evropský sociální fond v ČR
EVROPSKÁ UNIE
MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY
OP Vzdělávání pro konkurenceschopnost
INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

# Teleportation based Quantum Information Processing for coherent communication

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# Collaborators

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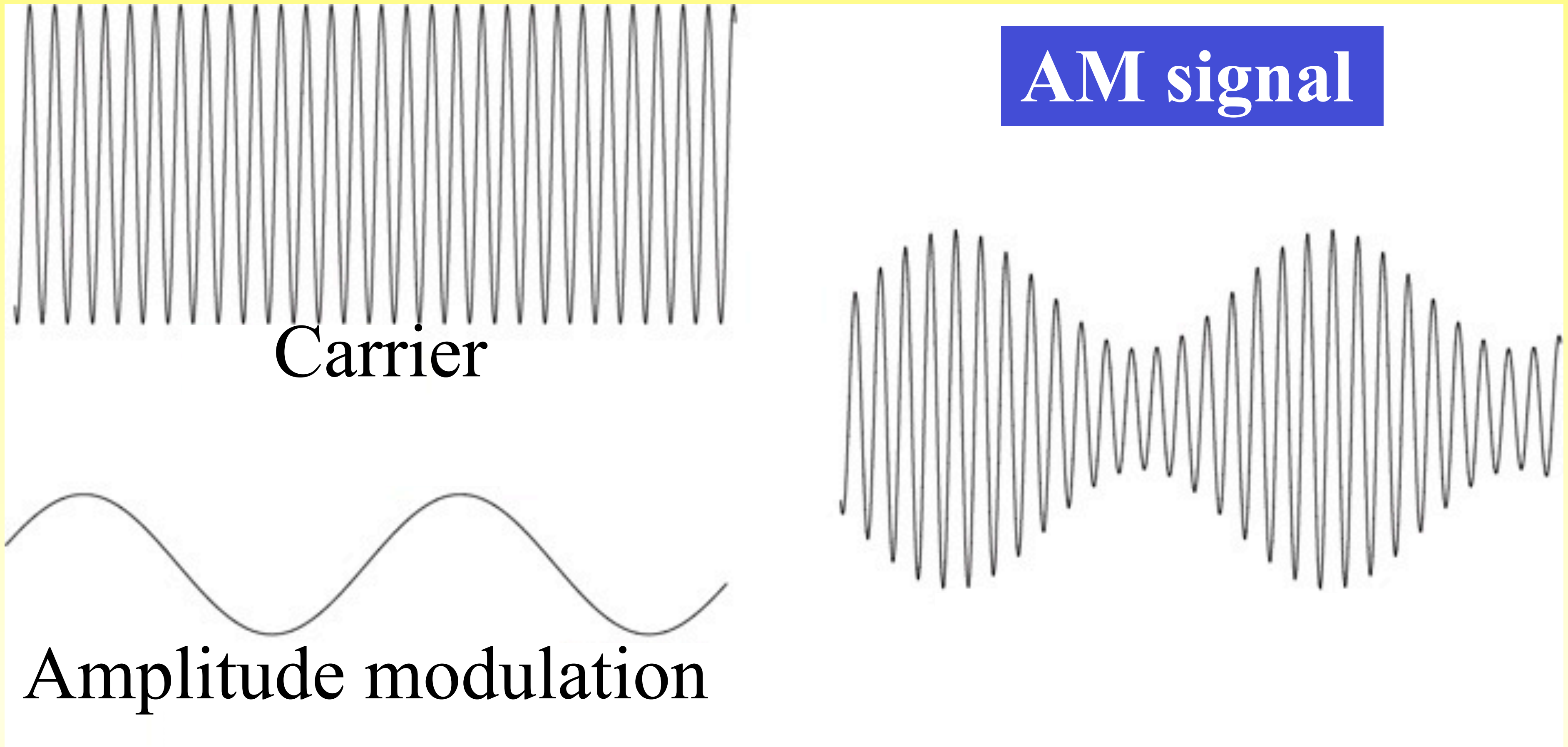
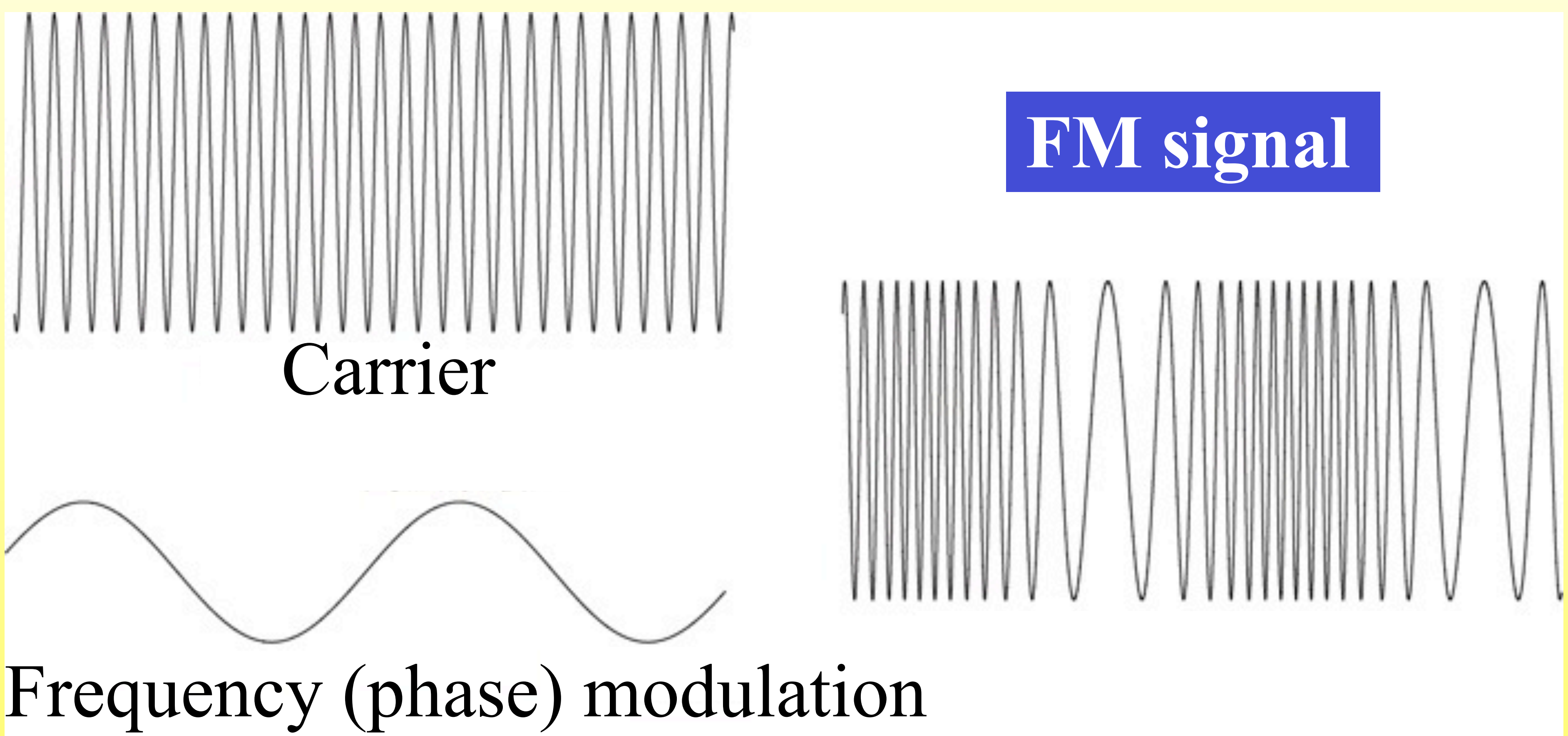
E. H. Huntington (UNSW@ADFA),
R. Filip (Palacky), L. Mista (Palacky), P. Marek (Palacky),
J. L. O'Brien (Bristol), A. Politi (Bristol), N. Yamamoto (Keio U),
P. K. Lam (ANU), T. Ralph (UQ), H. Wiseman (GU)

# AM and FM signals

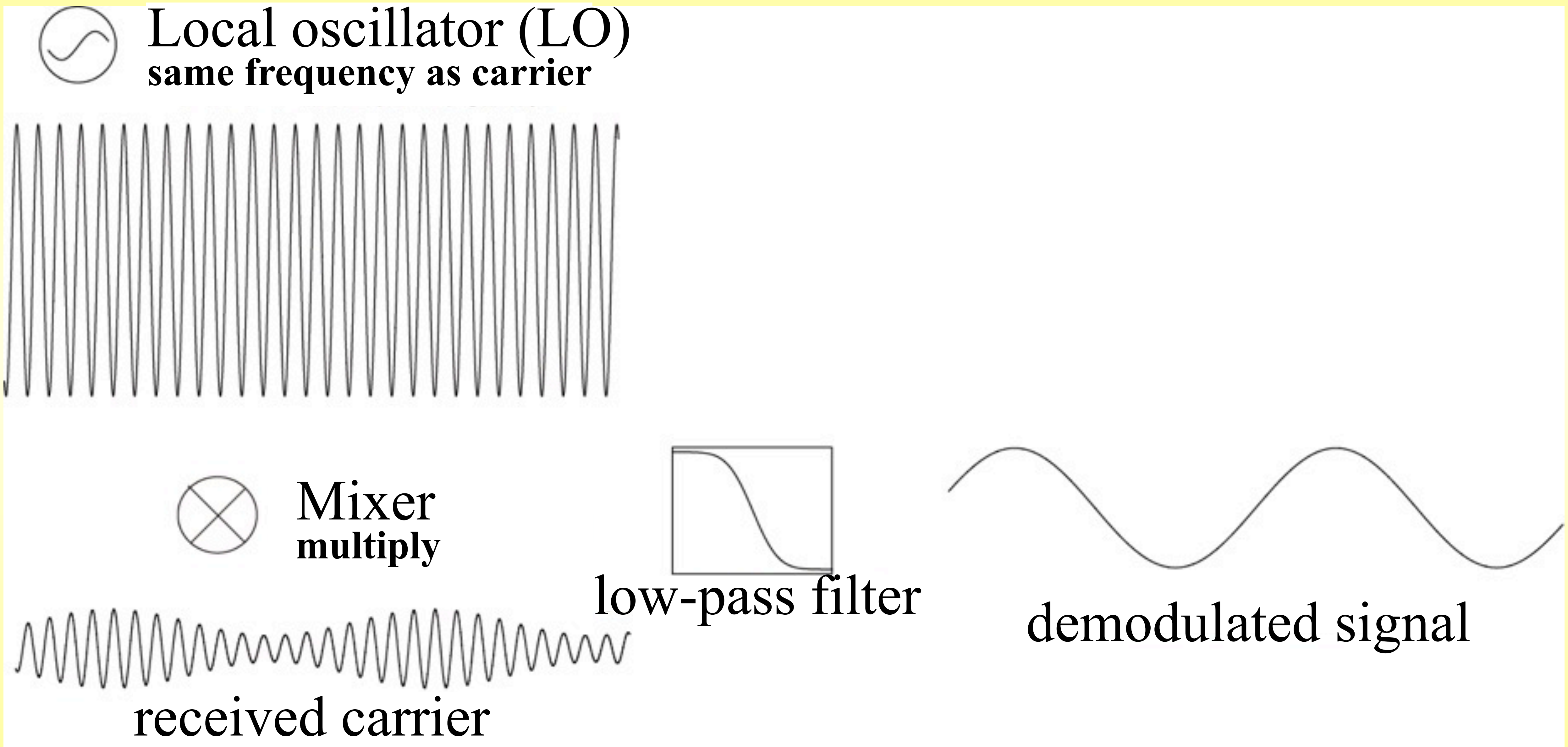
NHK
（AM）
594kHz



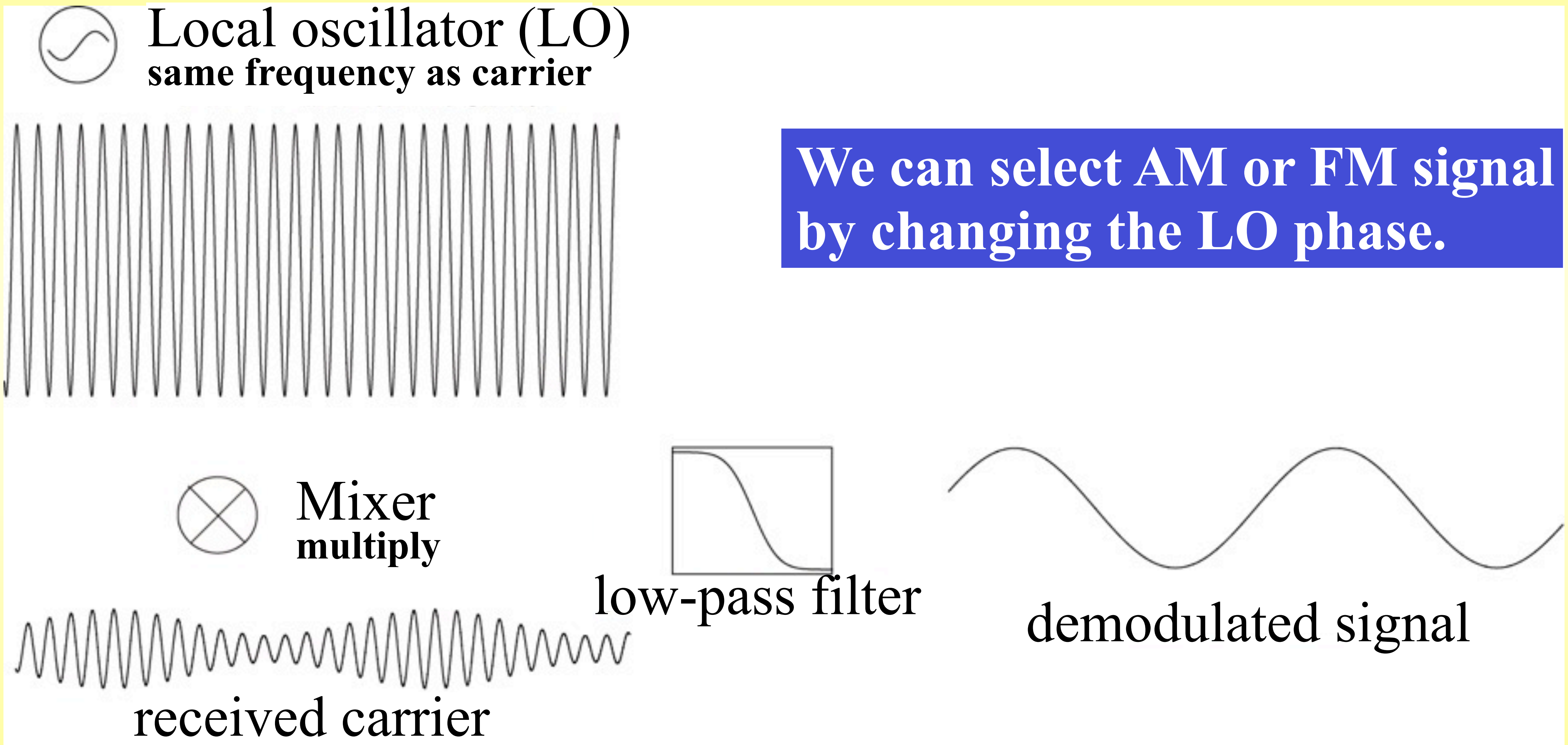

J-WAVE
（FM）
81.3MHz



# Homodyne detection



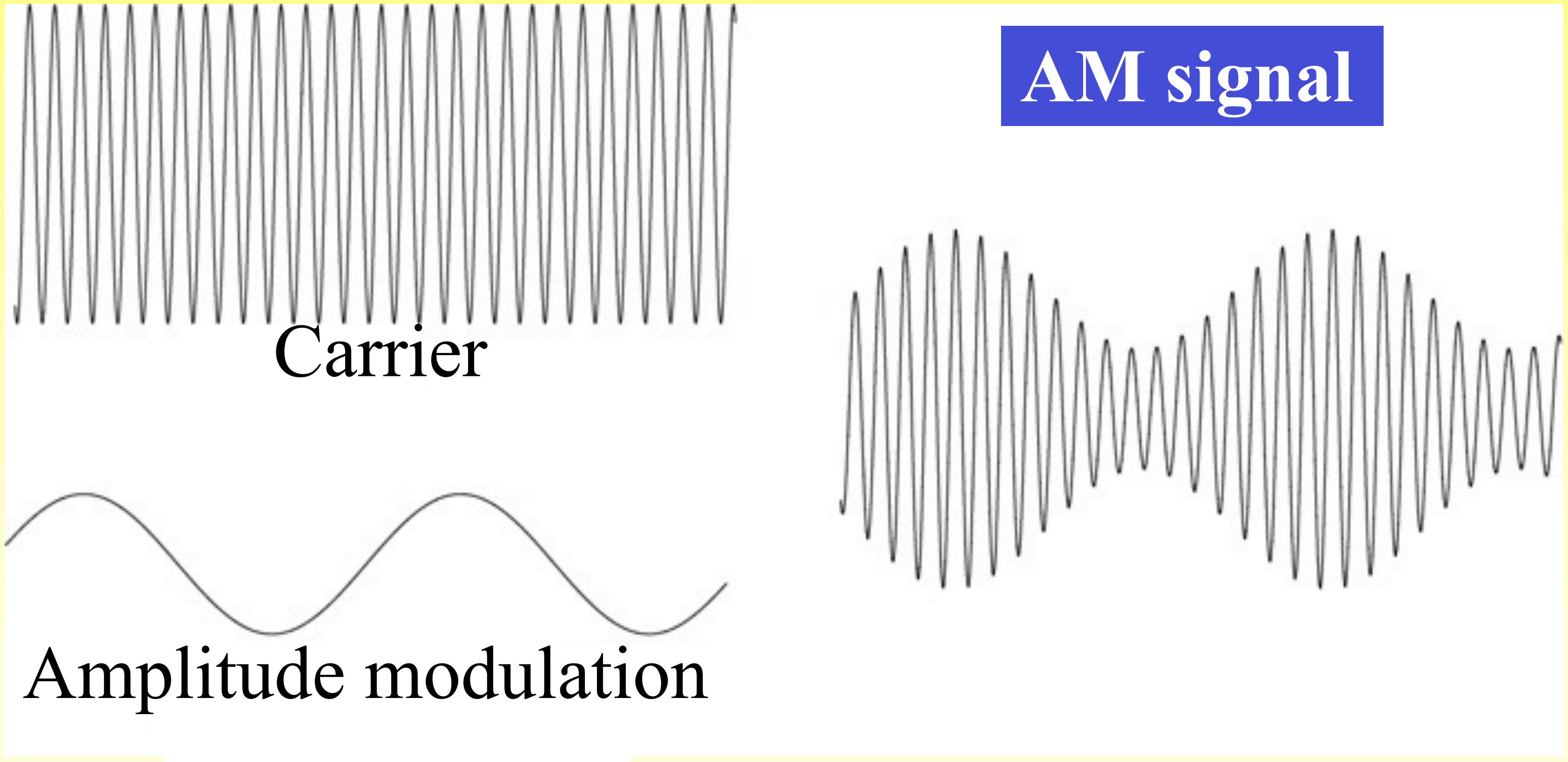
# Homodyne detection



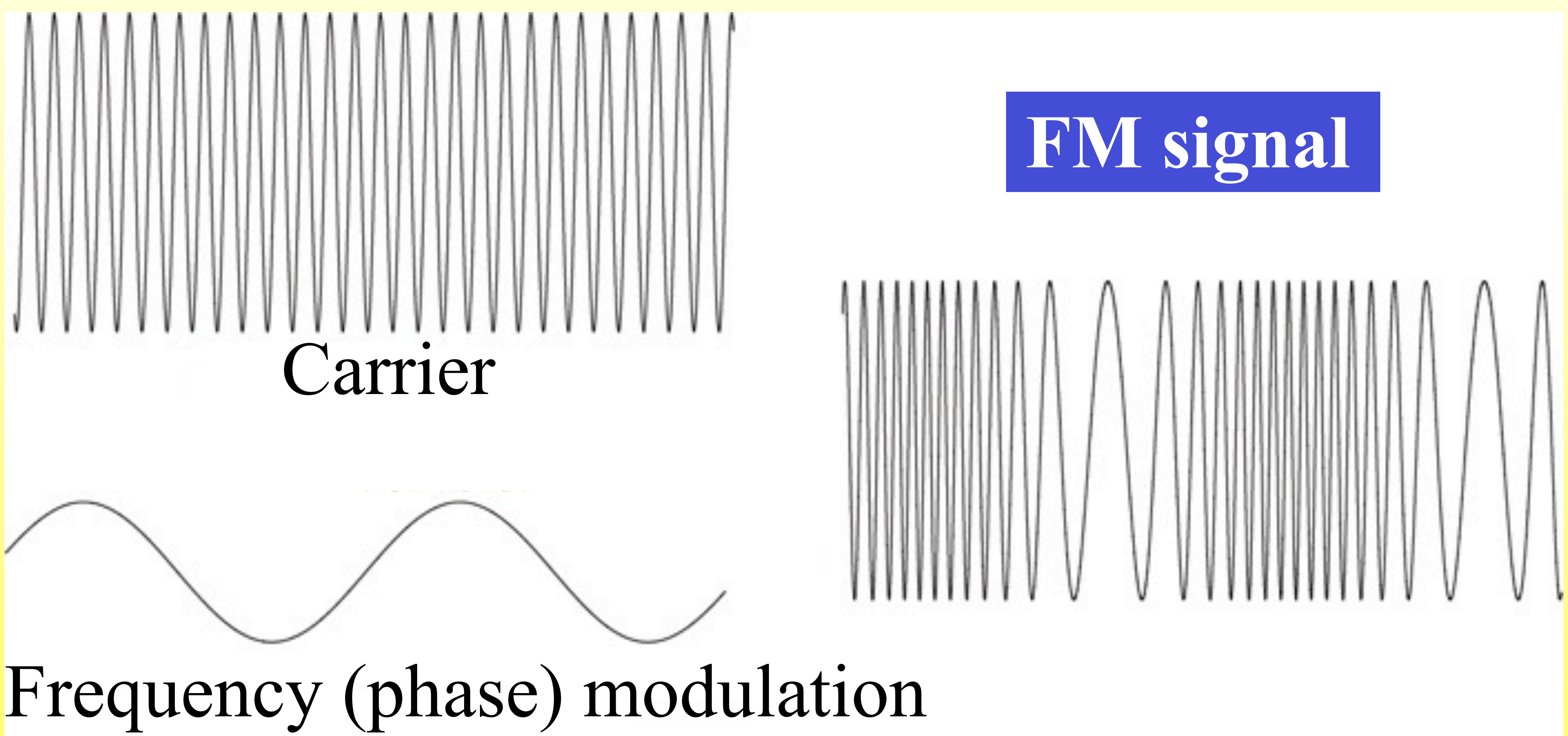

**We can select AM or FM signal by changing the LO phase.**

# AM and FM signals

NHK
（AM）
594kHz

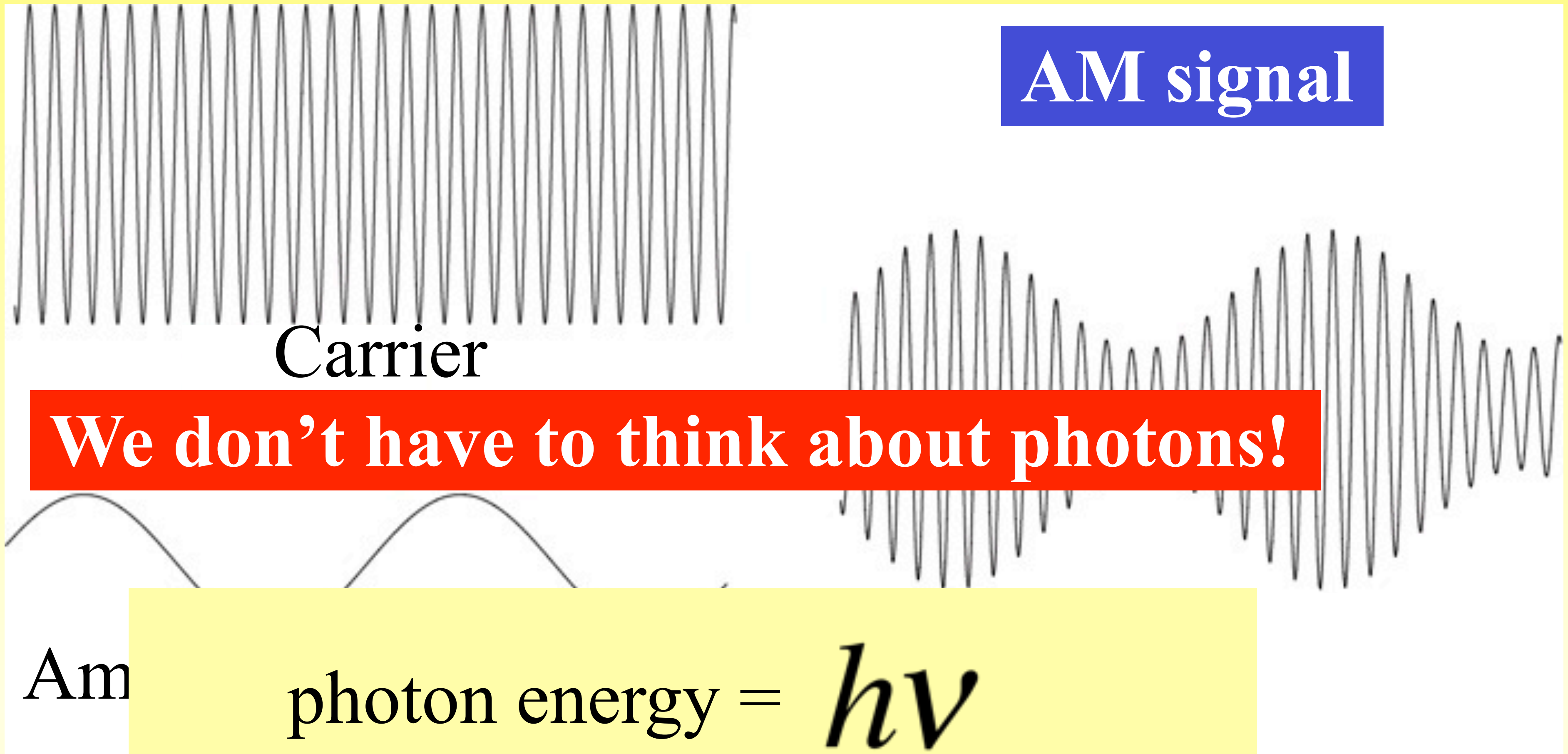



J-WAVE
（FM）
81.3MHz



# AM and FM signals

NHK
(AM)
594kHz

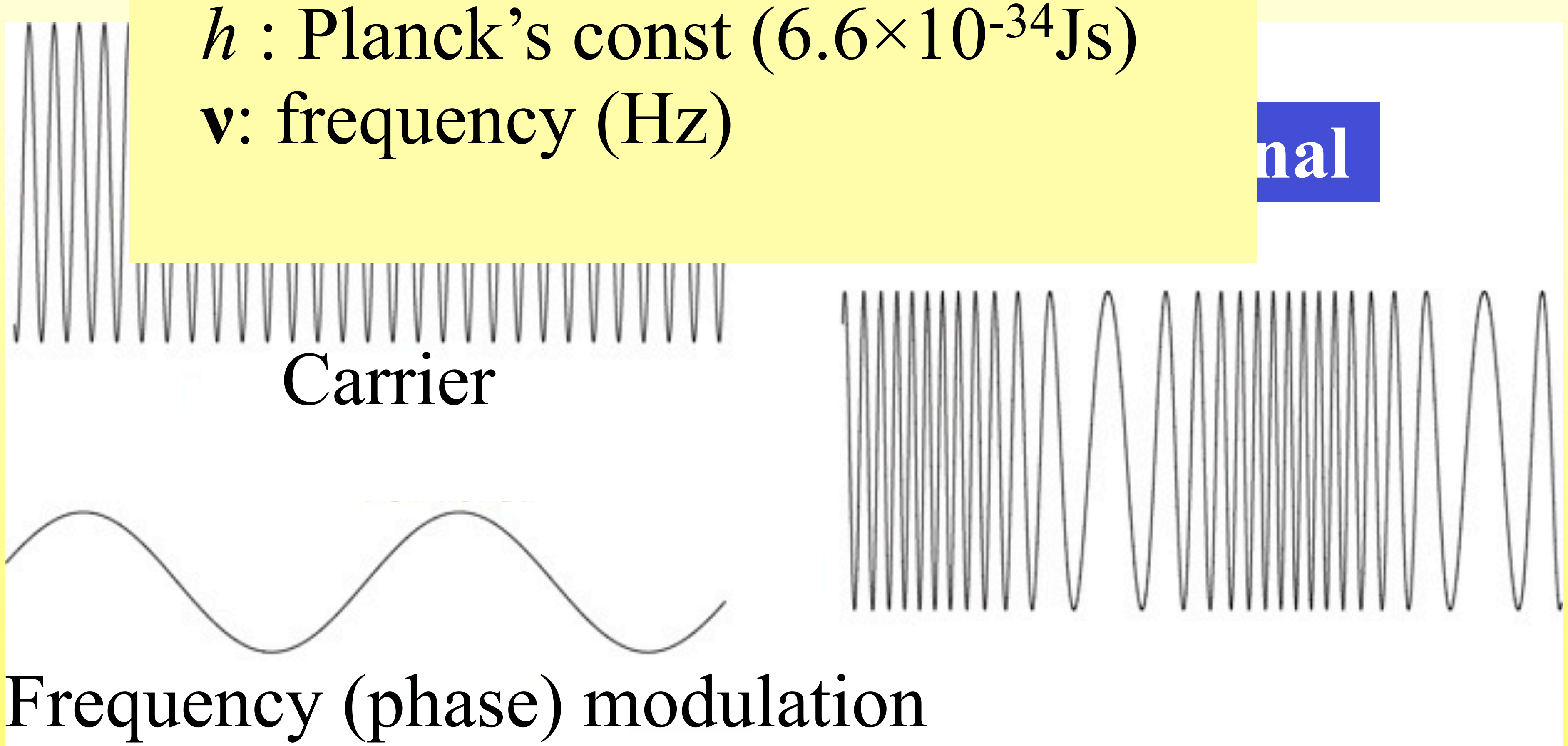



**We don’t have to think about photons!**

photon energy = $h\nu$

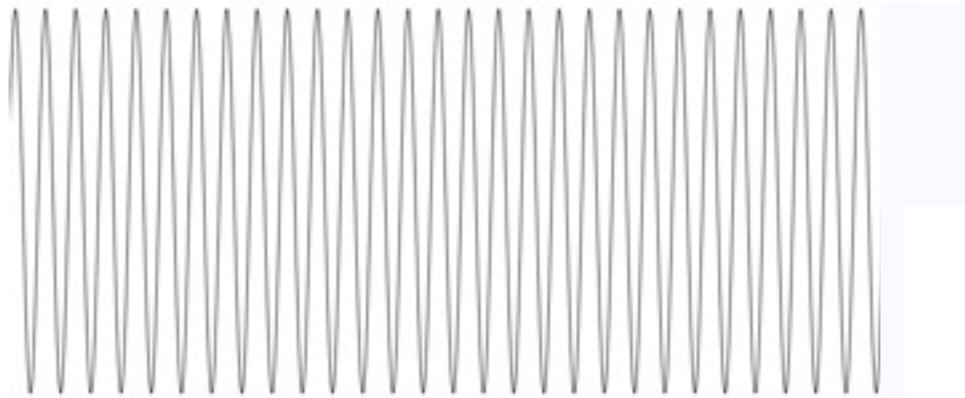
$h$ : Planck’s const ($6.6\times10^{-34}$Js)
**ν**: frequency (Hz)

J-WAVE
(FM)
81.3MHz



# AM and FM signals

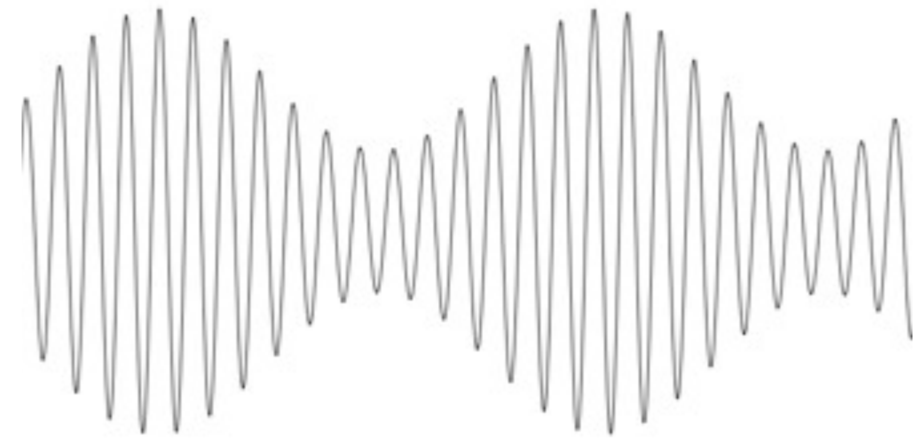
**Optical freq. 100THz**

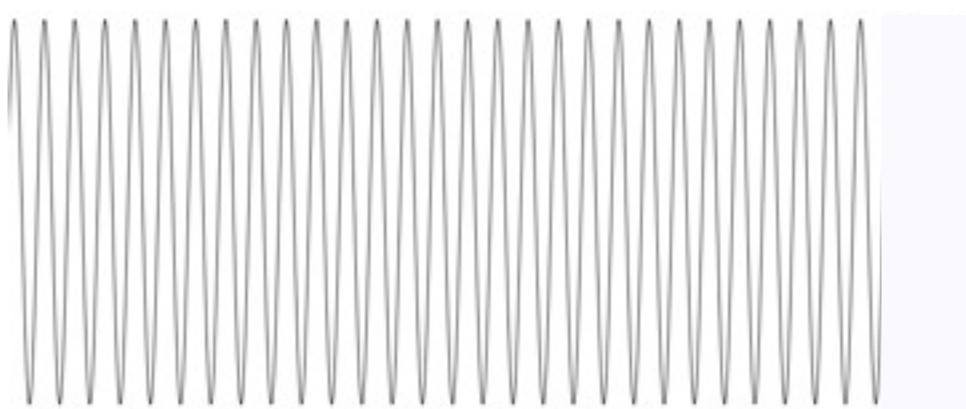


Carrier

Amplitude modulation

**AM signal**

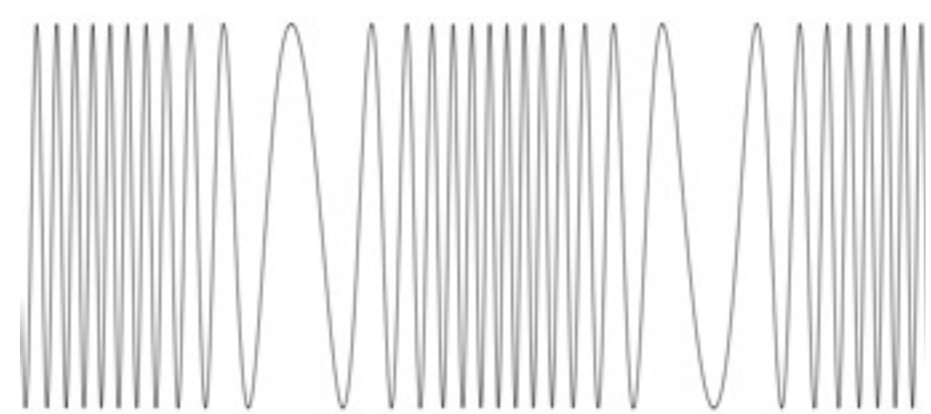




Carrier

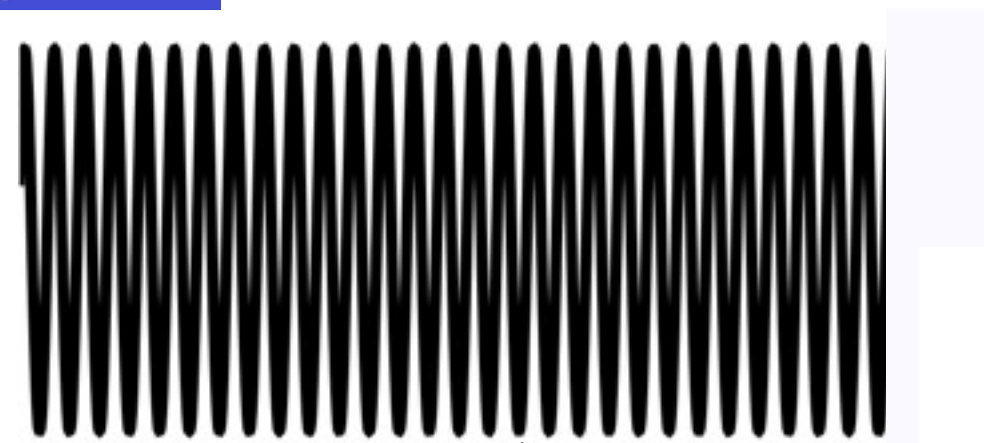
Frequency (phase) modulation

**FM signal**



# AM and FM signals

Optical freq. 100THz

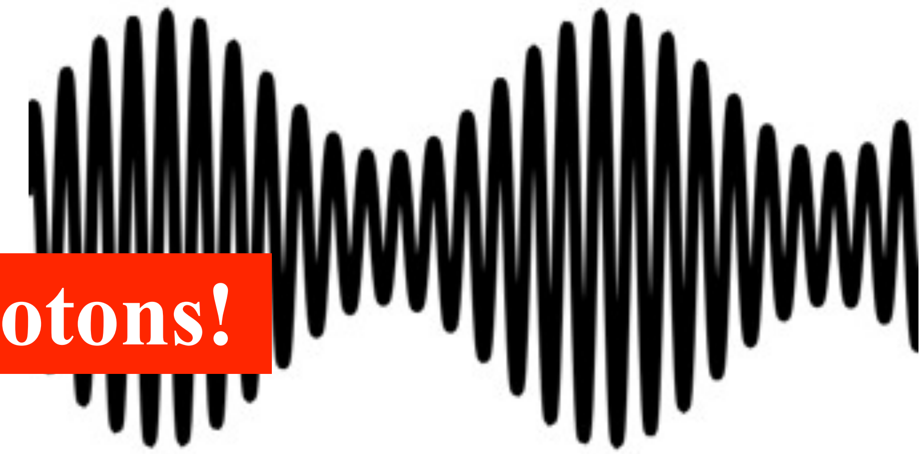


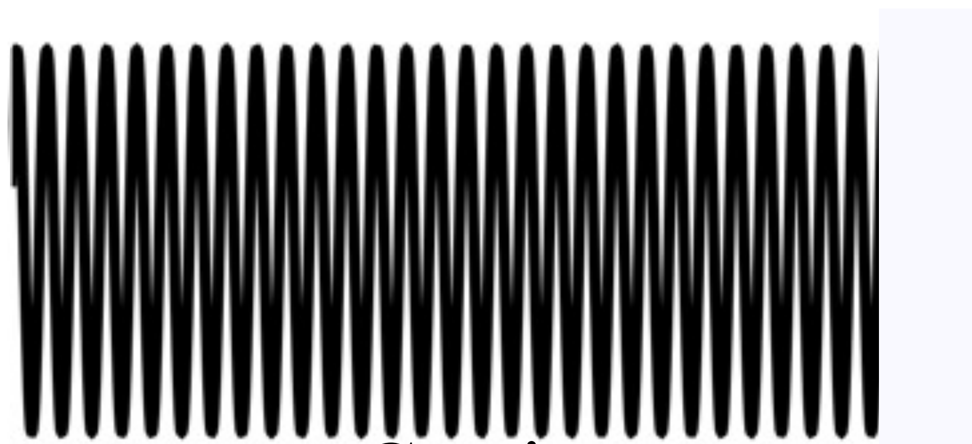
Carrier

We have to think about photons!

Amplitude modulation

AM signal

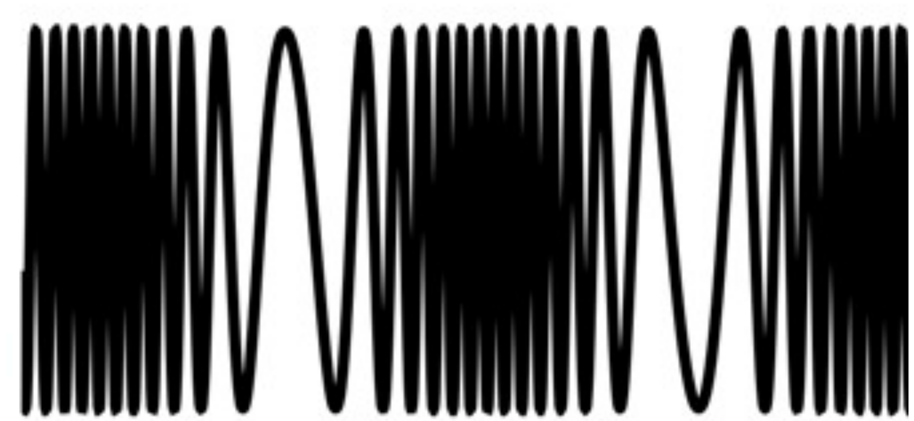




Carrier

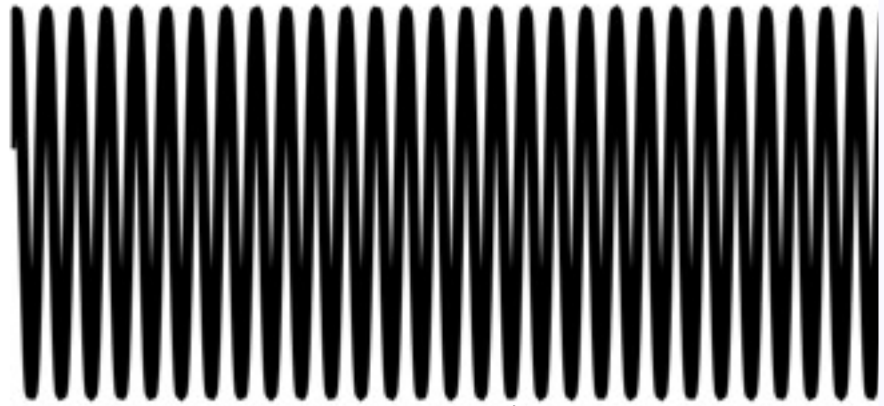
Frequency (phase) modulation

FM signal



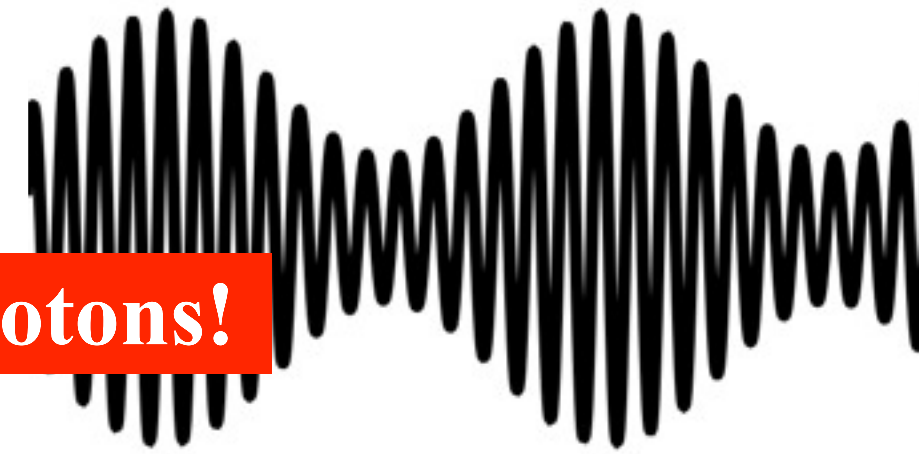
# AM and FM signals

Optical freq.
100THz



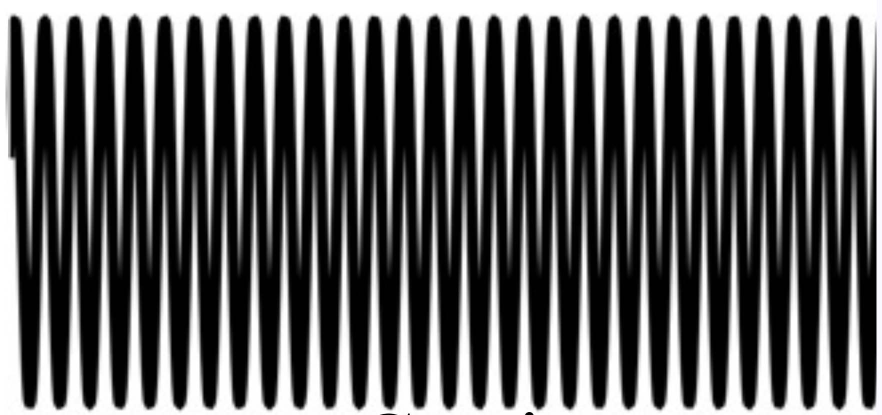
Carrier

AM signal



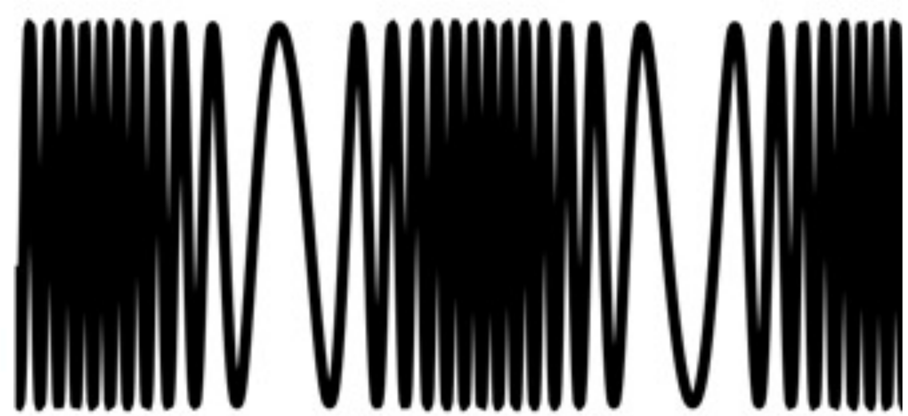
**We have to think about photons!**

**We have to think about the shot noise!**



Carrier

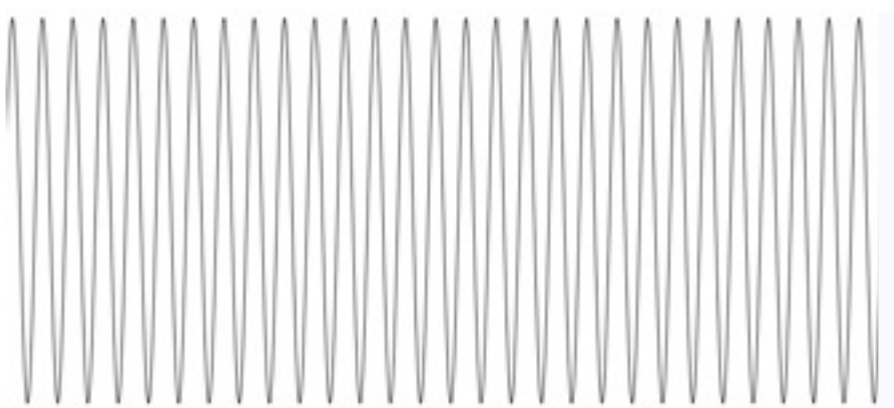
FM signal



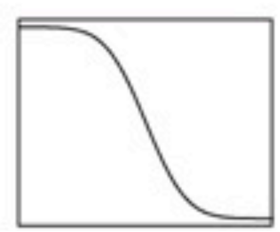
Frequency (phase) modulation

# Homodyne detection

Local oscillator (LO)
**same frequency as carrier**



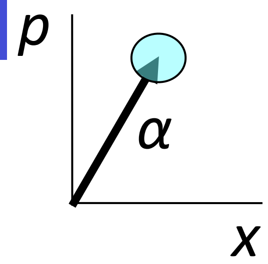
Mixer
**multiply**



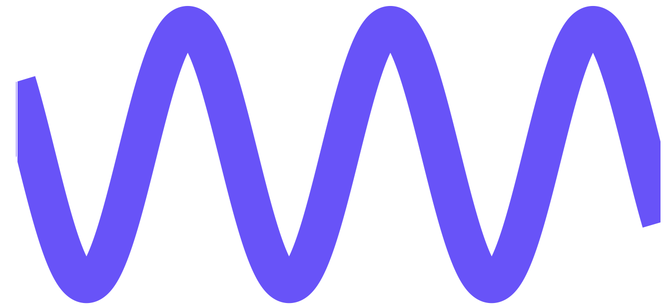
low-pass filter

received carrier

# Homodyne detection

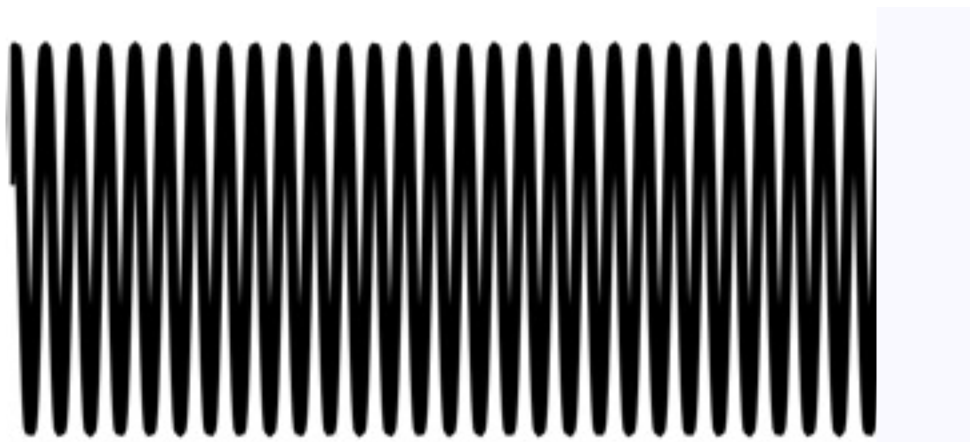



$|\alpha\rangle$



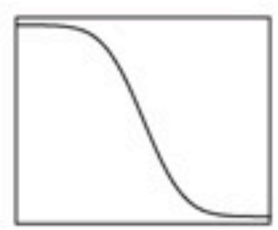
**Laser** scillator (LO)

**same frequency as carrier**



Mixer

**multiply**



low-pass filter

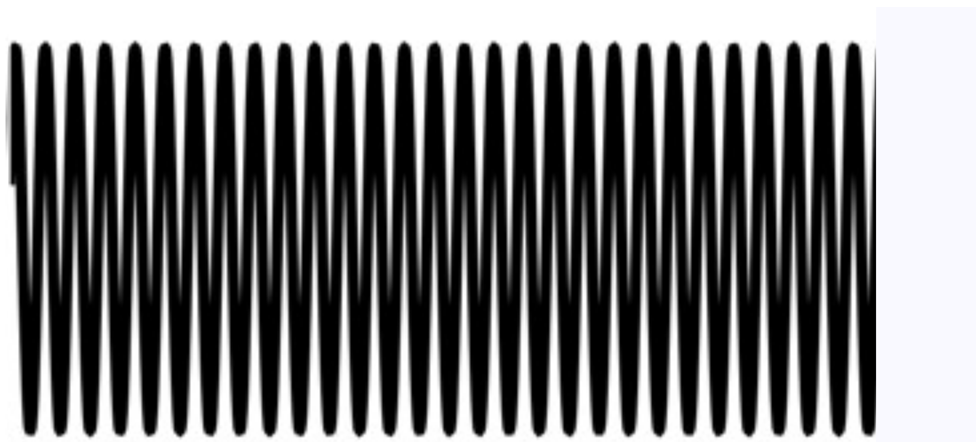
received carrier

# Homodyne detection

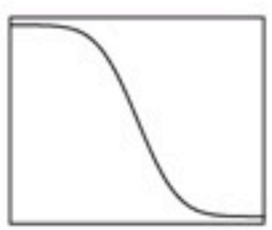

$|\alpha\rangle$

**Laser** scillator (LO)

**same frequency as carrier**



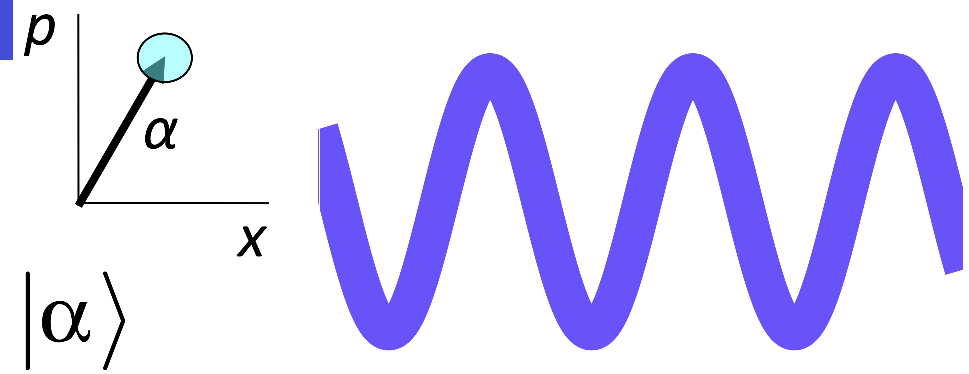
**Beam splitter**



low-pass filter

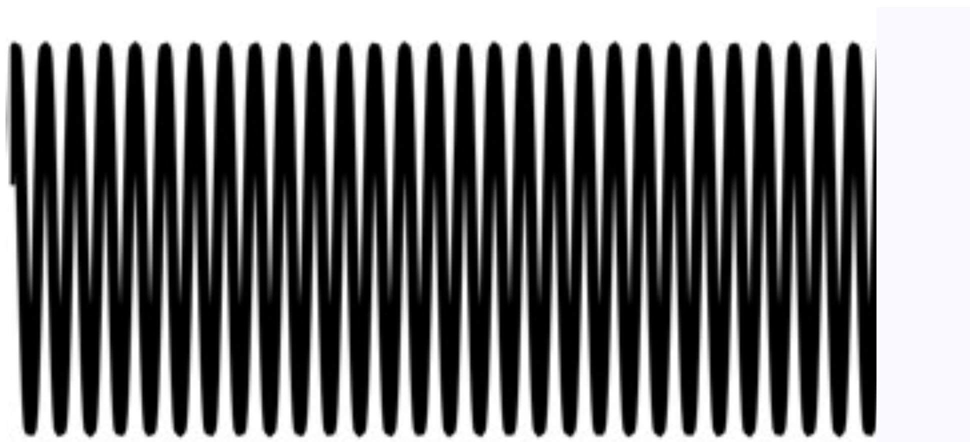
received carrier

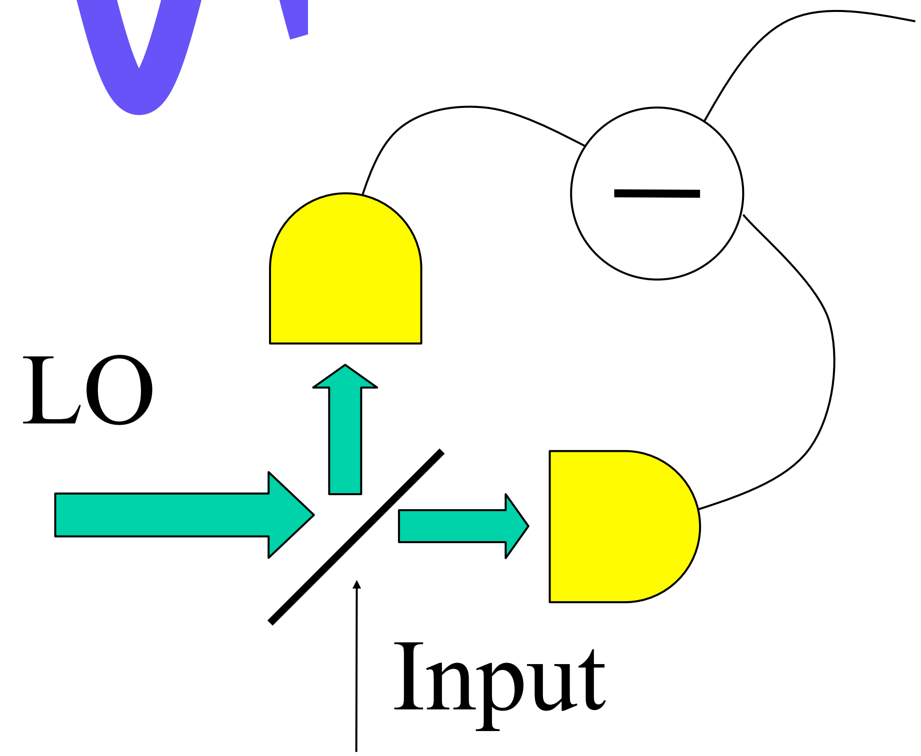
# Homodyne detection



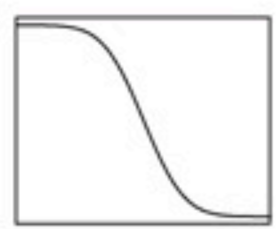

Laser scillator (LO)

