ILLINOIS

Entanglement-assisted Communication System for NASA's Deep-Space Missions: Feasibility Test and Conceptual Design

Using Quantum Mechanics to defeat Quantum Mechanics

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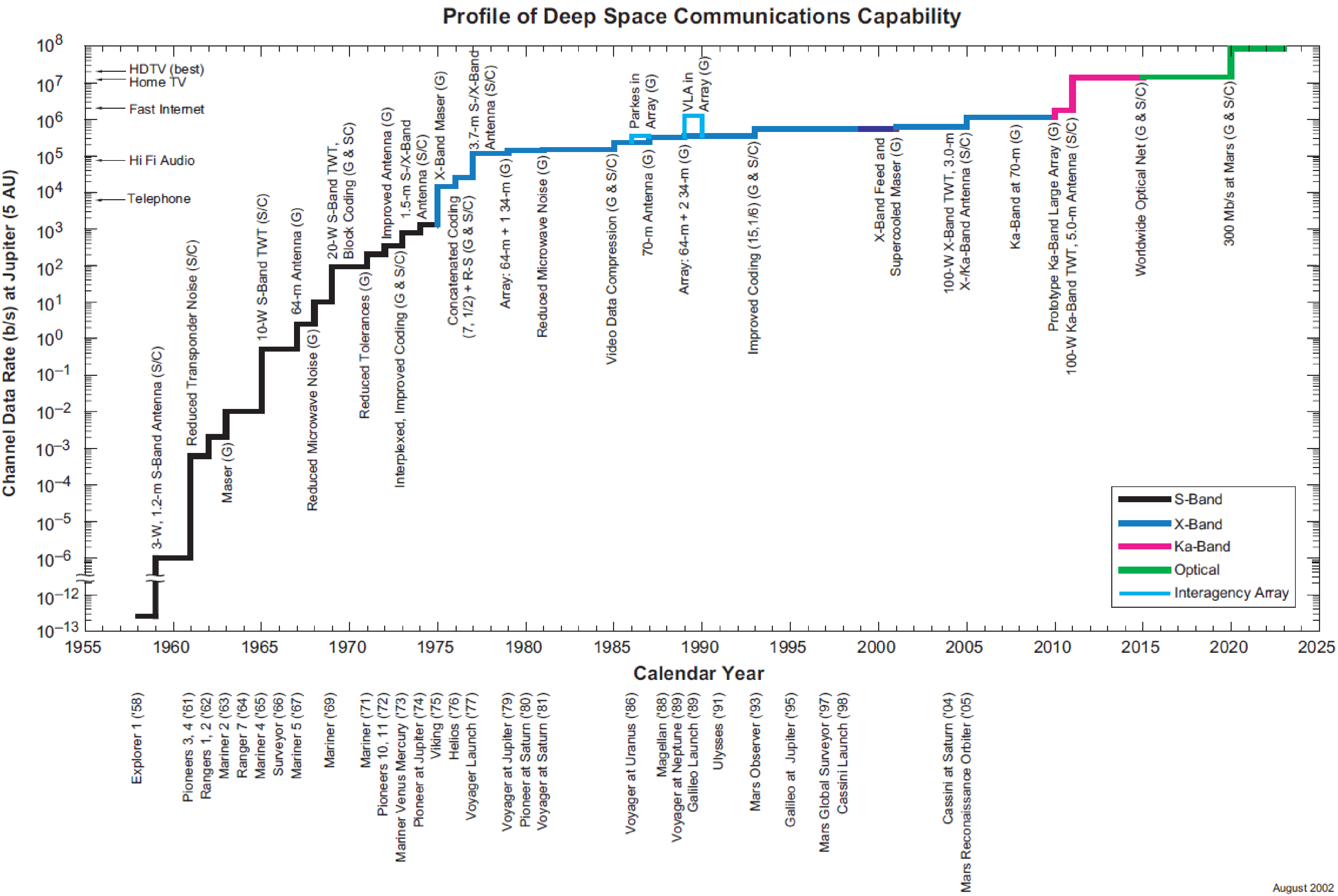
Herb Bernstein
(Hampshire College)

Outline

1. Motivation: What's the problem
2. Entanglement: What is it, and how does it help
3. Super-dense Coding: Recent and future data
4. Super-dense Teleportation: *Very* recent data
5. Other Options

NASA has a critical need for increased data communication rates. *We will explore the use of entanglement and hyper-entanglement (simultaneously in multiple photonic degrees of freedom) to achieve efficient code transmission beyond what is possible classically.*

History and Future of Deep Space Communication



The Problem

Space exploration necessarily requires communicating with far away probes.

- need to send instructions to them
- need to get data back from them

How to do this efficiently…

The Real Problem:

Space is BIG.

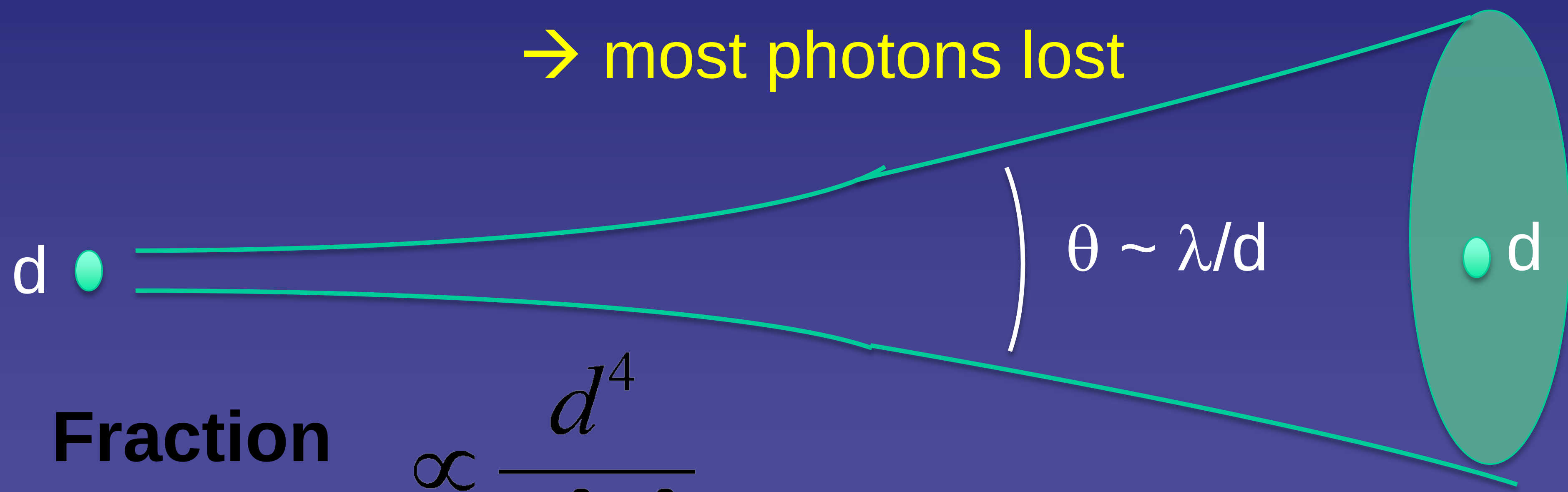
The Other Real Problem: QM!

Photons obey Uncertainty Principle

→ diffraction

→ beam is very big far away

→ most photons lost



Fraction collected: $\propto \frac{d^4}{\lambda^2 L^2}$

QM can *help*…

E.g., F_{mars} ~10^{-6} - 10^{-7}

Entanglement: What IS it?

Entanglement is

"*the* characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought" ––E. Schrödinger

Non-factorizable: can*not* be written as a product

$$|\text{“0”}\rangle_A|\text{“0”}\rangle_B + |\text{“1”}\rangle_A|\text{“1”}\rangle_B$$

Example (polarization "Bell states"):

$|HH\rangle + |VV\rangle = |45,45\rangle + |-45,-45\rangle$

$|HH\rangle - |VV\rangle = |45,-45\rangle + |-45,45\rangle$

$|HV\rangle + |VH\rangle = |45,45\rangle - |-45,-45\rangle$

$|HV\rangle - |VH\rangle = |45,-45\rangle - |-45,45\rangle$

(like the spin singlet: $|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$)

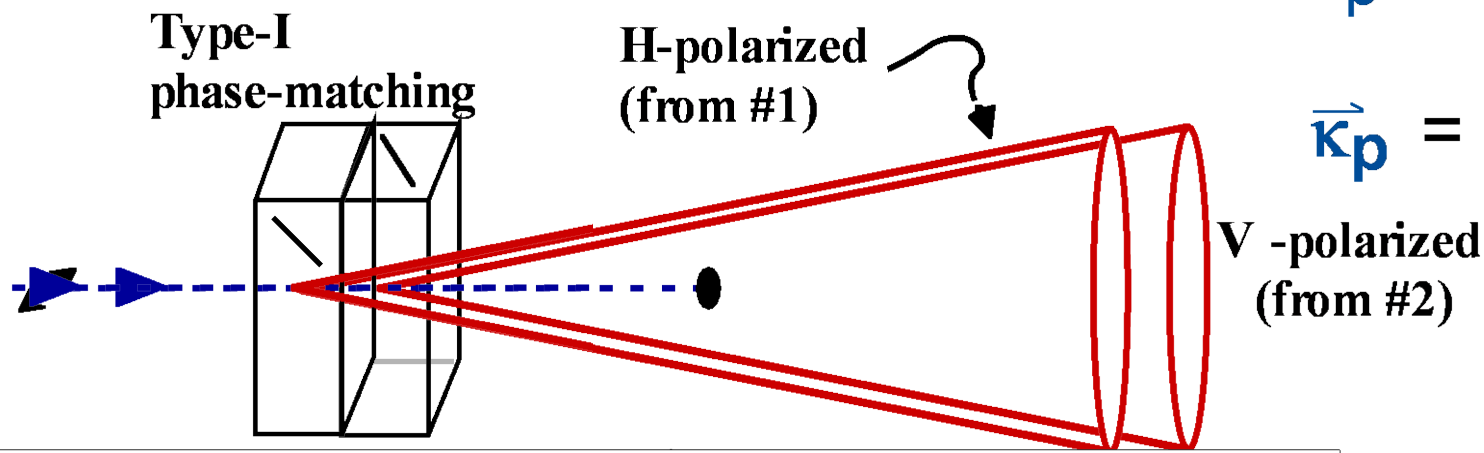
In an entangled state, neither particle has definite properties alone.
$\Rightarrow$ All the information is (nonlocally) stored in the *joint* properties.

