Downloading many-body continuous variable entanglement to qubits

Zhihua Han, Kero Lau

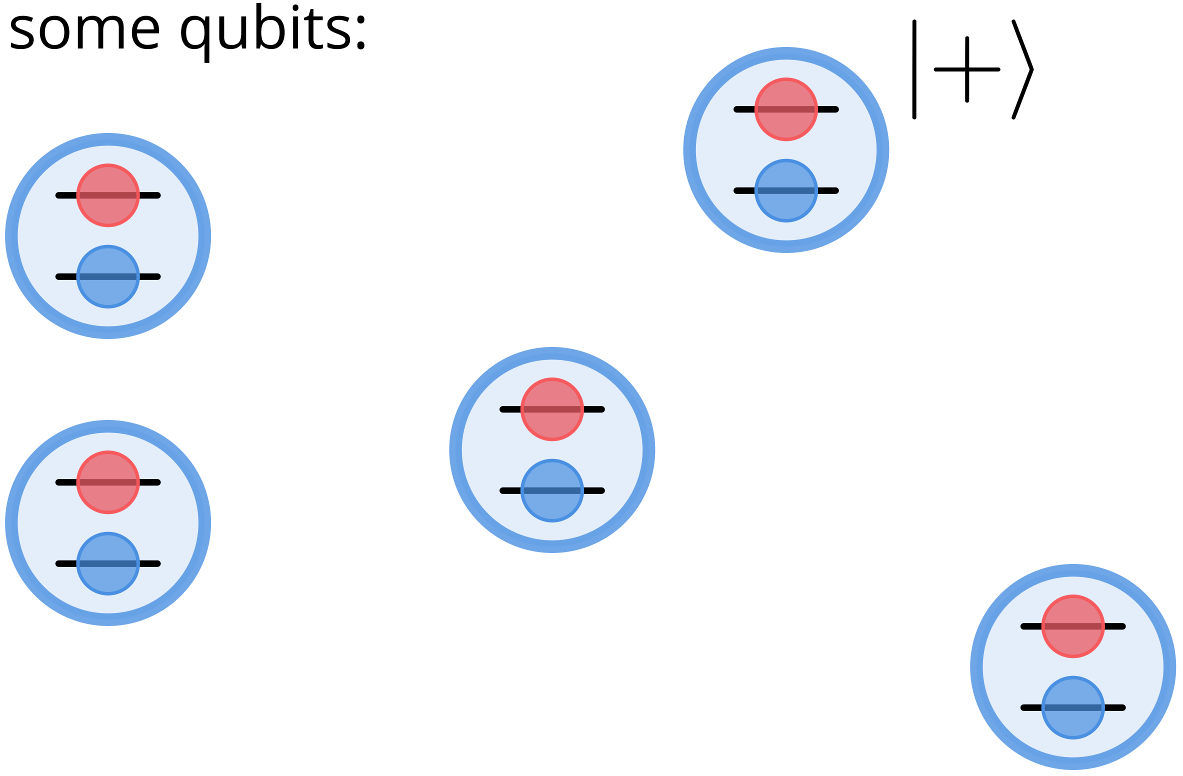
Simon Fraser University

Canadian Association of Physicists

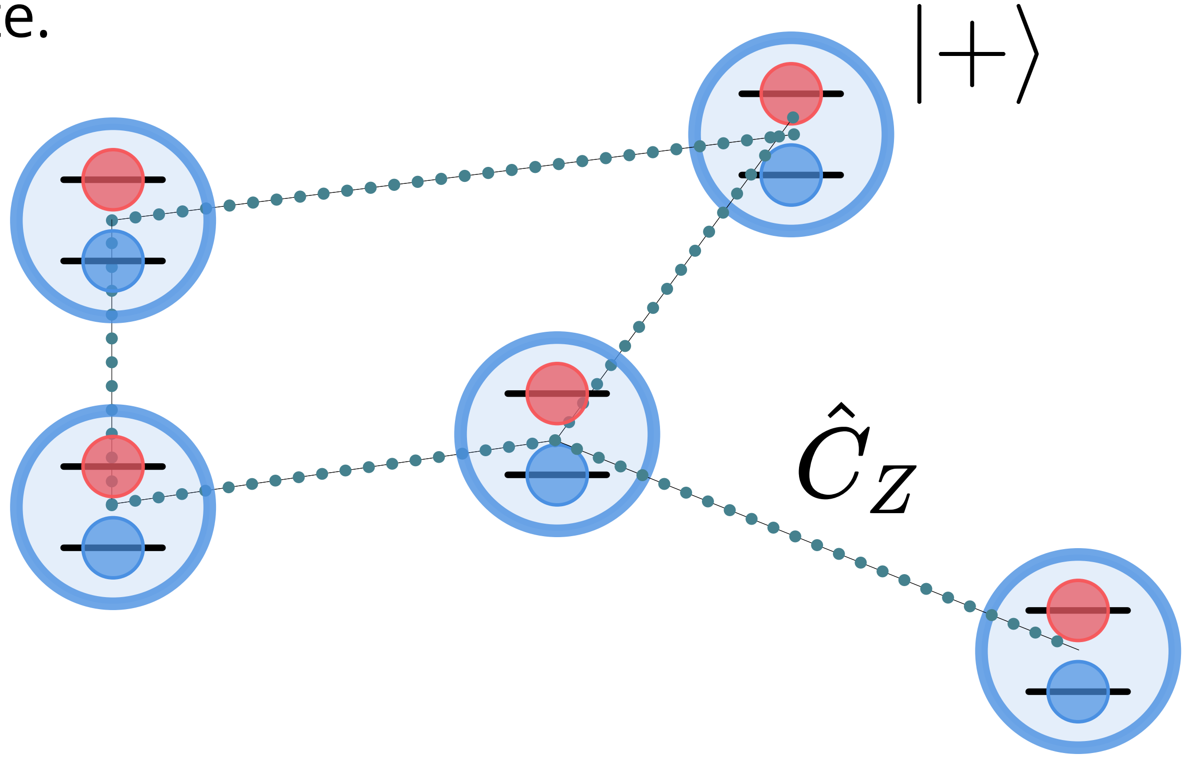
Association canadienne des physiciens et physiciennes

Qubit cluster state

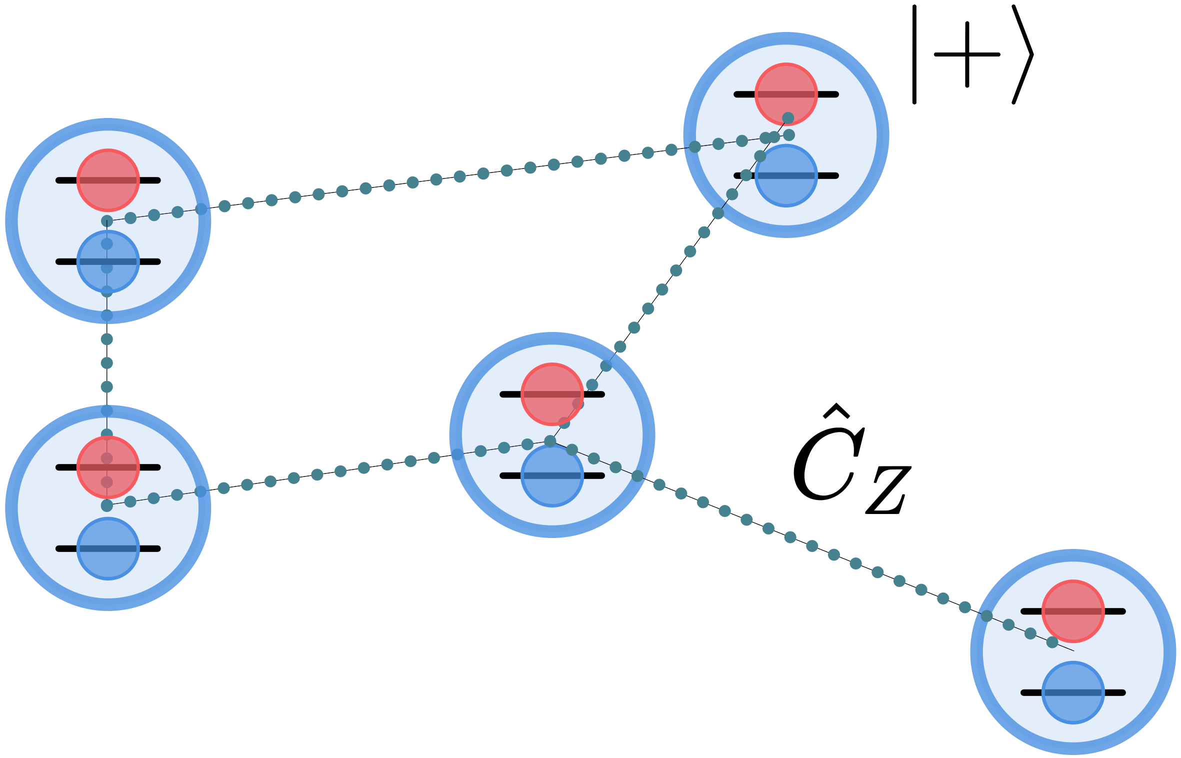
Imagine I have some qubits:



and now I entangle the edges with the CZ gate.

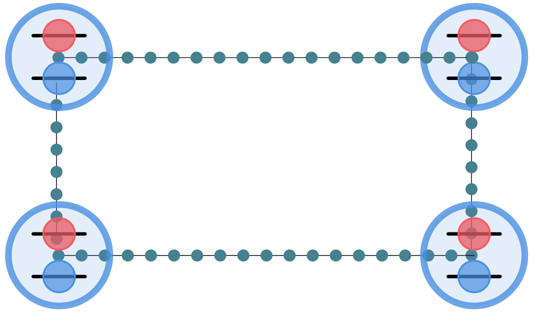


The quantum state specified by G is called
a **qubit cluster state.**



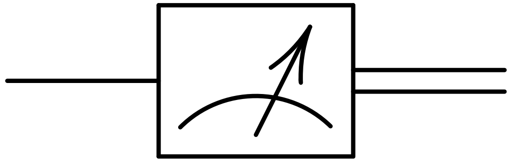
$$= |G\rangle = \prod_{i,j \in E} \hat{C}_{Z_{ij}} |+\rangle^{\otimes N}$$

Qubit cluster state



+

Single qubit measurements



→

Fault tolerant universal quantum computation

A One-Way Quantum Computer

Robert Raussendorf and Hans J. Briegel
Theoretische Physik, Ludwig-Maximilians-Universität München, Germany
(Received 25 October 2000)

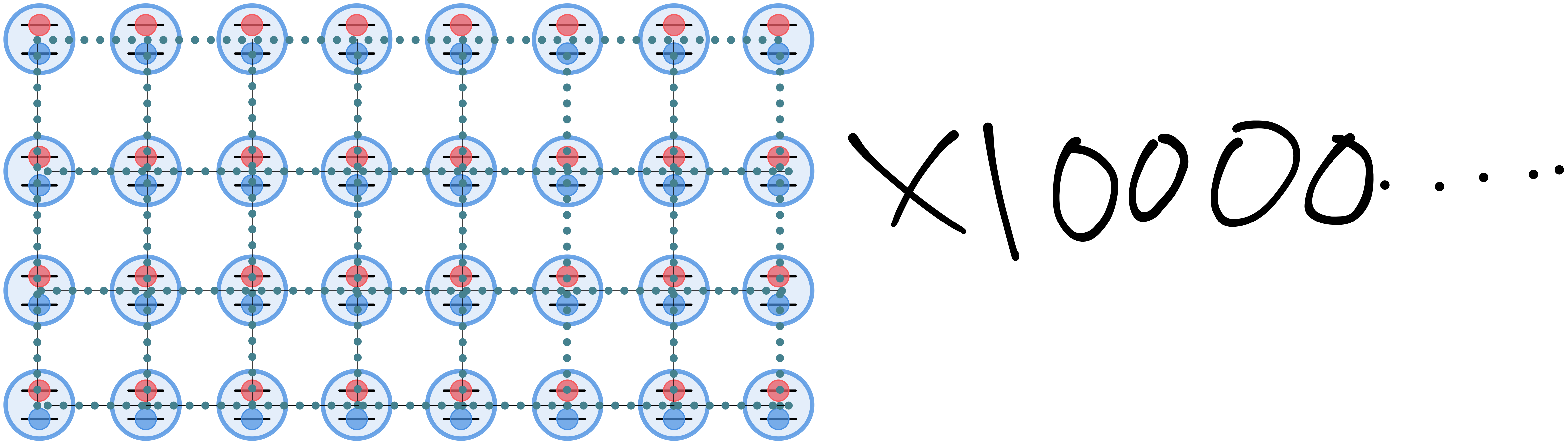
We present a scheme of quantum computation that consists entirely of one-qubit measurements on a particular class of entangled states, the cluster states. The measurements are used to imprint a quantum logic circuit on the state, thereby destroying its entanglement at the same time. Cluster states are thus one-way quantum computers and the measurements form the program.

DOI: 10.1103/PhysRevLett.86.5188 PACS numbers: 03.67.Lx, 03.65.Ud

(Raussendorf 2001)

Why we need qubit cluster state

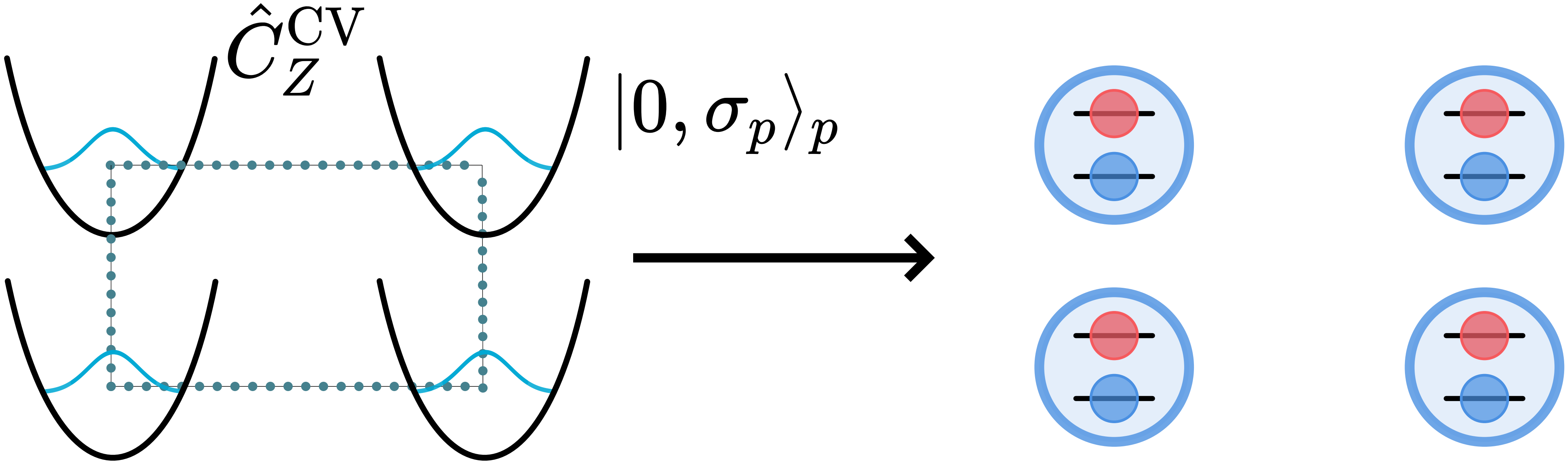
Qubit cluster state



Goal: Make many body entanglement in physical qubits

Entanglement Transfer Protocol

How do we make scalable qubit cluster states?



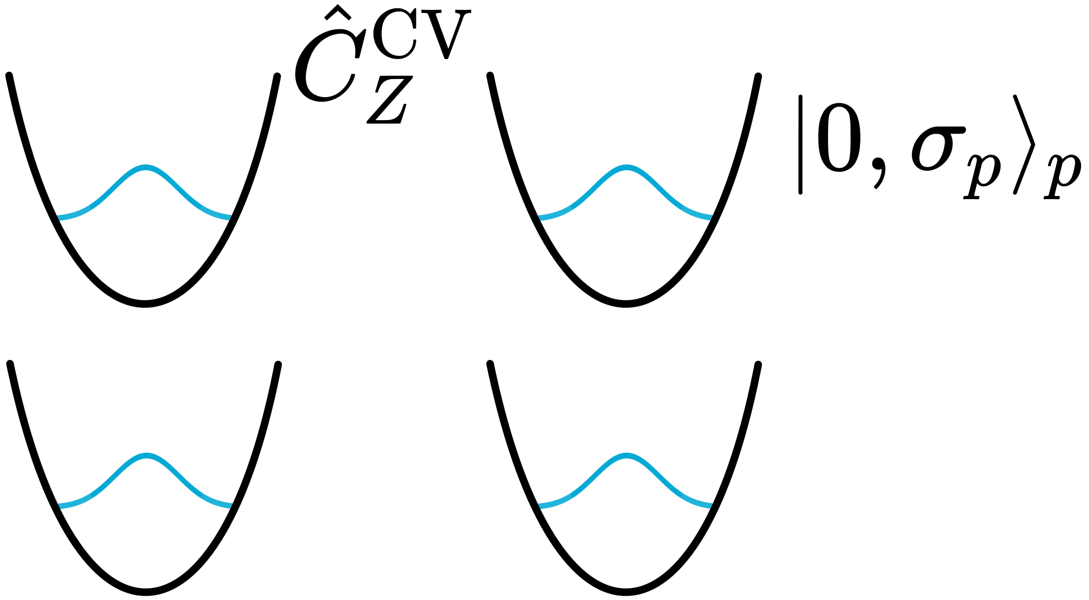
Continuous variable (CV) cluster state

Physical qubits

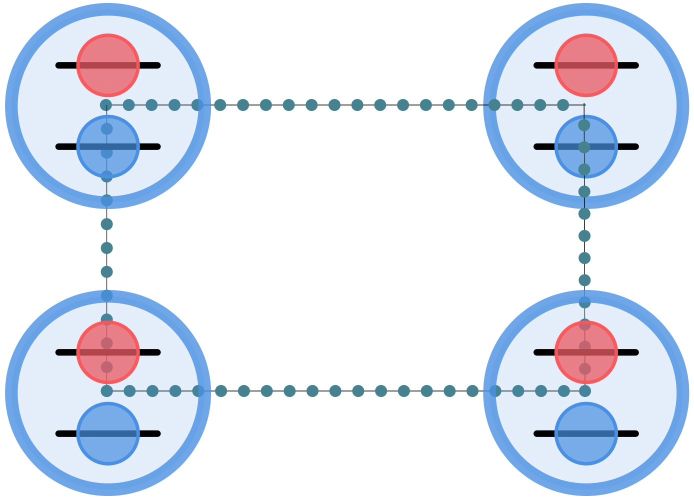
"Downloading entanglement from a CV cluster state"

Entanglement Transfer Protocol

How do we make scalable qubit cluster states?



Continuous variable (CV) cluster state

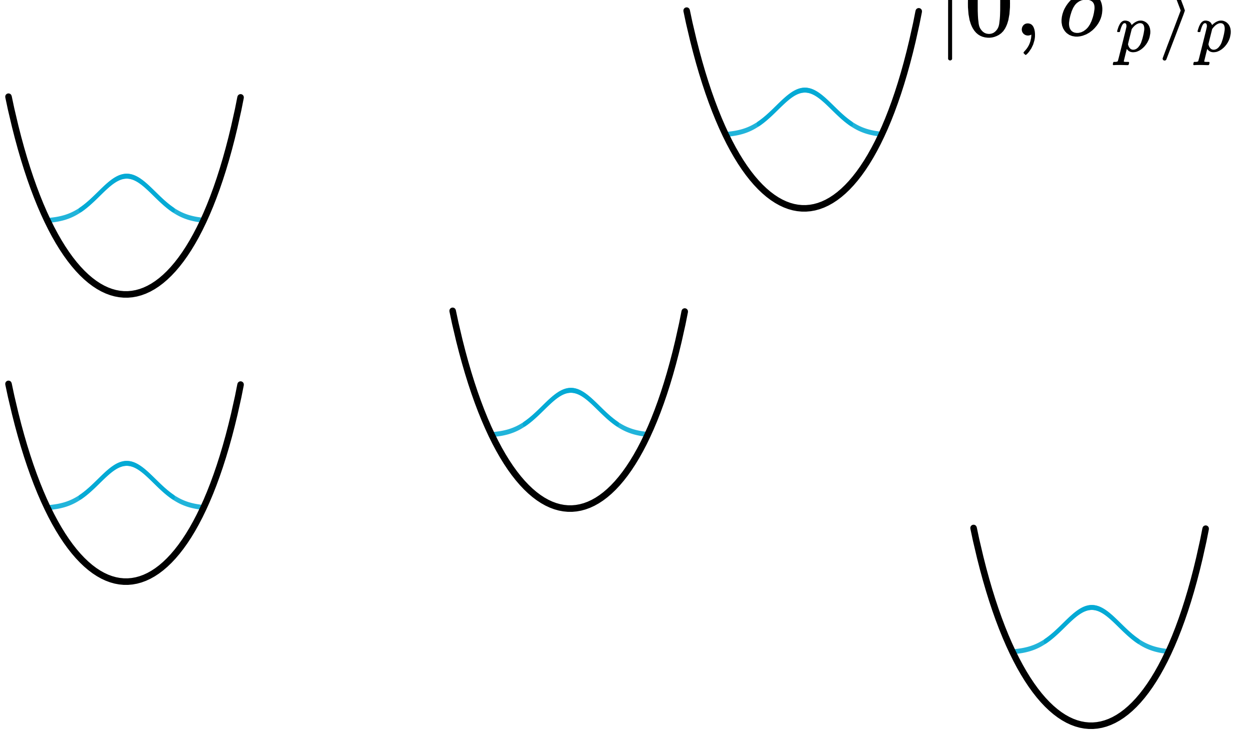


Qubit cluster state

Entanglement Transfer Protocol

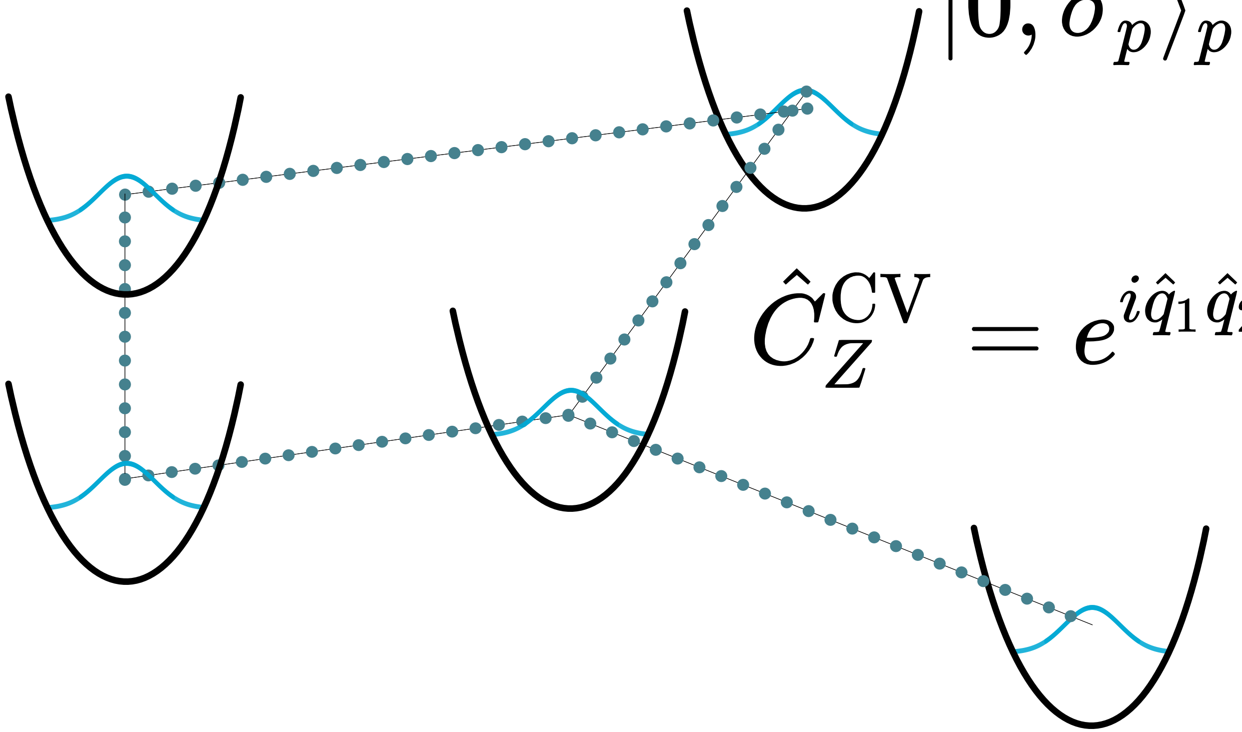
Now if I have some bosons:

$$|0, \sigma_p\rangle_p$$



CV cluster state

and entangle them with CV CZ gate:

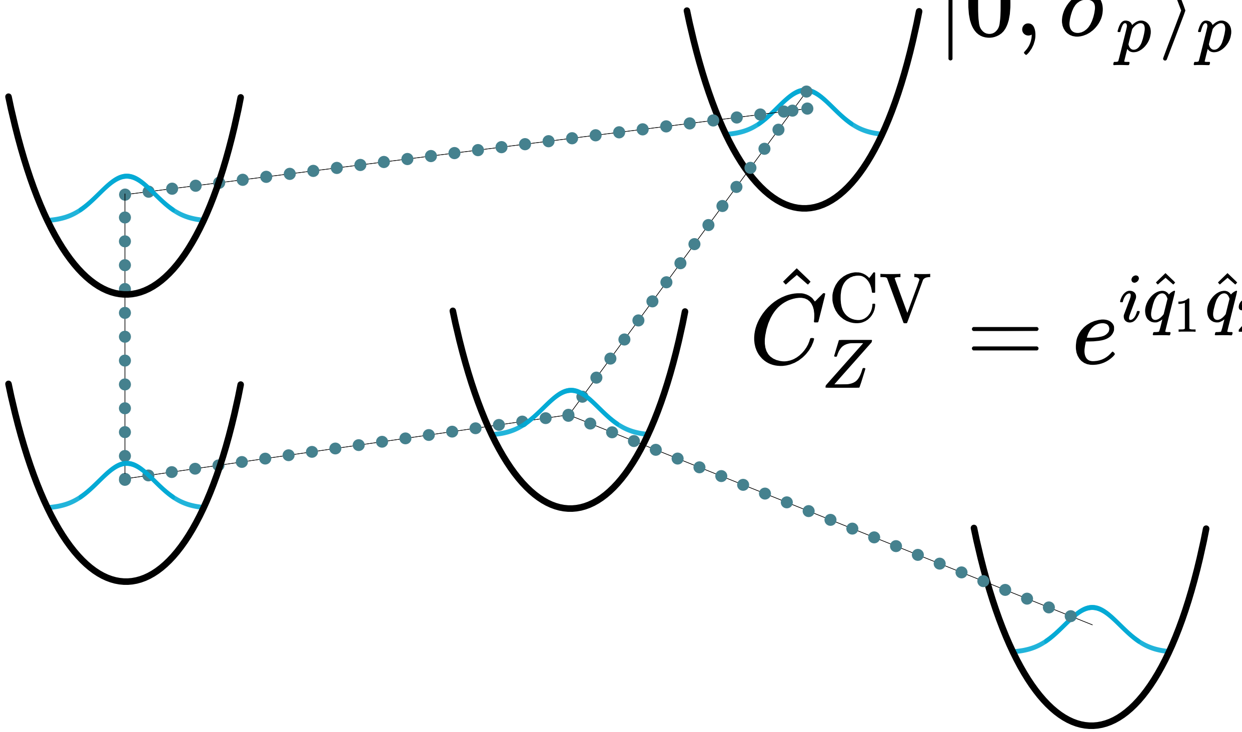


$$|0, \sigma_p\rangle_p$$

$$\hat{C}_Z^{\mathrm{CV}} = e^{i\hat{q}_1\hat{q}_2}$$

CV cluster state

We say it is a **CV cluster state.**



$$|0, \sigma_p\rangle_p$$

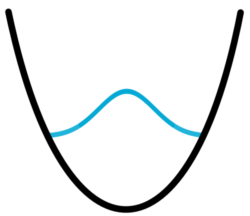
$$\hat{C}_Z^{\mathrm{CV}} = e^{i\hat{q}_1\hat{q}_2}$$

$$= |G\rangle^{\mathrm{CV}}$$

$$= \prod_{i,j\in E} \hat{C}_{Z_{ij}}^{\mathrm{CV}} |0, \sigma_p\rangle_p^{\otimes N}$$

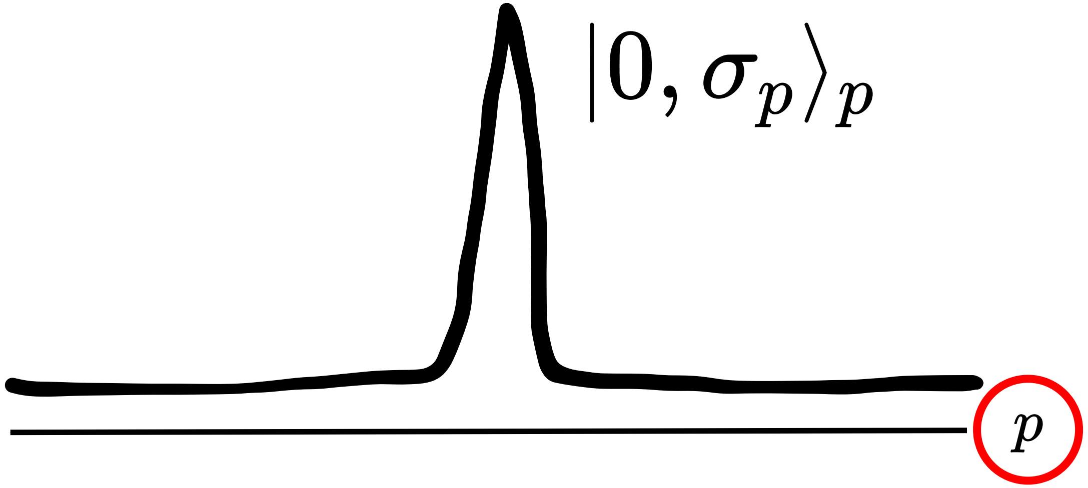
Finite vs Ideal CV cluster state

σ_p represents the variance of the squeezed state.



$|0, \sigma_p\rangle_p$

When $\sigma_p \to 0$, the CV cluster state is an **ideal CV cluster state.**



Finite vs Ideal CV cluster state

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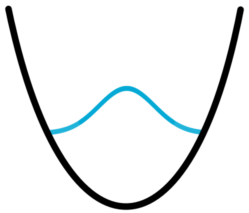
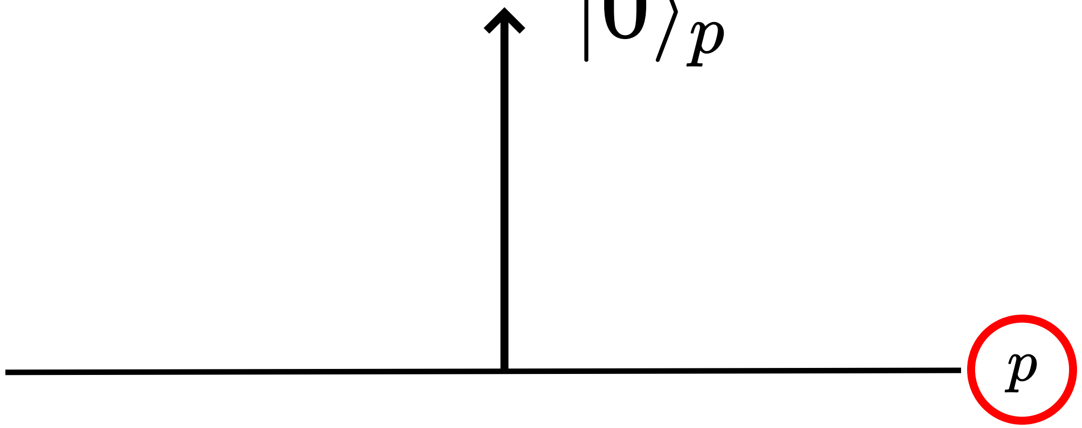


$|0, \sigma_p\rangle_p$

When $\sigma_p \to 0$, the CV cluster state is an **ideal CV cluster state.**

$|0\rangle_p$



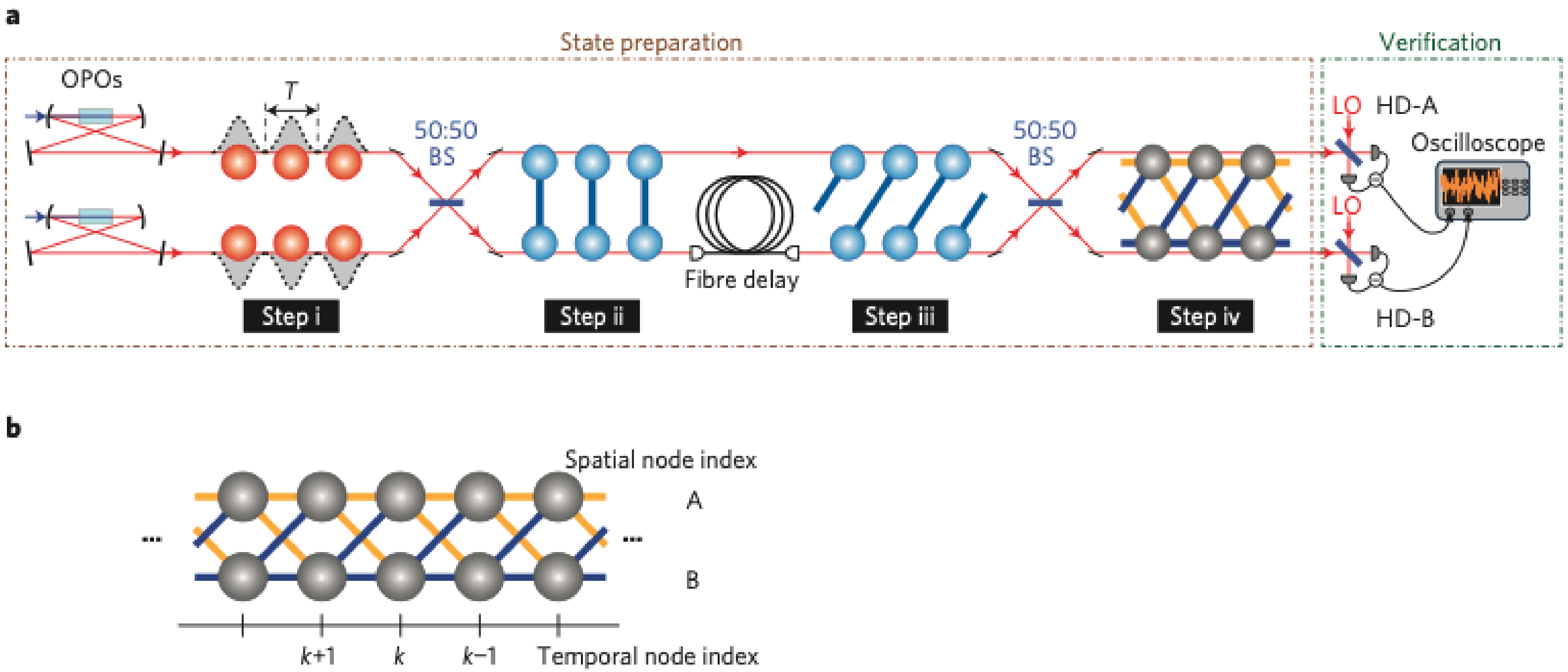
How to make CV cluster state

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]*

10000 modes! 1D, (Furusawa 2013)



How to make CV cluster state

RESEARCH ARTICLE | SEPTEMBER 27 2016

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

Jun-ichi Yoshikawa ; Shota Yokoyama; Toshiyuki Kaji; Chanond Sornphiphatphong; Yu Shiozawa; Kenzo Makino; Akira Furusawa

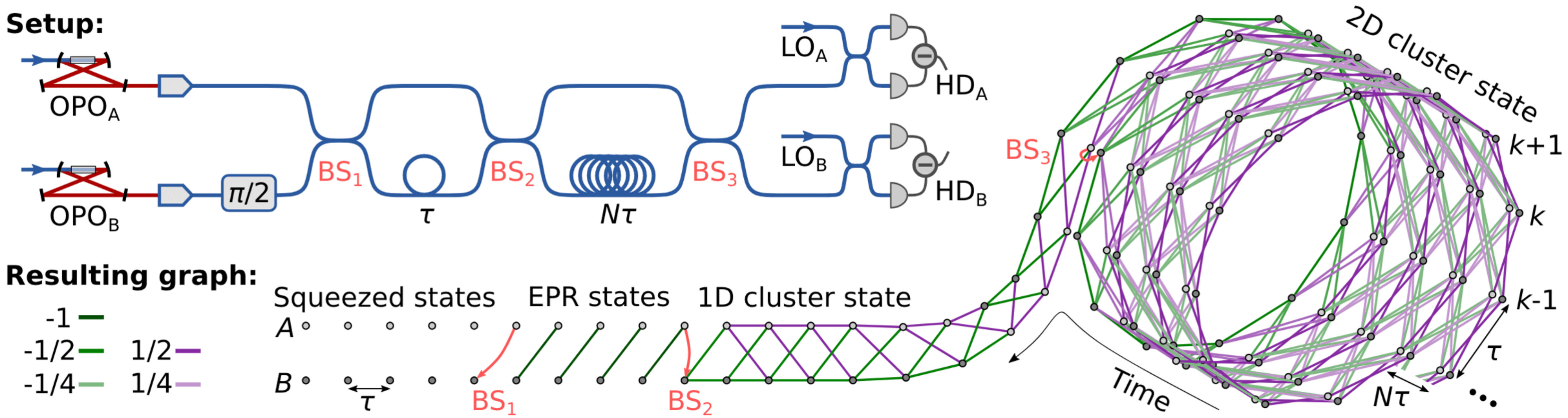
+ Author & Article Information

APL Photonics 1, 060801 (2016)

https://doi.org/10.1063/1.4962732 Article history

CHORUS

1 million modes, 1D, 2016



How to make CV cluster state

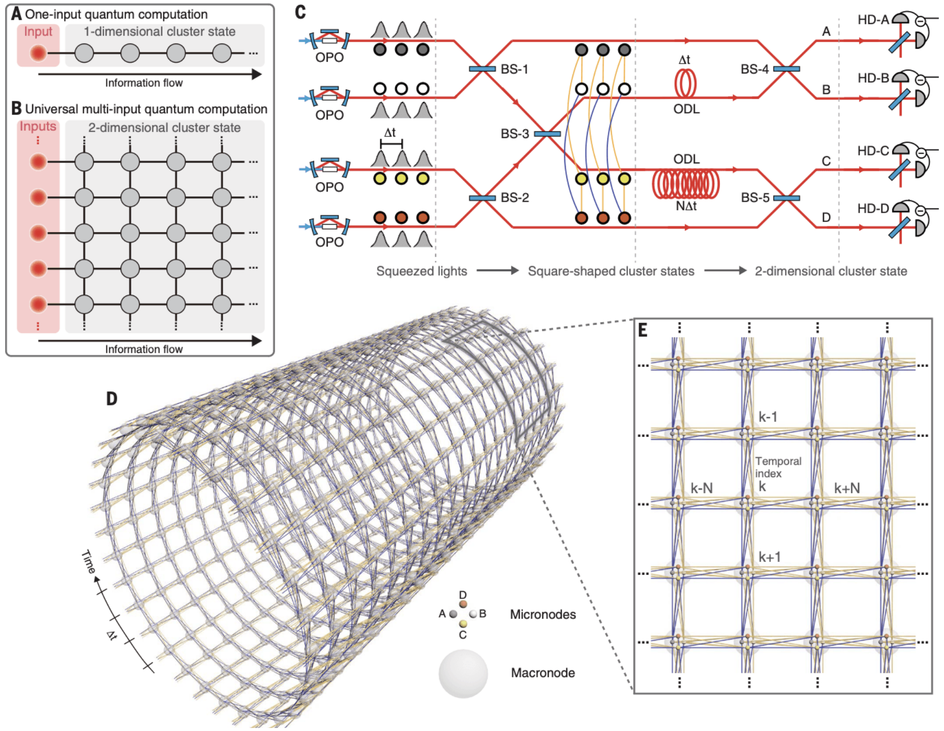
QUANTUM COMPUTING

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]*

Entanglement is the key resource for measurement-based quantum computing. It is stored in quantum states known as cluster states, which are prepared offline and enable quantum computing by means of purely local measurements. Universal quantum computing requires cluster states that are both large and possess (at least) a two-dimensional topology. Continuous-variable cluster states—based on bosonic modes rather than qubits—have previously been generated on a scale exceeding one million modes, but only in one dimension. Here, we report generation of a large-scale two-dimensional continuous-variable cluster state. Its structure consists of a 5- by 1240-site square lattice that was tailored to our highly scalable time-multiplexed experimental platform. It is compatible with Bosonic error-correcting codes that, with higher squeezing, enable fault-tolerant quantum computation.

