Quantum computing over the rainbow: the quantum optical frequency comb as a platform for measurement-based universal quantum computing

Olivier Pfister
University of Virginia

Quantum Fields and Quantum Information website:
https://sites.google.com/view/qfqi

Quantum computing over the rainbow: the quantum optical frequency comb as a platform for measurement-based universal quantum computing

OR

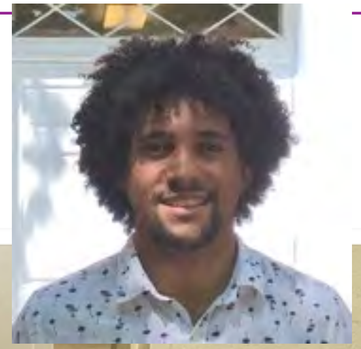
How I learned to stop worrying and love the comb

Olivier Pfister
University of Virginia

Quantum Fields and Quantum Information website:
https://sites.google.com/view/qfqi

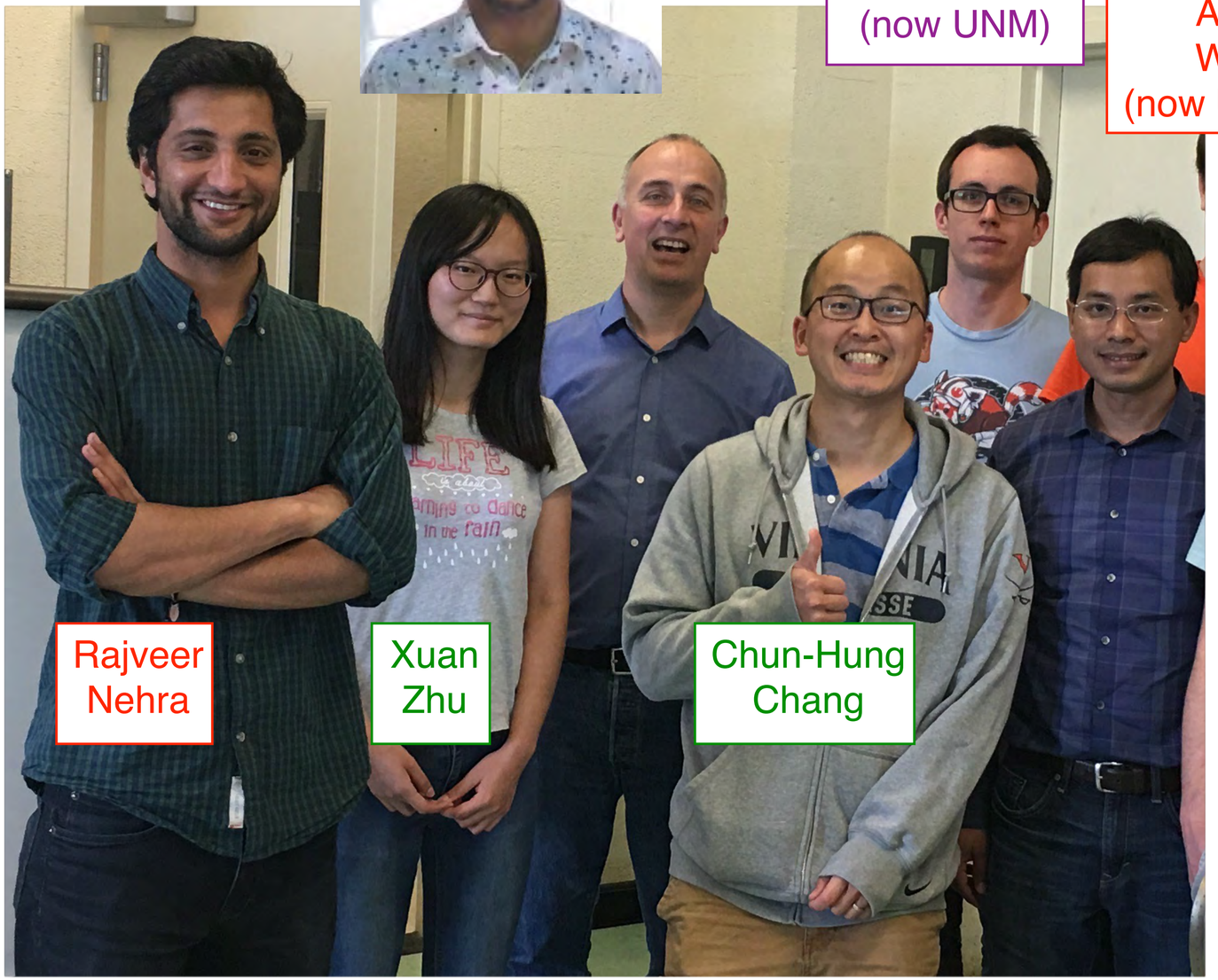
The QFQI group

Carlos González Arciniegas



Rafael Alexander (now UNM)

Aye Win (now U.OK.)



Rajveer Nehra

Xuan Zhu

Chun-Hung Chang

Miller Eaton

Collaborators

Avi
Pe'er
Bar-Ilan U.

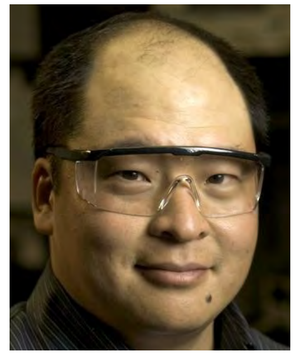
Paulo
Nussenzveig
U. São Paulo

Marcelo
Martinelli
U. São Paulo

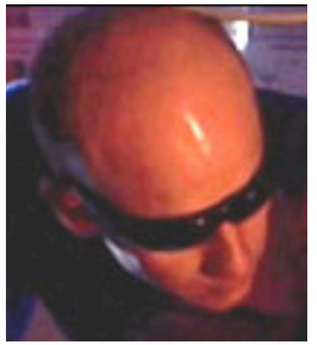
Andreas
Beling
UVA ECE

Joe
Campbell
UVA ECE

Xu
Yi
UVA ECE



Sae Woo
Nam
NIST



Thomas
Gerrits
NIST

Myungshik
Kim
Imperial
College

Leandro
Aolita
U. Fed. Rio
Janeiro

Nick
Menicucci
RMIT

Raf
Alexander
UNM

Israel
Klich
UVA

Simonetta
Liuti
UVA

Current projects

- Large-scale cluster-state entanglement
- Quantum state engineering and characterization (quantum error correction encodings)
- Quantum photonics on chip. Collab. w/ UVA ECE: Campbell, Beling, Yi
- Quantum simulation of nuclear physics
- Quantum simulation of condensed matter physics

Today I will address the first two topics.

Building a continuous-variable quantum computer with light

Gaussian quantum optics (fields)

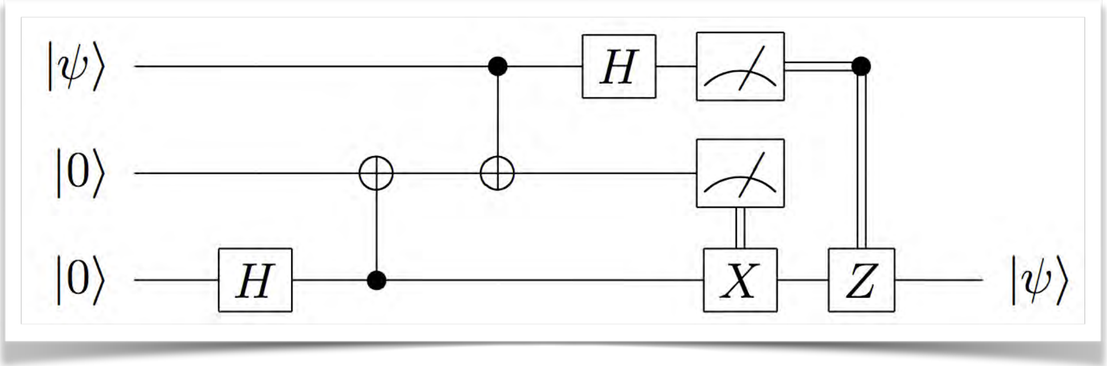
- Large-scale entanglement (squeezing)
- No postselection

Non-Gaussian quantum optics (photons)

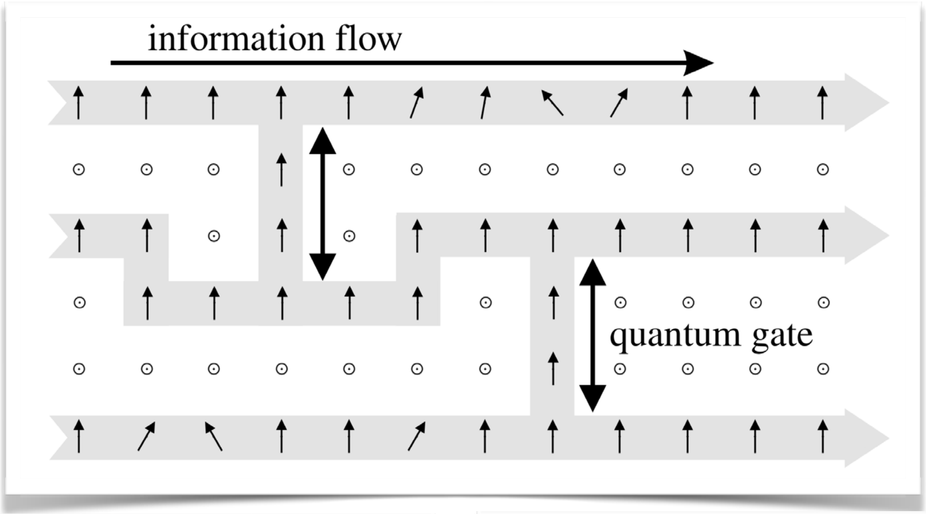
- Exponential speedup
- Quantum error correction

Two main flavors of universal quantum computing

1. Circuit-based



2. Measurement-based



VOLUME 86, NUMBER 22 PHYSICAL REVIEW LETTERS 28 MAY 2001

A One-Way Quantum Computer

Robert Raussendorf and Hans J. Briegel

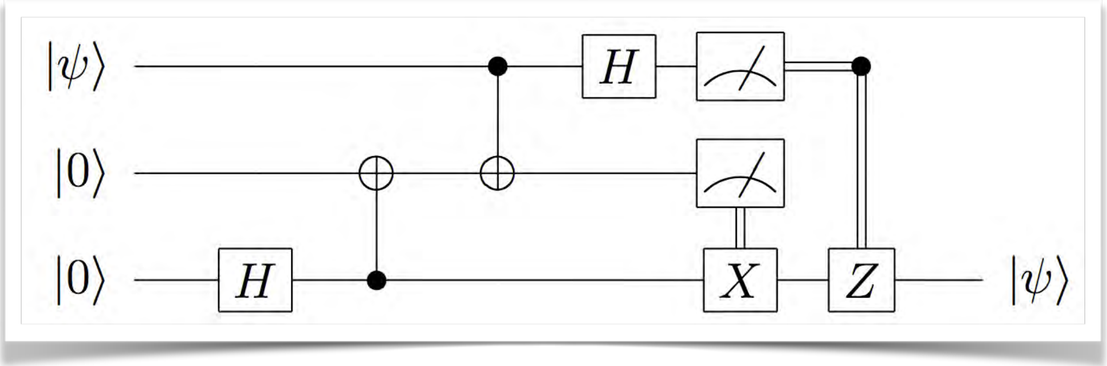
PRL **97,** 110501 (2006) PHYSICAL REVIEW LETTERS week ending 15 SEPTEMBER 2006

Universal Quantum Computation with Continuous-Variable Cluster States

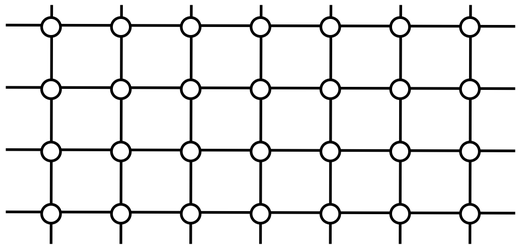
Nicolas C. Menicucci,[1,2,*] Peter van Loock,[3] Mile Gu,[1] Christian Weedbrook,[1] Timothy C. Ralph,[1] and Michael A. Nielsen[1]

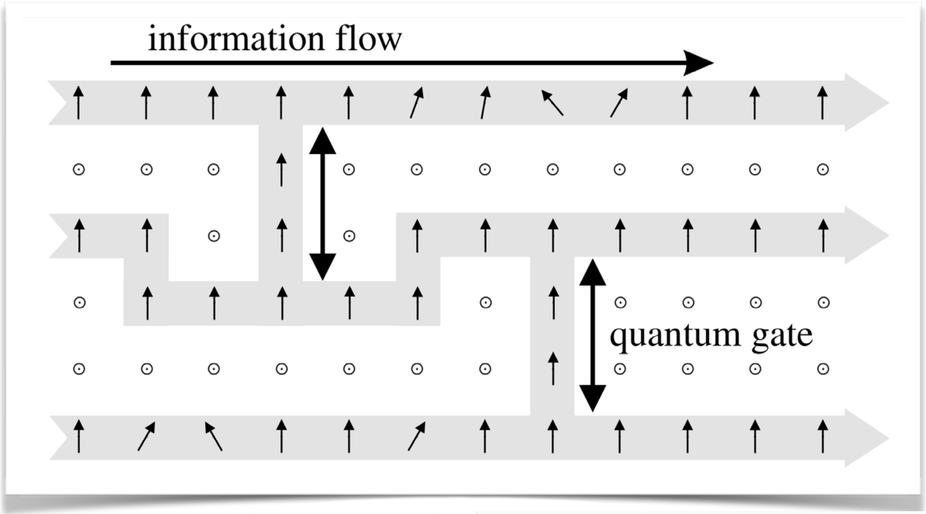
Two main flavors of universal quantum computing

1. Circuit-based



2. Measurement-based





VOLUME 86, NUMBER 22 PHYSICAL REVIEW LETTERS 28 MAY 2001

A One-Way Quantum Computer

Robert Raussendorf and Hans J. Briegel

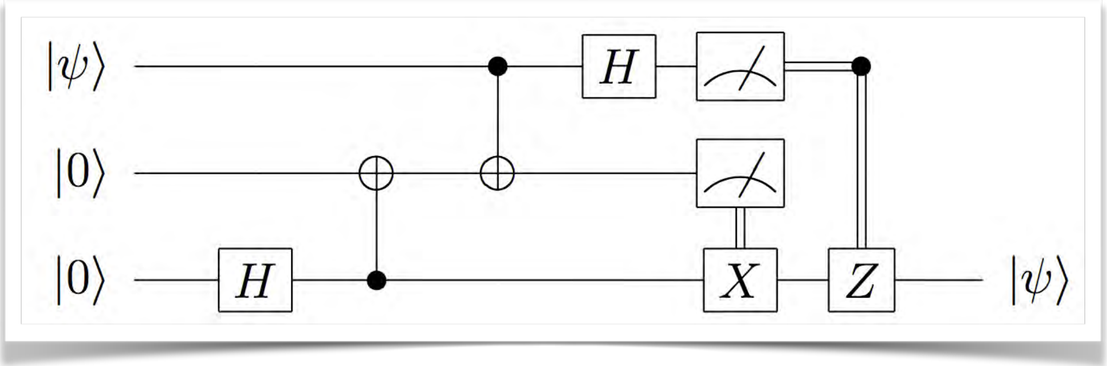
PRL 97, 110501 (2006) PHYSICAL REVIEW LETTERS week ending 15 SEPTEMBER 2006

Universal Quantum Computation with Continuous-Variable Cluster States

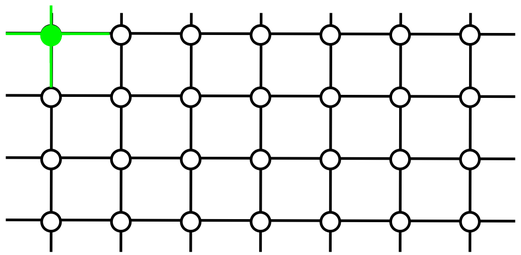
Nicolas C. Menicucci,[1,2,*] Peter van Loock,[3] Mile Gu,[1] Christian Weedbrook,[1]
Timothy C. Ralph,[1] and Michael A. Nielsen[1]

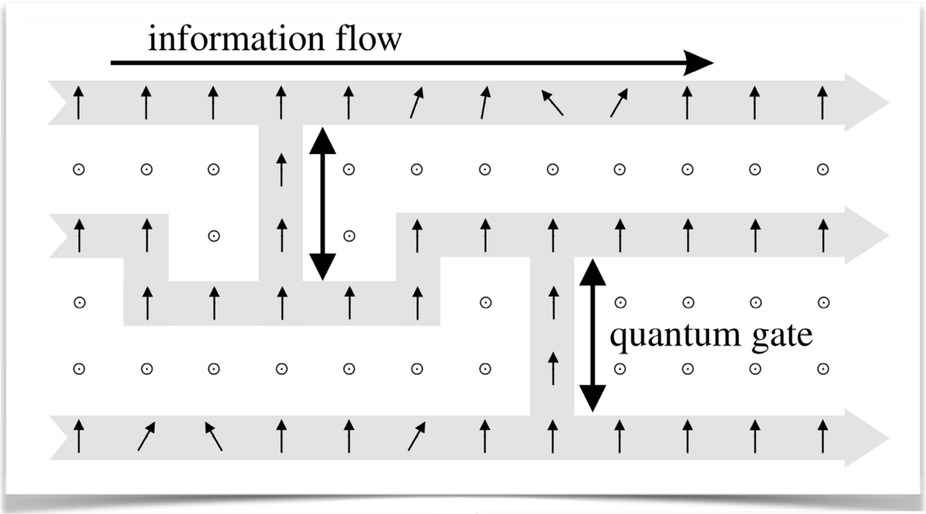
Two main flavors of universal quantum computing

1. Circuit-based



2. Measurement-based





VOLUME 86, NUMBER 22 PHYSICAL REVIEW LETTERS 28 MAY 2001

A One-Way Quantum Computer

Robert Raussendorf and Hans J. Briegel

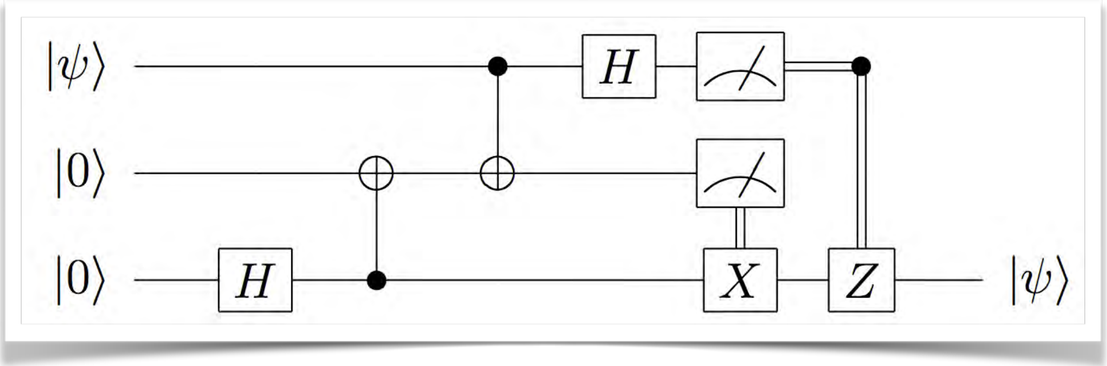
PRL 97, 110501 (2006) PHYSICAL REVIEW LETTERS week ending 15 SEPTEMBER 2006

Universal Quantum Computation with Continuous-Variable Cluster States

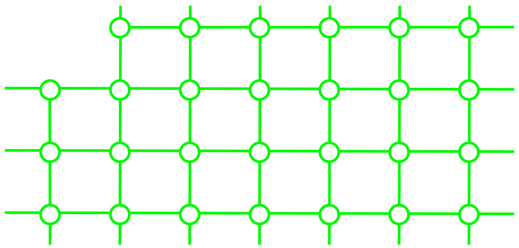
Nicolas C. Menicucci,[1,2,*] Peter van Loock,[3] Mile Gu,[1] Christian Weedbrook,[1] Timothy C. Ralph,[1] and Michael A. Nielsen[1]

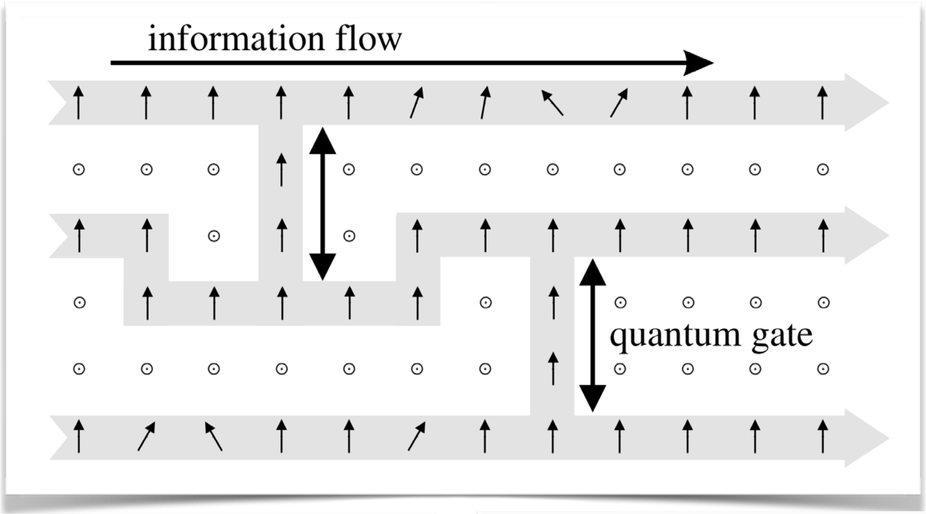
Two main flavors of universal quantum computing

1. Circuit-based



2. Measurement-based





VOLUME 86, NUMBER 22 PHYSICAL REVIEW LETTERS 28 MAY 2001

A One-Way Quantum Computer

Robert Raussendorf and Hans J. Briegel

PRL 97, 110501 (2006) PHYSICAL REVIEW LETTERS week ending 15 SEPTEMBER 2006

Universal Quantum Computation with Continuous-Variable Cluster States

Nicolas C. Menicucci,[1,2,*] Peter van Loock,[3] Mile Gu,[1] Christian Weedbrook,[1]
Timothy C. Ralph,[1] and Michael A. Nielsen[1]

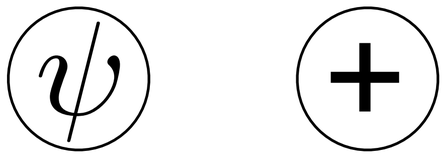
Teleportation as a qubit gate primitive

Teleportation as a qubit gate primitive

$$|\psi\rangle = \psi_0|0\rangle + \psi_1|1\rangle$$

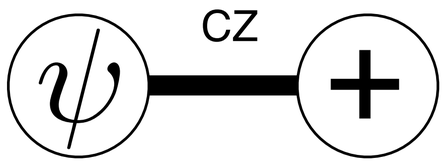
Teleportation as a qubit gate primitive

$$|\psi\rangle = \psi_0|0\rangle + \psi_1|1\rangle$$



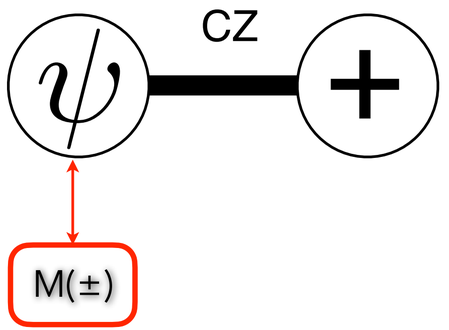
Teleportation as a qubit gate primitive

$$|\psi\rangle = \psi_0|0\rangle + \psi_1|1\rangle$$



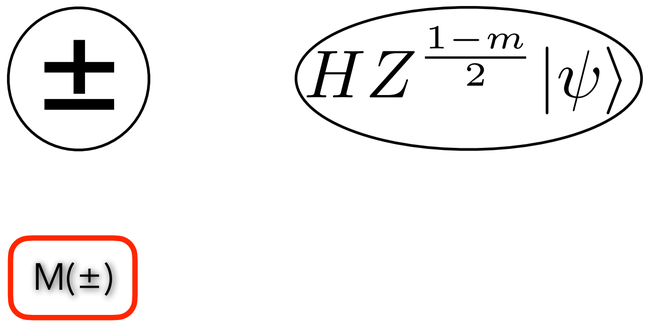
Teleportation as a qubit gate primitive

$$|\psi\rangle = \psi_0|0\rangle + \psi_1|1\rangle$$



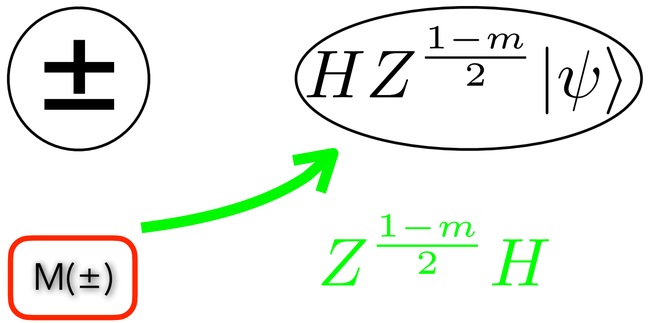
Teleportation as a qubit gate primitive

$$|\psi\rangle = \psi_0|0\rangle + \psi_1|1\rangle$$



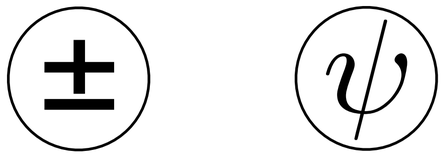
Teleportation as a qubit gate primitive

$$|\psi\rangle = \psi_0|0\rangle + \psi_1|1\rangle$$



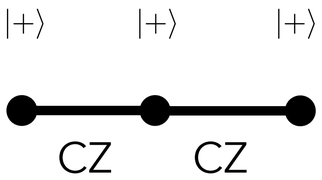
Teleportation as a qubit gate primitive

$$|\psi\rangle = \psi_0|0\rangle + \psi_1|1\rangle$$

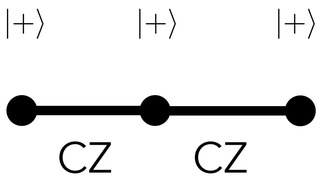


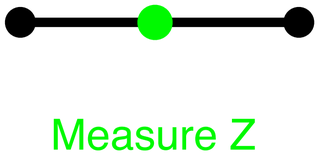
M(±)

Can also shape cluster states with measurements

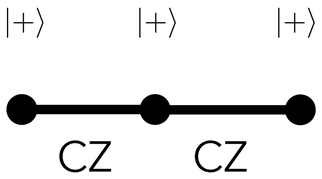


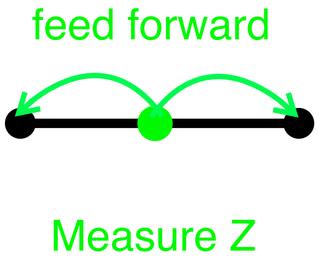
Can also shape cluster states with measurements



