Introduction to Quantum Computing and Quantum Networking

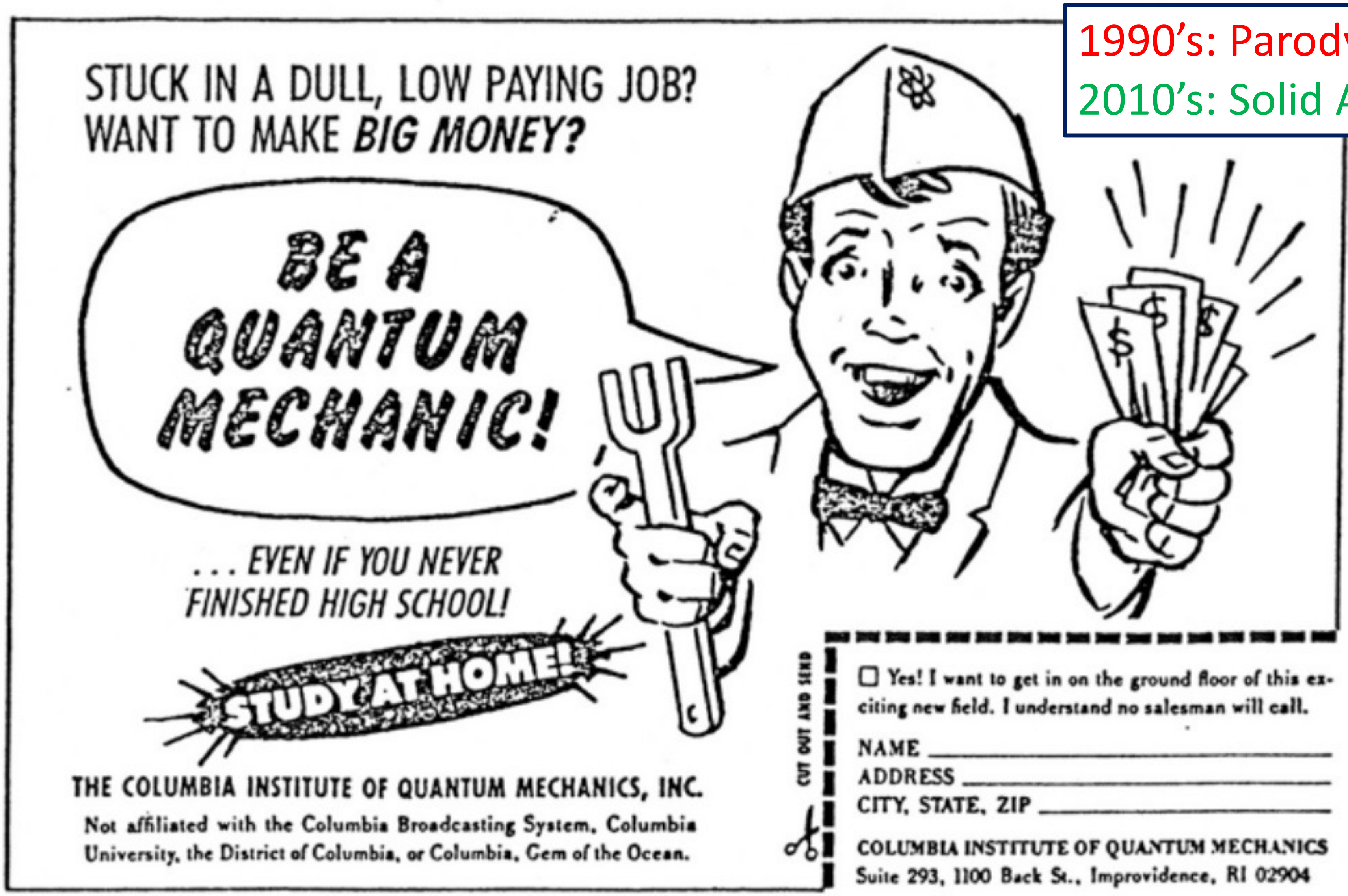
Paul Stankus, BNL Instrumentation

QuarkNet

9 July 2021

Brookhaven National Laboratory

1990’s: Parody
2010’s: Solid Advice



Today’s agenda:

- Brief re-acquaintance with QM
  - Randomness
  - Superposition
  - Basis and projection
- Quantum computing
  - Essential quantum advantage: Deutsch’s Algorithm
- Quantum networking
  - Quantum entanglement: where can I get some?
  - Quantum Cryptography, the new killer app
  - Entanglement as a resource, teleporting it around

Quantum randomness all around you

Some photons are reflected by window glass, others go straight through.

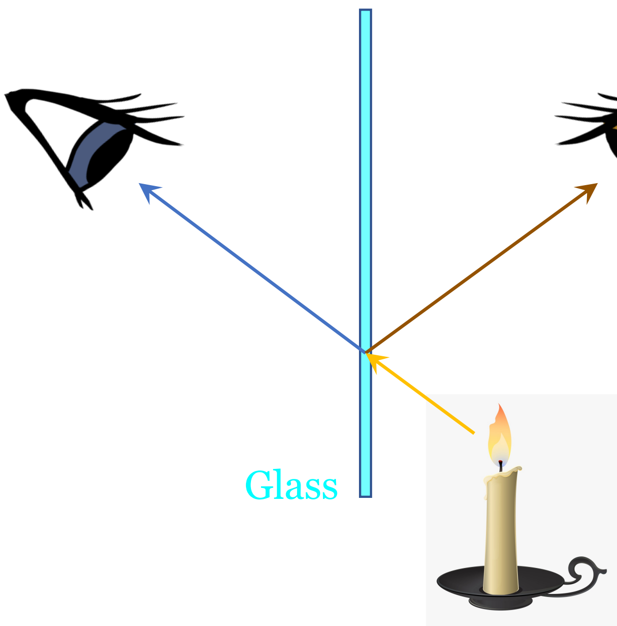
If photons are individual particles, how does each one make a decision?

Where is the randomness?

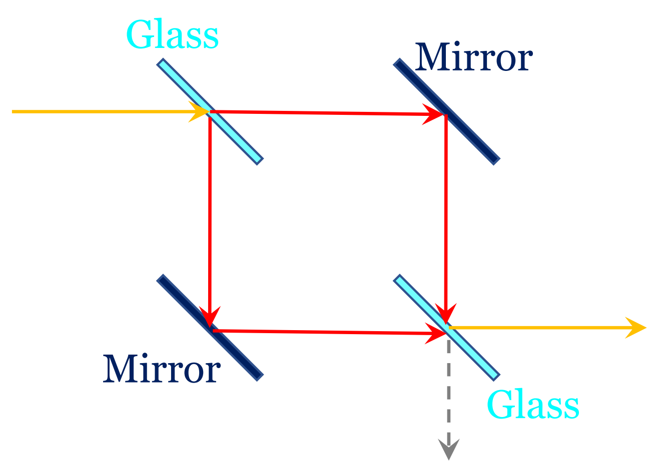
“The Road Not Taken”
-- Robert Frost

First guess: decision at each point

Left: Outcome 1 Right: Outcome 2



Intuitive but *provably incorrect*:

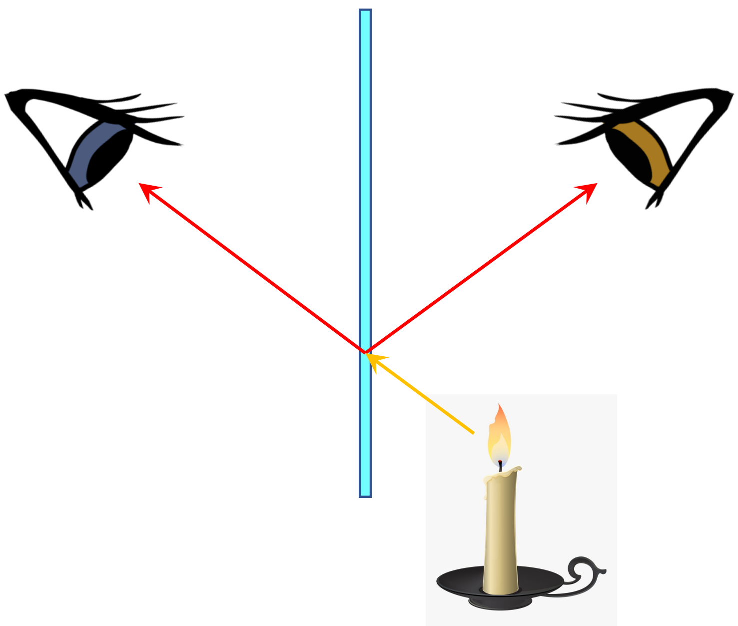


Mach-Zehnder Interferometer shows output at only one exit; photon *must* have taken both paths

Superposition: take *both* paths

"Of course people do go both ways." -- Scarecrow

Single outcome: $(|\text{Left}\rangle + |\text{Right}\rangle)/\sqrt{2}$



Superposition evolves until random outcome is determined at *detection* step

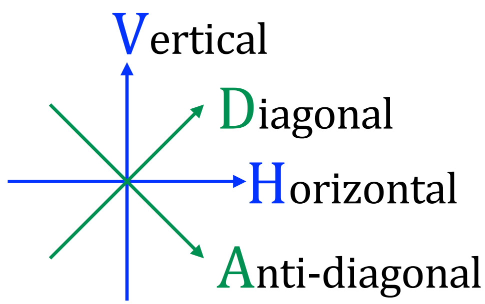
$$Prob(\text{Left}) = \left|\langle\text{Left}(|\text{Left}\rangle + |\text{Right}\rangle)/\sqrt{2}\right|^2$$

$$= \left|\underbrace{\langle\text{Left}|\text{Left}\rangle}_{=1}/\sqrt{2} + \underbrace{\langle\text{Left}|\text{Right}\rangle}_{=0}/\sqrt{2}\right|^2$$

$$= 1/2$$

All your bases are equivalent….

