Multipartite entanglement and sudden death in Quantum Optics: continuous variables domain
Part IV - Multicolor entanglement

Marcelo Martinelli

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

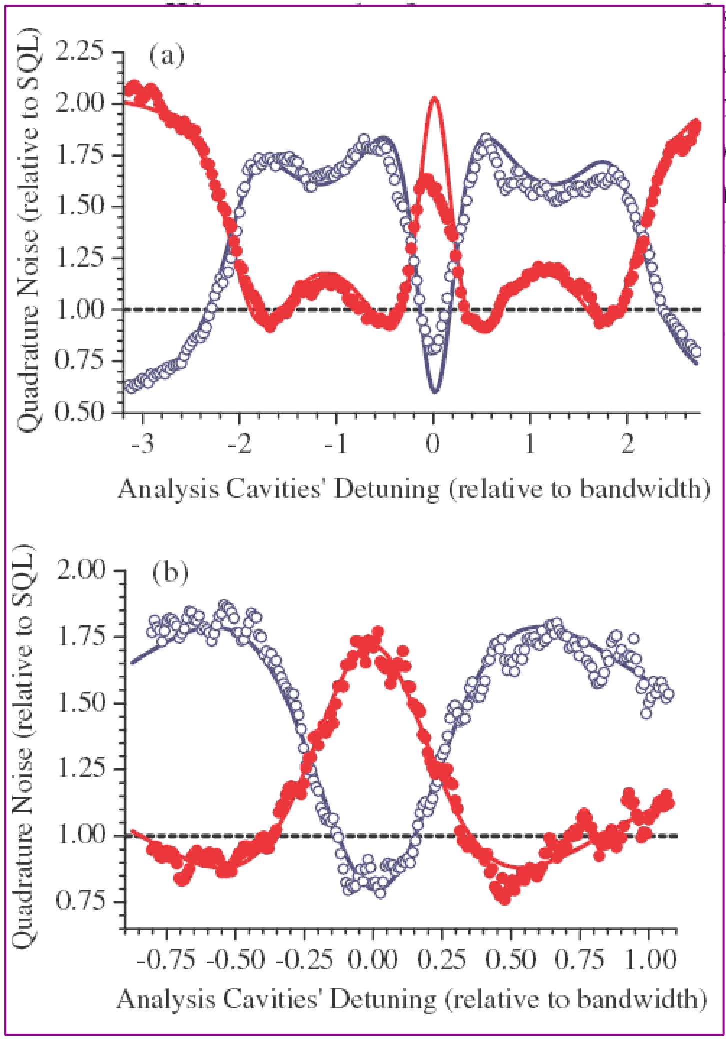
- Vacuum ($P_0 < P_{th}$, maximum entanglement)
- Intense beams ($P_0 > P_{th}$)

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

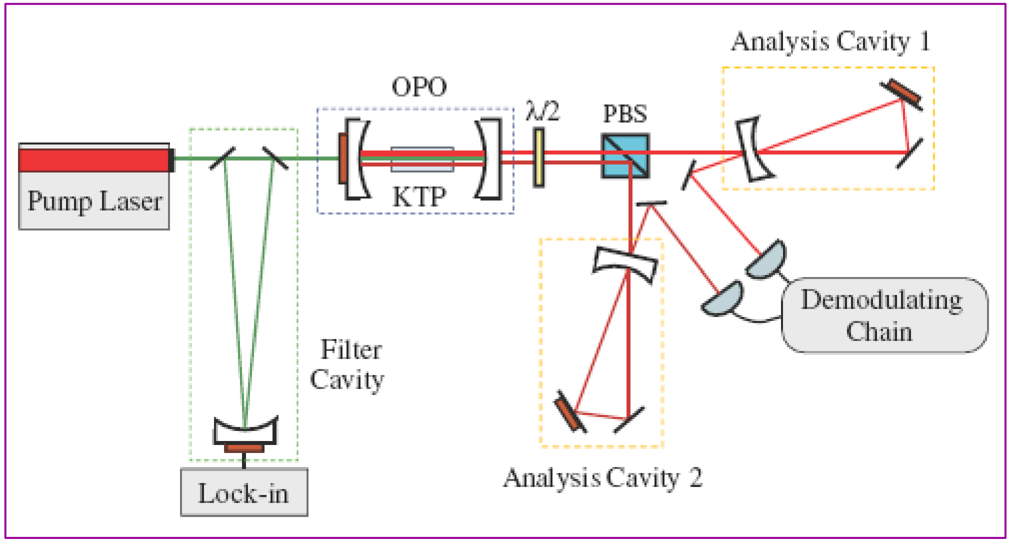
Set up

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

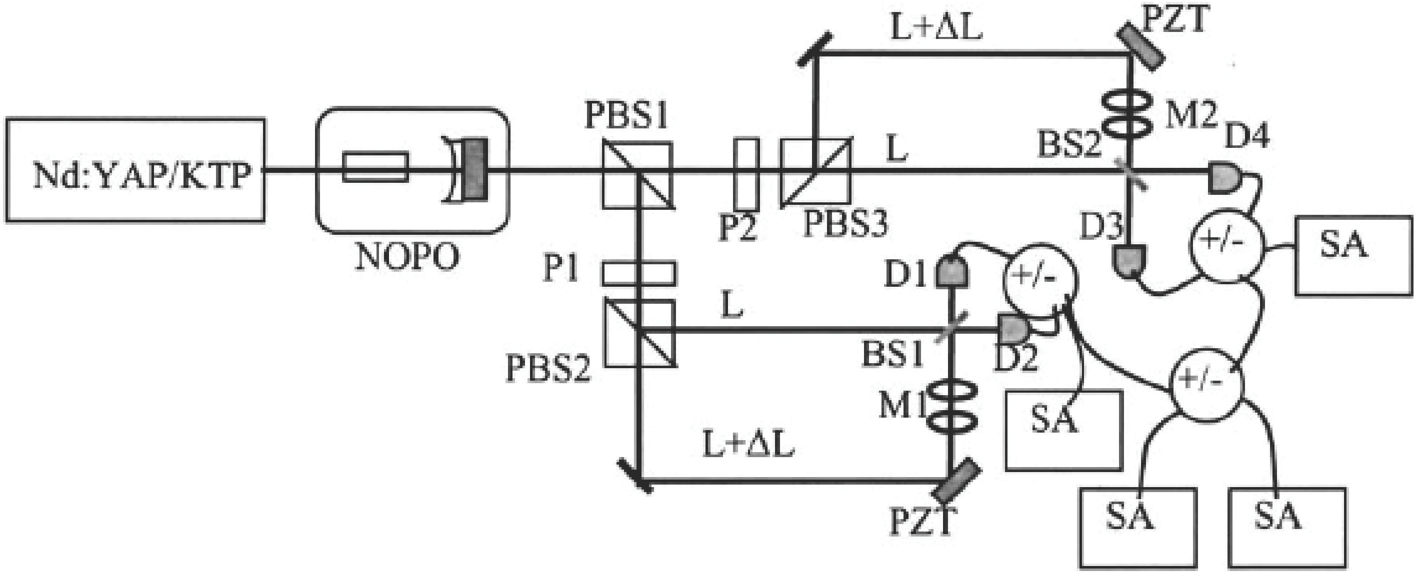


squeezed-state entanglement between the twin beams produced in
ing above threshold. In addition to the usual squeezing in the
beams, we have measured squeezing in the sum of phase
measure such phase anticorrelations between fields of different
its, wavelengths differ by ≈ 1 nm. Entanglement is demonstrated
Phys. Rev. Lett. **84**, 2722 (2000)] $\Delta^2\hat{p}_- + \Delta^2\hat{q}_+ = 1.41(2) < 2$.
potential applications such as the transfer of quantum information
agnetic spectrum.



Experimental demonstration of quantum entanglement between frequency-nondegenerate optical twin beams

Xiaolong Su, Aihong Tan, Xiaojun Jia, Qing Pan, Changde Xie, and Kunchi Peng
State Key Laboratory of Quantum Optics and Quantum Optics Devices, Institute of Opto-Electronics, Shanxi University, Taiyuan 030006, China



RAPID COMMUNICATIONS

PHYSICAL REVIEW A **74**, 041804(R) (2006)

Experimental continuous-variable entanglement from a phase-difference-locked optical parametric oscillator

Jietai Jing,* Sheng Feng,* Russell Bloomer, and Olivier Pfister†
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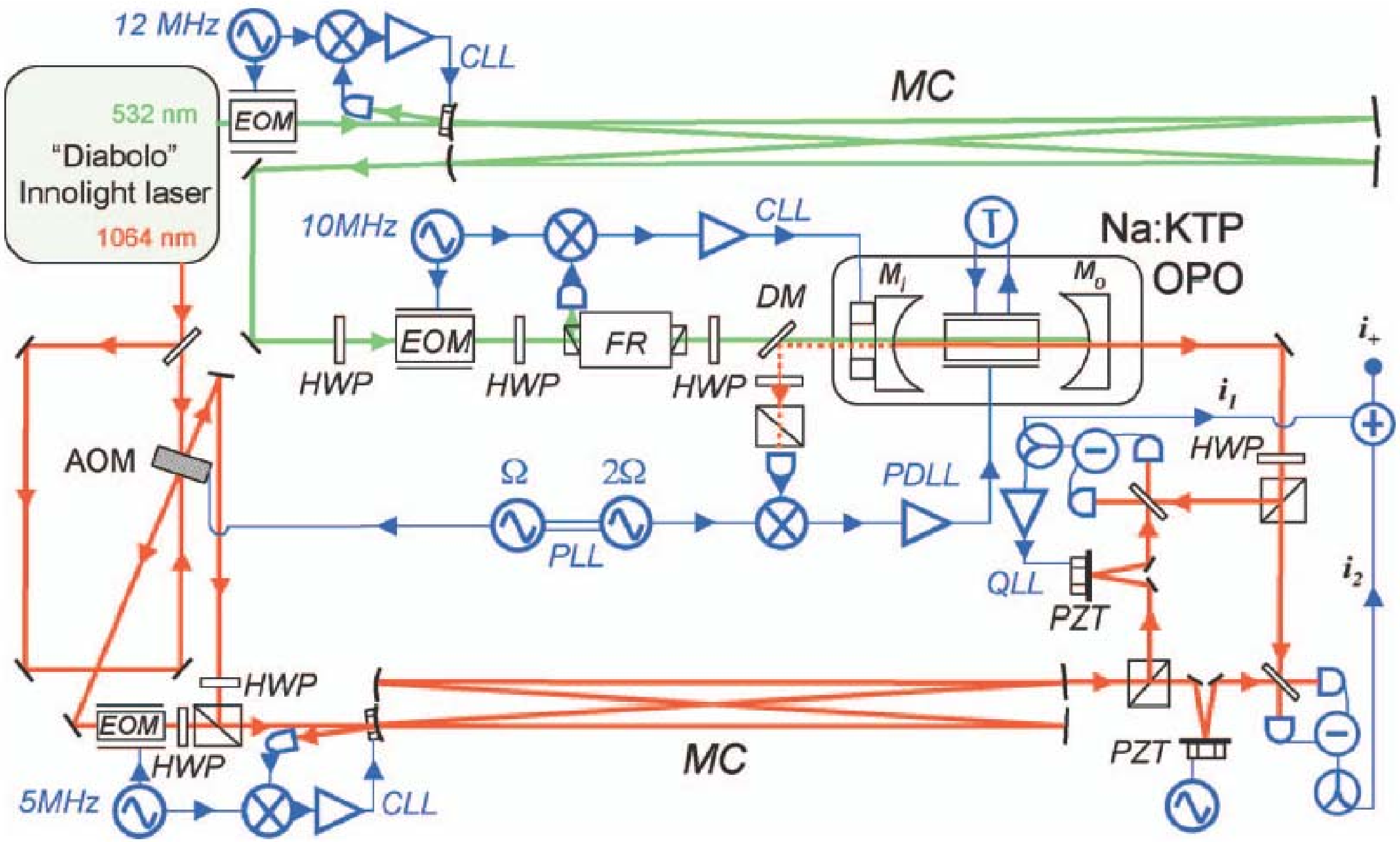
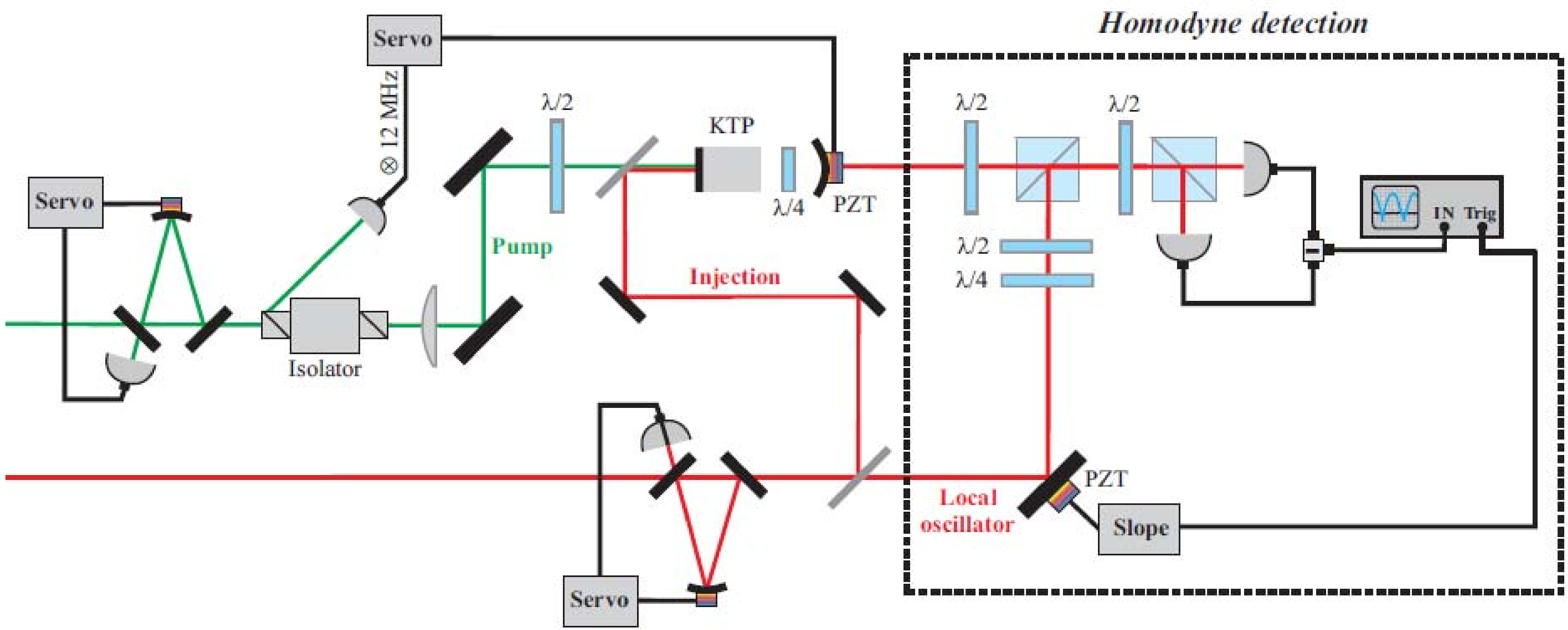
(Received 19 April 2006; published 16 October 2006)



Experimental demonstration of frequency-degenerate bright EPR beams with a self-phase-locked OPO

G. Keller, V. D'Auria, N. Treps, T. Coudreau†, J. Laurat, C. Fabre
Laboratoire Kastler Brossel, Université Pierre et Marie Curie, Ecole Normale Supérieure, CNRS, Case 74, 4 place Jussieu, 75252 Paris Cedex 05, France

