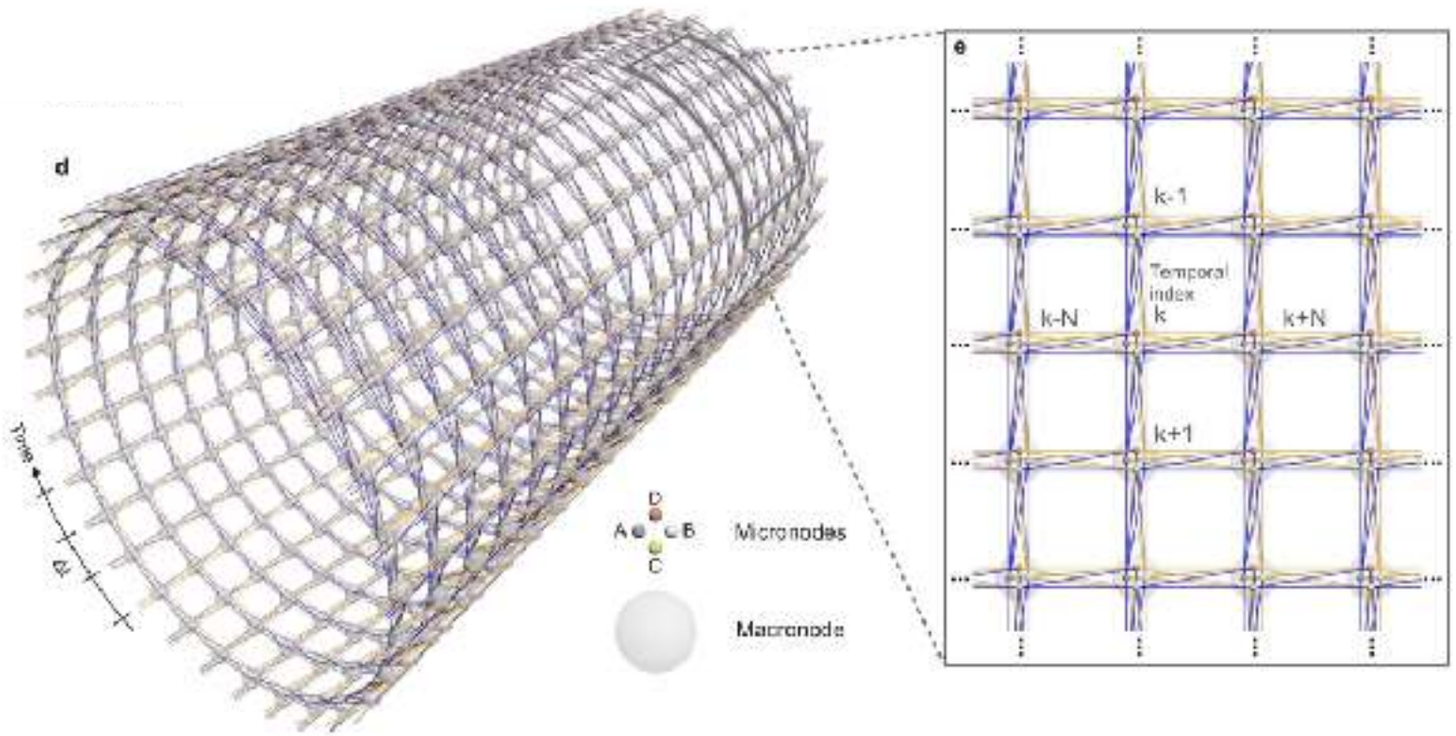


MOONSHOT
RESEARCH & DEVELOPMENT PROGRAM

Moonshot International Symposium for Goal 6

April 23, 2021

Development of Large-scale Fault-tolerant Universal Optical Quantum Computers

Akira Furusawa

Department of Applied Physics
School of Engineering
The University of Tokyo

RIKEN QUANTUM COMPUTING

Caltech

Unconditional Quantum Teleportation

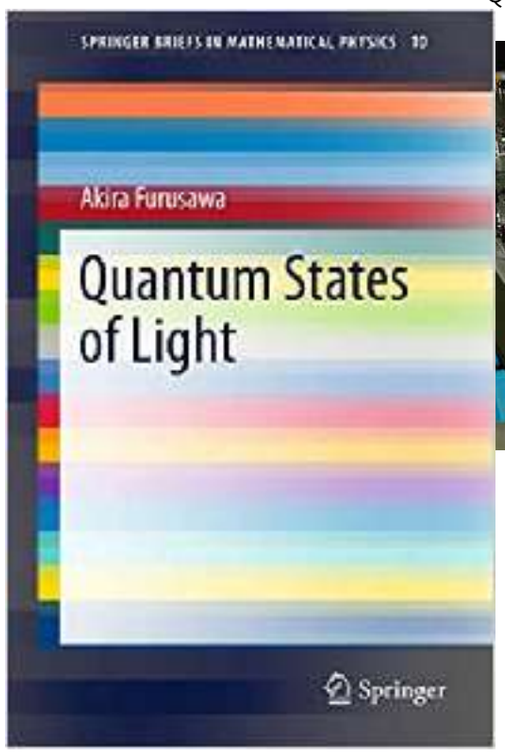
A. Furusawa, J. L. Sørensen, S. L. Braunstein, C. A. Fuchs, H. J. Kimble,* E. S. Polzik

23 OCTOBER 1998 VOL 282 SCIENCE www.sciencemag.org

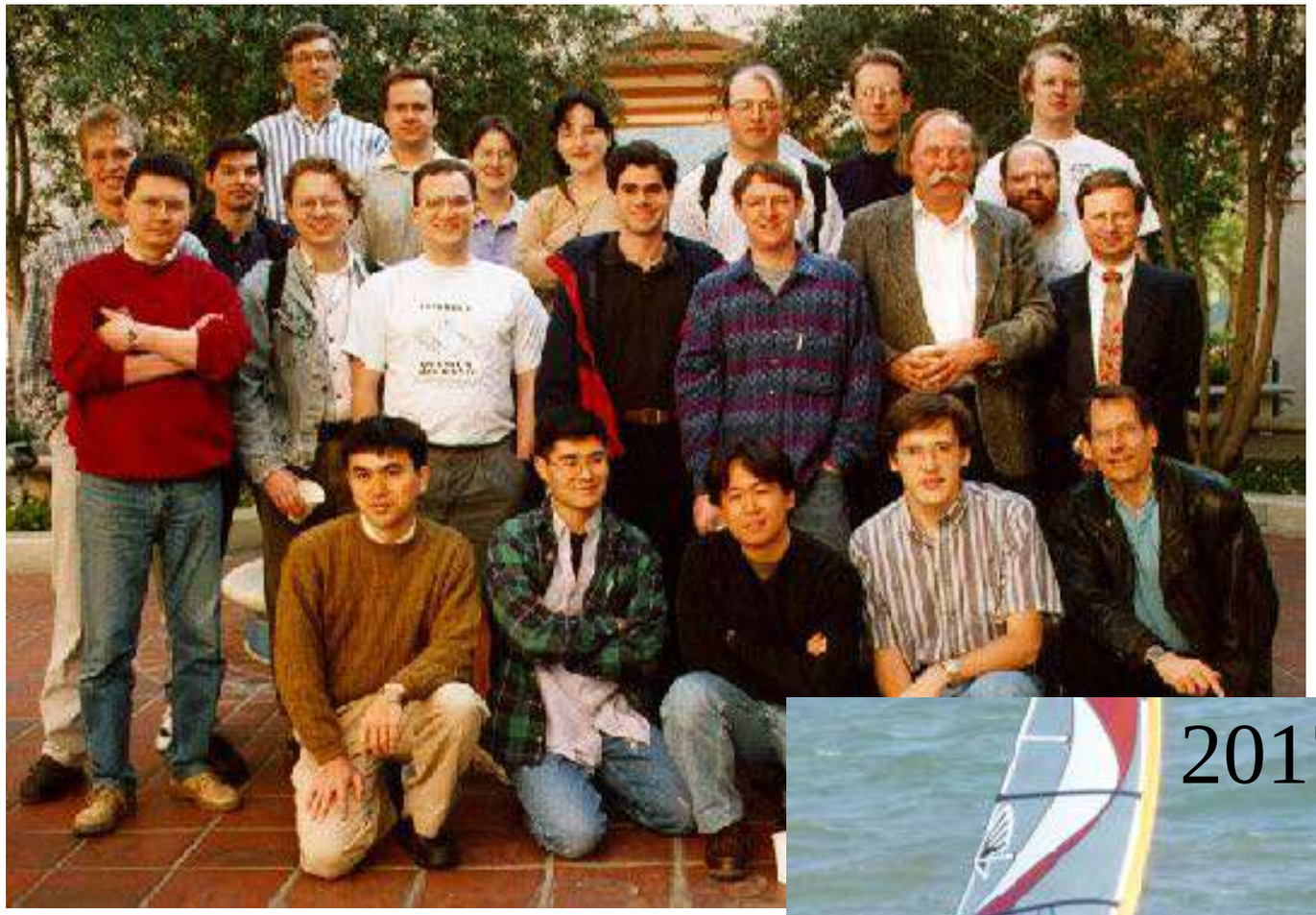
Akira Furusawa and Peter van Loock WILEY-VCH

