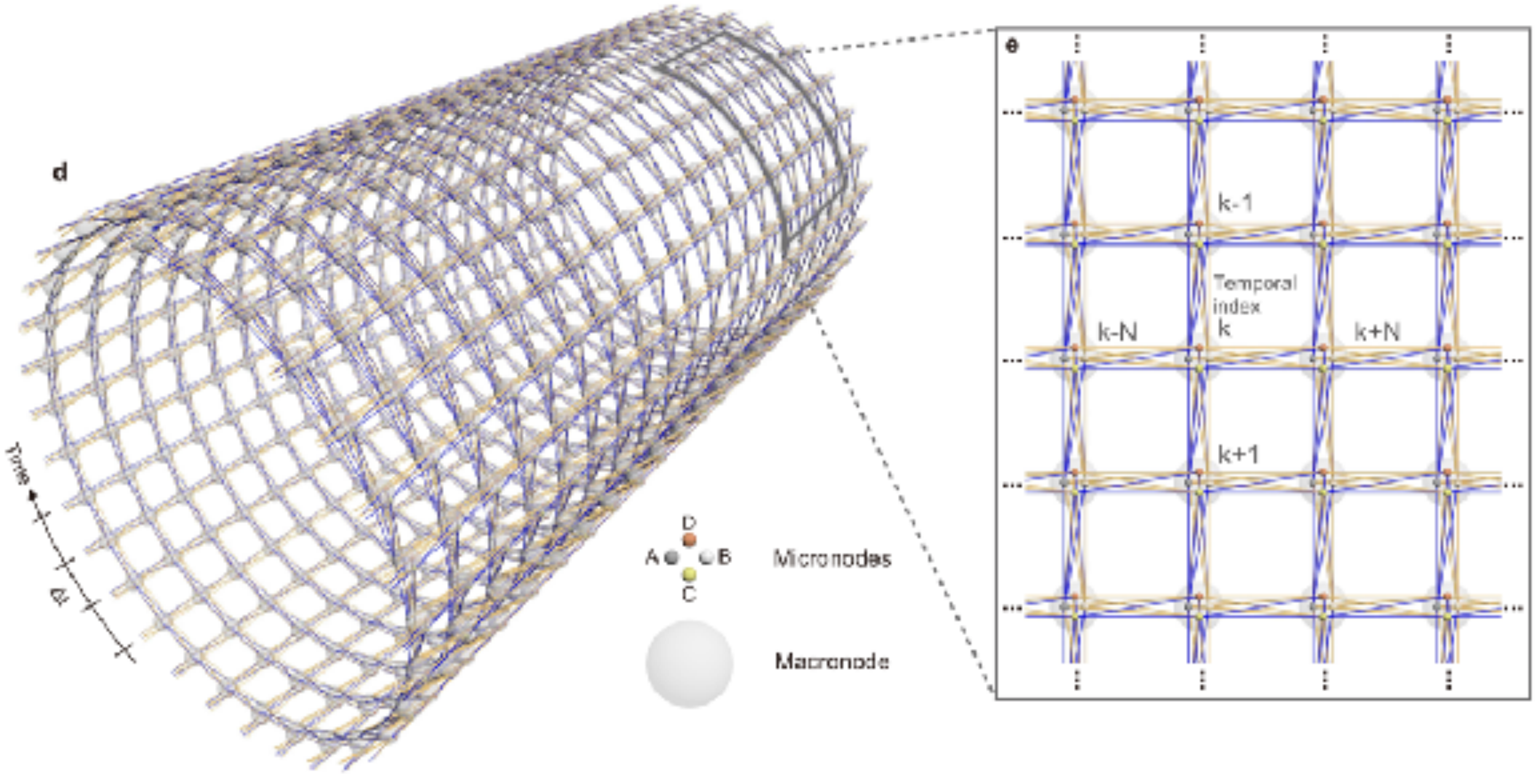


Summer School
New Advances in quantum information science and quantum technology
Samarkand, Uzbekistan
Sept 13, 2019

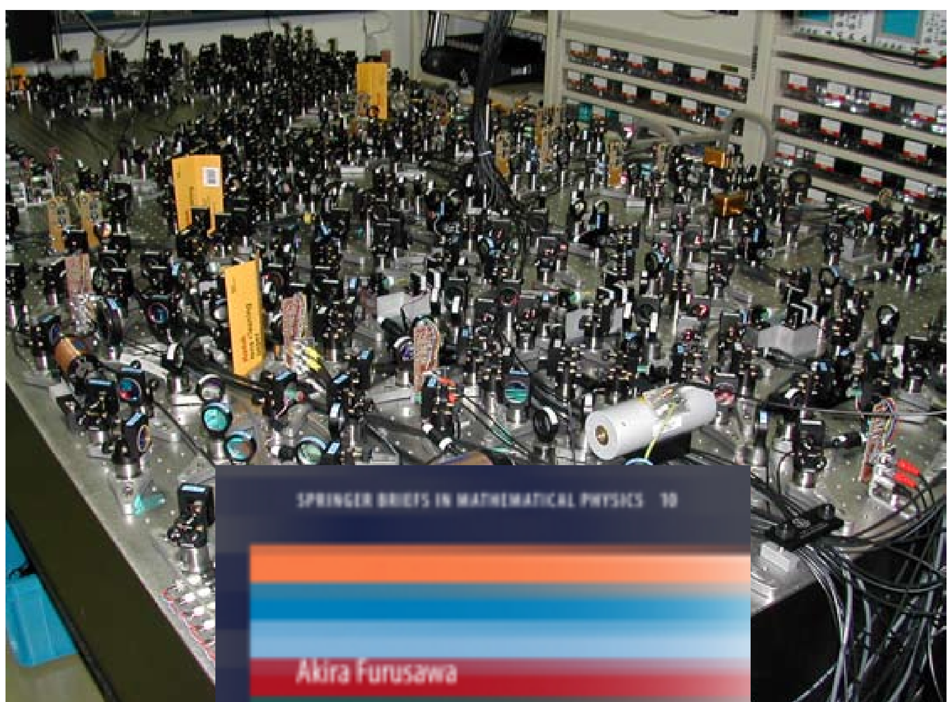
Large-scale quantum computing with quantum teleportation

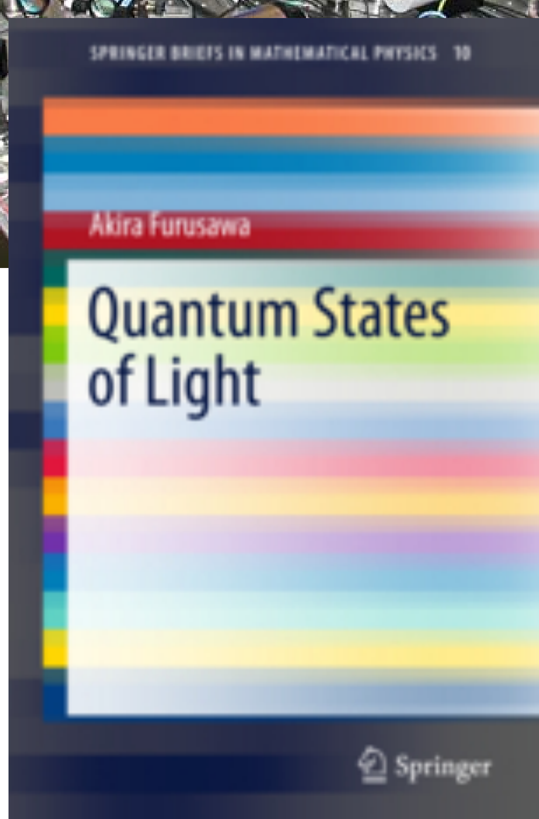
Akira Furusawa
Department of Applied Physics
School of Engineering
The University of Tokyo

Akira Furusawa and Peter van Loock   WILEY-VCH

Quantum Teleportation and Entanglement

A Hybrid Approach to Universal
Optical Quantum Information Processing





QUIC Caltech/MIT/USC   1997

古澤　明

略歴

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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

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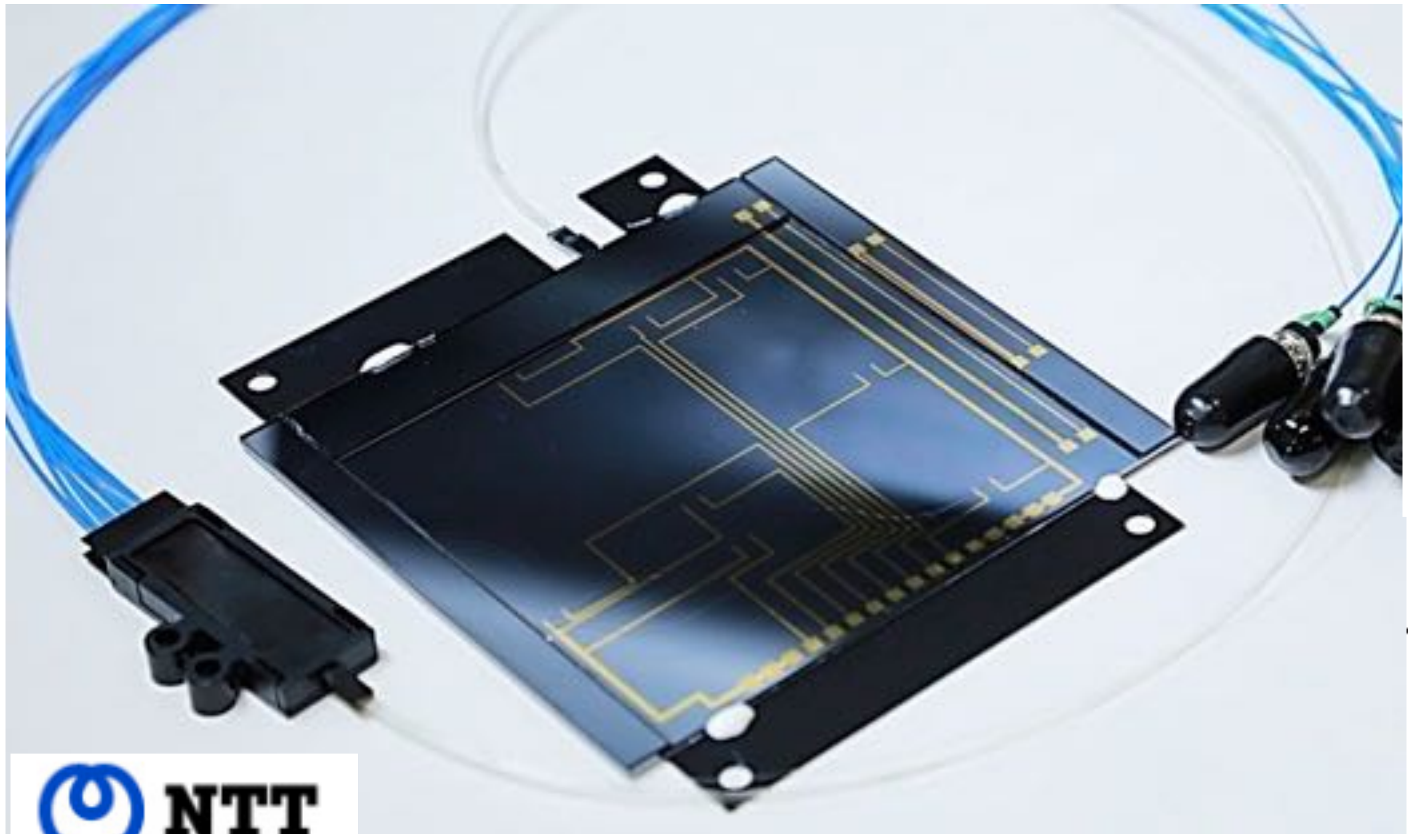
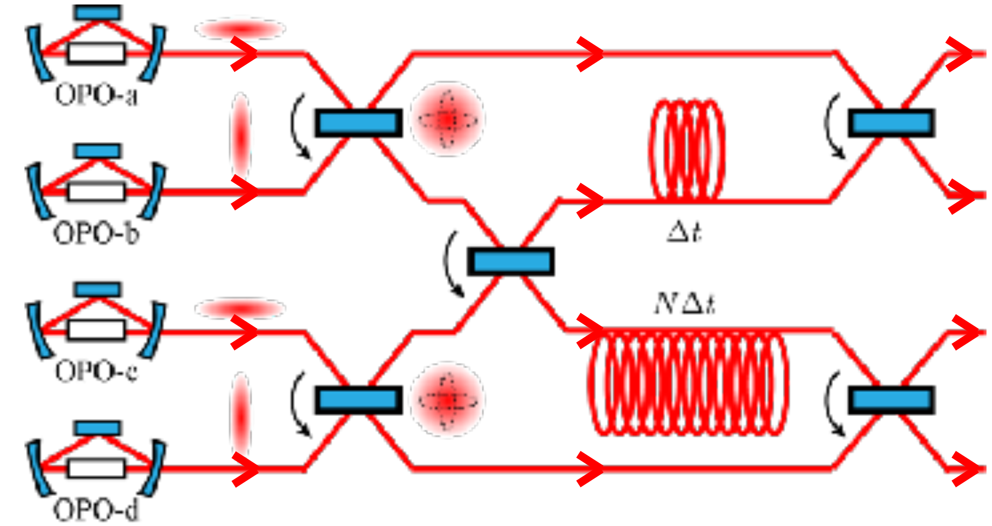
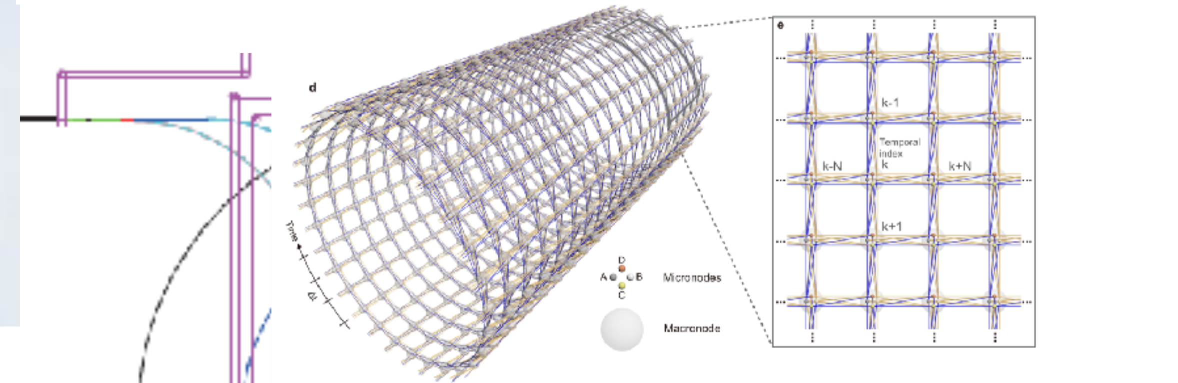
B. Charoensombutamon, M. Matsuyama, T. Yamashima,
T. Nakamura, Y. Ishizuka, T. Ebihara, H. Nishi, A. Funabashi

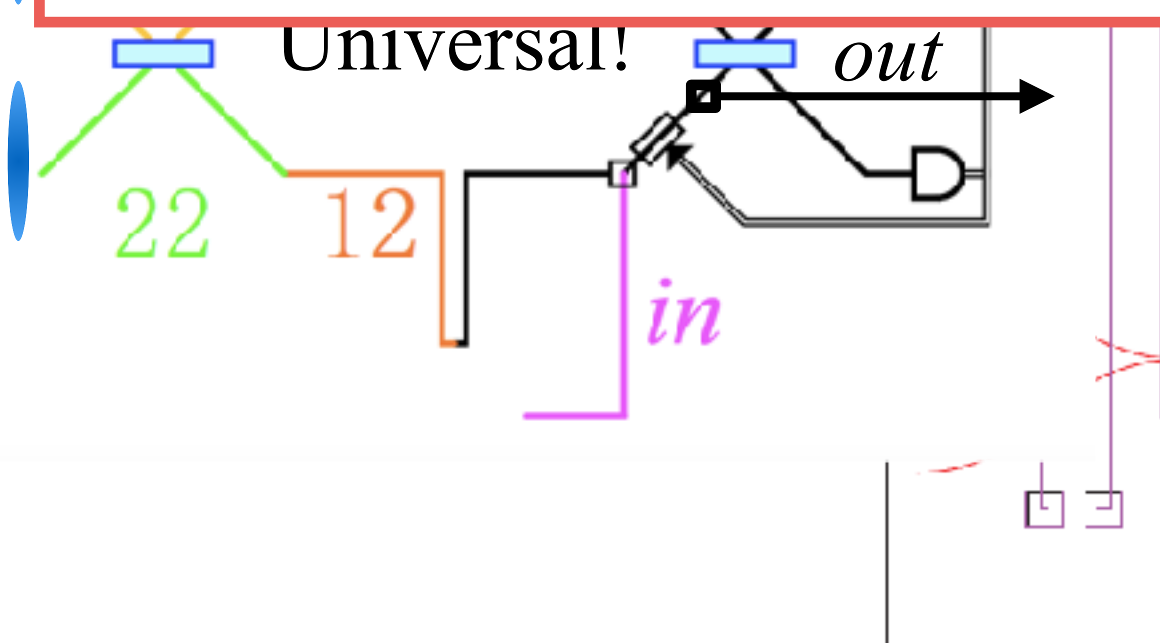
P. van Loock (Mainz), R. Filip (Palacky), P. Marek (Palacky),
J. L. O'Brien (Bristol), A. Politi (Southampton),
E. H. Huntington (ANU), T. Ralph (UQ), H. Wiseman (GU),
N. Menicucci (Sydney), R. Alexander (New Mexico),
H. Yonezawa (ADFA), S. Yokoyama (ADFA),
T. Hashimoto (NTT), T. Kashiwazaki (NTT), T.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

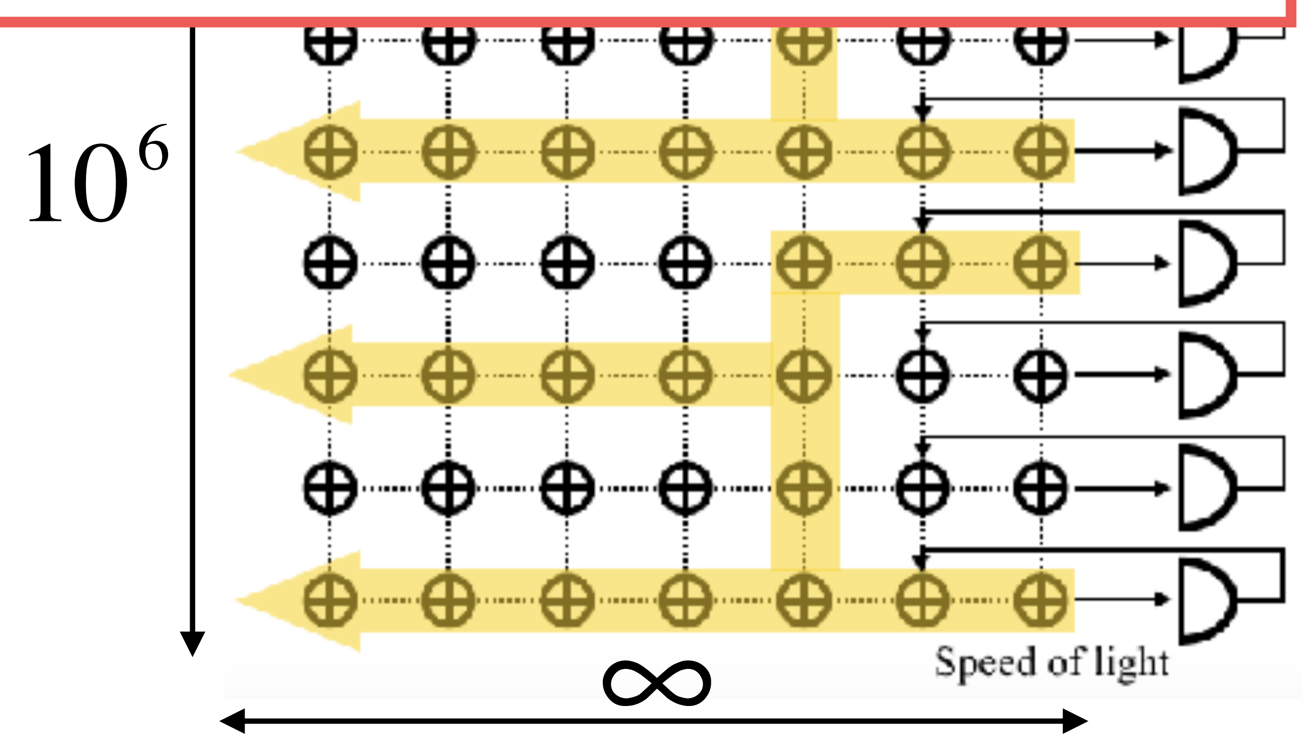


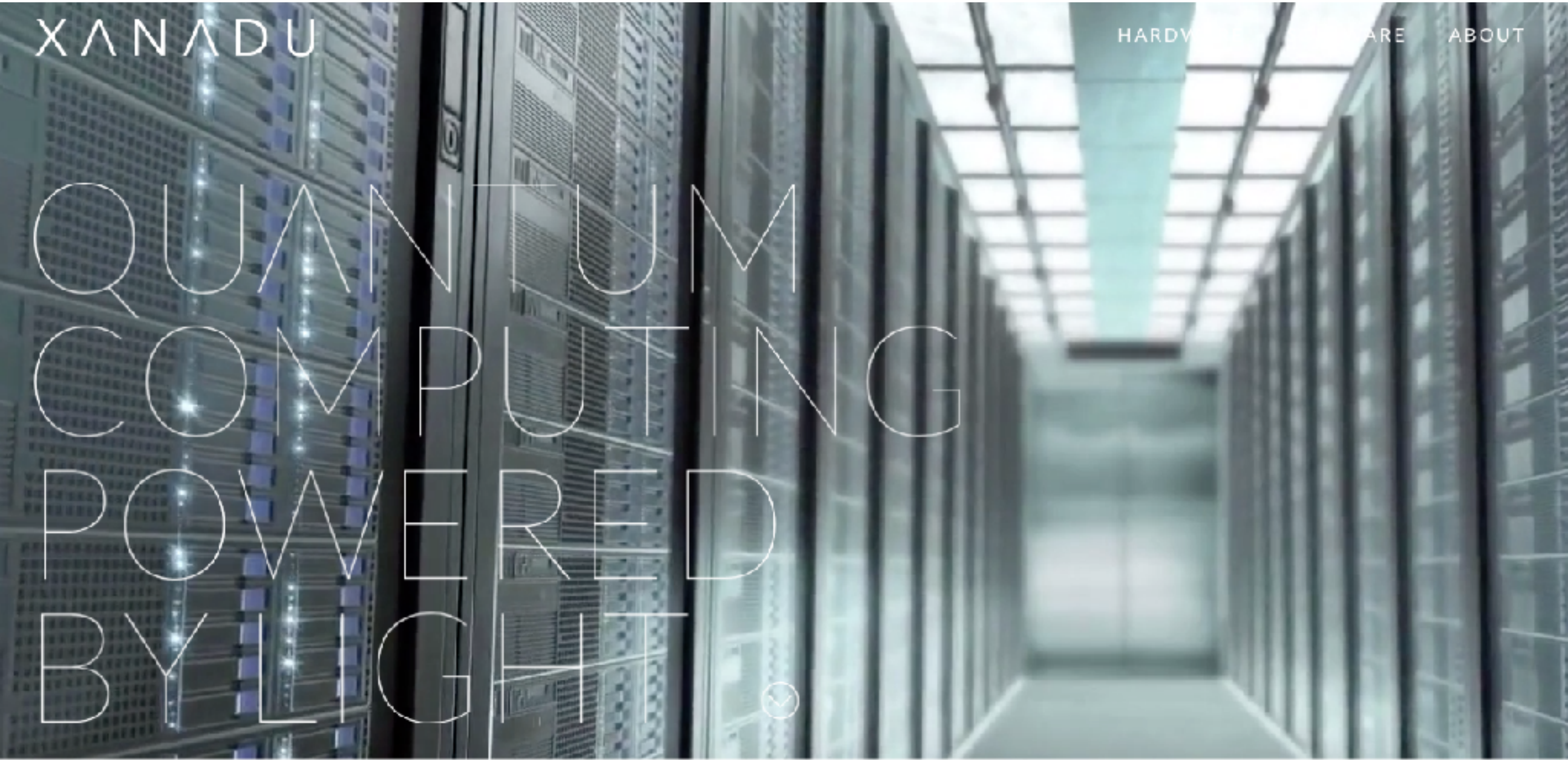




Large-scale quantum computing with quantum teleportation

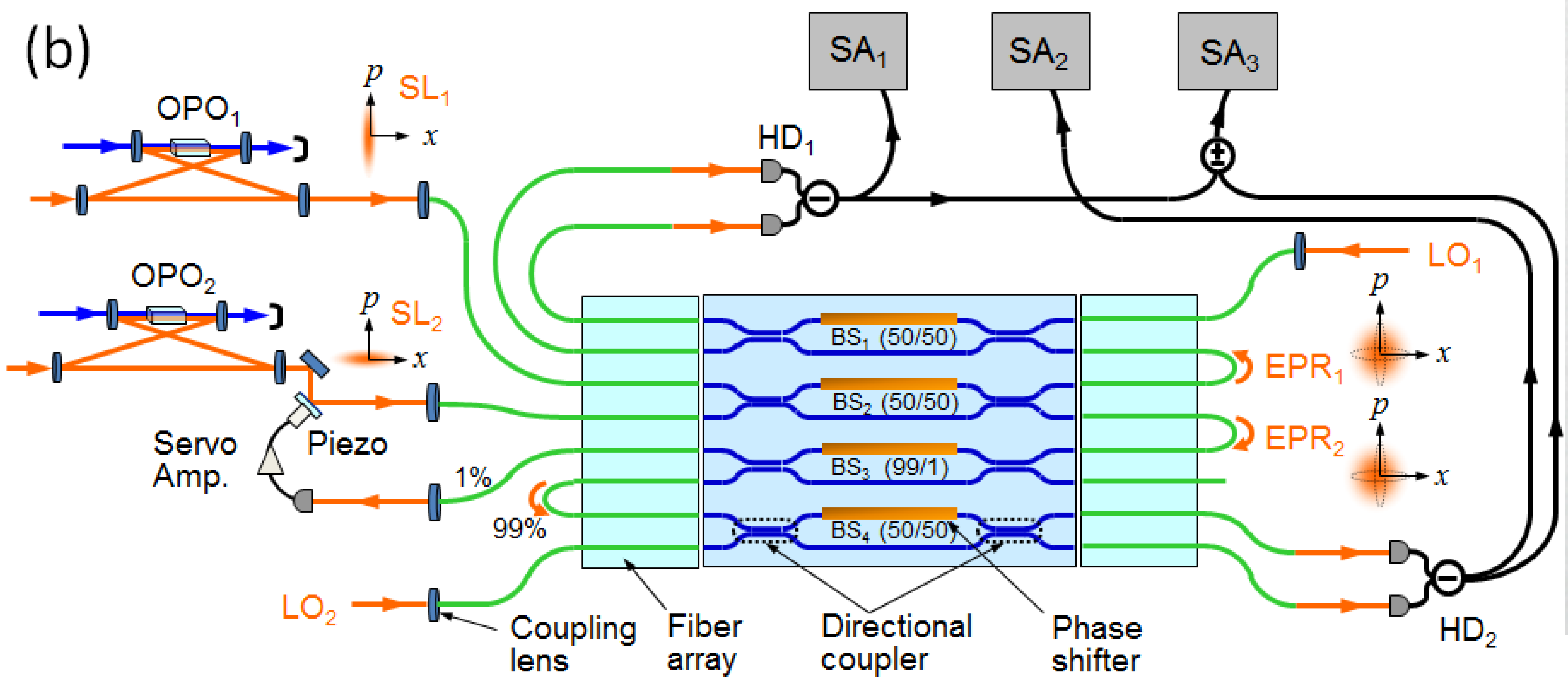


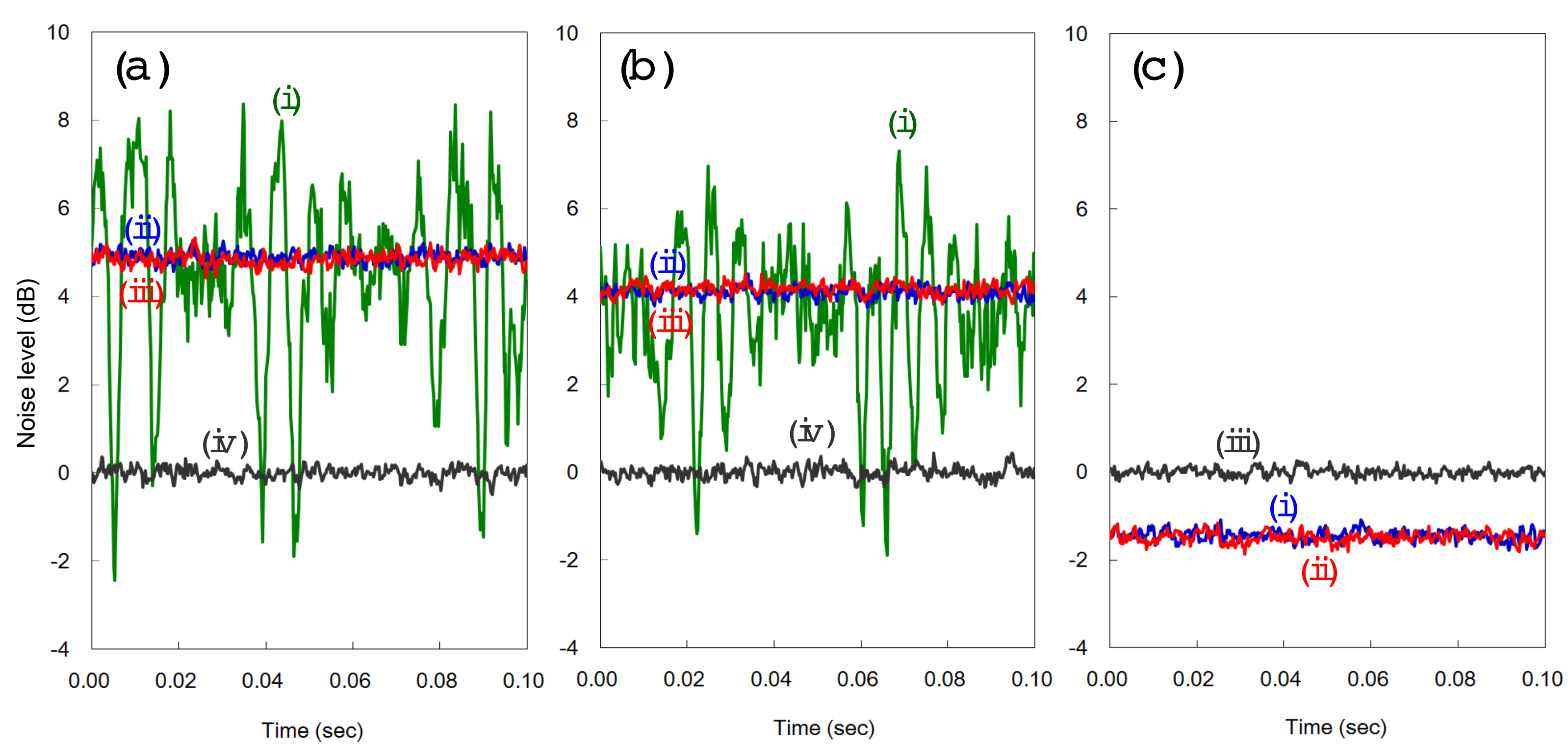




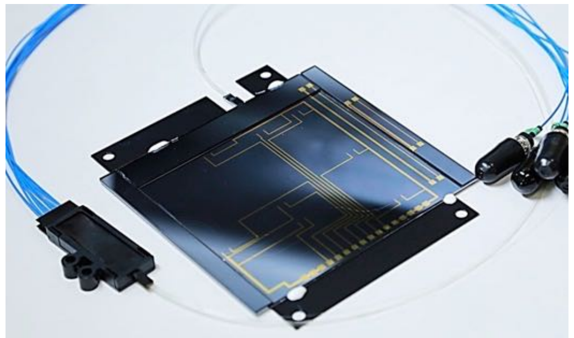
Xanadu (Toronto) is working on our scheme of quantum computing.

Continuous-variable entanglement on a chip



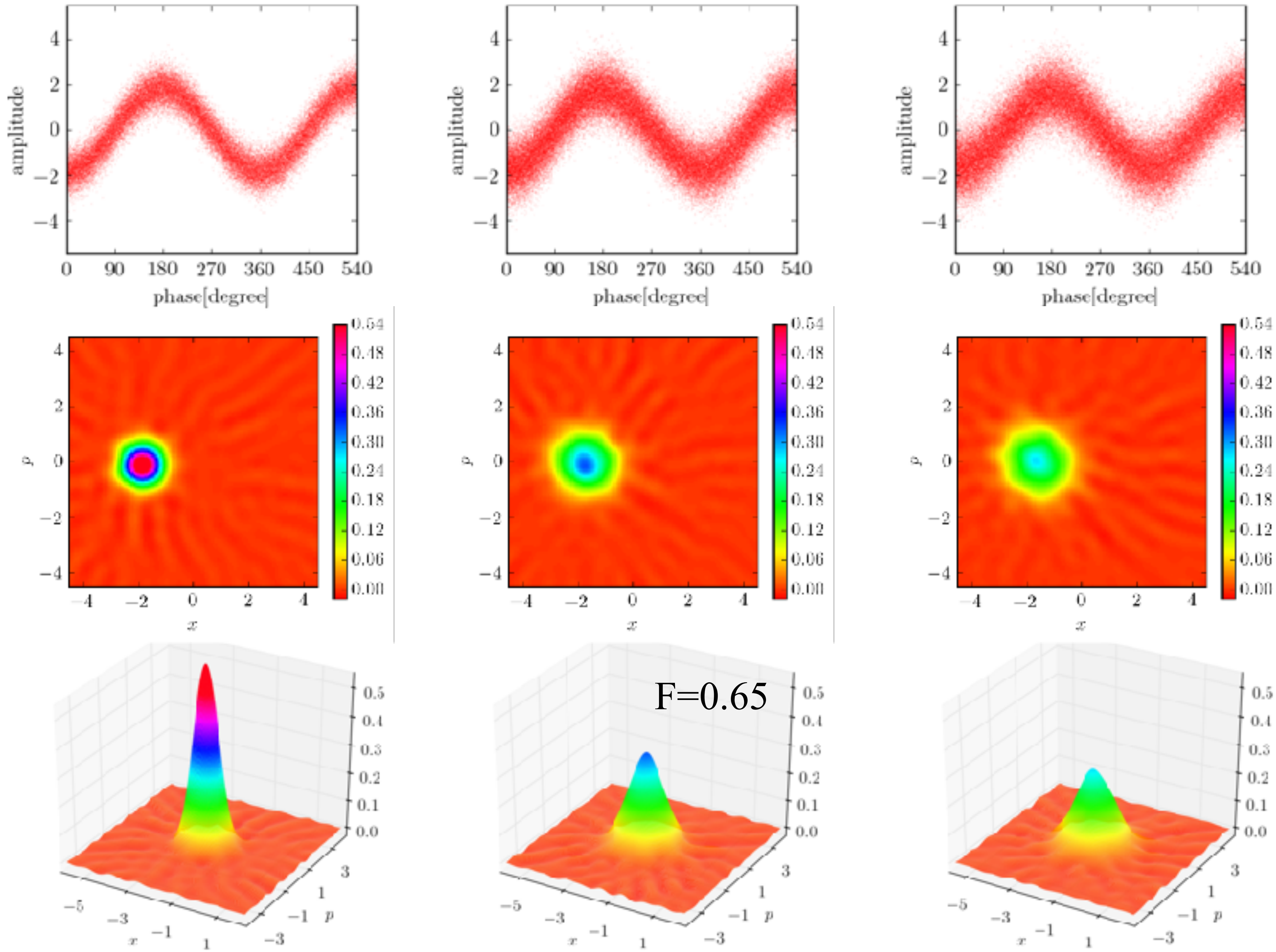


G. Masada, K. Miyata, A. Politi, T. Hashimoto, J. L. O'Brien and A. Furusawa, Nature Photonics 9, 316 (2015).



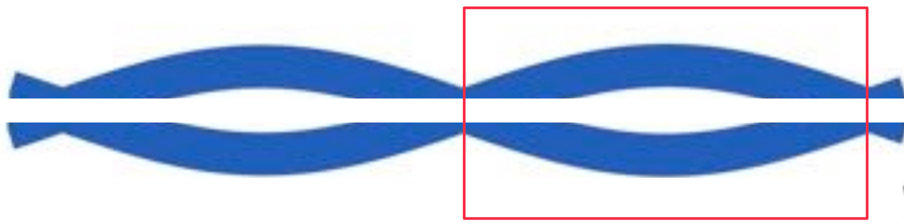
Quantum teleportation on a chip

Input | Quantum teleportation | Classical teleportation

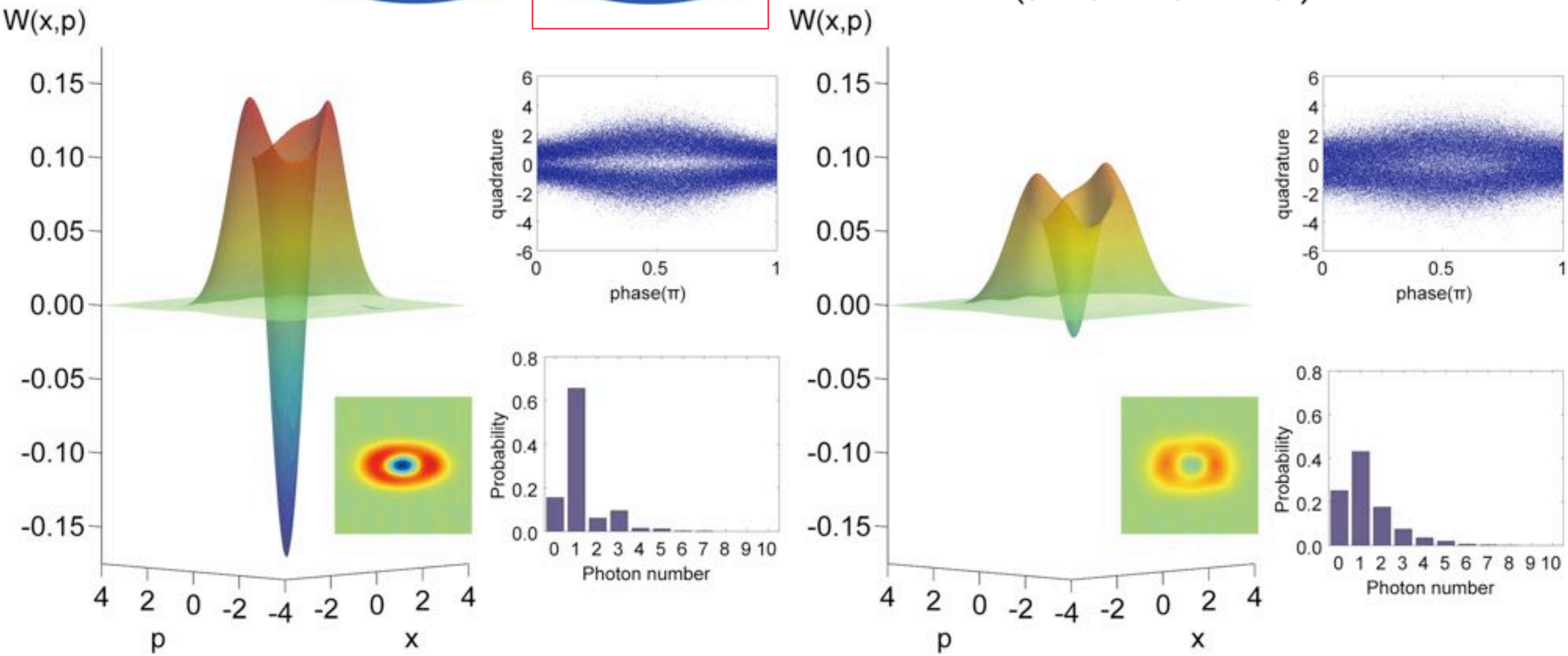


T. Serikawa et al., Annual meeting of physical society of Japan (2016) and CEWQO2017.

Teleportation of a Schrödinger cat state of light



$$N_\alpha\left(|\alpha\rangle - |-\alpha\rangle\right)$$



Input

Output

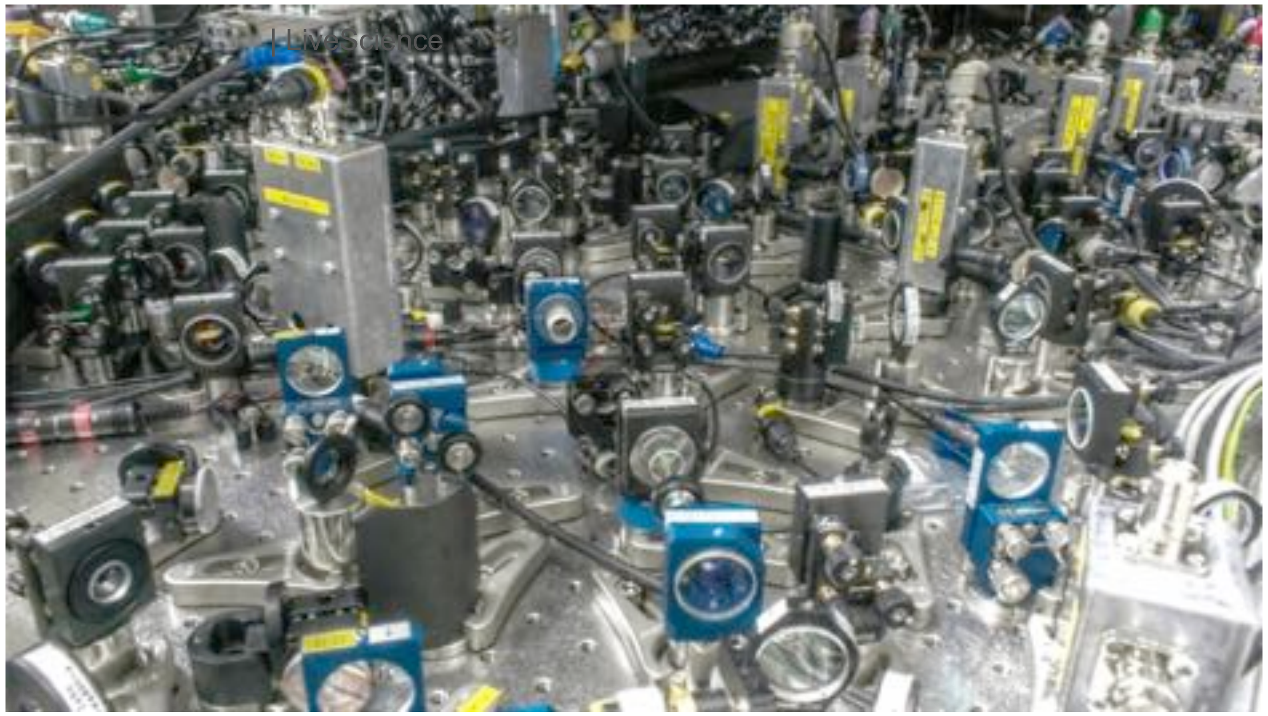
N. Lee, H. Benichi, Y. Takeno, S. Takeda, J. Webb, E. Huntington, & A. Furusawa, Science 332, 330 (2011)

