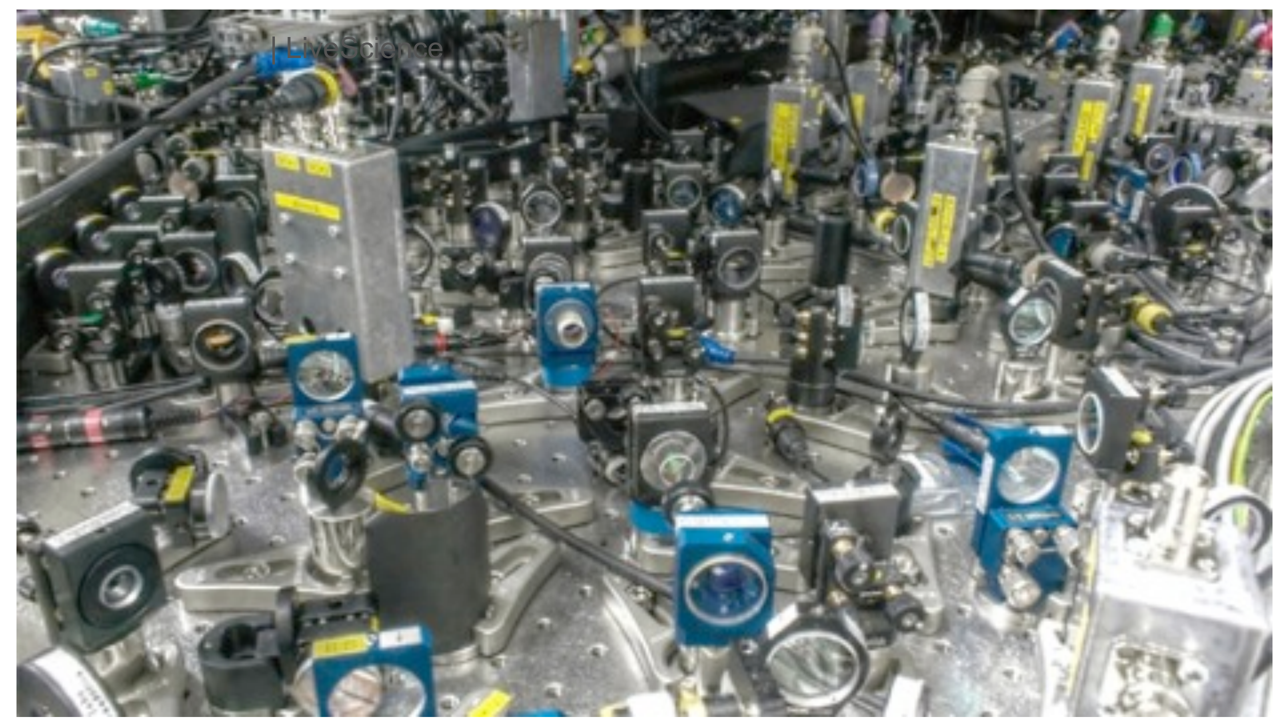
Theoretical Science Colloquium
Okochi Memorial Hall, Riken,
May 31, 2013

SCIENCE

Quantum Leap: Scientists Teleport Bits of Light

By Clara Moskowitz
Published April 14, 2011



Quantum information processing for coherent communication

Akira Furusawa

Department of Applied Physics, The University of Tokyo

Collaborators

A. Furusawa Univ. of Tokyo
H. Yonezawa, J. Yoshikawa,
S. Takeda, S. Yokoyama, K. Miyata, K. Makino, M. Fuwa,
C. Sornphiphatphong, H. Ogawa, T. Kaji, Y. Hashimoto,
H. Odan, S. Toba, T. Serikawa, S. Suzuki,
S. C. Armstrong (ANU), G. Masada (Tamagawa)

P. van Loock (Mainz), R. Filip (Palacky), L. Mista (Palacky),
P. Marek (Palacky), J. L. O'Brien (Bristol), A. Politi (UCSB),
E. H. Huntington (ADFA), T. Ralph (UQ), H. Wiseman (GU),
N. Menicucci (Sydney)

Physical process of

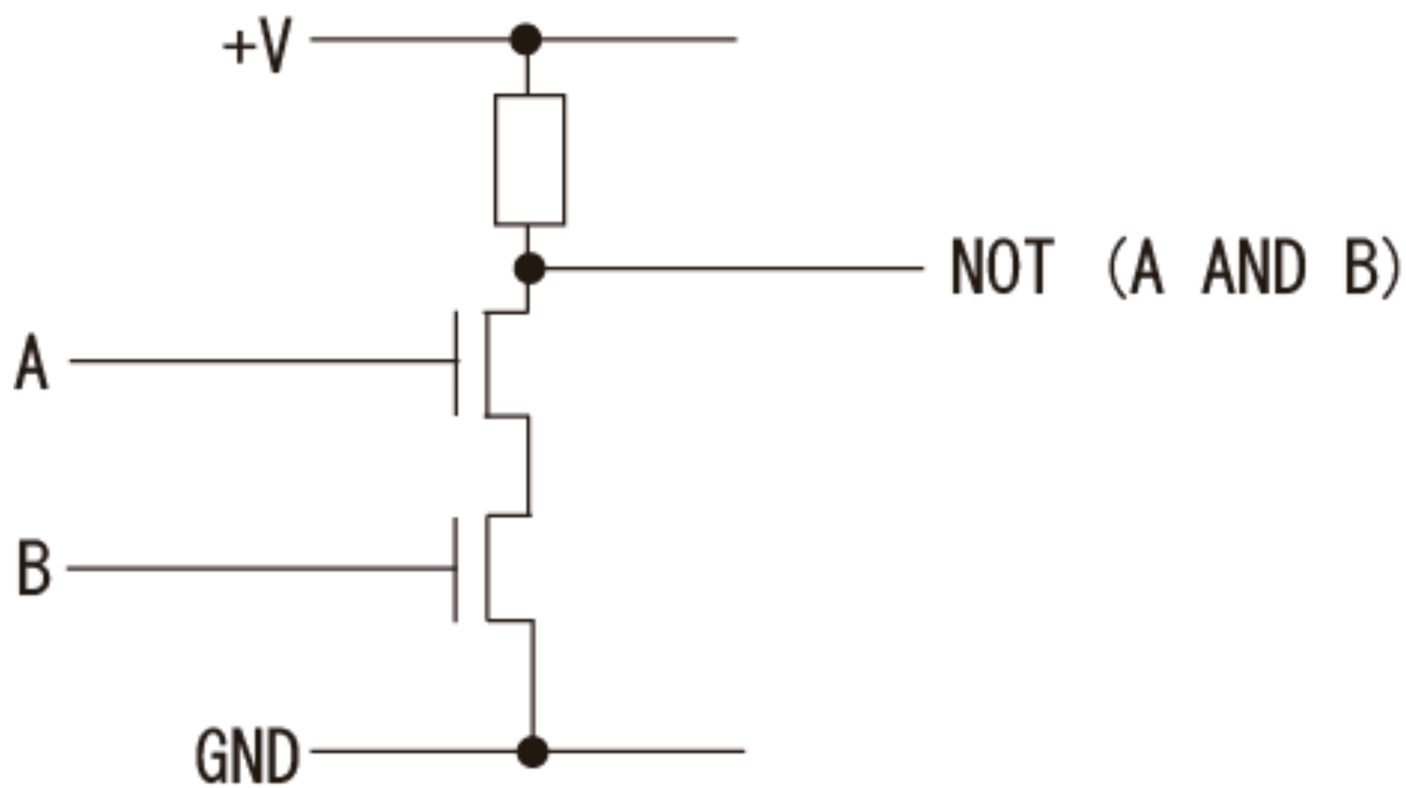
Information processing

encoding in physical systems → state transformation of physical systems → decoding from physical systems

Capacitor voltage

$$0 : V < V_S$$

$$1 : V > V_S$$



NAND gate

Physical process of

Quantum information processing

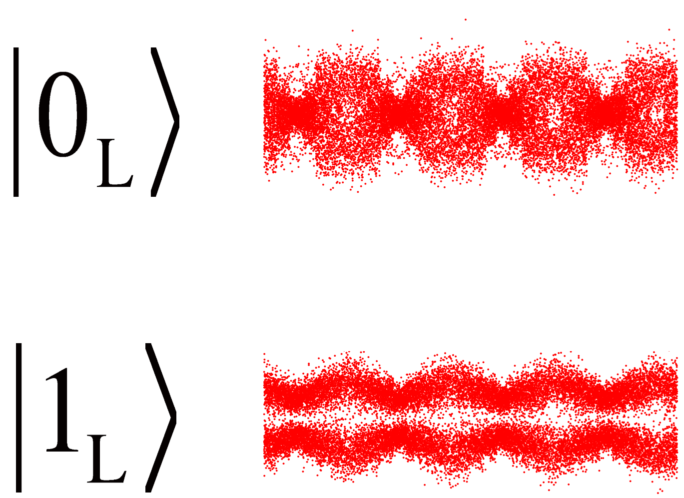
encoding in physical systems
quantum

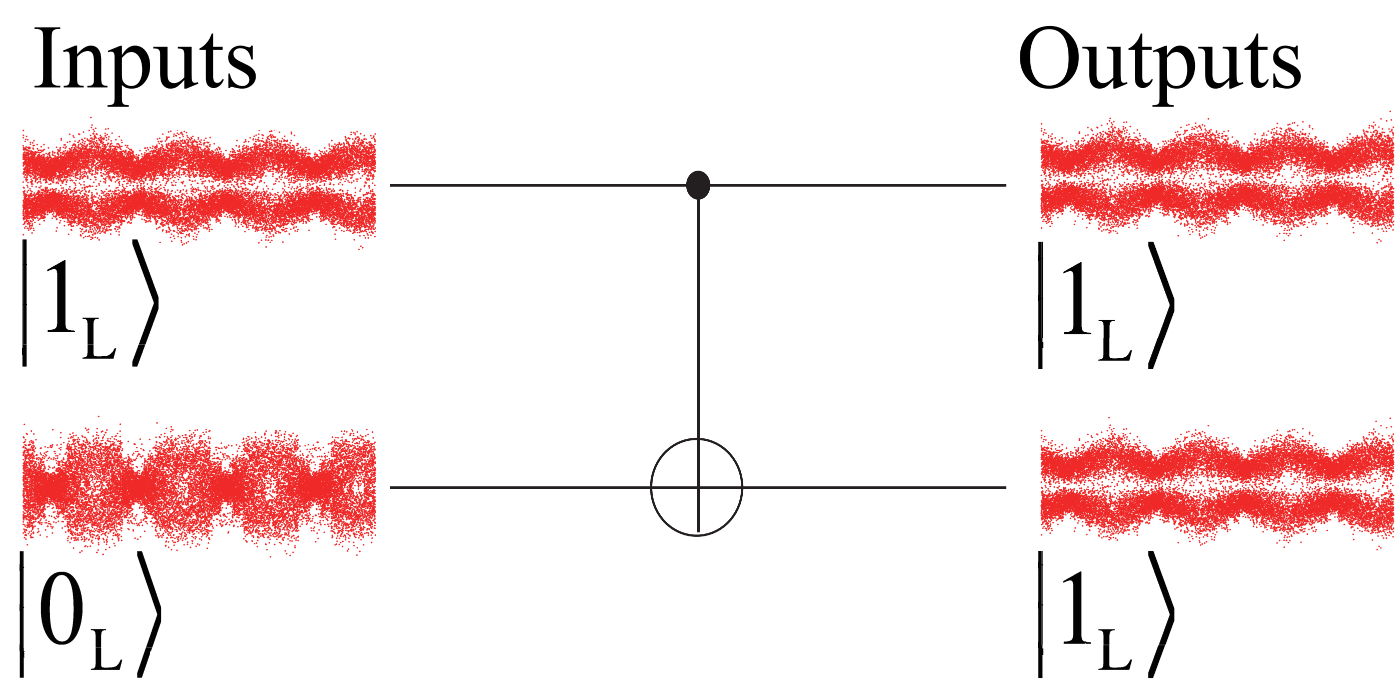
→

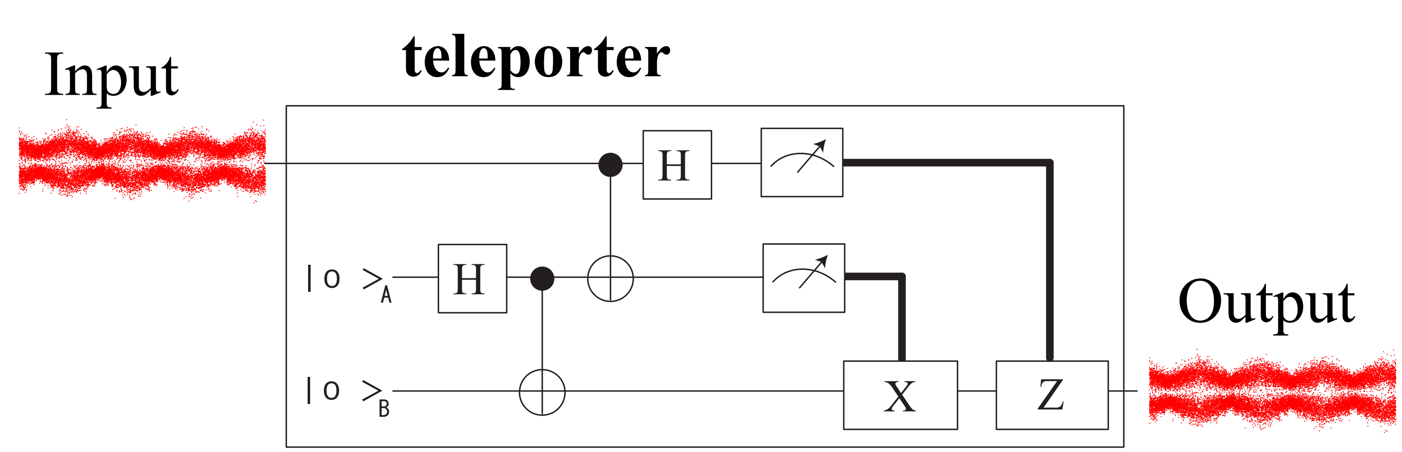
state transformation of physical systems
quantum

→

decoding from physical systems
quantum



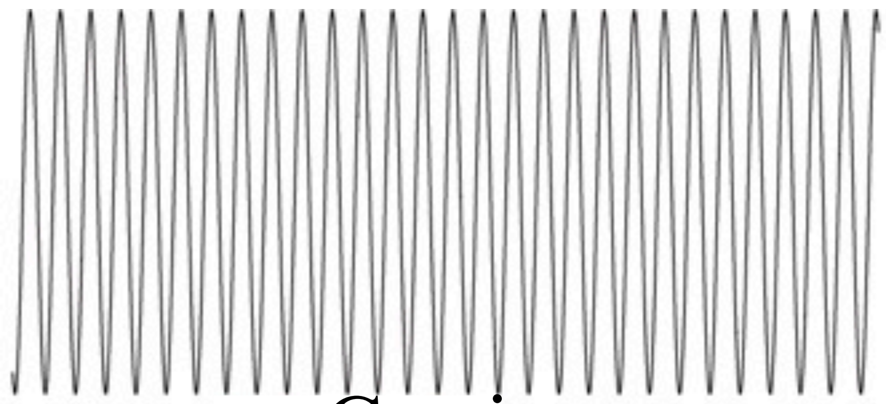




Coherent communication
and
Quantum information processing

AM and FM signals

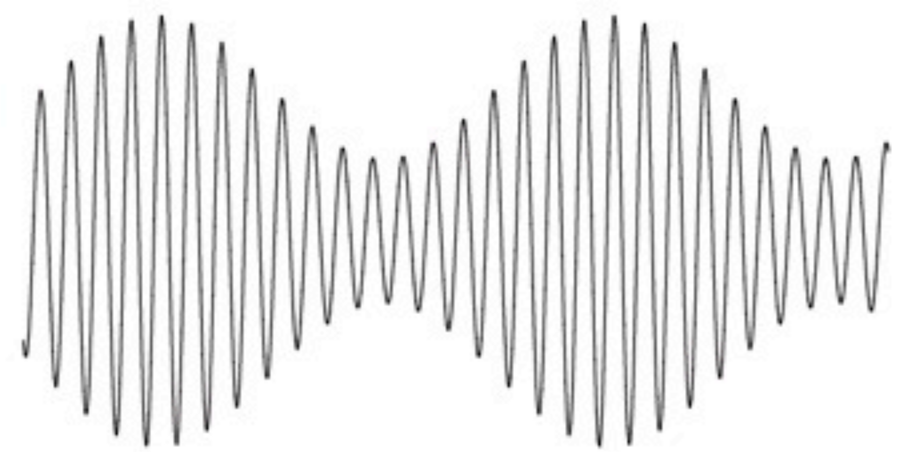
NHK
（AM）
594kHz



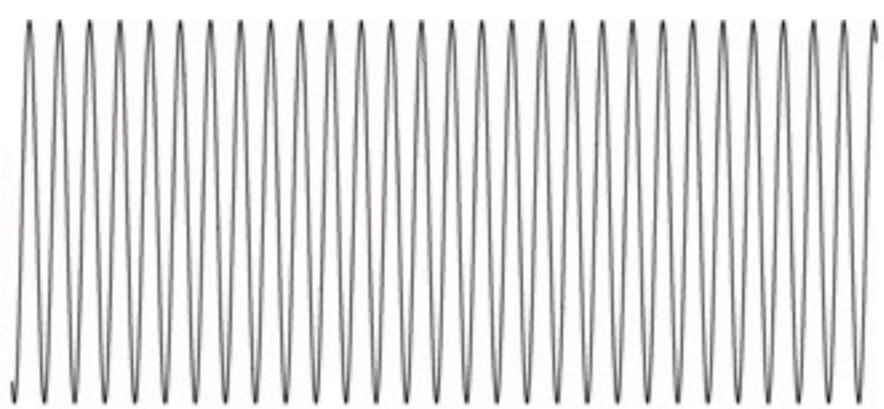
Carrier

Amplitude modulation

AM signal



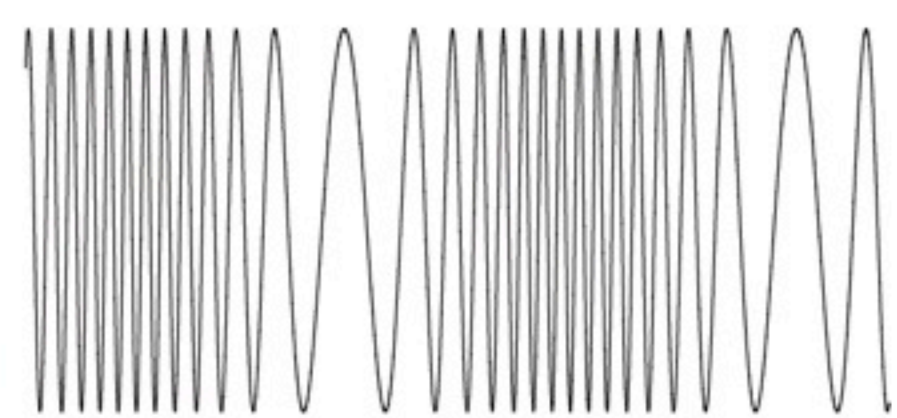
J-WAVE
（FM）
81.3MHz



Carrier

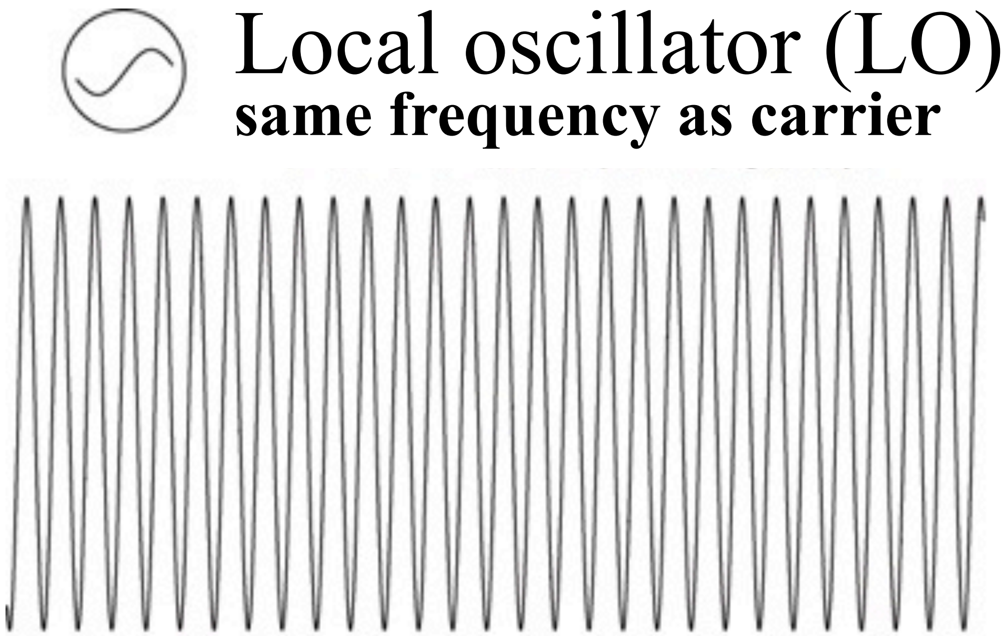
Frequency (phase) modulation

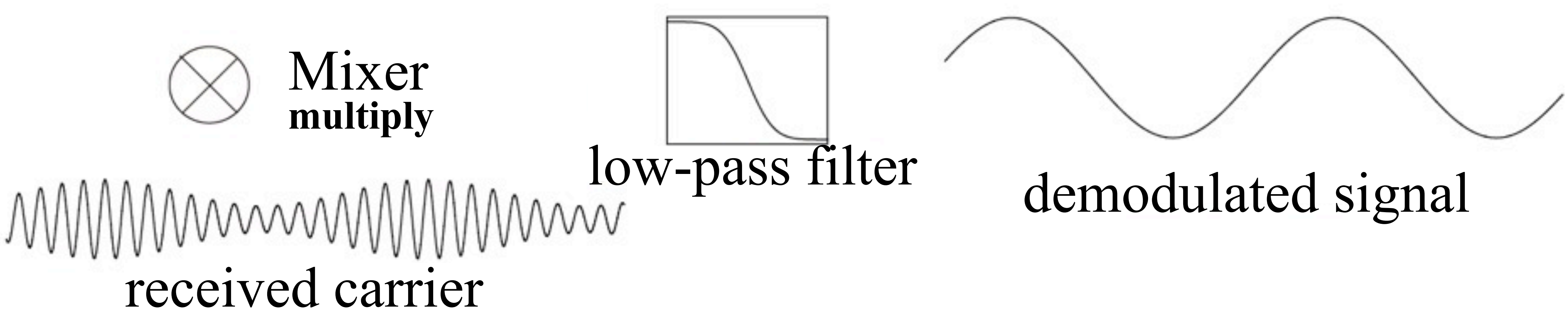
FM signal



Homodyne detection

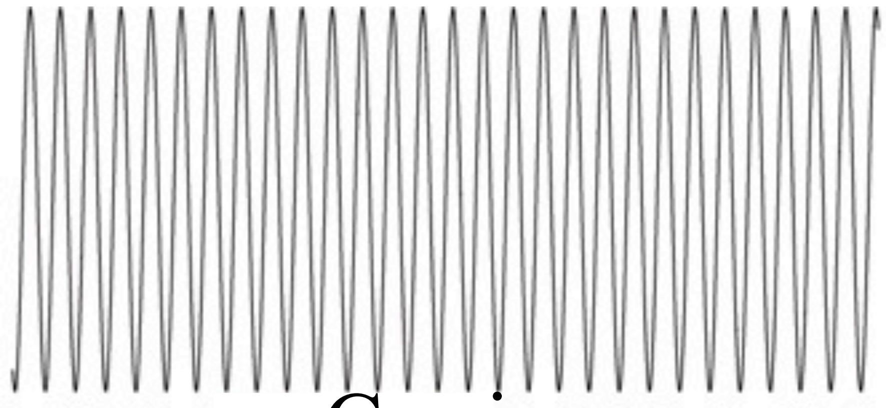
We can select AM or FM signal by changing the LO phase.





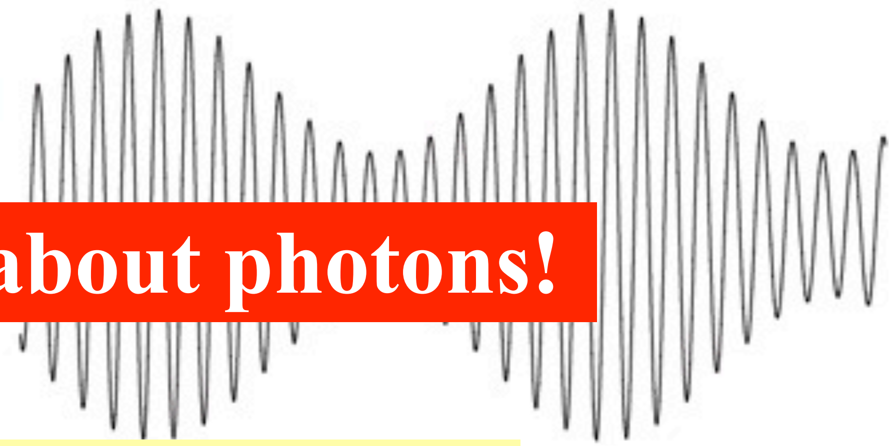
AM and FM signals

NHK (AM) 594kHz



Carrier

AM signal



We don't have to think about photons!