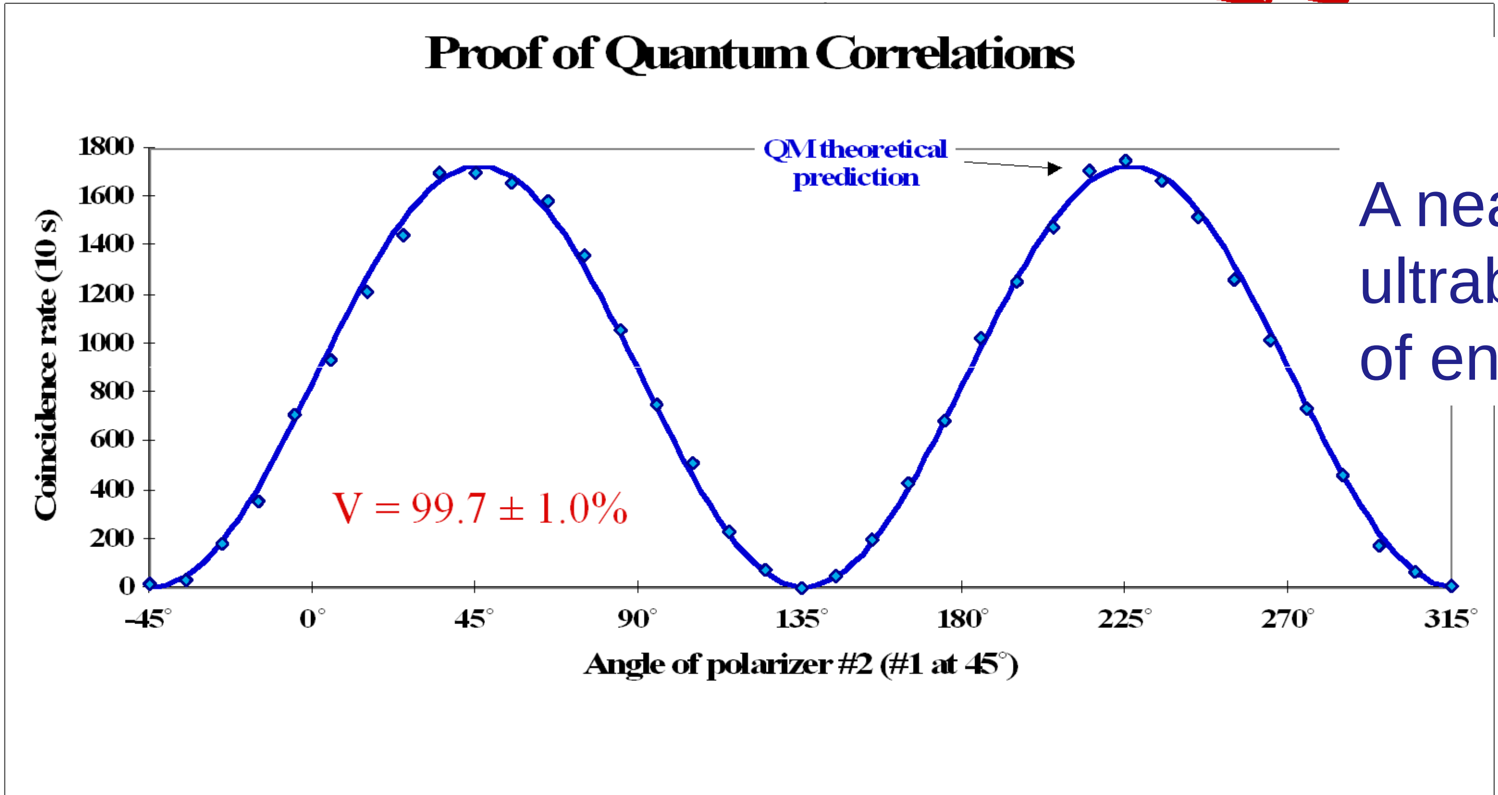
Two-crystal Polarization-Entangled Source

PGK et al. PRA (1999)

$\omega_p = \omega_s + \omega_i$

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

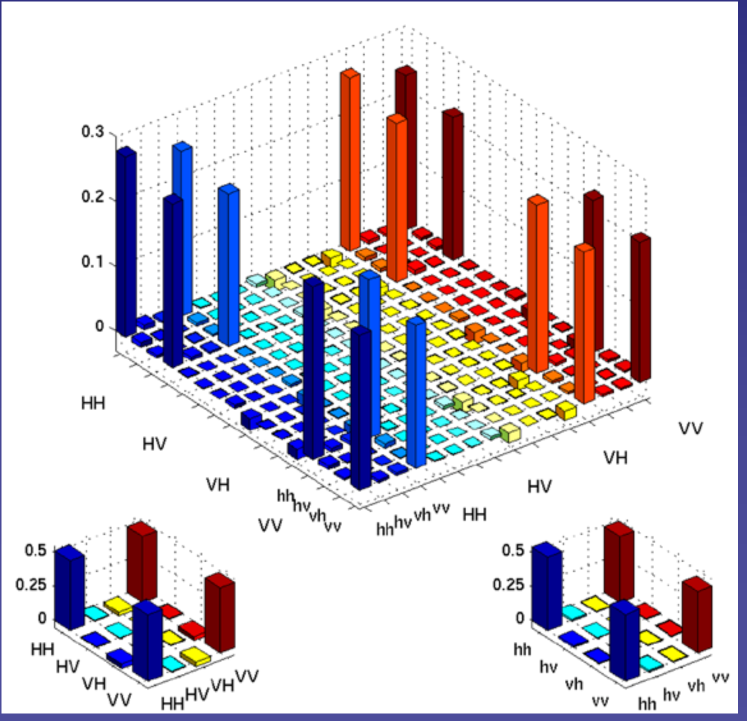




A near-perfect ultrabright source of entanglement

Photon Entanglements

- Polarization (spin)
- Linear momentum
- Orbital angular momentum/spatial mode
- Energy-Time
- ***Hyper-entangled!***



$$|\Phi^{+}\rangle \otimes |\phi^{+}\rangle$$

Maximally hyper-entangled state
F = 97%; T's > 94%

J. T. Barreiro et al., PRL **95**, 260501 (2005)

Hyper-entanglement: Particles (photons) simultaneously entangled in multiple DOFs

$$\underbrace{(|HH\rangle + |VV\rangle)}_{\text{polarization}} \otimes \underbrace{(\cdots + |\circlearrowright\circlearrowleft\rangle + \alpha|\bigcirc\bigcirc\rangle + |\circlearrowleft\circlearrowright\rangle + \cdots)}_{\text{orbital angular momentum}} \otimes \underbrace{\int d\omega A(\omega)|\omega, \omega_p - \omega\rangle}_{\text{energy}}$$

Large Hilbert space: $2 \otimes 2 \otimes \infty \otimes \infty \otimes \infty \otimes \infty$

-More efficient *n*-qubit transfer: T vs T^n

- **New capabilities in quantum info processing**
- **Full Bell-state analysis**
- **Novel tests of quantum nonlocality**
- **Superdense coding**
- **Process *non*-tomography**
- **Remote preparation of entangled states**
- **Bound-state preparation**
- **Multiplexed quantum cryptography**

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Entanglement: Why does/might it help?

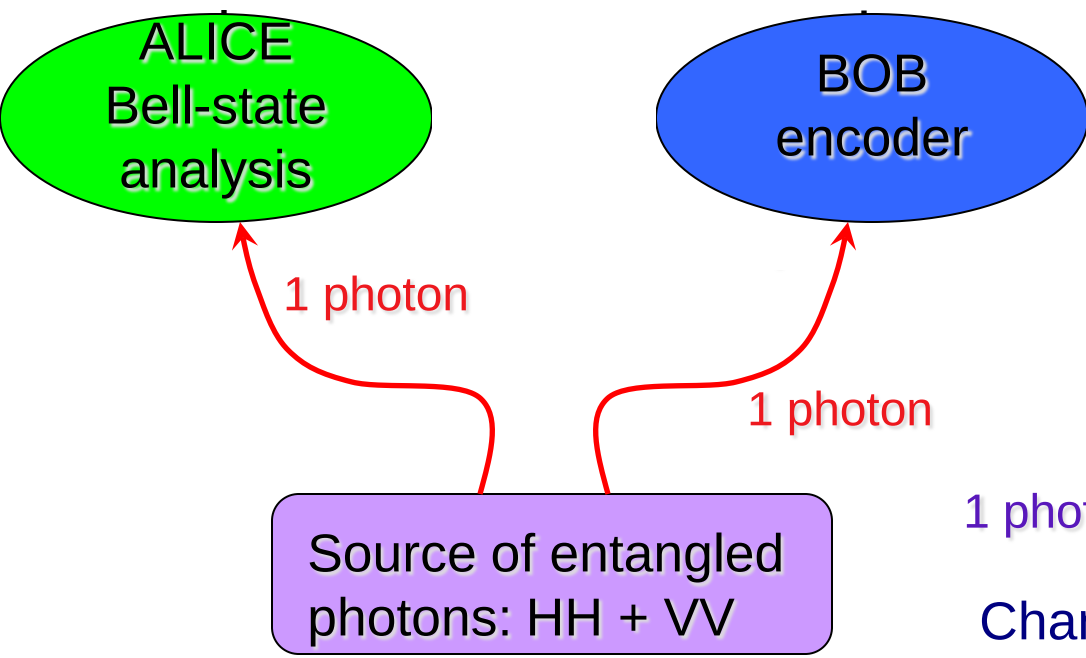
Physical Review Letters

VOLUME 69 | 16 NOVEMBER 1992 | NUMBER 20

Communication via One- and Two-Particle Operators on Einstein-Podolsky-Rosen States

Charles H. Bennett

IBM Research Division, T. J. Watson Research Center, Yorktown Heights, New York 10598



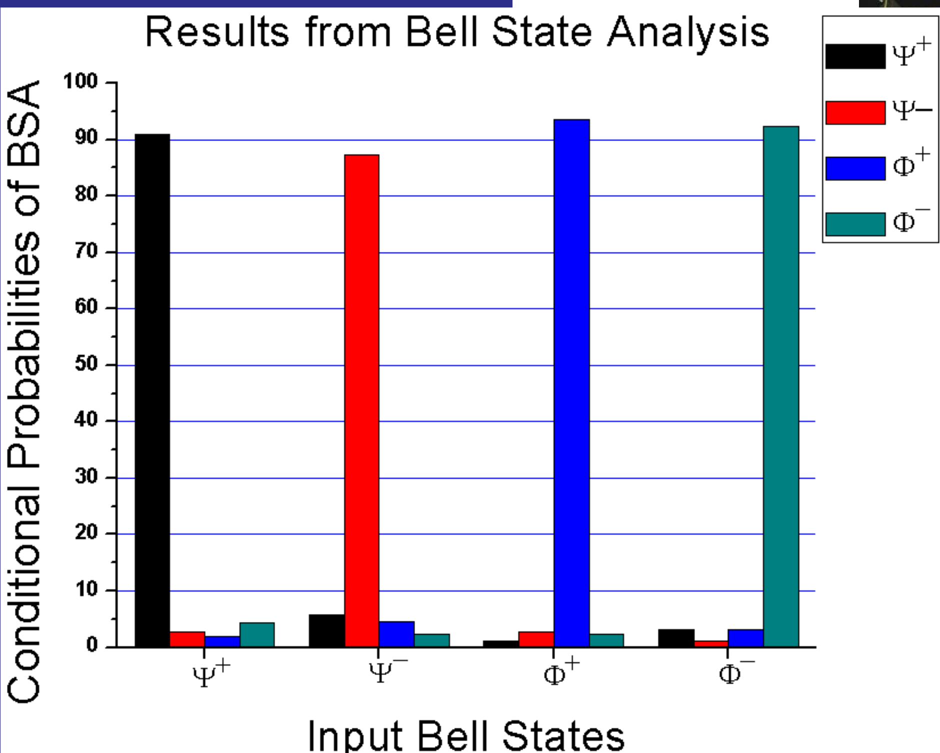
Bob's Transformation	Resulting State
I	HH + VV
H ↔ V	HV + VH
V → -V	HH - VV
H ↔ V, V→ -V	HV - VH