FOX NEWS .com Fair & Balanced

SCIENCE

Quantum Leap: Scientists Teleport Bits of Light

By Clara Moskowitz
Published April 14, 2011



ВЕСТИ

16.05.2011 20:50

Ученые из Японии телепортировали запутанный квант

Автор: Сергей Мингажев

ABC News

Scientists teleport Schrodinger's cat

By Carl Holm for ABC Science Online

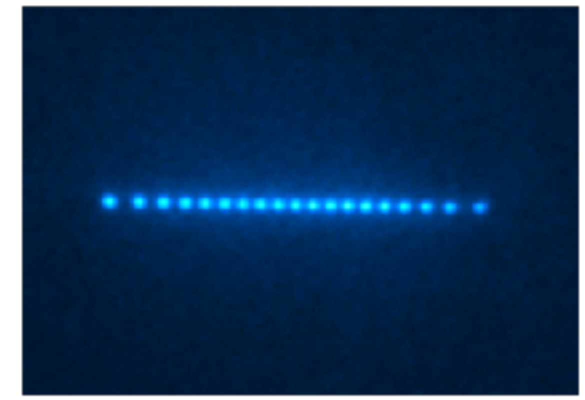
Updated Fri Apr 15, 2011 12:13pm AEST

N. Lee, H. Benichi, Y. Takeno, S. Takeda, J. Webb, E. Huntington, & A. Furusawa, Science 332, 330 (2011)

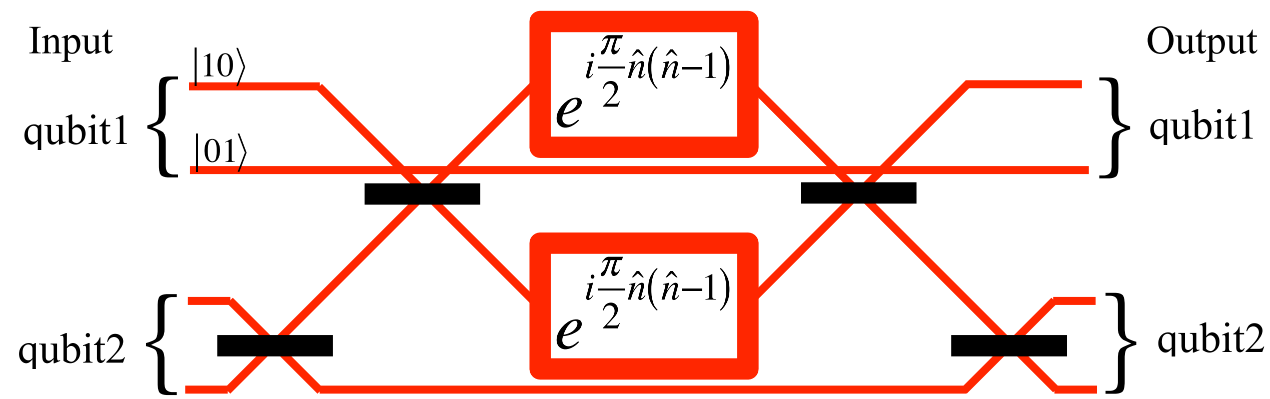
Encoding of quantum information

Qubit: "digital" encoding ("digital computing") $\{|0\rangle, |1\rangle\}$ **High fidelity**

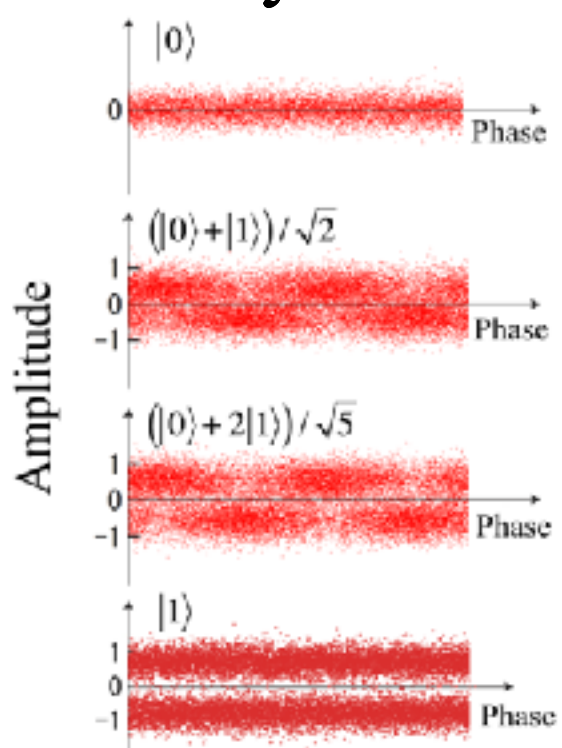
"Stationary" qubit: spin, ion, atom,
artificial atom (superconducting qubit)…



"Flying" qubit: photon



"Hybrid"



Conti… V): "analog" encoding ("analog computing") $\{|x\rangle\}$

…lex amplitude (amplitude and phase)
…cs, superconducting circuit

Physical qubit and Logical qubit for quantum error correction

Physical qubit: Photon, Spin, Atom, Artificial atom …

$$c_0|0\rangle + c_1|1\rangle = c_0|\leftrightarrow\rangle + c_1|\updownarrow\rangle,\ c_0|\uparrow\rangle + c_1|\downarrow\rangle,\ c_0|\mathrm{g}\rangle + c_1|\mathrm{e}\rangle$$

Logical qubit for quantum error correction: ex. nine-qubit code

$$c_0|0_\mathrm{L}\rangle + c_1|1_\mathrm{L}\rangle = c_0 \frac{|000\rangle + |111\rangle}{\sqrt{2}} \otimes \frac{|000\rangle + |111\rangle}{\sqrt{2}} \otimes \frac{|000\rangle + |111\rangle}{\sqrt{2}}$$
$$+ c_1 \frac{|000\rangle - |111\rangle}{\sqrt{2}} \otimes \frac{|000\rangle - |111\rangle}{\sqrt{2}} \otimes \frac{|000\rangle - |111\rangle}{\sqrt{2}}$$

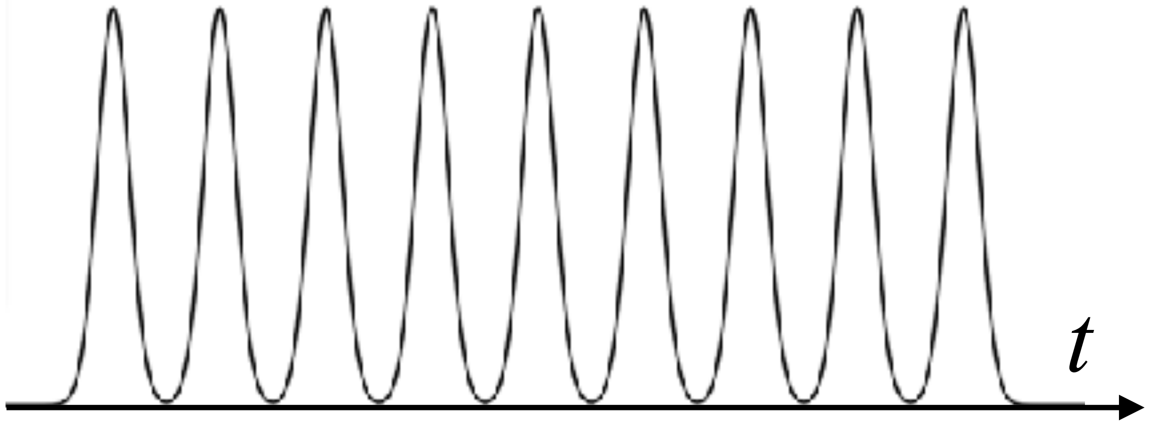
One logical qubit for quantum error correction = nine physical qubits

We need many physical qubits!!

We need many physical qubits!!

Photon is the best qubit!

Perfect uniformity
No crosstalk
Survive in room temperature
Time-domain multiplexing (flying qubit)
=> Logical qubit for quantum error correction
ex. nine-qubit code

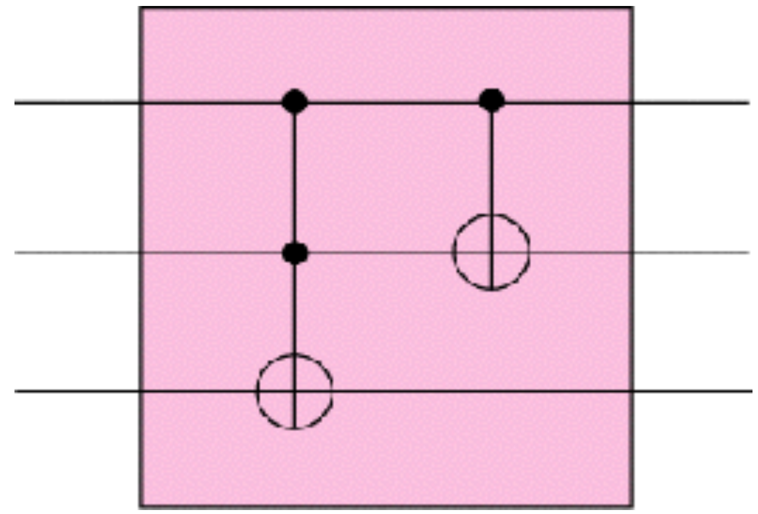


Nine wave-packets in one optical beam

Each wave-packet can be a logical qubit!

Quantum computing

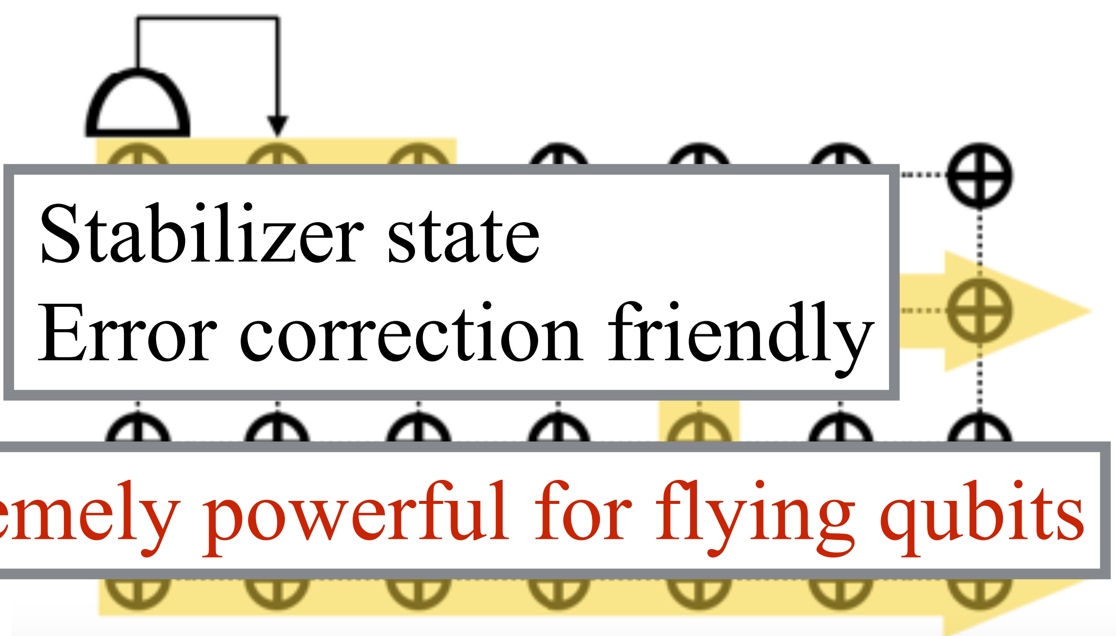
Quantum circuit model



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 teleportati

Stabilizer state
Error correction friendly

Extremely powerful for flying qubits

Changing measurement bases = changing operation

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

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

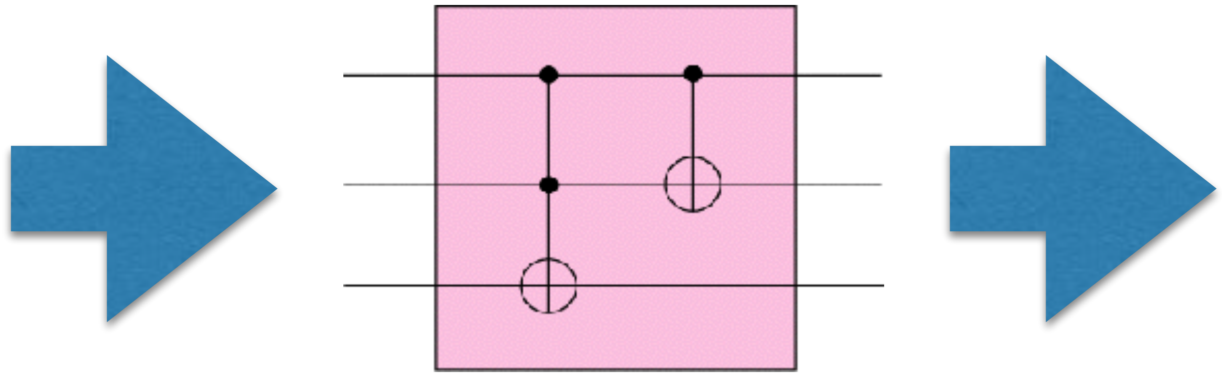
Continuous variable
N. C. Menicucci and P. van Loock et al. (2006)

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

Quantum computing with flying qubits (photons)

Quantum circuit model

flying qubits
photons

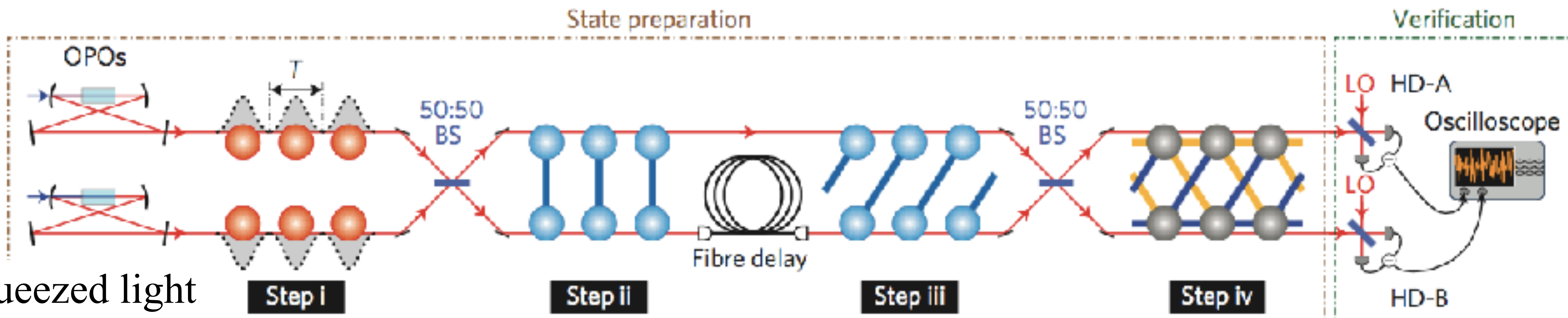


Large-scale quantum computing = large-scale optical setup
No flexibility of the setup (only one type of computing)

Measurement-based model

Ultra-large-scale CV cluster state!!

One-way quantum computing with time-domain multiplexing

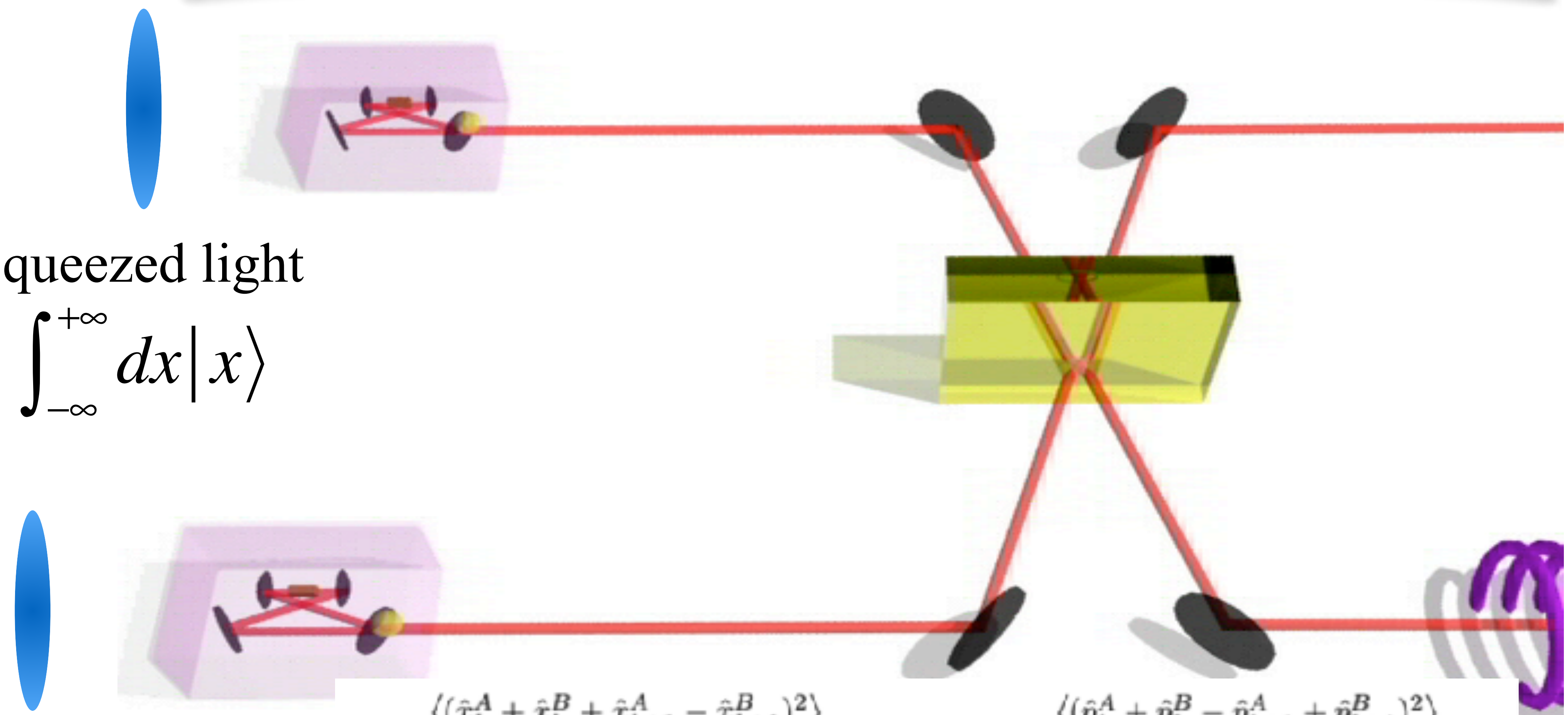


Squeezed light

10000-wave-packet CV cluster state (2013), one million (unlimited) (2016)

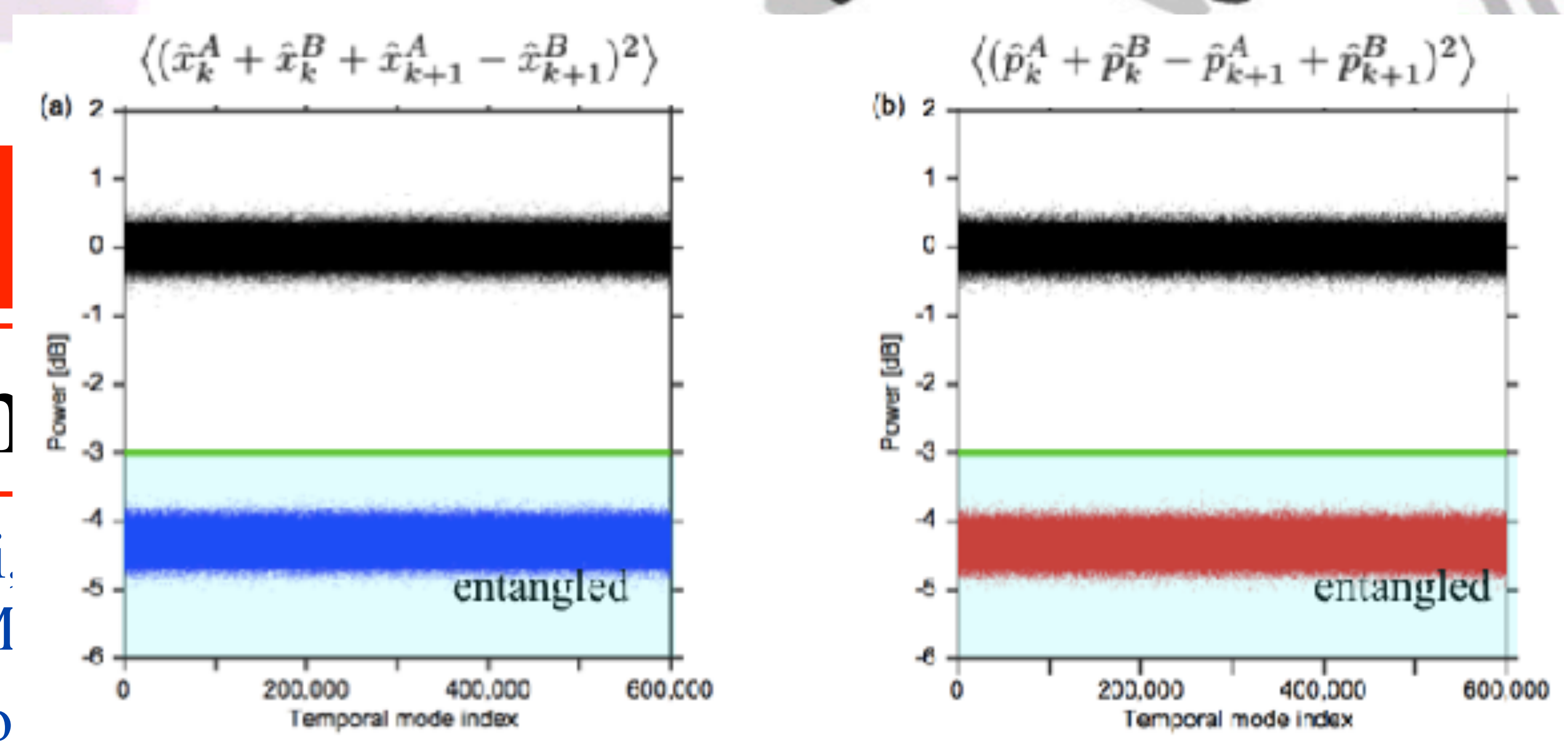
S. Yokoyama et al., Nature Photonics 7, 982 (2013).
J. Yoshikawa et al., APL Photonics 1, 060801 (2016).

Ultra-large-scale CV cluster state



Squeezed light

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



Unlimited ... nology

One-m ... nt!!

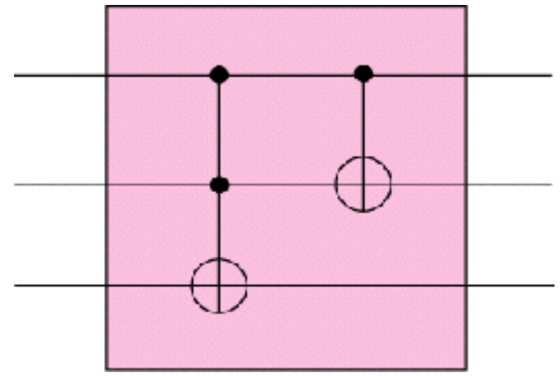
S. Yokoyama, R. Ukai ... Yoshikawa,
H. Yonezawa, N. C. M

J. Yoshikawa, S. Yoko ... , and A. Furusawa,
APL Photonics 1, 060801 (2016).

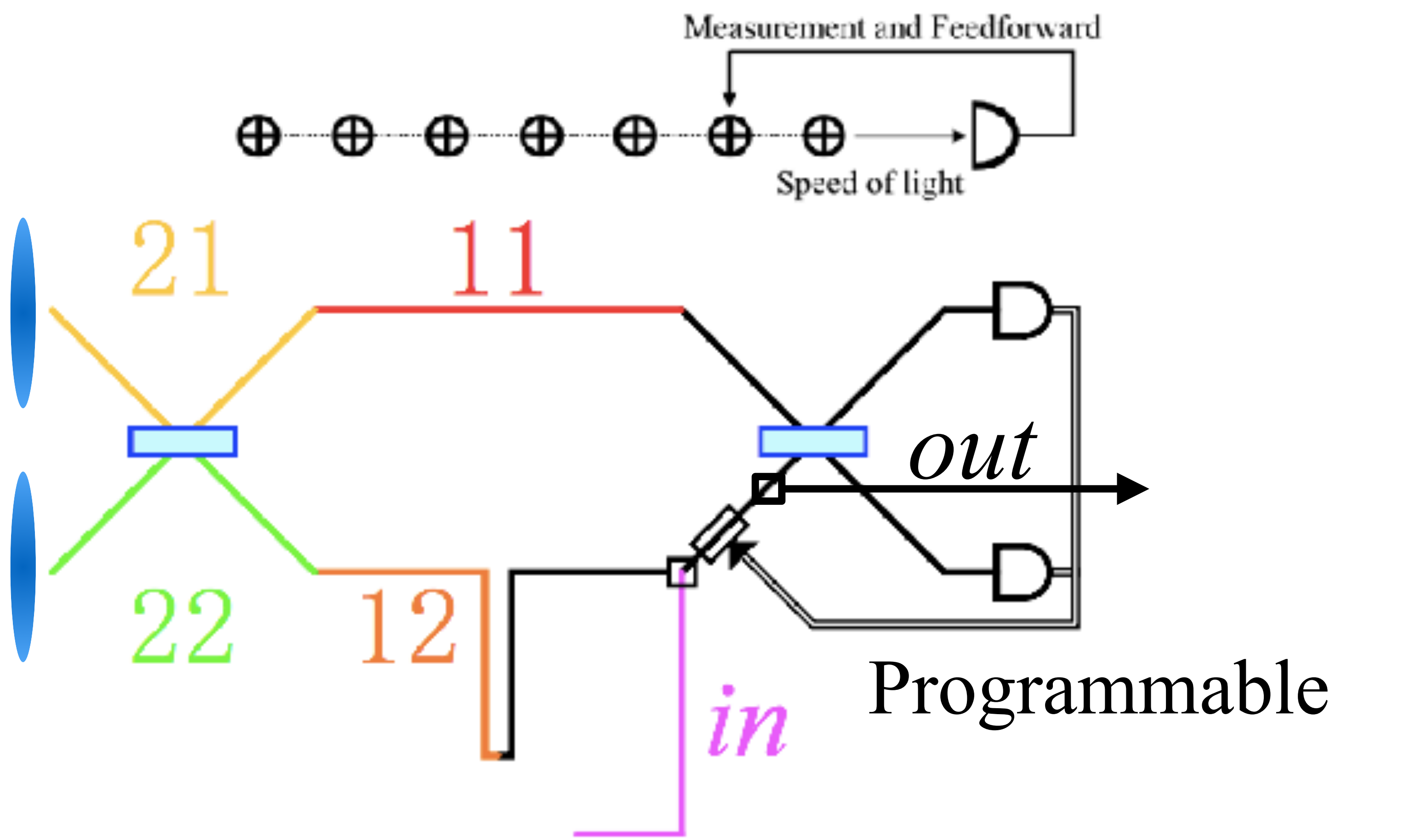
Quantum information processing with flying qubits (photons)

Quantum circuit model

flying qubits
photons

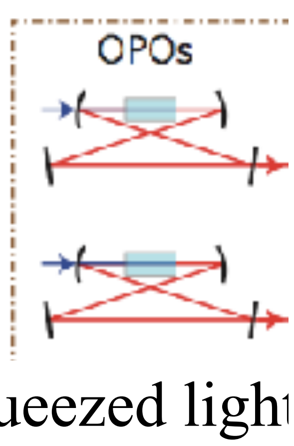


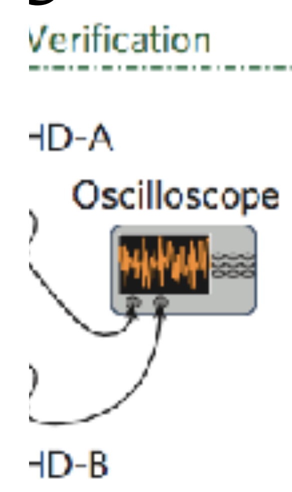
setup
g)



Measu
One-w

r state!!
g





1000
) (2016)

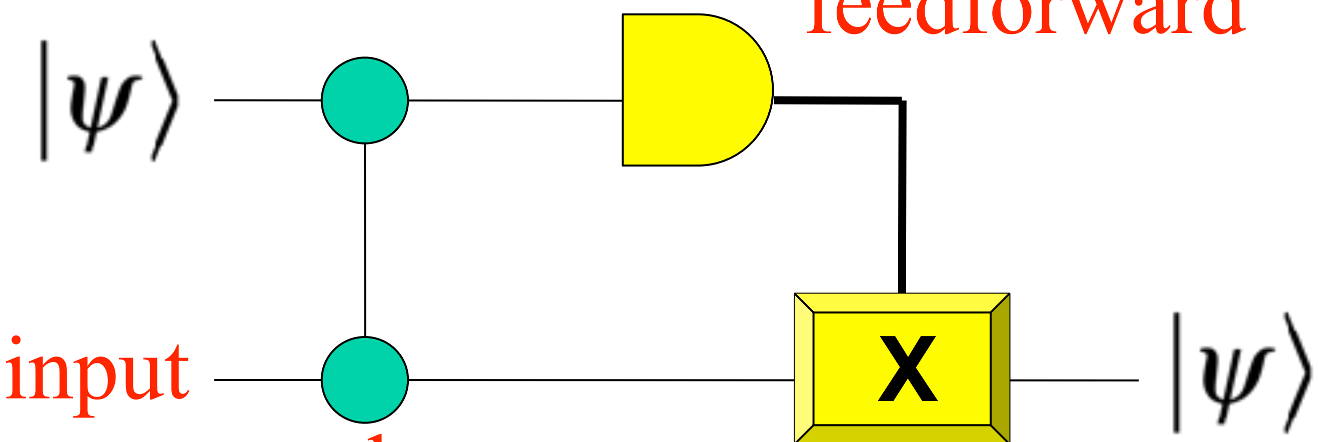
Large-scale quantum computing = fixed-size of the setup
Programmable

One-way quantum computing = sequential teleportation

Essence of quantum teleportation

qubit and CV

measurement and feedforward



Ancillary input

entanglement

CPhase gate

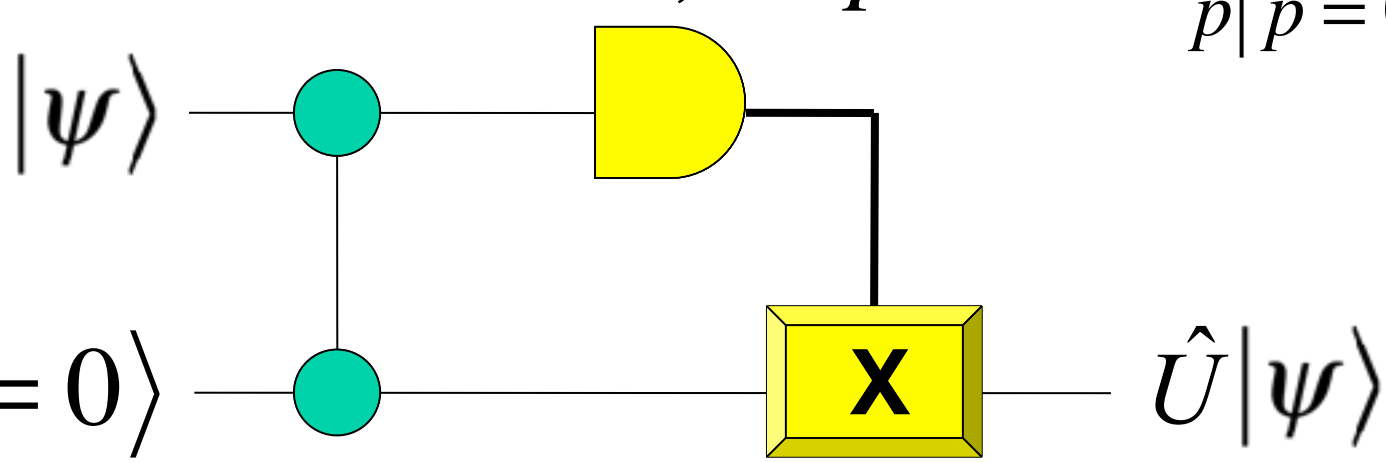
One-way quantum computing

qubit CV

$$\hat{U}^{\dagger}\hat{X}\hat{U},\ \hat{U}^{\dagger}\hat{p}\hat{U}$$

$$\hat{X}|+\rangle = |+\rangle$$

$$\hat{p}|p=0\rangle = 0$$



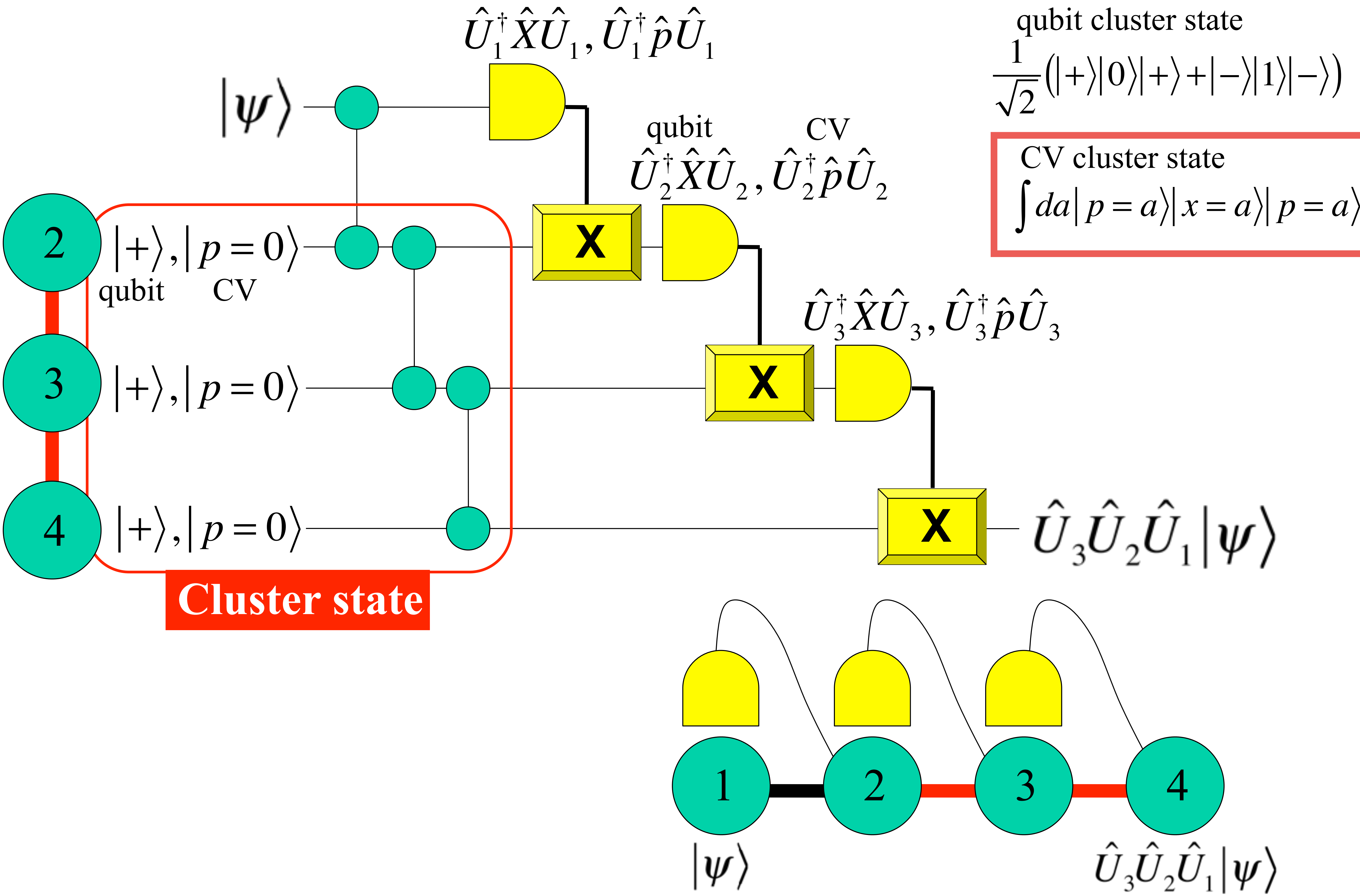
qubit CV

$$|+\rangle,\ |p=0\rangle$$

$$|+\rangle = (|0\rangle + |1\rangle)/\sqrt{2},\ |p=0\rangle = \int_{-\infty}^{+\infty} dx|x\rangle$$

