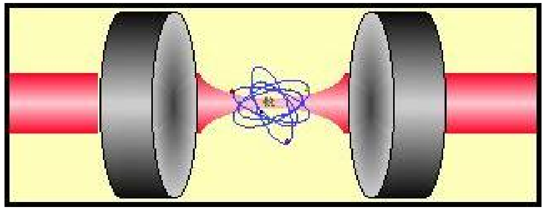
Luz e Átomos como ferramentas para Informação Quântica

Emaranhamento Multicor

Inst. de Física

USP

Marcelo Martinelli



Lab. de Manipulação Coerente de Átomos e Luz

INCT-IQ

FAPESP

CNPq
Conselho Nacional de Desenvolvimento Científico e Tecnológico

CAPES

Few words about entanglement characterization

- "EPR" criterion [M. D. Reid, PRA **40**, 913 (1989), M. D. Reid and P. D. Drummond, PRL **60**, 2731 (1988) & PRA **40**, 4493 (1989)]

$$\Delta^2 \hat{p}_{\rm inf} = \Delta^2 \hat{p}_1 \left(1 - \frac{\langle \delta\hat{p}_1 \delta\hat{p}_2 \rangle^2}{\Delta^2 \hat{p}_1 \Delta^2 \hat{p}_2} \right)$$

$$\delta\hat{p}_i = \hat{p}_i - \langle \hat{p}_i \rangle$$

$$\Delta^2 \hat{p}_{\rm inf}\, \Delta^2 \hat{q}_{\rm inf} \geq 1$$

Entanglement Test - DGCZ

- DGCZ separability criterion:

$$\rho = \sum_i p_i \ \rho_i = \sum_i p_i \ \rho_i^1 \otimes \rho_i^2 \qquad [\hat{q}_i, \hat{p}_j] = 2i\delta_{ij}$$

$$\hat{u} = a\hat{q}_1 + \frac{1}{a}\hat{q}_2, \qquad \hat{v} = a\hat{p}_1 - \frac{1}{a}\hat{p}_2,$$

Separability $\Rightarrow \langle(\Delta\hat{u})^2\rangle_\rho + \langle(\Delta\hat{v})^2\rangle_\rho \geq 2\ (a^2 + \frac{1}{a^2})$

Lu-Ming Duan, G. Giedke, J.I. Cirac, P. Zoller,
Inseparability criterion for continuous variable systems, Phys. Rev. Lett. **84**, 2722 (2000).

- After some (simple) algebra:

$$(\Delta^2 p_1 + \Delta^2 q_1 - 2)(\Delta^2 p_2 + \Delta^2 q_2 - 2) - (|c_p| + |c_q|)^2 \geq 0;$$

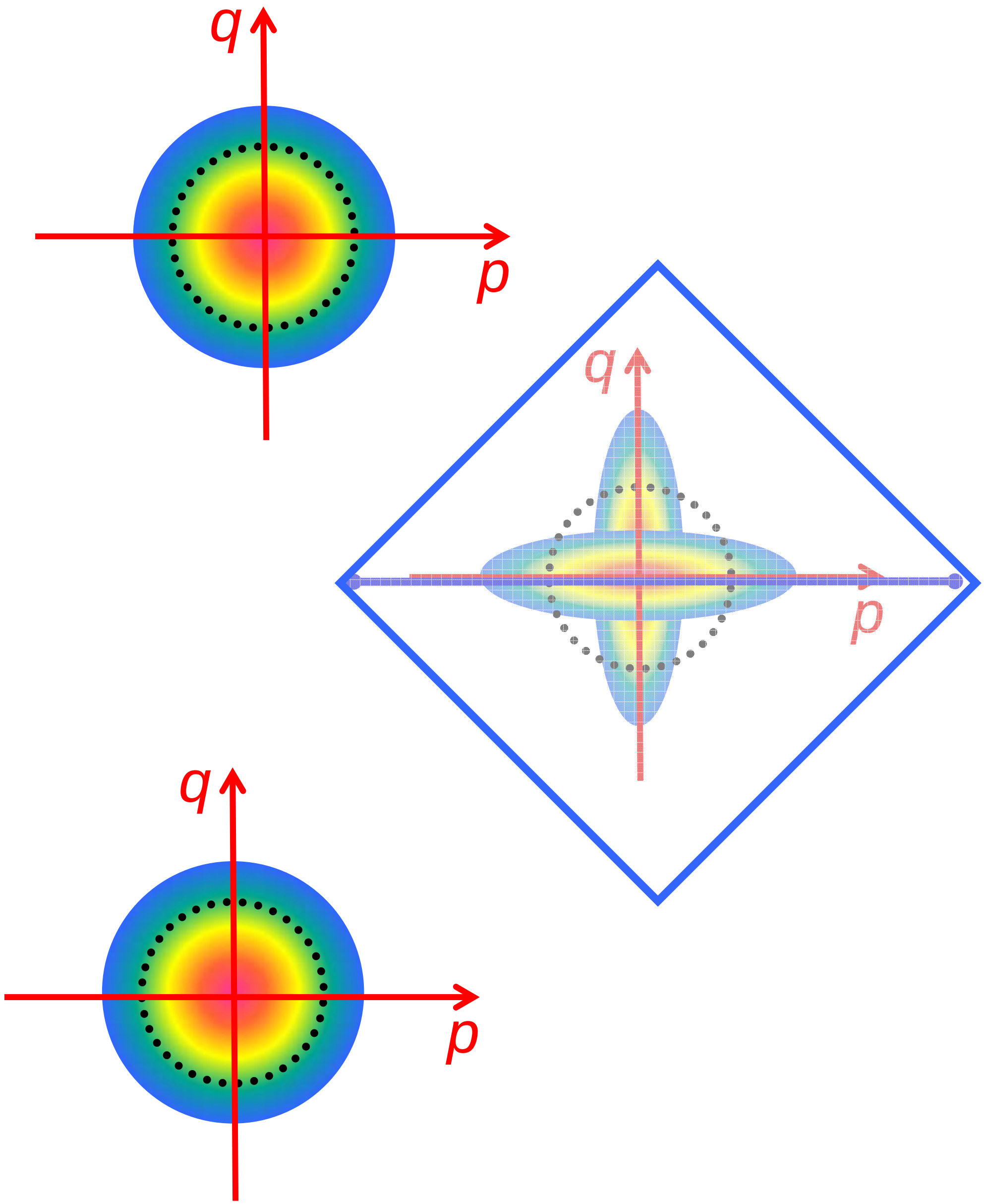
Entanglement Test - DGCZ

$$V = \begin{bmatrix} S_{p1} & C_{p1q1} & C_{p1p2} & C_{p1q2} \\ C_{p1q1} & S_{q1} & C_{q1p2} & C_{q1q2} \\ C_{p1p2} & C_{q1p2} & S_{p2} & C_{p2q2} \\ C_{p1q2} & C_{q1q2} & C_{p2q2} & S_{q2} \end{bmatrix}$$

$$C_{xixj} = \frac{1}{2}\langle\{x_i, x_j\}\rangle - \langle x_i\rangle\langle x_j\rangle \qquad S_{xj} = C_{xjxj}$$

$$(\Delta^2 p_1 + \Delta^2 q_1 - 2)(\Delta^2 p_2 + \Delta^2 q_2 - 2) - (|c_p| + |c_q|)^2 \geq 0;$$

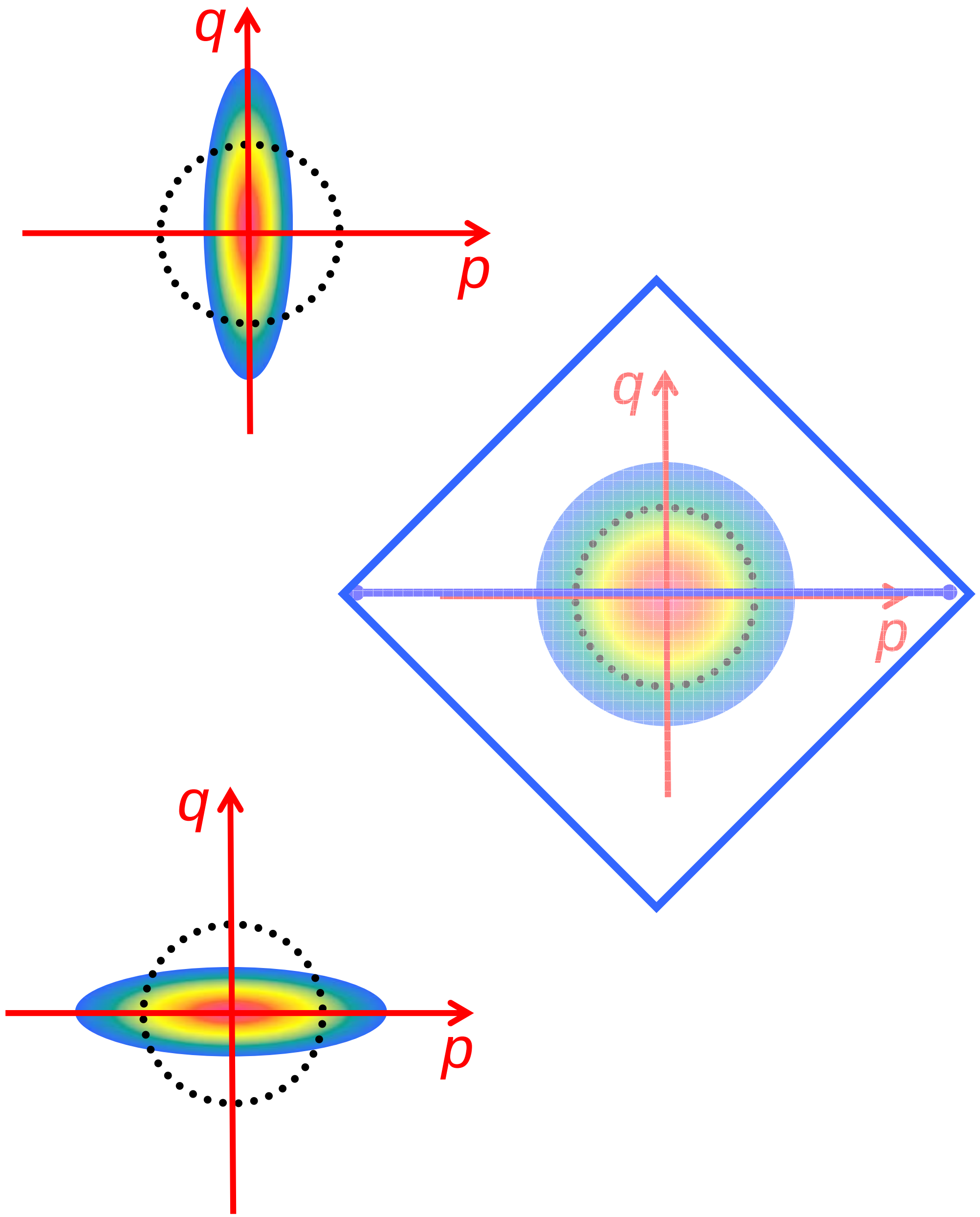
Entanglement Test - DGCZ



p_1+p_2 ,
q_1+q_2

p_1-p_2 ,
q_1-q_2

Entanglement Generation



p_1+p_2 ,
q_1+q_2

p_1-p_2 ,
q_1-q_2

Entanglement Test - Peres & Horodecki

- Positivity under Partial Transposition
  (discrete variables)

Separability Criterion for Density Matrices

Asher Peres*

PRL **77**, 1413 (1996)

$$\rho = \sum_A w_A \rho'_A \otimes \rho''_A \quad \Longrightarrow \quad \sigma = \sum_A w_A (\rho'_A)^T \otimes \rho''_A$$

non-negative eigenvalues -> Separability

Entanglement Test - Simon

- Continuous variables:

Peres-Horodecki Separability Criterion for Continuous Variable Systems

R. Simon

PRL **84**, 2726 (2000)

$$PT: \qquad W(q_1, p_1, q_2, p_2) \rightarrow W(q_1, p_1, q_2, -p_2)$$

$$V + \frac{i}{2}\Omega \geq 0 \quad \Rightarrow \quad \tilde{V} + \frac{i}{2}\Omega \geq 0$$

$$\tilde{V} = \Lambda V \Lambda$$

$$\Omega = \begin{pmatrix} J & 0 \\ 0 & J \end{pmatrix} \quad J = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

$$\Lambda = \mathrm{diag}(1, 1, 1, -1)$$

Simplectic Eigenvalues >1

Diagonalize: $-(\Omega\tilde{V})^2$

Entanglement Test - Simon

$$V = \begin{bmatrix} S_{p1} & C_{p1q1} & C_{p1p2} & C_{p1q2} \\ C_{p1q1} & S_{q1} & C_{q1p2} & C_{q1q2} \\ C_{p1p2} & C_{q1p2} & S_{p2} & C_{p2q2} \\ C_{p1q2} & C_{q1q2} & C_{p2q2} & S_{q2} \end{bmatrix}$$

$$C_{xixj} = \frac{1}{2}\langle\{x_i, x_j\}\rangle - \langle x_i\rangle\langle x_j\rangle$$

$$S_{xj} = C_{xjxj}$$

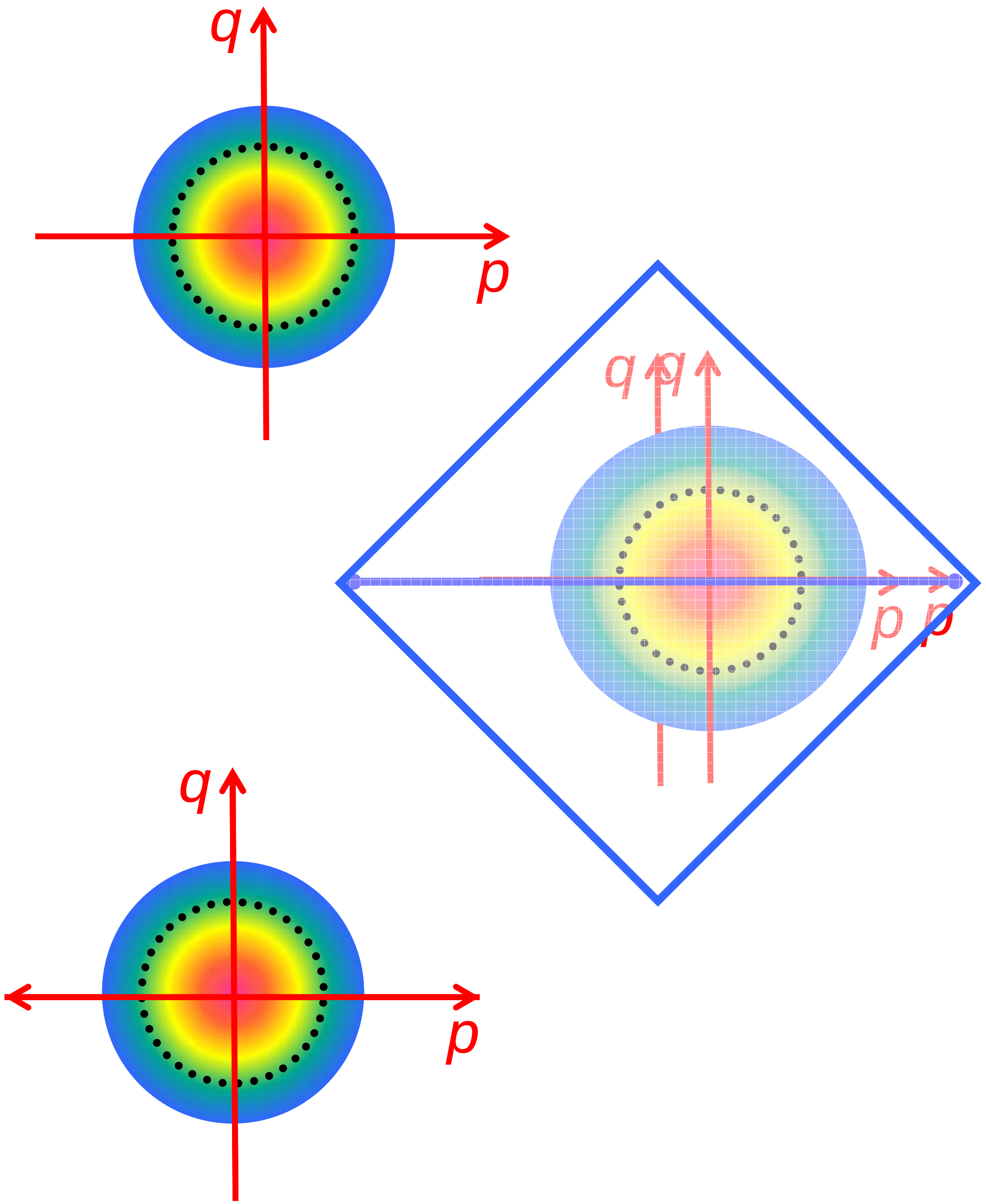
Entanglement Test - Simon

$$V = \begin{bmatrix} S_{p1} & C_{p1q1} & C_{p1p2} & -C_{p1q2} \\ C_{p1q1} & S_{q1} & C_{q1p2} & -C_{q1q2} \\ C_{p1p2} & C_{q1p2} & S_{p2} & -C_{p2q2} \\ -C_{p1q2} & -C_{q1q2} & -C_{p2q2} & S_{q2} \end{bmatrix}$$

$$C_{xixj} = \frac{1}{2}\langle\{x_i, x_j\}\rangle - \langle x_i\rangle\langle x_j\rangle$$

$$S_{xj} = C_{xjxj}$$

Entanglement Test - Simon



$p_1 - p_2$,
$q_1 + q_2$

$p_1 + p_2$,
$q_1 - q_2$

Tripartite Entanglement

- Extend DGCZ criterion to three variables

Detecting genuine multipartite continuous-variable entanglement

PHYSICAL REVIEW A **67**, 052315 (2003)

Peter van Loock[1] and Akira Furusawa[2]

$$\hat{u} \equiv h_1 \hat{x}_1 + h_2 \hat{x}_2 + h_3 \hat{x}_3, \quad \hat{v} \equiv g_1 \hat{p}_1 + g_2 \hat{p}_2 + g_3 \hat{p}_3,$$

$$\langle (\Delta \hat{u})^2 \rangle_\rho + \langle (\Delta \hat{v})^2 \rangle_\rho \geq f(h_1, h_2, h_3, g_1, g_2, g_3),$$

- Apply PPT to multiple partitions

Bound Entangled Gaussian States

R. F. Werner* and M. M. Wolf†

PHYSICAL REVIEW LETTERS
VOLUME 86, NUMBER 16
DOI: 10.1103/PhysRevLett.86.3658

Gaussian states of $1 \times N$ systems

ppt implies separability.

Covariance Matrix

$$V = \begin{bmatrix} S_{p1} & 0 & C_{p1p2} & 0 & C_{p1p0} & 0 \\ 0 & S_{q1} & 0 & C_{q1q2} & 0 & C_{q1q0} \\ C_{p1p2} & 0 & S_{p2} & 0 & C_{p2p0} & 0 \\ 0 & C_{q1q0} & 0 & S_{q2} & 0 & C_{q2q0} \\ C_{p1p0} & 0 & C_{p2p0} & 0 & S_{p0} & 0 \\ 0 & C_{q1q0} & 0 & C_{q2q0} & 0 & S_{q0} \end{bmatrix}$$

$$C_{xixj} = \frac{1}{2}\langle\{x_i, x_j\}\rangle - \langle x_i\rangle\langle x_j\rangle \qquad S_{xj} = C_{xjxj}$$

Twin beams ($P_0 > P_{th}$)

Squeezed vacuum ($P_0 < P_{th}$, degenerate)

$$V = \begin{bmatrix} S_{p-} & 0 & 0 & 0 & 0 & 0 \\ 0 & S_{q-} & 0 & 0 & 0 & 0 \\ 0 & 0 & S_{p+} & 0 & C_{p+p0} & 0 \\ 0 & 0 & 0 & S_{q+} & 0 & C_{q+q0} \\ 0 & 0 & C_{p+p0} & 0 & S_{p0} & 0 \\ 0 & 0 & 0 & C_{q+q0} & 0 & S_{q0} \end{bmatrix}$$

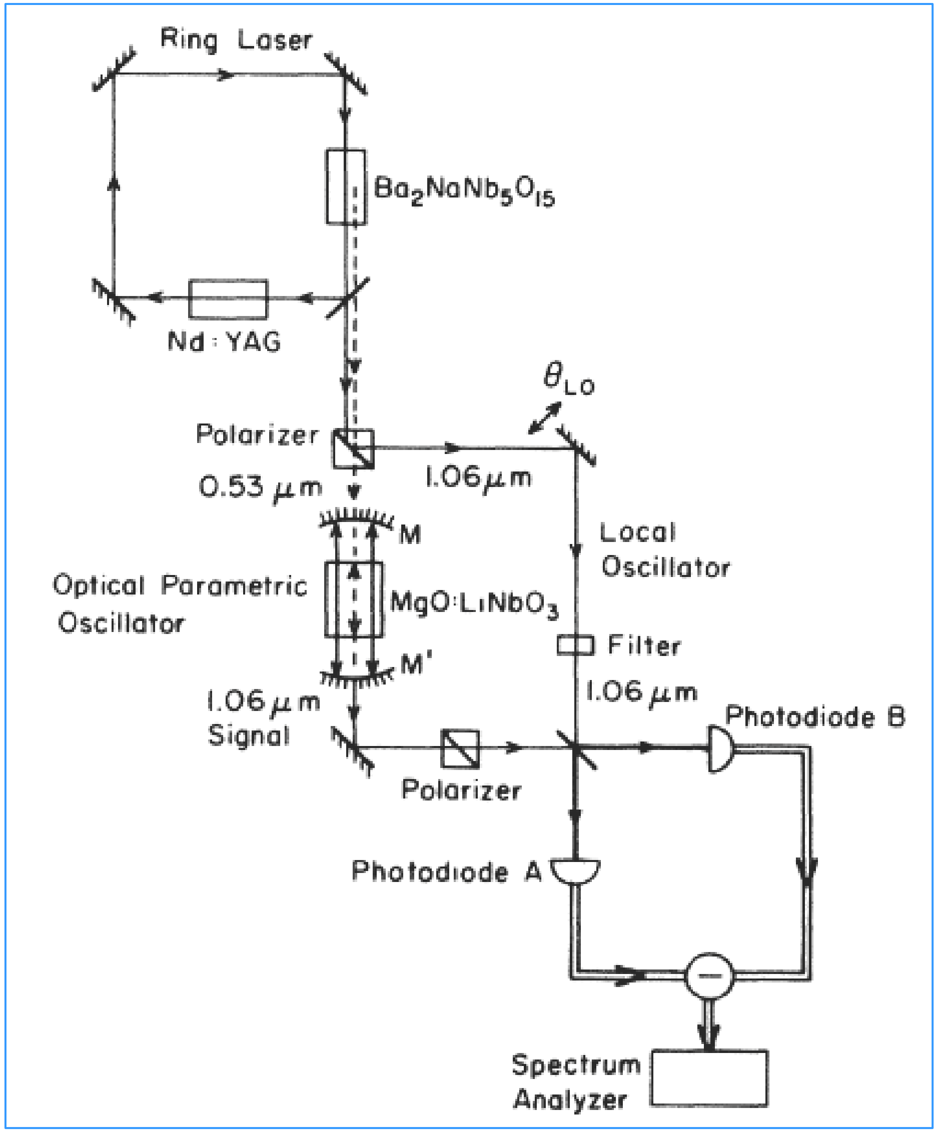
Entangled fields

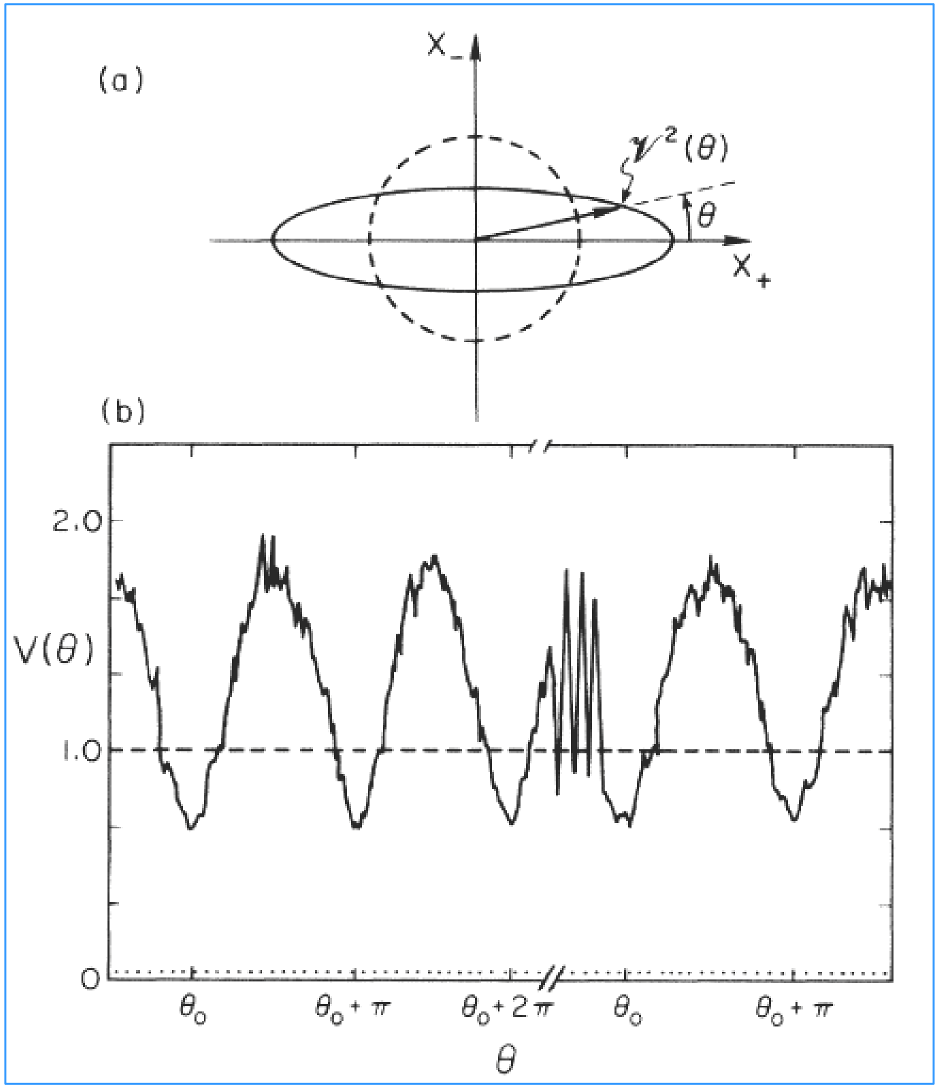
- Vacuum ($P_0 < P_{th}$, maximum entanglement)
- Intense beams ($P_0 > P_{th}$)

Pump Squeezing ($P_0 > P_{th}$)

Generation of Squeezed States by Parametric Down Conversion

Ling-An Wu, H. J. Kimble, J. L. Hall,[a] and Huifa Wu
Department of Physics, University of Texas at Austin, Austin, Texas 78712
(Received 11 September 1986)