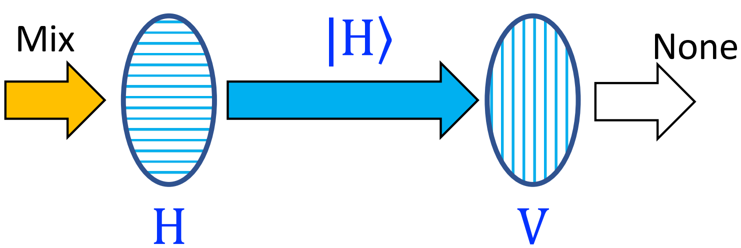
Classical E&M Polarizations



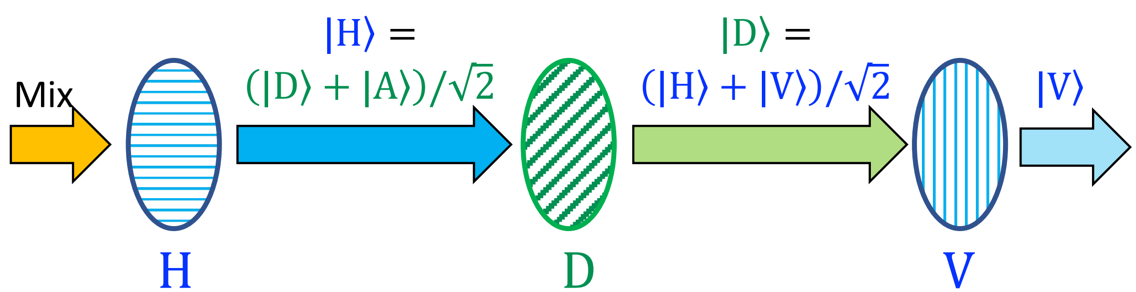
Quantum Mechanical Bases: $\{|H\rangle, |V\rangle\}$ $\{|D\rangle, |A\rangle\}$

$$|H\rangle = (|D\rangle + |A\rangle)/\sqrt{2}$$
$$|V\rangle = (|D\rangle - |A\rangle)/\sqrt{2}$$
$$|D\rangle = (|H\rangle + |V\rangle)/\sqrt{2}$$
$$|A\rangle = (|H\rangle - |V\rangle)/\sqrt{2}$$

Two polarizer experiment:



Three polarizer experiment:



Essentials of quantum computing:

- Initialize a non-classical superposition state at input
- Process “normally” but keep all computing components completely isolated from the outside world
- ***Note:*** all computation steps must be *reversible*, no information loss along the way
- Output state can be a non-classical superposition, need to interface carefully
- Cleverly choose a basis to measure the output, which will isolate the select information you want

Deutsch and the ur-algorithm

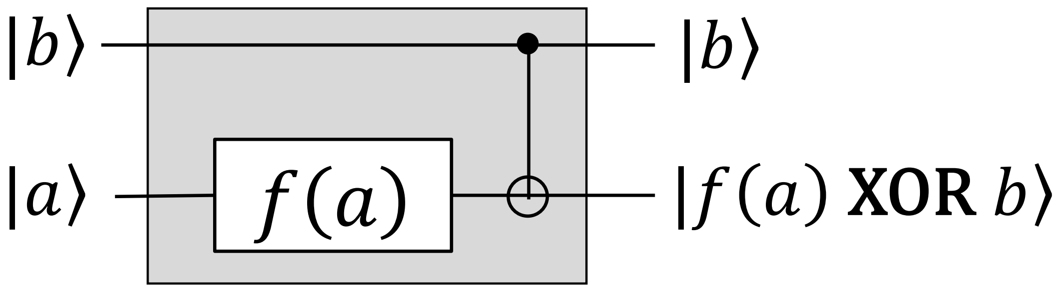
$$|a\rangle \;—\; \boxed{f(a)} \;—\; |X\rangle$$

A function $f(a)$ with a one-bit input $a \in \{0,1\}$
and a one-bit output $X \in \{0,1\}$

To fully map $f(a)$ we need to evaluate the function twice, $f(0)$ and $f(1)$

But if we can input a superposition $|a\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$ and measure the output carefully, we can answer the select question "Is $f(0) = f(1)$?" with only *one* evaluation of the function – quantum advantage!

Details, details...



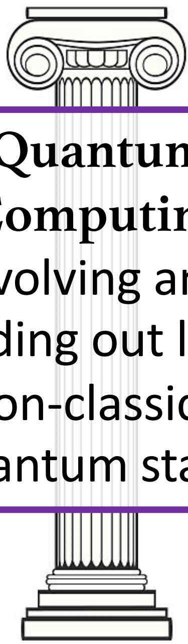
Embed $f(a)$ in a ***reversible*** quantum circuit with two input qubits $|a\rangle|b\rangle$ and two output qubits $|f(a)\ \mathbf{XOR}\ b\rangle|b\rangle$

1. Start with input qubits $|a\rangle|b\rangle$ in superposition state $(|0\rangle|0\rangle - |0\rangle|1\rangle + |1\rangle|0\rangle - |1\rangle|1\rangle)/2$

2. Run circuit with one evaluation of f(). Output qubits $|f(a)\ \mathbf{XOR}\ b\rangle|b\rangle$ are now in superposition state $(|f(0)\ \mathbf{XOR}\ 0\rangle|0\rangle - |f(0)\ \mathbf{XOR}\ 1\rangle|1\rangle + |f(1)\ \mathbf{XOR}\ 0\rangle|0\rangle - |f(1)\ \mathbf{XOR}\ 1\rangle|1\rangle)/2$

2. Measure upper output qubit in basis $|+\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$ and $|-\rangle = (|0\rangle - |1\rangle)/\sqrt{2}$ after some algebra discover $|+\rangle$ result when $f(0) = f(1)$ and $|-\rangle$ result when $f(0) \neq f(1)$

Quantum Computing, once all the rage…



Quantum Computing
Evolving and reading out large non-classical quantum states

Quantum Information Science & Technology

Quantum Computing
Evolving and reading out large non-classical quantum states

✓

Quantum Networking
Creating, storing and transporting large non-classical quantum states

✓✓

Quantum Sensors
Improving performance using non-classical quantum states

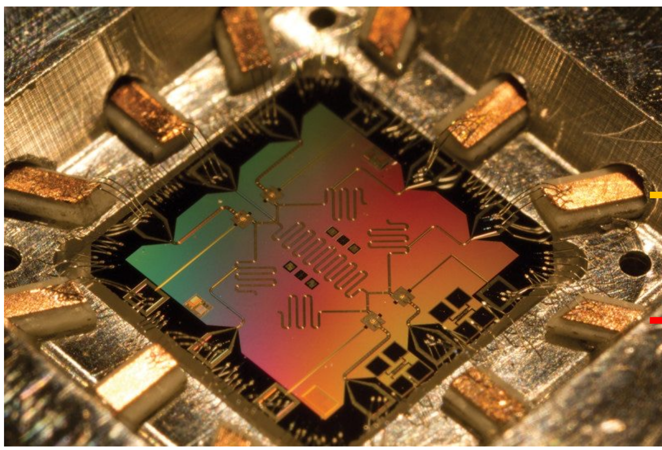
Quantum Simulators
Modelling quantum systems with easier quantum systems

"Gentlemen, what are the four pillars?" -- Dead Poets Society (1989)

A Two-(Qu)Bit Hilbert Space

Separable States
Classical-like

Non-Separable States
No classical analogue
"Entangled"



Qbit

Qbit

Quantum Computer

$$|00\rangle$$
$$|01\rangle$$
$$|10\rangle$$
$$|11\rangle$$

$$(|00\rangle + |11\rangle)/\sqrt{2}$$
$$(|00\rangle - |11\rangle)/\sqrt{2}$$
$$(|01\rangle + |10\rangle)/\sqrt{2}$$
$$(|01\rangle - |10\rangle)/\sqrt{2}$$

All the "oomph" of quantum technology comes from using more dimensions in multi-particle Hilbert space

Safety tip: No cloning allowed

Measuring a quantum system projects it into a basis state,
so some information on the initial state is inevitably lost:
no general classical copying

Quantum copying turns out to be forbidden by the **No-Cloning Theorem**;
more involved, can be seen as a consequence of information conservation

