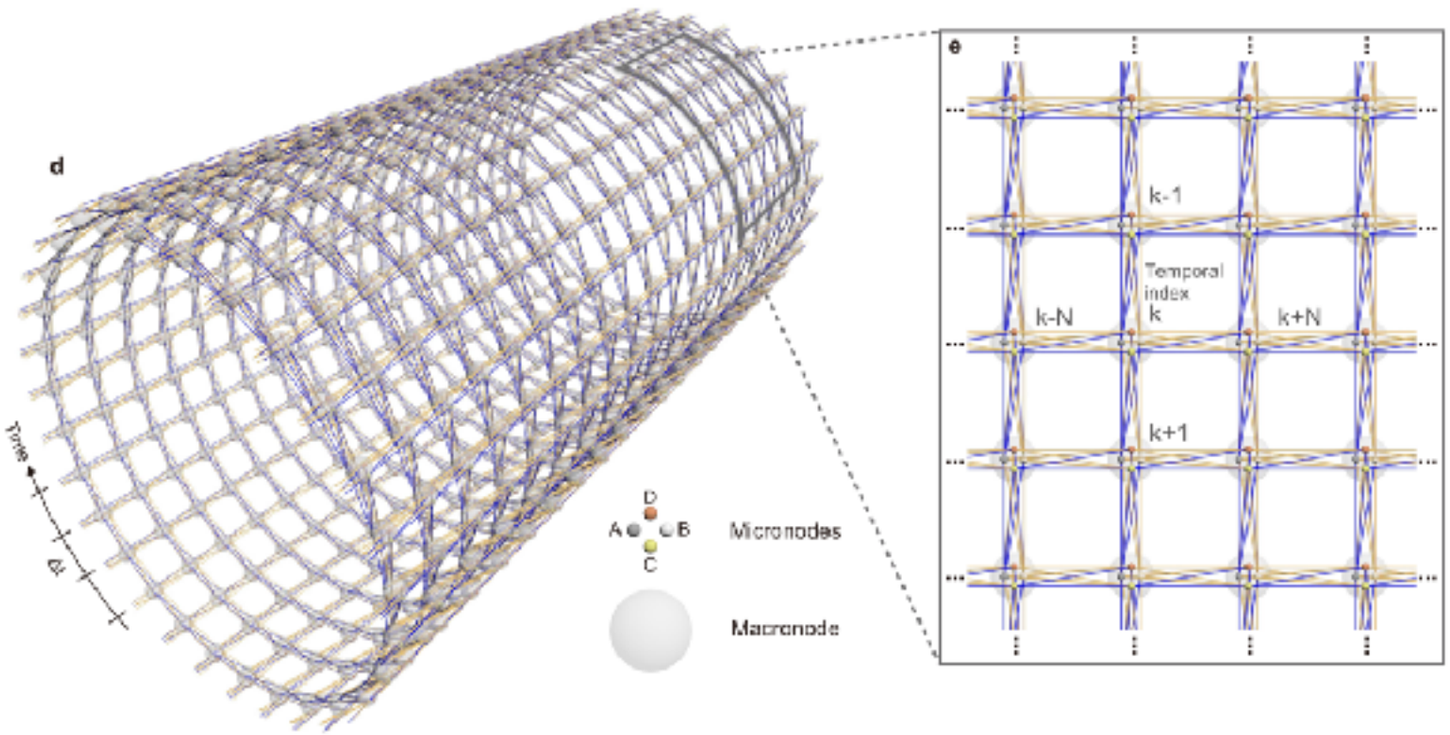


MOONSHOT
RESEARCH & DEVELOPMENT PROGRAM

UBC-iTHEMS-RQC workshop
August 24, 2021

Large-scale quantum computing with quantum teleportation

Akira Furusawa

Department of Applied Physics
School of Engineering
The University of Tokyo

RIKEN QUANTUM COMPUTING

Caltech

Unconditional Quantum Teleportation

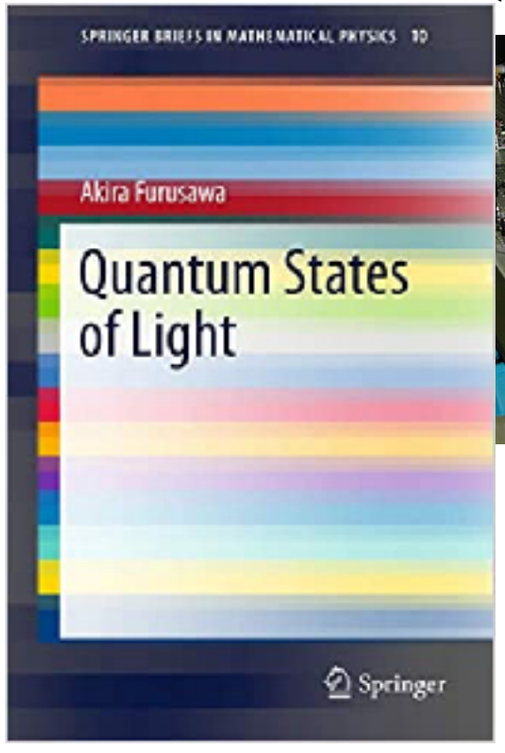
A. Furusawa, J. L. Sørensen, S. L. Braunstein, C. A. Fuchs, H. J. Kimble,* E. S. Polzik

23 OCTOBER 1998 VOL 282 SCIENCE www.sciencemag.org

Akira Furusawa and Peter van Loock WILEY-VCH

Quantum Teleportation and Entanglement

A Hybrid Approach to Universal Quantum Information Processing



QUIC Caltech/MIT/USC 1997

古澤　明

1984年　東京大学工学部物理工学科卒業

1986年　東京大学大学院工学系研究科物理工

（株）ニコン入社

1988-1990年　東京大学先端科学技術研究セ

1996-1998年　カリフォルニア工科大学客員

2000年　東京大学大学院工学系研究科物理工

2007年　東京大学大学院工学系研究科物理工

2021年　理化学研究所量子コンピュータ研究

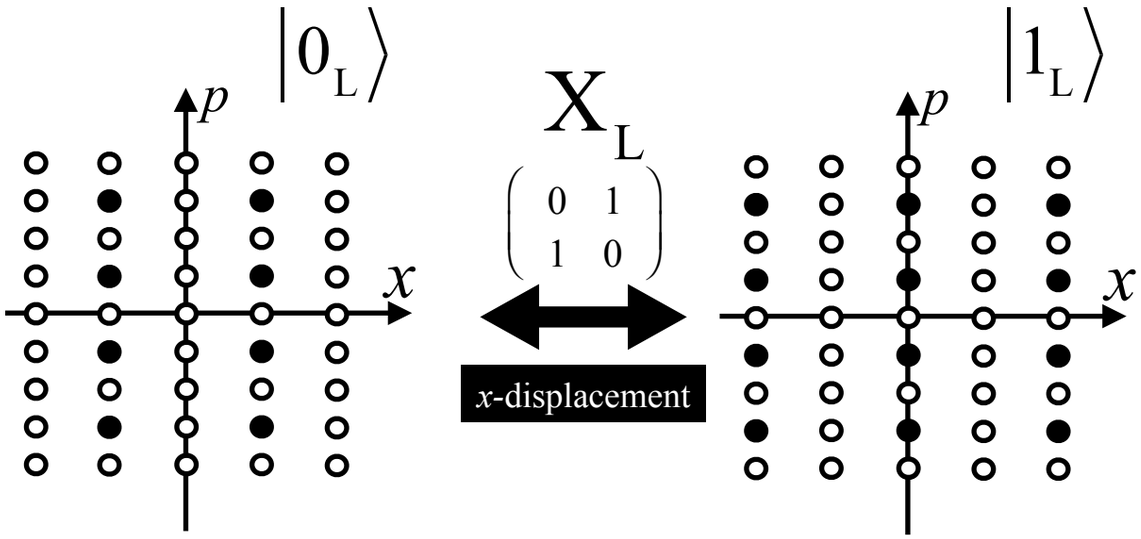
Collaborators

A. Furusawa The University of Tokyo, RIKEN
J. Yoshikawa, M. Endo, W. Asavanant, K. Fukui, K. Takase,
F. Okamoto, S. Konno, B. Charoensombutamon, T. Yamashima,
T. Nakamura, A. Kawasaki, T. Sonoyama, F. Hanamura, R. He,
B. Jeong, H. Nagayoshi, T. Nomura, S. Kimura, K. Takahashi,
Y. Chin, A. Sakaguchi (RIKEN)

P. van Loock (Mainz), R. Filip (Palacky), P. Marek (Palacky),
J. L. O'Brien (Bristol), A. Politi (Southampton),
E. H. Huntington (ANU), T. Ralph (UQ), H. Wiseman (GU),
N. Menicucci (Sydney), R. Alexander (New Mexico),
H. Yonezawa (ADFA), S. Yokoyama (ADFA),
H. Takahashi (UTokyo), S. Takeda (UTokyo),
T. Hashimoto (NTT), T. Kashiwazaki (NTT), T. Kazama (NTT),
K. Enbutsu (NTT), R. Kasahara (NTT), T. Umeki (NTT)

