QUANTUM THERMODYNAMICS AND PHASE CONJUGATION WITH STRUCTURED LIGHT BEAMS

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Florianópolis

BRICS CN-RU-BR joint seminar,
May, 2020

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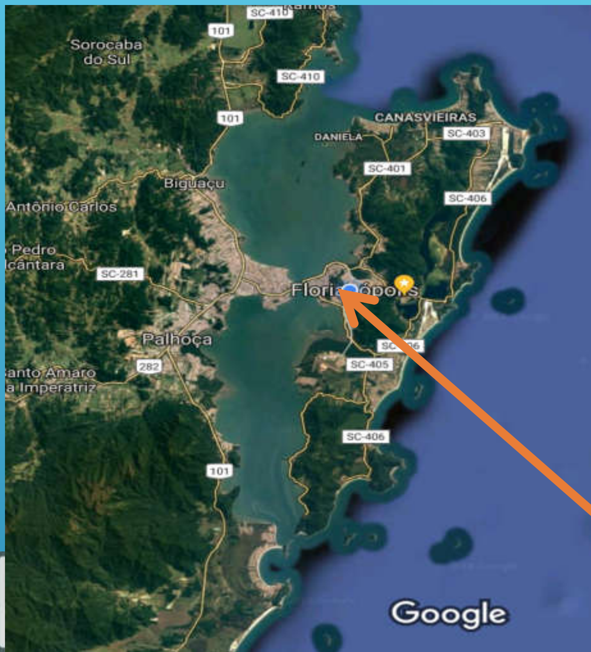

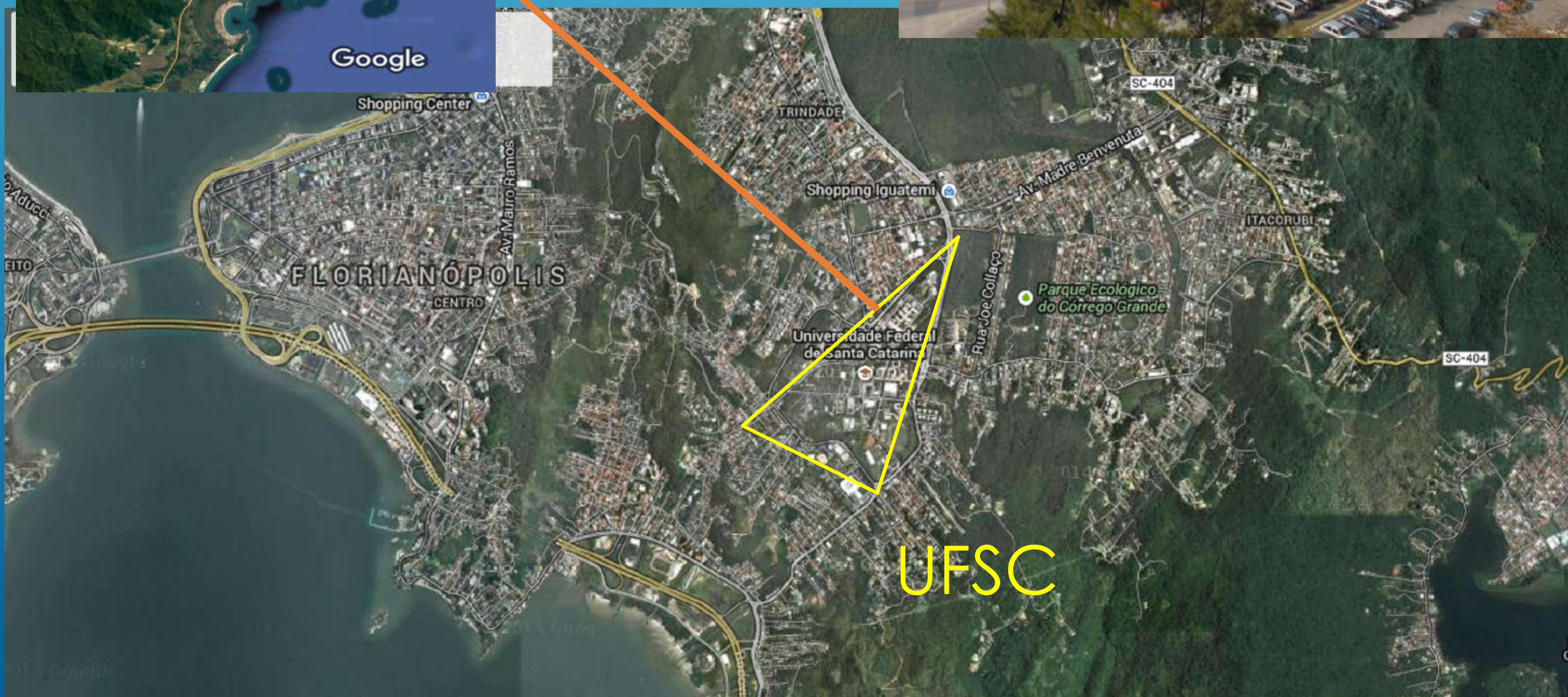

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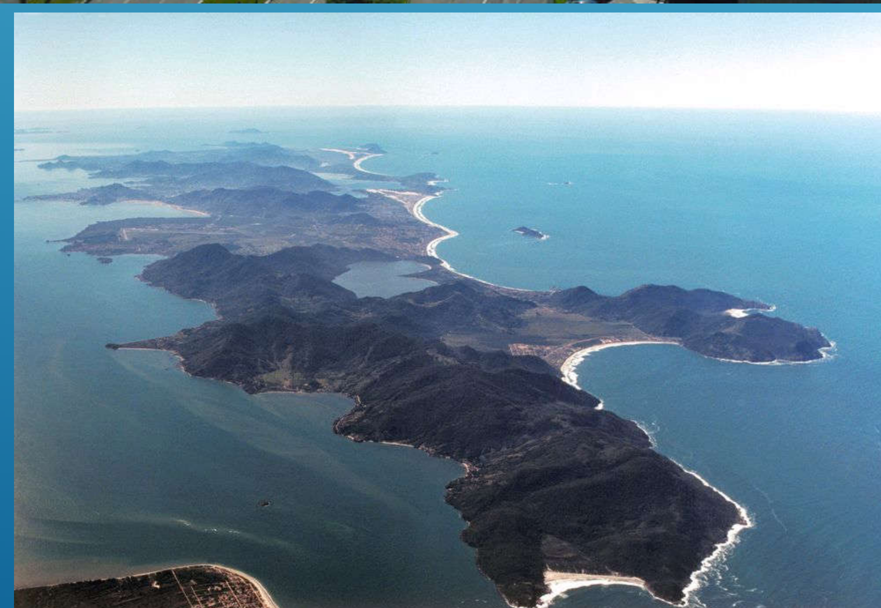

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Instituto Nacional de Ciência e Tecnologia de Informação Quântica

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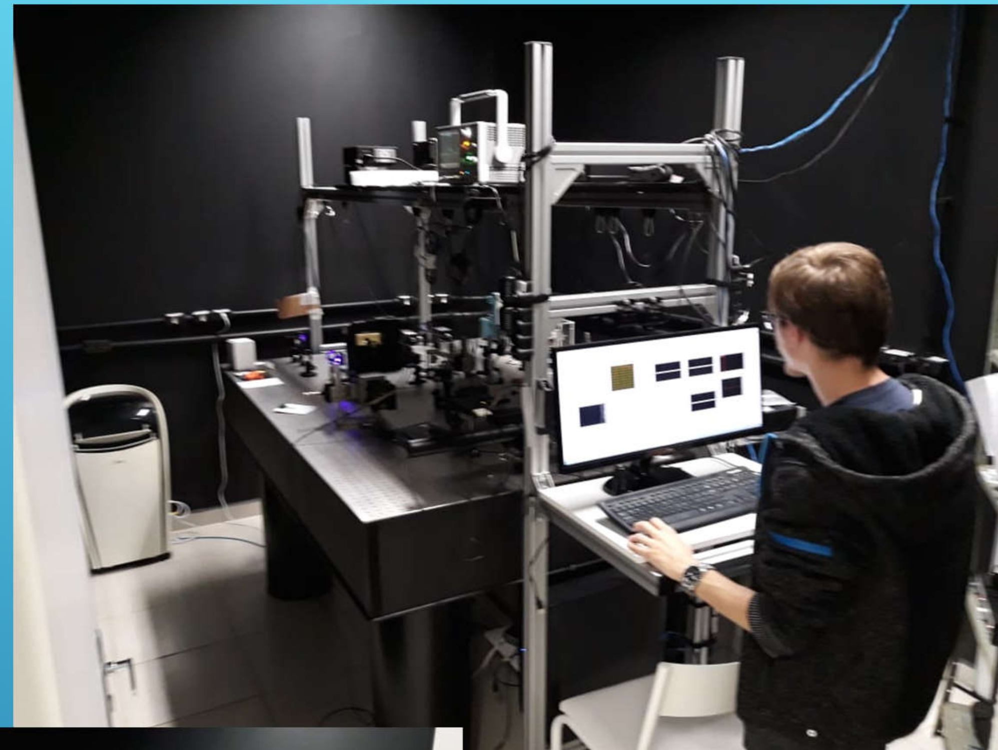
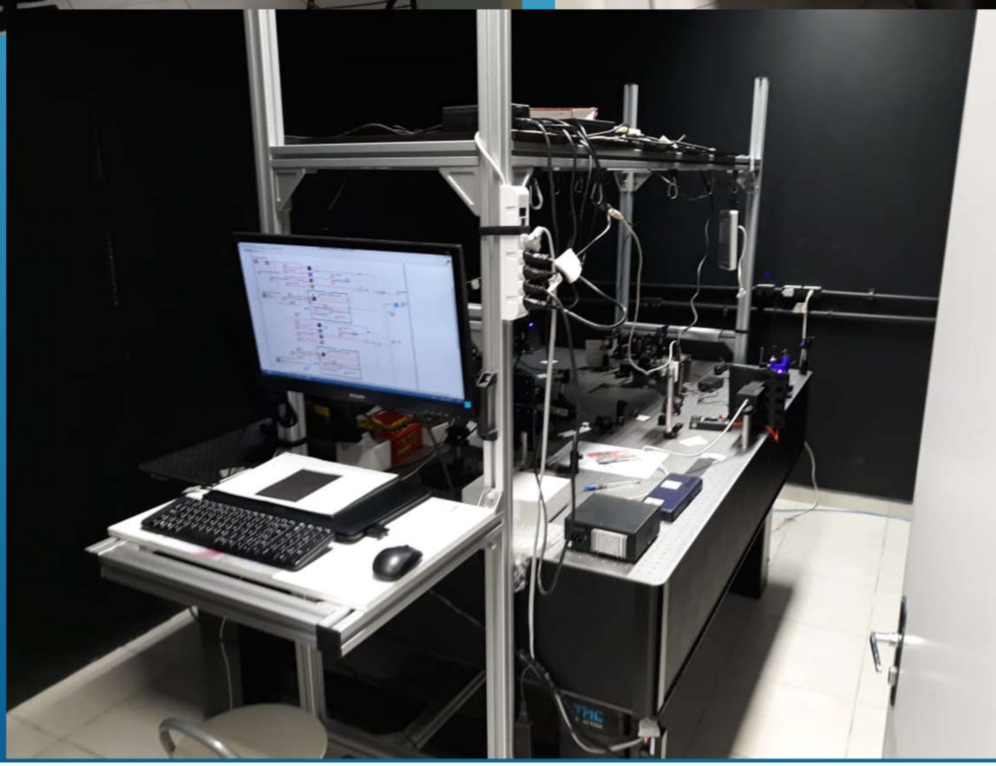
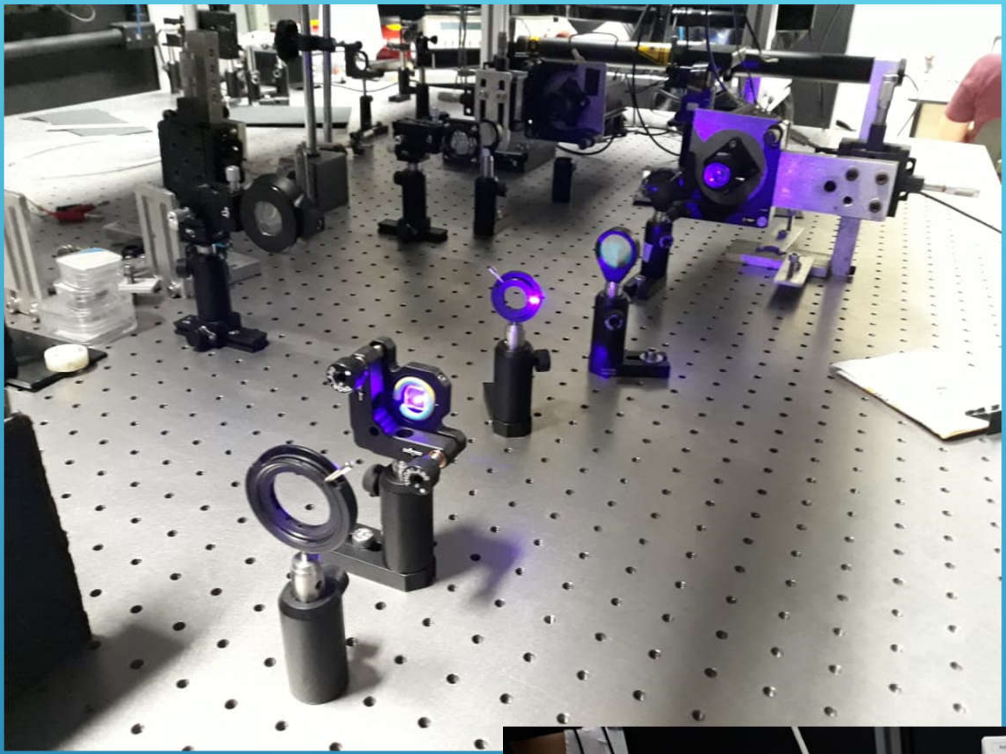
Laurent Vernac - Paris13
Philip Walther - U. Viena
Steve Walborn - UFRJ
Daniel Tasca - UFF
Mohammad Hashemi – Miami
Antonio Khoury - UFF
Miles Paddgett - U. Glasgow
Martin Lavery - U. Glasgow
Rafael Gomes – UFG
Andrew Forbes – U. Witwat.

