Quantum Lithography

From Quantum Metrology to Quantum Imaging—via Quantum Computing—and Back Again!

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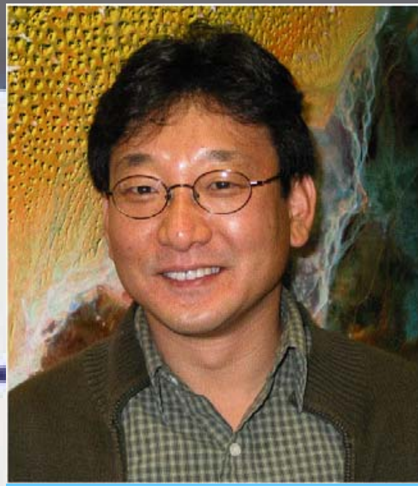
Quantum Imaging
MURI Kickoff
Rochester, 9 June 2005

JPL

Igor Kulikov, Deborah Jackson, JPD, Leo DiDomenico, Chris Adami, Ulvi Yurtsever, Hwang Lee, Federico Spedalieri, Marian Florescu, Vatche Sadarian

Not Shown:

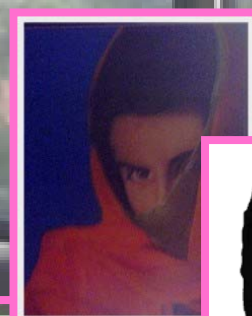
Colin Williams
Nicholas Cerf
Faroukh Vatan
George Hockney
Dima Strekalov
Dan Abrams
Matt Stowe
Lin Song
David Mitchell
Pieter Kok
Robert Gingrich
Lucia Florescu
Kishore Kapale
M. Ali Can
Alex Guillaume
Gabriel Durkin
Attila Bergou
Agedi Boto
Andrew Stimpson
Sean Huver
Greg Pierce
Erica Lively



Prof. Hwang Lee

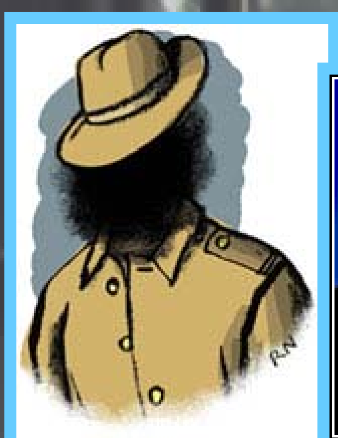
Dr. Pavel Lougovski

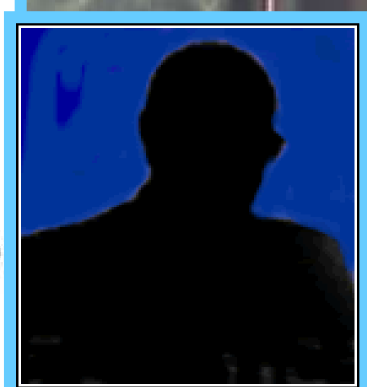
Dr. Hugo Cable

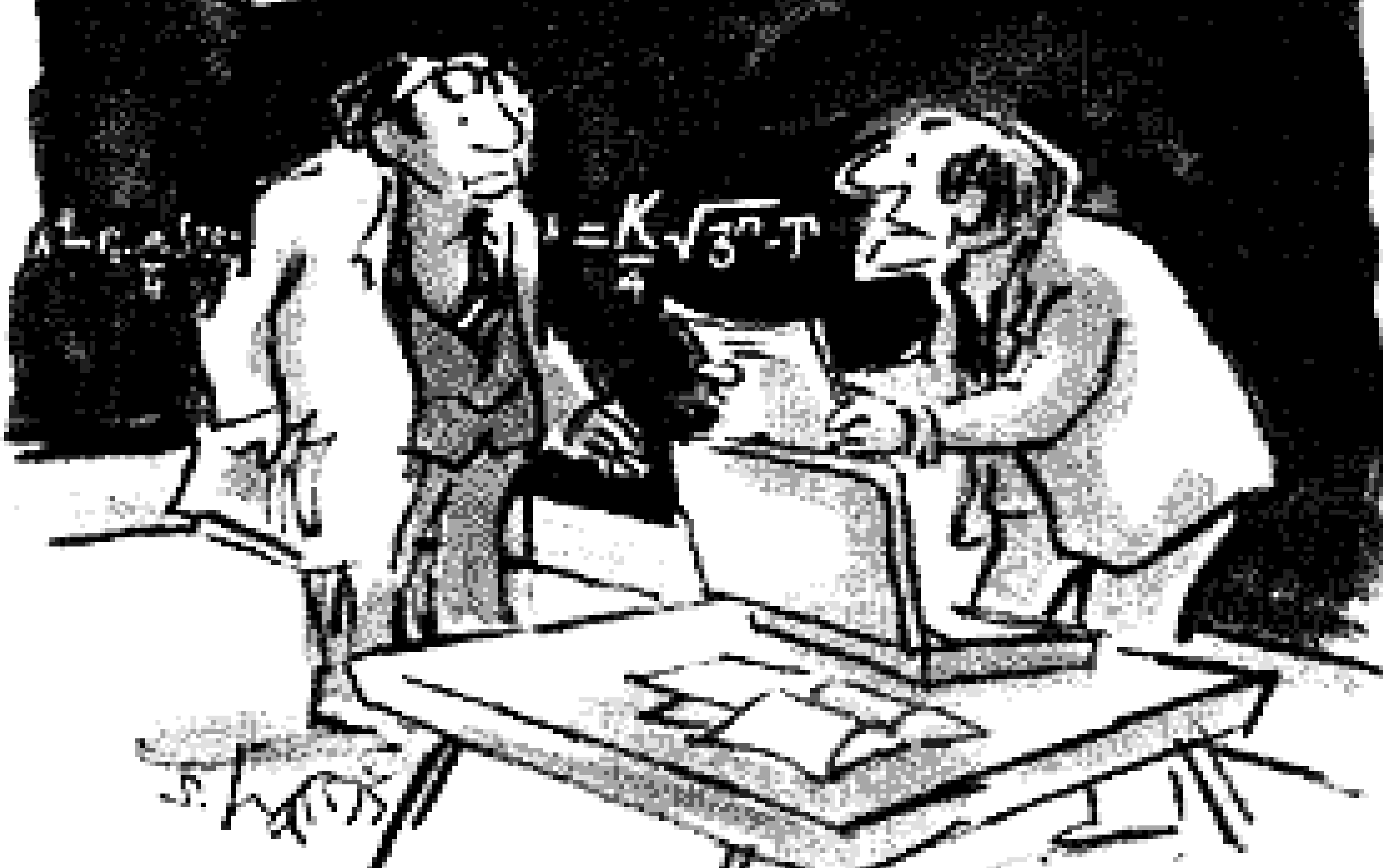


<u>Grads:</u>

- **Robert Beaird**
- **William Coleman**
- **Muxin Han**
- **Sean Huver**
- **Ganesh Selvaraj**
- **Sai Vinjanampathy**







"WHAT IT COMES DOWN TO IS THE GOVERNMENT WANTS TO KNOW HOW $\frac{K}{4}\sqrt{3^n}-T$ WILL HELP AMERICA."

Outline

1. Quantum Imaging, Metrology, & Computing
   - Heisenberg Limited Interferometry
   - The Quantum Rosetta Stone
   - The Road to Lithography
2. Quantum State Preparation
   - Nonlinearity from Projective Measurement
   - Show Down at High N00N!
3. Entangled N-Photon Absorption
   - Experiments with BiPhotons

Part I:

Quantum Metrology,

Imaging,

& Computing

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,*]

[1] *Jet Propulsion Laboratory, California Institute of Technology, Mail Stop 126-347, 4800 Oak Grove Drive, Pasadena, California 91109*

[2] *Informatics, University of Wales, Bangor LL57 1UT, United Kingdom*

(Received 4 January 2000)

Classical optical lithography is diffraction limited to writing features of a size $\lambda/2$ or greater, where λ is the optical wavelength. Using nonclassical photon-number states, entangled N at a time, we show that it is possible to write features of minimum size $\lambda/(2N)$ in an N-photon absorbing substrate. This result allows one to write a factor of N^2 more elements on a semiconductor chip. A factor of $N = 2$ can be achieved easily with entangled photon pairs generated from optical parametric down-conversion. It is shown how to write arbitrary 2D patterns by using this method.

PACS numbers: 42.50.Hz, 42.25.Hz, 42.65.–k, 85.40.Hp

Over 100 citations!

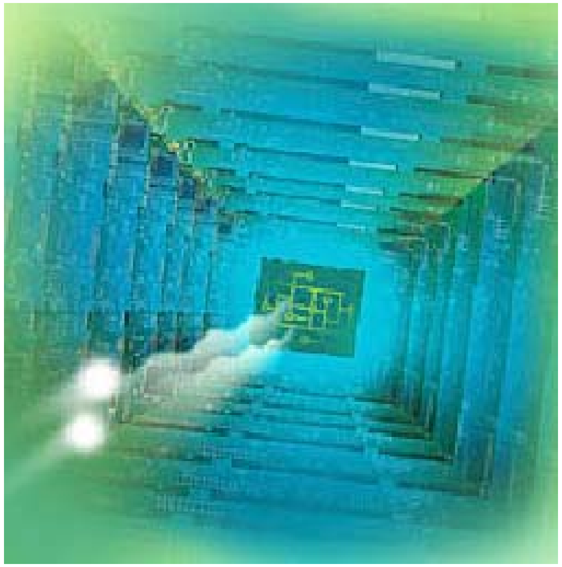
Has its own APS Physics & Astronomy Classification Scheme Number: PACS-42.50.St "Nonclassical interferometry, subwavelength lithography"

lithography

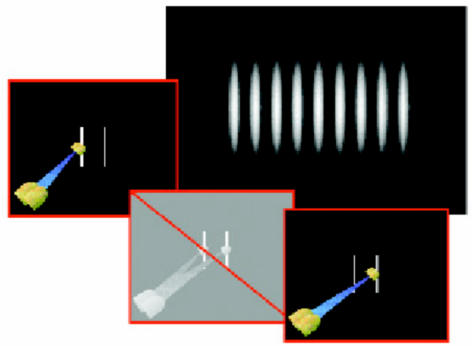
WHAT'S NEXT *New York Times*

Quantum Leap May Transform Chips

By IAN AUSTEN



Chicago Tribune



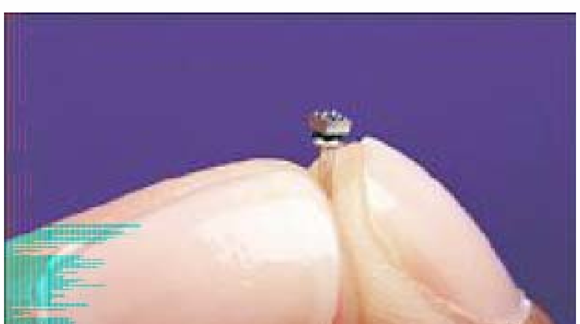
THE CHRISTIAN SCIENCE MONITOR

physics : Fine lines

PHILIP BALL **nature**

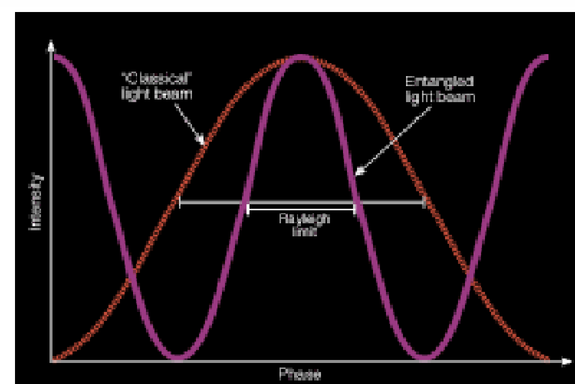
Science

Yoked Photons Break a Light Barrier

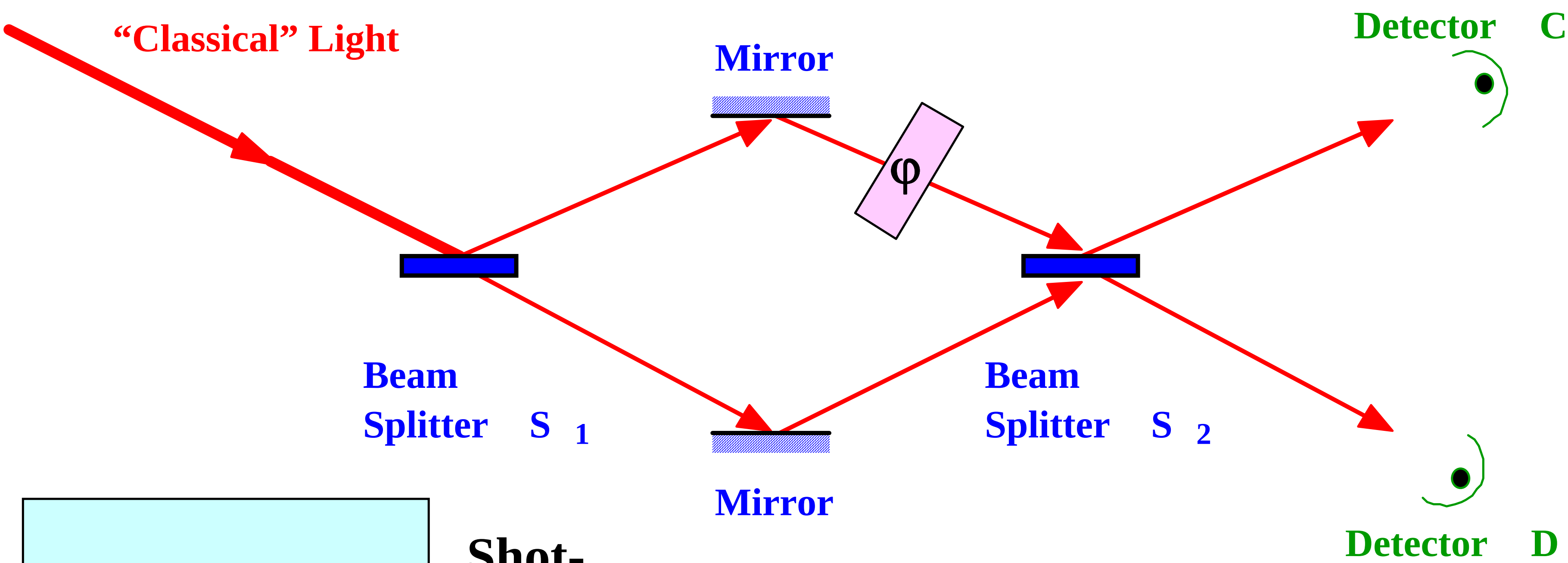


AMERICAN INSTITUTE OF PHYSICS

News Release
from Inside Science News Service



CLASSICAL OPTICAL INTERFEROMETER

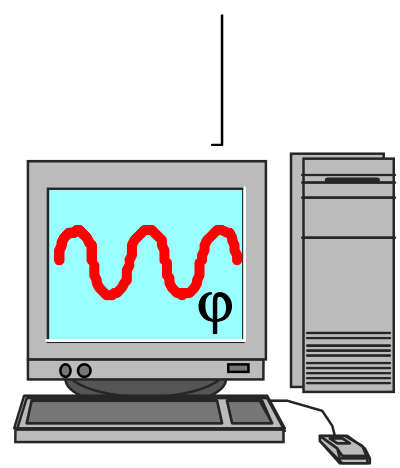


$$\Delta\varphi \propto \frac{1}{\sqrt{I}}$$

Shot-noise Limit

Phase Noise Scaling with Optical Intensity I .

$$\varphi = kx$$

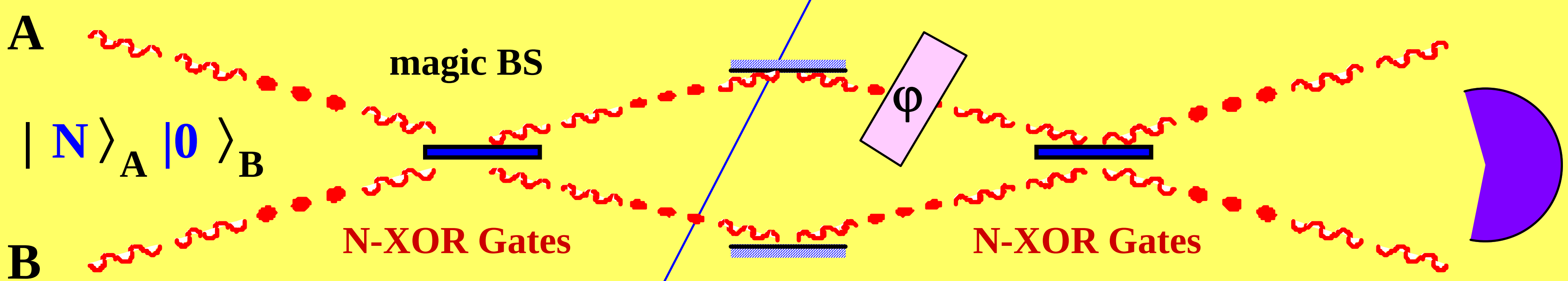


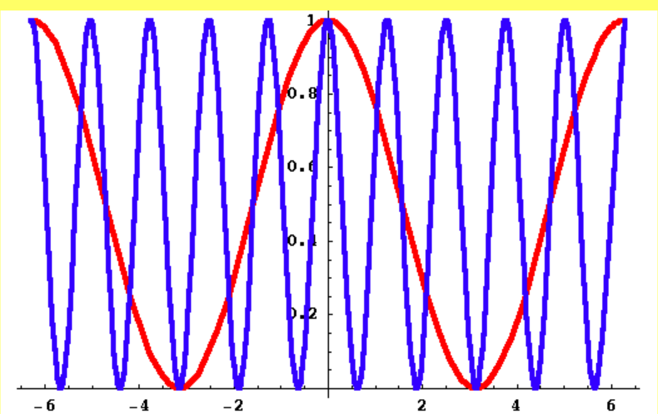
Entangled-State Interferometer

N Photons

$$|N\rangle_A |0\rangle_B + e^{iN\varphi} |0\rangle_A |N\rangle_B$$

N-Photon Detector





Oscillates N times as fast!