Quantum Teleportation and Entanglement

A Hybrid Approach to Universal Quantum Information Processing



QUIC Caltech/MIT/USC 1997



古澤　明

略歴

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学専攻修士課程修了

（株）ニコン入社

1988-1990年　東京大学先端科学技術研究センター研究員

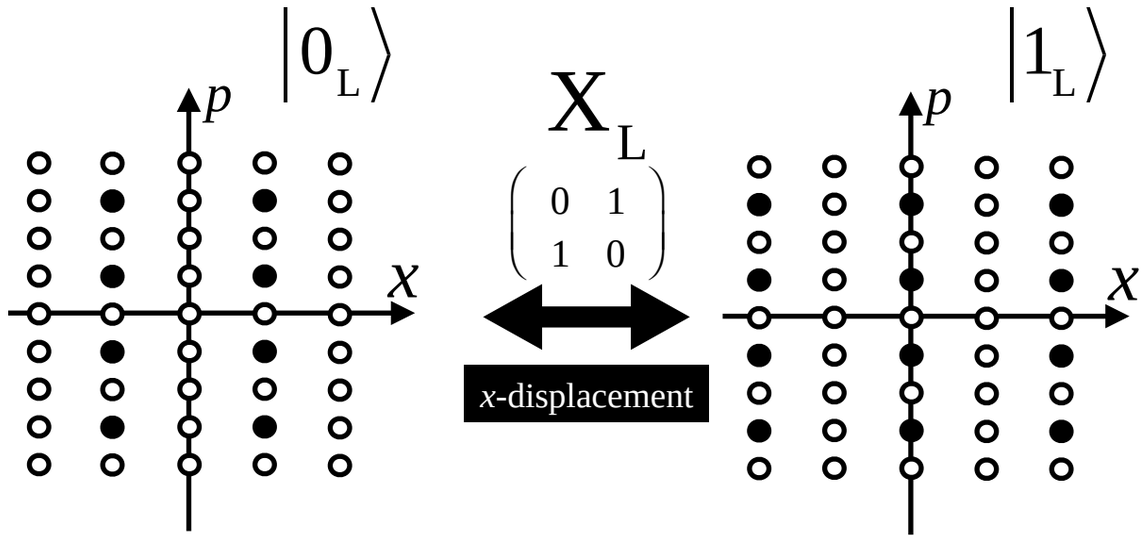
1996-1998年　カリフォルニア工科大学客員研究員

2000年　東京大学大学院工学系研究科物理工学専攻助教授

2007年　東京大学大学院工学系研究科物理工学専攻教授

GKP qubits
&
Logical operations

Logical qubits for
Quantum error correction



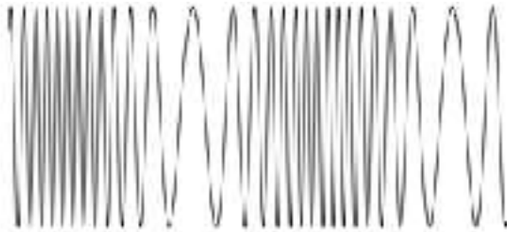
Complex amplitude

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

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

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

FM $\hat{p}$



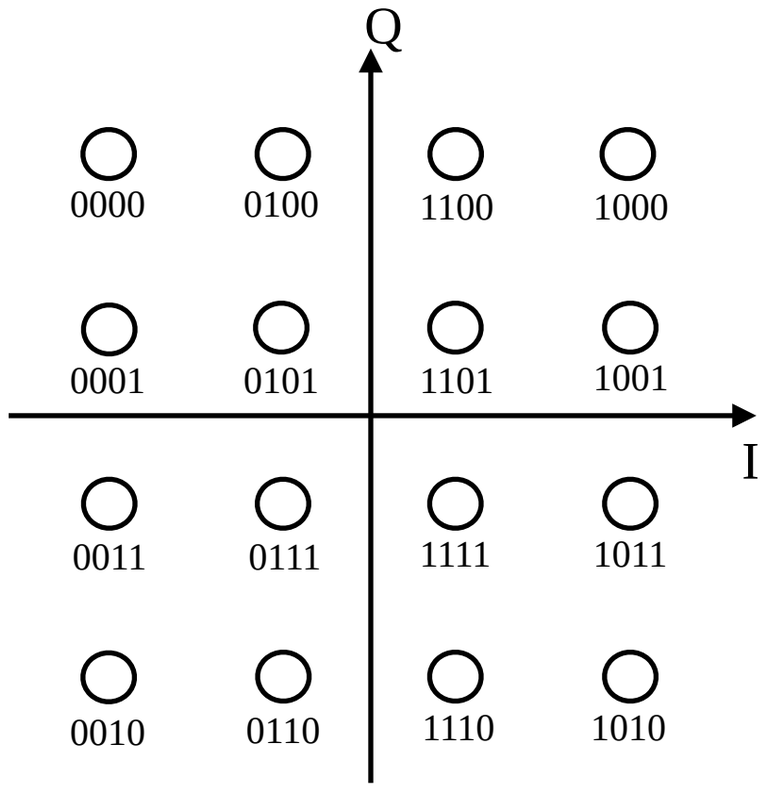
Quadrature Amplitude Modulation
QAM

Coherent communication

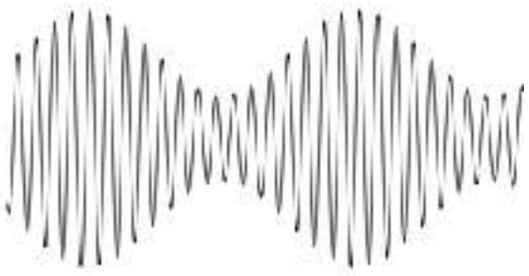
Radio

AM

FM



AM $\hat{x}$



GKP qubits
&
Logical operations

○ $+\infty$

● $-\infty$

Complex amplitude

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

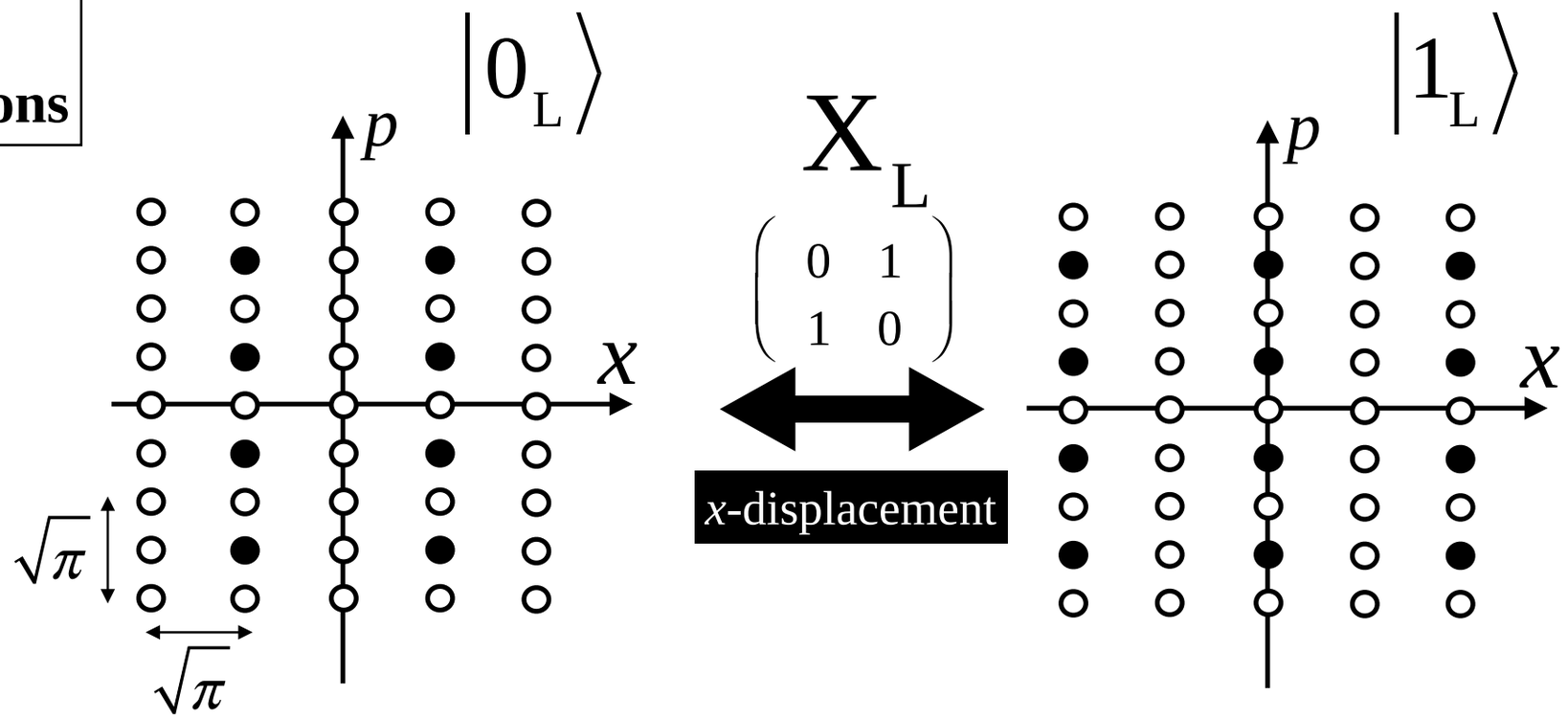
$\left[\hat{x}, \hat{p}\right] = \frac{i}{2}$