GKP qubits & Logical operations

Logical qubits for Quantum error correction



D. Gottesman et al. PRA **64,** 012310 (2001)

FM $\hat{p}$

Complex amplitude

$$\hat{a} = \hat{x} + i\hat{p}$$

$$\left[\hat{x}, \hat{p}\right] = \frac{i}{2}$$

$$\hbar = \frac{1}{2}$$

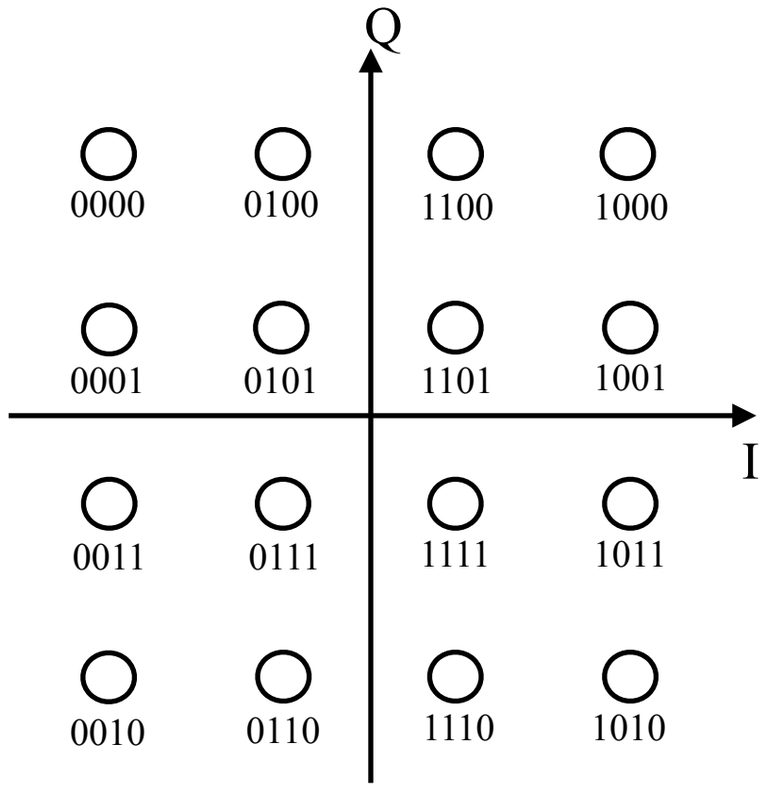
Quadrature Amplitude Modulation QAM

Coherent communication

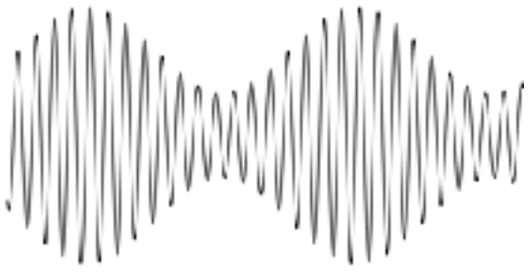
Radio

AM

FM



AM $\hat{x}$



GKP qubits & Logical operations

○ $+\infty$

● $-\infty$

Complex amplitude

$\hat{a} = \hat{x} + i\hat{p}$

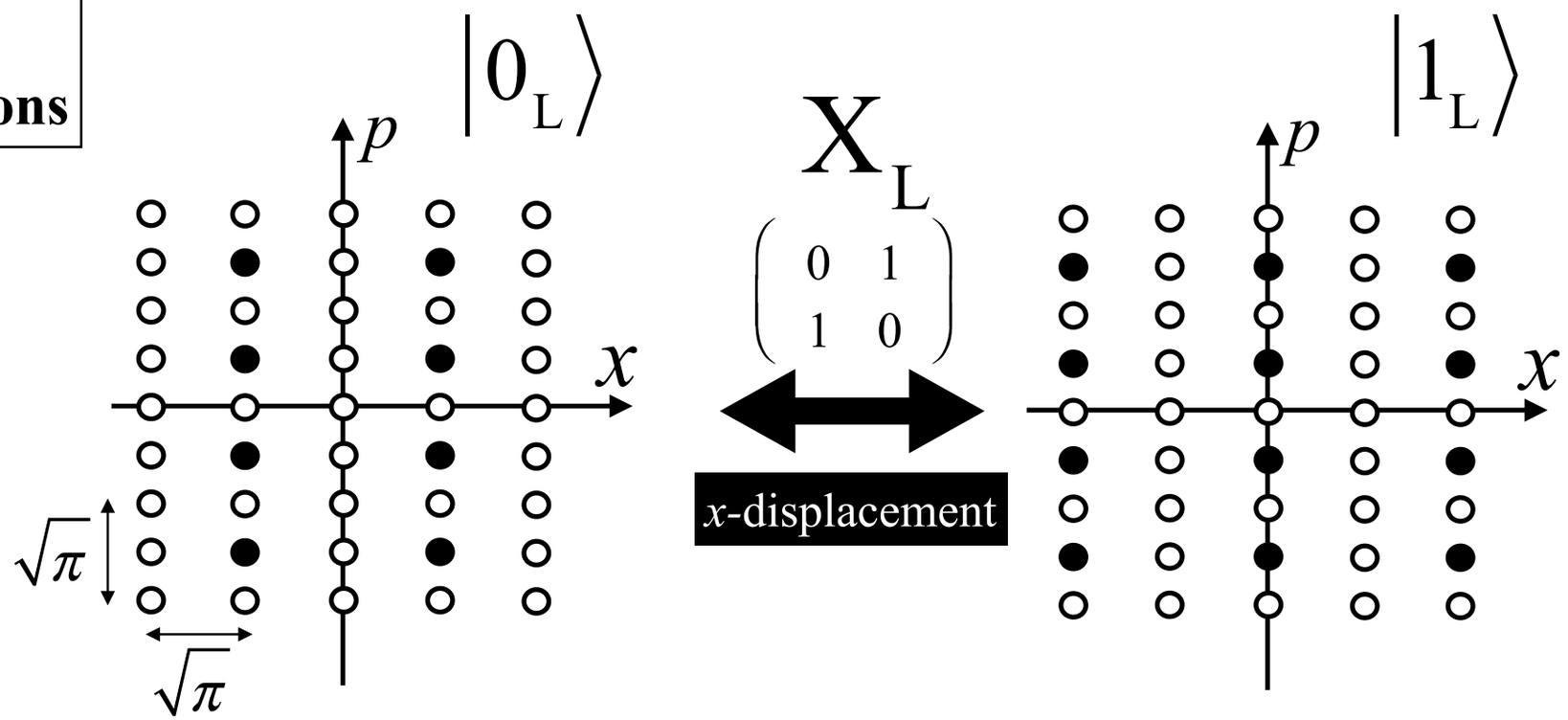
$\left[\hat{x}, \hat{p}\right] = \frac{i}{2}$

$\hbar = \frac{1}{2}$

Logical qubits for quantum error correction

Clifford

Gaussian



GKP qubits
&
Logical operations

○ $+\infty$

● $-\infty$

Complex amplitude

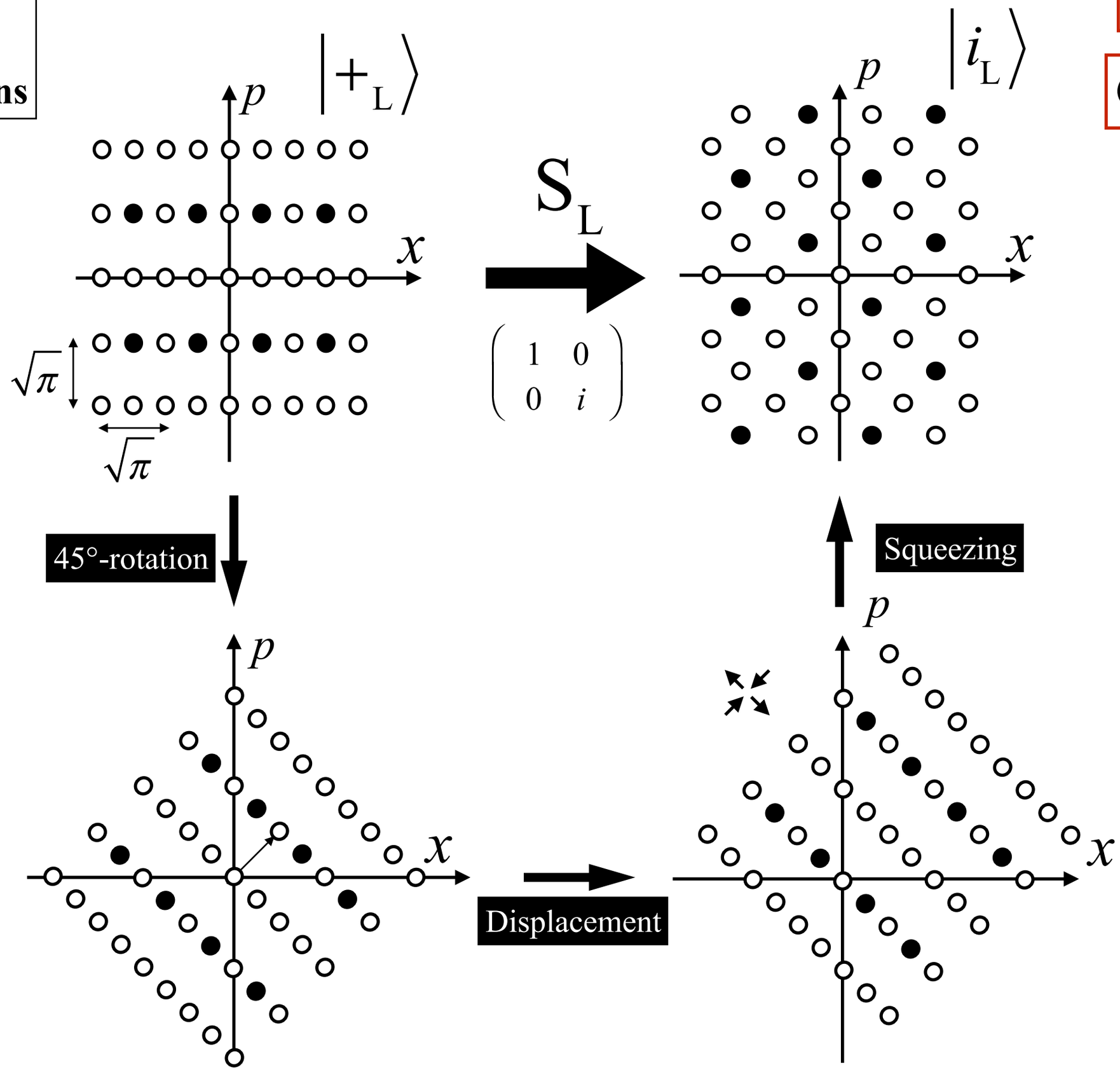
$\hat{a} = \hat{x} + i\hat{p}$

$\left[\hat{x}, \hat{p}\right] = \frac{i}{2}$

$\hbar = \frac{1}{2}$

Clifford

Gaussian

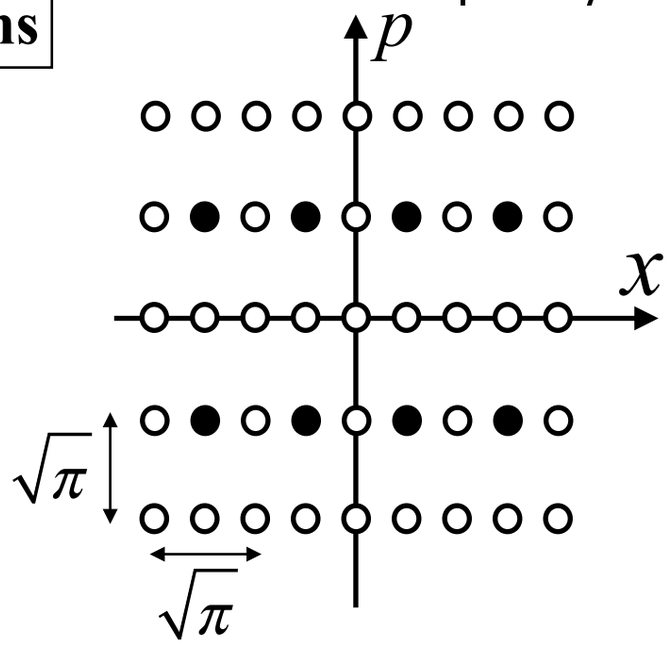


GKP qubits & Logical operations

○ $+\infty$

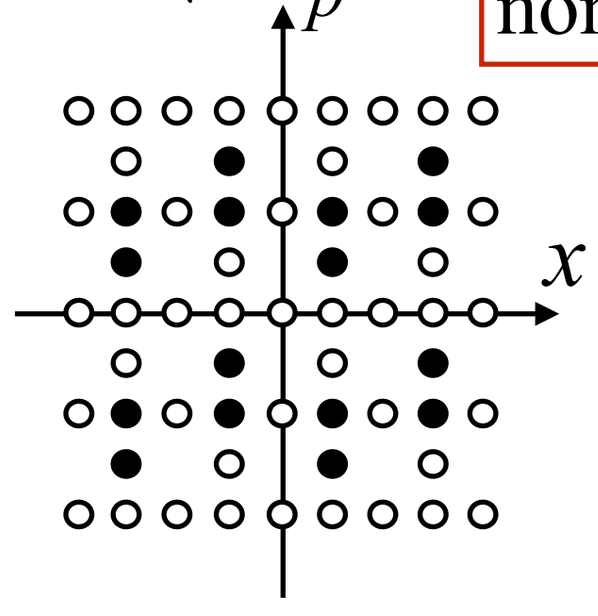
● $-\infty$

$$\left|+_{\mathrm{L}}\right\rangle = \frac{\left|0_{\mathrm{L}}\right\rangle + \left|1_{\mathrm{L}}\right\rangle}{\sqrt{2}}$$