Am

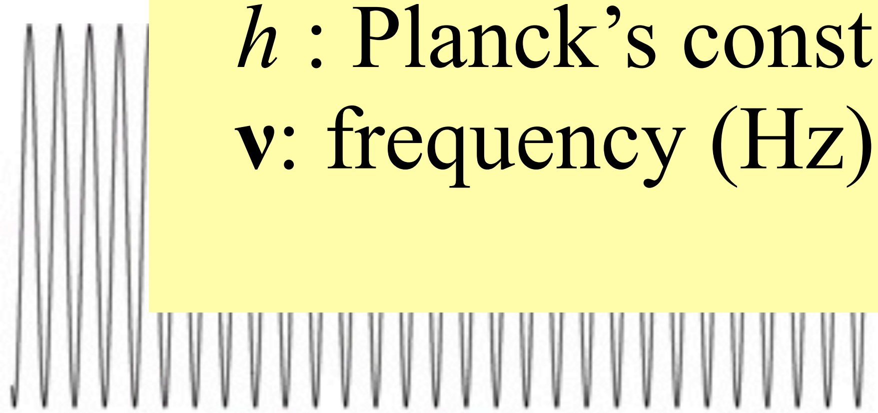
photon energy = $h\nu$

h : Planck's const (6.6×10^{-34}Js)

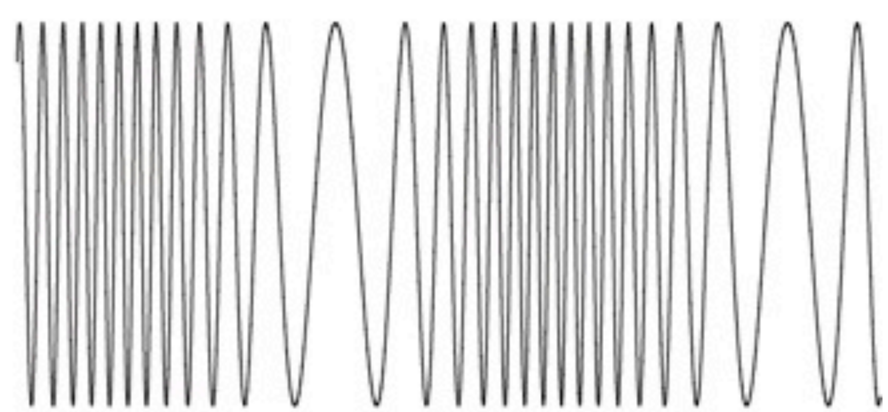
ν: frequency (Hz)

nal

J-WAVE (FM) 81.3MHz



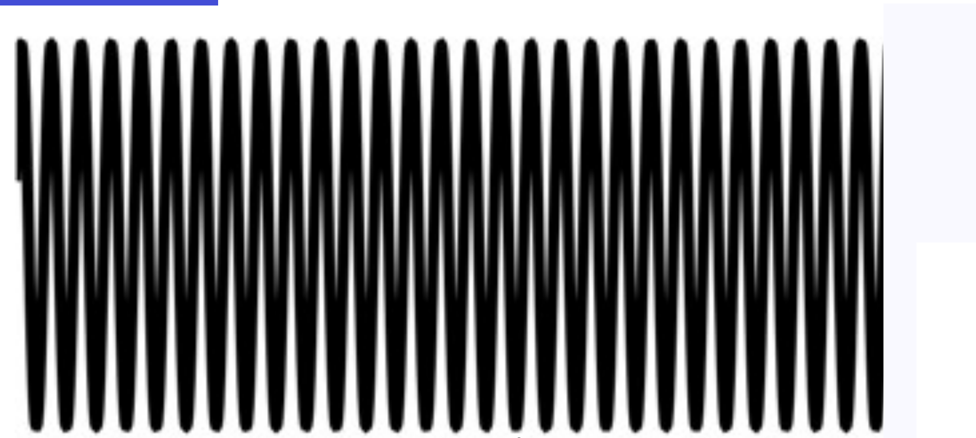
Carrier



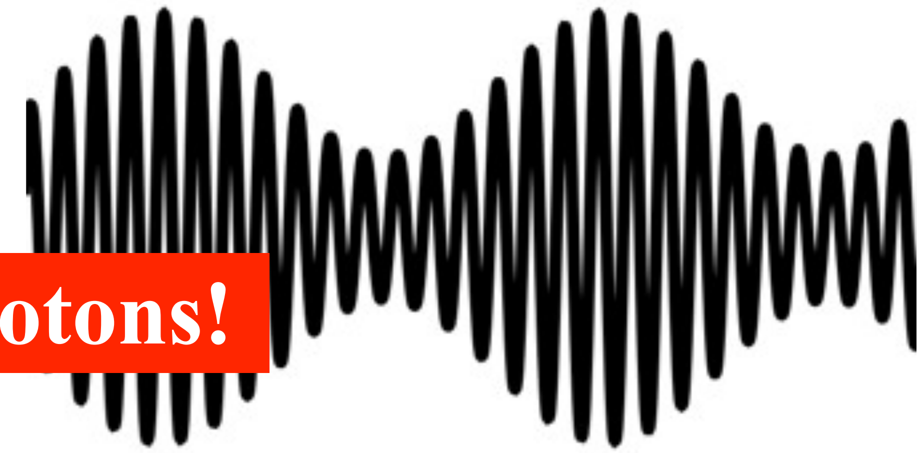
Frequency (phase) modulation

AM and FM signals

Freq of vis light 100THz

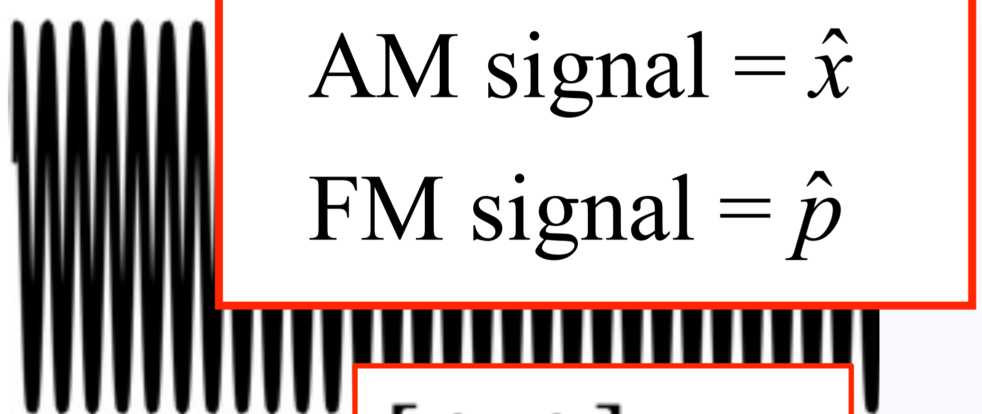


Carrier



AM signal

We have to think about photons!



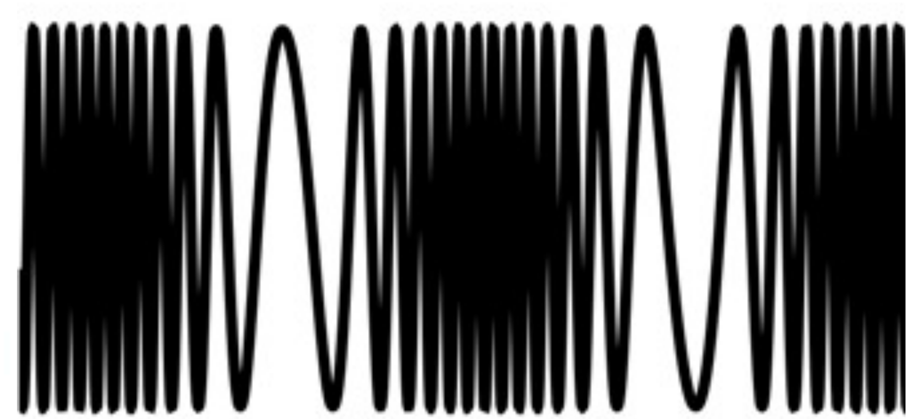
AM and FM signals become conjugate variables.

$$\text{AM signal} = \hat{x}$$

$$\text{FM signal} = \hat{p}$$

$$[\hat{x}, \hat{p}] = i\hbar$$

FM signal



Frequency (phase) modulation

Quantum optics

annihilation operator $\hat{a}$

$$[\hat{a}, \hat{a}^\dagger] = 1 \quad \left(\hbar = \frac{1}{2} \right)$$

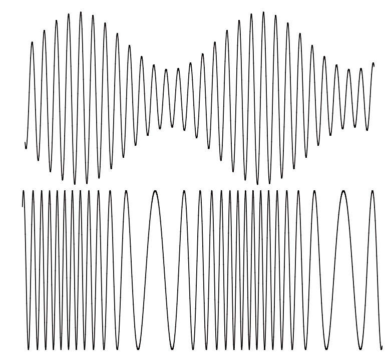
Photon-number units

quantum complex amplitude

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

$\hat{x}$: AM signal

$\hat{p}$: FM signal



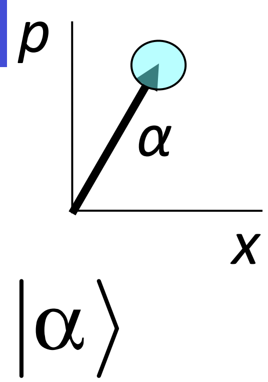
$$[\hat{x}, \hat{p}] = i\hbar \longleftrightarrow [\hat{x}, \hat{p}] = \frac{i}{2}$$

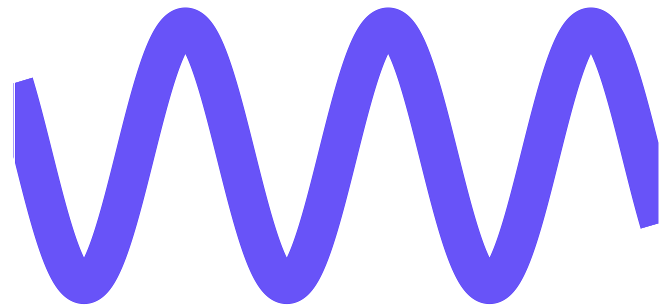
$\hat{x}$: position

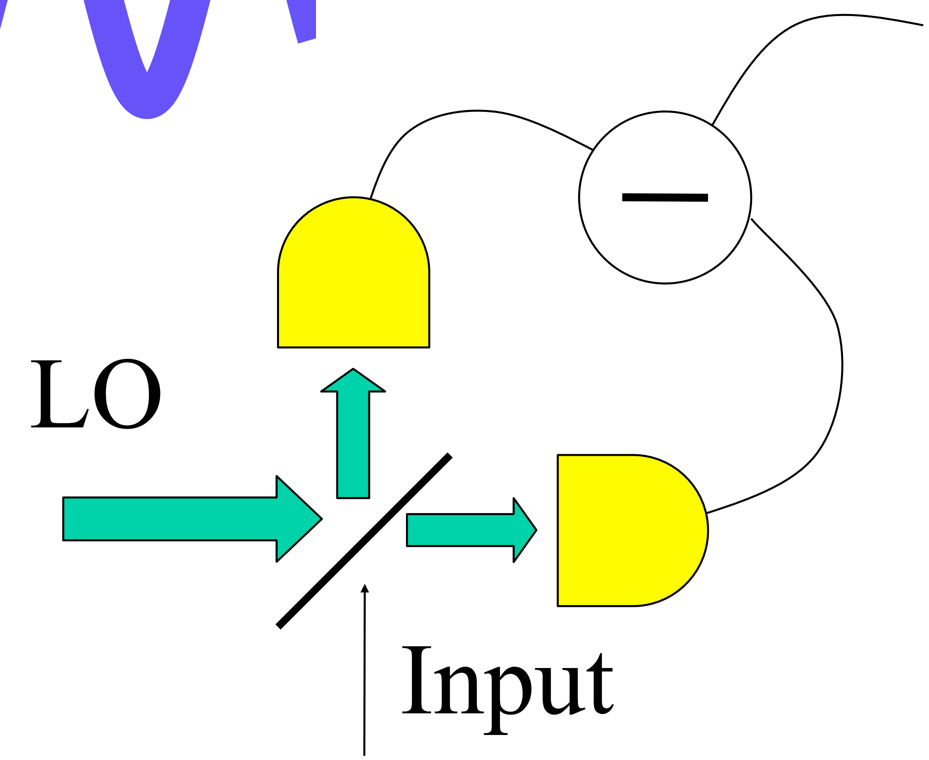
$\hat{p}$: momentum

Canonically conjugate variables

Homodyne detection

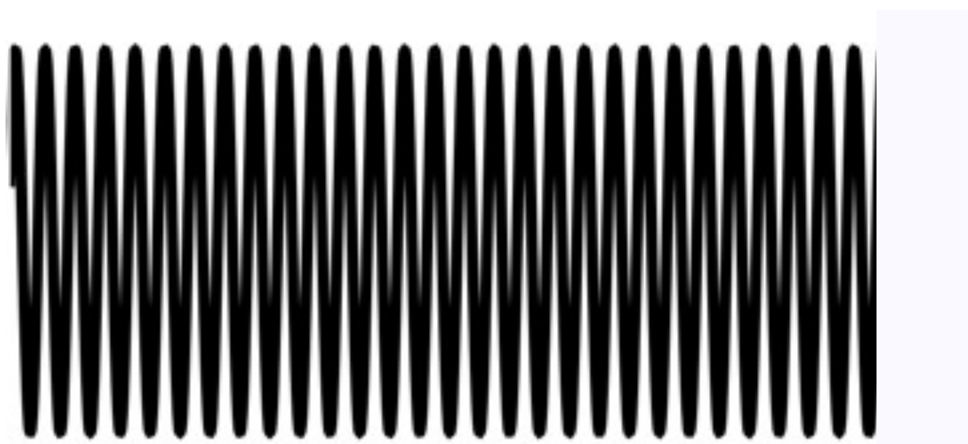




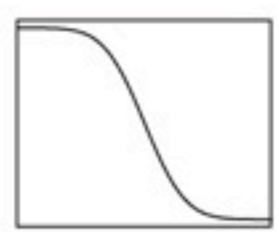


Laser scillator (LO)

same frequency as carrier



Beam splitter



low-pass filter

demodulated signal

With shot noise!

received carrier

Coherent communication

Shannon limit

An example of quantum version of coherent communication

Channel capacity beyond the Shannon limit

Beyond the shot-noise limit!

Sending station

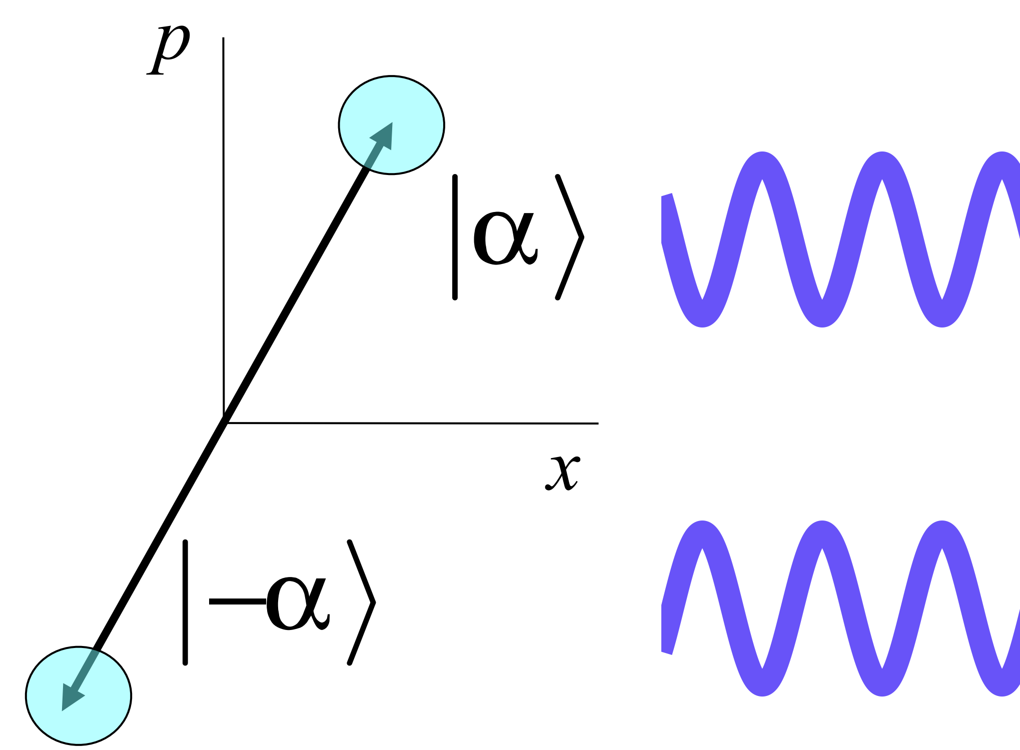
Encode

$$|00\rangle = |S_0\rangle = |\alpha\rangle|\alpha\rangle|\alpha\rangle$$

$$|01\rangle = |S_1\rangle = |\alpha\rangle|-\alpha\rangle|-\alpha\rangle$$

$$|10\rangle = |S_2\rangle = |-\alpha\rangle|-\alpha\rangle|\alpha\rangle$$

$$|11\rangle = |S_3\rangle = |-\alpha\rangle|\alpha\rangle|-\alpha\rangle$$



fiber

Receiving station

Collective measurement

Projection onto

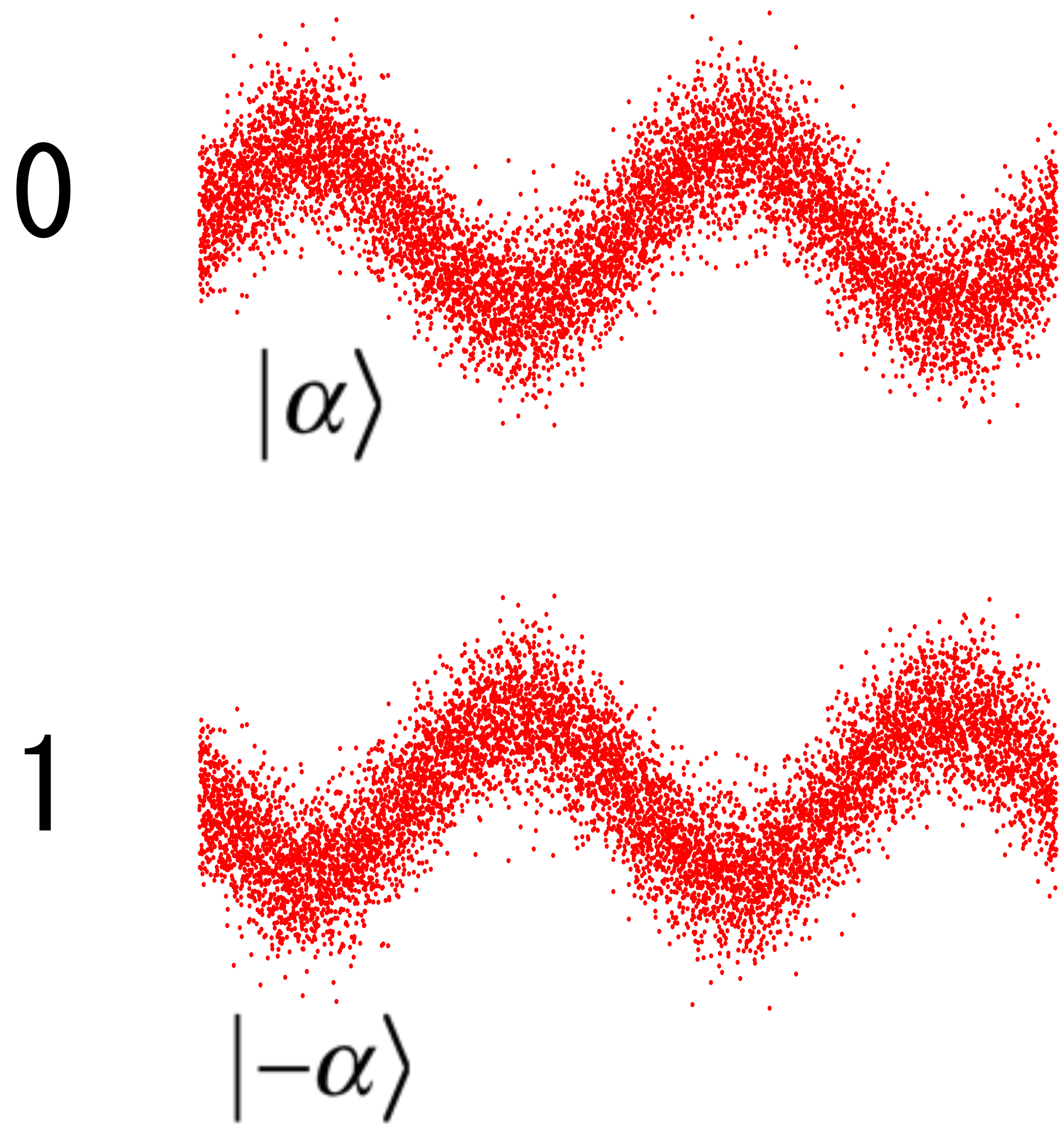
Decode

$$|\mu_i\rangle = \left(\sum_{k=0}^{3} |S_k\rangle\langle S_k|\right)^{-1/2} |S_i\rangle \quad (i = 0,1,2,3)$$

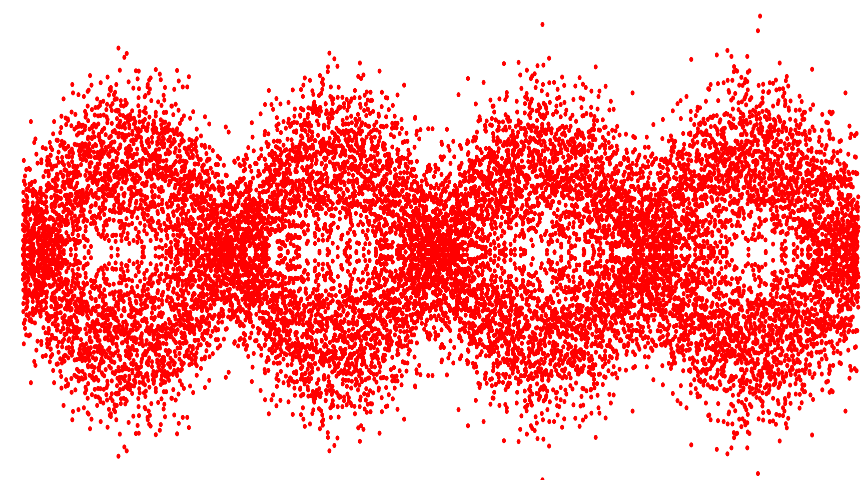
Orthogonal bases

M. Sasaki et al., Phys. Lett. A **236**, 1 (1997)

Coherent communication

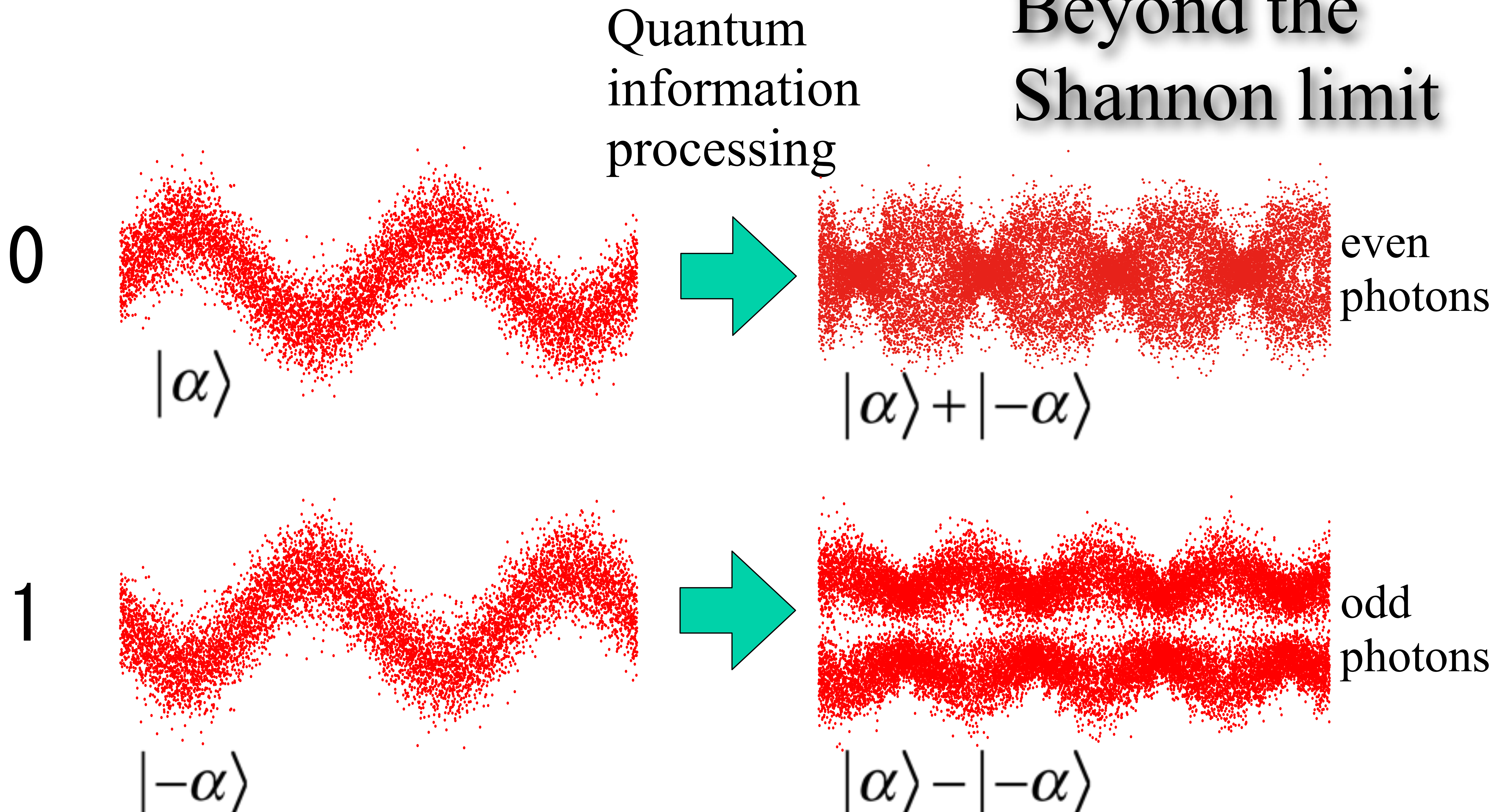


Shannon limit



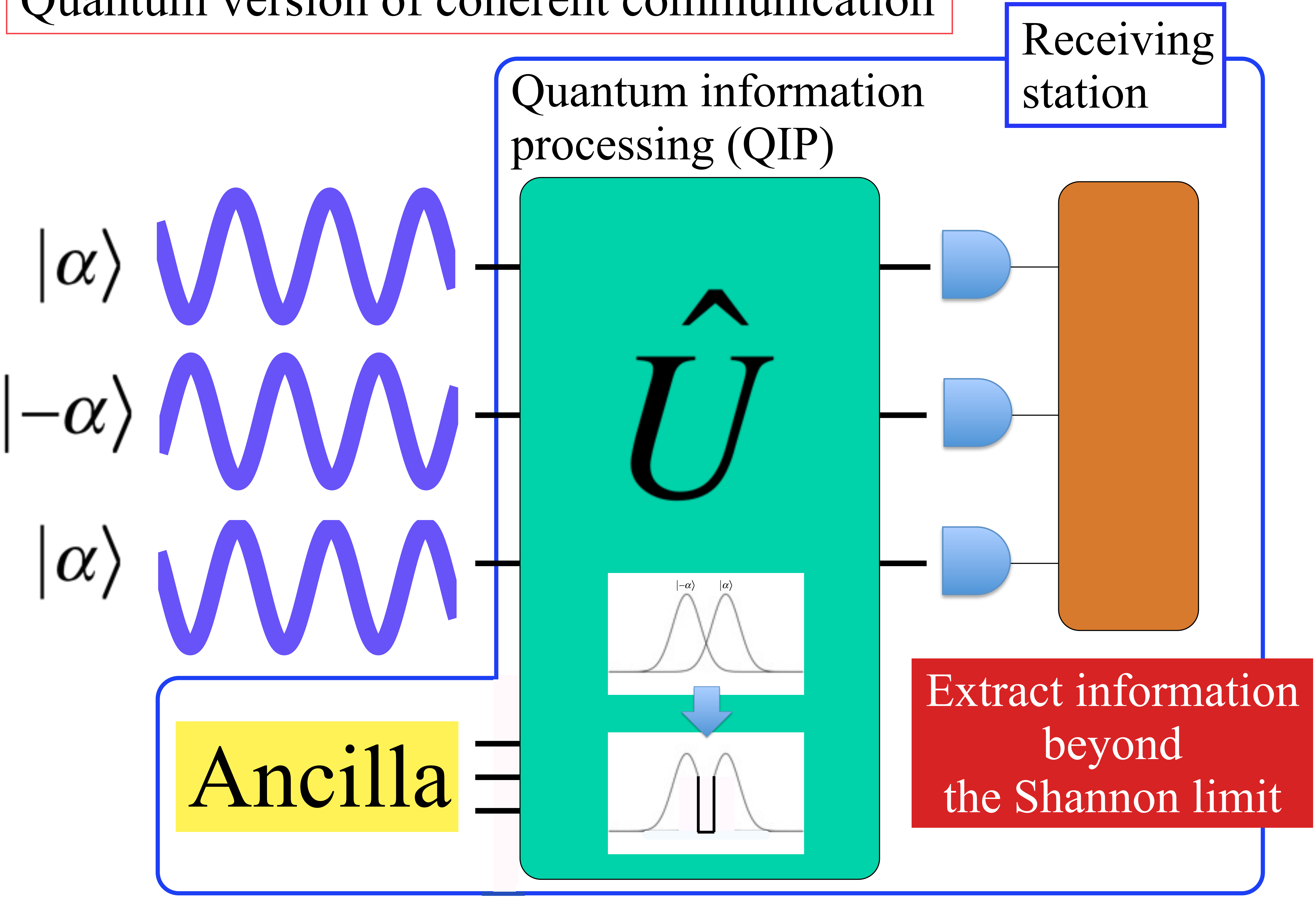
Coherent communication with QIP

Beyond the Shannon limit



Schrödinger cat states

Quantum version of coherent communication

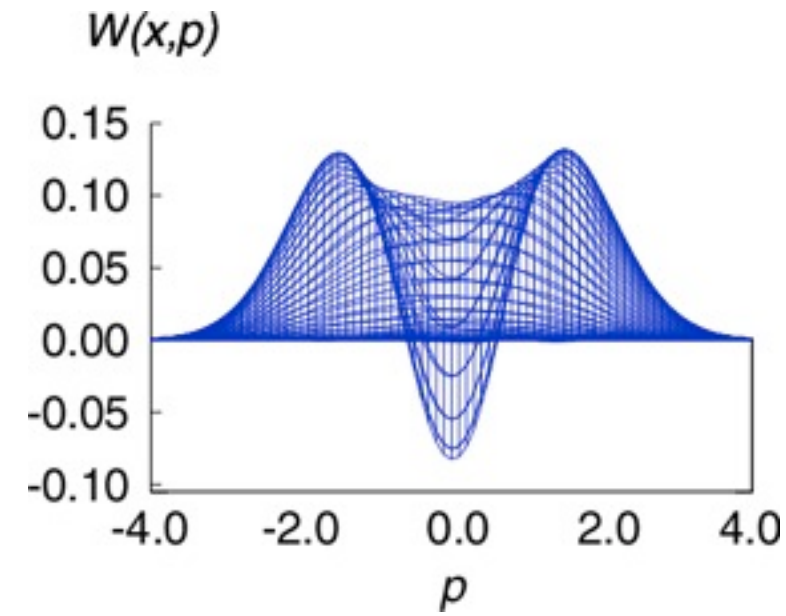


We have to handle cat states of light!!