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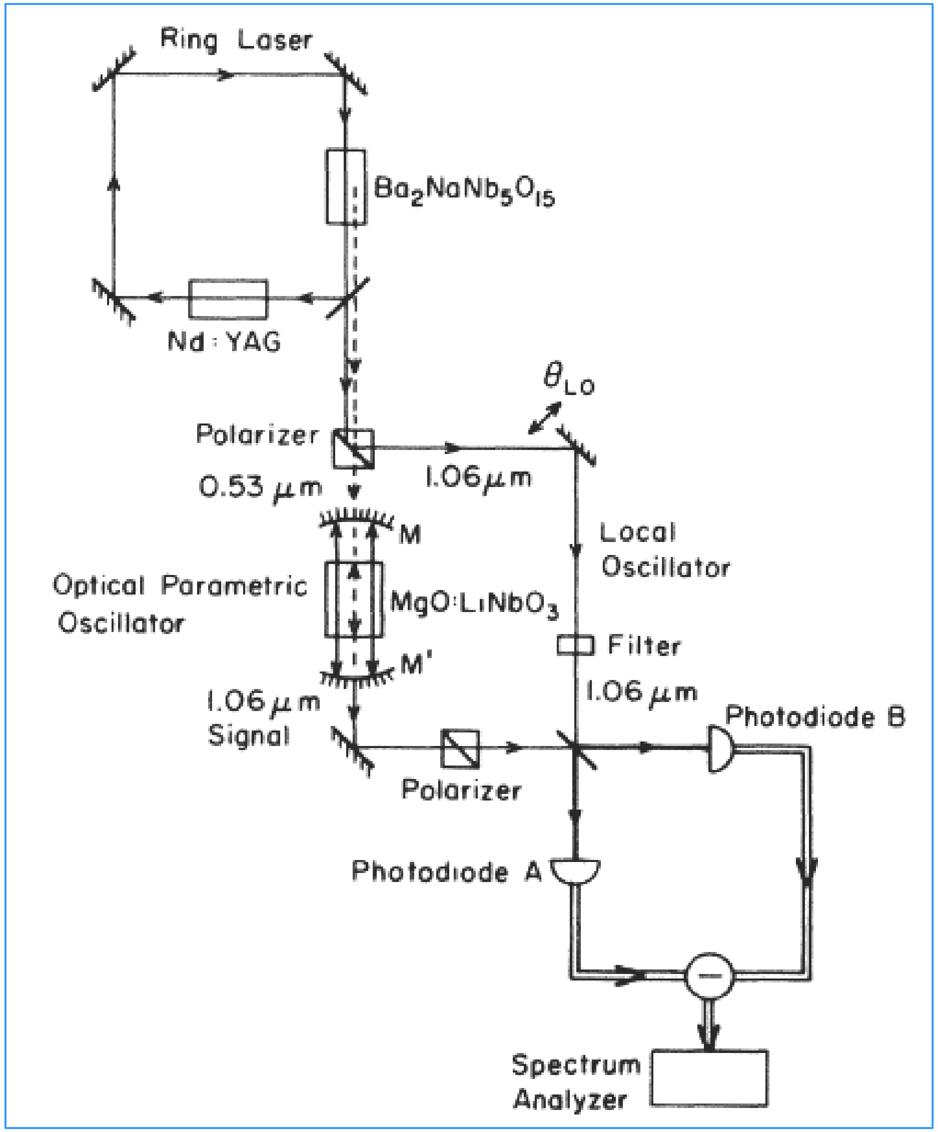
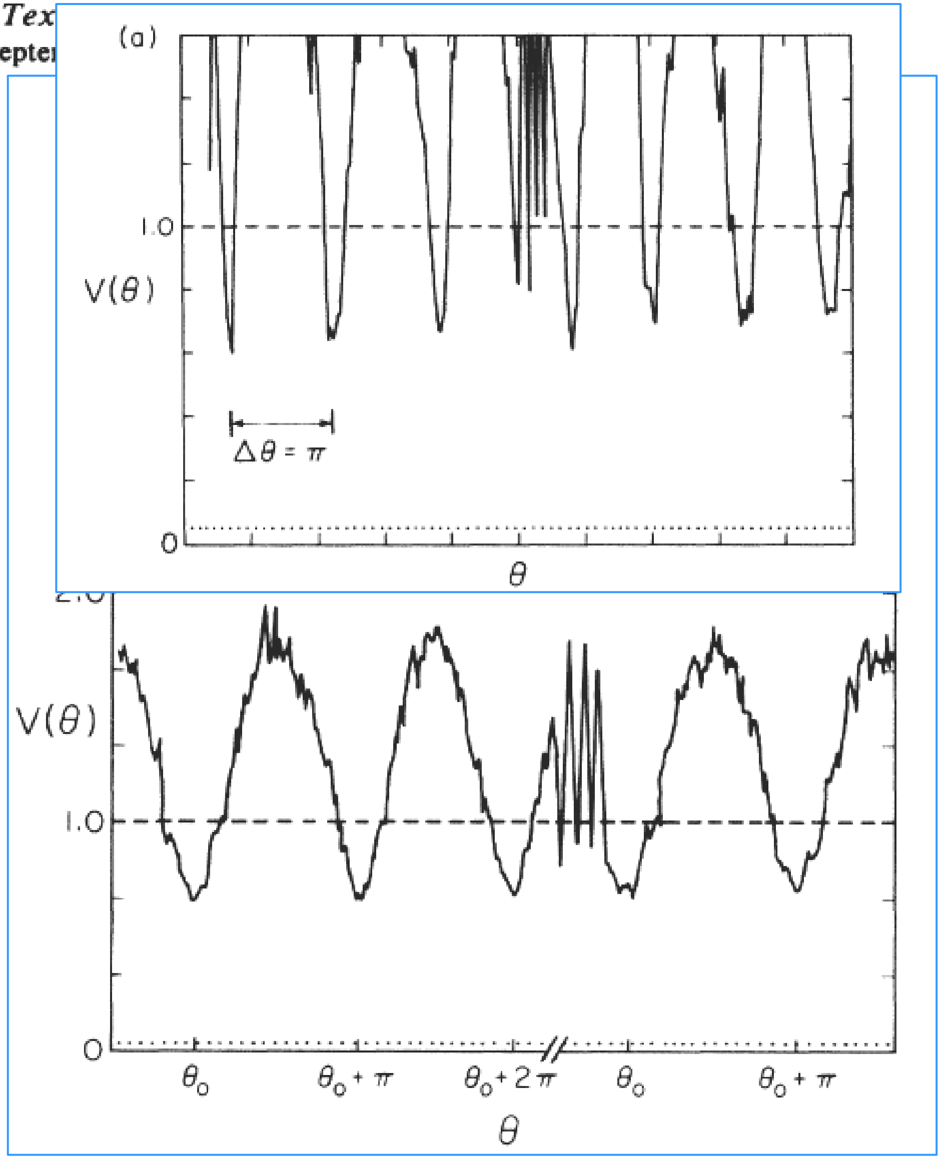


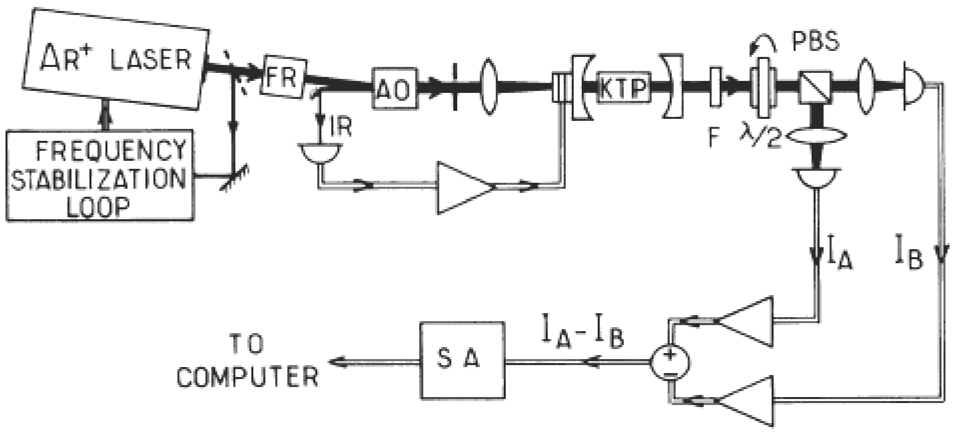


Observation of Quantum Noise Reduction on Twin Laser Beams

A. Heidmann, R. J. Horowicz, S. Reynaud, E. Giacobino, and C. Fabre
Laboratoire de Spectroscopie Hertzienne de l'Ecole Normale Supérieure, Université Pierre et Marie Curie, 75252 Paris Cedex 05, France

and

G. Camy
Laboratoire de Physique des Lasers, Université de Paris Nord, 93430 Villetaneuse, France
(Received 3 August 1987)



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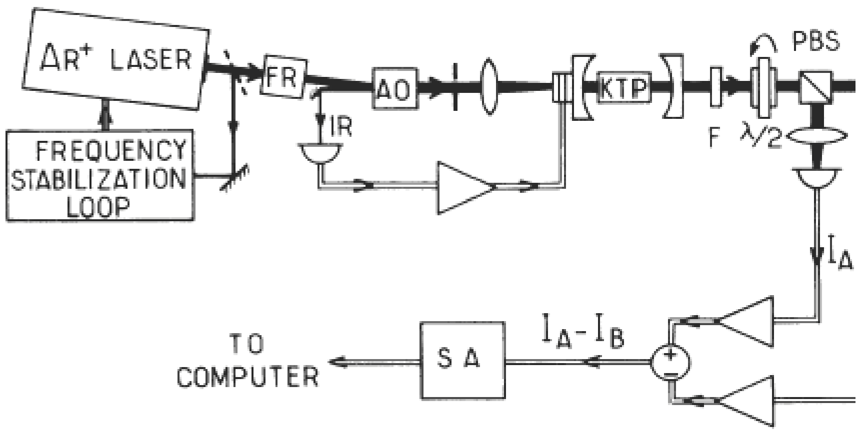
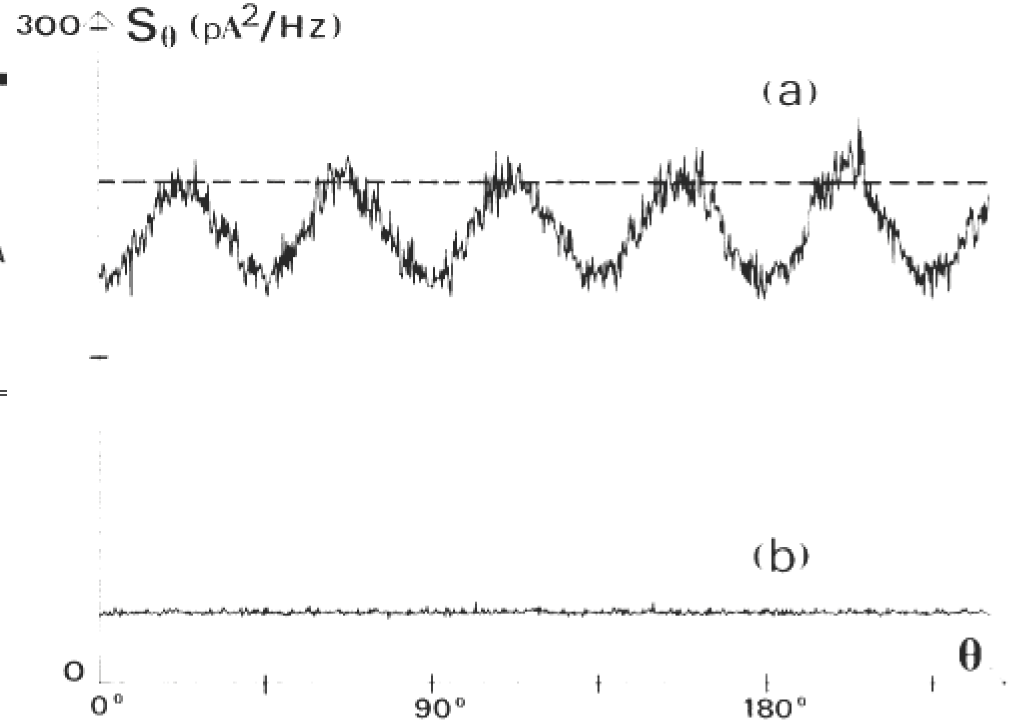




Europhys. Lett., **40** (1), pp. 25-30 (1997)

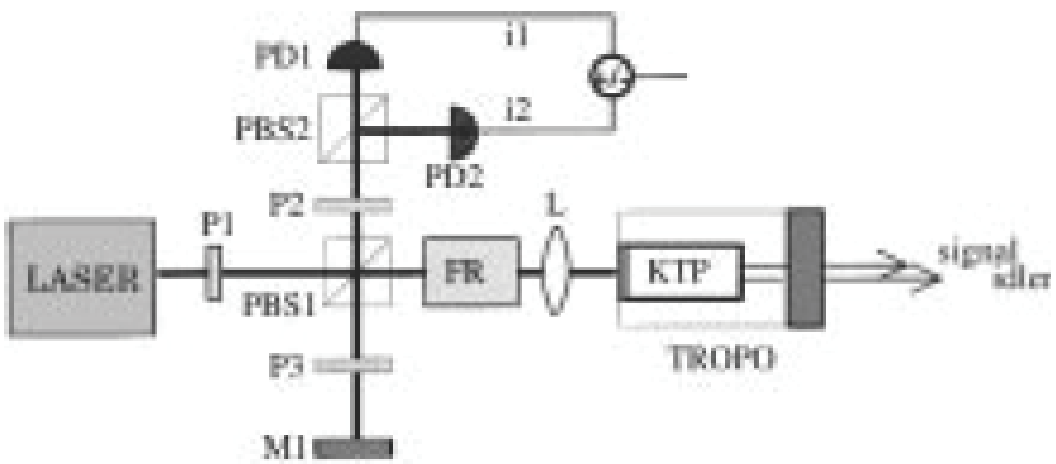
Observation of squeezing using cascaded nonlinearity

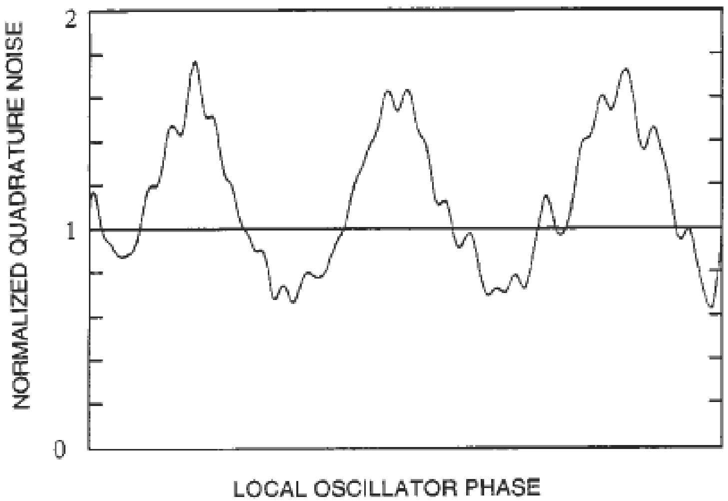
K. Kasai(*), Gao Jiangrui(**) and C. Fabre

Laboratoire Kastler Brossel(***) UPMC - Case 74 75252 Paris Cedex 05, France

(received 20 January 1997; accepted in final form 2 September 1997)

Abstract. – We have observed that the pump beam reflected by a triply resonant optical parametric oscillator, after a cascaded second-order nonlinear interaction in the crystal, is significantly squeezed. The maximum measured squeezing in our device is 30% (output beam squeezing inferred: 48%). The direction of the noise ellipse depends on the cavity detuning and can be adjusted from intensity squeezing to phase squeezing.





Realization of the Einstein-Podolsky-Rosen Paradox for Continuous Variables

Z. Y. Ou, S. F. Pereira, H. J. Kimble, and K. C. Peng[a]
Norman Bridge Laboratory of Physics 12-33, California Institute of Technology, Pasadena, California 91125
(Received 20 February 1992)

The Einstein-Podolsky-Rosen paradox is demonstrated experimentally for dynamical variables having a continuous spectrum. As opposed to previous work with discrete spin or polarization variables, the continuous optical amplitudes of a signal beam are inferred in turn from those of a spatially separated but strongly correlated idler beam generated by nondegenerate parametric amplification. The uncertainty product for the variances of these inferences is observed to be 0.70 ± 0.01, which is below the limit of unity required for the demonstration of the paradox.

VOLUME 68, NUMBER 25 PHYSICAL REVIEW LETTERS 22 JUNE 1992

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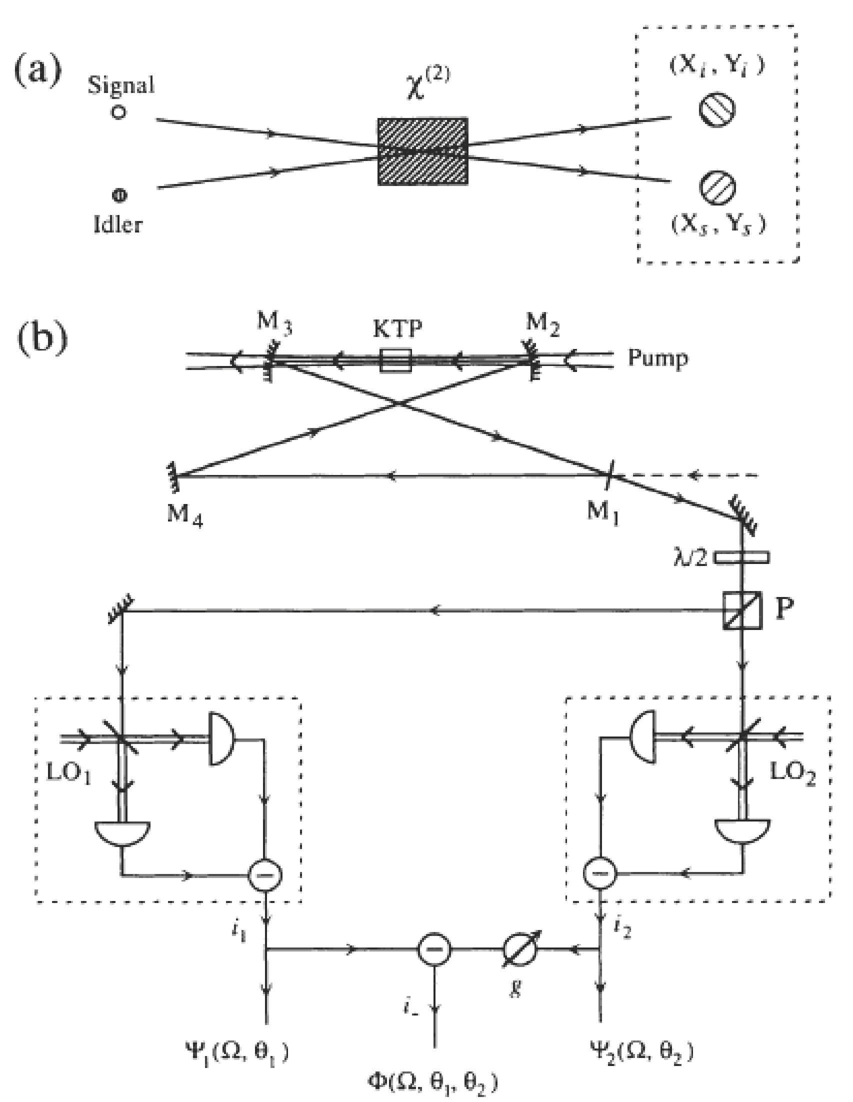
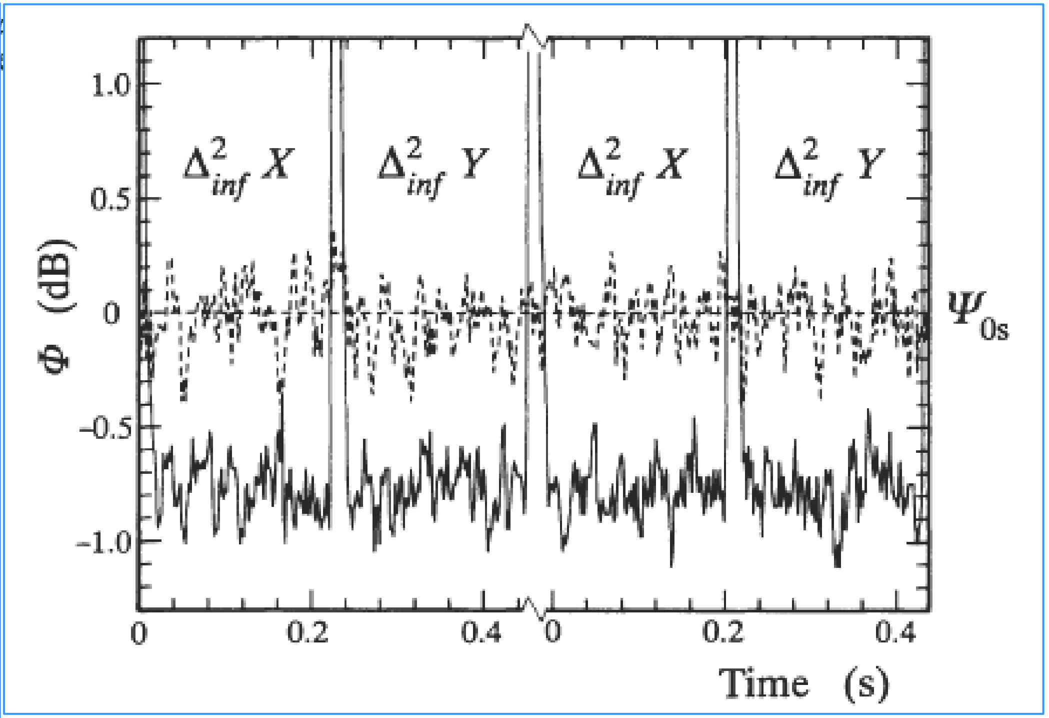
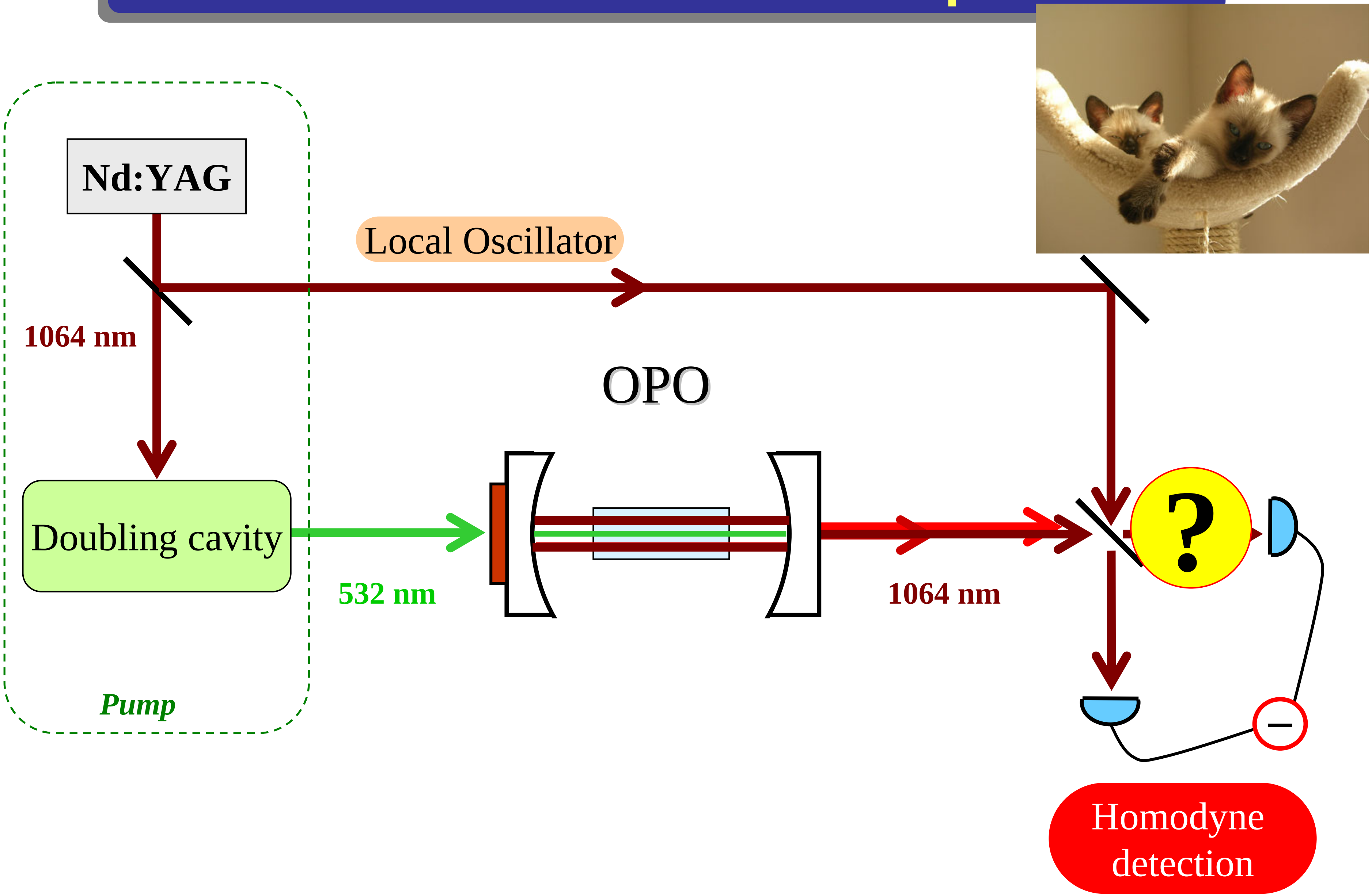




$$\Delta^2_{inf} X \, \Delta^2_{inf} Y = 0.70 \pm 0.01$$

How can we measure the phase?

