Schrödinger's Rainbow: The Renaissance in Quantum Optical Interferometry

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Quantum Computing Technologies (QCT) Group

Explorations Systems Autonomy, Sec. 367

http://cs.jpl.nasa.gov/qct.html/qat.html

CL#03-0987

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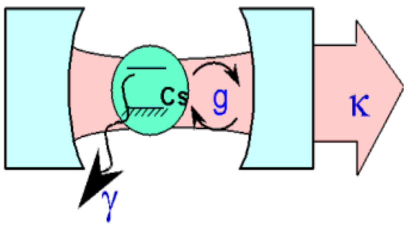
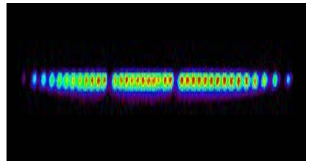
Quantum Technology: The Second Quantum Revolution

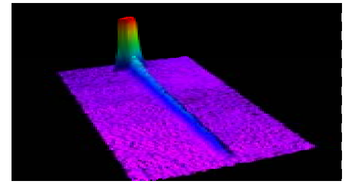
JP Dowling & GJ Milburn, *Phil. Transactions of the Royal Soc. of London*

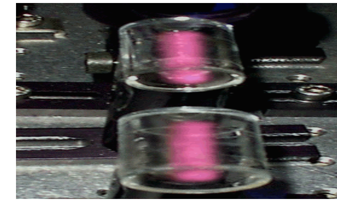




Ion Traps
Cavity QED
Linear Optics

Quantum Optics

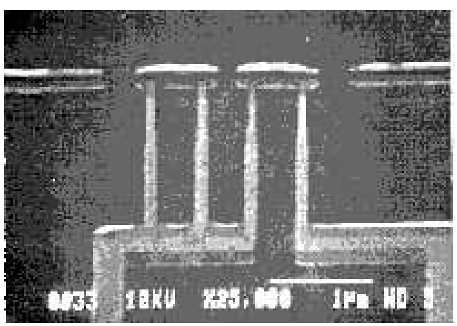




Quantum Atomics

Bose-Einstein
Atomic Coherence
Ion Traps

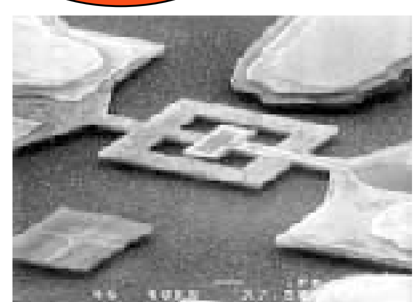
Quantum Information Processing



Coherent Quantum Electronics

Superconductors
Excitons
Spintronics

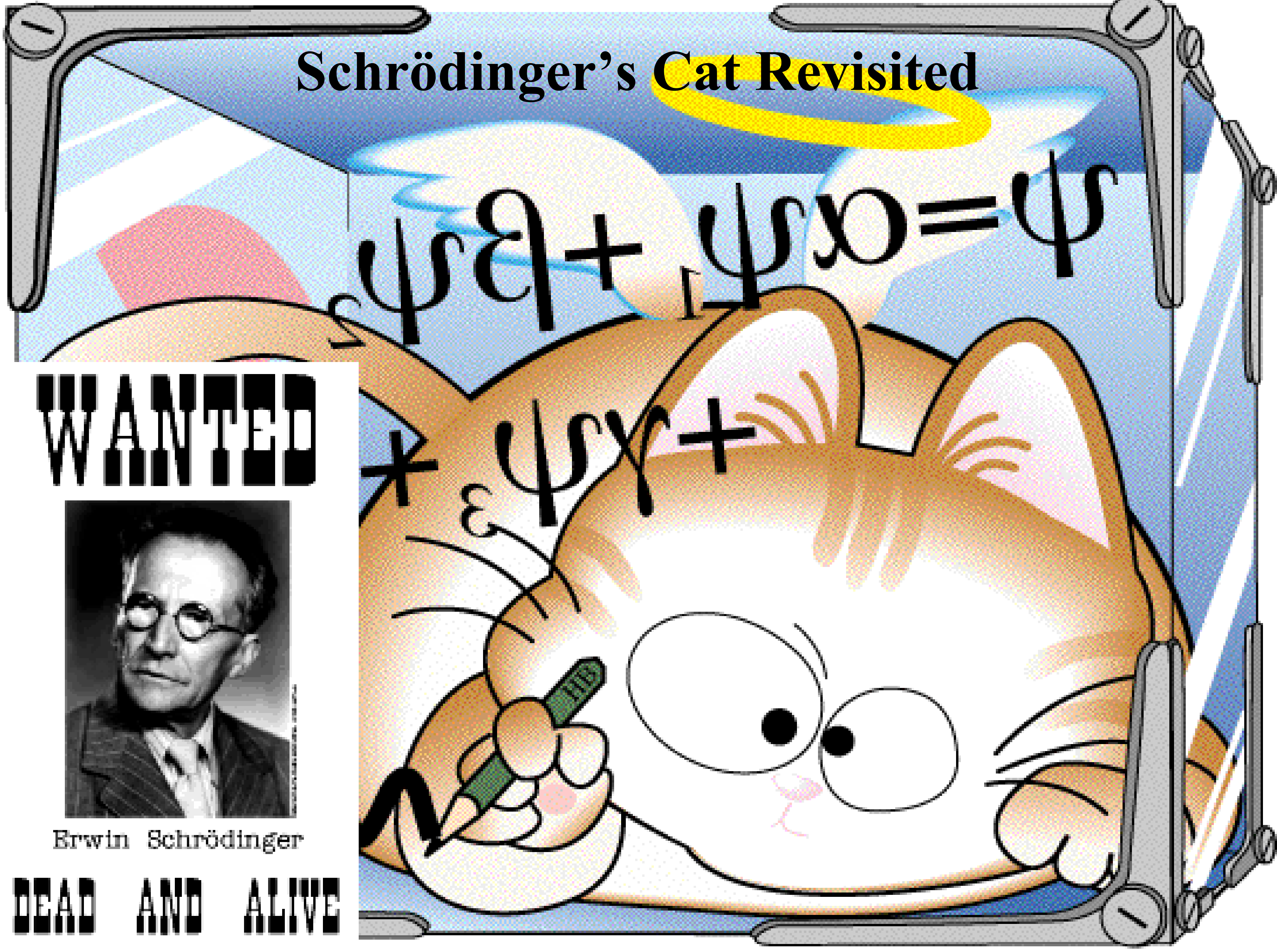
Quantum Mechanical Systems



Pendulums
Cantilevers
Phonons

Schrödinger's Cat and All That

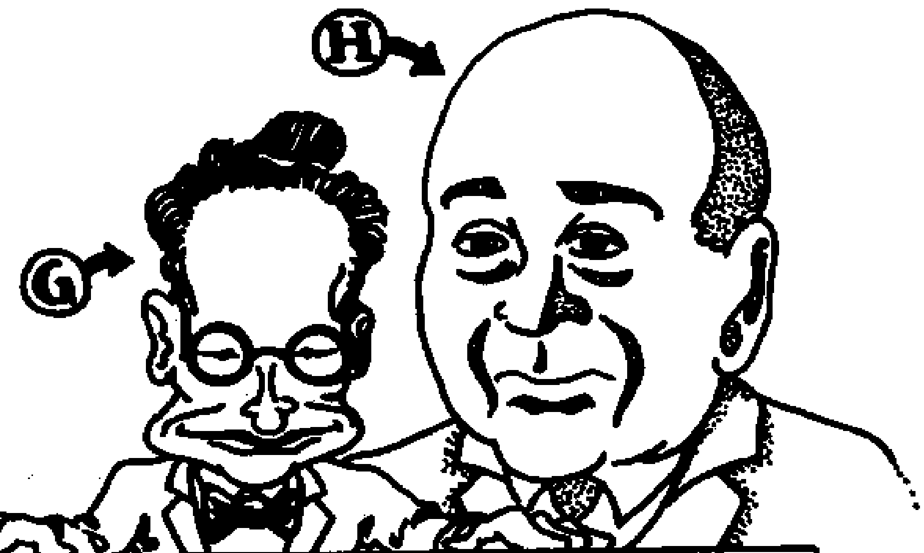
Schrödinger's Cat Revisited

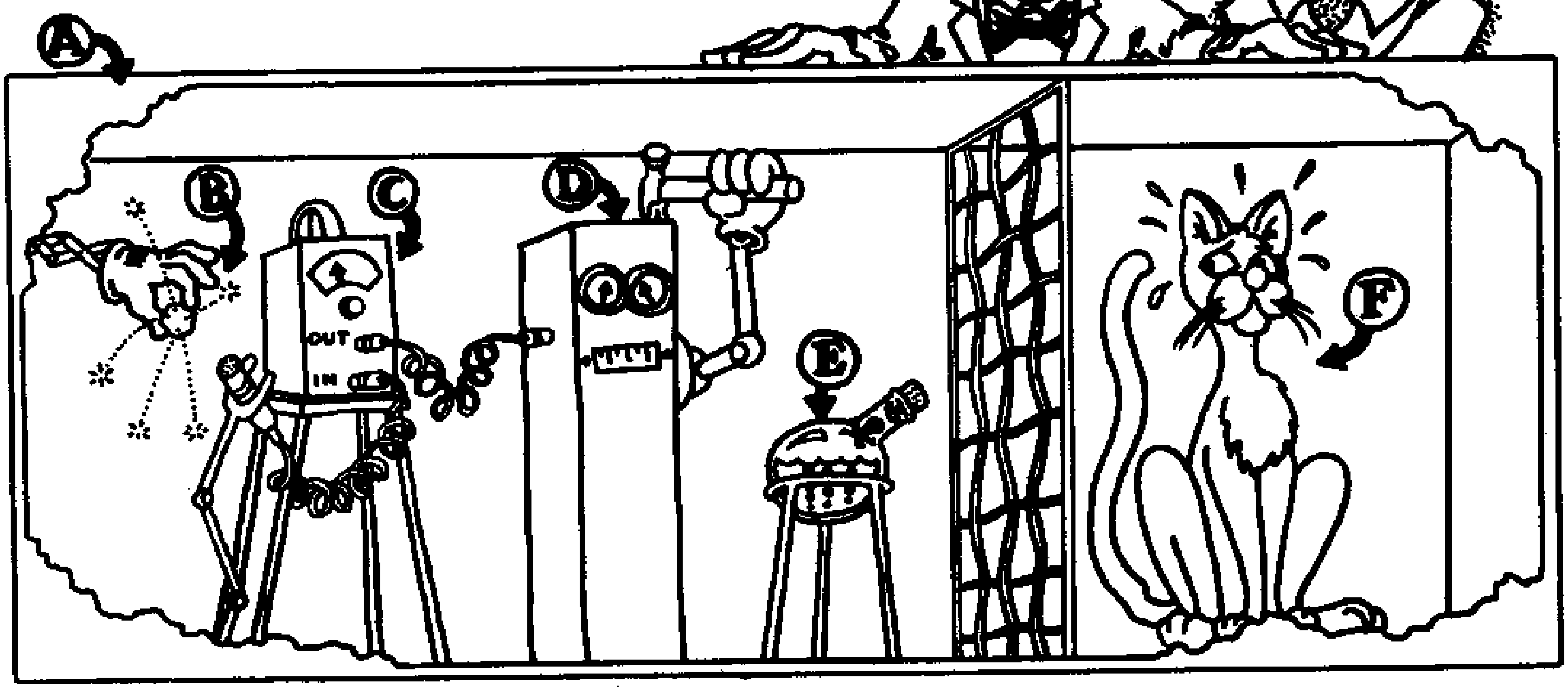


Quantum Kitty Review

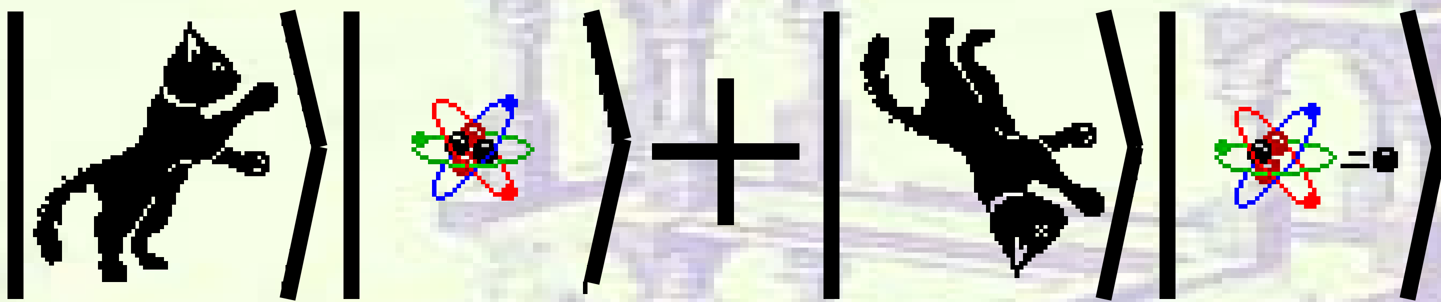
A sealed and insulated box (A) contains a radioactive source (B) which has a 50% chance during the course of the "experiment" of triggering Geiger counter (C) which activates a mechanism (D) causing a hammer to smash a flask of prussic acid (E) and killing the cat (F).

An observer (G) must open the box in order to collapse the state vector of the system into one of the two possible states. A second observer (H) may be needed to collapse the state vector of the larger system containing the first observer (G) and the apparatus (A-F). And so on ...





Paradox? What Paradox!?



(1.) The State of the Cat is "Entangled" with That of the Atom.

