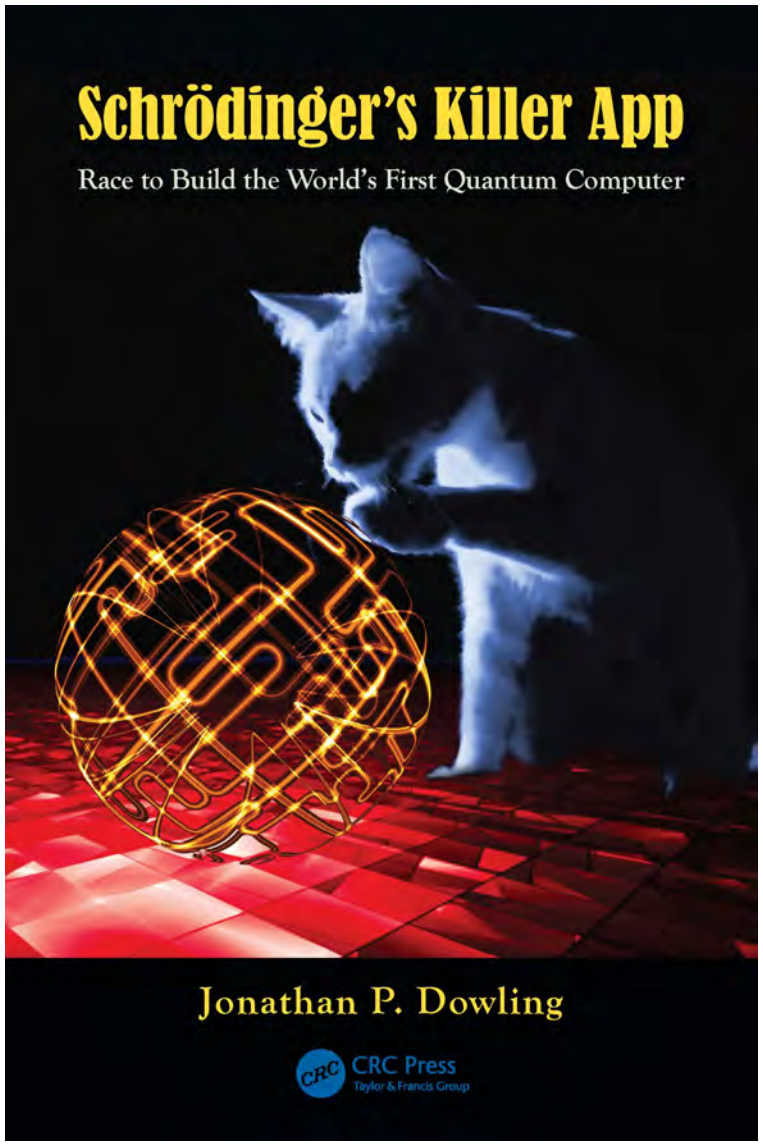
Schrödinger's Rainbow: The Renaissance in Quantum Optical Interferometry

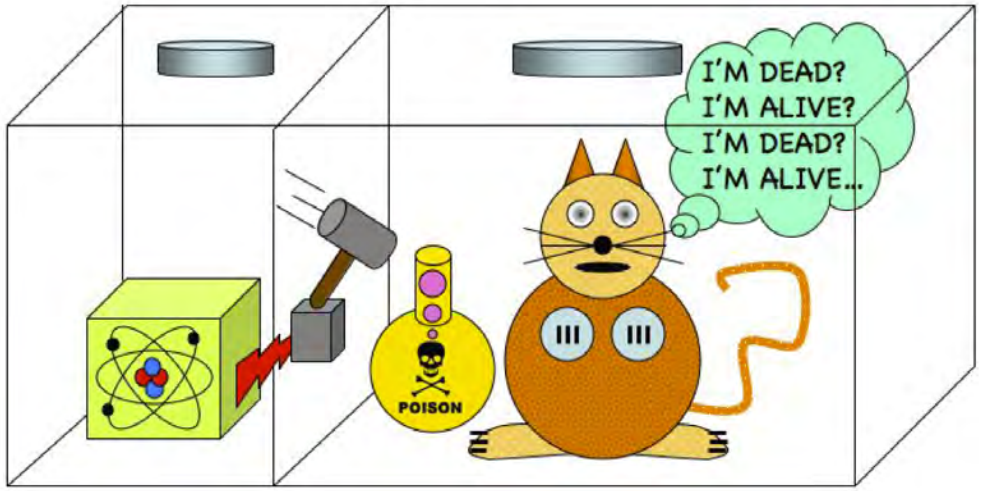
Jonathan P. Dowling

Quantum Science & Technologies (QST) Group
Hearne Institute for Theoretical Physics
Louisiana State University

IEEE Quantum Optics / Engineering Workshop
MIT Lincoln Labs, 16 April 2014

New Book Available @ CRC Press Booth for 15% Off!





7 ★★★★★ REVIEWS!

"I found myself LAUGHING OUT LOUD quite frequently."

"The book itself is fine and well-written … I can thoroughly recommend it."

Hearne Institute for Theoretical Physics
Quantum Science & Technologies Group

Photo: H.Cable, C.Wildfeuer, H.Lee, S.D.Huver, W.N.Plick, G.Deng, R.Glasser, S.Vinjanampathy, K.Jacobs, D.Uskov, J.P.Dowling, P.Lougovski, N.M.VanMeter, M.Wilde, G.Selvaraj, A.DaSilva

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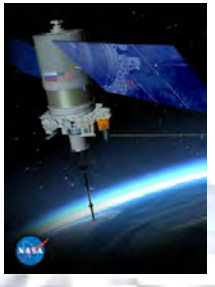
Bottom Inset : H . Broadus, C. Brignac, R.Cross, B.Gard, D.J.Lum, Keith Motes, G.M.Raterman, C.Sabottke,

Quantum Metrology

Quantum Imaging

Quantum Sensing



Quantum Computing

You Are Here!

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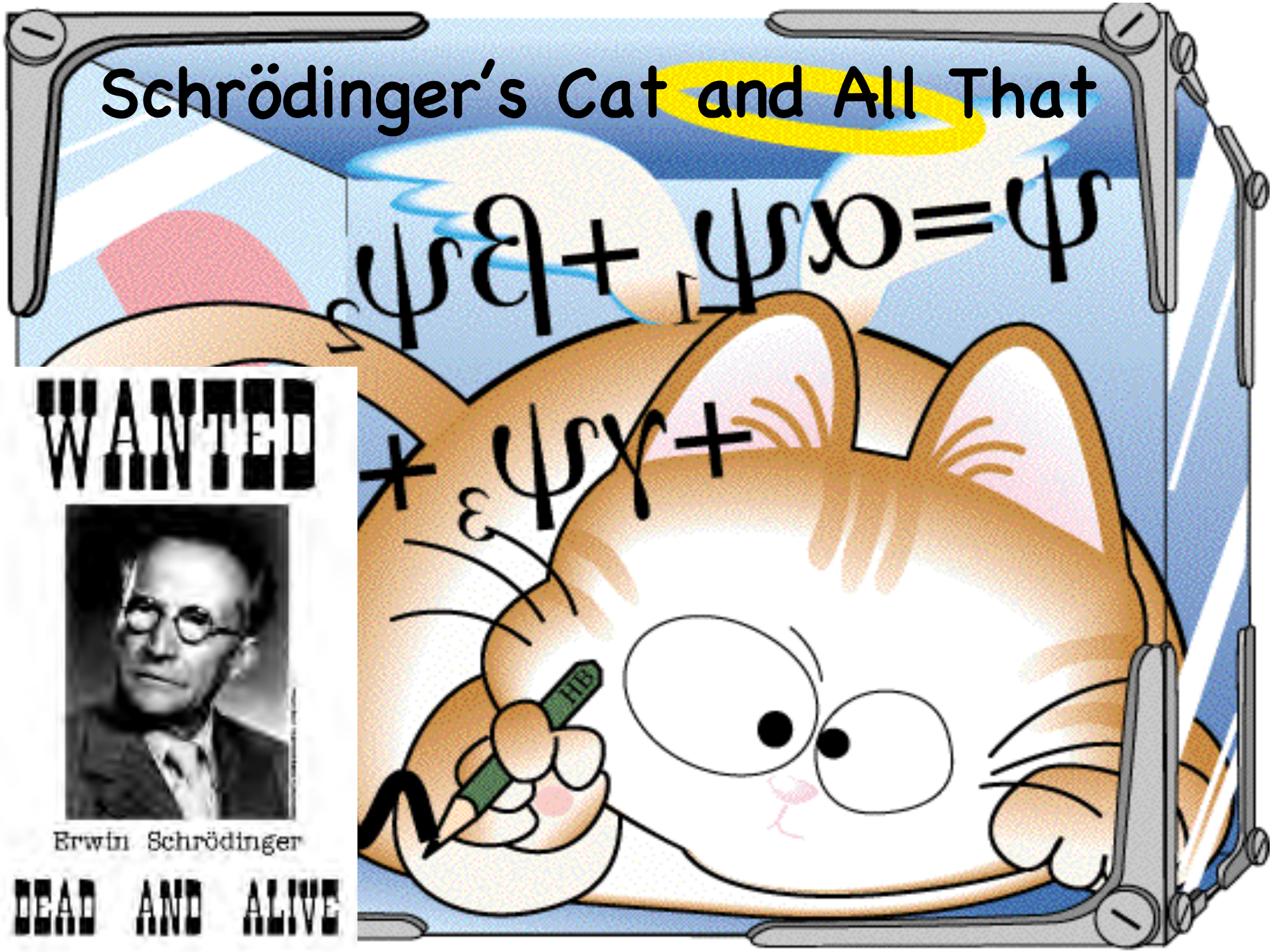
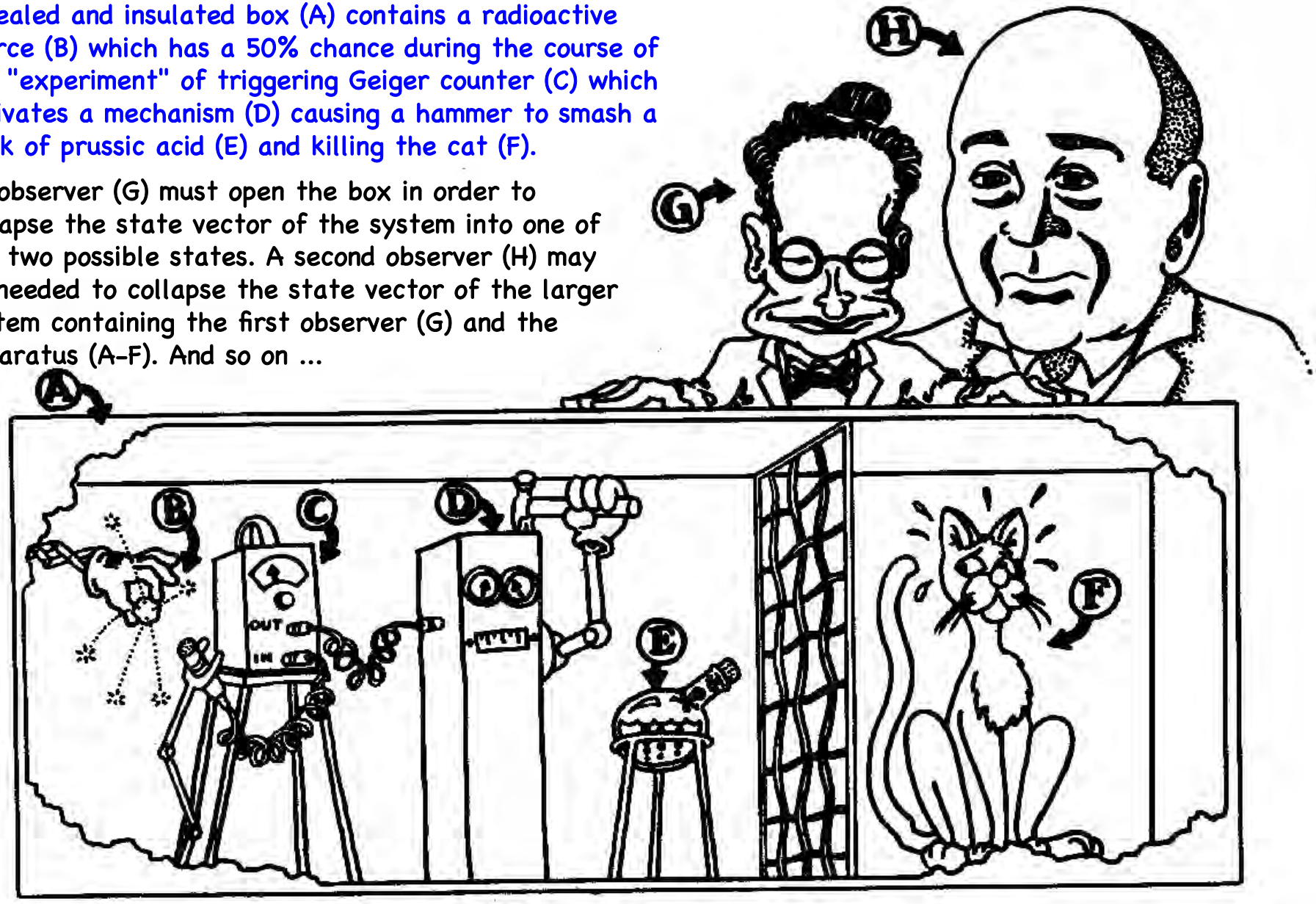
Schrödinger's Cat and All That



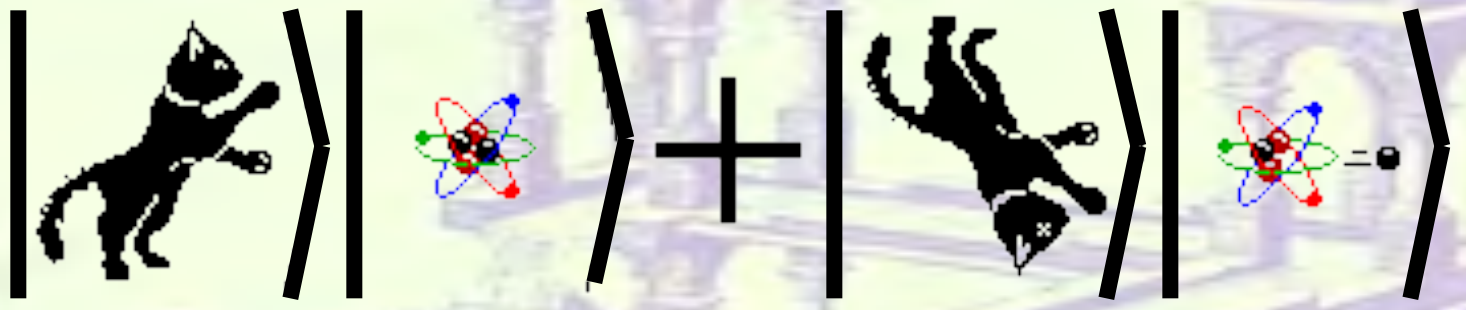
Quantum Kitty Review

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.

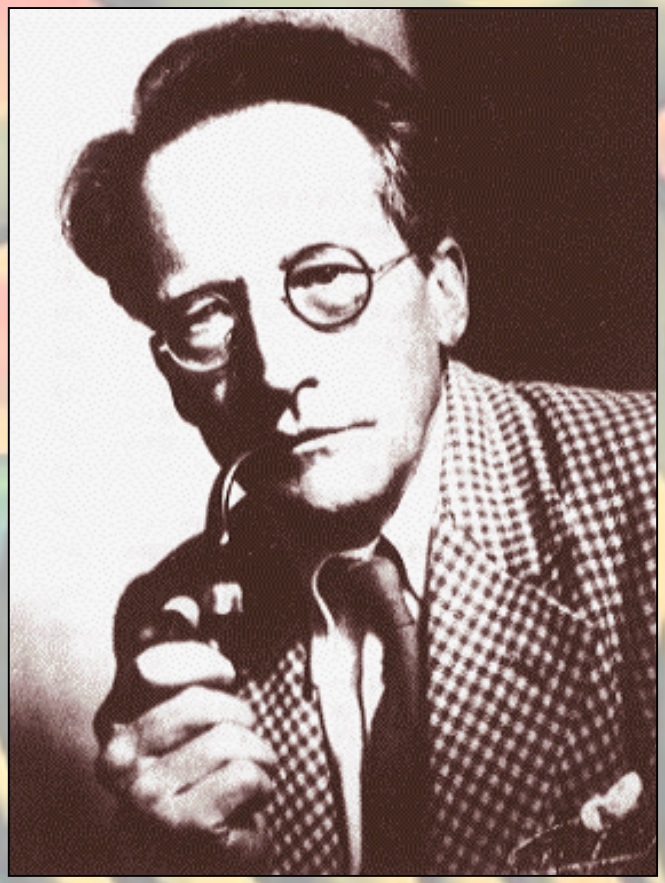
(2.) The Cat is in a Simultaneous Superposition of Dead & Alive.

