Optical Hybrid Quantum Teleportation and Its Application to Large-Scale Quantum Computing

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JST PRESTO

Optical Hybrid Quantum Teleportation and Its Application to Large-Scale Quantum Computing

Our group at the Univ. of Tokyo

Optical continuous-variable QIP

- Quantum teleportation
- Quantum gates
- Cluster-state generation
- Single-photon source

Our group at the Univ. of Tokyo

Collaborators

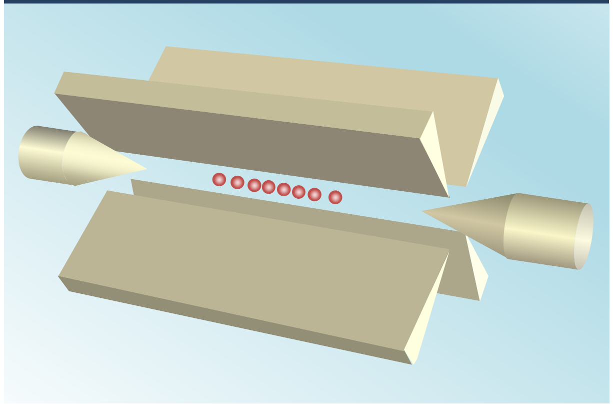
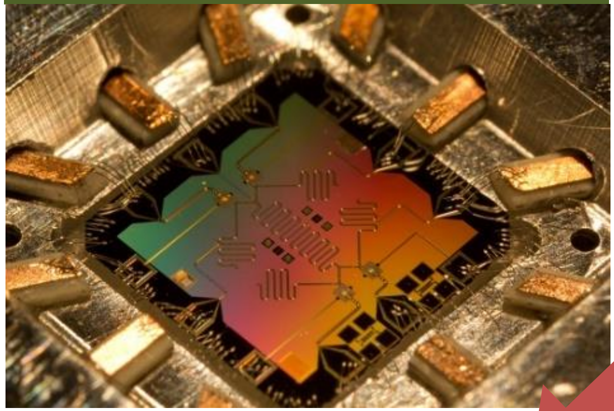
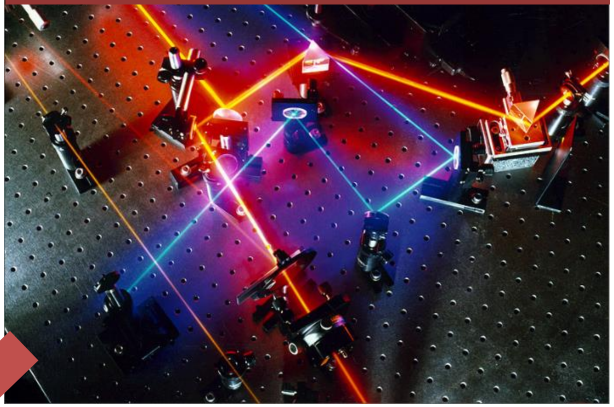
R. Filip

P. Marek

P. van Loock

Introduction

Various physical systems for quantum computing

Atom/Ion	Superconductor	Light
		

Advantages of optical QC

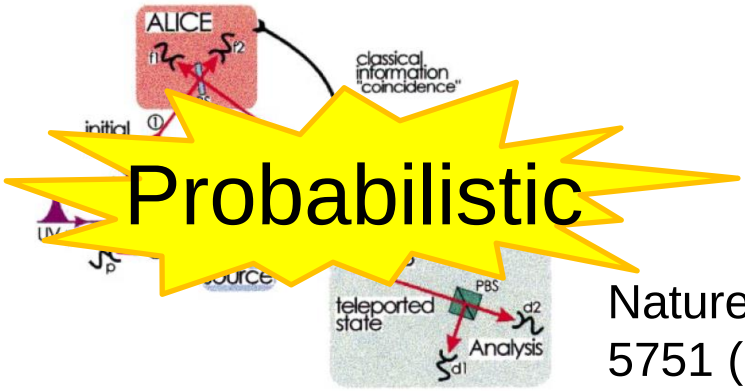
- No need for vacuum/cooling system
- Suitable for quantum communication

Obstacles for large-scale optical QC

- Probabilistic operations on qubits

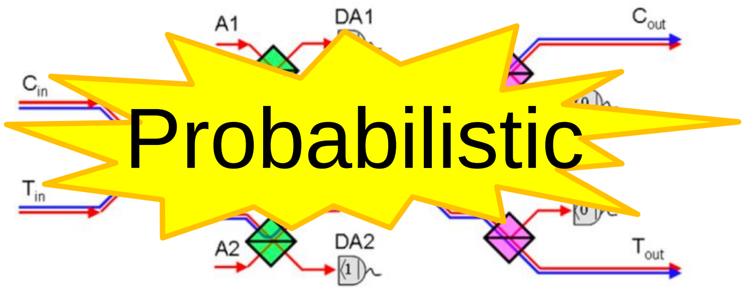
Introduction

Quantum teleportation



Nature **390**, 5751 (1997)

CNOT gate



PNAS **108**, 10067 (2011)

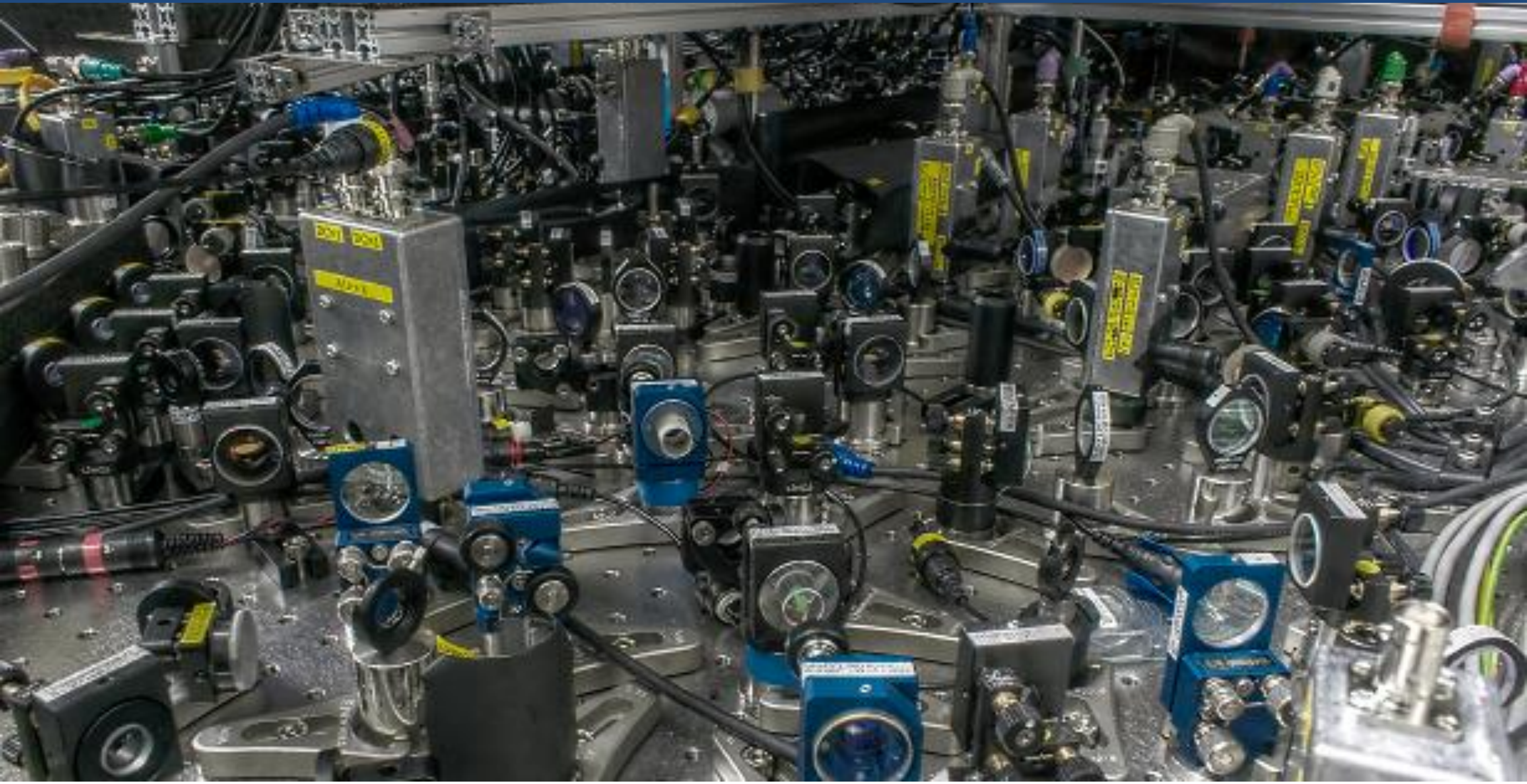
Quantum error correction

Nature **482**, 489 (2012)

<u>Obstacles for large-scale optical QC</u>

- Probabilistic operations on qubits

Introduction



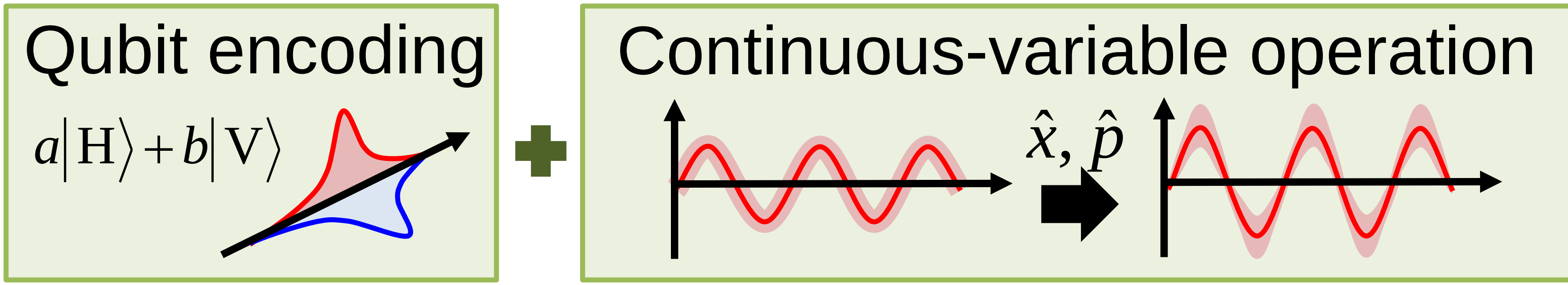
Obstacles for large-scale optical QC

- Probabilistic operations on qubits
- Not scalable, not programmable

Introduction

This talk: Our strategy for large-scale optical QC

✓Deterministic operation via hybrid approach

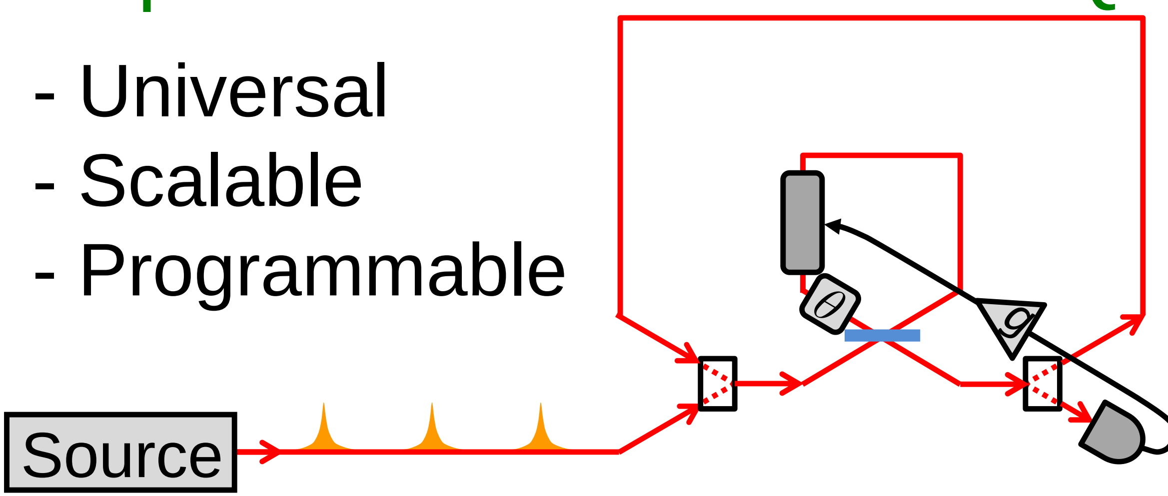


- CV quantum teleportation of qubits/qutrits
- CV quantum gates for qubits

✓Loop-based architecture for QC

- Universal
- Scalable
- Programmable

Takeda & Furusawa
PRL **119**, 120504 (2017)



Deterministic operation

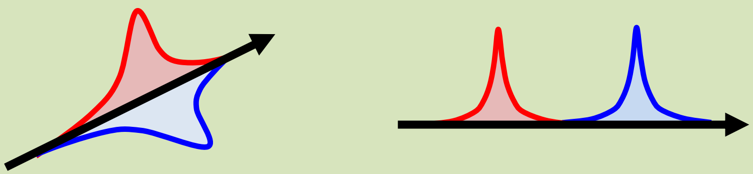
Optical Hybrid Quantum Teleportation and Its Application to Large-Scale Quantum Computing

Qubit vs CV: Physical encoding

Qubit

Digital encoding

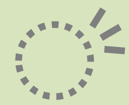
$$|\psi\rangle = a|1,0\rangle + b|0,1\rangle$$



Polarization   Time bins

Photon number

$$\hat{n} = \hat{a}^\dagger \hat{a}$$



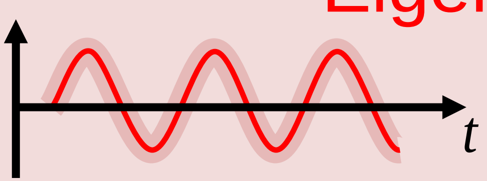
$|0\rangle$ $|1\rangle$ $|2\rangle$ …

Continuous variables

Analog encoding

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

Eigenstate



Quadratures

$$\hat{x} = \frac{\hat{a} + \hat{a}^\dagger}{\sqrt{2}}, \hat{p} = \frac{\hat{a} - \hat{a}^\dagger}{i\sqrt{2}}$$

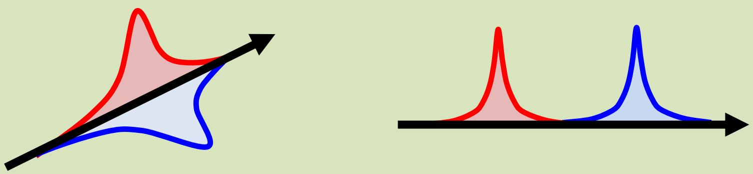
$$\hat{E}(t) \propto \hat{x}\sin\omega t + \hat{p}\cos\omega t$$

Qubit vs CV: Physical encoding

Qubit

Digital encoding

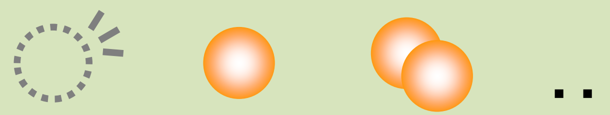
$$|\psi\rangle = a|1,0\rangle + b|0,1\rangle$$



Polarization Time bins

Photon number

$$\hat{n} = \hat{a}^{\dagger}\hat{a}$$



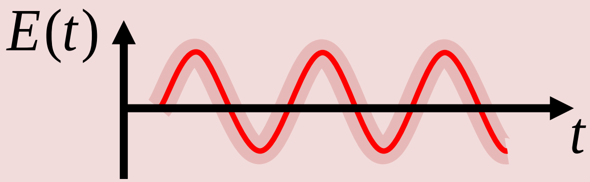
$|0\rangle$ $|1\rangle$ $|2\rangle$ …

Photon number basis

Continuous variables

Analog encoding

$$|\psi\rangle = \int_{-\infty}^{+\infty} \psi(x)|x\rangle dx = \sum_{n\geq 0} c_n |n\rangle$$



Quadratures

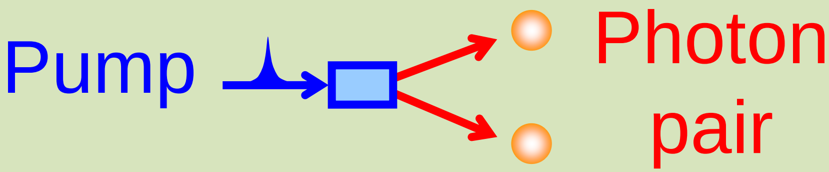
$$\hat{x} = \frac{\hat{a} + \hat{a}^{\dagger}}{\sqrt{2}}, \hat{p} = \frac{\hat{a} - \hat{a}^{\dagger}}{i\sqrt{2}}$$

$$\hat{E}(t) \propto \hat{x}\sin\omega t + \hat{p}\cos\omega t$$

Qubit vs CV: Tool box

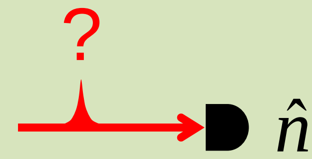
Qubit

Photon pair source



✕ Probabilistic

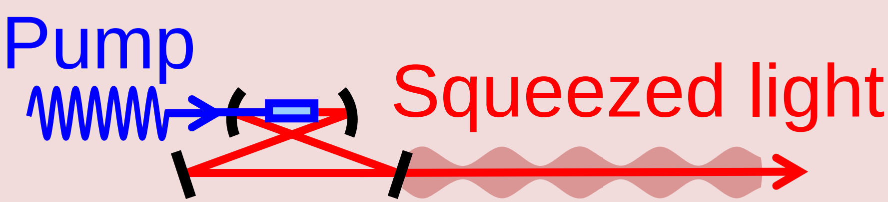
Photon counter



✕ Low efficiency & Probabilistic Bell meas.

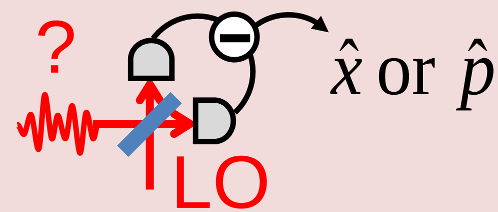
Continuous variables

Squeezed light source



✓Deterministic

Homodyne meas.

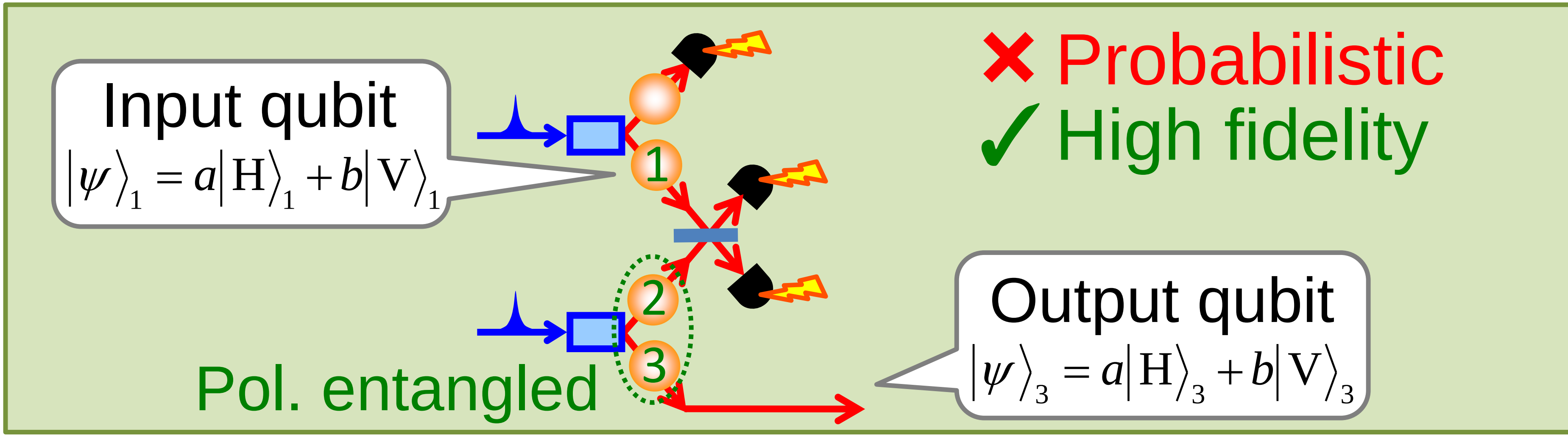


✓High efficiency & Deterministic Bell meas.

