EDIT School at BNL: Quantum Networking

– or –

Finally having some fun with quantum mechanics

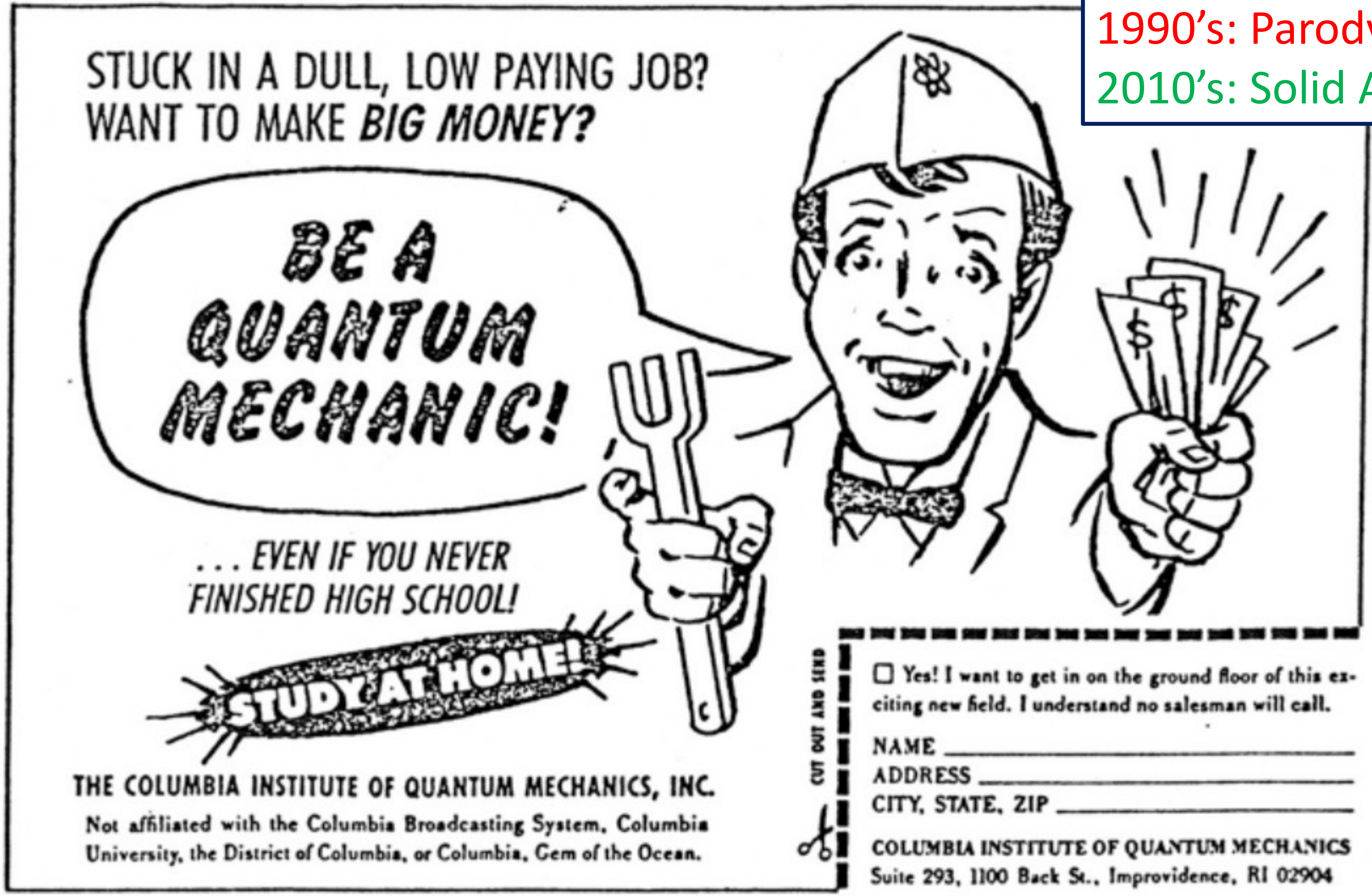
Paul Stankus, BNL

EDIT School

20 October 2023

BROOKHAVEN NATIONAL LABORATORY

1990’s: Parody
2010’s: Solid Advice



Quantum randomness all around you

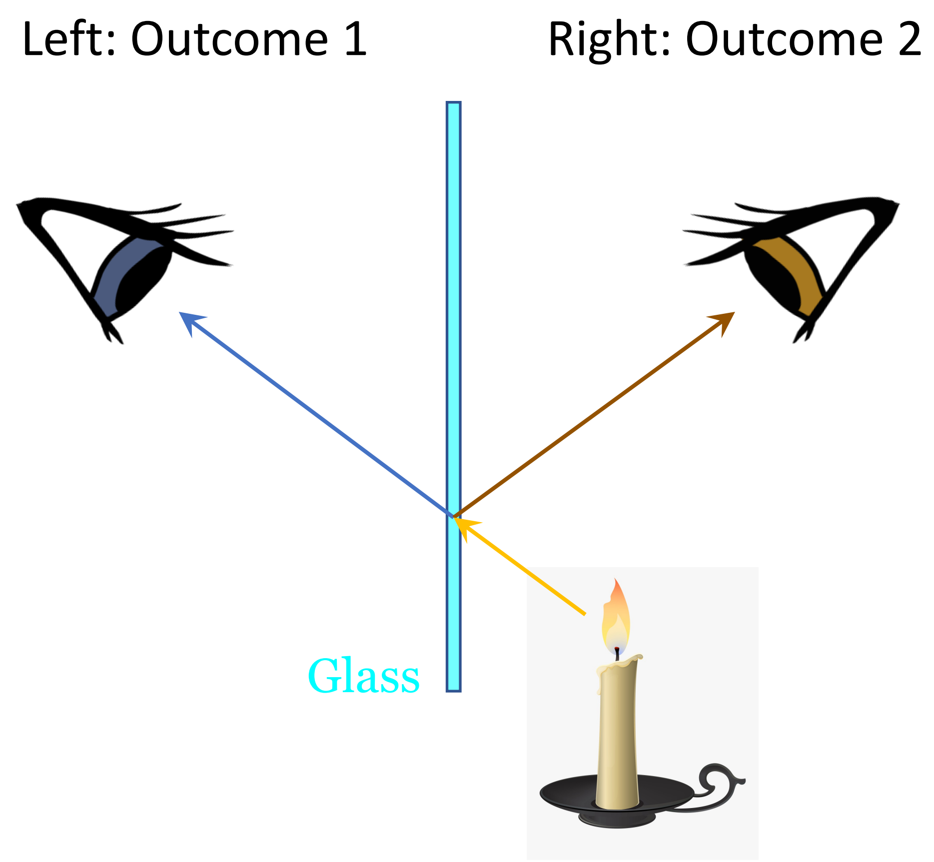
Some photons are reflected by window glass, others go straight through.

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

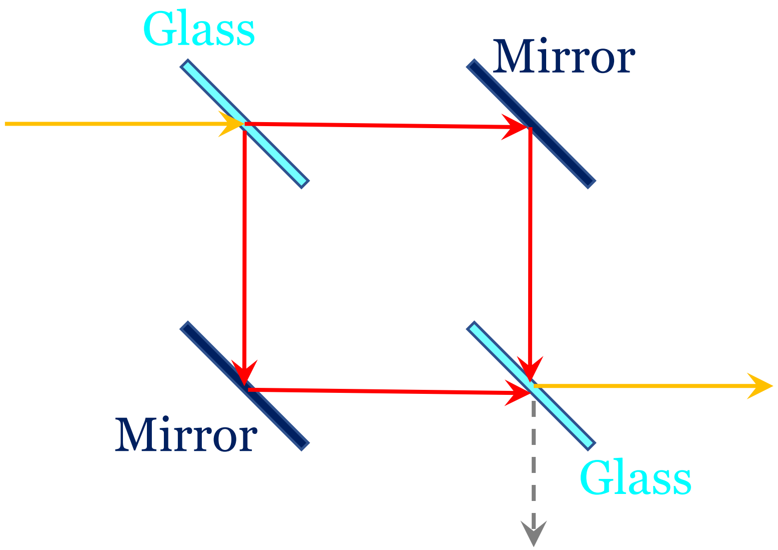
Where is the randomness?

First guess: decision at each point

“The Road Not Taken”
-- Robert Frost



Intuitive but *provably incorrect*:

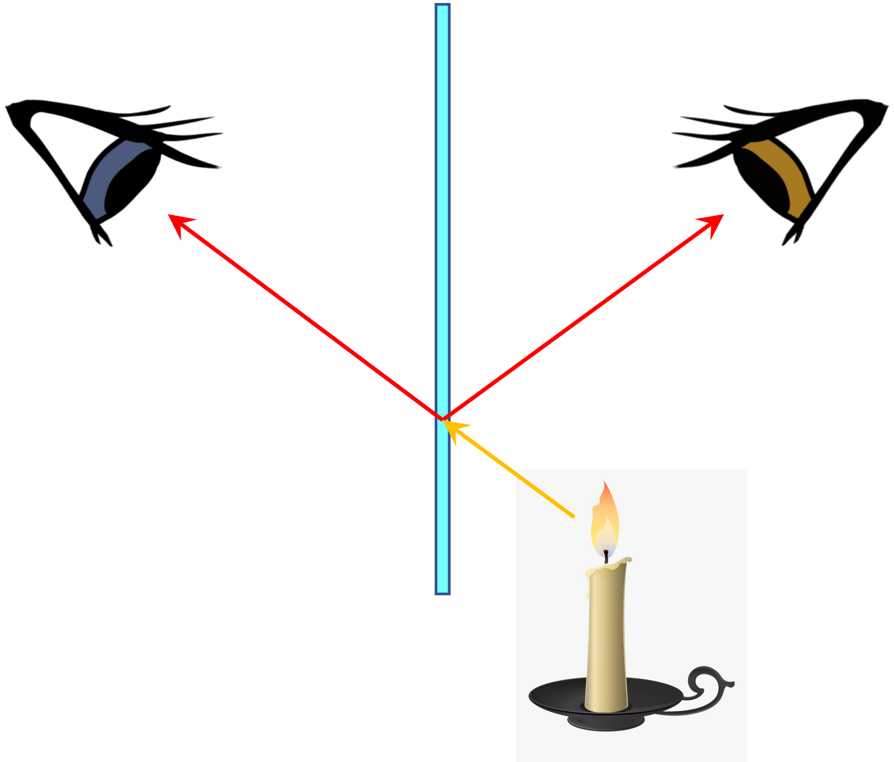


Mach-Zehnder Interferometer shows output at only one exit; photon *must* have taken both paths

Superposition: take *both* paths

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

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



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

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

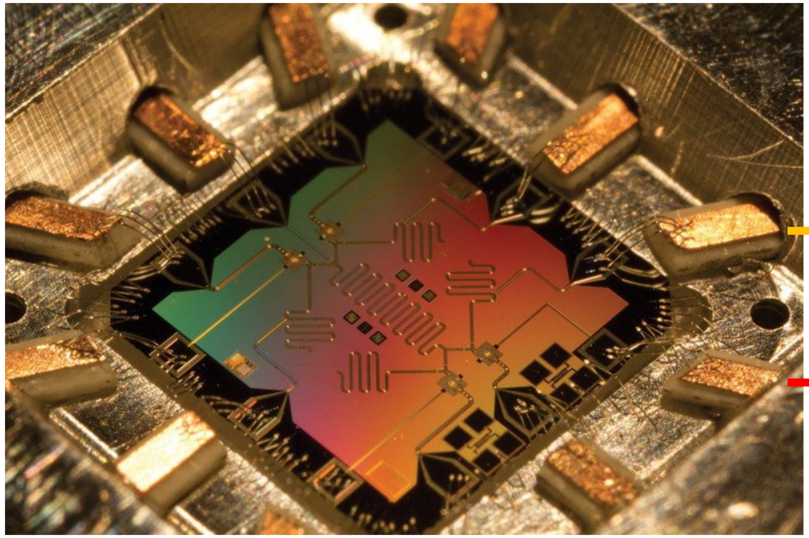
$$= \left|\underbrace{\langle \text{Left}|\text{Left}\rangle}_{=1}/\sqrt{2} + \underbrace{\langle \text{Left}|\text{Right}\rangle}_{=0}/\sqrt{2}\right|^2$$

$$= 1/2$$

A Two-(Qu)Bit Hilbert Space

Separable States
Classical-like

Non-Separable States
No classical analogue
"Entangled"



Qbit

Qbit

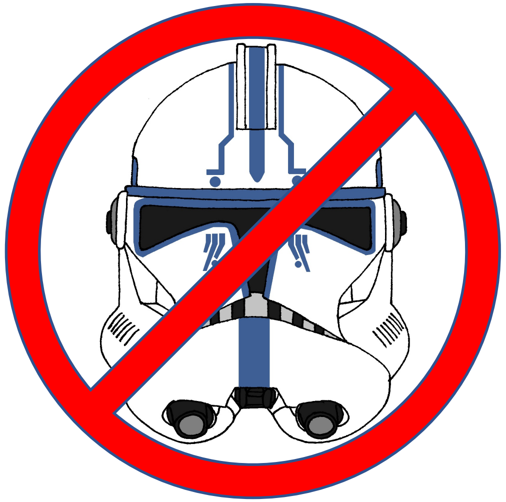
Quantum Computer

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

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

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

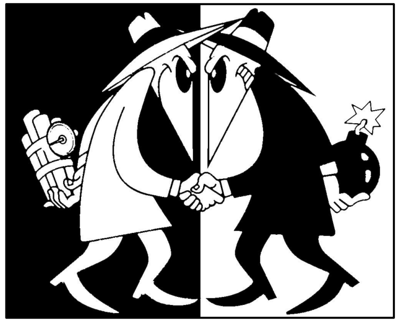
However, as long as a quantum state is not measured/projected then it *can* be