**same frequency as carrier**





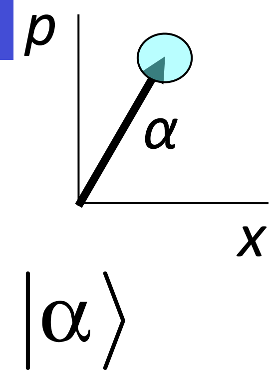

Beam splitter

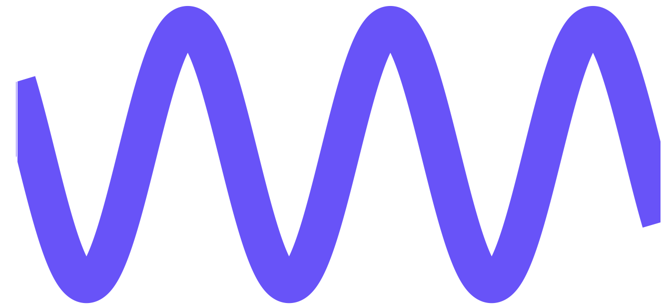


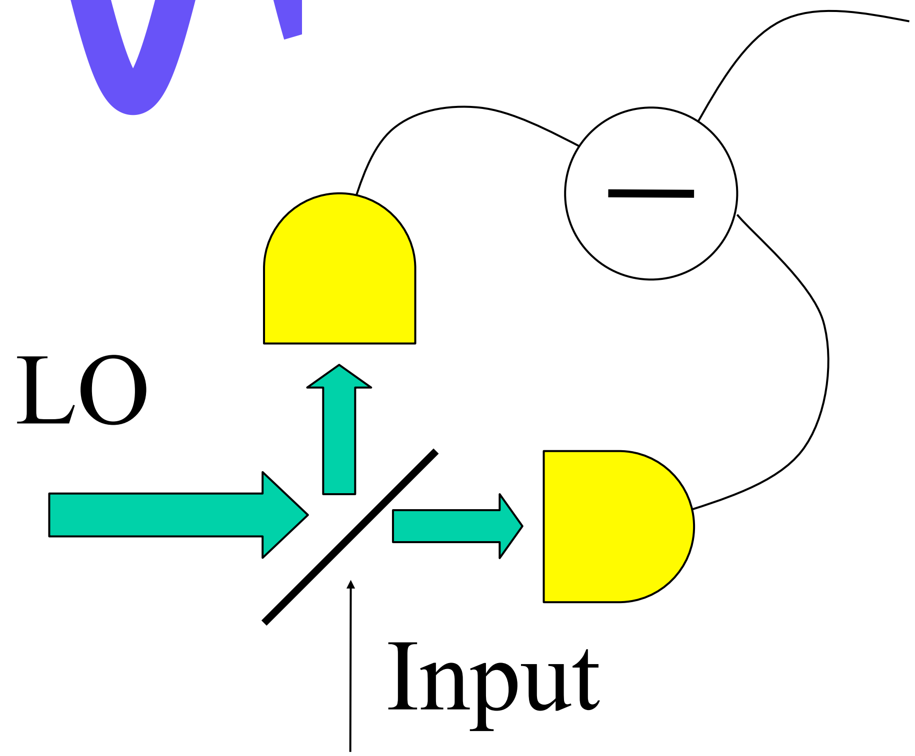
low-pass filter

received carrier

# Homodyne detection

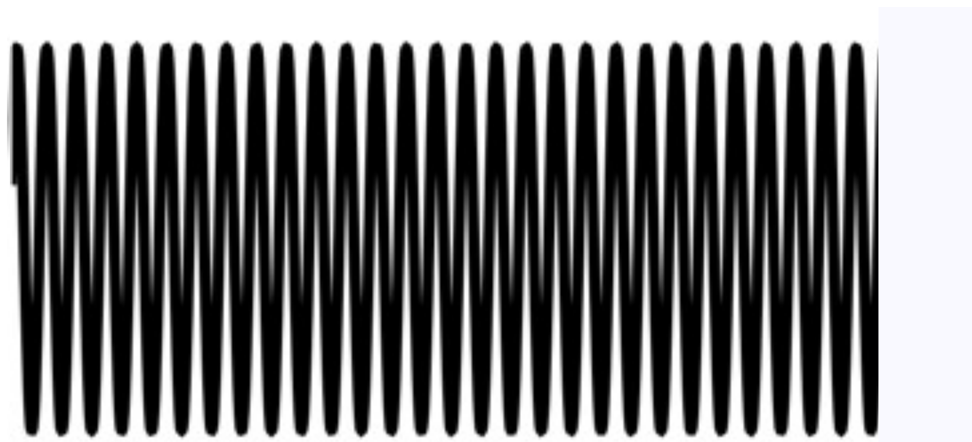


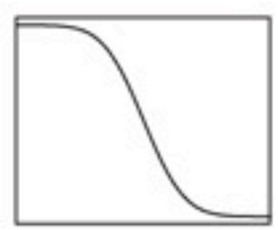



**Laser** scillator (LO)

**same frequency as carrier**



**Beam splitter**



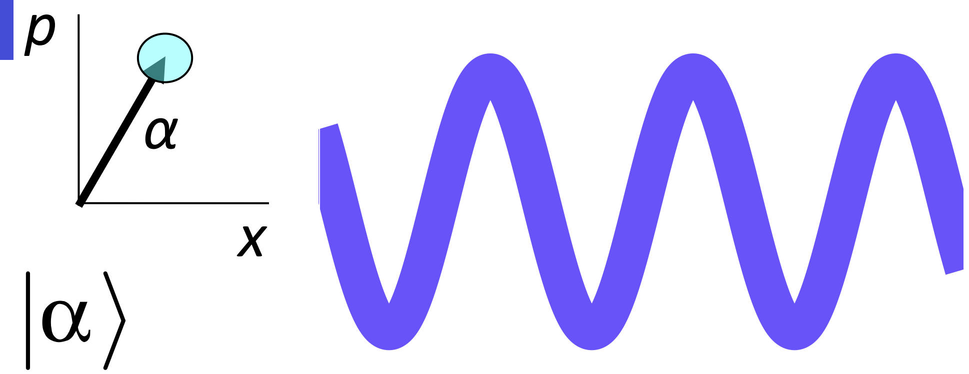
low-pass filter

demodulated signal

**With shot noise!**

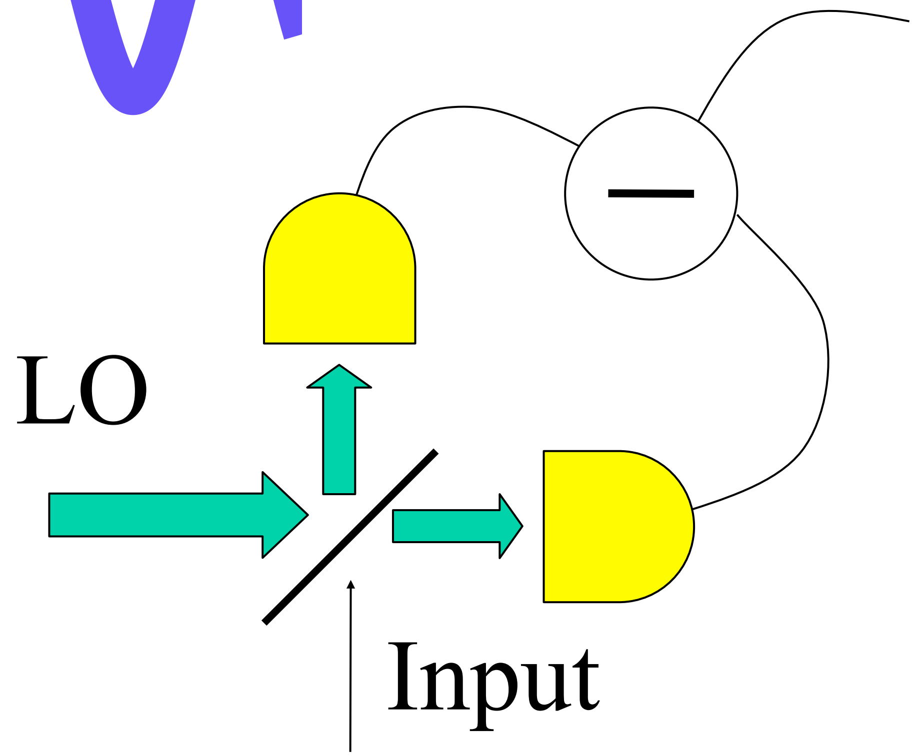
received carrier

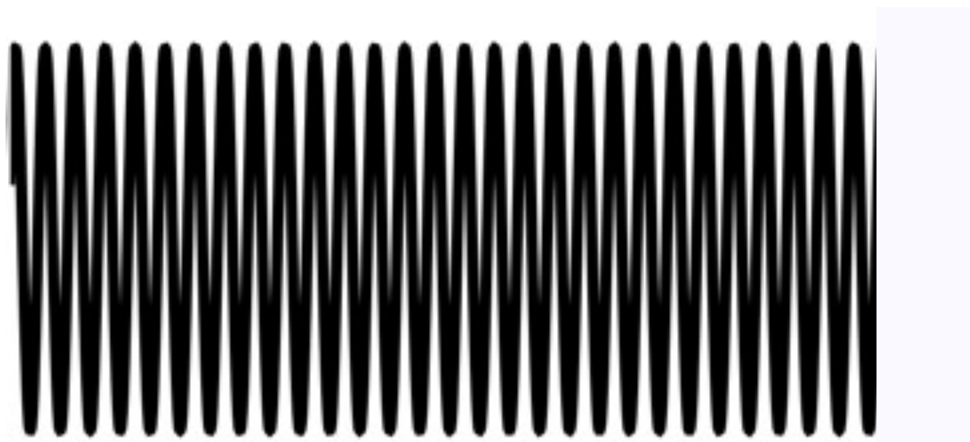
# Homodyne detection



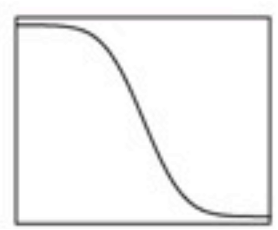

**Laser** scillator (LO)

**same frequency as carrier**



**Beam splitter**



low-pass filter

demodulated signal

**With shot noise!**

**Shannon limit!**

received carrier

Coherent communication

2011年8月24日水曜日

# An example of quantum version of coherent communication

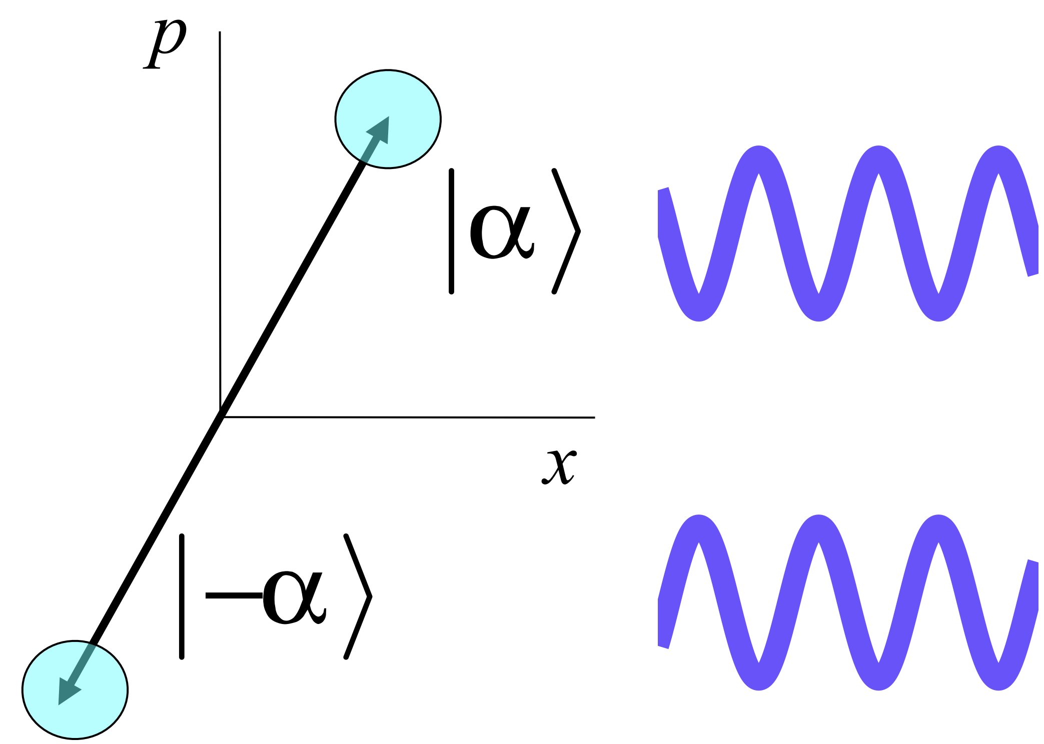
**Channel capacity beyond the Shannon limit**

**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)

## An example of quantum version of coherent communication

**Channel capa**

**Beyond the shot-noise limit!**

Sending station

**Encode**

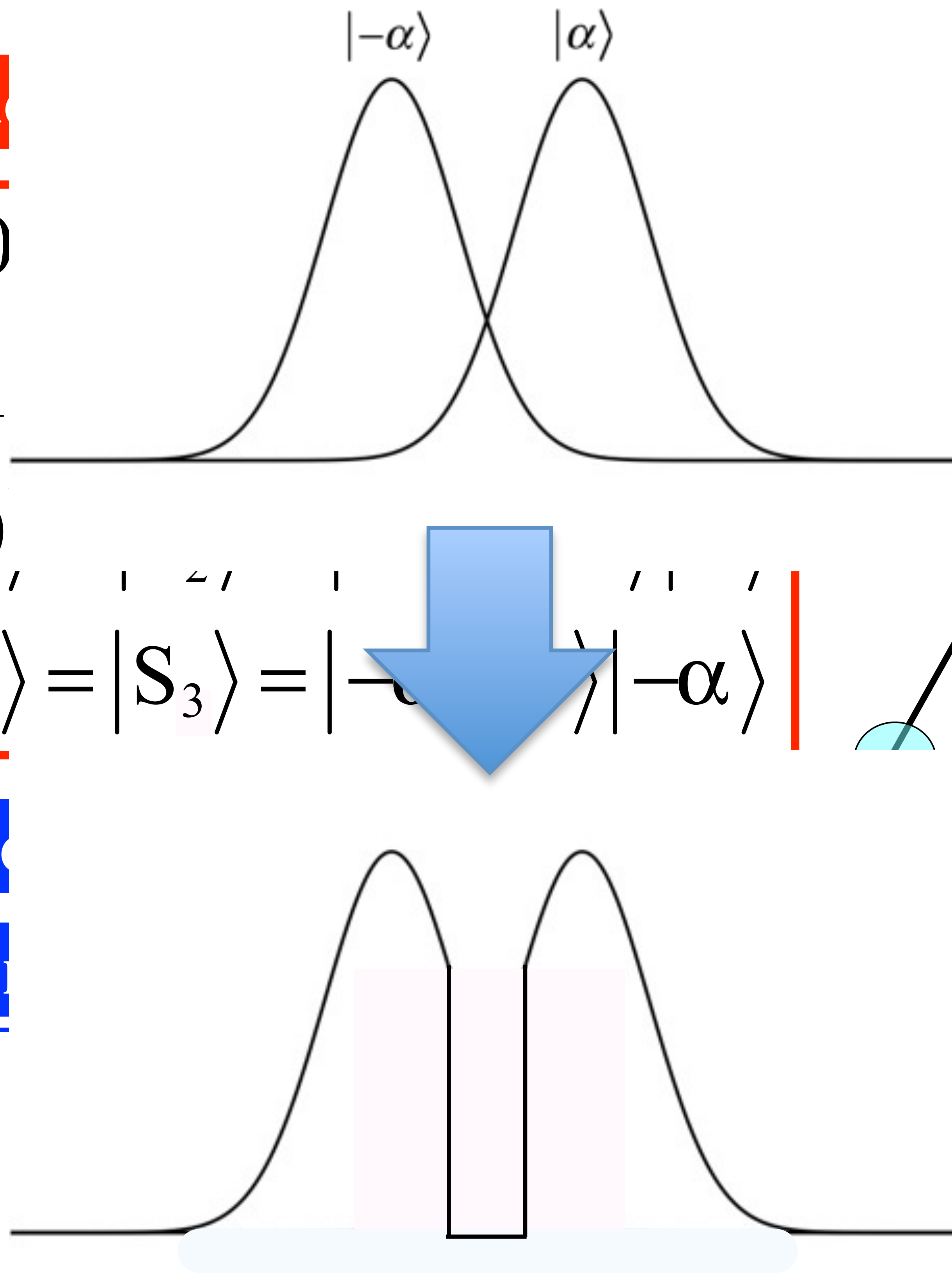
$|00$

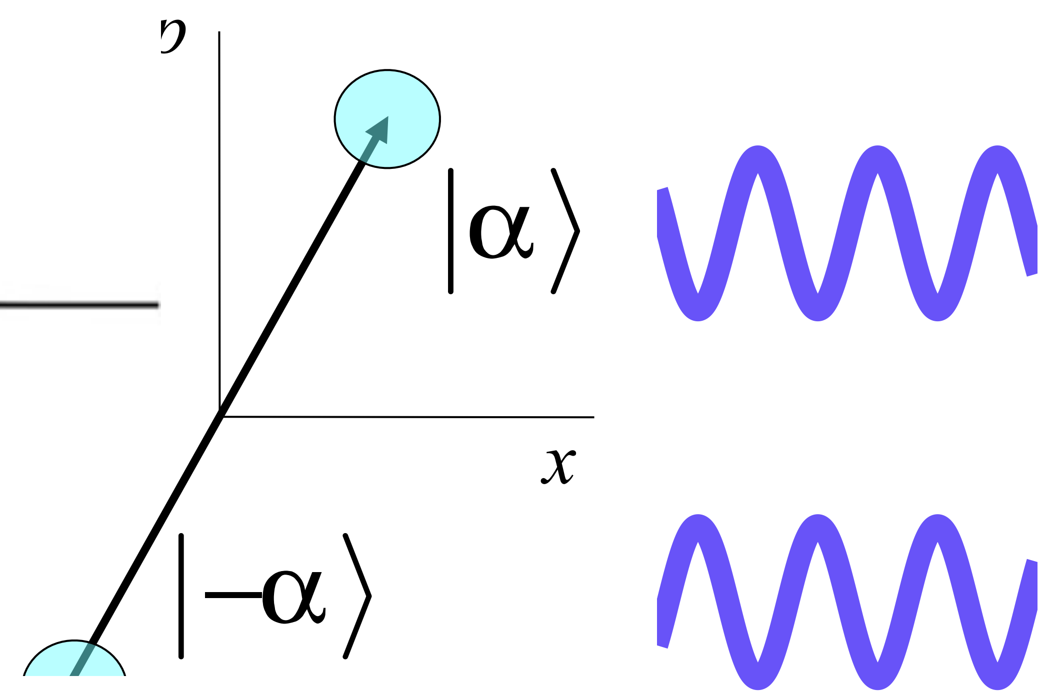
$|01$

$|10$

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

fiber




Receiving station

**C**

**P**

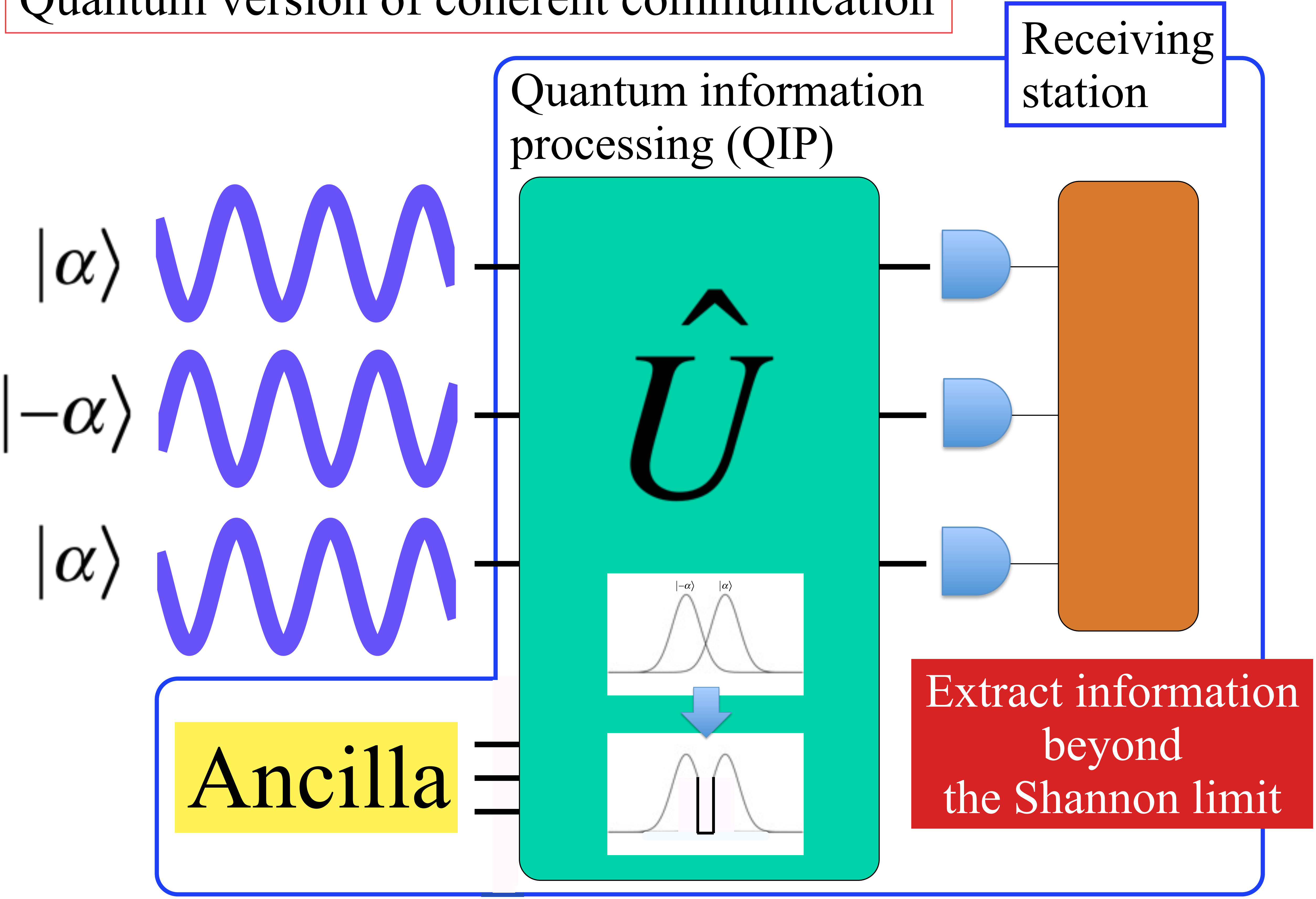
**Decode**

$|\mu_i$

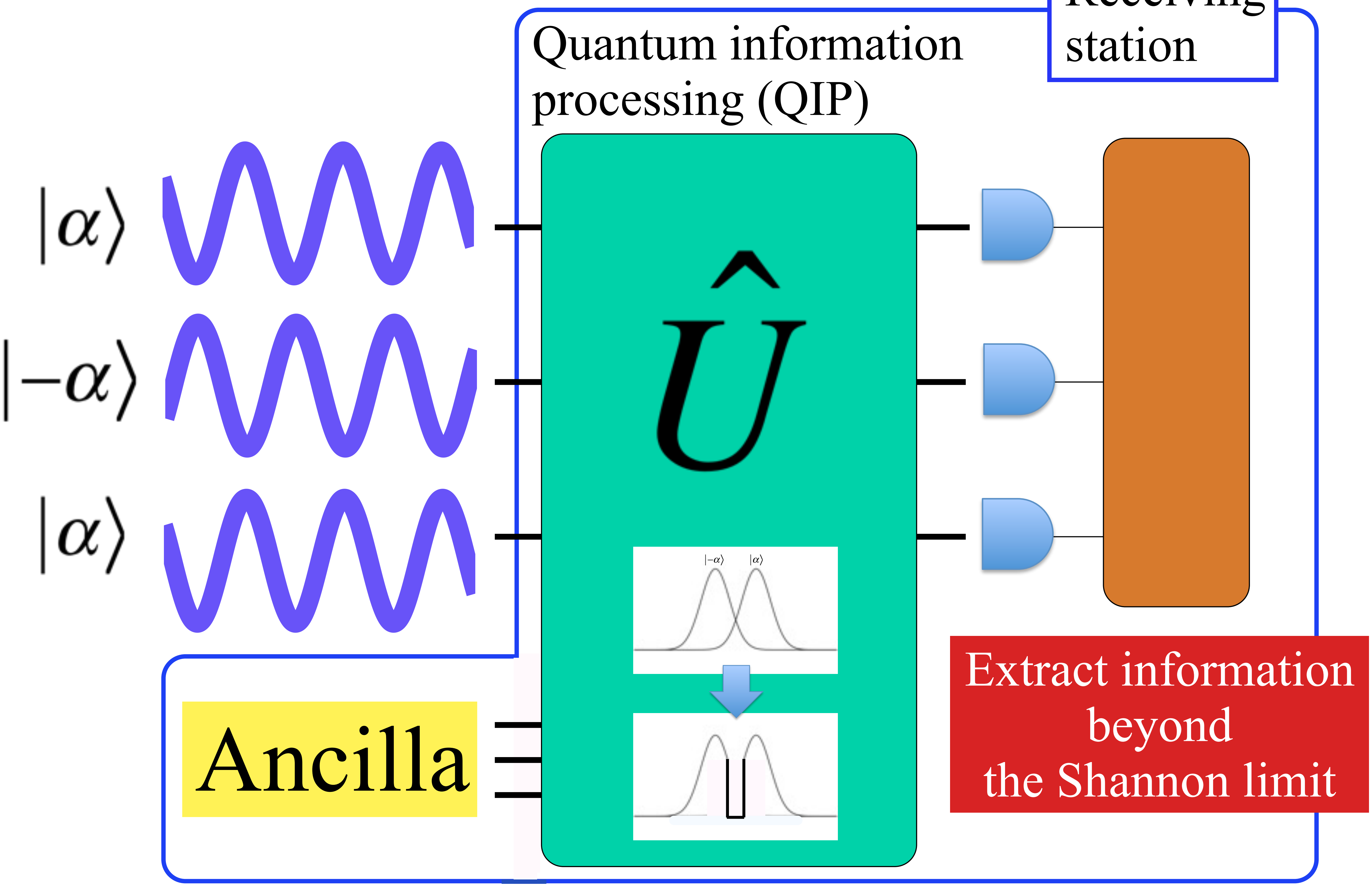
$0,1,2,3)$

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

# Quantum version of coherent communication



# Quantum version of coherent communication




We need QIP for coherent states of light!!

# Schrödinger cat states

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

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

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

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

# *Schrödinger cat states*

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

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# *Schrödinger cat states*

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

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

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

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# *Schrödinger cat states*

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

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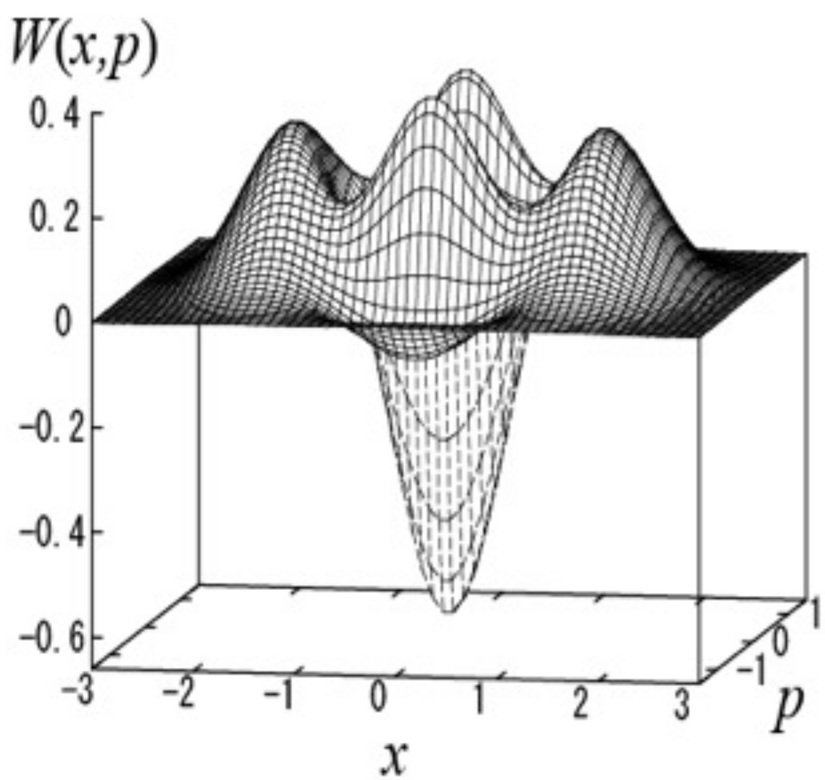


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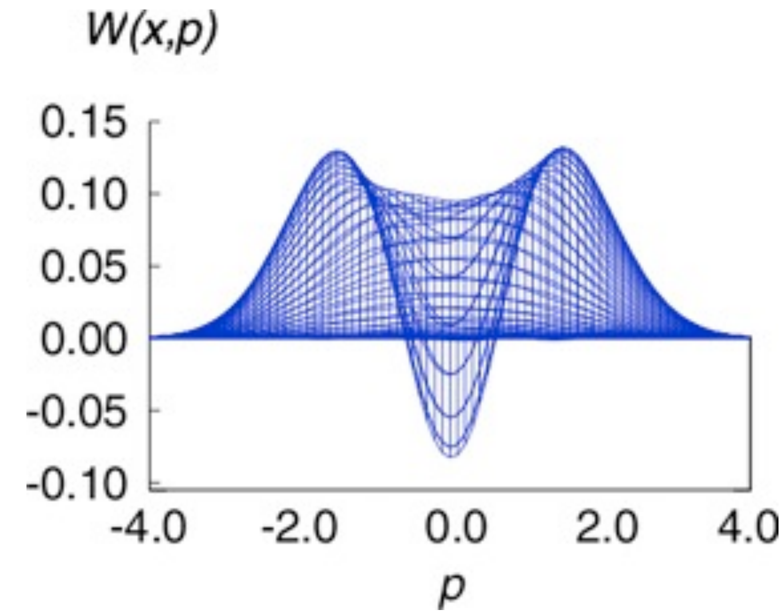
# Schrödinger cat states

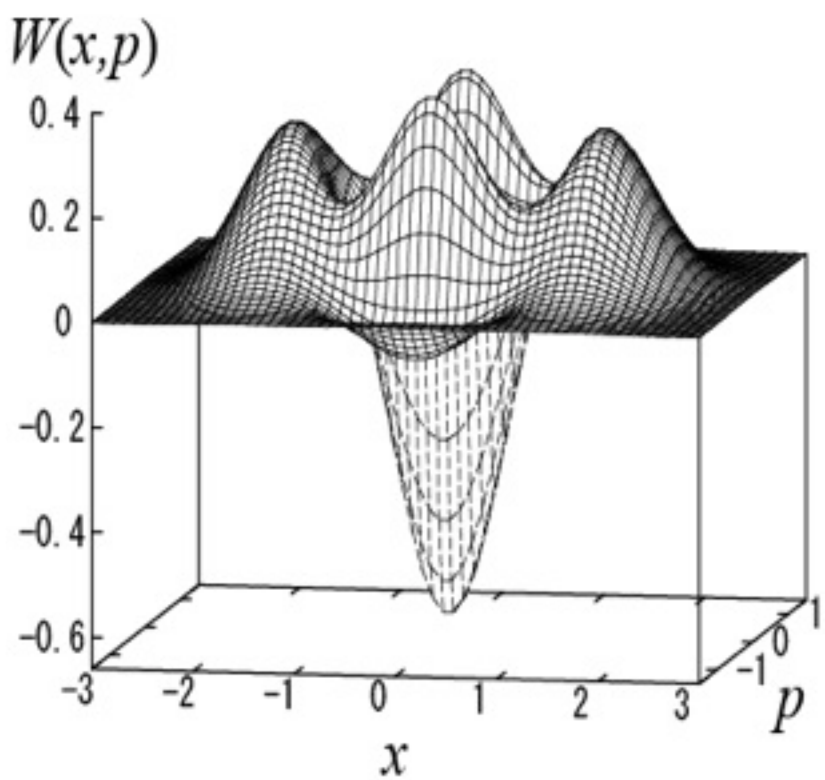
$$N_\alpha\left(|\alpha\rangle-|-\alpha\rangle\right)$$

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




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

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




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

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

**Schrödinger picture**

| | qubits | continuous variables |
|---|---|---|
| computational basis | $\{\lvert 0\rangle, \lvert 1\rangle\}$ bit flip $\sigma_x$ | $\{\lvert x\rangle\}$ $x$-displacement $\hat{X}(s) = e^{-2is\hat{p}}$ |
| | Hadamard ↓ | Fourier ↓ |
| conjugate basis | $\{\lvert +\rangle, \lvert -\rangle\}$ phase flip $\sigma_z$ | $\{\lvert p\rangle\}$ $p$-displacement $\hat{Z}(s) = e^{2is\hat{x}}$ |

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

CNOT $\lvert x\rangle\lvert x'\rangle \to \lvert x\rangle\lvert x + x' \bmod 2\rangle$

QND $\lvert x\rangle\lvert x'\rangle \to \lvert x\rangle\lvert x + x'\rangle$

**Schrödinger picture**

| | qubits | | continuous variables | |
|---|---|---|---|---|
| computational basis | $\{\|0\rangle,\|1\rangle\}$ | bit flip $\sigma_x$ | $\{\|x\rangle\}$ | $x$-displacement $\hat{X}(s)=e^{-2is\hat{p}}$ |
| | Hadamard ↓ | | Fourier ↓ | |
| conjugate basis | $\{\|+\rangle,\|-\rangle\}$ | phase flip $\sigma_z$ | $\{\|p\rangle\}$ | $p$-displacement $\hat{Z}(s)=e^{2is\hat{x}}$ |

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

$N_\alpha(|\alpha\rangle+|-\alpha\rangle)$

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

CNOT $|x\rangle|x'\rangle\rightarrow|x\rangle|x+x'\,\mathrm{mod}\,2\rangle$

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

**Schrödinger picture**

qubits

continuous variables

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

$N_\alpha(|\alpha\rangle + |-\alpha\rangle)$

computational basis $\{|0\rangle, |1\rangle\}$ bit flip $\sigma_x$ ⇐ $\{|x\rangle\}$ $x$-displacement $\hat{X}(s) = e^{-2is\hat{p}}$

Hadamard ⇓ ⇓ Fourier

conjugate basis $\{|+\rangle, |-\rangle\}$ phase flip $\sigma_z$ $\{|p\rangle\}$ $p$-displacement $\hat{Z}(s) = e^{2is\hat{x}}$

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

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

**Heisenberg picture**

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

$$\hat{x}|x\rangle = x|x\rangle$$

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

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

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

**Schrödinger picture**

qubits — continuous variables

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

$N_\alpha(|\alpha\rangle + |-\alpha\rangle)$

computational basis $\{|0\rangle, |1\rangle\}$ bit flip $\sigma_x$ ← $\{|x\rangle\}$ $x$-displacement $\hat{X}(s) = e^{-2is\hat{p}}$

Hadamard ↓ — Fourier ↓

conjugate basis $\{|+\rangle, |-\rangle\}$ phase flip $\sigma_z$ — $\{|p\rangle\}$ $p$-displacement $\hat{Z}(s) = e^{2is\hat{x}}$

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

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

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

**Heisenberg picture**

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

$\hat{x}|x\rangle = x|x\rangle$

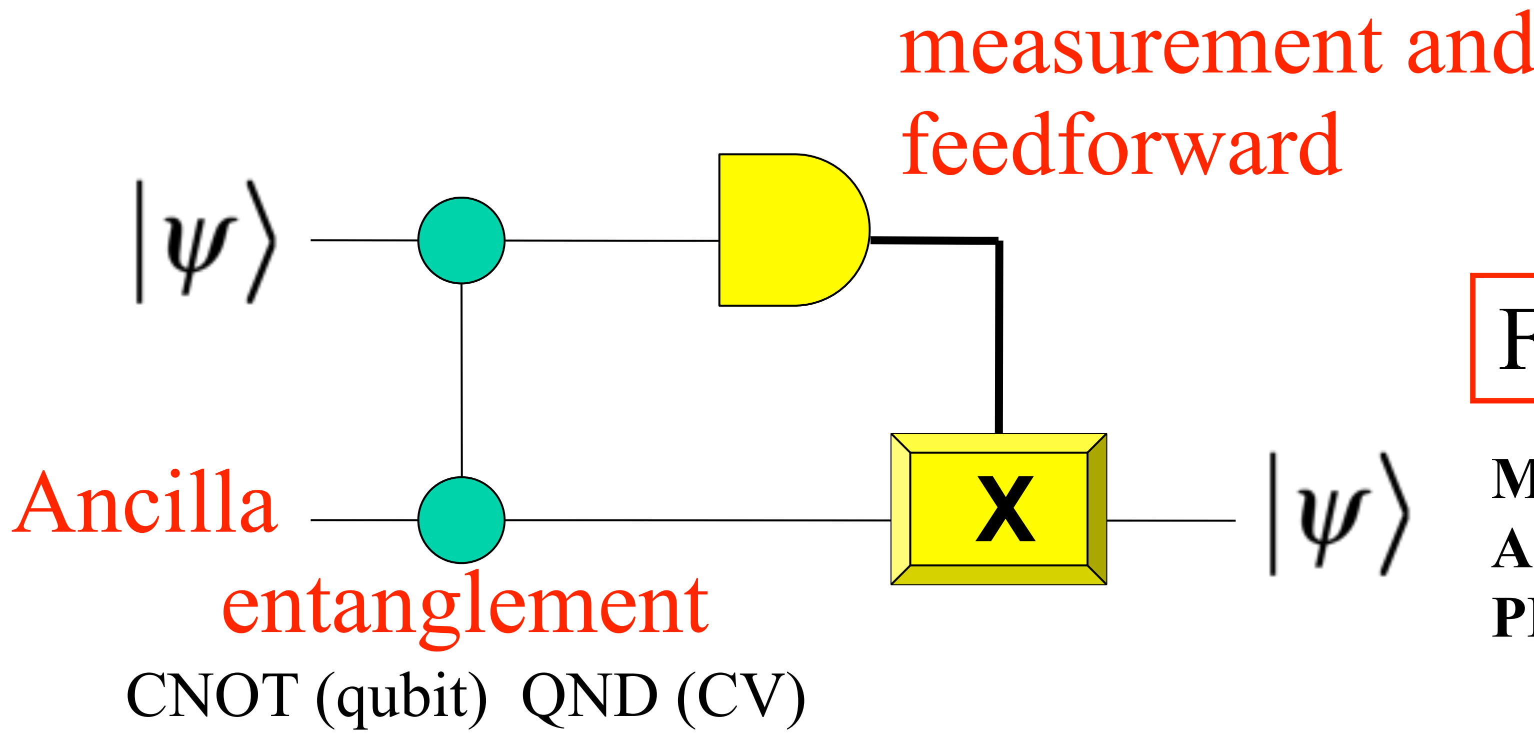
$\hat{p}|p\rangle = p|p\rangle$

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

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

$\boxed{\begin{array}{l} \text{AM signal} = \hat{x} \\ \text{FM signal} = \hat{p} \end{array}}$

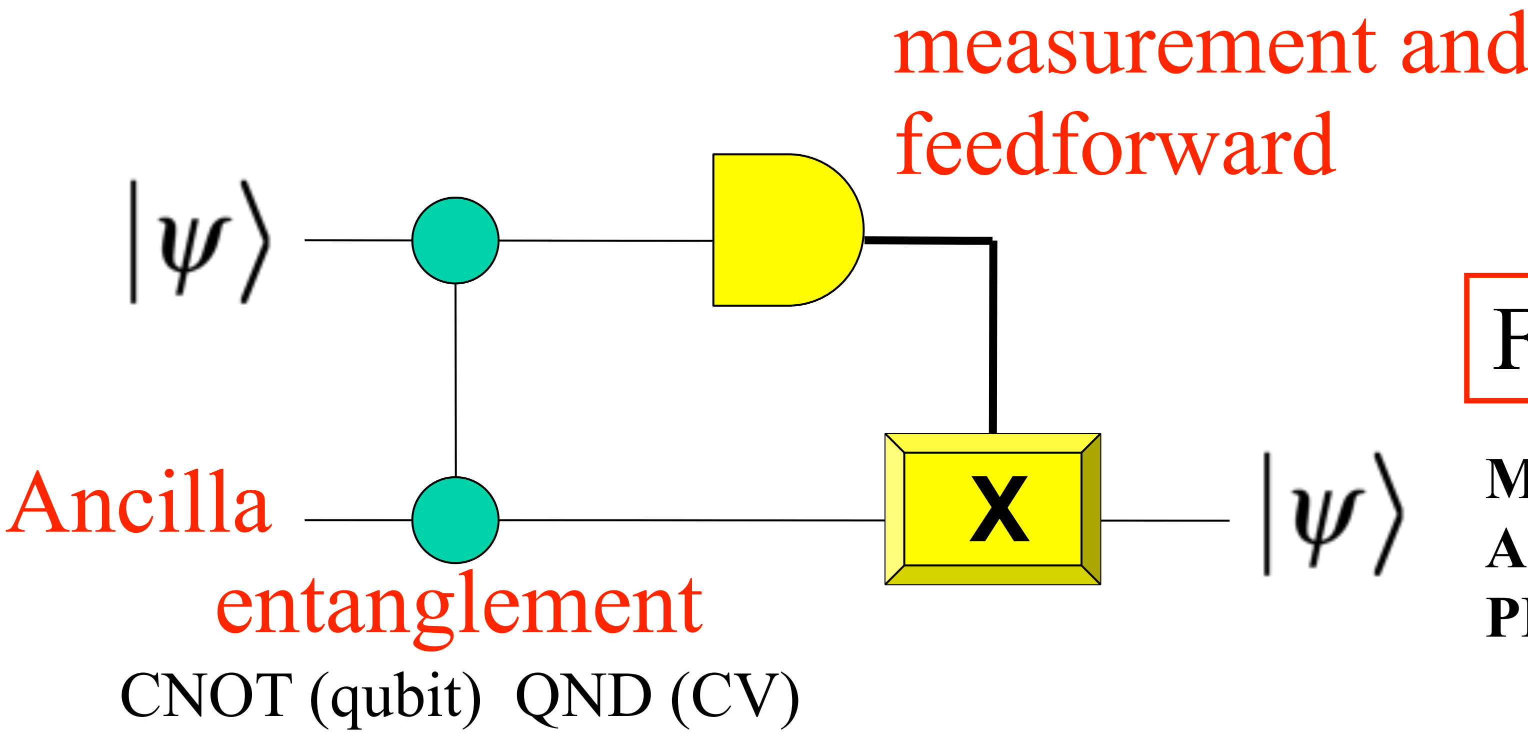
# *Generalized teleportation*




$\boxed{\text{Fidelity} = 0.83}$

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

# *Generalized teleportation*

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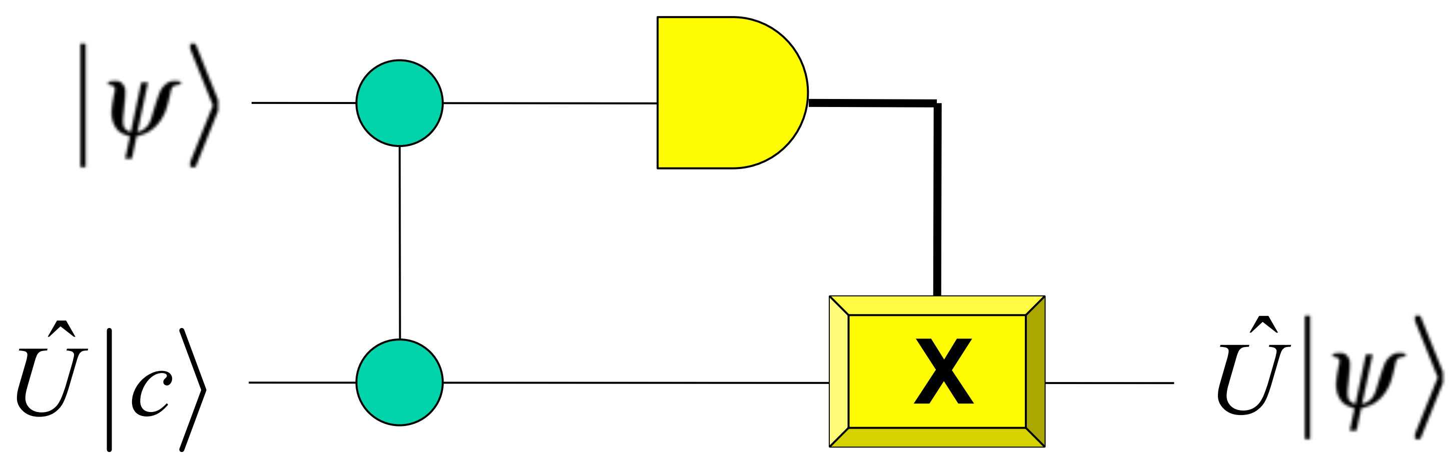
## Teleportation based quantum information processing 1



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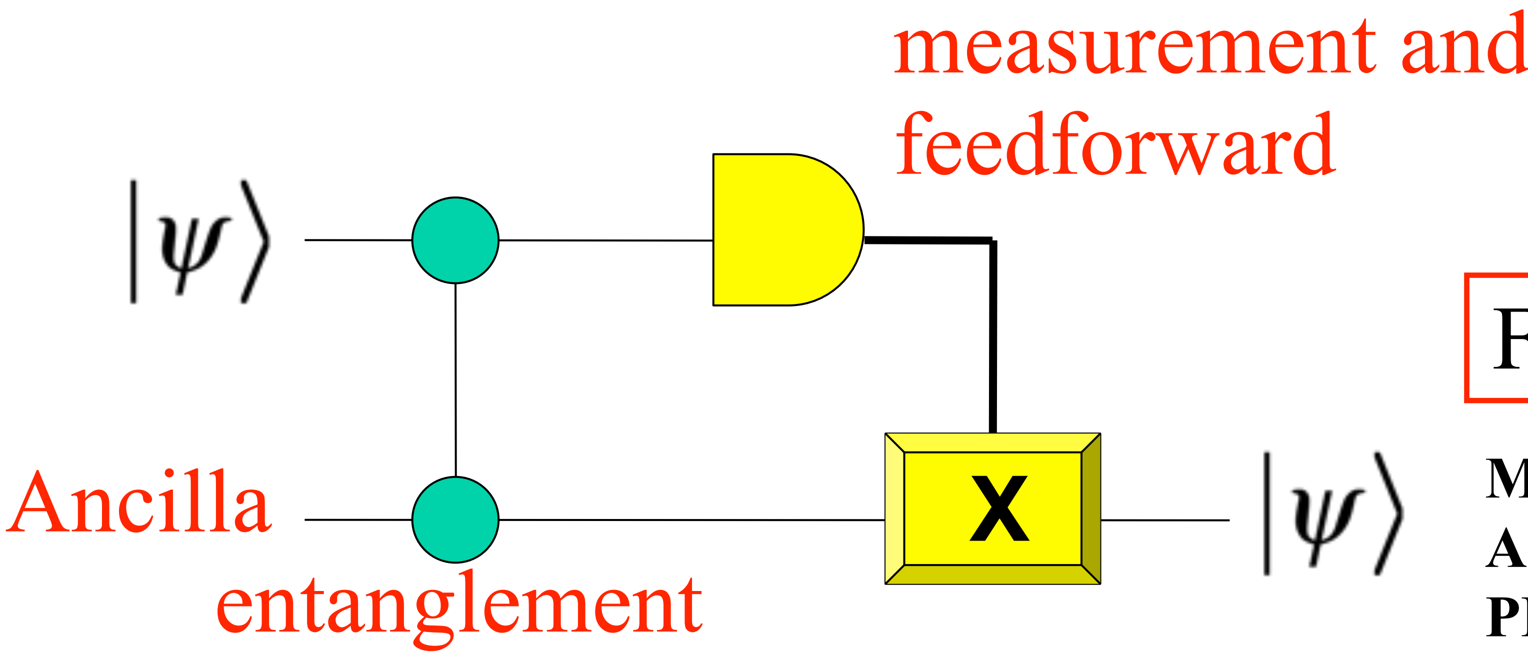
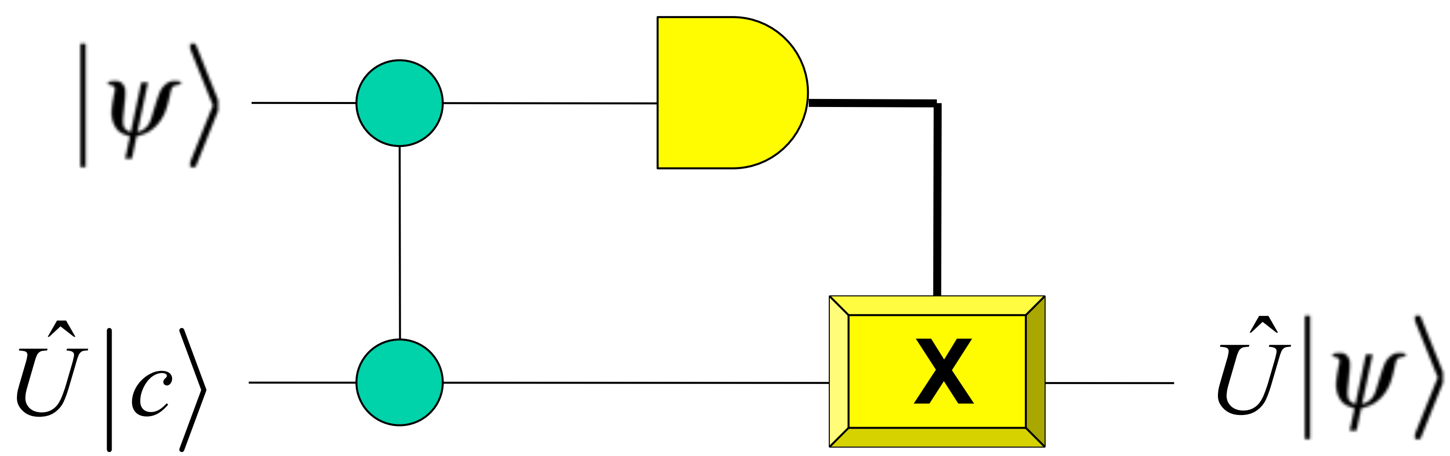



CNOT (qubit) QND (CV)

Fidelity = 0.83

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

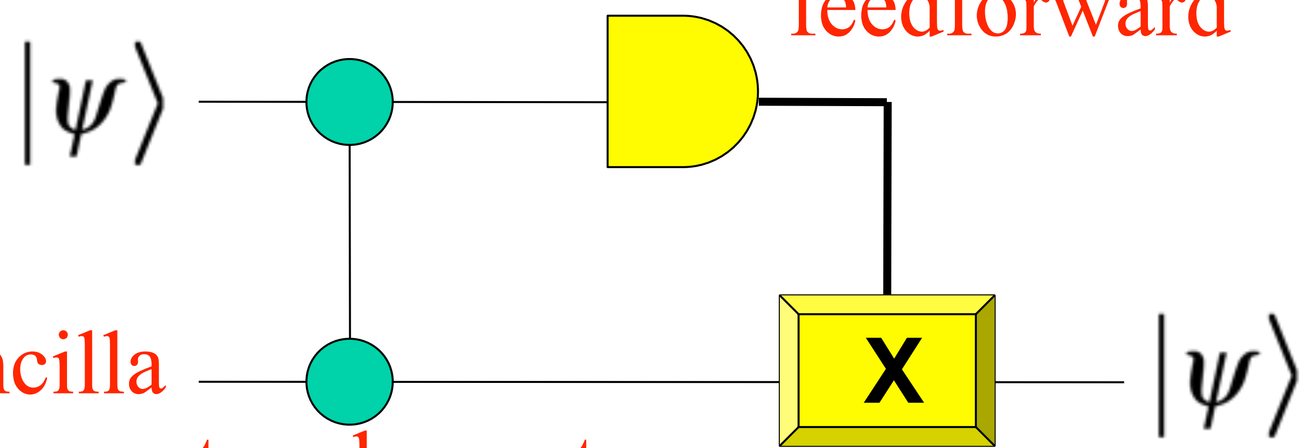
Teleportation based quantum information processing 1




state preparation

# *Generalized teleportation*

measurement and feedforward




entanglement

CNOT (qubit) QND (CV)

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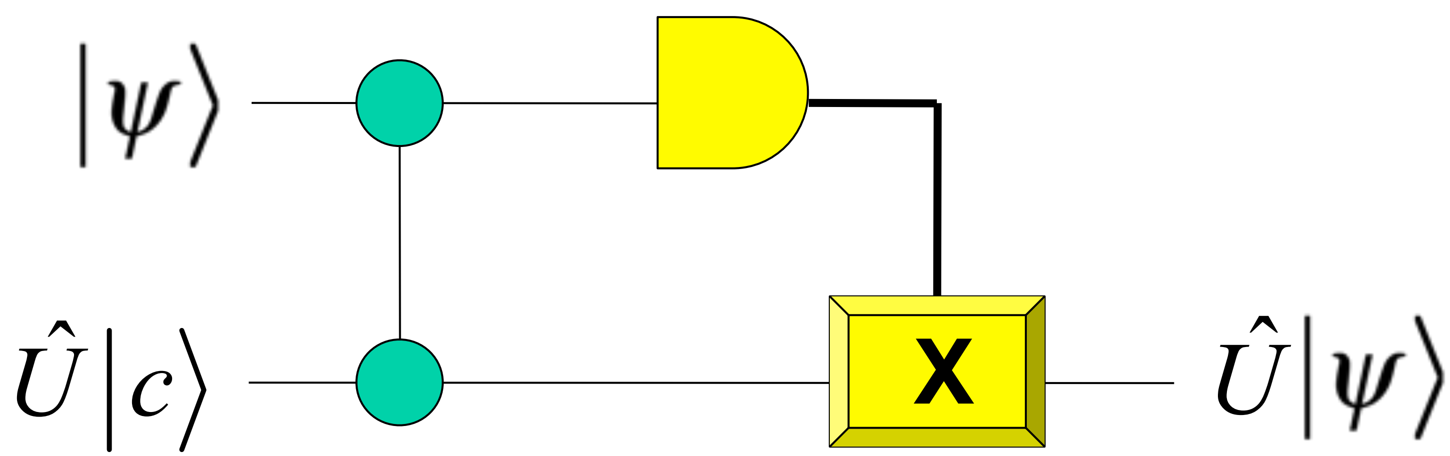
Teleportation based quantum information processing 1

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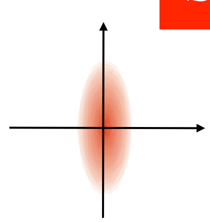
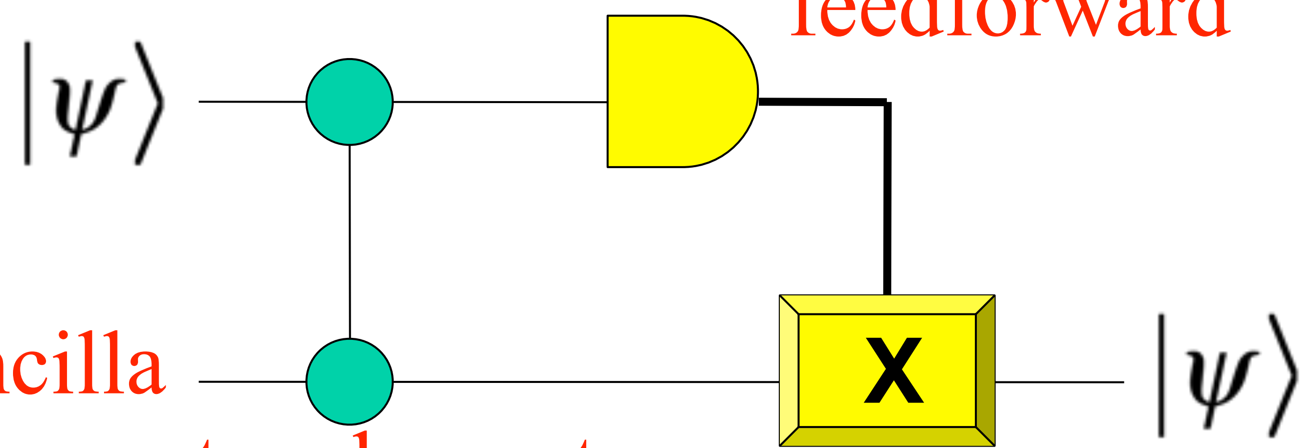


$\hat{S}(r)|0\rangle$ squeezed vacuum

Universal squeezer

# *Generalized teleportation*

measurement and feedforward

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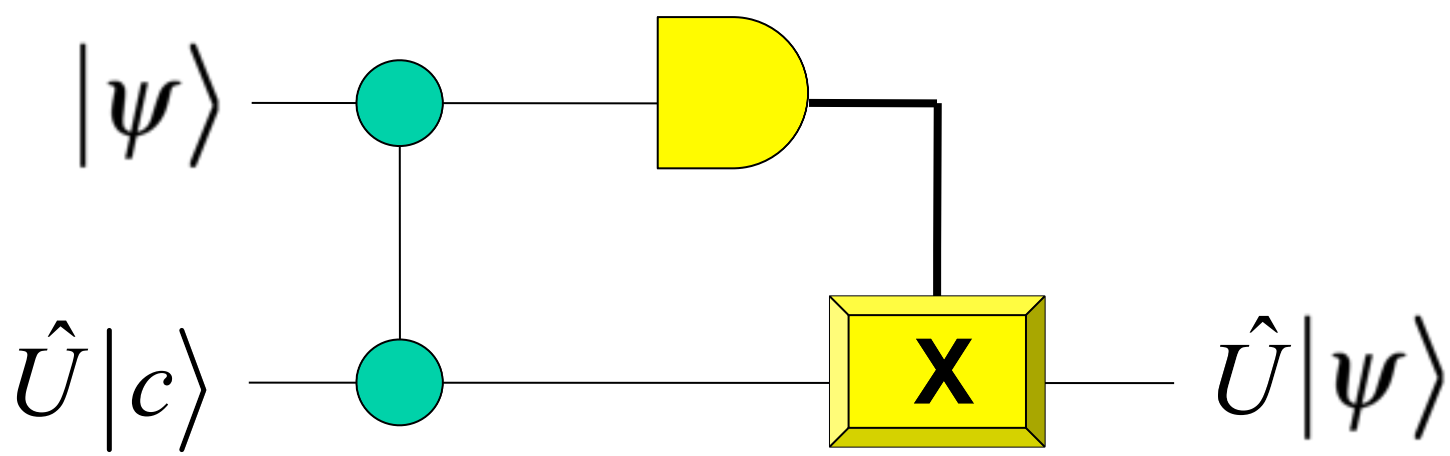
**M. Yukawa, H. Benichi, A. Furusawa**
**PRA 77, 022314 (2008)**

