Optical continuous-variable cluster states

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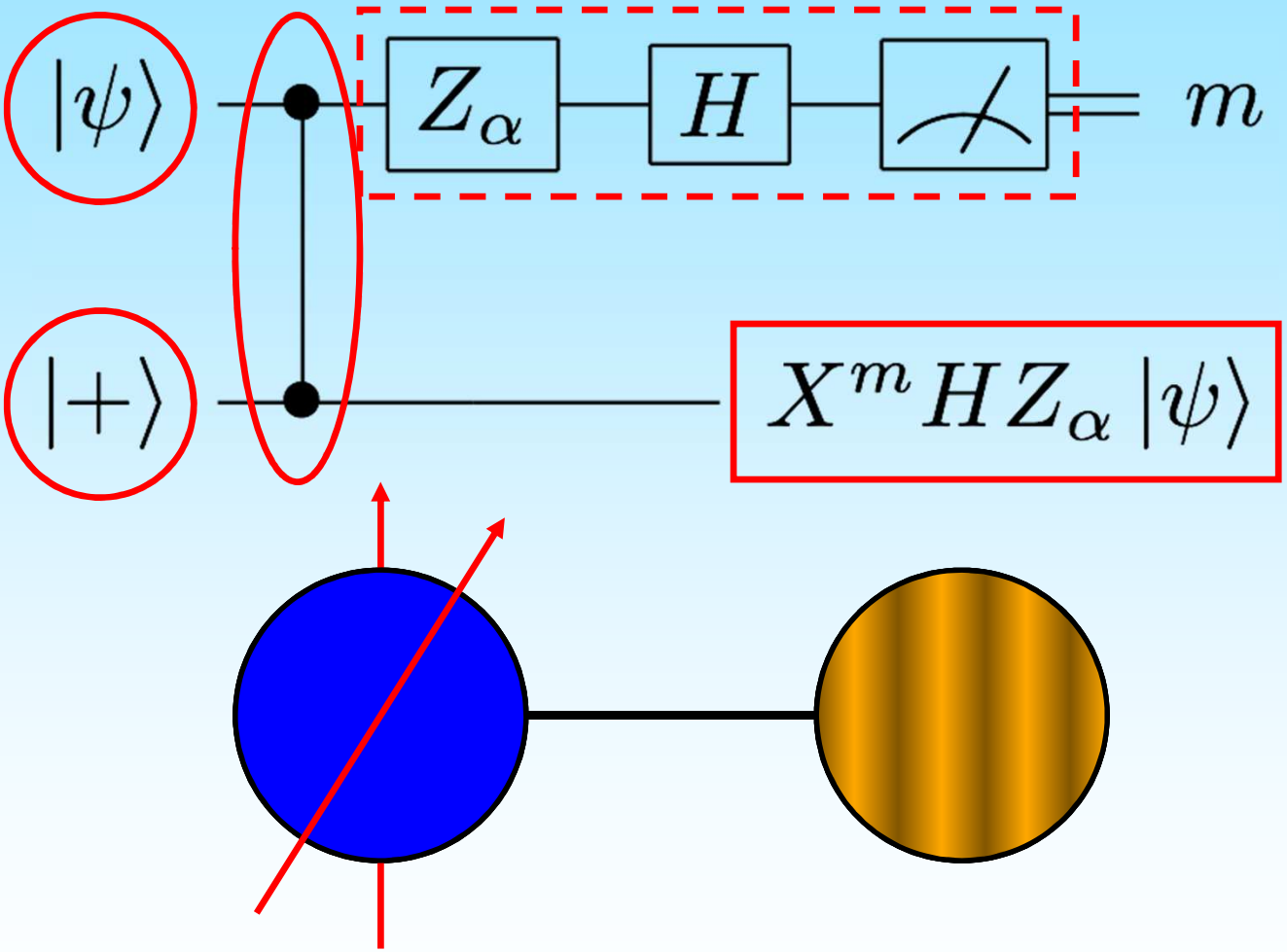