$$\mathrm{T_L} \quad \begin{pmatrix} 1 & 0 \\ 0 & e^{i\frac{\pi}{4}} \end{pmatrix}$$

$$\frac{\left|0_{\mathrm{L}}\right\rangle + e^{i\frac{\pi}{4}}\left|1_{\mathrm{L}}\right\rangle}{\sqrt{2}}$$



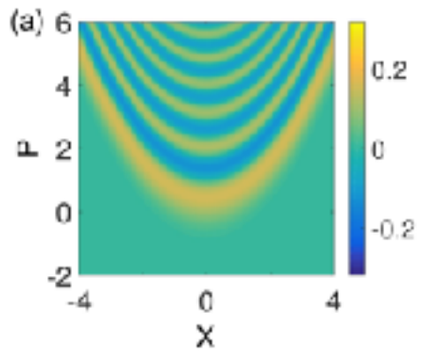
non-Clifford

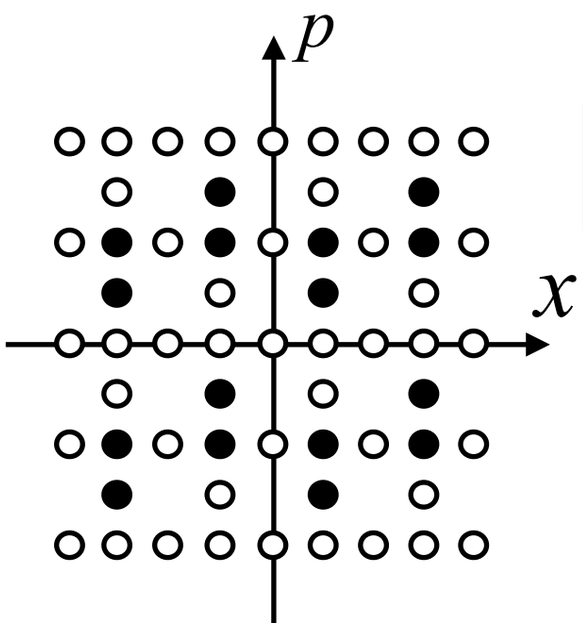
non-Gaussian

$$\hat{U}_{\mathrm{T}} = \exp\left[i\frac{\pi}{4}\left\{ 2\left(\frac{\hat{x}}{\sqrt{\pi}}\right)^3 + \left(\frac{\hat{x}}{\sqrt{\pi}}\right)^2 - 2\frac{\hat{x}}{\sqrt{\pi}} \right\} \right]$$

Cubic phase | Shear | Displacement

Cubic phase state





$$\left|\mathrm{T_L}\right\rangle = \frac{\left|0_{\mathrm{L}}\right\rangle + e^{i\frac{\pi}{4}}\left|1_{\mathrm{L}}\right\rangle}{\sqrt{2}}$$

$$\mathrm{CNOT_L} \quad \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

Clifford

Gaussian

QND

Squeezing

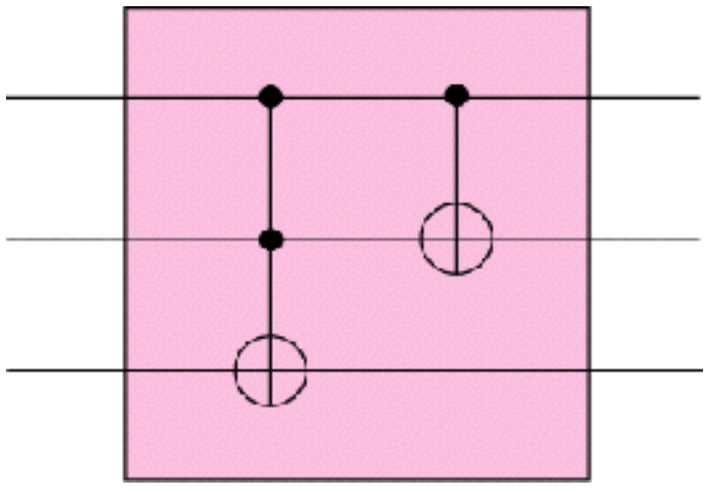
Beam splitter

CV gate teleportation

Gaussian operations and measurement

Quantum computing

Quantum circuit model



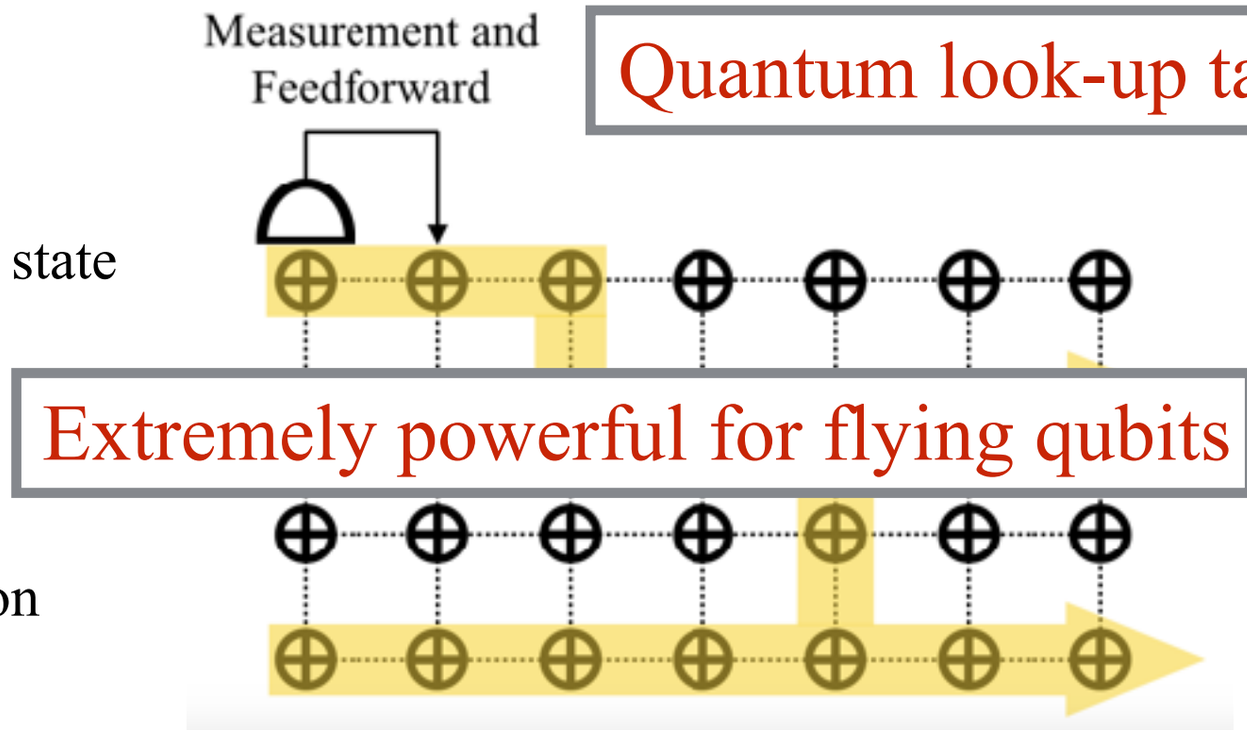
Qubit
R. P. Feynman (1980)

Continuous variable
S. Lloyd and S. L. Braunstein (1999)

Measurement-based model (one-way quantum computing)

Large-scale entangled state (Cluster state)
Measurement and Feedforward

Sequential teleportation



Qubit
R. Raussendorf
and H. J. Briegel (2001)

$$\oplus = (|0\rangle + |1\rangle)/\sqrt{2}$$

Continuous variable
N. C. Menicucci and
P. van Loock et al. (2006)

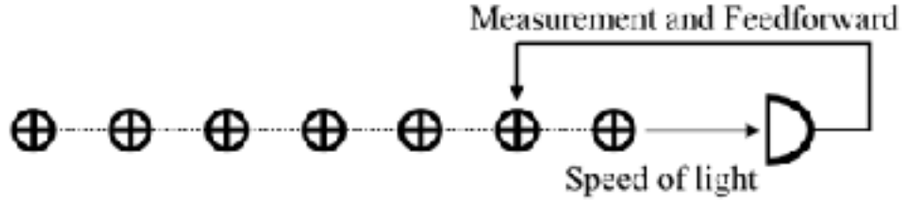
$$\oplus = \int_{-\infty}^{+\infty} dx |x\rangle$$

Quantum computing with flying qubits (photons)