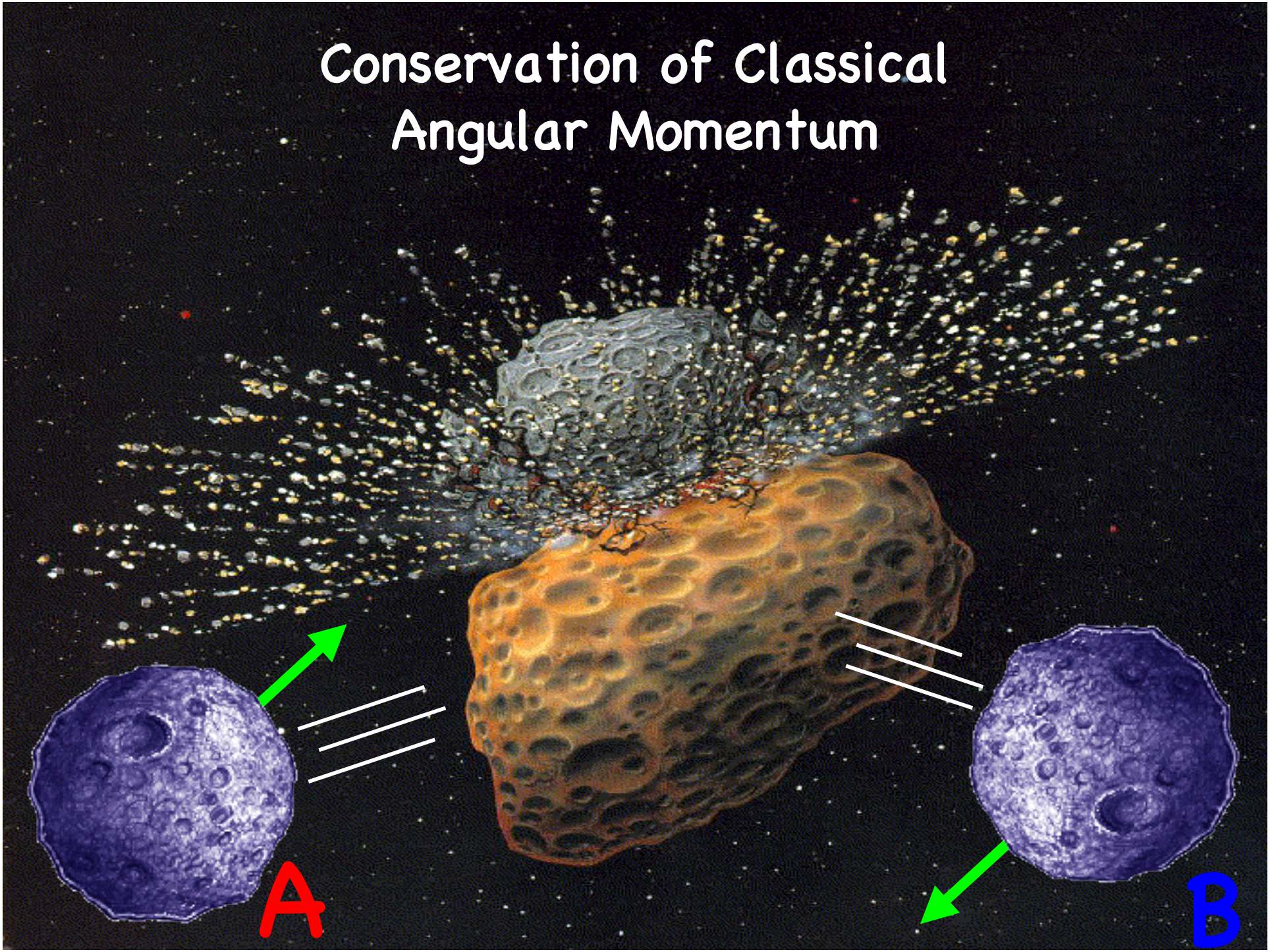
(3.) Observers are Required to "Collapse" the Cat to Dead or Alive

Quantum Entanglement

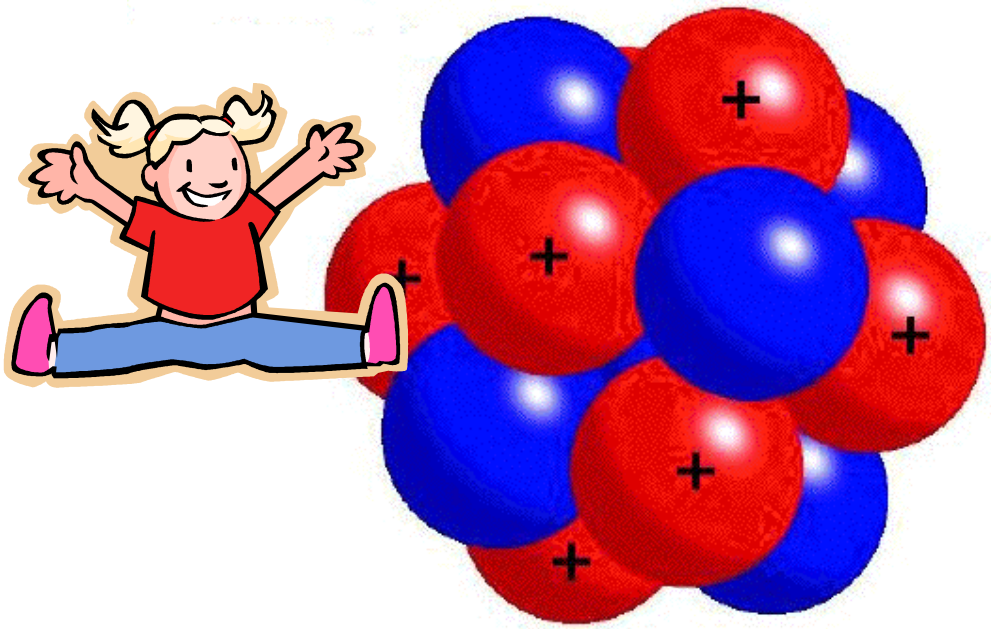
"Quantum entanglement is *the* characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought."

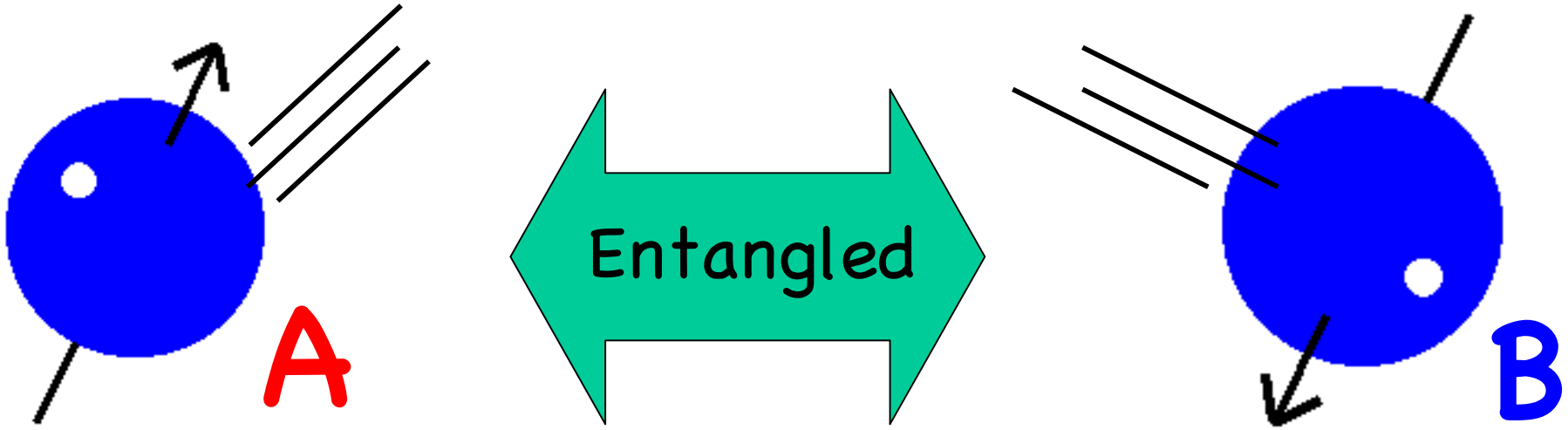
— Erwin Schrödinger




Conservation of Classical
Angular Momentum
A
B

Conservation of Quantum Spin

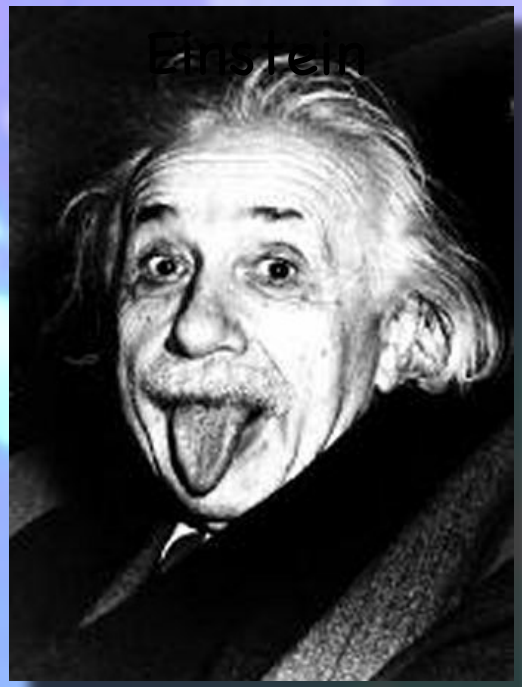




"EINSTEIN ATTACKS QUANTUM THEORY!"

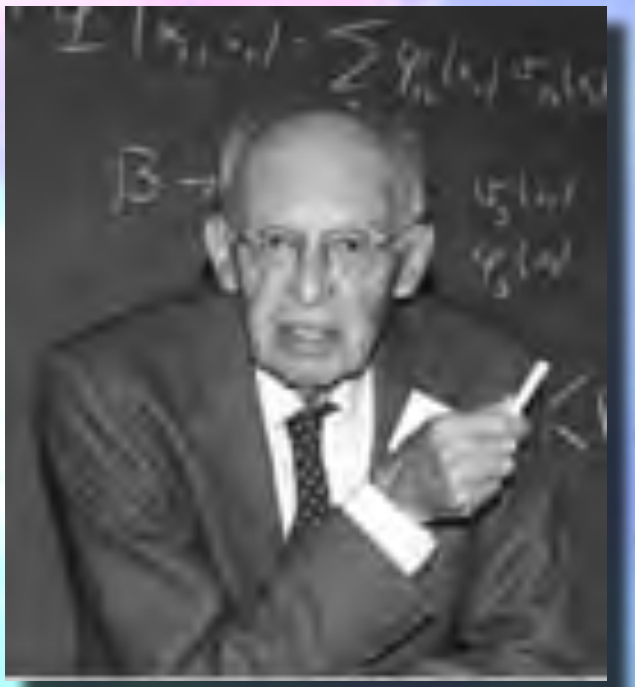
— New York Times, 04 May 1935

Albert Einstein



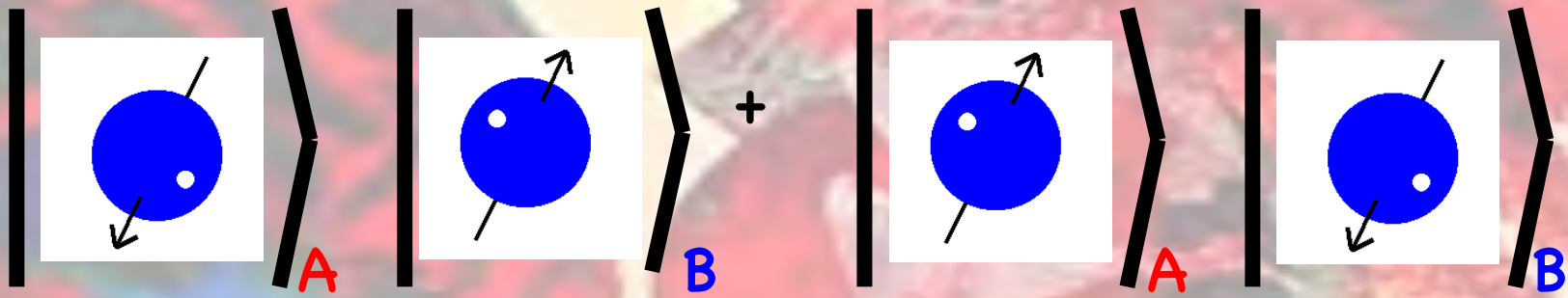
Boris Podolsky

Nathan Rosen

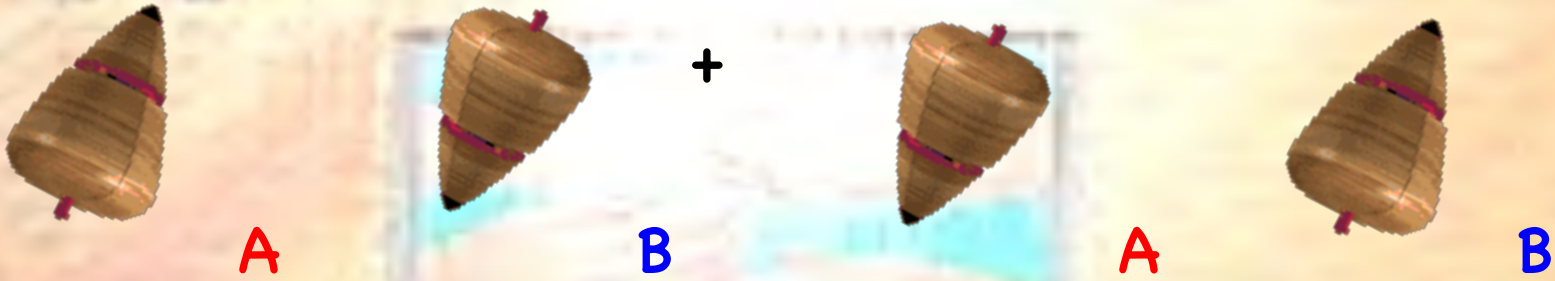


"If, without in any way disturbing a system, we can predict with certainty ... the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity."

Hidden Variable Theory



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



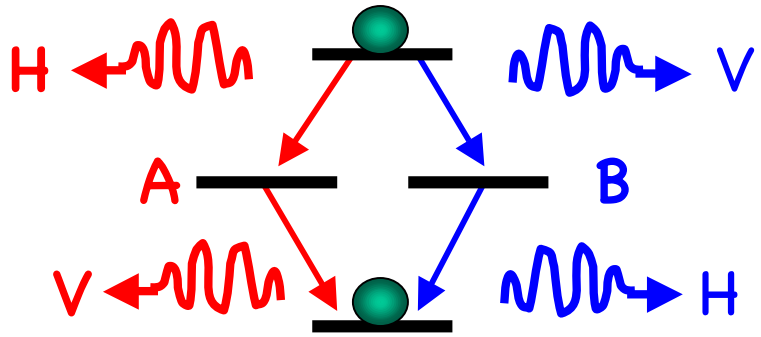
...Be Replaced by Some Sort of Local, Statistical, Classical (Hidden Variable) Theory?

For Whom the Bell Tolls?

