Equivalent gate noise on macronode cluster state architectures

Blayney Walshe
Ben Q. Baragiola, Rafael N. Alexander, Nicolas C. Menicucci

CENTRE FOR QUANTUM COMPUTATION & COMMUNICATION TECHNOLOGY
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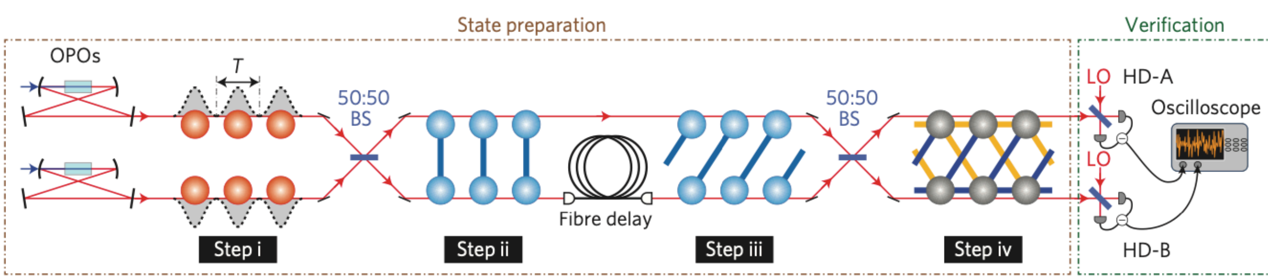
Experimental efforts

LETTERS
PUBLISHED ONLINE: 17 NOVEMBER 2013 | DOI: 10.1038/NPHOTON.2013.287
nature photonics

Ultra-large-scale continuous-variable cluster states multiplexed in the time domain

Shota Yokoyama[1], Ryuji Ukai[1], Seiji C. Armstrong[1,2], Chanond Sornphiphatphong[1], Toshiyuki Kaji[1], Shigenari Suzuki[1], Jun-ichi Yoshikawa[1], Hidehiro Yonezawa[1], Nicolas C. Menicucci[3] and Akira Furusawa[1]*



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Experimental efforts

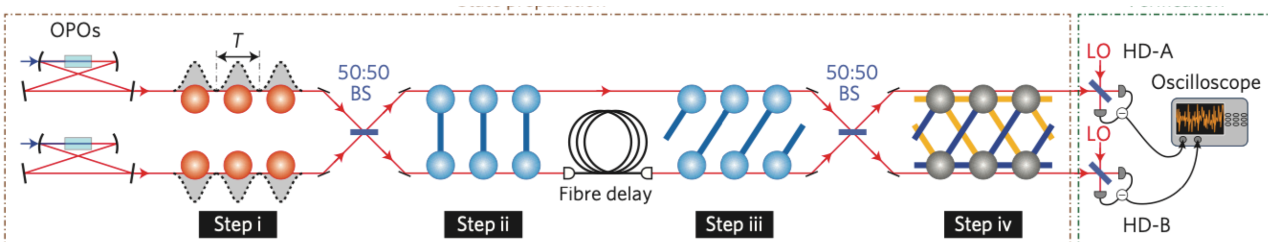
Invited Article: Generation of one-million-mode continuous-variable cluster state by unlimited time-domain multiplexing

Jun-ichi Yoshikawa,[1] Shota Yokoyama,[1,2] Toshiyuki Kaji,[1] Chanond Sornphiphatphong,[1] Yu Shiozawa,[1] Kenzo Makino,[1] and Akira Furusawa[1,a]

[1]*Department of Applied Physics, School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan*

[2]*Centre for Quantum Computation and Communication Technology, School of Engineering and Information Technology, University of New South Wales, Canberra, Australian Capital Territory 2600, Australia*

(Received 23 June 2016; accepted 1 September 2016; published online 27 September 2016)

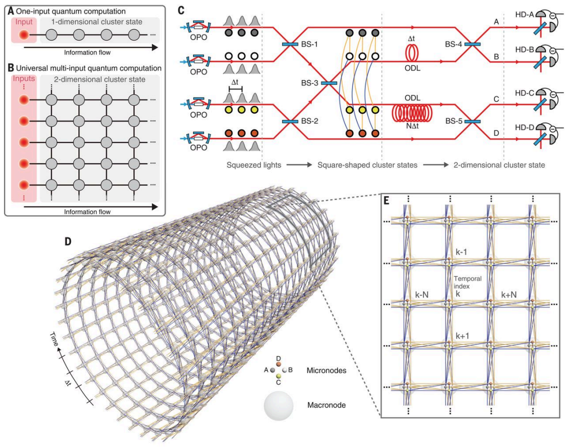


Experimental efforts

QUANTUM COMPUTING

Generation of time-domain-multiplexed two-dimensional cluster state

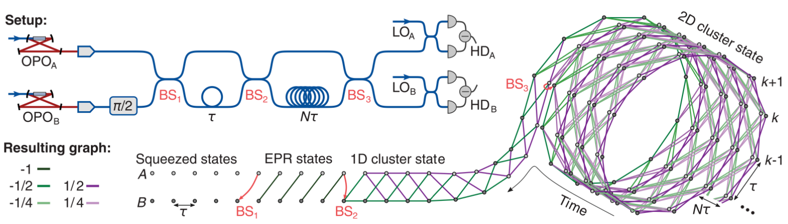
Warit Asavanant[1], Yu Shiozawa[1], Shota Yokoyama[2], Baramee Charoensombutamon[1], Hiroki Emura[1], Rafael N. Alexander[3], Shuntaro Takeda[1,4], Jun-ichi Yoshikawa[1], Nicolas C. Menicucci[5], Hidehiro Yonezawa[2], Akira Furusawa[1]*



QUANTUM COMPUTING

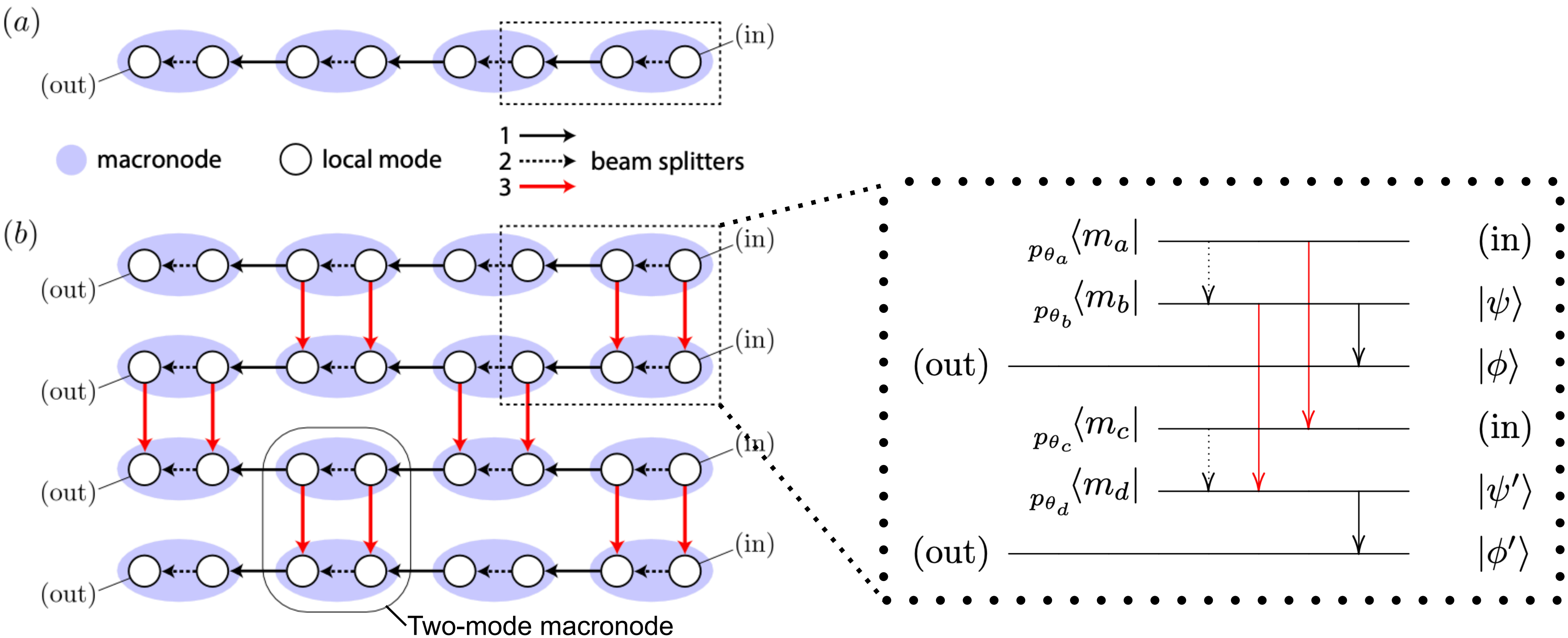
Deterministic generation of a two-dimensional cluster state

Mikkel V. Larsen*, Xueshi Guo, Casper R. Breum, Jonas S. Neergaard-Nielsen, Ulrik L. Andersen*



Streamline QC

Quad rail lattice (QRL)



PHYSICAL REVIEW A **104**, 062427 (2021)

Streamlined quantum computing with macronode cluster states

Blayney W. Walshe,[1,*] Rafael N. Alexander,[1] Nicolas C. Menicucci,[1] and Ben Q. Baragiola[1,2]
[1]*Centre for Quantum Computation and Communication Technology, School of Science, RMIT University, Melbourne, VIC 3000, Australia*
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(Received 10 September 2021; accepted 19 November 2021; published 16 December 2021)

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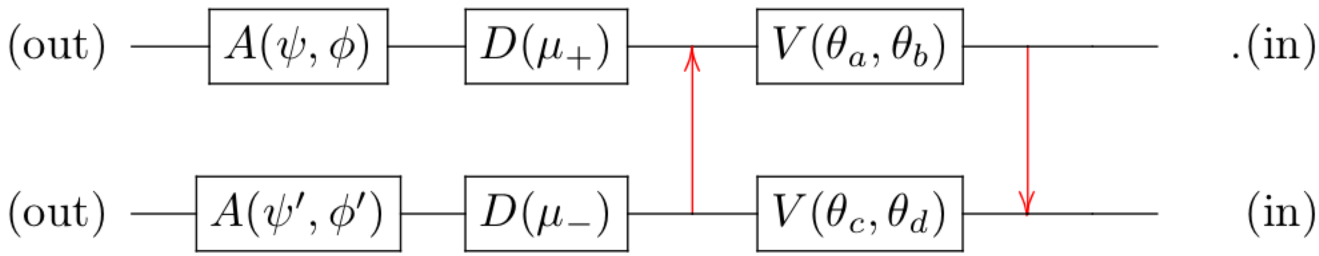
Quad rail lattice (QRL)

Two-mode gate



$$\mu_{a,b} := \frac{-m_a e^{i\theta_b} - m_b e^{i\theta_a}}{\sin(2\theta_-)} \qquad \mu_\pm = \frac{\mu_{c,d} \pm \mu_{a,b}}{\sqrt{2}}$$

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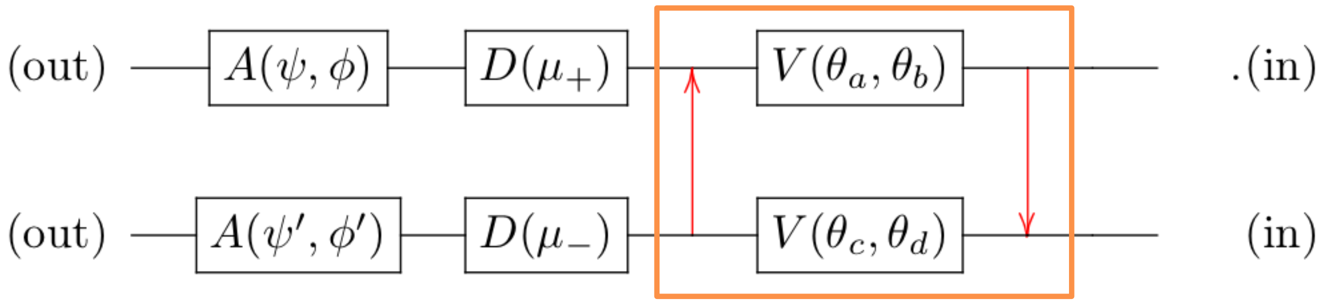
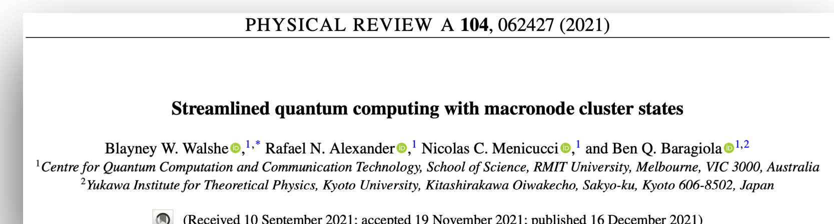
Two-mode gate



General two-mode gate

$$\mu_{a,b} := \frac{-m_a e^{i\theta_b} - m_b e^{i\theta_a}}{\sin(2\theta_-)}$$

$$\mu_\pm = \frac{\mu_{c,d} \pm \mu_{a,b}}{\sqrt{2}}$$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Streamlined QC

Quad rail lattice (QRL)

Gaussian unitaries that implement the Clifford group on GKP encoded states:

$$\underbrace{\{\hat{I}, \hat{F}, \hat{P}(\pm 1), \hat{\mathrm{C}}_Z(\pm 1)\}}_{\text{CV unitaries}} \longmapsto \underbrace{\{\hat{I}, \hat{H}, \sqrt{\hat{Z}}, \hat{\mathrm{C}}_Z\}}_{\text{GKP Cliffords}}$$

$\{\theta_a, \theta_b\}$	$\hat{V}(\boldsymbol{\theta})$	Logical Gate
$\{\frac{\pi}{2}, 0\}$	$\hat{I}$	$\bar{I}$
$\{\frac{3\pi}{4}, \frac{\pi}{4}\}$	$\hat{F}$	$\bar{H}$
$\{\frac{\pi}{2}, \frac{\pi}{2} \mp \chi\}$	$\hat{P}(\pm 1)$	$\bar{P}$

$\{\theta_a, \theta_b, \theta_c, \theta_d\}$	$\hat{V}^{(2)}(\boldsymbol{\theta})$	Logical Gate
$\{\frac{\pi}{2}, \frac{\pi}{2} \pm \chi, \frac{\pi}{2}, \frac{\pi}{2} \mp \chi\}$	$\hat{\mathrm{C}}_Z(\pm 1)$	$\bar{\mathrm{C}}_Z$
$\{0, \frac{\pi}{2}, \frac{\pi}{2}, 0\}$	SWAP	$\overline{\mathrm{SWAP}}$
$\{\frac{\pi}{2}, 0, \frac{\pi}{2}, 0\}$	$\hat{I} \otimes \hat{I}$	$\bar{I} \otimes \bar{I}$
$\{\frac{3\pi}{4}, \frac{\pi}{4}, \frac{3\pi}{4}, \frac{\pi}{4}\}$	$\hat{F} \otimes \hat{F}$	$\bar{H} \otimes \bar{H}$
$\{\frac{\pi}{2}, \frac{\pi}{2} \mp \chi, \frac{\pi}{2}, \frac{\pi}{2} \mp \chi\}$	$\hat{P}(\pm 1) \otimes \hat{P}(\pm 1)$	$\bar{P} \otimes \bar{P}$

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$\{\theta_a, \theta_b\}$	$\hat{V}(\boldsymbol{\theta})$	Logical Gate
$\{\frac{\pi}{2}, 0\}$	$\hat{I}$	$\bar{I}$
$\{\frac{3\pi}{4}, \frac{\pi}{4}\}$	$\hat{F}$	$\bar{H}$
$\{\frac{\pi}{2}, \frac{\pi}{2} \mp \chi\}$	$\hat{P}(\pm 1)$	$\bar{P}$

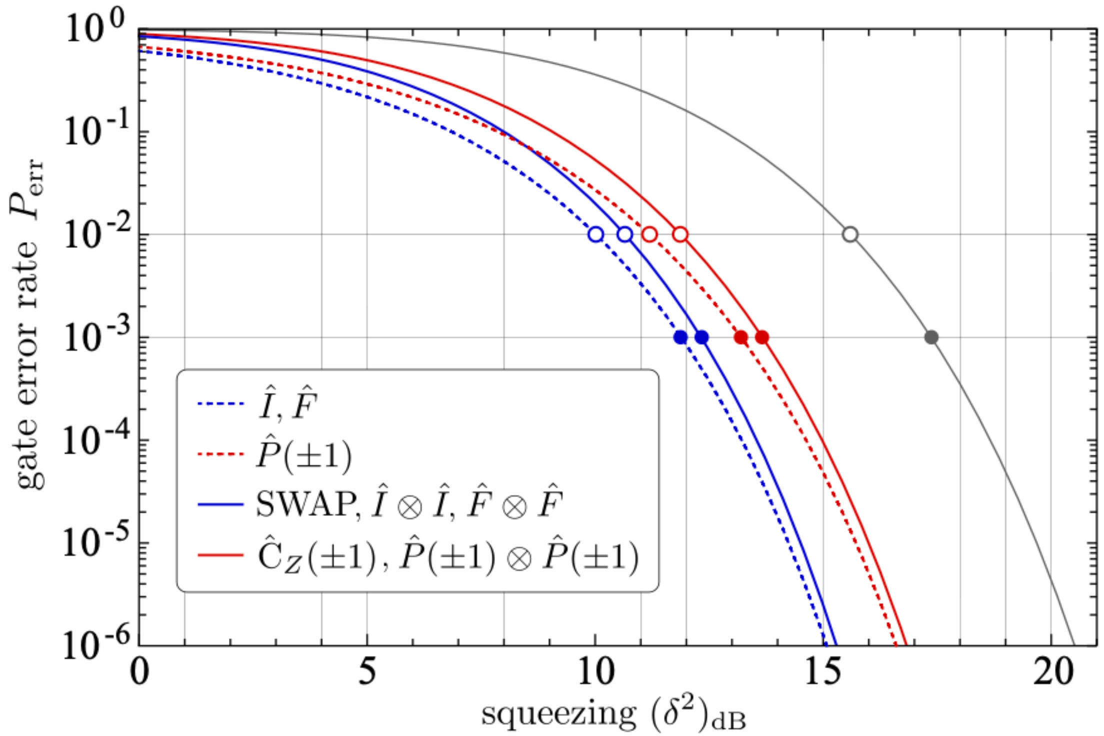
$\{\theta_a, \theta_b, \theta_c, \theta_d\}$	$\hat{V}^{(2)}(\boldsymbol{\theta})$	Logical Gate
$\{\frac{\pi}{2}, \frac{\pi}{2} \pm \chi, \frac{\pi}{2}, \frac{\pi}{2} \mp \chi\}$	$\hat{\mathrm{C}}_Z(\pm 1)$	$\bar{\mathrm{C}}_Z$
$\{0, \frac{\pi}{2}, \frac{\pi}{2}, 0\}$	SWAP	$\overline{\mathrm{SWAP}}$
$\{\frac{\pi}{2}, 0, \frac{\pi}{2}, 0\}$	$\hat{I} \otimes \hat{I}$	$\bar{I} \otimes \bar{I}$
$\{\frac{3\pi}{4}, \frac{\pi}{4}, \frac{3\pi}{4}, \frac{\pi}{4}\}$	$\hat{F} \otimes \hat{F}$	$\bar{H} \otimes \bar{H}$
$\{\frac{\pi}{2}, \frac{\pi}{2} \mp \chi, \frac{\pi}{2}, \frac{\pi}{2} \mp \chi\}$	$\hat{P}(\pm 1) \otimes \hat{P}(\pm 1)$	$\bar{P} \otimes \bar{P}$

$$\chi = \arctan 2$$

Squeezing level by gate error rate

Quad rail lattice (QRL)

Gate	Error rate: 10^{-2}				Error rate: 10^{-3}			
	Ref. [26]	Ref. [29]	Ref. [20]	ours	Ref. [26]	Ref. [29]	Ref. [20]	ours
$\hat{I}$	14.0	13.2	11.8	10.0	15.9	15.0	13.6	11.9
$\hat{F}$	14.8	14.9	11.8	10.0	16.8	16.7	13.6	11.9
$\hat{P}(\pm 1)$	14.4	15.2	12.5	11.2	16.4	17.1	14.5	13.7
$\hat{C}_Z(\pm 1)$	15.6	-	-	11.9	17.4	-	-	13.7
$\hat{F}\hat{F}\hat{C}_Z$	-	16.0	13.2	-	-	17.6	15.0	-



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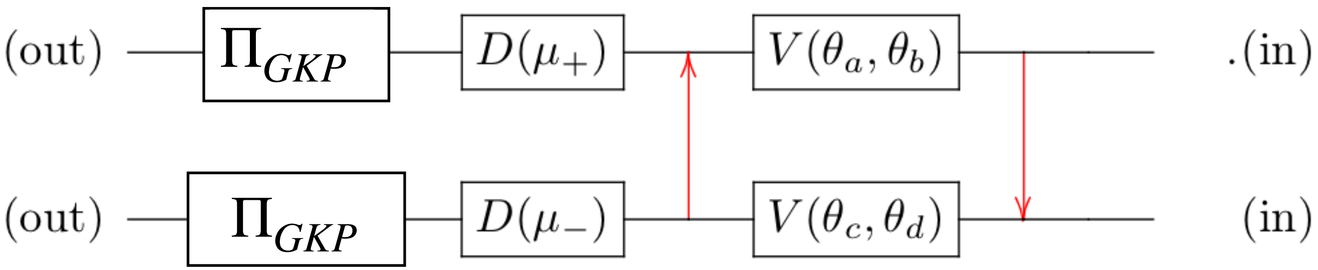
Noise Accumulation

Quad rail lattice (QRL)



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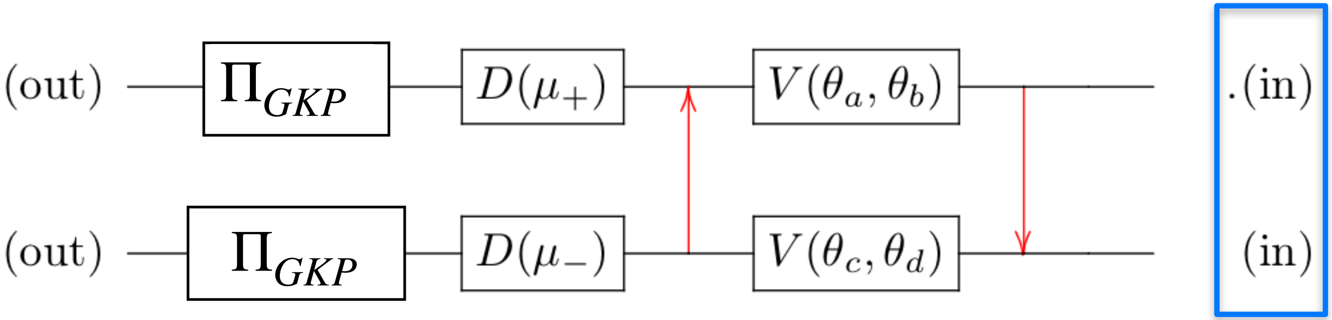
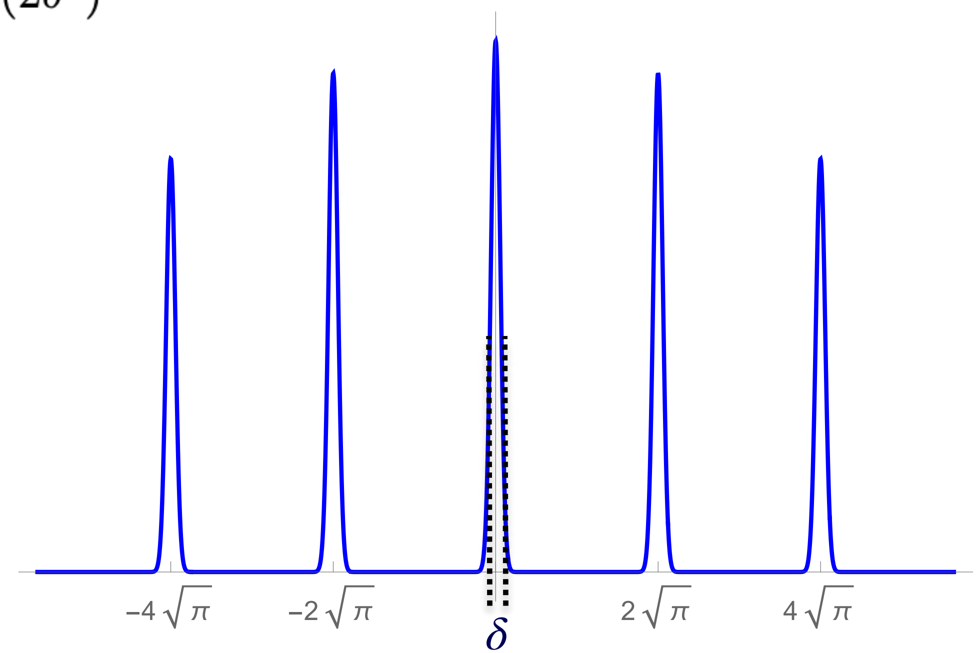
Noise Accumulation

Quad rail lattice (QRL)



$$(\delta^2)_{\mathrm{dB}} = -10\log_{10}(2\delta^2)$$



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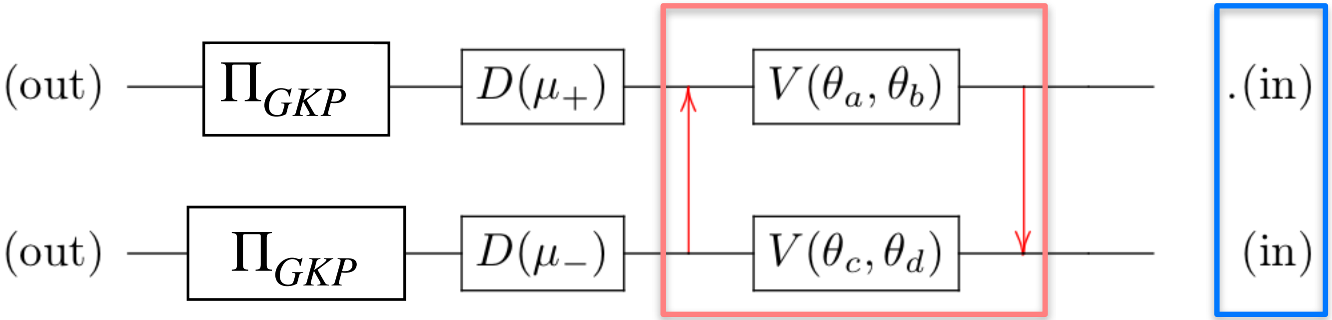
Noise Accumulation

Quad rail lattice (QRL)