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

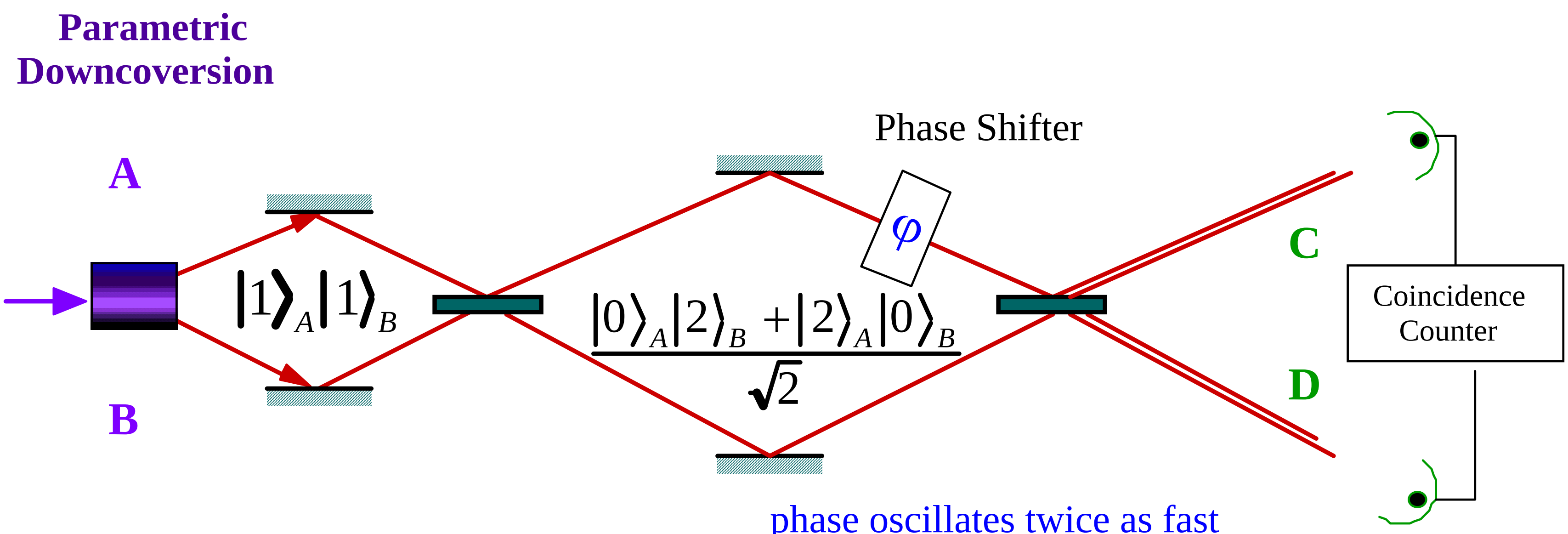
$$\frac{1+\cos N\varphi}{2}$$ **correlated**

Heisenberg Limit

$\varphi = \mathbf{kx}$

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

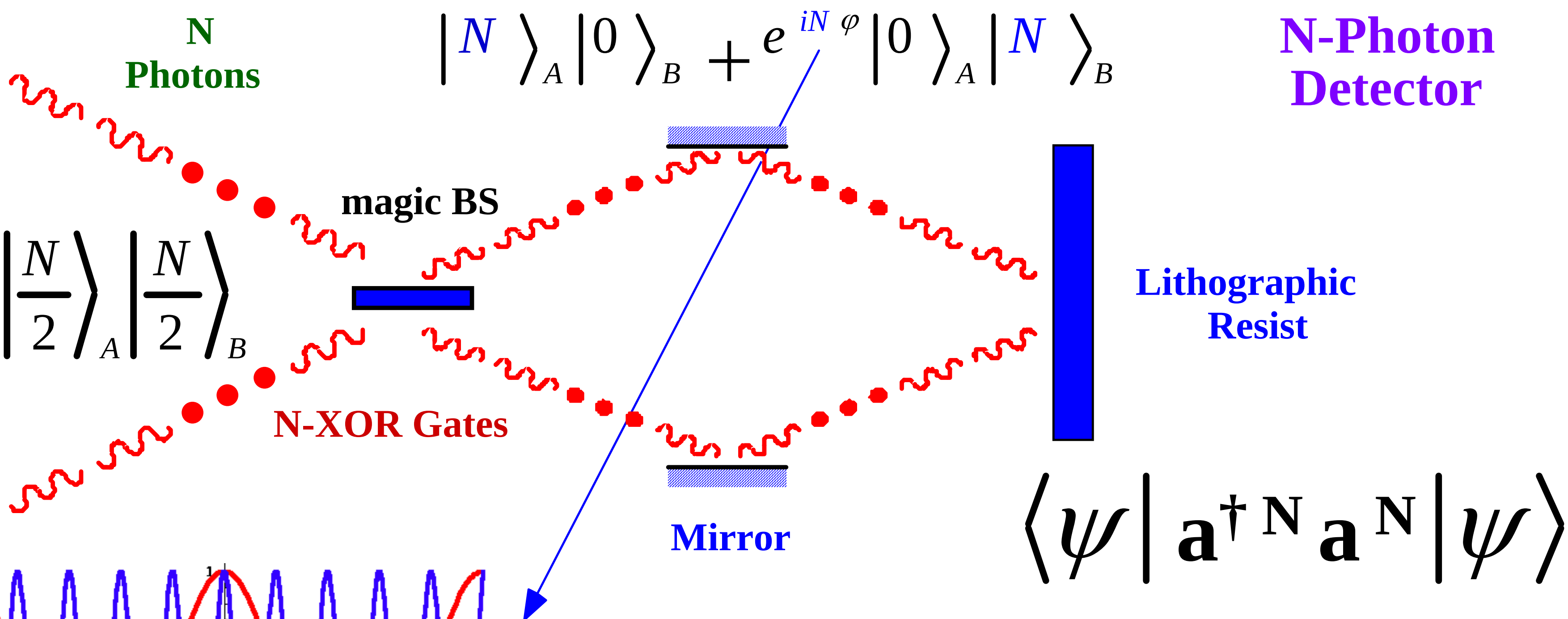
ORIGIN OF THE LITHO EFFECT
SHOMI FOR N=2

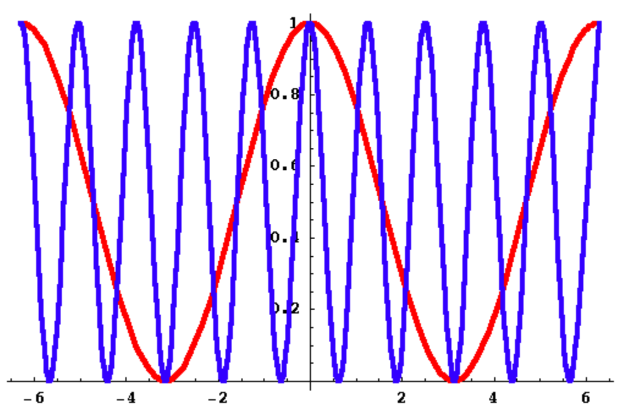


$$\frac{|0\rangle_A|2\rangle_B+|2\rangle_A|0\rangle_B}{\sqrt{2}} \rightarrow \frac{|0\rangle_A|2\rangle_B+e^{2i\varphi}|2\rangle_A|0\rangle_B}{\sqrt{2}}$$

FROM QUANTUM INTERFEROMETRY TO QUANTUM LITHOGRAPHY

Agedi N. Boto, Daniel S. Abrams, Colin P. Williams, and Jonathan P. Dowling, *Physical Review Letters* **85** (25 September 2000) 2733–2736





Oscillates in REAL Space!

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

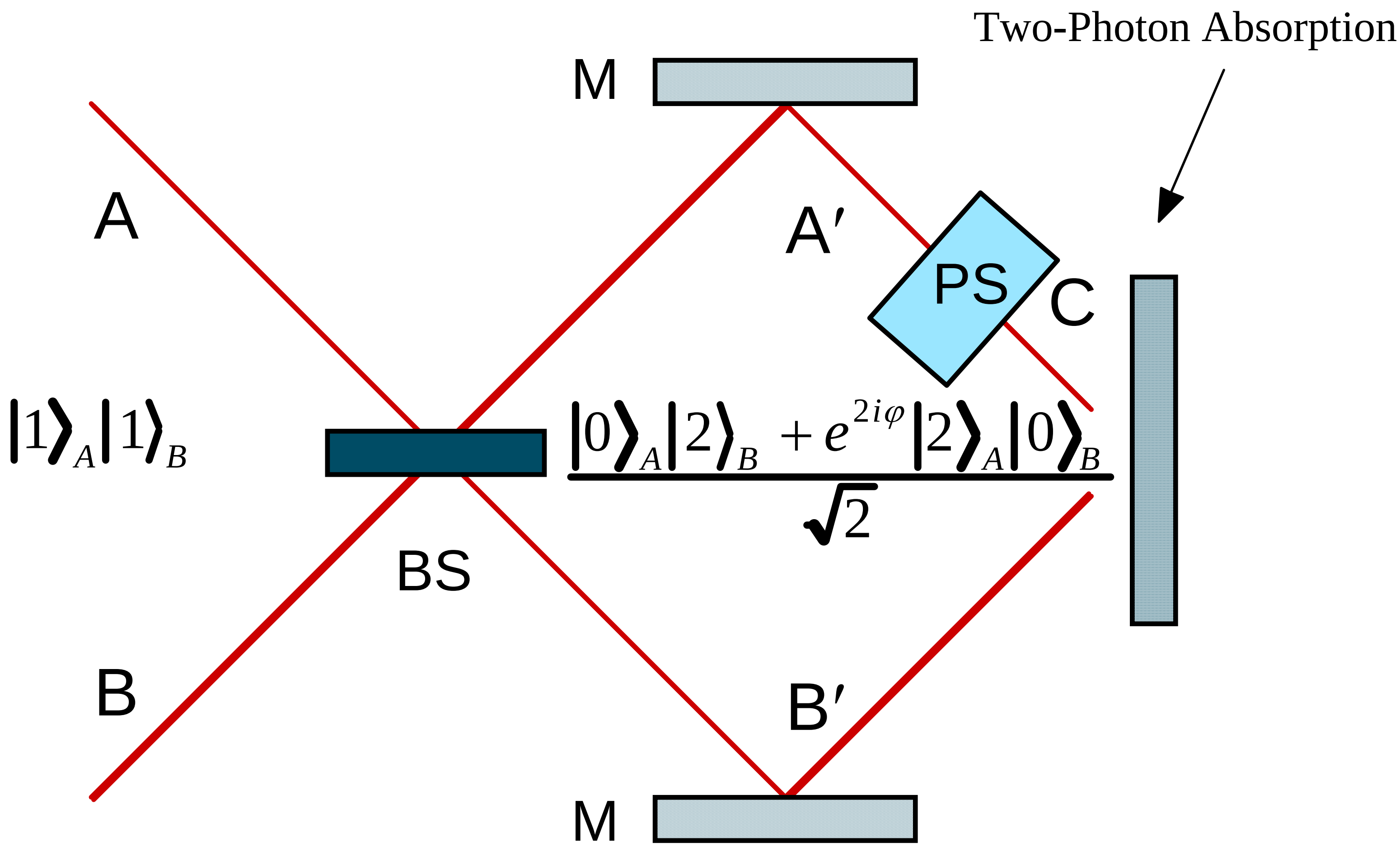
$$\frac{1+\cos N\varphi}{2}$$ **correlated**

φ = **kx**

φ →Nφ

λ →λ/N

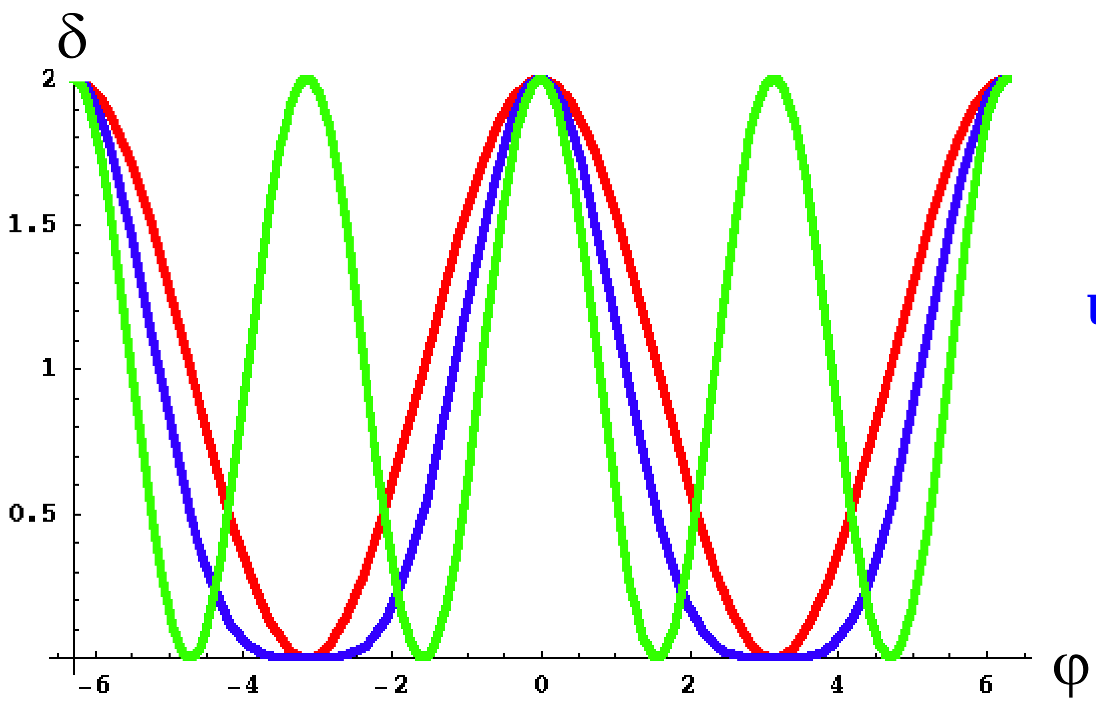
EASY (BUT USELESS?) FOR N=2



Parametric Downcoversion

TWO-PHOTON ABSORPTION RATE

$$\hat{\delta}_N = \left(\hat{e}^\dagger\right)^N \left(\hat{e}\right)^N / N!$$ **deposition operator**



1-photon

$$1 + \cos\varphi$$

uncorrelated 2-photon

$$\left(1 + \cos\varphi\right)^2$$

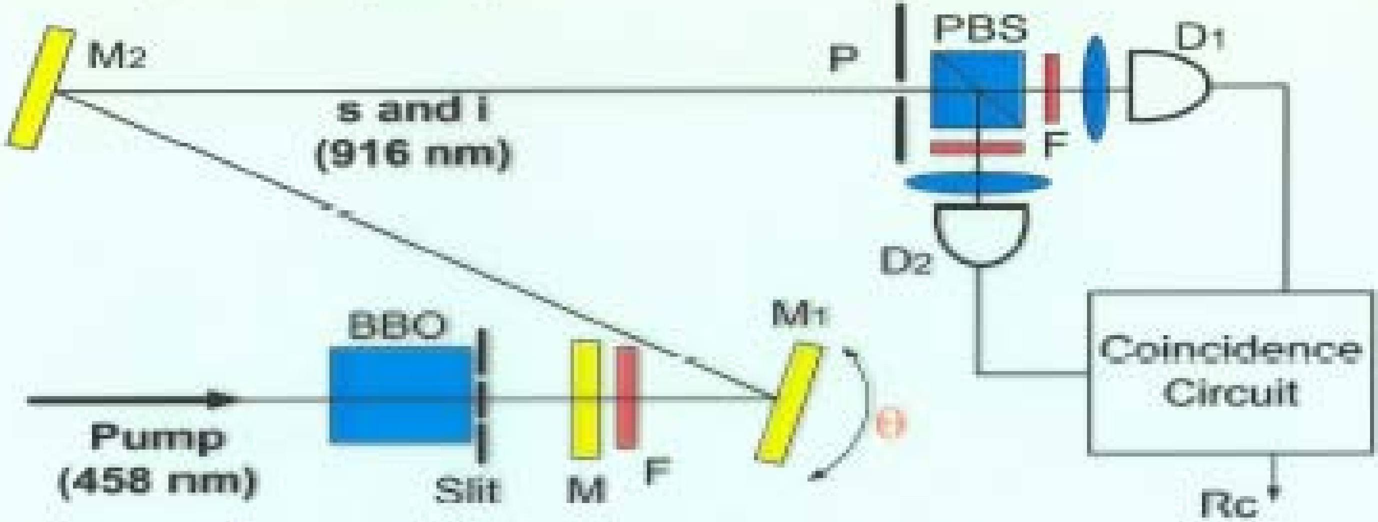
correlated 2-photon

$$1 + \cos 2\varphi$$

Beats Rayleigh Diffraction Limit by Factor of Two!

Quantum lithography: setup

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



Two-photon source: Degenerate Collinear type-II SPDC

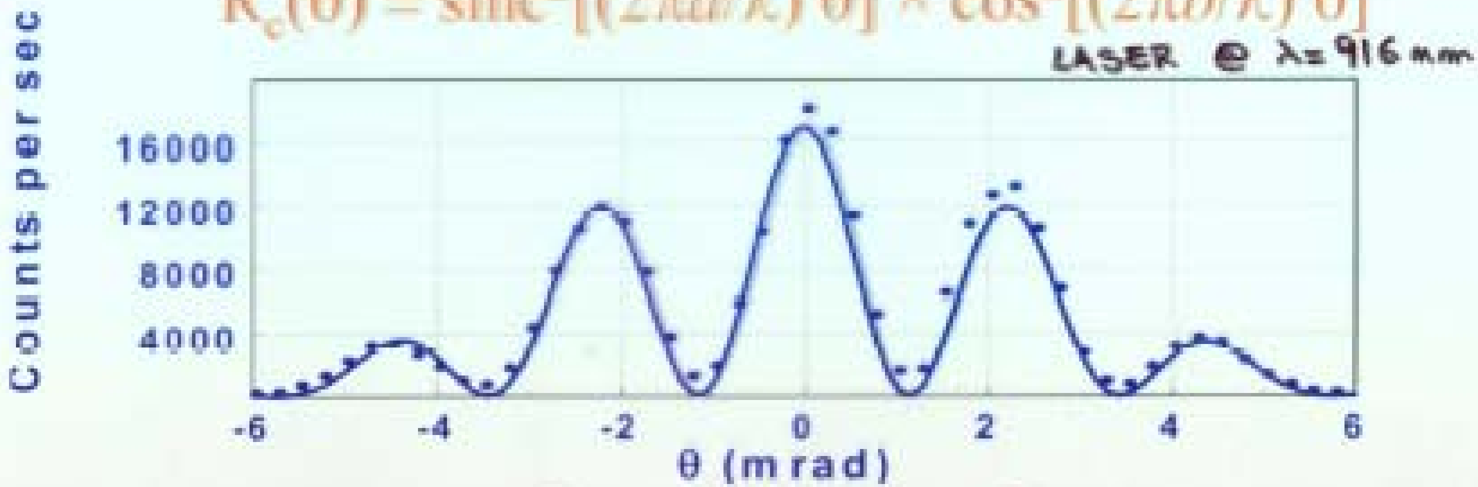
✓Double-slit VERY close to the crystal ⇒ $\Delta\phi << b/\mathrm{D}$

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

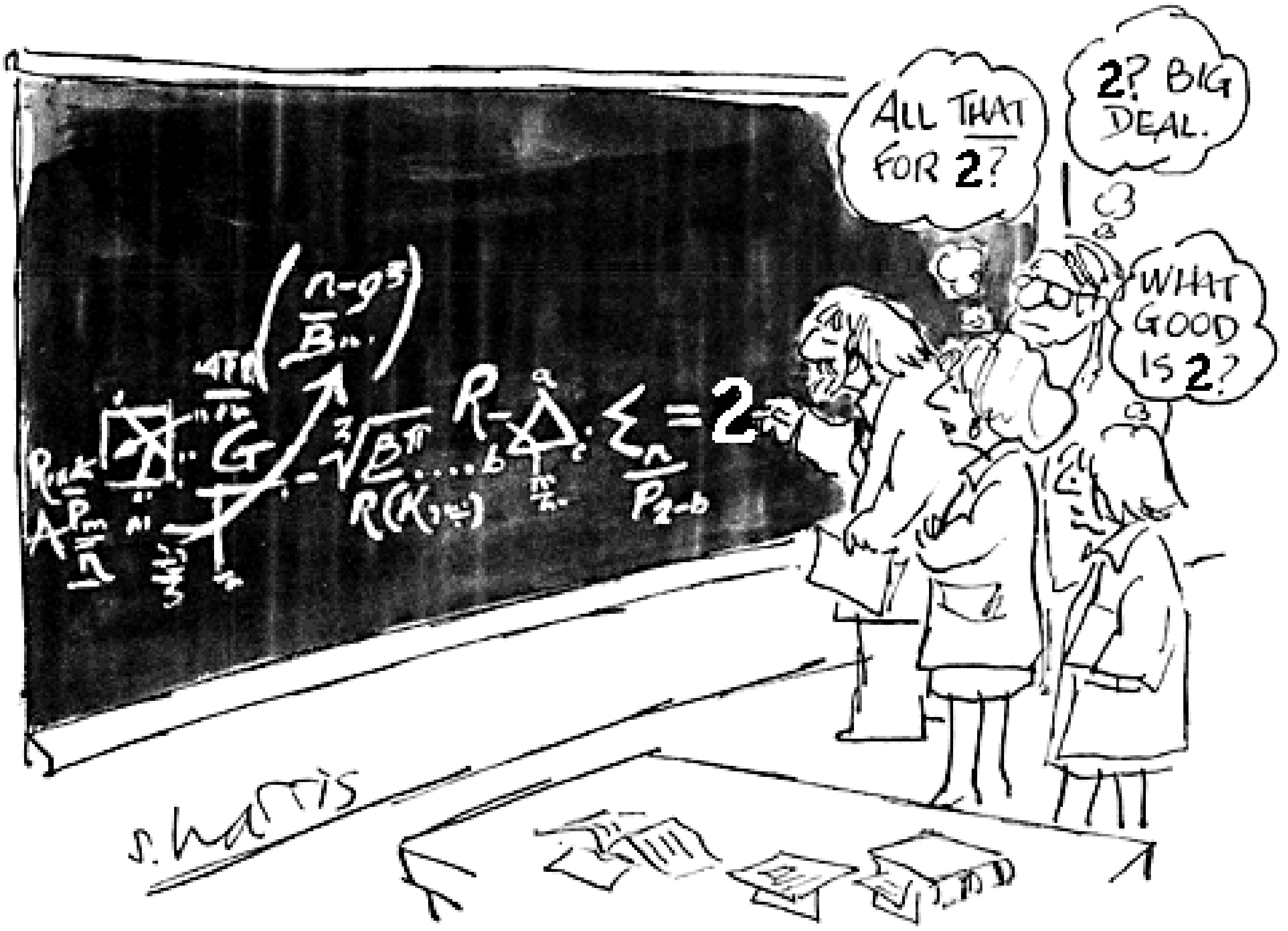
$\Delta\phi$=scattering angle inside the crystal; b=distance between slits; D=distance between input face of crystal and double slit

Results

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



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


ALL THAT FOR 2?
2? BIG DEAL.
WHAT GOOD IS 2?
S. Harris

Part II: Quantum State Preparation — How High is "High N00N*"?