Qubit vs CV: Quantum Teleportation

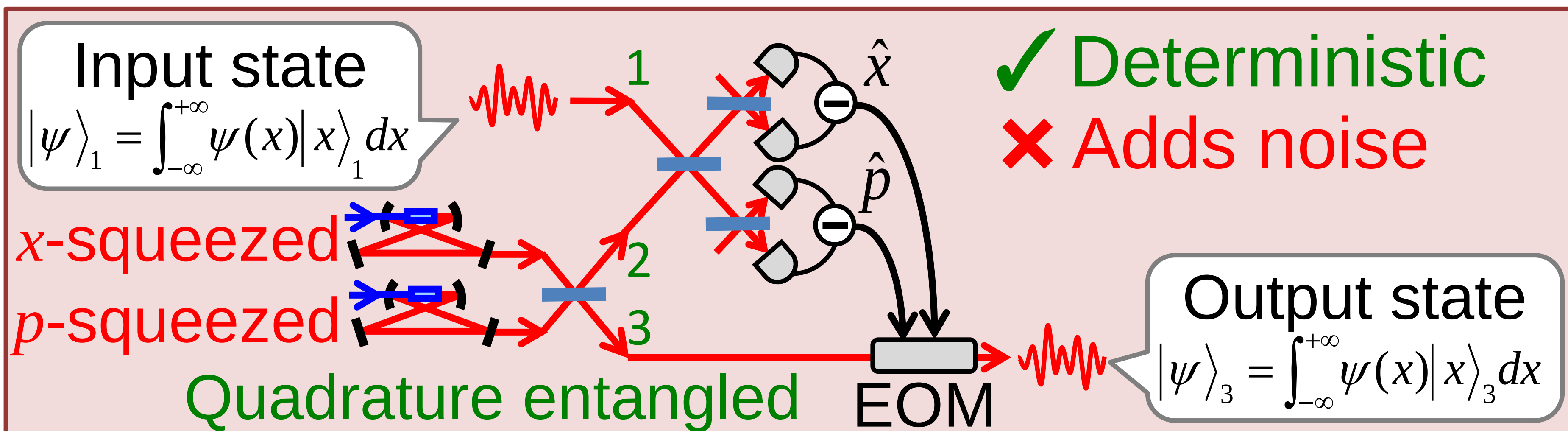
Qubit

Bouwmeester *et al*., Nature **390**, 5751 (1997)



Continuous variables

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



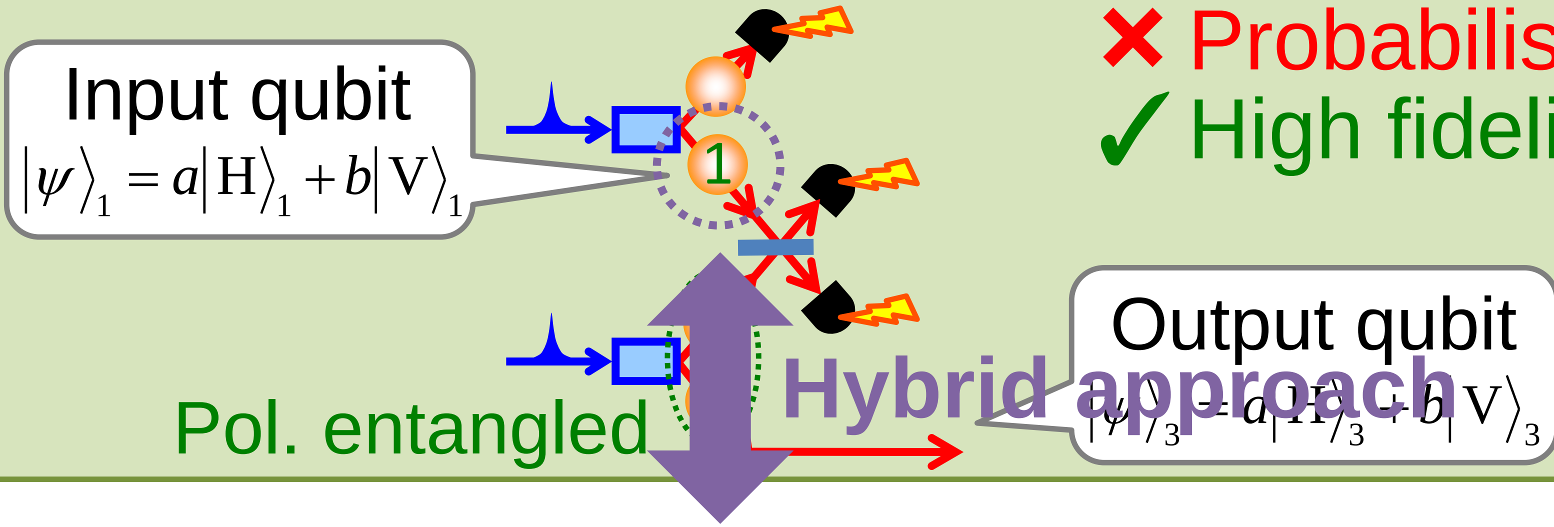
Qubit vs CV: Quantum Teleportation

Qubit

Bouwmeester *et al*., Nature **390**, 5751 (1997)

✗ Probabilistic

✓ High fidelity

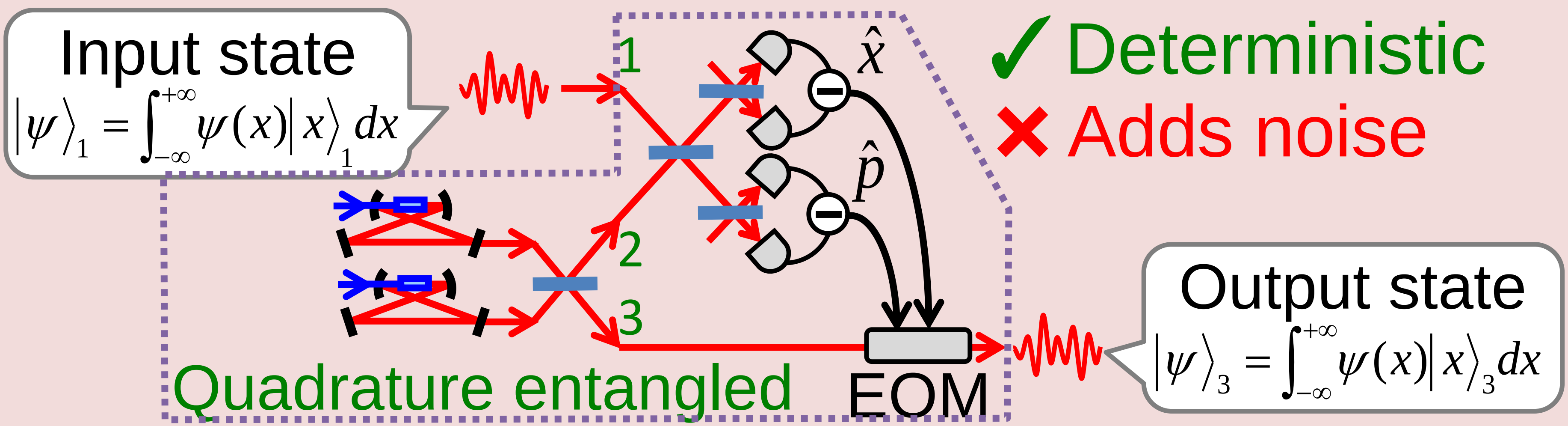


Continuous variables

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

✓ Deterministic

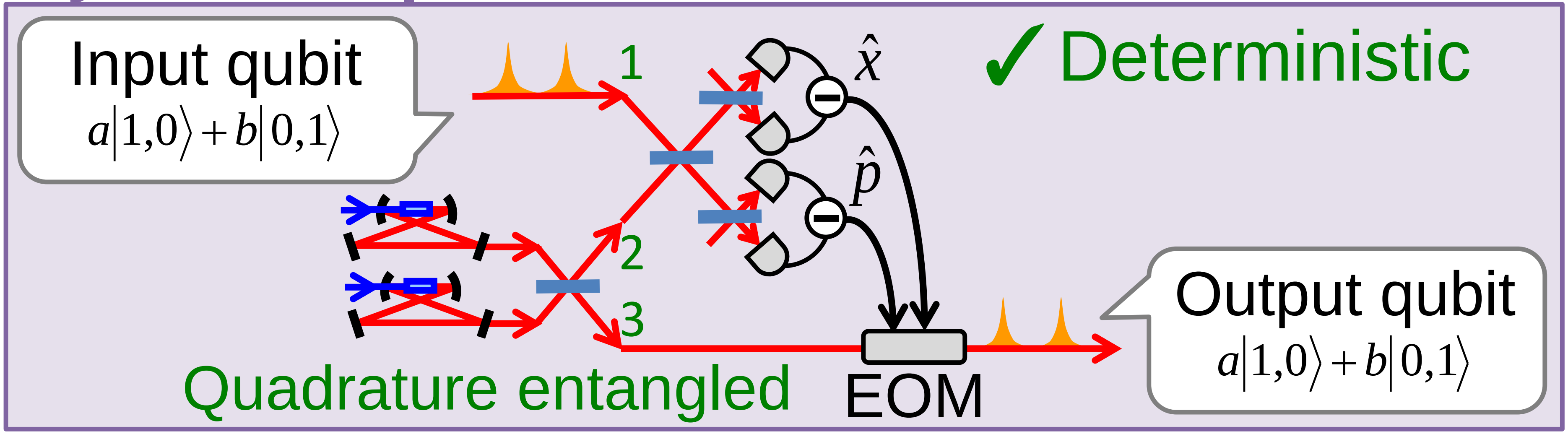
✗ Adds noise



Hybrid Quantum Teleportation

Hybrid Teleportation

<u>Takeda</u> *et al.*, Nature **500**, 315 (2013)



Hybrid Quantum Teleportation

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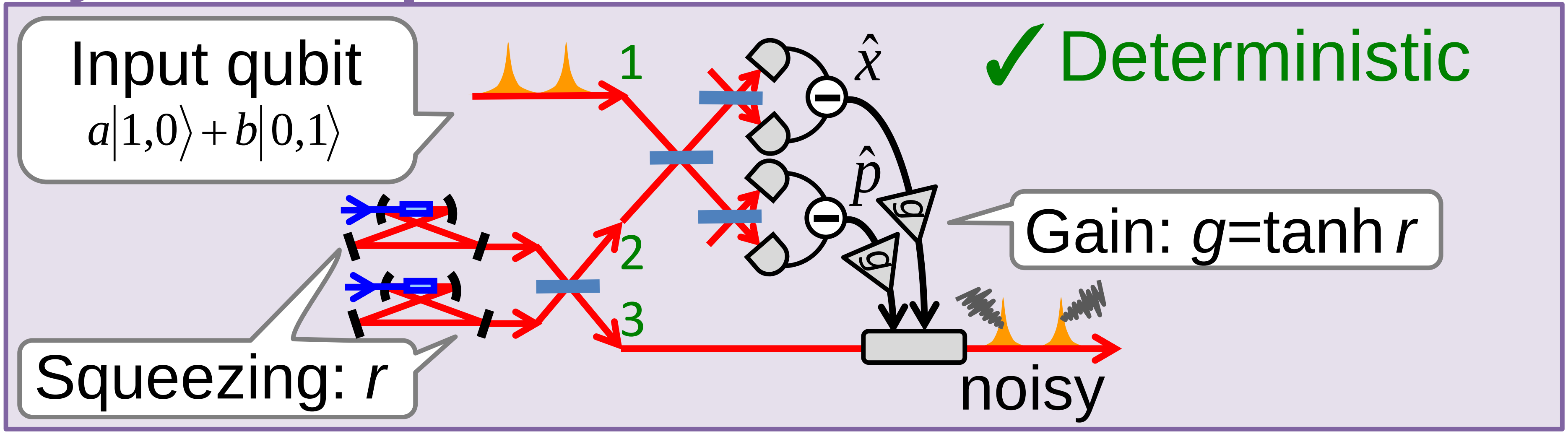
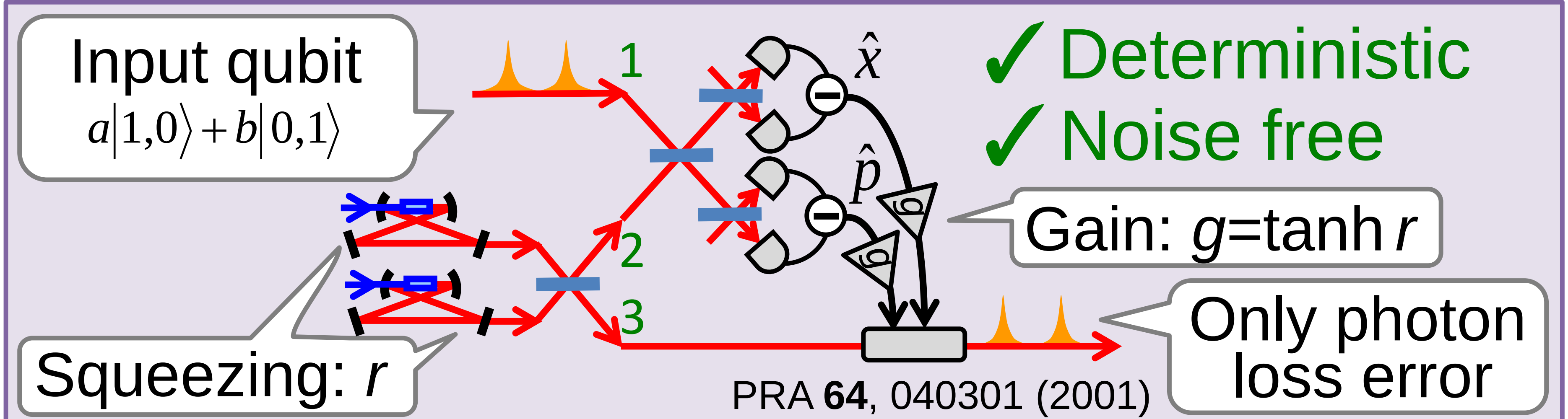


Hybrid Quantum Teleportation

Hybrid Teleportation

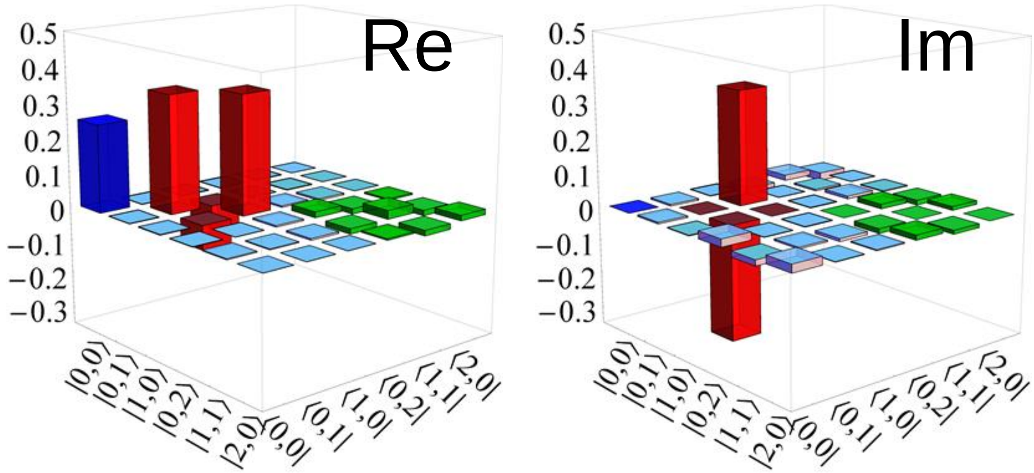
Takeda *et al.*, Nature **500**, 315 (2013)



Hybrid Quantum Teleportation

Before teleportation

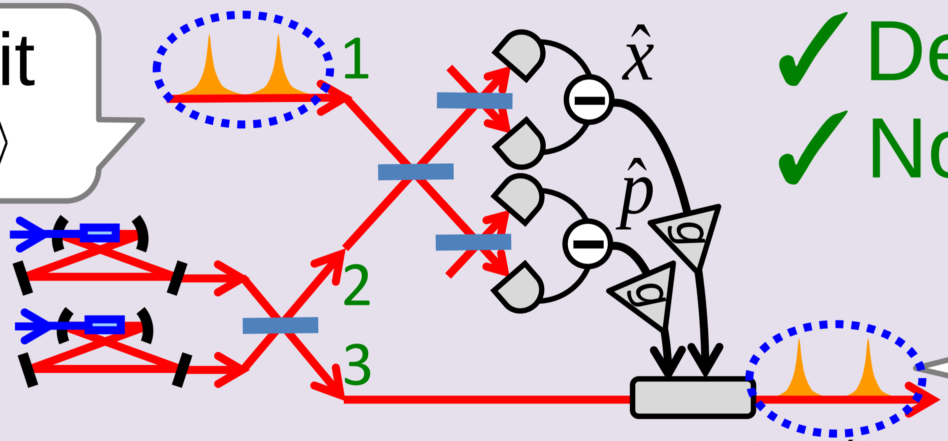
$$\sum_{k,l,m,n} \rho_{klmn} |k,l\rangle\langle m,n|$$



Hybrid Teleportation

Takeda *et al.*, Nature **500**, 315 (2013)

Input qubit
$a|1,0\rangle + b|0,1\rangle$



✓ Deterministic
✓ Noise free

PRA **64**, 040301 (2001)

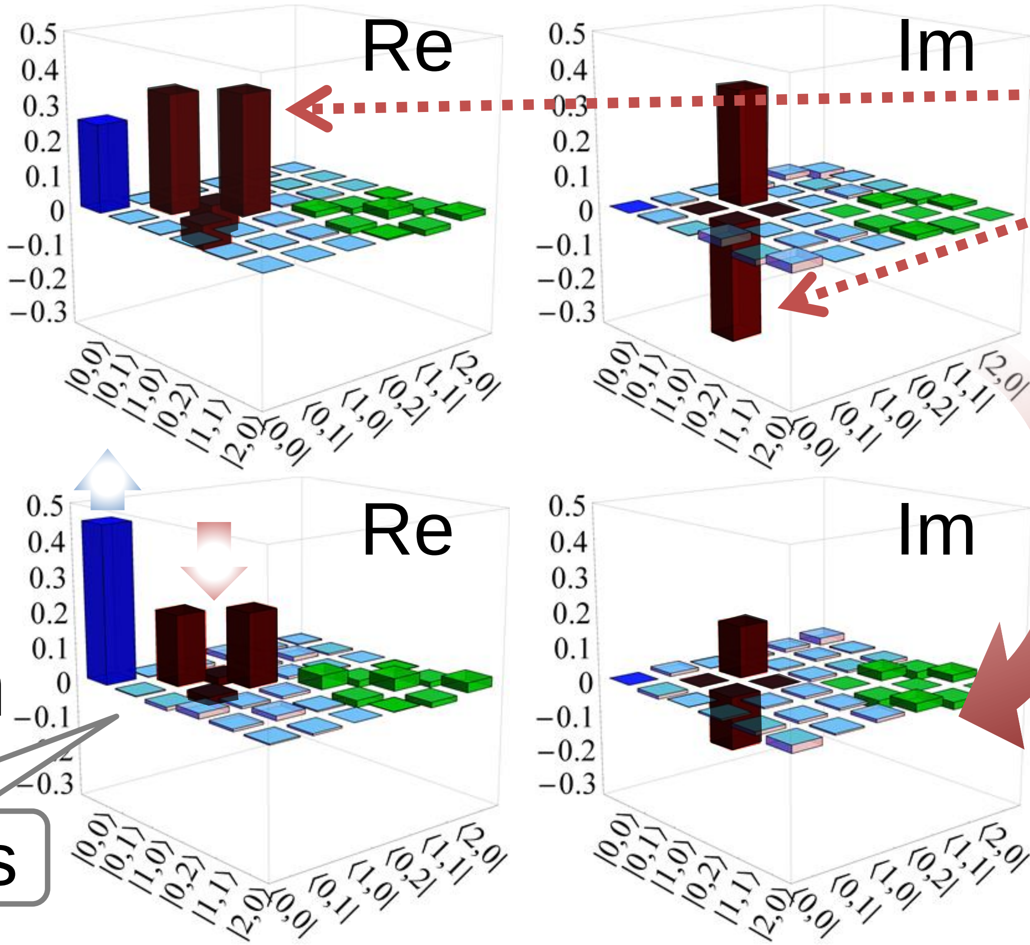
Only photon loss error

Hybrid Quantum Teleportation

Before teleportation

$$\sum_{k,l,m,n} \rho_{klmn} |k,l\rangle\langle m,n|$$

After teleportation



Photon loss

qubit

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

Overall fidelity **82±1%** > Classical limit

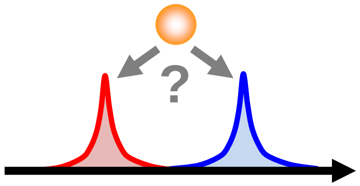
First deterministic teleportation of photonic qubits

Takeda *et al.*, Nature **500**, 315 (2013)

➡ How can we overcome the photon loss error?