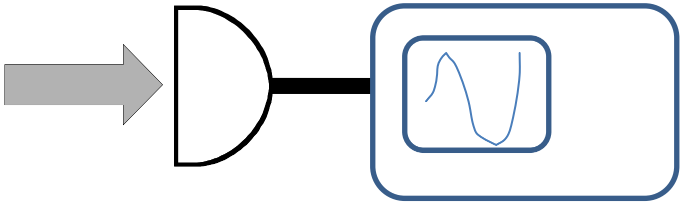



ONLY THEIR MOTHER CAN TELL THEM APART.
TWINS
AN IVAN REITMAN FILM
ARNOLD SCHWARZENEGGER DANNY DEVITO "TWINS" KELLY PRESTON CHLOE WEBB BONNIE BARTLETT WRITTEN BY WILLIAM DAVIES &

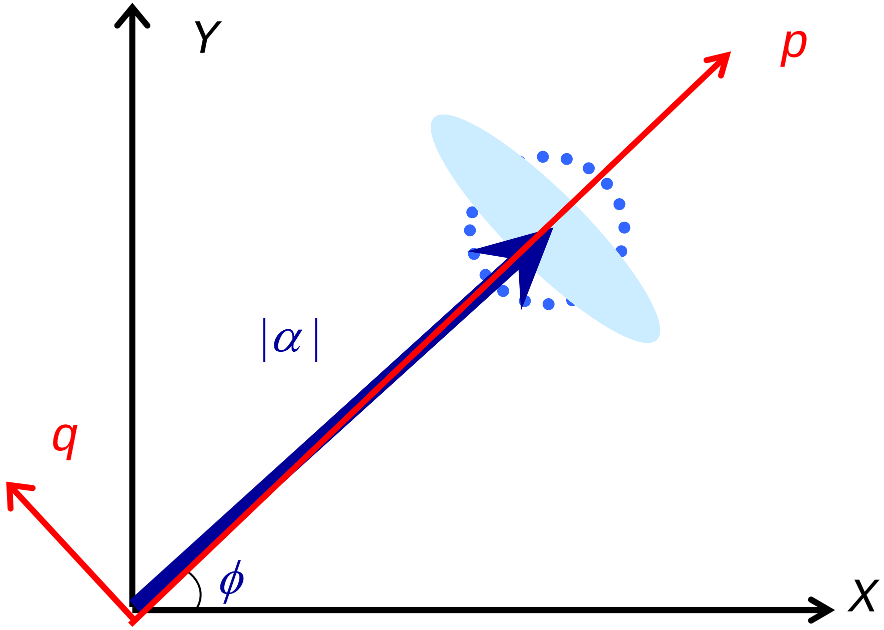
And if we look for a complete characterization of the OPO, we have to measure three fields of diferent colors!

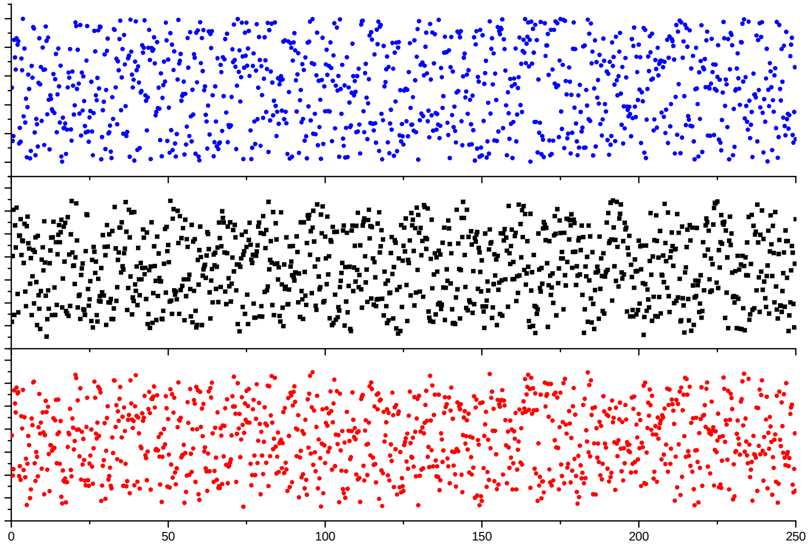
Is it possible to perform a homodyne measurement without a local oscillator?

Measurement of the Field in the time domain

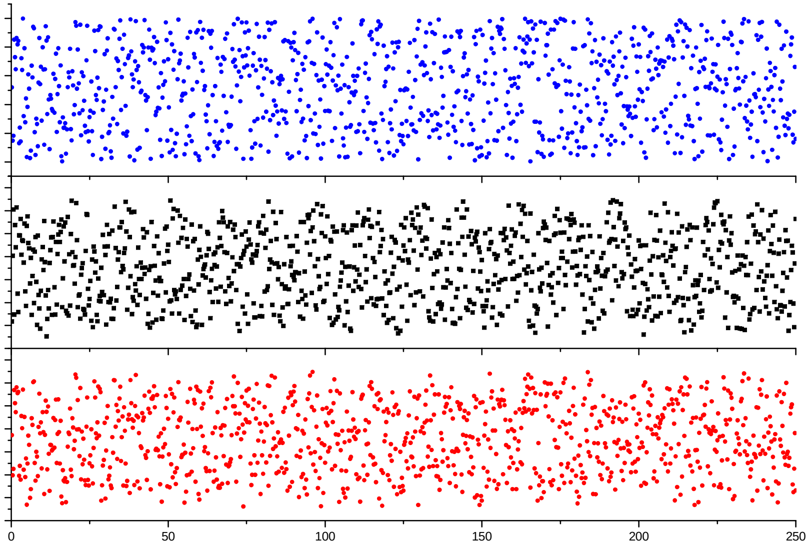


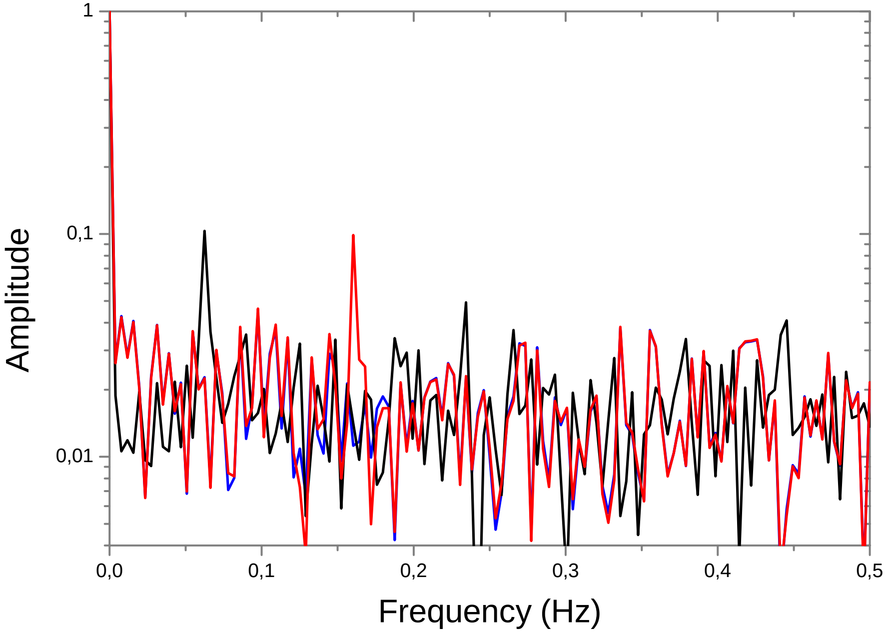
$$\hat{n} = |\alpha|^2 + |\alpha|\delta\hat{p}$$





Measurement of the Field in the frequency domain





Measurement of the Field in the frequency domain

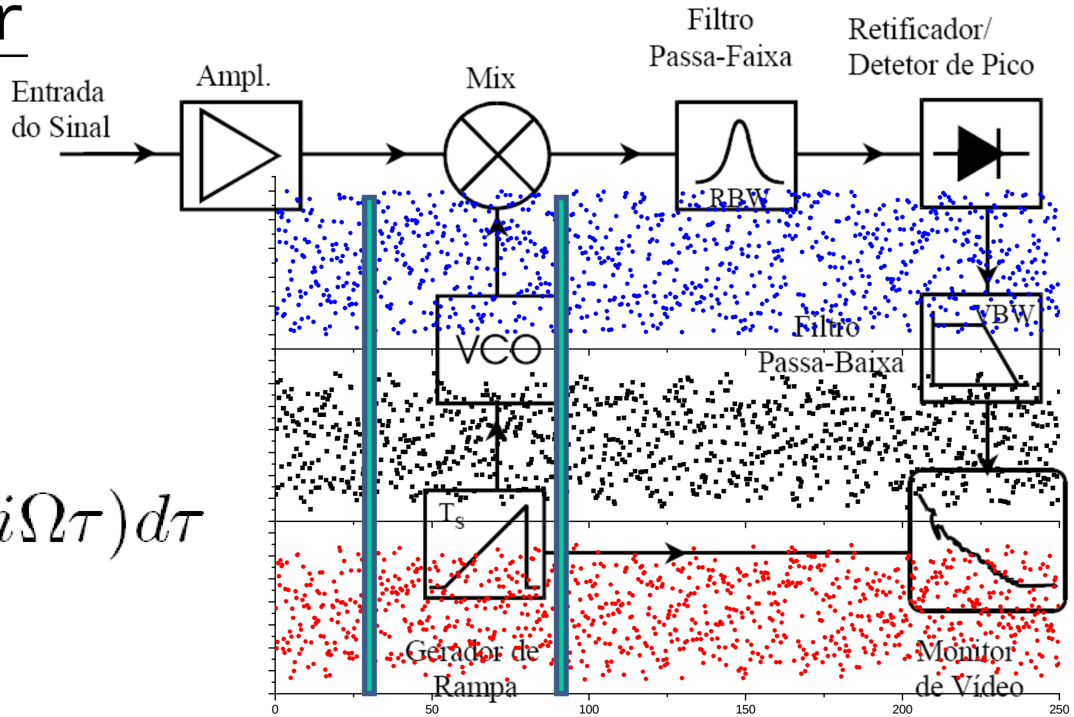
$$\hat{a}(t) = \int_{-\infty}^{\infty} \hat{a}(\Omega) \exp(-i\Omega t)\, d\Omega.$$

$$\hat{a}(\Omega) = \hat{x}(\Omega) + i\hat{y}(\Omega)$$

Spectrum Analyser

$$\langle \hat{X}(t)\hat{X}(t+\tau)\rangle =$$

$$\int \hat{X}(\Omega)\hat{X}(-\Omega)exp(i\Omega\tau)d\tau$$



Measurement of the Field in the frequency domain

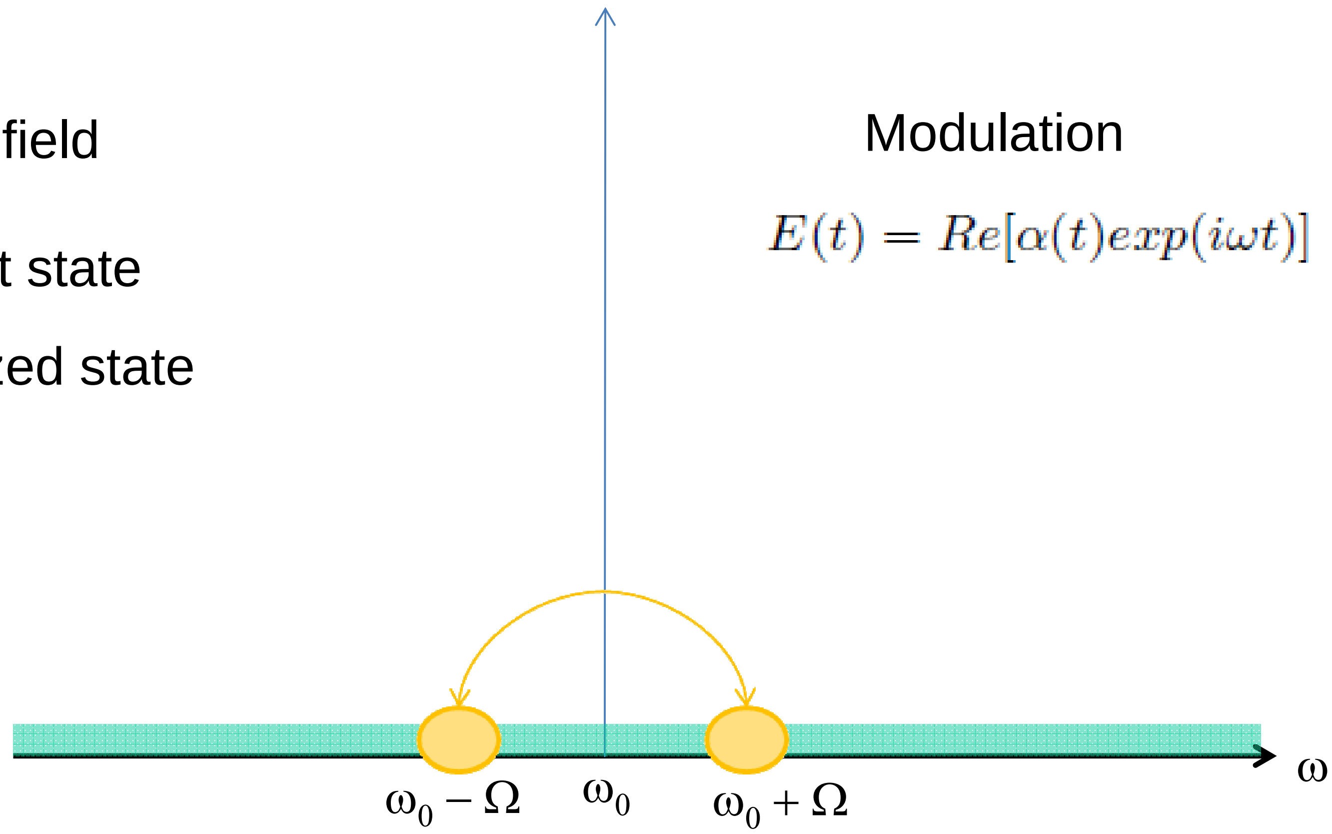
A classic field

Coherent state

Squeezed state

Modulation

$$E(t) = Re[\alpha(t) exp(i\omega t)]$$



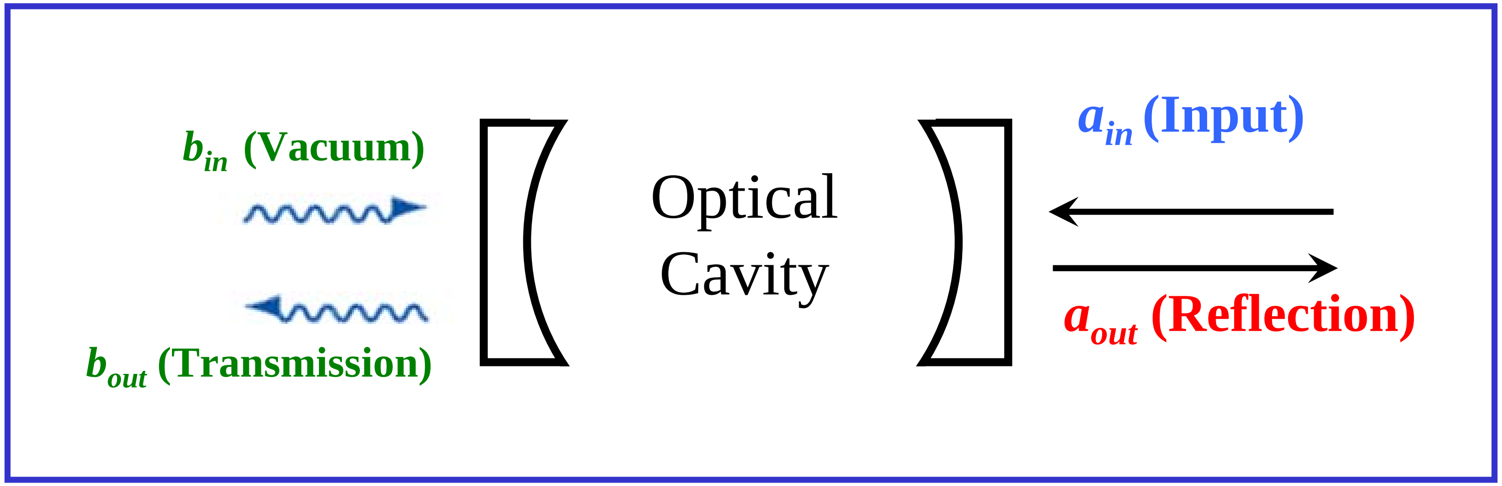
Amplitude $\alpha(t) = A[1 + 2\kappa cos(\Omega t)]$

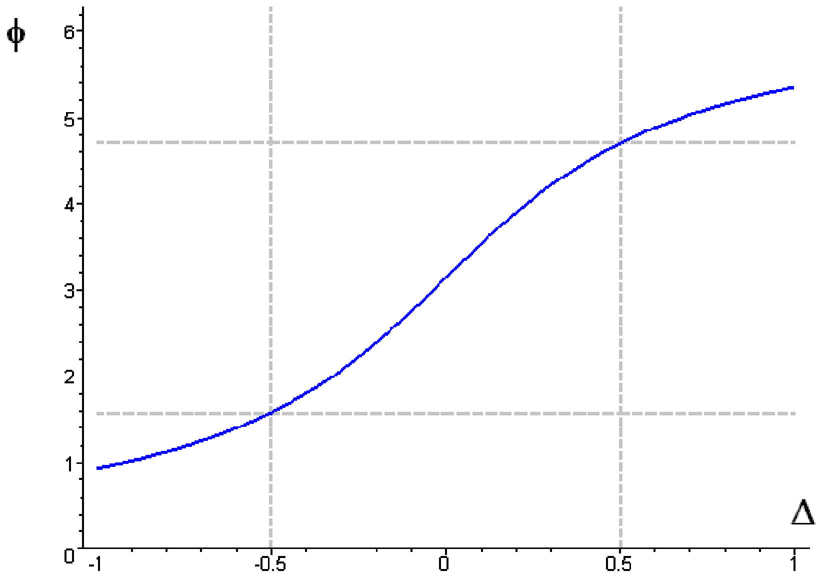
$$E(t) = A\,Re\{\kappa exp[i(\omega - \Omega)t] + exp(i\omega t) + \kappa exp[i(\omega + \Omega)t]\}$$

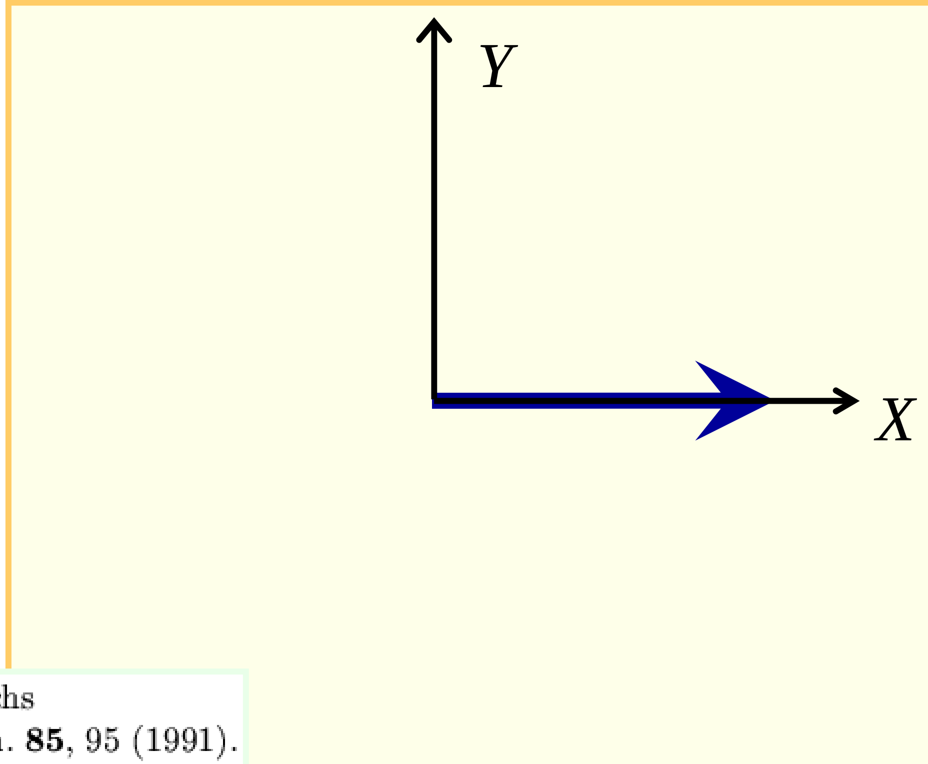
Phase $\alpha(t) = A exp[2i\kappa cos(\Omega t)] \simeq A[1 + 2i\kappa cos(\Omega t)]$

$$E(t) = A\,Re\{i\kappa exp[i(\omega - \Omega)t] + exp(i\omega t) + i\kappa exp[i(\omega + \Omega)t]\}$$

Phase Rotation of Noise Ellipse





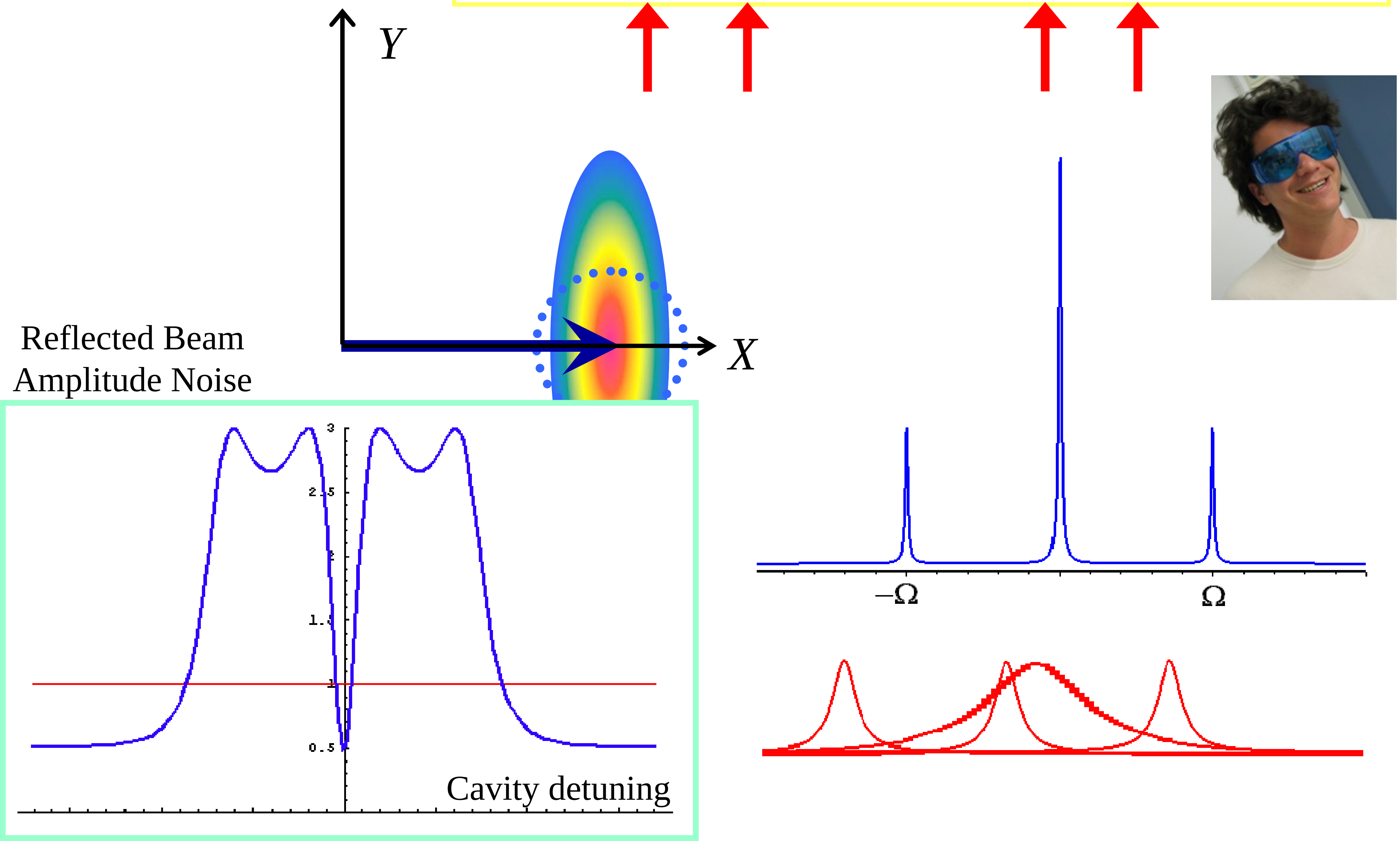


P. Galatola, L.A. Lugiato, M.G. Porreca, P. Tombesi e G. Leuchs
System control by variation of the squeezing phase, Opt. Comm. **85**, 95 (1991).

Alessandro S. Villar, *The conversion of phase to amplitude fluctuations of a light beam by an optical cavity*
American Journal of Physics **76**, pp. 922-929 (2008).

$$\delta p_{in} = \delta a_{in}(\Omega) + \delta a^{\dagger}_{in}(-\Omega)$$

$$\delta p_{out} = \cdots\cdots\cdots \, \delta a_{in}(\Omega) + \cdots\cdots\cdots \, \delta a^{\dagger}_{in}(-\Omega)$$

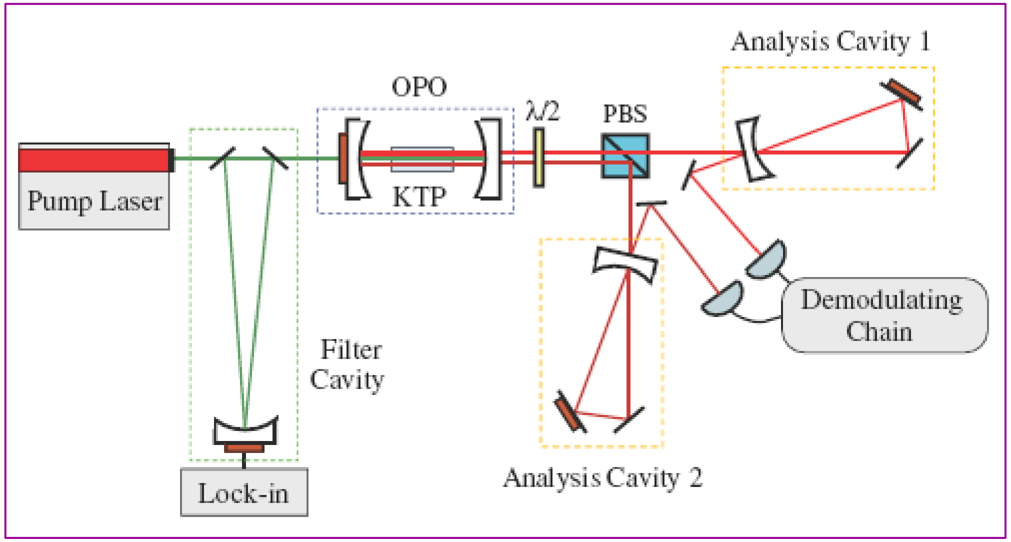


Generation of Bright Two-Color Continuous Variable Entanglement

A. S. Villar, L. S. Cruz, K. N. Cassemiro, M. Martinelli, and P. Nussenzveig*

Instituto de Física, Universidade de São Paulo, Caixa Postal 66318, 05315-970 São Paulo, São Paulo, Brazil

We present the first measurement of squeezed-state entanglement between the twin beams produced in an optical parametric oscillator operating above threshold. In addition to the usual squeezing in the intensity difference between the twin beams, we have measured squeezing in the sum of phase quadratures. Our scheme enables us to measure such phase anticorrelations between fields of different frequencies. In the present measurements, wavelengths differ by ≈ 1 nm. Entanglement is demonstrated according to the Duan *et al.* criterion [Phys. Rev. Lett. **84**, 2722 (2000)] $\Delta^2\hat{p}_- + \Delta^2\hat{q}_+ = 1.41(2) < 2$. This experiment opens the way for new potential applications such as the transfer of quantum information between different parts of the electromagnetic spectrum.



