Optical Computing Based on Transverse Spatial Modulation of Light

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Florianópolis - Brazil

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Mini-symposium on Sensor Network Localization and Dynamical Distance Geometry

Quantum Information group GIQSUL – Federal University of Santa Catarina

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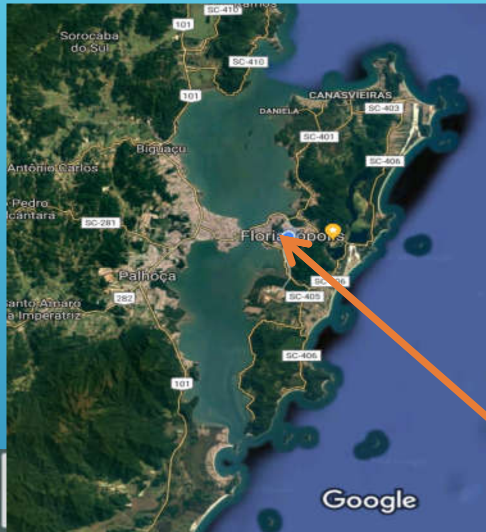

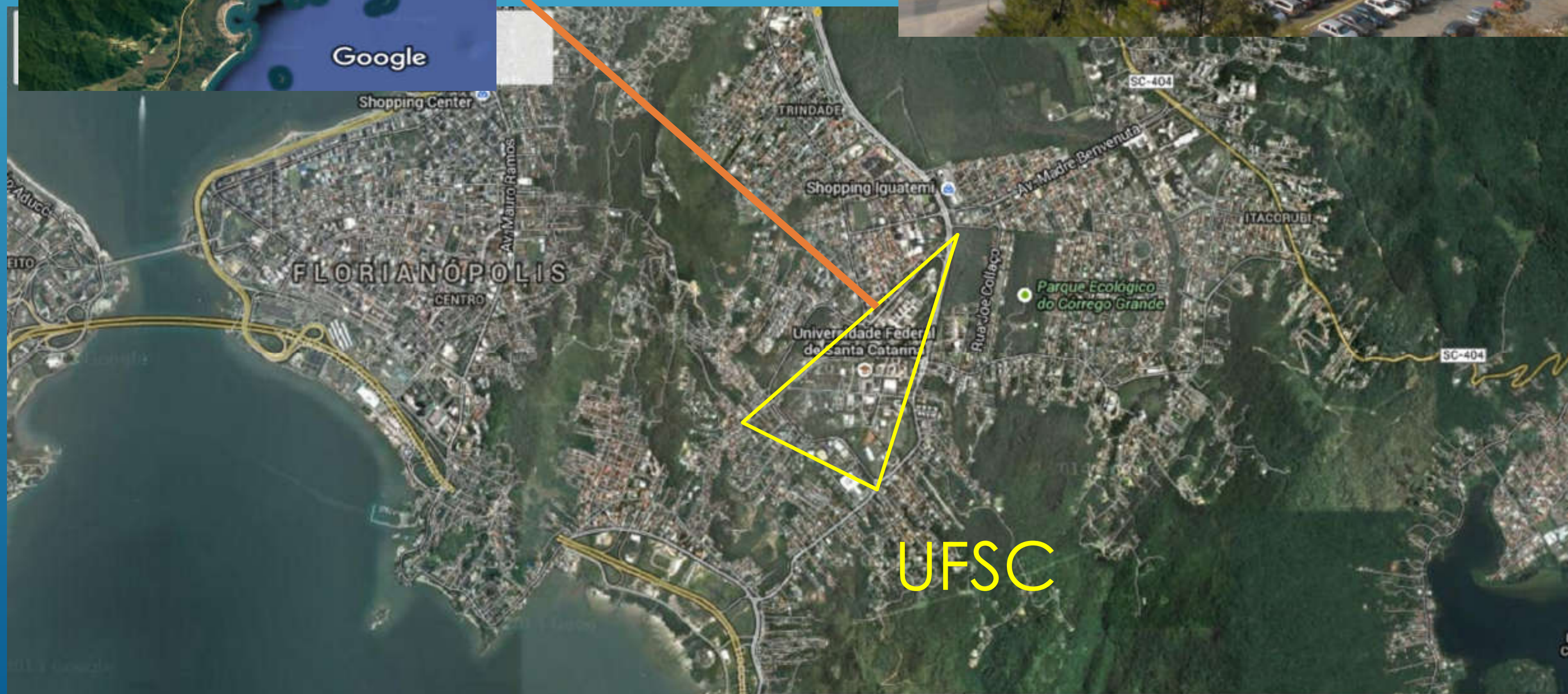

Florianópolis – SC - Brazil

Department of Physics – UFSC
GIQSUL – Optics and Quantum Information

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Antonio Mucherino – U. Rennes
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Sergei Kulik – U. Moscow
Xiasong Ma – U. Nanjing
Paula Borges Monteiro - IFSC
Willamys C. S. Silva - UFAL

Quantum Computation
Quantum Advantage

2020 Optical setup

2019 superconductor chip

QUANTUM COMPUTING

Quantum computational advantage using photons

Han-Sen Zhong[1,2]*, Hui Wang[1,2]*, Yu-Hao Deng[1,2]*, Ming-Cheng Chen[1,2]*, Li-Chao Peng[1,2], Yi-Han Luo[1,2], Jian Qin[1,2], Dian Wu[1,2], Xing Ding[1,2], Yi Hu[1,2], Peng Hu[3], Xiao-Yan Yang[3], Wei-Jun Zhang[3], Hao Li[3], Yuxuan Li[4], Xiao Jiang[1,2], Lin Gan[4], Guangwen Yang[4], Lixing You[3], Zhen Wang[3], Li Li[1,2], Nai-Le Liu[1,2], Chao-Yang Lu[1,2]†, Jian-Wei Pan[1,2]†

Zhong *et al.*, *Science* **370**, 1460–1463 (2020)   18 December 2020

Article

Quantum supremacy using a programmable superconducting processor

https://doi.org/10.1038/s41586-019-1666-5
Received: 22 July 2019
Accepted: 20 September 2019
Published online: 23 October 2019

Frank Arute[1], Kunal Arya[1], Ryan Babbush[1], Dave Bacon[1], Joseph C. Bardin[1,2], Rami Barends[1], Rupak Biswas[3], Sergio Boixo[1], Fernando G. S. L. Brandao[1,4], David A. Buell[1], Brian Burkett[1], Yu Chen

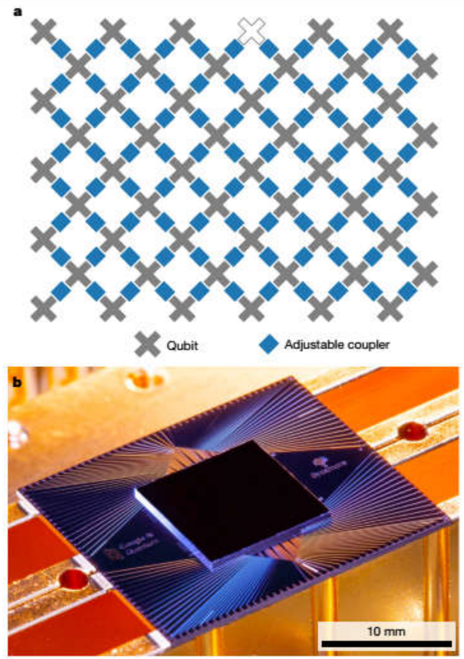

Fig. 1 | The Sycamore processor. a, Layout of processor, showing a rectangular array of 54 qubits (grey), each connected to its four nearest neighbours with couplers (blue). The inoperable qubit is outlined. **b**, Photograph of the Sycamore chip.

Quantum Computation
Quantum Advantage

2020 Optical setup

QUANTUM COMPUTING

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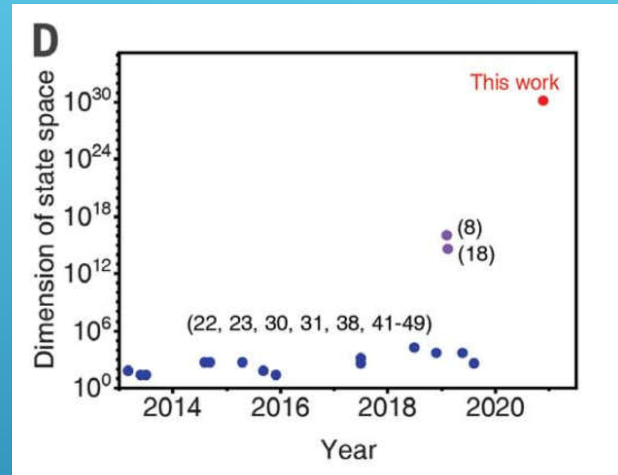
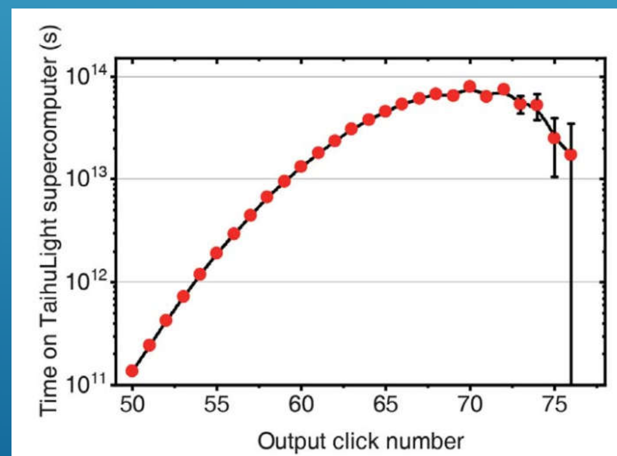
Zhong *et al.*, *Science* **370**, 1460–1463 (2020) 18 December 2020



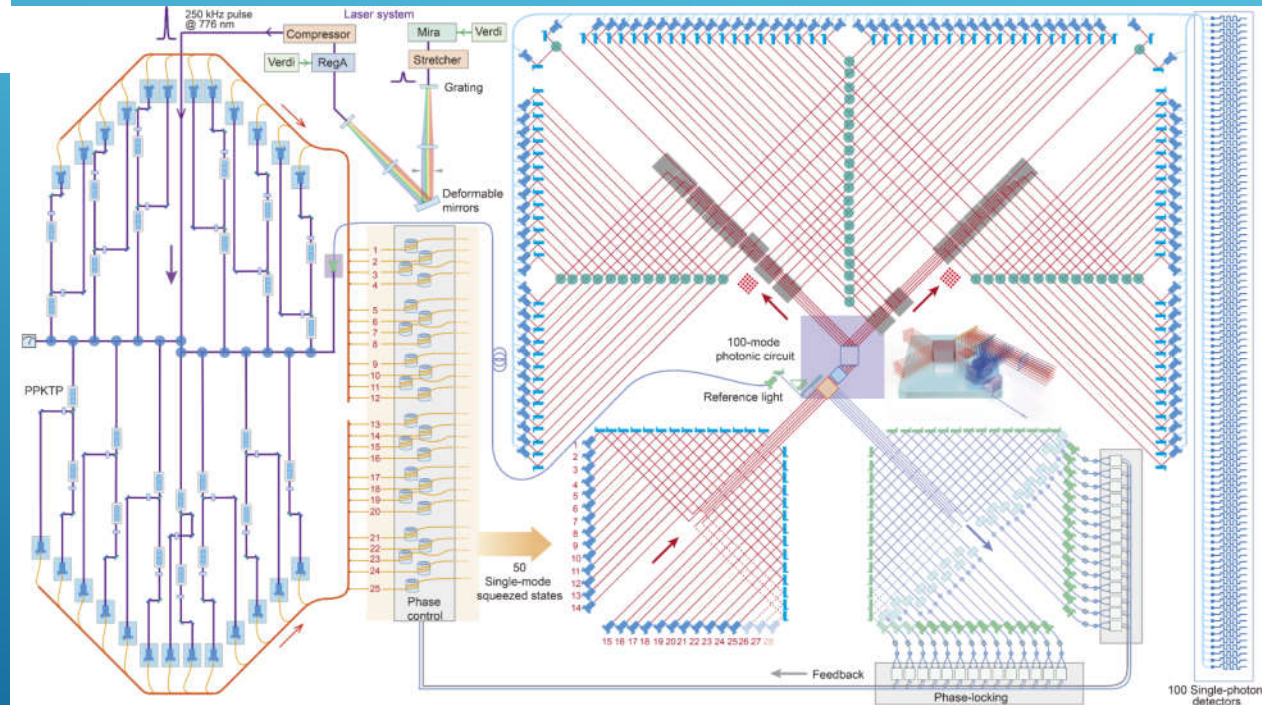


Photonic Computation
Quantum Advantage

QUANTUM COMPUTING

Quantum computational advantage using photons

Han-Sen Zhong[1,2]*, Hui Wang[1,2]*, Yu-Hao Deng[1,2]*, Ming-Cheng Chen[1,2]*, Li-Chao Peng[1,2], Yi-Han Luo[1,2], Jian Qin[1,2], Dian Wu[1,2], Xing Ding[1,2], Yi Hu[1,2], Peng Hu[3], Xiao-Yan Yang[3], Wei-Jun Zhang[3], Hao Li[3], Yuxuan Li[4], Xiao Jiang[1,2], Lin Gan[4], Guangwen Yang[4], Lixing You[3], Zhen Wang[3], Li Li[1,2], Nai-Le Liu[1,2], Chao-Yang Lu[1,2]†, Jian-Wei Pan[1,2]†