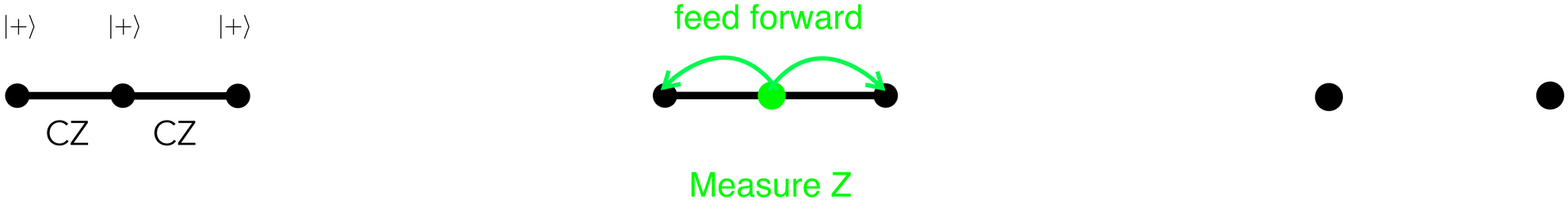


Can also shape cluster states with measurements

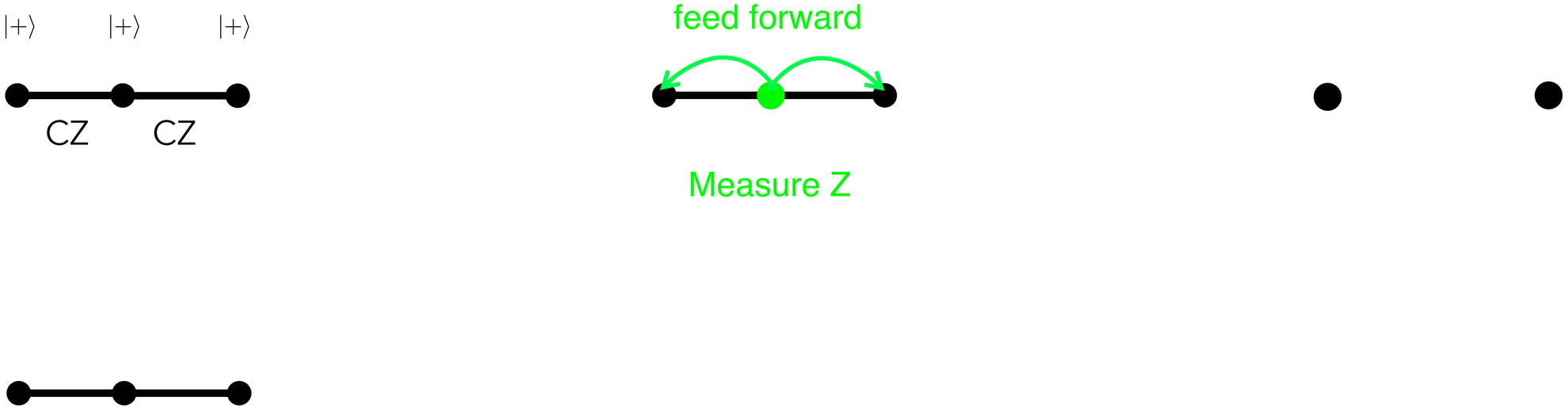




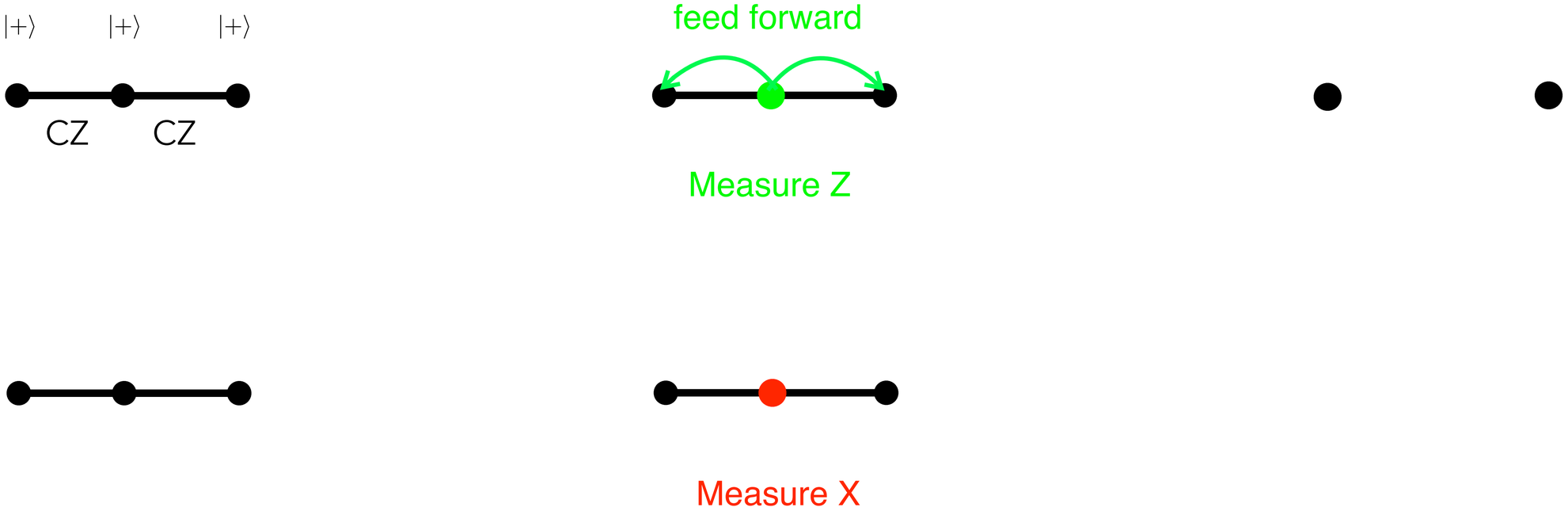
Can also shape cluster states with measurements



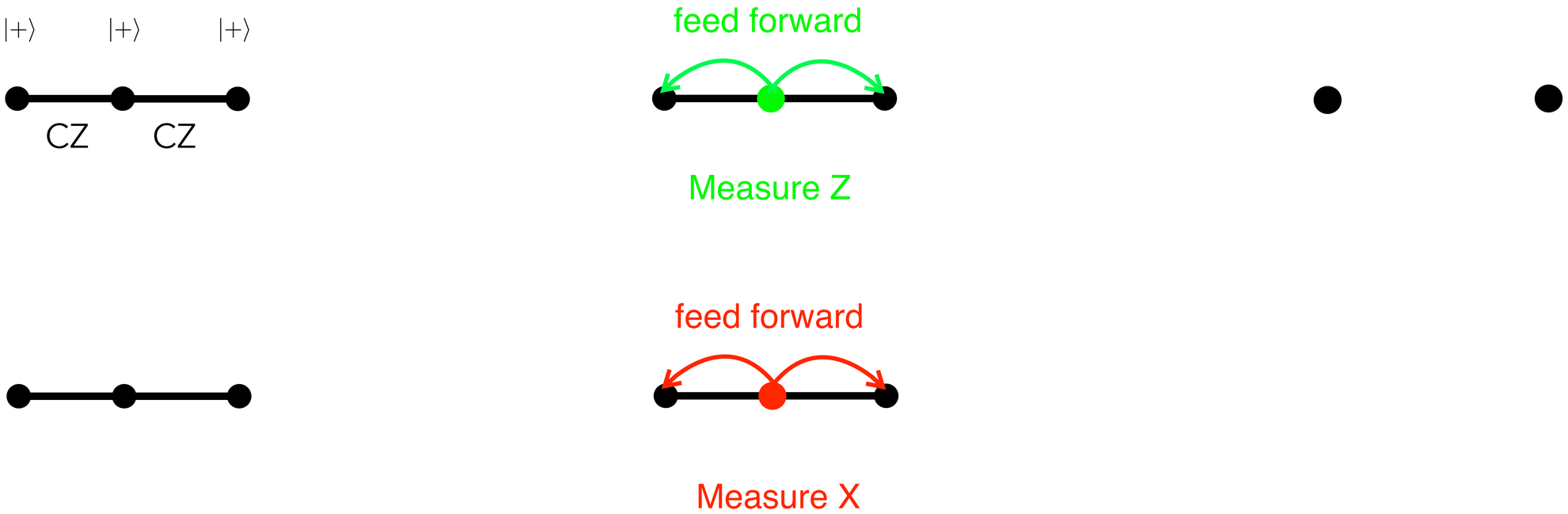
Can also shape cluster states with measurements



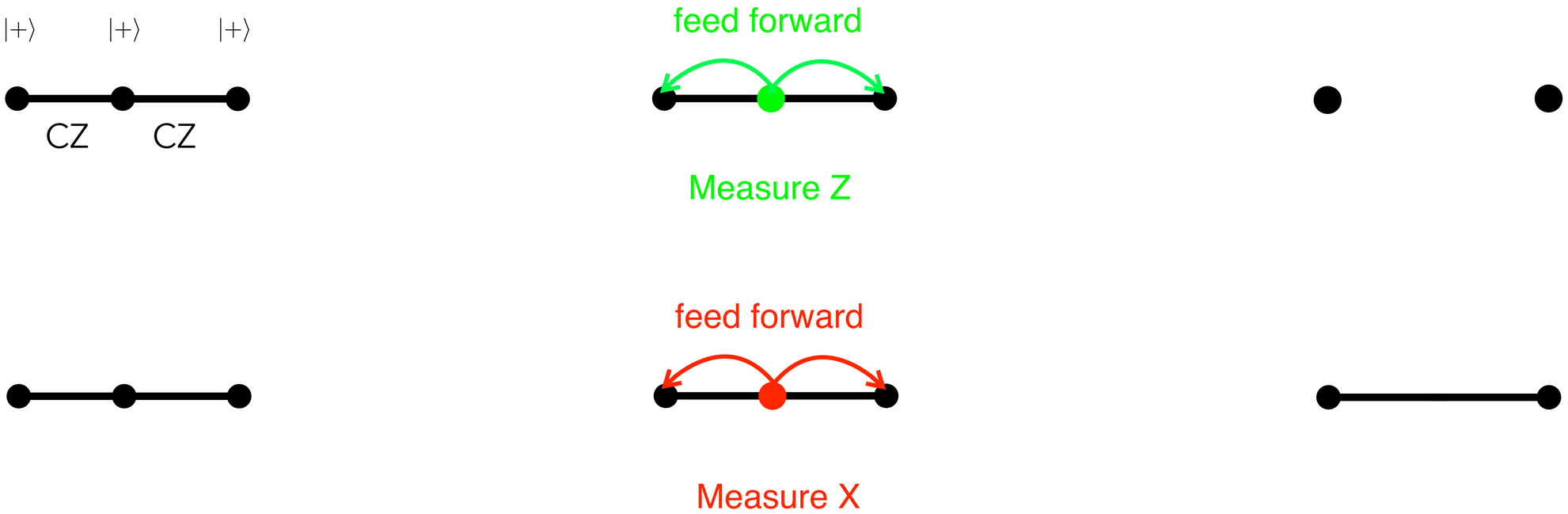
Can also shape cluster states with measurements



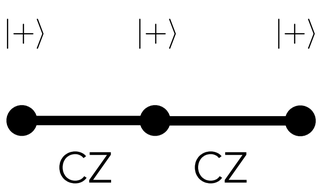
Can also shape cluster states with measurements

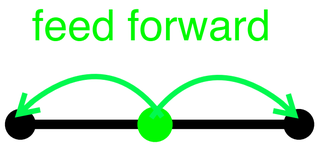


Can also shape cluster states with measurements

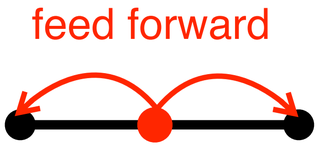


Can also shape cluster states with measurements

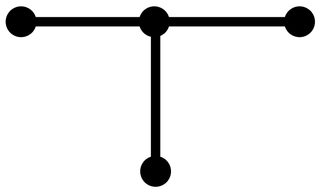




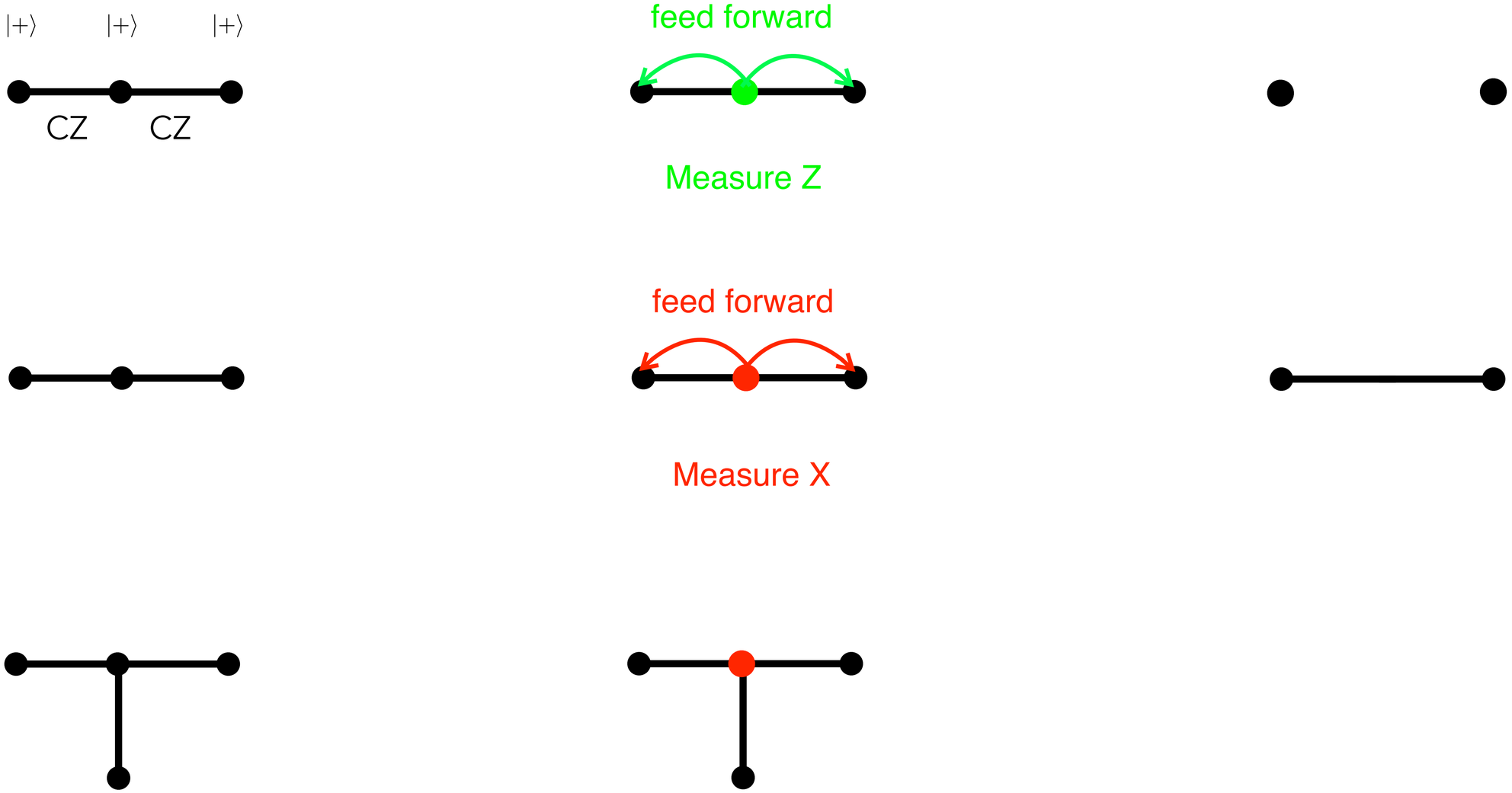
Measure Z



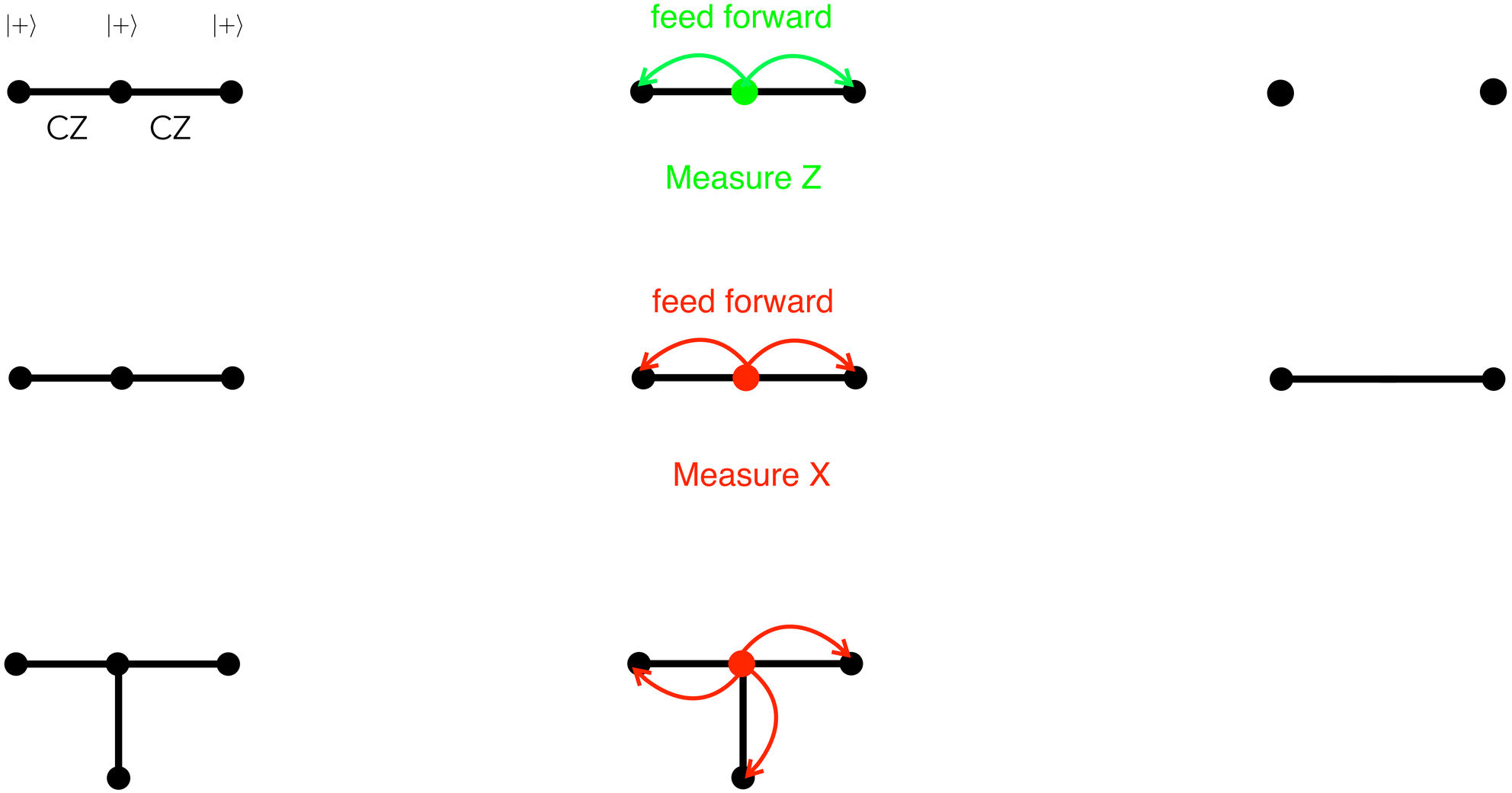
Measure X



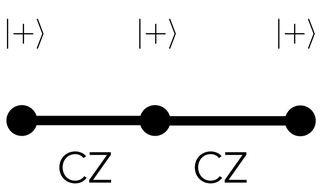
Can also shape cluster states with measurements

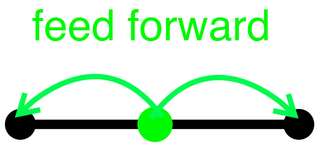


Can also shape cluster states with measurements

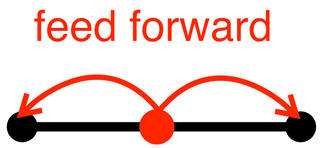


Can also shape cluster states with measurements

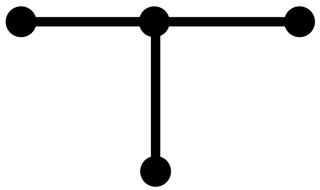


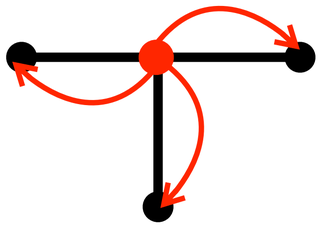


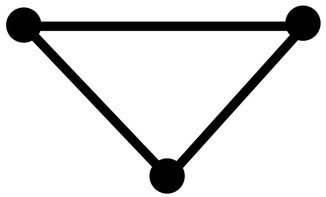
Measure Z



Measure X







Discrete vs. *continuous* variables, qubits vs. *qumodes*

$$Q = \frac{1}{\sqrt{2}}(a + a^\dagger)$$

$$P = \frac{i}{\sqrt{2}}(a^\dagger - a)$$

$$[Q, P] = i$$

$$\Delta Q \Delta P = \frac{1}{2}$$

Qubits

$$\{|\,0\,\rangle, |\,1\,\rangle\}$$

e.g. eigenstates of Sz

$$|\psi\rangle = \psi_0|0\rangle + \psi_1|1\rangle$$

Hadamard transform

$$\{|\pm\rangle\} = \{|\,0\,\rangle \pm |\,1\,\rangle\}$$

e.g. eigenstates of Sx

$$|\,00\,\rangle + |\,11\,\rangle$$

Bell state

Qumodes

$$\{|\,q\,\rangle\}_{q\in\mathbb{R}}$$

e.g. eigenstates of Q: position / amplitude quadr.

$$|\psi\rangle = \int \psi(q)|q\rangle dq$$

Fourier transform

$$\{|\,p\,\rangle\}_{p\in\mathbb{R}} = \left\{\int e^{ipq}\,|\,q\,\rangle\; dq\right\}_{p\in\mathbb{R}}$$

e.g. eigenstates of P: momentum / phase quadr.

$$\int |\,q\,\rangle_1\,|\,q\,\rangle_2\; dq$$

EPR state

O. Pfister, ***Continuous-variable quantum computing in the quantum optical frequency comb****, J Phys B* ***53****, 012001 (2020).*

Discrete vs. continuous variables,

$$Q = \frac{1}{\sqrt{2}}(a + a^\dagger)$$

$$P = \frac{i}{\sqrt{2}}(a^\dagger - a)$$

$$[Q, P] = i$$

$$\Delta Q \Delta P = \frac{1}{2}$$

Qubits

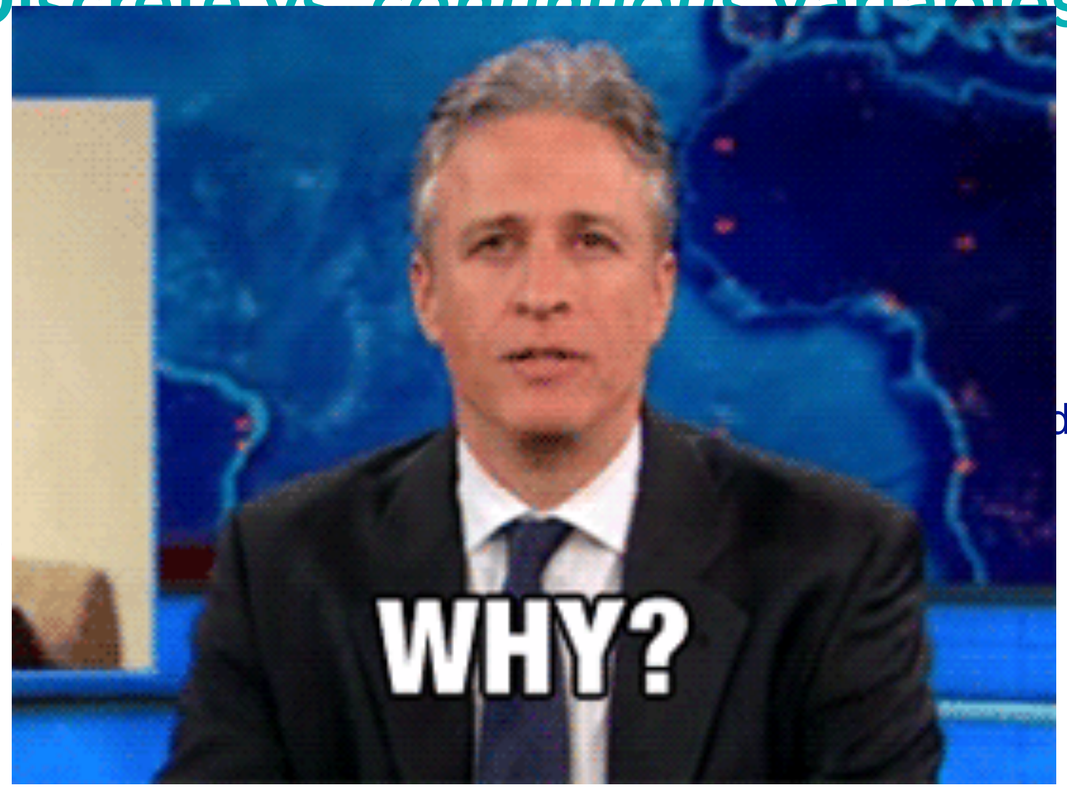
$$\{|0\rangle, |1\rangle\}$$

e.g. eigenstates of Sz

de quadr.

$$|\psi\rangle = \psi_0|0\rangle +$$

Hadamard transform



$$\{|\pm\rangle\} = \{|0\rangle \pm |1\rangle\}$$

e.g. eigenstates of Sx

$$\{|p\rangle\}_{p\in\mathbb{R}} = \left\{\int e^{ipq}\,|q\rangle\,dq\right\}_{p\in\mathbb{R}}$$

e.g. eigenstates of P: momentum / phase quadr.

$$|00\rangle + |11\rangle$$

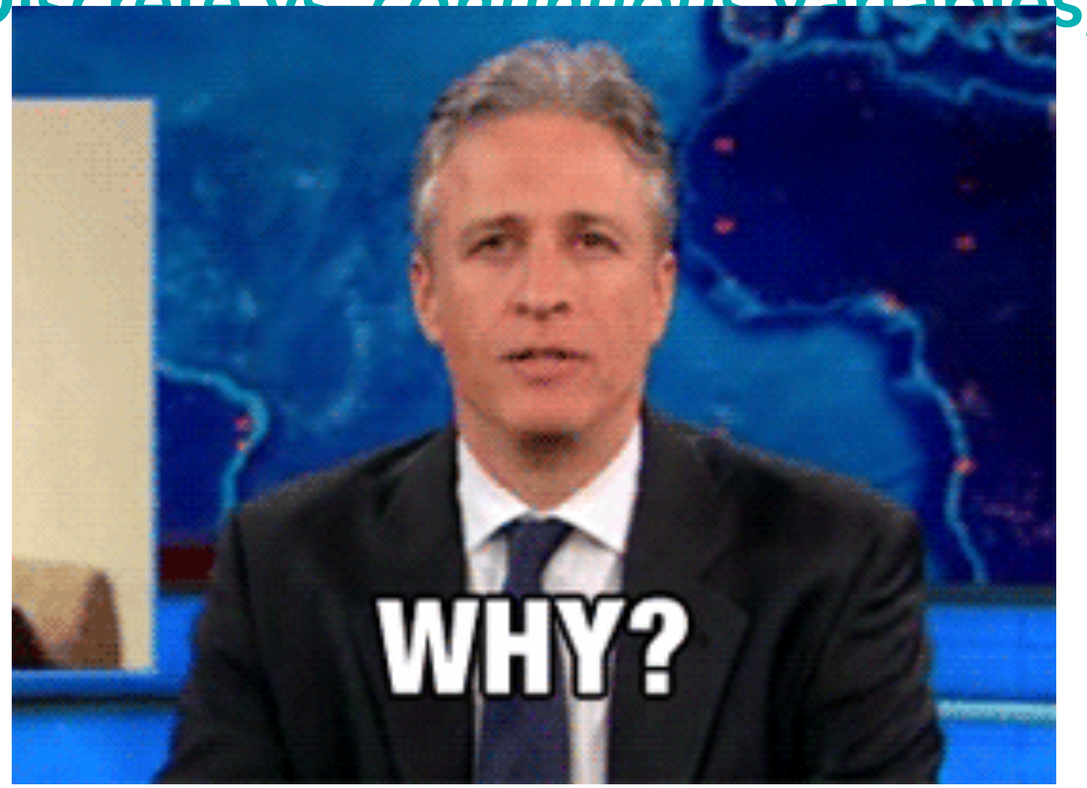
Bell state

$$\int |q\rangle_1 |q\rangle_2\, dq$$

EPR state

O. Pfister, ***Continuous-variable quantum computing in the quantum optical frequency comb****, J Phys B* ***53****, 012001 (2020).*

Discrete vs. continuous variables,



$$Q = \frac{1}{\sqrt{2}}(a + a^\dagger)$$

$$P = \frac{i}{\sqrt{2}}(a^\dagger - a)$$

$$[Q, P] = i$$

$$\Delta Q \Delta P = \frac{1}{2}$$

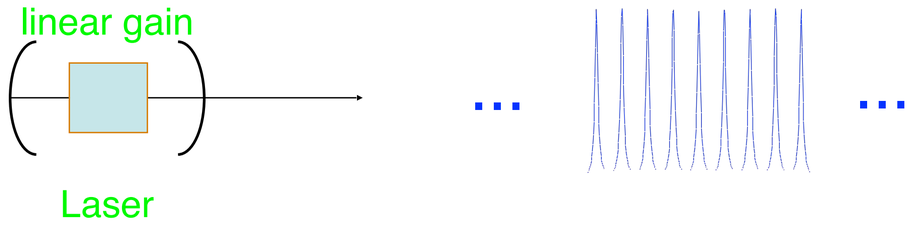
Because CV SCALE

O. Pfister, ***Continuous-variable quantum computing in the quantum optical frequency comb****, J Phys B* ***53****, 012001 (2020).*

Gaussian quantum optics (EM fields)

A good starting point: the quantum optical frequency comb

The eigenmodes of a cavity form a large ensemble of classically coherent modes

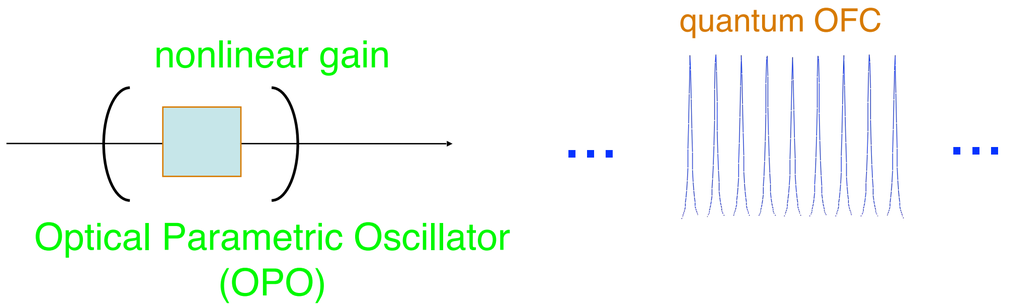



John L. Hall


Theodor W. Hänsch

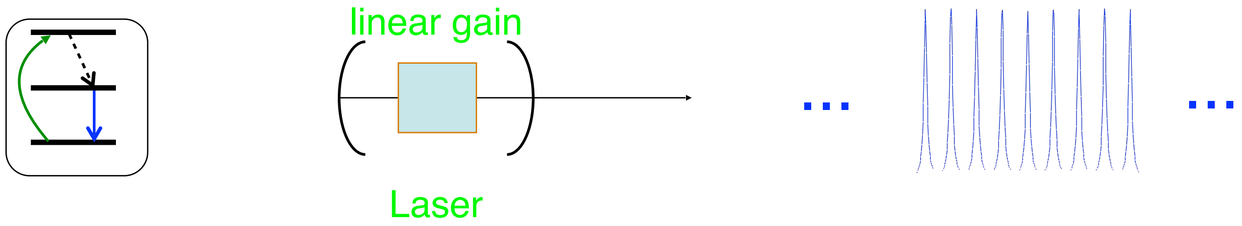
Carrier-envelope-phase locked mode-locked laser = **optical frequency comb (OFC)**
(10^6 modes oscillating in phase)

Why not turn the QOFC into a quantum computer?