Ancilla

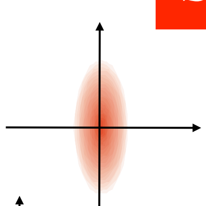
entanglement

CNOT (qubit) QND (CV)

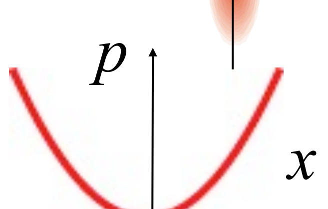
## Teleportation based quantum information processing 1




state preparation



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



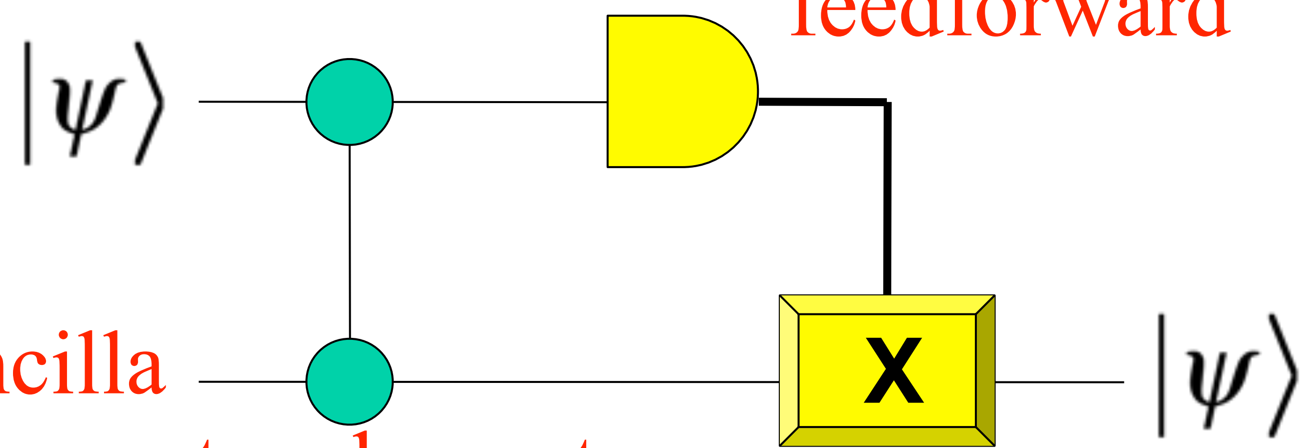

$\int dx\, e^{ikx^3}|x\rangle$ cubic phase state

Universal squeezer

Cubic phase gate

# *Generalized teleportation*

measurement and
feedforward




Ancilla

entanglement

CNOT (qubit) QND (CV)

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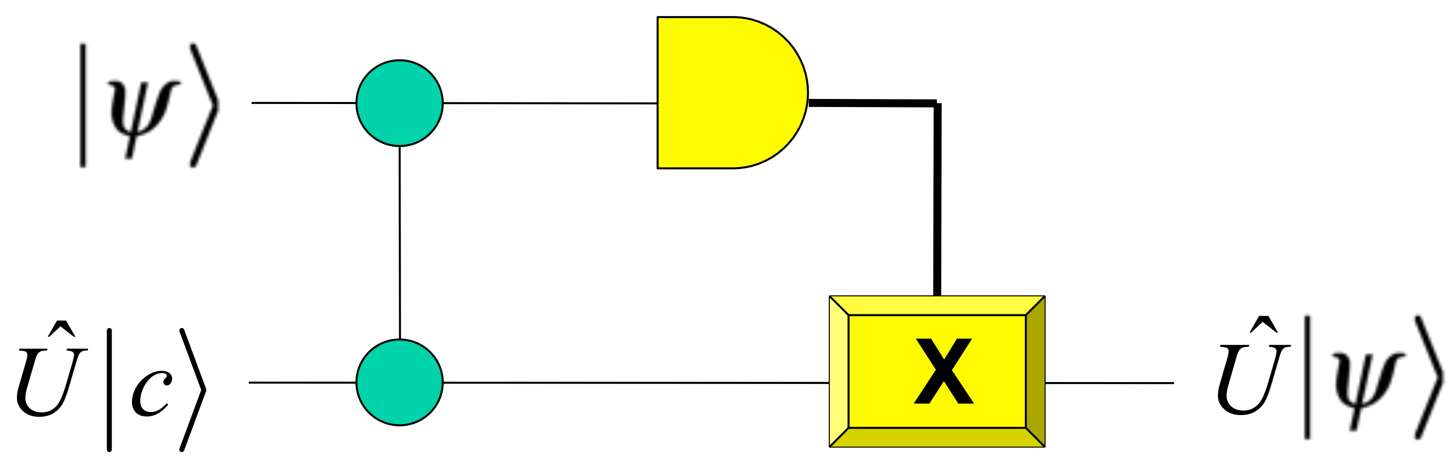


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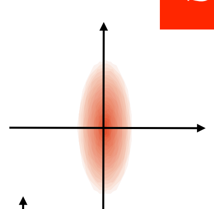
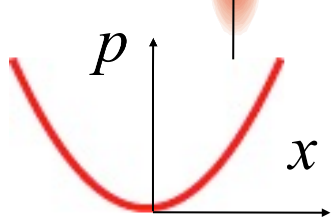


$\hat{S}(r)|0\rangle$ squeezed vacuum

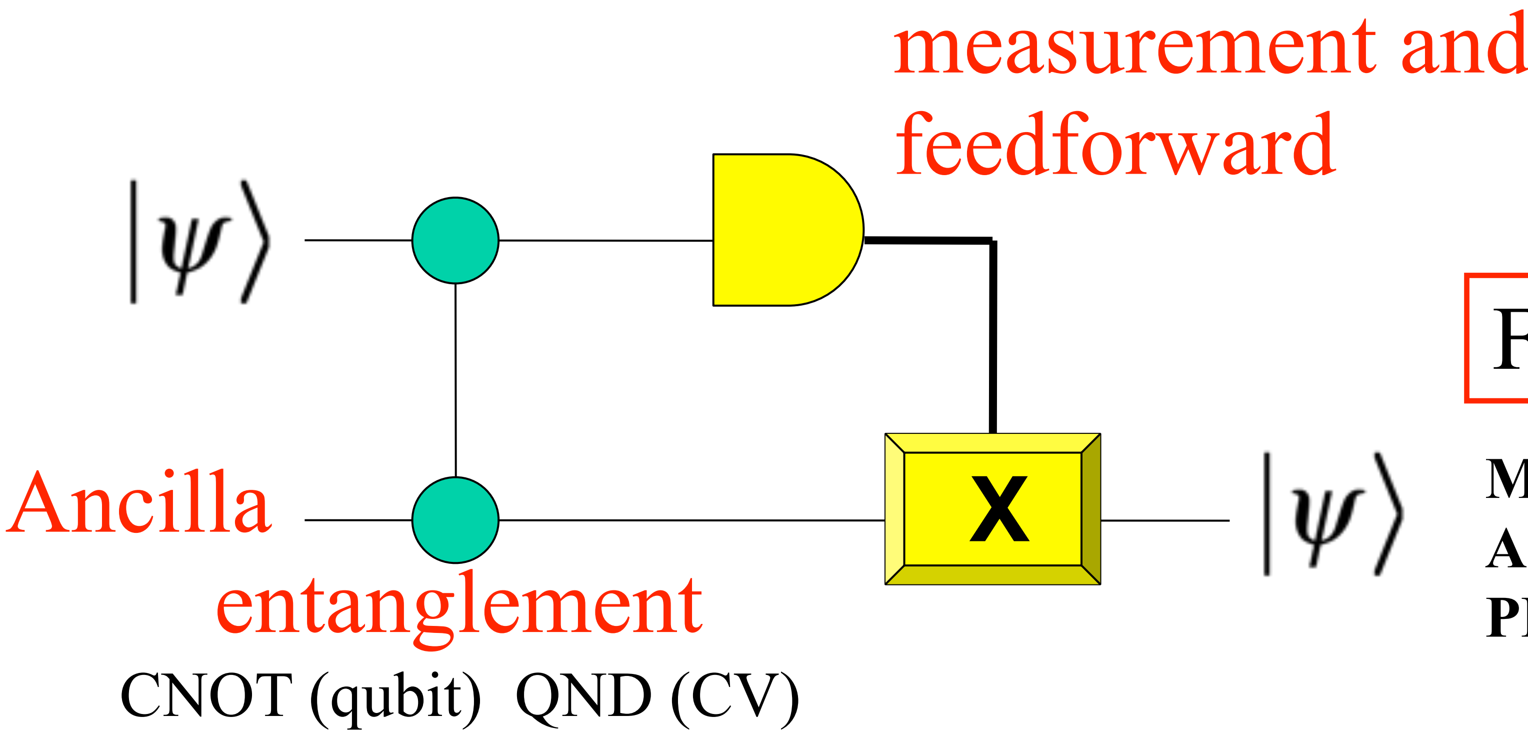



$\int dx\, e^{ikx^3}|x\rangle$ cubic phase state

Universal squeezer

CV π/8 gate

# *Generalized teleportation*

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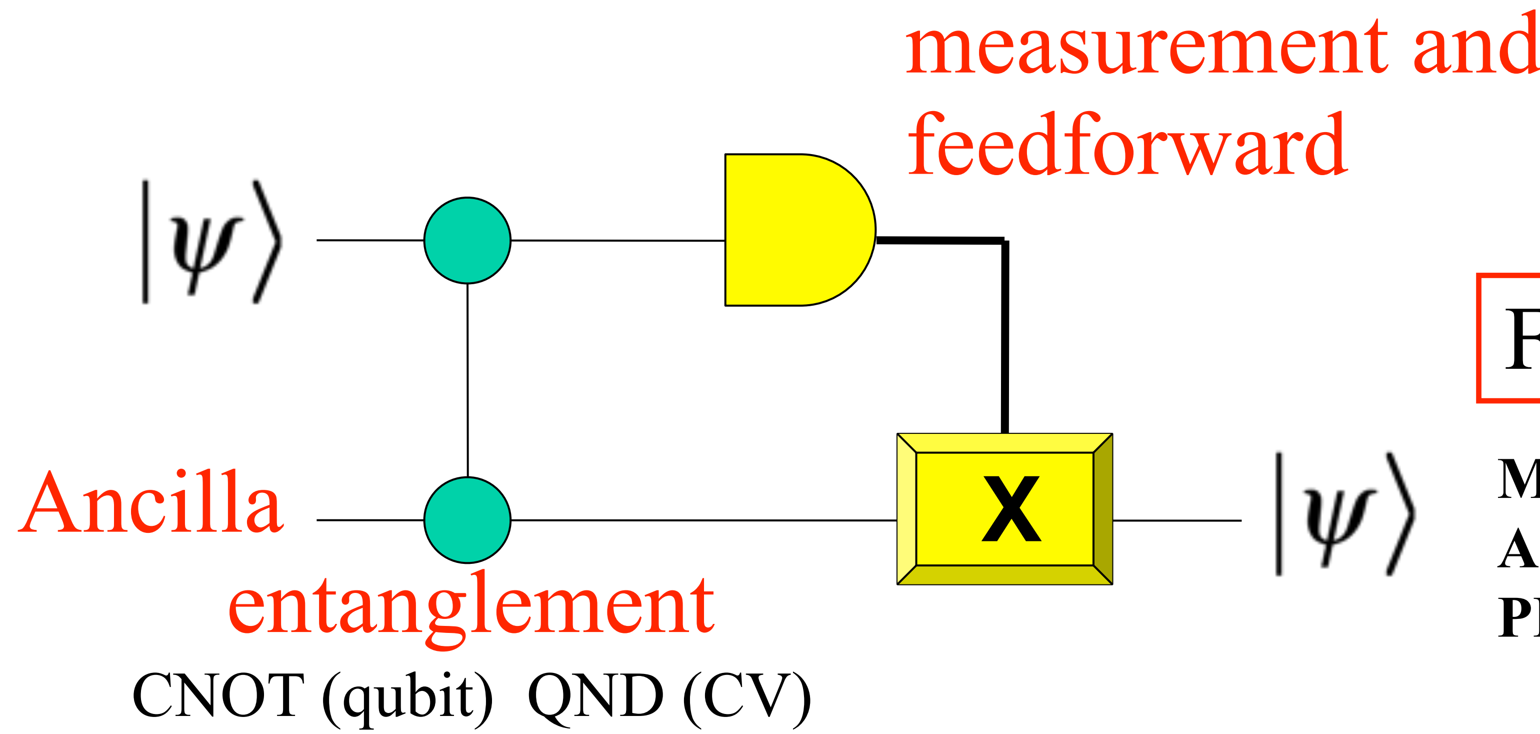
# *Generalized teleportation*

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**M. Yukawa, H. Benichi, A. Furusawa**
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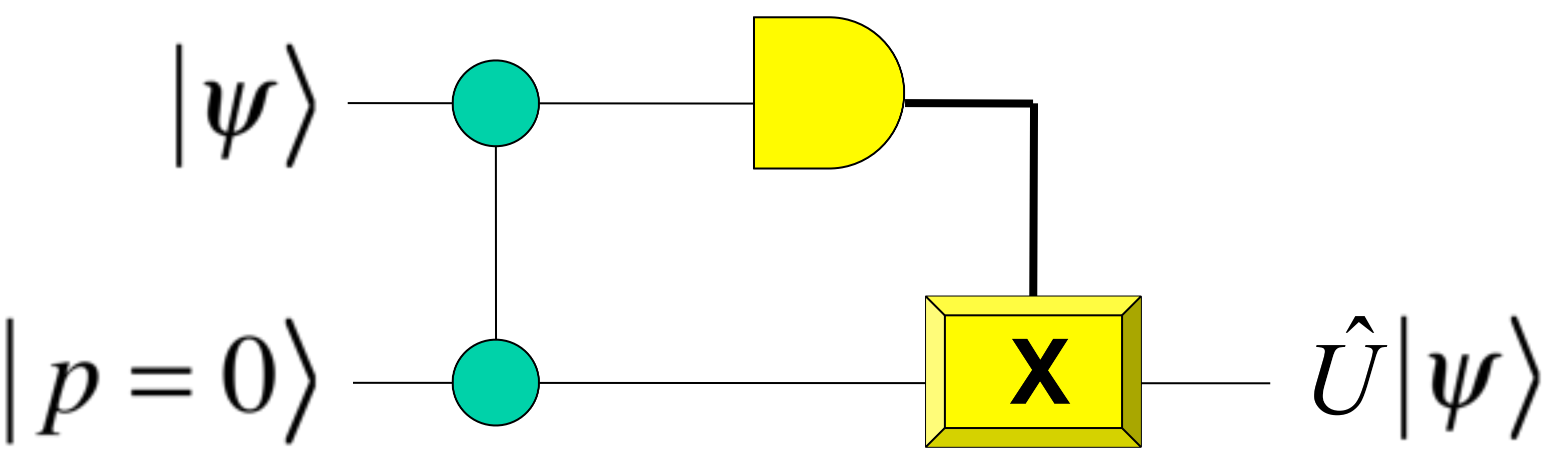
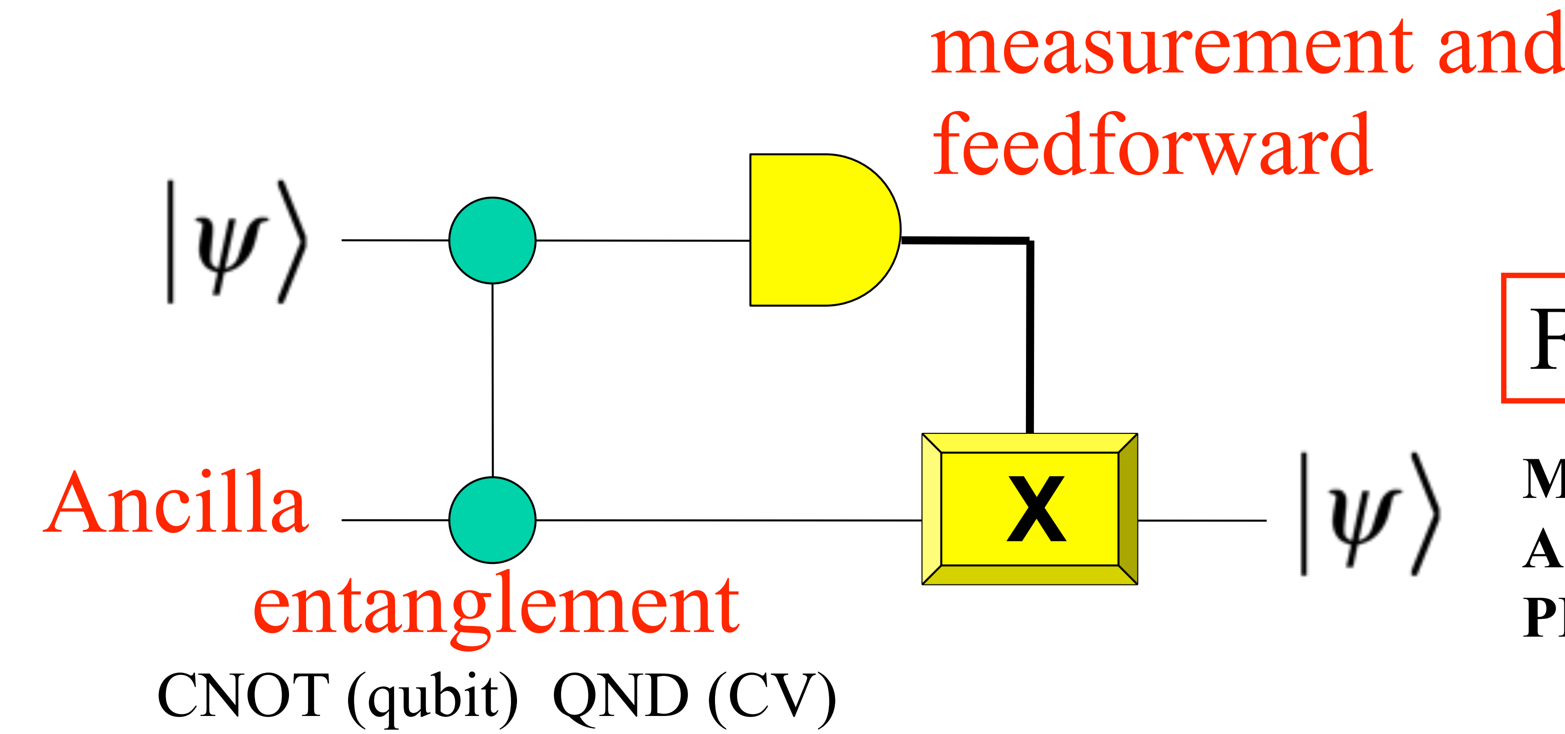
Teleportation based quantum information processing 2




one-way quantum computation with cluster states

# *Generalized teleportation*

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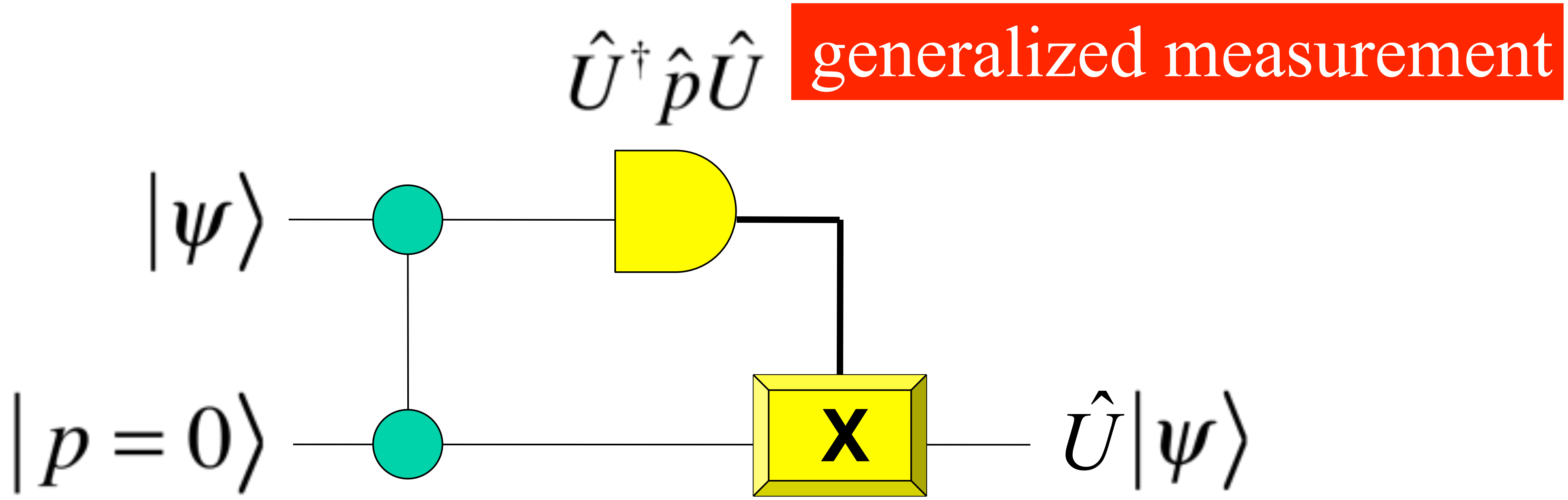
M. Yukawa, H. Benichi, A. Furusawa
PRA 77, 022314 (2008)

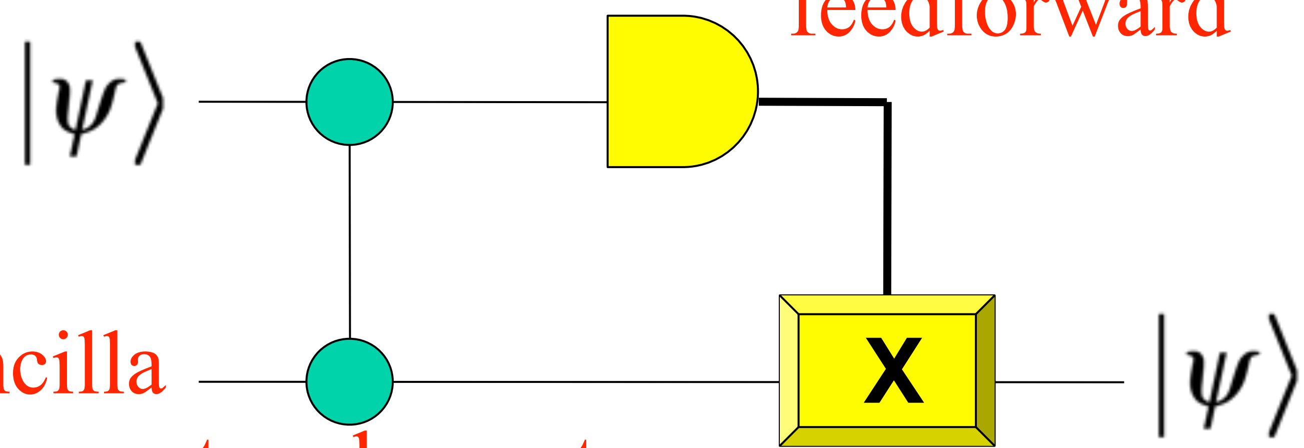
Teleportation based quantum information processing 2




one-way quantum computation with cluster states

# *Generalized teleportation*

measurement and feedforward

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**PRA 77, 022314 (2008)**

Ancilla

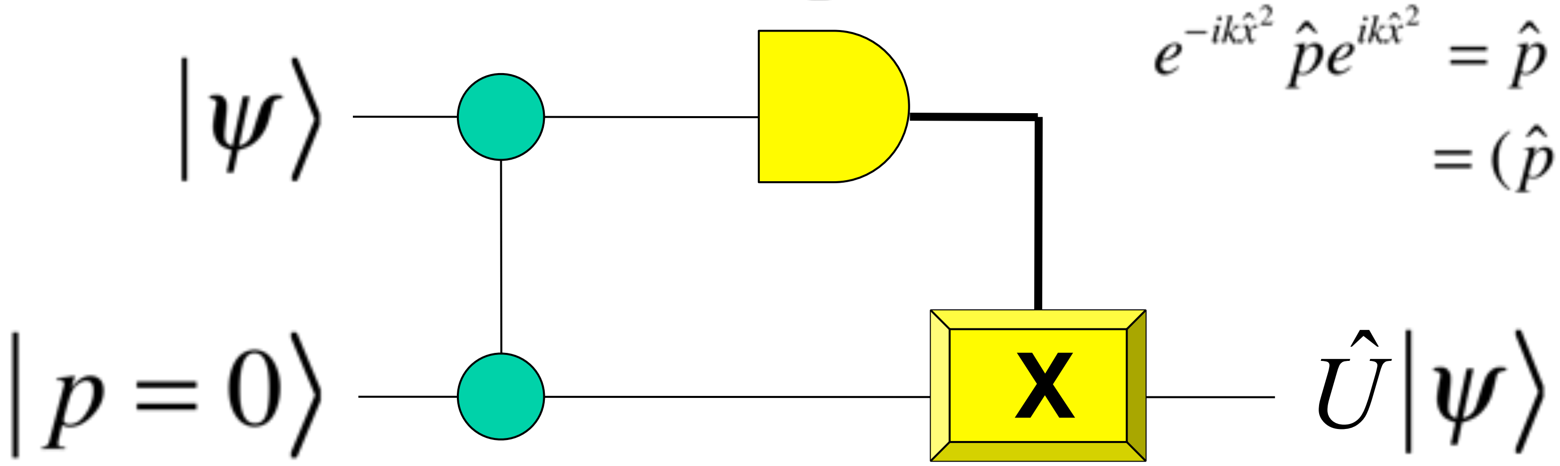
entanglement

CNOT (qubit) QND (CV)

Teleportation based quantum information processing 2

$\hat{U}^\dagger \hat{p} \hat{U}$ generalized measurement

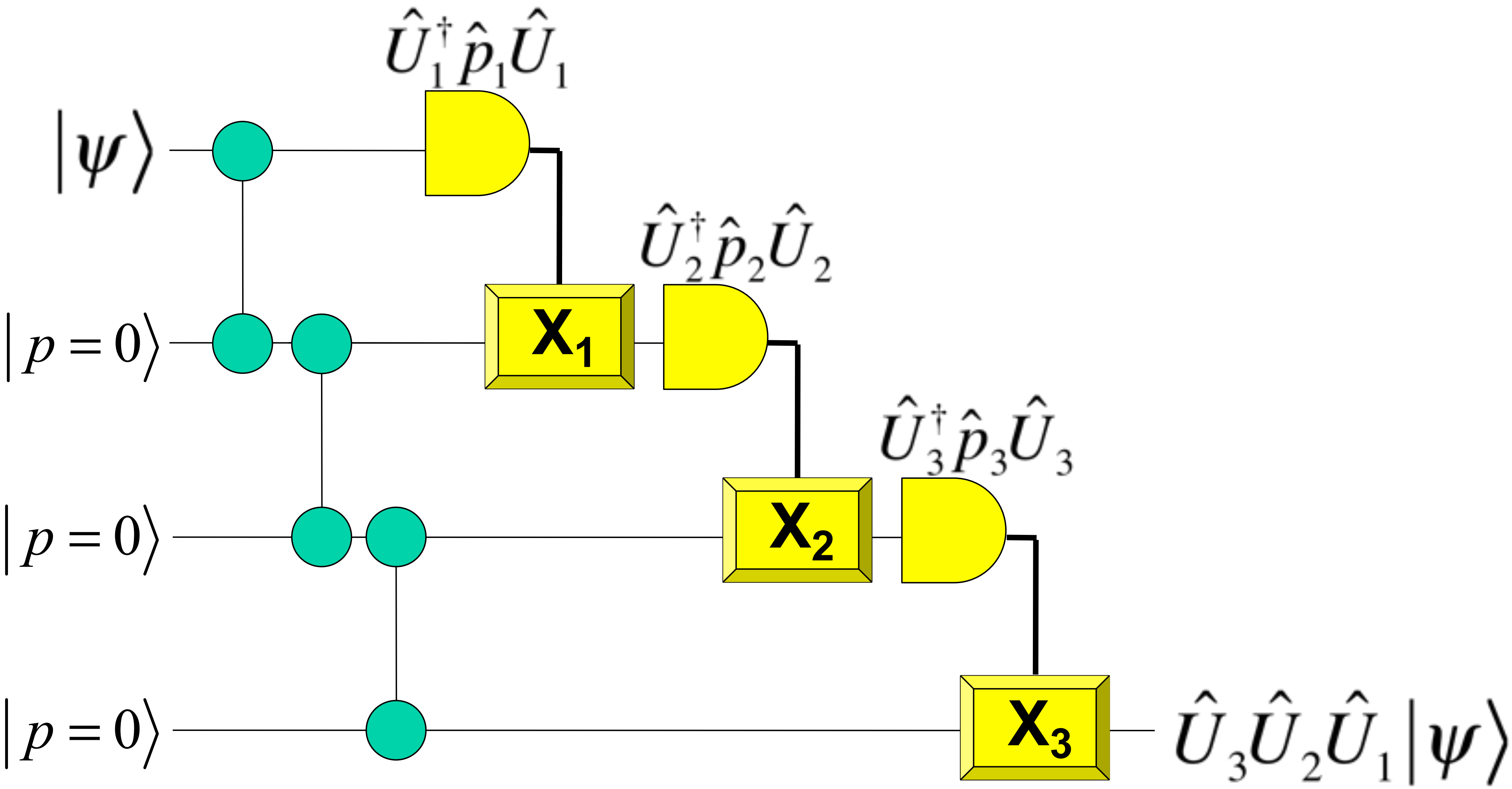
$$e^{-ik\hat{x}^2}\hat{p}e^{ik\hat{x}^2} = \hat{p} + k\hat{x}$$
$$= (\hat{p}\cos\theta - \hat{x}\sin\theta)/\cos\theta$$
$$\theta = \tan^{-1}(-k)$$




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

one-way quantum computation with cluster states

# one-way quantum computation with cluster states



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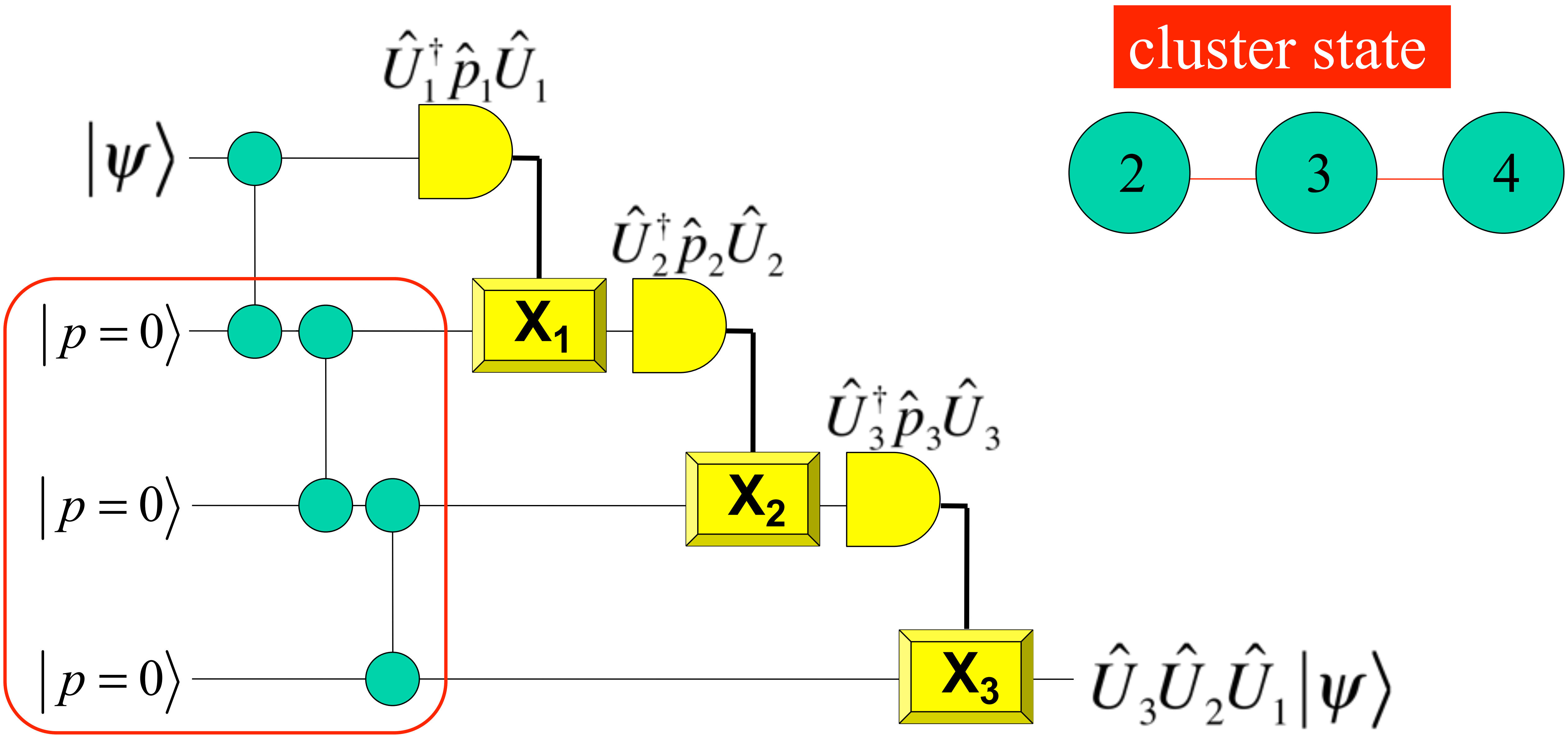

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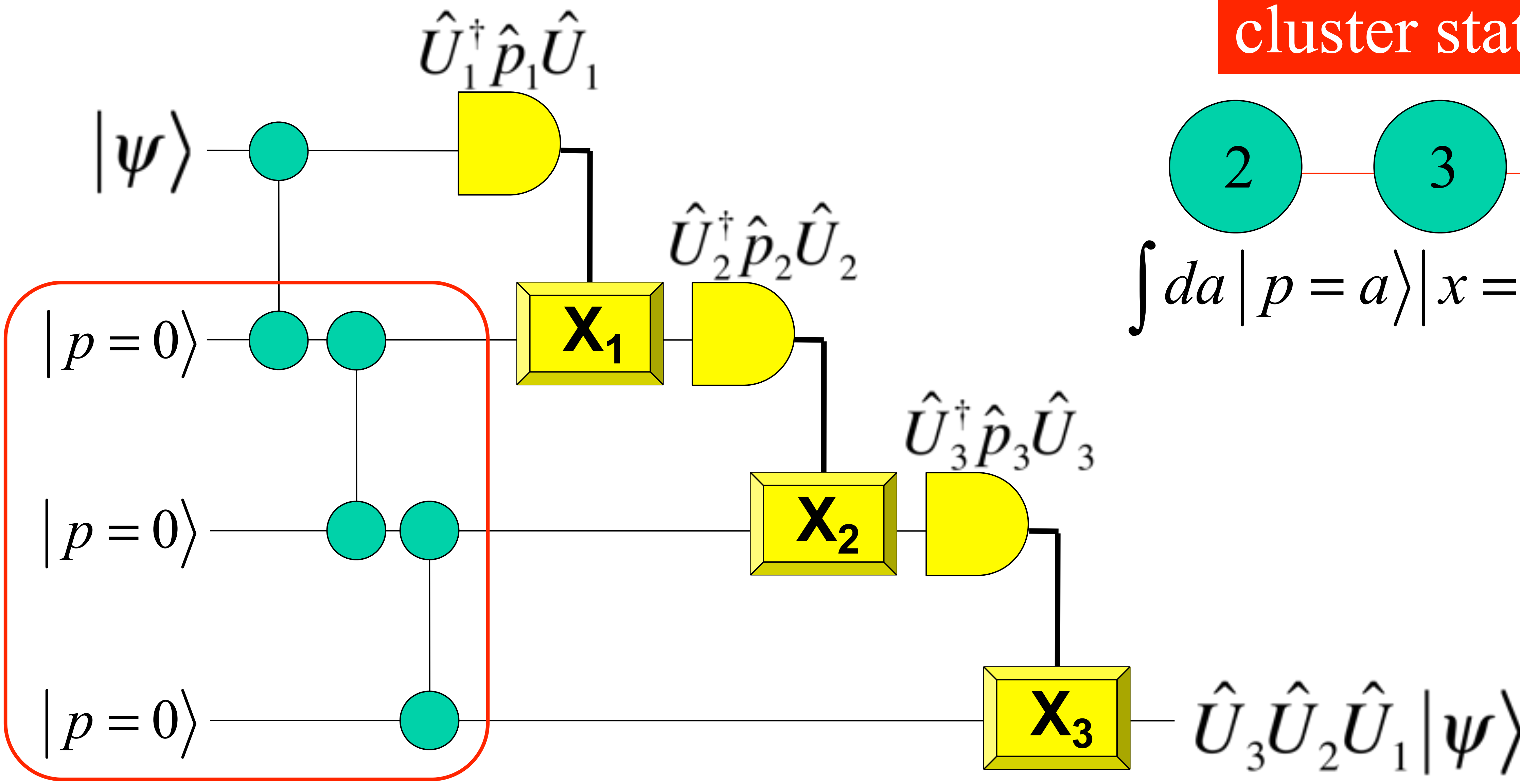
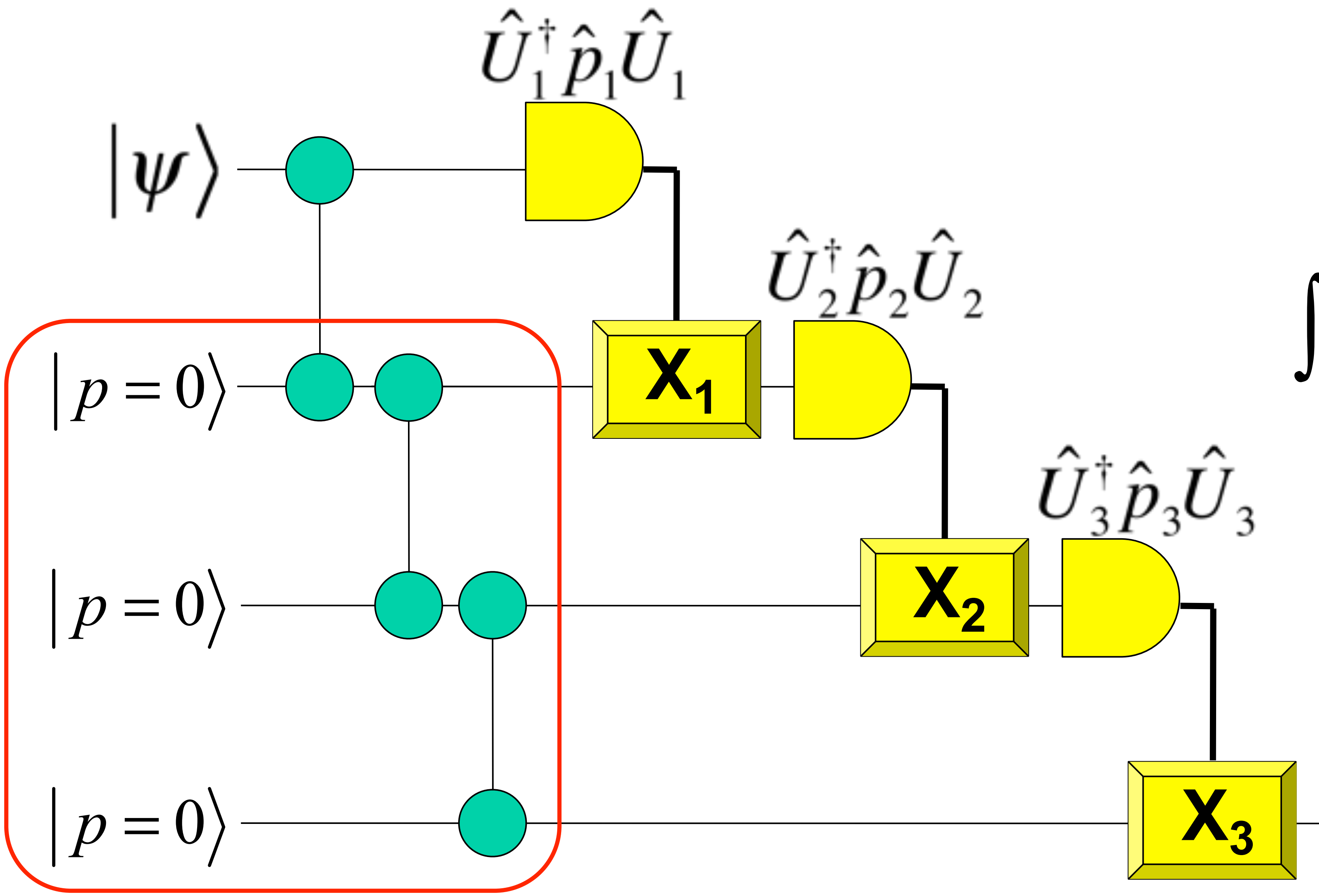



cluster state

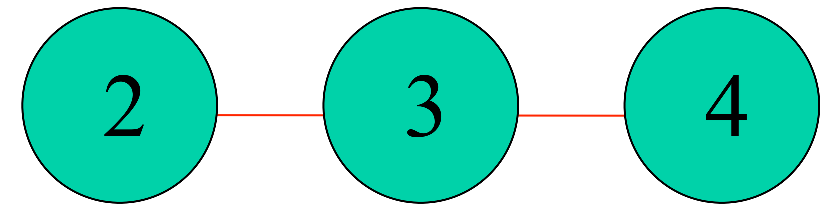


$$\int da\, |p=a\rangle |x=a\rangle |p=a\rangle$$

# one-way quantum computation with cluster states




## cluster state

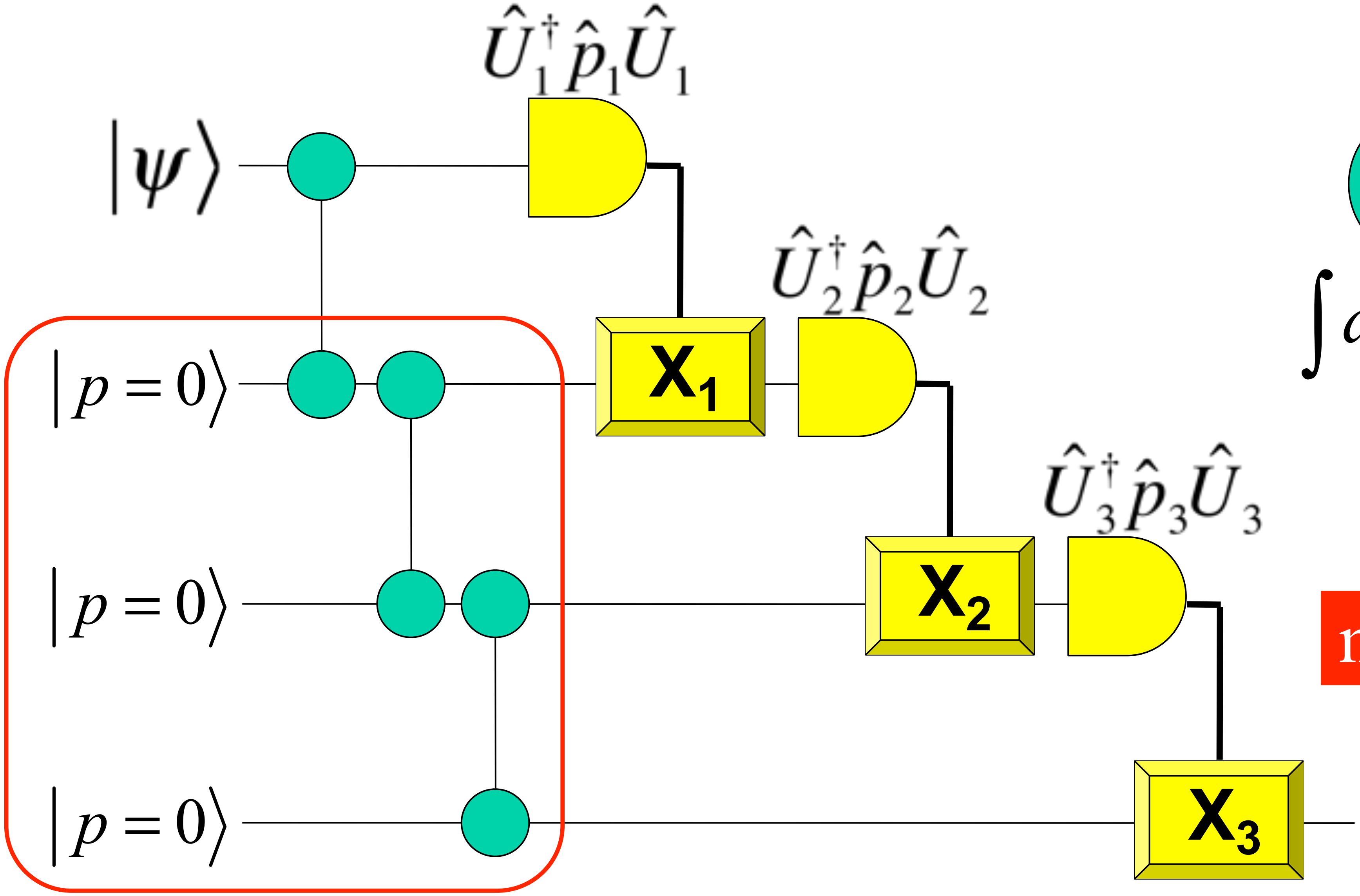



$$\int da\,|p=a\rangle|x=a\rangle|p=a\rangle$$

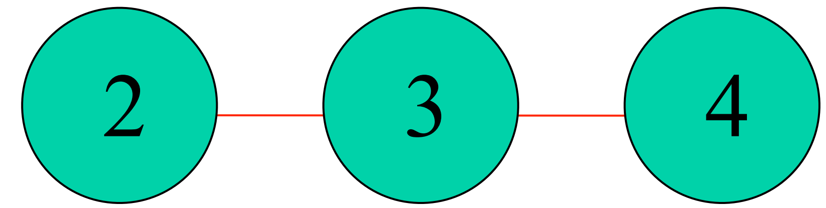
$$\frac{1}{\sqrt{2}}\left(|+\rangle|0\rangle|+\rangle+|-\rangle|1\rangle|-\rangle\right)$$

$$|+\rangle=\frac{1}{\sqrt{2}}\left(|0\rangle+|1\rangle\right),\ |-\rangle=\frac{1}{\sqrt{2}}\left(|0\rangle-|1\rangle\right)$$

# one-way quantum computation with cluster states




## cluster state



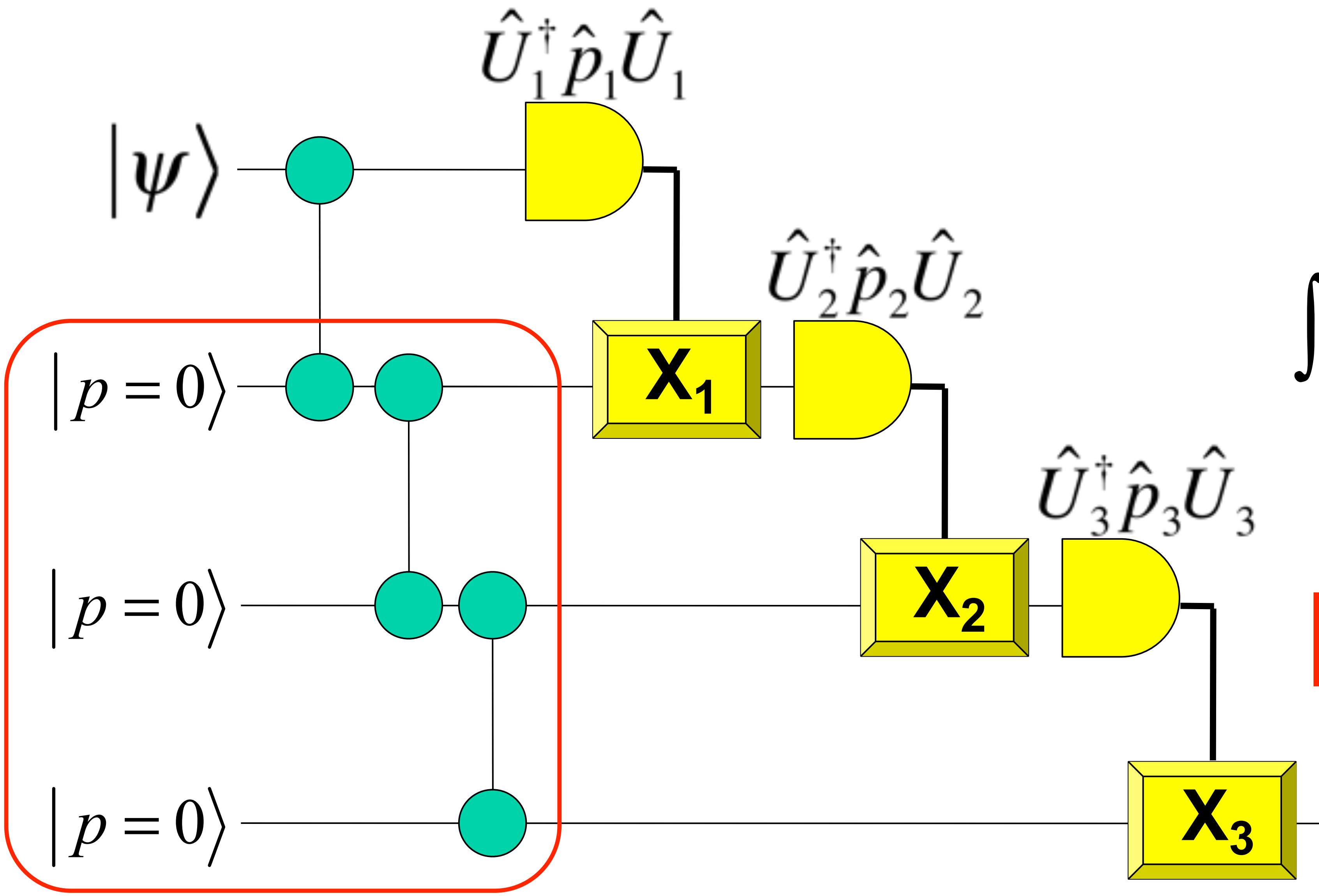

$$\int da\, |p=a\rangle |x=a\rangle |p=a\rangle$$

$$\frac{1}{\sqrt{2}}\left(|+\rangle|0\rangle|+\rangle + |-\rangle|1\rangle|-\rangle\right)$$

$$|+\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle + |1\rangle\right),\ |-\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle - |1\rangle\right)$$

## multipartite entanglement

# one-way quantum computation with cluster states

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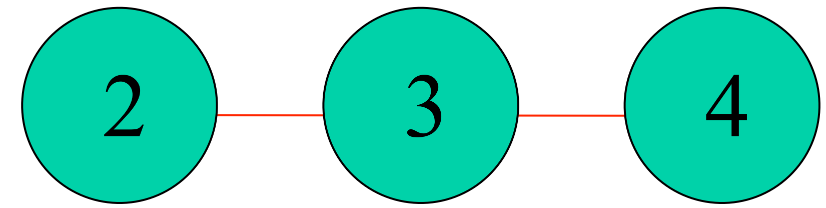


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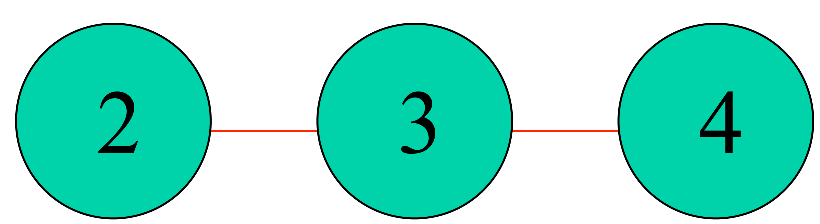

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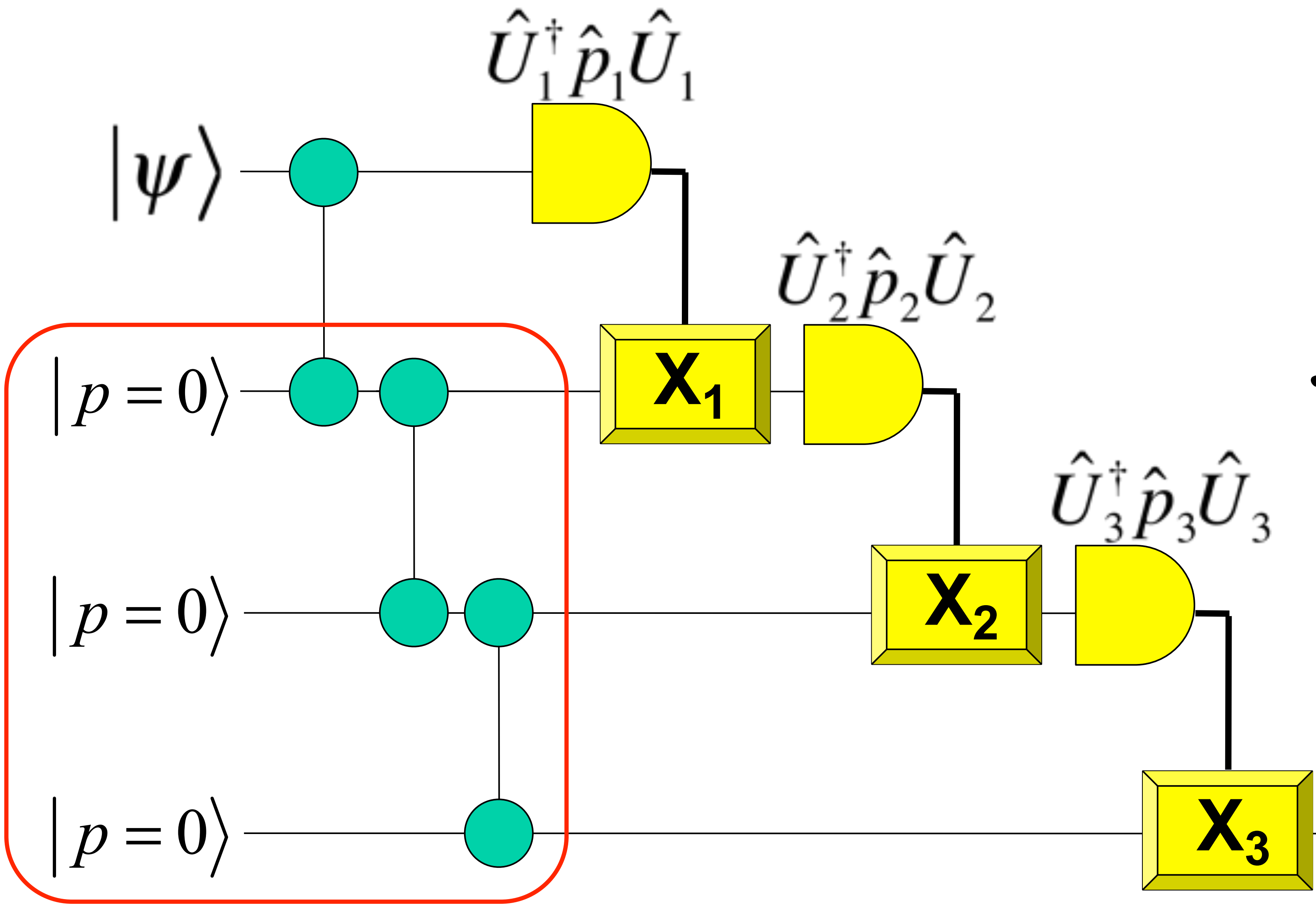


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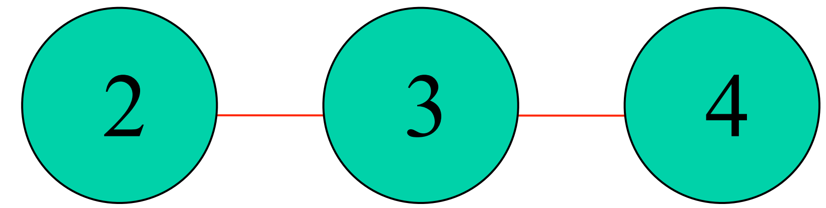