Quantum circuit model

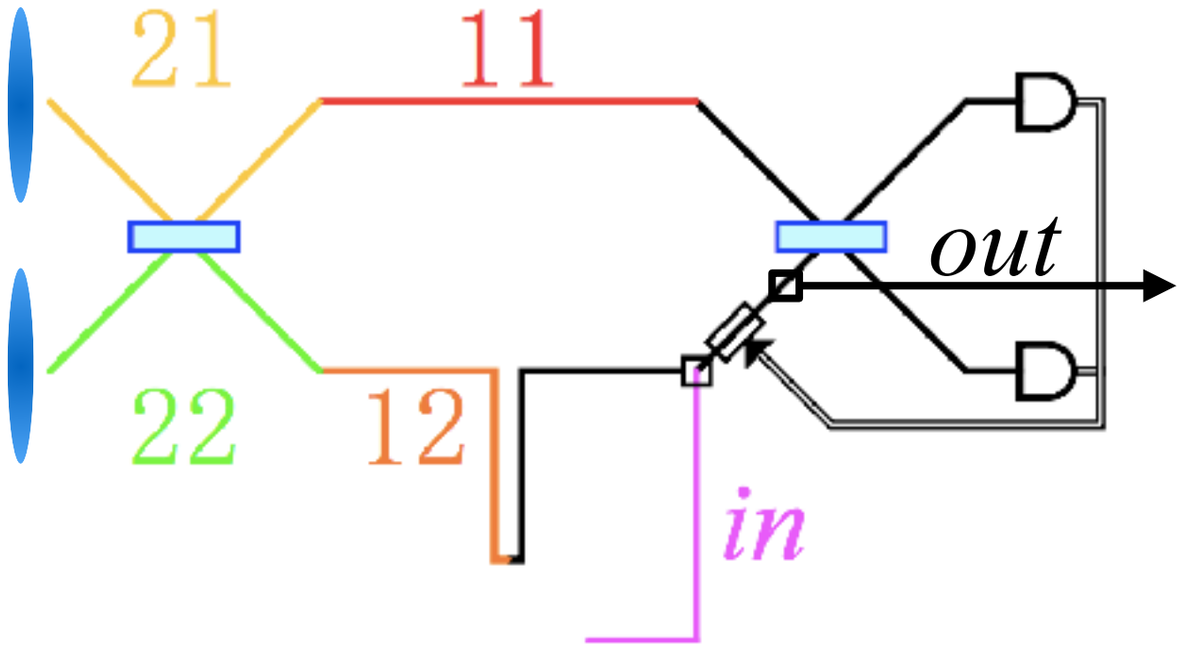
flying qubits

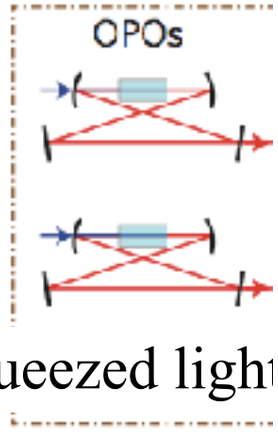
Traveling wave → Measurement within laser coherence time
No decoherence!!
We can do it forever!!



Measu

One-w





Squeezed light

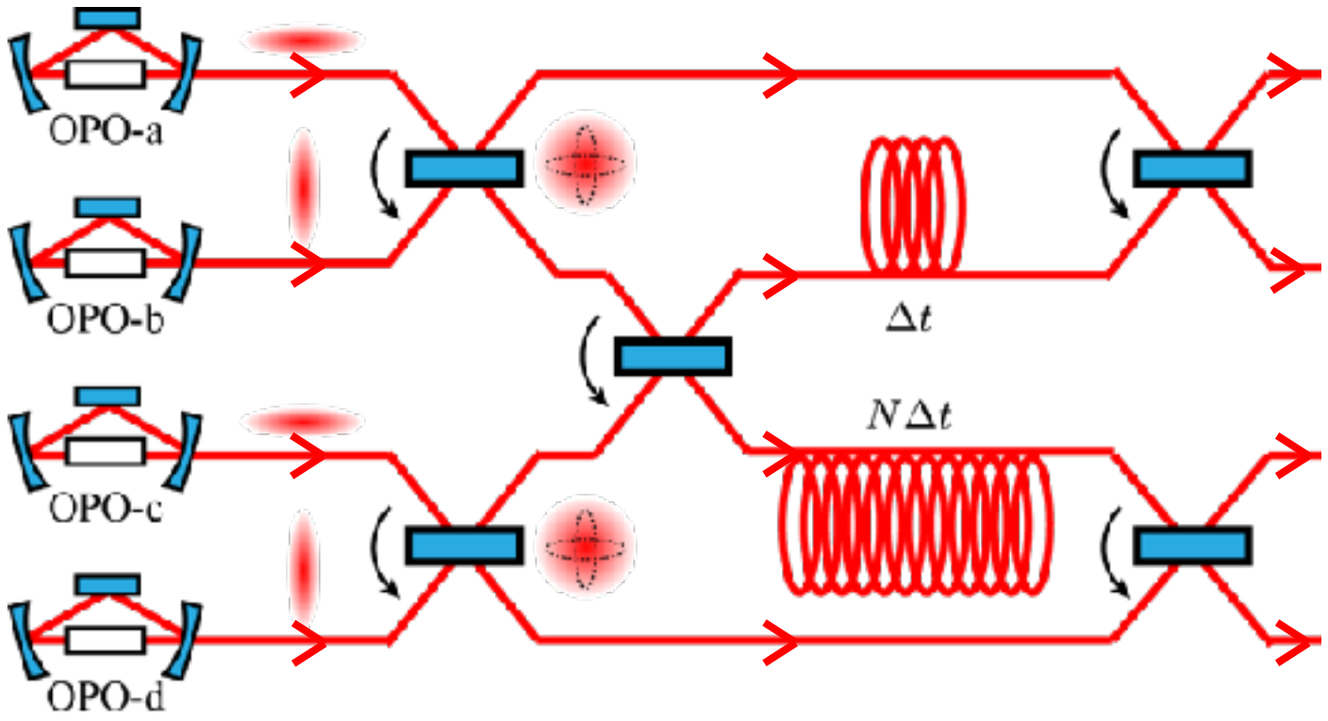
1000

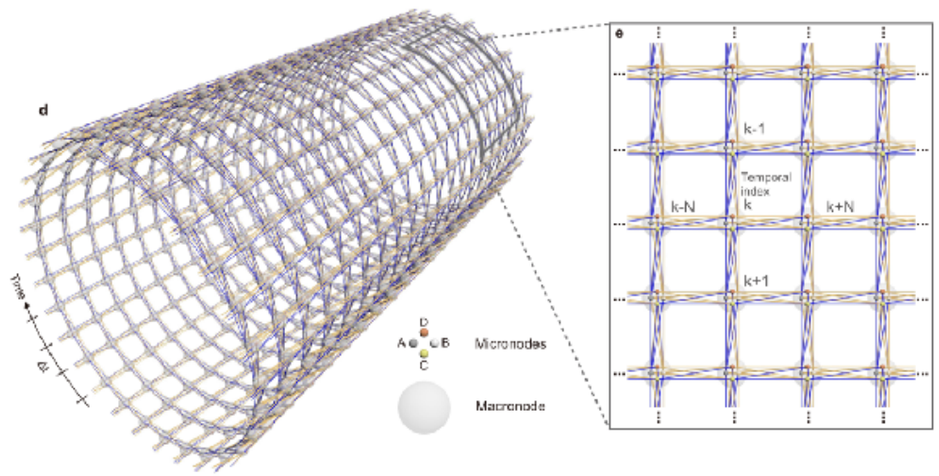
) (2016)

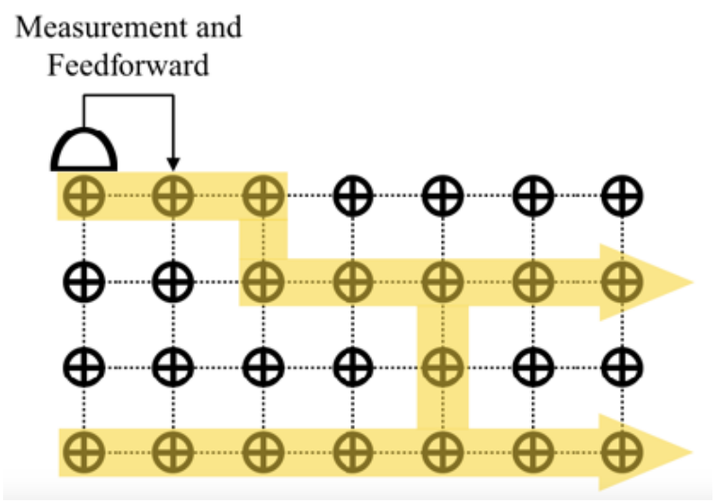
Large-scale quantum computing = fixed-size of the setup
Programmable

Time-domain multiplexed 2D cluster state

Quantum look-up table







QUANTUM COMPUTING

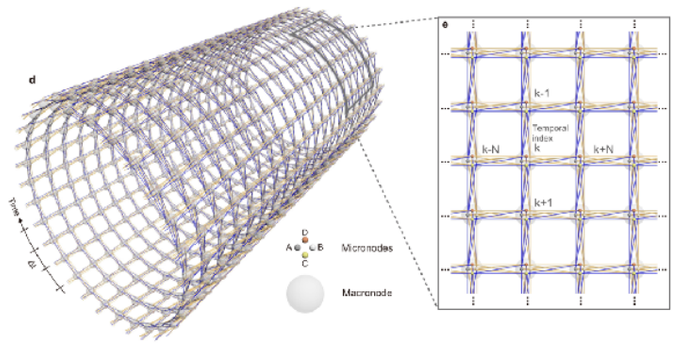
Generation of time-domain-multiplexed two-dimensional cluster state

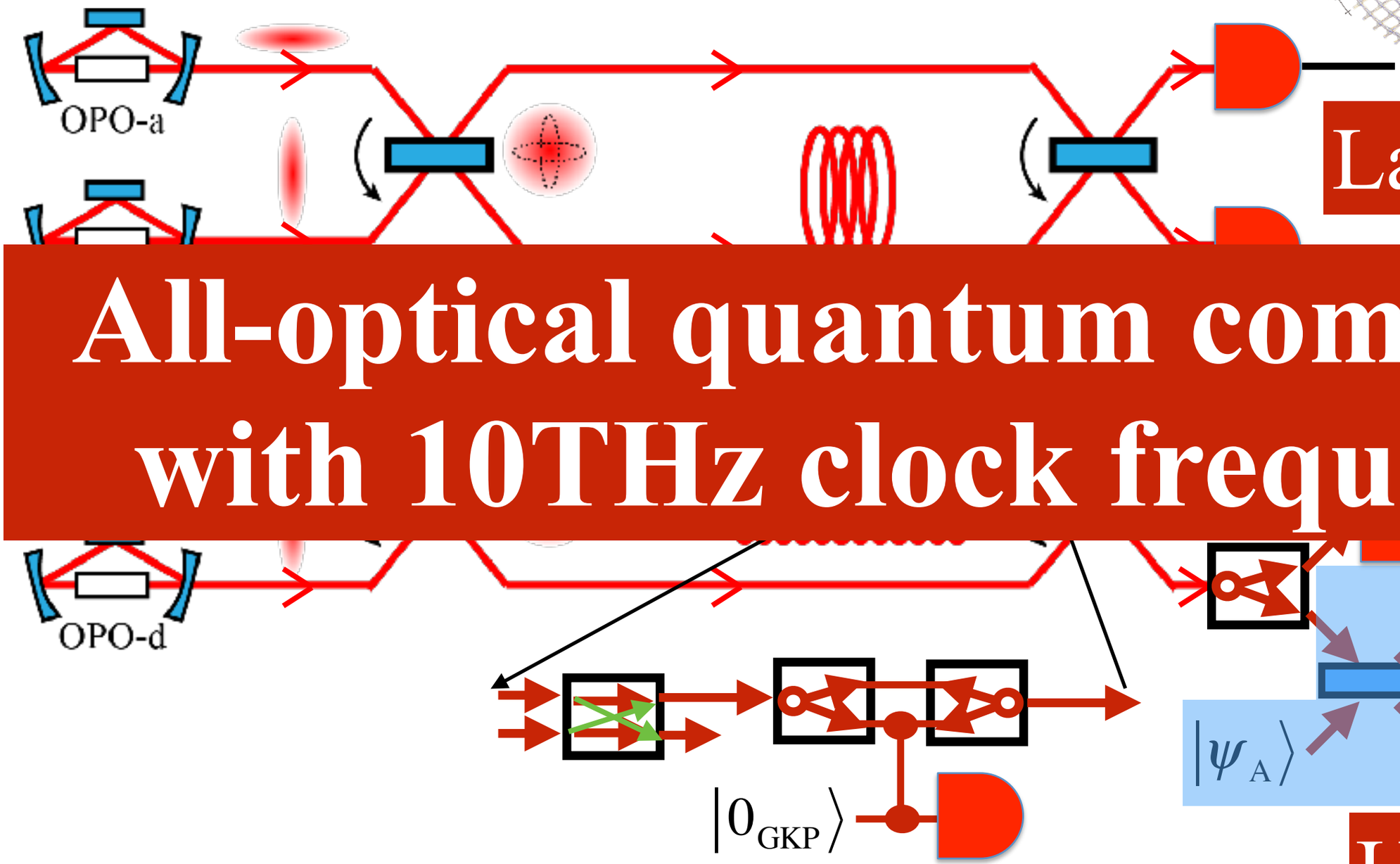
Science 366, 373 (2019)