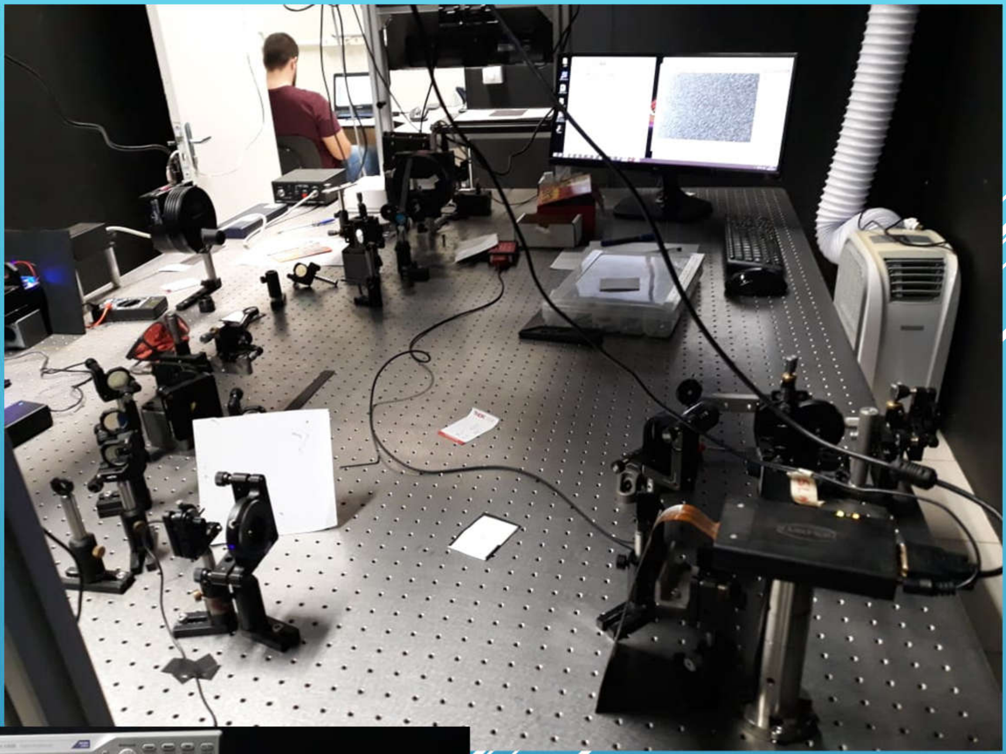
GIQSUL Quantum Optics Laboratory

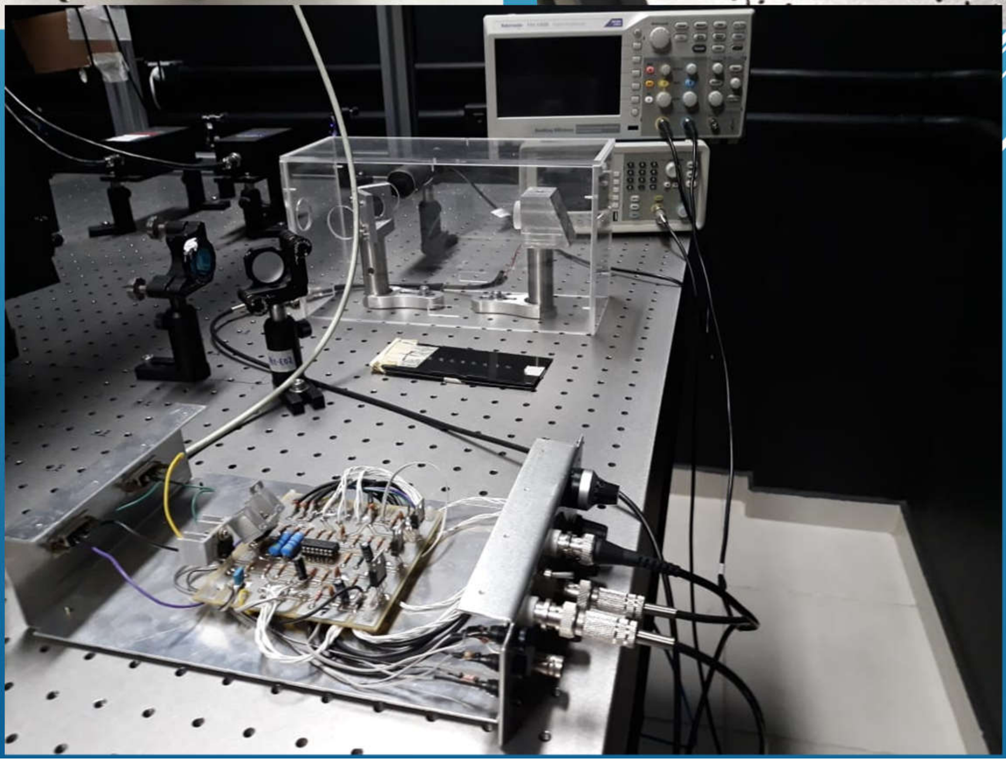




GIQSUL Quantum Optics Laboratory

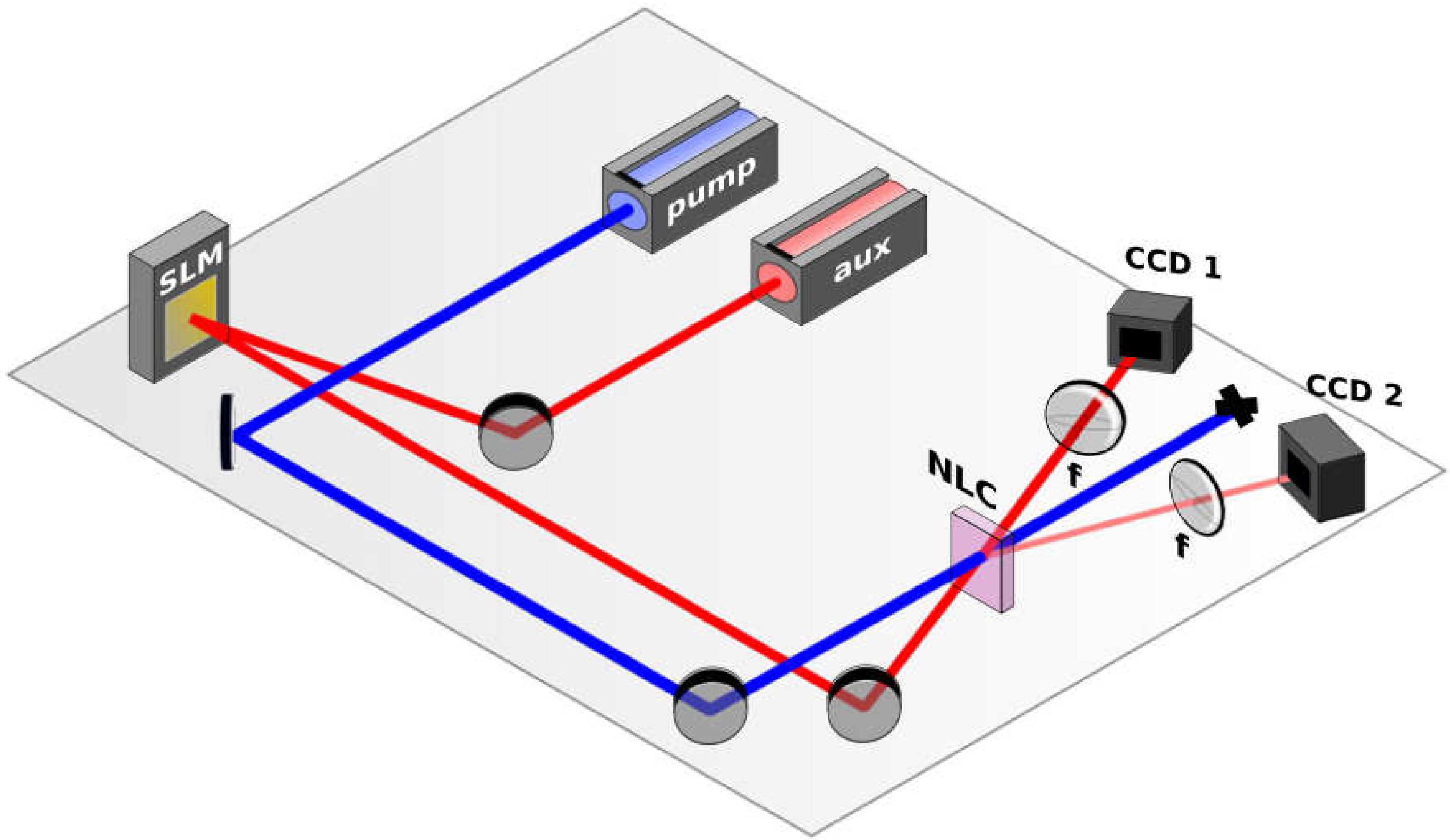






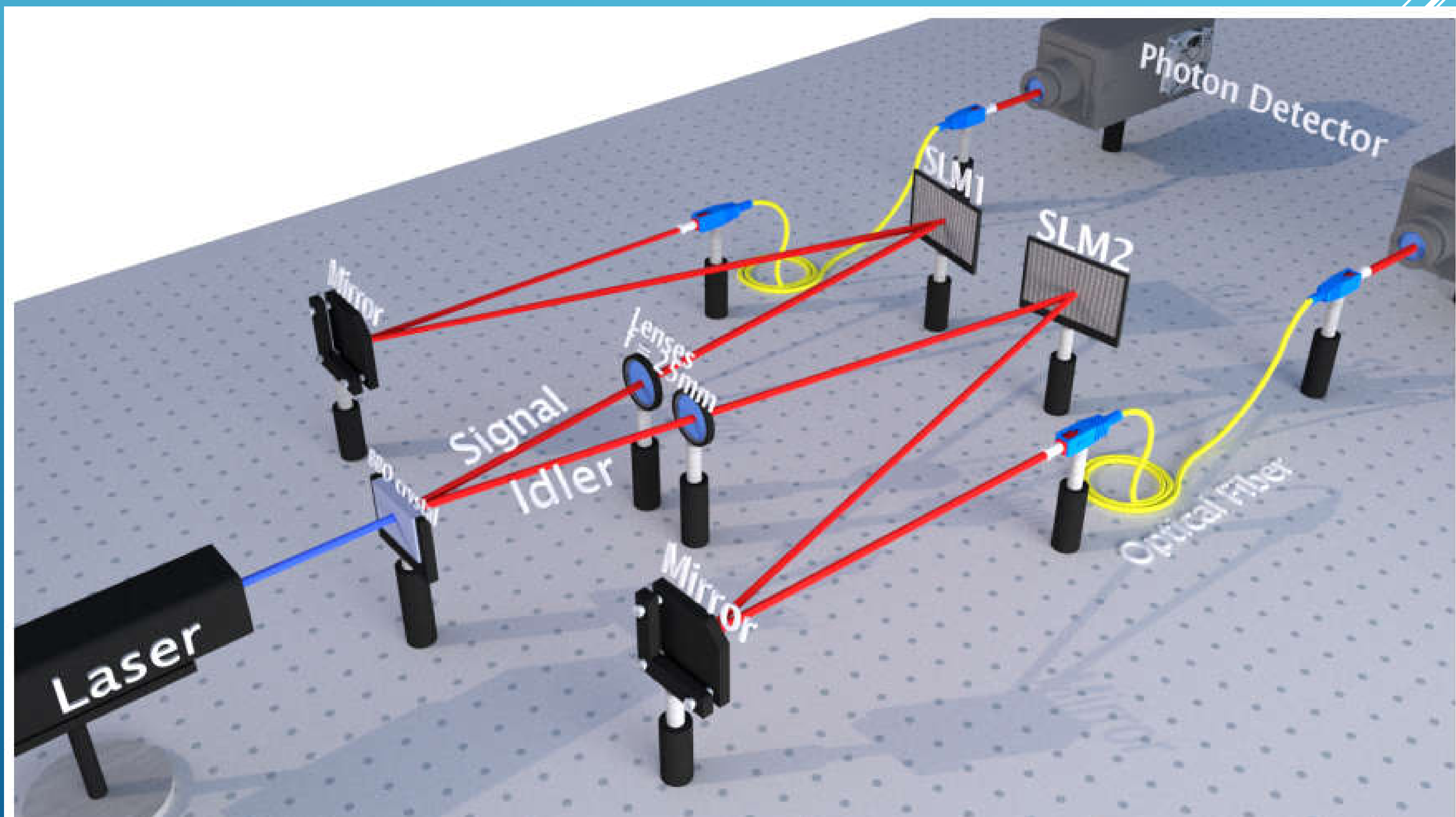
StimPDC – Vector Vortex Beams

Marcelo, André, Willamys, Nara, Renné, Rafael



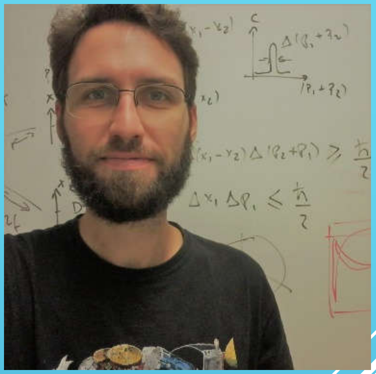
SPDC - Quantum Thermo

Thomas, Guilherme, Nara, Renné, Rafael, Vitor

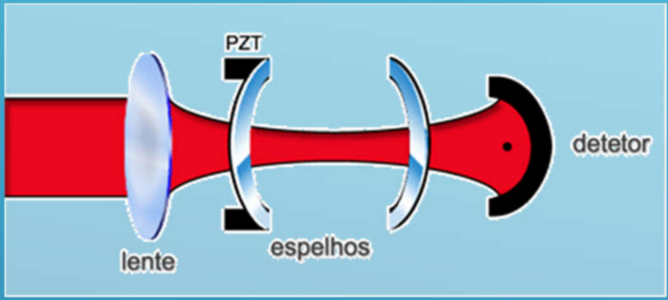


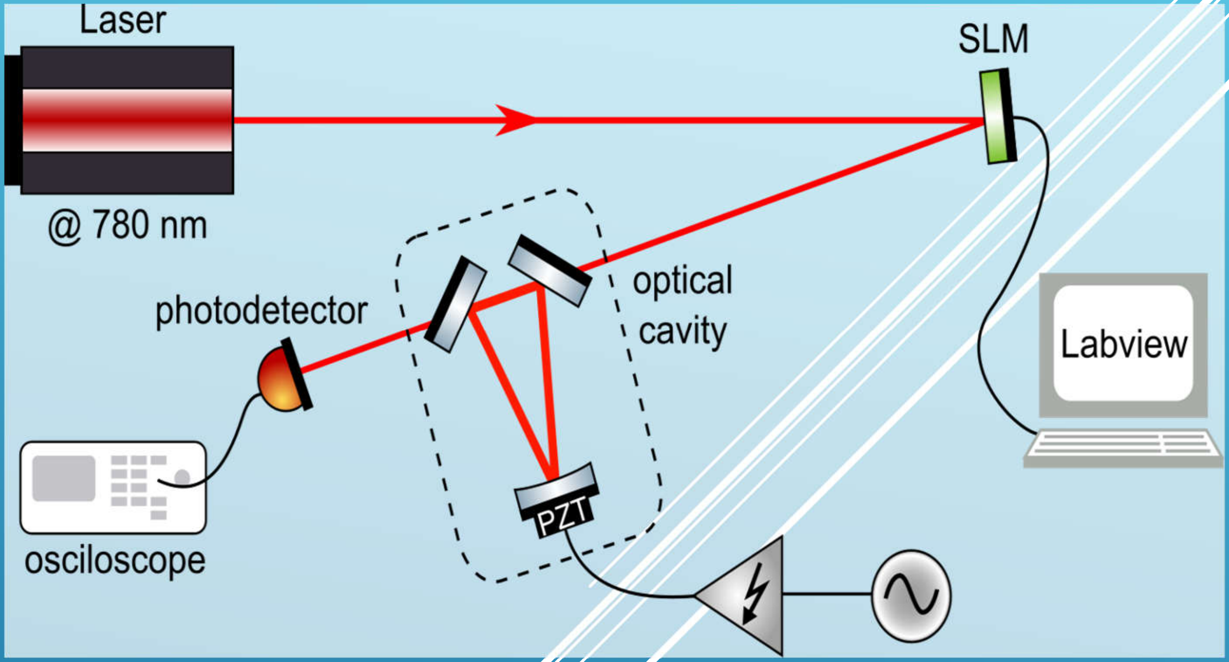
Optical cavity

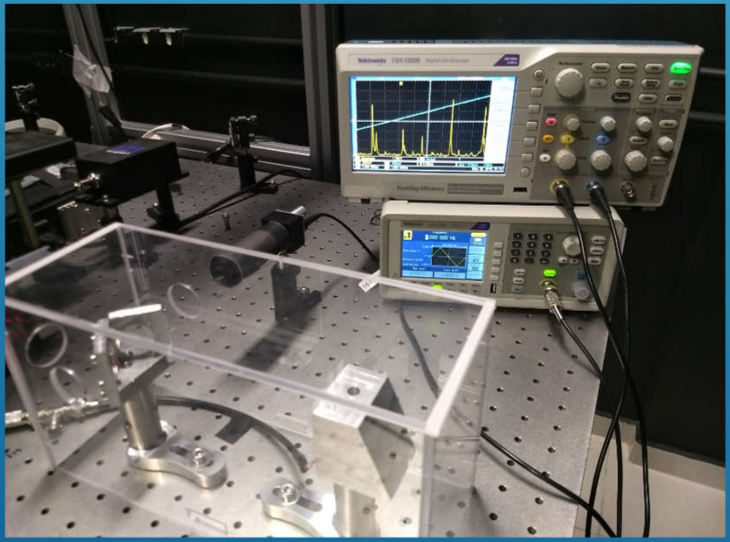
Renné

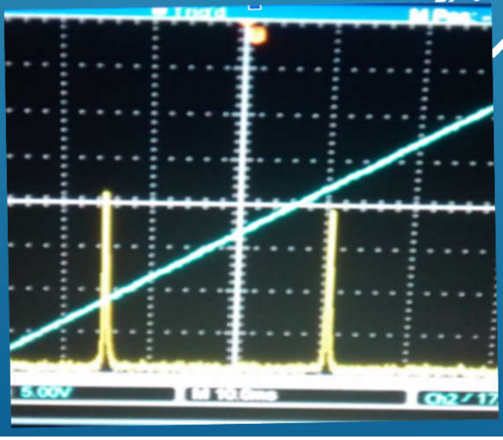


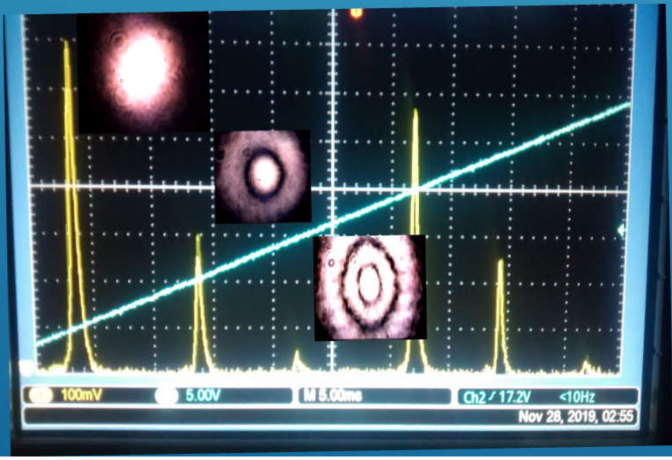
Gustavo, Giovanni, Cássia, Bernard, Daniel, Maria











Quantum Thermodynamics

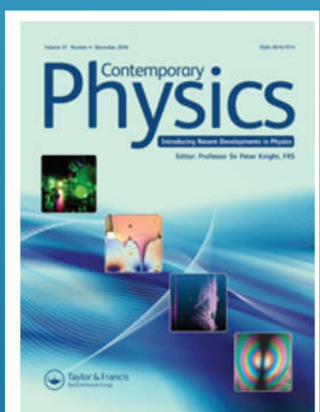
Introduction to Quantum Thermodynamics: History and Prospects

Robert Alicki

Ronnie Kosloff

Quantum Thermodynamics is a continuous dialogue between two independent theories: Thermodynamics and Quantum Mechanics. Whenever the two theories have addressed the same phenomena new insight has emerged.

arXiv:1801.08314v2 [quant-ph] 31 May 2018



Sai Vinjanampathy & Janet Anders

, DOI: 10.1080/00107514.2016.1201896

Quantum thermodynamics is an emerging research field aiming to extend standard thermodynamics and non-equilibrium statistical physics to ensembles of sizes well below the thermodynamic limit, in non-equilibrium situations, and with the full inclusion of quantum effects. Fueled by experimental advances and the potential of future nanoscale applications this research effort is pursued by scientists with different backgrounds, including statistical physics, many-body theory, mesoscopic physics and quantum information theory, who bring various tools and methods to the field. A multitude of theoretical questions are being addressed ranging from issues of thermalisation of quantum systems and various definitions of "work", to the efficiency and power of quantum engines. This overview provides a perspective on a

Highlights from Brazilian Physical Society

PHYSICAL REVIEW LETTERS **122,** 240602 (2019)

Efficiency of a Quantum Otto Heat Engine Operating under a Reservoir at Effective Negative Temperatures

Rogério J. de Assis,[1] Taysa M. de Mendonça,[2] Celso J. Villas-Boas,[2] Alexandre M. de Souza,[3] Roberto S. Sarthour,[3] Ivan S. Oliveira,[3] and Norton G. de Almeida[1]
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[2]*Departamento de Física, Universidade Federal de São Carlos, 13565-905, São Carlos, São Paulo, Brazil*
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(Received 13 December 2018; revised manuscript received 2 March 2019; published 19 June 2019)

We perform an experiment in which a quantum heat engine works under two reservoirs, one at a positive spin temperature and the other at an effective negative spin temperature, i.e., when the spin system presents population inversion. We show that the efficiency of this engine can be greater than that when both reservoirs are at positive temperatures. We also demonstrate the counterintuitive result that the Otto efficiency can be beaten only when the quantum engine is operating in the finite-time mode.