Hybrid Quantum Teleportation

Our qubit: $\left|\psi\right\rangle = a\left|1,0\right\rangle + b\left|0,1\right\rangle$



Increase # of photons

Error-correction code against photon loss

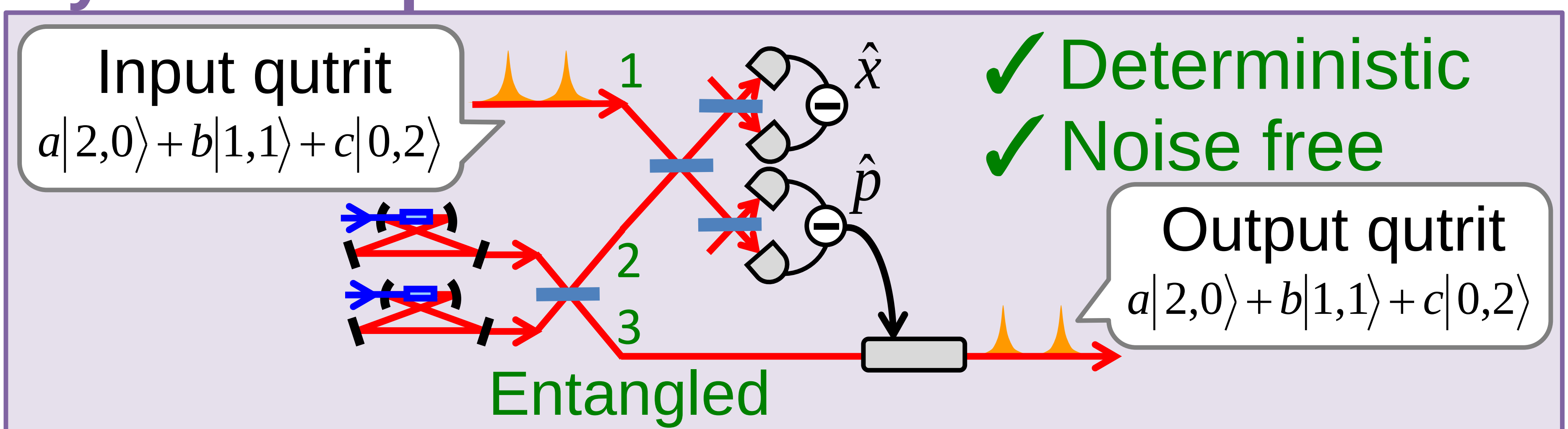
- Bosonic code: $\left|\psi\right\rangle = \alpha\left(\left|0,4\right\rangle + \left|4,0\right\rangle\right)/\sqrt{2} + \beta\left|2,2\right\rangle$

PRA **56**, 1114 (1997)

- NOON code: $\left|\psi\right\rangle = \alpha\left(\left|0,2\right\rangle + \left|2,0\right\rangle\right)\otimes\left(\left|0,2\right\rangle + \left|2,0\right\rangle\right)/2 + \beta\left|1,1\right\rangle\otimes\left|1,1\right\rangle$

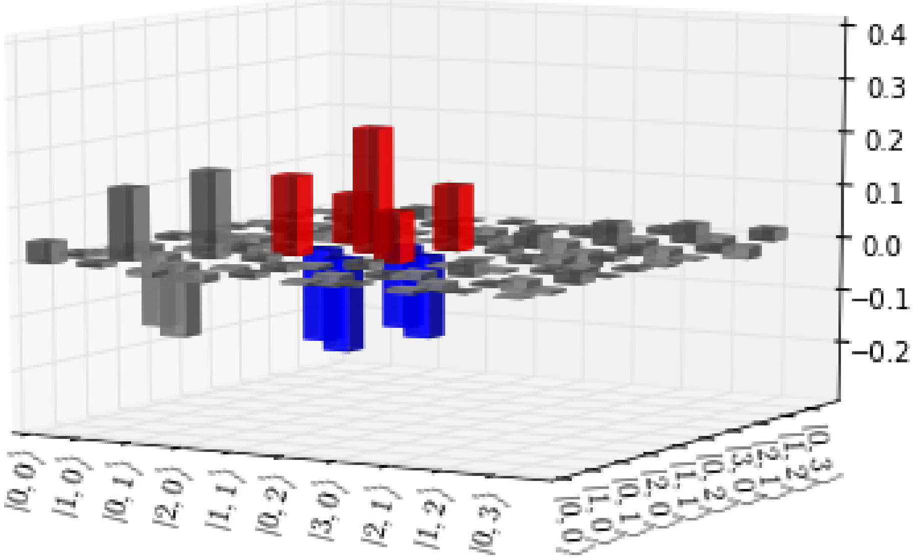
PRA **94**, 012311 (2016)

Hybrid Teleportation

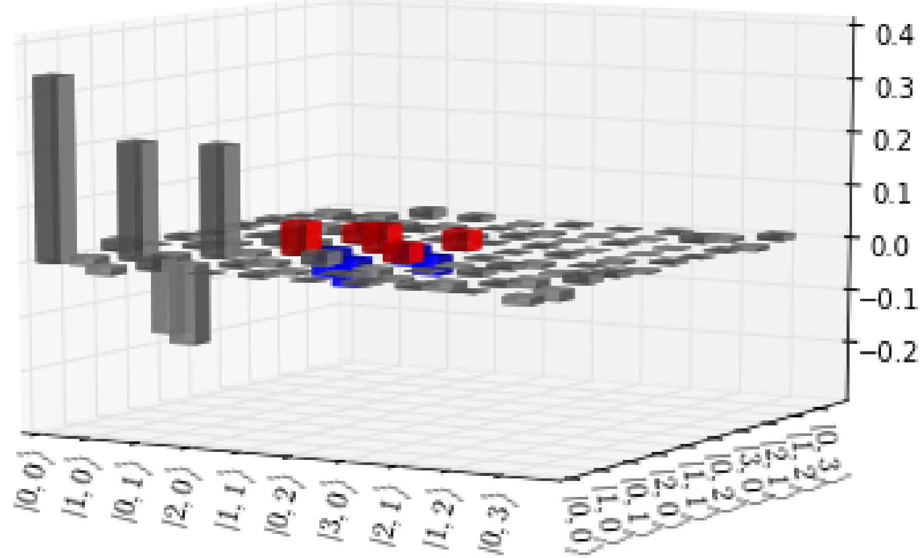


Hybrid Quantum Teleportation

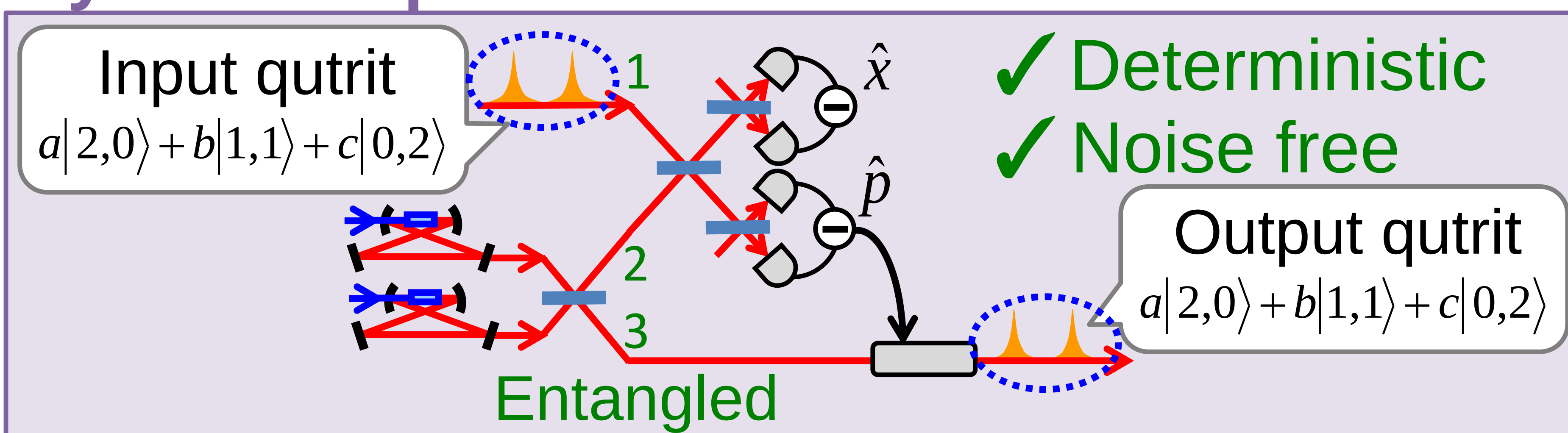
Before teleportation



After teleportation

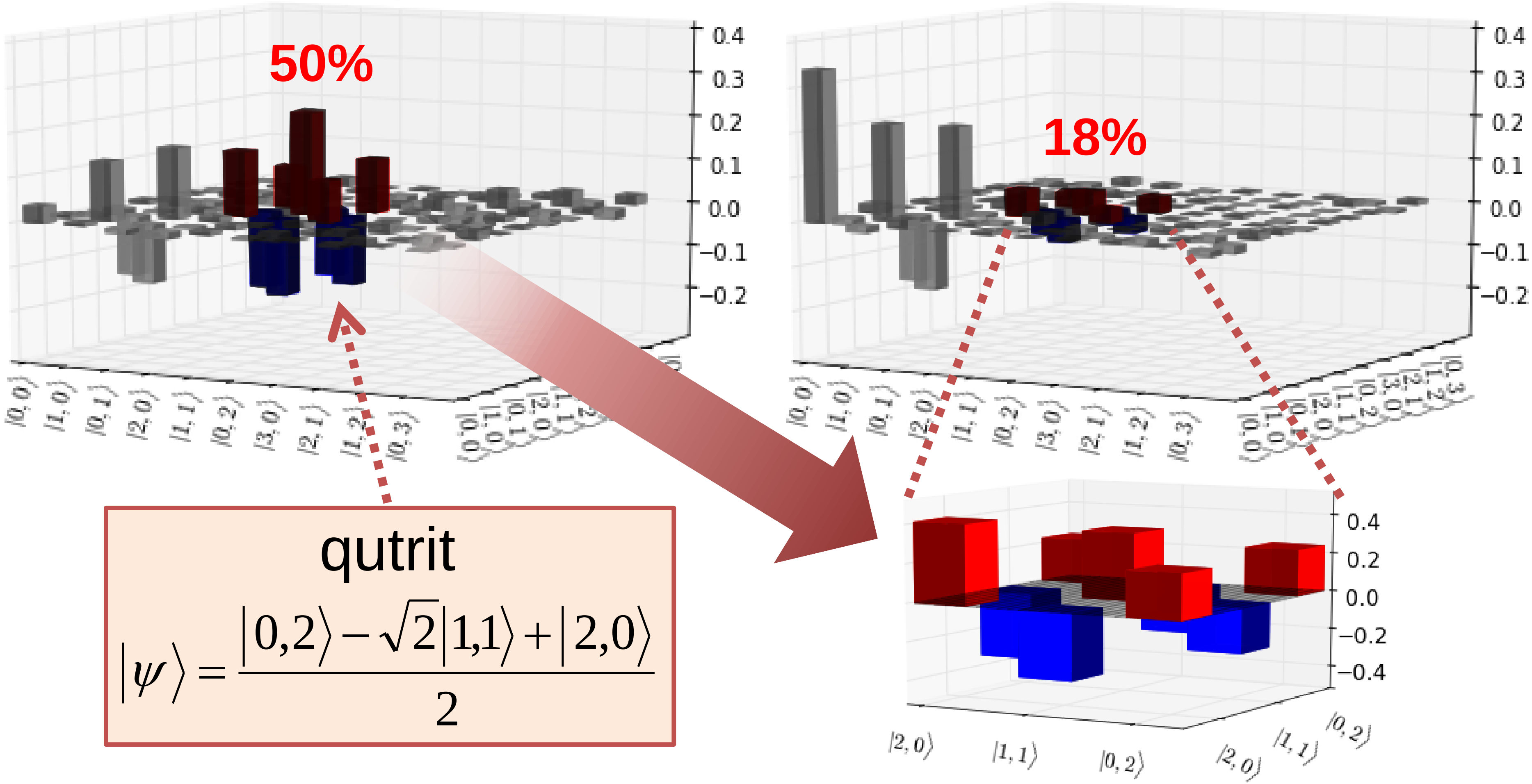


Hybrid Teleportation



Hybrid Quantum Teleportation

Before teleportation | After teleportation



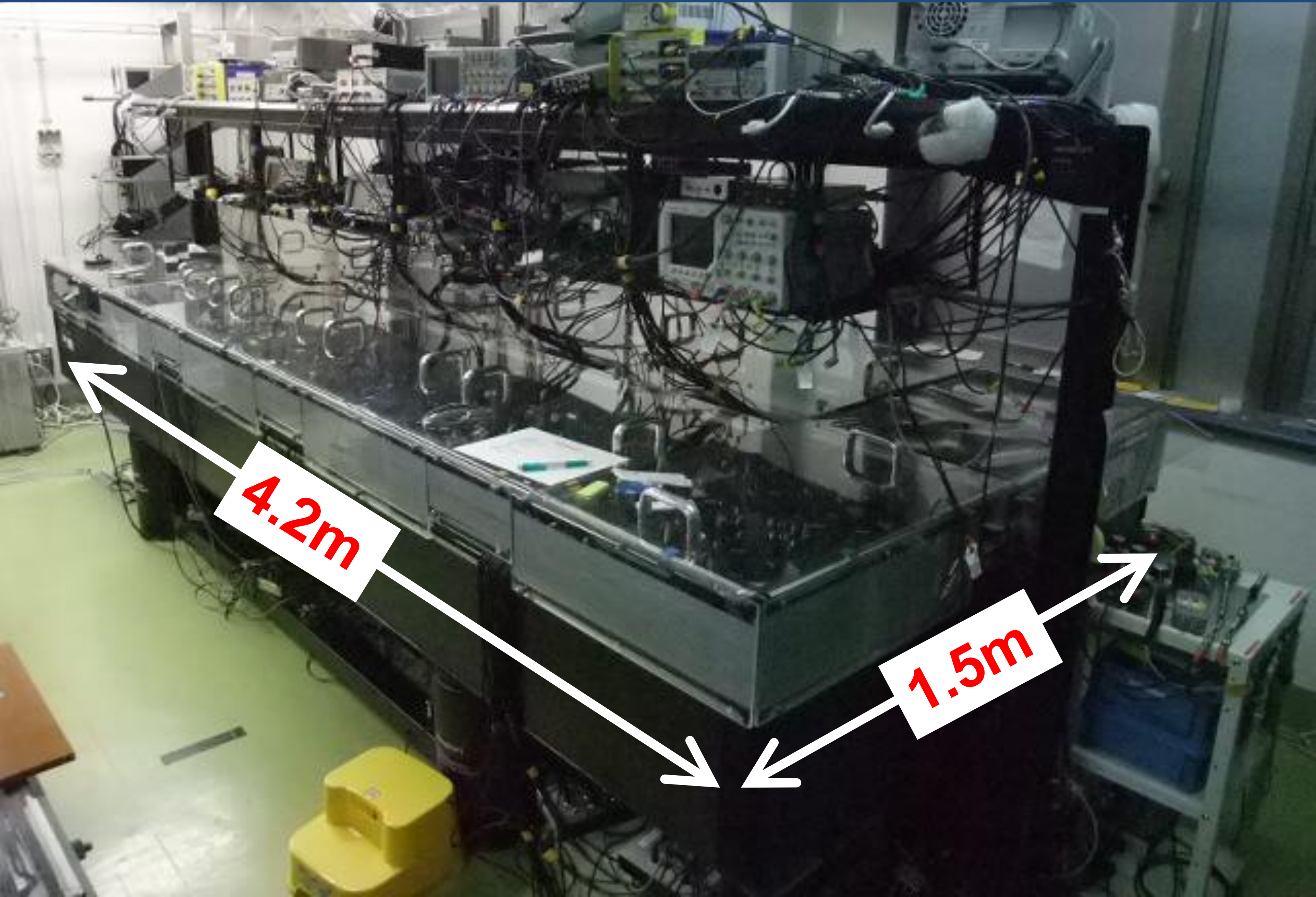
$$|\psi\rangle = \frac{|0,2\rangle - \sqrt{2}|1,1\rangle + |2,0\rangle}{2}$$

Fidelity in 3x3 subspace: **0.71** > 0.5 (classical limit)

➡ **Successful teleportation of qutrits**

Okada *et al.*, CLEO Europe EB-4.3 (2017)

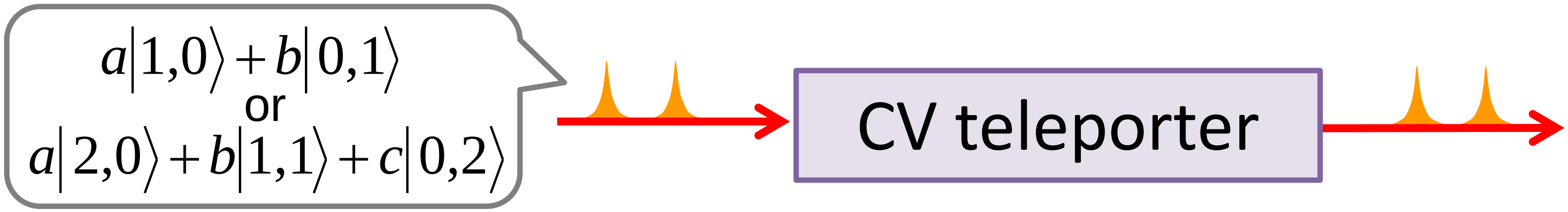
Hybrid Quantum Teleportation



Summary of our hybrid QT experiments

- Teleportation of time-bin qubit & qutrit

Takeda *et al*., Nature **500**, 315 (2013); Okada *et al*., CLEO Europe EB-4.3 (2017)

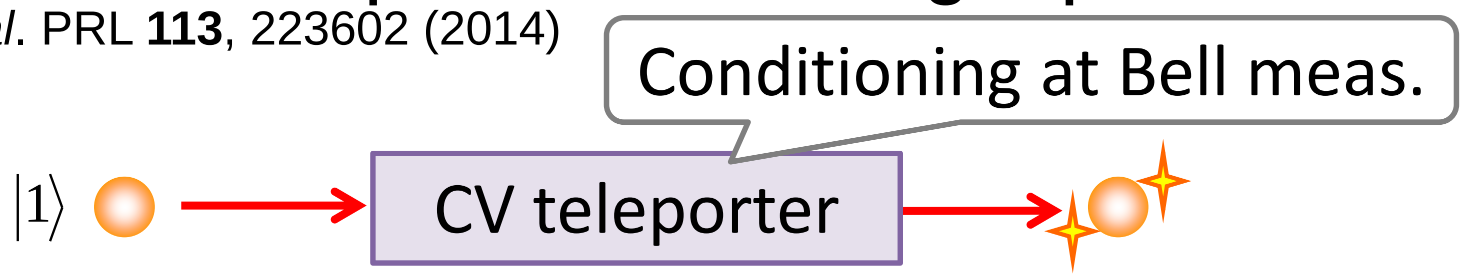


- Teleportation of single-photon entanglement

Takeda *et al*., PRL **114**, 100501 (2015)

- Conditional teleportation of single photon

Fuwa *et al*. PRL **113**, 223602 (2014)