A good starting point: the quantum optical frequency comb

The eigenmodes of a cavity form a large ensemble of classically coherent modes

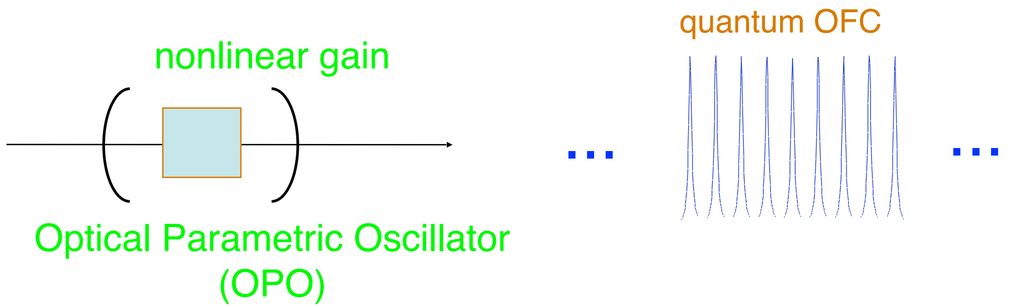



John L. Hall


Theodor W. Hänsch

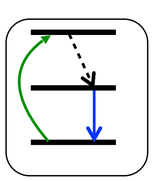
Carrier-envelope-phase locked mode-locked laser = **optical frequency comb (OFC)**
(10^6 modes oscillating in phase)

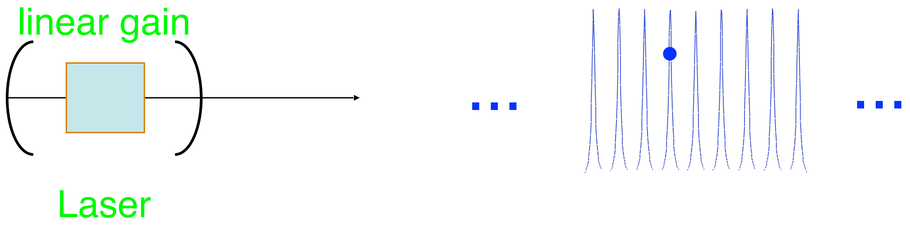
Why not turn the QOFC into a quantum computer?



A good starting point: the quantum optical frequency comb

The eigenmodes of a cavity form a large ensemble of classically coherent modes



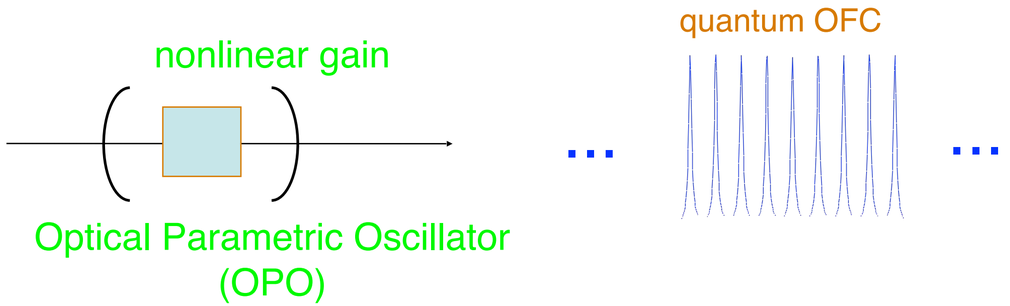



John L. Hall


Theodor W. Hänsch

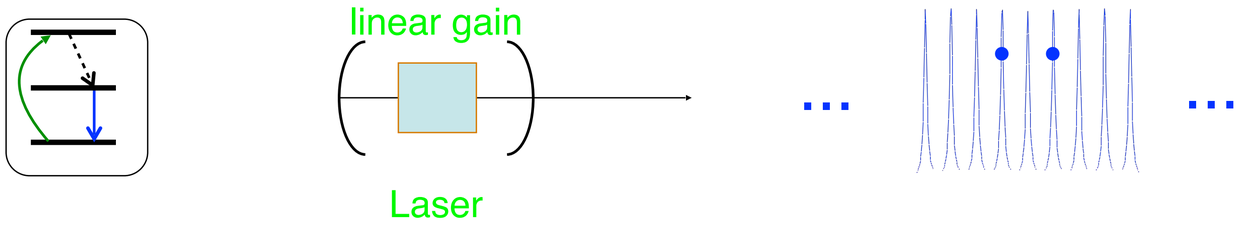
Carrier-envelope-phase locked mode-locked laser = **optical frequency comb (OFC)**
(10^6 modes oscillating in phase)

Why not turn the QOFC into a quantum computer?



A good starting point: the quantum optical frequency comb

The eigenmodes of a cavity form a large ensemble of classically coherent modes

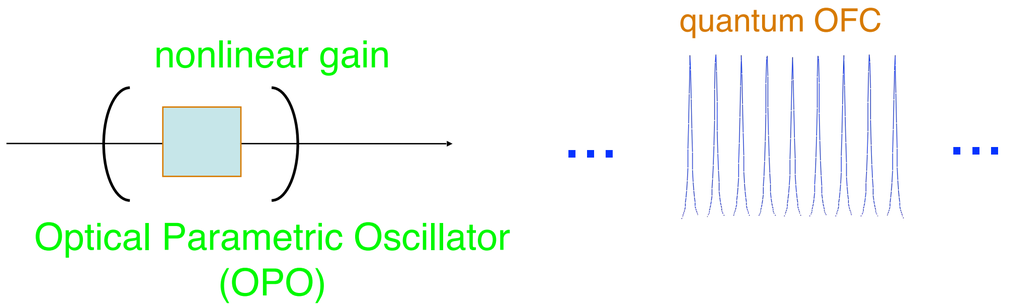


John L. Hall

Theodor W. Hänsch

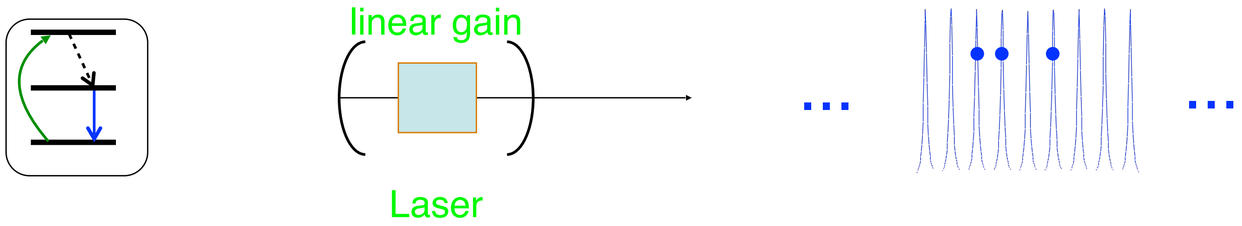
Carrier-envelope-phase locked mode-locked laser = **optical frequency comb (OFC)**
(10^6 modes oscillating in phase)

Why not turn the QOFC into a quantum computer?



A good starting point: the quantum optical frequency comb

The eigenmodes of a cavity form a large ensemble of classically coherent modes

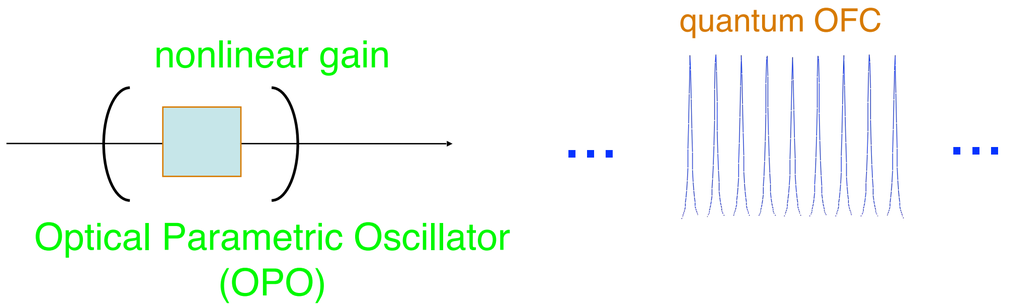



John L. Hall


Theodor W. Hänsch

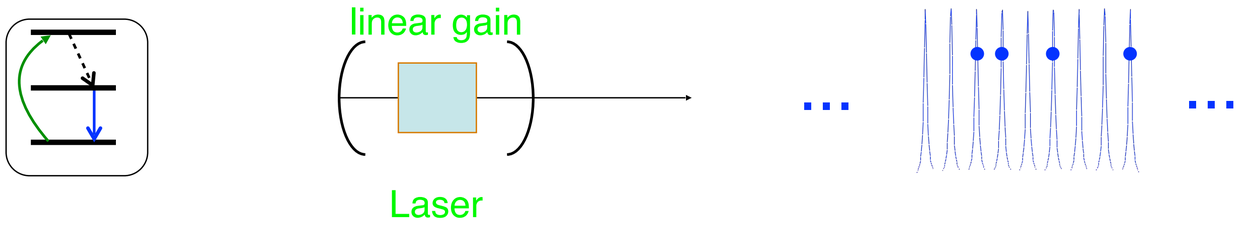
Carrier-envelope-phase locked mode-locked laser = **optical frequency comb (OFC)**
(10^6 modes oscillating in phase)

Why not turn the QOFC into a quantum computer?



A good starting point: the quantum optical frequency comb

The eigenmodes of a cavity form a large ensemble of classically coherent modes

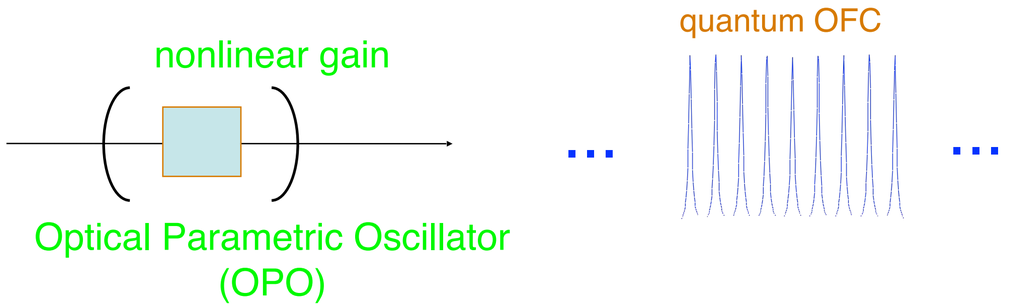


John L. Hall

Theodor W. Hänsch

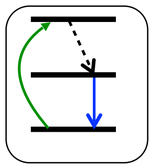
Carrier-envelope-phase locked mode-locked laser = **optical frequency comb (OFC)**
(10^6 modes oscillating in phase)

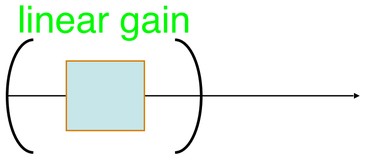
Why not turn the QOFC into a quantum computer?

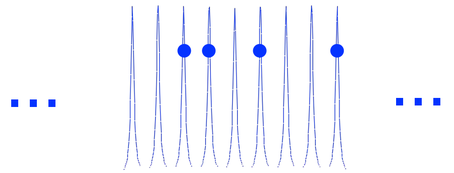


A good starting point: the quantum optical frequency comb

The eigenmodes of a cavity form a large ensemble of classically coherent modes



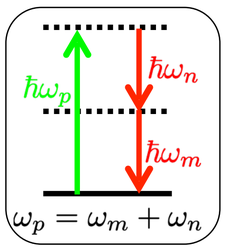


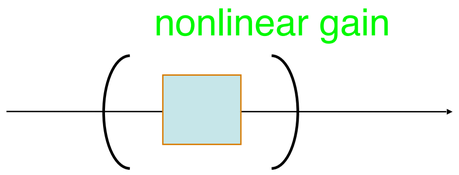


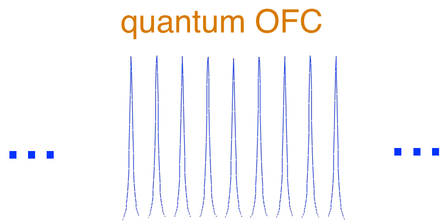
John L. Hall Theodor W. Hänsch

Carrier-envelope-phase locked mode-locked laser = **optical frequency comb (OFC)**
(10^6 modes oscillating in phase)

Why not turn the QOFC into a quantum computer?

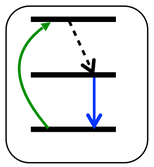


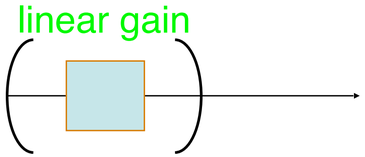


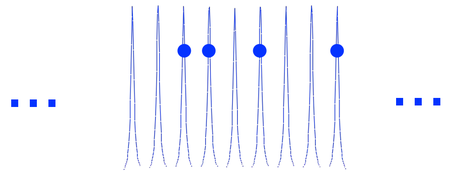


A good starting point: the quantum optical frequency comb

The eigenmodes of a cavity form a large ensemble of classically coherent modes





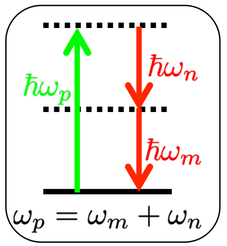


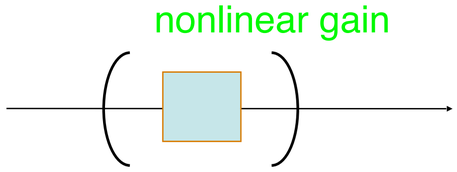
John L. Hall

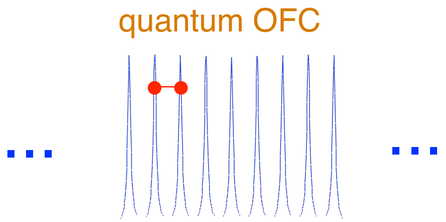
Theodor W. Hänsch

Carrier-envelope-phase locked mode-locked laser = **optical frequency comb (OFC)**
(10^6 modes oscillating in phase)

Why not turn the QOFC into a quantum computer?

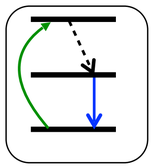


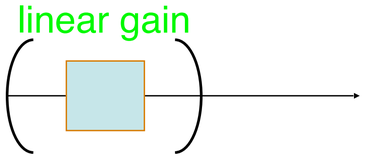


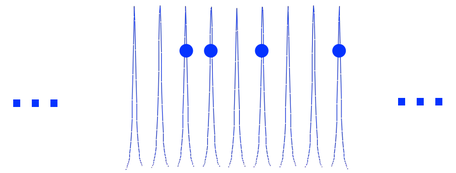


A good starting point: the quantum optical frequency comb

The eigenmodes of a cavity form a large ensemble of classically coherent modes





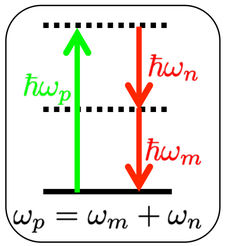


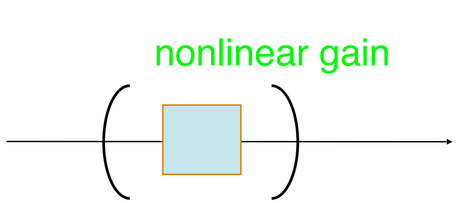
John L. Hall

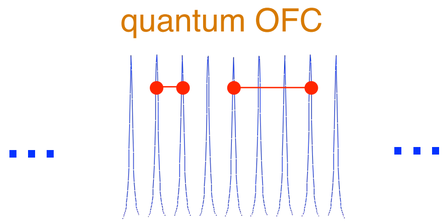
Theodor W. Hänsch

Carrier-envelope-phase locked mode-locked laser = **optical frequency comb (OFC)**
(10^6 modes oscillating in phase)

Why not turn the QOFC into a quantum computer?

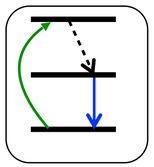


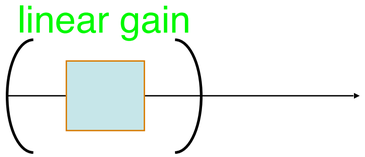


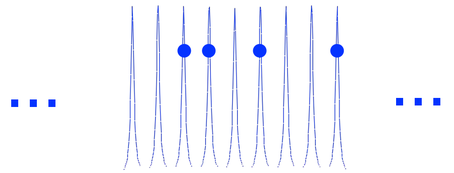


A good starting point: the quantum optical frequency comb

The eigenmodes of a cavity form a large ensemble of classically coherent modes





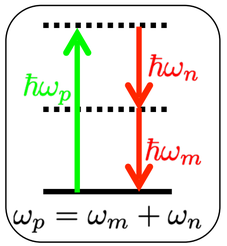


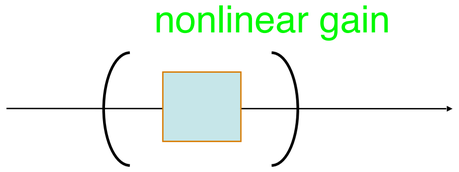
John L. Hall

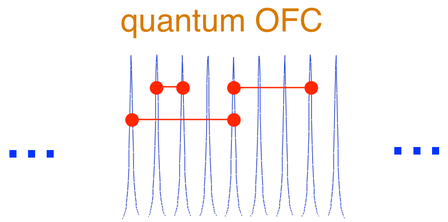
Theodor W. Hänsch

Carrier-envelope-phase locked mode-locked laser = **optical frequency comb (OFC)**
(10^6 modes oscillating in phase)

Why not turn the QOFC into a quantum computer?

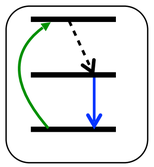


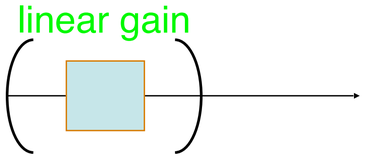


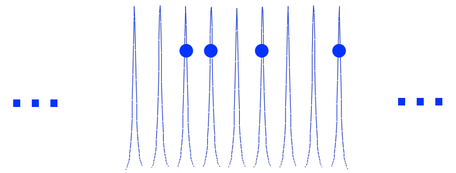


A good starting point: the quantum optical frequency comb

The eigenmodes of a cavity form a large ensemble of classically coherent modes





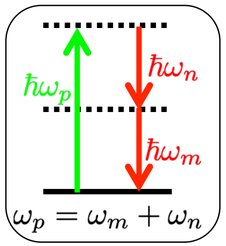


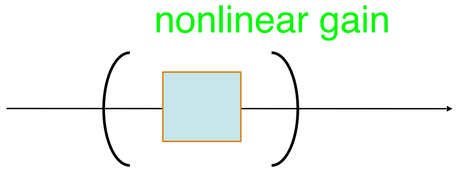
John L. Hall

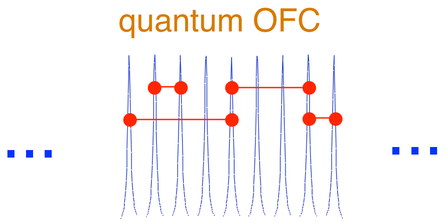
Theodor W. Hänsch

Carrier-envelope-phase locked mode-locked laser = **optical frequency comb (OFC)**
(10^6 modes oscillating in phase)

Why not turn the QOFC into a quantum computer?

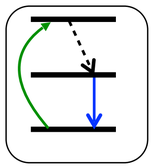


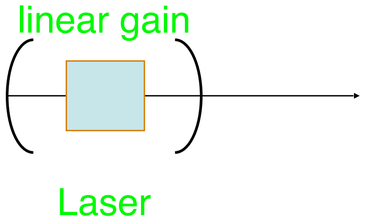


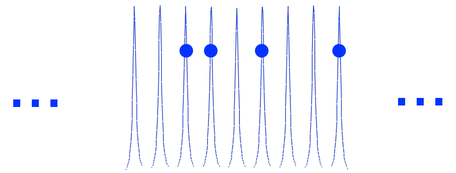


A good starting point: the quantum optical frequency comb

The eigenmodes of a cavity form a large ensemble of classically coherent modes





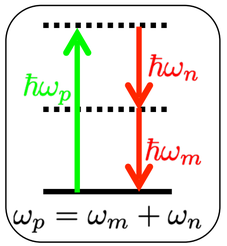


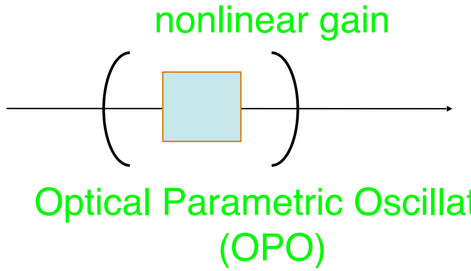
John L. Hall

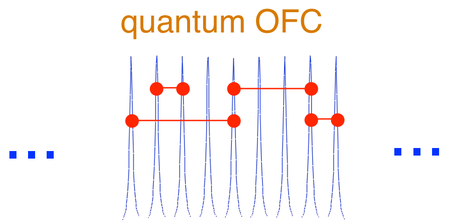
Theodor W. Hänsch

Carrier-envelope-phase locked mode-locked laser = **optical frequency comb (OFC)**
(10^6 modes oscillating in phase)

Why not turn the QOFC into a quantum computer?