DOI: 10.1103/PhysRevLett.122.240602

Highlights from Brazilian Physical Society

nature COMMUNICATIONS

ARTICLE

https://doi.org/10.1038/s41467-019-10333-7 OPEN

Reversing the direction of heat flow using quantum correlations

Kaonan Micadei[1,2,8], John P.S. Peterson[3,8], Alexandre M. Souza[3], Roberto S. Sarthour[3], Ivan S. Oliveira[3], Gabriel T. Landi[4], Tiago B. Batalhão[5,6], Roberto M. Serra[1,7] & Eric Lutz[2]

Heat spontaneously flows from hot to cold in standard thermodynamics. However, the latter theory presupposes the absence of initial correlations between interacting systems. We here experimentally demonstrate the reversal of heat flow for two quantum correlated spins-1/2, initially prepared in local thermal states at different effective temperatures, employing a Nuclear Magnetic Resonance setup. We observe a spontaneous energy flow from the cold to the hot system. This process is enabled by a trade off between correlations and entropy that we quantify with information-theoretical quantities. These results highlight the subtle interplay of quantum mechanics, thermodynamics and information theory. They further provide a mechanism to control heat on the microscale.

Highlights from Brazilian Physical Society

npj | Quantum Information

www.nature.com/npjqi

ARTICLE OPEN

The role of quantum coherence in non-equilibrium entropy production

Jader P. Santos[1], Lucas C. Céleri[2], Gabriel T. Landi[1] and Mauro Paternostro[3]

Thermodynamic irreversibility is well characterized by the entropy production arising from non-equilibrium quantum processes. We show that the entropy production of a quantum system undergoing open-system dynamics can be formally split into a term that only depends on population unbalances, and one that is underpinned by quantum coherences. This allows us to identify a genuine quantum contribution to the entropy production in non-equilibrium quantum processes. We discuss how these features emerge both in Lindblad-Davies differential maps and finite maps subject to the constraints of thermal operations. We also show how this separation naturally leads to two independent entropic conservation laws for the global system-environment dynamics, one referring to the redistribution of populations between system and environment and the other describing how the coherence initially present in the system is distributed into local coherences in the environment and non-local coherences in the system-environment state. Finally, we discuss how the processing of quantum coherences and the incompatibility of non-commuting measurements leads to fundamental limitations in the description of quantum trajectories and fluctuation theorems.

npj Quantum Information (2019)5:23 ; https://doi.org/10.1038/s41534-019-0138-y

Highlights from Brazilian Physical Society

PHYSICAL REVIEW LETTERS **121,** 160604 (2018)

Editors' Suggestion   Featured in Physics

Experimental Determination of Irreversible Entropy Production in out-of-Equilibrium Mesoscopic Quantum Systems

M. Brunelli,[1] L. Fusco,[2] R. Landig,[3,*] W. Wieczorek,[4] J. Hoelscher-Obermaier,[5,6] G. Landi,[7] F. L. Semião,[8] A. Ferraro,[2] N. Kiesel,[5] T. Donner,[3] G. De Chiara,[2] and M. Paternostro[2]

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[3]*Institute for Quantum Electronics, ETH Zürich, 8093 Zürich, Switzerland*
[4]*Department of Microtechnology and Nanoscience, Chalmers University of Technology, 412 96 Göteborg, Sweden*
[5]*University of Vienna, Faculty of Physics, Vienna Center for Quantum Science and Technology (VCQ), Boltzmanngasse 5, 1090 Vienna, Austria*
[6]*Leibniz University Hannover, Institute for Gravitational Physics (Albert-Einstein-Institute), Callinstraße 38, 30167 Hannover, Germany*
[7]*Instituto de Física da Universidade de São Paulo, 05314-970 São Paulo, Brazil*
[8]*Centro de Ciências Naturais e Humanas, Universidade Federal do ABC, 09210-170 Santo André, São Paulo, Brazil*

(Received 3 July 2018; published 17 October 2018)

By making use of a recently proposed framework for the inference of thermodynamic irreversibility in bosonic quantum systems, we experimentally measure and characterize the entropy production rates in the nonequilibrium steady state of two different physical systems—a micromechanical resonator and a Bose-Einstein condensate—each coupled to a high finesse cavity and hence also subject to optical loss. Key features of our setups, such as the cooling of the mechanical resonator and signatures of a structural quantum phase transition in the condensate, are reflected in the entropy production rates. Our work demonstrates the possibility to explore irreversibility in driven mesoscopic quantum systems and paves the way to a systematic experimental assessment of entropy production beyond the microscopic limit.

DOI: 10.1103/PhysRevLett.121.160604

Highlights from Brazilian Physical Society

PHYSICAL REVIEW LETTERS **120,** 063604 (2018)

Steady State Entanglement beyond Thermal Limits

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[1]*Dipartimento di Fisica, Università di Pavia, via Bassi 6, I-27100 Pavia, Italy*
[2]*CNRS and Université Grenoble Alpes, Institut Néel, F-38042 Grenoble, France*
[3]*Instituto de Física, Universidade Federal do Rio de Janeiro, CP68528, Rio de Janeiro, Rio de Janeiro 21941-972, Brazil*

(Received 1 October 2017; revised manuscript received 13 December 2017; published 8 February 2018)

Classical engines turn thermal resources into work, which is maximized for reversible operations. The quantum realm has expanded the range of useful operations beyond energy conversion, and incoherent resources beyond thermal reservoirs. This is the case of entanglement generation in a driven-dissipative protocol, which we hereby analyze as a continuous quantum machine. We show that for such machines the more irreversible the process, the larger the concurrence. Maximal concurrence and entropy production are reached for the hot reservoir being at negative effective temperature, beating the limits set by classic thermal operations on an equivalent system.

DOI: 10.1103/PhysRevLett.120.063604

Highlights from Brazilian Physical Society

PRL **118,** 150601 (2017) PHYSICAL REVIEW LETTERS week ending 14 APRIL 2017

Enhancing the Charging Power of Quantum Batteries

Francesco Campaioli,[1,*] Felix A. Pollock,[1] Felix C. Binder,[2] Lucas Céleri,[3] John Goold,[4] Sai Vinjanampathy,[5,6] and Kavan Modi[1,†]

[1]*School of Physics and Astronomy, Monash University, Victoria 3800, Australia*
[2]*School of Physical & Mathematical Sciences, Nanyang Technological University, 637371 Singapore, Singapore*
[3]*Instituto de Física, Universidade Federal de Goiás, Caixa Postal 131, 74001-970, Goiânia, Brazil*
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(Received 20 December 2016; revised manuscript received 14 February 2017; published 12 April 2017)

Can collective quantum effects make a difference in a meaningful thermodynamic operation? Focusing on energy storage and batteries, we demonstrate that quantum mechanics can lead to an enhancement in the amount of work deposited per unit time, i.e., the charging power, when N batteries are charged collectively. We first derive analytic upper bounds for the collective *quantum advantage* in charging power for two choices of constraints on the charging Hamiltonian. We then demonstrate that even in the absence of quantum entanglement this advantage can be extensive. For our main result, we provide an upper bound to the achievable quantum advantage when the interaction order is restricted; i.e., at most k batteries are interacting. This constitutes a fundamental limit on the advantage offered by quantum technologies over their classical counterparts.

DOI: 10.1103/PhysRevLett.118.150601

Highlights from Brazilian Physical Society

PRL **118,** 220601 (2017) PHYSICAL REVIEW LETTERS week ending 2 JUNE 2017

Wigner Entropy Production Rate

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(Received 6 March 2017; revised manuscript received 10 April 2017; published 1 June 2017)

The characterization of irreversibility in general quantum processes is an open problem of increasing technological relevance. Yet, the tools currently available to this aim are mostly limited to the assessment of dynamics induced by equilibrium environments, a situation that often does not match the reality of experiments at the microscopic and mesoscopic scale. We propose a theory of irreversible entropy production that is suited for quantum systems exposed to general, nonequilibrium reservoirs. We illustrate our framework by addressing a set of physically relevant situations that clarify both the features and the potential of our proposal.

DOI: 10.1103/PhysRevLett.118.220601

Highlights from Brazilian Physical Society

Selected for a Viewpoint in *Physics*
PRL **117,** 240502 (2016) PHYSICAL REVIEW LETTERS week ending 9 DECEMBER 2016

Experimental Rectification of Entropy Production by Maxwell's Demon in a Quantum System

Patrice A. Camati,[1] John P. S. Peterson,[2] Tiago B. Batalhão,[1] Kaonan Micadei,[1] Alexandre M. Souza,[2] Roberto S. Sarthour,[2] Ivan S. Oliveira,[2] and Roberto M. Serra[1,3,*]

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[2]*Centro Brasileiro de Pesquisas Físicas, Rua Dr. Xavier Sigaud 150, 22290-180 Rio de Janeiro, Rio de Janeiro, Brazil*

[3]*Department of Physics, University of York, York YO10 5DD, United Kingdom*

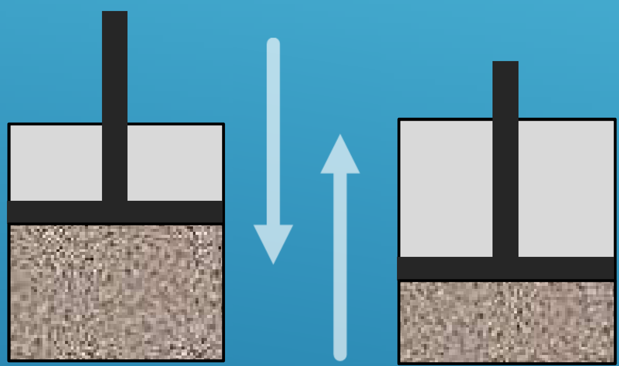
(Received 26 May 2016; published 5 December 2016)

Maxwell's demon explores the role of information in physical processes. Employing information about microscopic degrees of freedom, this "intelligent observer" is capable of compensating entropy production (or extracting work), apparently challenging the second law of thermodynamics. In a modern standpoint, it is regarded as a feedback control mechanism and the limits of thermodynamics are recast incorporating information-to-energy conversion. We derive a trade-off relation between information-theoretic quantities empowering the design of an efficient Maxwell's demon in a quantum system. The demon is experimentally implemented as a spin-1/2 quantum memory that acquires information, and employs it to control the dynamics of another spin-1/2 system, through a natural interaction. Noise and imperfections in this protocol are investigated by the assessment of its effectiveness. This realization provides experimental evidence that the irreversibility in a nonequilibrium dynamics can be mitigated by assessing microscopic information and applying a feed-forward strategy at the quantum scale.

DOI: 10.1103/PhysRevLett.117.240502

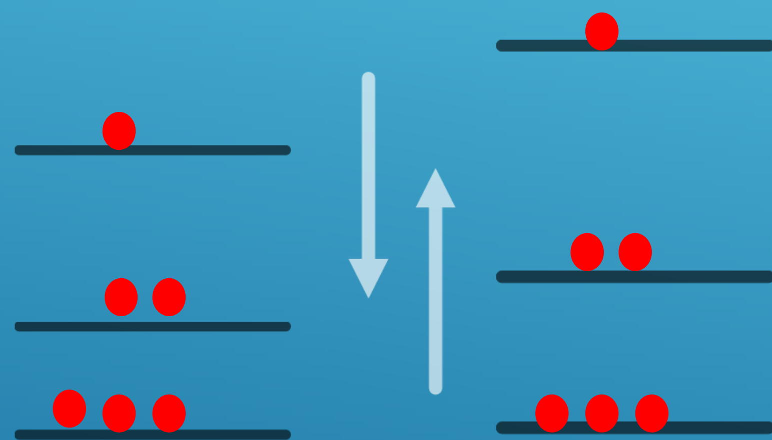
Thermodynamics and Quantum Systems

Classical work
Adiabatic process



$$W = \Delta U$$

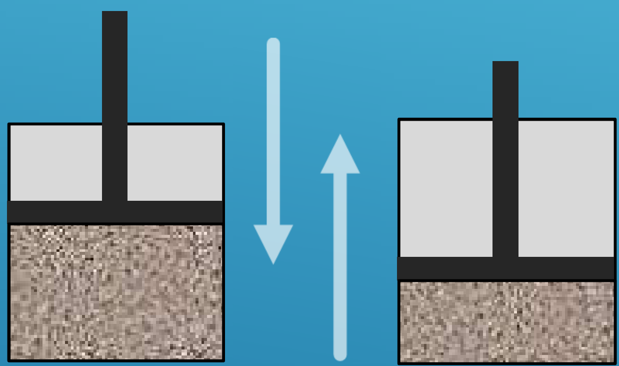
Work for Quantum
systems in equilibrium
Adiabatic (slow) process



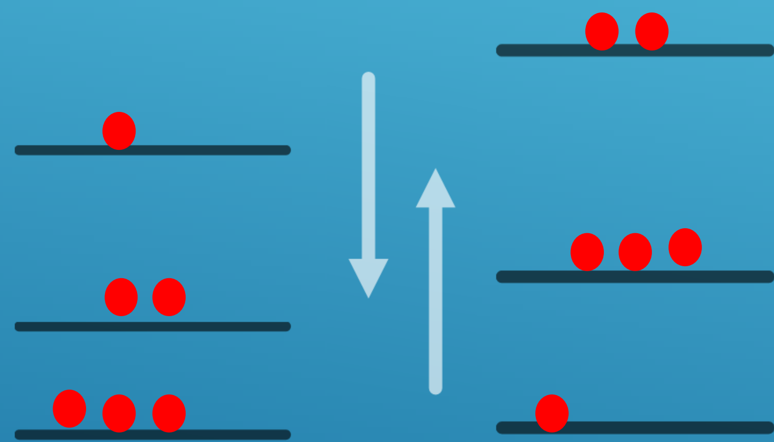
$$W = \Delta F$$

Thermodynamics and Quantum Systems

Classical work
Non adiabatic



Work for Quantum systems
Non adiabatic (fast) process



$$W < \Delta F$$

Fluctuation Relations and Quantum Systems

VOLUME 78, NUMBER 14 PHYSICAL REVIEW LETTERS 7 APRIL 1997

Nonequilibrium Equality for Free Energy Differences

C. Jarzynski*
Institute for Nuclear Theory, University of Washington, Seattle, Washington 98195
(Received 7 June 1996)

An expression is derived for the equilibrium free energy difference between two configurations of a system, in terms of an ensemble of *finite-time* measurements of the work performed in parametrically switching from one configuration to the other. Two well-known identities emerge as limiting cases of this result. [S0031-9007(97)02845-7]

Equation (1) is an inequality. By contrast, the new result derived in this paper is the following *equality*:

$$\overline{\exp(-\beta W)} = \exp(-\beta \Delta F), \tag{2a}$$

or, equivalently,

$$\Delta F = -\beta^{-1} \ln \overline{\exp(-\beta W)}, \tag{2b}$$

where $\beta \equiv 1/k_B T$. This result, which is independent of both the path γ from A to B, and the rate at which the

parameters are switched along the path, is surprising: It says that we can extract equilibrium information (ΔF) from the ensemble of *nonequilibrium* (finite-time) measurements described above.

technical note, cond-mat/0009244

Jarzynski Relations for Quantum Systems and Some Applications

Hal Tasaki[1]

Two-measurements protocol
Work distribution

$$P(\mathcal{W}) = \sum_{m,n} p_{m,n} \delta\left[\mathcal{W} - \left(\varepsilon_m^F - \varepsilon_n^I\right)\right],$$

Equation (1) is an inequality. By contrast, the new result derived in this paper is the following *equality*:

$$\overline{\exp(-\beta W)} = \exp(-\beta \Delta F), \tag{2a}$$

or, equivalently,

$$\Delta F = -\beta^{-1} \ln \overline{\exp(-\beta W)}, \tag{2b}$$

where $\beta \equiv 1/k_B T$. This result, which is independent of both the path γ from A to B, and the rate at which the

Free energy refers to a thermal state buildt using the final Hamiltonian

$$\rho_S^F = \mathrm{e}^{-\beta H_F}/Z$$

$$\langle e^{-\beta W} \rangle \equiv \int dW\, P(W) e^{-\beta W} = e^{-\beta \Delta F}$$

C. Jarzynski, H. T. Quan, and S. Rahav, Phys. Rev. X 5, 031038 (2015)

Analogy between the paraxial wave equation and 2D Schrödinger equation

Helmholtz equation

$$\nabla^2 A + k^2 A = 0$$

Helmholtz paraxial equation:

$$\nabla_T^2 A + 2ik\frac{\partial A}{\partial z} = 0$$

Time dependent Schrödinger equation:

$$\nabla^2 \psi + i\frac{2m}{\hbar}\frac{\partial \psi}{\partial t} = 0$$

Optical Analogy

$$i\hbar\frac{\partial \psi(x,t)}{\partial t} = \left(-\hbar^2\frac{\partial^2}{\partial x^2} + V(x)\right)\psi(x,t)$$

$$\frac{i}{k}\frac{\partial \psi(x,z)}{\partial z} = \left(-\frac{1}{2k^2}\frac{\partial^2}{\partial x^2} + n(x)\right)\psi(x,z)$$

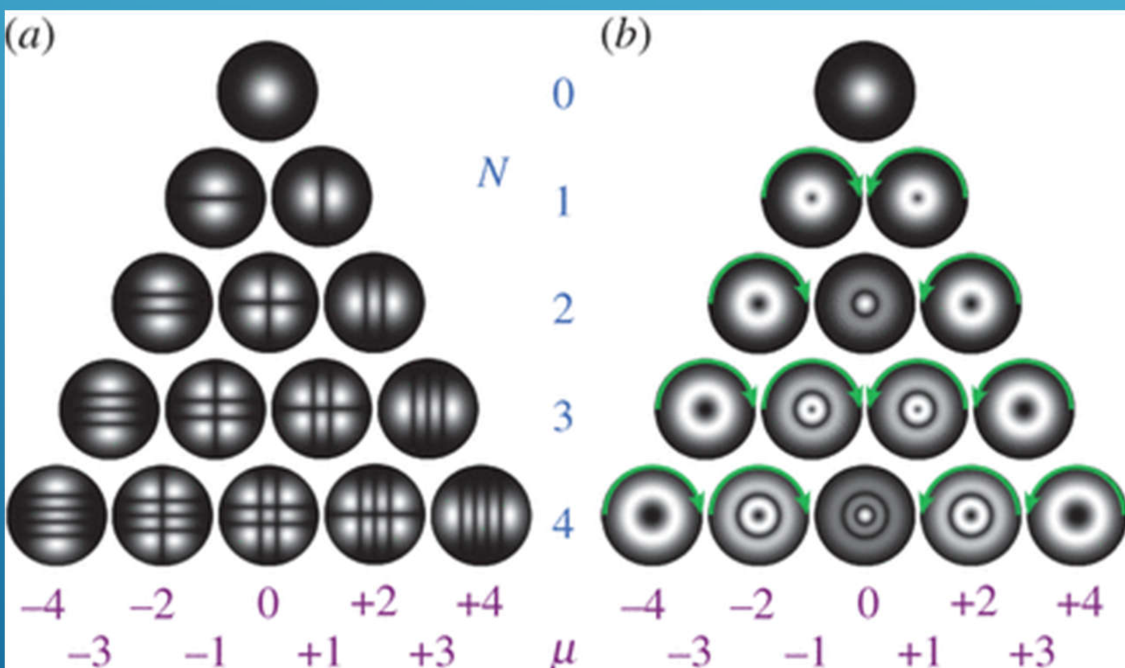
$$n(x) = n_0 - \frac{1}{2}n_1 x^2$$

D. Marcuse. Light Transmission Optics . (Van Nostrand Reinhold Company, New York, 1982).

Quantum Harmonic Oscillator

$$\frac{i}{k}\frac{\partial\psi(x,z)}{\partial z} = \left(-\frac{1}{2k^2}\frac{\partial^2}{\partial x^2} + n(x)\right)\psi(x,z)$$

$$n(x) = n_0 - \frac{1}{2}n_1 x^2$$



Hamiltonian (2D)

$$H = (N_r + N_l + 1)\hbar\omega$$

$$L_z = (N_r - N_l)\hbar$$

Eigen energies

$$\varepsilon_{\ell p} = (|\ell| + 2p + 1)\hbar\omega$$

P=0

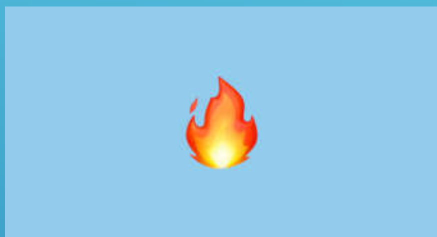
$$\varepsilon_{\ell} = (|\ell| + 1)\hbar\omega$$