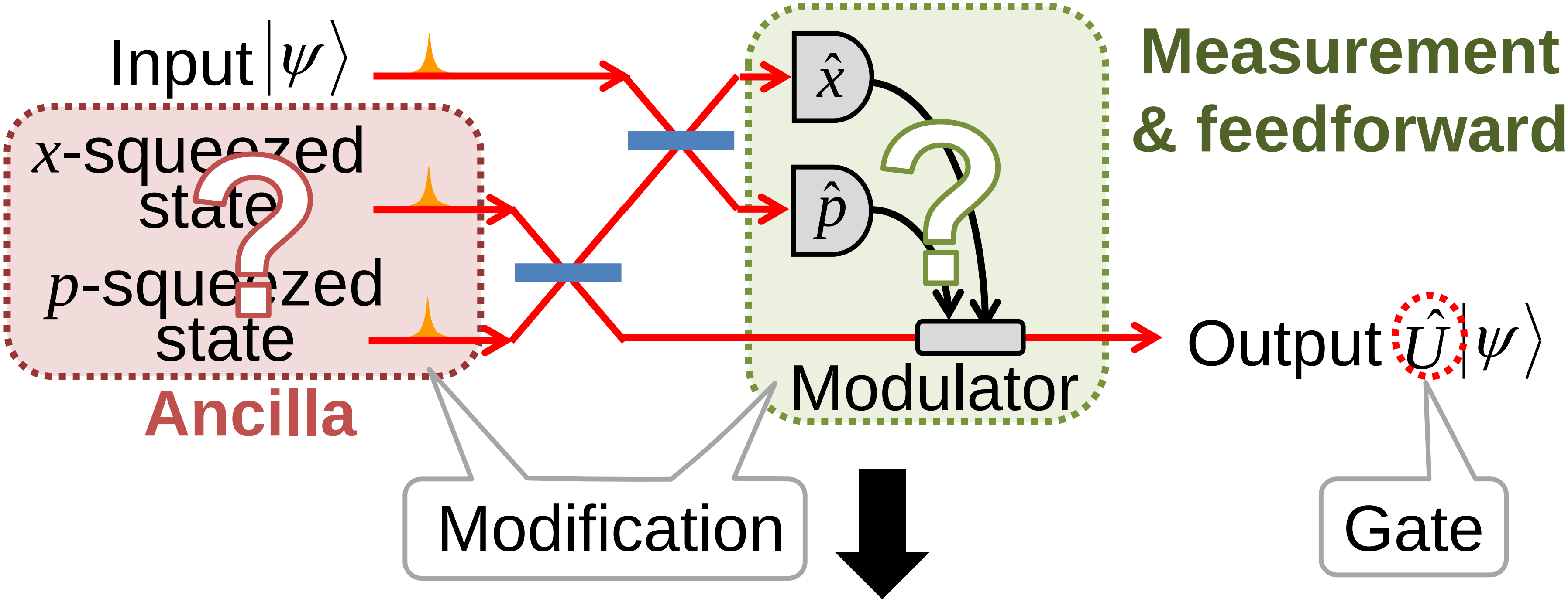
Basic hybrid qubit-CV technologies are ready

Optical Hybrid Quantum Teleportation and Its Application to Large-Scale Quantum Computing

1. Introduction
2. Hybrid quantum teleportation
3. **Teleportation-based quantum gates**
4. Toward large-scale quantum computing

Teleportation-based quantum gates

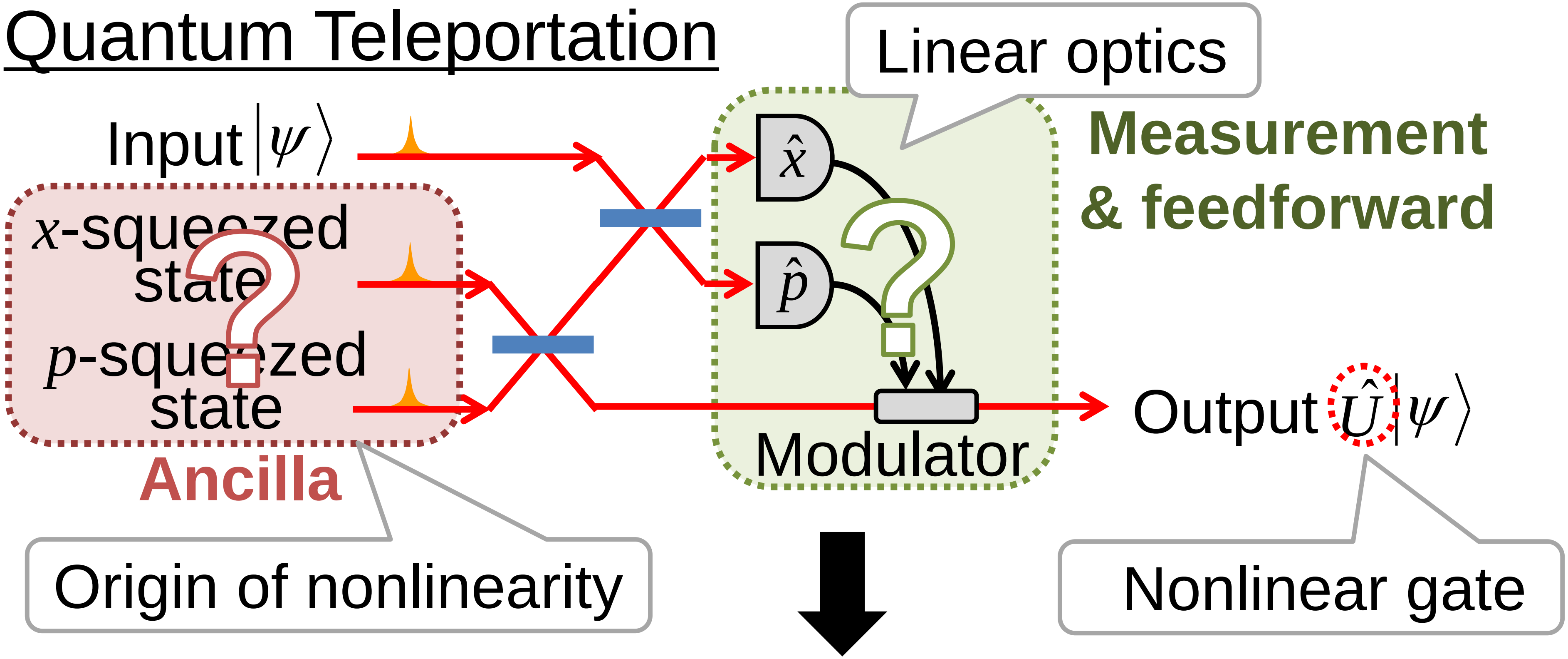
Quantum Teleportation



"Teleportation-based quantum gate"

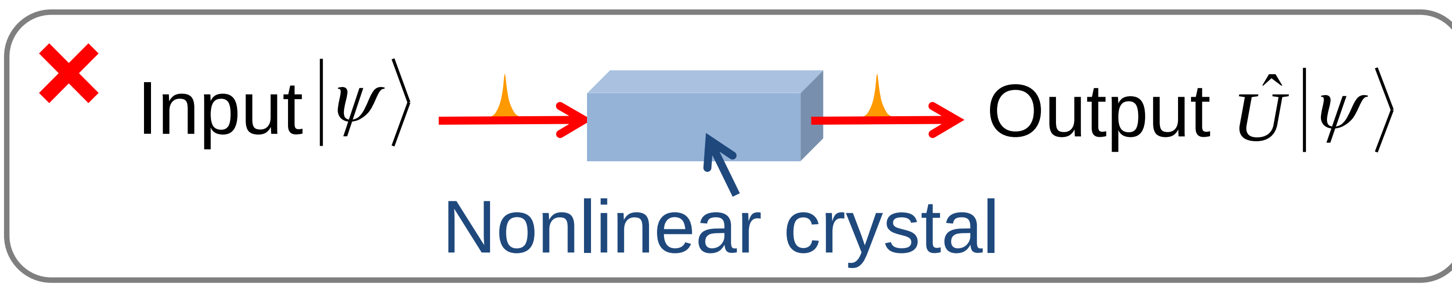
Teleportation-based quantum gates

Quantum Teleportation

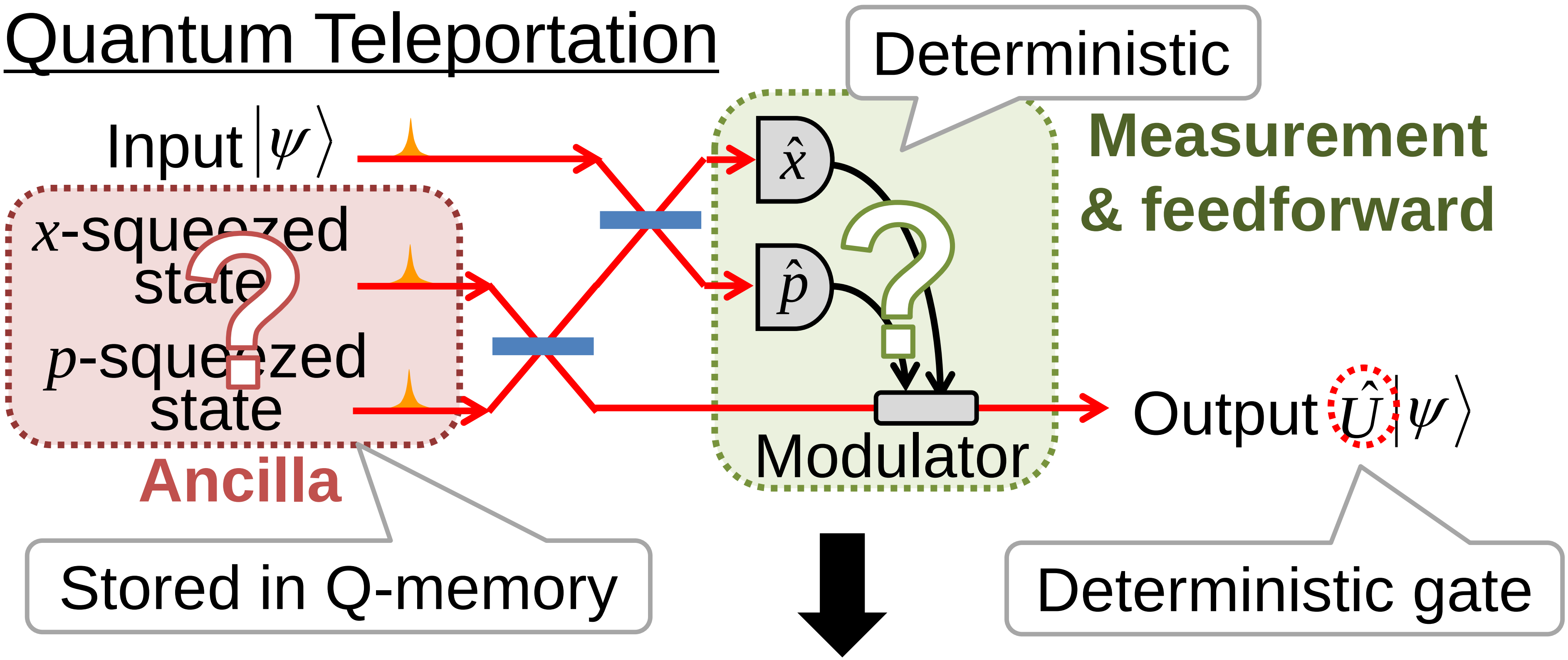


“Teleportation-based quantum gate”

- Only linear optics required & ancillae give nonlinearity



Teleportation-based quantum gates



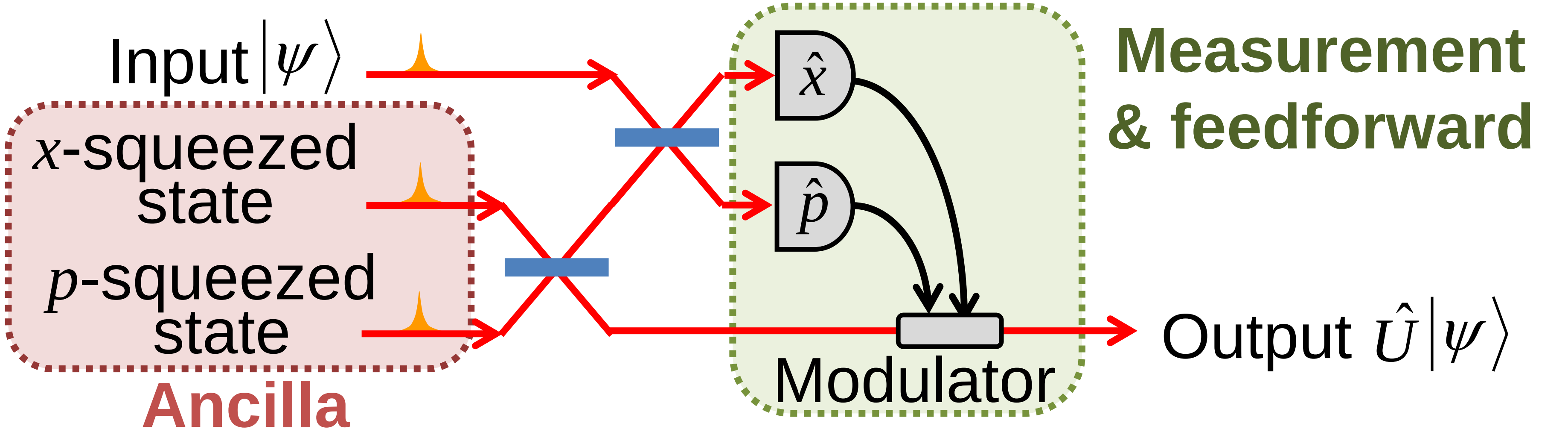
"Teleportation-based quantum gate"

- Only linear optics required & ancillae give nonlinearity
- Deterministic gate once ancillae are prepared

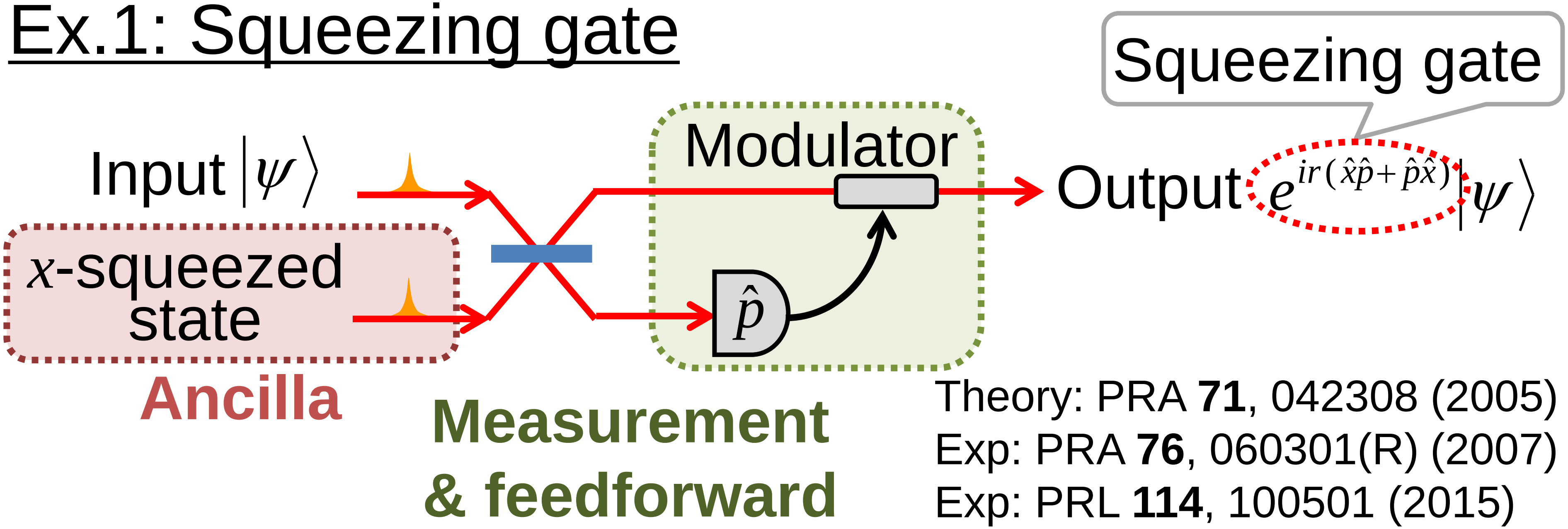
Out Q-memory experiments: PRX **3**, 041028 (2013); Sci. Adv. **2**, e1501772 (2016)

Teleportation-based quantum gates

Quantum Teleportation

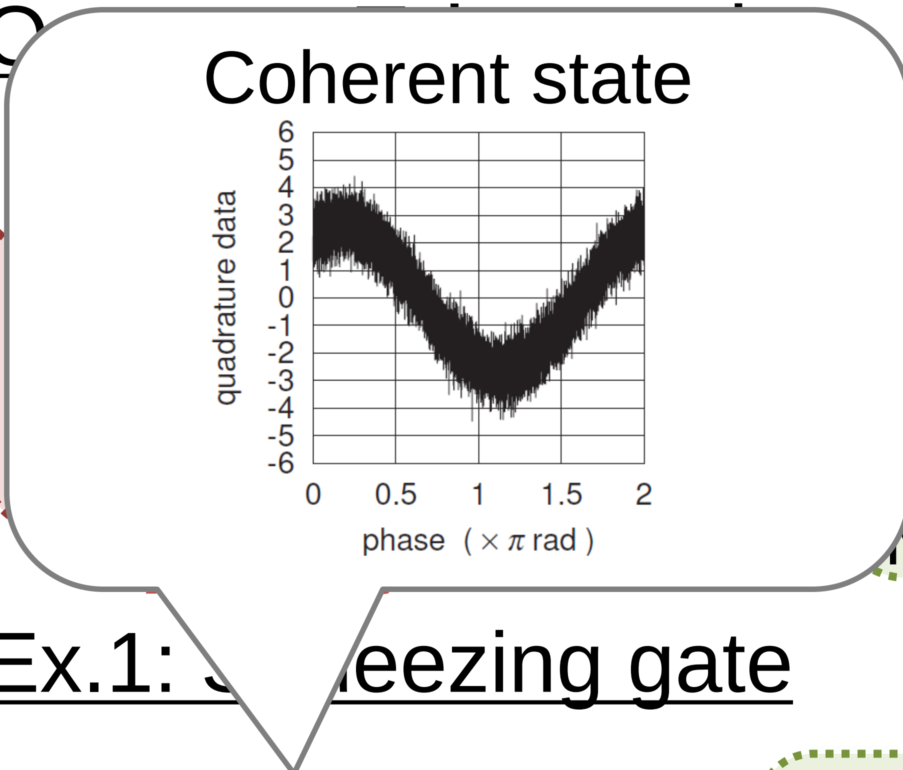


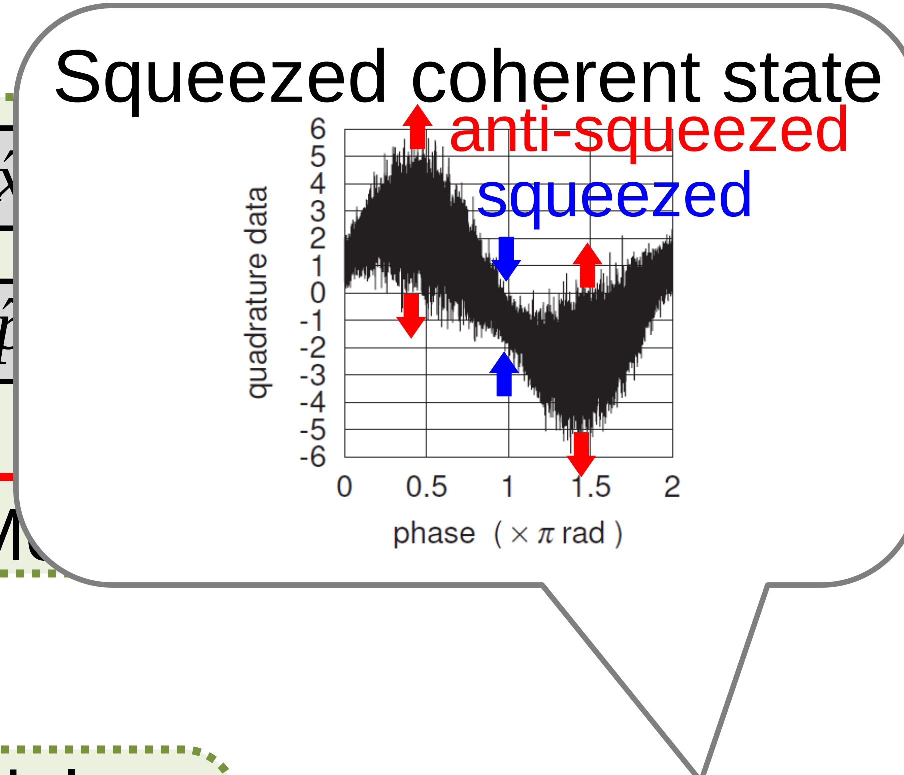
Ex.1: Squeezing gate



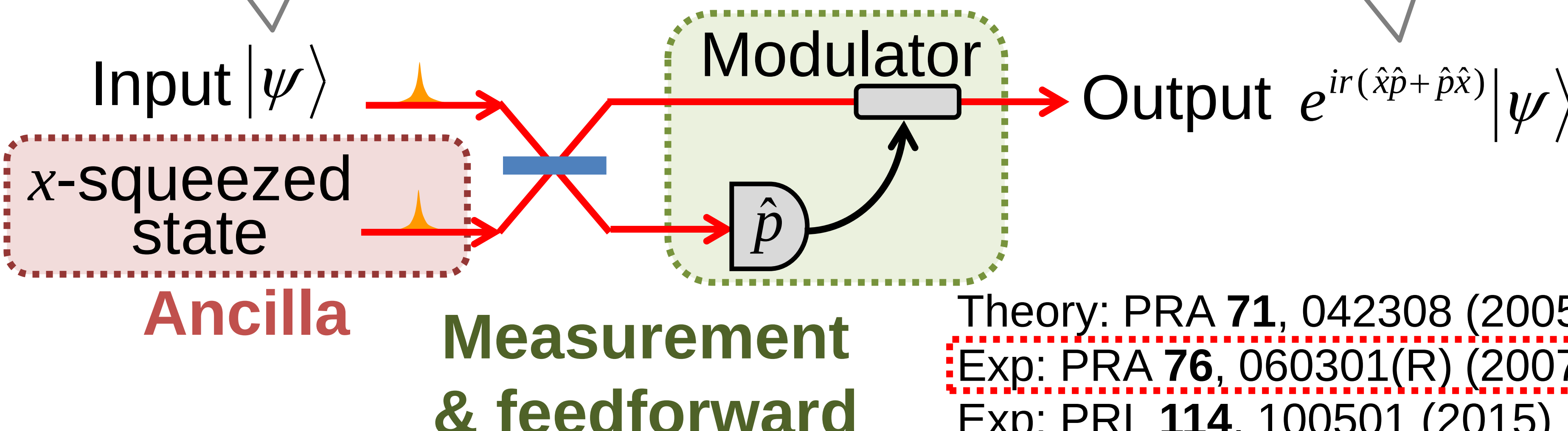
Theory: PRA **71**, 042308 (2005)
Exp: PRA **76**, 060301(R) (2007)
Exp: PRL **114**, 100501 (2015)