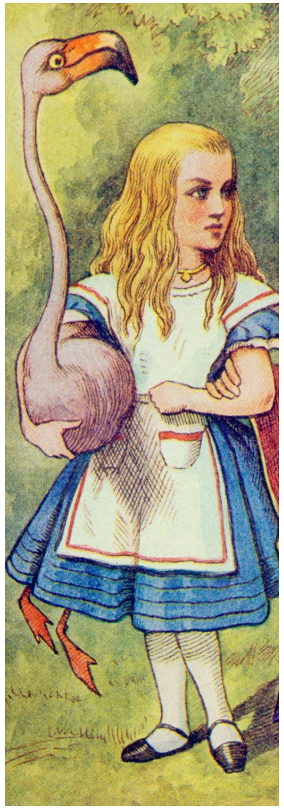
- Converted between physical qubit types (Transduction)
- Carried, carefully, over long distances (Networking)
- Stored and read back (Quantum memories)
- Destroyed in one place and re-incarnated in the same state somewhere else (Teleportation, Entanglement Swapping)

Quantum Crytography

Make uncertainty work *for* you

Quantum Cryptography: New killer app





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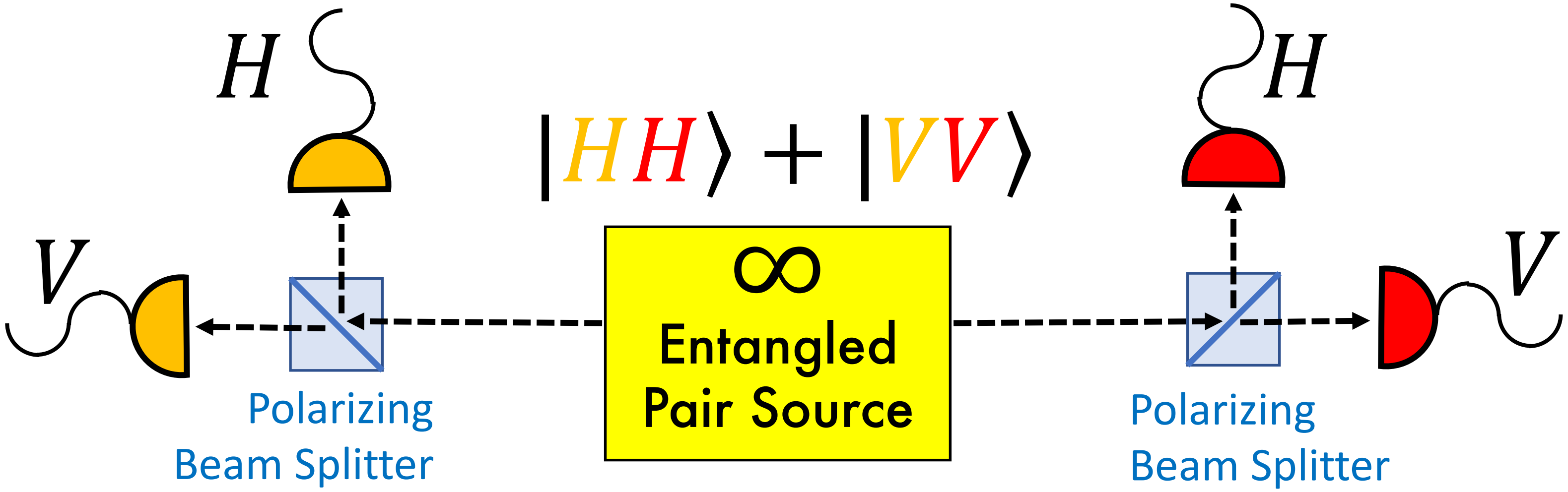
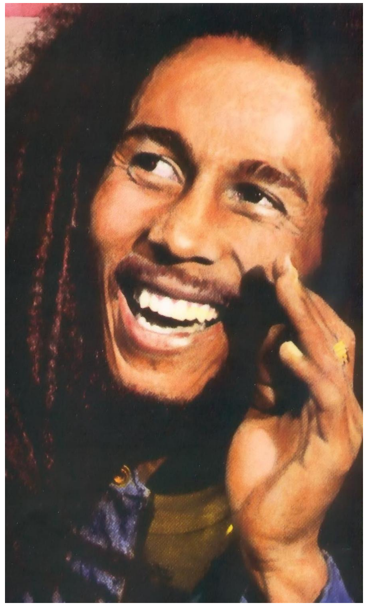


H
V
V
H
V
H

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

H
V
V
H
V
H



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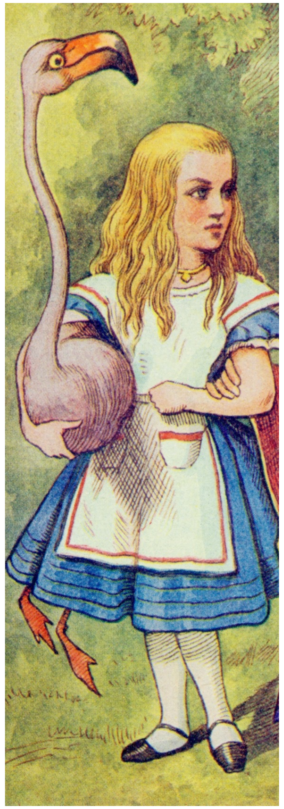
Quantum Cryptography: Vulnerability?



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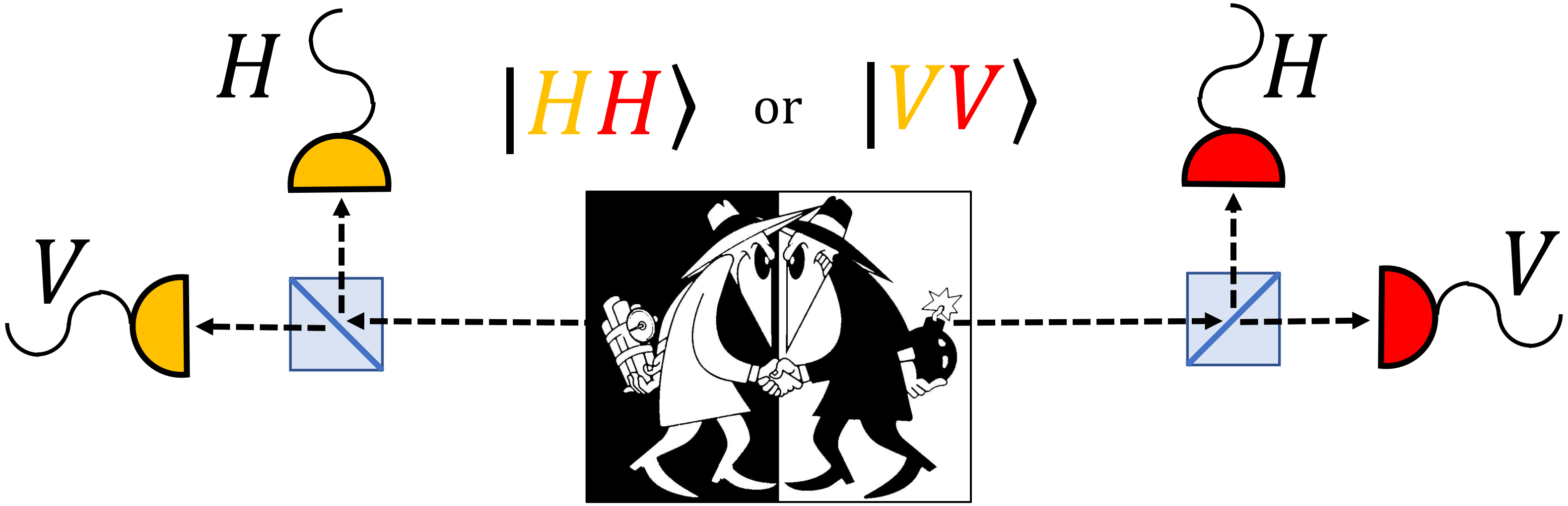
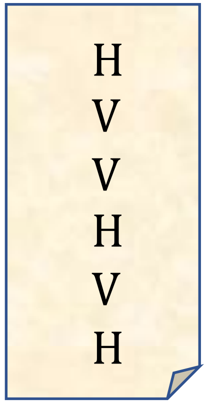
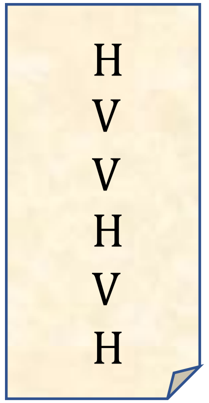
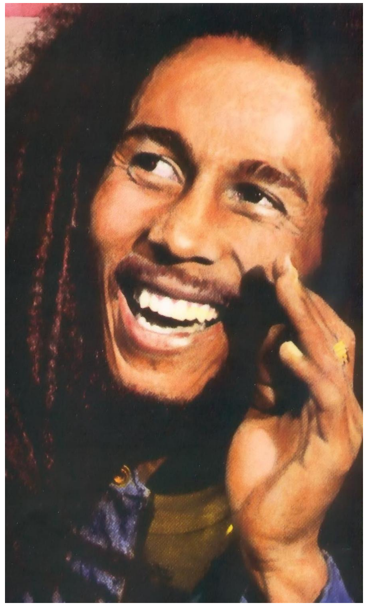




Interlopers can imitate the same effect by sending HH or VV at random, and they will then know the key





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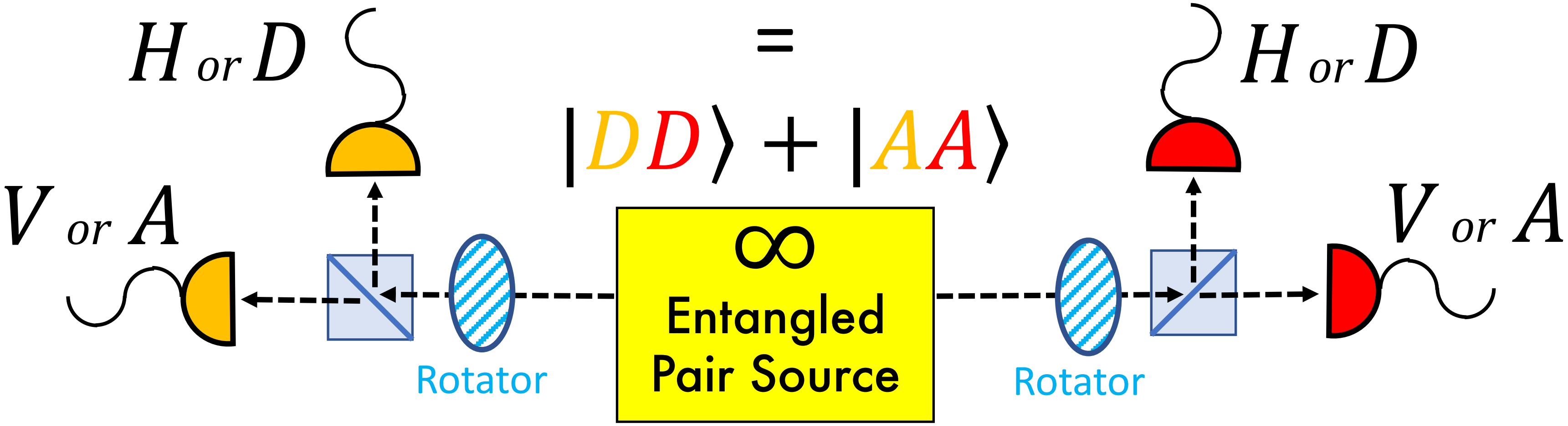
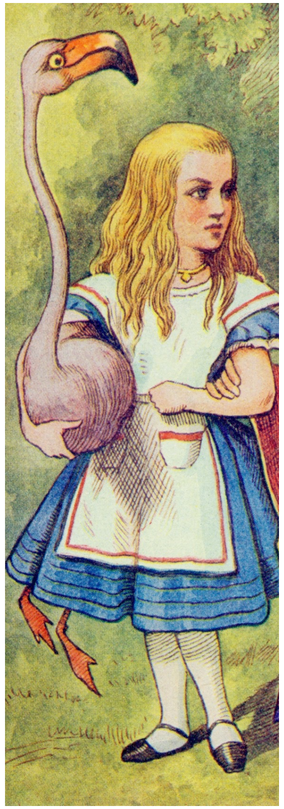
Quantum Cryptography: QM for the win

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



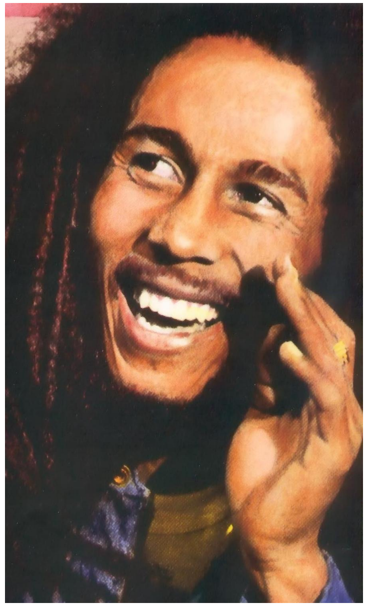


ALICE

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



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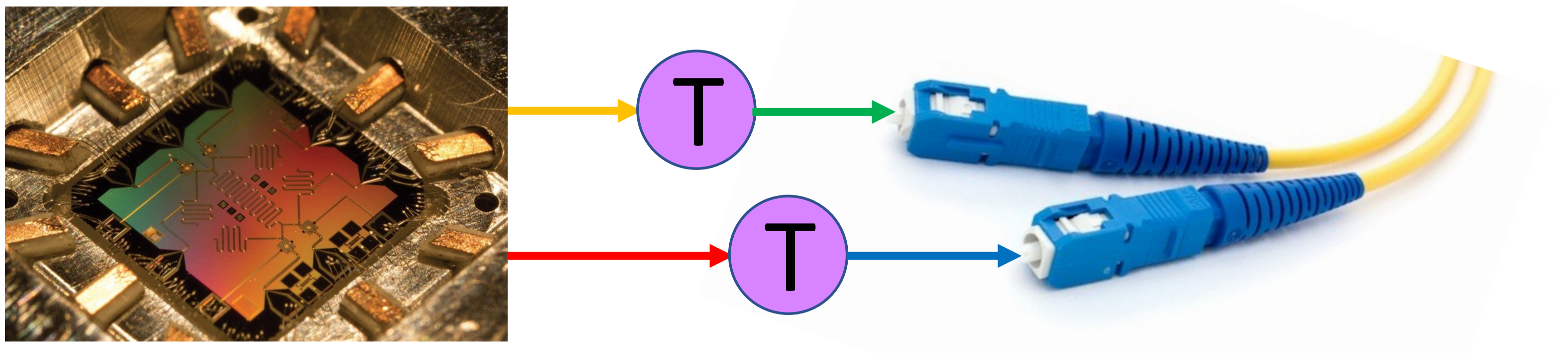
Quantum Transduction