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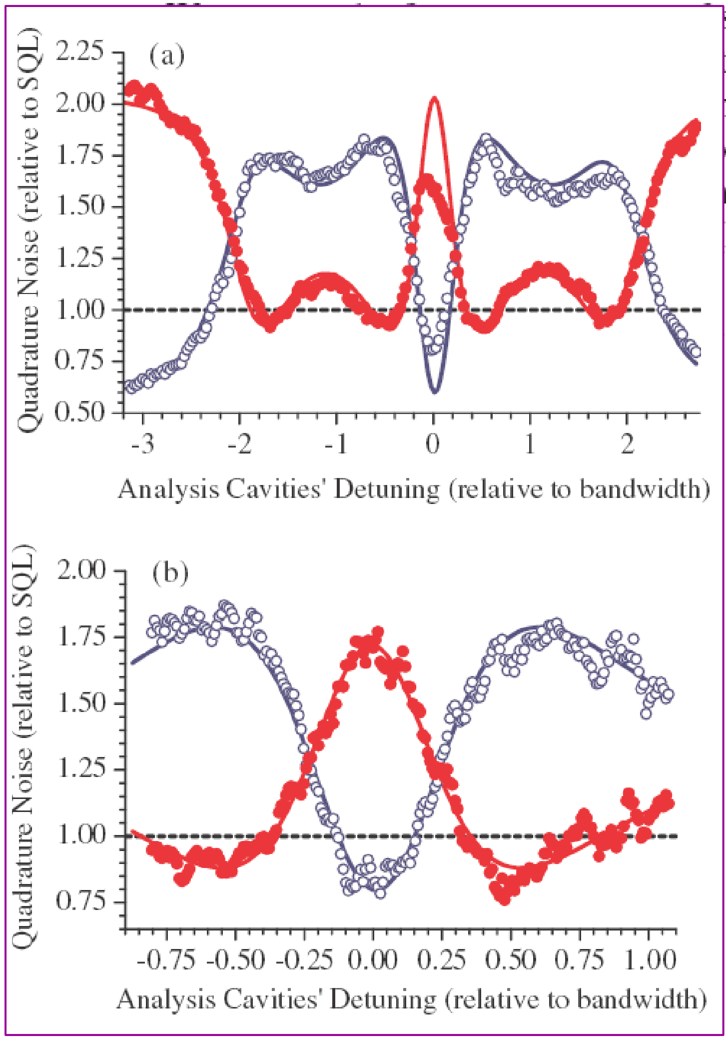

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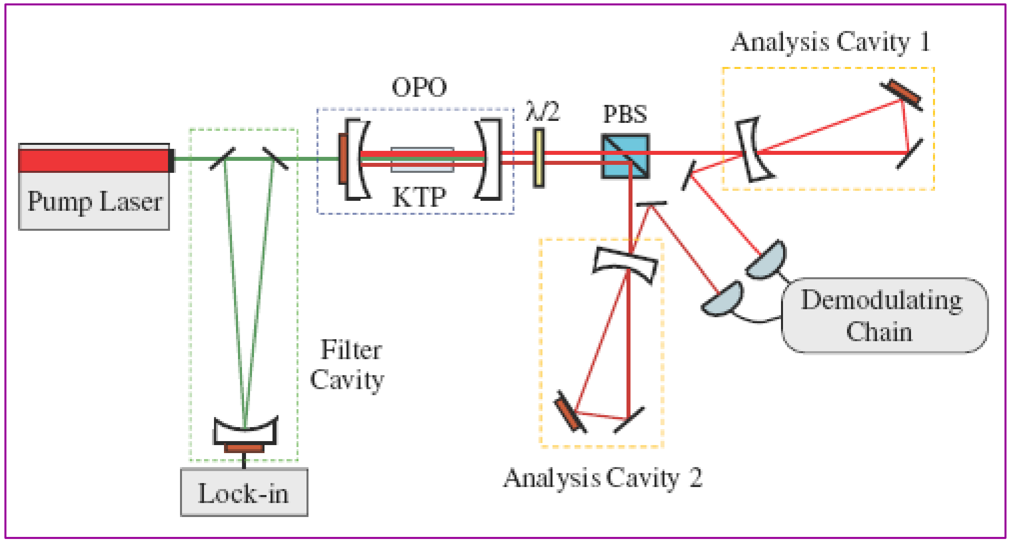
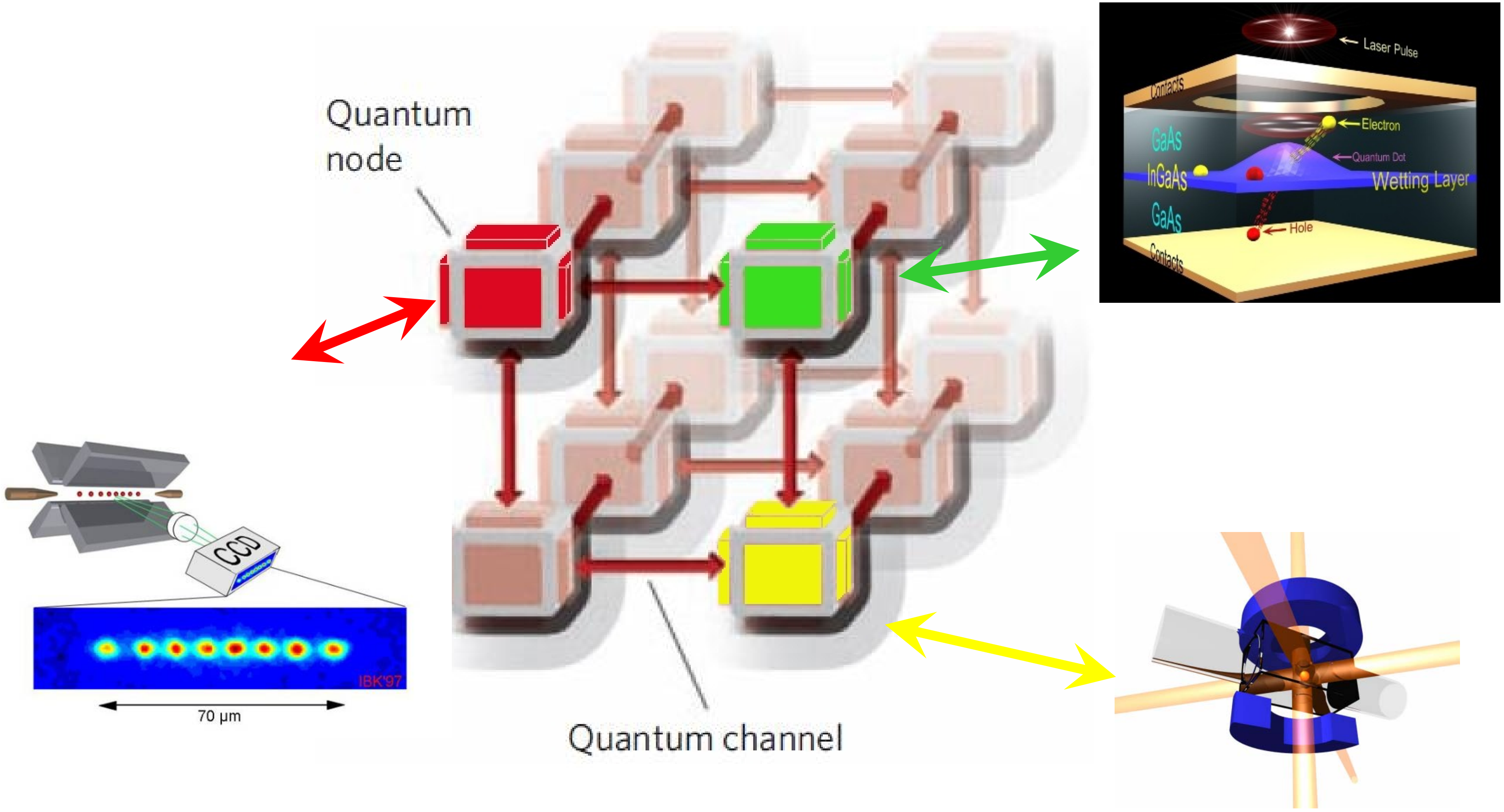


NATURE|Vol 453|19 June 2008|doi:10.1038/nature07127

The quantum internet

H. J. Kimble[1]

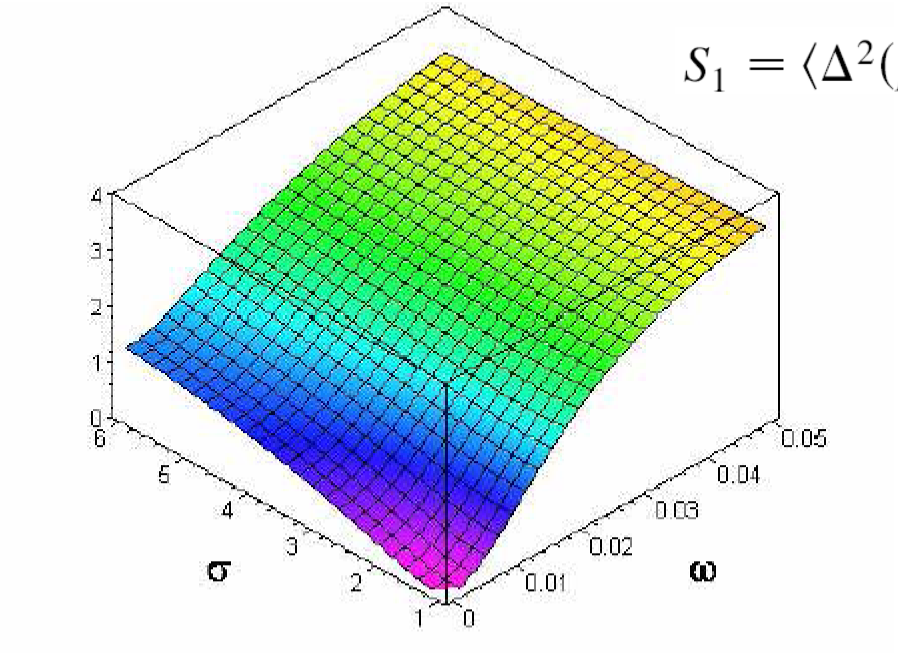


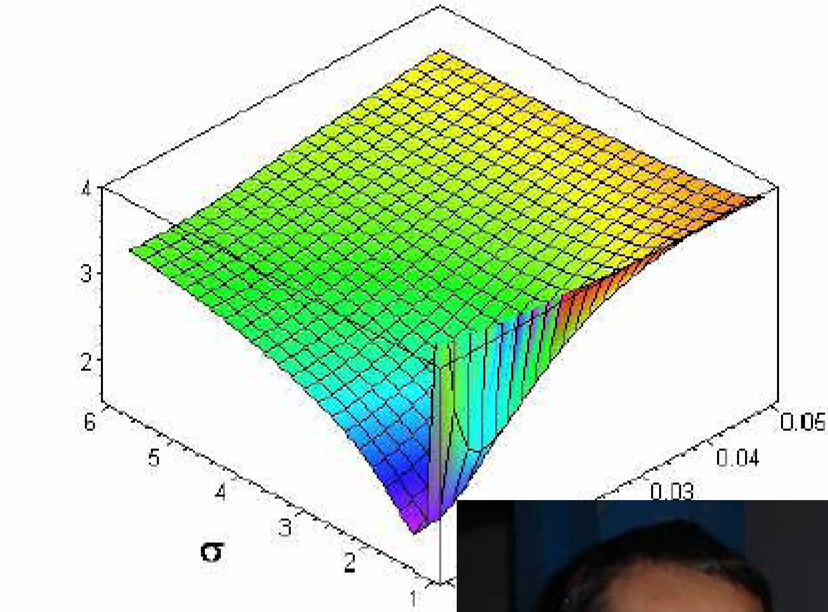
PRL 97, 140504 (2006) PHYSICAL REVIEW LETTERS week ending 6 OCTOBER 2006

Direct Production of Tripartite Pump-Signal-Idler Entanglement in the Above-Threshold Optical Parametric Oscillator

A. S. Villar,[1] M. Martinelli,[1] C. Fabre,[2] and P. Nussenzveig[1,*]

$$S_1 = \langle \Delta^2(\hat{p}_1 - \hat{p}_2) \rangle + \langle \Delta^2(\hat{q}_1 + \hat{q}_2 - \alpha_0 \hat{q}_0) \rangle \geq 4$$





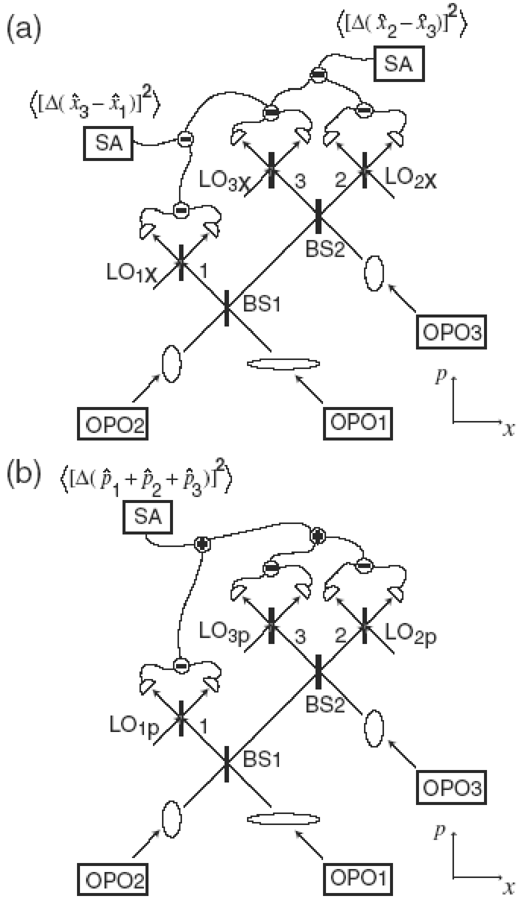
$$S_2 = \langle \Delta^2(\hat{p}_0 + \hat{p}_1) \rangle + \langle \Delta^2(\hat{q}_1 + \alpha_2 \hat{q}_2 - \hat{q}_0) \rangle \geq 4$$

$$S_3 = \langle \Delta^2(\hat{p}_0 + \hat{p}_2) \rangle + \langle \Delta^2(\alpha_1 \hat{q}_1 + \hat{q}_2 - \hat{q}_0) \rangle \geq 4$$

Experimental Creation of a Fully Inseparable Tripartite Continuous-Variable State

Takao Aoki,* Nobuyuki Takei, Hidehiro Yonezawa, Kentaro Wakui, Takuji Hiraoka, and Akira Furusawa
Department of Applied Physics, School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

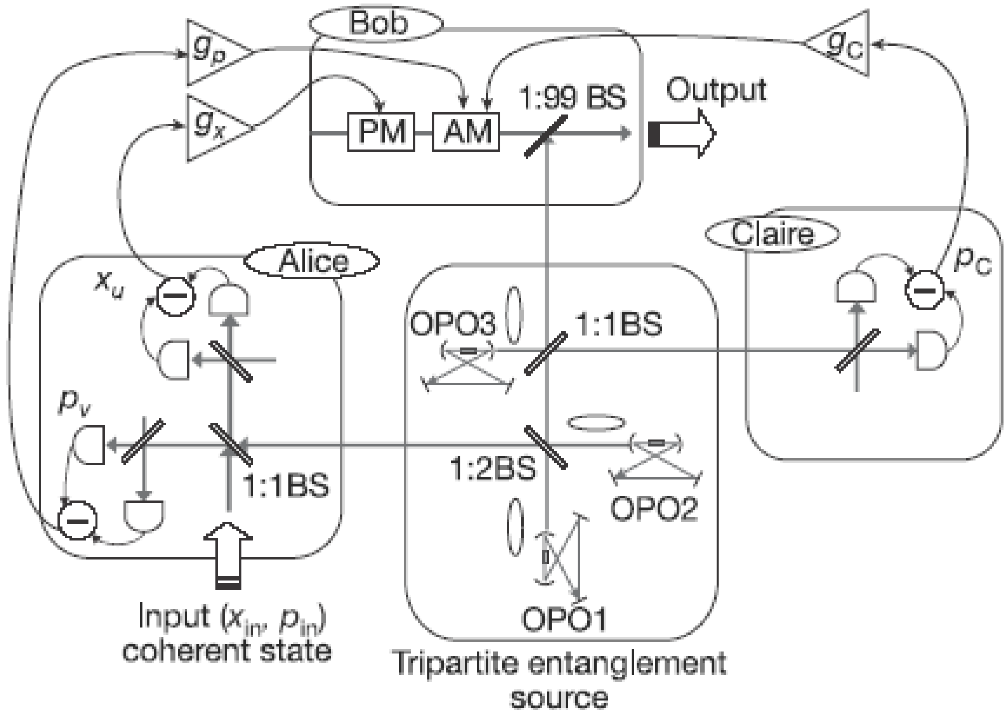
Peter van Loock
Quantum Information Theory Group, Zentrum für Moderne Optik, Universität Erlangen-Nürnberg, 91058 Erlangen, Germany



Demonstration of a quantum teleportation network for continuous variables

Hidehiro Yonezawa[1,2], **Takao Aoki**[1,2] **& Akira Furusawa**[1,2]

[1]*Department of Applied Physics, School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan*
[2]*CREST, Japan Science and Technology Agency, 1-1-9 Yaesu, Chuo-ku, Tokyo 103-0028, Japan*



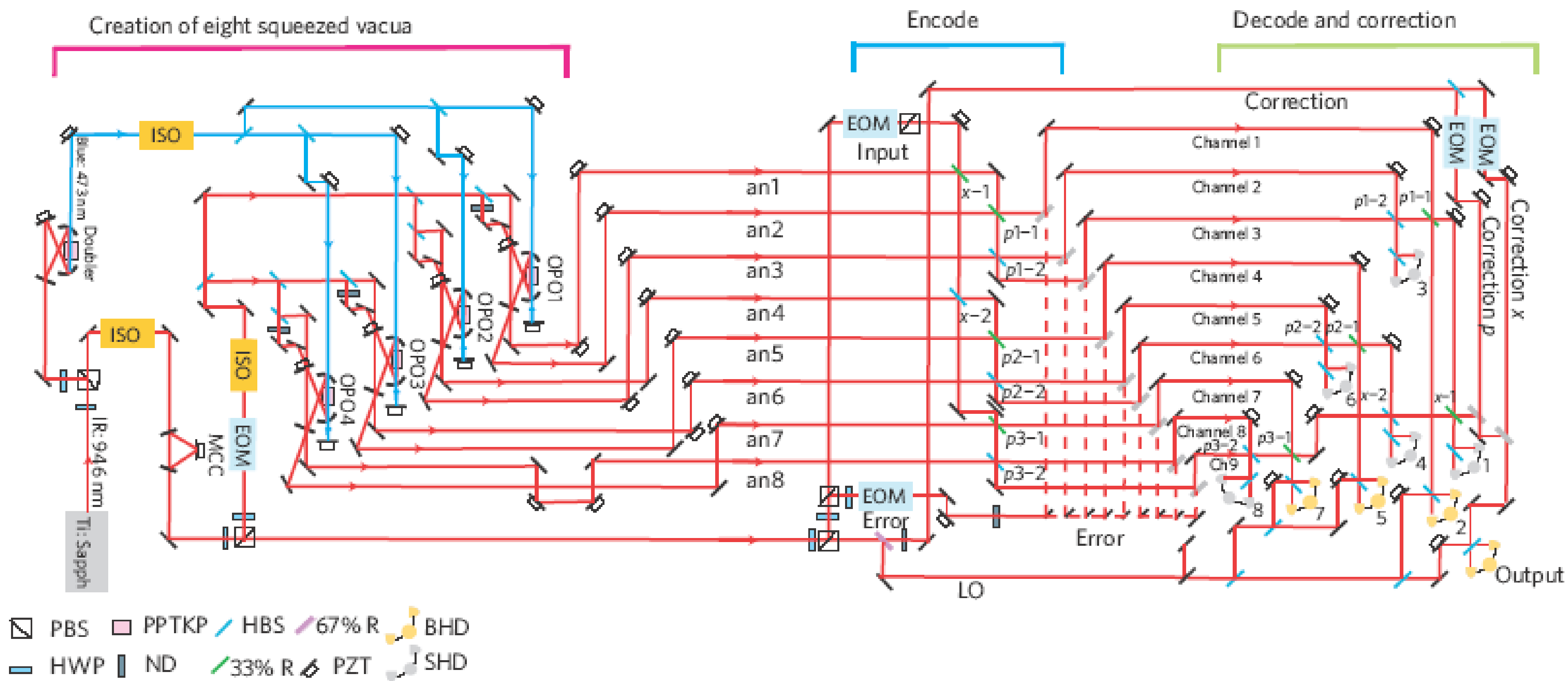
nature physics

LETTERS

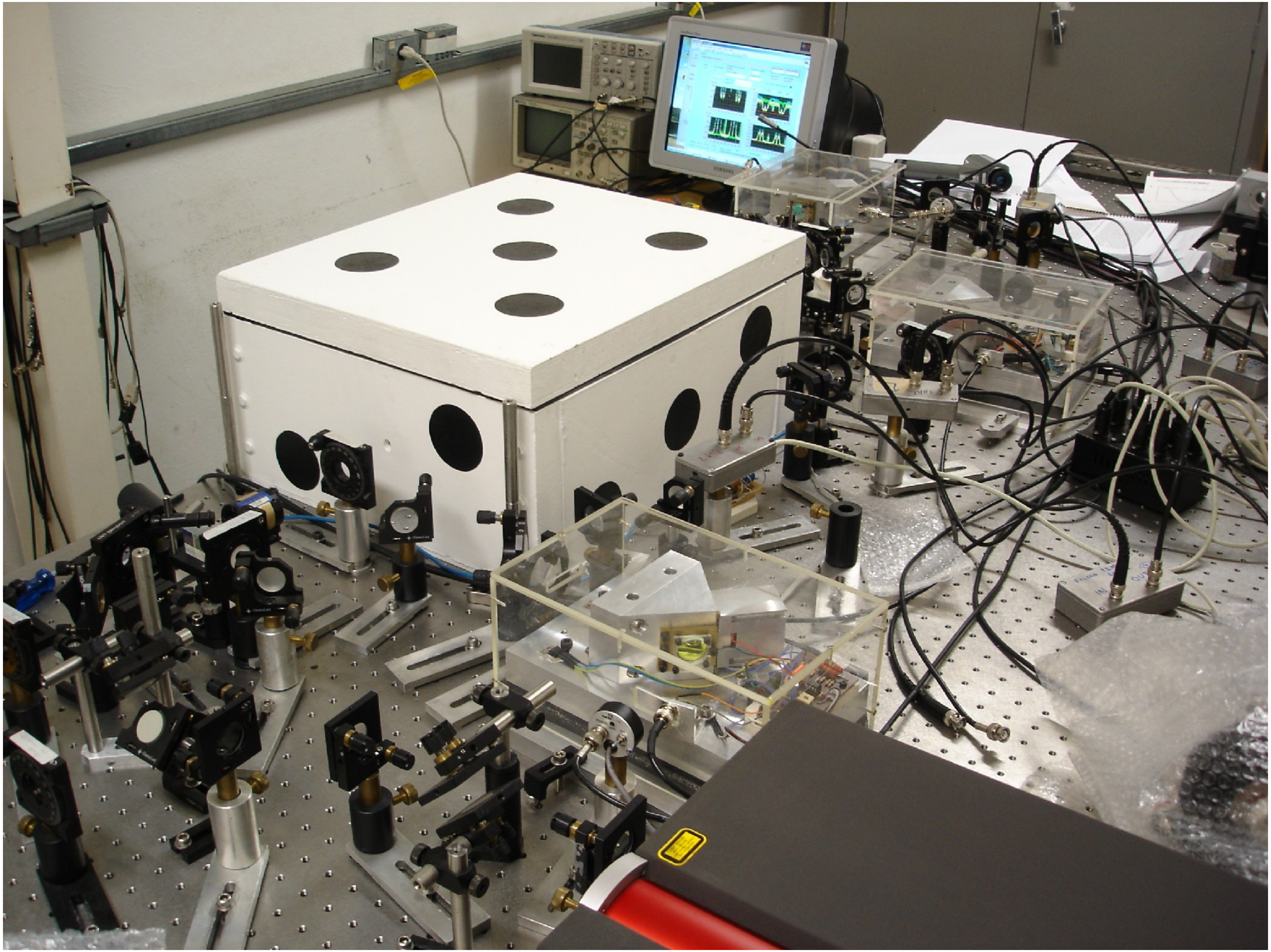
PUBLISHED ONLINE: 28 JUNE 2009 | DOI: 10.1038/NPHYS1309

Quantum error correction beyond qubits

Takao Aoki[1*], Go Takahashi[1,2], Tadashi Kajiya[1,2], Jun-ichi Yoshikawa[1,2], Samuel L. Braunstein[3], Peter van Loock[4] and Akira Furusawa[1,2†]



Tripartite entanglement?



