superposition of two states

- The cat is a quantum object / Make it a quantum object

- It can be awake and asleep
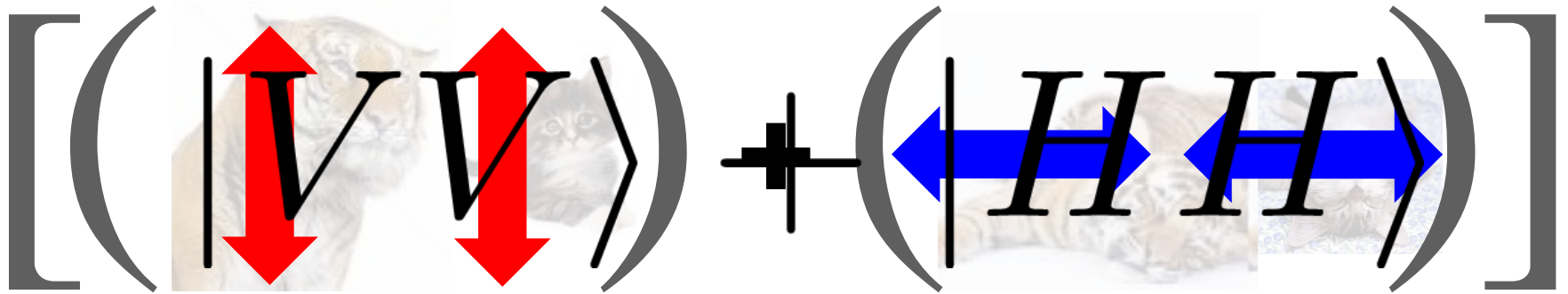
- If we check, it will be in only one of the states

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

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

Properties of Entanglement

at least

"It takes ˅ two to tangle."

J. Eberly, 2015

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

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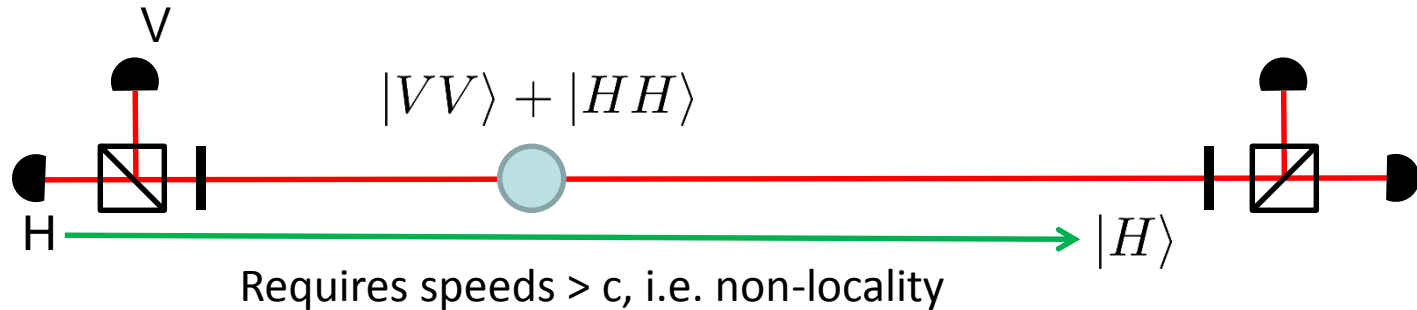classical lines of thought"

—E. Schrödinger

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

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

spukhafte Fernwirkung

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)

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Strong Loophole-Free Test of Local Realism[*]

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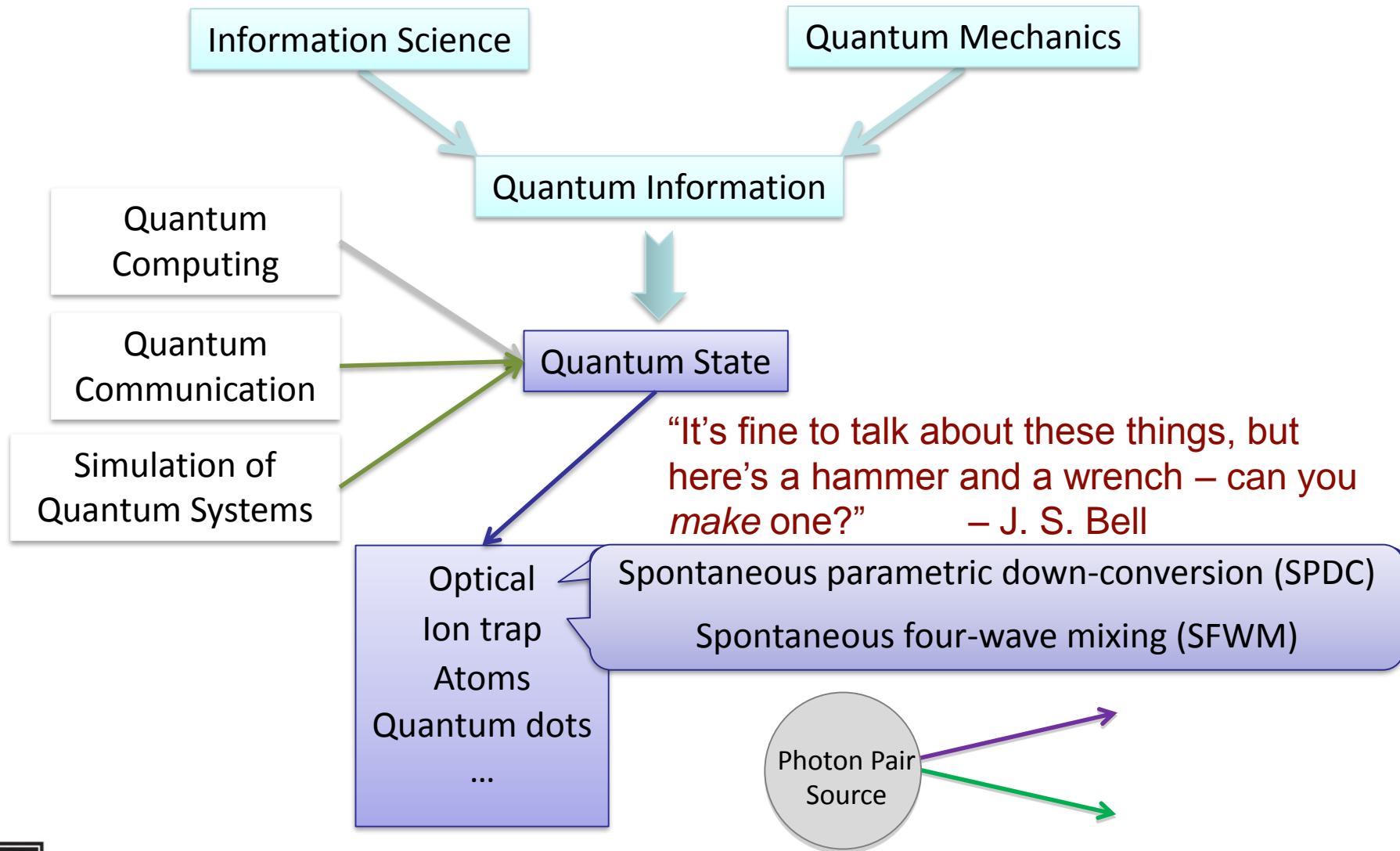[9]*ICREA-Institució Catalana de Recerca i Estudis Avançats, 08015 Barcelona, Spain*
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(Received 10 November 2015; published 16 December 2015)