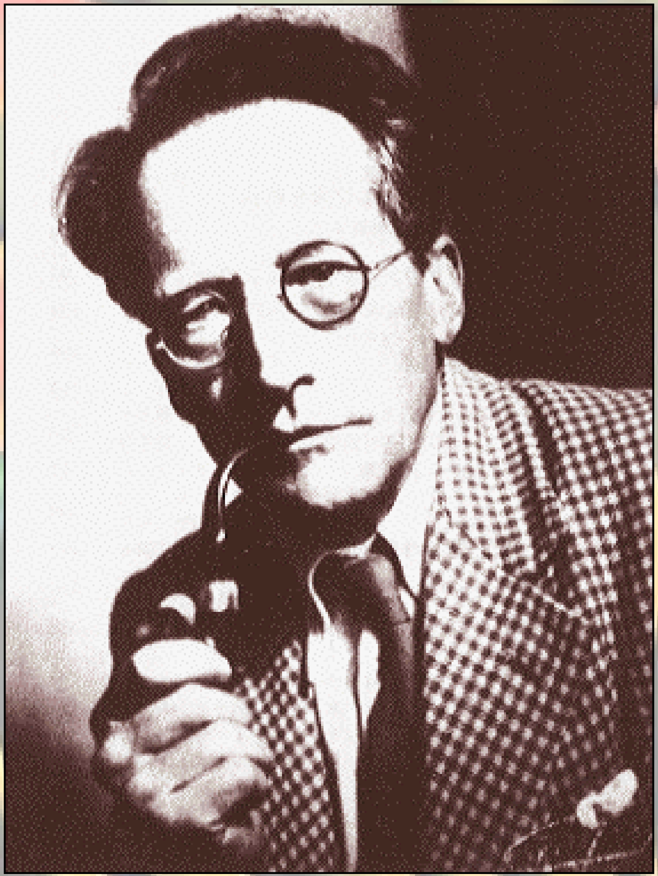
(2.) The Cat is in a Simultaneous Superposition of Dead & Alive.

(3.) Observers are Required to "Collapse" the Cat to Dead or Alive

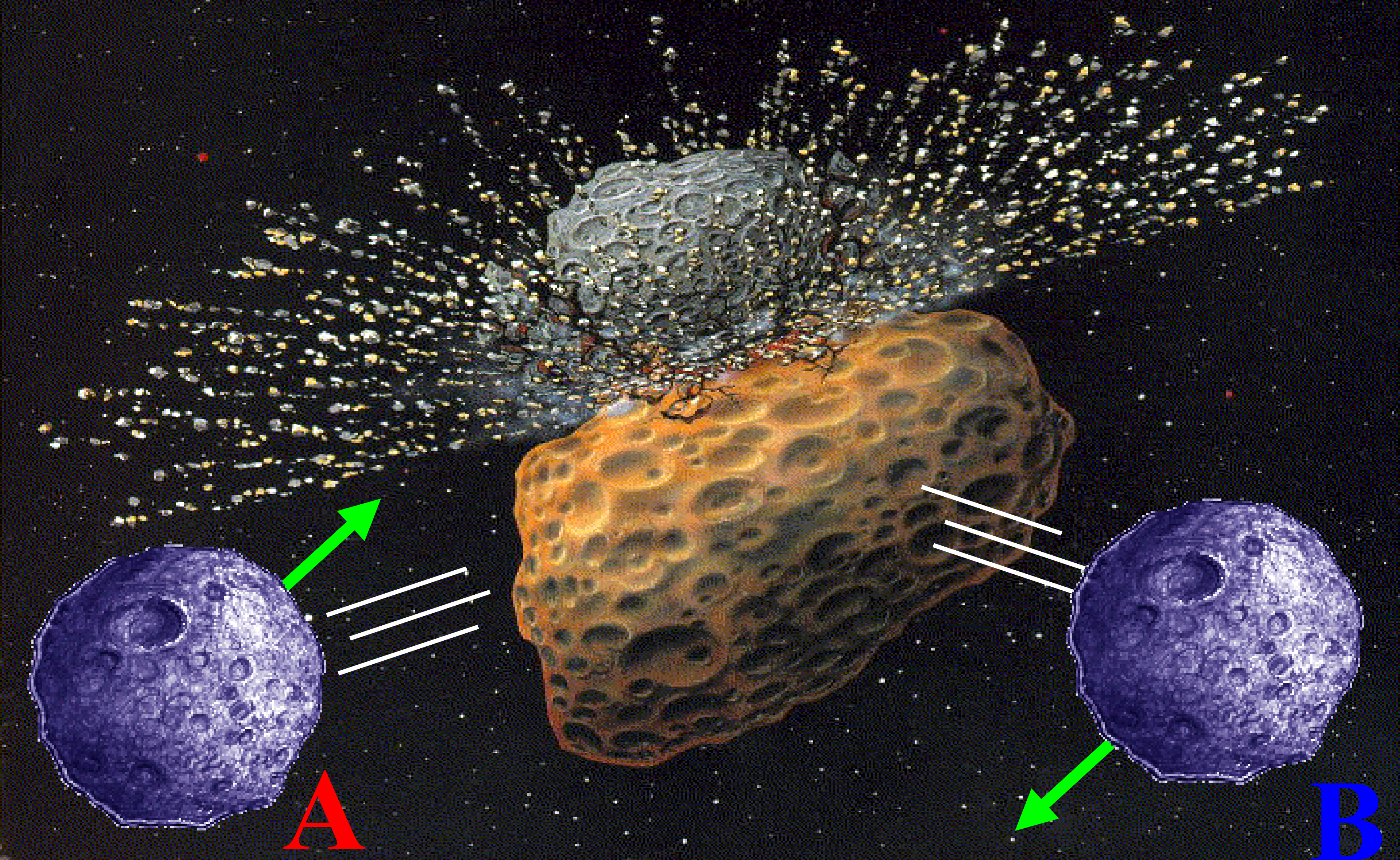
Quantum Entanglement

"Quantum entanglement is *the* characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought."

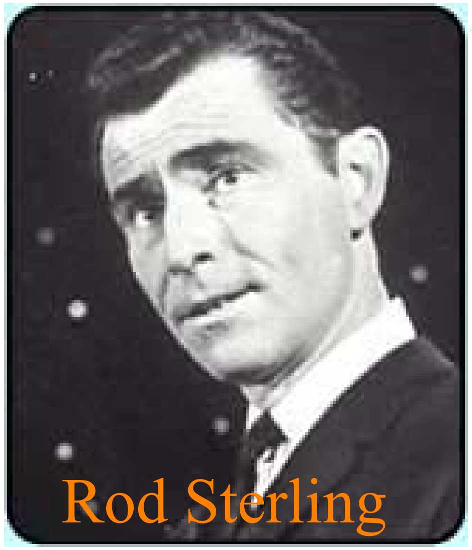
— Erwin Schrödinger

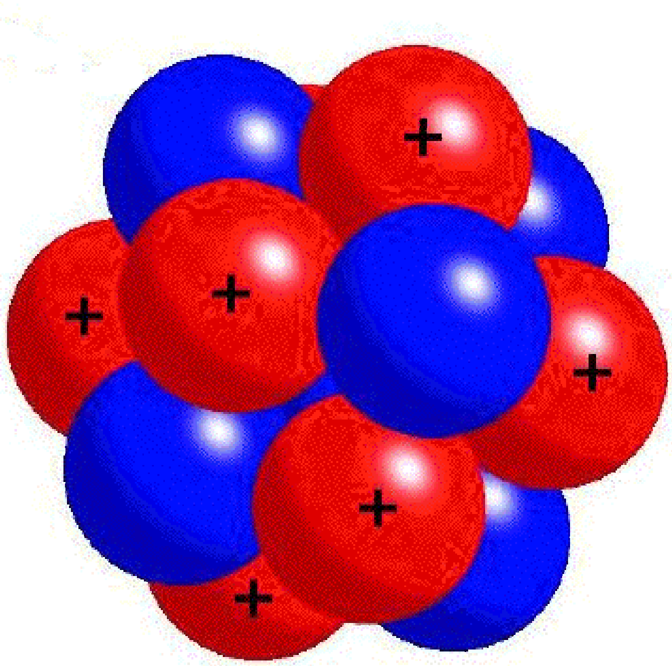


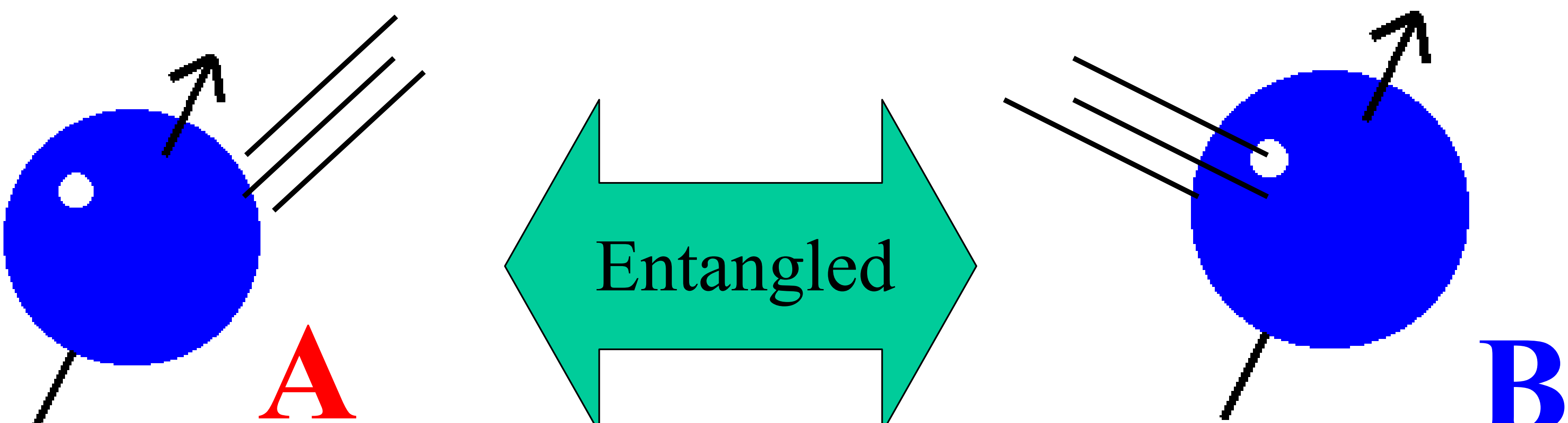
Conservation of Classical Angular Momentum