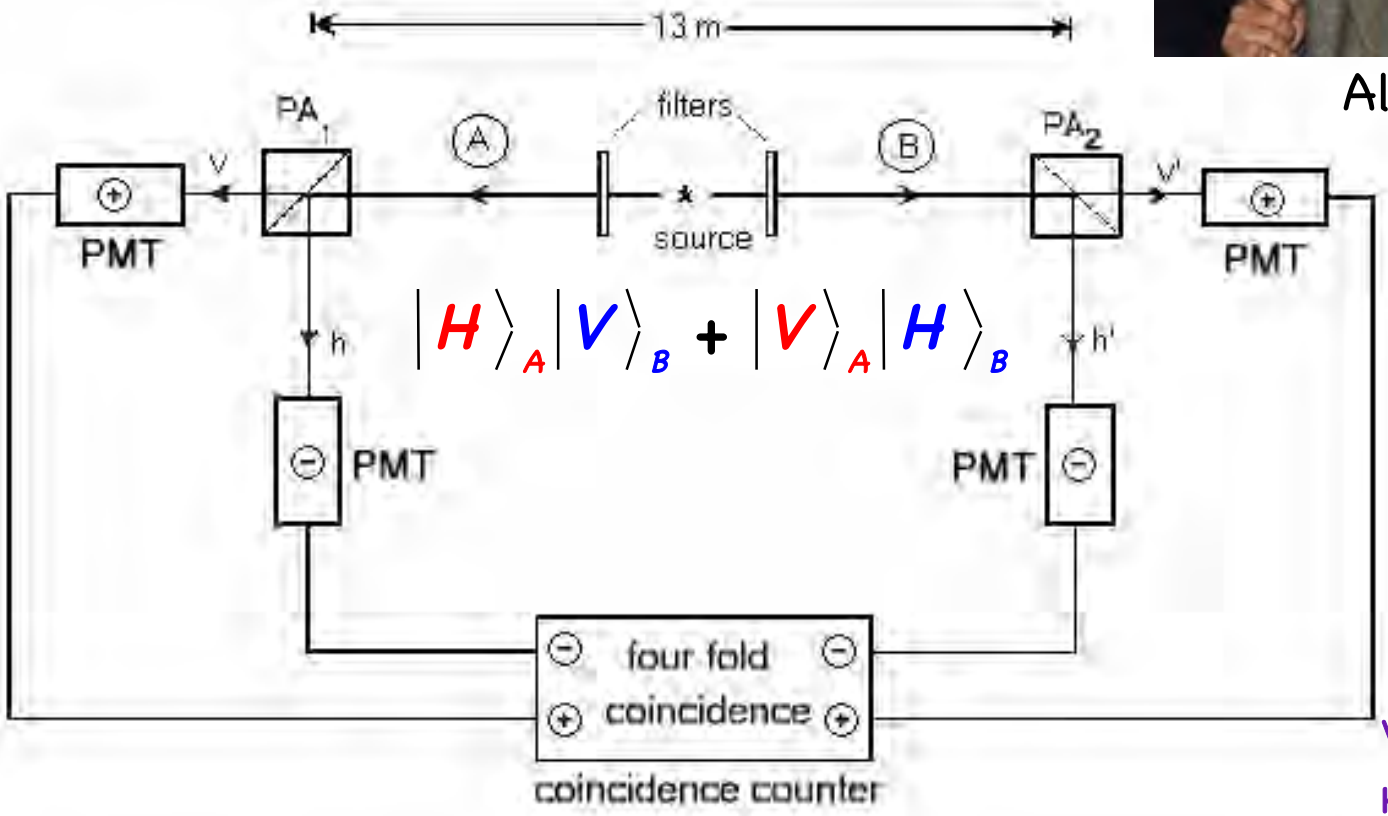
No! The physical predictions of quantum theory disagree with those of any local (classical) hidden-variable theory!

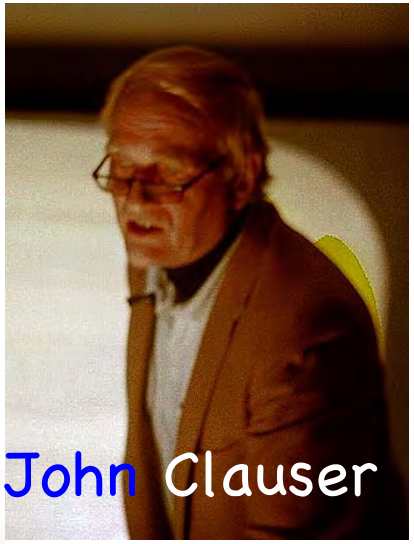
Clauser (1978) & Aspect (1982) Experiments

Two-Photon Atomic Decay



Alain Aspect





John Clauser

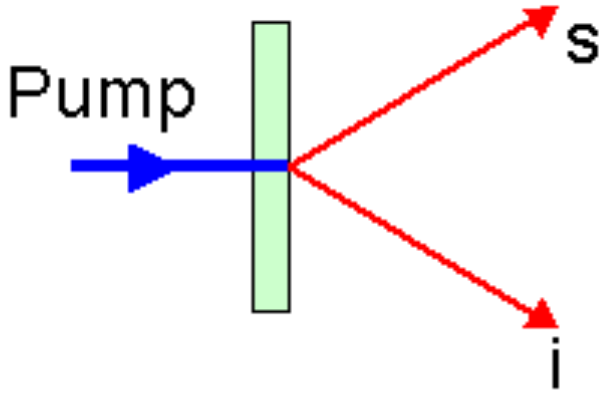
V= Vertical Polarization

H = Horizontal Polarization

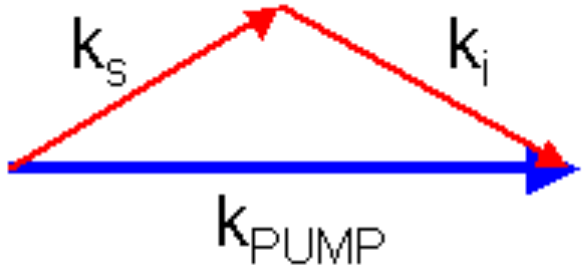

Quantum Light — Over the Rainbow

Parametric Downconversion: Type I

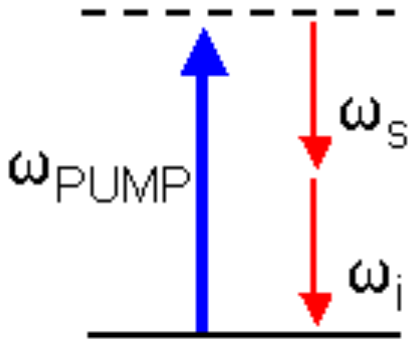
Downconversion



Momentum is conserved..



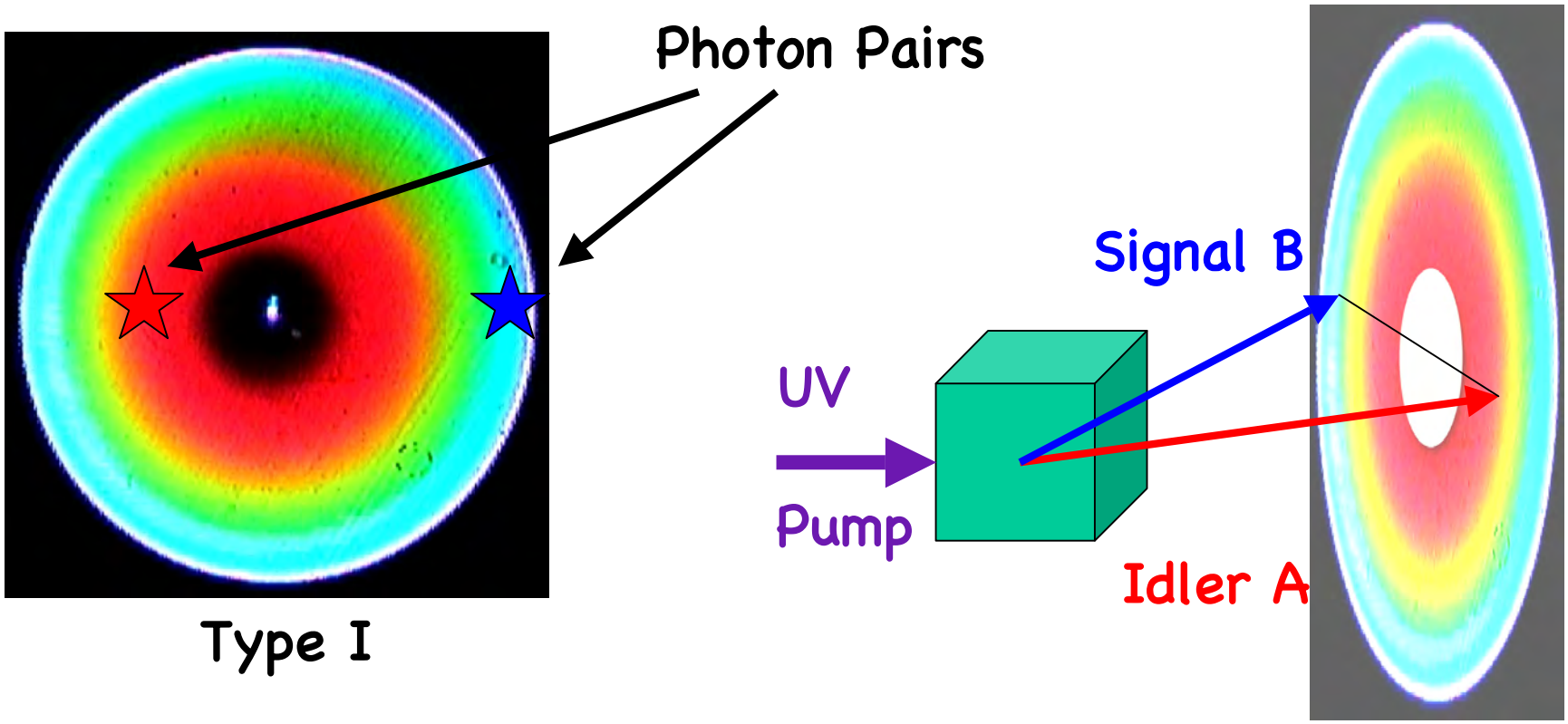
..as well as energy



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

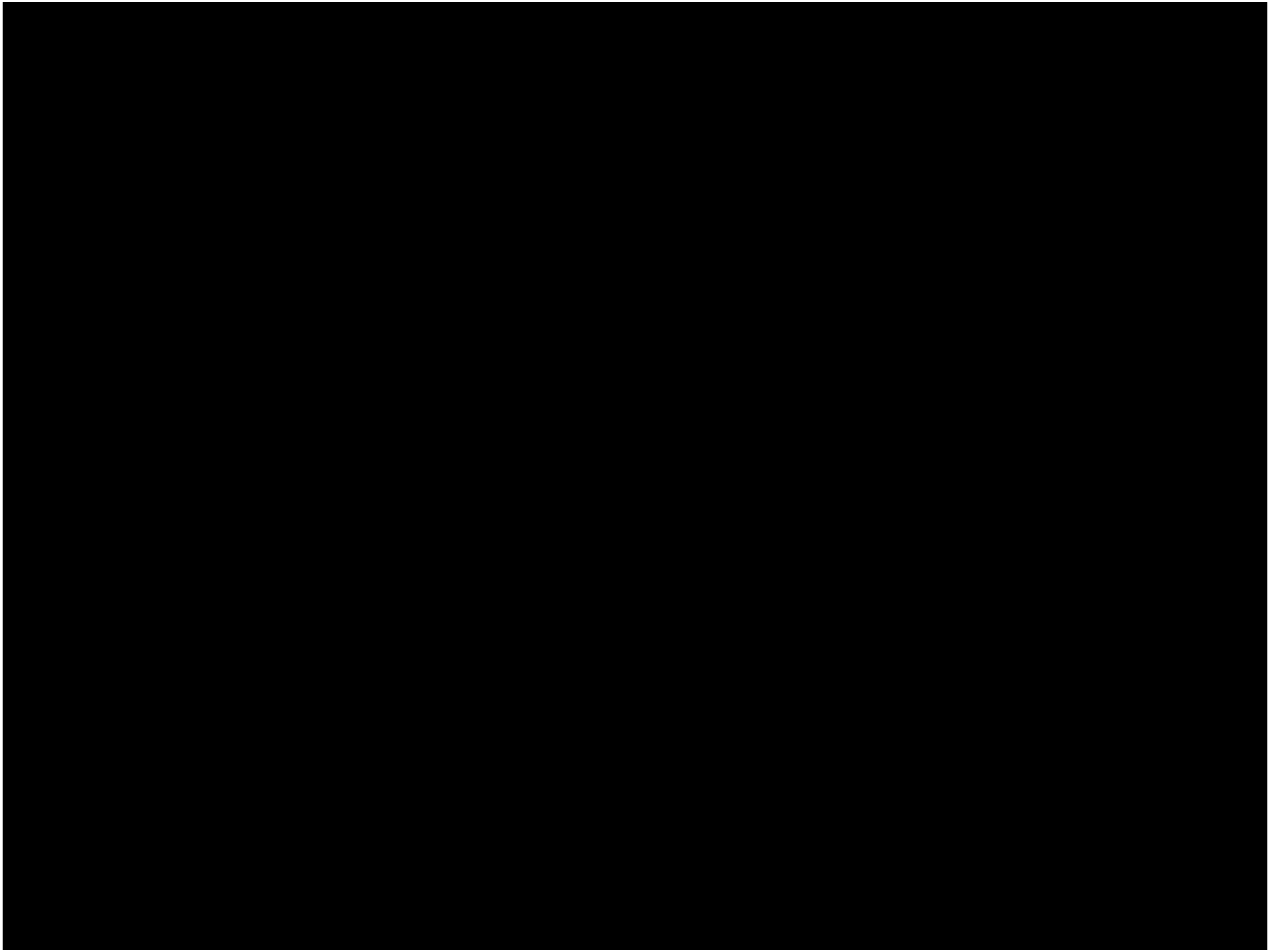
- A pump photon is spontaneously converted into two lower frequency photons in a material with a nonzero $\chi^{(2)}$

Parametric Downconversion: Type I

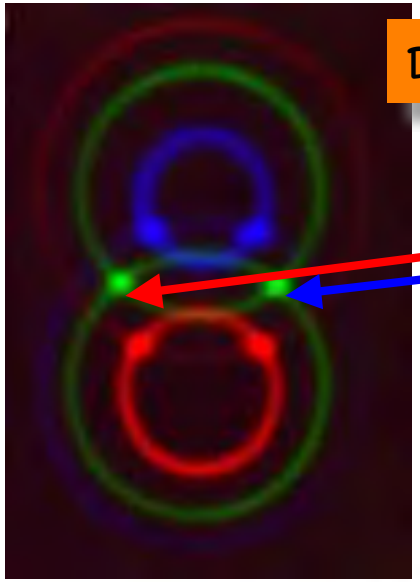


Degenerate (Entangled) Case: $\omega_s=\omega_i$

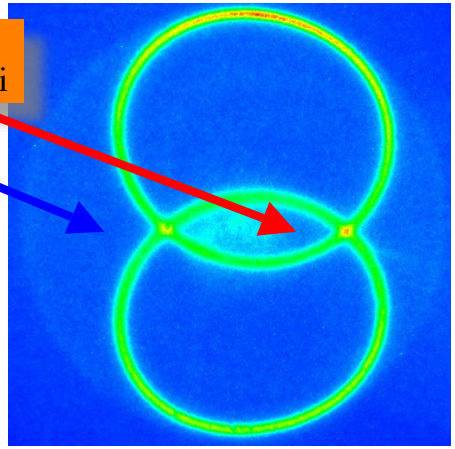
$$|\omega_s,\ \varphi_s,\ k_s\ \rangle_A|\omega_i,\ \varphi_i,\ \mathbf{k}_s\ \rangle_B+|\omega_i,\ \varphi_i,\ \mathbf{k}_i\ \rangle_A|\omega_s,\ \varphi_s,\ \mathbf{k}_s\ \rangle_B$$