23 June 2008 / Vol. 16, No. 13 / OPTICS EXPRESS 9351

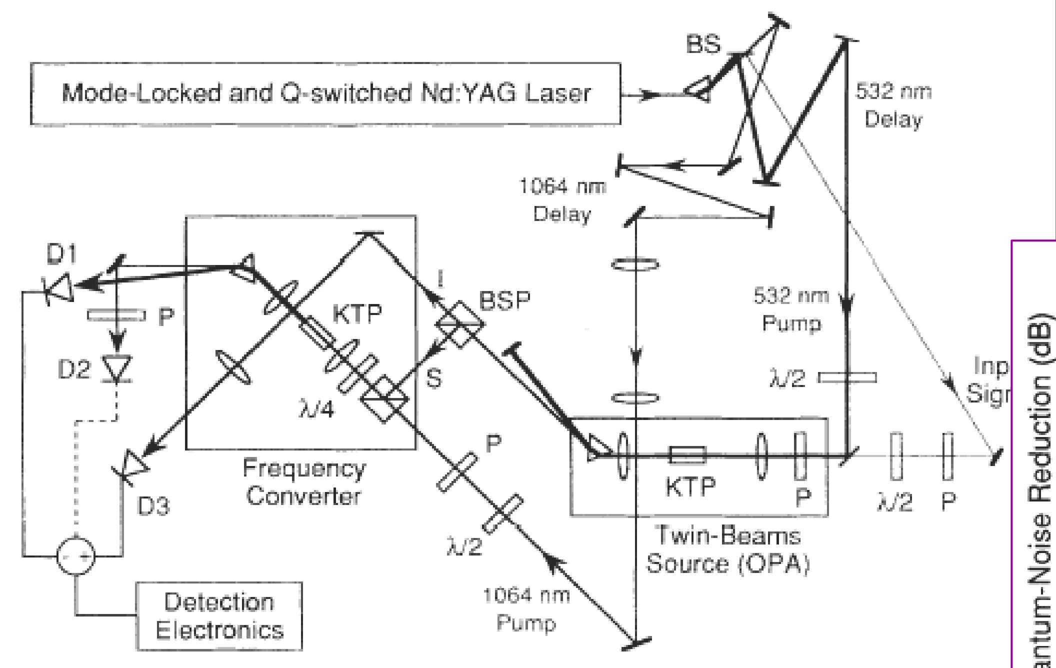


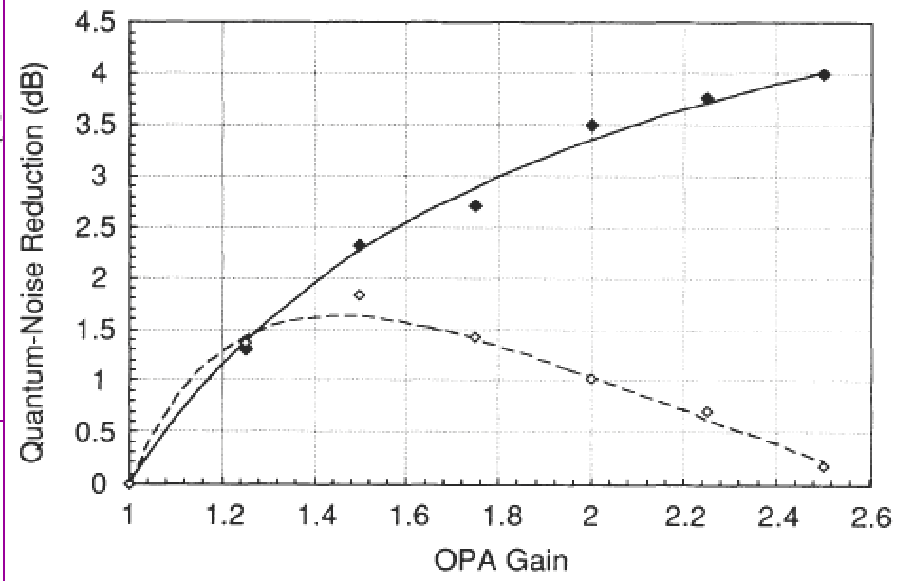
Observation of Quantum Frequency Conversion

Jianming Huang and Prem Kumar

Department of Electrical Engineering and Computer Science, Northwestern University, Evanston, Illinois 60208

Quantum frequency conversion, a process with which an input beam of light can be converted into an output beam of a different frequency while preserving the quantum state, is experimentally demonstrated for the first time. Nonclassical intensity correlation ($\simeq$3 dB) between two beams at 1064 nm is used as the input quantum property. When the frequency of one of the beams is converted from 1064 to 532 nm, nonclassical intensity correlations ($\simeq$1.5 dB) appear between the up-converted beam and the remaining beam. Our measurements are in excellent agreement with the quantum theory of frequency conversion. The development of tunable sources of novel quantum light states seems possible.

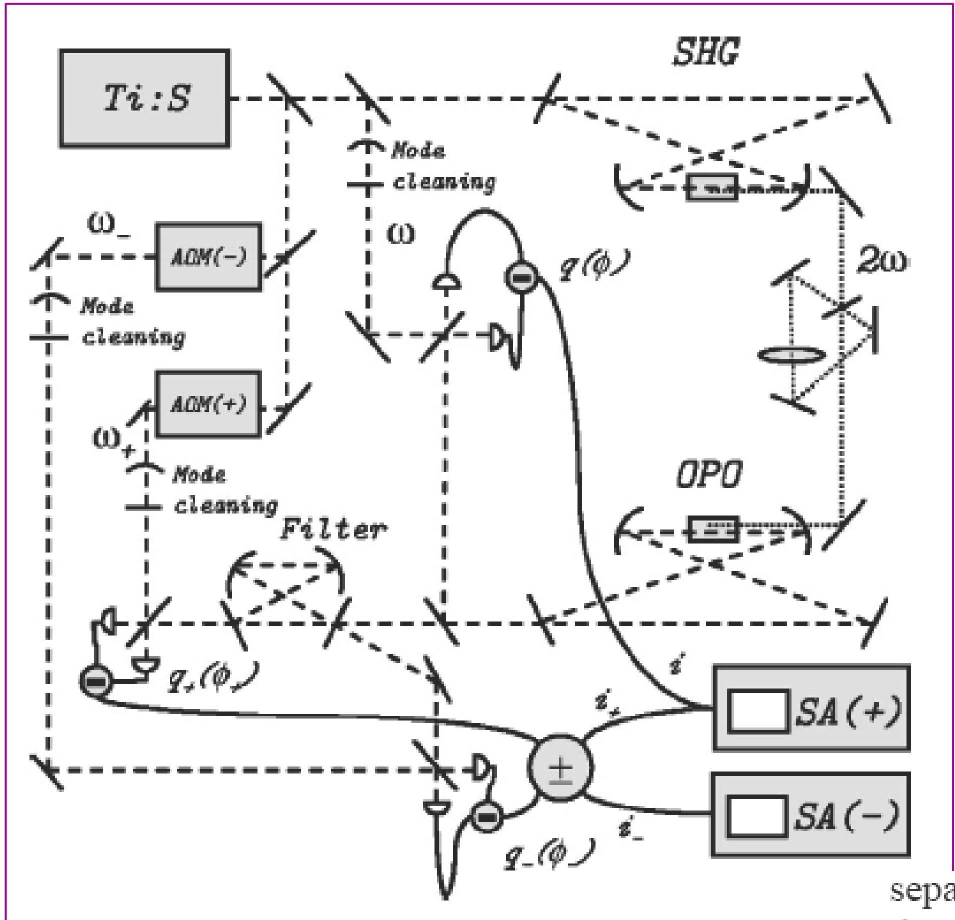


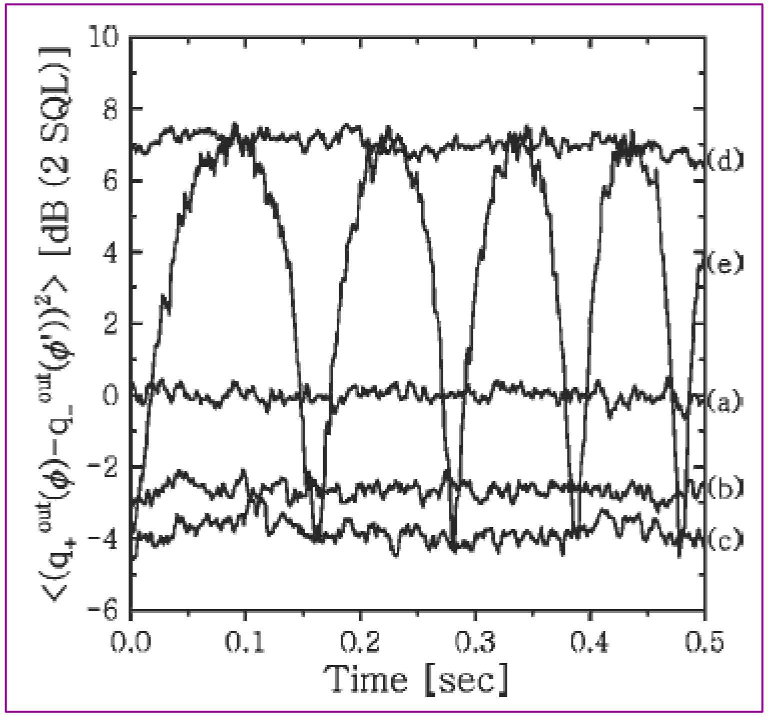


PHYSICAL REVIEW A, **66**, 033802 (2002)

Narrow-band frequency tunable light source of continuous quadrature entanglement

Christian Schori, Jens L. Sørensen,* and Eugene S. Polzik
QUANTOP-Danish National Research Foundation Centre for Quantum Optics, Institute of Physics and Astronomy, University of Aarhus, DK-8000 Aarhus, Denmark



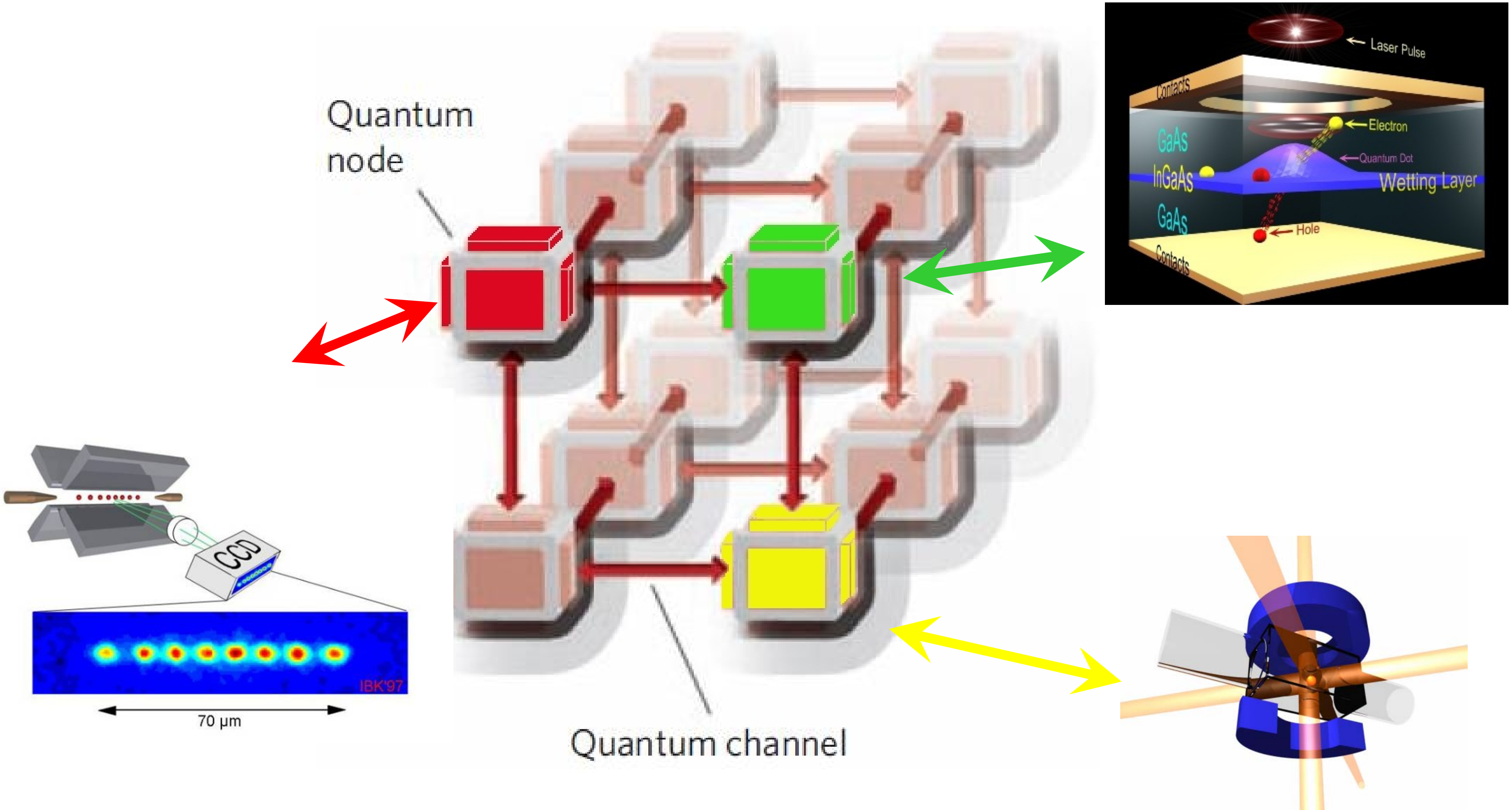


separated entangled optical fields. In this paper we have used the OPO cavity resonances adjacent to the frequency degenerate mode, resulting in entangled fields separated by 740 MHz corresponding to two OPO cavity-free spectrum

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

The quantum internet

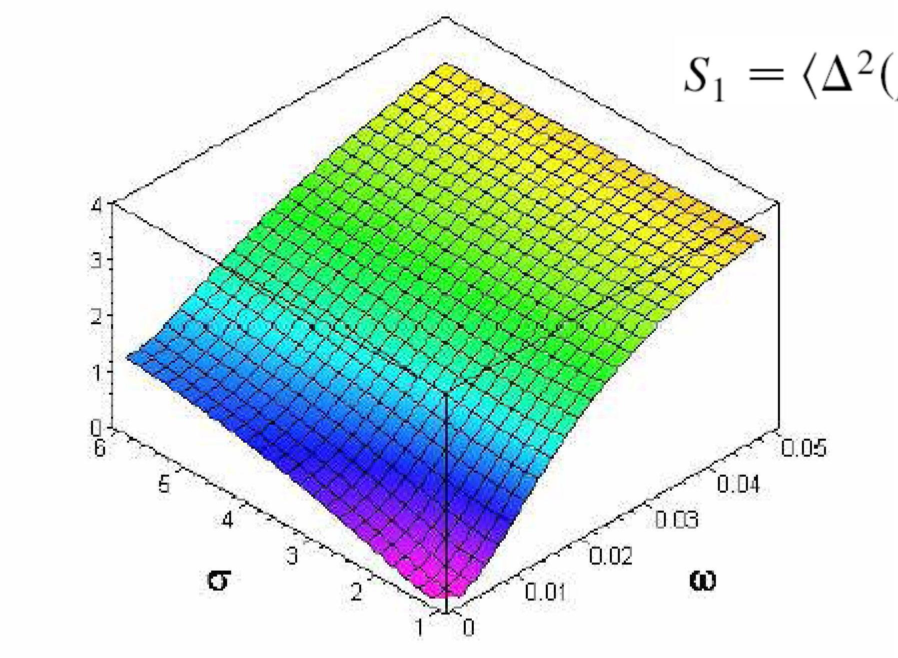
H. J. Kimble[1]

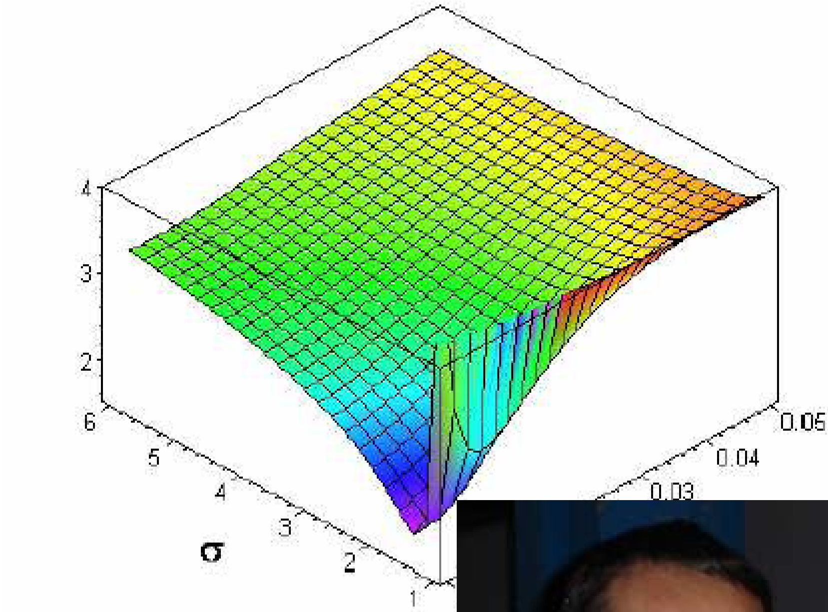


Direct Production of Tripartite Pump-Signal-Idler Entanglement in the Above-Threshold Optical Parametric Oscillator