*Rejected terms: Big "0NN0" and Large "P00P" States….

Canonical Metrology: Quantum Informatic Point of View

Suppose we have an ensemble of N states $|\varphi\rangle = (|0\rangle + e^{i\varphi}|1\rangle)/\sqrt{2}$,
and we measure the following observable: $A = |0\rangle\langle 1| + |1\rangle\langle 0|$

The expectation value is given by: $\langle\varphi|A|\varphi\rangle = N\cos\varphi$
and the variance $(\Delta A)^2$ is given by: $N(1-\cos^2\varphi)$

The unknown phase can be estimated with accuracy:

$$\Delta\varphi = \frac{\Delta A}{|d\langle A\rangle/d\varphi|} = \frac{1}{\sqrt{N}}$$

note the square-root

This is the standard shot-noise limit.

"Quantum Lithography, entanglement and Heisenberg-limited parameter estimation," Pieter Kok, Samuel L. Braunstein, and Jonathan P. Dowling, Journal of Optics B 6, (27 July 2004) S811-S815

Quantum Lithography & Metrology

Now we consider the state $|\varphi_N\rangle = (|N,0\rangle + |0,N\rangle)/\sqrt{2}$,

and we measure $A_N = |0,N\rangle\langle N,0| + |N,0\rangle\langle 0,N|$

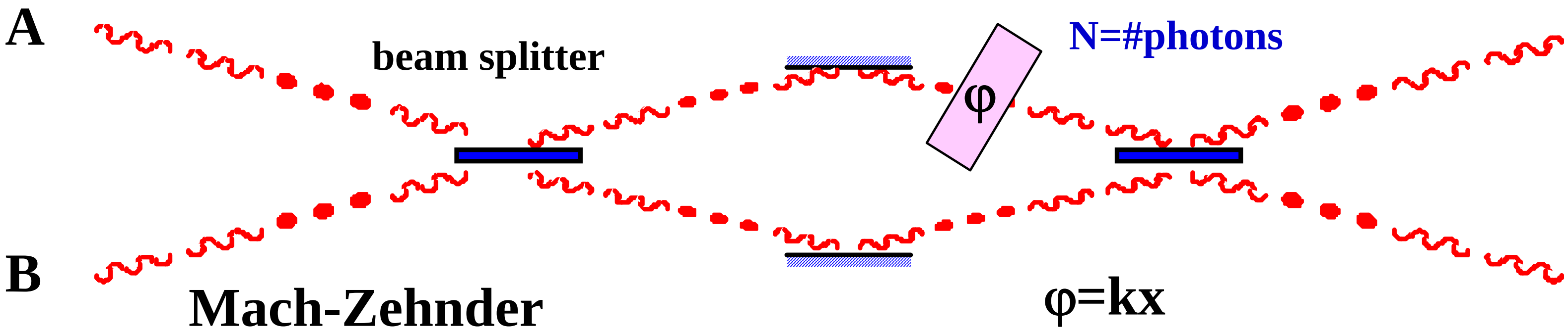
Quantum Lithography*: $\langle \varphi_N | A_N | \varphi_N \rangle = \cos N\varphi$ ← high Frequency (litho effect)

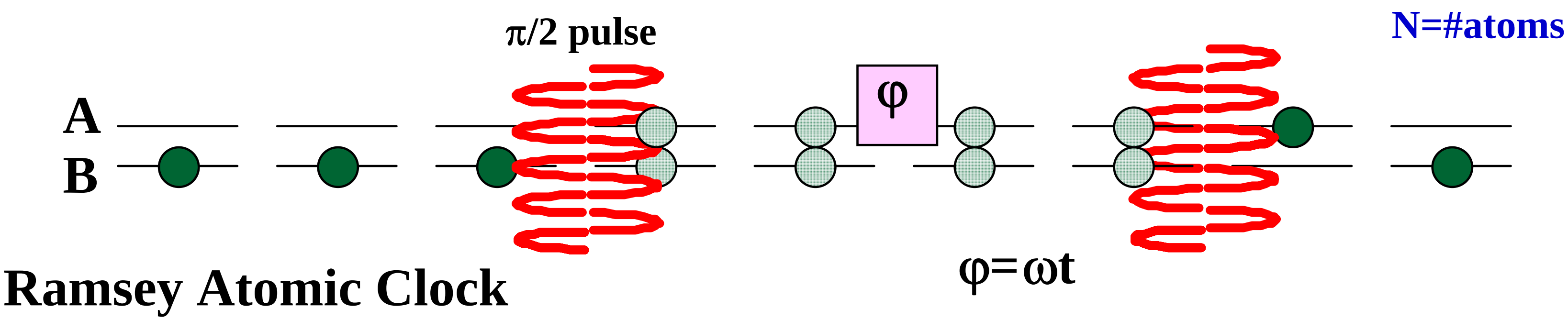
Quantum Metrology: $$\Delta\varphi_H = \frac{\Delta A_N}{|d\langle A_N\rangle/d\varphi|} = \frac{1}{N}$$ ← no square-root!

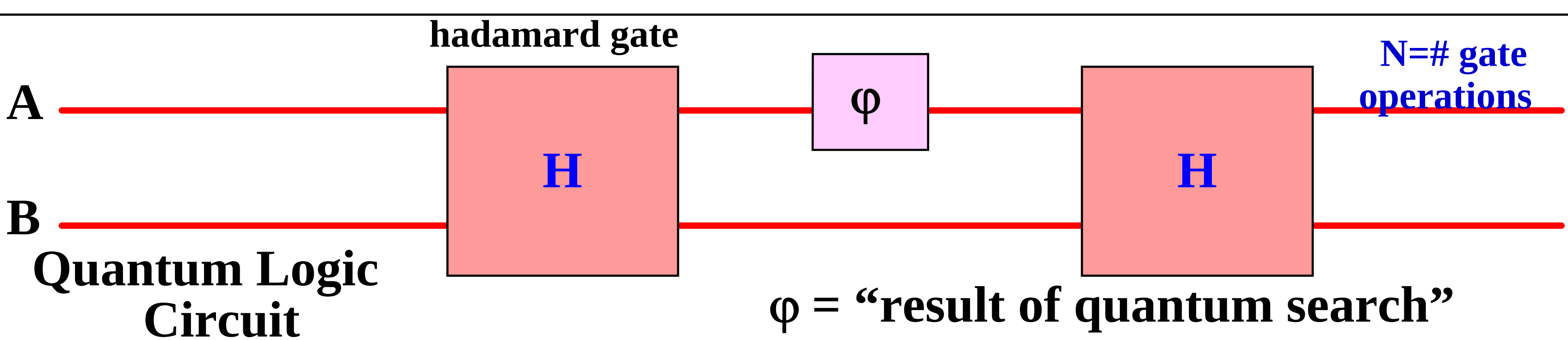
*A.N. Boto, P. Kok, D.S. Abrams, S.L. Braunstein, C.P. Williams, and J.P. Dowling, *Phys. Rev. Lett.* **85**, 2733 (2000).
P. Kok, H. Lee, and J.P. Dowling, *Phys. Rev. A* **65**, 052104 (2002).

FROM QUANTUM COMPUTING TO QUANTUM INTERFEROMETRY

Entanglement gives $1/\sqrt{N}$ to $1/N$ resolution improvement in each case!







ATOMIC CLOCK INTERFEROMETER

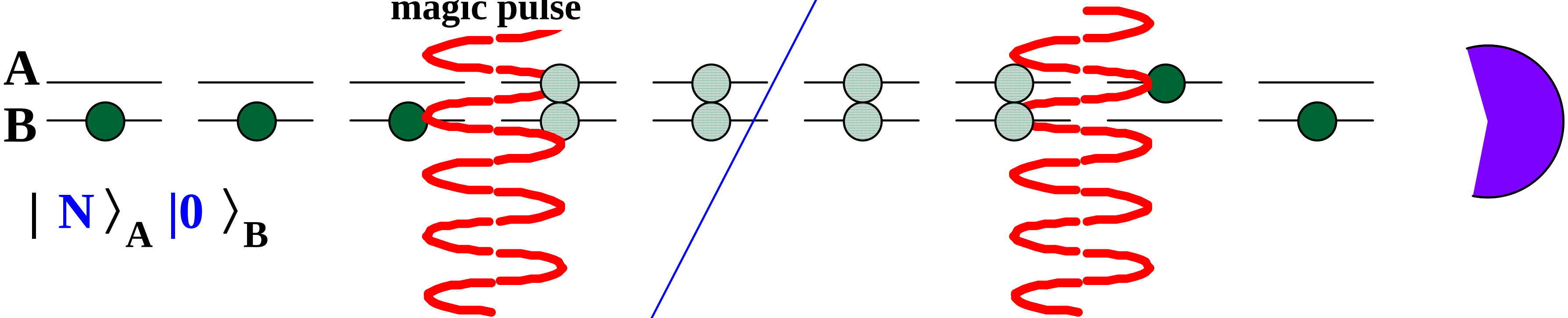
S. F. Huelga, C. Macchiavello, T. Pellizzar, A. K. Ekert, M. B. Plenio, and J. I. Cirac, Phys. Rev. Lett. 79, 3865 1997.

N Two-Level Atoms

$$|N\rangle_A|0\rangle_B + e^{iN\varphi}|0\rangle_A|N\rangle_B$$

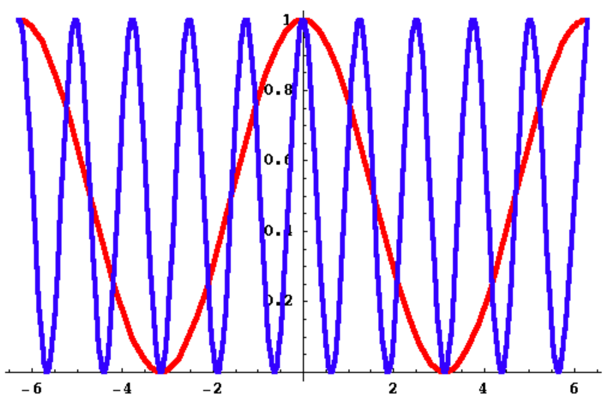
N-Atom Detector

magic pulse



$|N\rangle_A |0\rangle_B$

N-XOR Gates **N-XOR Gates**



Oscillates N times as fast!

Requires Strong Nonlinearity!

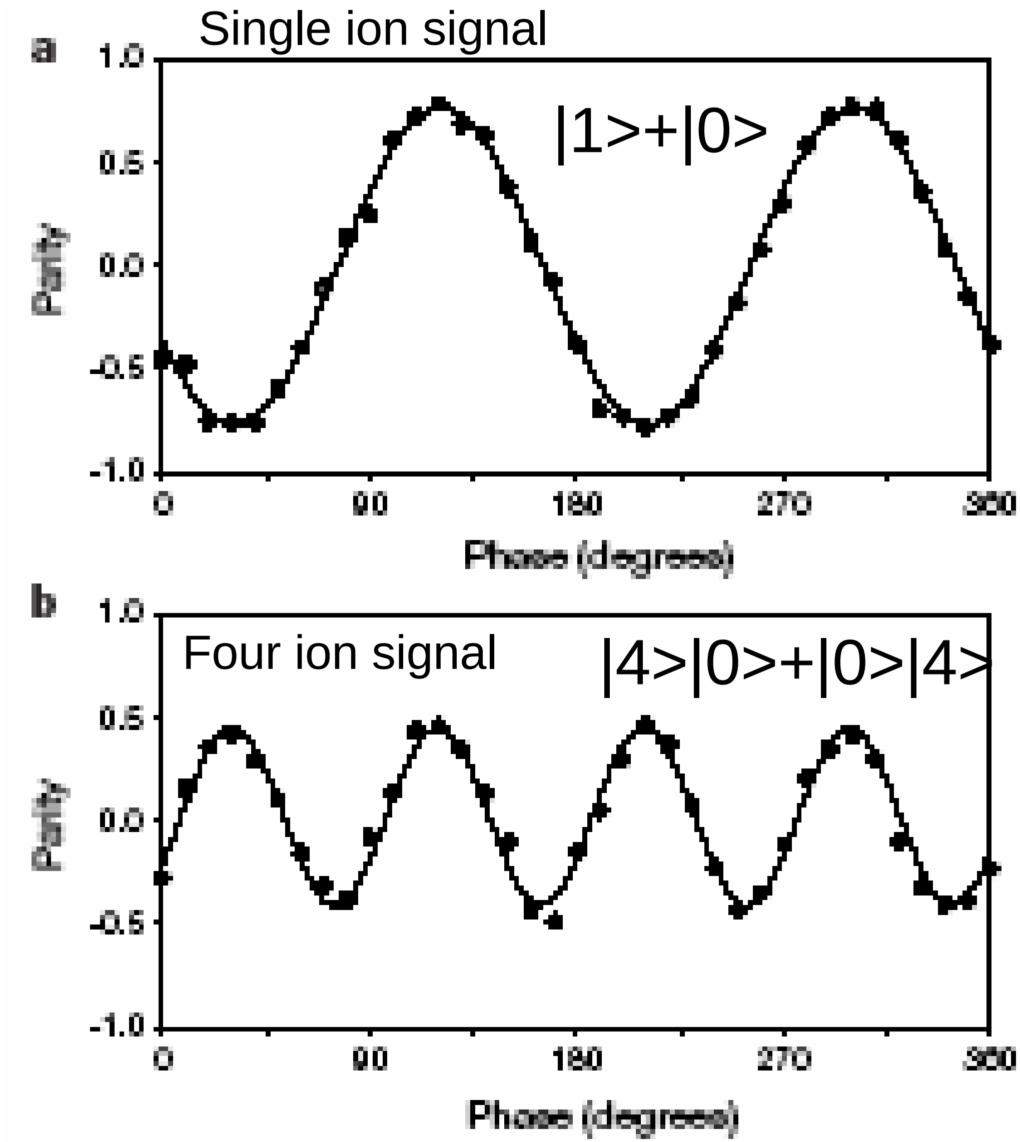
$$\frac{1+\cos\varphi}{2}$$ **uncorrelated**

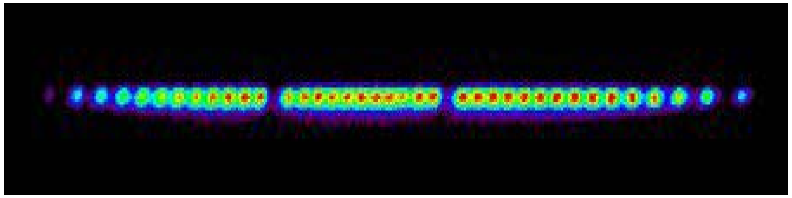
$$\frac{1+\cos N\varphi}{2}$$ **correlated**

$\varphi = \omega T$

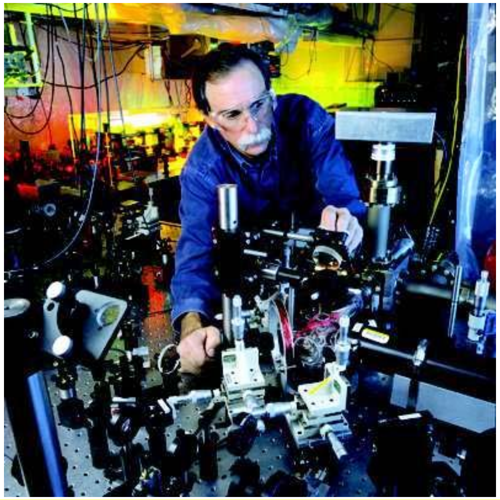
$\Delta\varphi: 1/\sqrt{N} \rightarrow 1/N$

Experimental N00N State of Four Ions in Atomic Clock Quantum Computer





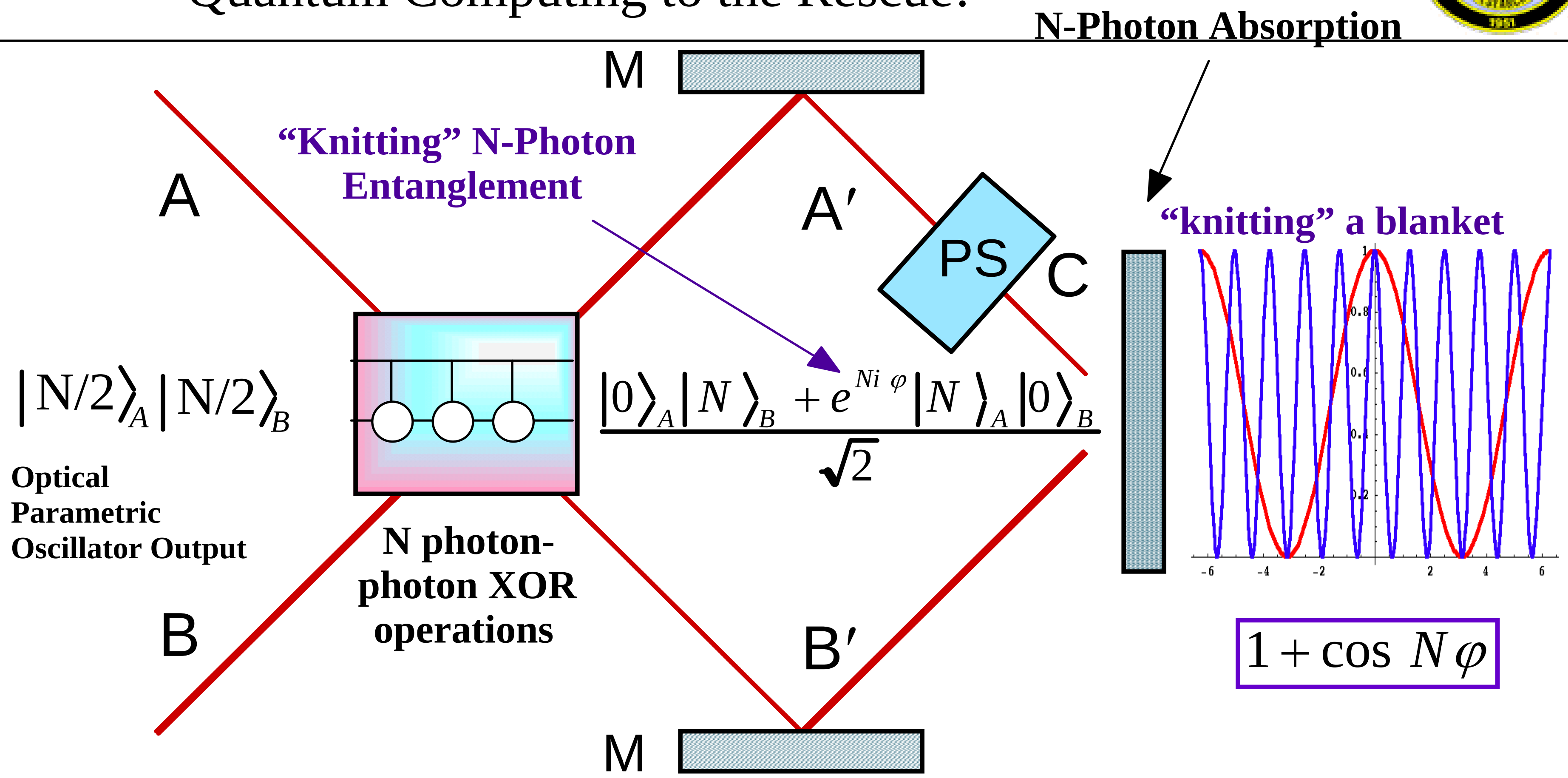
Trapped Ions



Sackett CA, Kielpinski D, King BE, Langer C, Meyer V, Myatt CJ, Rowe M, Turchette QA, Itano WM, Wineland DJ, Monroe IC
NATURE 404 (6775): 256-259 MAR 16 2000

THE CASE FOR GENERAL N

Quantum Computing to the Rescue!