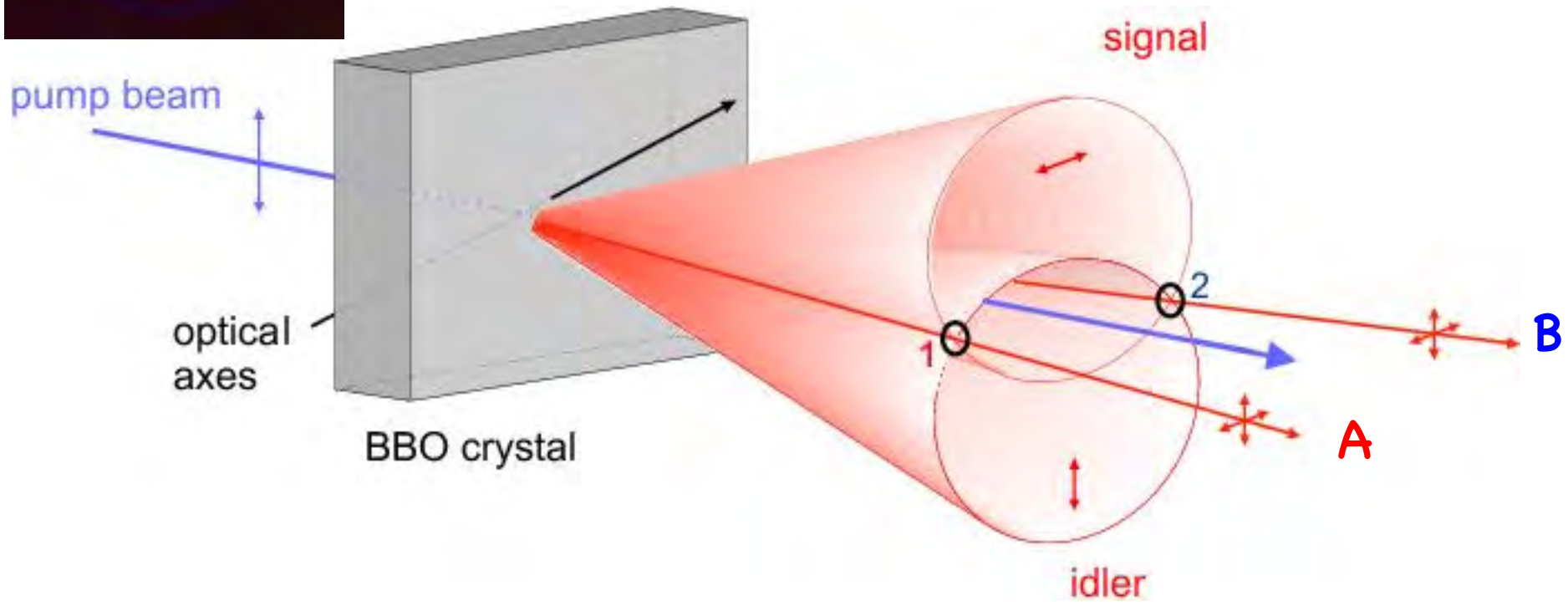
Parametric Downconversion: Type II



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



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

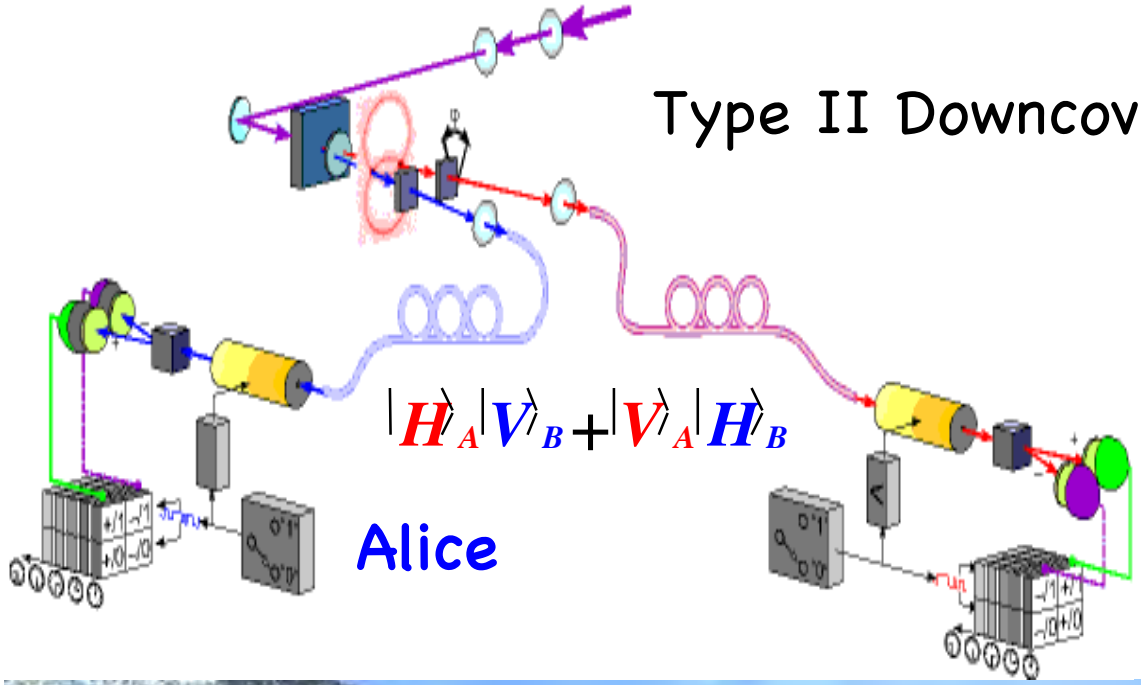


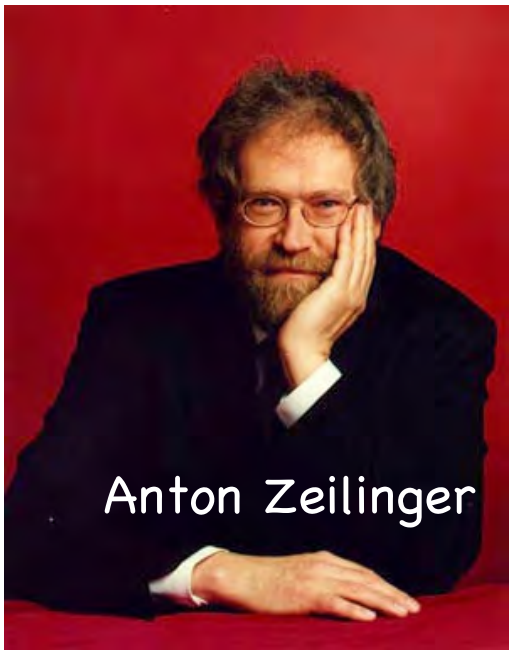
Type II Phasematching in BBO Crystal Pumped at 351nm

Signal and Idler shown from 500 nm to 1200 nm

Putting Entangled Light to Work

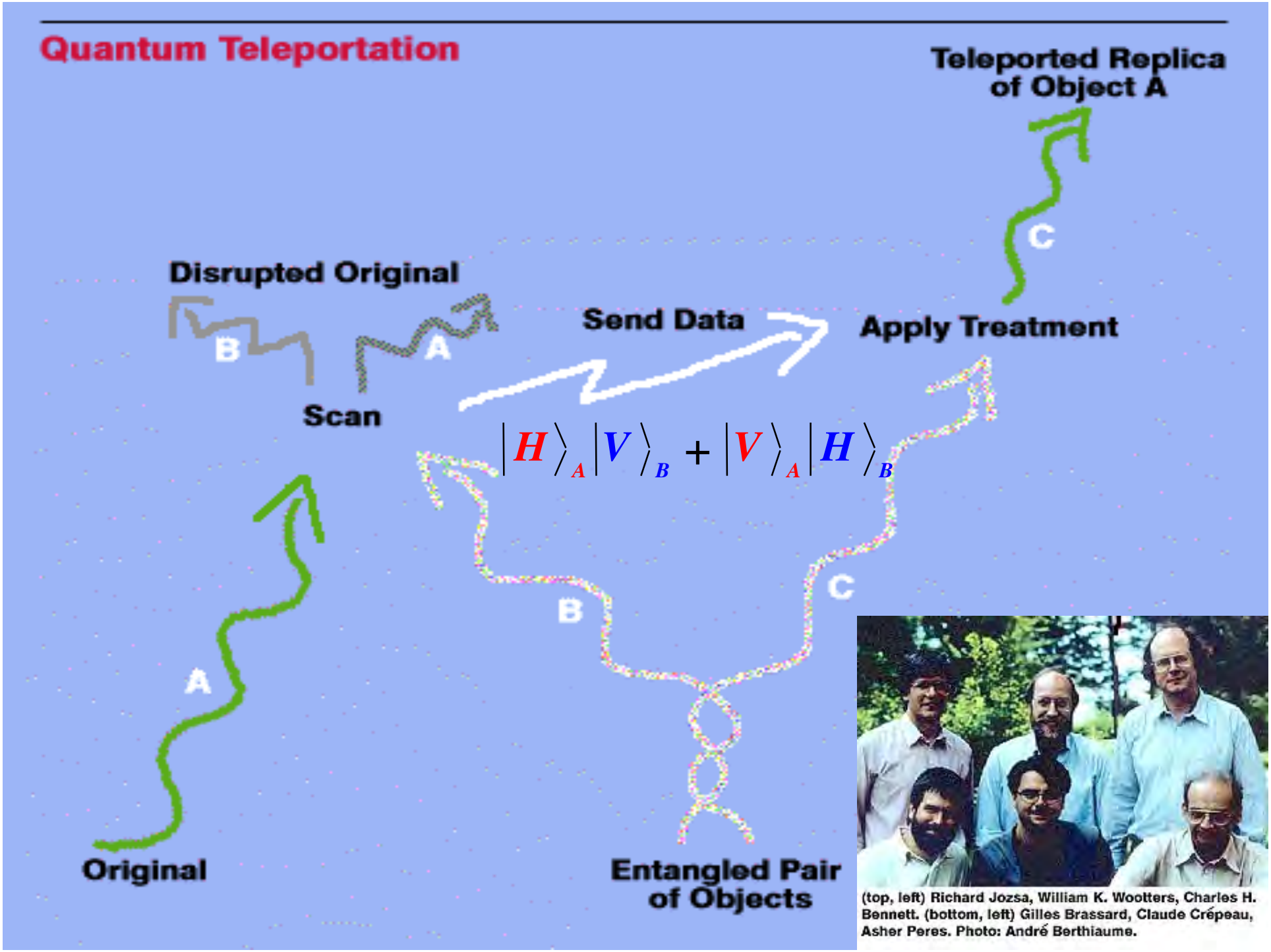
Tests of Bell's Inequalities at Innsbruck





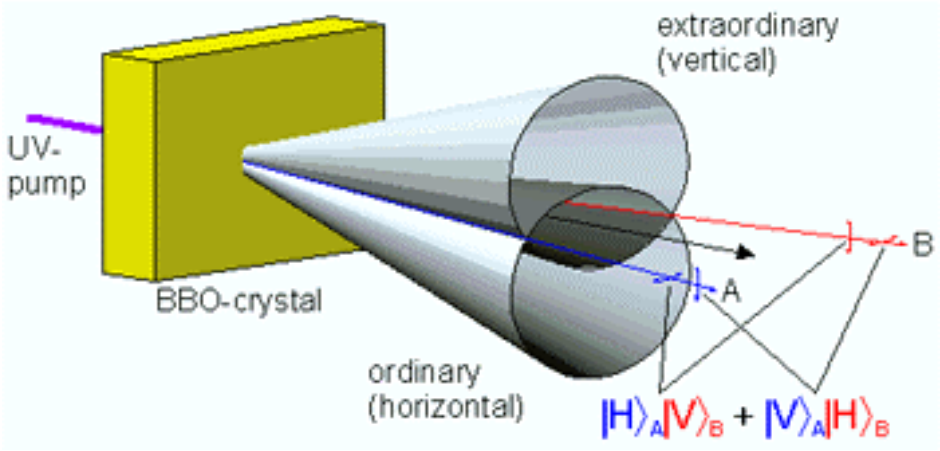
Quantum Teleportation

Quantum Teleportation

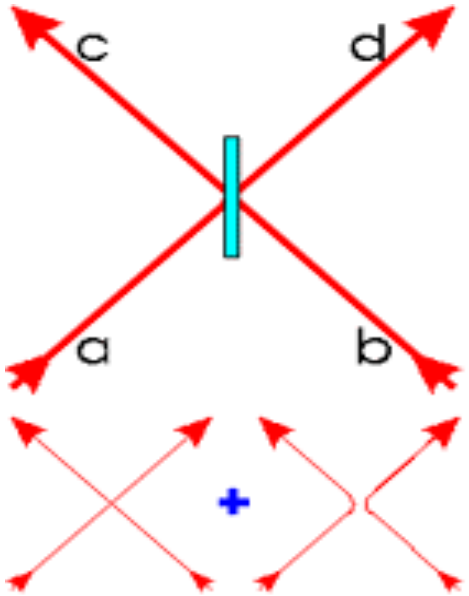


(top, left) Richard Jozsa, William K. Wootters, Charles H. Bennett. (bottom, left) Gilles Brassard, Claude Crépeau, Asher Peres. Photo: André Berthiaume.