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]*

Goal

Optical parametric amplifier





Large scale!

All-optical quantum computer with 10THz clock frequency

Fault tolerant!

Universal!

GKP qubits
&
Logical operations

○ $+\infty$

● $-\infty$

Complex amplitude

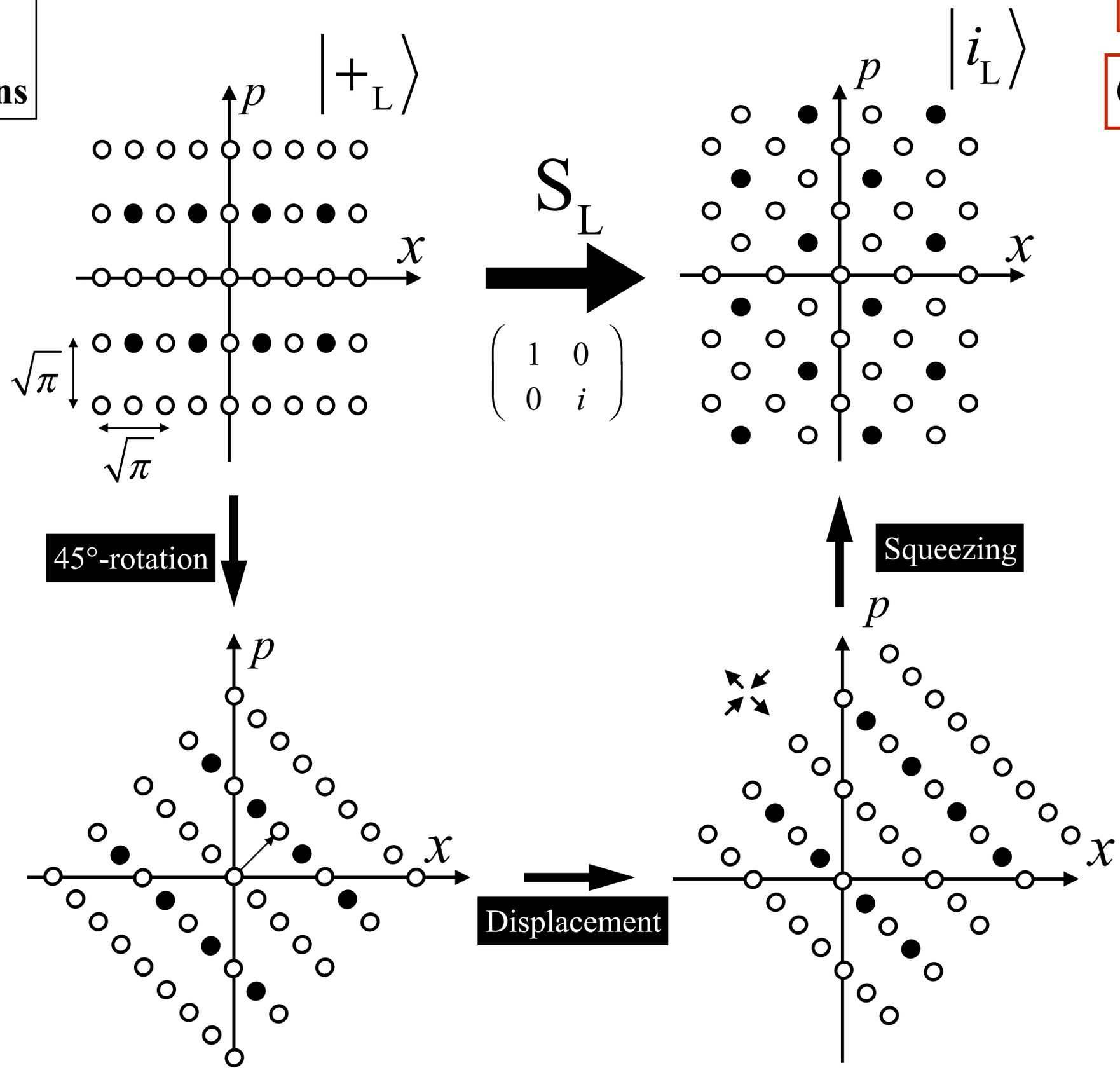
$\hat{a} = \hat{x} + i\hat{p}$

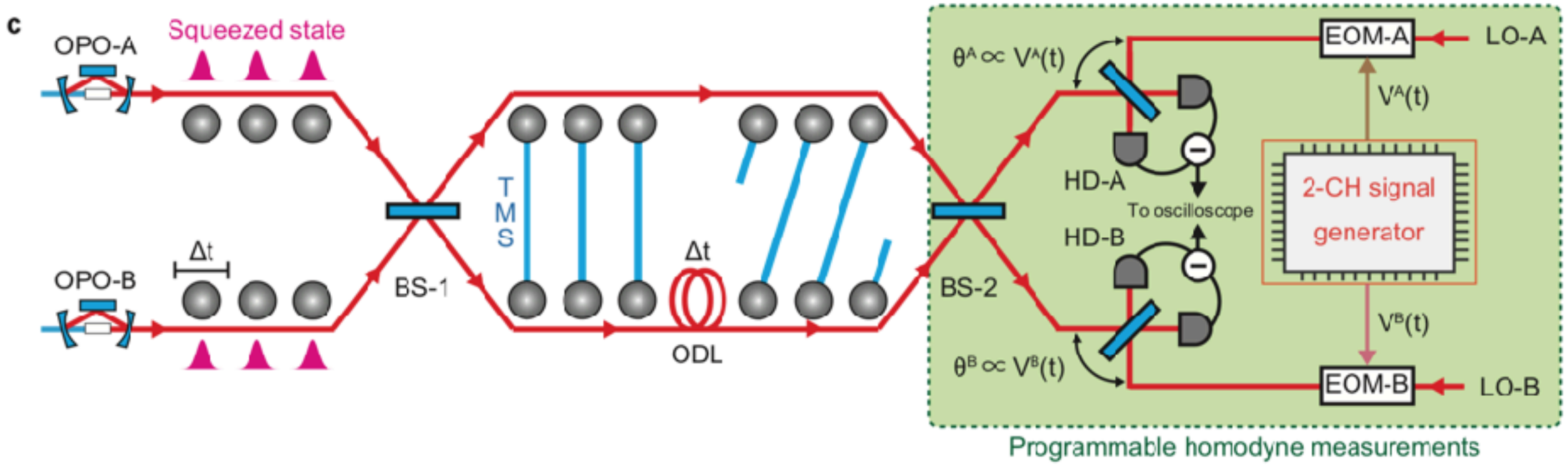
$\left[\hat{x}, \hat{p}\right] = \frac{i}{2}$

$\hbar = \frac{1}{2}$

Clifford

Gaussian





Phase rotation

$$\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

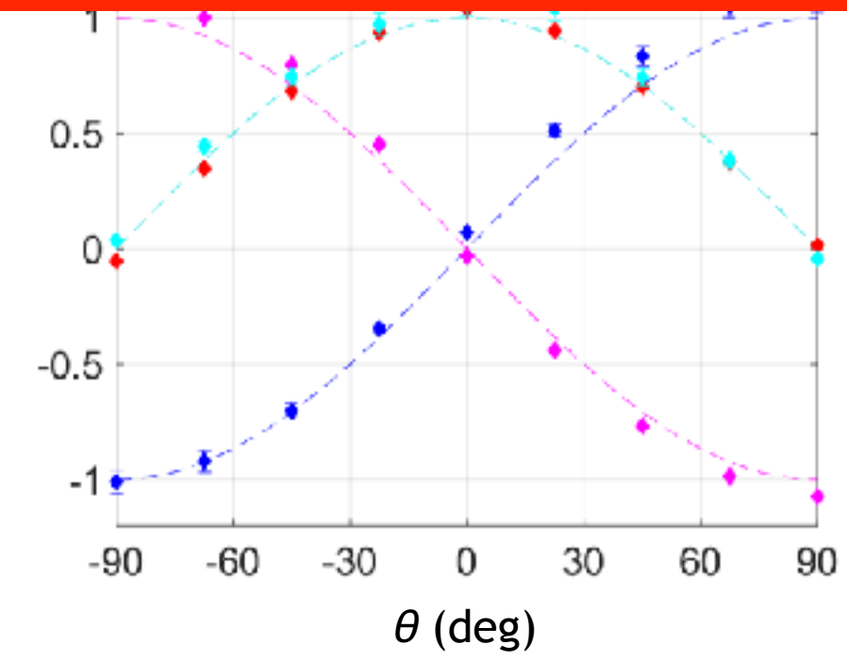
Shear

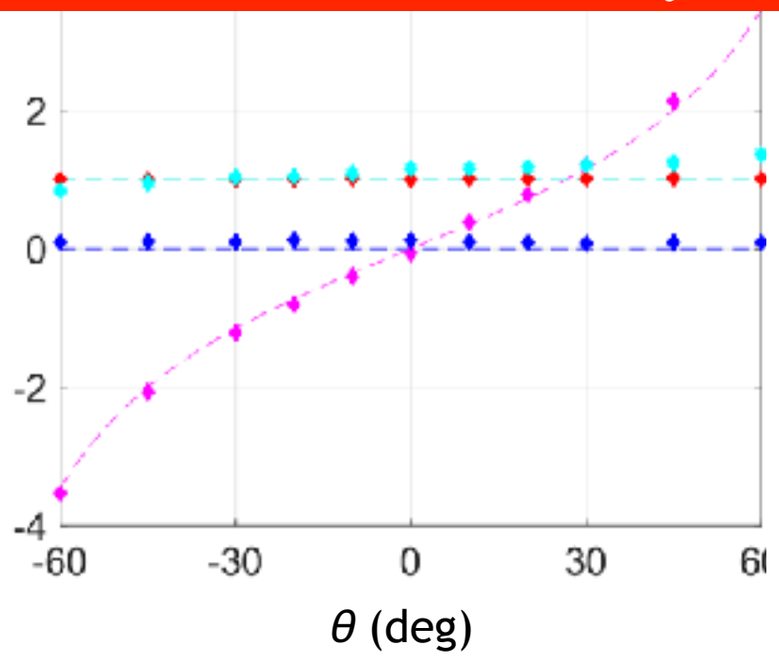
$$\begin{pmatrix} 1 & 0 \\ 2\tan\theta & 1 \end{pmatrix}$$