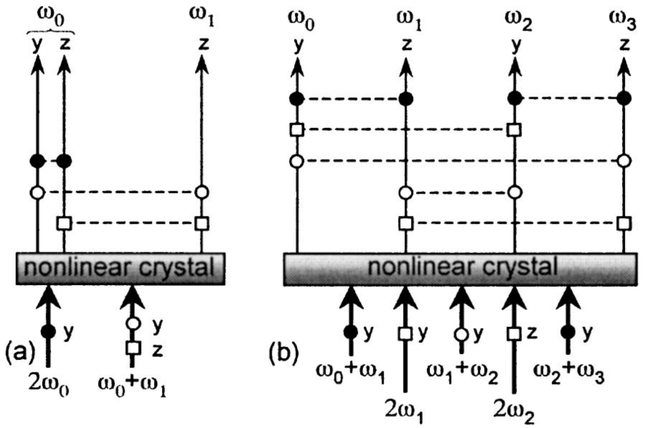


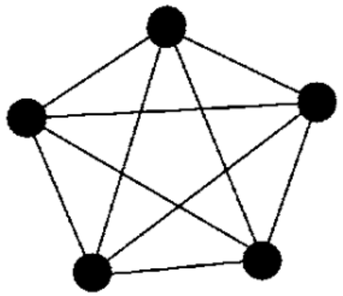
Multipartite cluster entanglement
in one fell swoop:
a top-down, large-scale quantum register

PHYSICAL REVIEW A **70**, 020302(R) (2004)

Multipartite continuous-variable entanglement from concurrent nonlinearities

Olivier Pfister,* Sheng Feng, Gregory Jennings, Raphael Pooser, and Daruo Xie



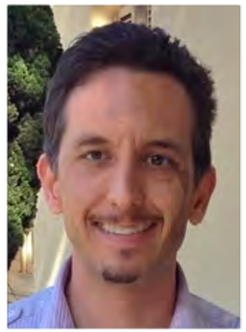


PHYSICAL REVIEW A **72**, 053805 (2005)

Bright tripartite entanglement in triply concurrent parametric oscillation

A. S. Bradley and M. K. Olsen
ARC Centre of Excellence for Quantum-Atom Optics, School of Physical Sciences, University of Queensland, Brisbane, Queensland 4072, Australia

O. Pfister and R. C. Pooser



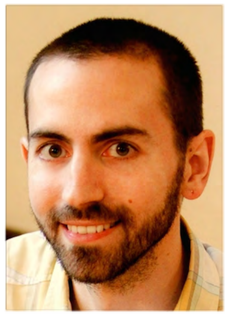
PRL **101,** 130501 (2008)

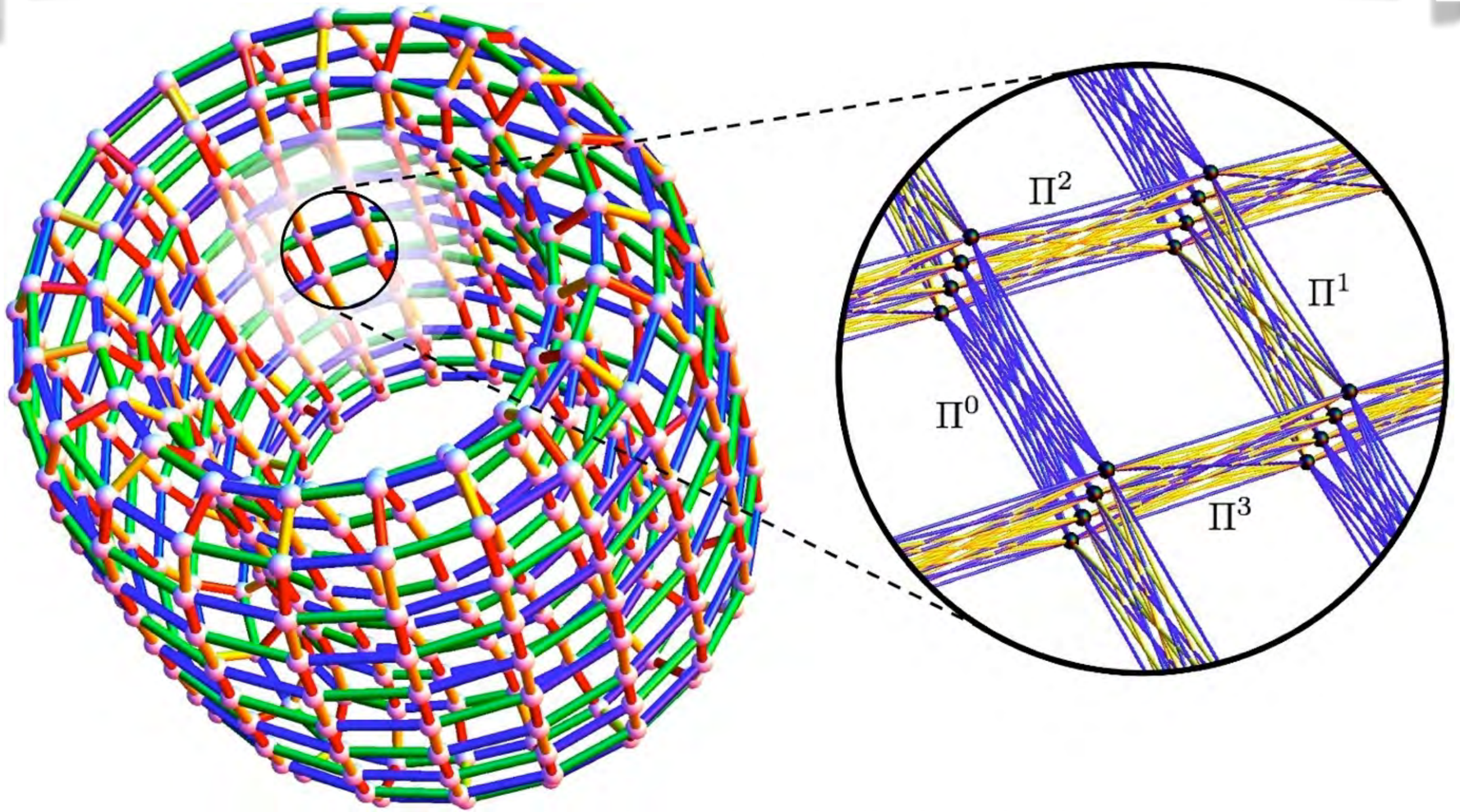
Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS

week ending
26 SEPTEMBER 2008

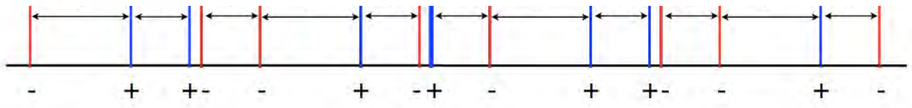
One-Way Quantum Computing in the Optical Frequency Comb

Nicolas C. Menicucci,[1,2] Steven T. Flammia,[3] and Olivier Pfister[4]





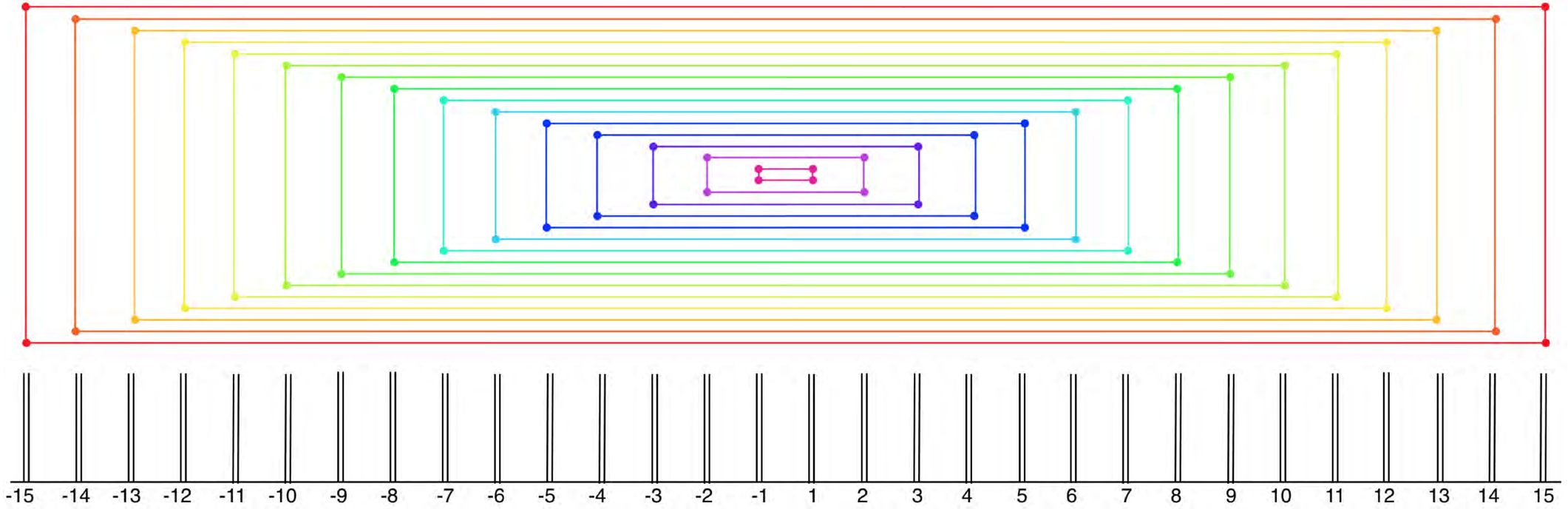
15 pump modes into YZY, ZZZ, ZYY



PRL 107, 030505 (2011) PHYSICAL REVIEW LETTERS week ending 15 JULY 2011

Parallel Generation of Quadripartite Cluster Entanglement in the Optical Frequency Comb

Matthew Pysher,[1] Yoshichika Miwa,[2] Reihaneh Shahrokhshahi,[1] Russell Bloomer,[1] and Olivier Pfister[1,*]



Entanglement gets scaled up in an optical frequency comb

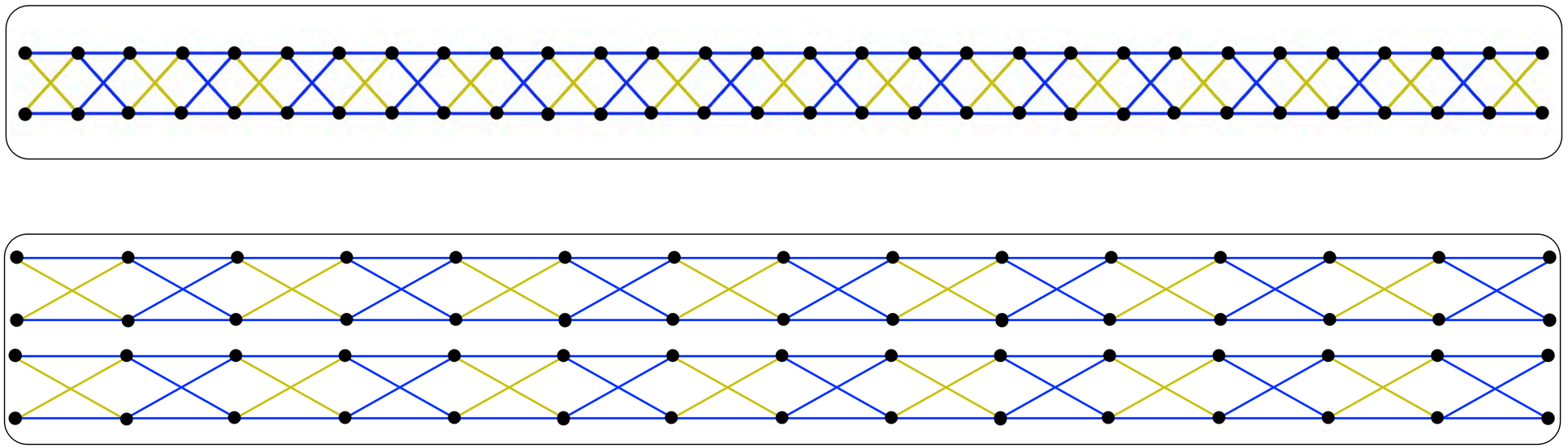
Using a single nonlinear optical element, researchers have entangled dozens of the comb's optical modes.

www.physicstoday.org September 2011 Physics Today 21

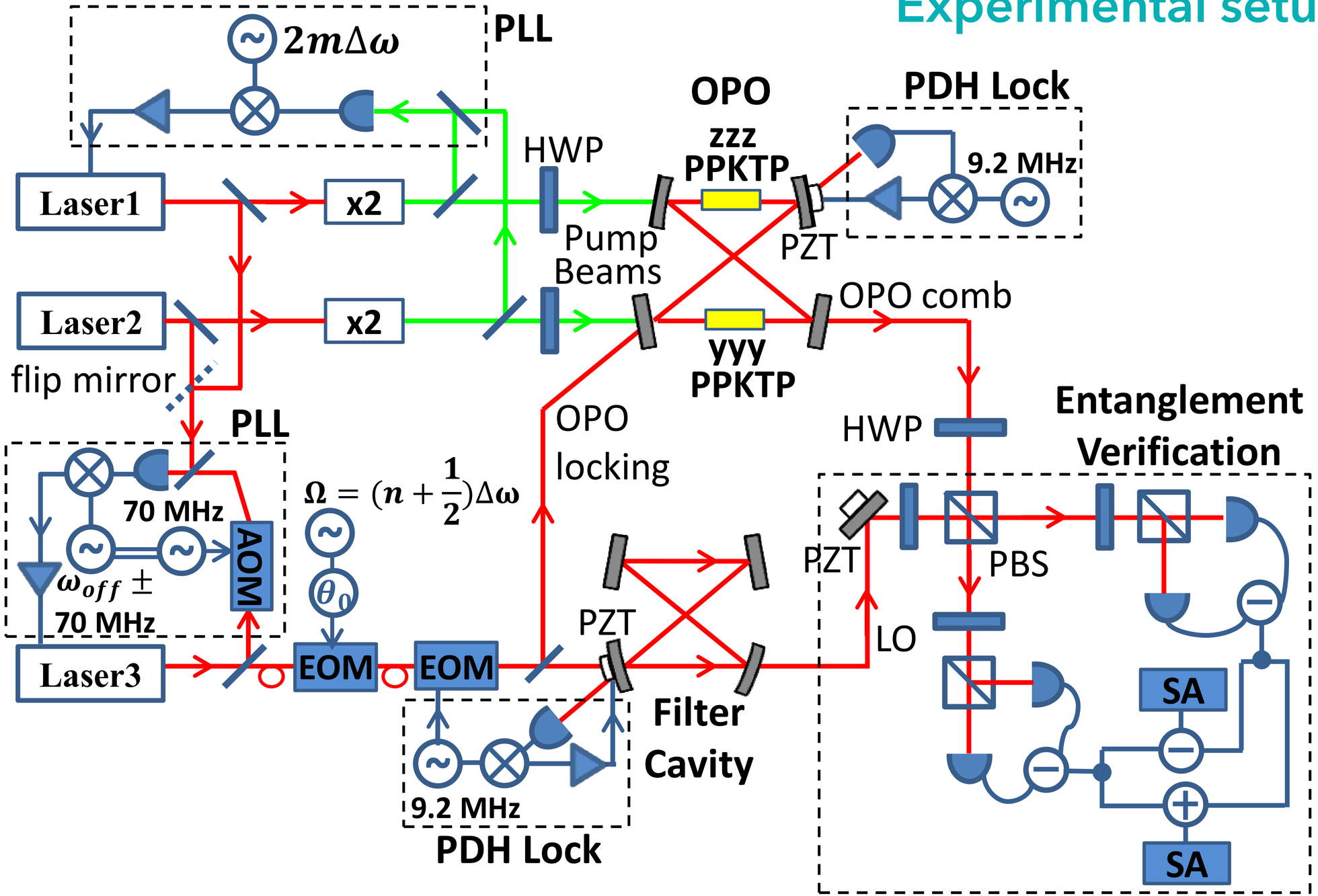
PRL **112,** 120505 (2014) PHYSICAL REVIEW LETTERS week ending 28 MARCH 2014

Experimental Realization of Multipartite Entanglement of 60 Modes of a Quantum Optical Frequency Comb

Moran Chen,[1] Nicolas C. Menicucci,[2,*] and Olivier Pfister[1,†]
[1]*Department of Physics, University of Virginia, Charlottesville, Virginia 22903, USA*
[2]*School of Physics, The University of Sydney, Sydney, New South Wales 2006, Australia*

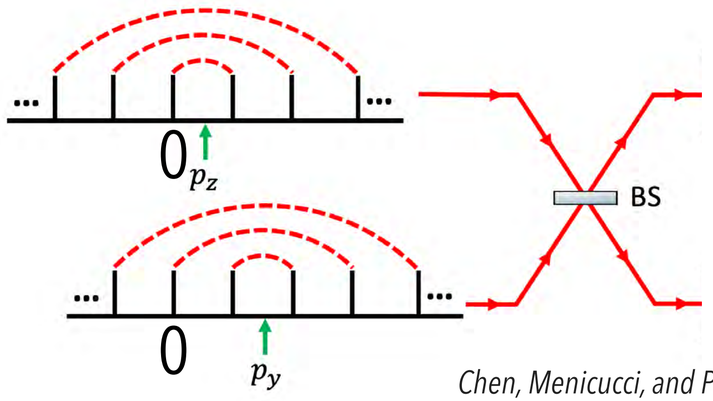


Experimental setup



Interfering quantum combs

Interference between identical frequencies of different combs

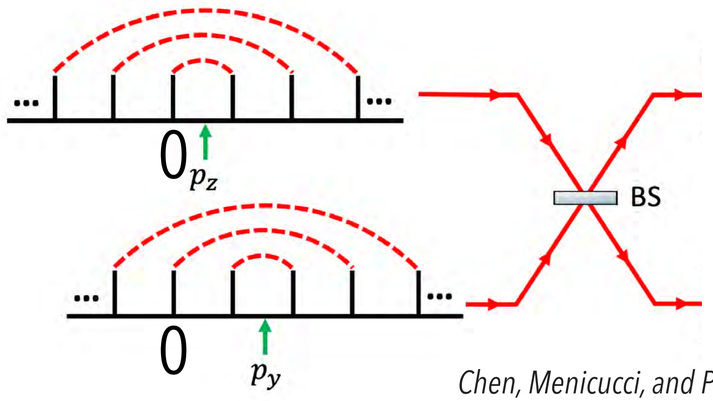


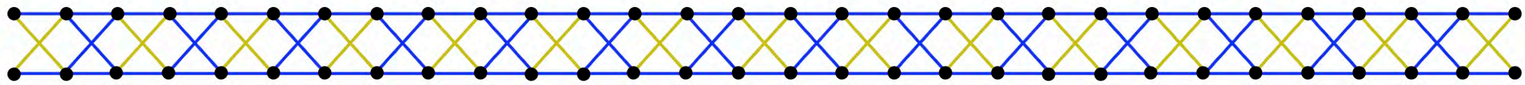
~10^4 modes long

Chen, Menicucci, and Pfister, ***Experimental realization of multipartite entanglement of 60 modes of a quantum optical frequency comb****, PRL 112, 120505 (2014)*

Interfering quantum combs

Interference between identical frequencies of different combs



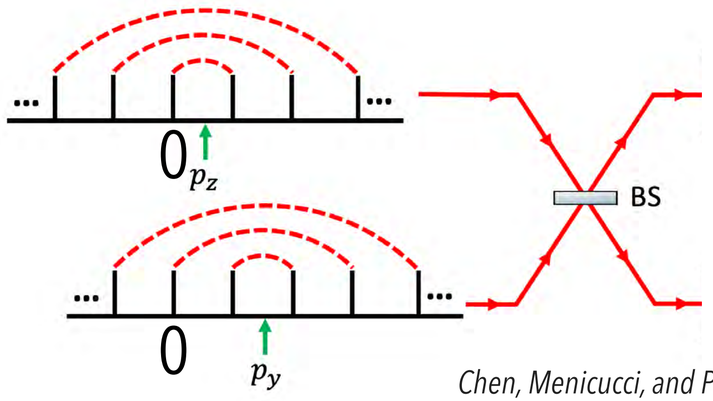


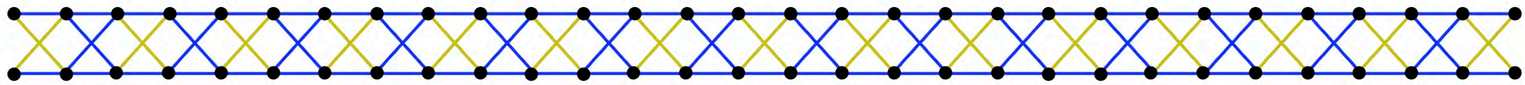
~10^4 modes long

Chen, Menicucci, and Pfister, ***Experimental realization of multipartite entanglement of 60 modes of a quantum optical frequency comb****, PRL 112, 120505 (2014)*

Interfering quantum combs

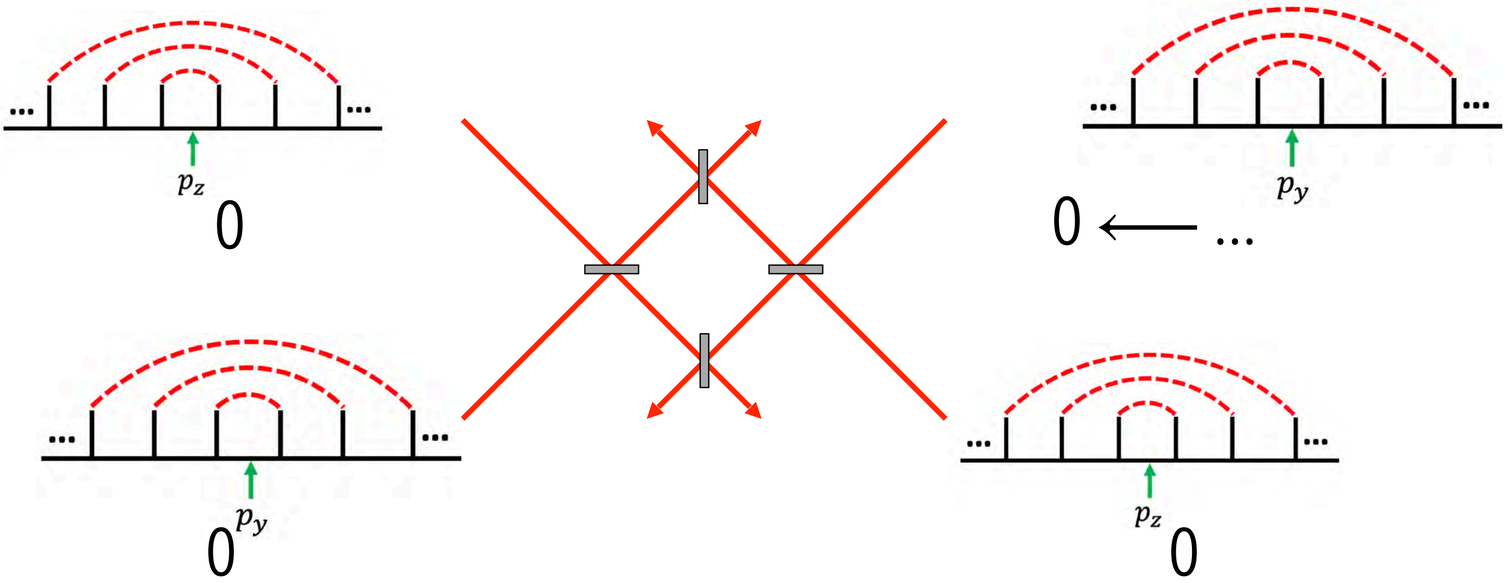
Interference between identical frequencies of different combs





~10^4 modes long

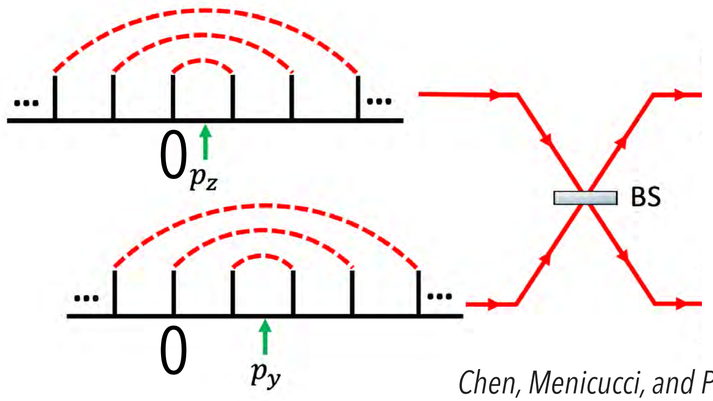
Chen, Menicucci, and Pfister, ***Experimental realization of multipartite entanglement of 60 modes of a quantum optical frequency comb****, PRL 112, 120505 (2014)*

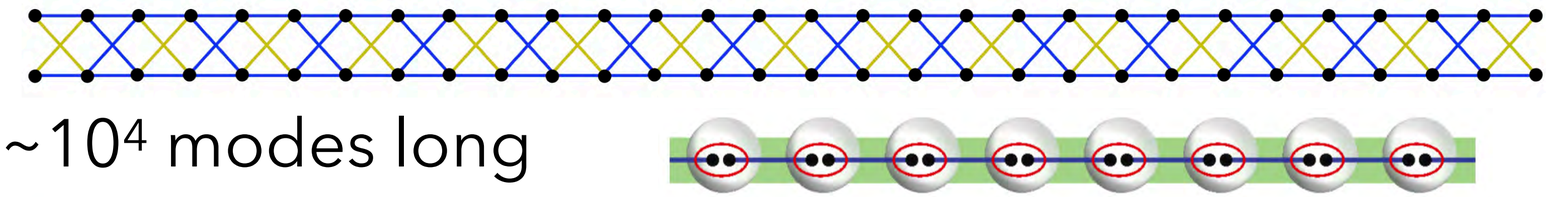


Wang, Chen, Menicucci, and Pfister, ***Weaving quantum optical frequency combs into hypercubic cluster states****, PRA 90, 032325 (2014)*

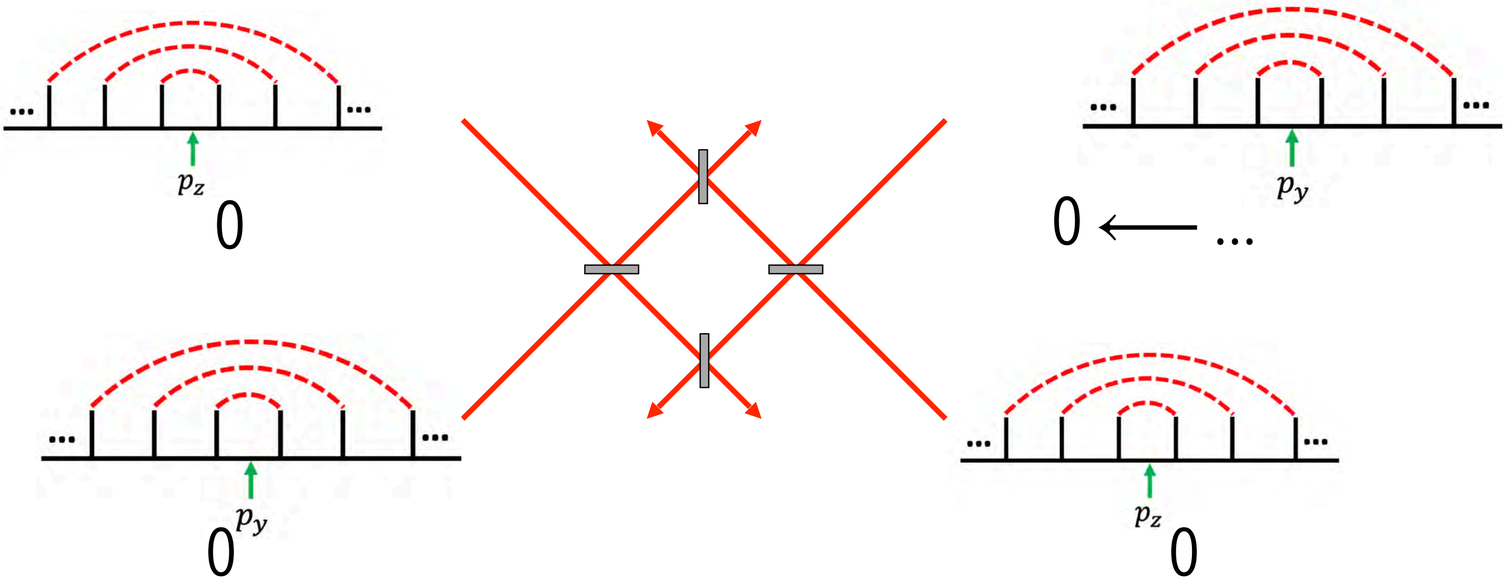
Interfering quantum combs

Interference between identical frequencies of different combs





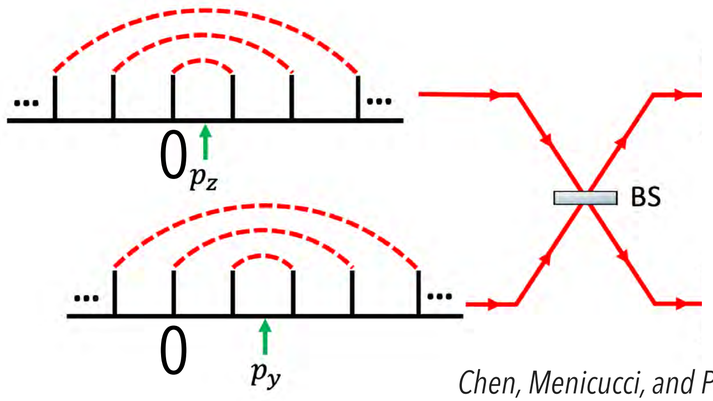
Chen, Menicucci, and Pfister, ***Experimental realization of multipartite entanglement of 60 modes of a quantum optical frequency comb****, PRL 112, 120505 (2014)*

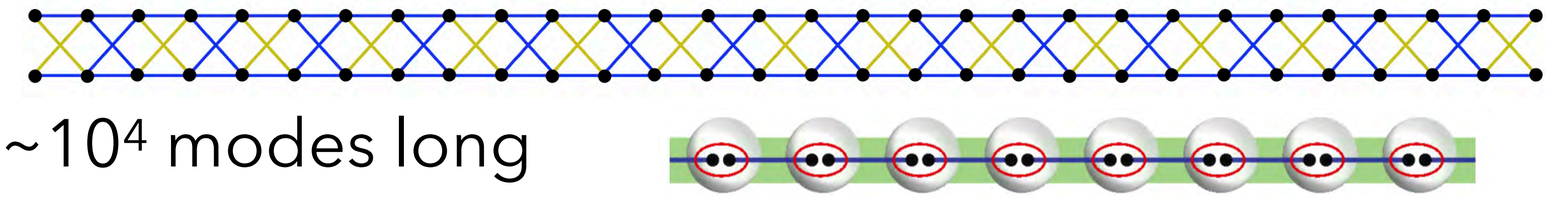


Wang, Chen, Menicucci, and Pfister, ***Weaving quantum optical frequency combs into hypercubic cluster states****, PRA 90, 032325 (2014)*