Schrödinger cat states

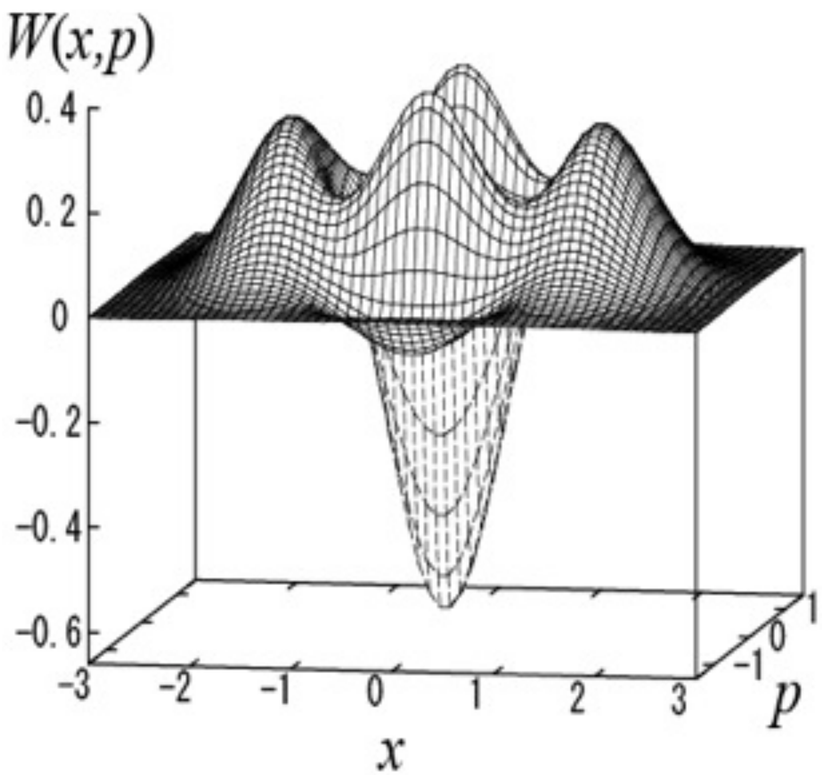
$$N_\alpha\left(|\alpha\rangle - |-\alpha\rangle\right)$$ odd photons

$$N_\alpha\left(|\alpha\rangle + |-\alpha\rangle\right)$$ even photons



K. Wakui et al.,
Opt. Exp. 15, 3568 (2007)

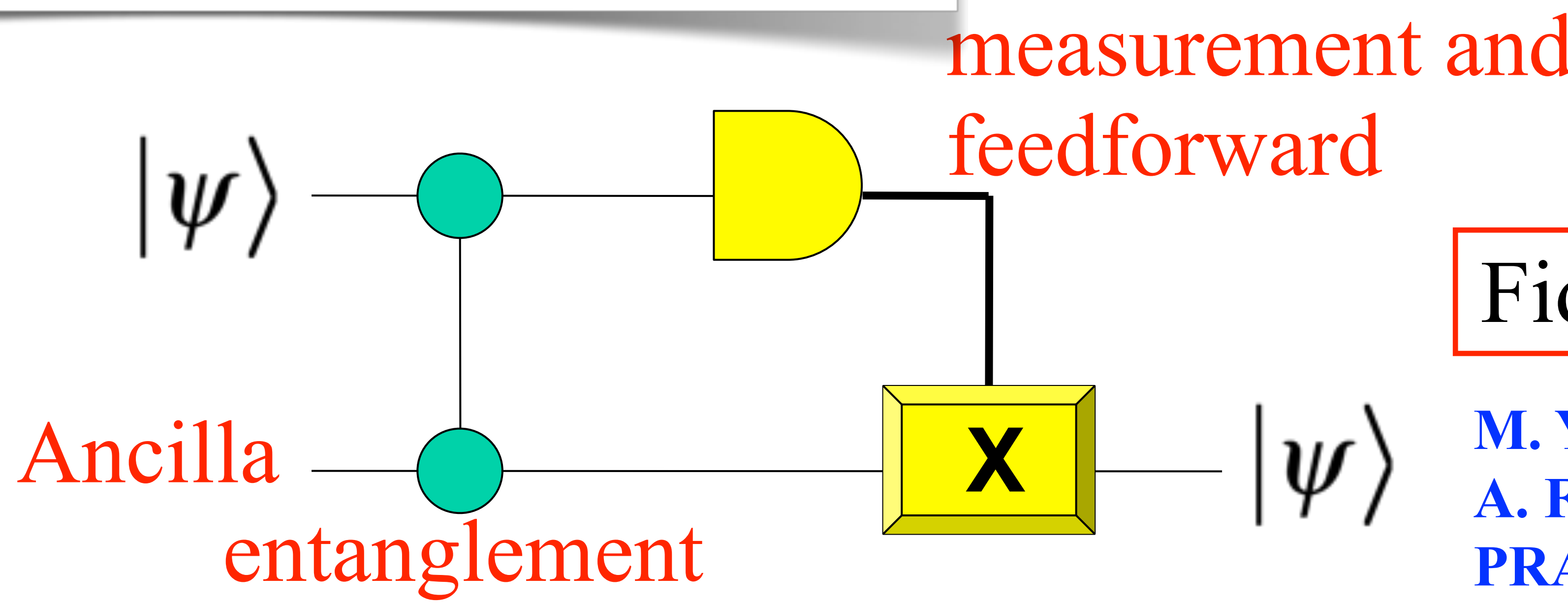
H. Takahashi et al.,
Phys. Rev. Lett. 101, 233605 (2008)



$$|\alpha\rangle = e^{-\frac{|\alpha|^2}{2}} \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} |n\rangle$$

$$|-\alpha\rangle = e^{-\frac{|\alpha|^2}{2}} \sum_{n=0}^{\infty} \frac{(-\alpha)^n}{\sqrt{n!}} |n\rangle$$

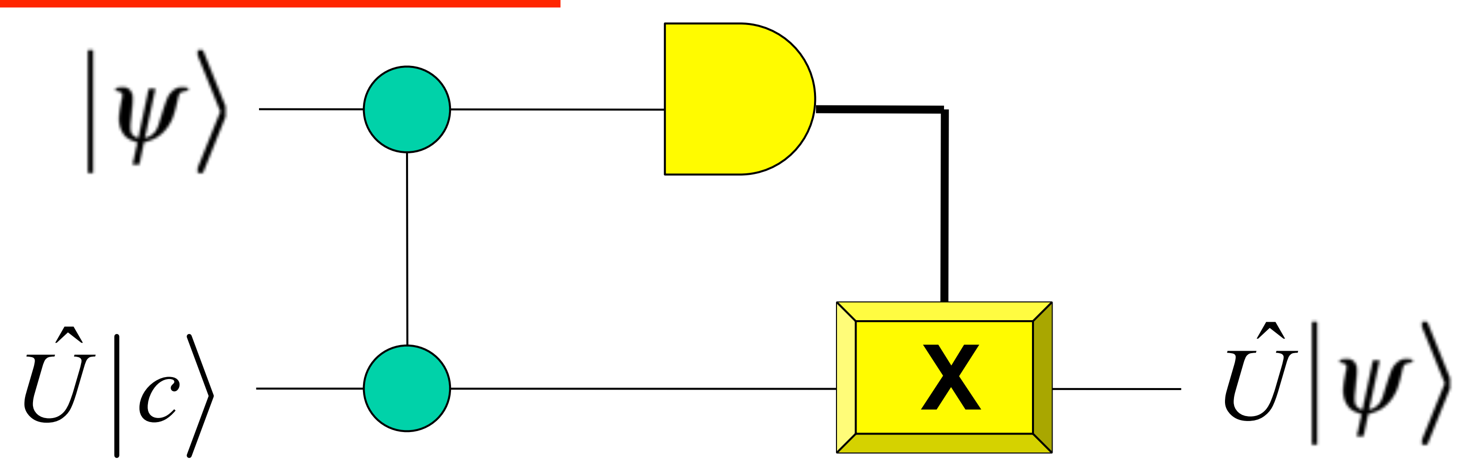
Generalized teleportation



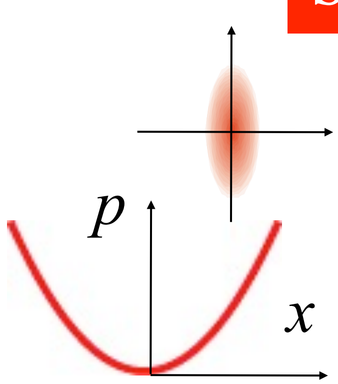
Fidelity = 0.83

M. Yukawa, H. Benichi, A. Furusawa
PRA 77, 022314 (2008)

Gate teleportation



state preparation



$\hat{S}(r)|0\rangle$ squeezed vacuum

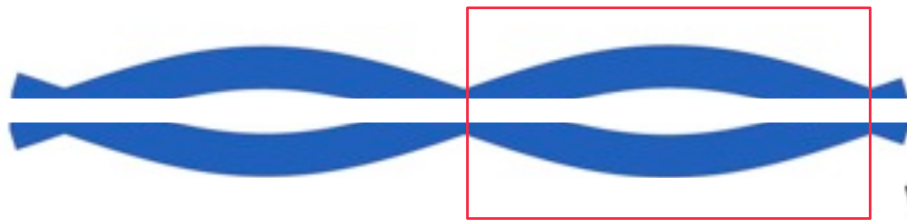
$e^{ik\hat{x}^3}|p=0\rangle$ cubic phase state

Universal squeezer

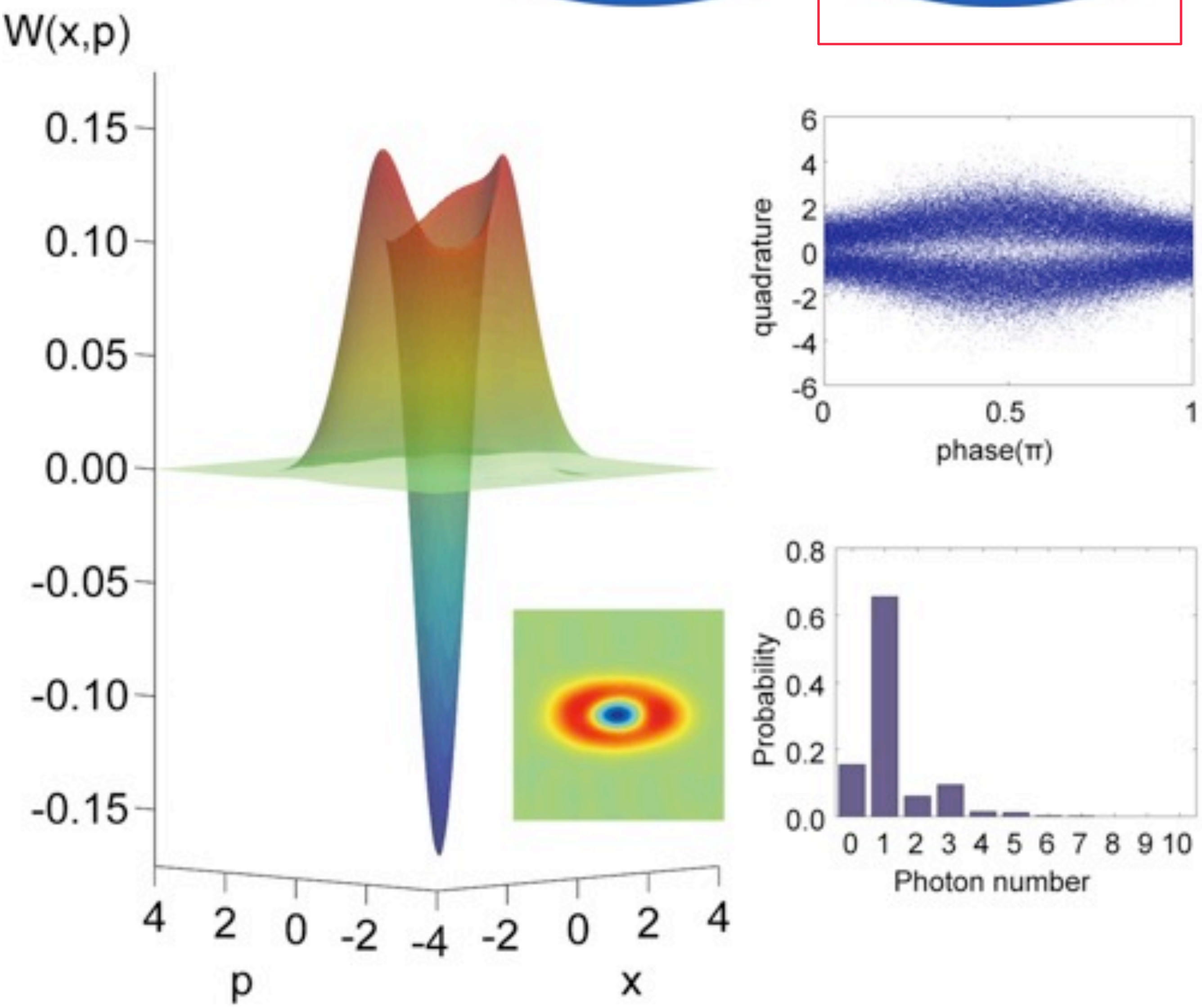
CV $\pi/8$ gate

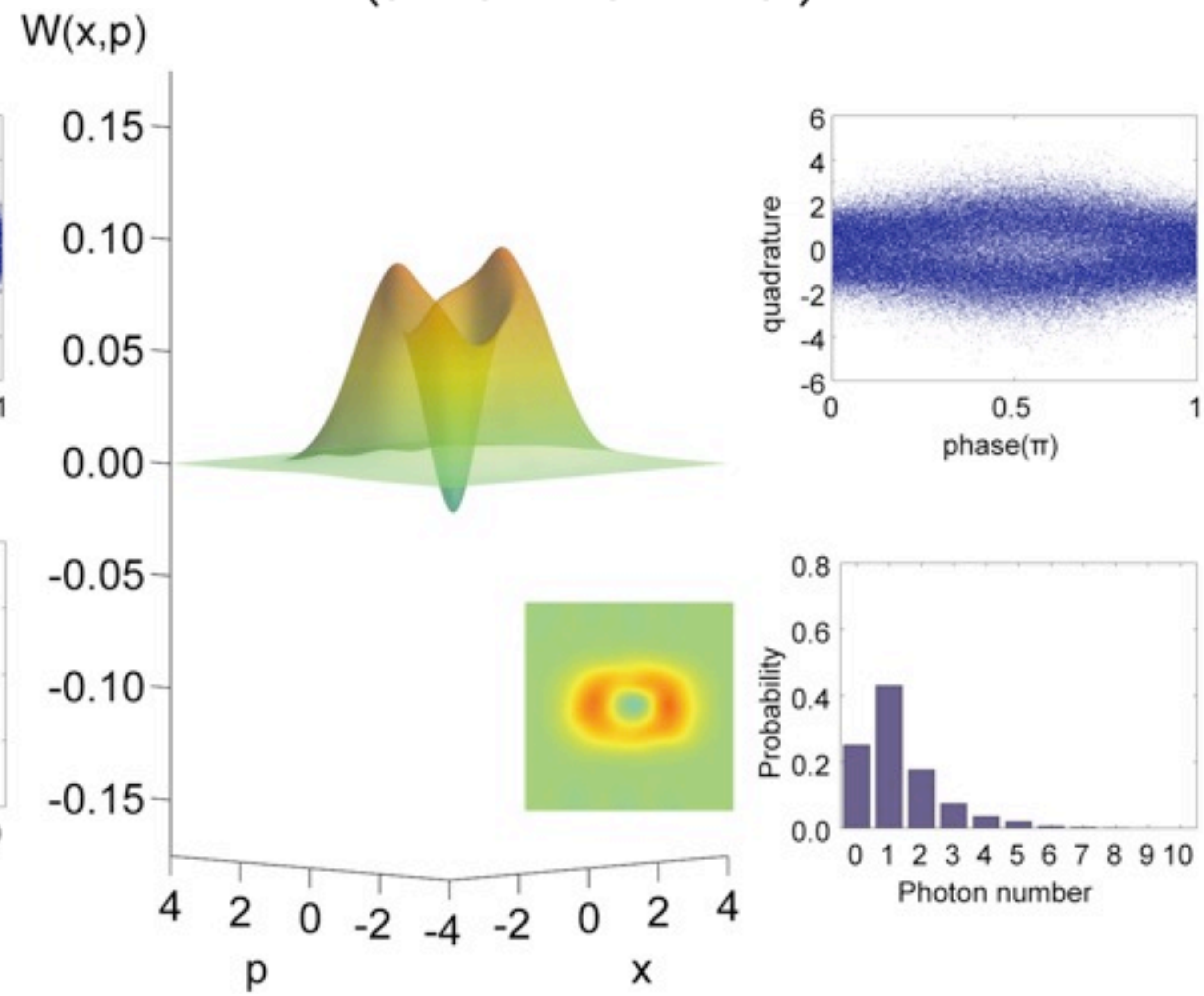
First step of teleportation based QIP for coherent states

Teleportation of a Schrödinger cat state of light



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





Input

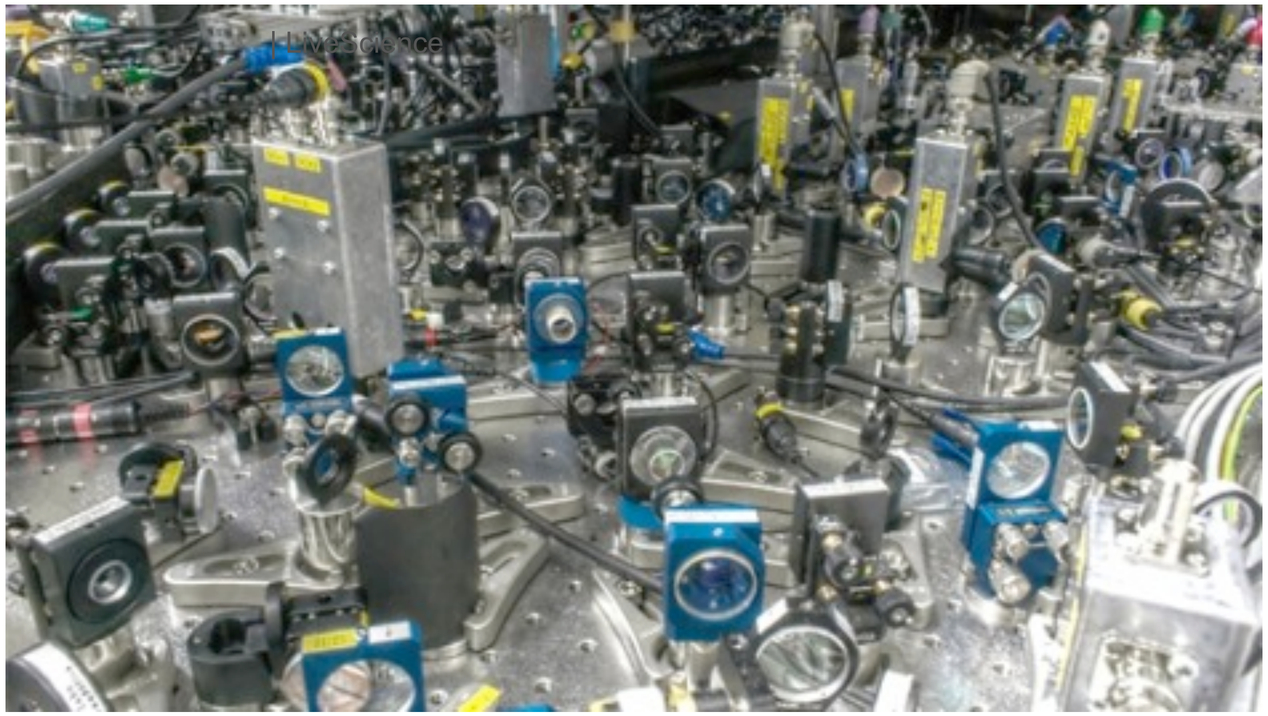
Output

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

SCIENCE

Quantum Leap: Scientists Teleport Bits of Light

By Clara Moskowitz
Published April 14, 2011



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

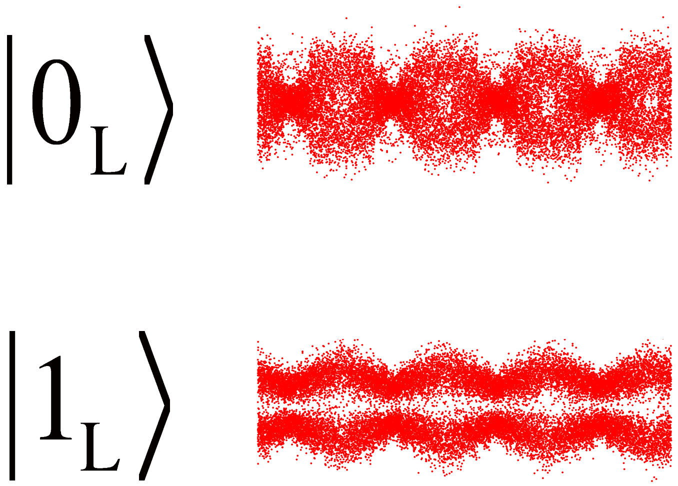
Updated Fri Apr 15, 2011 12:13pm AEST

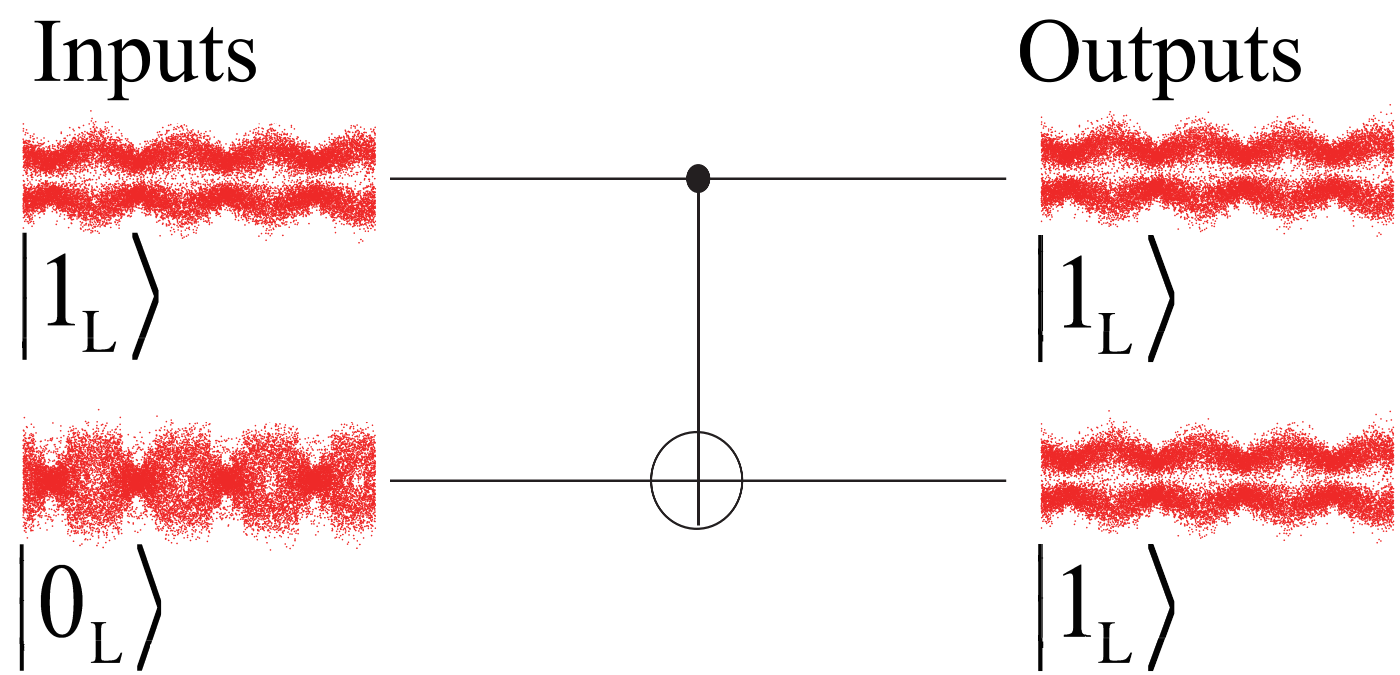
N. Lee, H. Benichi, Y. Takeno, S. Takeda, J. Webb, E. Huntington, & A. Furusawa, Science 332, 330 (2011)

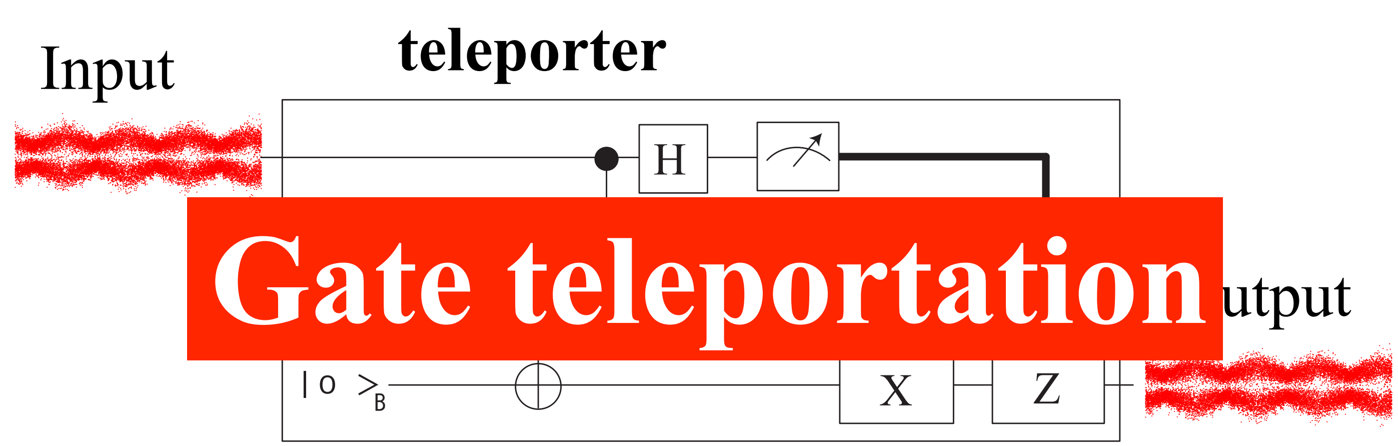
Physical process of

Quantum information processing

encoding in physical systems **quantum** → state transformation of physical systems **quantum** → decoding from physical systems **quantum**







Gate teleportation

What is quantum teleportation?