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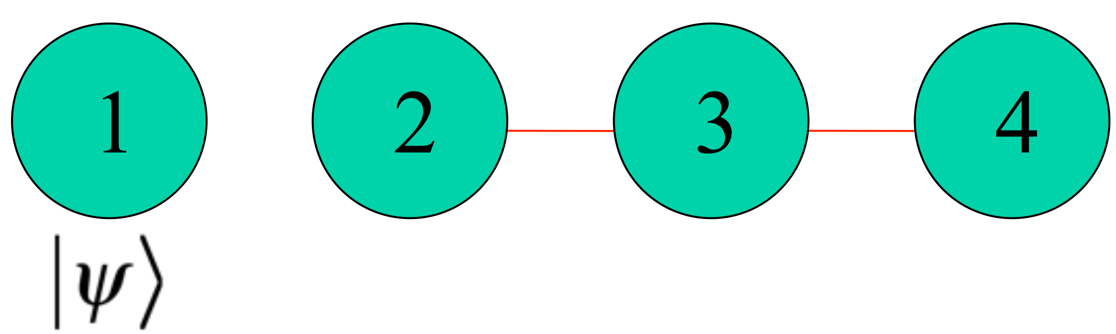
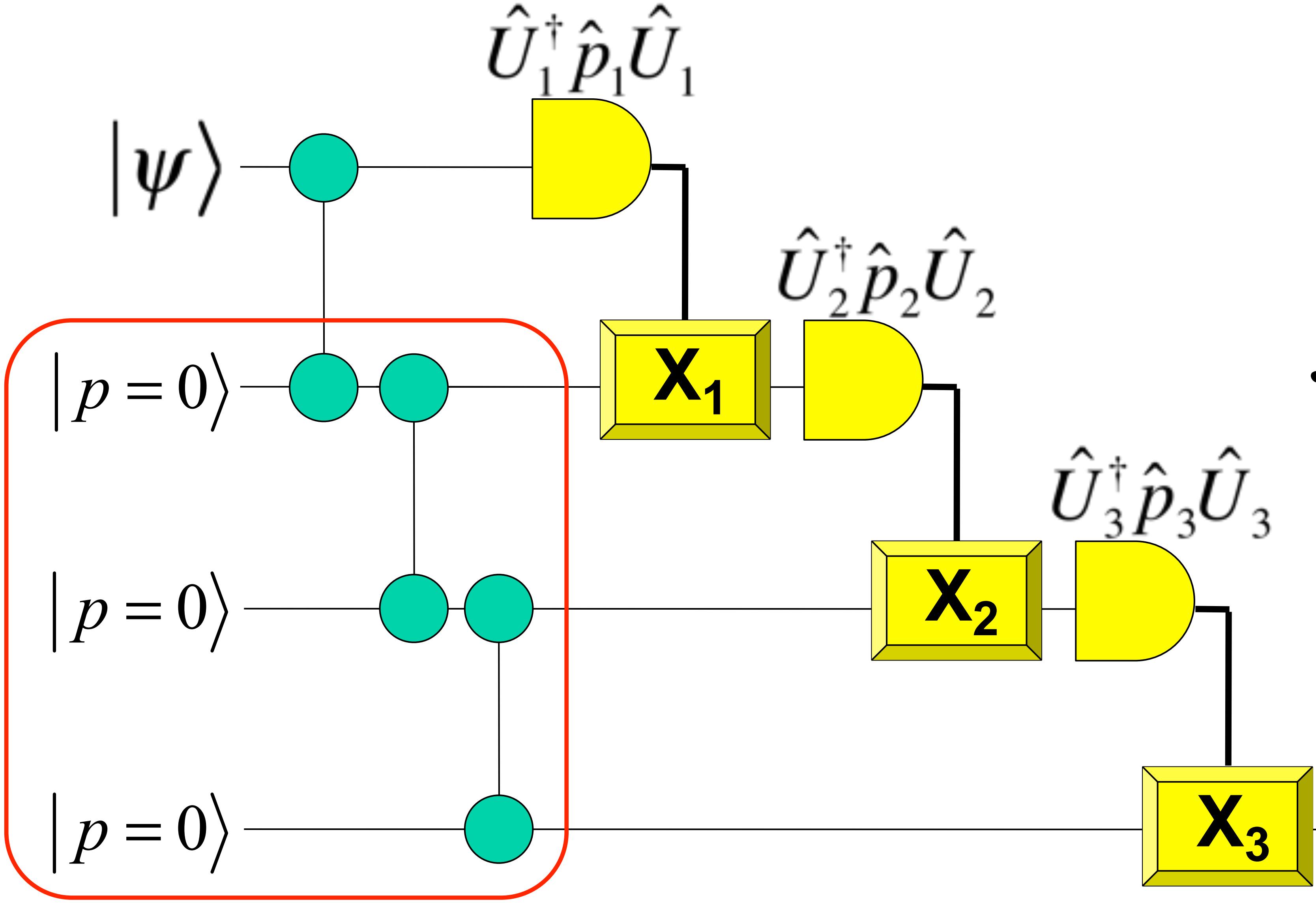
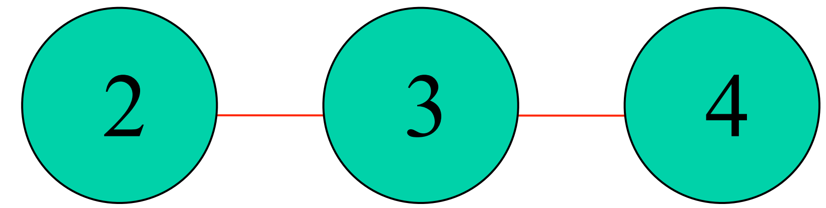


# one-way quantum computation with cluster states




$$\hat{U}_3 \hat{U}_2 \hat{U}_1 |\psi\rangle$$

**cluster state**

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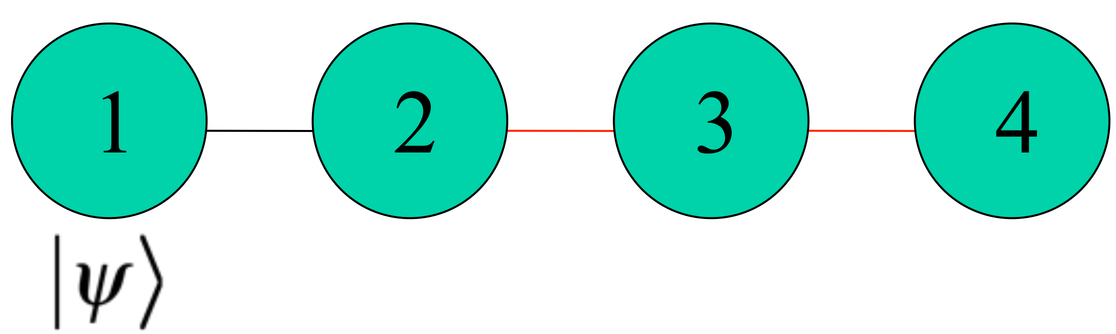
**multipartite entanglement**



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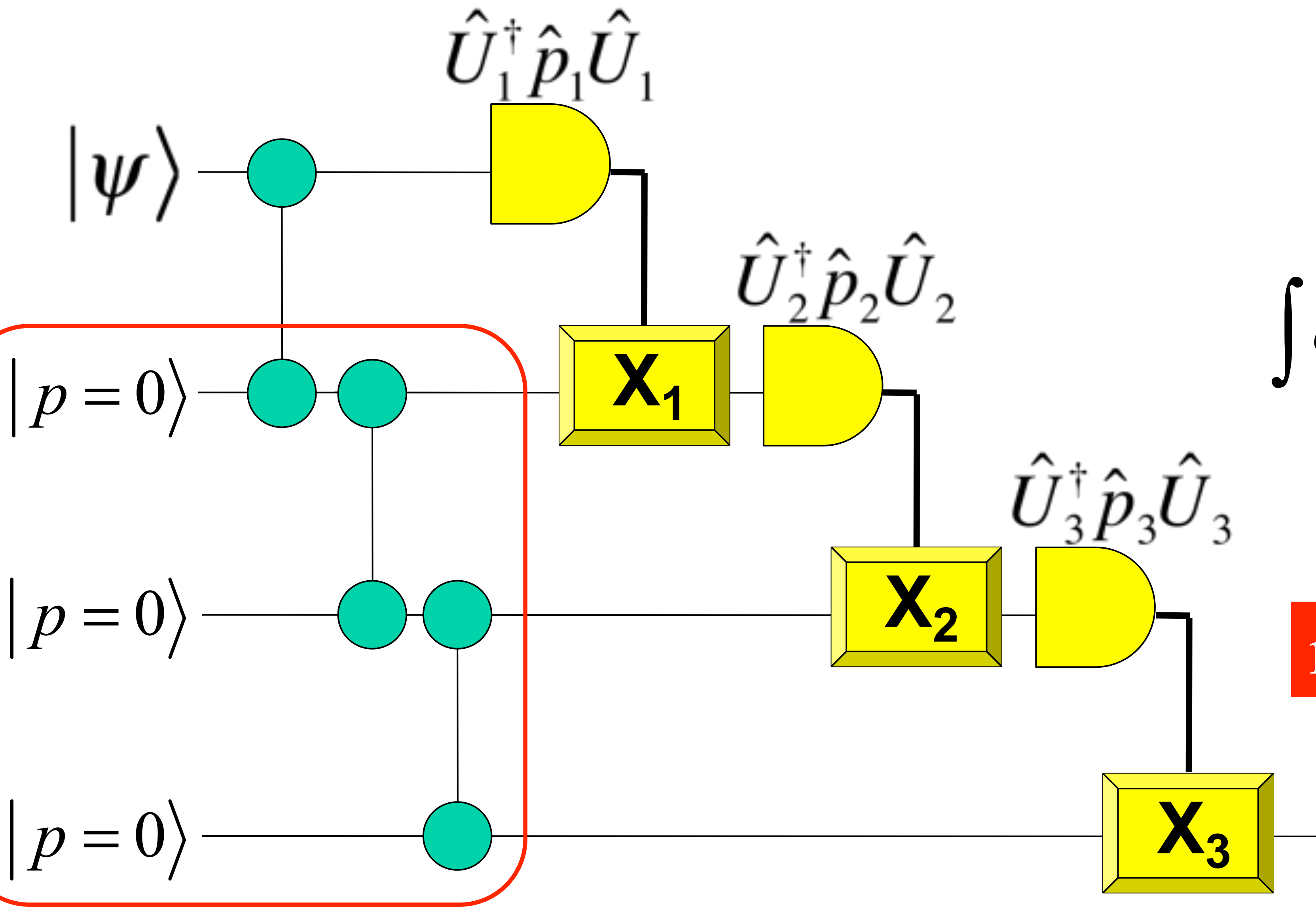
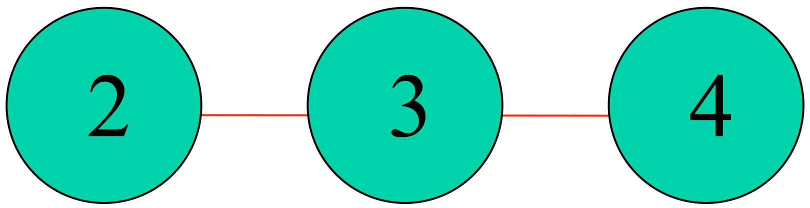



cluster state

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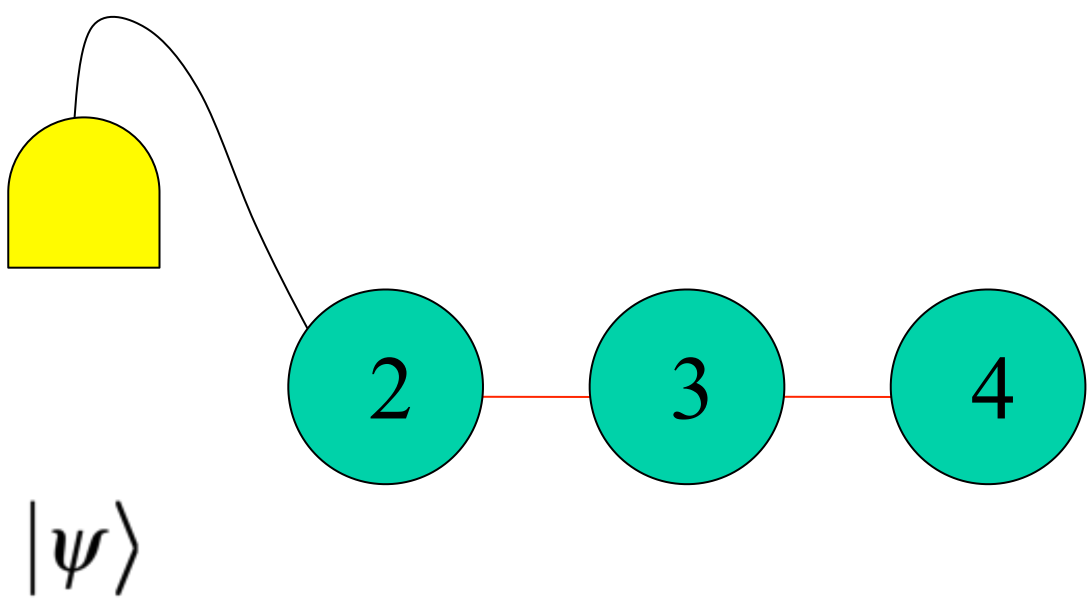

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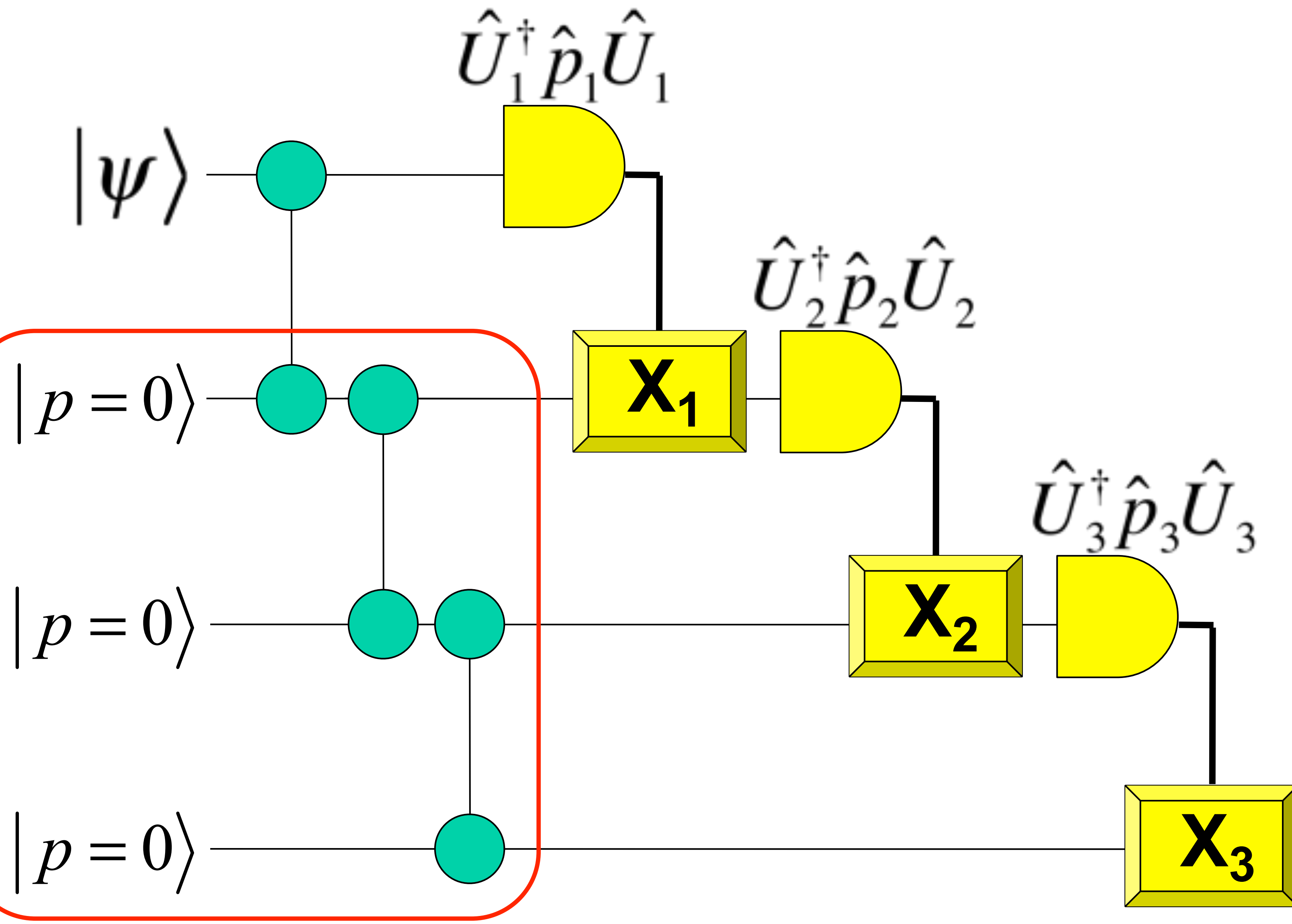
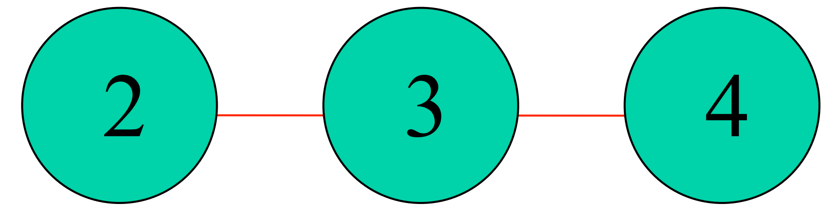



## cluster state

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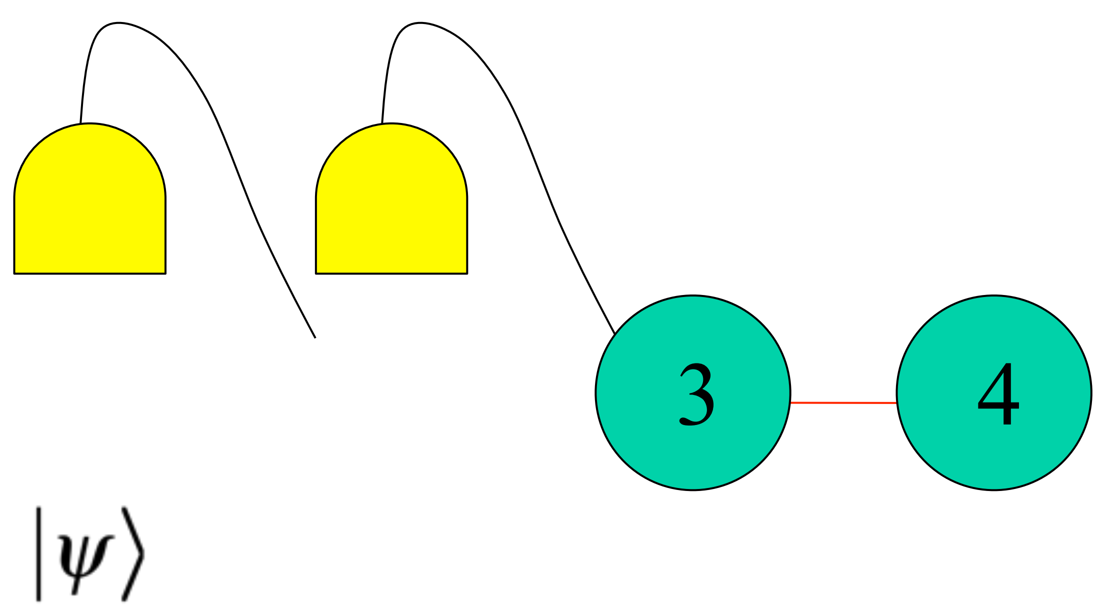
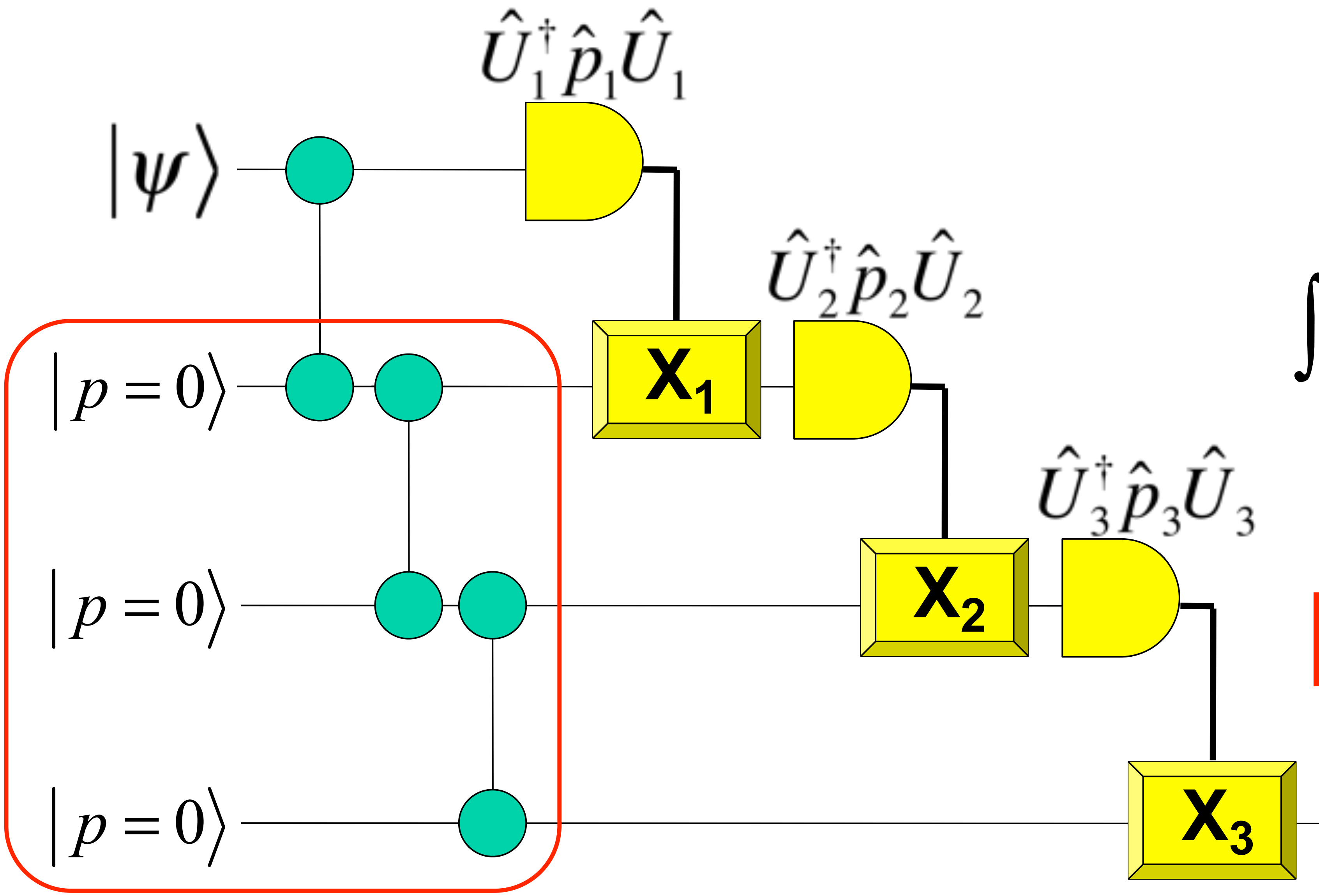
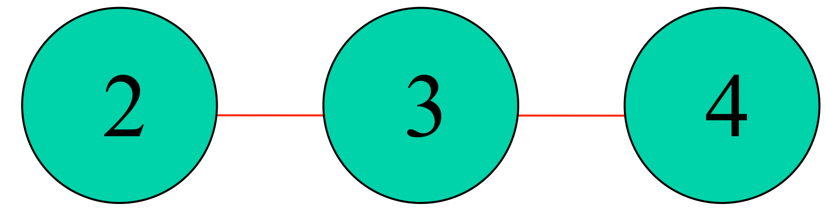


# one-way quantum computation with cluster states




**cluster state**

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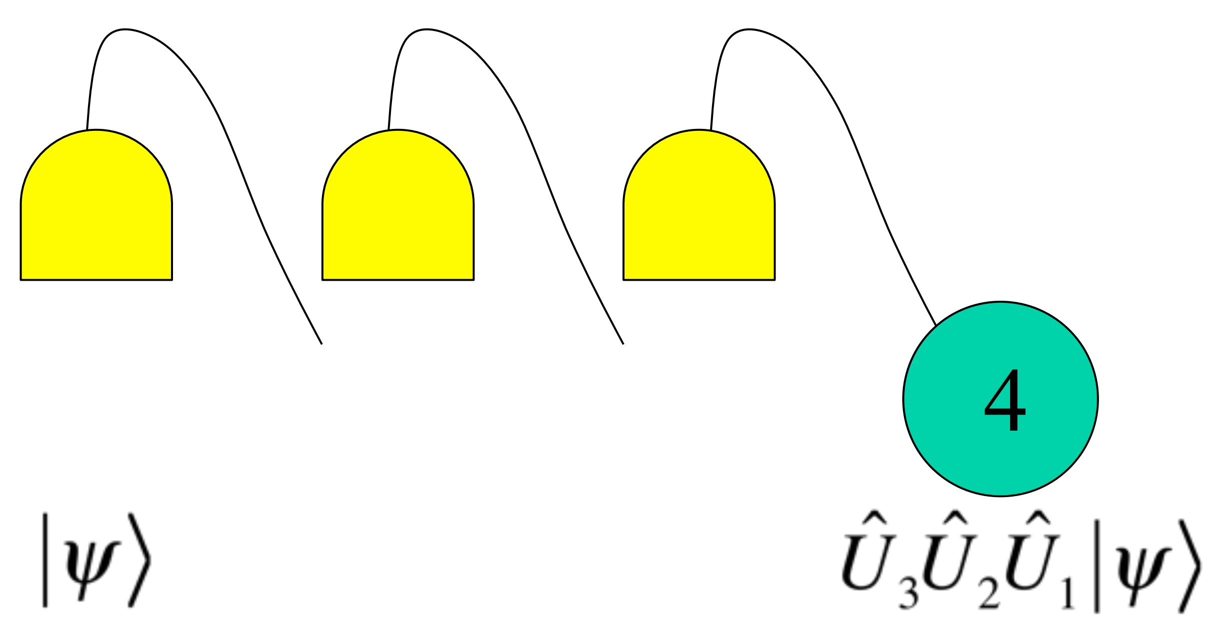
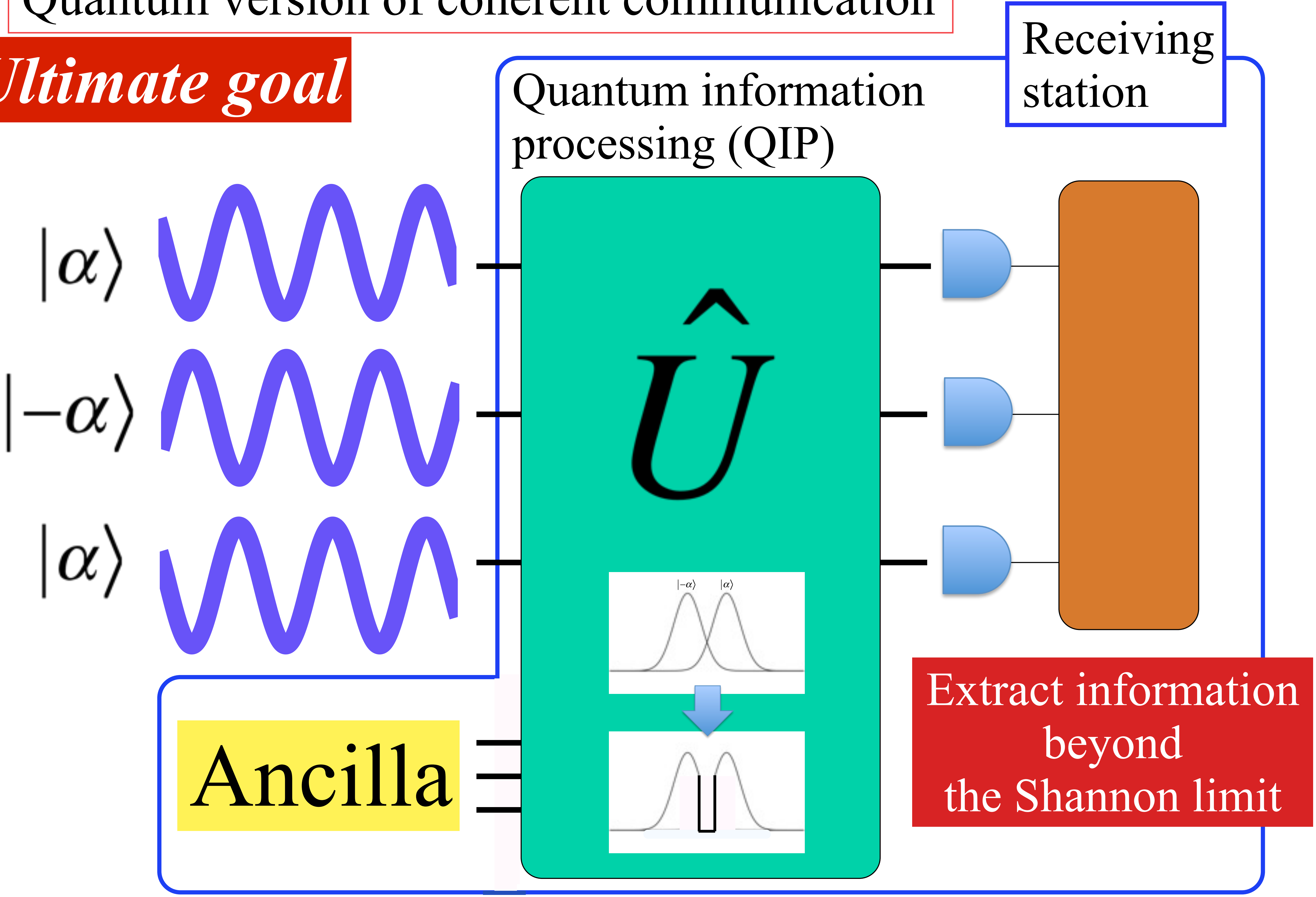
**multipartite entanglement**



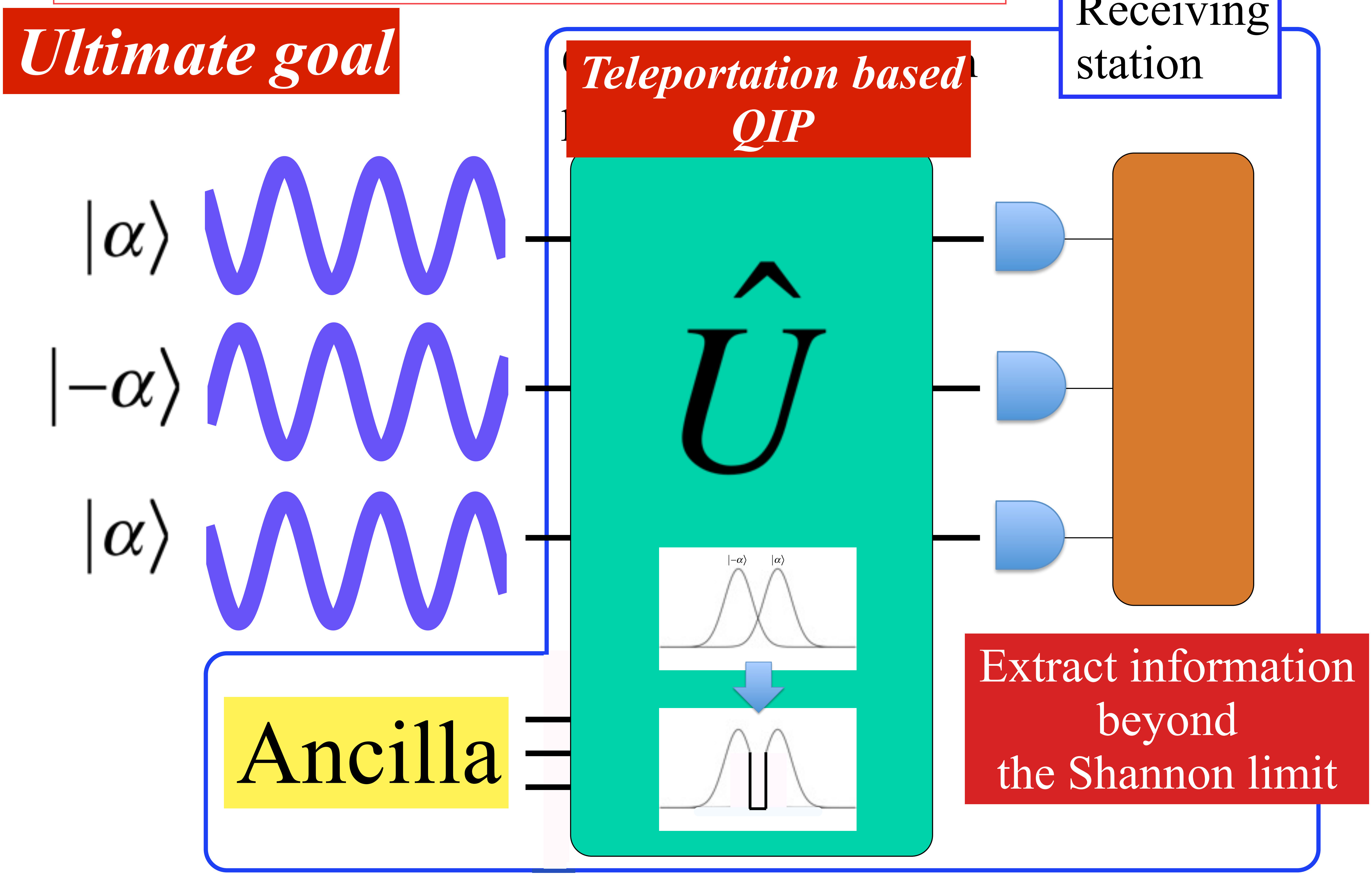
Quantum version of coherent communication

***Ultimate goal***




We need QIP for coherent states of light!!

Quantum version of coherent communication

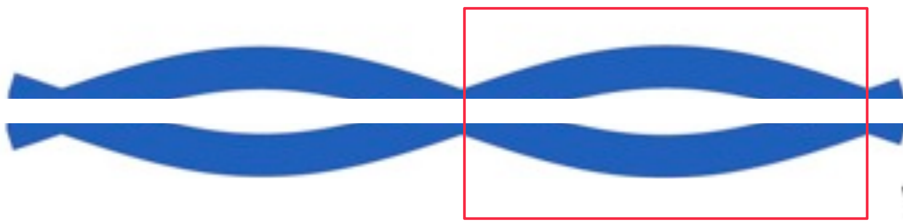



We need QIP for coherent states of light!!

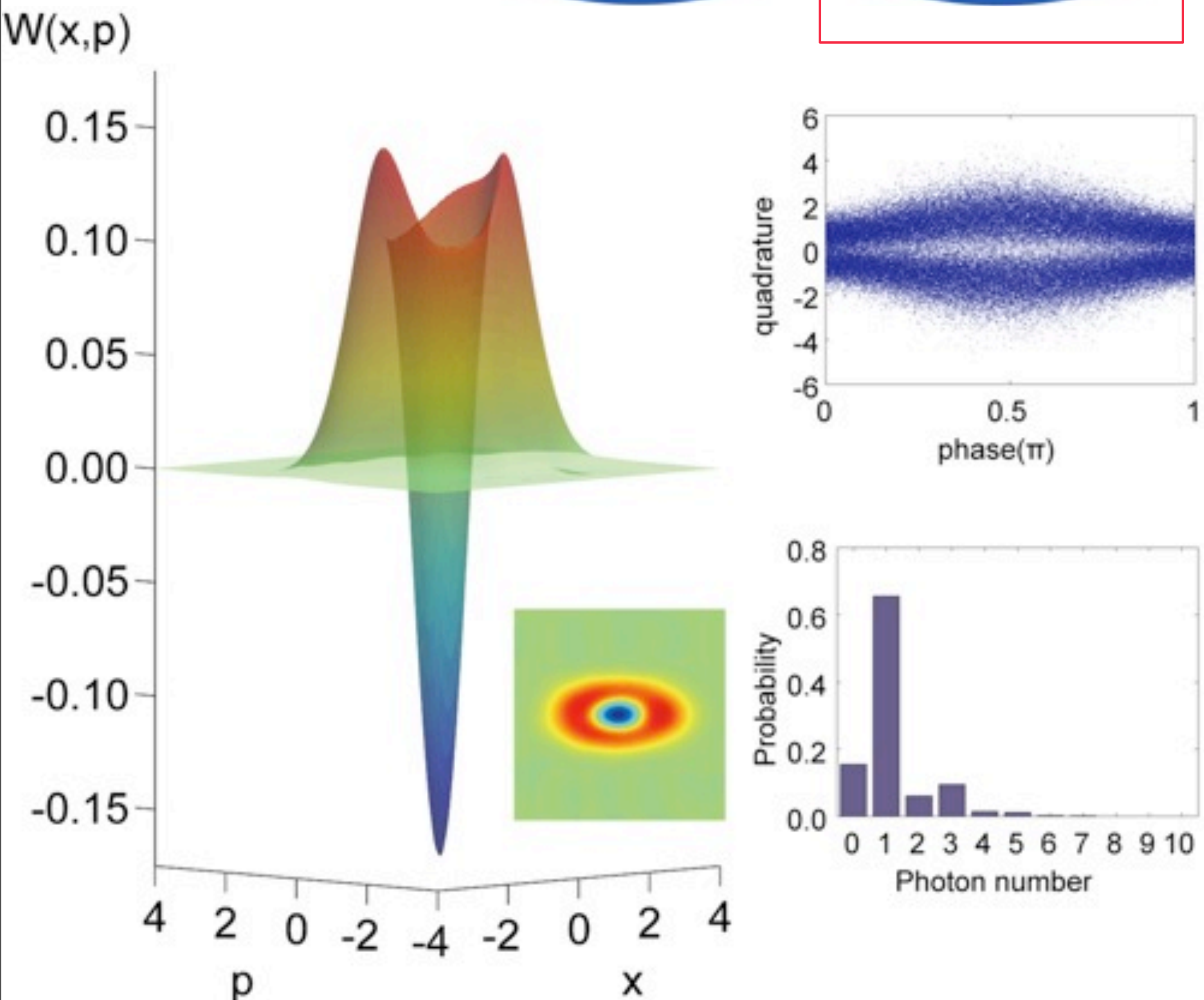
# In this talk,

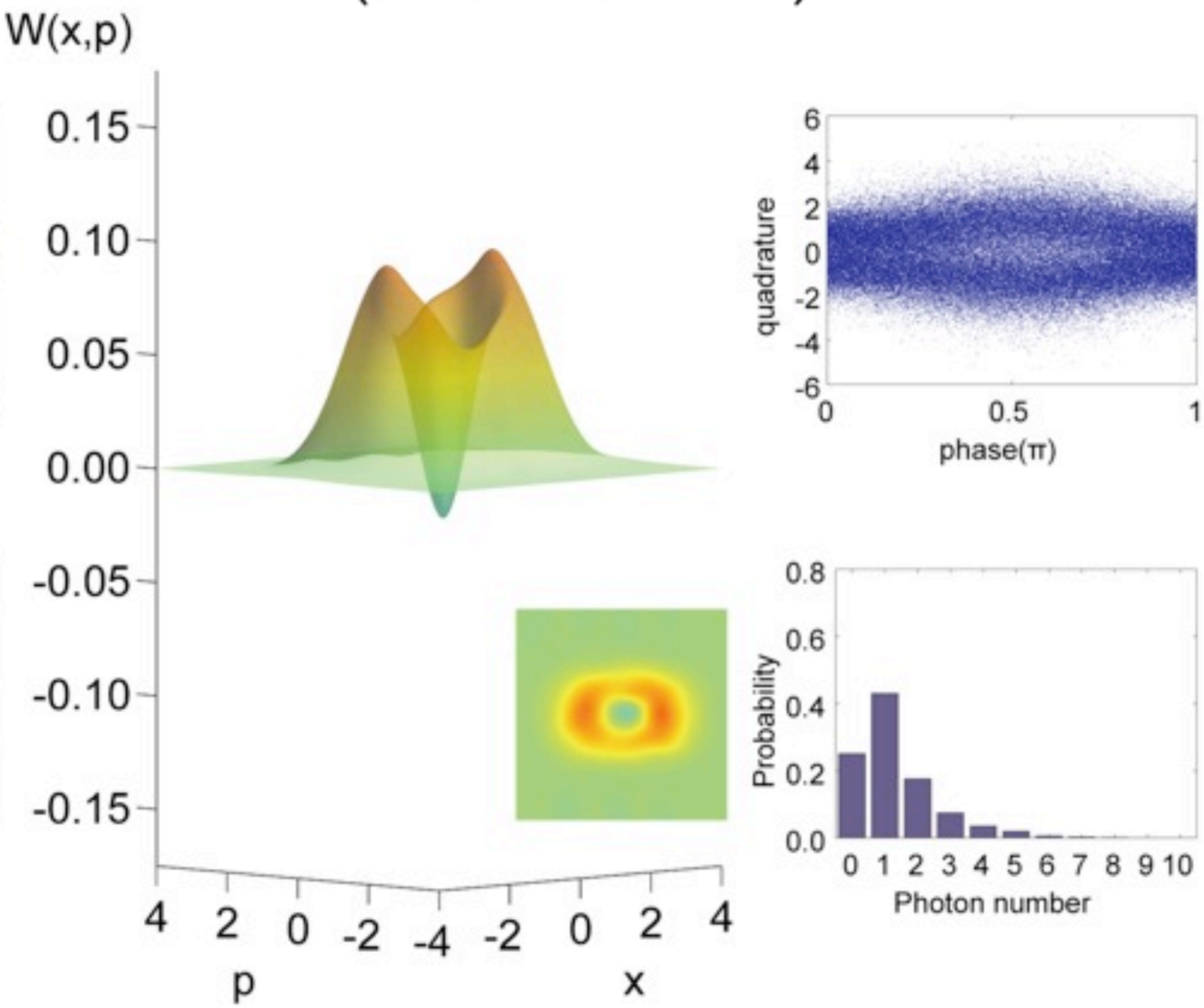
## First step of teleportation based QIP for coherent states

Teleportation of a Schrödinger cat state of light



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



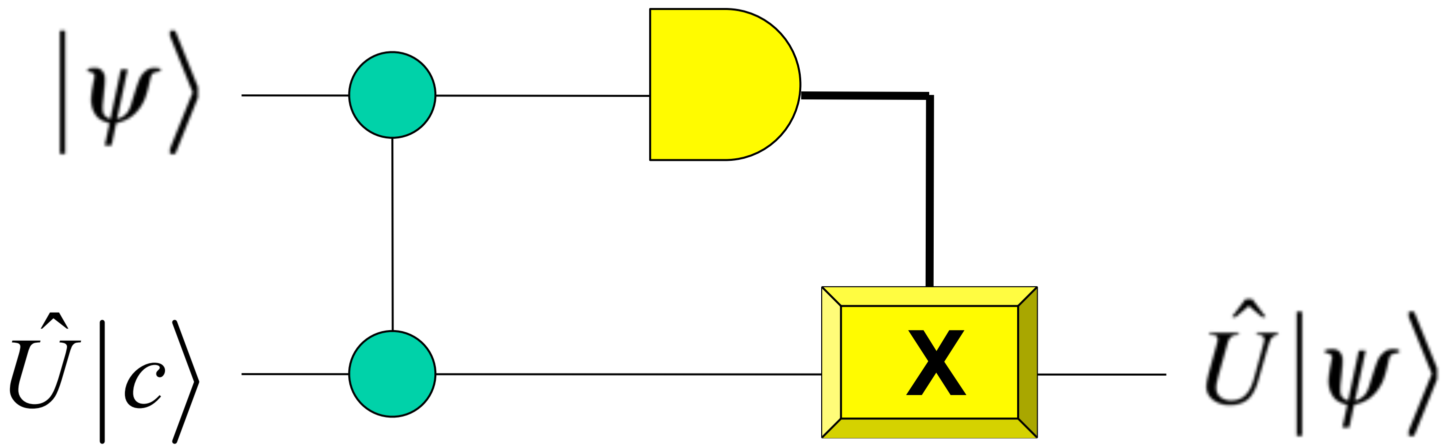



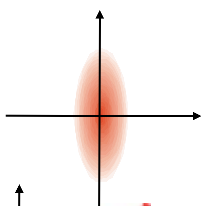

Input

Output

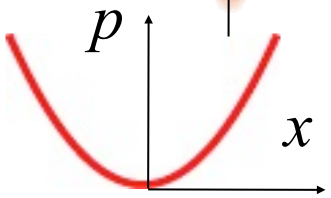
N. Lee, H. Benichi, Y. Takeno, S. Takeda, J. Webb, E. Huntington, & A. Furusawa, Science 332, 330 (2011)

## Teleportation based quantum information processing



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

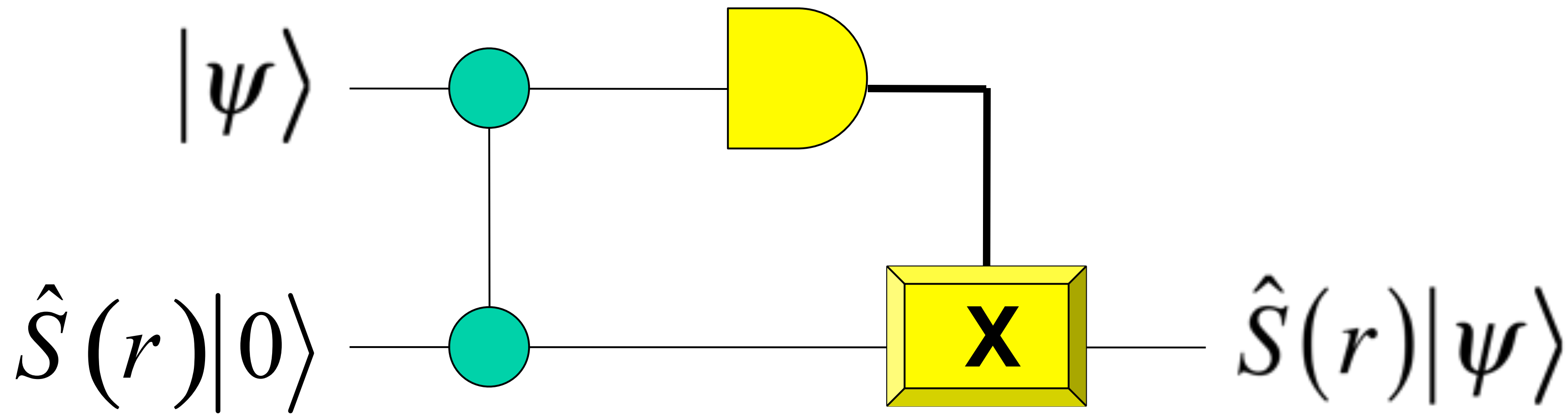


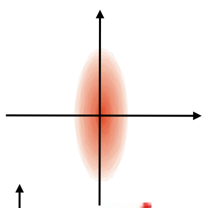

$\int dx\, e^{ikx^3}|x\rangle$ cubic phase state

**Universal squeezer**

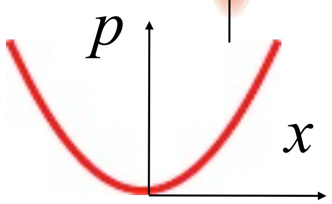
**Cubic phase gate**

# Teleportation based quantum information processing



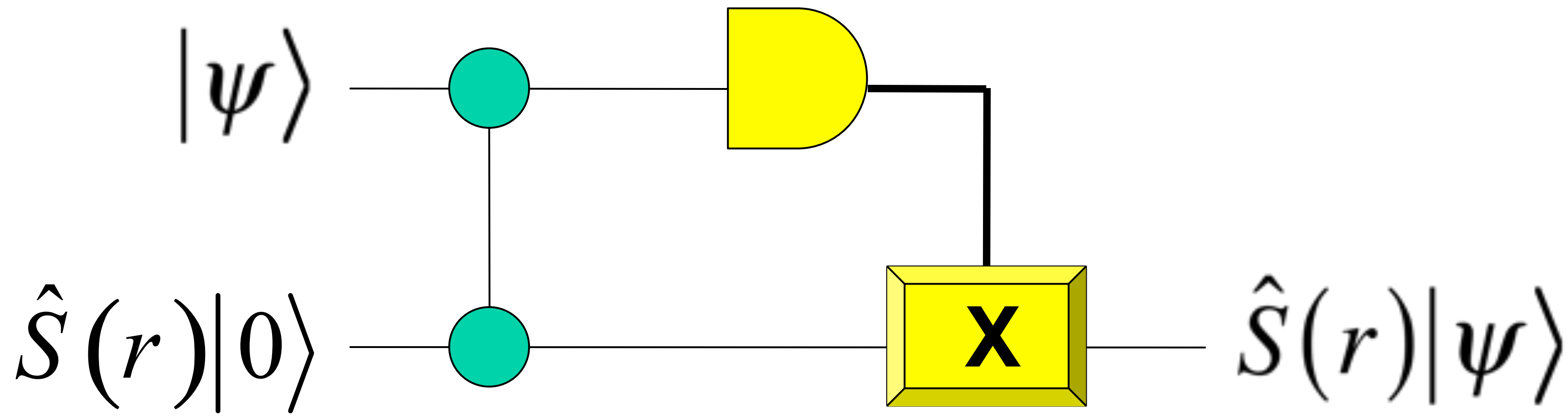



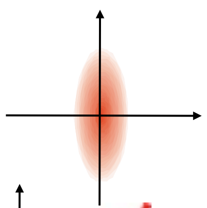
$\hat{S}(r)|0\rangle$ squeezed vacuum — **Universal squeezer**



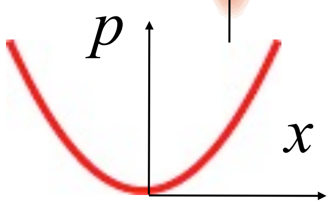

$\int dx\, e^{ikx^3}|x\rangle$ cubic phase state — **Cubic phase gate**

# Teleportation based quantum information processing

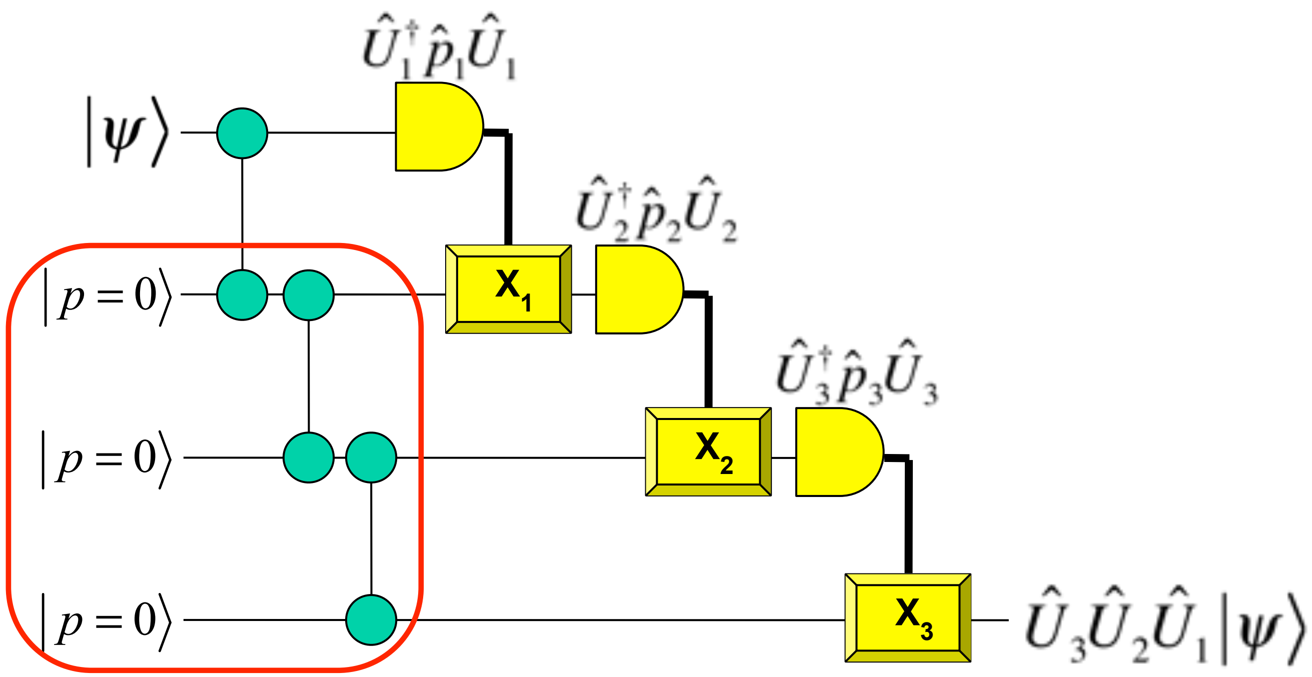


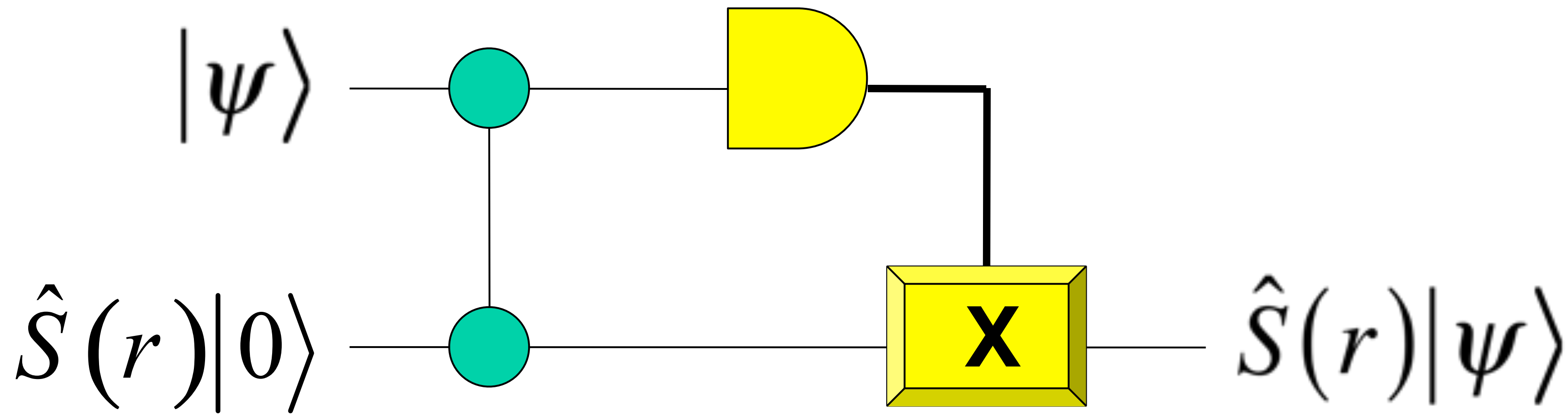
$\hat{S}(r)|0\rangle$ squeezed vacuum — Universal squeezer

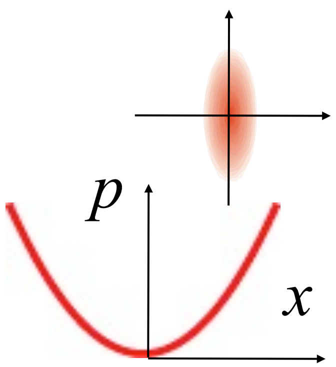



$\int dx\, e^{ikx^3}|x\rangle$ cubic phase state — Cubic phase gate



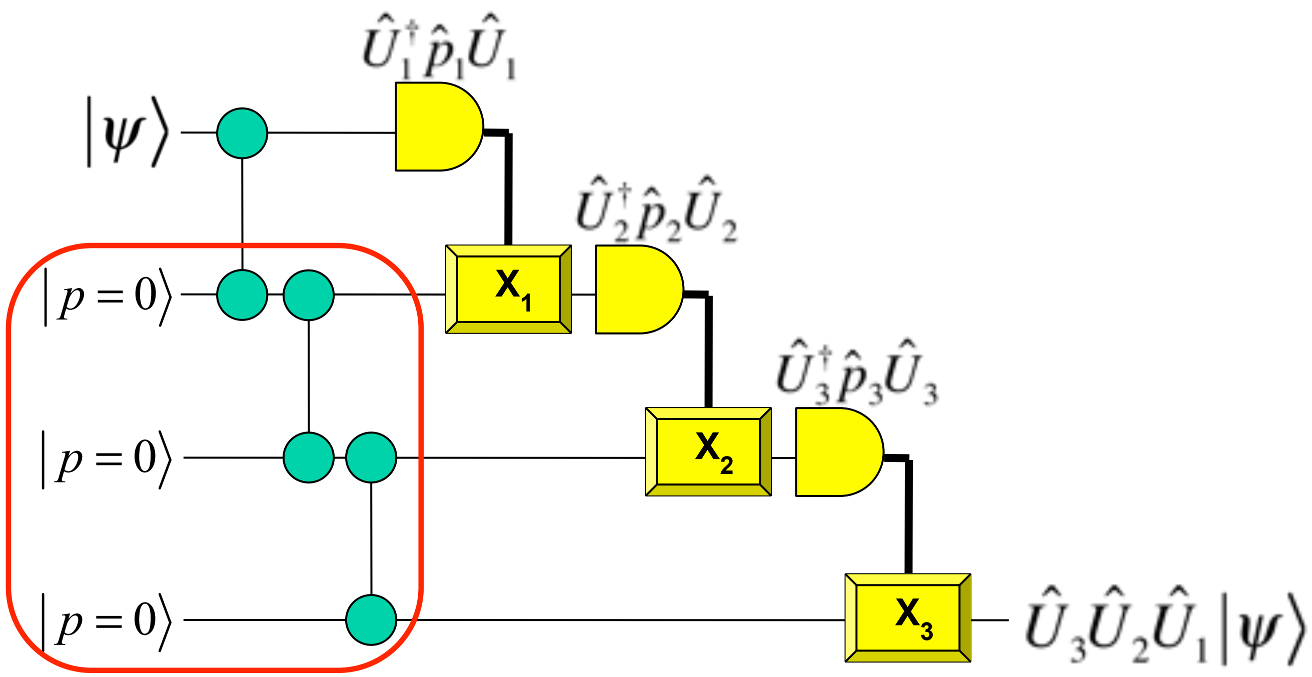
# Teleportation based quantum information processing