How to network quantum computers together

Quantum Transduction

RoW = “Rest of the World”

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



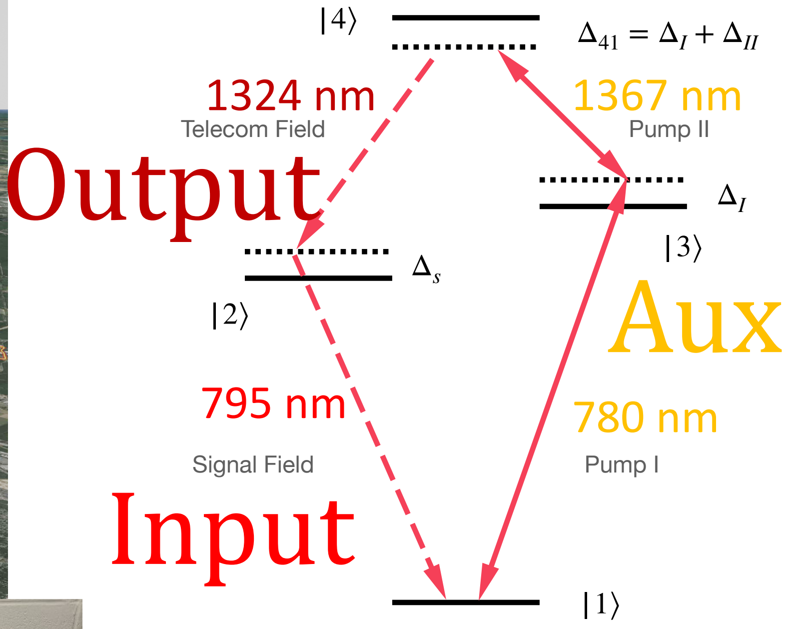
Quantum Computer (QC)

Quantum Transmission Channel (QTC)

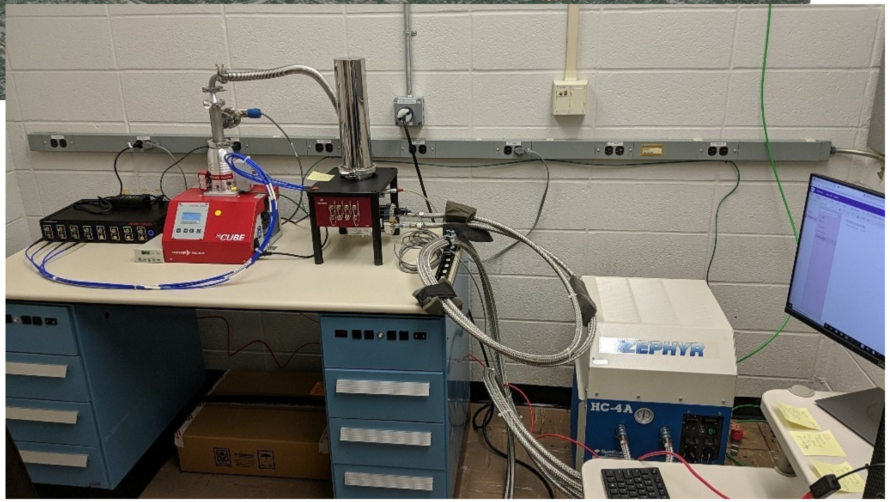
A necessary condition for quantum transduction is that the final state Φ' of the rest of the world is the same *independent* of the state of the qubits; this is equivalent to saying there is no interaction between the physical qubits and the outside world, e.g. no information leakage.

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

Frequency conversion and transport SBU to BNL

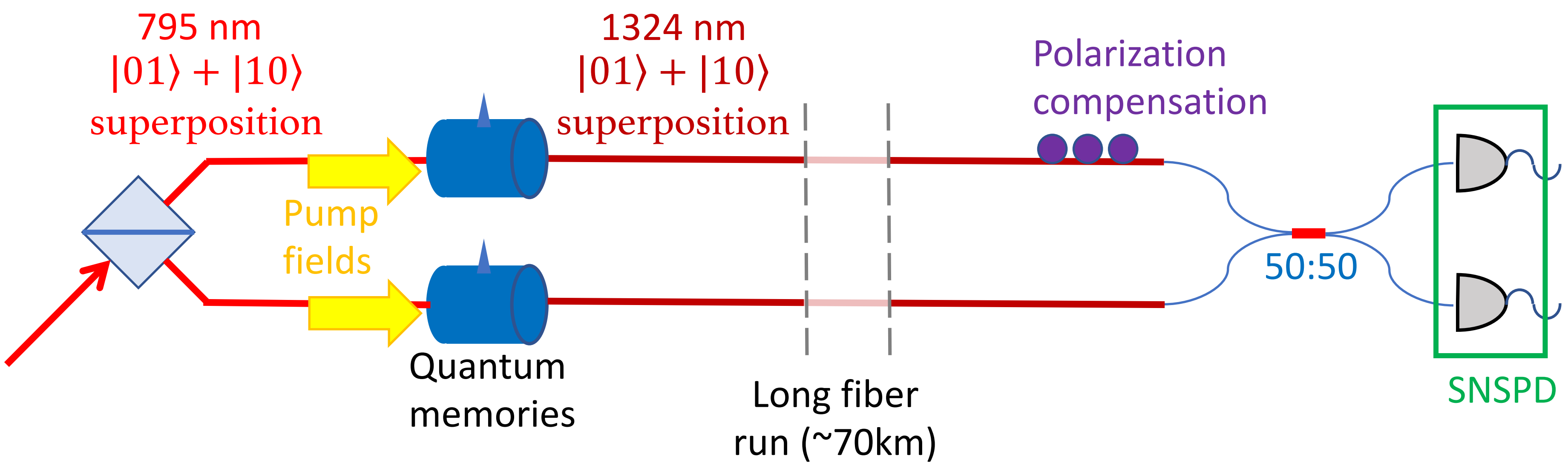


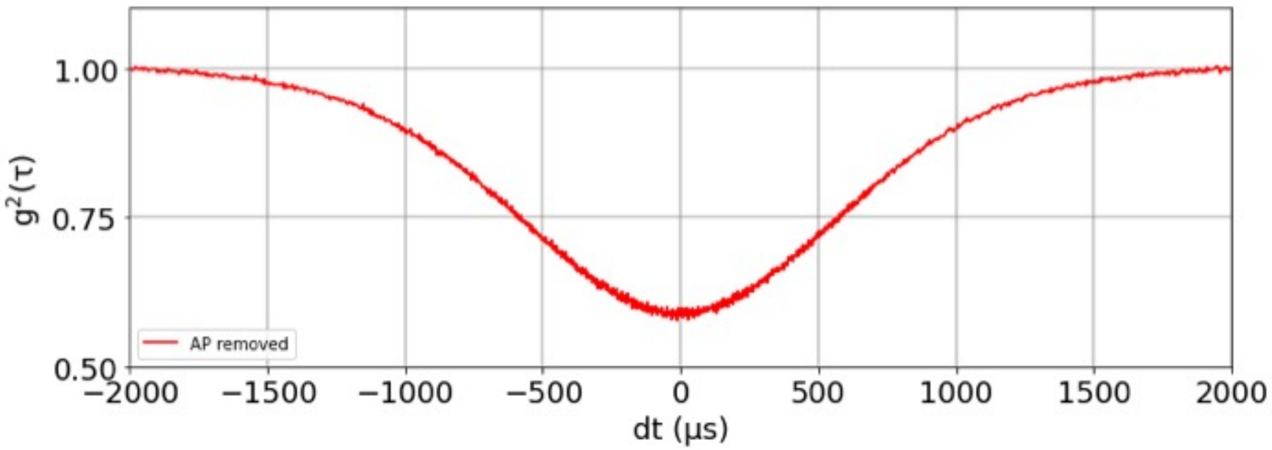
Superconducting Nanowire Single Photon Detector (SNSPD) at BNL



^{87}Rb level diagram for 795nm to 1324nm conversion through **four-wave mixing**

Demo: photon interference *after* conversion





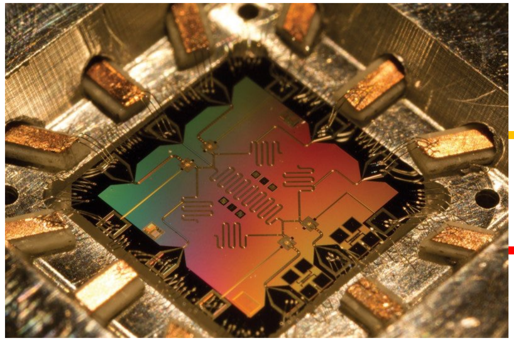
Du, et.al., quant-ph/2101.12742v1

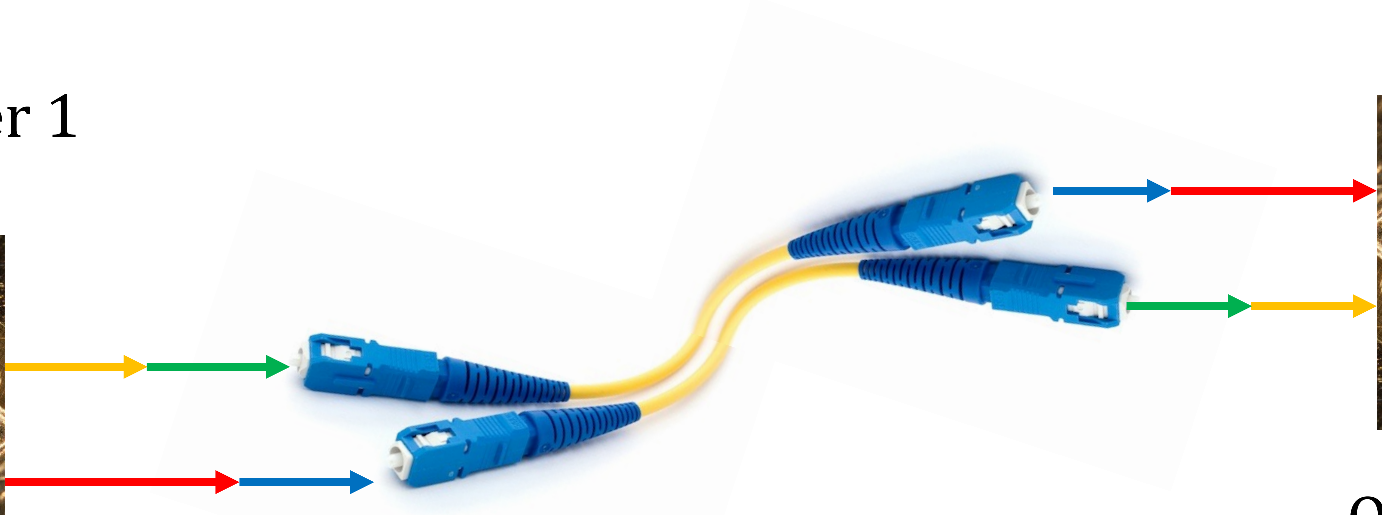
Anti-correlation between the two detector channels shows that subsequent photons “steer” the same way, showing that superposition is preserved through conversion *and* transmission.