5x1240 modes, 2D, (Furusawa 2019)



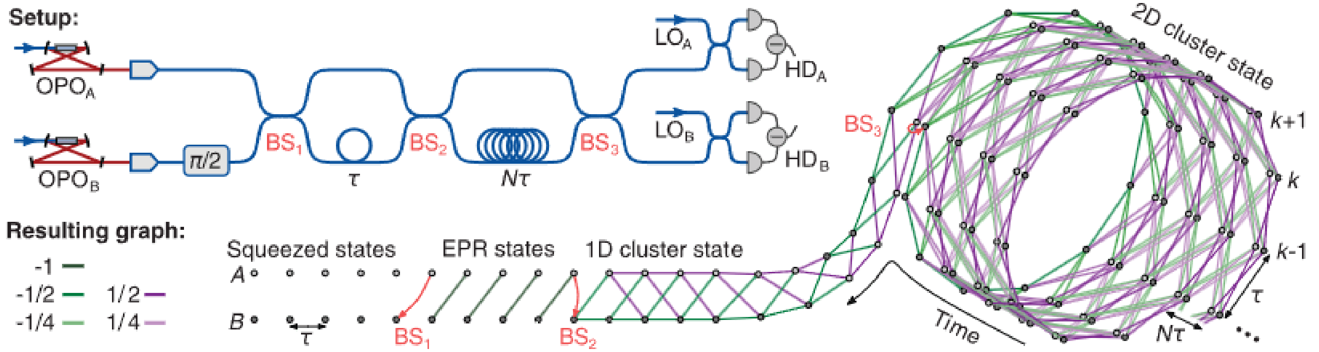
24x1250, 2D (Andersen 2019)

QUANTUM COMPUTING

Deterministic generation of a two-dimensional cluster state

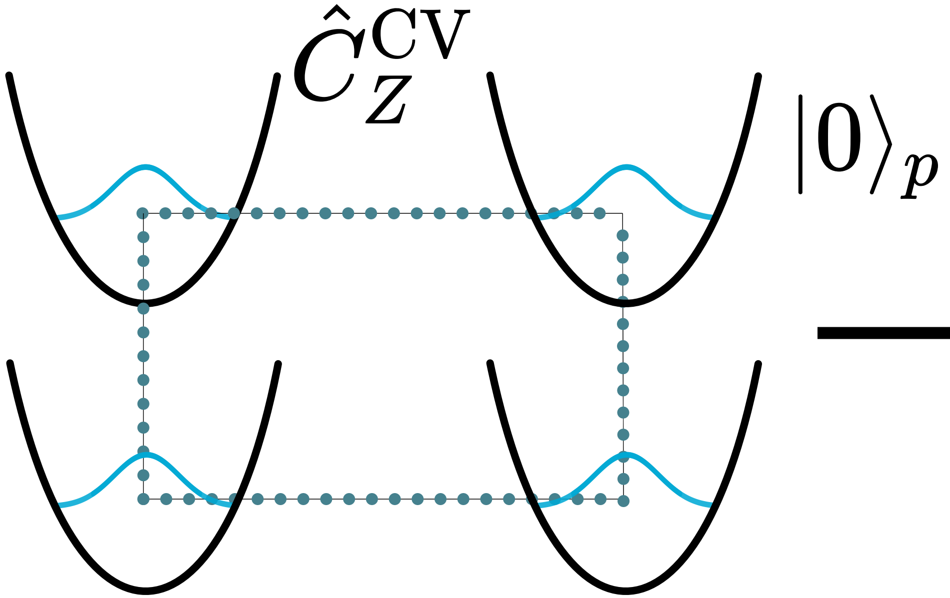
Mikkel V. Larsen*, Xueshi Guo, Casper R. Breum, Jonas S. Neergaard-Nielsen, Ulrik L. Andersen*

Measurement-based quantum computation offers exponential computational speed-up through simple measurements on a large entangled cluster state. We propose and demonstrate a scalable scheme for the generation of photonic cluster states suitable for universal measurement-based quantum computation. We exploit temporal multiplexing of squeezed light modes, delay loops, and beam-splitter transformations to deterministically generate a cylindrical cluster state with a two-dimensional (2D) topological structure as required for universal quantum information processing. The generated state consists of more than 30,000 entangled modes arranged in a cylindrical lattice with 24 modes on the circumference, defining the input register, and a length of 1250 modes, defining the computation depth. Our demonstrated source of two-dimensional cluster states can be combined with quantum error correction to enable fault-tolerant quantum computation.

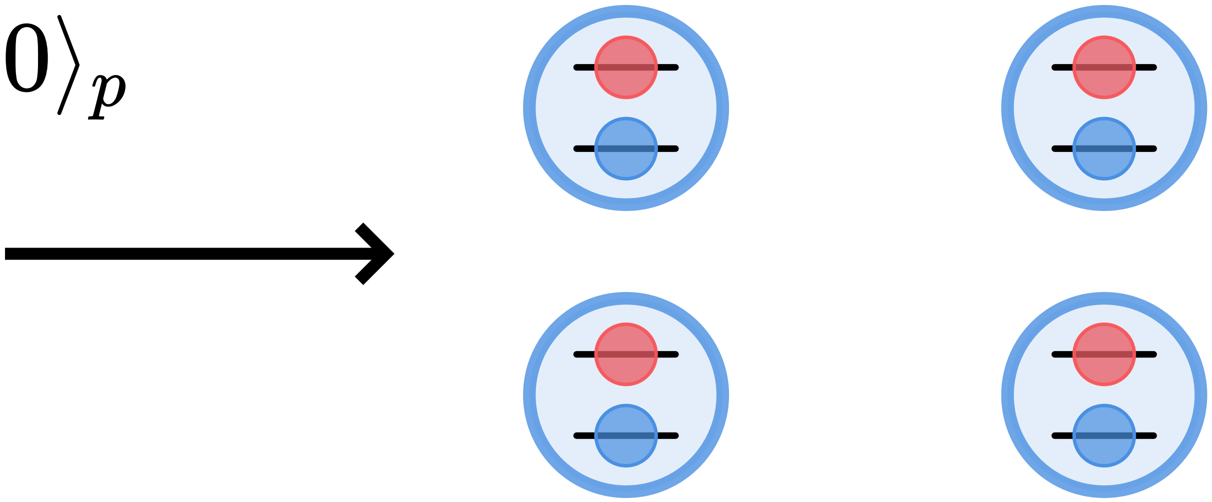


Entanglement transfer protocol

How to perform entanglement transfer?



Continuous variable (CV) cluster state

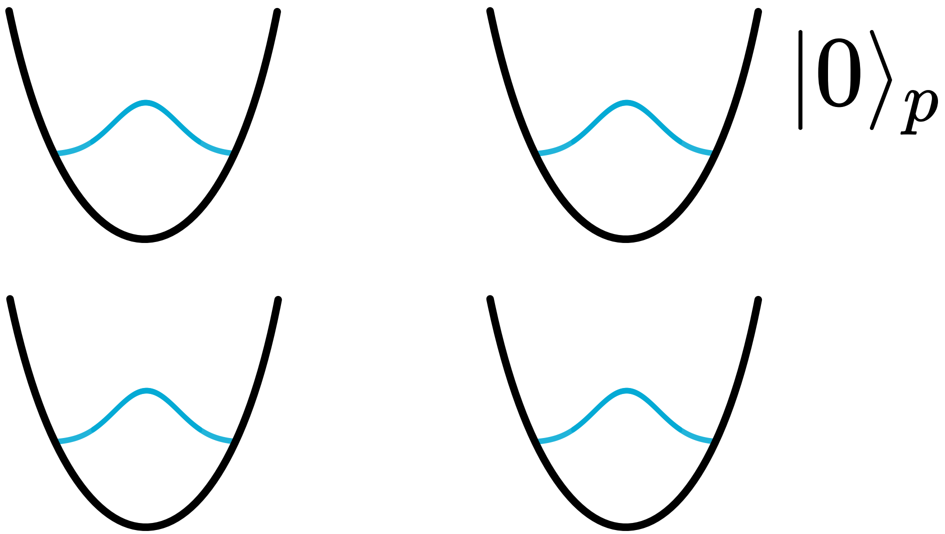


Physical qubits

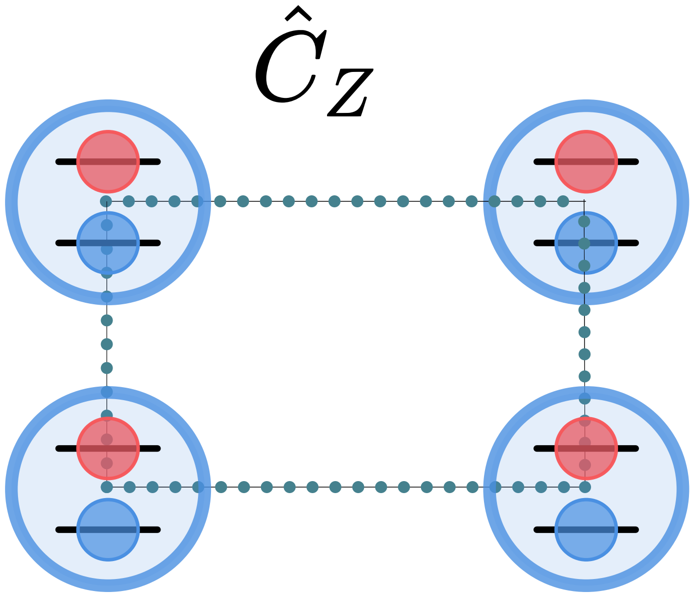
$$\hat{C}_Z^{\mathrm{CV}} = e^{i\hat{q}_1\hat{q}_2}$$

$$\hat{C}_Z = \mathbf{diag}(1, 1, 1, -1)$$

How to perform entanglement transfer?



Continuous variable (CV) cluster state



Qubit cluster state

$$\hat{C}_Z^{\mathrm{CV}} = e^{i\hat{q}_1\hat{q}_2}$$

$$\hat{C}_Z = \mathbf{diag}(1, 1, 1, -1)$$

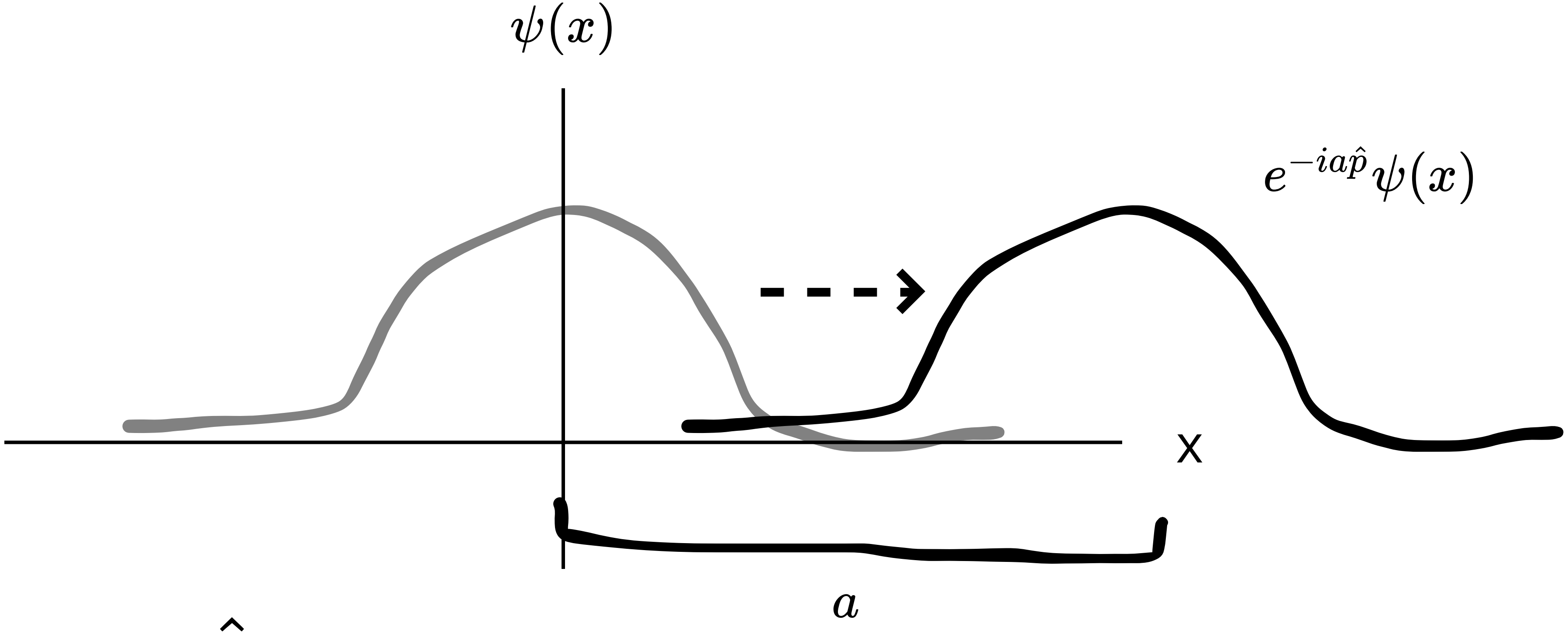
How to perform entanglement transfer?

We need:

- A CV cluster state*
- $\hat{q}$ quadrature homodyne detection
- Conditional displacement gate $\hat{C}_D$

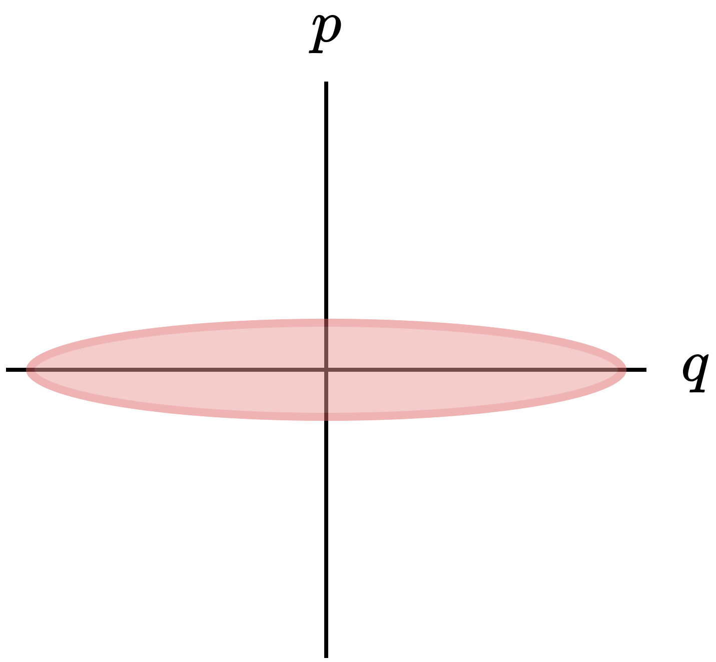
$$\hat{C}_D = |0\rangle\langle 0|\hat{I} + |1\rangle\langle 1|\hat{D}_q(\sqrt{\pi})$$

Displacement gate of strength a shifts the state.



$$\hat{D}_q(a)|x\rangle := |x + a\rangle$$

Displacement gate of strength a shifts the state.



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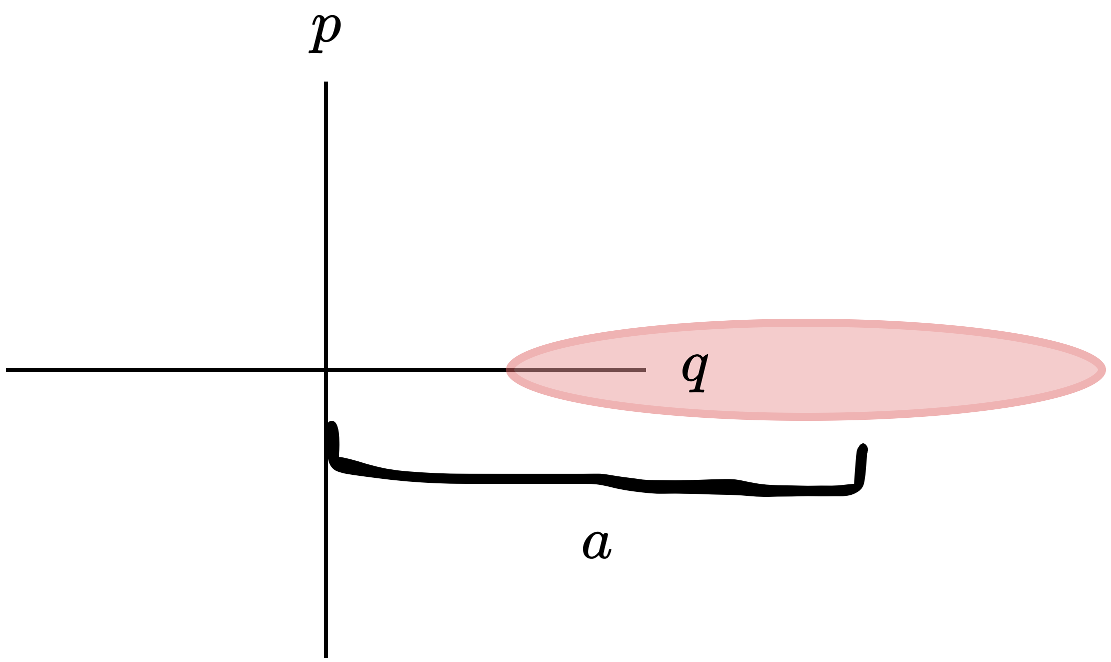
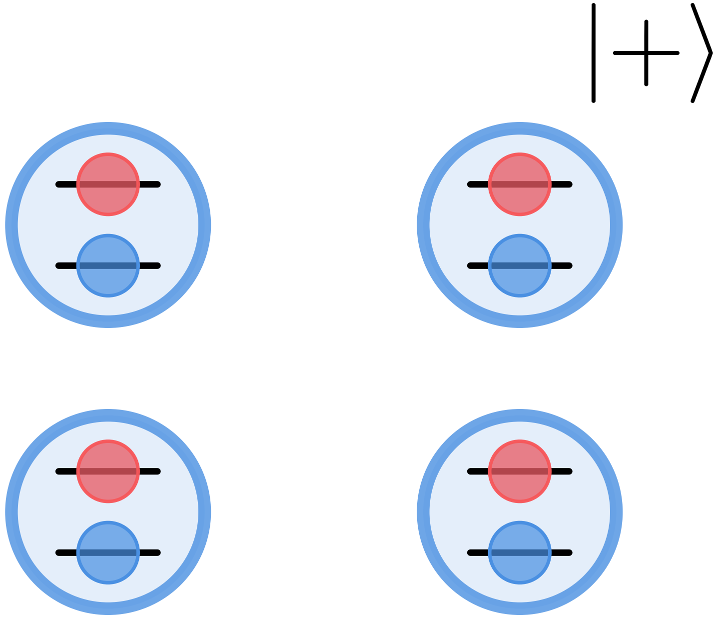
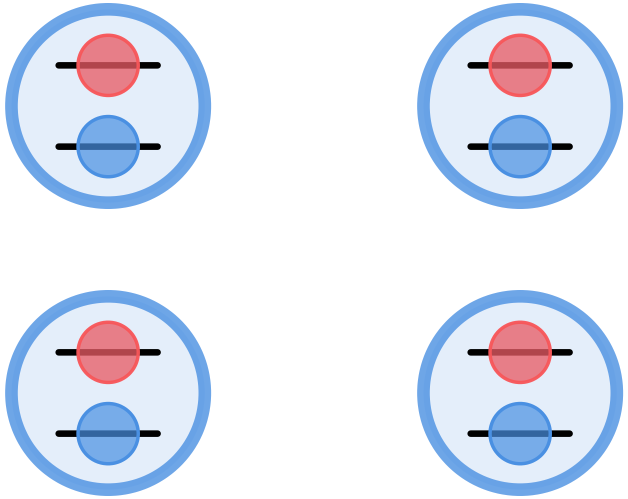


$$\hat{D}_q(a)|x\rangle := |x + a\rangle$$

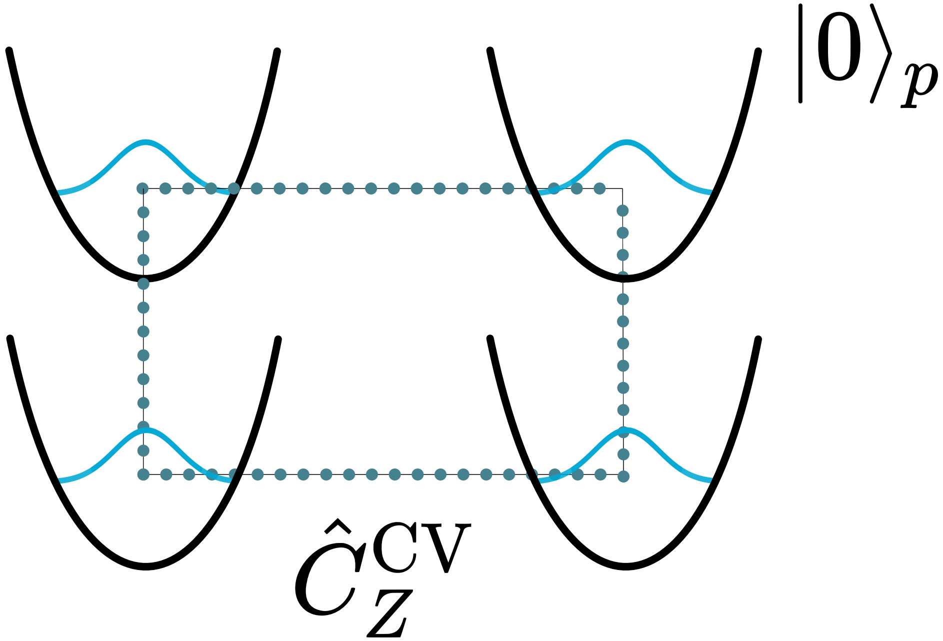
ETP: Overview



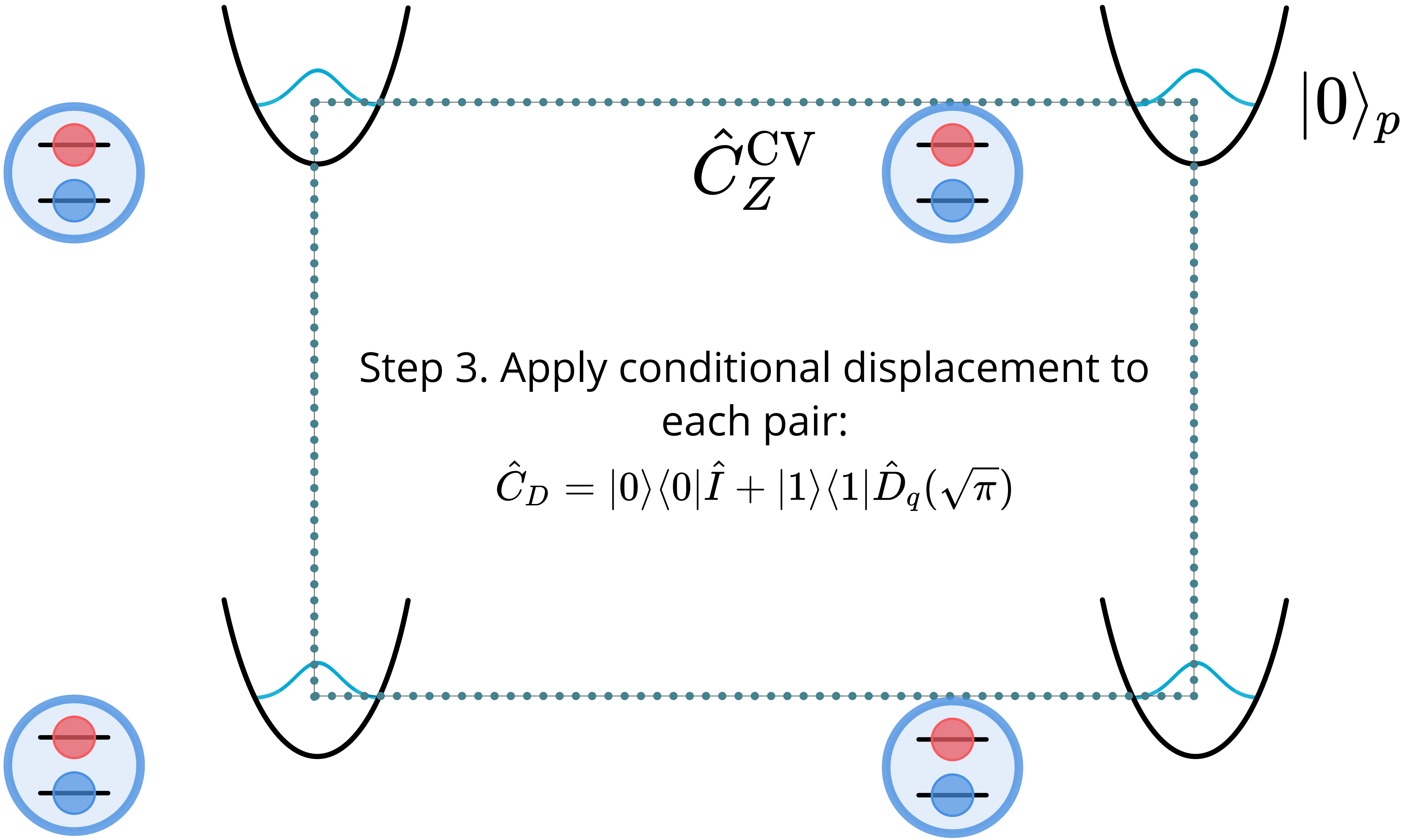
1. Initialize all qubits to $|+\rangle$.



Step 2: Get a CV cluster state.



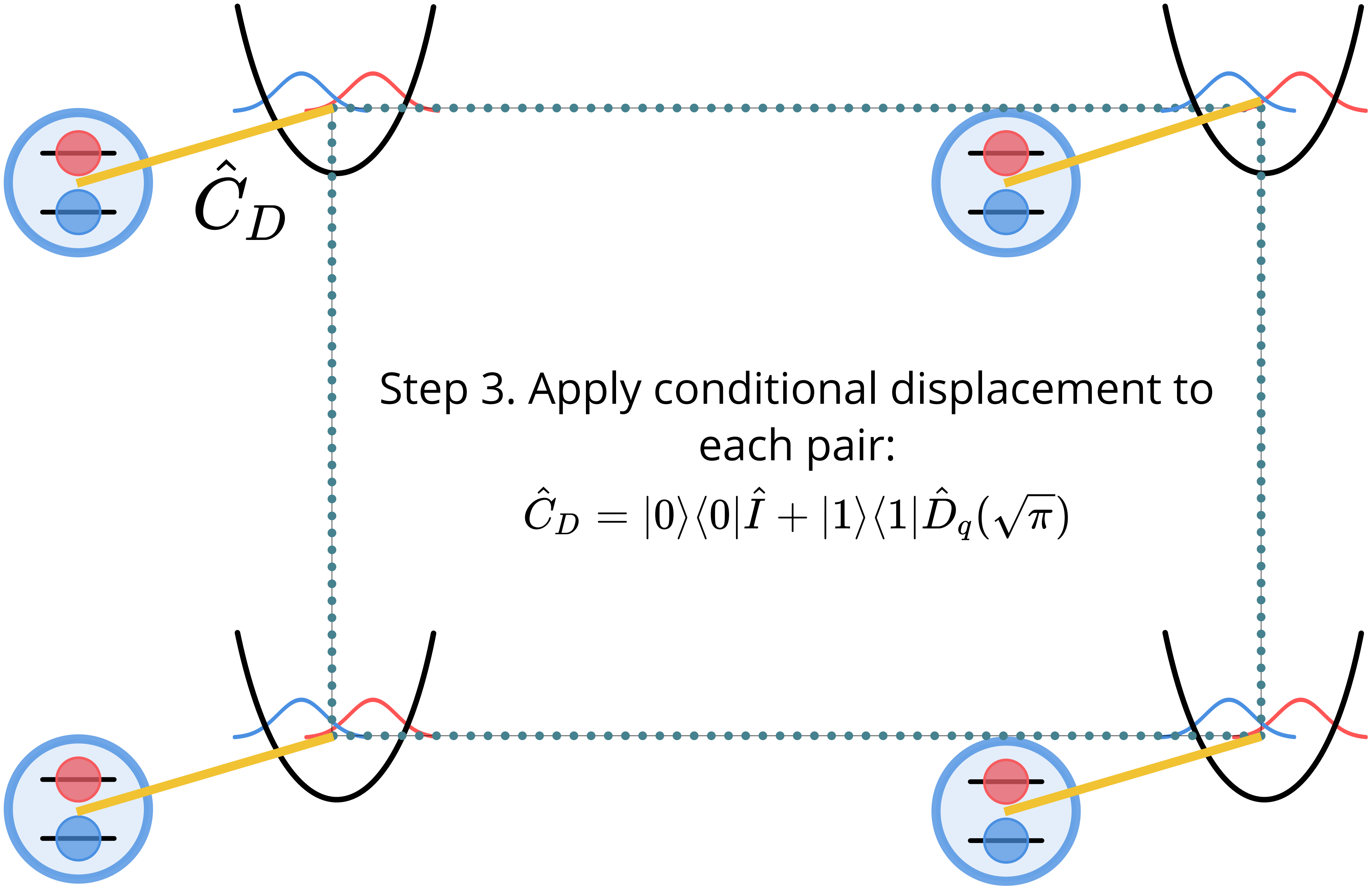
ETP: Overview



Step 3. Apply conditional displacement to each pair:

$$\hat{C}_D = |0\rangle\langle 0|\hat{I} + |1\rangle\langle 1|\hat{D}_q(\sqrt{\pi})$$

ETP: Overview



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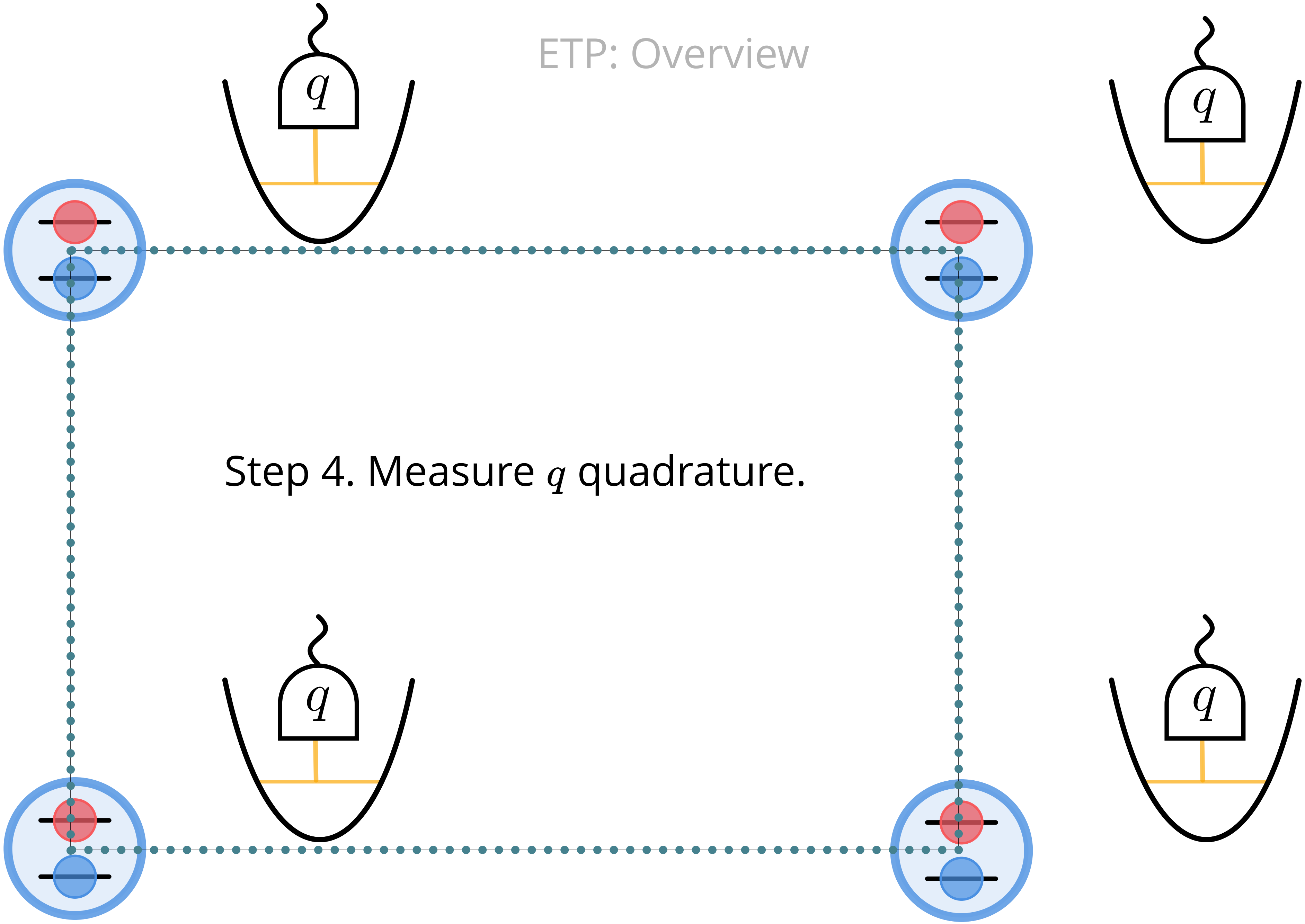
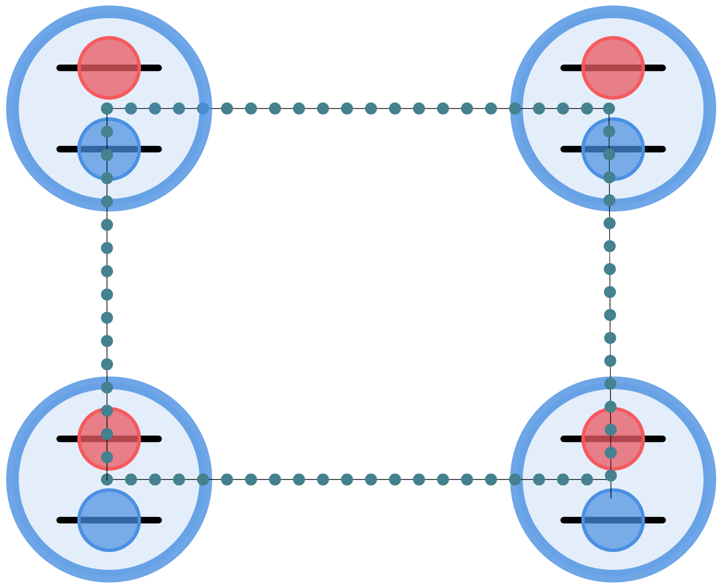

q
q
Step 4. Measure q quadrature.
q
q

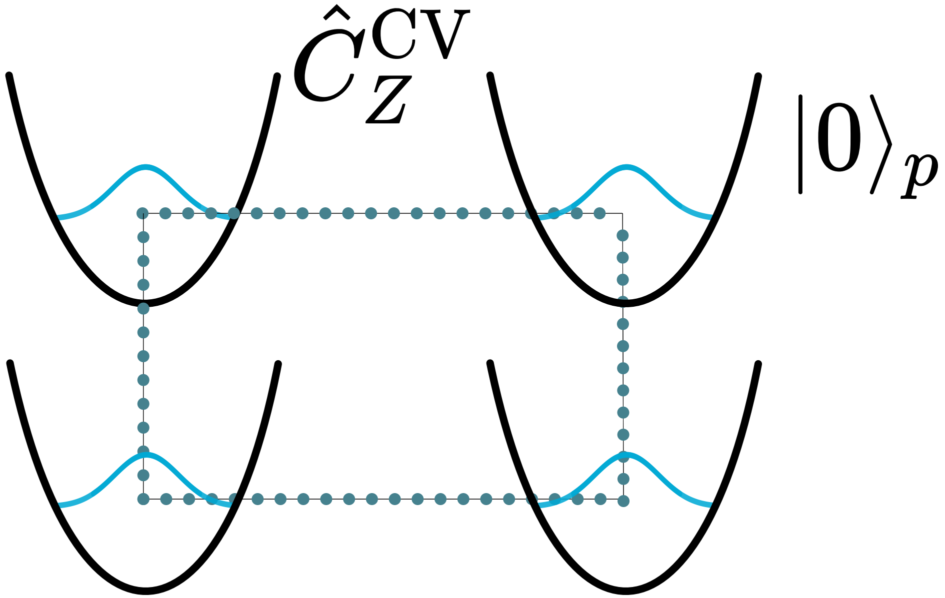
You now have a qubit cluster state!