Beats Rayleigh Diffraction Limit by Factor of N (!)

The Importance of CNOT

If we want to manipulate quantum systems for communication and computation, we must be able to do logical operations on the quantum bits (or qubits).

In particular, we need the so-called controlled-NOT that acts on two qubits:

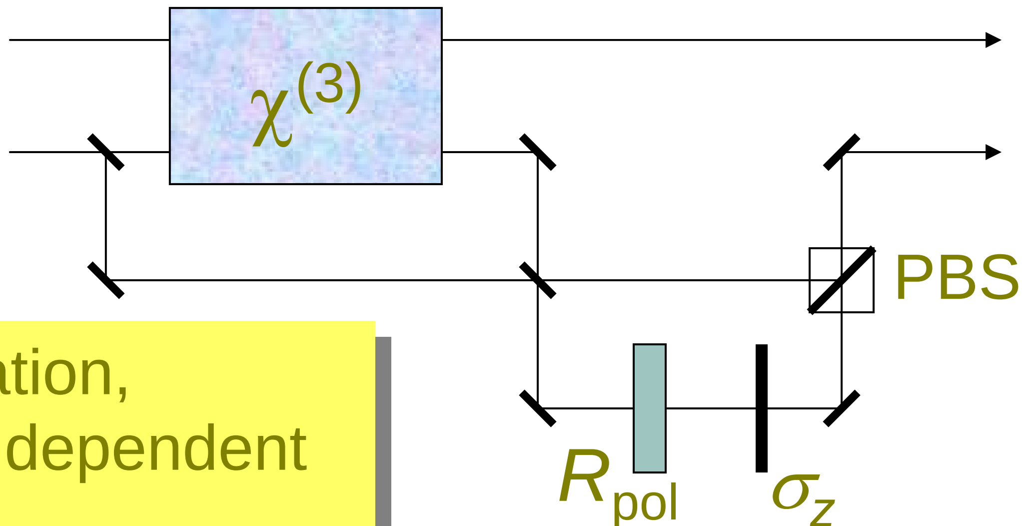
$$|0\rangle\,|0\rangle \rightarrow |0\rangle\,|0\rangle$$
$$|0\rangle\,|1\rangle \rightarrow |0\rangle\,|1\rangle$$
$$|1\rangle\,|0\rangle \rightarrow |1\rangle\,|1\rangle$$
$$|1\rangle\,|1\rangle \rightarrow |1\rangle\,|0\rangle$$

The first stays the same, and the second flips iff the first is a **1.**
This means we need a NONLINEAR photon-photon interaction.

Optical CNOT with Nonlinearity

The controlled-NOT can be implemented using a Kerr medium:

$|0\rangle = |H\rangle$ Polarization
$|1\rangle = |V\rangle$ Qubits



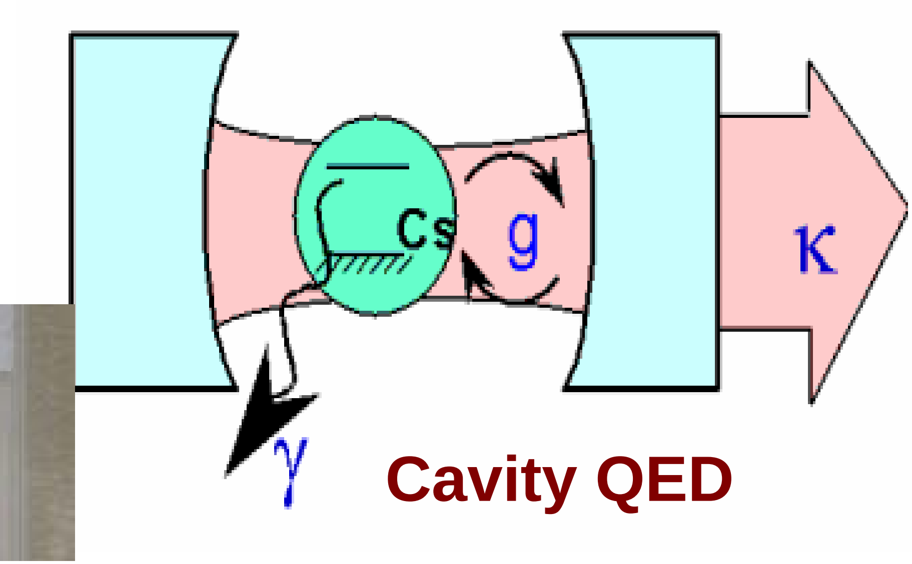
R is a $\pi/2$ polarization rotation, followed by a polarization dependent phase shift π.

Unfortunately, the interaction $\chi^{(3)}$ is extremely weak*: 10^{-22} at the single photon level — This is **not practical**!

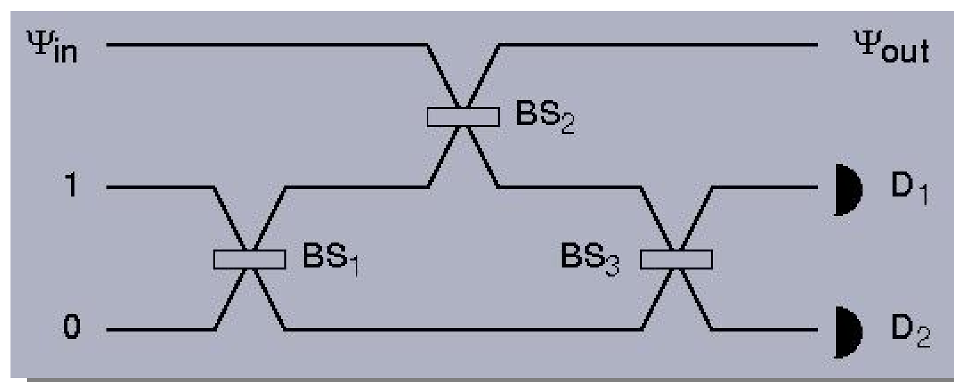
*R.W. Boyd, *J. Mod. Opt.* **46**, 367 (1999).

Two Roads to Photon C-NOT

I. Enhance Nonlinear Interaction with a Cavity, EIT, etc., — Kimble, Haroche, *et al.*



II. Exploit Nonlinearity of Measurement — Knill, LaFlamme, Milburn, Franson, et *al.*



The K.L.M. paper*

Qubits are represented by a photon in two optical modes:

Using path-entanglement, extra optical modes and **projective measurements**, we can do quantum gates, including CNOT.

The big surprise is that we can do this efficiently without Kerr!

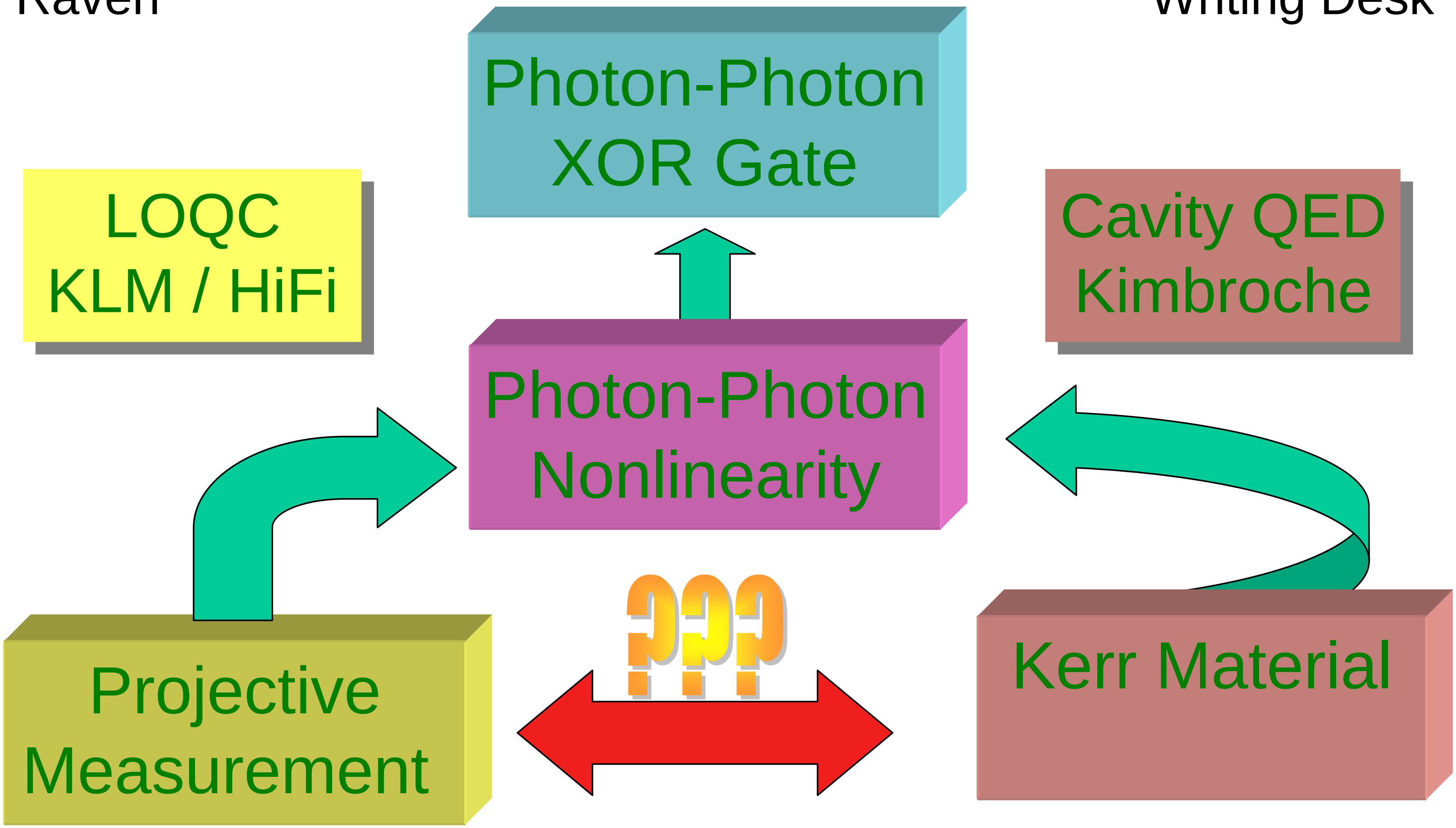
Quantum computing may still be a long shot, but what about quantum **metrology** and quantum **communication**?

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

WHEN IS A KERR NONLINEARITY LIKE A PROJECTIVE MEASUREMENT?

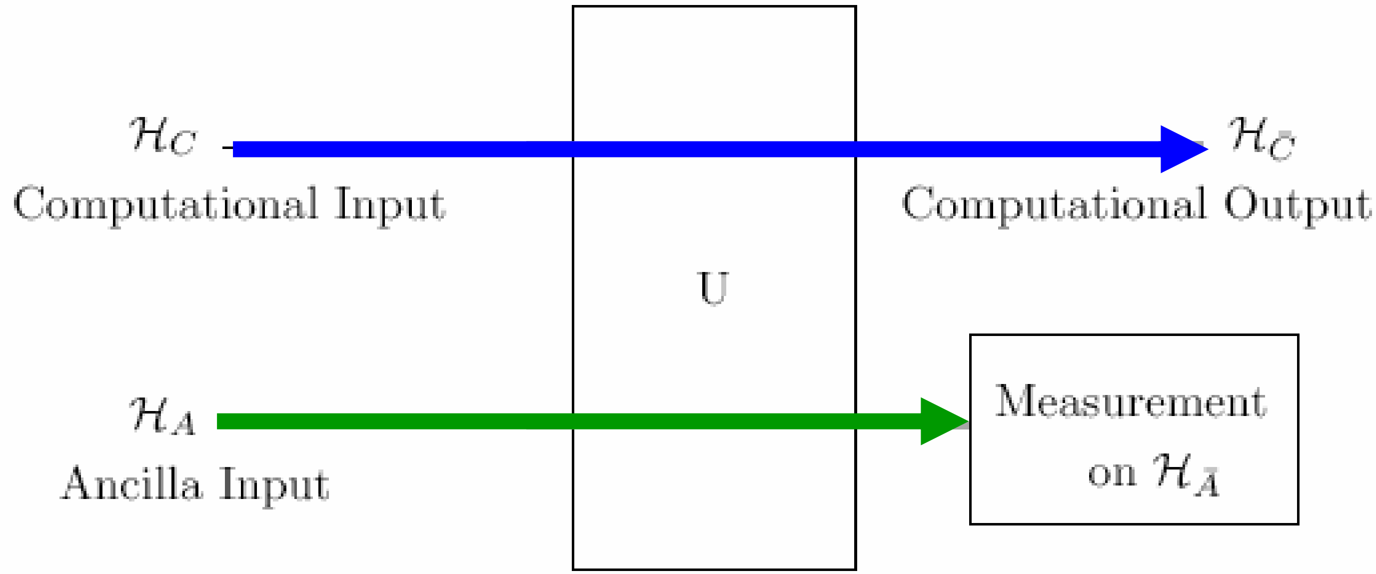
Raven

Writing Desk



"Conditional Linear-Optical Measurement Schemes Generate Effective Photon Nonlinearities," G. G. Lapaire, Pieter Kok, Jonathan P. Dowling, J. E. Sipe, Physical Review A 68 (01 October 2003) 042314 (1-11)

No longer limited by the nonlinearities we find in *Nature! (or PRL)*.



NON-Unitary Gates → Effective Nonlinear Gates

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

KLM CNOT Hamiltonian

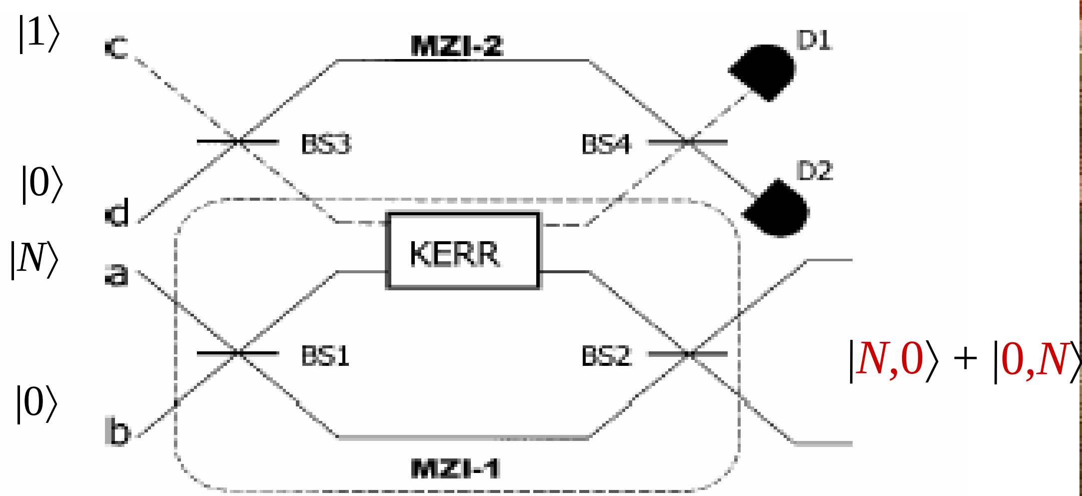
$$Q = \frac{\pi\hbar}{2}(3 + a_b^\dagger(1 - \hat{n}_b) + (1 - \hat{n}_b)a_b)\hat{n}_a.$$

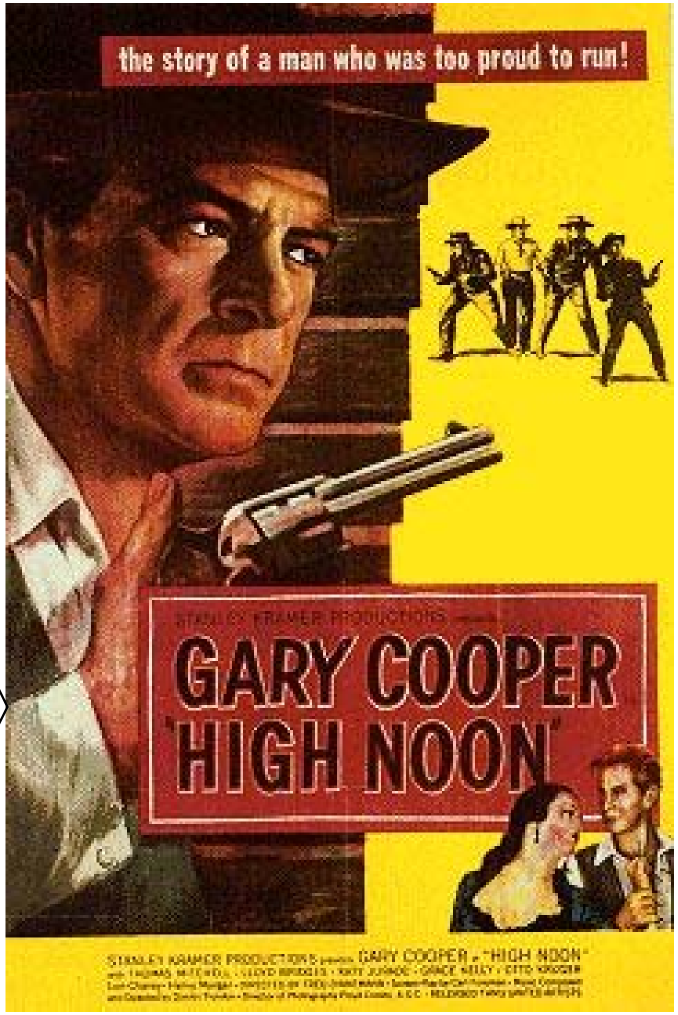
Franson CNOT Hamiltonian

Showdown at High N00N!