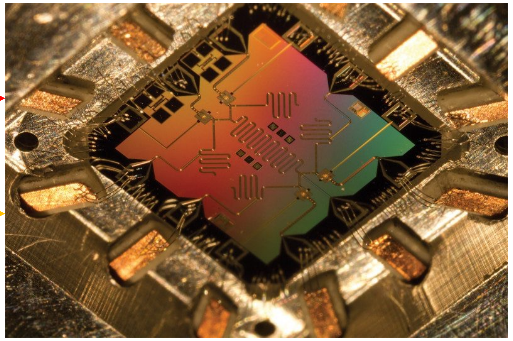
Networked quantum computers

$$|XY\rangle_{QC1}\,|00\rangle_{QTC}\,|\Phi\rangle_{RoW} \rightarrow |XY\rangle_{QTC}\,|\Phi'\rangle_{RoW} \rightarrow |00\rangle_{QTC}\,|XY\rangle_{QC2}\,|\Phi''\rangle_{RoW}$$

Quantum Computer 1 (QC1)







Quantum Transmission Channel (QTC)

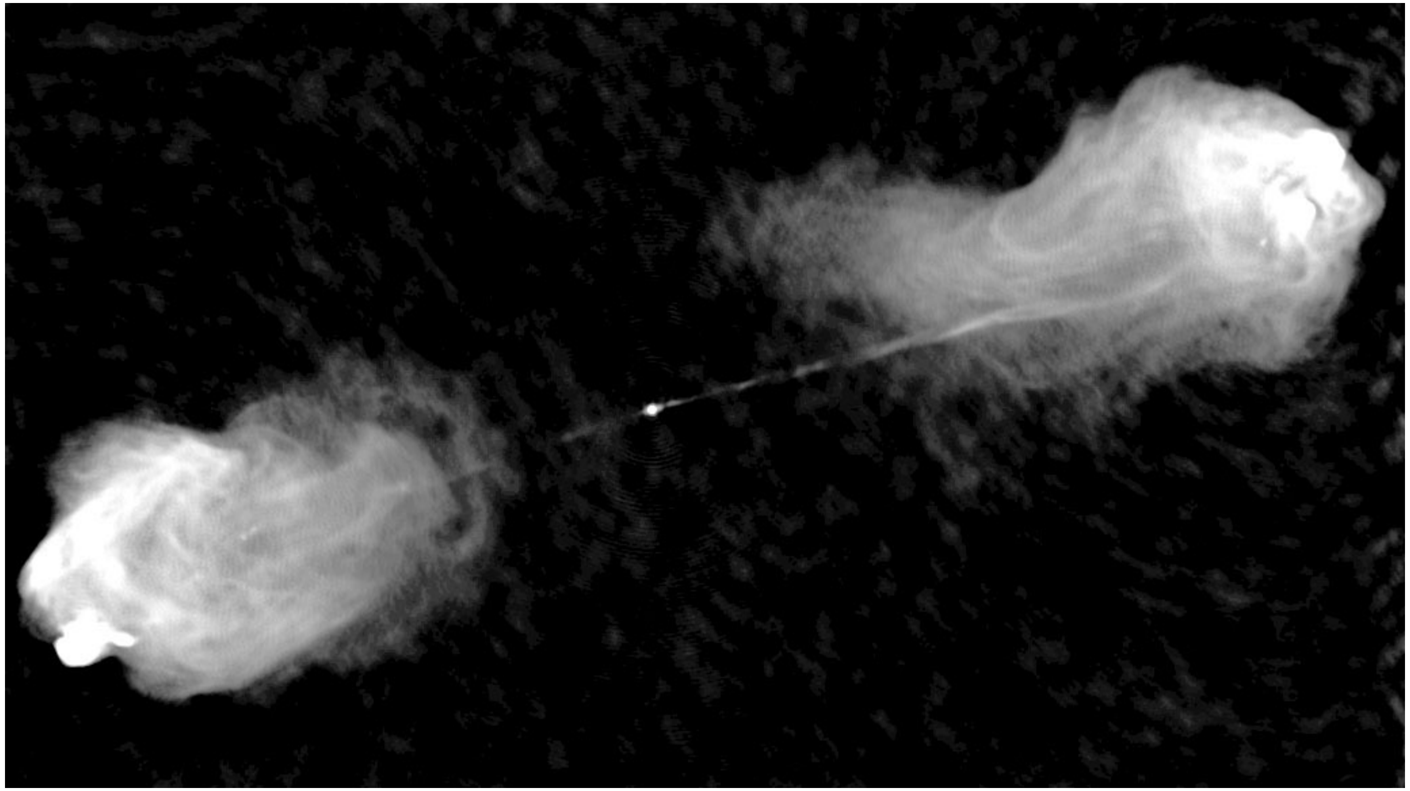
Quantum Computer 2 (QC2)

Goal: To be able to ”pick up” an arbitrary quantum state of two (or more) physical qubits, “carry” them across a long distance without disturbing/measuring them, and “deliver” the (still-unknown) state into the physical qubits of a second system.

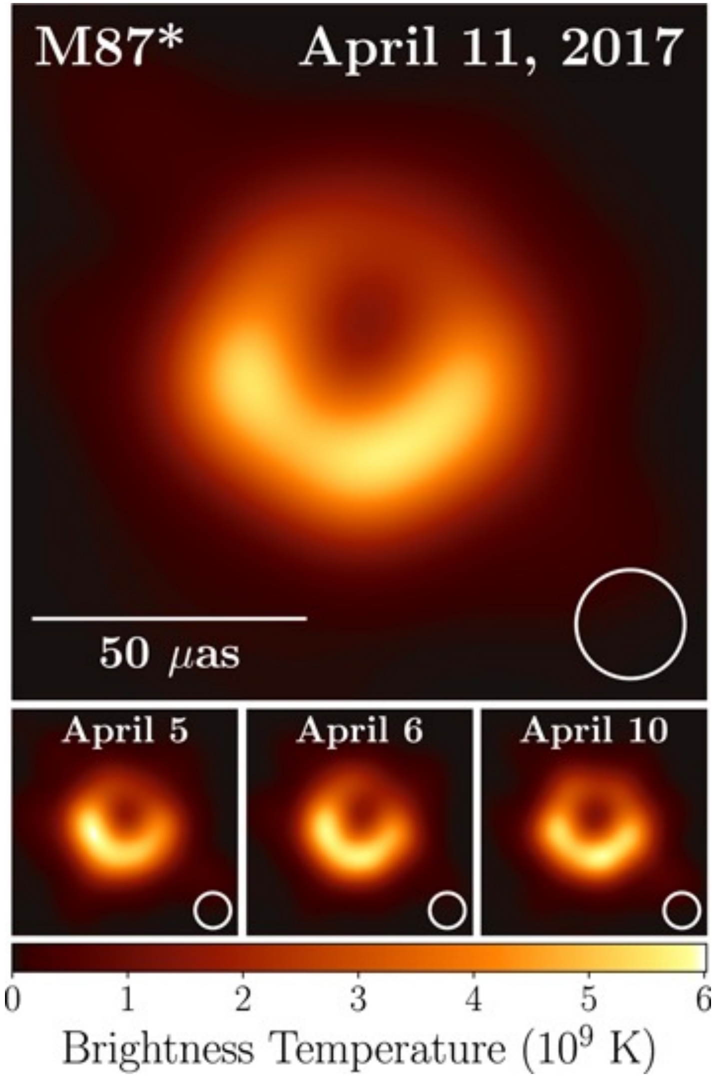
Quantum-Enhanced Astronomy

Quantum networks -> longer baselines -> higher resolutions -> more science!

Interferometry is good



Radio source Cygnus A imaged at 6cm

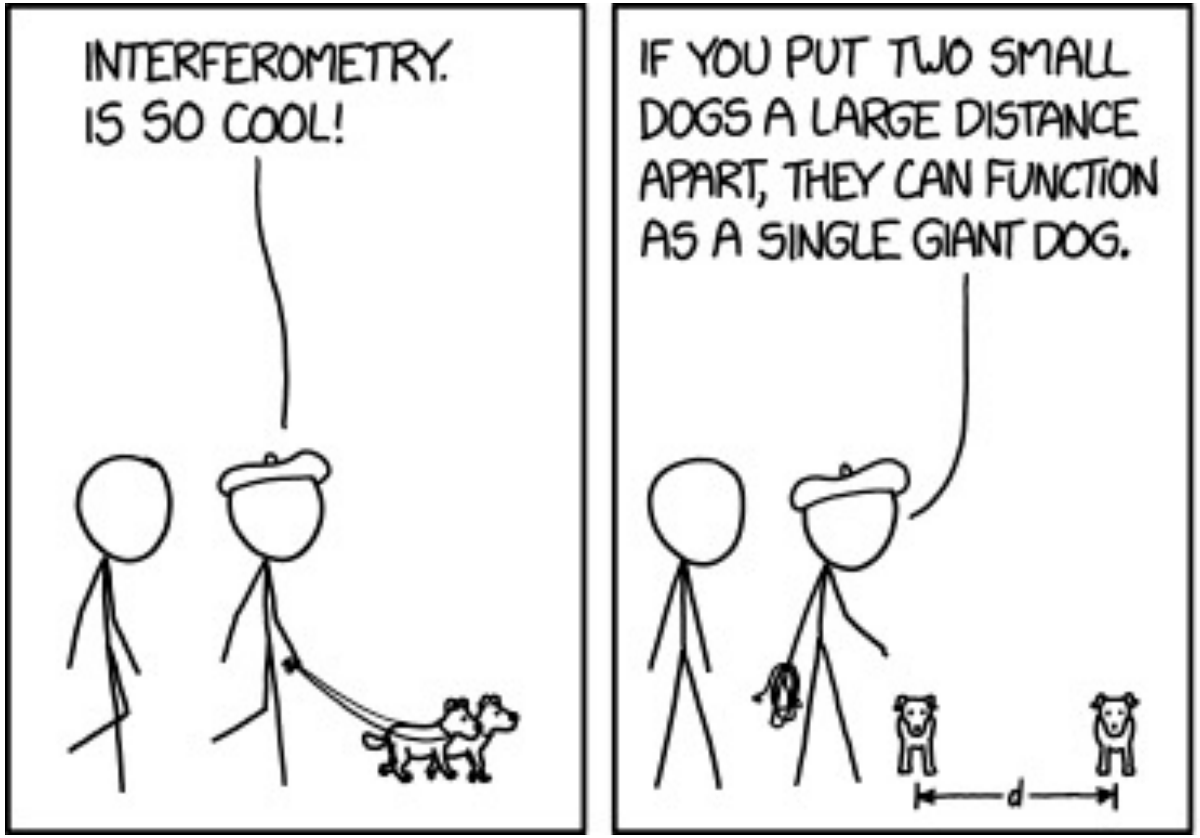


Center of M87 imaged at 1.3mm

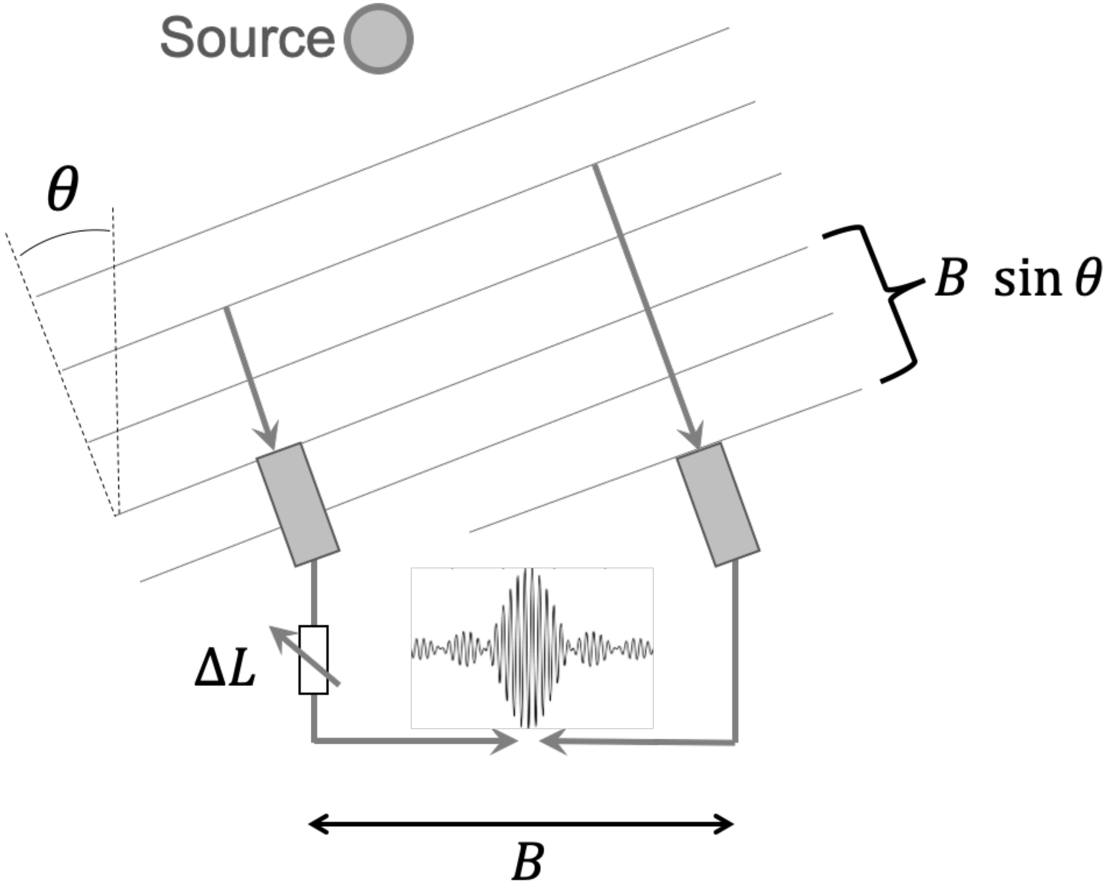
2019 ApJL 875

Idea: Separate apertures over long baselines

Michelson Stellar Interferometer ca.1890



https://xkcd.com/1922/



Interference fringe pattern sensitive to features of angular size $\Delta\theta \sim \lambda / B$

Contrast *visibility* measures Fourier component of source distribution at $k \sim B / \lambda$

Idea: Separate functions of photon capture, photon transport, and photon interference

PRL 109, 070503 (2012) PHYSICAL REVIEW LETTERS week ending 17 AUGUST 2012

Longer-Baseline Telescopes Using Quantum Repeaters

Daniel Gottesman*
Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada

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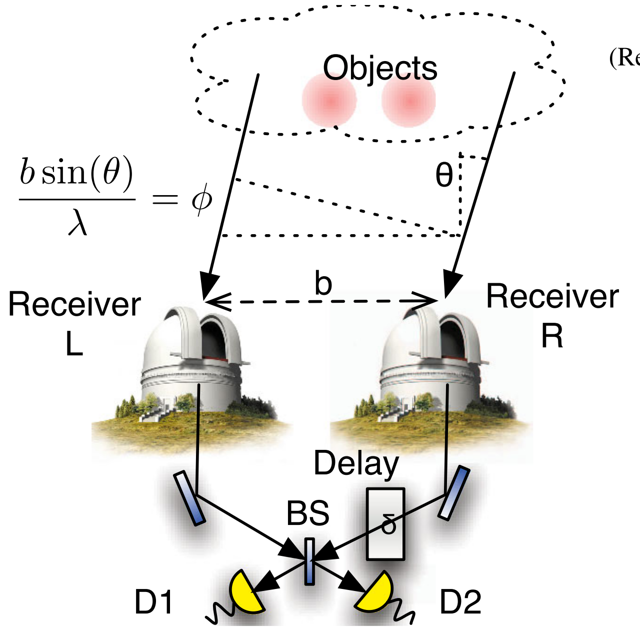
Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada