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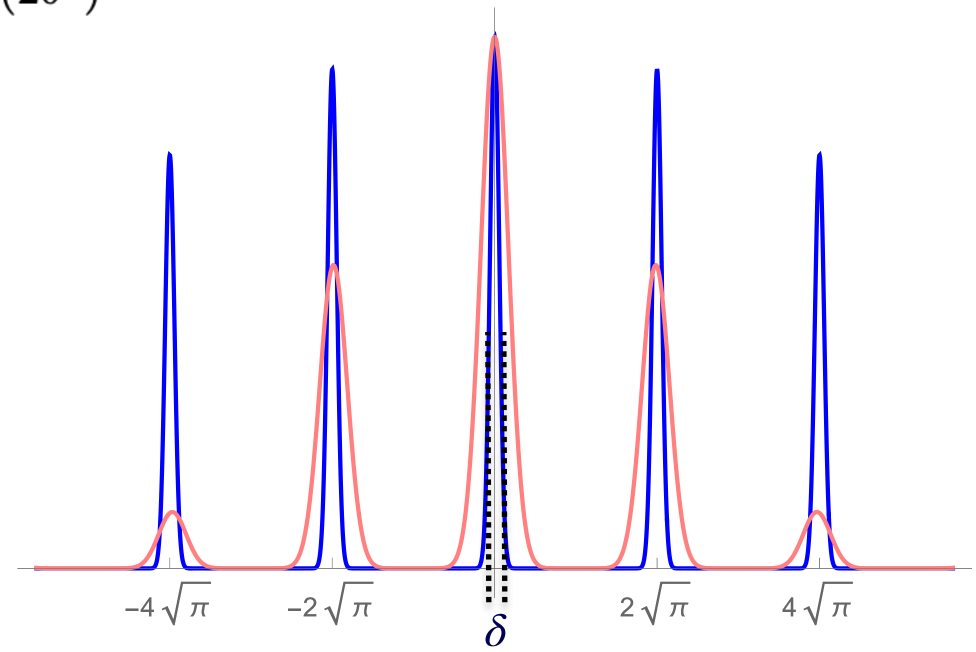

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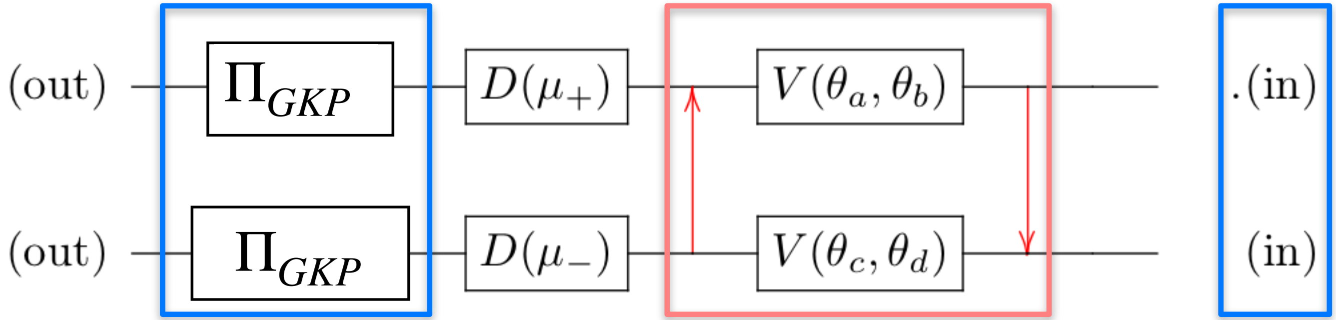
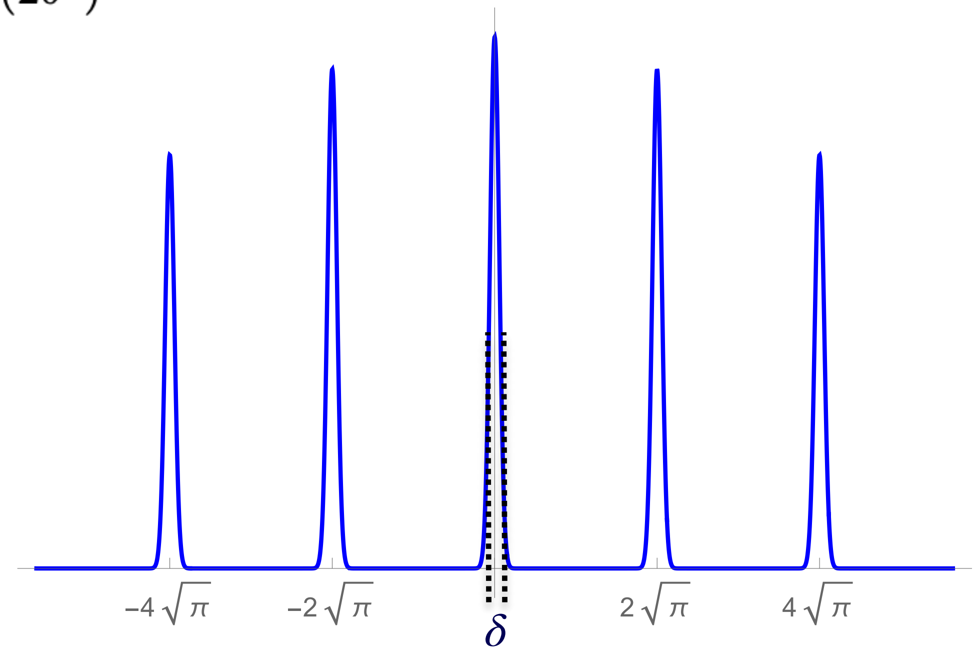
Noise Accumulation

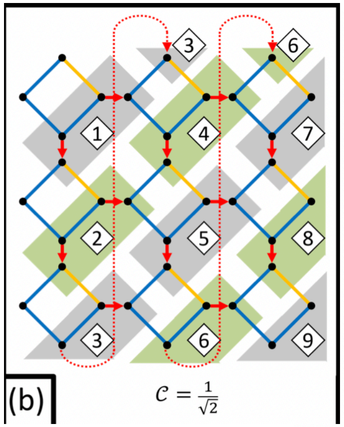
Quad rail lattice (QRL)



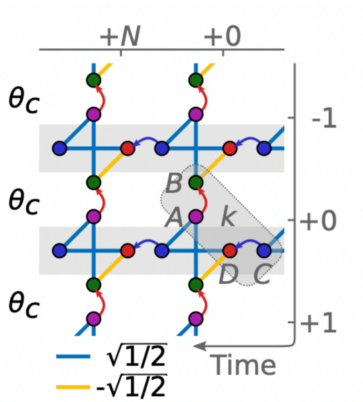
$$(\delta^2)_{\mathrm{dB}} = -10 \log_{10}(2\delta^2)$$



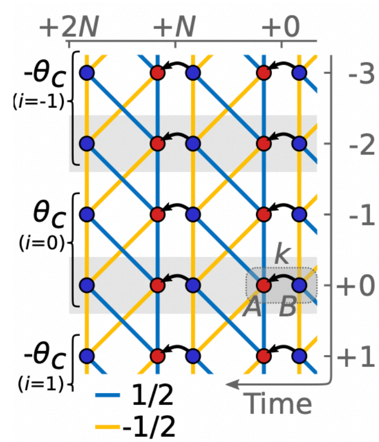
Equivalent noise of two-mode macronode-based cluster states



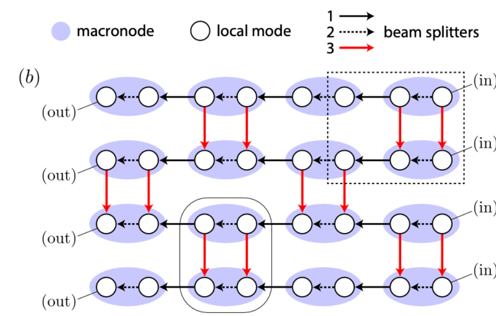
Bilayer Square Lattice. Alexander, 2018



Modified Bilayer Square Lattice. Alexander, 2018



Double Bilayer Square Lattice. Larsen, 2020



Quad-rail Lattice. Walshe, 2021

Various groups work with different types of macronode cluster state. Reported squeezing requirements for error rates of 10^{-2} range from 16-17.5 dB

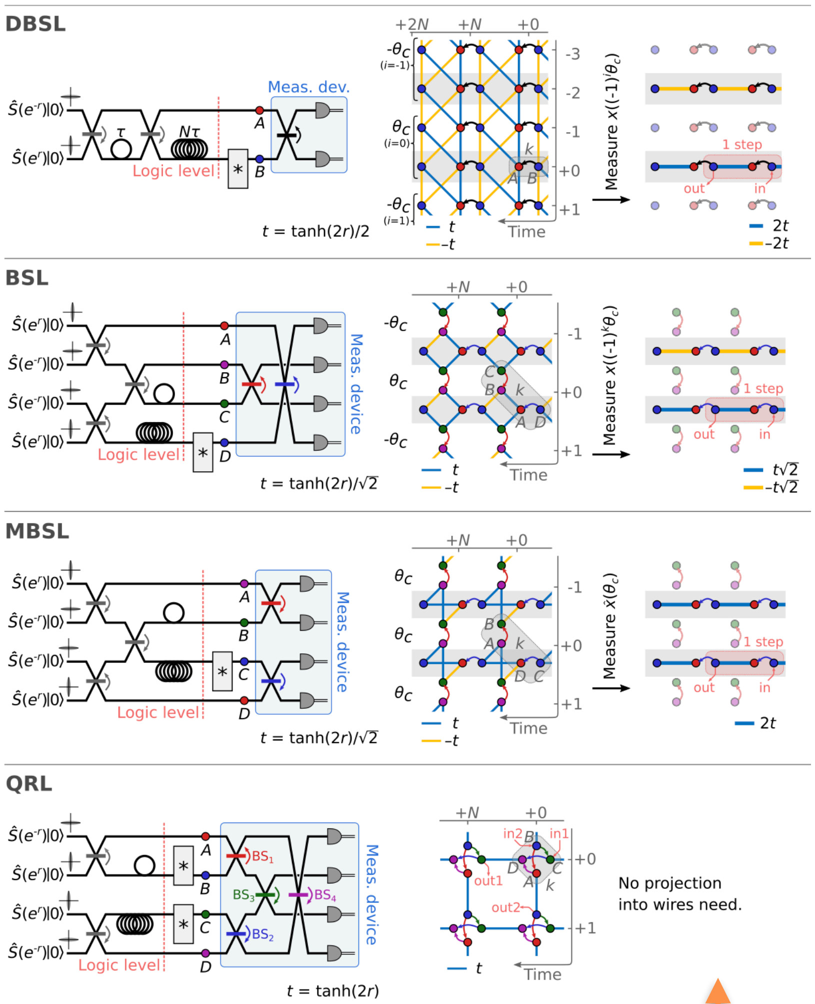
Cluster state projection

Double bilayer square lattice

Bilayer square lattice

Modified bilayer square lattice

Quad rail lattice



PHYSICAL REVIEW A **102**, 042608 (2020)

Architecture and noise analysis of continuous-variable quantum gates using two-dimensional cluster states

Mikkel V. Larsen,* Jonas S. Neergaard-Nielsen, and Ulrik L. Andersen†
Center for Quantum Macroscopic Quantum States (bigQ), Department of Physics, Technical University of Denmark, Fysikvej, 2800 Kongens Lyngby, Denmark

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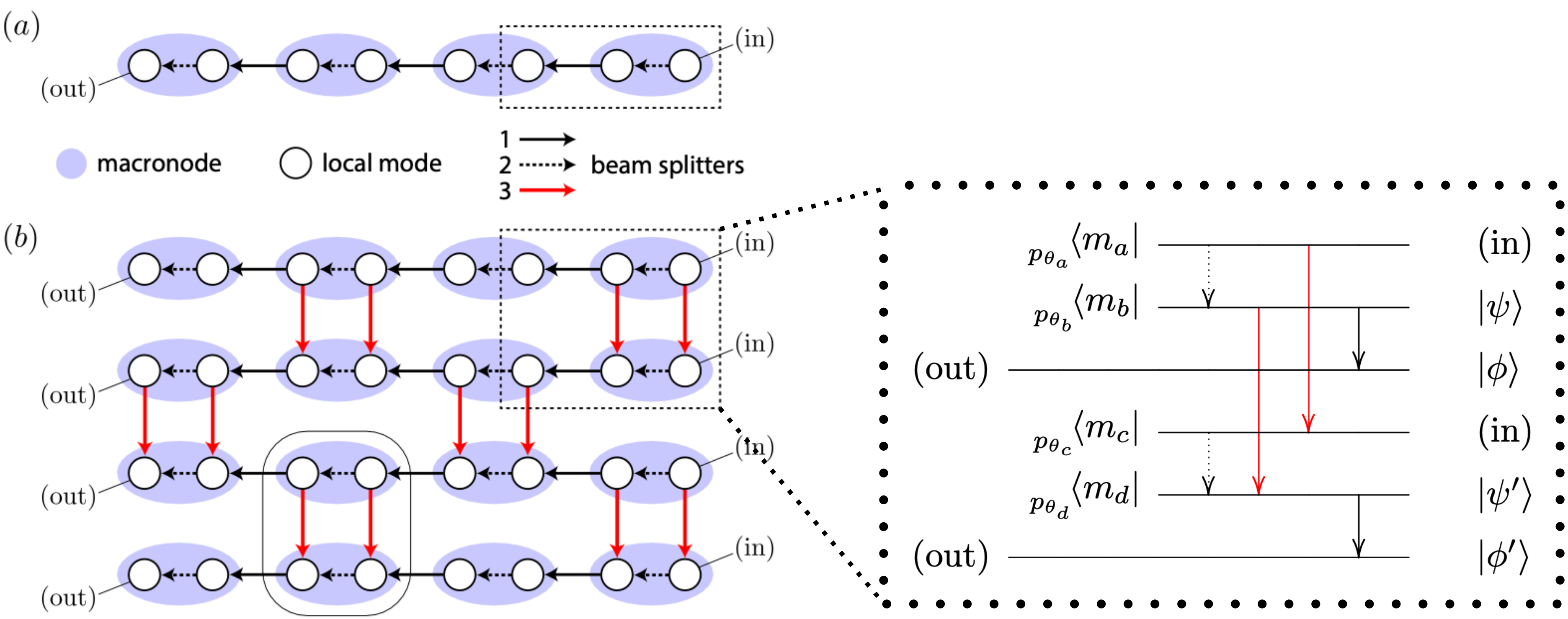
Arbitrary Streamlined QC

Quad rail lattice (QRL)



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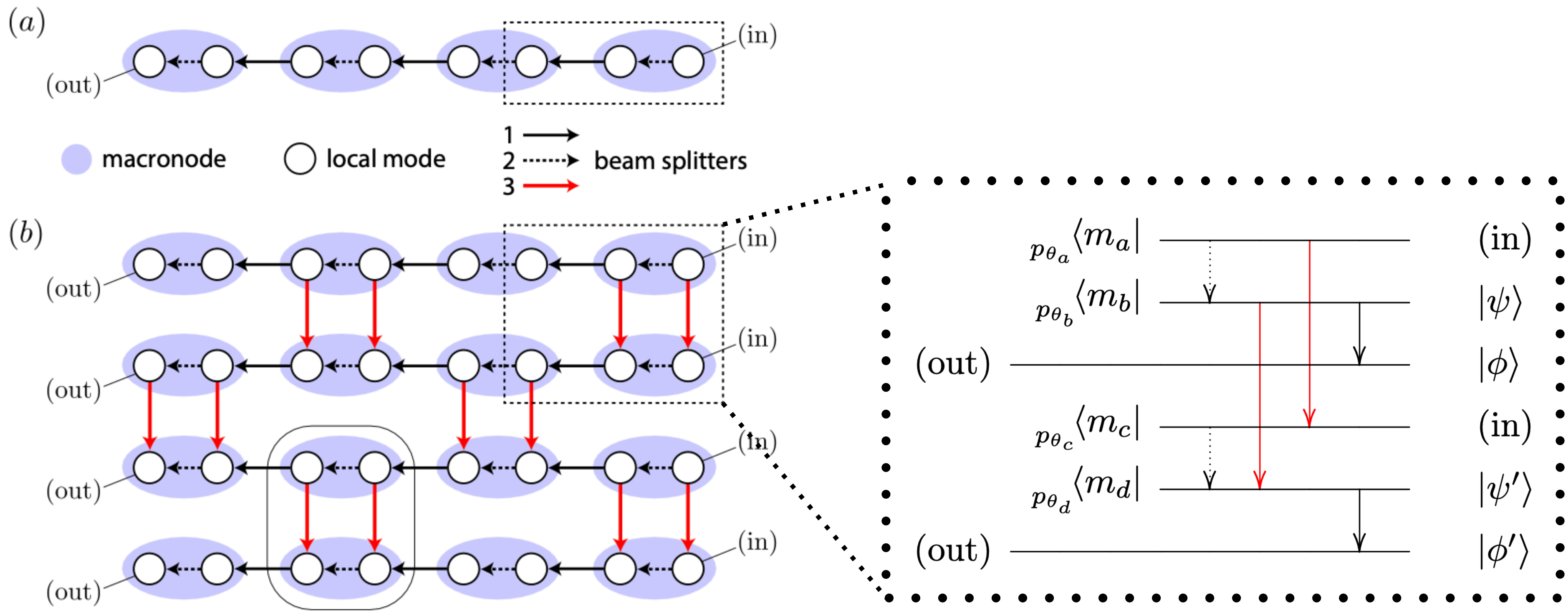

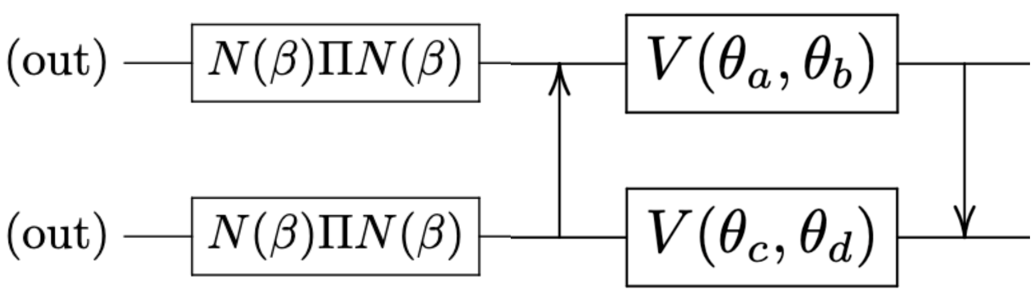

Arbitrary Streamlined QC

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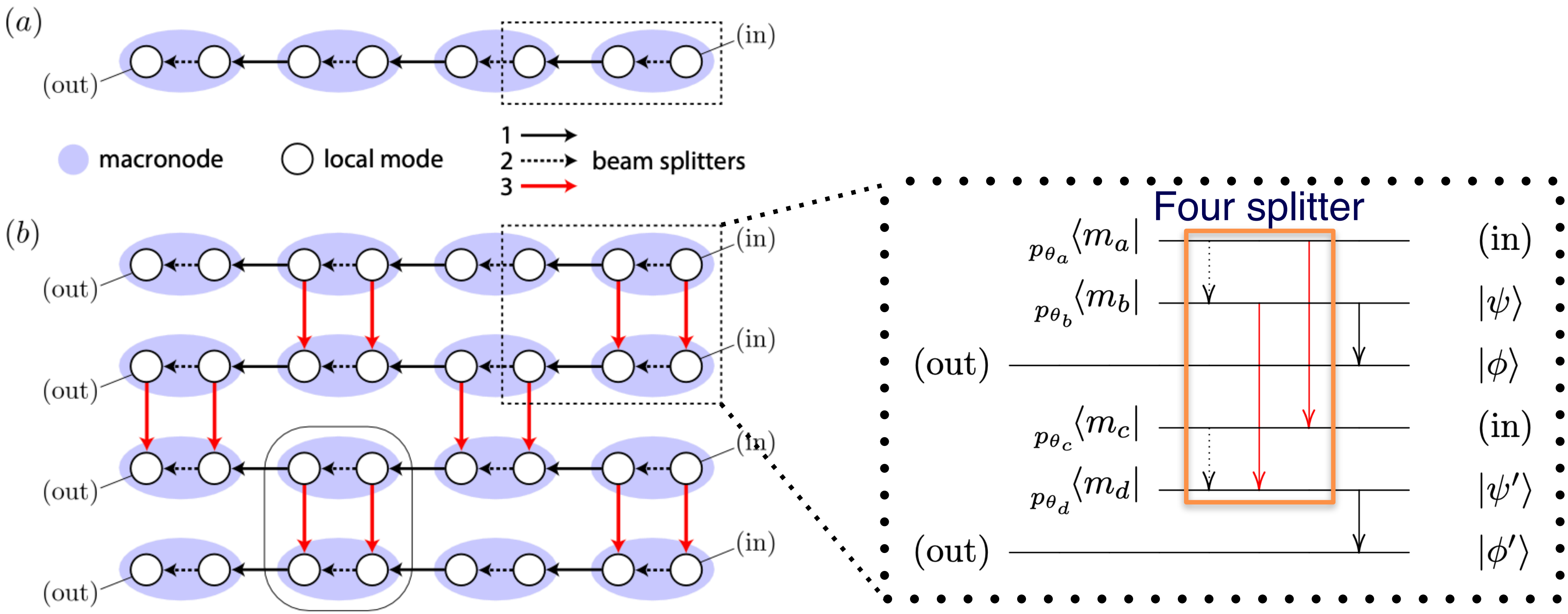
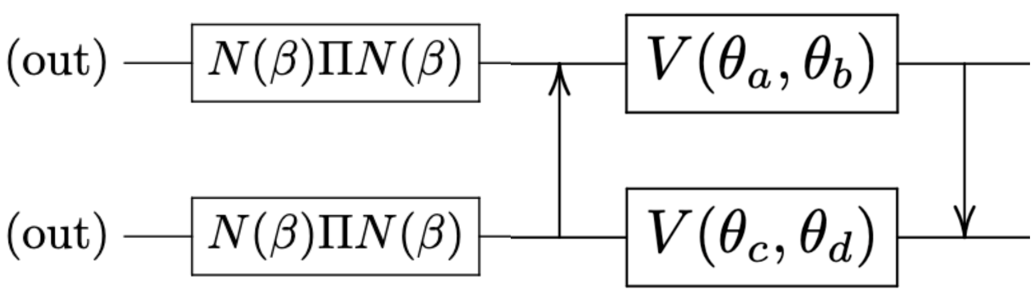
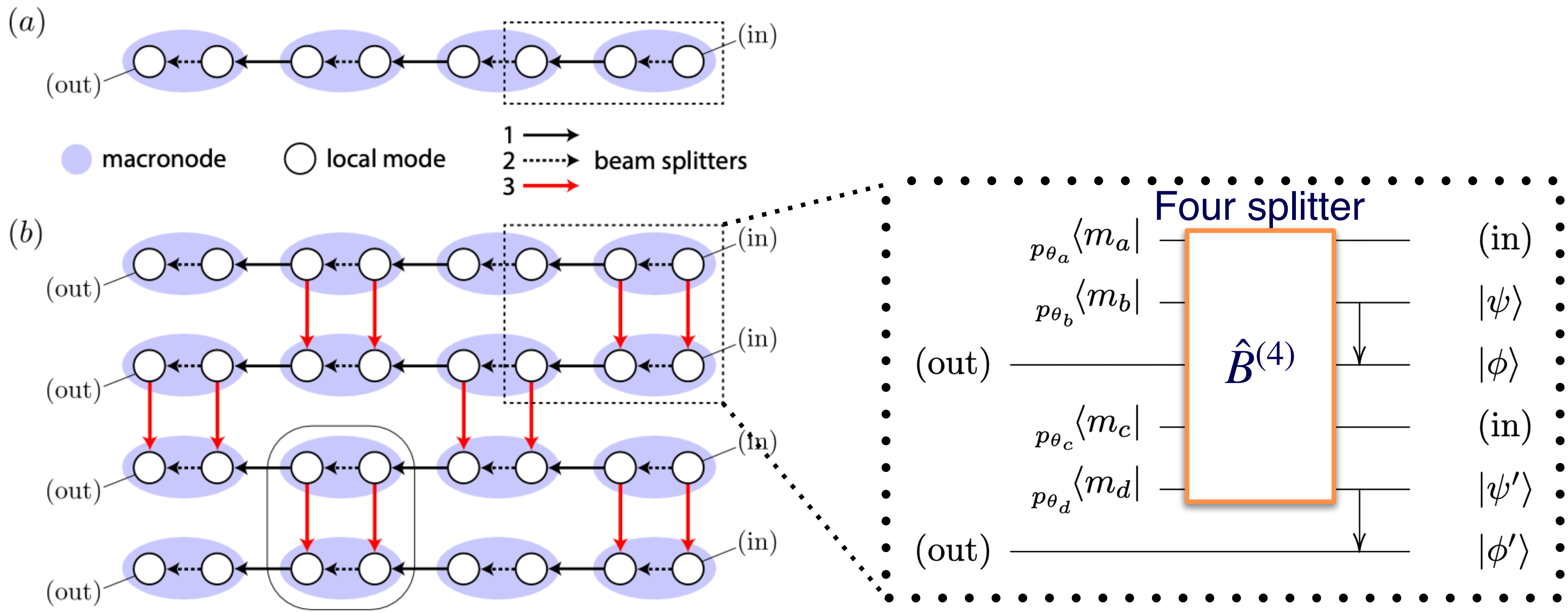
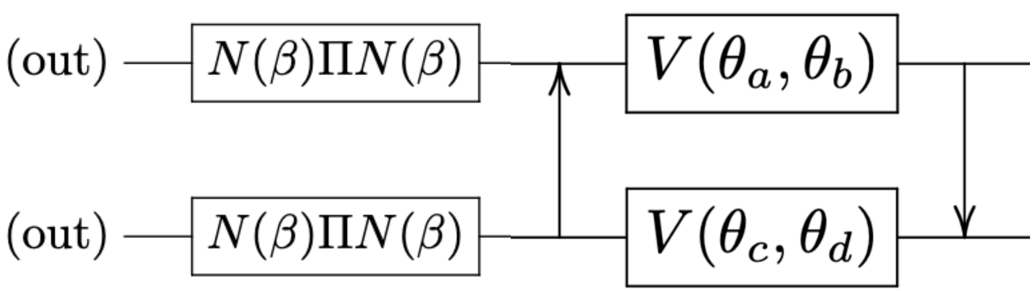