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 Computing

Quantum Communication

Simulation of Quantum Systems

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):

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

$$\vec{\kappa_p} = \vec{\kappa_s} + \vec{\kappa_i} \quad \dagger$$

$\chi^{(2)}$
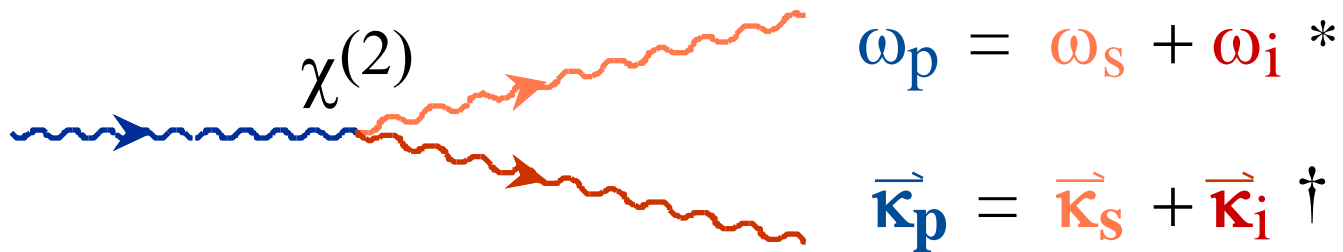
*Energy conservation → energy entanglement