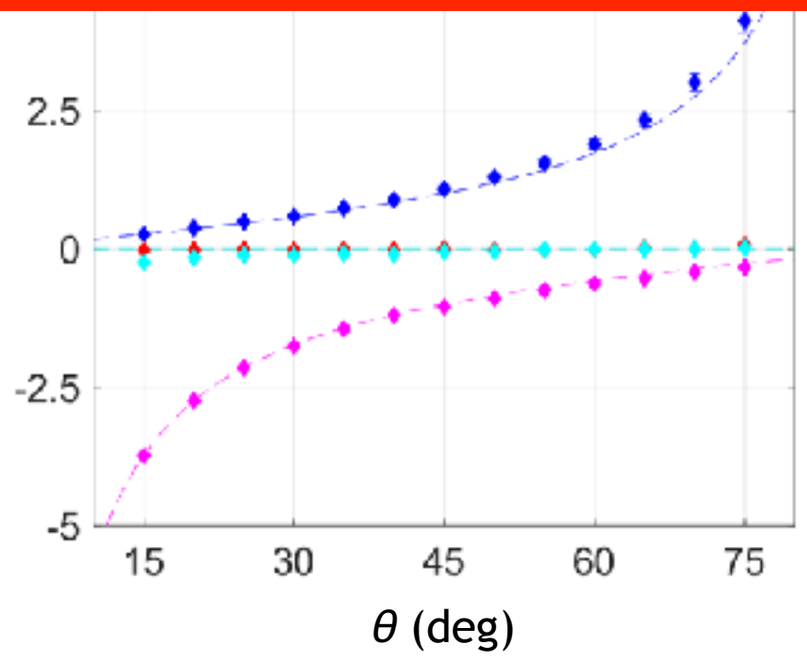
Squeezing

$$\begin{pmatrix} 0 & \tan\theta \\ -1/\tan\theta & 0 \end{pmatrix}$$

Clifford universality!!







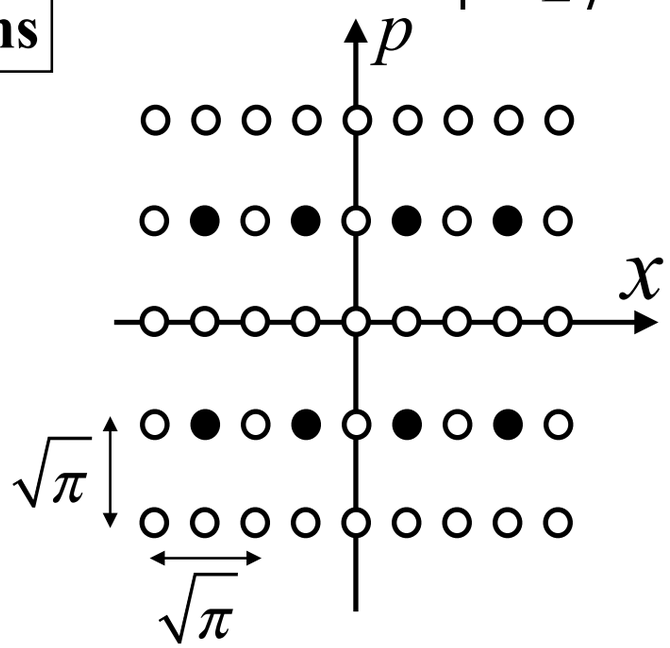
W. Asavanant et al., arXiv:2006.537 [quant-ph].

GKP qubits & Logical operations

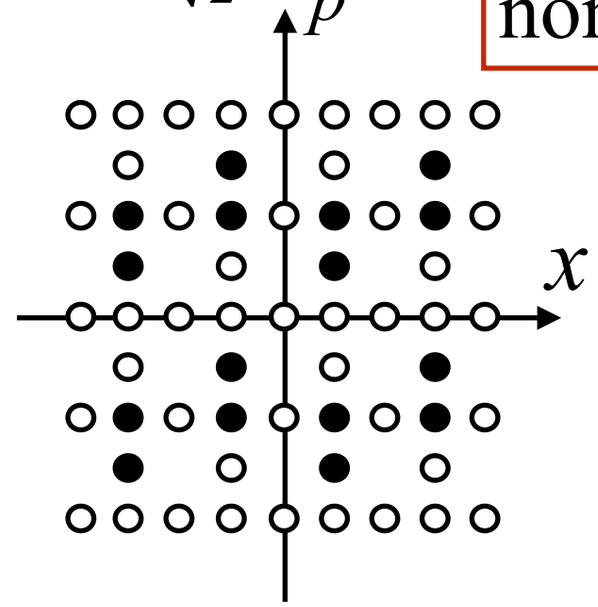
○ $+\infty$

● $-\infty$

$$\left|+_{\mathrm{L}}\right\rangle = \frac{\left|0_{\mathrm{L}}\right\rangle + \left|1_{\mathrm{L}}\right\rangle}{\sqrt{2}}$$



$$\mathrm{T_L} \quad \begin{pmatrix} 1 & 0 \\ 0 & e^{i\frac{\pi}{4}} \end{pmatrix}$$



$$\frac{\left|0_{\mathrm{L}}\right\rangle + e^{i\frac{\pi}{4}}\left|1_{\mathrm{L}}\right\rangle}{\sqrt{2}}$$

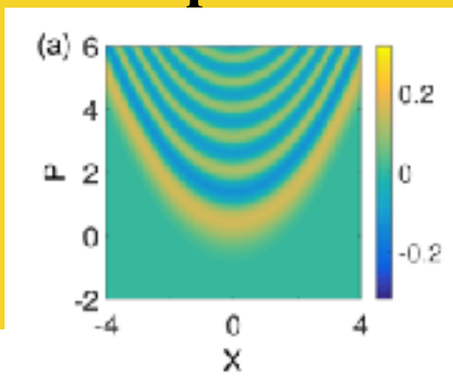
non-Clifford

non-Gaussian

$$\hat{U}_{\mathrm{T}} = \exp\left[i\frac{\pi}{4}\left\{ 2\left(\frac{\hat{x}}{\sqrt{\pi}}\right)^3 + \left(\frac{\hat{x}}{\sqrt{\pi}}\right)^2 - 2\frac{\hat{x}}{\sqrt{\pi}} \right\} \right]$$

Cubic phase | Shear | Displacement

Cubic phase state



$$\mathrm{CNOT_L} \quad \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

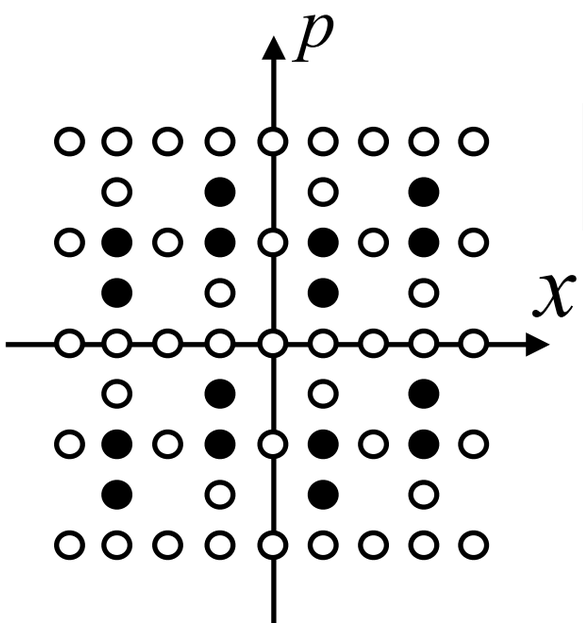
Clifford

Gaussian

QND

Squeezing

Beam splitter



$$\left|\mathrm{T_L}\right\rangle = \frac{\left|0_{\mathrm{L}}\right\rangle + e^{i\frac{\pi}{4}}\left|1_{\mathrm{L}}\right\rangle}{\sqrt{2}}$$

CV gate teleportation

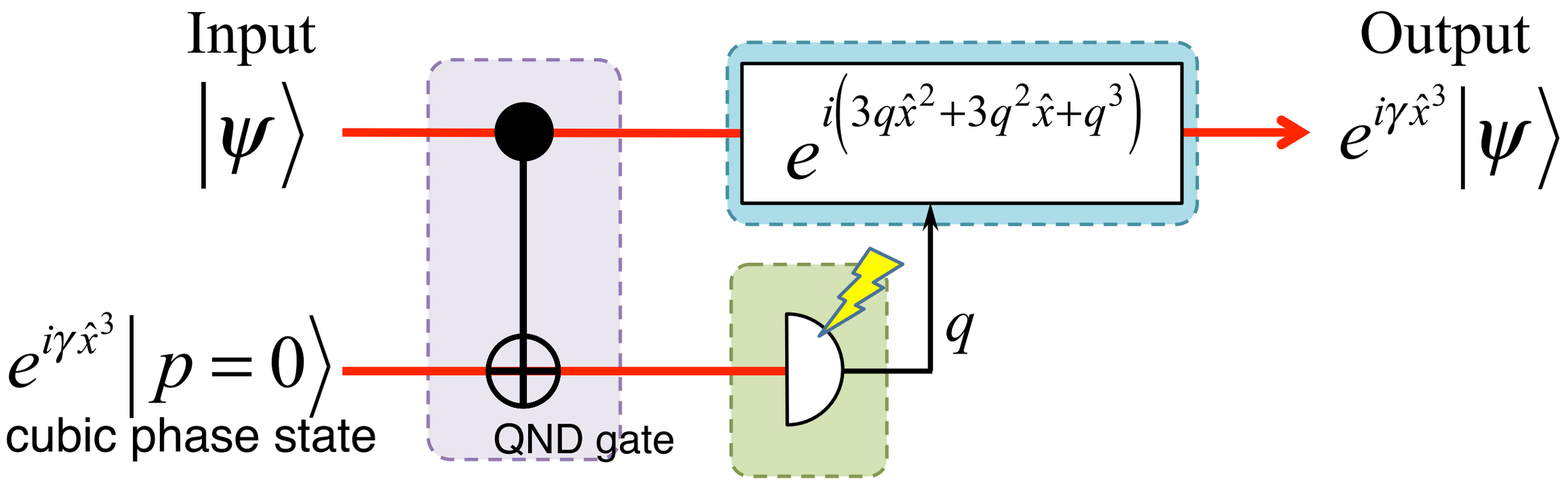
Gaussian operations and measurement

Cubic phase gate with gate teleportation

Fault tolerant!