Set up

Quantum Correlations between pump, signal and idler for $P_0 > P_{th}$

$$V = \begin{bmatrix} S_{p1} & 0 & C_{p1p2} & 0 & C_{p1p0} & 0 \\ 0 & S_{q1} & 0 & C_{q1q2} & 0 & C_{q1q0} \\ C_{p1p2} & 0 & S_{p2} & 0 & C_{p2p0} & 0 \\ 0 & C_{q1q2} & 0 & S_{q2} & 0 & C_{q2q0} \\ C_{p1p0} & 0 & C_{p2p0} & 0 & S_{p0} & 0 \\ 0 & C_{q1q0} & 0 & C_{q2q0} & 0 & S_{q0} \end{bmatrix}$$

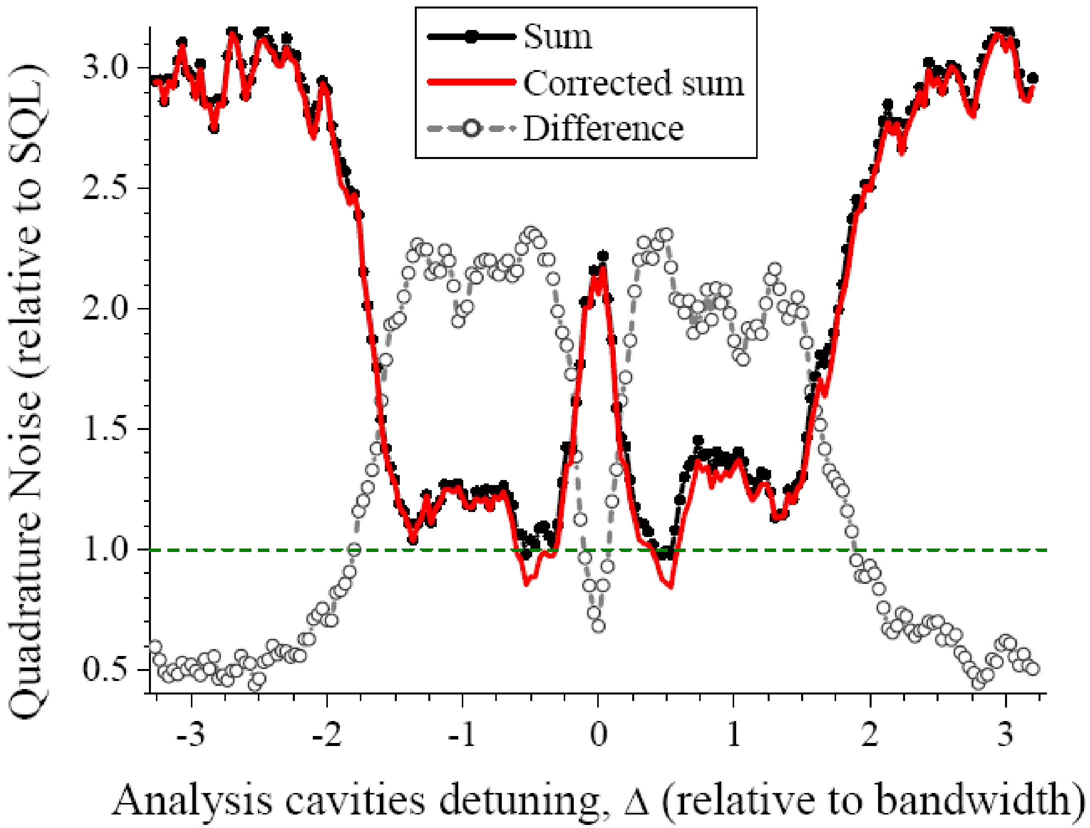
K. N. Cassemiro *et al.* Opt. Lett. **32**, 695 (2007)

K. N. Cassemiro *et al.* Opt. Exp. **15**, 18326 (2007)

N. B. Grosse *et al.* PRL **100**, 243601 (2008) (degenerate case)

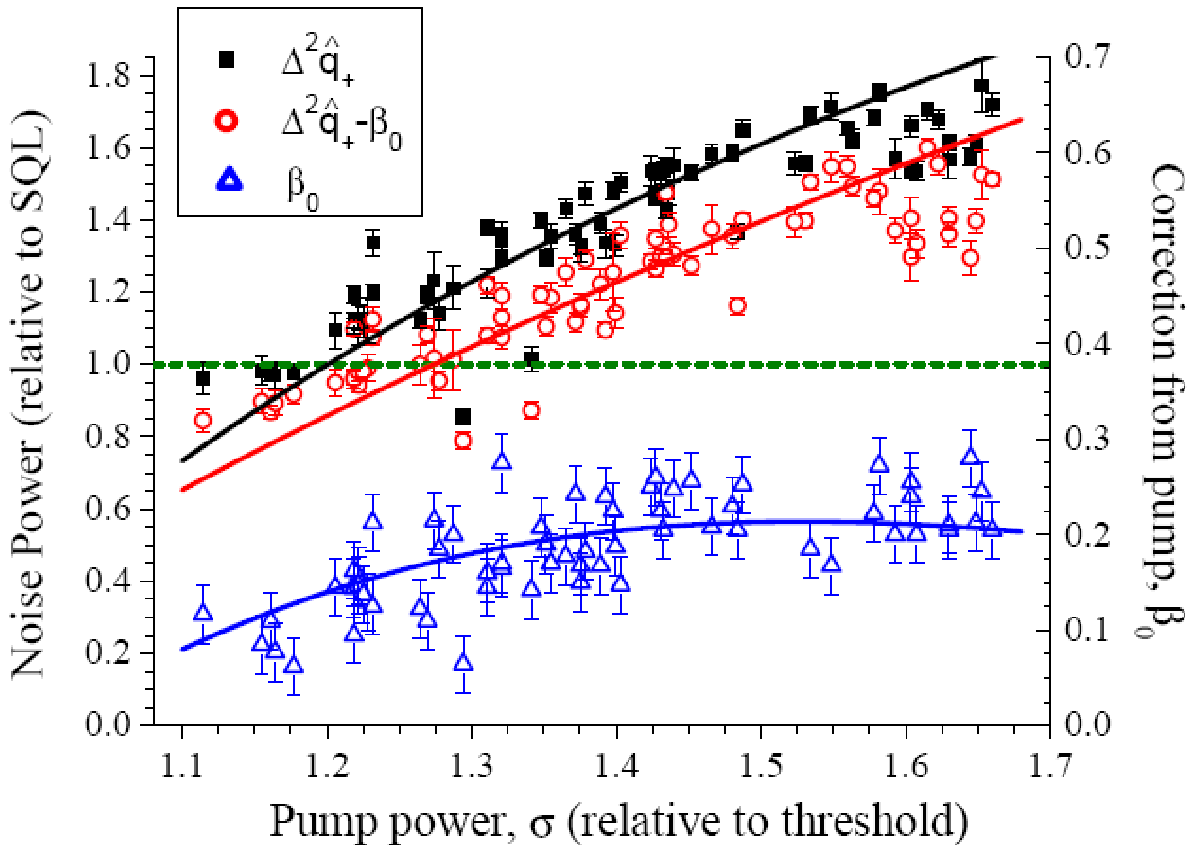
Three-color quantum correlations

K. N. Cassemiro *et al.* Opt. Lett. **32**, 695 (2007)



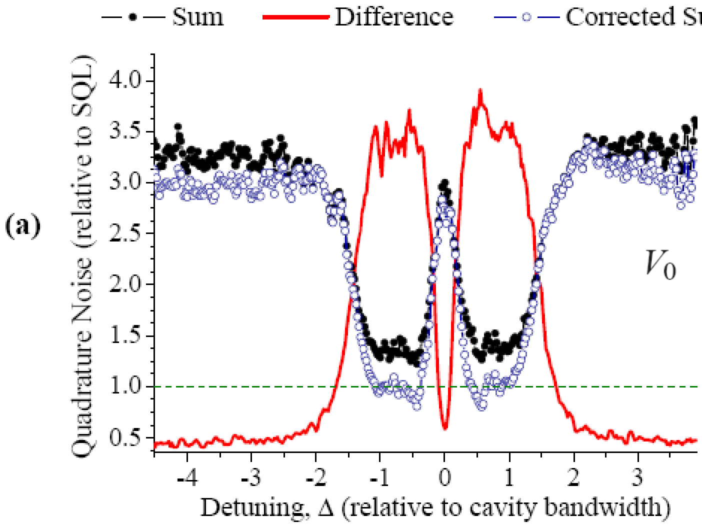
$$\Delta^2\hat{p}_- + \Delta^2(\hat{q}_+ - \alpha_0\,\hat{p}_0) \geq 2\ , \quad \text{with} \quad \alpha_0 = \frac{C_{\hat{p}_0\hat{q}_+}}{\Delta^2\hat{p}_0}$$

$$\Delta^2\hat{p}_- + \Delta^2\hat{q}_+ - \beta_0 \geq 2\,, \quad \text{with} \quad \beta_0 = \frac{C^2_{\hat{p}_0\hat{q}_+}}{\Delta^2\hat{p}_0}$$

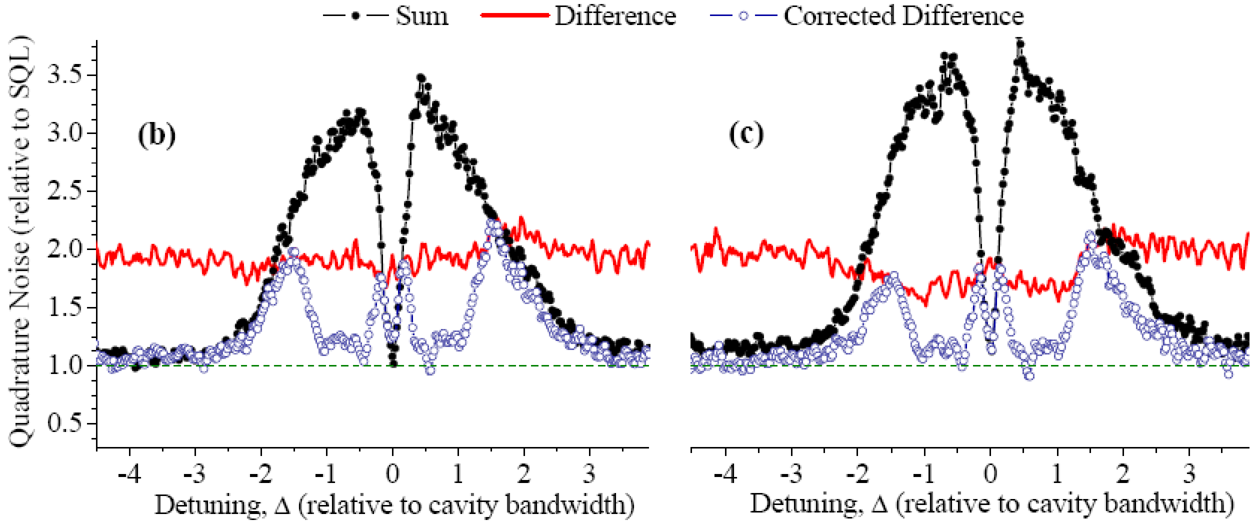


The quest for three-color entanglement…

K. N. Cassemiro *et al.* Opt. Exp. **15**, 18326 (2007)

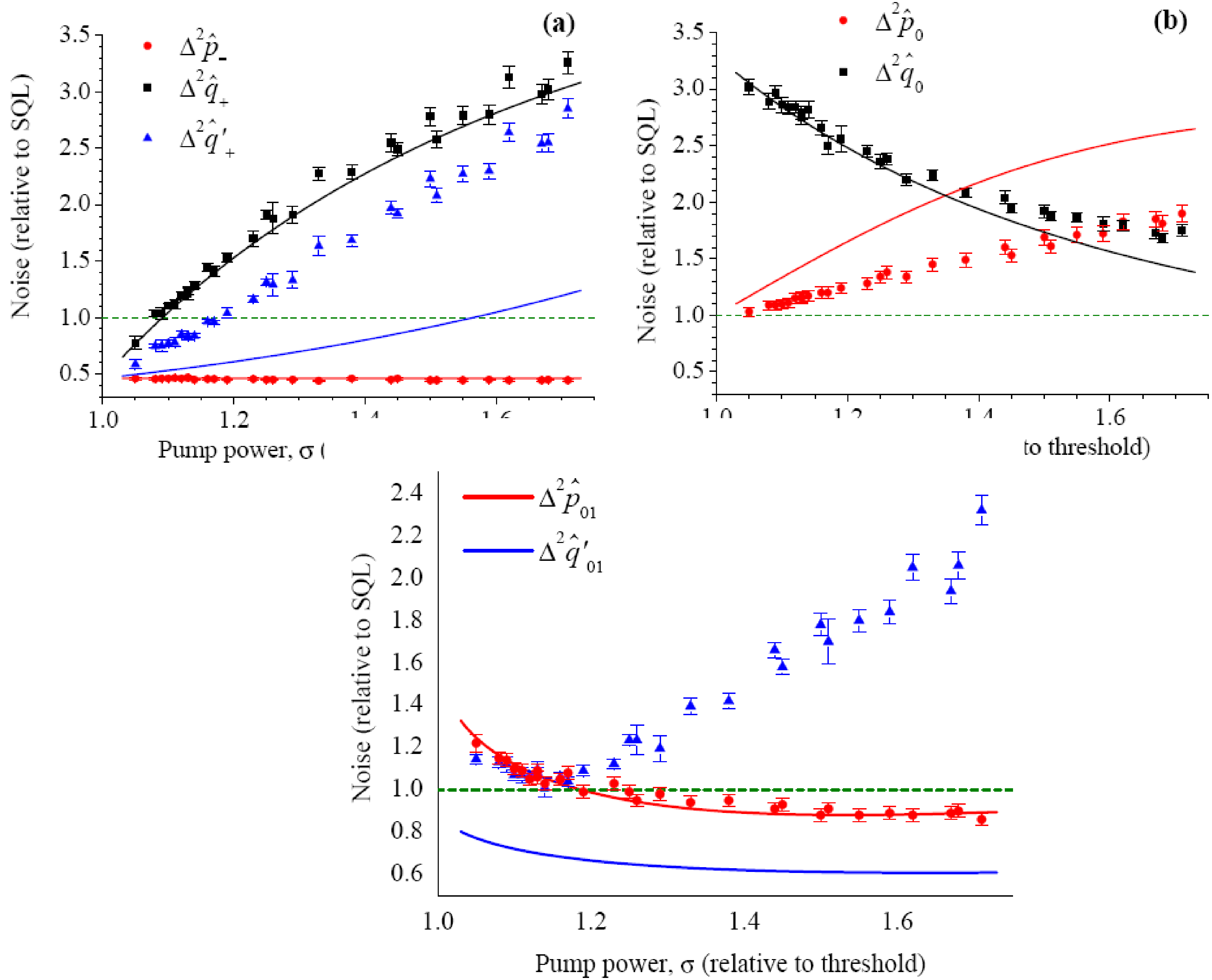


$$V_0 = \Delta^2\left(\frac{\hat{p}_1 - \hat{p}_2}{\sqrt{2}}\right) + \Delta^2\left(\frac{\hat{q}_1 + \hat{q}_2}{\sqrt{2}} - \alpha_0 \hat{q}_0\right) \geq 2$$



$$V_1 = \Delta^2\left(\frac{\hat{p}_0 + \hat{p}_1}{\sqrt{2}}\right) + \Delta^2\left(\frac{\hat{q}_1 - \hat{q}_0}{\sqrt{2}} + \alpha_2 \hat{q}_2\right) \geq 2$$

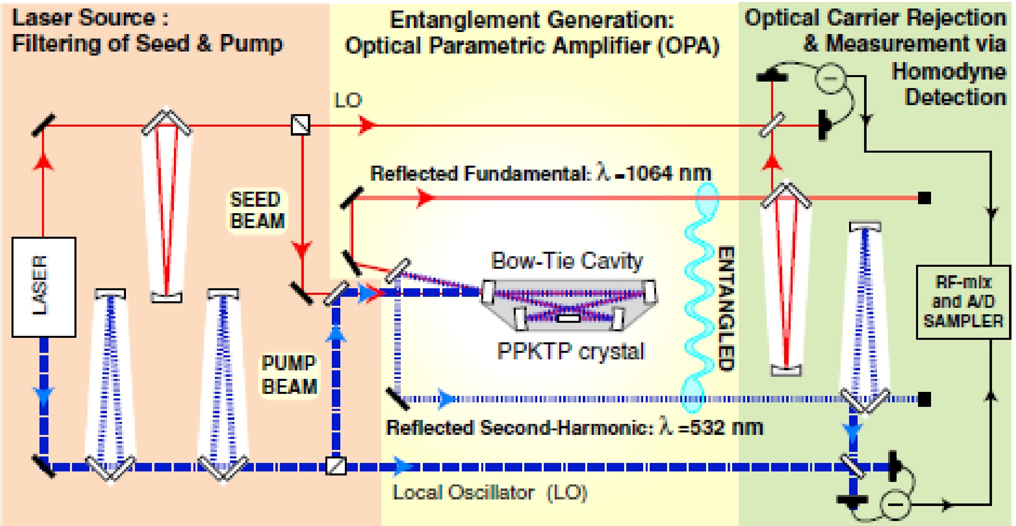
$$V_2 = \Delta^2\left(\frac{\hat{p}_0 + \hat{p}_2}{\sqrt{2}}\right) + \Delta^2\left(\frac{\hat{q}_2 - \hat{q}_0}{\sqrt{2}} + \alpha_1 \hat{q}_1\right) \geq 2$$

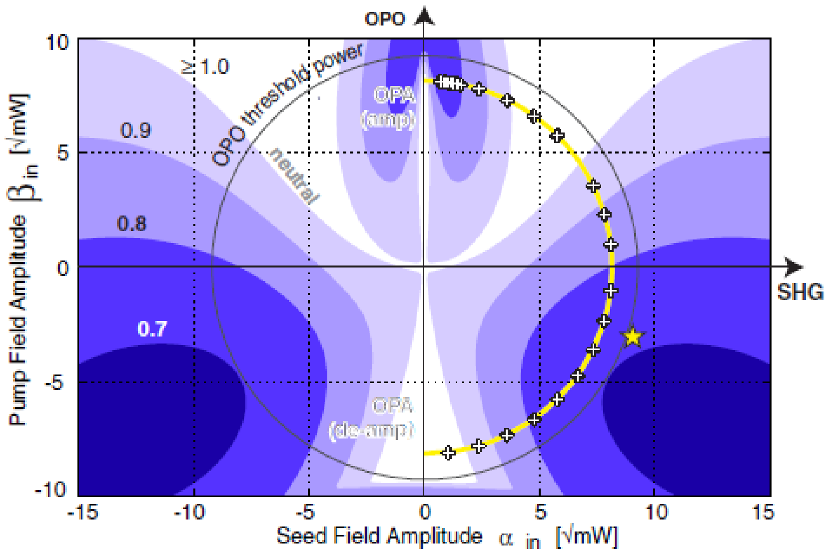


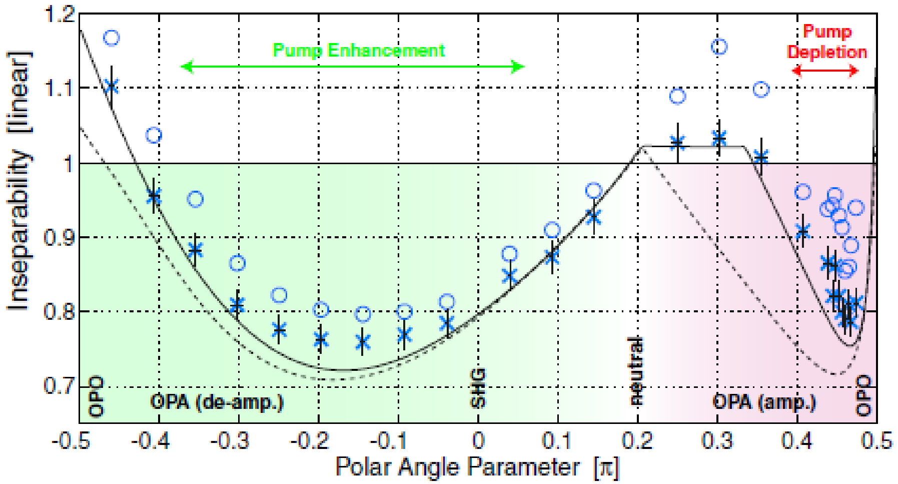
(a)
(b)
Noise (relative to SQL)
Pump power, σ (relative to threshold)
$\Delta^2\hat{p}_-$
$\Delta^2\hat{q}_+$
$\Delta^2\hat{q}'_+$
$\Delta^2\hat{p}_0$
$\Delta^2\hat{q}_0$
$\Delta^2\hat{p}_{01}$
$\Delta^2\hat{q}'_{01}$

Observation of Entanglement between Two Light Beams Spanning an Octave in Optical Frequency

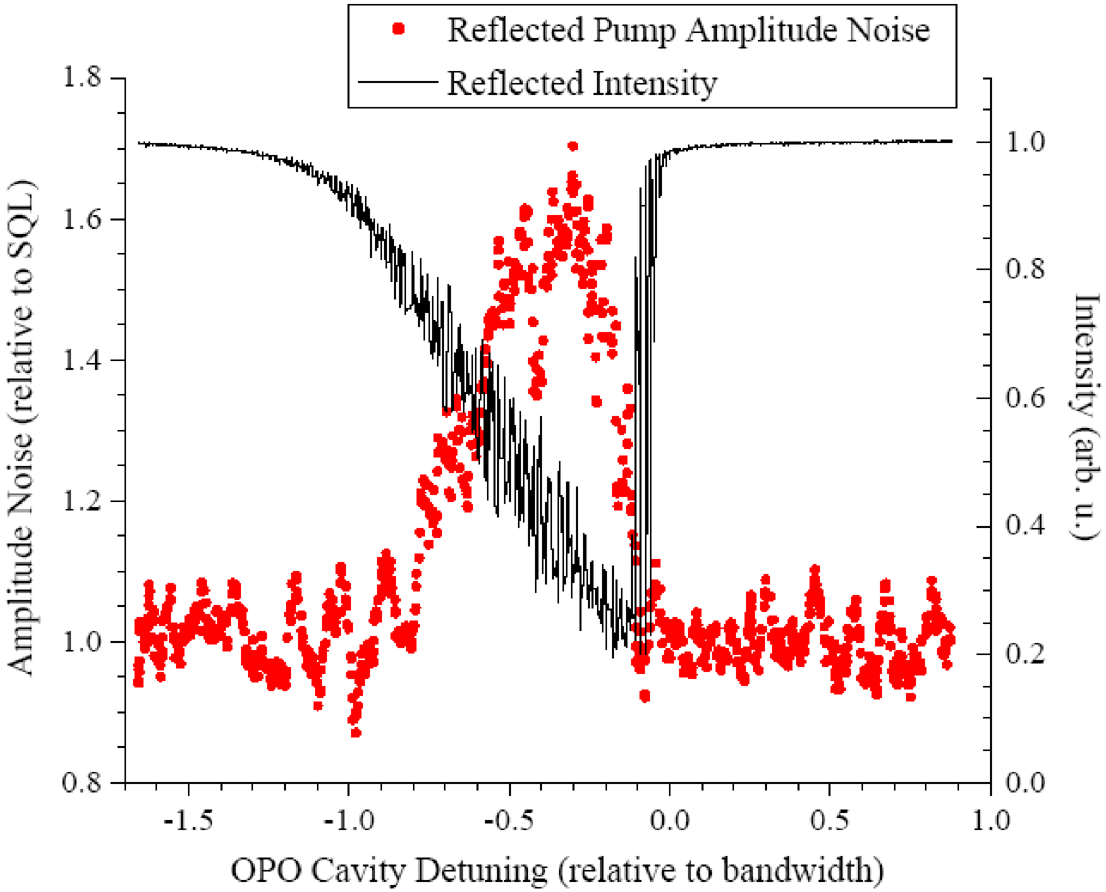
Nicolai B. Grosse,[1] Syed Assad,[1,2] Moritz Mehmet,[3] Roman Schnabel,[3] Thomas Symul,[1] and Ping Koy Lam[1]







Noise in the reflected pump!



An open question: What is the source of the noise in the crystal?

Entanglement in the above-threshold optical parametric oscillator

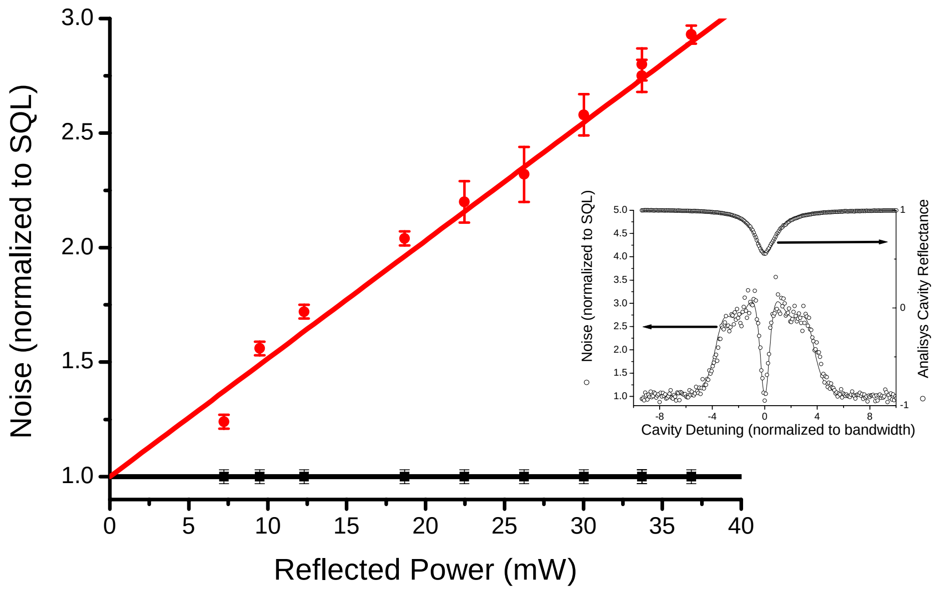
Alessandro S. Villar and Katiúscia N. Cassemiro

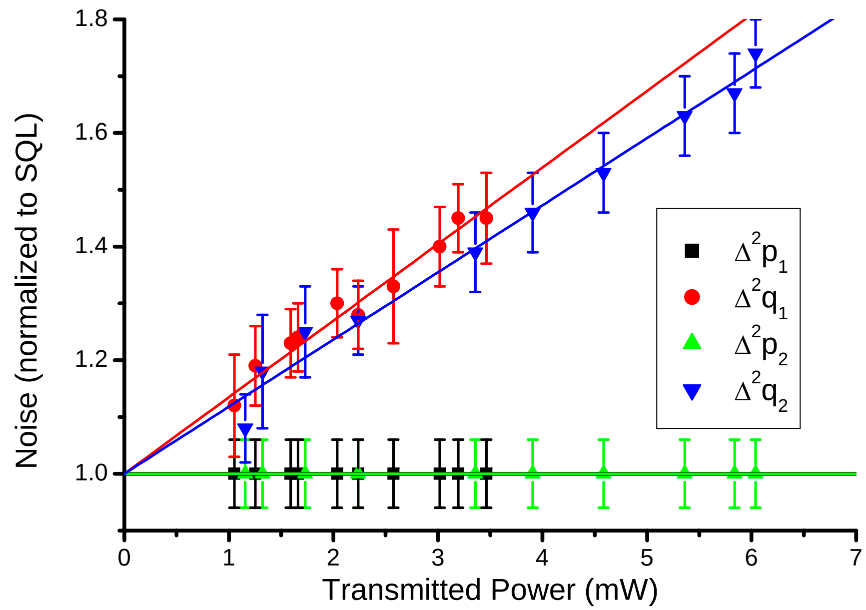
Kaled Dechoum and Antonio Z. Khoury

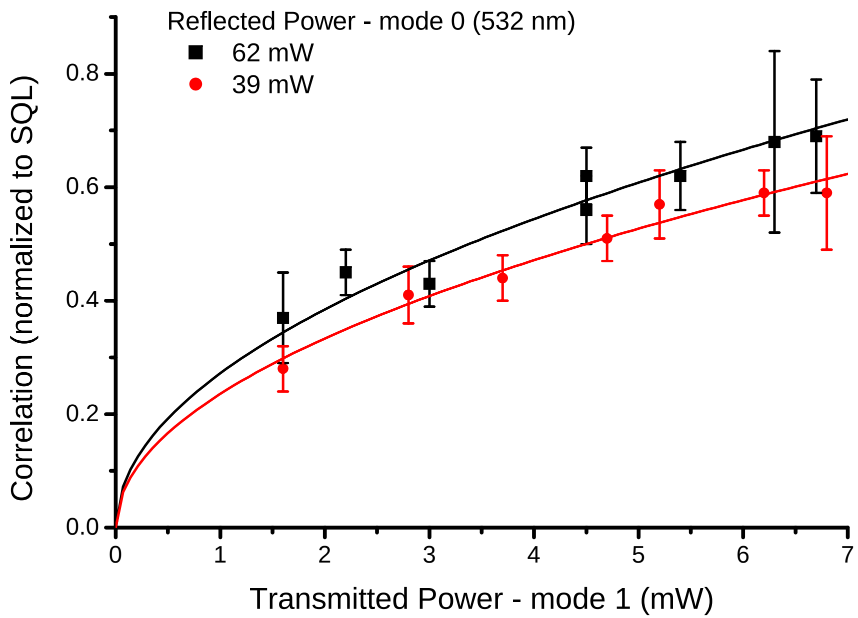
Marcelo Martinelli and Paulo Nussenzveig

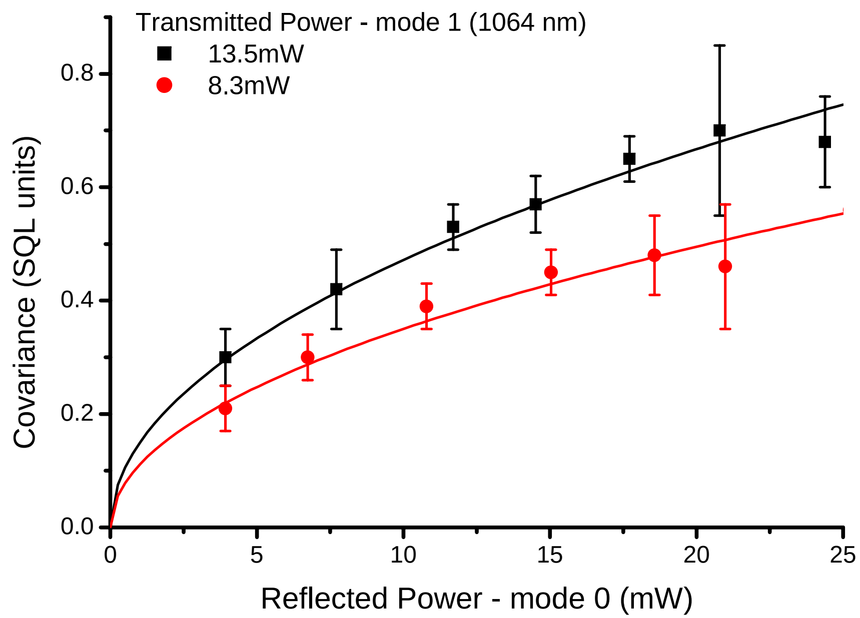
Vol. 24, No. 2/February 2007/J. Opt. Soc. Am. B 249

Noise is everywhere!