†Momentum conservation → momentum entanglement

Type-I phase-matching

Photons have identical polarizations
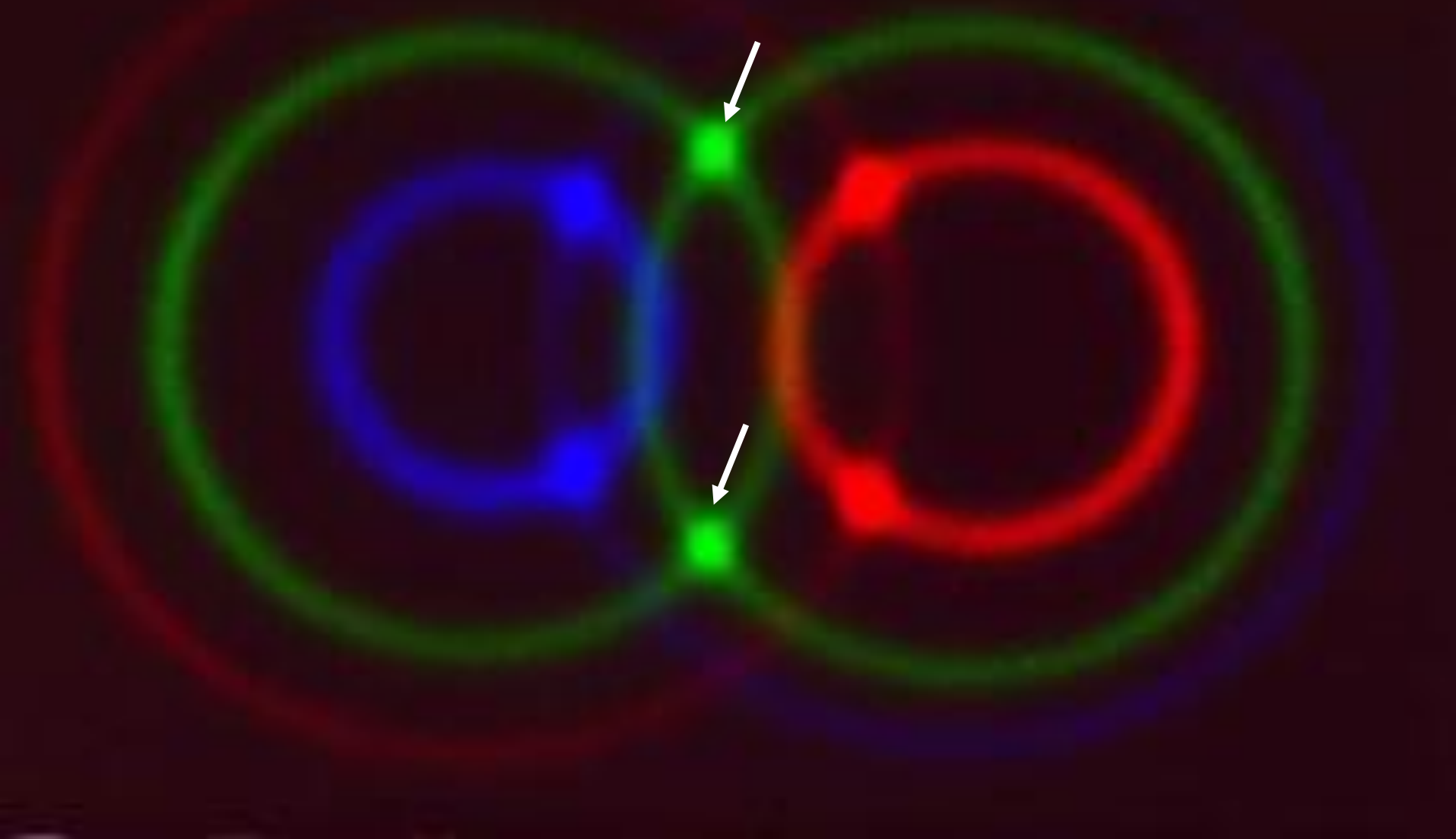
e

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o

Polarization Entanglement

e

o

o

$\hat{c}$

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

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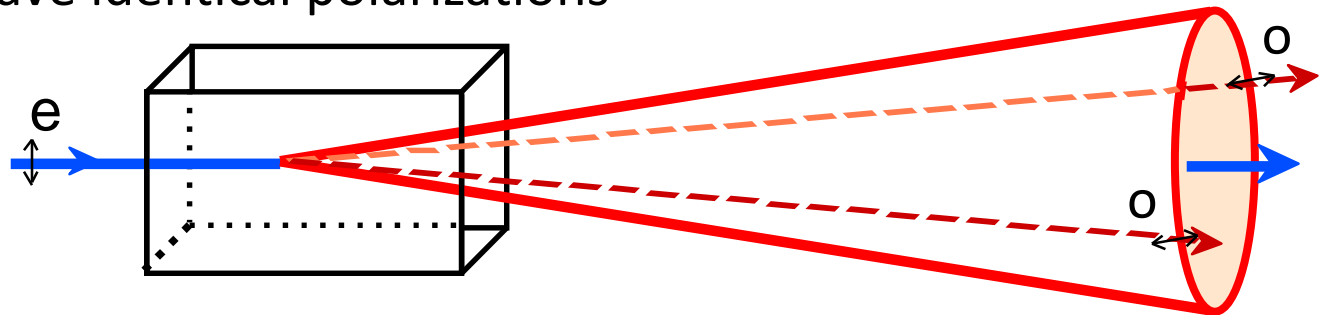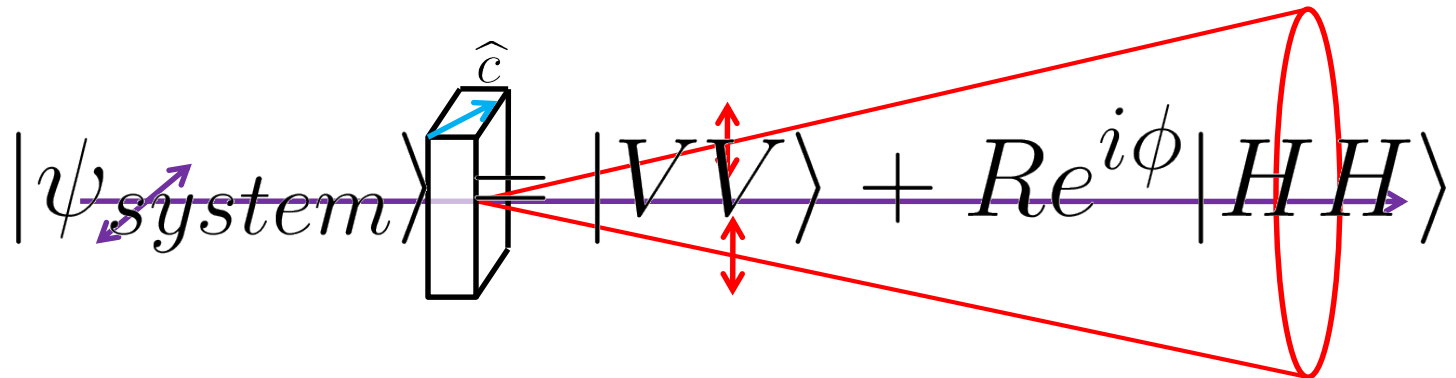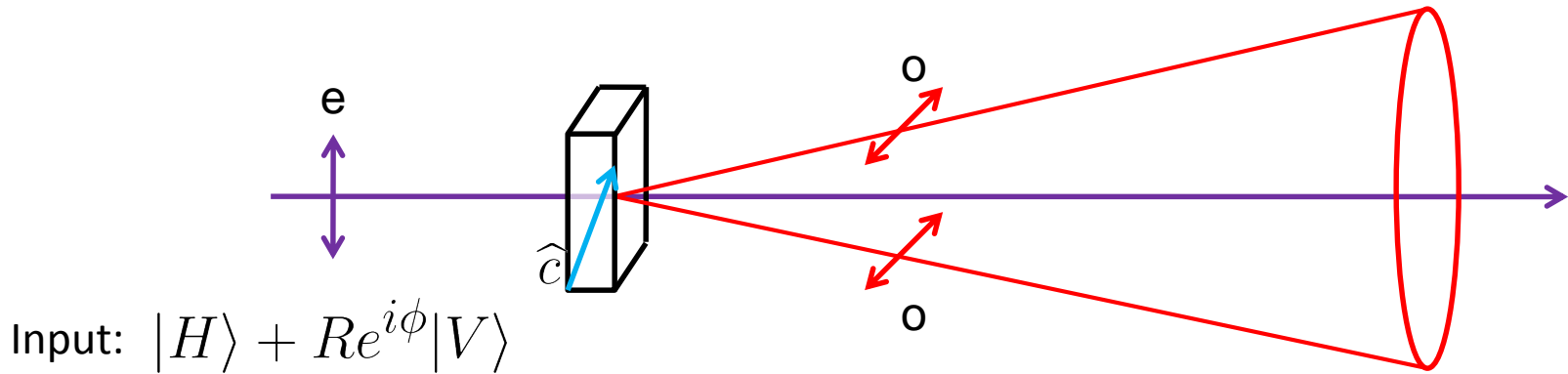
$$|\psi_{system}\rangle = |VV\rangle + Re^{i\phi}|HH\rangle$$