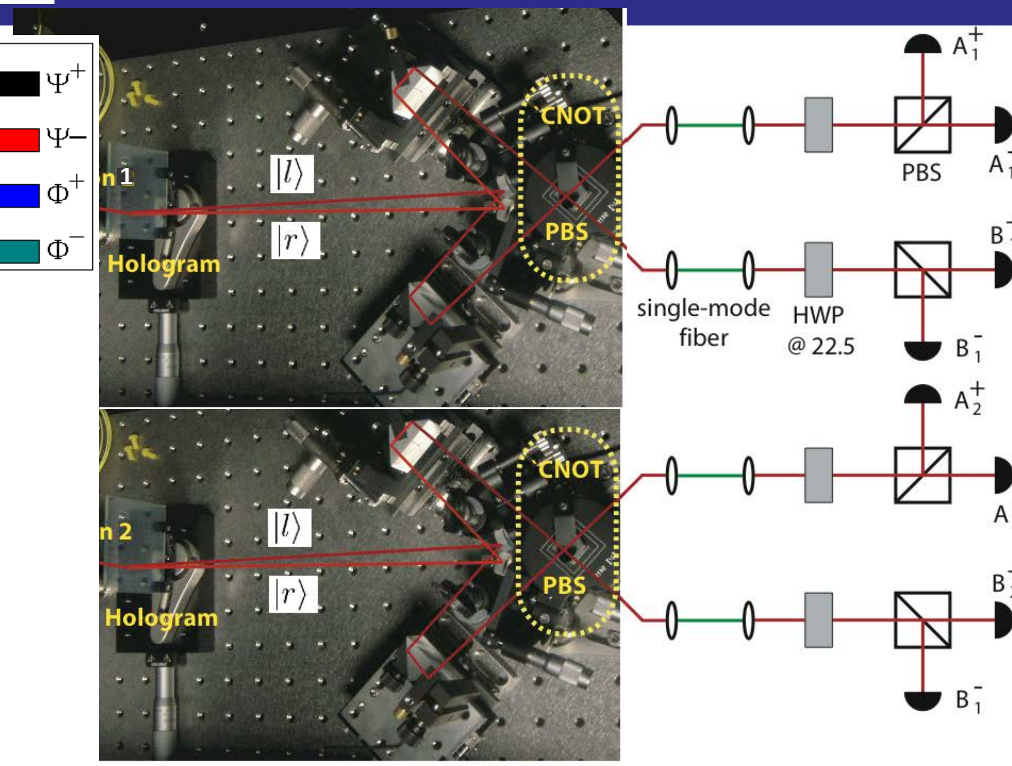
1 photon carries 2 bits of info:

Channel cap. = $\log_2 4$ = 2 bits/photon

Quantum SuperDense Coding

Polarization Bell states: $\begin{pmatrix} \Phi^{\pm} \\ \Psi^{\pm} \end{pmatrix} \otimes \psi^{+}$ Spatial mode Ancillary DOF





$<P_{success}>= 95\%$

State	Detector signature			
$\vert\Phi^{\pm}\rangle$	$A_1^+ A_2^{\pm}$	$B_1^+ B_2^{\pm}$	$A_1^- A_2^{\mp}$	$B_1^- B_2^{\mp}$
$\vert\Psi^{\pm}\rangle$	$A_1^+ B_2^{\pm}$	$B_1^+ A_2^{\pm}$	$A_1^- B_2^{\mp}$	$B_1^- A_2^{\mp}$

Implement high-capacity quantum superdense coding: Barreiro, Wei, PGK, Nat. Phys. **4**, 282 (2008)

Walborn et al., PRA 68, 042313 (2003)

Super- and Hyper-dense Coding

“Classically”: only 1 bit can be transferred/ photon*

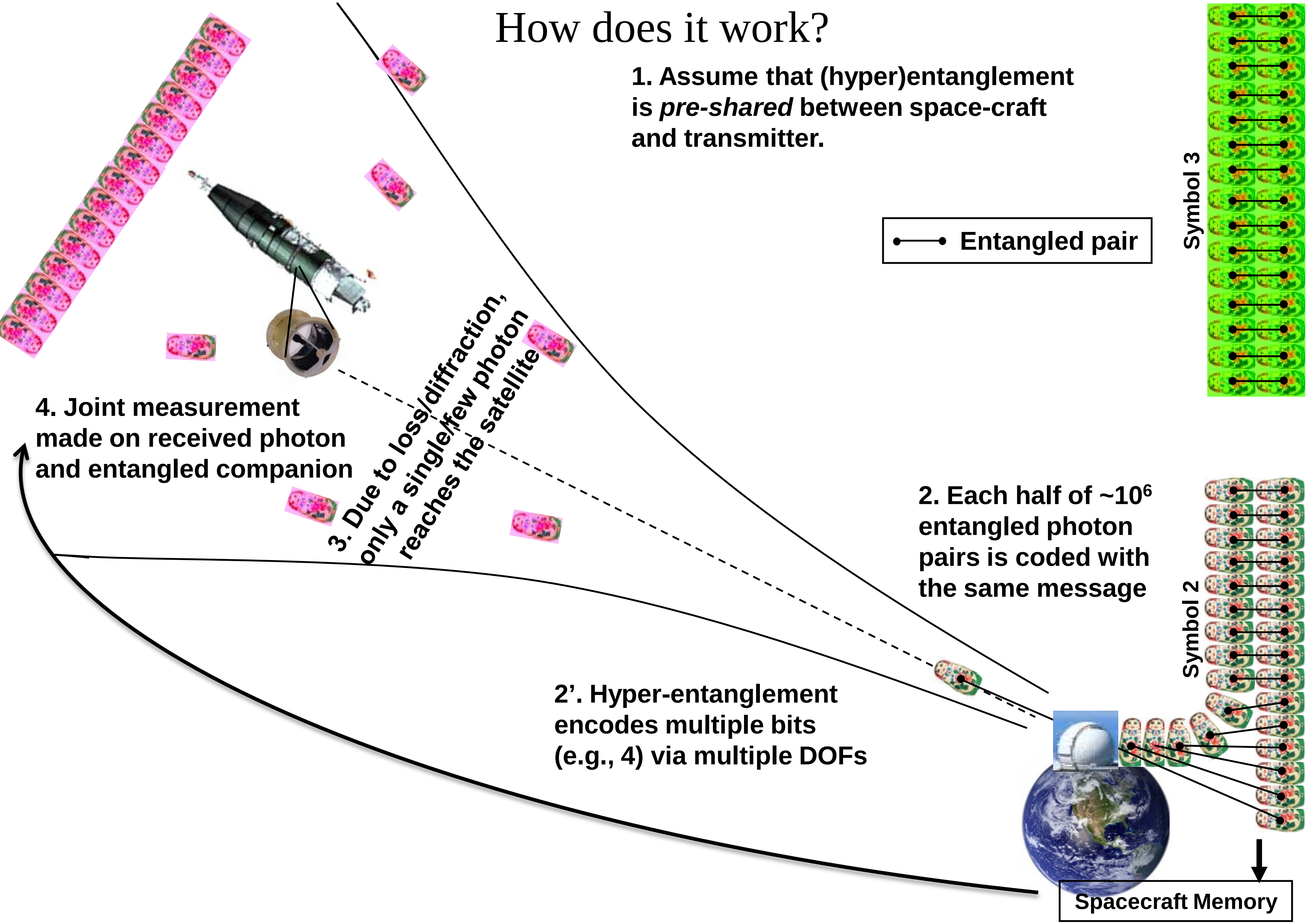
Super-dense Coding: up to 2 bits/photon
Our group: 1.63 bit/photon (world record)

Hyper-dense Coding – Use simultaneous entanglement in multiple DOFs:
E.g., Bob can send one of 16 states.
Alice can decode up to 7: up to 2.8 bits/photon

⇒ This is one of our main experimental goals for the rest of Phase I

Deep-Space Quantum Communication

How does it work?



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Hyper-entanglement-enhanced *quantum* communication ("Super-dense Teleportation")

A full communication 'portfolio' should include transmission of **quantum information:**

Binary digit -- "bit"	Quantum bit -- "qubit"
0, 1	$\|0\rangle, \|1\rangle, (\|0\rangle + \|1\rangle)/\sqrt{2}$
copyable	*unclonable*

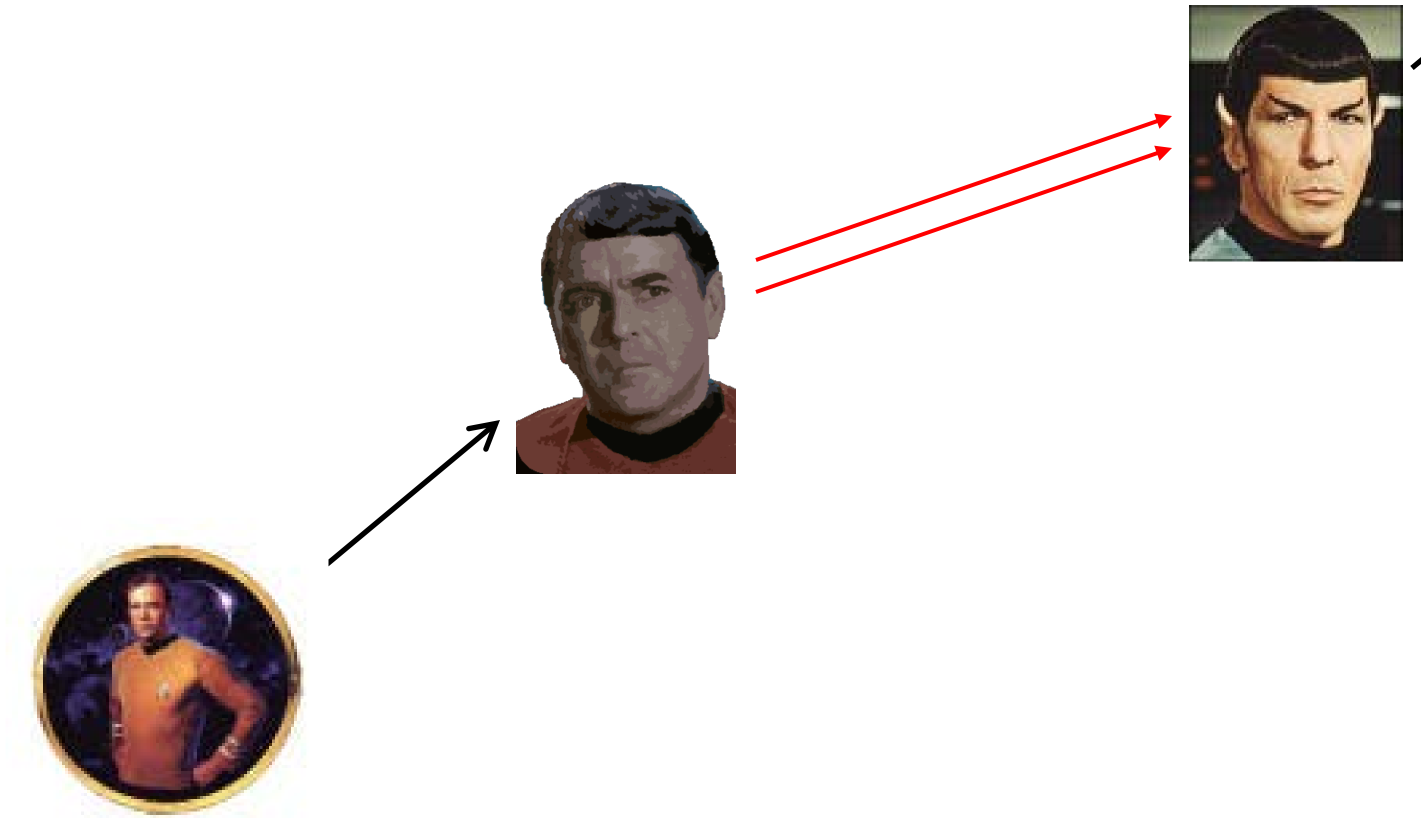
Because of superpositions, the qubit has an *infinite* amount more information (2 continuous parameters*):

