

Quantum Computation via Communication

*One path to efficient and scalable
quantum computation*

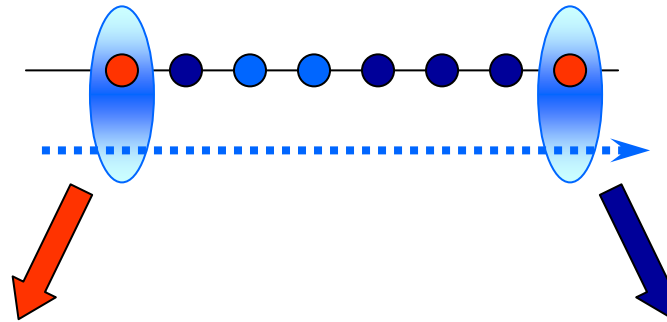
Kae Nemoto
(National Institute of Informatics, Tokyo)

Universal quantum computation

- We need **two types of operations**:
 - Single-qubit operation
 - Accessibility to each qubit is necessary.
 - Control on each qubit is required.
 - Two-qubit operation
 - Conditional operation such as Control-NOT (CNOT) gate requires two-qubit operation.
- Single-qubit operations and two-qubit operations are a kind of trade-off.
- For example,
 - Weak coupling system:
 - Single-qubit operation – easy, low decoherence
 - Two-qubit operation – very difficult
 - Strong coupling system:
 - Single-qubit manipulation – difficult operation and measurement,
 - Two-qubit operation – natural coupling, high decoherence.
- Can we give up to do both in the same mechanism?

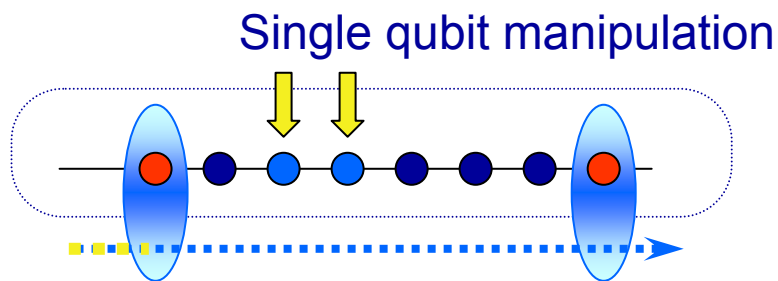
Our QIP System

Two-qubit operation
= quantum communication between two qubits

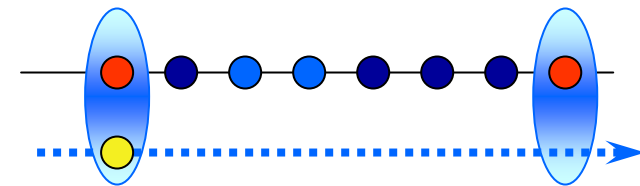


Qubit Quantum Computational System

All Qubit Computation



Continuous Variable



Flying Qubits

Qubits are better in quantum computation
Continuous variables are better in quantum communication

All Optics Quantum Computation

In collaboration with:

Bill Munro

Tim Spiller

Hewlett Packard Labs(Bristol, UK)

Linear Optics Quantum Computation

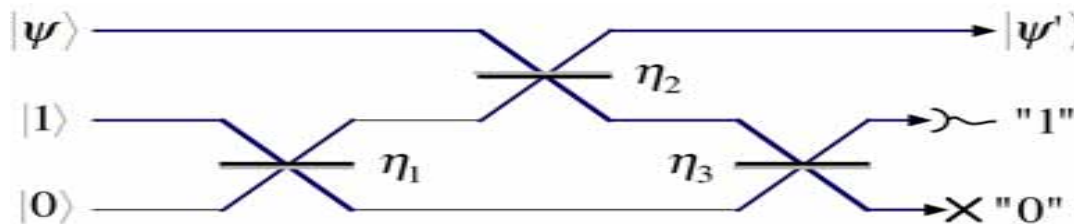
- Optics implementation:
 - Low decoherence, easy one qubit rotation.
 - Two-qubit operation is difficult. (Lack of optical nonlinearity)



■ Linear optical quantum computation

- The key trick are **non-deterministic operations**,

$$c_0|0\rangle + c_1|1\rangle + c_2|2\rangle \rightarrow c_0|0\rangle + c_1|1\rangle - c_2|2\rangle$$