How do we make: $|N,0\rangle + |0,N\rangle$

With a ***large*** Kerr non-linearity*:

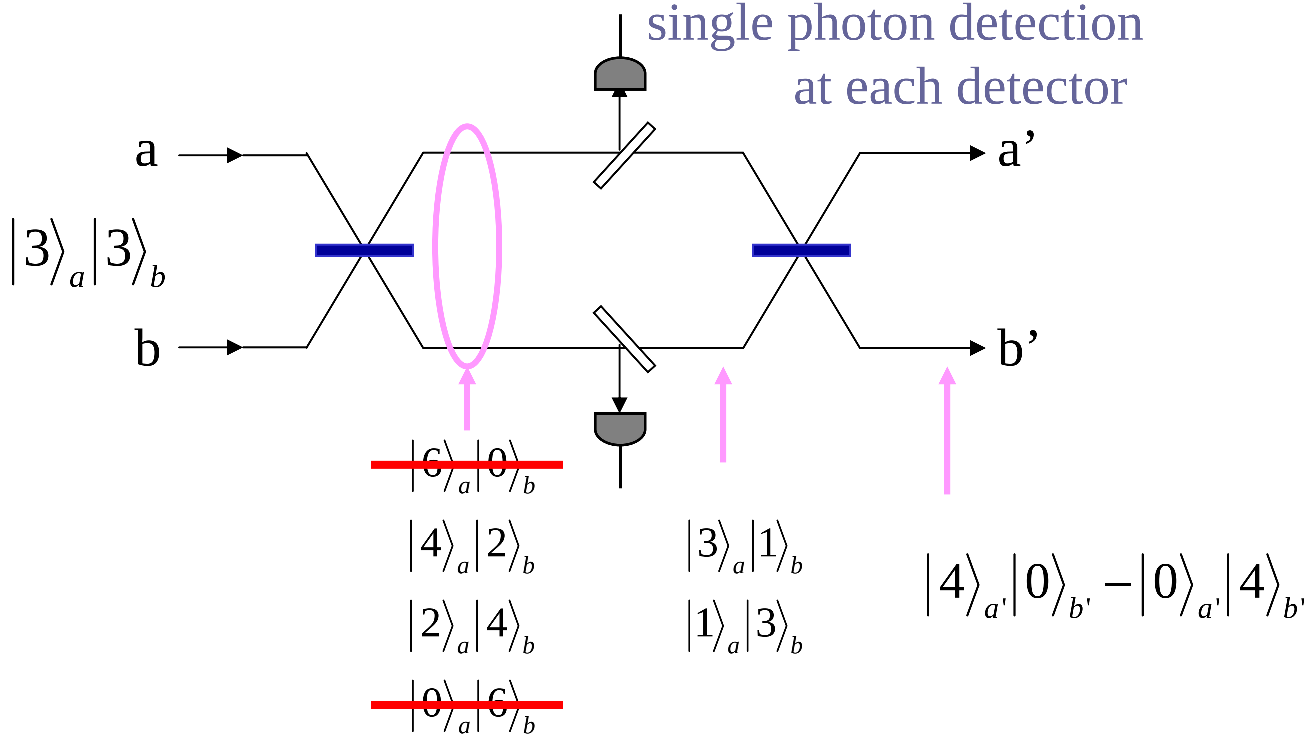




But this is not practical… need $\chi_3 = \pi$!

***Molmer K, Sorensen A, PRL 82 (1999) 1835;** **C. Gerry, and R.A. Campos, *PRA* 64, 063814 (2001).**

Projective Measurements to the Rescue



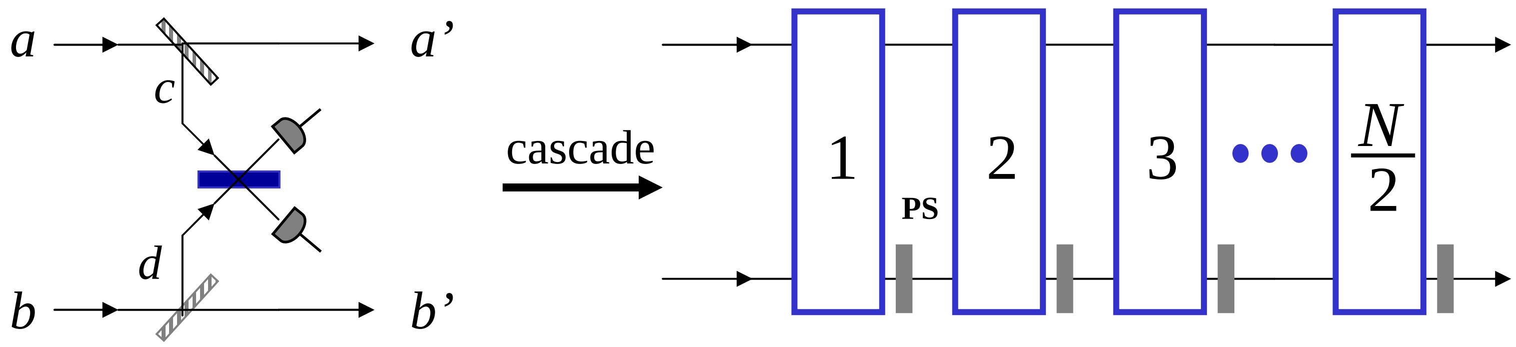
Probability of success: (event-ready) $\frac{3}{64}$

Best we found: $\frac{3}{16}$

H. Lee, P. Kok, N.J. Cerf, and J.P. Dowling, *Phys. Rev. A* **65**, R030101 (2002).

Projective Measurements

P. Kok, H. Lee, and J.P. Dowling, *Phys. Rev. A* **65**, 0512104 (2002).



$$|N,N\rangle \rightarrow |N\text{-}2,N\rangle + |N,N\text{-}2\rangle$$

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

$$p_1 = \frac{1}{2} N\,(N\text{-}1)\; T^{2N\text{-}2}\, R^2 \;\underset{N\rightarrow\infty}{\longrightarrow}\; \frac{1}{2e^2}$$

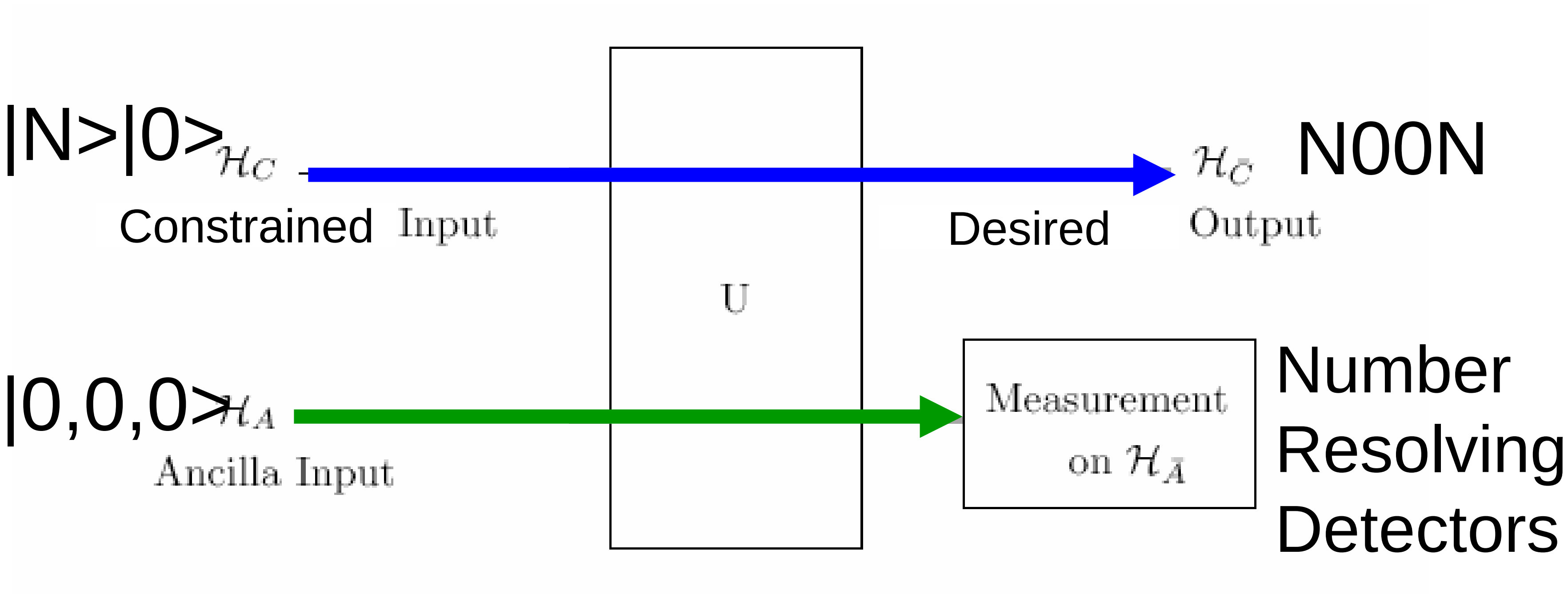
with T = (N–1)/N and R = 1–T

the consecutive phases are given by:

$$\varphi_k = \frac{2\pi k}{N/2}$$

Schemes based on non-detection have been proposed by Fiurásek 68 (2003) 042325; and Zou, PRA 66 (2002) 014102; see also Pryde, PRA 68 (2003) 052315.

Efficient Scheme for Generating N00N-State Generating Schemes



Given constraints on input, ancillae, and measurement scheme, does a U exist that produces the desired output and if so find the U which produces the desired output with the highest fidelity.

High-N00N Photons—The Experiments!

Protocol Implemented in *Nature*….

Quantum physics

High NOON for photons

Dirk Bouwmeester

NATURE | VOL 429 | 13 MAY 2004 |

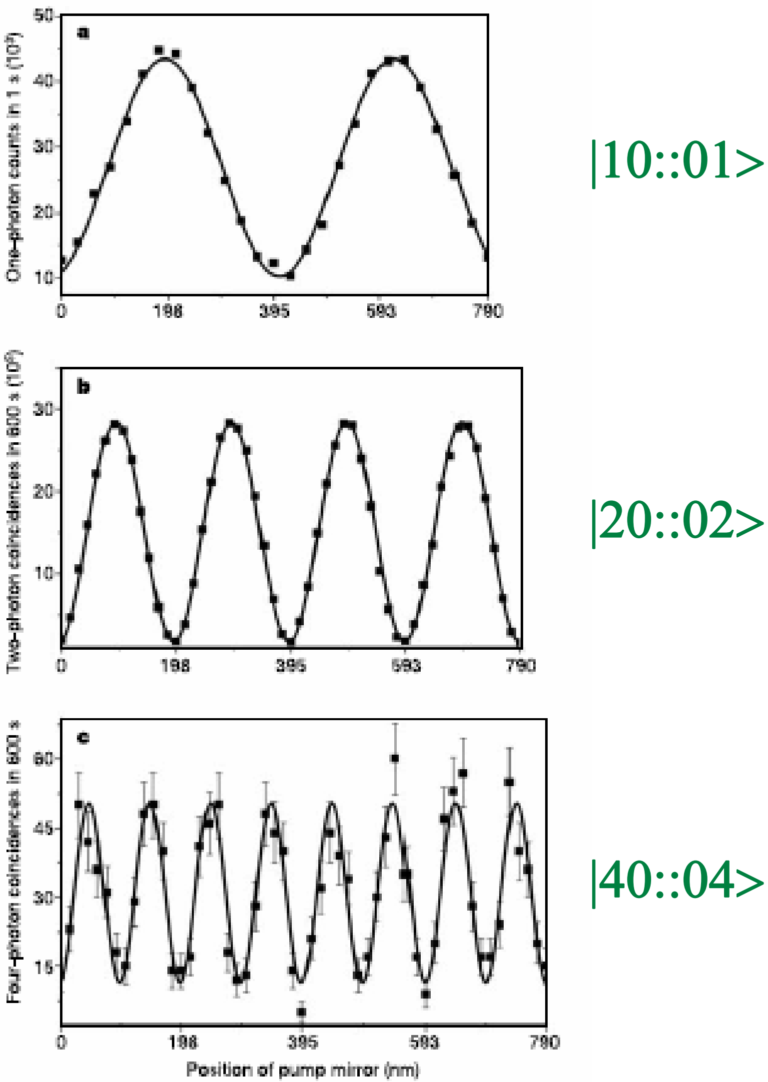
Entangled photons conspire to create interference patterns that would normally be associated with a wavelength much smaller than that of the individual photons — beating the diffraction limit.

It would be more interesting if $|N0,0N\rangle$ states could be generated with $N>2$ but using photons produced by light sources that have a wavelength of at least $\lambda/2$. The existence of such states — dubbed 'high NOON' states by Jonathan Dowling — would be an unambiguous demonstration that the diffraction limit has been beaten. This is exactly what Mitchell *et al.*[2] and Walther *et al.*[3] have achieved, with $|N0,0N\rangle$ states for $N=3$ and $N=4$, respectively.

$$|N::0\rangle_{a,b} = \frac{1}{\sqrt{2}}\left(|N,0\rangle_{a,b} + |0,N\rangle_{a,b}\right)$$

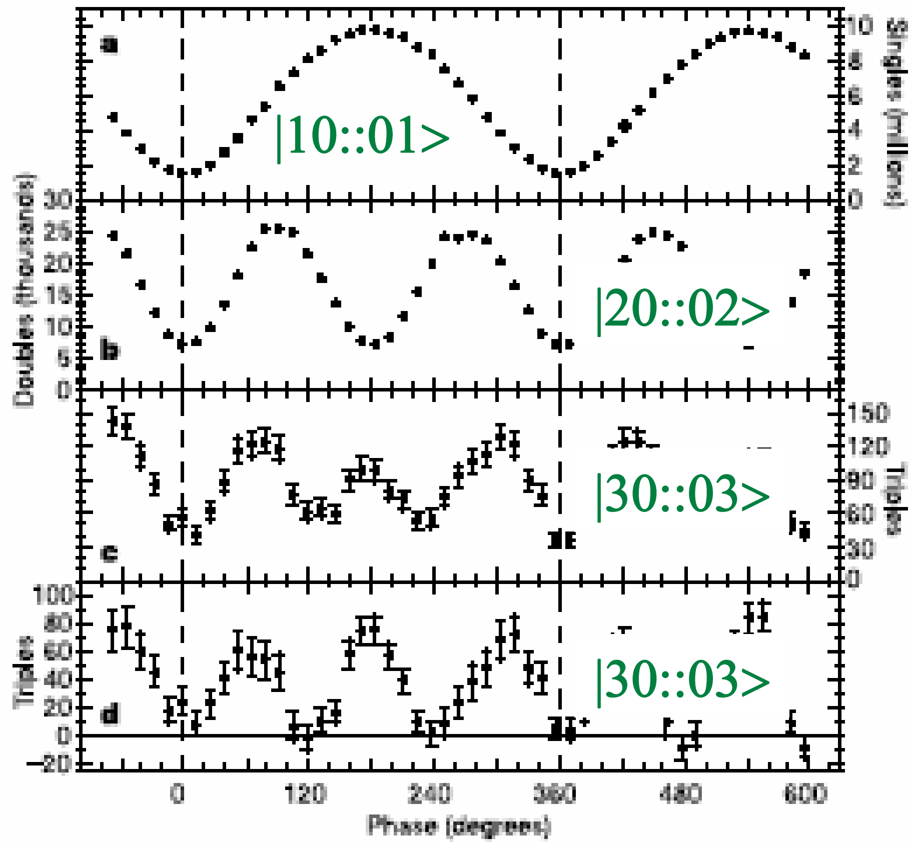
De Broglie wavelength of a non-local four-photon state

Philip Walther[1], Jian-Wei Pan[1,*], Markus Aspelmeyer[1], Rupert Ursin[1], Sara Gasparoni[1] & Anton Zeilinger[1,2]



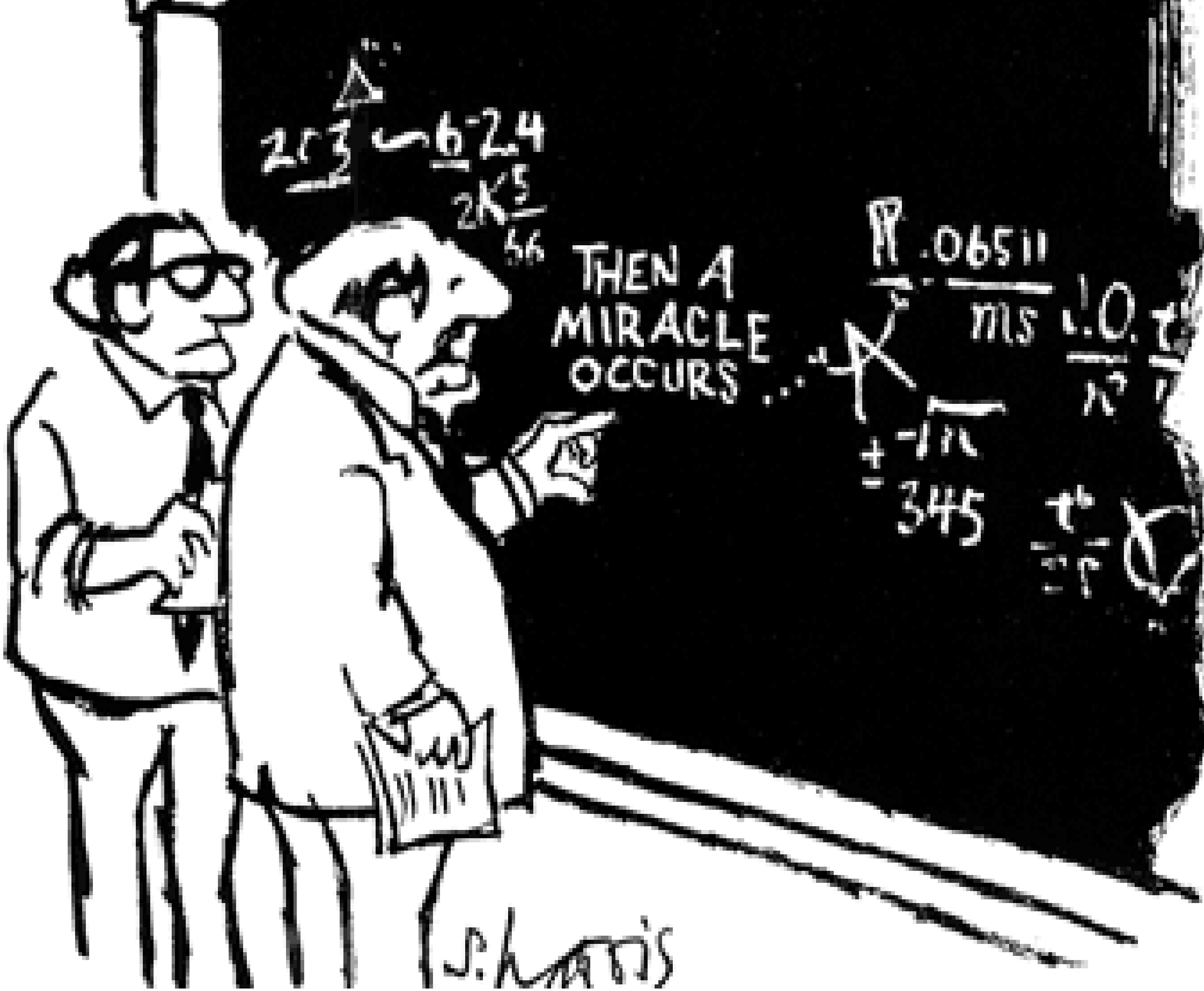
Super-resolving phase measurements with a multiphoton entangled state

M. W. Mitchell, J. S. Lundeen & A. M. Steinberg



Part III:

N-Photon Absorbing Resists and the Entangled Photon Cross Section



“I think you should be more explicit here in step two.”

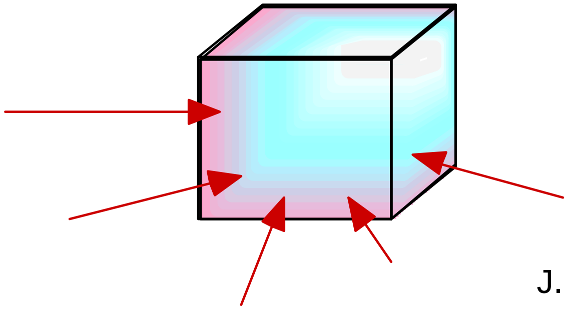
SCALING LAWS

Uncorrelated N-Photon Absorption Probability

$$P \propto I^N$$

Correlated N-Photon Absorption Probability

$$P \propto I$$



P is the probability of finding N photons in a unit volume per unit time. Hence low intensities for entangled photons will do.