$$|\psi\rangle = \cos\theta\,|0\rangle + e^{i\phi}\sin\theta\,|1\rangle$$

* like latitude and longitude

Quantum Teleportation

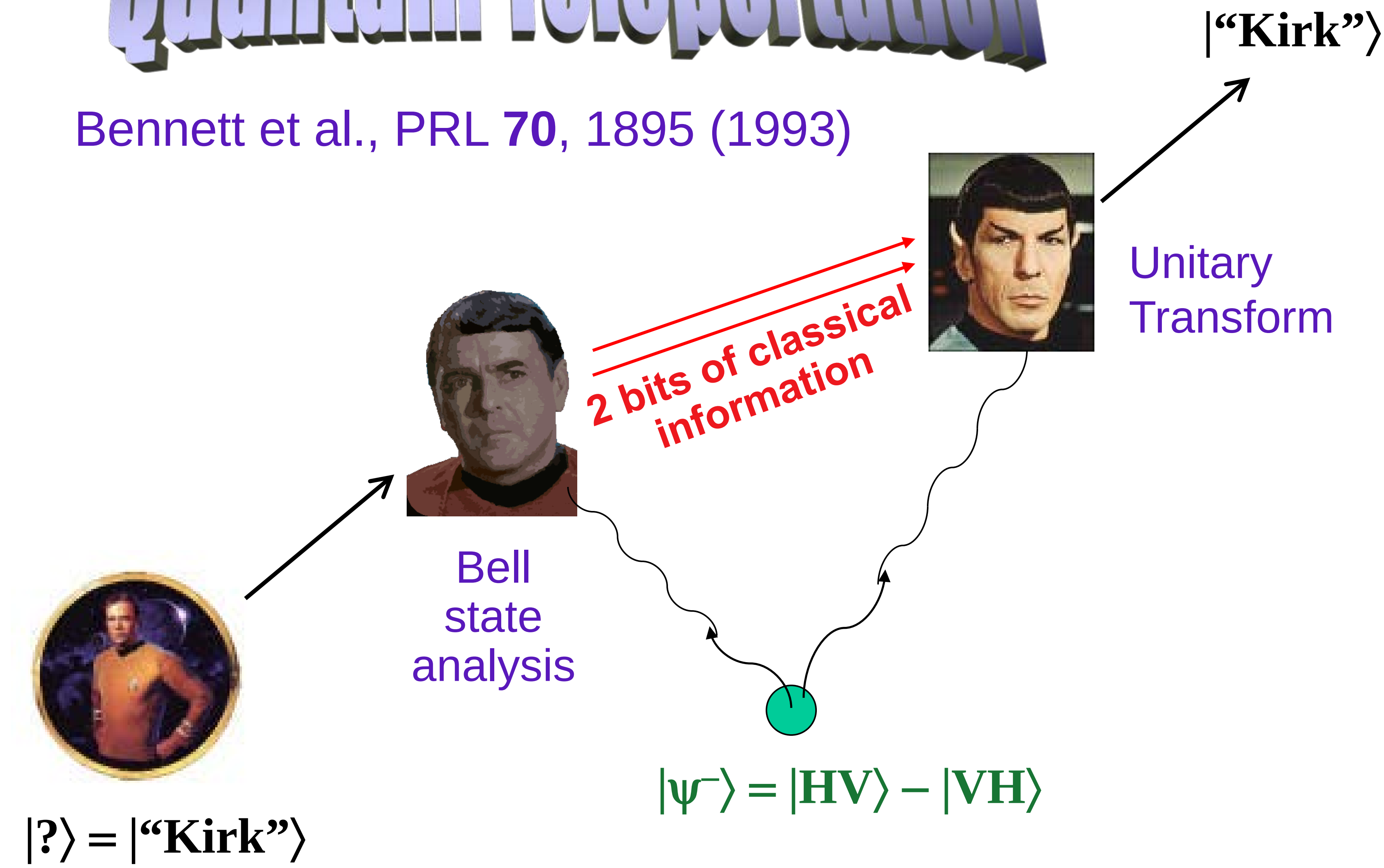
$|\text{“Kirk”}\rangle$



$|?\rangle = |\text{“Kirk”}\rangle$

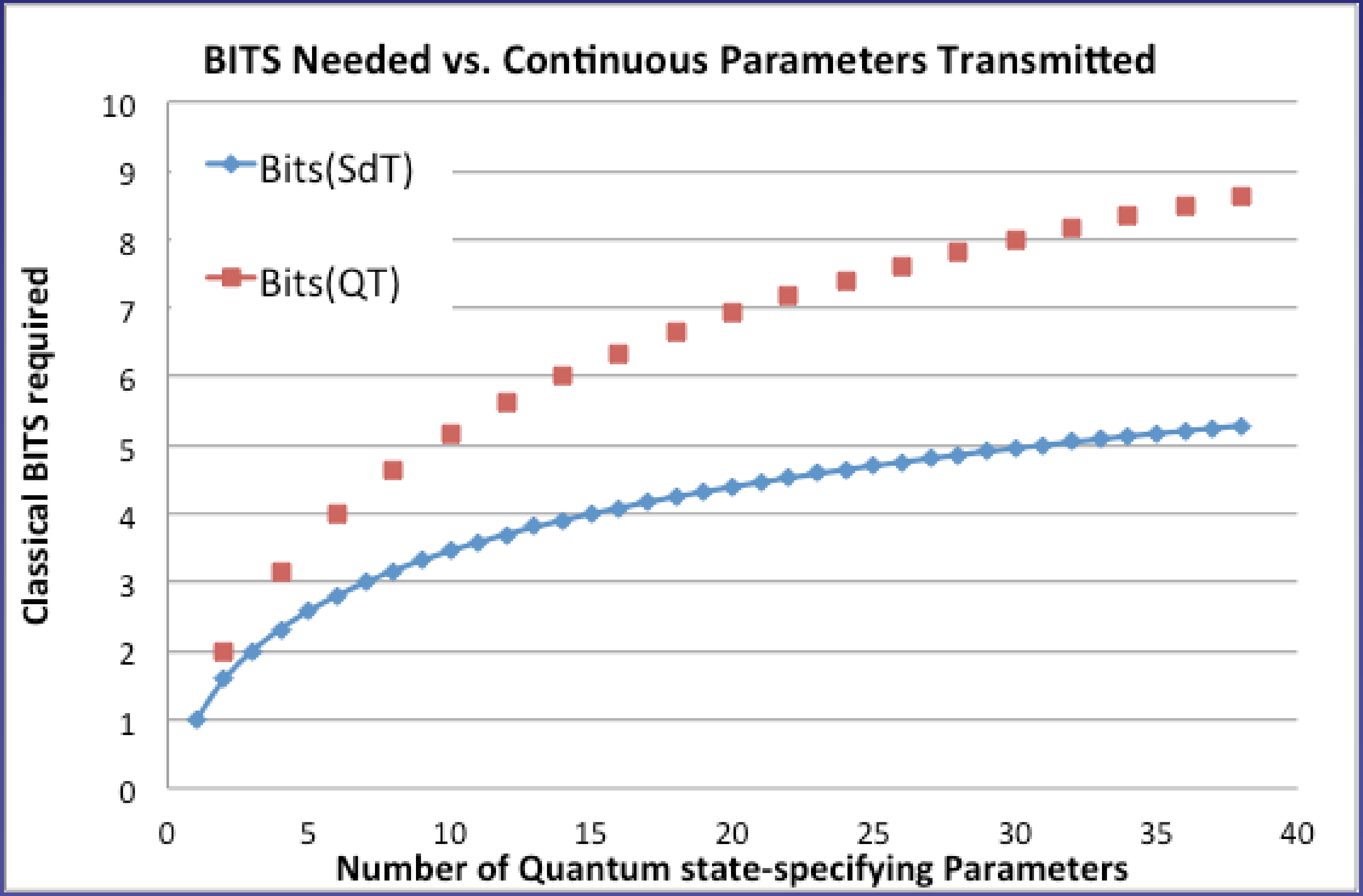
Quantum Teleportation

Bennett et al., PRL **70**, 1895 (1993)