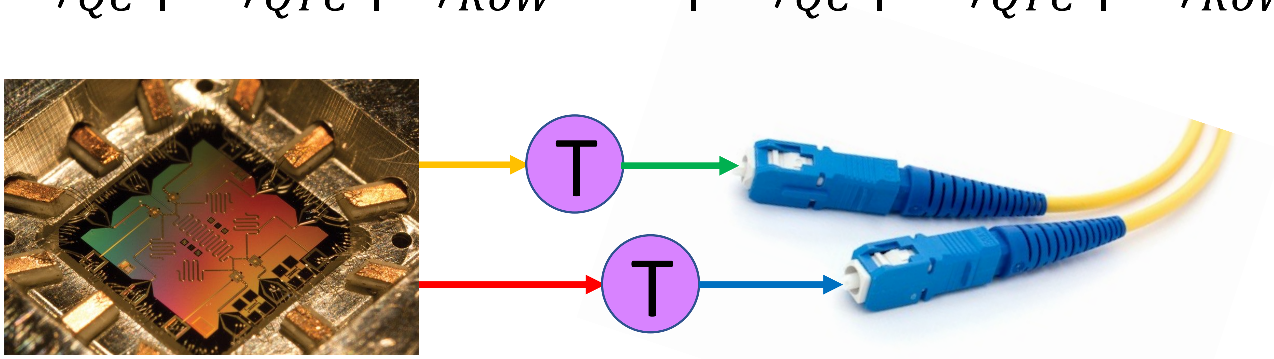
However, as long as a quantum state is not measured/projected
then it *can* be

- Converted between physical qubit types (Transduction)
- Carried, carefully, over long distances (Networking)
- Stored and read back (Quantum memories)
- Destroyed in one place and re-incarnated in the same state somewhere else (Teleportation, Entanglement Swapping)

Quantum Transduction

RoW = "Rest of the World"

$$|XY\rangle_{QC}\,|00\rangle_{QTC}\,|\Phi\rangle_{RoW} \;\rightarrow\; |00\rangle_{QC}\,|XY\rangle_{QTC}\,|\Phi'\rangle_{RoW}$$



Quantum Computer (QC)

Quantum Transmission Channel (QTC)

A necessary condition for quantum transduction is that the final state Φ' of the rest of the world is the same *independent* of the state of the qubits; this is equivalent to saying there is no interaction between the physical qubits and the outside world, e.g. no information leakage.

Linearity: $(|10\rangle_{QC} + |01\rangle_{QC})\,|00\rangle_{QTC}\,|\Phi\rangle_{RoW} \;\rightarrow\; |00\rangle_{QC}\,(|10\rangle_{QTC} + |01\rangle_{QTC})\,|\Phi'\rangle_{RoW}$

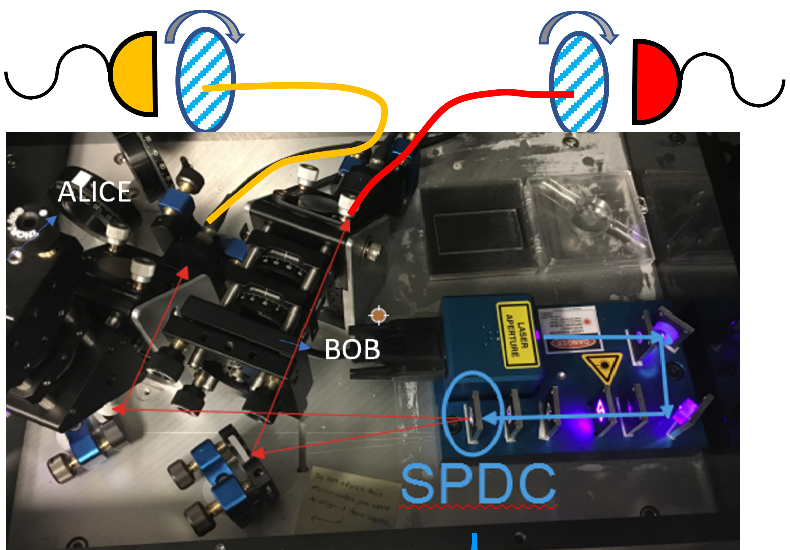
PWS currently PI for BNL LDRD to demonstrate quantum transduction between superconducting resonators and room-temperature photons, mediated by atomic vapor; details to follow.

Entanglement as a *resource*

Entangled pairs can be created, transmitted, and stored -- *where can I get some*?