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

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





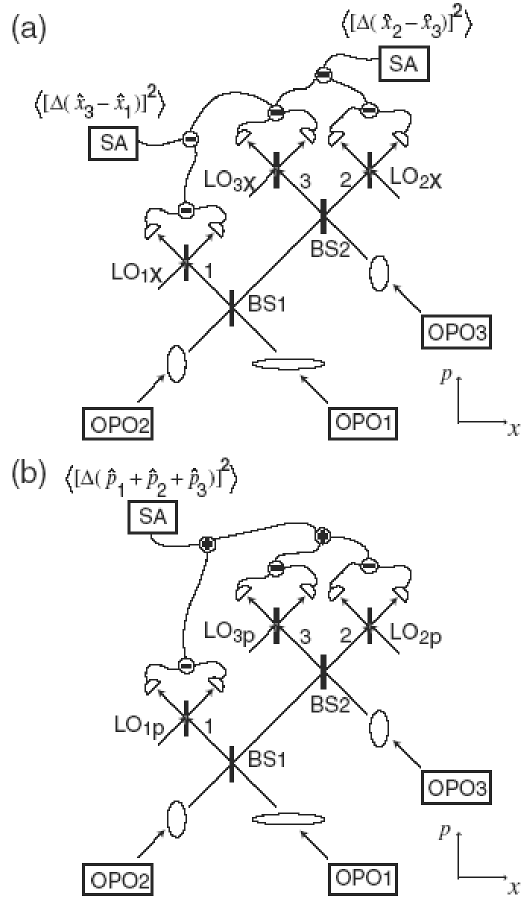
$$S_2 = \langle \Delta^2(\hat{p}_0 + \hat{p}_1) \rangle + \langle \Delta^2(\hat{q}_1 + \alpha_2 \hat{q}_2 - \hat{q}_0) \rangle \geq 4$$

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

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

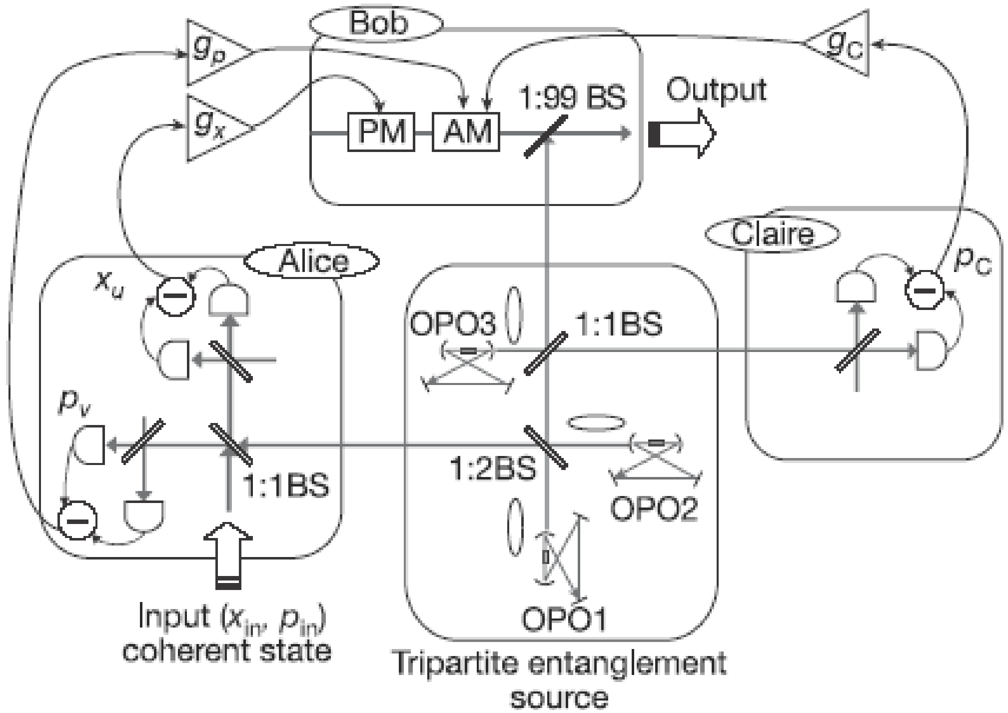
Peter van Loock
Quantum Information Theory Group, Zentrum für Moderne Optik, Universität Erlangen-Nürnberg, 91058 Erlangen, Germany



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*



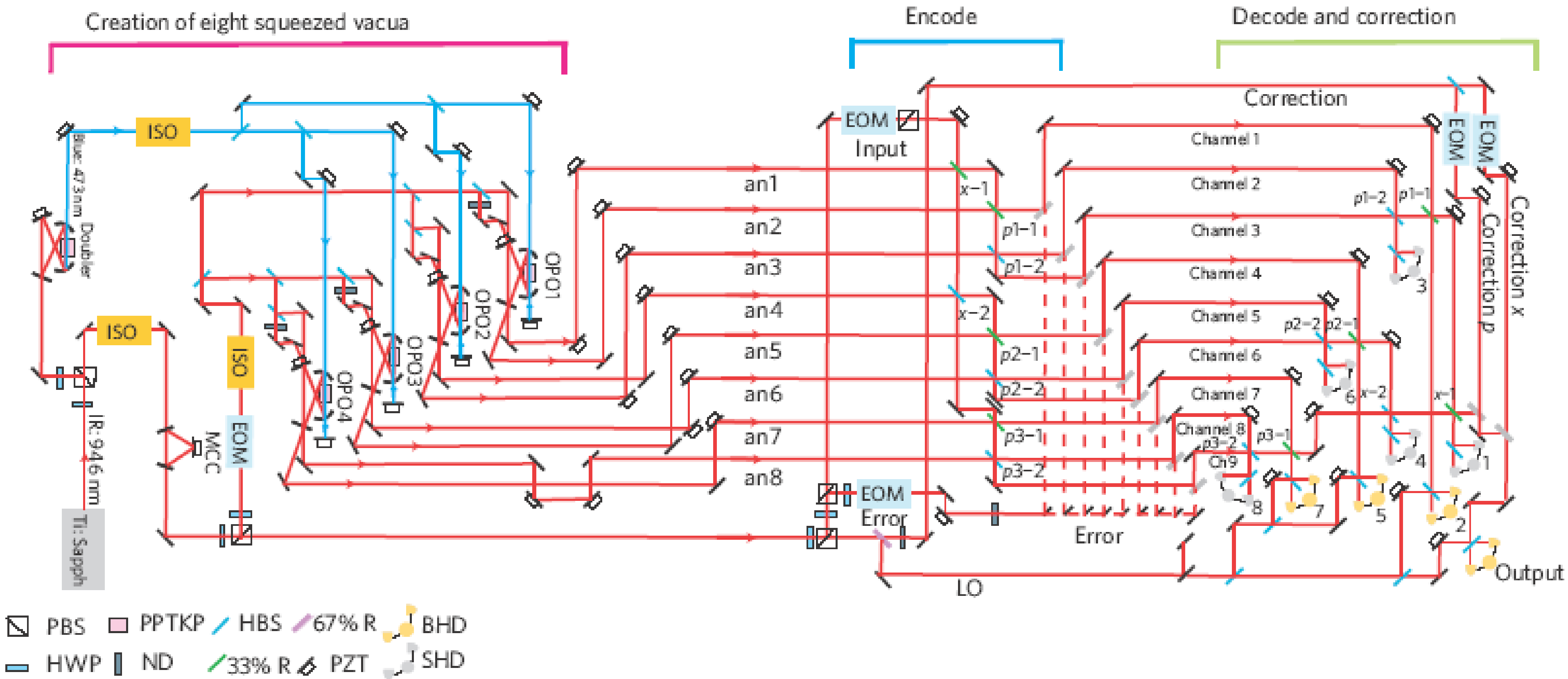
nature physics

LETTERS

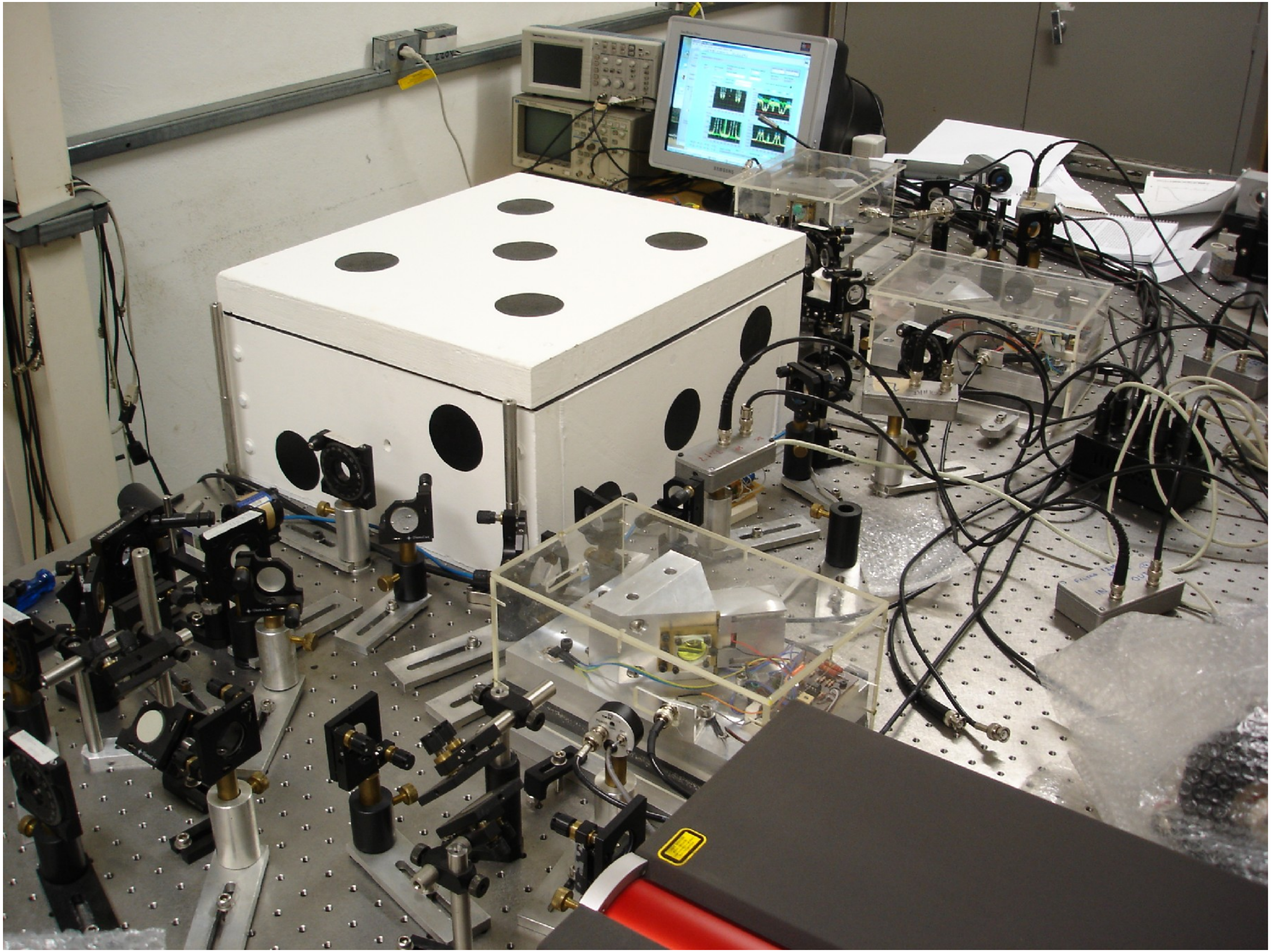
PUBLISHED ONLINE: 28 JUNE 2009 | DOI: 10.1038/NPHYS1309

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?



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

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

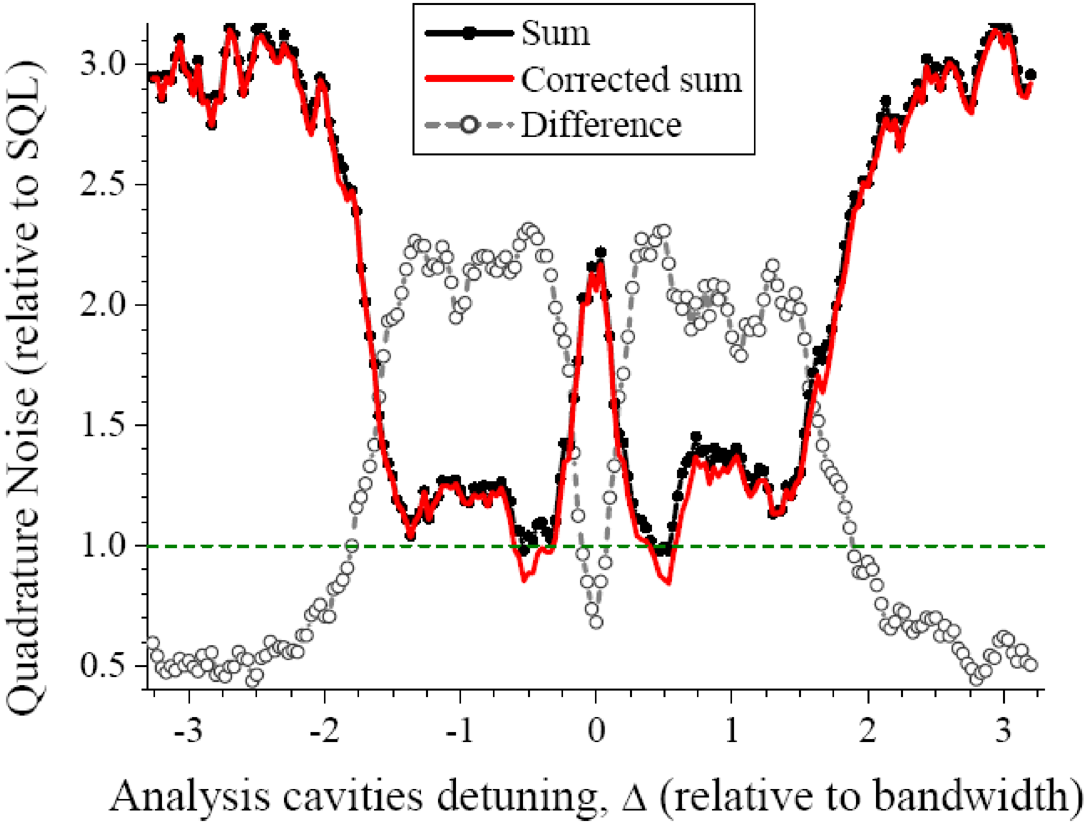
K. N. Cassemiro *et al.* Opt. Lett. **32**, 695 (2007)