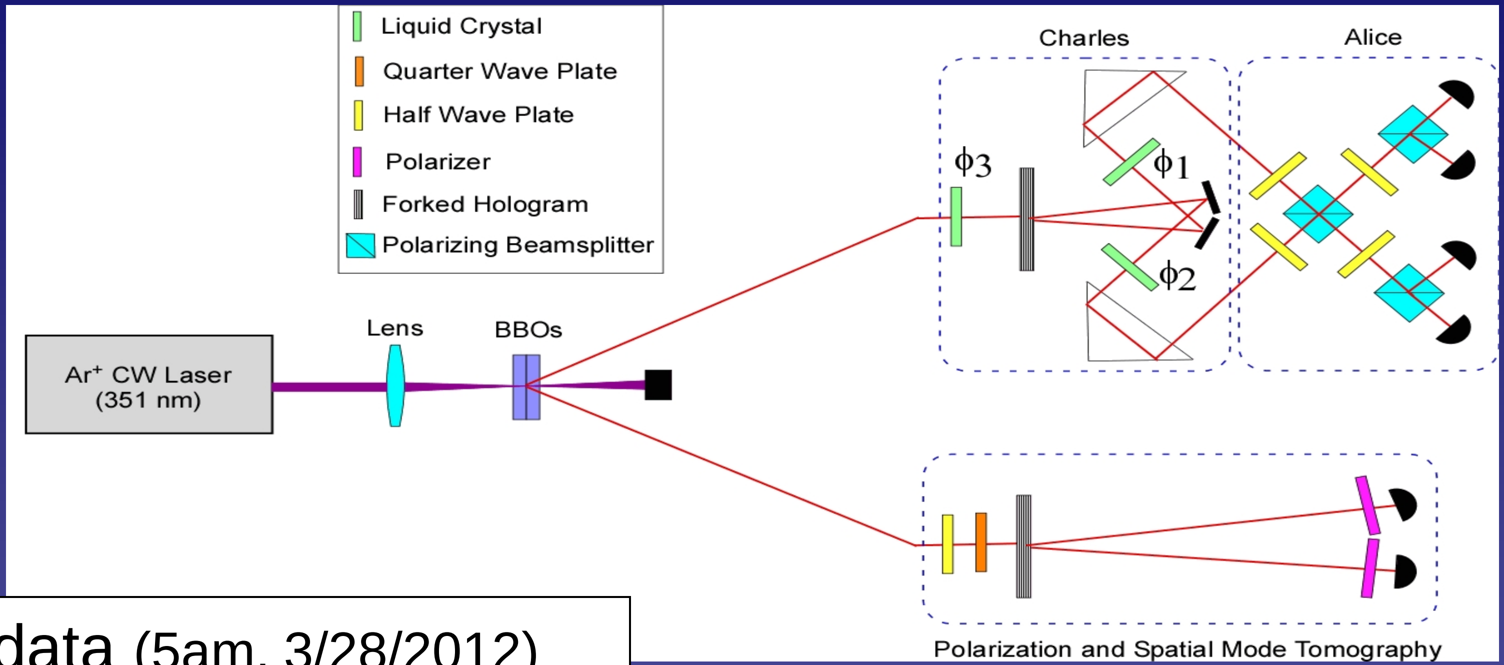
"*Super-dense* Teleportation"

By using a restricted set of quantum states, it's possible to transfer as many parameters, with fewer classical resources. $|\psi\rangle = |0\rangle + e^{i\alpha}|1\rangle + e^{i\beta}|2\rangle + \ldots$

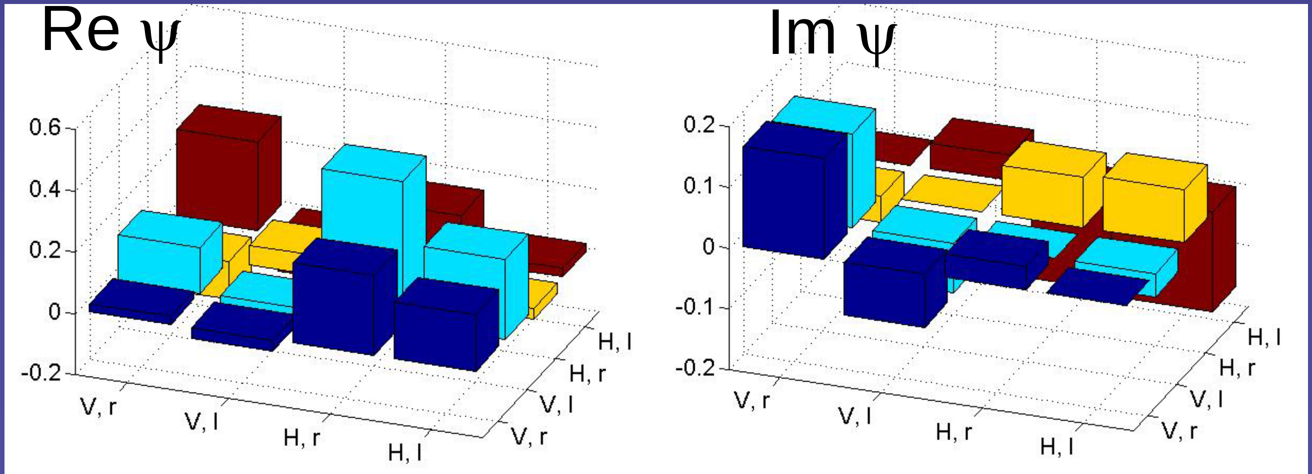


Super-dense Teleportation

Remotely prepare $|\psi\rangle = |0\rangle + e^{i\alpha}|1\rangle + e^{i\beta}|2\rangle + e^{i\gamma}|3\rangle$



First data (5am, 3/28/2012)



Send

$\alpha = 270°$

$\beta = 346$

$\gamma = 0°$

Fidelity → 82%

Kwiat's Quantum Clan (2012)

Graduate Students:

- Kevin McCusker
- Aditya Sharma
- Kevin Zielnicki
- Trent Graham
- Brad Christensen
- Rebecca Holmes

Undergraduates:

- Daniel Kumor
- David Schmid
- Mae Teo
- Jia Jun ("JJ") Wong
- Ben Chng
- Zhaoqi Leng
- Joseph Nash
- Cory Alford
- Brian Huang

Post-Doc: Jian Wang

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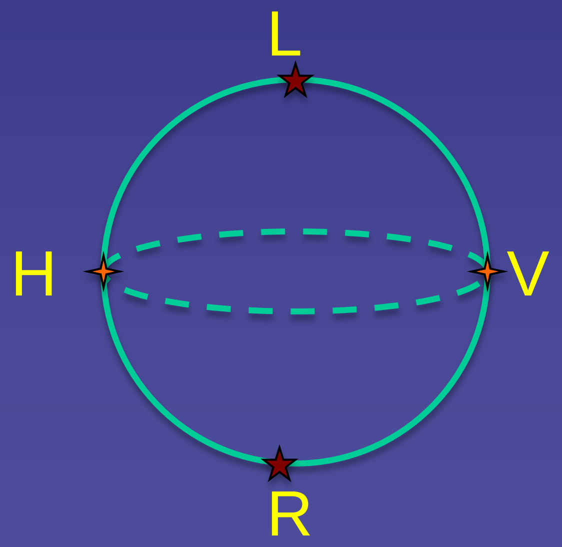
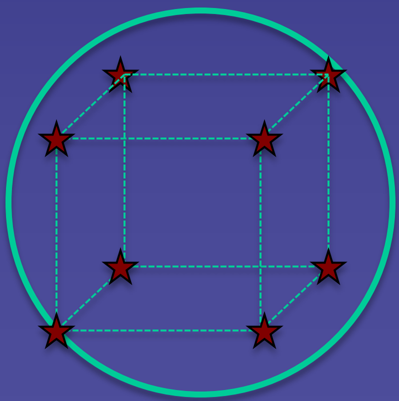
Other Potential Methods to Improve *Classical* Channel Capacity

-Multi-photon Optimal Quantum State Discrimination

If you have only one qubit, then only 2 quantum states (= 1 bit) may be reliable distinguished:



With multiple copies, one may be able to discriminate more states ("messages") efficiently (especially with <u>adaptive</u> techniques):



E.g.,
8 states
→ 3 bits

-Quantum Super-additivity ("2 heads are better than 2!")

Summary

1. Motivation: *NASA* has a critical need for increased data rates.
2. Entanglement: Nonlocal quantum correlations in one/more DOFs
3. Super-dense Coding: Nonlocal quantum correlations in one/more DOFs
4. Super-dense Teleportation: Remotely prepare quantum state with reduced classical communication. First DATA!
5. Other Options: Adaptive, multi-photon state discrimination, …

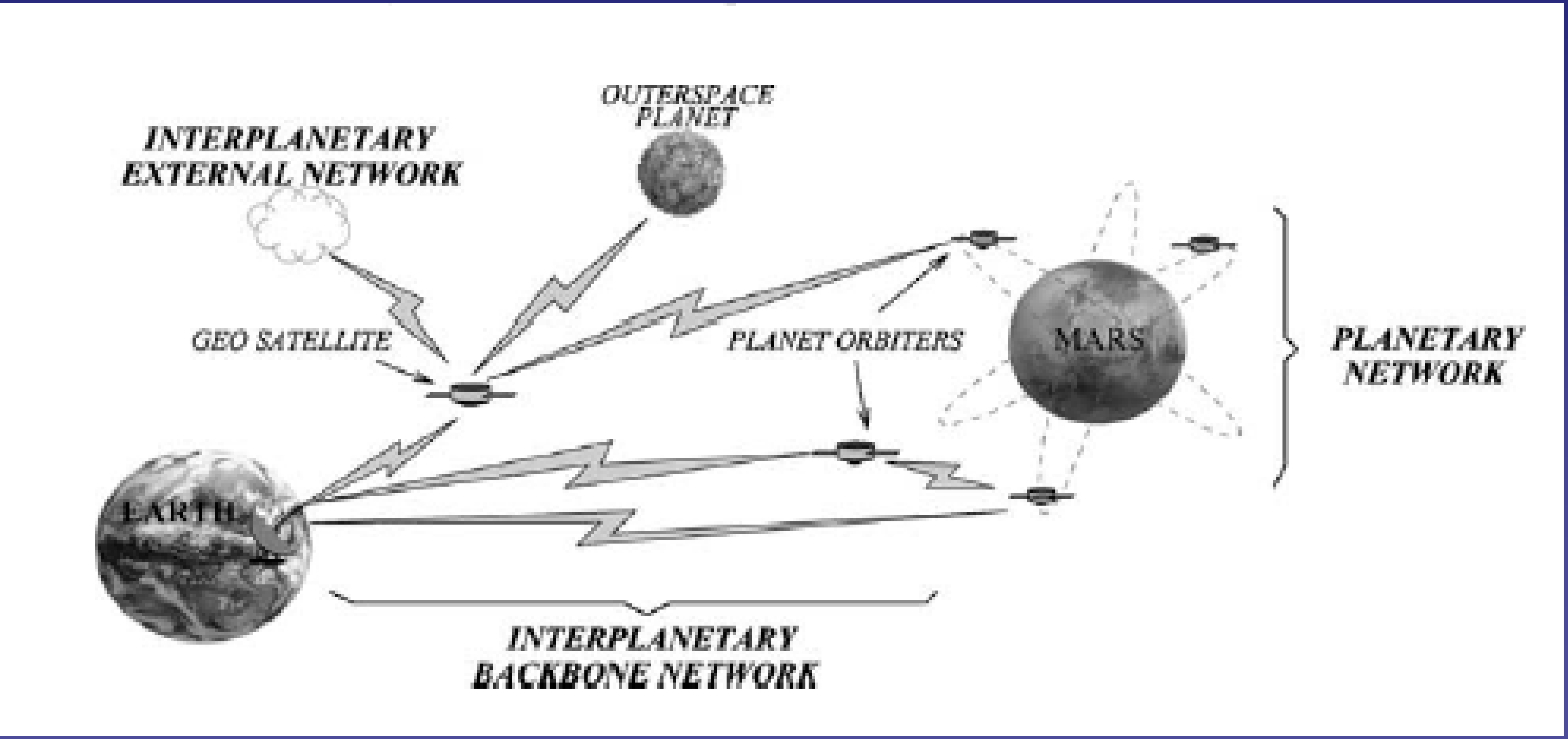
We will explore the use of entanglement and hyper-entanglement (simultaneously in multiple photonic degrees of freedom) to achieve efficient code transmission beyond what is possible classically.