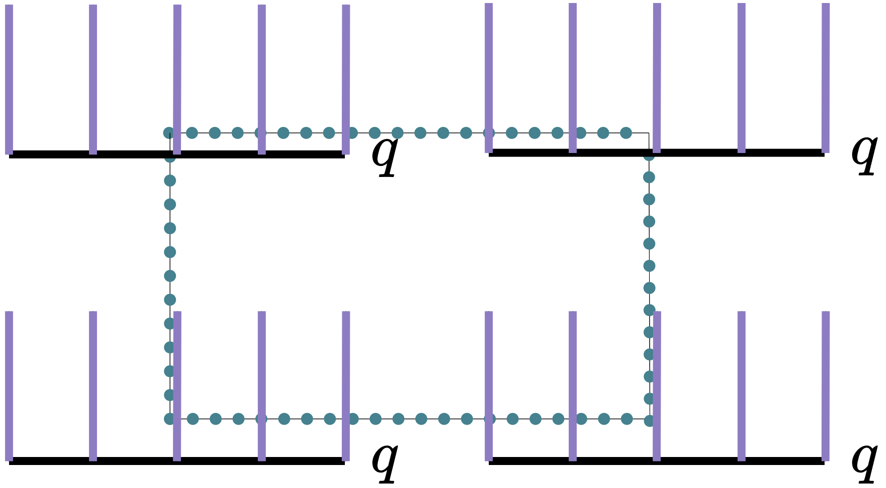
But why does it work?

Qubit cluster inside CV cluster

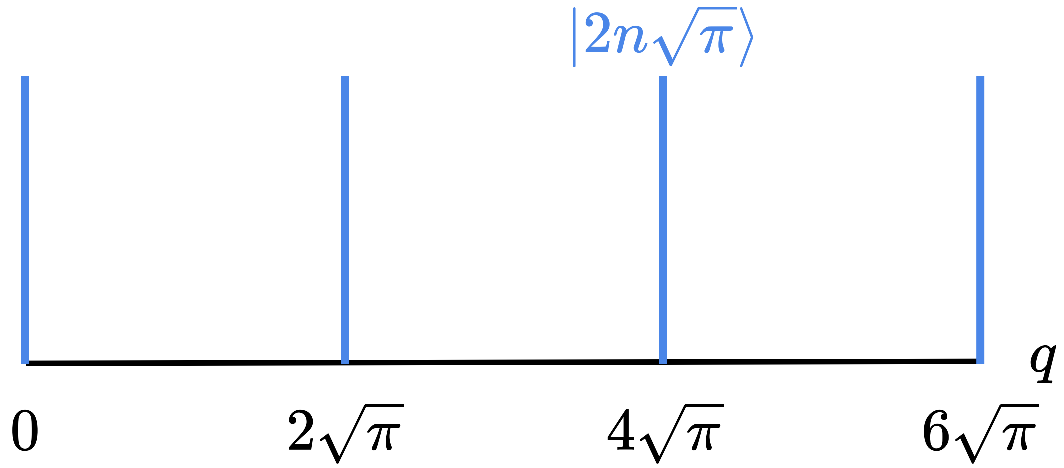
We show there is a hidden qubit cluster state inside a CV cluster state!



CV cluster state



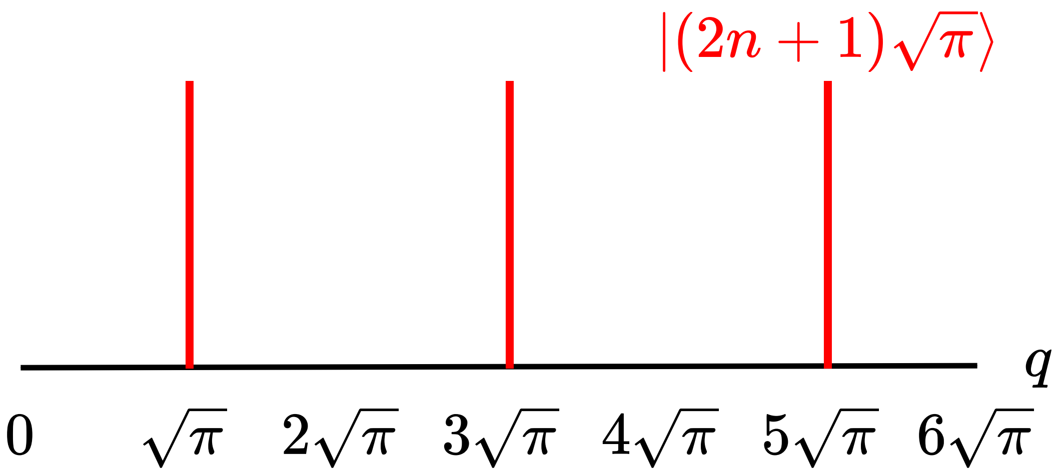
$$|0\rangle_{\text{GKP}} = \sum_{n=-\infty}^{\infty} |2n\sqrt{\pi}\rangle_q$$



Gottesman-Kitaev-Preskill (GKP state)

GKP Background

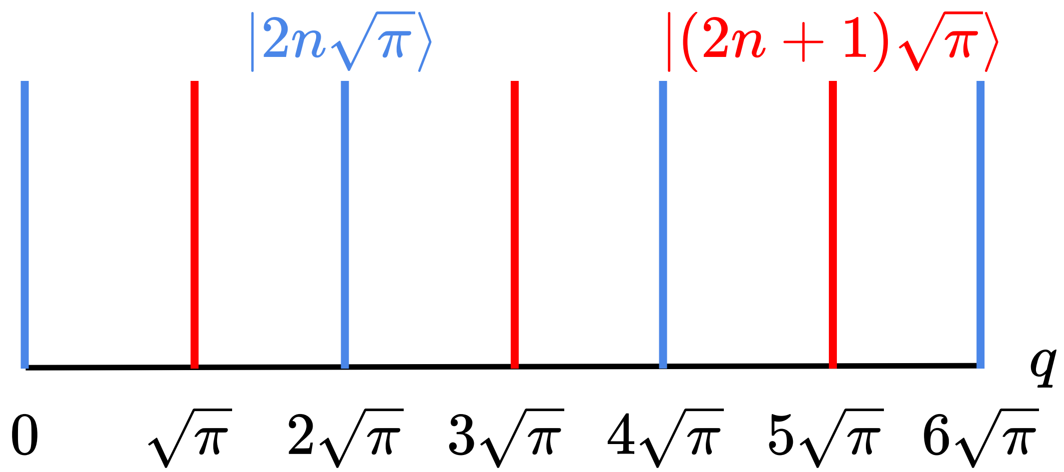
$$|1\rangle_{\text{GKP}} = \sum_{n=-\infty}^{\infty} |(2n+1)\sqrt{\pi}\rangle_q$$



$$\hat{X}^{\text{GKP}} = e^{-i\sqrt{\pi}\hat{p}} = \hat{D}_q(\sqrt{\pi})$$

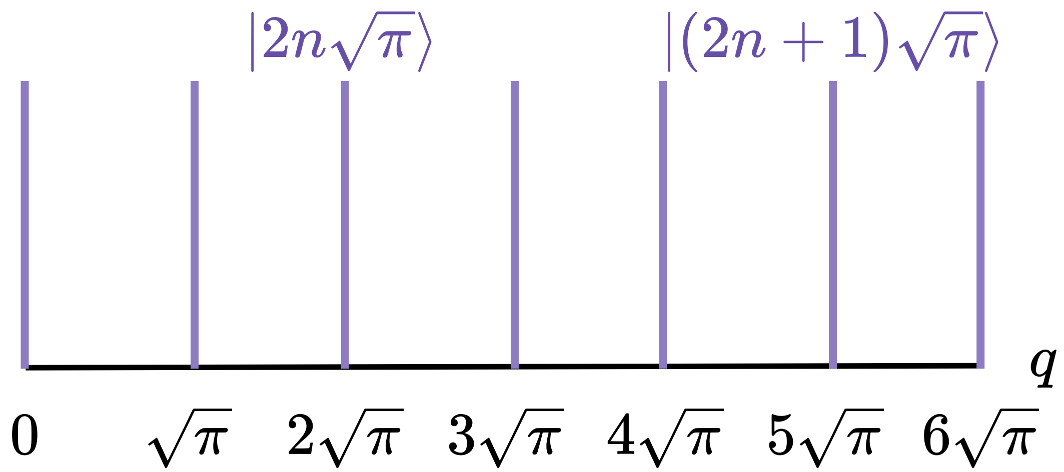
GKP Background

$$|0\rangle_{\text{GKP}} = \sum_{n=-\infty}^{\infty} |2n\sqrt{\pi}\rangle_q$$
$$|1\rangle_{\text{GKP}} = \sum_{n=-\infty}^{\infty} |(2n+1)\sqrt{\pi}\rangle_q$$

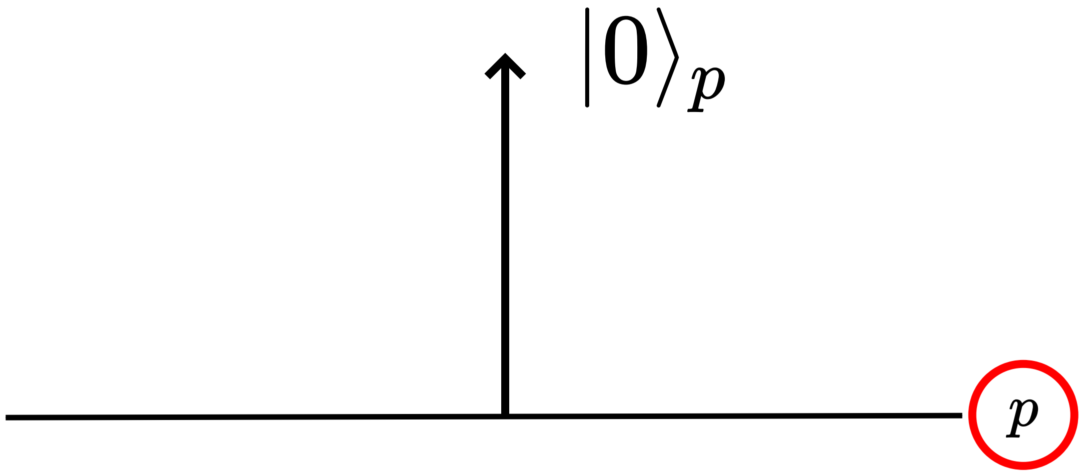


GKP Background

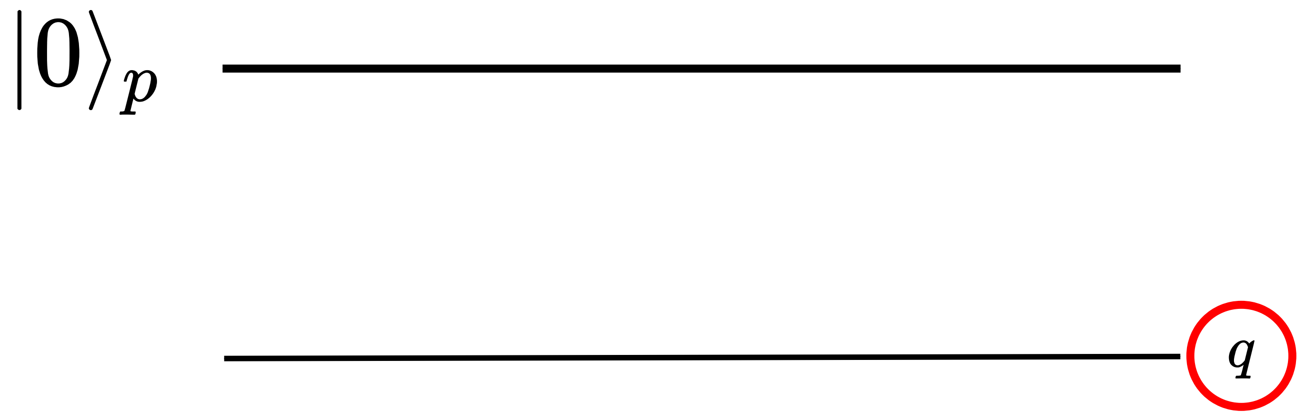
$$|+\rangle_{\mathrm{GKP}} = \sum_{n=-\infty}^{\infty} |n\sqrt{\pi}\rangle_q = \frac{1}{\sqrt{2}}(|0\rangle_{\mathrm{GKP}} + |1\rangle_{\mathrm{GKP}})$$



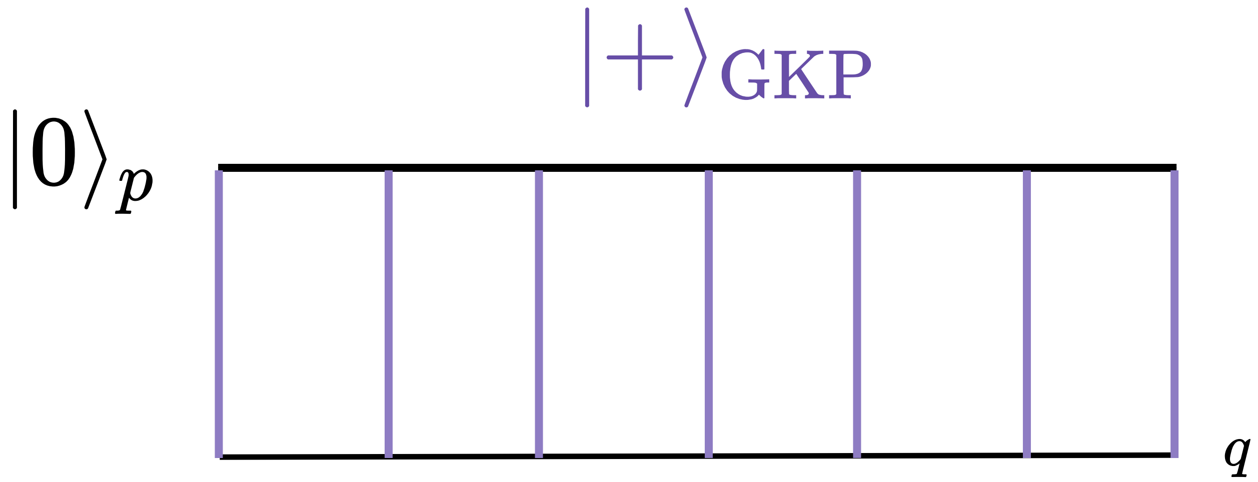
Node of ideal CV cluster



Node of ideal CV cluster



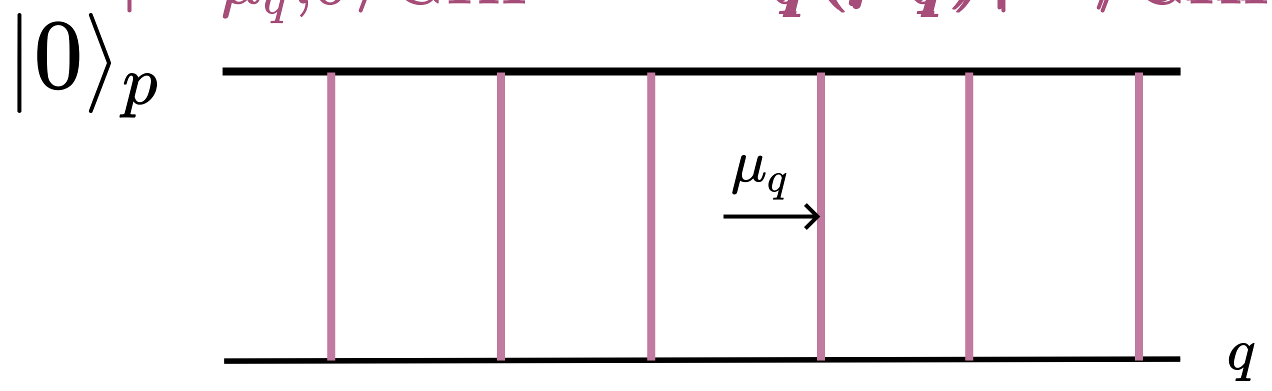
Node of ideal CV cluster



GKP state

Displaced GKP

$$|+_{\mu_q,0}\rangle_{\mathrm{GKP}} \equiv \hat{\boldsymbol{D}}_{\boldsymbol{q}}(\boldsymbol{\mu}_{\boldsymbol{q}})|+\rangle_{\mathbf{GKP}}$$



Displaced GKP state

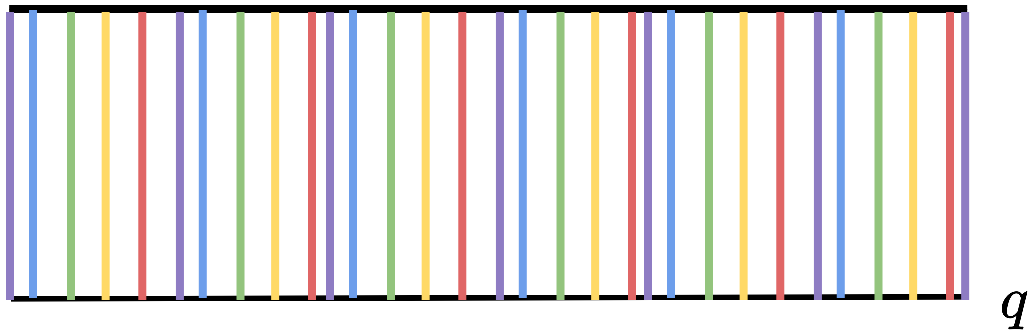
(Glancy 2006)

$$\mu_q \in [-\frac{\sqrt{\pi}}{2}, -\frac{\sqrt{\pi}}{2})$$

Node of ideal CV cluster is superposition of displaced GKP

$$|+_{\mu_q,0}\rangle_{\text{GKP}} \equiv \hat{D}_q(\mu_q)|+\rangle_{\text{GKP}}$$

$|0\rangle_p$

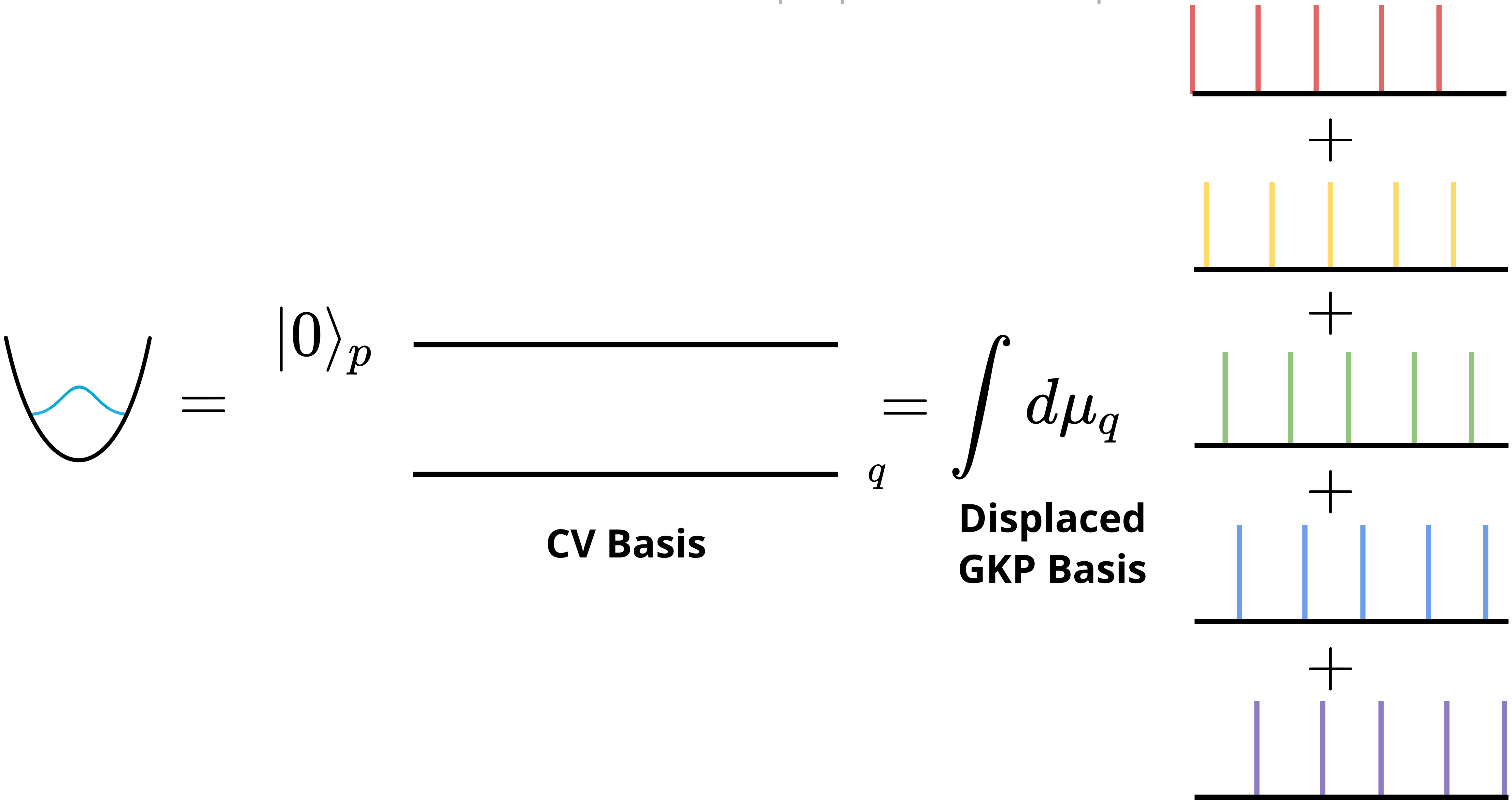


Displaced GKP Basis

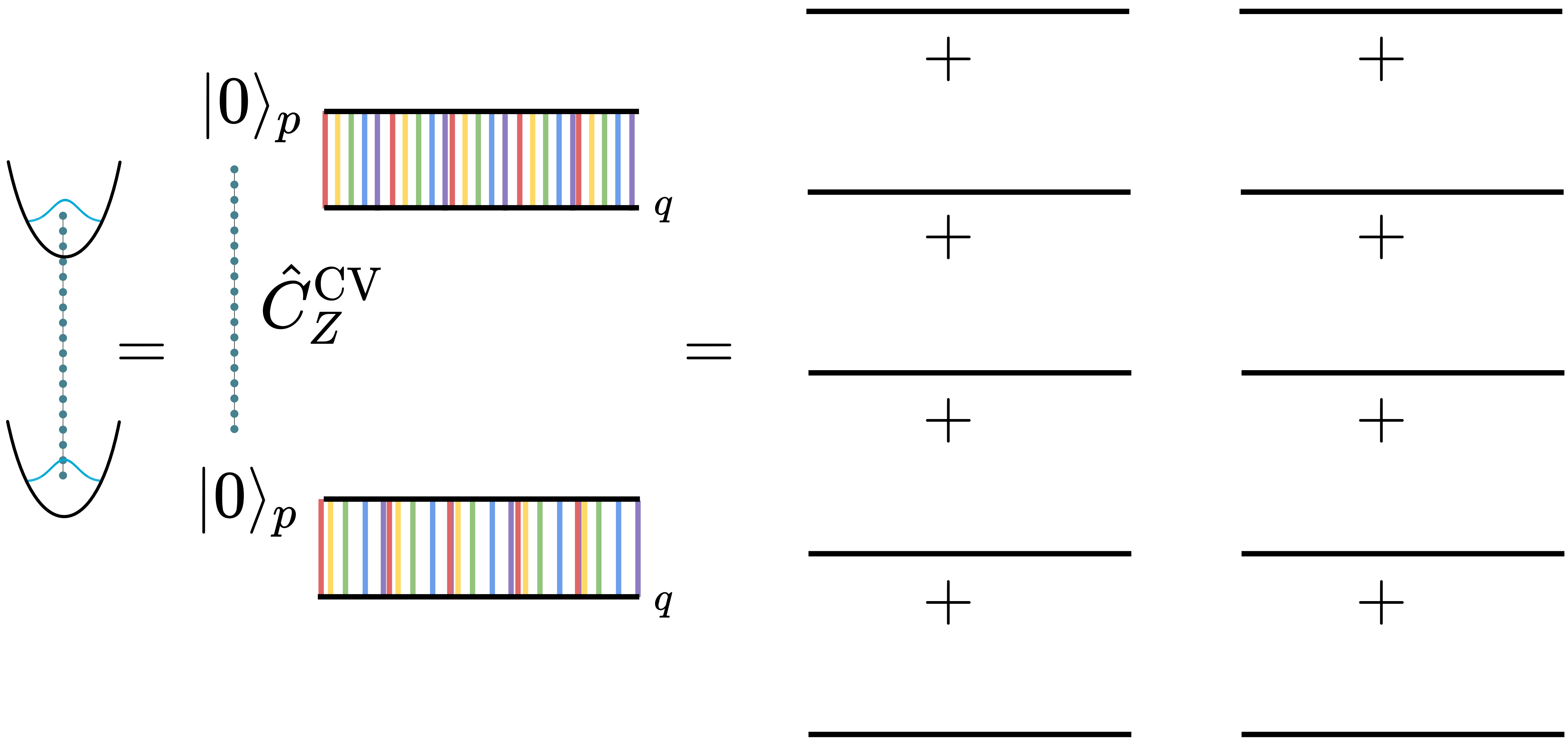
(Glancy 2006)

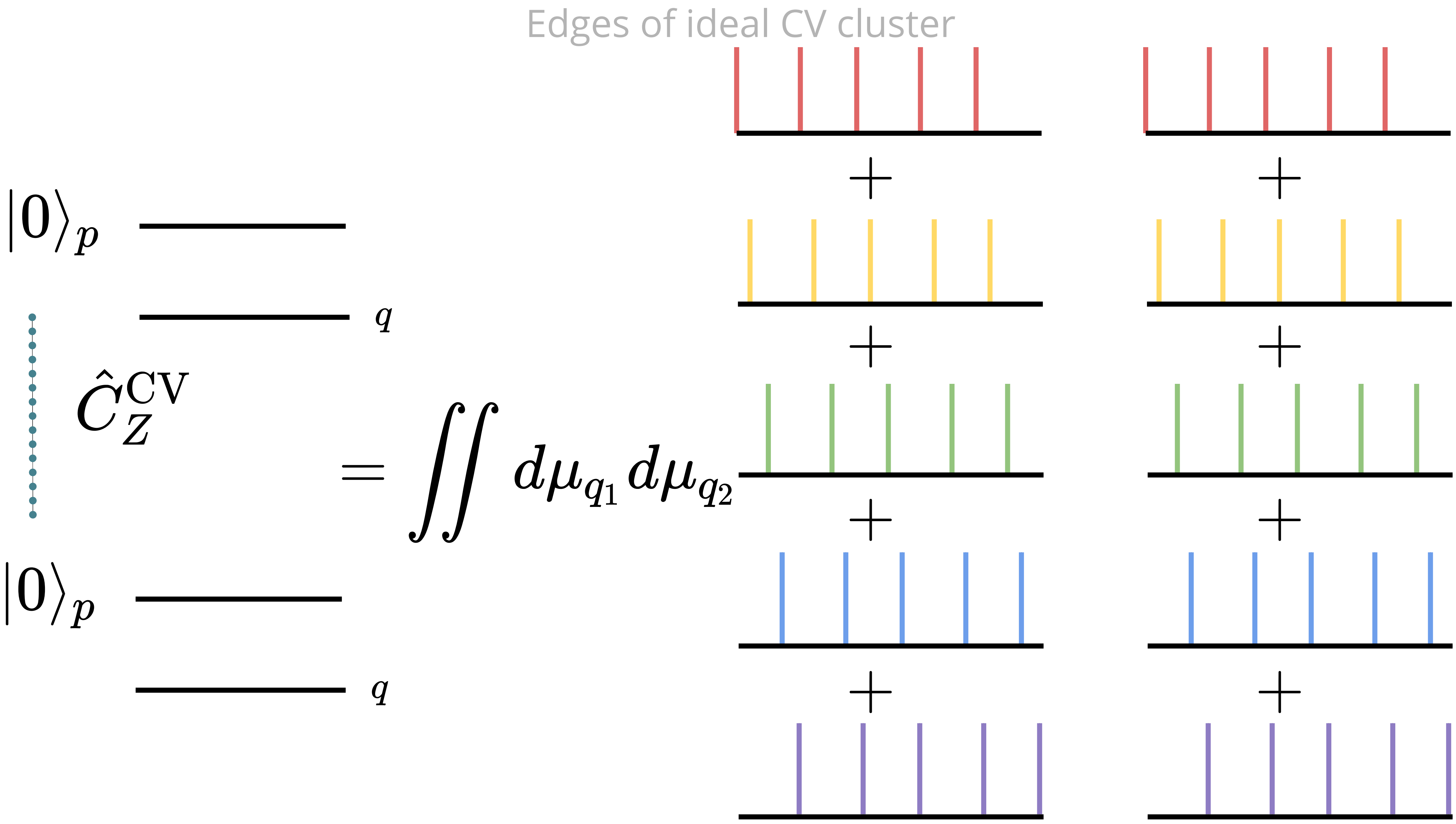
So if we integrate over μ_q, we should form an ideal $|0\rangle_p$ state.