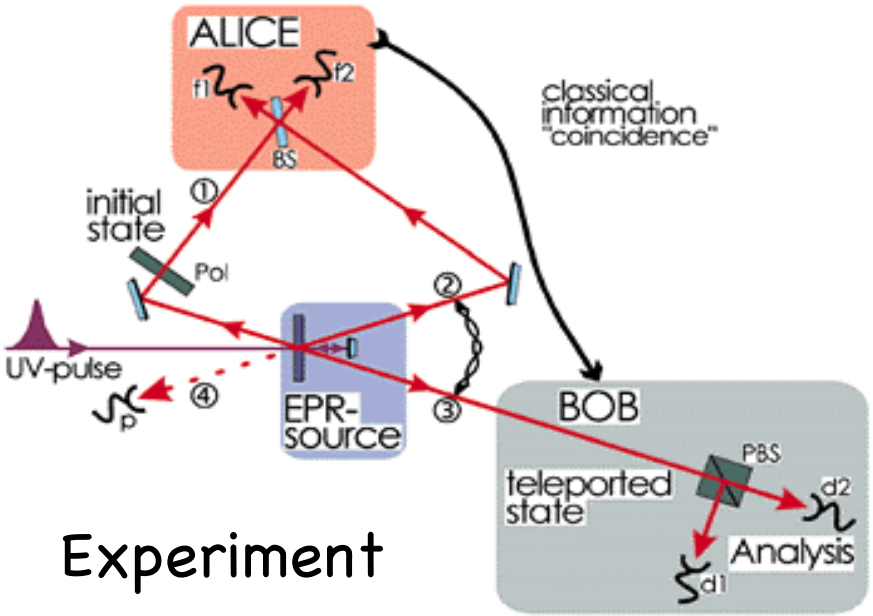
Teleportation Experiment at Innsbruck



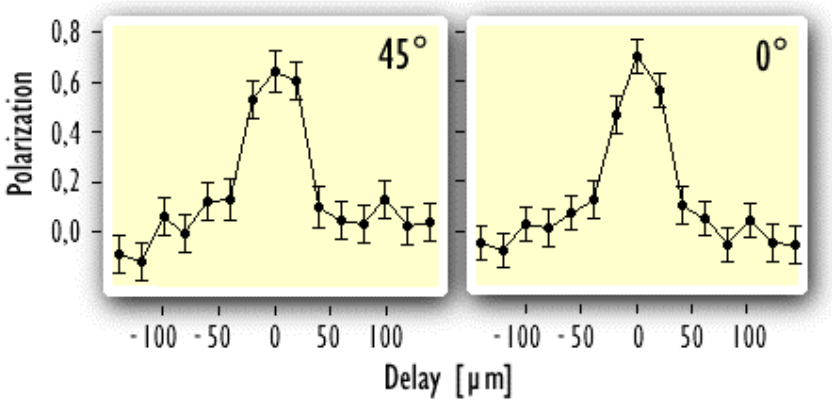
EPR Source

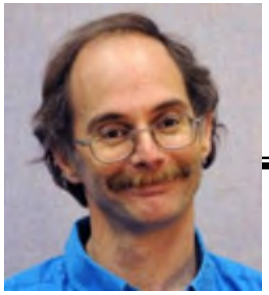


Bell State Analysis



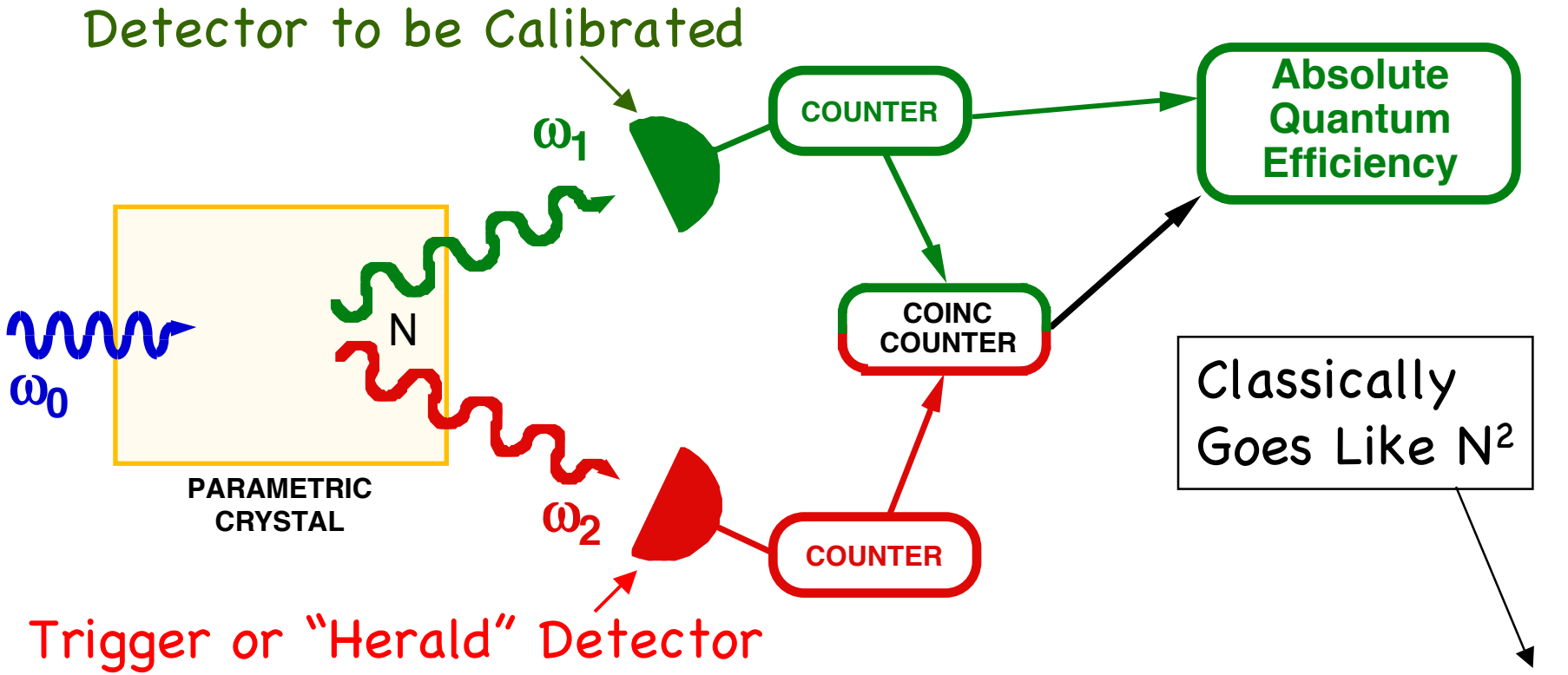
Experiment





Detector Quantum Efficiency Scheme

Alan Migdall



No External Standards Needed!

Two-photon processes in faint biphoton fields

DMITRY V. STREKALOV†, MATTHEW C. STOWE†,
MARIA V. CHEKHOVA‡ and JONATHAN P. DOWLING†

JOURNAL OF MODERN OPTICS, 2002,
VOL. 49, NO. 14/15, 2349–2364

Abstract. The goal of this research is to determine and study a physical system that will enable a fast and intrinsically two-photon detector, which would be of interest for quantum information and metrology applications. We consider two types of two-photon processes that can be observed using a very faint, but quantum-correlated *biphoton* field. These are optical up-conversion and an external photoelectric effect. We estimate the correlation enhancement factor for the biphoton light compared to coherent light, report and discuss the preliminary experimental results.

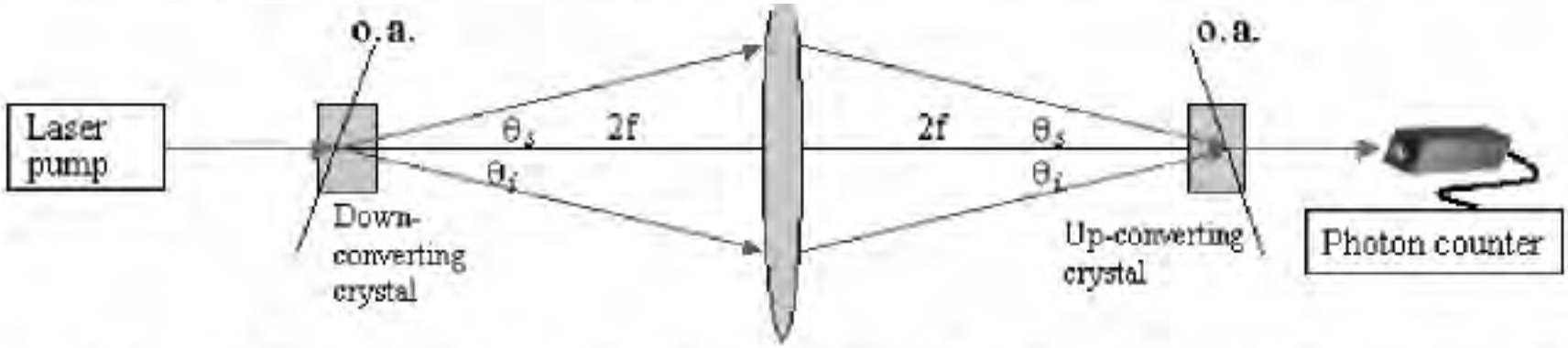


Figure 2. A conceptual drawing of the experiment on up-conversion of biphoton light. O.A. stands for the optical axes of the nonlinear crystals.

Nonlinear Interactions with an Ultrahigh Flux of Broadband Entangled Photons

Barak Dayan, Avi Pe'er, Asher A. Friesem, and Yaron Silberberg

A complete quantum-mechanical analysis [22] shows that the rate of SFG events with correlated pairs (i.e., photons generated from the same pump mode) indeed includes a term that depends linearly on the intensity:

$$R_c \propto \Delta_{\mathrm{DC}}(n^2 + n). \tag{2}$$

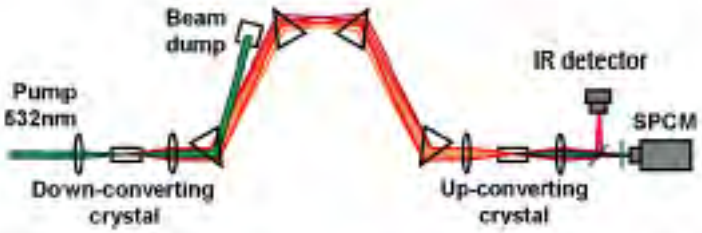


FIG. 1 (color online). Experimental layout. Entangled photons generated by down-conversion of a pump laser in one crystal are imaged through a set of four dispersion prisms onto a second crystal to generate the SFG photons. The entangled-photon beam is separated from the SFG photons by a harmonic-separator mirror and its power is measured by an InGaAs detector. The SFG photons are further filtered by 532 nm line filters and are counted with a single-photon counting module.

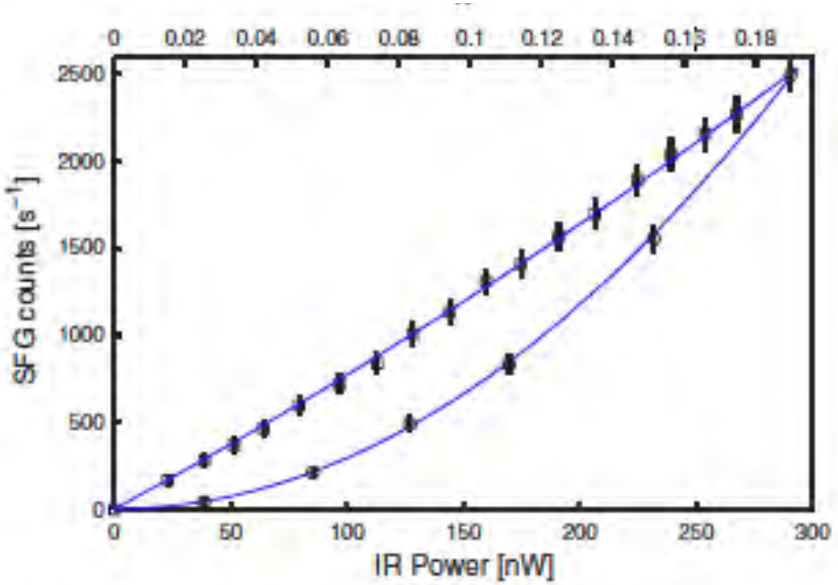
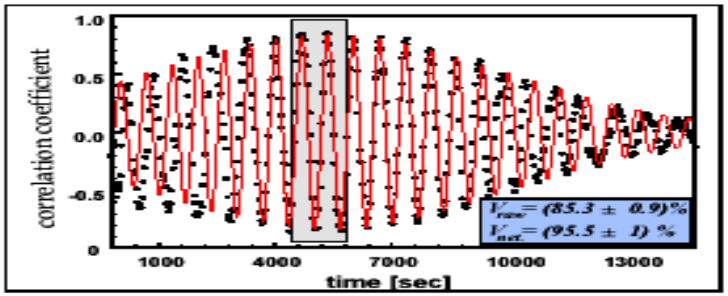


FIG. 2 (color online). Power dependence of SFG with entangled photons. When the down-converted IR power is reduced by optical attenuators, the SFG rate drops quadratically: circles, experimental; line, quadratic fit, exactly like classical light sources. However, when the IR power is reduced by decreasing the pump-laser power, thus reducing the photon-pair production rate, the SFG rate decreases in a close-to-linear manner, as quantum mechanically predicted: squares, experimental; line, calculated $\alpha(n + n^2)$, with α chosen to fit. The log-log slope of these measurements varies from 1.01 at the lowest powers to 1.14 at the highest powers.

Ekert Scheme Quantum Cryptography at University of Geneva

System Under Lake Geneva



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

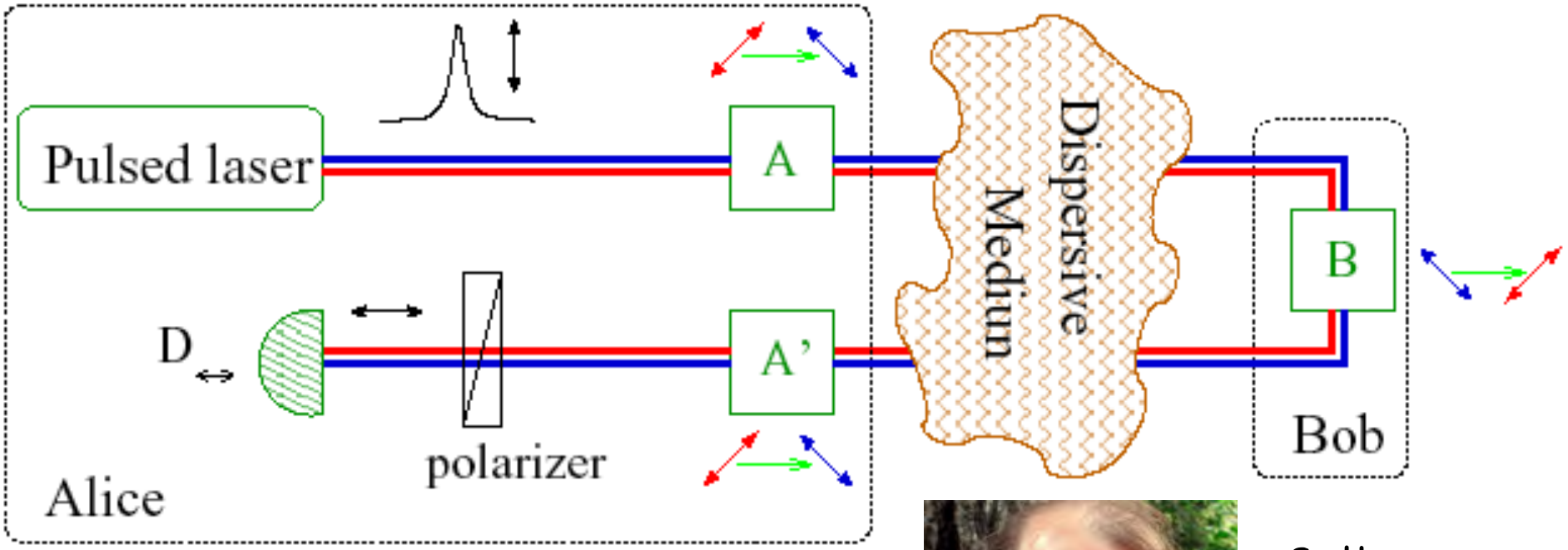
$$|\psi_{s,i}\rangle = \frac{1}{\sqrt{2}}\left(|s\rangle_s|s\rangle_i + e^{i\phi}|l\rangle_s|l\rangle_i\right)$$

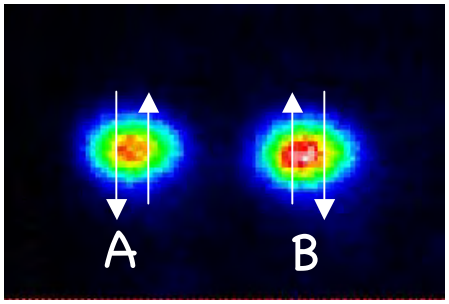
Nicolas Gisin

Bob and "Charly" Share Random Crypto Key

Quantum Clock Synchronization

Entangled Photons Can Synchronize Clocks Past the Turbulent Atmosphere!

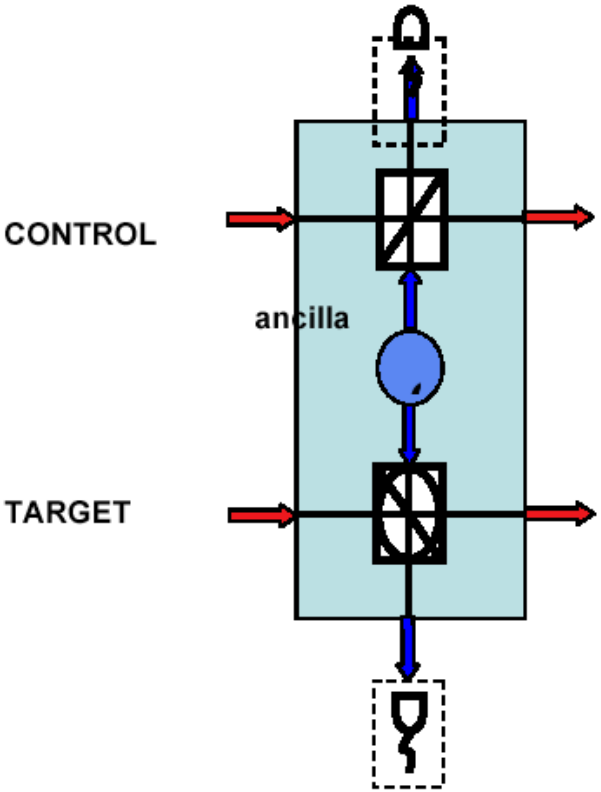




Seth
Lloyd
MIT

Quantum Computing

Entangled Photons are a Resource for Scalable Quantum Computation!



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

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

Gerard Milburn
University Of Queensland

WHY IS A KERR NONLINEARITY LIKE A PROJECTIVE MEASUREMENT?