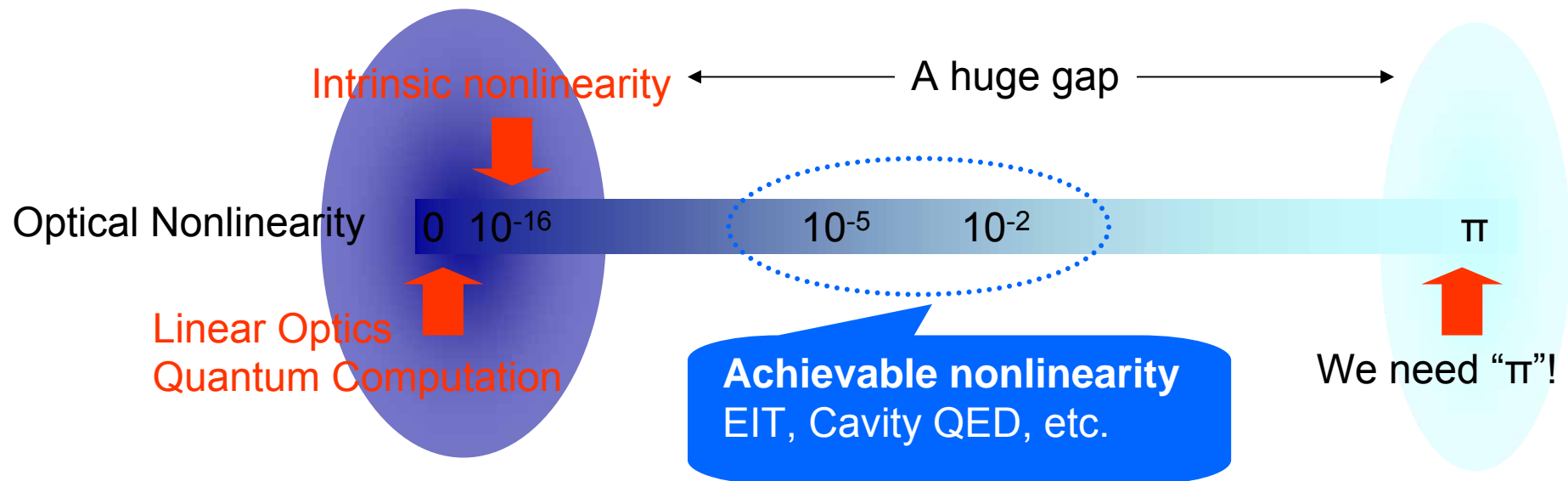
the gate heralded

The source of huge overhead

- and the gate teleportation. (Use off-line resource)
 - The scheme scales polynomial.
- Two-qubit operation can be constructed in a scalable manner, however the scalability is very bad.

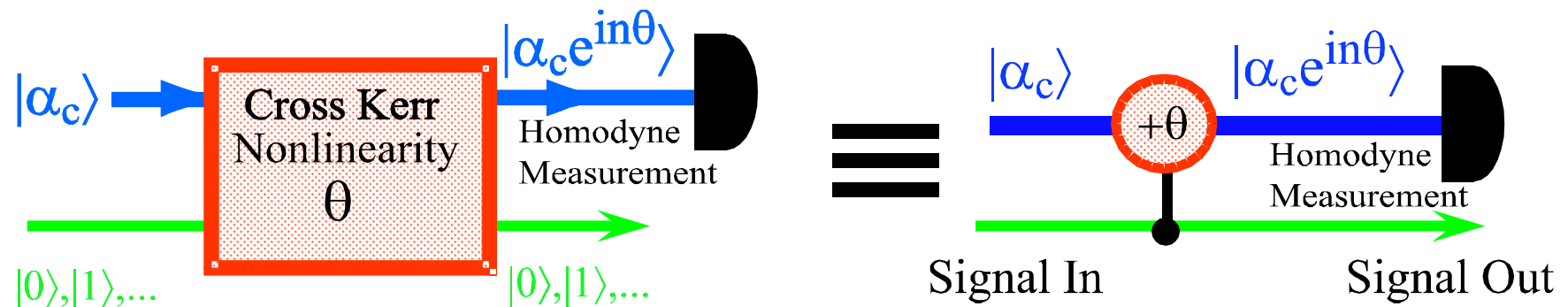
In the Huge Gap

- Linear optics quantum computation hide nonlinearity in single photon source and detection.
 - What is the physical resources for optical universal quantum computation.
- Intrinsic nonlinearity is too small for nonlinear gates.
 - Is new scheme available to exploit weak nonlinearities?



A Physical Primitive

- A physical primitive: a weak nonlinear interaction between signal and coherent state.



- Using the physical primitive, we construct the non-trivial elements for universal quantum computation.
 - The physical primitive + linear optical elements = Universal Quantum Computation

Photon Dumber Detection and Single Photon Generation

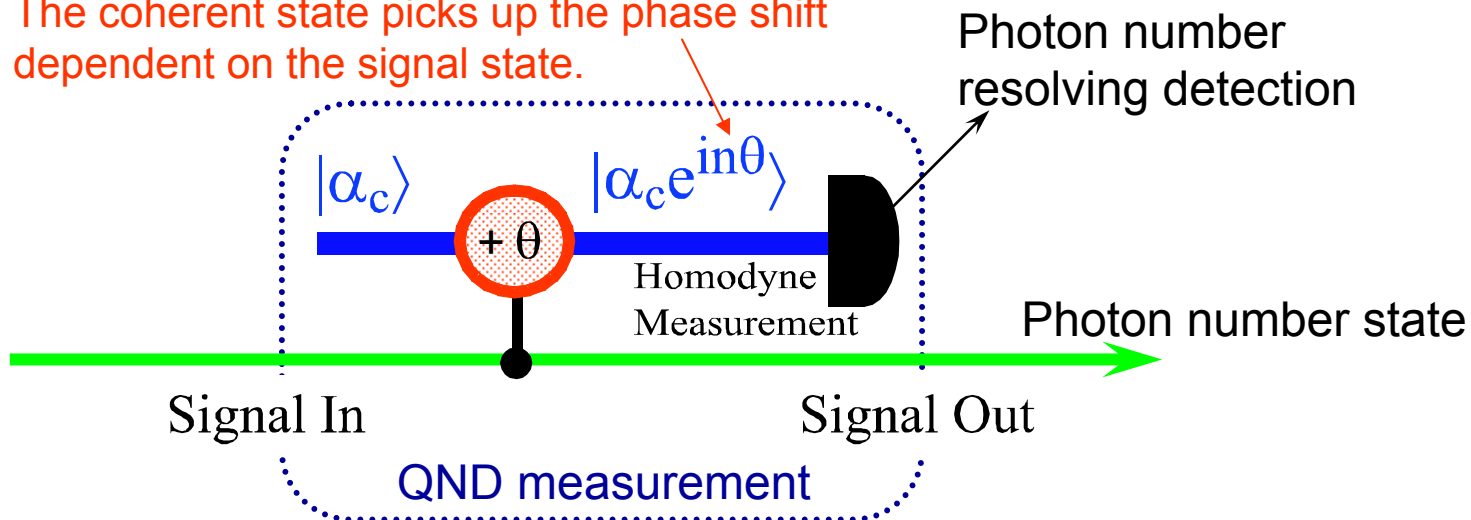
- Nonlinearity in single photon source and photon-number detection



- The QND measurement scheme

- Small nonlinearity can be exponentially enhanced by the intensity of probe mode.

The coherent state picks up the phase shift dependent on the signal state.