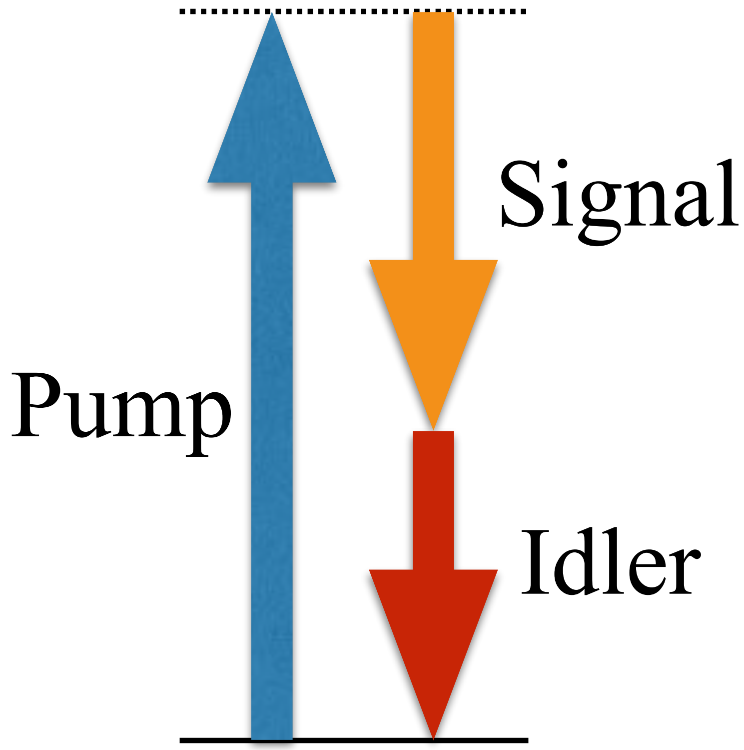
One-way quantum computing = sequential teleportation

One-way quantum computing with a cluster state



Deterministic creation of CV entanglement with squeezed states

Optical parametric process



Signal-idler entanglement

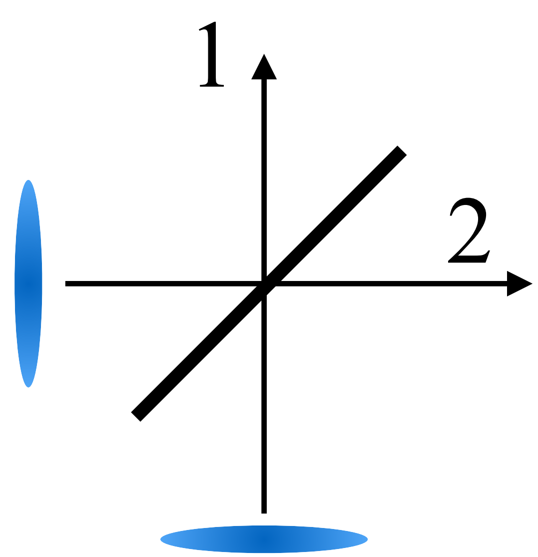
$$\sum_{n=0}^{\infty} (\tanh r)^n \, |n\rangle_{\text{signal}} |n\rangle_{\text{idler}}$$

$$\approx \int dx \, |x\rangle_{\text{signal}} |x\rangle_{\text{idler}} = \int dp \, |p\rangle_{\text{signal}} |-p\rangle_{\text{idler}}$$

Complex amplitude $a = x + ip$

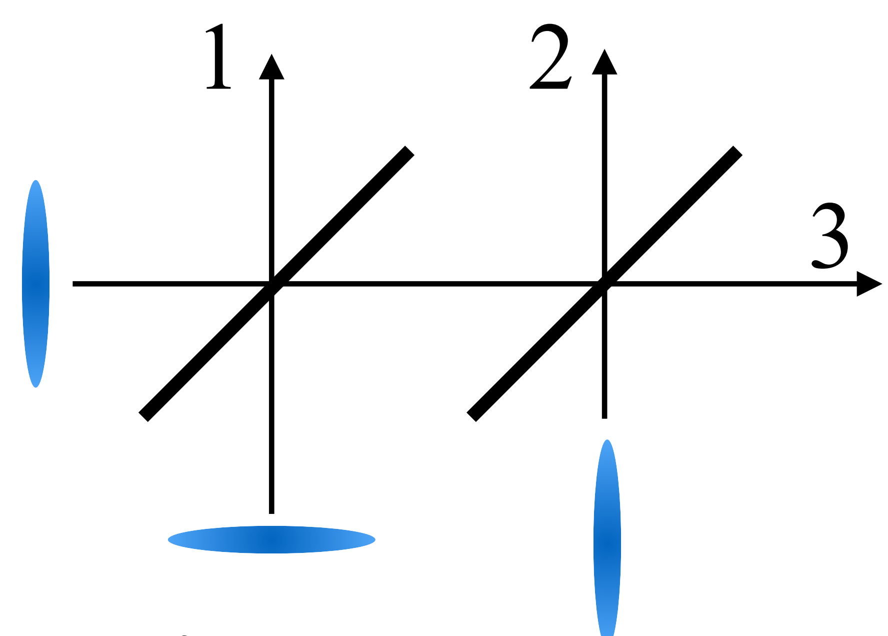
$\lambda_{\text{signal}} = \lambda_{\text{idler}}$

Squeezed state (squeezed vacuum)



$$\sum_{n=0}^{\infty} (\tanh r)^n \, |n\rangle_1 |n\rangle_2 \approx \int dx \, |x\rangle_1 |x\rangle_2$$

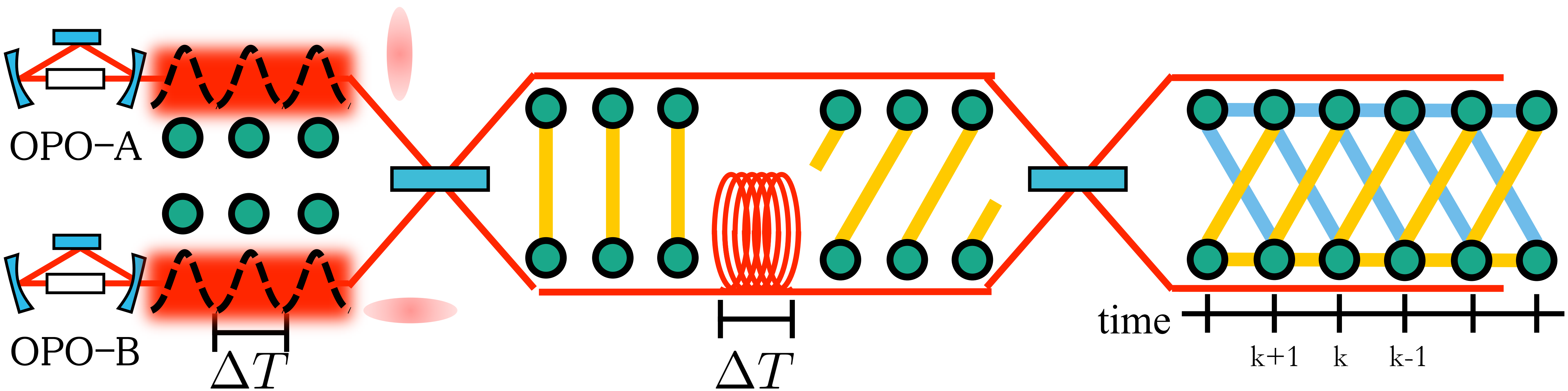
Einstein-Podolski-Rosen (EPR) state



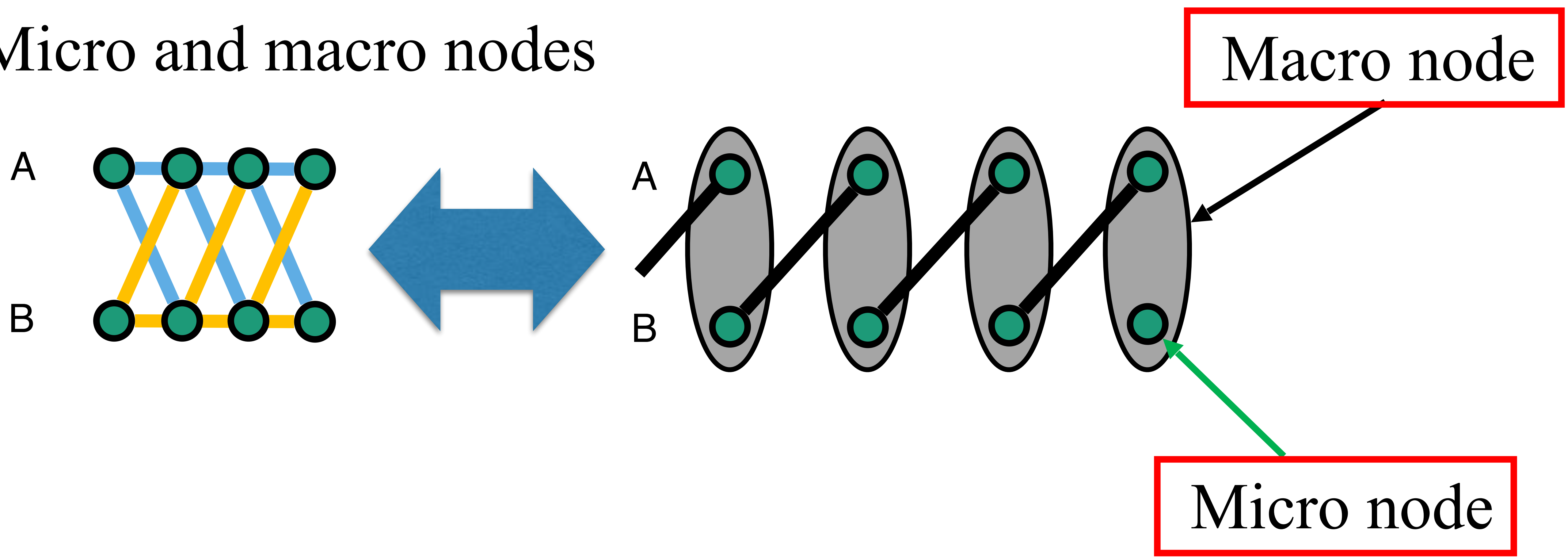
$$\approx \int da \, |p = a\rangle_1 |x = a\rangle_2 |p = a\rangle_3$$

3-mode cluster state

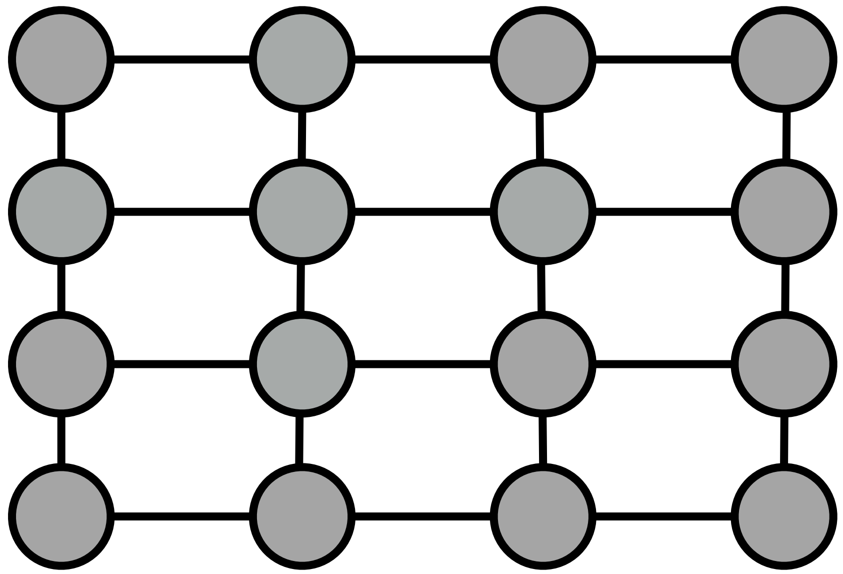
Linear CV cluster state

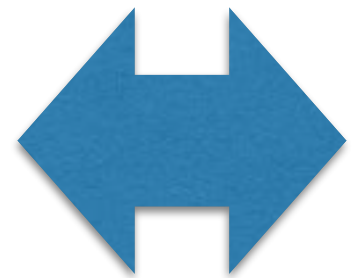


Micro and macro nodes



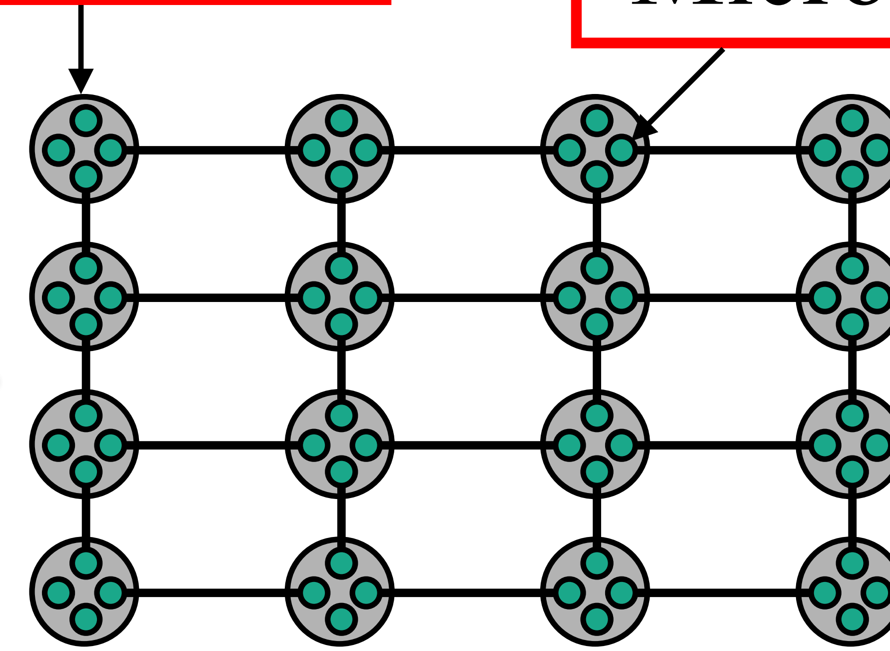
2D CV cluster state





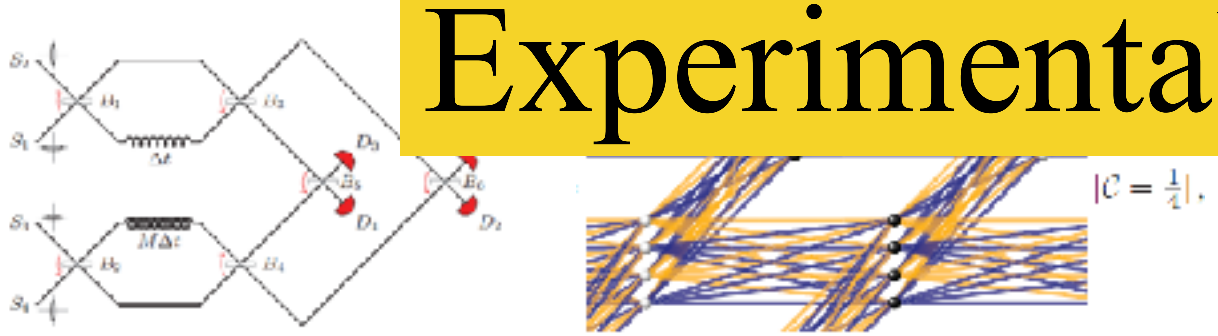
Macro node

Micro node

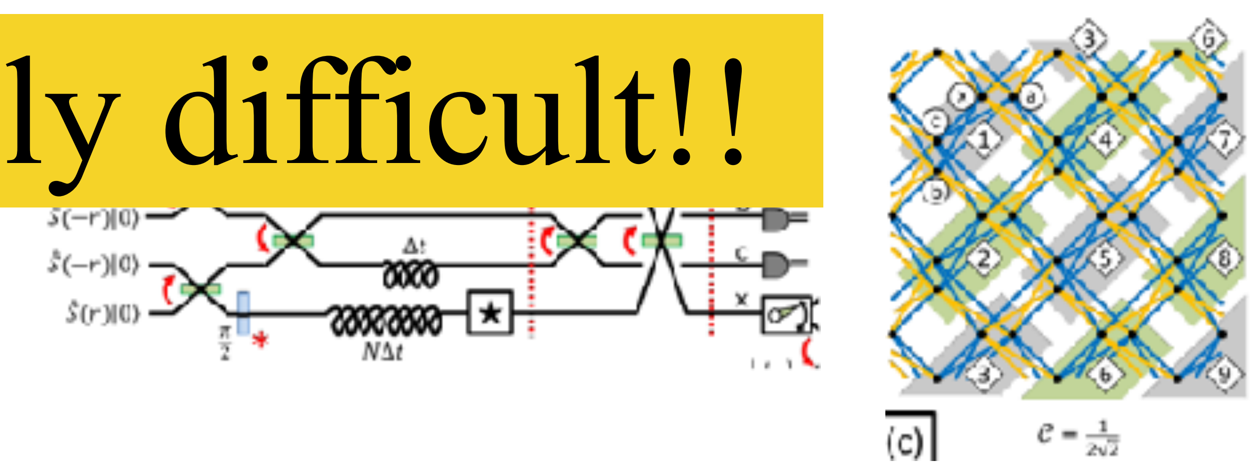


Quad-rail lattice

Bilayer square lattice



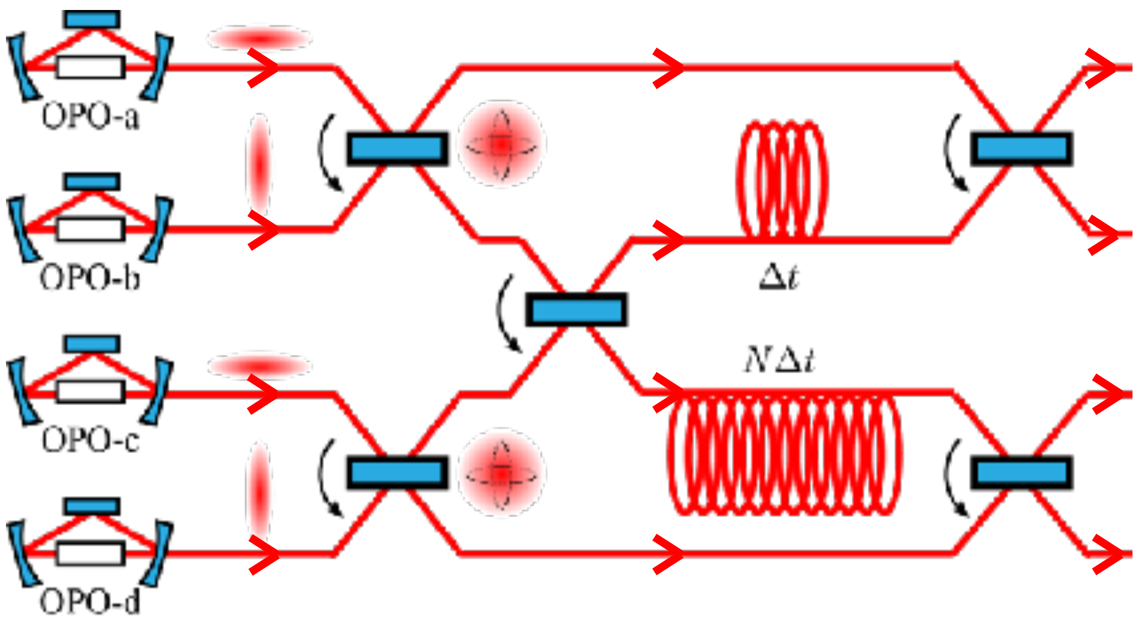
Experimentally difficult!!

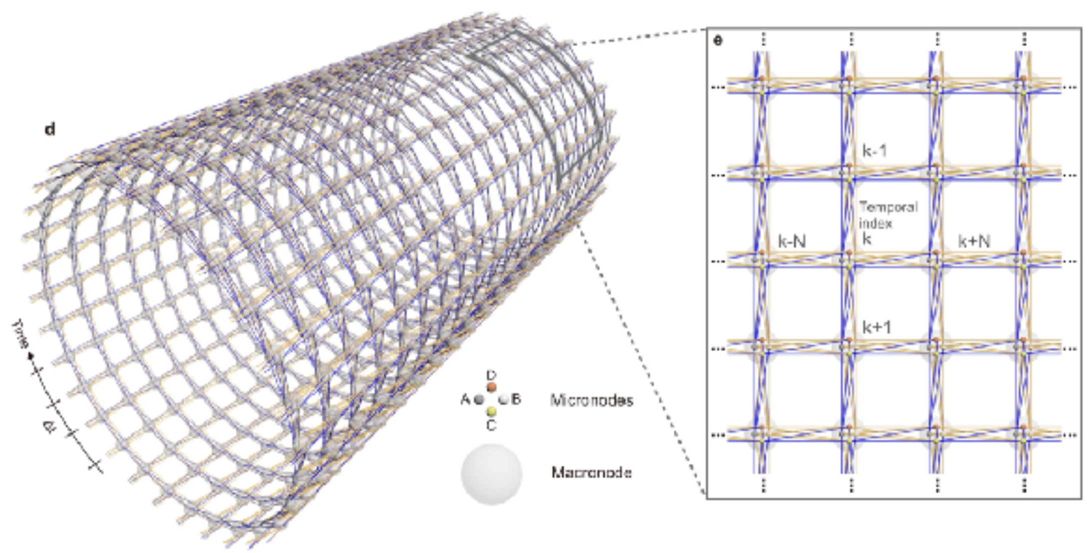


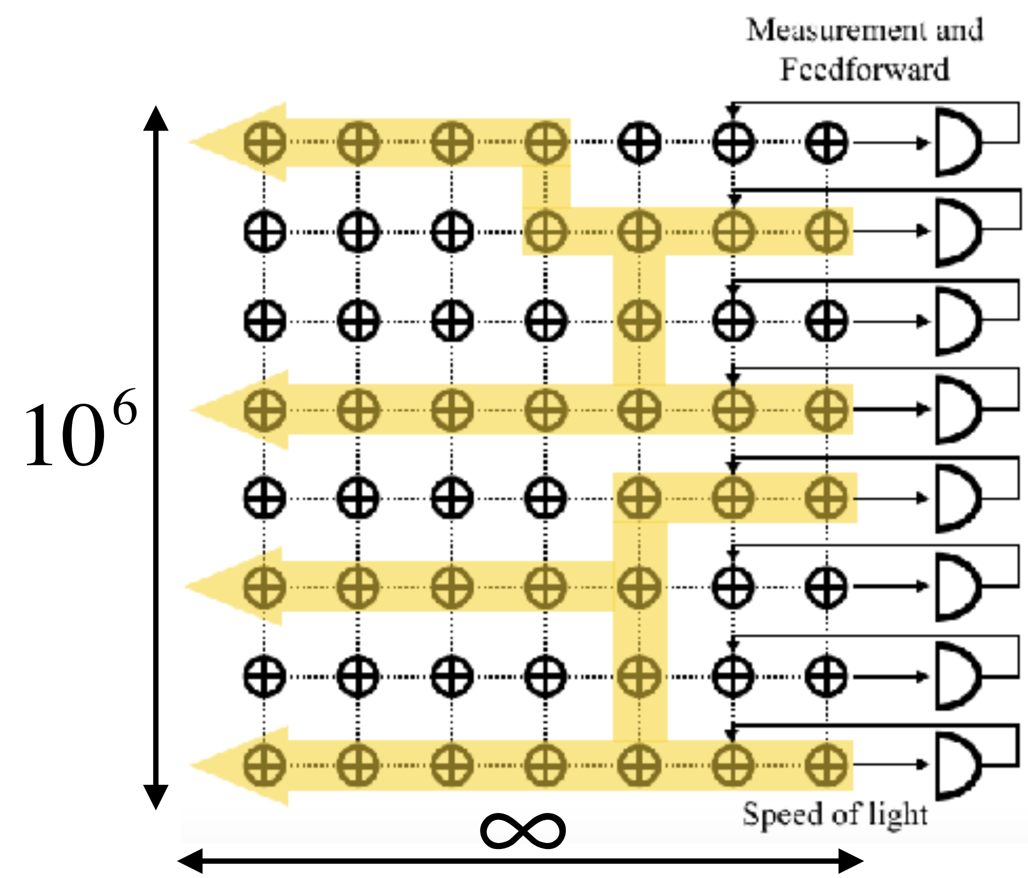
N. C. Menicucci, PRA 83, 062314 (2011).

R. Alexander et al., PRA 97, 032302 (2018).

Deterministic creation of 2D CV cluster state and unlimited one-way CV quantum computing

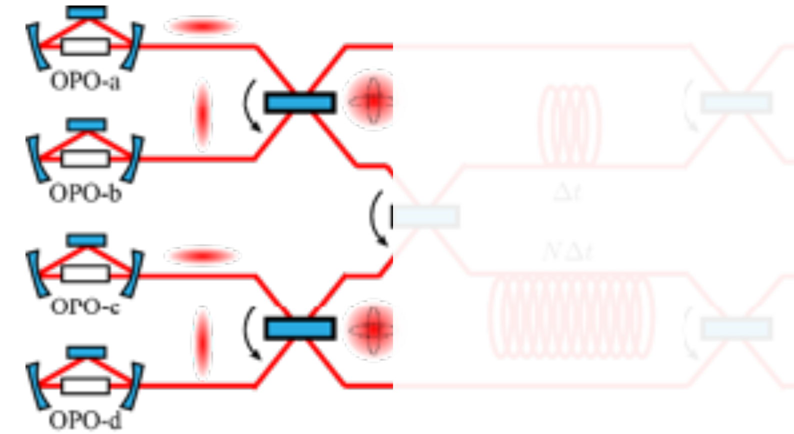




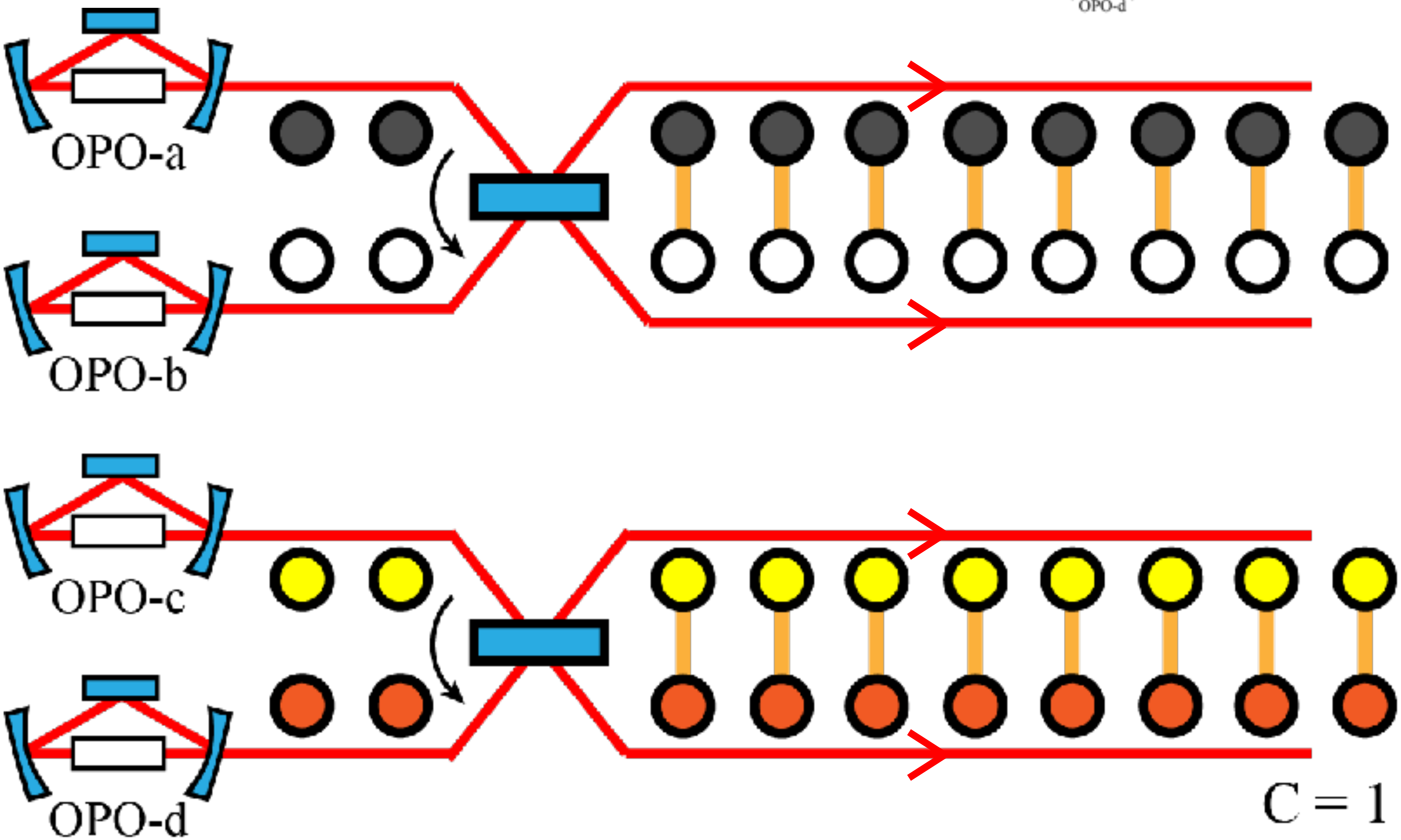


Any size of 2D continuous-variable cluster states can be created with four squeezed vacua, five beam splitters, and two optical delays!!

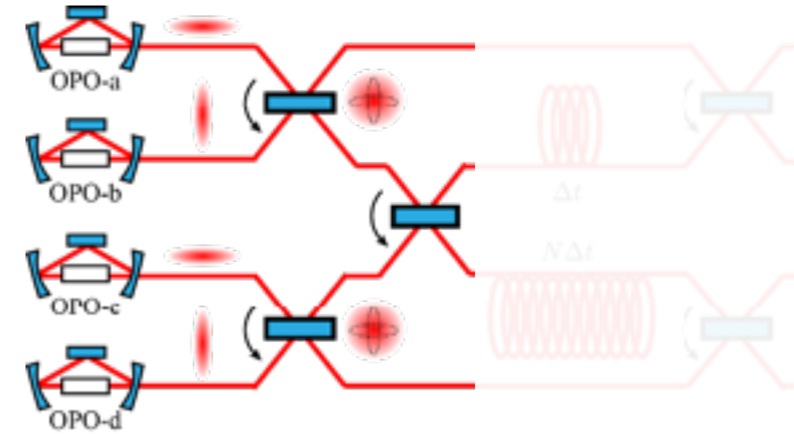
W. Asavanant, Master Thesis, Univ. Tokyo (2018)