Teleportation-based quantum gates





Ex.1: Squeezing gate



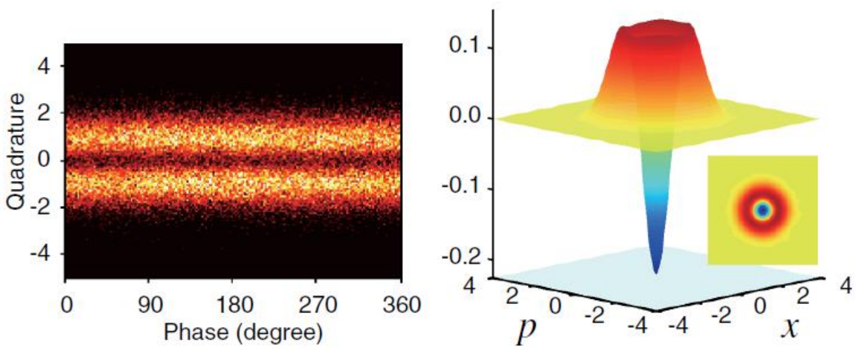
Theory: PRA **71**, 042308 (2005)

Exp: PRA **76**, 060301(R) (2007)

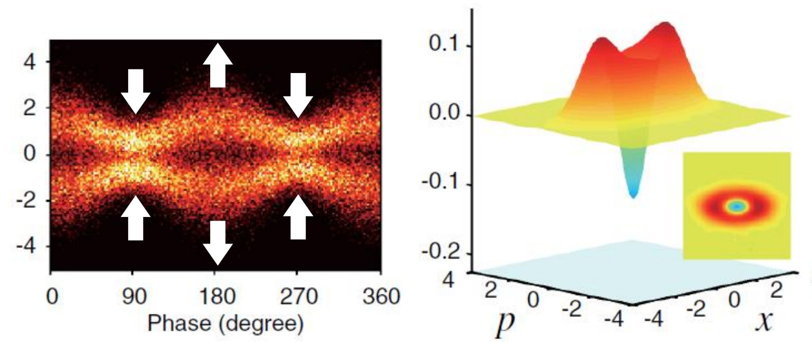
Exp: PRL **114**, 100501 (2015)

Teleportation-based quantum gates

Single photon

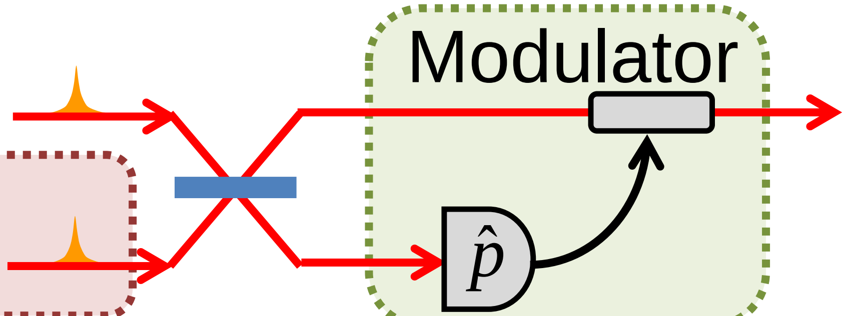


Squeezed single photon



Ex.1: S eezing gate

Input $|\psi\rangle$



Output $e^{ir(\hat{x}\hat{p}+\hat{p}\hat{x})}|\psi\rangle$

x-squeezed state

Ancilla

Measurement & feedforward

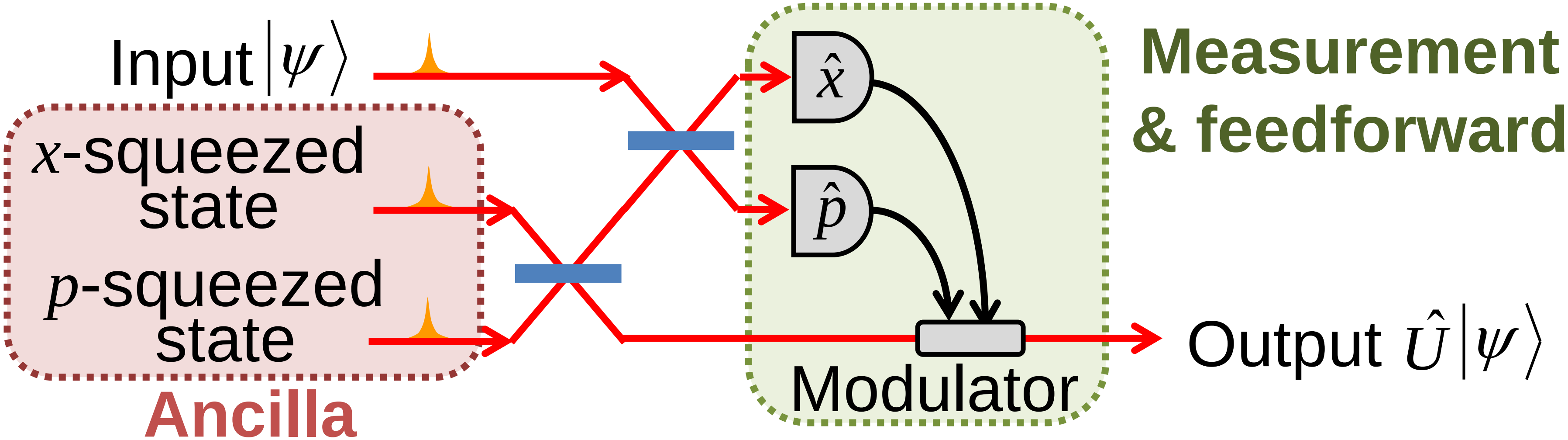
Theory: PRA **71**, 042308 (2005)

Exp: PRA **76**, 060301(R) (2007)

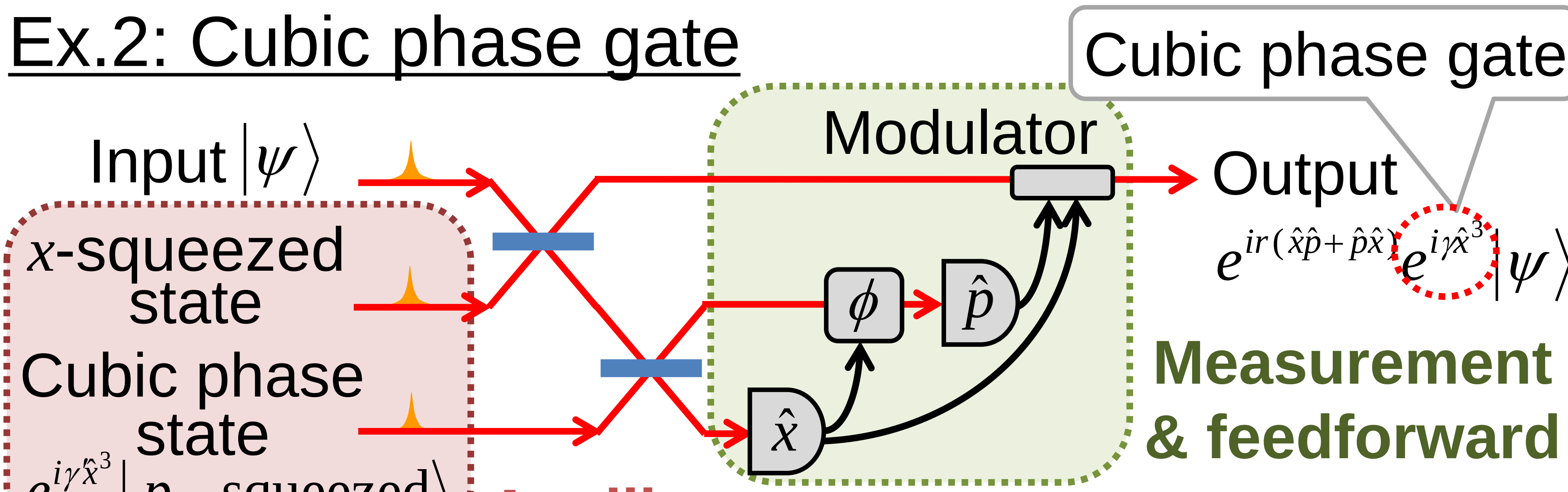
Exp: PRL **114**, 100501 (2015)

Teleportation-based quantum gates

Quantum Teleportation



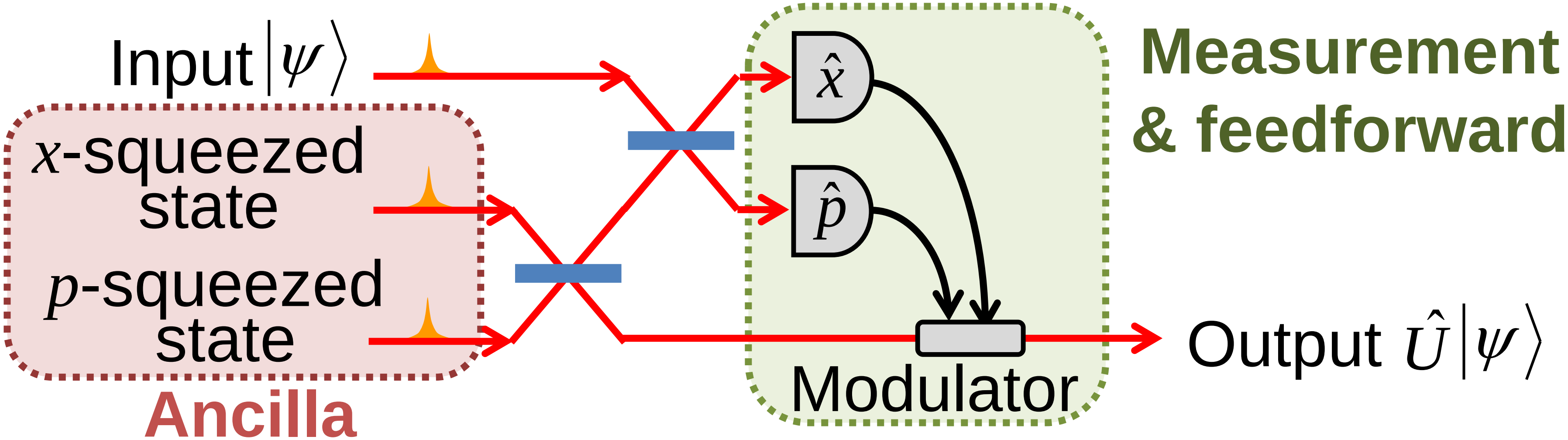
Ex.2: Cubic phase gate



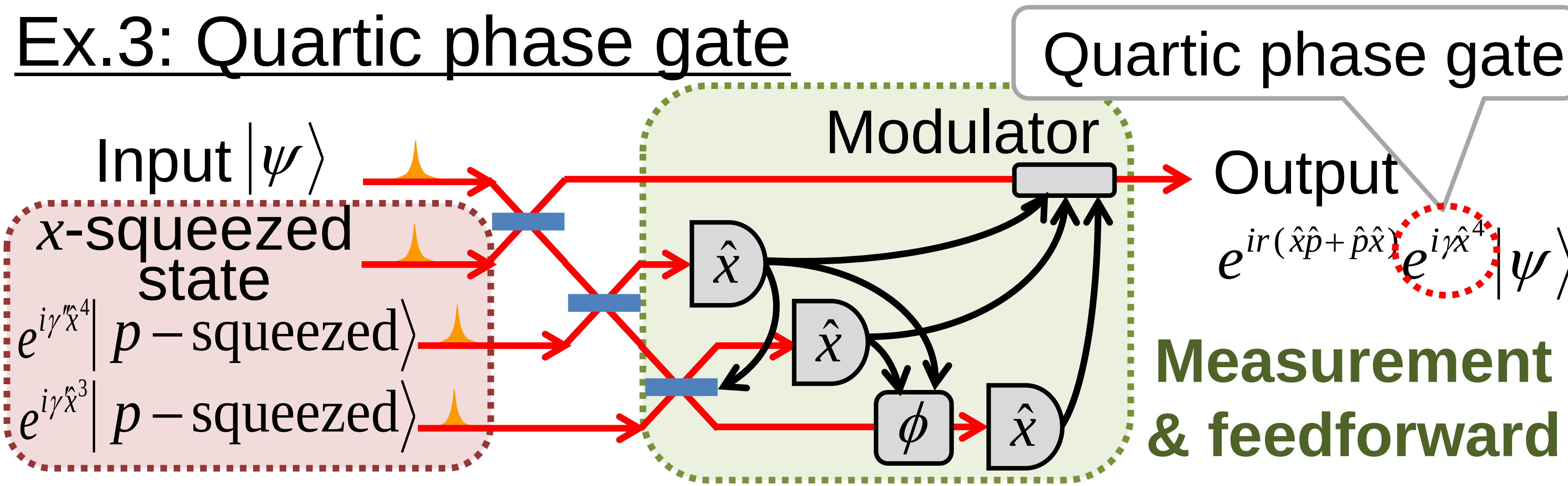
Theory: PRA **93**, 022301 (2016)

Teleportation-based quantum gates

Quantum Teleportation



Ex.3: Quartic phase gate



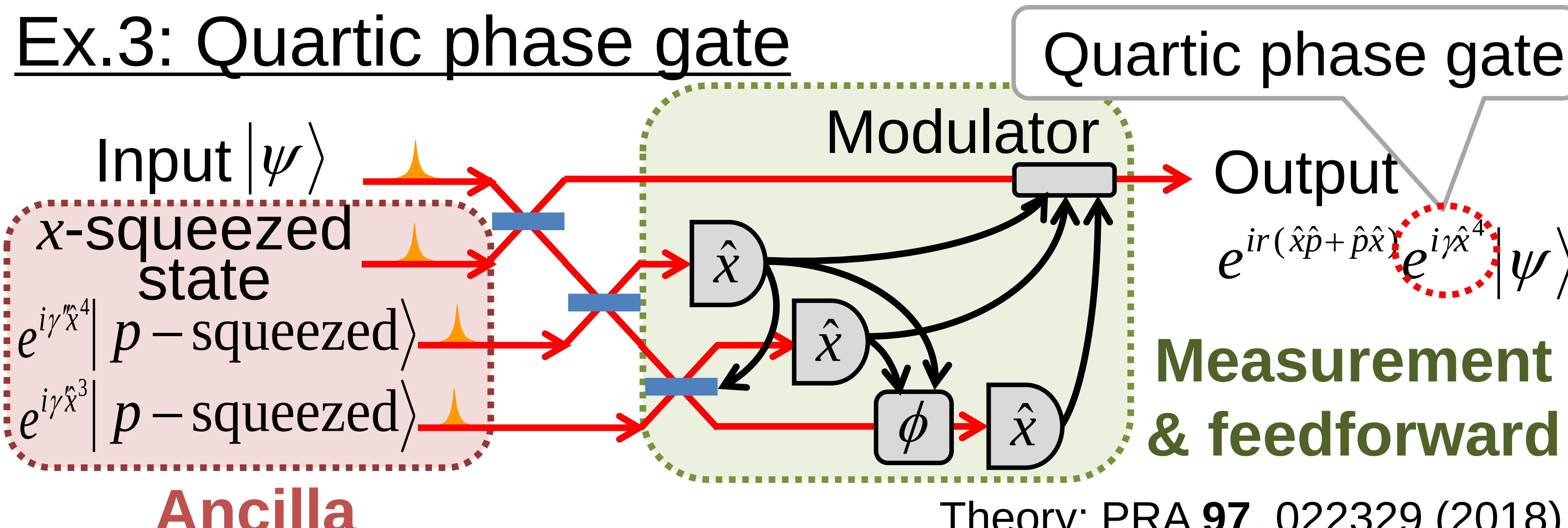
Theory: PRA **97**, 022329 (2018)

Teleportation-based quantum gates

Arbitrary-order phase gate is possible

$$|\psi\rangle \rightarrow e^{i\gamma\hat{x}^n}|\psi\rangle$$

Ex.3: Quartic phase gate



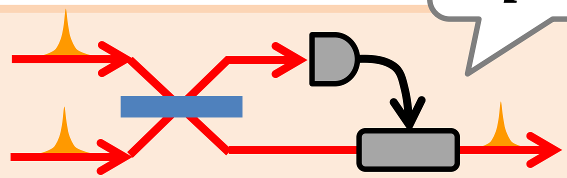
Theory: PRA **97**, 022329 (2018)

Universal quantum gate set

Universal gate set for CVs

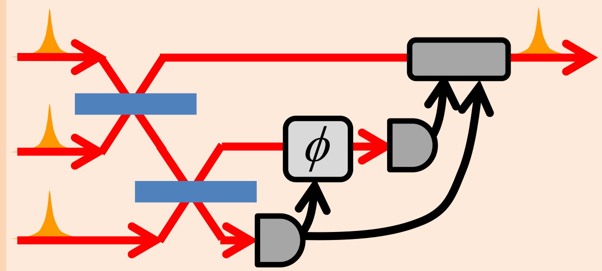
PRL **82**, 1784 (1999)

Squeezing gate



$\hat{x}\hat{p}+\hat{p}\hat{x}$

Cubic phase gate

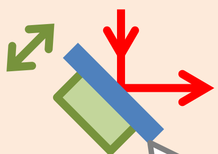


$\hat{x}^3$

Displace

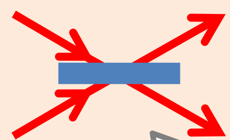
$a\hat{x} - b\hat{p}$

Phase shift



$\hat{x}^2 + \hat{p}^2$

Beam splitter



$\hat{x}_1\hat{p}_2 - \hat{p}_1\hat{x}_2$

1st & 2nd order $\hat{H}$: N_1, N_2

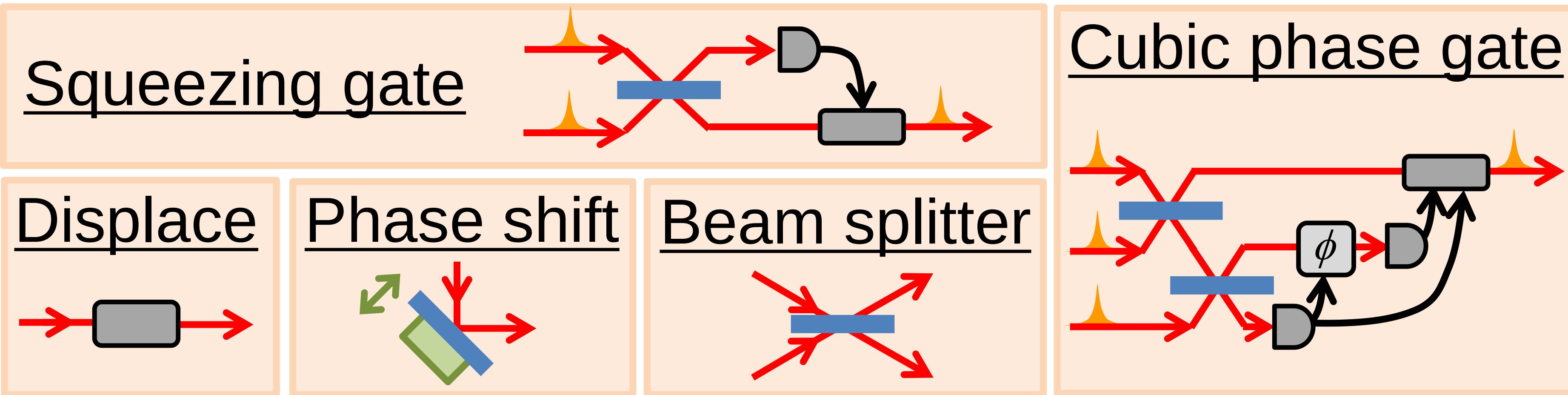
3rd order $\hat{H}$: $N_1 + N_2 - 2$

$$e^{i\hat{H}_1\delta t}e^{i\hat{H}_2\delta t}e^{-i\hat{H}_1\delta t}e^{-i\hat{H}_2\delta t} \approx e^{-i[\hat{H}_1,\hat{H}_2]\delta t^2}$$