Photonic Computation
Quantum Advantage/Boson Sampling

2012

Boson Sampling on a Photonic Chip

Justin B. Spring,[1]* Benjamin J. Metcalf,[1] Peter C. Humphreys,[1] W. Steven Kolthammer,[1] Xian-Min Jin,[1,2] Marco Barbieri,[1] Animesh Datta,[1] Nicholas Thomas-Peter,[1] Nathan K. Langford,[1,3] Dmytro Kundys,[4] James C. Gates,[4] Brian J. Smith,[1] Peter G. R. Smith,[4] Ian A. Walmsley[1]*

15 FEBRUARY 2013 VOL 339 **SCIENCE**

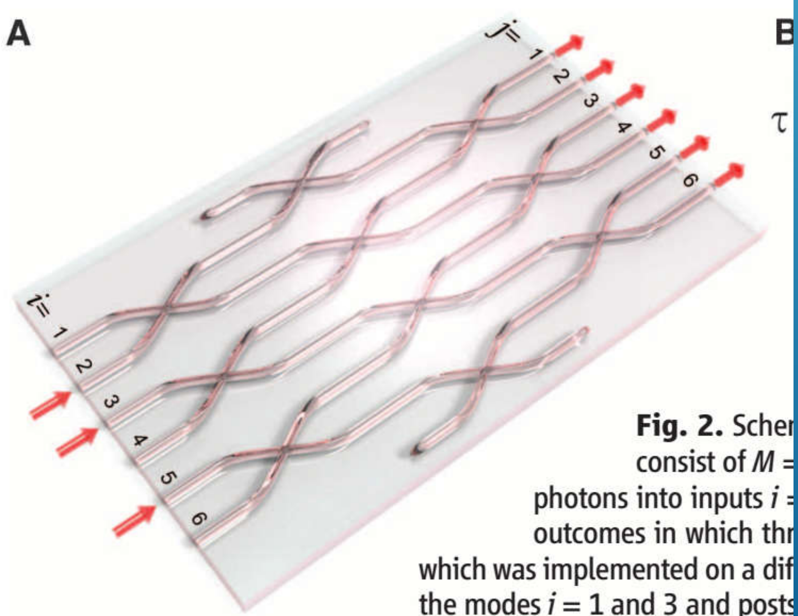


Fig. 2. Scher
consist of M =
photons into inputs i =
outcomes in which thr
which was implemented on a dif
the modes i = 1 and 3 and posts

3 photons
6 modes

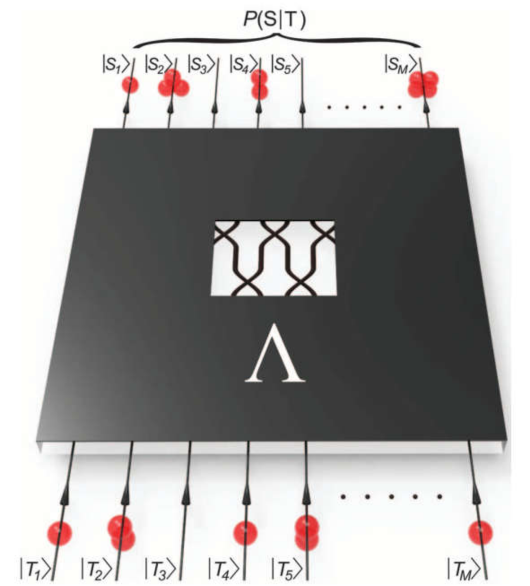
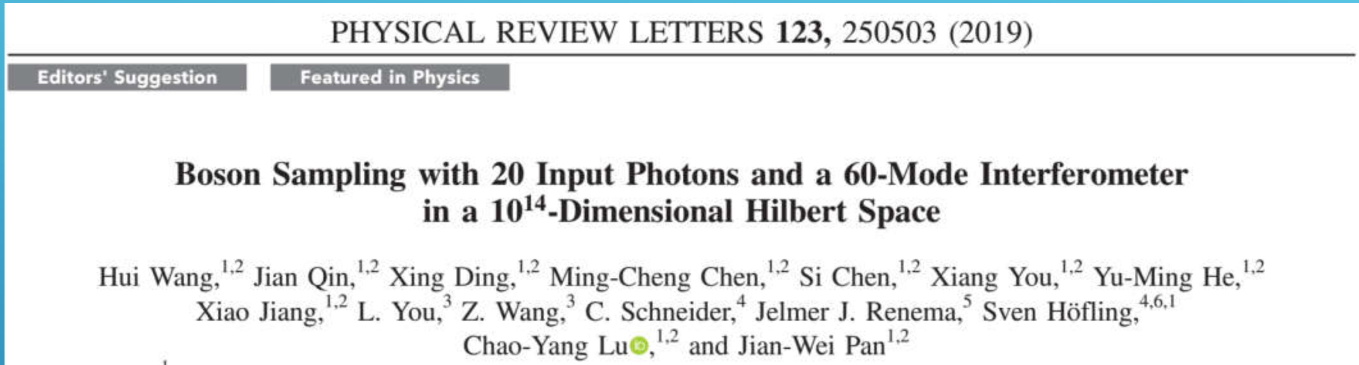


Fig. 1. Model of quantum boson sampling. Given a specified initial number state $|\mathbf{T}\rangle = |T_1 \ldots T_M\rangle$ and linear transformation Λ, a QBSM efficiently samples from the distribution $P(\mathbf{S}|\mathbf{T})$ of possible outcomes $|\mathbf{S}\rangle = |S_1 \ldots S_M\rangle$.

$$P(\mathbf{S}|\mathbf{T}) = |\langle \mathbf{S}|\Psi_{\text{out}}\rangle|^2 = \frac{|\mathrm{Per}(\mathbf{\Lambda}^{(\mathbf{S},\mathbf{T})})|^2}{\prod_{j=1}^{M} S_j! \prod_{i=1}^{M} T_i!}$$

Photonic Computation
Quantum Advantage/Boson Sampling



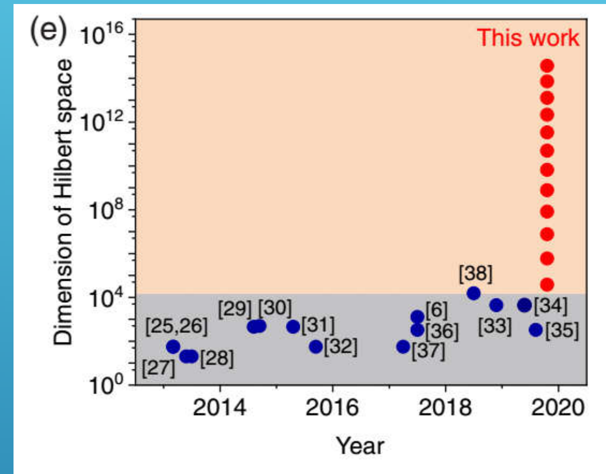
PHYSICAL REVIEW LETTERS **123**, 250503 (2019)

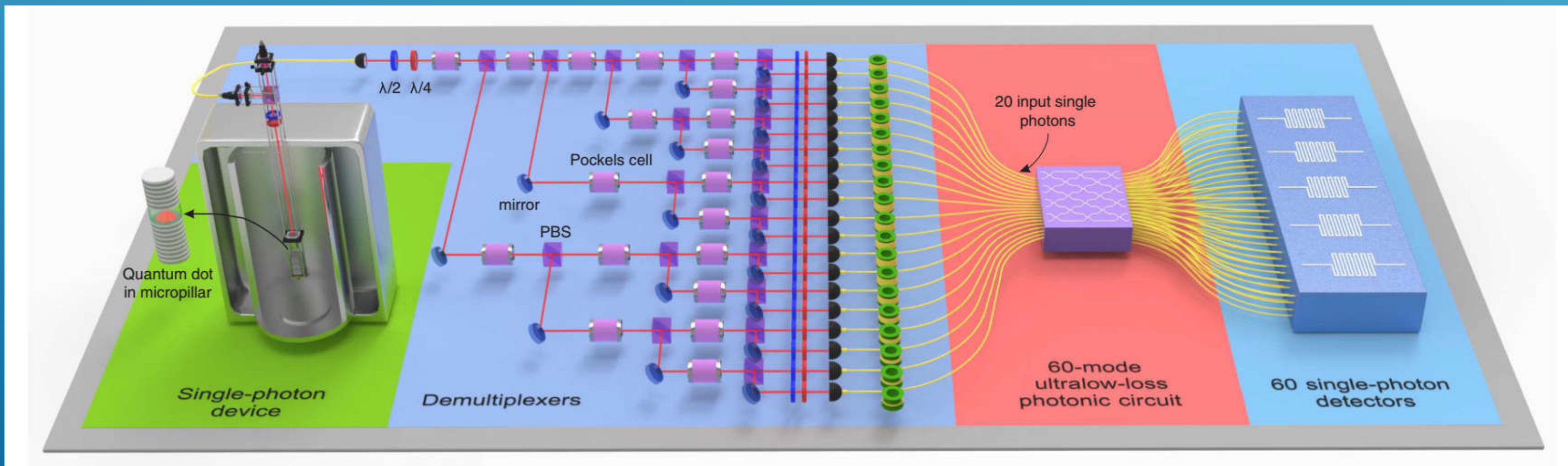
Editors' Suggestion | Featured in Physics

Boson Sampling with 20 Input Photons and a 60-Mode Interferometer in a 10^{14}-Dimensional Hilbert Space

Hui Wang,[1,2] Jian Qin,[1,2] Xing Ding,[1,2] Ming-Cheng Chen,[1,2] Si Chen,[1,2] Xiang You,[1,2] Yu-Ming He,[1,2] Xiao Jiang,[1,2] L. You,[3] Z. Wang,[3] C. Schneider,[4] Jelmer J. Renema,[5] Sven Höfling,[4,6,1] Chao-Yang Lu,[1,2] and Jian-Wei Pan[1,2]

2019





20 photons
60 modes

Photonic Computation
GaussianBoson Sampling

2020

QUANTUM COMPUTING

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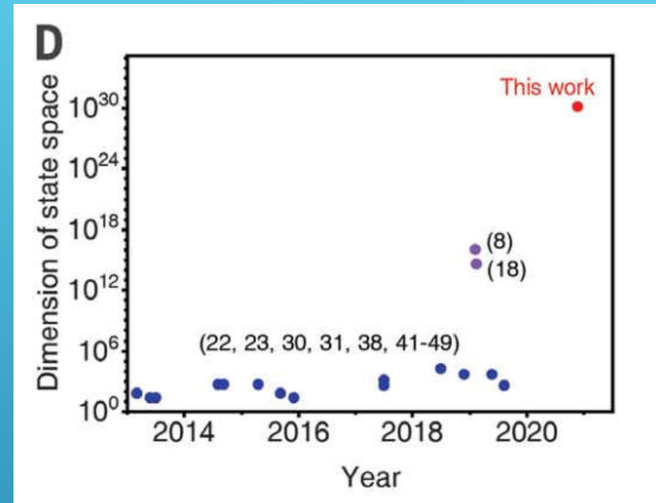
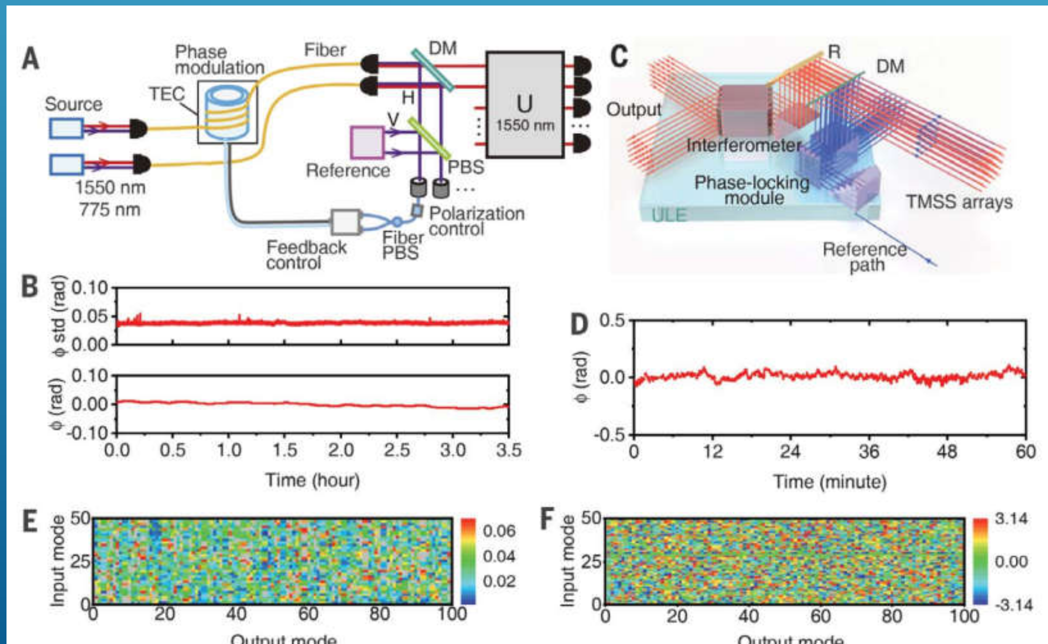
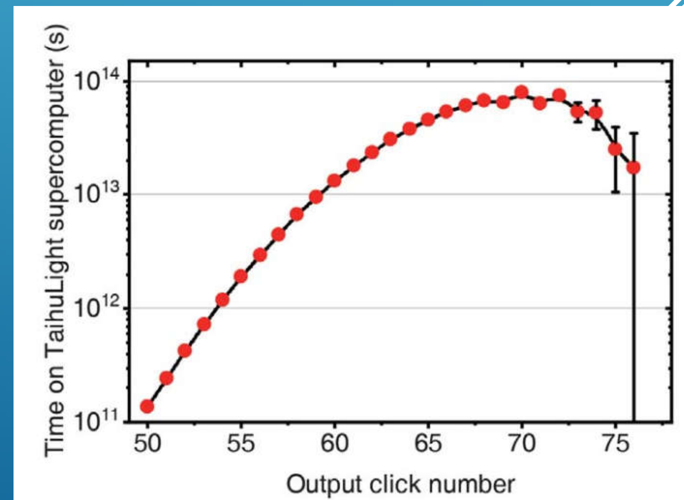
Han-Sen Zhong[1,2]*, Hui Wang[1,2]*, Yu-Hao Deng[1,2]*, Ming-Cheng Chen[1,2]*, Li-Chao Peng[1,2], Yi-Han Luo[1,2], Jian Qin[1,2], Dian Wu[1,2], Xing Ding[1,2], Yi Hu[1,2], Peng Hu[3], Xiao-Yan Yang[3], Wei-Jun Zhang[3], Hao Li[3], Yuxuan Li[4], Xiao Jiang[1,2], Lin Gan[4], Guangwen Yang[4], Lixing You[3], Zhen Wang[3], Li Li[1,2], Nai-Le Liu[1,2], Chao-Yang Lu[1,2]†, Jian-Wei Pan[1,2]†