Figure credits:
Phil. Trans. R. Soc. A
Swings and roundabouts: optical Poincaré spheres for polarization and Gaussian beams, M. R. Dennis, M. A. Alonso, DOI: 10.1098/rsta.2015.0441

Two-measurement protocol

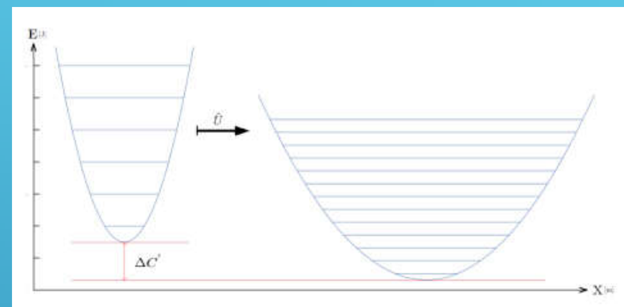
Initial state

$\rho_T = e^{-\beta\epsilon}/Z$

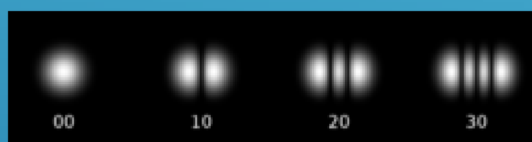


$$H_I = \frac{p^2}{2m} + \frac{m}{2} w_1^2 x$$

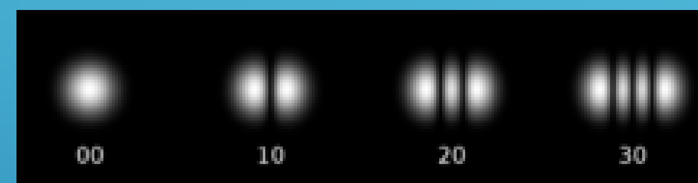
Unitary Process(fast)



$$H_I = \frac{p^2}{2m} + \frac{m}{2} w_2^2 x$$



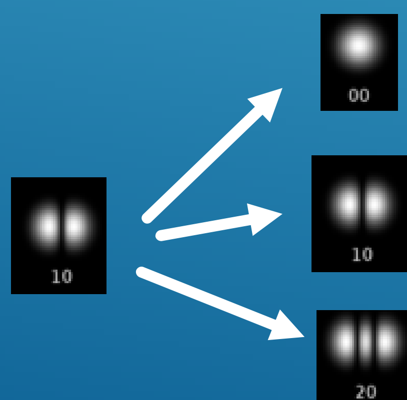
First measurement



Second measurement

Repeat several times to obtain the transition probabilities

ε_i



$$W_1 = \varepsilon_{f1} - \varepsilon_i$$

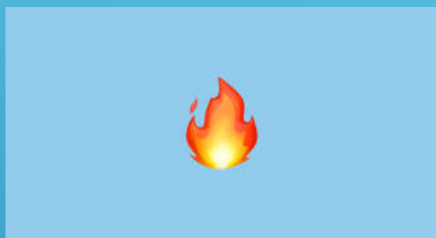
$$W_3 = \varepsilon_{f2} - \varepsilon_i$$

$$W_3 = \varepsilon_{f3} - \varepsilon_i$$

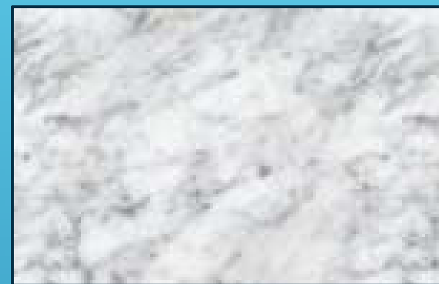
Two-measurement protocol - Work distribution - LG modes

Initial state

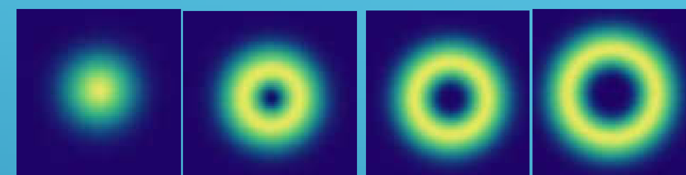
$\rho_T = e^{-\beta|\ell|}/Z$



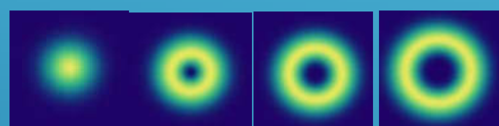
SLM phase mask



$H = (N_r + N_l + 1)\hbar\omega$



$H = (N_r + N_l + 1)\hbar\omega$



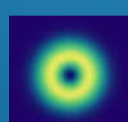
First measurement

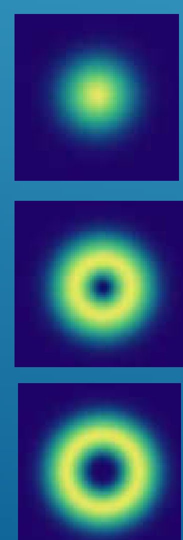
Second measurement

Repeat several times to obtain the transition probabilities

$p_{\ell'|\ell}$

Transition probabilities





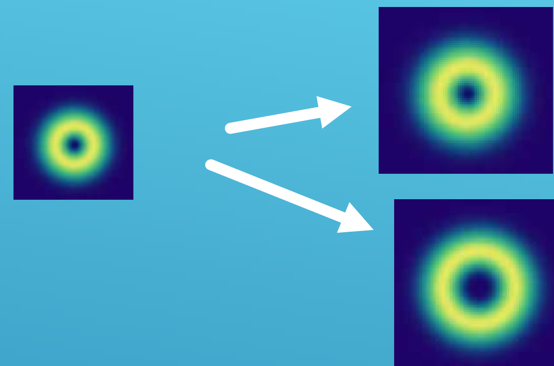
$W_1 = |\ell|_{f1} - |\ell|_i$

$W_3 = |\ell|_{f2} - |\ell|_i$

$W_3 = |\ell|_{f3} - |\ell|_i$

Two-measurement protocol

$$p_{\ell\ell'} = p_\ell \, p_{\ell'|\ell}$$



Measured transition probabilities

$$p_{\ell'|\ell}$$

$$p_\ell = \frac{e^{-\beta\varepsilon_\ell}}{Z}$$

Thermal distribution coefficients

Work distribution

$$P(W) = \sum_{\ell,\ell'} p_{\ell\ell'} \delta(W - W_{\ell\ell'})$$

Jarzynski's relation

$$\langle e^{-\beta W} \rangle \equiv \int dW \, P(W) e^{-\beta W} = e^{-\beta \Delta F}$$

Work distribution for optical analog Quantum Harmonic Oscillators

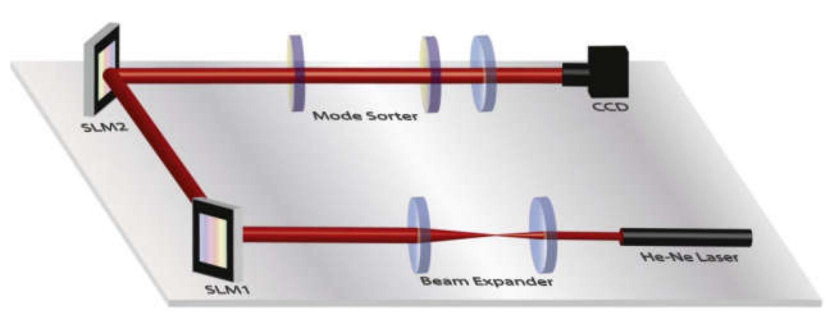
J. Phys. Commun. **2** (2018) 035012
https://doi.org/10.1088/2399-6528/aab178

Journal of Physics Communications

PAPER

Experimental study of quantum thermodynamics using optical vortices

R Medeiros de Araújo[1], T Häffner[1], R Bernardi[1], D S Tasca[2], M P J Lavery[3], M J Padgett[4], A Kanaan[1], L C Céleri[5] and P H Souto Ribeiro[1,6]