* G. J. Milburn and D. F. Walls, Phys. Rev. A 30, 56 (1984), N Imoto, et. al., Phys. Rev. A 32, 3287 (1985)

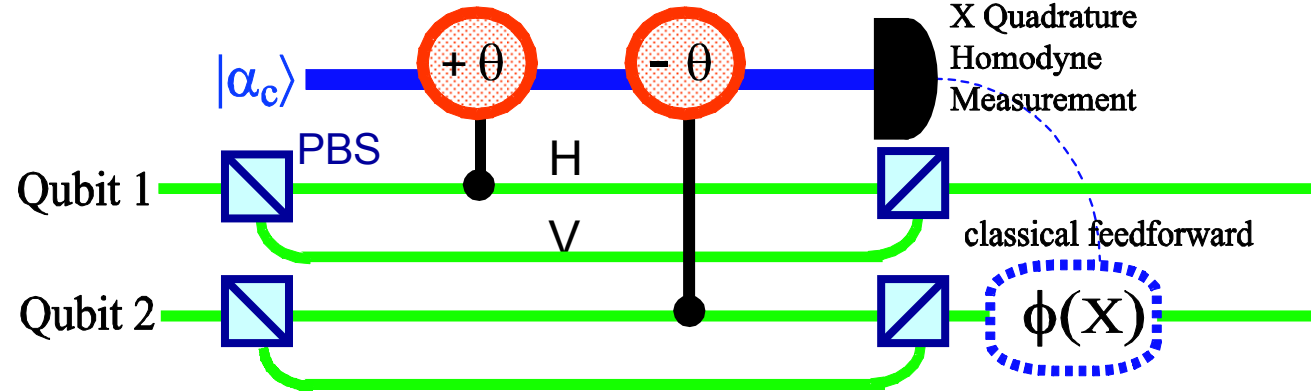
A Primitive Gate: Two-qubit Parity Detector

- QND measurement can be used to do parity measurement.

Input states:

$$|\Psi_{in}\rangle_1 = c_0|H\rangle + c_1|V\rangle$$

$$|\Psi_{in}\rangle_2 = d_0|H\rangle + d_1|V\rangle$$

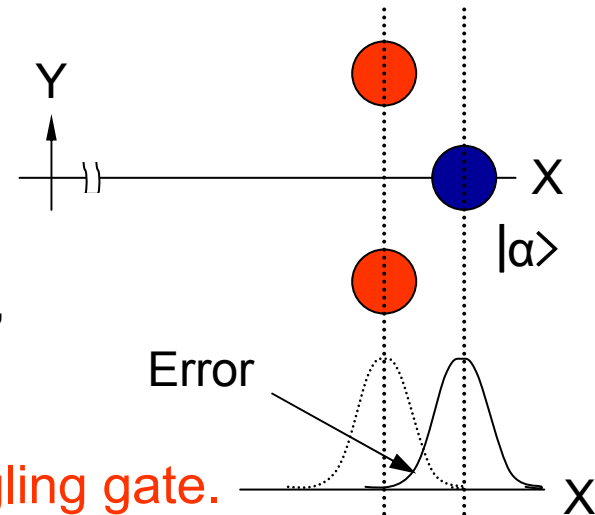


Output state before the measurement:

Kae Nemoto, *et. al.*, PRL 93, 260502 (2004)

$$|\Psi_T\rangle = c_0 d_0 |HH\rangle |\alpha\rangle + c_1 d_1 |VV\rangle |\alpha\rangle + c_0 d_1 |HV\rangle |\alpha e^{i\theta}\rangle + c_1 d_0 |VH\rangle |\alpha e^{i\theta}\rangle$$

Dependent on the measurement outcome, we can distinguish these two states.



- This parity measurement works as an entangling gate.

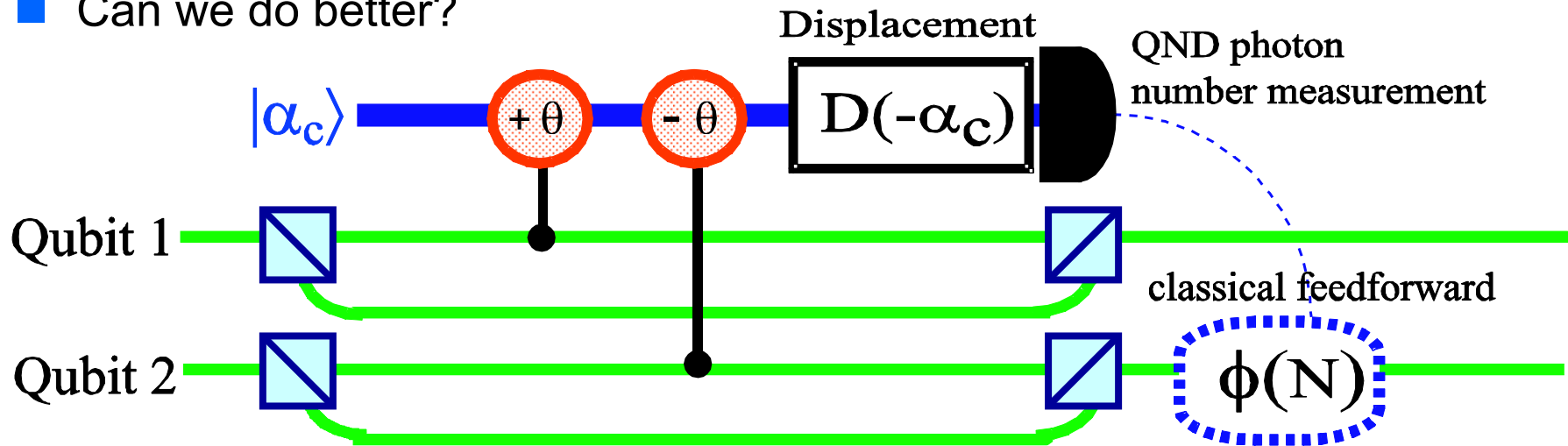
S Barrett, *et. al.*, PRA 71, 060302R (2005)

A more efficient parity gate

- Our previous two parity gates scaled their nonlinearity efficiency as

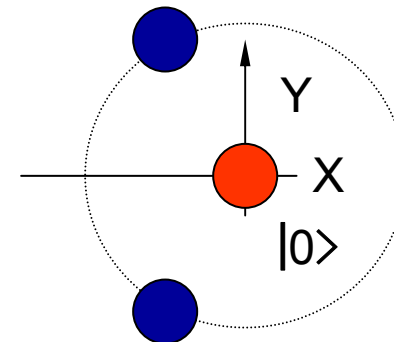
$$\alpha\theta^2 \sim \pi$$

- Can we do better?