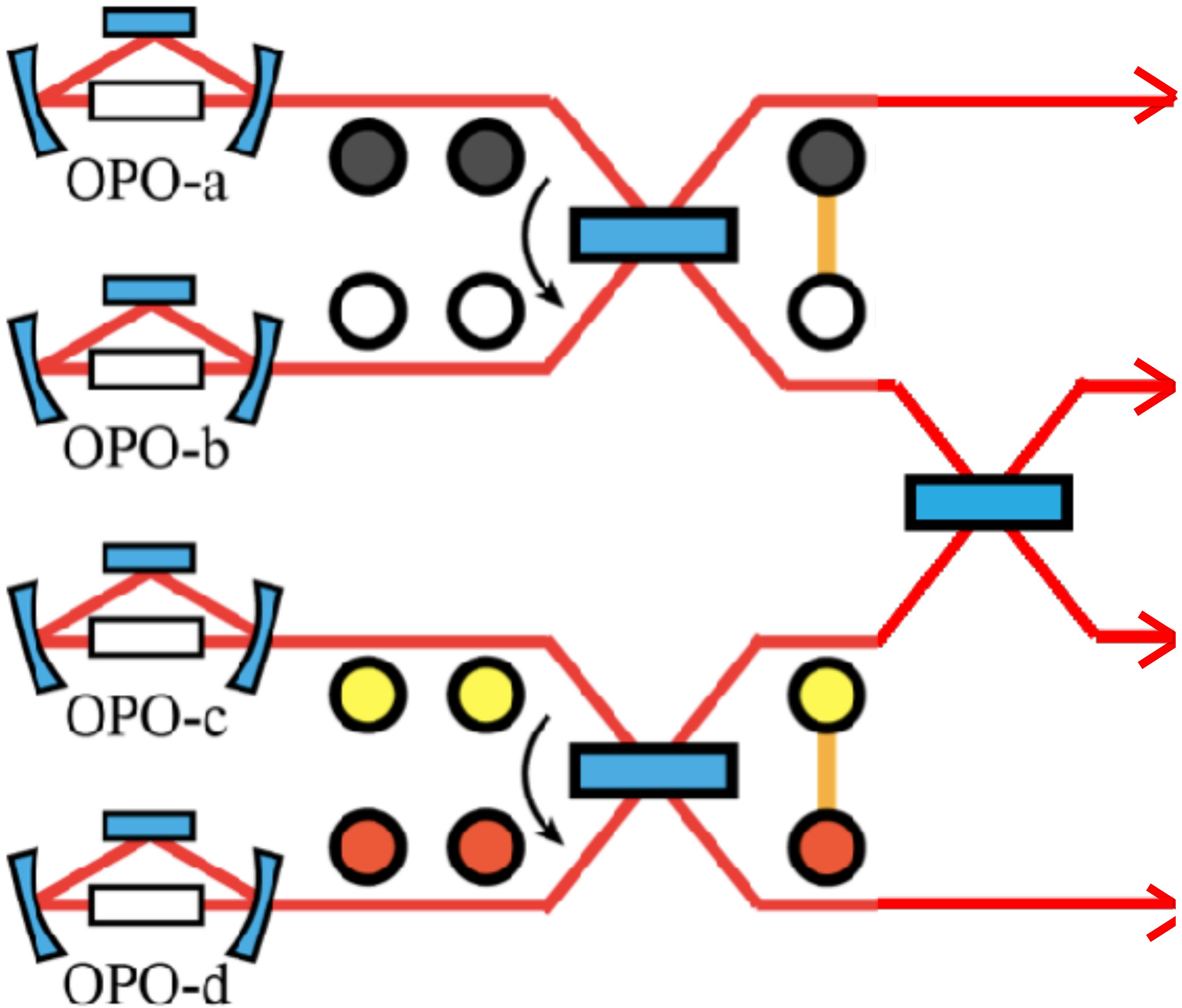


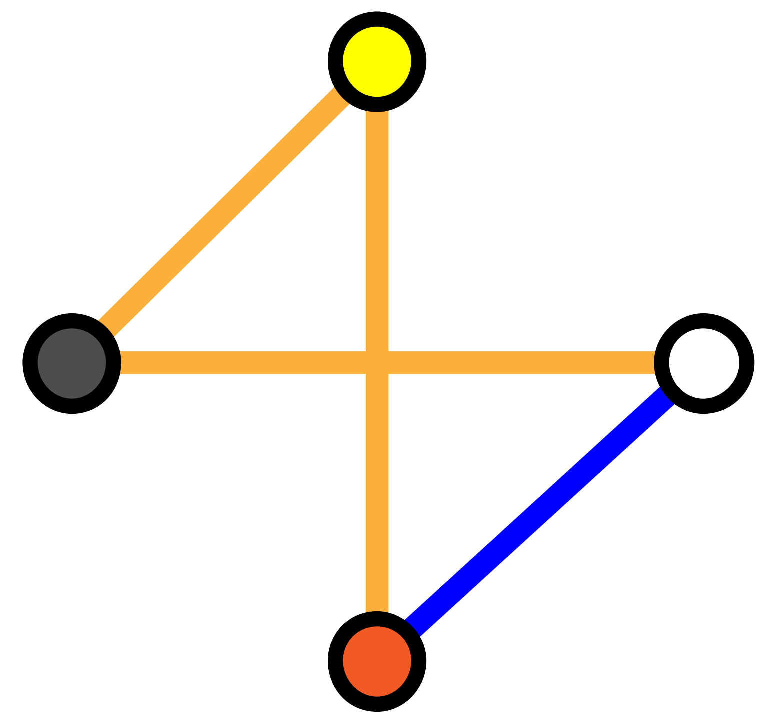
OPO-a
OPO-b
OPO-c
OPO-d



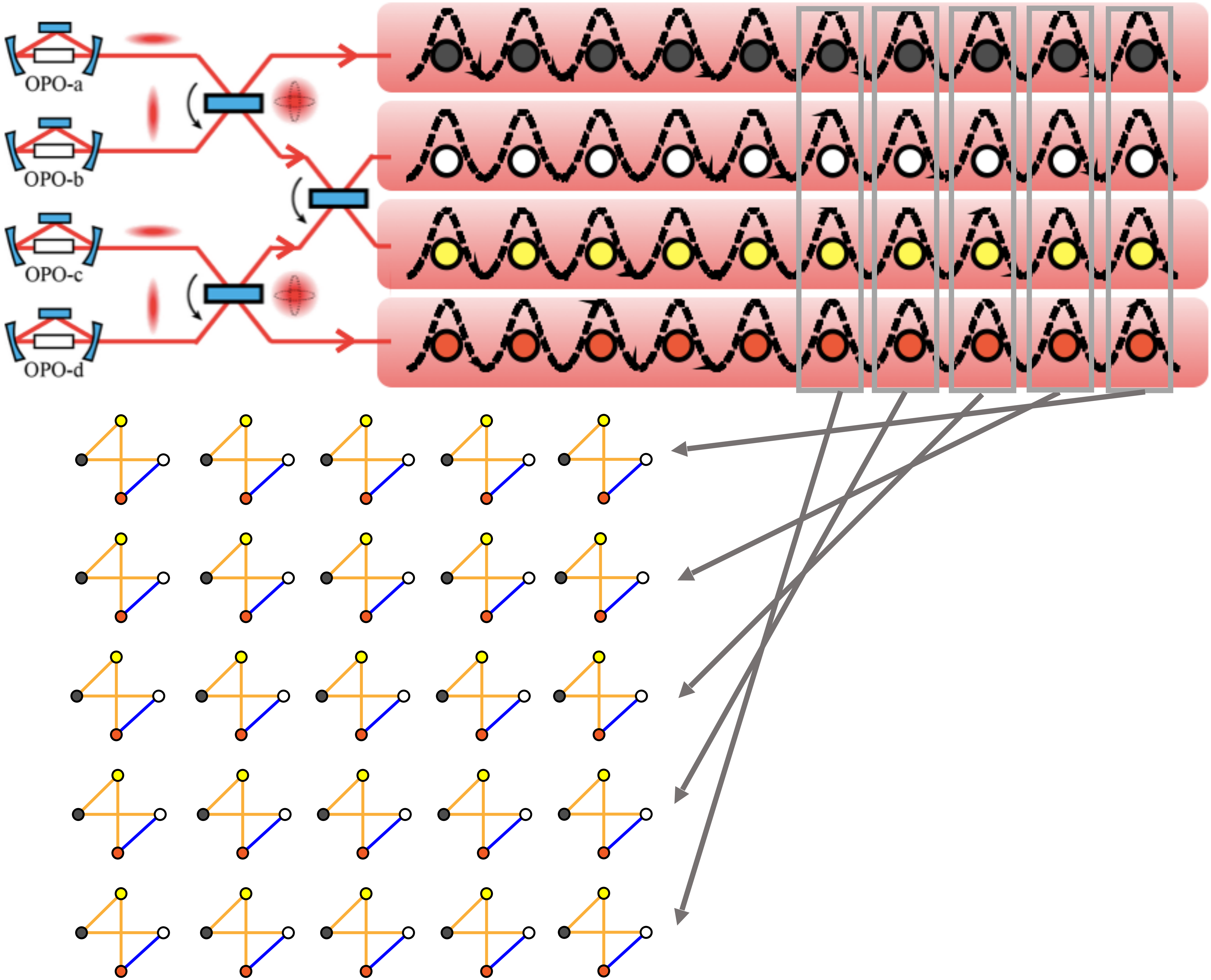
OPO-a
OPO-b
OPO-c
OPO-d
C = 1

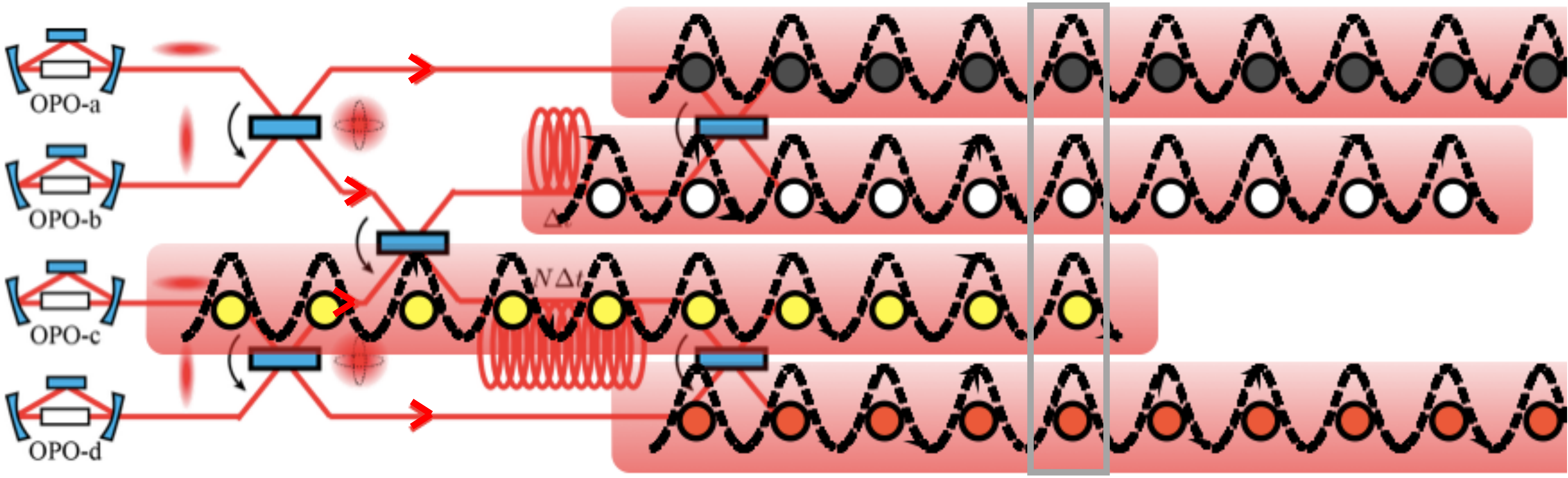


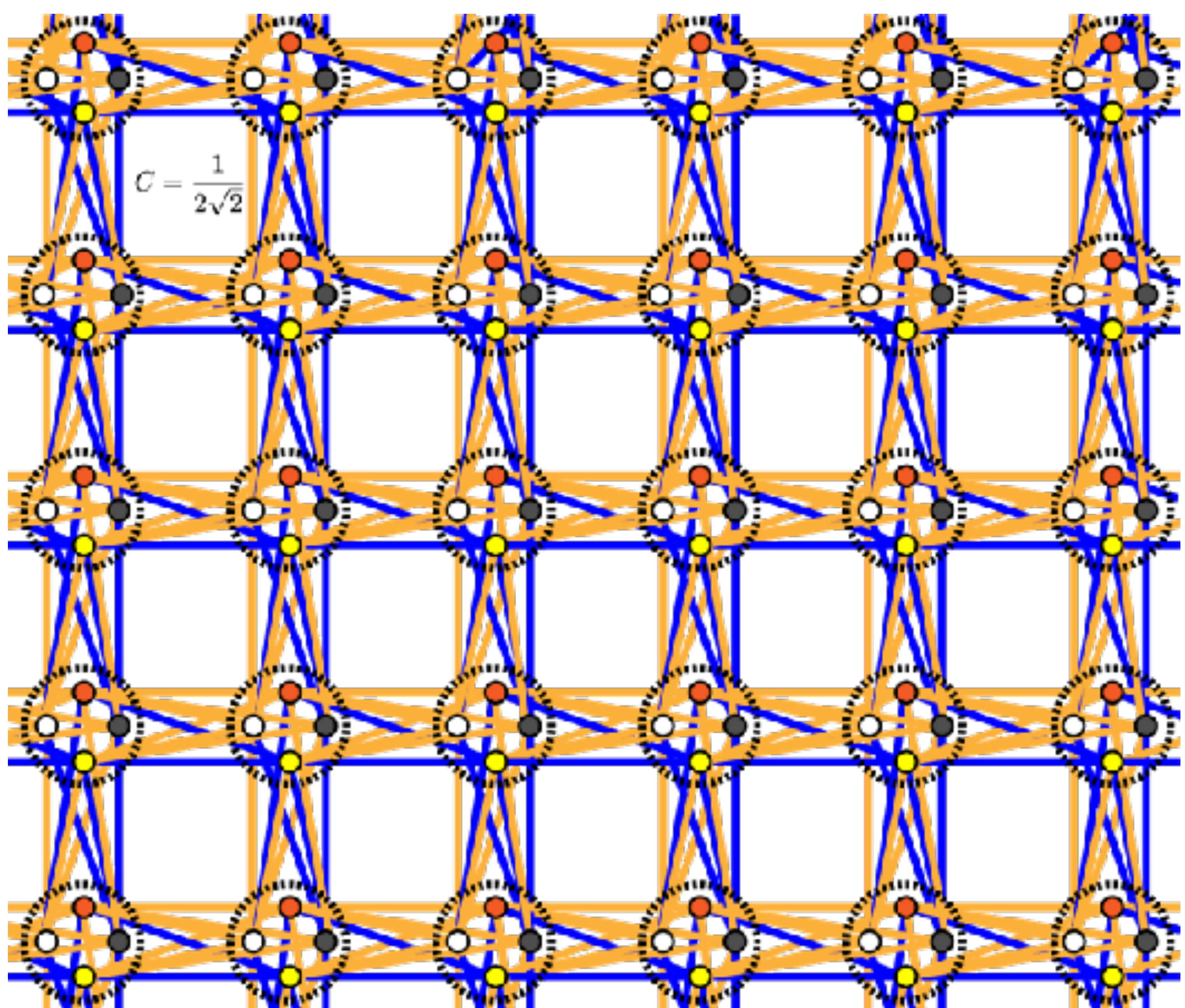


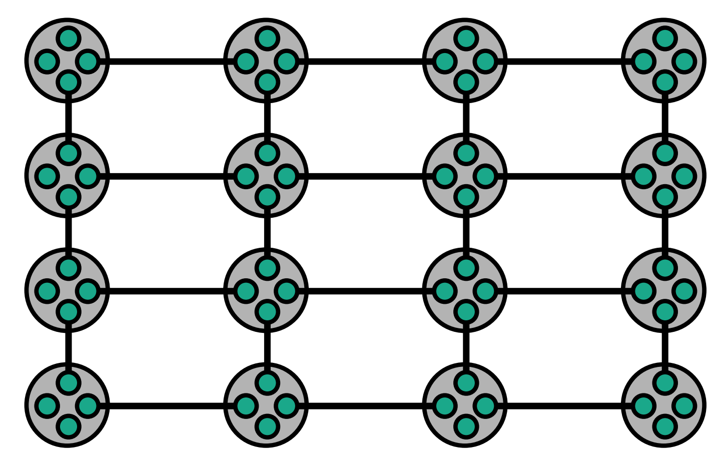


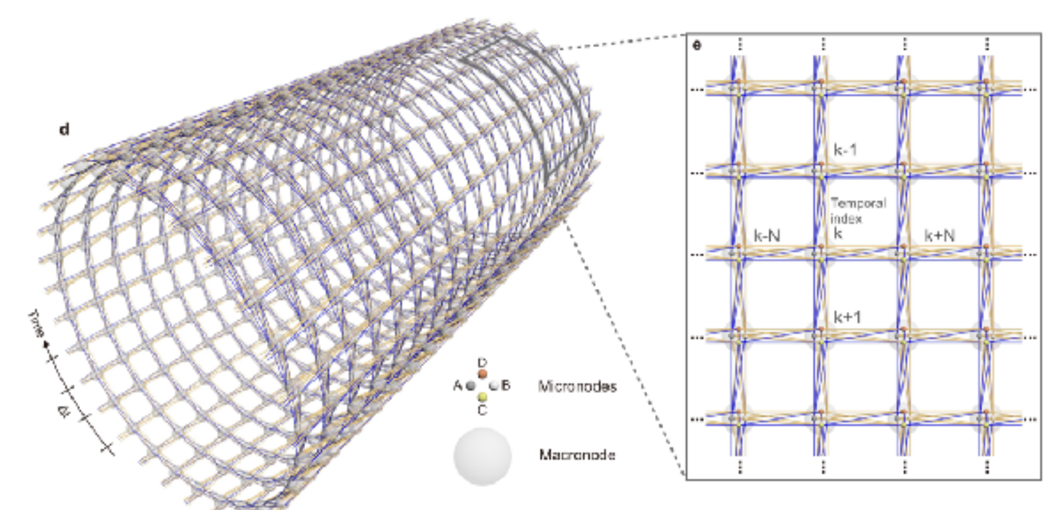
$$C = \frac{1}{\sqrt{2}}$$


OPO-a
OPO-b
OPO-c
OPO-d


OPO-a
OPO-b
OPO-c
OPO-d
$N\Delta t$

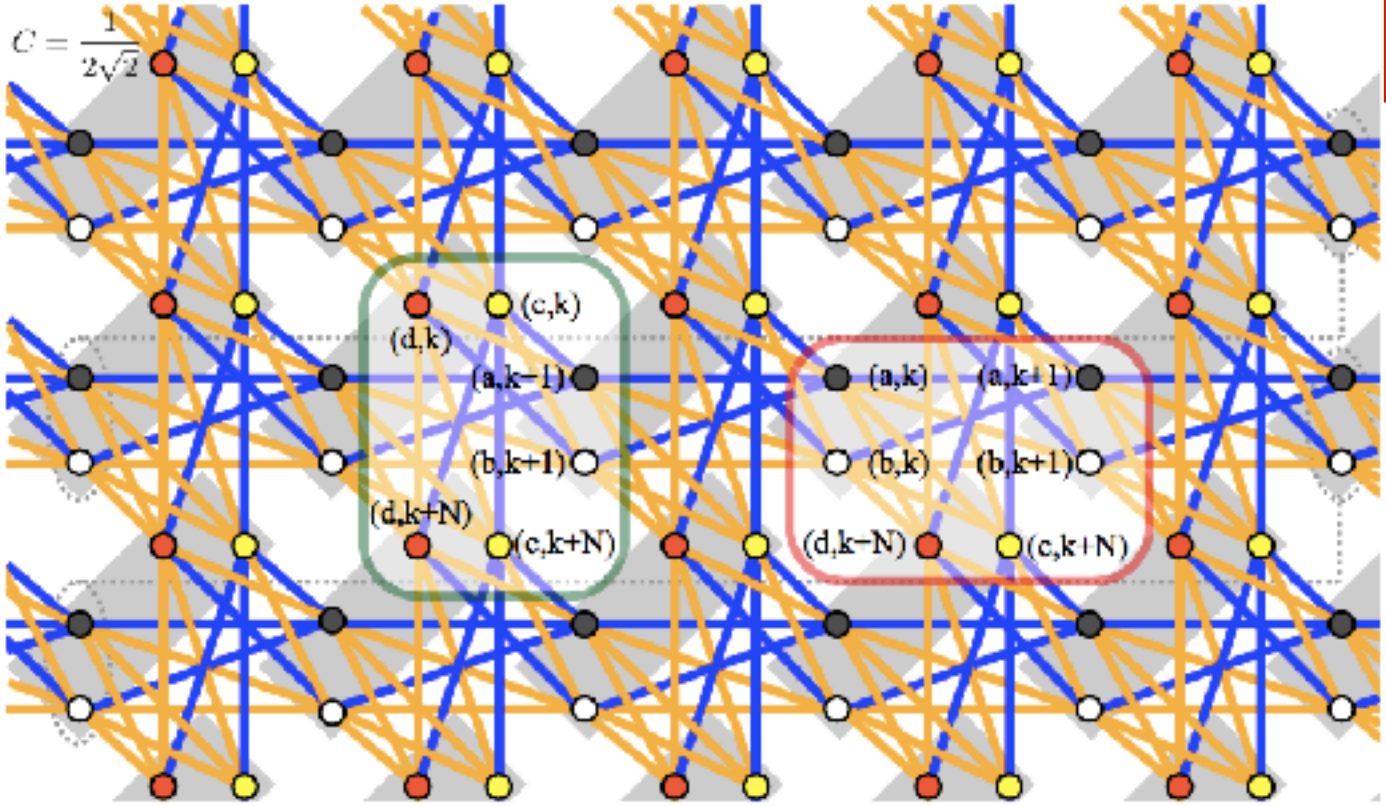

$C = \frac{1}{2\sqrt{2}}$




d
e
k-1
Temporal index k
k-N
k+N
k+1
Micronodes
Macronode

The van Loock-Furusawa criteria

P. van Loock and A. Furusawa, PRA 67, 052315(2003).



$$\hat{X}_k^1 = \hat{x}_k^A + \hat{x}_k^B - \frac{1}{\sqrt{2}}\left(-\hat{x}_{k+1}^A + \hat{x}_{k+1}^B + \hat{x}_{k+N}^C + \hat{x}_{k+N}^D\right)$$

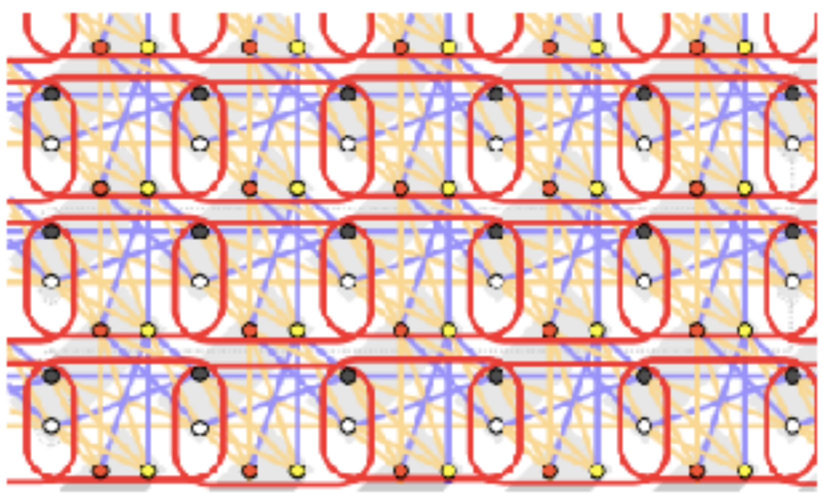
$$\hat{P}_k^1 = \hat{p}_k^A + \hat{p}_k^B + \frac{1}{\sqrt{2}}\left(-\hat{p}_{k+1}^A + \hat{p}_{k+1}^B + \hat{p}_{k+N}^C + \hat{p}_{k+N}^D\right)$$

$$\hat{X}_k^2 = \hat{x}_k^C - \hat{x}_k^D - \frac{1}{\sqrt{2}}\left(-\hat{x}_{k+1}^A + \hat{x}_{k+1}^B - \hat{x}_{k+N}^C - \hat{x}_{k+N}^D\right)$$

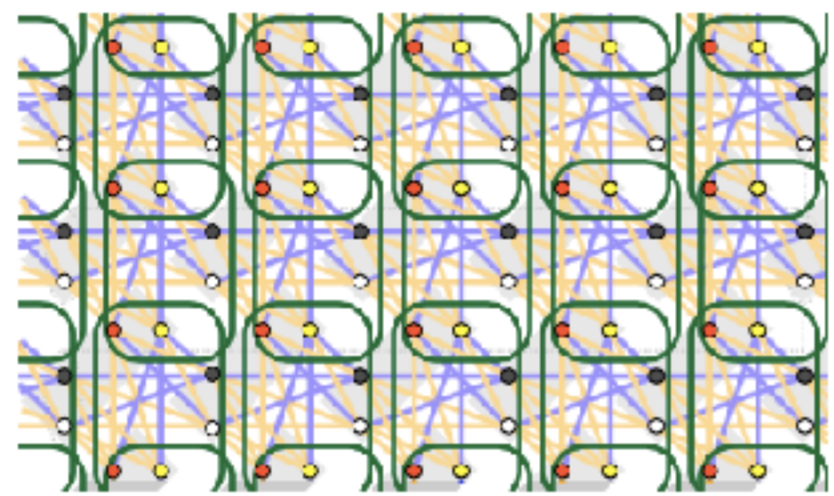
$$\hat{P}_k^2 = \hat{p}_k^C - \hat{p}_k^D + \frac{1}{\sqrt{2}}\left(-\hat{p}_{k+1}^A + \hat{p}_{k+1}^B - \hat{p}_{k+N}^C - \hat{p}_{k+N}^D\right)$$

$$\left\langle \Delta^2 \hat{X}_k^1 \right\rangle < \frac{\hbar}{\sqrt{2}}$$

$$\left\langle \Delta^2 \hat{P}_k^1 \right\rangle < \frac{\hbar}{\sqrt{2}}$$



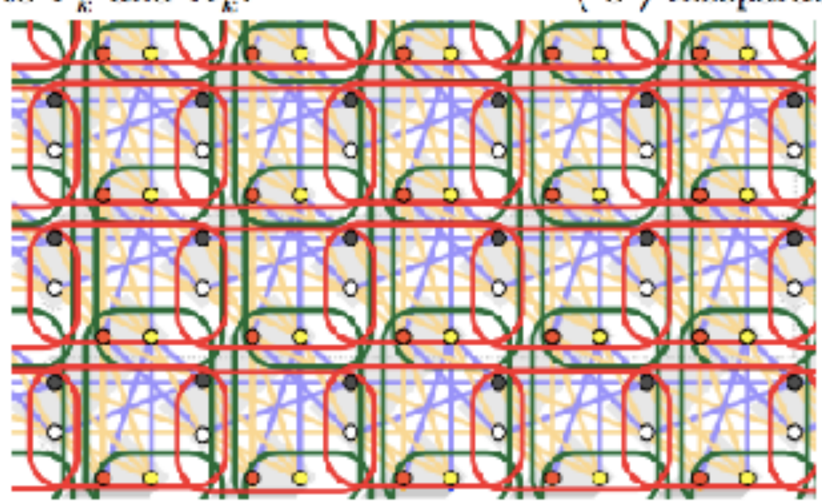
(a) Inseparability due to $\hat{P}_k^1$ and $\hat{X}_k^1$.



(b) Inseparability due to $\hat{P}_k^2$ and $\hat{X}_k^2$.

$$\left\langle \Delta^2 \hat{X}_k^2 \right\rangle < \frac{\hbar}{\sqrt{2}}$$

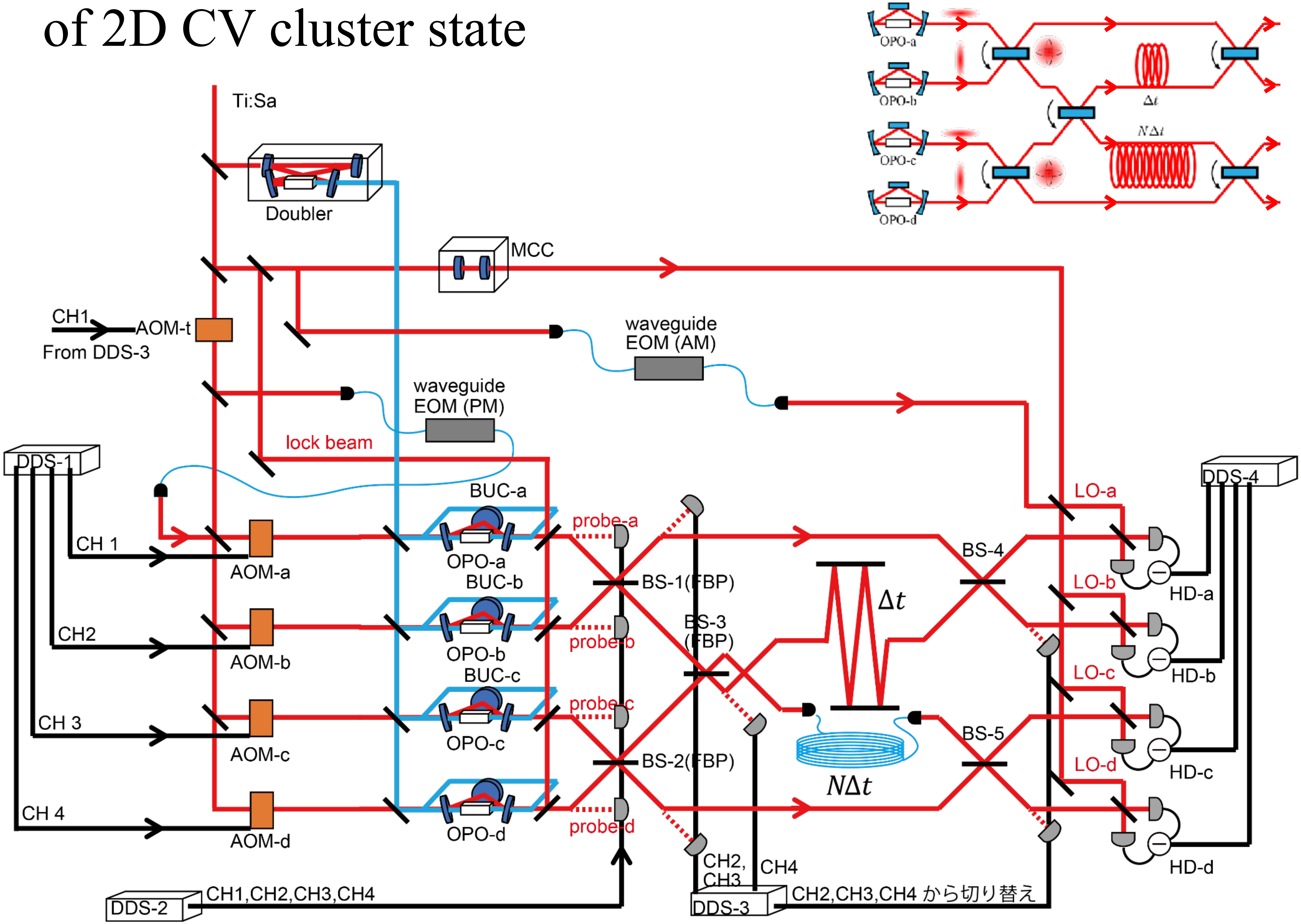
$$\left\langle \Delta^2 \hat{P}_k^2 \right\rangle < \frac{\hbar}{\sqrt{2}}$$



(c) Full multipartite inseparability

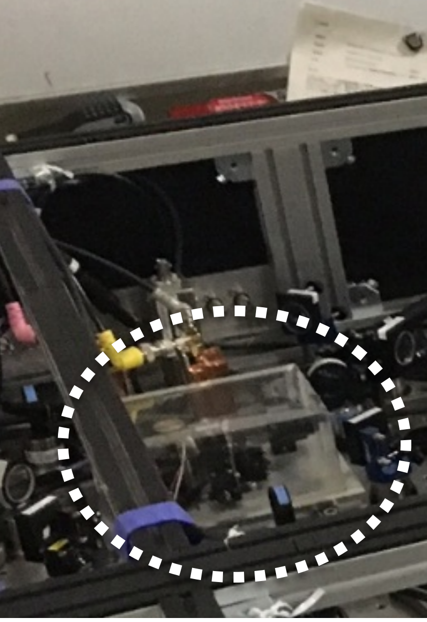
4.5 dB of squeezing

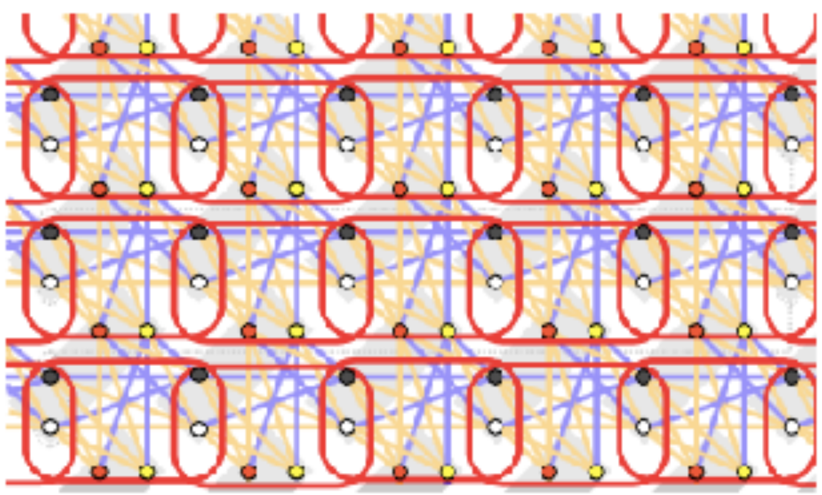
Experimental setup for deterministic creation of 2D CV cluster state



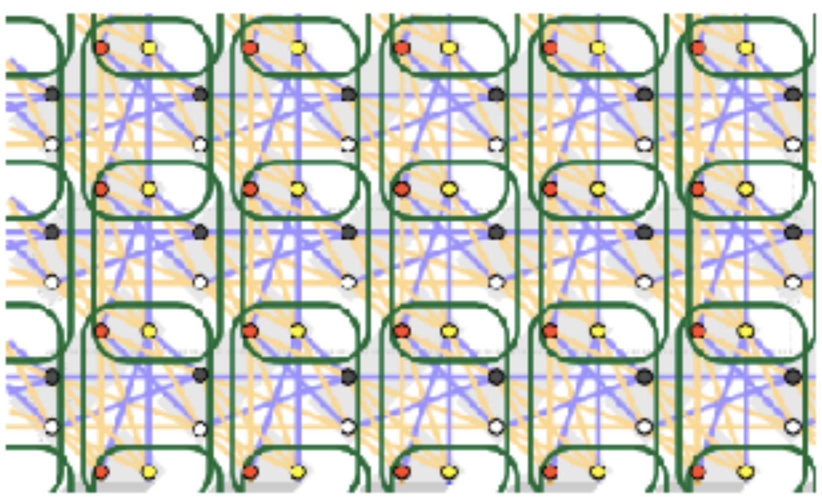
We succeeded in creation of a 2D cluster state of 5 x 5000 !!

W. Asavanant, Y. Shiozawa, S. Yokoyama, B. Charoensombutamon, H. Emura, R. N. Alexander, S. Takeda, J. Yoshikawa, N. C. Menicucci, H. Yonezawa, and A. Furusawa, arXiv:1903.03918 [quant-ph]

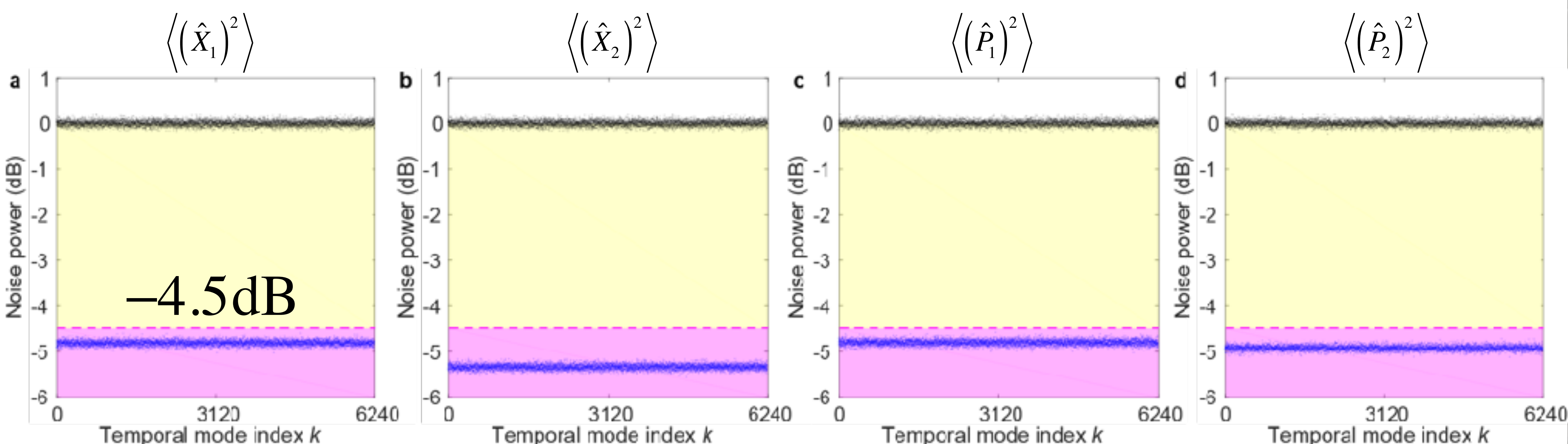




(a) Inseparability due to $\hat{P}^1_k$ and $\hat{X}^1_k$.



(b) Inseparability due to $\hat{P}^2_k$ and $\hat{X}^2_k$.

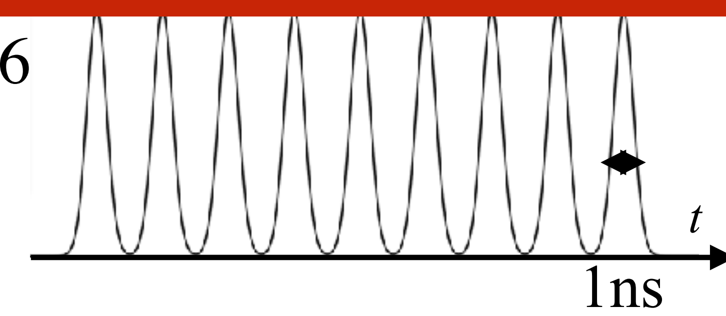


Each wave-packet can be a logical qubit!

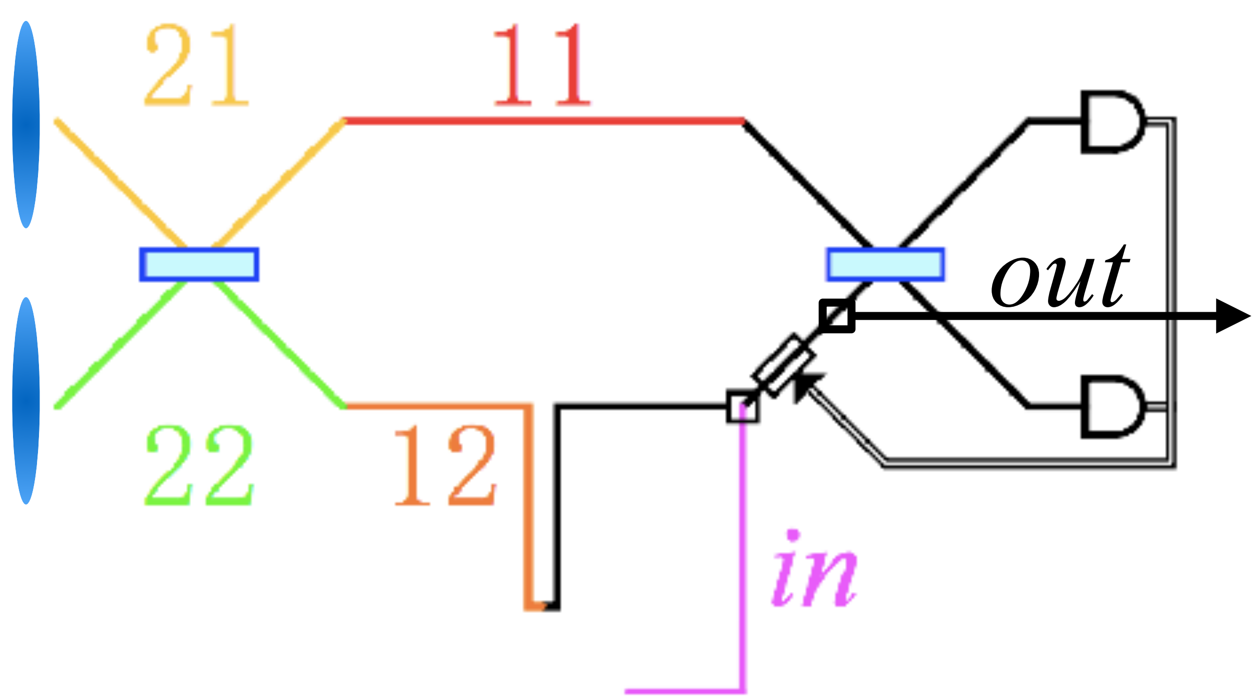
Each wave-packet can contain more than one photon!

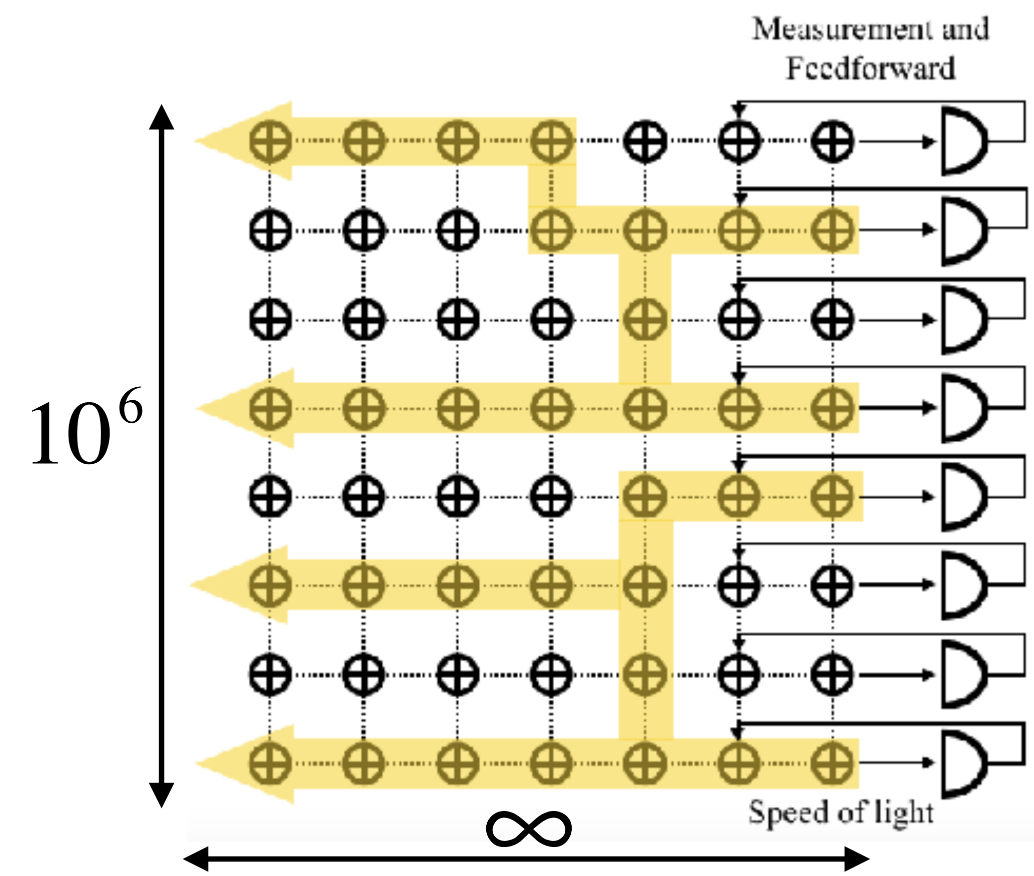
Degree of freedom of photon number

$$\frac{1\ \text{ms}}{1\ \text{ns}} = 10^6$$



Operating time Unlimited!