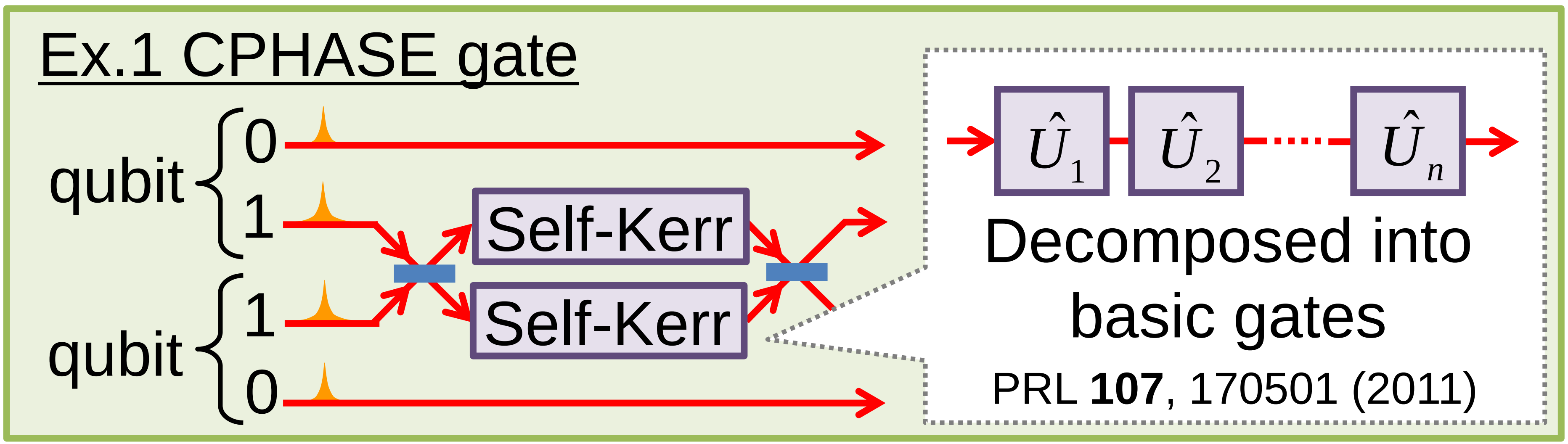
➡ Higher order $\hat{H}$ can be created

Universal quantum gate set

Universal gate set for CVs PRL **82**, 1784 (1999)

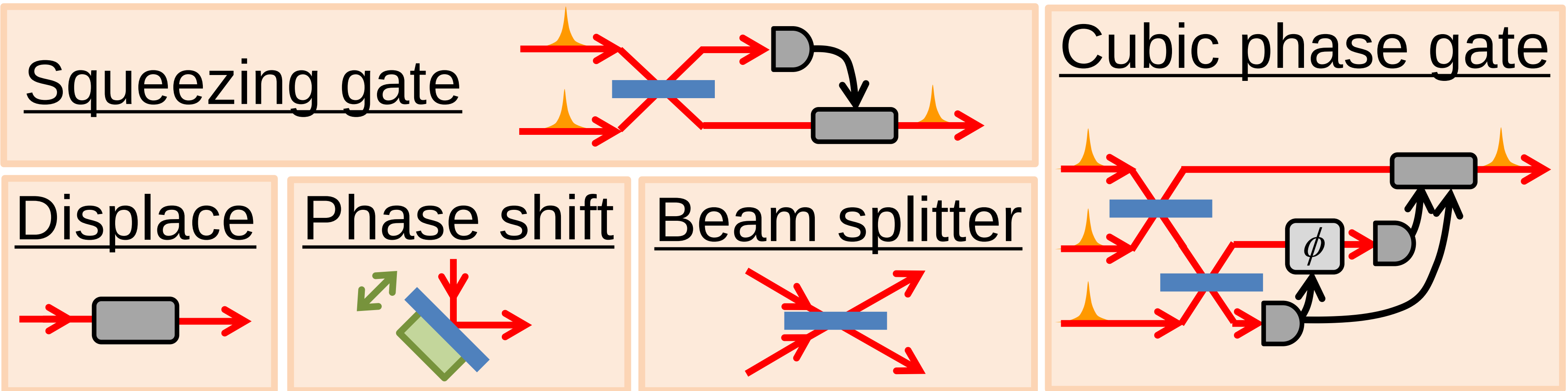


Universal gate set for qubits is also available



Universal quantum gate set

Universal gate set for CVs PRL **82**, 1784 (1999)



Universal gate set for qubits is also available

Ex.2 Gottesman-Kitaev-Preskill qubit

$\alpha|0_L\rangle + \beta|1_L\rangle$, where

$$\begin{cases} |0_L\rangle = \sum_{s\in Z} \left| x = 2s\sqrt{\pi} \right\rangle \\ |1_L\rangle = \sum_{s\in Z} \left| x = (2s+1)\sqrt{\pi} \right\rangle \end{cases}$$

$\hat{x}$-eigenstates

Universal QC with CV gates & error correction possible

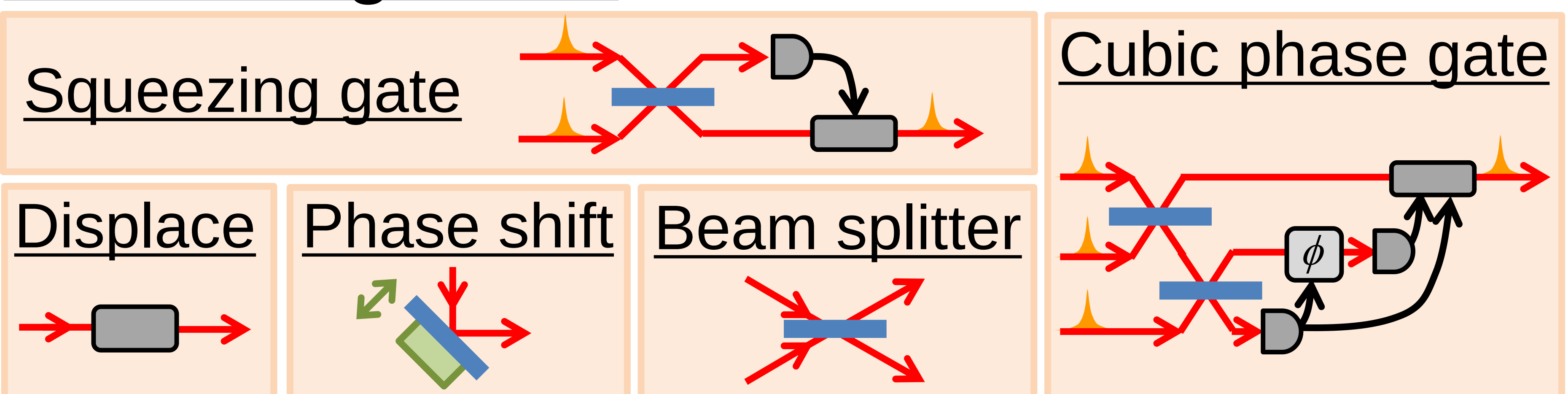
PRA **64**, 012310 (2001)

Teleportation-based quantum gates

- Only linear optics required & ancillae give nonlinearity
- Deterministic gate once ancillae are prepared

Examples
- Squeezing gate ⇒ already demonstrated
- Cubic phase gate ⇒ to be demonstrated
- Arbitrary-order phase gate ⇒ possible

Universal gate set



Ultimate goal: deterministic qubit quantum computation

Optical Hybrid Quantum Teleportation and Its Application to Large-Scale Quantum Computing

1. Introduction
2. Hybrid quantum teleportation
3. Teleportation-based quantum gates
4. **Toward large-scale quantum computing**

Large-scale quantum computing

Problems for large-scale optical QC

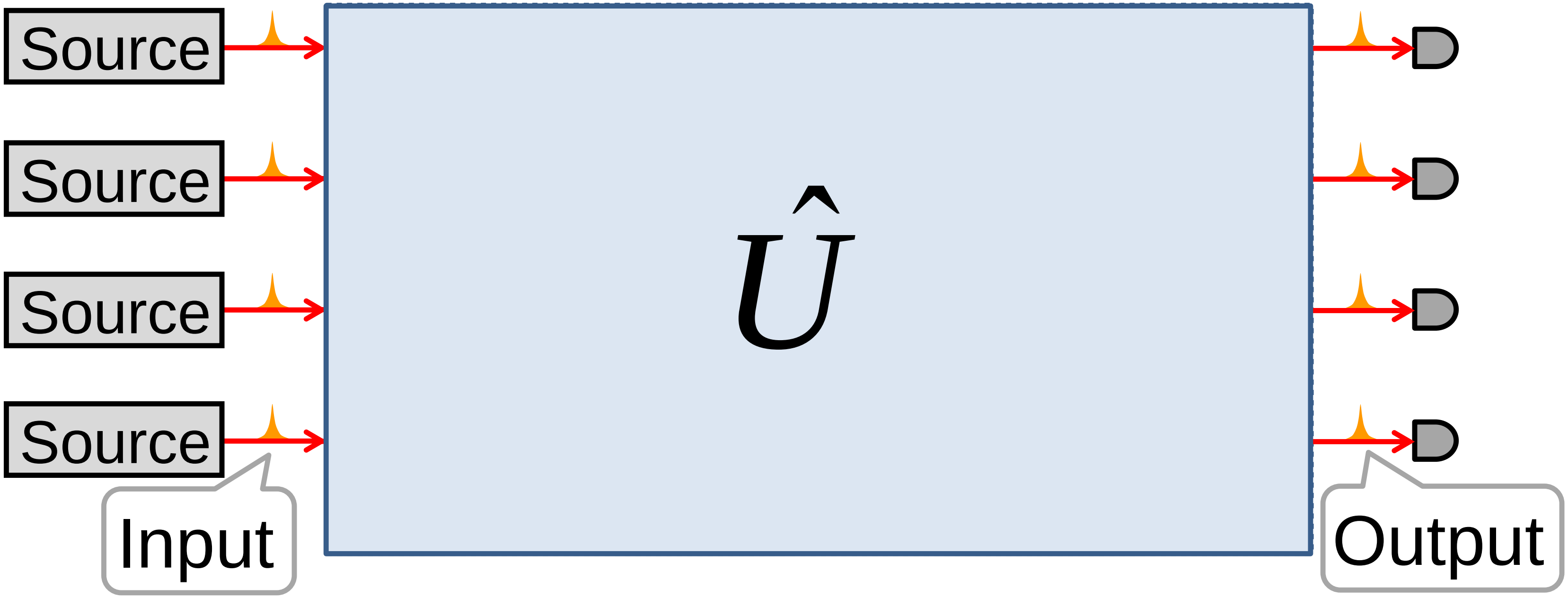
✕ Not Scalable

Much more resources & space needed

✕ Not Programmable

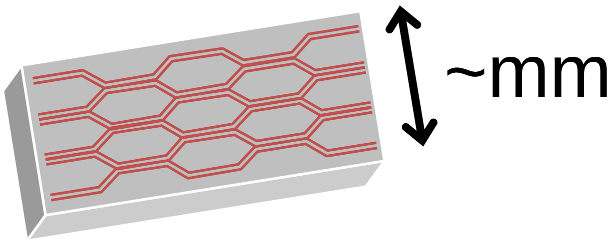
Different optical circuit for different calculation

Typical optical QC



Large-scale quantum computing

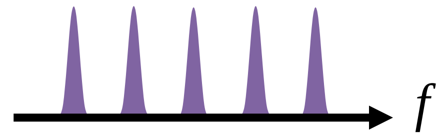
Waveguide chip



Science **349**, 711 (2015)
Nat. Photon. **11**, 447 (2017)

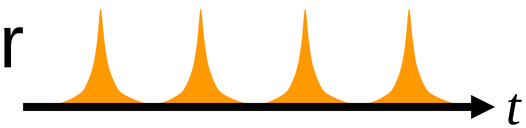
One-way QC

Freq. multiplexed cluster state



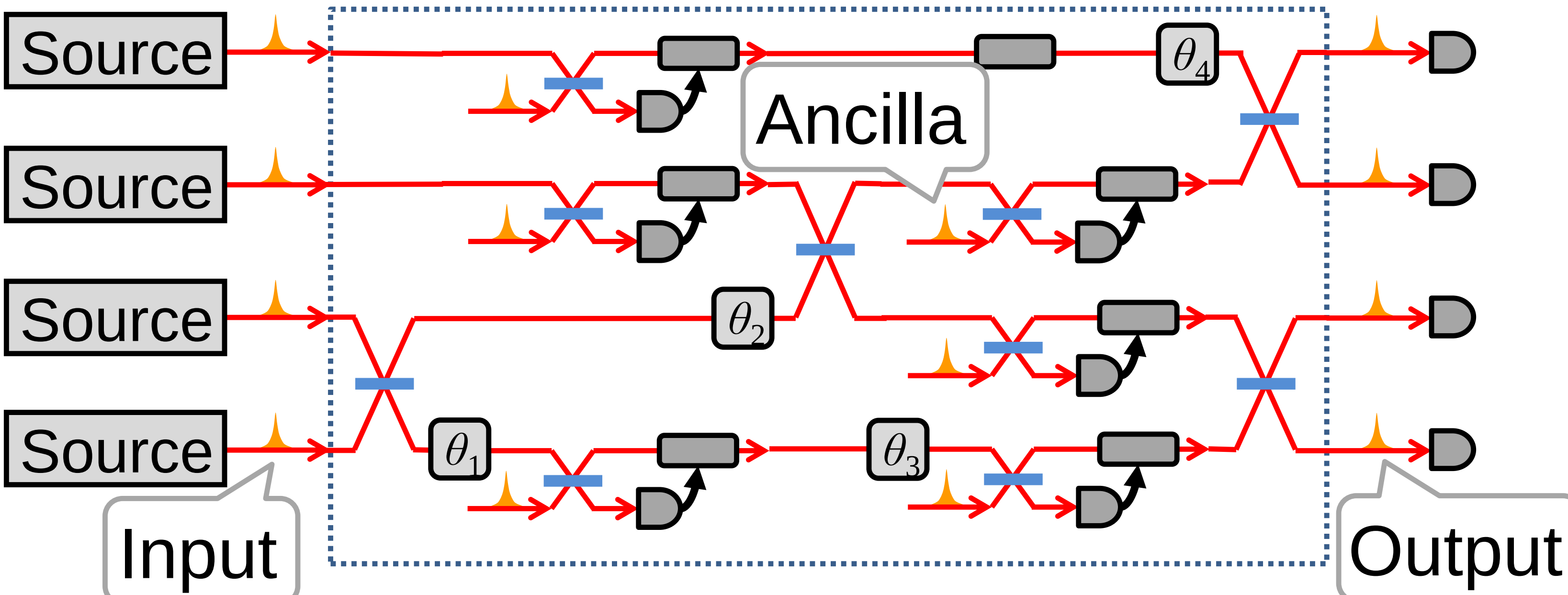
or

Time multiplexed cluster state



Nat. Photon. **7**, 982 (2013)
PRL **112**, 120505 (2014)

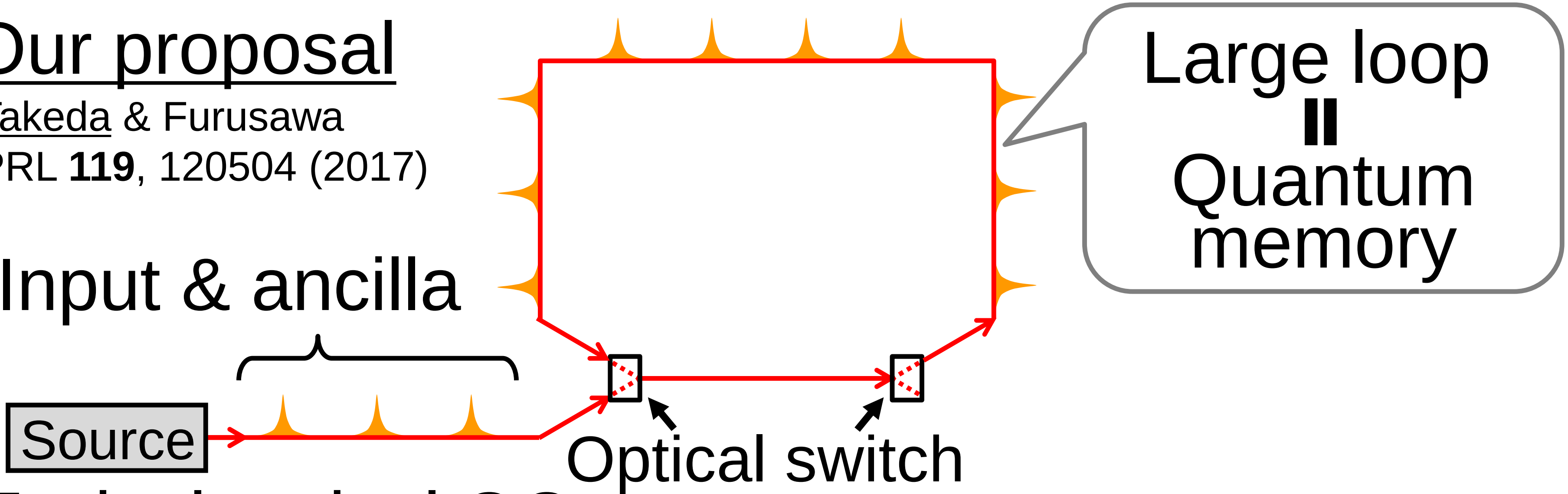
Typical optical QC



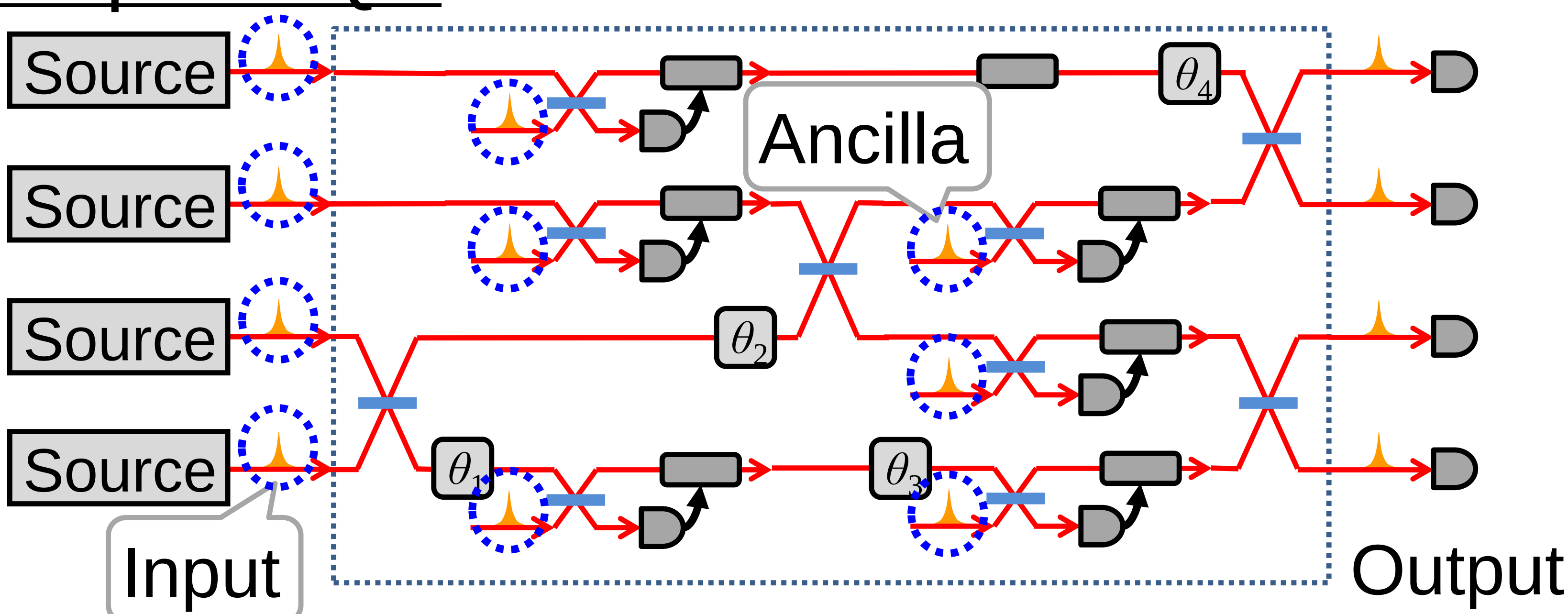
Loop-based architecture for QC

Our proposal

Takeda & Furusawa
PRL **119**, 120504 (2017)