Quantum entanglement

position : X
momentum : P

position : −X
momentum : −P

Einstein-Podlsky-Rosen (EPR) paradox

Quantum teleportation

simu
of A

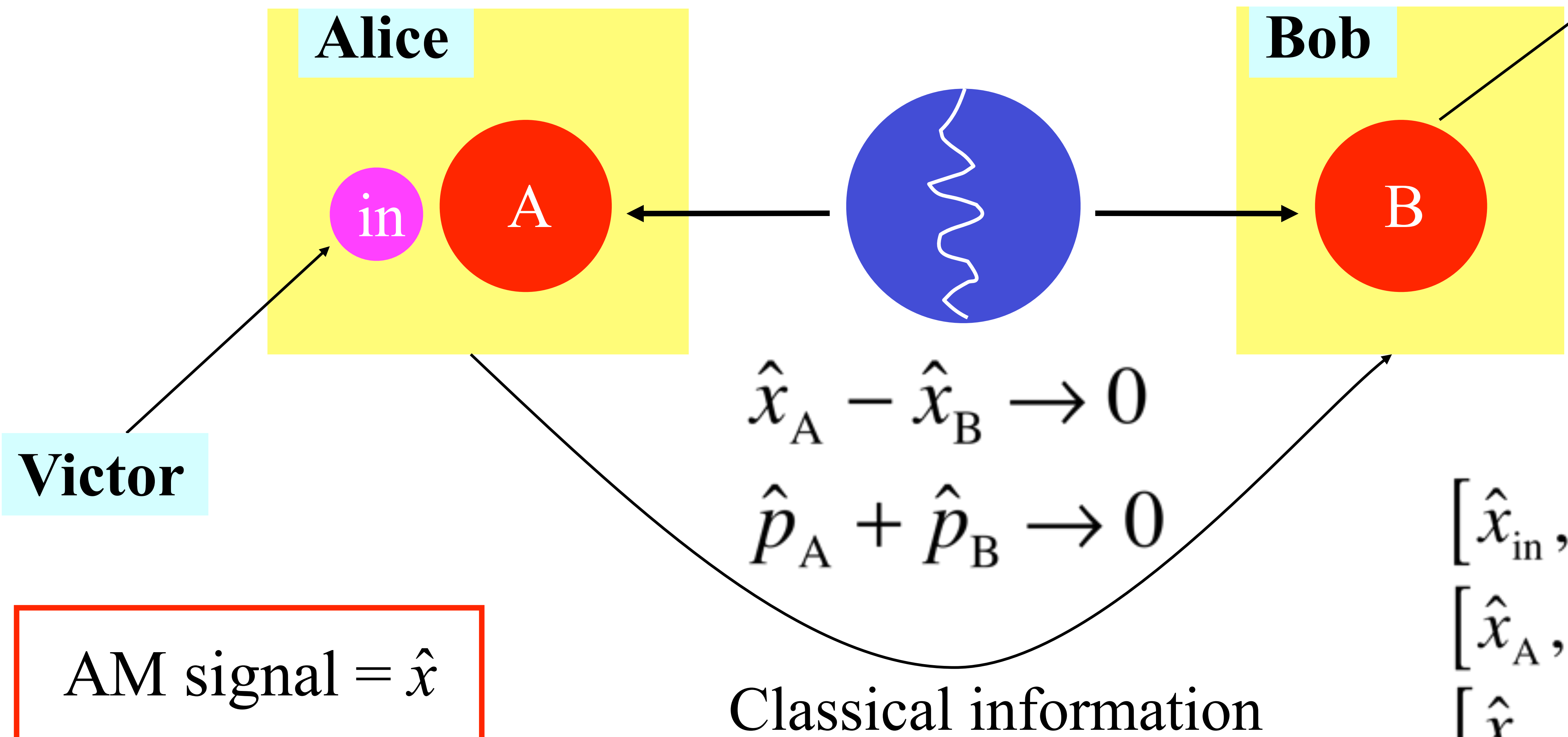
$$x_{\text{in}} - x_{\text{A}} = X$$

$$p_{\text{in}} + p_{\text{A}} = P$$

t

$$x_{\text{B}} = x_{\text{in}} - X - (x_{\text{A}} - x_{\text{B}})$$

$$p_{\text{B}} = p_{\text{in}} - P + (p_{\text{A}} + p_{\text{B}})$$



$$\hat{x}_{\text{A}} - \hat{x}_{\text{B}} \to 0$$

$$\hat{p}_{\text{A}} + \hat{p}_{\text{B}} \to 0$$

$$[\hat{x}_{\text{in}}, \hat{p}_{\text{in}}] = i\hbar$$

$$[\hat{x}_{\text{A}}, \hat{p}_{\text{A}}] = i\hbar$$

$$[\hat{x}_{\text{B}}, \hat{p}_{\text{B}}] = i\hbar$$

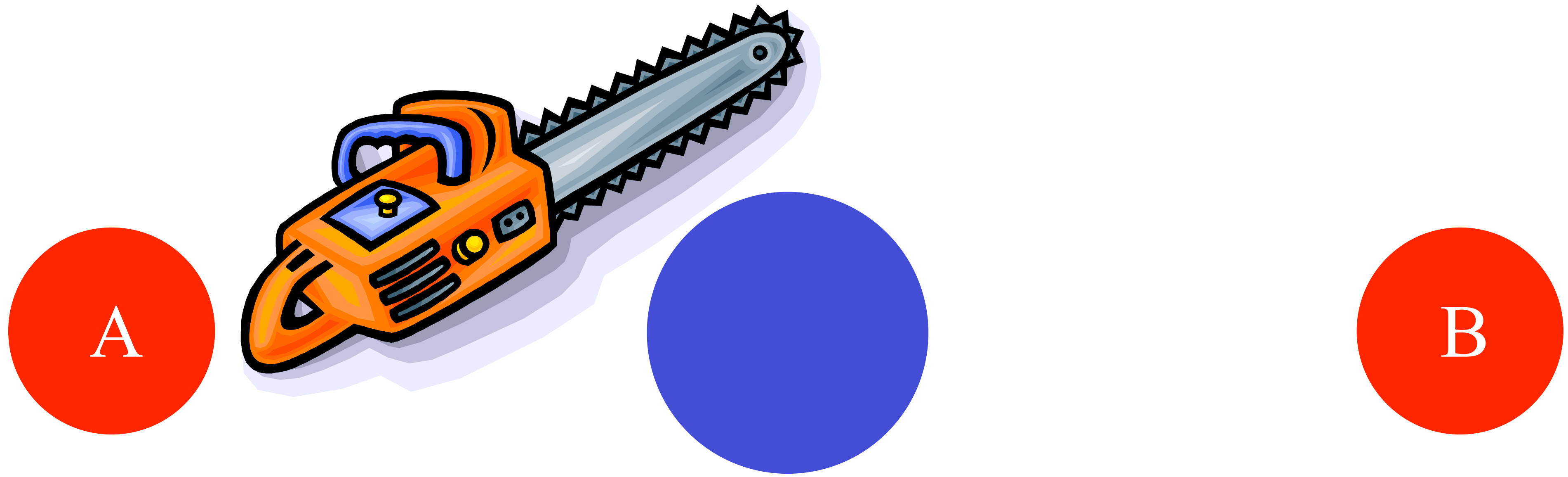
AM signal $= \hat{x}$

FM signal $= \hat{p}$

$$[\hat{x}_{\text{A}} - \hat{x}_{\text{B}}, \hat{p}_{\text{A}} + \hat{p}_{\text{B}}] = 0$$

Creation of optical entanglement

creation of entanglement



$$\hat{x}_A - \hat{x}_B \rightarrow 0$$

$$\hat{p}_A + \hat{p}_B \rightarrow 0$$

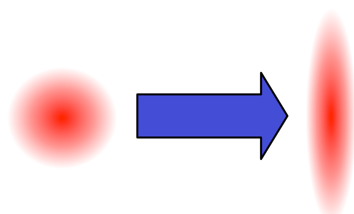
AM signal = $\hat{x}$

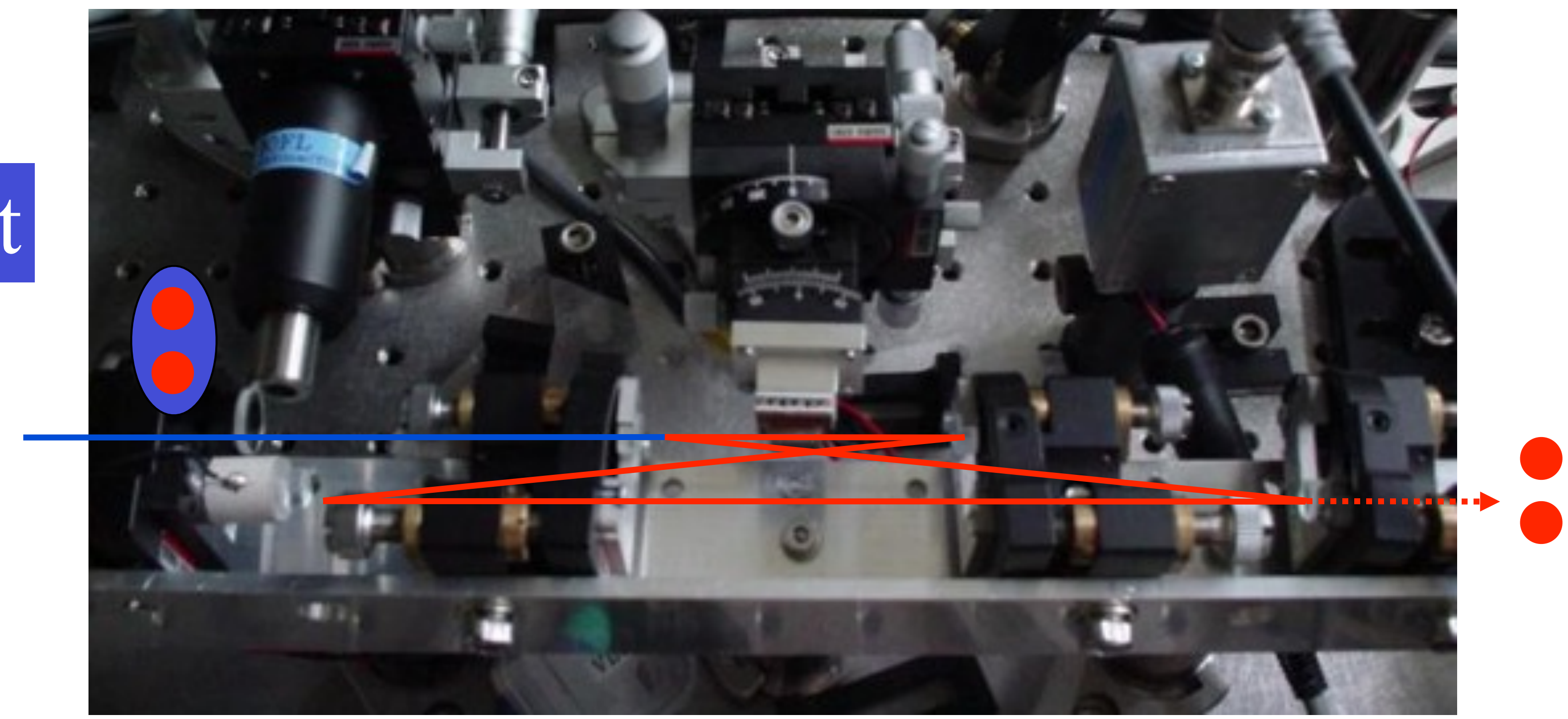
FM signal = $\hat{p}$

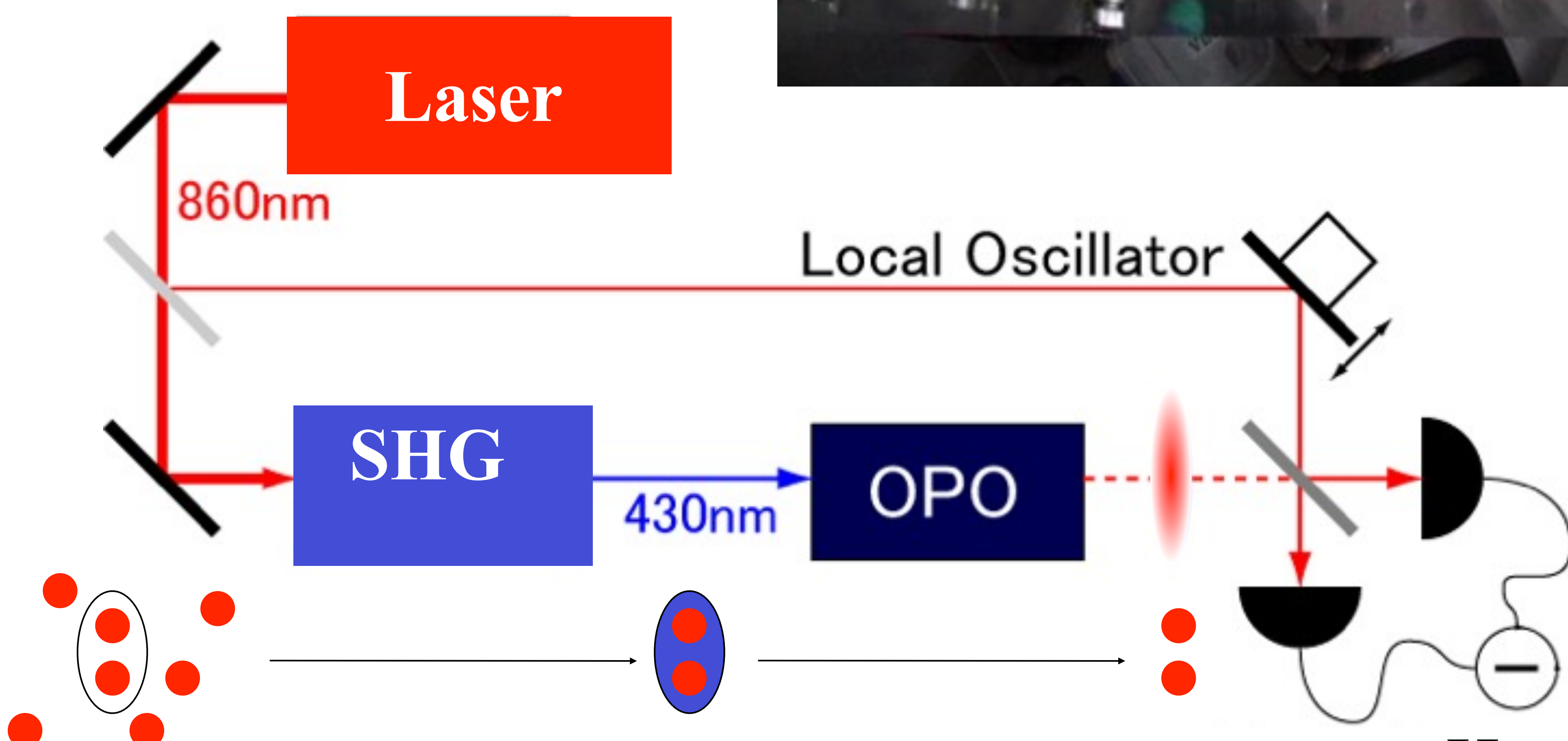
Particle

Optical parametric oscillator (OPO)

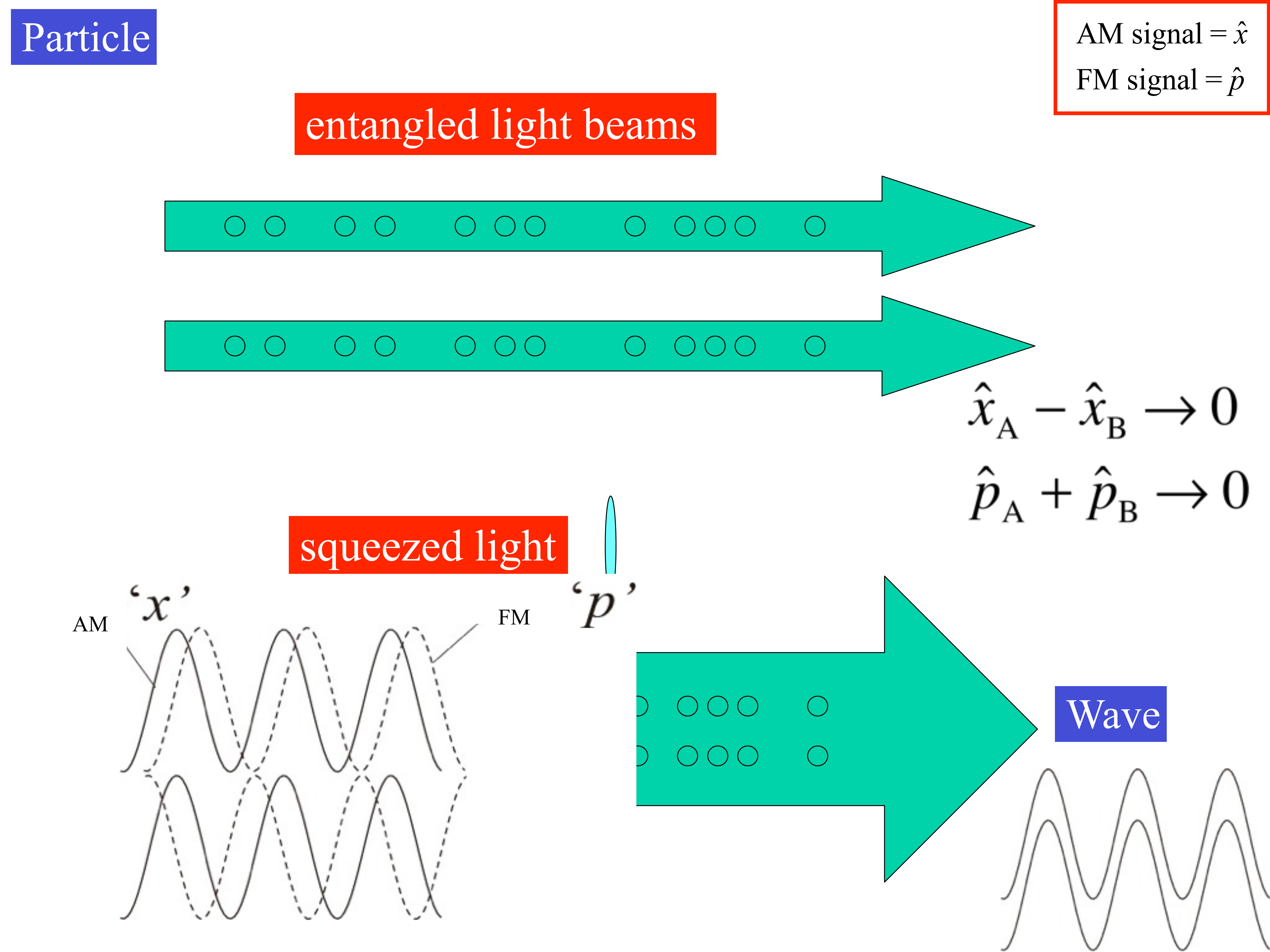
generation of squeezed light







Homodyne measurement

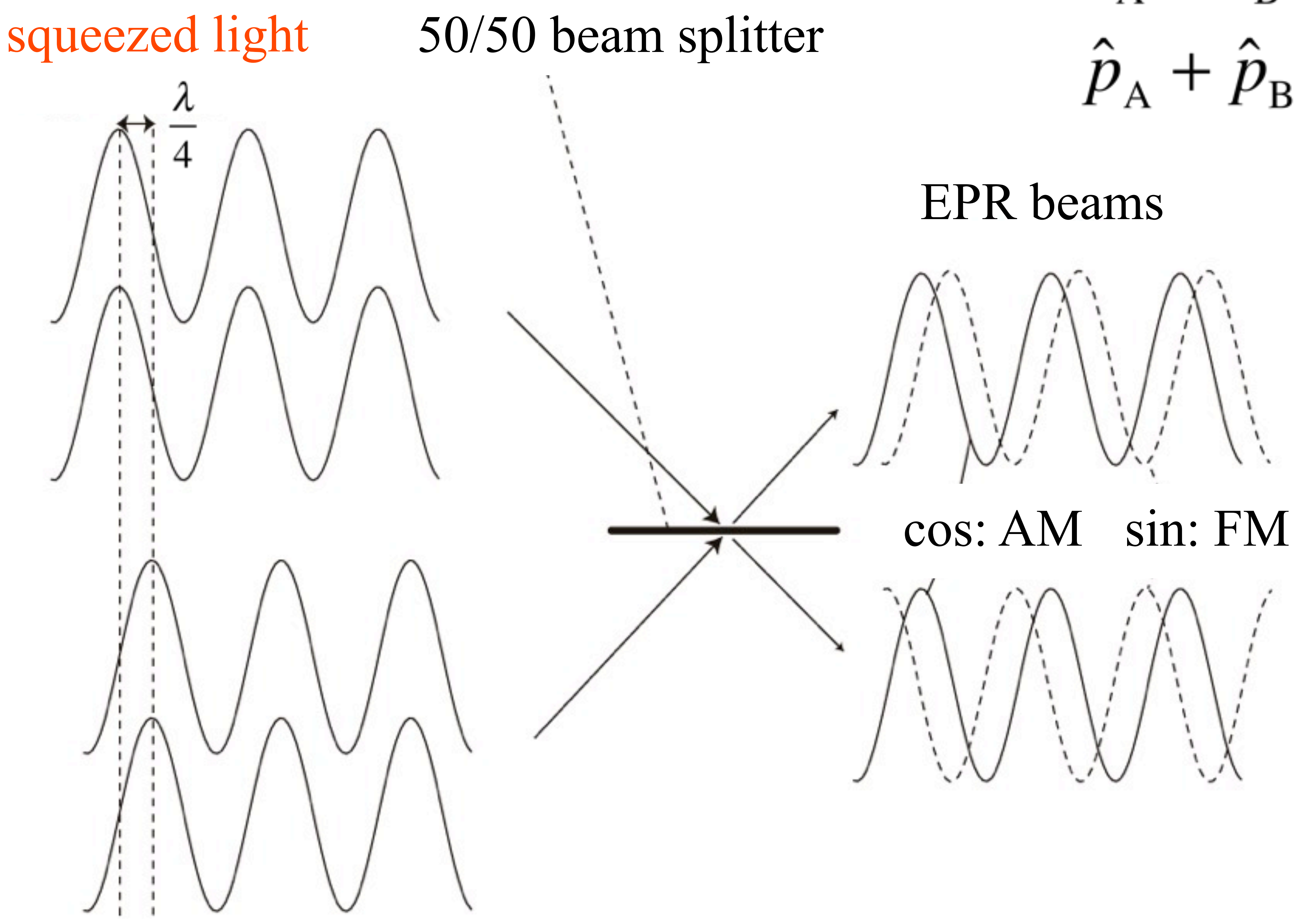


Particle
AM signal = $\hat{x}$
FM signal = $\hat{p}$
entangled light beams
$\hat{x}_A - \hat{x}_B \rightarrow 0$
$\hat{p}_A + \hat{p}_B \rightarrow 0$
squeezed light
'x'
AM
FM
'p'
Wave

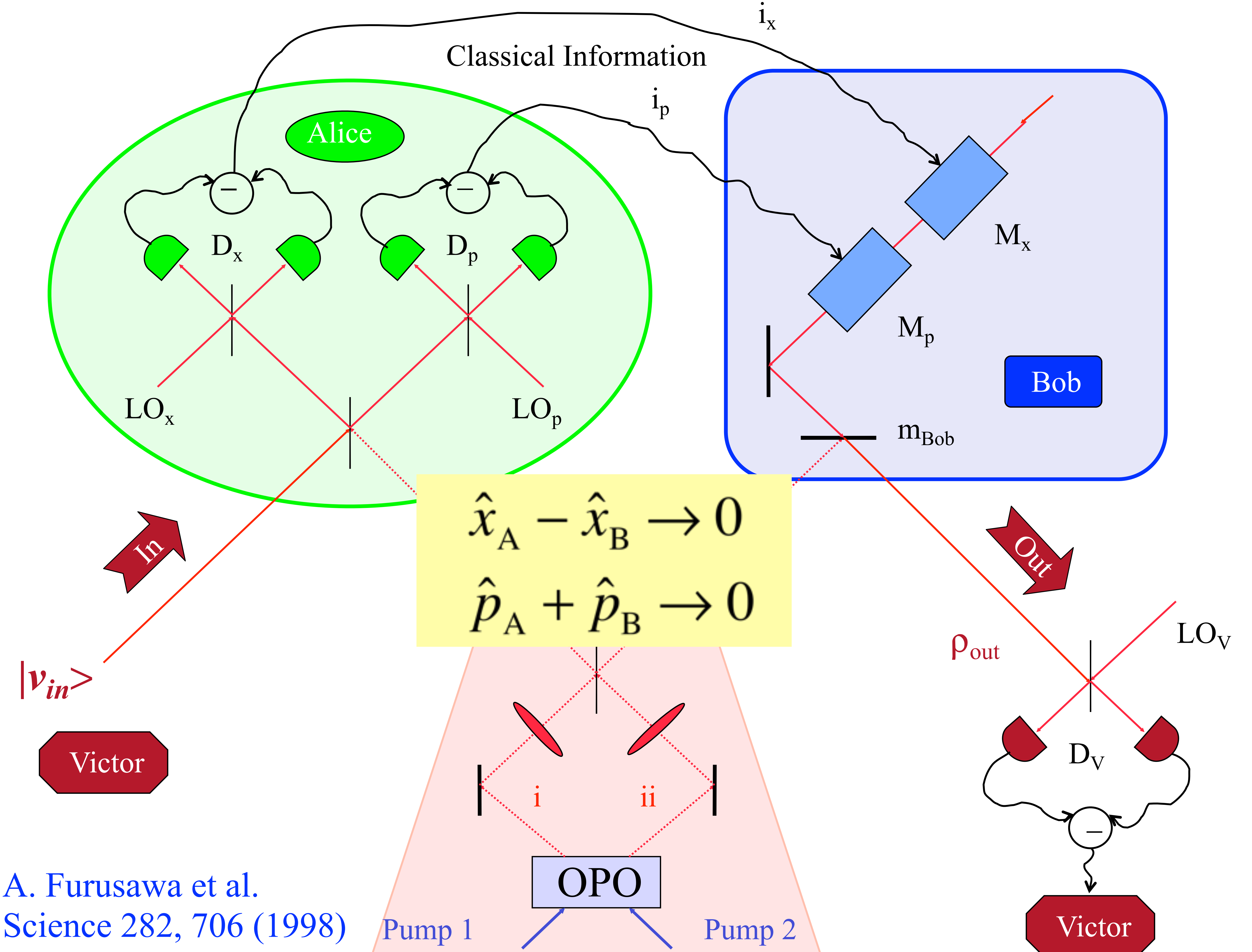
Wave

$$\hat{x}_A - \hat{x}_B \to 0$$

$$\hat{p}_A + \hat{p}_B \to 0$$

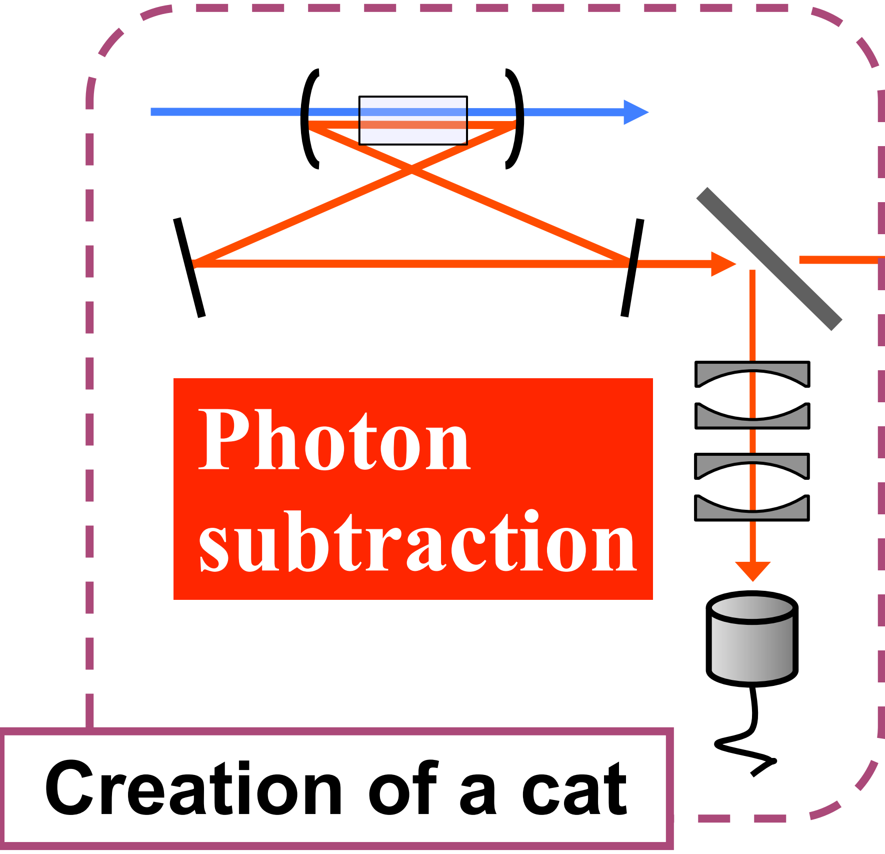


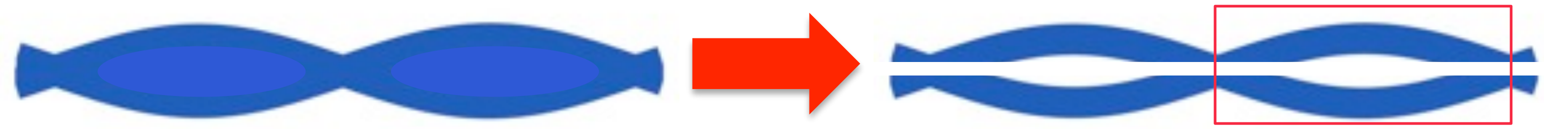
entanglement generation with squeezed light beams