Conservation of Quantum Spin

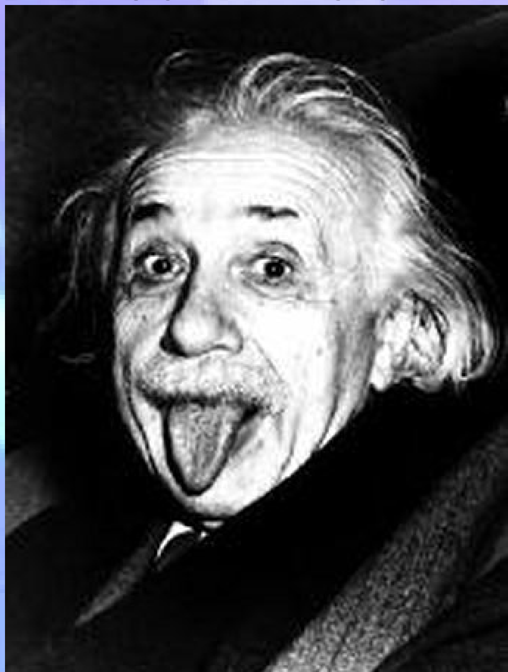




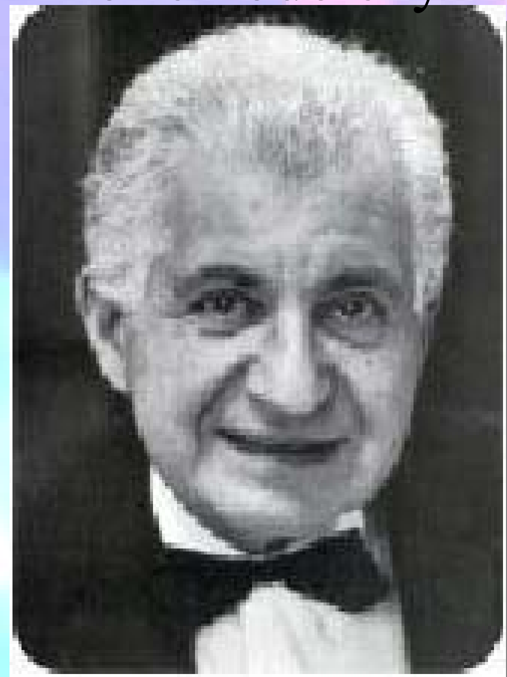


Einstein, Podolsky, Rosen (EPR) Paradox

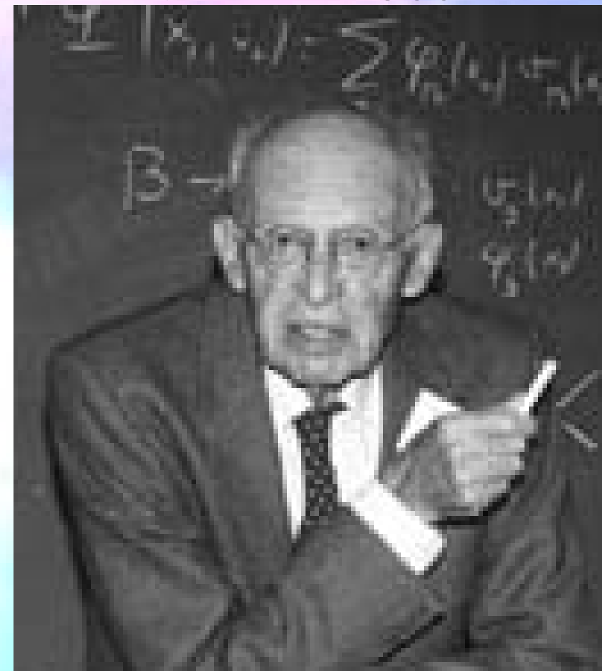
Albert Einstein



Boris Podolsky

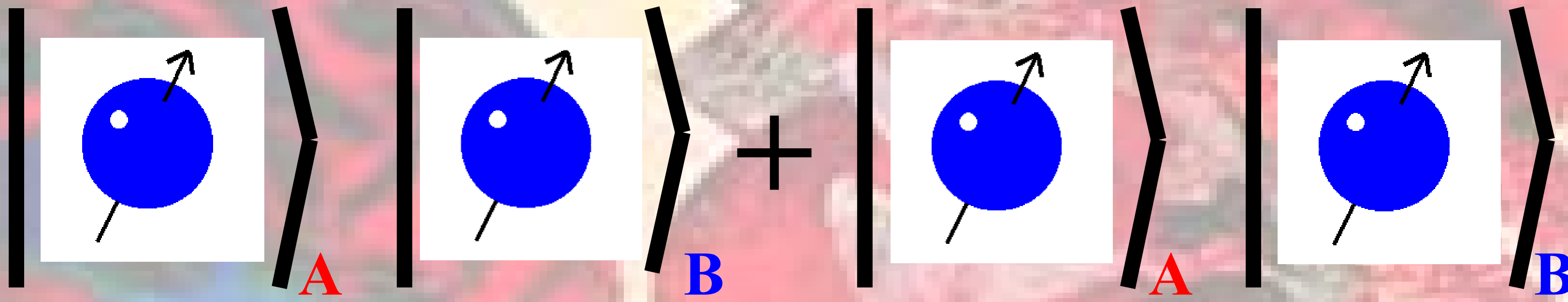


Nathan Rosen

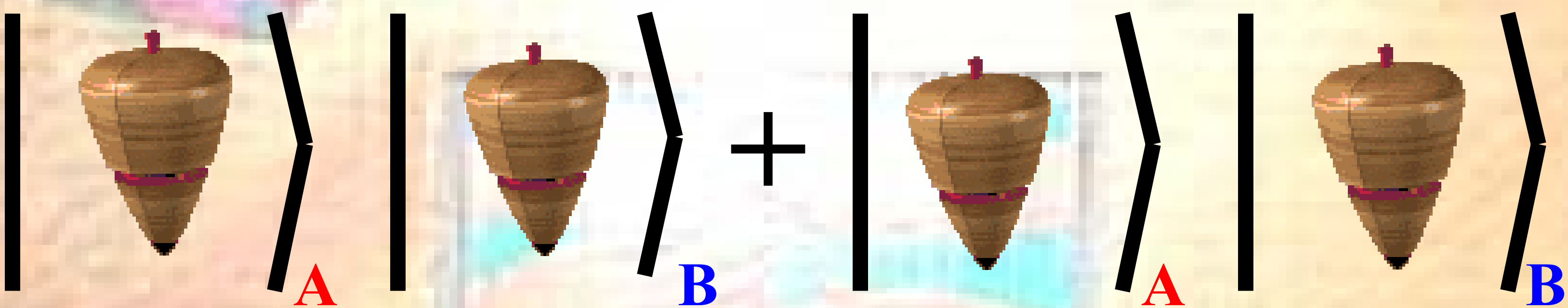


“If, without in any way disturbing a system, we can predict with certainty ... the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity."

Hidden Variable Theory



Can the Spooky, Action-at-a-distance Predictions (Entanglement) of Quantum Mechanics…



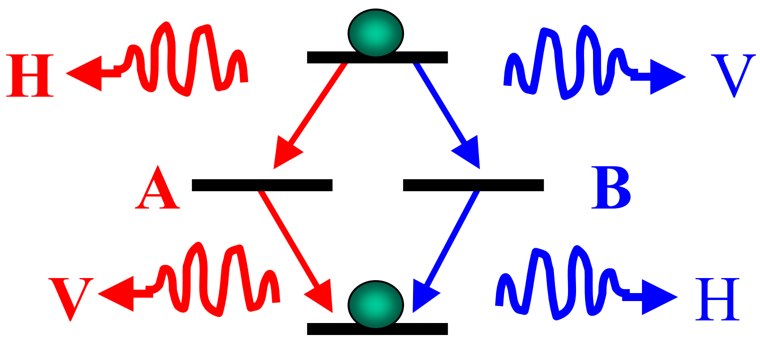
…Be Replaced by Some Sort of Local, Statistical, Classical (Hidden Variable) Theory?

NO!—Bell's Inequality

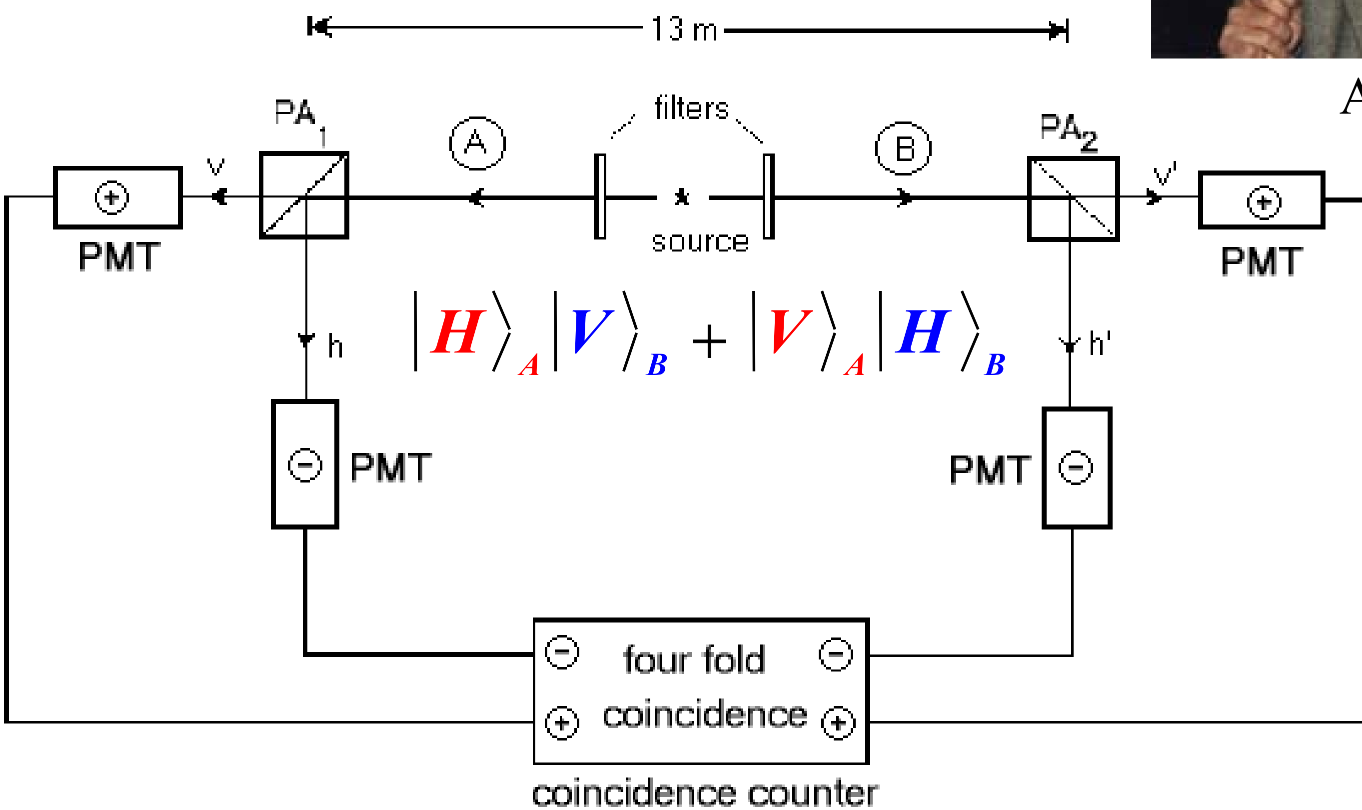
The physical predictions of quantum theory disagree with those of any local (classical) hidden-variable theory!

Clauser (1978) & Aspect (1982) Experiments

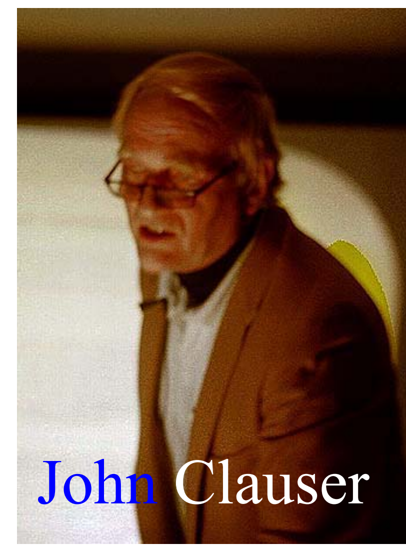
Two-Photon Atomic Decay



Alain Aspect



$$|H\rangle_A |V\rangle_B + |V\rangle_A |H\rangle_B$$



John Clauser

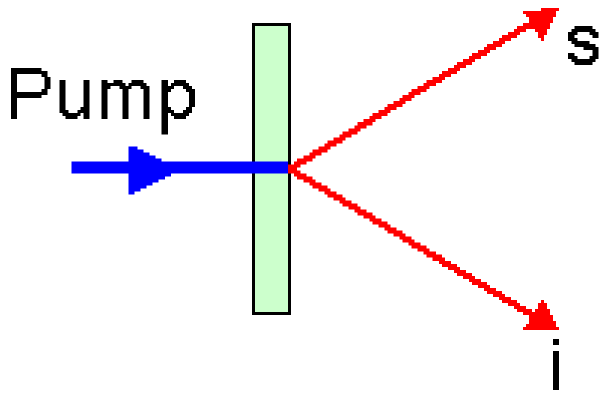
V= Vertical Polarization

H = Horizontal Polarization


Quantum Light—Over the Rainbow

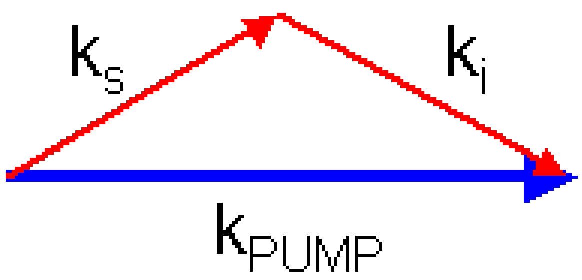
Parametric Downconversion: Type I

Downconversion

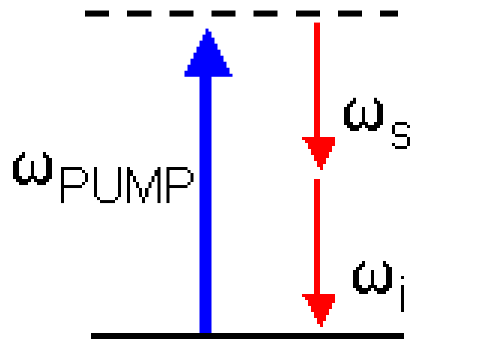


- A pump photon is spontaneously converted into two lower frequency photons in a material with a nonzero $\chi^{(2)}$

Momentum is conserved..

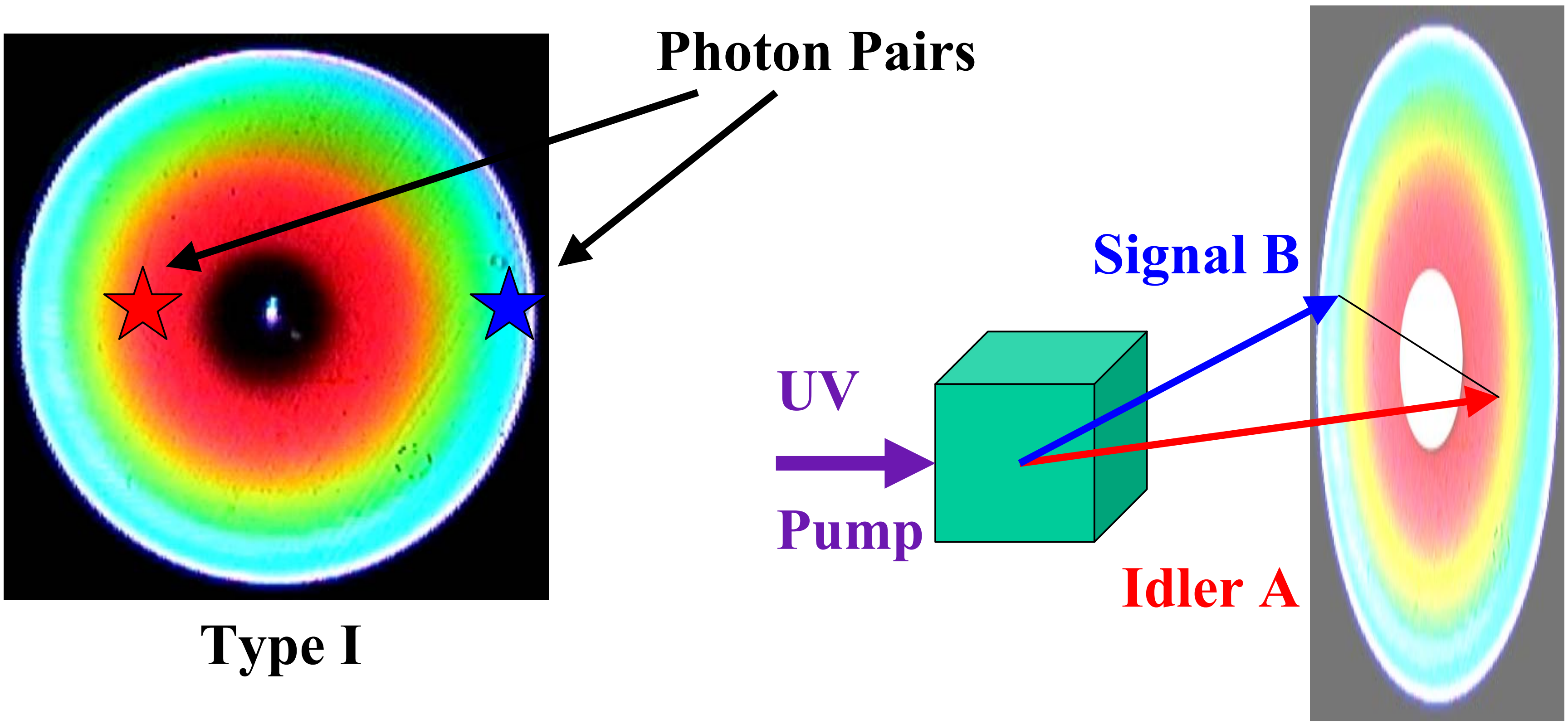


..as well as energy



$$\varphi_{PUMP} = \varphi_s + \varphi_i$$

Parametric Downconversion: Type I



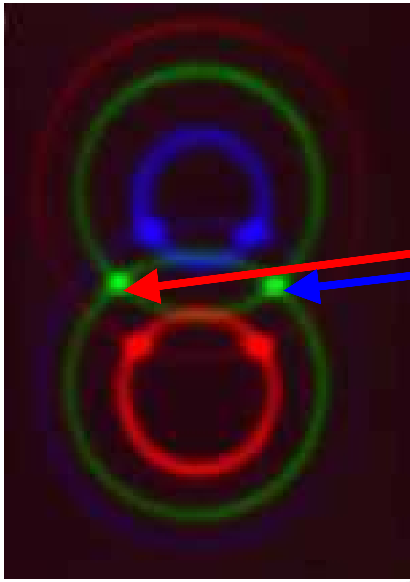
Degenerate (Entangled) Case: $\omega_s = \omega_i$

$$|\omega_s,\ \varphi_s,\ \mathbf{k}_s\rangle_A |\omega_i,\ \varphi_i,\ \mathbf{k}_s\rangle_B + |\omega_i,\ \varphi_i,\ \mathbf{k}_i\rangle_A |\omega_s,\ \varphi_s,\ \mathbf{k}_s\rangle_B$$