Zhong *et al.*, *Science* **370**, 1460–1463 (2020)   18 December 2020







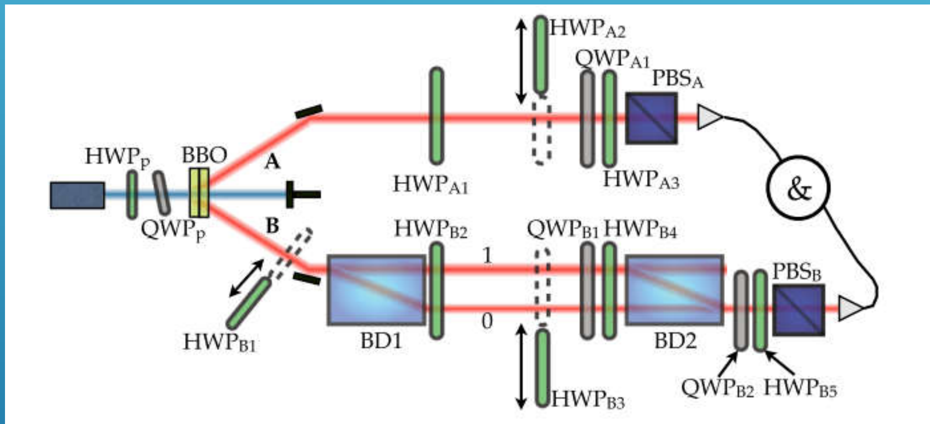
50 SMSS
100 modes

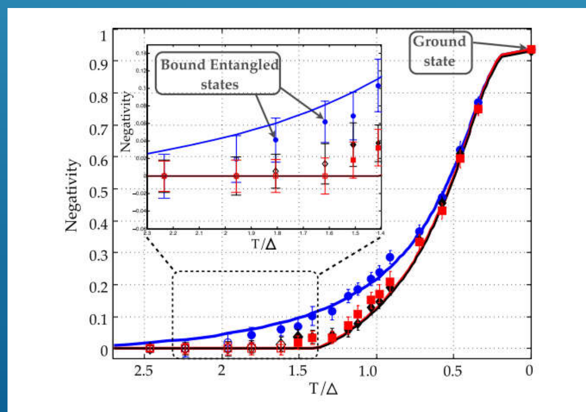
3-qubit Optical Quantum Simulation

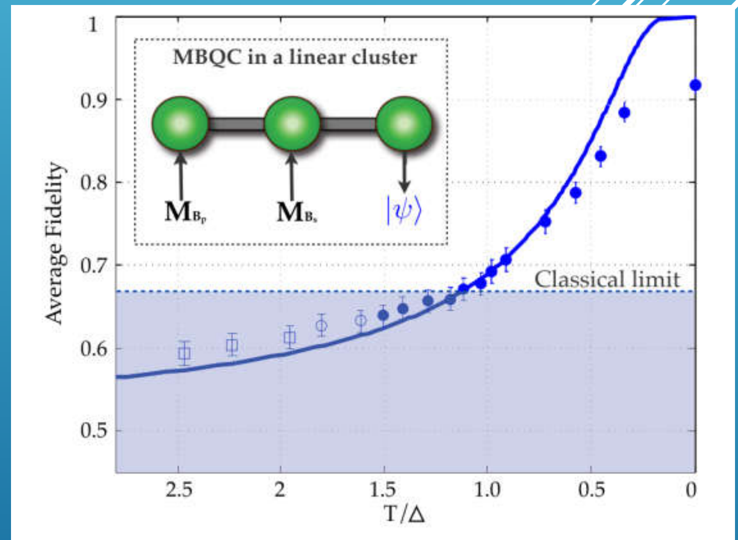
PRL **112,** 160501 (2014) PHYSICAL REVIEW LETTERS week ending 25 APRIL 2014

Linear-Optical Simulation of the Cooling of a Cluster-State Hamiltonian System

G. H. Aguilar,[1] T. Kolb,[1] D. Cavalcanti,[2] L. Aolita,[3] R. Chaves,[4] S. P. Walborn,[1] and P. H. Souto Ribeiro[1]







Quantum simulation with classical light: Analogy between the paraxial wave equation and 2D Schrödinger equation

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

$\nabla_T^2 A + 2ik\frac{\partial A}{\partial z} = 0$ Helmholtz paraxial equation:

Time dependent Schrödinger equation: $\nabla^2 \psi + i\frac{2m}{\hbar}\frac{\partial \psi}{\partial t} = 0$

Quantum simulation:

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

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

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

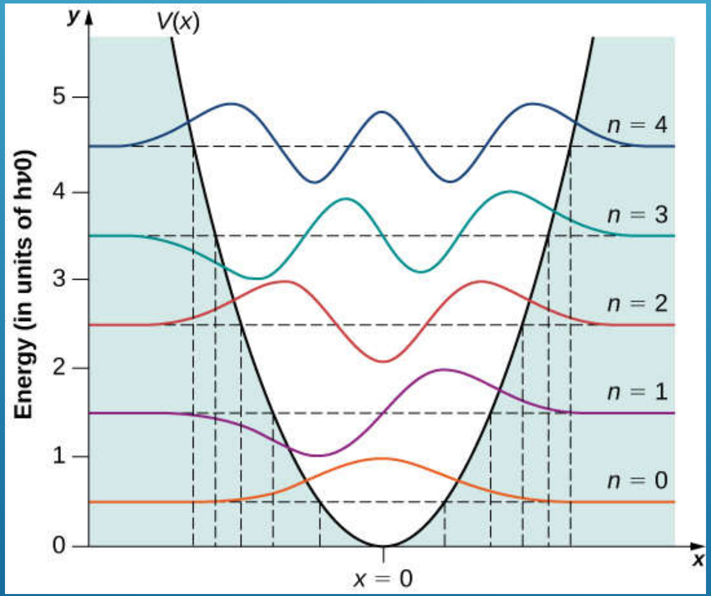
D. Marcuse. Light Transmission Optics . (Van Nostrand Reinhold Company, New York, 1982).

Quantum simulation with classical light: Analogy between the paraxial wave equation and 2D Schrödinger equation

Quantum Harmonic Oscillator

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

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



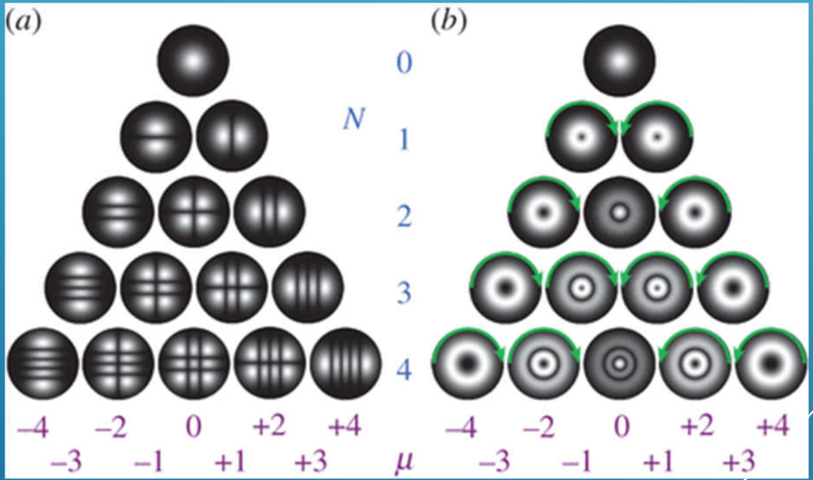
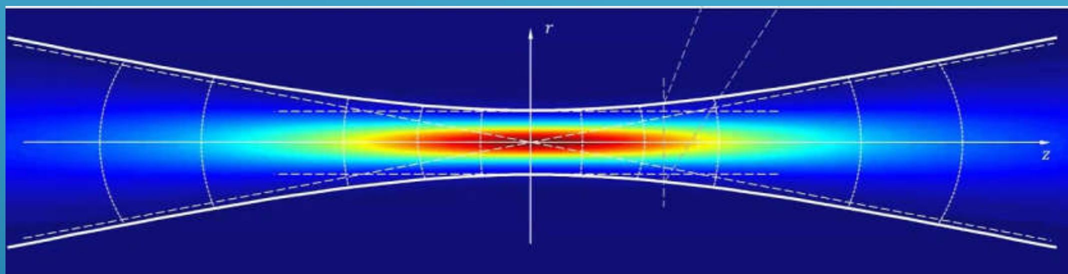
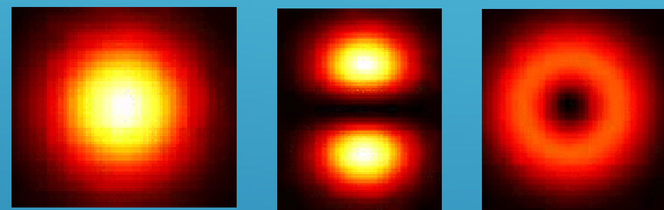


Figure credits:
Phil. Trans. R. Soc. A
Swings and roundabouts: optical Poincaré spheres for polarization and Gaussian beams, M. R. Dennis, M. A. Alonso,
DOI: 10.1098/rsta.2015.0441

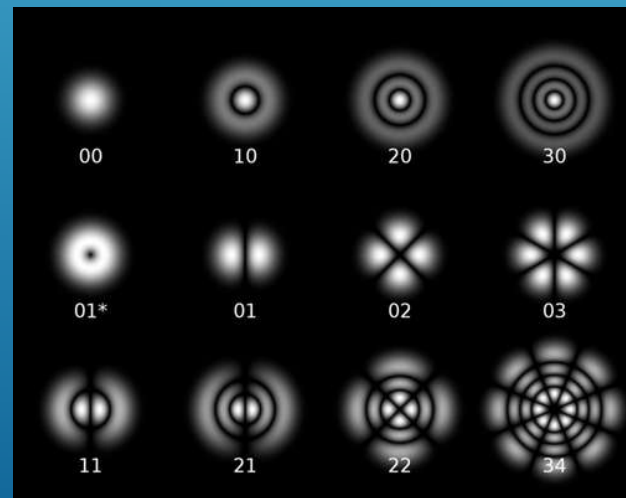
Quantum simulation with classical light: Analogy between the paraxial wave equation and 2D Schrödinger equation