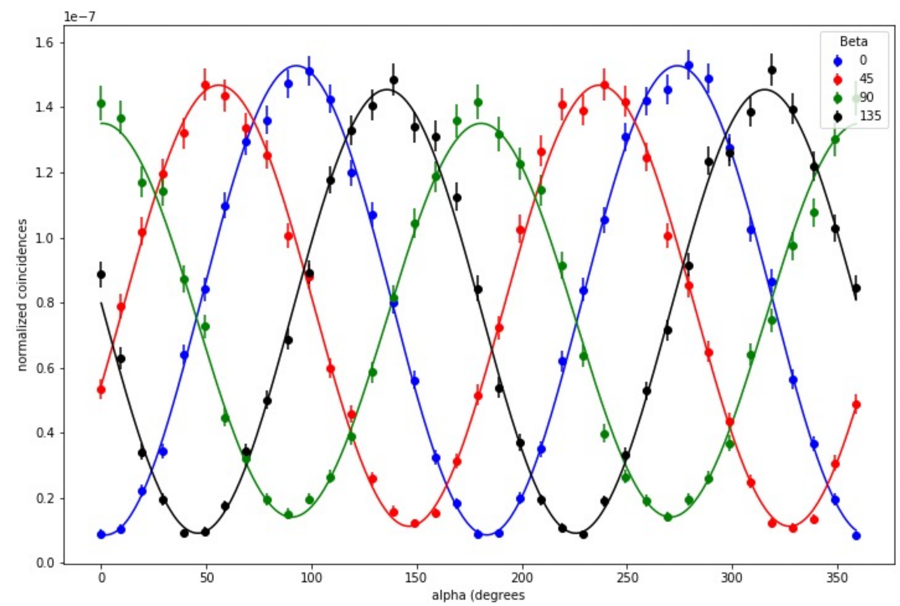
$$|HH\rangle + |VV\rangle$$

Note: $|HH\rangle + |VV\rangle = |DD\rangle + |AA\rangle$

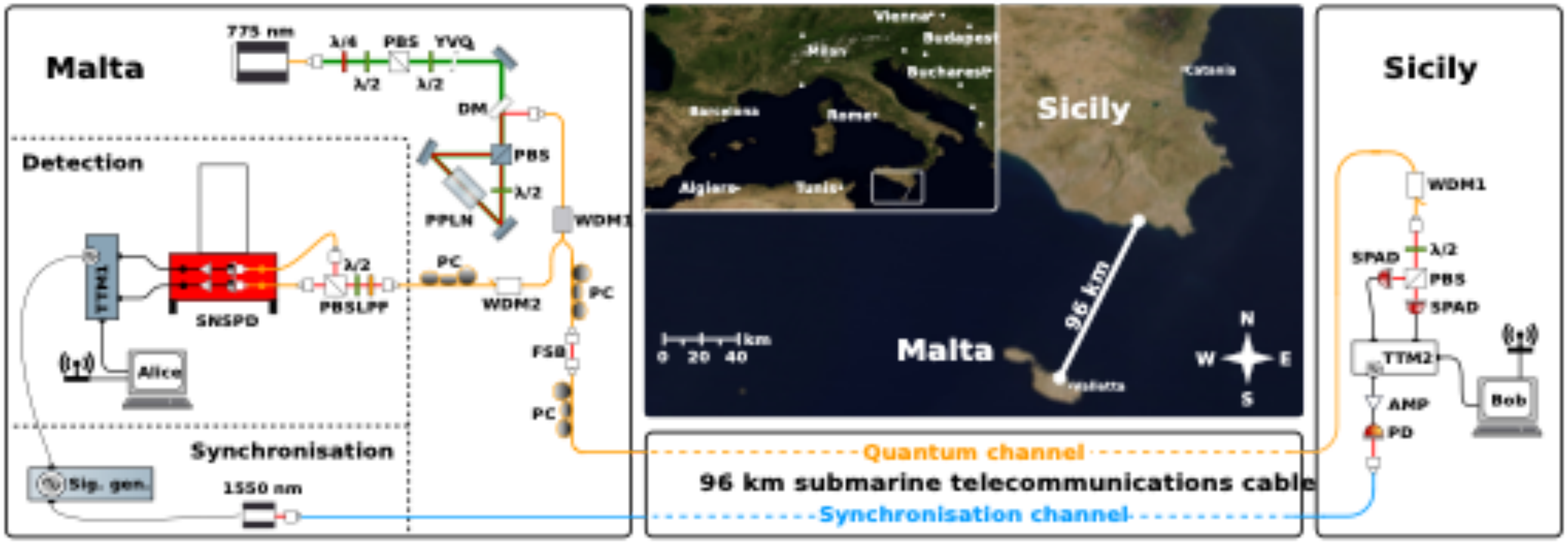


Polarization Entangled Photon Pair Creation

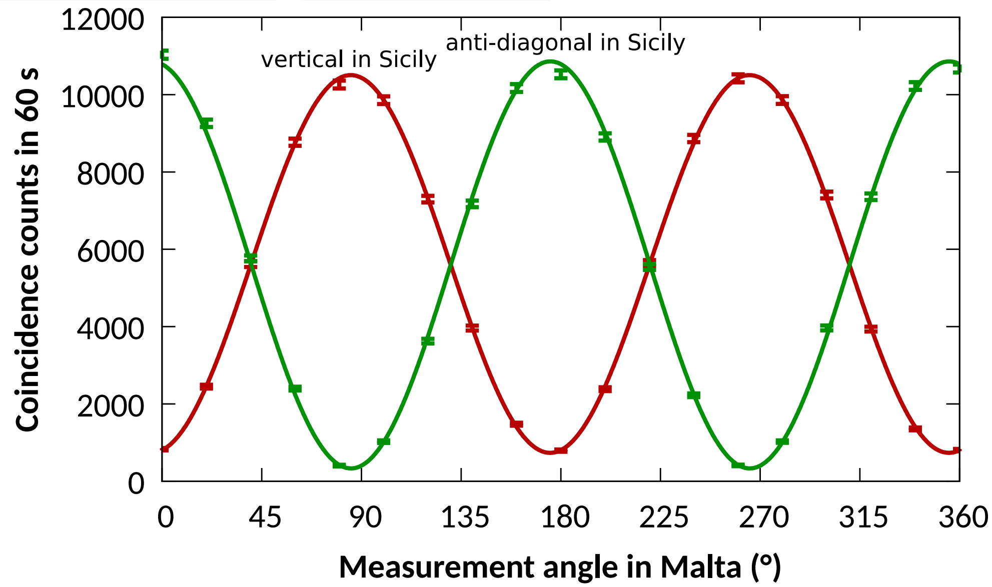
Pair Rate



Polarizer angles



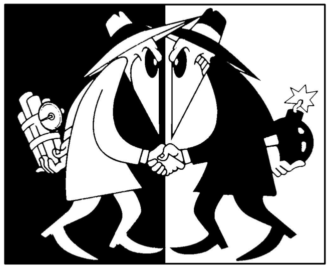
[arXiv:1803.00583](https://arxiv.org/abs/1803.00583)
[quant-ph]

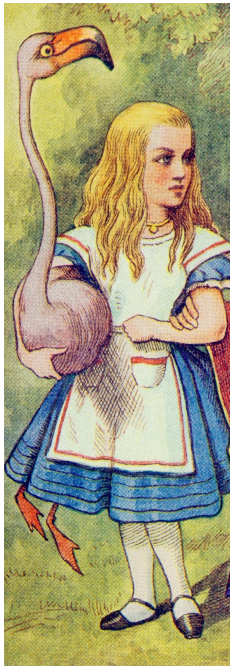


In-field entanglement distribution over a 96 km-long submarine optical fibre*

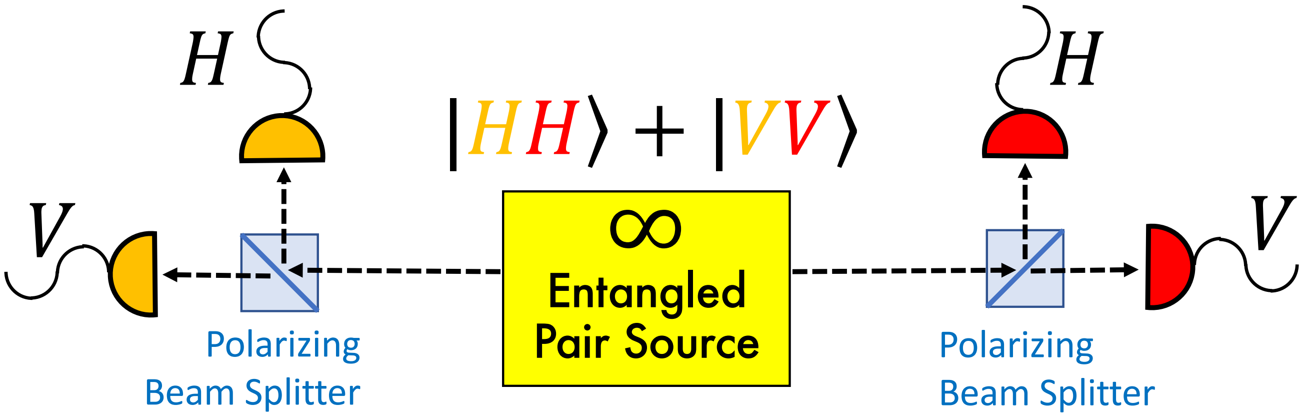
Sören Wengerowsky,[1,2,†] Siddarth Koduru Joshi,[1,2] Fabian Steinlechner,[1,2] Julien R. Zichi,[3,4] Sergiy. M. Dobrovolskiy,[4] René van der Molen,[4] Johannes W. N. Los,[4] Val Zwiller,[3,4] Marijn A. M. Versteegh,[3] Alberto Mura,[5] Davide Calonico,[5] Massimo Inguscio,[6,7] Hannes Hübel,[8] Anton Zeilinger,[1,9] André Xuereb,[10] and Rupert Ursin[1,2,‡]

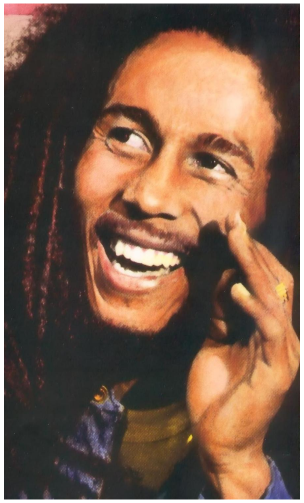
Quantum Cryptography: New killer app





ALICE





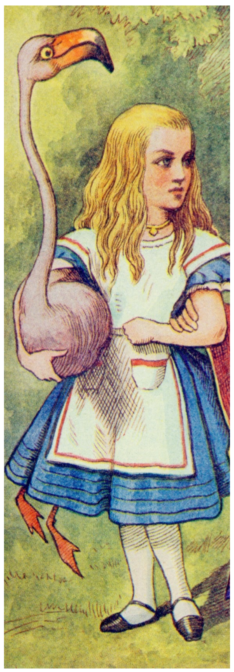
BOB

H
V
V
H
V
H

Random but perfectly correlated observations at two stations constitute a ***quantum key*** for cryptography

H
V
V
H
V
H

Quantum Cryptography: Vulnerability?



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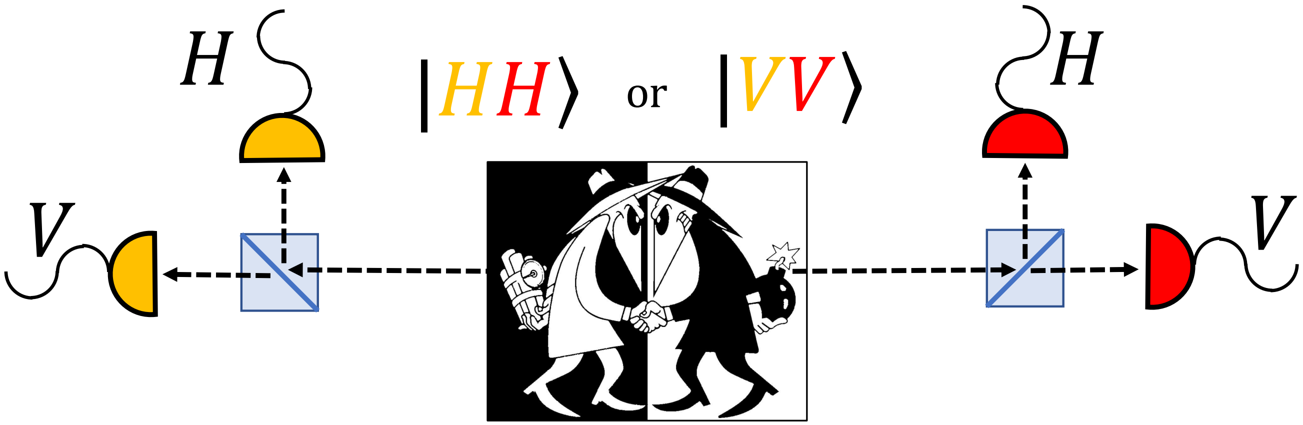
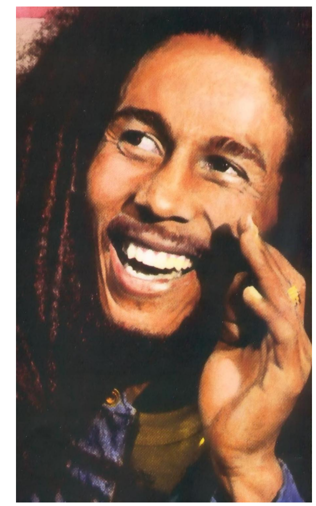


H
V
V
H
V
H

Interlopers can imitate the same effect by sending HH or VV at random, and they will then know the key