Node of ideal CV cluster is superposition of displaced GKP

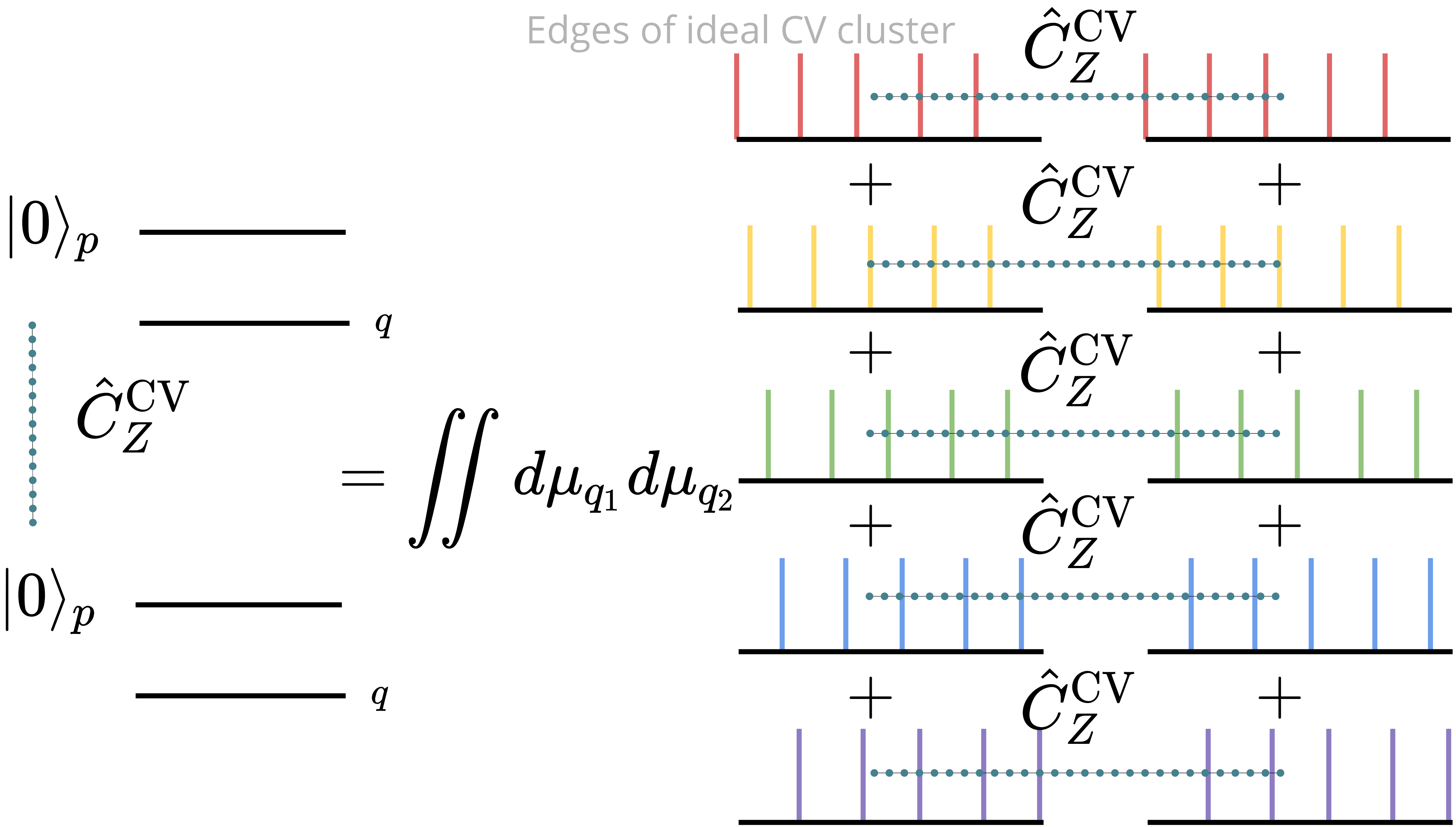


Edges of ideal CV cluster





Edges of ideal CV cluster
$|0\rangle_p$
q
$\hat{C}_Z^{\mathrm{CV}}$
$|0\rangle_p$
q
$= \iint d\mu_{q_1} d\mu_{q_2}$
+
+
+
+
+
+
+
+



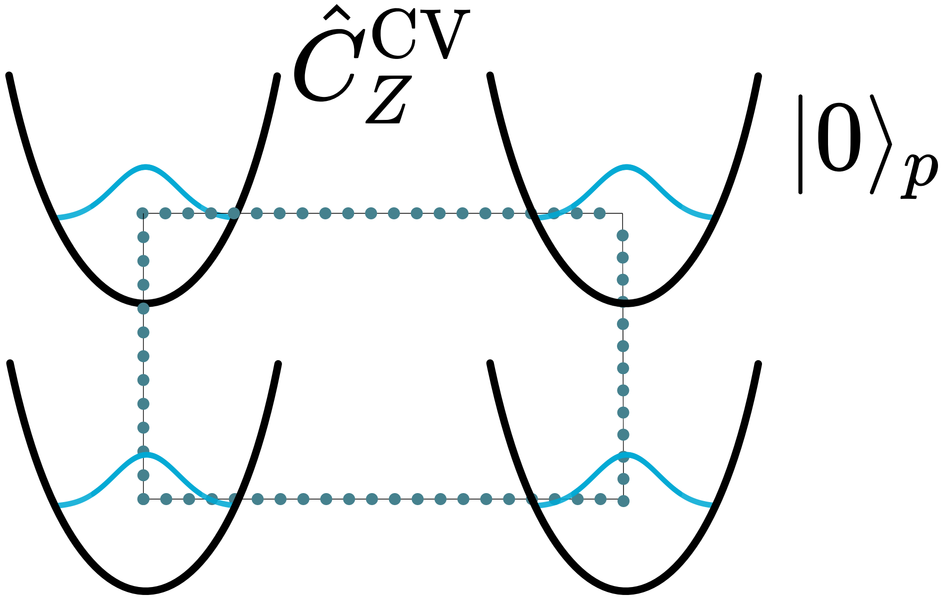
Edges of ideal CV cluster
$|0\rangle_p$
q
$\hat{C}_Z^{\mathrm{CV}}$
$|0\rangle_p$
q
$= \iint d\mu_{q_1} d\mu_{q_2}$
$\hat{C}_Z^{\mathrm{CV}}$
$+$
$\hat{C}_Z^{\mathrm{CV}}$
$+$
$+$
$\hat{C}_Z^{\mathrm{CV}}$
$+$
$+$
$\hat{C}_Z^{\mathrm{CV}}$
$+$
$+$
$\hat{C}_Z^{\mathrm{CV}}$
$+$

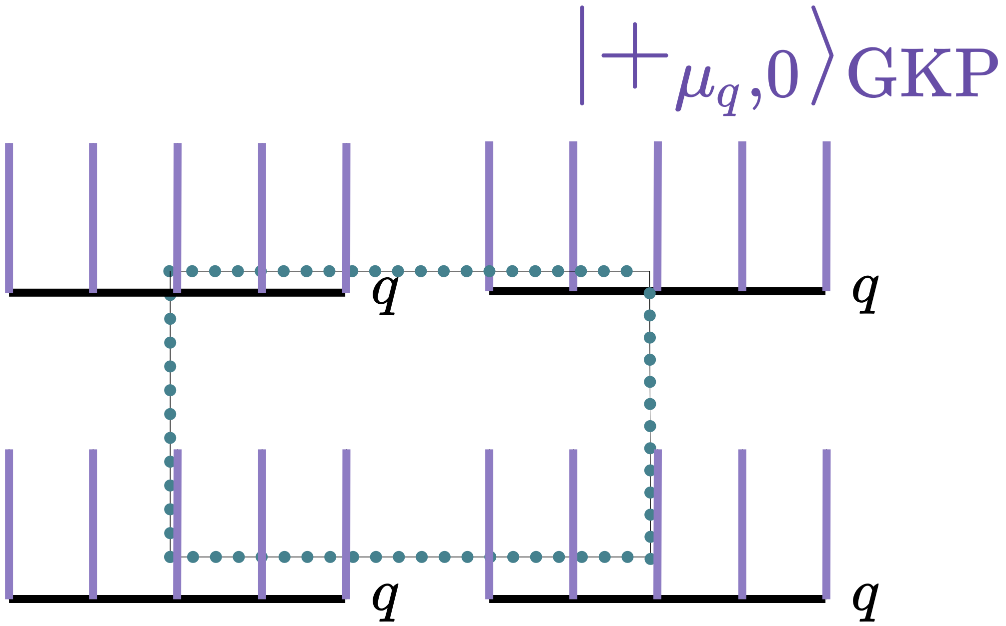
Node of ideal CV cluster is displaced GKP

Nodes of a ideal CV cluster state

is a superposition of

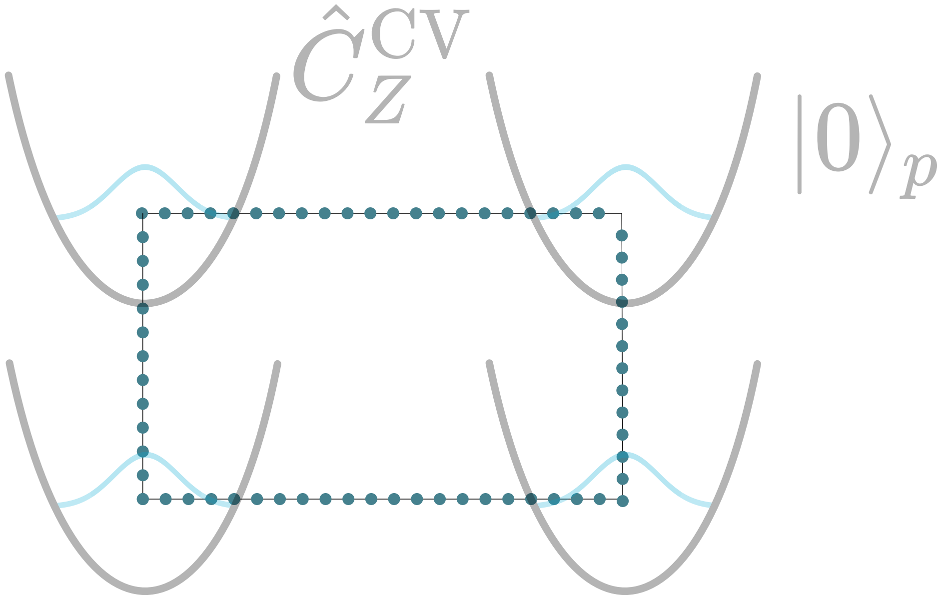
Displaced GKP states



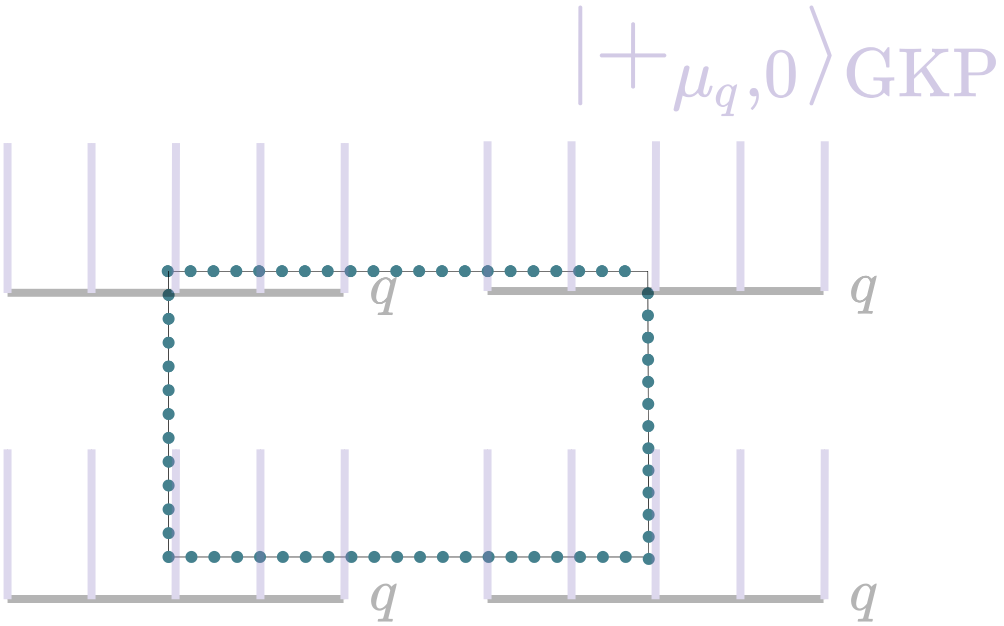


Edge of ideal CV cluster is GKP CZ

The edges of the CV cluster state?



GKP CZ gate



$$\hat{C}_Z^{\mathrm{CV}} = e^{i\hat{q}_1\hat{q}_2}$$

$$|+\rangle_{\mathrm{GKP}} = \sum_{n=-\infty}^{\infty} |n\sqrt{\pi}\rangle_q$$

$$\hat{C}_Z^{\mathrm{CV}} |++\rangle_{\mathrm{GKP}} = ?$$

Substitute definition

$$\hat{C}_Z^{\mathrm{CV}} = e^{i\hat{q}_1\hat{q}_2}$$

$$|+\rangle_{\mathrm{GKP}} = \sum_{n=-\infty}^{\infty} |n\sqrt{\pi}\rangle_q$$

$$e^{i\hat{q}_1\hat{q}_2} \sum_{n_1,n_2} |n_1\sqrt{\pi}\rangle_q |n_2\sqrt{\pi}\rangle_q = ?$$

Apply $\hat{q}$

$$\hat{C}_Z^{\mathrm{CV}} = e^{i\hat{q}_1\hat{q}_2}$$

$$|+\rangle_{\mathrm{GKP}} = \sum_{n=-\infty}^{\infty} |n\sqrt{\pi}\rangle_q$$

$$e^{i\pi n_1 n_2} \sum_{n_1,n_2} |n_1\sqrt{\pi}\rangle_q |n_2\sqrt{\pi}\rangle_q = ?$$

Expand into even and odd sums

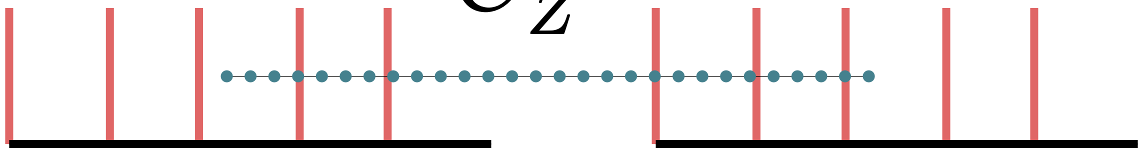
$$e^{i\pi n_1 n_2} \sum_{n_1,n_2} |n_1\sqrt{\pi}\rangle_q |n_2\sqrt{\pi}\rangle_q = ?$$

n_1 or n_2 even $\implies$ $n_1 n_2$ is even

$$\sum_{n_1 \text{ or } n_2 \text{ even}} |n_1\sqrt{\pi}\rangle_q |n_2\sqrt{\pi}\rangle_q = |00\rangle_{\mathrm{GKP}} + |01\rangle_{\mathrm{GKP}} + |10\rangle_{\mathrm{GKP}}$$

Edge of ideal CV cluster is logical CZ

$\hat{C}_Z^{\mathrm{CV}}$



$$\hat{C}_Z^{\mathrm{CV}} \left|++\right\rangle_{\mathrm{GKP}}$$

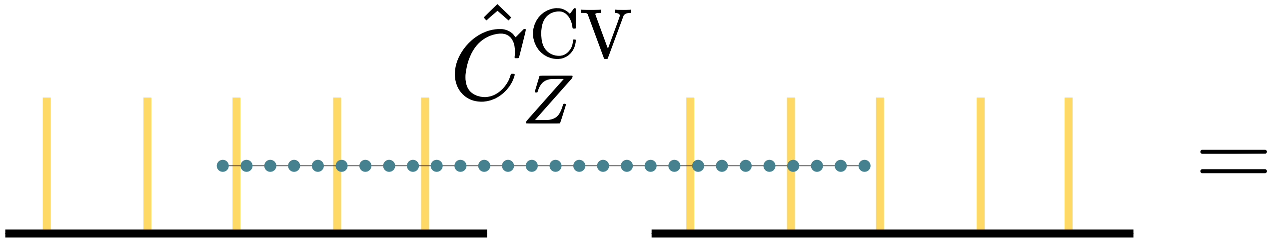
$$= \sum_{n_1,n_2} e^{i\pi n_1 n_2} |n_1\sqrt{\pi}\rangle_q |n_2\sqrt{\pi}\rangle_q$$

$$= \frac{1}{2}\left(|00\rangle_{\mathrm{GKP}} + |01\rangle_{\mathrm{GKP}} + |10\rangle_{\mathrm{GKP}} - |11\rangle_{\mathrm{GKP}}\right)$$

$$\equiv \hat{C}_Z^{\mathrm{GKP}} \left|++\right\rangle_{\mathrm{GKP}}$$

Logical qubit CZ gate on GKP states!

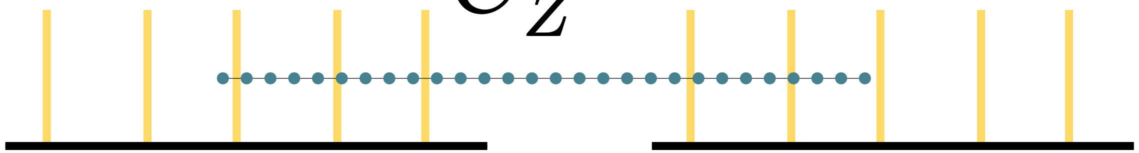
Edge of ideal CV cluster is logical CZ



What about CV CZ on a displaced GKP state?

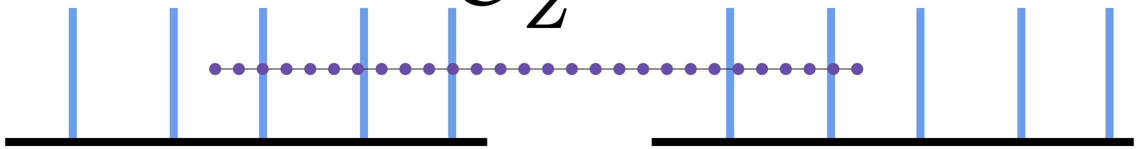
Edge of ideal CV cluster is logical CZ

$$\hat{C}_Z^{\mathrm{CV}}$$



$$\begin{bmatrix} \mu_{q_1} \\ \mu_{q_2} \\ \mu_{p_1} \\ \mu_{p_2} \end{bmatrix} = $$

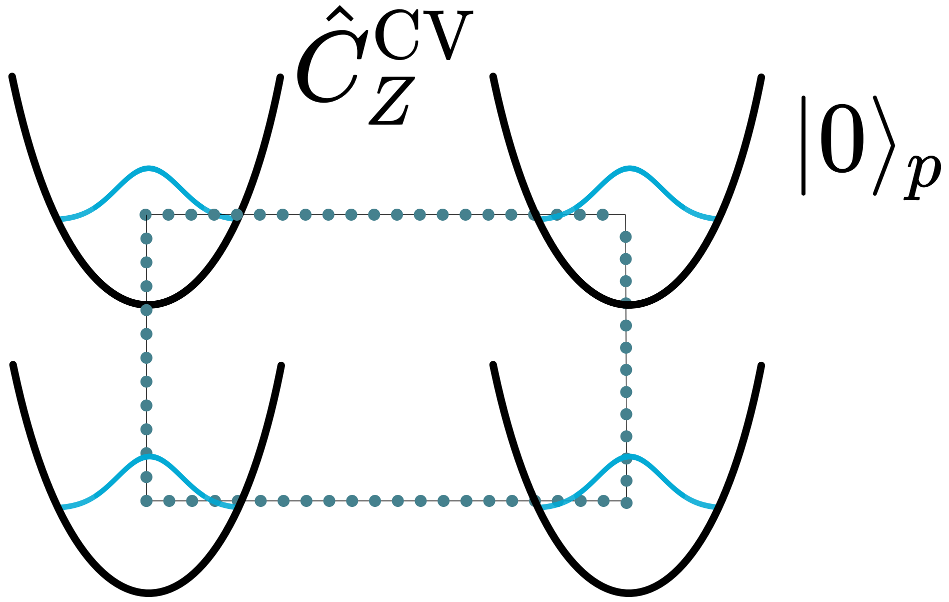
$$\hat{C}_Z^{\mathrm{GKP}}$$



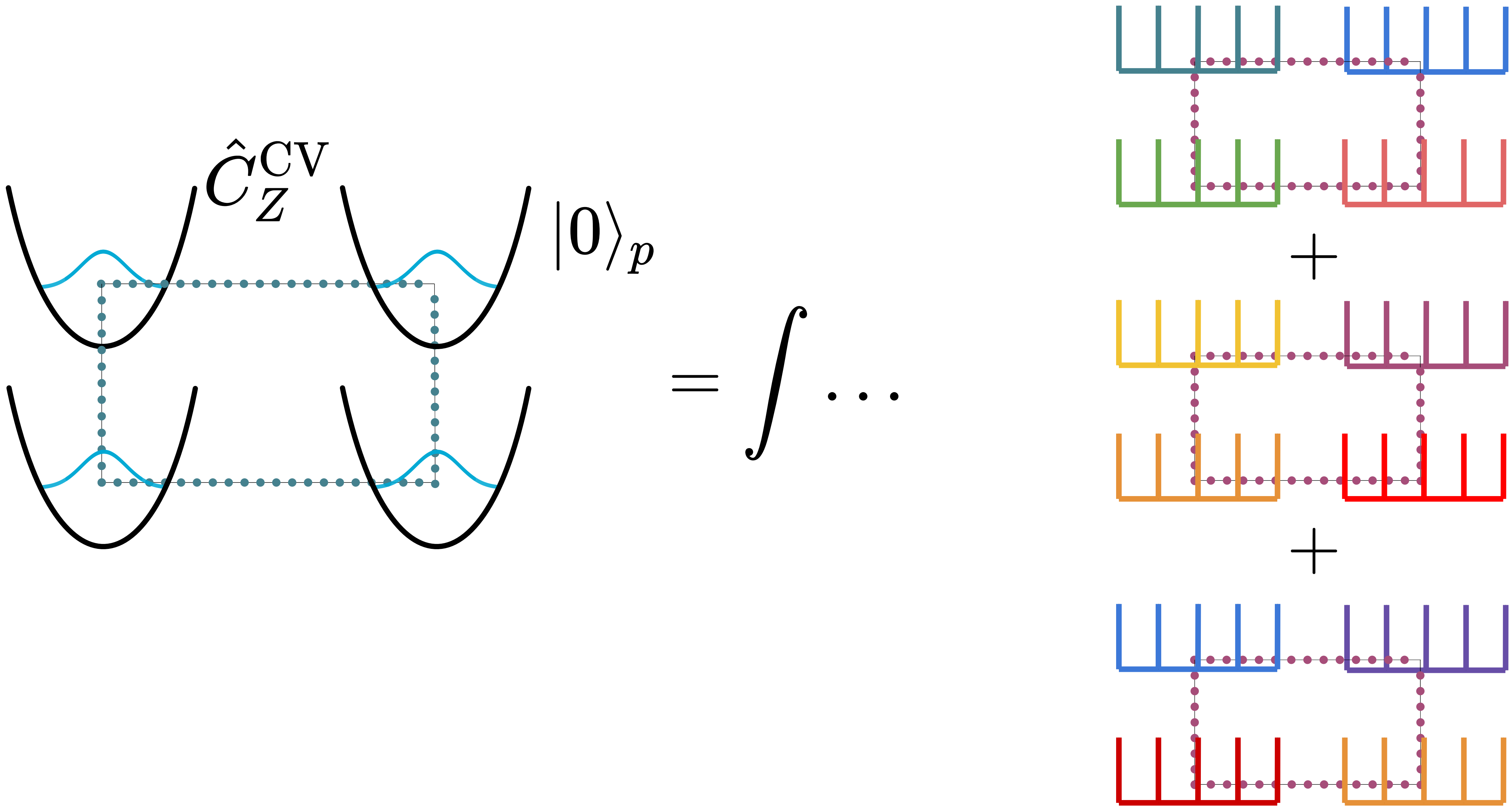
$$\begin{bmatrix} \mu_{q_1} \\ \mu_{q_2} \\ \mu_{p_1} + \mu_{q_2} \\ \mu_{p_2} + \mu_{q_1} \end{bmatrix}$$

CV CZ gate on displaced GKP state = GKP CZ on displaced GKP state.

Displaced GKP cluster inside a CV cluster

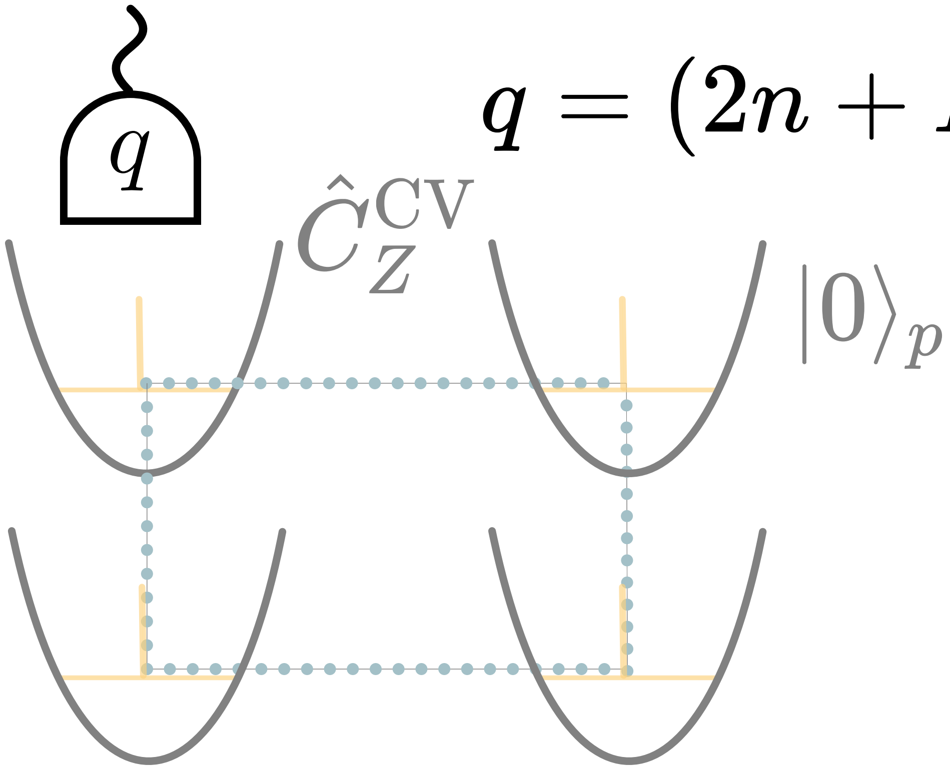


Displaced GKP cluster inside a CV cluster

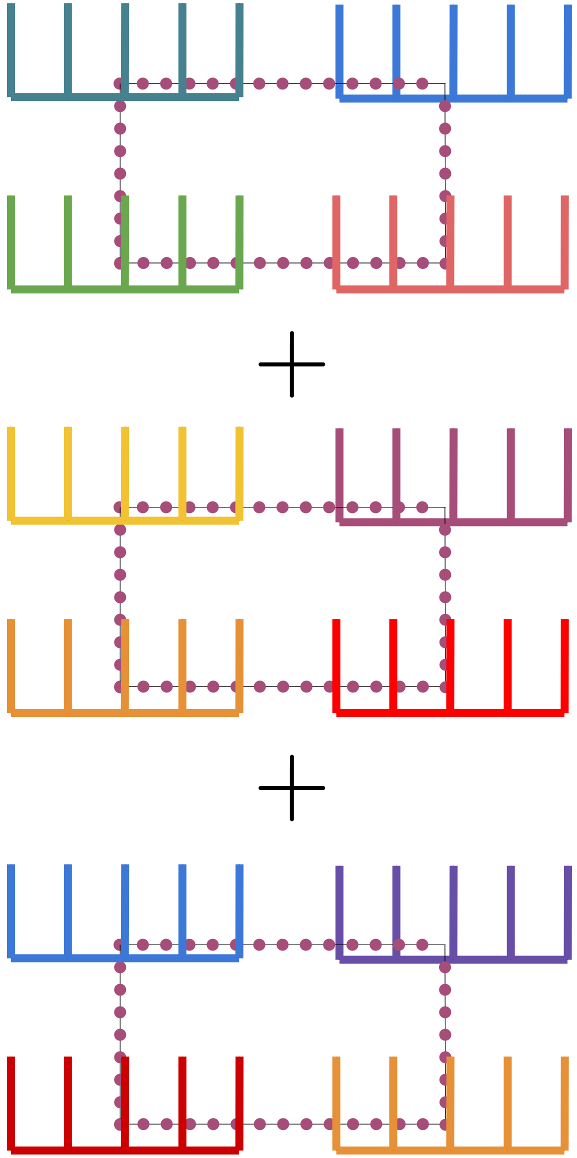


Homodyne detection collapses the GKP cluster

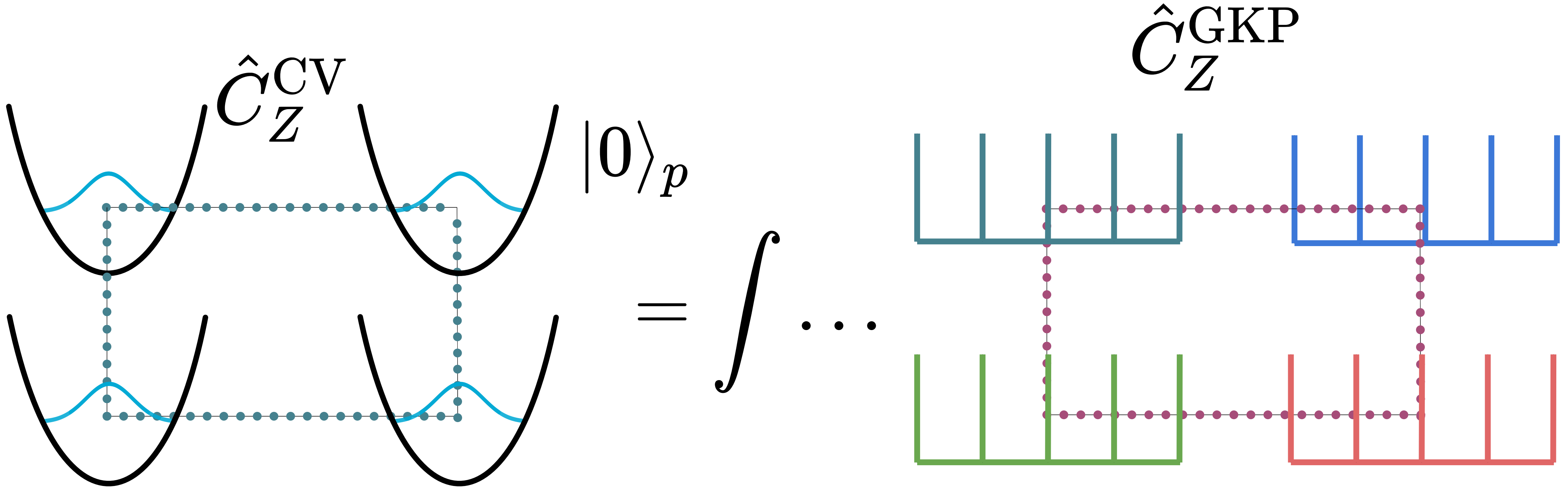
$$q = (2n + L)\sqrt{\pi} + \mu_q$$



$$= \int \ldots$$



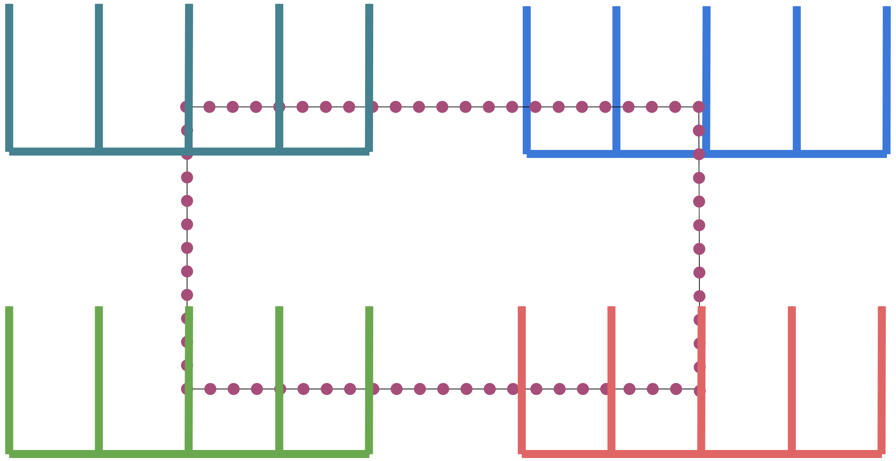
Displaced GKP cluster inside a CV cluster

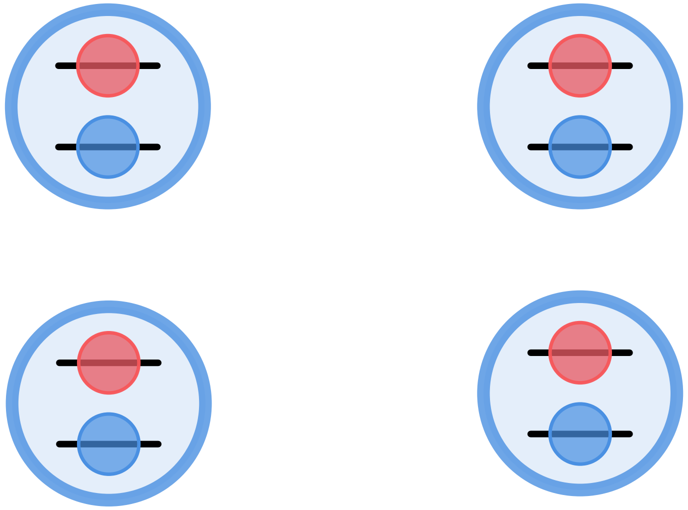


Displaced GKP cluster state inside a CV cluster... How to get the entanglement out?

Displaced GKP cluster to qubit cluster

$\hat{C}_Z^{\mathrm{GKP}}$ $|+_{\mu_q,\mu_p}\rangle_{\mathrm{GKP}}$





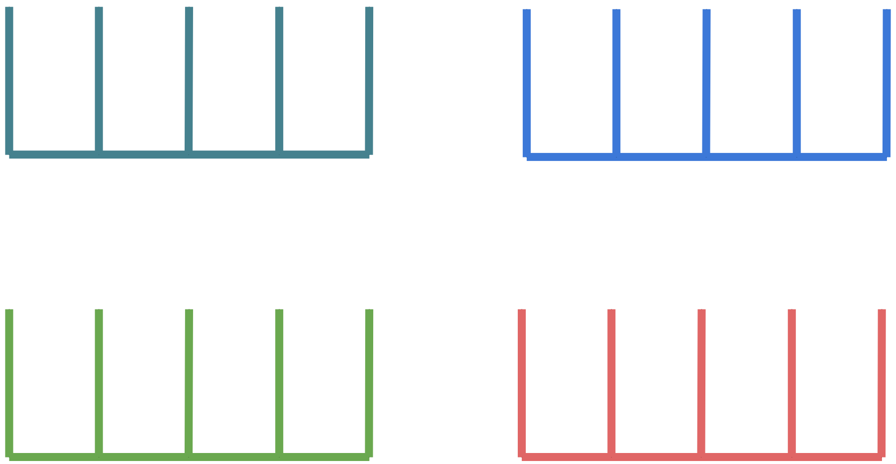
Interpret the GKP cluster as a qubit cluster.

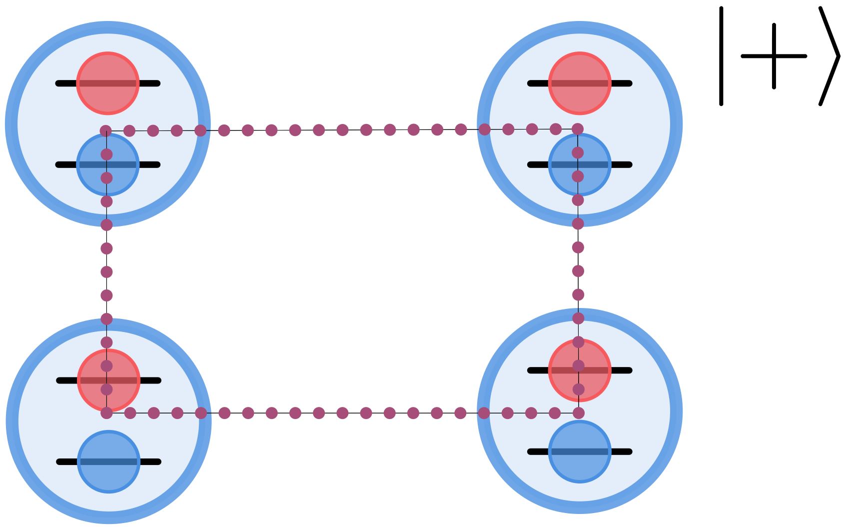
We perform qubit-qubit quantum teleportation.

Displaced GKP cluster to qubit cluster

$$\hat{C}_Z^{\mathrm{GKP}} = \mathrm{diag}(1,1,1,-1)$$

$$\hat{C}_Z = \mathrm{diag}(1,1,1,-1)$$

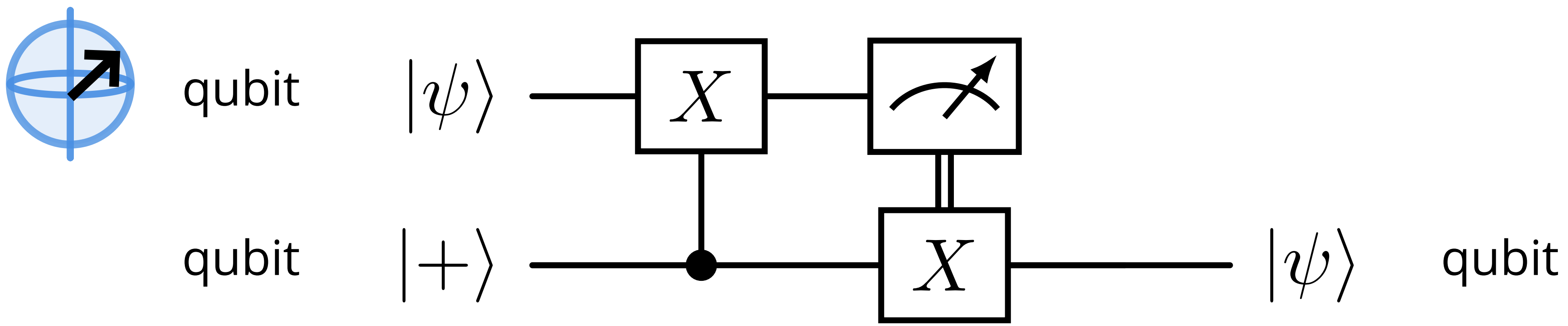




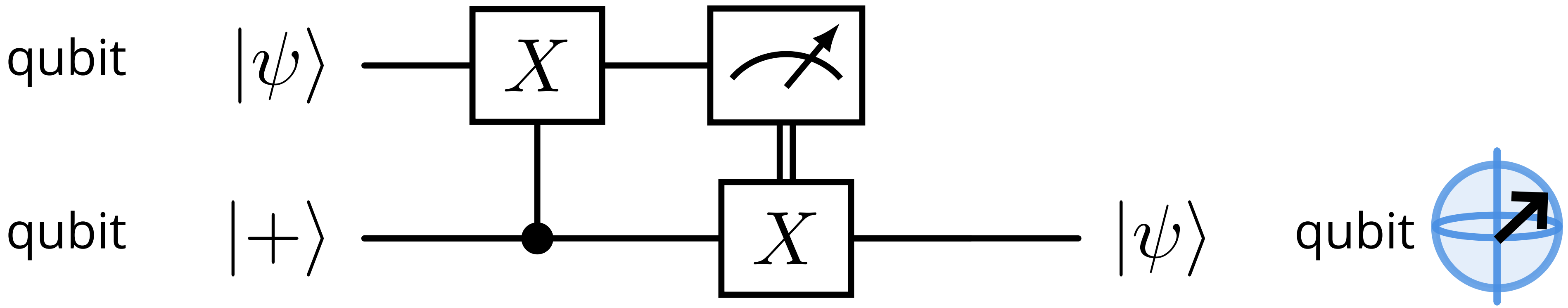
Interpret the GKP cluster as a qubit cluster.

We perform qubit-qubit quantum teleportation.