- Use a displacement $D(-\alpha)$ and then a QND photon number measurement

$$|\Psi_T\rangle = [c_0 d_0 |HH\rangle + c_1 d_1 |VV\rangle] |0\rangle + [c_0 d_1 |HV\rangle + (-1)^n c_1 d_0 |VH\rangle] |n\rangle$$

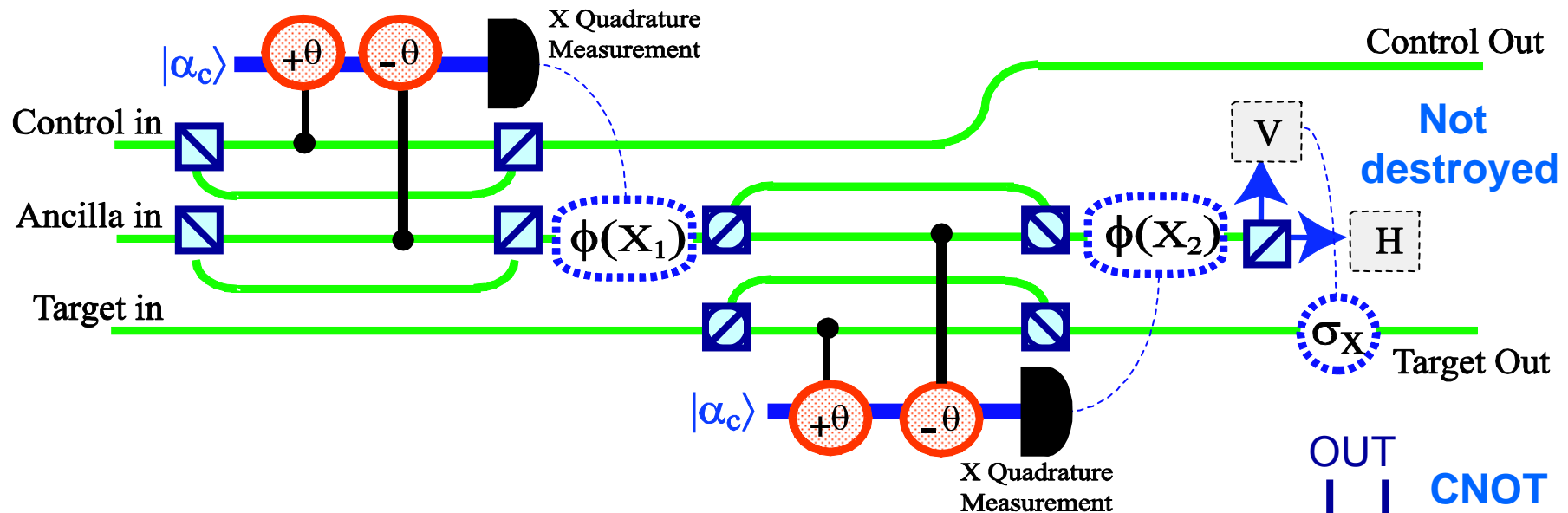


- scales now as

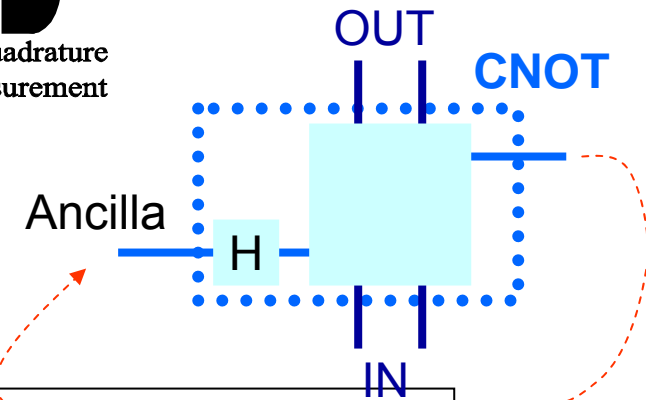
$$\alpha\theta \sim \pi$$

A CNOT gate

- The entangling gate can be used to construct CNOT gate.
- Based on the Franson CNOT gate*, we use the entangling gate and PBS and 45-PBS gates.



- This CNOT gate is near-deterministic.
 - Requires five small nonlinear gates.
 - Computational circuit requires $n+1$ qubits!!



* T.B.Pittman, *et. al.*, Phys. Rev. A 64, 062311 (2001); *ibid* PRA, 68, 032316 (2003)

Physical Primitives: Physical Requirements for Universal QC

- Necessary and sufficient requirements for universal quantum computation.
 - ▣ What essential physical elements make quantum computation universal?
 - **Physical primitives.**
 - A source of coherent states
 - Efficient homodyne detection
 - Linear optical elements and classical control (feed-forward)
 - **A source of non-zero weak optical nonlinearities**
 - ▣ Physical primitives \leftrightarrow Universal gate set
 - ▣ The set of physical primitives give a practically different scalability