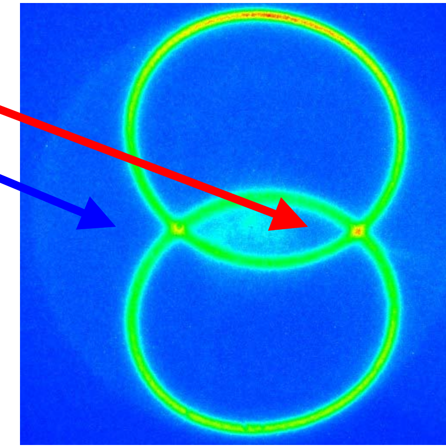
Parametric Downconversion: Type I

QuickTime™ and a Sorenson Video decompressor are needed to see this picture.

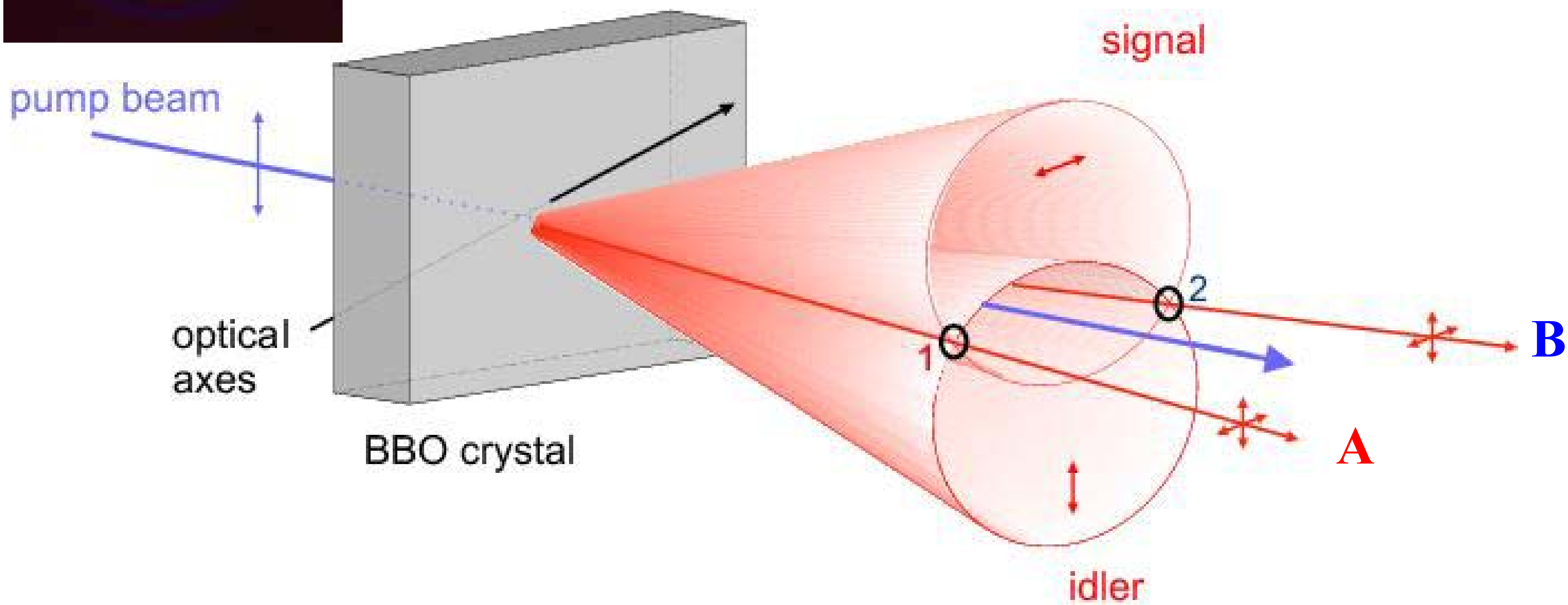
Parametric Downconversion: Type II



Degenerate (Entangled) Case: $\omega_s = \omega_i$



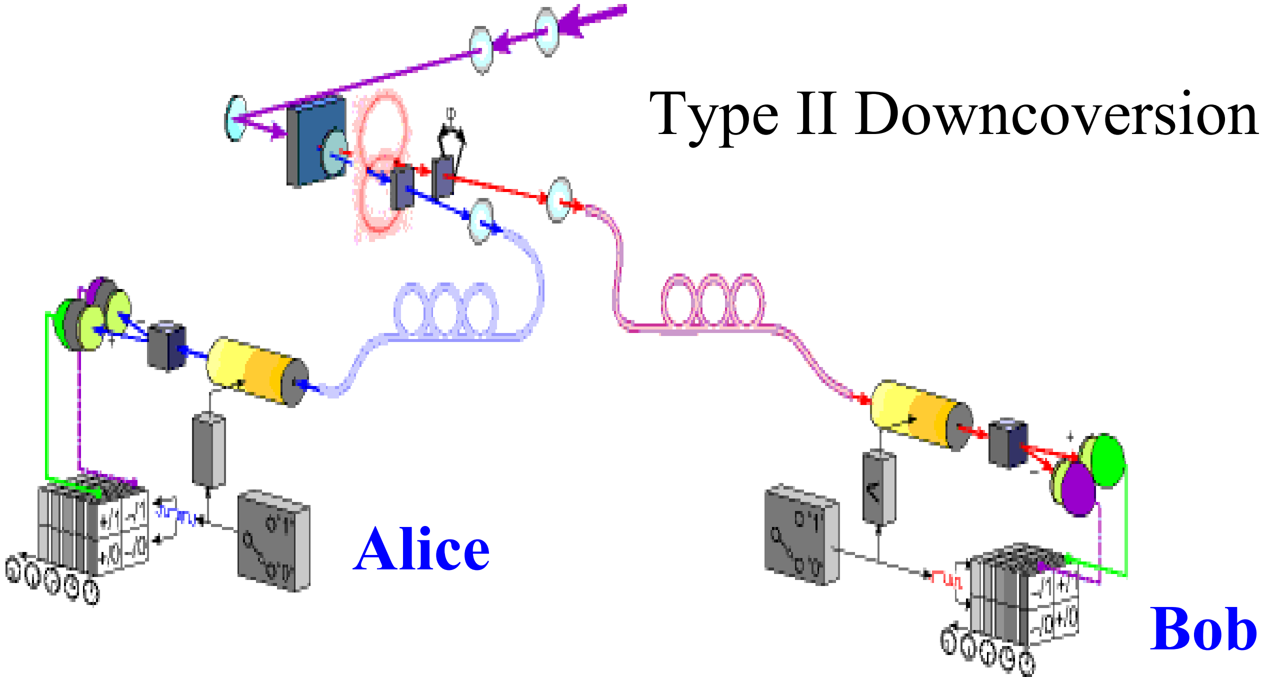
$$\left|H\right\rangle_A \left|V\right\rangle_B + \left|V\right\rangle_A \left|H\right\rangle_B$$

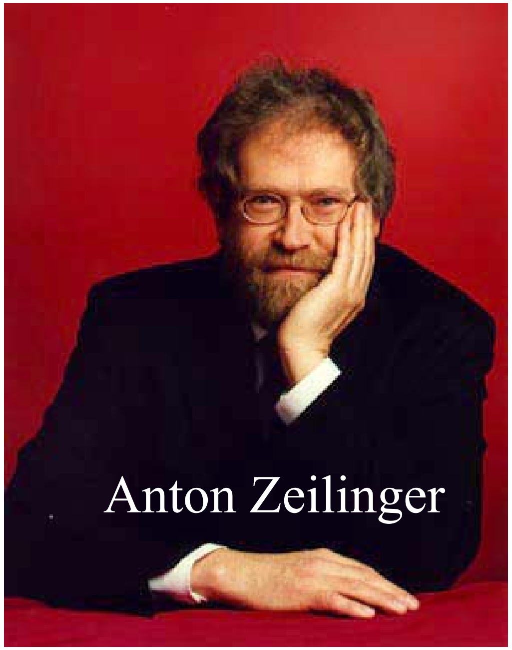


QuickTime™ and a Animation decompressor are needed to see this picture.

Putting Entangled Light to Work

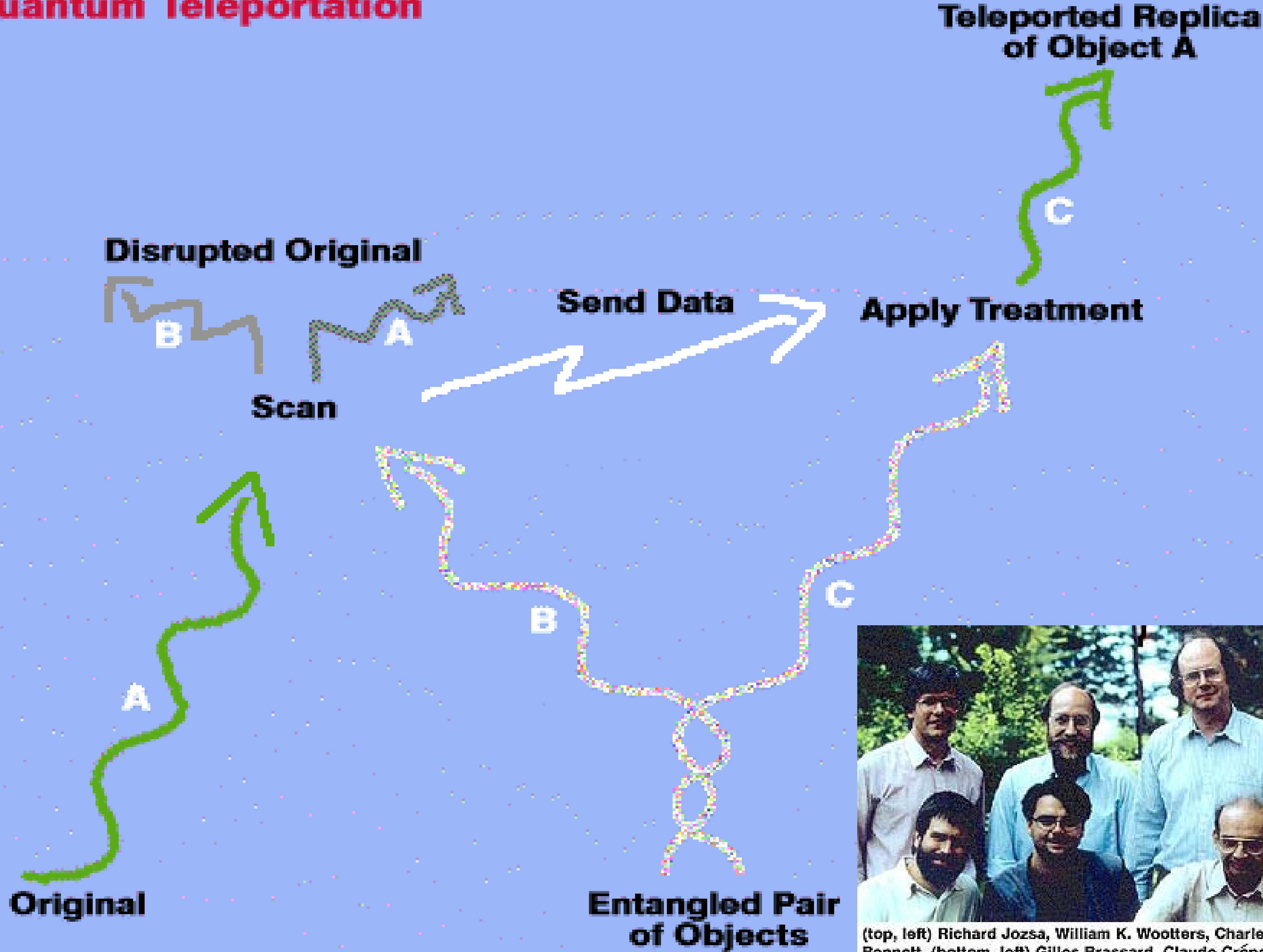
Tests of Bell's Inequalities at Innsbruck