Proof of Quantum Correlations

QM theoretical prediction

V = 99.7 ± 1.0%
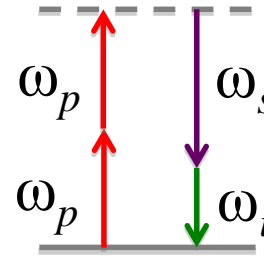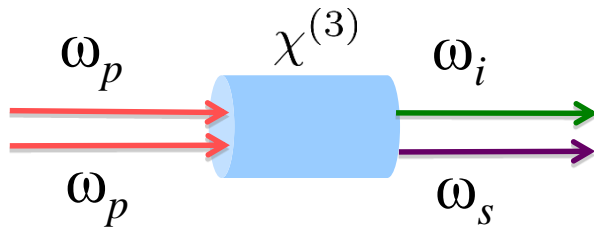
Angle of polarizer #2 (#1 at 45Þ)
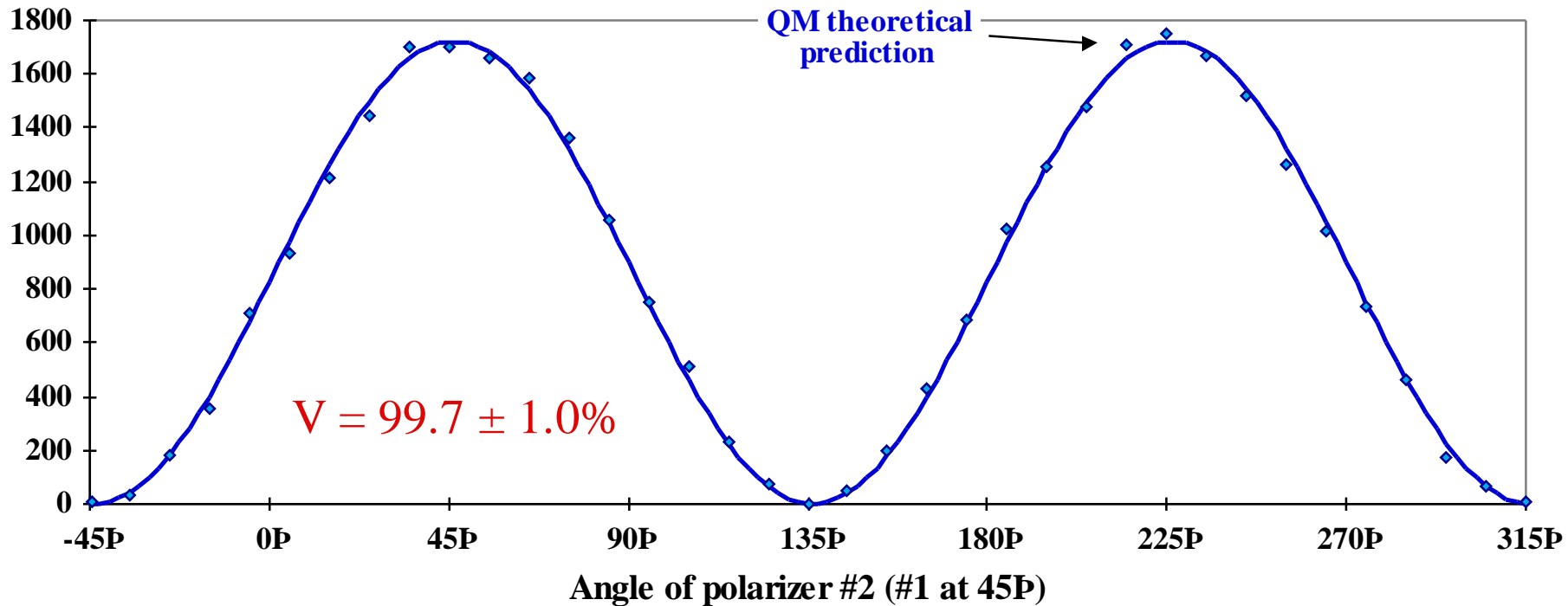
Near-perfect quantum behavior

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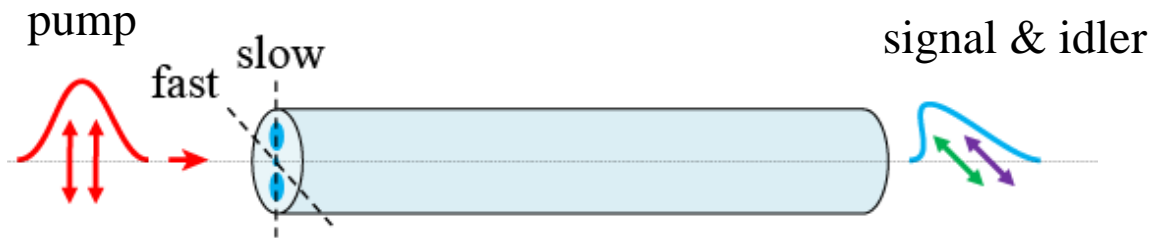
Spontaneous four-wave mixing
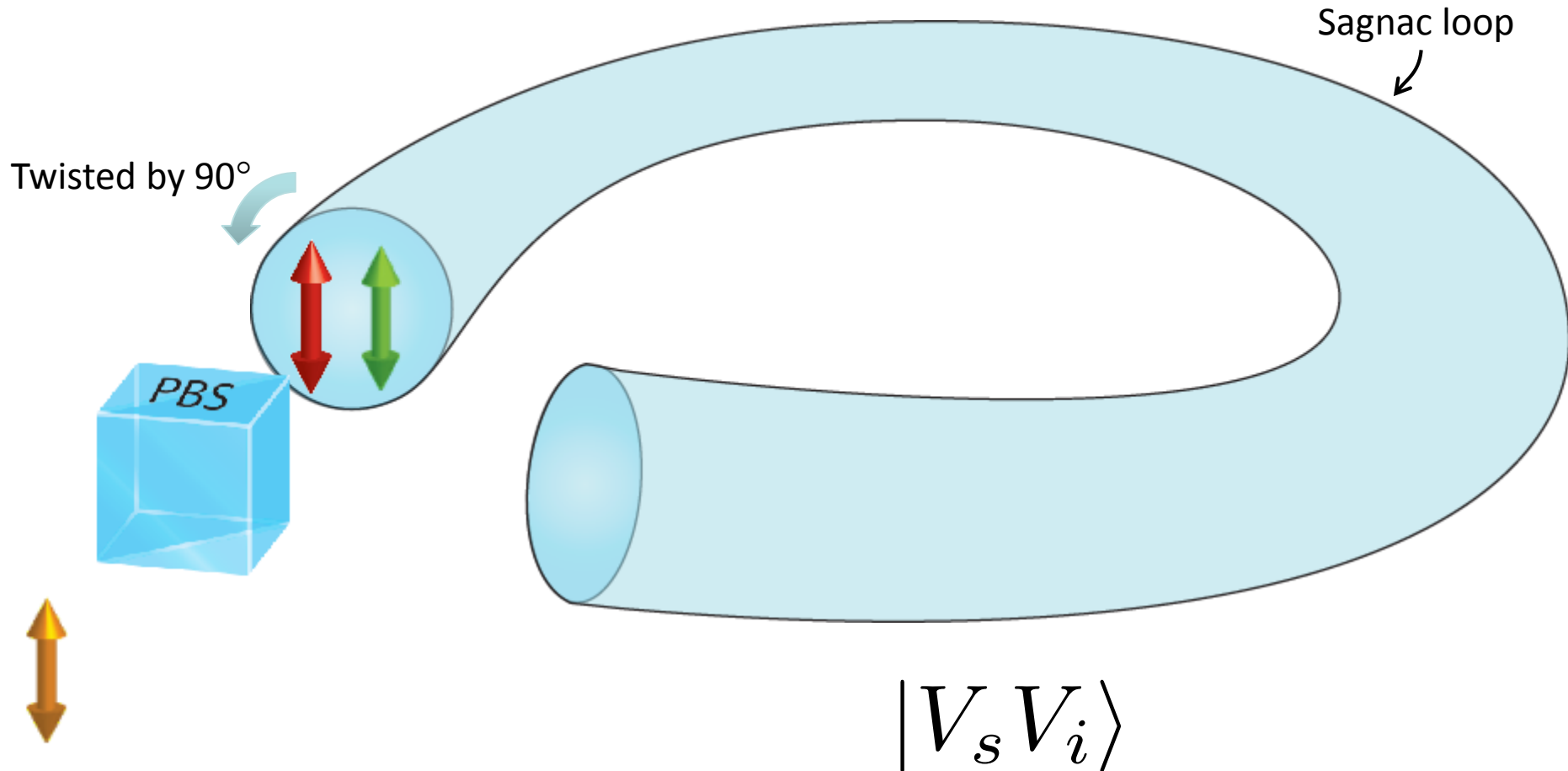