Gaussian beams





Laguerre-Gaussian beams, Hermite-Gaussian beams and linear combinations



Quantum Simulation Using Classical Light

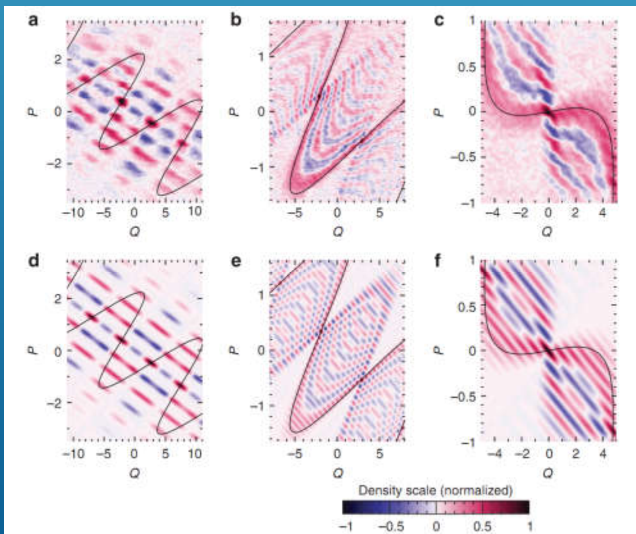
nature COMMUNICATIONS

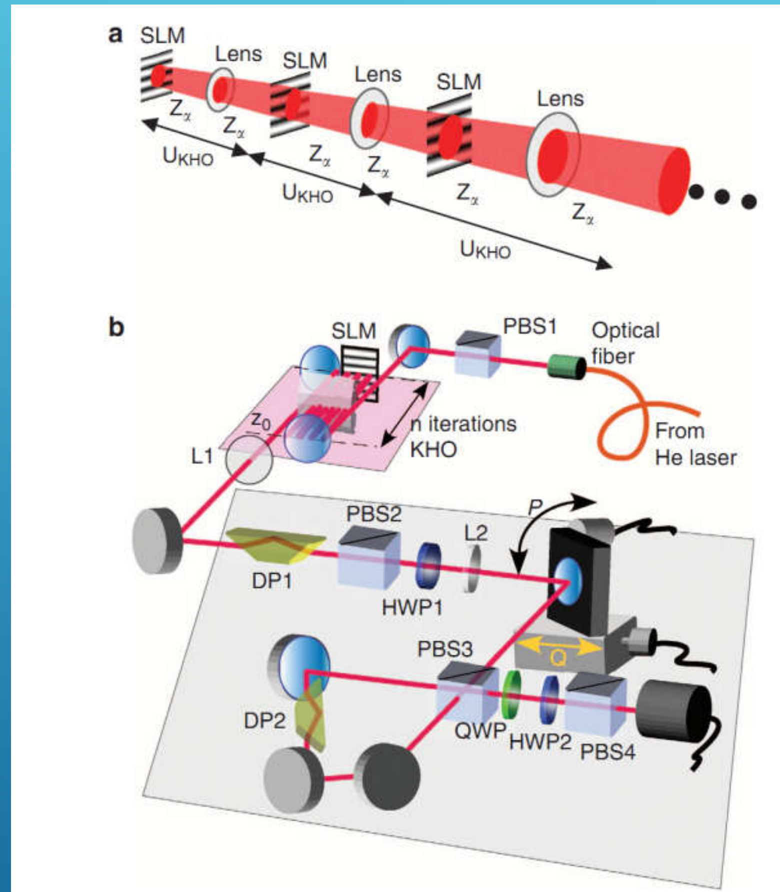
ARTICLE

Received 18 Sep 2012 | Accepted 19 Oct 2012 | Published 20 Nov 2012 DOI: 10.1038/ncomms2214

Experimental observation of quantum chaos in a beam of light

Gabriela B. Lemos[1], Rafael M. Gomes[1], Stephen P. Walborn[1], Paulo H. Souto Ribeiro[1] & Fabricio Toscano[1]





Emulating a quantum harmonic oscillator to study quantum thermodynamics

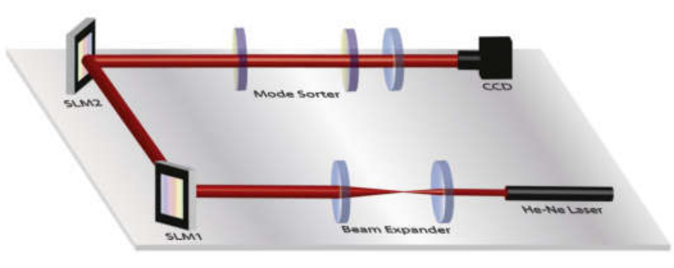
J. Phys. Commun. 2 (2018) 035012 https://doi.org/10.1088/2399-6528/aab178

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]



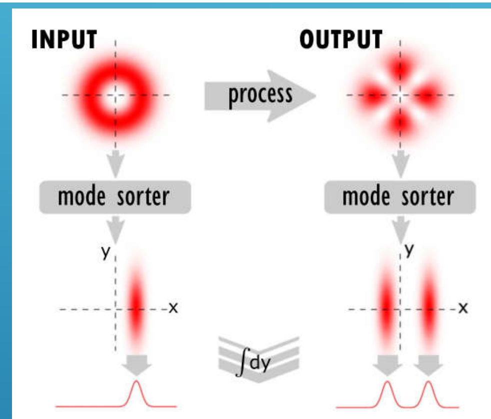
$$H = (N_r + N_l + 1)\hbar\omega$$

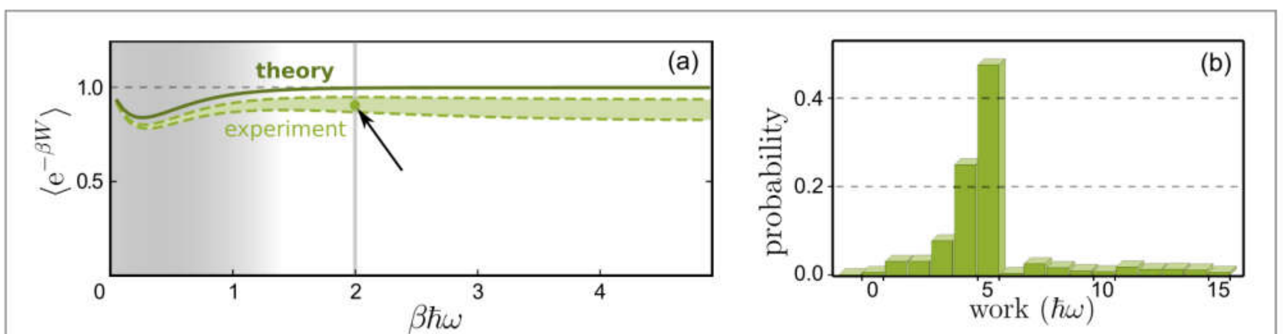
$$L_z = (N_r - N_l)\hbar$$

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

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

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



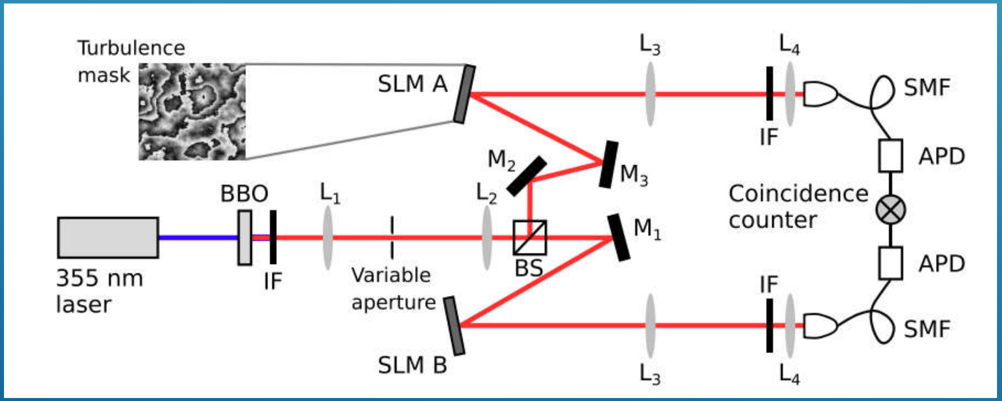


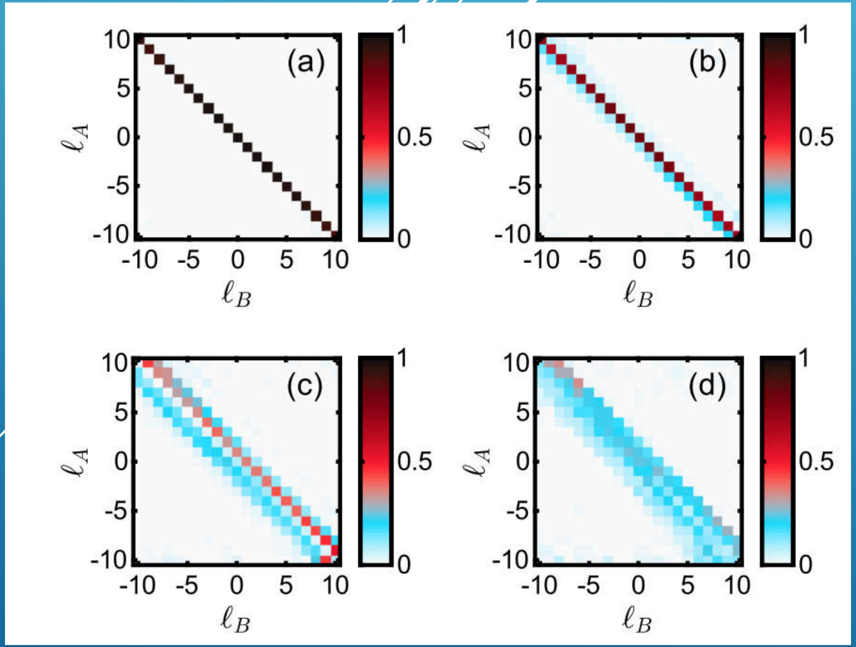
Experimental study of quantum thermodynamics using entangled photons

PHYSICAL REVIEW A **101**, 052113 (2020)

Experimental study of the generalized Jarzynski 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. Soares,[2] R. J. de Assis,[3] L. C. Céleri,[3,4,†] and A. Forbes[5,‡]



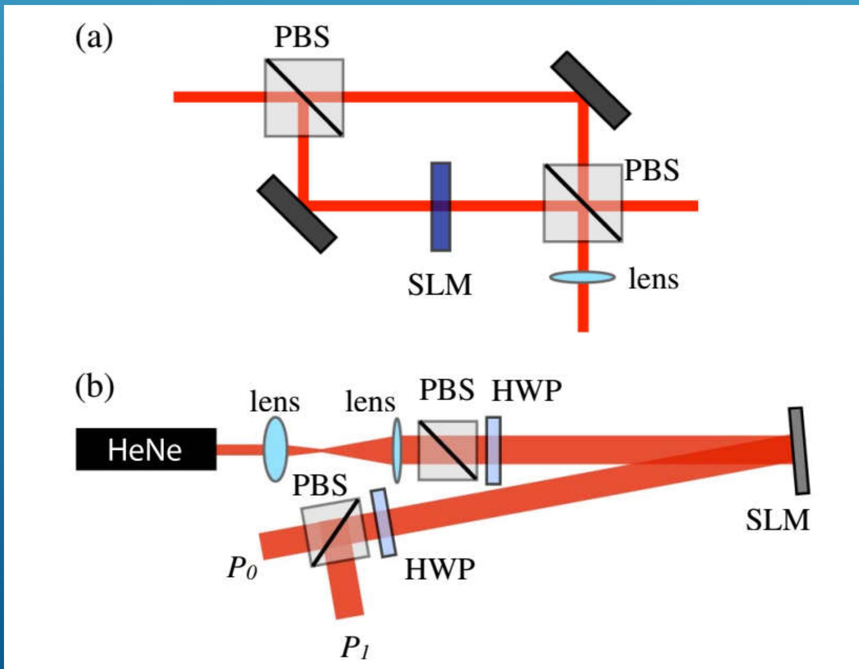


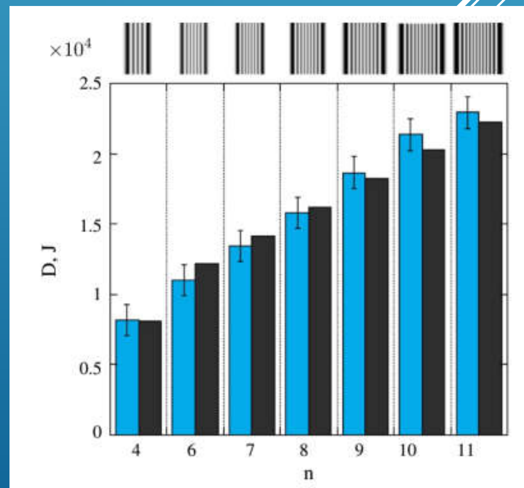
Optical integration

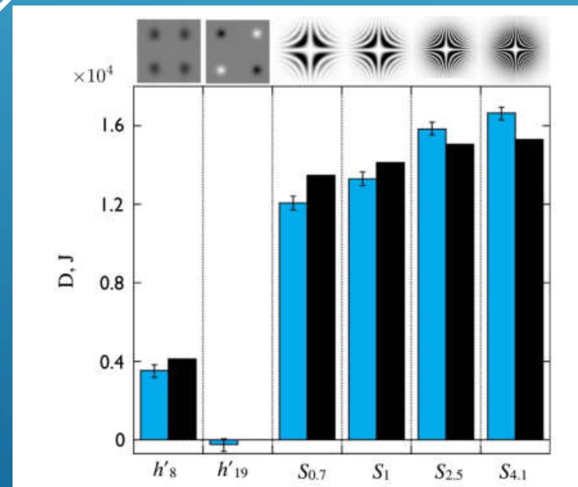
J. Opt. Soc. Am. A / Vol. 31, No. 4 / April 2014

Optical integration of a real-valued function by measurement of a Stokes parameter