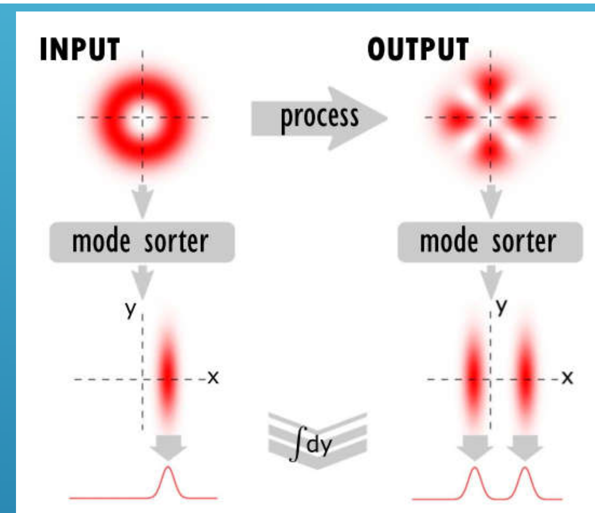
$$H = (N_r + N_l + 1)\hbar\omega$$

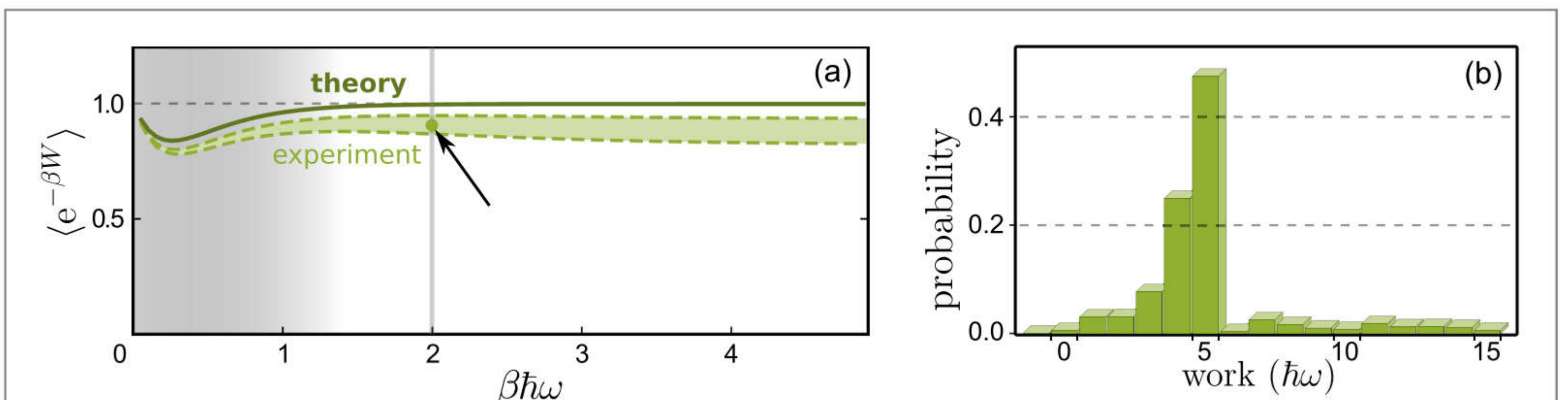
$$L_z = (N_r - N_l)\hbar$$

Energy: $\varepsilon_{\ell p} = (|\ell| + 2p + 1)\hbar\omega$

Angular momentum: $\lambda_\ell = \hbar\ell$

$$\varepsilon_\ell = (|\ell| + 1)\hbar\omega$$





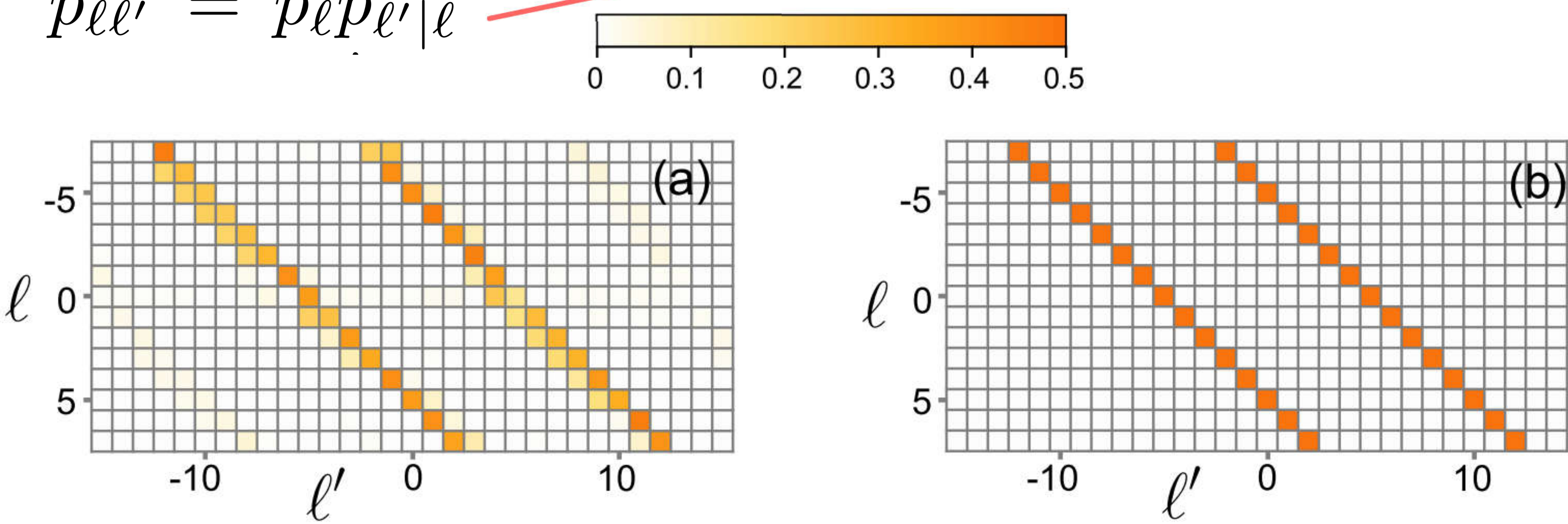
Results: Transition probabilities

$$P(W) = \sum_{\ell} p_{\ell\ell'} \delta\left(W - W_{\ell\ell'}\right)$$

$p_\ell \rightarrow$ thermal distribution weight

$$p_{\ell\ell'} = p_\ell p_{\ell'|\ell}$$

$p_{\ell'|\ell}$

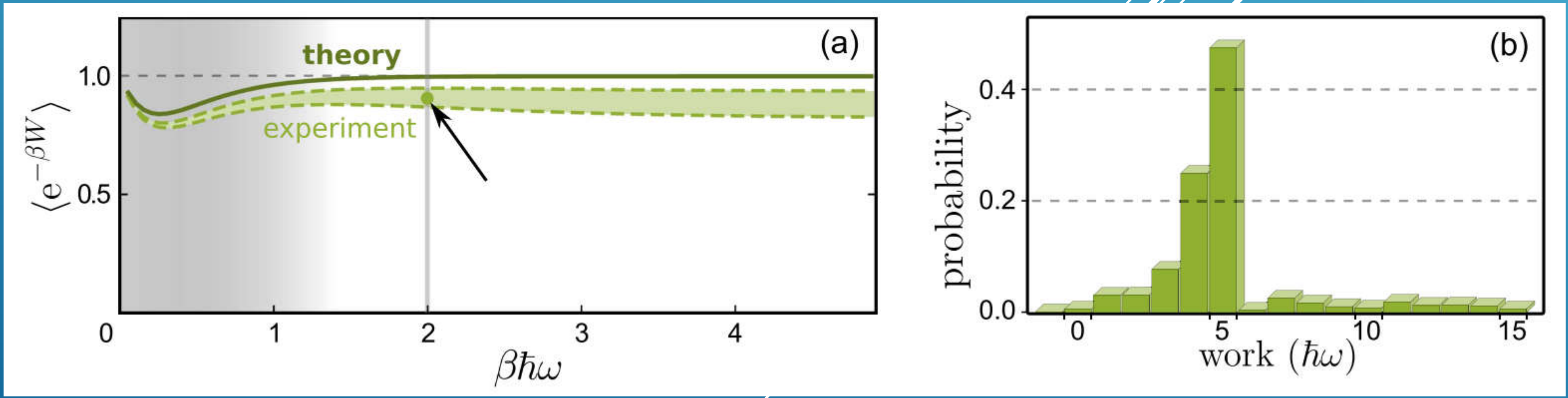


$$W_{\ell,\ell'} = |\ell'| - |\ell|$$

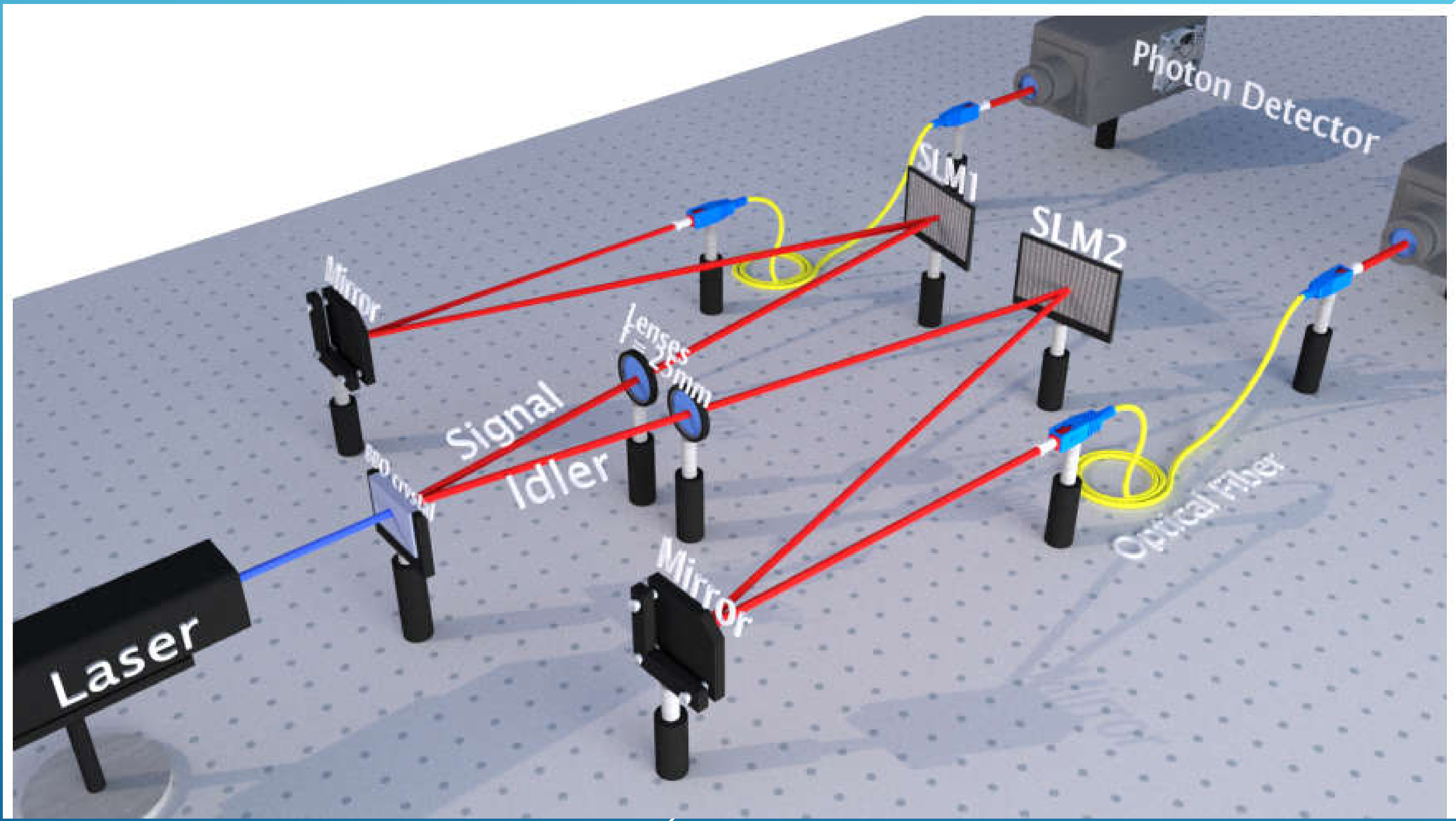
Results: Fluctuation relations

$$\langle e^{-\beta W} \rangle \equiv \int dW\, P(W) e^{-\beta W} = e^{-\beta \Delta F}$$

$$\Delta F = 0 \rightarrow \langle e^{-\beta W} \rangle = 1$$



Setup with entangled photons



Setup with entangled photons

PHYSICAL REVIEW A **88**, 012312 (2013)

Orbital-angular-momentum entanglement in turbulence

A. Hamadou Ibrahim,[1,2] Filippus S. Roux,[1] Melanie McLaren,[1,3] Thomas Konrad,[2] and Andrew Forbes[1,2,3]
[1] *CSIR National Laser Centre, P. O. Box 395, Pretoria 0001, South Africa*
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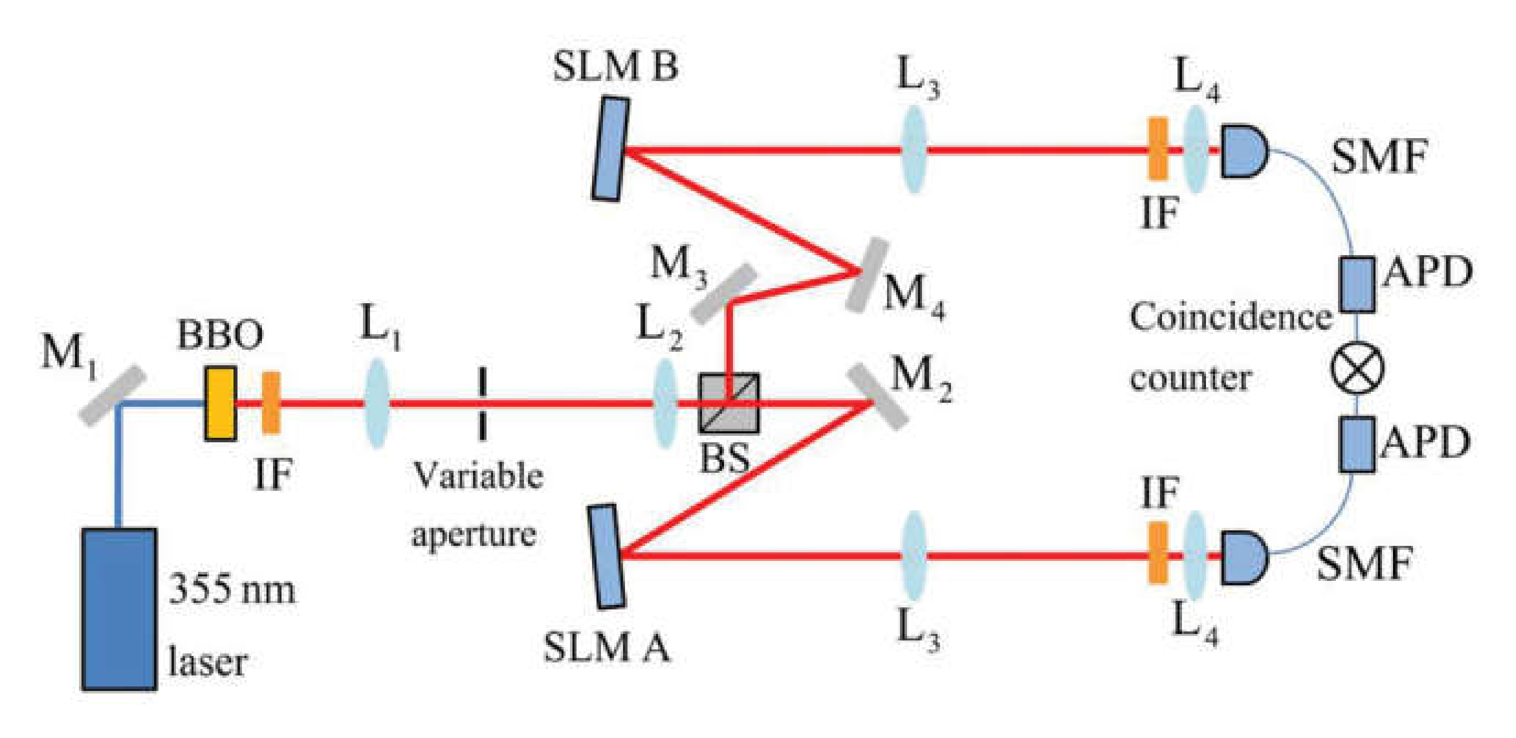
[3] *Laser Research Institute, University of Stellenbosch, Stellenbosch 7602, South Africa*
(Received 19 April 2013; published 11 July 2013)

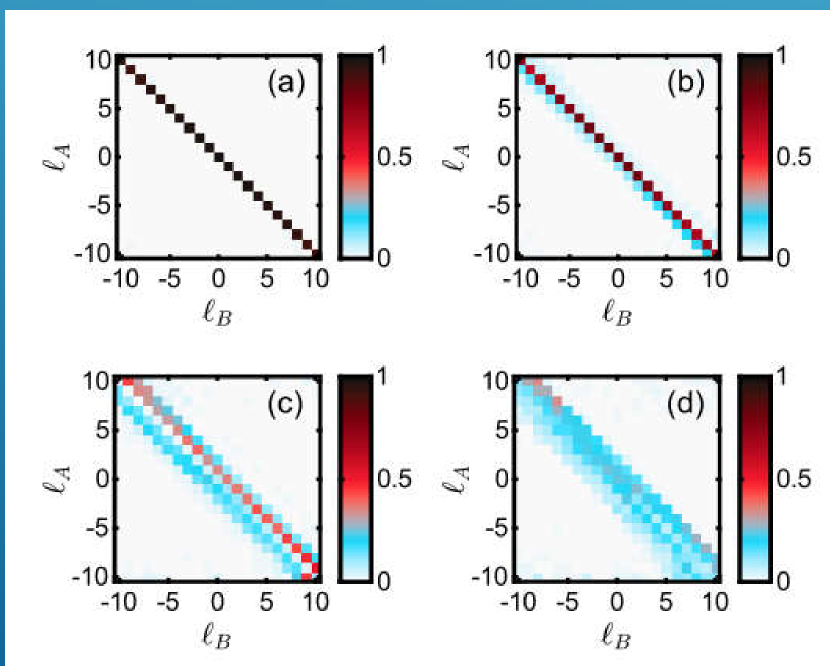


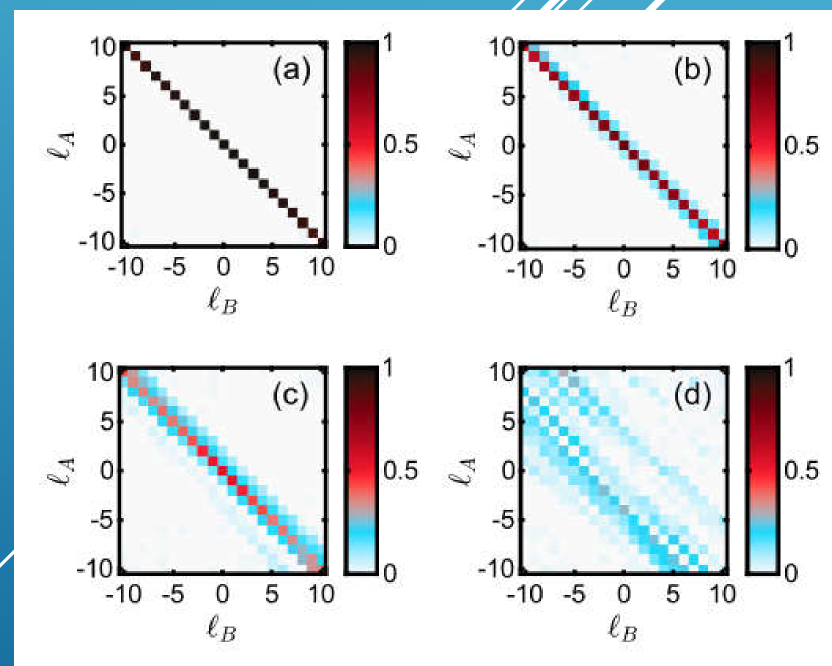
Setup with entangled photons

Experimental Study of the Generalized Jarzysnki's Fluctuation Relation Using Entangled Photons

P. H. Souto Ribeiro,[1,*] T. Häffner,[1] G. L. Zanin,[1] N. Rubiano da Silva,[1] R. Medeiros de Araújo,[1] W. C. S. Silva,[2] R. J. de Assis,[3] L. C. Céleri,[3,4,†] and A. Forbes[5,‡]

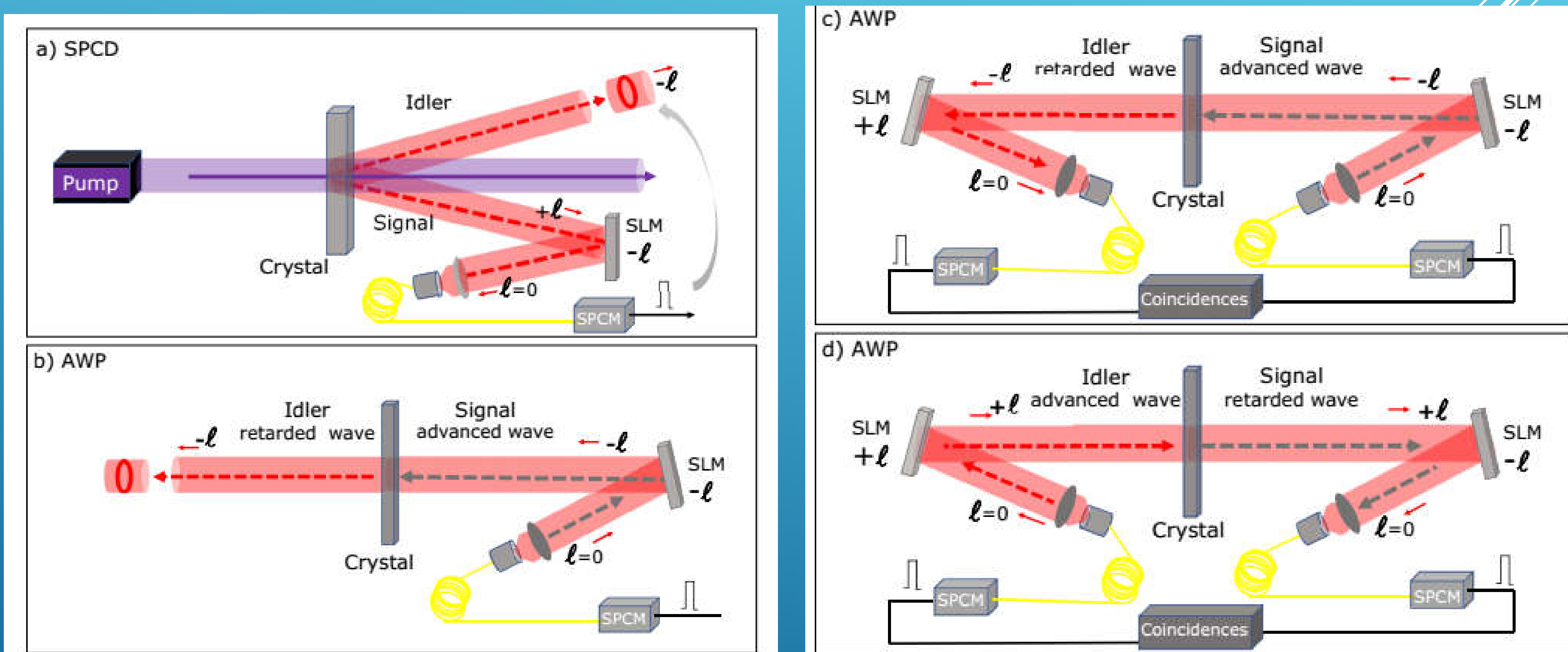
[1]*Departamento de Física, Universidade Federal de Santa Catarina, CEP 88040-900, Florianóplis, SC, Brazil*
[2]*Departamento de Física, Universidade Federal de Alagoas, Arapiraca, AL, 57309-005, Brazil*
[3]*Institute of Physics, Federal University of Goiás, 74690-900, Goiânia, GO, Brazil*
[4]*Department of Physical Chemistry, University of the Basque Country UPV/EHU, Apartado 644, E-48080 Bilbao, Spain*
[5]*School of Physics, University of the Witwatersrand, Johannesburg, South Africa*





To appear in Phys. Rev. A

Remote state preparation and Klyshko advanced wave picture (AWP)



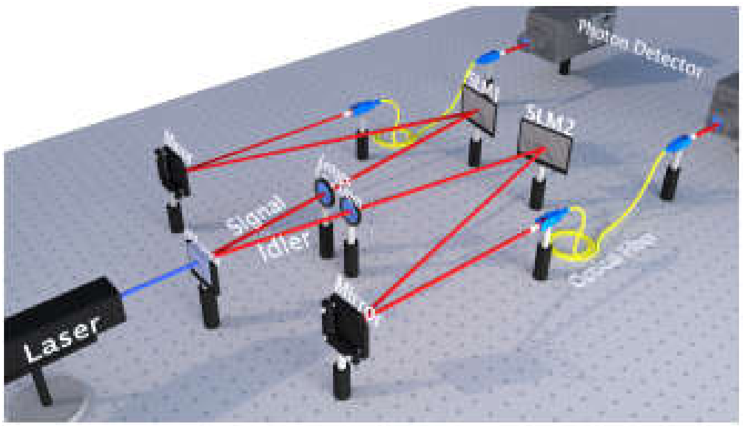
Two-photon optics: diffractlon, holography, and transformation of two-dimensional signals, A.V. Belinskii, D.N. Klyshko, JETP, Vol. 78, No. 3, p. 259 (March 1994)
(Russian original - ZhETF, Vol. 105, No. 3, p. 487, March 1994)

arXiv:2001.08178v1 [quant-ph] 22 Jan 2020

Remote preparation of single photon vortex thermal states

T. Häffner,[1] G. L. Zanin,[1] R. M. Gomes,[2] L. C. Céleri,[2,3,*] and P. H. Souto Ribeiro[1,†]

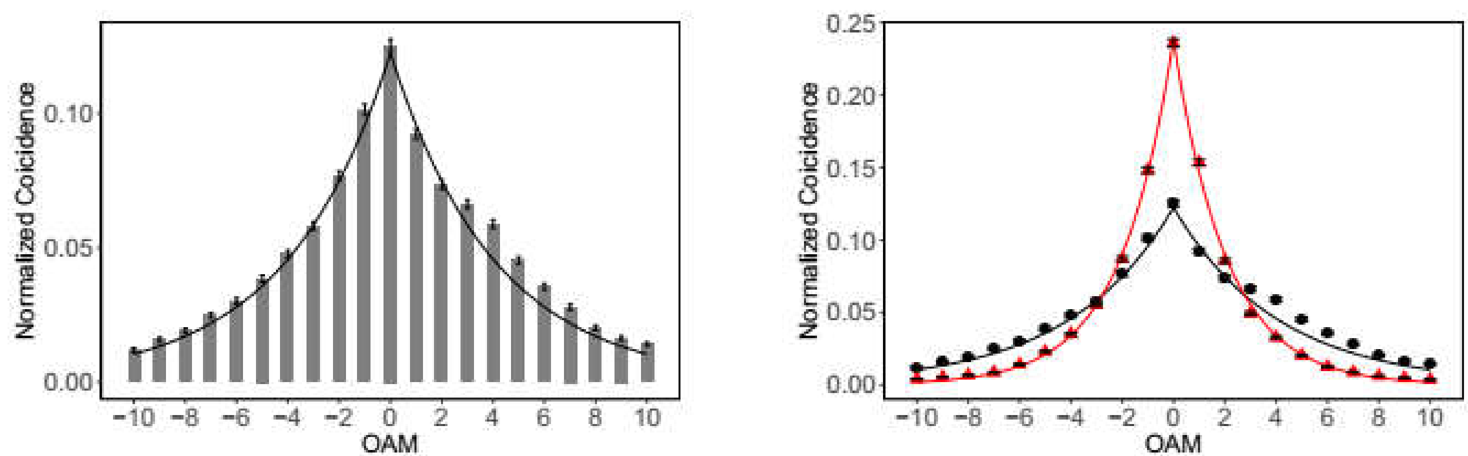
[1] *Departamento de Física, Universidade Federal de Santa Catarina, CEP 88040-900, Florianóplis, SC, Brazil*
[2] *Institute of Physics, Federal University of Goiás, 74690-900, Goiânia, GO, Brazil*
[3] *Department of Physical Chemistry, University of the Basque Country UPV/EHU, Apartado 644, E-48080 Bilbao, Spain*