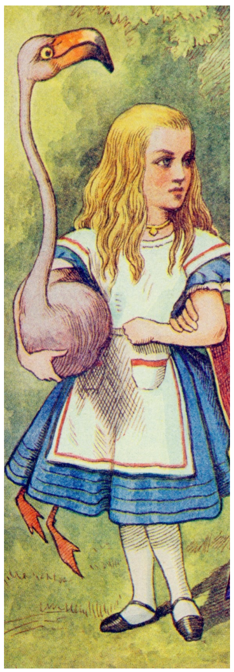
H
V
V
H
V
H



BOB

Quantum Cryptography: QM for the win

$$|HH\rangle + |VV\rangle = |DD\rangle + |AA\rangle$$



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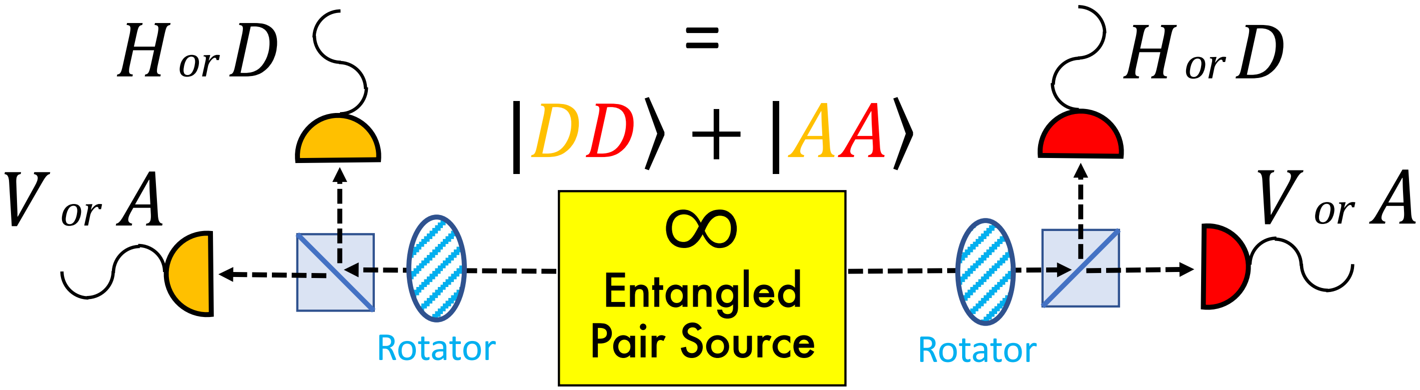
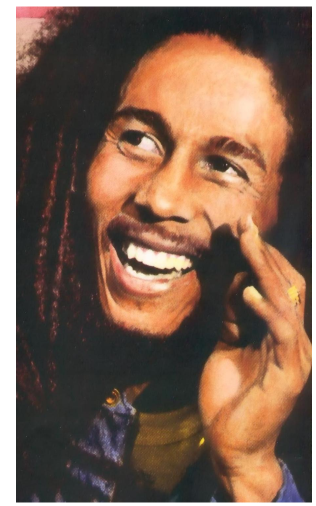




BOB

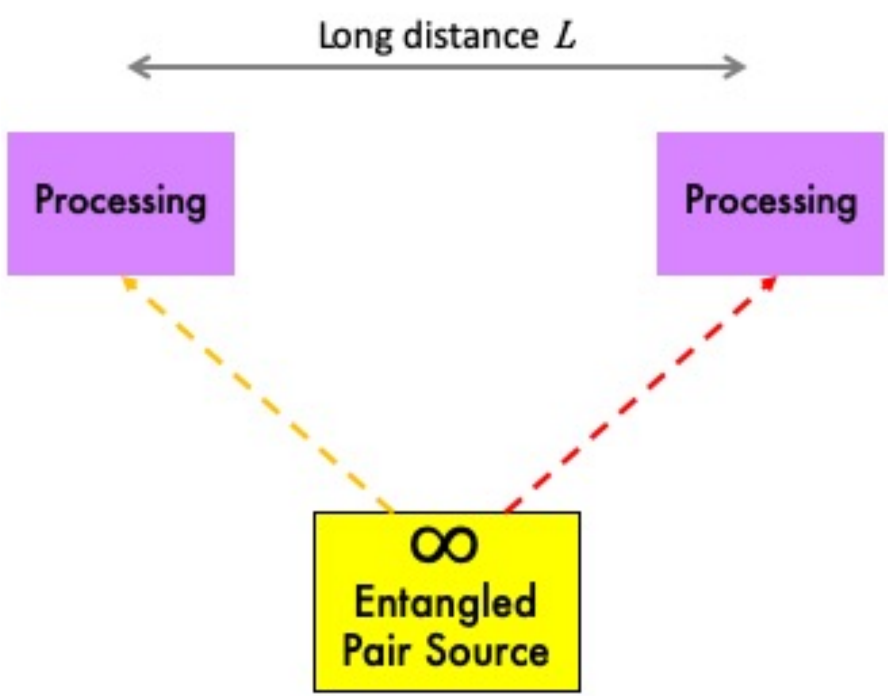
HV: H
HV: V
DA: A
HV: H
DA: D
DA: A

Choose basis HV or AD *randomly* at each station, results are correlated when basis choices are the same; *cannot be imitated*

HV: H
DA: D
DA: A
HV: H
HV: V
DA: A

Going the distance

Transmission of single photons over fiber limited to <100 Km – but remember, no cloning/copying, so nothing like a standard classical repeater/amplifier is possible



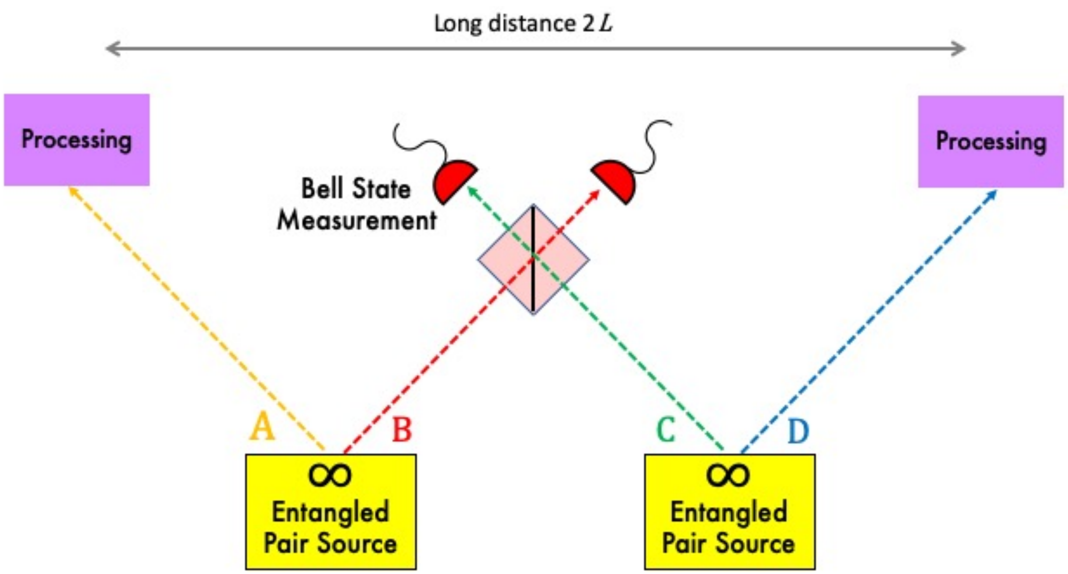
How to go farther? First we recall the set of fully entangled states, called the Bell State Basis:

$$(|HH\rangle + |VV\rangle)/\sqrt{2} \stackrel{\text{def}}{=} |\Phi^+\rangle$$
$$(|HH\rangle - |VV\rangle)/\sqrt{2} \stackrel{\text{def}}{=} |\Phi^-\rangle$$
$$(|HV\rangle + |VH\rangle)/\sqrt{2} \stackrel{\text{def}}{=} |\Psi^+\rangle$$
$$(|HV\rangle - |VH\rangle)/\sqrt{2} \stackrel{\text{def}}{=} |\Psi^-\rangle$$

One-hop *quantum repeater*

Initial wavefunction has two independent entangled pairs, *AB* and *CD*

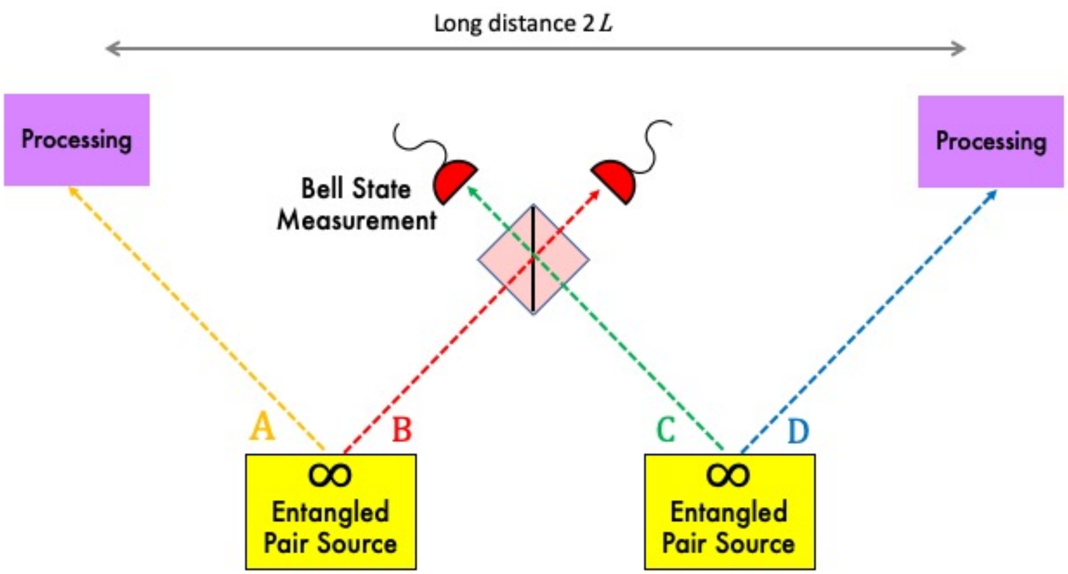
$$\psi = (|HH\rangle + |VV\rangle)\,(|HH\rangle + |VV\rangle)/2 = |\Phi^+\rangle_{AB}|\Phi^+\rangle_{CD}$$