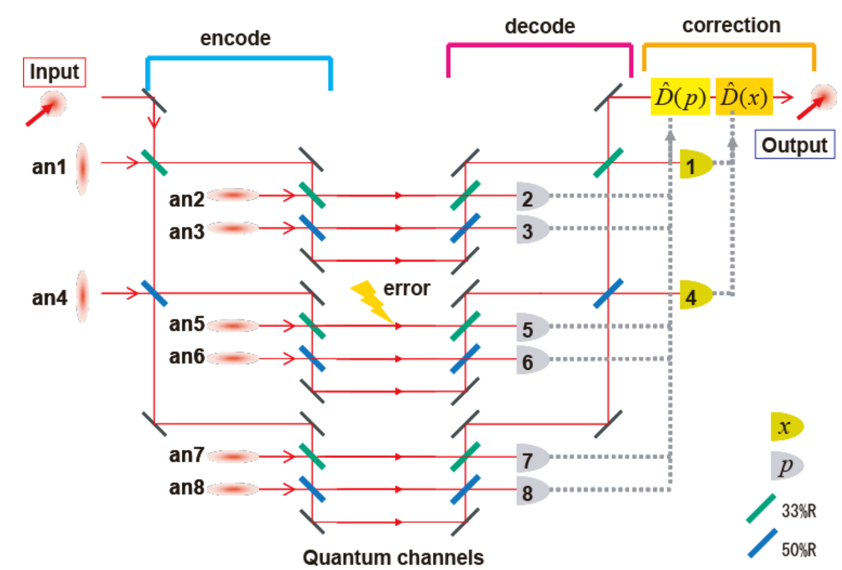


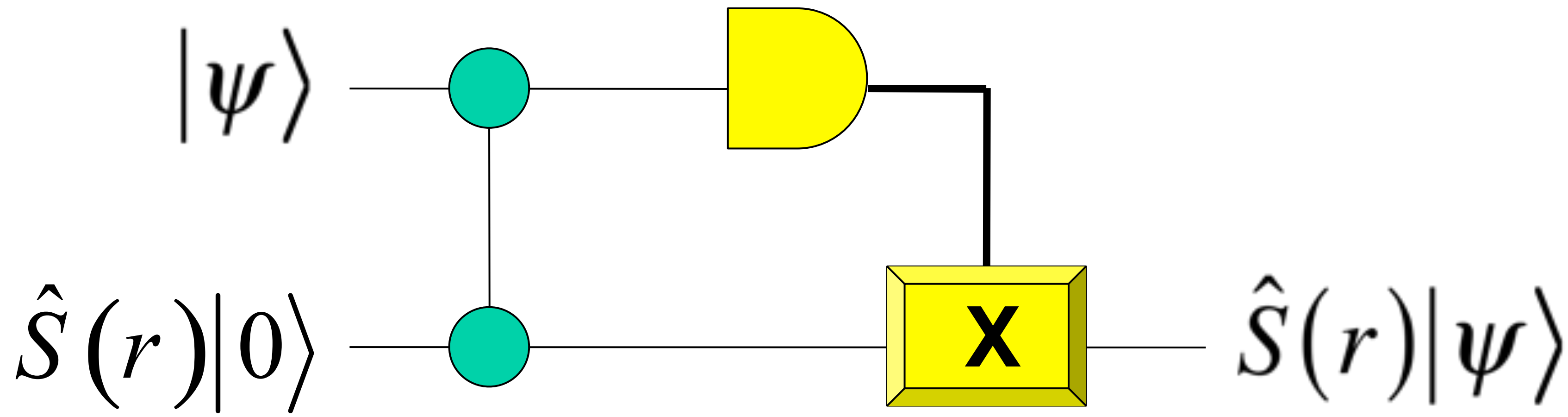

$\hat{S}(r)|0\rangle$ squeezed vacuum **Universal squeezer**

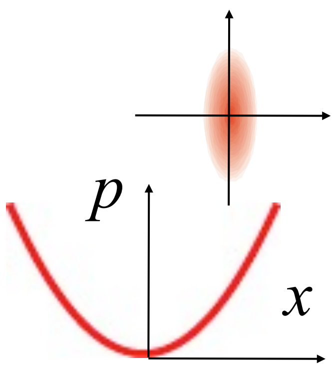
$\int dx\, e^{ikx^3}|x\rangle$ cubic phase state **Cubic phase gate**



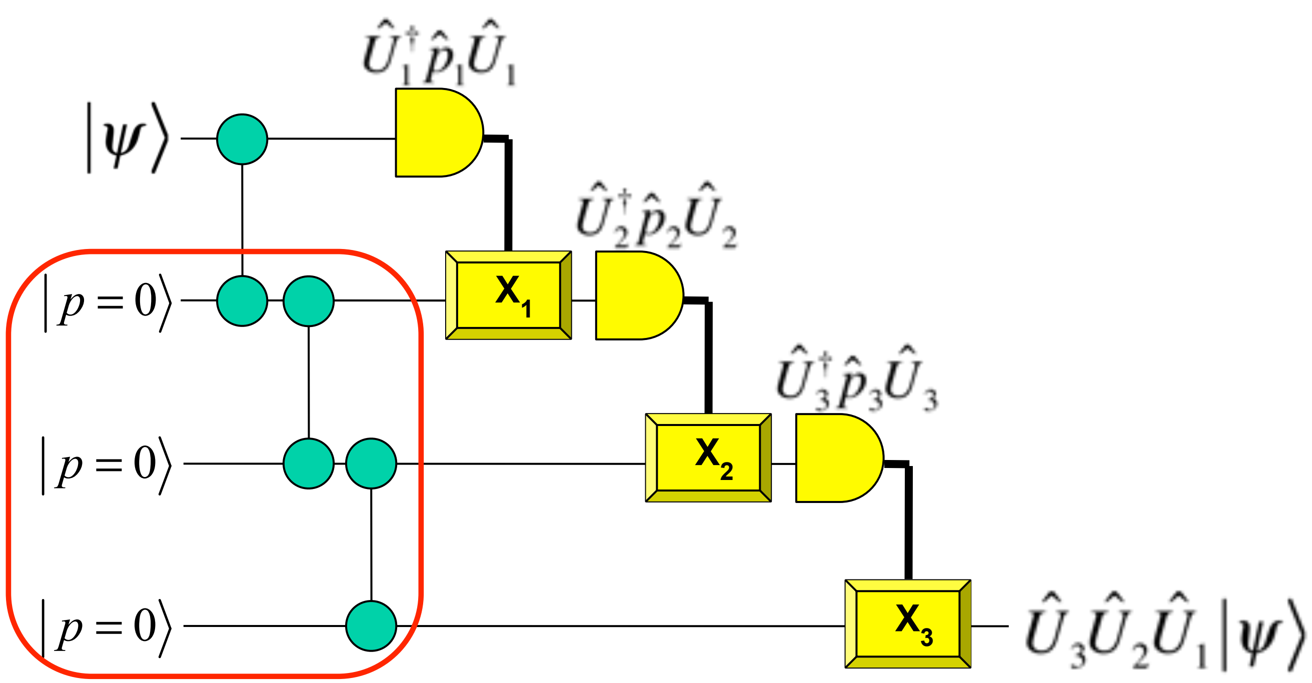
# Teleportation based quantum information processing

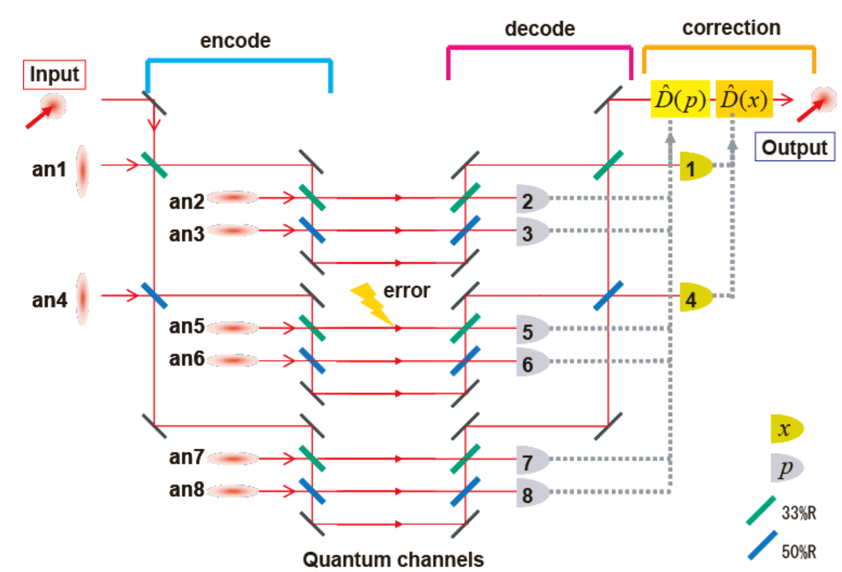


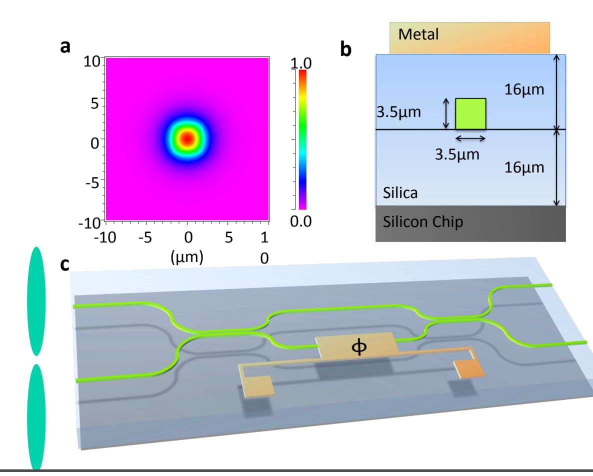




$\hat{S}(r)|0\rangle$ squeezed vacuum — Universal squeezer

$\int dx\, e^{ikx^3}|x\rangle$ cubic phase state — Cubic phase gate

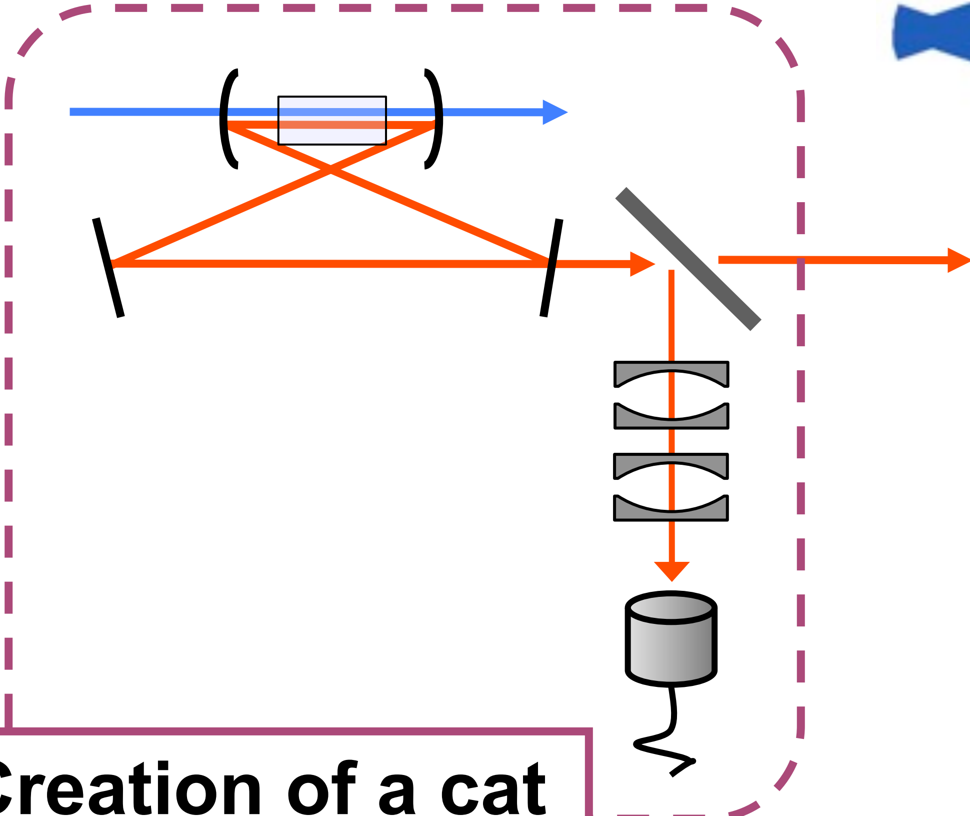


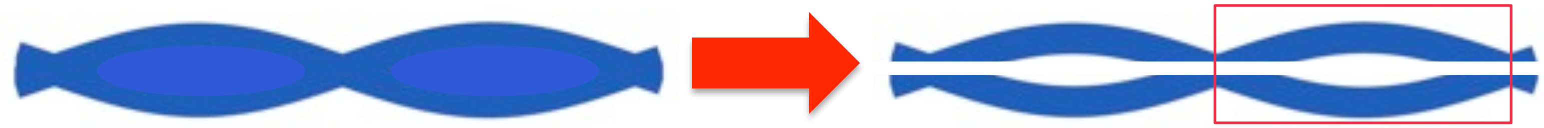



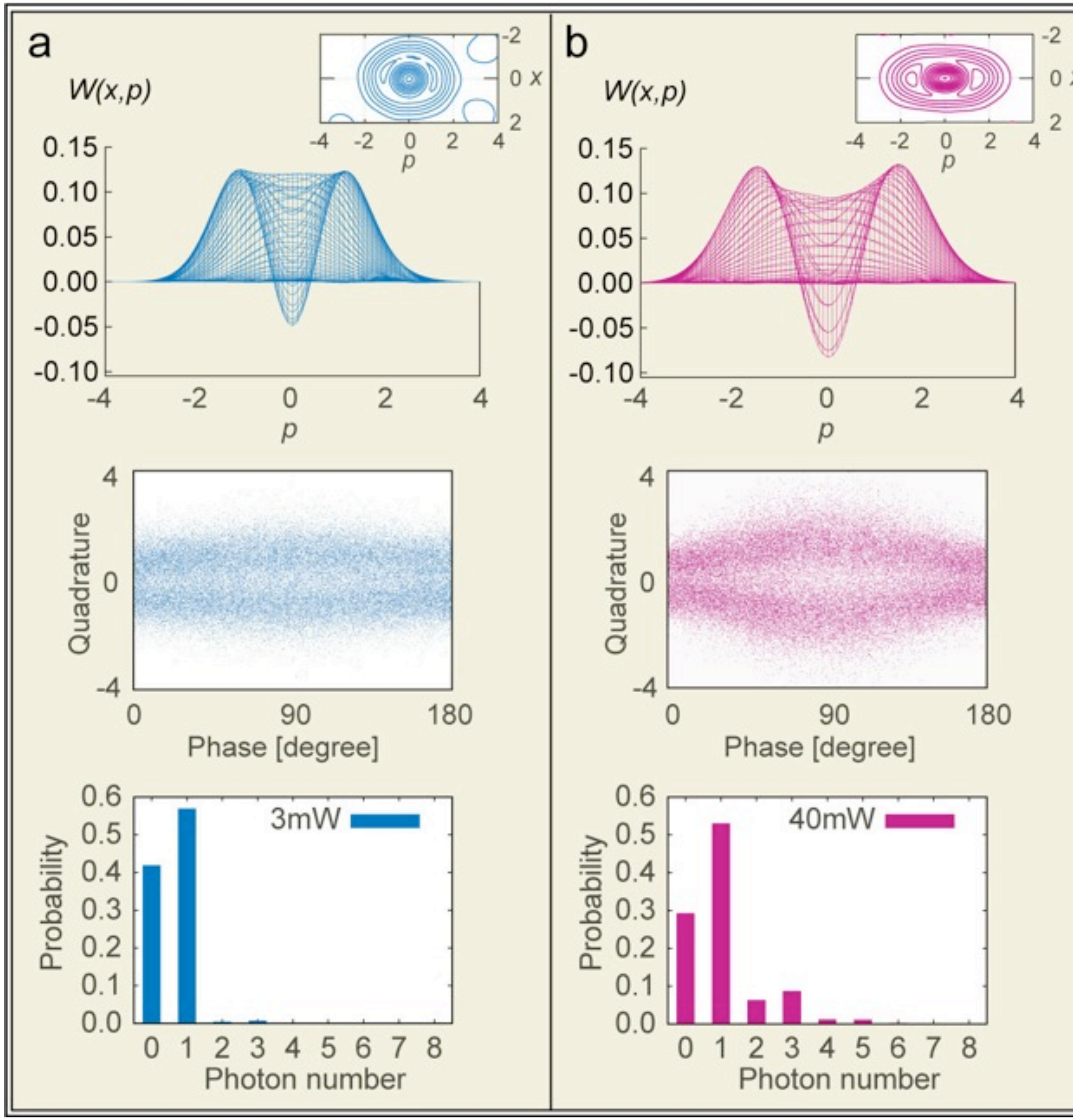
# Teleportation of
# a Schrödinger cat state of light

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



**Creation of a cat**






**Defined in time-domain**

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

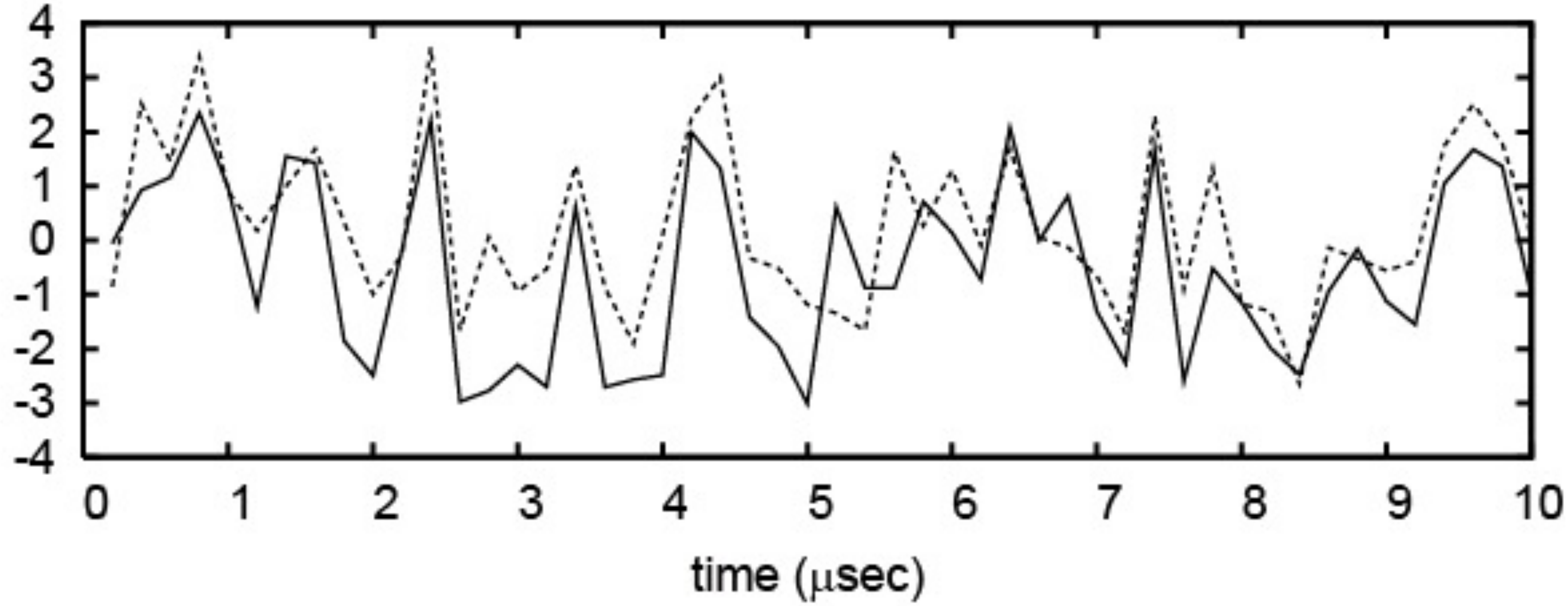
$$|\alpha\rangle - |-\alpha\rangle = e^{-\frac{|\alpha|^2}{2}} \sum_{n=0}^{\infty} \frac{\alpha^{2n+1}}{\sqrt{(2n+1)!}} |2n+1\rangle$$

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

# Time-domain EPR correlation

Alice ——
Bob ........

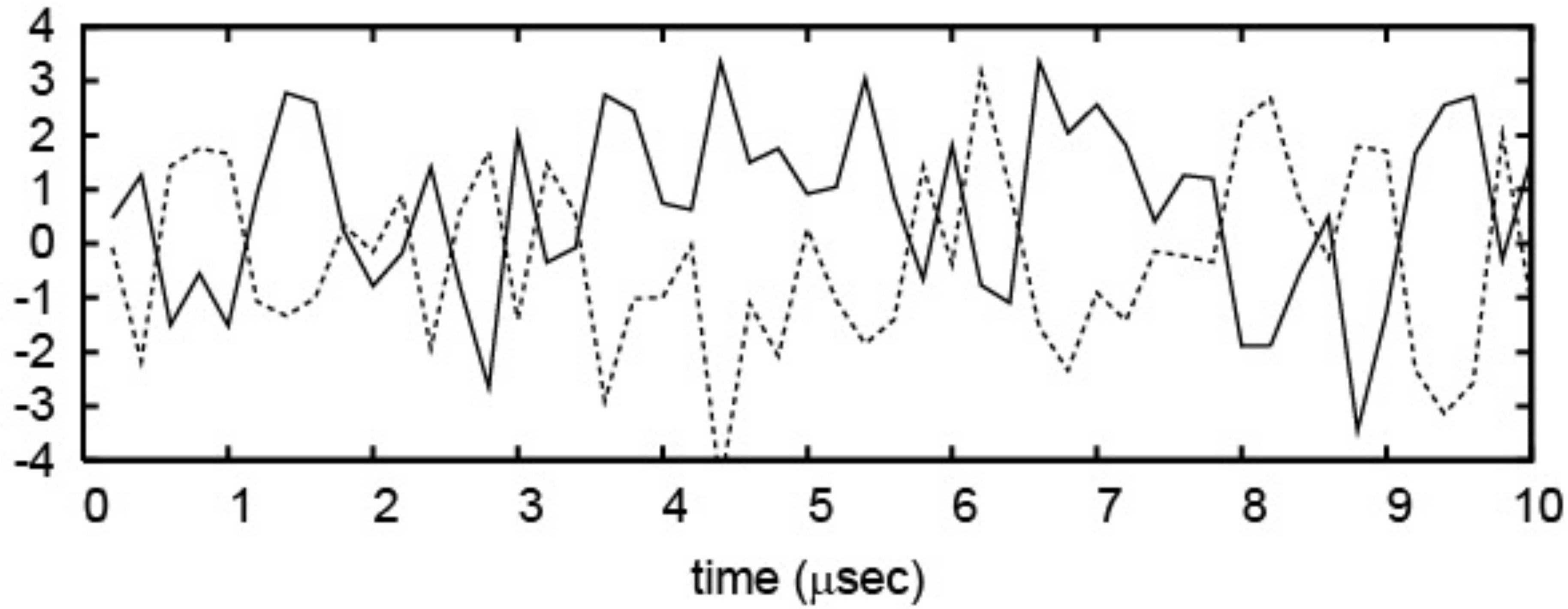
*x* measurements




**EPR**

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

*p* measurements

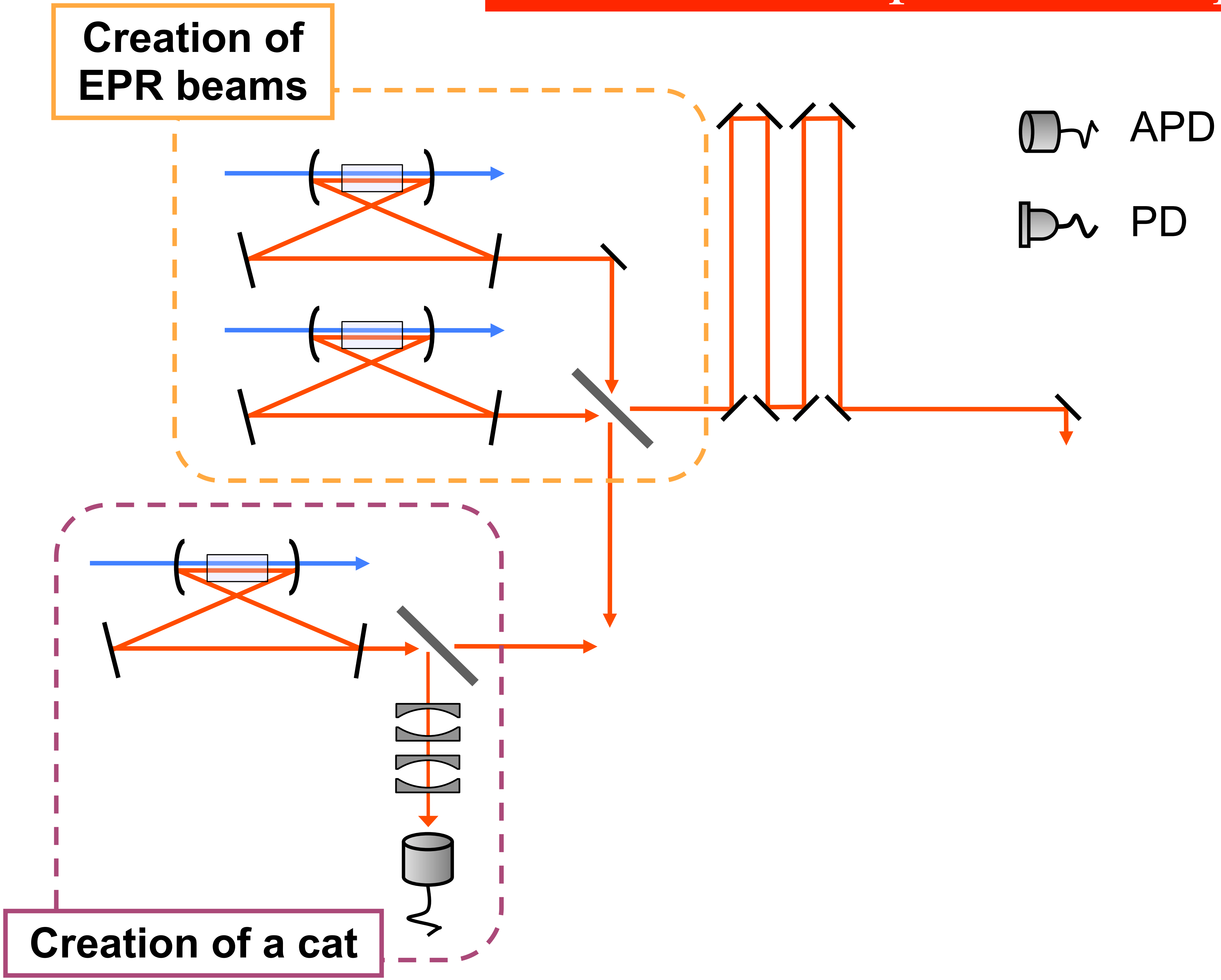



$$\text{AM signal} = \hat{x}_{\text{noise}}$$

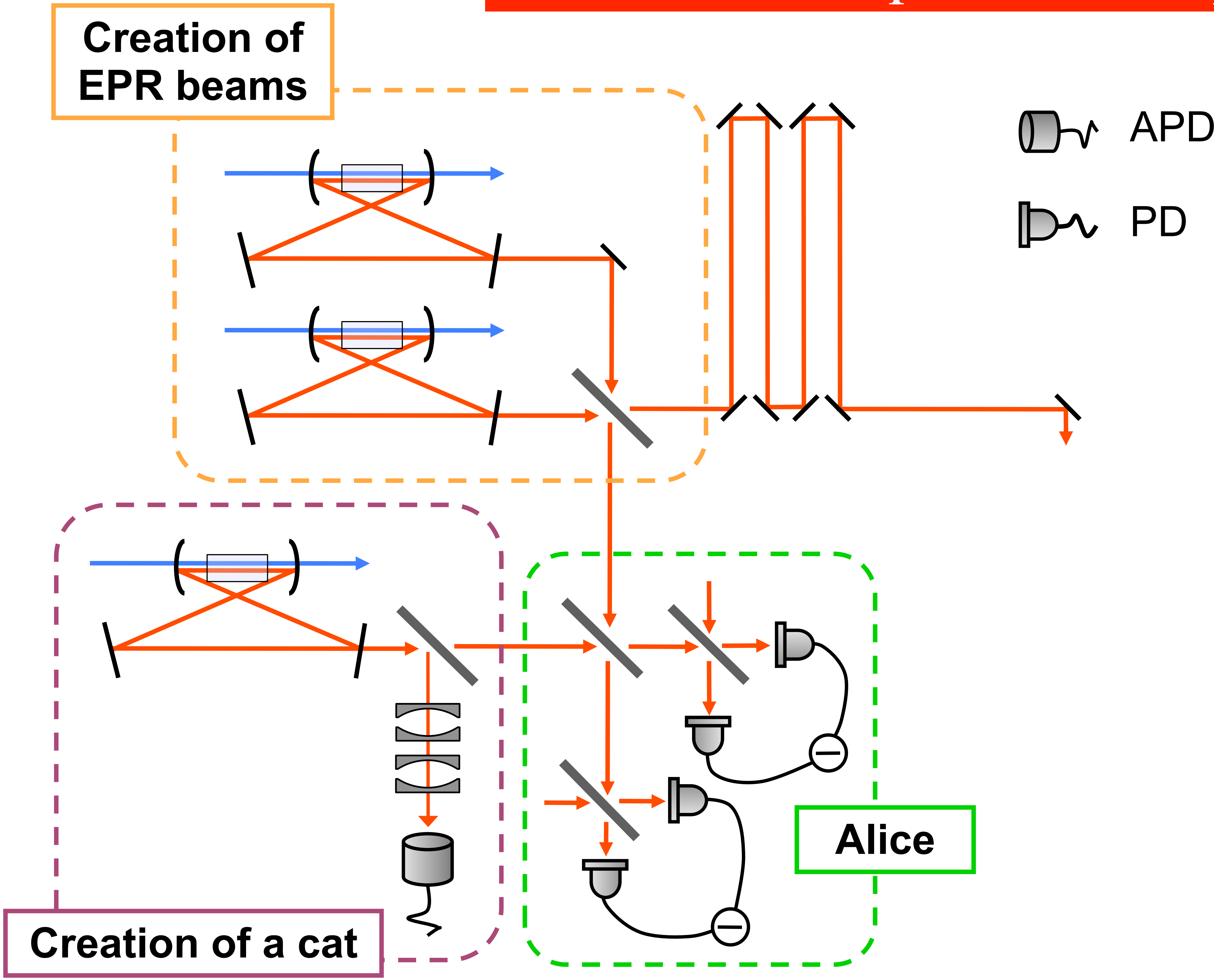
$$\text{FM signal} = \hat{p}_{\text{noise}}$$

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

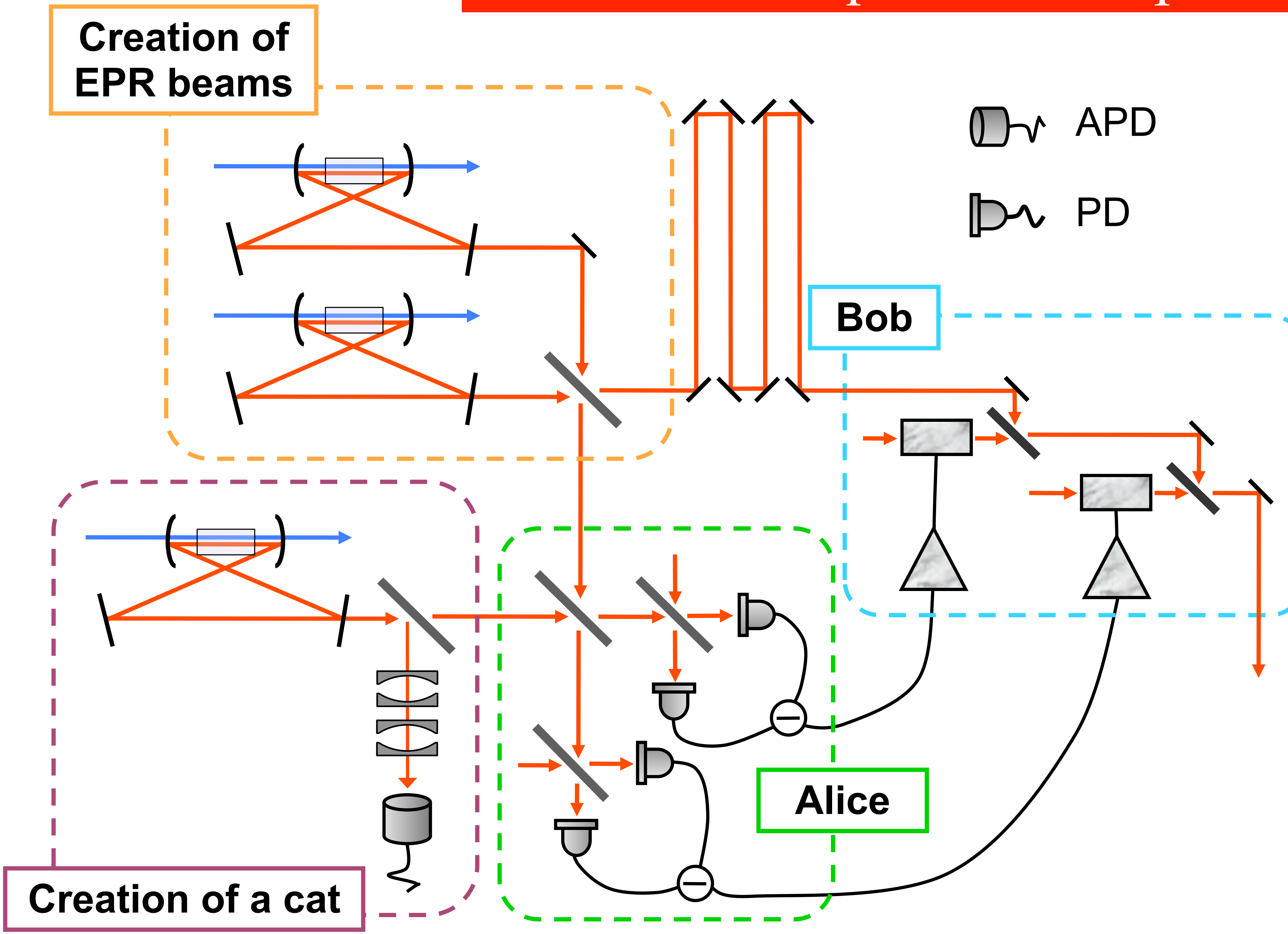
# Time-domain quantum teleportation



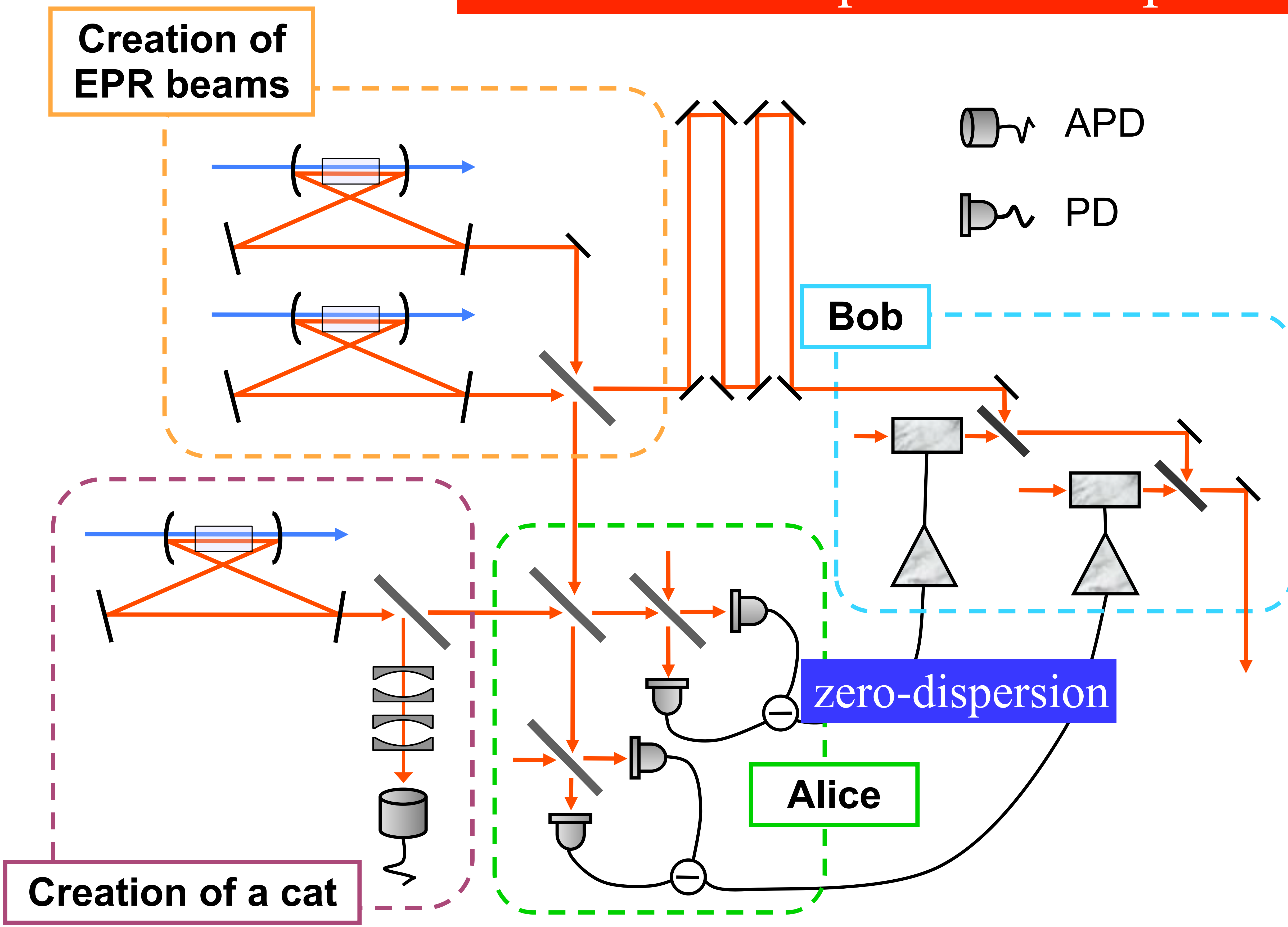
# Time-domain quantum teleportation



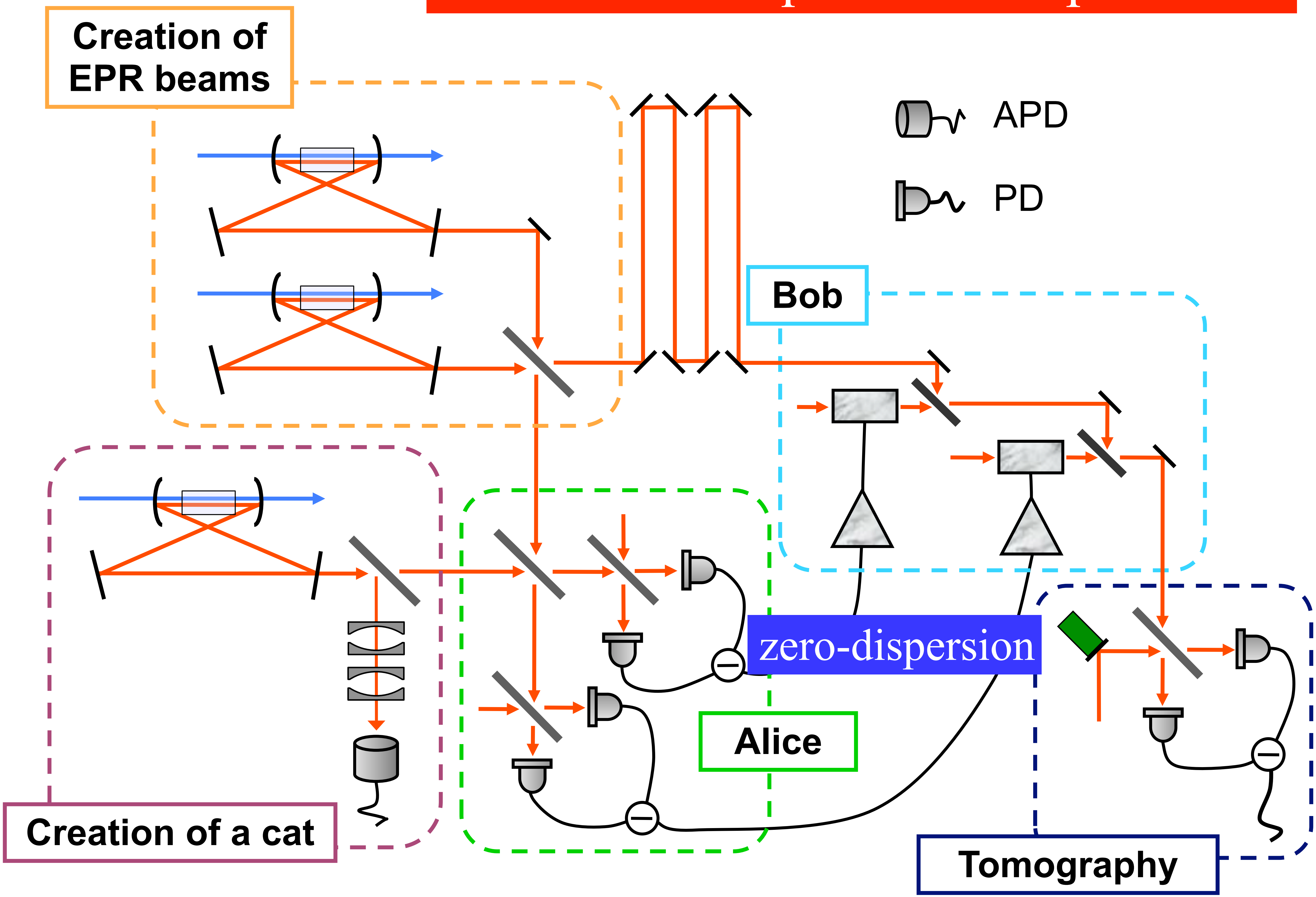
# Time-domain quantum teleportation

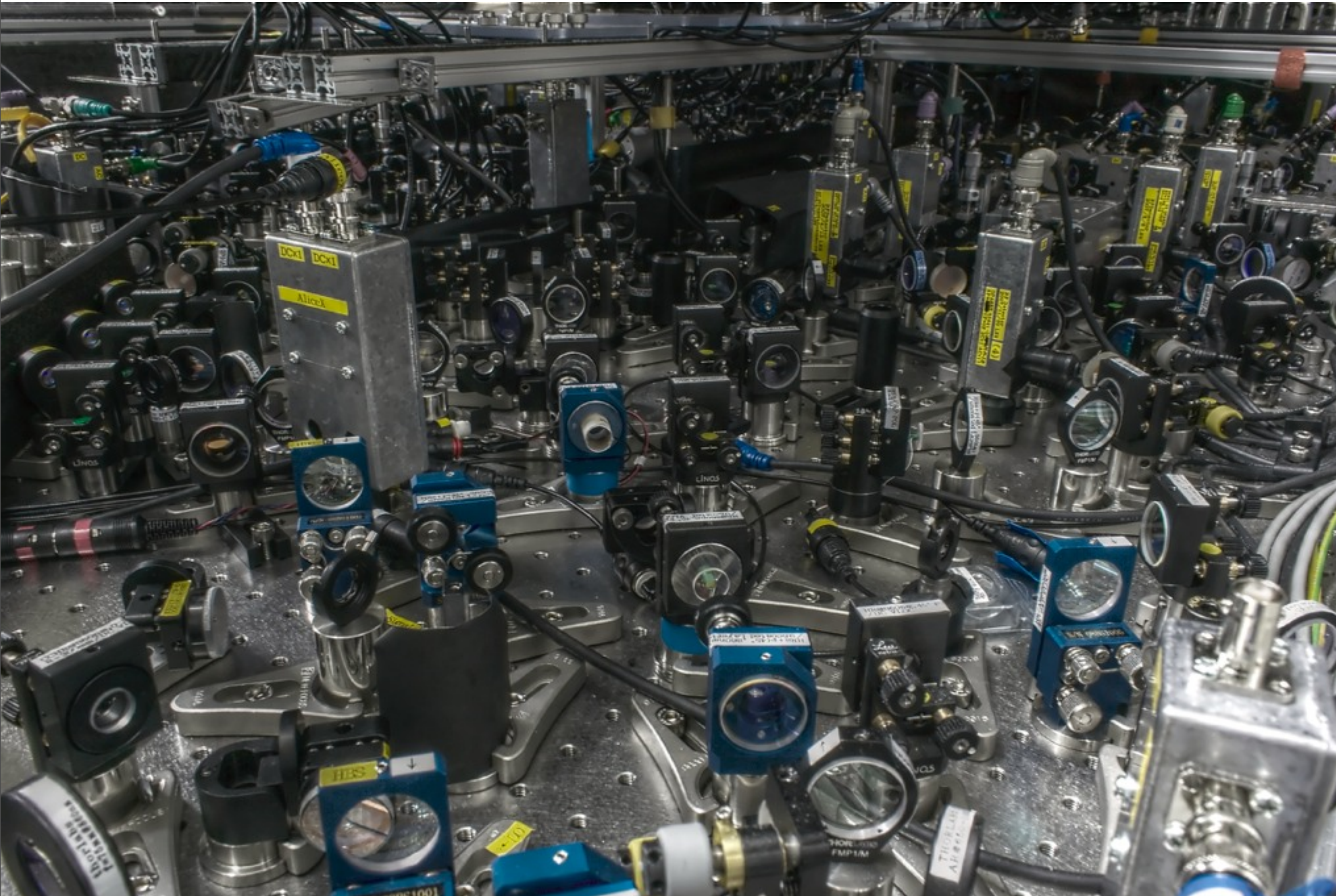


# Time-domain quantum teleportation

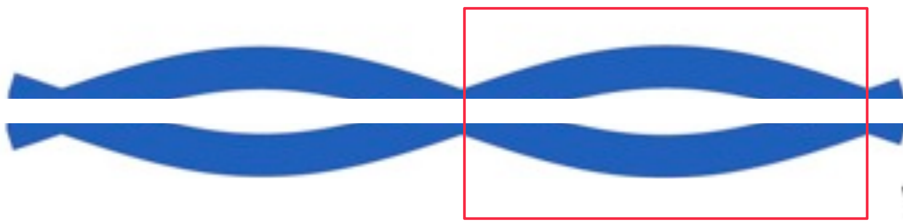


# Time-domain quantum teleportation

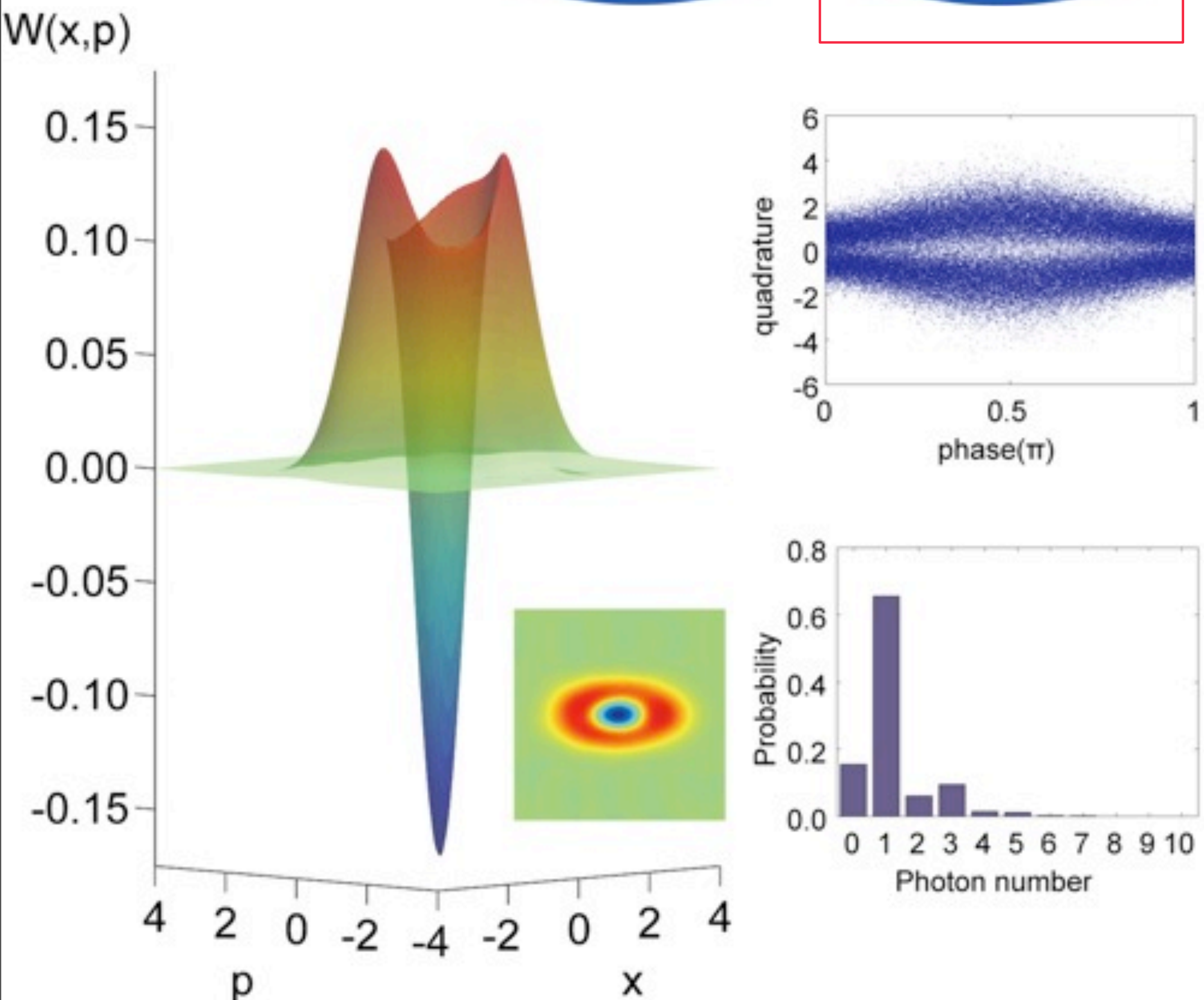



DCx1
DCx1
AliceX
LINOS
HBS

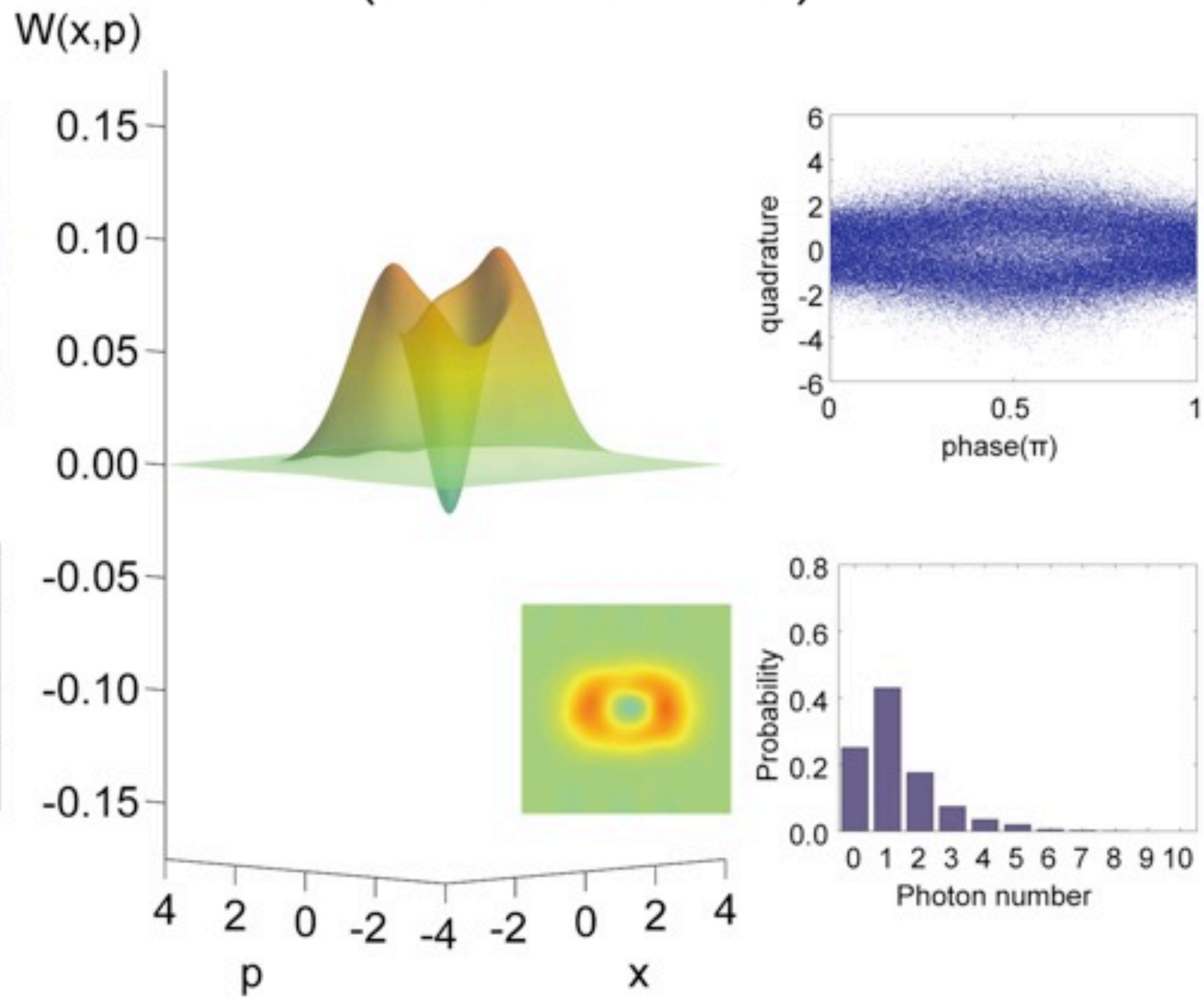
# Teleportation of a Schrödinger cat state of light



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




Input




Output

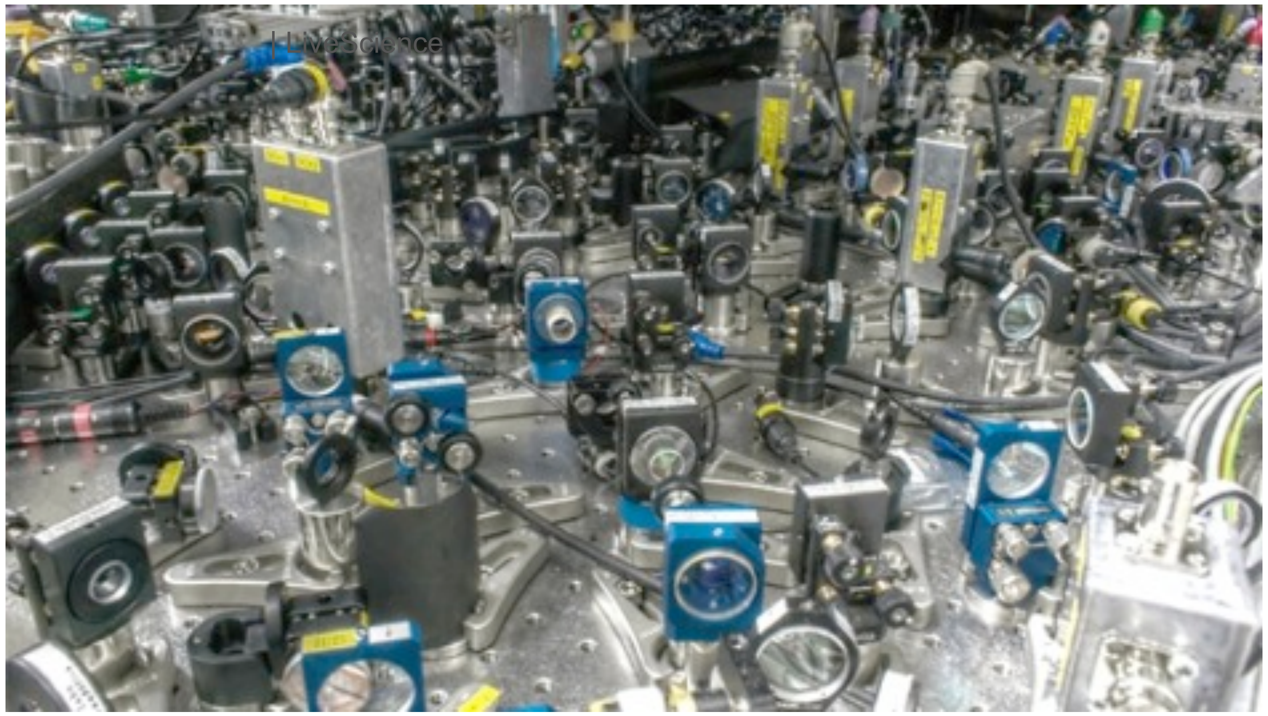
N. Lee, H. Benichi, Y. Takeno, S. Takeda, J. Webb, E. Huntington, & A. Furusawa, Science 332, 330 (2011)