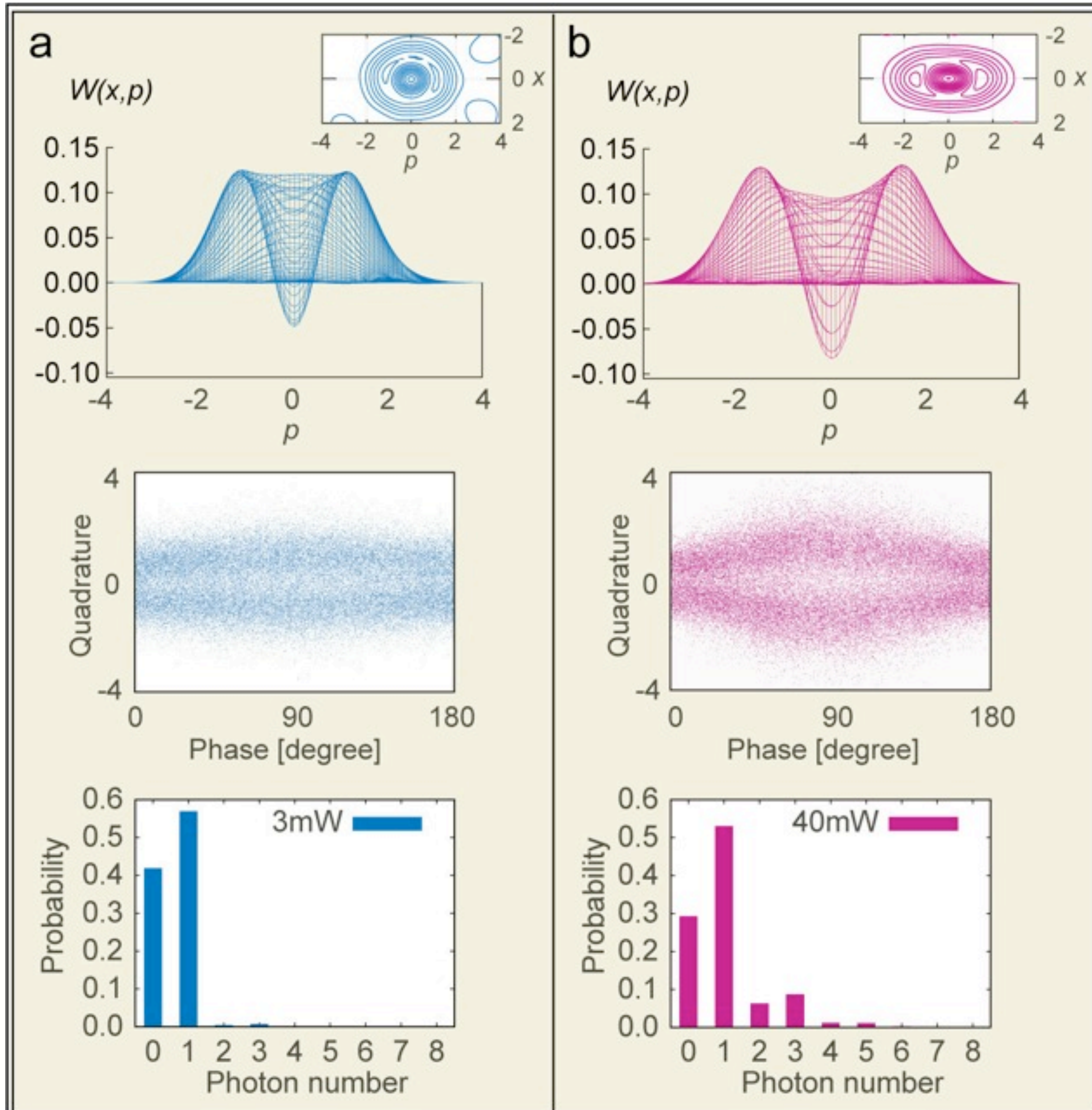


A. Furusawa et al.
Science 282, 706 (1998)

Teleportation of
a Schrödinger cat state of light







Defined in time-domain

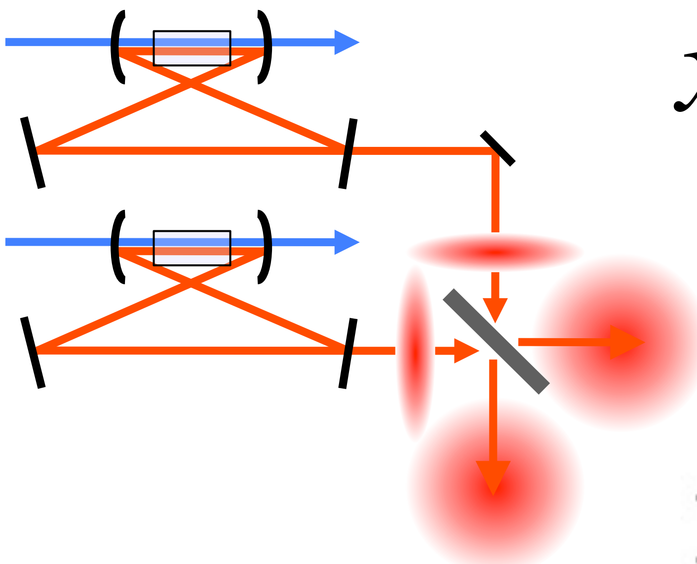
$$\hat{S}(r)|0\rangle = \frac{1}{\sqrt{\cosh r}} \sum_{n=0}^{\infty} \frac{\sqrt{(2n)!}}{2^n n!} \tanh^n r \, |2n\rangle$$

$$|\alpha\rangle - |-\alpha\rangle = e^{-\frac{|\alpha|^2}{2}} \sum_{n=0}^{\infty} \frac{\alpha^{2n+1}}{\sqrt{(2n+1)!}} |2n+1\rangle$$

K. Wakui, H. Takahashi, A. Furusawa, M. Sasaki, Opt. Exp. **15**, 3568 (2007)

Time-domain EPR correlation

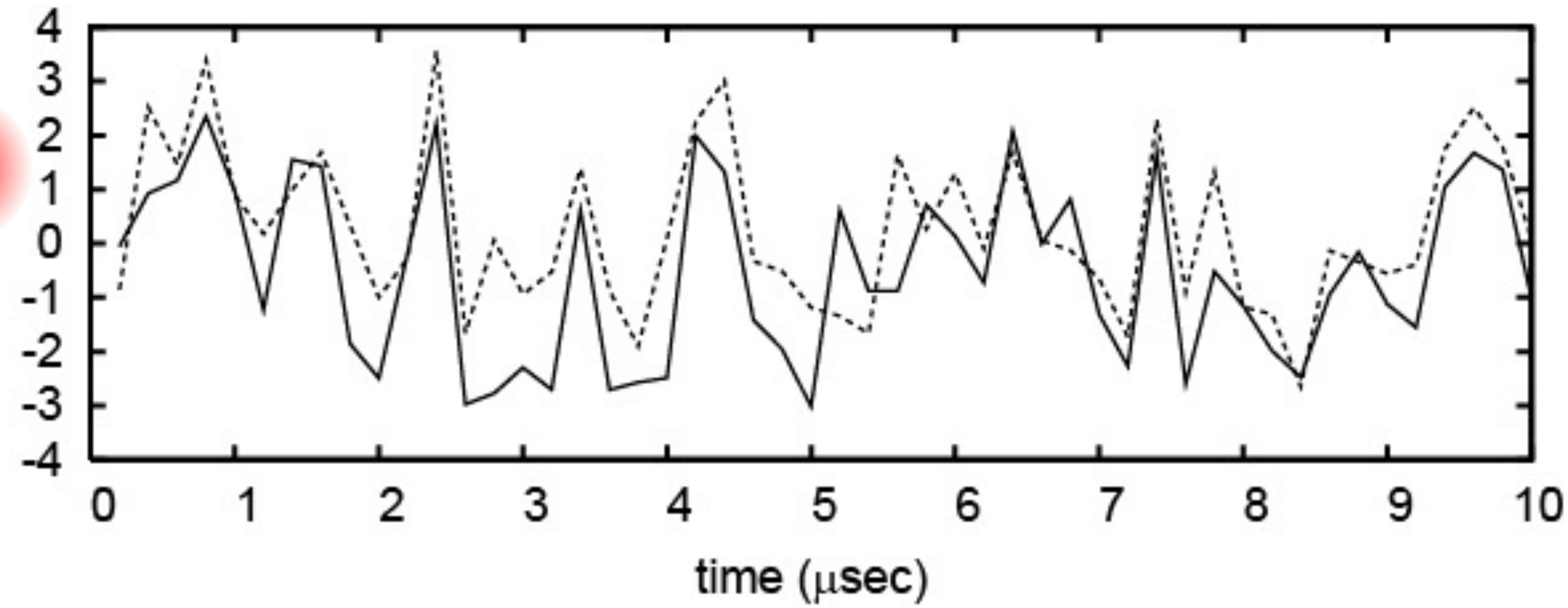
Alice ———
Bob ....



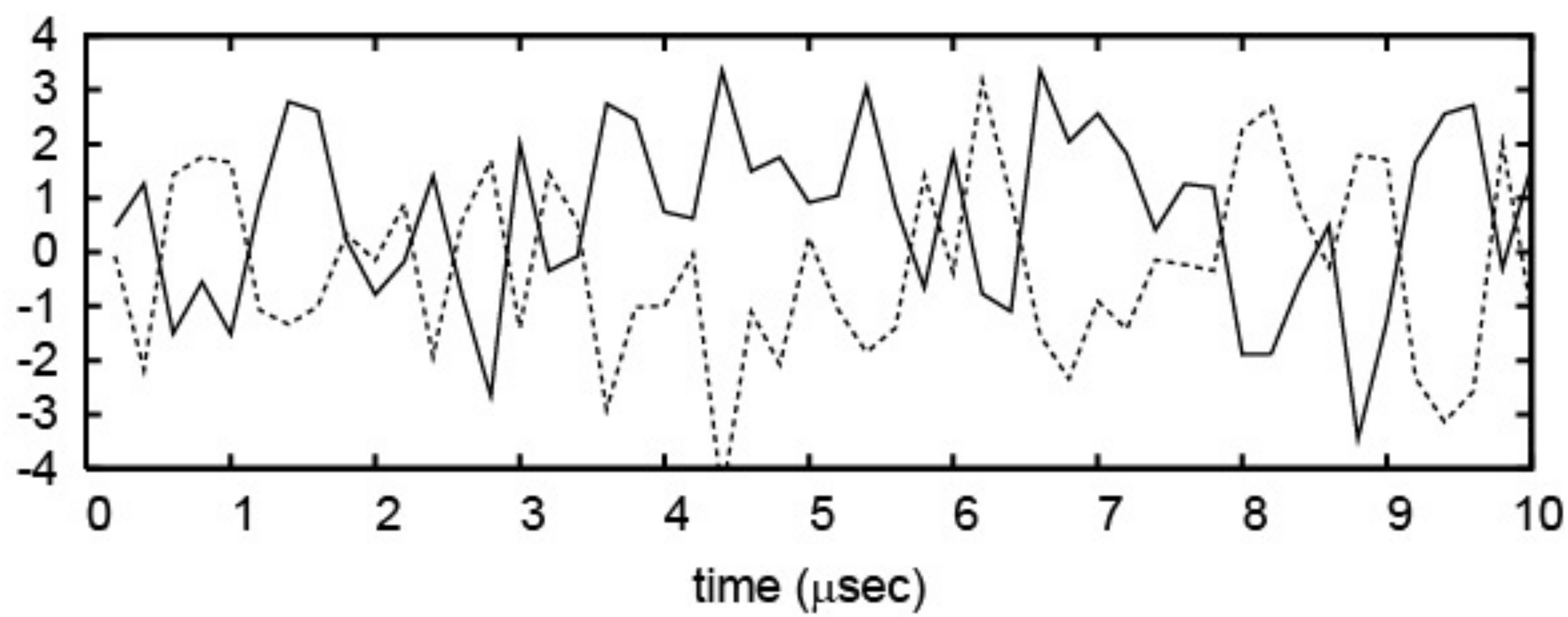
$$\begin{cases} \hat{x}_A - \hat{x}_B \to 0 \\ \hat{p}_A + \hat{p}_B \to 0 \end{cases}$$

$$\text{AM signal}_{\text{noise}} = \hat{x}$$
$$\text{FM signal}_{\text{noise}} = \hat{p}$$

x measurements

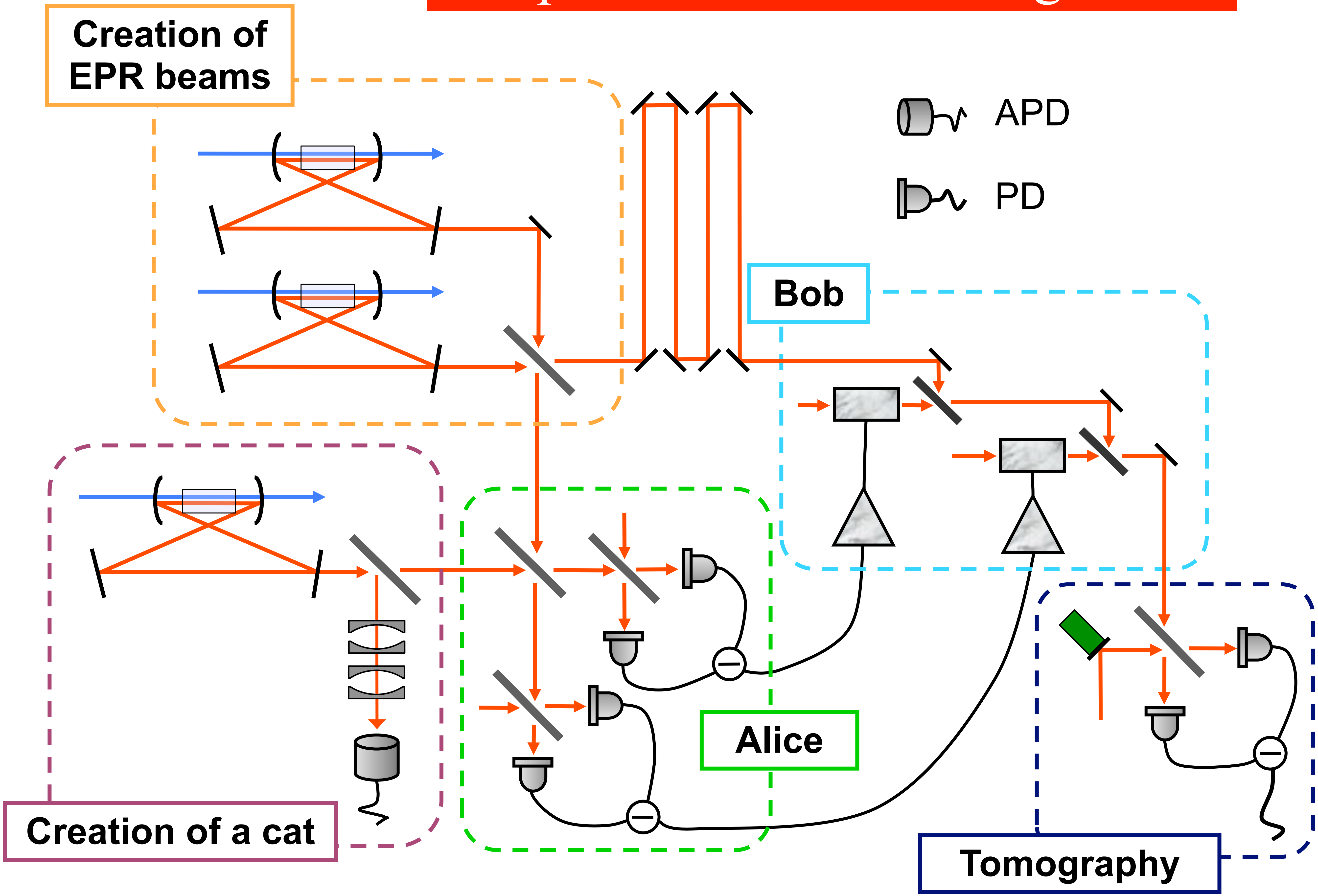


p measurements

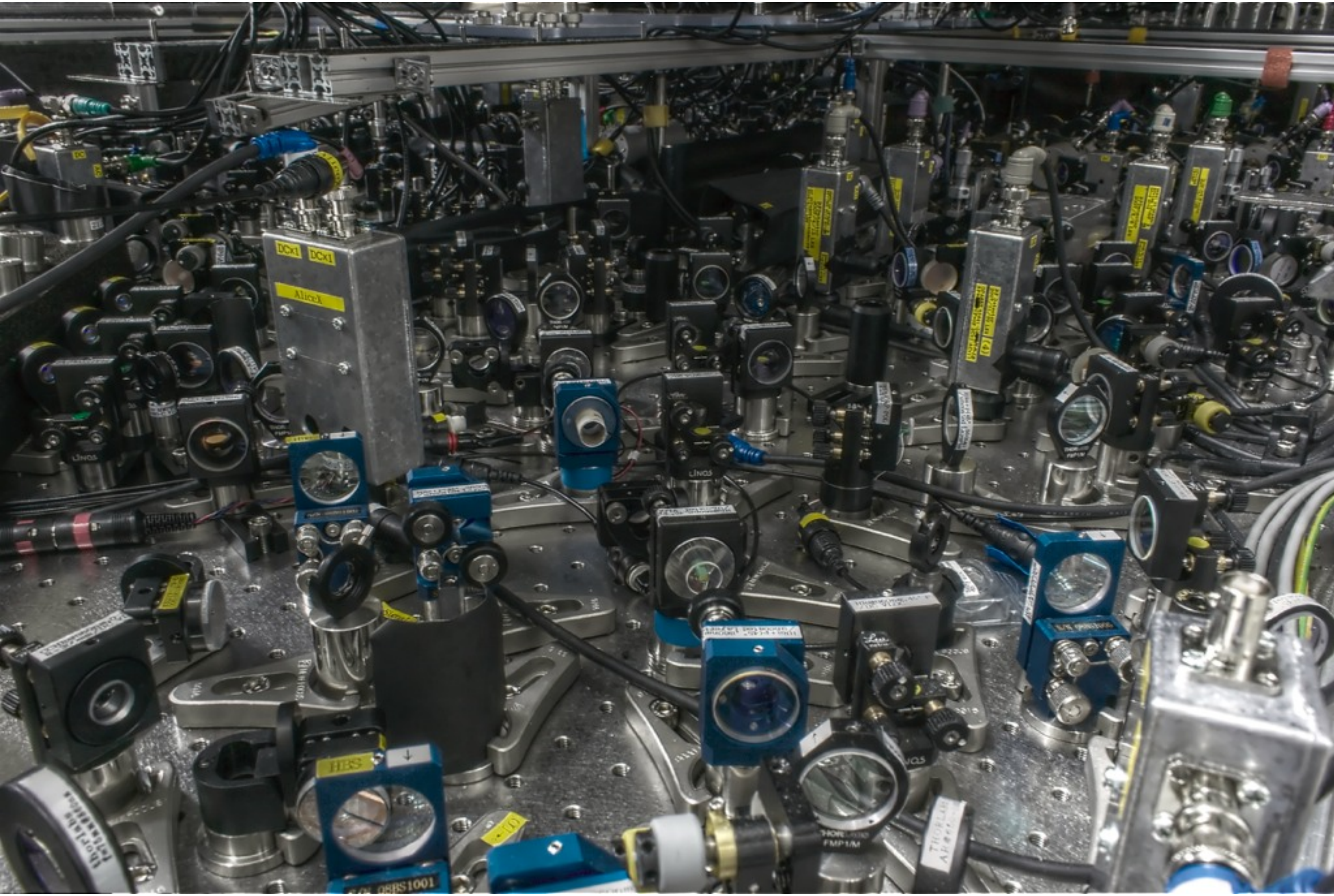


N. Takei, N. Lee, D. Moriyama, J. S. Neergaard-Nielsen, A. Furusawa, Phys. Rev. A 74, 060101(R) (2006)

Teleportation of Schrödinger cats

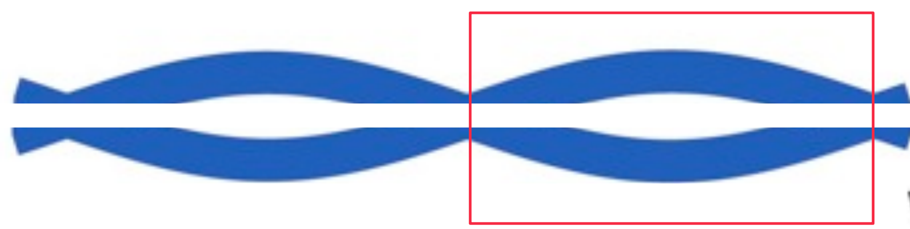


N. Lee, H. Benichi, Y. Takeno, S. Takeda, J. Webb, E. Huntington, & A. Furusawa, Science 332, 330 (2011)

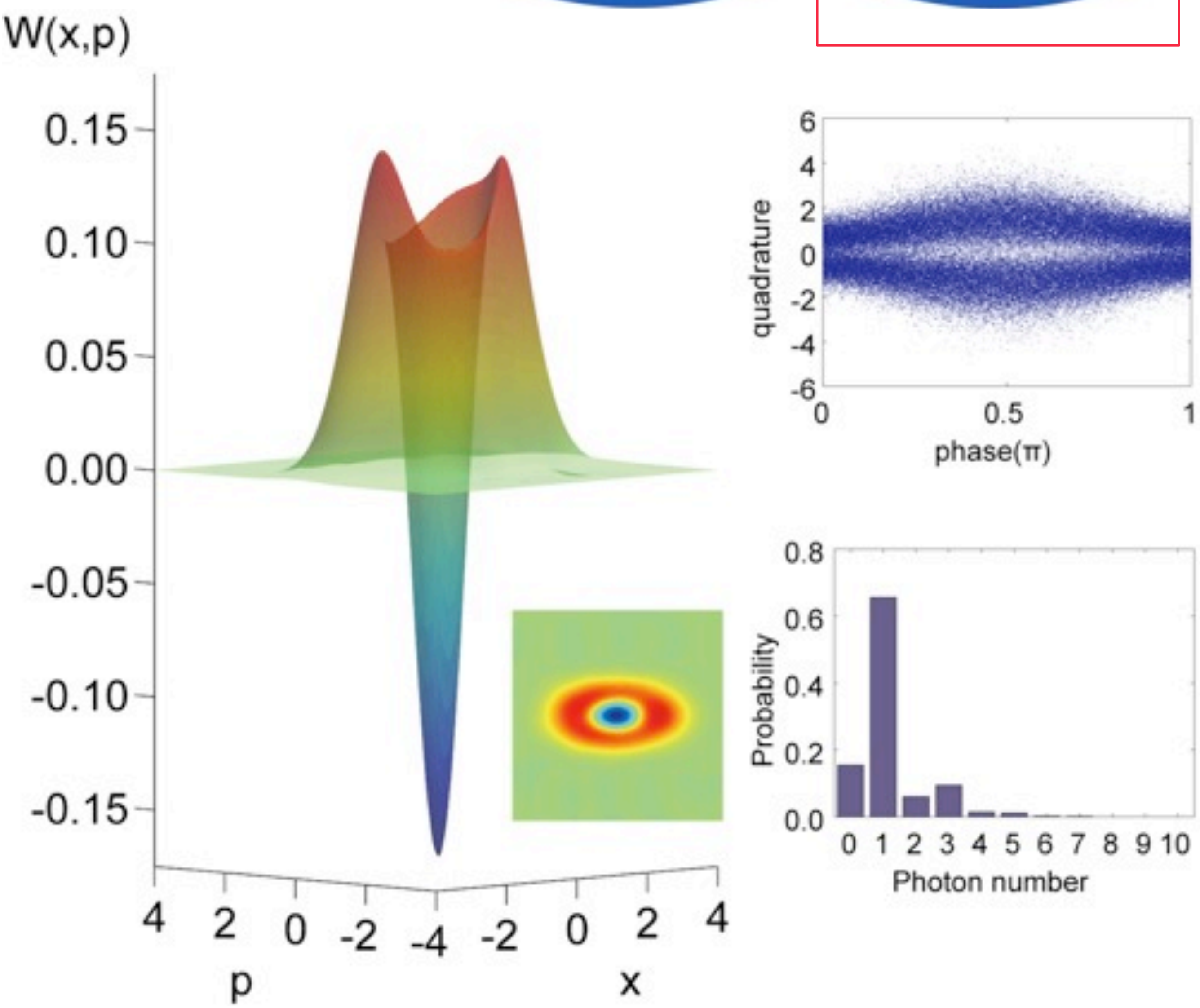


N. Lee, H. Benichi, Y. Takeno, S. Takeda, J. Webb, E. Huntington, & A. Furusawa, Science 332, 330 (2011)

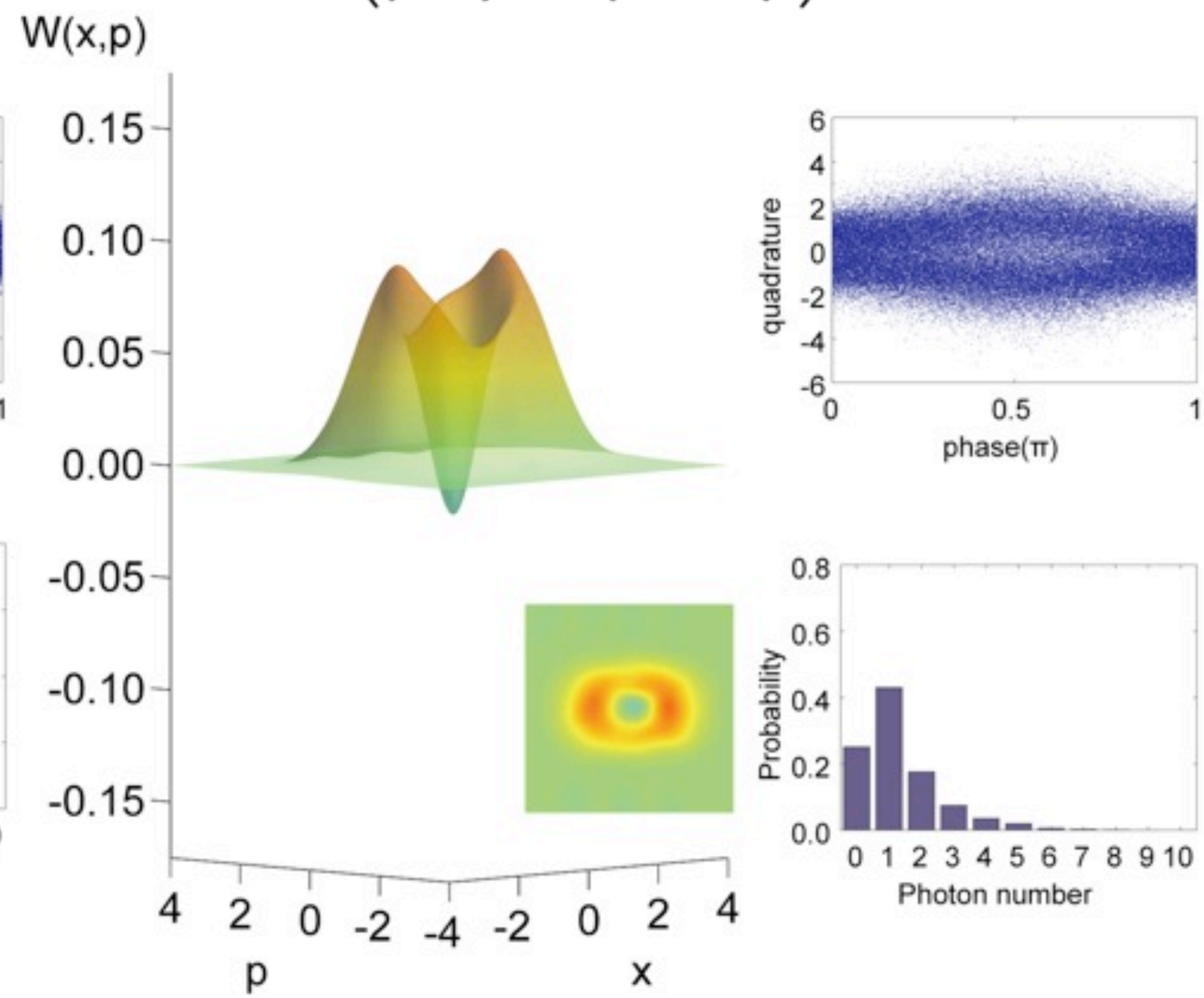
Teleportation of a Schrödinger cat state of light