One-hop *quantum repeater*

After some algebra we can re-group *A* with *D* and *B* with *C*

$$\psi = |\Phi^+\rangle_{AD}|\Phi^+\rangle_{BC} + |\Phi^-\rangle_{AD}|\Phi^-\rangle_{BC} + |\Psi^+\rangle_{AD}|\Psi^+\rangle_{BC} + |\Psi^-\rangle_{AD}|\Psi^-\rangle_{BC}$$

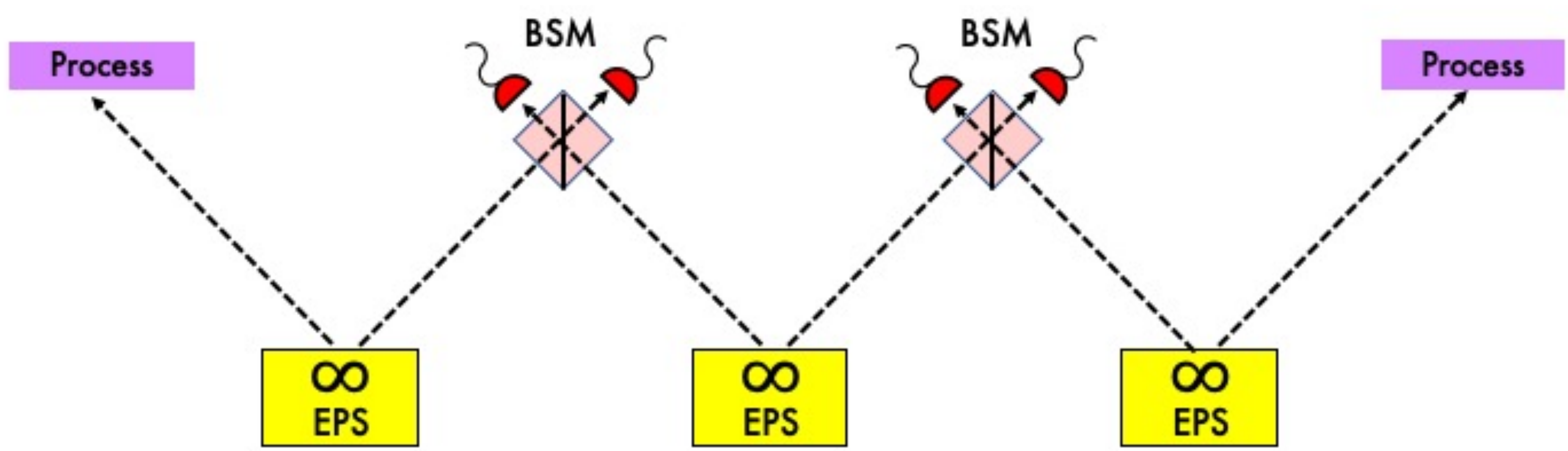


Measurement/projection of the *BC* pair in the Bell State basis will partially collapse the 4-particle wavefunction and leave the *AD* pair in *a fully entangled state*!

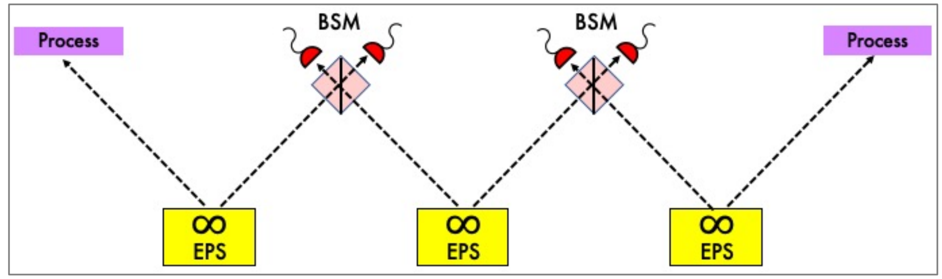
"Entanglement Swapping"

Repeat as necessary

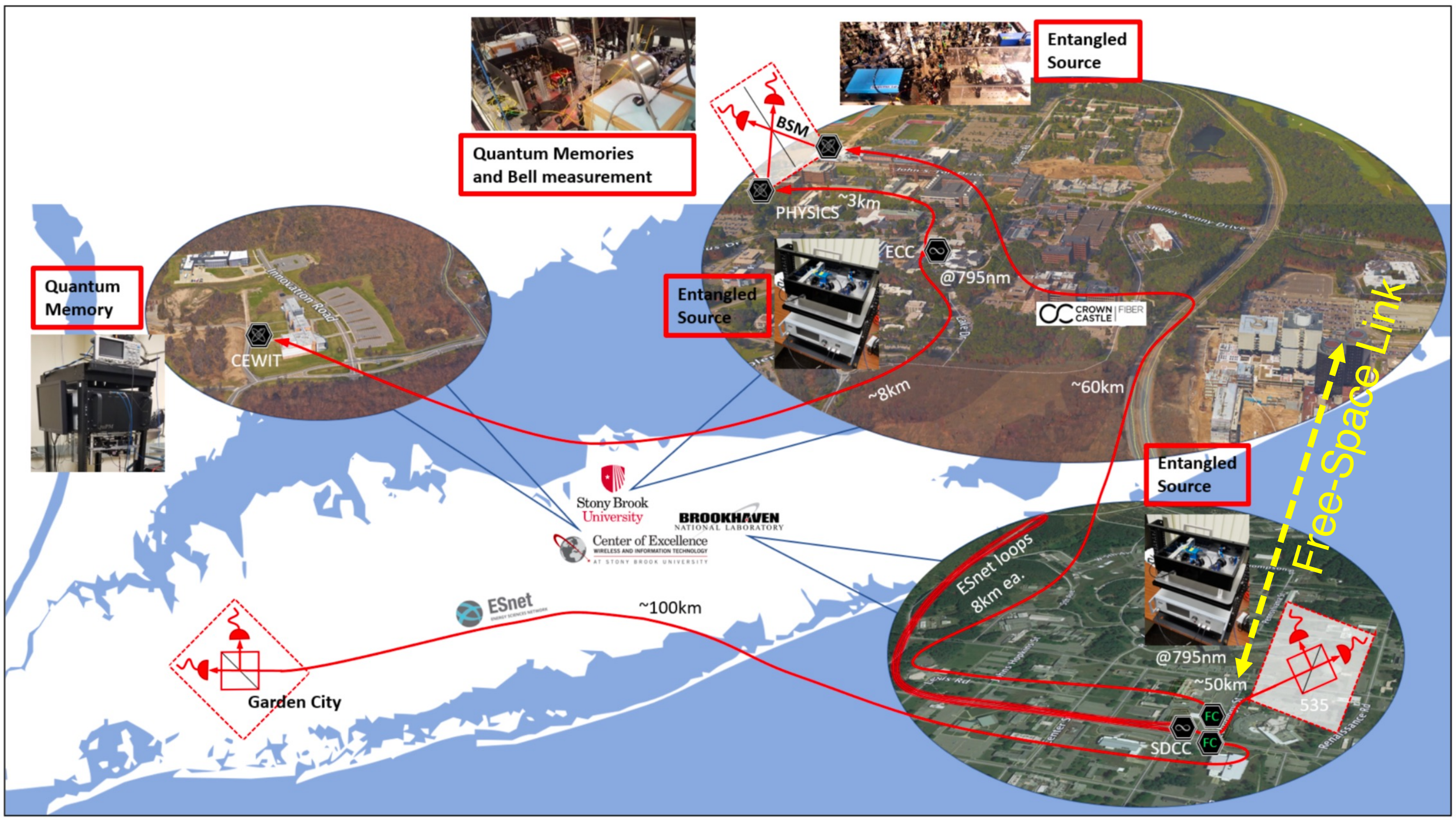
In principle we can chain repeater stages for as many hops as are needed to go the desired distance, as long as we can generate the intermediate entangled pairs – a form of **teleportation** using *entanglement as a resource*.



Q-LAN (really)