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

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

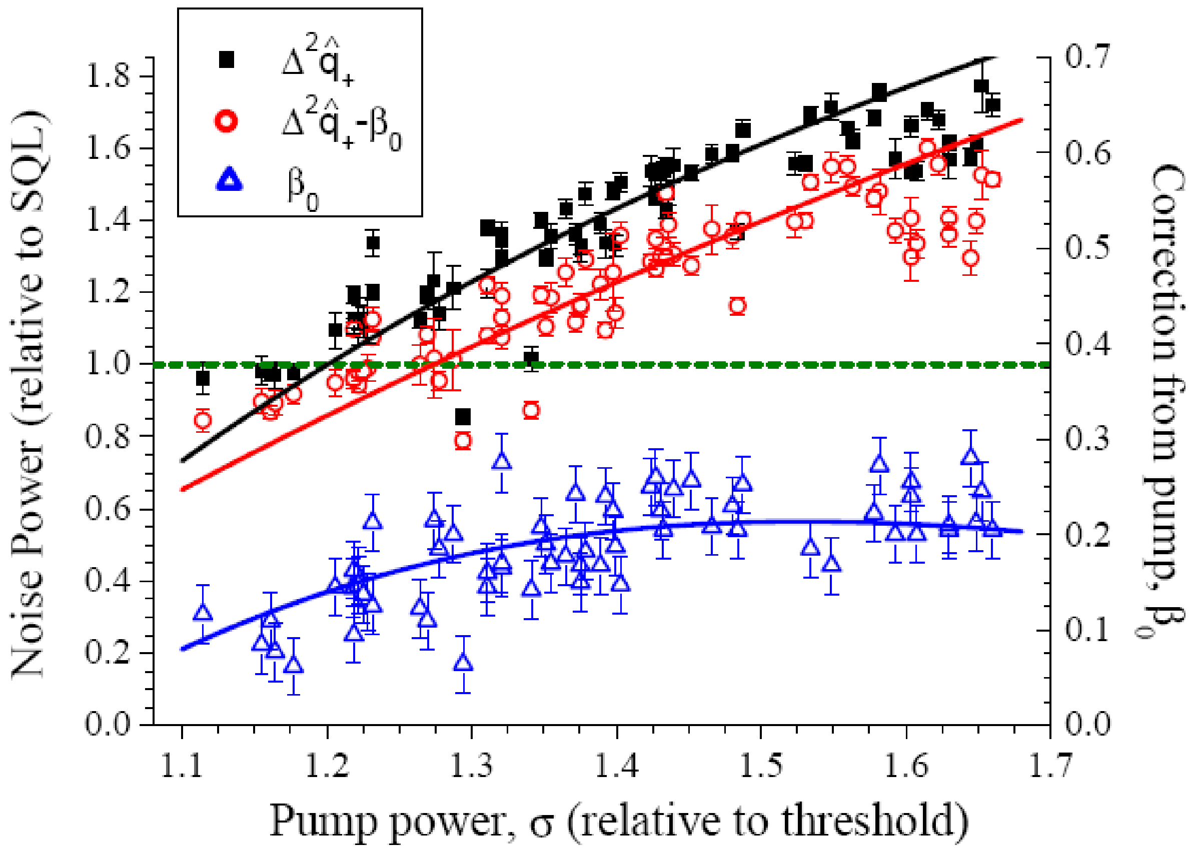
Three-color quantum correlations

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



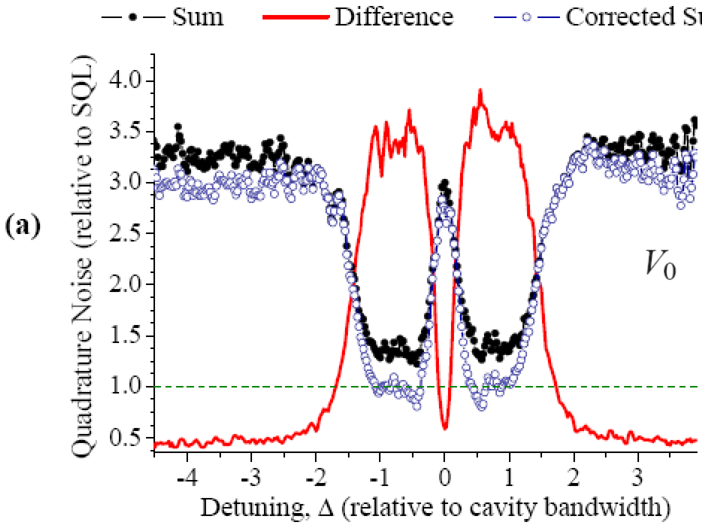
$$\Delta^2 \hat{p}_- + \Delta^2(\hat{q}_+ - \alpha_0\, \hat{p}_0) \geq 2\ , \quad \text{with} \quad \alpha_0 = \frac{C_{\hat{p}_0 \hat{q}_+}}{\Delta^2 \hat{p}_0}$$

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

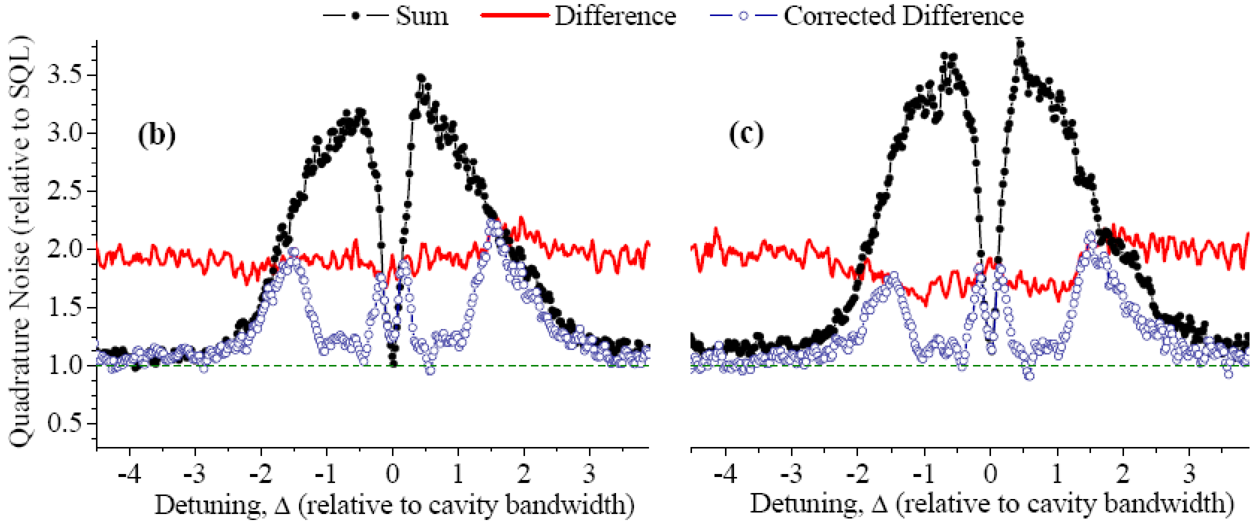


The quest for three-color entanglement…

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

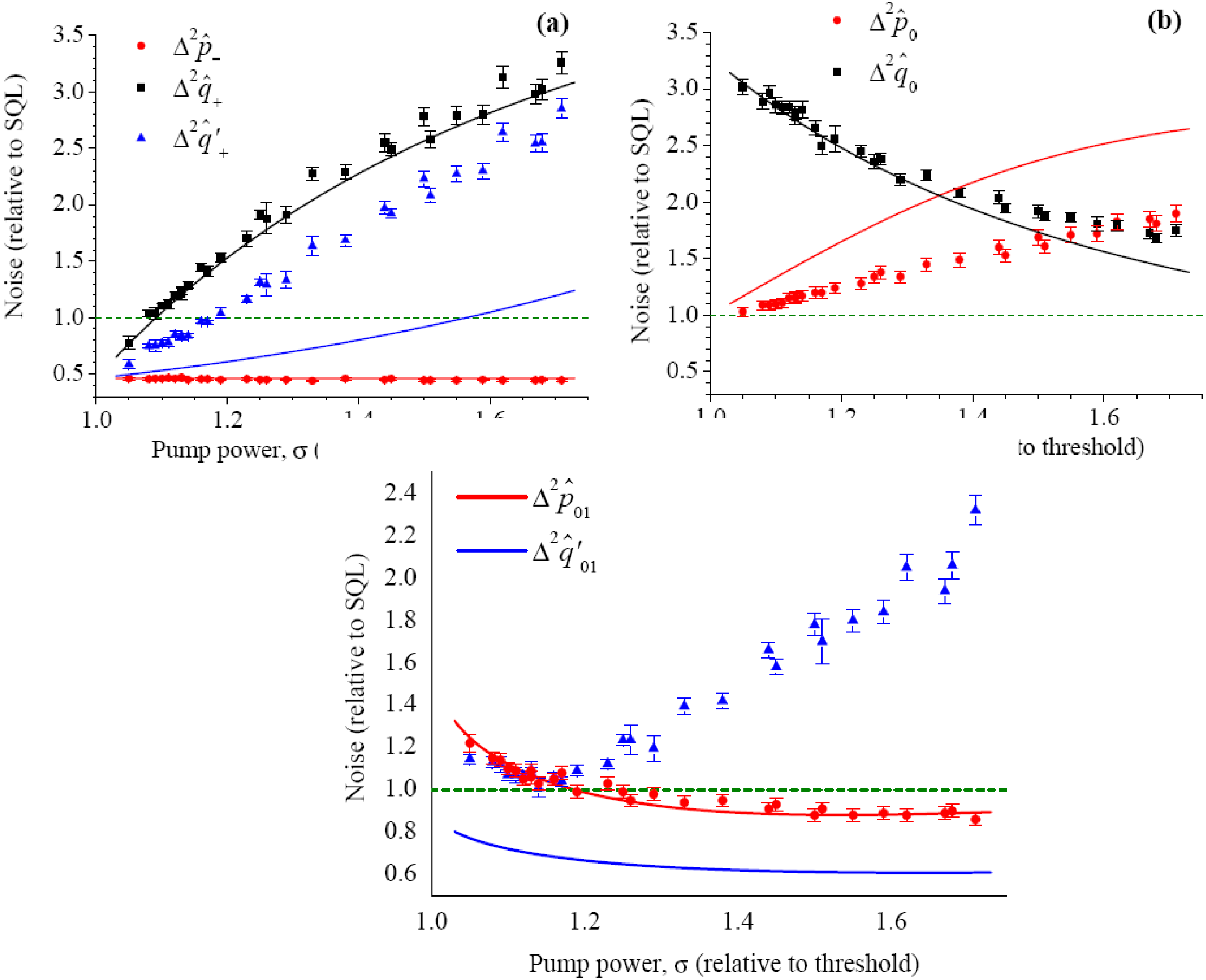


$$V_0 = \Delta^2\left(\frac{\hat{p}_1-\hat{p}_2}{\sqrt{2}}\right) + \Delta^2\left(\frac{\hat{q}_1+\hat{q}_2}{\sqrt{2}}-\alpha_0\hat{q}_0\right) \geq 2$$



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

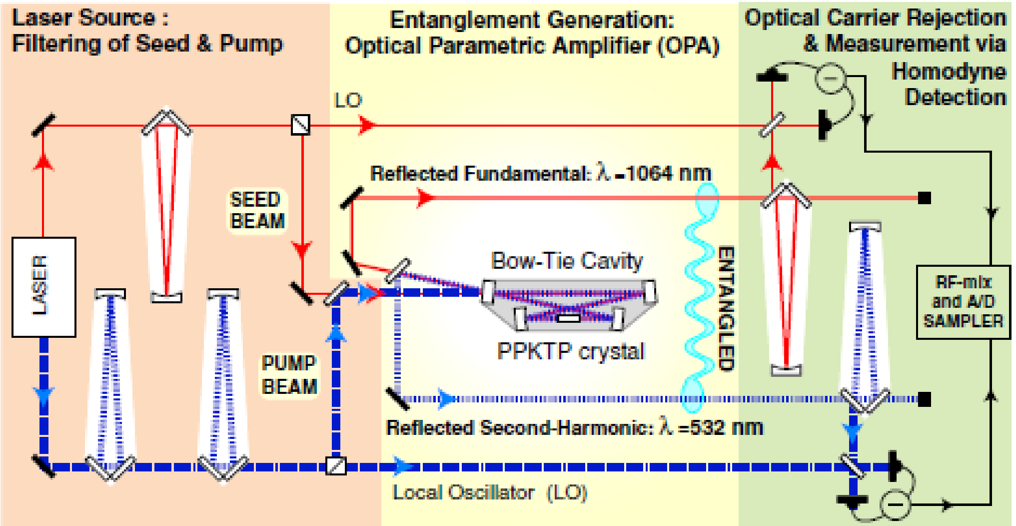
$$V_2 = \Delta^2\left(\frac{\hat{p}_0+\hat{p}_2}{\sqrt{2}}\right) + \Delta^2\left(\frac{\hat{q}_2-\hat{q}_0}{\sqrt{2}}+\alpha_1\hat{q}_1\right) \geq 2$$

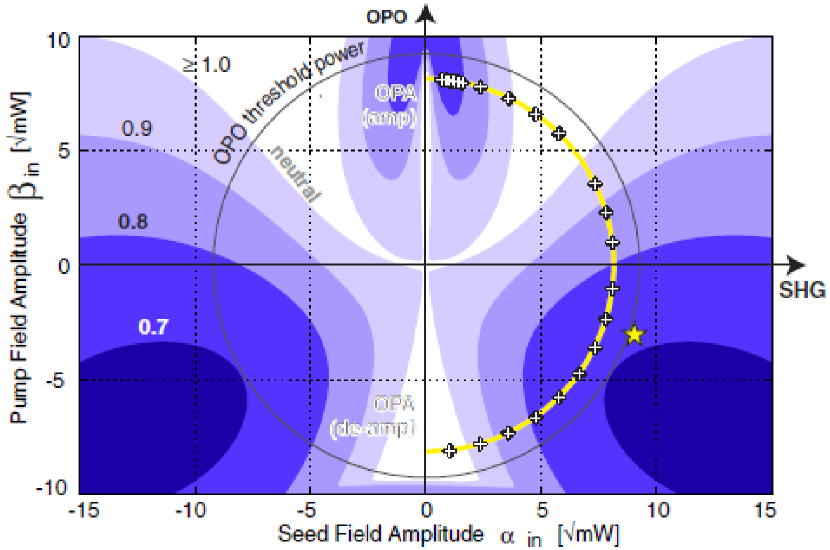


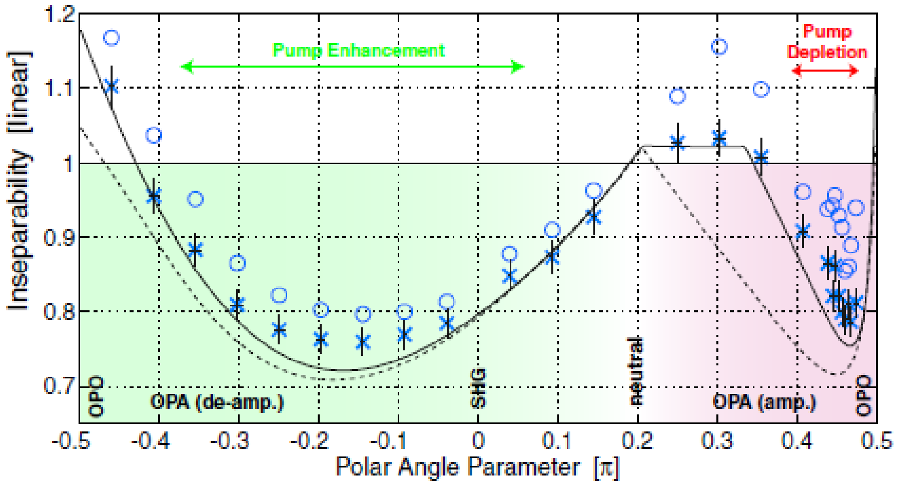
(a)
$\Delta^2\hat{p}_-$
$\Delta^2\hat{q}_+$
$\Delta^2\hat{q}'_+$
Noise (relative to SQL)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
1.0
1.2
1.6
Pump power, σ (
(b)
$\Delta^2\hat{p}_0$
$\Delta^2\hat{q}_0$
Noise (relative to SQL)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
1.6
to threshold)
$\Delta^2\hat{p}_{01}$
$\Delta^2\hat{q}'_{01}$
Noise (relative to SQL)
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
1.0
1.2
1.4
1.6
Pump power, σ (relative to threshold)