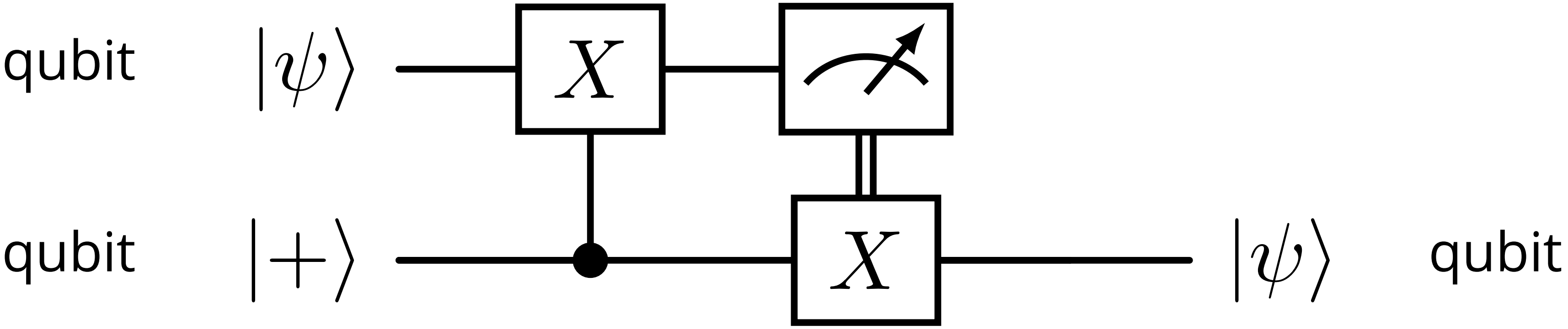
One bit teleportation

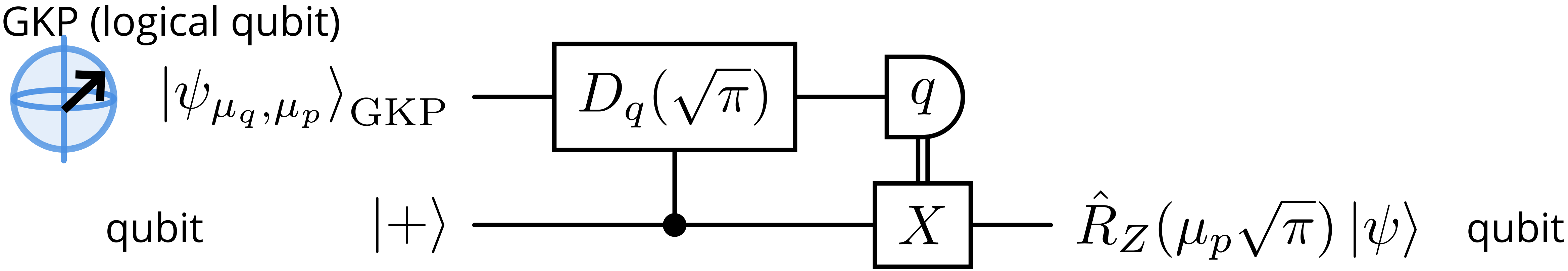


One bit teleportation



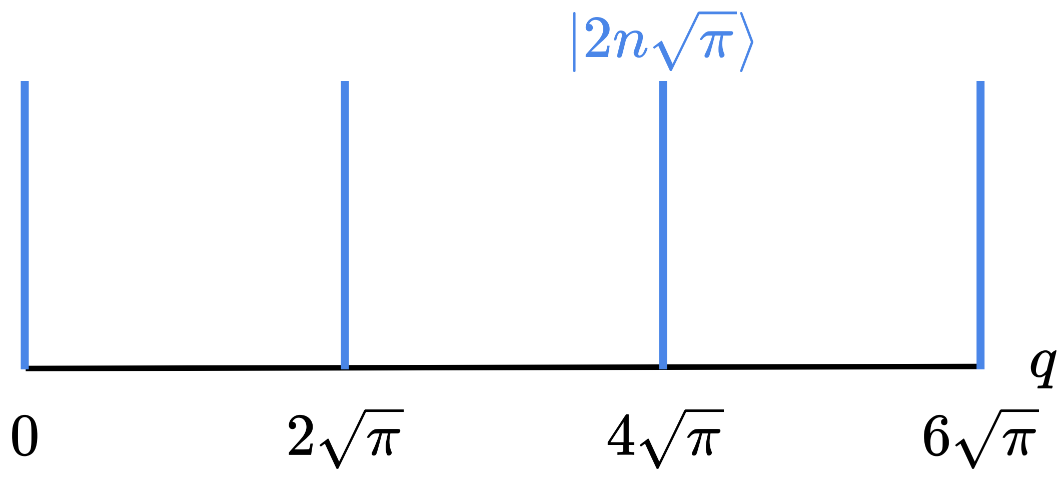
GKP-qubit one bit teleportation

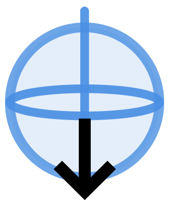




teleportation by products

$$|0\rangle_{\mathrm{GKP}} = \sum_{n=-\infty}^{\infty} |2n\sqrt{\pi}\rangle_q$$

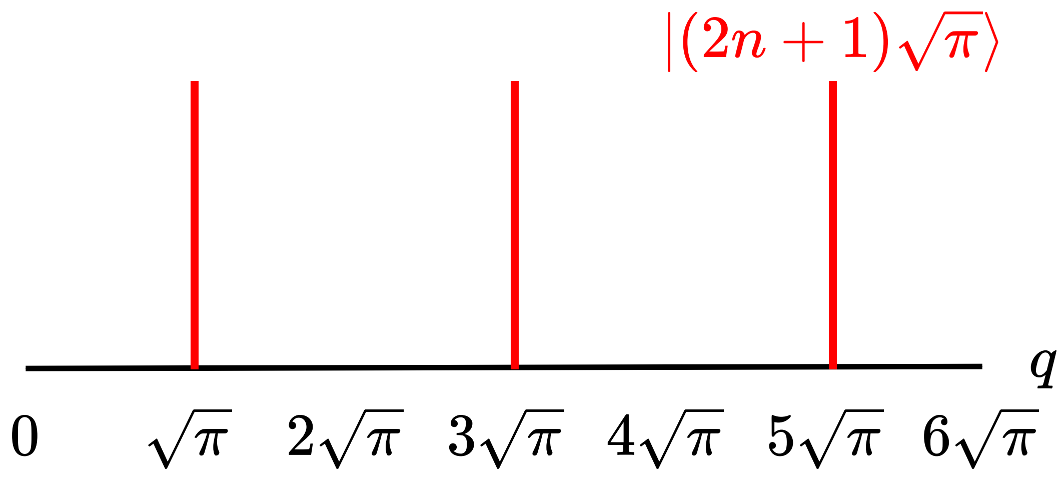


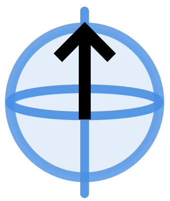


Gottesman-Kitaev-Preskill (GKP state)

GKP-qubit one bit teleportation: X gate

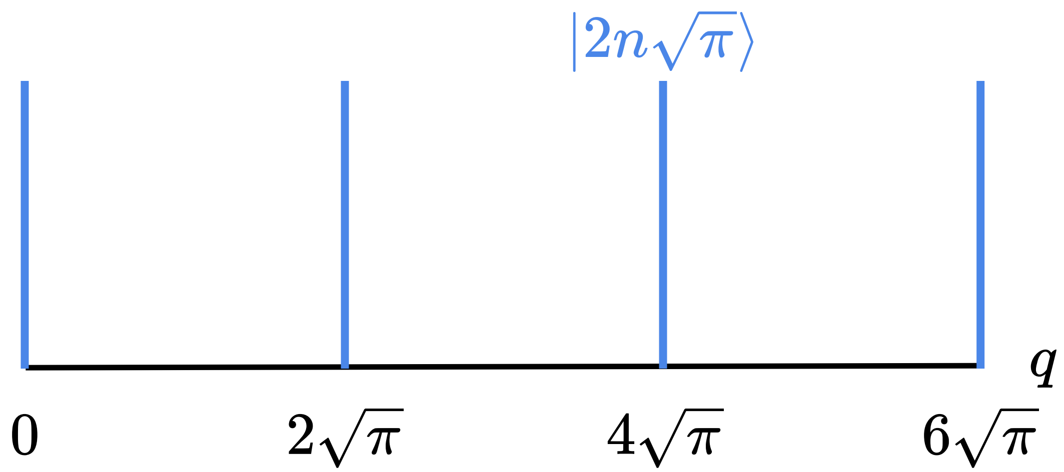
$$|1\rangle_{\text{GKP}} = \sum_{n=-\infty}^{\infty} |(2n+1)\sqrt{\pi}\rangle_q$$

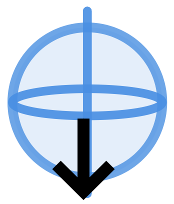




$$\hat{X}^{\text{GKP}} = e^{-i\sqrt{\pi}\hat{p}} = \hat{D}_q(\sqrt{\pi})$$

$$|0\rangle_{\text{GKP}} = \sum_{n=-\infty}^{\infty} |2n\sqrt{\pi}\rangle_q$$

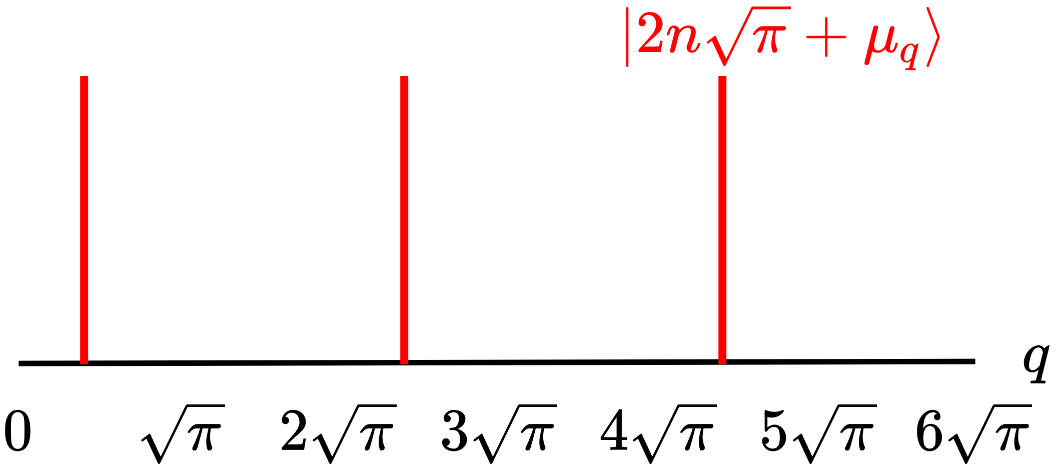


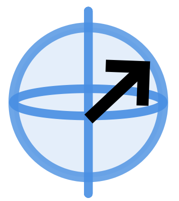


Gottesman-Kitaev-Preskill (GKP state)

μ_q, μ_p as rotational X, Z

$$|1\rangle_{\mathrm{GKP}} = \sum_{n=-\infty}^{\infty} |(2n+1)\sqrt{\pi}\rangle_q$$

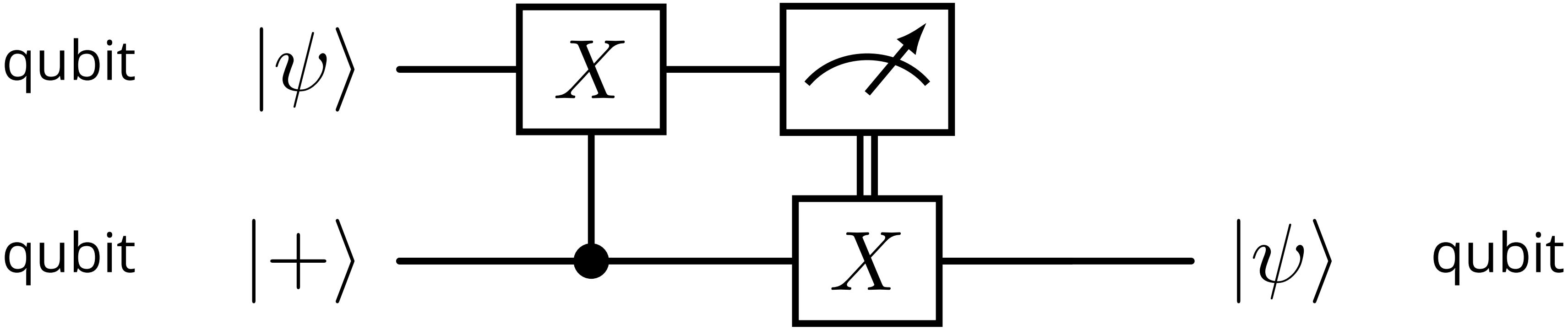


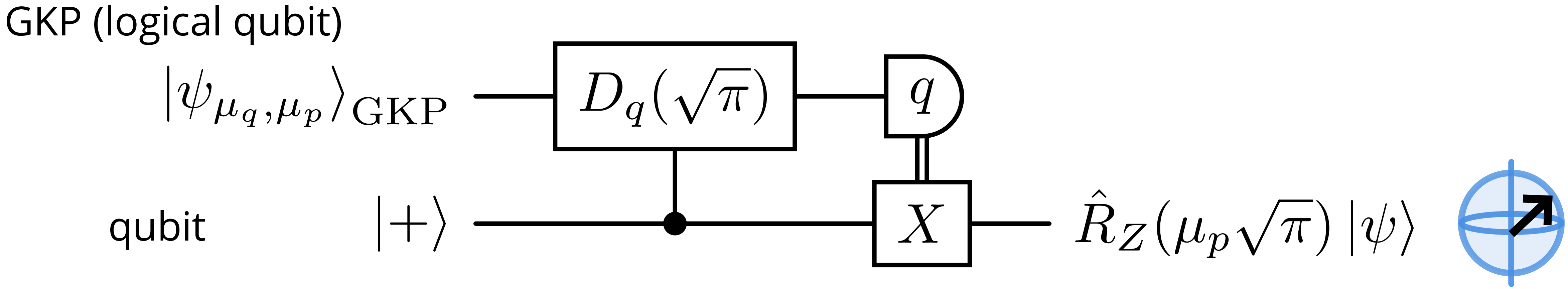


μ_q: Rotational X gate

μ_p: Rotational Z gate

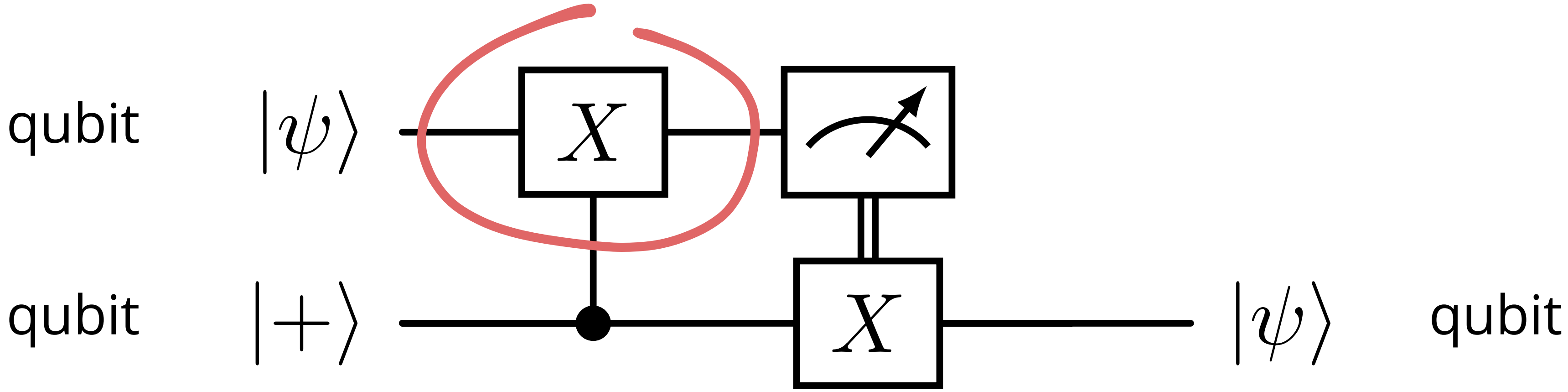
GKP-qubit one bit teleportation

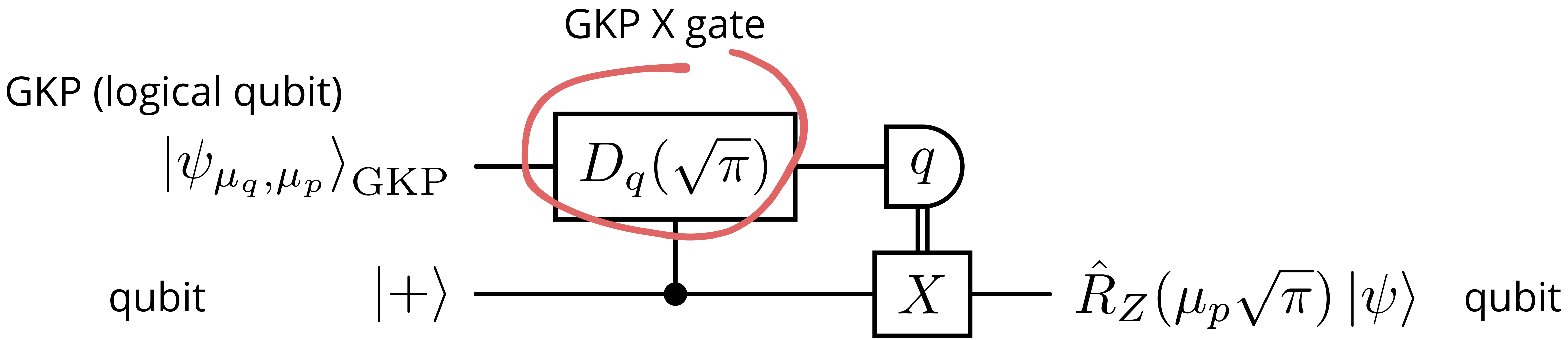




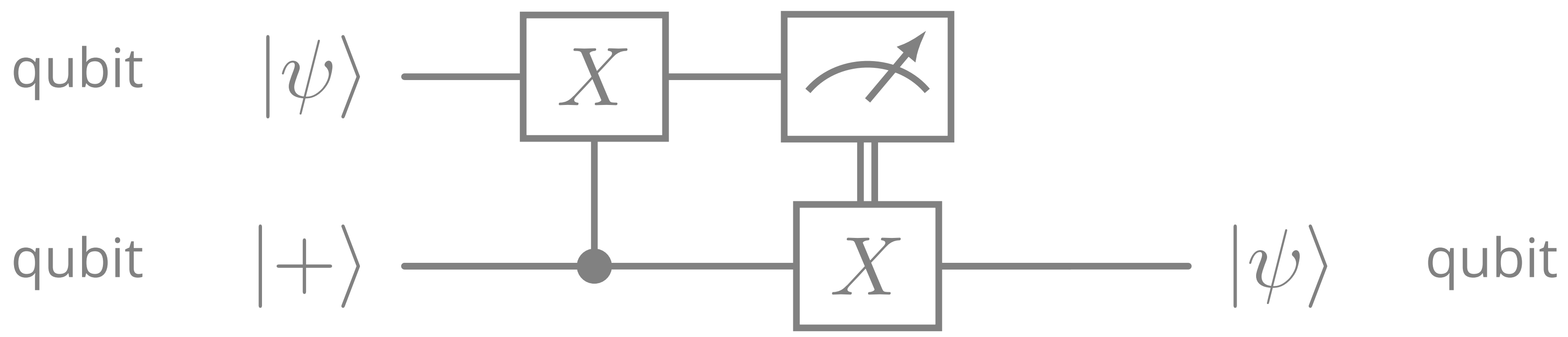
teleportation by products

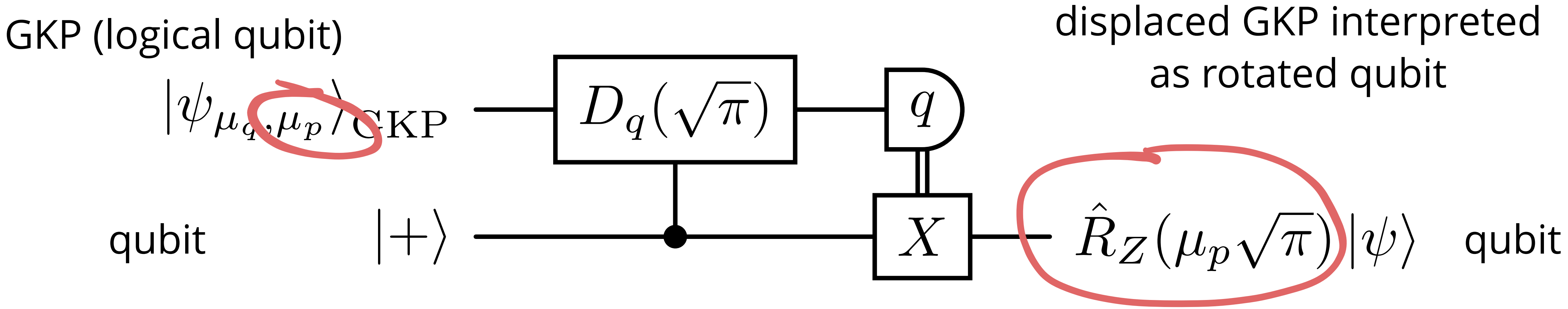
GKP-qubit one bit teleportation: X gate



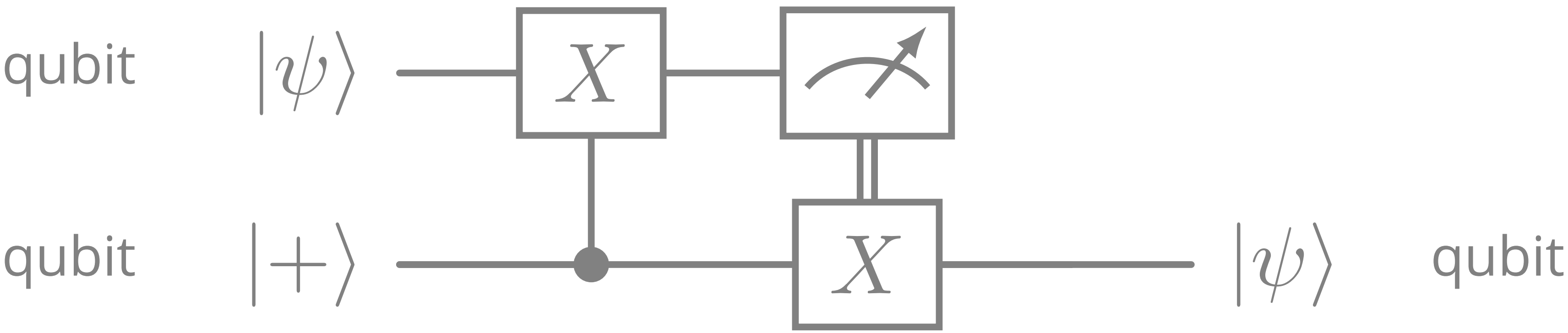


GKP-qubit one bit teleportation: μ_p

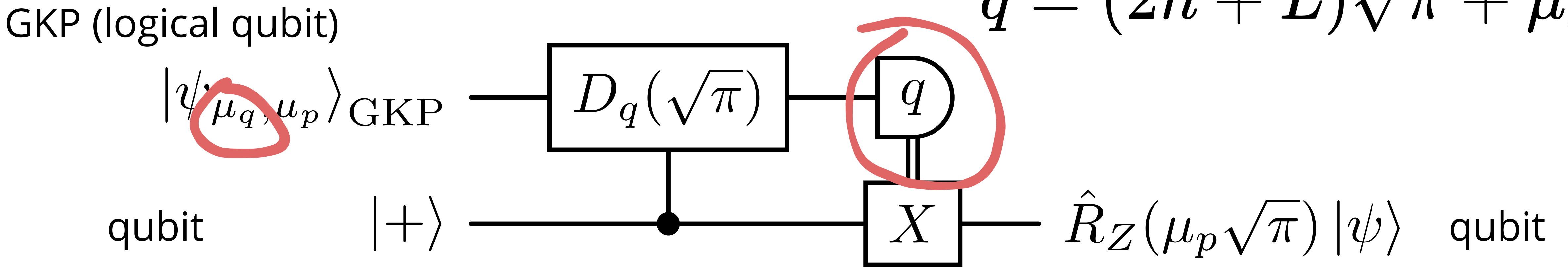




GKP-qubit one bit teleportation: μ_q



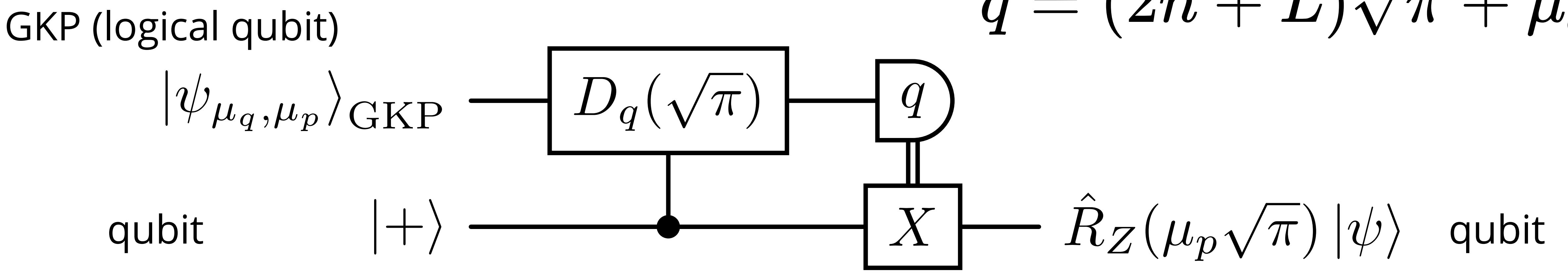
$$q = (2n + L)\sqrt{\pi} + \mu_q$$



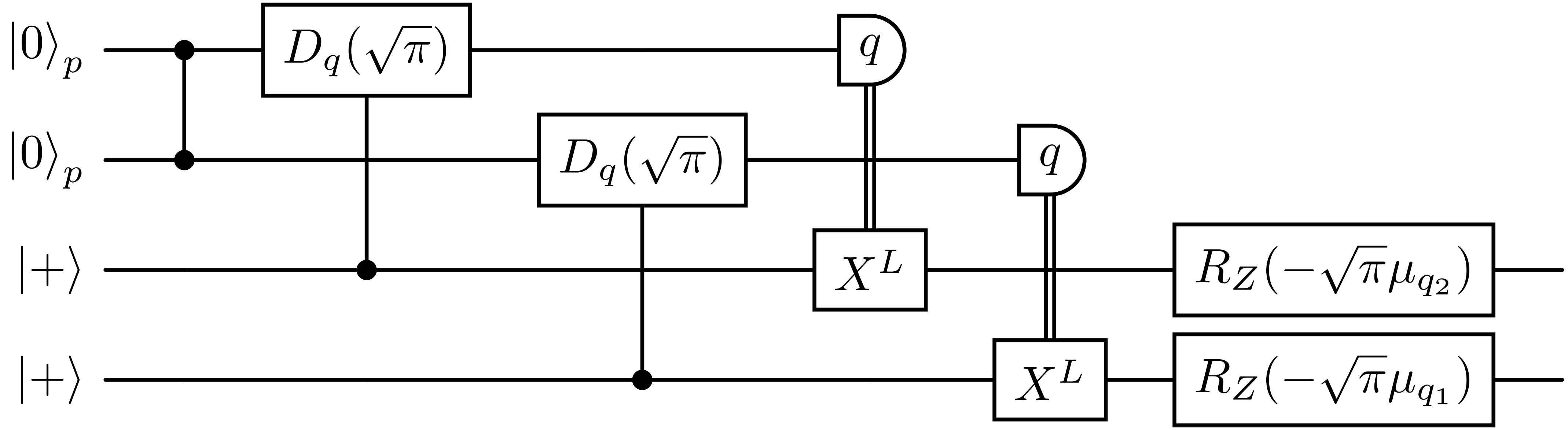
Homodyne detection roles:

1. Collapsing the superposition into some GKP cluster
2. Quantum teleportation
3. Need μ_q to correct phase shifts due to CV CZ

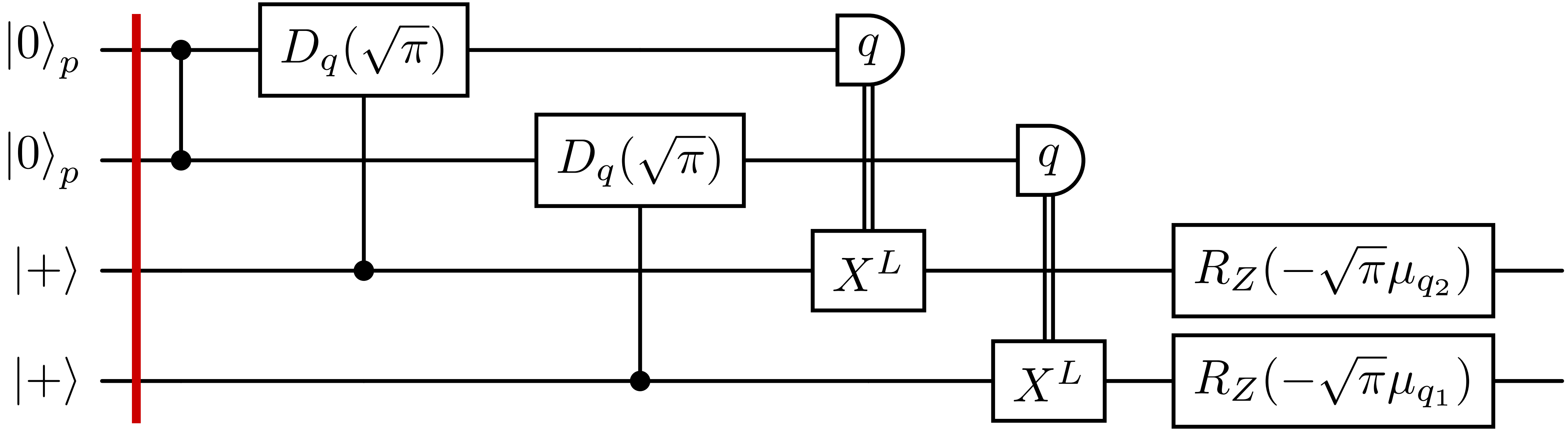
$$q = (2n + L)\sqrt{\pi} + \mu_q$$



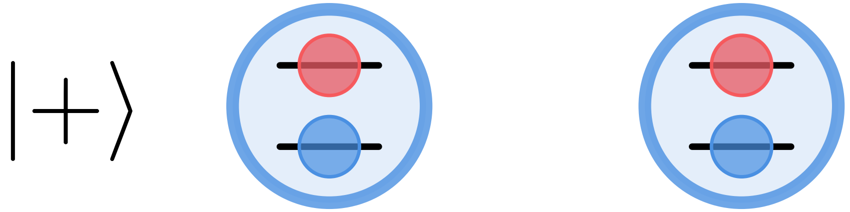
Entanglement transfer protocol: Recap



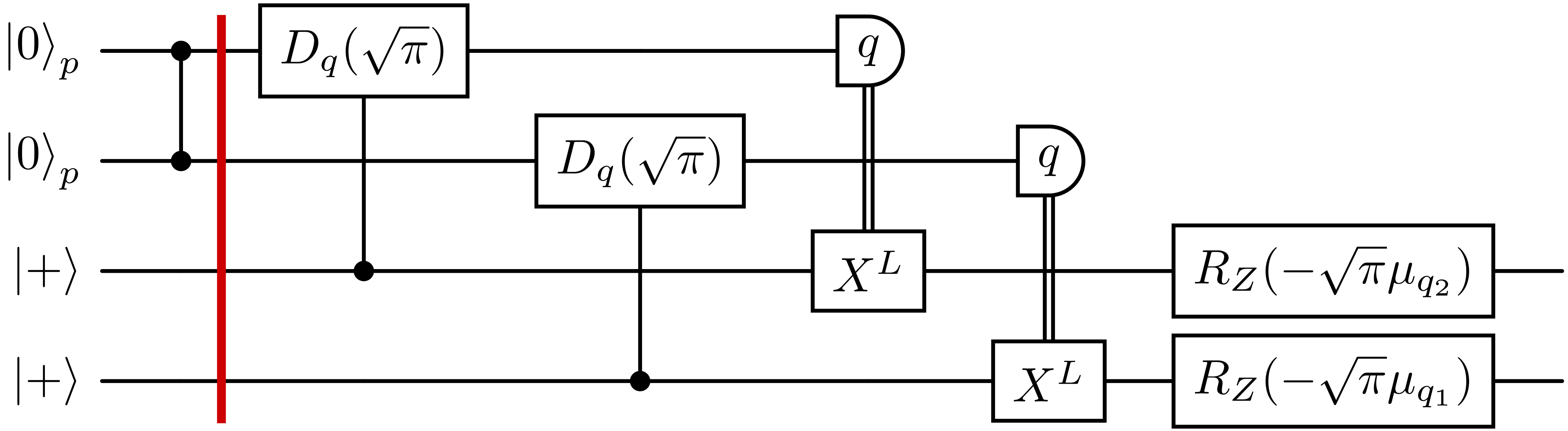
Entanglement transfer protocol: Recap

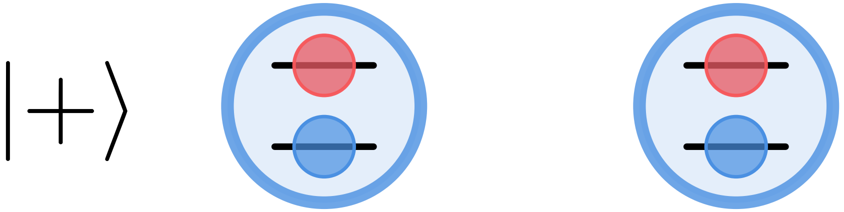


1. Initialize all qubits to $|+\rangle$.

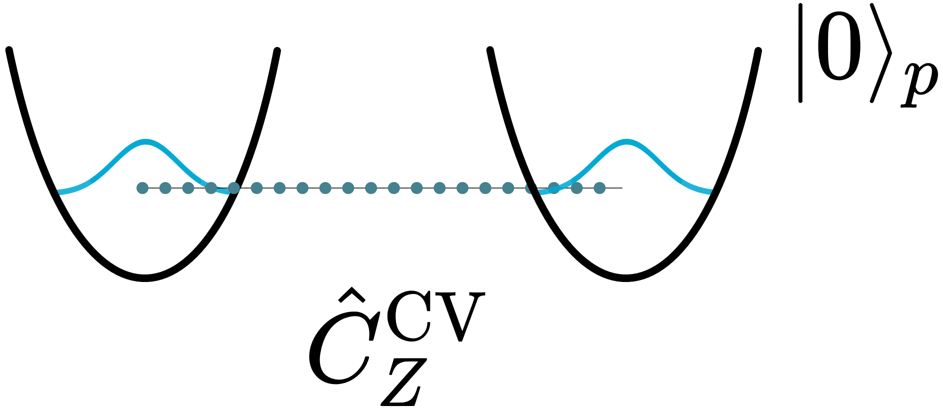


Entanglement transfer protocol: Recap

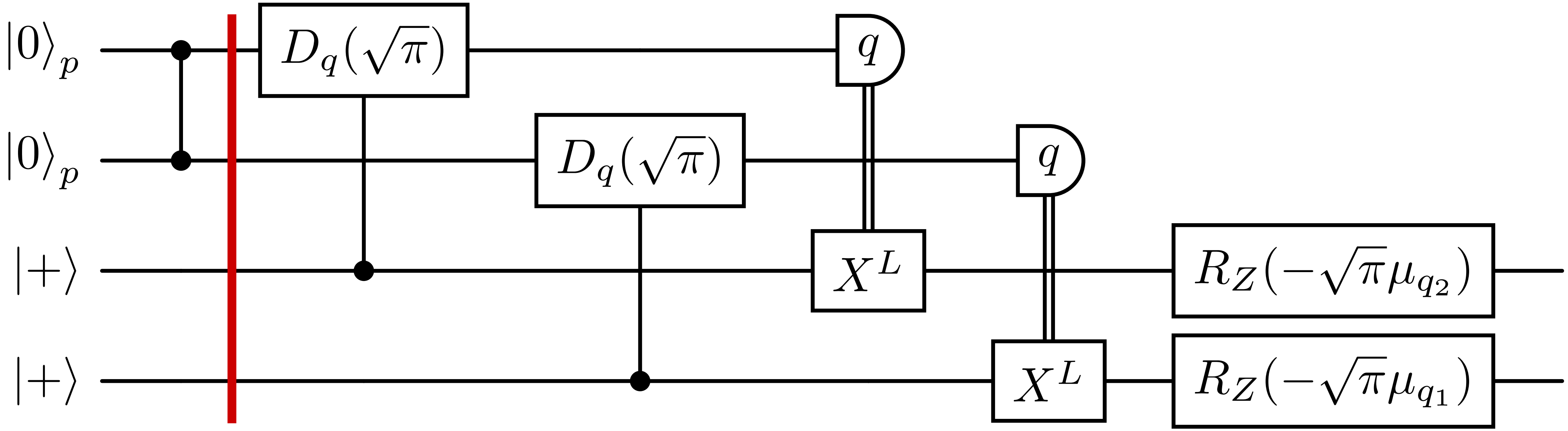




2. Create a CV cluster state.

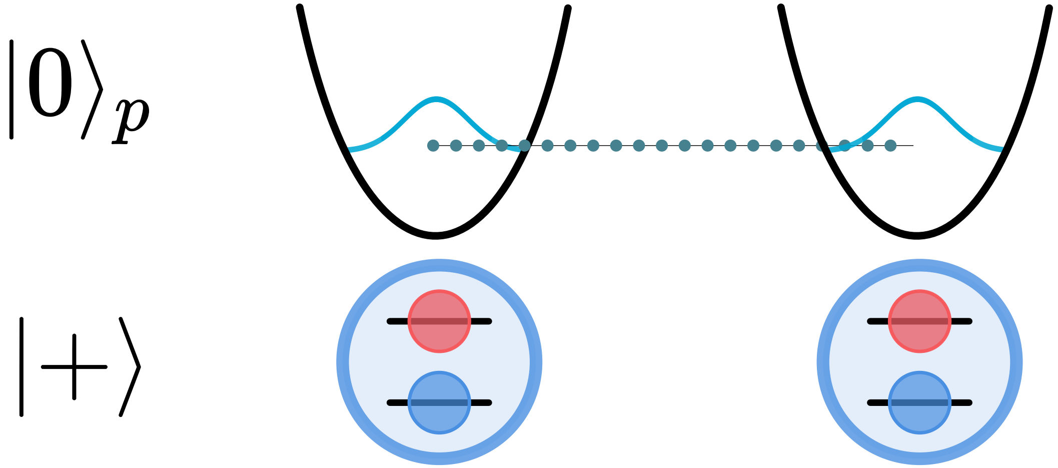


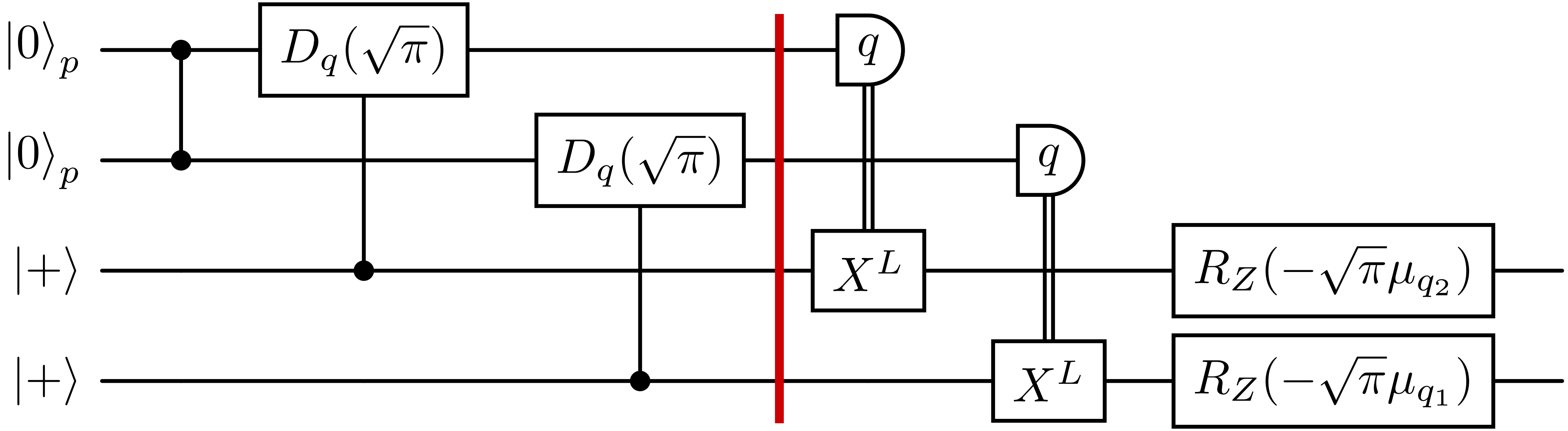
Entanglement transfer protocol: Recap



Step 3. Apply conditional displacement to each pair:

$$\hat{C}_D = |0\rangle\langle 0|\hat{I} + |1\rangle\langle 1|\hat{D}_q(\sqrt{\pi})$$