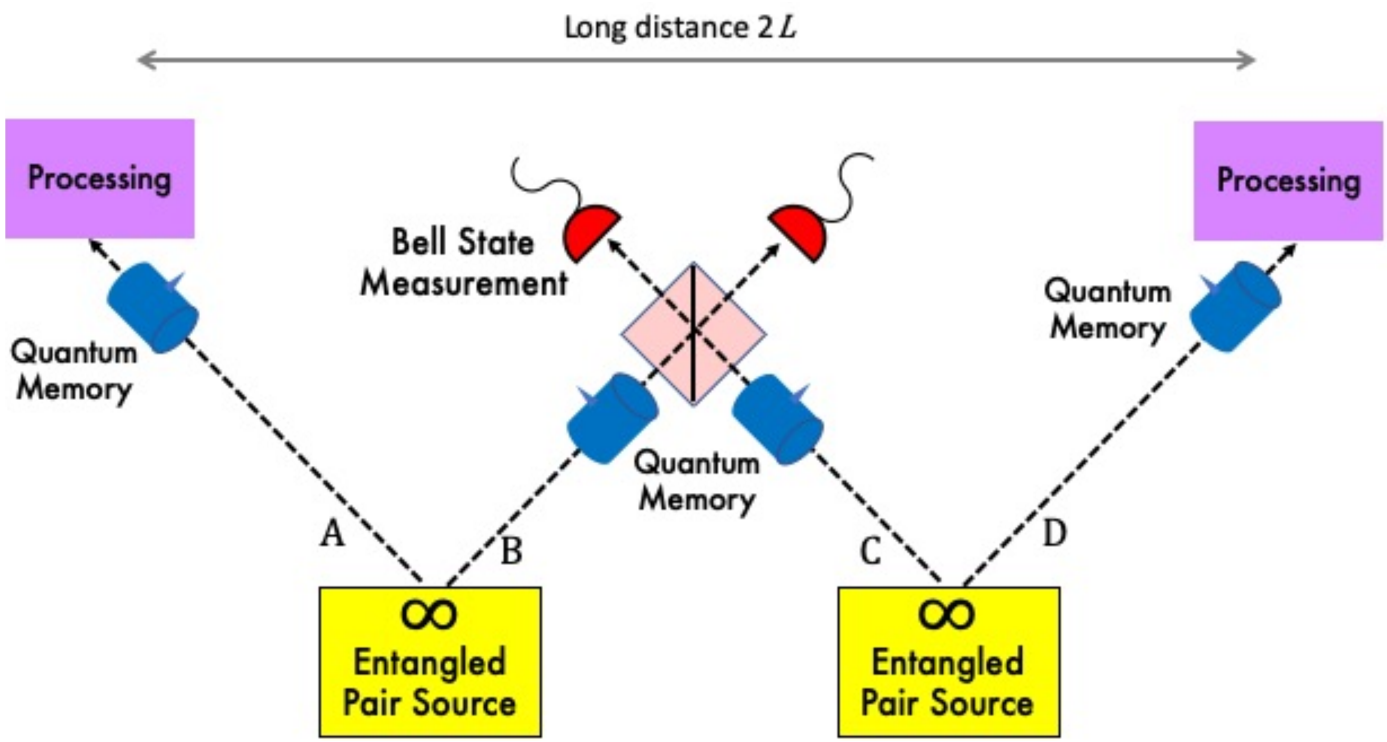


Theory



Practice

Memories and persistence



In practice, the generation and transmission of photons is *probabilistic*, and so the simple repeater depends on fortunate coincidence.

We can de-skew and greatly improve efficiency by storing successful transmissions in quantum memories.

Electromagnetically Induced Transparency (EIT)

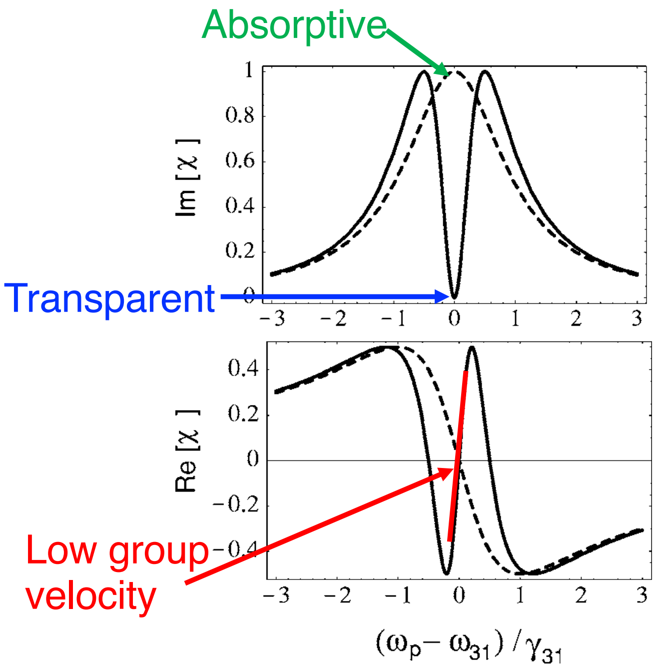
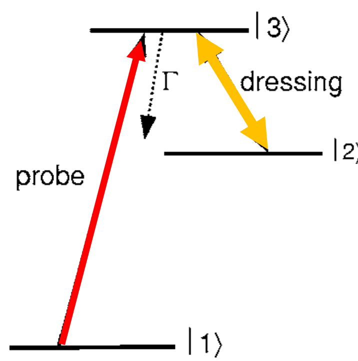
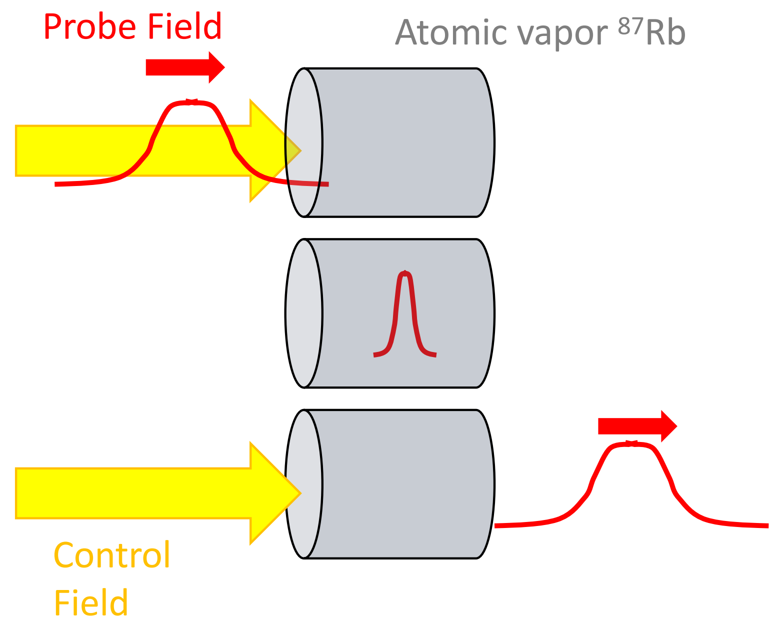


FIG. 1. Susceptibility as a function of the frequency ω_p of the applied field relative to the atomic resonance frequency ω_{31}, for a radiatively broadened two-level system with radiative width γ_{31} (dashed line) and an EIT system with resonant coupling field (solid line): top, imaginary part of $\chi^{(1)}$ characterizing absorption; bottom, real part of $\chi^{(1)}$ determining the refractive properties of the medium.



"Dark State Polariton"

$$|1\rangle - \frac{\Omega_P}{\Omega_C}|2\rangle$$



Storage is a *coherent* effect across all atoms in the vapor; non-projective

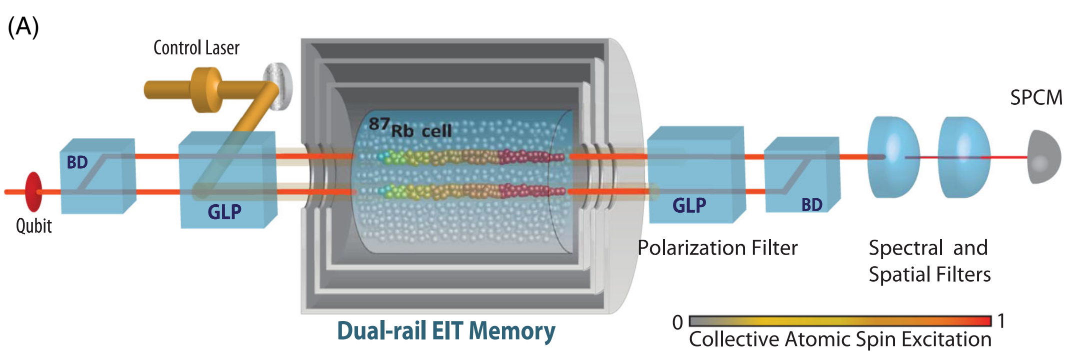
Fleischhauer, Imamoglu, Marangos, RMP **77**, 2005
Fleischhauer & Lukin, PRL **84**, 2000

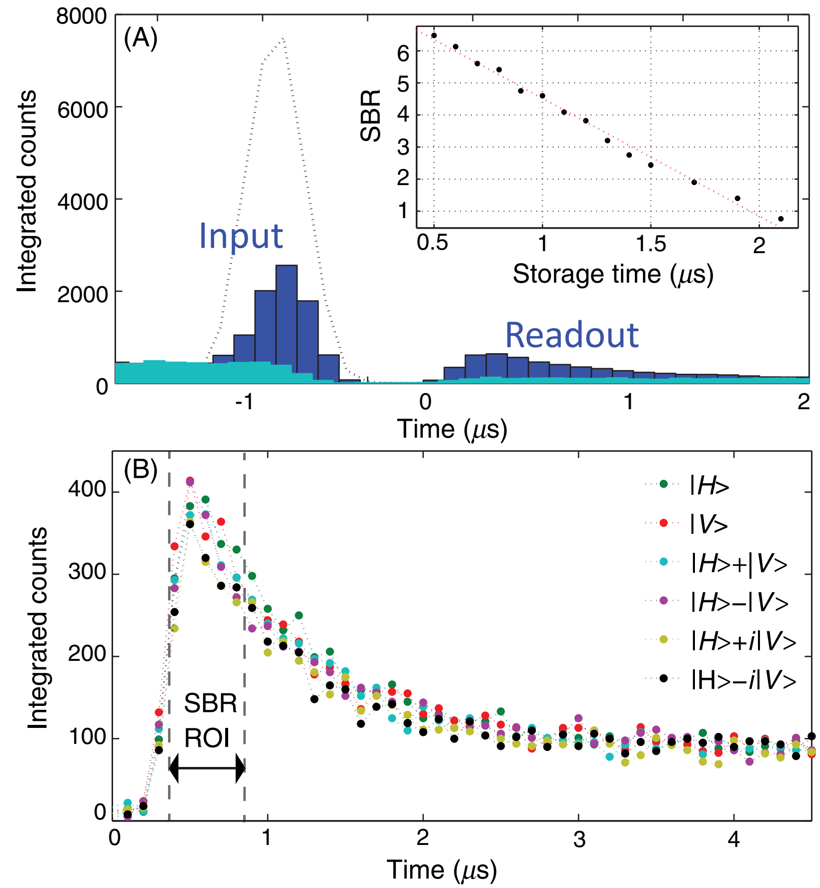
Room-temperature quantum memories

PHYSICAL REVIEW APPLIED **8**, 034023 (2017)