Typical optical QC



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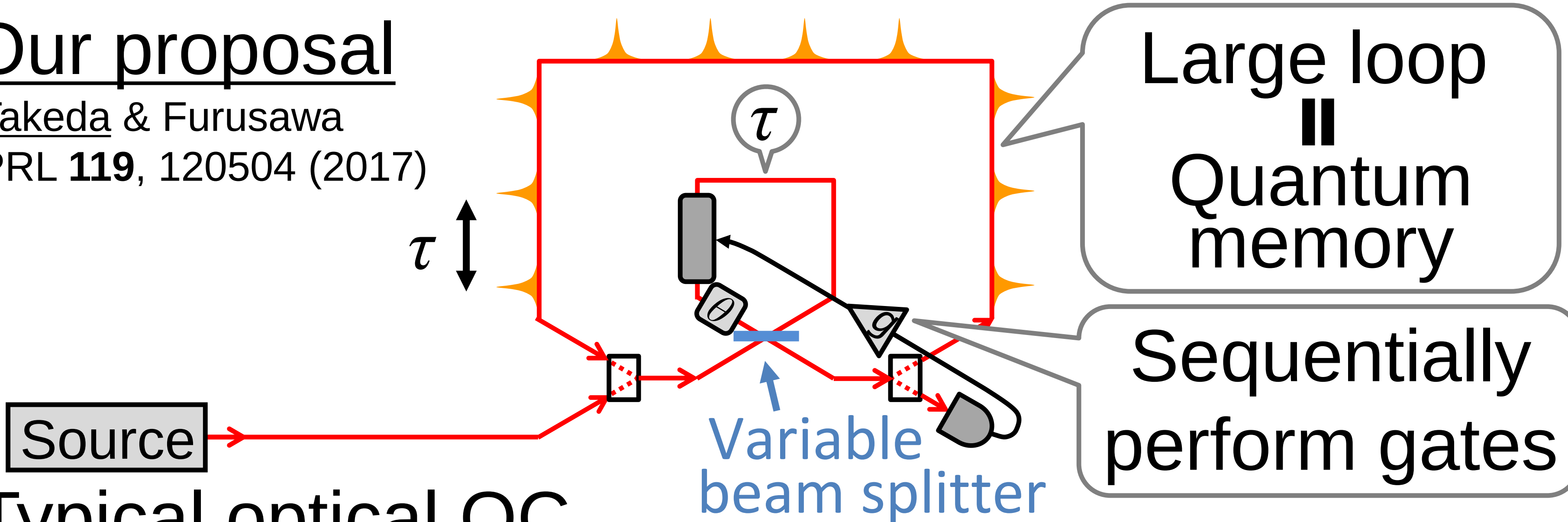
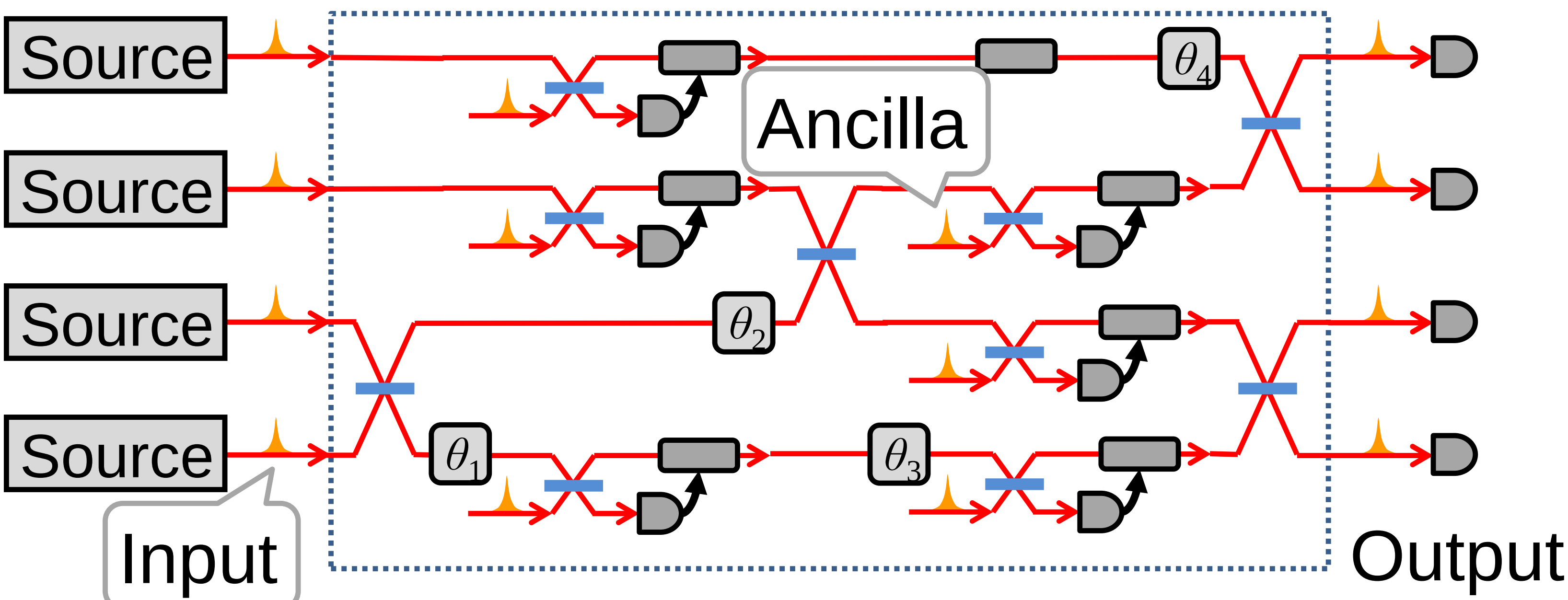


Typical optical QC



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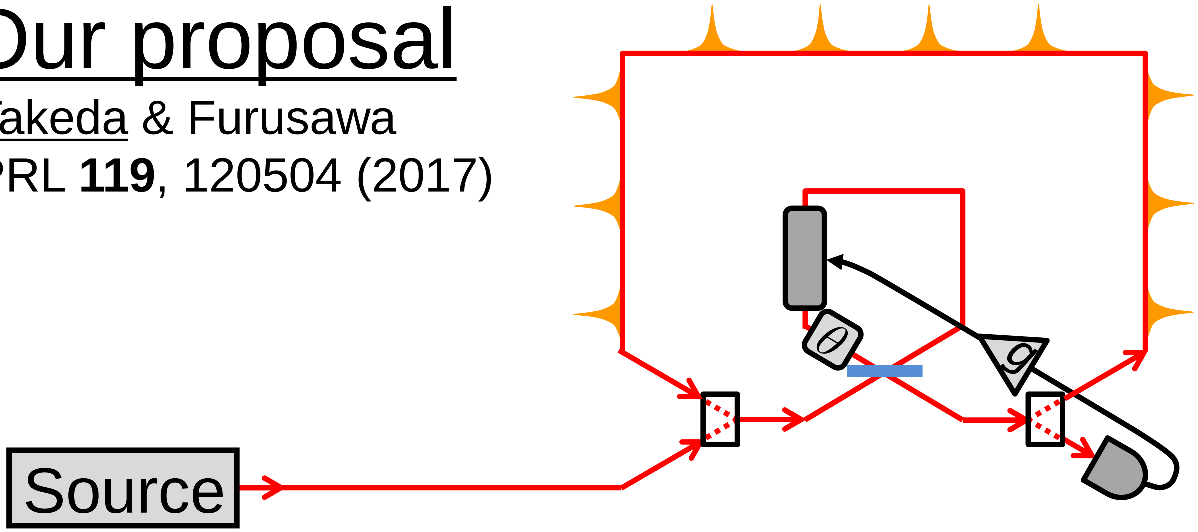
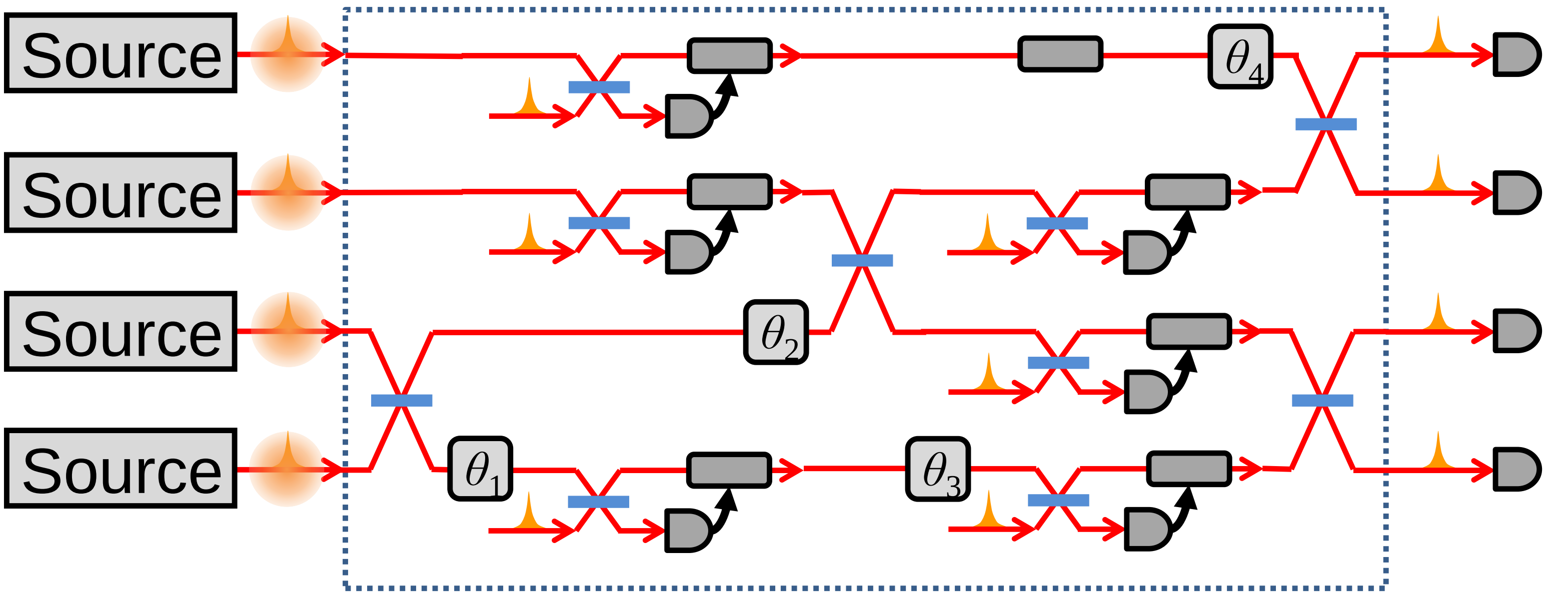
PRL **119**, 120504 (2017)



Typical optical QC



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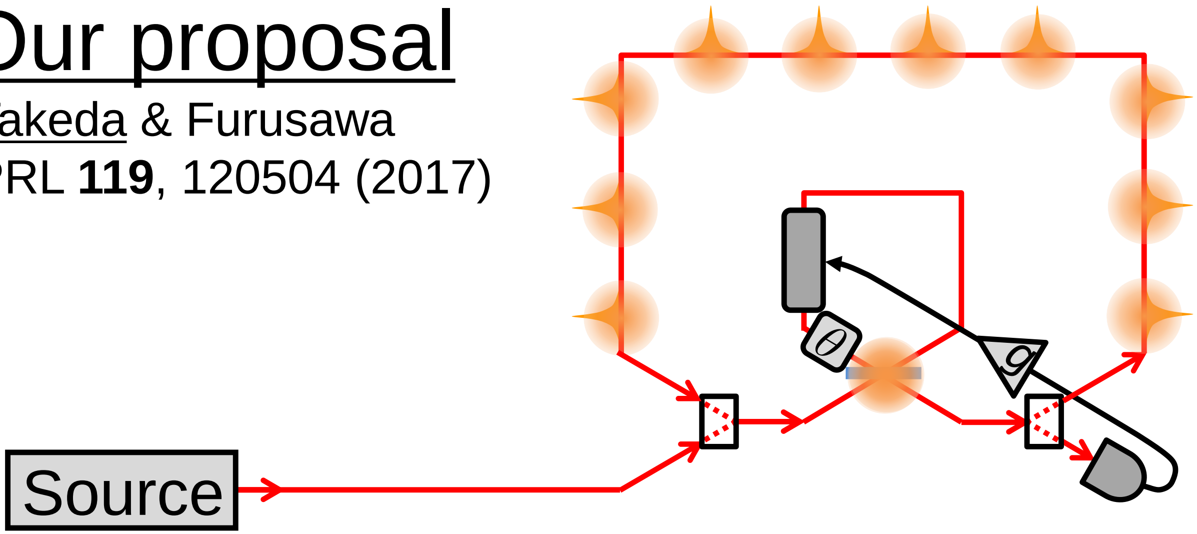
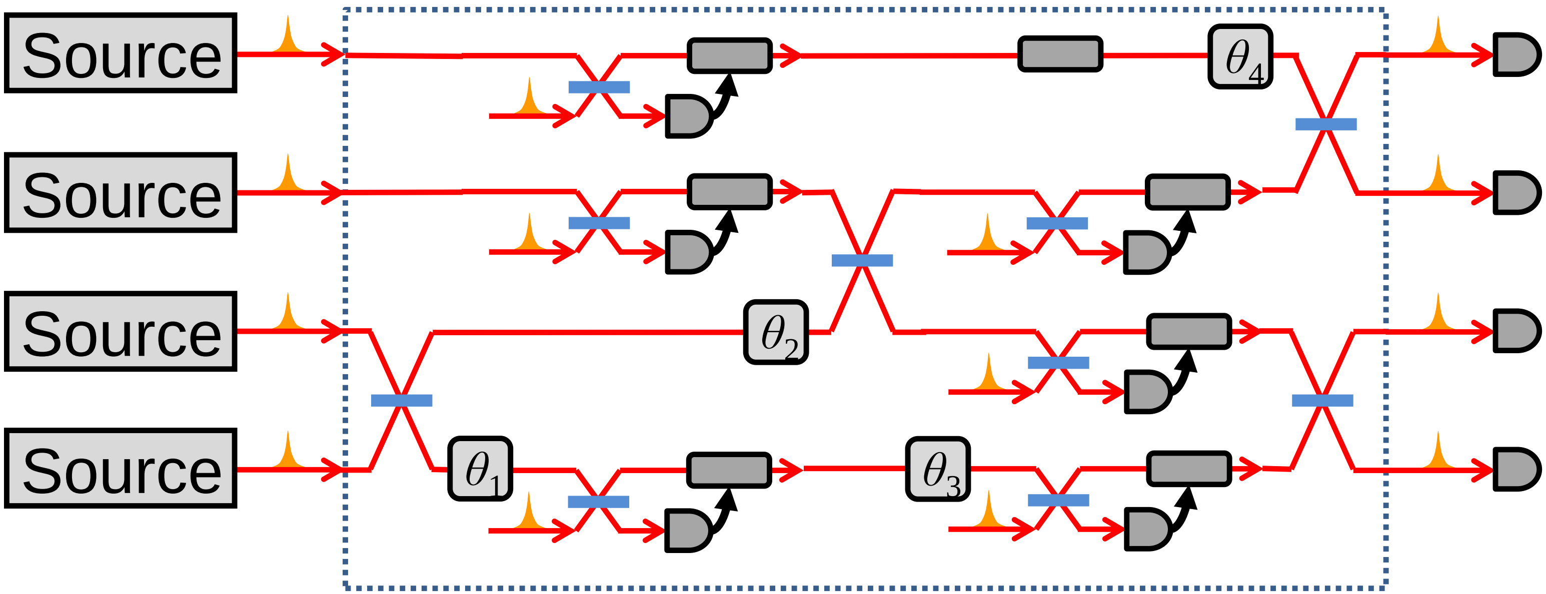
Takeda & Furusawa
PRL **119**, 120504 (2017)



Typical optical QC



Loop-based architecture for QC

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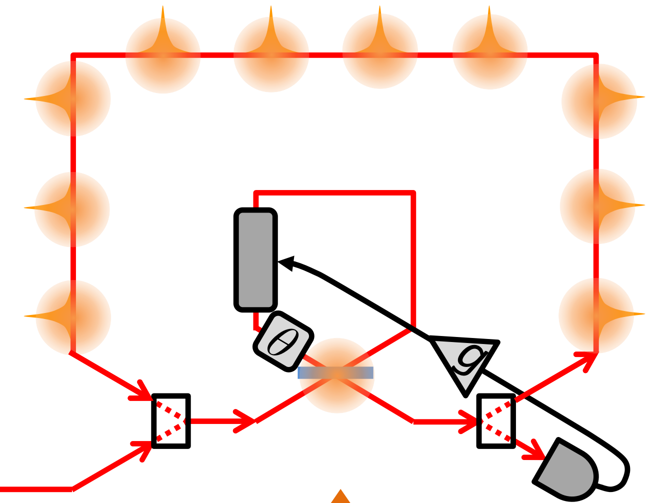
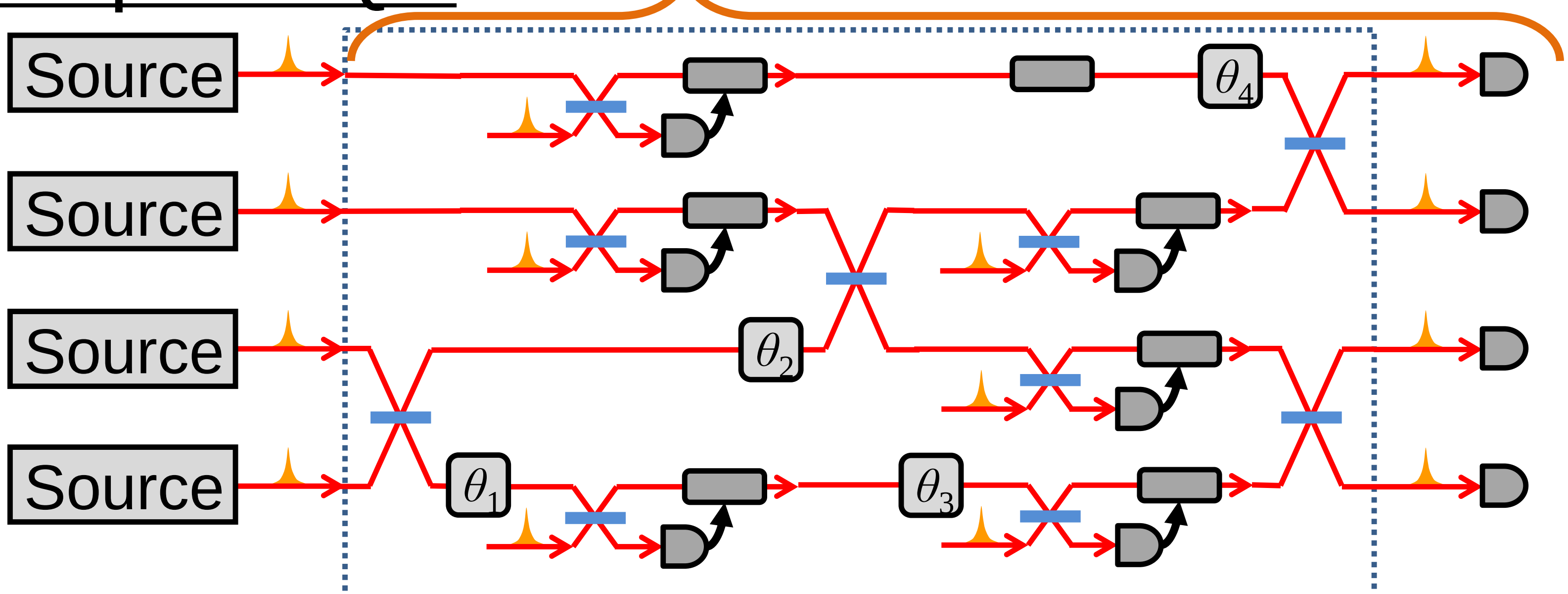
Takeda & Furusawa
PRL **119**, 120504 (2017)