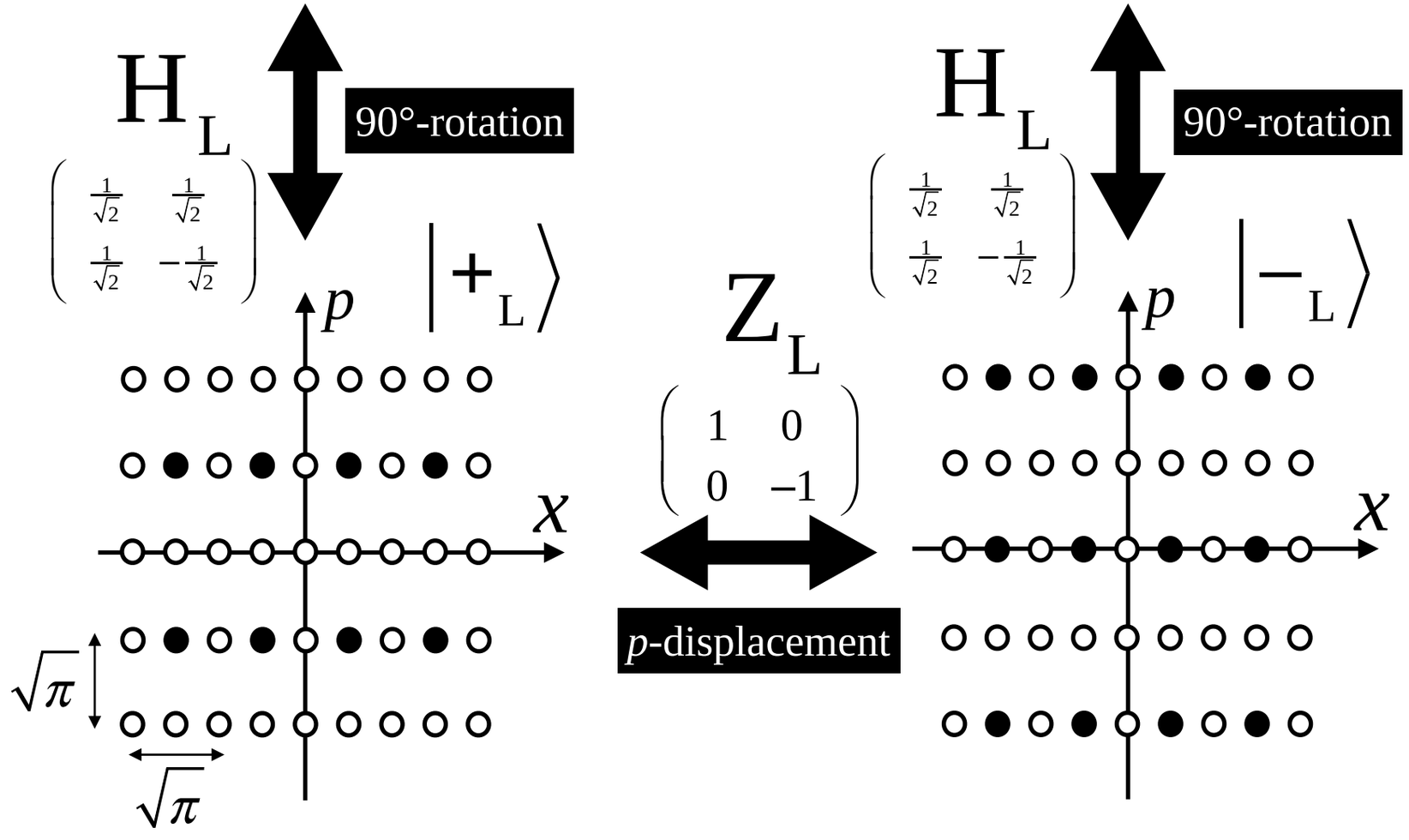
$\hbar = \frac{1}{2}$

Logical qubits for quantum error correction

Clifford

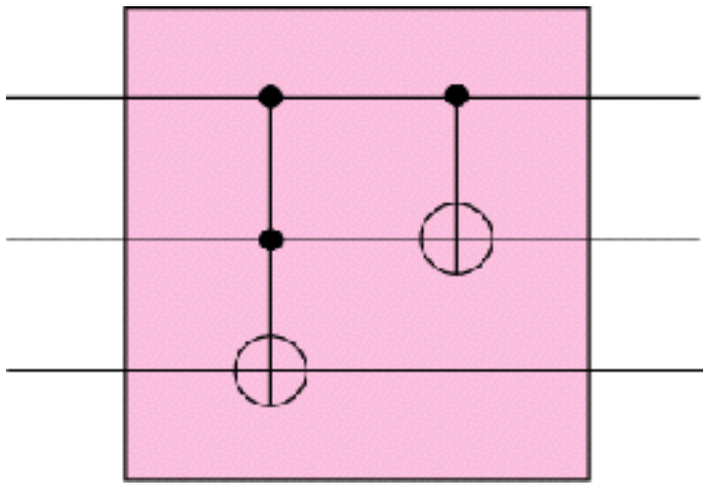
Gaussian





Quantum computing

Quantum circuit model



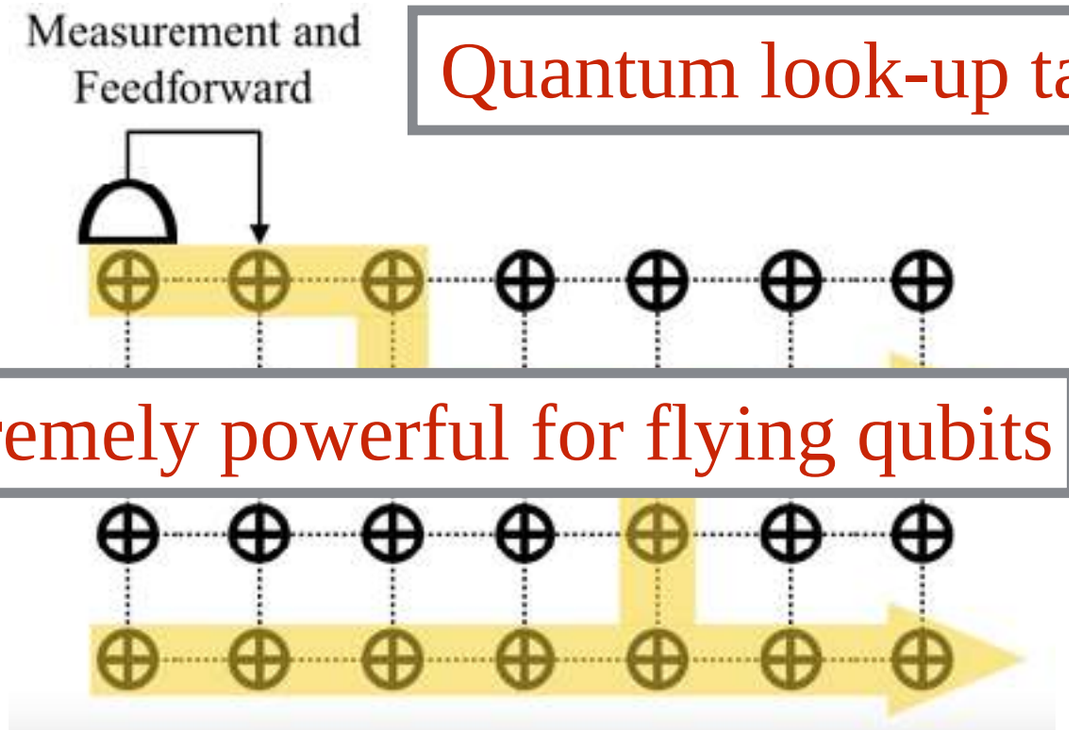
Qubit
R. P. Feynman (1980)

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



Changing measurement bases = changing operation

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

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

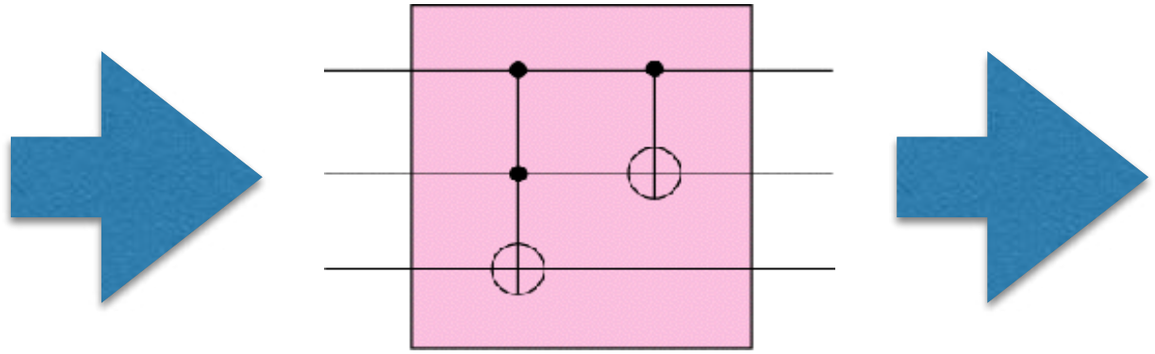
Continuous variable
N. C. Menicucci and P. van Loock et al. (2006)

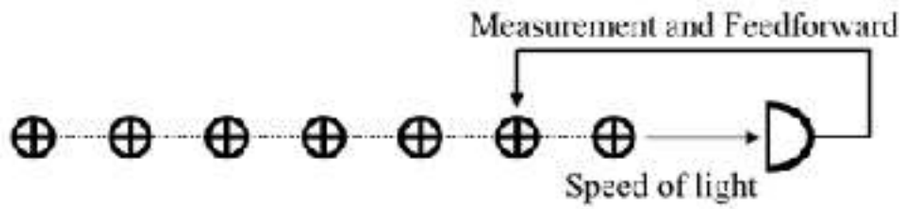
$$\oplus = \int_{-\infty}^{+\infty} dx |x\rangle$$

Quantum computing with flying qubits (photons)

Quantum circuit model

flying qubits
photons



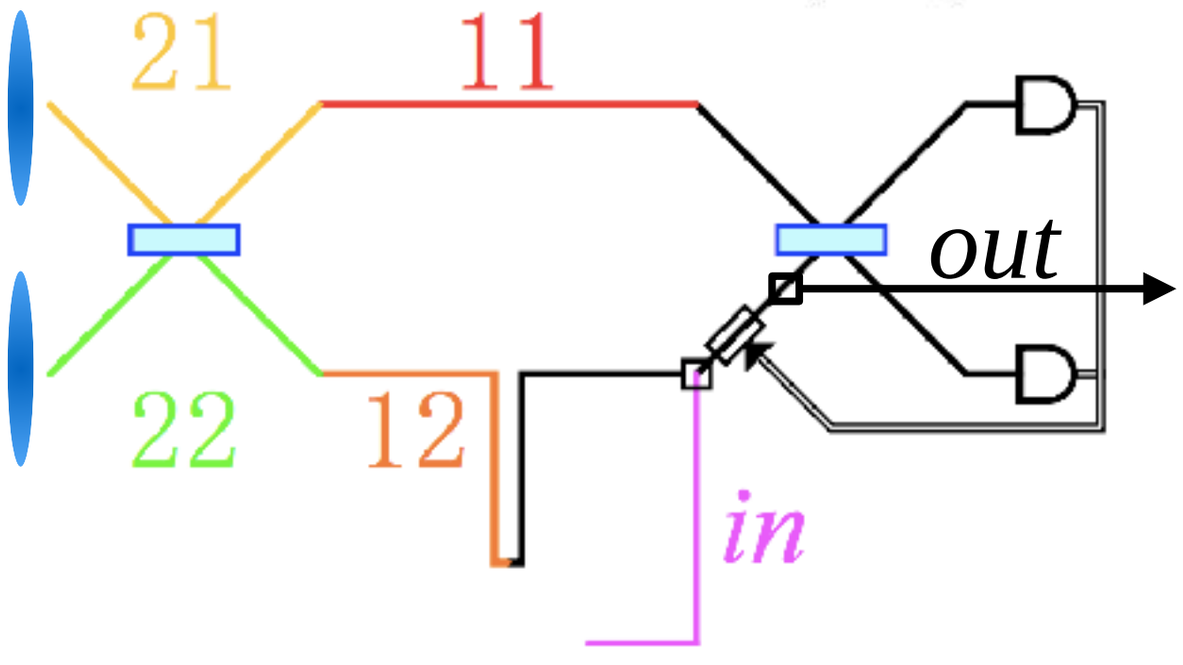


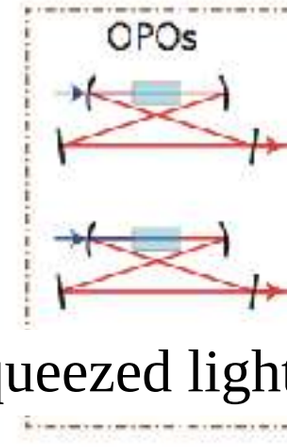
setup
g)

r state!!