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

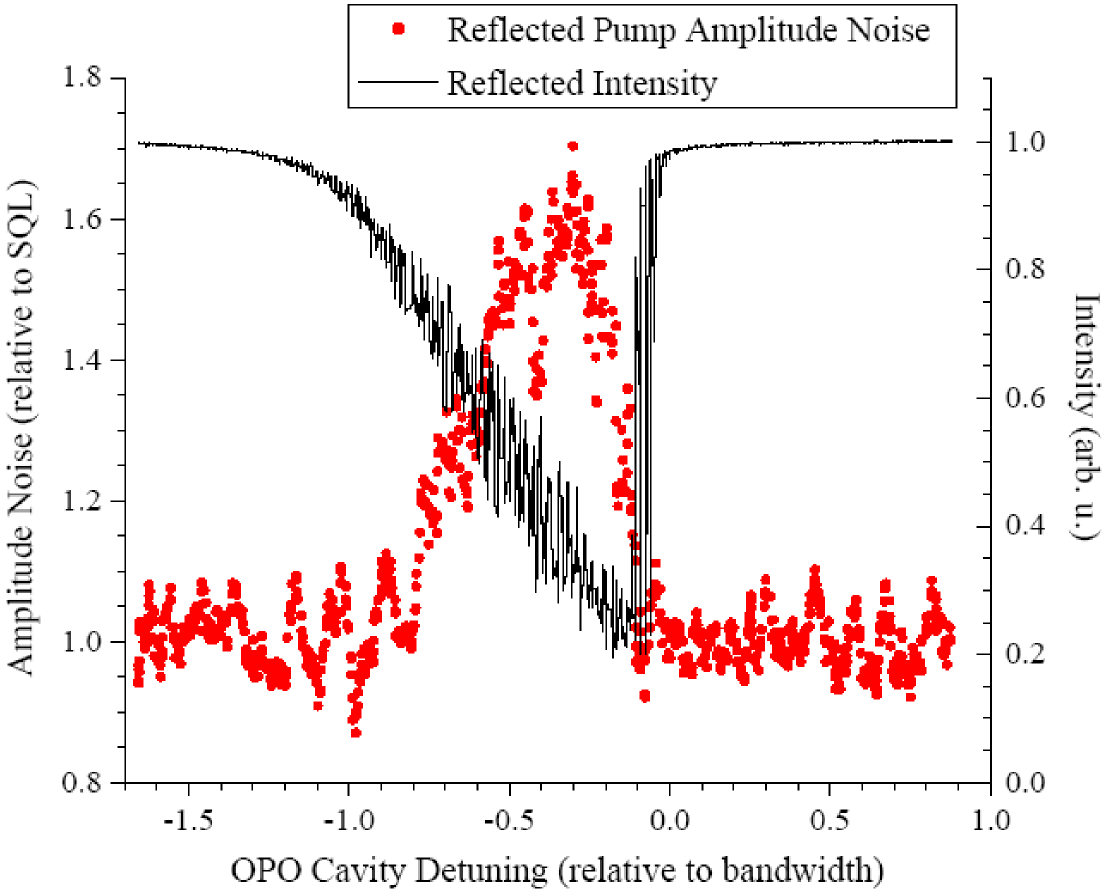
Nicolai B. Grosse,[1] Syed Assad,[1,2] Moritz Mehmet,[3] Roman Schnabel,[3] Thomas Symul,[1] and Ping Koy Lam[1]







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

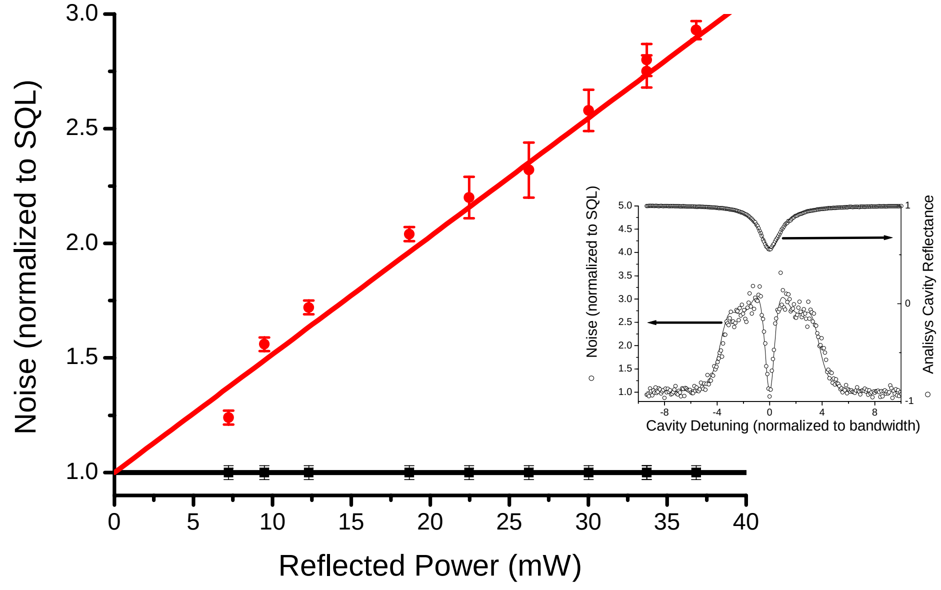
Alessandro S. Villar and Katiúscia N. Cassemiro

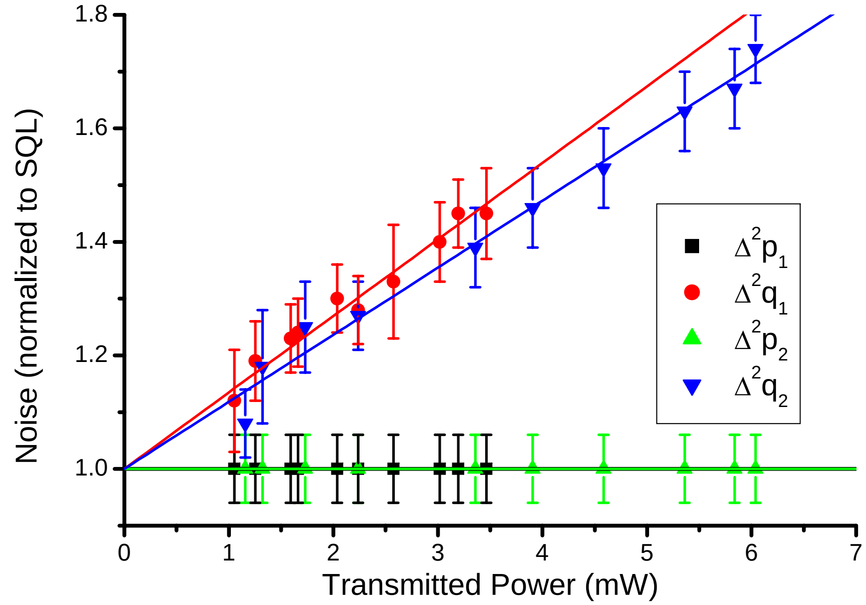
Kaled Dechoum and Antonio Z. Khoury

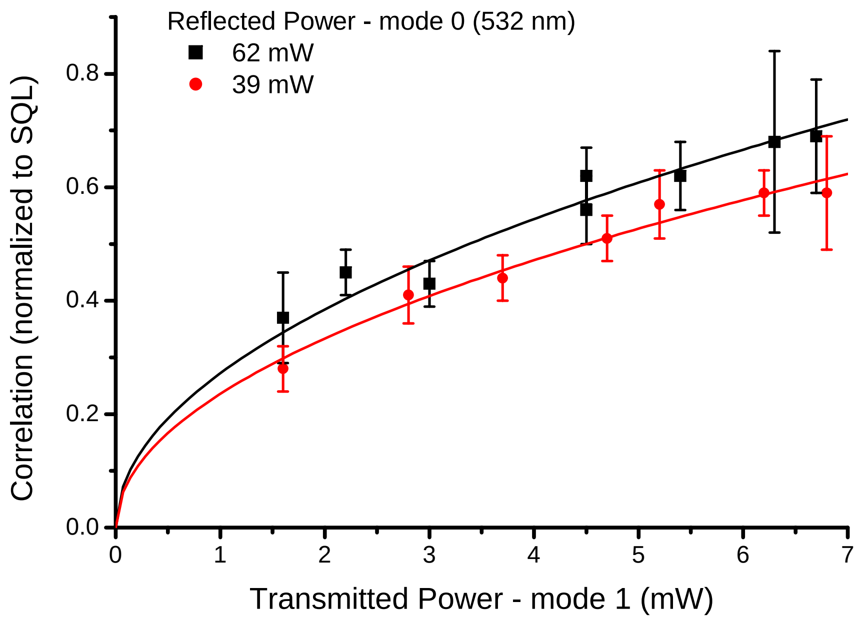
Marcelo Martinelli and Paulo Nussenzveig

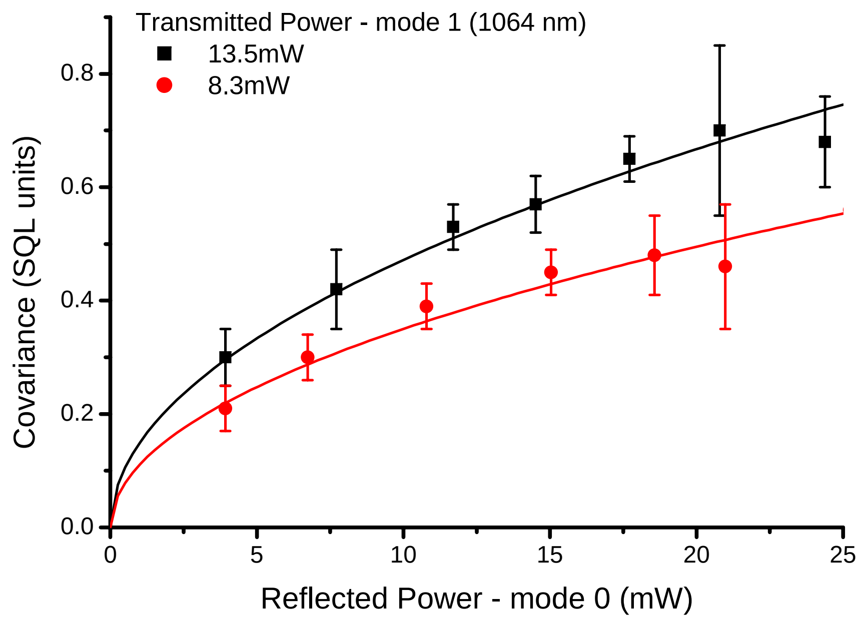
Vol. 24, No. 2/February 2007/J. Opt. Soc. Am. B 249

Noise is everywhere!









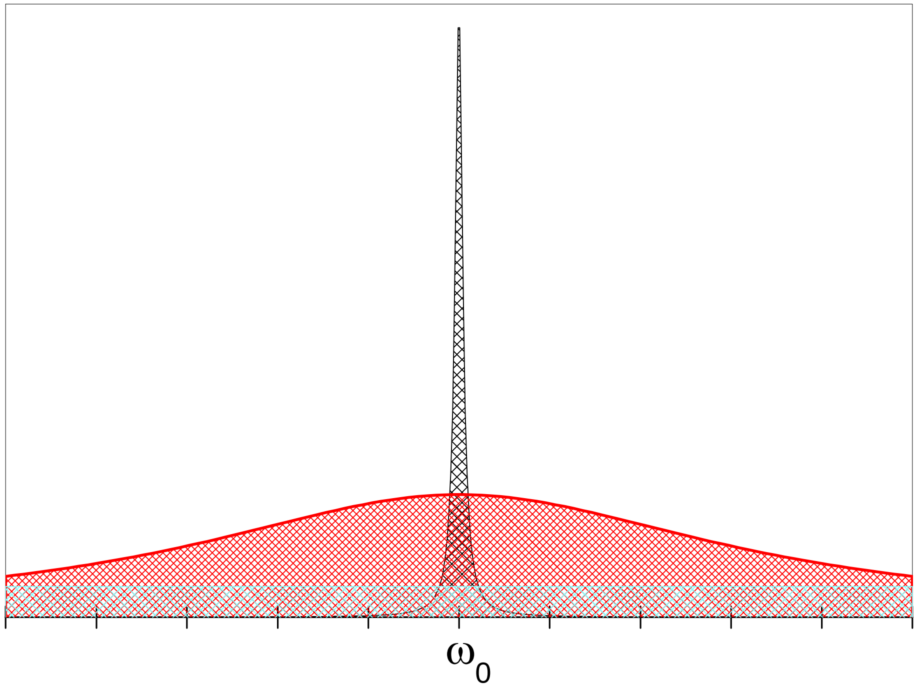
Is the noise inside the crystal...

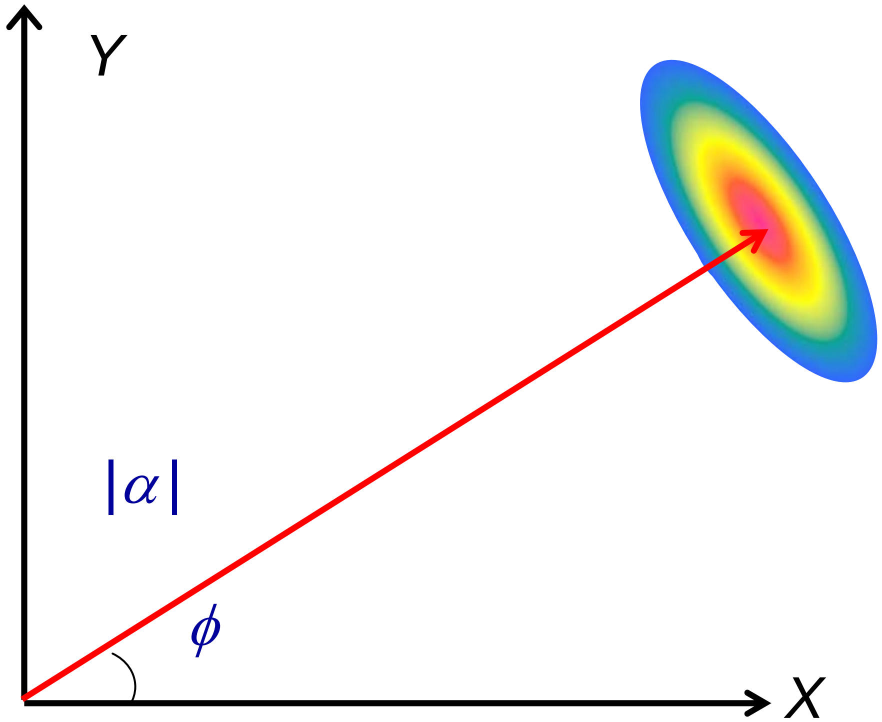
as a random modulation of the refractive index?

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]

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

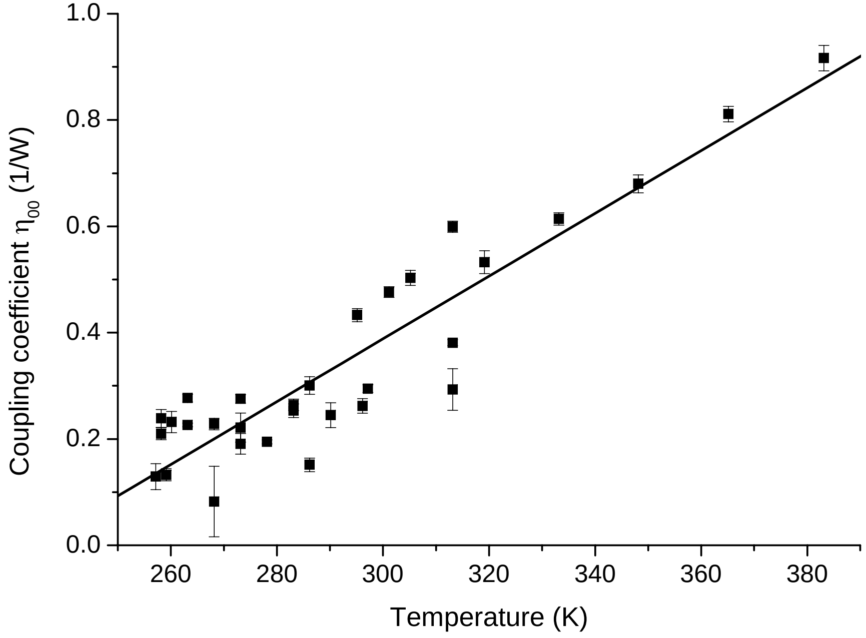
$$\begin{aligned} \langle \delta Q_j(\Omega)\delta Q_k(-\Omega)\rangle &= \\ & k_j k_k \frac{n_j^3 n_k^3}{4hc}\, l_c^3 \;\; c_{jk}(\Omega) \left(\frac{\ell\sqrt{\lambda_j\lambda_k}}{\pi w_{jk}^2}\right)\sqrt{P_j P_k} \\ &= \eta_{jk}\sqrt{P_j P_k}\,. \end{aligned}$$