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



Input



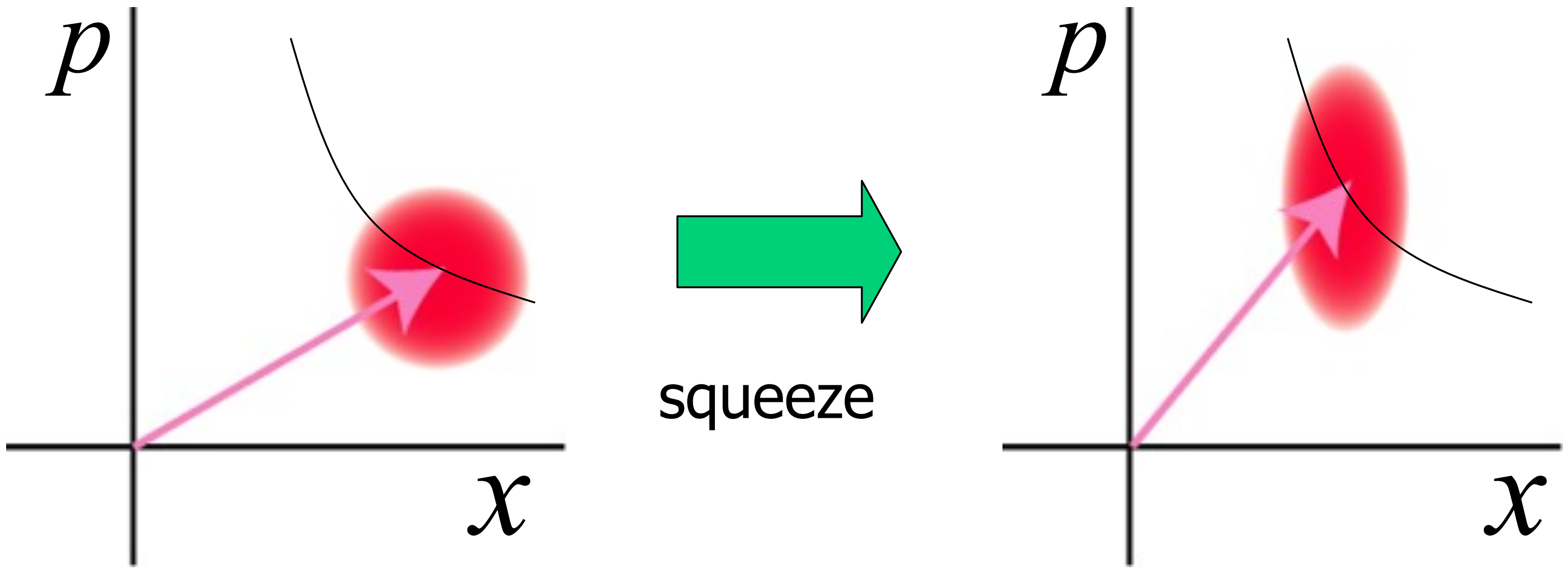
Output

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

High-fidelity universal squeezers
QND gate
One-way quantum information processing with a QND gate

Gate teleportation

High-fidelity universal squeezer

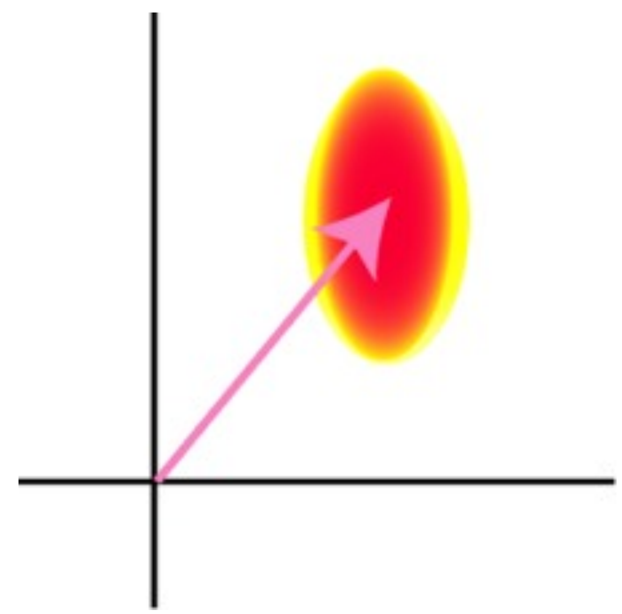


squeezing

$$\hat{x} \Rightarrow \frac{\hat{x}}{c}$$

$$\hat{p} \Rightarrow c\hat{p}$$

In reality



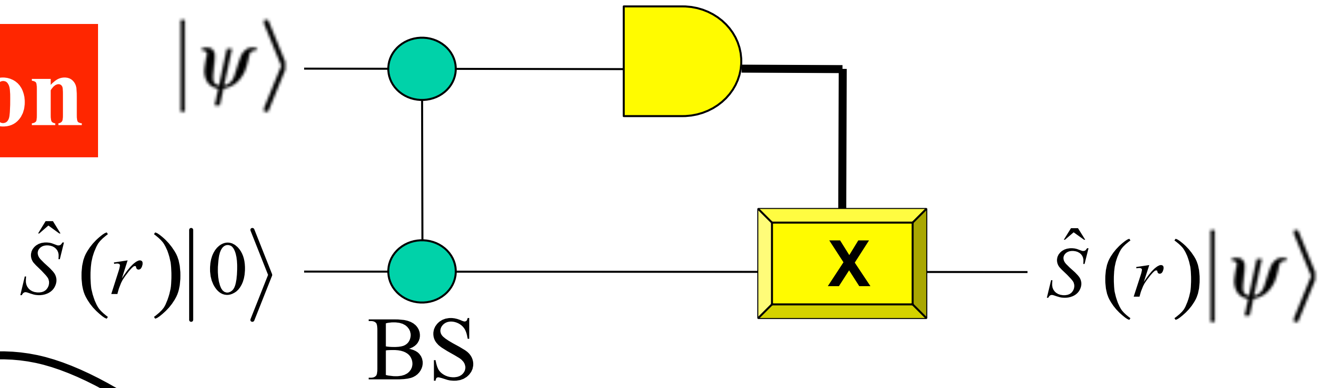
on average

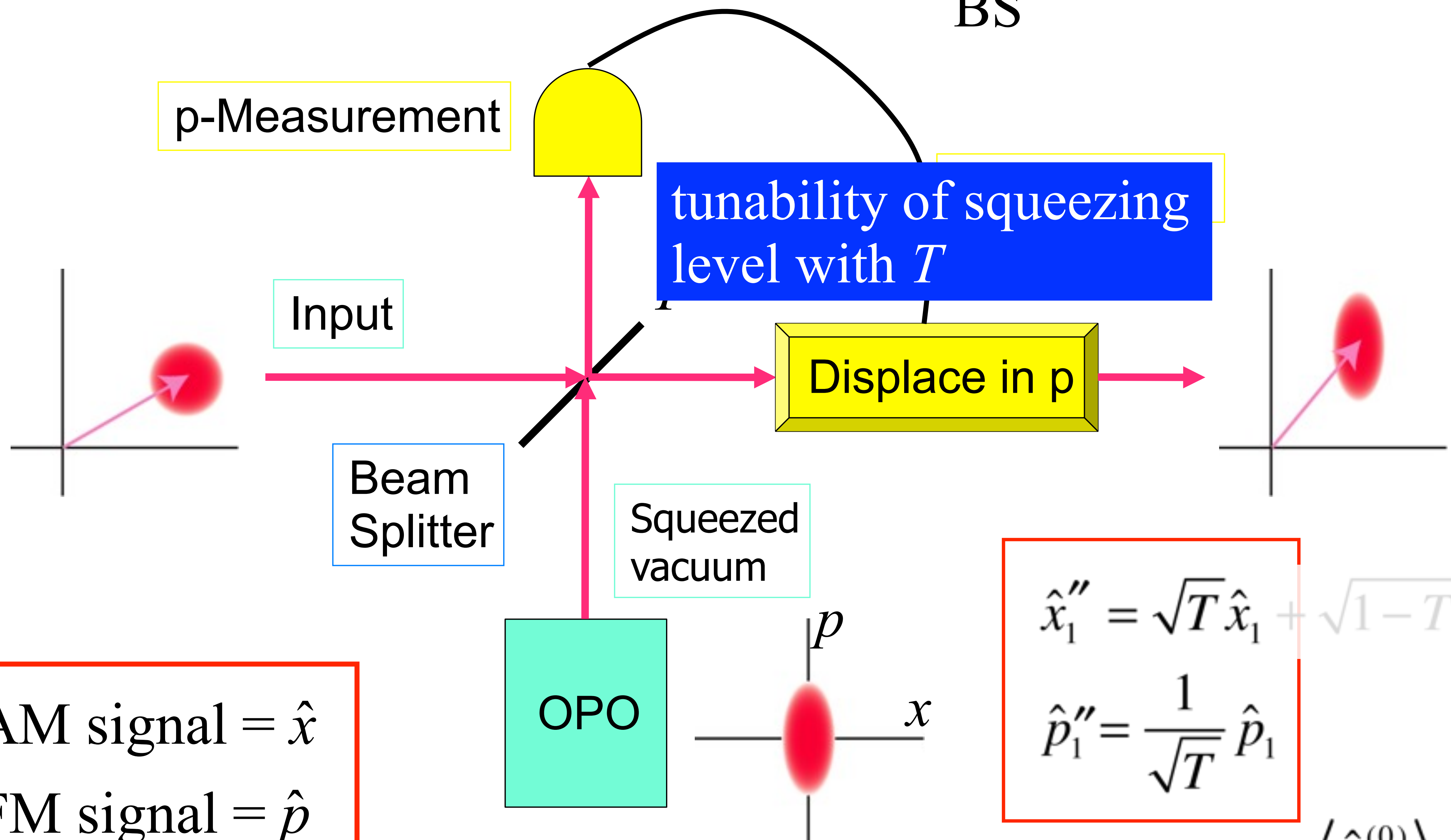
$$\langle \hat{x} \rangle \Rightarrow \left\langle \frac{\hat{x}}{c} \right\rangle$$

$$\langle \hat{p} \rangle \Rightarrow \langle c\hat{p} \rangle$$

High-fidelity universal squeezer with measurement and feedforward

gate teleportation





$$\hat{x}_1'' = \sqrt{T}\,\hat{x}_1 + \sqrt{1-T}\,\hat{x}_A^{(0)} e^{-r}$$

$$\hat{p}_1'' = \frac{1}{\sqrt{T}}\,\hat{p}_1$$

$$\langle \hat{x}_A^{(0)} \rangle = 0$$

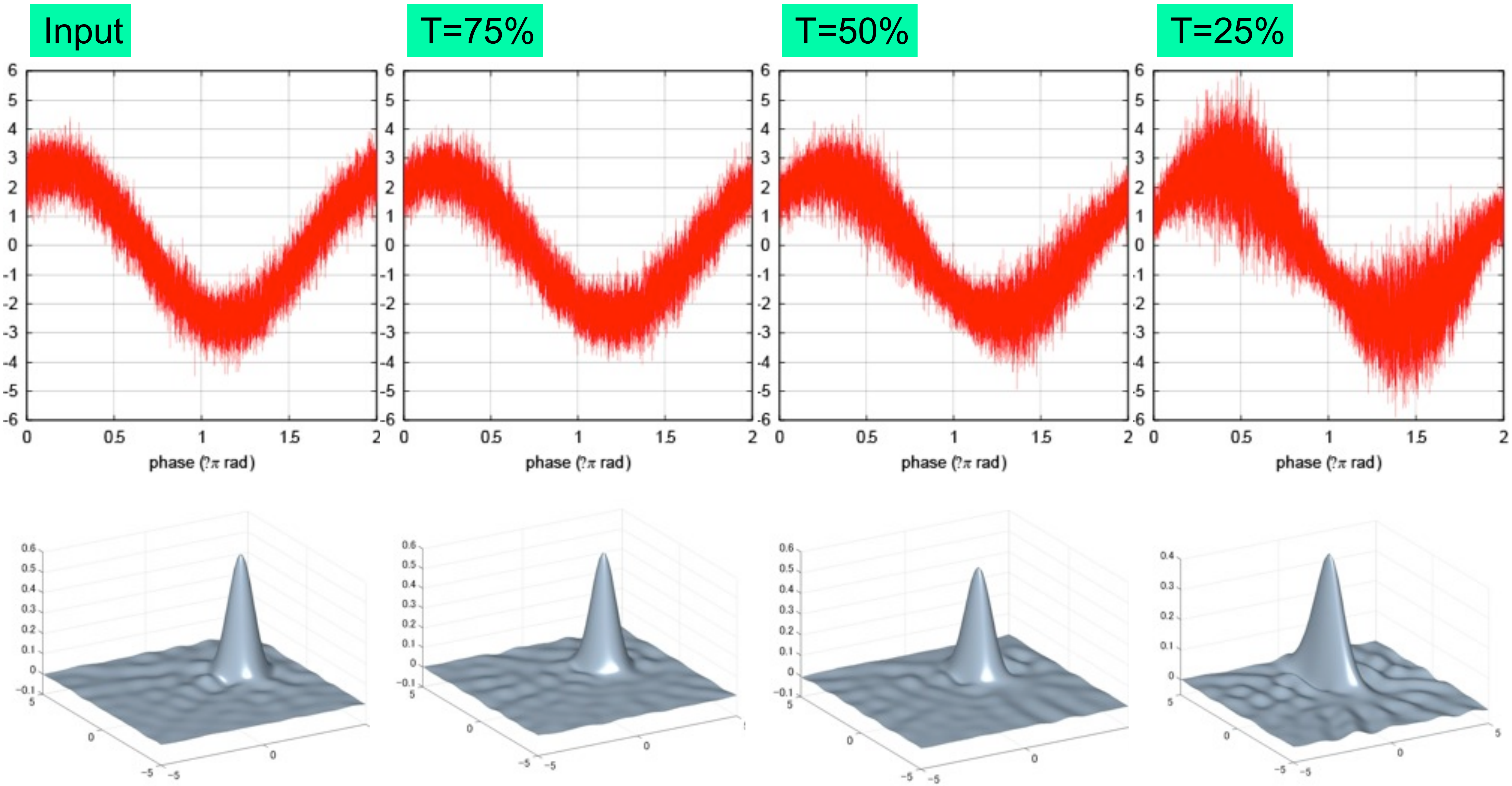
AM signal $= \hat{x}$

FM signal $= \hat{p}$

R. Filip, P. Marek, and U. L. Andersen, Phys. Rev. A **71**, 042308 (2005)

Output of High-fidelity squeezer

ancilla: -5dB of squeezing



J. Yoshikawa, T. Hayashi, T. Akiyama, N. Takei, A. Huck, U. L. Andersen, and A. Furusawa, Phys. Rev. A 76, 060301(R) (2007).

$$\hat{U}_{\text{QND}} = e^{-i2G\hat{x}_1\hat{p}_2}$$

Quantum Non-Demolition (QND) interaction

QND gate

$$\hat{U}_{\text{QND}}^{-1}\hat{x}_1\hat{U}_{\text{QND}} = \hat{x}_1$$

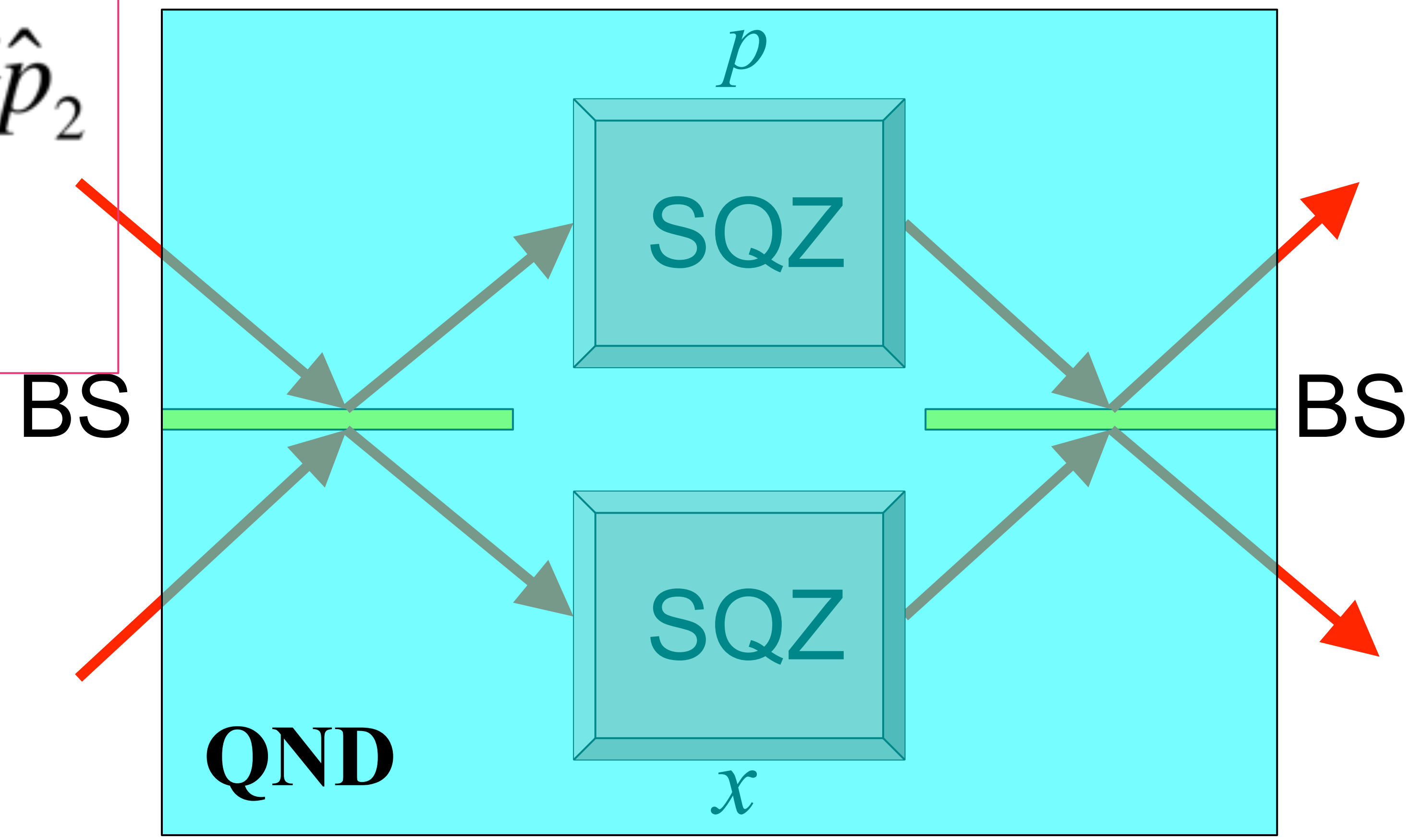
$$\hat{U}_{\text{QND}}^{-1}\hat{x}_2\hat{U}_{\text{QND}} = \hat{x}_2 + G\hat{x}_1$$

$$\hat{U}_{\text{QND}}^{-1}\hat{p}_1\hat{U}_{\text{QND}} = \hat{p}_1 - G\hat{p}_2$$

$$\hat{U}_{\text{QND}}^{-1}\hat{p}_2\hat{U}_{\text{QND}} = \hat{p}_2$$

$$e^{-2i\hat{x}_1\hat{p}_2}\left|x_1\right\rangle\otimes\left|x_2\right\rangle = \left|x_1\right\rangle\otimes\left|x_1 + x_2\right\rangle$$

CV-CNOT gate (G=1)



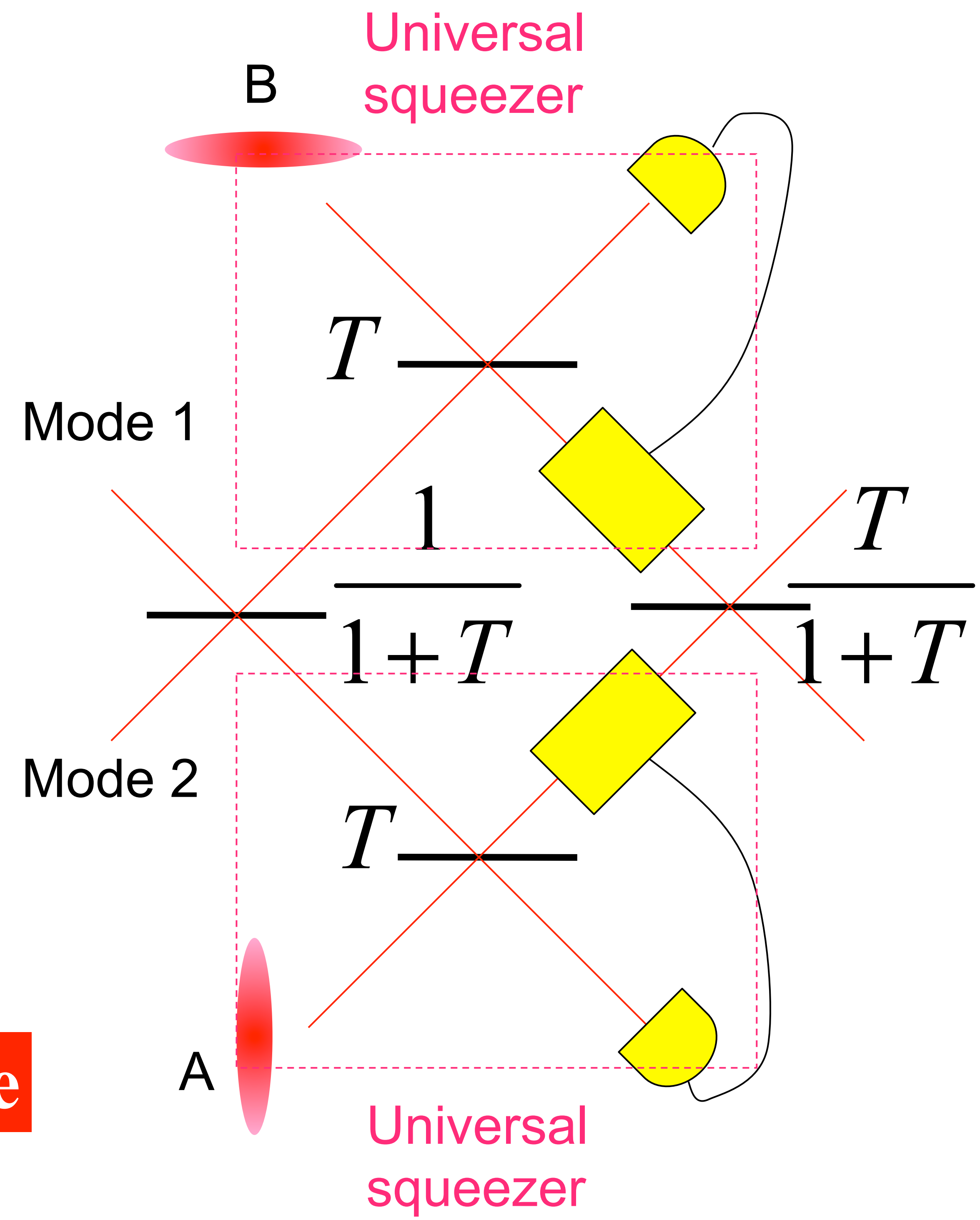
QND interaction with universal squeezers

$$\hat{x}_1' = \hat{x}_1 - \sqrt{\frac{1-T}{1+T}}\hat{x}_A^{(0)}e^{-r}$$

$$\hat{x}_2' = \hat{x}_2 + \left(\frac{1}{\sqrt{T}} - \sqrt{T}\right)\hat{x}_1 + \sqrt{T\frac{1-T}{1+T}}\hat{x}_A^{(0)}e^{-r}$$

$$\hat{p}_1' = \hat{p}_1 - \left(\frac{1}{\sqrt{T}} - \sqrt{T}\right)\hat{p}_2 + \sqrt{T\frac{1-T}{1+T}}\hat{x}_B^{(0)}e^{-r}$$