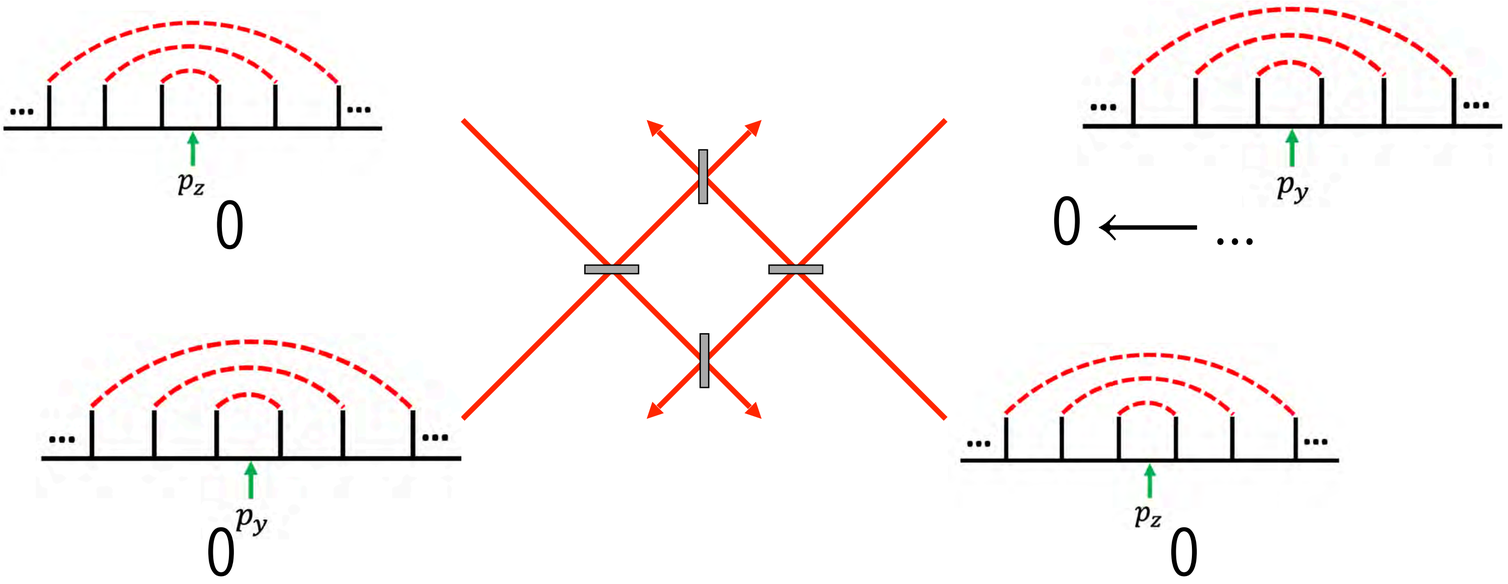
Interfering quantum combs

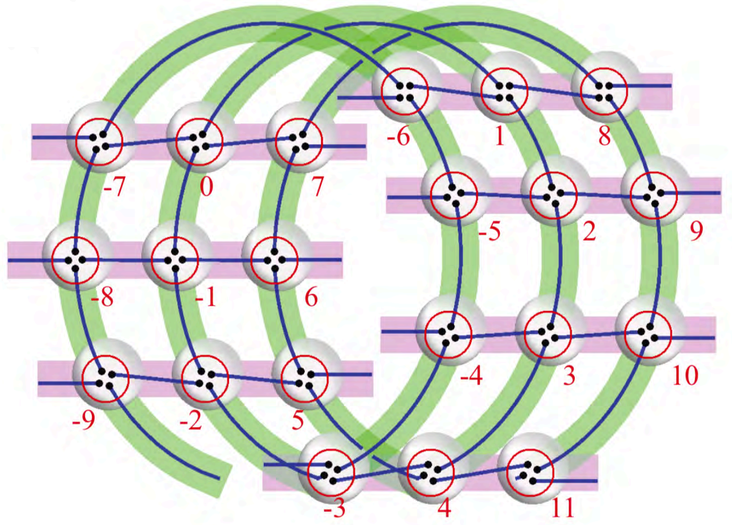
Interference between identical frequencies of different combs





Chen, Menicucci, and Pfister, ***Experimental realization of multipartite entanglement of 60 modes of a quantum optical frequency comb****, PRL 112, 120505 (2014)*





Wang, Chen, Menicucci, and Pfister, ***Weaving quantum optical frequency combs into hypercubic cluster states****, PRA 90, 032325 (2014)*

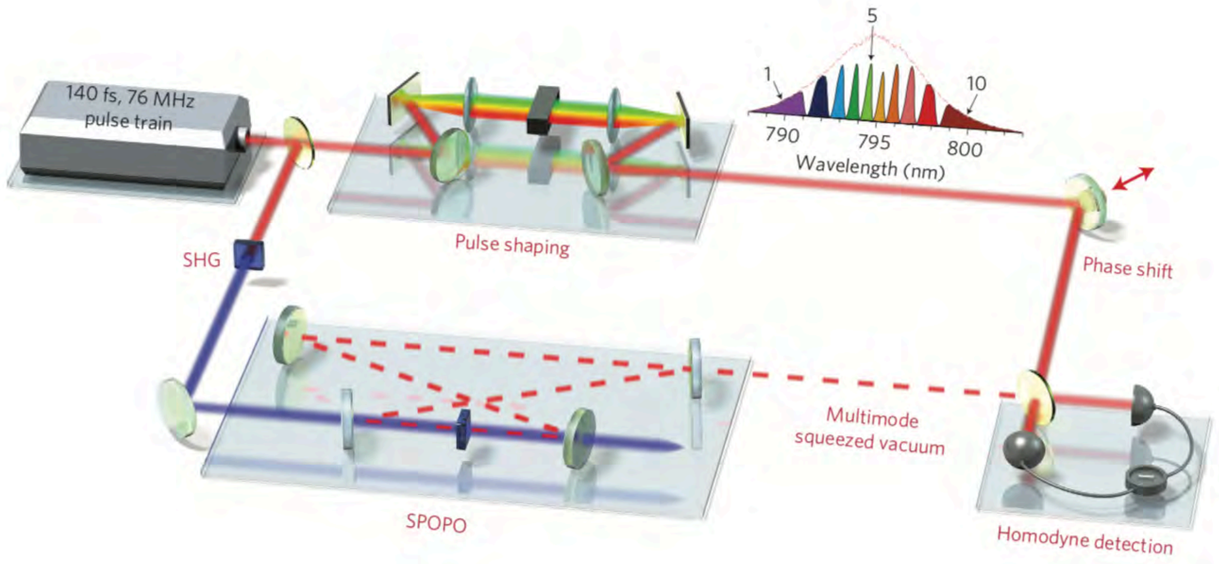
nature photonics

LETTERS

PUBLISHED ONLINE: 15 DECEMBER 2013 | DOI: 10.1038/NPHOTON.2013.340

Wavelength-multiplexed quantum networks with ultrafast frequency combs

Jonathan Roslund, Renné Medeiros de Araújo, Shifeng Jiang, Claude Fabre and Nicolas Treps*

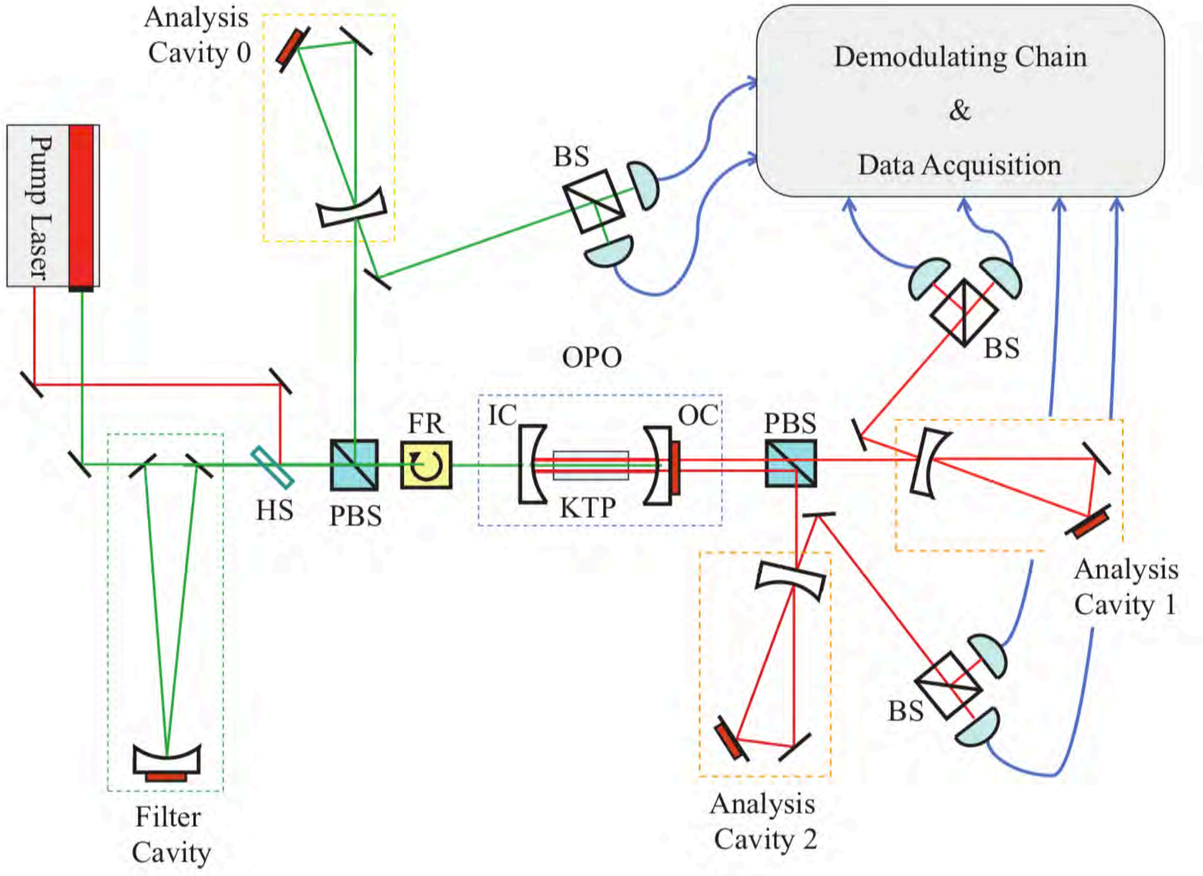


PHYSICAL REVIEW LETTERS **121,** 073601 (2018)

Featured in Physics

Hexapartite Entanglement in an above-Threshold Optical Parametric Oscillator

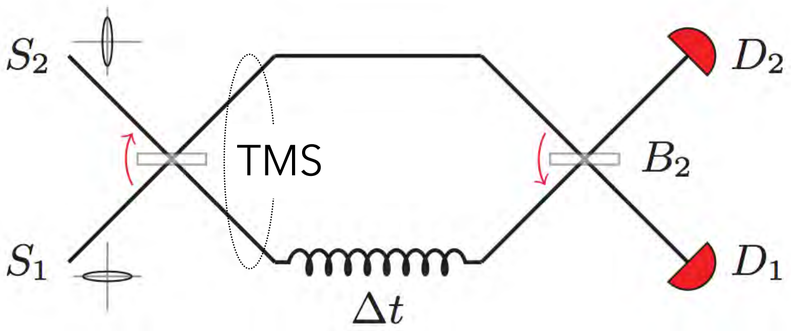
F. A. S. Barbosa,[1] A. S. Coelho,[2,3] L. F. Muñoz-Martínez,[4] L. Ortiz-Gutiérrez,[5]
A. S. Villar,[6] P. Nussenzveig,[7] and M. Martinelli[7,*]

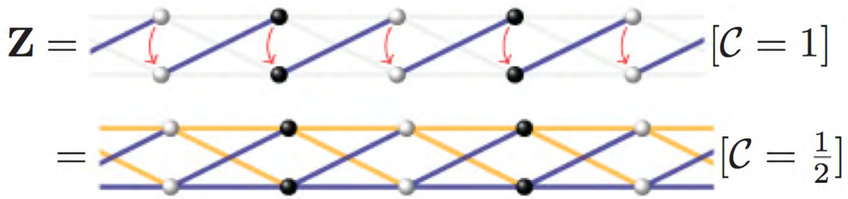


PHYSICAL REVIEW A **83**, 062314 (2011)

Temporal-mode continuous-variable cluster states using linear optics

Nicolas C. Menicucci





"Dual-rail quantum wire"

- Akira Furusawa's group: *sequential* entanglement of 10^4 qumodes (2 at a time)

LETTERS
PUBLISHED ONLINE: 17 NOVEMBER 2013 | DOI: 10.1038/NPHOTON.2013.287
nature photonics

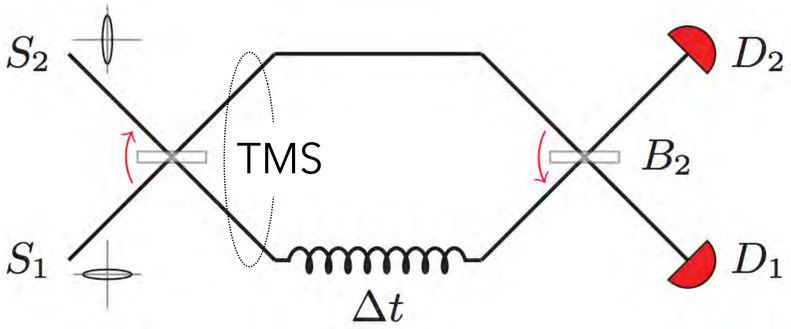
Ultra-large-scale continuous-variable cluster states multiplexed in the time domain

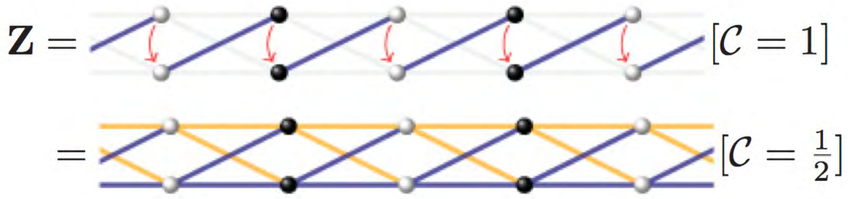
Shota Yokoyama[1], Ryuji Ukai[1], Seiji C. Armstrong[1,2], Chanond Sornphiphatphong[1], Toshiyuki Kaji[1], Shigenari Suzuki[1], Jun-ichi Yoshikawa[1], Hidehiro Yonezawa[1], Nicolas C. Menicucci[3] and Akira Furusawa[1]*

PHYSICAL REVIEW A **83**, 062314 (2011)

Temporal-mode continuous-variable cluster states using linear optics

Nicolas C. Menicucci





"Dual-rail quantum wire"

10^6

- Akira Furusawa's group: *sequential* entanglement of 10^4 qumodes (2 at a time)

APL PHOTONICS **1**, 060801 (2016)

Invited Article: Generation of one-million-mode continuous-variable cluster state by unlimited time-domain multiplexing

Jun-ichi Yoshikawa,[1] Shota Yokoyama,[1,2] Toshiyuki Kaji,[1] Chanond Sornphiphatphong,[1] Yu Shiozawa,[1] Kenzo Makino,[1] and Akira Furusawa[1,a]

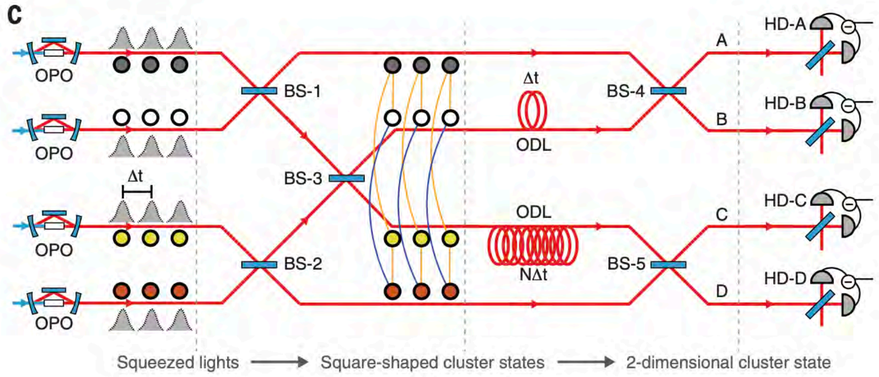
2D cluster states have arrived

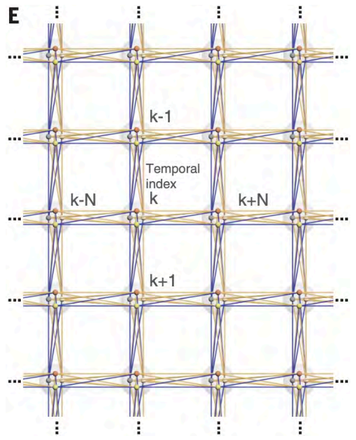
QUANTUM COMPUTING

Generation of time-domain-multiplexed two-dimensional cluster state

Warit Asavanant[1], Yu Shiozawa[1], Shota Yokoyama[2], Baramee Charoensombutamon[1], Hiroki Emura[1], Rafael N. Alexander[3], Shuntaro Takeda[1,4], Jun-ichi Yoshikawa[1], Nicolas C. Menicucci[5], Hidehiro Yonezawa[2], Akira Furusawa[1]*

Asavanant *et al.*, *Science* **366**, 373–376 (2019) 18 October 2019



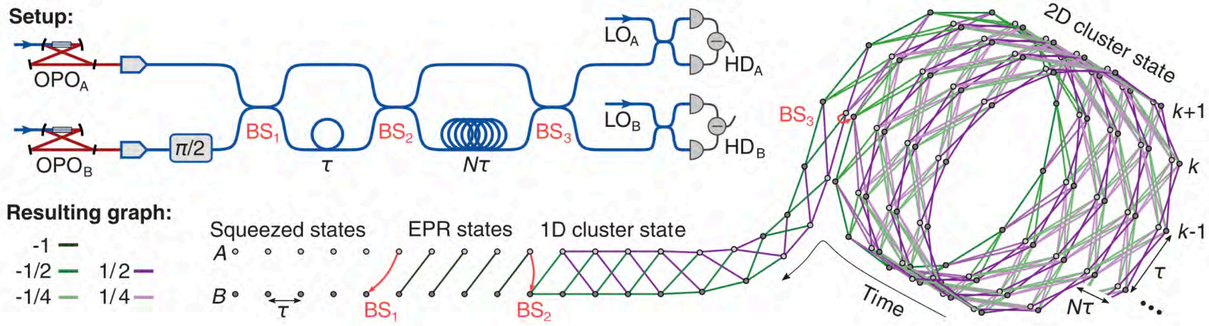


QUANTUM COMPUTING

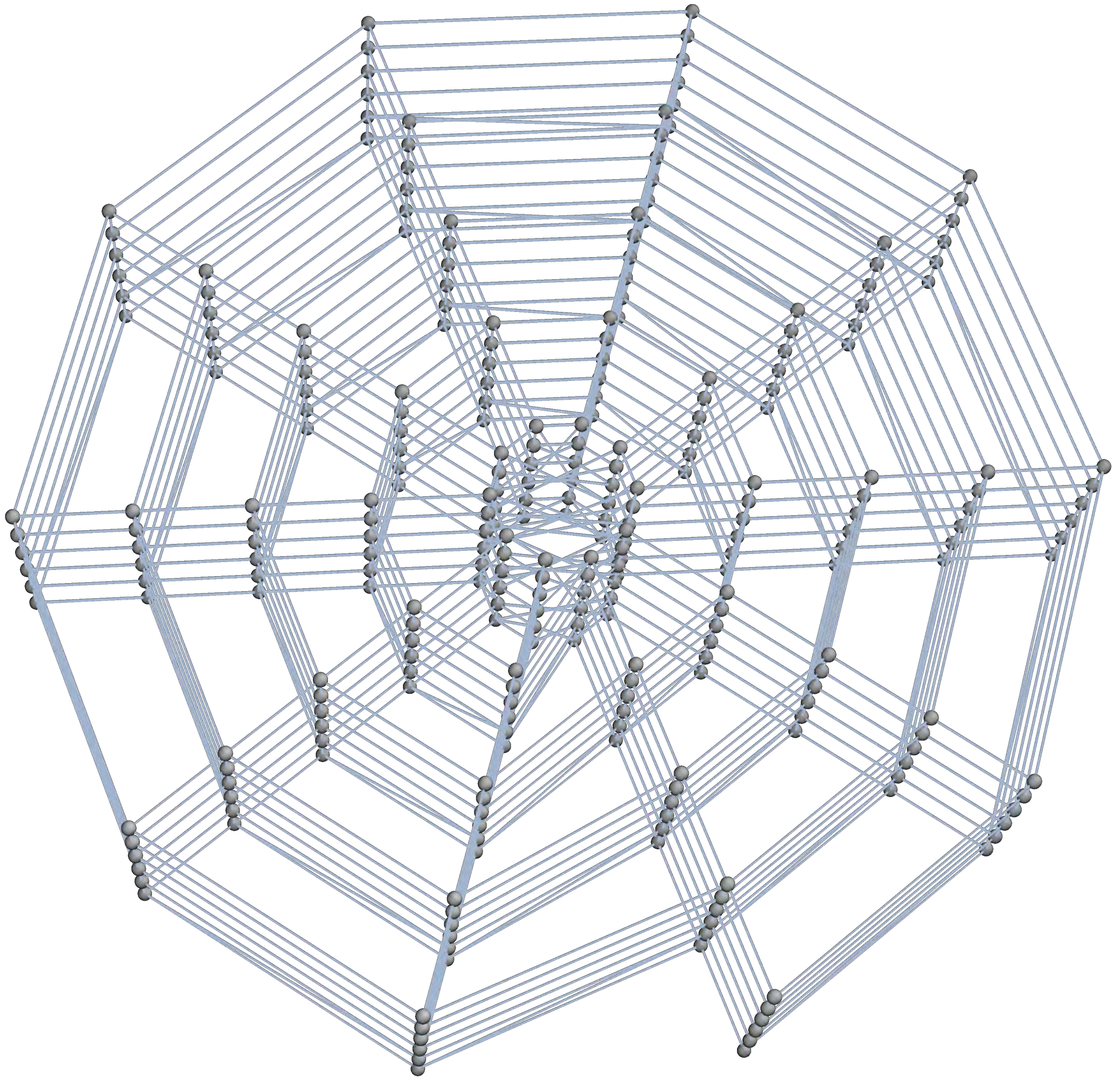
Deterministic generation of a two-dimensional cluster state

Mikkel V. Larsen*, Xueshi Guo, Casper R. Breum, Jonas S. Neergaard-Nielsen, Ulrik L. Andersen*

Larsen *et al.*, *Science* **366**, 369–372 (2019) 18 October 2019

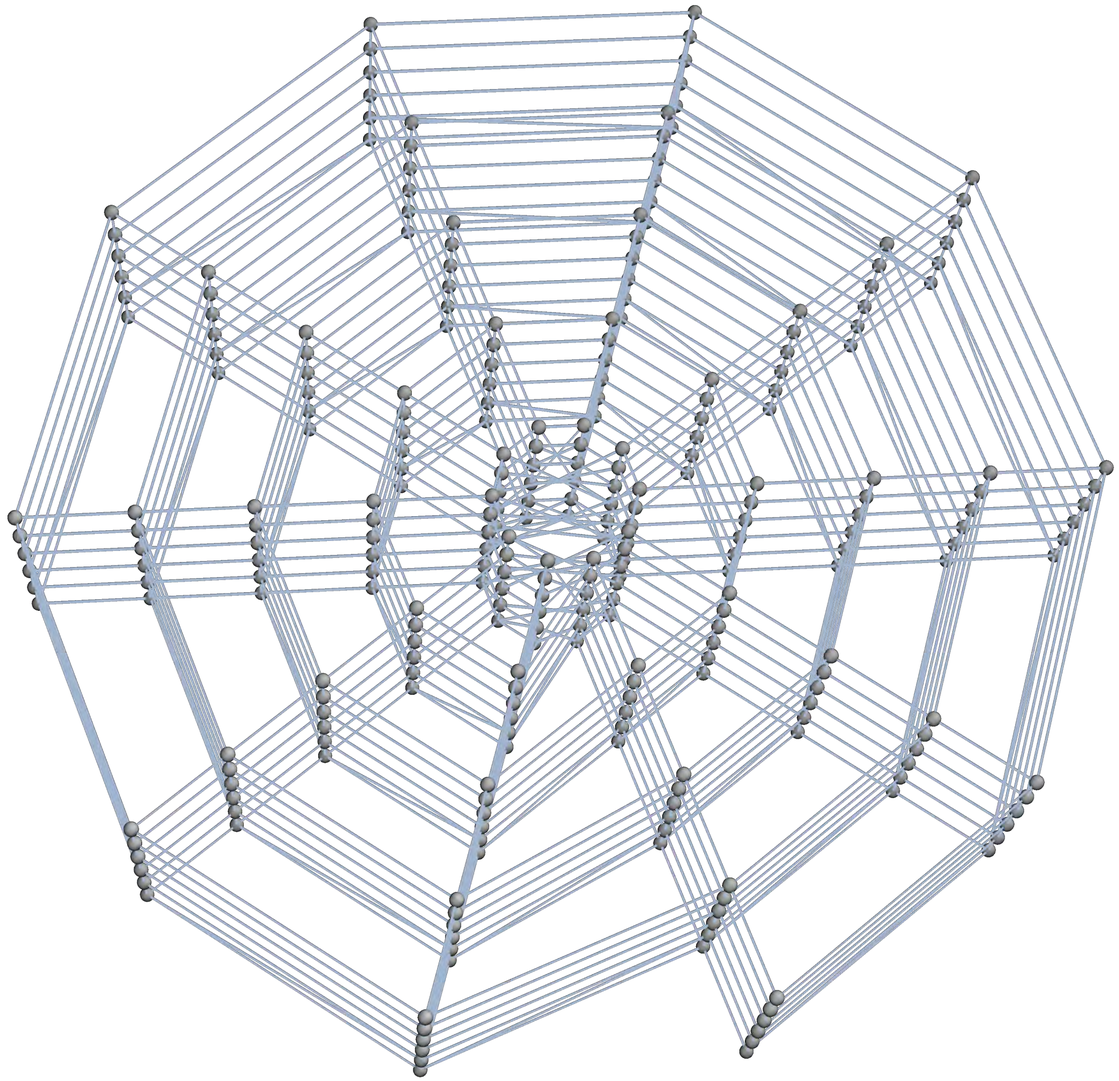


3D states (and beyond) just around the corner are

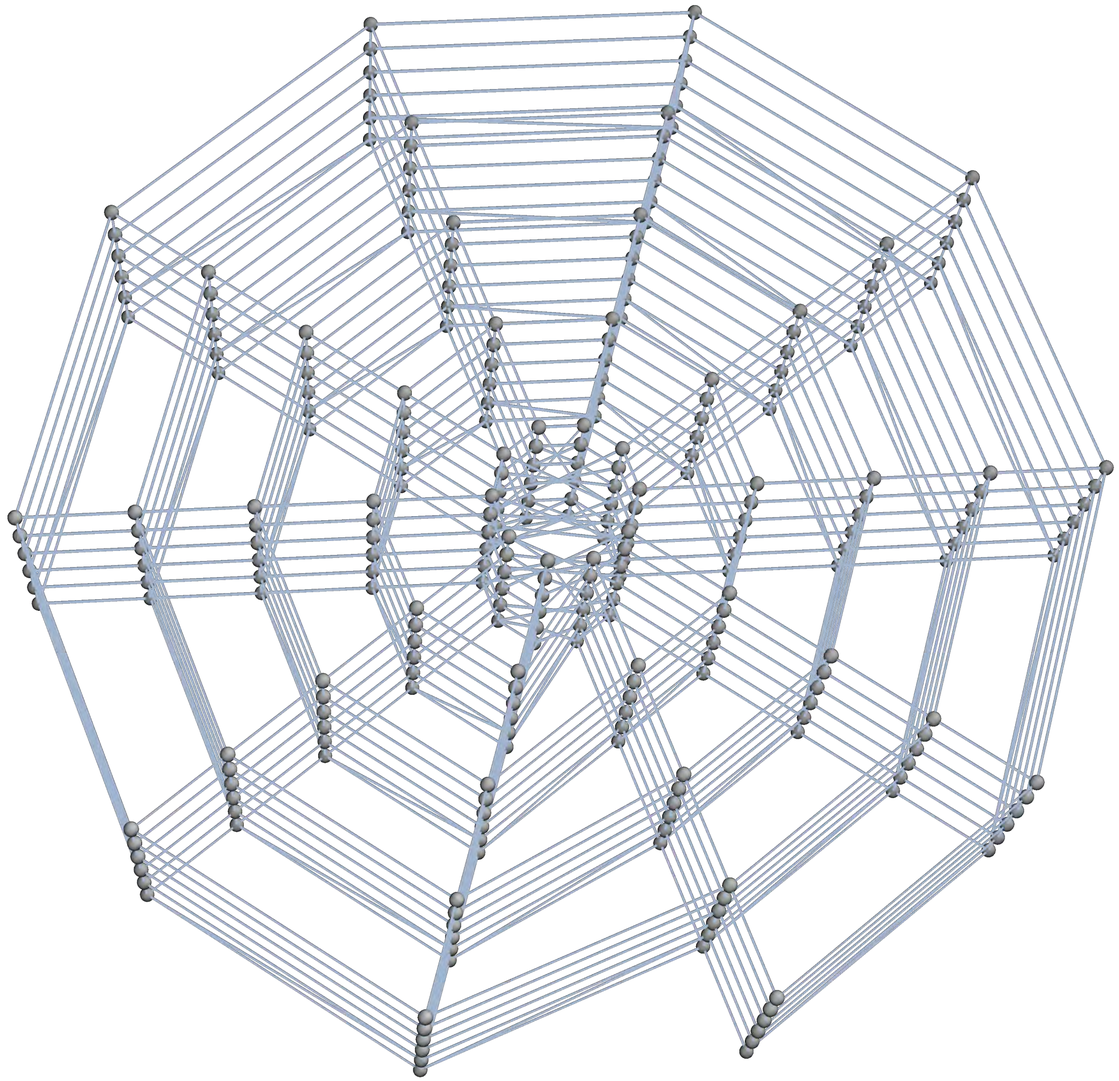


3D states (and beyond) just around the corner are

3D states (and beyond) just around the corner are



3D states (and beyond) just around the corner are



ELSEVIER

Available online at www.sciencedirect.com
SCIENCE DIRECT®

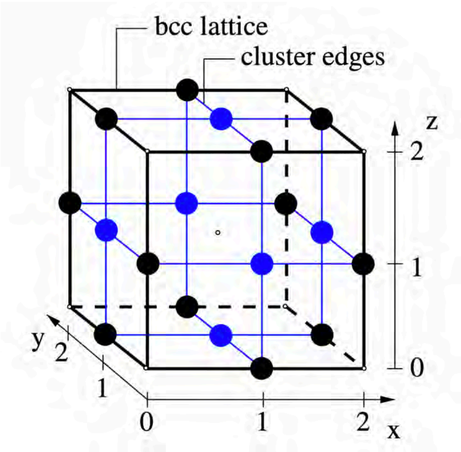
Annals of Physics 321 (2006) 2242–2270

ANNALS of PHYSICS

www.elsevier.com/locate/aop

A fault-tolerant one-way quantum computer

R. Raussendorf [a,*], J. Harrington [b], K. Goyal [a]



Take-home message

The generation of sophisticated, QC-universal cluster states on a very large scale (thousands of qumodes) is

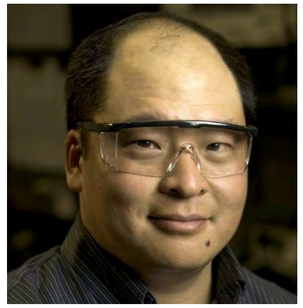
EASY

over continuous variables and is also

highly compatible with an integrated optics approach. (Stay tuned.)