G. B. Lemos,[1,2,3,*] P. H. Souto Ribeiro,[1] and S. P. Walborn[1]



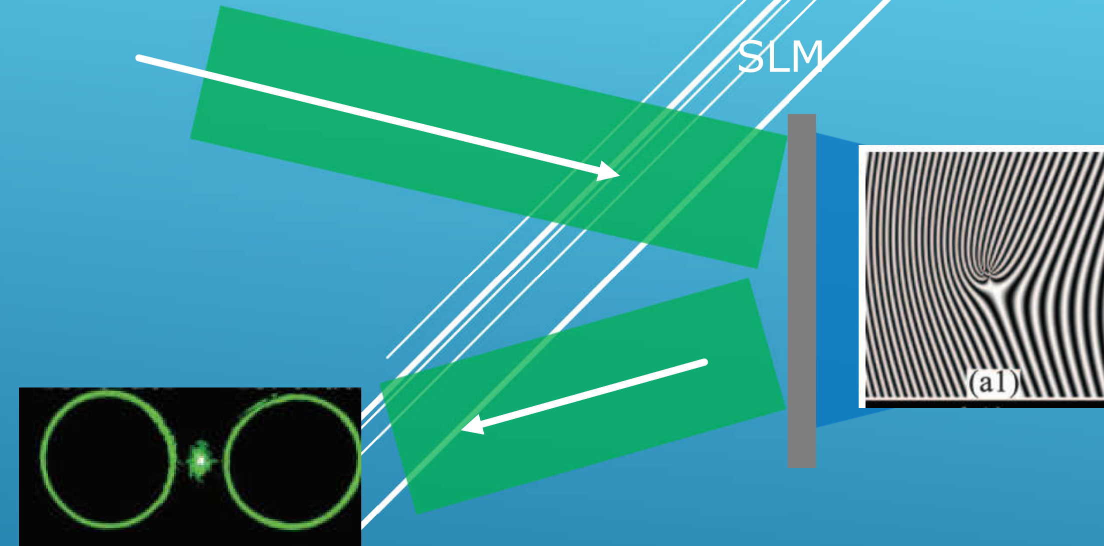




SLM

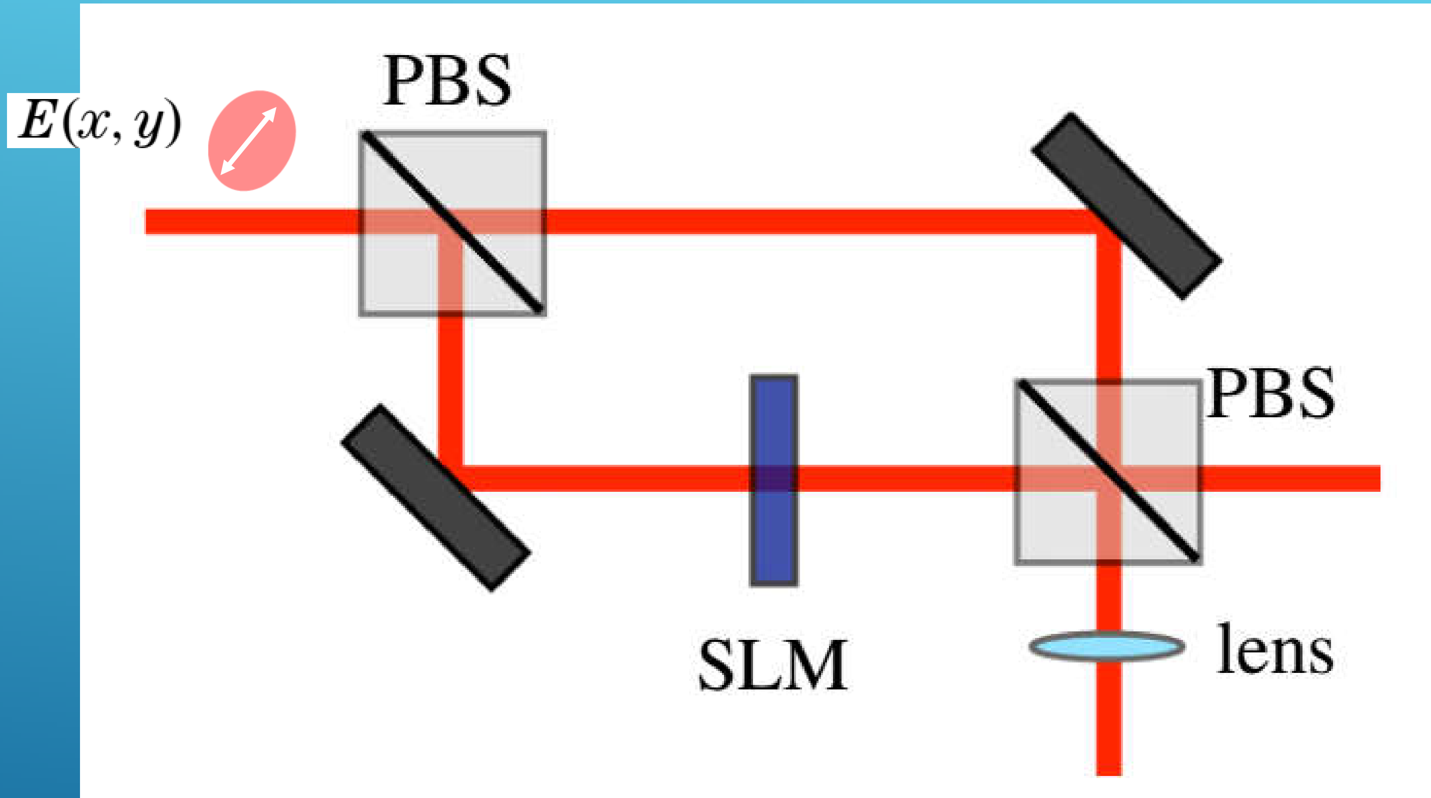
Spatial Light Modulator

Laser projection based on SLM *(Holoeye Photonics AG)*

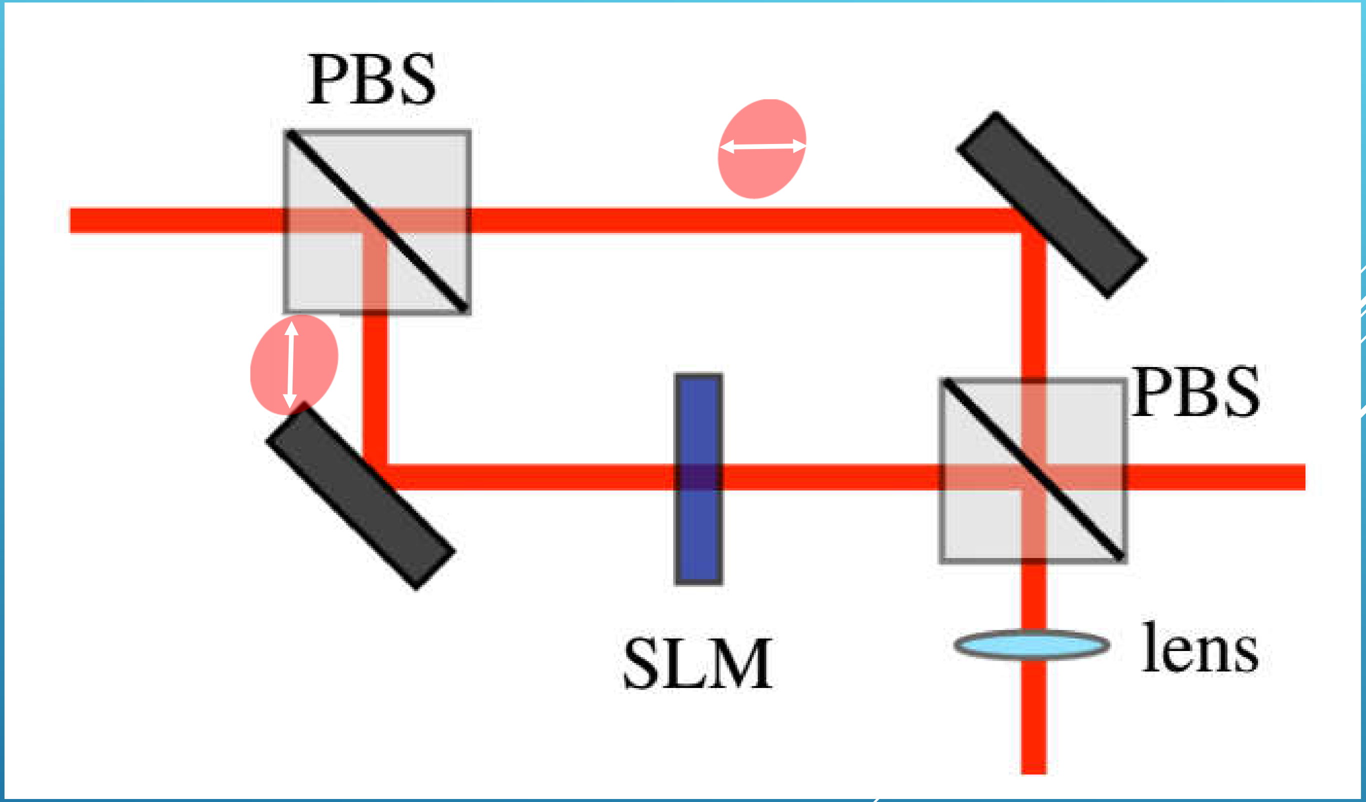


HAIXIANG MA, et al.
Vol. 42, No. 1 / January 1 2017 / Optics Letters

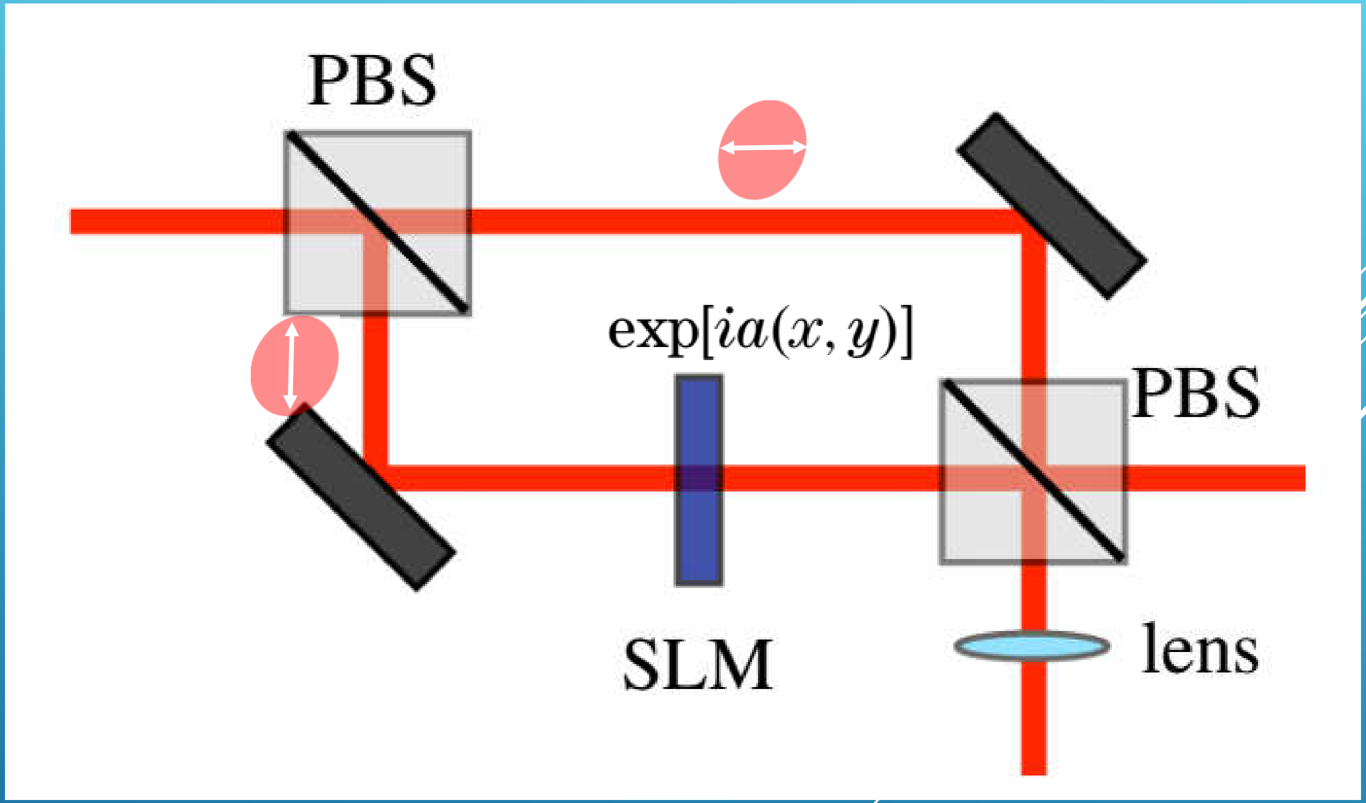
Optical integration



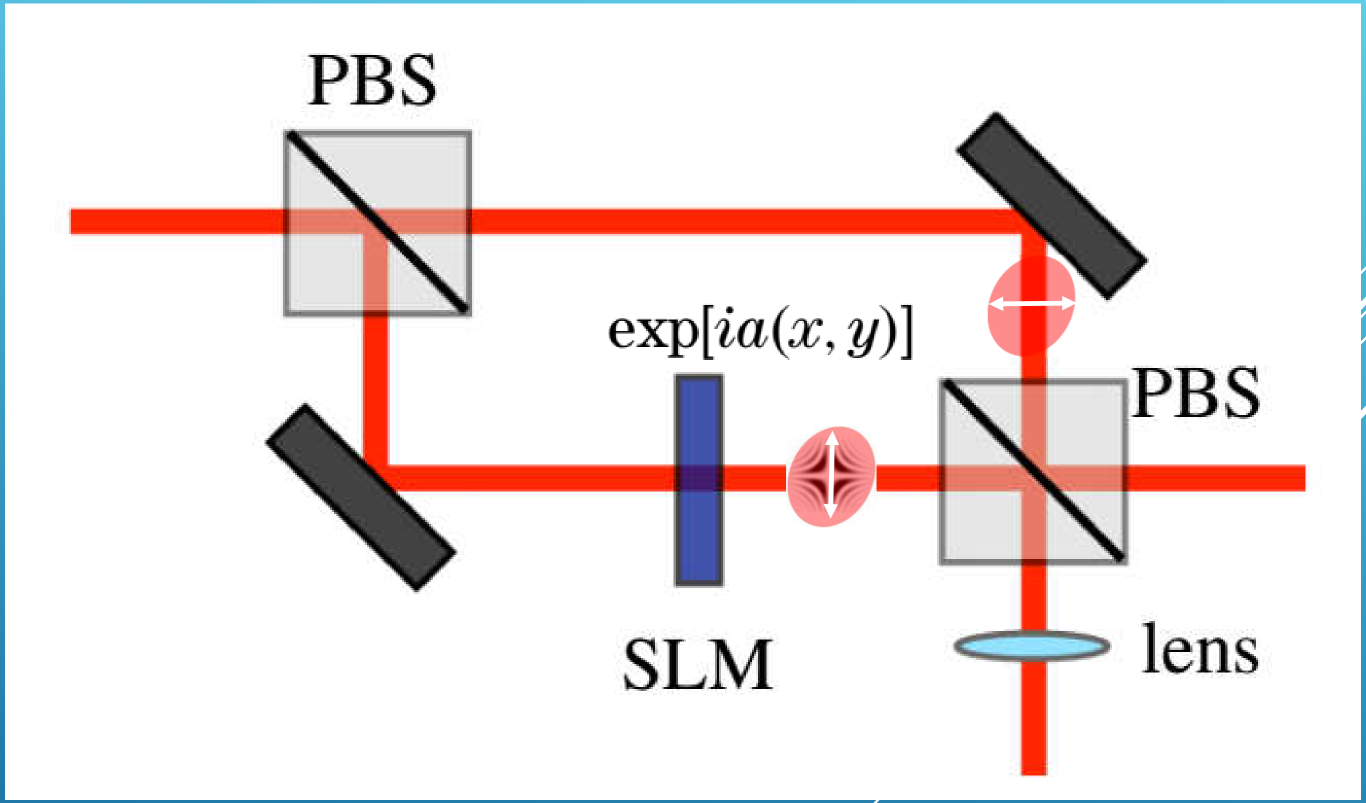
Optical integration



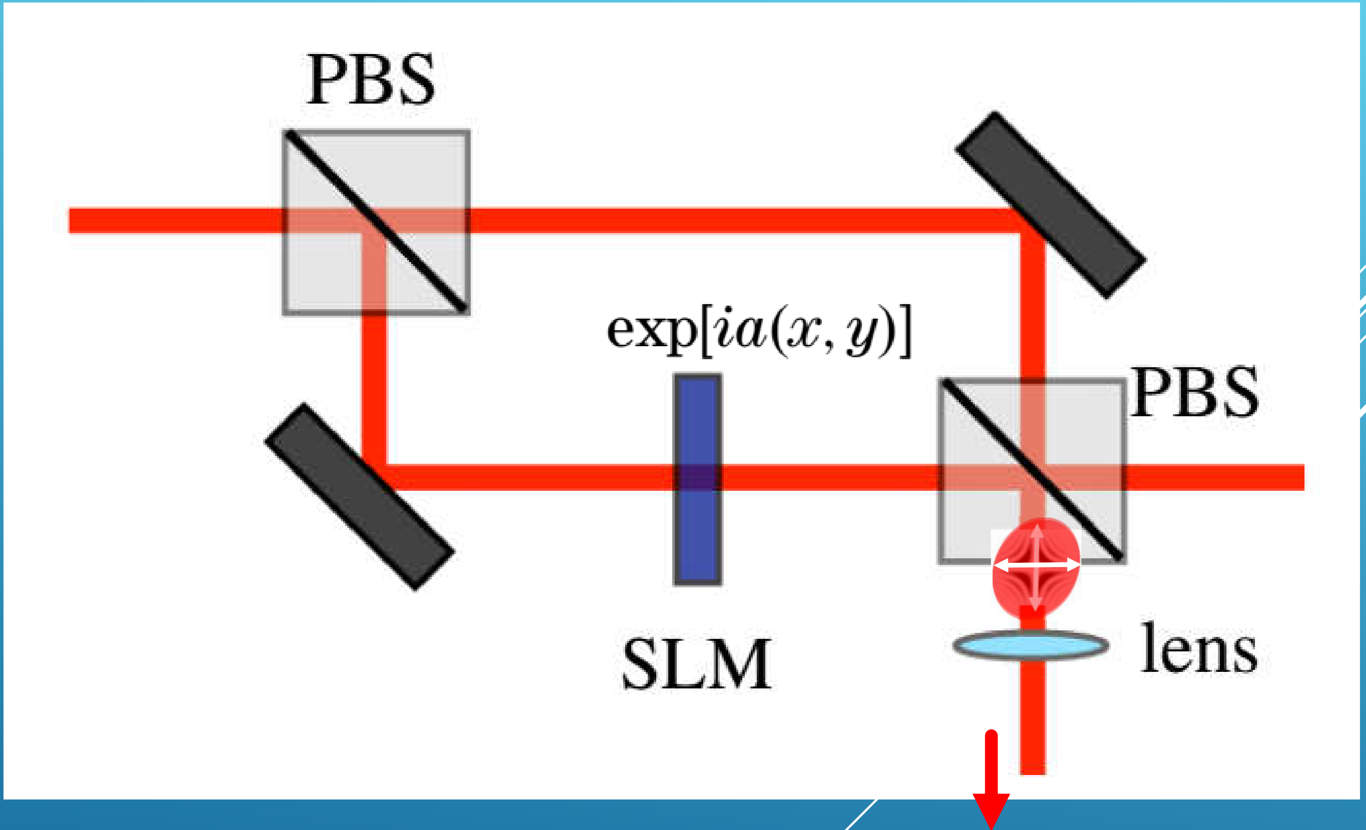
Optical integration



Optical integration

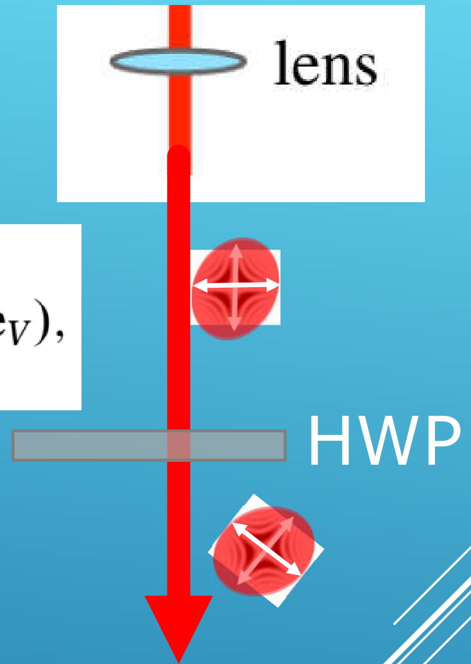


Optical integration



$$\mathbf{E}_{\mathrm{o}}(x,y) = \frac{E(x,y)}{\sqrt{2}}\left(e^{ia(x,y)}\mathbf{e}_H + \mathbf{e}_V\right),$$

Optical integration