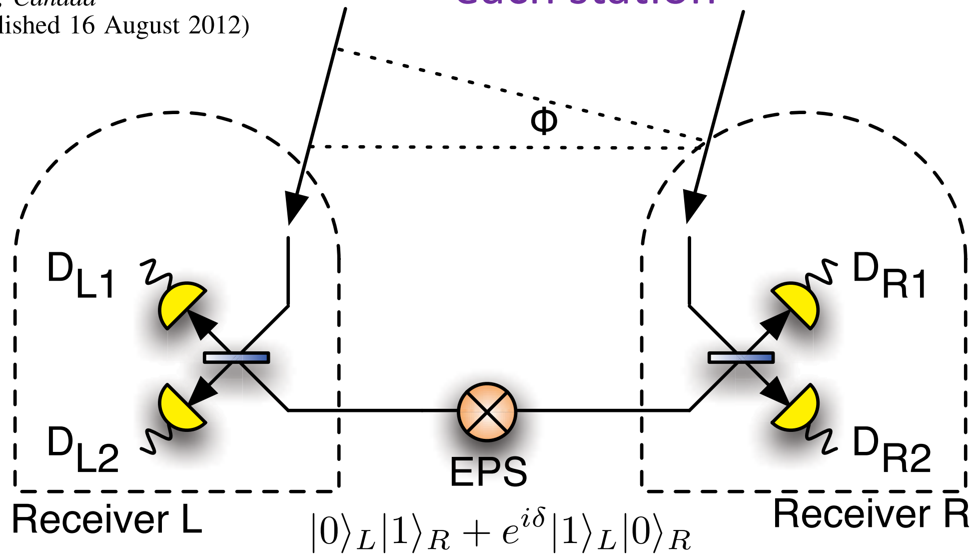
(Received 25 October 2011; revised manuscript received 22 May 2012; published 16 August 2012)

Standard Michelson
Single sky photon
interferes with itself



GJC: Sky photon is mixed with a single "ground" photon at each station

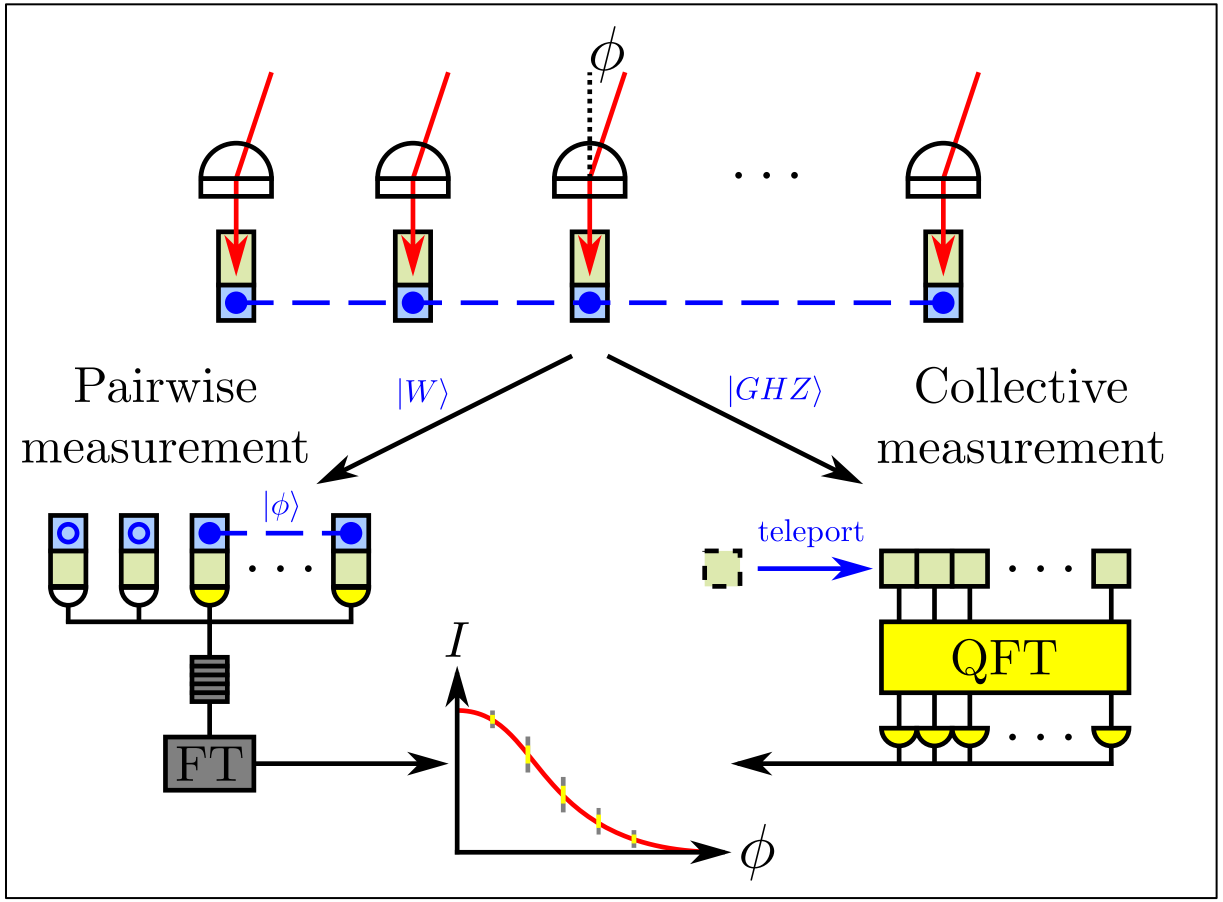
The single ground photon is assumed delivered through a ***quantum network*** which can provide entanglement on demand



PHYSICAL REVIEW LETTERS **123,** 070504 (2019)

Optical Interferometry with Quantum Networks

E. T. Khabiboulline,[1,*] J. Borregaard,[1,2] K. De Greve,[1] and M. D. Lukin[1]



More futuristically: Two kinds of group teleportation from telescope collectors to a central interferometer or quantum computer, using mildly exotic |W> state or more exotic |GHZ> states.

Let's assume it all works; what kind of physics can we do?

HEP astro-physics using interferometry

- Parallax & binary distancing: improved cosmology
- Proper motions: local dark matter patterns
- Microlensing: see motions and shape changes, GR tests
- Exoplanets: spectra & imaging with dynamic nulling
- Gravitational waves at low (μHz) frequencies

Further ideas are encouraged!

Points to take home:

Non-classical quantum states can be created and transported, with superpositions intact, over long distances via quantum networks.

Two-photon (and multi-photon) states are natural candidates to go long distances at room temperature.

Entangled states as a resource have many applications, including secure communications, quantum computer networking, and quantum enhanced interferometry; see following talks for more.

The future is quantum! The goal of a future quantum internet will provide entanglement to arbitrary pairs of users on demand.

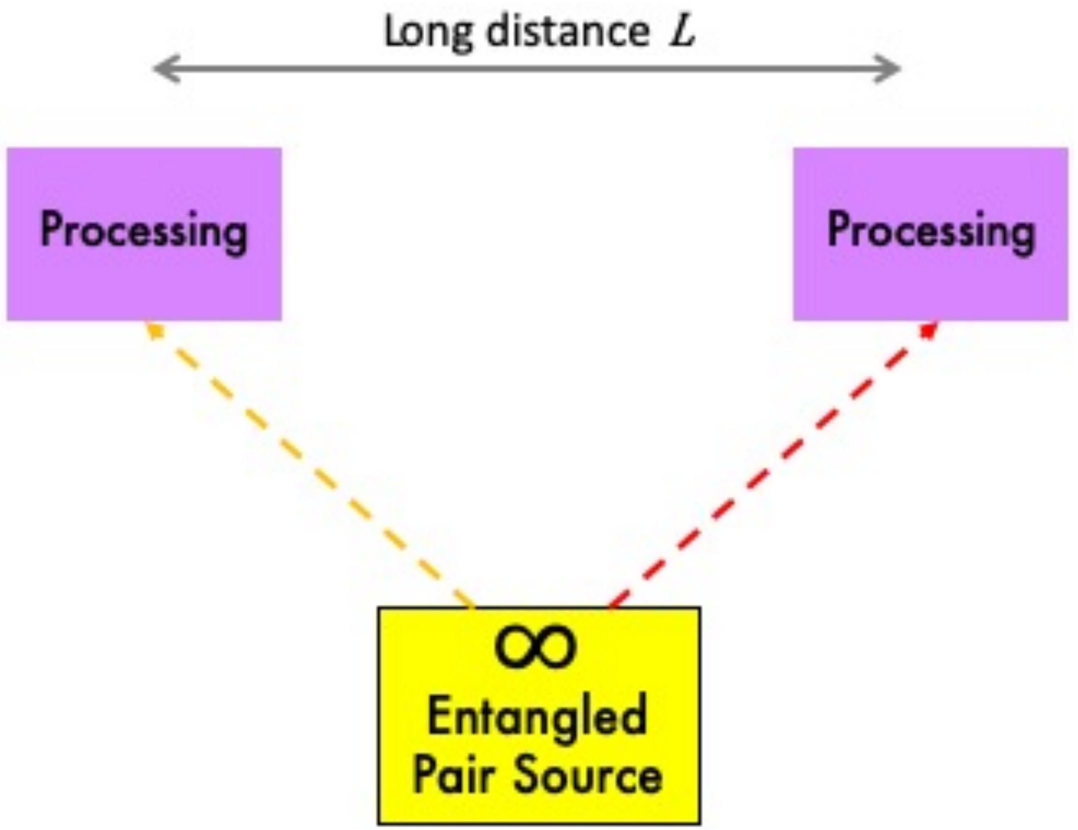
Extras and backups

Quantum repeaters

One is good, and two are better (if handled correctly)

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



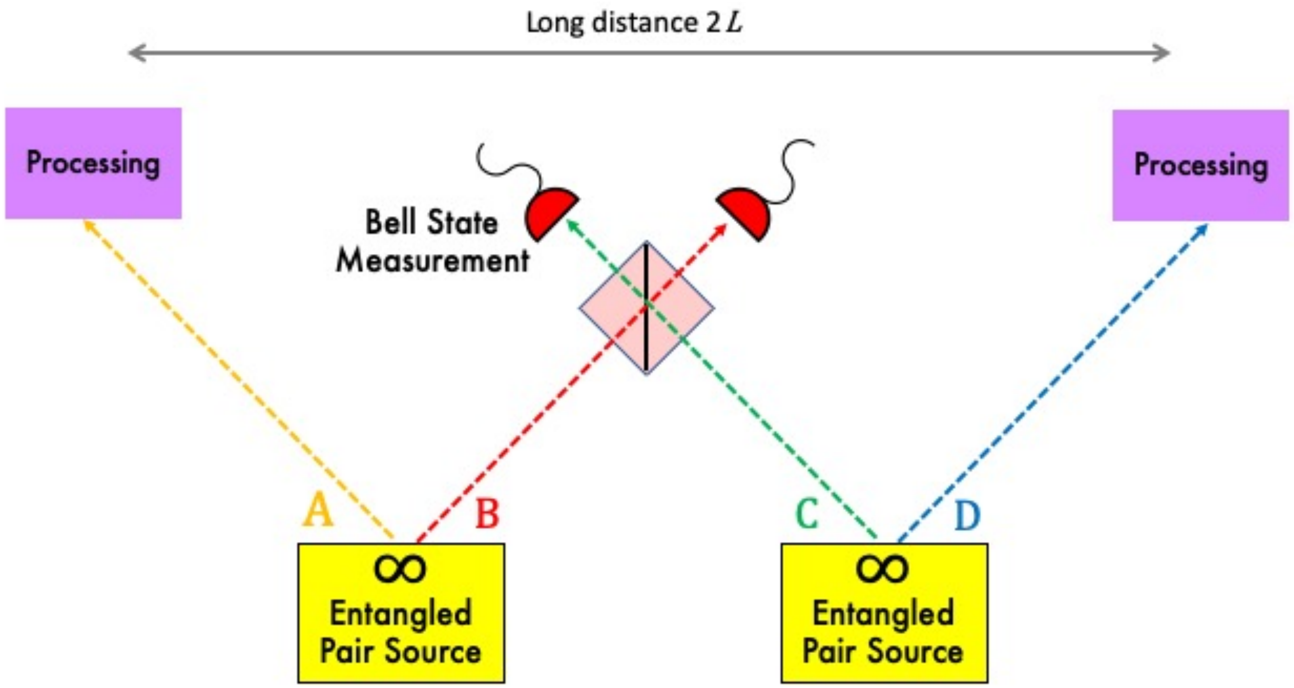
How to go farther? First we recall the set of fully entangled states, called the Bell State Basis:

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

One-hop *quantum repeater*

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

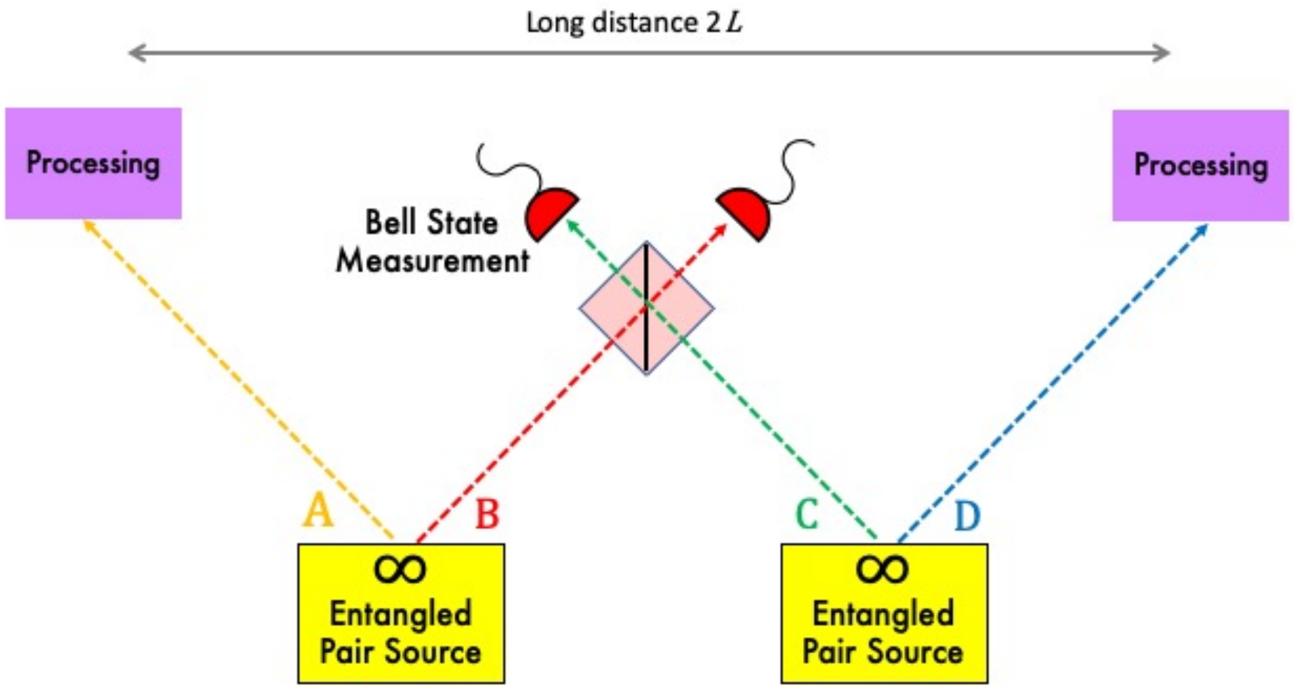
$$\psi = (|HH\rangle + |VV\rangle)\,(|HH\rangle + |VV\rangle)/2 = |\Phi^+\rangle_{AB}|\Phi^+\rangle_{CD}$$



One-hop *quantum repeater*

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

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

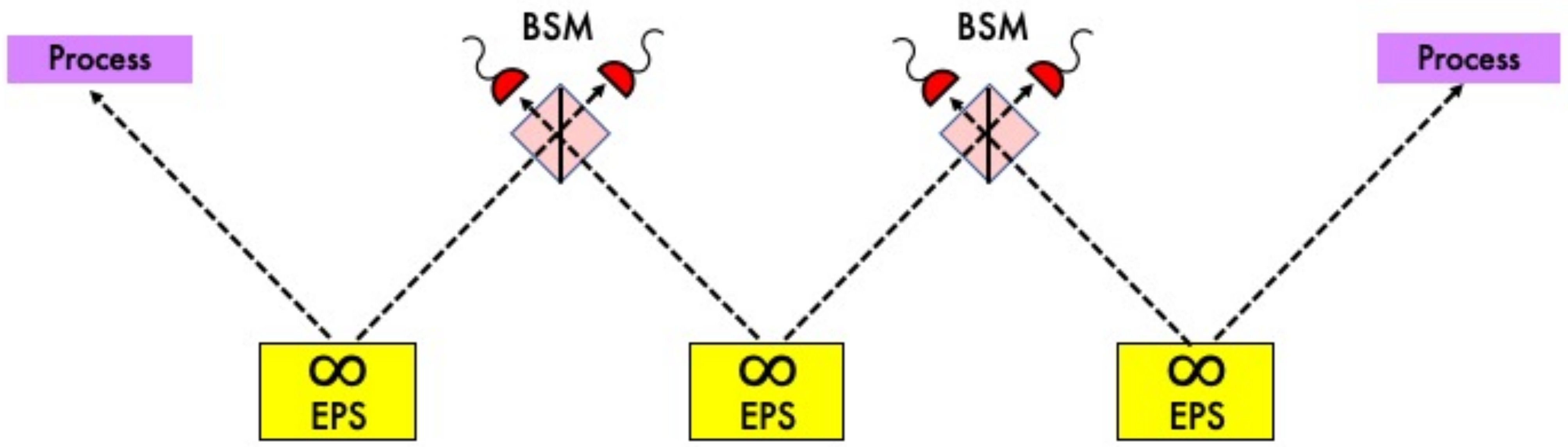


Measurement/projection of the *BC* pair in the Bell State basis will partially collapse the 4-particle wavefunction and leave the *AD* pair in *a fully entangled state*!

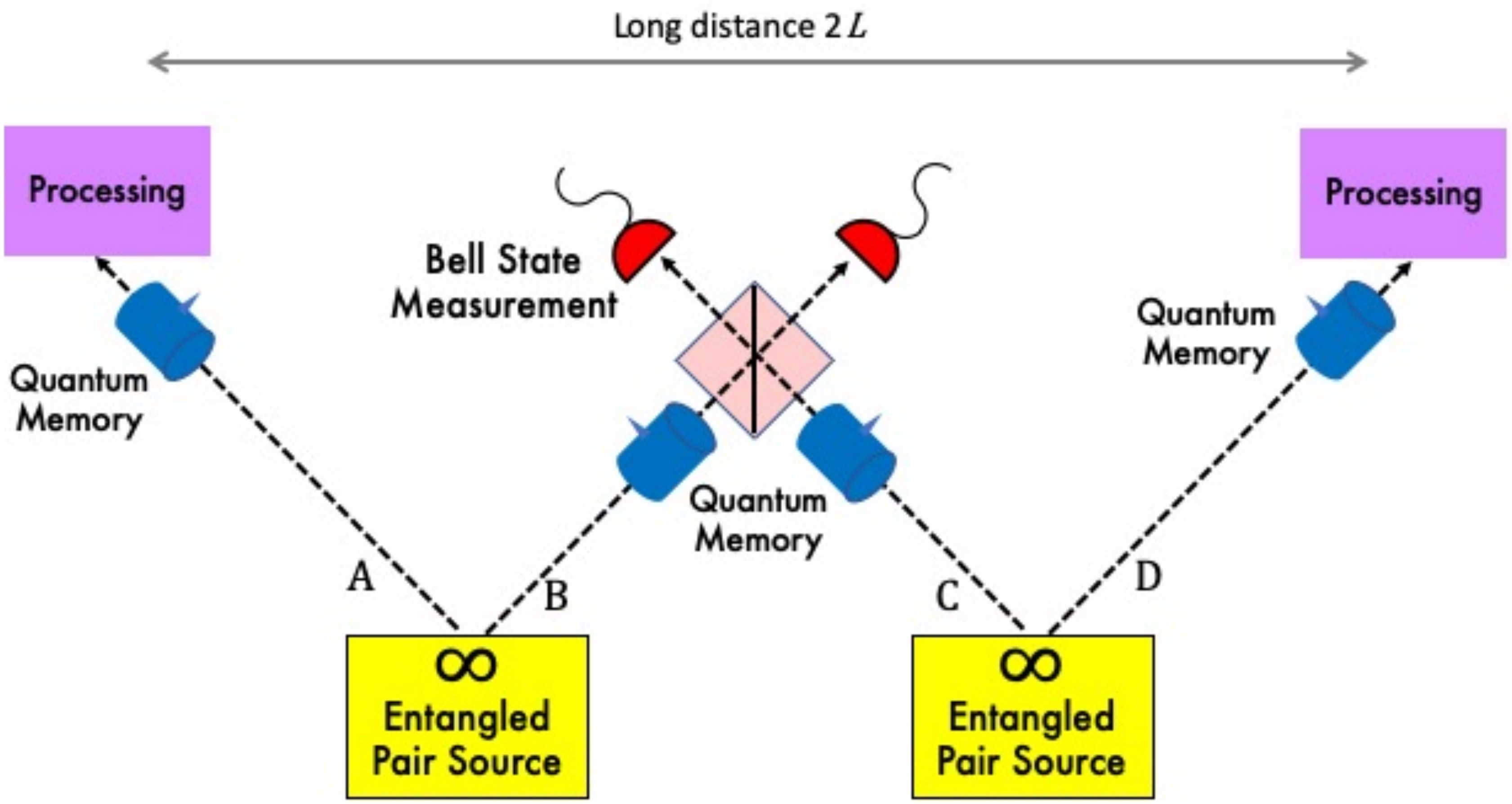
"Entanglement Swapping"

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*.



Memories and persistence



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

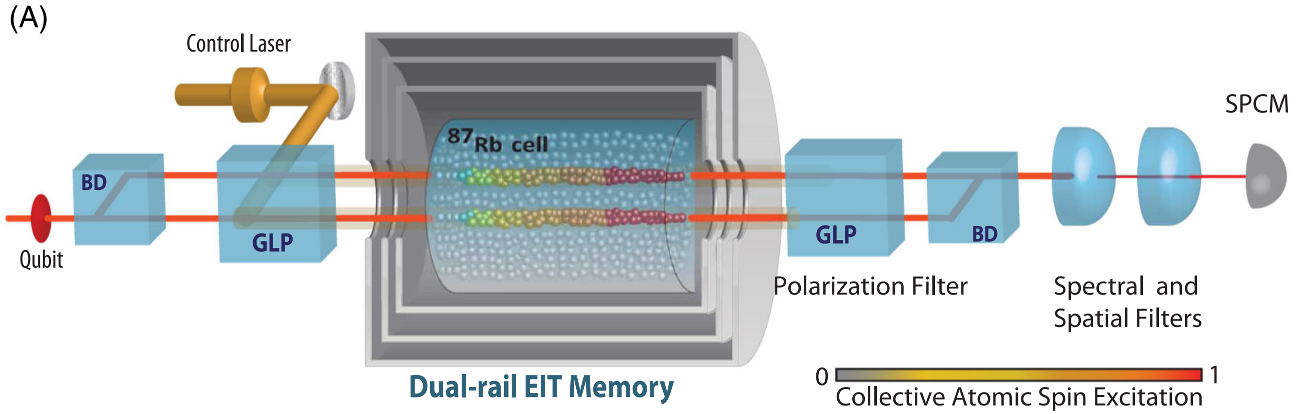
We can de-skew and greatly improve efficiency by storing successful transmissions in quantum memories.

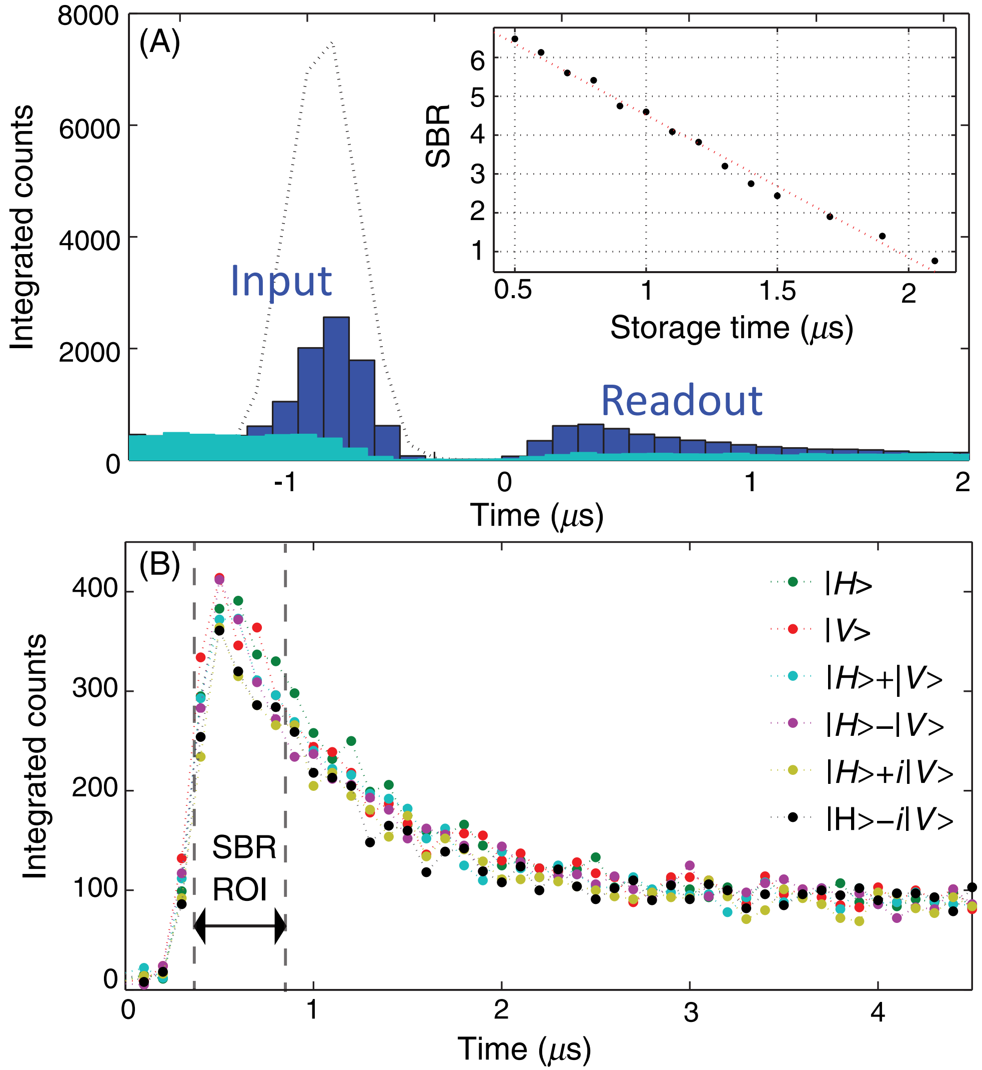
Room-temperature quantum memories

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)





Electromagnetically Induced Transparency (EIT)