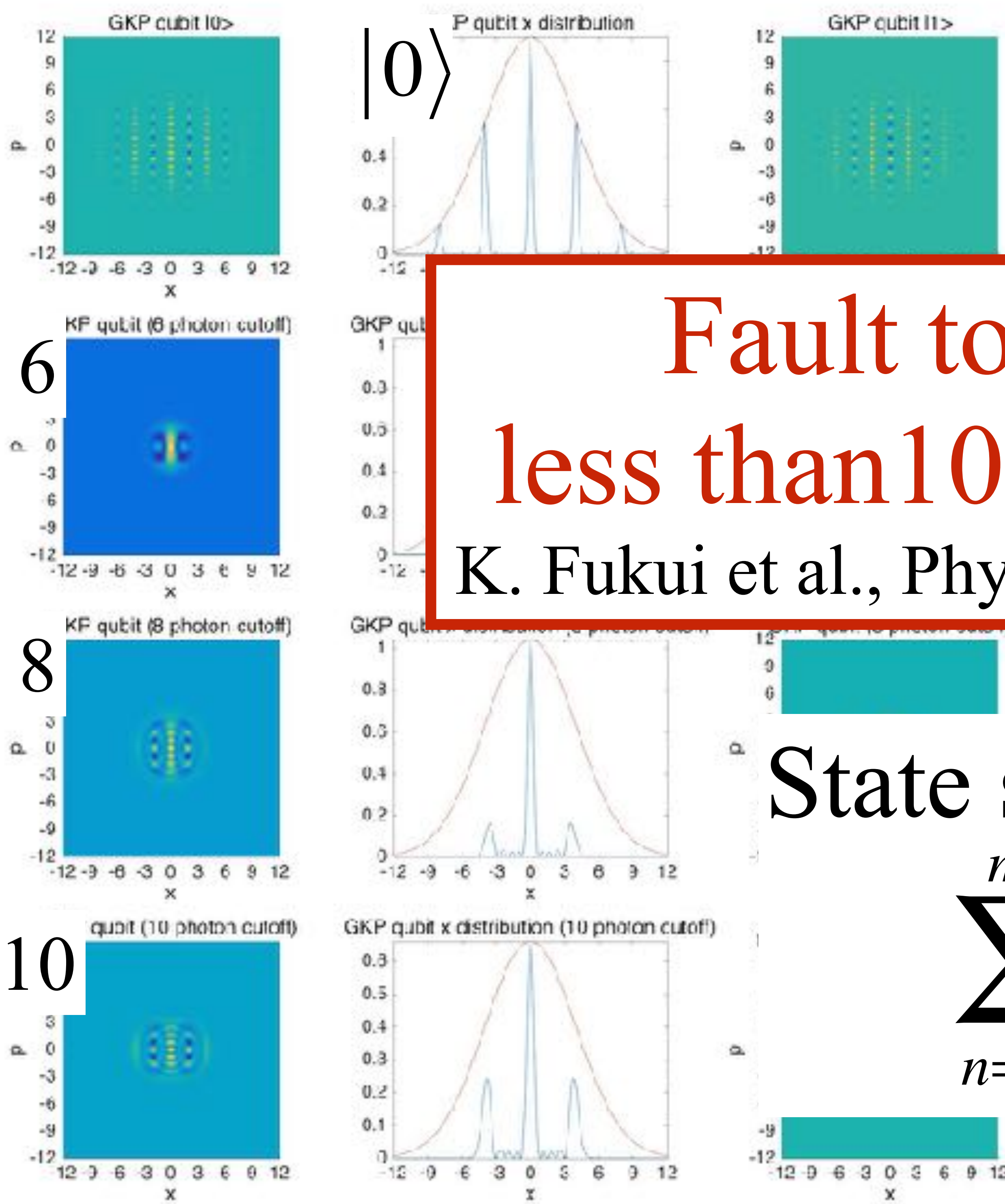
Measurement within laser coherence time!

$$200\text{ns} \times 10^6 = 0.2\text{s} \gg 1\text{ms}$$

J. Yoshikawa et al., APL Photonics 1, 060801 (2016)

GKP qubit : error rate 10^{-6} with 2

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

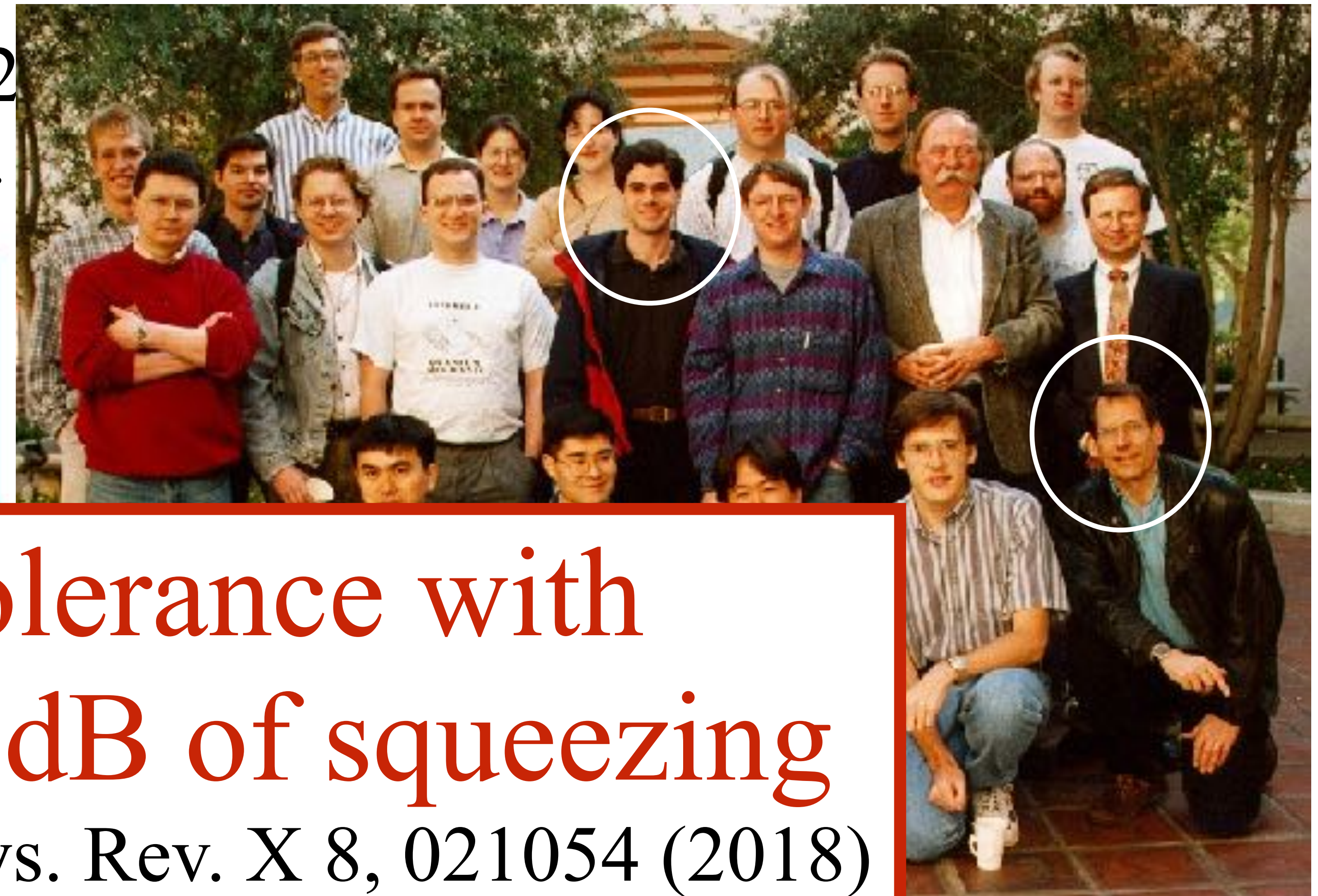


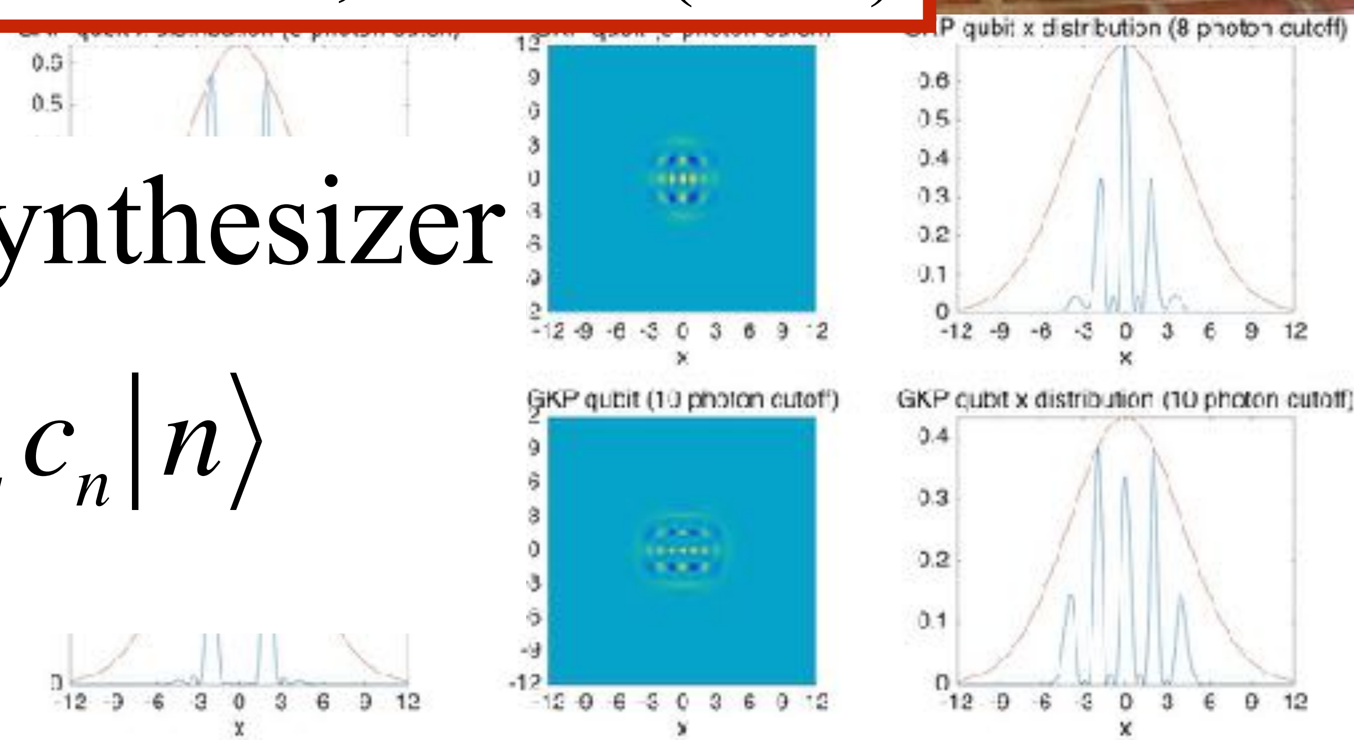
$|0\rangle$

6

8

10





Fault tolerance with less than10dB of squeezing

K. Fukui et al., Phys. Rev. X 8, 021054 (2018)

State synthesizer

$$\sum_{n=0}^{m} c_n |n\rangle$$

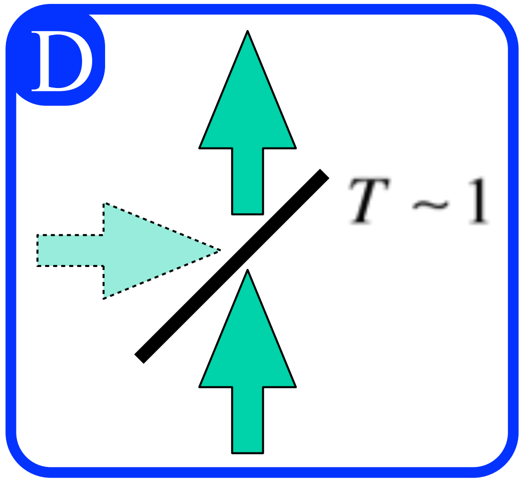
$$P_{\text{error}} = e^{-n/2} \qquad n=10,\ 6.7\times10^{-3} \qquad n=20,\ 4.5\times10^{-5}$$

The world record of squeezing

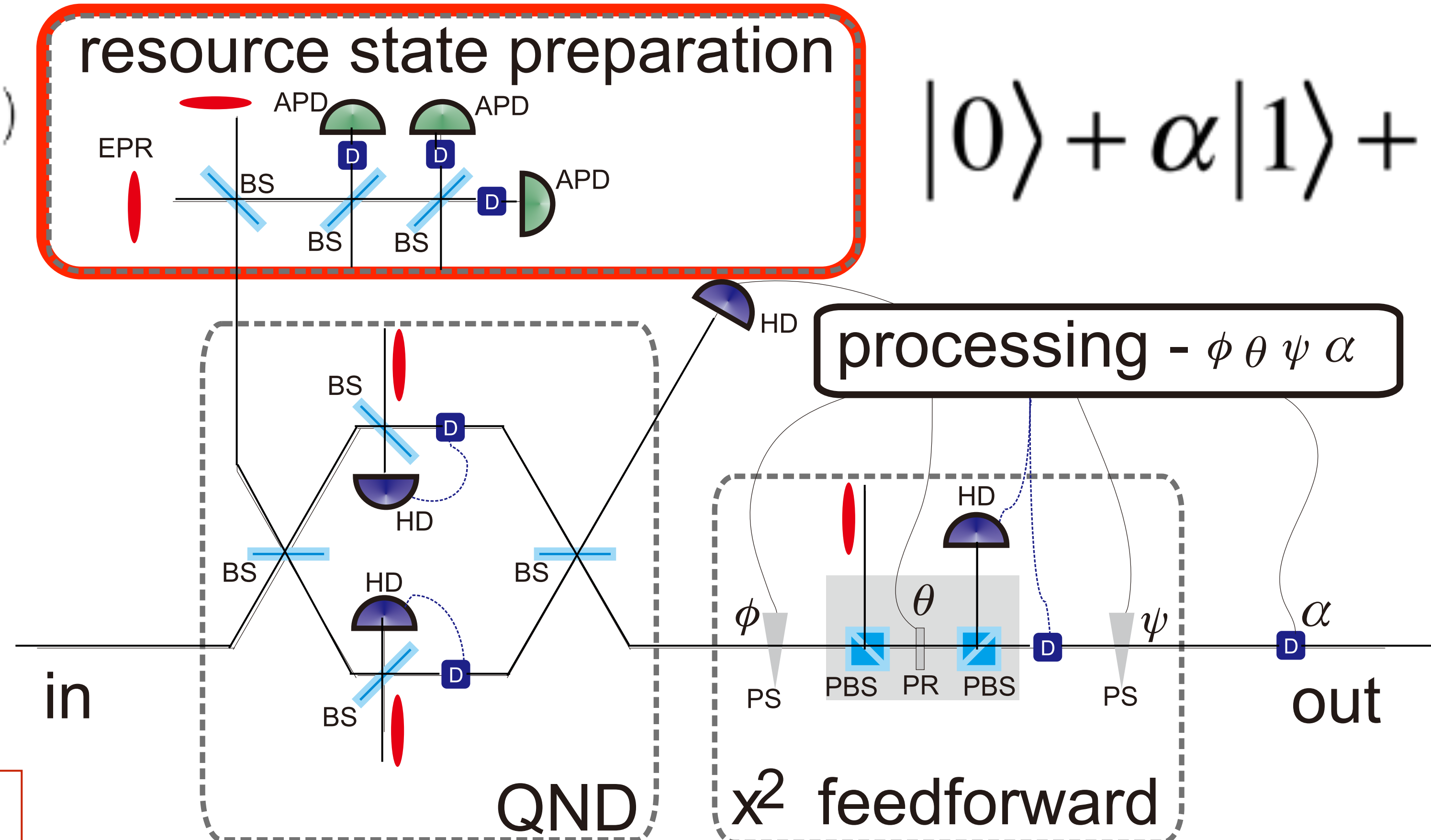
15dB squeezing

H. Vahlbruch et al., PRL 117, 110801 (2016)

$$\sqrt{1-q^2}\sum_{n=0}^{\infty} q^n |n\rangle_S |n\rangle_I$$
$$\approx \sqrt{1-q^2}\left(|0\rangle_S|0\rangle_I + q|1\rangle_S|1\rangle_I + q^2|2\rangle_S|2\rangle_I + q^3|3\rangle_S|3\rangle_I\right)$$



P. Marek, R. Filip, A. Furusawa, Phys. Rev. A **84**, 053802 (2011)

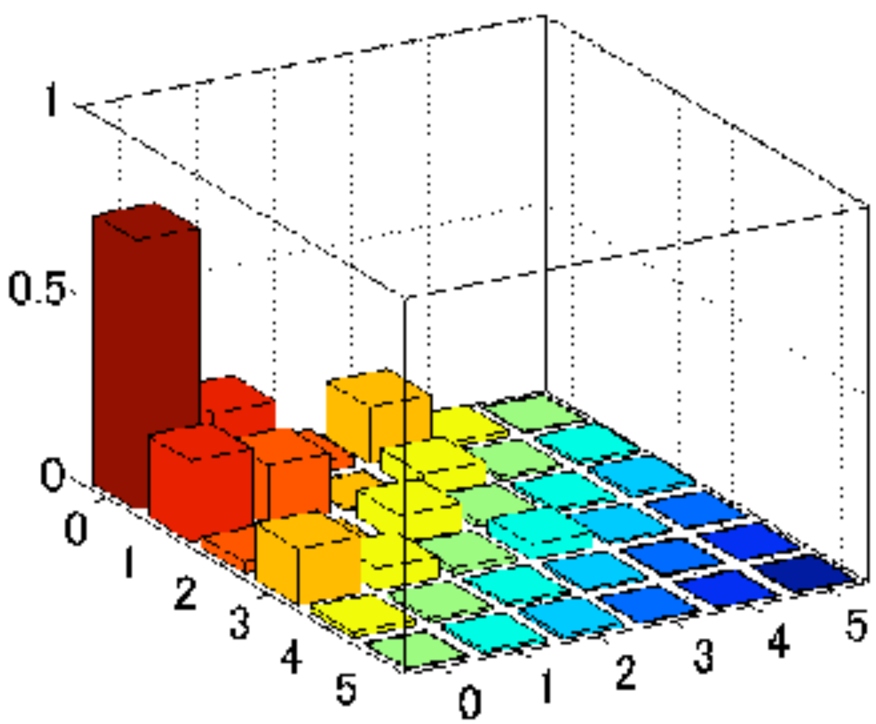


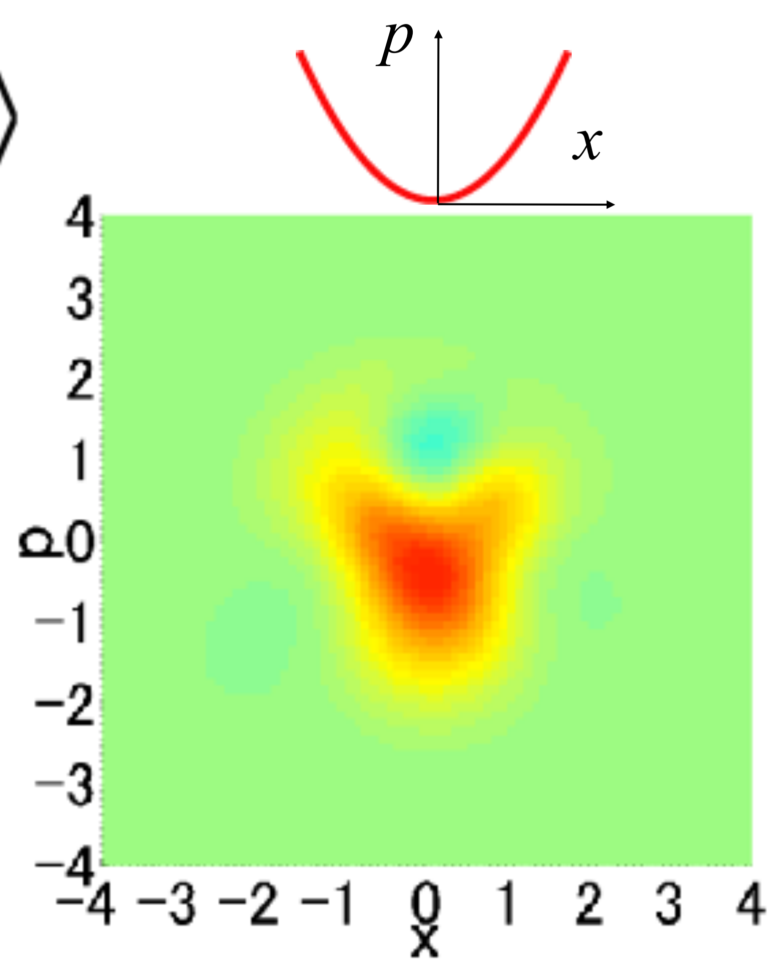
$$|0\rangle + \alpha|1\rangle + \beta|3\rangle$$

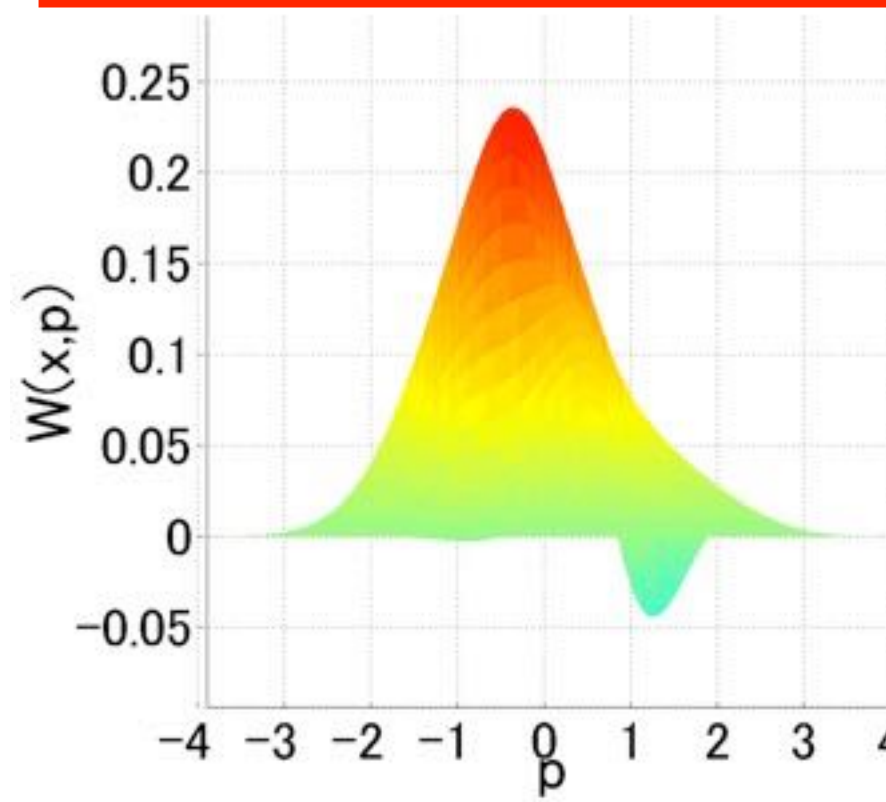
Approximate cubic phase state
CV version of a magic state

$$|0\rangle + 0.53|1\rangle + 0.43|3\rangle$$

without any correction!!



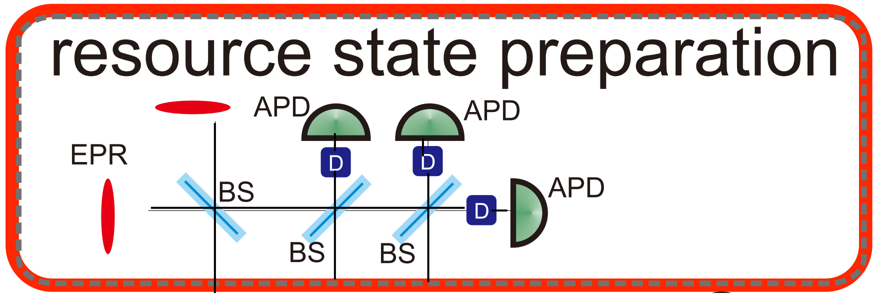


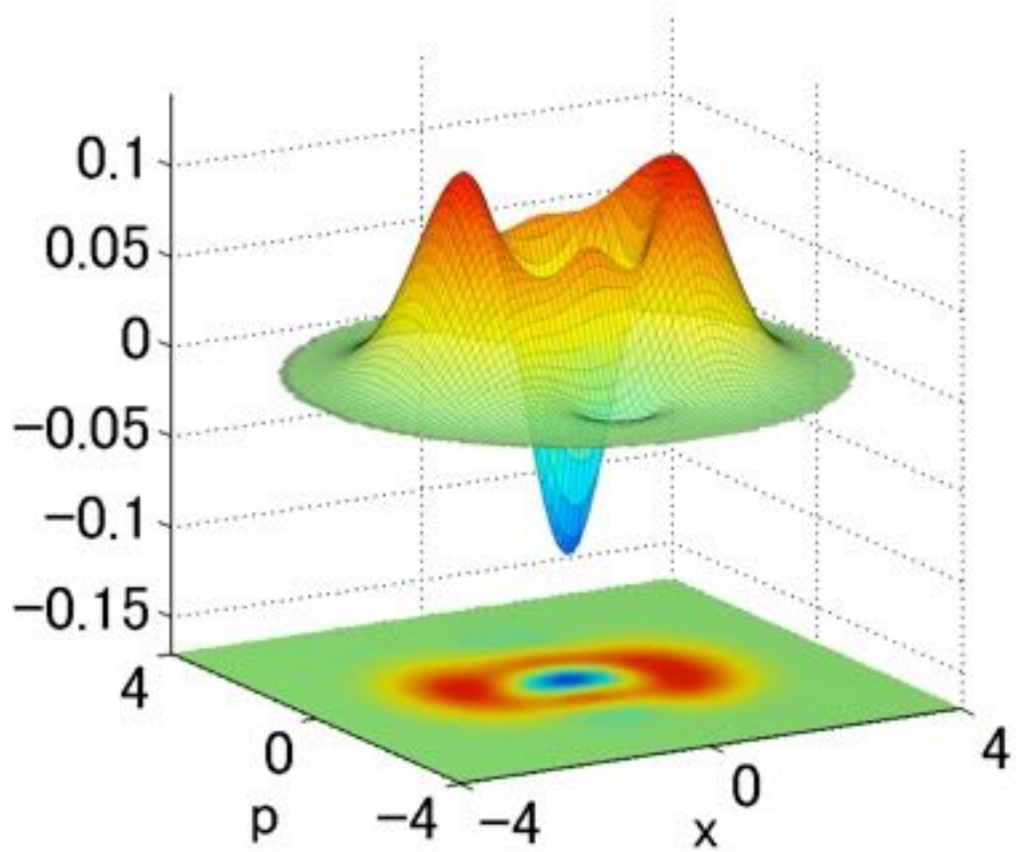


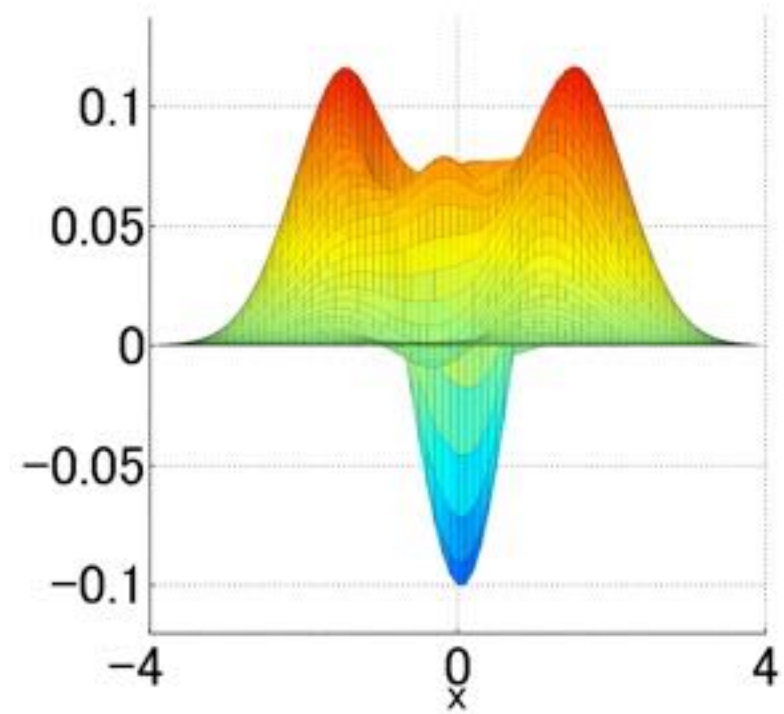
M. Yukawa, K. Miyata, H. Yonezawa, P. Marek, R. Filip, and A. Furusawa, Phys. Rev. A **88**, 053816 (2013)

$|1\rangle + \alpha|3\rangle$

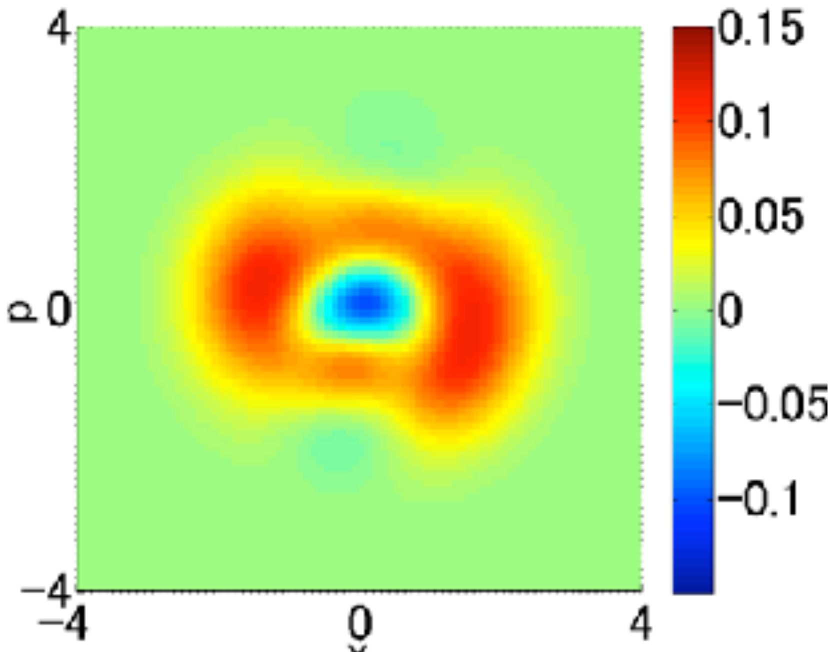
Schrödinger cat state
A bigger cat!

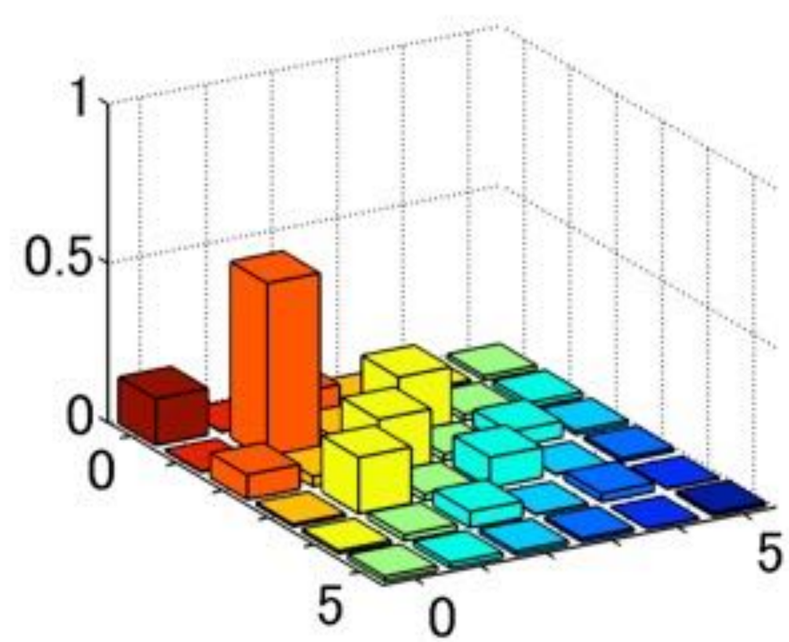






without any correction!!



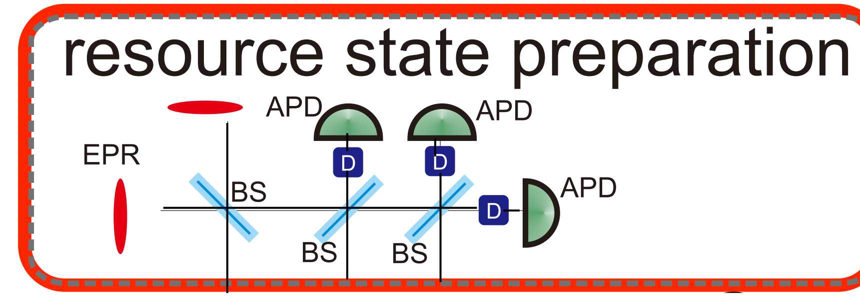


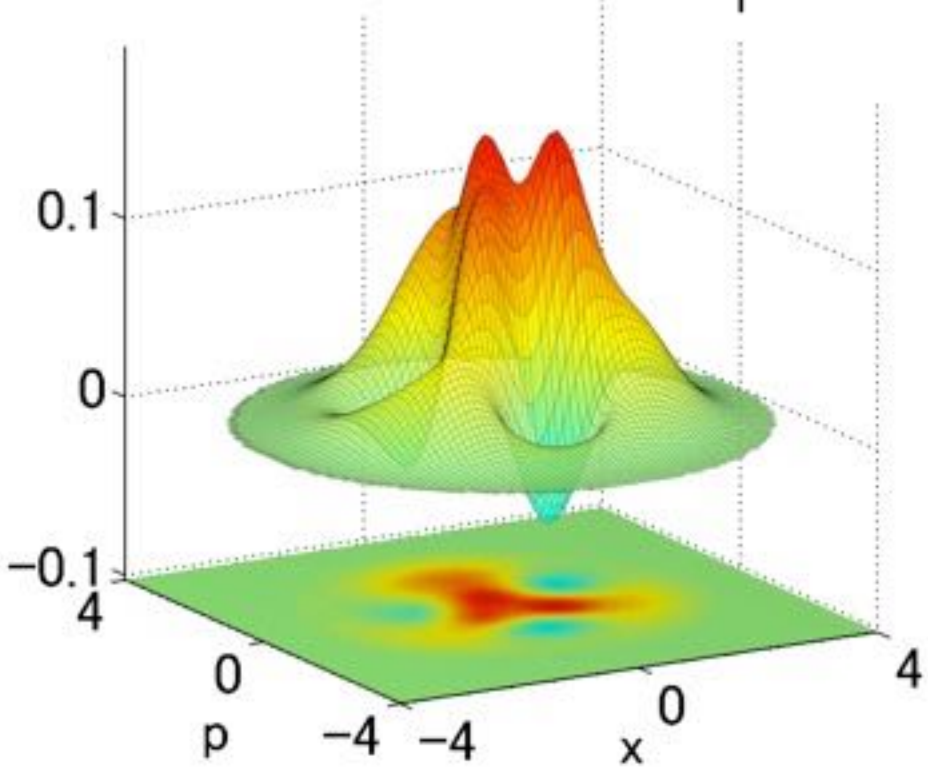
M. Yukawa *et al.*, Optics Express **21**, 5529 (2013)

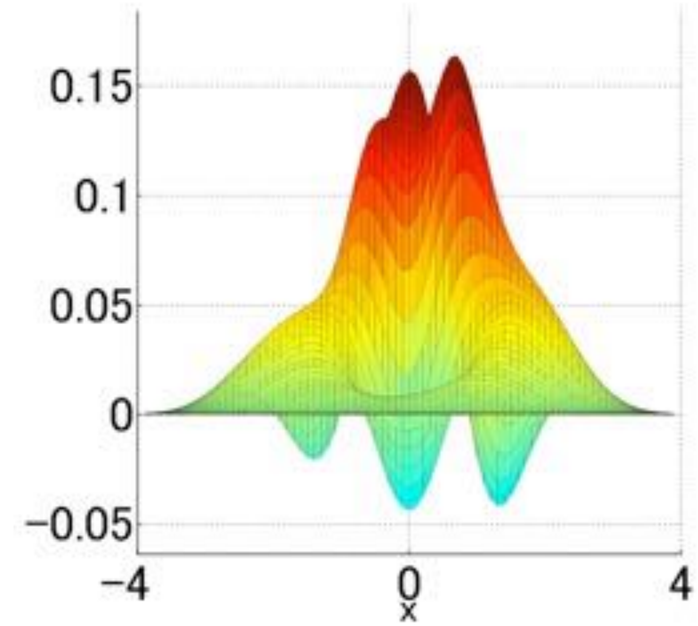
$$|0\rangle + \frac{\alpha^3}{\sqrt{6}}|3\rangle$$

Three-headed cat state

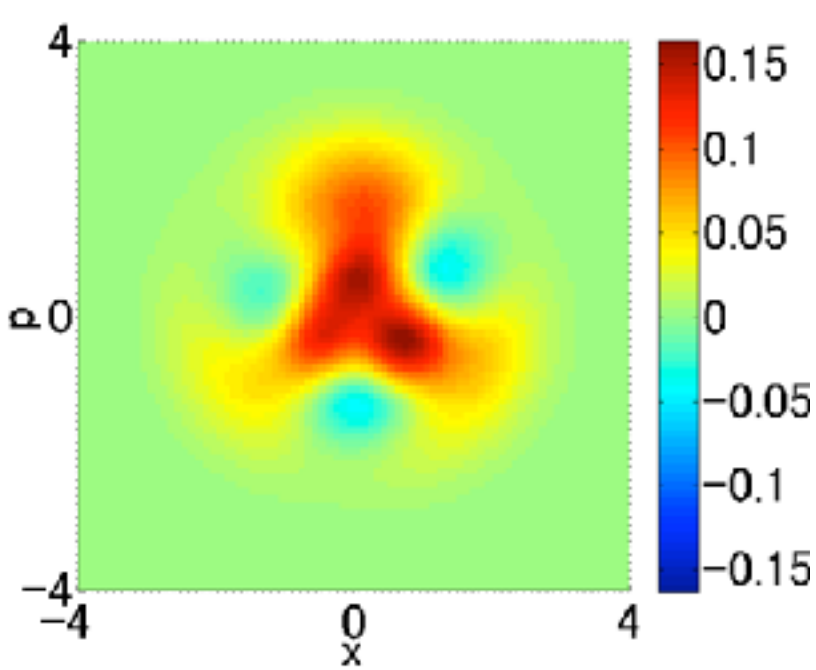
$$|\alpha\rangle + \left|\alpha e^{i\frac{2\pi}{3}}\right\rangle + \left|\alpha e^{-i\frac{2\pi}{3}}\right\rangle$$

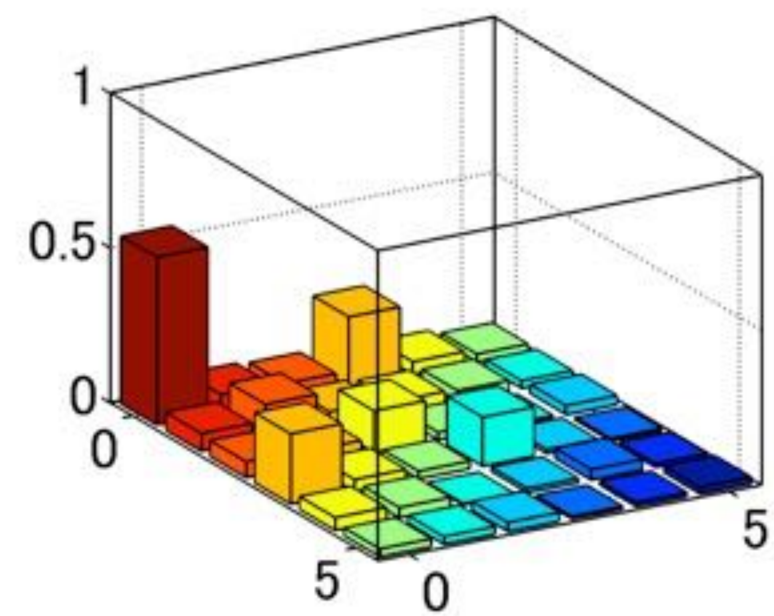






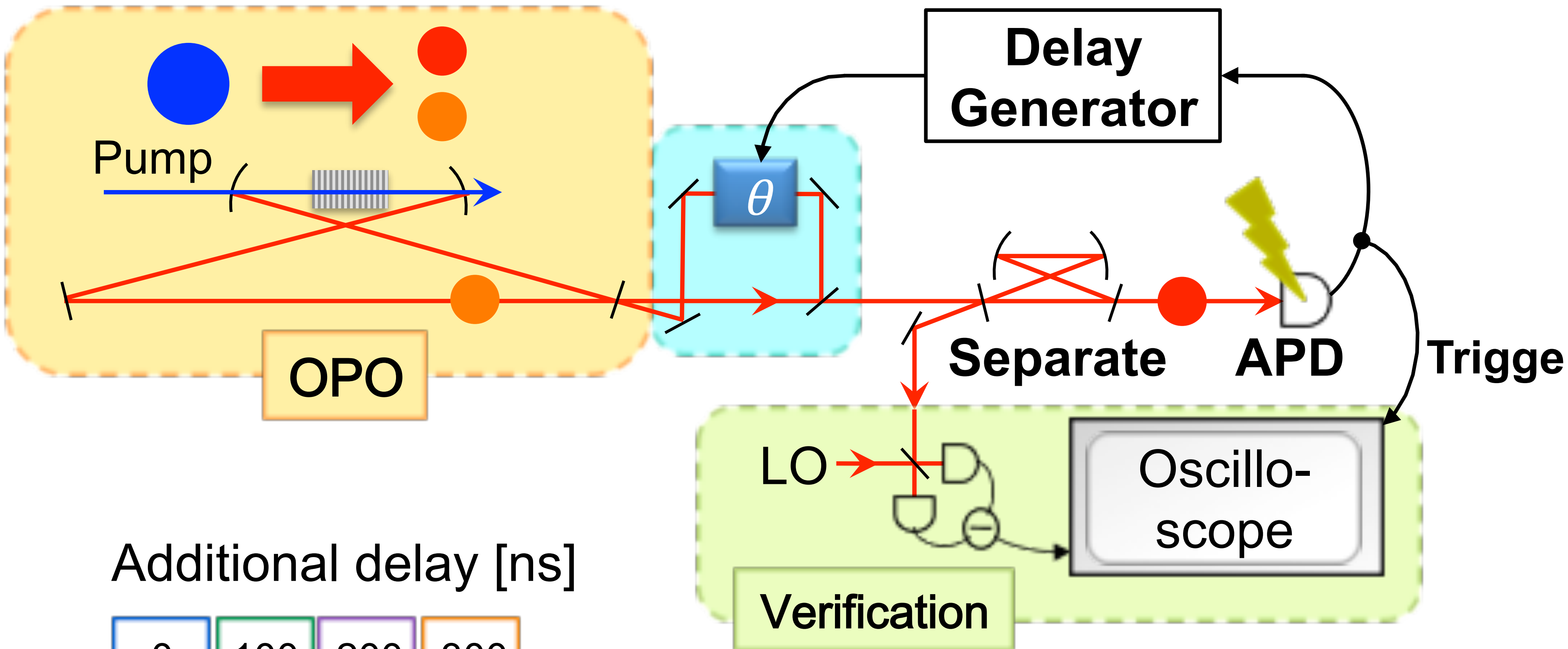
without any correction!!