Schrödinger picture

D. Gottesman et al. PRA **64,** 012310 (2001)



Gate teleportation

Cubic phase gate with gate teleportation

Fault tolerant

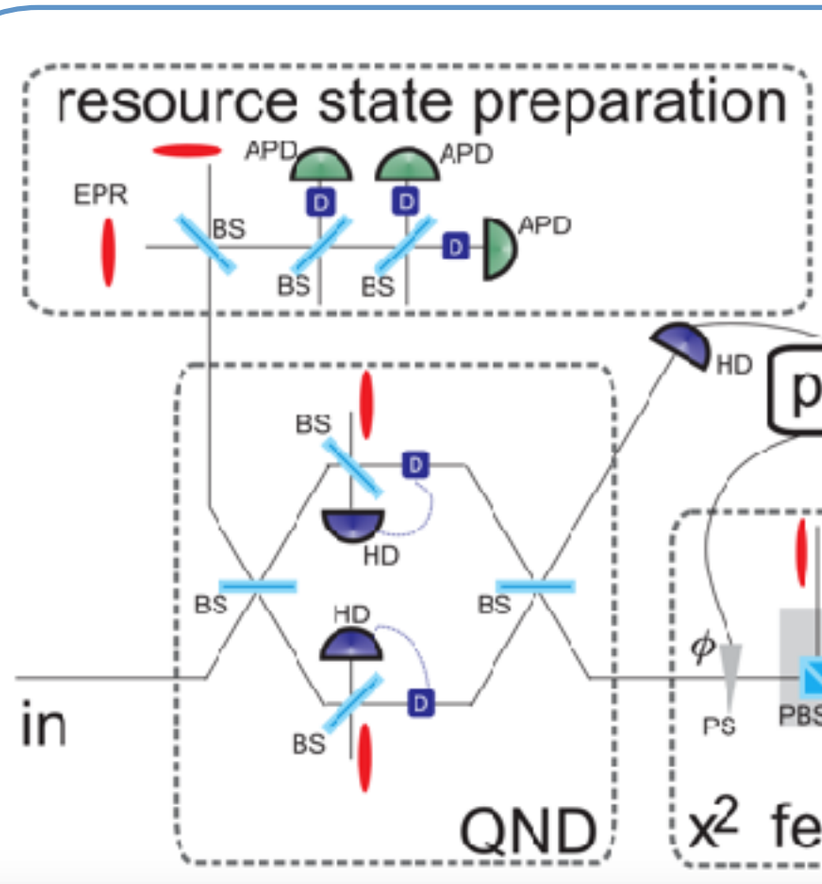
D. Gottesman et al. PRA **64,** 012310 (2001)

Heisenberg picture

Input $\hat{a}_{in}$

$e^{i\left(3q\hat{x}^2+3q^2\hat{x}+q^3\right)}$

Output $\hat{a}_{out}$



Too complicated !!

$$\hat{p}_{out} = \hat{p}_{in} + 3\gamma\hat{x}_{in}^2$$

Too low fidelity !!

Quantum information ↔ Classical information

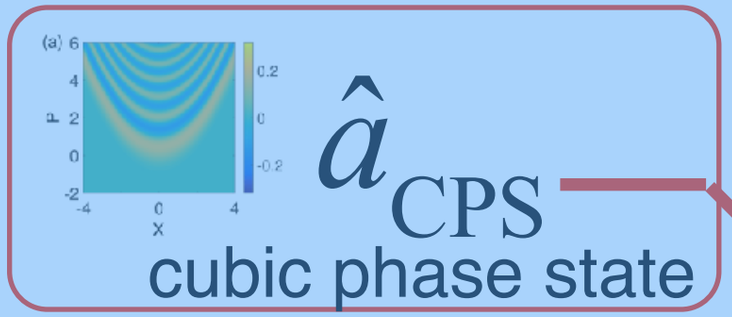
Quantum duty

P. Marek et al. PRA **84,** 053801 (2011)

High fidelity !!

gate teleportation

Universal!



$\hat{a}_{\mathrm{CPS}}$

cubic phase state

$\hat{a}_{\mathrm{sq}}$

squeezed vacuum

$x \rightarrow \theta = \arctan 3\sqrt{2}\gamma x$

$p_\theta = p' \cos\theta + x' \sin\theta$

nonlinear measurement

$\hat{a}_{\mathrm{in}}$

input

$\hat{D}$

p-displacement

$\hat{a}_{\mathrm{out}}$

output

Quantum noise reduction with nonclassical states of light

Optical nonlinearity can be created with classical nonlinear feedforward.
(classical electrical circuit = 100% fidelity)

Nonclassicality can be created with nonclassical ancillary inputs.