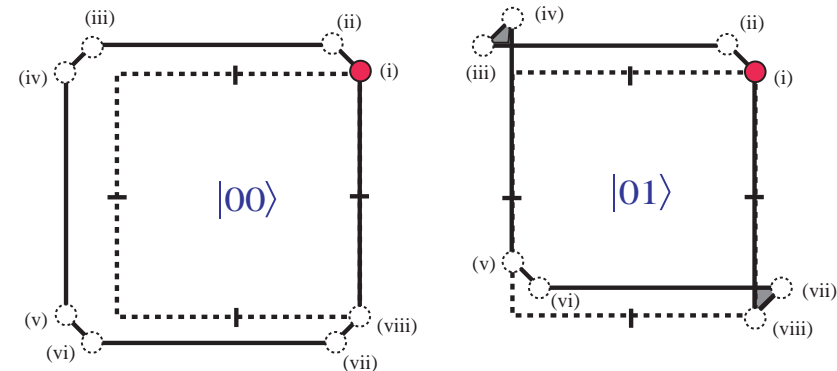
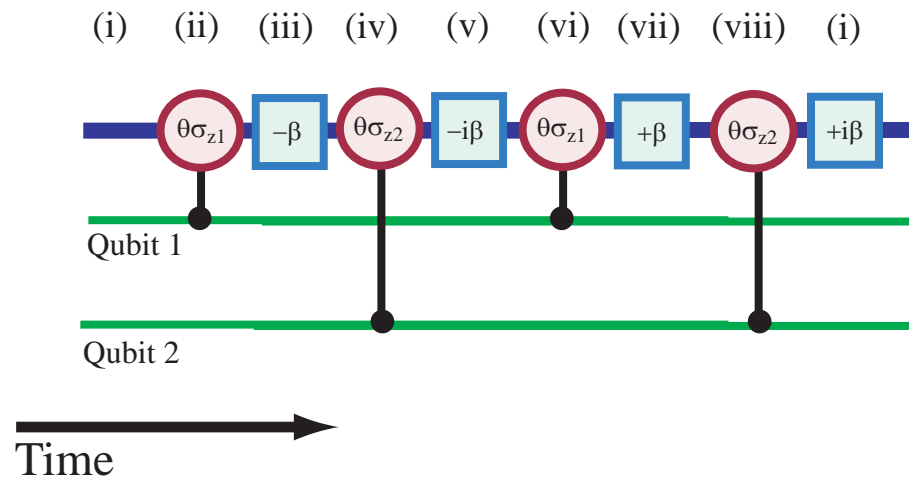
QND logic model	Physical primitives \approx Logic gates
LOQC	Physical primitives \ll Logic gates

- This criteria can be applied for other physical systems and are computational model free.

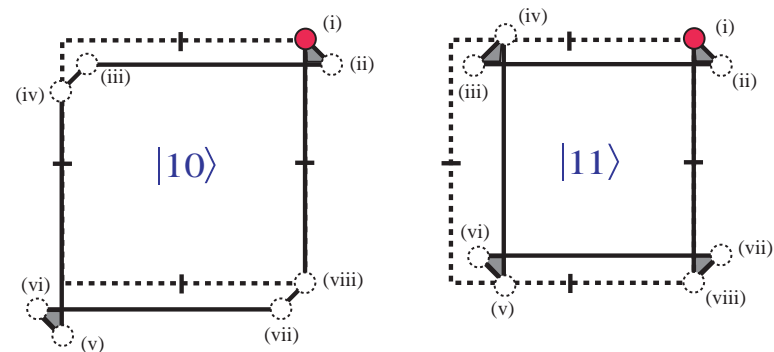
K, Nemoto, *et. al.*, PLA (2005)

The measurement free gate

- Using the controlled rotation interaction with un-conditional displacements we can create a measurement free gate.
- It uses four controlled rotations and 4 displacements



Evolution of the Probe beam



- This enables the nature generation of a CPhase gate where the phase shift is

$$\alpha\theta \sim \sqrt{\frac{\pi}{4}}$$

Hybrid QIP Systems

Quantum computation via communication
from optics to SQUIDs

In collaboration with:

Bill Munro
Tim Spiller
(Hewlett Packard Labs)

Sam Braunstein
(York University)

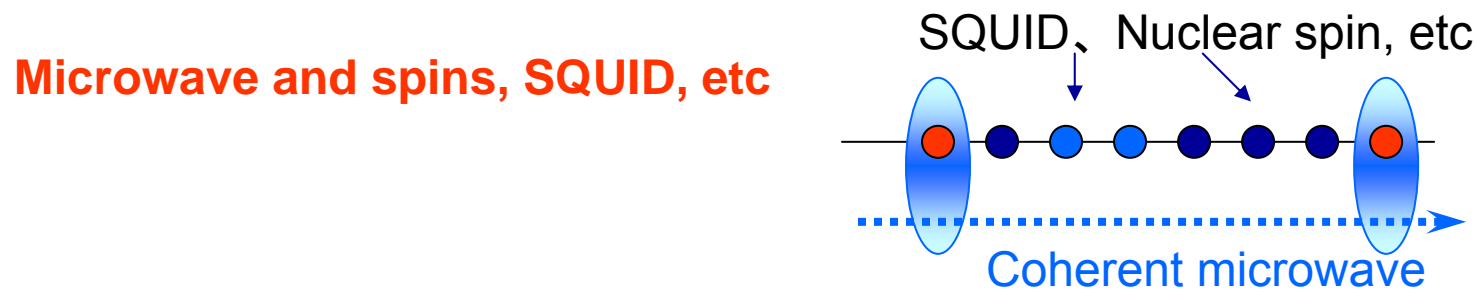
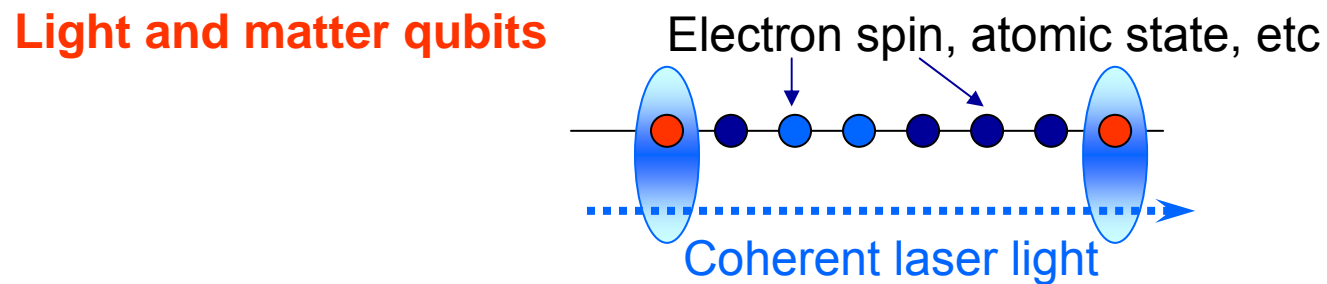
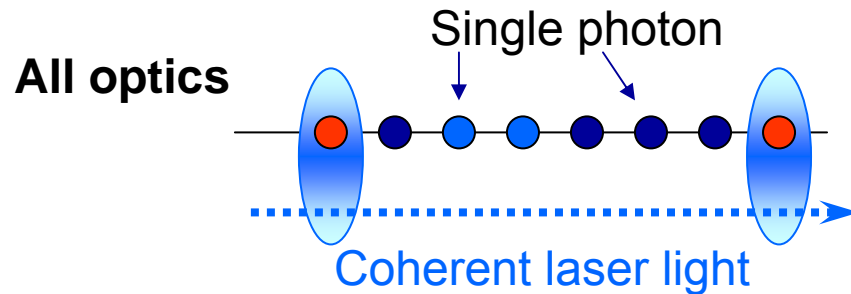
Gerard Milburn
(University of Queensland)