Conservation of energy

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

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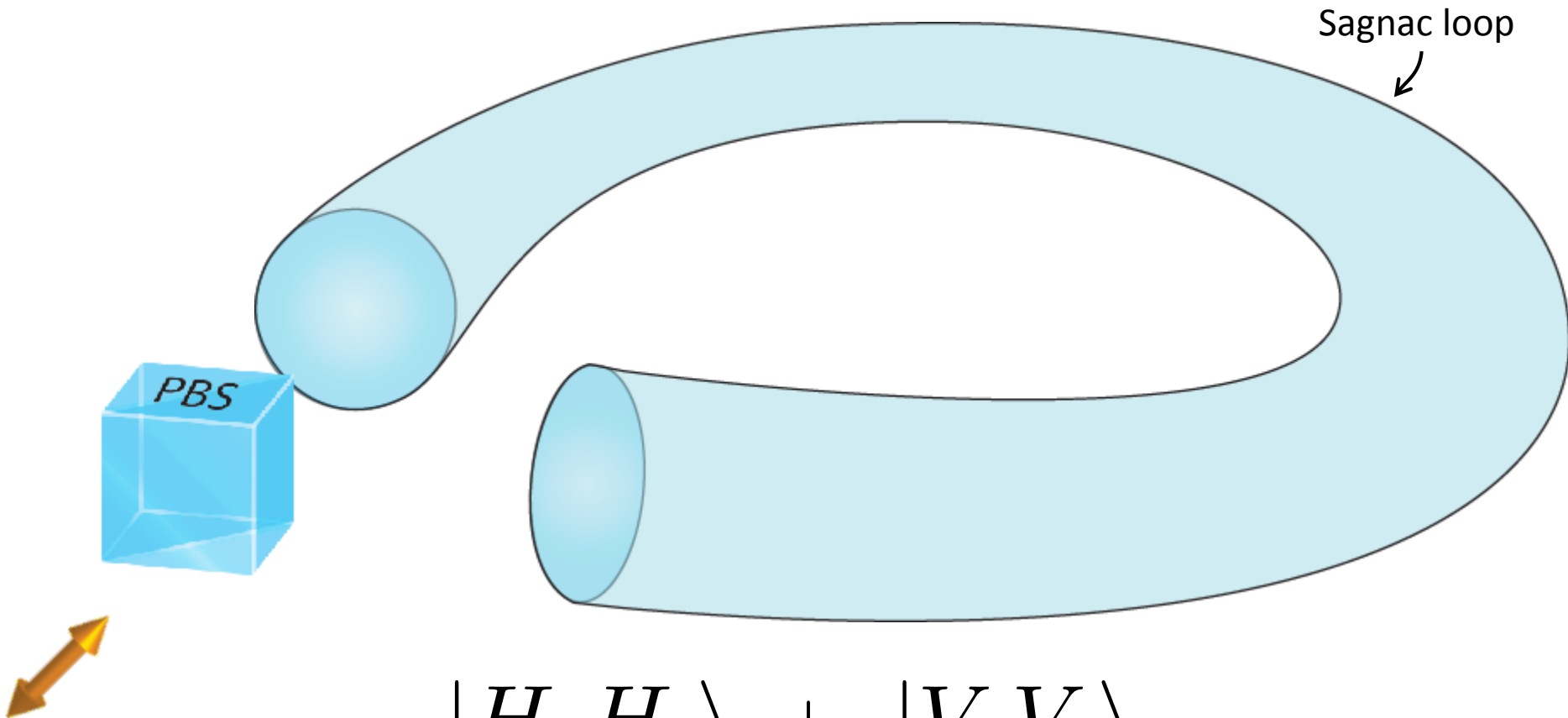
Generation of polarization entanglement

Sagnac loop

Twisted by 90°

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.

Why are entangled states important?

- Responsible for quantum measurements and decoherence

- Central to demonstrations of quantum nonlocality (e.g., Bell's inequalities, GHZ, 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

Classical Cryptography

USA TODAY:

NATION

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
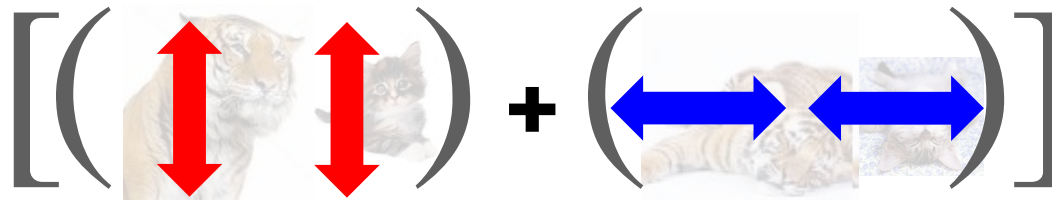Sent: Friday, March 1, 2014 11:40 AM
To: 'Virginia Lorenz'
Subject: Physics

Hi Virginia,
…

- There is no indication of eavesdropping

- Security relies on computational difficulty of factoring the public key

Quantum Key Distribution

$$[(\uparrow\uparrow) + (\leftrightarrow\leftrightarrow)]$$

Security is guaranteed by the laws of quantum physics!