J. Javanainen and P. L. Gould, PRA **41**, 5088 (1990).

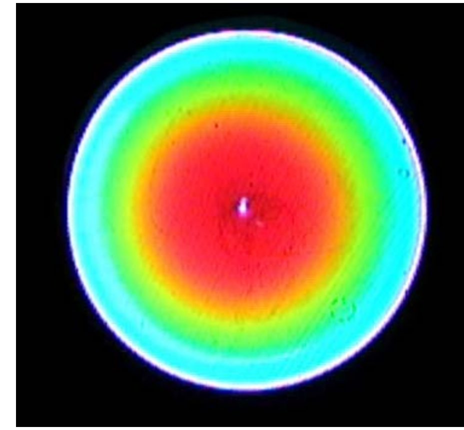
J. Perina, Jr., B. E. A. Saleh, and M. C. Teich, PRA **57**, 3972 (1998).

Experiment: Georgiades NP, Polzik ES, Kimble HJ, Quantum interference in two-photon excitation with squeezed and coherent fields, PHYSICAL REVIEW A 59 (1): 676-690 JAN 1999

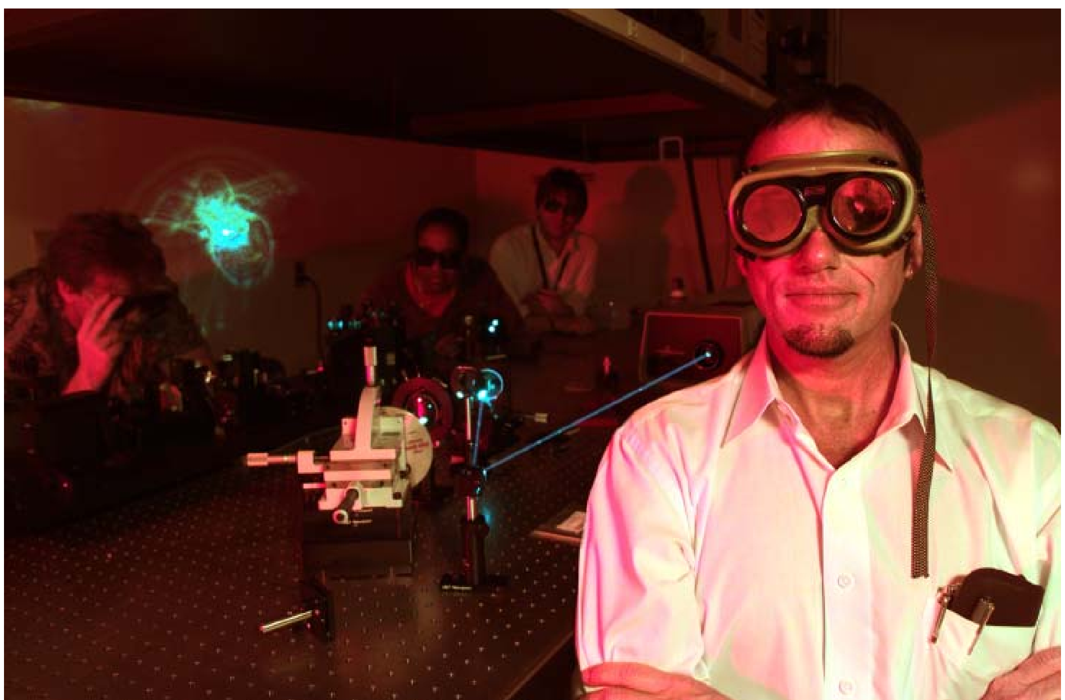
JPL Quantum Optical Internet Testbed

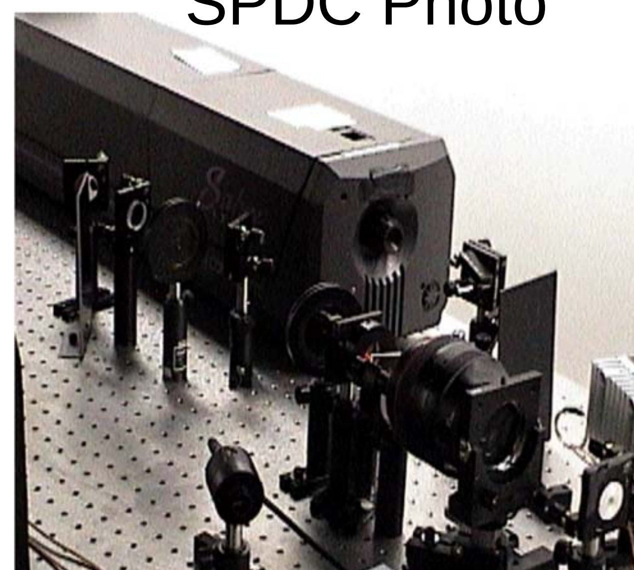
- **QCT Group Quantum Optics Lab**
- **Single Photon Sources and Calibration**
- **Optical Imaging, Computing, and SATCOM**

SATCOM



SPDC Photo





JOURNAL OF MODERN OPTICS, 2002, VOL. 49, NO. 3/4, 519–527

Taylor & Francis
Taylor & Francis Group

Two-photon interferometry for high-resolution imaging

DMITRY V. STREKALOV* and JONATHAN P. DOWLING

Quantum Computing Technologies Group, Jet Propulsion Laboratory, California Institute of Technology, MS 300-123, 4800 Oak Grove Drive, Pasadena, CA 91109, USA

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

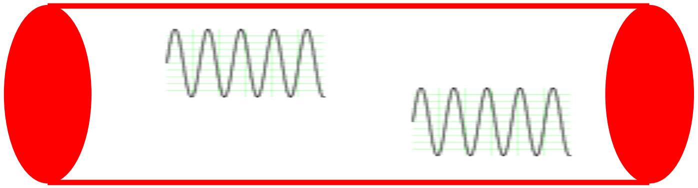
Taylor & Francis
Taylor & Francis Group

Two-photon processes in faint biphoton fields

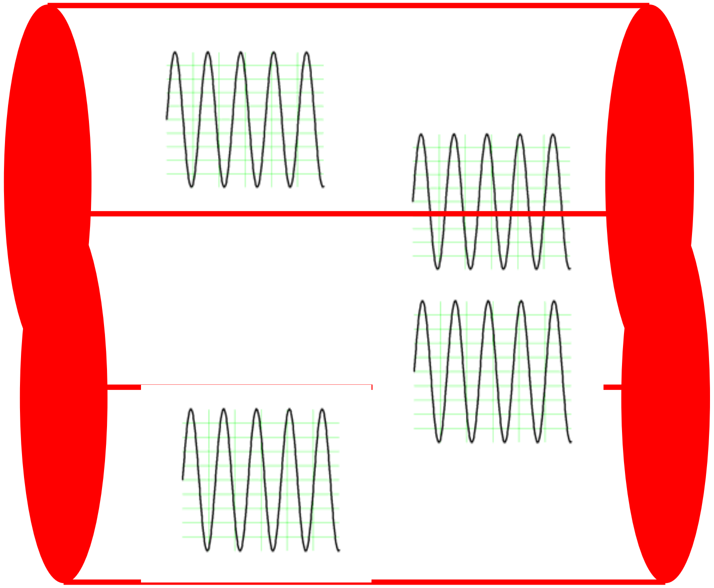
DMITRY V. STREKALOV†, MATTHEW C. STOWE†, MARIA V. CHEKHOVA‡ and JONATHAN P. DOWLING†

I versus I^2

I

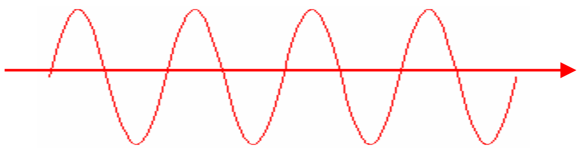


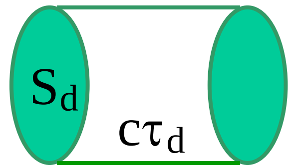
I^2



Two-photon "Bucket" Detector in a Coherent Field

Coherence (mode) volume V_c Detection volume V_d





$$p(n) = \frac{\left(<n> \frac{V_d}{V_c}\right)^n}{n!} e^{-<n>\frac{V_d}{V_c}}$$

$$p(n) = \frac{<n>^n}{n!} e^{-<n>}$$

Probability to get exactly one: $p_1 = <n> \frac{V_d}{V_c} e^{-<n>\frac{V_d}{V_c}}$

Probability to get exactly two: $p_2 = \frac{1}{2}\left(<n> \frac{V_d}{V_c}\right)^2 e^{-<n>\frac{V_d}{V_c}}$

…

$\frac{V_d}{V_c} > 1$ multi-mode detector $\frac{V_d}{V_c} < 1$ sub-mode detector

"To get" does not always mean "to detect". Any pair can be detected with probability $\eta^{(2)}$ so the probability to detect 2 out of *n* is

$$p_{2|n} = \eta^{(2)} C_n^2$$

$$\frac{<n>}{V_c} = \frac{I}{c\hbar\omega},$$

And the mean number of pair detections (for small $\eta^{(2)}$) is

$$P_{cl}^{(2)} = \eta^{(2)} e^{-<n>\frac{V_d}{V_c}} \sum_{k=2}^{\infty} \frac{\left(<n> \frac{V_d}{V_c}\right)^k}{k!} C_k^2 = \frac{\eta^{(2)}}{2}\left(<n> \frac{V_d}{V_c}\right)^2 = \frac{\eta^{(2)}}{2}\left(\frac{IV_d}{c\hbar\omega}\right)^2$$

Two-photon “bucket” detector in a biphoton field

If V_{corr} is smaller than V_d ,

$$P_q^{(2)} = \eta^{(2)} \frac{<n>}{2} \frac{V_d}{V_c} e^{-\frac{<n>}{2}\frac{V_d}{V_c}}$$

$$= \frac{\eta^{(2)}}{2} \frac{IV_d}{c\hbar\omega} e^{-\frac{IV_d}{2c\hbar\omega}}$$

Ratio of detection rates for biphoton and coherent fields of the same intensity:

$$\frac{P_{bph}^{(2)}}{P_{coh}^{(2)}} \approx \frac{c\hbar\omega}{IV_d} e^{-\frac{IV_d}{2c\hbar\omega}}$$

For weak fields:

$$\frac{P_{bph}^{(2)}}{P_{coh}^{(2)}} \approx \frac{c\hbar\omega}{IV_d}$$

Which is consistent with the earlier result

[D.N. Klyshko, Sov. Phys. JETP ***56****, 753 (1982)]*

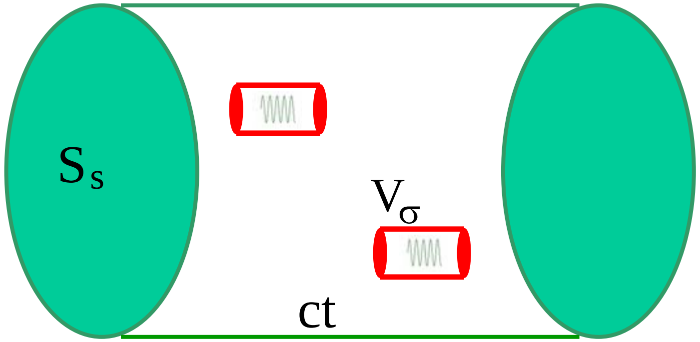
$$\frac{P_{bph}^{(2)}}{P_{coh}^{(2)}} \approx \frac{M}{<n>}$$

where

$$M = \frac{V_d}{V_c}$$

is the number of detected modes.

Two-photon Absorption in Bulk Media: "Virtual Detectors"



Distribution of singles ("virtual detectors")

in the sample volume V_d = ct S_s is

$$p(n) = \frac{\left(< n > \frac{V_d}{V_c}\right)^n}{n!} e^{-<n>\frac{V_d}{V_c}}$$

For each "virtual detector", in the case of Poissonian statistics :

$$p'(n) = \frac{1}{n!}\left(< n > \eta^{(2)}\frac{V_\sigma}{V_c}\right)^n e^{-<n>\eta^{(2)}\frac{V_\sigma}{V_c}}$$

So the probability that is will fire is:

$$P_f = 1 - p'(0) \approx < n > \eta^{(2)}\frac{V_\sigma}{V_c}$$

and the mean-number of absorbed photon pairs will be:

$$N(t) = \sum_{n=0}^{\infty} n\, p(n)\, P_f = < n >^2 \eta^{(2)}\frac{V_\sigma V_s}{V_c^2}\frac{t}{\tau_c}$$

$$= \left(\frac{I}{c\hbar\omega}\right)^2 \eta^{(2)} V_\sigma V_s \frac{t}{\tau_c}$$

As expected, the two-photon signal from uncorrelated light is quadratic in intensity and linear with respect to the exposure time.

In the case of photon pairs that are correlated within the volume V_{corr} ,

$$P_f = \eta^{(2)} \begin{cases} 1 & V_{corr} < V_\sigma \quad \text{“if there is one, there is always the other”} \\ \dfrac{V_\sigma}{V_{corr}} & V_{corr} > V_\sigma \quad \text{“if there is one, there may be the other”} \end{cases}$$

Then the mean-number of absorbed photon pairs is

$$N(t) = \frac{I}{c\hbar\omega} \frac{t}{\tau_c} \eta^{(2)} V_s \begin{cases} 1 & V_{corr} < V_\sigma \\ \dfrac{V_\sigma}{V_{corr}} & V_{corr} > V_\sigma \end{cases}$$

Comparing with the result for uncorrelated light, we get for equal exposure times

$$\frac{N_{corr}}{N_{coh}} = \frac{I_{corr}}{I_{coh}} \frac{\tau_c^{coh}}{\tau_c^{corr}} \frac{c\hbar\omega}{I_{coh}} \min\left\{\frac{1}{V_\sigma}, \frac{1}{V_{corr}}\right\}$$

We can also compare a SW exposure of duration ***t*** with correlated light to a pulse exposure with coherent light. In this case we get

$$\frac{N_{corr}}{N_{coh}} = \frac{I_{corr}}{I_{coh}} \frac{t}{\tau_c^{corr}} \frac{c\hbar\omega}{I_{coh}} \min\left\{\frac{1}{V_\sigma}, \frac{1}{V_{corr}}\right\}$$

For order-of-magnitude estimate $\min\left\{\frac{1}{V_\sigma}, \frac{1}{V_{corr}}\right\} \approx \left(\lambda^2 \tau_0 c\right)^{-1}$

λ = 700 nm, τ_0 = 100 fs, $\Delta\lambda$ = 100 nm, I_{corr}= 5 W/m^2

I_{coh} ~ 1 GW/cm^2

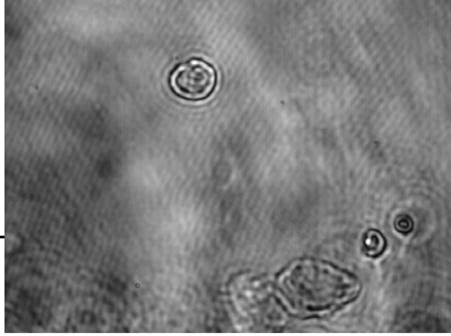
$$\frac{N_{corr}}{N_{coh}} \approx 0.3\, t\ [\mathrm{s}]$$

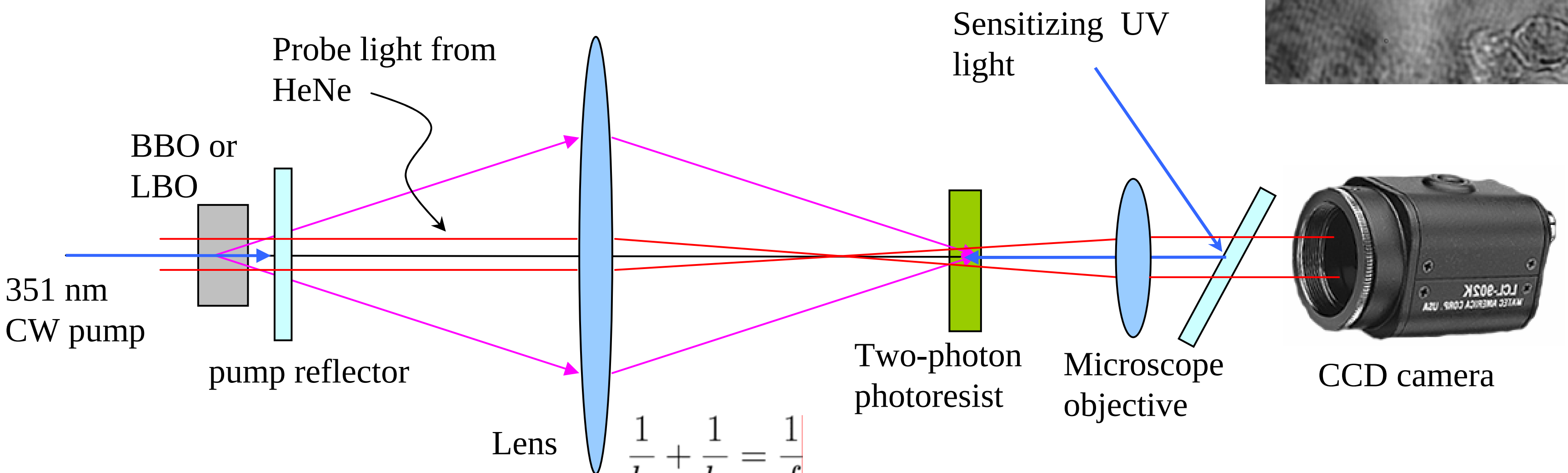
It should be possible to get exposure in 3 seconds!