$$\hat{p}_2' = \hat{p}_2 + \sqrt{\frac{1-T}{1+T}}\hat{p}_B^{(0)}e^{-r}$$



$$G = \frac{1}{\sqrt{T}} - \sqrt{T}$$

$G = 1$ **QND gate**

$T = 0.38$

-4.2 dB of squeezing

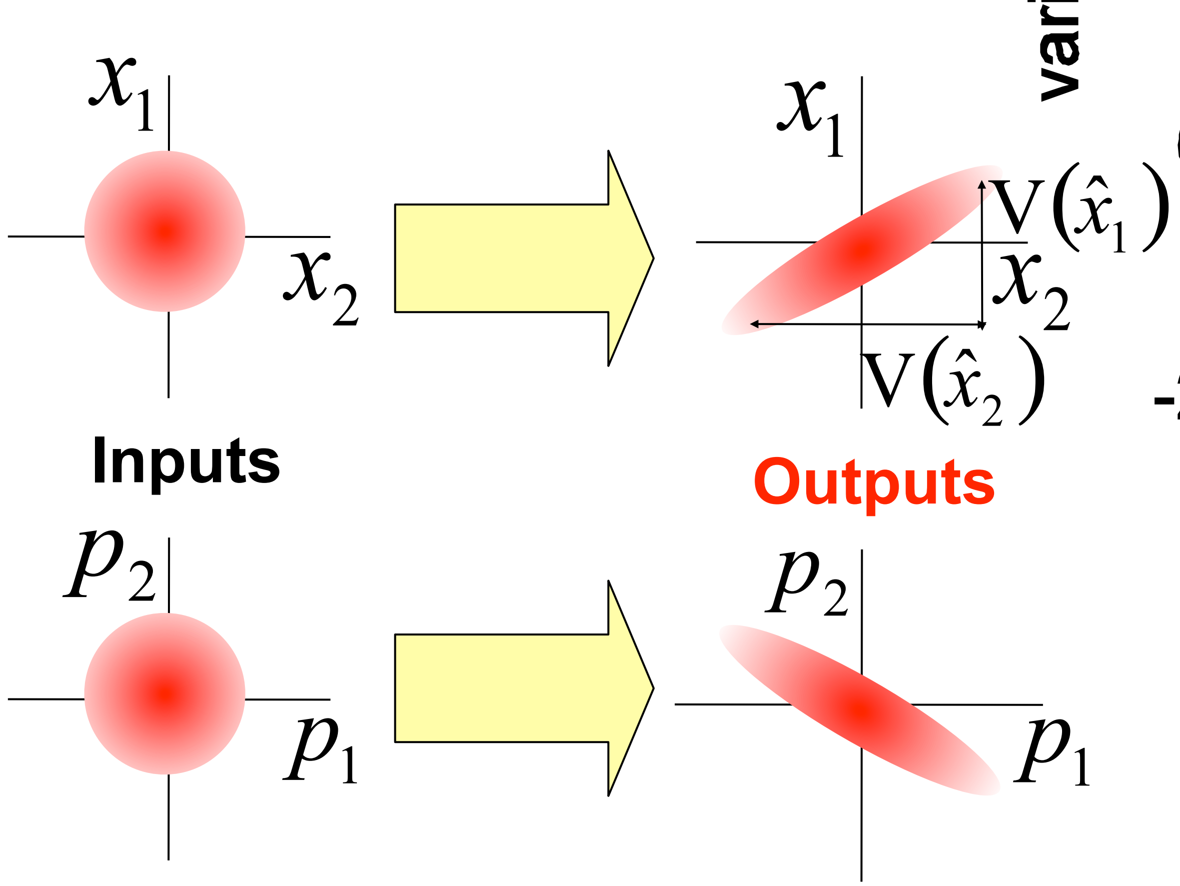
Experimental results

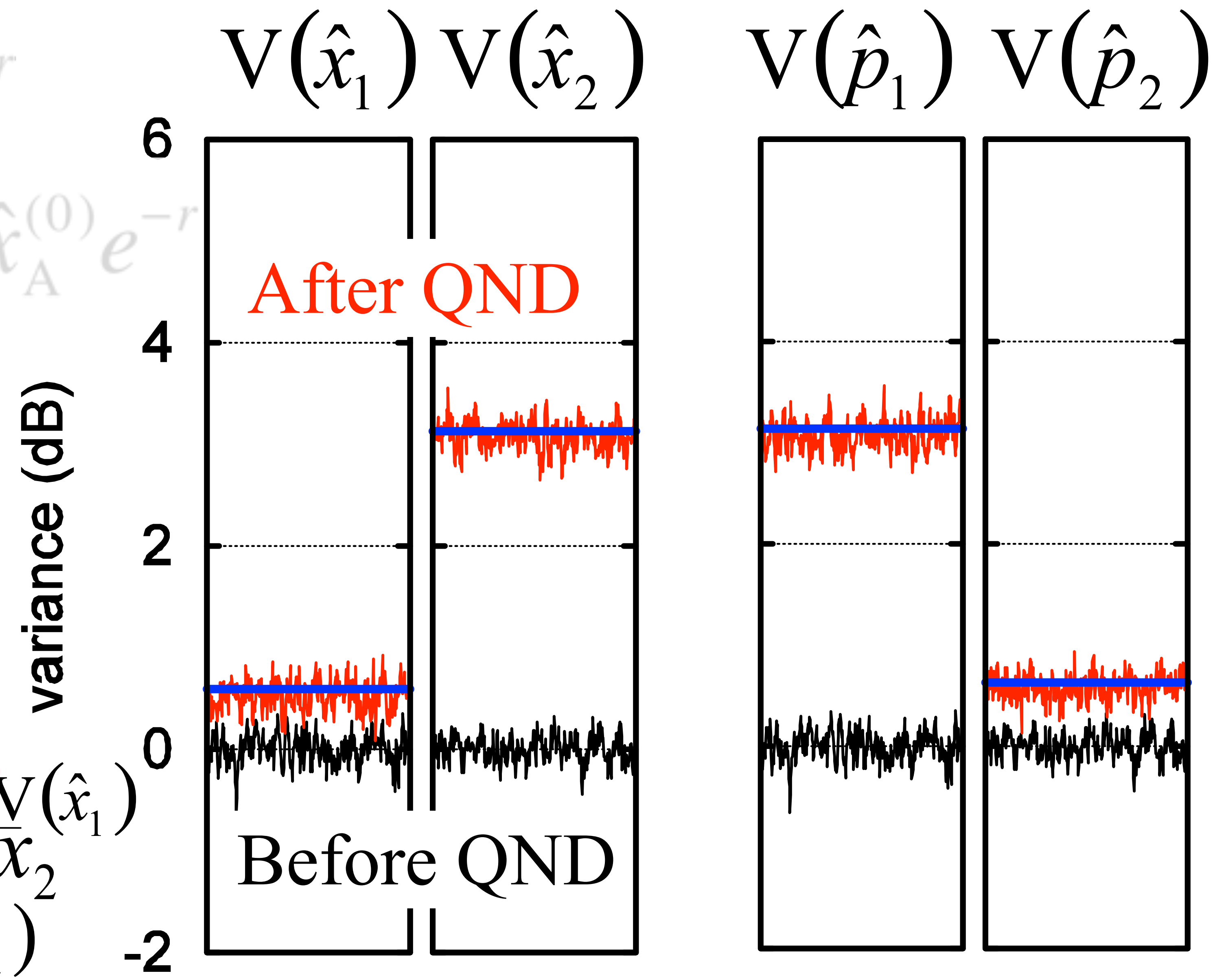
$$\hat{x}_1^{\text{out}} = \hat{x}_1^{\text{in}} - 0.67\hat{x}_A^{(0)}e^{-r}$$

$$\hat{x}_2^{\text{out}} = \hat{x}_2^{\text{in}} + \hat{x}_1^{\text{in}} + 0.41\hat{x}_A^{(0)}e^{-r}$$

$$\hat{p}_1^{\text{out}} = \hat{p}_1^{\text{in}} - \hat{p}_2^{\text{in}}$$

$$\hat{p}_2^{\text{out}} = \hat{p}_2^{\text{in}}$$





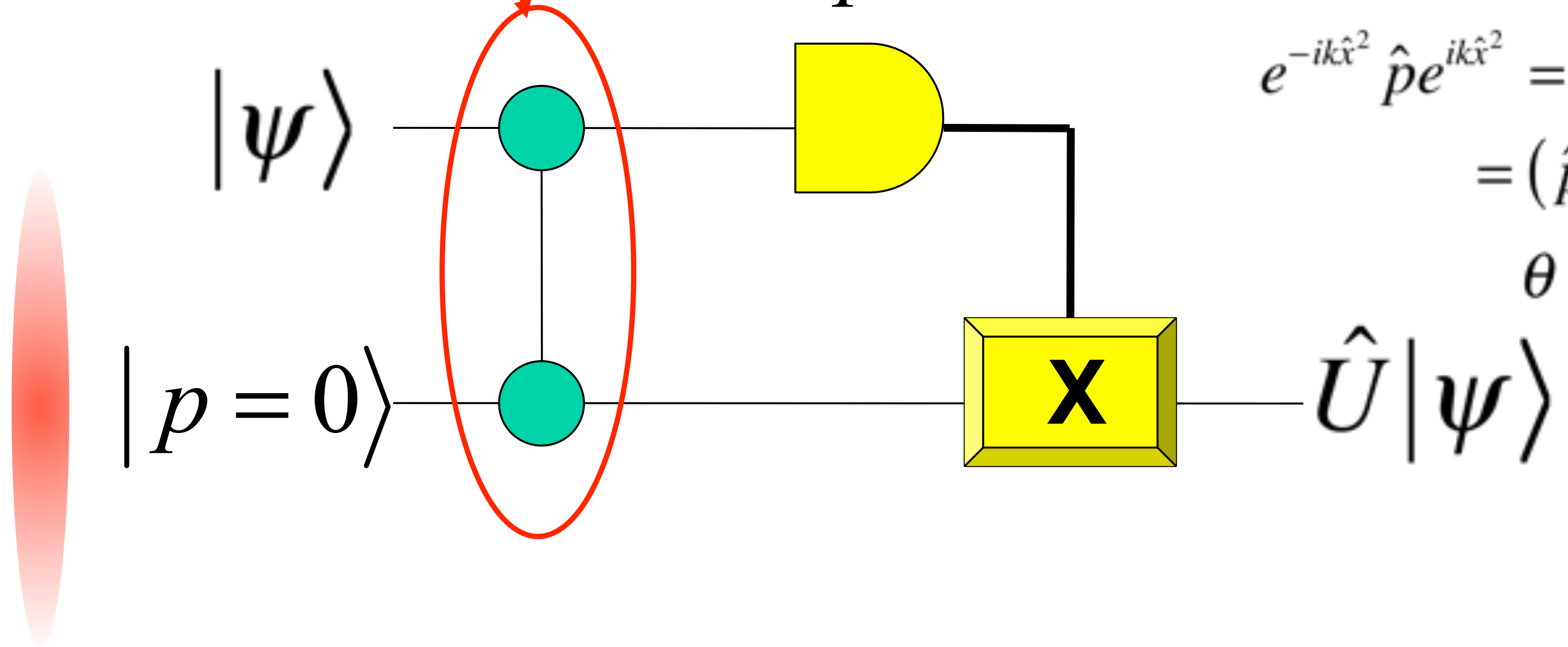
Theoretical values with finite squeezing of ancillae: -4.9dB

J. Yoshikawa et al., Phys. Rev. Lett. 101, 250501 (2008)

One-way QIP with an entangling QND gate

QND gate

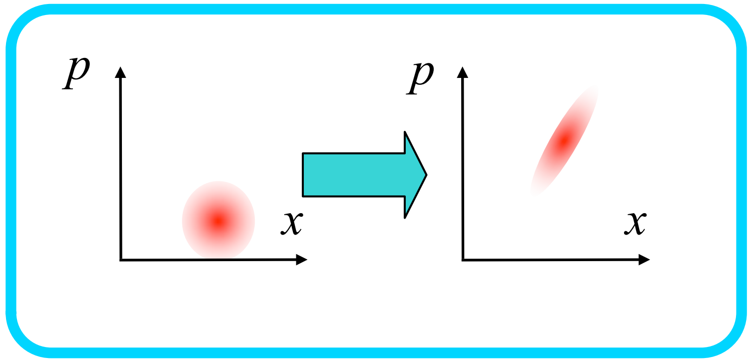
$\hat{U}^{\dagger}\hat{p}U$ change the measurement basis



$$e^{-ik\hat{x}^2}\hat{p}e^{ik\hat{x}^2} = \hat{p} + k\hat{x}$$
$$= (\hat{p}\cos\theta - \hat{x}\sin\theta)/\cos\theta$$
$$\theta = \tan^{-1}(-k)$$

$\hat{U} = e^{ik\hat{x}^2}$

Homodyne measurement



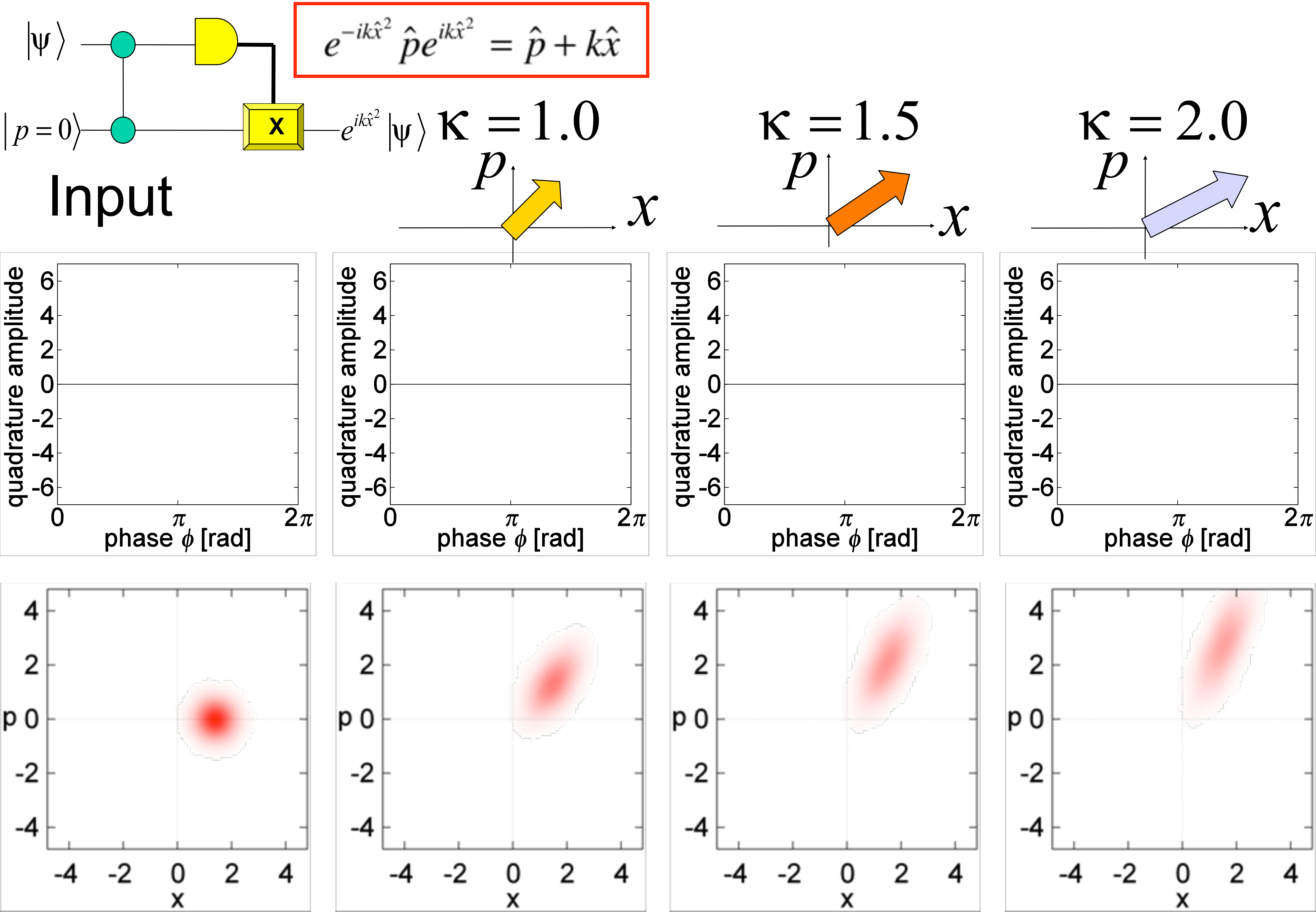
rotation — squeezing — rotation

$$e^{ik\hat{x}^2} = e^{-i(\cot^{-1}\eta)\hat{n}} e^{(\ln\eta)2\hat{x}\hat{p}} e^{i(\cot^{-1}\eta)\hat{n}} \qquad \eta = \left(\sqrt{k^2+4} + |k|\right)/2$$

Y. Miwa, J. Yoshikawa, P. van Loock and A. Furusawa, Phys. Rev. A 80, 050303(R) (2009)

One-way quantum computing with an entangling QND gate

$$e^{-ik\hat{x}^2}\,\hat{p}\,e^{ik\hat{x}^2} = \hat{p} + k\hat{x}$$



Teleportation of time-bin qubits with a CV teleporter

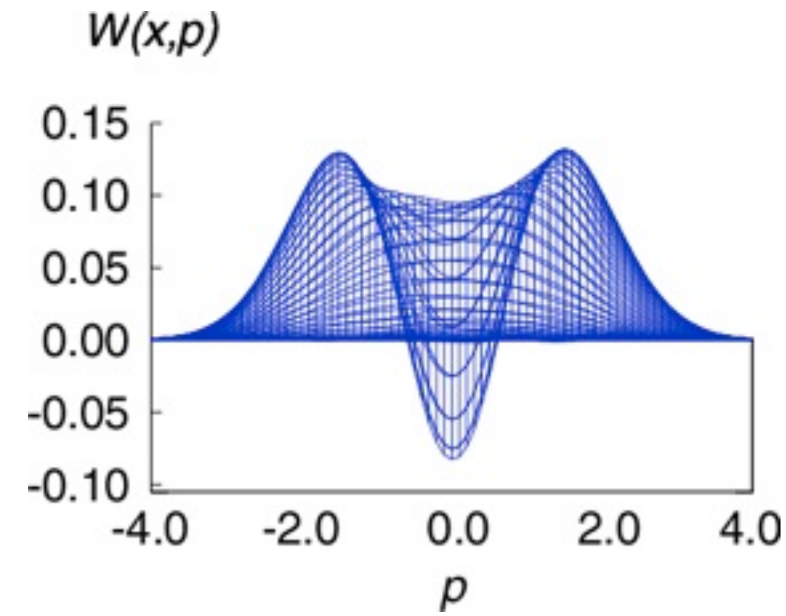
Deterministic teleportation of optical qubits

Hybrid quantum information processing

Schrödinger cat states

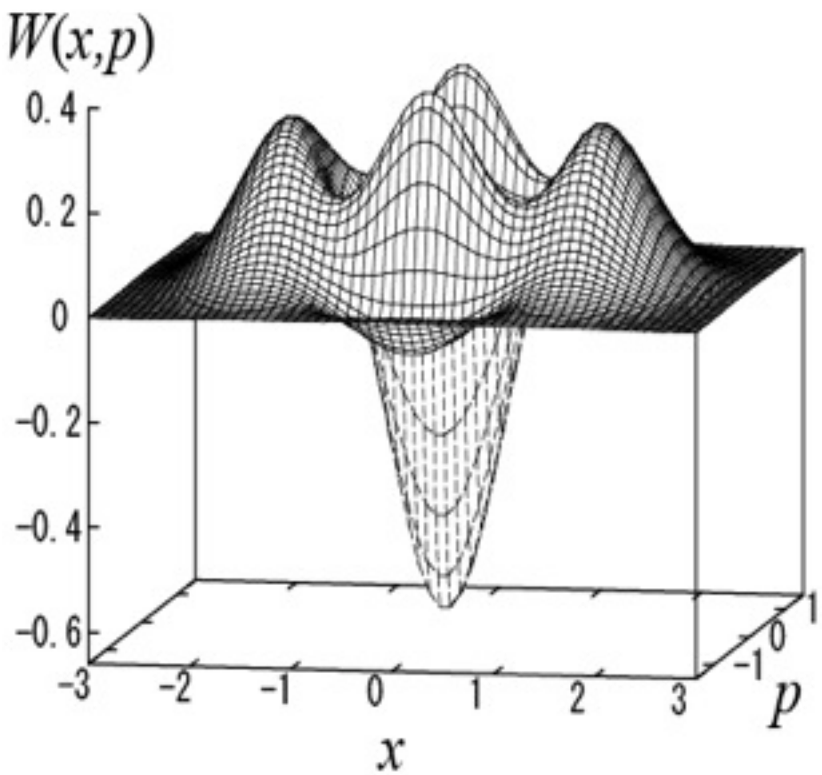
$$|0\rangle : N_\alpha \left(|\alpha\rangle - |-\alpha\rangle \right)$$ odd photons

$$|1\rangle : N_\alpha \left(|\alpha\rangle + |-\alpha\rangle \right)$$ even photons



K. Wakui et al.,
Opt. Exp. 15, 3568 (2007)

H. Takahashi et al.,
Phys. Rev. Lett. 101, 233605 (2008)

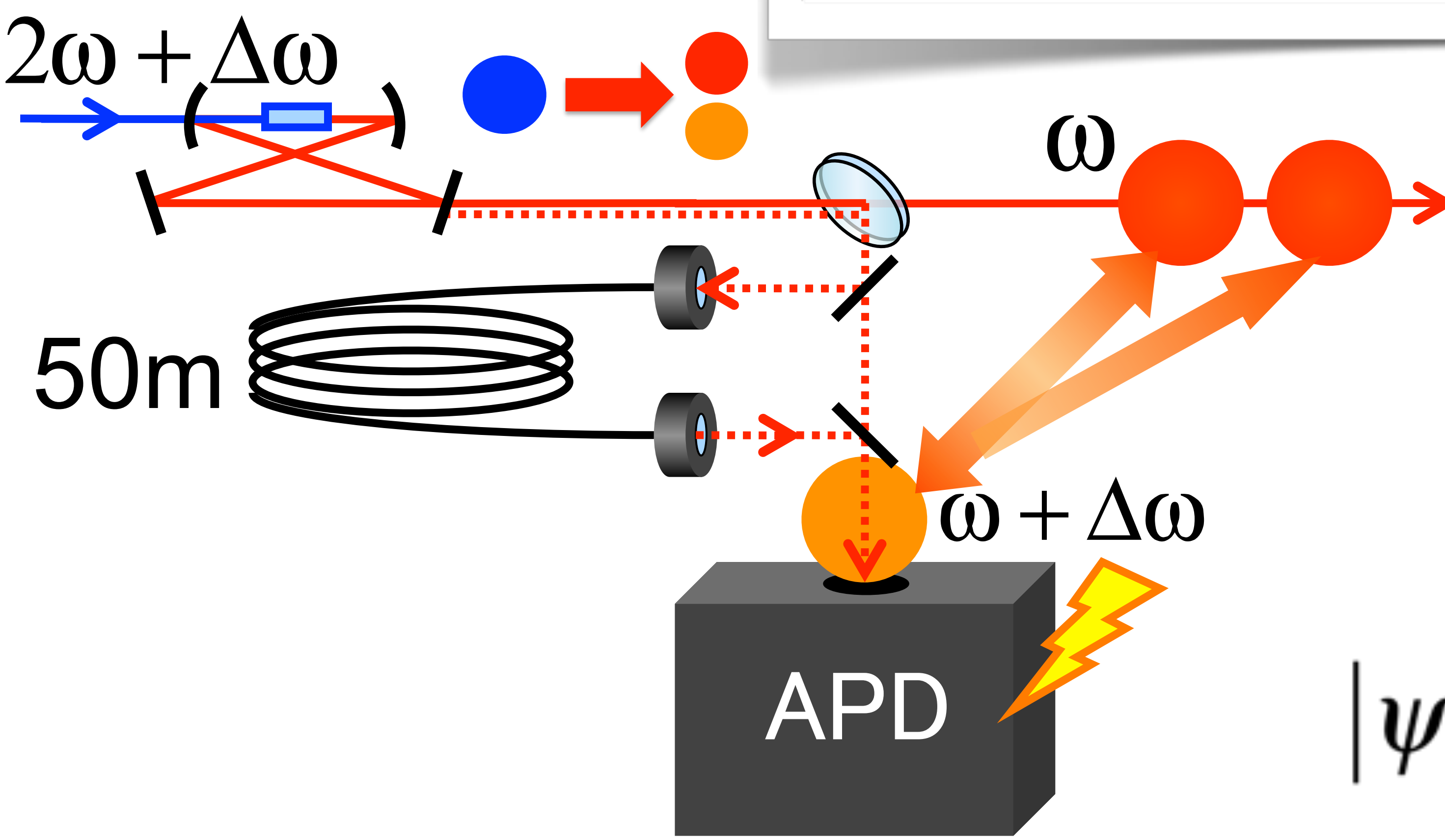


$$|\alpha\rangle = e^{-\frac{|\alpha|^2}{2}} \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} |n\rangle$$

$$|-\alpha\rangle = e^{-\frac{|\alpha|^2}{2}} \sum_{n=0}^{\infty} \frac{(-\alpha)^n}{\sqrt{n!}} |n\rangle$$

Now working on

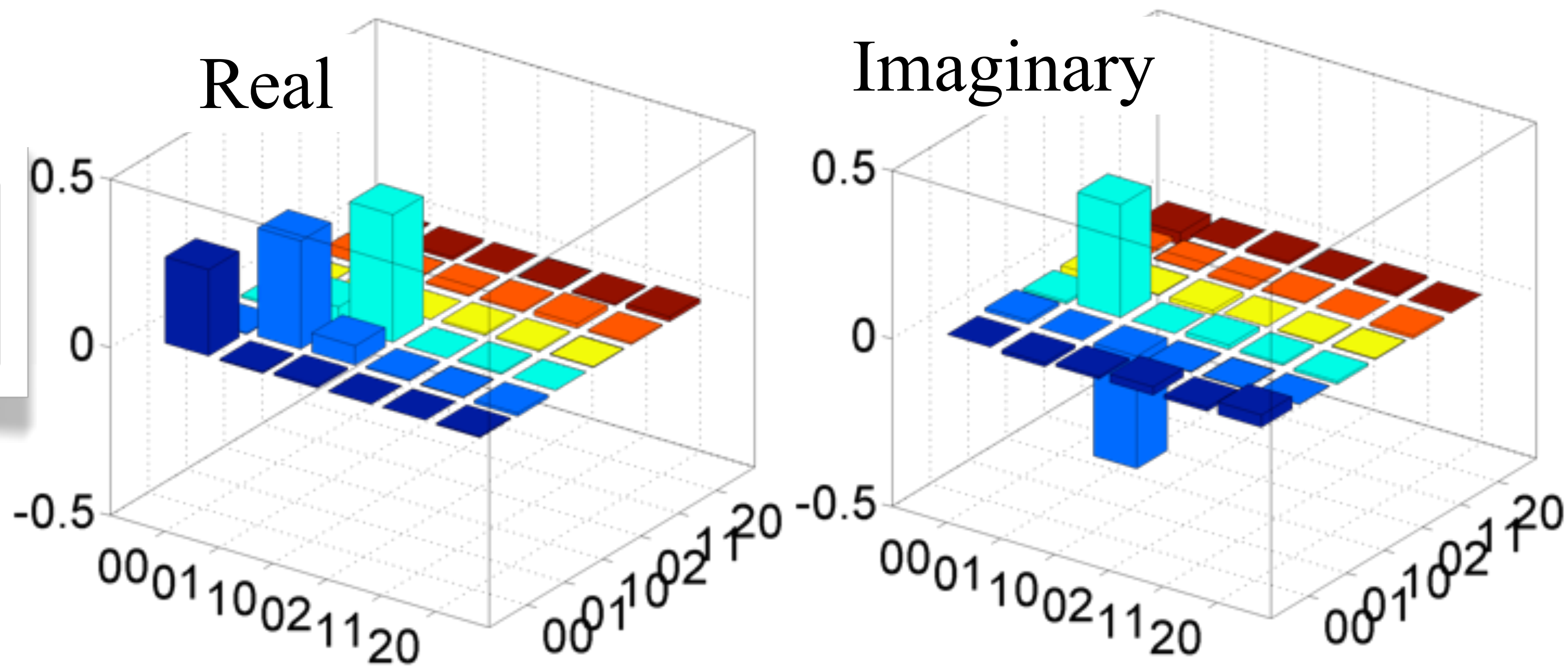
Teleportation of time-bin qubits



$$|\psi\rangle = c_0|1,0\rangle + c_1 e^{i\phi}|0,1\rangle$$

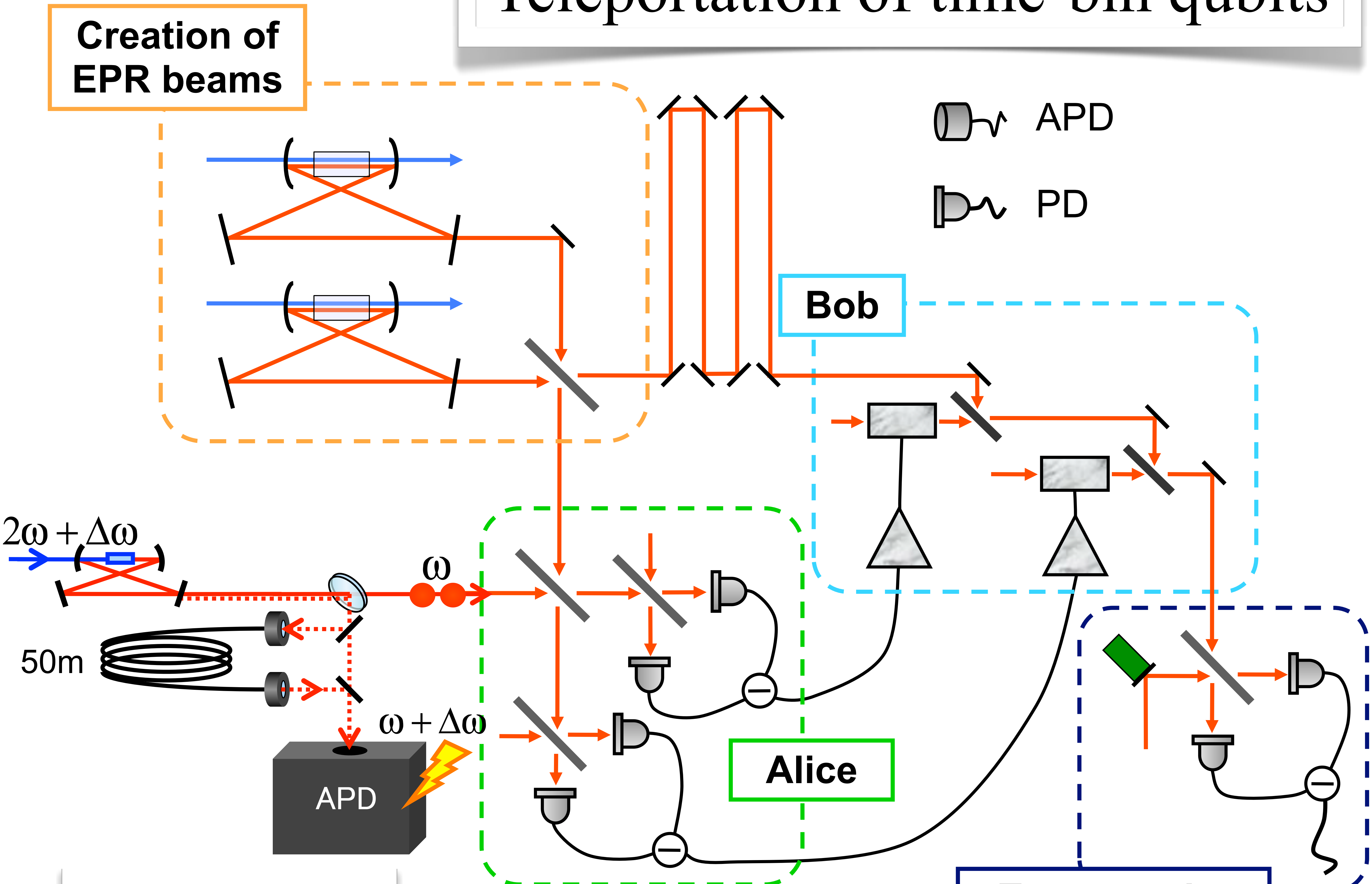
$$|\psi\rangle = \frac{|1,0\rangle - i|0,1\rangle}{\sqrt{2}}$$