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

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

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

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



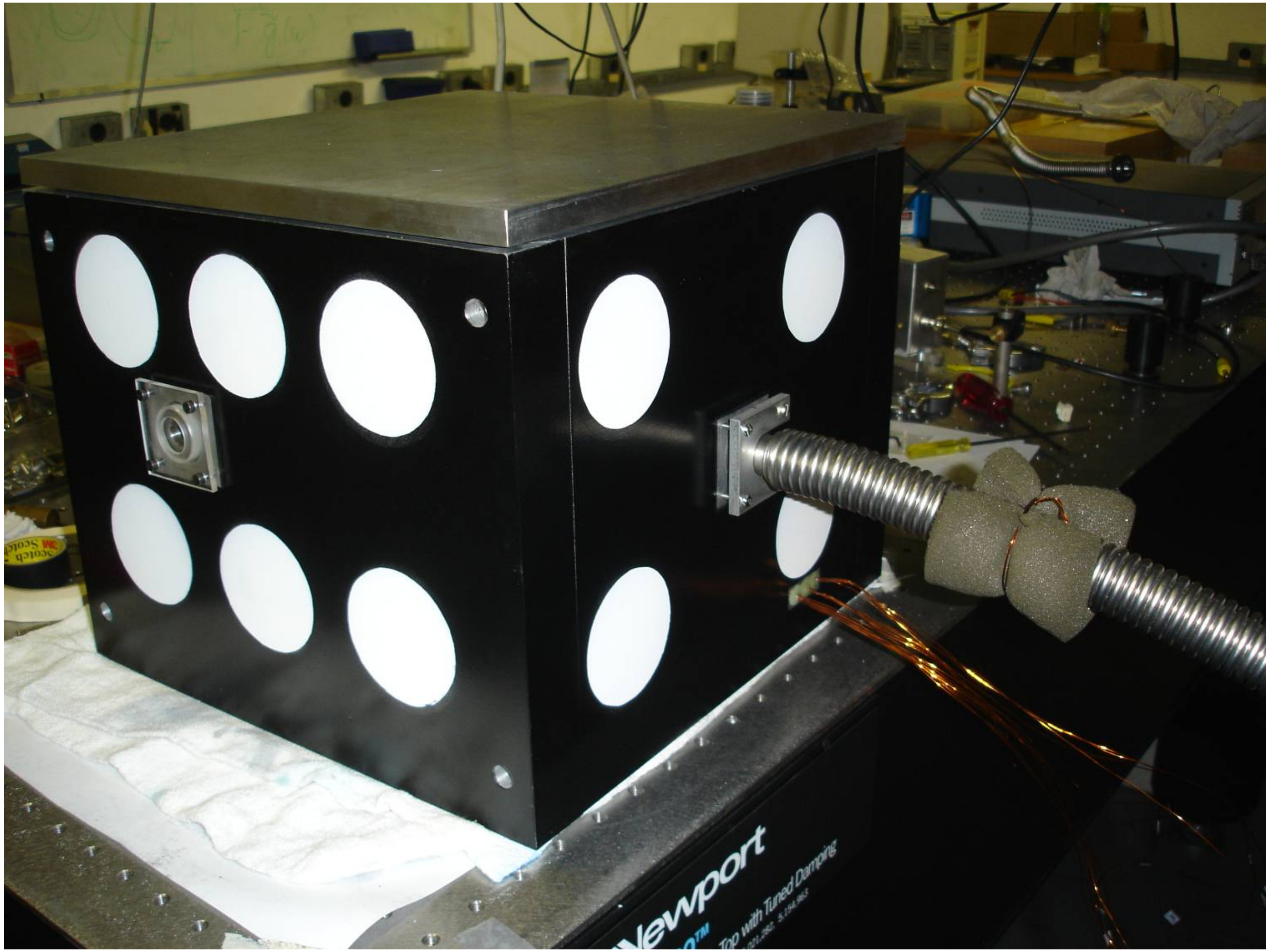
$$\vec{X} = [\delta\hat{p}_0, \delta\hat{q}_0, \delta\hat{p}_1, \delta\hat{q}_1, \delta\hat{p}_2, \delta\hat{q}_2]^T$$

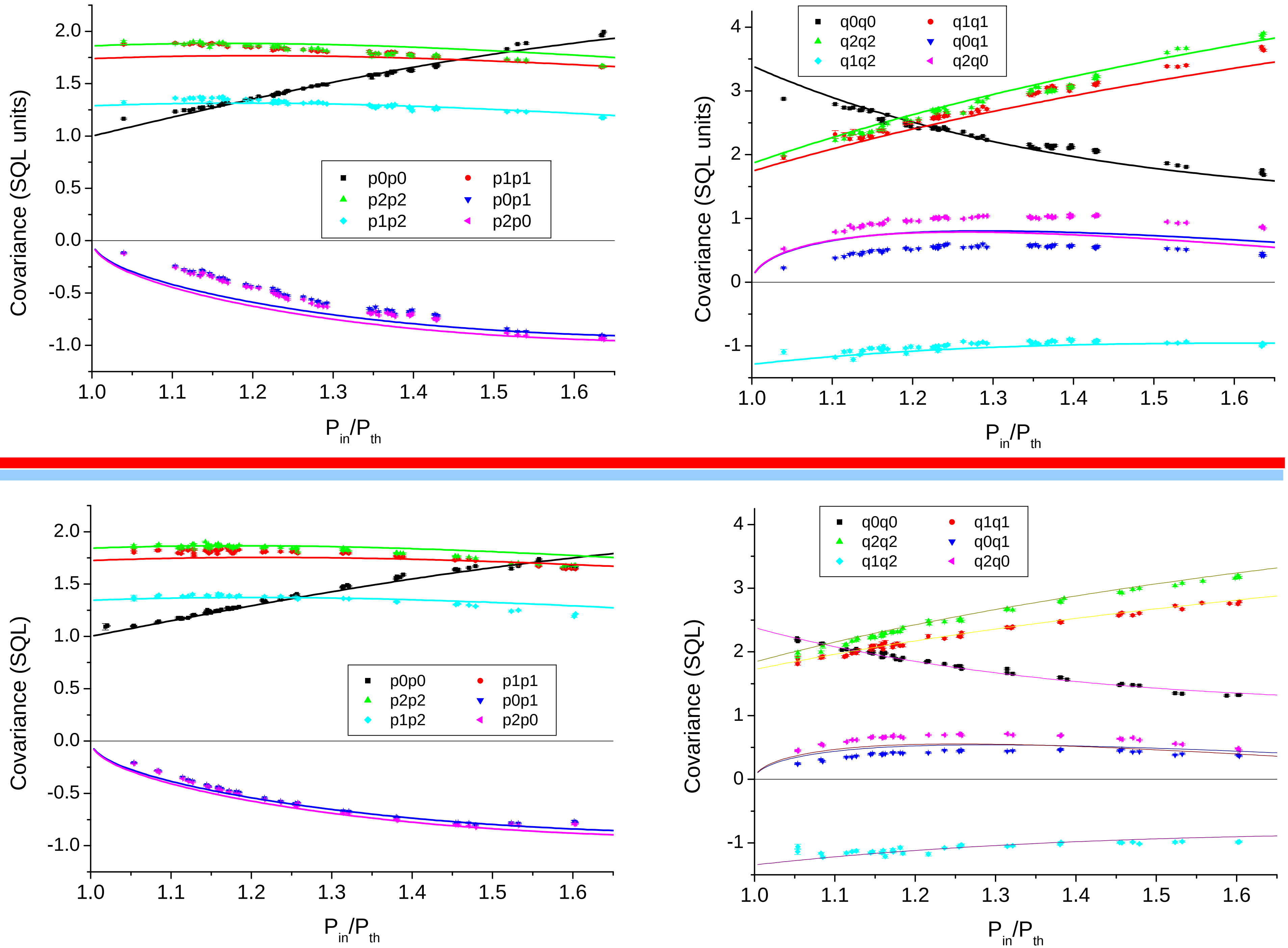
$$\tau\frac{\partial}{\partial t}\vec{X} = \boldsymbol{M}_A\vec{X} + \boldsymbol{M}_\gamma\vec{X}_1^{in} + \boldsymbol{M}_\mu\vec{X}_2^{in} + \vec{Q}$$

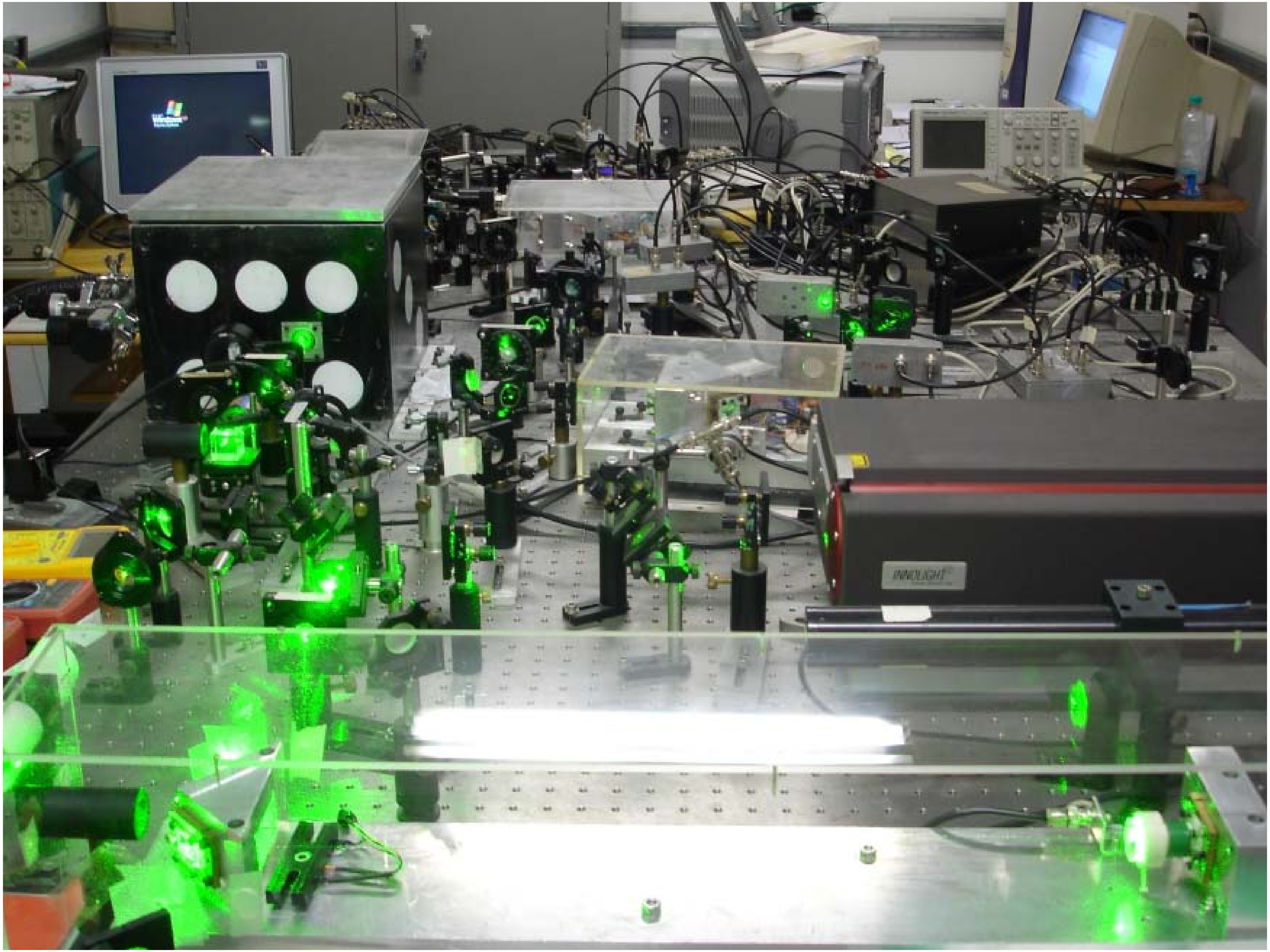
$$\vec{X}^{out}(\Omega) = \boldsymbol{M}_\gamma\vec{X}(\Omega) - \vec{X}_1^{in}$$

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

Way to go




Covariance (SQL units)
Covariance (SQL)
P_{in}/P_{th}
p0p0 p1p1 p2p2 p0p1 p1p2 p2p0
q0q0 q1q1 q2q2 q0q1 q1q2 q2q0
2.0 1.5 1.0 0.5 0.0 -0.5 -1.0
4 3 2 1 0 -1
1.0 1.1 1.2 1.3 1.4 1.5 1.6

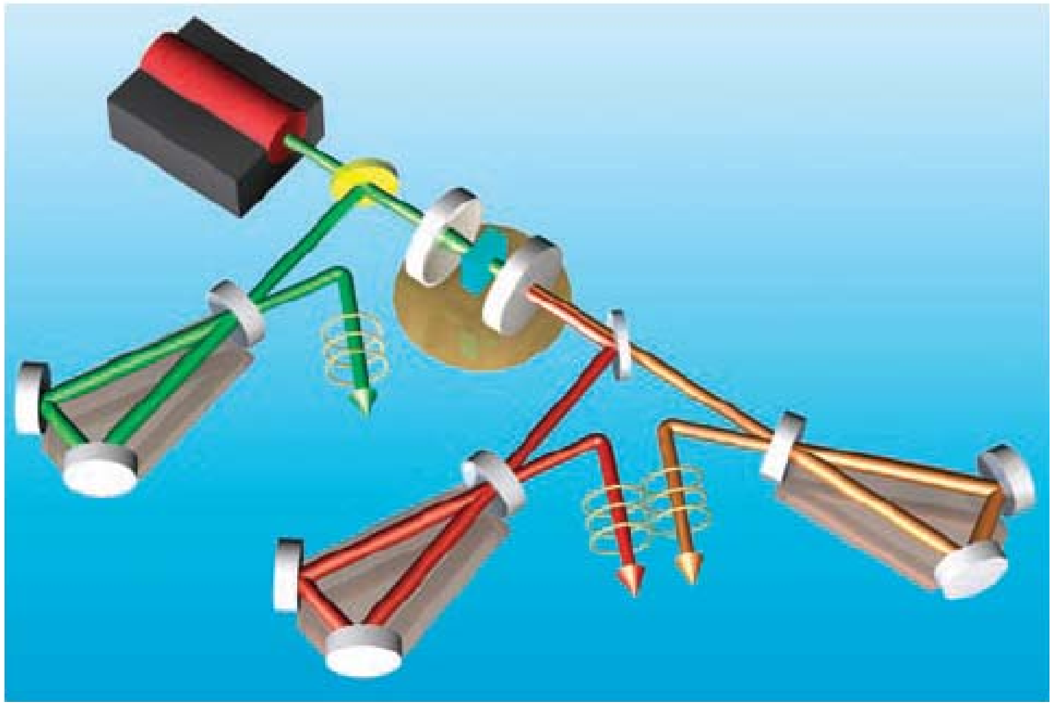

INNOLIGHT

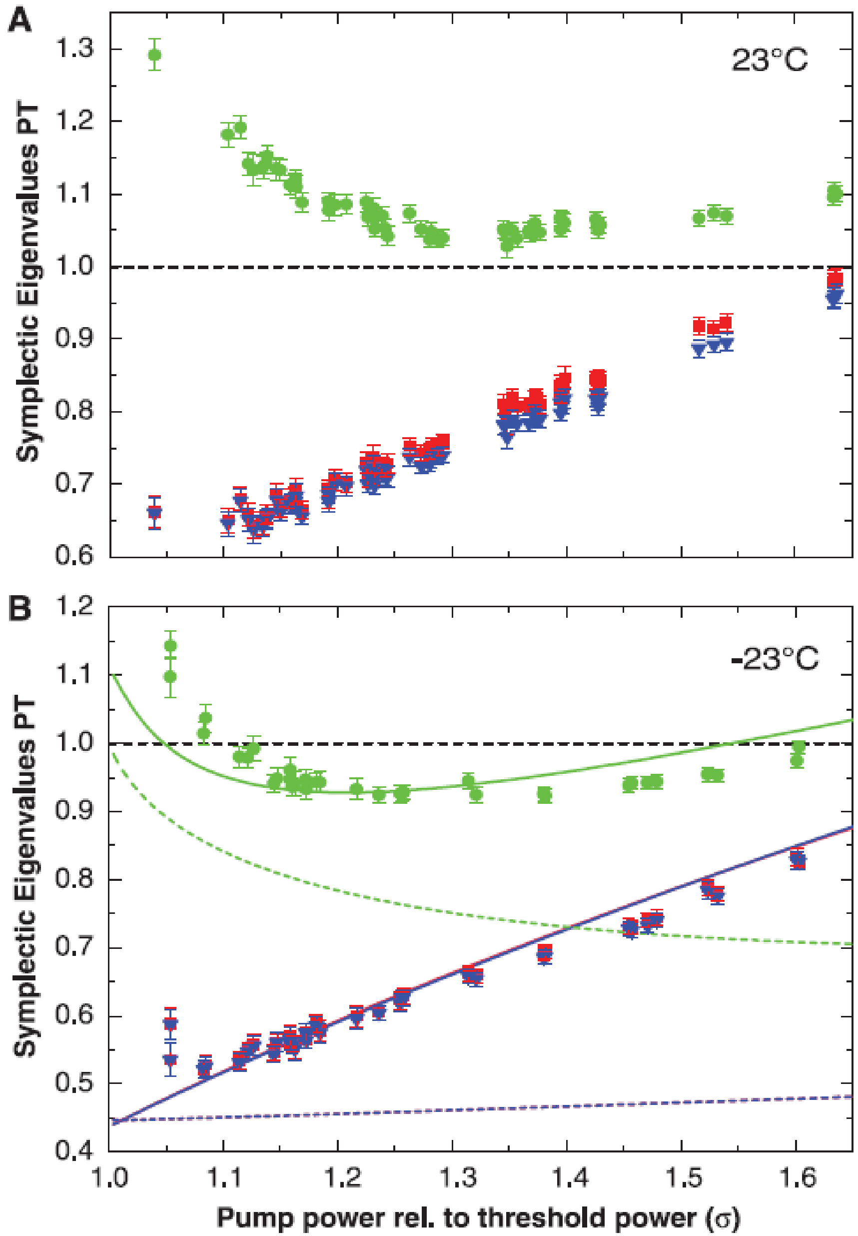
Three-Color Entanglement
A. S. Coelho, *et al.*
Science **326**, 823 (2009);

Three-Color Entanglement

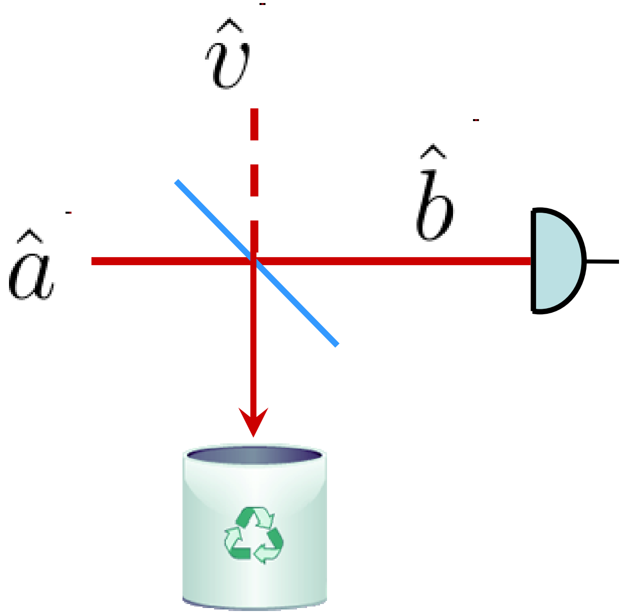
A. S. Coelho,[1] F. A. S. Barbosa,[1] K. N. Cassemiro,[2] A. S. Villar,[2,3] M. Martinel

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).