Arbitrary Streamlined QC

Arbitrary four splitter





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Arbitrary Streamlined QC

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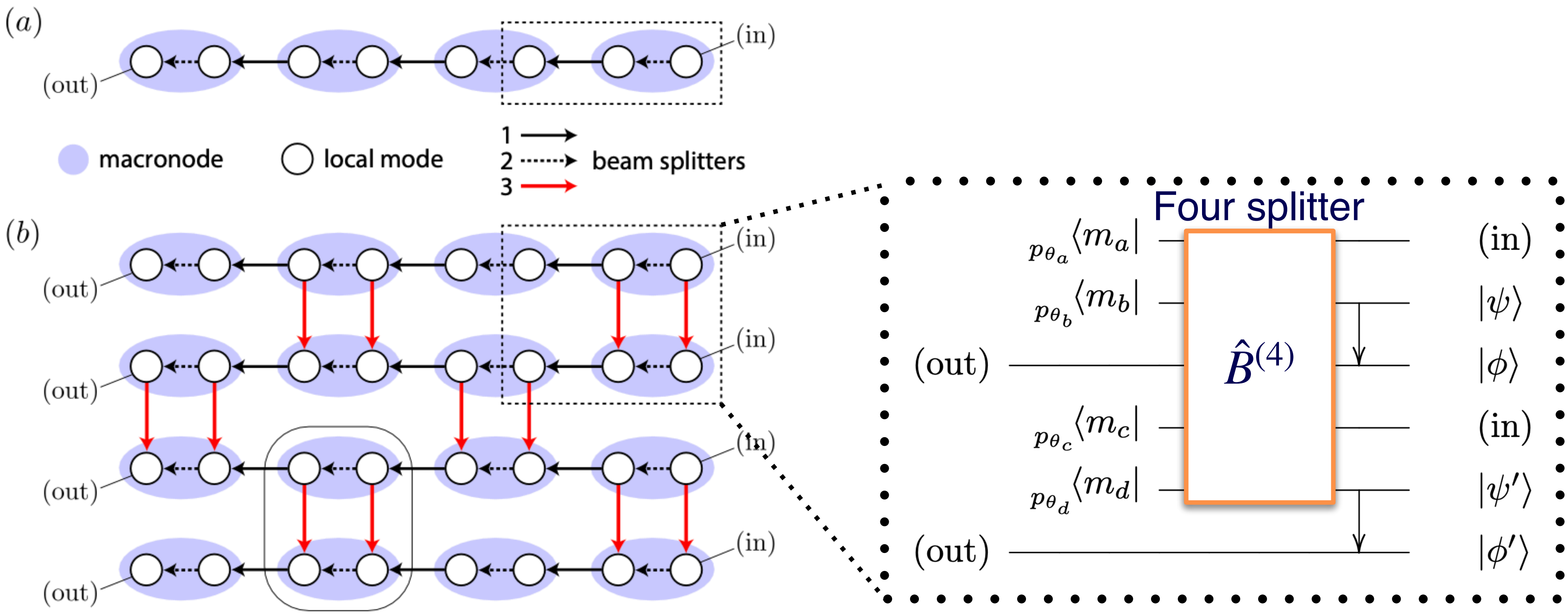

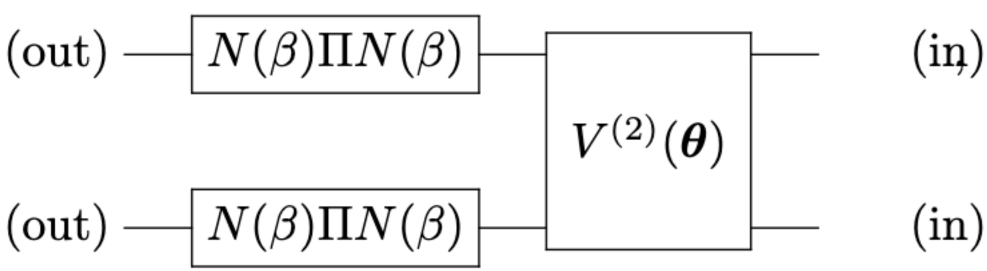

Arbitrary Streamlined QC

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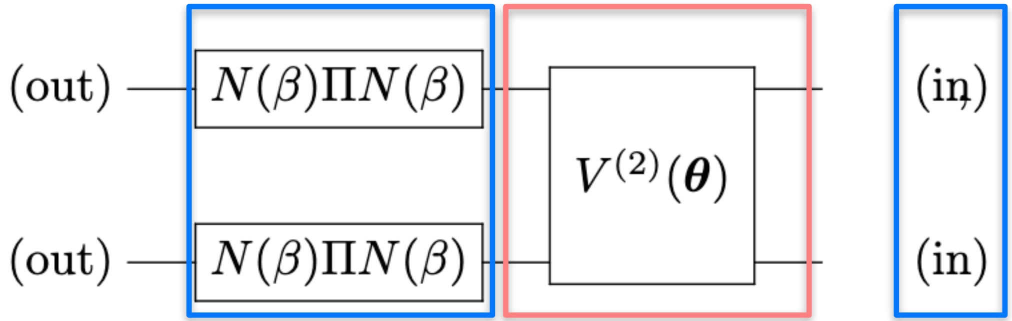

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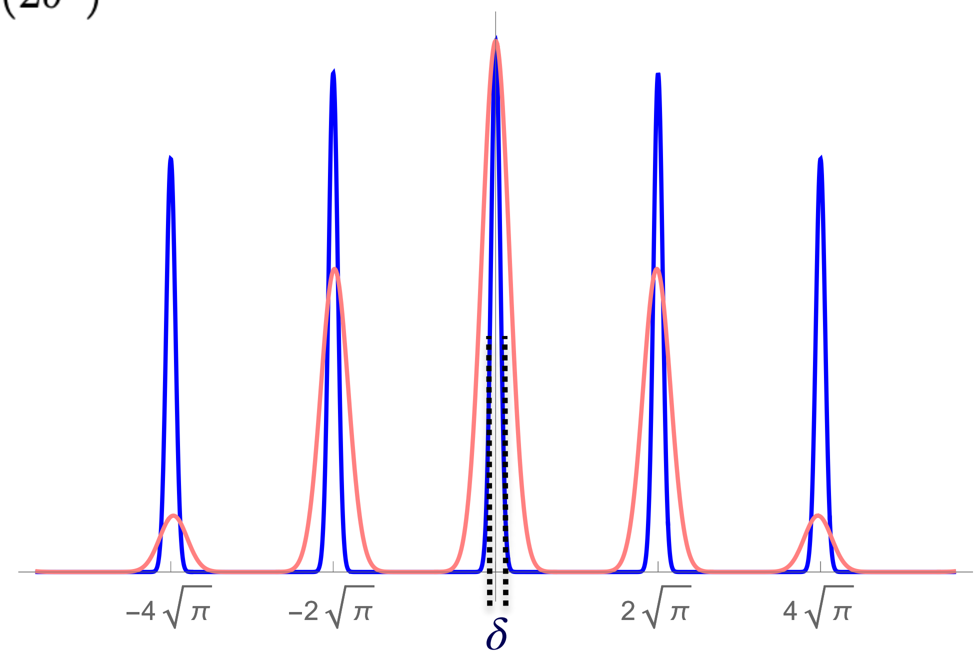

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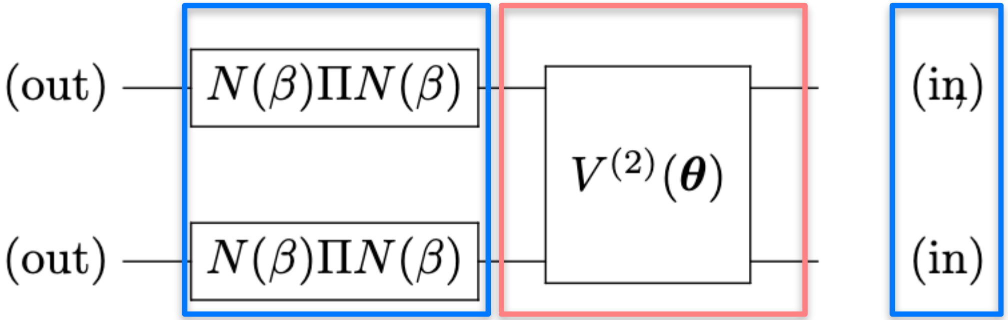
Arbitrary Streamlined QC

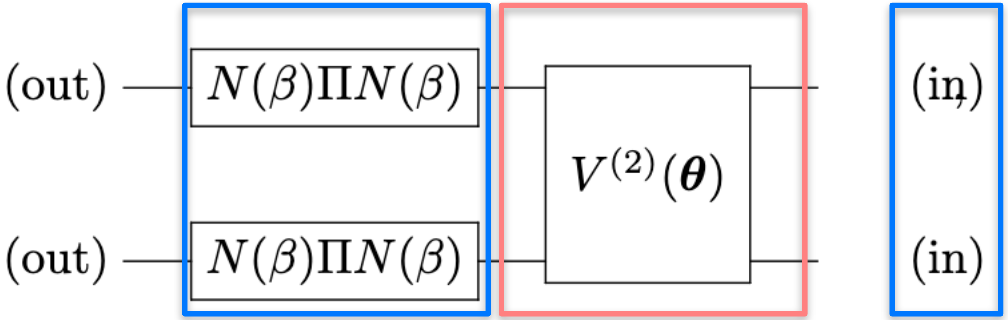
Arbitrary four splitter



The only piece that depends on the beam splitter network is $\hat{V}^{(2)}$

Arbitrary Streamlined QC

Arbitrary four splitter



The only piece that depends on the beam splitter network is $\hat{V}^{(2)}$

If we can do the same gate in a single step in each architecture, we will have the same noise properties in each architecture.

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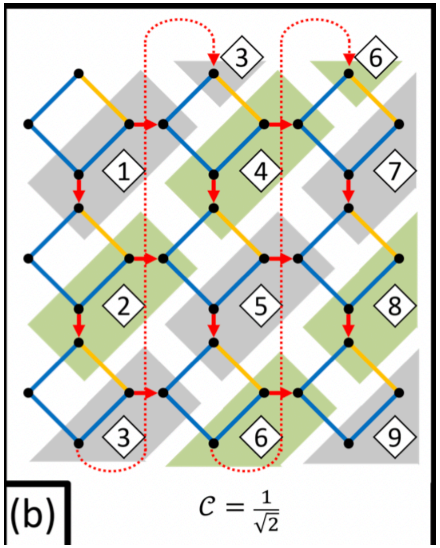
Bilayer square lattice four splitter

Bilayer square lattice (BSL)



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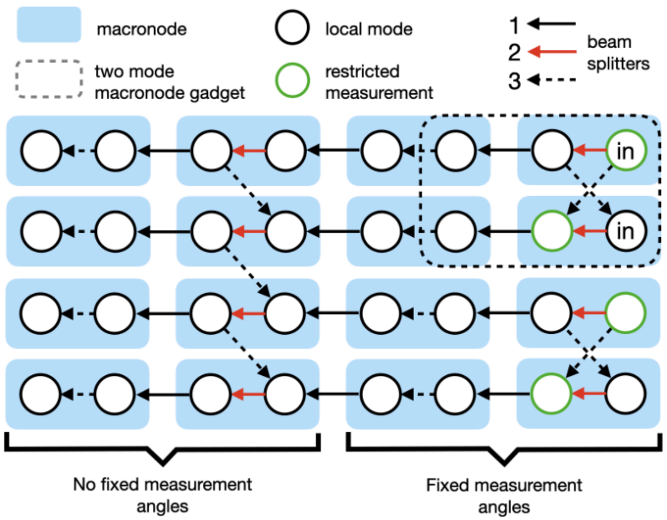
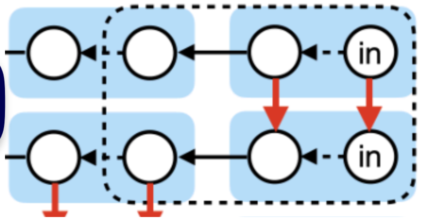
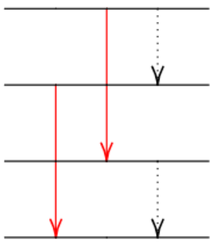


Bilayer square lattice (BSL)

Four splitter

QRL



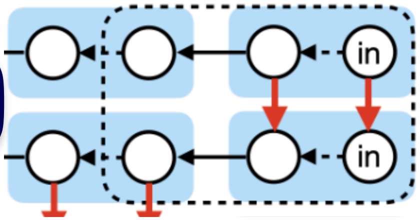
$\hat{B}^{(4)}_{\text{QRL}} =$ 

$$\mathbf{B}^{(4)}_{\text{QRL}} = \frac{1}{2}\begin{bmatrix} 1 & -1 & -1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & 1 & 1 \end{bmatrix}$$

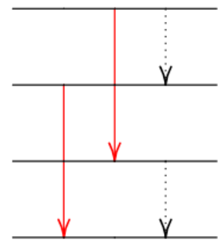
Four splitter

Bilayer square lattice (BSL)

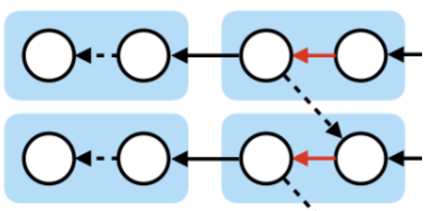
QRL



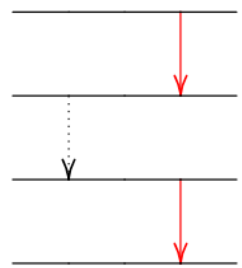
$$\hat{B}^{(4)}_{\mathrm{QRL}} =$$



$$\mathbf{B}^{(4)}_{\mathrm{QRL}} = \frac{1}{2}\begin{bmatrix} 1 & -1 & -1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & 1 & 1 \end{bmatrix}$$



$$\hat{B}^{(4)}_{\mathrm{BSL}} =$$



$$\mathbf{B}^{(4)}_{\mathrm{BSL}} = \frac{1}{2}\begin{bmatrix} \sqrt{2} & -\sqrt{2} & 0 & 0 \\ 1 & 1 & -1 & 1 \\ 1 & 1 & 1 & -1 \\ 0 & 0 & \sqrt{2} & \sqrt{2} \end{bmatrix}$$

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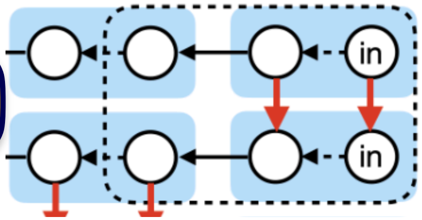
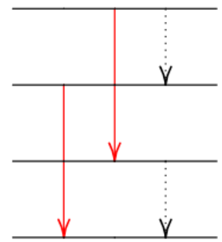
Four splitter

Bilayer square lattice (BSL)

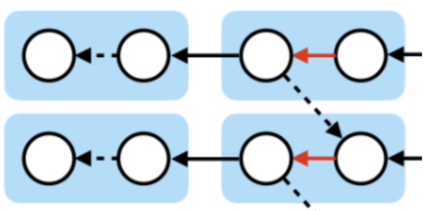
QRL



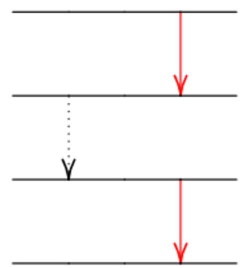
$\hat{B}^{(4)}_{\mathrm{QRL}} =$



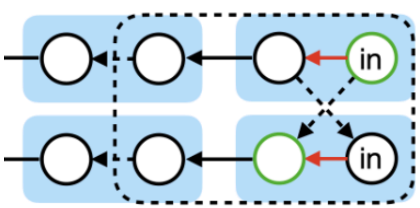
$$\mathbf{B}^{(4)}_{\mathrm{QRL}} = \frac{1}{2}\begin{bmatrix} 1 & -1 & -1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & 1 & 1 \end{bmatrix}$$



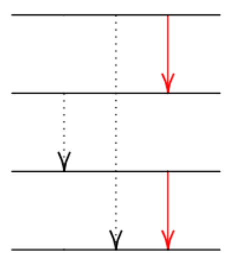
$\hat{B}^{(4)}_{\mathrm{BSL}} =$



$$\mathbf{B}^{(4)}_{\mathrm{BSL}} = \frac{1}{2}\begin{bmatrix} \sqrt{2} & -\sqrt{2} & 0 & 0 \\ 1 & 1 & -1 & 1 \\ 1 & 1 & 1 & -1 \\ 0 & 0 & \sqrt{2} & \sqrt{2} \end{bmatrix}$$



$\hat{B}^{(4)}_{\mathrm{cBSL}} =$



$$\mathbf{B}^{(4)}_{\mathrm{cBSL}} = \frac{1}{2}\begin{bmatrix} 1 & -1 & -1 & -1 \\ 1 & 1 & -1 & 1 \\ 1 & 1 & 1 & -1 \\ 1 & -1 & 1 & 1 \end{bmatrix}$$

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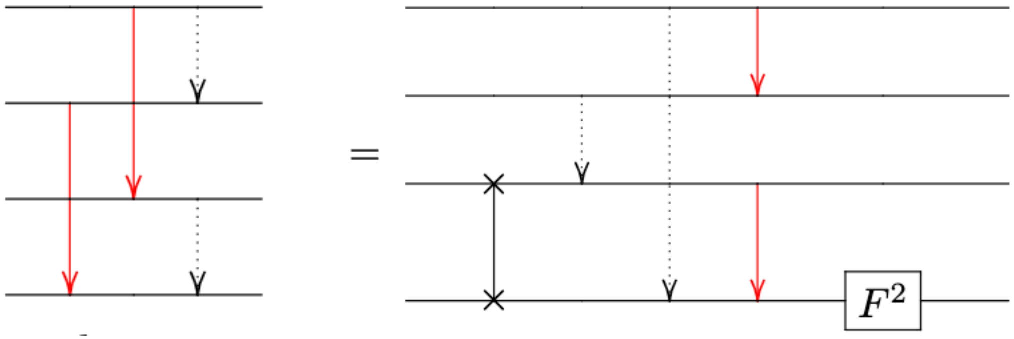
Four splitter equivalence

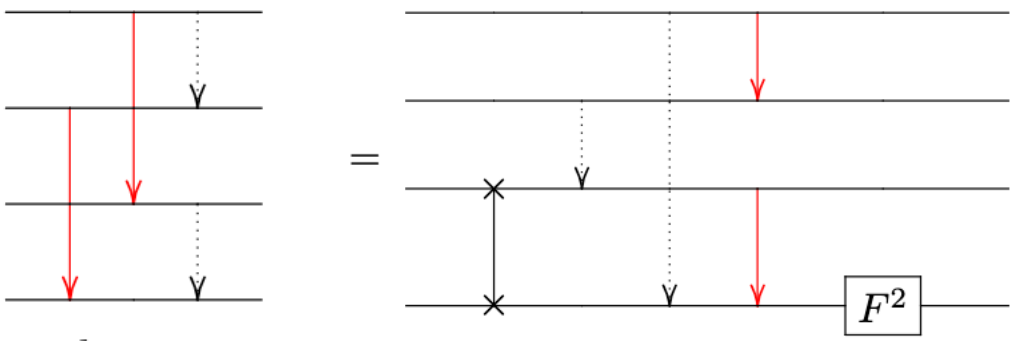
Bilayer square lattice (BSL)



All four splitters belong to a single equivalence class that permits 3 operations:

Four splitter equivalence

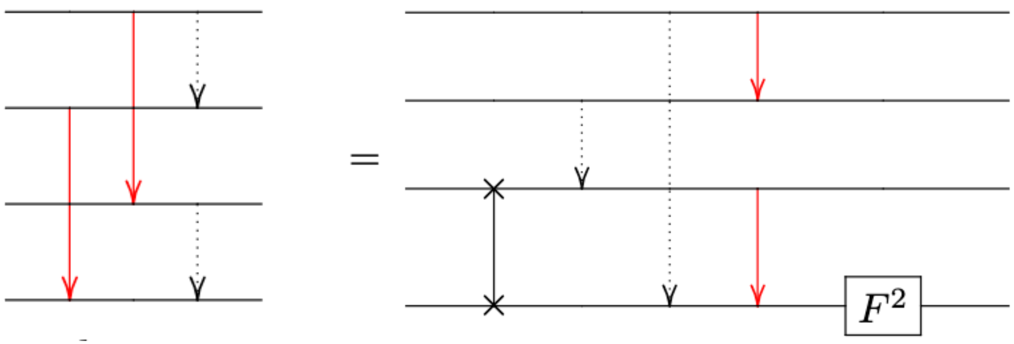
Bilayer square lattice (BSL)



All four splitters belong to a single equivalence class that permits 3 operations:

1. SWAP gates *after* the four splitter (to the left)

Four splitter equivalence

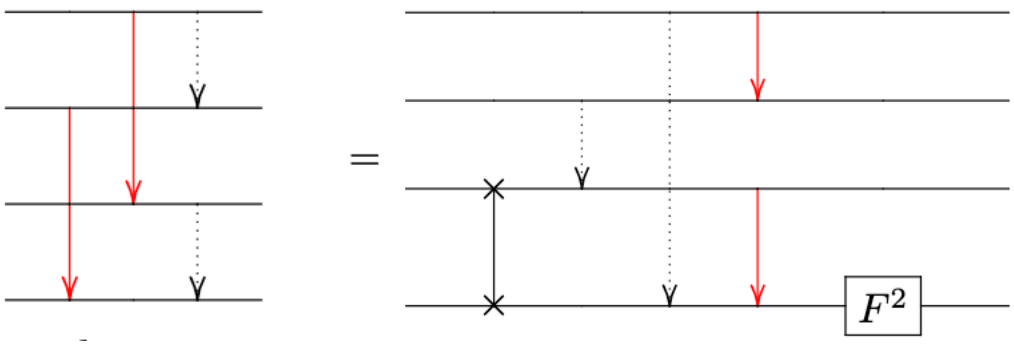


All four splitters belong to a single equivalence class that permits 3 operations:

1. SWAP gates *after* the four splitter (to the left)

$$\frac{1}{2}\begin{bmatrix} 1 & -1 & -1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & 1 & 1 \end{bmatrix}$$

Four splitter equivalence



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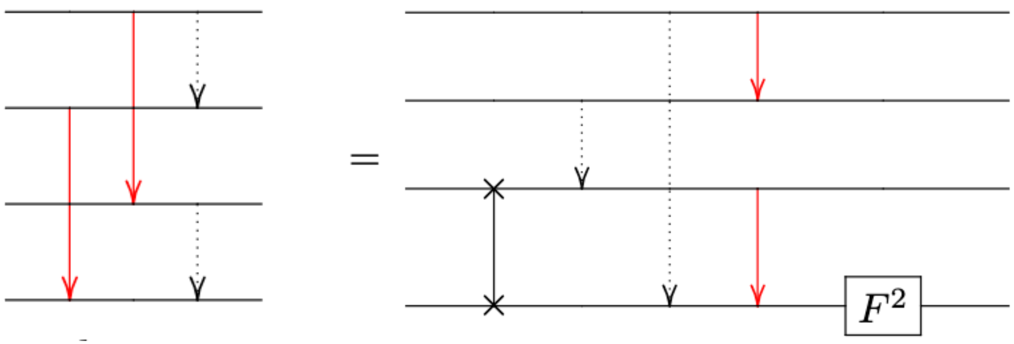
1. SWAP

$$\frac{1}{2}\begin{bmatrix} 1 & -1 & -1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & 1 & 1 \end{bmatrix}$$

Four splitter equivalence



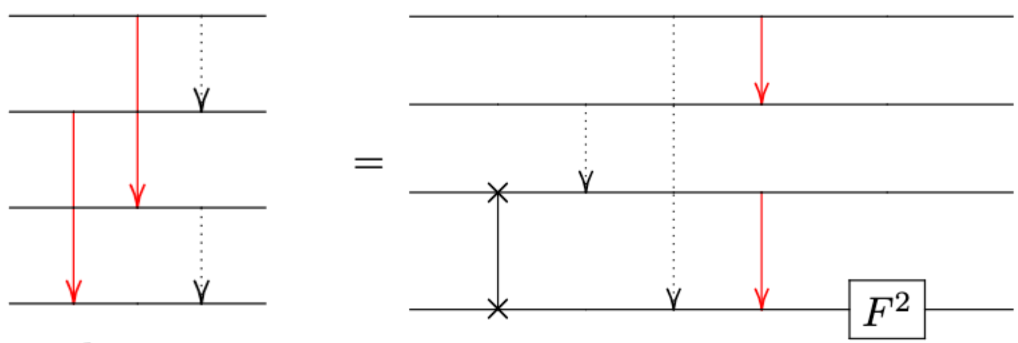
All four splitters belong to a single equivalence class that permits 3 operations:

1. SWAP gates *after* the four splitter (to the left)
2. $\hat{F}^2$ gates on any wires *after* the four splitter (to the left)

1. SWAP

$$\frac{1}{2}\begin{bmatrix} 1 & -1 & -1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & 1 & 1 \end{bmatrix}$$

Four splitter equivalence



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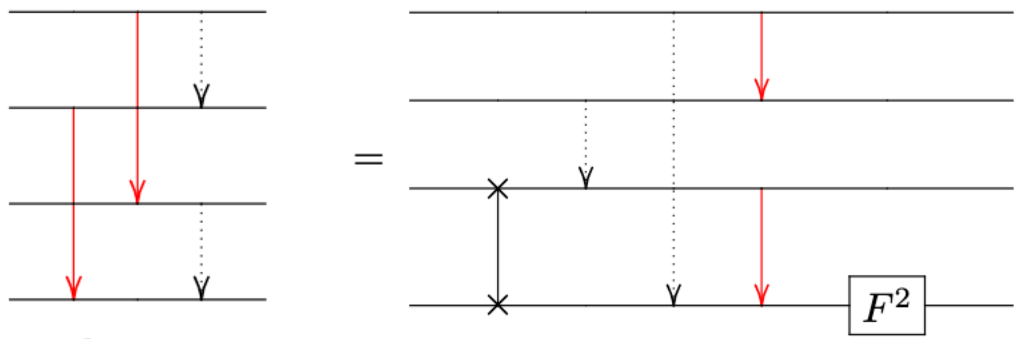
1. SWAP

2. $\hat{F}^2$

$$\frac{1}{2}\begin{bmatrix} 1 & -1 & -1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & 1 & -1 \\ -1 & -1 & -1 & -1 \end{bmatrix}$$

Bilayer square lattice (BSL)

Four splitter equivalence



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1. SWAP gates *after* the four splitter (to the left)
2. $\hat{F}^2$ gates on any wires *after* the four splitter (to the left)
3. An $\hat{F}^2$ on any single wire *before* the four splitter (to the right)

1. SWAP

2. $\hat{F}^2$

$$\frac{1}{2}\begin{bmatrix} 1 & -1 & -1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & 1 & -1 \\ -1 & -1 & -1 & -1 \end{bmatrix}$$

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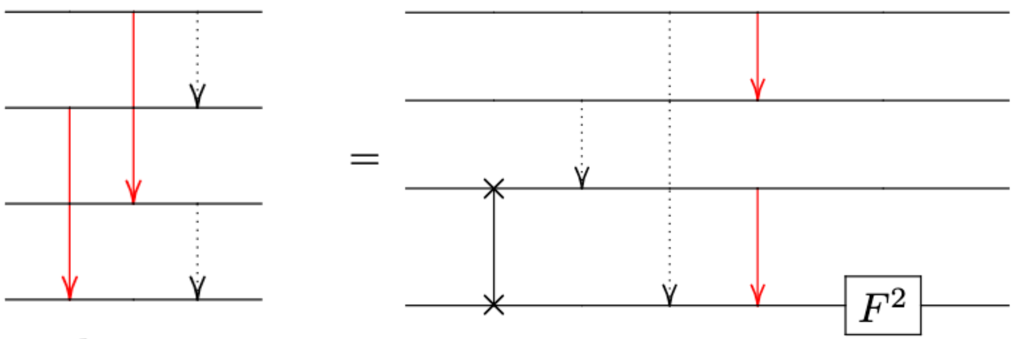
Bilayer square lattice (BSL)

Four splitter equivalence



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2. $\hat{F}^2$ gates on any wires *after* the four splitter (to the left)
3. An $\hat{F}^2$ on any single wire *before* the four splitter (to the right)