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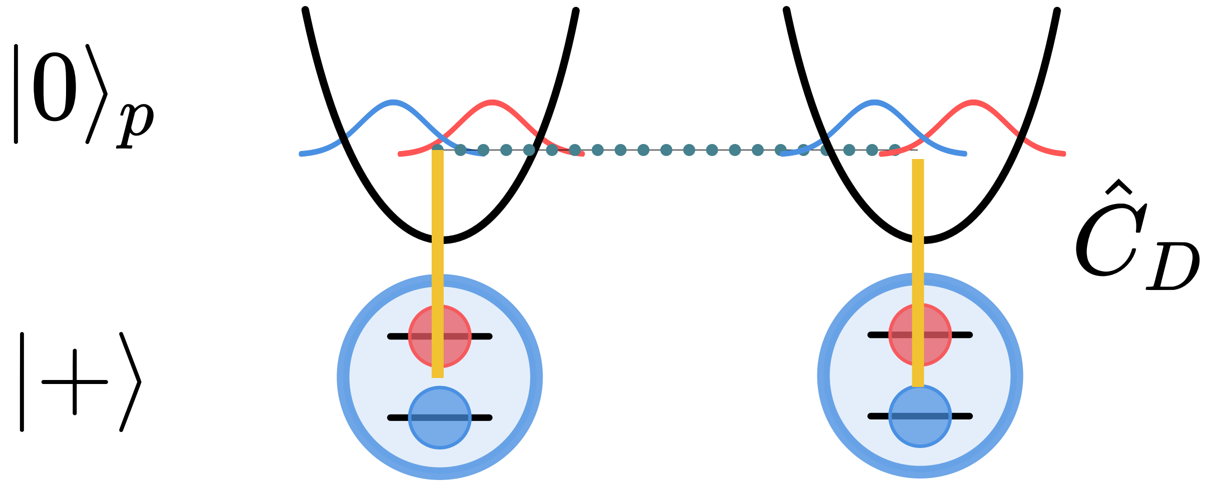
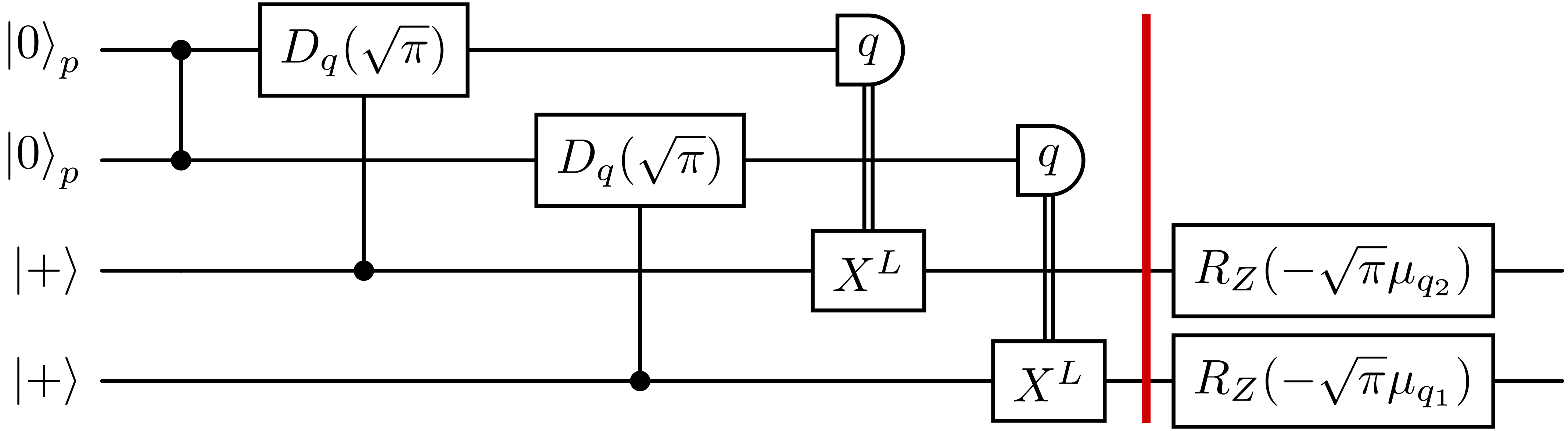
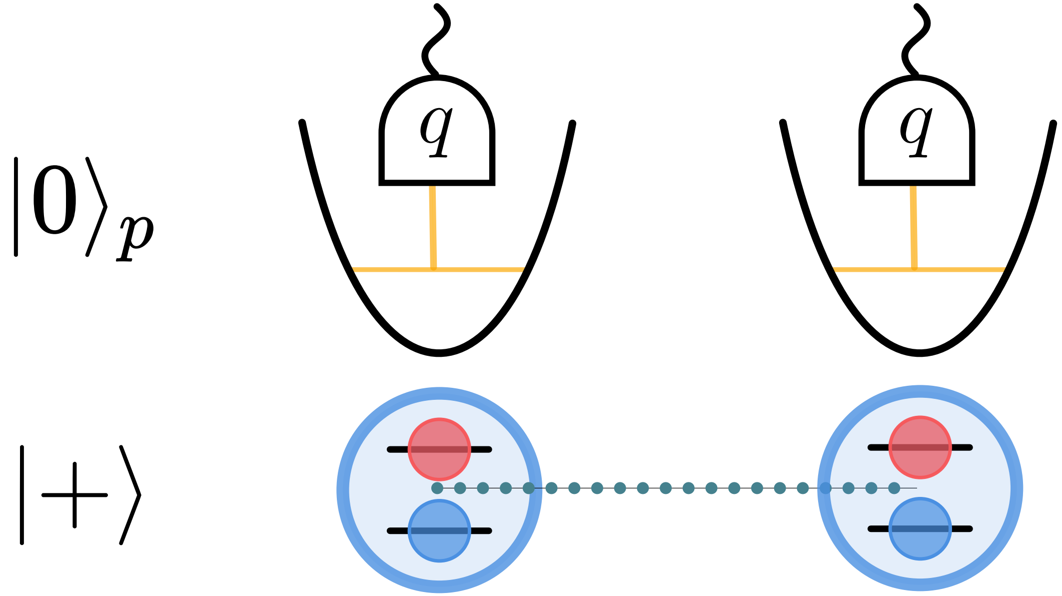


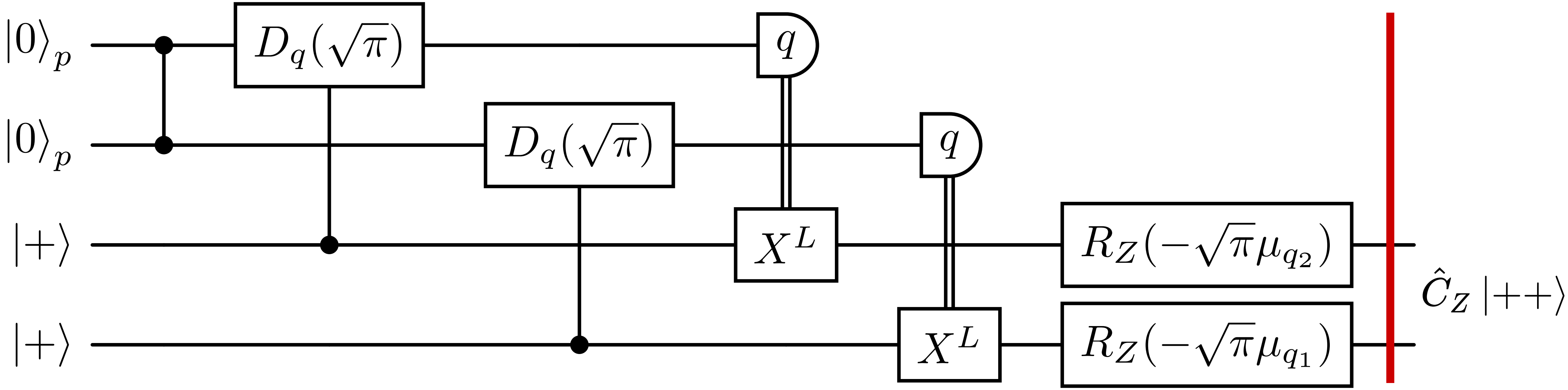
Entanglement transfer protocol: Recap



Step 4. Measure the q quadrature.

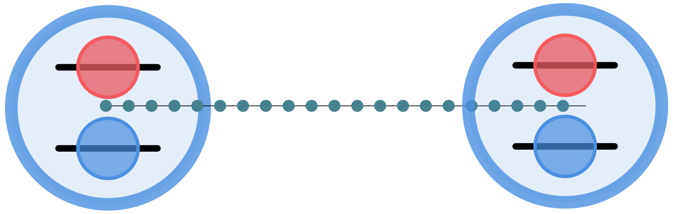


Entanglement transfer protocol: Recap



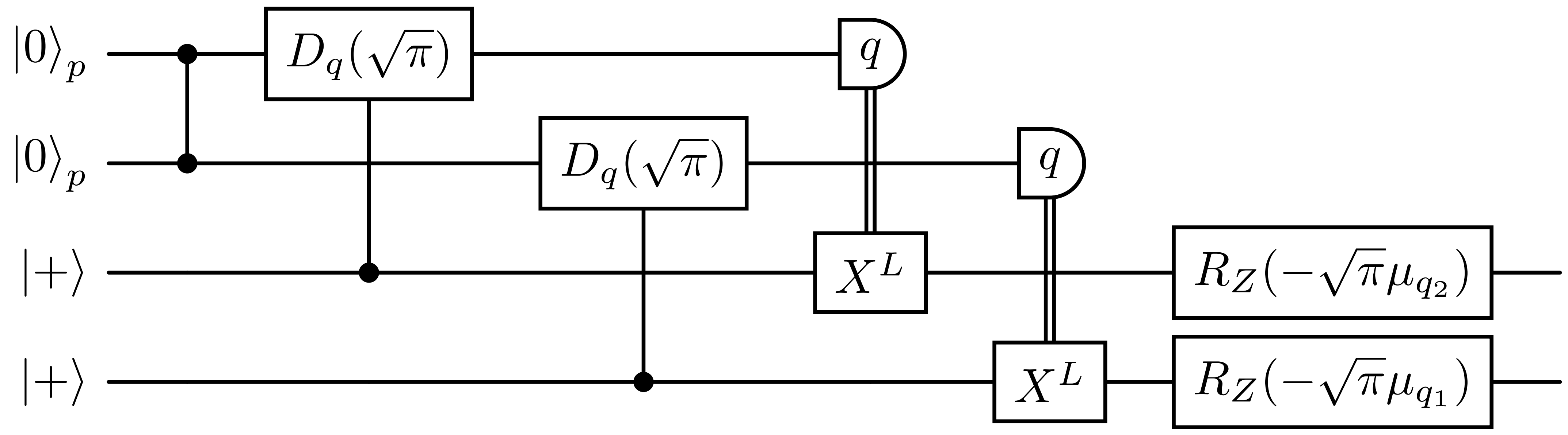
Step 5. Correct by products.

$|+\rangle$

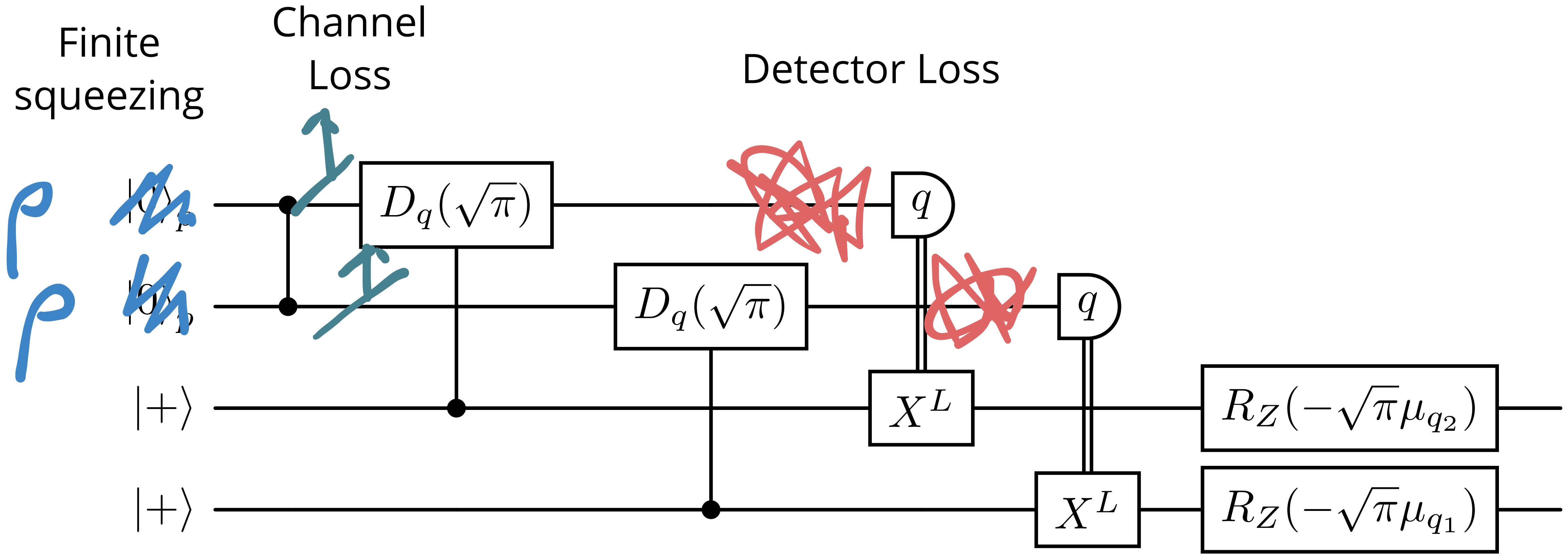


Entanglement transfer protocol: Loss

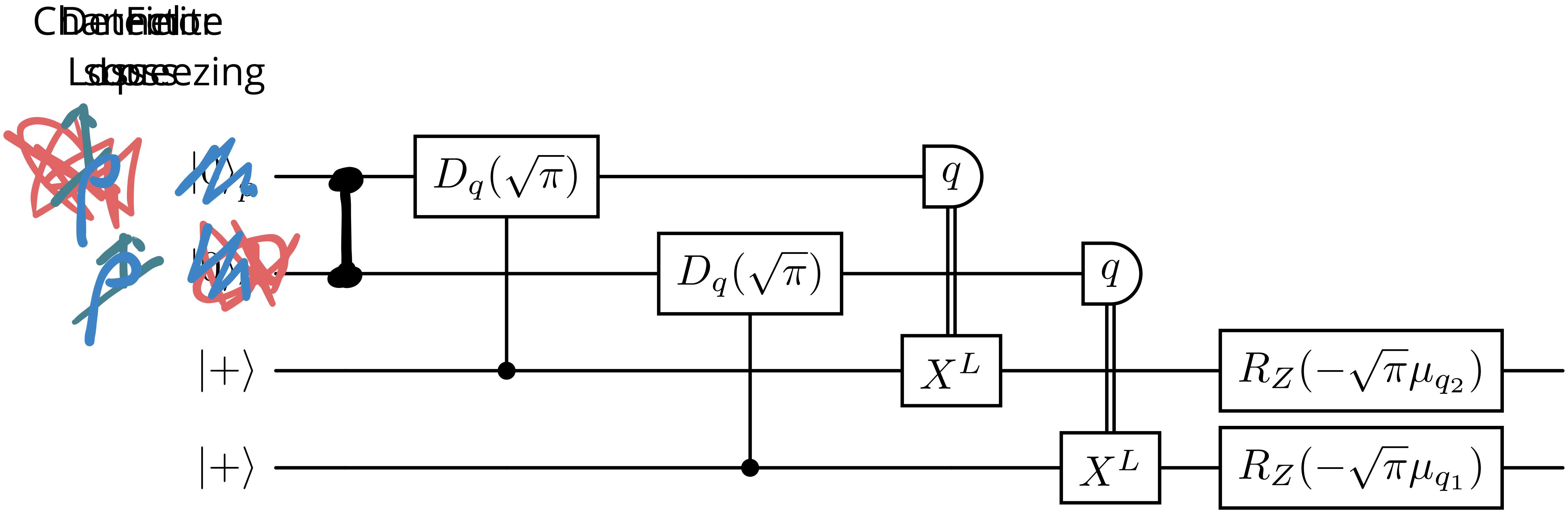
1. Ideal CV cluster $\rightarrow$ perfect qubit cluster
2. No GKP states in the protocol



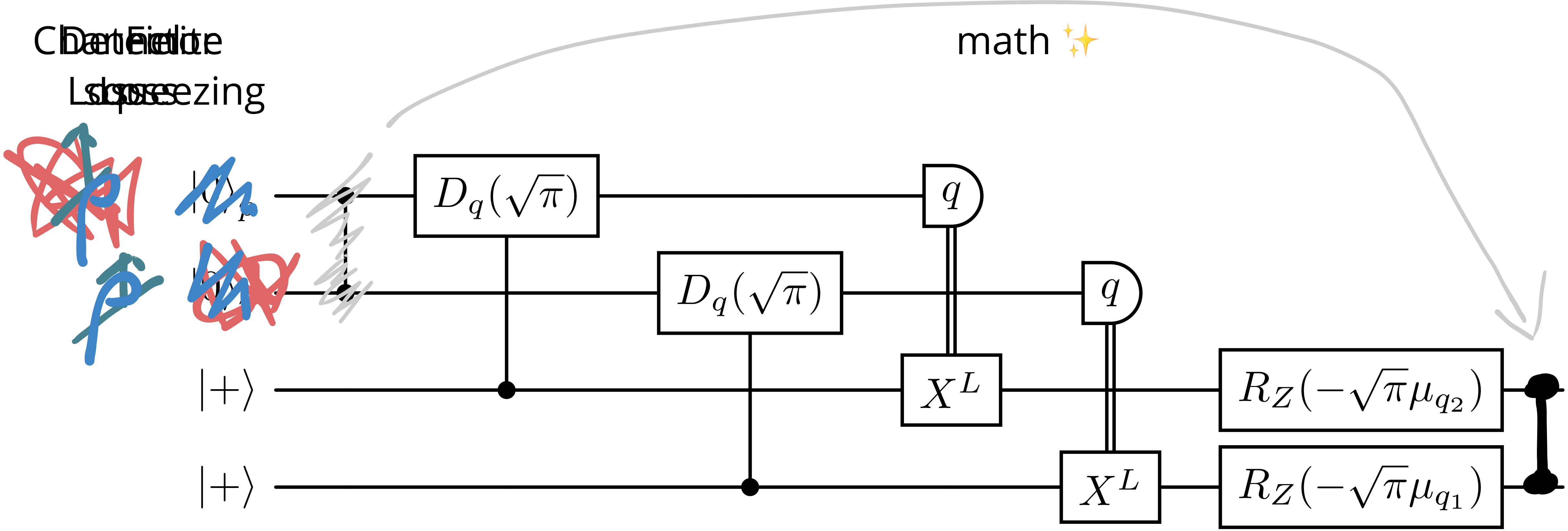
Entanglement transfer protocol: Loss



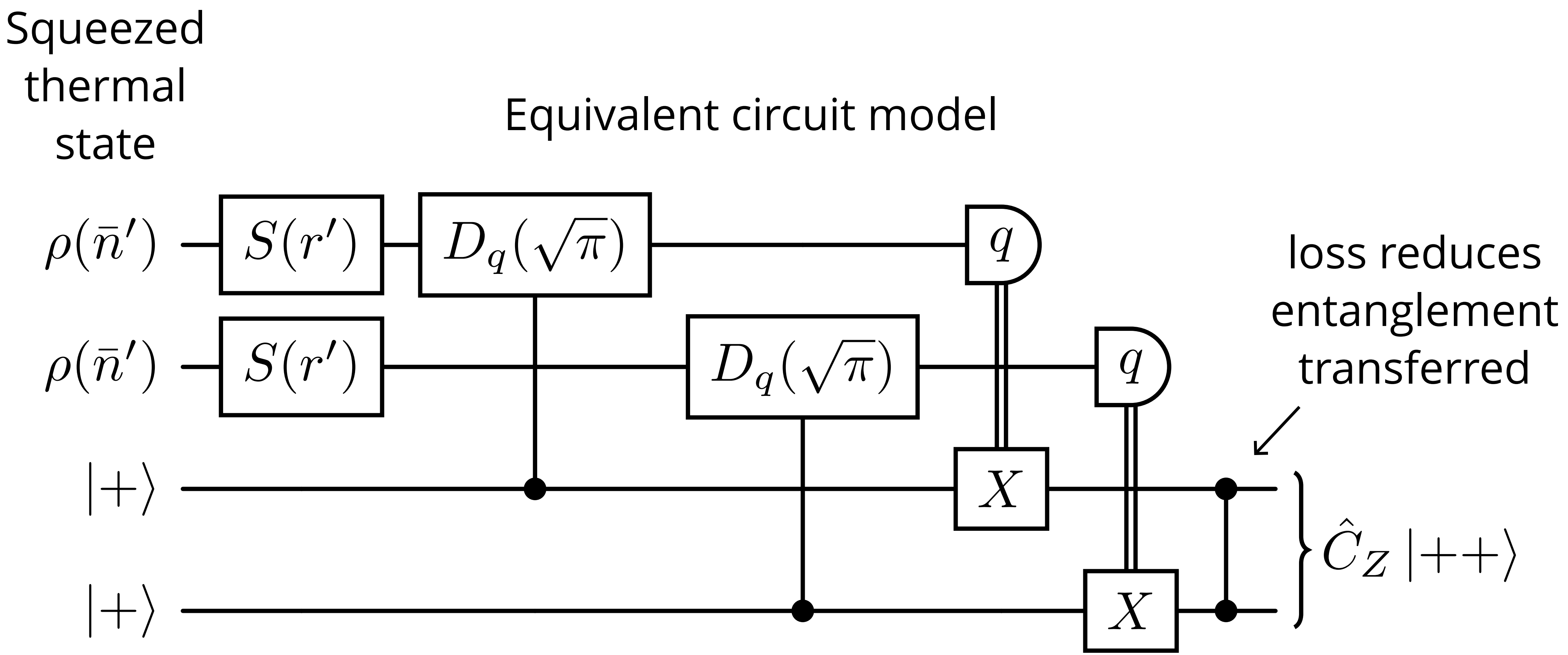
Entanglement transfer protocol: Loss



Entanglement transfer protocol: Loss

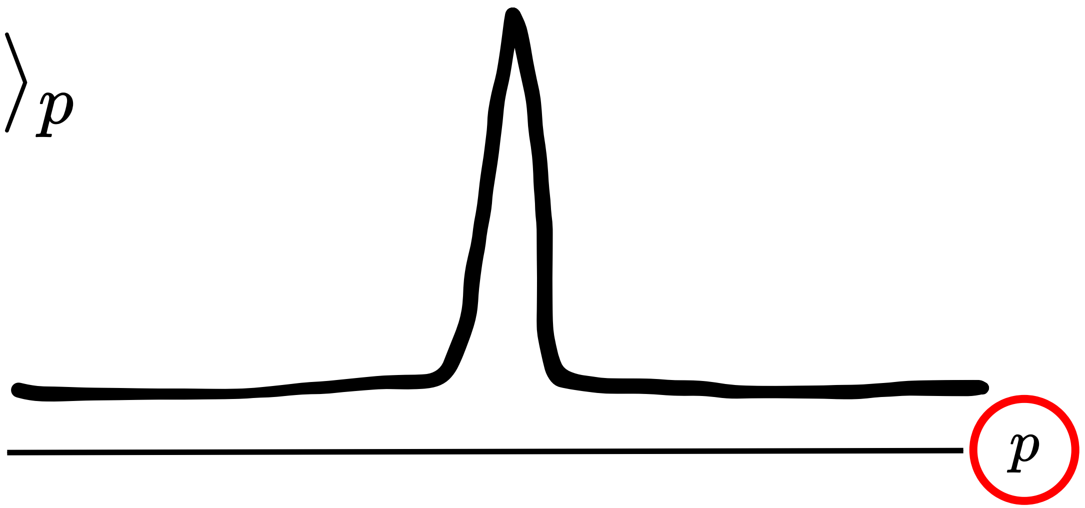


Entanglement transfer protocol: Loss



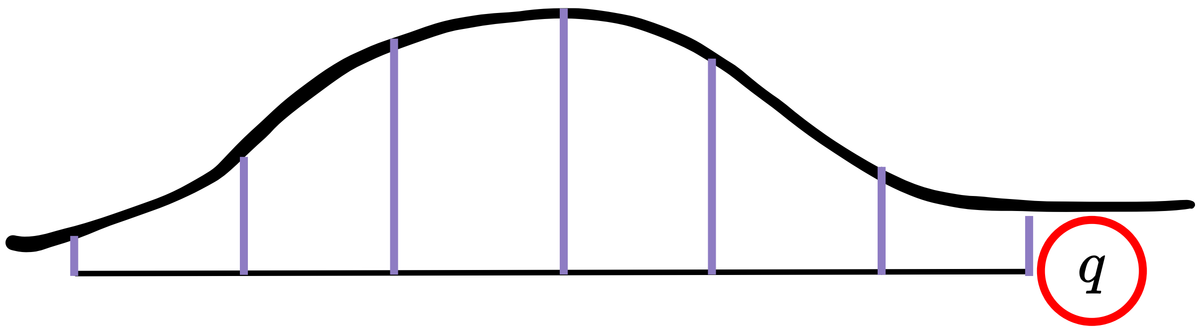
Finite squeezing:

$|0, \sigma_p\rangle_p$



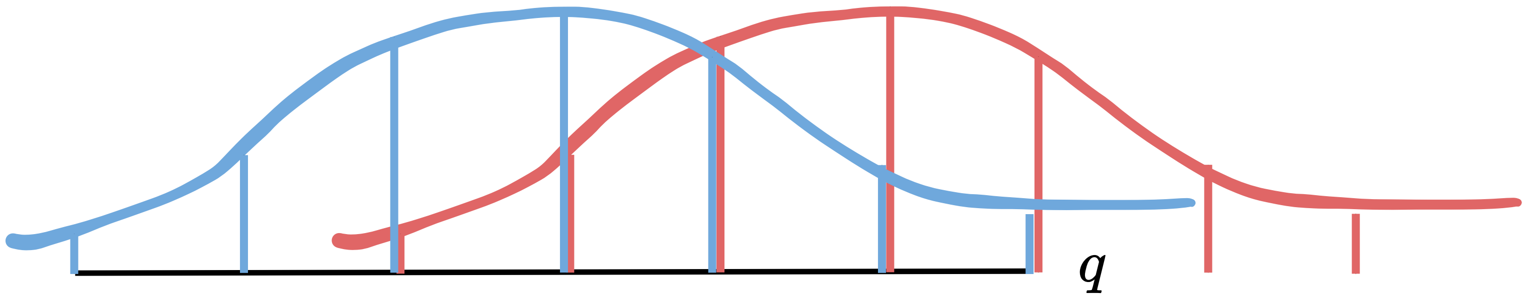
Finite squeezing:

$$|0, \sigma_p\rangle_p$$

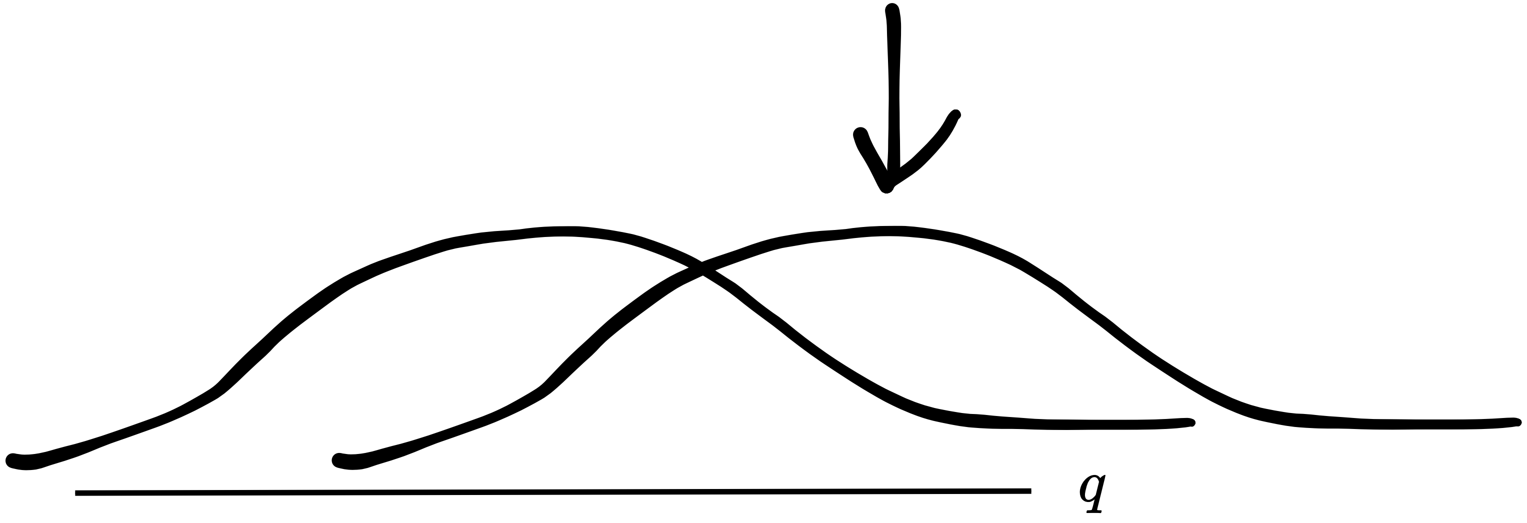


After conditional displacement:

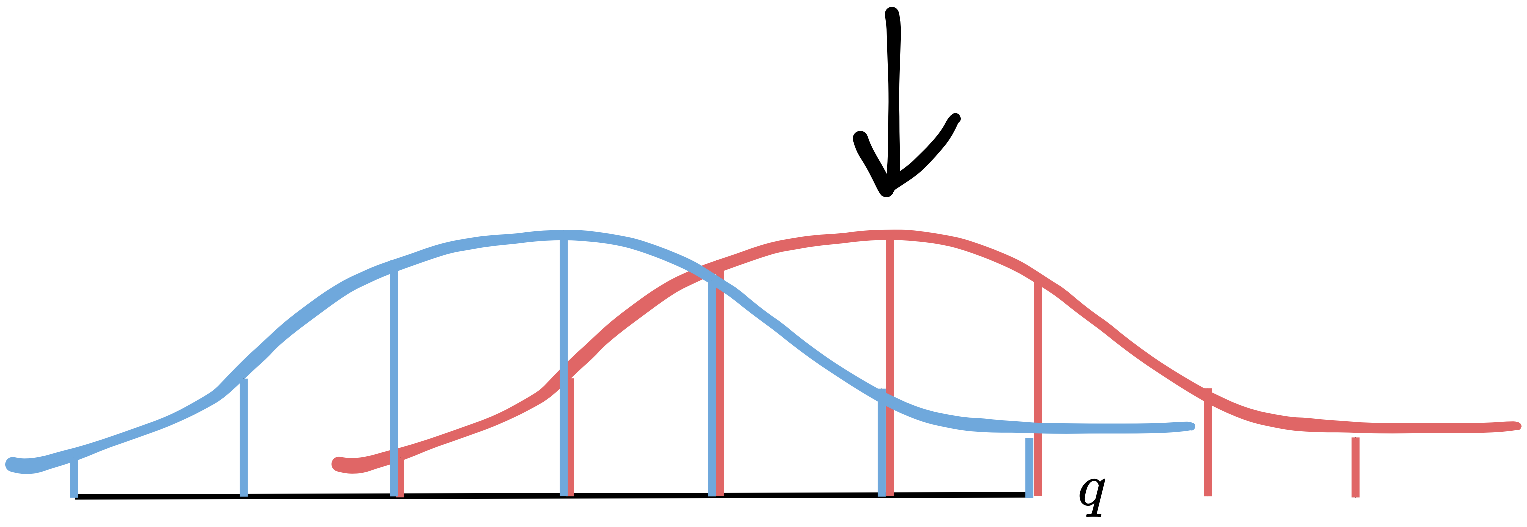
$$|0, \sigma_p\rangle_p\, |0\rangle^{\text{Qubit}} \qquad \hat{D}_q(\sqrt{\pi})|0, \sigma_p\rangle_p\, |1\rangle^{\text{Qubit}}$$



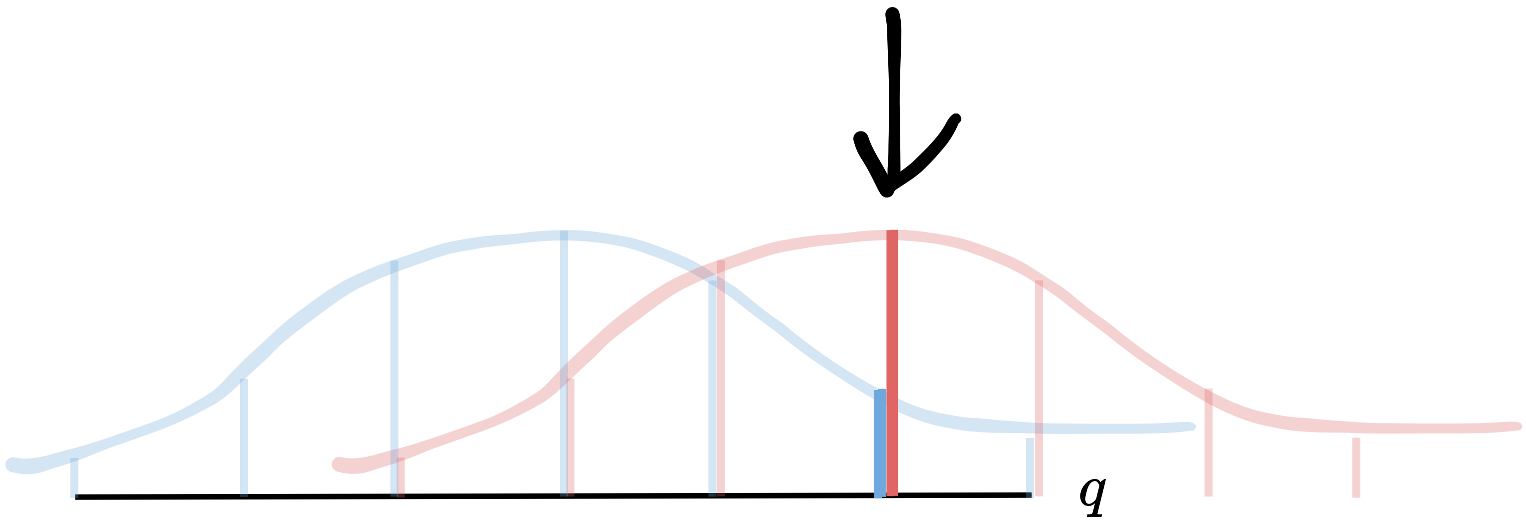
Now, the probability of measuring q:



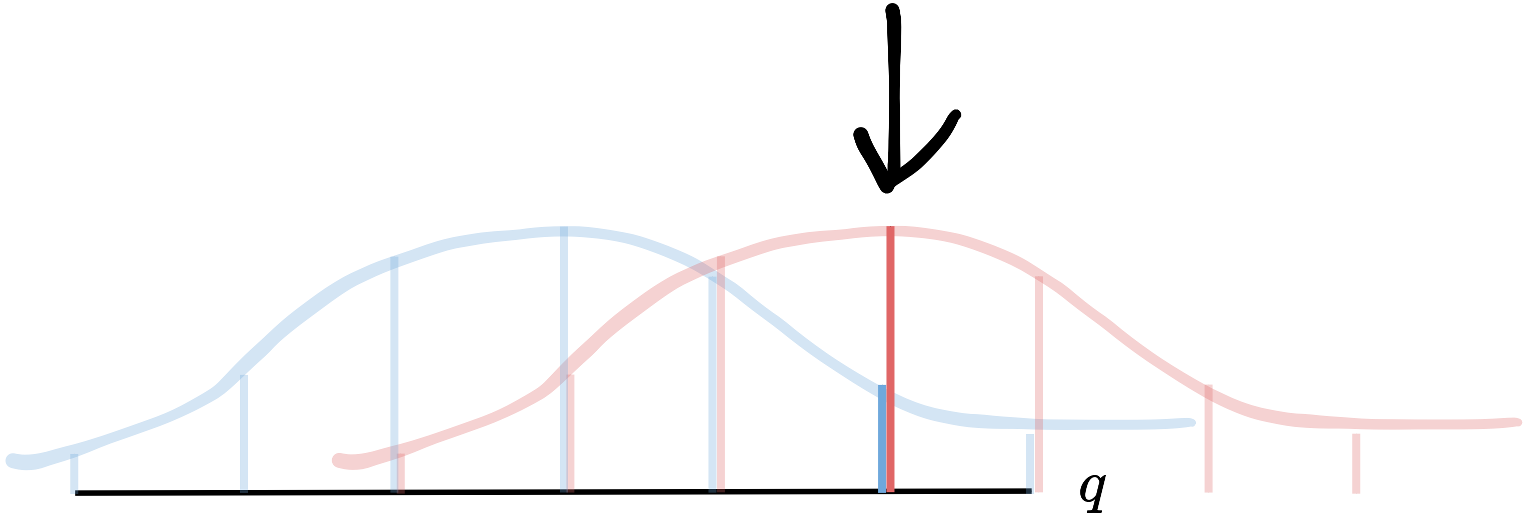
The displaced GKP state after measuring q:



The displaced GKP state after measuring q:



The displaced GKP state after measuring q:



The qubit is: $|0\rangle + |1\rangle$

Amplitude imbalance error

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We can correct the qubit by performing weak measurement POVMs M_0, M_1.