K. Miyata, H. Ogawa, P. Marek, R. Filip, H. Yonezawa, J. Yoshikawa, and A. Furusawa, PRA **93**, 022301 (2016)

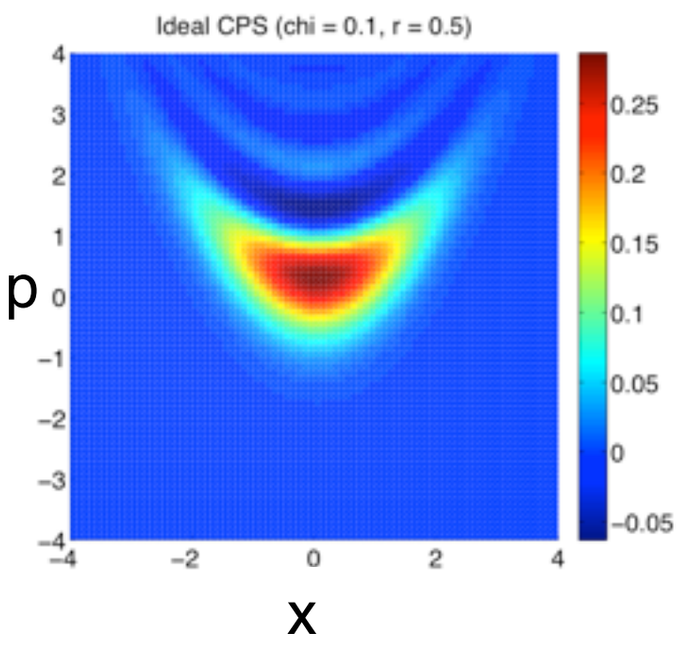
Cubic phase state

Schrödinger picture

$$e^{i\gamma\hat{x}^3}\left|\, p=0\right\rangle$$

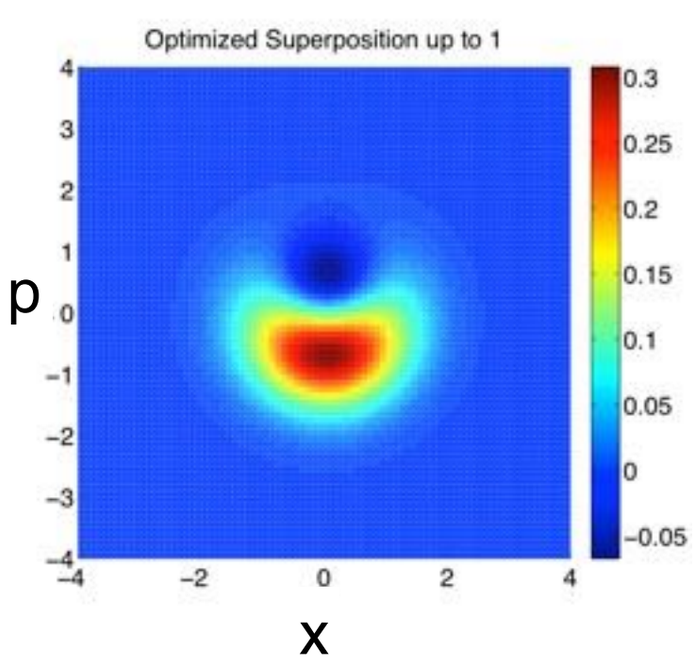
Heisenberg picture

$$\hat{p}_{\mathrm{CPS}}-3\gamma\hat{x}^2_{\mathrm{CPS}}=0$$



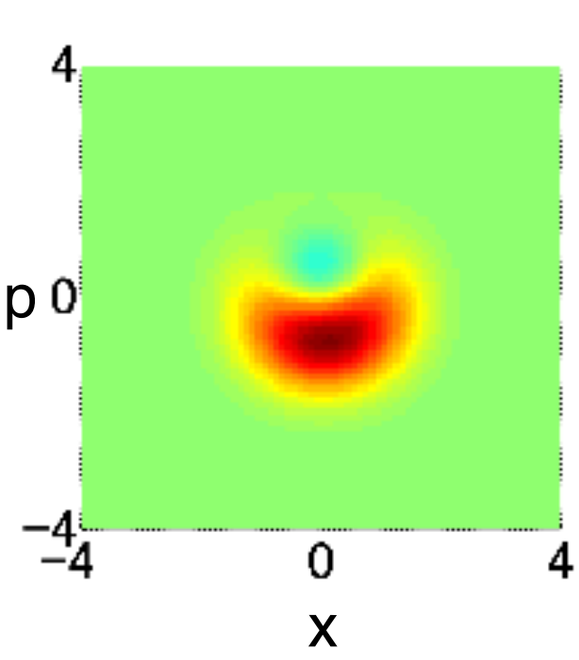
Simulation

- finite squeezing



Simulation

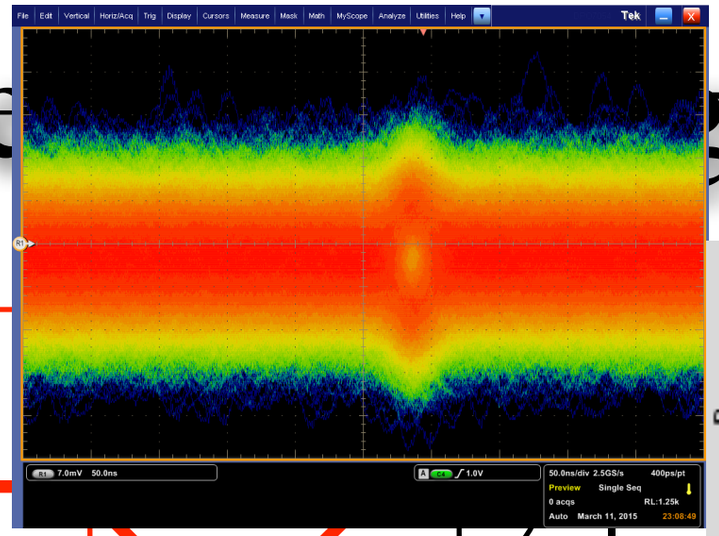
- 0 & 1 photon

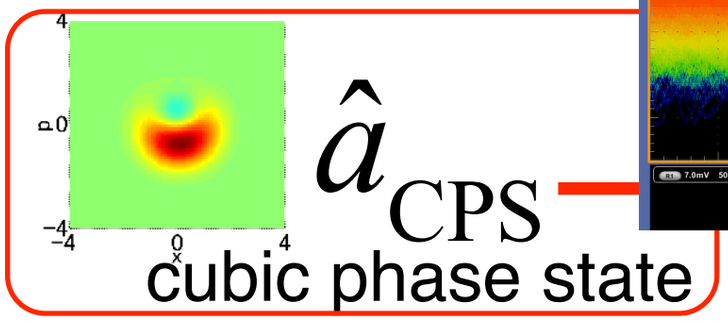


Experiment

- 0 & 1 photon

Cubic phase gate teleportation



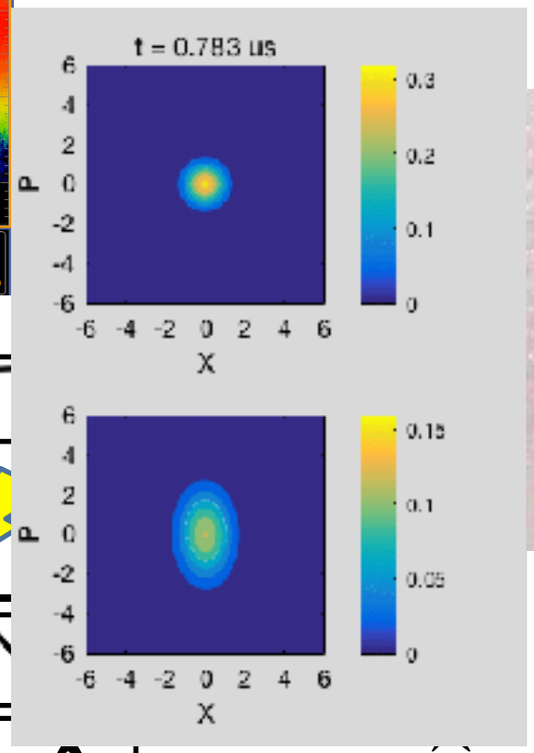


$\hat{a}_{\mathrm{CPS}}$

cubic phase state

$\hat{a}_{\mathrm{sq}}$

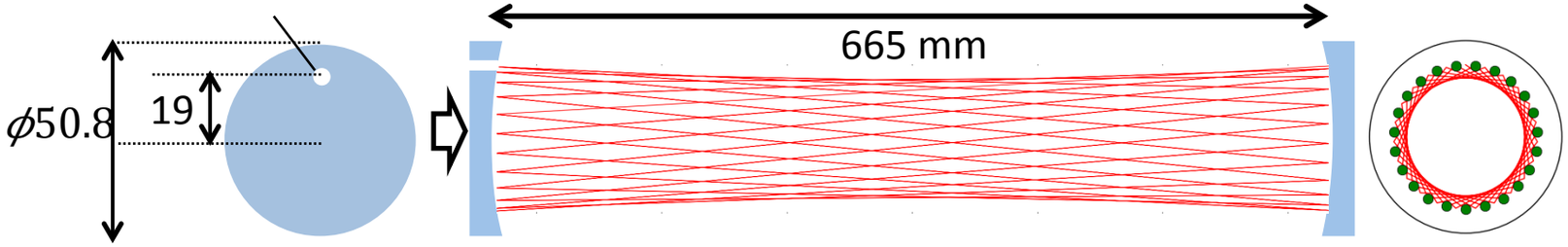
squeezed vacuum



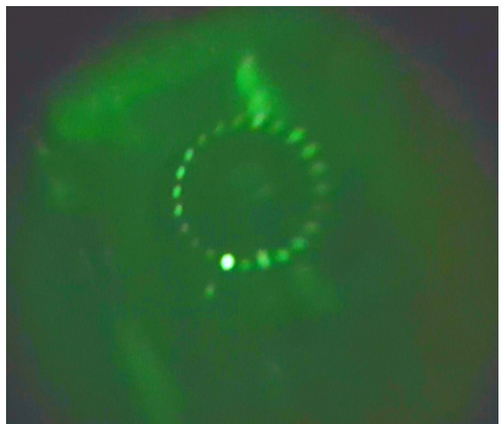
$\hat{a}_{\mathrm{in}}$

$\hat{D}$

$\hat{a}_{\mathrm{out}}$



30m optical delay



3.5 m

Asymmetric OPO

1.5 m

Broadband OPO

Feedforward

Cubic phase state

Classical channel

17.4m delay Herriott Cell

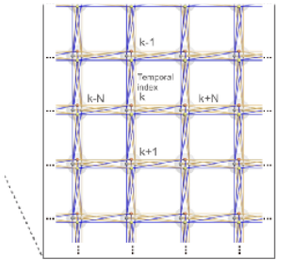
645mm

Delay lines

31.3m delay Herriott Cell

665mm

All-optical phase-sensitive detection for ultra-fast quantum computation



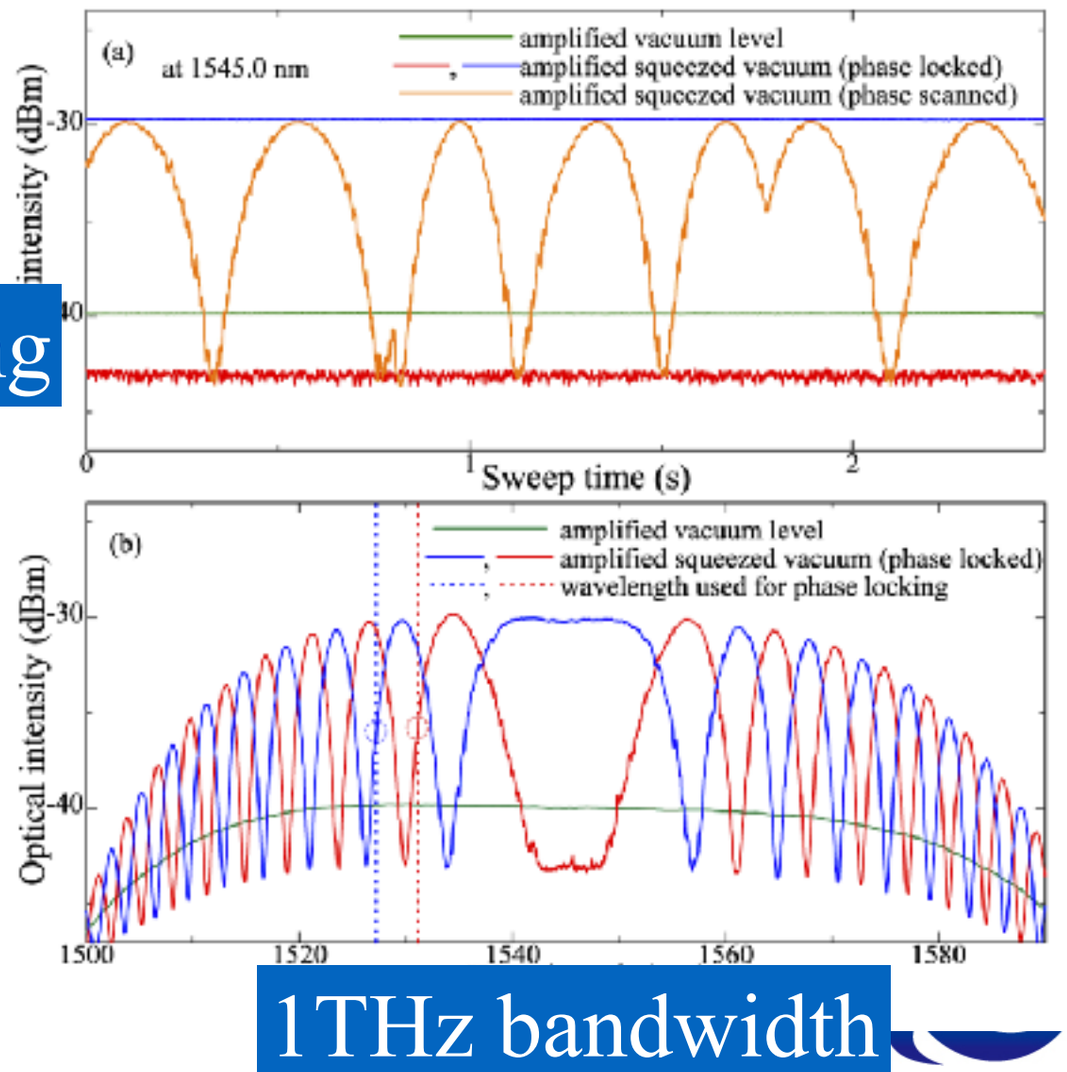
NAOTO TAKANASHI,[1] ASUKA INOUE,[2] TAKAHIRO KASHIWAZAKI,[2] TAKUSHI KAZAMA,[2] KOJI ENBUTSU,[2] RYOICHI KASAHARA,[2] TAKESHI UMEKI,[2] AND AKIRA FURUSAWA[1,*]

[1]*Department of Applied Physics, School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan*

[2]*NTT Device Technology Labs, NTT Corporation, 3-1, Morinosato Wakamiya, Atsugi, Kanagawa 243-0198, Japan*

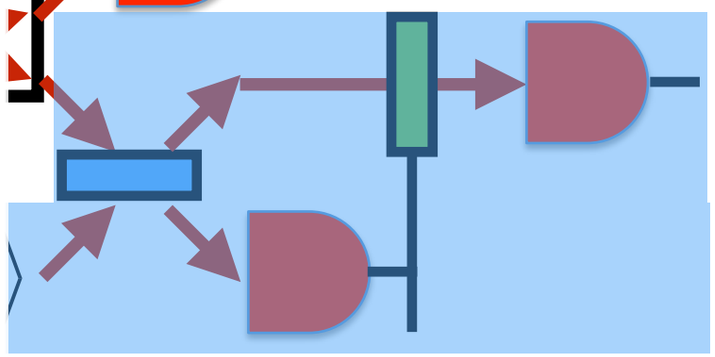
[*]*akiraf@ap.t.u-tokyo.a*

A
with 1
3dB squeezing



1THz bandwidth

cale!
ter
quency



Universal!

MOONSHOT
RESEARCH & DEVELOPMENT PROGRAM