Typical optical QC

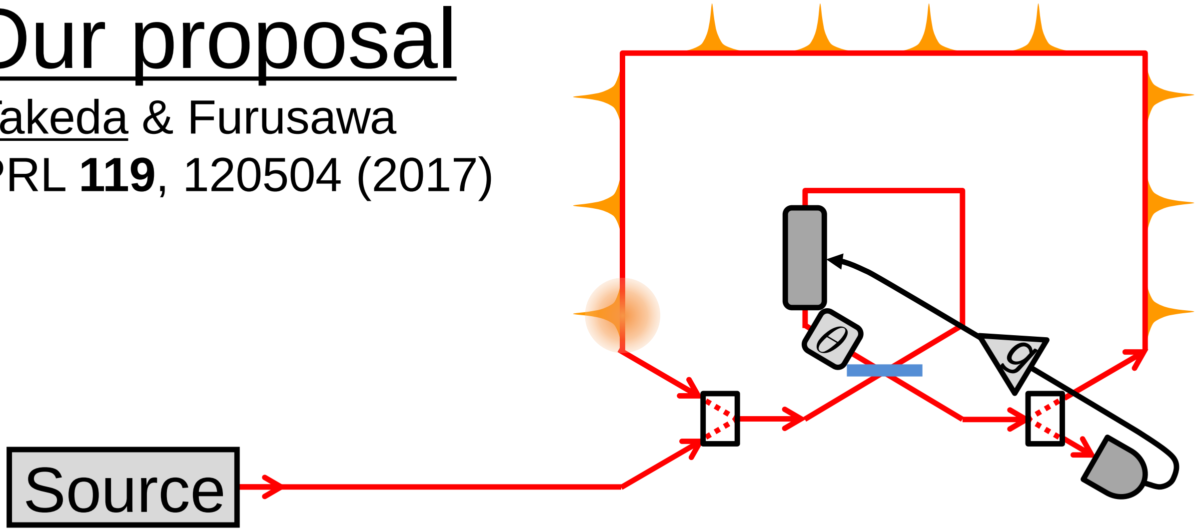
“All-in-one” circuit



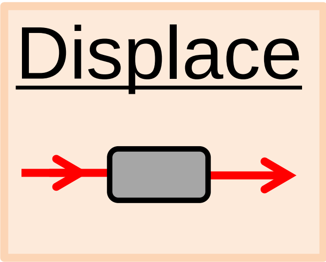
How to implement CV gates

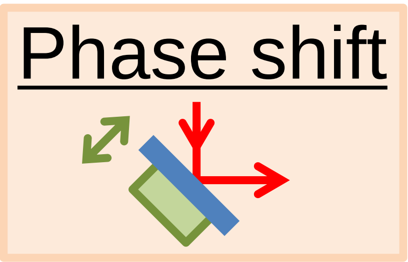
Our proposal

Takeda & Furusawa
PRL **119**, 120504 (2017)



Are 5 elementary gates implementable? ⇒ **Yes!**

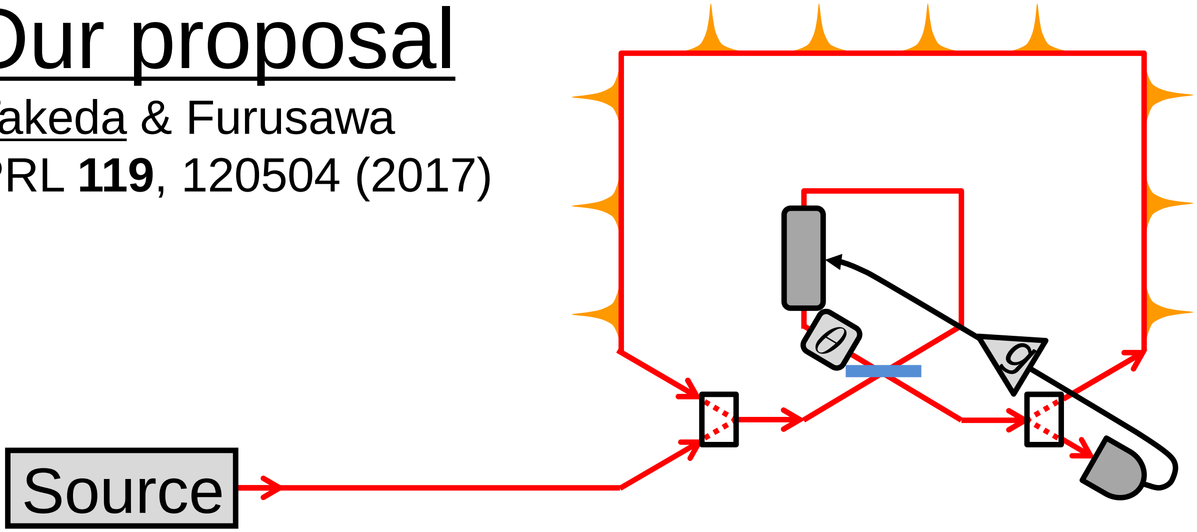




Gate implementation in loop circuit

Our proposal

Takeda & Furusawa
PRL **119**, 120504 (2017)



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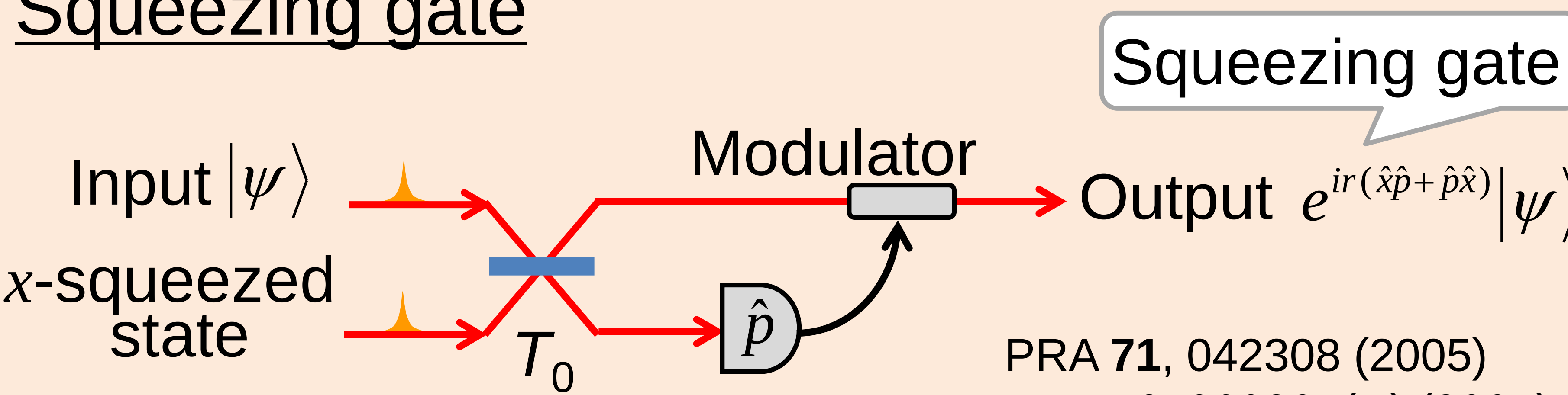
Squeezing gate

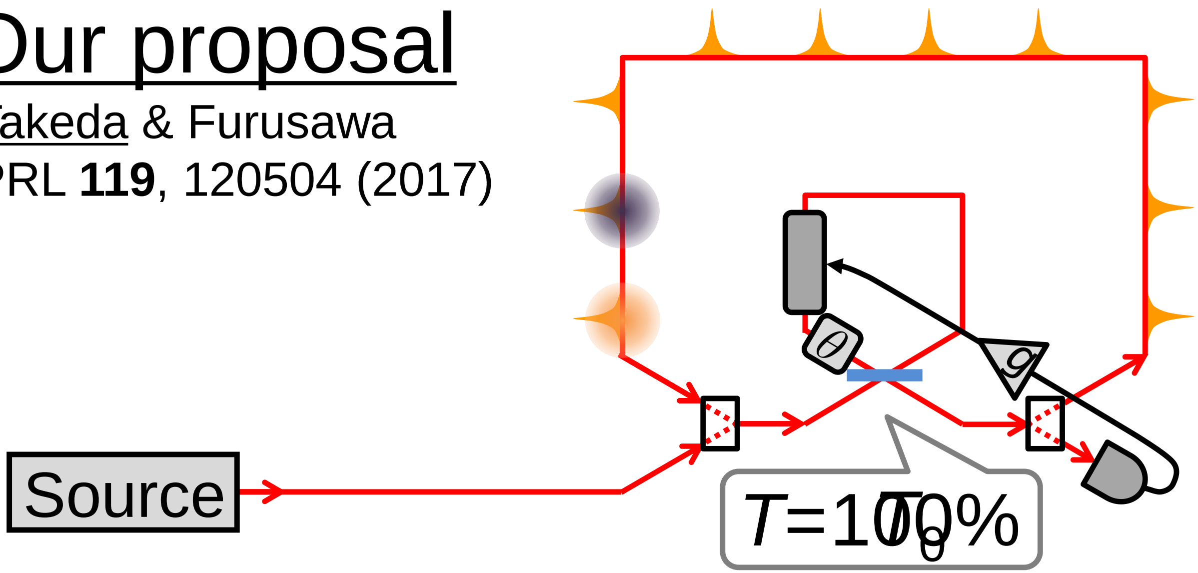


PRA **71**, 042308 (2005)
PRA **76**, 060301(R) (2007)

Gate implementation in loop circuit

Our proposal

Takeda & Furusawa
PRL **119**, 120504 (2017)



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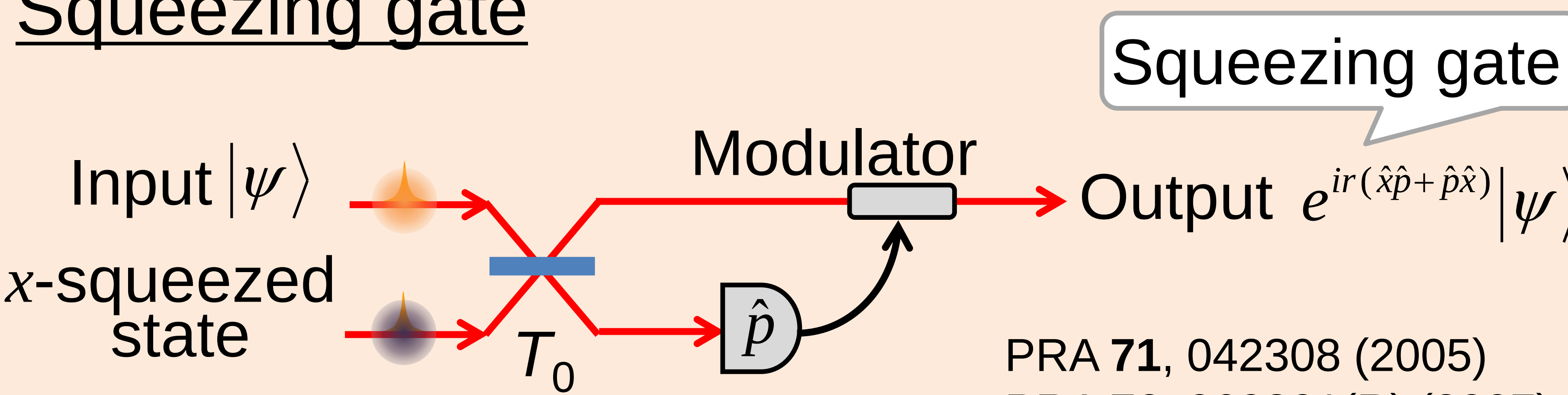
Squeezing gate



PRA **71**, 042308 (2005)
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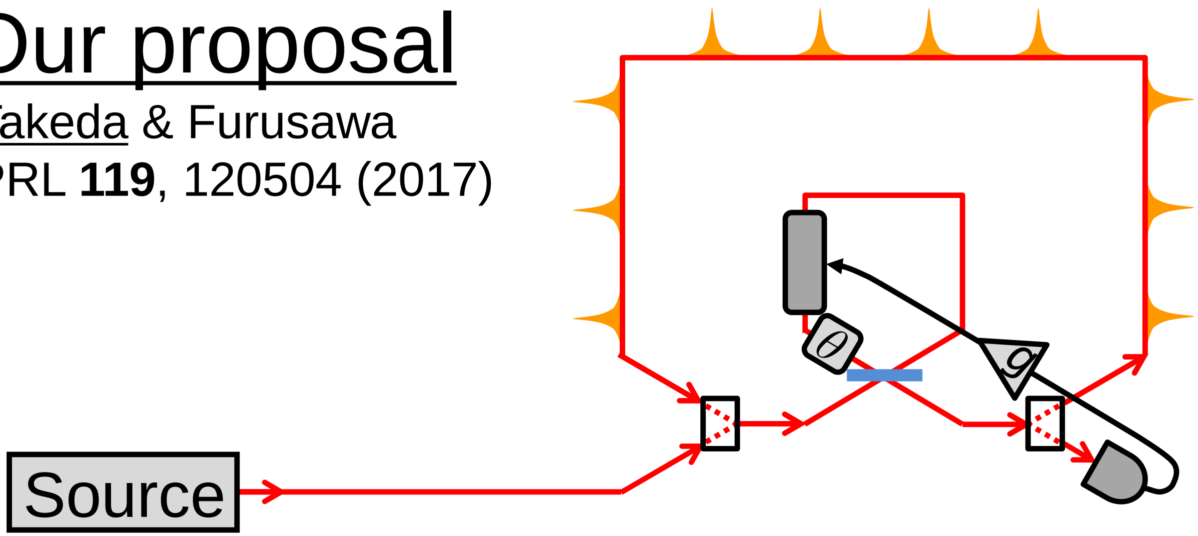

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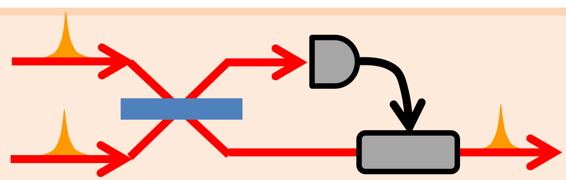
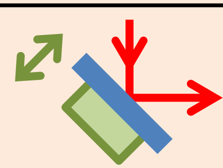
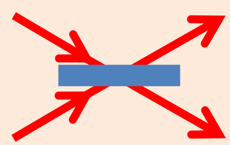


Displace

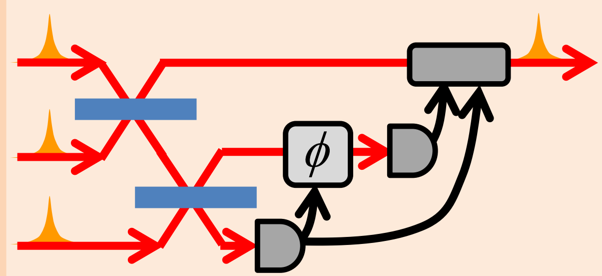
Phase shift



Beam splitter



Cubic phase gate

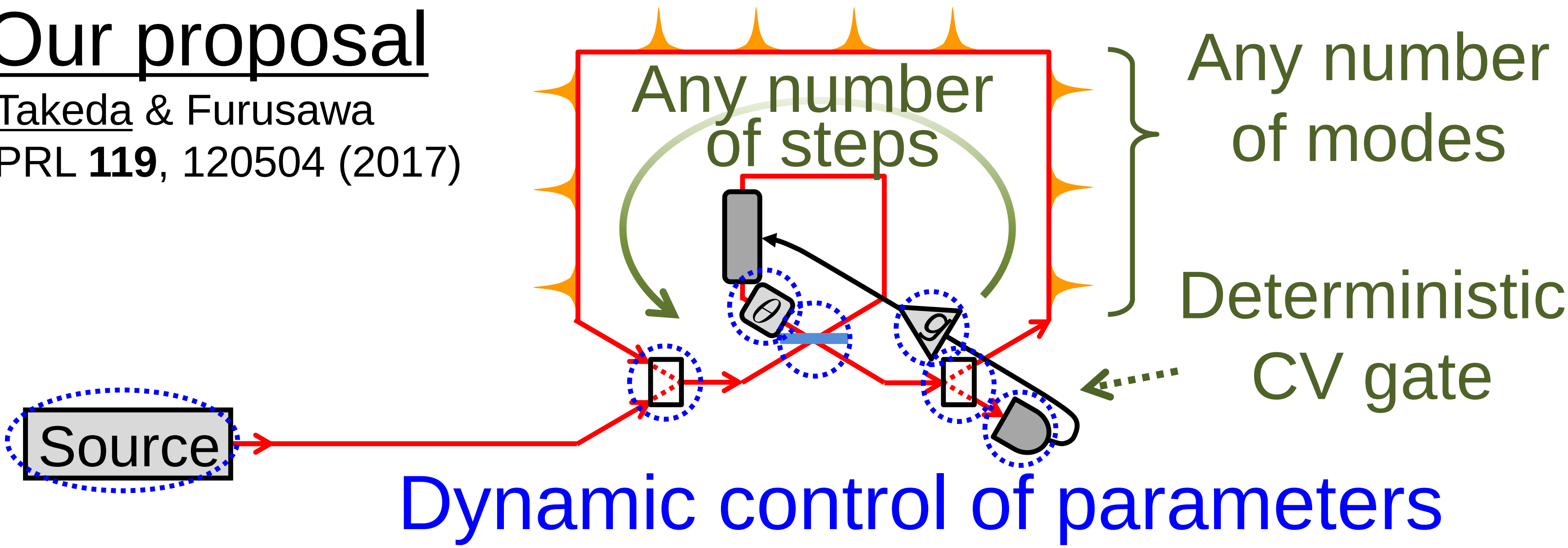


Universal quantum computation is possible

Gate implementation in loop circuit

Our proposal

Takeda & Furusawa
PRL **119**, 120504 (2017)



Features

✓ Universal QC for both CV and qubits
✓ Scalable (minimum resources required)
✓ Programmable

Optical Hybrid Quantum Teleportation and Its Application to Large-Scale Quantum Computing

1. Introduction
2. Hybrid quantum teleportation
3. Large-scale quantum computing
4. **Summary**

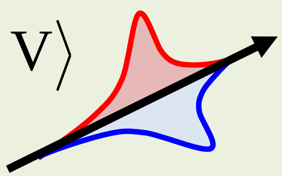
Introduction

This talk: Our strategy for large-scale optical QC

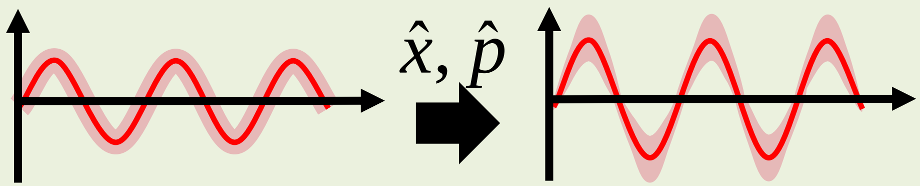
✓Deterministic operation via hybrid approach

Qubit encoding

$a|\mathrm{H}\rangle + b|\mathrm{V}\rangle$



Continuous-variable operation

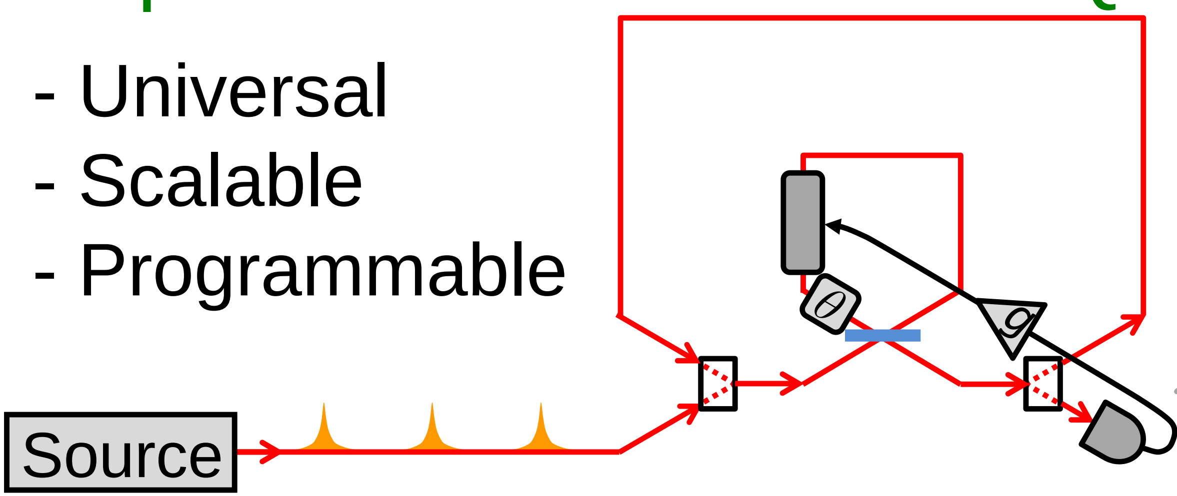


- CV quantum teleportation of qubits/qutrits
- CV quantum gates for qubits

✓Loop-based architecture for QC

- Universal
- Scalable
- Programmable

Takeda & Furusawa
PRL **119**, 120504 (2017)



Deterministic operation