Ekert Protocol (1991): Generate entangled photon pair.

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/

A

B

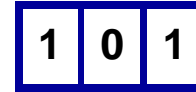- Eavesdropping without being detected is impossible because measurement changes the correlations

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:

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

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

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

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

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

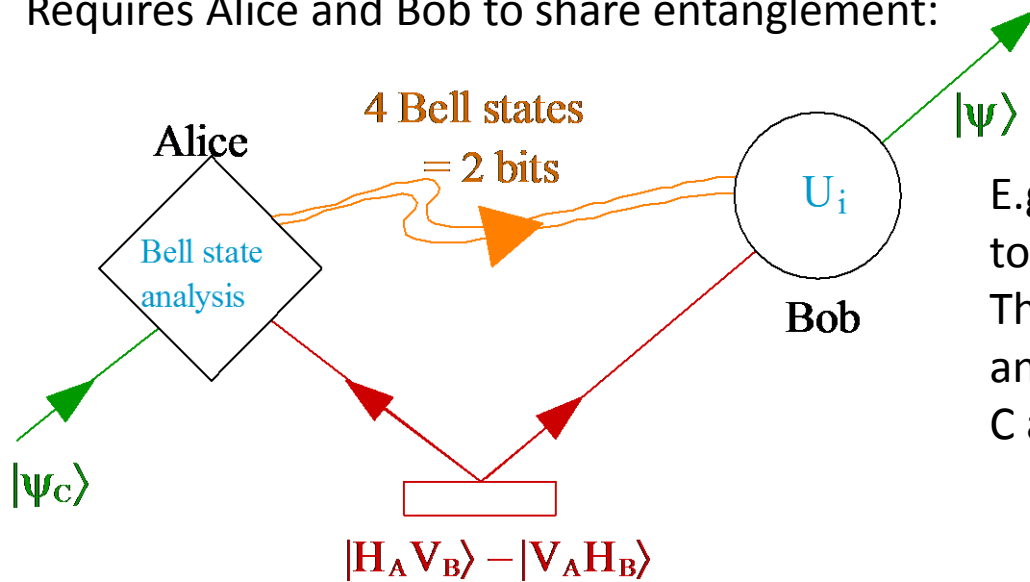2-Qubit interactions lead to entangled states.

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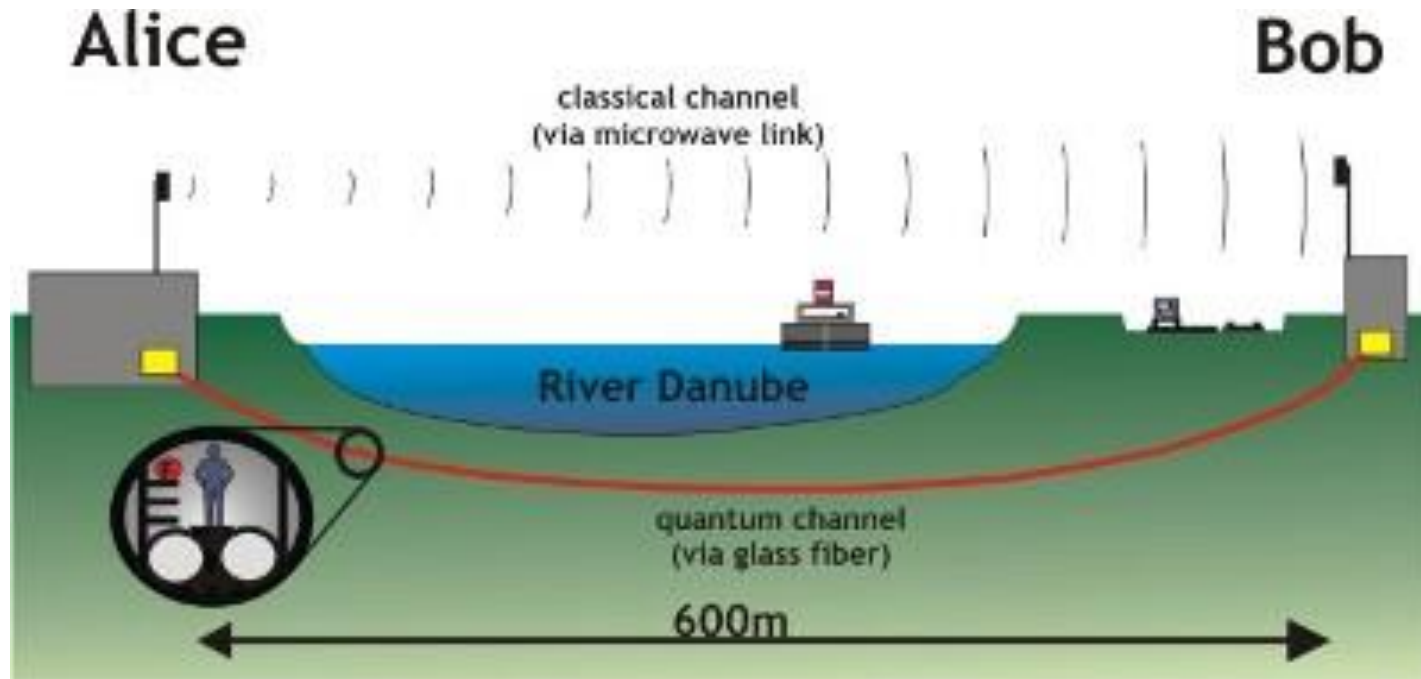
Remarks:
- The original state is gone.
- Neither Alice nor Bob know what it was.
- Requires classical communication – no superluminal signaling.
- Bell state analysis is hard.