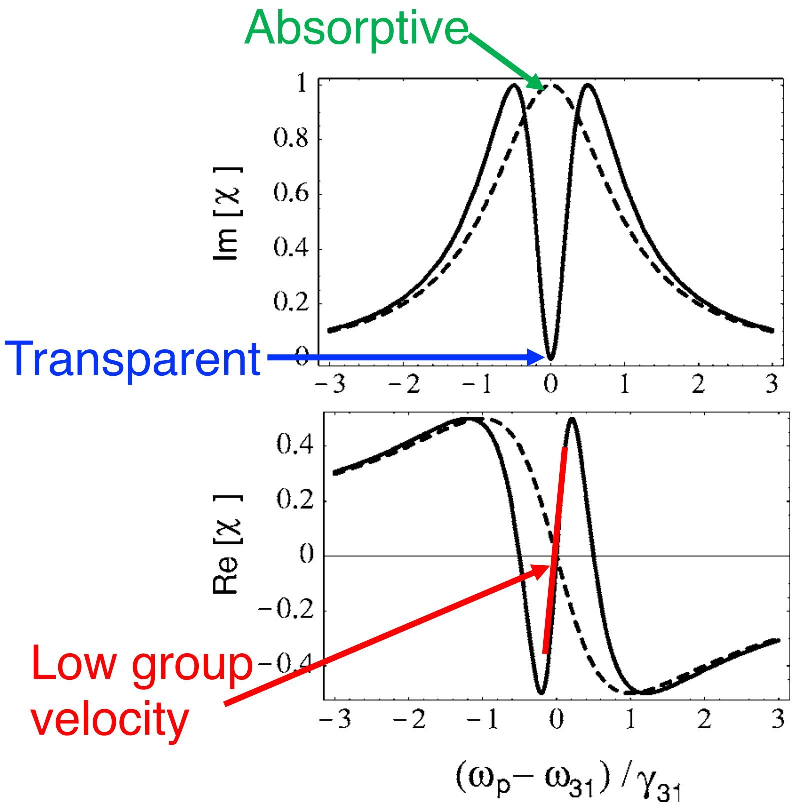
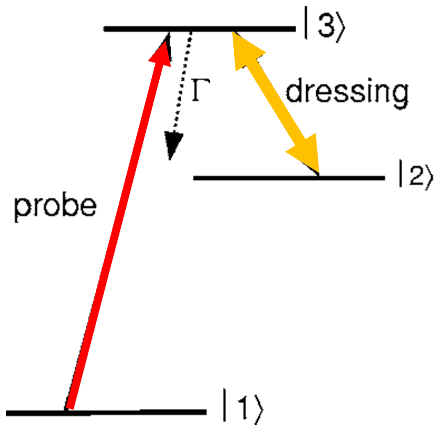
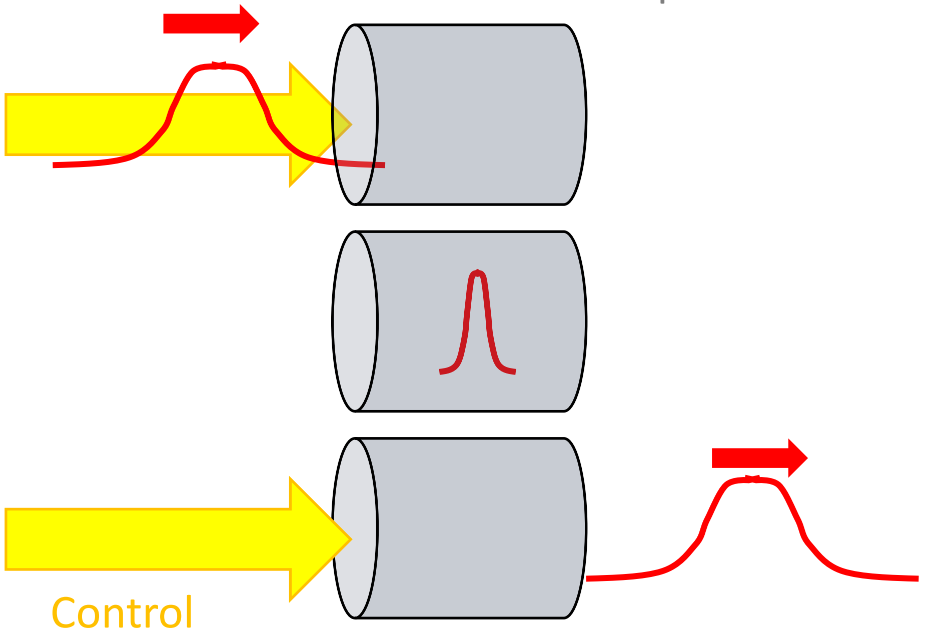


FIG. 1. Susceptibility as a function of the frequency ω_p of the applied field relative to the atomic resonance frequency ω_{31}, for a radiatively broadened two-level system with radiative width γ_{31} (dashed line) and an EIT system with resonant coupling field (solid line): top, imaginary part of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

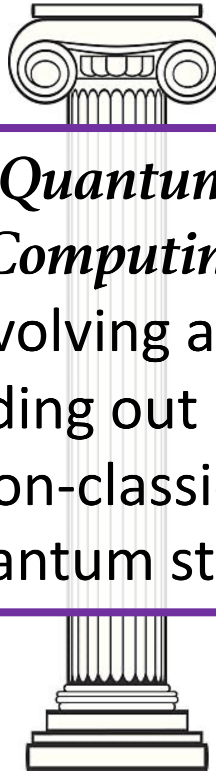
Fleischhauer, Imamoglu, Marangos, RMP **77**, 2005

Fleischhauer & Lukin, PRL **84**, 2000

The quantum internet

“The future, Mr. Gittes, the future!”

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

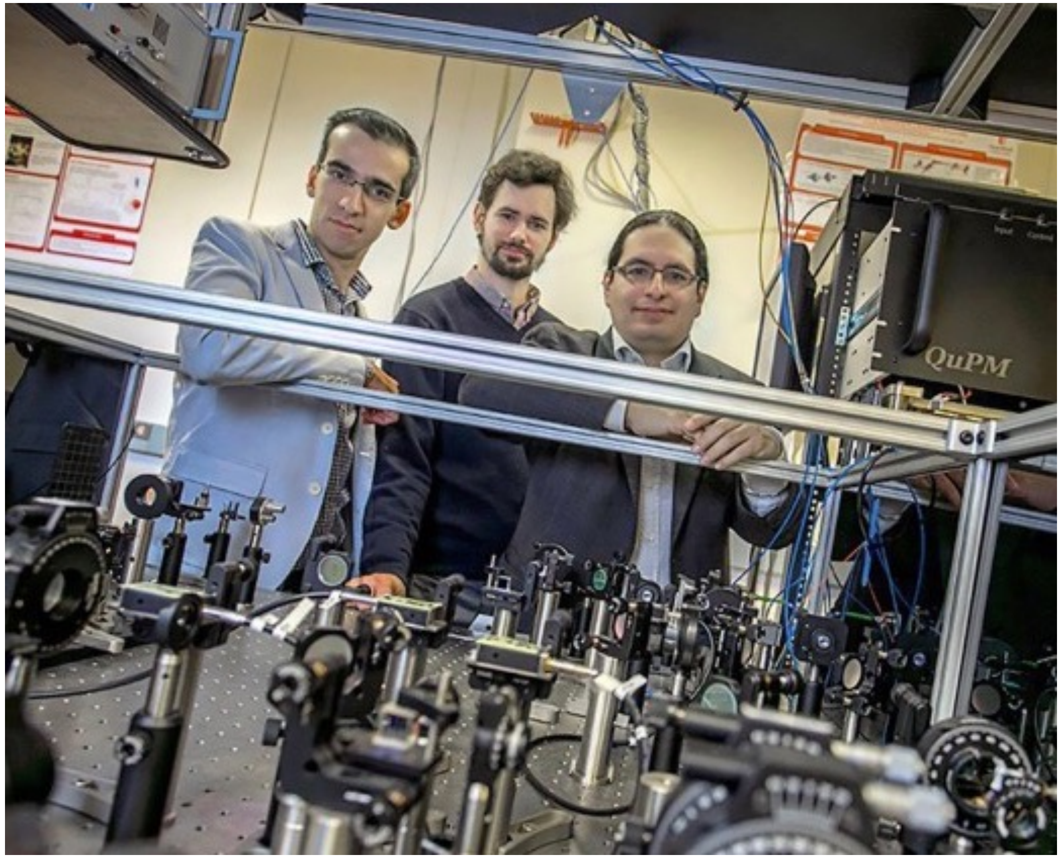
"Gentlemen, what are the four pillars?" -- Dead Poets Society (1989)

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"