Peter van Loock
(NII)

Rod Van Meter
(Keio University)

Computational Qubits and CV communication bus

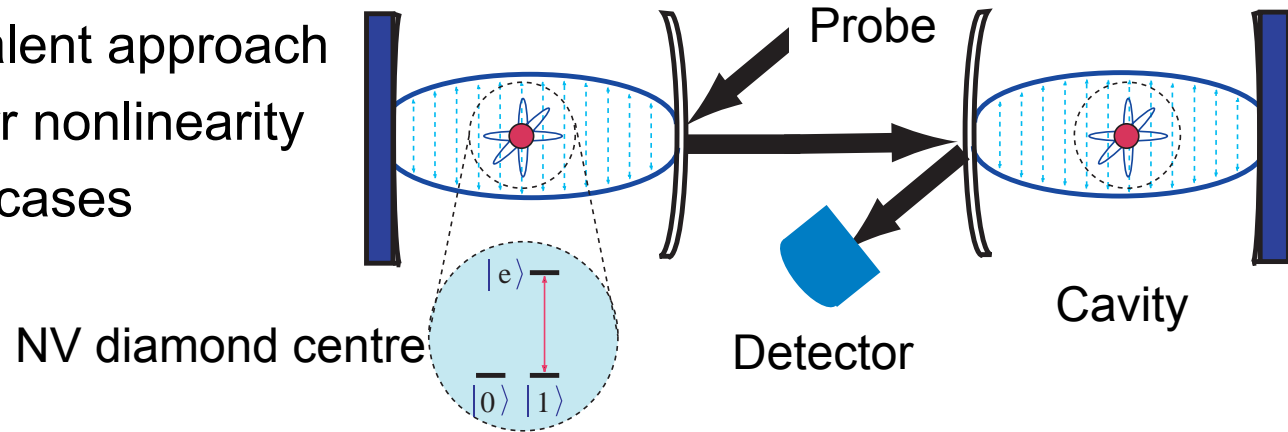
- Hybrid systems
= Computational Qubits + Continuous variable communication bus
- Variations:



- More variations...

Controlled Rotations: A QND based approach

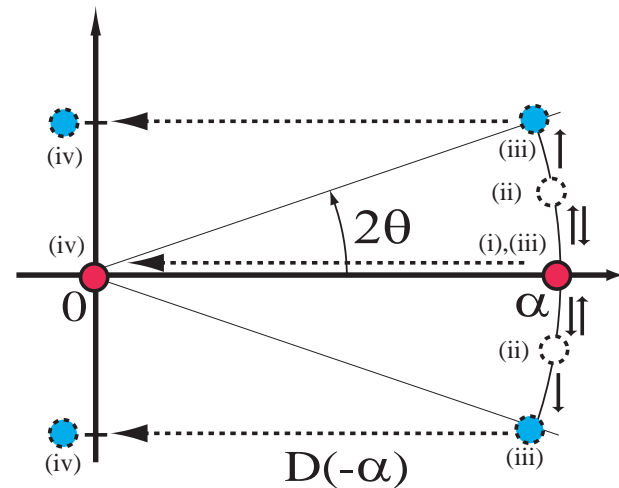
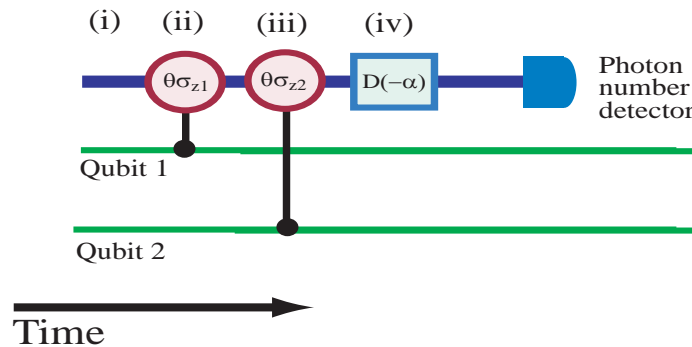
- This is the equivalent approach to our cross-Kerr nonlinearity for the all optical cases



- In cavity QED we have in the dissipative limit a natural interaction of the form

$$U = \text{Exp}[i \theta \hat{n}_p \hat{\sigma}_z]$$

- Now consider the circuit



$$|\Psi_T\rangle = [c_0 d_0 |\uparrow\downarrow\rangle + c_1 d_1 |\downarrow\uparrow\rangle] |0\rangle + [c_0 d_1 |\uparrow\uparrow\rangle + (-1)^n c_1 d_0 |\downarrow\downarrow\rangle] |n\rangle$$

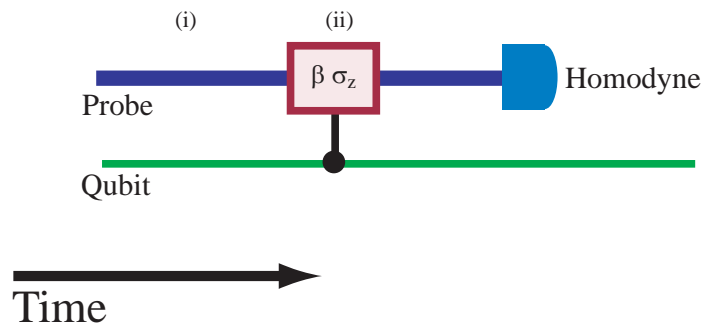
What about controlled displacements?