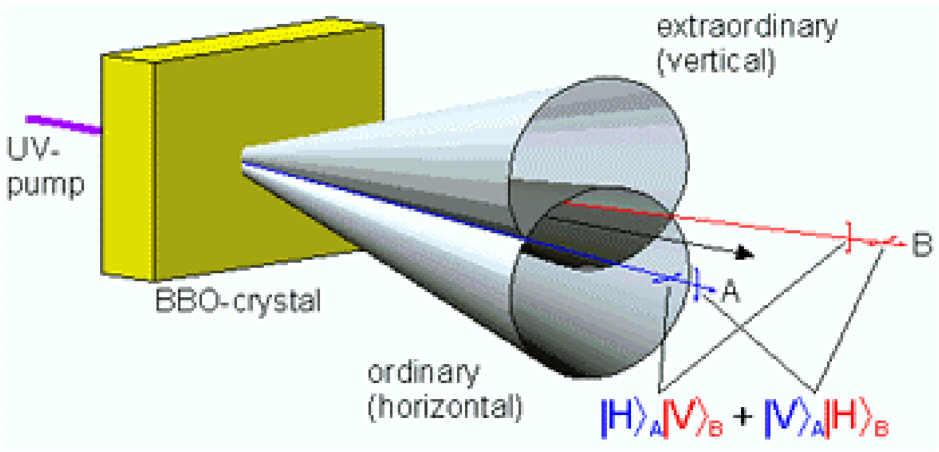
Quantum Teleportation

Quantum Teleportation

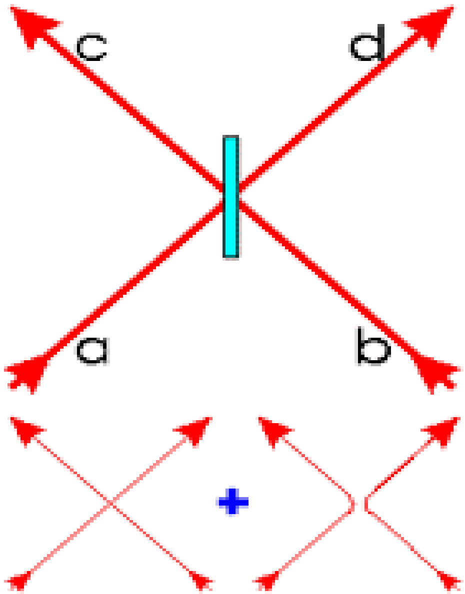


(top, left) Richard Jozsa, William K. Wootters, Charles H. Bennett. (bottom, left) Gilles Brassard, Claude Crépeau, Asher Peres. Photo: André Berthiaume.

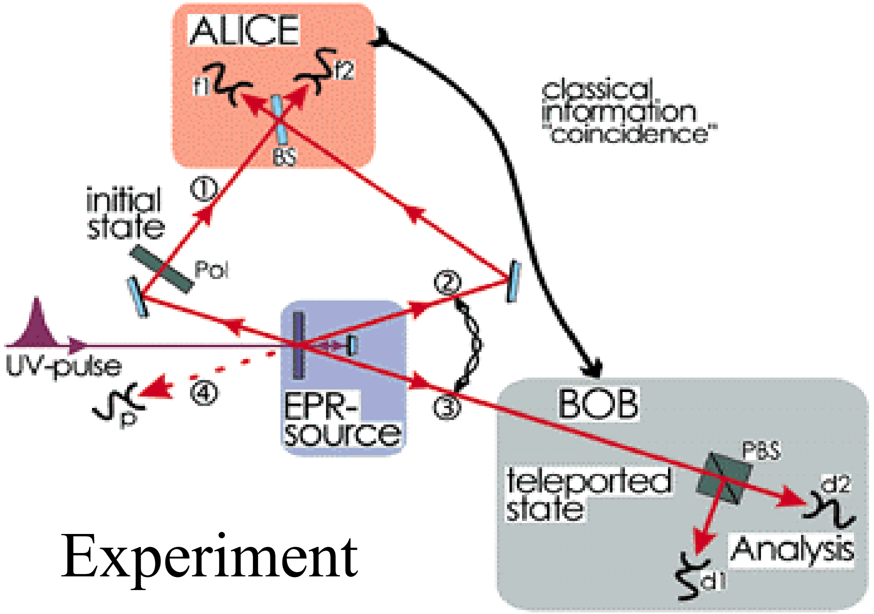
Teleportation Experiment at Innsbruck



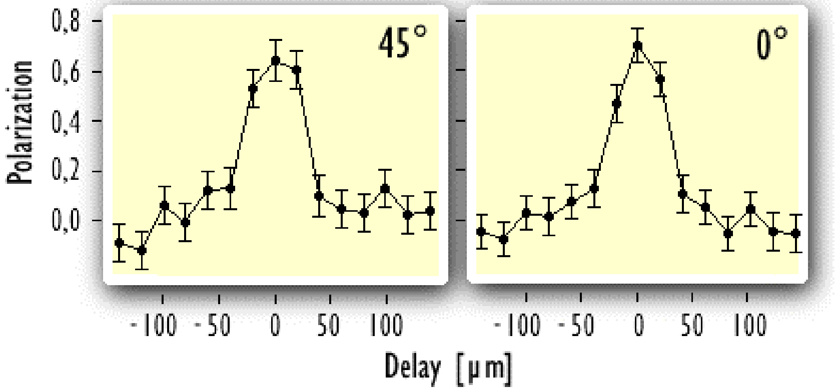
EPR Source



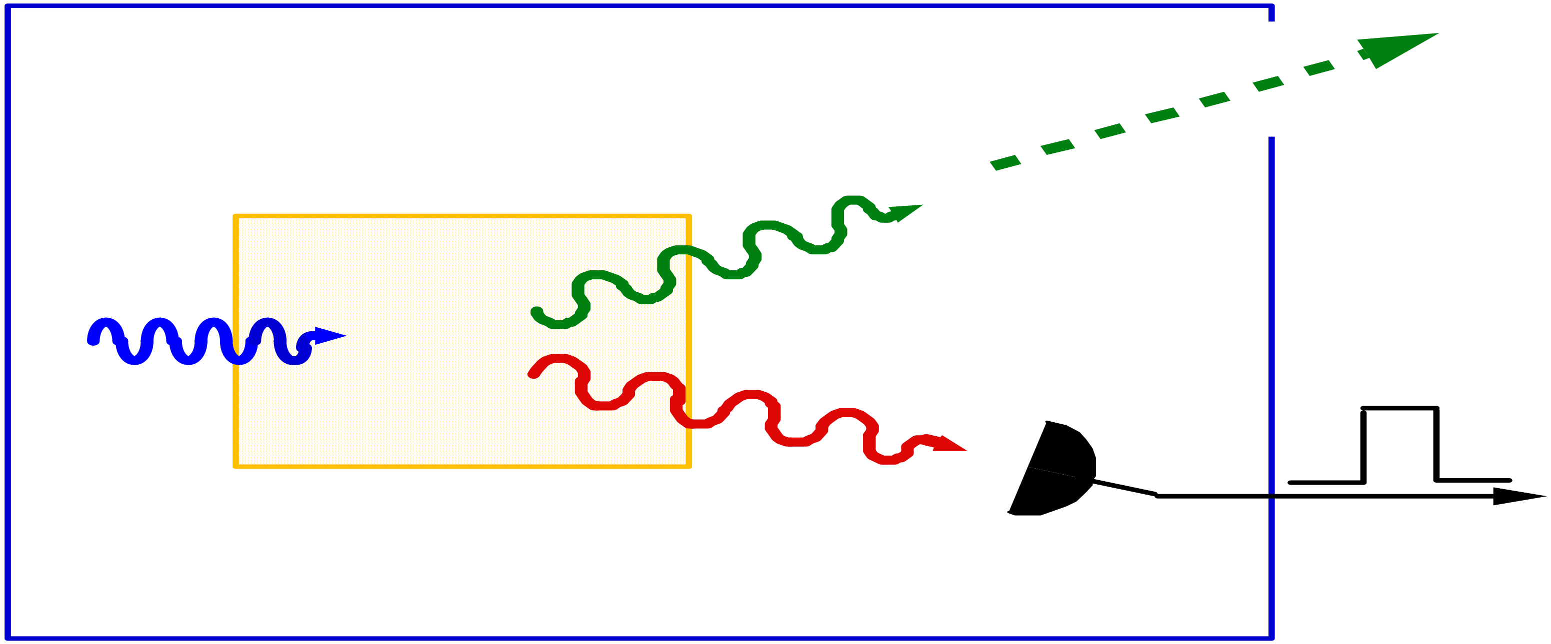
Bell State Analysis



Experiment



NIST Heralded Photon Absolute Light Source

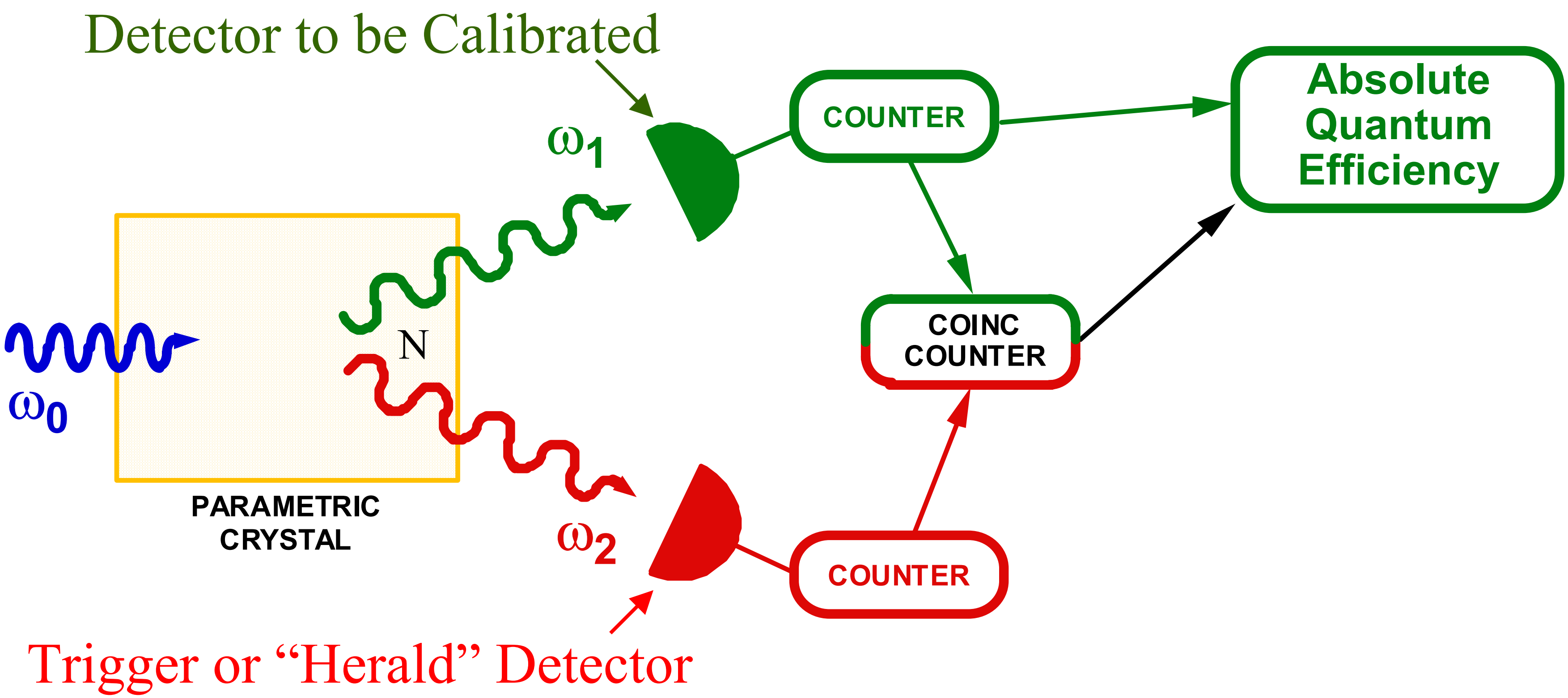


Output characteristics :

photon #	➔	known
photon timing	➔	known
wavelength	➔	known
direction	➔	known
polarization	➔	known

Alan Migdall

Detector Quantum Efficiency Scheme

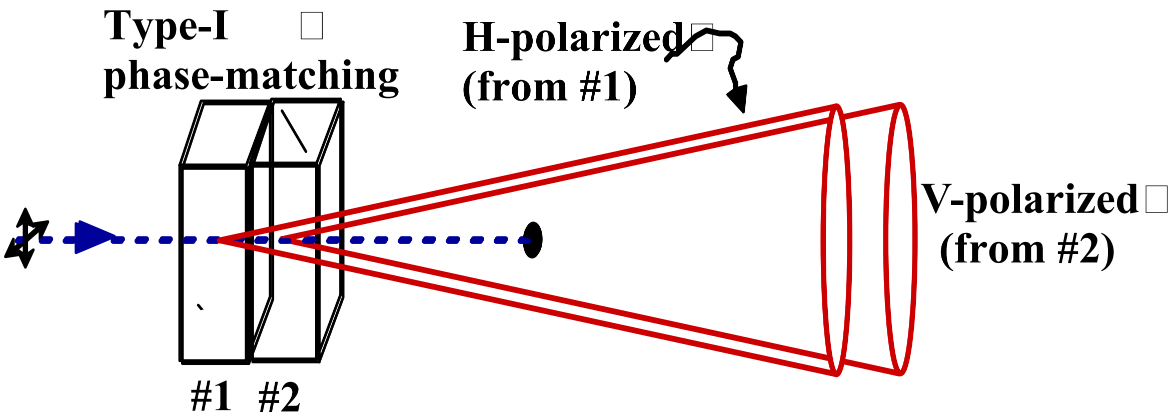


$N_1 = \eta_1 N$ $\quad N_2 = \eta_2 N$ $\quad N_C = \eta_1 \eta_2 N$

$$\eta_1 = N_C / N_2$$

No External Standards Needed!