Photon-Photon CNOT Gate

Linear Optical QC "KLM"

Cavity QED EIT

Photon-Photon Nonlinearity

???

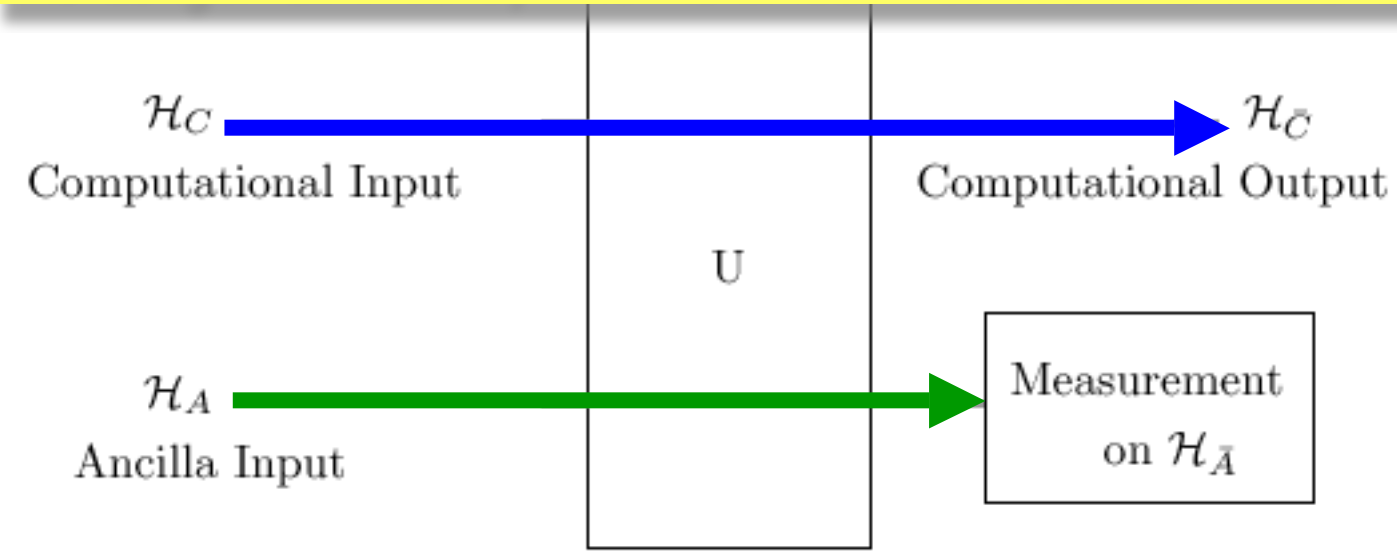
Projective Measurement

Kerr Material

Projective Measurement Yields Effective Kerr Nonlinearity!

G. G. Lapaire, P. Kok, JPD, J. E. Sipe, PRA 68 (2003) 042314

A Revolution in Nonlinear Optics at the Few Photon Level:
No Longer Limited by the Nonlinearities We Find in *Nature!*



NON-Unitary Gates → Effective Nonlinear Gates

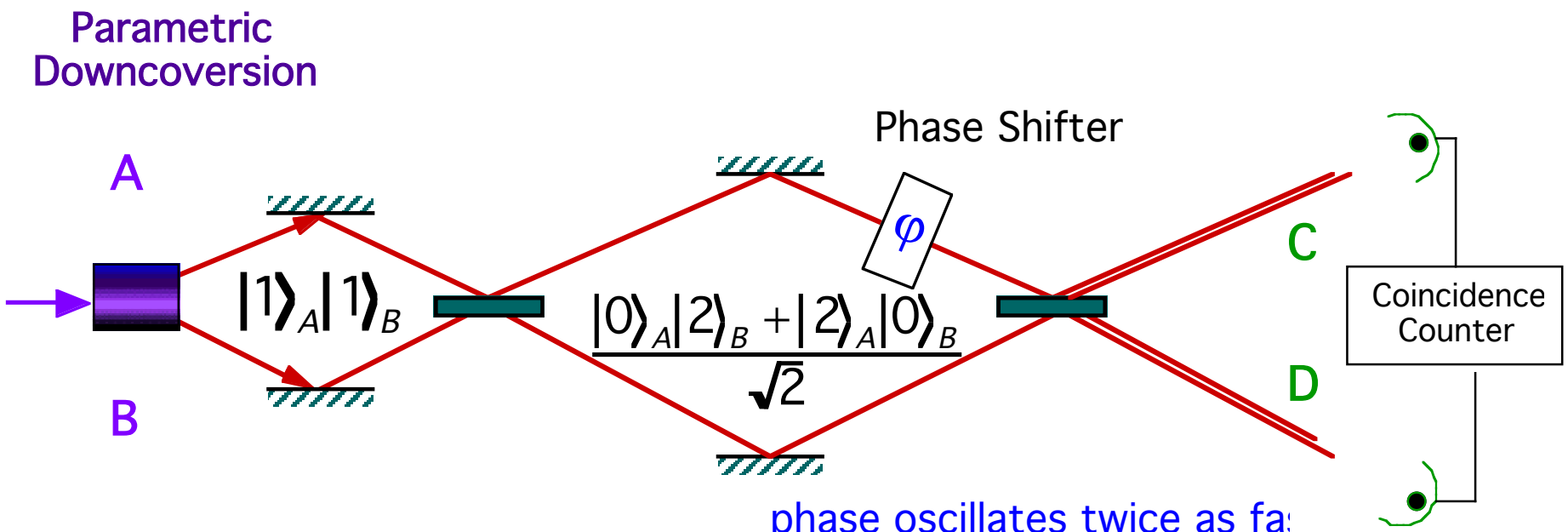
$$Q = \frac{\pi\hbar}{2}(5\hat{n} - \hat{n}^2)$$

KLM CSIGN: Self Kerr

$$Q = \frac{\pi\hbar}{2}(3 + a_b^\dagger(1-\hat{n}_b) + (1-\hat{n}_b)a_b)\hat{n}_a$$

Franson CNOT: Cross Kerr

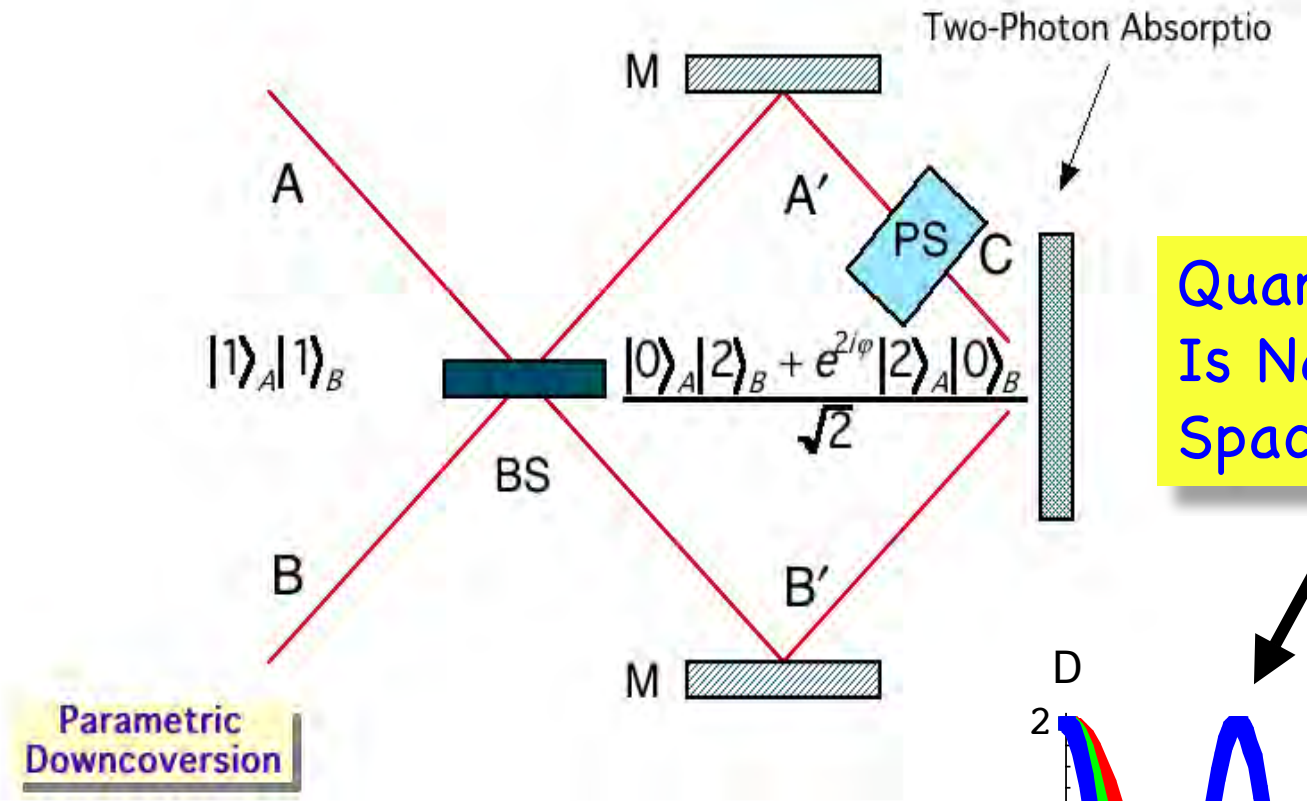
The Hong-Ou-Mandel Effect



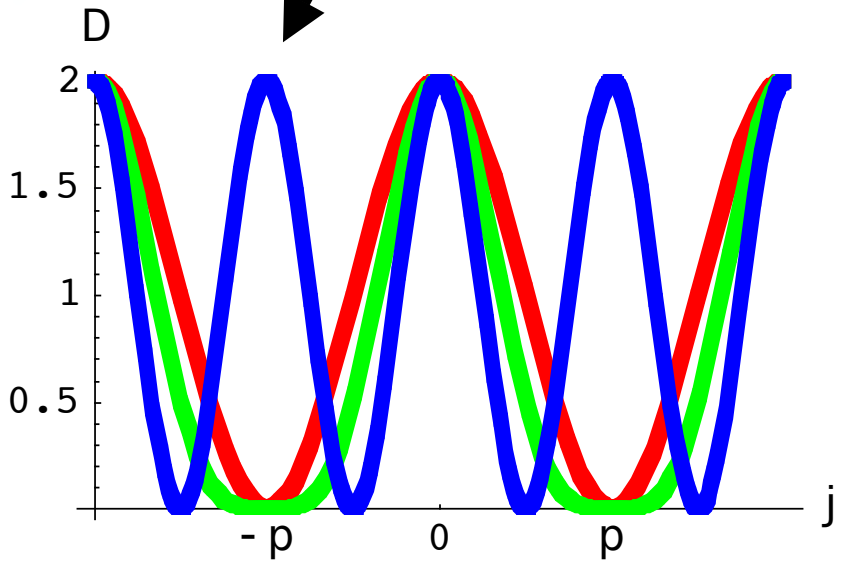
$$\frac{|0\rangle_A|2\rangle_B + |2\rangle_A|0\rangle_B}{\sqrt{2}} \rightarrow \frac{|0\rangle_A|2\rangle_B + e^{2i\varphi}|2\rangle_A|0\rangle_B}{\sqrt{2}}$$

Leonard Mandel

Quantum Optical Lithography



Quantum Peak
Is Narrower and
Spacing is HALVED!

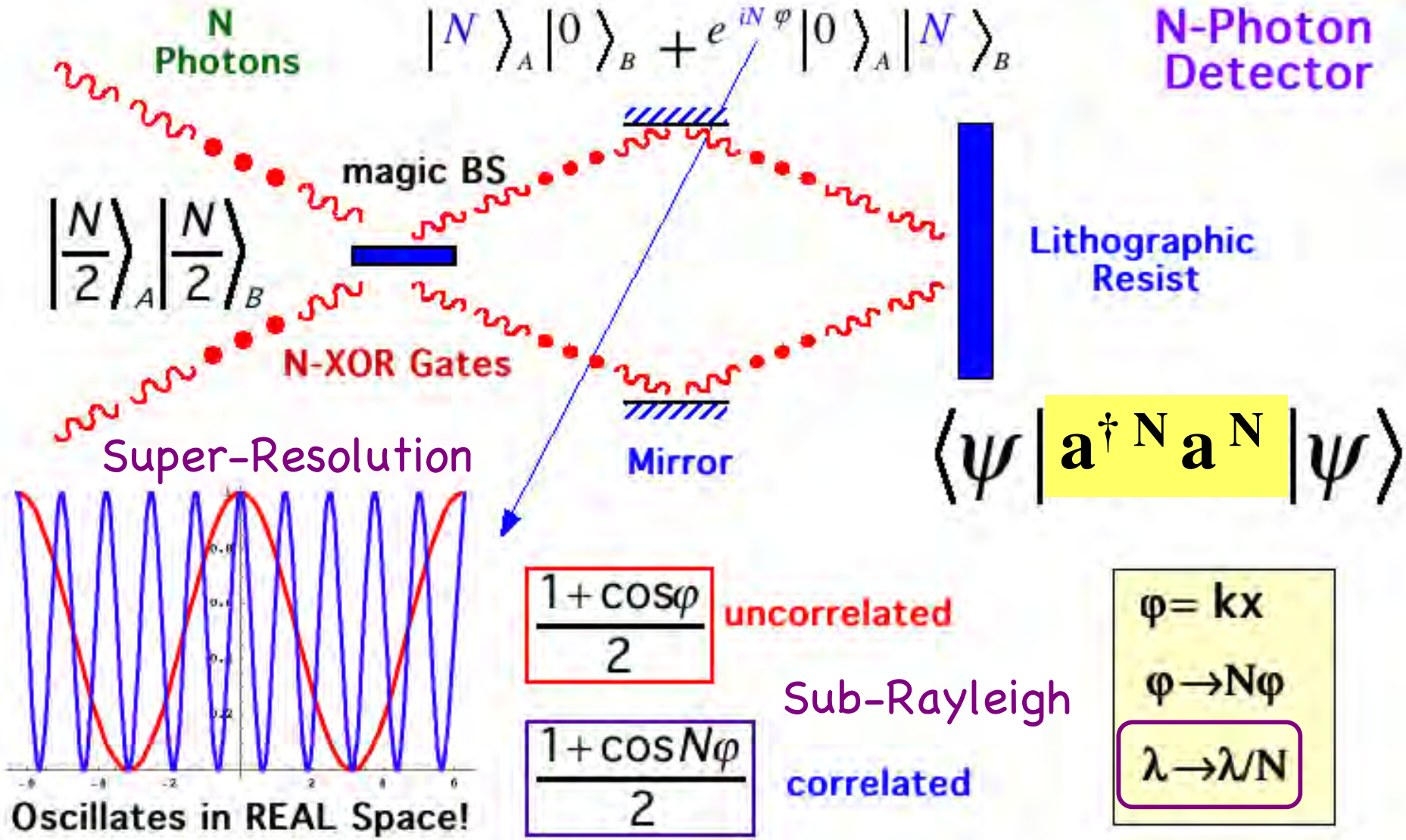


Classical One-Photon Absorption —
Classical Two-Photon Absorption —
Quantum Two-Photon Absorption —