$$\mathbf{E}_{\mathrm{o}}(x,y) = \frac{E(x,y)}{\sqrt{2}}\left(e^{ia(x,y)}\mathbf{e}_H + \mathbf{e}_V\right),$$

$$\mathbf{E}_{\mathrm{o}}(x,y) = E(x,y)\left(\frac{1+e^{ia(x,y)}}{2}\mathbf{e}_{+} + \frac{1-e^{ia(x,y)}}{2}\mathbf{e}_{-}\right),$$

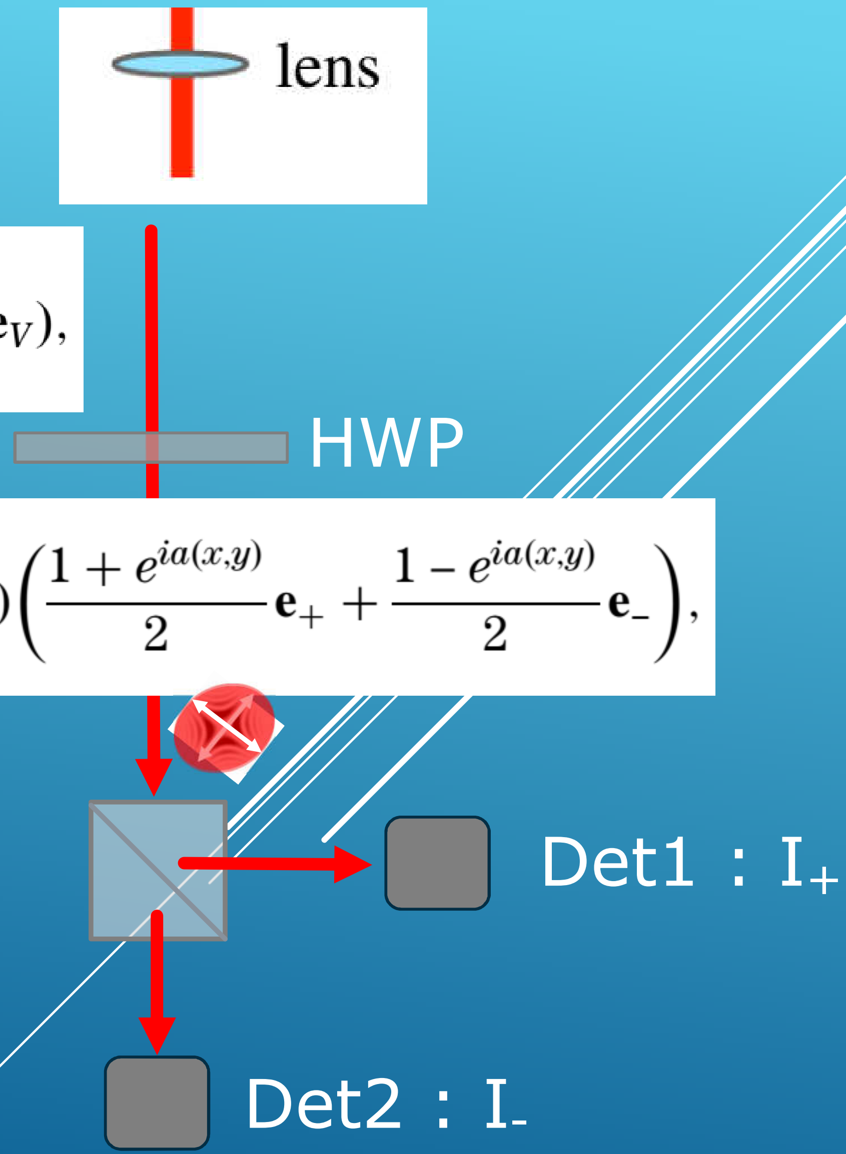
Optical integration

$$\mathbf{E}_o(x,y) = \frac{E(x,y)}{\sqrt{2}}\left(e^{ia(x,y)}\mathbf{e}_H + \mathbf{e}_V\right),$$

$$\mathbf{E}_o(x,y) = E(x,y)\left(\frac{1+e^{ia(x,y)}}{2}\mathbf{e}_+ + \frac{1-e^{ia(x,y)}}{2}\mathbf{e}_-\right),$$

$$I_\pm = \iint |E(x,y)|^2\left\{\frac{1}{2} \pm \frac{1}{4}\left(e^{ia(x,y)} + e^{-ia(x,y)}\right)\right\}\mathrm{d}x\mathrm{d}y,$$

$$I_\pm = \iint |E(x,y)|^2\frac{1}{2}\{1 \pm \cos[a(x,y)]\}\mathrm{d}x\mathrm{d}y.$$