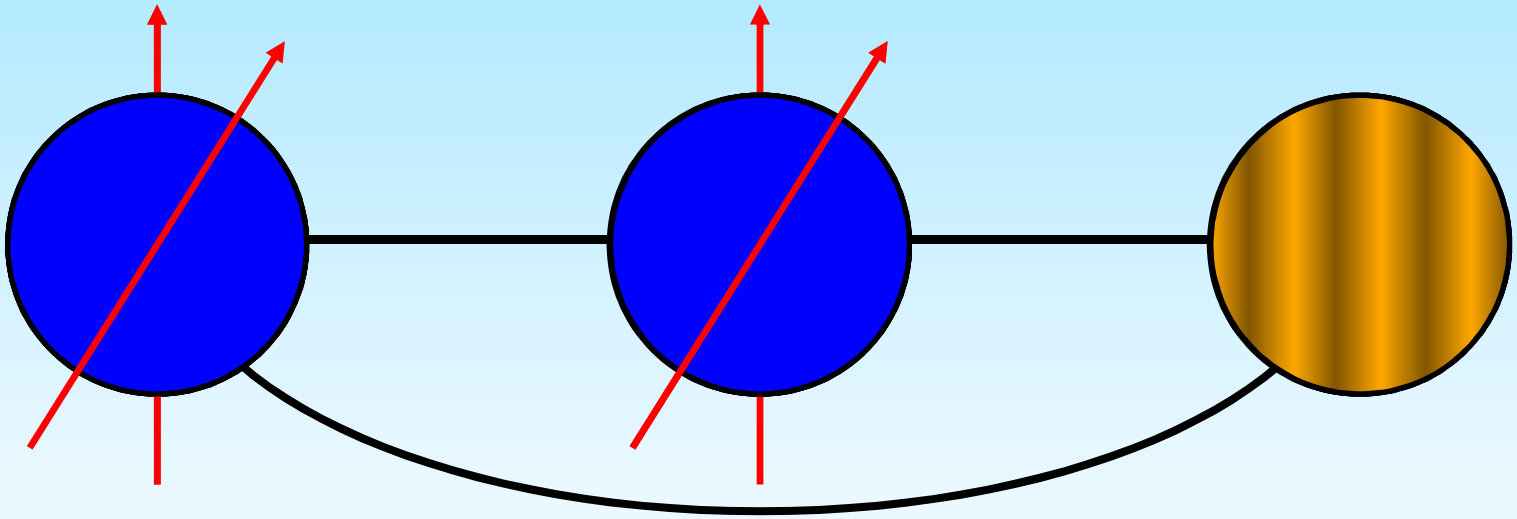
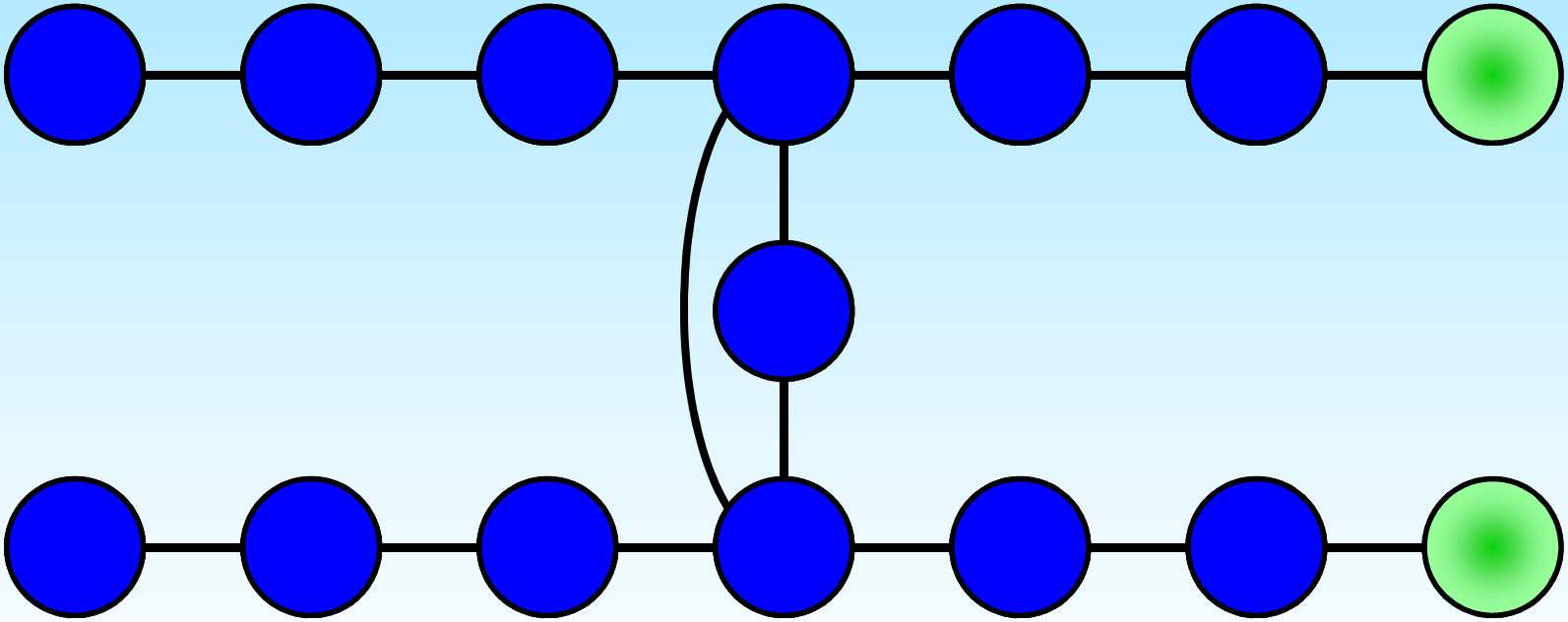
Teleportation "Lite"