How far can we go?

“To infinity… and beyond.*”

* Not intended to represent our proposed timeline, budget or required resources.

NASA's vision for construction of planetary and interplanetary networks



from Charles B Shah
cbshah@cse.buffalo.edu

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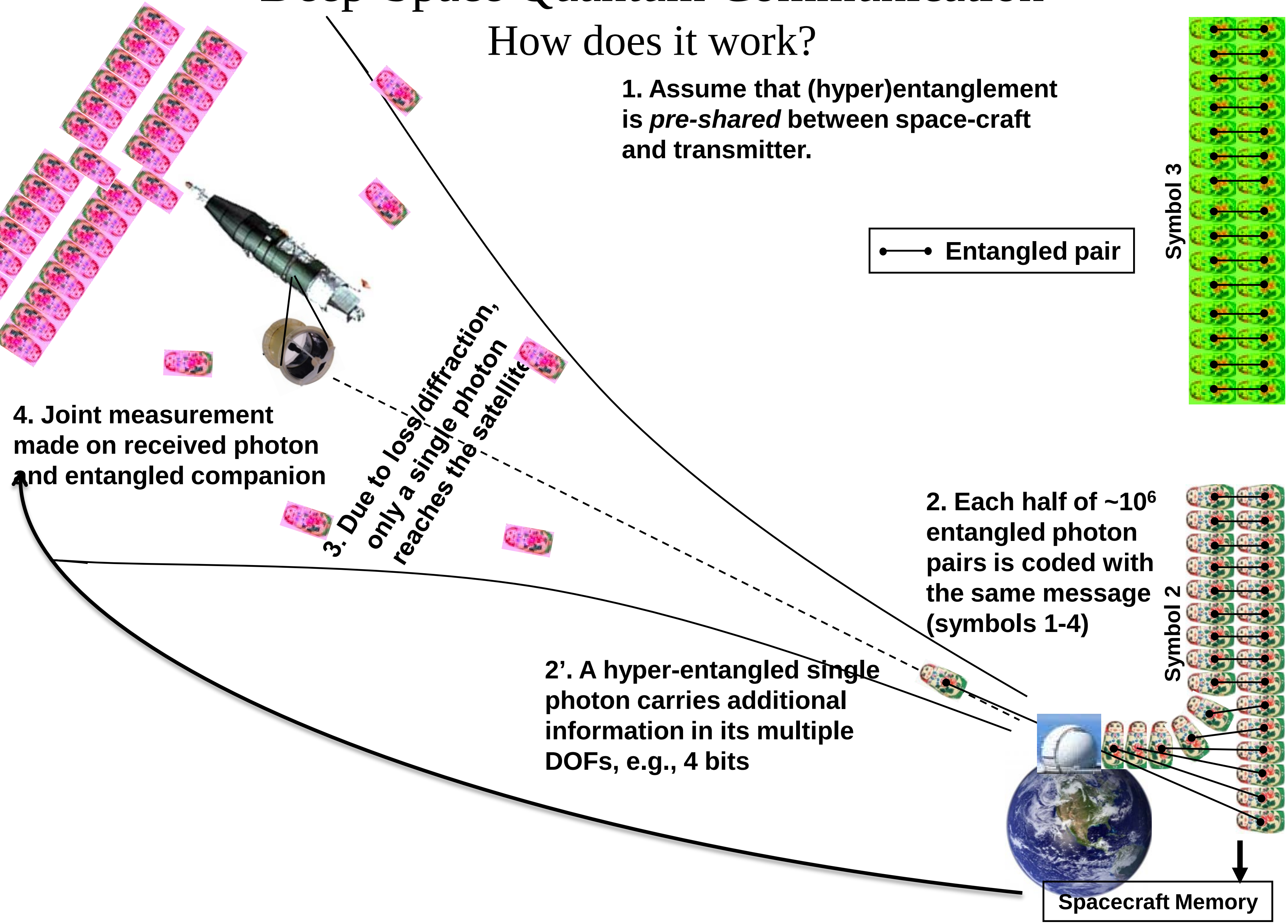

Deep-Space Quantum Communication

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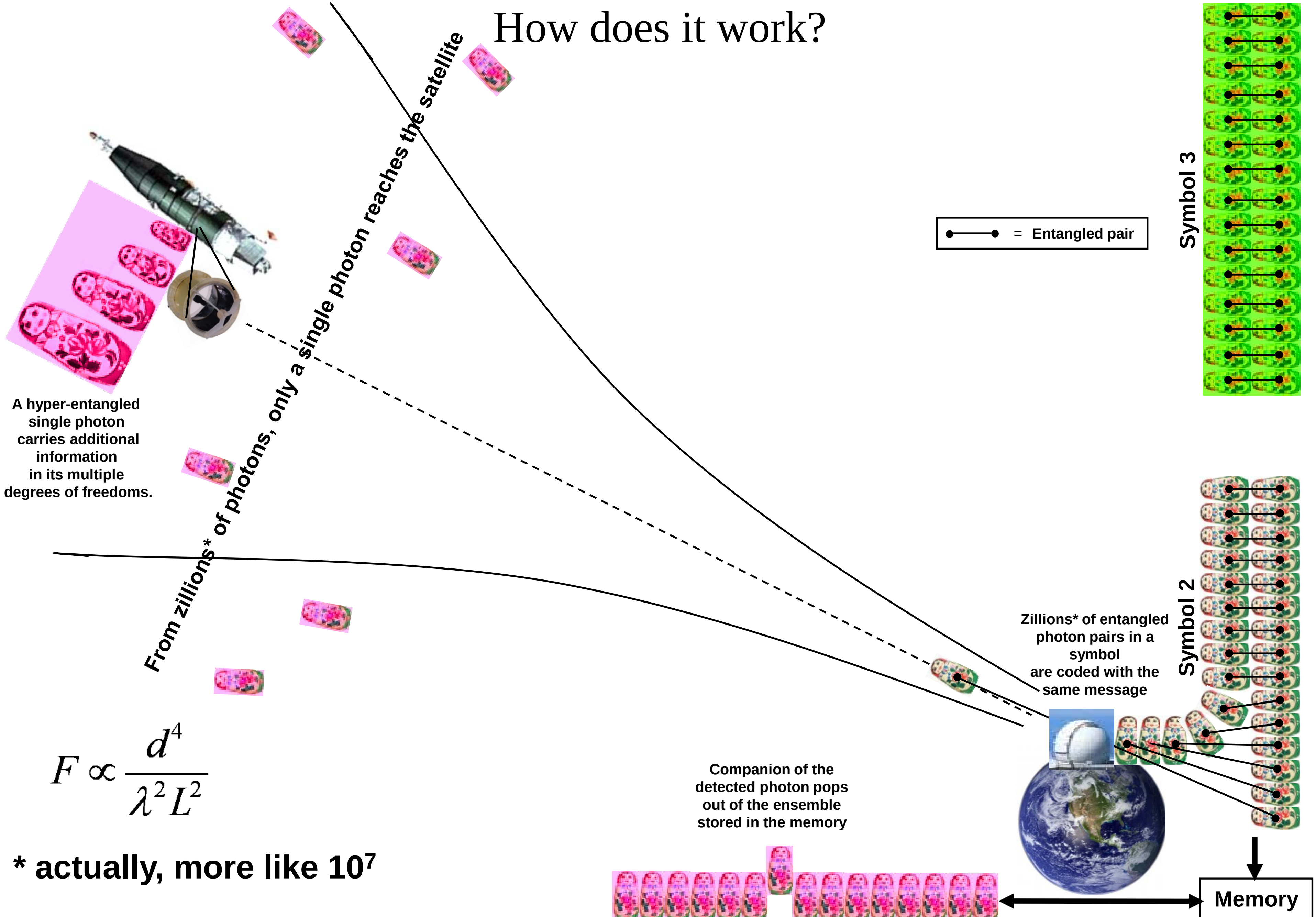
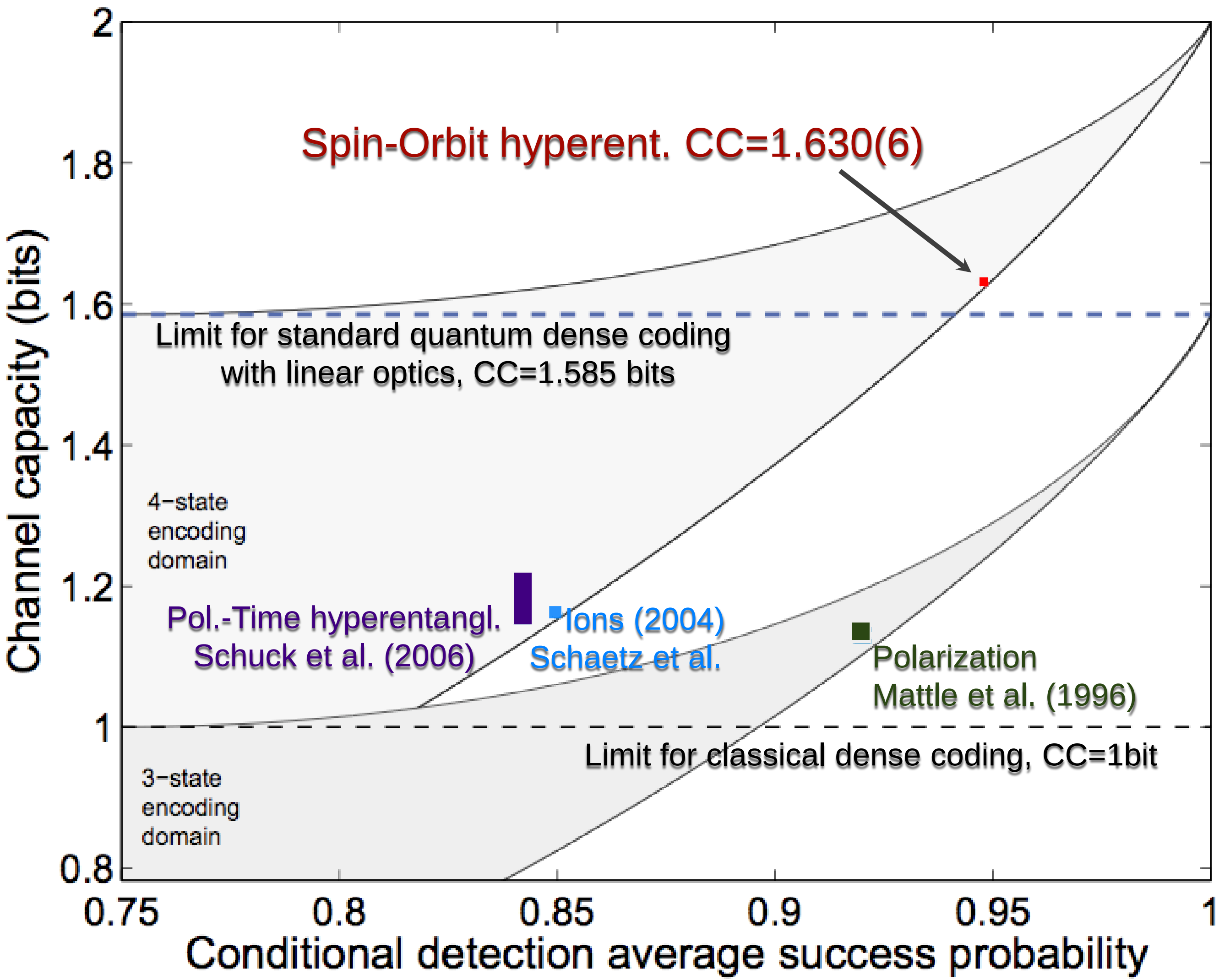


$$F \propto \frac{d^4}{\lambda^2 L^2}$$

* actually, more like 10^7

Experimentally reported CC for quantum dense coding

CC = 2.81 bits*



Barreiro, Wei, PGK, Nat. Phys. **4**, 282 (2008)