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**

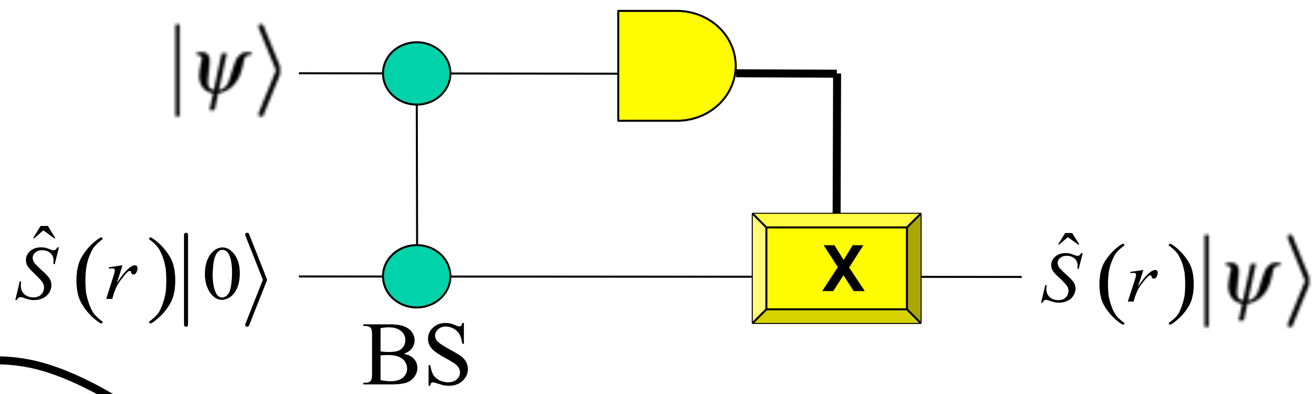
**Updated Fri Apr 15, 2011 12:13pm AEST**

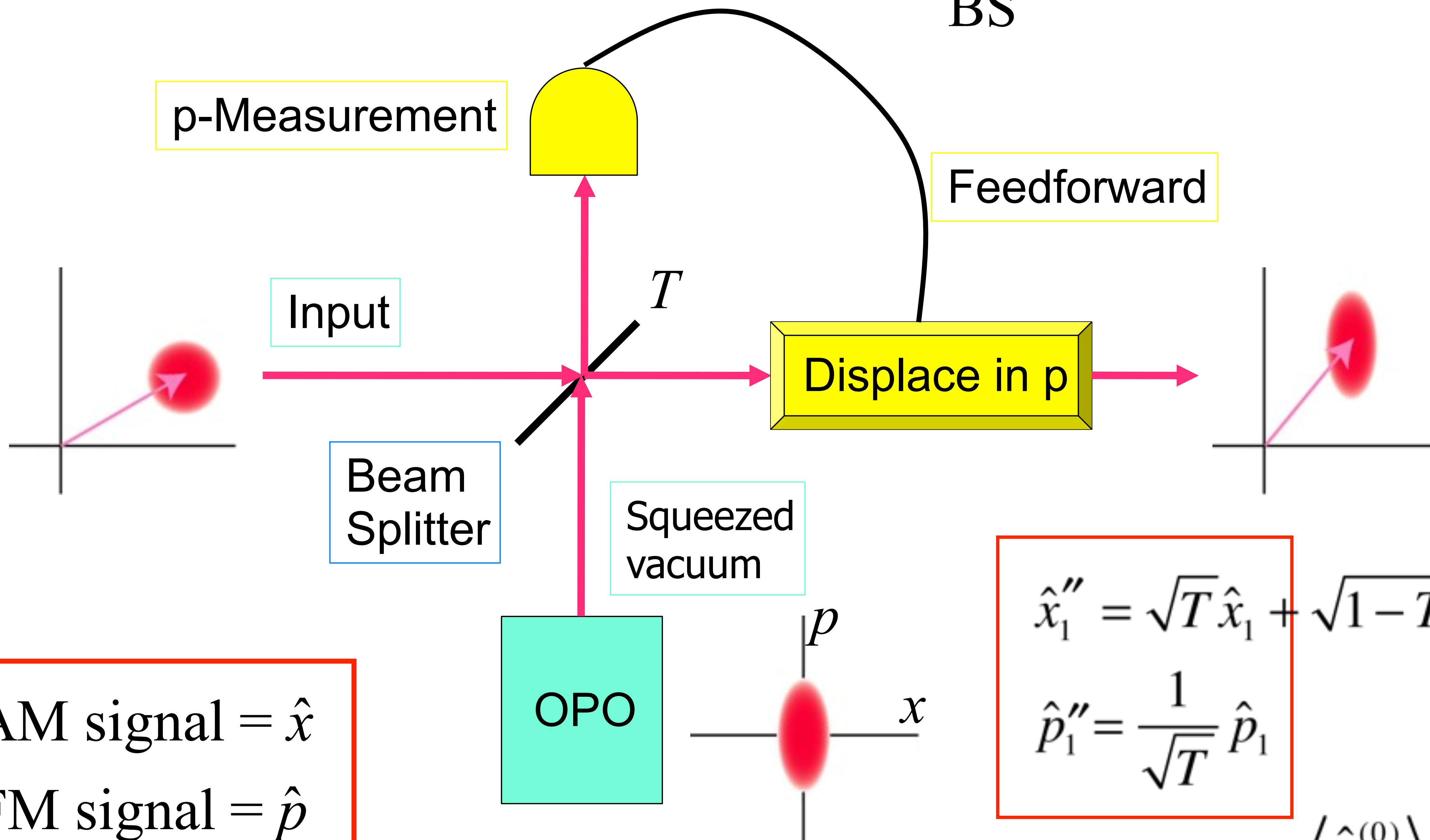
**N. Lee, H. Benichi, Y. Takeno, S. Takeda, J. Webb, E. Huntington, & A. Furusawa, Science 332, 330 (2011)**

# Teleportation based Quantum Information processing

# High-fidelity universal squeezer with measurement and feedforward

## generalized teleportation




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

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

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

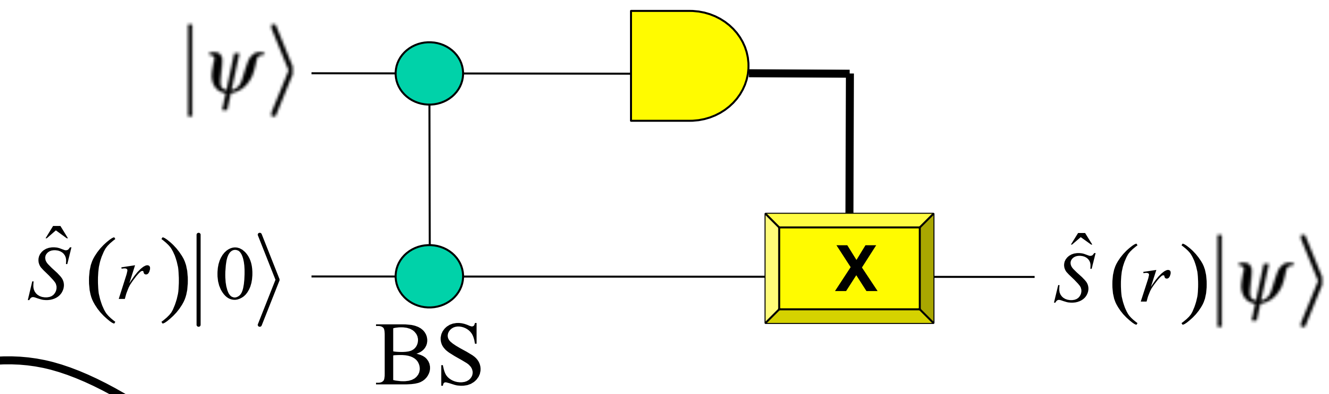
AM signal $= \hat{x}$

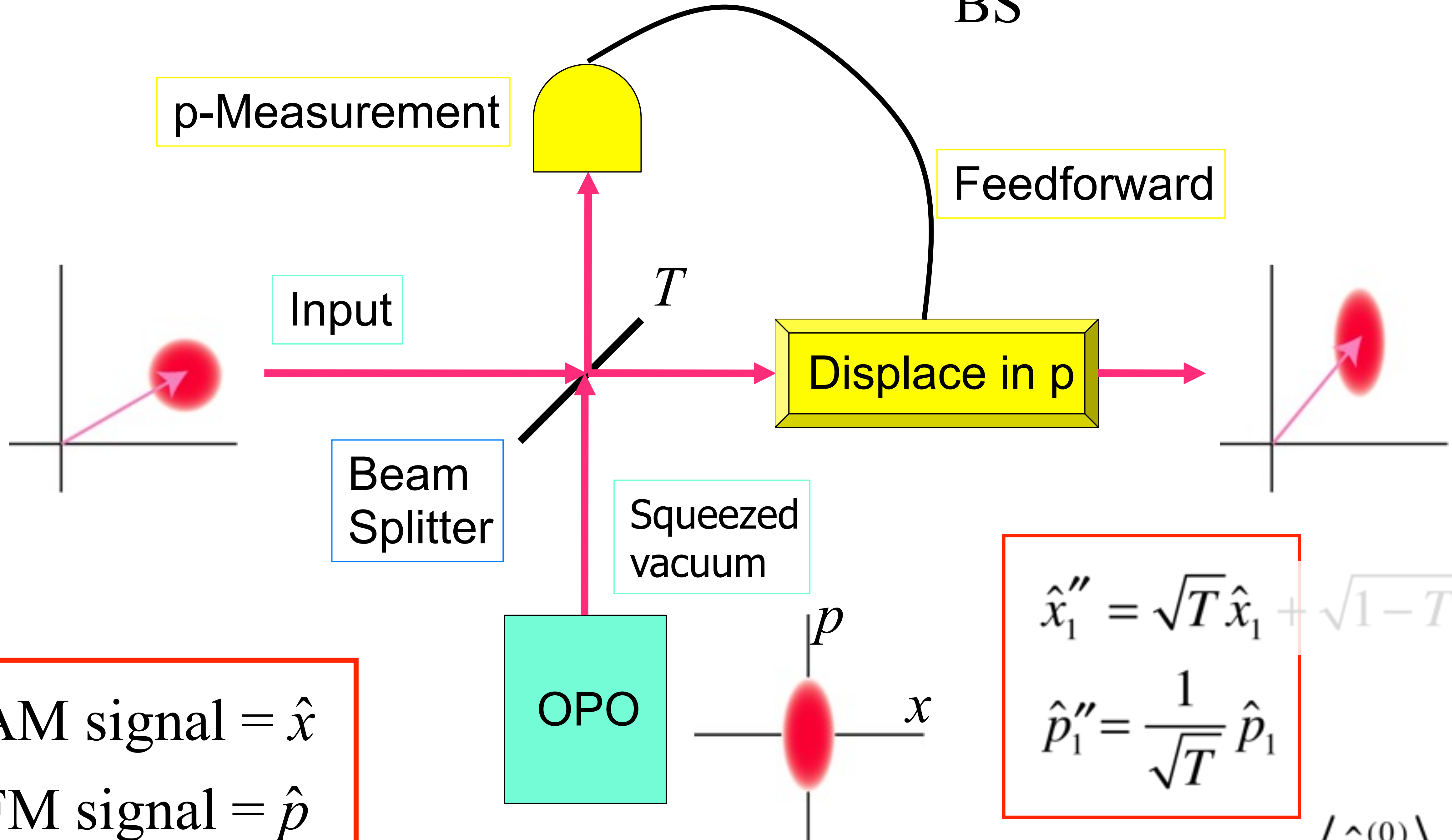
FM signal $= \hat{p}$

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

# High-fidelity universal squeezer with measurement and feedforward

**generalized teleportation**

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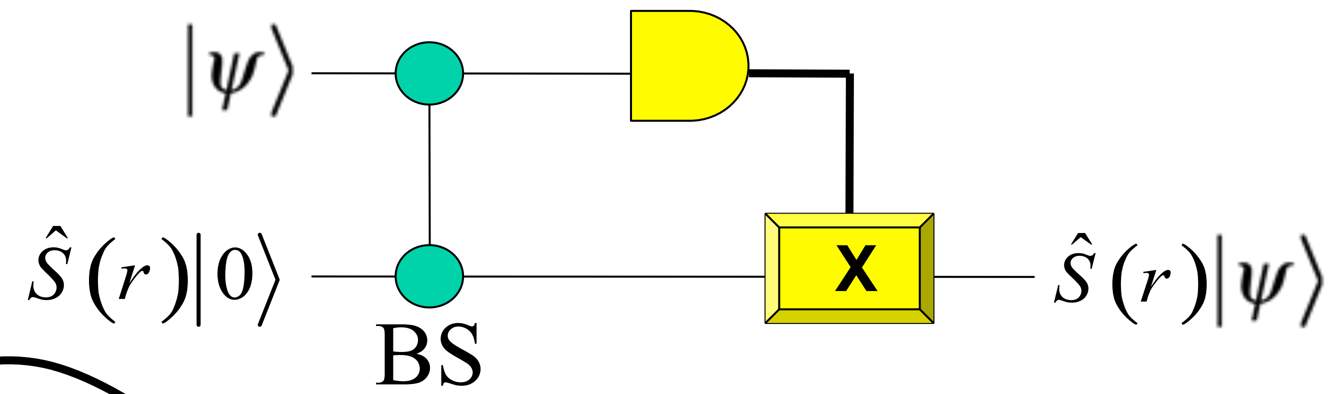


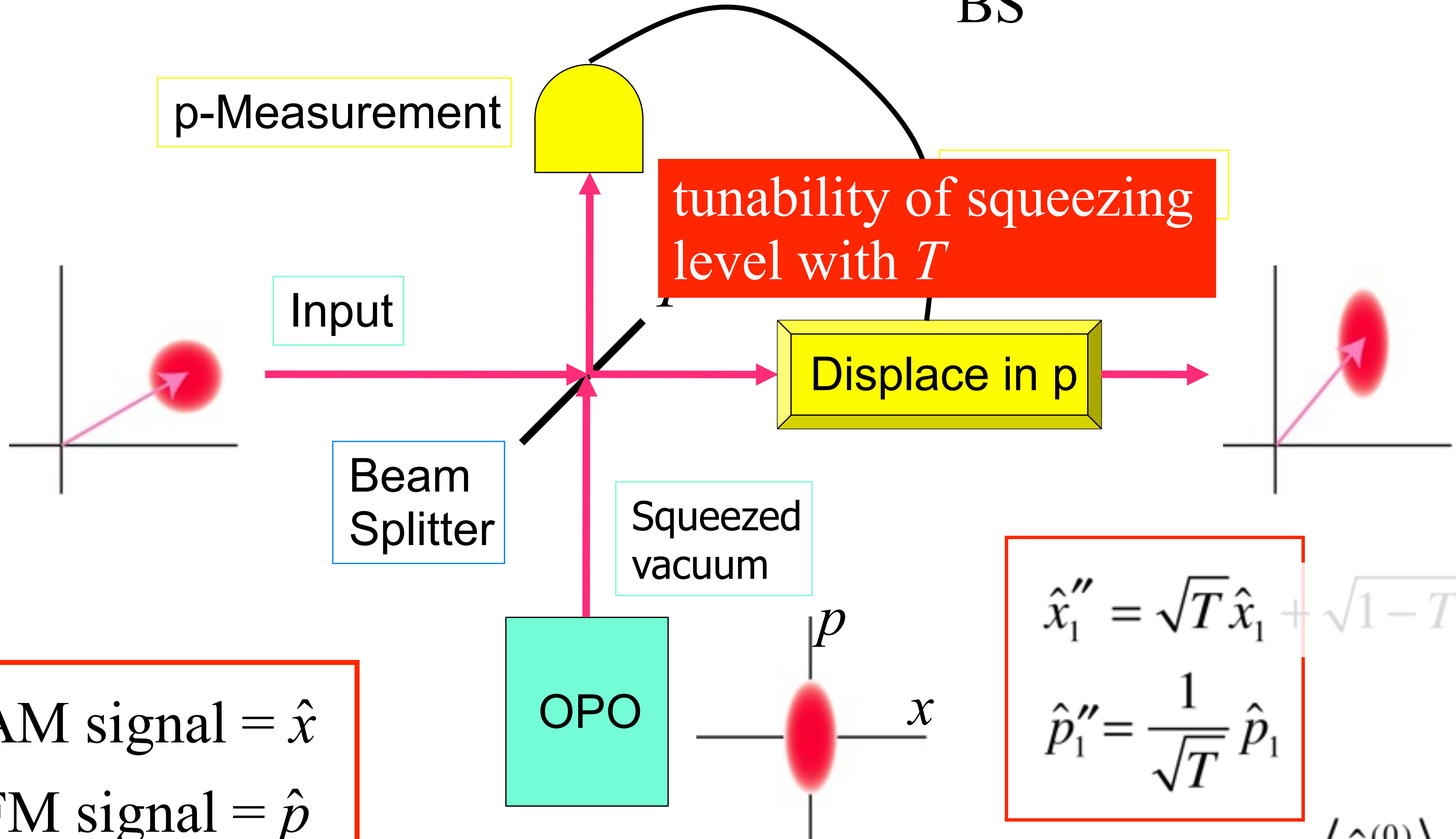


tunability of squeezing level with $T$

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

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

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AM signal $= \hat{x}$

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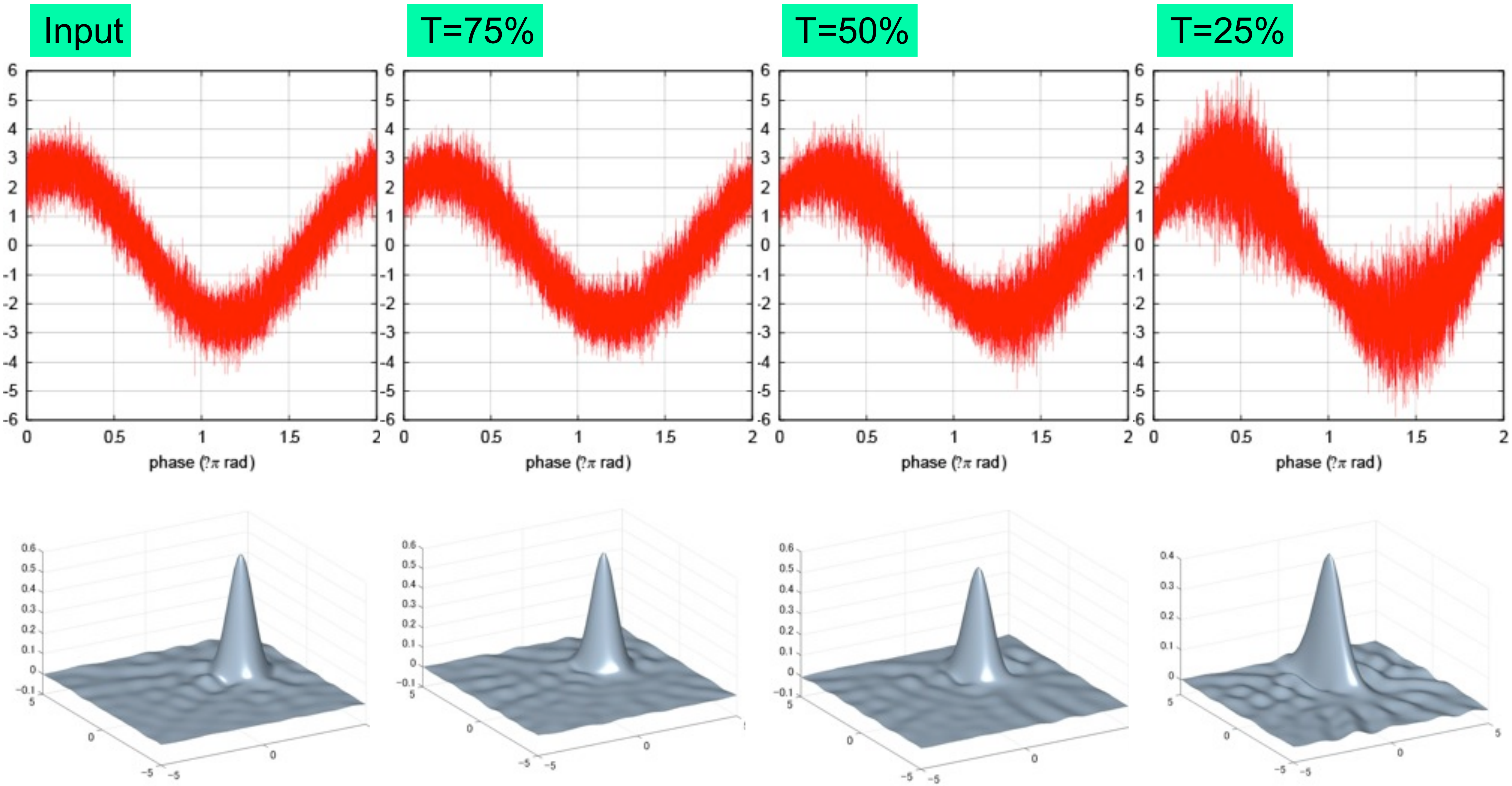
R. Filip, P. Marek, and U. L. Andersen, PRA **71**, 042308 (2005)

# 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).

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

Quantum Non-Demolition (QND) interaction

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

Quantum Non-Demolition (QND) interaction

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

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

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

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

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

Quantum Non-Demolition (QND) interaction

**QND gate**

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

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

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

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

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

CV-CNOT gate ($G$=1)

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

Quantum Non-Demolition (QND) interaction

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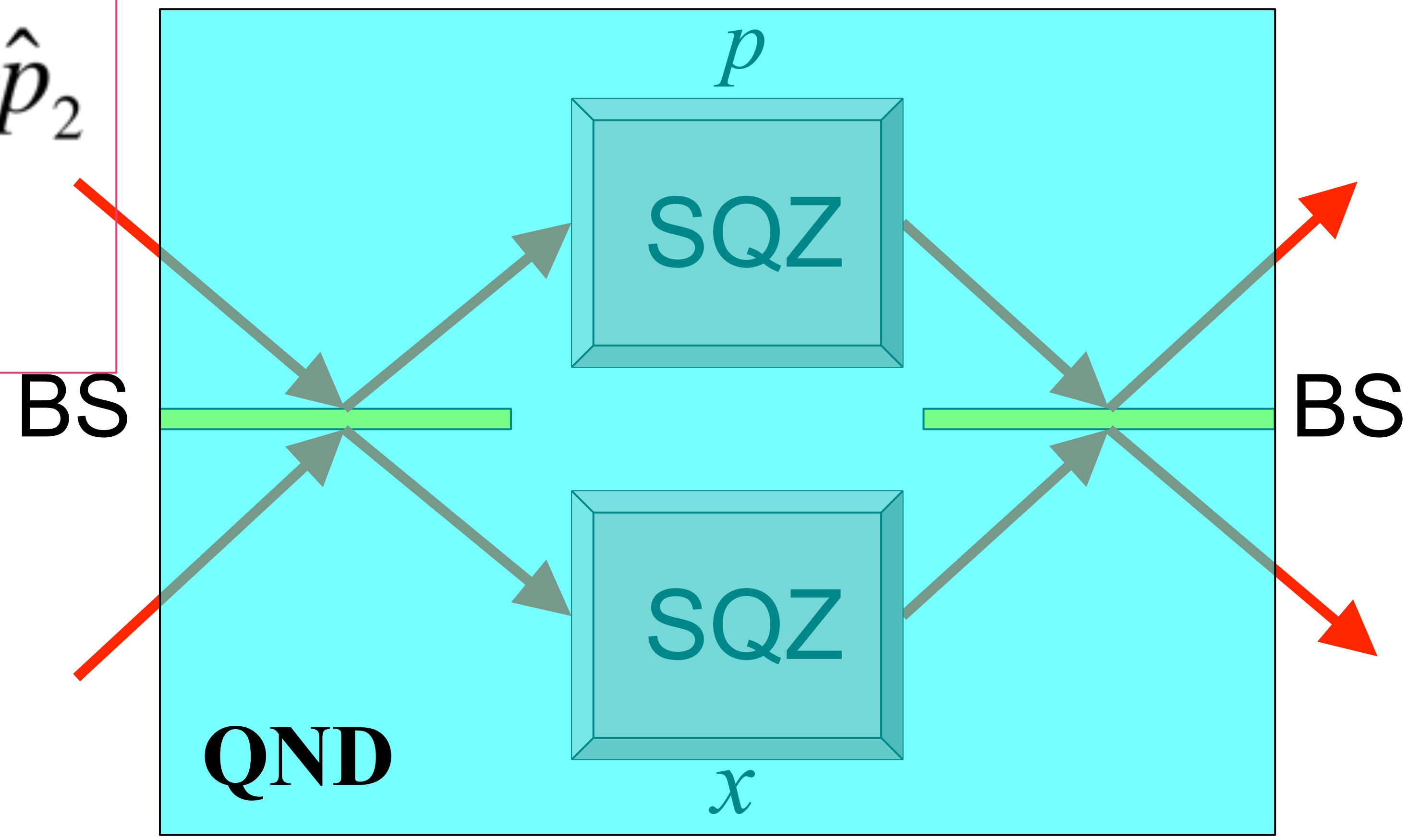
CV-CNOT gate ($G$=1)



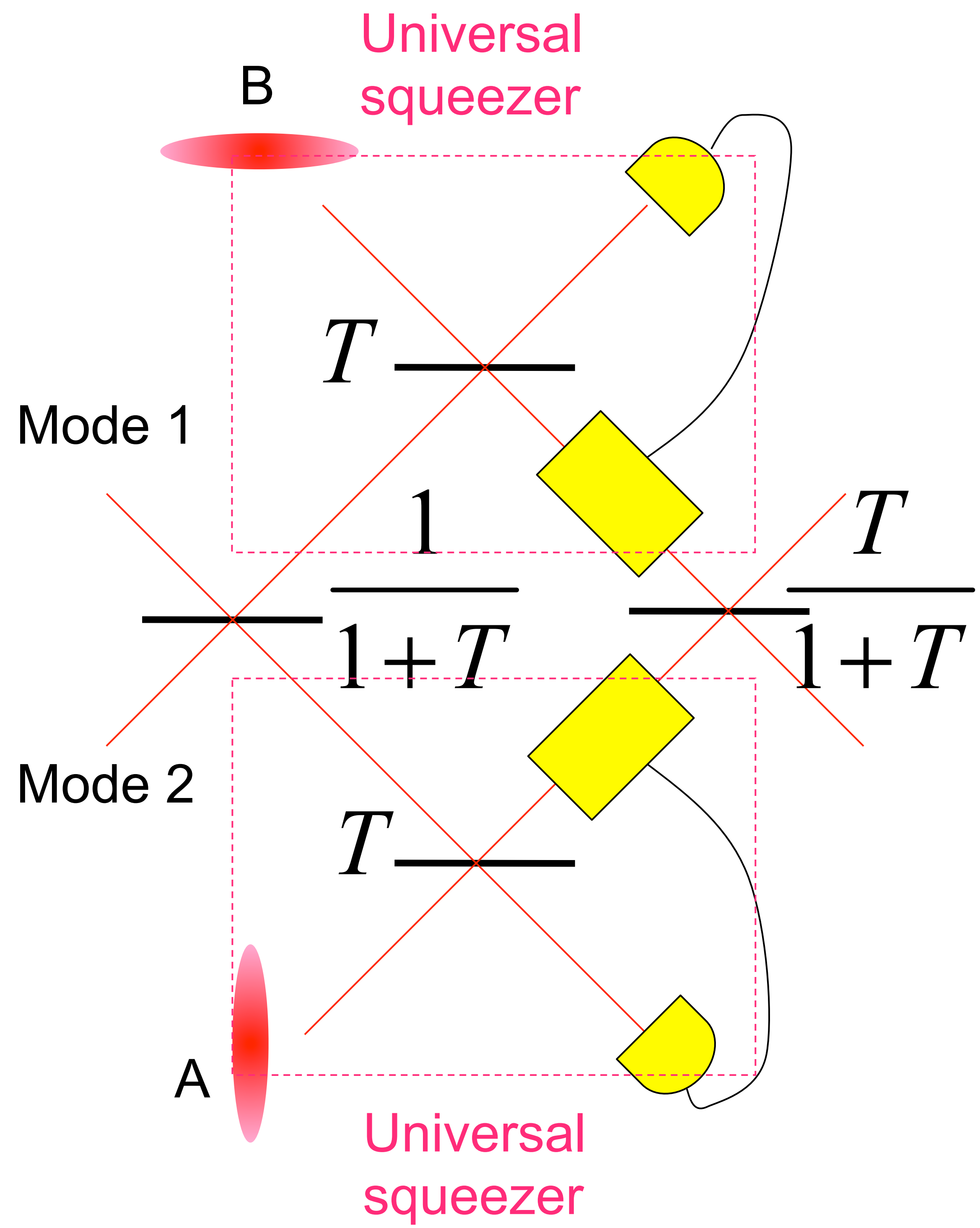
# QND interaction with universal squeezers

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

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

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

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



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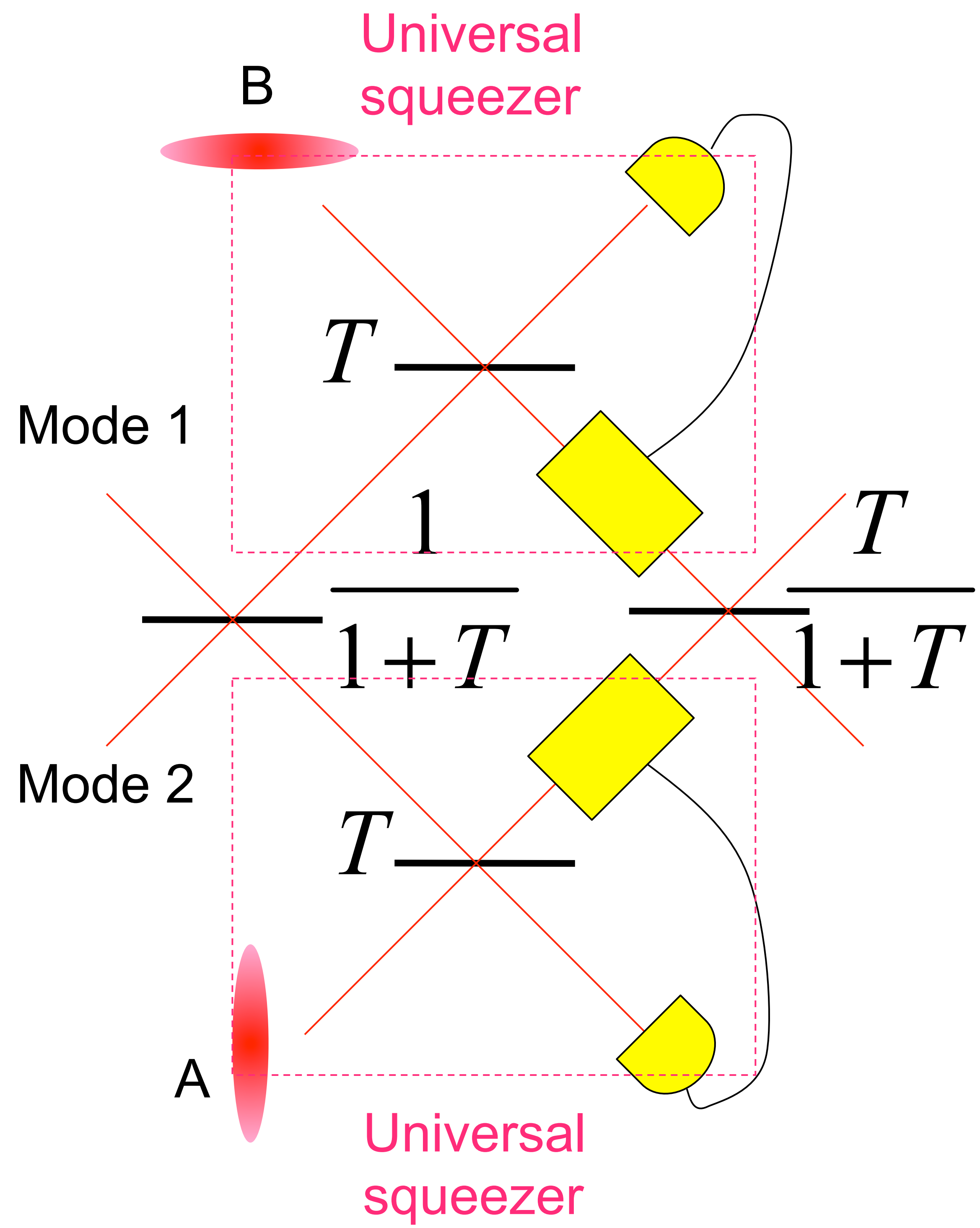

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$$\hat{x}_1' = \hat{x}_1 - \sqrt{\frac{1-T}{1+T}}\hat{x}_{\mathrm{A}}^{(0)}e^{-r}$$

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

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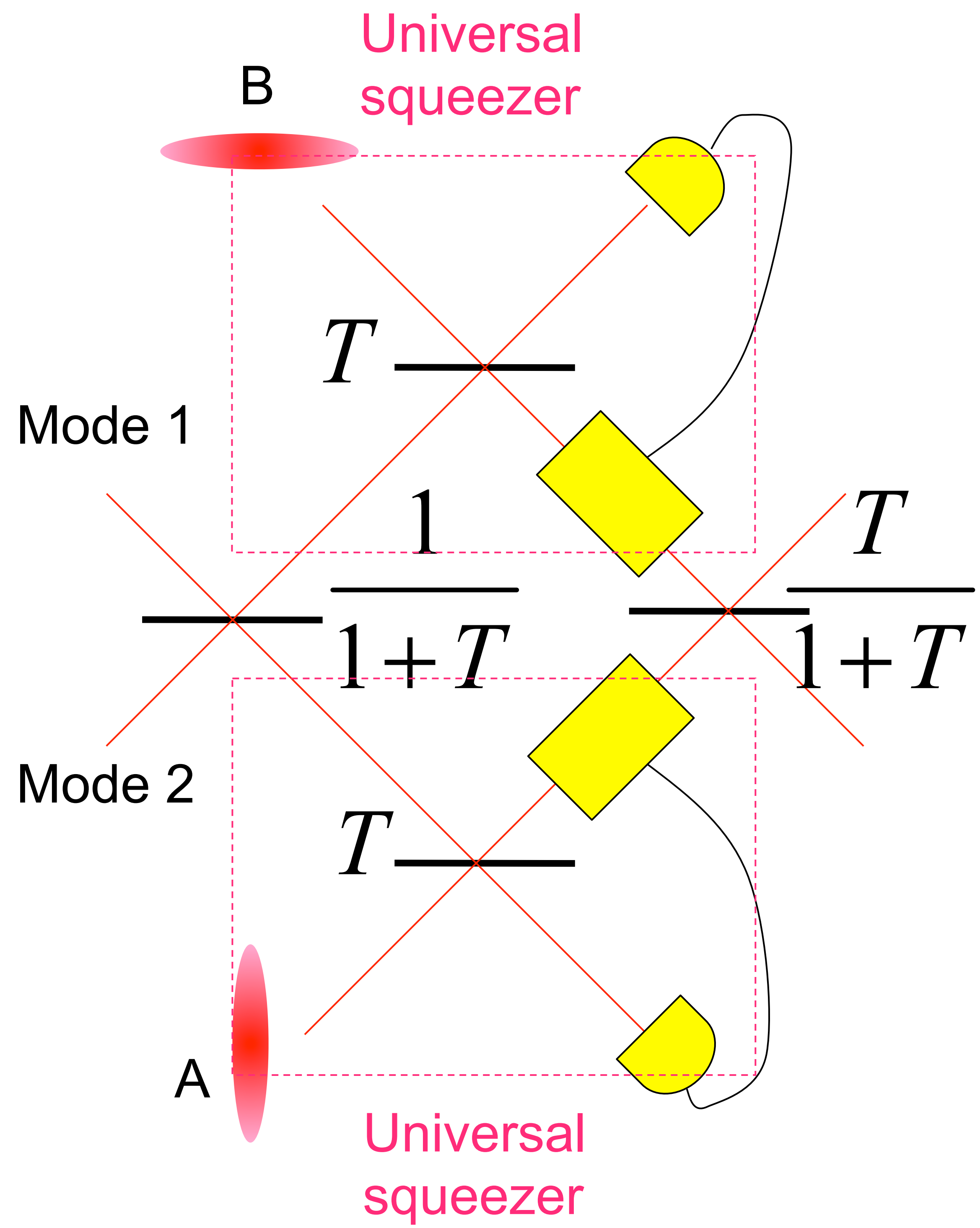
$$\hat{p}_2' = \hat{p}_2 + \sqrt{\frac{1-T}{1+T}}\hat{p}_{\mathrm{B}}^{(0)}e^{-r}$$

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



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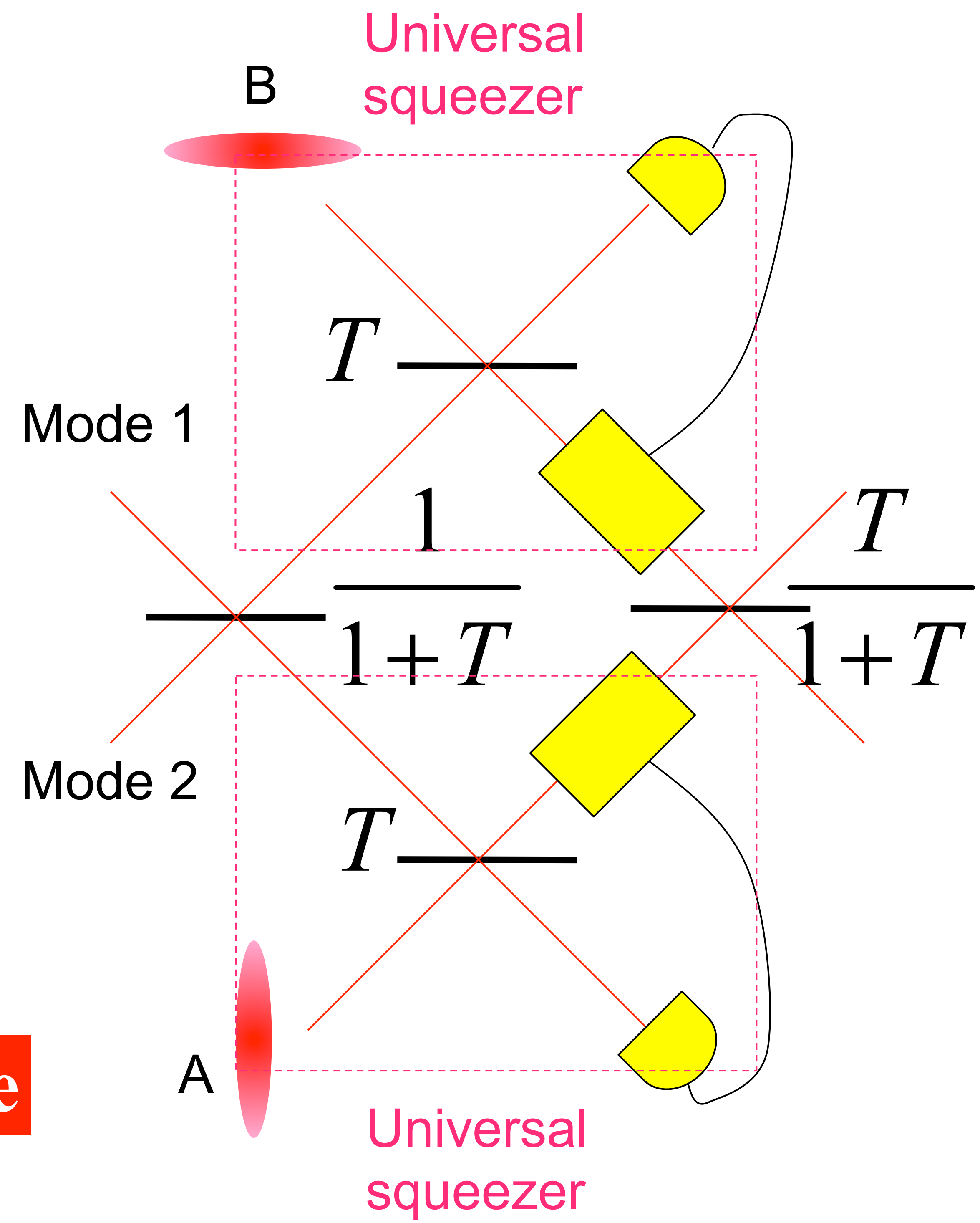
$$\hat{p}_1' = \hat{p}_1 - \boxed{\left(\frac{1}{\sqrt{T}} - \sqrt{T}\right)}\hat{p}_2 + \sqrt{T\,\frac{1-T}{1+T}}\,\hat{x}_B^{(0)} e^{-r}$$

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




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

$G = 1$ **QND gate**

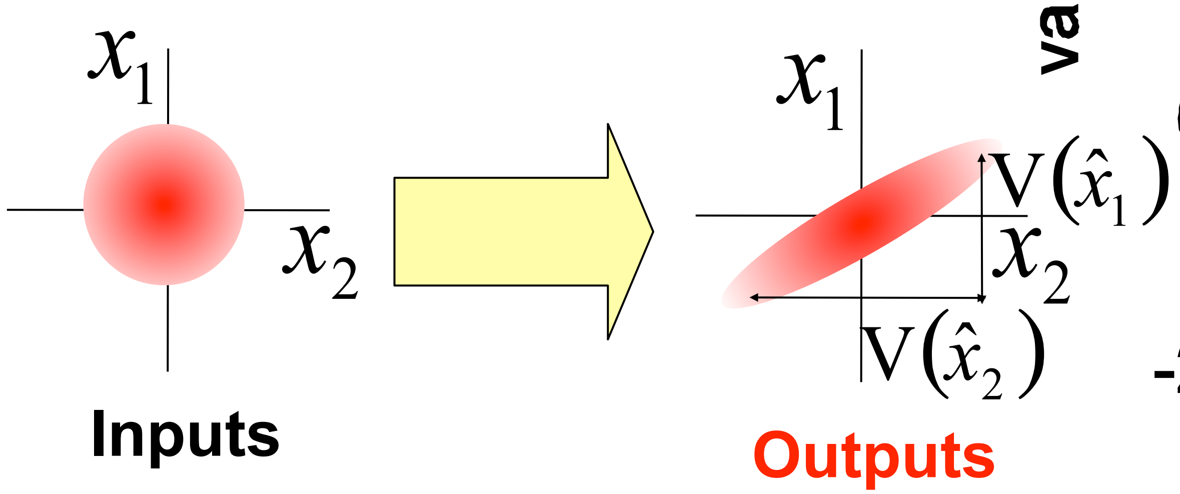
$T = 0.38$

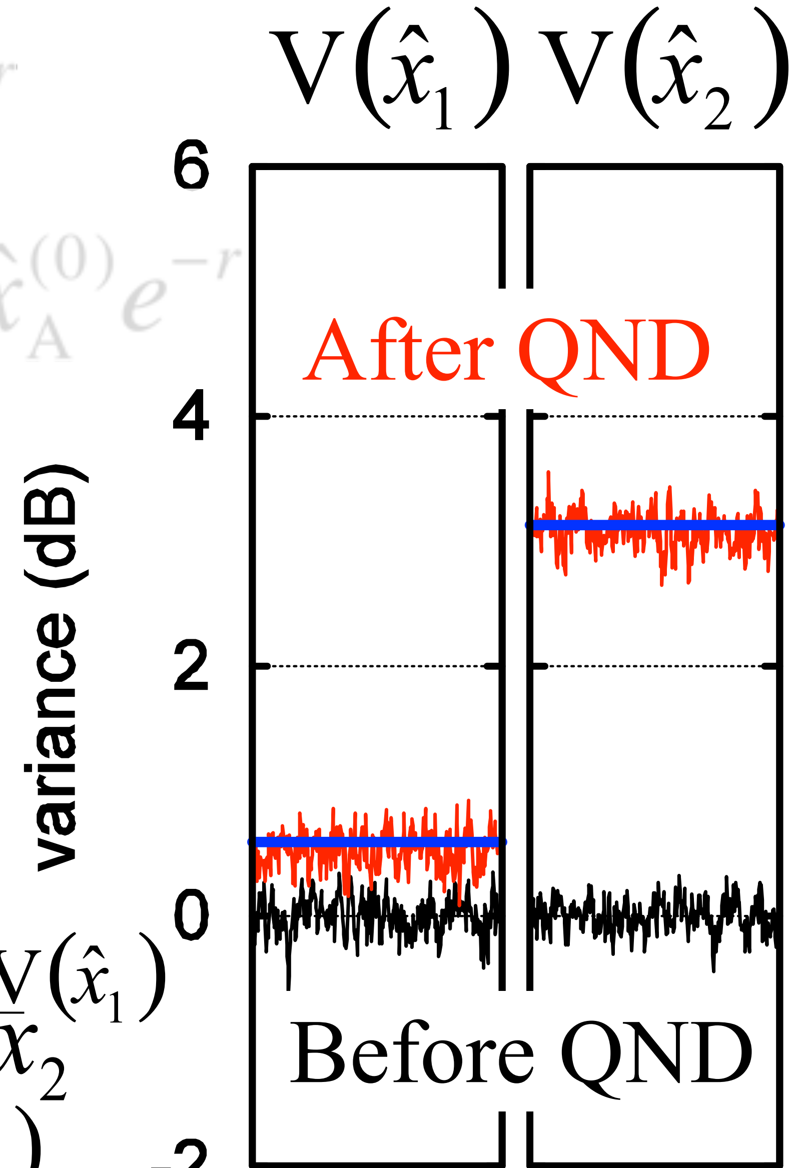
-4.2 dB of squeezing

# Experimental results

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

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




**Theoretical values with finite squeezing of ancillae: -4.9dB**

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

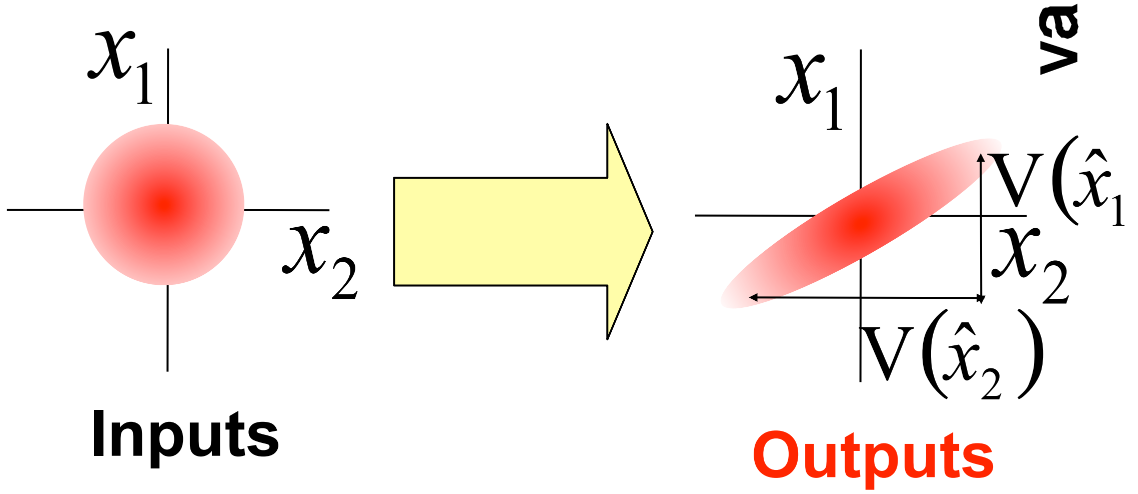
# Experimental results

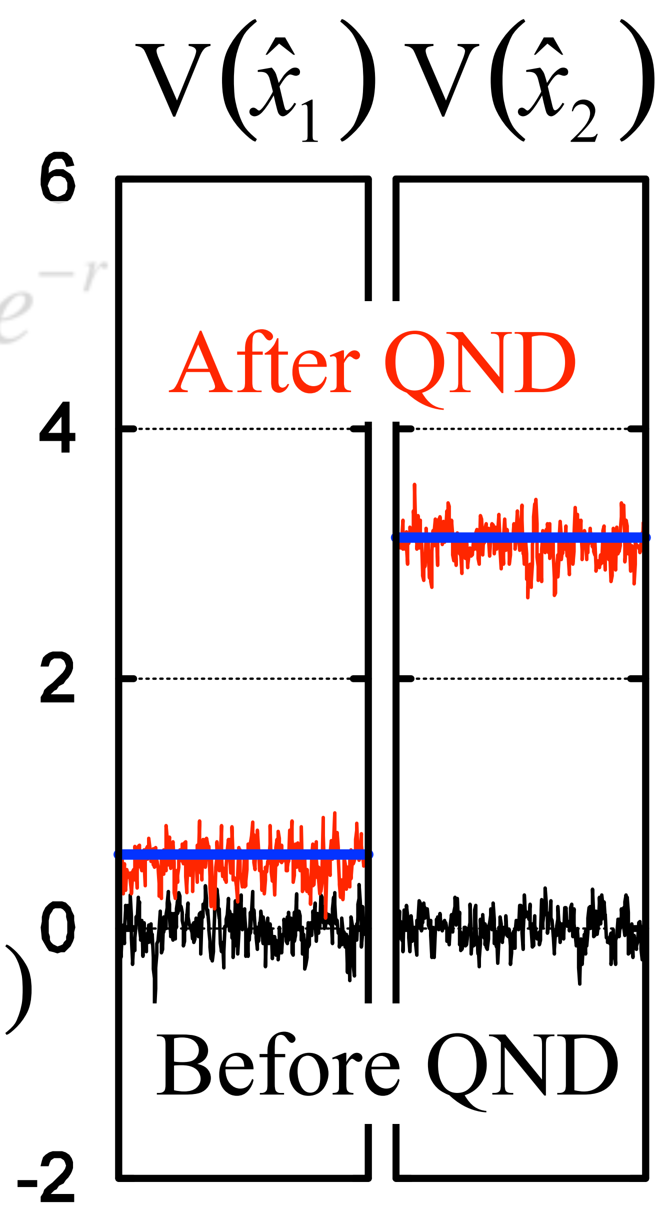
$$\hat{x}_1^{\mathrm{out}} = \hat{x}_1^{\mathrm{in}} - 0.67\hat{x}_{\mathrm{A}}^{(0)}e^{-r}$$

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

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

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




Theoretical values
with finite squeezing of ancillae: -4.9dB

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

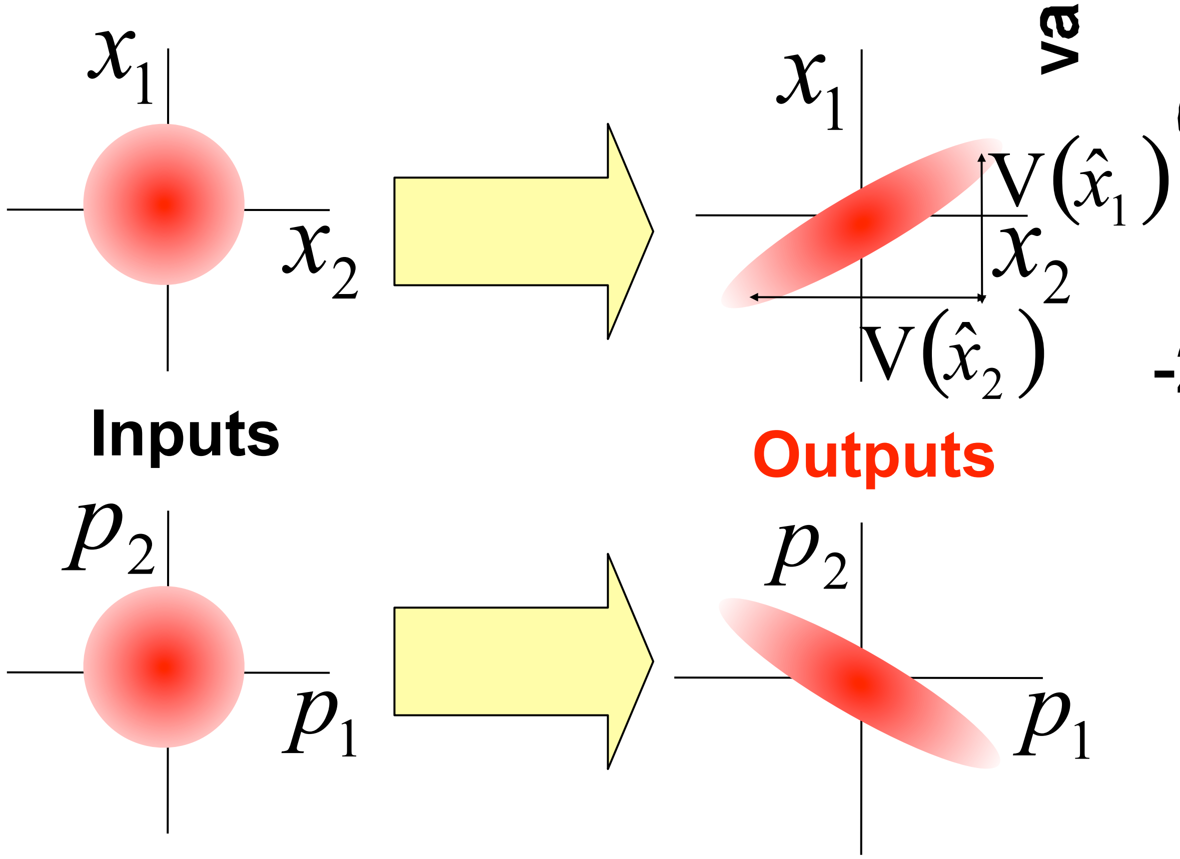
# Experimental results

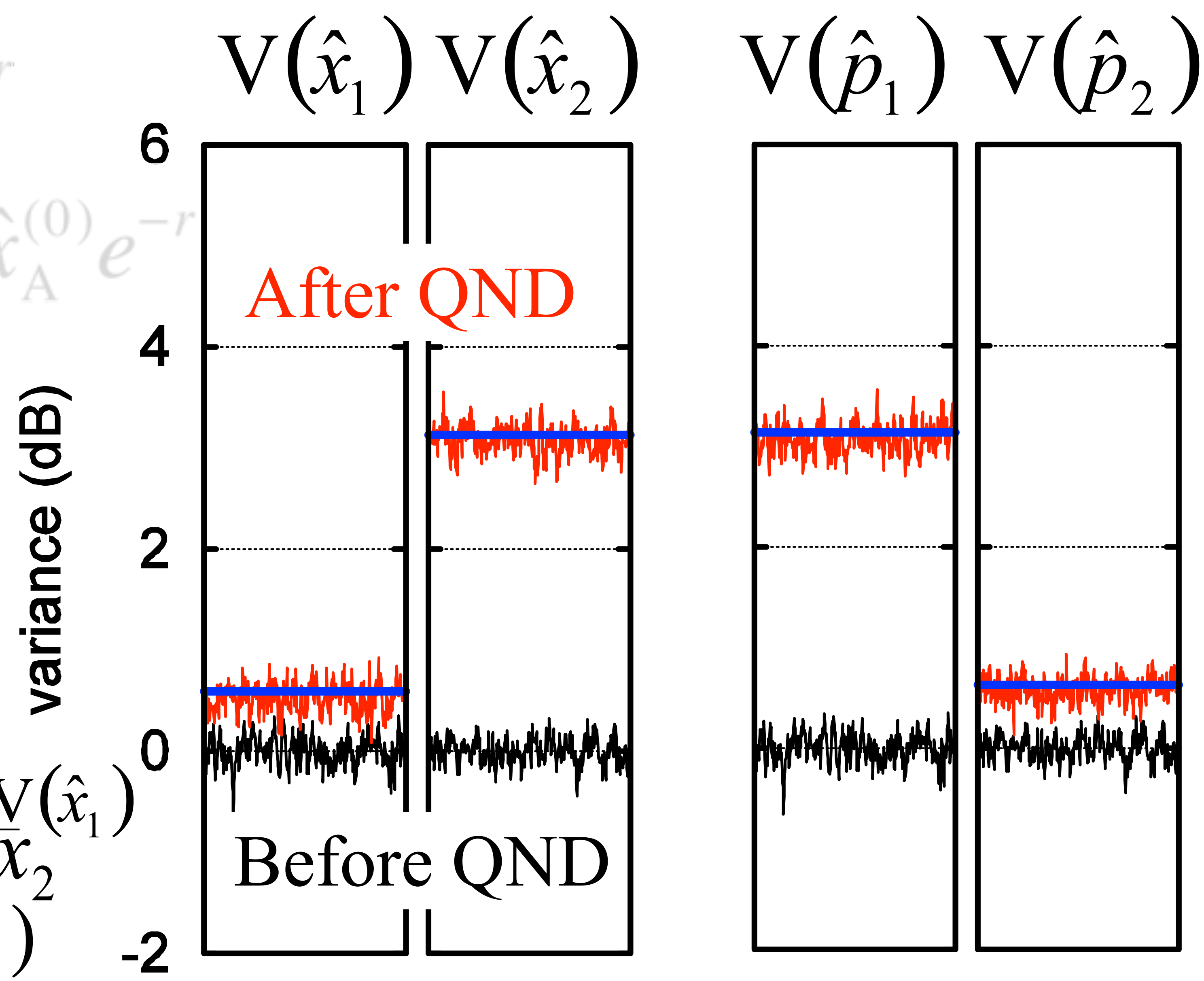
$$\hat{x}_1^{\text{out}} = \hat{x}_1^{\text{in}} - 0.67\hat{x}_A^{(0)}e^{-r}$$