Measu
One-w

g





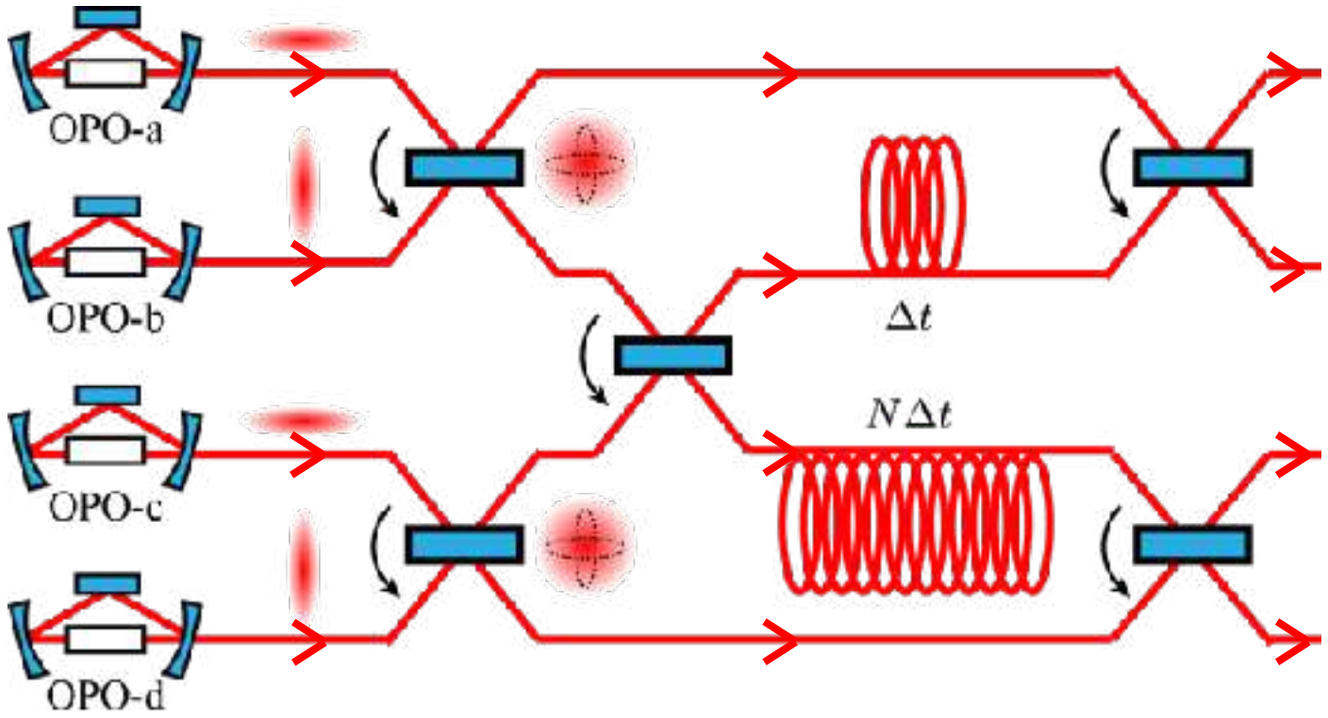
Squeezed light

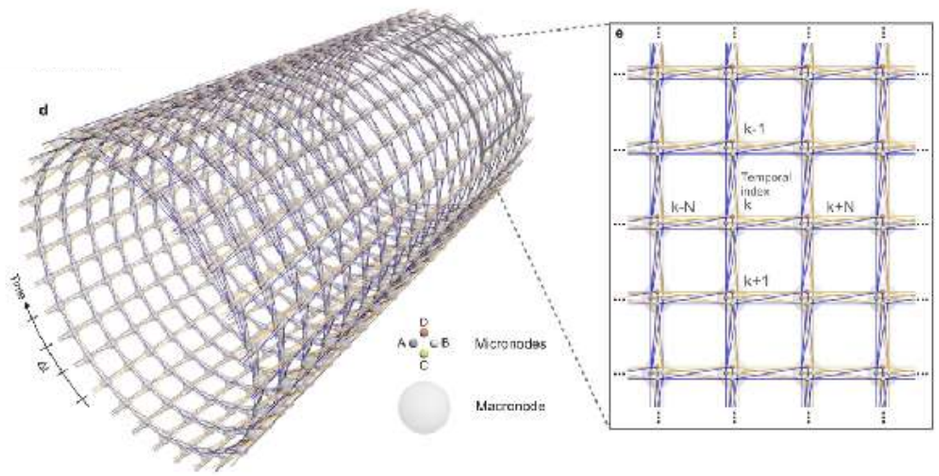
100( ) (2016)

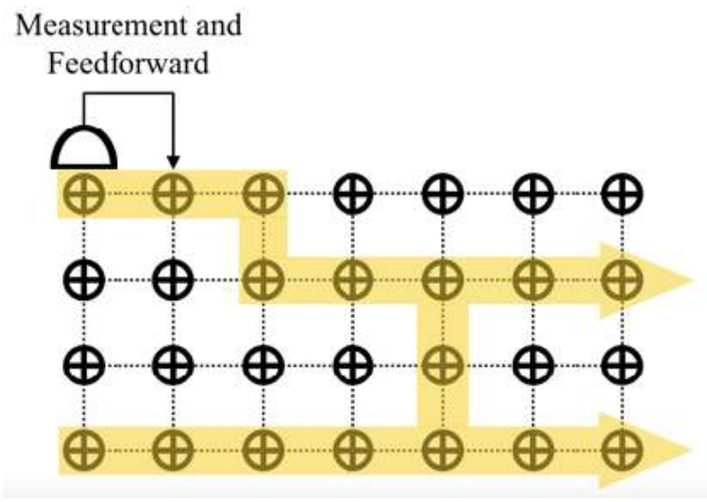
Large-scale quantum computing = fixed-size of the setup
Programmable

Time-domain multiplexed 2D cluster state

Quantum look-up table





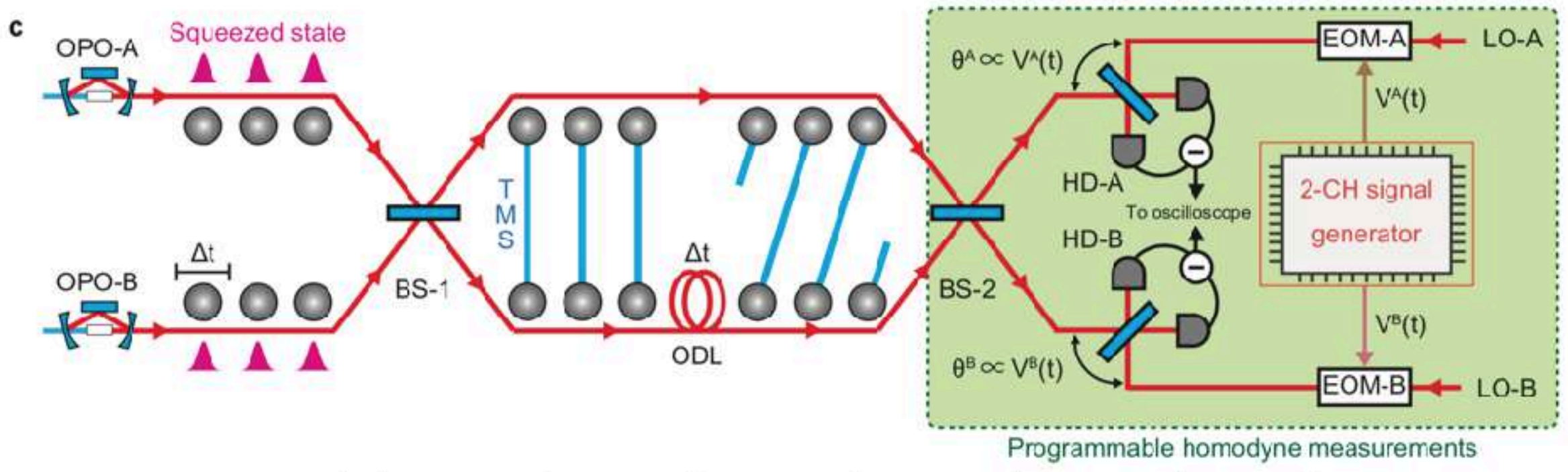


QUANTUM COMPUTING

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]*



Phase rotation

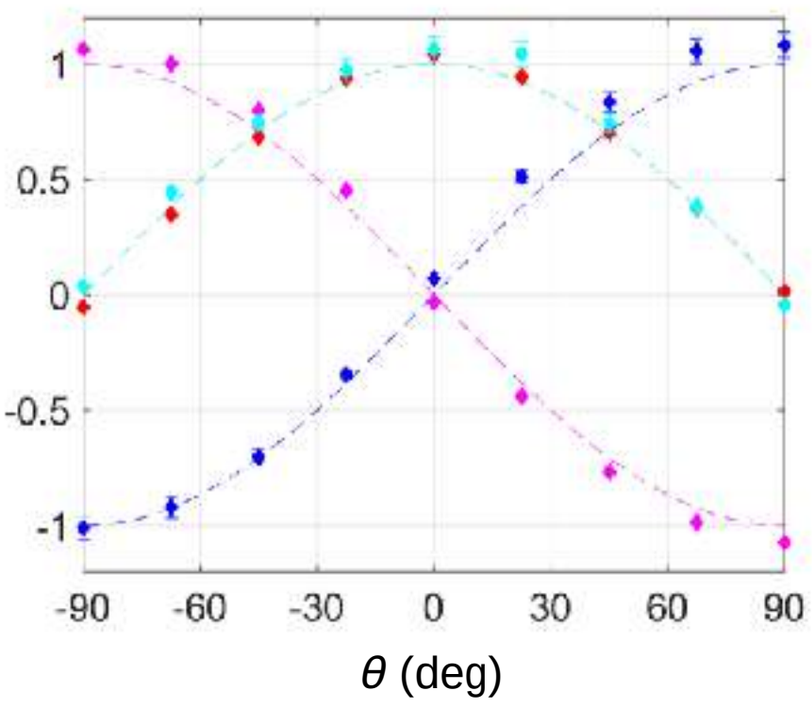
$$\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