FROM QUANTUM INTERFEROMETRY TO QUANTUM LITHOGRAPHY

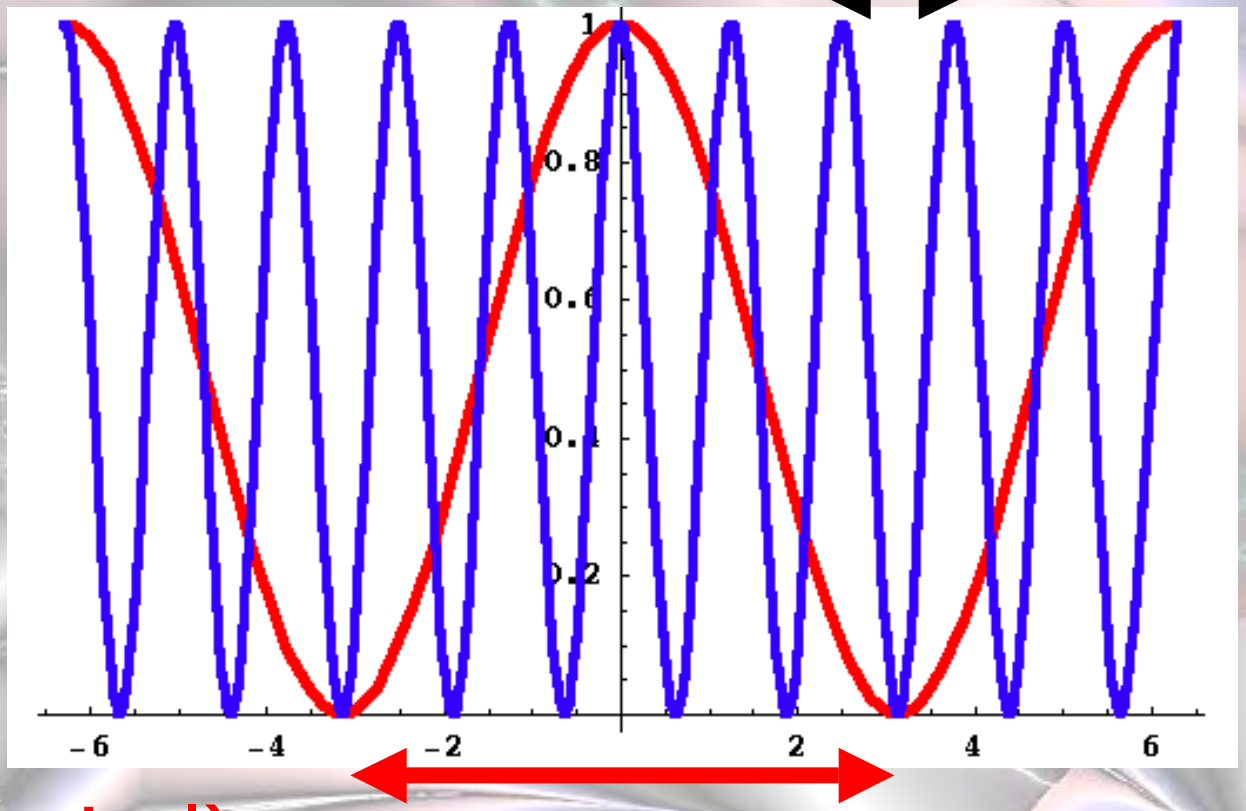
WITH HIGH "N00N" STATES!

AN Boto, DS Abrams, CP Williams, JPD, PRL 85 (2000) 2733



Quantum Imaging: Super-Resolution

λ/N



N=1 (classical)

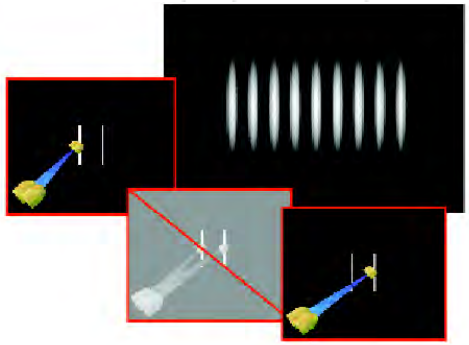
N=5 (N00N)

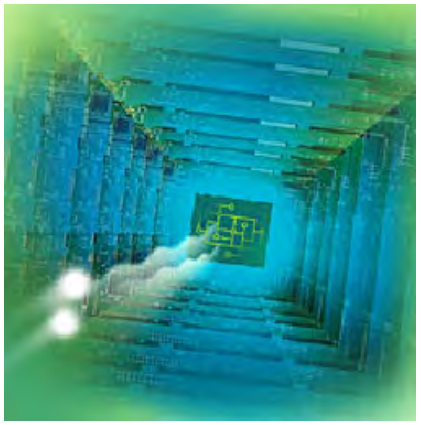
λ

VOLUME 85, NUMBER 13 PHYSICAL REVIEW LETTERS 25 SEPTEMBER 2000

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,*]





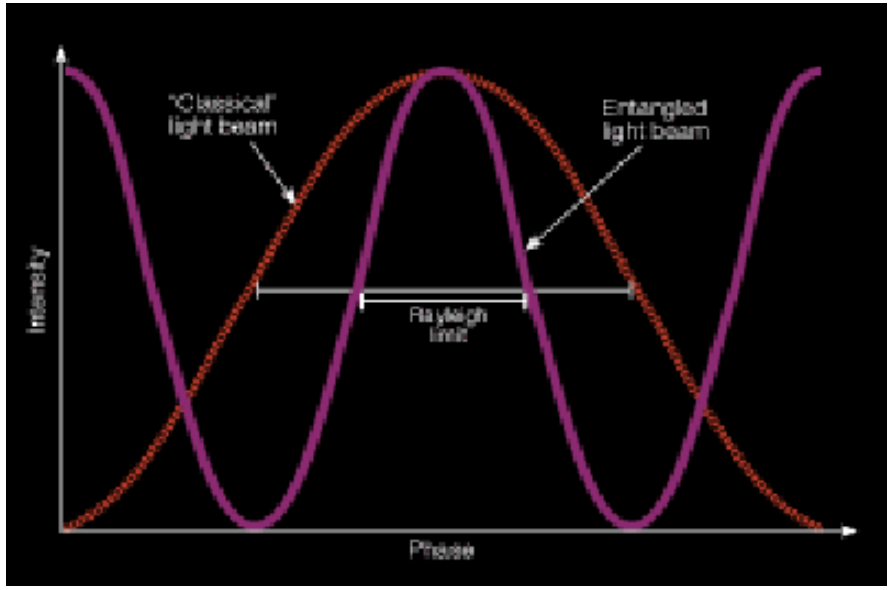
WHAT'S NEXT New York Times

Quantum Leap May Transform Chips

By IAN AUSTEN

physics : Fine lines

PHILIP BALL nature



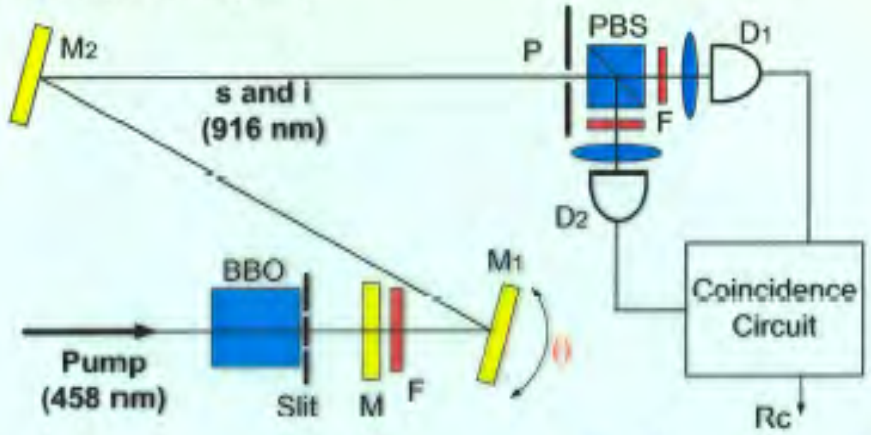
Science

Yoked Photons Break a Light Barrier

Quantum Lithography Experiment

Quantum lithography: setup

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



Two-photon source: Degenerate Collinear type-II SPDC

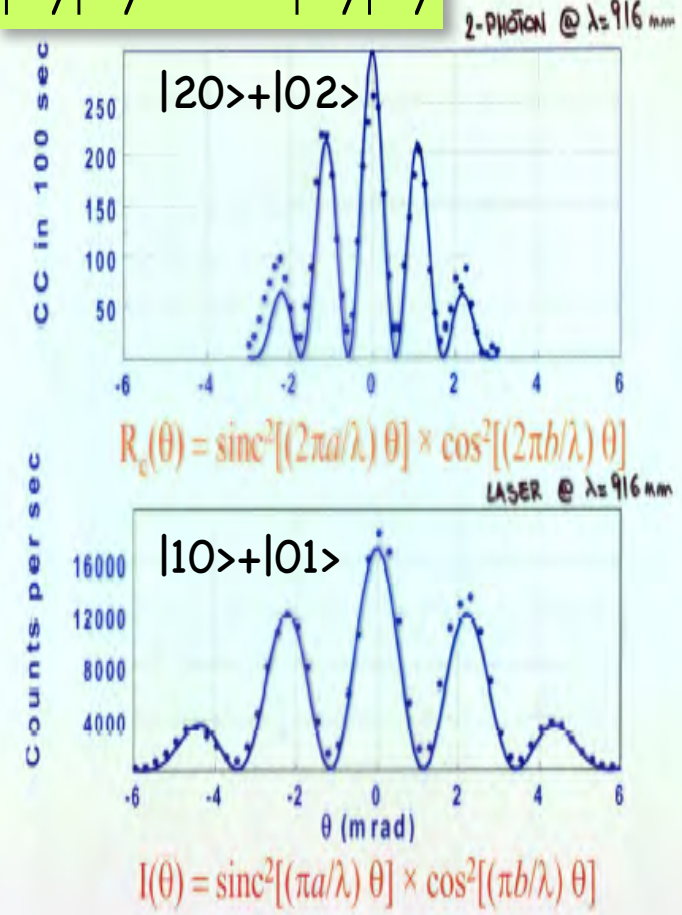
✓Double-slit VERY close to the crystal $\Rightarrow \Delta\phi << b/D$

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

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

Low N00N

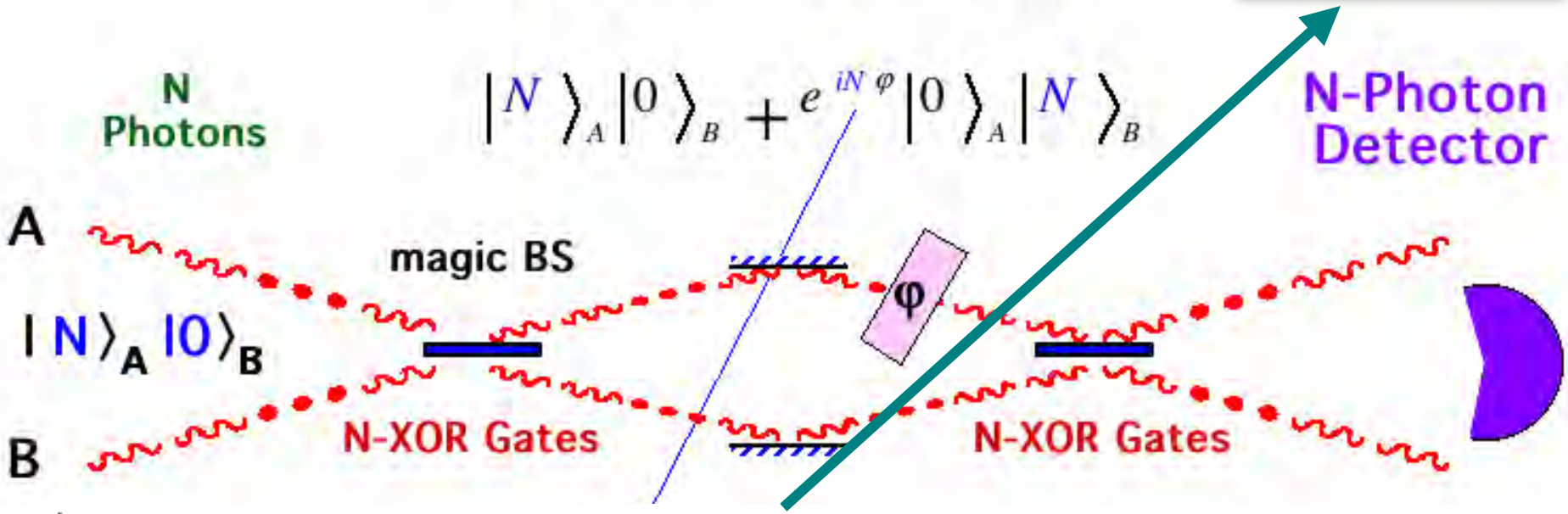
$|2\rangle|0\rangle + e^{i2\varphi}|0\rangle|2\rangle$



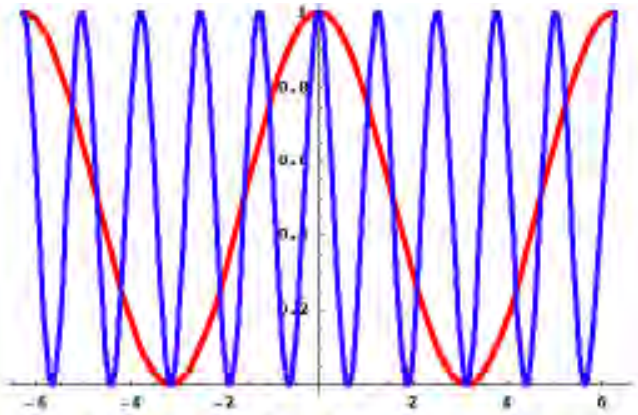
MACH-ZEHNDER INTERFEROMETER

Quantum Metrology

H.Lee, P.Kok, JPD, J Mod Opt **49**, (2002) 2325



† We call the state of the form $|N,\phi> + |\phi,N>$ the NOON state, and the High NOON state a large N.



Oscillates N times as fas

$$\frac{1+\cos\varphi}{2}$$ uncorrelated

$$\frac{1+\cos N\varphi}{2}$$ correlated

Shot noise

$\varphi = kx$

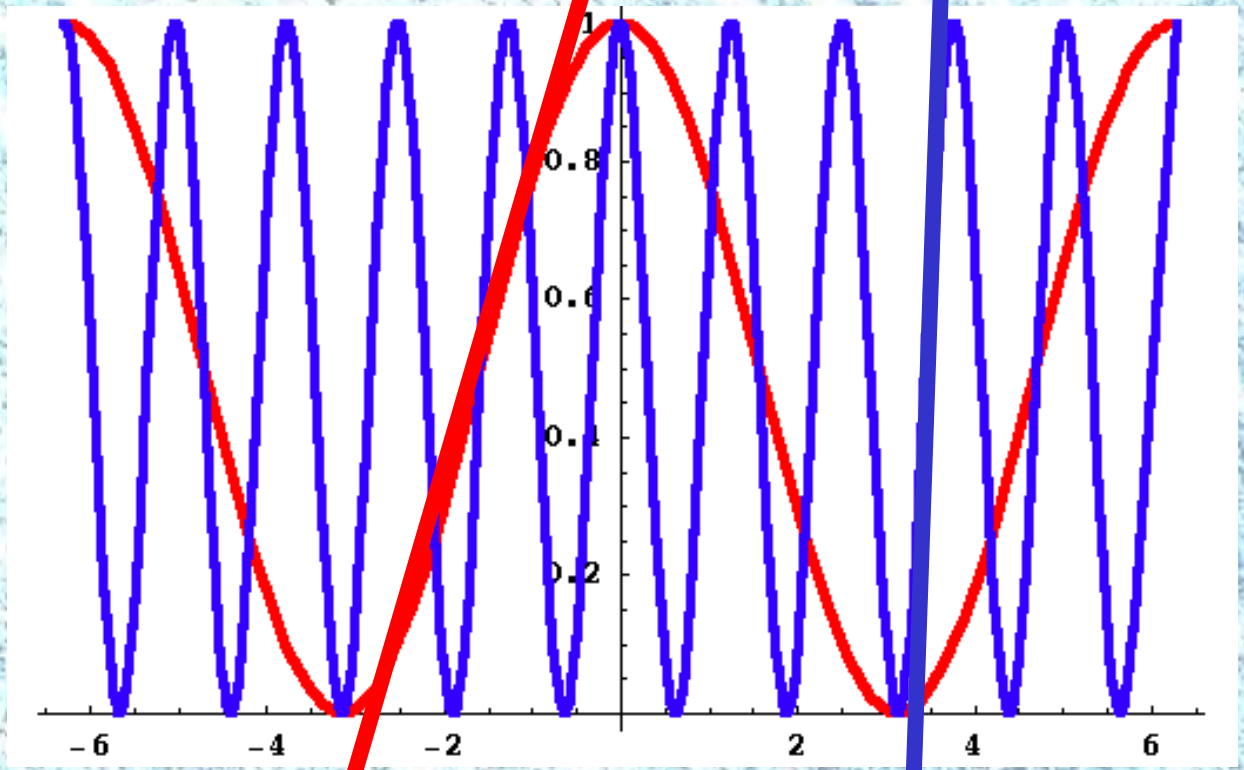
$\Delta\varphi: 1/\sqrt{N} \to 1/N$

Heisenberg

Quantum Metrology: Super-Sensitivity

N=1 (classical)
N=5 (N00N)

$$\Delta\varphi = \frac{\Delta\hat{P}}{\left| d\left\langle \hat{P} \right\rangle / d\varphi \right|}$$