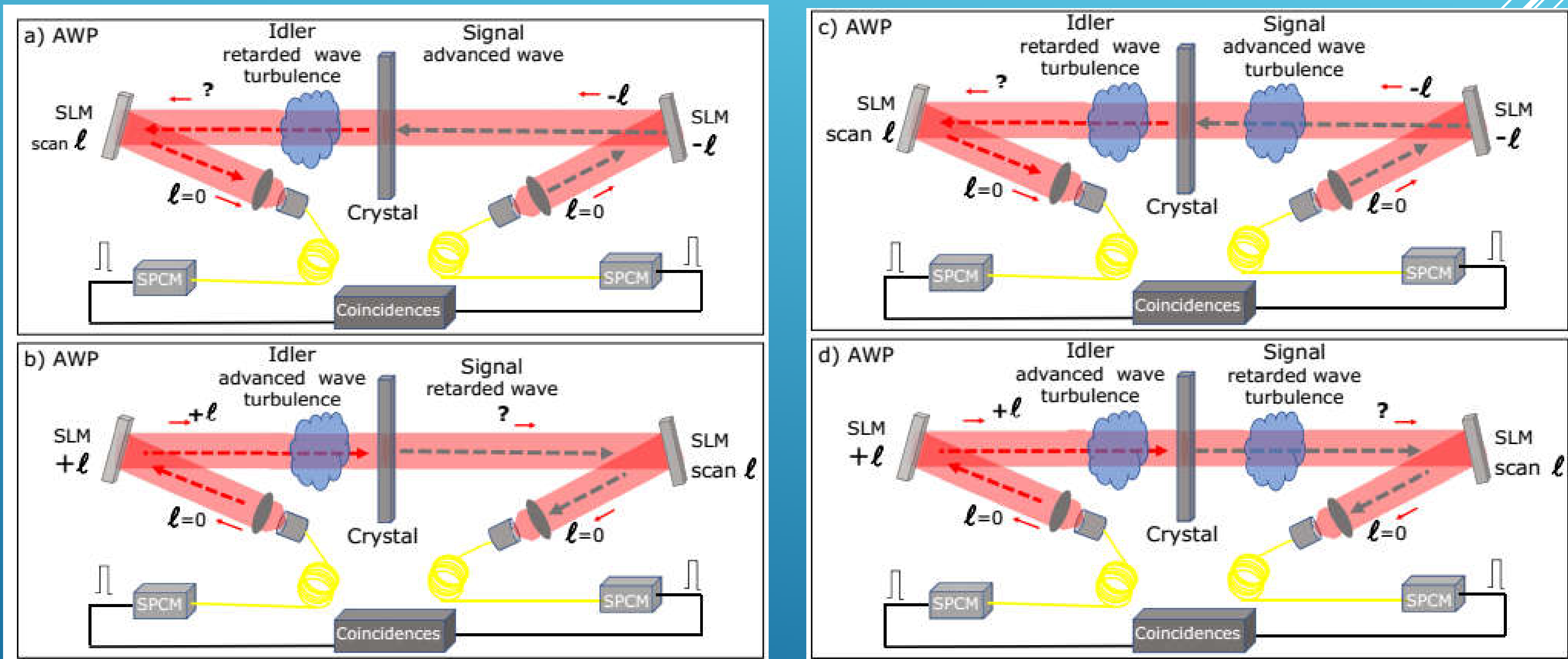
PHYSICAL REVIEW A **68**, 050301(R) (2003)

Quantum spiral bandwidth of entangled two-photon states

J. P. Torres, A. Alexandrescu, and Lluis Torner
ICFO–Institut de Ciencies Fotoniques, and Department of Signal Theory and Communications, Universitat Politecnica de Catalunya, 08034 Barcelona, Spain
(Received 13 June 2003; published 19 November 2003)

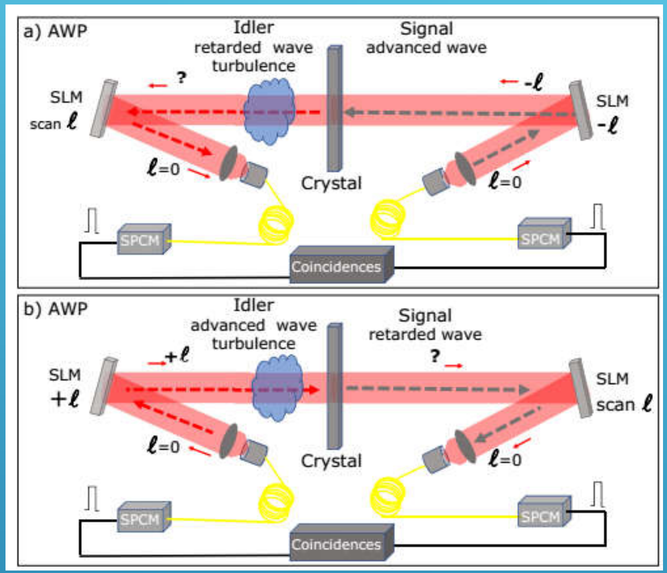


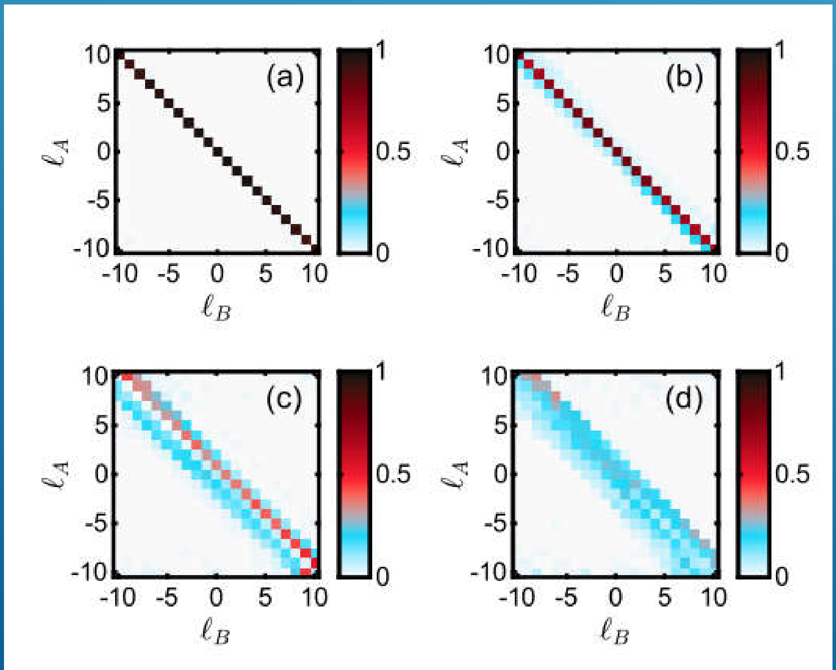
Remote state preparation and AWP



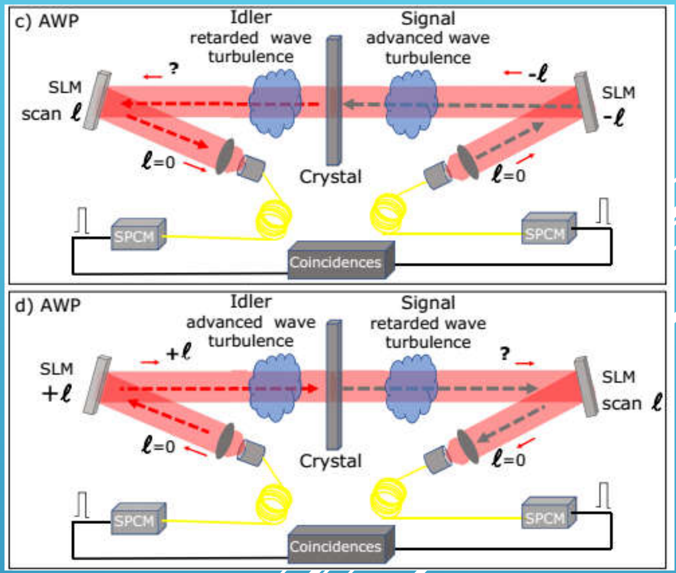
Results

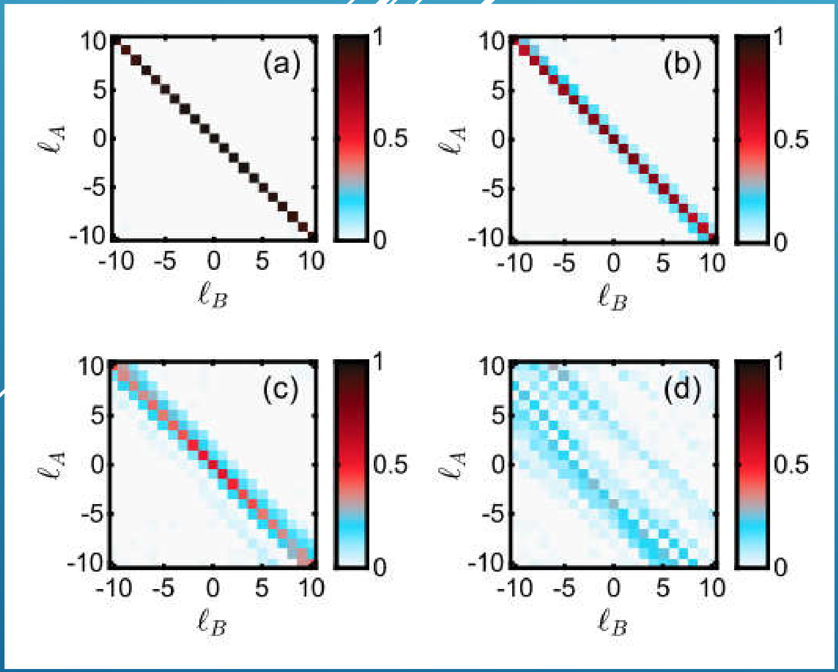
Single sided channel





Double sided channel

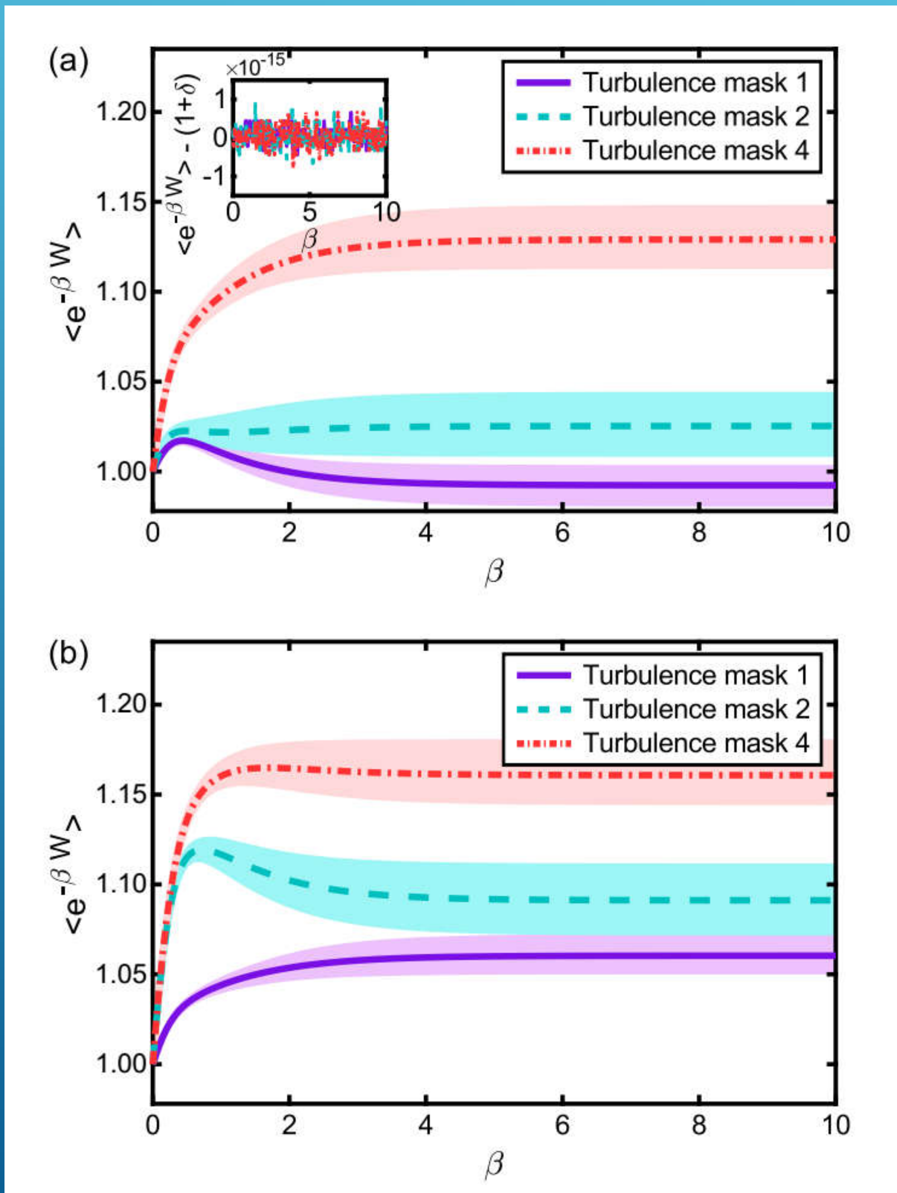




Results

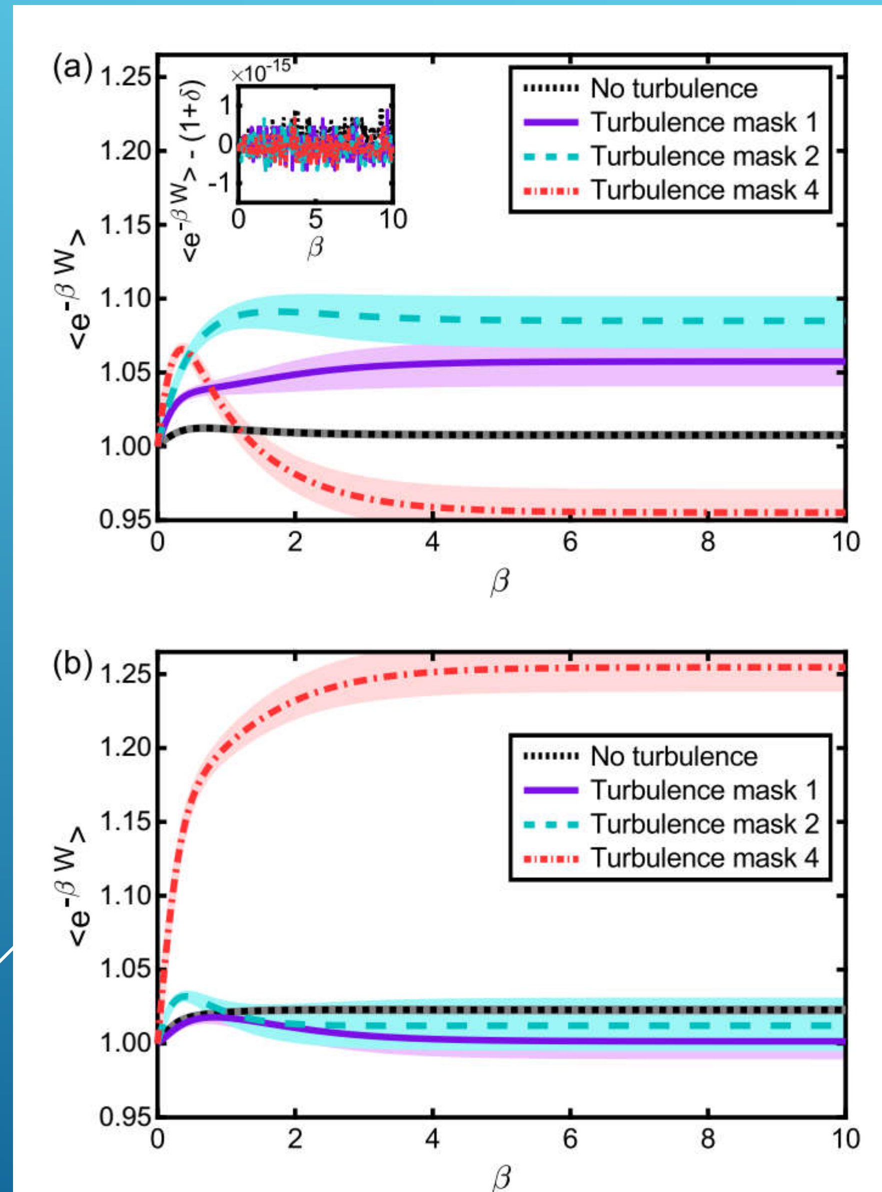
Single sided channel

$$< e^{-\beta W} > \neq 1$$



Double sided channel

$$< e^{-\beta W} > \neq 1$$



Discussion

$$< e^{-\beta W} > \neq 1 \text{ ???}$$

- Change in free energy ΔF ? No, the Hamiltonian does not change.