*[R.A. Borisov et al., Appl. Phys. B **67**, 765 (1998)]*

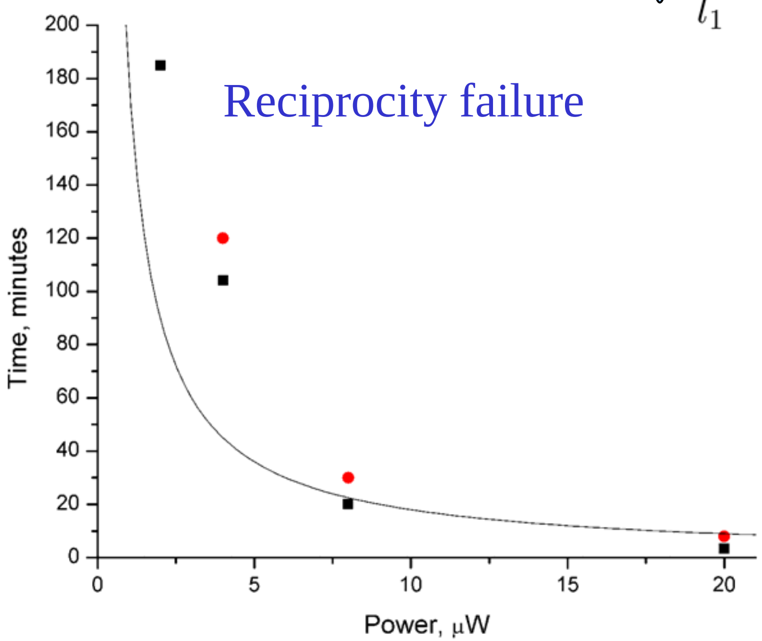
*[Y. Boiko et al., Opt. Express **8**, 571 (2001)]*

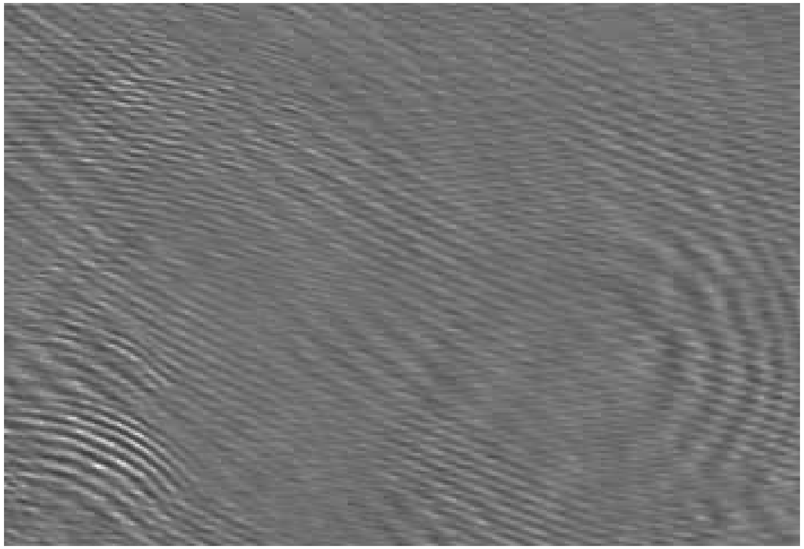
Two-photon Lithography Experiment

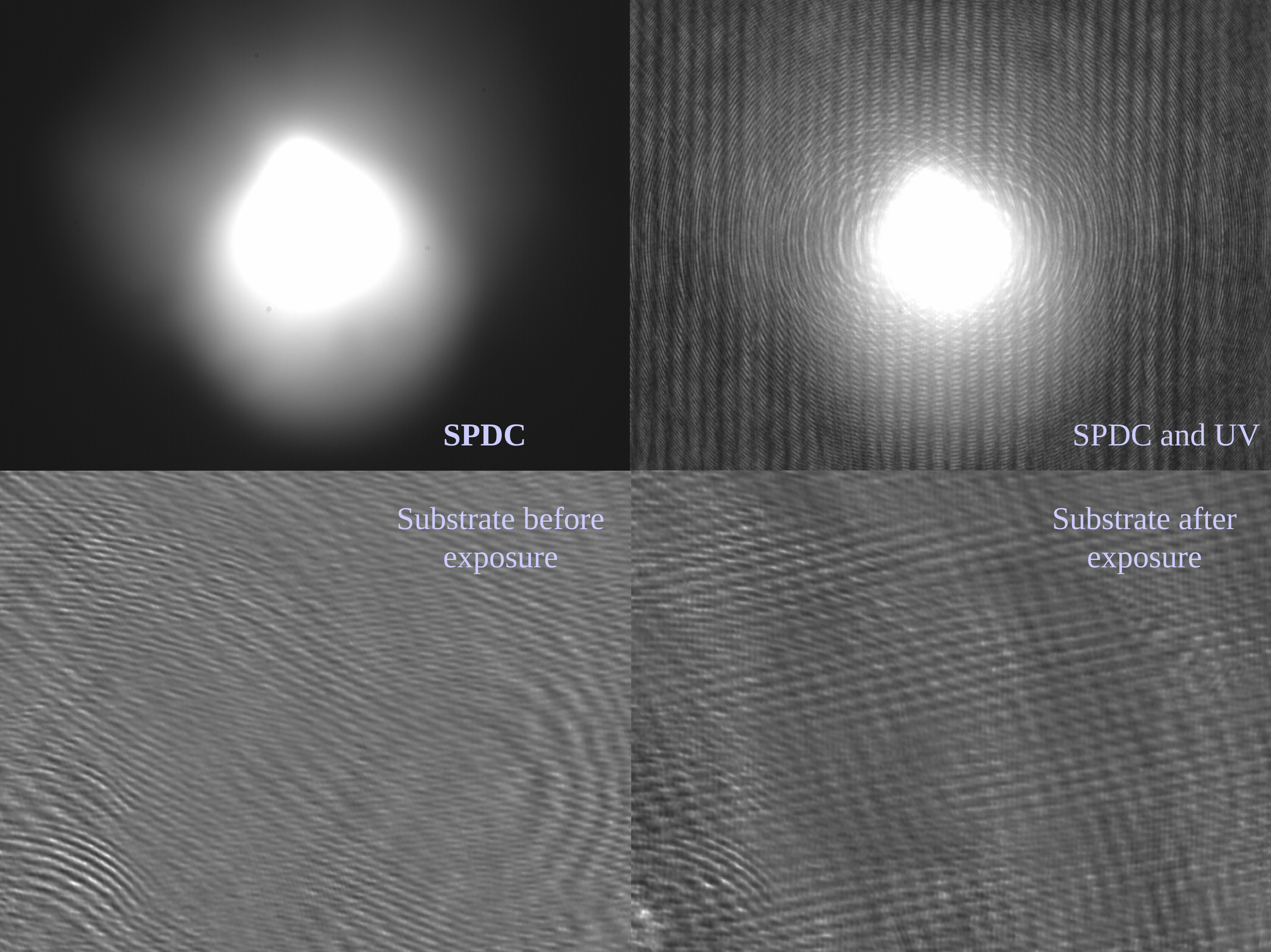




$$\frac{1}{l_1}+\frac{1}{l_2}=\frac{1}{f}$$

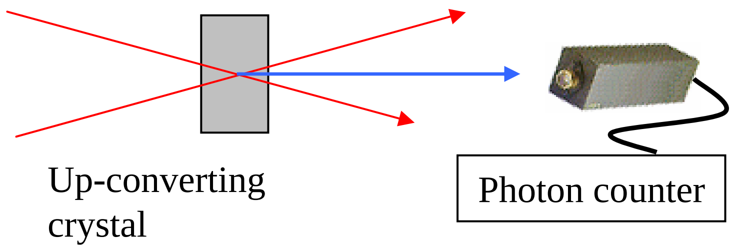





SPDC
SPDC and UV
Substrate before exposure
Substrate after exposure

Detection by Coherent Up-Conversion

$$\omega_s + \omega_i = \omega_p,$$
$$\vec{k}_s + \vec{k}_i = \vec{k}_p,$$



Number of detected modes M = $\dfrac{V_d}{V_c}$

$$V = \Delta k_x \Delta k_y \Delta k_z \Delta x \Delta y \Delta z$$

For a single mode, $V = (2\pi)^3$

For coherent light, $R_{coh} = \eta^{(2)} M_c < n > < n >$

$\sim \chi^{(2)}$ — number of "first" photons — number of "second" photons

For two-photon (SPDC) light, $R_{spdc} = \eta^{(2)} M_{spdc} < n >$

$$\xi \equiv \frac{R_{spdc}}{R_{coh}} = \frac{M_{spdc} < n >_{spdc}}{M_{coh} < n >_{coh}^2}$$

The number of modes *M* is $$M = \frac{V}{(2\pi)^3} = \frac{AL}{(2\pi)^3} \frac{k^2}{c} \Delta\Omega \Delta\omega$$

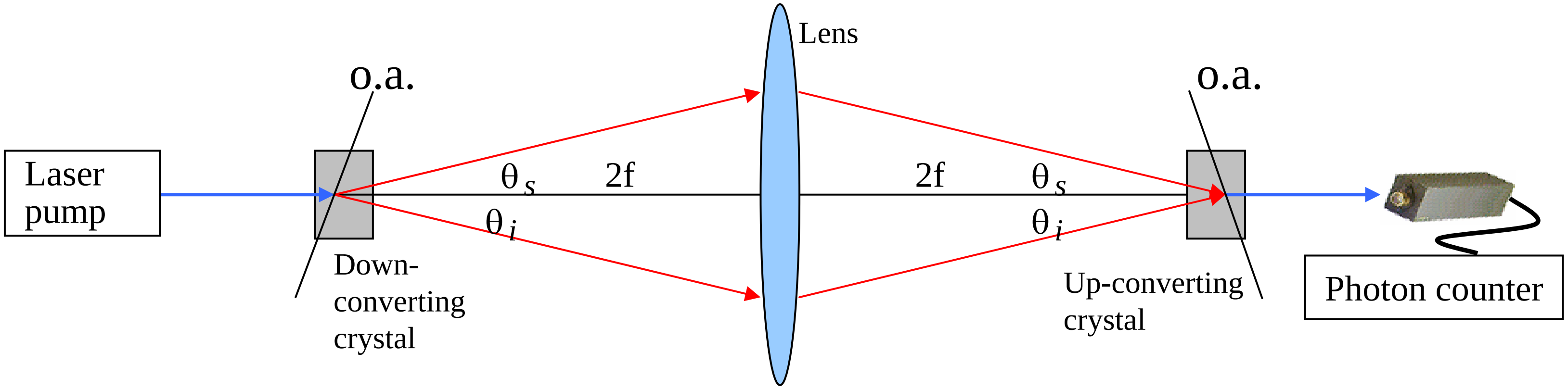
Comparing for equal intensities: $$\xi = \frac{\hbar c \Delta\Omega_{coh} \Delta\omega_{coh}}{I \lambda^3}.$$

Estimates:

$I \approx 5\, W/m^2$ $\Delta\omega_{coh} \approx 4 \times 10^{13}\, s^{-1}$ $\Delta\Omega \approx 2\pi\theta_d^2 \approx 3 \times 10^{-4}$ st. radians

$$\xi \approx 200$$

Correlation-Enhanced Optical Up-Conversion

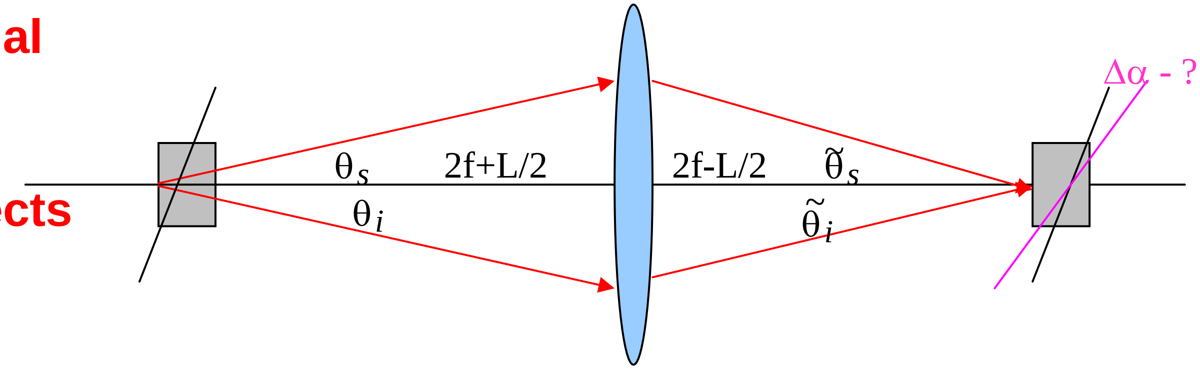


For coherent CW pump:
1W pump $\longrightarrow 10^{-5}$ W of SH

50 nW pump $\longrightarrow 1.5{*}10^{-20}$ W
or about 0.3 photons/s of SH

With the biphoton enhancement factor 200 and we expected about 40 photons/s signal.

In the experiment, the signal was lower because of alignment and focusing angular errors and the effects of an extended source.



Nonlinear Interactions with an Ultrahigh Flux of Broadband Entangled Photons

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(Received 19 October 2004; published 2 February 2005)

We experimentally demonstrate sum-frequency generation with entangled photon pairs, generating as many as 40 000 photons per second, visible even to the naked eye. The nonclassical nature of the interaction is exhibited by a linear intensity dependence of the nonlinear process. The key element in our scheme is the generation of an ultrahigh flux of entangled photons while maintaining their nonclassical properties. This is made possible by generating the down-converted photons as broadband as possible, orders of magnitude wider than the pump. This approach can be applied to other nonlinear interactions, and may become useful for various quantum-measurement tasks.

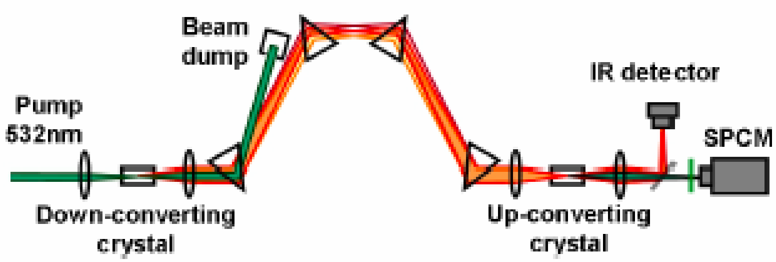
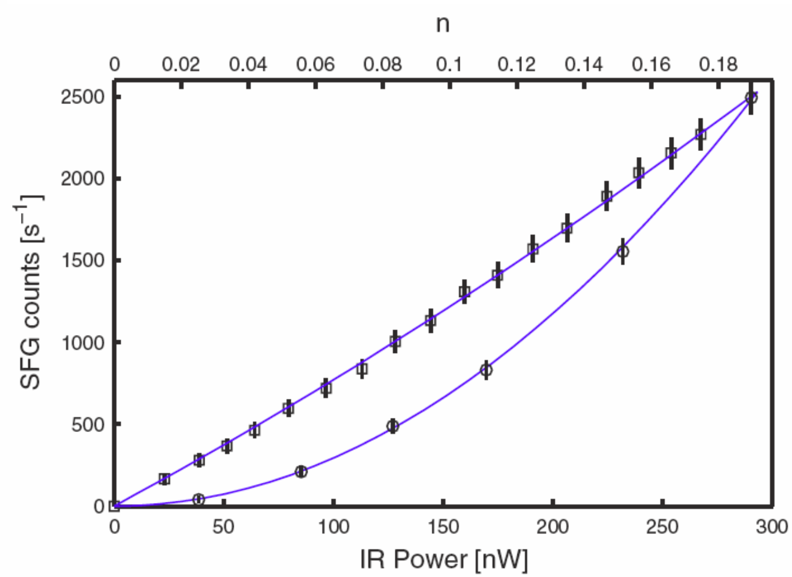
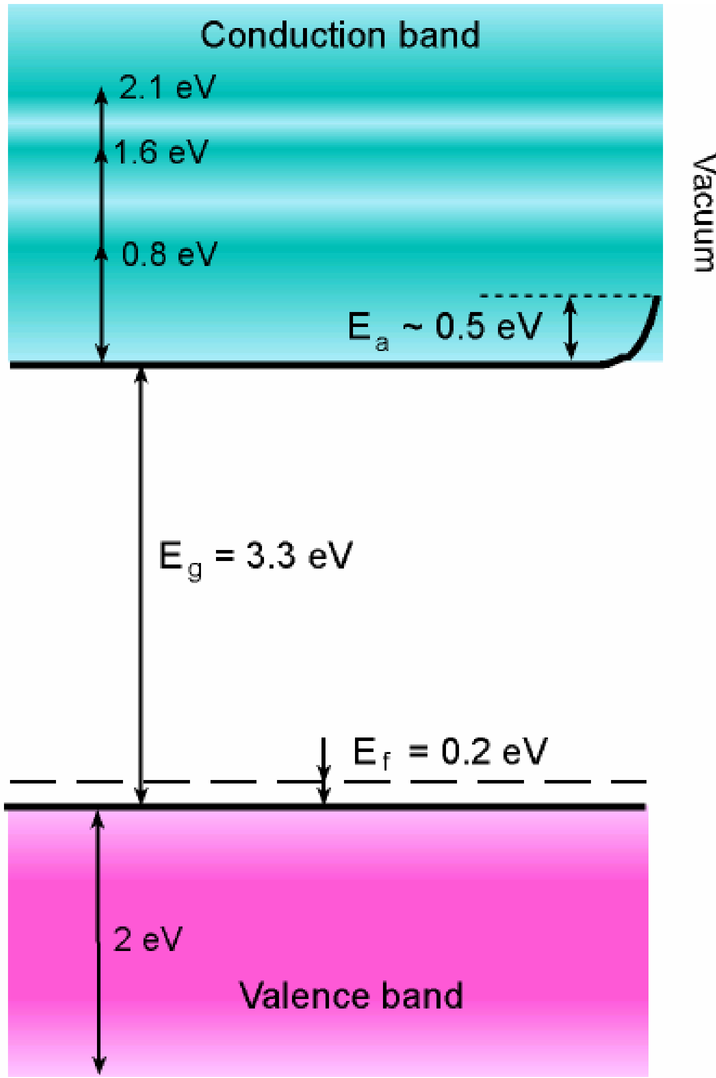


FIG. 1 (color online). Experimental layout. Entangled photons generated by down-conversion of a pump laser in one crystal are imaged through a set of four dispersion prisms onto a second crystal to generate the SFG photons. The entangled-photon beam is separated from the SFG photons by a harmonic-separator 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.

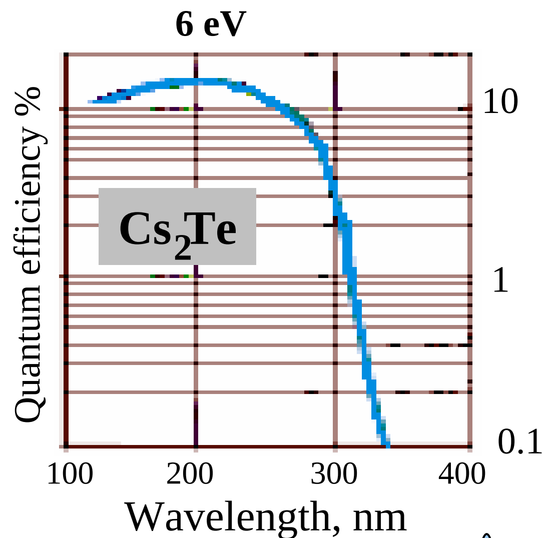


Photoelectric Effect in CsTe$_2$ Photocathode

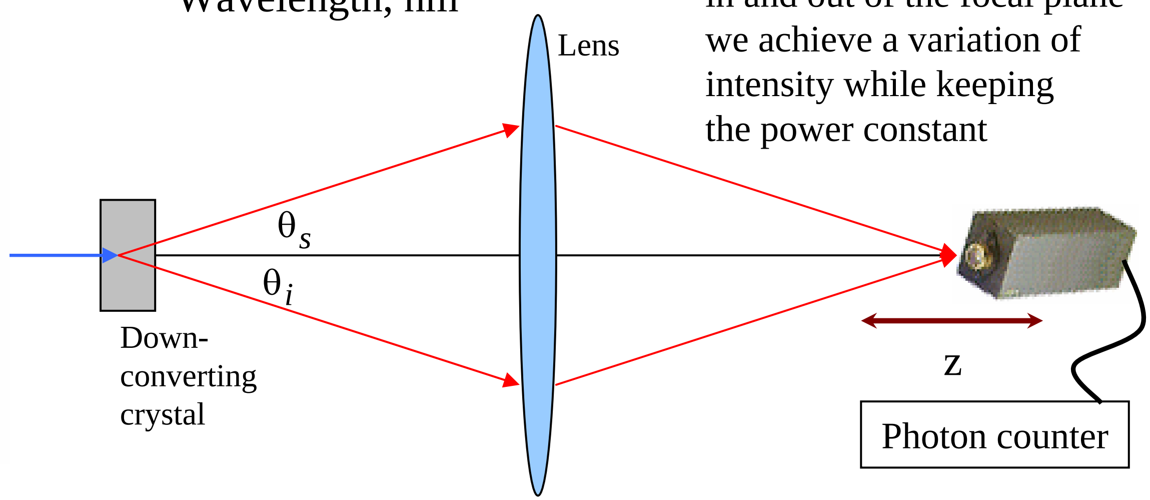
Build a detector sensitive to photon pairs, but not to single photons.