Dual-homodyne Tomography



S. Takeda, T. Mizuta, M. Fuwa, J. Yoshikawa, H. Yonezawa, and A. Furusawa, Phys. Rev. A 87, 043803 (2013)

Teleportation of time-bin qubits



Time-bin qubit

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

Realization of on-demand single-photon source

Quantum memory

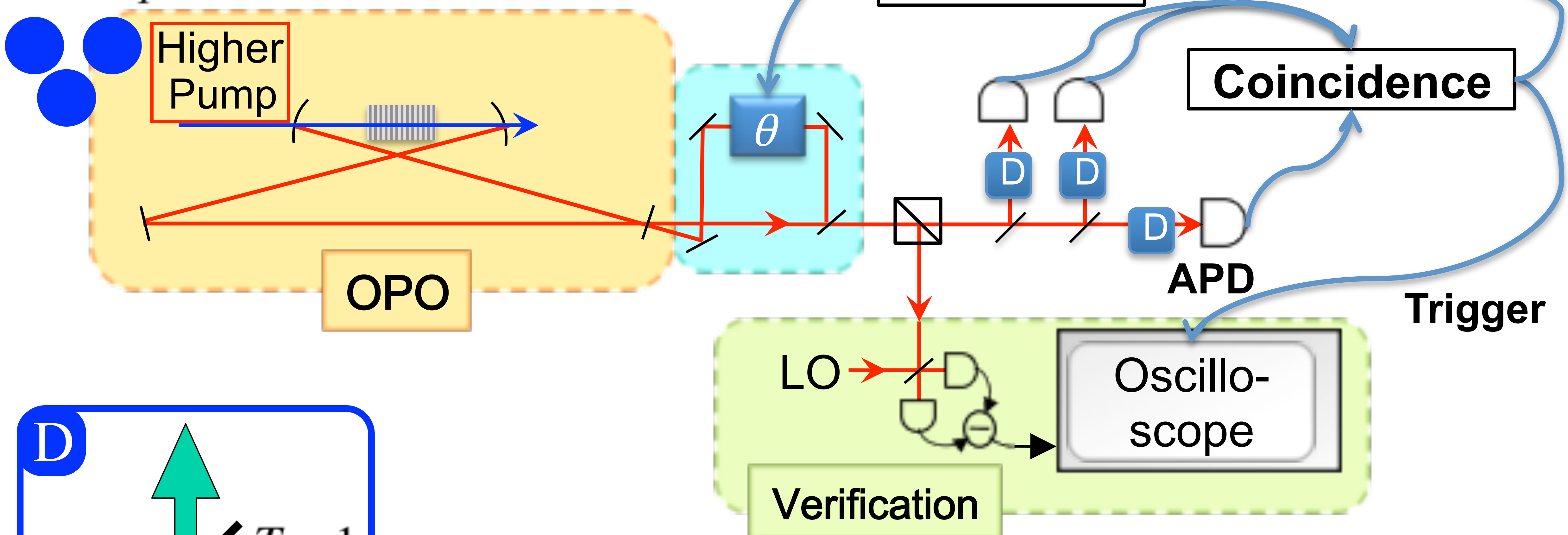
K. Makino, J. Yoshikawa, S. Kurata, P. van Loock, and A. Furusawa, FiO2012, FTh1C.3

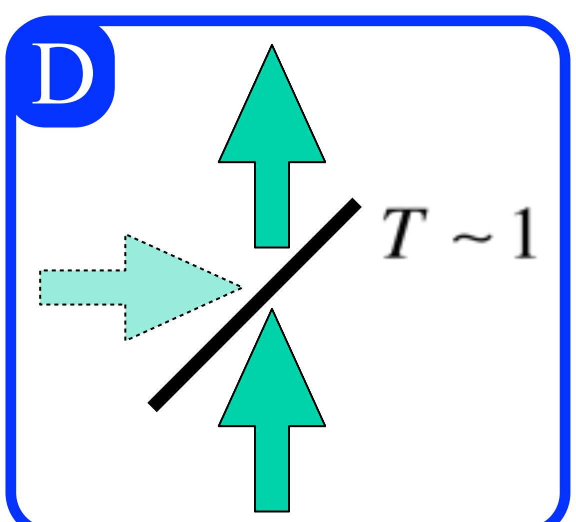
State generation and quantum memory

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

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

$$q = \tanh r$$



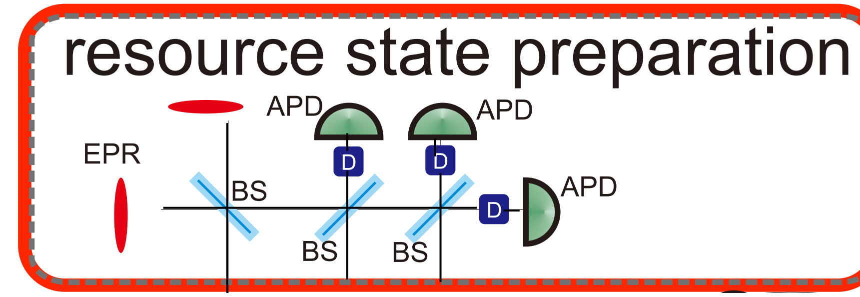


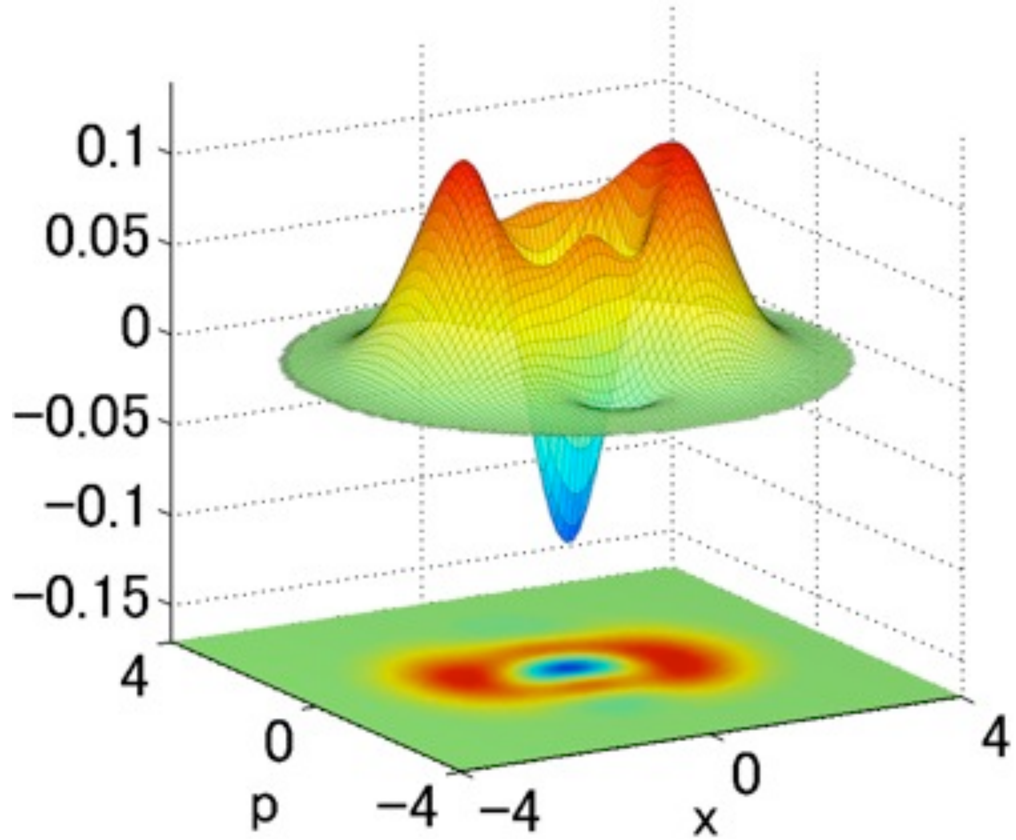
$$|\psi\rangle = a|0\rangle + b|1\rangle + c|2\rangle + d|3\rangle$$

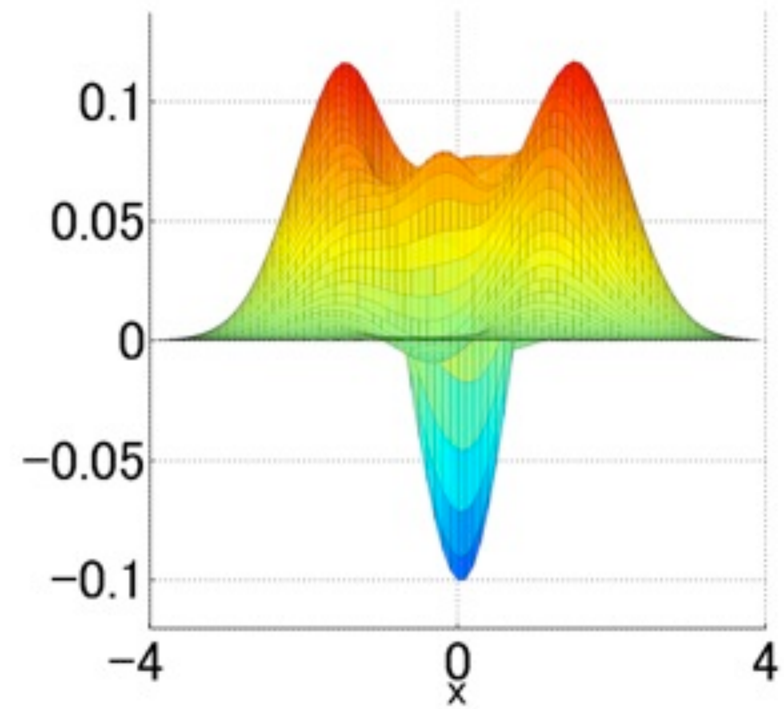
$$|1\rangle + \frac{\alpha^2}{\sqrt{6}}|3\rangle$$

Schrödinger cat state

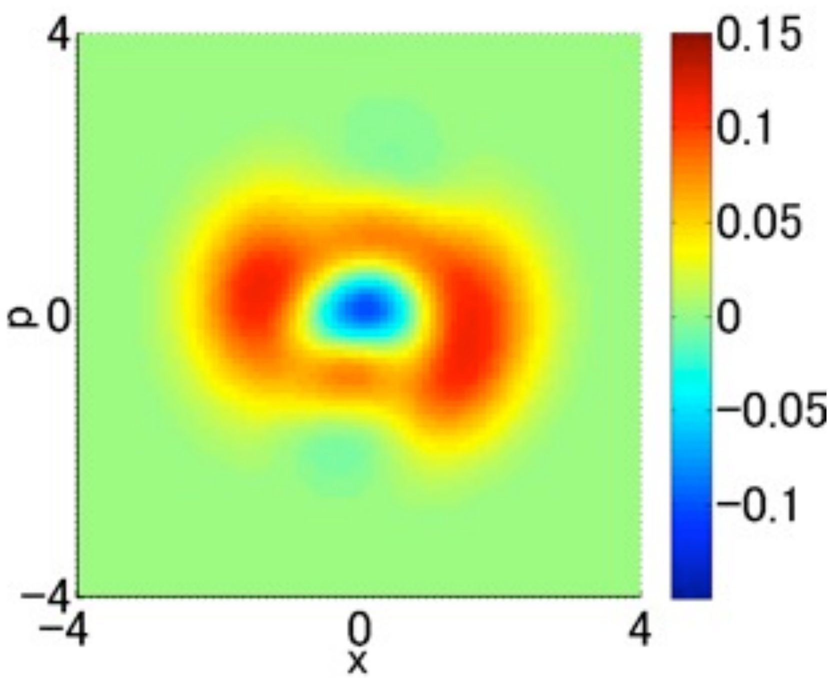
A bigger cat!

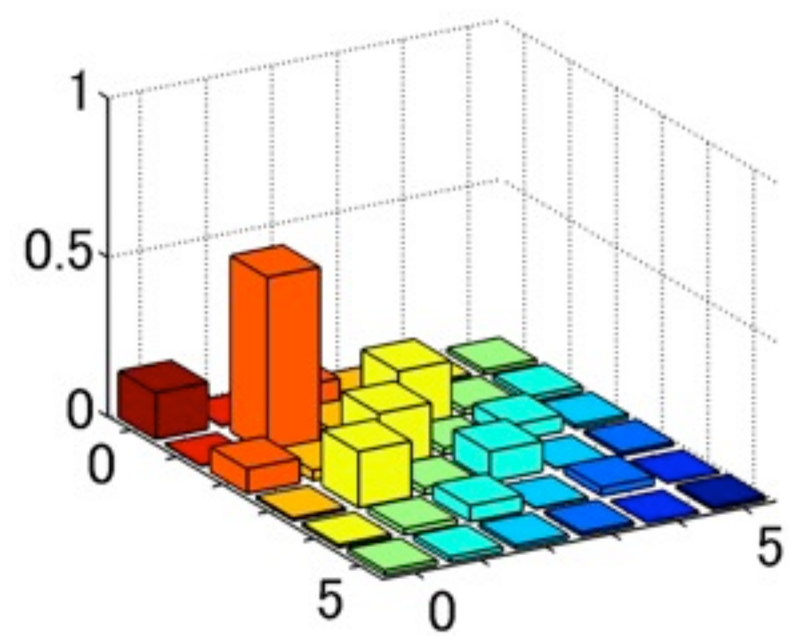






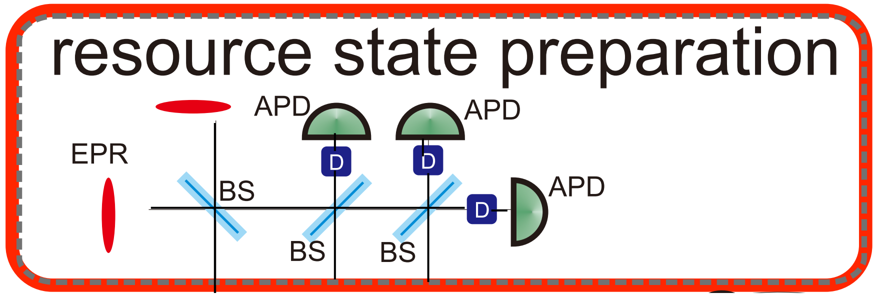
without any correction!!





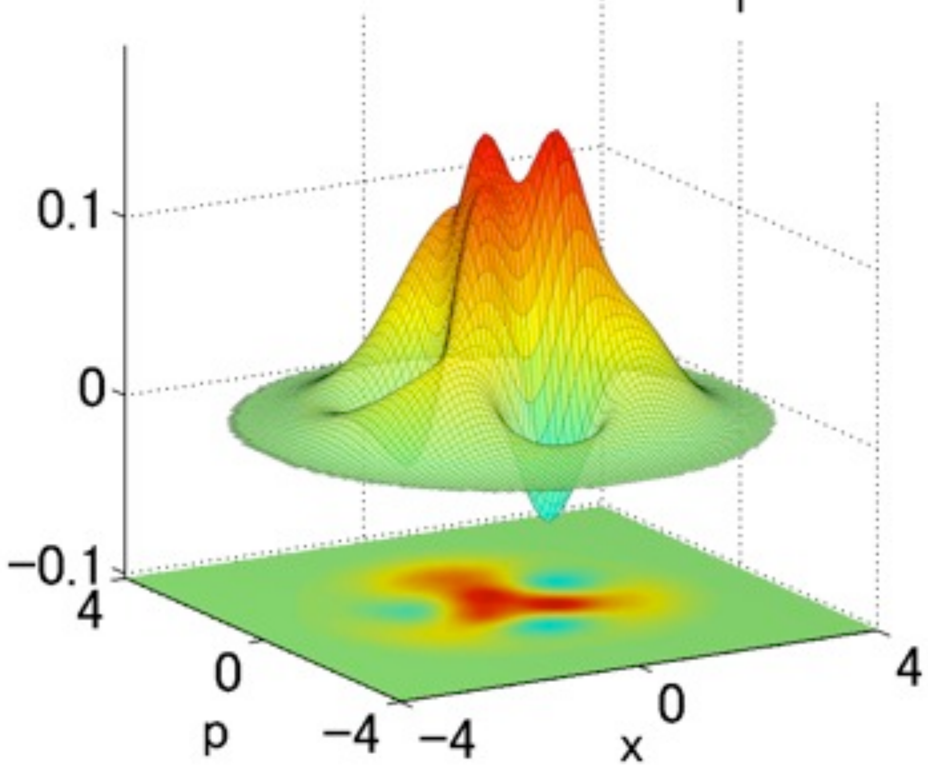
M. Yukawa *et al.*, Optics Express **21**, 5529 (2013)

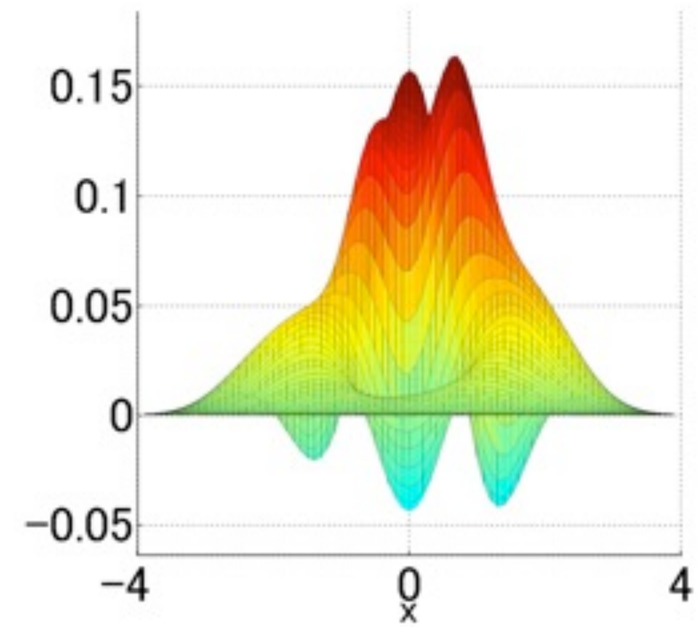
$$|0\rangle + \frac{\alpha^3}{\sqrt{6}}|3\rangle$$



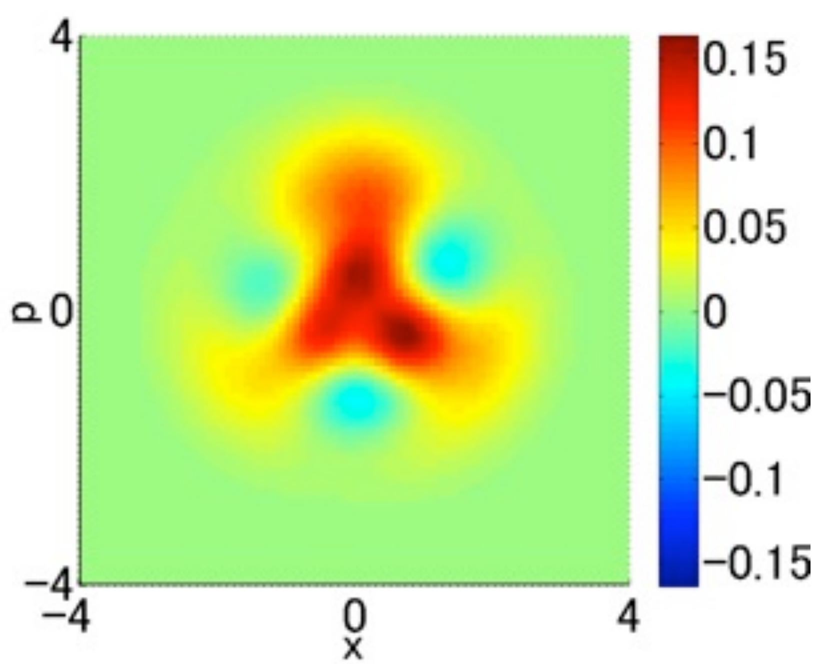
Three-headed cat state

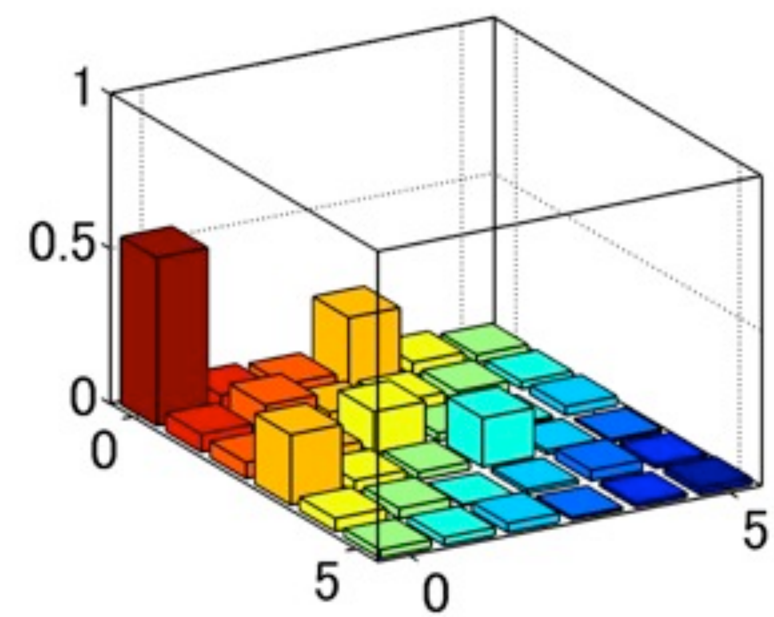
$$|\alpha\rangle + \left|\alpha e^{i\frac{2\pi}{3}}\right\rangle + \left|\alpha e^{-i\frac{2\pi}{3}}\right\rangle$$





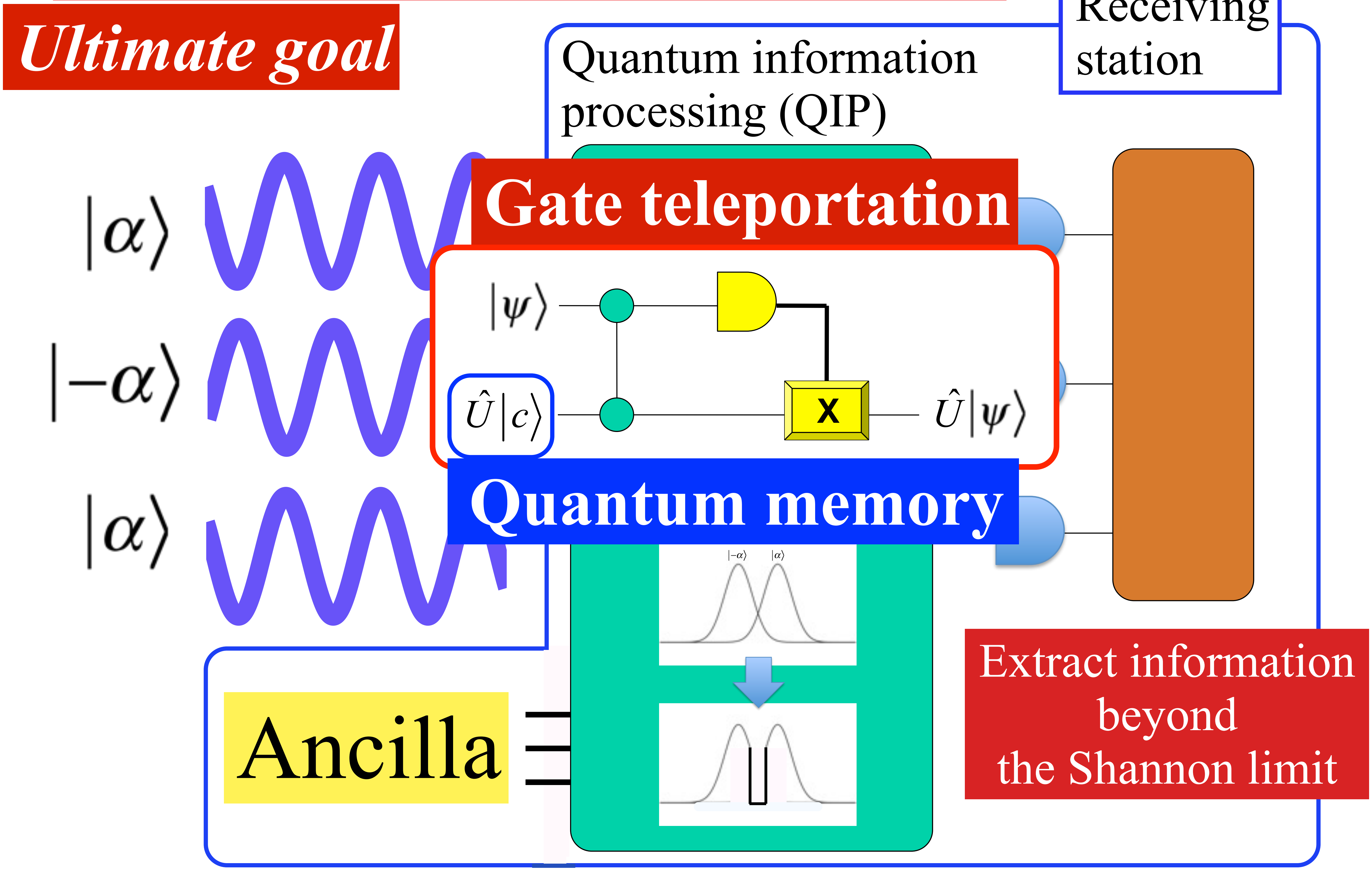
without any correction!!





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

Quantum version of coherent communication



We have to handle cat states of light!!