Characterizing Two-Photon Entanglement

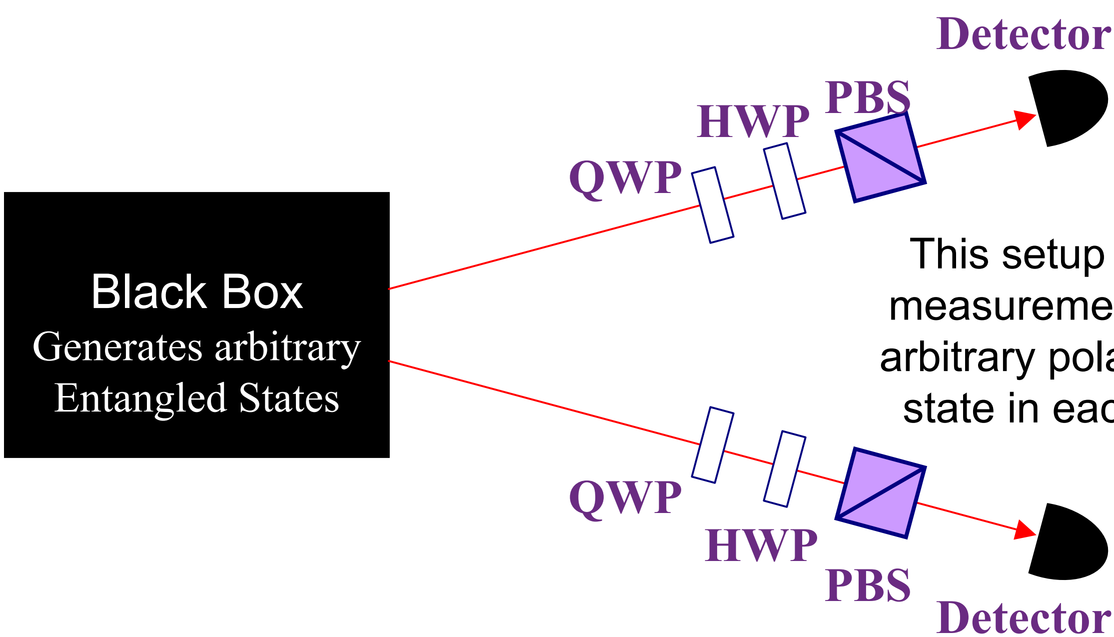


Kwiat Super-Bright Source

Any two-photon tomography requires 16 of these measurements.

Examples

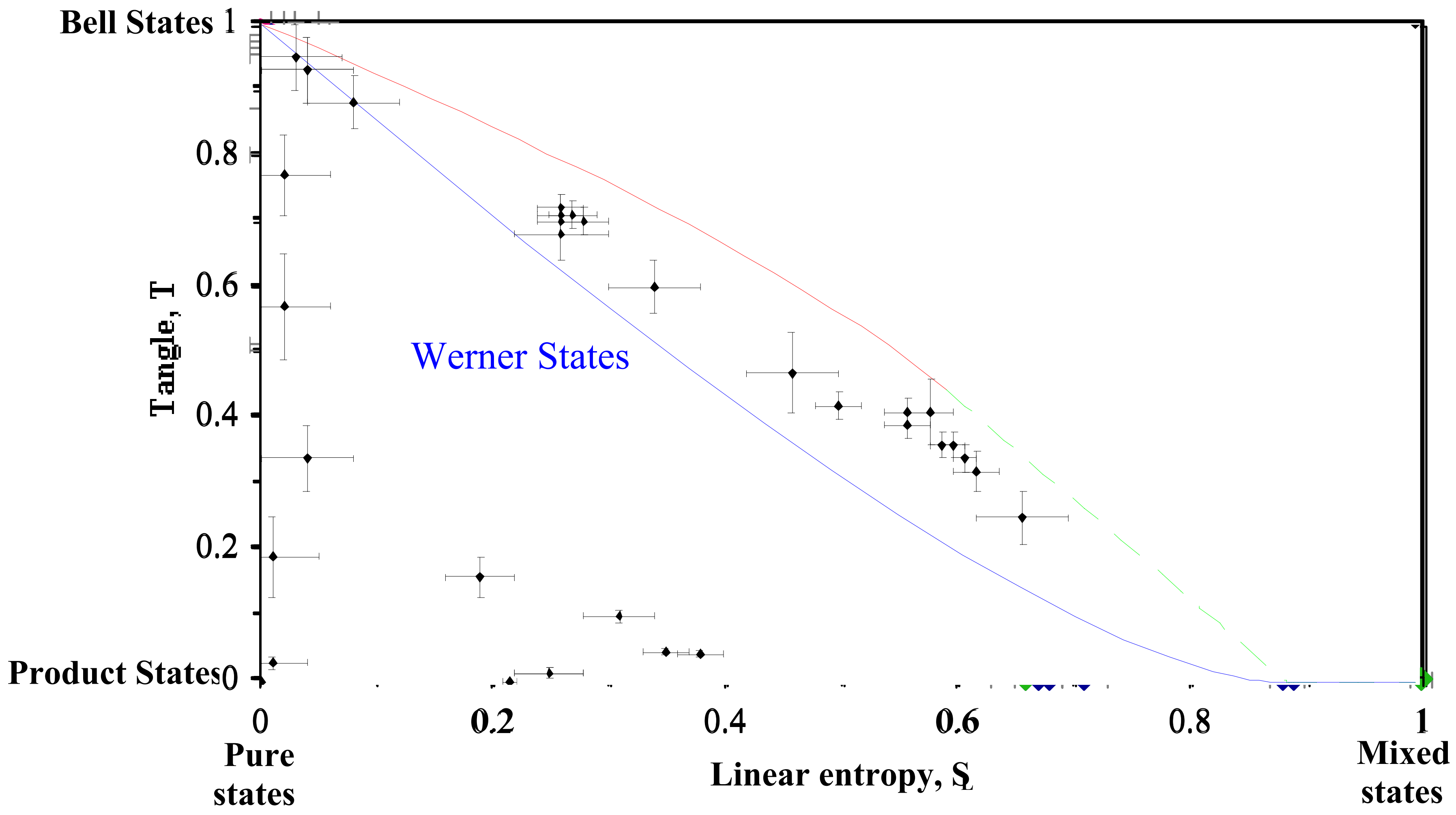
Arm 1	Arm 2
H	V
H	R
D	D



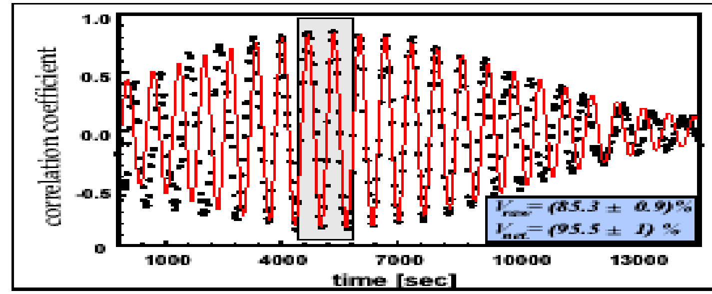
This setup allows measurement of an arbitrary polarization state in each arm.

Paul Kwiat
U. Illinois

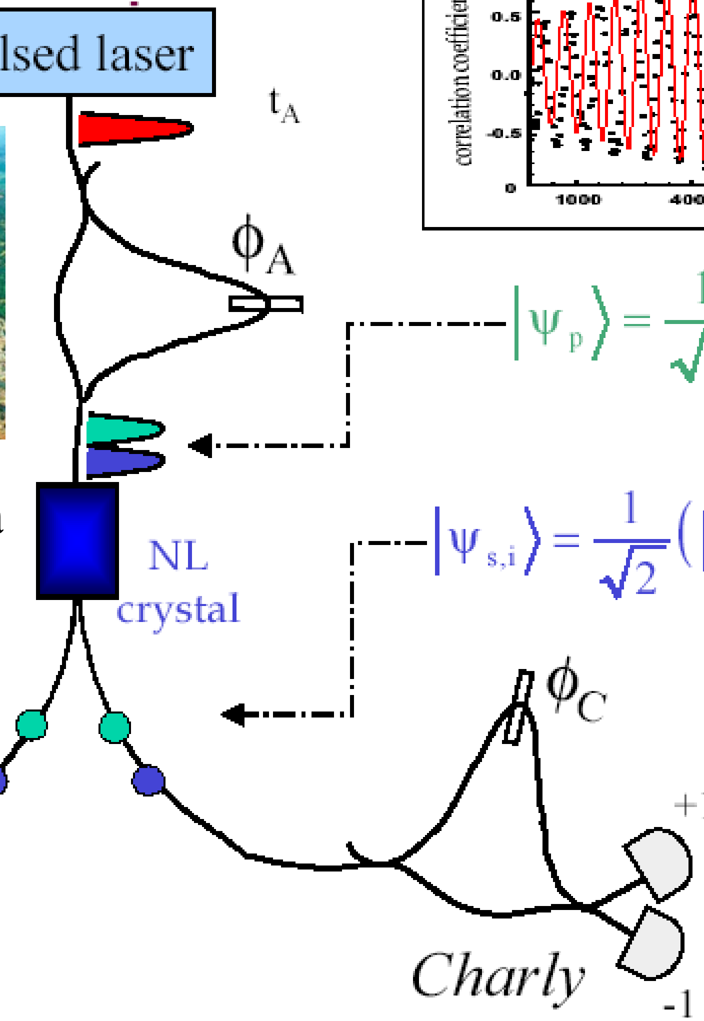
Characterization of Entangled States



Quantum Cryptography at University of Geneva



System Under Lake Geneva



$$|\psi_p\rangle = \frac{1}{\sqrt{2}}\left(|s\rangle_p + e^{i\phi}|l\rangle_p\right)$$

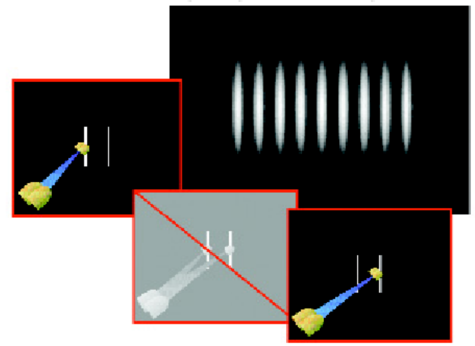
$$|\psi_{s,i}\rangle = \frac{1}{\sqrt{2}}\left(|s\rangle_s|s\rangle_i + e^{i\phi}|l\rangle_s|l\rangle_i\right)$$

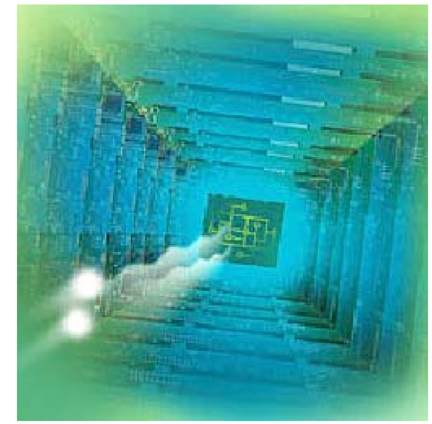
Bob and "Charly" Share Random Crypto Key

Nicolas Gisin

Quantum Interferometric Optical Lithography: Exploiting Entanglement to Beat the Diffraction Limit

Agedi N. Boto,[1] Pieter Kok,[2] Daniel S. Abrams,[1] Samuel L. Braunstein,[2]
Colin P. Williams,[1] and Jonathan P. Dowling[1,*]