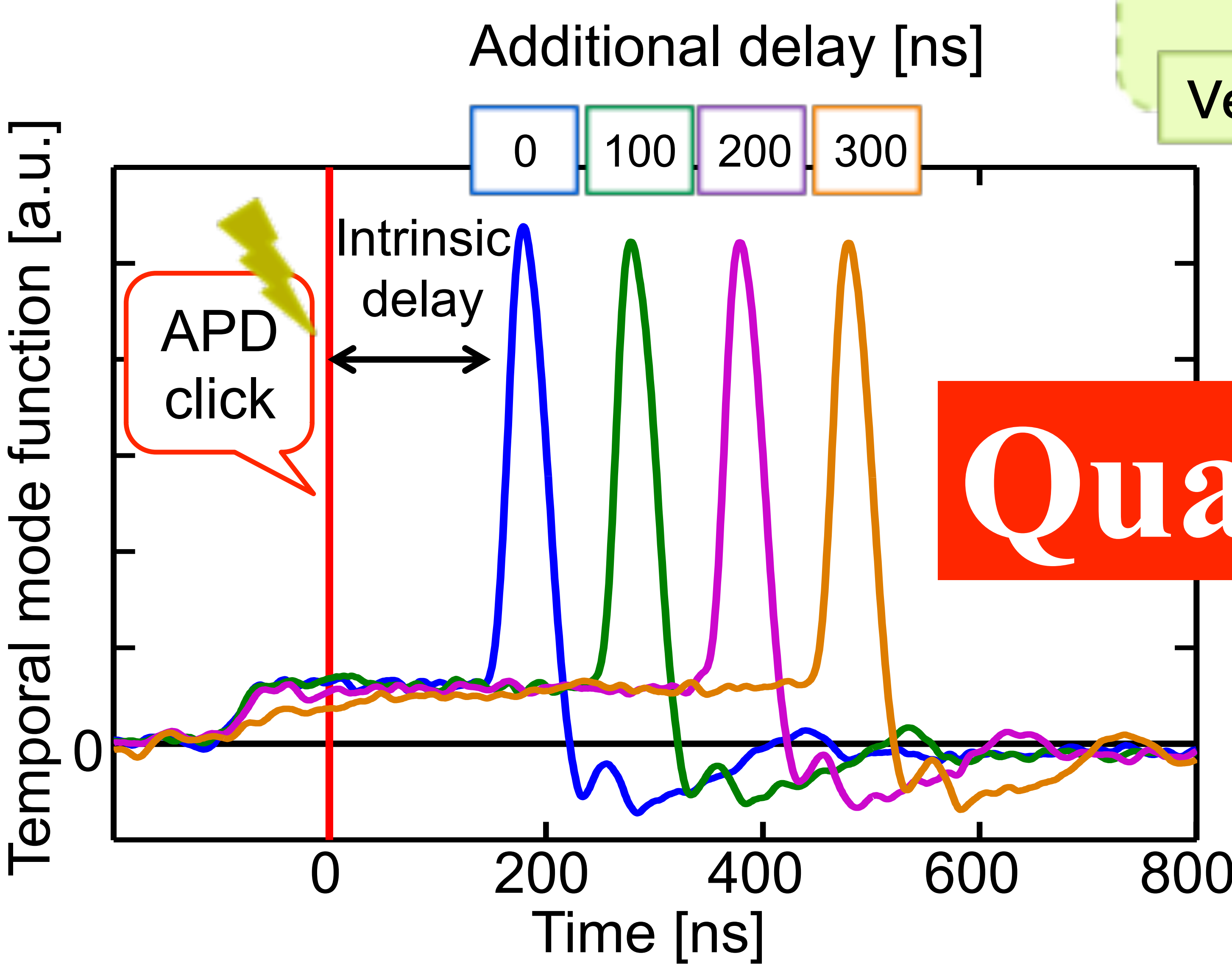




M. Yukawa *et al.*, Optics Express **21**, 5529 (2013)

Controllable Delay in Heralded Single Photons

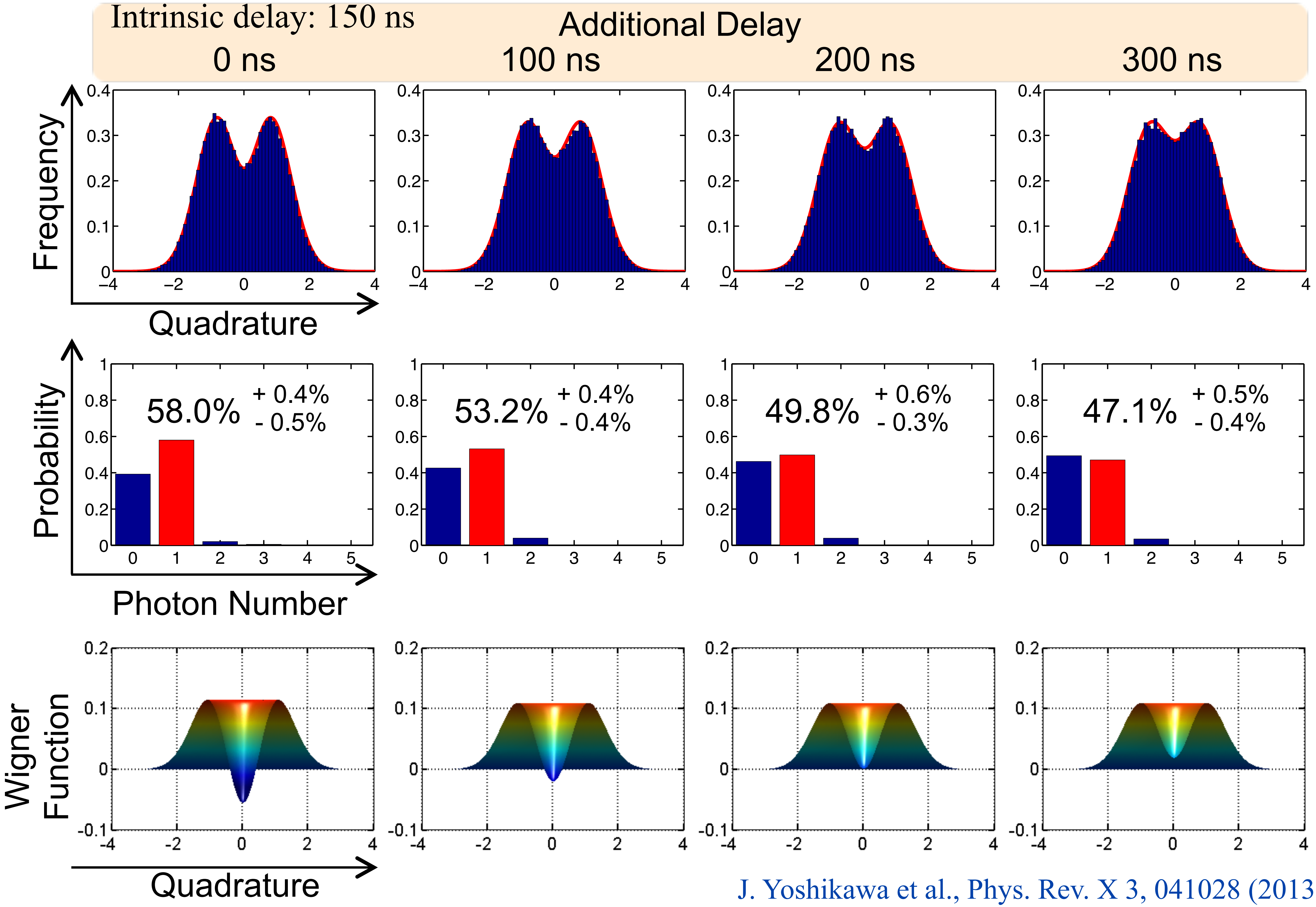




Quantum memory

J. Yoshikawa et al., Phys. Rev. X 3, 041028 (2013)

Experimental Results of Delayed Photons



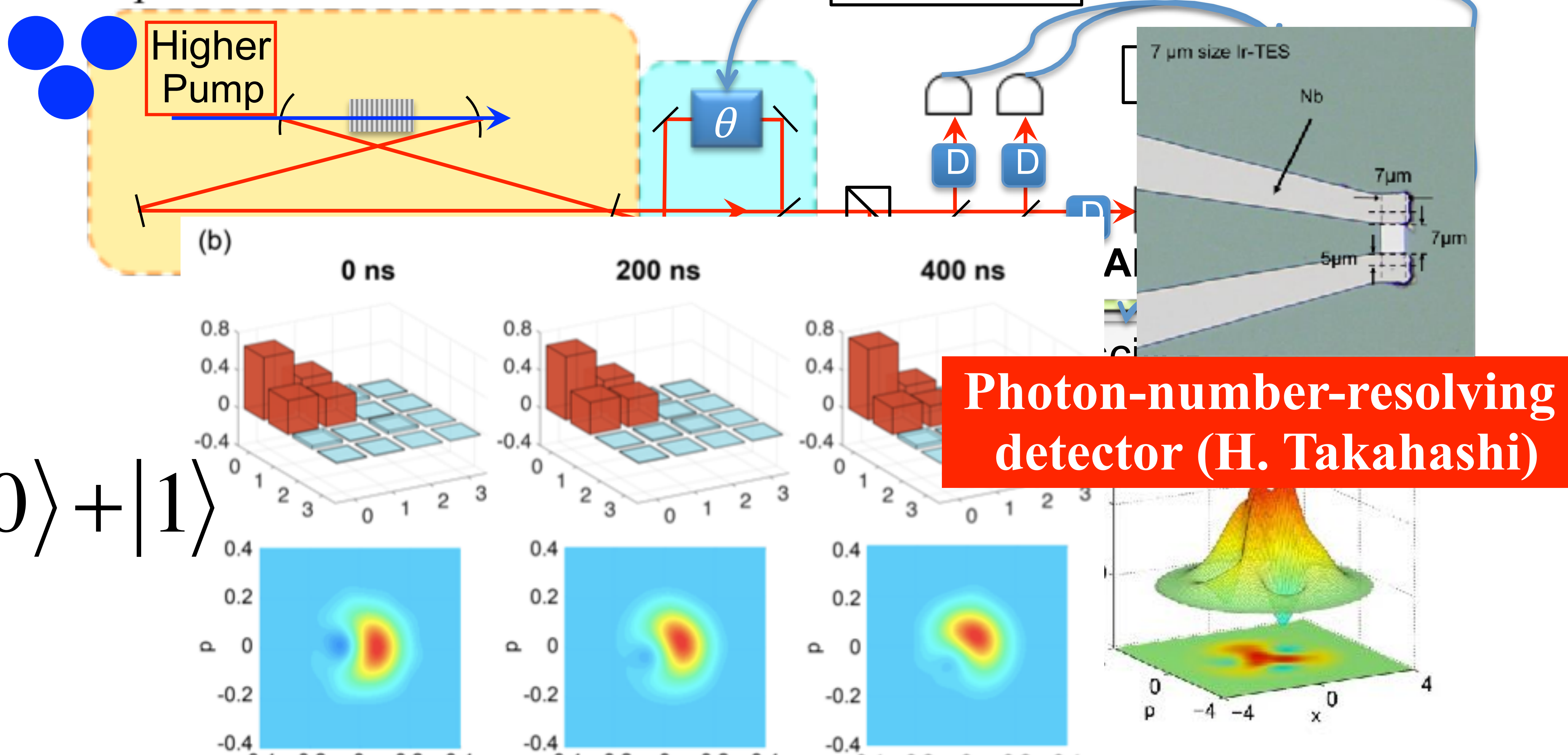
J. Yoshikawa et al., Phys. Rev. X 3, 041028 (2013)

State generation and quantum memory

$$\sqrt{1-q^2}\sum_{n=0}^{\infty} q^n |n\rangle_S |n\rangle_I$$

$$\approx \sqrt{1-q^2}\left(|0\rangle_S|0\rangle_I + q|1\rangle_S|1\rangle_I + q^2|2\rangle_S|2\rangle_I + q^3|3\rangle_S|3\rangle_I\right)$$

$$q = \tanh r$$



$$|0\rangle + |1\rangle$$

Y. Hashimoto et al., arXiv:1810.10741

Universality of quantum computing

“Computational basis”

Quantum states for quantum computing

“Qubits”

$$|\psi_2\rangle = c_0|0\rangle + c_1|1\rangle = \sum_{n=0}^{1} c_n|n\rangle$$

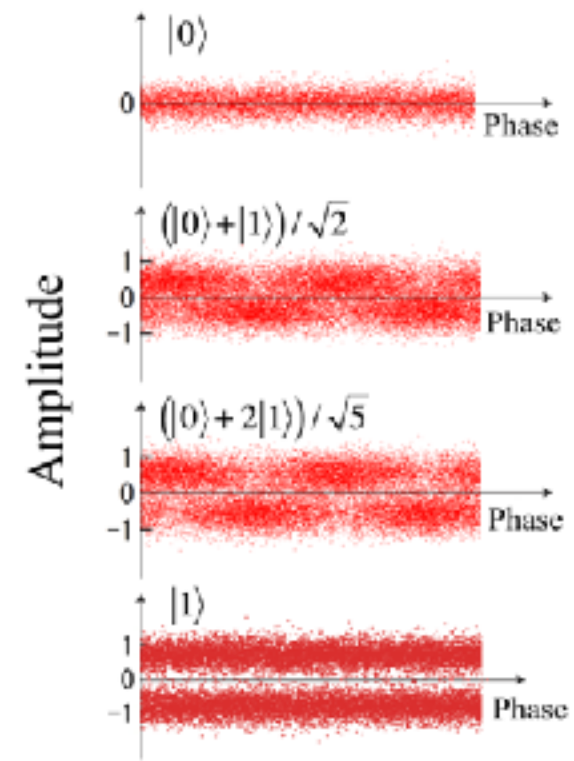
$$c_n = \langle n|\psi_2\rangle \ (n = 0,1)$$

“Continuous variables” (CV)

$$|\psi\rangle = \int_{-\infty}^{\infty} dx\, \psi(x)|x\rangle$$

$$\psi(x) = \langle x|\psi\rangle$$

“Hybrid”



Schrödinger picture

Universal gate sets

Qubits

computational basis $\{|0\rangle, |1\rangle\}$ bit flip σ_x

Hadamard

conjugate basis $\{|+\rangle, |-\rangle\}$ phase flip σ_z

$|\pm\rangle = \frac{|0\rangle \pm |1\rangle}{\sqrt{2}}$

CNOT $|x\rangle|x'\rangle \rightarrow |x\rangle|x + x' \bmod 2\rangle$

Continuous variables

Clifford

$\{|x\rangle\}$ x-displacement $\hat{X}(s) = e^{-2is\hat{p}}$

Fourier

$\{|p\rangle\}$ p-displacement $\hat{Z}(s) = e^{2is\hat{x}}$

QND $|x\rangle|x'\rangle \rightarrow |x\rangle|x + x'\rangle$

Non-Clifford

π/8 gate $T = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\frac{\pi}{4}} \end{pmatrix}$

Magic state

stabilizer formalism

Cubic phase gate $e^{i\gamma\hat{x}^3}|\psi\rangle$

Cubic phase state

Heisenberg picture

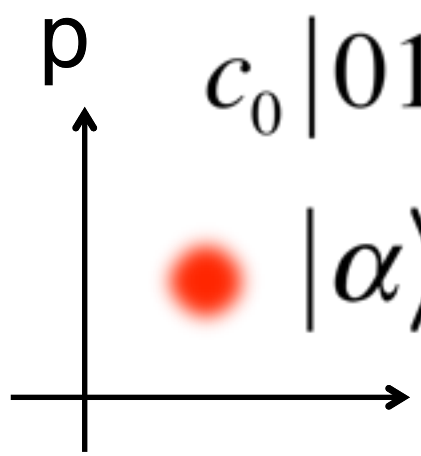
$$e^{-i\gamma\hat{x}^3}\hat{x}e^{i\gamma\hat{x}^3} = \hat{x}$$

$$e^{-i\gamma\hat{x}^3}\hat{p}e^{i\gamma\hat{x}^3} = \hat{p} + \frac{3}{2}\gamma\hat{x}^2$$

Universality of quantum computing

Quantum state of light

$c_0|01\rangle + c_1|10\rangle$



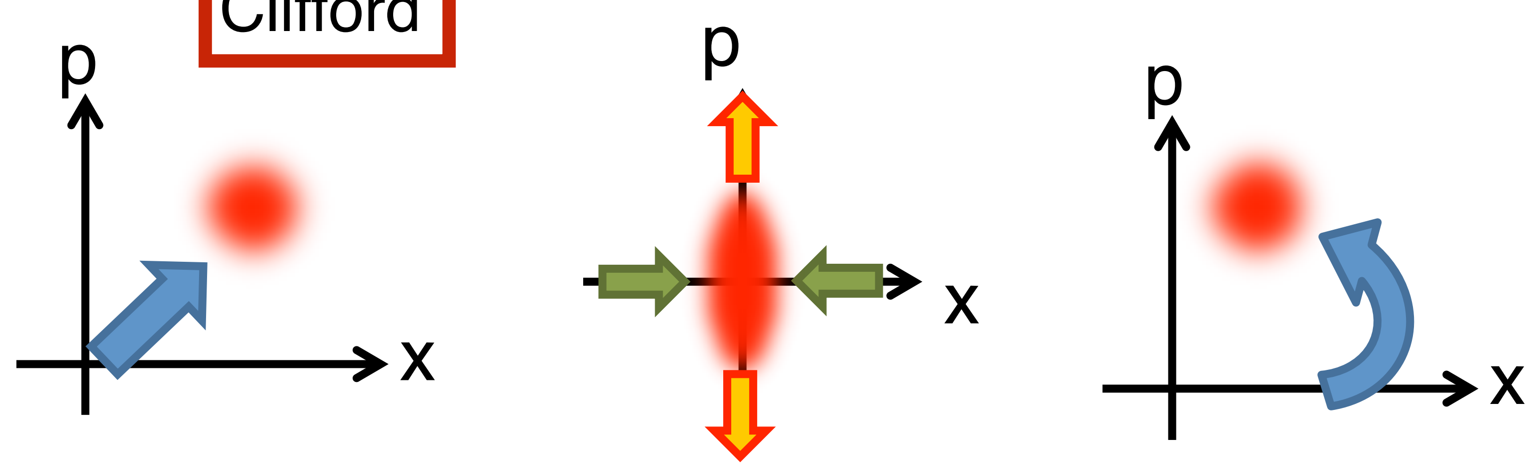
$|\alpha\rangle$

We need at least **one** non-linear gate

S. Lloyd and S. L. Braunstein, PRL **82**, 1784 (1999)

Linear (Gaussian) operations

Clifford



Displacement — σ_x σ_z

Squeezing+BS — CNOT

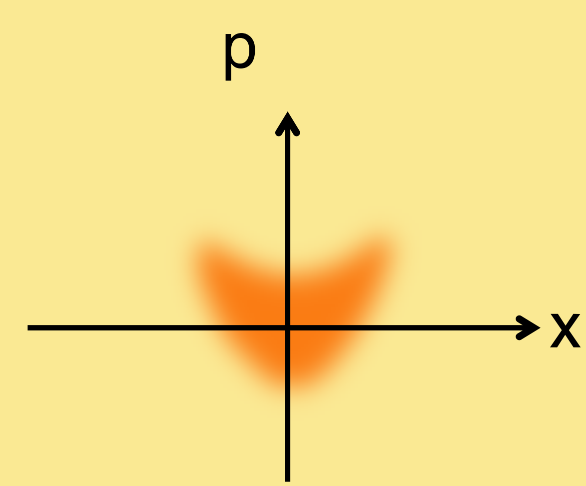
Rotation — H

Non-linear (non-Gaussian) operations

Non-Clifford

Cubic phase gate

$$\hat{U} = e^{i\chi x^3}$$



π/8 gate

Cubic phase gate with gate teleportation

Schrödinger picture

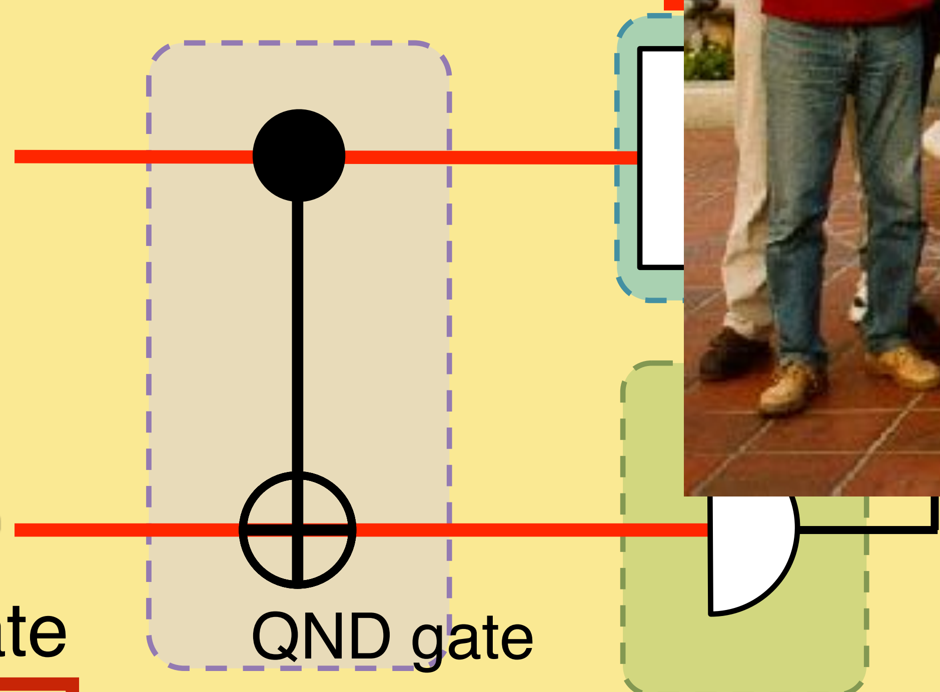
Input

$|\psi\rangle$

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

cubic phase state

CV magic state



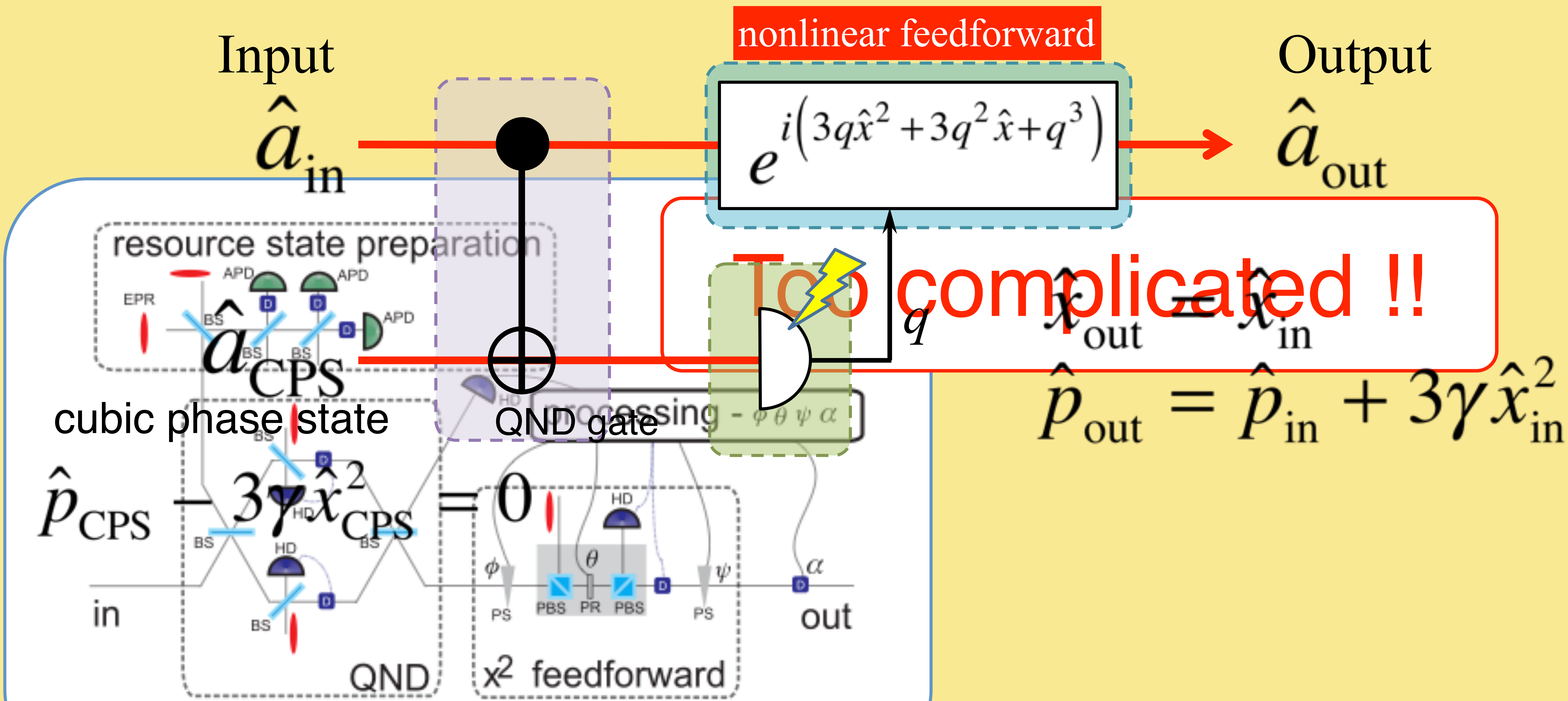
Gate teleportation

Cubic phase gate with gate teleportation

Fault tolerant

Heisenberg picture

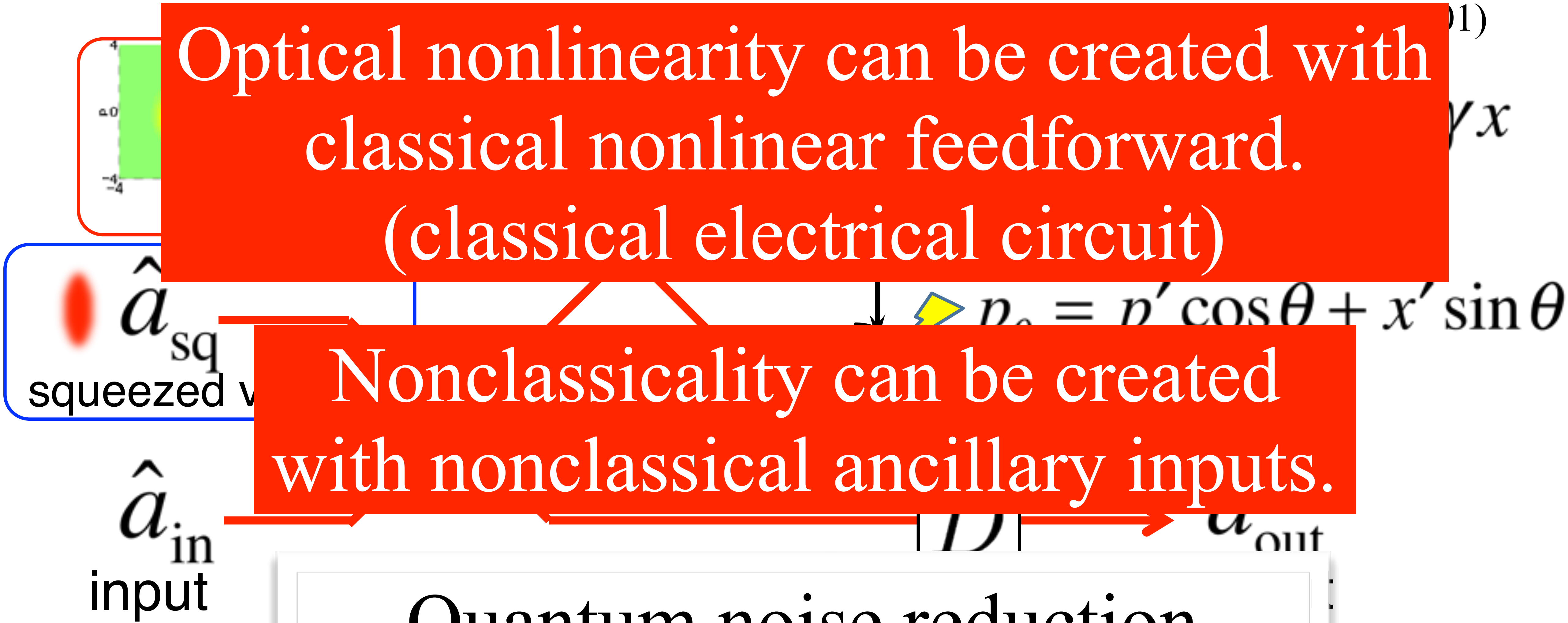
Gottesman et al. PRA **64,** 012310 (2001)



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

P. Marek et al. PRA **84,** 053802 (2011)

Cubic phase gate with gate teleportation



Optical nonlinearity can be created with classical nonlinear feedforward. (classical electrical circuit)

Nonclassicality can be created with nonclassical ancillary inputs.