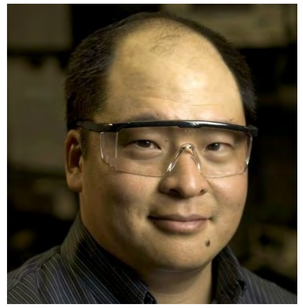
Non-Gaussian quantum optics (photons)

An experimentally accessible non-Gaussian operation: photon-number detection



Sae Woo Nam
(NIST)

Aaron Miller
(Quantum Opus)



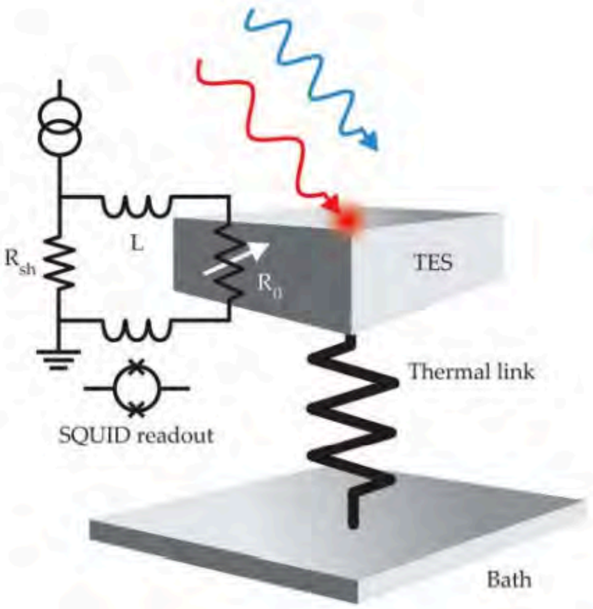
Sae Woo Nam
(NIST)

An experimentally accessible non-Gaussian operation: photon-number detection

POVM set $\equiv \{|\, n \,\rangle\langle\, n \,|\}_{n=0,\ldots,n_{\max}}$ (ideally!)

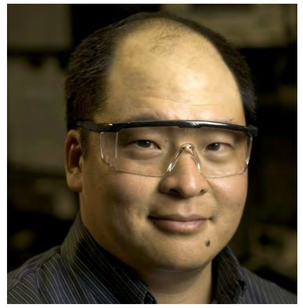
Aaron Miller
(Quantum Opus)

Superconducting transition-edge sensor



Physics Today **71**, 8, 28 (2018)

An experimentally accessible non-Gaussian operation: photon-number detection

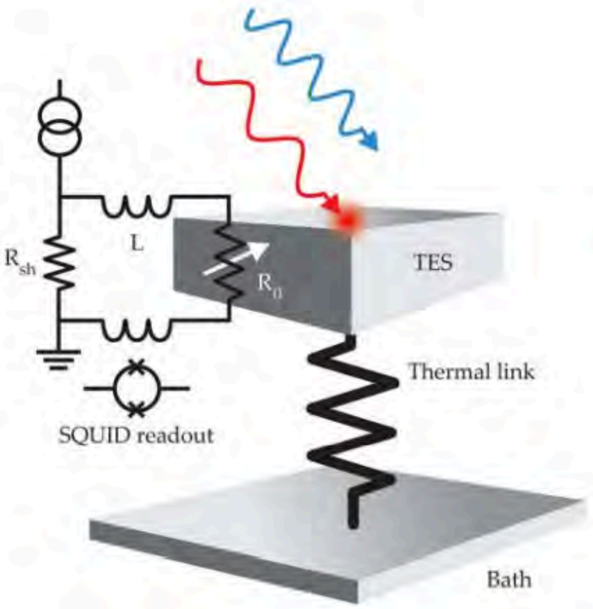


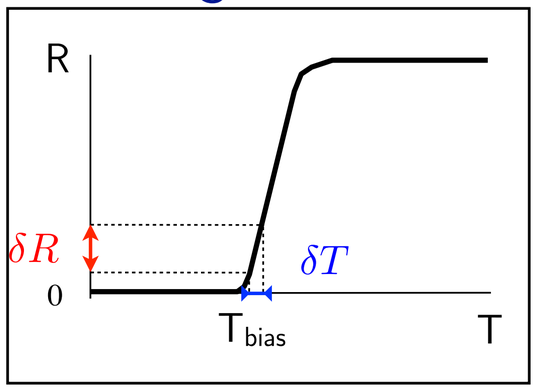
Sae Woo Nam
(NIST)

POVM set $\equiv \{|\, n \,\rangle\langle\, n \,|\}_{n=0,\ldots,n_{\max}}$ (ideally!)

Aaron Miller
(Quantum Opus)

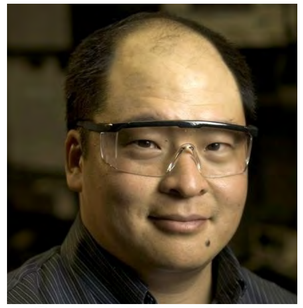
Superconducting transition-edge sensor





Physics Today **71**, 8, 28 (2018)

An experimentally accessible non-Gaussian operation: photon-number detection

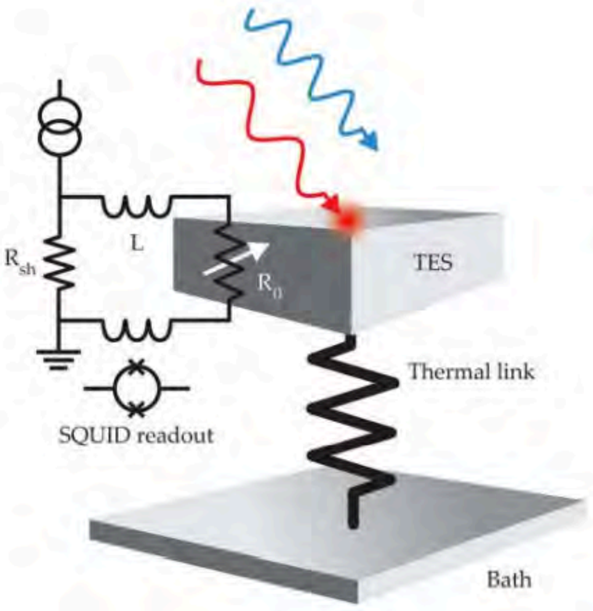


Sae Woo Nam
(NIST)

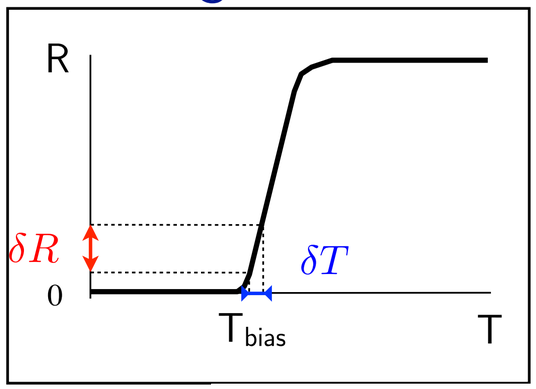
POVM set ≡ $\{|\, n \,\rangle\langle\, n \,|\}_{n=0,\ldots,n_{\max}}$ (ideally!)

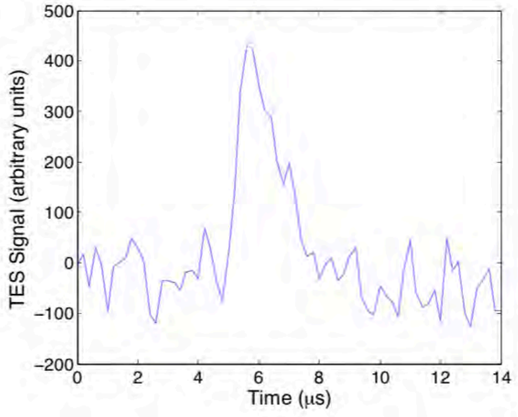
Aaron Miller
(Quantum Opus)

Superconducting transition-edge sensor

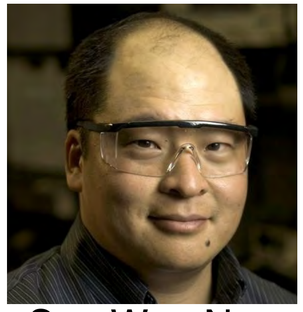


Physics Today **71**, 8, 28 (2018)





An experimentally accessible non-Gaussian operation: photon-number detection

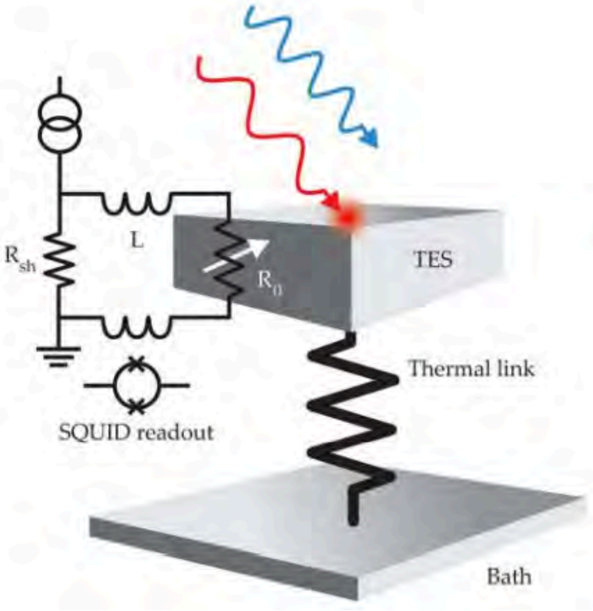


Sae Woo Nam
(NIST)

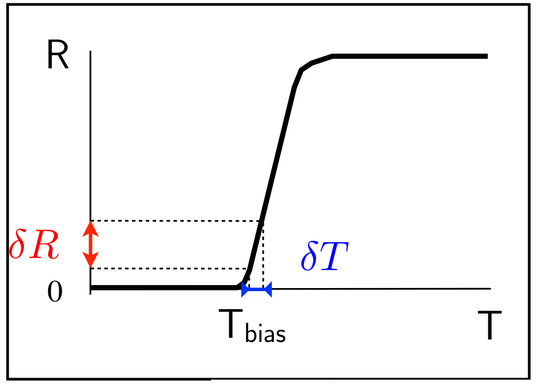
POVM set ≡ $\{|\,n\,\rangle\langle\,n\,|\}_{n=0,\ldots,n_{\max}}$ (ideally!)

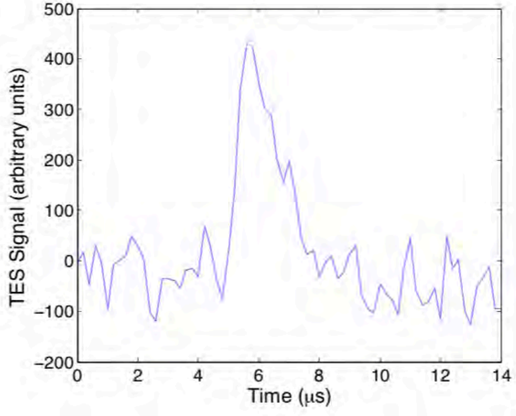
Aaron Miller
(Quantum Opus)

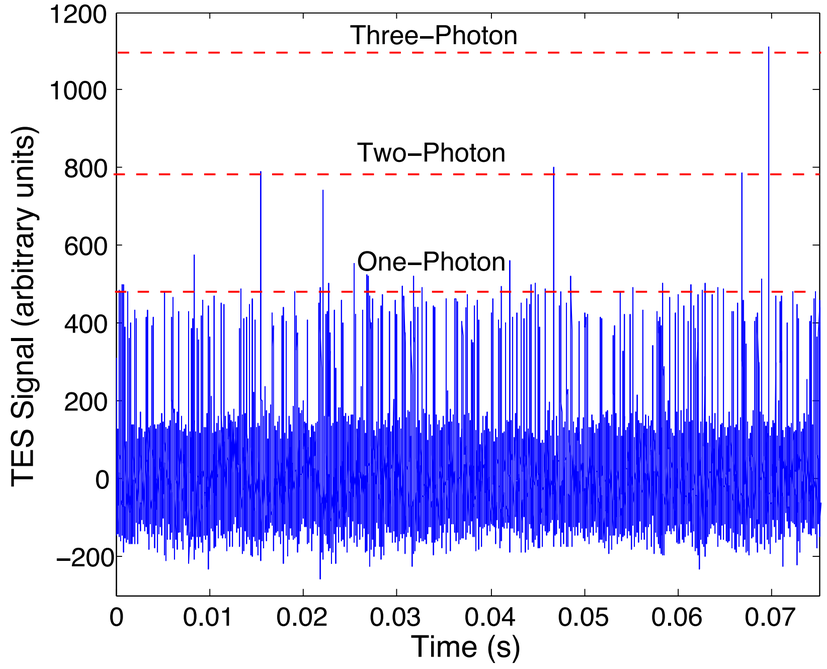
Superconducting transition-edge sensor



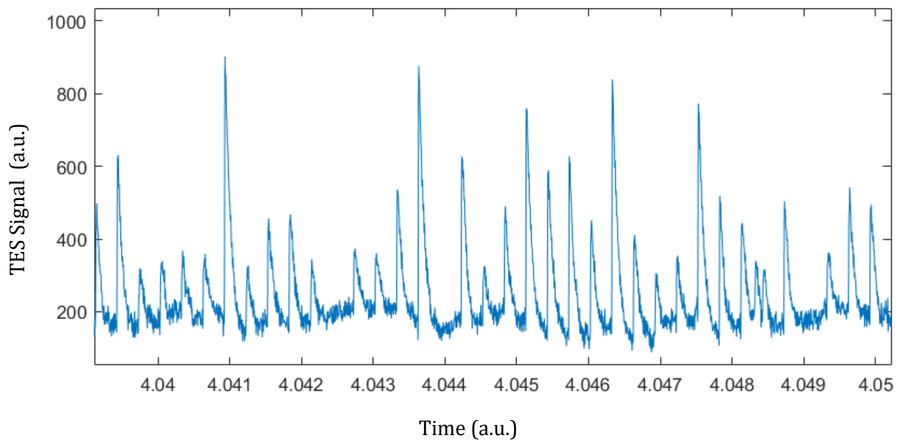
Physics Today **71**, 8, 28 (2018)