- Heat generation? No, the system is suposed to be closed, but if it is open, there is no heat bath.

- Information Exchange? No, see Sagawa and Tasaki, PRL 104, 090602 (2010) – Measurement and feedack => Maxwell's demon

- Difference between Forward and Backward processes in the AWP ?

- Non unitarity/unital – simulating turbulence with SLM was made averaging 30 rounds of measurement with 30 masks.

Generalized Fluctuation Relation

PHYSICAL REVIEW E **89**, 012127 (2014)

Jarzynski equality for quantum stochastic maps

Alexey E. Rastegin[1] and Karol Życzkowski[2,3]
[1]*Department of Theoretical Physics, Irkutsk State University, Gagarin Bv. 20, Irkutsk 664003, Russia*
[2]*Institute of Physics, Jagiellonian University, ul. Reymonta 4, 30-059 Kraków, Poland*
[3]*Center for Theoretical Physics, Polish Academy of Sciences, al. Lotników 32/46, 02-668 Warszawa, Poland*
(Received 25 July 2013; revised manuscript received 19 October 2013; published 17 January 2014)

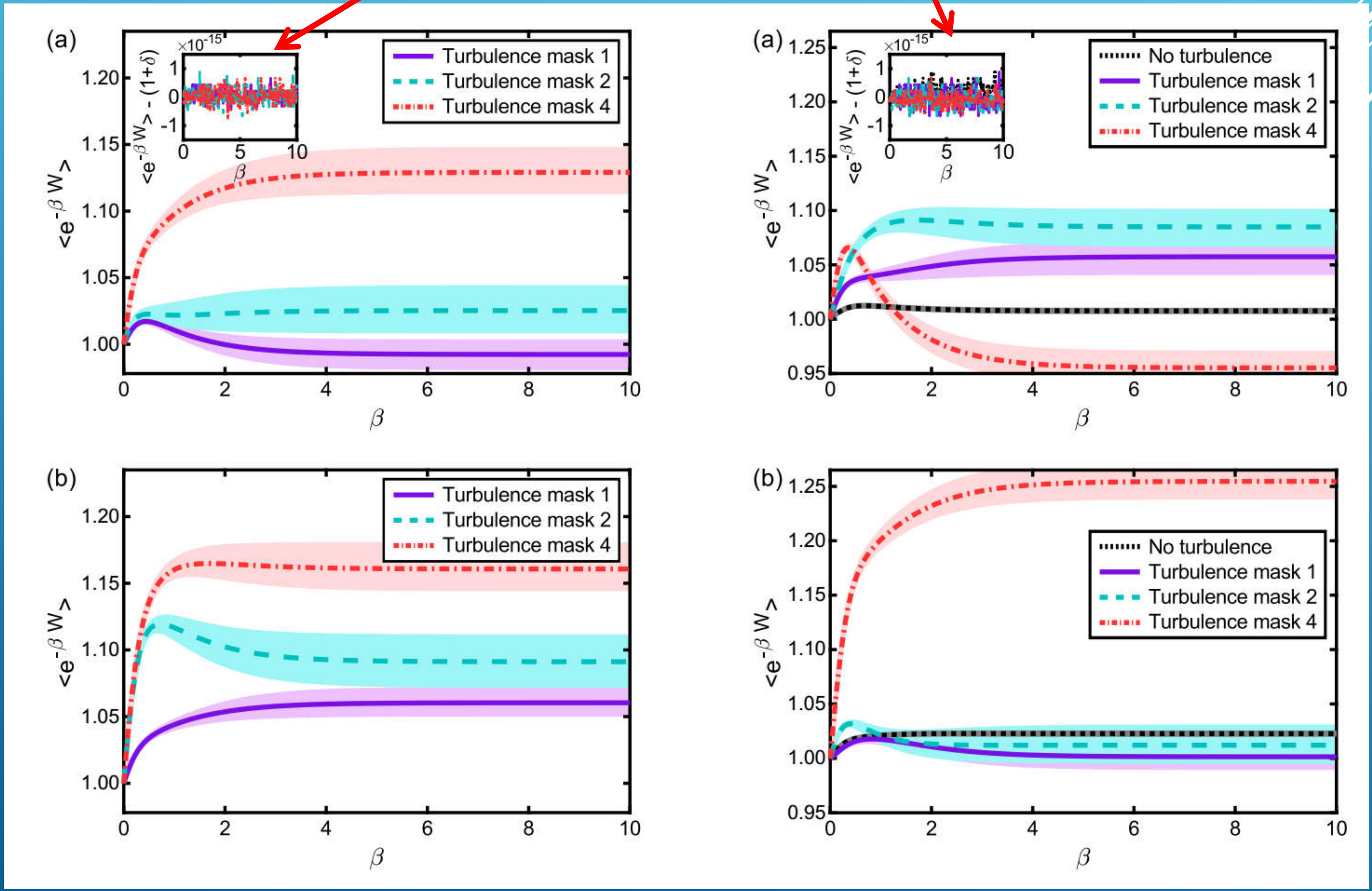
$$\langle e^{\beta W} \rangle = \mathrm{e}^{-\beta \Delta F}(1+\delta)$$

$$\delta = \mathrm{Tr}[\rho_\beta G_\Phi], \text{ with } G_\Phi = \Phi(\rho^*) - \rho^*$$

$$\rho^* \to \text{identity}$$

Generalized Fluctuation Relation

$$< e^{-\beta W} > - (1 - \delta)$$



Generalized Second Law

PHYSICAL REVIEW E **89**, 012127 (2014)

Jarzynski equality for quantum stochastic maps

Alexey E. Rastegin[1] and Karol Życzkowski[2,3]

[1] *Department of Theoretical Physics, Irkutsk State University, Gagarin Bv. 20, Irkutsk 664003, Russia*

[2] *Institute of Physics, Jagiellonian University, ul. Reymonta 4, 30-059 Kraków, Poland*

[3] *Center for Theoretical Physics, Polish Academy of Sciences, al. Lotników 32/46, 02-668 Warszawa, Poland*

(Received 25 July 2013; revised manuscript received 19 October 2013; published 17 January 2014)

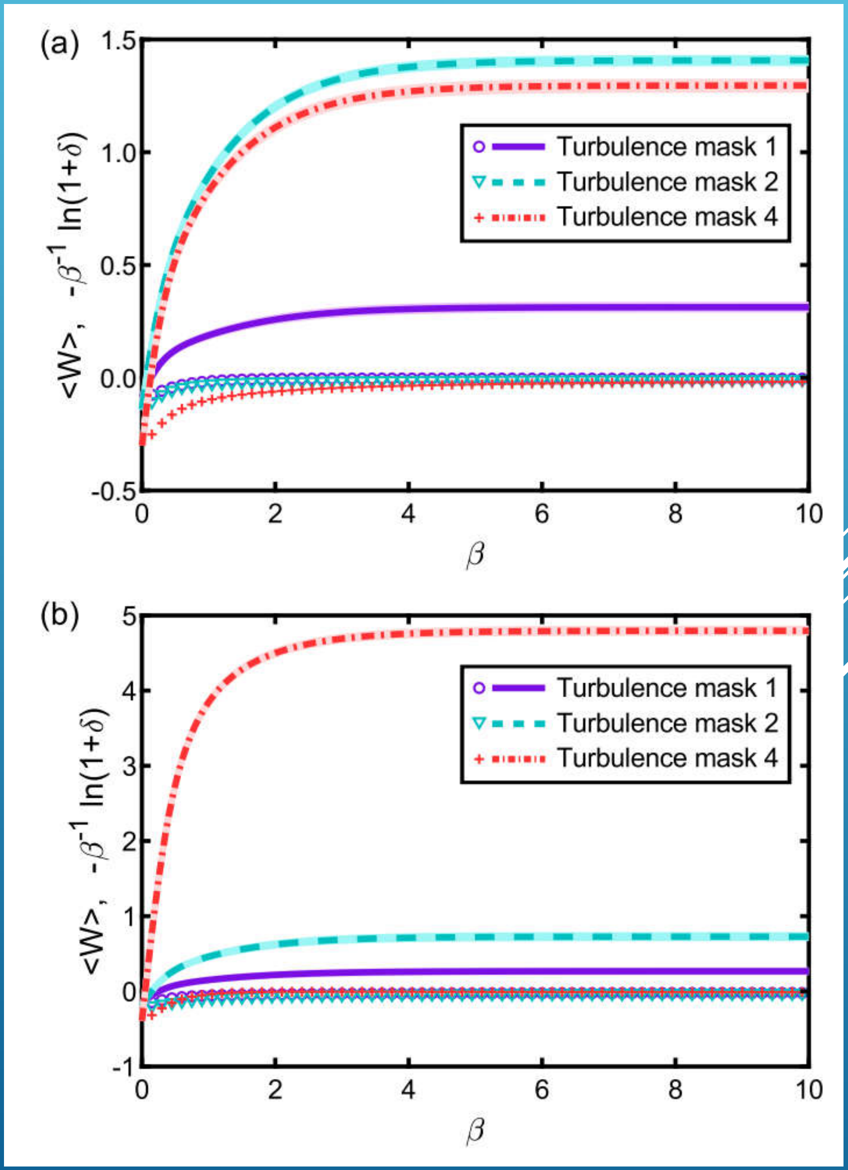
$$\langle W \rangle - \Delta F \geq -\beta^{-1} \ln(1+\delta).$$

$$\delta = \mathrm{Tr}[\rho_\beta G_\Phi], \text{ with } G_\Phi = \Phi(\rho^*) - \rho^*$$

$\rho^* \rightarrow$ identity

Generalized Second Law

$$\langle W \rangle - \Delta F \geq -\beta^{-1} \ln(1 + \delta).$$



ACS Photonics

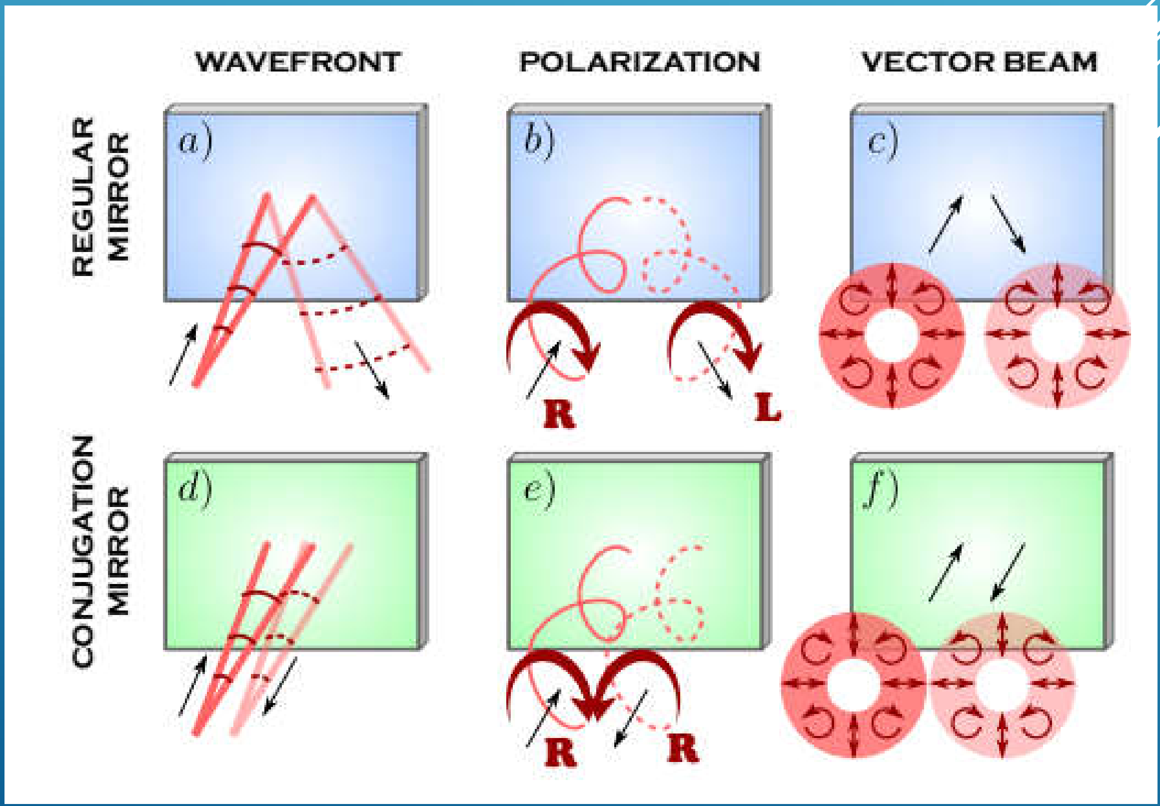
Article

Cite This: ACS Photonics 2020, 7, 249−255

pubs.acs.org/journal/apchd5

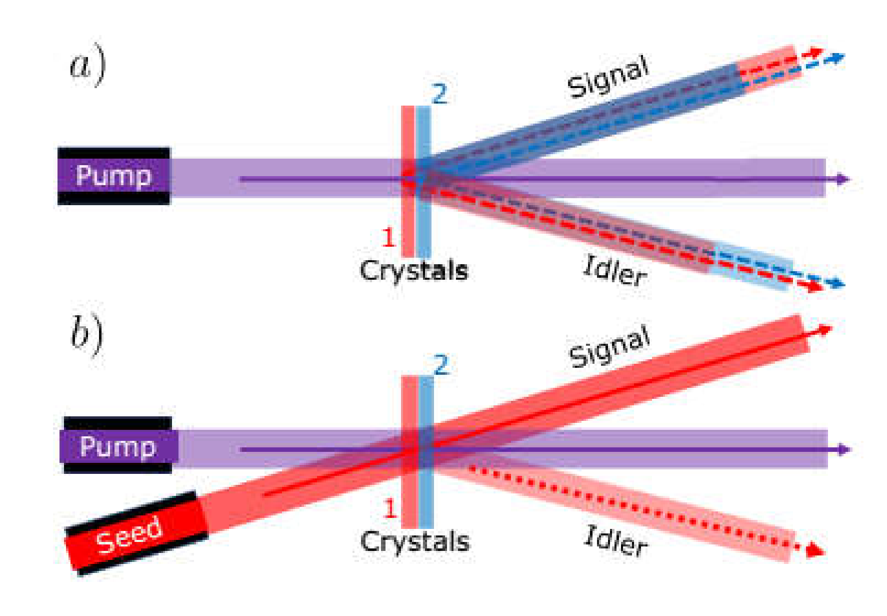
Real-Time Phase Conjugation of Vector Vortex Beams

André G. de Oliveira,*,† Marcelo F. Z. Arruda,†,‡ Willamys C. Soares,§ Stephen P. Walborn,‖ Rafael M. Gomes,⊥ Renné Medeiros de Araújo,† and Paulo H. Souto Ribeiro†



Real-Time Phase Conjugation of Vector Vortex Beams

Theory



Pump beam

$$|\vartheta_p, \varphi_p\rangle = \cos\frac{\vartheta_p}{2}|H\rangle + e^{i(\varphi_p-\Phi)}\sin\frac{\vartheta_p}{2}|V\rangle$$

SPDC state

$$|\psi\rangle_{s,i} = \cos\frac{\vartheta_p}{2}|V\rangle_s|V\rangle_i + e^{i\varphi_p}\sin\frac{\vartheta_p}{2}|H\rangle_s|H\rangle_i$$

Definitions

$$|\pm\vartheta_s, \varphi_s\rangle = \cos\frac{\vartheta_s}{2}|H\rangle \pm e^{i\varphi_s}\sin\frac{\vartheta_s}{2}|V\rangle$$

$$|\alpha\rangle = \sin\frac{\vartheta_p}{2}\cos\frac{\vartheta_s}{2}|H\rangle + e^{-i(\varphi_p+\varphi_s)}\cos\frac{\vartheta_p}{2}\sin\frac{\vartheta_s}{2}|V\rangle$$

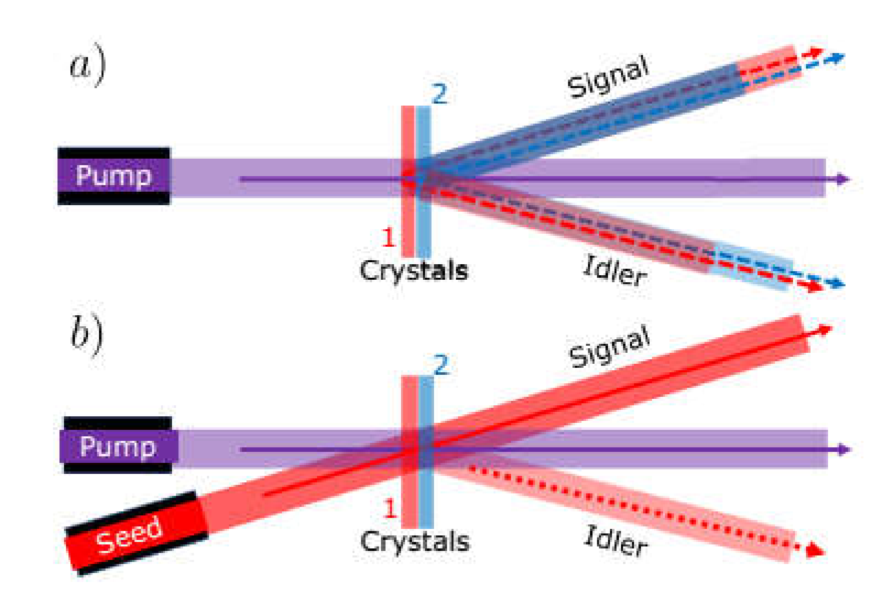
$$|\beta\rangle = \sin\frac{\vartheta_p}{2}\sin\frac{\vartheta_s}{2}|H\rangle - e^{-i(\varphi_p+\varphi_s)}\cos\frac{\vartheta_p}{2}\cos\frac{\vartheta_s}{2}|V\rangle$$

SPDC state

$$|\psi\rangle_{s,i} = |+\vartheta_s, \varphi_s\rangle|\alpha\rangle + |-\vartheta_s, \varphi_s\rangle|\beta\rangle$$

Real-Time Phase Conjugation of Vector Vortex Beams

Theory



Pump, signal/seed and idler states

$$\vec{S}_\mu = \begin{pmatrix} \cos\vartheta_\mu \\ \sin\vartheta_\mu \cos\varphi_\mu \\ \sin\vartheta_\mu \sin\varphi_\mu \end{pmatrix} = \begin{pmatrix} \sin\theta_\mu \cos\phi_\mu \\ \sin\theta_\mu \sin\phi_\mu \\ \cos\theta_\mu \end{pmatrix}$$