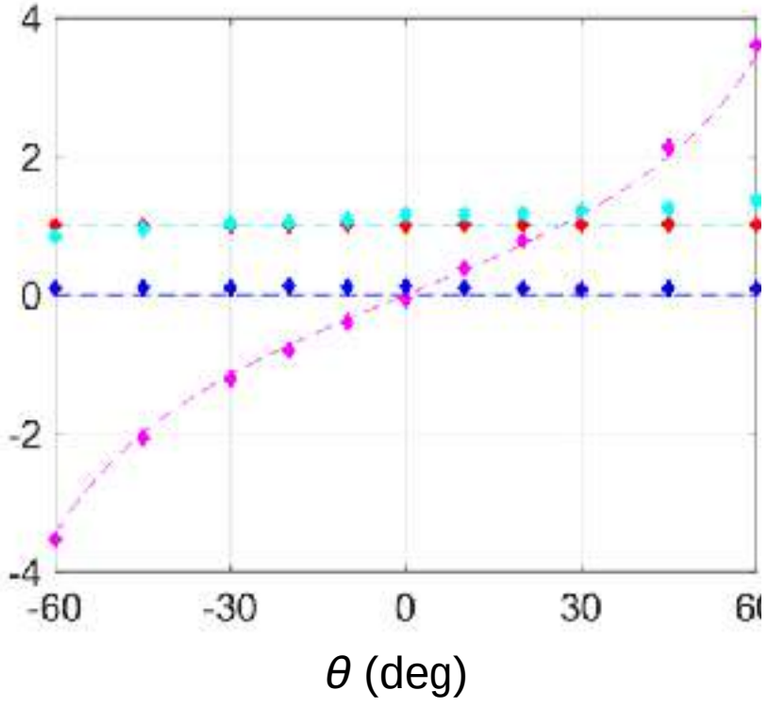
Shear

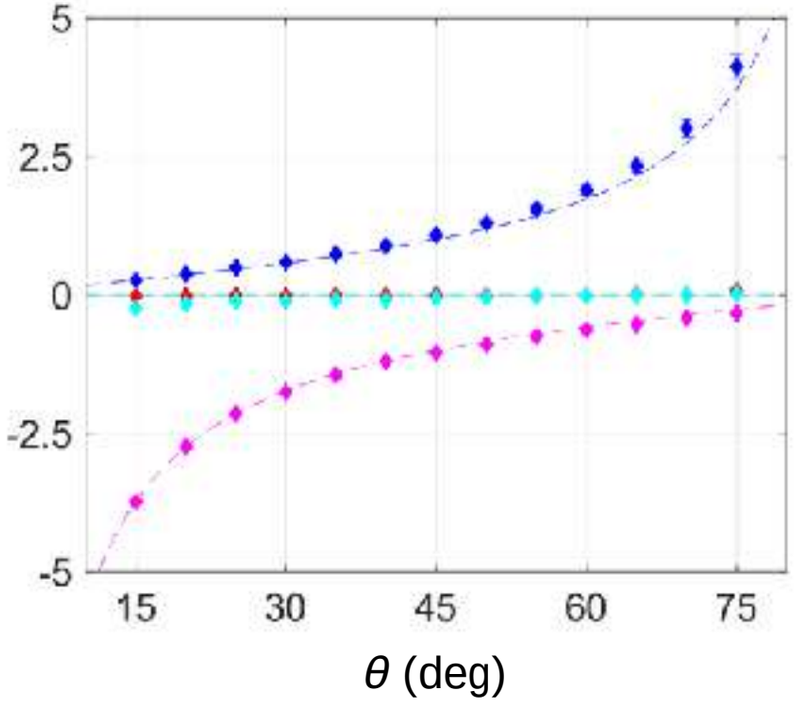
$$\begin{pmatrix} 1 & 0 \\ 2\tan\theta & 1 \end{pmatrix}$$