Optical integration

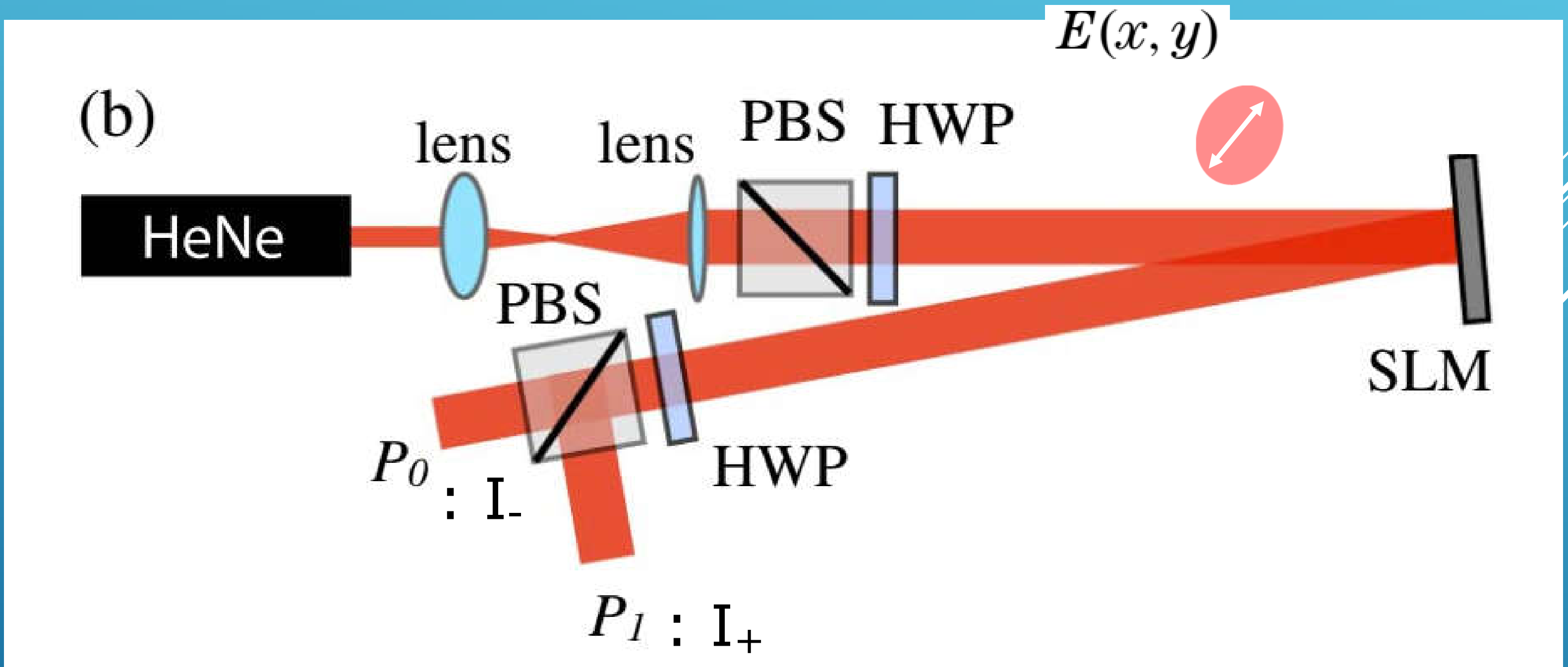
$$I_{\pm} = \iint |E(x,y)|^2 \frac{1}{2}\{1 \pm \cos[a(x,y)]\}\mathrm{d}x\mathrm{d}y.$$

$$a(x,y) = \arccos[f(x,y)],$$

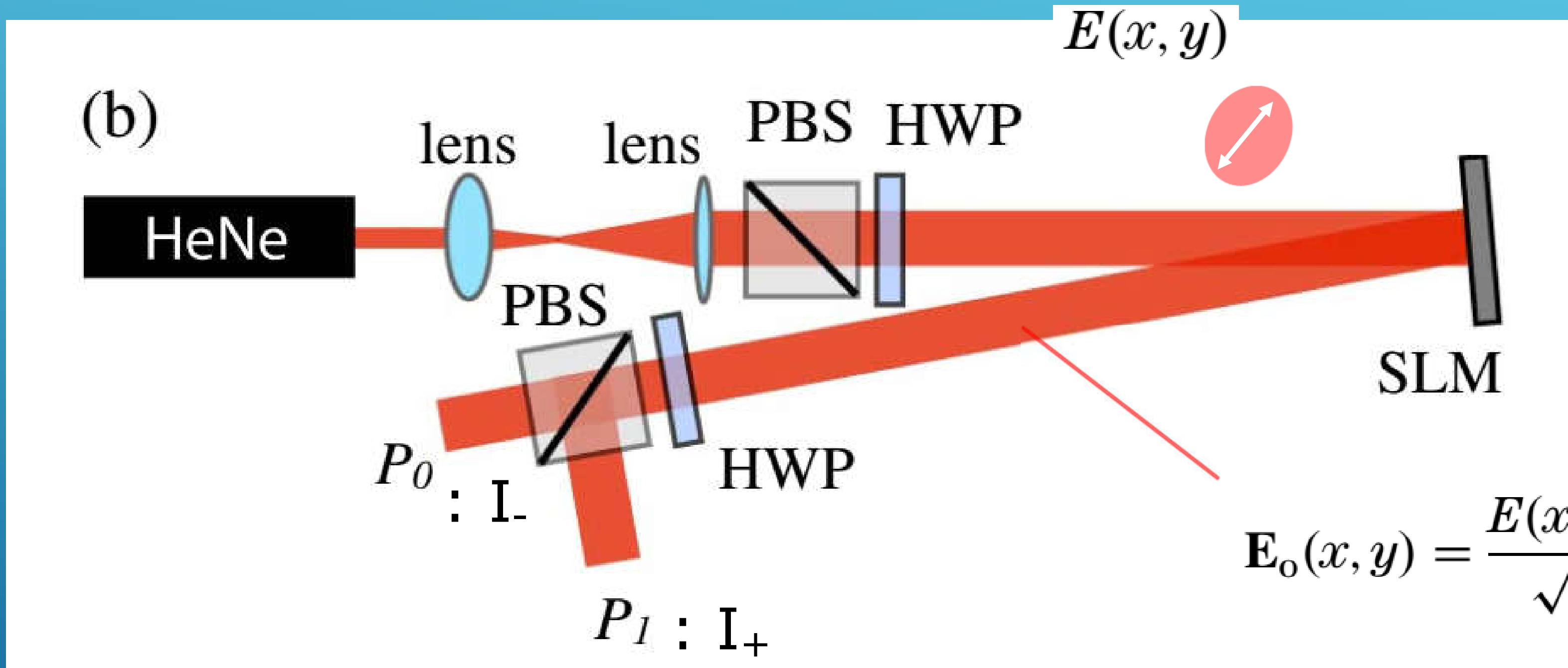
$$D = \iint |E(x,y)|^2 f(x,y)\mathrm{d}x\mathrm{d}y.$$

$$D = I_+ - I_-$$

Optical integration using reflective SLM

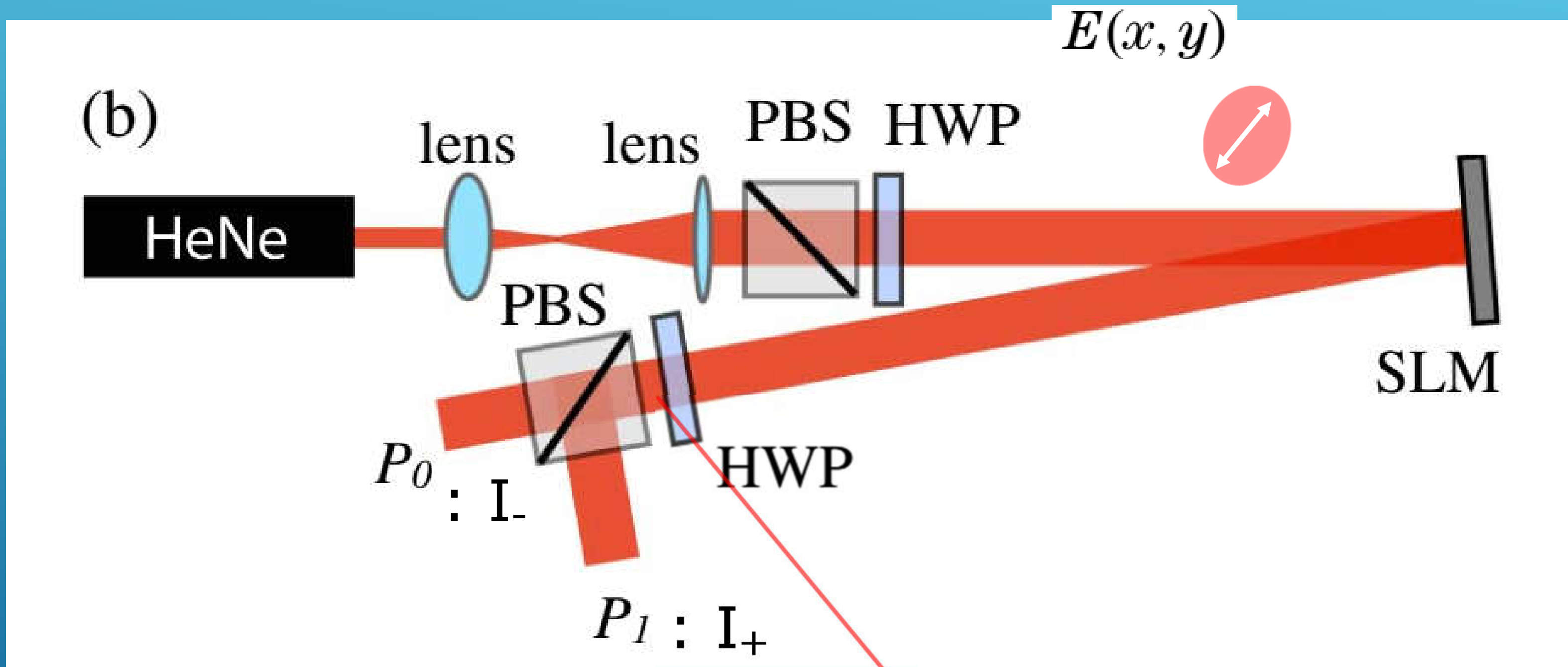


Optical integration using reflective SLM



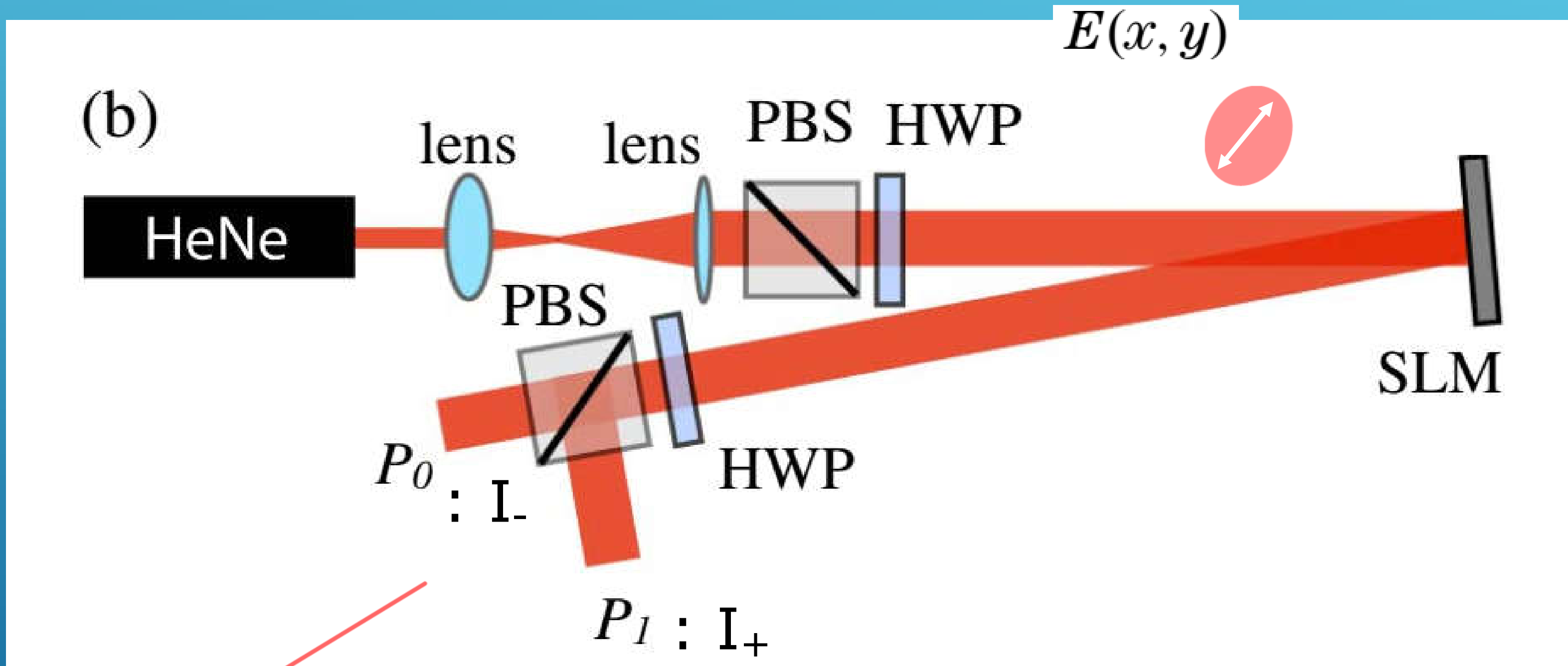
$$\mathbf{E}_{\mathrm{o}}(x,y) = \frac{E(x,y)}{\sqrt{2}}(e^{ia(x,y)}\mathbf{e}_H + \mathbf{e}_V),$$

Optical integration using reflective SLM



$$\mathbf{E}_o(x,y) = E(x,y)\left(\frac{1+e^{ia(x,y)}}{2}\mathbf{e}_+ + \frac{1-e^{ia(x,y)}}{2}\mathbf{e}_-\right),$$