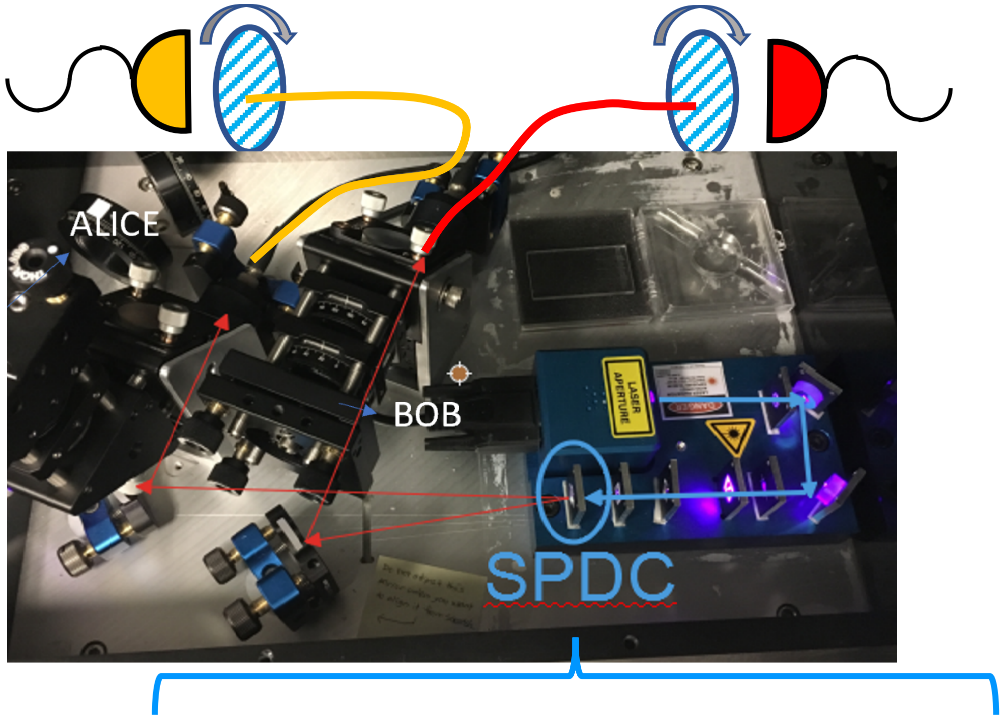
-- Sam Goldwyn

Entanglement as a *resource*

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

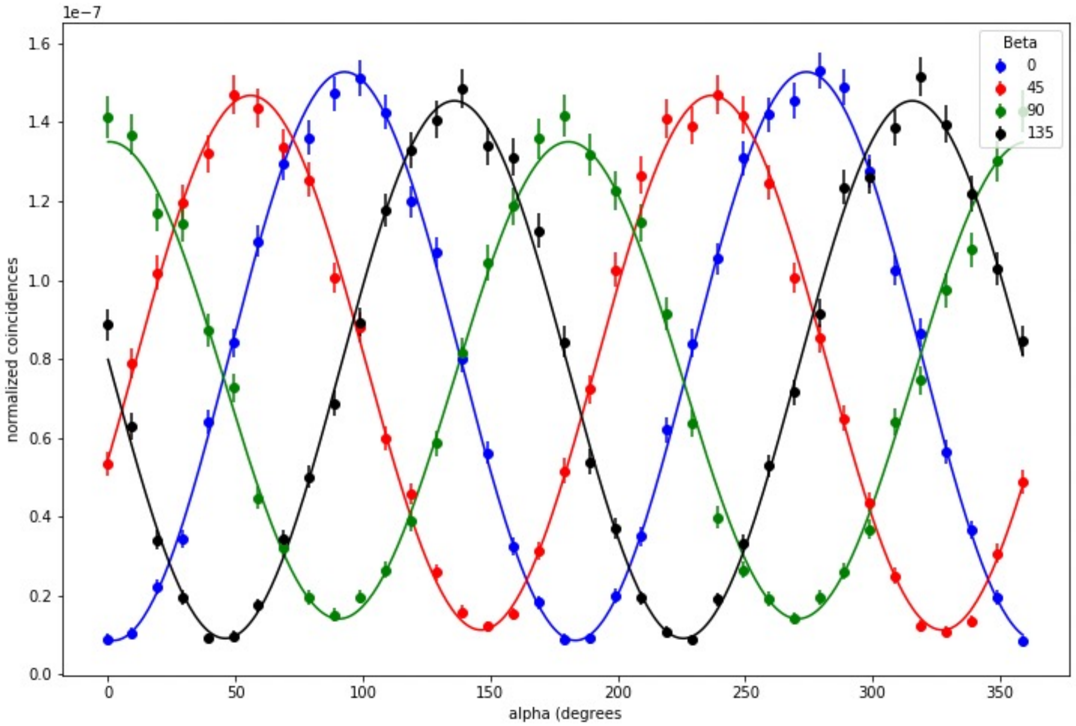
$$|HH\rangle + |VV\rangle$$

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

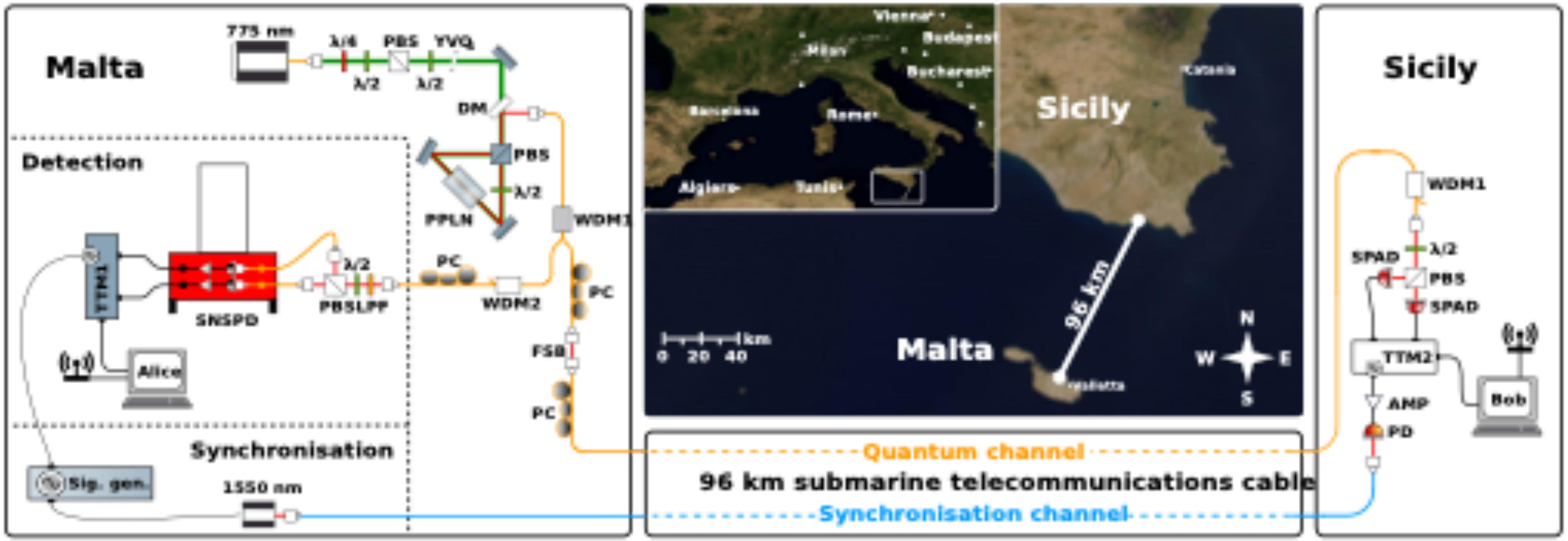


Polarization Entangled Photon Pair Creation

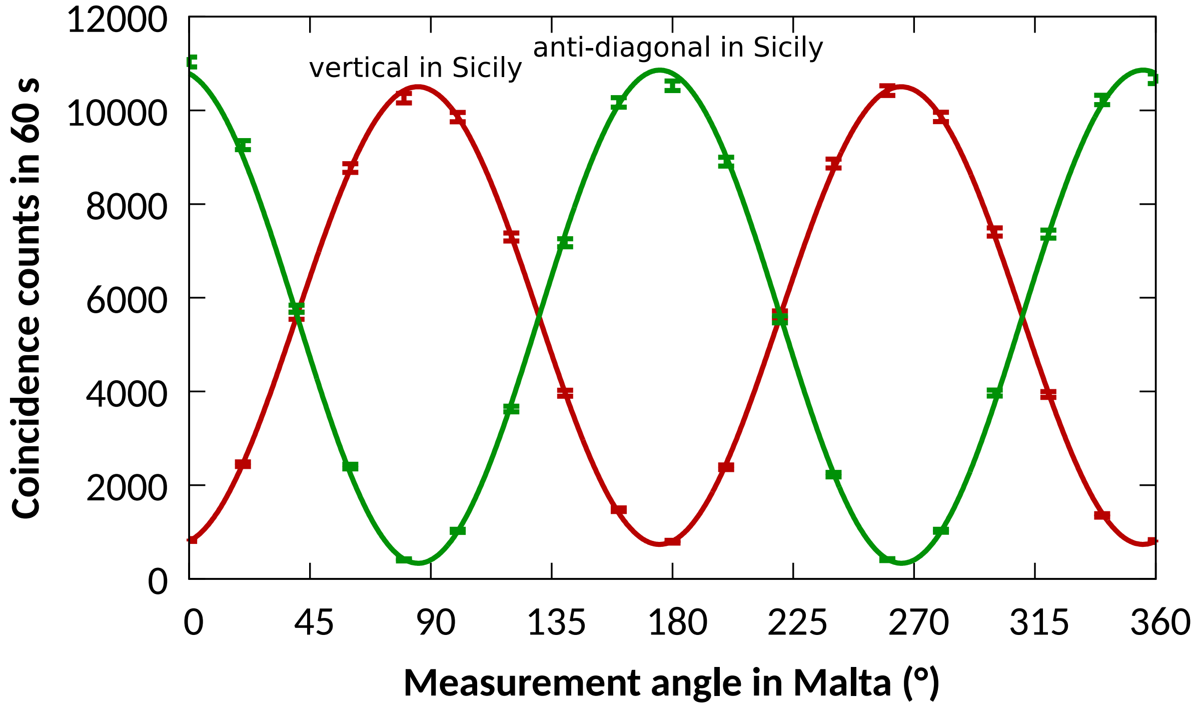
Pair Rate



Polarizer angles



arXiv:1803.00583 [quant-ph]



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

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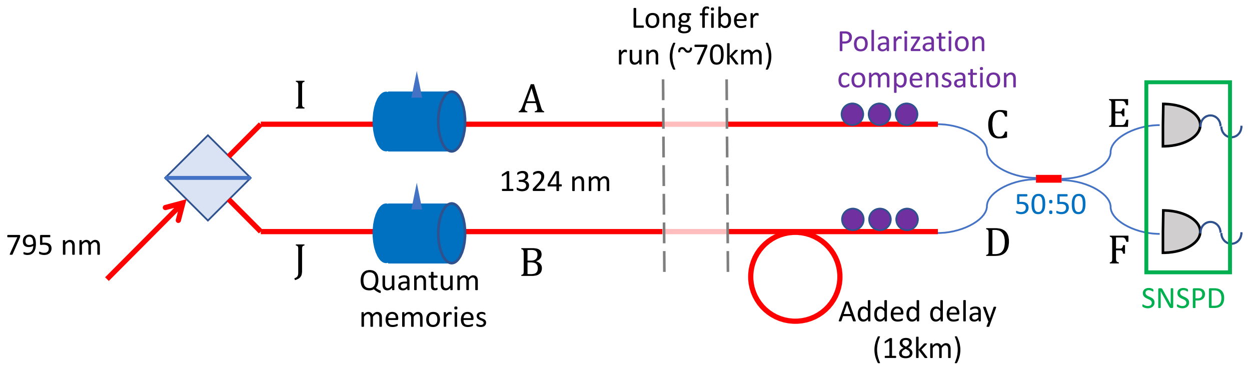
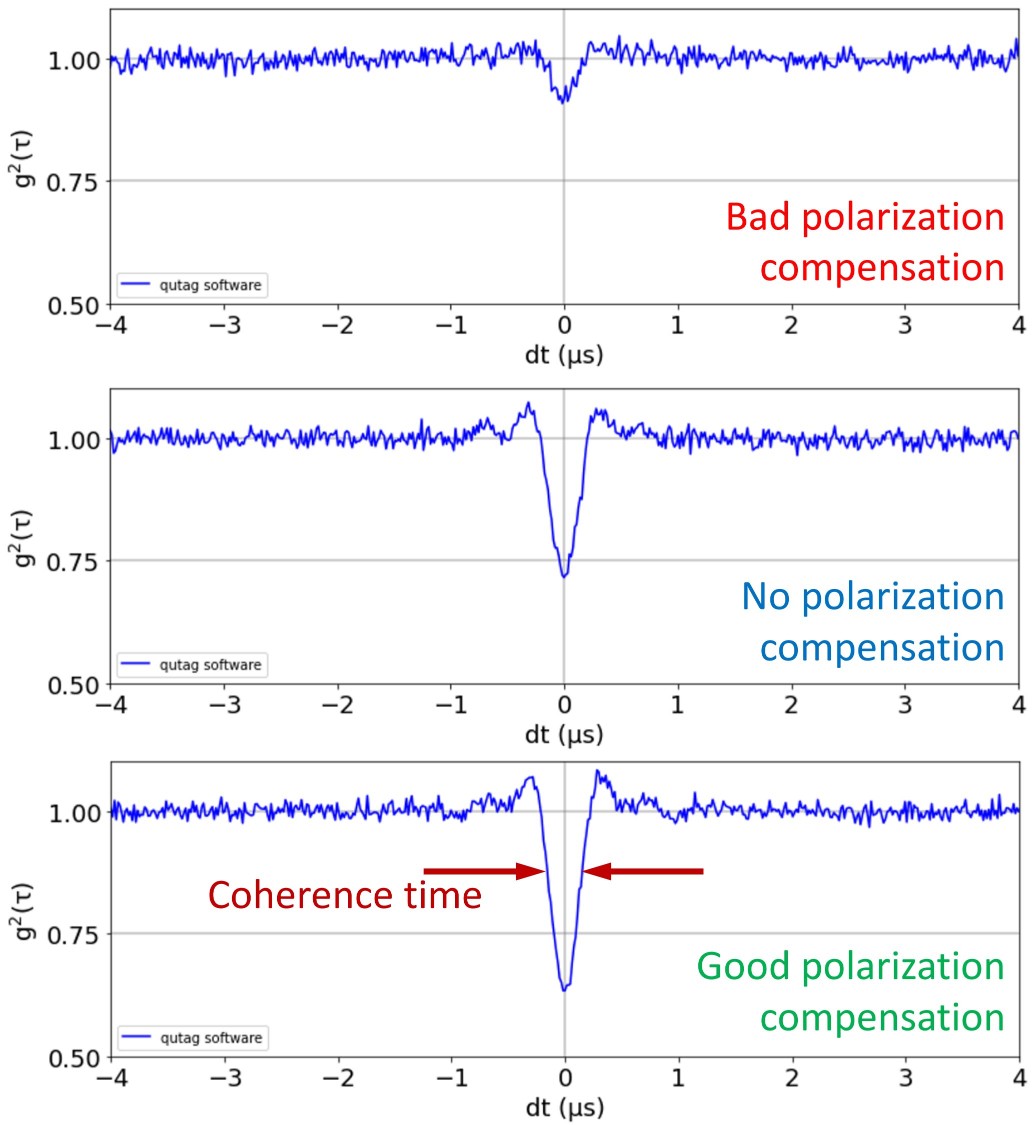
Hong-Ou-Mandel Two-Photon Interference



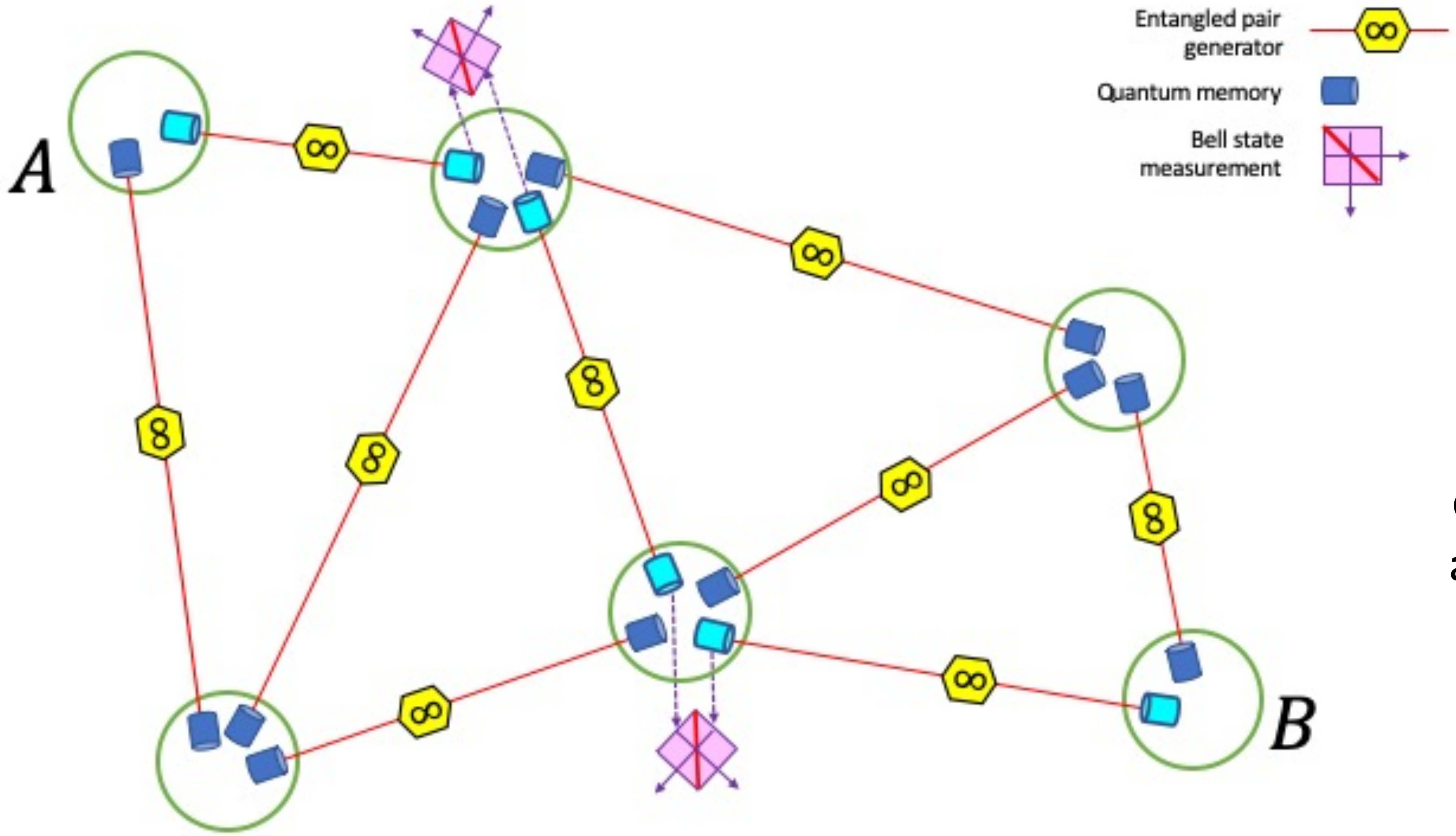
With added delay, we look for two independent photons arriving at the final beam splitter.

Hong-Ou-Mandel (HOM) interference dip shows that the two photons are *indistinguishable*



Du, et.al., quant-ph/2101.12742v1

First-generation *Quantum Internet*



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