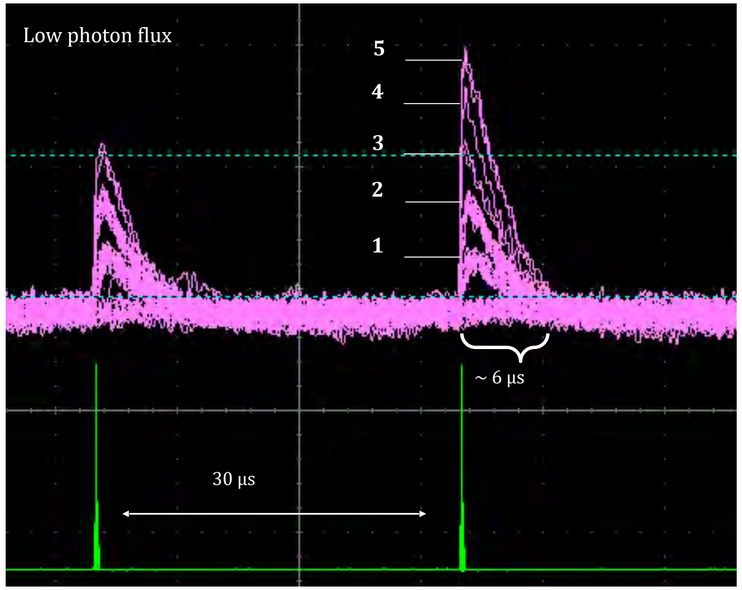


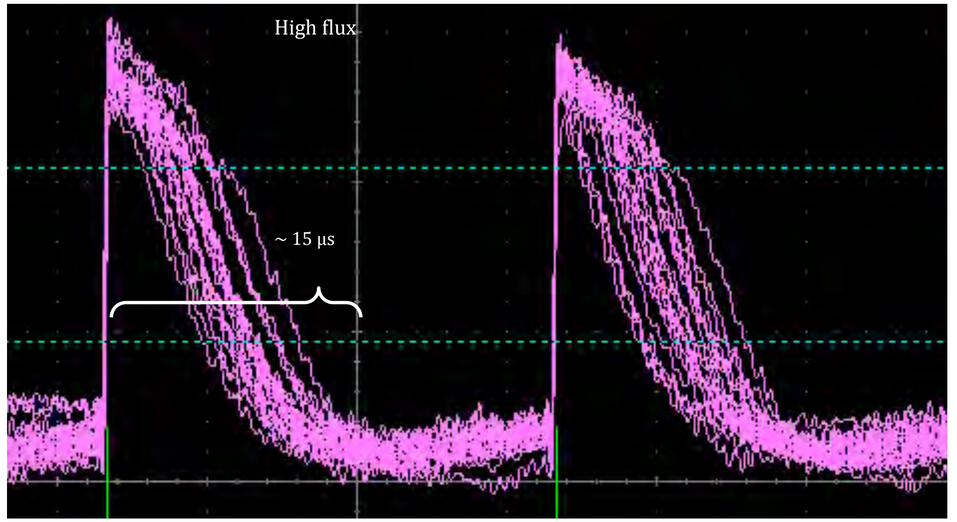




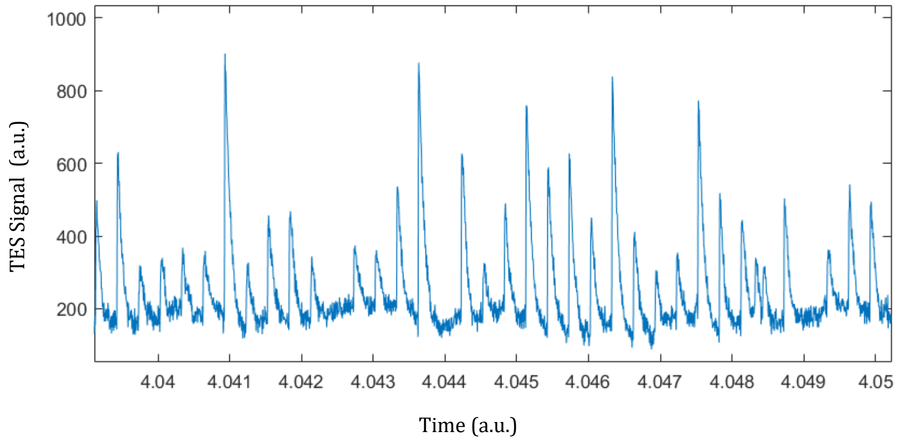
Processing TES signal: PNR detection

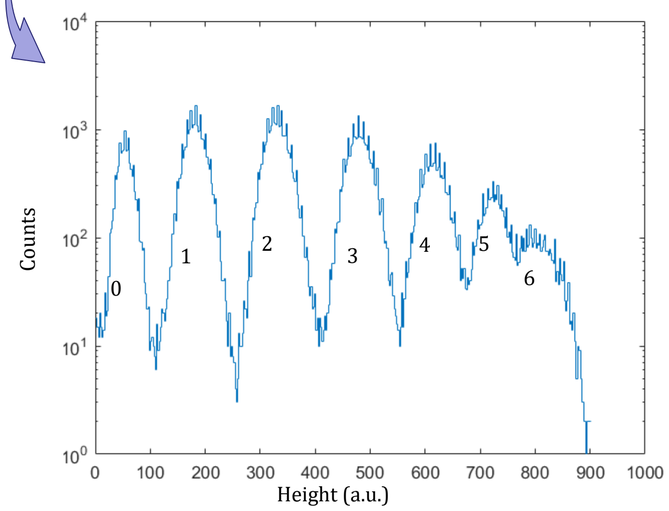


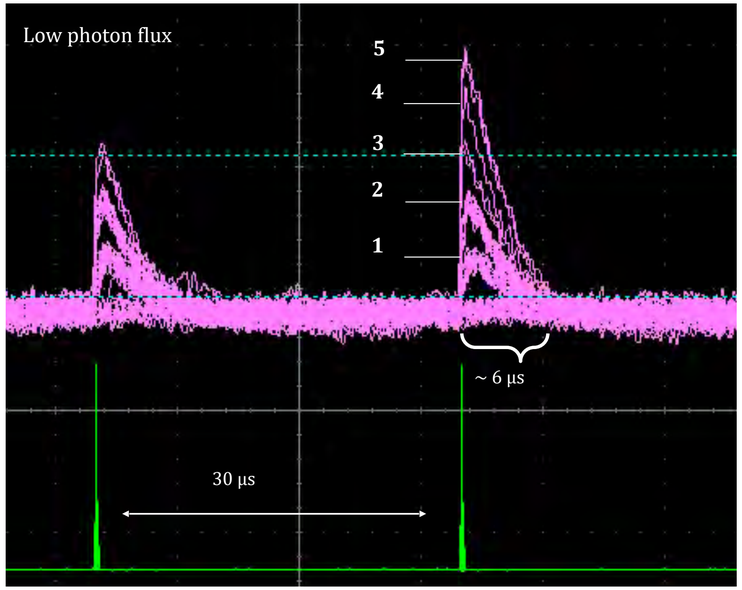


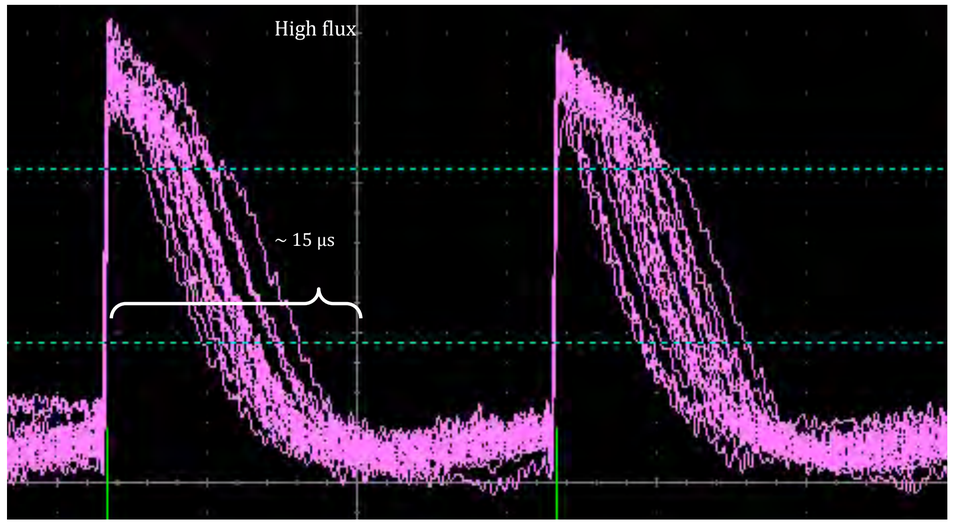


Processing TES signal: PNR detection

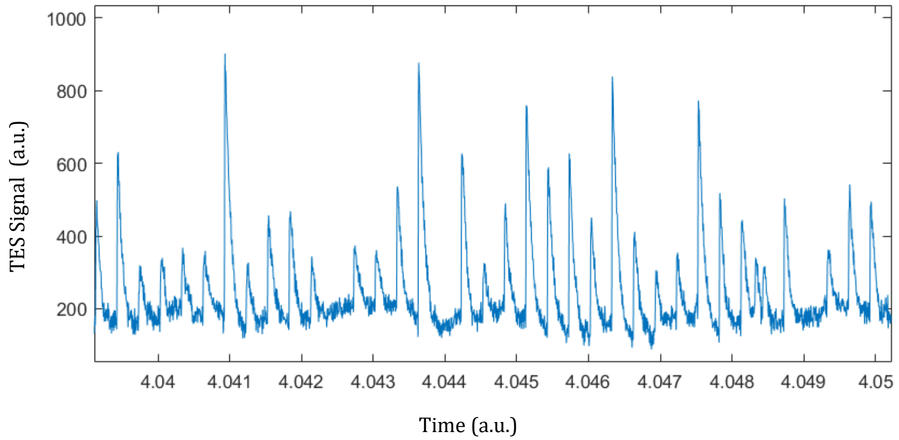


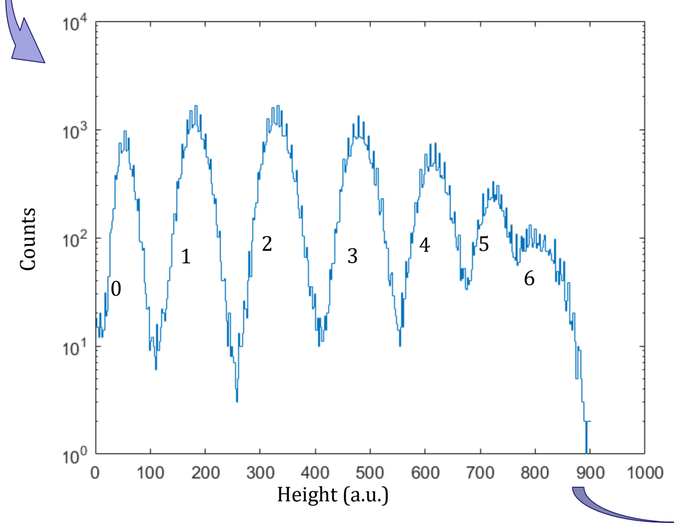


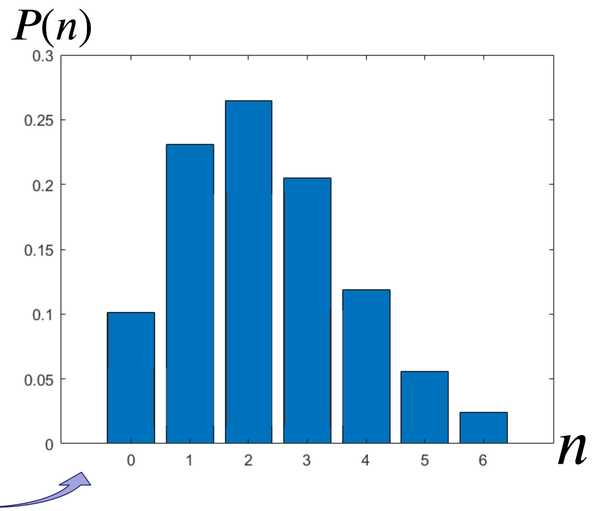


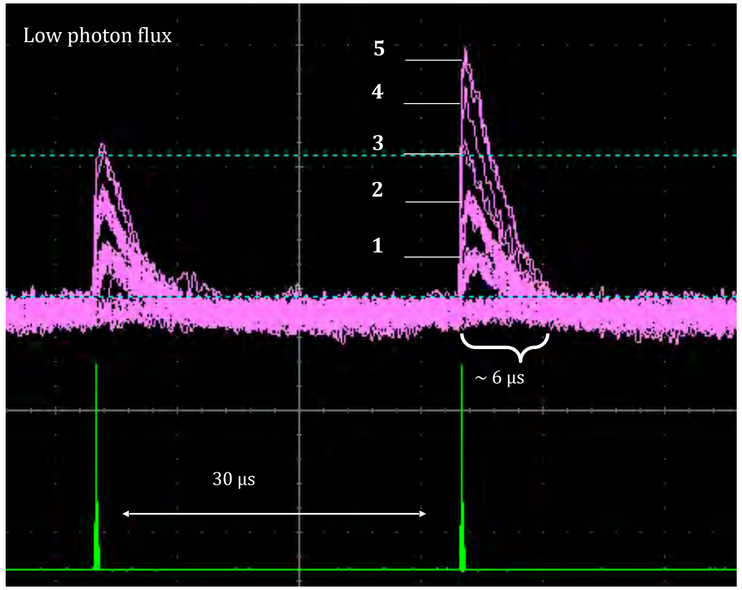


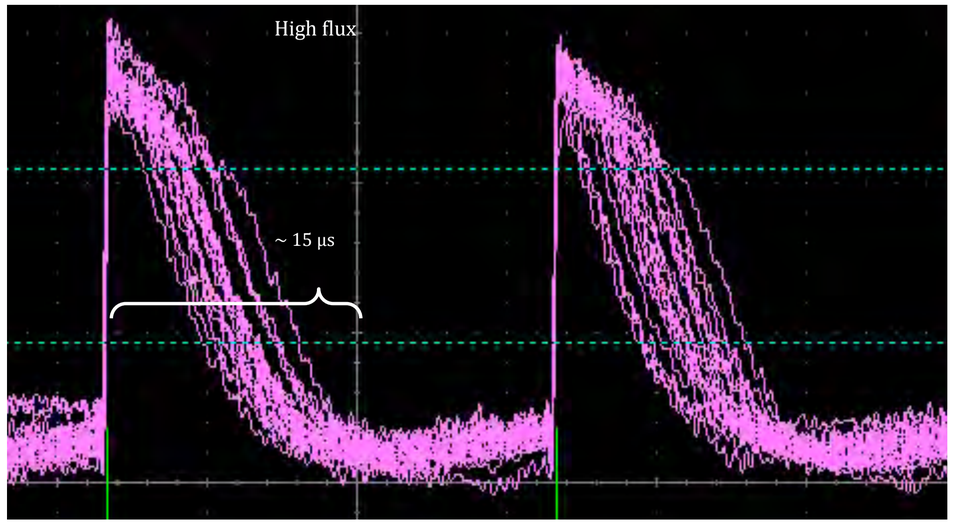
Processing TES signal: PNR detection



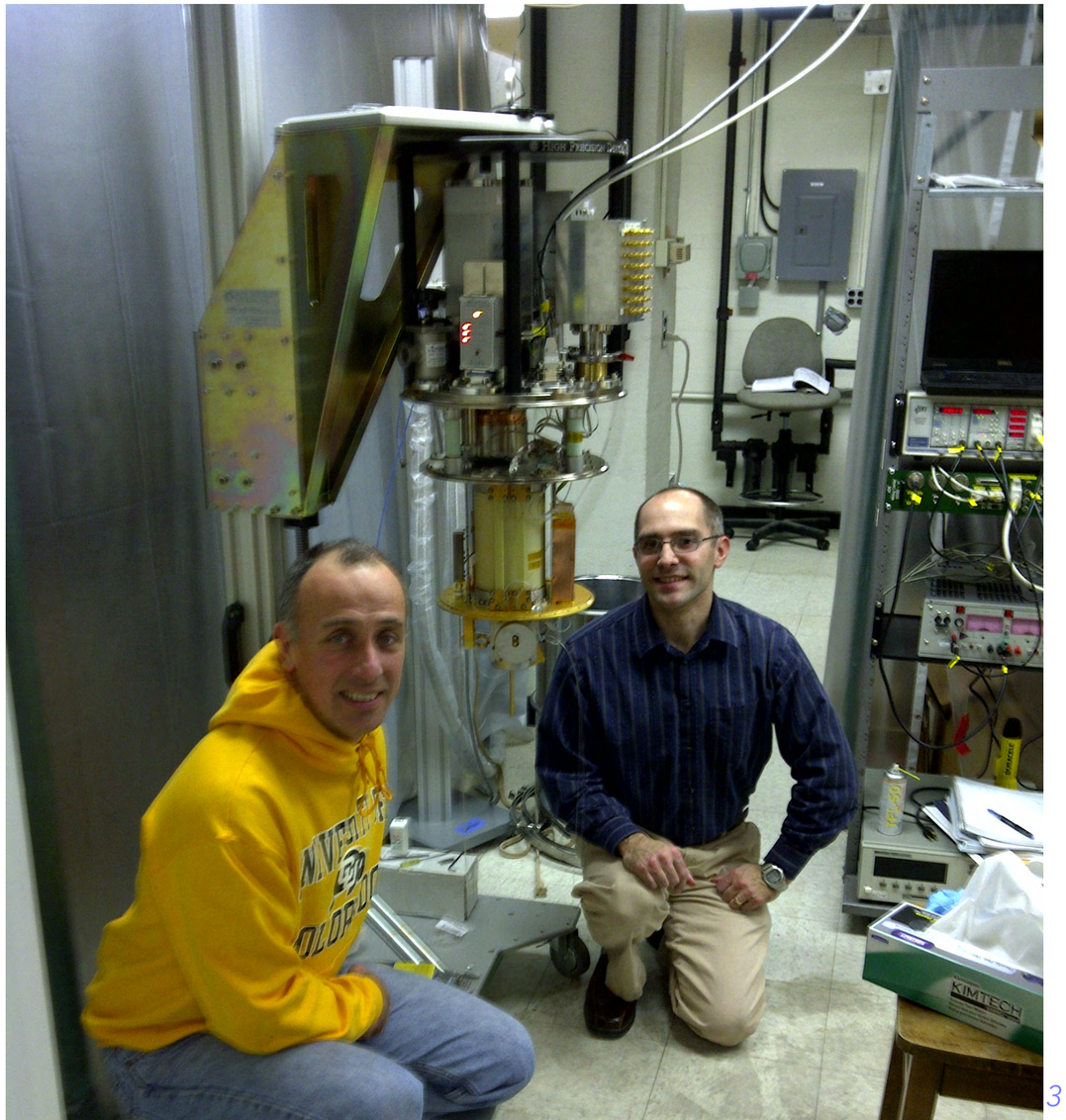


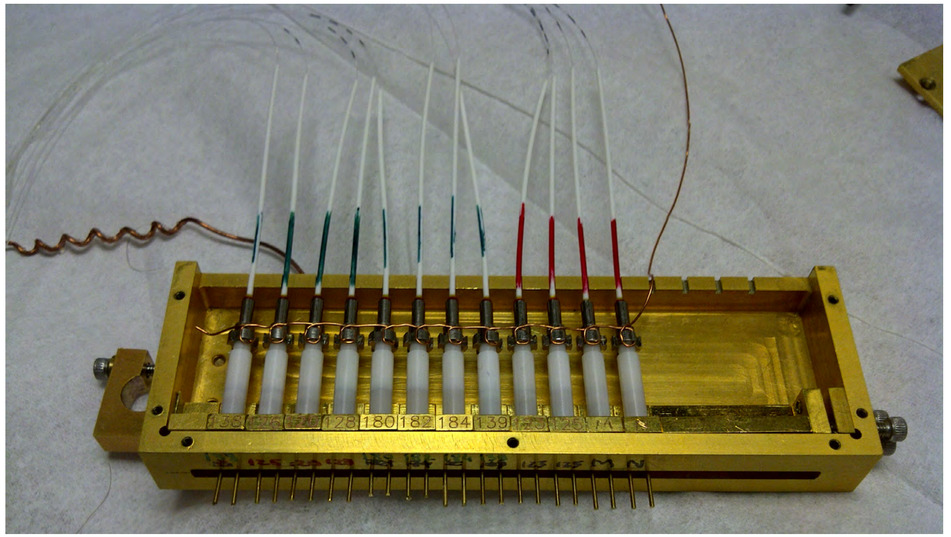


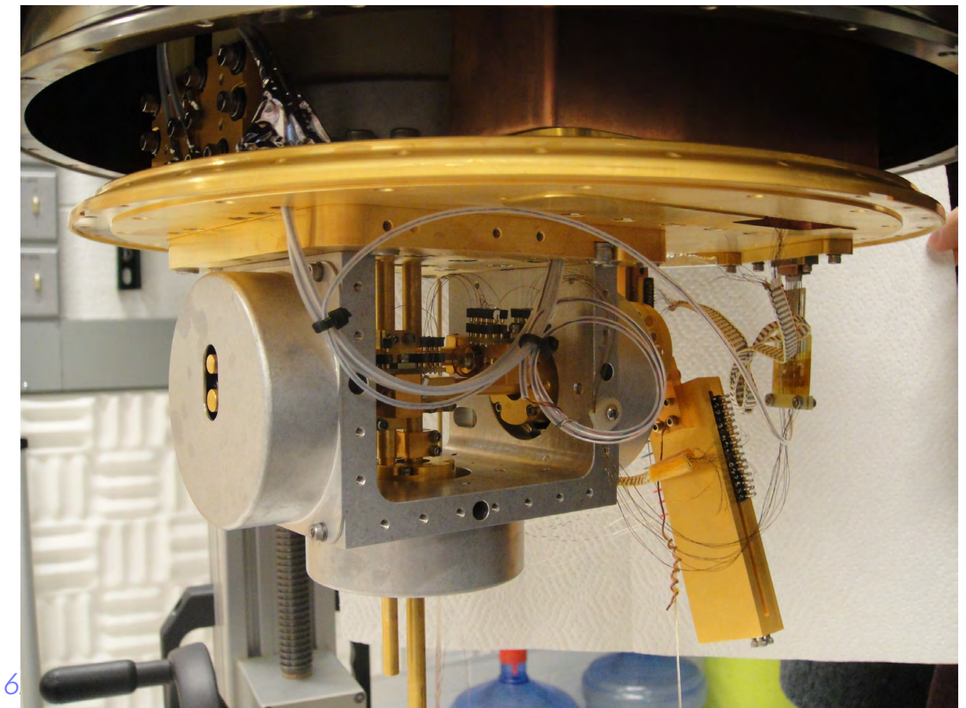




TES @ PfisterLabs







Quantum tomography with photon counting

S. Wallentowitz & W. Vogel, PRA (1996)
K. Banaszek & W. Wódkiewicz, PRL (1996)

WIGNER FUNCTION

$$W(q,p) = \frac{1}{2\pi}\int_{-\infty}^{\infty} e^{iyp} \left\langle q - \frac{y}{2} \middle| \rho \middle| q + \frac{y}{2} \right\rangle dy$$

- Only function whose marginals yield the quantum probability distributions
- Can be NONPOSITIVE (i.e., nonGaussian for a pure state)

Quantum tomography with photon counting

S. Wallentowitz & W. Vogel, PRA (1996)
K. Banaszek & W. Wódkiewicz, PRL (1996)

WIGNER FUNCTION $$W(q,p) = \frac{1}{2\pi}\int_{-\infty}^{\infty} e^{iyp} \left\langle q - \frac{y}{2} \middle| \rho \middle| q + \frac{y}{2} \right\rangle dy$$

- Only function whose marginals yield the quantum probability distributions
- Can be NONPOSITIVE (i.e., nonGaussian for a pure state)

$$W_{\hat{\rho}}(\alpha) = \frac{1}{\pi} Tr[\hat{\rho} D(\alpha)(-1)^{\hat{n}} D^{\dagger}(\alpha)] \qquad \alpha := q + ip$$

$$W_{\hat{\rho}}(\alpha) = \frac{1}{\pi} Tr[D^{\dagger}(\alpha)\hat{\rho} D(\alpha)(-1)^{\hat{n}}]$$

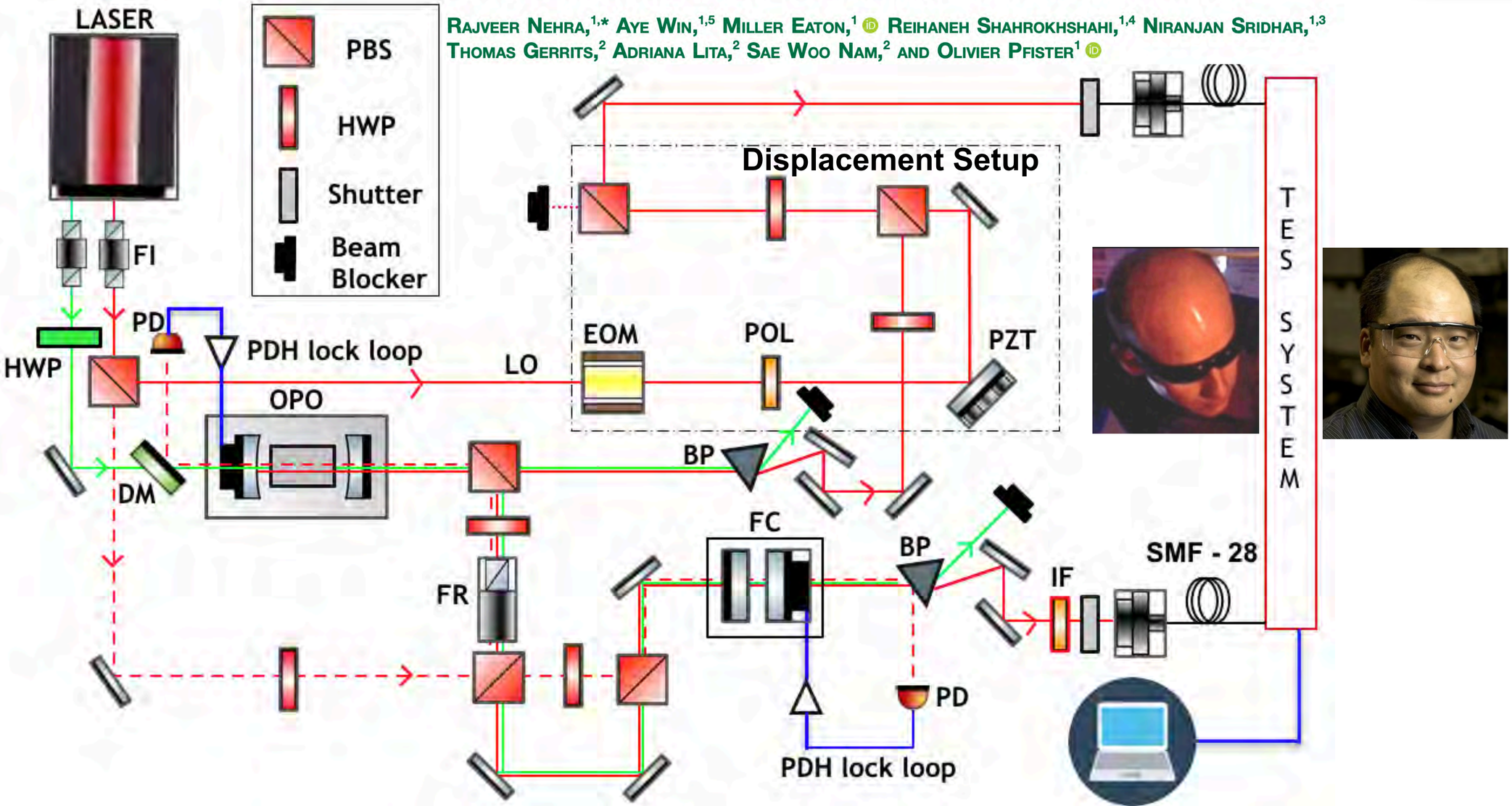
- Expectation value of the photon-number parity
- Easily measured directly with photon-number-resolving detection
- Raster scan of phase space by amplitude/phase shifts gives whole W(q,p)

Research Article Vol. 6, No. 10 / October 2019 / Optica 1356

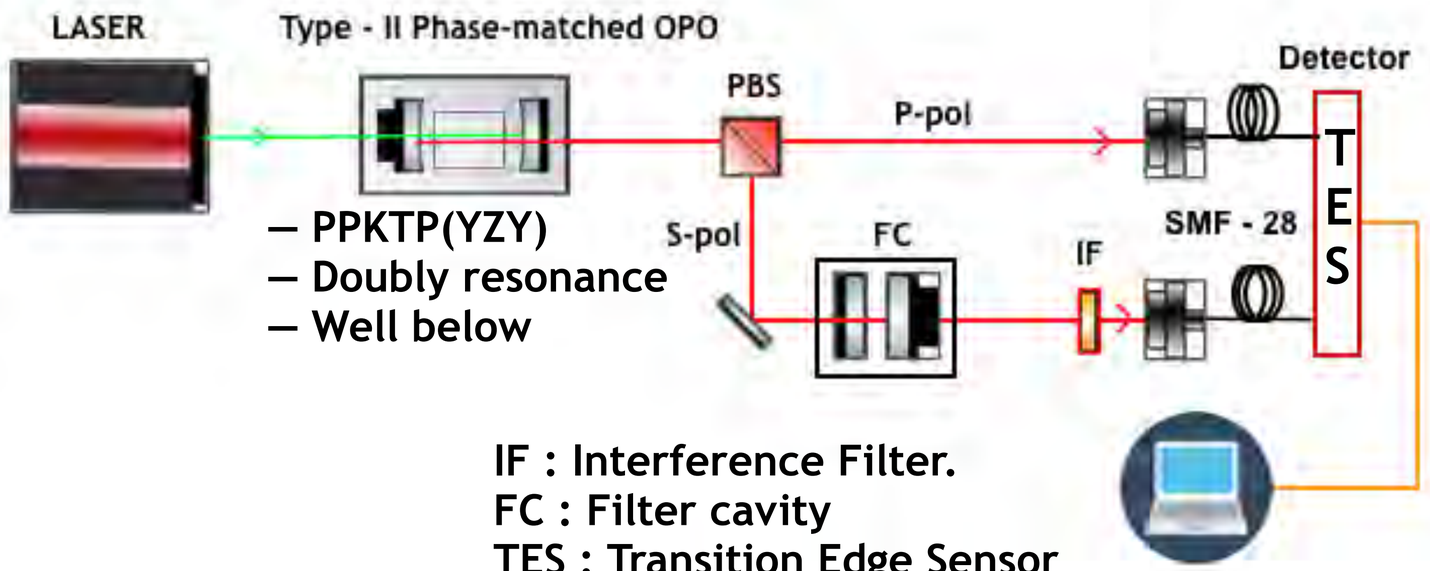
optica

State-independent quantum state tomography by photon-number-resolving measurements

Rajveer Nehra,[1,*] Aye Win,[1,5] Miller Eaton,[1] Reihaneh Shahrokhshahi,[1,4] Niranjan Sridhar,[1,3] Thomas Gerrits,[2] Adriana Lita,[2] Sae Woo Nam,[2] and Olivier Pfister[1]

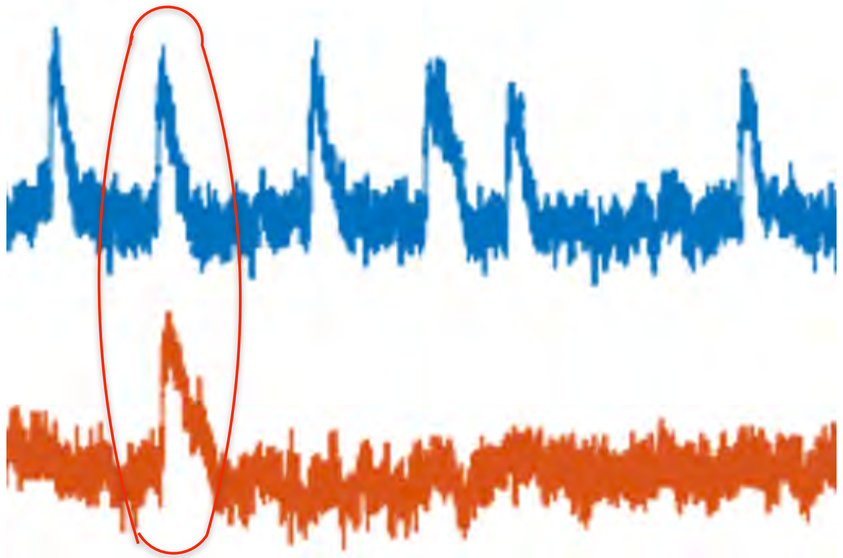


Nd: YAG
532 nm,
FWHM = 1kHz



– PPKTP(YZY)
– Doubly resonance
– Well below

IF : Interference Filter.
FC : Filter cavity
TES : Transition Edge Sensor



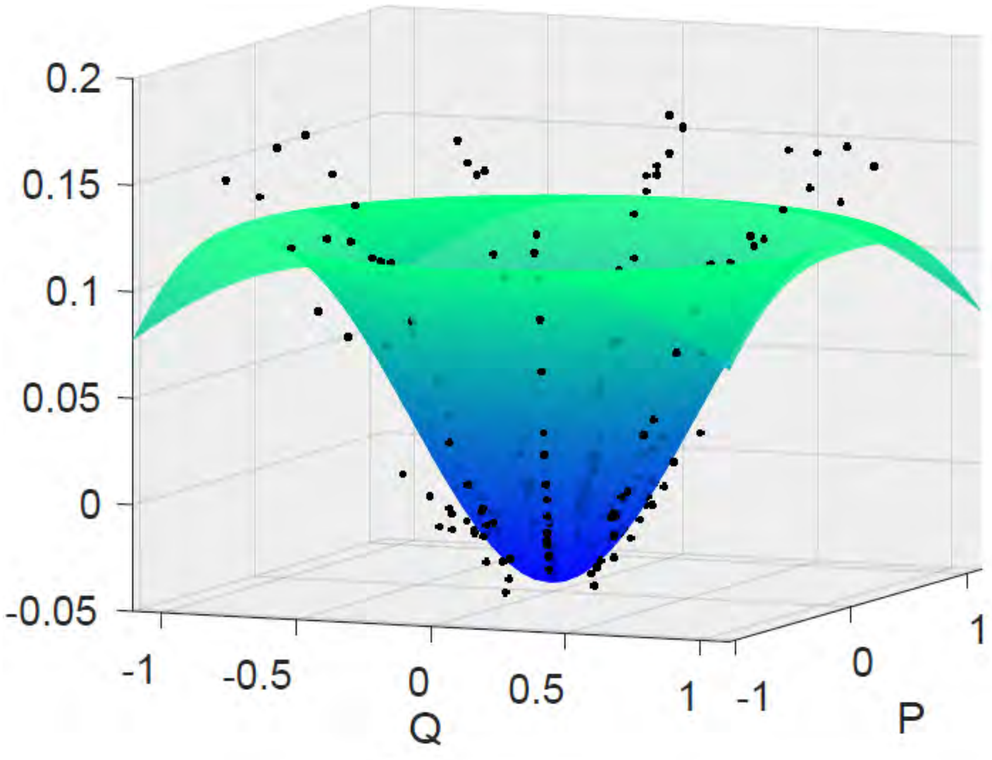
Heralded(Signal) Channel

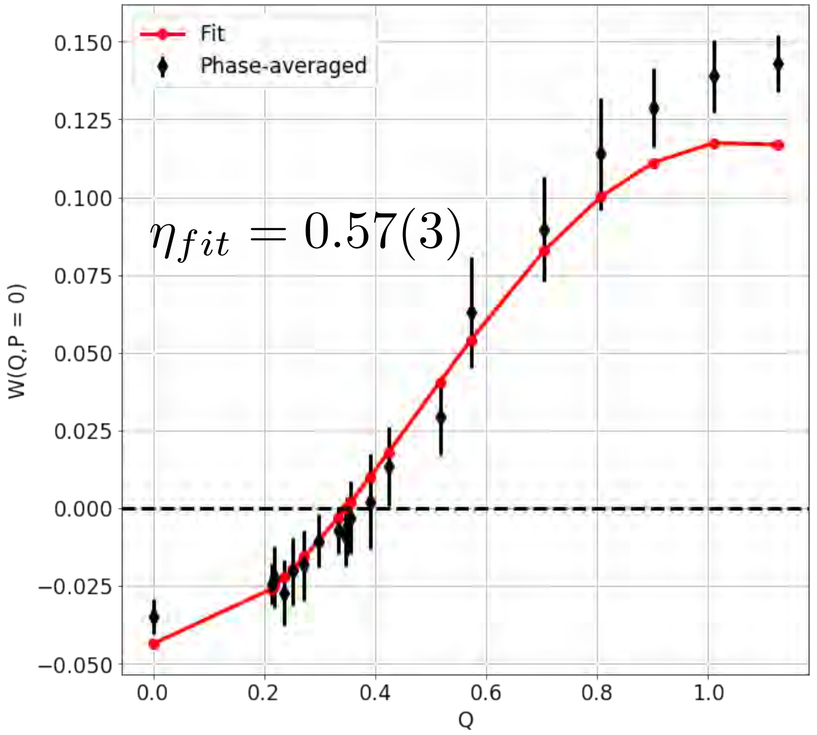
Heralding(idler) Channel

$$\eta_h = \frac{N_c}{N_i} = 0.58(2)$$

Overall efficiency of the signal path.