Squeezing

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



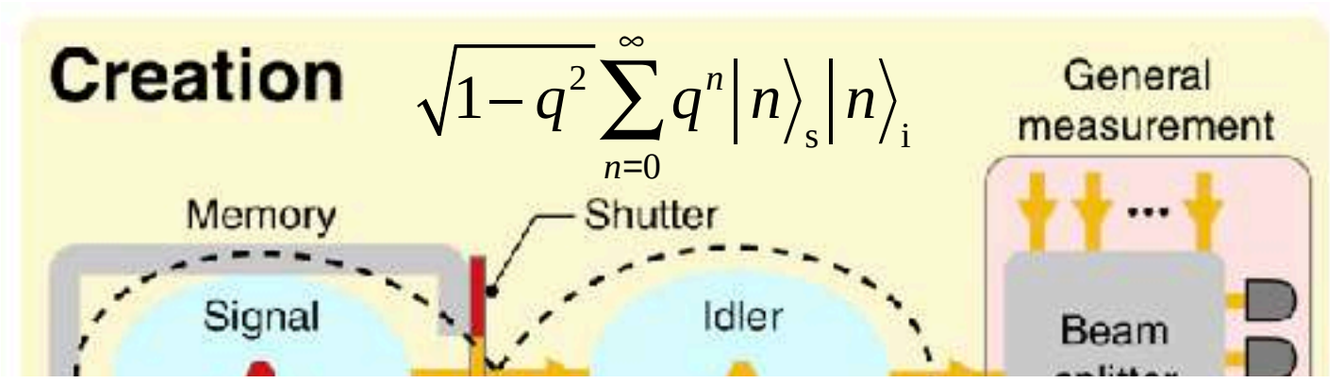


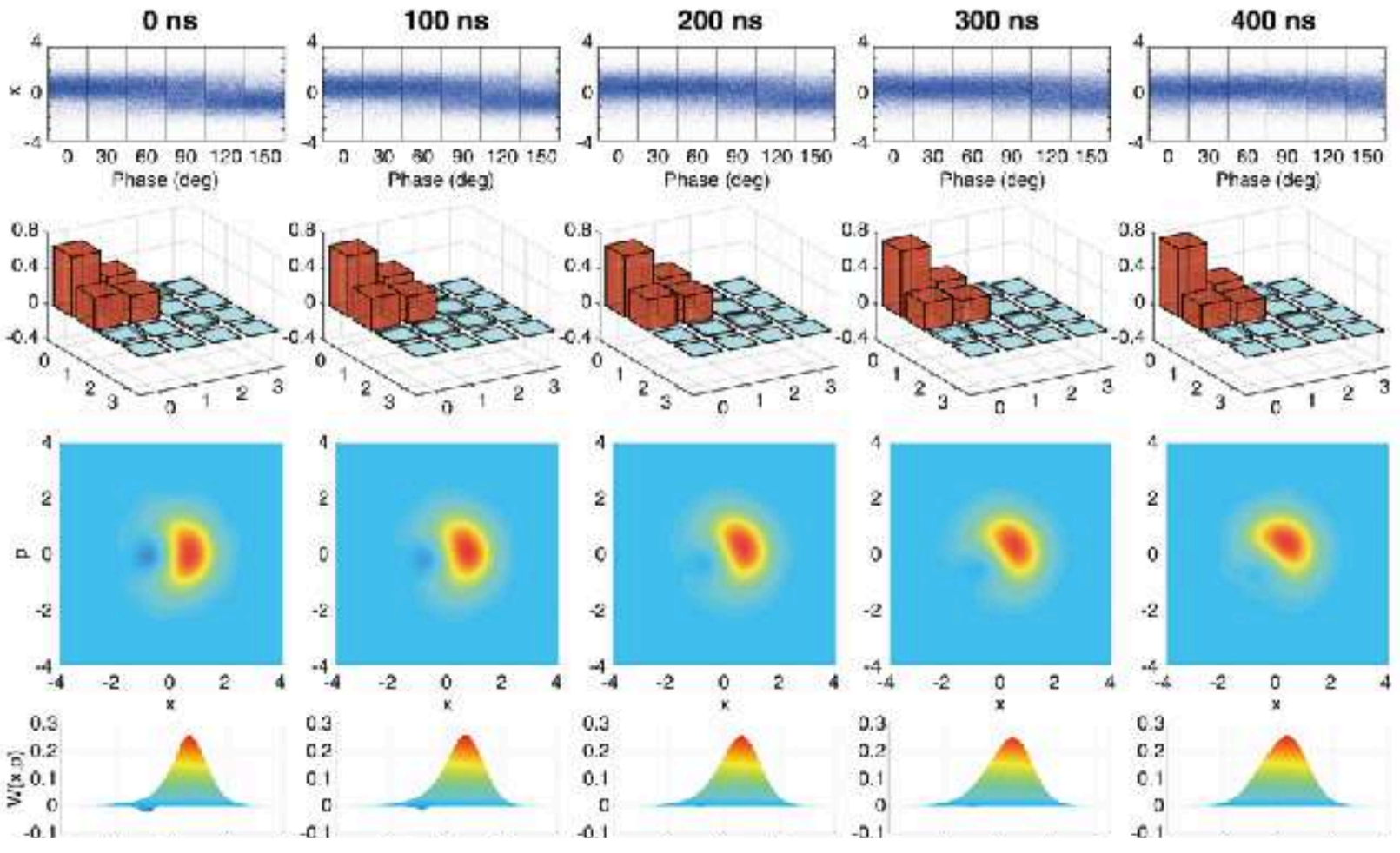


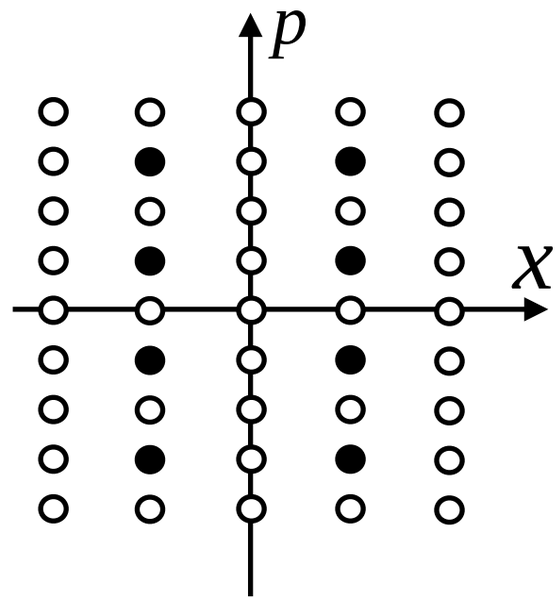
W. Asavanant et al., arXiv:2006.537 [quant-ph].