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

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

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

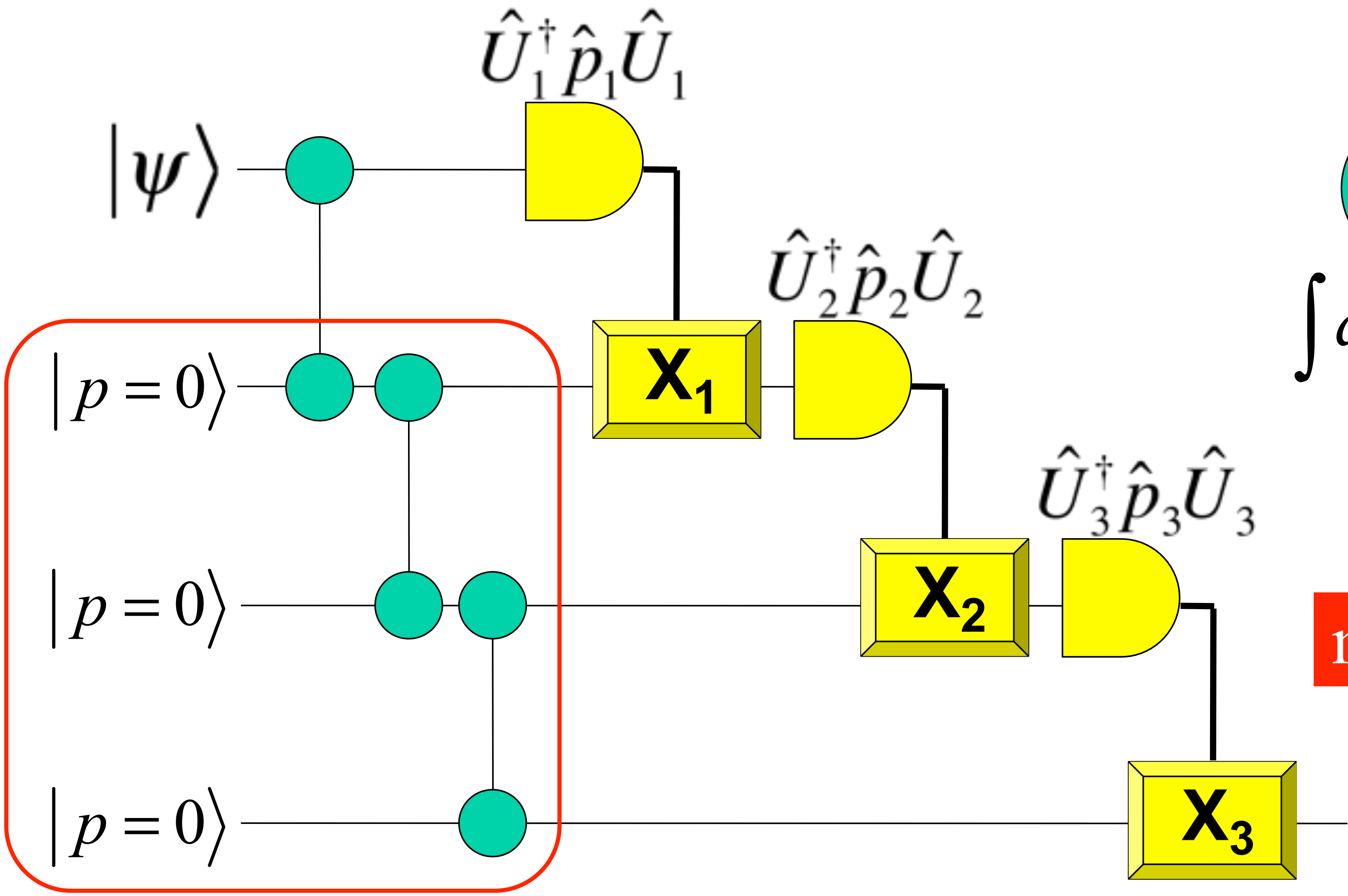


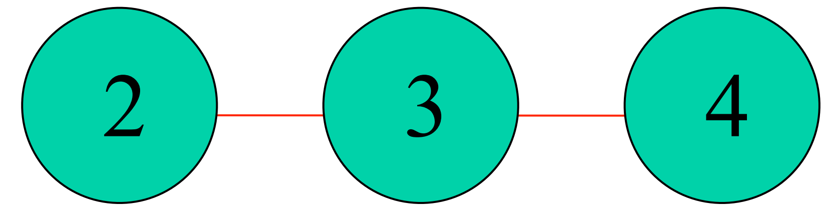

**Theoretical values with finite squeezing of ancillae: -4.9dB**

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

# one-way quantum computation with cluster states




cluster state

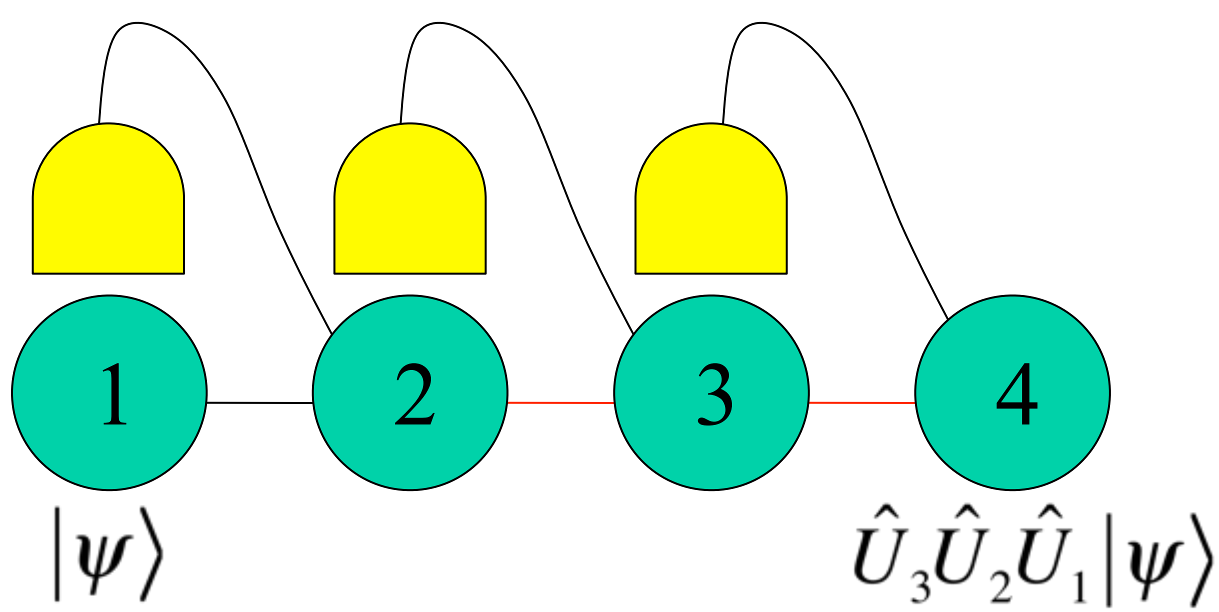



$$\int da\,|p=a\rangle|x=a\rangle|p=a\rangle$$

$$\frac{1}{\sqrt{2}}\left(|+\rangle|0\rangle|+\rangle+|-\rangle|1\rangle|-\rangle\right)$$

$$|+\rangle=\frac{1}{\sqrt{2}}\left(|0\rangle+|1\rangle\right),\ |-\rangle=\frac{1}{\sqrt{2}}\left(|0\rangle-|1\rangle\right)$$

multipartite entanglement



# Definitions of qubit and CV cluster states

**qubit** **Schrödinger picture**

$$\sigma_x^{(a)} \bigotimes_{a' \in ngbh(a)} \sigma_z^{(a')} \left|\Phi\right\rangle_C = \pm\left|\Phi\right\rangle_C$$

# Definitions of qubit and CV cluster states

**qubit** **Schrödinger picture**

$$\sigma_x^{(a)} \bigotimes_{a' \in ngbh(a)} \sigma_z^{(a')} \left|\Phi\right\rangle_C = \pm\left|\Phi\right\rangle_C$$

**CV** **Schrödinger picture**

$$\hat{X}_a(s_a) \prod_{a' \in ngbh(a)} \hat{Z}_{a'}(s_a)\left|\Phi\right\rangle_C = \left|\Phi\right\rangle_C$$

# Definitions of qubit and CV cluster states

**qubit** Schrödinger picture

$$\sigma_x^{(a)} \bigotimes_{a' \in ngbh(a)} \sigma_z^{(a')} \left|\Phi\right\rangle_C = \pm \left|\Phi\right\rangle_C$$

**CV** Schrödinger picture

$$\hat{X}_a(s_a) \prod_{a' \in ngbh(a)} \hat{Z}_{a'}(s_a) \left|\Phi\right\rangle_C = \left|\Phi\right\rangle_C$$

$$e^{-2is_a\left(\hat{p}_a - \sum_{a' \in ngbh(a)} \hat{x}_{a'}\right)} \left|\Phi\right\rangle_C = \left|\Phi\right\rangle_C$$

# Definitions of qubit and CV cluster states

**qubit** **Schrödinger picture**

$$\sigma_x^{(a)} \bigotimes_{a' \in ngbh(a)} \sigma_z^{(a')} |\Phi\rangle_C = \pm |\Phi\rangle_C$$

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# Definitions of qubit and CV cluster states

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**Heisenberg picture**

$$\hat{p}_a - \sum_{a' \in ngbh(a)} \hat{x}_{a'} = 0$$

# Definitions of qubit and CV cluster states

**qubit** **Schrödinger picture**

$$\sigma_x^{(a)} \bigotimes_{a' \in ngbh(a)} \sigma_z^{(a')} |\Phi\rangle_C = \pm |\Phi\rangle_C$$

**CV** **Schrödinger picture**

$$e^{-2is_a\left(\hat{p}_a - \sum_{a' \in ngbh(a)} \hat{x}_{a'}\right)} |\Phi\rangle_C = |\Phi\rangle_C$$

**Heisenberg picture**

$$\hat{p}_a - \sum_{a' \in ngbh(a)} \hat{x}_{a'} = 0$$

**Nonclassical correlation**

AM signal $= \hat{x}$

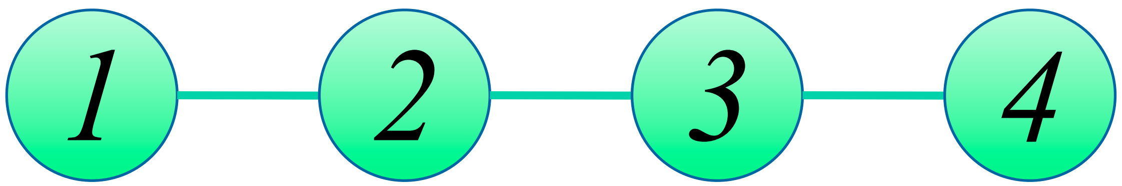
FM signal $= \hat{p}$

Entanglement

# 4-mode cluster states

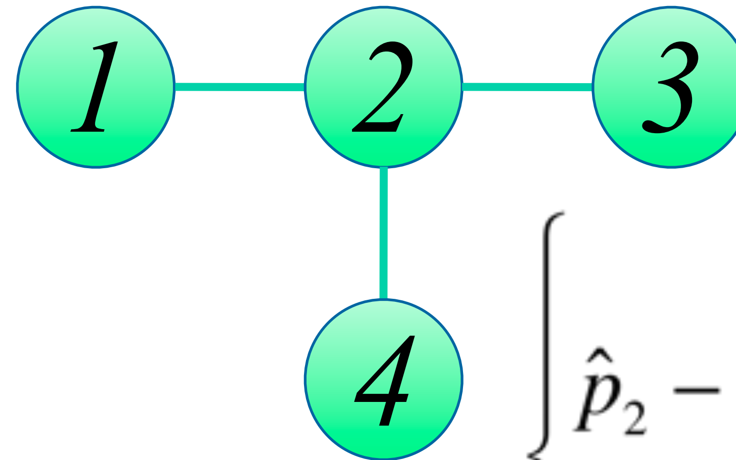
AM signal $= \hat{x}$
FM signal $= \hat{p}$

## Linear 4-mode



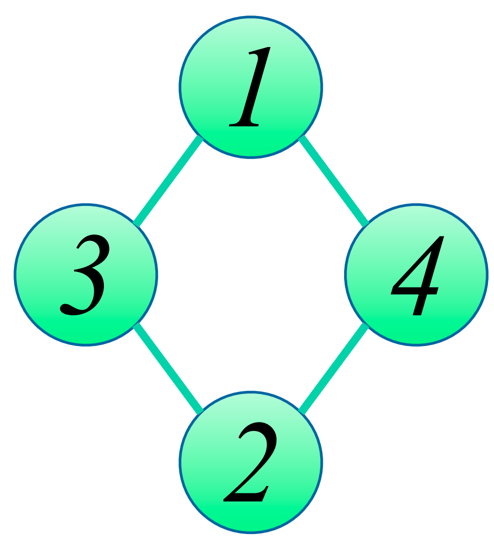

$$\begin{cases} \hat{p}_1 - \hat{x}_2 \to 0 \\ \hat{p}_2 - \hat{x}_1 - \hat{x}_3 \to 0 \\ \hat{p}_3 - \hat{x}_2 - \hat{x}_4 \to 0 \\ \hat{p}_4 - \hat{x}_3 \to 0 \end{cases}$$

## T-shape



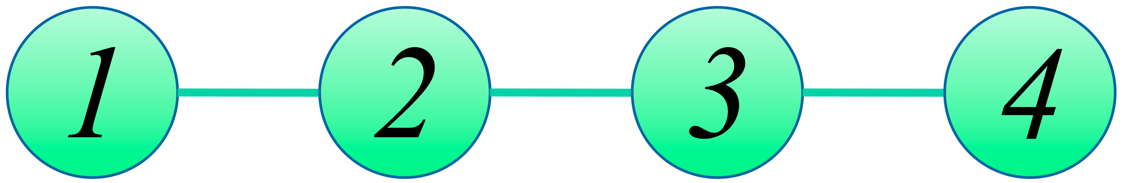

$$\begin{cases} \hat{p}_1 - \hat{x}_2 \to 0 \\ \hat{p}_2 - \hat{x}_1 - \hat{x}_2 - \hat{x}_3 \to 0 \\ \hat{p}_3 - \hat{x}_2 \to 0 \\ \hat{p}_4 - \hat{x}_2 \to 0 \end{cases}$$

## Diamond-shape

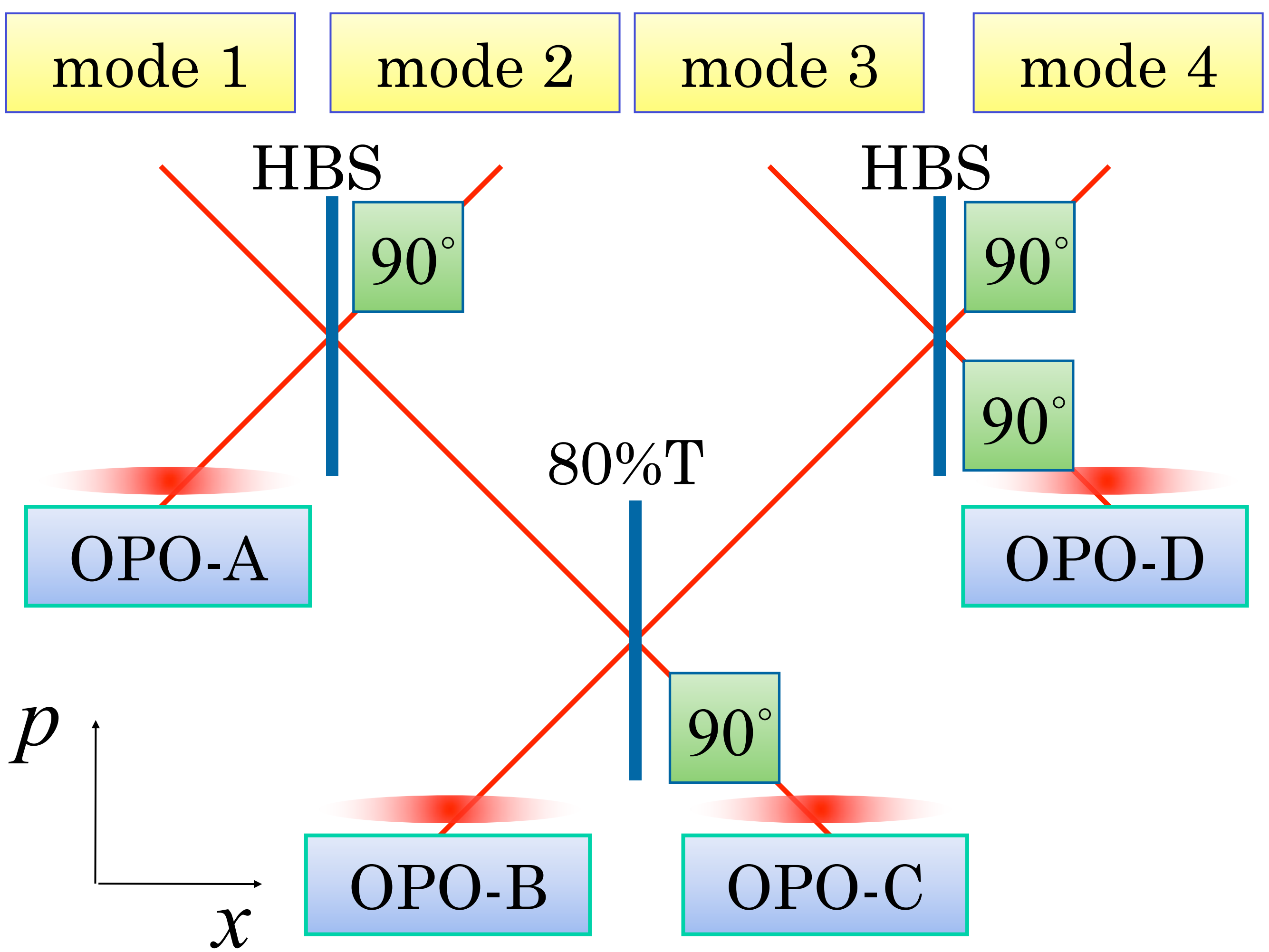



$$\begin{cases} \hat{p}_1 - \hat{x}_3 - \hat{x}_4 \to 0 \\ \hat{p}_2 - \hat{x}_3 - \hat{x}_4 \to 0 \\ \hat{p}_3 - \hat{x}_1 - \hat{x}_2 \to 0 \\ \hat{p}_4 - \hat{x}_1 - \hat{x}_2 \to 0 \end{cases}$$

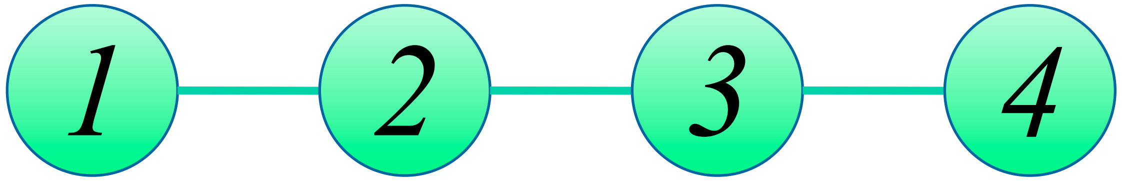
# Generation of cluster states with squeezed vacua



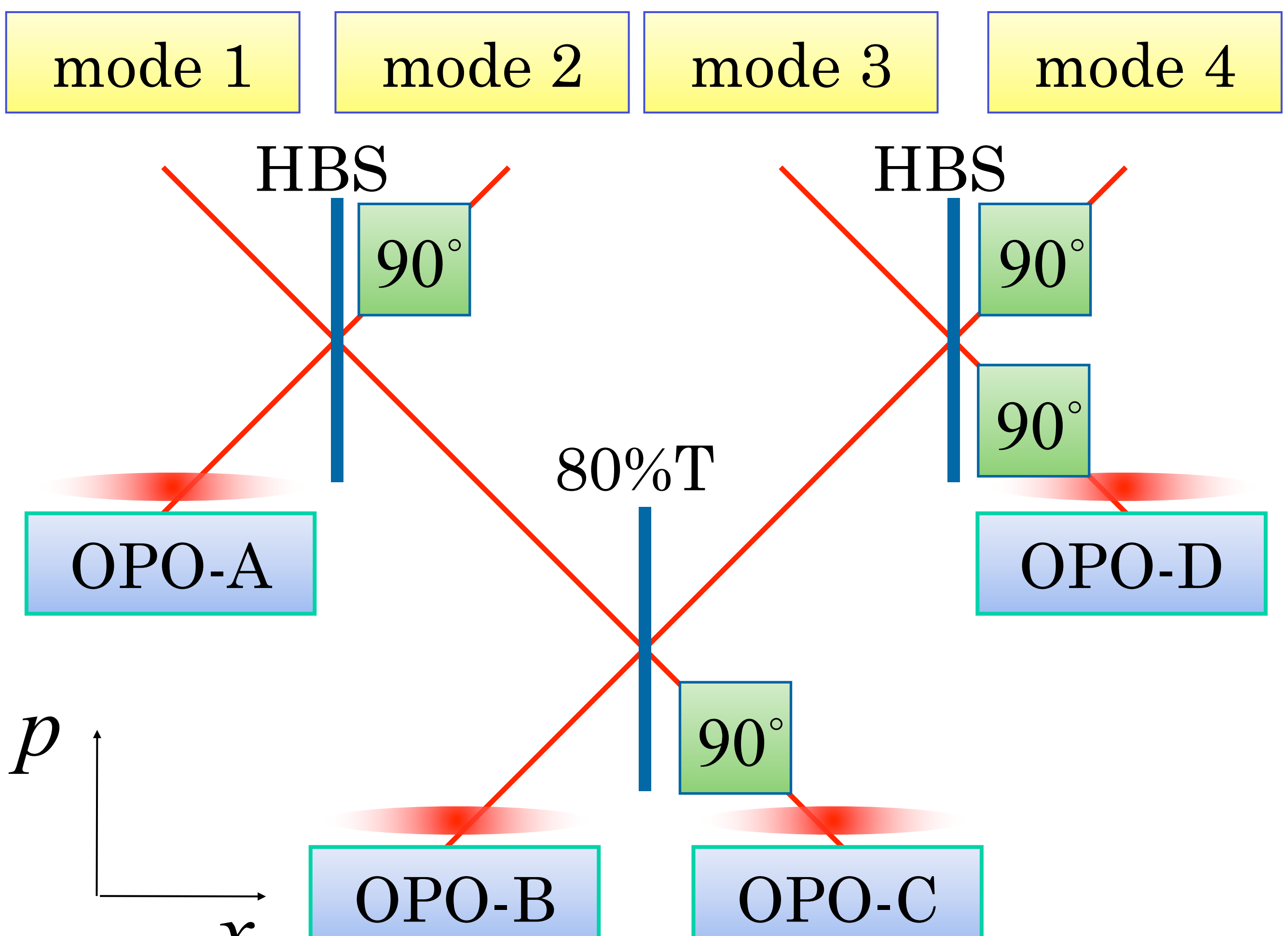

$$\begin{cases} \hat{p}_1 - \hat{x}_2 = \sqrt{2}e^{-r_1}\hat{p}_1^{(0)} \to 0 \quad (r \to \infty) \\ \hat{p}_2 - \hat{x}_1 - \hat{x}_3 = -\sqrt{\frac{5}{2}}e^{-r_3}\hat{p}_3^{(0)} - \sqrt{\frac{1}{2}}e^{-r_4}\hat{p}_4^{(0)} \to 0 \\ \hat{p}_3 - \hat{x}_2 - \hat{x}_4 = \sqrt{\frac{1}{2}}e^{-r_1}\hat{p}_1^{(0)} - \sqrt{\frac{5}{2}}e^{-r_2}\hat{p}_2^{(0)} \to 0 \\ \hat{p}_4 - \hat{x}_3 = -\sqrt{2}e^{-r_4}\hat{p}_4^{(0)} \to 0 \end{cases}$$

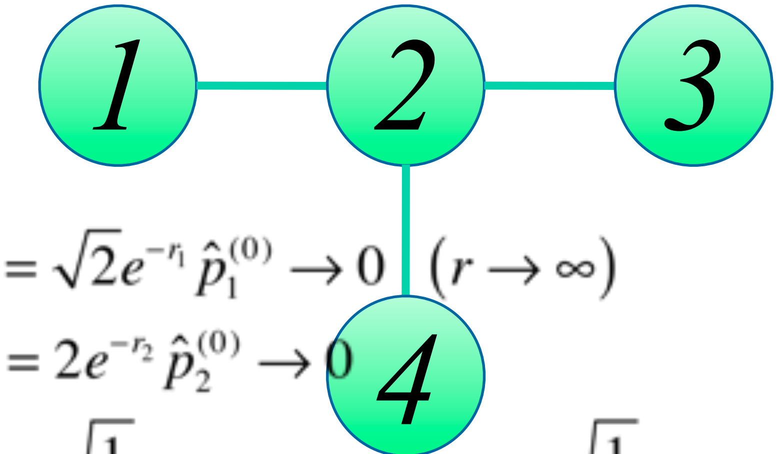


# Generation of cluster states with squeezed vacua

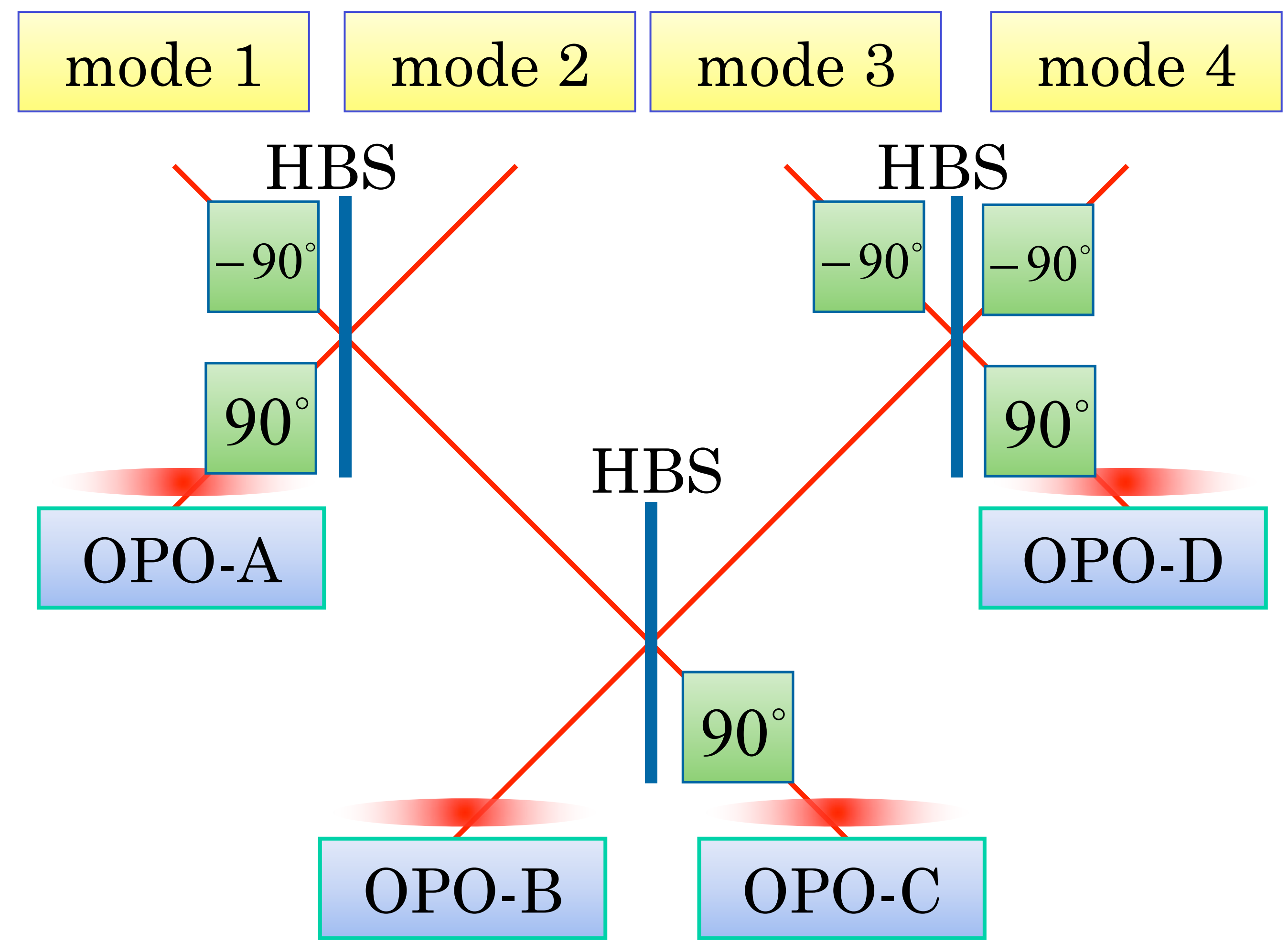



$$
\begin{cases}
\hat{p}_1 - \hat{x}_2 = \sqrt{2}e^{-r_1}\hat{p}_1^{(0)} \to 0 \quad (r \to \infty) \\
\hat{p}_2 - \hat{x}_1 - \hat{x}_3 = -\sqrt{\frac{5}{2}}e^{-r_3}\hat{p}_3^{(0)} - \sqrt{\frac{1}{2}}e^{-r_4}\hat{p}_4^{(0)} \to 0 \\
\hat{p}_3 - \hat{x}_2 - \hat{x}_4 = \sqrt{\frac{1}{2}}e^{-r_1}\hat{p}_1^{(0)} - \sqrt{\frac{5}{2}}e^{-r_2}\hat{p}_2^{(0)} \to 0 \\
\hat{p}_4 - \hat{x}_3 = -\sqrt{2}e^{-r_4}\hat{p}_4^{(0)} \to 0
\end{cases}
$$

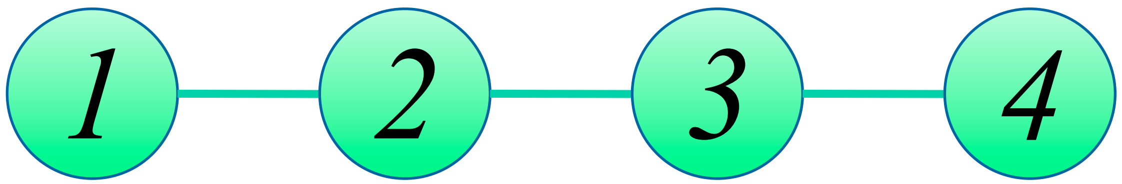


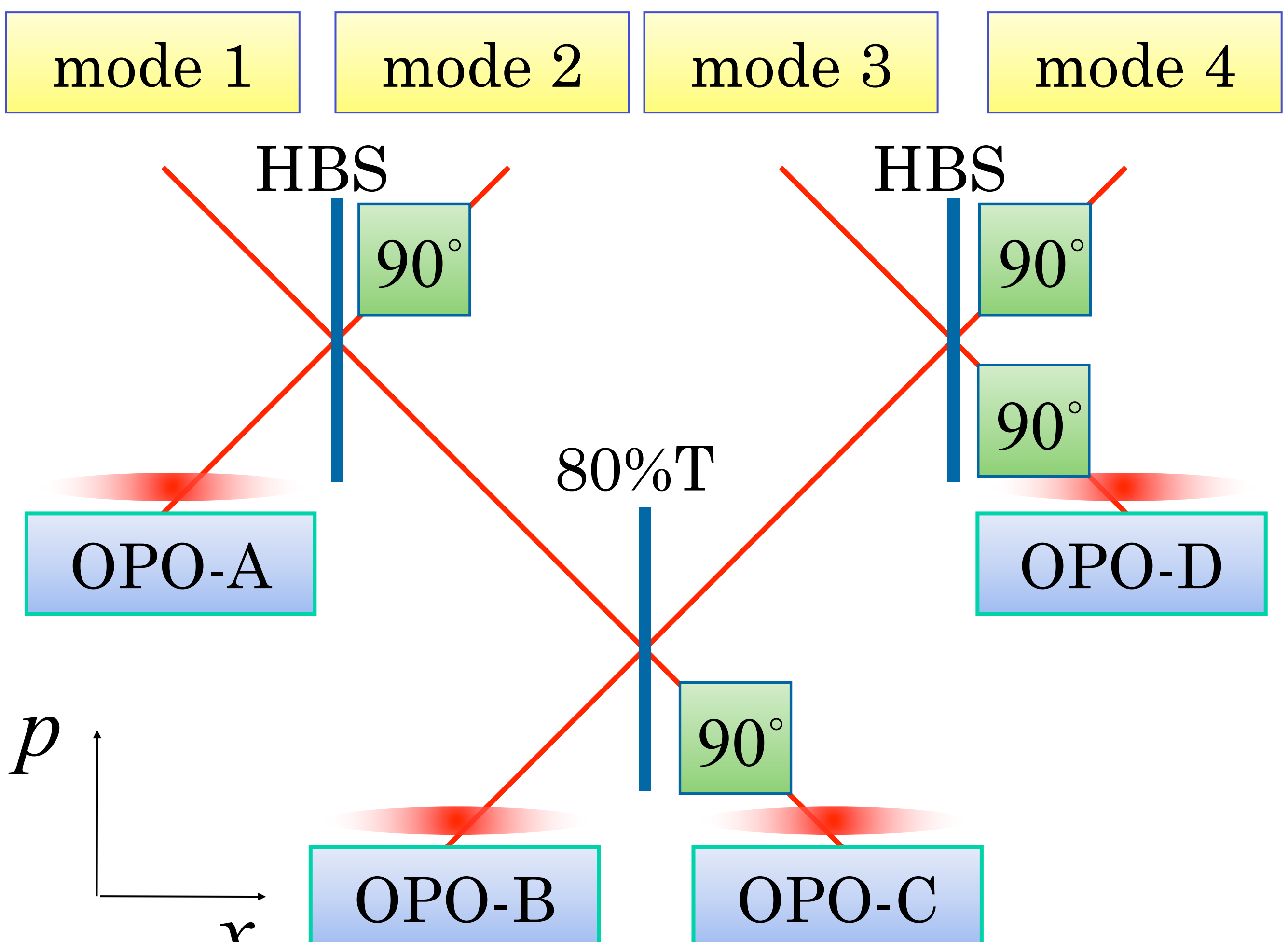

$$
\begin{cases}
\hat{p}_1 - \hat{x}_2 = \sqrt{2}e^{-r_1}\hat{p}_1^{(0)} \to 0 \quad (r \to \infty) \\
\hat{p}_2 - \hat{x}_1 - \hat{x}_2 - \hat{x}_3 = 2e^{-r_2}\hat{p}_2^{(0)} \to 0 \\
\hat{p}_3 - \hat{x}_2 = \sqrt{\frac{1}{2}}e^{-r_1}\hat{p}_1^{(0)} + e^{-r_3}\hat{p}_3^{(0)} + \sqrt{\frac{1}{2}}e^{-r_4}\hat{p}_4^{(0)} \to 0 \\
\hat{p}_4 - \hat{x}_2 = \sqrt{\frac{1}{2}}e^{-r_1}\hat{p}_1^{(0)} + e^{-r_3}\hat{p}_3^{(0)} - \sqrt{\frac{1}{2}}e^{-r_4}\hat{p}_4^{(0)} \to 0
\end{cases}
$$

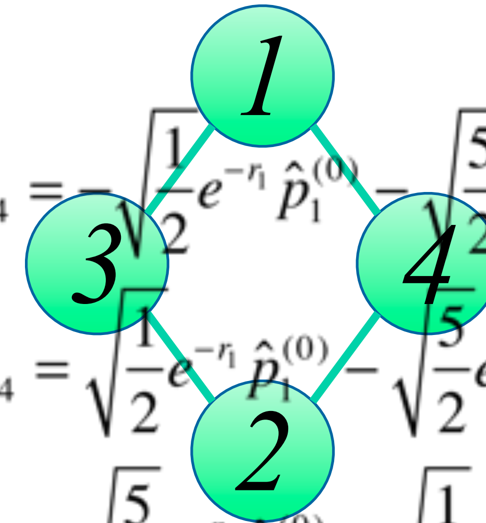


# Generation of cluster states with squeezed vacua

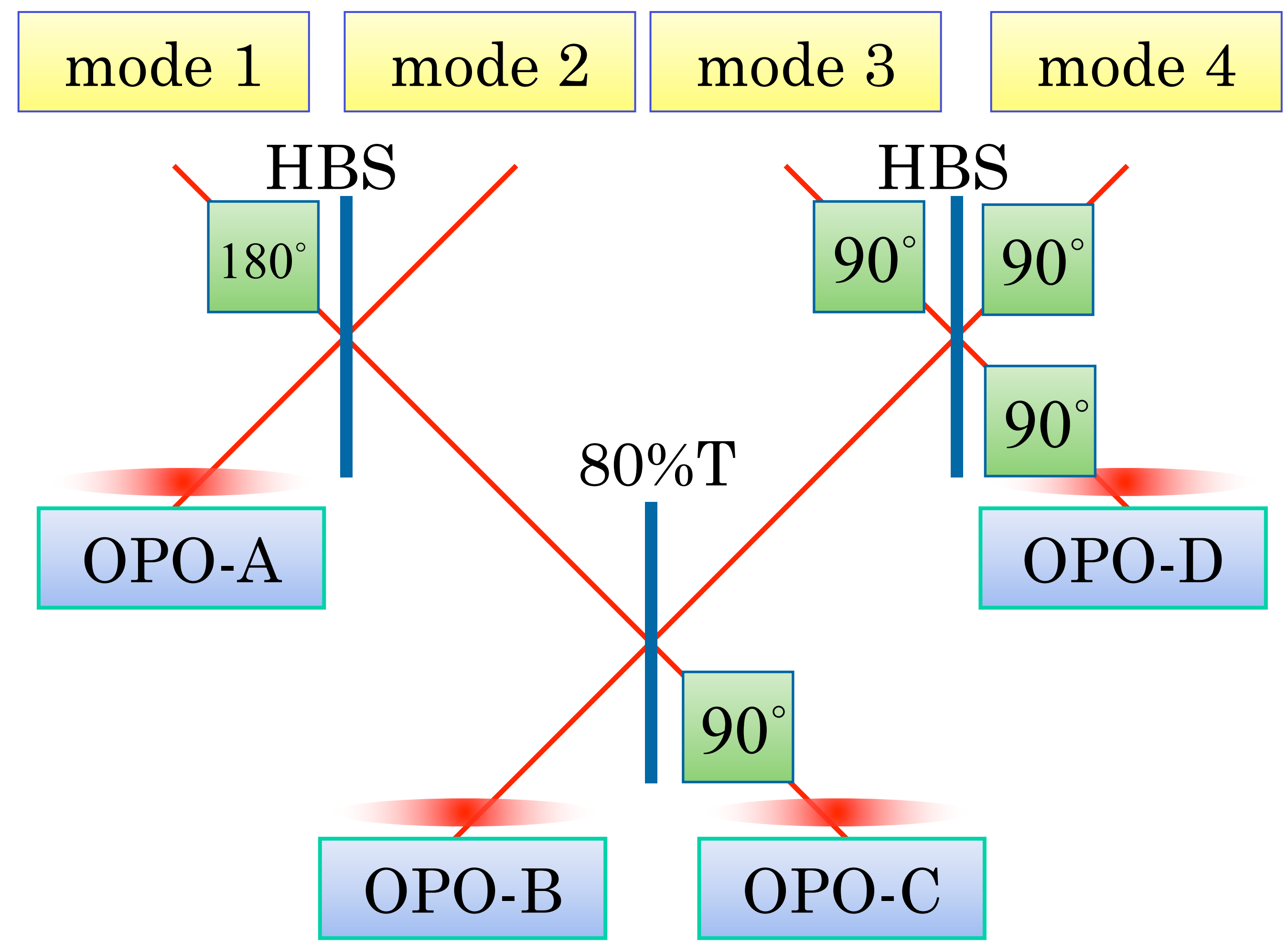



$$\begin{cases} \hat{p}_1 - \hat{x}_2 = \sqrt{2}e^{-r_1}\hat{p}_1^{(0)} \to 0 \quad (r \to \infty) \\ \hat{p}_2 - \hat{x}_1 - \hat{x}_3 = -\sqrt{\frac{5}{2}}e^{-r_3}\hat{p}_3^{(0)} - \sqrt{\frac{1}{2}}e^{-r_4}\hat{p}_4^{(0)} \to 0 \\ \hat{p}_3 - \hat{x}_2 - \hat{x}_4 = \sqrt{\frac{1}{2}}e^{-r_1}\hat{p}_1^{(0)} - \sqrt{\frac{5}{2}}e^{-r_2}\hat{p}_2^{(0)} \to 0 \\ \hat{p}_4 - \hat{x}_3 = -\sqrt{2}e^{-r_4}\hat{p}_4^{(0)} \to 0 \end{cases}$$



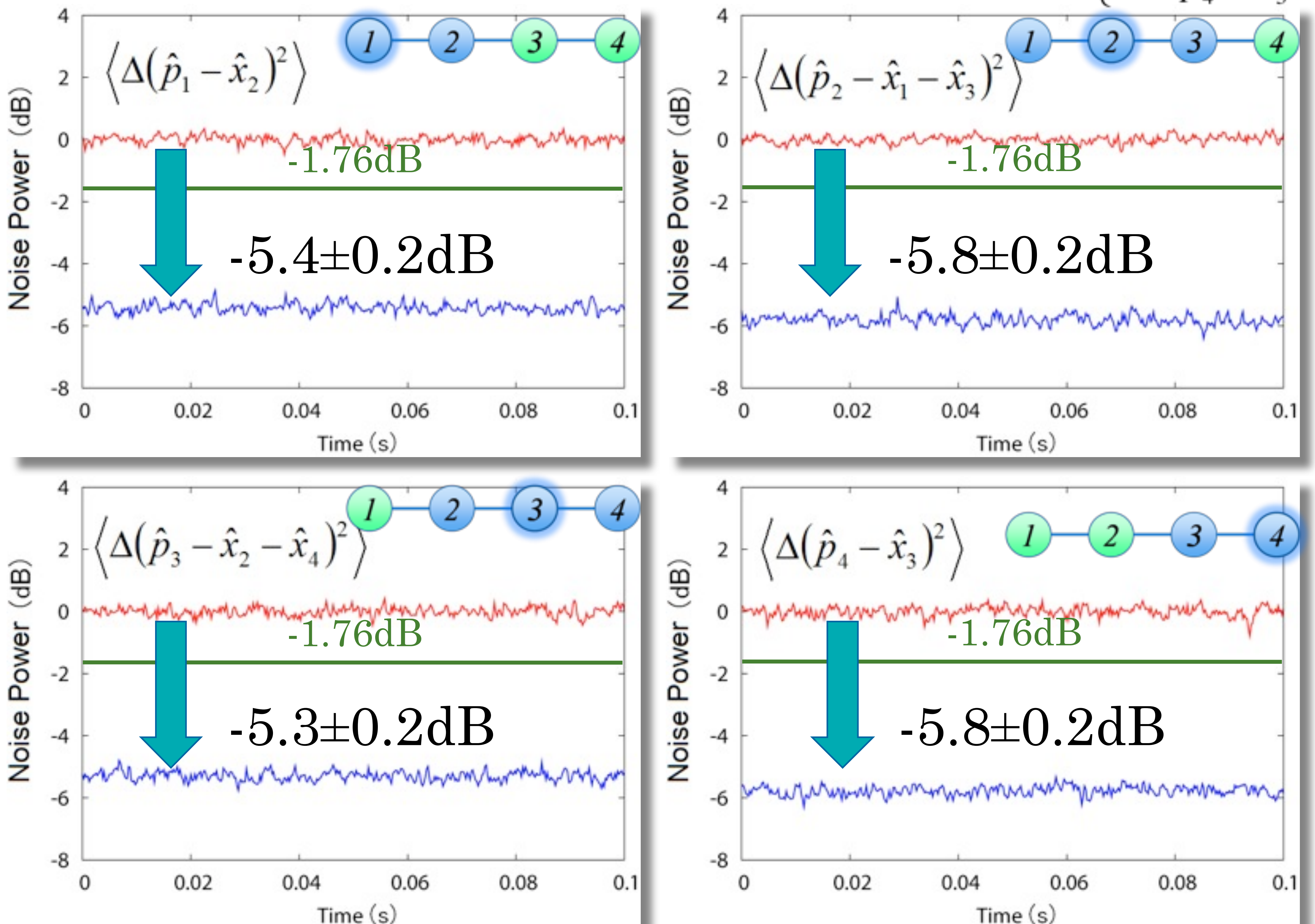

$$\begin{cases} \hat{p}_1 - \hat{x}_3 - \hat{x}_4 = -\sqrt{\frac{1}{2}}e^{-r_1}\hat{p}_1^{(0)} - \sqrt{\frac{5}{2}}e^{-r_2}\hat{p}_2^{(0)} \to 0 \\ \hat{p}_2 - \hat{x}_3 - \hat{x}_4 = \sqrt{\frac{1}{2}}e^{-r_1}\hat{p}_1^{(0)} - \sqrt{\frac{5}{2}}e^{-r_2}\hat{p}_2^{(0)} \to 0 \\ \hat{p}_3 - \hat{x}_1 - \hat{x}_2 = \sqrt{\frac{5}{2}}e^{-r_3}\hat{p}_3^{(0)} + \sqrt{\frac{1}{2}}e^{-r_4}\hat{p}_4^{(0)} \to 0 \\ \hat{p}_4 - \hat{x}_1 - \hat{x}_2 = \sqrt{\frac{5}{2}}e^{-r_3}\hat{p}_3^{(0)} - \sqrt{\frac{1}{2}}e^{-r_4}\hat{p}_4^{(0)} \to 0 \end{cases}$$




OPO
Kodak
lens cleaning
paper

# 4-mode linear cluster type multipartite entanglement

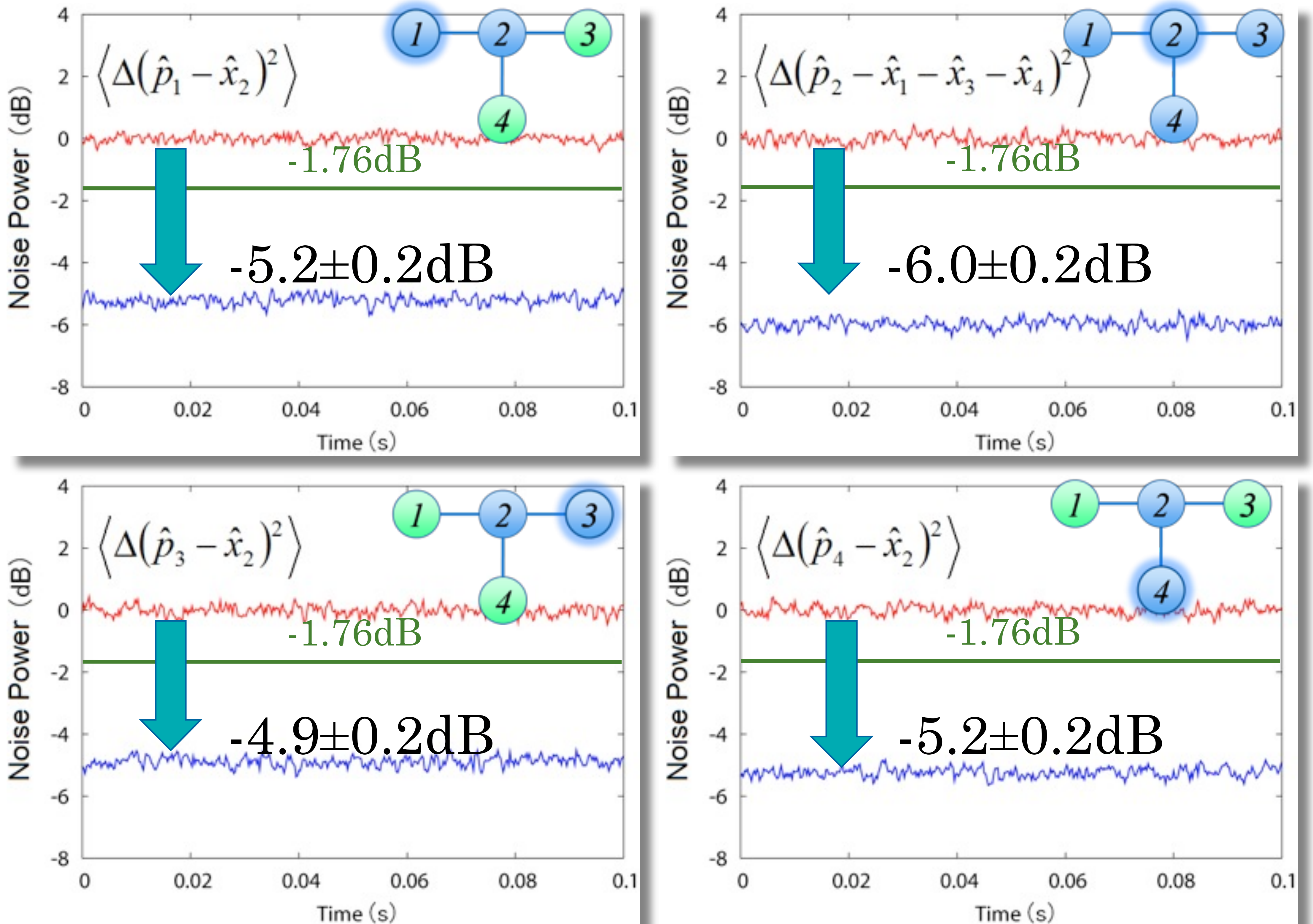
$$\begin{cases} \hat{p}_1 - \hat{x}_2 \to 0 \\ \hat{p}_2 - \hat{x}_1 - \hat{x}_3 \to 0 \\ \hat{p}_3 - \hat{x}_2 - \hat{x}_4 \to 0 \\ \hat{p}_4 - \hat{x}_3 \to 0 \end{cases}$$




**M. Yukawa, R. Ukai, P. van Loock, and A. Furusawa, Phys. Rev. A 78, 012301 (2008)**

# 4-mode T-shape cluster type multipartite entanglement

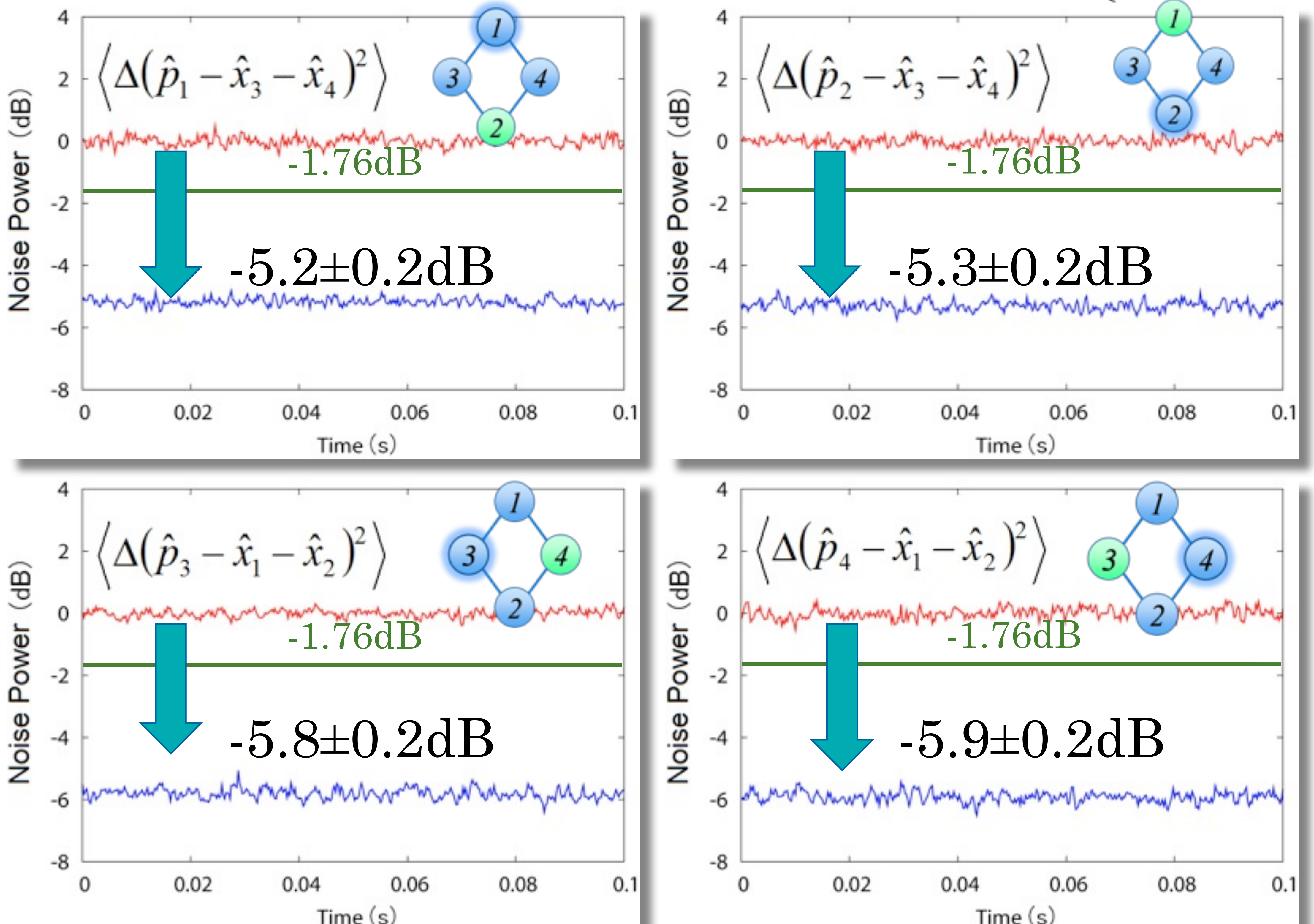
$$\begin{cases} \hat{p}_1 - \hat{x}_2 \to 0 \\ \hat{p}_2 - \hat{x}_1 - \hat{x}_2 - \hat{x}_3 \to 0 \\ \hat{p}_3 - \hat{x}_2 \to 0 \\ \hat{p}_4 - \hat{x}_2 \to 0 \end{cases}$$




M. Yukawa, R. Ukai, P. van Loock, and A. Furusawa, Phys. Rev. A 78, 012301 (2008)

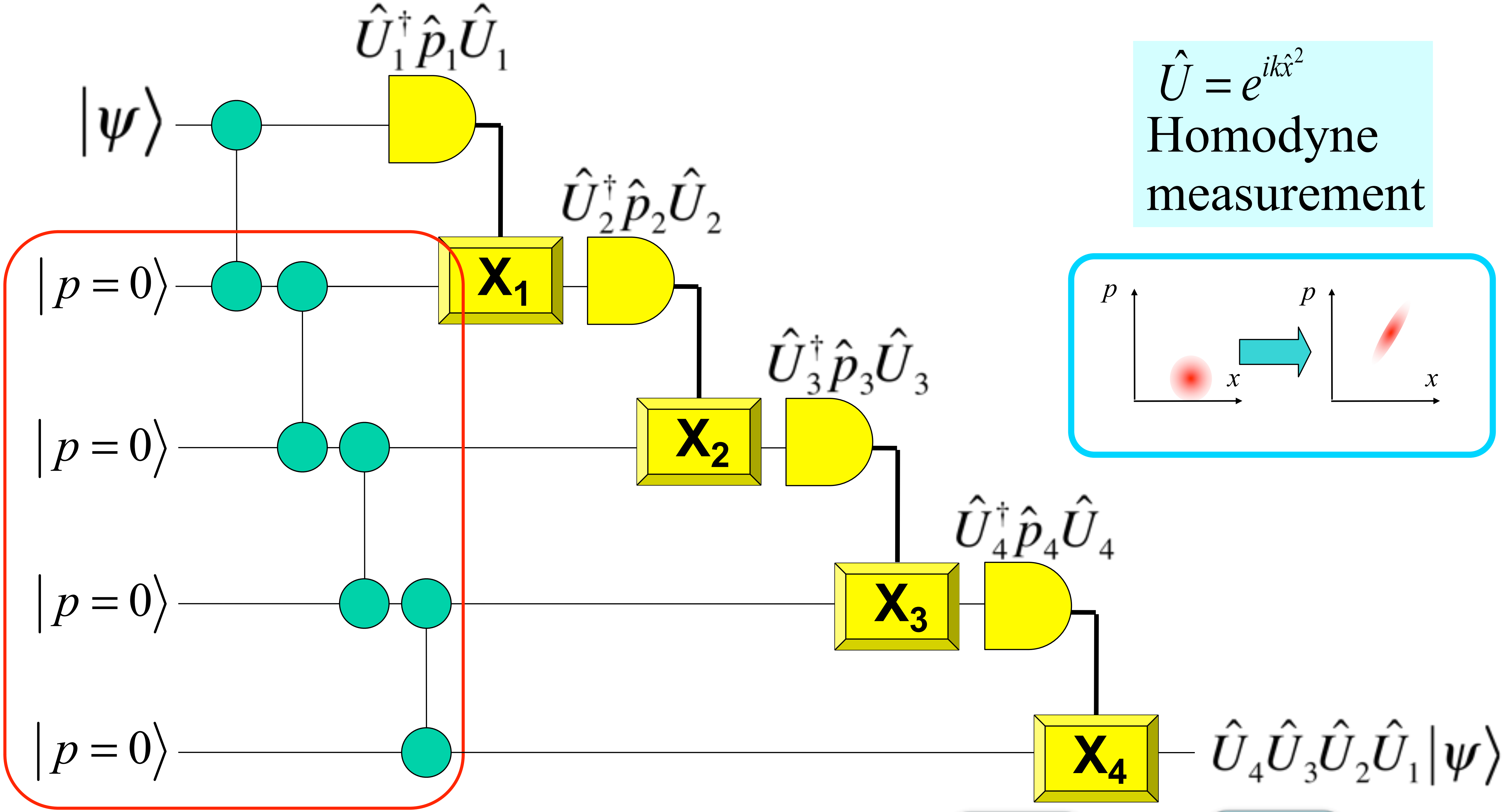
# 4-mode diamond-shape cluster type multipartite entanglement

$$\begin{cases} \hat{p}_1 - \hat{x}_3 - \hat{x}_4 \to 0 \\ \hat{p}_2 - \hat{x}_3 - \hat{x}_4 \to 0 \\ \hat{p}_3 - \hat{x}_1 - \hat{x}_2 \to 0 \\ \hat{p}_4 - \hat{x}_1 - \hat{x}_2 \to 0 \end{cases}$$