Ultralow-Noise Room-Temperature Quantum Memory for Polarization Qubits

Mehdi Namazi, Connor Kupchak, Bertus Jordaan, Reihaneh Shahrokhshahi, and Eden Figueroa
Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794-3800, USA
(Received 27 July 2016; revised manuscript received 14 August 2017; published 25 September 2017)



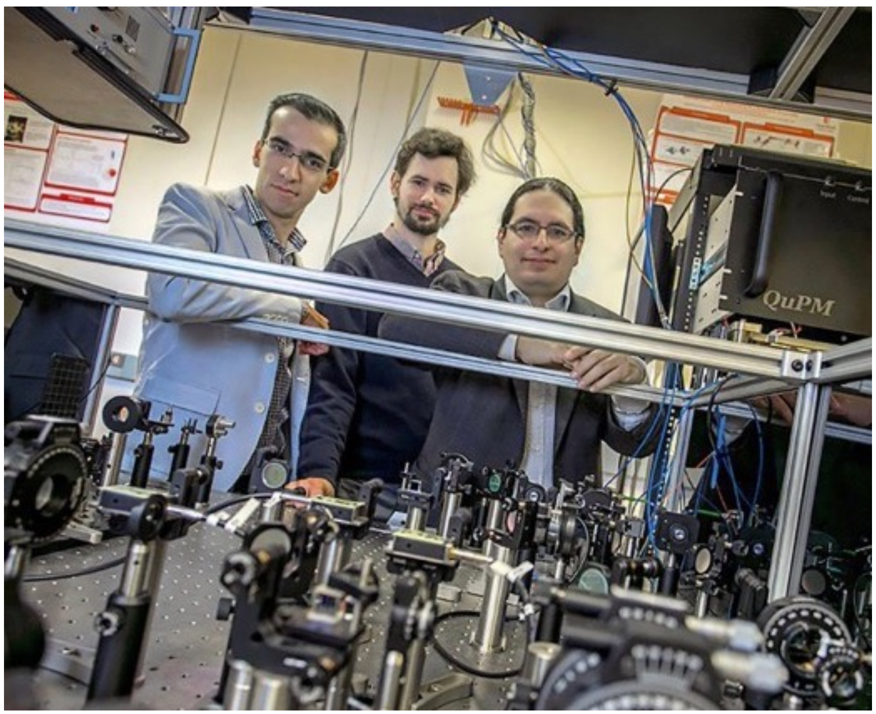


TECHNOLOGY

The Quantum Internet Will Blow Your Mind. Here's What It Will Look Like

October 2020

DISCOVER



Mehdi Namazi, Mael Flament, Prof. Eden Figueroa

"There is no such thing as *good* publicity or *bad* publicity; there is only *more* publicity and *less* publicity"

-- Sam Goldwyn

2020 media coverage

RESEARCH NEWS

The Key Device Needed for a Quantum Internet

June 30, 2020 • *Physics* 13, 104

As researchers worldwide work toward a potential quantum internet, a major roadblock remains: How to build a device called a quantum repeater.

physics.aps.org/articles/v13/104

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US Takes an Important Step Toward Quantum Internet

A recent experiment has created a one-way quantum network between two labs, reaching a milestone on the path to creating a quantum internet.

https://www.insidescience.org/news/us-takes-important-step-toward-quantum-internet

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The quantum internet | The Big Idea

By Jodi Goldberg | Published October 6 | Updated October 7 | The Big Idea | FOX 5 NY

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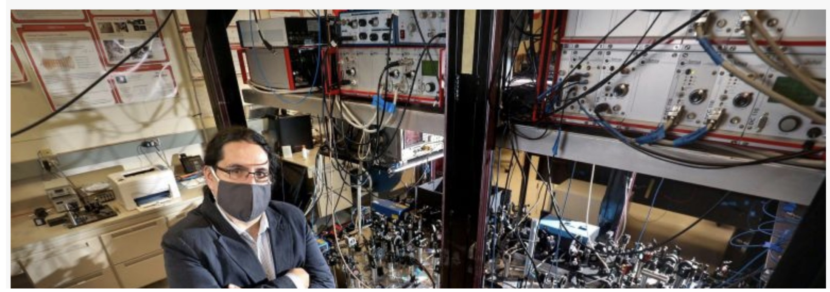
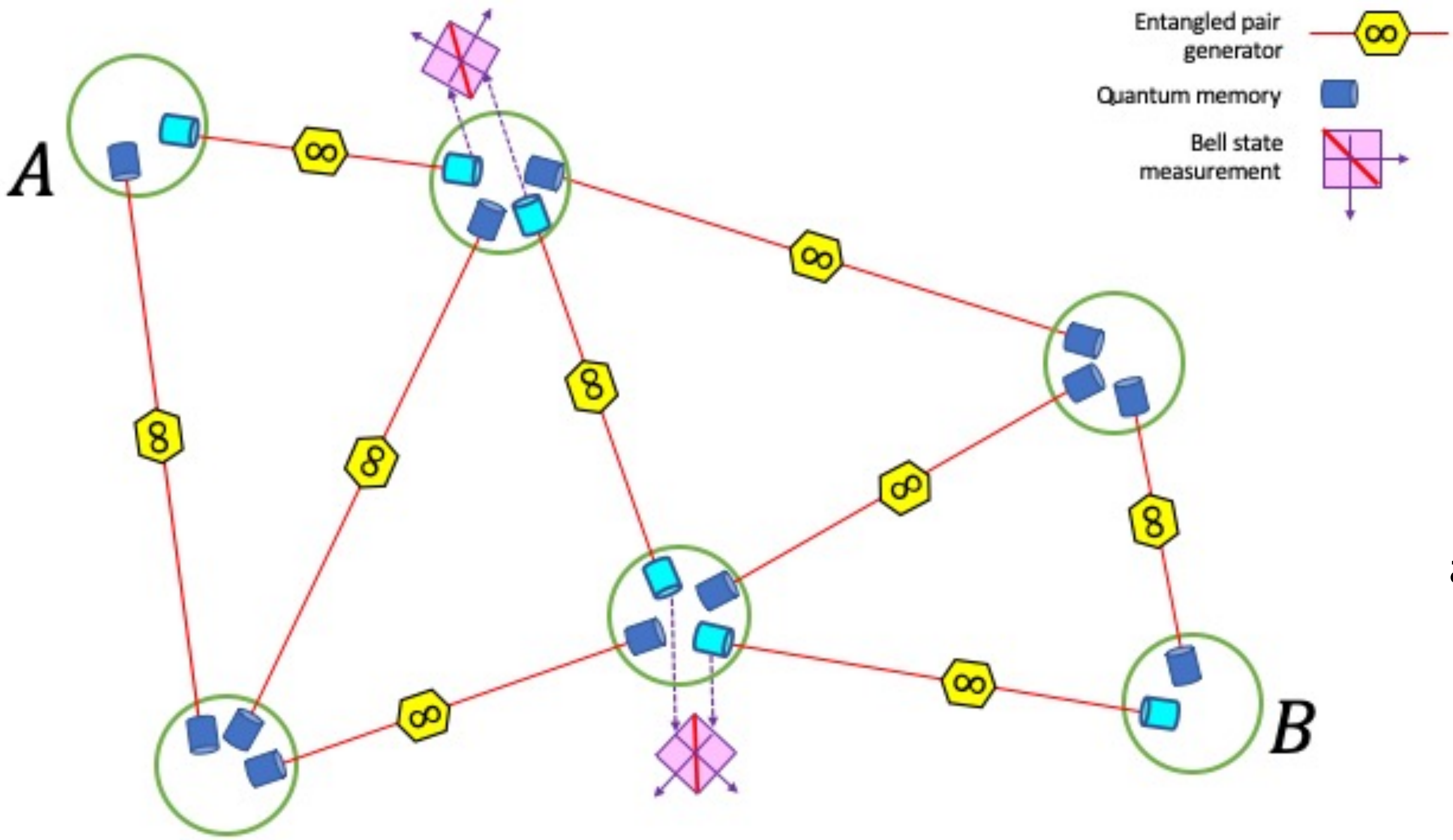
LI researchers work to create quantum internet



newsday.com/business/technology/quantum-internet-stony-brookhaven-laboratory-1.49712001

First-generation *Quantum Internet*



With links and memories, we can deliver entanglement to any pair of users on request

Points to take home:

- Quantum mechanics, once an obscure and un-intuitive annoyance, is now a working tool set for a variety of tasks
- Exploit – create, evolve, selectively measure – non-classical superposition/entangled states, even among macroscopic objects
- Quantum computing gets the most hype, but the other pillars – networking, sensors, simulators -- are now also becoming stars
- Our BNL/SBU collaboration is well along in building the first Quantum Local Area Network for entanglement distribution on Long Island