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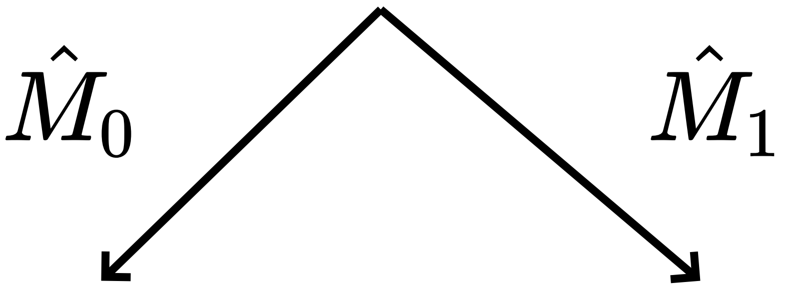
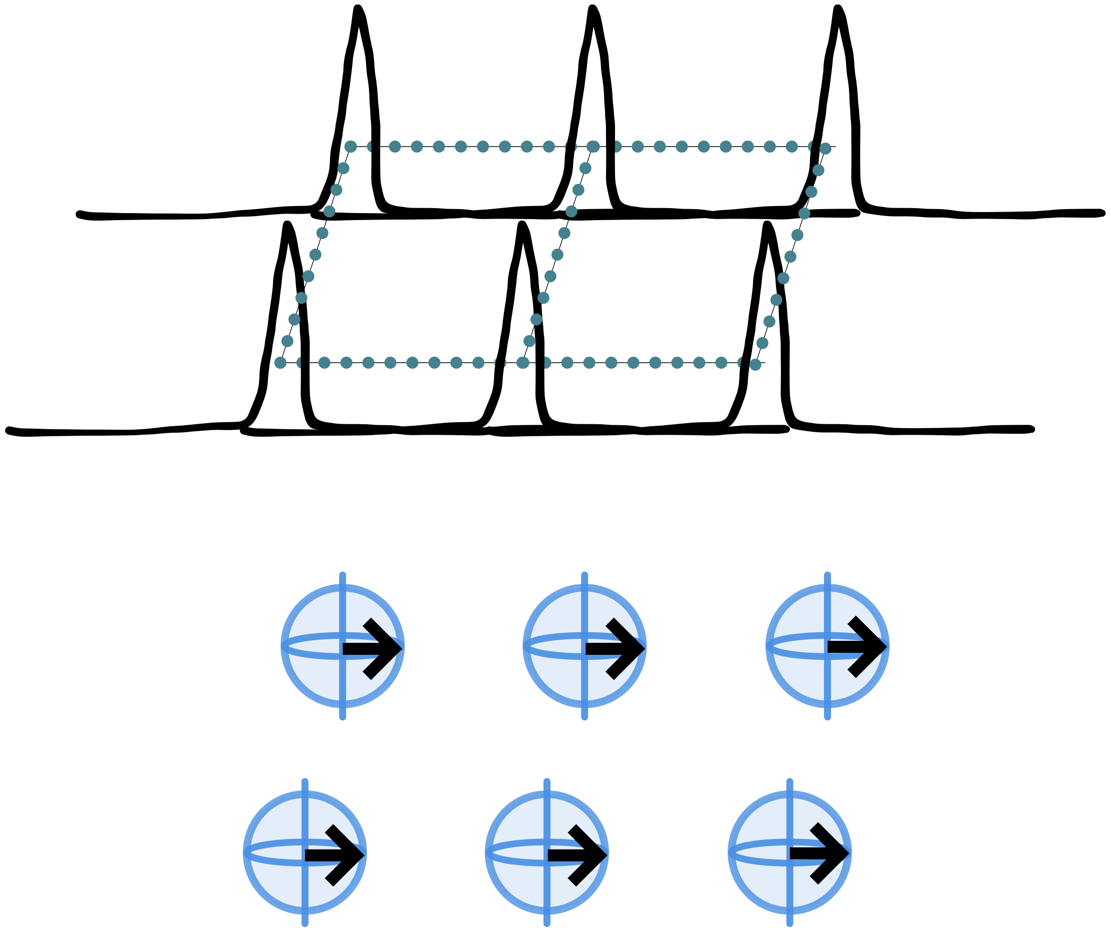


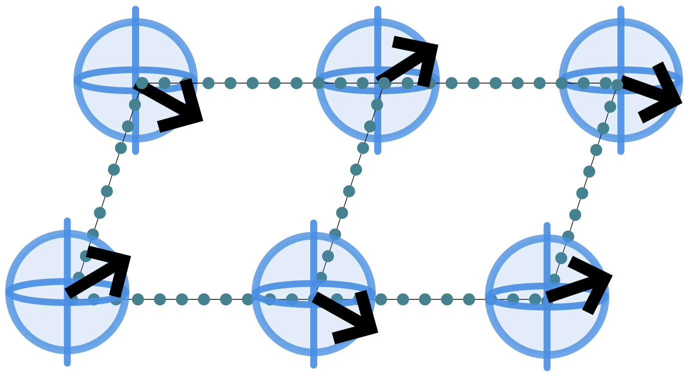
Success: $1-p$ $|0\rangle + |1\rangle$

Failure: p $|1\rangle$

Finitely squeezed CV cluster state

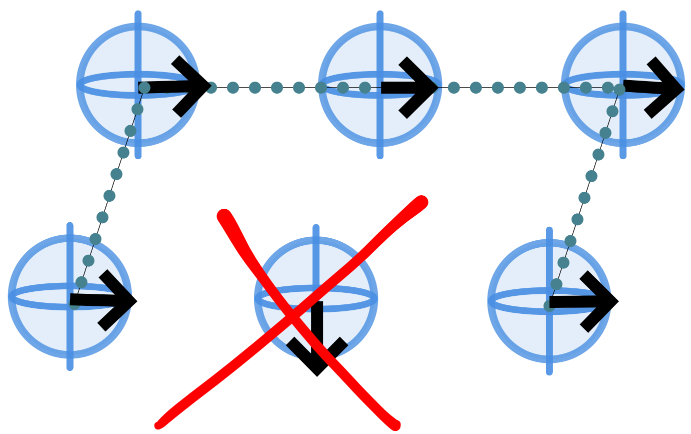


Amplitude imbalance error!

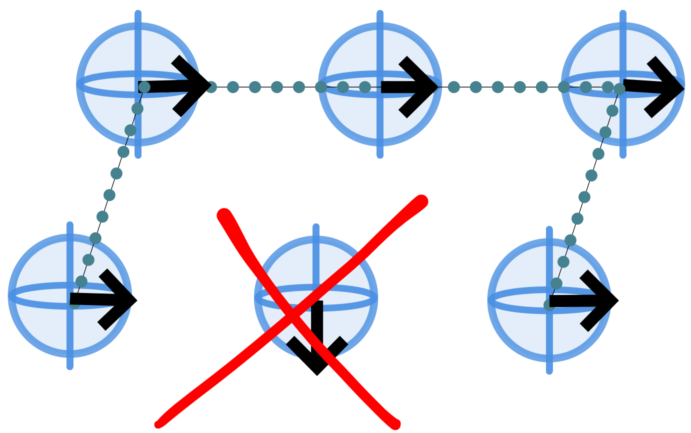


Loss: Finite Squeezing

After weak measurement:

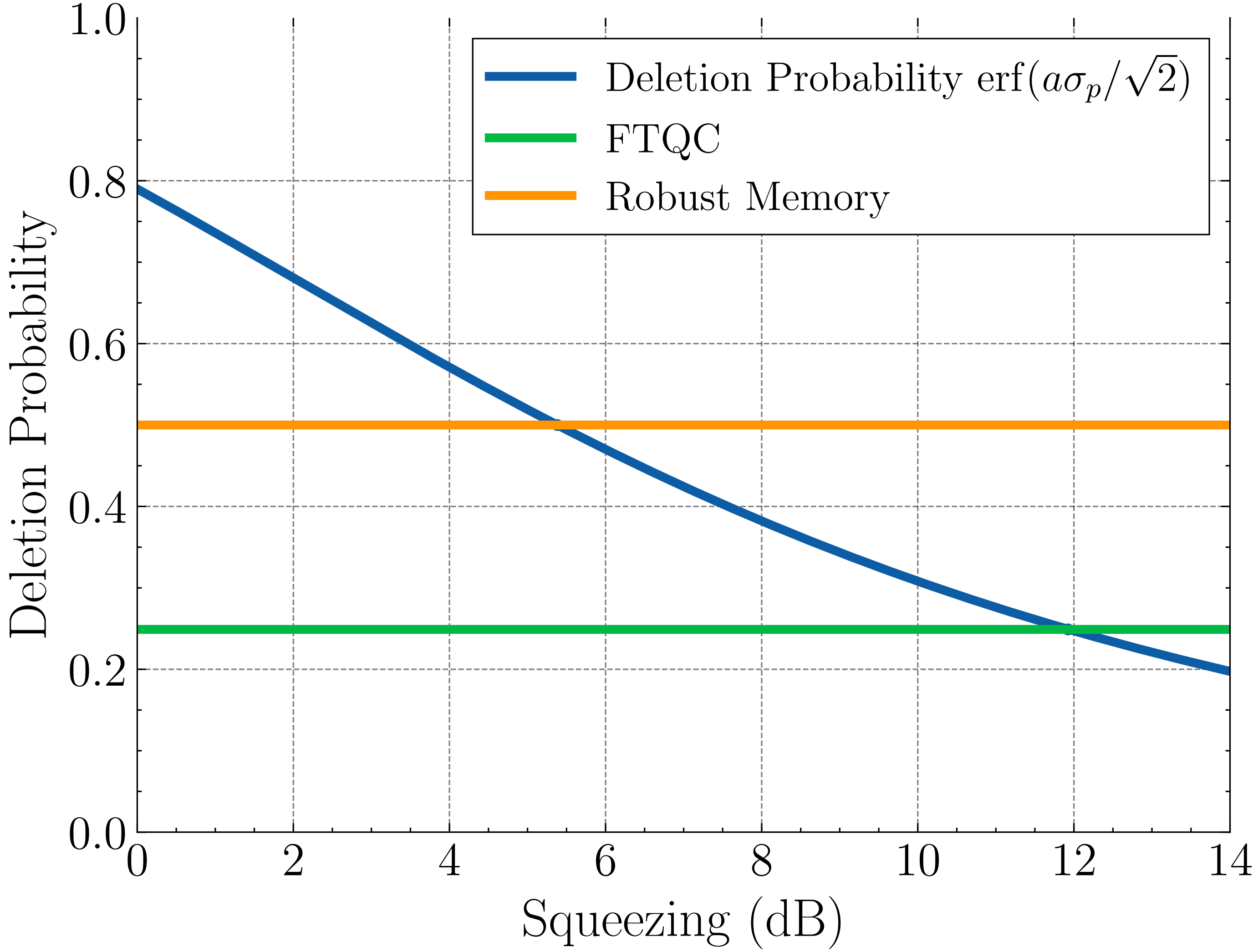


Can convert initial squeezing error to deletion error!



Failure: p

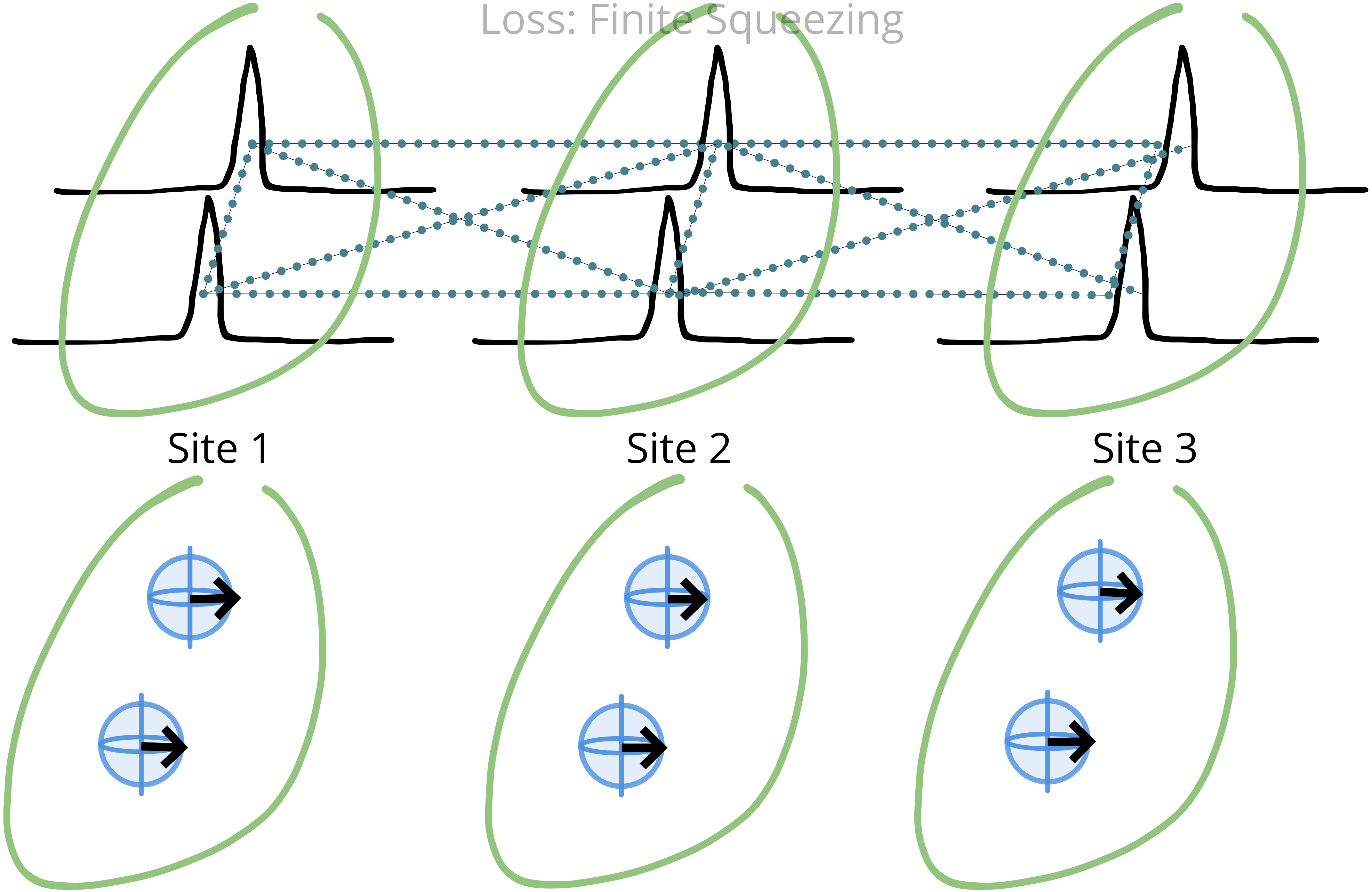
Loss: Finite Squeezing



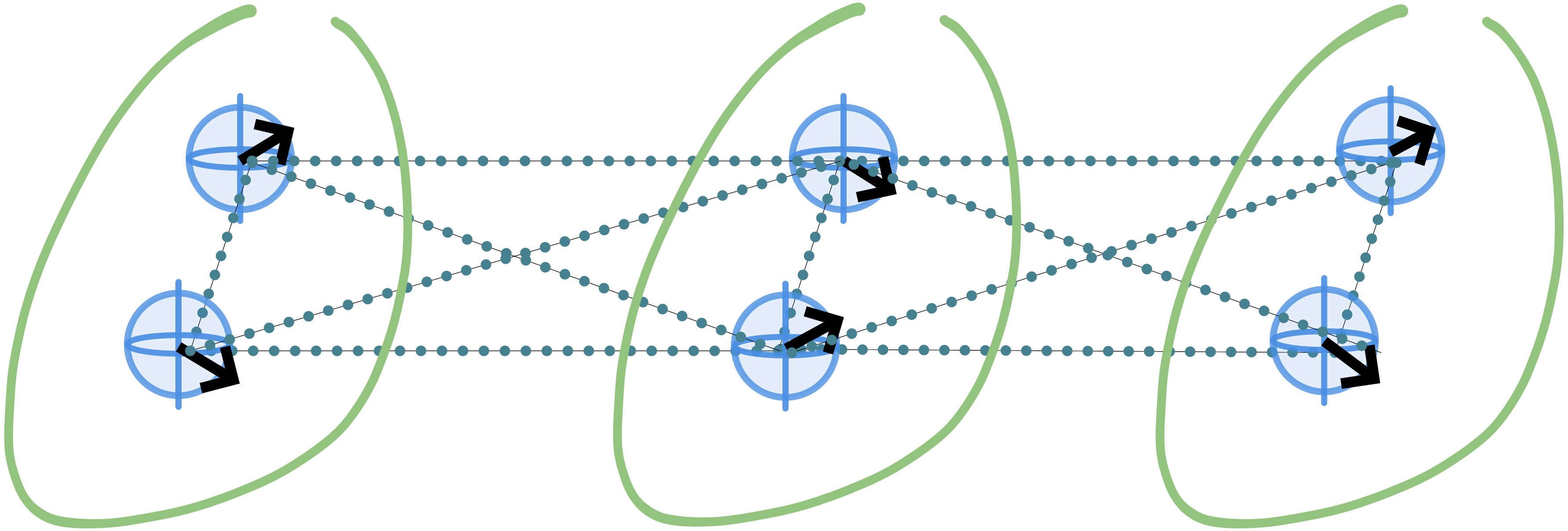
(Stace 2009)

(Barrett and Stace 2010)

Failure: p

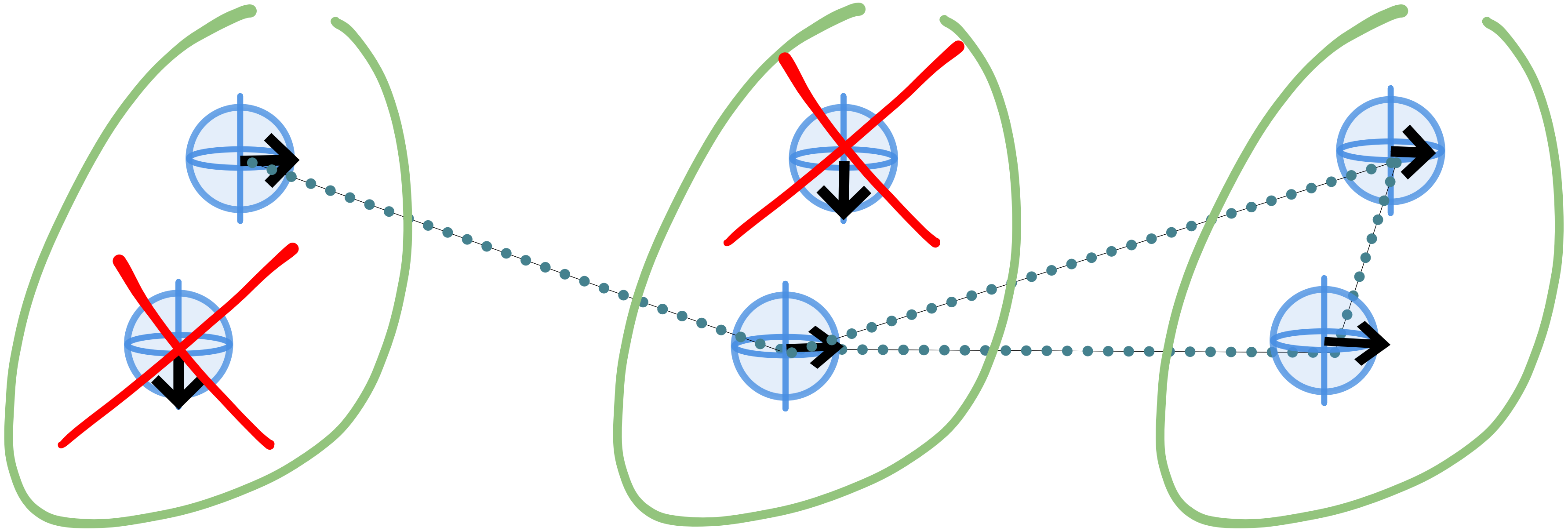

Loss: Finite Squeezing
Site 1
Site 2
Site 3

Loss: Finite Squeezing

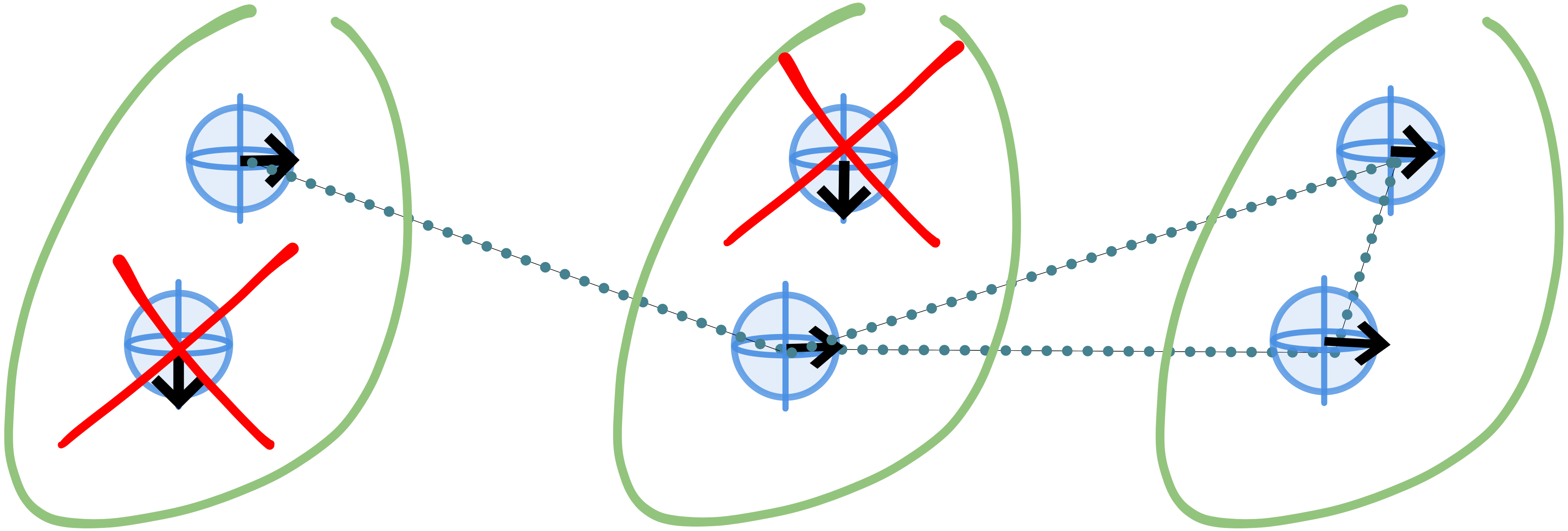


Loss: Finite Squeezing

After weak measurement:

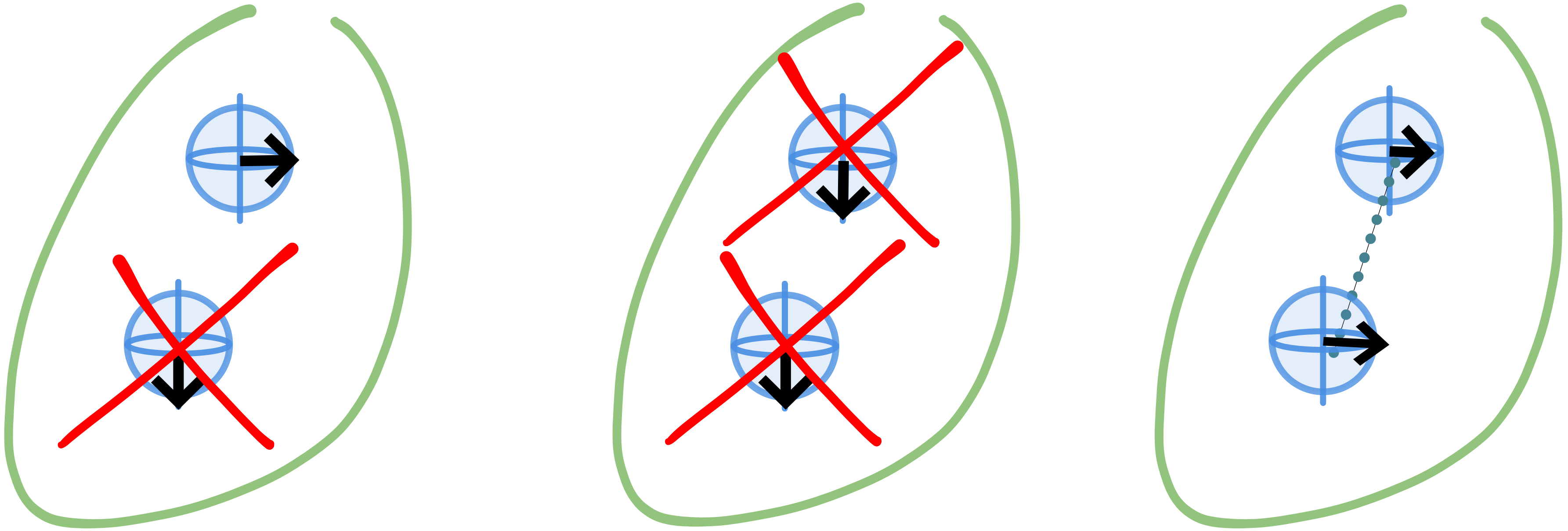


Dual rail encoding (n=2)



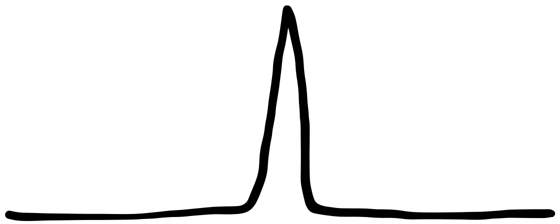
In order to break entanglement between
site 1 and 3 both qubits has to be deleted.

Dual rail encoding (n=2)

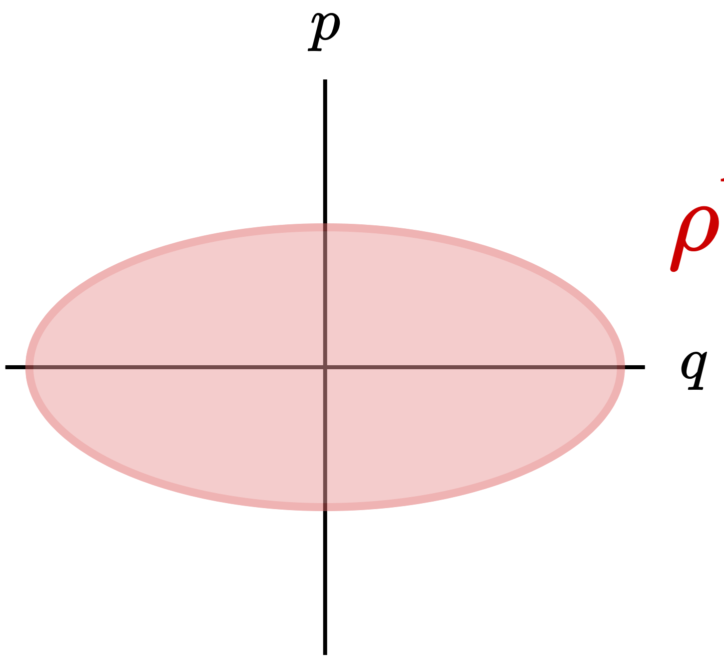


Deletion probability of a site: p^n

What happens to the qubit if you send in a squeezed thermal state?



$= \rho$

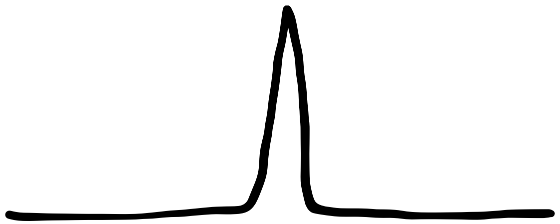


ρ^{thermal}

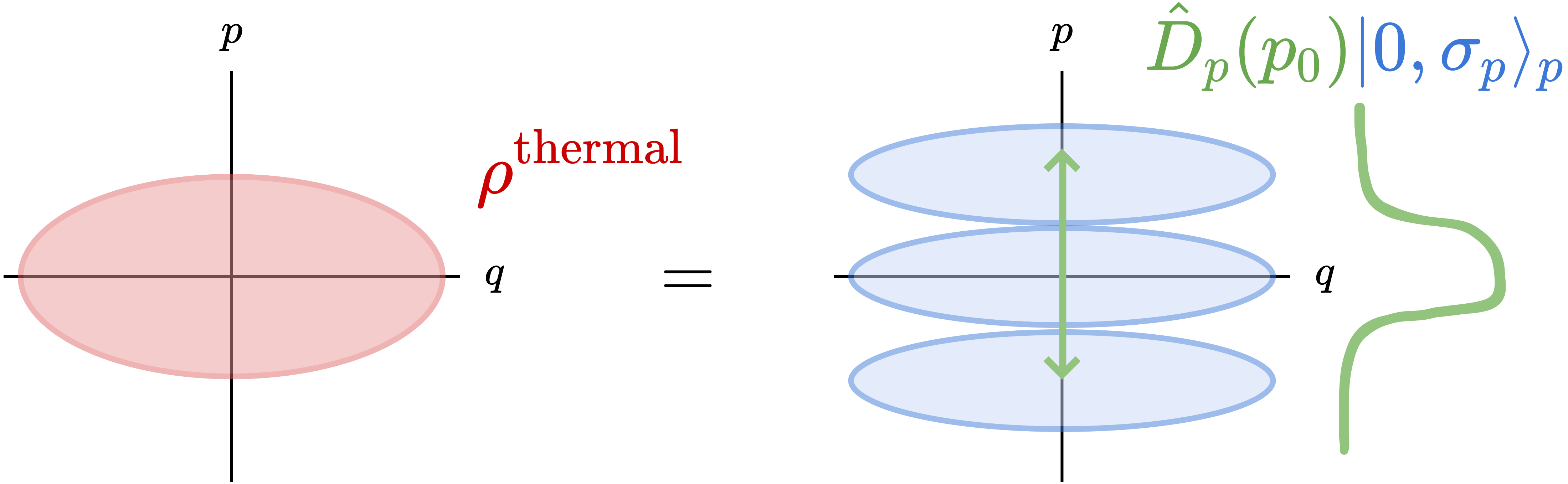
Squeezed thermal state

Loss: Channel and detector loss

What happens to the qubit if you send in a squeezed thermal state?