- So far we have seen the power of controlled rotations and un-conditional displacements.
- Are other controlled operations naturally available. The answer is yes!!!
- In many physical systems we have a controlled displacement whose evolution is given by

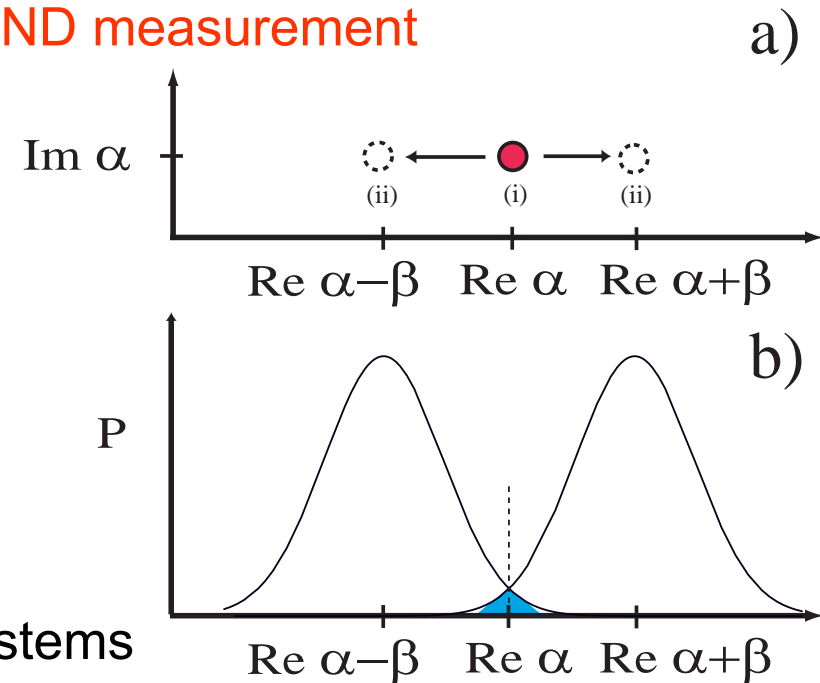
$$U = \text{Exp}[i \theta \hat{x}_p \hat{\sigma}_z]$$

- This can obviously be used to do a **QND measurement**

- Measure the state of the matter qubit by the probe beam

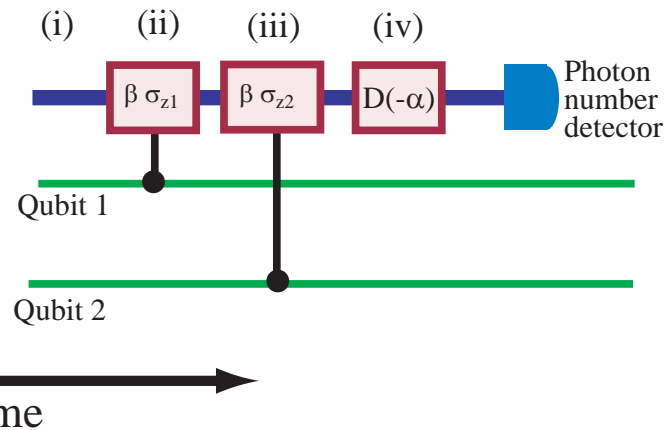


- Has been done in a number of systems

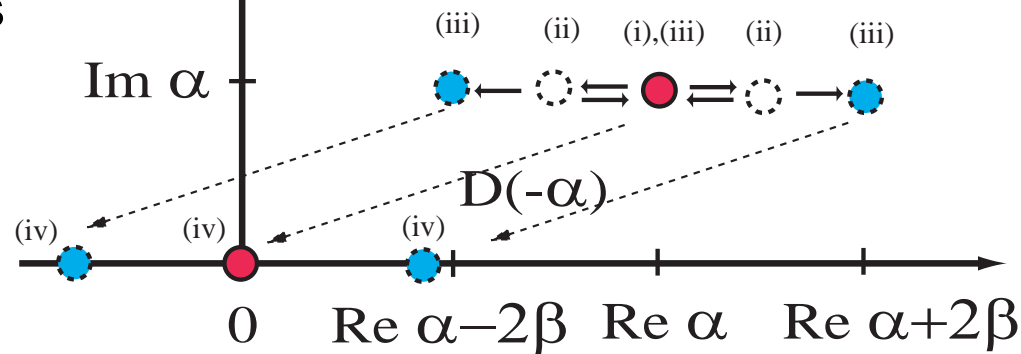


Displacement based Parity Gates

- We can build the analog of the controlled rotation parity gate.
- For instance, consider the circuit