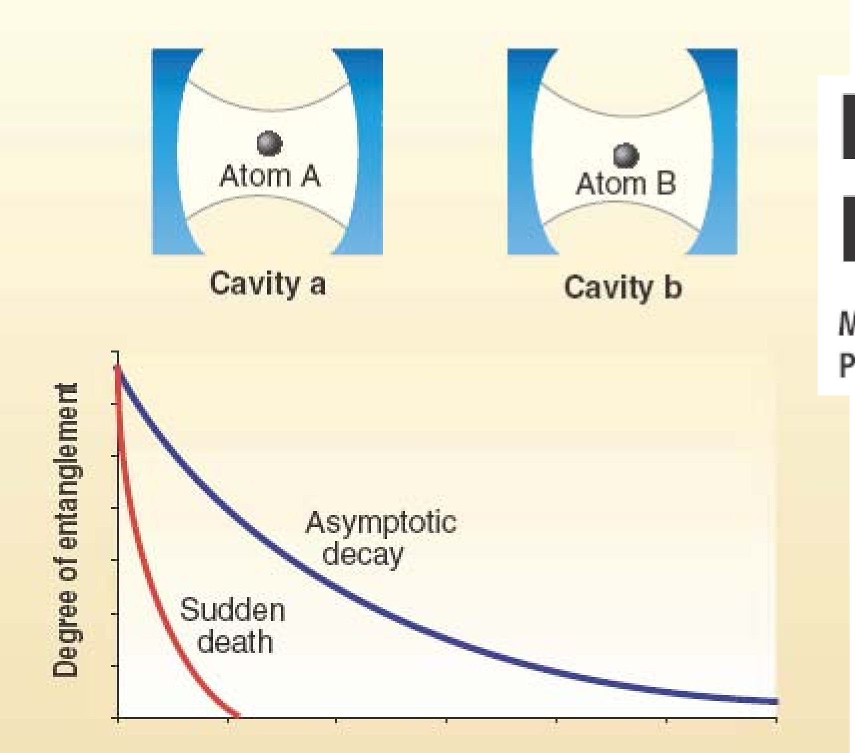
Also an entangled state

REVIEW

30 JANUARY 2009 VOL 323 SCIENCE

Sudden Death of Entanglement

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

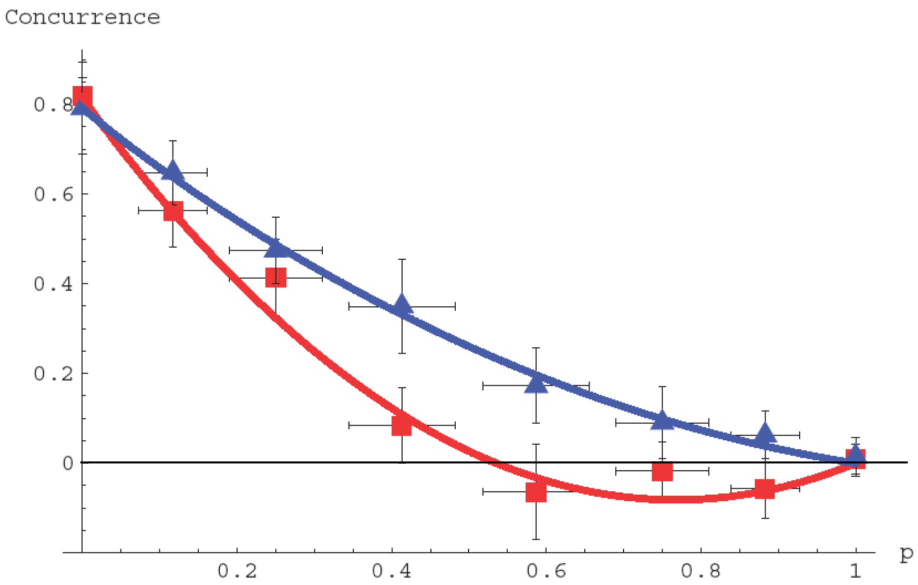


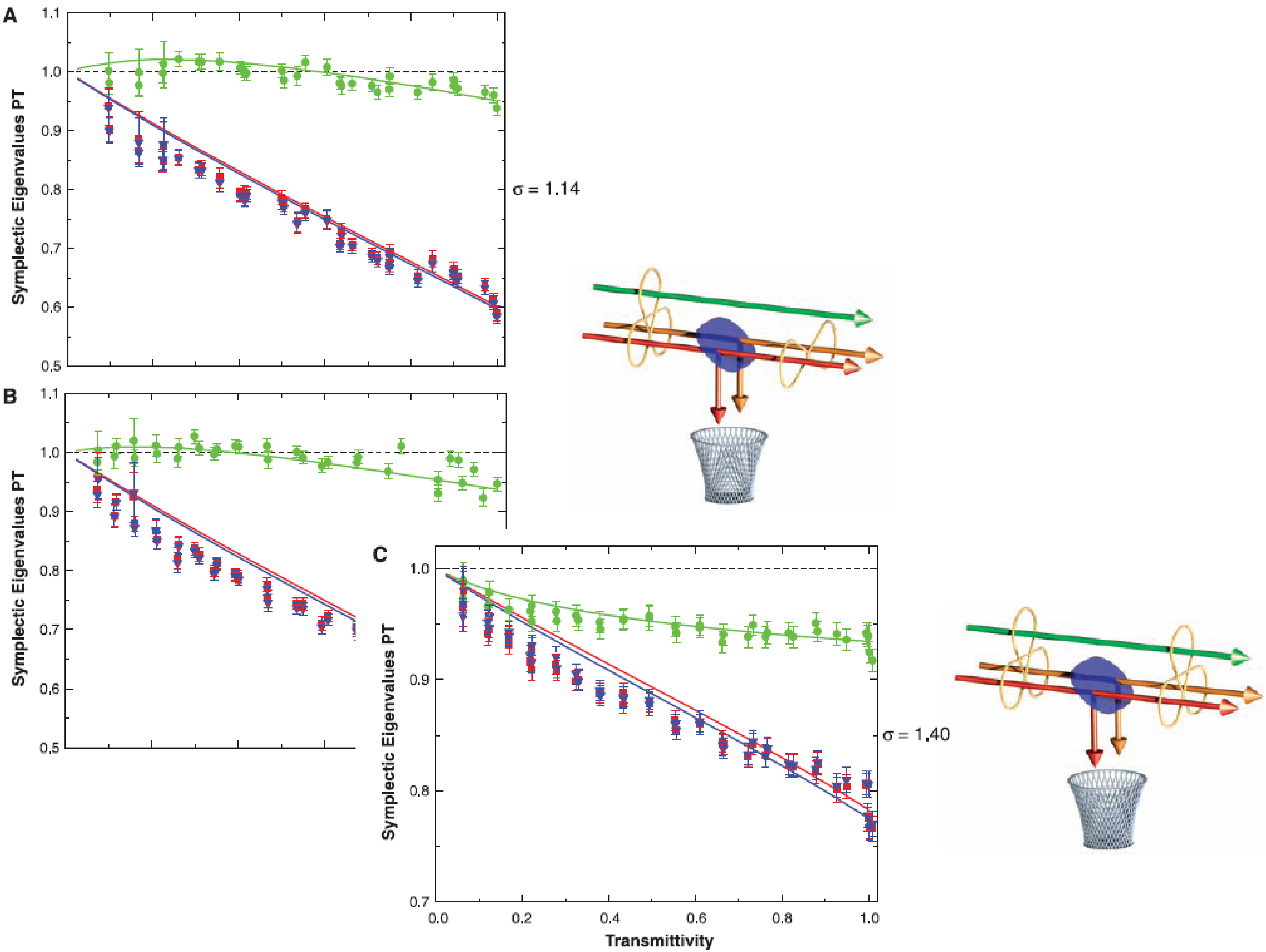
REPORTS

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*

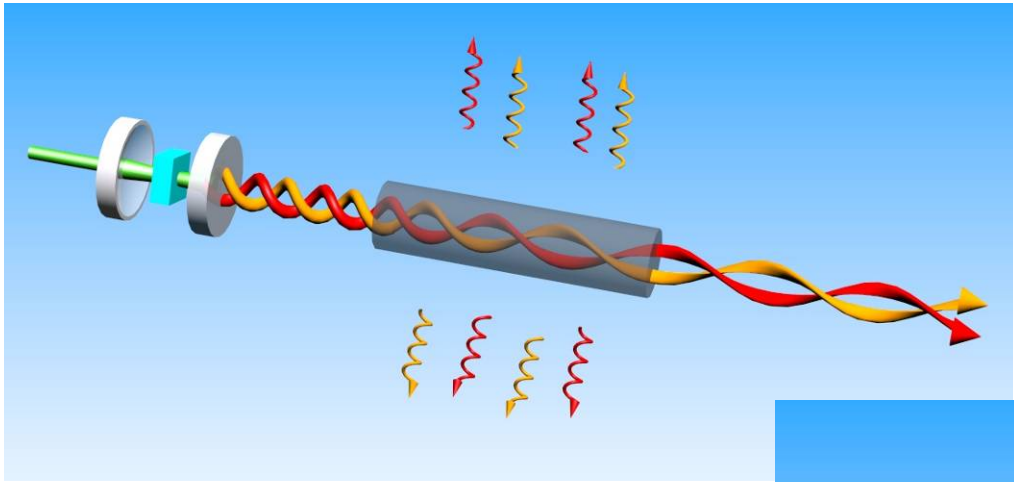
SCIENCE VOL 316 27 APRIL 2007





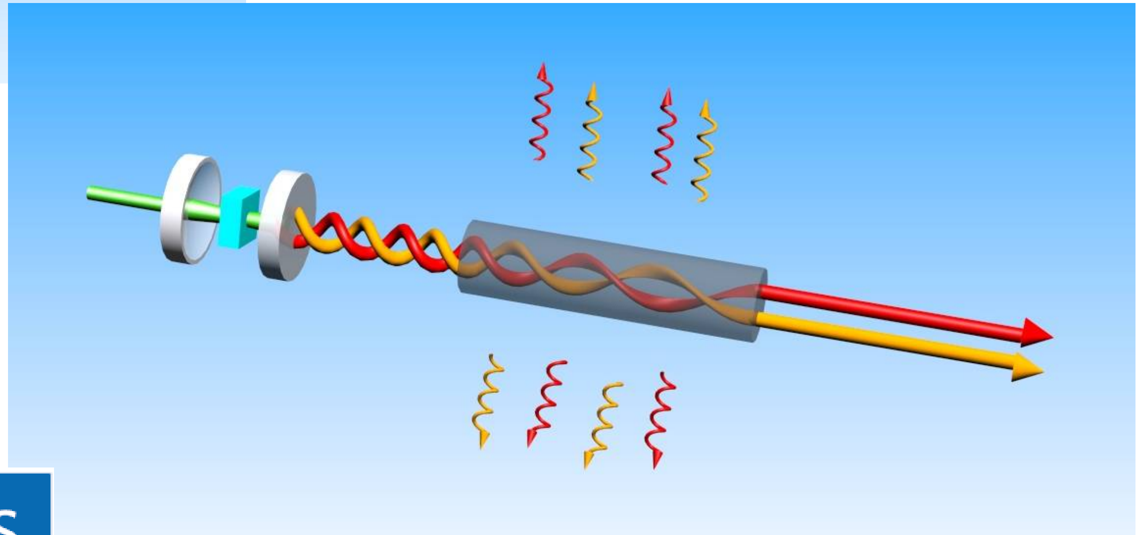
A
B
C
Symplectic Eigenvalues PT
Transmittivity
σ = 1.14
σ = 1.40
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.0
0.2
0.4
0.6
0.8
1.0

Disentanglement for a Bipartite & Gaussian state



Scenario (1):
robust entanglement

Scenario (2):
disentanglement



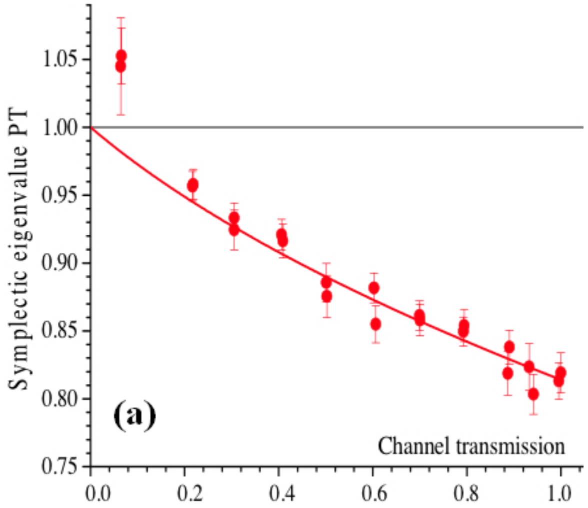
nature photonics LETTERS | DOI: 10.1038/NPHOTON.2010.222

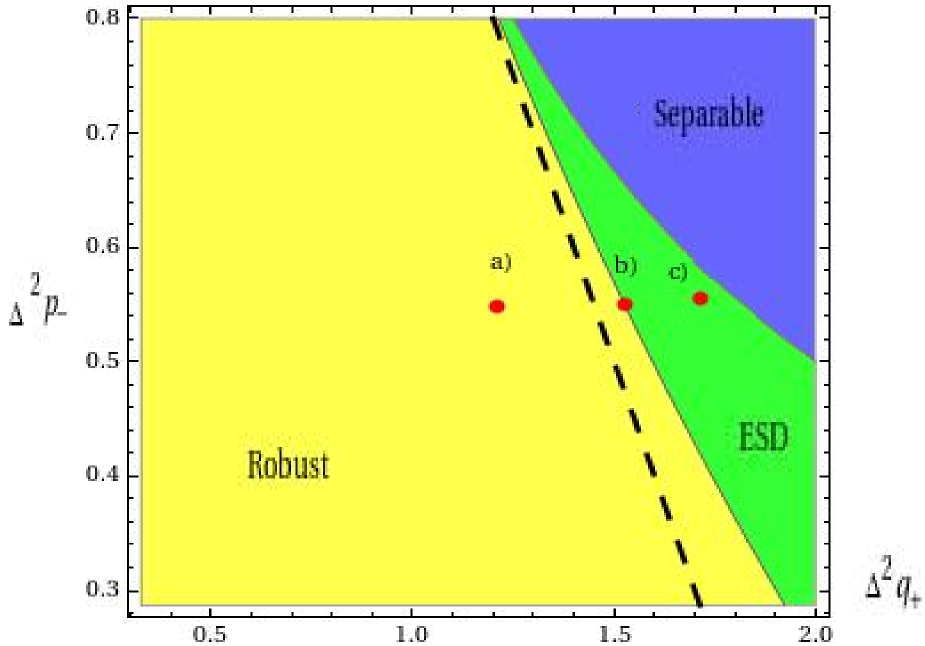
Robustness of bipartite Gaussian entangled beams propagating in lossy channels