1. SWAP

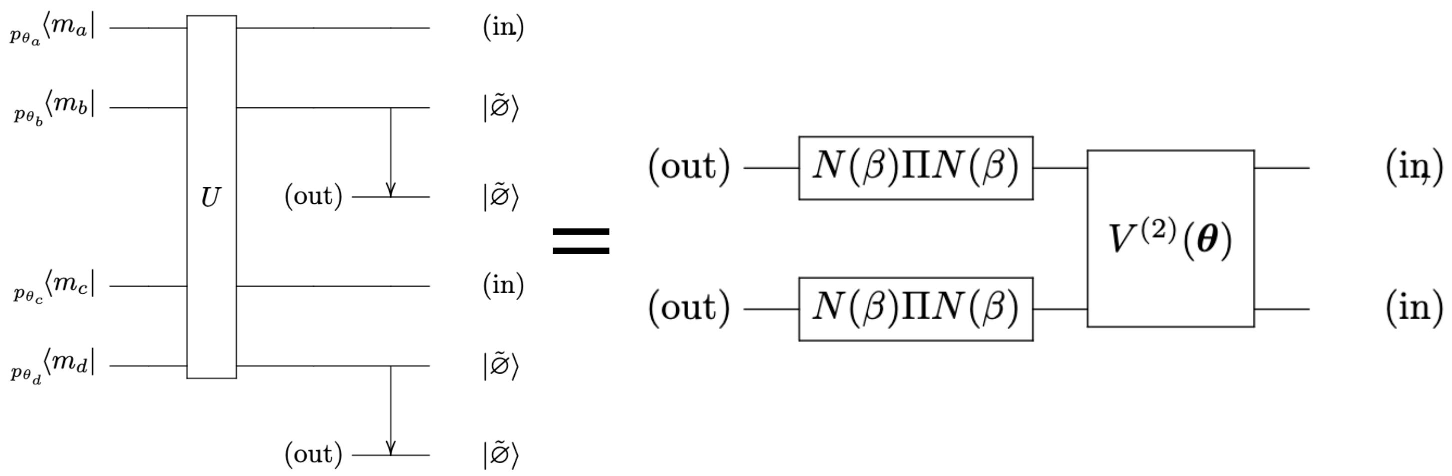
$$\frac{1}{2}\begin{bmatrix} 1 & -1 & -1 & -1 \\ 1 & 1 & -1 & +1 \\ 1 & -1 & 1 & +1 \\ -1 & -1 & -1 & +1 \end{bmatrix}$$

2. $\hat{F}^2$

3. $\hat{F}^2$

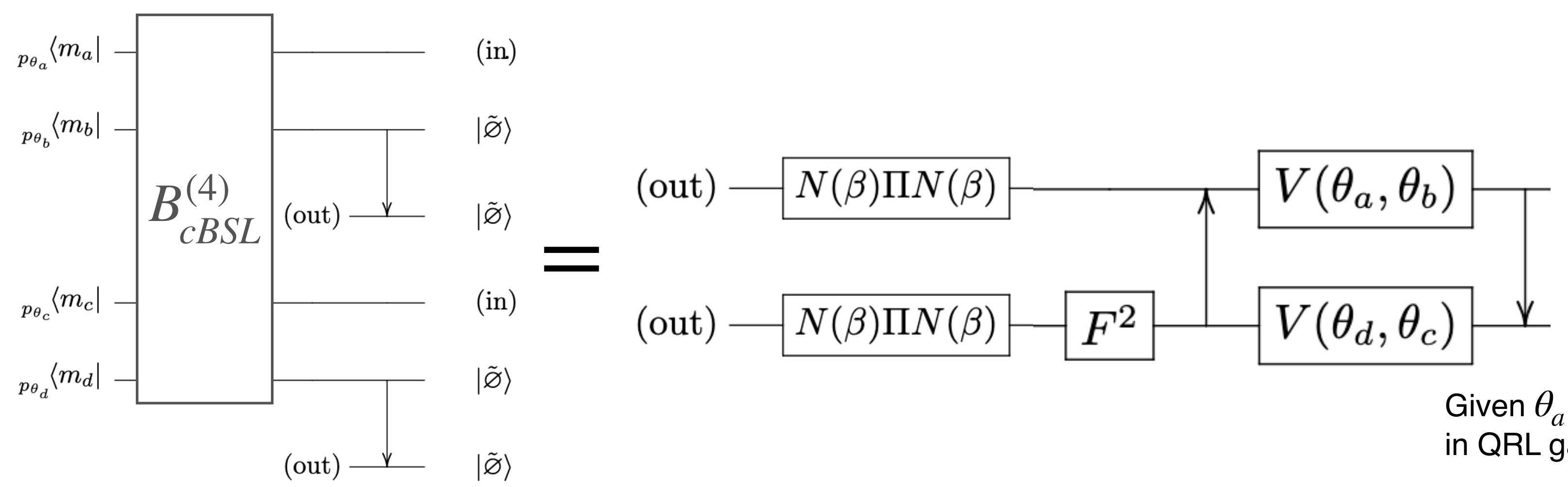
BSL reduction

Bilayer square lattice (BSL)



Bilayer square lattice (BSL)

BSL reduction



Given $\theta_a = \theta_d$ in QRL gate

Dictionary of single step two-mode gates

These two-mode gates can each be done in a single step, minimising the noise added by the operation. Noise which is independent of the architecture chosen.

Architecture	QRL	BSL	DBSL	Mikkel-splitter
Mapping	$\{\theta_a, \theta_b, \theta_c, \theta_d\}$	$\{\theta_a, \theta_b, \theta_d, \theta_c\}\|_{\theta_a=\theta_c}$	$\{\theta_a, \theta_c, \theta_d, \theta_b\}\|_{\theta_a=\theta_d}$	$\{\theta_a, \theta_b, \theta_d, \theta_c\}\|_{\theta_b=\theta_d}$
$\hat{C}_Z[1]$	$\{\frac{\pi}{2}, \frac{\pi}{2} \pm \chi, \frac{\pi}{2}, \frac{\pi}{2} \mp \chi\}$	$\{\frac{\pi}{2}, \frac{\pi}{2} \pm \chi, \frac{\pi}{2} \mp \chi, \frac{\pi}{2}\}$	$\{\frac{\pi}{2}, \frac{\pi}{2} \pm \chi, \frac{\pi}{2} \mp \chi, \frac{\pi}{2}\}$	**
SWAP	$\{0, \frac{\pi}{2}, \frac{\pi}{2}, 0\}$	**	**	**
$\hat{I} \otimes \hat{I}$	$\{\frac{\pi}{2}, 0, \frac{\pi}{2}, 0\}$	$\{\frac{\pi}{2}, 0, 0, \frac{\pi}{2}\}$	$\{\frac{\pi}{2}, 0, 0, \frac{\pi}{2}\}$	$\{\frac{\pi}{2}, 0, 0, \frac{\pi}{2}\}$
$\hat{F} \otimes \hat{F}$	$\{\frac{3\pi}{4}, \frac{\pi}{4}, \frac{3\pi}{4}, \frac{\pi}{4}\}$	$\{\frac{3\pi}{4}, \frac{\pi}{4}, \frac{\pi}{4}, \frac{3\pi}{4}\}$	$\{\frac{3\pi}{4}, \frac{\pi}{4}, \frac{\pi}{4}, \frac{3\pi}{4}\}$	$\{\frac{3\pi}{4}, \frac{\pi}{4}, \frac{\pi}{4}, \frac{3\pi}{4}\}$
$\hat{P}(1) \otimes \hat{P}(1)$	$\{\frac{\pi}{2}, \frac{\pi}{2} \mp \chi, \frac{\pi}{2}, \frac{\pi}{2} \mp \chi\}$	$\{\frac{\pi}{2}, \frac{\pi}{2} \mp \chi, \frac{\pi}{2} \mp \chi, \frac{\pi}{2}\}$	$\{\frac{\pi}{2}, \frac{\pi}{2} \mp \chi, \frac{\pi}{2} \mp \chi, \frac{\pi}{2}\}$	$\{\frac{\pi}{2}, \frac{\pi}{2} \mp \chi, \frac{\pi}{2} \mp \chi, \frac{\pi}{2}\}$

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Additional Slides

Typical thresholds

PRL **112,** 120504 (2014) PHYSICAL REVIEW LETTERS week ending 28 MARCH 2014

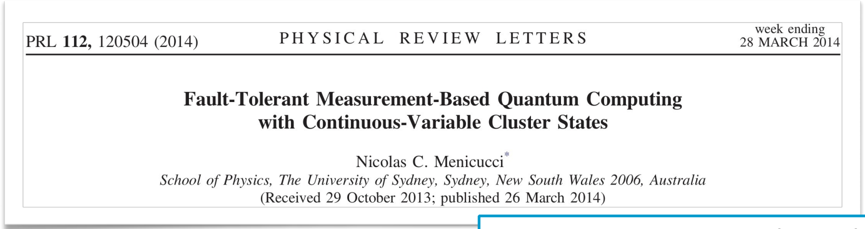
Fault-Tolerant Measurement-Based Quantum Computing with Continuous-Variable Cluster States

Nicolas C. Menicucci*
School of Physics, The University of Sydney, Sydney, New South Wales 2006, Australia

(Received 29 October 2013; published 26 March 2014)

PRL **112**, 120504 (2014)

Typical thresholds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~15.6 – 20.5 dB

for qubit error rates 10^{-2} – 10^{-6}

(depends on qubit code employed)

Typical thresholds

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PHYSICAL REVIEW X **8**, 021054 (2018)

High-Threshold Fault-Tolerant Quantum Computation with Analog Quantum Error Correction

Kosuke Fukui, Akihisa Tomita, and Atsushi Okamoto
Graduate School of Information Science and Technology, Hokkaido University, Kita14-Nishi9, Kita-ku, Sapporo 060-0814, Japan

Keisuke Fujii
Department of Physics, Graduate School of Science, Kyoto University, Kitashirakawa-Oiwakecho, Sakyo-ku, Kyoto 606-8502, Japan

PRX **8**, 021054 (2018)

PRX QUANTUM **2**, 030325 (2021)

Fault-Tolerant Continuous-Variable Measurement-based Quantum Computation Architecture

Mikkel V. Larsen,[1,*] Christopher Chamberland,[2,3,‡] Kyungjoo Noh,[2,3,‡] Jonas S. Neergaard-Nielsen,[1] and Ulrik L. Andersen[1,†]

PRX Quantum **2**, 030325 (2021)

PHYSICAL REVIEW A **101**, 012316 (2020)

Editors' Suggestion

Fault-tolerant bosonic quantum error correction with the surface–Gottesman-Kitaev-Preskill code

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Blueprint for a Scalable Photonic Fault-Tolerant Quantum Computer

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Quantum **5**, 392 (2021)

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PRX Quantum **2**, 040353 (2021)

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~10 – 18 dB
based on topological codes

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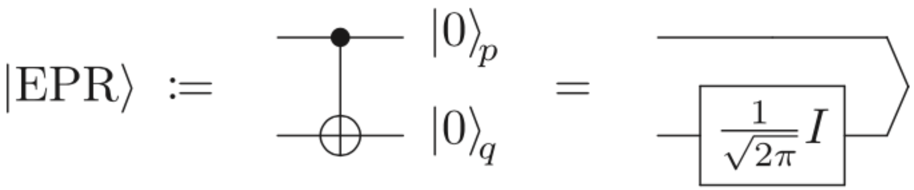
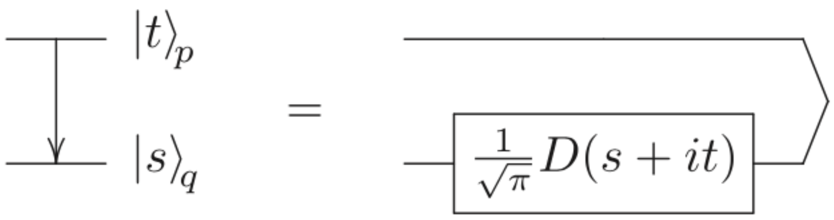
PRX Quantum **2**, 040353 (2021)

The teleported gate





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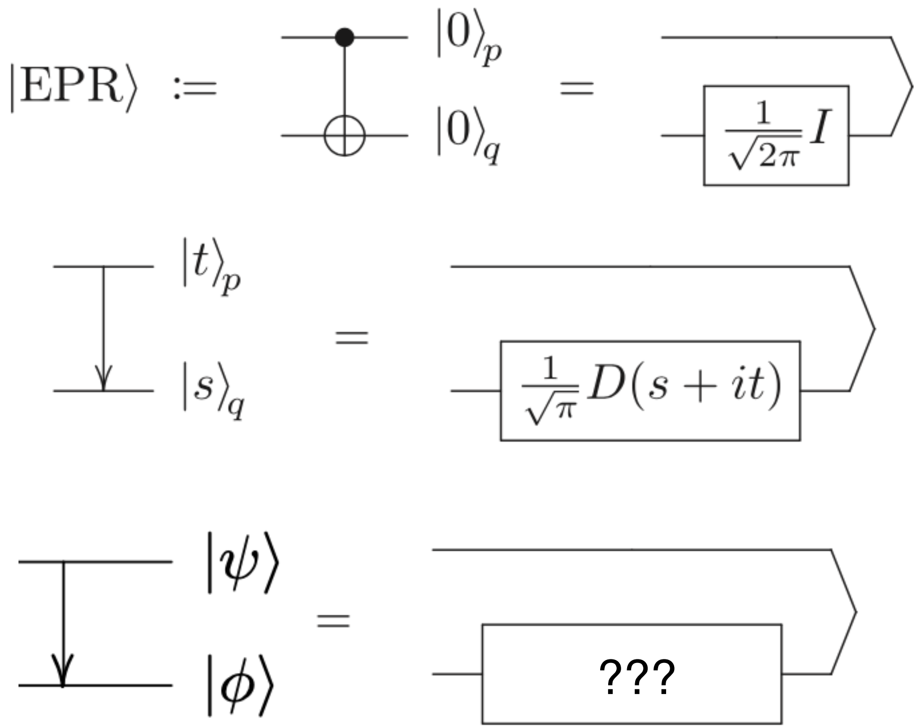

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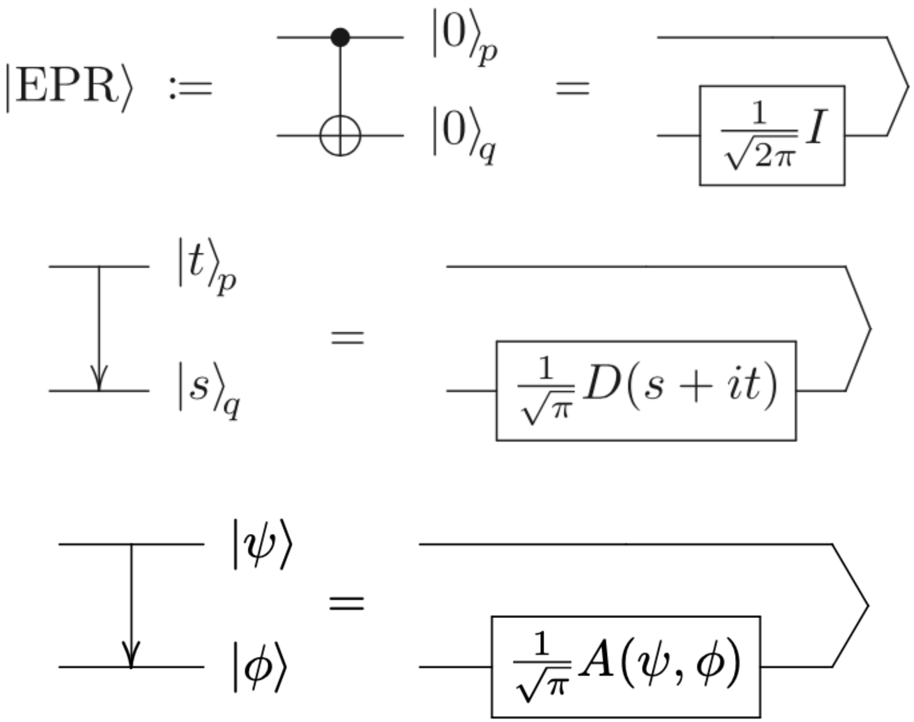

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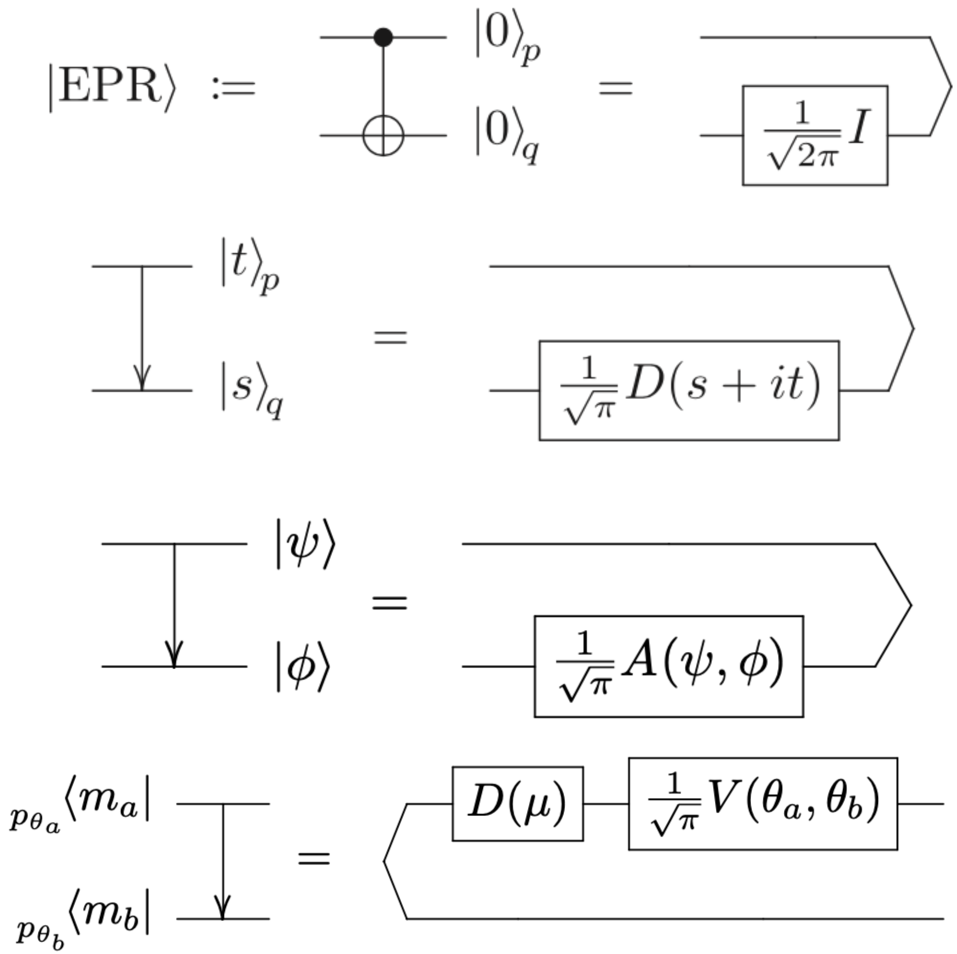
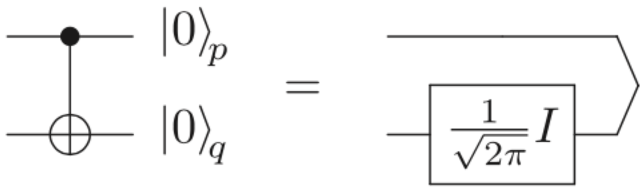


The teleported gate

$|\mathrm{EPR}\rangle :=$



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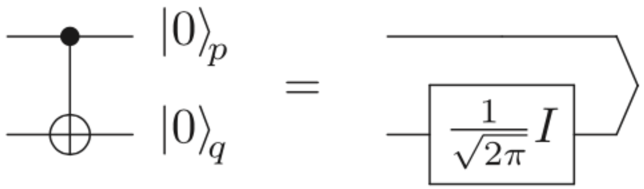

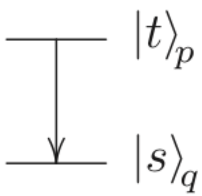

$=$

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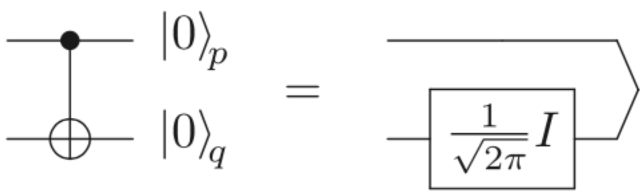

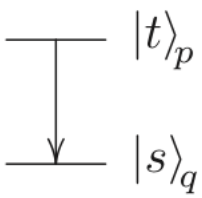

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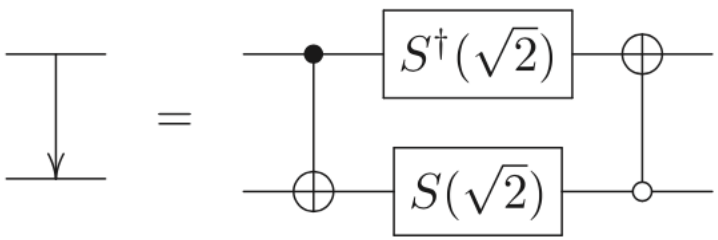
Beamsplitter decomposition



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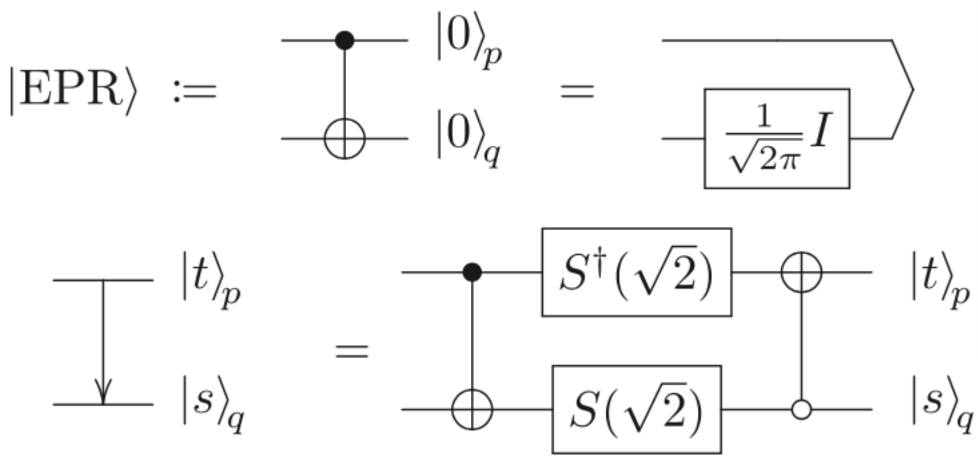

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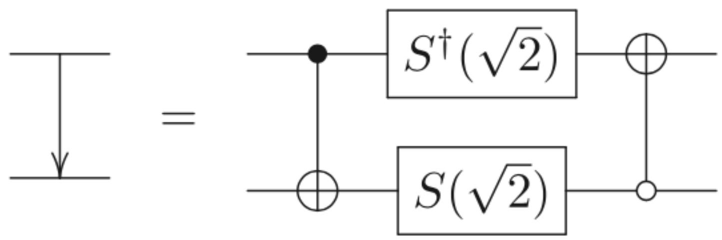

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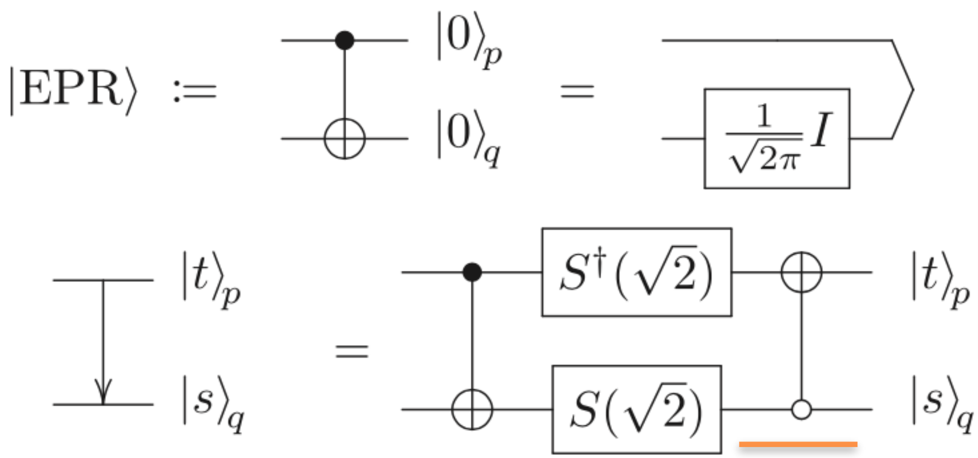

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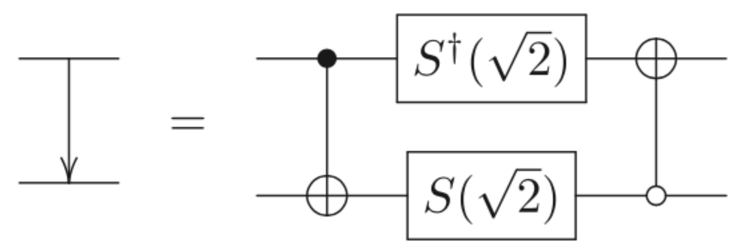

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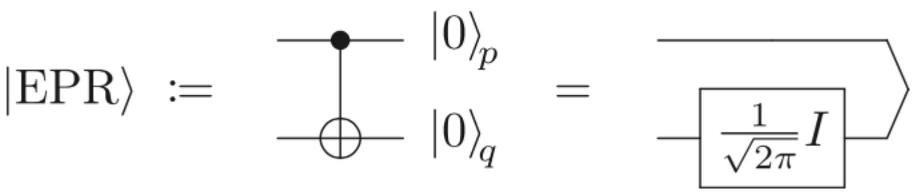