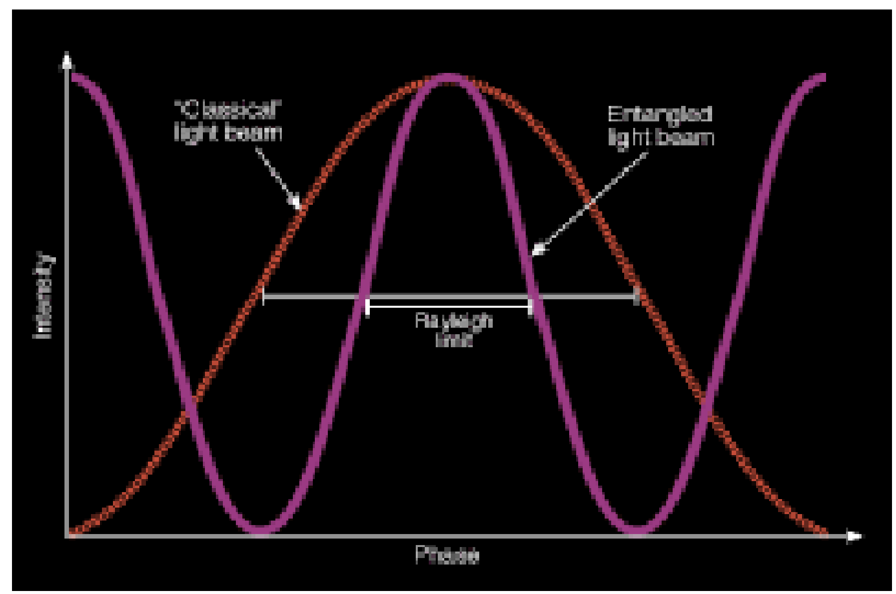
WHAT'S NEXT *New York Times*

Quantum Leap May Transform Chips

By IAN AUSTEN

physics : Fine lines

PHILIP BALL nature

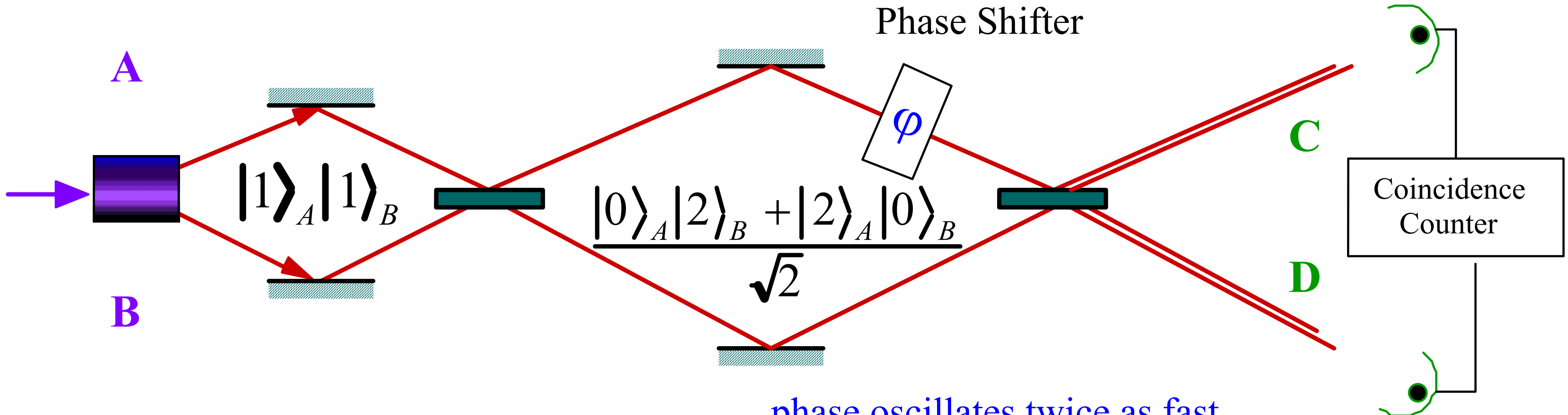


Science

Yoked Photons Break a Light Barrier

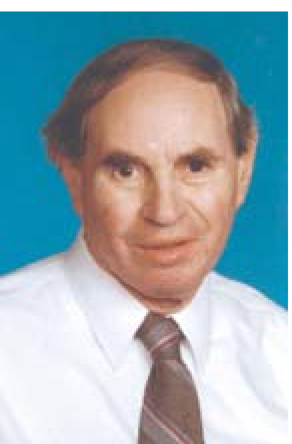
The Hong-Ou-Mandel Effect

Parametric Downcoversion



phase oscillates twice as fast

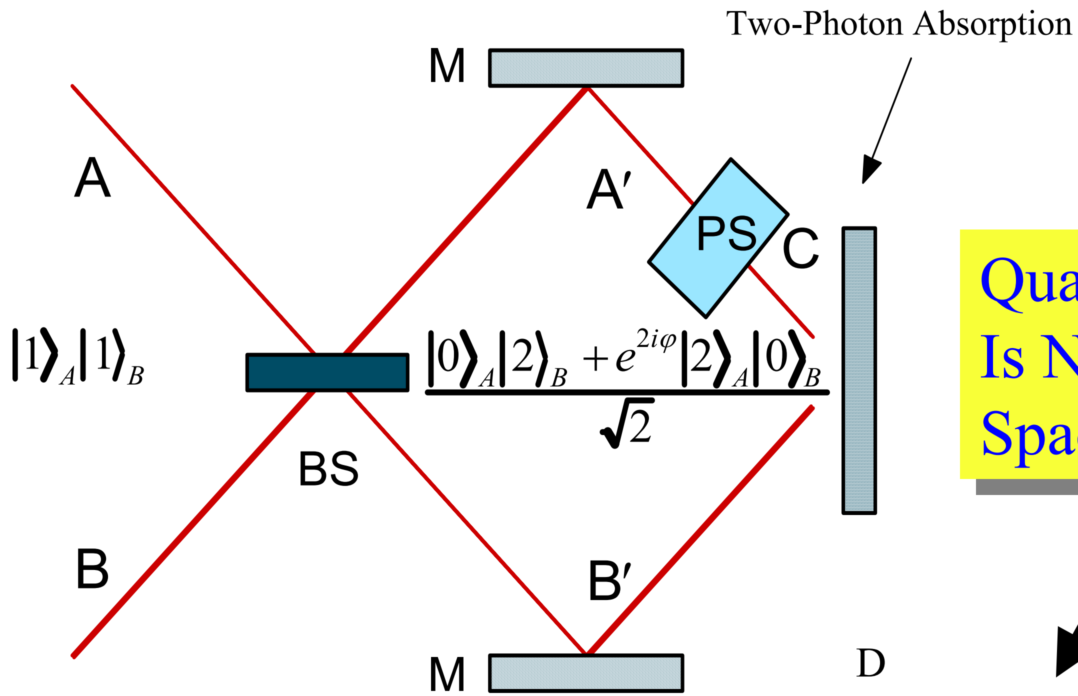
$$\frac{|0\rangle_A|2\rangle_B+|2\rangle_A|0\rangle_B}{\sqrt{2}} \rightarrow \frac{|0\rangle_A|2\rangle_B+e^{2i\varphi}|2\rangle_A|0\rangle_B}{\sqrt{2}}$$



Leonard Mandel

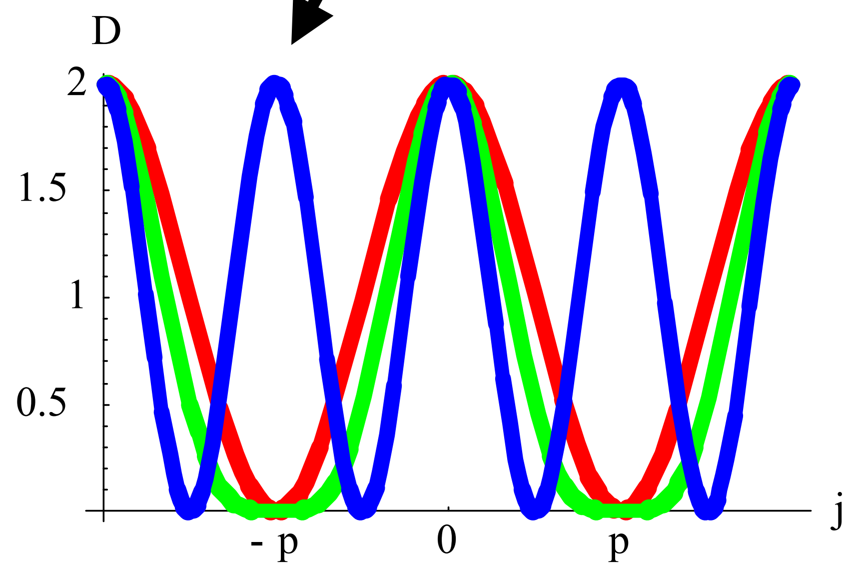
JPL

Quantum Optical Lithography



Quantum Peak
Is Narrower and
Spacing is HALVED!

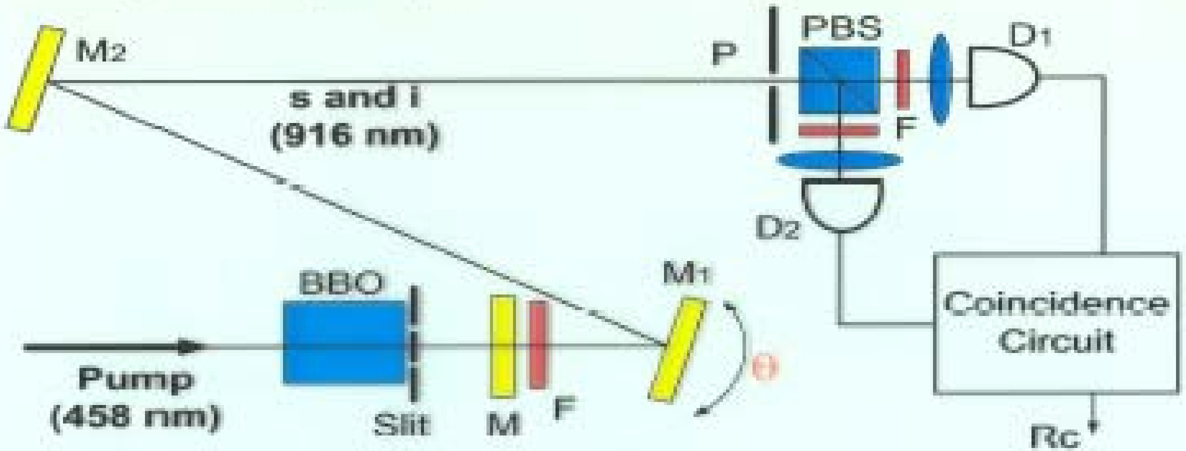
Parametric Downcoversion



Classical One-Photon Absorption —
Classical Two-Photon Absorption —
Quantum Two-Photon Absorption —

Quantum lithography: setup

- **Milena D'Angelo, Maria V. Chekhova, and Yanhua Shih, PRL 87, 013602 (2001)**



Two-photon source: Degenerate Collinear type-II SPDC

✓Double-slit VERY close to the crystal ⇒ $\Delta\phi << b/D$

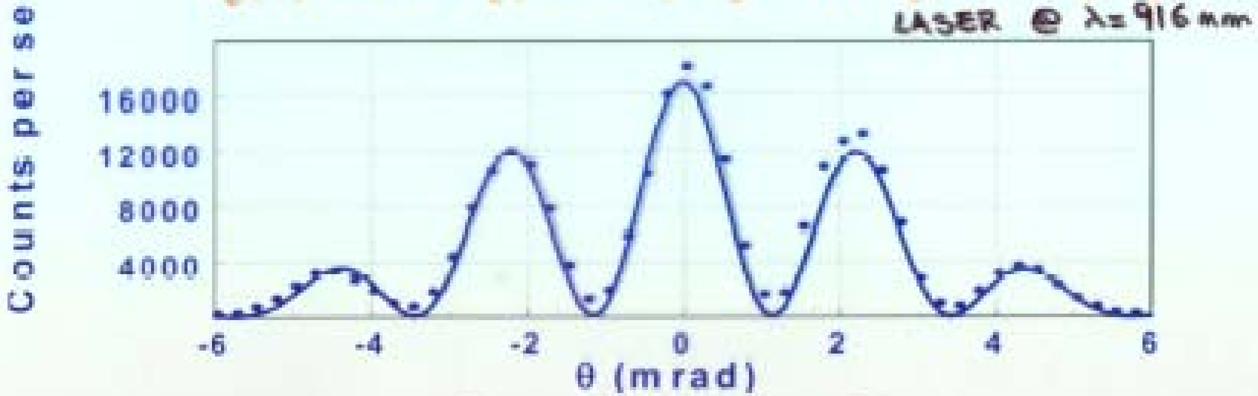
$$\rightarrow |\psi\rangle = \varepsilon(a_s^\dagger a_i^\dagger + b_s^\dagger b_i^\dagger)|0\rangle$$

$\Delta\phi$=scattering angle inside the crystal; b=distance between slits; D=distance between input face of crystal and double slit

University of Maryland Experiment

Results

$$R_c(\theta) = \mathrm{sinc}^2[(2\pi a/\lambda)\,\theta] \times \cos^2[(2\pi b/\lambda)\,\theta]$$

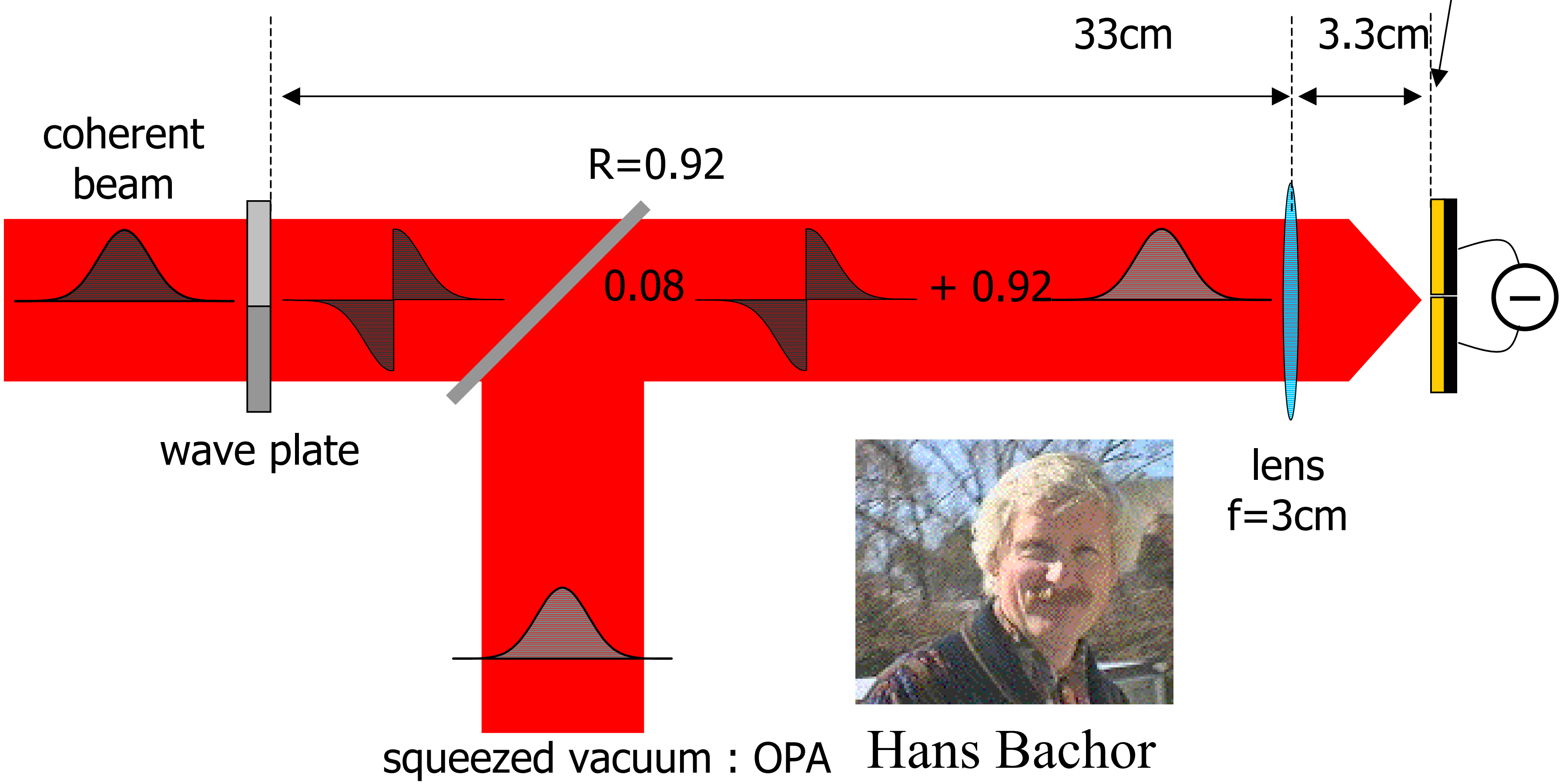


$$I(\theta) = \mathrm{sinc}^2[(\pi a/\lambda)\,\theta] \times \cos^2[(\pi b/\lambda)\,\theta]$$