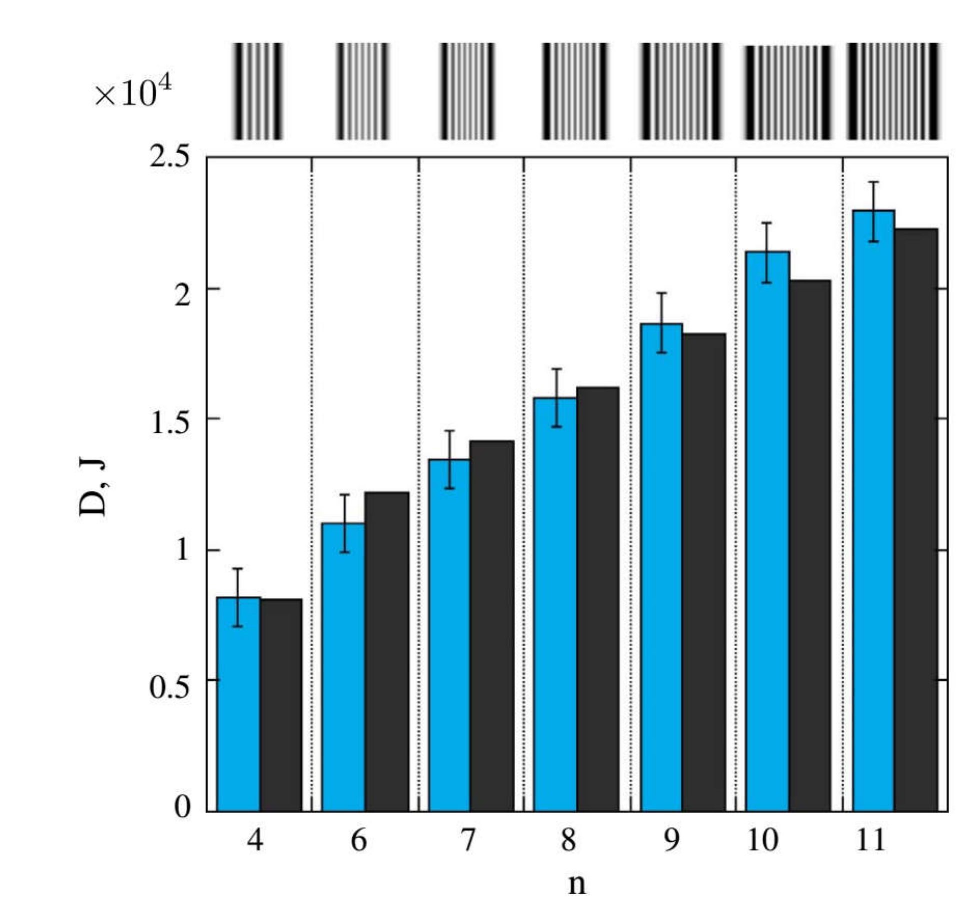
Optical integration using reflective SLM



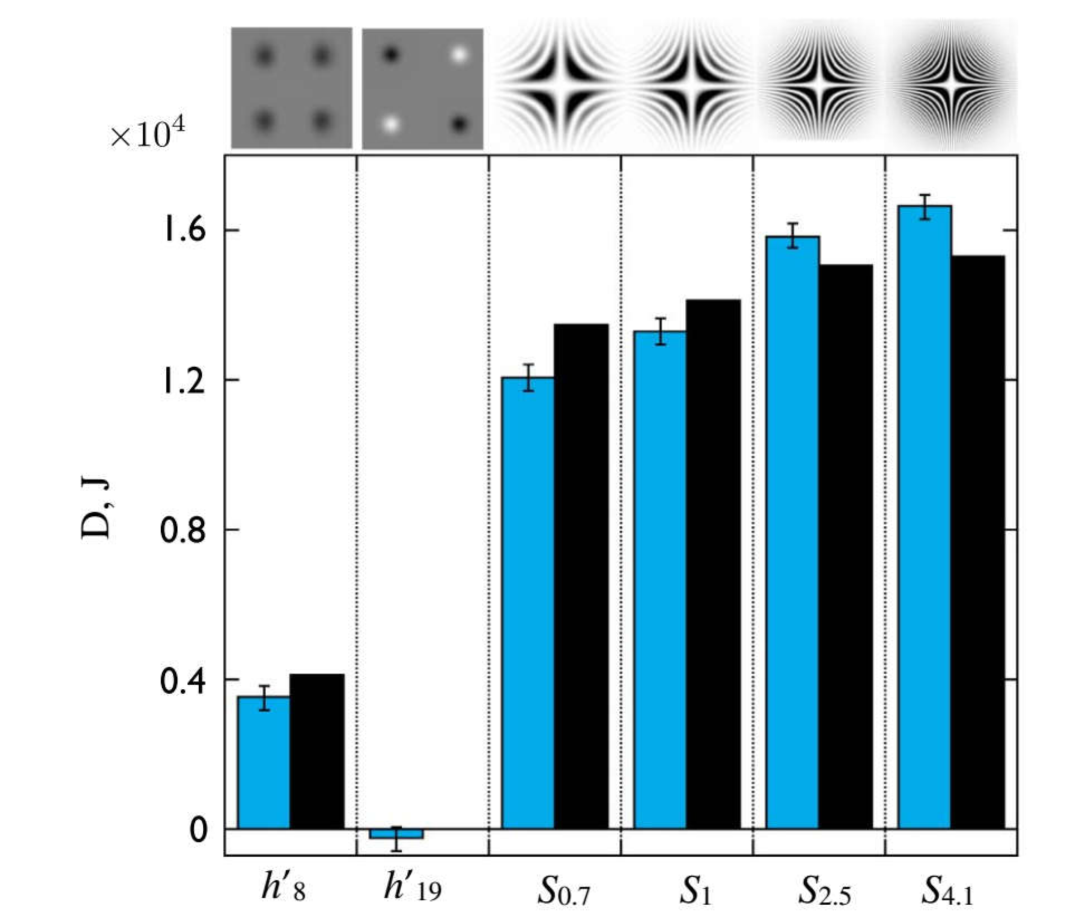
$$I_\pm = \iint |E(x,y)|^2 \frac{1}{2}\{1 \pm \cos[a(x,y)]\}\mathrm{d}x\mathrm{d}y.$$

Examples of optical integration

1D functions



2D functions

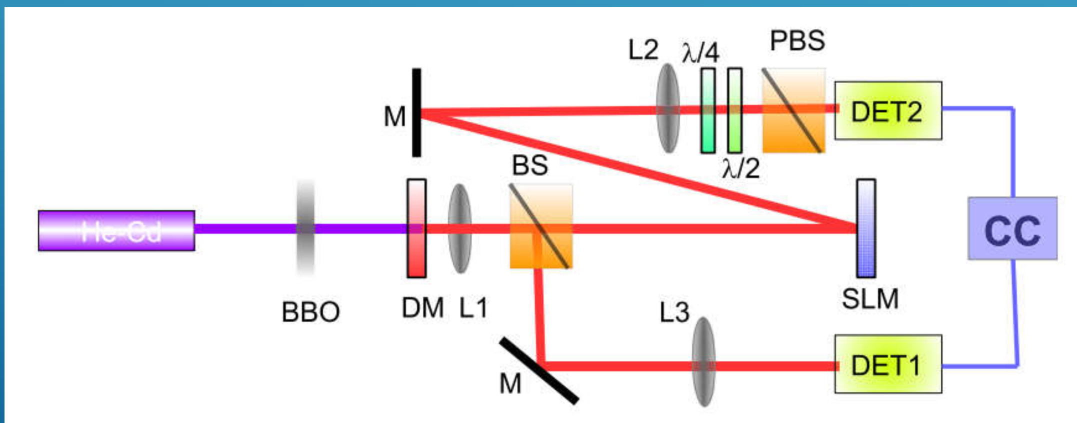


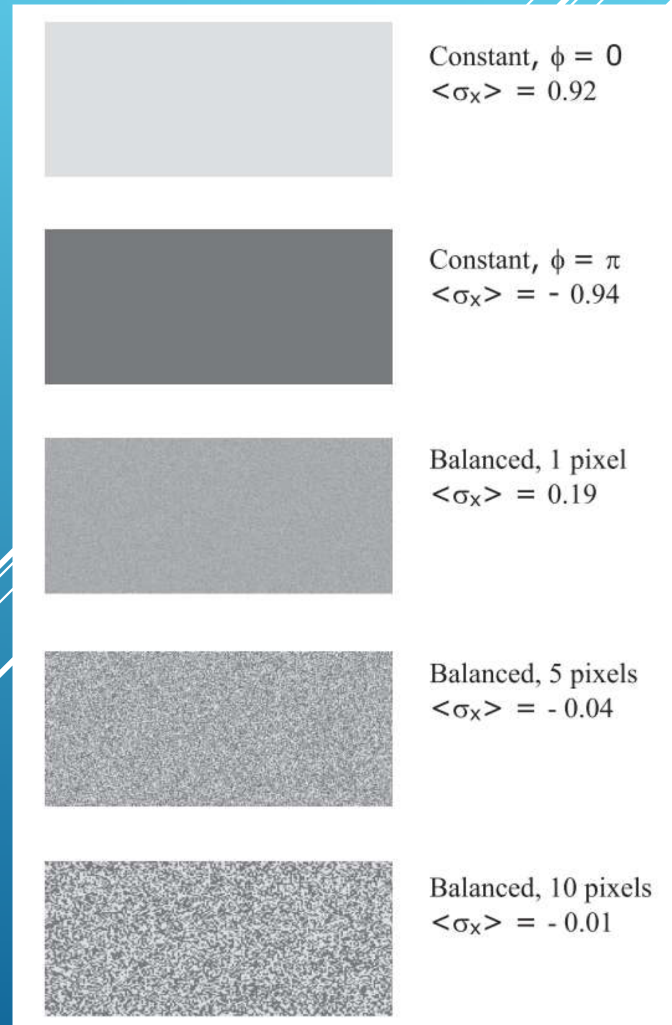
Optical computation of a quantum algorithm: Deustch-Jozsa

PHYSICAL REVIEW A **92**, 012337 (2015)

Deterministic quantum computation with one photonic qubit

M. Hor-Meyll, D. S. Tasca, S. P. Walborn, and P. H. Souto Ribeiro*





What about Dynamical Distance Geometry?

Solving the One-dimensional Distance Geometry Problem by Optical Computing

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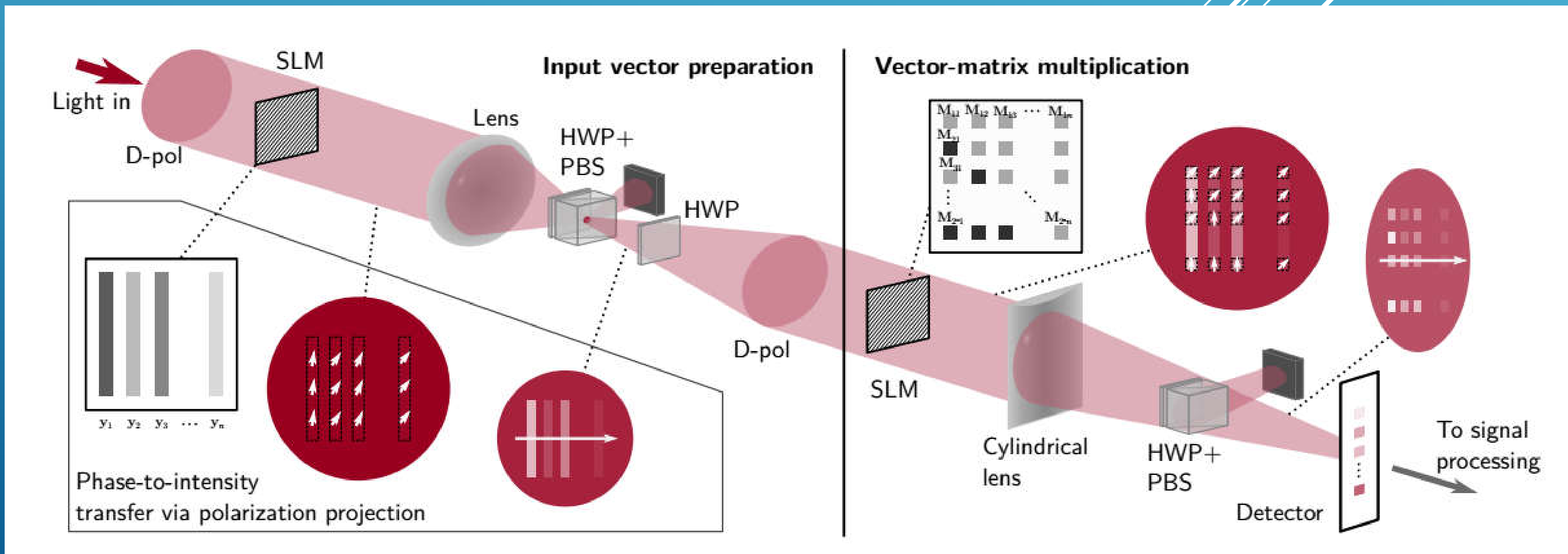
arXiv:2105.12118v1 [cs.ET] 25 May 2021



Thank you!