*Wei / Barreiro / Kwiat, PRA (2007)

Two-crystal Polarization-Entangled Source

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$\omega_p = \omega_s + \omega_i$

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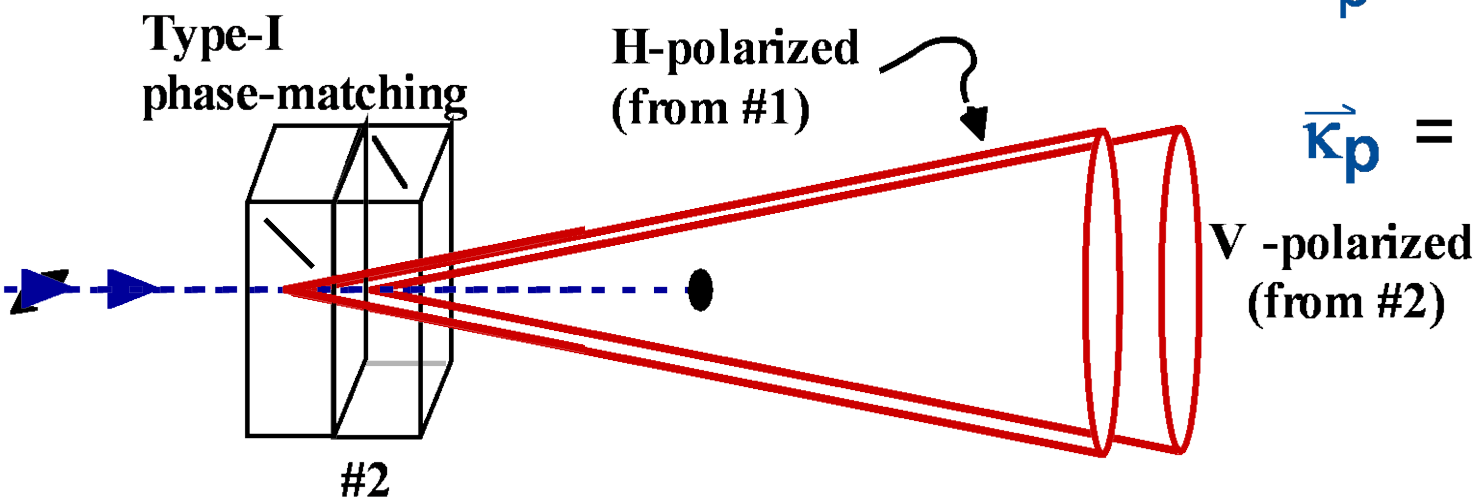


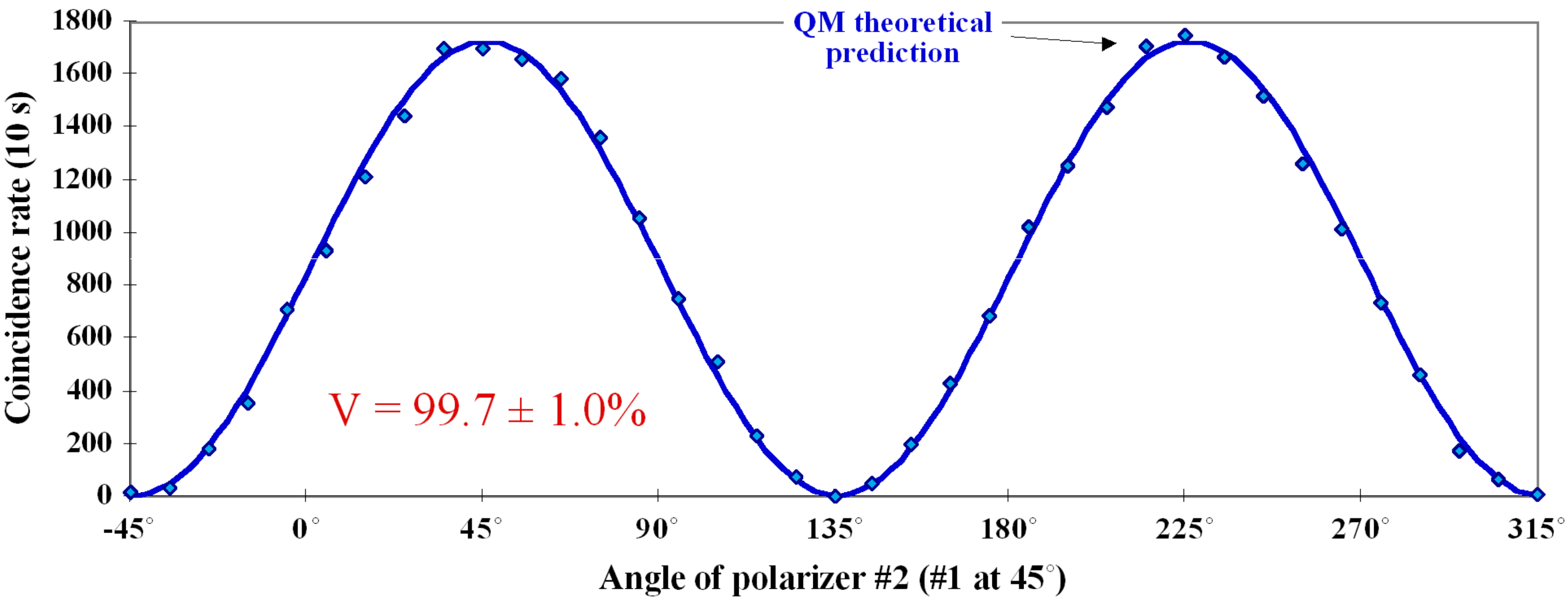
$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle_1|H\rangle_2\right.$$

Tune pump polarization: Nonmax. entangled states PRL **83**, 3103 (1999)

Spatial-compensation: all pairs have same phase ϕ OptExp.**13**, 8951 (2005

Temporal pre-compensation: works with fs-laser OptExp.**17,** 18920 (2009)

Proof of Quantum Correlations



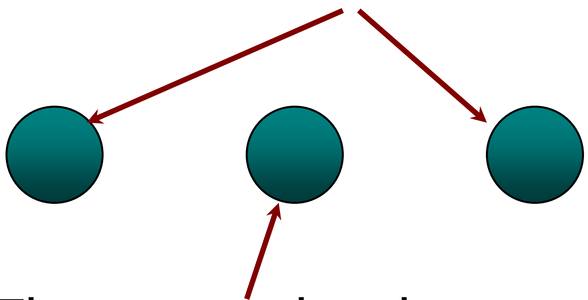
$$|H\rangle|H\rangle + |V\rangle|V\rangle = |45\rangle|45\rangle + |-45\rangle|-45\rangle$$

- Near-perfect quantum behavior
- Ultrabright source

Why hyperentanglement helps… an intuitive view:

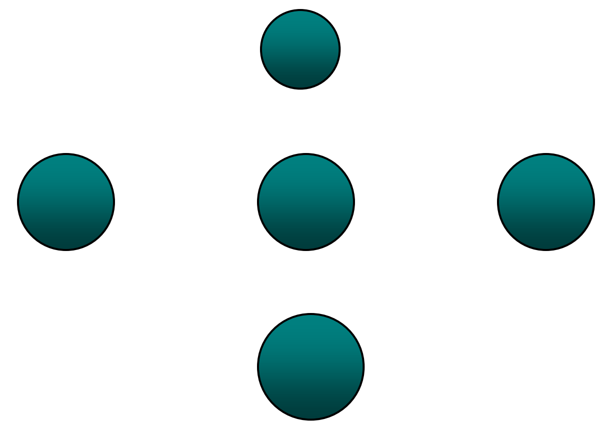
Without hyperentanglement:

Can only reliably distinguish these



These *two* give the same experimental signature

With hyperentanglement:

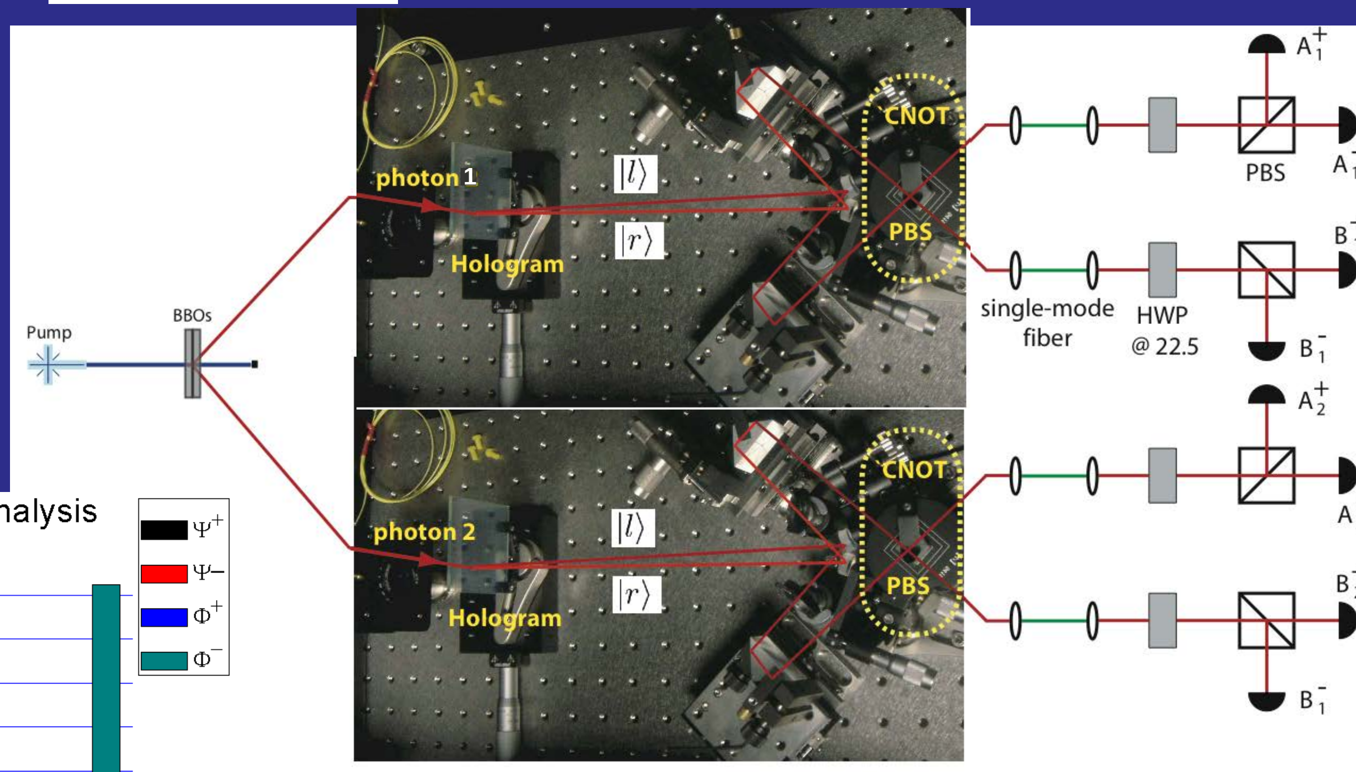


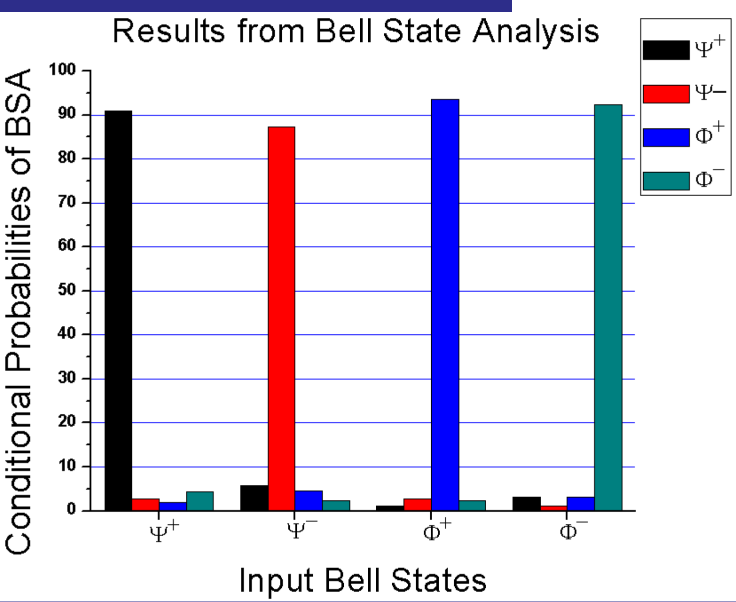
Can reliably distinguish all four polarization Bell states

Hyperentanglement allows access to enlarged Hilbert space

Bell-state analysis

Polarization Bell states: $\begin{pmatrix} \Phi^{\pm} \\ \Psi^{\pm} \end{pmatrix} \otimes \psi^{+}$ Spatial mode Ancillary DOF





State	Detector signature			
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Walborn et al., PRA 68, 042313 (2003)

Outline

1. Entangled/Hyper-entangled State Preparation
2. Bell State Analysis
3. Direct Characterization of Quantum Dynamics
4. Hyper-entangled QKD

Entanglement: Why does/might it help?

Entanglement is

“*the* characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought” **––E. Schrödinger**

Non-factorizable: can*not* be written as a product ⇒ Entanglement

Example (“Bell states”): $|HH\rangle + |VV\rangle = |45,45\rangle + |-45,-45\rangle$

$|HH\rangle - |VV\rangle = |45,-45\rangle + |-45,45\rangle$

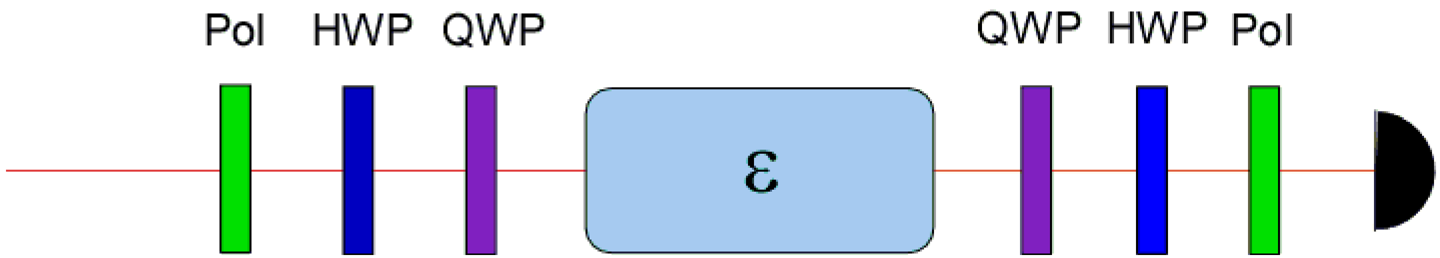
$|HV\rangle + |VH\rangle = |45,45\rangle - |-45,-45\rangle$

$|HV\rangle - |VH\rangle = |45,-45\rangle - |-45,45\rangle$

(like the spin singlet: $|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$)

In an entangled state, neither particle has definite properties alone.
⇒All the information is (nonlocally) stored in the *joint* properties.

Review of Standard Quantum Process Tomography (SQPT)

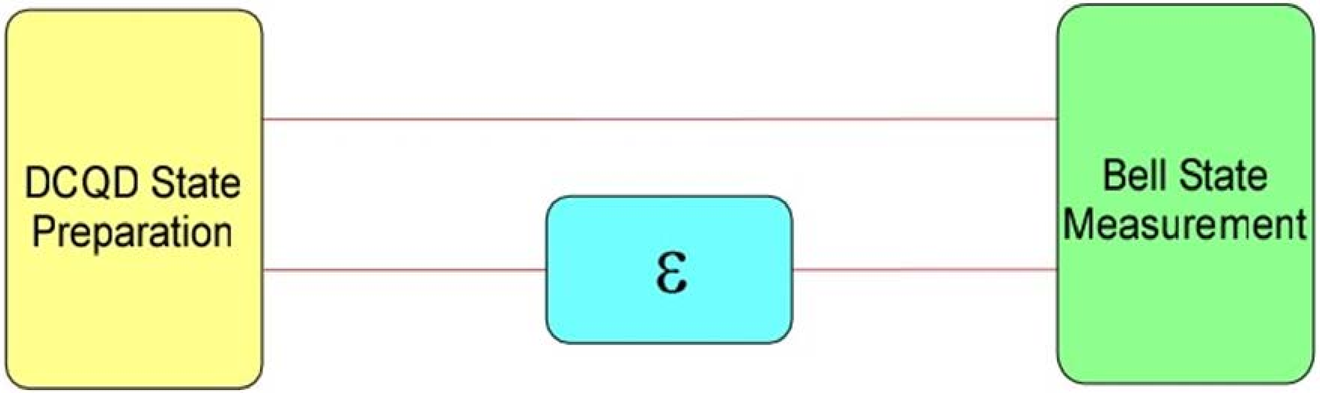


- Quantum processes may be represented by a χ matrix:

$$\varepsilon(\rho) = \sum_{m,n=0}^{3} \chi_{mn} \sigma_m \rho \sigma_n^{\dagger}$$

- Multiple quantum state tomographies are required to characterize ε.
- A general n-qubit process tomography requires 16^n measurements, e.g., 1-qubit process: full state tomography (4 measurements each) for each of 4 input states.

Direct Characterization of Quantum Dynamics (DCQD)*



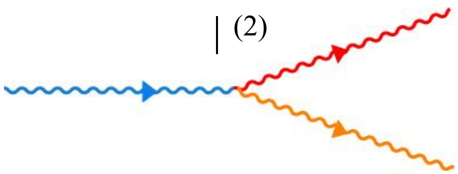
- It is possible to use a larger Hilbert space to decrease the number of required measurements. Only 4^n required.
- DCQD uses entangled states to characterize processes.
- No tomography, only 2-qubit gates (e.g., Bell state analysis)** [other reduced-measurement schemes require n-qubit interactions].

* M. Mohseni and D. A. Lidar, Phys. Rev. Lett. **97**, 170501 (2006)

** Z.-W. Wang et al., PRA **75**, 044304 (2007); W.-T. Liu et al., PRA **77**, 032328 (2008)

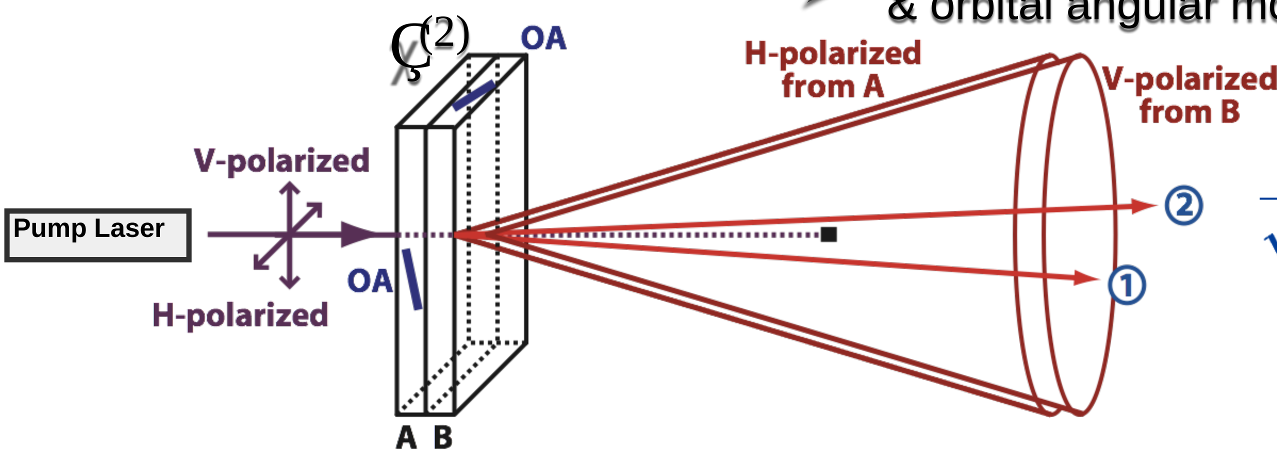
Polarization-entangled pairs generated by two-crystal source

Spontaneous Parametric Down Conversion
Type-I phase matching



Conservation of energy → Energy entanglement

Conservation of momentum → Linear momentum entanglement & orbital angular momentum entanglement



$$\frac{1}{\sqrt{2}}(|H_1H_2\rangle + |V_1V_2\rangle)$$

Maximal polarization entanglement

Tune pump polarization: nonmax. entangled states PRL **83**, 3103 (1999)

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(and BiBO)

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