μ = p, s, i

Signal state as a function of pump and seed

$$\vec{S}_i = \frac{1}{2} \begin{pmatrix} S_{s,1} - S_{p,1} \\ S_{p,2}S_{s,2} - S_{p,3}S_{s,3} \\ -S_{s,2}S_{p,3} - S_{p,2}S_{s,3} \end{pmatrix}$$

Real-Time Phase Conjugation of Vector Vortex Beams

Theory

Pump

$$\vec{S}_i = (S_{s,1}, S_{s,2}, -S_{s,3})^T = \vec{S}_s^{\,*}$$

Pump

$$\vec{S}_i = (S_{s,1}, -S_{s,2}, S_{s,3})^T,$$

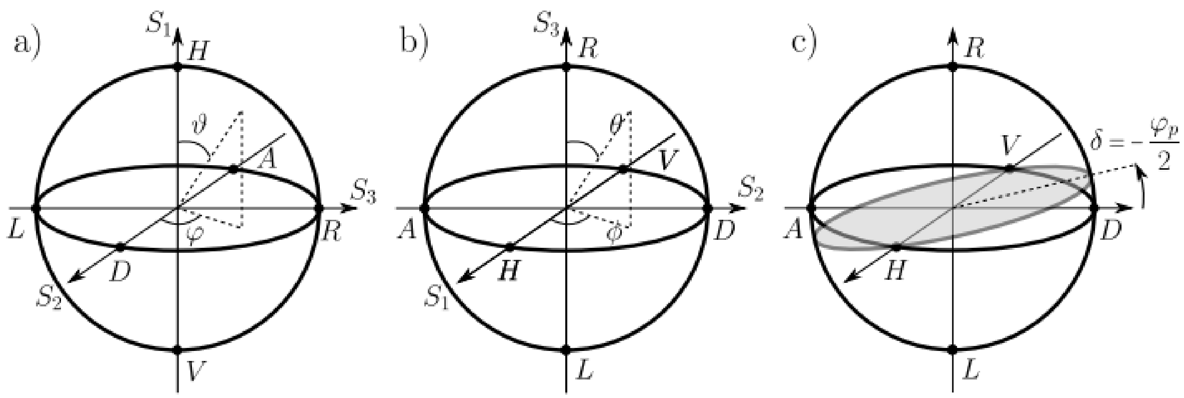
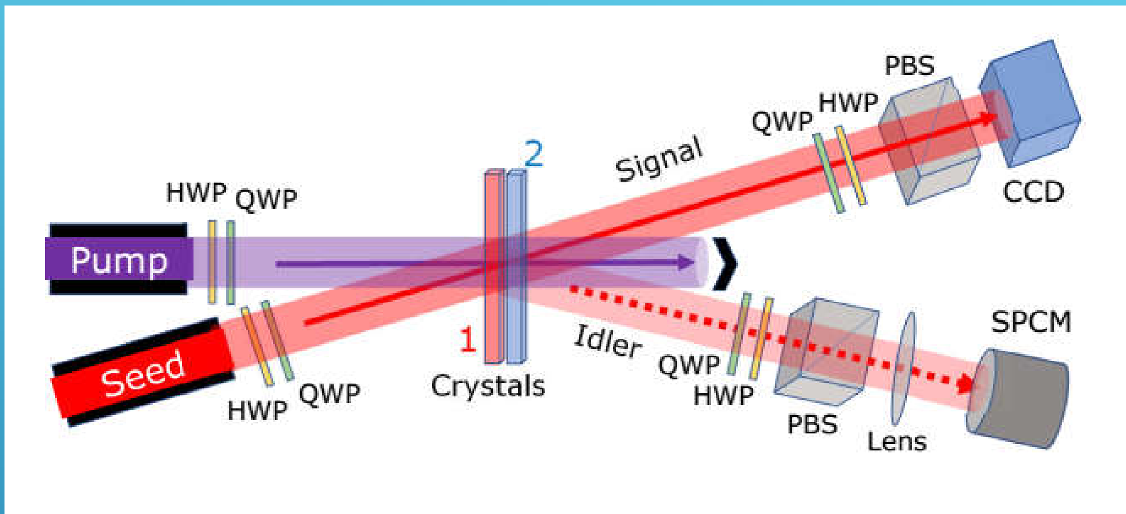


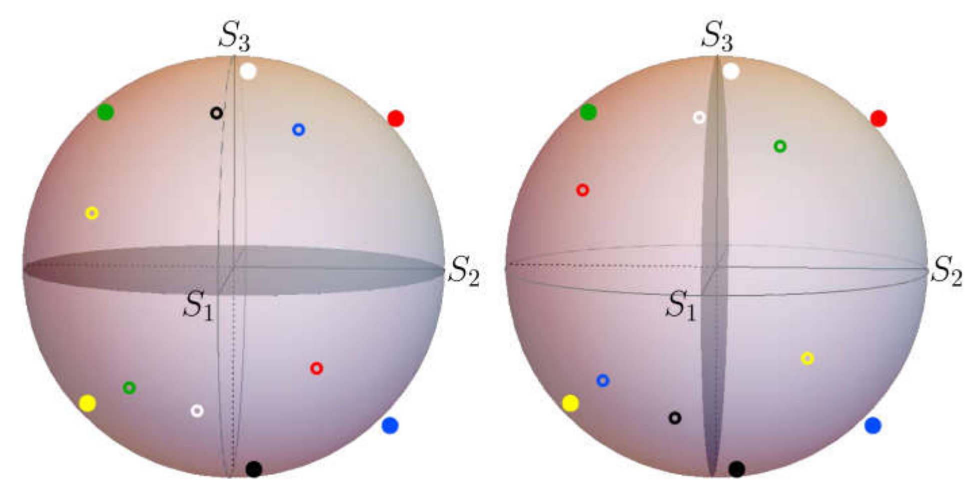
FIG. 3: Poincaré sphere with N/S poles given by a) H/V polarization, b) R/L polarization and c) Signal and idler polarizations are mirror images through the δ-rotated conjugation plane in StimPDC when $\vartheta_p = \pi/2$.

Real-Time Phase Conjugation of Vector Vortex Beams

Experimental setup

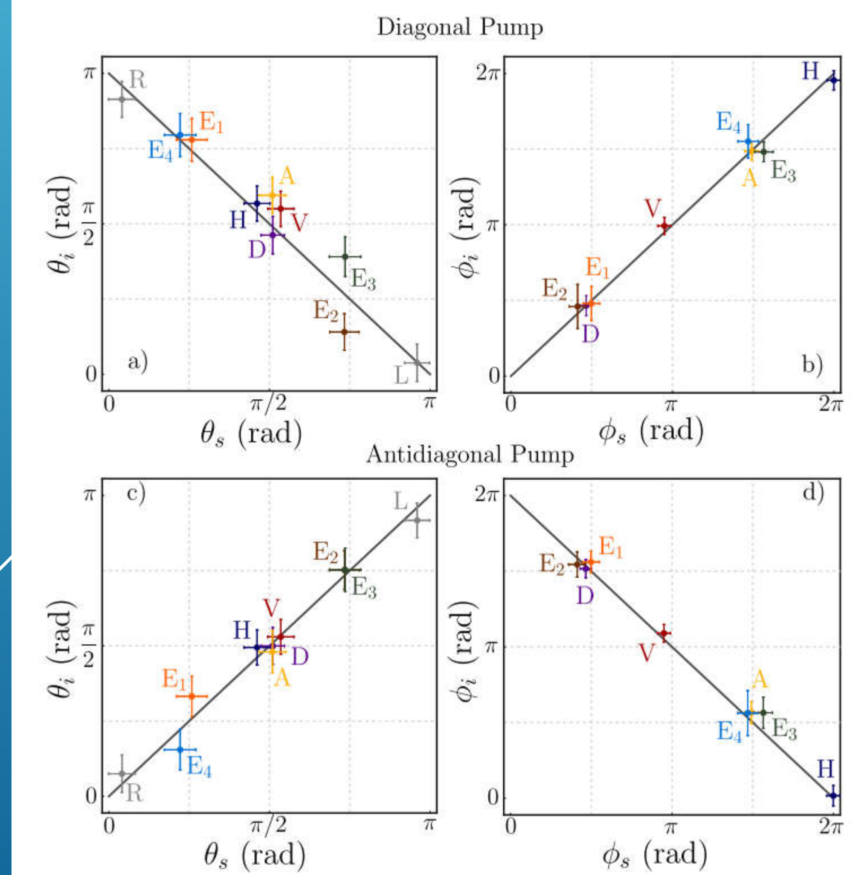


Experimental results



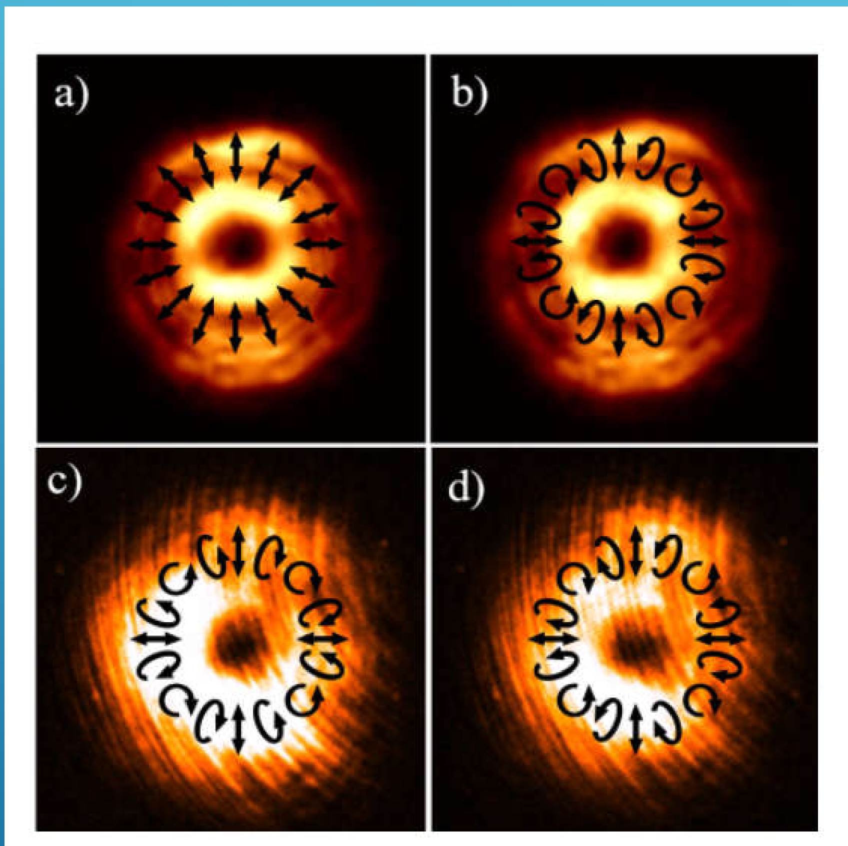
a) Diagonal Pump
b) Antidiagonal Pump

Experimental results

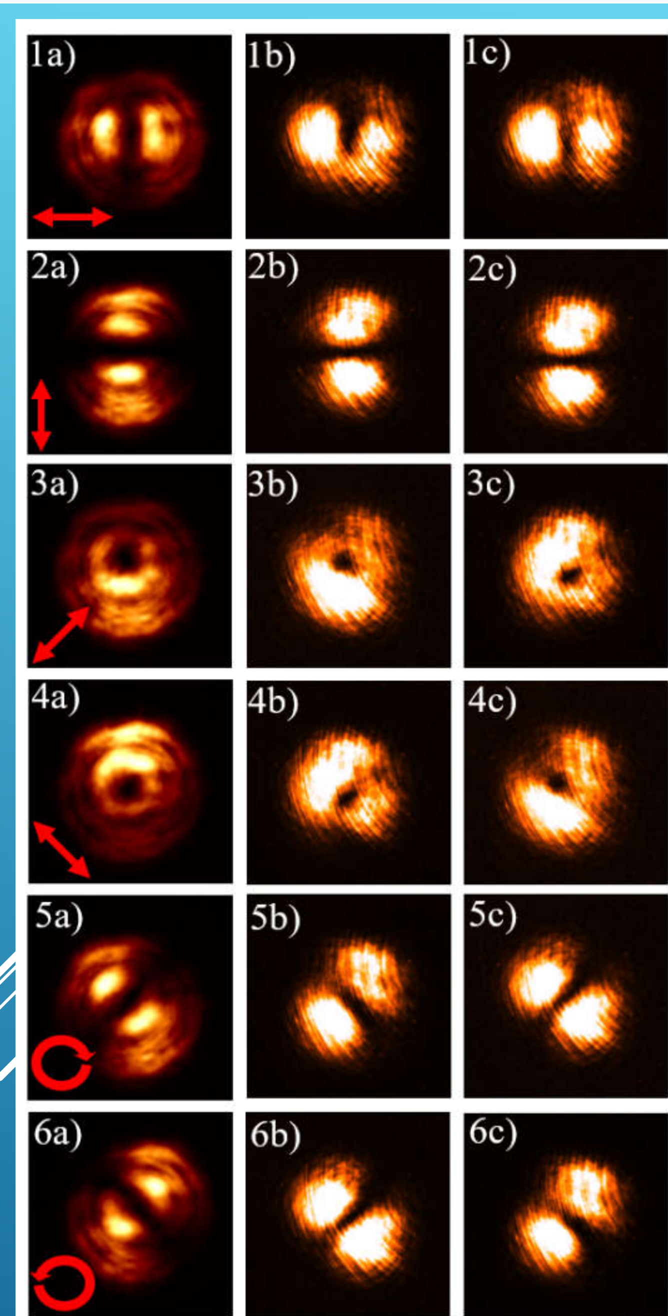


Real-Time Phase Conjugation of Vector Vortex Beams

Vortex beam phase conjugation



a) Vector seed, b) Seed transformed
c) Idler conjugated, d) Idler NC

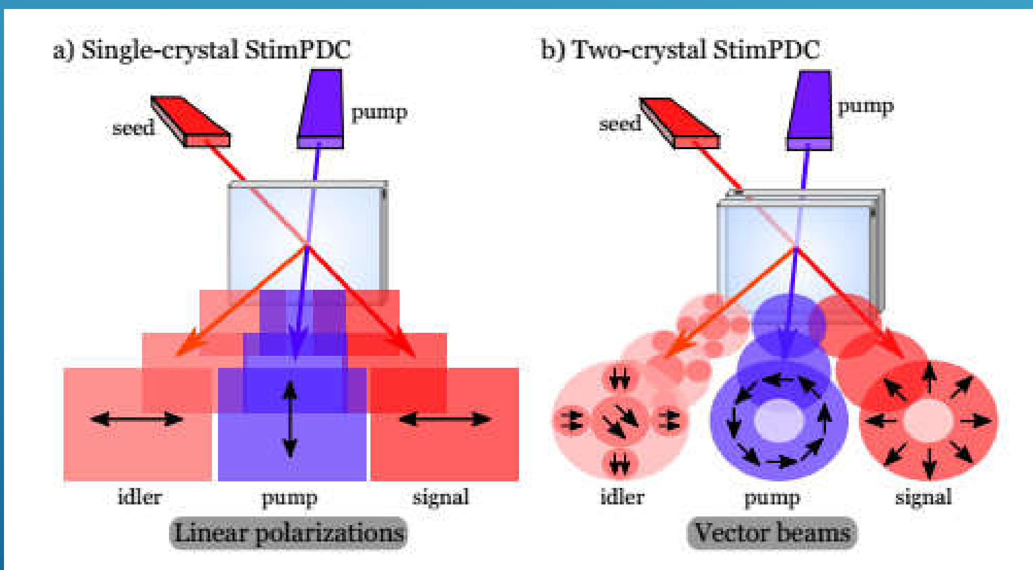


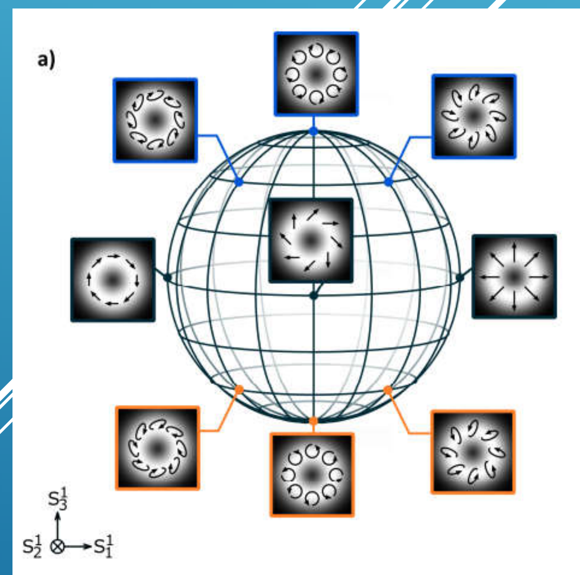
Polarization projections, seed, idler conj, idler NC arXiv:2005.01855v1 [physics.optics] 4 May 2020

Quantum-optical Description of Phase Conjugation of Vector Vortex Beams in Stimulated Parametric Down Conversion

A. G. de Oliveira,[1] N. Rubiano da Silva,[1] R. Medeiros de Araújo,[1] P. H. Souto Ribeiro,[1,*] and S. P. Walborn[2,3,4]

[1] Departamento de Física, Universidade Federal de Santa Catarina, CEP 88040-900, Florianóplis, SC, Brazil
[2] Instituto de Física, Universidade Federal do Rio de Janeiro, Caixa Postal 68528, Rio de Janeiro, RJ 21941-972, Brazil
[3] Departamento de Física, Universidad de Concepción, 160-C Concepción, Chile
[4] Millennium Institute for Research in Optics, Universidad de Concepción, 160-C Concepción, Chile





$$\hat{\varrho}_i^{stim} = \sum_{j,k=H,V} \gamma_{\bar{j}}\gamma^*_{\bar{k}}\delta^*_j\delta_k \left|j,\Phi^*_j\right\rangle \left\langle k,\Phi^*_k\right|$$

Submitted to Phys. Rev. Applied

Conclusions and Perspectives

- Quantum Thermodynamics with Gaussian beams and entanglement brings new insights

- Converting information into work, optical heat engines ??

- Experimental study of Fluctuation Relations
  - out of Equilibrium physics

- Vector/vector vortex beam phase conjugation in StimPDC

- Anisotropic wavefront reconstruction

Looking forward to have you visiting us here

Thank you!