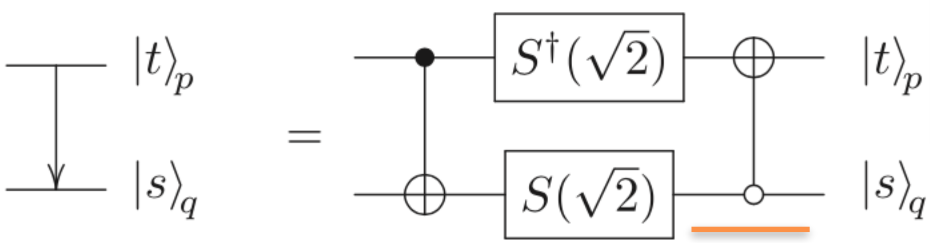

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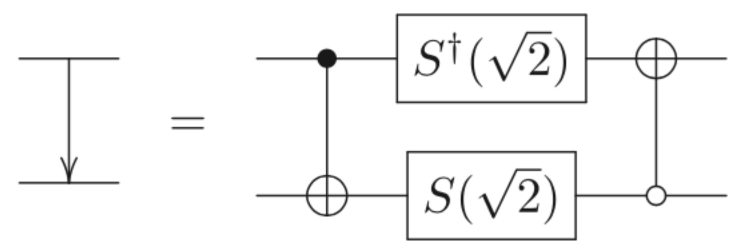
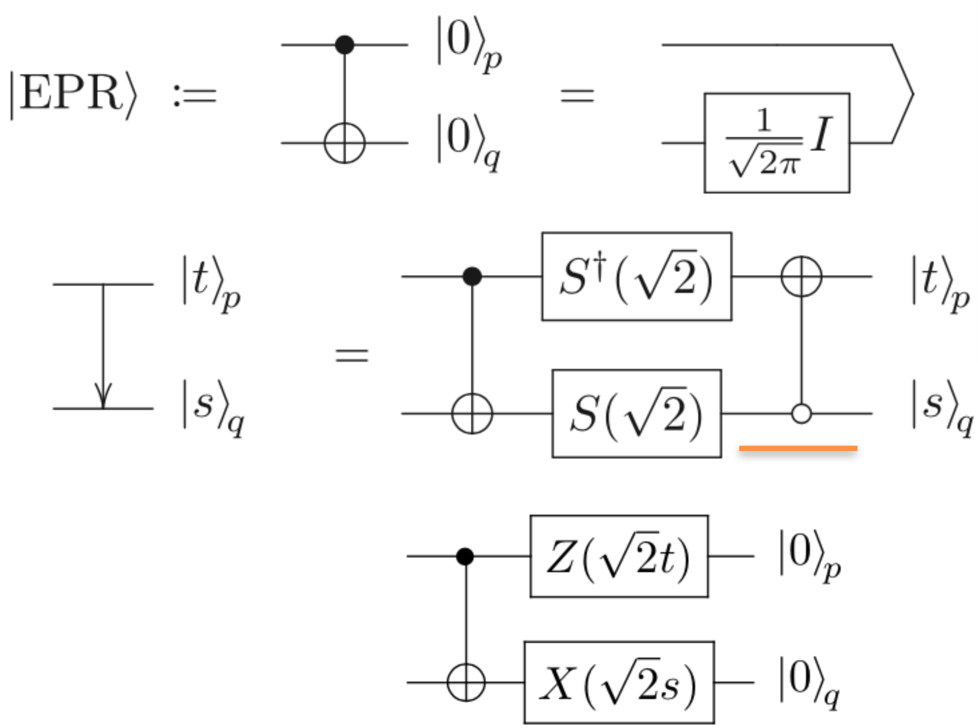
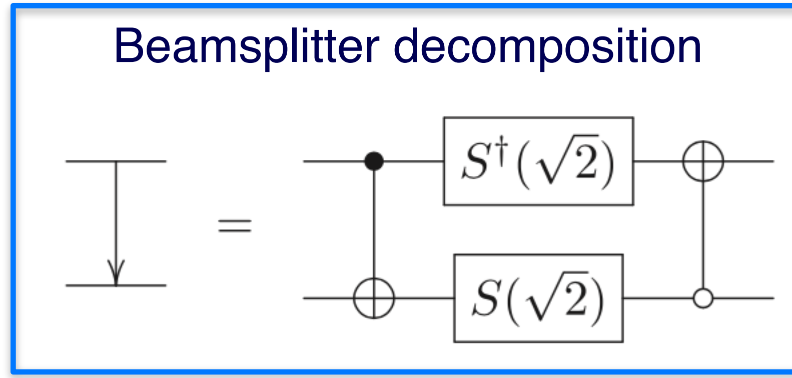


$$e^{i\hat{p}_1\otimes\hat{q}_2} \to e^{ist}$$

The teleported gate





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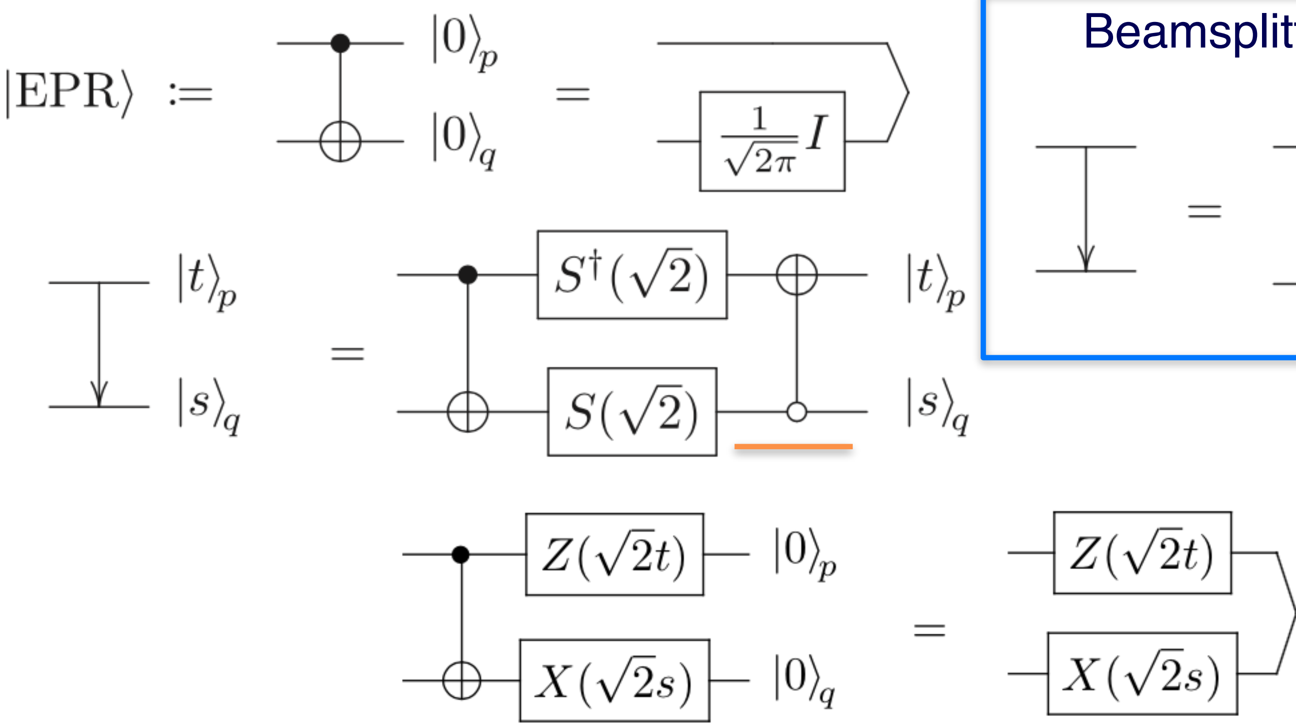

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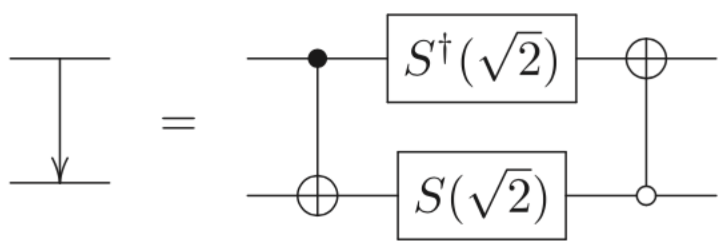
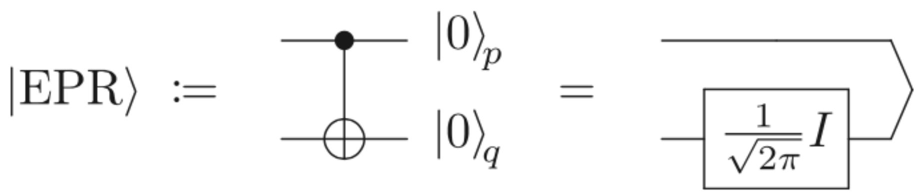
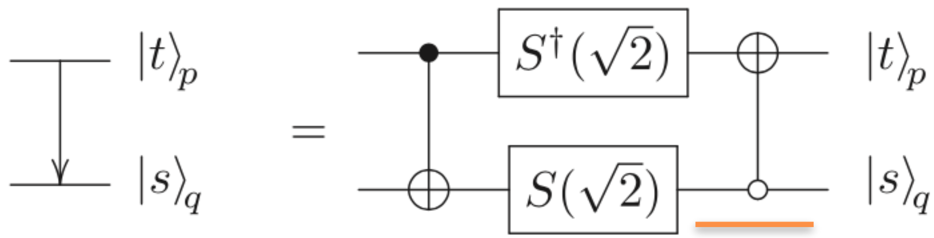


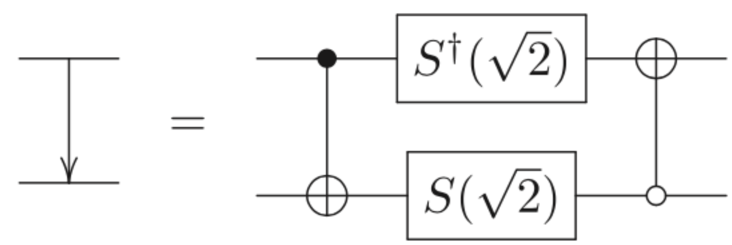
$$e^{i\hat{p}_1 \otimes \hat{q}_2} \rightarrow e^{ist}$$

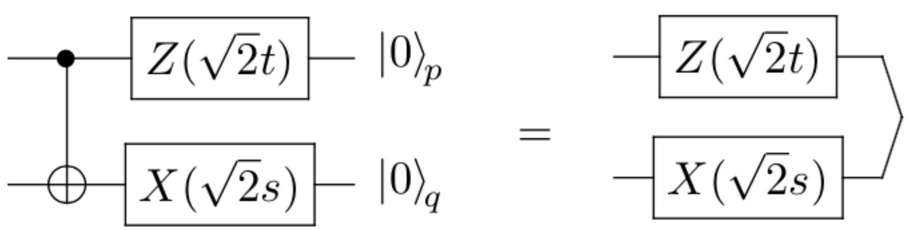
The teleported gate





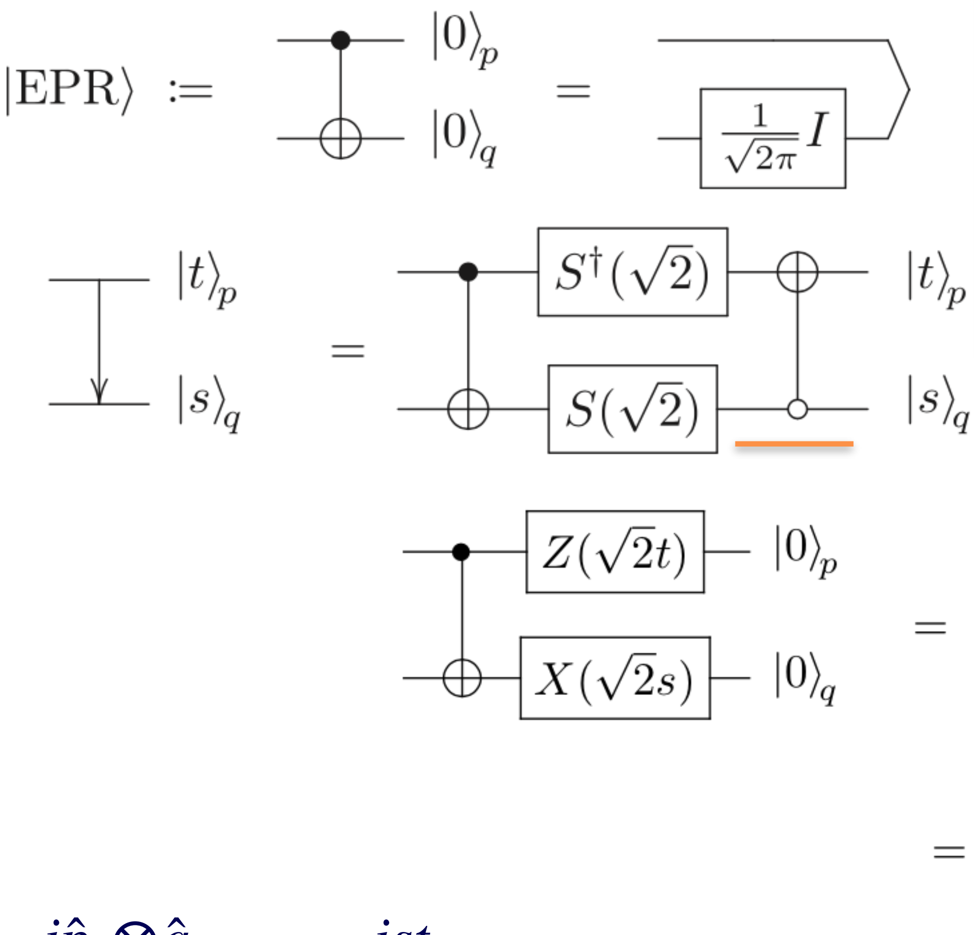
Beamsplitter decomposition

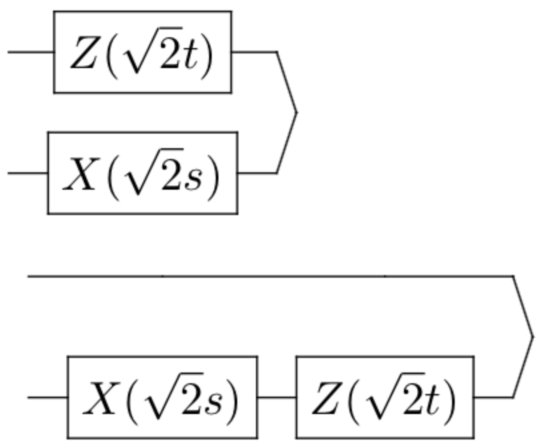




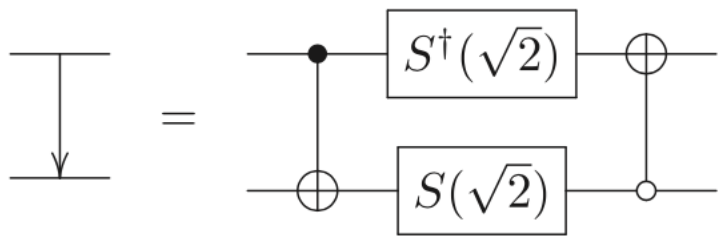
$$e^{i\hat{p}_1 \otimes \hat{q}_2} \to e^{ist}$$

The teleported gate



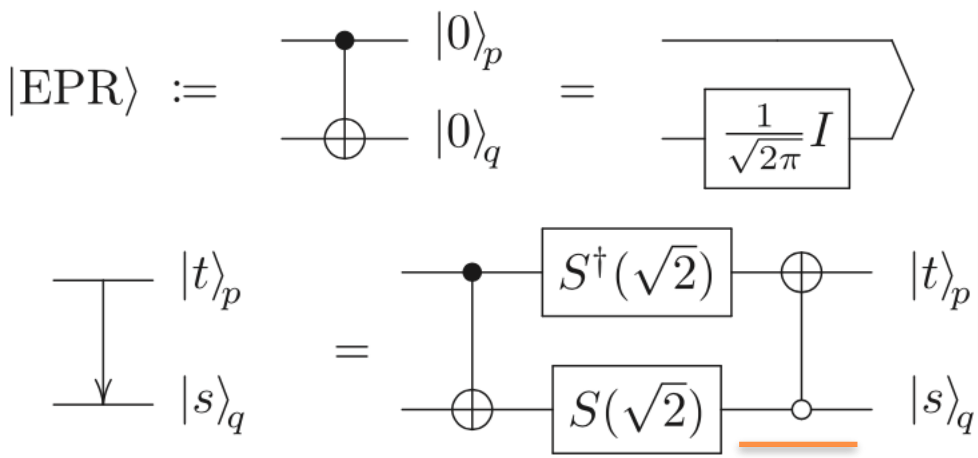


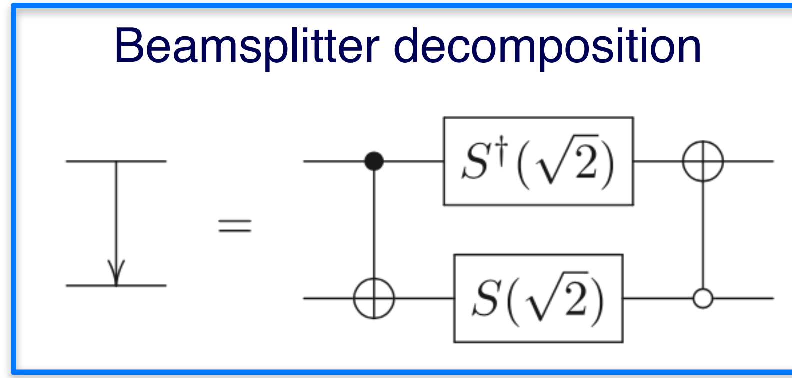
Beamsplitter decomposition

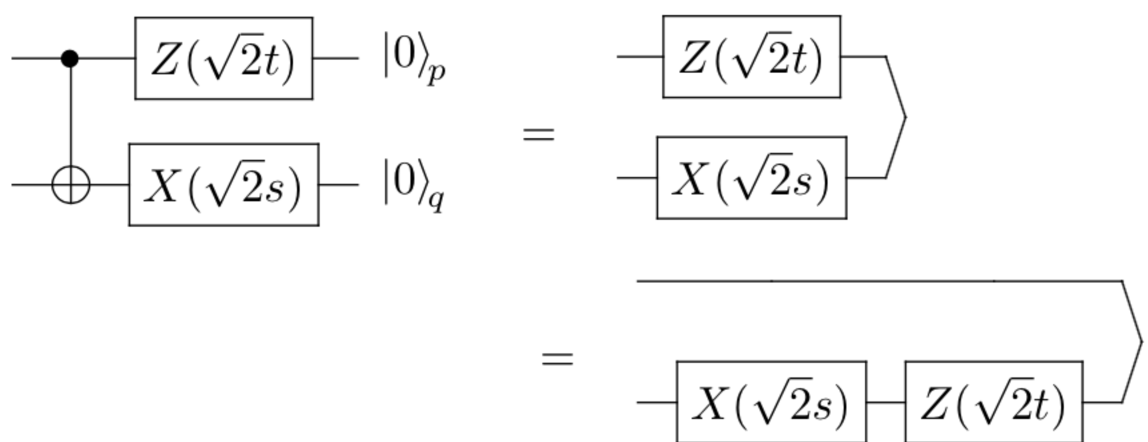


$$e^{i\hat{p}_1 \otimes \hat{q}_2} \rightarrow e^{ist}$$

The teleported gate







$$\hat{D}(\alpha) = e^{i\alpha_R\alpha_I}\hat{X}(\sqrt{2}\alpha_R)\hat{Z}(\sqrt{2}\alpha_I)$$

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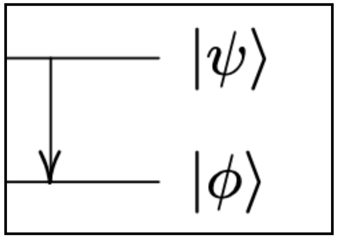
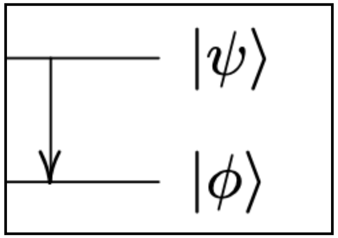
The teleported gate



$$\hat{B}_{1,2}|\psi\rangle_1|\phi\rangle_2$$

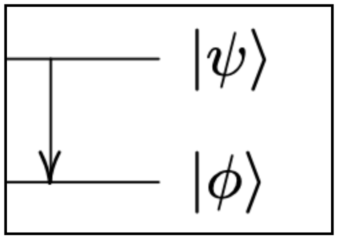
The teleported gate



$$|\psi\rangle = \int dt \; \widetilde{\psi}(t)\,|t\rangle_p \qquad |\phi\rangle = \int ds \; \phi(s)\,|s\rangle_q$$

$$\hat{B}_{1,2}\,|\psi\rangle_1\,|\phi\rangle_2$$

The teleported gate

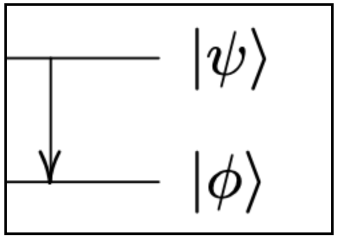


$$|\psi\rangle = \int dt\ \widetilde{\psi}(t)\,|t\rangle_p \qquad |\phi\rangle = \int ds\ \phi(s)\,|s\rangle_q$$

Substitute into the equation:

$$\hat{B}_{1,2}\,|\psi\rangle_1\,|\phi\rangle_2$$

The teleported gate

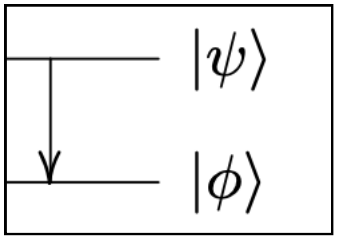


$$|\psi\rangle = \int dt\ \widetilde{\psi}(t)\,|\,t\rangle_p \qquad |\,\phi\rangle = \int ds\ \phi(s)\,|\,s\rangle_q$$

Substitute into the equation:

$$\hat{B}_{1,2}\,|\,\psi\rangle_1\,|\,\phi\rangle_2 = \hat{B}_{1,2}\int dt\ ds\ \widetilde{\psi}(t)\phi(s)\,|\,t\rangle_{p_1}\,|\,s\rangle_{q_2}$$

The teleported gate



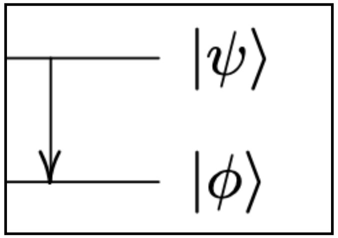
$$|\psi\rangle = \int dt \; \widetilde{\psi}(t)\,|t\rangle_p \qquad |\phi\rangle = \int ds \; \phi(s)\,|s\rangle_q$$

Substitute into the equation:

$$\hat{B}_{1,2}\,|\psi\rangle_1\,|\phi\rangle_2 = \hat{B}_{1,2}\int dt\; ds\; \widetilde{\psi}(t)\phi(s)\,|t\rangle_{p_1}\,|s\rangle_{q_2}$$

$$= \int dt\; ds\; \widetilde{\psi}(t)\phi(s)\; \hat{B}_{1,2}\,|t\rangle_{p_1}\,|s\rangle_{q_2}$$

The teleported gate



$$|\psi\rangle = \int dt\ \widetilde{\psi}(t)\,|\,t\rangle_p \qquad |\phi\rangle = \int ds\ \phi(s)\,|\,s\rangle_q$$

Substitute into the equation:

$$\begin{aligned}
\hat{B}_{1,2}\,|\psi\rangle_1\,|\phi\rangle_2 &= \hat{B}_{1,2}\int dt\ ds\ \widetilde{\psi}(t)\phi(s)\,|\,t\rangle_{p_1}\,|\,s\rangle_{q_2} \\
&= \int dt\ ds\ \widetilde{\psi}(t)\phi(s)\ \hat{B}_{1,2}\,|\,t\rangle_{p_1}\,|\,s\rangle_{q_2} \\
&= \int dt\ ds\ \widetilde{\psi}(t)\phi(s)\ \hat{D}_2(s+it)\,|\,EPR\rangle
\end{aligned}$$

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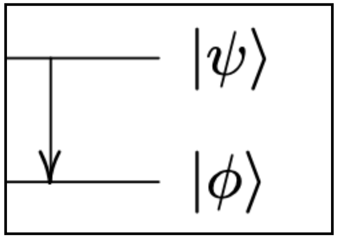
The teleported gate

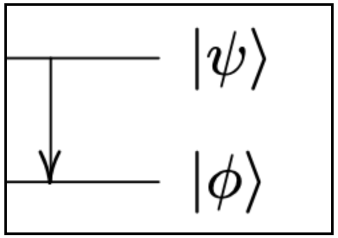


$$|\psi\rangle = \int dt\ \widetilde{\psi}(t)\,|t\rangle_p \qquad |\phi\rangle = \int ds\ \phi(s)\,|s\rangle_q$$

Substitute into the equation:

$$\begin{aligned}
\hat{B}_{1,2}|\psi\rangle_1|\phi\rangle_2 &= \hat{B}_{1,2}\int dt\ ds\ \widetilde{\psi}(t)\phi(s)\,|t\rangle_{p_1}|s\rangle_{q_2} \\
&= \int dt\ ds\ \widetilde{\psi}(t)\phi(s)\ \hat{B}_{1,2}|t\rangle_{p_1}|s\rangle_{q_2} \\
&= \int dt\ ds\ \widetilde{\psi}(t)\phi(s)\ \hat{D}_2(s+it)\,|EPR\rangle \\
&= \int d^2\alpha\ \widetilde{\psi}(\alpha_I)\phi(\alpha_R)\ \hat{D}_2(\alpha)\,|EPR\rangle
\end{aligned}$$

The teleported gate

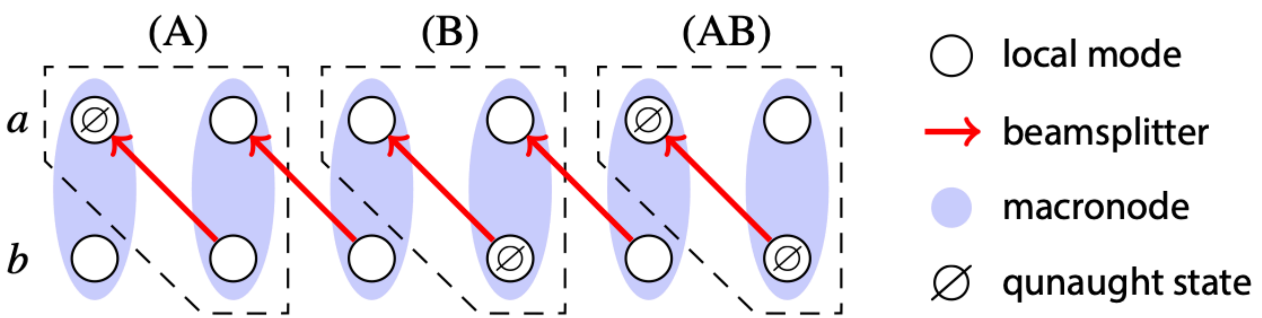


$$|\psi\rangle = \int dt\ \widetilde{\psi}(t)\,|t\rangle_p \qquad |\phi\rangle = \int ds\ \phi(s)\,|s\rangle_q$$

Substitute into the equation:

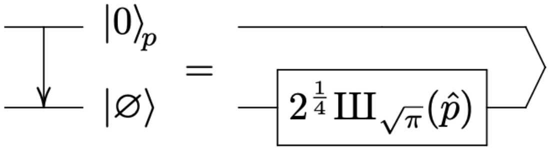
$$\begin{aligned}
\hat{B}_{1,2}|\psi\rangle_1|\phi\rangle_2 &= \hat{B}_{1,2}\int dt\ ds\ \widetilde{\psi}(t)\phi(s)\,|t\rangle_{p_1}|s\rangle_{q_2} \\
&= \int dt\ ds\ \widetilde{\psi}(t)\phi(s)\ \hat{B}_{1,2}|t\rangle_{p_1}|s\rangle_{q_2} \\
&= \int dt\ ds\ \widetilde{\psi}(t)\phi(s)\ \hat{D}_2(s+it)\,|EPR\rangle \\
&= \int d^2\alpha\ \widetilde{\psi}(\alpha_I)\phi(\alpha_R)\ \hat{D}_2(\alpha)\,|EPR\rangle \\
&= \hat{A}_2(\psi,\phi)\,|EPR\rangle
\end{aligned}$$