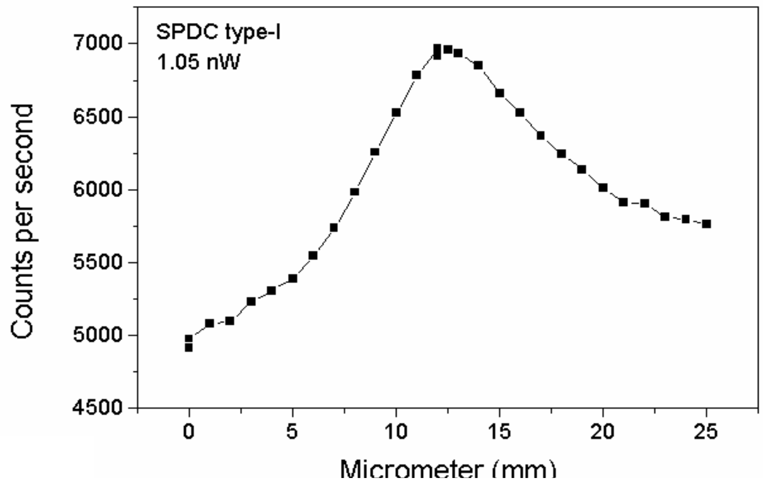
E.g.: [T. Hattori et al., Jpn. J. Appl. Phys. 39, 4793 (2000)] studied two-photon response of PMTs with 15 fs pulses.

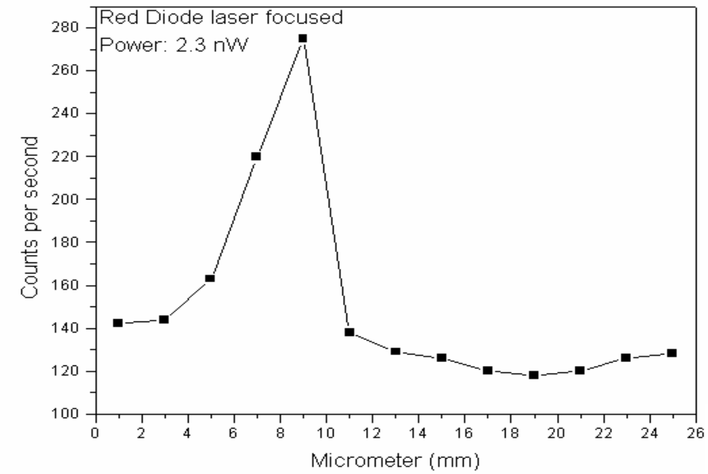


By moving the photocathode in and out of the focal plane we achieve a variation of intensity while keeping the power constant

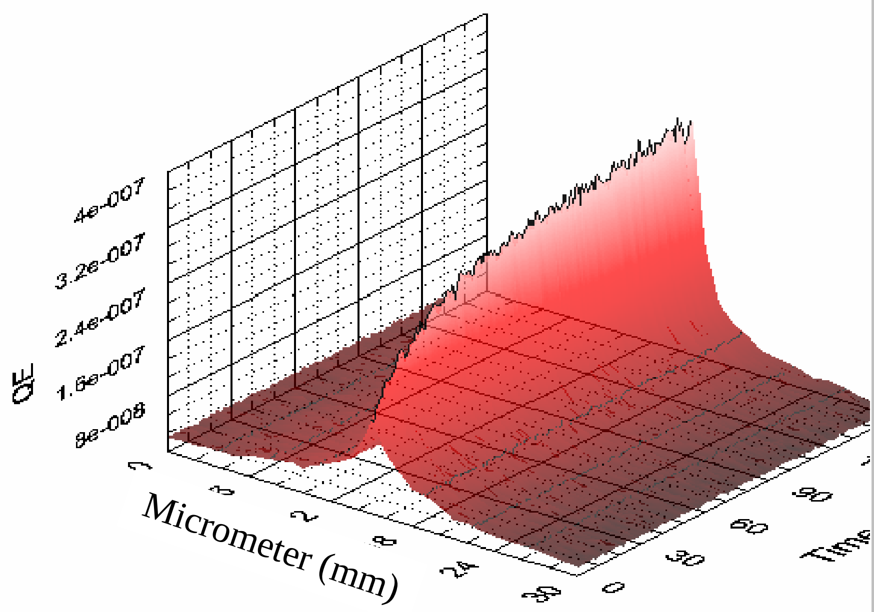


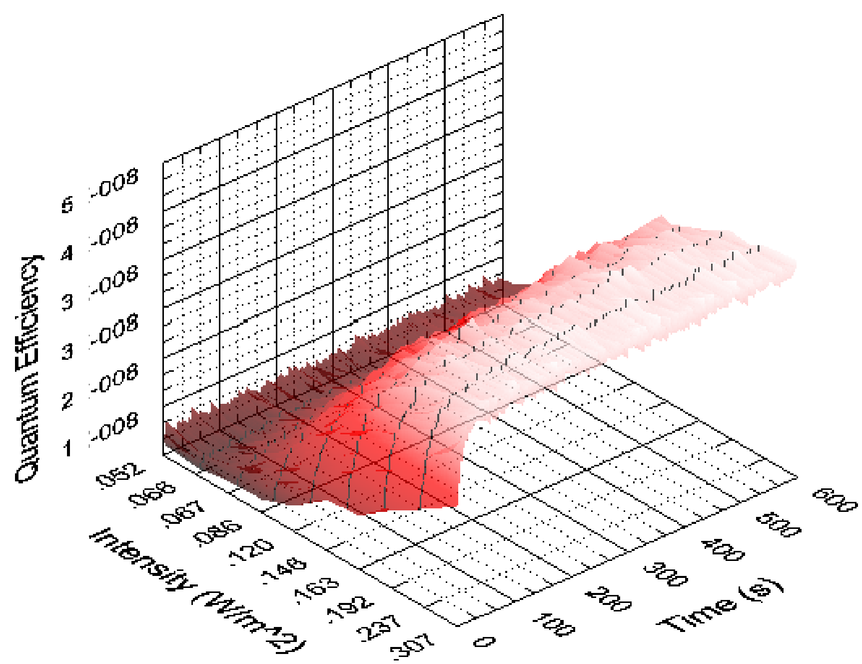
The results obtained with SPDC and with attenuated laser light (at 650 nm = 1.9 eV) look similar:





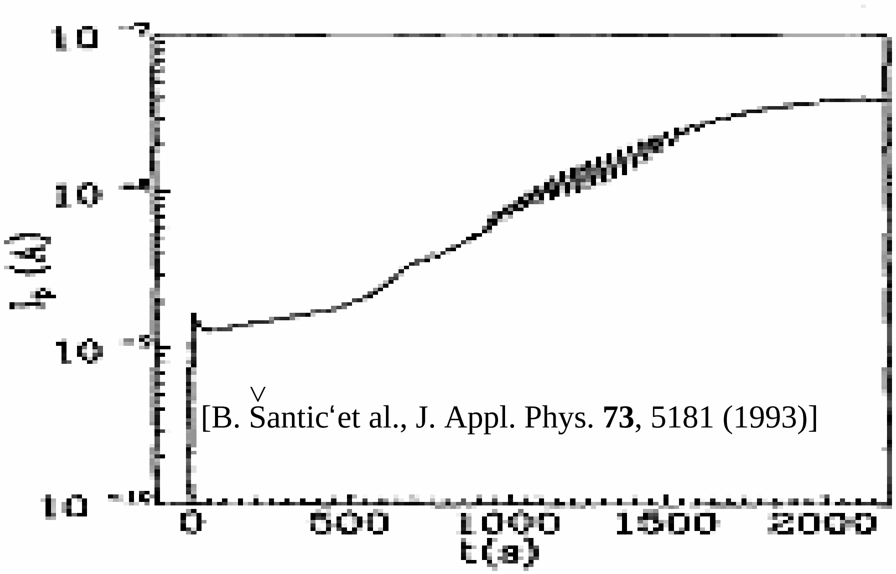
In addition to being nonlinear, the photocathode response is time-dependent:

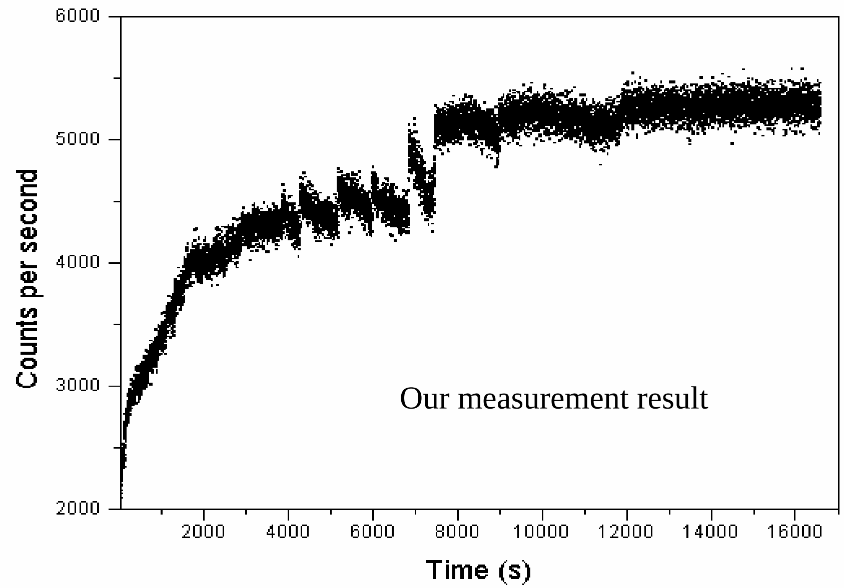




<u>We therefore observe a photosensitization effect</u> resembling the experimental observations by *[B. Šantić et al., J. Appl. Phys.* ***73****, 5181 (1993)]* for photoconductive current in GaAs at 70 K.

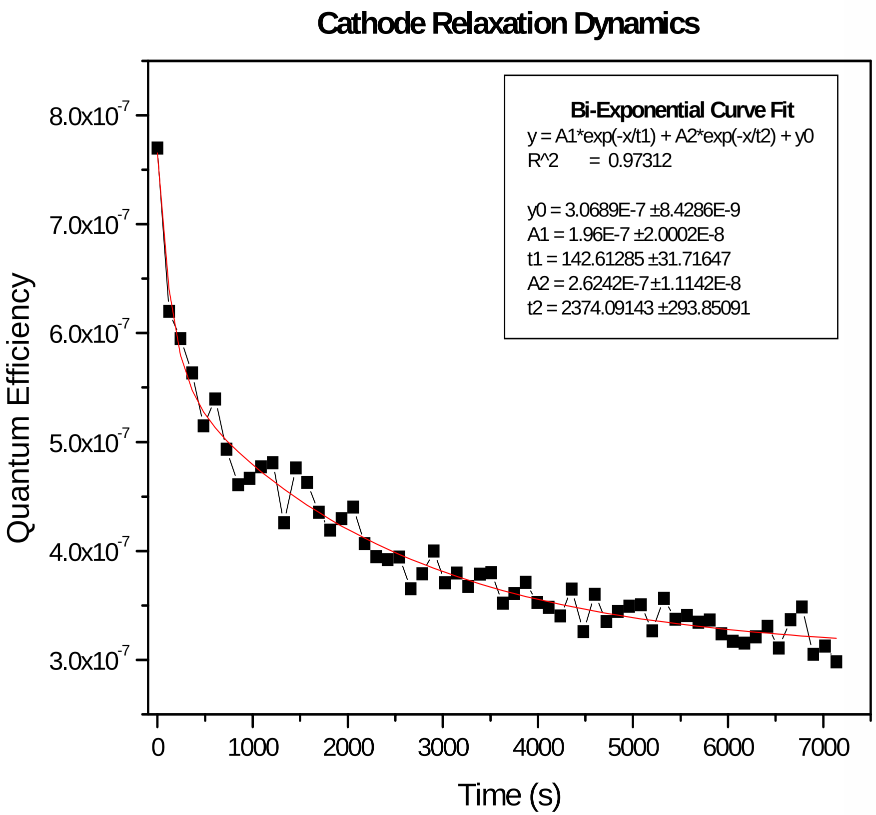
This effect may be explained as the filling of deep traps.

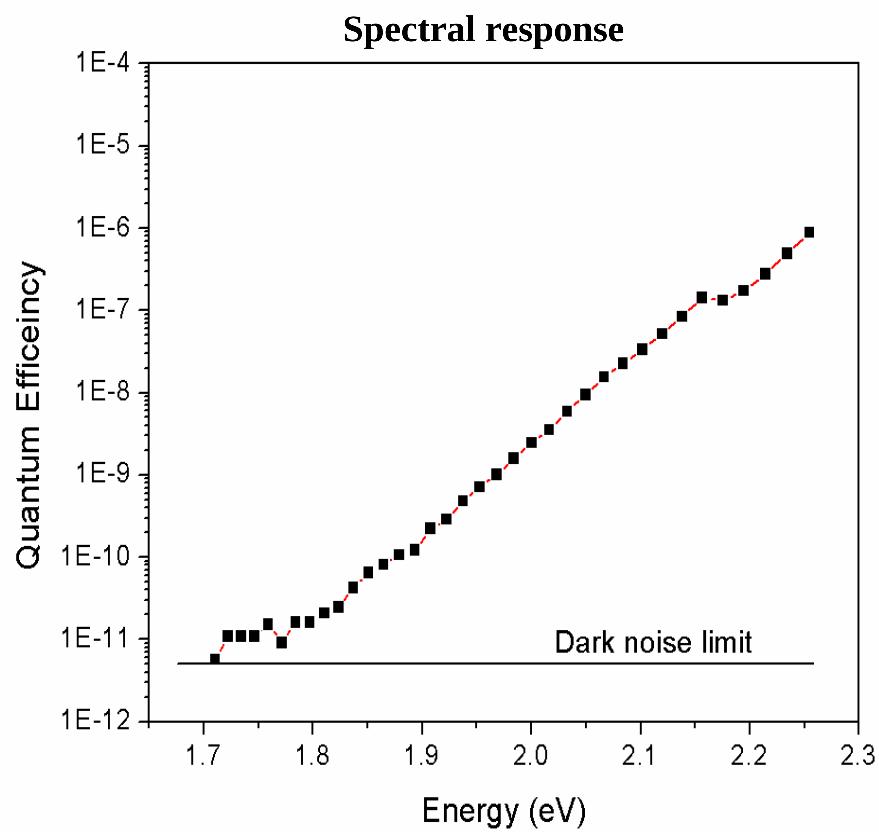




The "trapped" or intermediate states we observe have extremely long lifetime at room temperature! Studying their dynamical and spectral properties may be interesting for material characterization, and may suggest the way the Cs_2Te photocathode can be used for photon pair detection.

Relaxation Dynamics and Spectral Two-photon Sensitivity

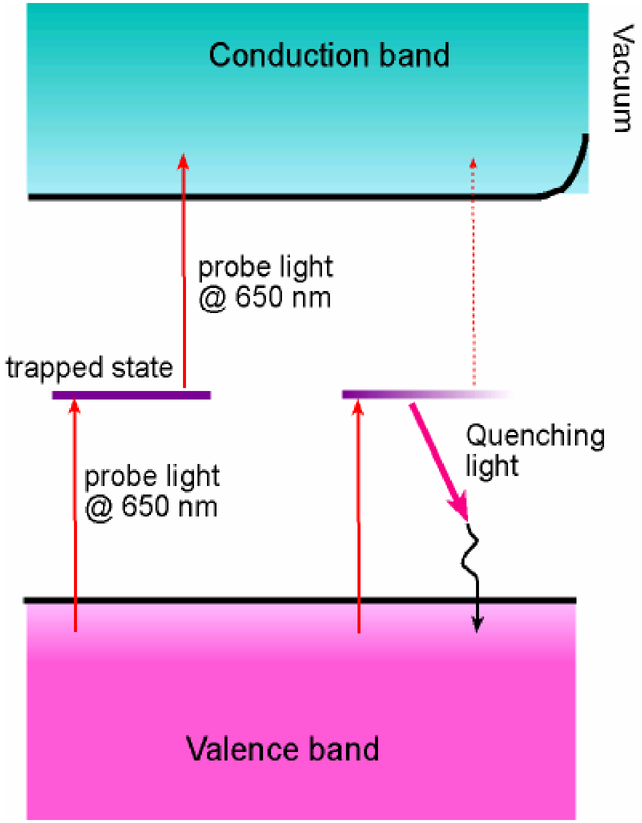


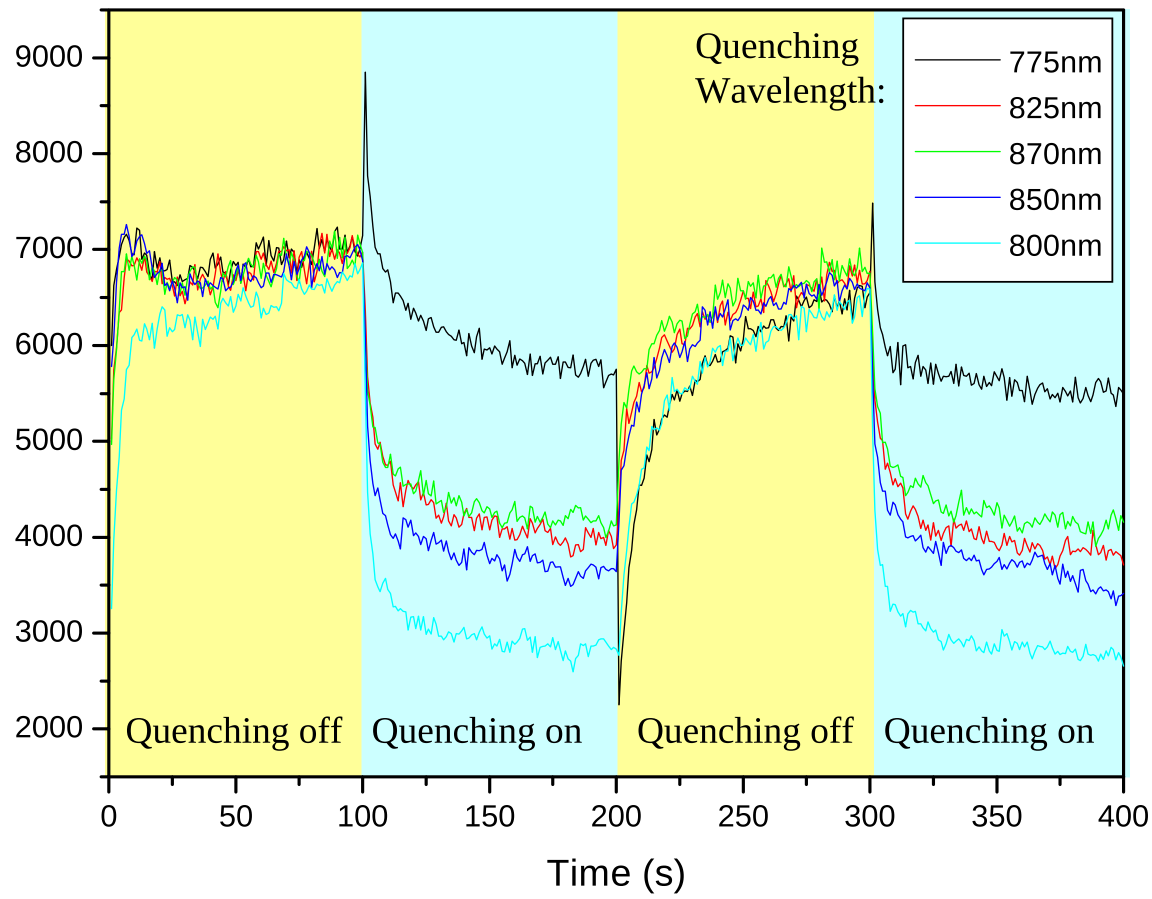


The normalized response (quantum efficiency) of a previously sensitized photocathode decay fits a bi-exponential law. This indicates the presence of at least two metastable levels inside the bandgap, with very long life time.

Quenching Effect

The long-lived intermediate states can be de-populated by external radiation (the quenching effect)





This result suggests that a long-lived intermediate state is at least 1.6 eV (which corresponds to 775 nm) deep from the conduction band edge.

Conclusions

1. Quantum Imaging, Metrology, & Computing
   - Heisenberg Limited Interferometry
   - The Quantum Rosetta Stone
   - The Road to Lithography
2. Quantum State Preparation
   - Nonlinearity from Projective Measurement
   - Show Down at High N00N!
3. Entangled N-Photon Absorption
   - Experiments with BiPhotons