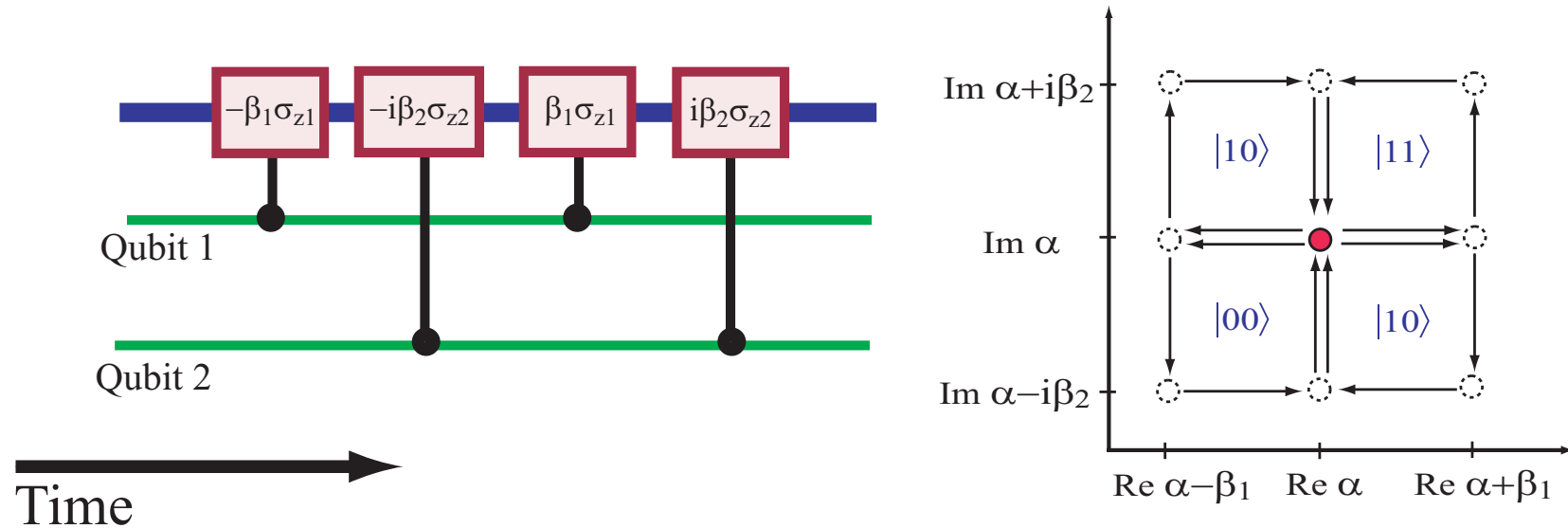
- It is straight forward to show that in phase space, the probe beam evolves as



$$|\Psi_T\rangle = [c_0 d_0 |\uparrow\downarrow\rangle + c_1 d_1 |\downarrow\uparrow\rangle] |0\rangle + [c_0 d_1 |\uparrow\uparrow\rangle + (-1)^n c_1 d_0 |\downarrow\downarrow\rangle] |n\rangle$$

Geometrical Phase Gate with Conditional Displacement

- A new scheme using conditional displacement interaction
 - Geometrical Phase gate:



CPhase gate:

$$\begin{aligned} |00\rangle &\rightarrow |00\rangle \\ |01\rangle &\rightarrow |01\rangle \\ |10\rangle &\rightarrow |10\rangle \\ |11\rangle &\rightarrow -|11\rangle \end{aligned}$$

$$\left(\begin{array}{l} \sigma_{z2} \rightarrow \sigma_{x2} \\ \text{CPhase gate} \rightarrow \text{CNOT gate} \end{array} \right)$$

Distributed Quantum Computation

- Scalable universal quantum computation

Model-free technology

Cluster state approach, etc
(Applicable to other
computation schemes)

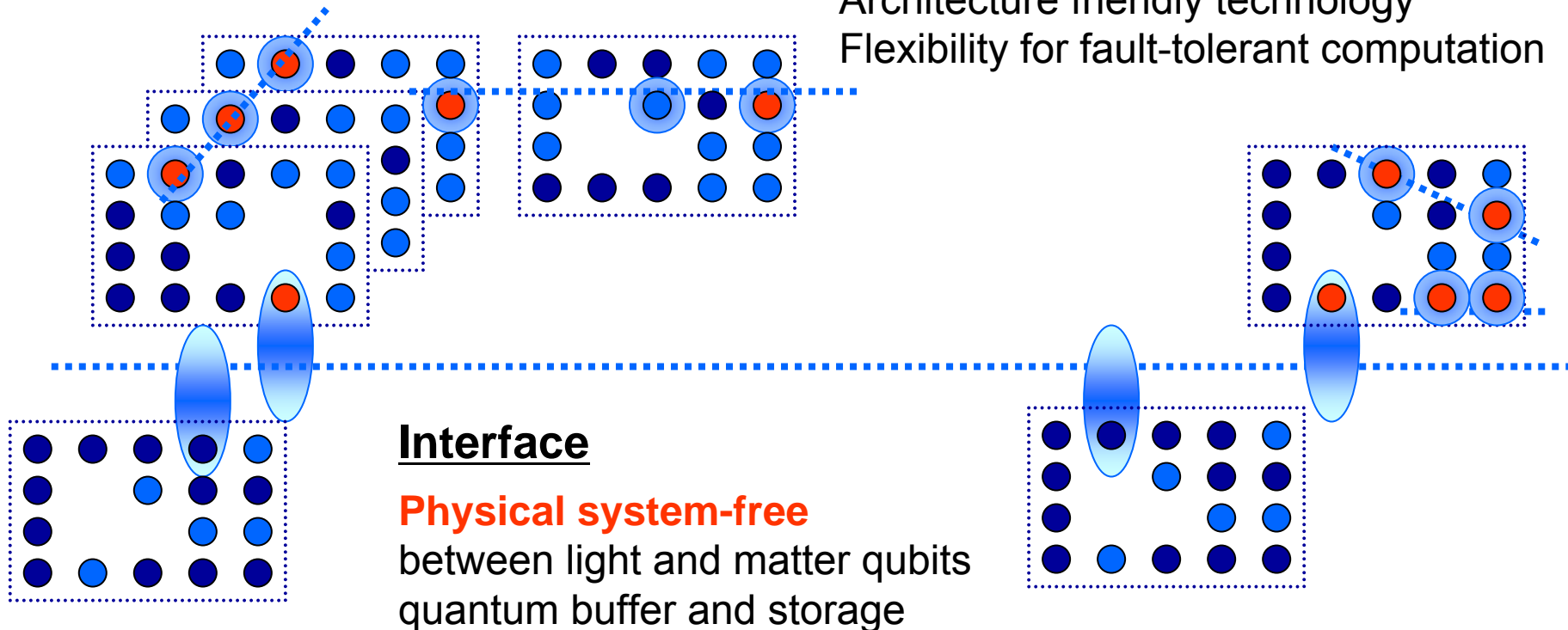
Gate distribution

Scale-free structure

- short to large distance
- small to large scale computation

Architecture friendly technology

Flexibility for fault-tolerant computation



END