$= \rho$

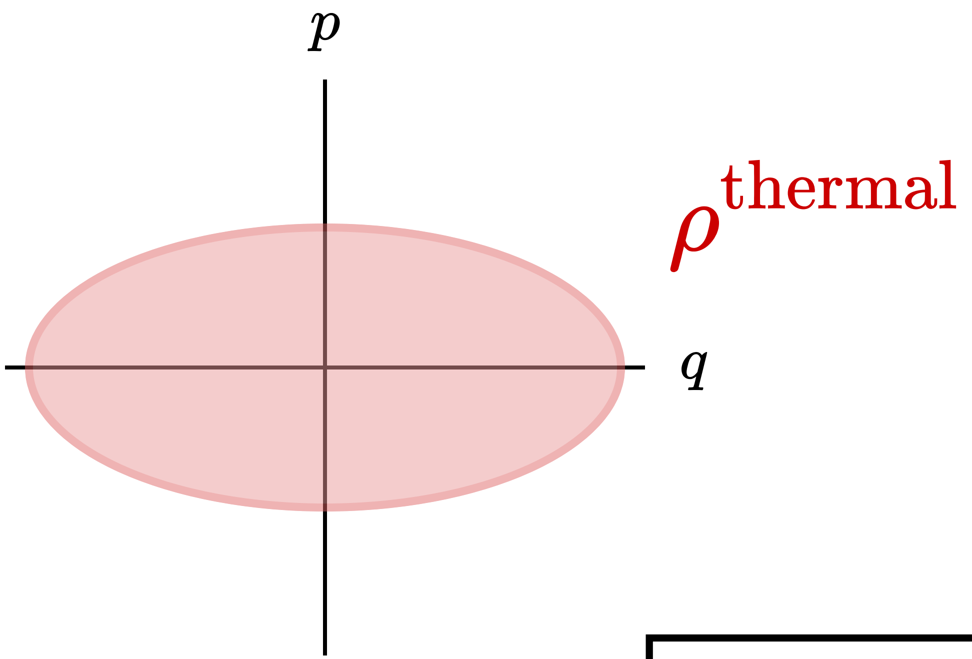


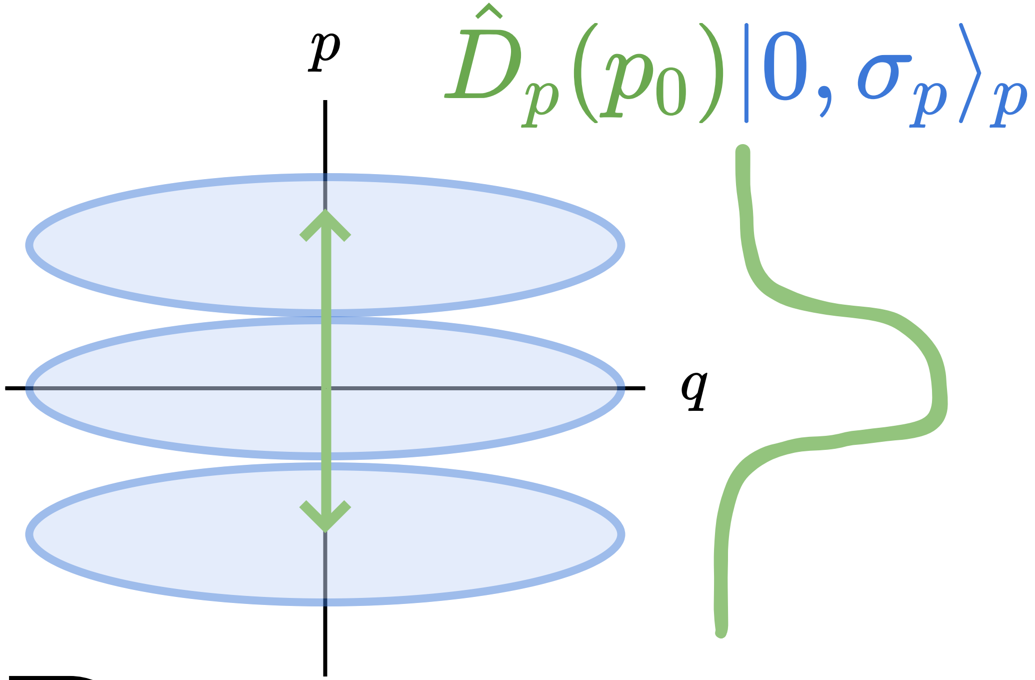
Squeezed thermal state

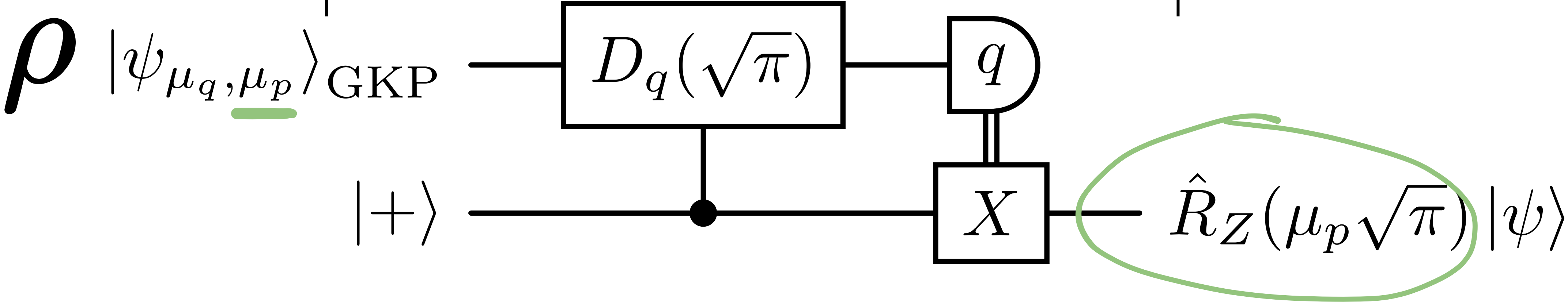
Mixture of squeezed states

Loss: Channel and detector loss

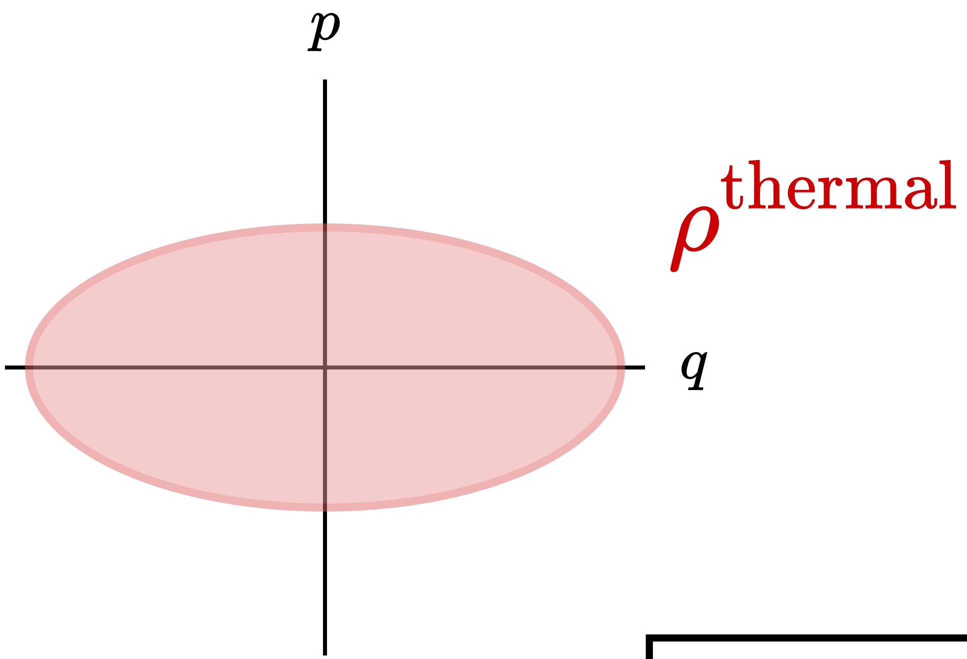
What happens to the qubit if you send in a squeezed thermal state?

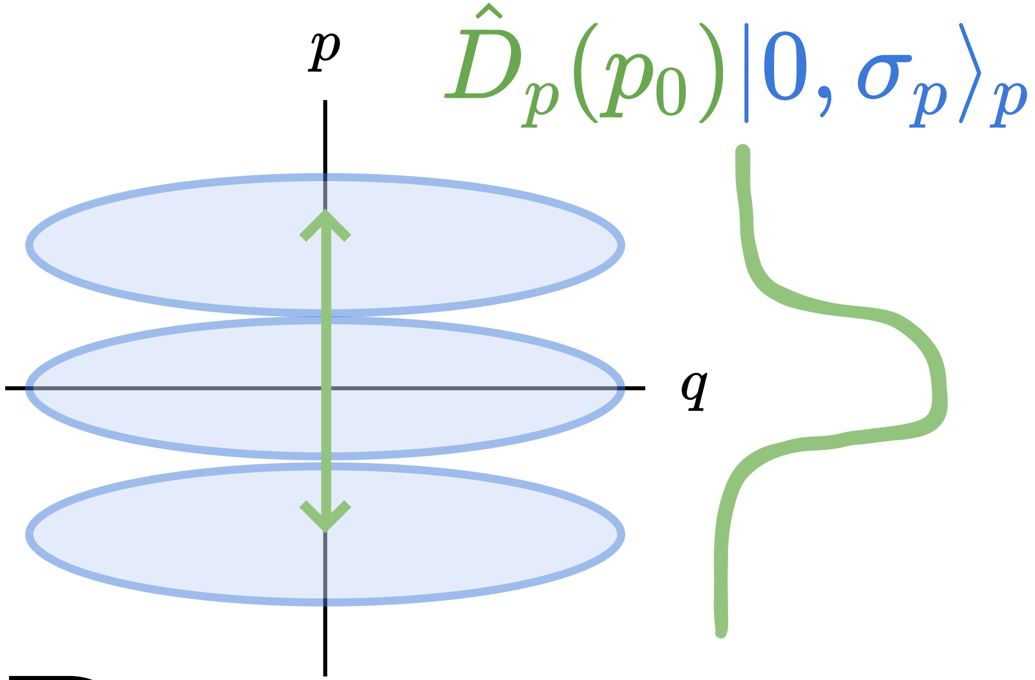




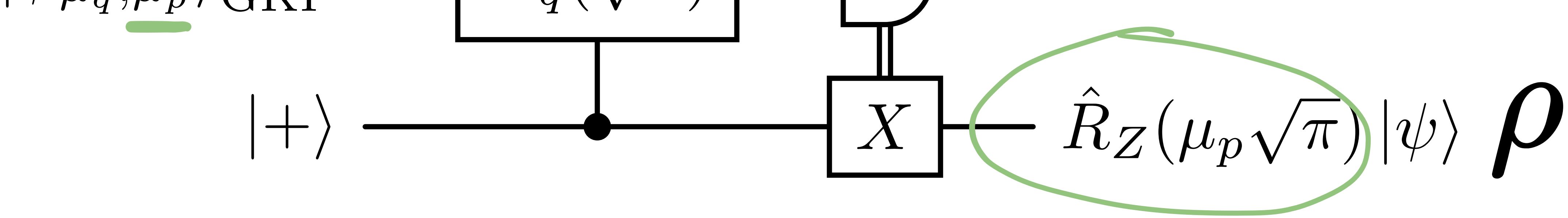


What happens to the qubit if you send in a squeezed thermal state?



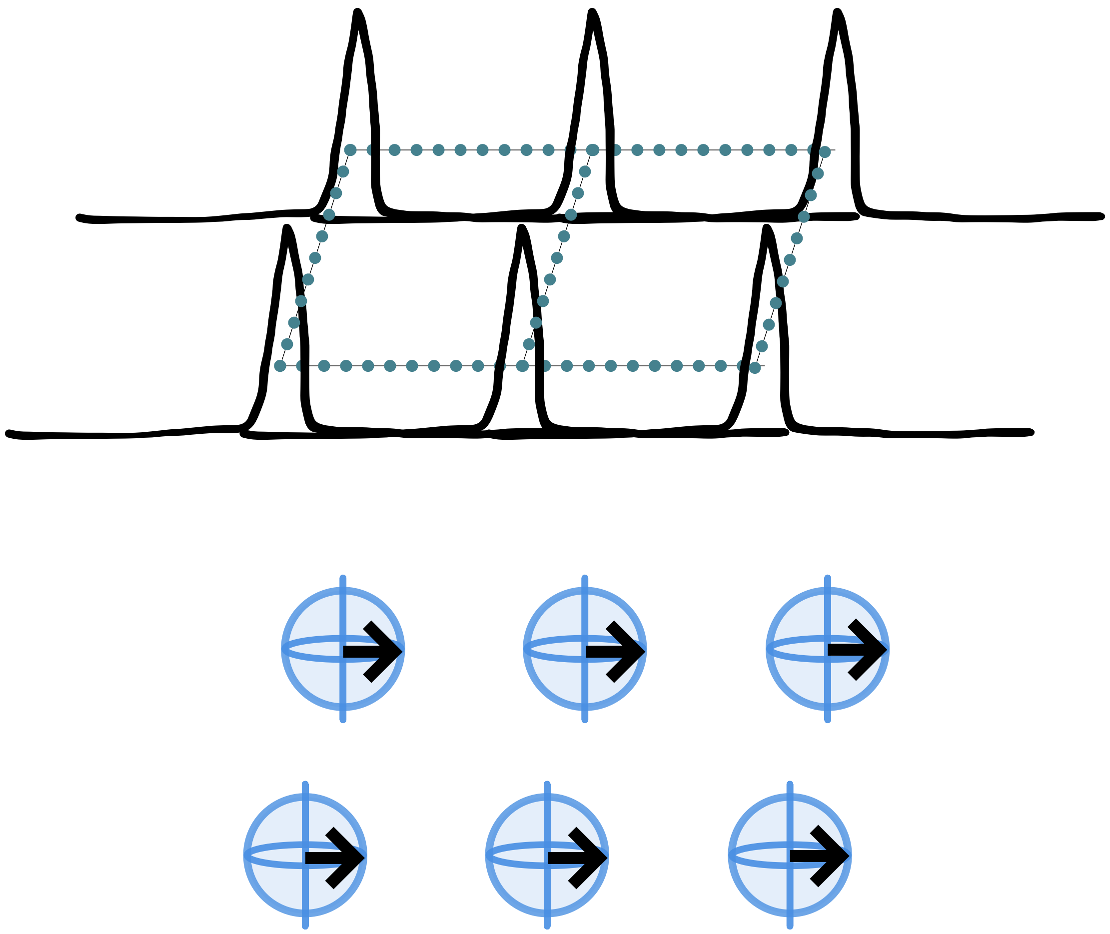


Qubit dephases



Weak conditional displacement

Suppose $\hat{C}_D$ is 3 times weaker



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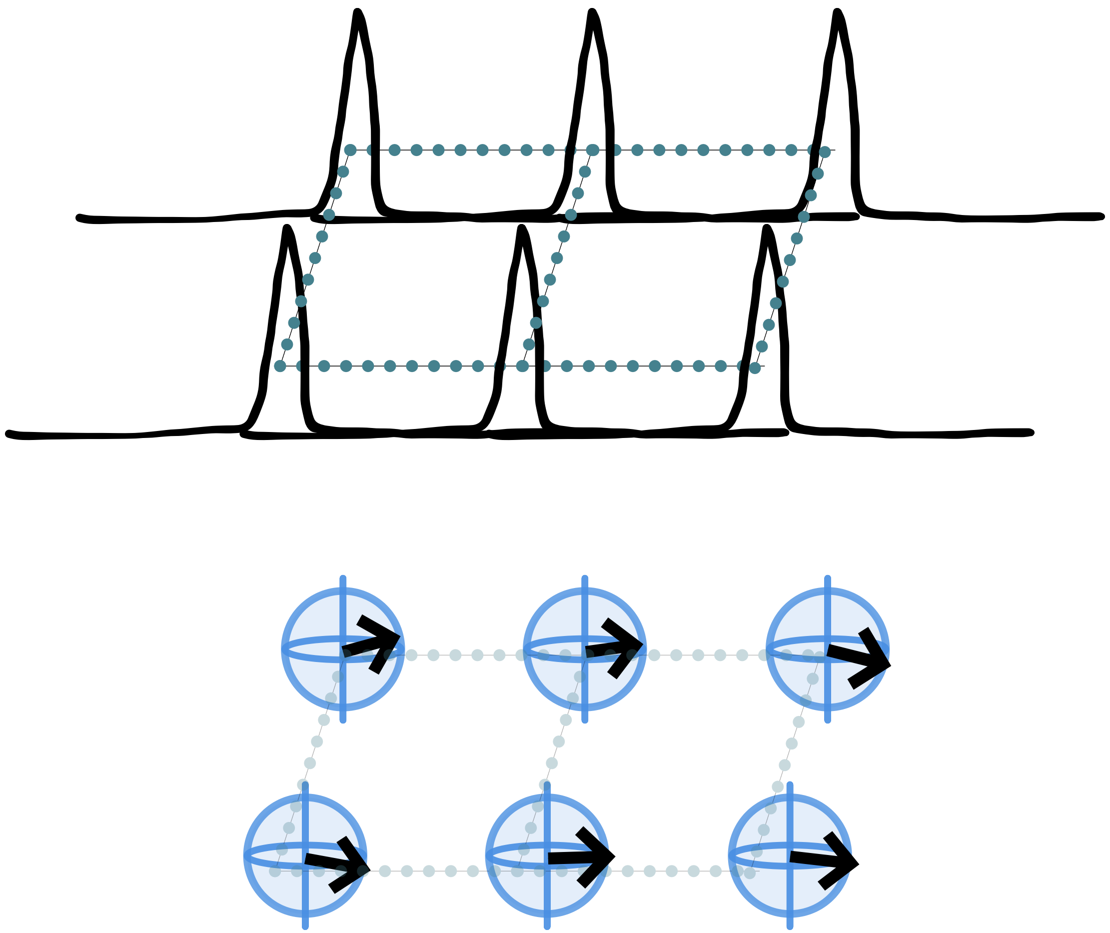

Weak conditional displacement

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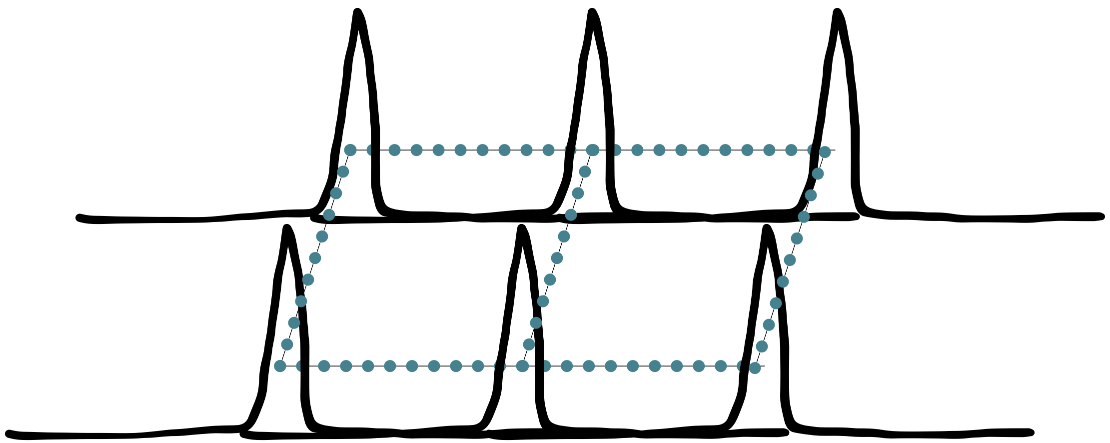
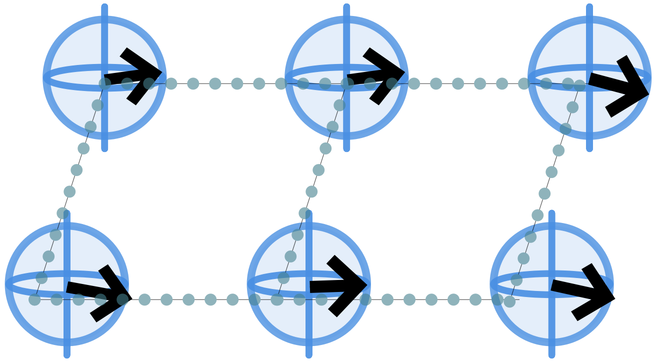
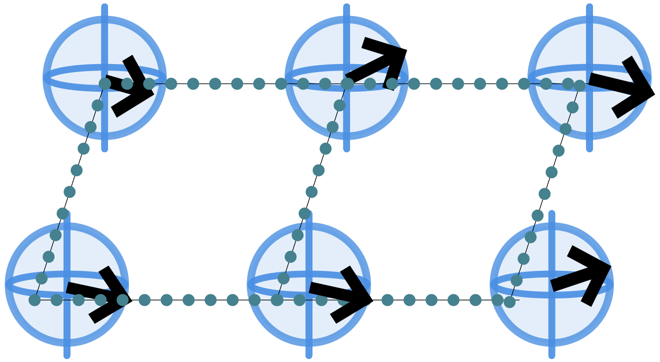




Weak conditional displacement

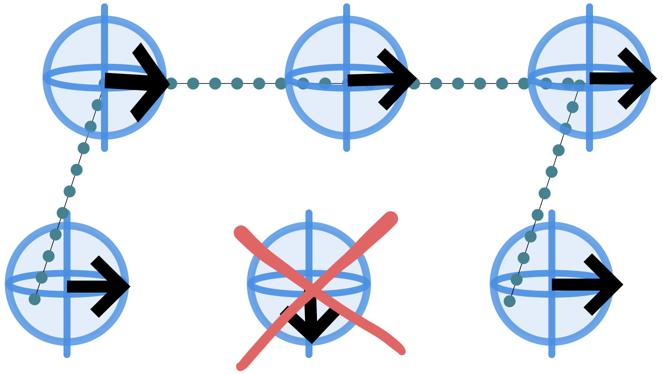
Suppose $\hat{C}_D$ is 3 times weaker

Weak conditional displacement can be cancelled out by performing entanglement transfer more times.

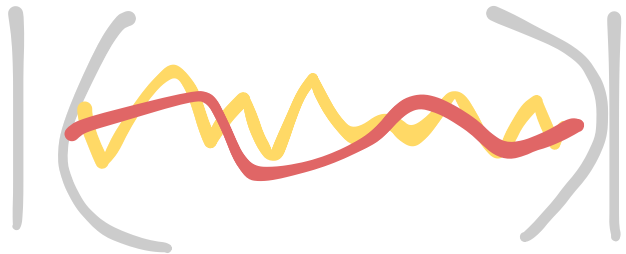


Suppose $\hat{C}_D$ is 3 times weaker

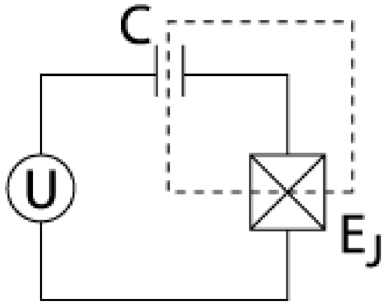
Only one round of weak measurement correction.



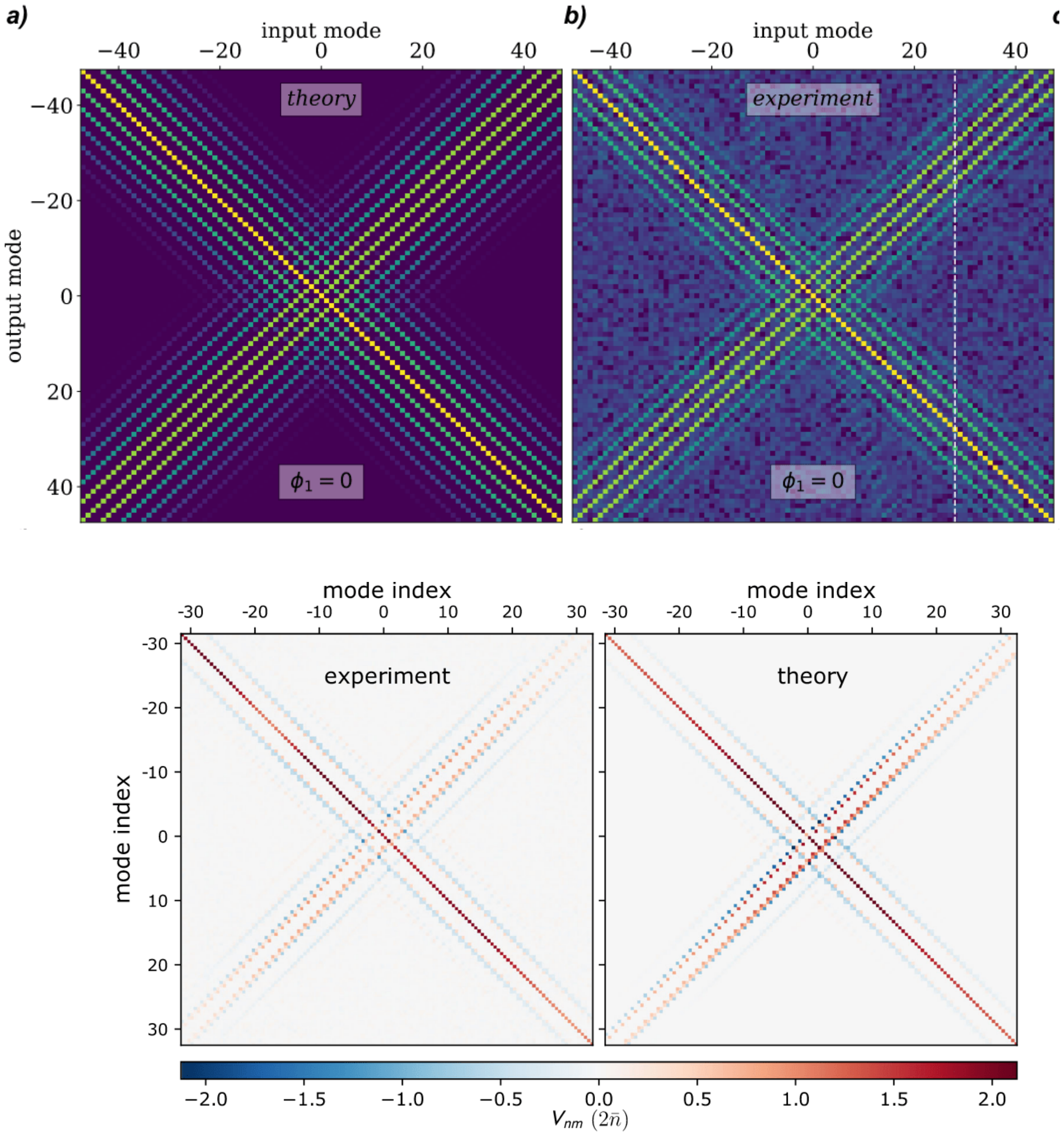
Possible implementations: Superconducting qubits



CV cluster: Frequency comb in microwave resonator



Transmon



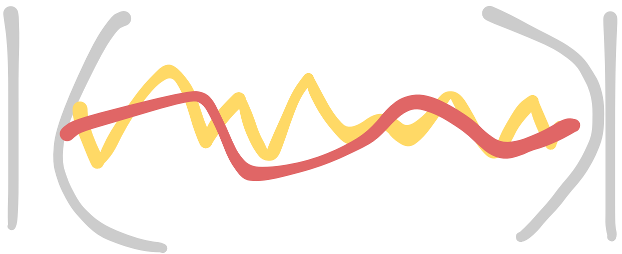
95 correlated modes

(Hernández 2024)

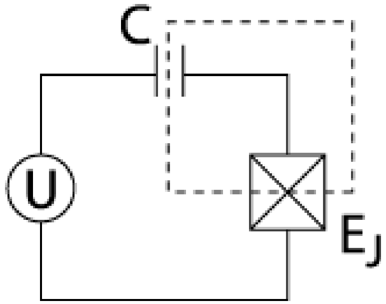
64 correlated modes

(Jolin 2023)

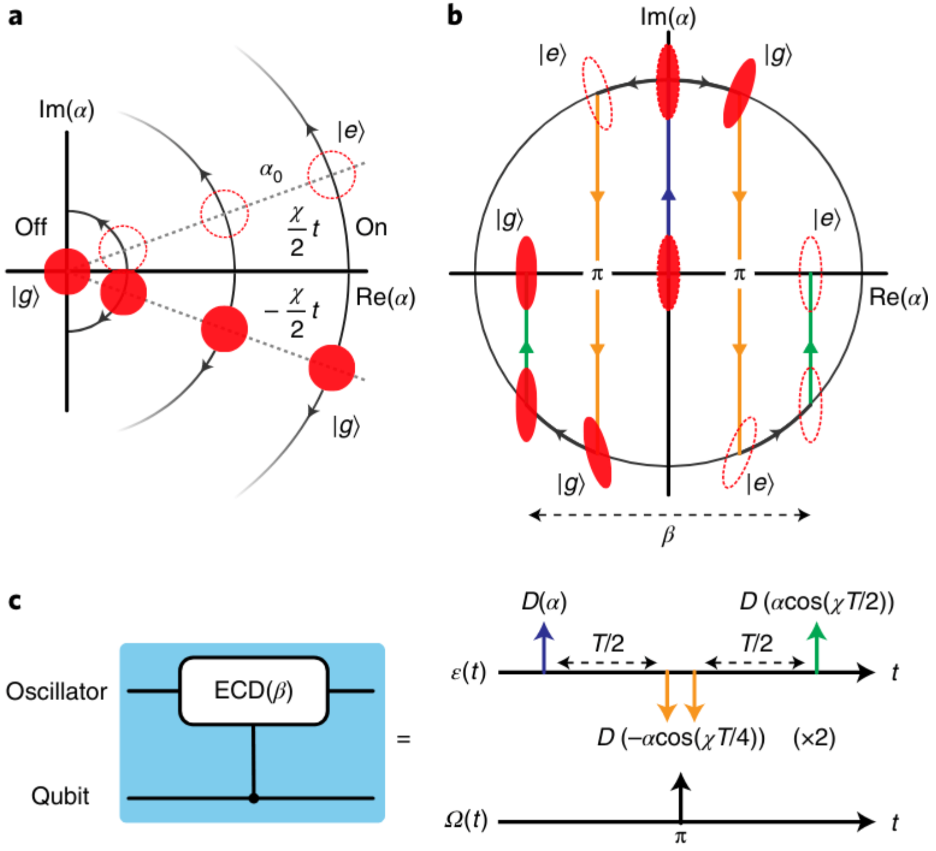
Possible implementations: Superconducting qubits



CV cluster: Frequency comb
in microwave resonator

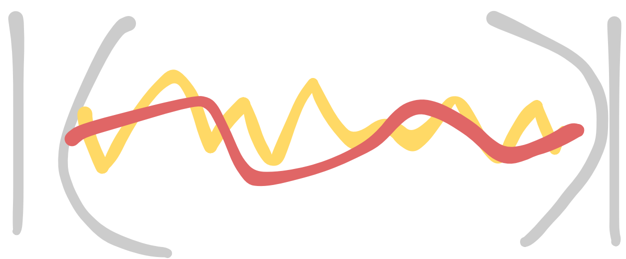


Transmon

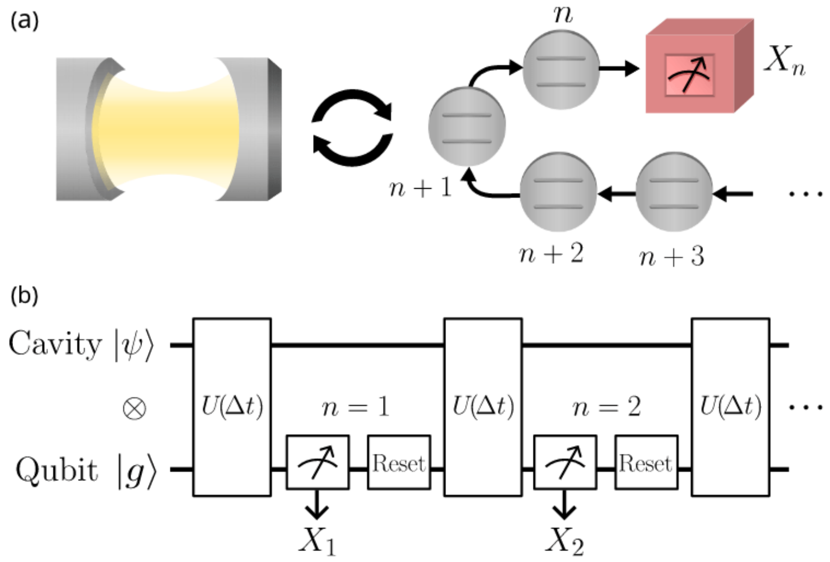


Conditional displacement:
ECD gate (A. Eickbusch 2018)

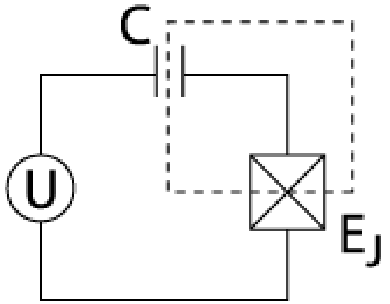
Possible implementations: Superconducting qubits



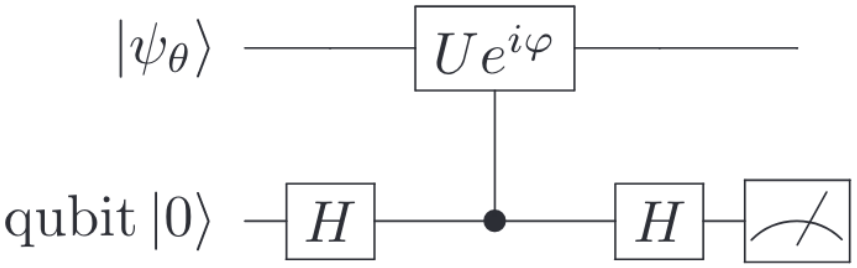
CV cluster: Frequency comb in microwave resonator



Qubitdyne detection (Strandberg 2023)

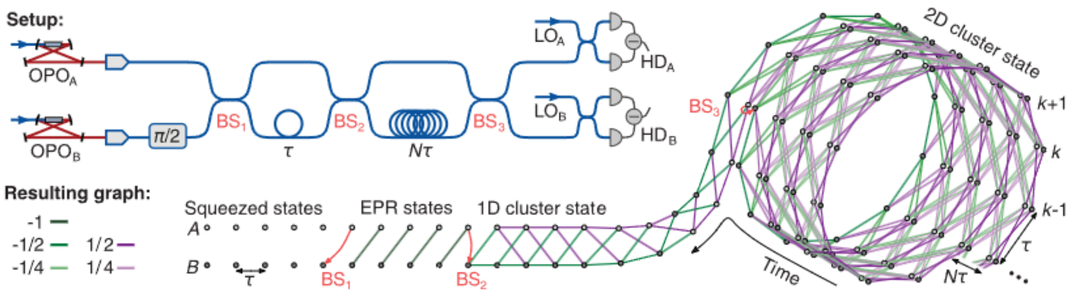


Transmon

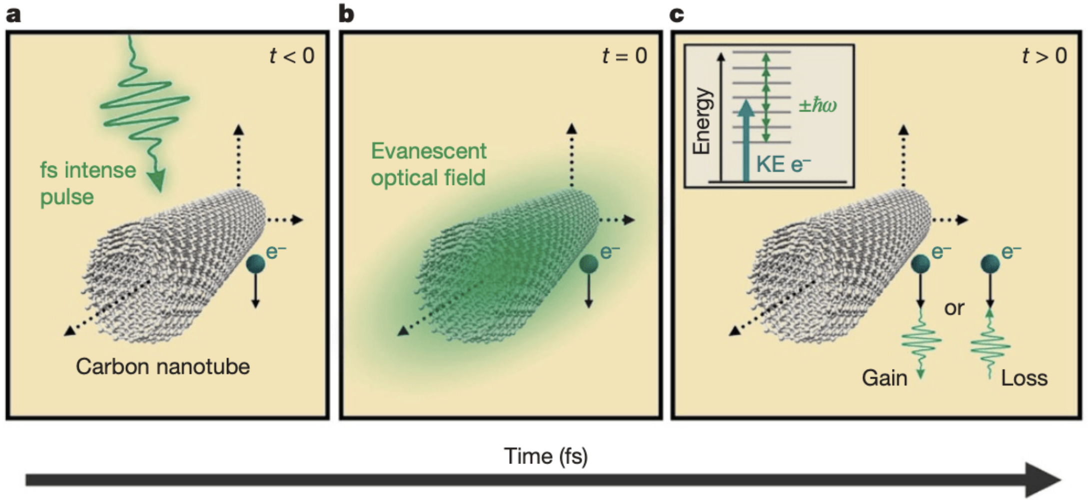


Quantum Phase Estimation (Terhal and Weigand 2016)

Possible implementations: Free electron qubits



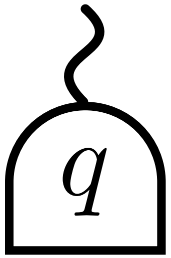
CV cluster: Furusawa protocol



CD gate: Photon-induced near-field electron microscopy (Barwick 2009)

Free electron qubits

(Reinhardt 2021, Baranes 2024)



Homodyne detection

Possible implementations: Summary

	Superconducting qubit + microwave cavity	**Free electron qubits**
CV cluster state	Frequency comb in cavity	Optics
Conditional displacement	Echoed conditional displacement gate (ECD gate)	PINEM (photon-induced near field electron microscopy)
Homodyne detection	Quantum phase estimation Qubitdyne detection	Homodyne detection
Qubit	Transmon	Free electrons

Downloading many-body continuous variable entanglement to qubits

- **We can make many body entanglement in qubits!!**
- Entanglement transfer from CV cluster state to qubit cluster state is possible
- Quality of the qubit cluster state depends on the initial state
- Weak measurement protocol and qubit deletion protocol can reduce requirements
- 6dB squeezing for robust quantum memory
- 12dB squeezing for fault tolerant quantum computing
- No GKP states needed in protocol
- arXiV in progress

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CRSNG

SFU

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