Experimental results



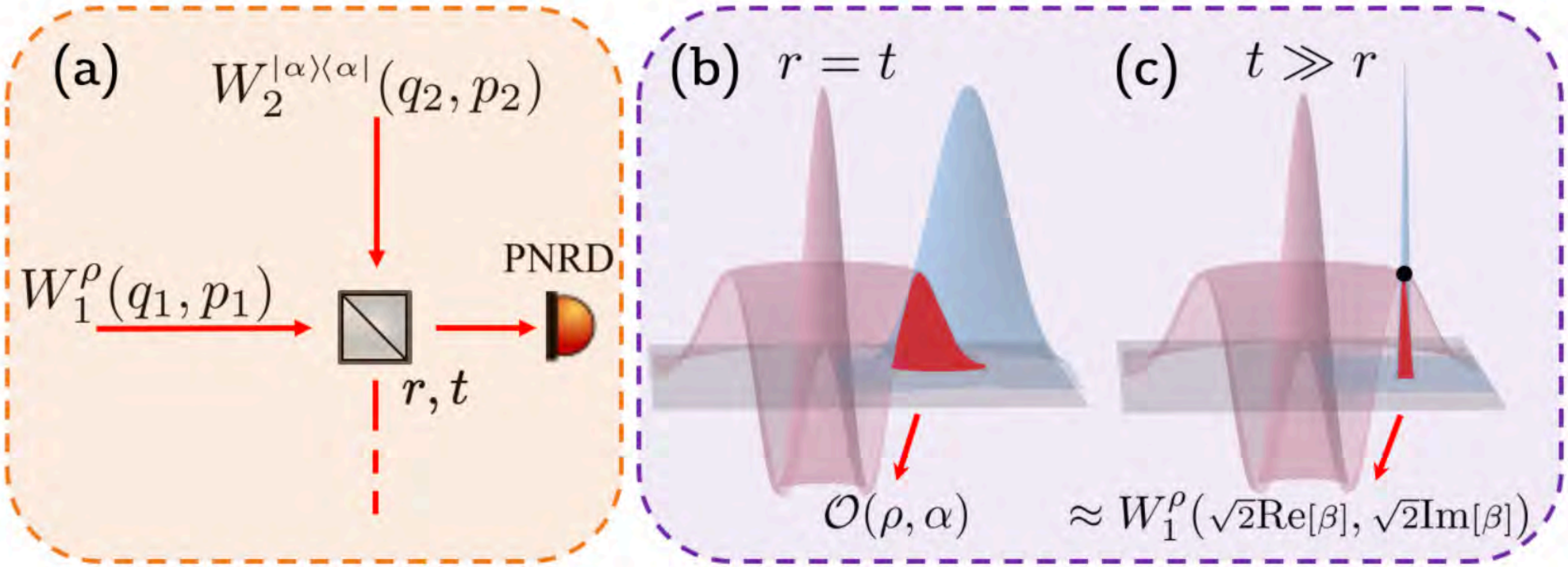


★ Negativity was observed in the raw data without any inference or correcting for losses.

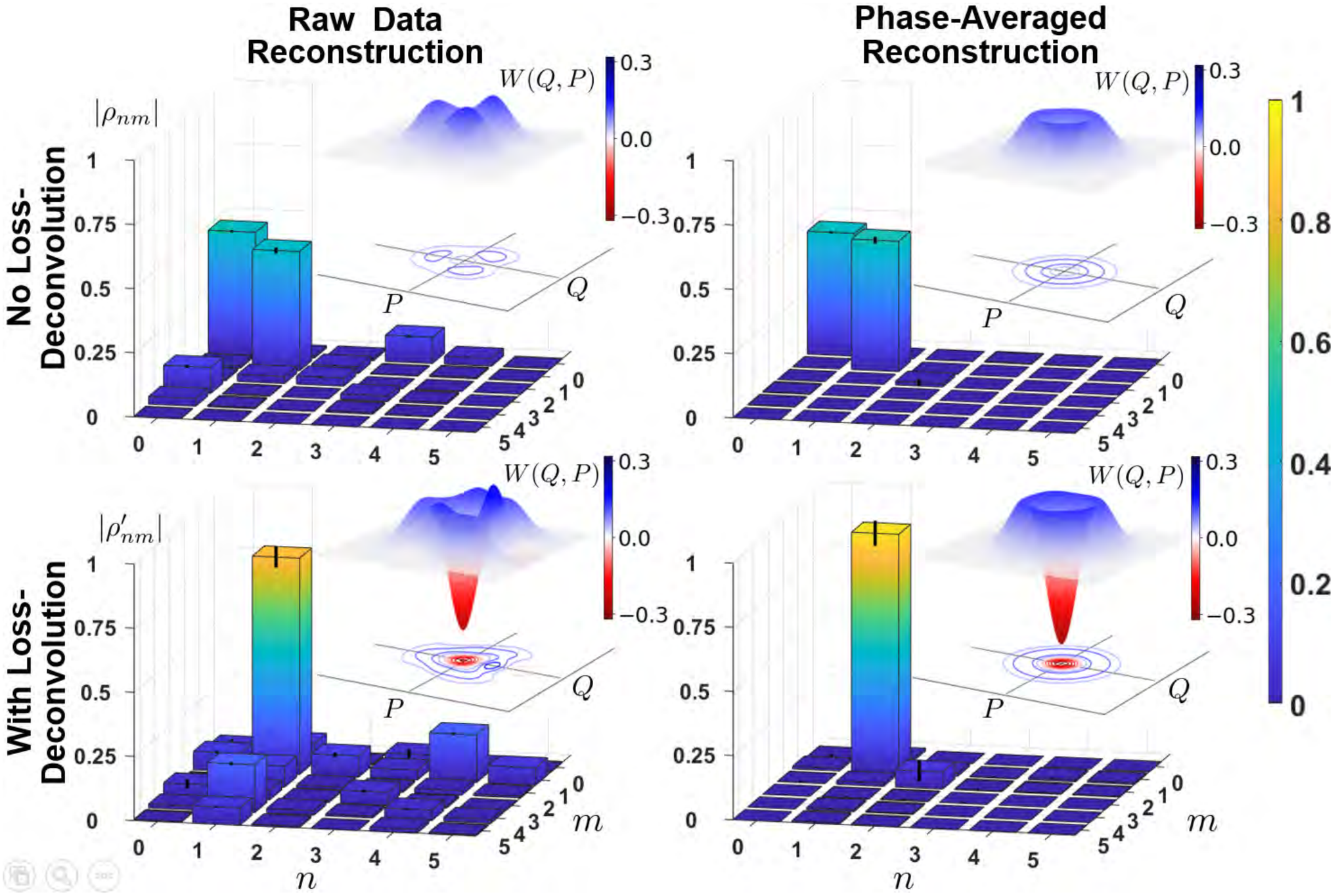
An even better way to do it

Generalized overlap quantum state tomography

Rajveer Nehra,[1,*] Miller Eaton,[1,†] Carlos González-Arciniegas,[1] M. S. Kim,[2,3] Thomas Gerrits,[4] Adriana Lita,[4] Sae Woo Nam,[4] and Olivier Pfister[1,‡]



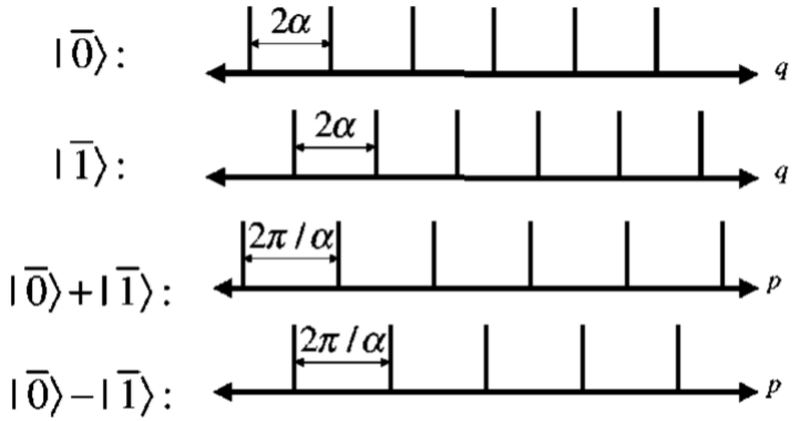
- **Efficient reconstruction** using semidefinite programming


Raw Data Reconstruction
Phase-Averaged Reconstruction
No Loss-Deconvolution
With Loss-Deconvolution
$|\rho_{nm}|$
$|\rho'_{nm}|$
$W(Q,P)$
0.3
0.0
−0.3
1
0.75
0.5
0.25
0
0 1 2 3 4 5
5 4 3 2 1 0
P
Q
n
m
1
0.8
0.6
0.4
0.2
0

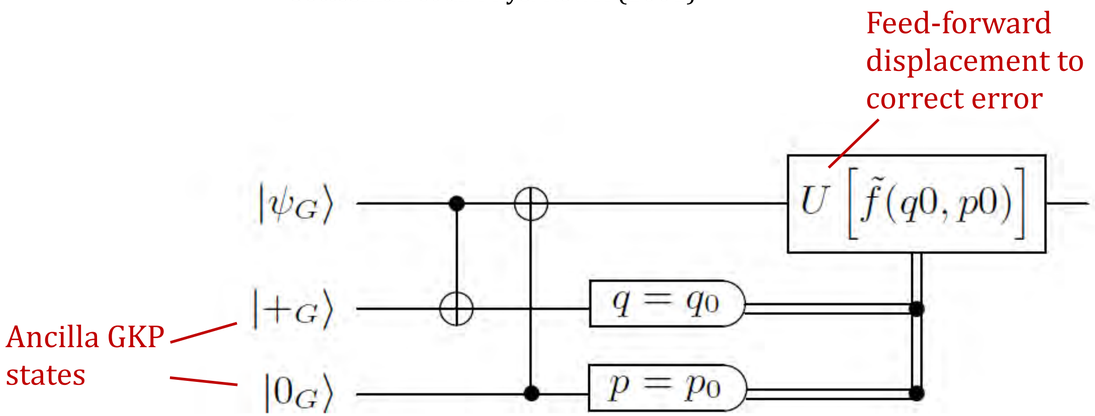
Non-Gaussian resources => quantum error correction
Gottesman-Kitaev-Preskill (GKP) States

Simultaneous eigenstates of

$X = e^{-i\hat{P}\alpha}, \quad Z = e^{\frac{i\pi}{\alpha}\hat{Q}}$



Gottesman et al. Phys. Rev. A (2001)

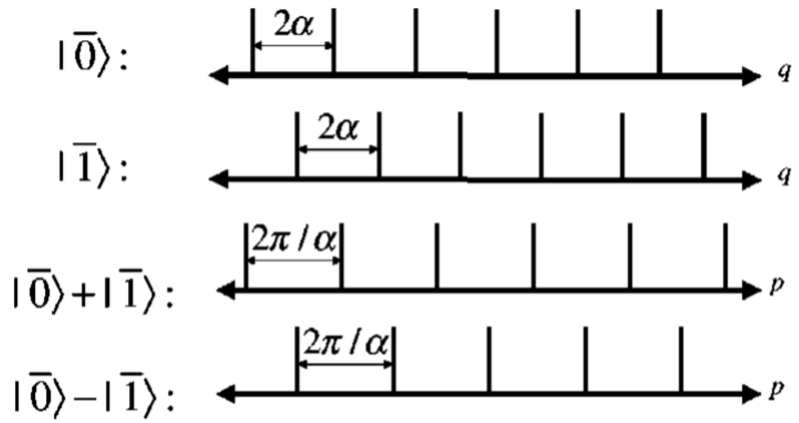


Tzitrin et al. arXiv preprint arXiv:1910.03673 (2019).

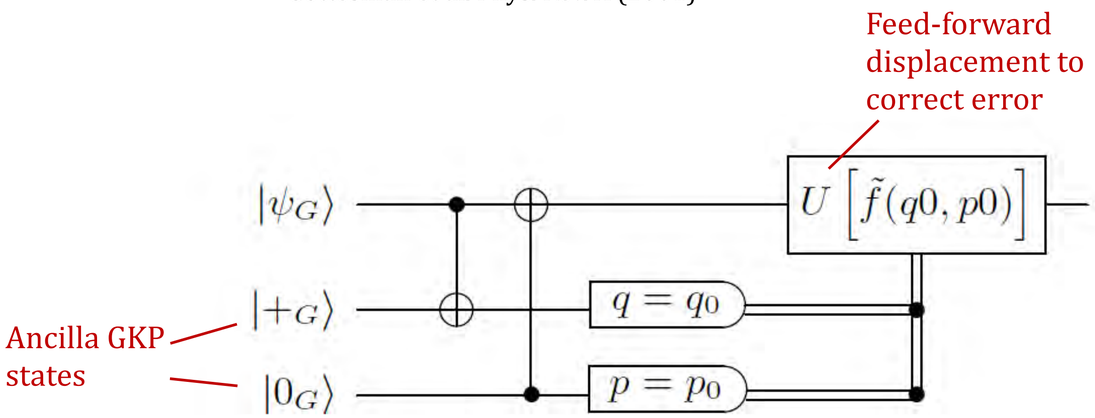
Non-Gaussian resources => quantum error correction
Gottesman-Kitaev-Preskill (GKP) States

Simultaneous eigenstates of

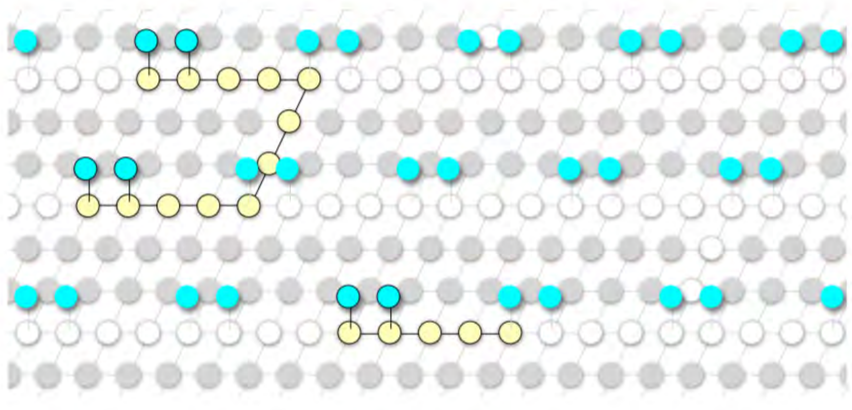
$$X = e^{-i\hat{P}\alpha}, \quad Z = e^{\frac{i\pi}{\alpha}\hat{Q}}$$



Gottesman et al. Phys. Rev. A (2001)



Tzitrin et al. arXiv preprint arXiv:1910.03673 (2019).



Cluster state nodes

GKP states

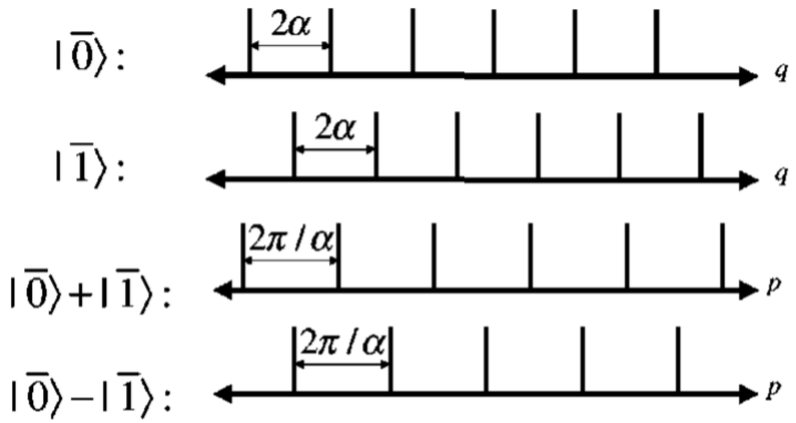
Error corrected

Walshe, et al. *Physical Review A* (2019).

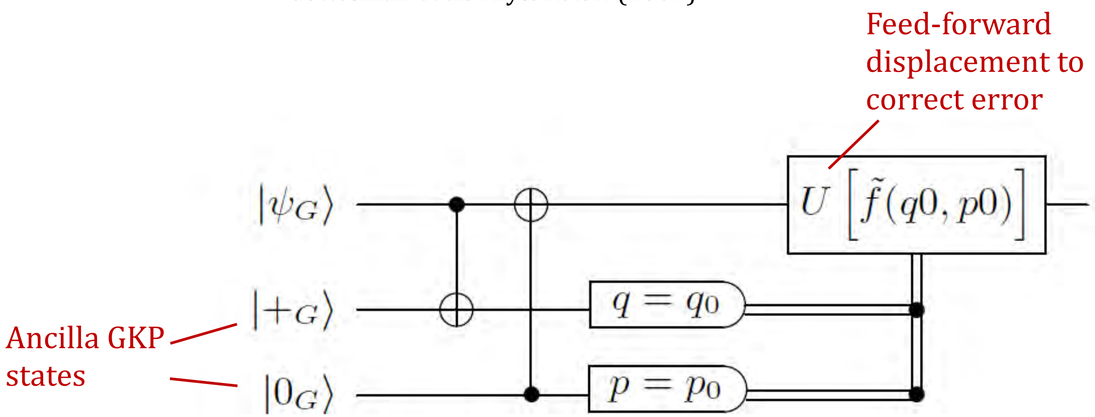
Non-Gaussian resources => quantum error correction
Gottesman-Kitaev-Preskill (GKP) States

Simultaneous eigenstates of

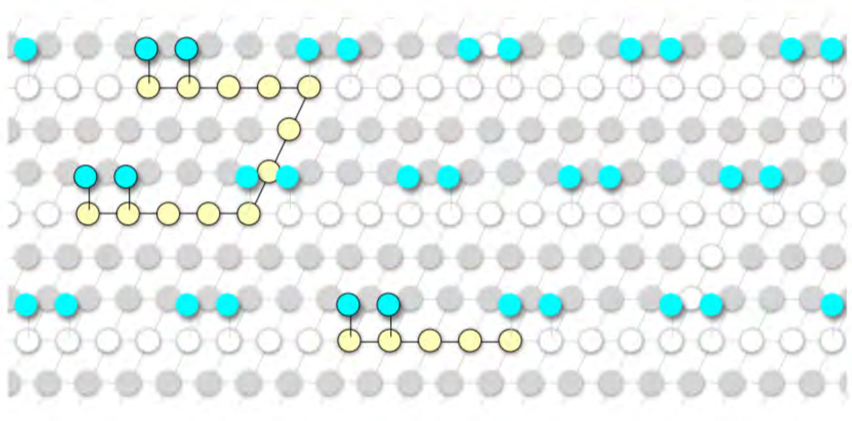
$X = e^{-i\hat{P}\alpha}, \quad Z = e^{\frac{i\pi}{\alpha}\hat{Q}}$



Gottesman et al. Phys. Rev. A (2001)

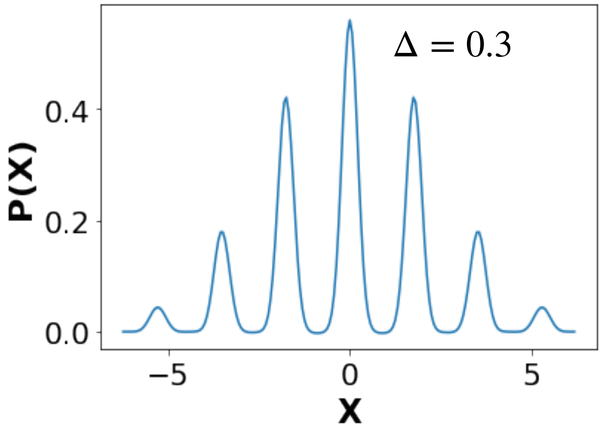


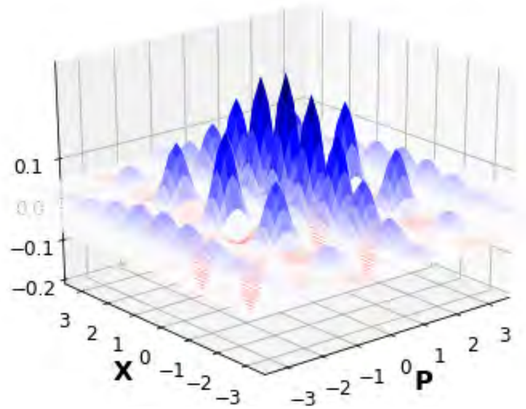
Tzitrin et al. arXiv preprint arXiv:1910.03673 (2019).



Walshe, et al. *Physical Review A* (2019).

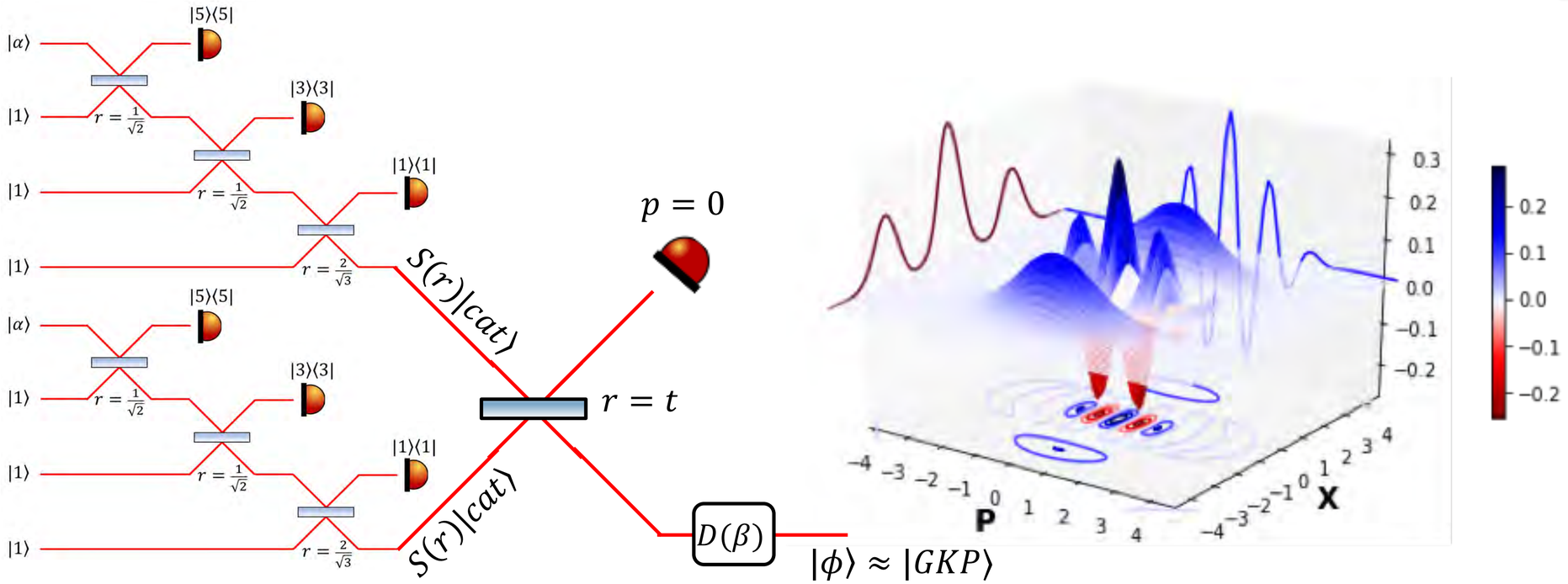
Realistic implementation: Delta spikes → peak width Δ





$$\left|\bar{0}\right\rangle \propto e^{\Delta^2\hat{N}} \sum_{n_1,n_2=-\infty}^{\infty} e^{-in_1\hat{P}\sqrt{\pi}} e^{in_2\hat{Q}\sqrt{\pi}} \left|vac\right\rangle$$

Quantum engineering of GKP states for CV quantum error correction



H. M. Vasconcelos, L. Sanz, and S. Glancy, "All-optical generation of states for 'Encoding a qubit in an oscillator,'" *Opt. Lett., OL*, vol. 35, no. 19, pp. 3261–3263, Oct. 2010.

M. Eaton, R. Nehra, and O. Pfister, ***Non-Gaussian and Gottesman-Kitaev-Preskill state preparation by photon catalysis****, New Journal of Physics* ***21****, 113034 (2019).*

BIG PICTURE: beating lattice-gauge QCD calculations on classical supercomputers

Quantum Algorithms for Quantum Field Theories

Stephen P. Jordan,[1]* Keith S. M. Lee,[2] John Preskill[3]

1 JUNE 2012 VOL 336 **SCIENCE** www.sciencemag.org

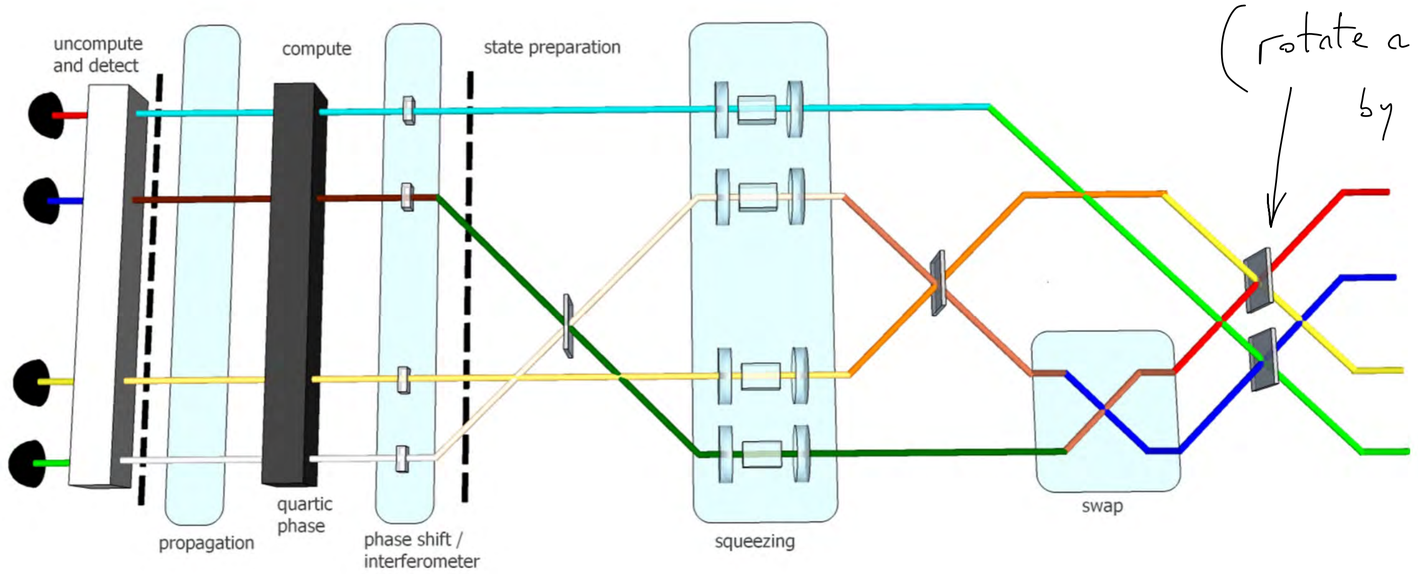
$$\mathcal{A} = \langle \text{out}|T \exp\left\{ i \int_{-T}^{T} dt [H_{\text{int}}(t) + H_{\text{c.t.}}(t)] \right\} |\text{in}\rangle$$

ϕ^4 term

PHYSICAL REVIEW A **92**, 063825 (2015)

Quantum simulation of quantum field theory using continuous variables

Kevin Marshall,[1] Raphael Pooser,[2,3] George Siopsis,[3,*] and Christian Weedbrook[4]



(rotate all beamsplitters by 90°...)

Conclusion

Conclusion

The quantum optical frequency comb is a viable platform for universal quantum computing

Conclusion

The quantum optical frequency comb is a viable platform for universal quantum computing

- **LARGE-SCALE** Gaussian entanglement
  - No postselection
  - Universal measurement-based QC, strictly equivalent to qubit model

Conclusion

The quantum optical frequency comb is a viable platform for universal quantum computing

- **LARGE-SCALE** Gaussian entanglement
  - No postselection
  - Universal measurement-based QC, strictly equivalent to qubit model

- **FAULT TOLERANT** non-Gaussian technology for universal QC

Conclusion

The quantum optical frequency comb is a viable platform for universal quantum computing

- **LARGE-SCALE** Gaussian entanglement
  - No postselection
  - Universal measurement-based QC, strictly equivalent to qubit model
- **FAULT TOLERANT** non-Gaussian technology for universal QC
- **INTEGRABLE** in photonic circuits

Conclusion

The quantum optical frequency comb is a viable platform for universal quantum computing

- **LARGE-SCALE** Gaussian entanglement
  - No postselection
  - Universal measurement-based QC, strictly equivalent to qubit model
- **FAULT TOLERANT** non-Gaussian technology for universal QC
- **INTEGRABLE** in photonic circuits
- **TRANSLATABLE** to any bosonic mode:
  - microwave cavity photons
  - phonons
  - transverse spatial modes (Hermite- or Laguerre-Gauss)
  - temporal modes

A lesson in research from Ted Hänsch...