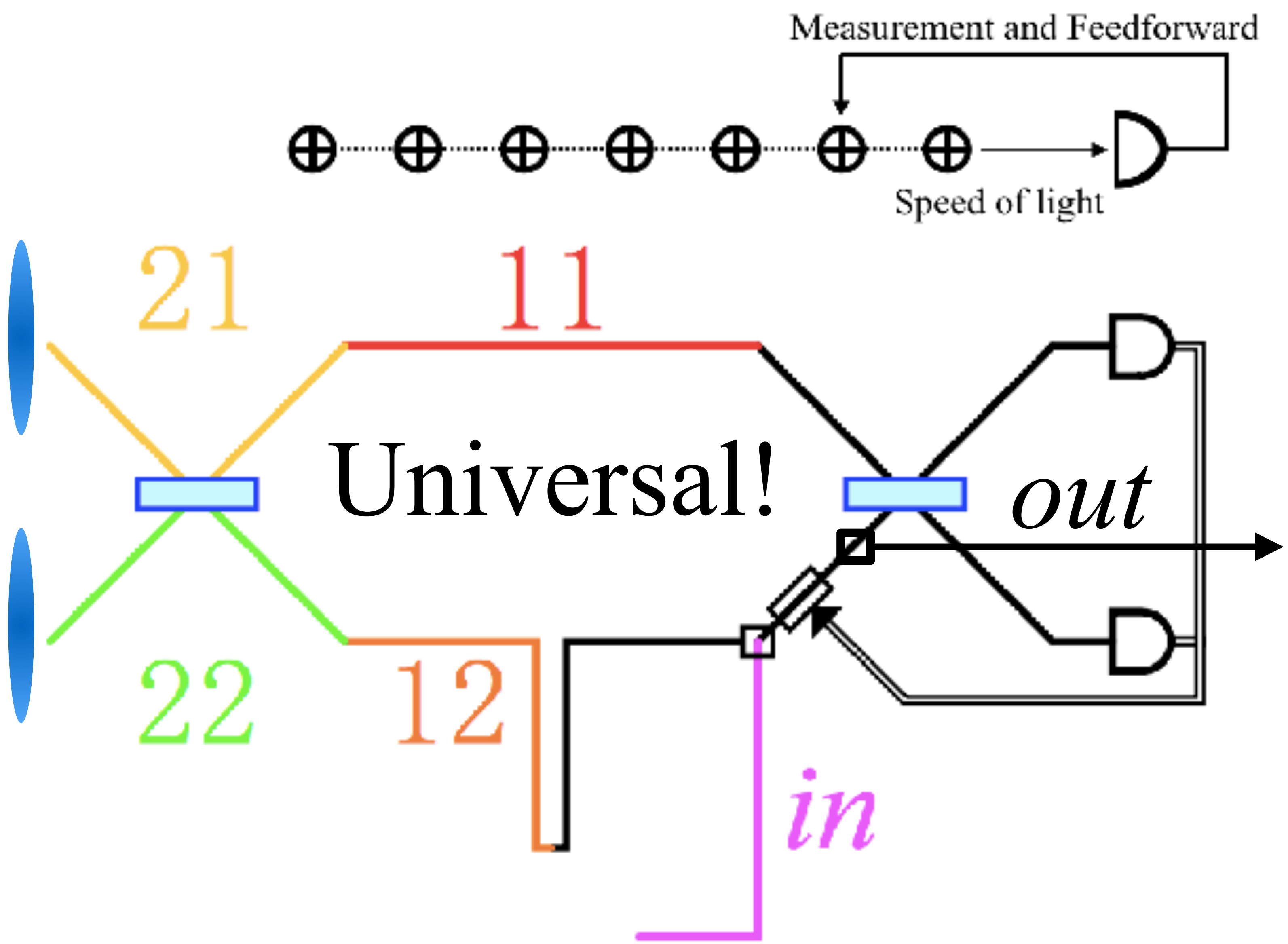
Quantum noise reduction with nonclassical states of light

$$\hat{x}_{out} = \frac{1}{\sqrt{2}}\hat{x}_{in} \ldots \frac{\ldots}{\sqrt{2}}\hat{x}_{sq}$$

$$\hat{p}_{out} = \sqrt{2}\left(\hat{p}_{in} + \frac{3}{2\sqrt{2}}\gamma\hat{x}_{in}^2\right) + \left(\hat{p}_{CPS} - 3\gamma\hat{x}_{CPS}^2\right) + \frac{3}{2}\gamma\left(\hat{x}_{sq}^2 + 2\hat{x}_{in}\hat{x}_{sq}\right)$$

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

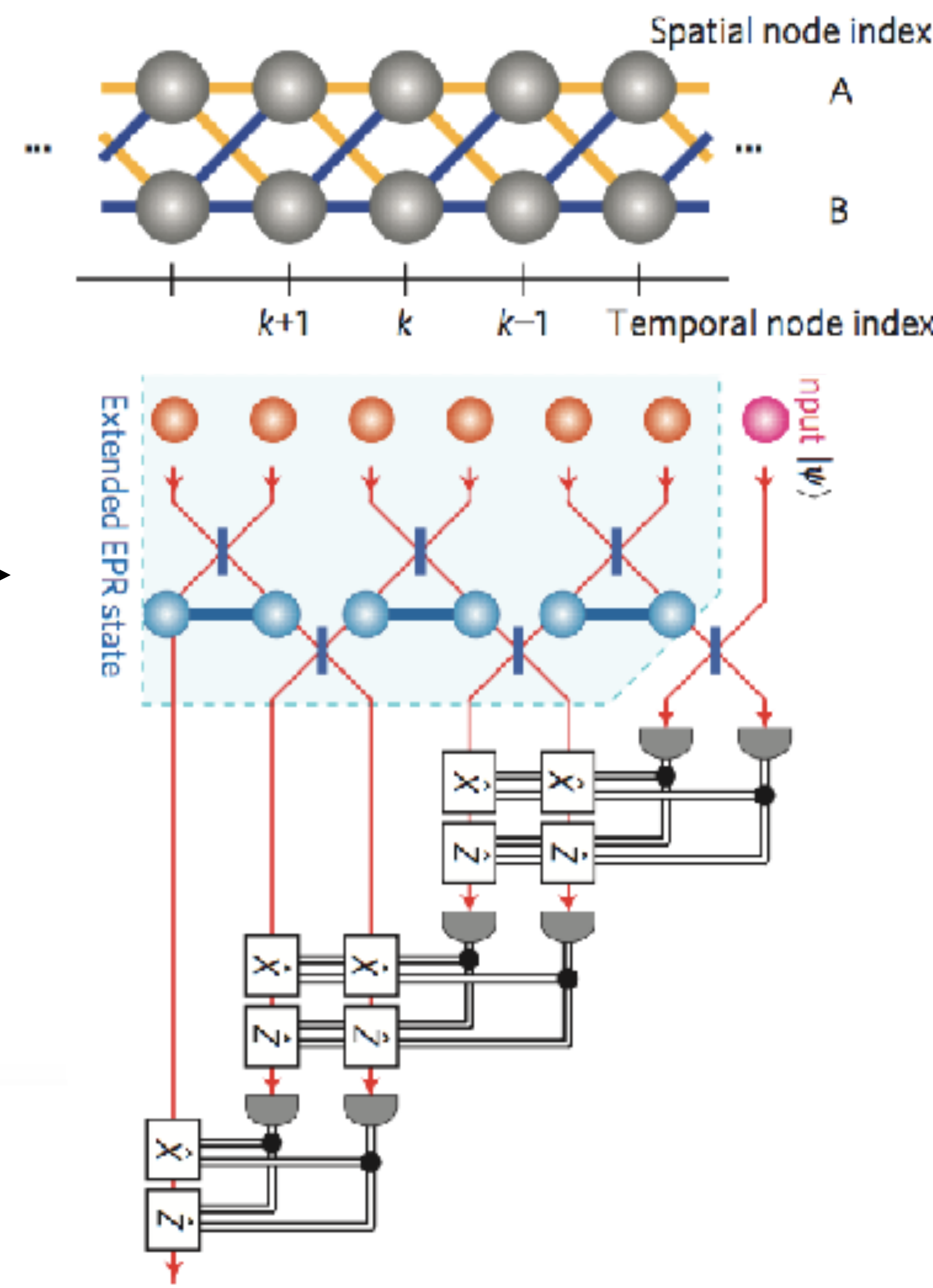
Unlimited one-way universal quantum computing



single-mode operations

Homodyne measurement:
universal Gaussian operations

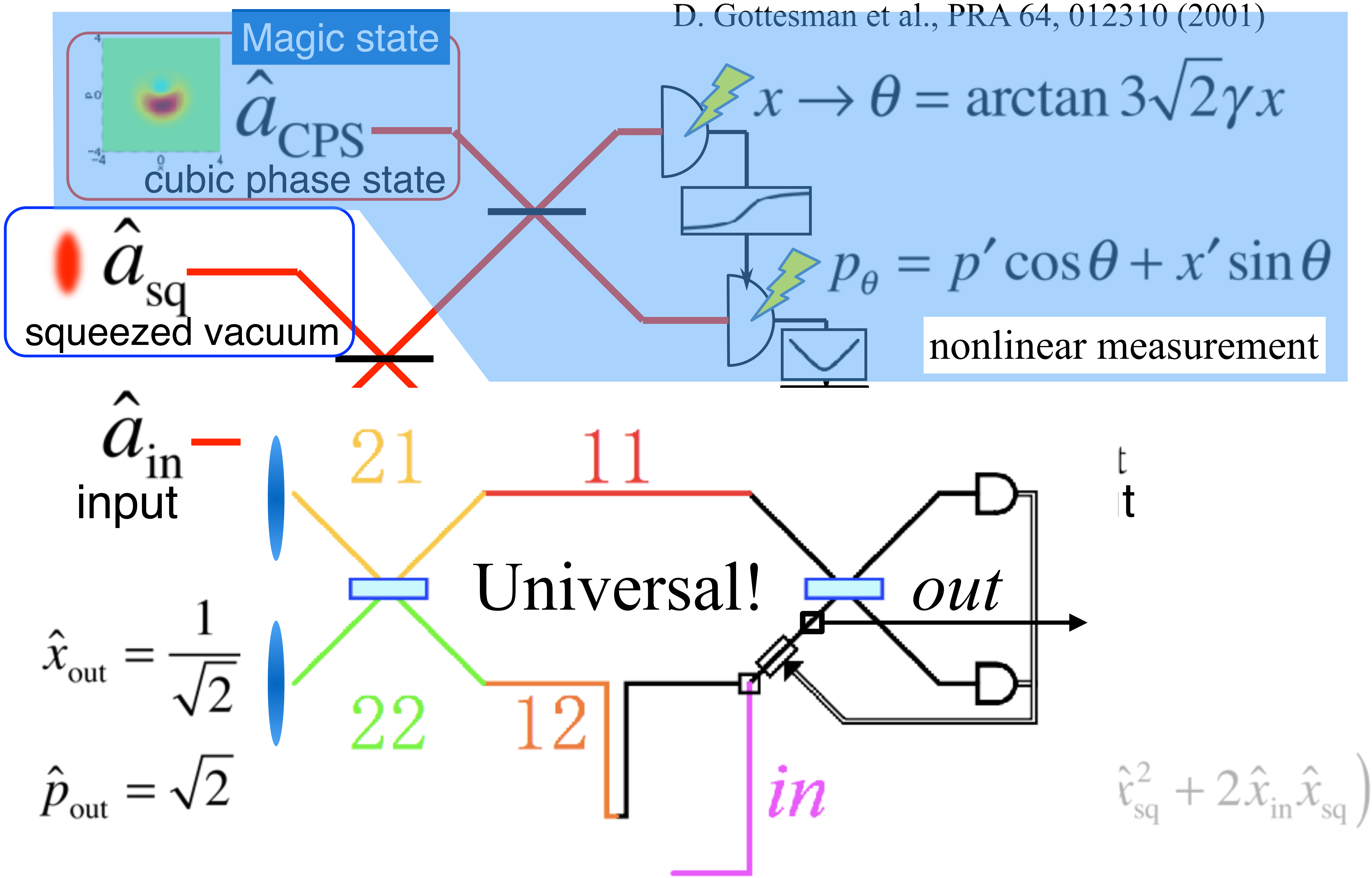
+ one nonlinear measurement:
universal operations



sequential quantum teleportation

S. Yokoyama et al.,
Nature Photonics 7, 982 (2013).

Cubic phase gate with gate teleportation



K. Miyata, H. Ogaw … A **93**, 022301 (2016)

Cubic phase state

Schrödinger picture

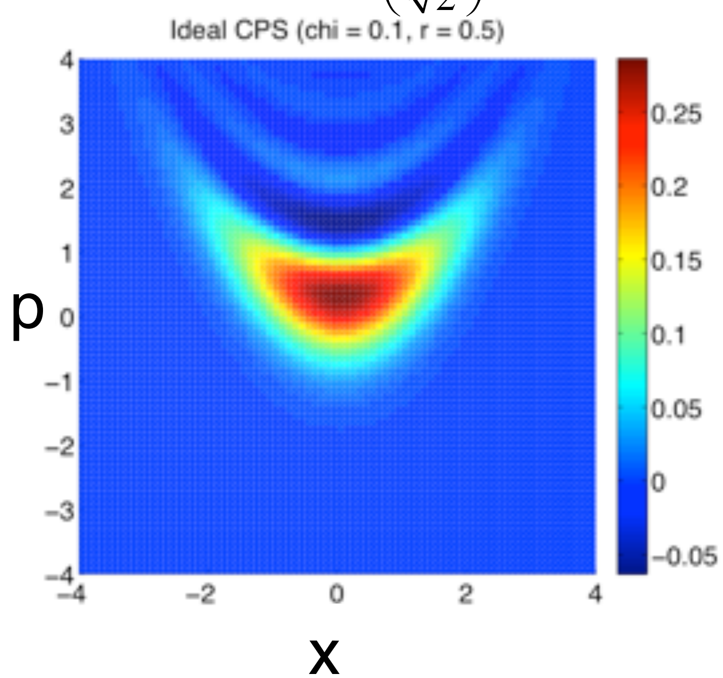
$$e^{i\gamma\hat{x}^3}\,|\,p=0\rangle$$

$$\begin{pmatrix} 1 & 0 \\ 0 & e^{i\frac{\pi}{4}} \end{pmatrix}\begin{pmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{pmatrix} = \frac{|0\rangle + e^{i\frac{\pi}{4}}|1\rangle}{\sqrt{2}}$$

Magic state

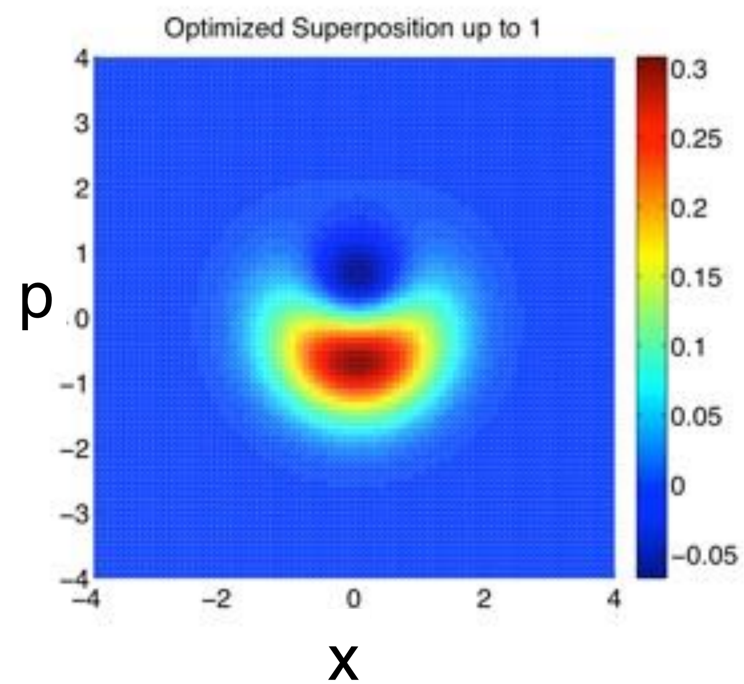
Heisenberg picture

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



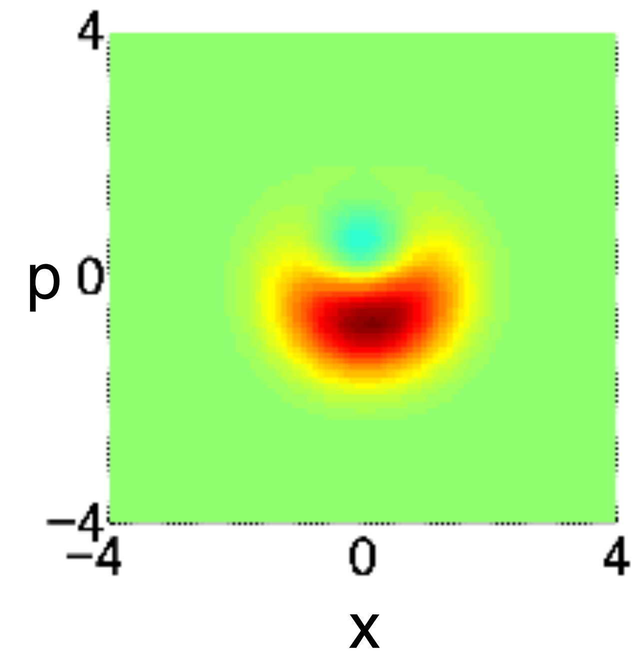
Simulation

- finite squeezing



Simulation

- 0 & 1 photon

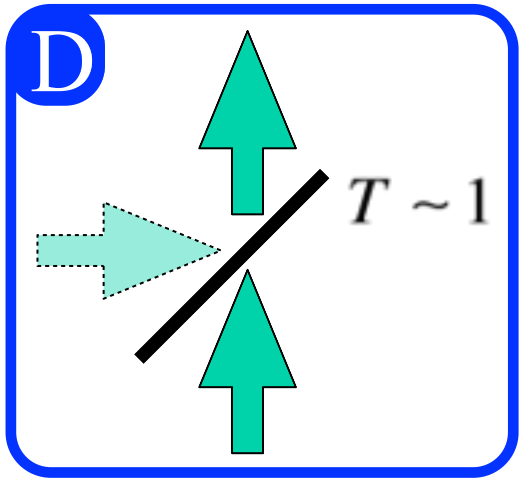


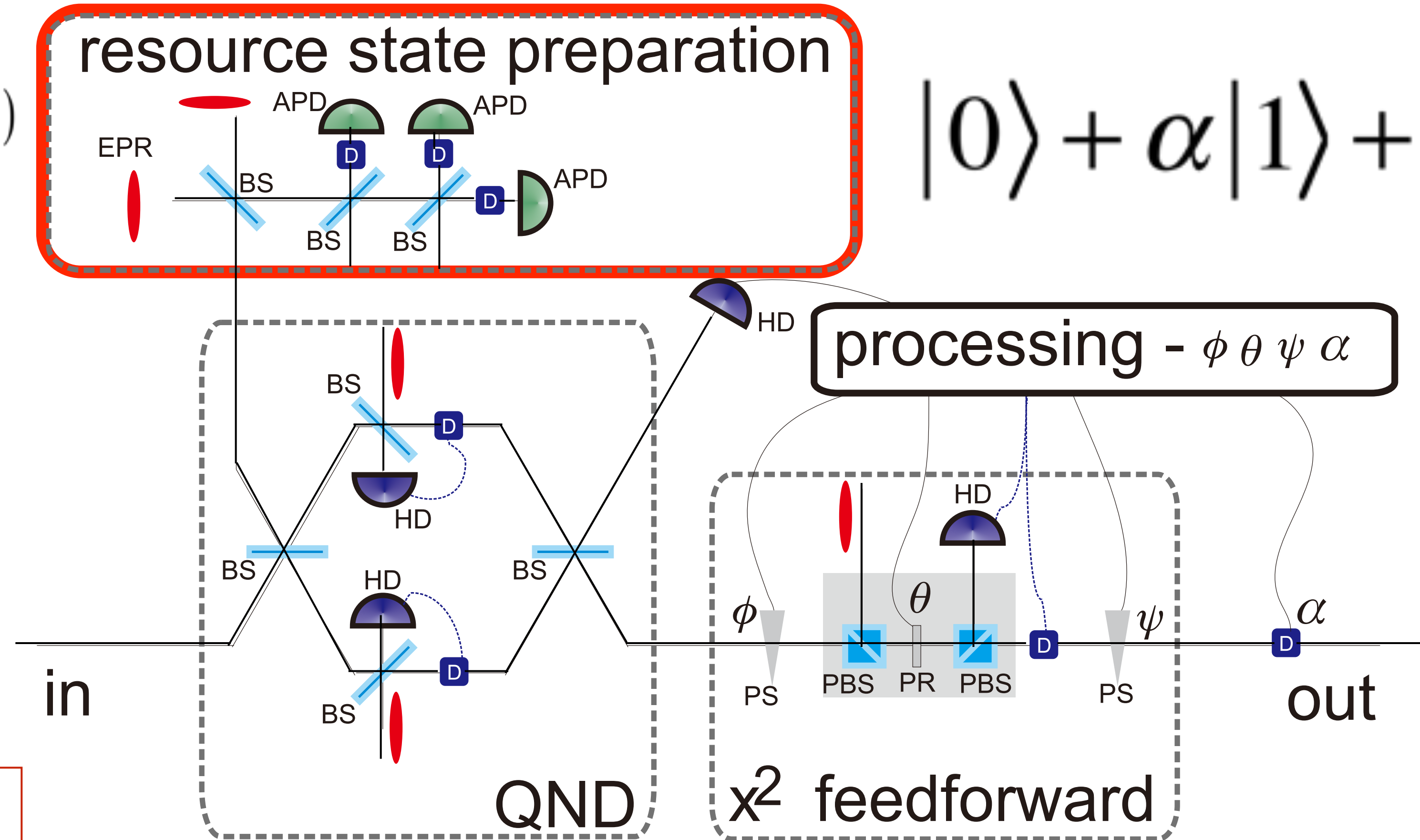
Experiment

- 0 & 1 photon

$$\sqrt{1-q^2}\sum_{n=0}^{\infty} q^n |n\rangle_S |n\rangle_I$$

$$\approx \sqrt{1-q^2}\left(|0\rangle_S|0\rangle_I + q|1\rangle_S|1\rangle_I + q^2|2\rangle_S|2\rangle_I + q^3|3\rangle_S|3\rangle_I\right)$$



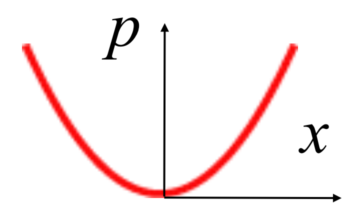


$$|0\rangle + \alpha|1\rangle + \beta|3\rangle$$

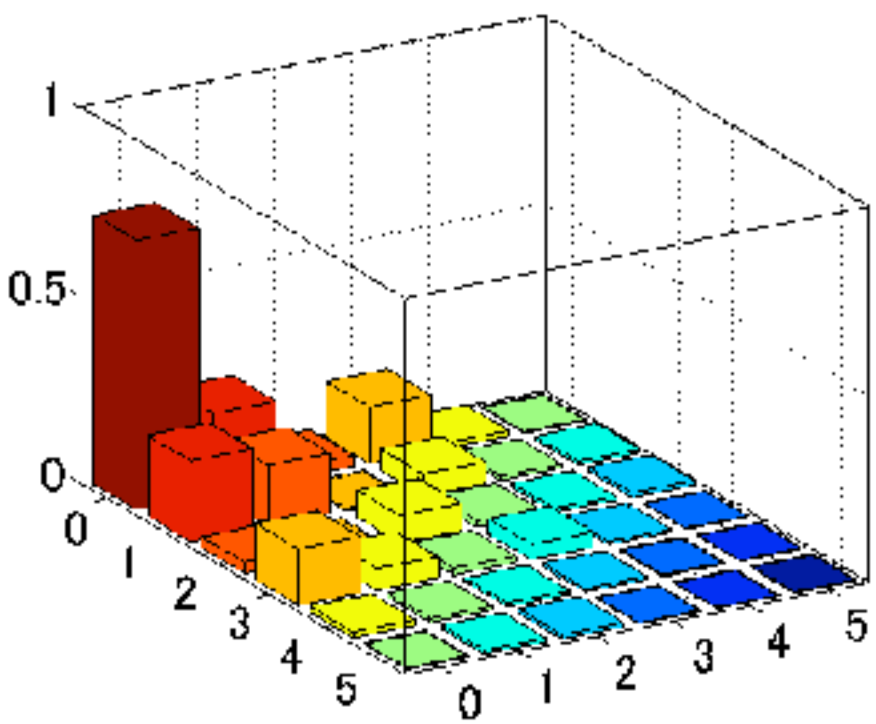
P. Marek, R. Filip, A. Furusawa, Phys. Rev. A **84**, 053802 (2011)

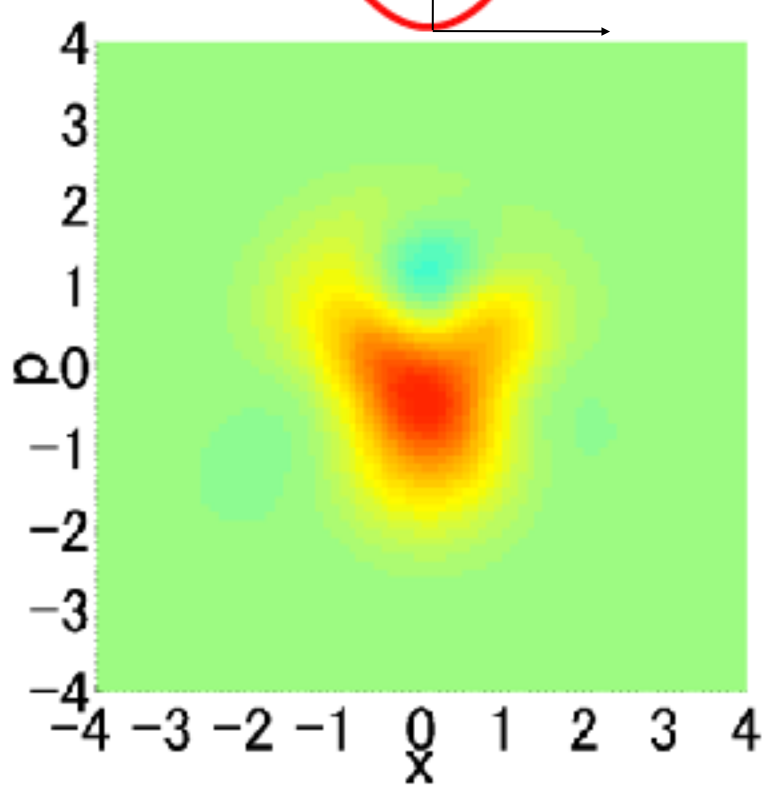
Approximate cubic phase state
CV version of a magic state

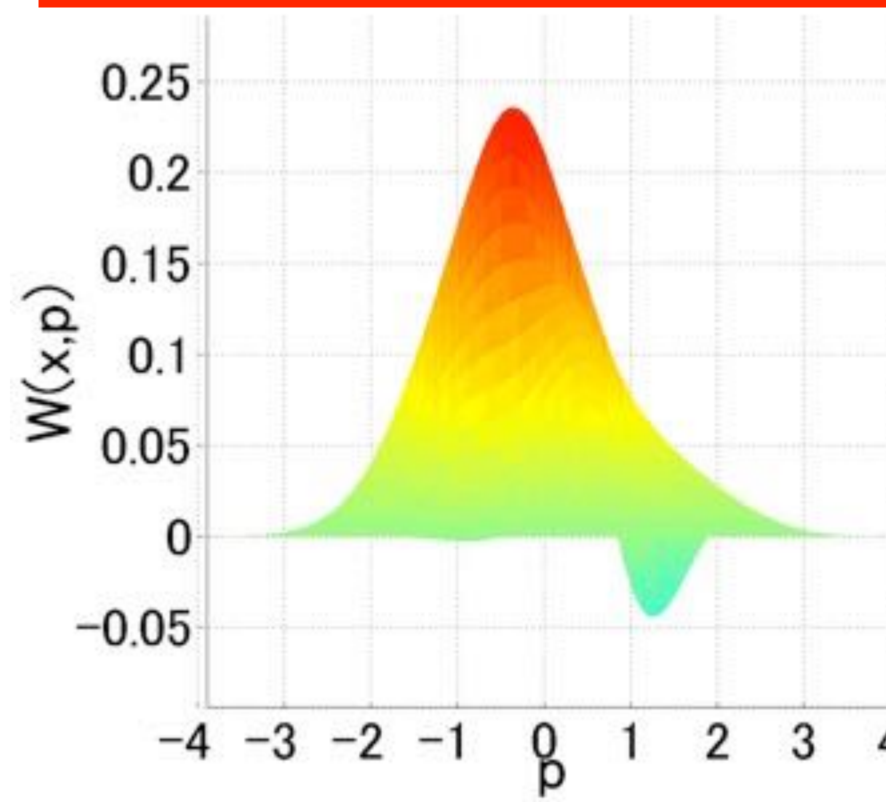
$$|0\rangle + 0.53|1\rangle + 0.43|3\rangle$$



without any correction!!

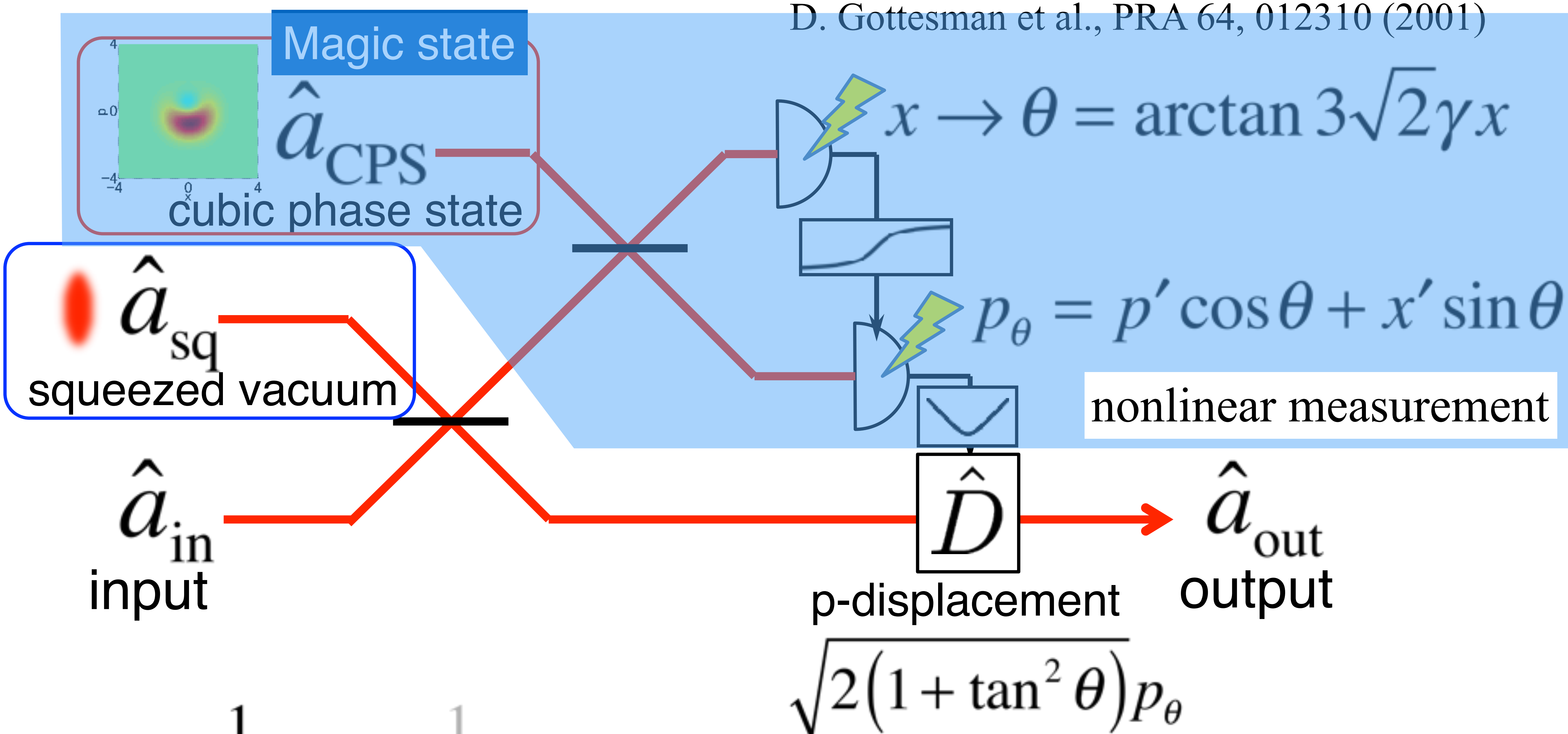






M. Yukawa, K. Miyata, H. Yonezawa, P. Marek, R. Filip, and A. Furusawa, Phys. Rev. A **88**, 053816 (2013)

How to realize a nonlinear gate with gate teleportation
Cubic phase gate (CV version of a π/8 gate)



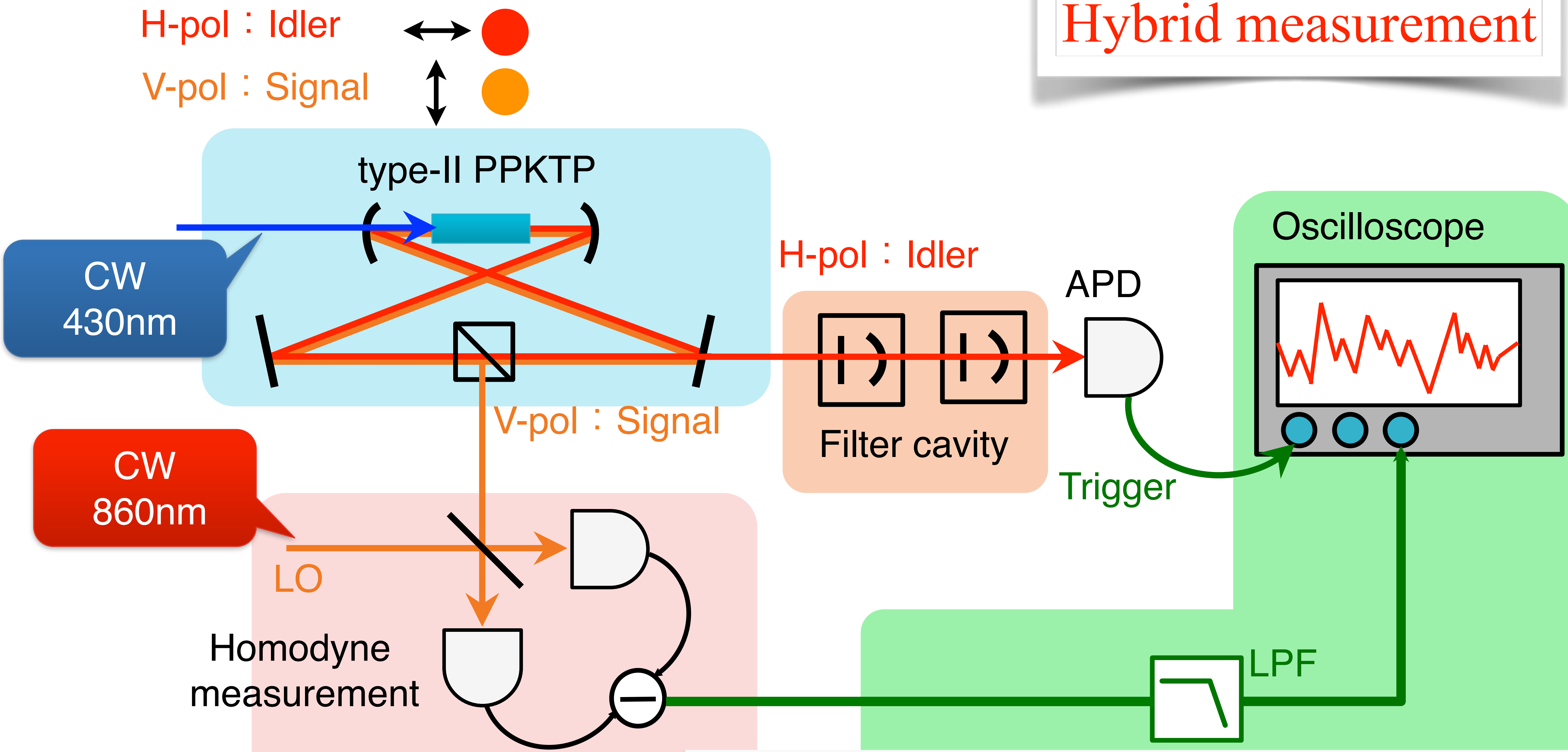
$$\hat{x}_{\mathrm{out}} = \frac{1}{\sqrt{2}}\hat{x}_{\mathrm{in}} - \frac{1}{\sqrt{2}}\hat{x}_{\mathrm{sq}}$$

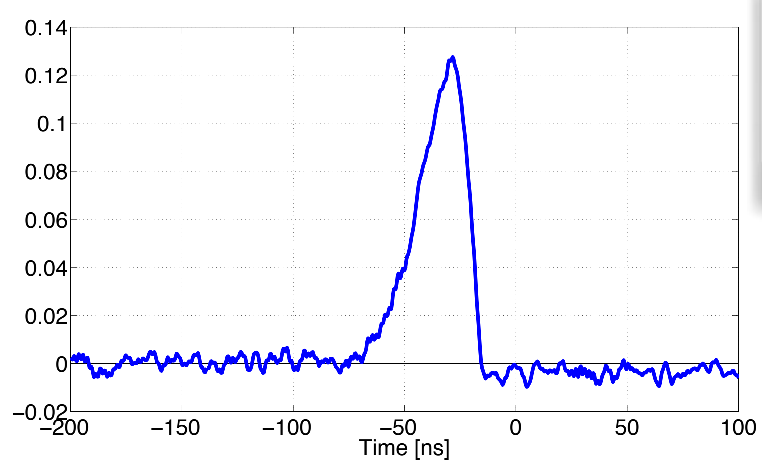
$$\hat{p}_{\mathrm{out}} = \sqrt{2}\left(\hat{p}_{\mathrm{in}} + \frac{3}{2\sqrt{2}}\gamma\hat{x}_{\mathrm{in}}^2\right) + \left(\hat{p}_{\mathrm{CPS}} - 3\gamma\hat{x}_{\mathrm{CPS}}^2\right) + \frac{3}{2}\gamma\left(\hat{x}_{\mathrm{sq}}^2 + 2\hat{x}_{\mathrm{in}}\hat{x}_{\mathrm{sq}}\right)$$

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

Real-time quadrature-amplitude measurement of single photons

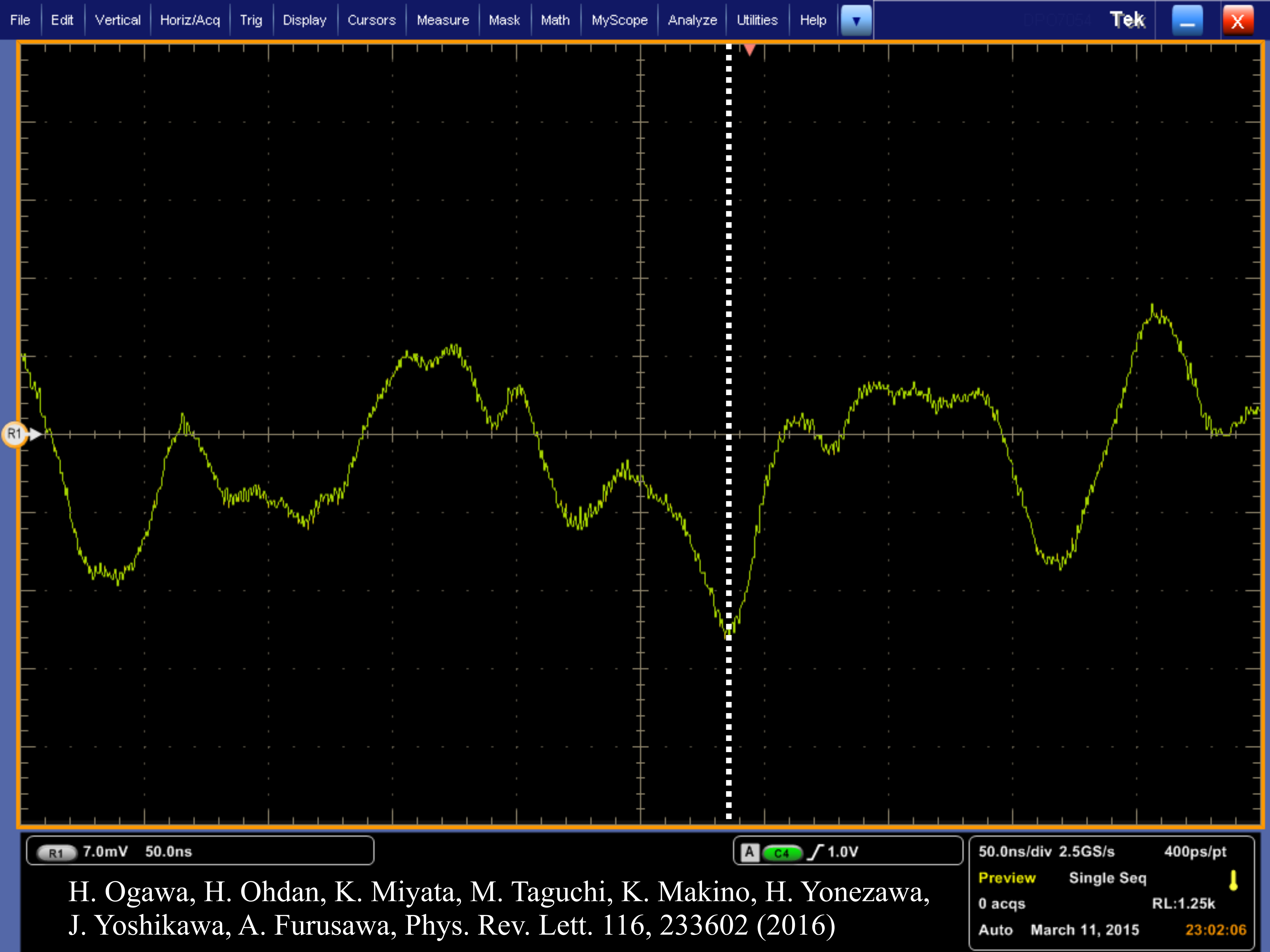
Hybrid measurement





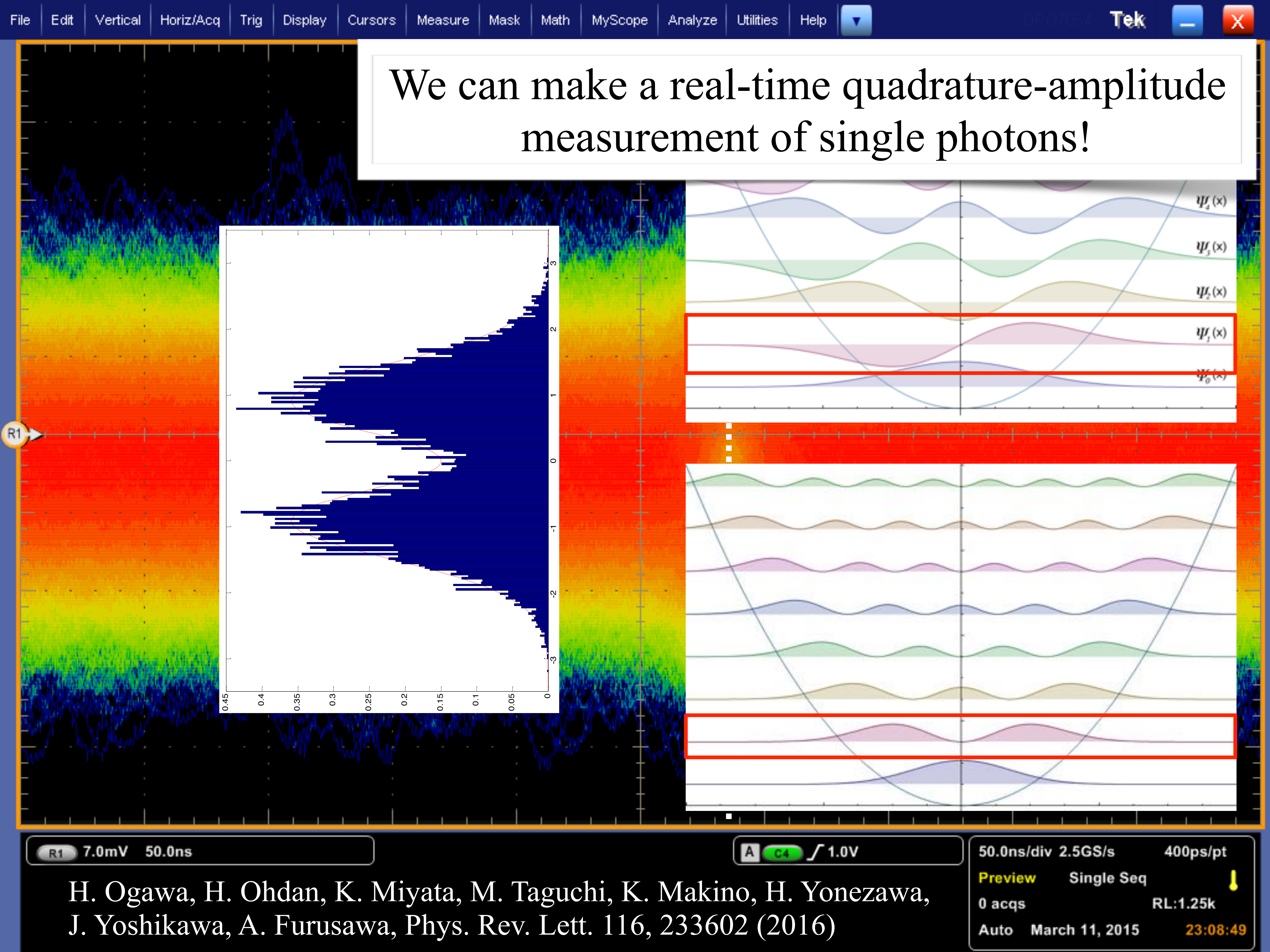
Continuous temporal-mode-matching

H. Ogawa, H. Ohdan, K. Miyata, M. Taguchi,
K. Makino, H. Yonezawa, J. Yoshikawa, A. Furusawa,
Phys. Rev. Lett. 116, 233602 (2016)