Error correction with the teleported gate

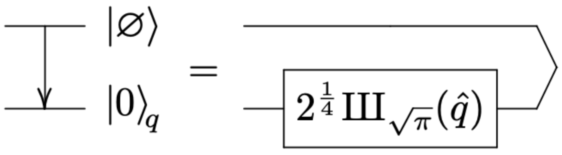


$$\hat{A}(\psi,\phi) := \iint d^2\alpha\, \tilde{\psi}(\alpha_I)\phi(\alpha_R)\hat{D}(\alpha)$$

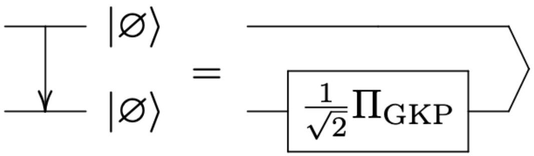
(A)



(B)



(AB)



Two qunaught states (AB)

$$\hat{A}(\psi, \phi) := \iint d^2\alpha \, \tilde{\psi}(\alpha_I)\phi(\alpha_R)\hat{D}(\alpha)$$

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Two qunaught states (AB)

$$\hat{A}(\psi, \phi) := \iint d^2\alpha\, \tilde{\psi}(\alpha_I)\phi(\alpha_R)\hat{D}(\alpha)$$

$$\hat{A}(\varnothing, \varnothing) = \iint d^2\alpha\, \text{III}_{\sqrt{2\pi}}(\alpha_R)\text{III}_{\sqrt{2\pi}}(\alpha_I)\hat{D}(\alpha)$$

Two qunaught states (AB)

$$\hat{A}(\psi, \phi) := \iint d^2\alpha \, \tilde{\psi}(\alpha_I)\phi(\alpha_R)\hat{D}(\alpha)$$

$$\hat{A}(\varnothing, \varnothing) = \iint d^2\alpha \, \text{III}_{\sqrt{2\pi}}(\alpha_R)\text{III}_{\sqrt{2\pi}}(\alpha_I)\hat{D}(\alpha)$$

$$\hat{D}(\alpha) = e^{i\alpha_R\alpha_I}\hat{X}(\sqrt{2}\alpha_R)\hat{Z}(\sqrt{2}\alpha_I) \qquad e^{i\alpha_R\alpha_I} \to e^{i2\pi} = 1$$

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Two qunaught states (AB)

$$\hat{A}(\psi, \phi) := \iint d^2\alpha \, \tilde{\psi}(\alpha_I)\phi(\alpha_R)\hat{D}(\alpha)$$

$$\hat{A}(\varnothing, \varnothing) = \iint d^2\alpha \, \text{III}_{\sqrt{2\pi}}(\alpha_R)\text{III}_{\sqrt{2\pi}}(\alpha_I)\hat{D}(\alpha)$$

$$\hat{D}(\alpha) = e^{i\alpha_R\alpha_I}\hat{X}(\sqrt{2}\alpha_R)\hat{Z}(\sqrt{2}\alpha_I) \qquad e^{i\alpha_R\alpha_I} \to e^{i2\pi} = 1$$

$$\hat{A}(\varnothing, \varnothing) = \pi\sqrt{2}\,\text{III}_{\sqrt{\pi}}(\hat{p})\text{III}_{\sqrt{\pi}}(\hat{q})$$

Two qunaught states (AB)

$$\hat{A}(\psi,\phi) := \iint d^2\alpha\, \tilde{\psi}(\alpha_I)\phi(\alpha_R)\hat{D}(\alpha)$$

$$\hat{A}(\varnothing,\varnothing) = \iint d^2\alpha\, Ш_{\sqrt{2\pi}}(\alpha_R) Ш_{\sqrt{2\pi}}(\alpha_I)\hat{D}(\alpha)$$

$$\hat{D}(\alpha) = e^{i\alpha_R\alpha_I}\hat{X}(\sqrt{2}\alpha_R)\hat{Z}(\sqrt{2}\alpha_I) \qquad e^{i\alpha_R\alpha_I} \to e^{i2\pi} = 1$$

$$\hat{A}(\varnothing,\varnothing) = \pi\sqrt{2}\, Ш_{\sqrt{\pi}}(\hat{p}) Ш_{\sqrt{\pi}}(\hat{q})$$

$$= \sqrt{\frac{\pi}{2}}\, \hat{\Pi}_{\mathrm{GKP}}.$$

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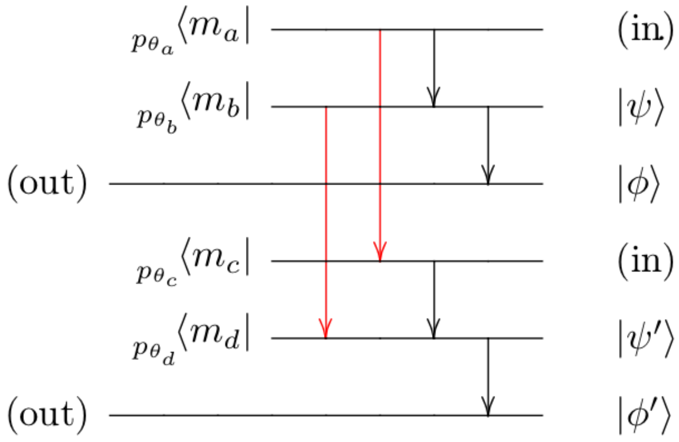
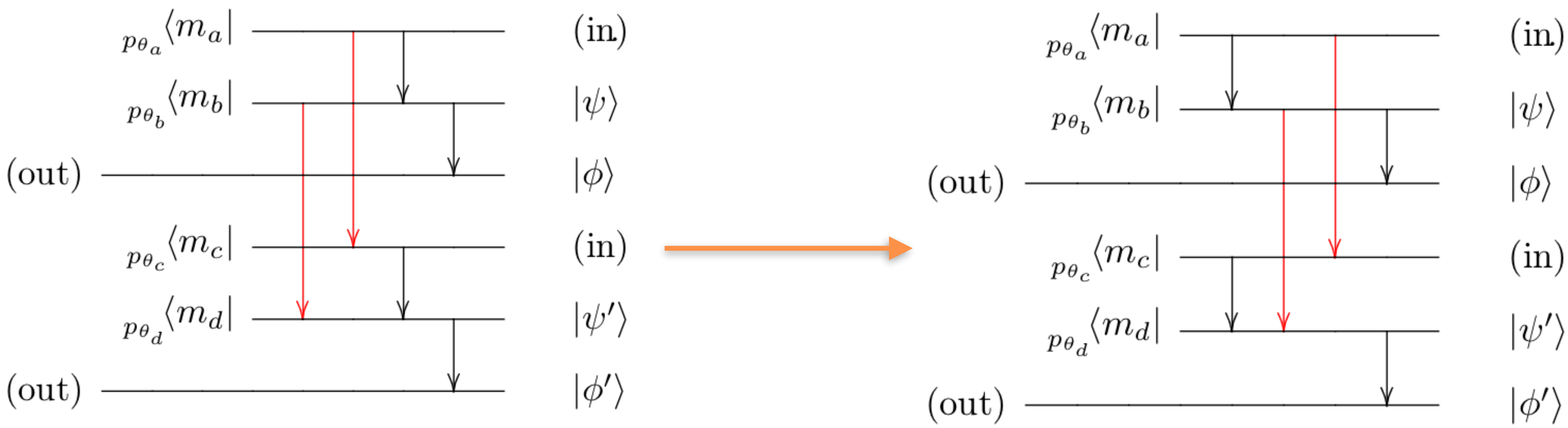
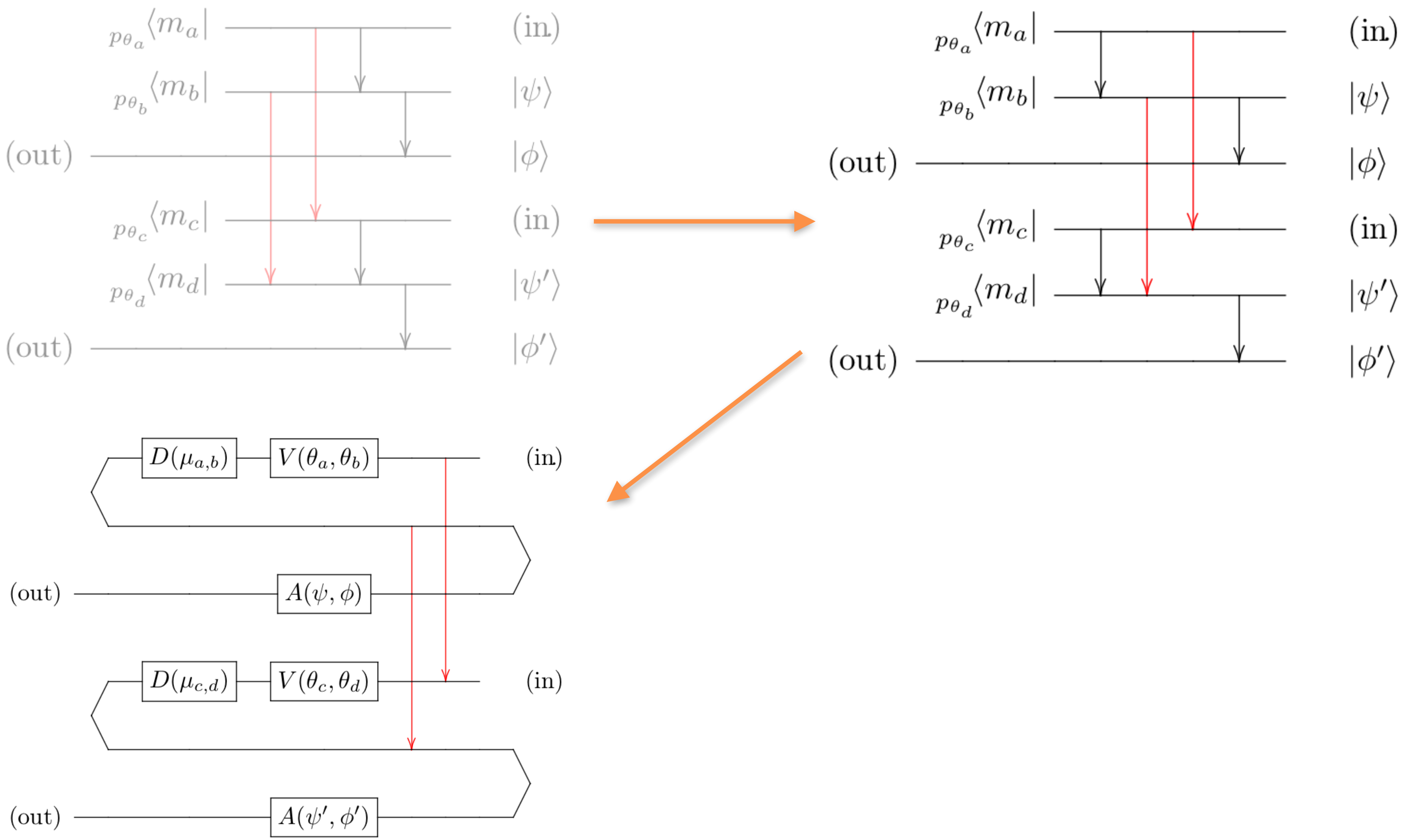
Two-mode gate



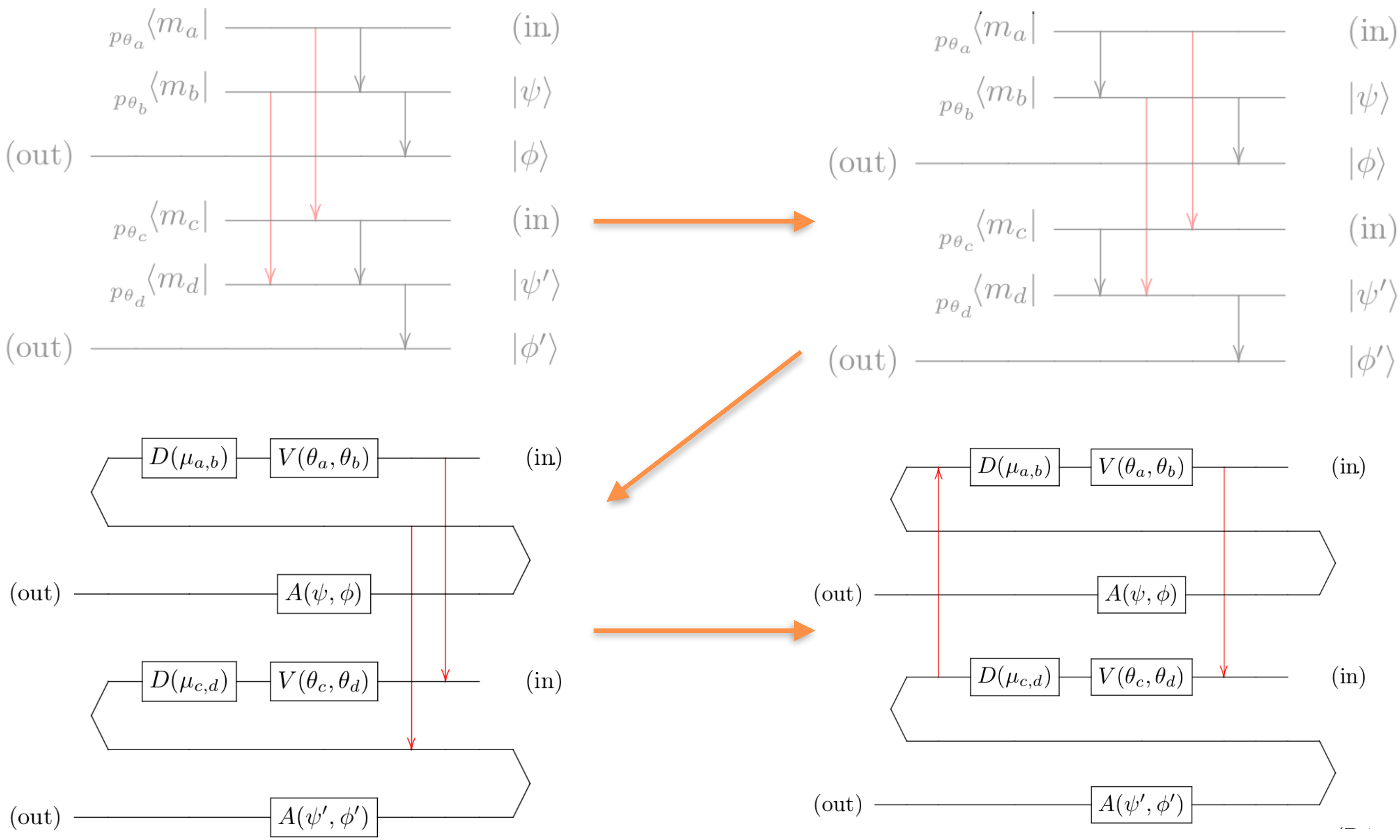
Two-mode gate



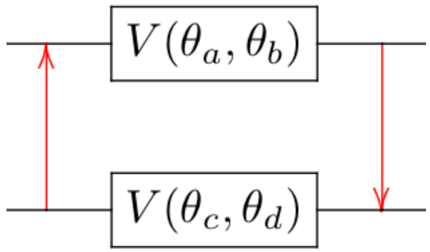
Two-mode gate



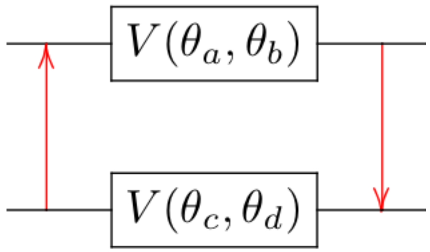
Two-mode gate



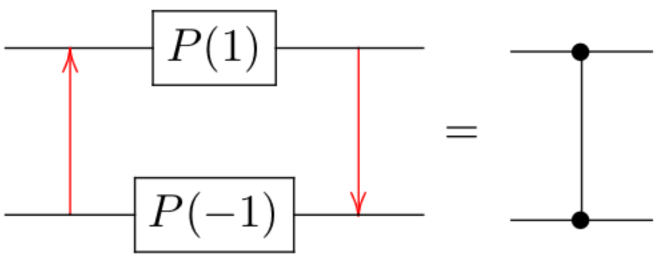
Two-mode gate



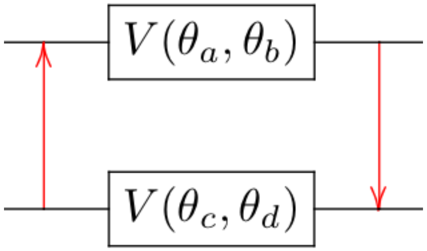
Two-mode gate



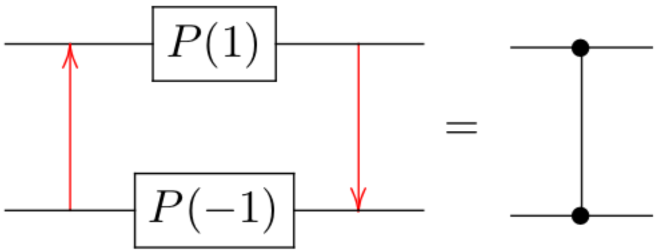
Cz gate:



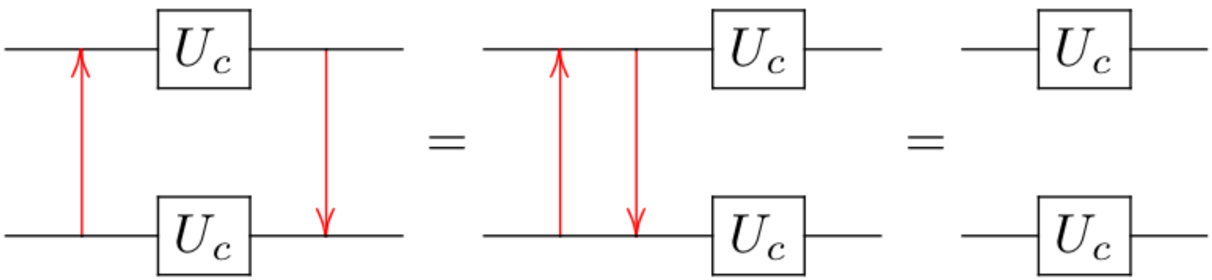
Two-mode gate



Cz gate:



Disentangled gate:



GKP with GBS

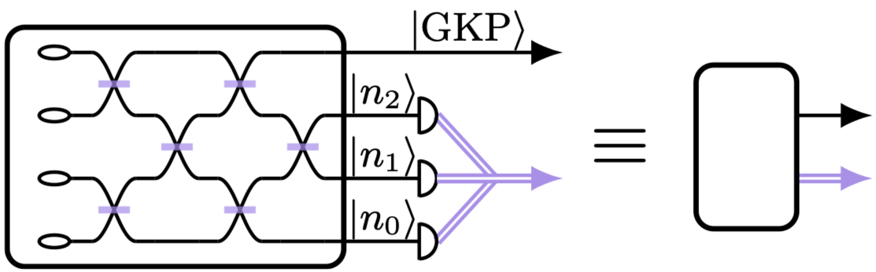


Figure 1: GBS devices for state preparation. (left) A single integrated photonic device implementing GBS-based preparation of non-Gaussian states based on the schemes presented in Refs. [27–30]. The emitted light from one output port is in a chosen non-Gaussian state subject to obtaining the correct click pattern $\{n_i\}$ at the PNR detectors connected to the remaining output ports. The double purple lines represent classical logic, which is used to trigger a switch on the emitted port. (right) A simplified representation of a single GBS device.

Blueprint for a Scalable Photonic Fault-Tolerant Quantum Computer

J. Eli Bourassa[1,2,*], Rafael N. Alexander[1,3,4,*], Michael Vasmer[5,6], Ashlesha Patil[1,7], Ilan Tzitrin[1,2], Takaya Matsuura[1,8], Daiqin Su[1], Ben Q. Baragiola[1,4], Saikat Guha[1,7], Guillaume Dauphinais[1], Krishna K. Sabapathy[1], Nicolas C. Menicucci[1,4], and Ish Dhand[1]

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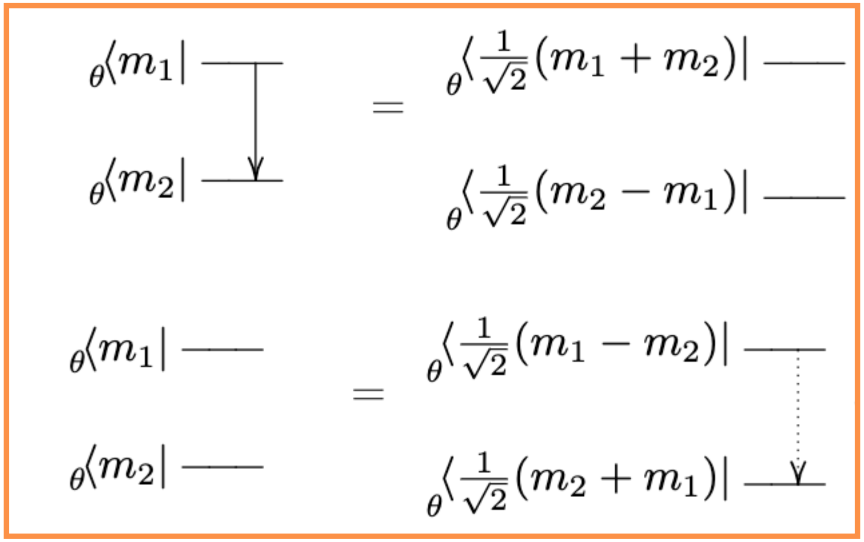
Virtual beam splitter

$$
\begin{array}{l} {}_{\theta}\langle m_1| \\ {}_{\theta}\langle m_2| \end{array} = \begin{array}{l} {}_{\theta}\langle \frac{1}{\sqrt{2}}(m_1 + m_2)| \\ {}_{\theta}\langle \frac{1}{\sqrt{2}}(m_2 - m_1)| \end{array}
$$

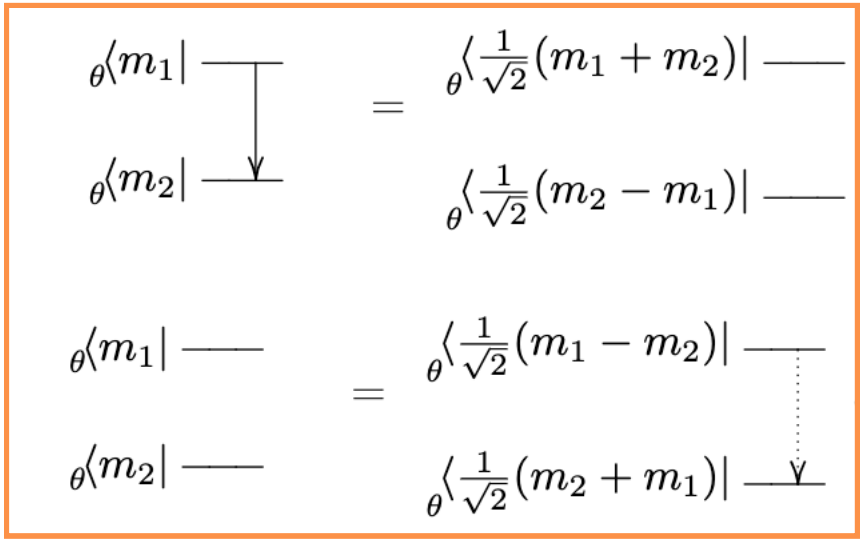
$$
\begin{array}{l} {}_{\theta}\langle m_1| \\ {}_{\theta}\langle m_2| \end{array} = \begin{array}{l} {}_{\theta}\langle \frac{1}{\sqrt{2}}(m_1 - m_2)| \\ {}_{\theta}\langle \frac{1}{\sqrt{2}}(m_2 + m_1)| \end{array}
$$

Virtual beam splitter



$$
\begin{aligned}
\hat{B}_{1,2}|s\rangle_{q_1}|t\rangle_{q_2} &= e^{-iq_1p_2}\hat{S}_1^\dagger(\sqrt{2})\hat{S}_2(\sqrt{2})e^{ip_1q_2}|s\rangle_{q_1}|t\rangle_{q_2} && (10)\\
&= e^{-iq_1p_2}\hat{S}_1^\dagger(\sqrt{2})\hat{S}_2(\sqrt{2})|s-t\rangle_{q_1}|t\rangle_{q_2} && (11)\\
&= e^{-iq_1p_2}\left|\tfrac{1}{\sqrt{2}}(s-t)\right\rangle_{q_1}|\sqrt{2}t\rangle_{q_2} && (12)\\
&= \left|\tfrac{1}{\sqrt{2}}(s-t)\right\rangle_{q_1}\left|\tfrac{1}{\sqrt{2}}(s+t)\right\rangle_{q_2}
\end{aligned}
$$

Virtual beam splitter



$$\begin{aligned}
\hat{B}_{1,2}|s\rangle_{q_1}|t\rangle_{q_2} &= e^{-iq_1p_2}\hat{S}_1^\dagger(\sqrt{2})\hat{S}_2(\sqrt{2})e^{ip_1q_2}|s\rangle_{q_1}|t\rangle_{q_2} && (10)\\
&= e^{-iq_1p_2}\hat{S}_1^\dagger(\sqrt{2})\hat{S}_2(\sqrt{2})|s-t\rangle_{q_1}|t\rangle_{q_2} && (11)\\
&= e^{-iq_1p_2}\left|\tfrac{1}{\sqrt{2}}(s-t)\right\rangle_{q_1}|\sqrt{2}t\rangle_{q_2} && (12)\\
&= \left|\tfrac{1}{\sqrt{2}}(s-t)\right\rangle_{q_1}\left|\tfrac{1}{\sqrt{2}}(s+t)\right\rangle_{q_2}
\end{aligned}$$

$$\hat{B}_{1,2}^\dagger \boldsymbol{x}\hat{B}_{1,2} = \boldsymbol{S}_{\hat{B}_{1,2}}\boldsymbol{x} = \frac{1}{\sqrt{2}}\begin{bmatrix}\hat{q}_1 - \hat{q}_2\\ \hat{q}_1 + \hat{q}_2\\ \hat{p}_1 - \hat{p}_2\\ \hat{p}_1 + \hat{p}_2\end{bmatrix}$$

Virtual beam splitter

$$
{}_{\theta}\langle m_1| \quad {}_{\theta}\langle m_2| \quad = \quad {}_{\theta}\langle \tfrac{1}{\sqrt{2}}(m_1 + m_2)| \quad {}_{\theta}\langle \tfrac{1}{\sqrt{2}}(m_2 - m_1)|
$$

$$
{}_{\theta}\langle m_1| \quad {}_{\theta}\langle m_2| \quad = \quad {}_{\theta}\langle \tfrac{1}{\sqrt{2}}(m_1 - m_2)| \quad {}_{\theta}\langle \tfrac{1}{\sqrt{2}}(m_2 + m_1)|
$$

$$
\begin{aligned}
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&= e^{-iq_1p_2}\hat{S}_1^{\dagger}(\sqrt{2})\hat{S}_2(\sqrt{2})|s-t\rangle_{q_1}|t\rangle_{q_2} && (11)\\
&= e^{-iq_1p_2}\left|\tfrac{1}{\sqrt{2}}(s-t)\right\rangle_{q_1}|\sqrt{2}t\rangle_{q_2} && (12)\\
&= \left|\tfrac{1}{\sqrt{2}}(s-t)\right\rangle_{q_1}\left|\tfrac{1}{\sqrt{2}}(s+t)\right\rangle_{q_2}
\end{aligned}
$$

$$
\hat{B}_{1,2}^{\dagger}\boldsymbol{x}\hat{B}_{1,2} = \boldsymbol{S}_{\hat{B}_{1,2}}\boldsymbol{x} = \frac{1}{\sqrt{2}}\begin{bmatrix}\hat{q}_1 - \hat{q}_2\\ \hat{q}_1 + \hat{q}_2\\ \hat{p}_1 - \hat{p}_2\\ \hat{p}_1 + \hat{p}_2\end{bmatrix}
$$