$dP_N/d\varphi$

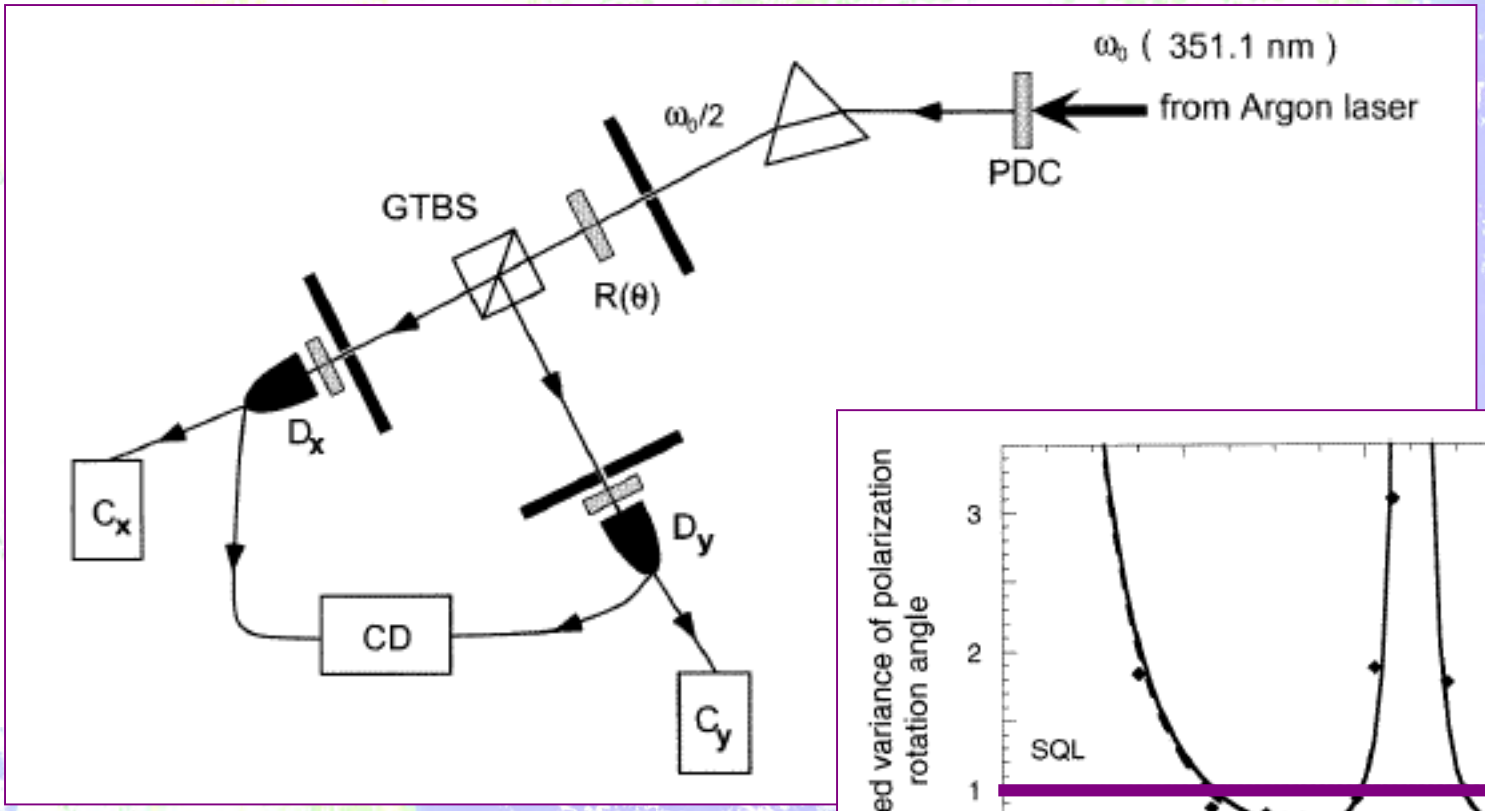
$dP_1/d\varphi$

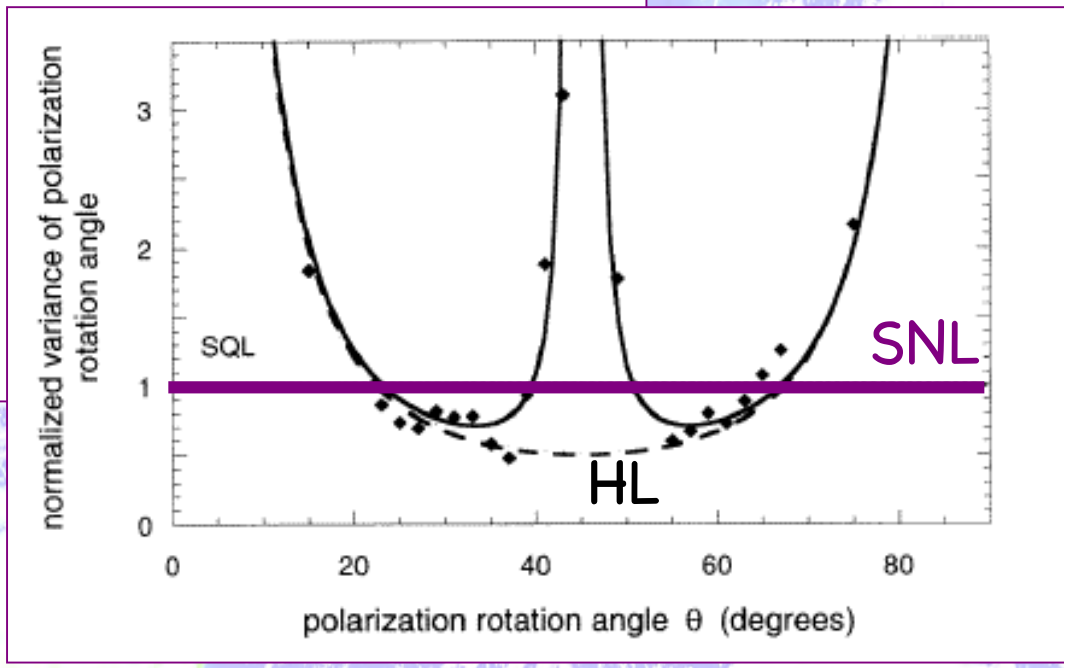
Shotnoise Limit:
$\Delta\varphi_1 = 1/\sqrt{N}$

Heisenberg Limit:
$\Delta\varphi_N = 1/N$

Sub-Shot-Noise Interferometric Measurements With Two-Photon N00N States

A Kuzmich and L Mandel; Quantum Semiclass. Opt. **10** (1998) 493–500.





Low N00N

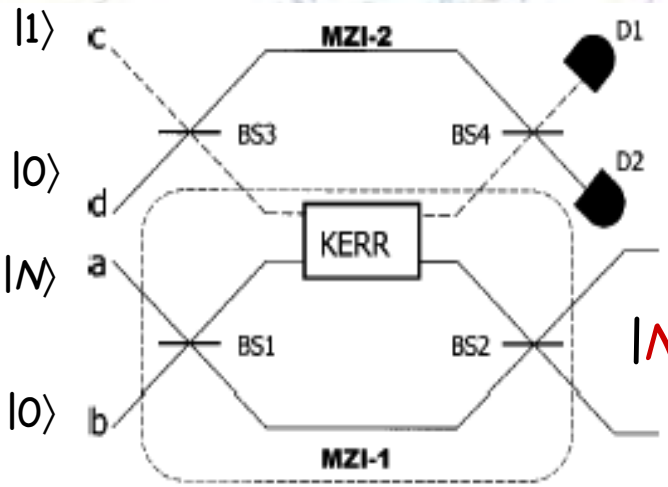
$$|2\rangle|0\rangle + e^{i2\varphi}|0\rangle|2\rangle$$

Showdown at High-NOON!

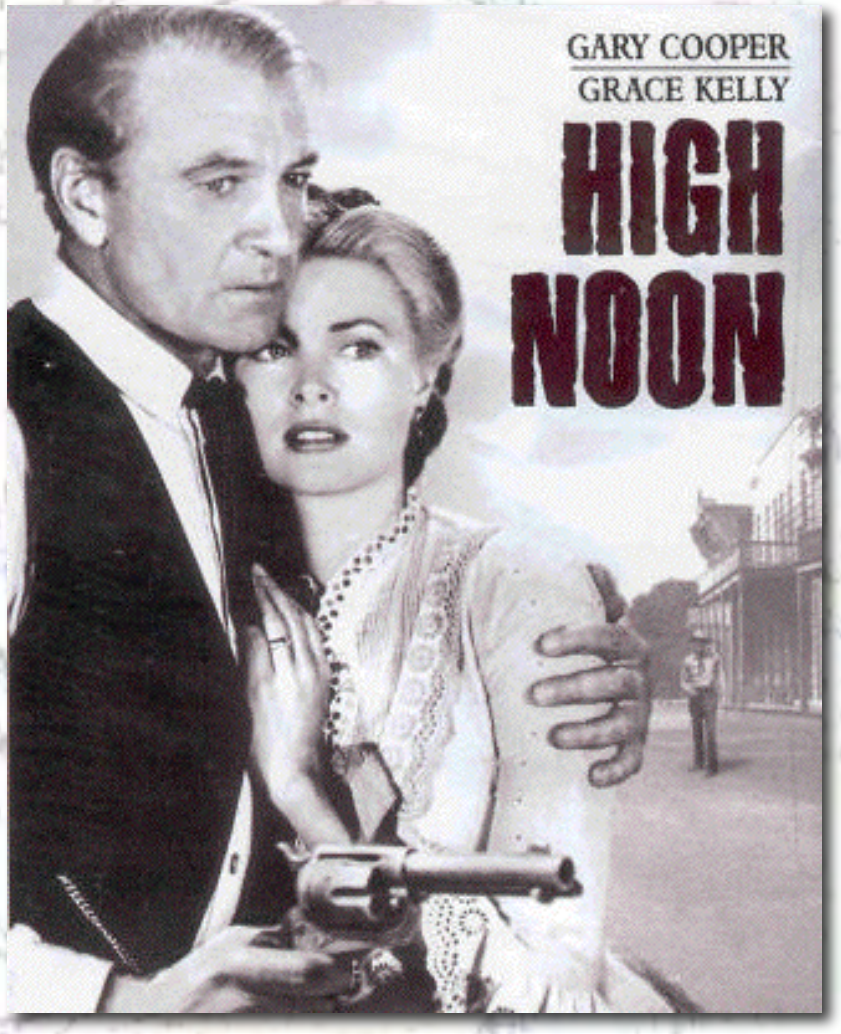
How do we make **High**-NOON!?

$$|N,0\rangle + |0,N\rangle$$

With a large cross-Kerr nonlinearity!* $H = \kappa\, a^\dagger a\, b^\dagger b$



$|N,0\rangle + |0,N\rangle$



This is not practical! — need $\kappa = \pi$ but $\kappa = 10^{-22}$!

*C Gerry, and RA Campos, *Phys. Rev. A* **64**, 063814 (2001).

WHY IS A KERR NONLINEARITY LIKE A PROJECTIVE MEASUREMENT?

Photon-Photon CNOT Gate

Linear Optical QC "KLM"

Cavity QED EIT

Photon-Photon Nonlinearity

!!!

Projective Measurement

Kerr Material

FIRST LINEAR-OPTICS BASED HIGH-N00N GENERATOR PROPOSAL

Success probability approximately 5% for 4-photon output.

Scheme conditions on the detection of one photon at each detector

mode *a*

mode *b*

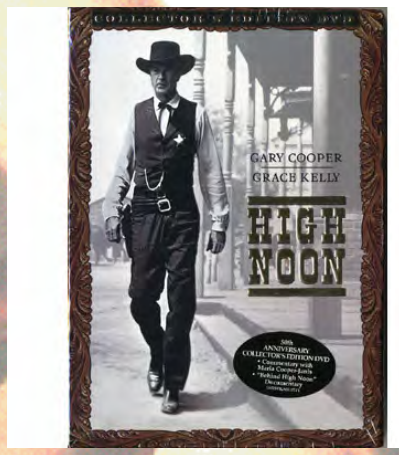
$|3\rangle_a|3\rangle_b$

e.g. component of light from an optical parametric oscillator

$|6\rangle_a|0\rangle_b$
$|4\rangle_a|2\rangle_b$
$|2\rangle_a|4\rangle_b$
$|0\rangle_a|6\rangle_b$

$|1\rangle_a|3\rangle_b$
$|3\rangle_a|1\rangle_b$

$|4\rangle_a|0\rangle_b - |0\rangle_a|4\rangle_b$

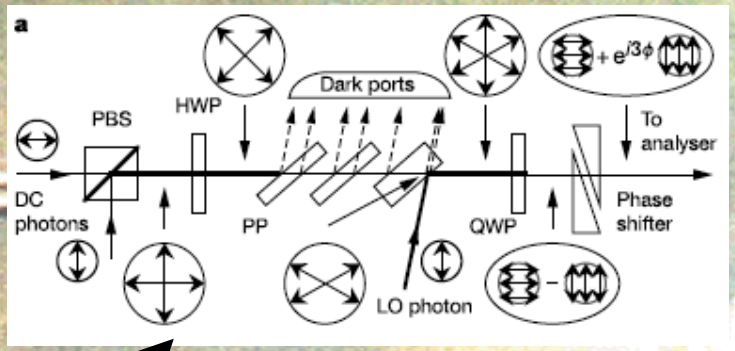


H Lee, P Kok, NJ Cerf and JP Dowling, PRA **65**, 030101 (2002).
JCF Matthews, A Politi, D Bonneau, JL O'Brien, PRL 107, 163602 (2011)

N00N State Experiments

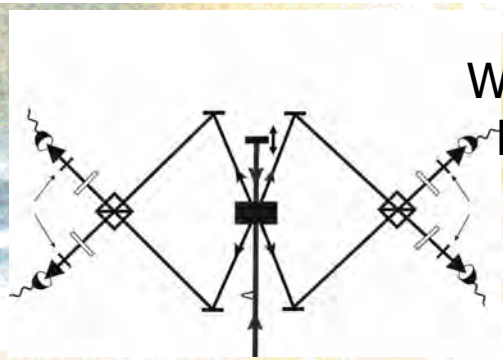
1990's
2-photon

Rarity, (1990)
Ou, et al. (1990)
Shih (1990)
Kuzmich (1998)
Shih (2001)



Mitchell,…,Steinberg
Nature (13 MAY)
Toronto

2004
3, 4-photon
Super-resolution only

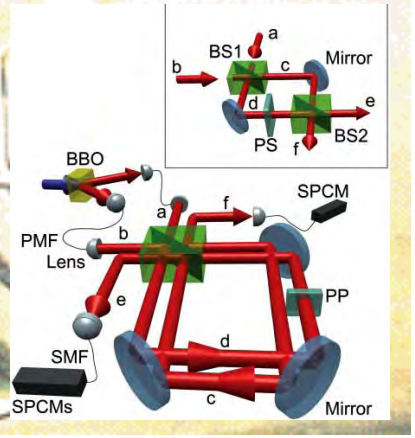


Walther,…,Zeilinger
Nature (13 MAY)
Vienna

6-photon Super-resolution Only!
Resch,…,White
PRL (2007)
Queensland

2007
4-photon
Super-sensitivity
&
Super-resolution

Nagata,…,Takeuchi,
Science (04 MAY)



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There's a Great Future in Entangled Photons!


Vielen Dank!