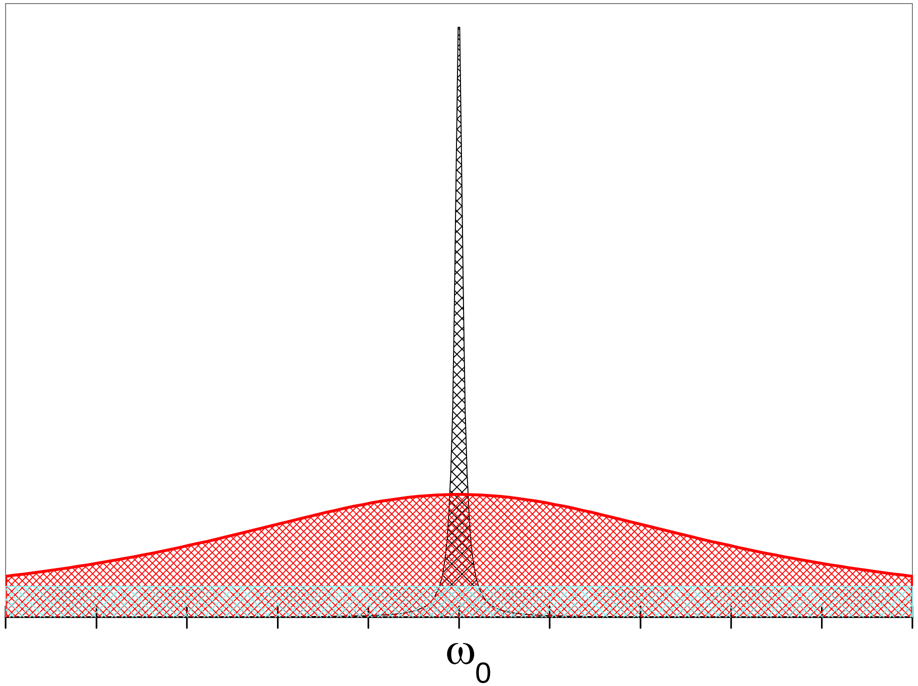
Is the noise inside the crystal…

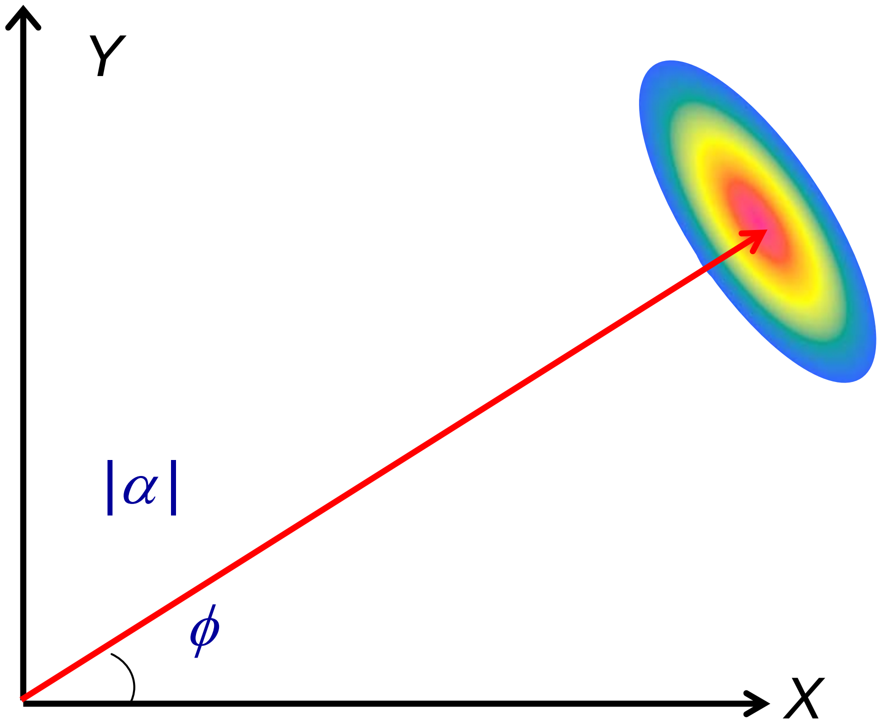
as a random modulation of the refractive index?

Grosse *et al.* PRL **100** 243601(2008)

GAWBS?

Or phonon scattering?





PHYSICAL REVIEW A **79**, 063816 (2009)

Extra phase noise from thermal fluctuations in nonlinear optical crystals

J. E. S. César,[1] A. S. Coelho,[1] K. N. Cassemiro,[2] A. S. Villar,[3] M. Lassen,[4] P. Nussenzveig,[1] and M. Martinelli[1]

$$\delta Q_j(\Omega) = \frac{n_j k_j}{2\varepsilon_j}\alpha_j \int |u_j^{(h)}(\vec{r})|^2 \delta\varepsilon_j(\vec{r},\Omega)\, dx\, dy\, dz$$

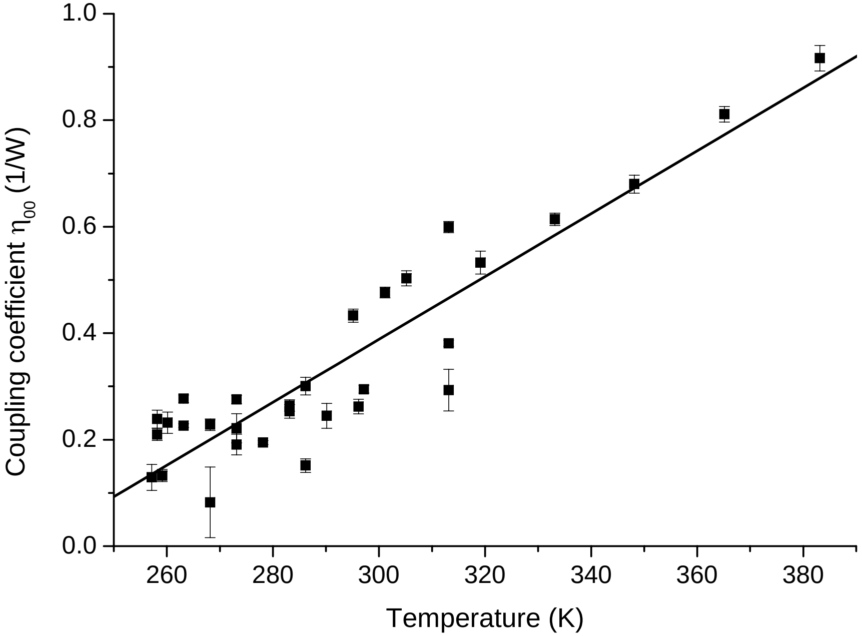
$$\begin{aligned}\langle \delta Q_j(\Omega)\delta Q_k(-\Omega)\rangle &= \\ & k_j k_k \frac{n_j^3 n_k^3}{4hc}\, l_c^3 \;\; c_{jk}(\Omega) \left(\frac{\ell\sqrt{\lambda_j\lambda_k}}{\pi w_{jk}^2}\right)\sqrt{P_j P_k} \\ &= \eta_{jk}\sqrt{P_j P_k}\,.\end{aligned}$$

$\eta_{00} = 0.53/W$, $\eta_{11} = 0.15/W$, and $\eta_{22} = 0.14/W$.

$\eta_{01} = 0.14/W$, $\eta_{02} = 0.15/W$, and $\eta_{12} = 0.087/W$.

$$\eta_{jk} < \sqrt{\eta_{jj}\eta_{kk}}$$

$$\eta_{00}(T) = [5.92(46)10^{-3} \times T/K - 1.38(13)]/W$$



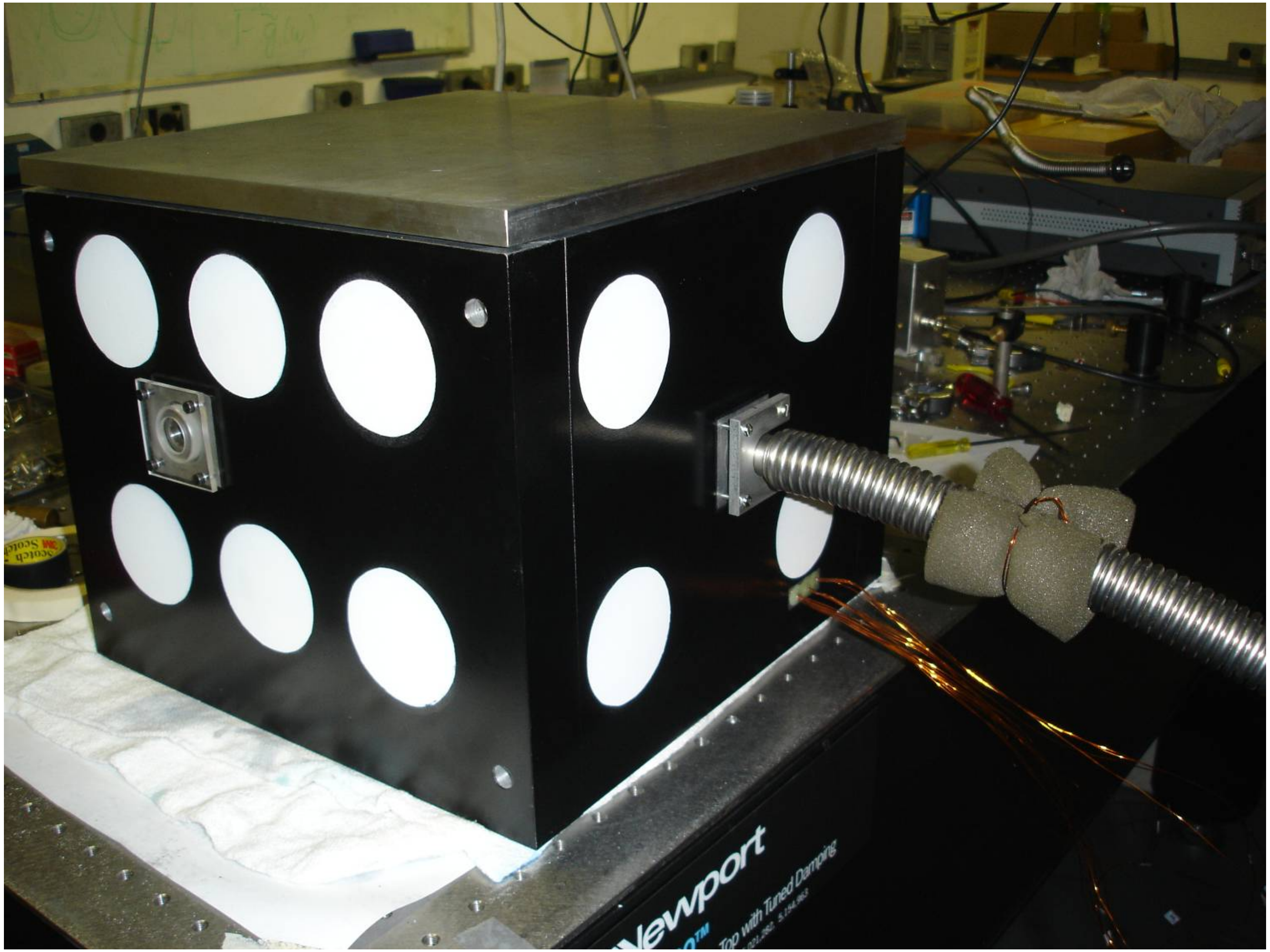
$$\vec{X} = [\delta\hat{p}_0, \delta\hat{q}_0, \delta\hat{p}_1, \delta\hat{q}_1, \delta\hat{p}_2, \delta\hat{q}_2]^T$$

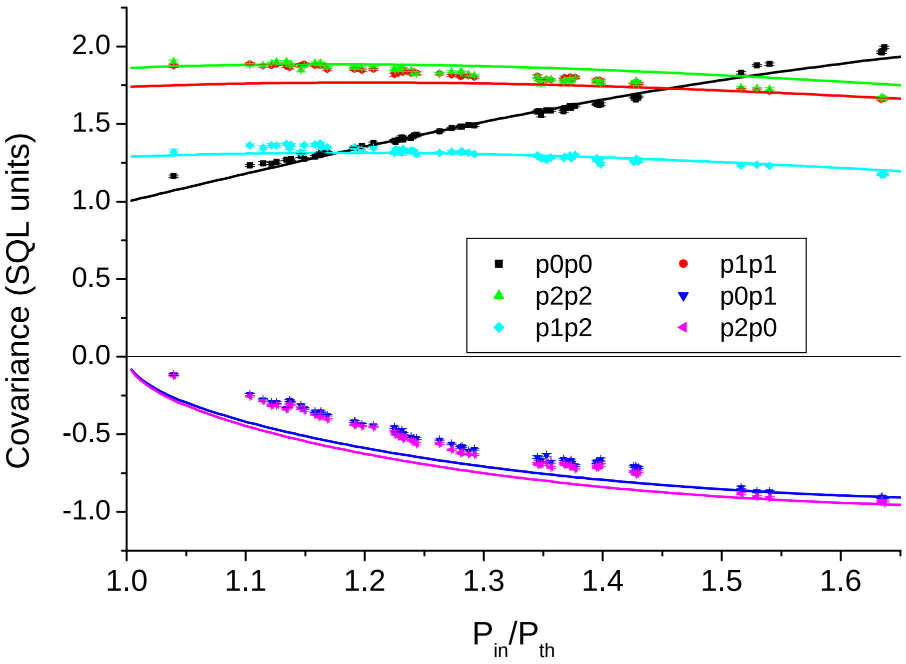
$$\tau \frac{\partial}{\partial t}\vec{X} = \boldsymbol{M}_A \vec{X} + \boldsymbol{M}_\gamma \vec{X}_1^{in} + \boldsymbol{M}_\mu \vec{X}_2^{in} + \vec{Q}$$

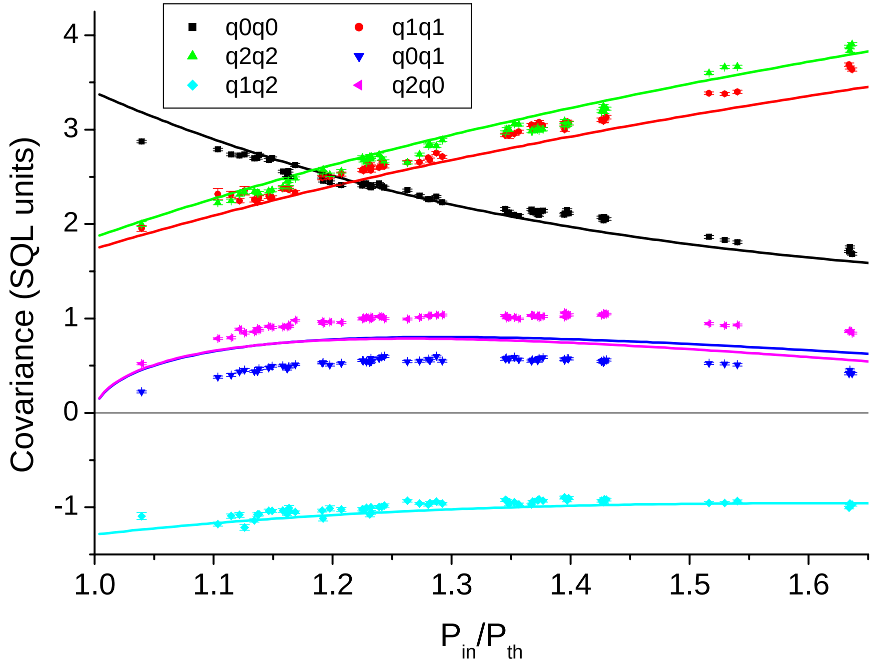
$$\vec{X}^{out}(\Omega) = \boldsymbol{M}_\gamma \vec{X}(\Omega) - \vec{X}_1^{in}$$

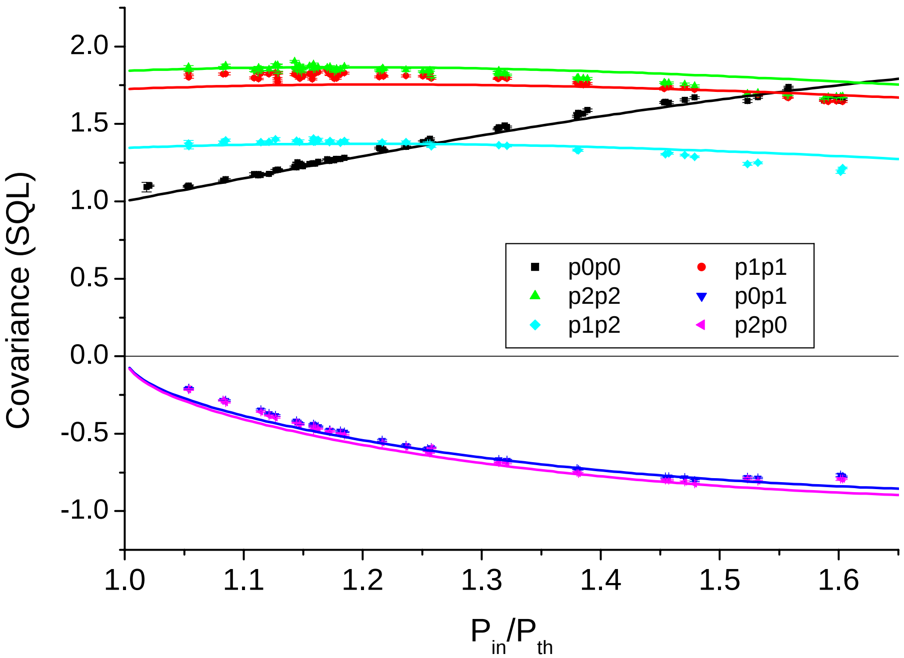
$$\boldsymbol{V} = \boldsymbol{I} + \boldsymbol{V}_{pure} + \boldsymbol{V}_{loss} + \boldsymbol{V}_{phase}$$

Way to go




Covariance (SQL units)
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
1.0
1.1
1.2
1.3
1.4
1.5
1.6
P_in/P_th
p0p0
p1p1
p2p2
p0p1
p1p2
p2p0


Covariance (SQL units)
4
3
2
1
0
-1
1.0
1.1
1.2
1.3
1.4
1.5
1.6
P_in/P_th
q0q0
q1q1
q2q2
q0q1
q1q2
q2q0


Covariance (SQL)
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
1.0
1.1
1.2
1.3
1.4
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1.6
P_in/P_th
p0p0
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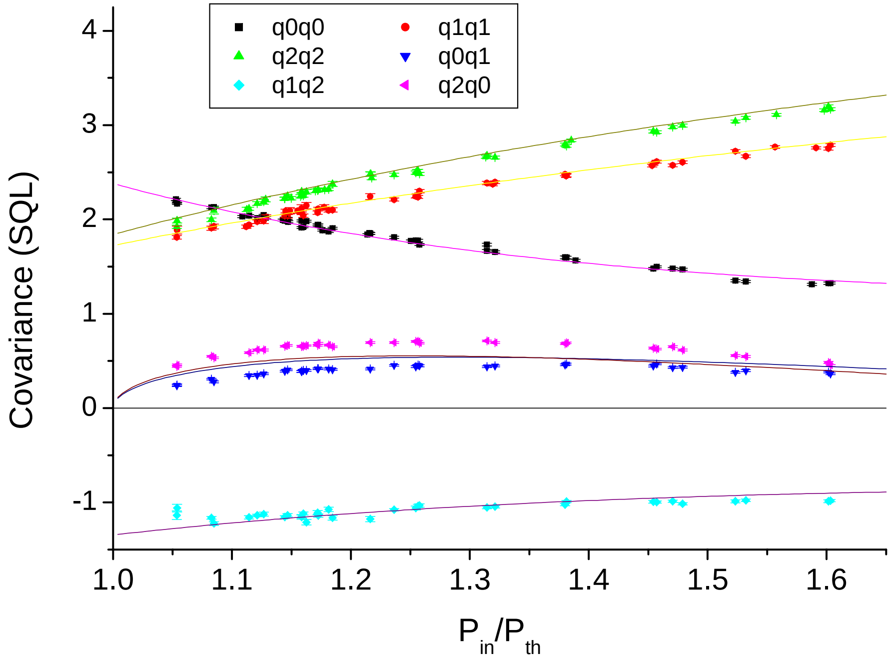
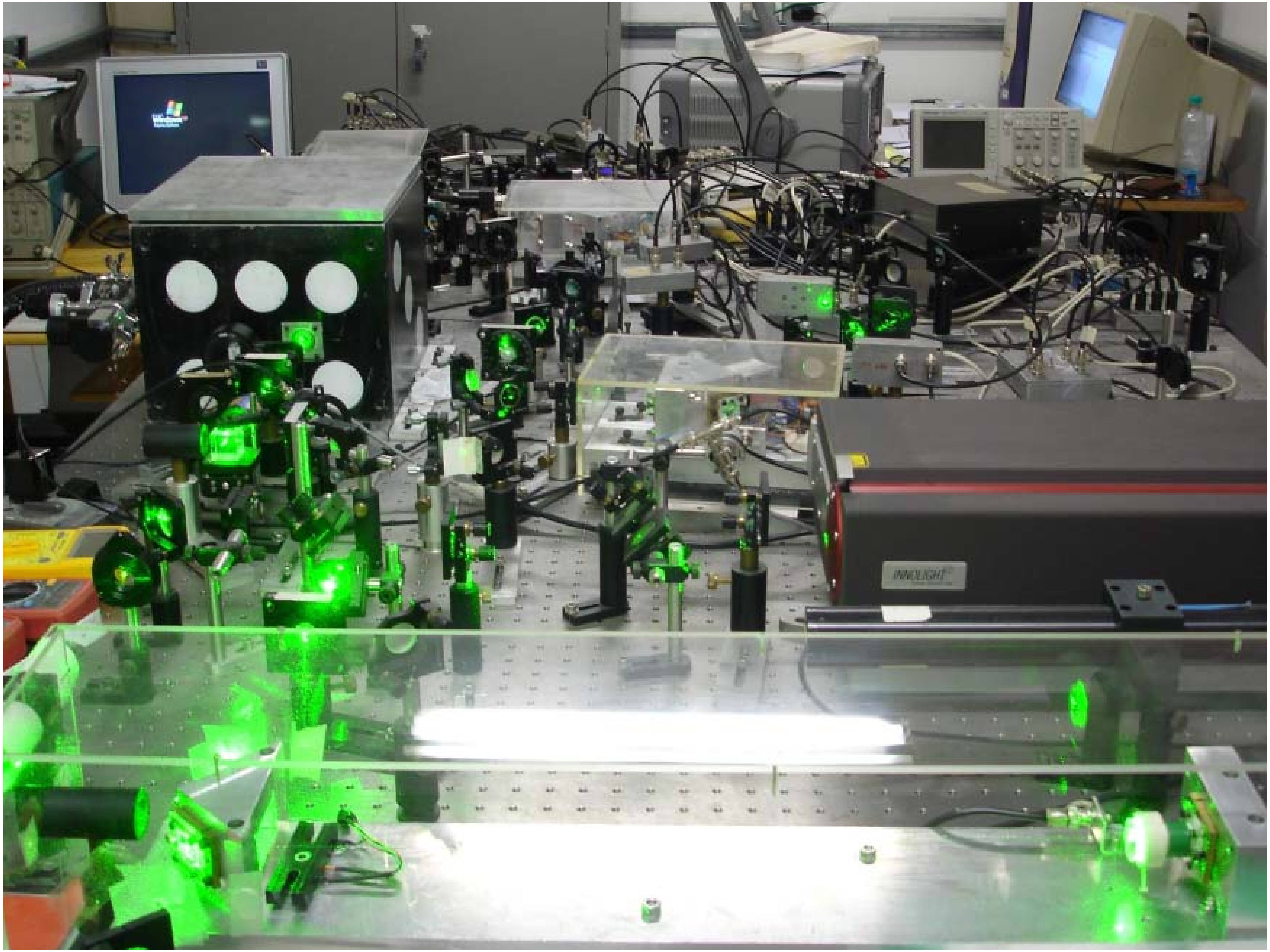
p2p2
p0p1
p1p2
p2p0


Covariance (SQL)
4
3
2
1
0
-1
1.0
1.1
1.2
1.3
1.4
1.5
1.6
P_in/P_th
q0q0
q1q1
q2q2
q0q1
q1q2
q2q0

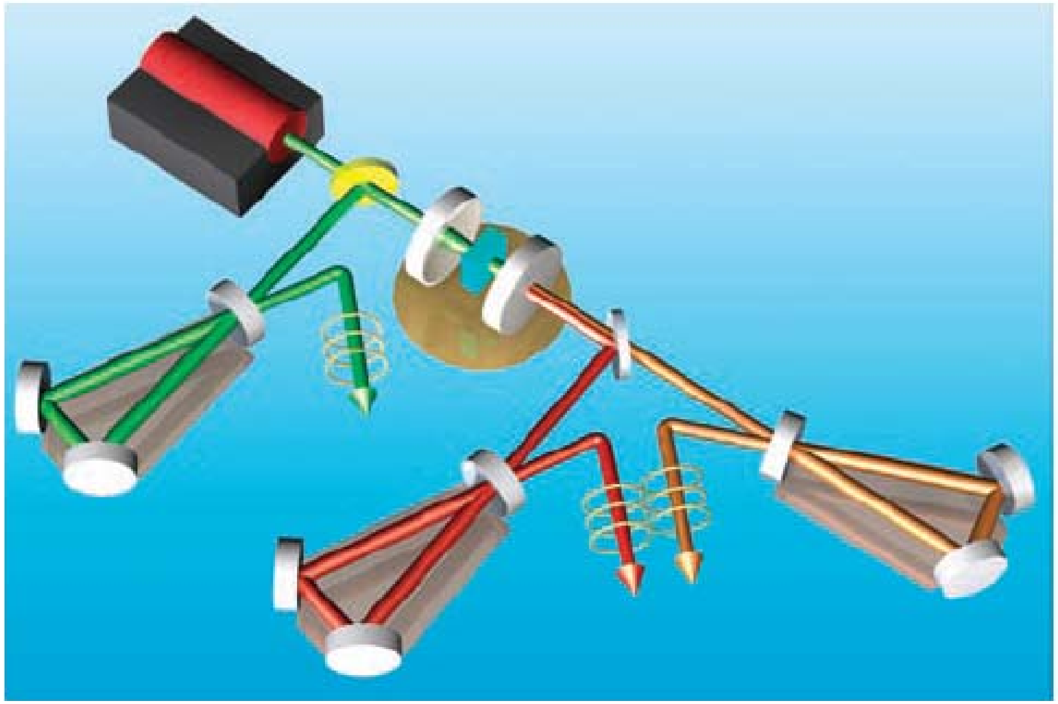

INNOLIGHT

Three-Color Entanglement
A. S. Coelho, *et al.*
Science **326**, 823 (2009);
DOI: 10.1126/science.1178683

Three-Color Entanglement

A. S. Coelho,[1] F. A. S. Barbosa,[1] K. N. Cassemiro,[2] A. S. Villar,[2,3] M. Martinelli,[1] P. Nussenzveig[1]*

Entanglement is an essential quantum resource for the acceleration of information processing as well as for sophisticated quantum communication protocols. Quantum information networks are expected to convey information from one place to another by using entangled light beams. We demonstrated the generation of entanglement among three bright beams of light, all of different wavelengths (532.251, 1062.102, and 1066.915 nanometers). We also observed disentanglement for finite channel losses, the continuous variable counterpart to entanglement sudden death.