You can know $\hat{q}_1$ and $\hat{q}_2$ perfectly

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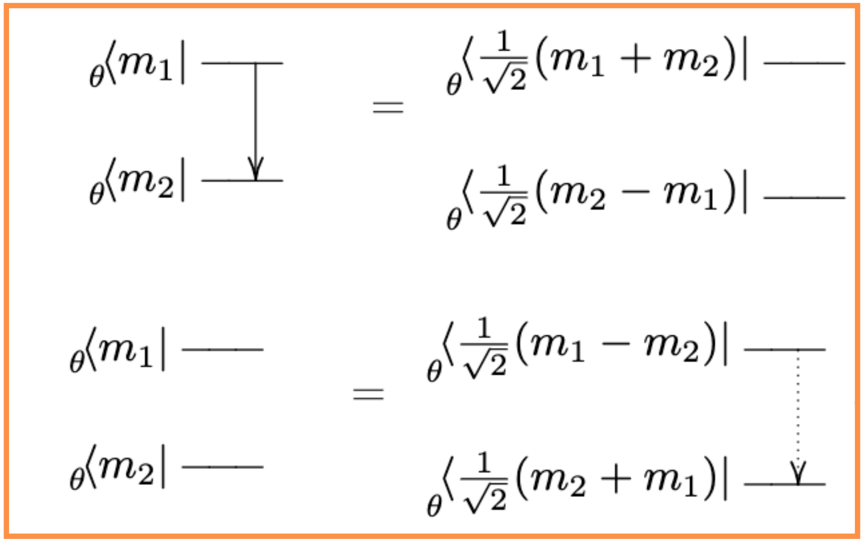
Virtual beam splitter



$$
\begin{aligned}
\hat{B}_{1,2}|s\rangle_{q_1}|t\rangle_{q_2} &= e^{-iq_1p_2}\hat{S}_1^\dagger(\sqrt{2})\hat{S}_2(\sqrt{2})e^{ip_1q_2}|s\rangle_{q_1}|t\rangle_{q_2} && (10)\\
&= e^{-iq_1p_2}\hat{S}_1^\dagger(\sqrt{2})\hat{S}_2(\sqrt{2})|s-t\rangle_{q_1}|t\rangle_{q_2} && (11)\\
&= e^{-iq_1p_2}\left|\tfrac{1}{\sqrt{2}}(s-t)\right\rangle_{q_1}|\sqrt{2}t\rangle_{q_2} && (12)\\
&= \left|\tfrac{1}{\sqrt{2}}(s-t)\right\rangle_{q_1}\left|\tfrac{1}{\sqrt{2}}(s+t)\right\rangle_{q_2}
\end{aligned}
$$

$$
\hat{B}_{1,2}^\dagger \boldsymbol{x}\hat{B}_{1,2} = \boldsymbol{S}_{\hat{B}_{1,2}}\boldsymbol{x} = \frac{1}{\sqrt{2}}\begin{bmatrix}\hat{q}_1-\hat{q}_2\\ \hat{q}_1+\hat{q}_2\\ \hat{p}_1-\hat{p}_2\\ \hat{p}_1+\hat{p}_2\end{bmatrix}
$$

You can know $\hat{q}_1$ and $\hat{q}_2$ perfectly

You cannot know $\hat{q}_1$ and $\hat{p}_1$, or $\hat{q}_2$ and $\hat{p}_2$ at the same time

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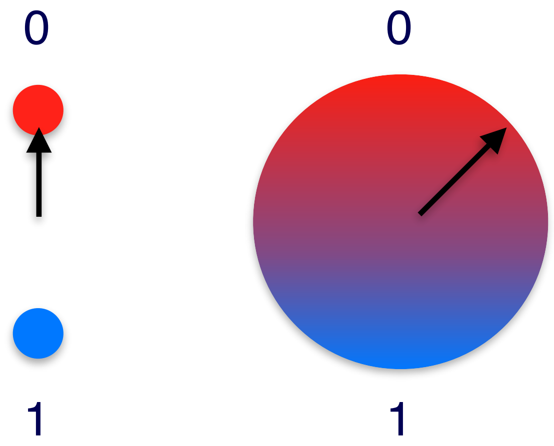
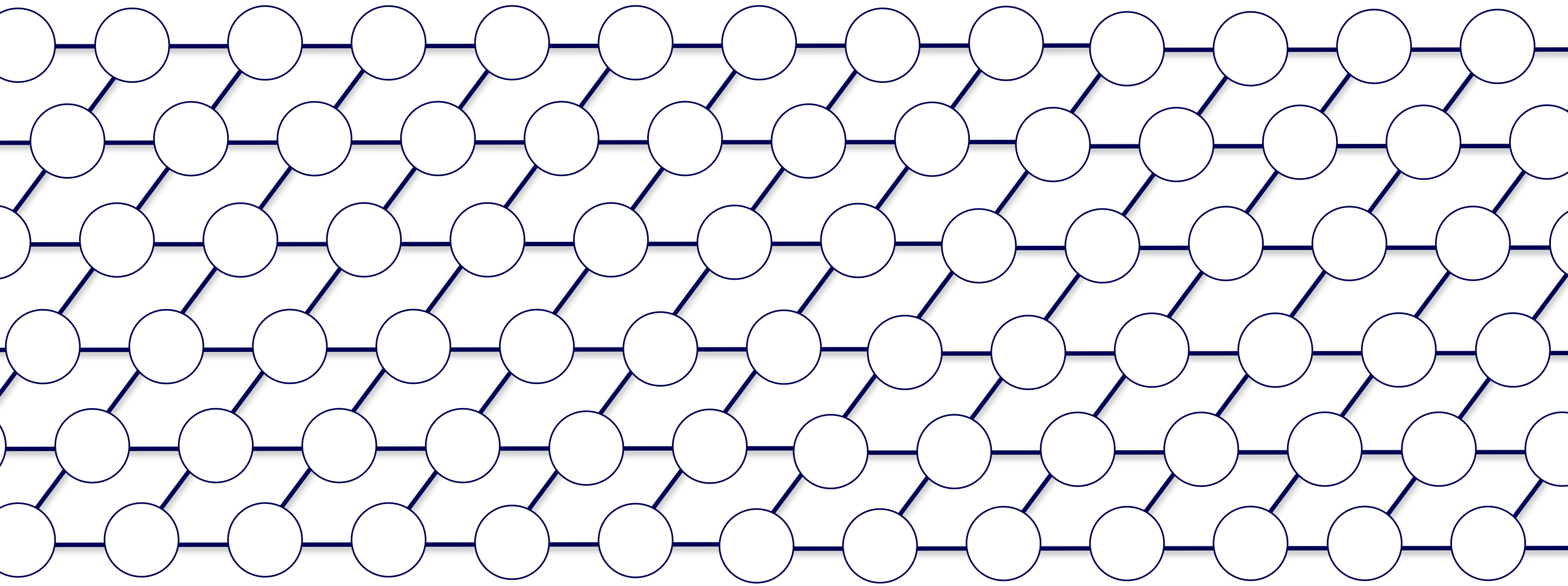
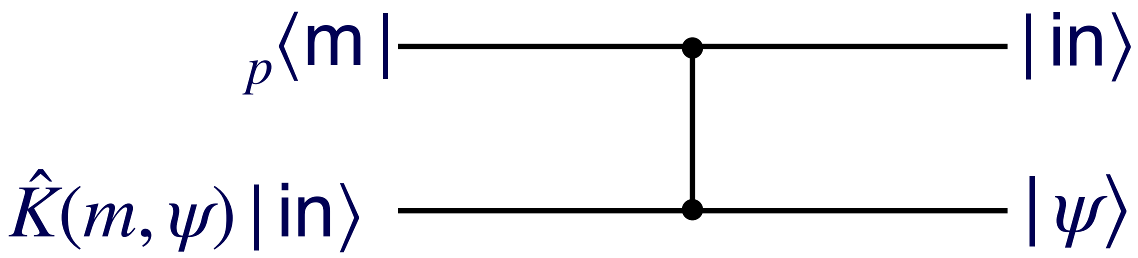
Classic vs. Quantum



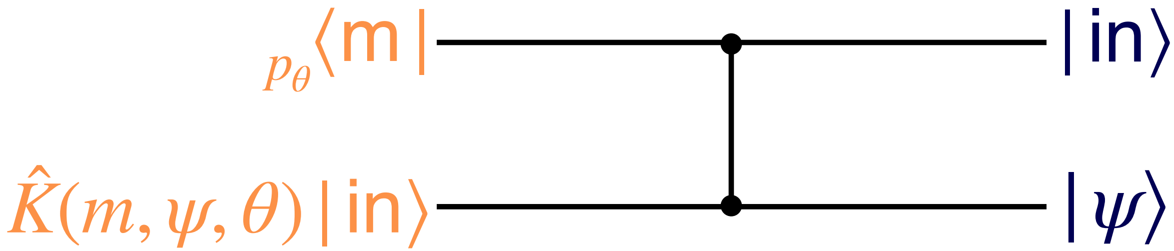
Continuous variable measurement-based quantum computing



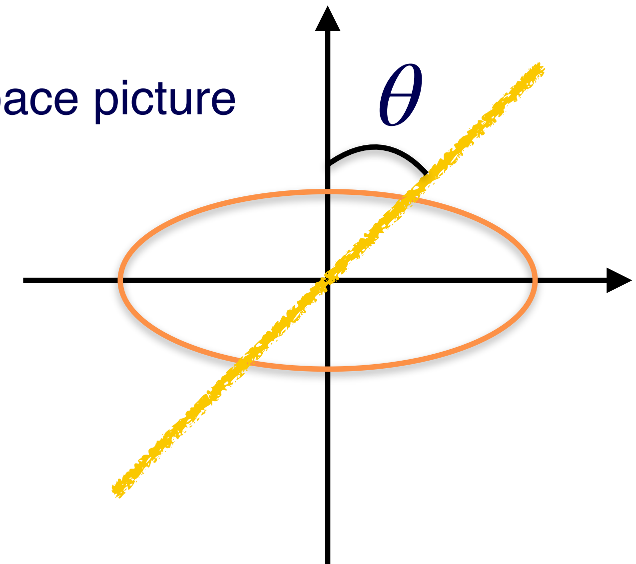
Teleportation



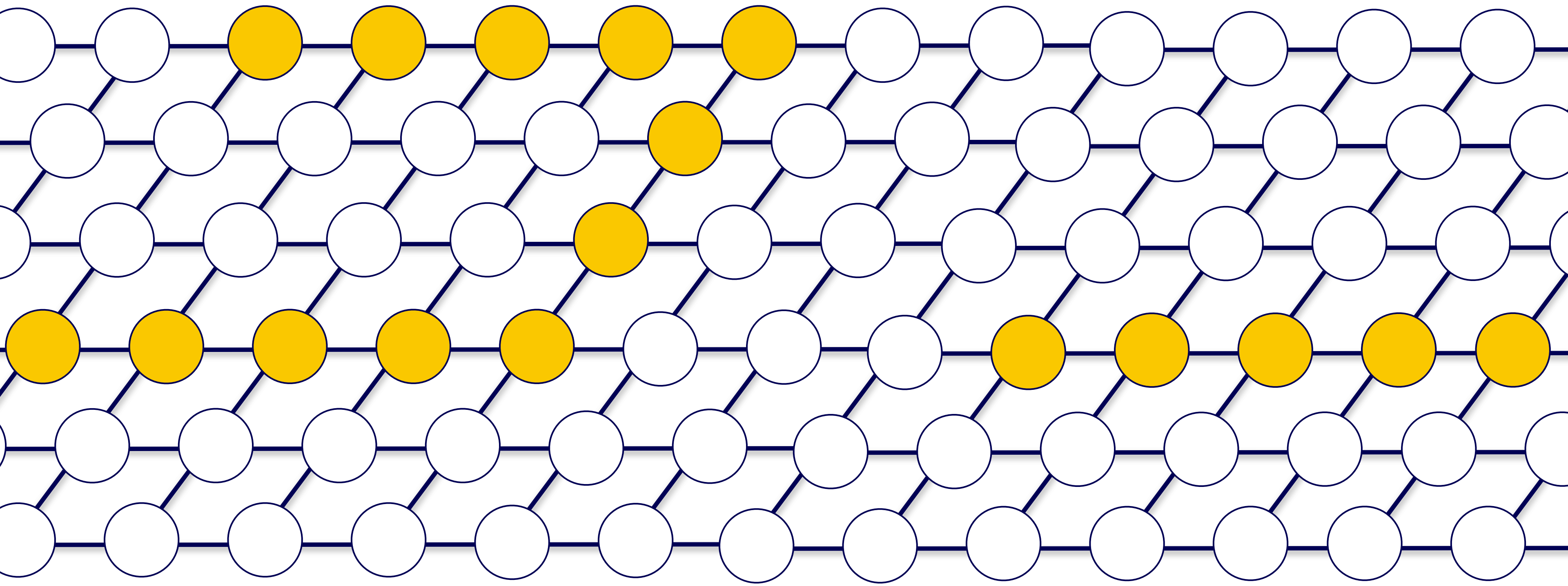
Teleportation



Phase-space picture



Two- and one-mode gates



Defining a qubit

PHYSICAL REVIEW A, VOLUME 64, 012310

Encoding a qubit in an oscillator

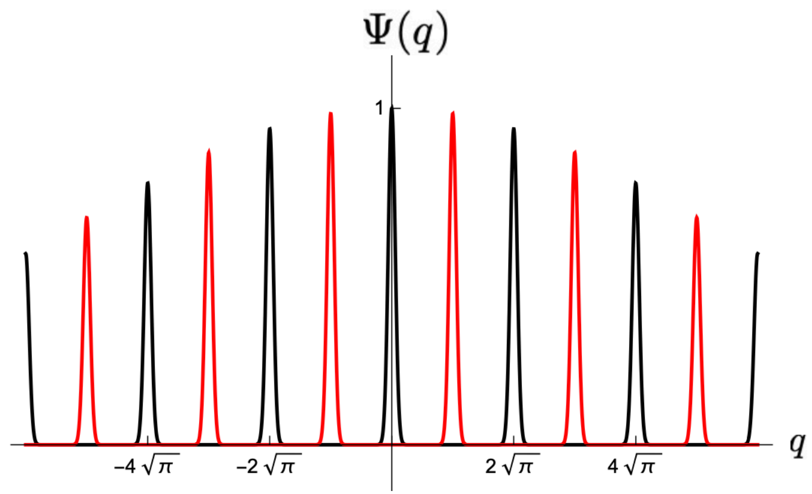
Daniel Gottesman,[1,2,*] Alexei Kitaev,[1,†] and John Preskill[3,‡]
[1]*Microsoft Corporation, One Microsoft Way, Redmond, Washington 98052*
[2]*Computer Science Division, EECS, University of California, Berkeley, California 94720*
[3]*Institute for Quantum Information, California Institute of Technology, Pasadena, California 91125*
(Received 9 August 2000; published 11 June 2001)

PHYSICAL REVIEW A **73**, 012325 (2006)

Error analysis for encoding a qubit in an oscillator

S. Glancy* and E. Knill†
Mathematical and Computing Science Division, Information Technology Laboratory, National Institute of Standards and Technology, Boulder, Colorado 80301, USA
(Received 14 October 2005; published 19 January 2006)

- $\left\langle \Psi(q) \middle| \tilde{0}_L \right\rangle$
- $\left\langle \Psi(\mathrm{q}) \middle| \tilde{1}_L \right\rangle$



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Defining a qubit

PHYSICAL REVIEW A, VOLUME 64, 012310

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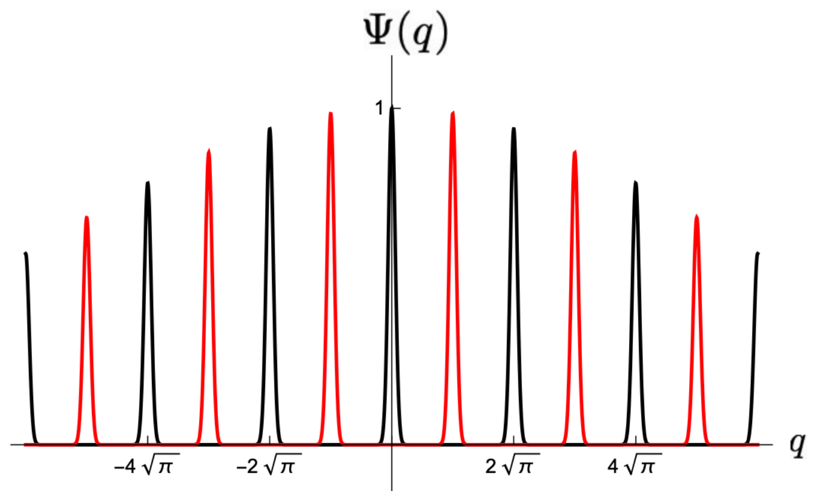

$$|\varnothing\rangle := \int ds\, Ш_{\sqrt{2\pi}}(s) |s\rangle_q$$

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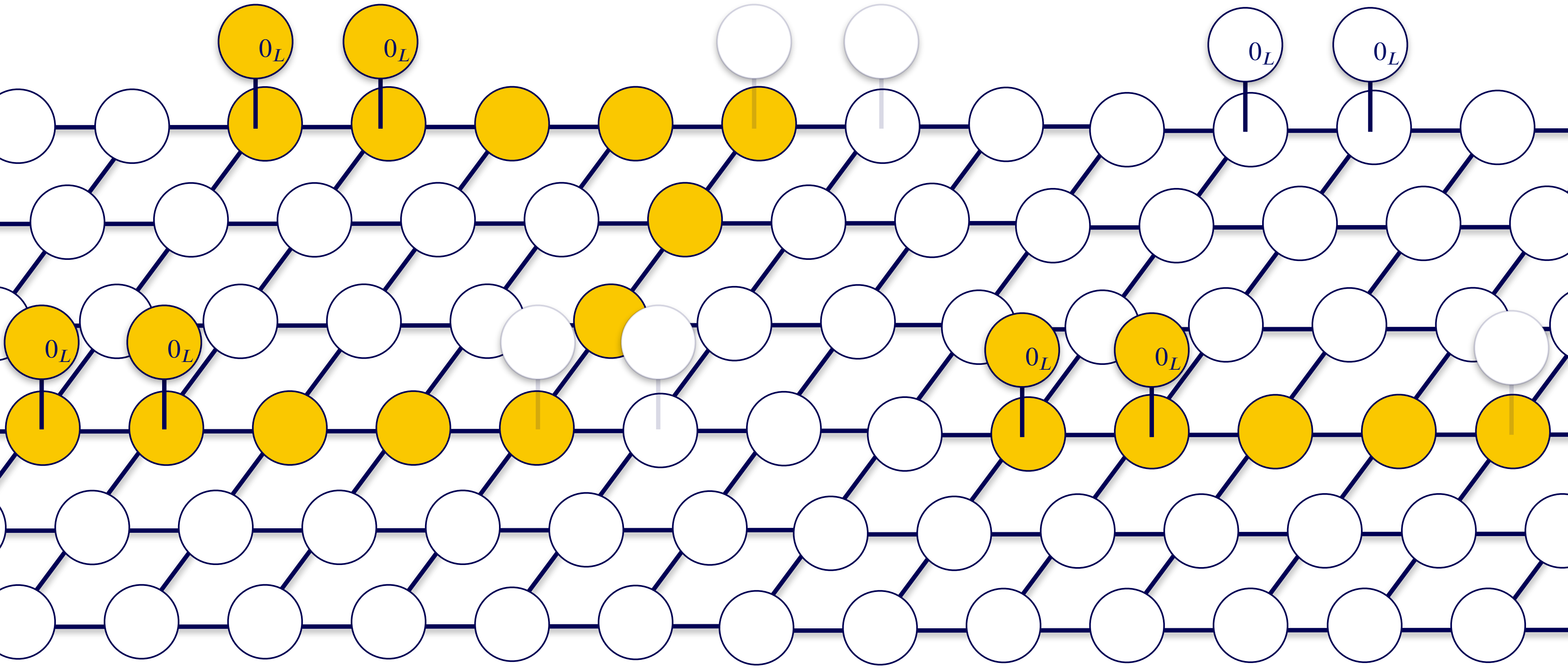
GKP error correction



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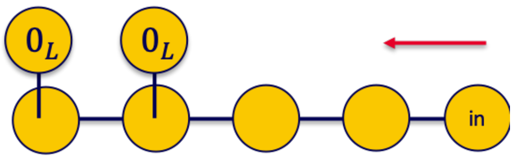
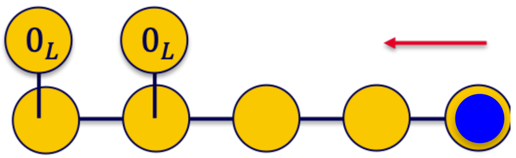
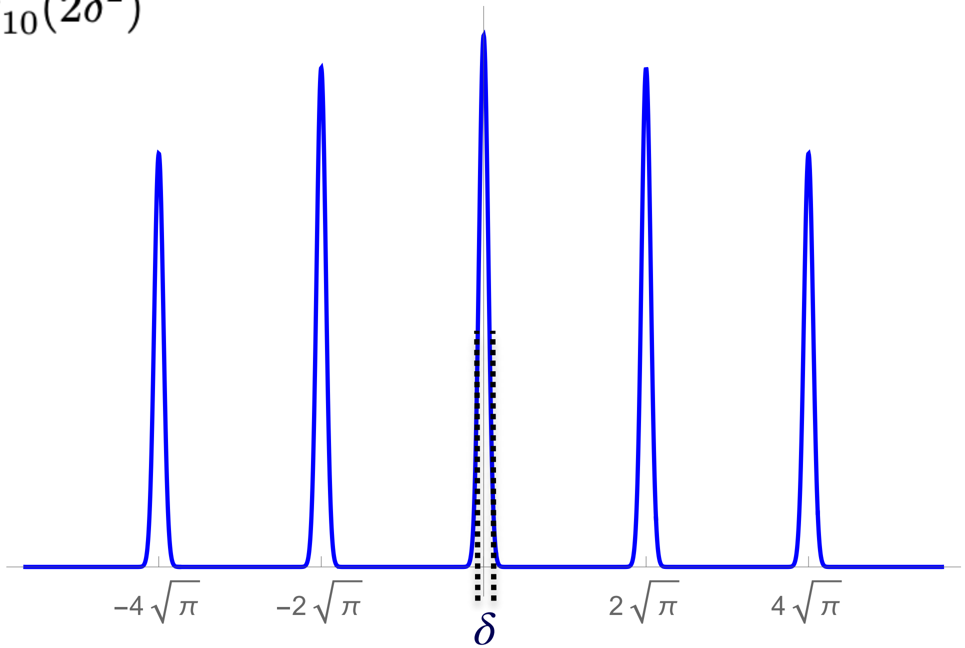
Noise Accumulation



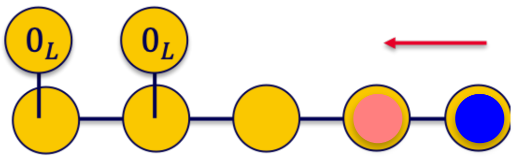
Noise Accumulation



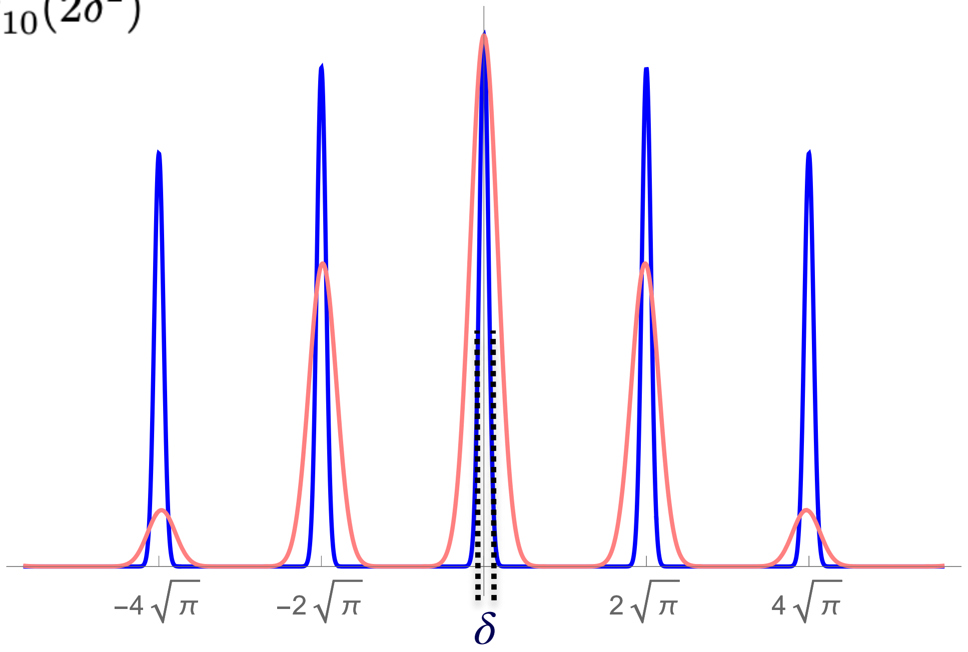
$$(\delta^2)_{\mathrm{dB}} = -10\log_{10}(2\delta^2)$$



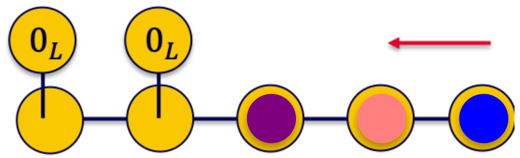
Noise Accumulation



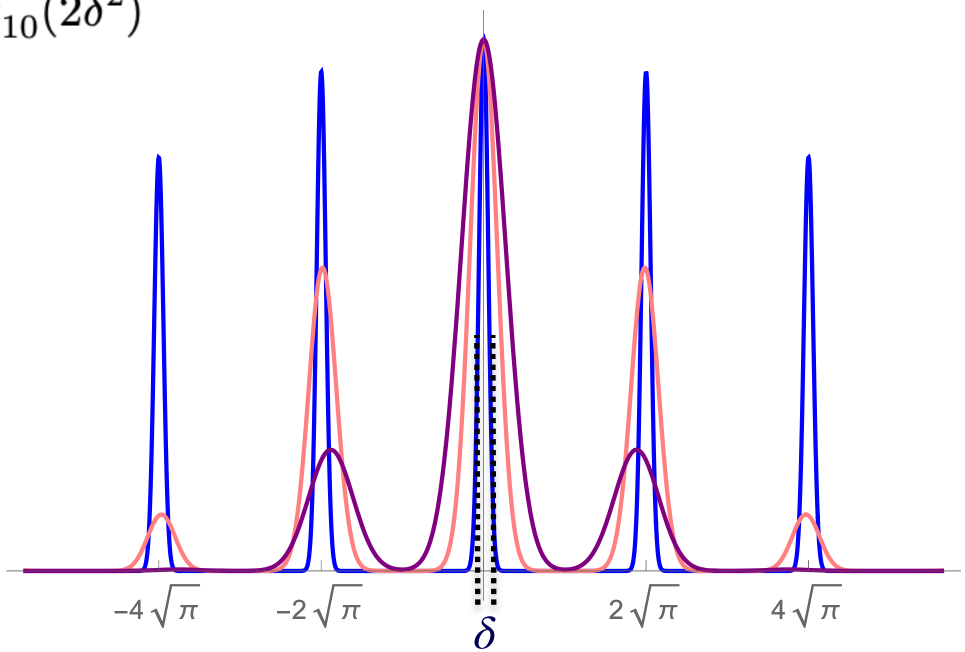
$$(\delta^2)_{\text{dB}} = -10\log_{10}(2\delta^2)$$