Yanhua Shih

$$\Delta x_{classical} = \lambda, \quad \Delta x_{shotnoise} = \frac{\lambda}{\sqrt{N}}, \quad \Delta x_{Heisenberg} = \frac{\lambda}{N}$$

Image of the wave plate plane with waist=300μm

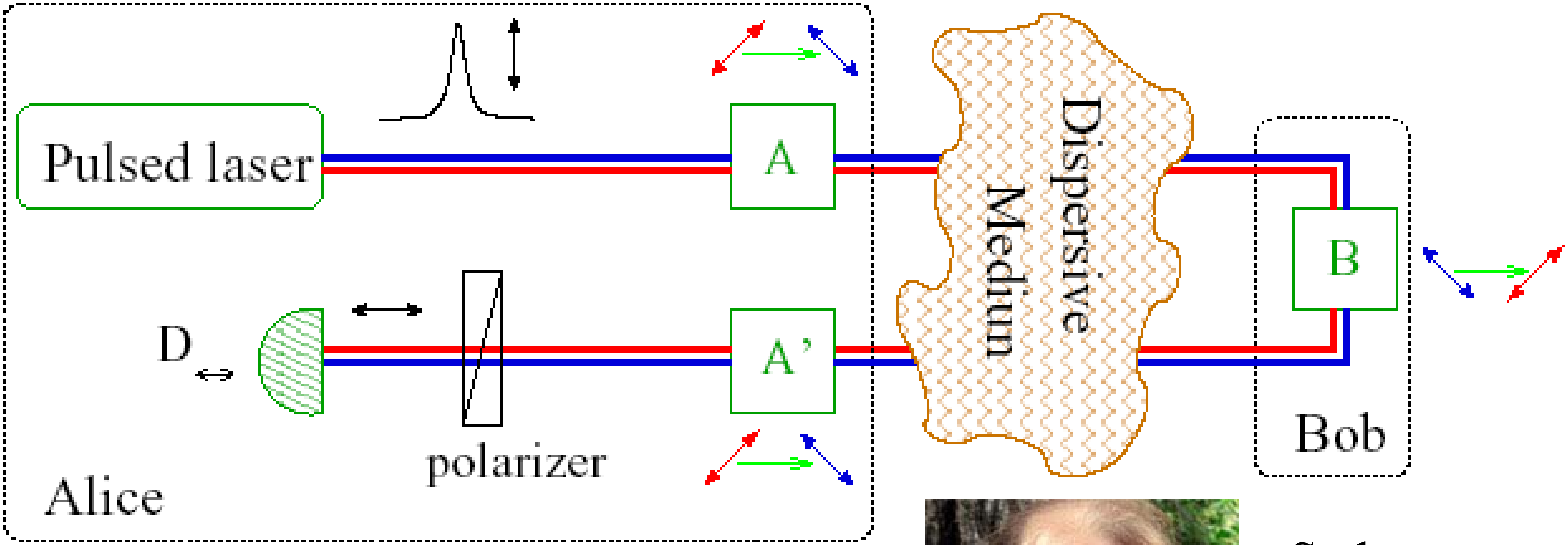


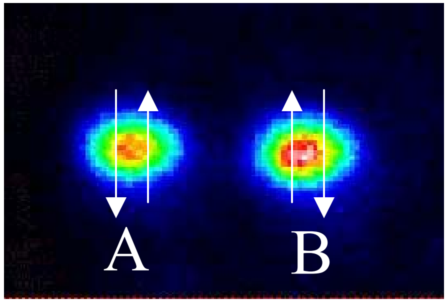
Hans Bachor

Australian National University

Quantum Clock Synchronization

Entangled Photons Can Synchronize Past the Turbulent Atmosphere!

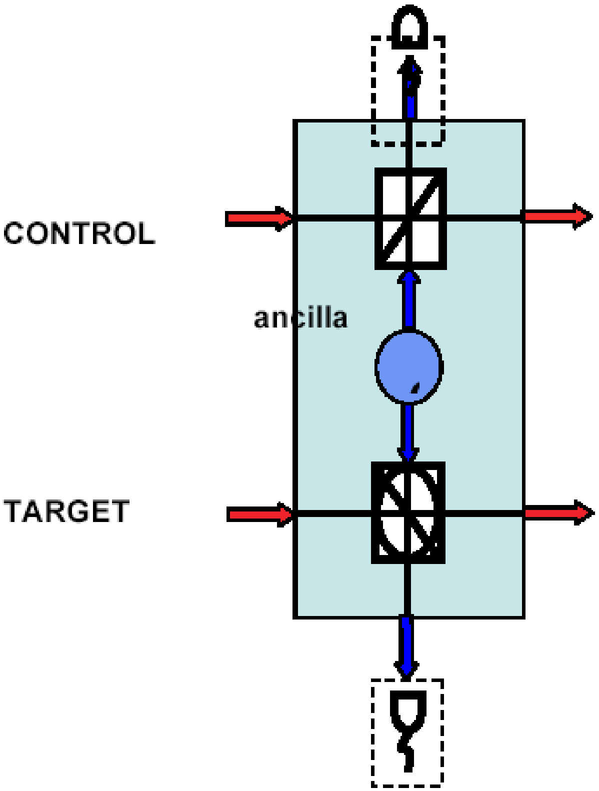




Seth
Lloyd
MIT

Quantum Computing

Entangled Photons are a Resource for Scalable Quantum Computation!



E. Knill, R. Laflamme and G. Milburn, Nature 409, 46, (2001)

Quantum Controlled-NOT Gate using and Entangled-Light Source, Beam Splitters, and Detectors.

Gerard Milburn
University Of Queensland

JPL Quantum Optical Internet Testbed

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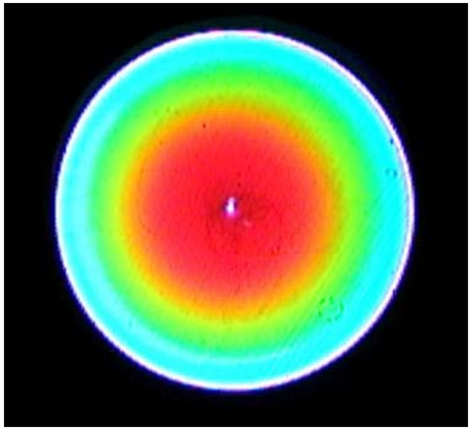
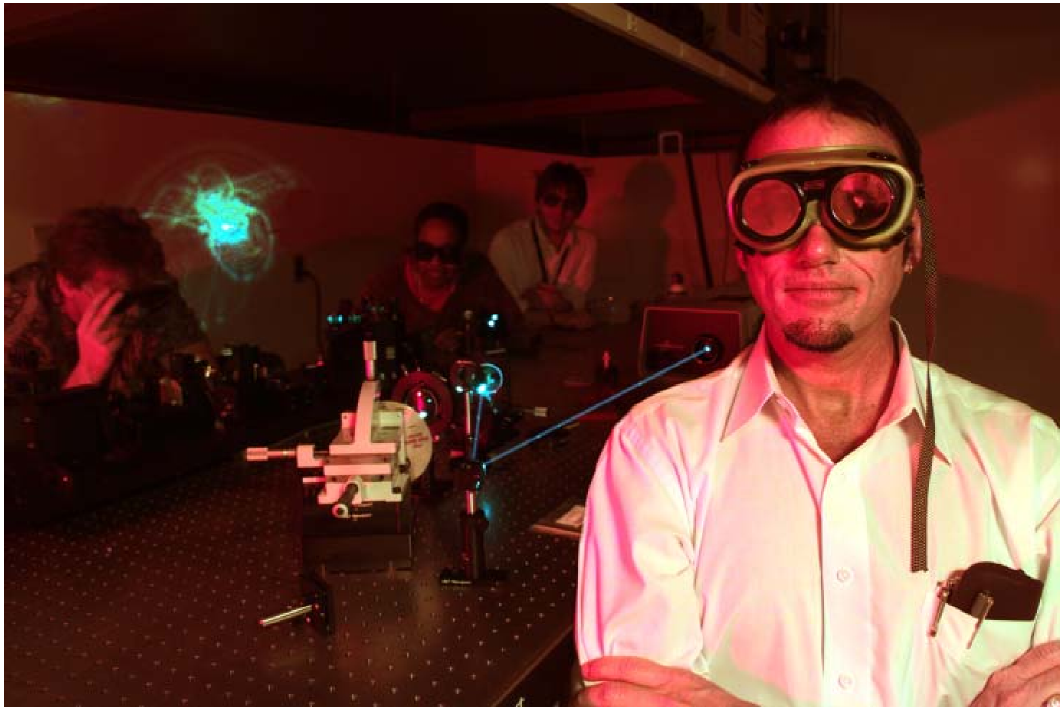
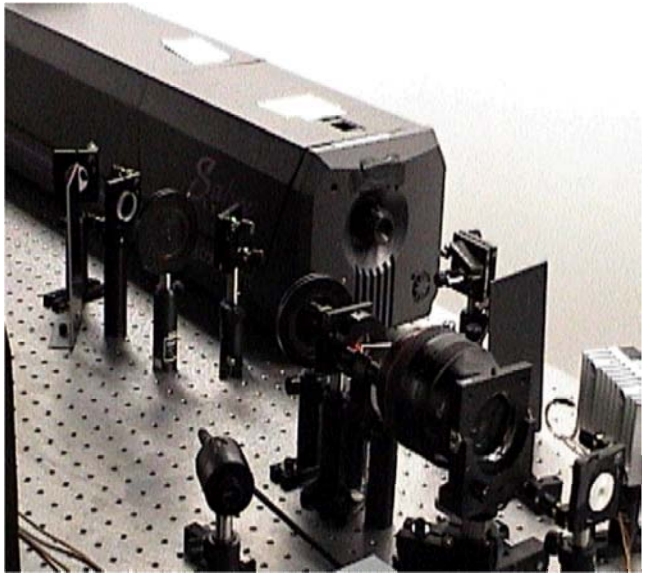
- **QCT Group Quantum Optics Lab**
- **Single Photon Sources and Calibration**
- **Optical Imaging, Computing, and SATCOM**



Entangled Photons





JPL Single Photon Detector Foundry

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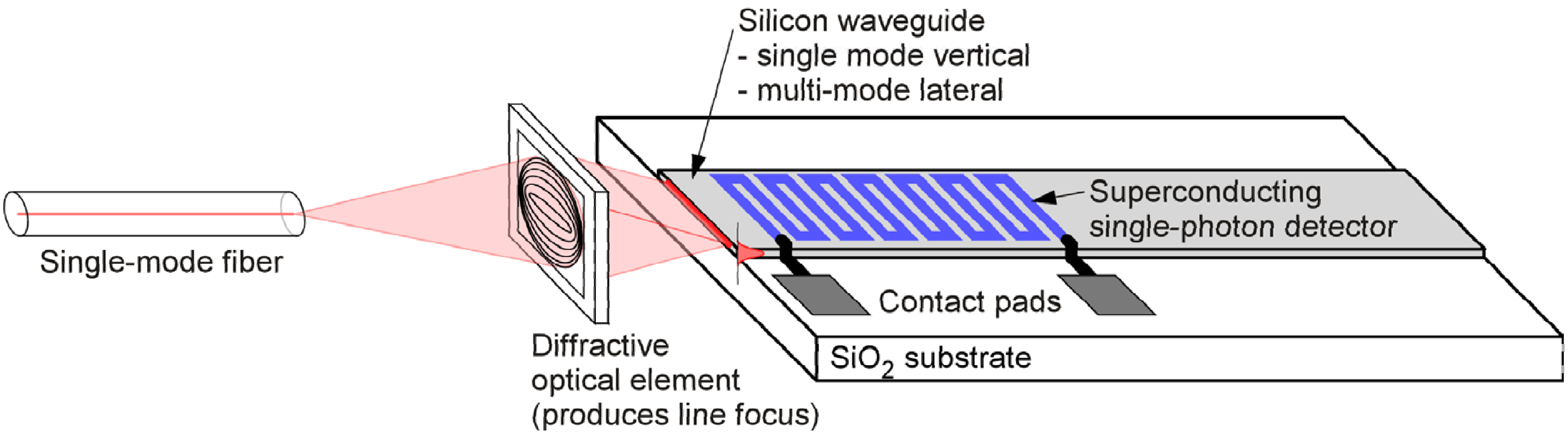

- **We propose to develop a US Government single photon detector foundry at the Jet Propulsion Laboratory.**

- **This facility will provide a vertically integrated, completely in-house capability to develop, design, fabricate, test, and optically characterize ultra-fast, thin-film, superconducting, single-photon detectors.**

- **These detectors are targeted for use in wide-bandwidth, optical, quantum key distribution (QKD) for the DoD, as well as US intelligence, commercial, and academic applications.**


The Yellow-Brick Roadmap

Further Reading

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