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)]
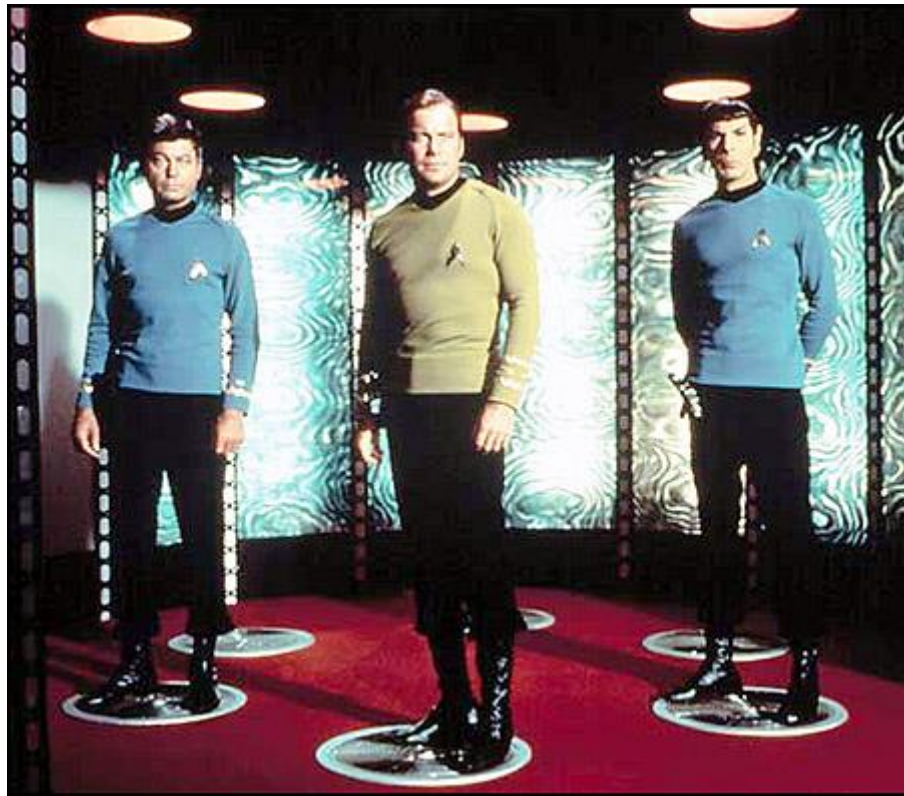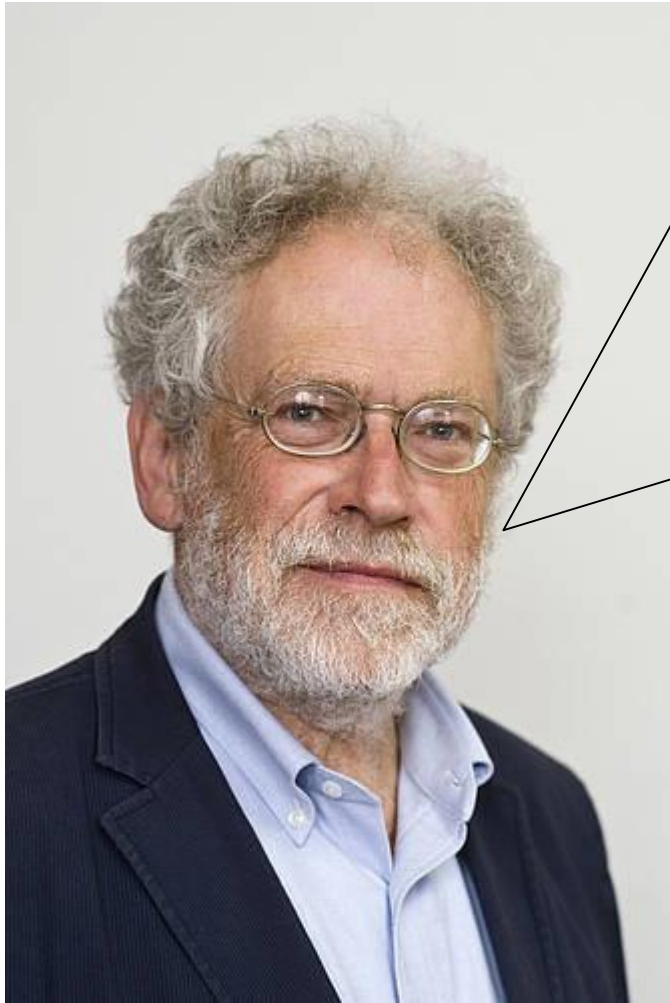

- Now demonstrated teleportation of entanglement, other degrees of freedom, continuous variables, energy states of ions, 2-qubits …

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

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.

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.
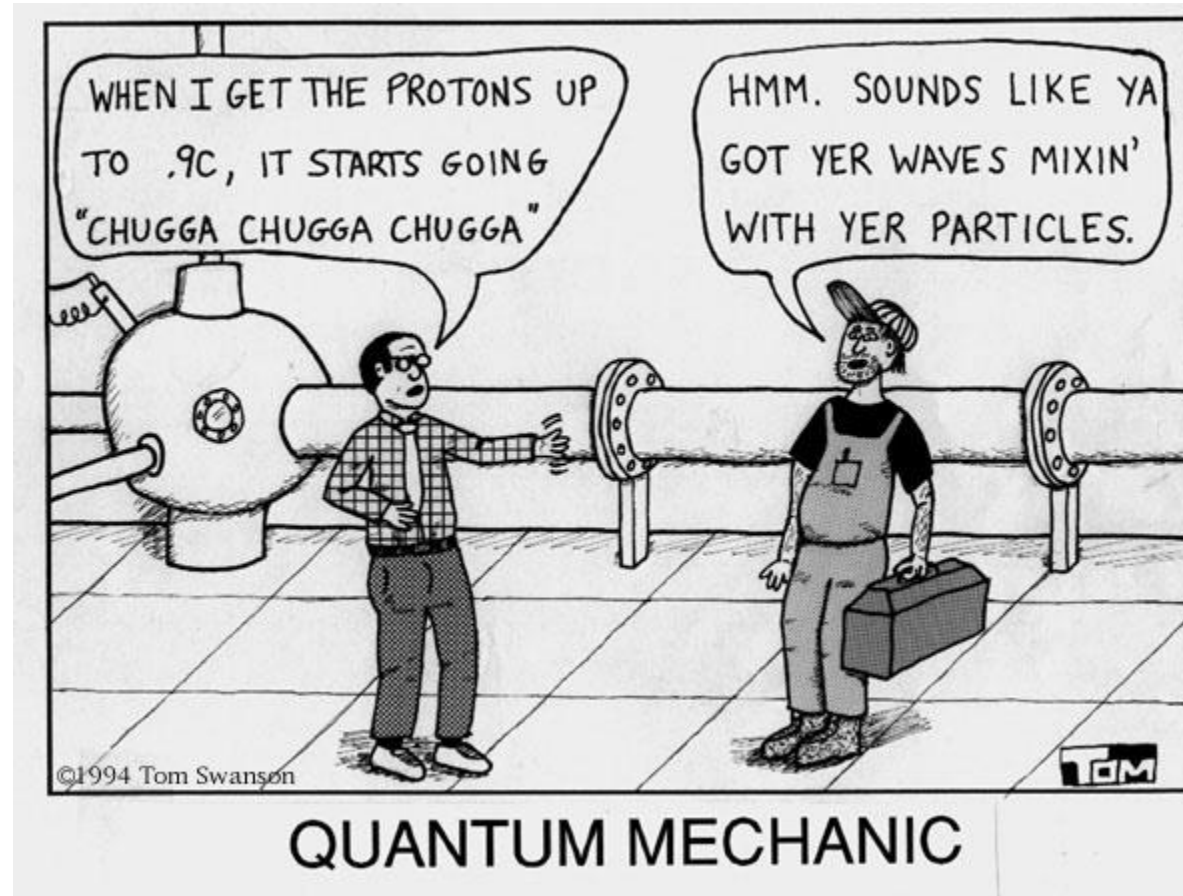
…

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.