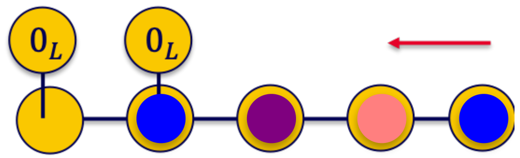
Noise Accumulation



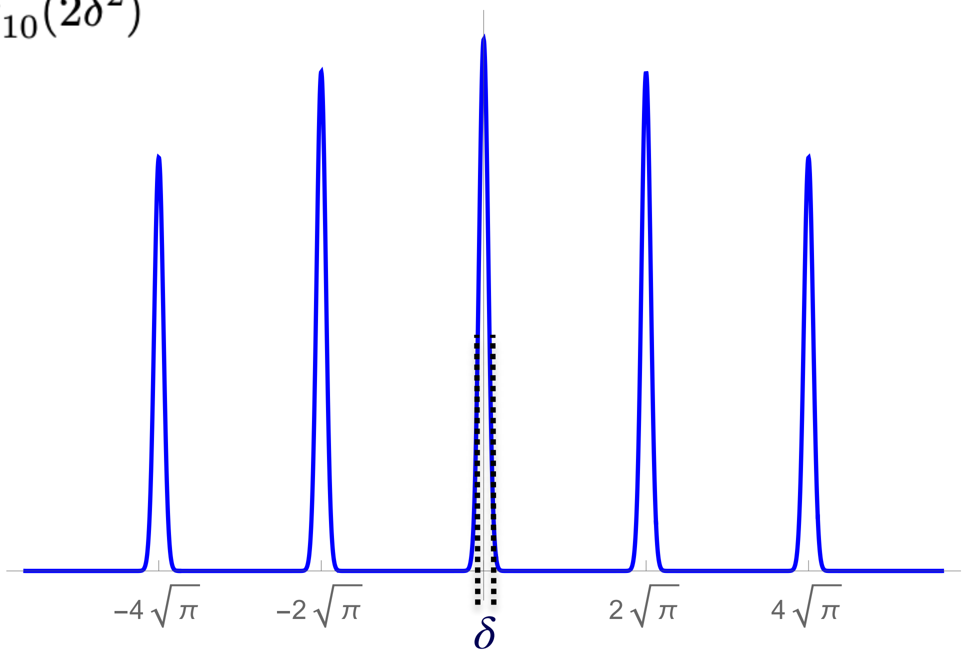
$$(\delta^2)_{\mathrm{dB}} = -10\log_{10}(2\delta^2)$$



Noise Accumulation



$$(\delta^2)_{\mathrm{dB}} = -10\log_{10}(2\delta^2)$$



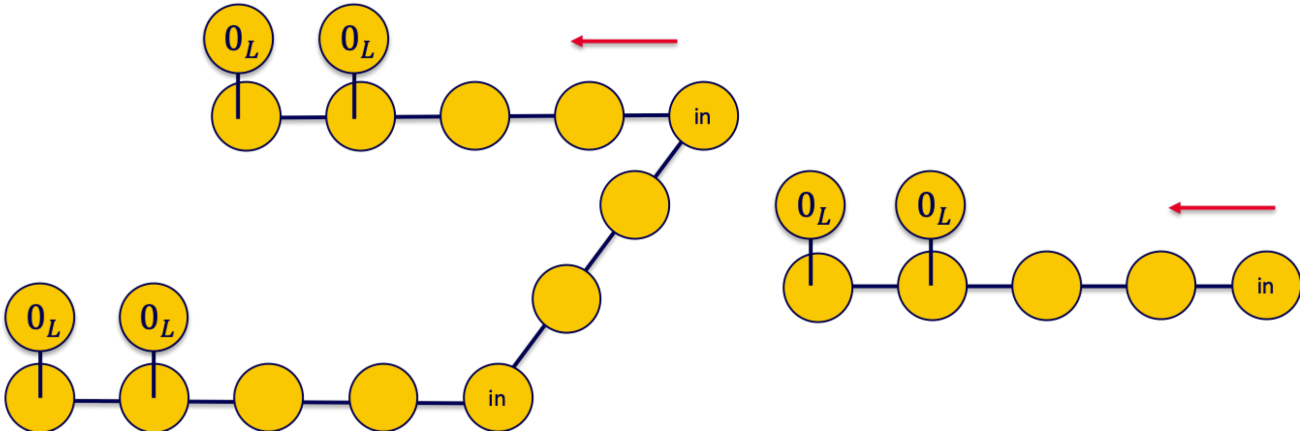
Fault-tolerant continuous variable measurement-based quantum computing

PRL 112, 120504 (2014) PHYSICAL REVIEW LETTERS week ending 28 MARCH 2014

Fault-Tolerant Measurement-Based Quantum Computing with Continuous-Variable Cluster States

Nicolas C. Menicucci*
School of Physics, The University of Sydney, Sydney, New South Wales 2006, Australia

(Received 29 October 2013; published 26 March 2014)



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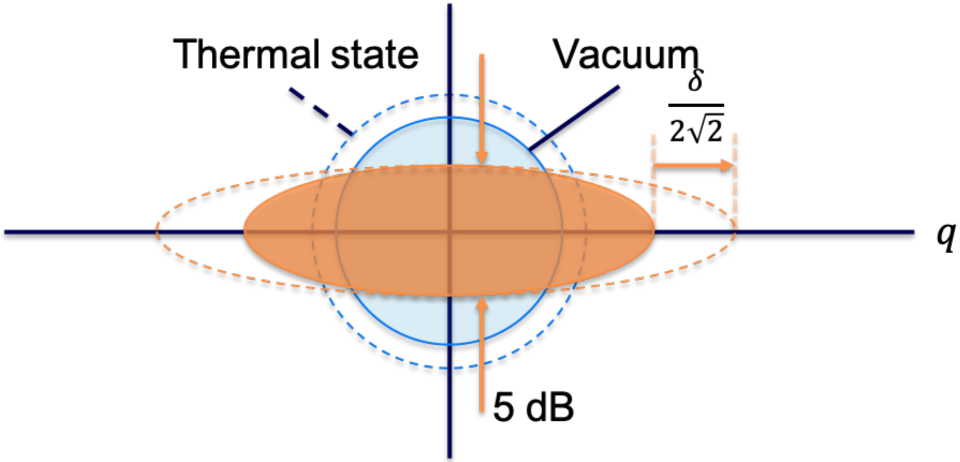
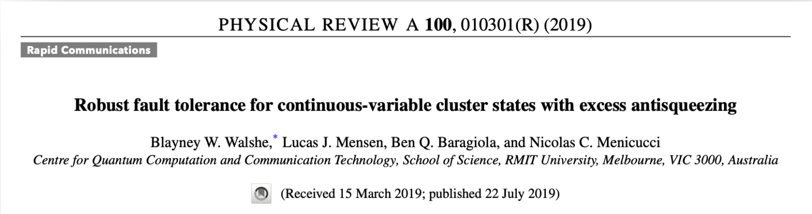
Robust fault tolerance



Error Rate	Squeezing (dB)
10^{-6}	20.5 dB
10^{-3}	17.4 dB
1 %	15.6 dB



PHYSICAL REVIEW A **100**, 010301(R) (2019)
Rapid Communications

Robust fault tolerance for continuous-variable cluster states with excess antisqueezing

Blayney W. Walshe,* Lucas J. Mensen, Ben Q. Baragiola, and Nicolas C. Menicucci
Centre for Quantum Computation and Communication Technology, School of Science, RMIT University, Melbourne, VIC 3000, Australia

(Received 15 March 2019; published 22 July 2019)

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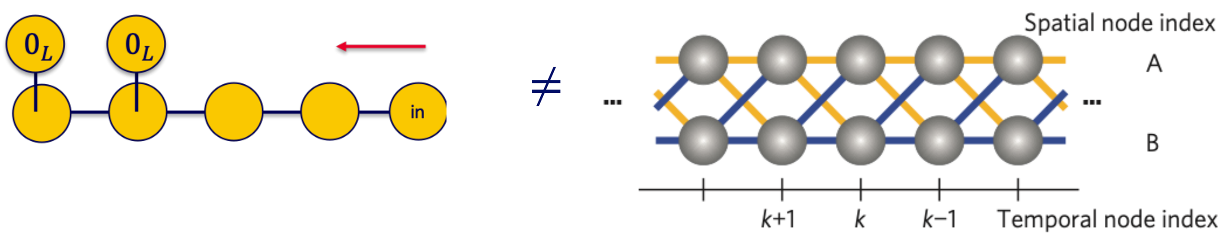
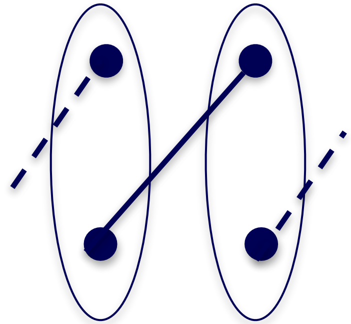
Using the experimentally accessible resource





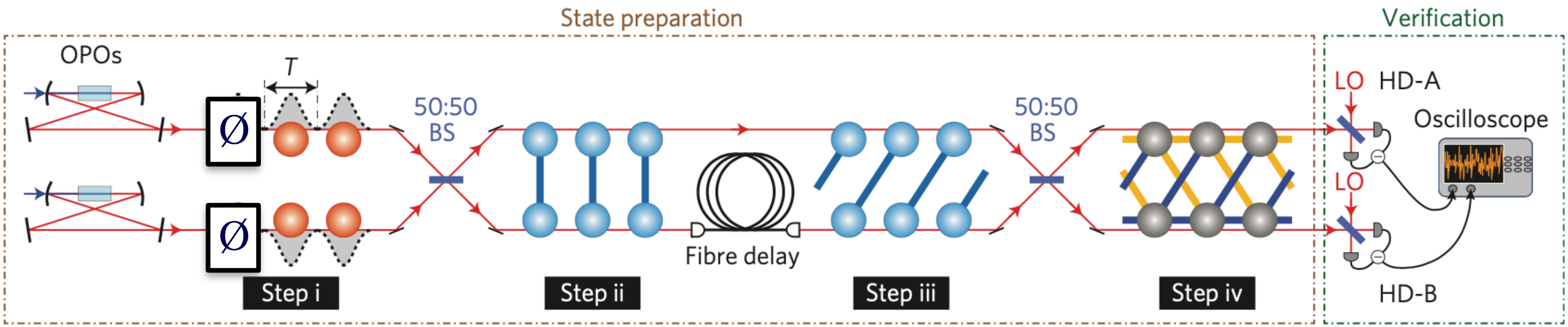
Simplified view

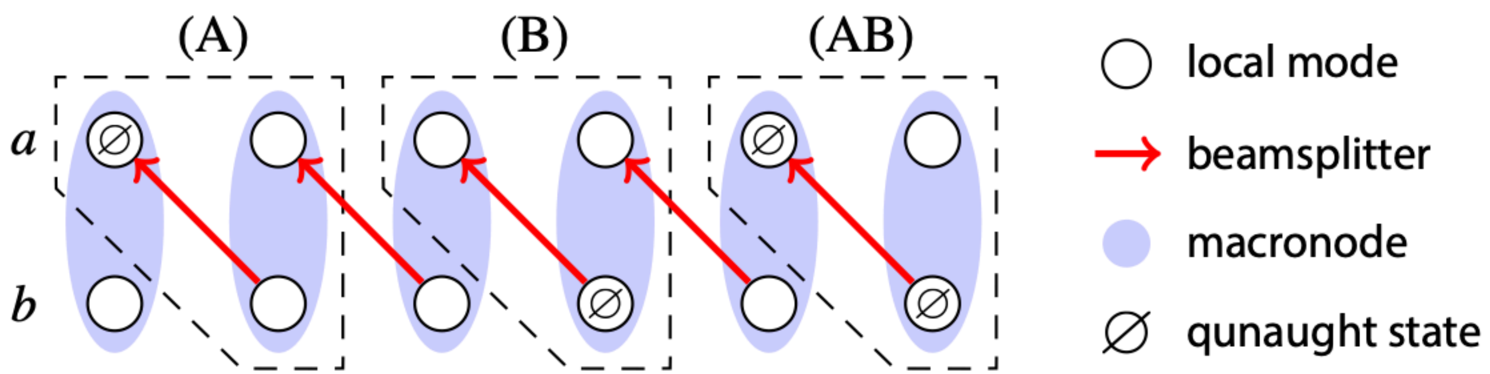
PHYSICAL REVIEW A **90**, 062324 (2014)

Noise analysis of single-mode Gaussian operations using continuous-variable cluster states

Rafael N. Alexander,[1,*] Seiji C. Armstrong,[2,3] Ryuji Ukai,[2] and Nicolas C. Menicucci[1]
[1]*School of Physics, The University of Sydney, NSW, 2006, Australia*
[2]*Department of Applied Physics, School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan*
[3]*Centre for Quantum Computation and Communication Technology, Department of Quantum Science, The Australian National University, Canberra, ACT 0200, Australia*
(Received 15 November 2013; revised manuscript received 12 October 2014; published 15 December 2014)

Error Correction on the Macronode Wire





$$|\varnothing\rangle := \int ds\, Ш_{\sqrt{2\pi}}(s)|s\rangle_q$$

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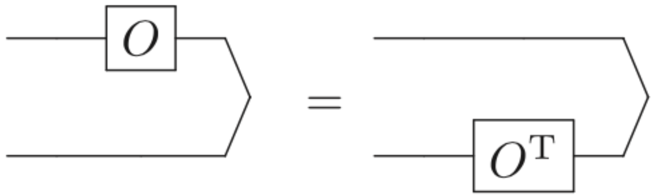
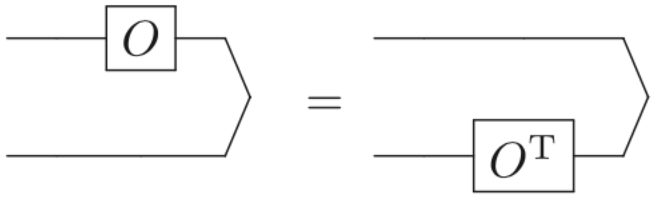
Bounce rules



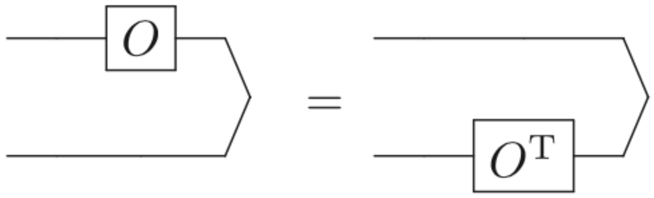
Bounce rules



$$\hat{q}^T = \hat{q}$$

$$\hat{p}^T = -\hat{p}$$

Bounce rules



$$\hat{q}^T = \hat{q}$$

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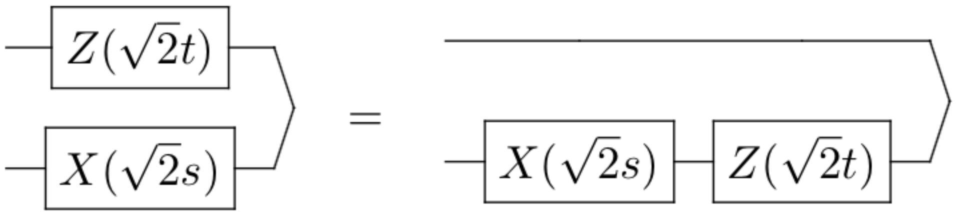
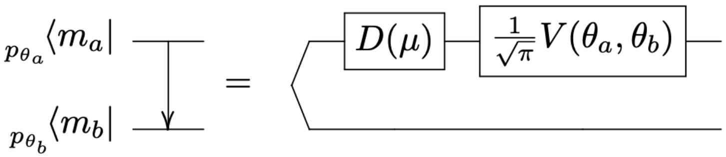
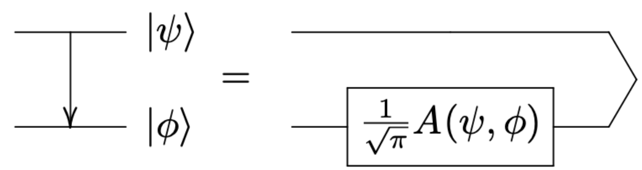
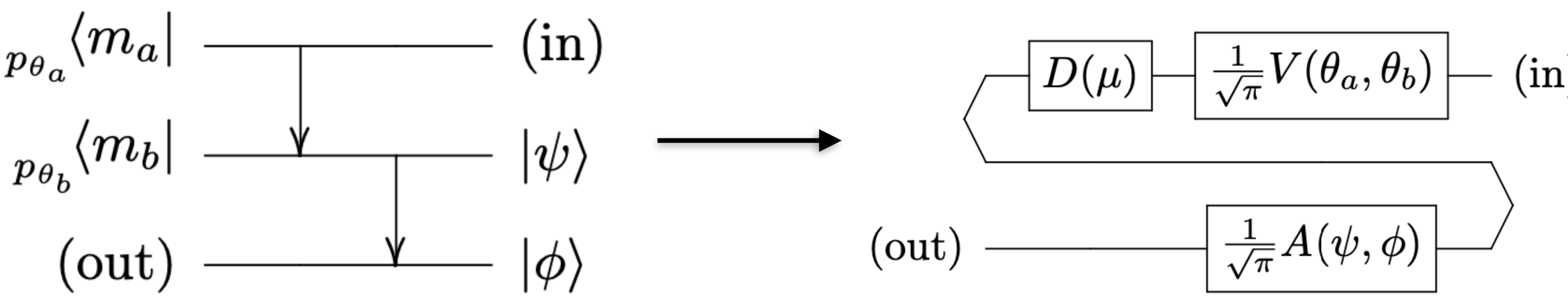


Circuit identities







PHYSICAL REVIEW A **102**, 062411 (2020)

Continuous-variable gate teleportation and bosonic-code error correction

Blayney W. Walshe,[1,*] Ben Q. Baragiola,[1] Rafael N. Alexander,[1,2] and Nicolas C. Menicucci[1]
[1]*Centre for Quantum Computation and Communication Technology, School of Science, RMIT University, Melbourne, Victoria 3000, Australia*
[2]*Center for Quantum Information and Control, University of New Mexico, Albuquerque, New Mexico 87131, USA*

(Received 15 September 2020; accepted 10 November 2020; published 15 December 2020)

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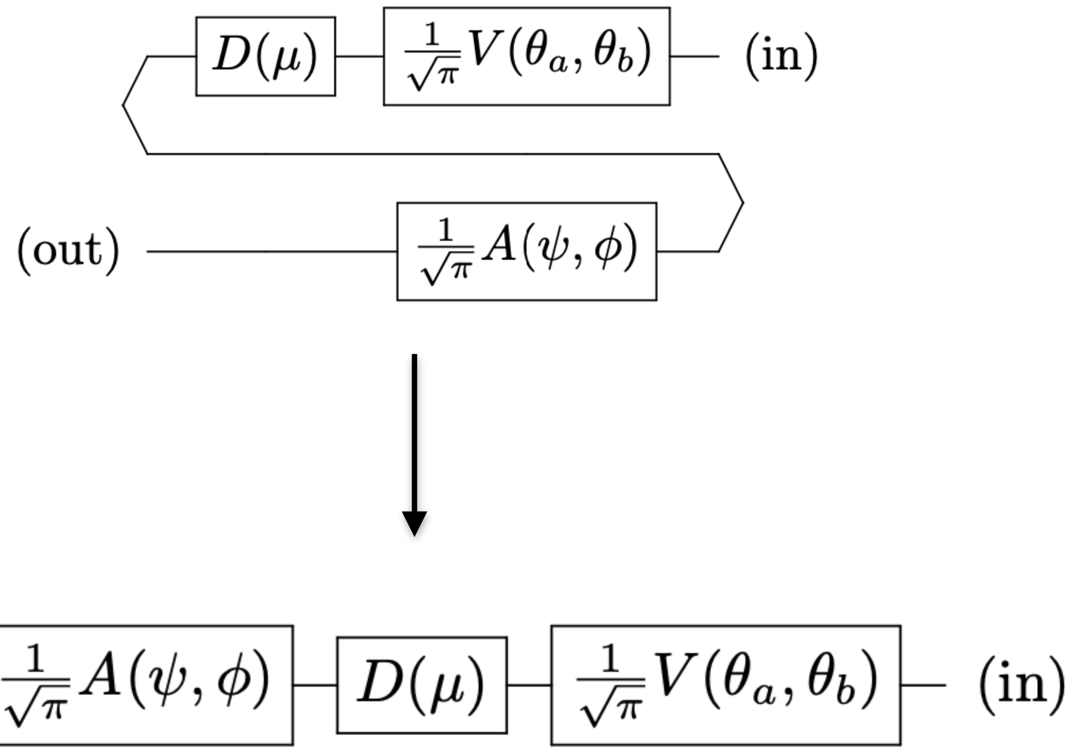
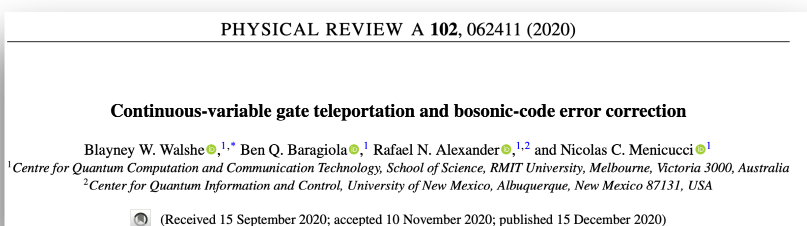
Kraus operator for a macronode measurement





PHYSICAL REVIEW A **102**, 062411 (2020)

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Kraus operator for a macronode measurement

$$\hat{K}(m_a, m_b) = \frac{1}{\pi} \underline{\hat{A}(\psi, \phi)} \hat{D}(\mu) \underline{\hat{V}(\theta_a, \theta_b)}$$

PHYSICAL REVIEW A **102**, 062411 (2020)

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RMIT UNIVERSITY

Kraus operator for a macronode measurement

$$\hat{K}(m_a, m_b) = \frac{1}{\pi}\hat{A}(\psi, \phi)\hat{D}(\mu)\hat{V}(\theta_a, \theta_b)$$

$$\hat{V}(\theta_a, \theta_b) \coloneqq \hat{R}(\theta_+ - \tfrac{\pi}{2})\hat{S}(\tan\theta_-)\hat{R}(\theta_+)$$

$$\theta_\pm = \frac{\theta_a \pm \theta_b}{2}$$

PHYSICAL REVIEW A **102**, 062411 (2020)

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RMIT UNIVERSITY

Kraus operator for a macronode measurement

$$\hat{K}(m_a, m_b) = \frac{1}{\pi} \underline{\hat{A}(\psi, \phi)} \hat{D}(\mu) \underline{\hat{V}(\theta_a, \theta_b)}$$

$$\hat{V}(\theta_a, \theta_b) := \hat{R}(\theta_+ - \tfrac{\pi}{2}) \hat{S}(\tan \theta_-) \hat{R}(\theta_+)$$

$$\hat{A}(\psi, \phi) := \iint d^2\alpha \, \tilde{\psi}(\alpha_I) \phi(\alpha_R) \hat{D}(\alpha)$$

$$\theta_\pm = \frac{\theta_a \pm \theta_b}{2}$$

PHYSICAL REVIEW A **102**, 062411 (2020)

Continuous-variable gate teleportation and bosonic-code error correction

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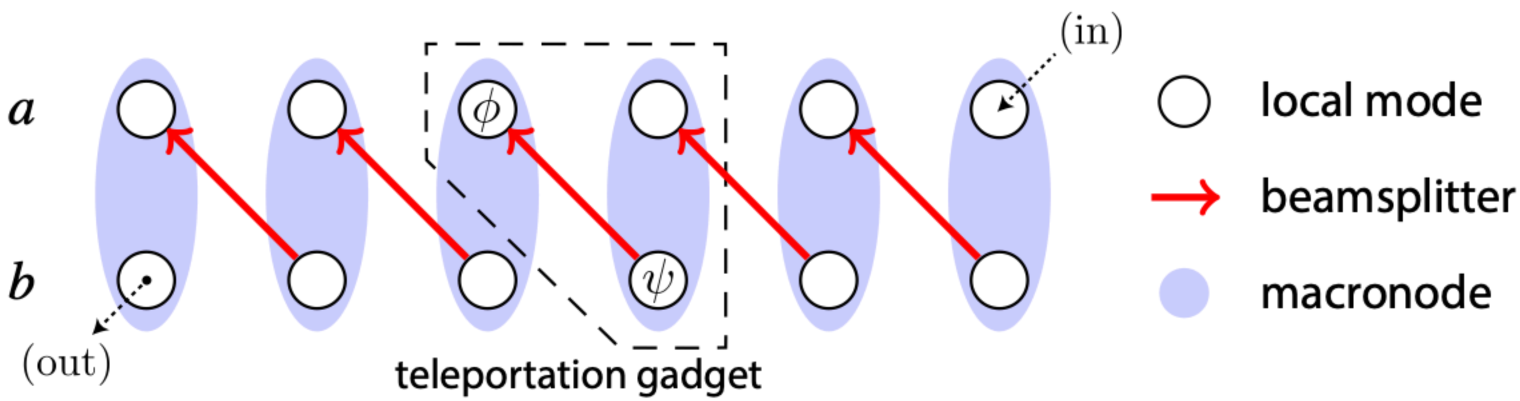
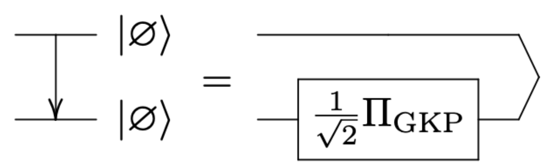
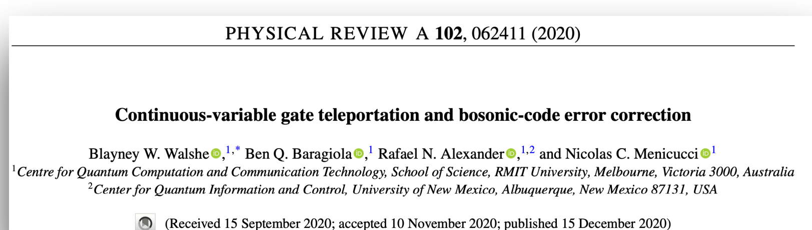
The teleported gate



$$\hat{A}(\psi,\phi) := \iint d^2\alpha\, \tilde{\psi}(\alpha_I)\phi(\alpha_R)\hat{D}(\alpha)$$





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