With Prof. Takahashi

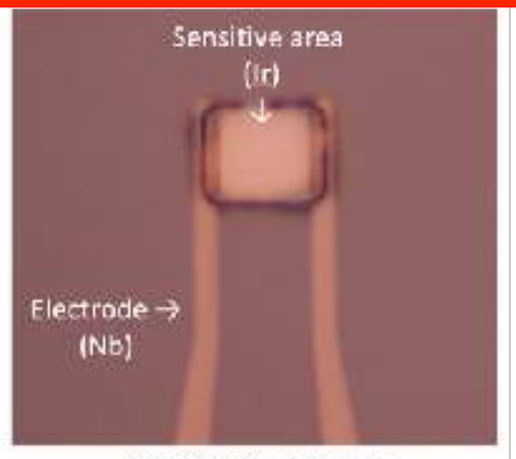
Deterministic state synthesizer



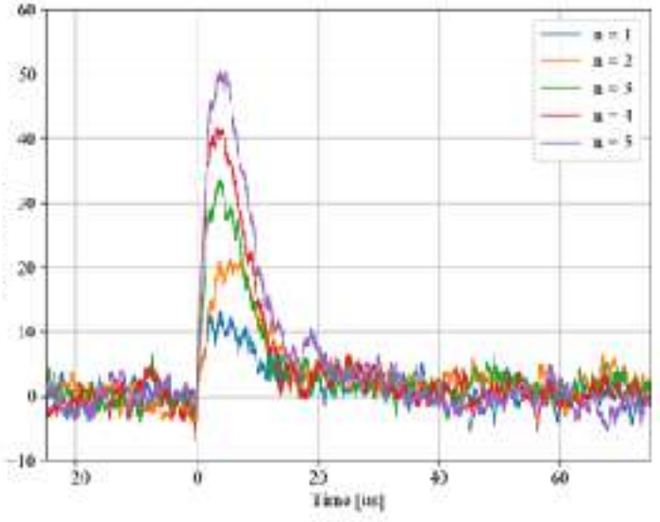




Photon-number-resolving detector



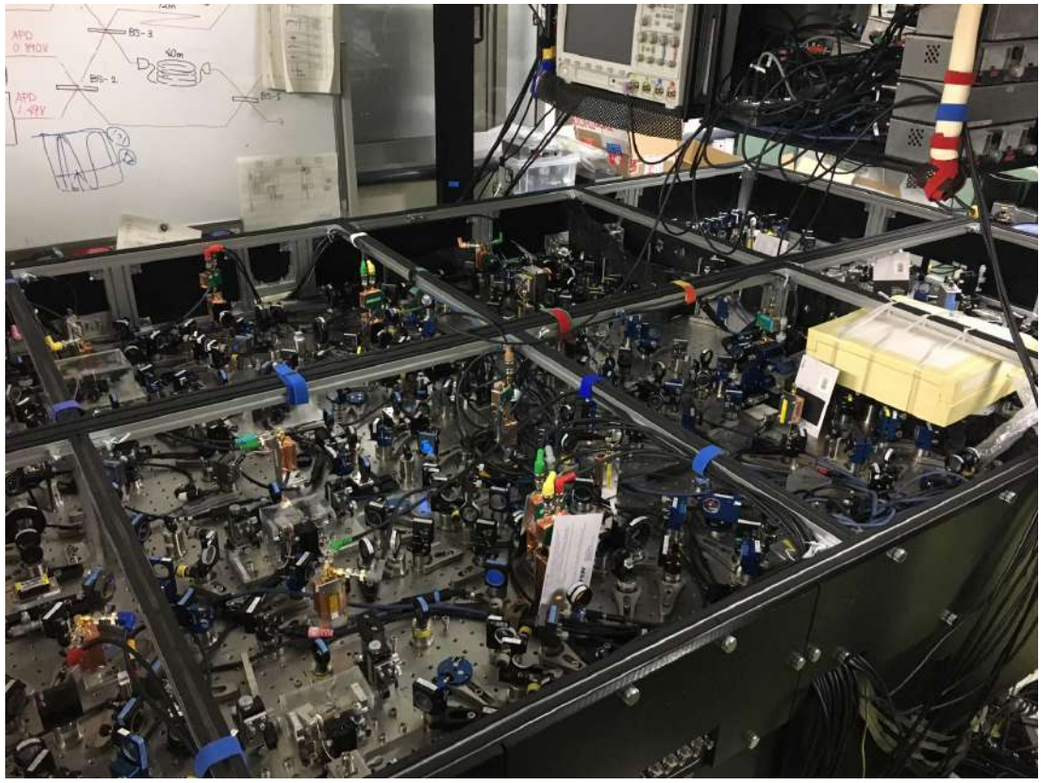
$8 \times 8\ \mu m^2$ element



Y. Hashimoto et al., Phys. Rev. Lett. 123, 113603 (2019)

With NTT people

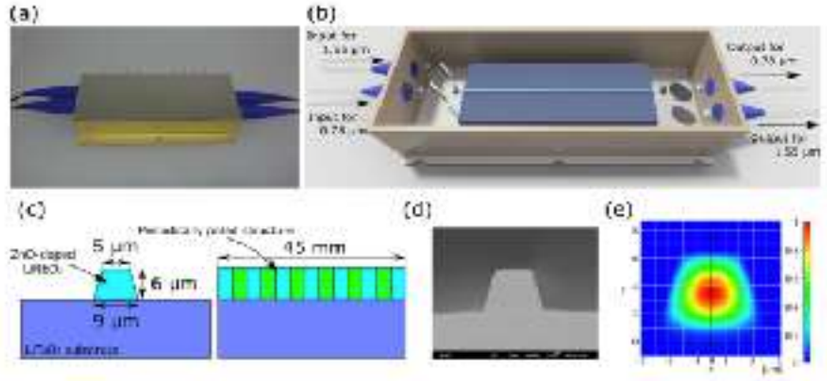
At UTokyo

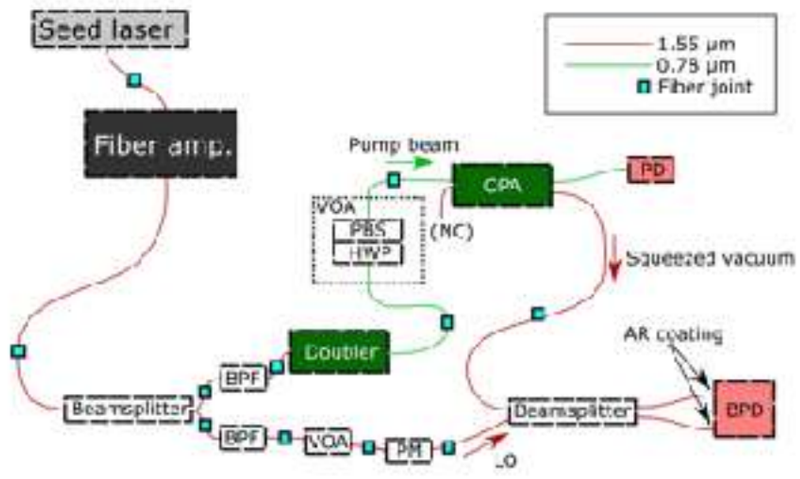


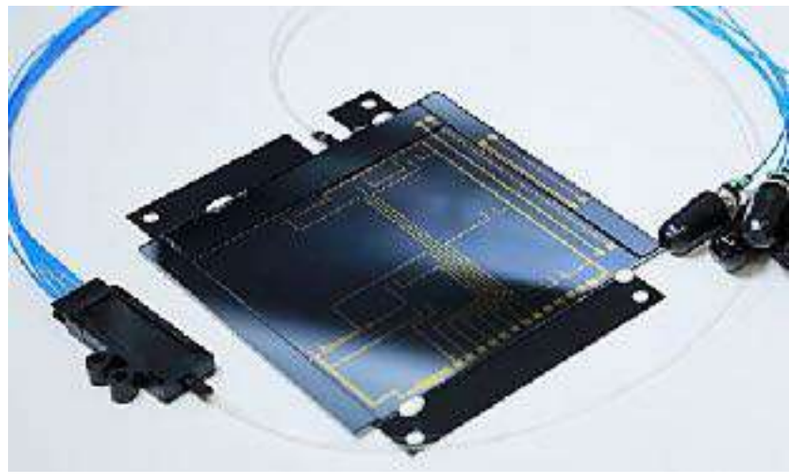
Carrier wavelength: 860 nm

Actual machine

Cloud







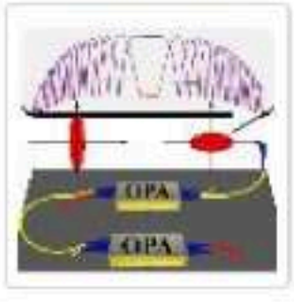
Carrier wavelength: 1550 nm

APL Photonics

Continuous-wave 6-dB-squeezed light with 2.5-THz-bandwidth from single-mode PPLN waveguide

Cite as: APL Photonics 5, 036104 (2020); https://doi.org/10.1063/1.5142437