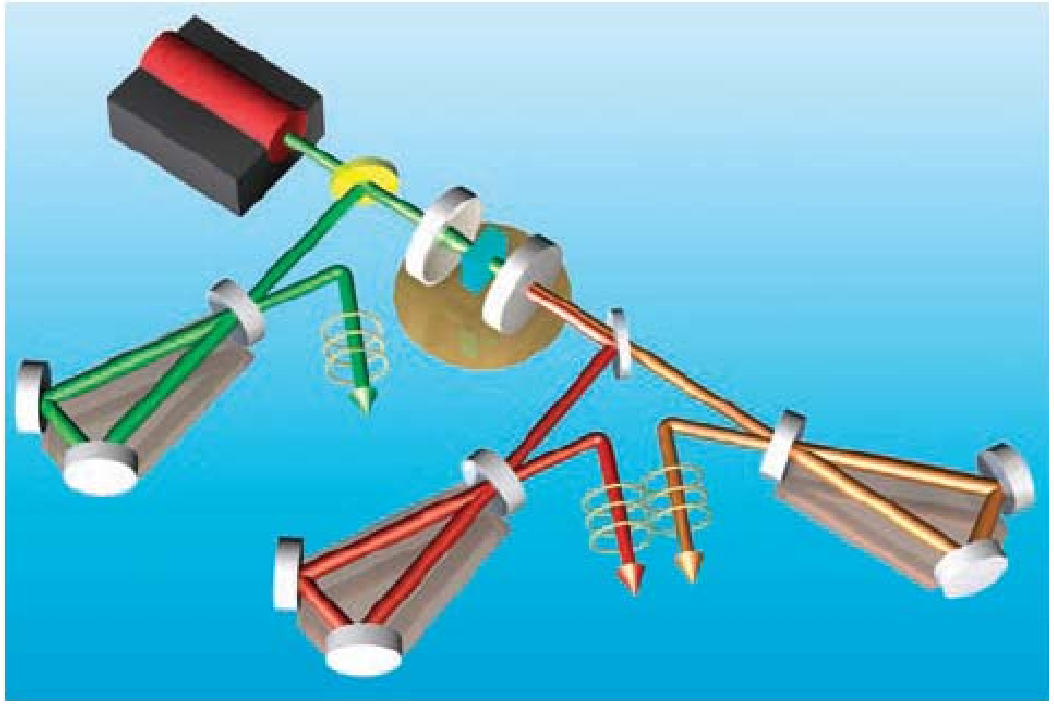


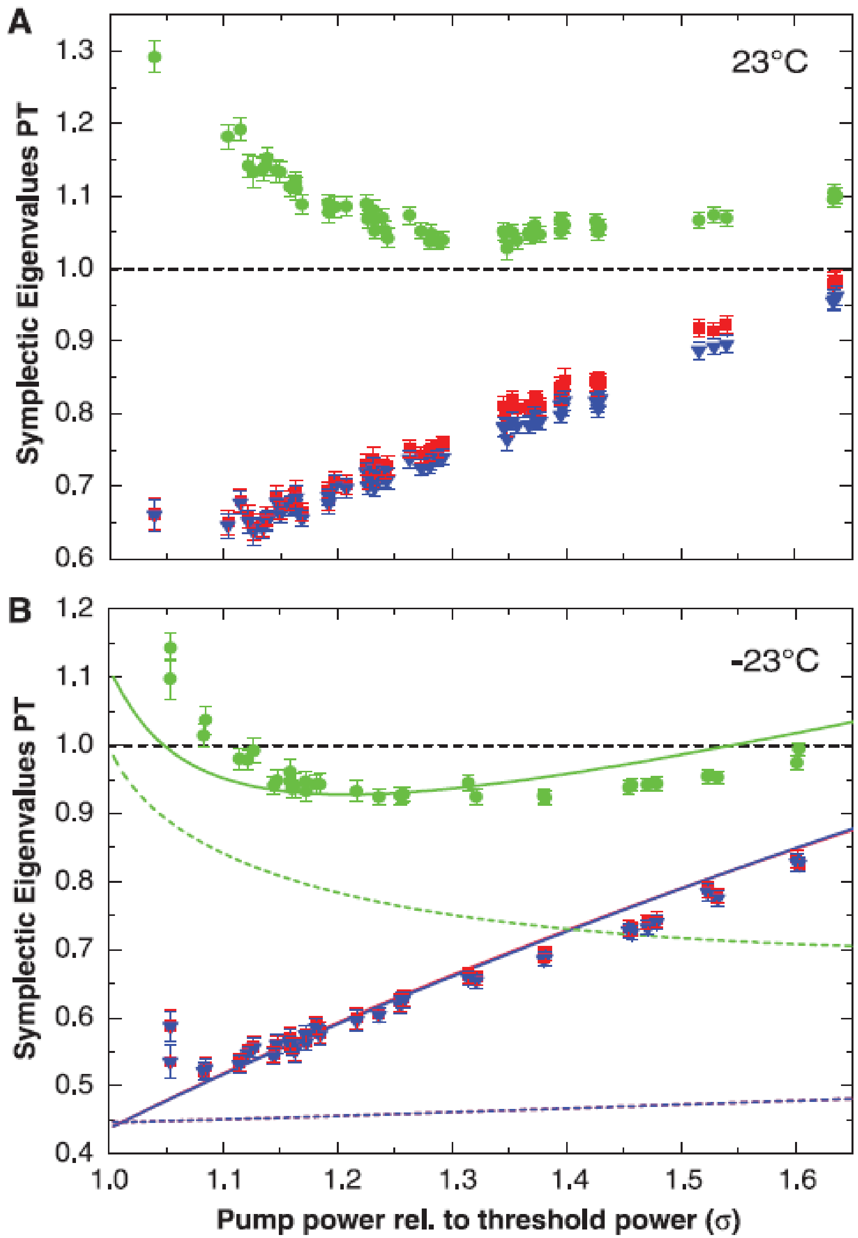
Three-Color Entanglement
A. S. Coelho, *et al.*
Science **326**, 823 (2009);

Three-Color Entanglement

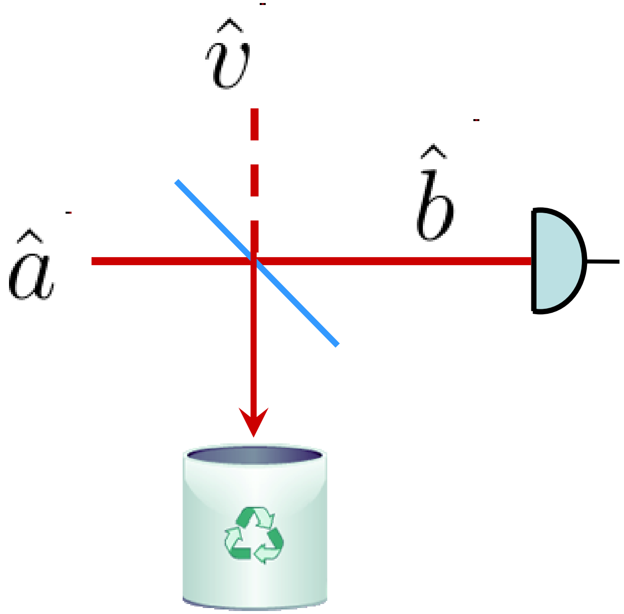
A. S. Coelho,[1] F. A. S. Barbosa,[1] K. N. Cassemiro,[2] A. S. Villar,[2,3] M. Martinel

Entanglement is an essential quantum resource for the acceleration of inforr
well as for sophisticated quantum communication protocols. Quantum inforr
expected to convey information from one place to another by using entangle
demonstrated the generation of entanglement among three bright beams of
wavelengths (532.251, 1062.102, and 1066.915 nanometers). We also obser
for finite channel losses, the continuous variable counterpart to entanglemer





The effect of losses



$$\hat{b} = \sqrt{\eta}\hat{a} + \sqrt{1-\eta}\hat{v}$$

$$\hat{X}_{b,\varphi} = \sqrt{\eta}\hat{X}_{a,\varphi} + \sqrt{1-\eta}\hat{X}_{b,\varphi}$$

$$\Delta\hat{X}^2_{b,\varphi} = \eta\Delta\hat{X}^2_{a,\varphi} + (1-\eta)\Delta\hat{X}^2_{v,\varphi}$$

$$\Delta\hat{X}^2_{b,\varphi} - 1 = \eta\left(\Delta\hat{X}^2_{a,\varphi} - 1\right)$$

The problem of decoherence

Is the main problem for an eventual quantum computer, operating over many entangled qubits.

What is the limit for this entanglement?

Interaction with the environment!

Why producing and keeping them is a hard task?

Decoherence: as if the environment where continuously measuring the system!

Famous example:
Schrödinger Cat Paradox (1935).

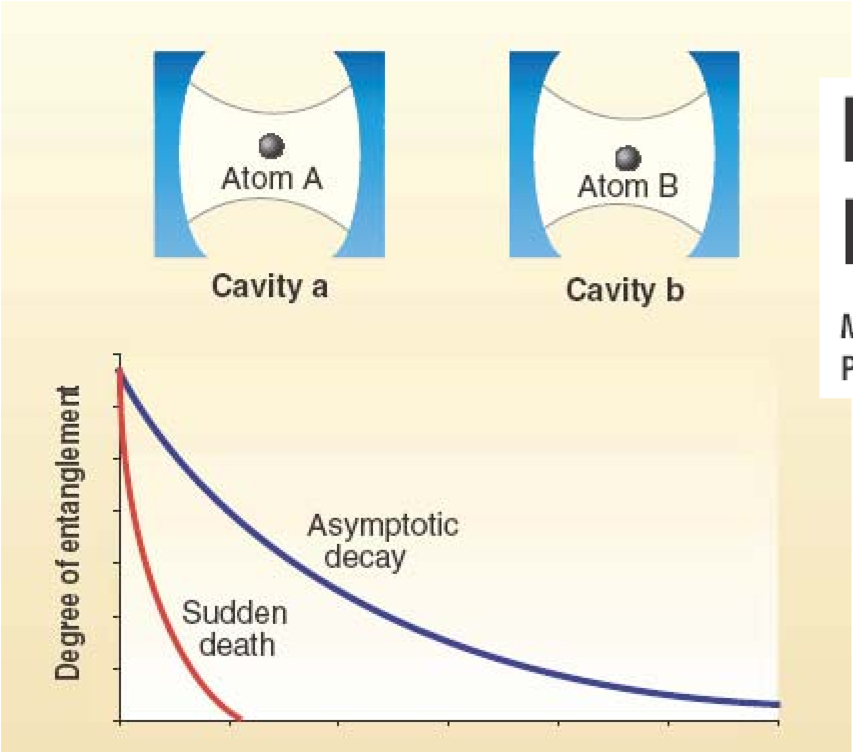
Also an entangled state

REVIEW

30 JANUARY 2009 VOL 323 SCIENCE

Sudden Death of Entanglement

Ting Yu[1*] and J. H. Eberly[2*]

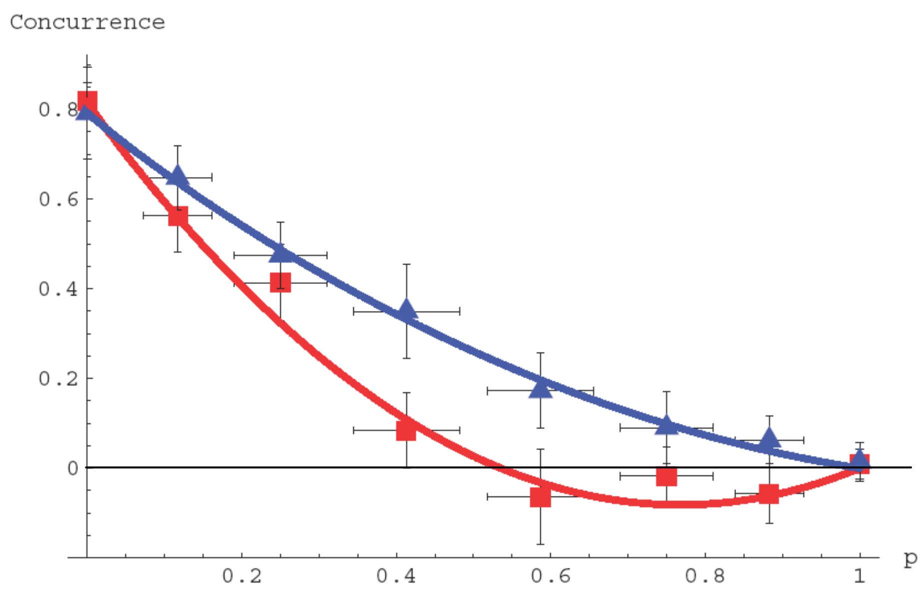


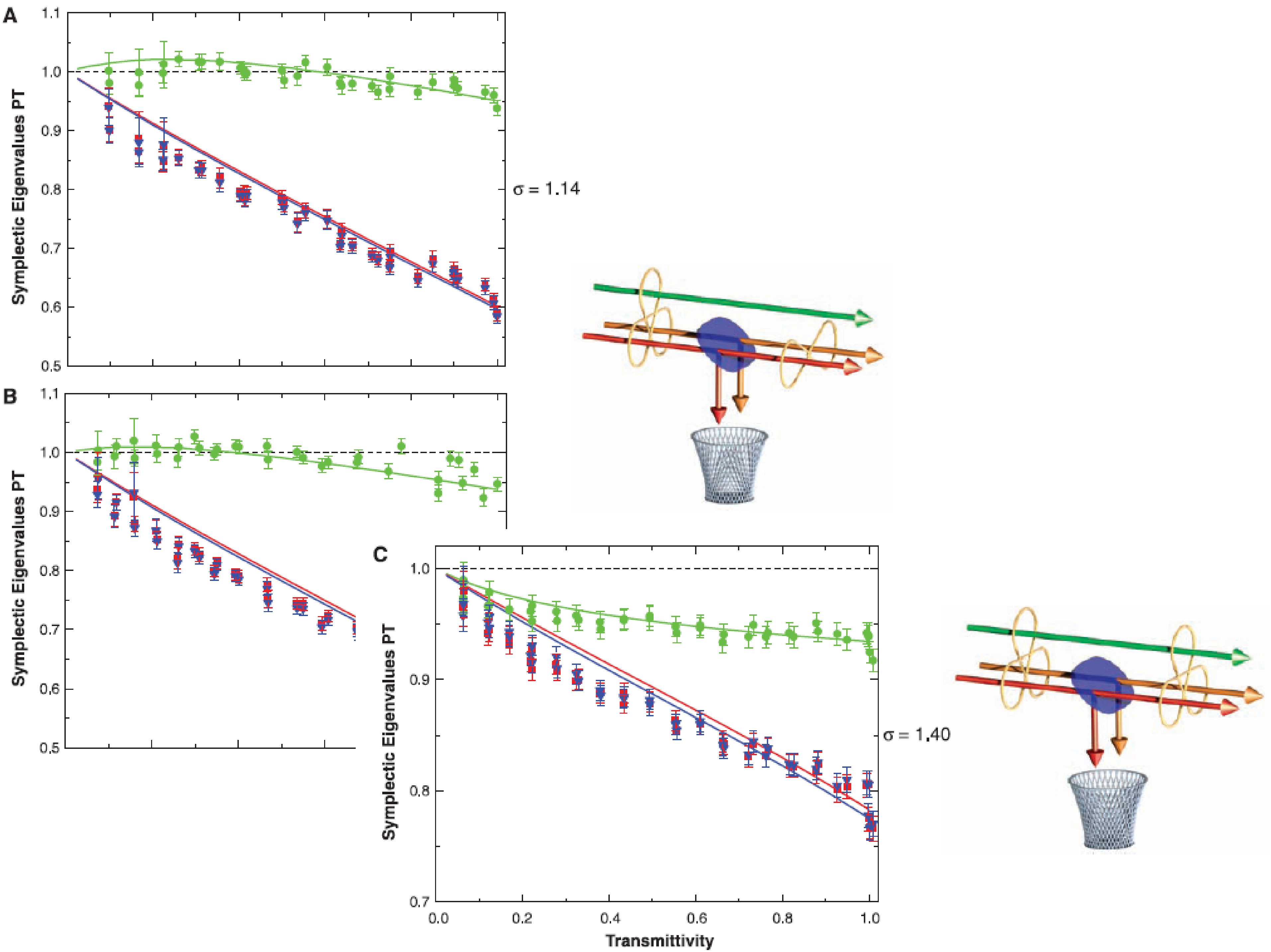
REPORTS

Environment-Induced Sudden Death of Entanglement

M. P. Almeida, F. de Melo, M. Hor-Meyll, A. Salles, S. P. Walborn, P. H. Souto Ribeiro, L. Davidovich*

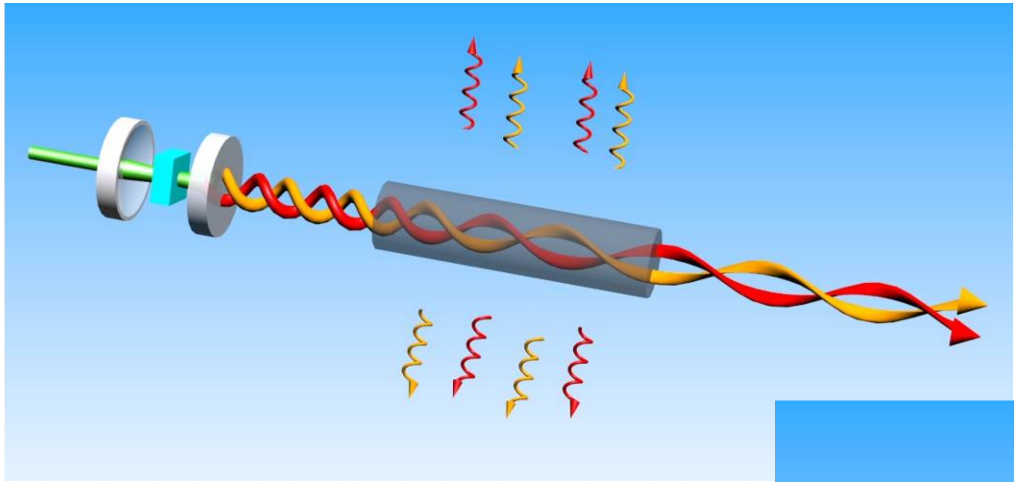
SCIENCE VOL 316 27 APRIL 2007





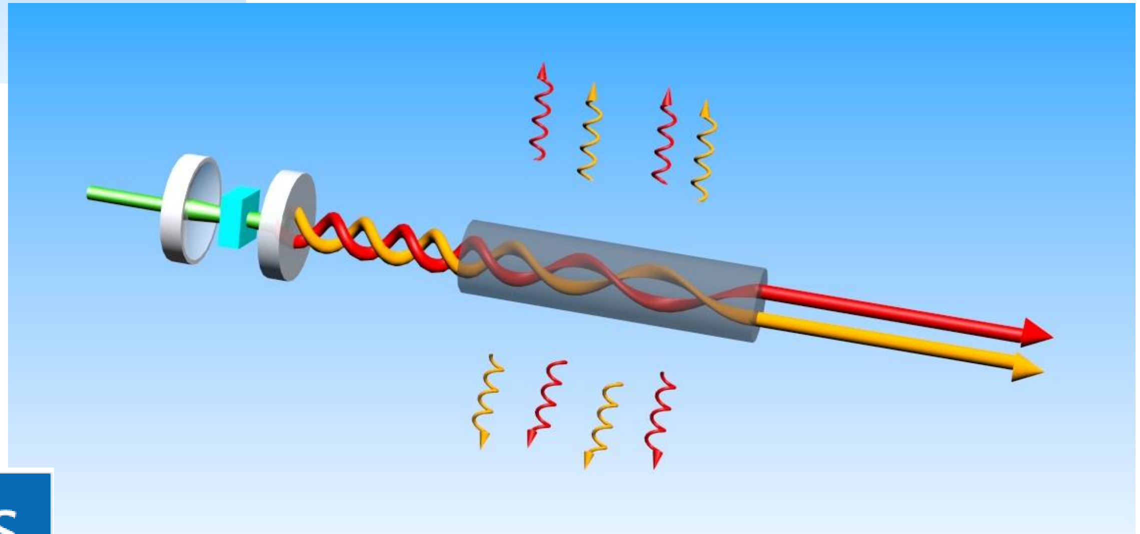
A
B
C
Symplectic Eigenvalues PT
σ = 1.14
σ = 1.40
Transmittivity

Disentanglement for a Bipartite & Gaussian state



Scenario (1):
robust entanglement

Scenario (2):
disentanglement



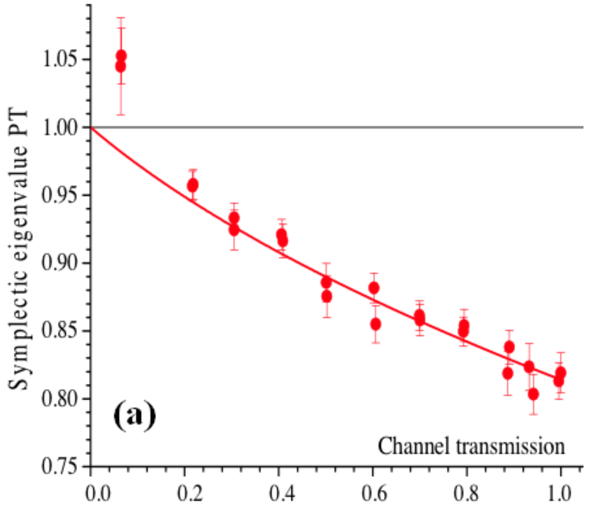
nature photonics LETTERS | DOI: 10.1038/NPHOTON.2010.222

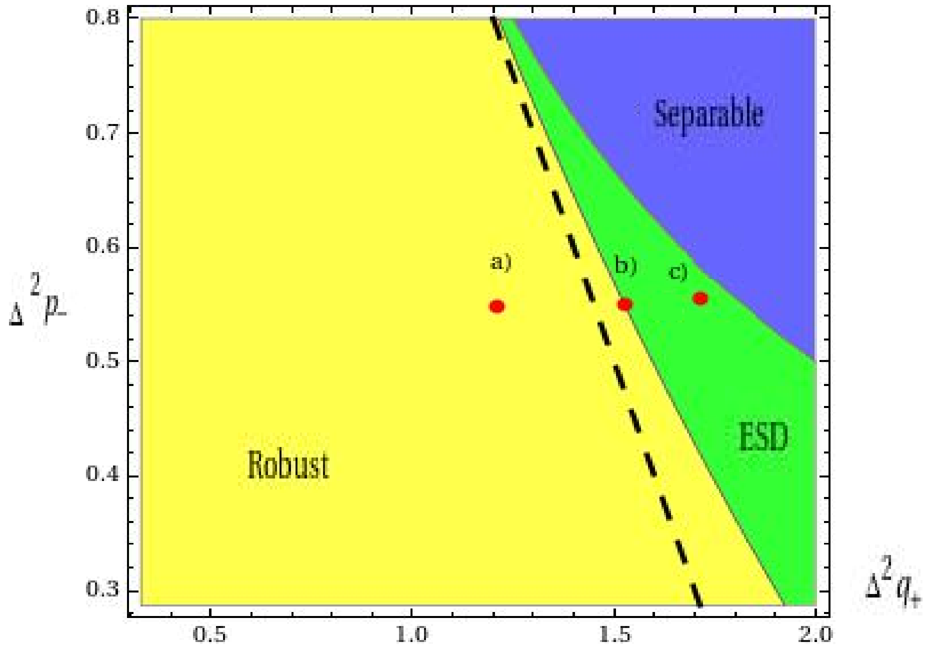
Robustness of bipartite Gaussian entangled beams propagating in lossy channels

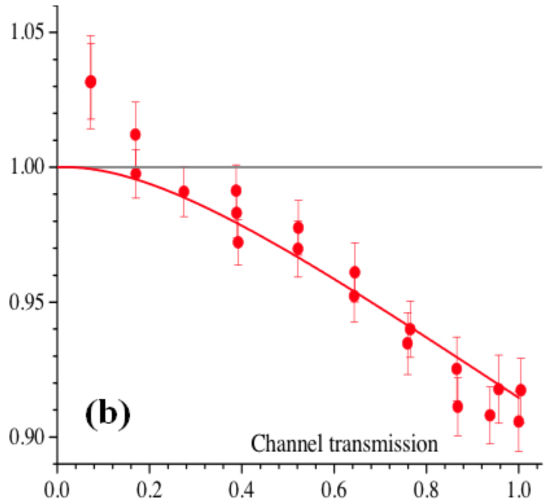
F. A. S. Barbosa[1], A. S. Coelho[1], A. J. de Faria[1], K. N. Cassemiro[2], A. S. Villar[2,3], P. Nussenzveig[1] and M. Martinelli[1]*