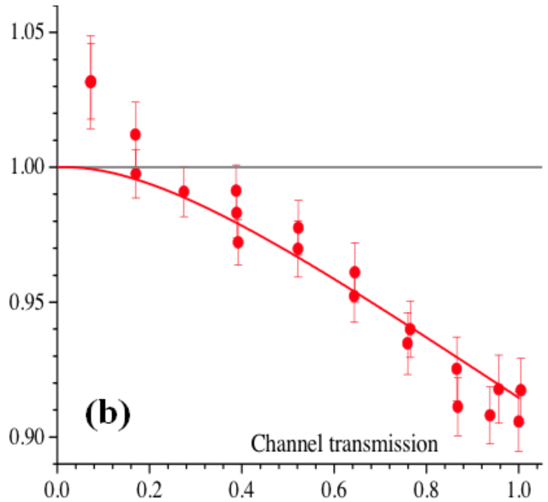
F. A. S. Barbosa[1], A. S. Coelho[1], A. J. de Faria[1], K. N. Cassemiro[2], A. S. Villar[2,3], P. Nussenzveig[1] and M. Martinelli[1]*

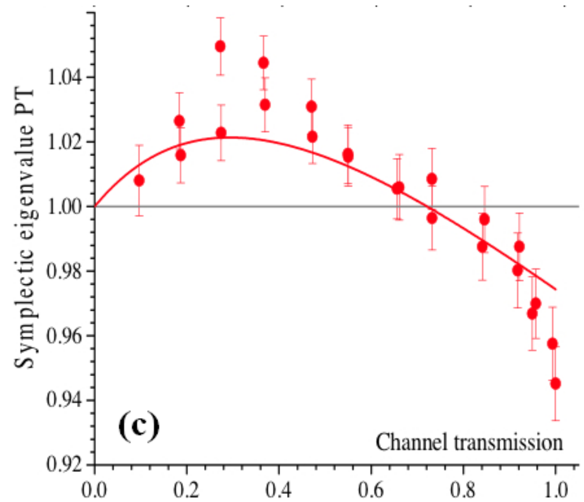

MORT SUBITE
GUEUZE
MORT SUBITE
KRIEK

Disentanglement for a simpler model: Attenuation on a single beam









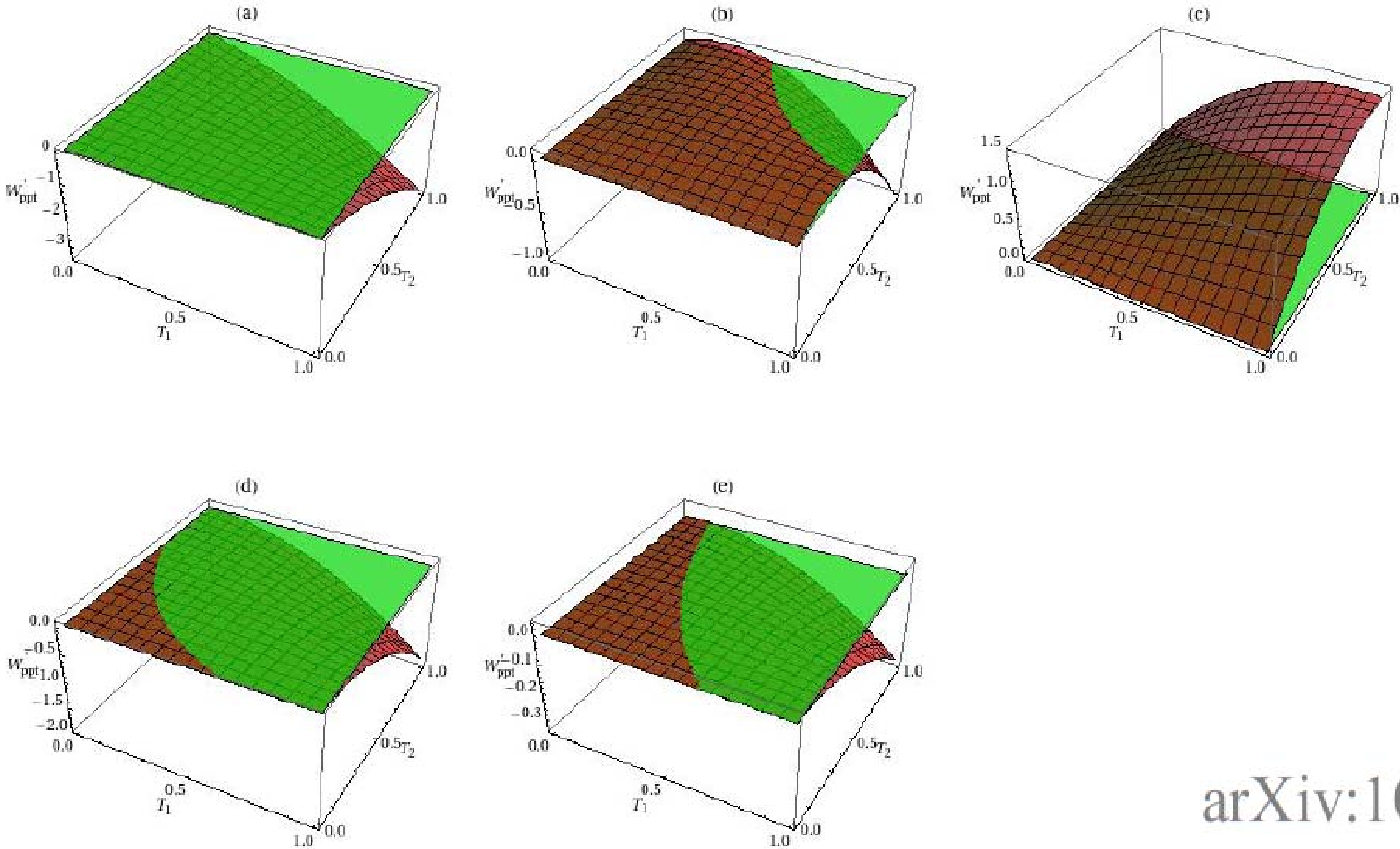
Tighter conditions for transmission of quantum entanglement!

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]

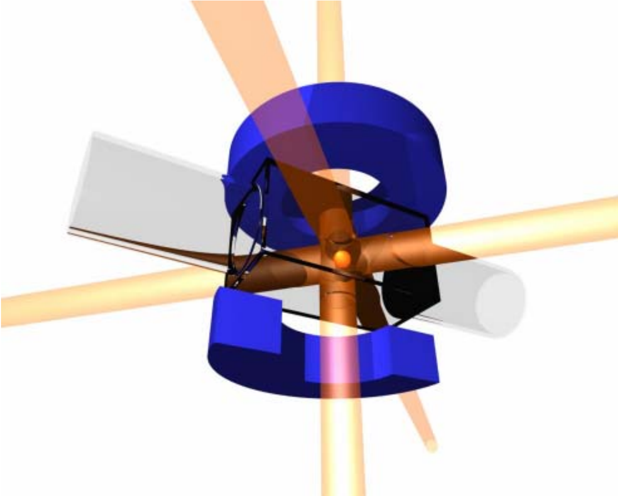
Duan (optimized)

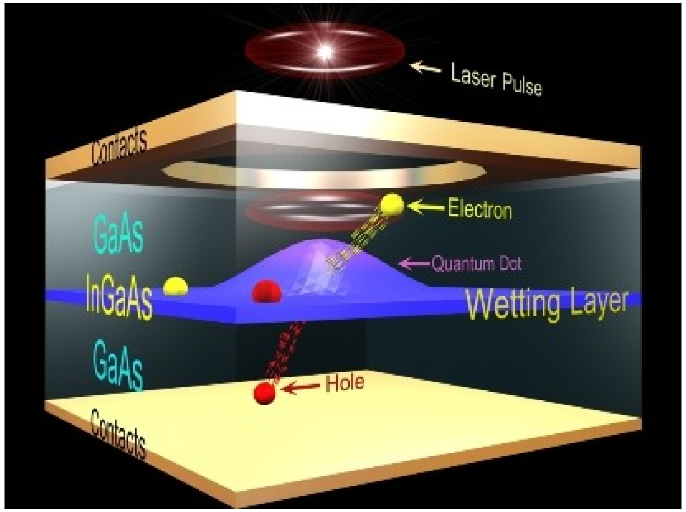
$$(\Delta^2 p_1 + \Delta^2 q_1 - 2)(\Delta^2 p_2 + \Delta^2 q_2 - 2) - (|c_p| + |c_q|)^2 \geq 0;$$

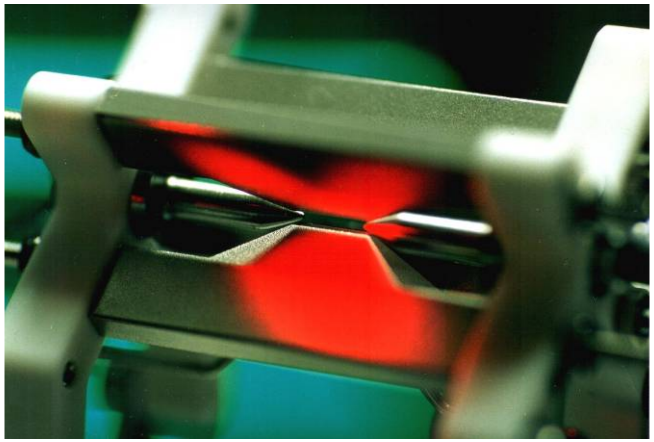


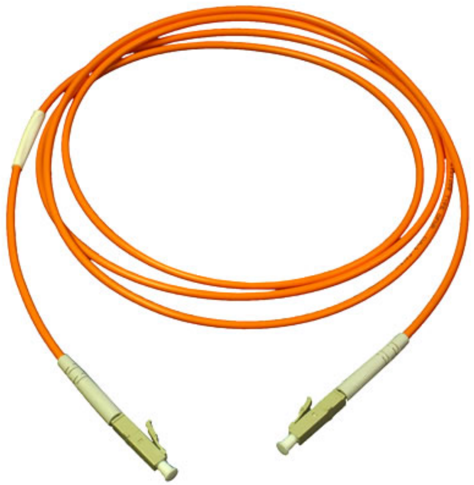
arXiv:1009.4255v1

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









Raiders of the Lost Entanglement

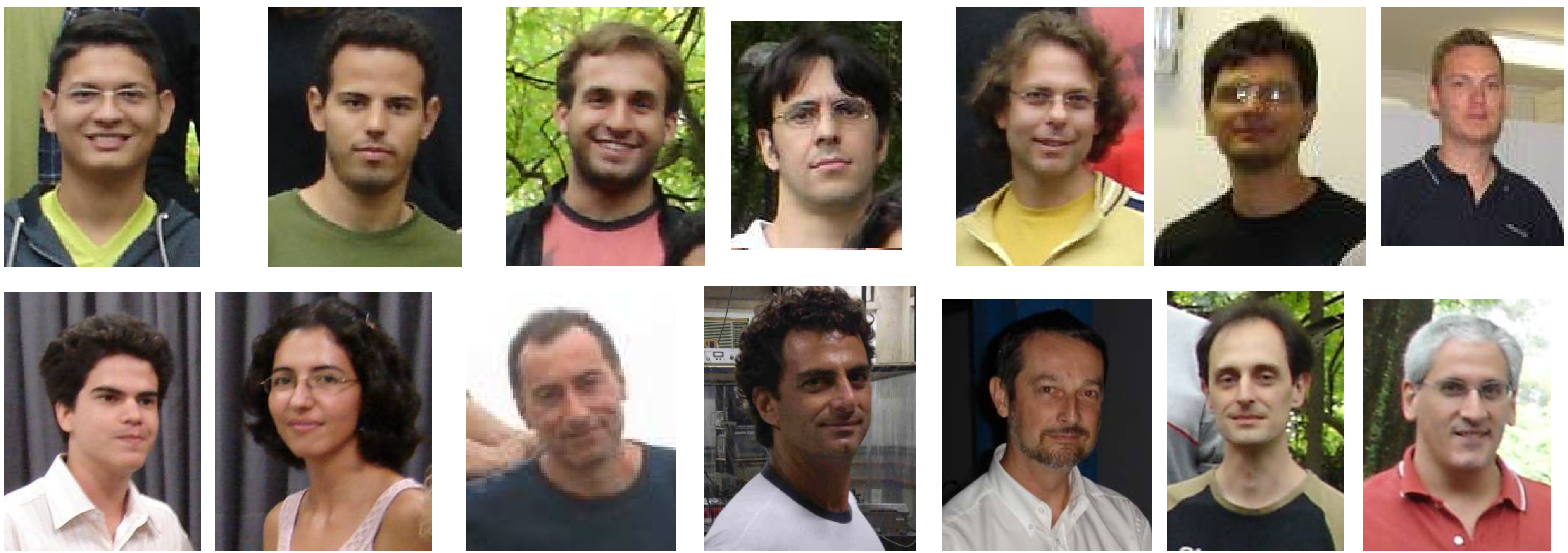
Felippe Barbosa Antônio Sales Jonatas César

Alencar Faria Luciano Cruz Paulo Valente

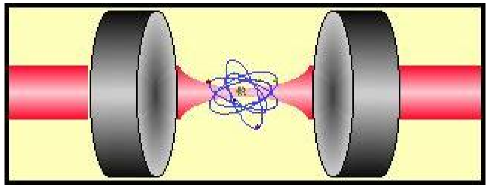
Mikael Lassen (MPI) Alessandro Villar

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)

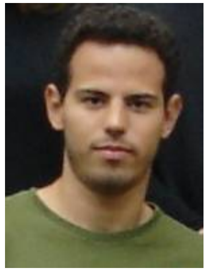
Antônio Sales (PhD – MSc 2008)

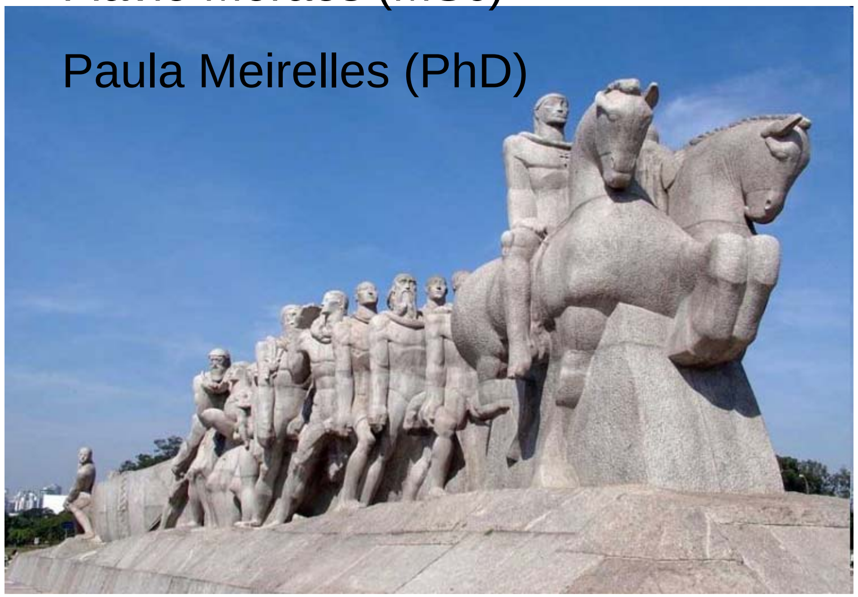
Felippe Barbosa (PhD – MSc 2008)

Hans Marin Torres (MSc)

Flávio Moraes (MSc)

Paula Meirelles (PhD)





Muchas Gracias

FAPESP CNPq
Conselho Nacional de Desenvolvimento Científico e Tecnológico
CAPES

Los invito a visitarnos!

Y quién sabe quedarse un poco por allá!