Submitted: 13 December 2019 . Accepted: 01 March 2020 . Published Online: 30 March 2020

Takahiro Kashiwazaki, Naoto Takanashi, Taichi Yamashima, Takushi Kazama, Koji Enbutsu, Ryoichi Kasahara, Takeshi Umeki, and Akira Furusawa



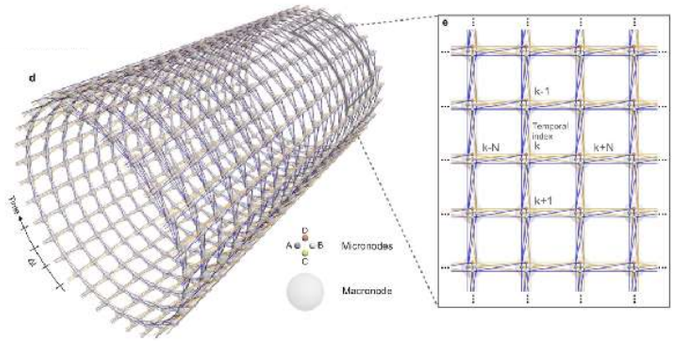
All-optical phase-sensitive detection for ultra-fast quantum computation

Naoto Takanashi, Asuka Inoue, Takahiro Kashiwazaki, Takushi Kazama, Koji Enbutsu, Ryoichi Kasahara, Takeshi Umeki, and Akira Furusawa

Optics Express Vol. 28, Issue 23, pp. 34916-34926 (2020) • https://doi.org/10.1364/OE.405832

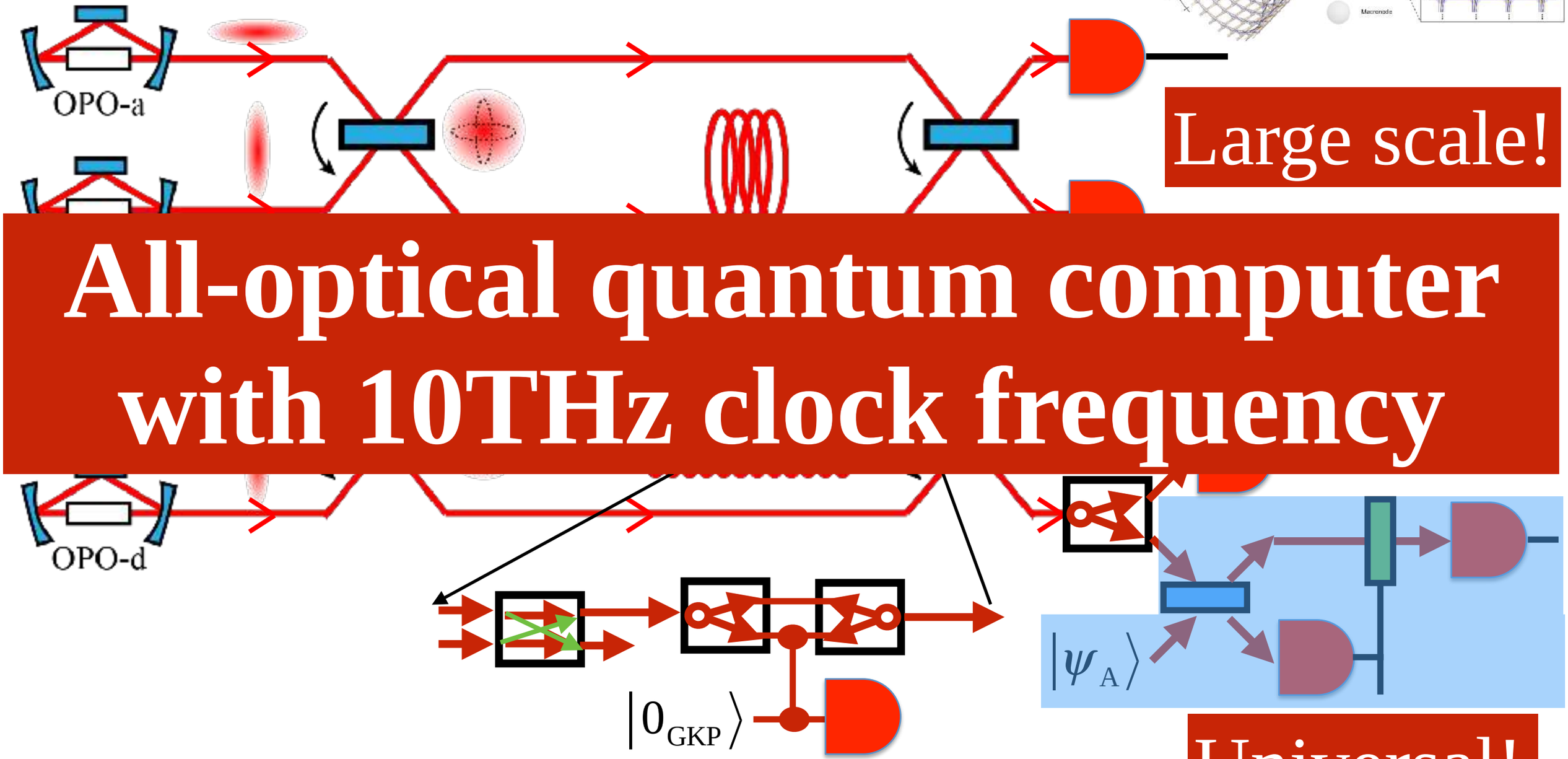
Goal

Optical parametric amplifier



Large scale!

All-optical quantum computer with 10THz clock frequency



Fault tolerant!

Universal!