Anton Zeilinger

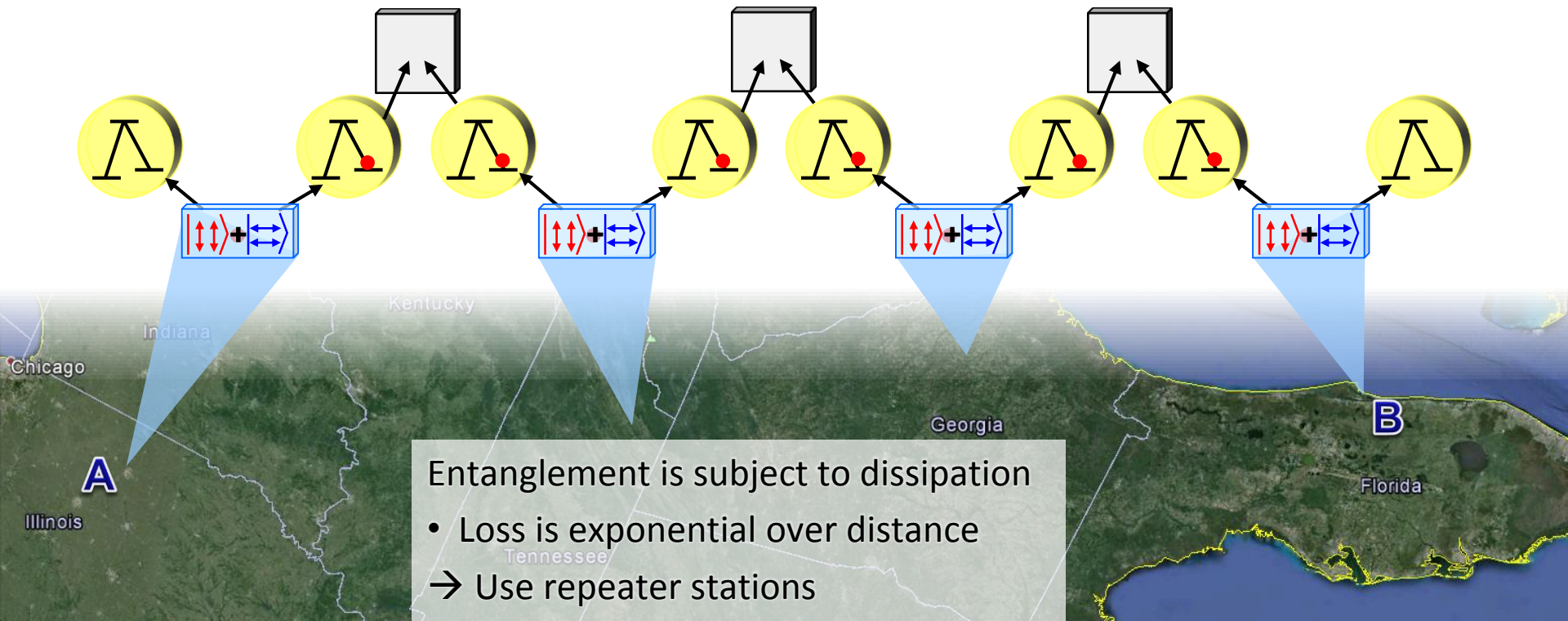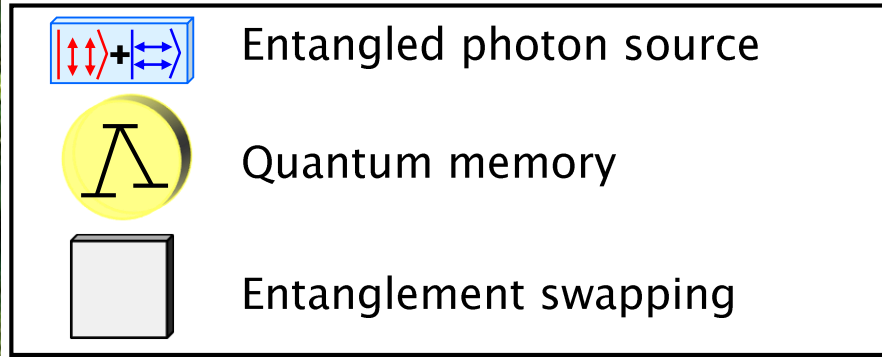http://www.signandsight.com/features/614.html

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 important and useful!

Long-Distance QKD

Entangled photon source

Quantum memory

Entanglement swapping

Entanglement is subject to dissipation

- Loss is exponential over distance

→ Use repeater stations

Binary digit -- "bit"   Quantum bit -- "qubit"

          0, 1 $|0\rangle, |1\rangle, (|0\rangle + |1\rangle)/\sqrt{2}$

          copyable   *unclonable*

          Physical realization of qubits → any 2 level system

2-level atom: $|g\rangle, |e\rangle$ spin-1/2: $|\uparrow\rangle, |\downarrow\rangle$ polarization: $|H\rangle, |V\rangle$
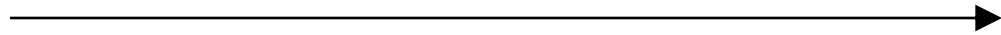

All 2-level systems are created equal, but some are more equal than others!

Quantum communication → photons

Quantum storage → atomic vapors, spins

Scaleable circuits → ions, solid state systems

"Quantum" phenomena ⎯⎯⎯⎯⎯⎯⎯⎯⎯⎯⎯⎯⟶

Superposition   Interference   Wave-   Intrinsic   Entanglement
                               particle   randomness in
                               duality   measurement