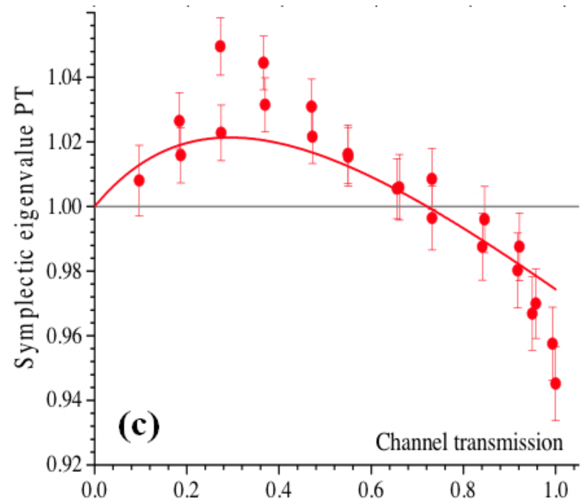

MORT SUBITE
GUEUZE
MORT SUBITE
GUEUZE
MORT SUBITE
KRIEK
MORT SUBITE
KRIEK

Disentanglement for a simpler model: Attenuation on a single beam









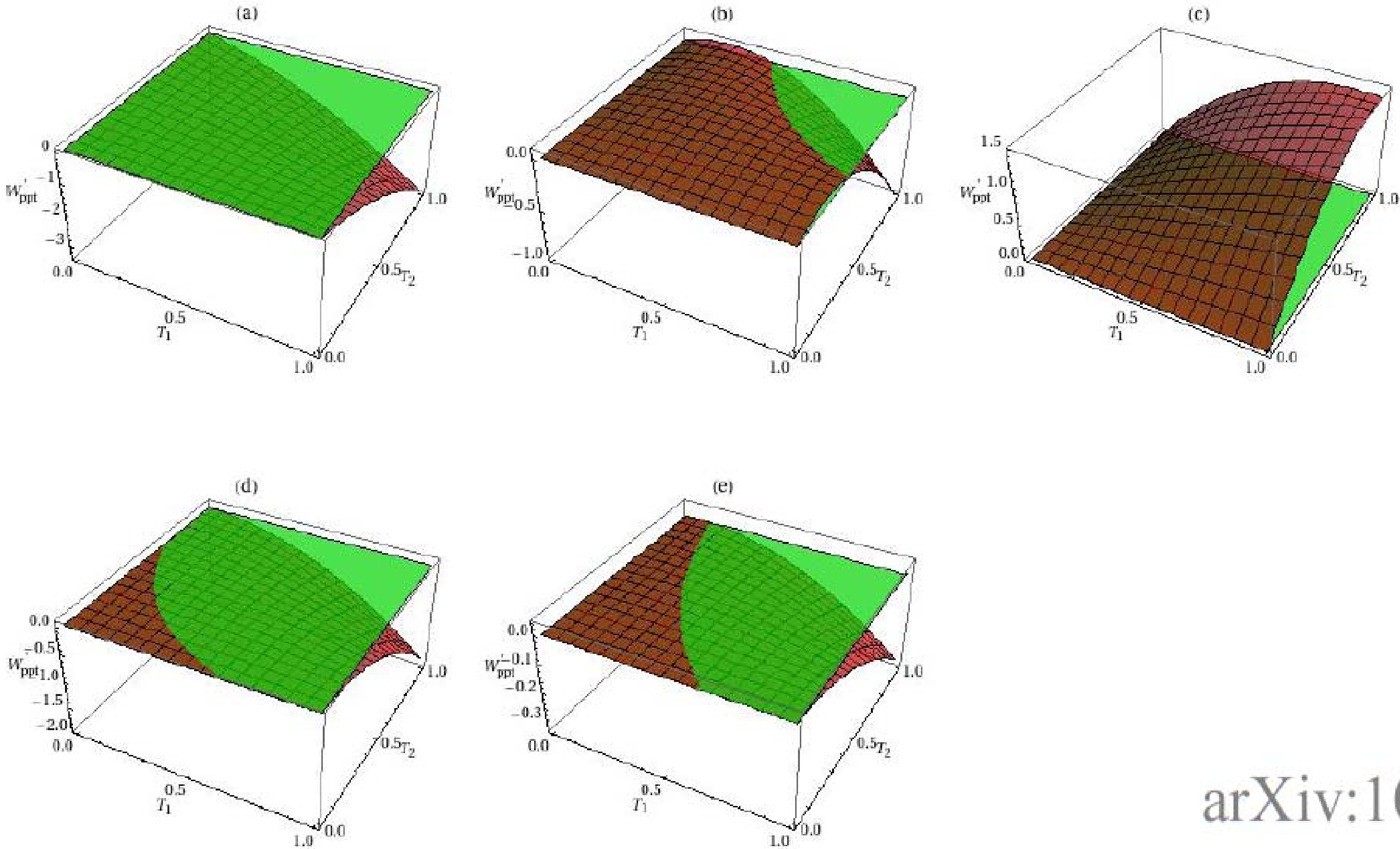
Tighter conditions for transmission of quantum entanglement!

Early Stage Disentanglement in Bipartite Continuous-Variable Systems

F. A. S. Barbosa[1], A. S. Coelho[1], A. J. de Faria[1], K. N. Cassemiro[2], A. S. Villar[2,3], and M. Martinelli[1]

Duan (optimized)

$$(\Delta^2 p_1 + \Delta^2 q_1 - 2)(\Delta^2 p_2 + \Delta^2 q_2 - 2) - (|c_p| + |c_q|)^2 \geq 0;$$



arXiv:1009.4255v1

What's next?

The sideband problem: non-unitary purity for unitary operations?

Are we missing something in our S(Ω) measurement?

Quantum state of an injected TROPO above threshold: purity, Glauber function and photon number distribution

T. Golubeva[1], Yu. Golubev[1], C. Fabre[2], and N. Treps[2,a]

Eur. Phys. J. D 46, 179–193 (2008)
DOI: 10.1140/epjd/e2007-00290-6

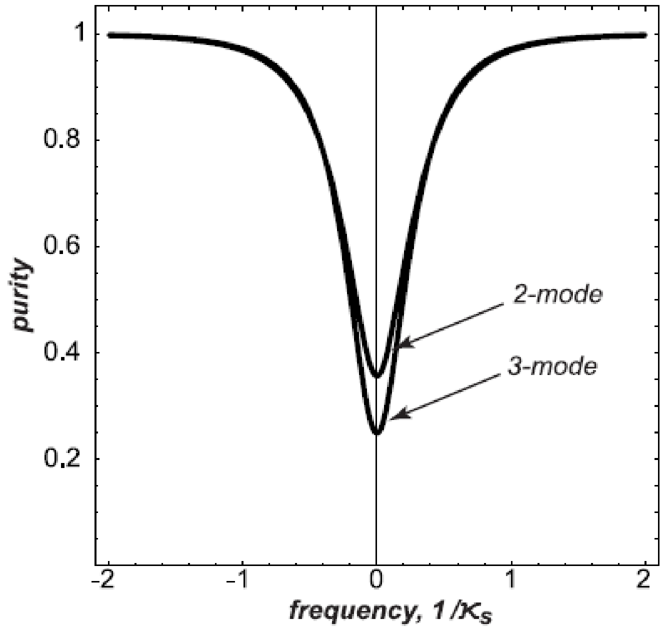
YES WE ARE!

S(Ω) includes information in the complex part (ignored up to the moment).

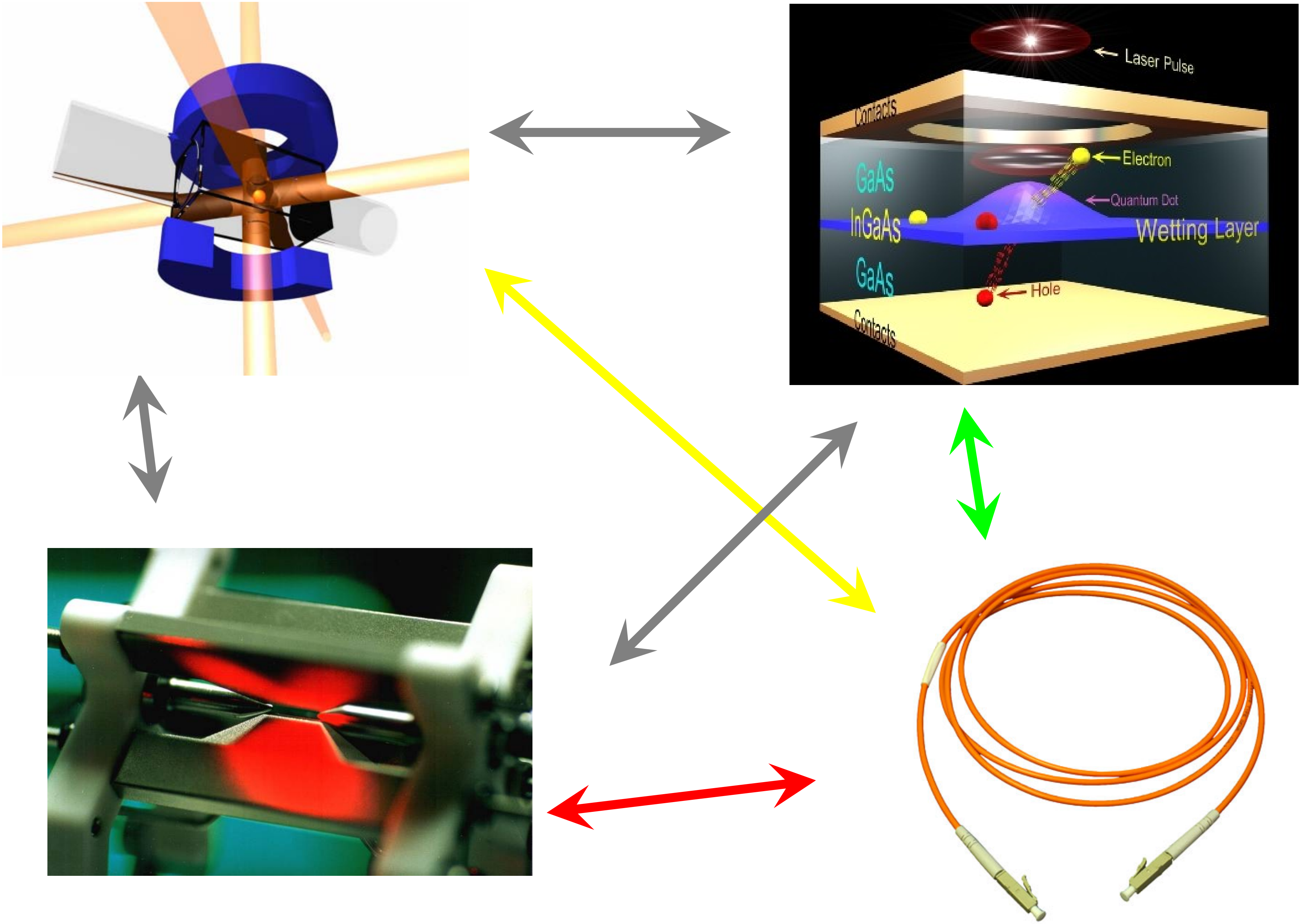
And represents a pair of sidebands!

V is not 6 x 6, it is 12 x 12 (2 quadratures of 2 sidebands of 3 modes)

And we are measuring it right now!

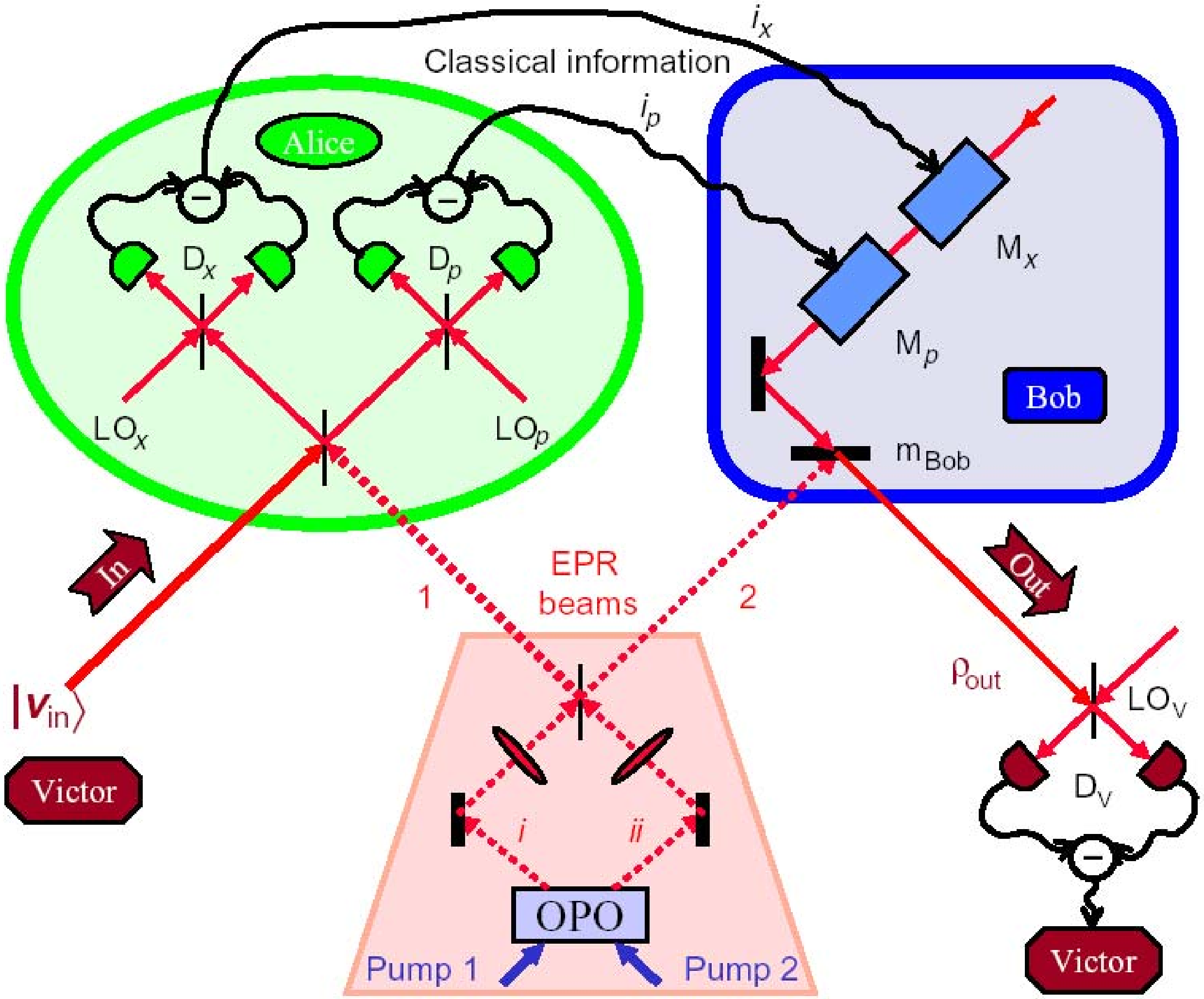


More to follow: use the OPO as a colored entangling tool



Teleportation

Unconditional Quantum Teleportation
A. Furusawa, *et al.*
Science **282**, 706 (1998);



Teleportation

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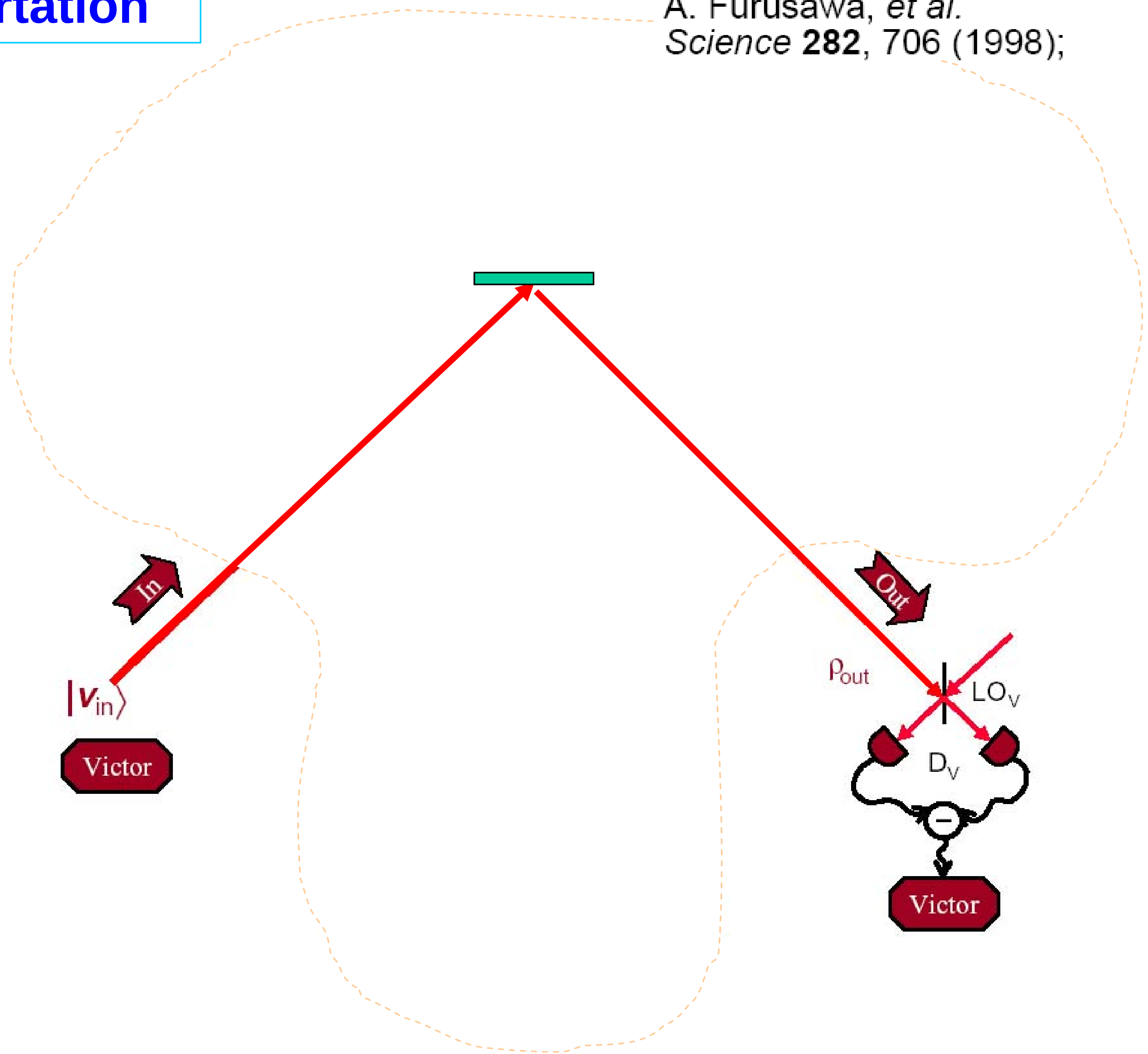
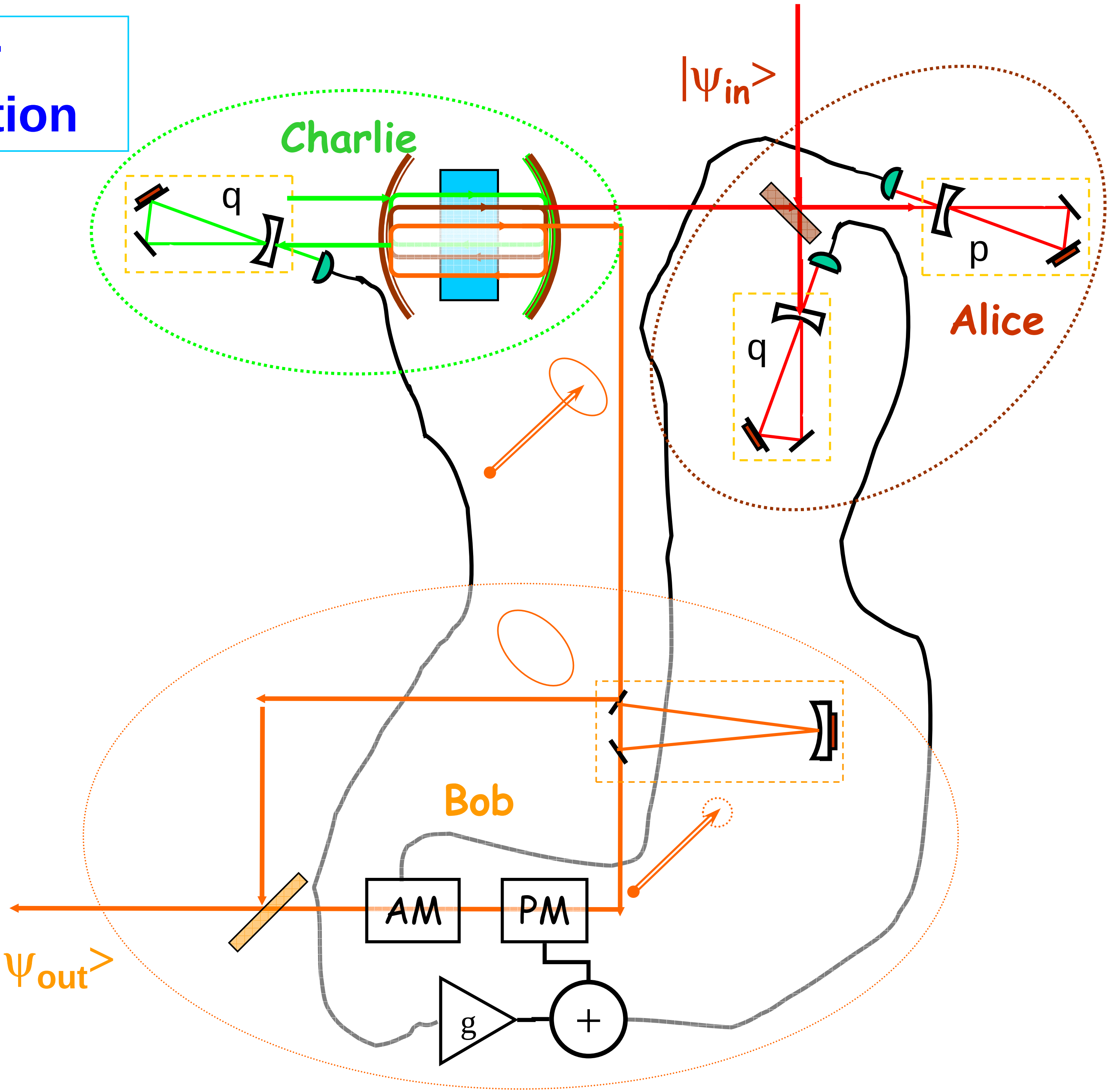
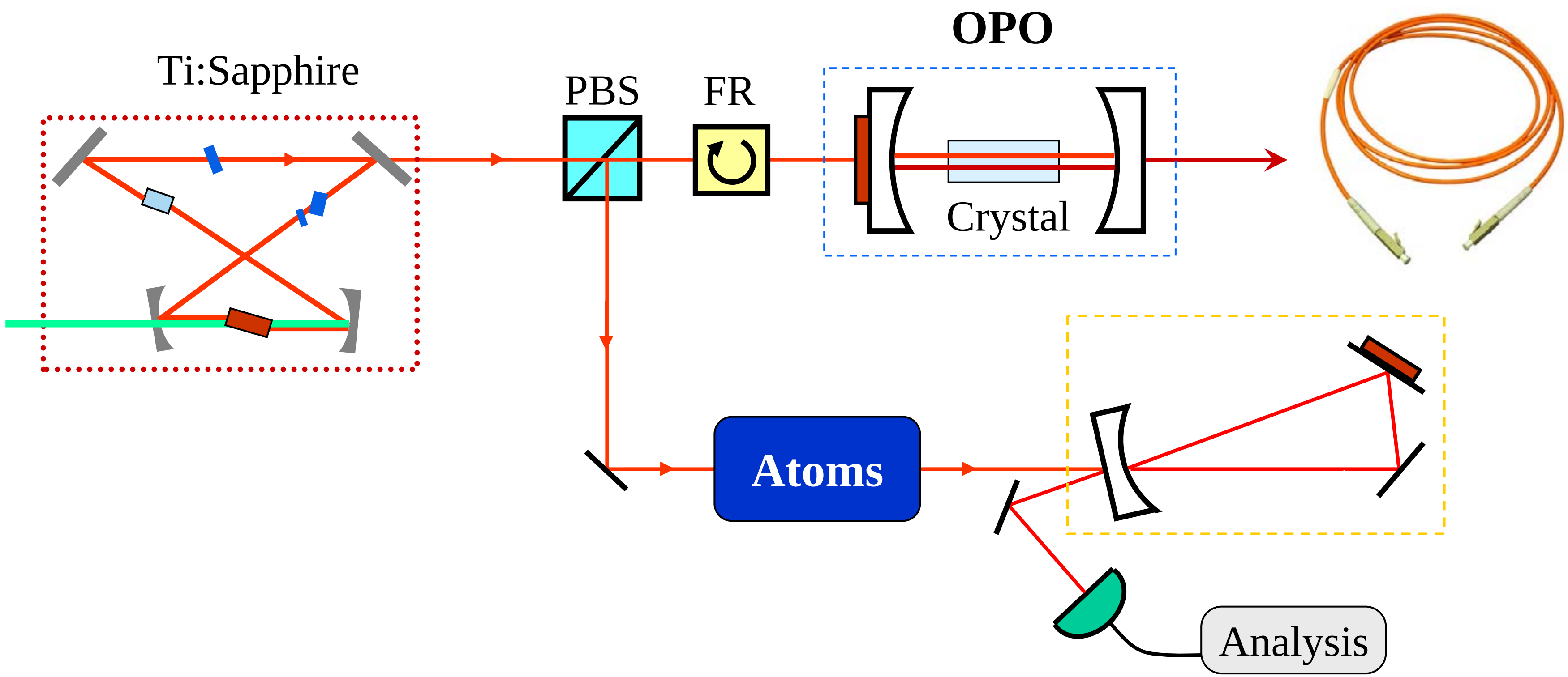


Multicolor Teleportation



Light – Matter Interaction



Raiders of the Lost Entanglement

Felippe Barbosa Antônio Sales Jonatas César

Alencar Faria Luciano Cruz Paulo Valente

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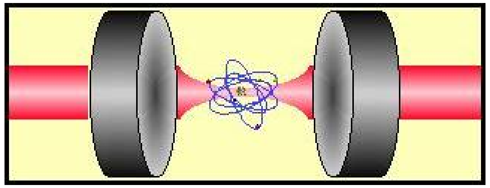
Katiúscia Cassemiro Kaled Dechoum A. Zelaquett Khoury

Claude Fabre (LKB) Marcelo Martinelli Paulo Nussenzveig



Laboratório de Manipulação Coerente de Átomos e Luz

Paulo Nussenzveig (1996)

Marcelo Martinelli (2004)

Alessandro Villar (Post-doc)

Márcio Heráclyto (Post-doc)

Antônio Sales (PhD – MSc 2008)

Felippe Barbosa (PhD – MSc 2008)

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Paula Meirelles (PhD)