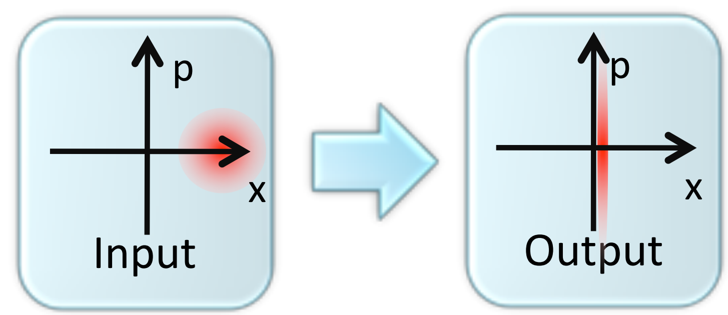



M. Yukawa, R. Ukai, P. van Loock, and A. Furusawa, Phys. Rev. A 78, 012301 (2008)

# one-way quantum computation with cluster states




Four-mode linear cluster state

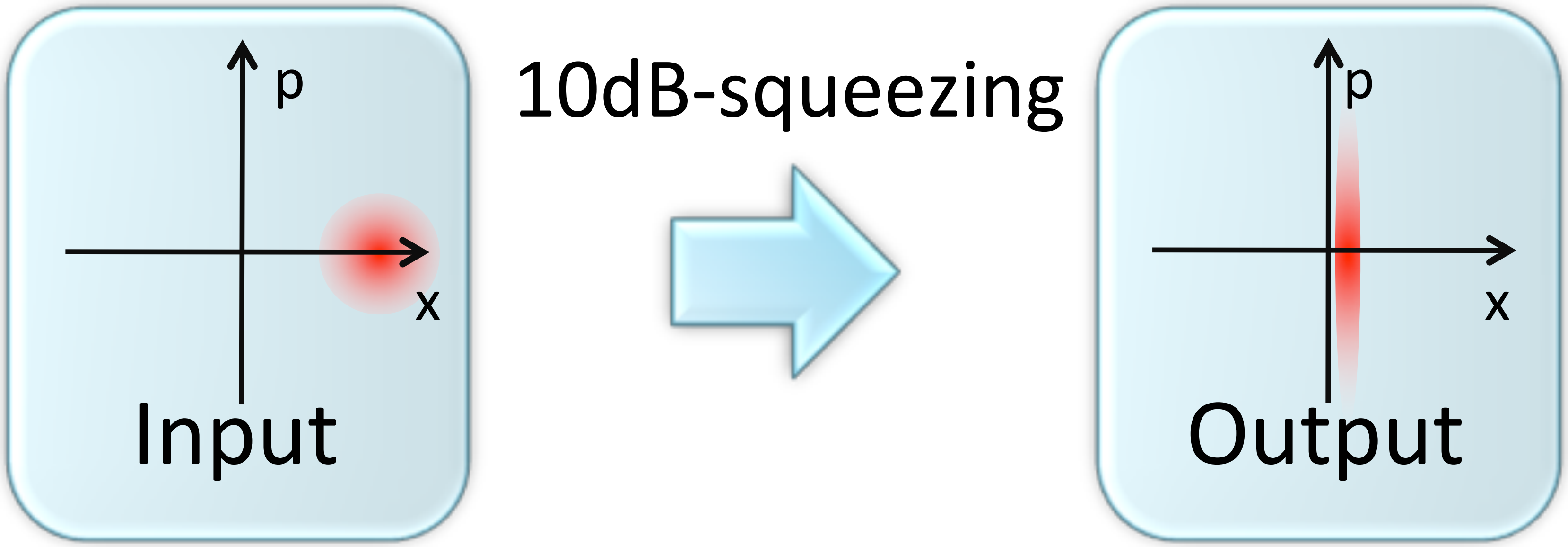


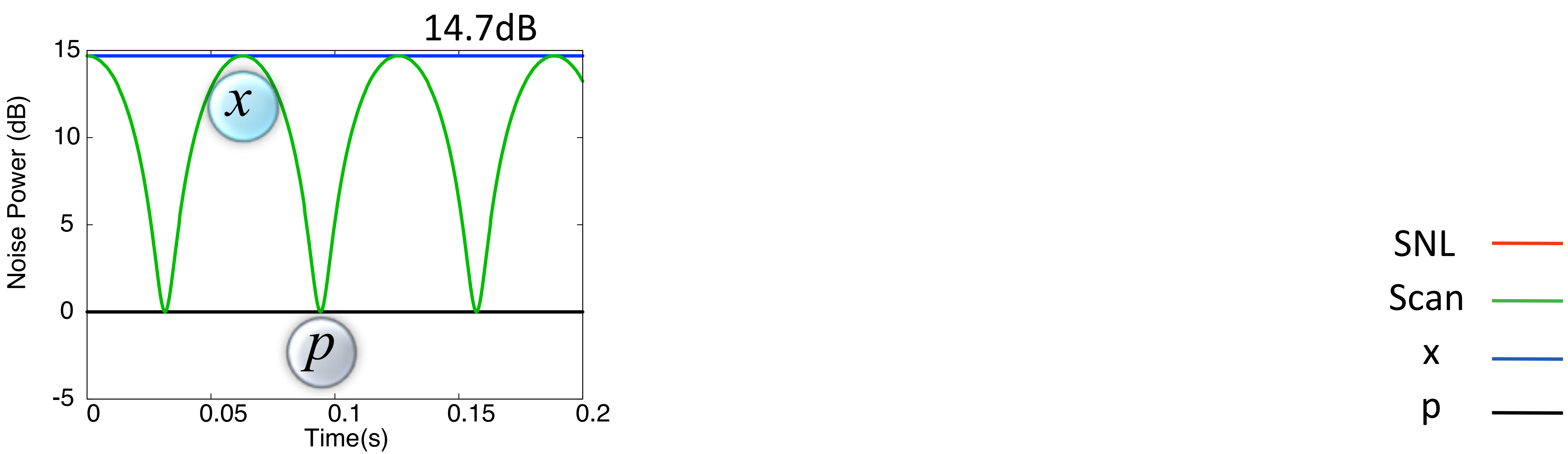

**Pure squeezing**

**R. Ukai, N. Iwata, Y. Shimokawa, S. C. Armstrong, A. Politi, J. Yoshikawa, P. van Loock & A. Furusawa, Phys. Rev. Lett. 106, 240504 (2011)**

# Squeezing operation with a four-mode linear cluster state

**Theoretical predictions**

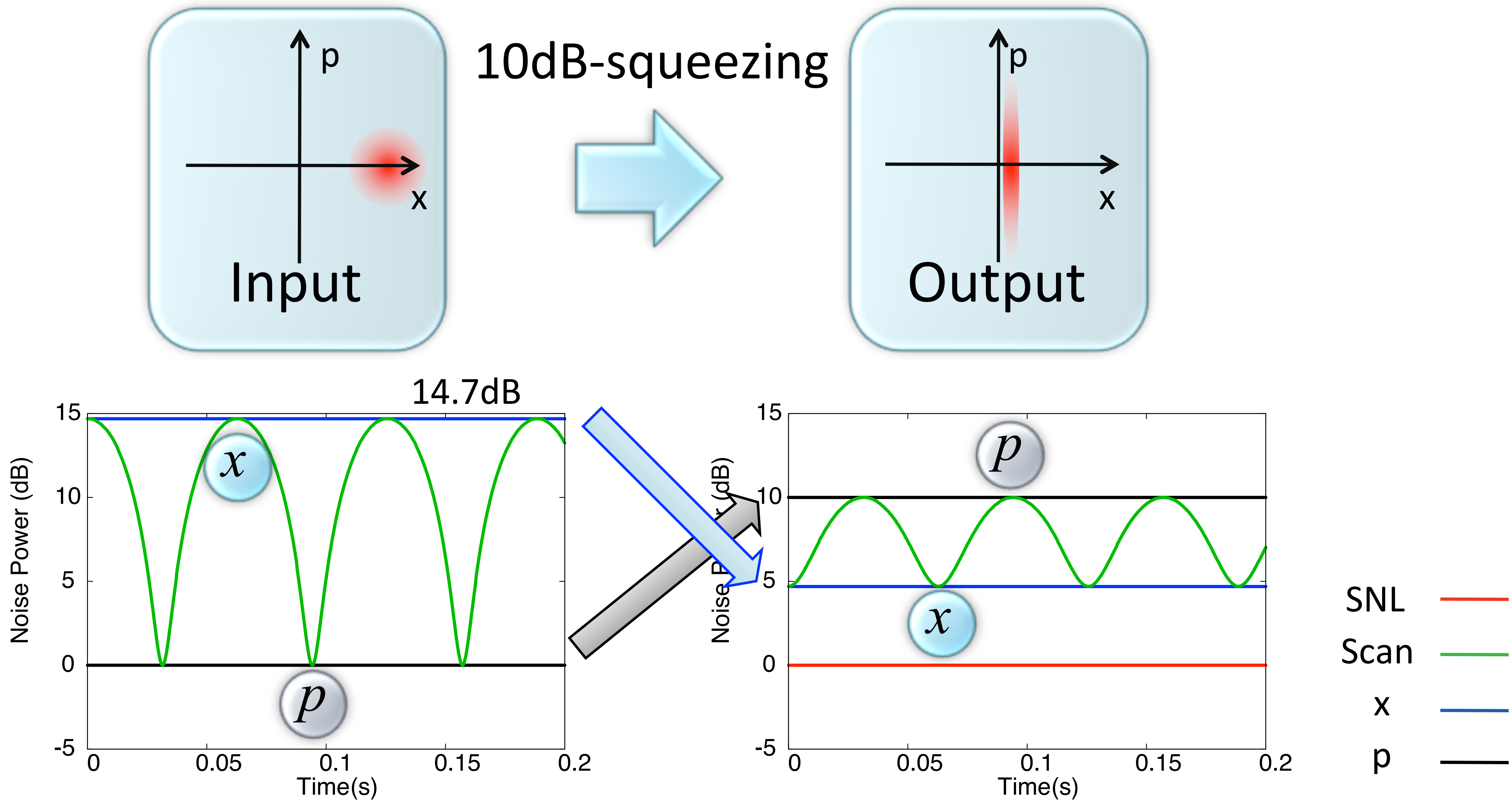



R. Ukai, N. Iwata, Y. Shimokawa, S. C. Armstrong, A. Politi, J. Yoshikawa, P. van Loock & A. Furusawa, Phys. Rev. Lett. 106, 240504 (2011)

# Squeezing operation with a four-mode linear cluster state

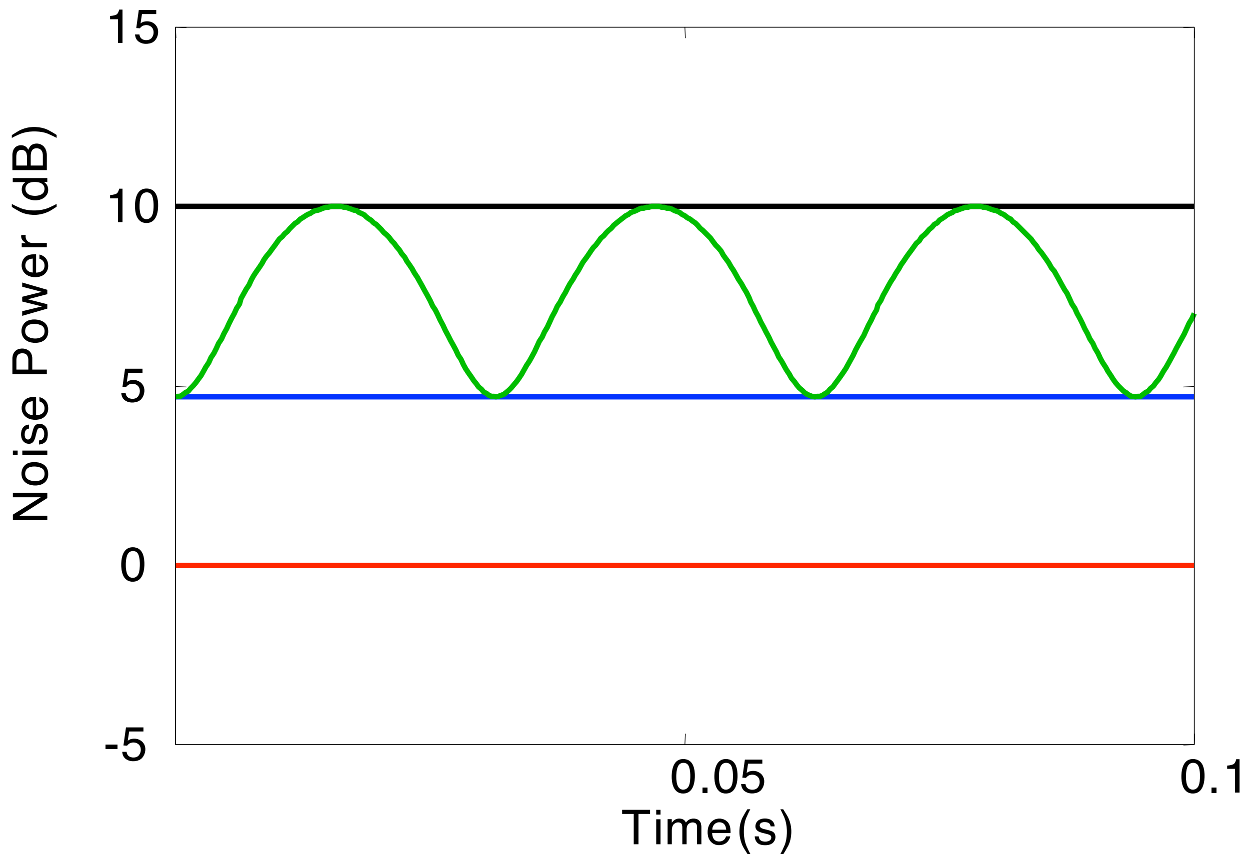
**Theoretical predictions**




R. Ukai, N. Iwata, Y. Shimokawa, S. C. Armstrong, A. Politi, J. Yoshikawa, P. van Loock & A. Furusawa, Phys. Rev. Lett. 106, 240504 (2011)

# Squeezing operation with a four-mode linear cluster state

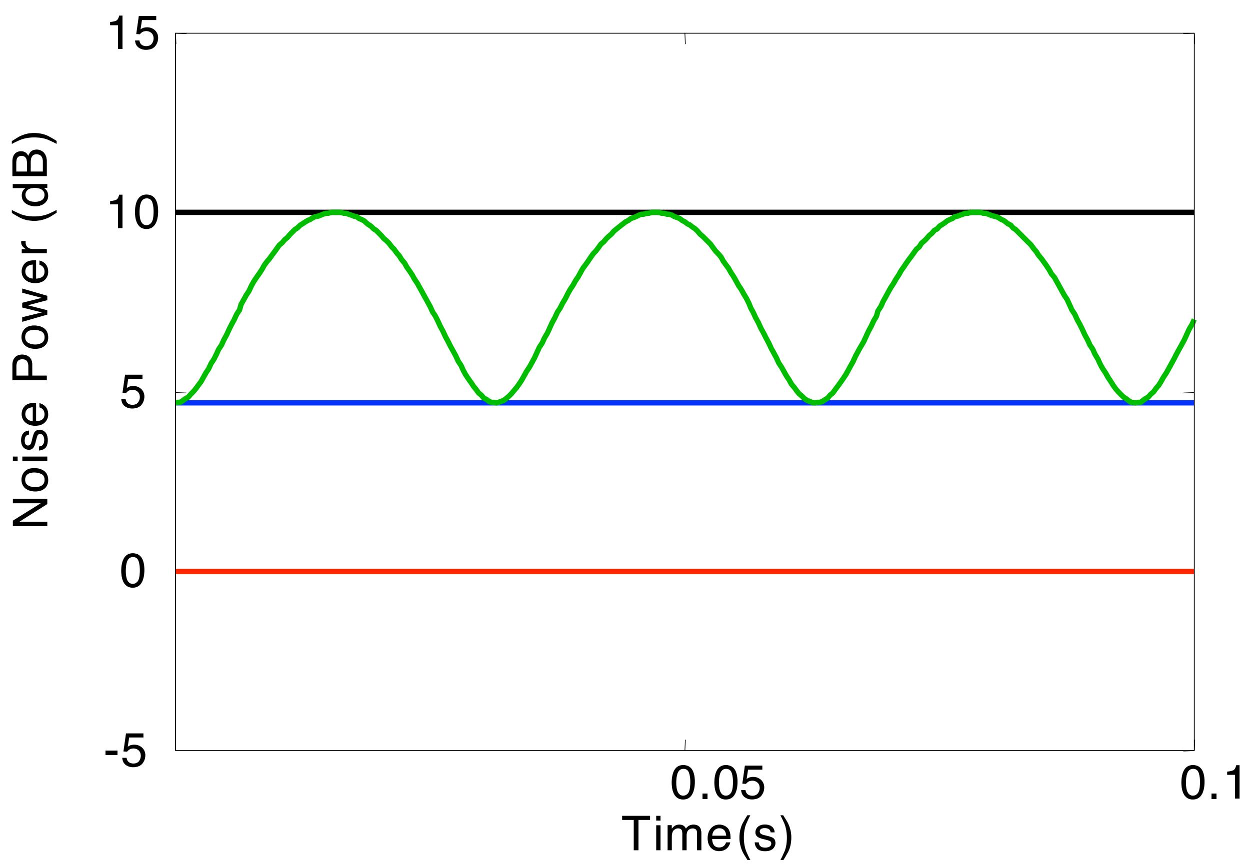
## Theoretical predictions



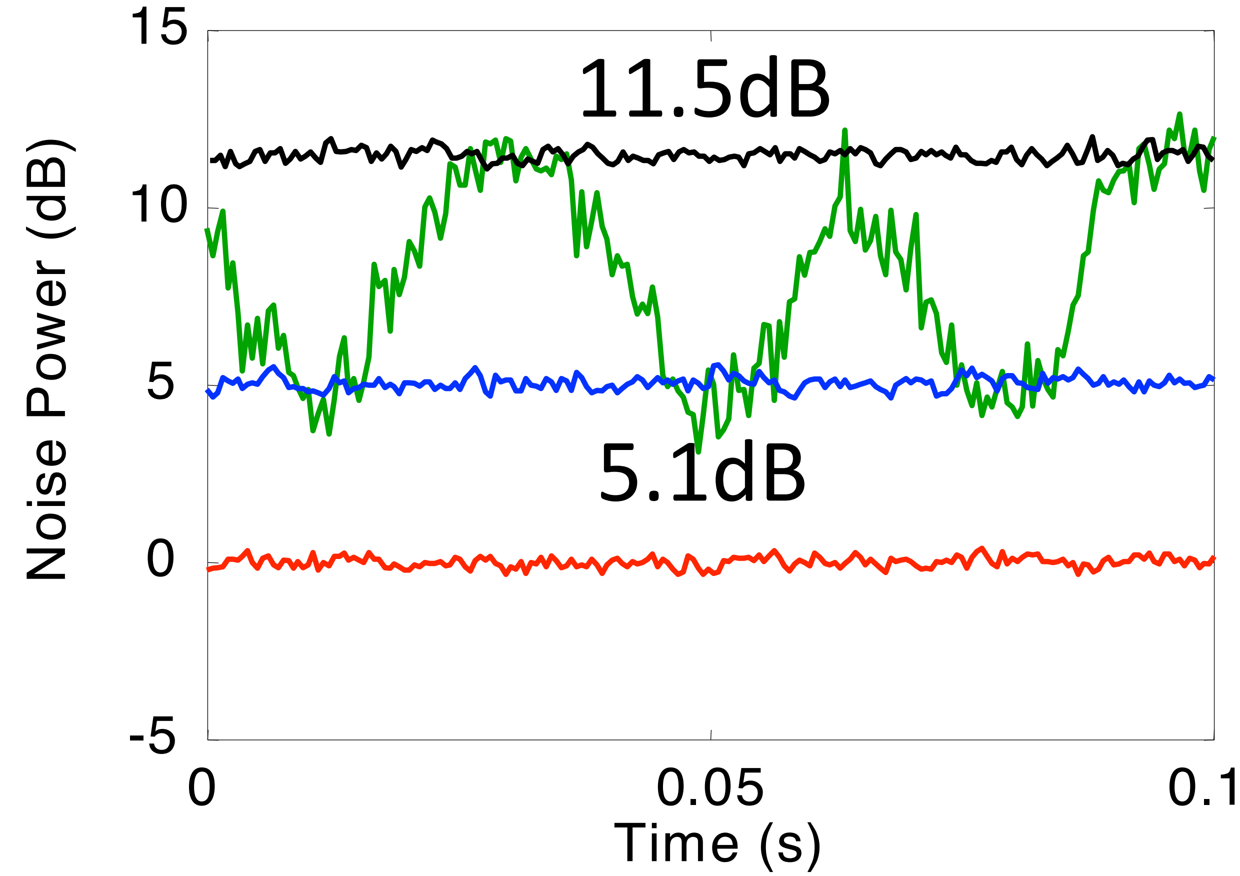

R. Ukai, N. Iwata, Y. Shimokawa, S. C. Armstrong, A. Politi, J. Yoshikawa, P. van Loock & A. Furusawa, Phys. Rev. Lett. 106, 240504 (2011)

# Squeezing operation with a four-mode linear cluster state

## Theoretical predictions



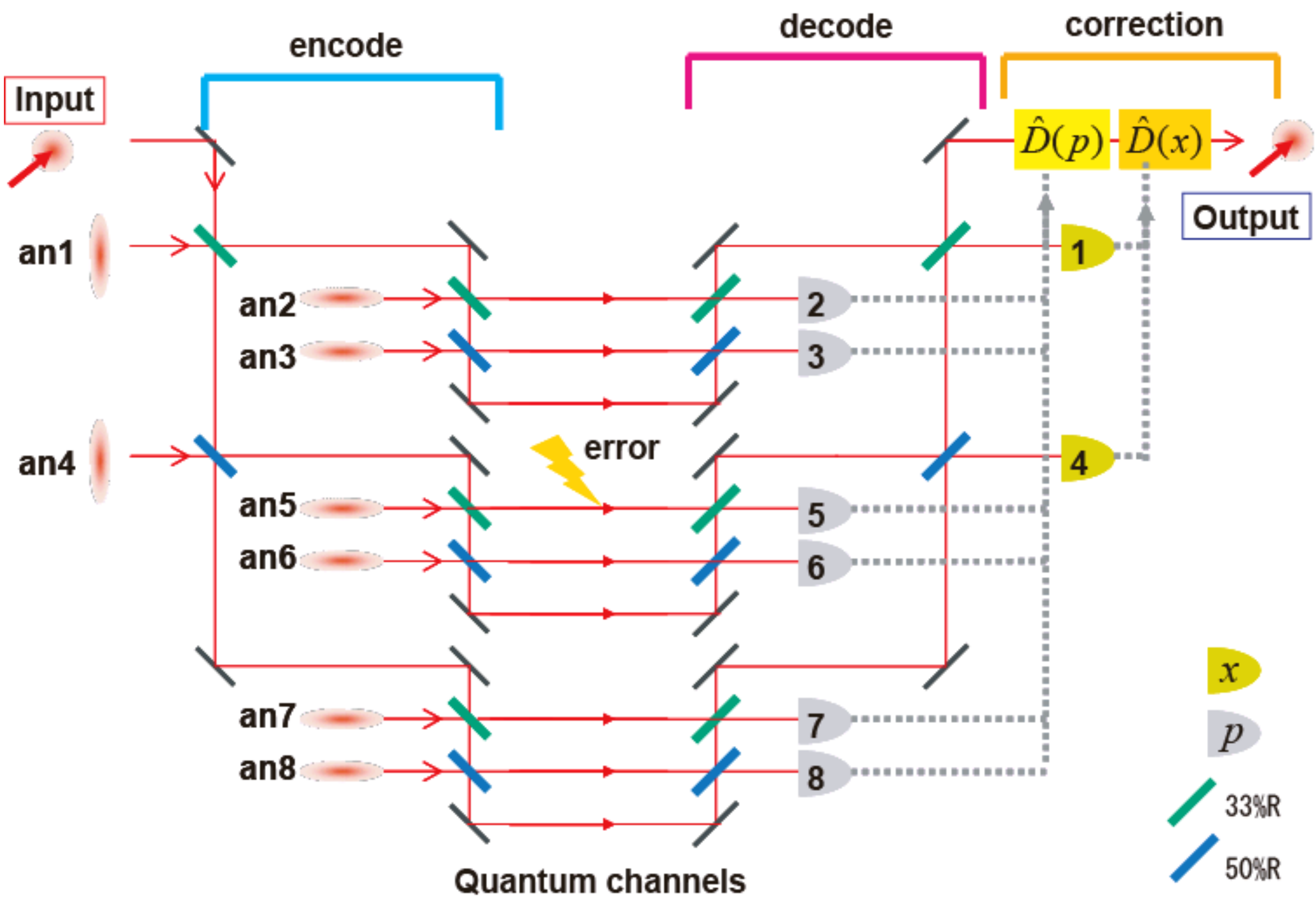

## Experimental results

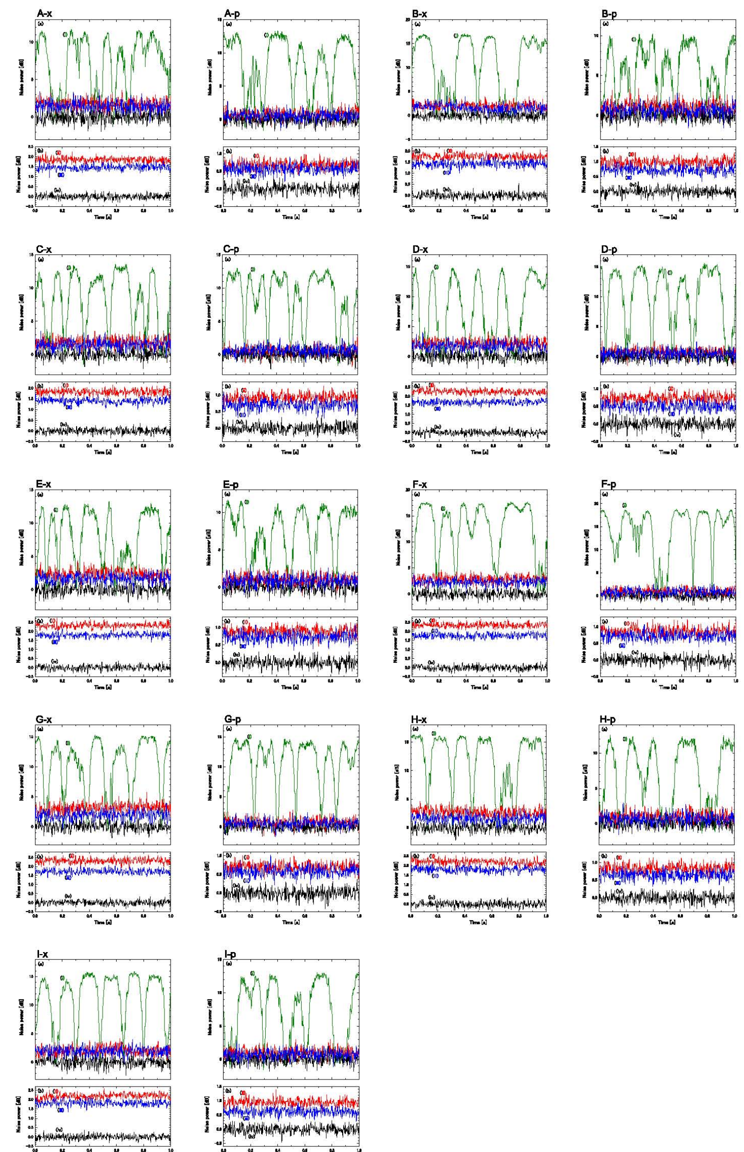




**R. Ukai, N. Iwata, Y. Shimokawa, S. C. Armstrong, A. Politi, J. Yoshikawa, P. van Loock & A. Furusawa, Phys. Rev. Lett. 106, 240504 (2011)**

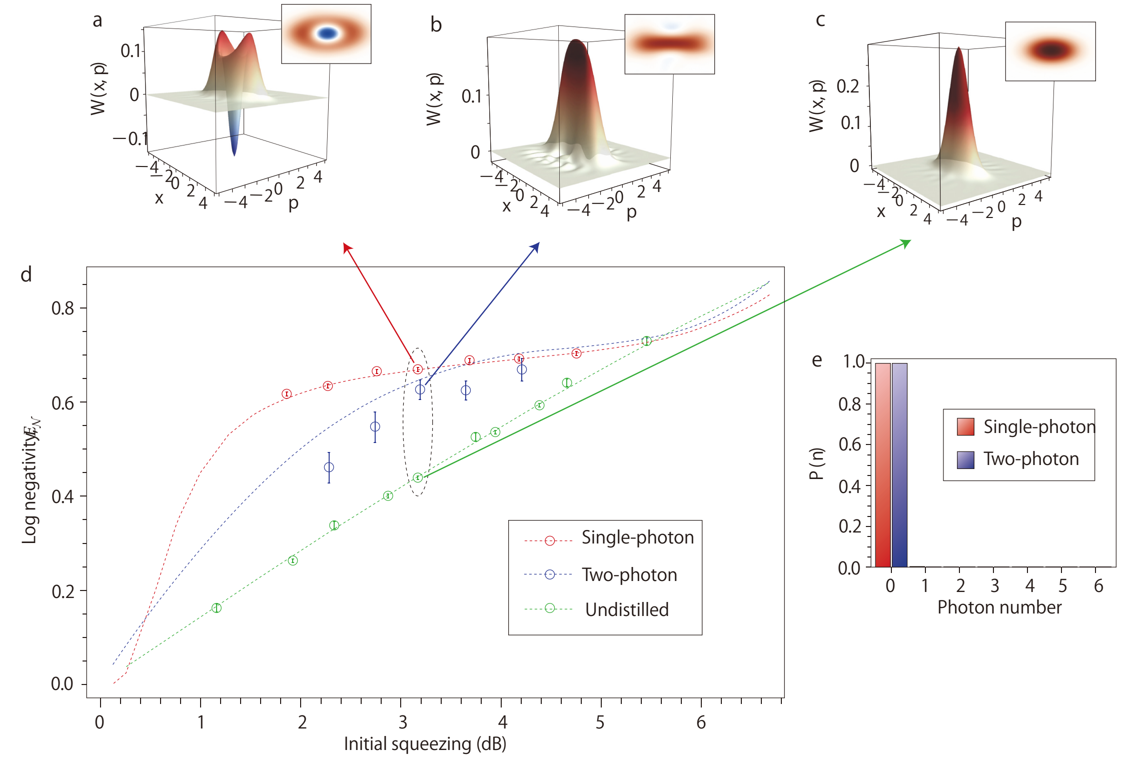
# Quantum error correction for continuous variables

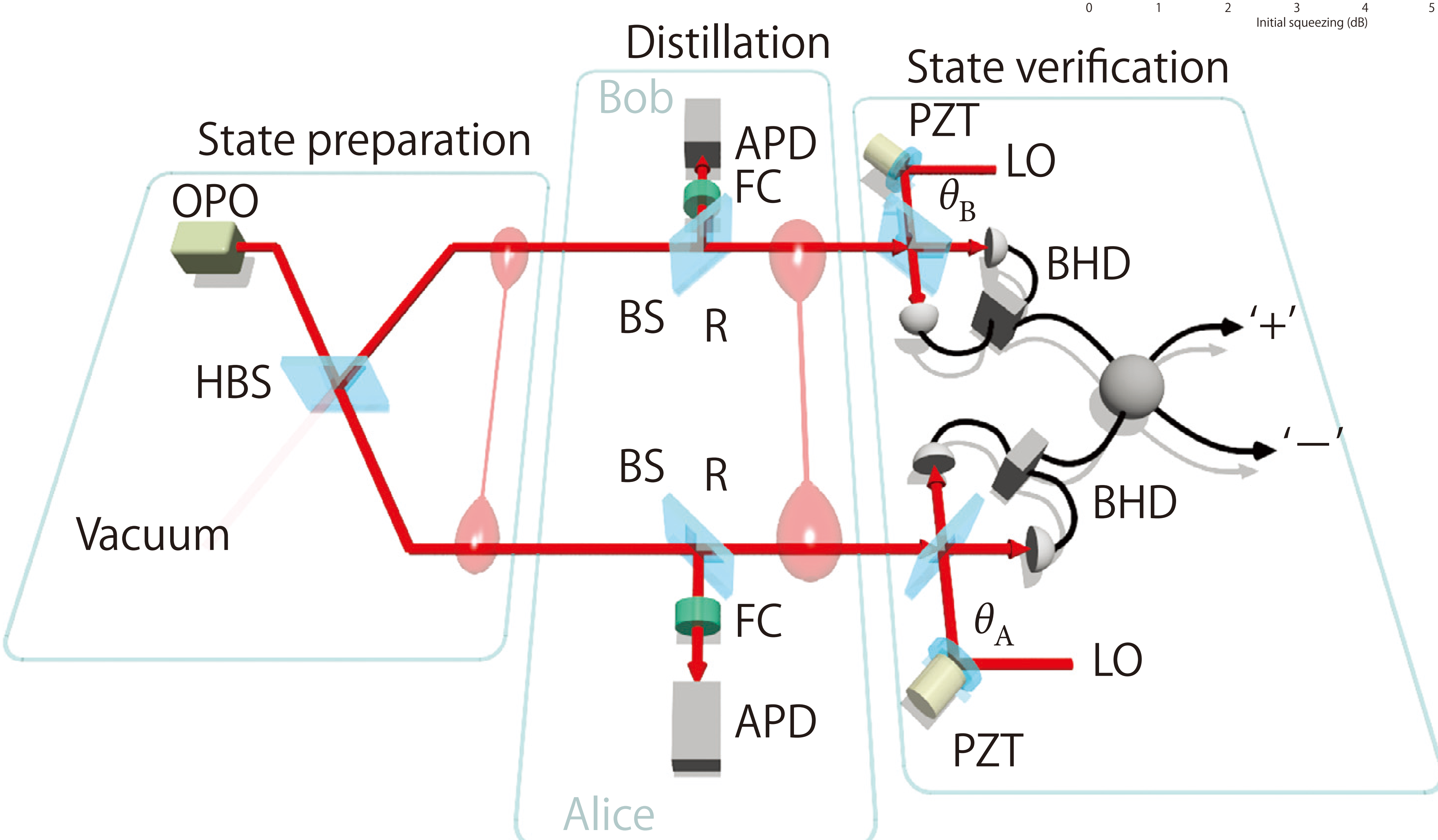


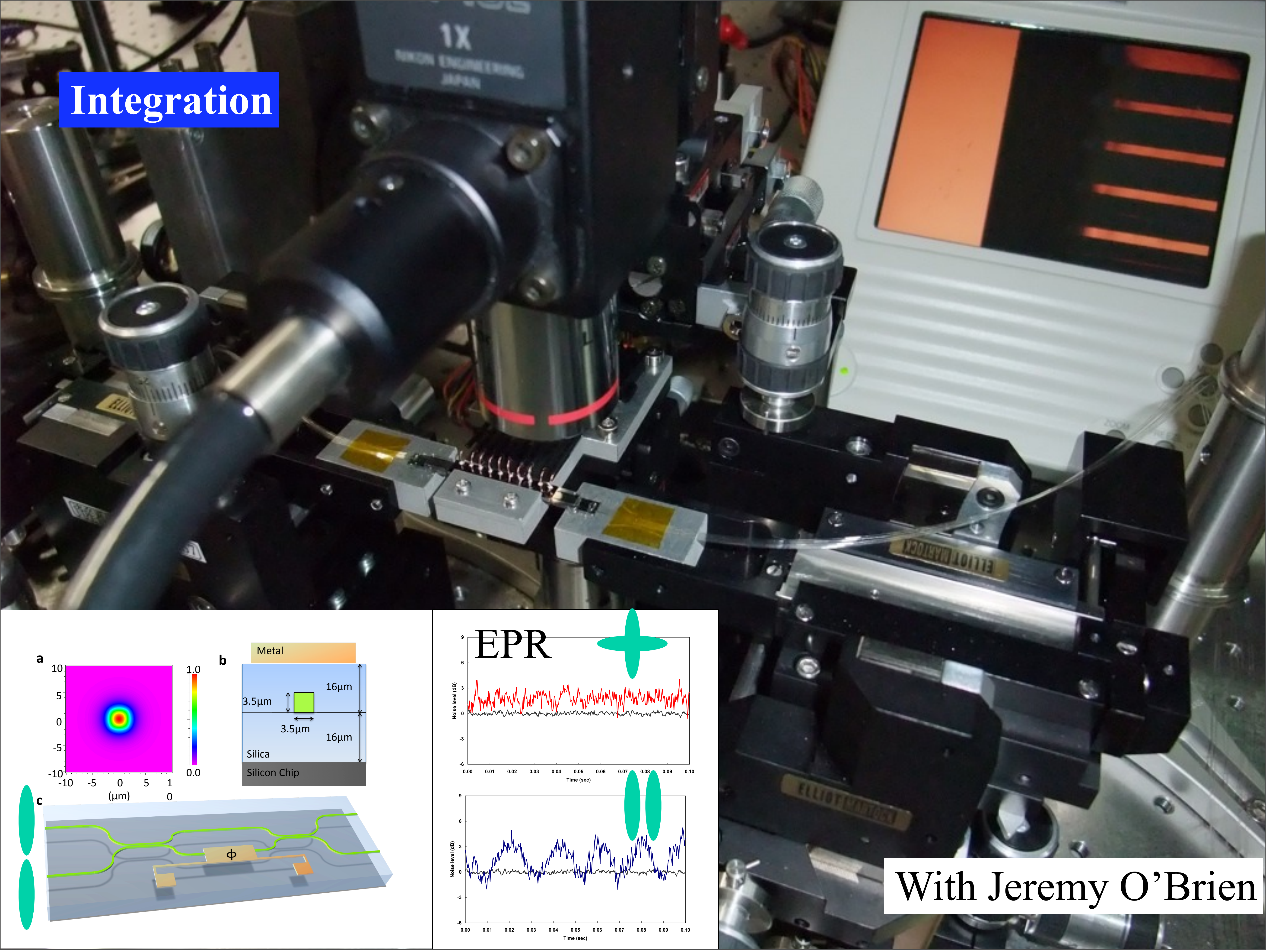
T. Aoki, G. Takahashi, T. Kajiya, J. Yoshikawa, S. L. Braunstein, P. van Loock, and A. Furusawa
Nature Physics 5, 541 (2009)

# Entanglement distillation for Gaussian states with non-Gaussian operation



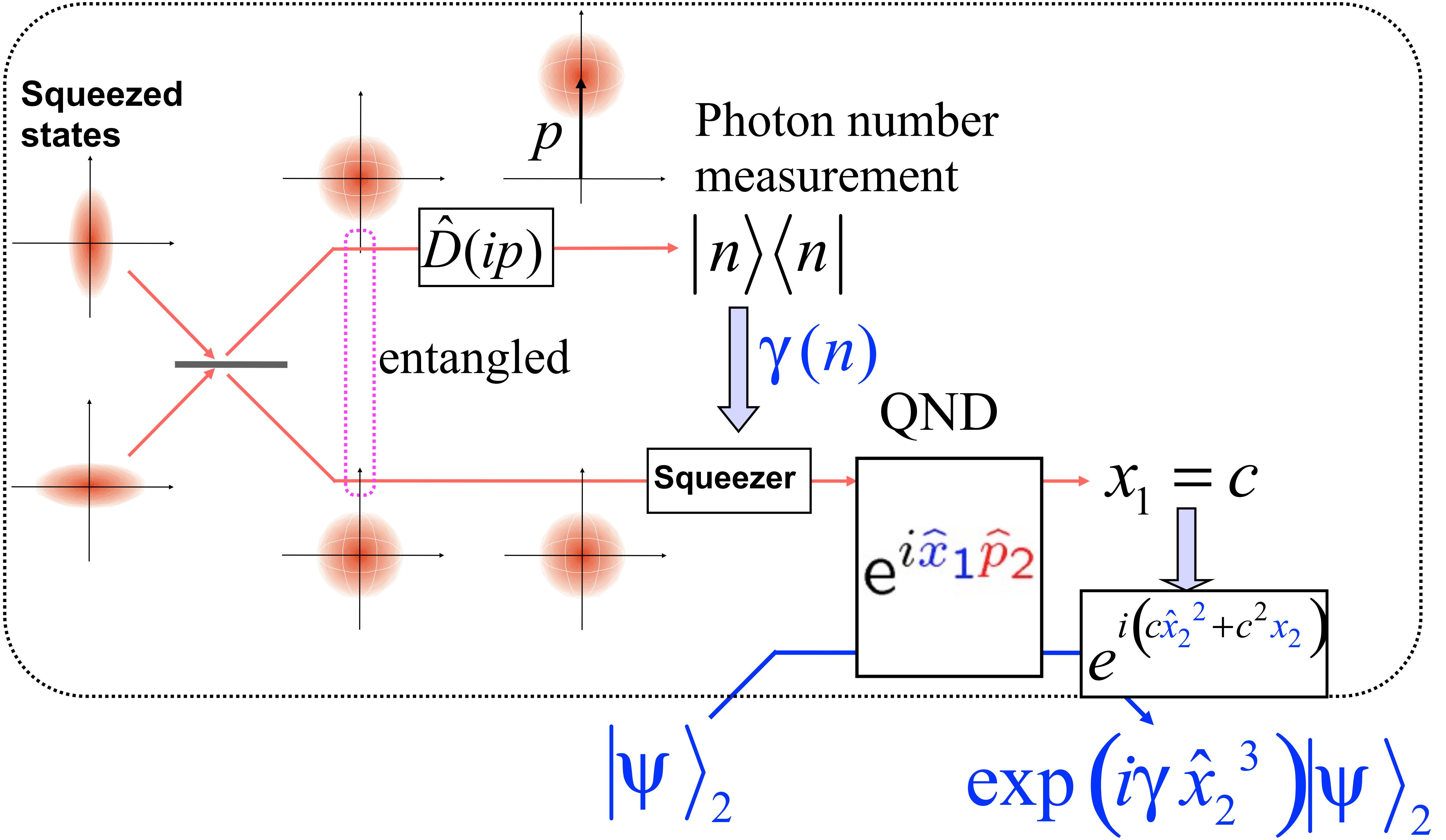

H. Takahashi, J. S. Neergaard-Nielsen, M. Takeuchi, M. Takeoka, K. Hayasaka, A. Furusawa, M. Sasaki, Nature Photonics 4, 178 (2010)


Integration
1X
a
b
c
Metal
16µm
3.5µm
3.5µm
16µm
Silica
Silicon Chip
(µm)
1.0
0.0
Φ
EPR
Noise level (dB)
Time (sec)
With Jeremy O'Brien

# Measurement induced nonlinearity

Cubic phase gate: $\hat{V}_\gamma = \exp\left(i\gamma\,\hat{x}^3\right)$

**Gottesman, et al. PRA64, 012310 (2001).**



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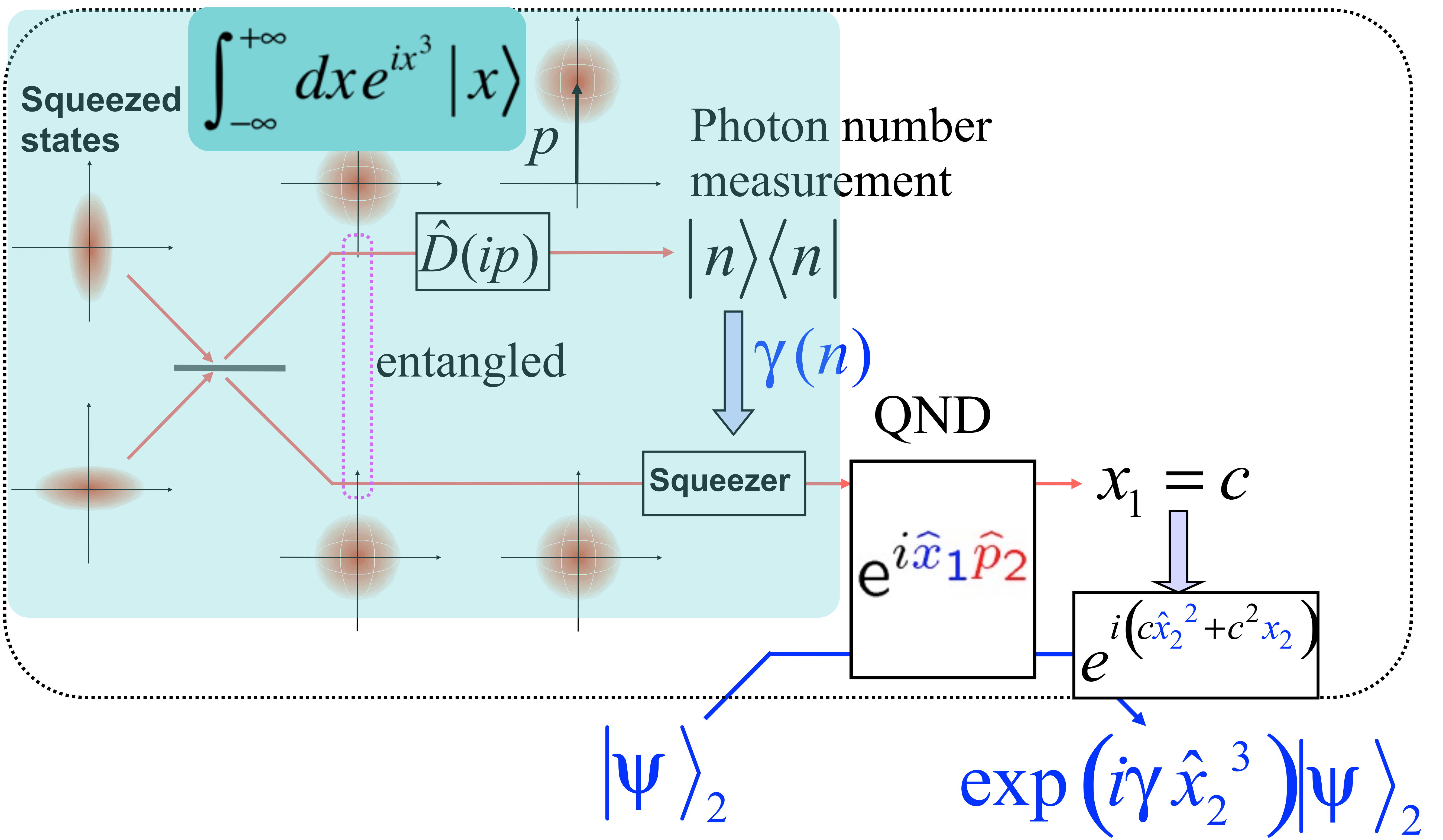

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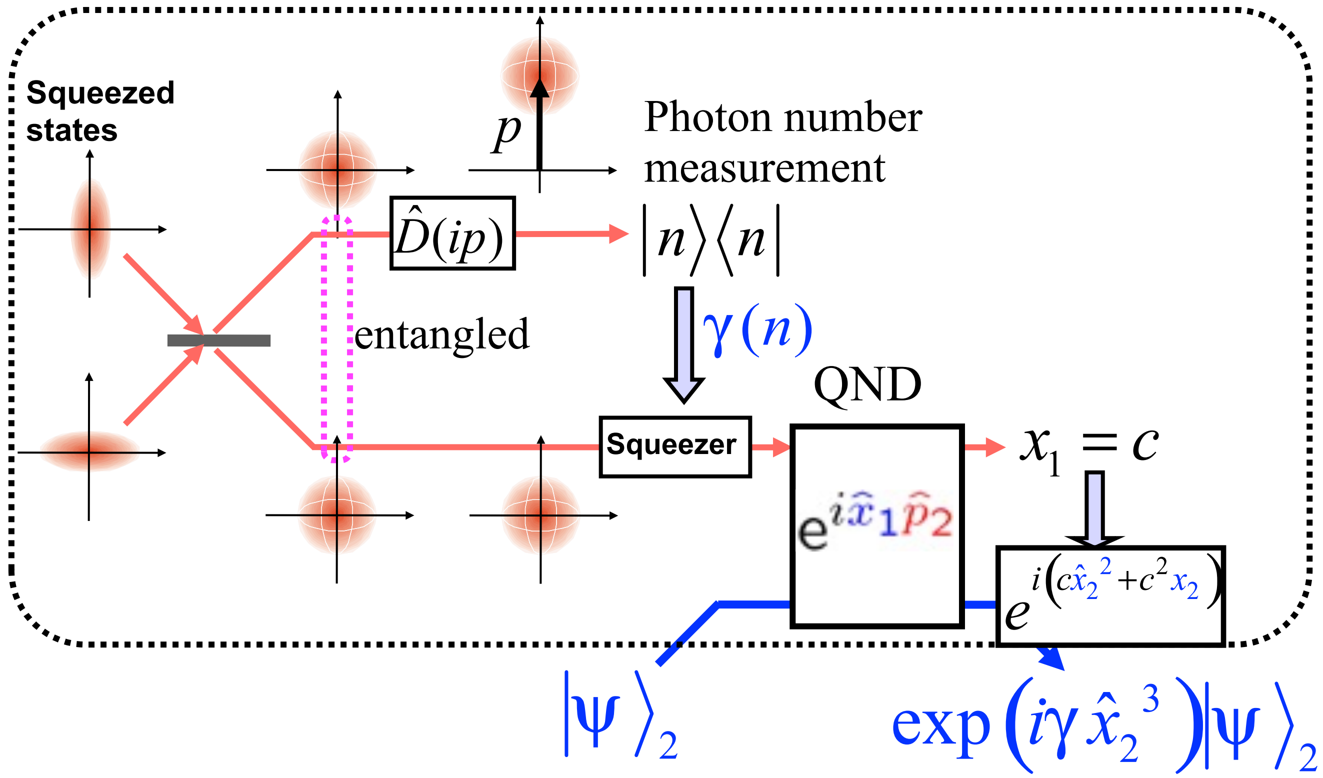
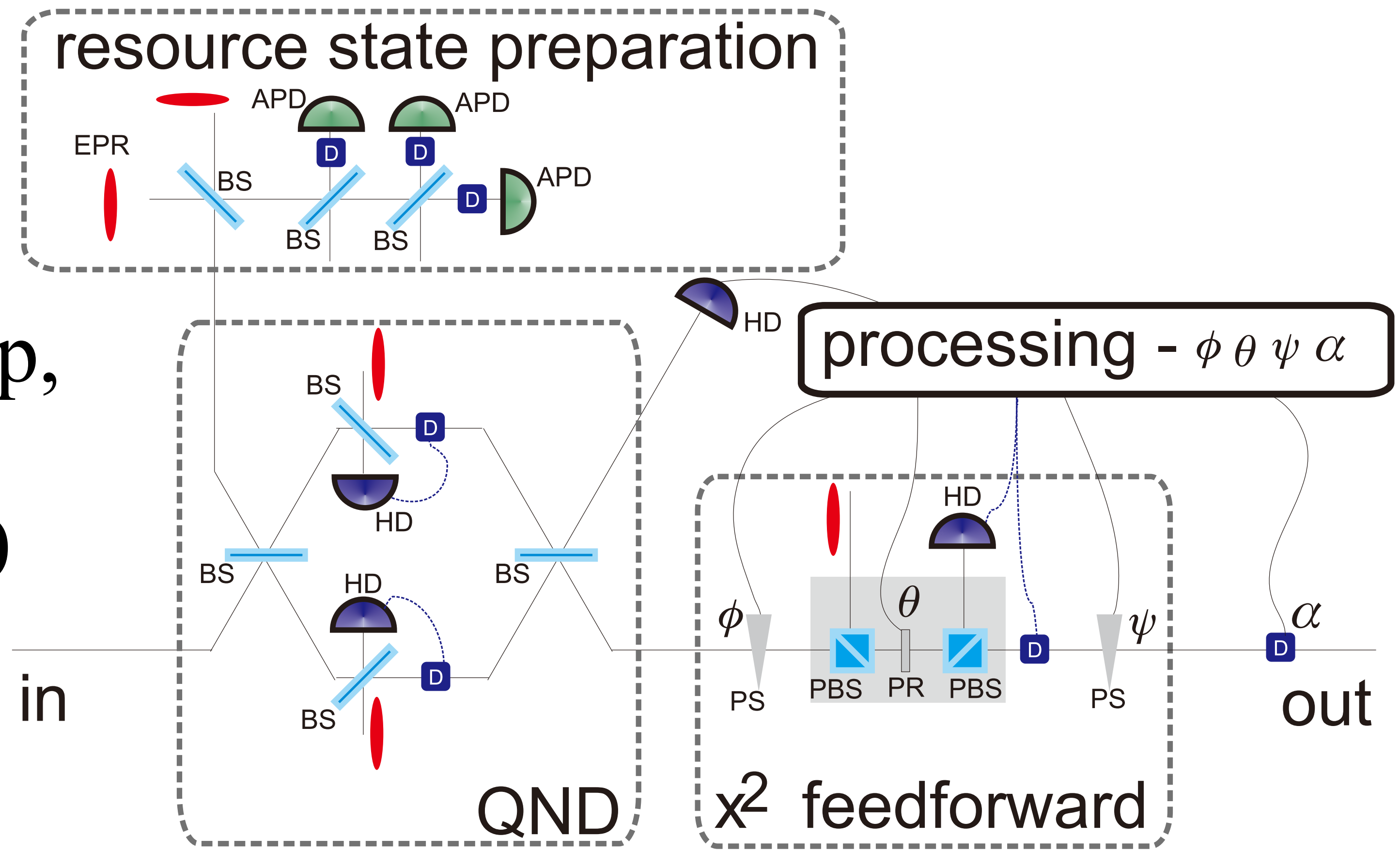
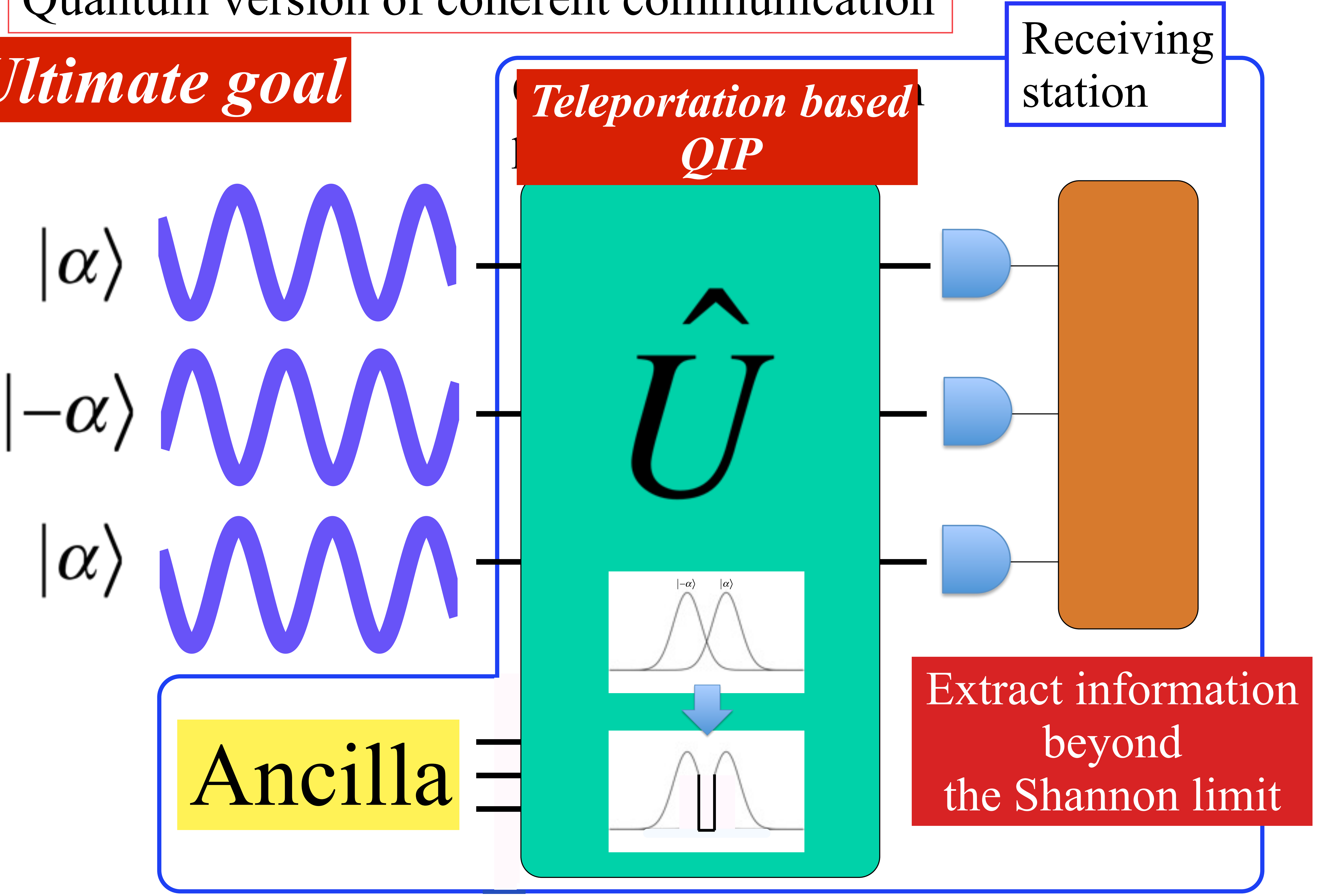



P. Marek, R. Filip, A. Furusawa, arXiv:1105:4950 [quant-ph]



Quantum version of coherent communication

***Ultimate goal***




We need QIP for coherent states of light!!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Akira Furusawa and Peter van Loock

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# Quantum Teleportation and Entanglement

A Hybrid Approach to Universal Quantum Information Processing