H. Ogawa, H. Ohdan, K. Miyata, M. Taguchi, K. Makino, H. Yonezawa, J. Yoshikawa, A. Furusawa, Phys. Rev. Lett. 116, 233602 (2016)

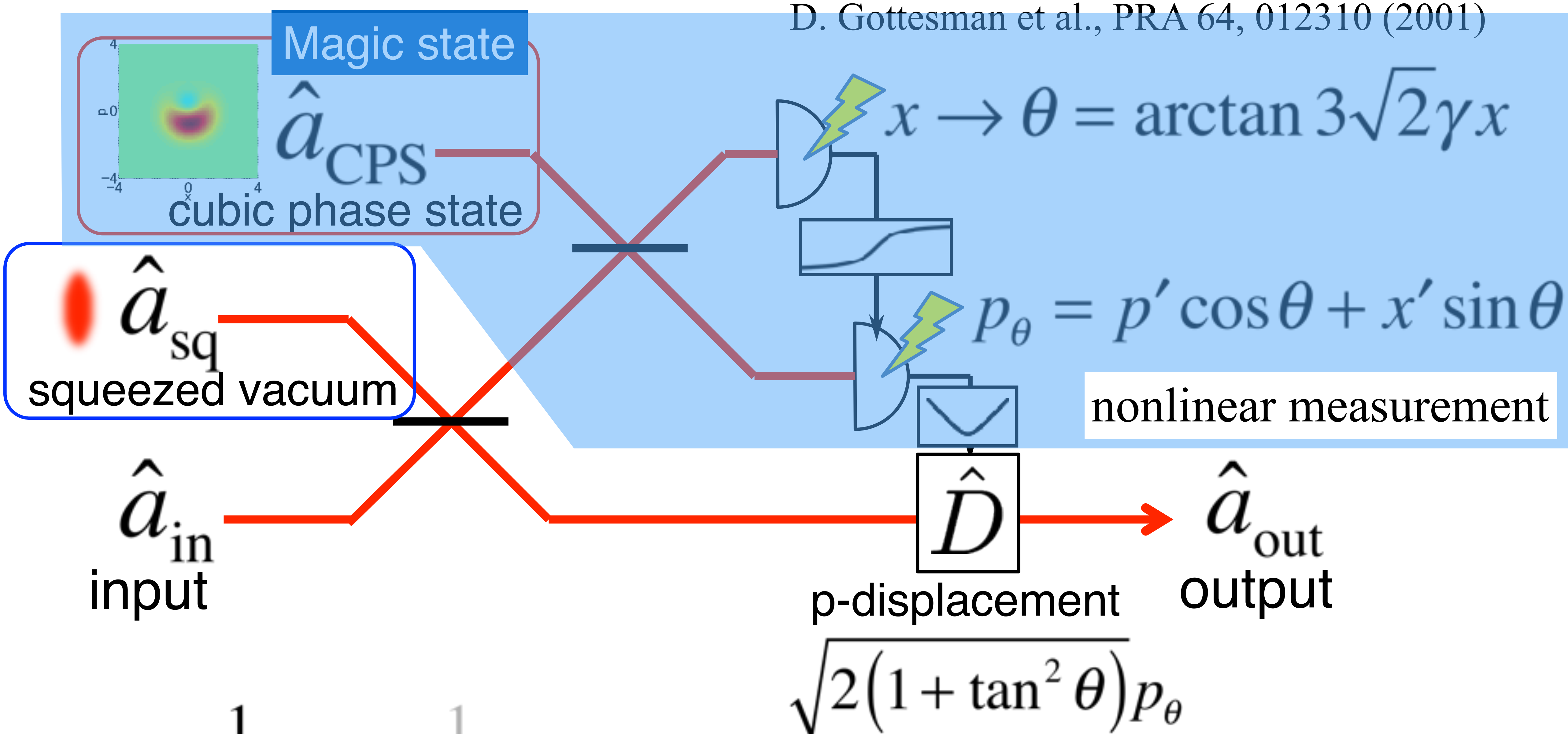
We can make a real-time quadrature-amplitude measurement of single photons!



H. Ogawa, H. Ohdan, K. Miyata, M. Taguchi, K. Makino, H. Yonezawa, J. Yoshikawa, A. Furusawa, Phys. Rev. Lett. 116, 233602 (2016)

How to realize a nonlinear gate with gate teleportation
Cubic phase gate (CV version of a π/8 gate)

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

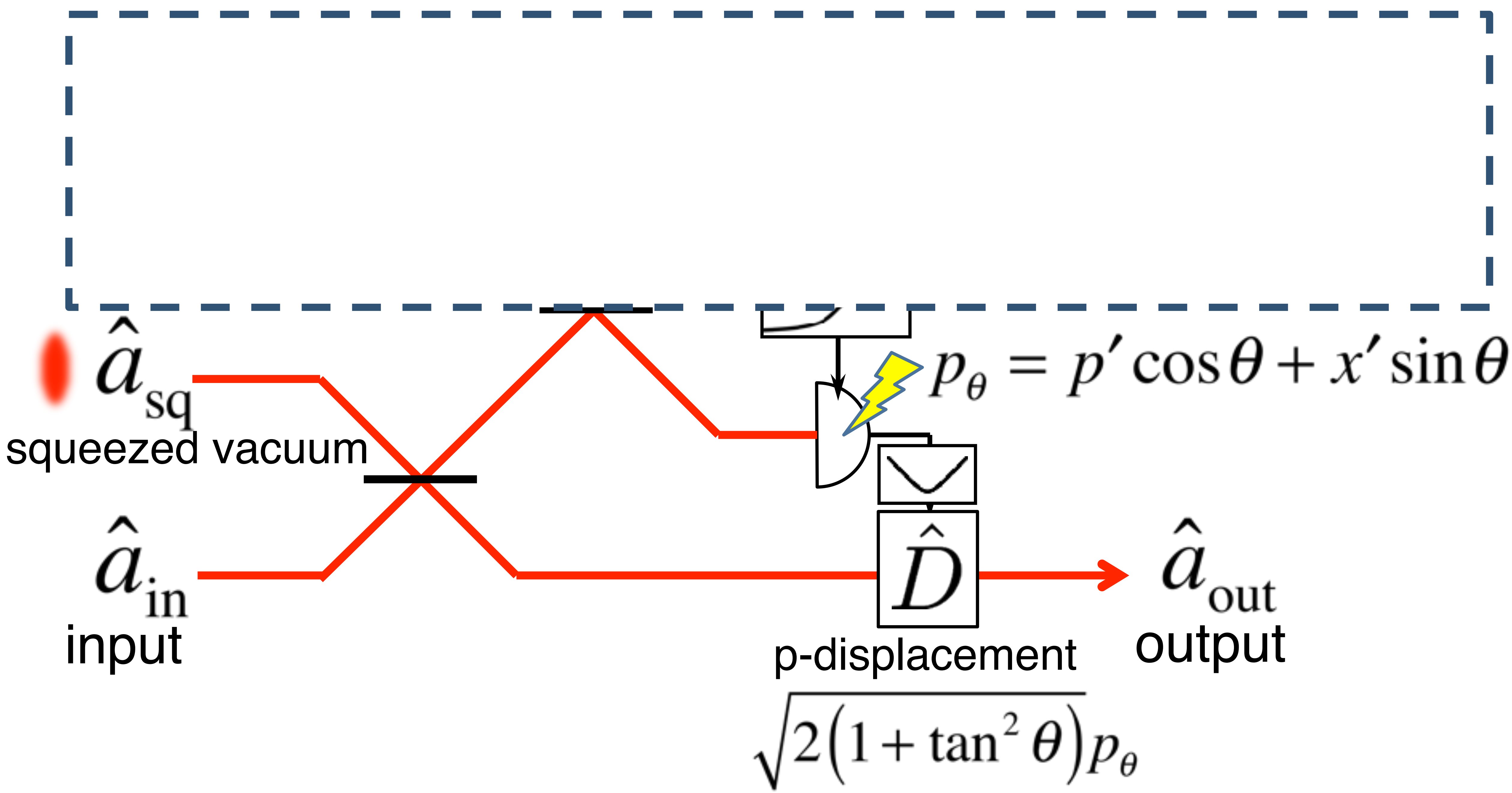


$$\hat{x}_{\mathrm{out}} = \frac{1}{\sqrt{2}}\hat{x}_{\mathrm{in}} - \frac{1}{\sqrt{2}}\hat{x}_{\mathrm{sq}}$$

$$\hat{p}_{\mathrm{out}} = \sqrt{2}\left(\hat{p}_{\mathrm{in}} + \frac{3}{2\sqrt{2}}\gamma\hat{x}_{\mathrm{in}}^2\right) + \left(\hat{p}_{\mathrm{CPS}} - 3\gamma\hat{x}_{\mathrm{CPS}}^2\right) + \frac{3}{2}\gamma\left(\hat{x}_{\mathrm{sq}}^2 + 2\hat{x}_{\mathrm{in}}\hat{x}_{\mathrm{sq}}\right)$$

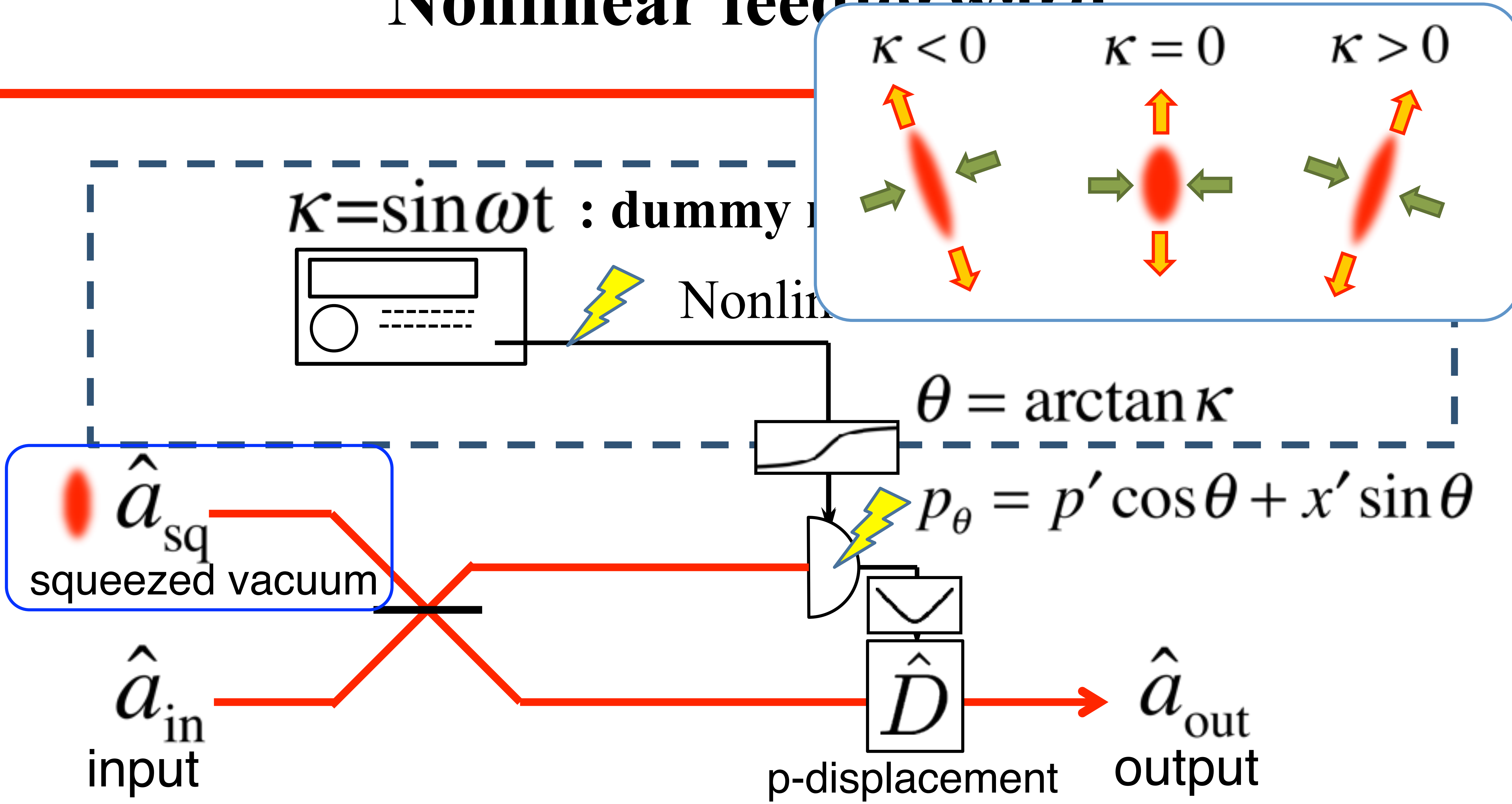
K. Miyata, H. Ogawa, P. Marek, R. Filip, H. Yonezawa, J. Yoshikawa, and A. Furusawa, PRA **93**, 022301 (2016)

Nonlinear feedforward



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

Nonlinear feedforward



$$\sqrt{2\left(1+\kappa^2\right)}\,p_\theta$$

$$\hat{x}_{out} = \frac{1}{\sqrt{2}}\hat{x}_{in} - \frac{1}{\sqrt{2}}\hat{x}_{sq}$$

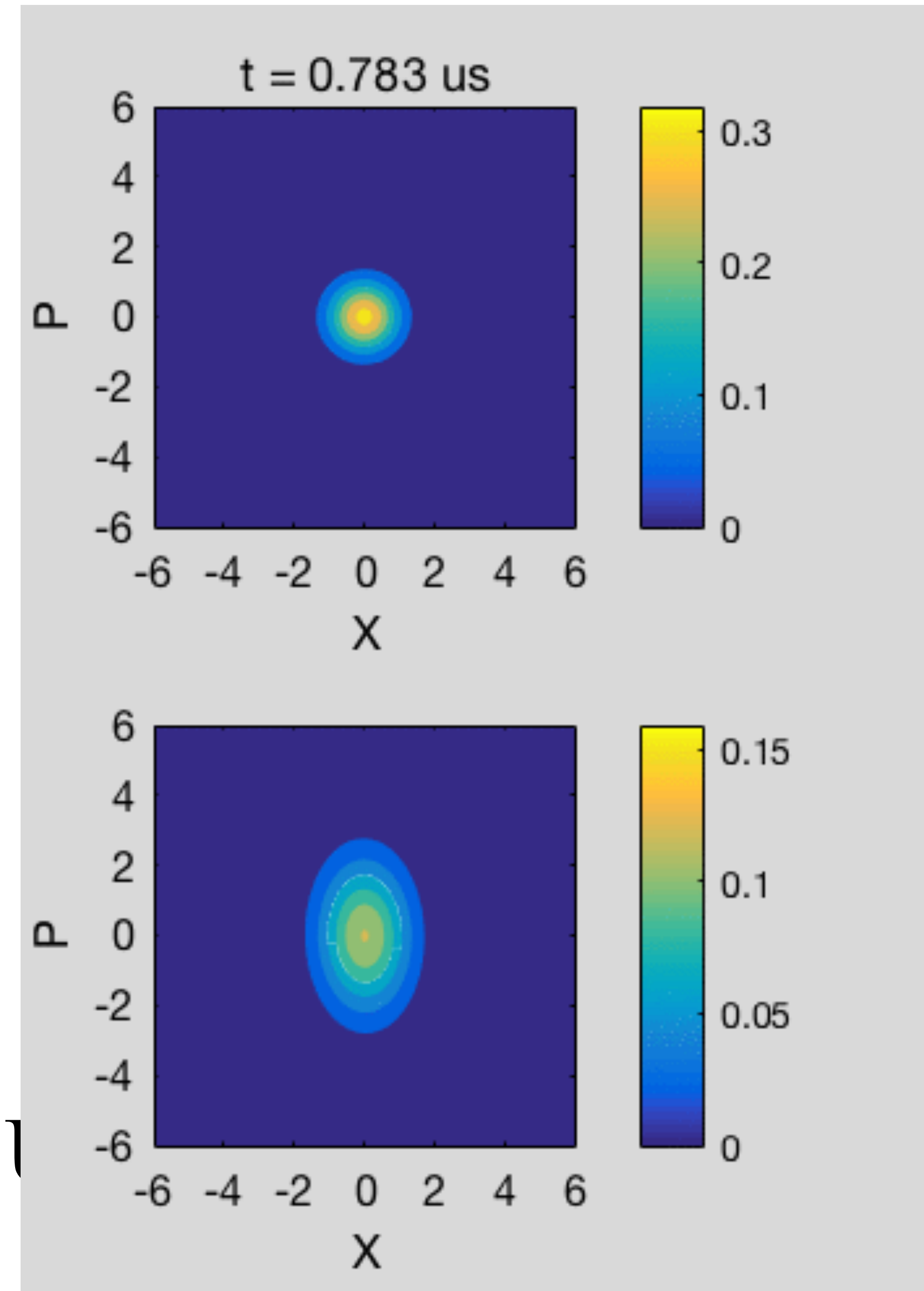
$$\hat{p}_{out} = \sqrt{2}\left(\hat{p}_{in} + \frac{\kappa}{2}\hat{x}_{in}\right) + \frac{\kappa}{\sqrt{2}}\hat{x}_{sq}$$

Dynamic squeezing gate

measurement result

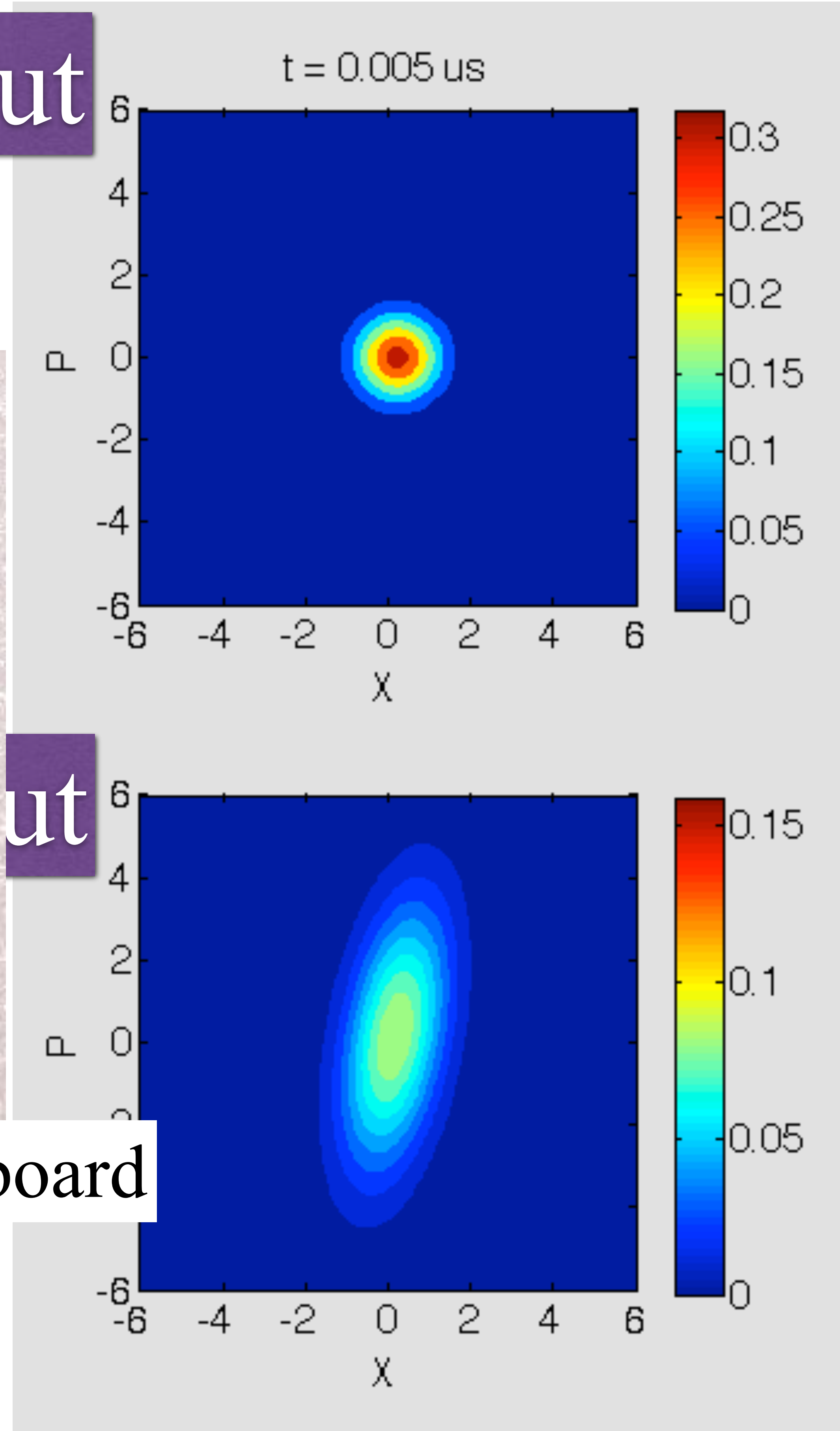
$\kappa = \sin \omega t$

$\omega = 1\,\mathrm{MHz}$



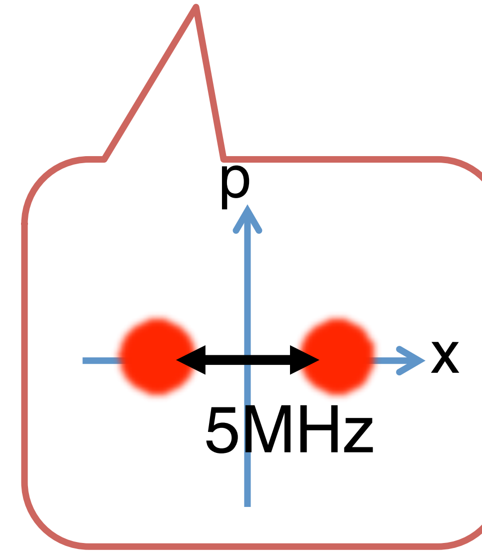
Dynamic squeezing gate

Input



ut

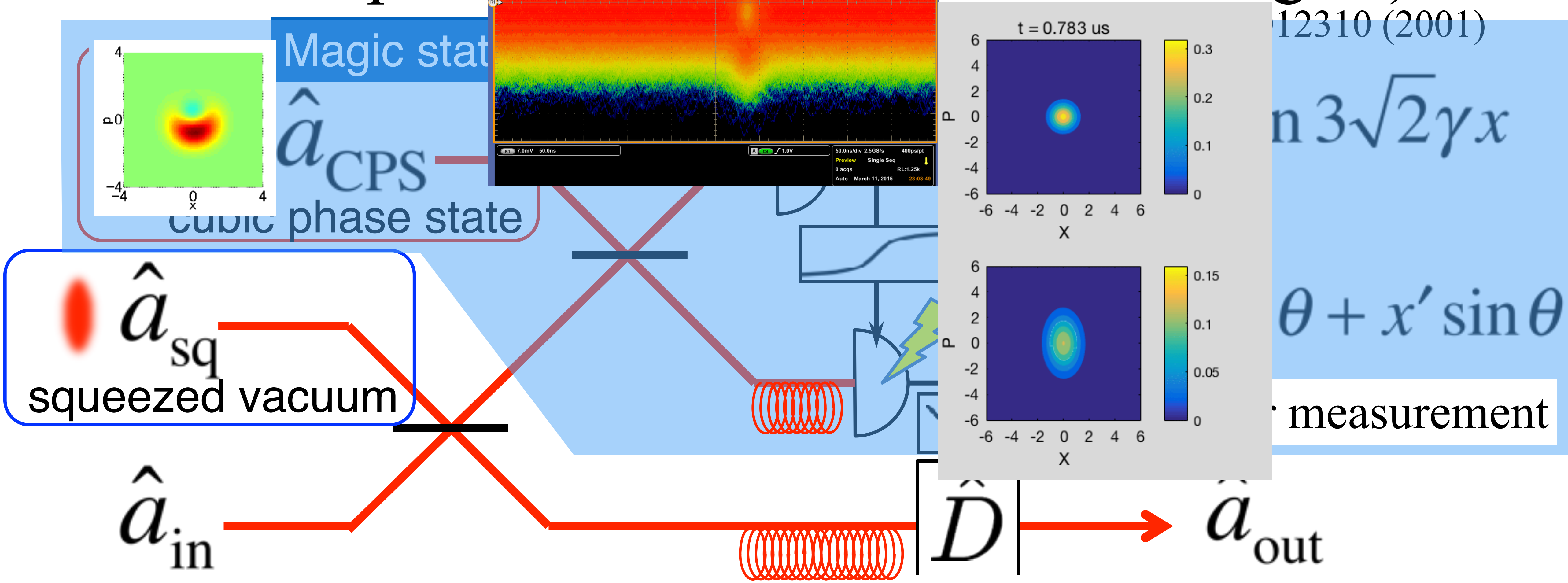
board

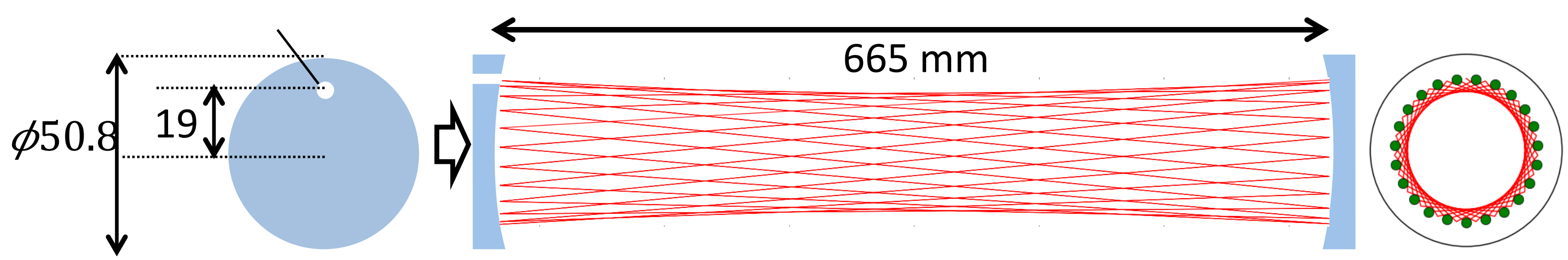


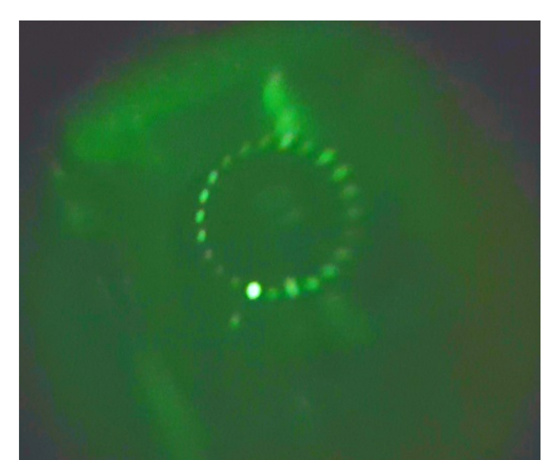
Time-varying Hamiltonian!

K. Miyata, H. Ogawa, P. Marek, R. Filip, H. Yonezawa, J. Yoshikawa, A. Furusawa, PRA 90, 060302(R) (2014)

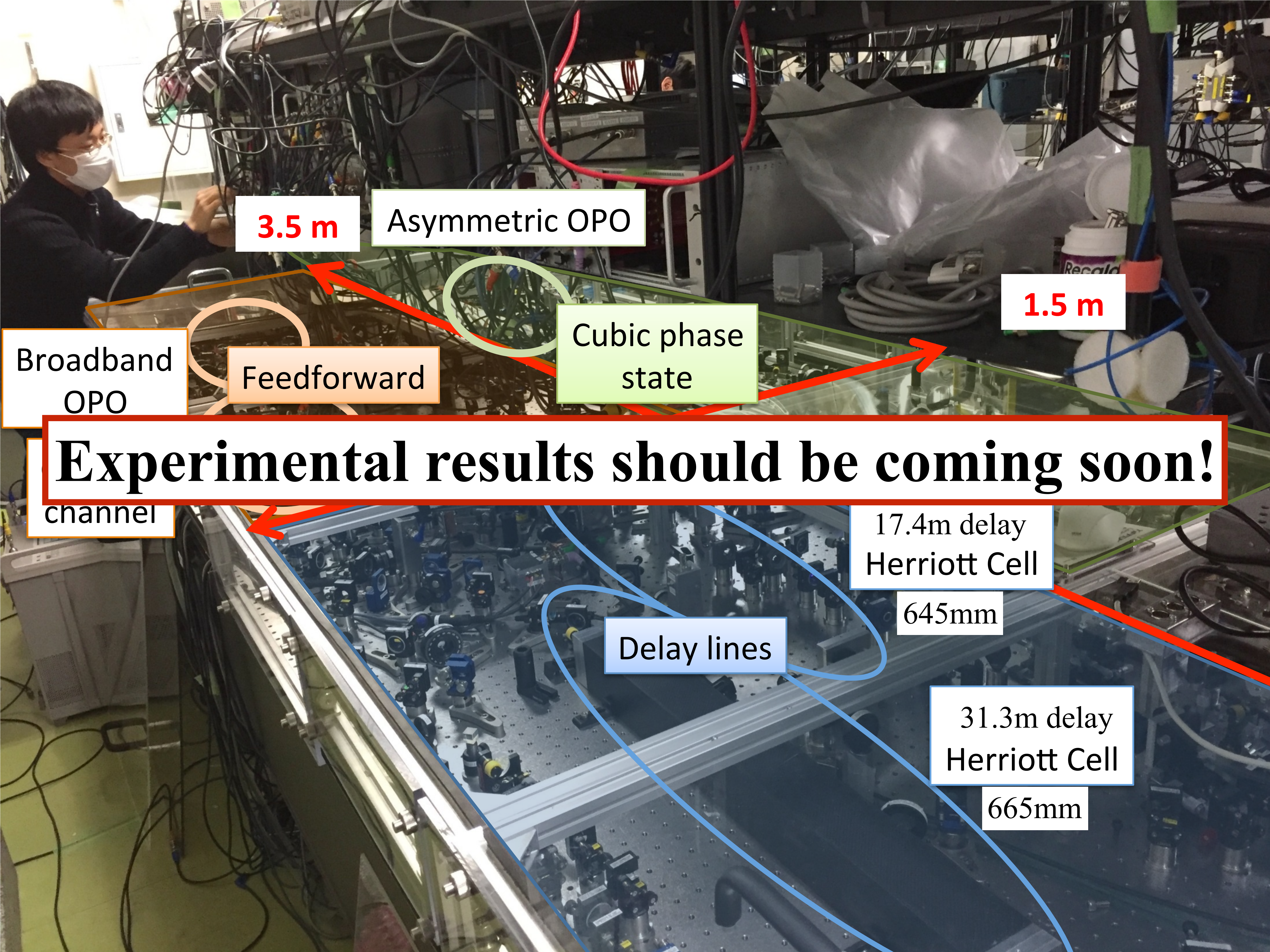
How to realize a … with gate teleportation
Cubic phas… …ion of a π/8 gate)



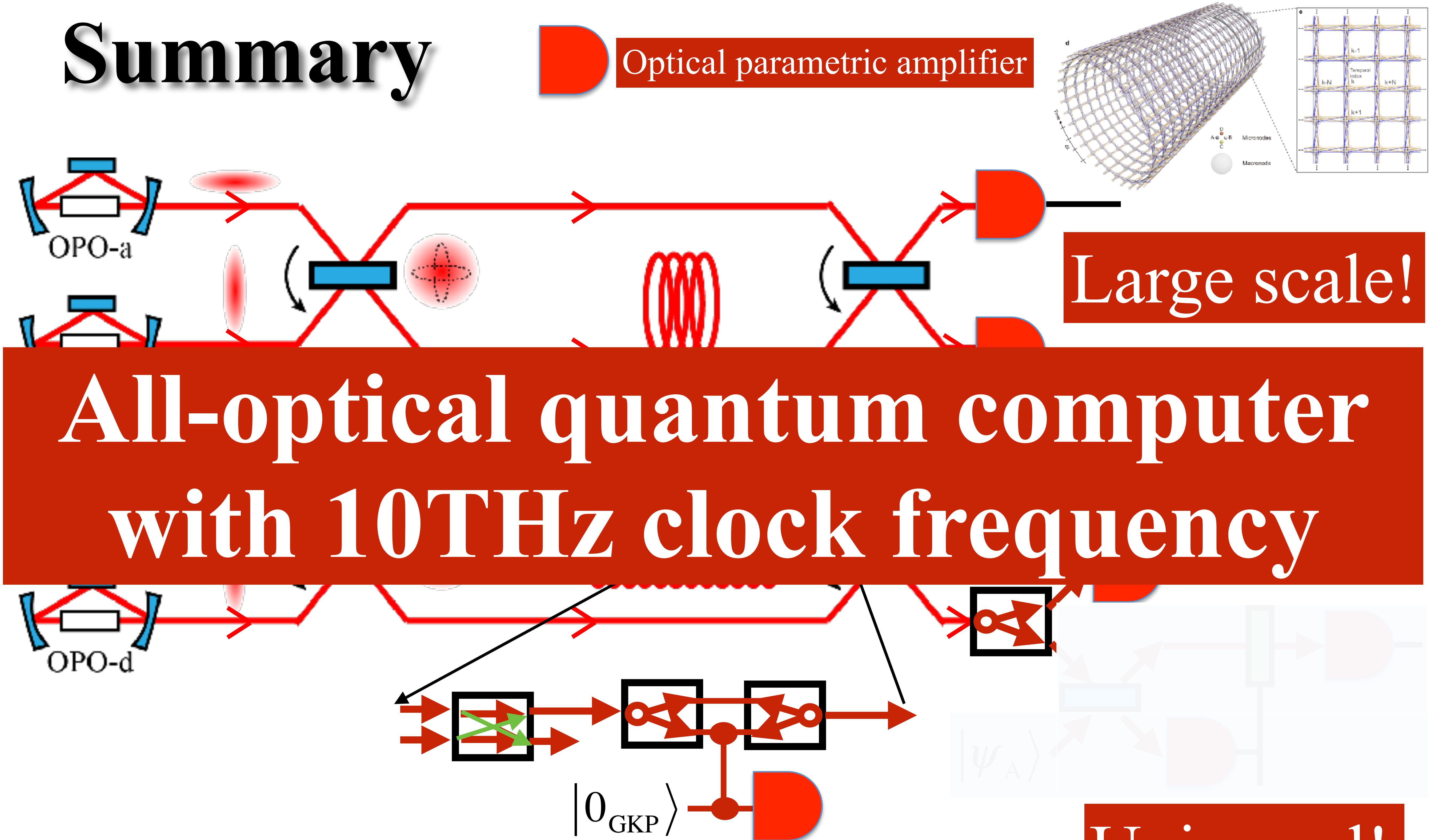




30m optical delay


3.5 m
Asymmetric OPO
1.5 m
Broadband OPO
Feedforward
Cubic phase state
Experimental results should be coming soon!
channel
17.4m delay Herriott Cell
645mm
Delay lines
31.3m delay Herriott Cell
665mm

Summary



Large scale!

All-optical quantum computer with 10THz clock frequency

Universal!

Fault tolerant!

B. Q. Baragiola et al., arXiv:1903.00012