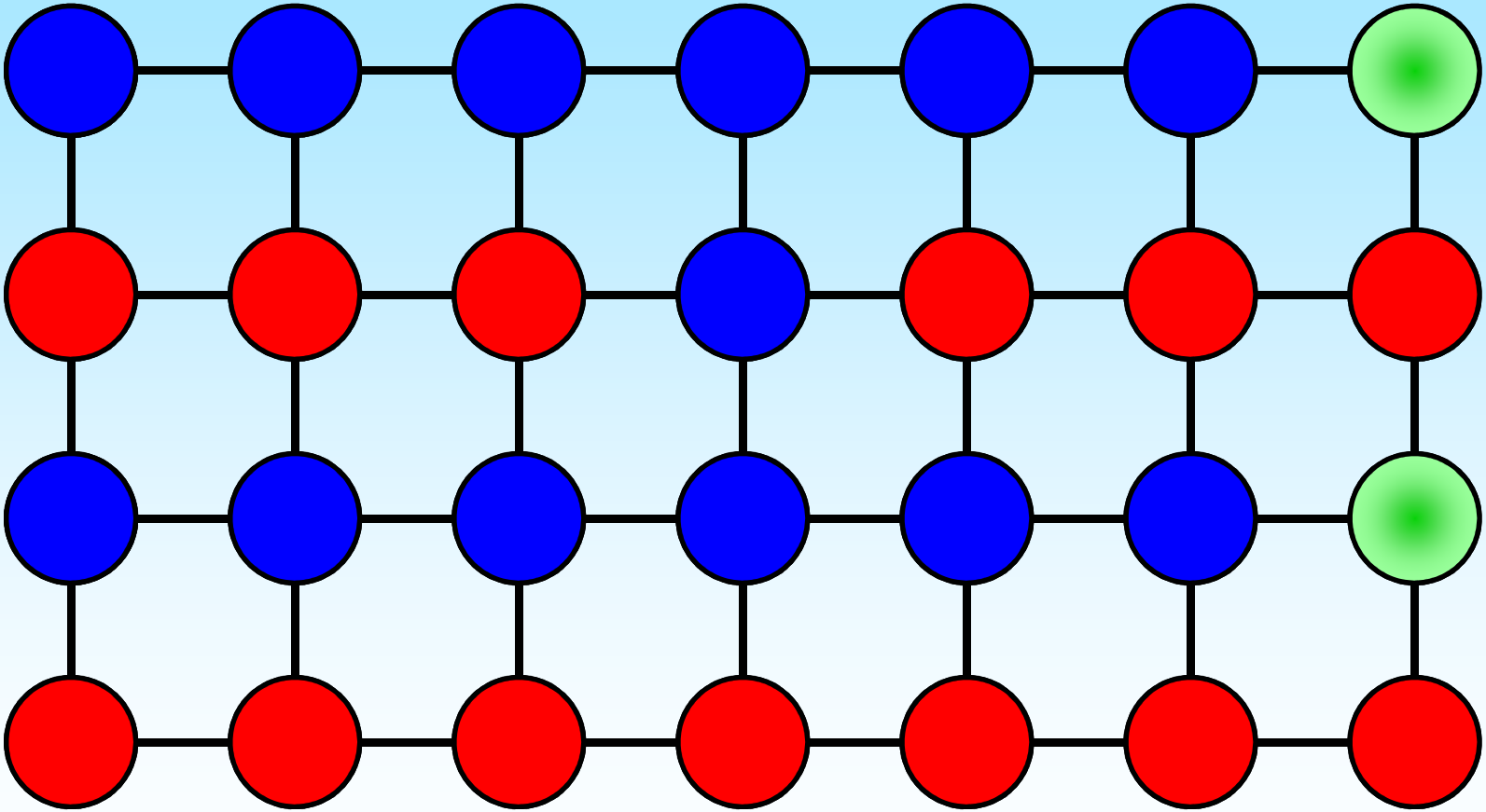
Teleportation



Teleportation Network

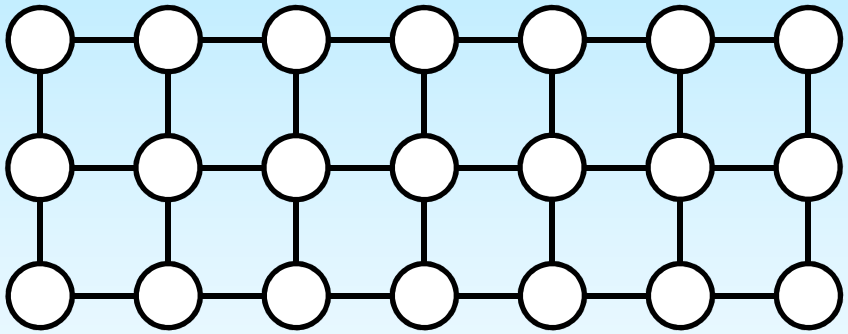


Cluster State



Continuous-Variable Clusters

- Construct CV clusters same way as for qubits
  - circles: $|+\rangle$ becomes zero-momentum eigenstate
  - edges: In CV case, $\mathrm{C}_Z = \exp(i\hat{q}_1 \otimes \hat{q}_2)$



- Every CV cluster state has a corresponding graph (just as for qubits)

NCM, P. van Loock, M. Gu, *et al.*, PRL **97**, 110501 (2006)

Optical Implementation

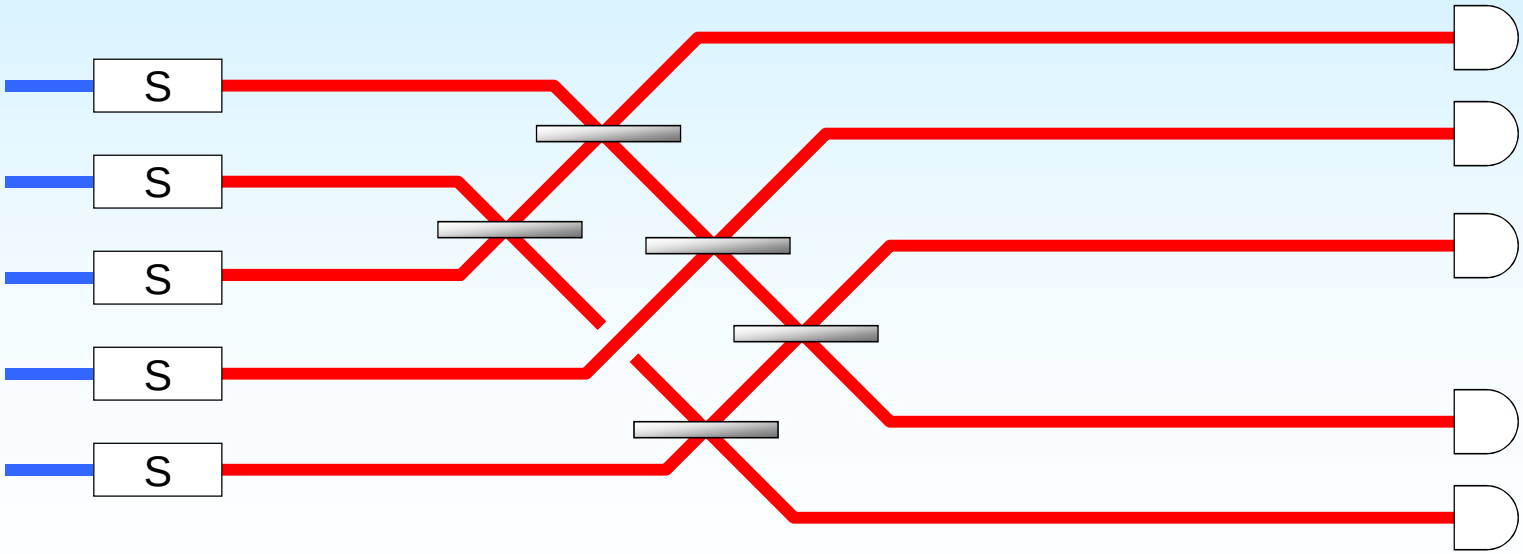
- 1 mode = 1 node
  - $q = a + a^\dagger$
  - $p = -i(a - a^\dagger)$
- Problem: momentum eigenstates have infinite energy (unphysical)
  - Use *finitely* squeezed vacuum states
  - Physical states ⇒ faulty ⇒ errors in computation
  - No “magic pill”—need fault tolerance from start
    - M. Ohliger, K. Kieling, J. Eisert, arXiv:1004.0081
    - H. Cable, D. Browne, arXiv:1008.4855
- C_Z gate can be accomplished with beam splitters and weak inline squeezing (hard!)

Measurements

- Only single-mode projective measurements are required for universal QC
- Homodyne detection (quadrature measurement) alone allows for all *multimode* Gaussian operations
  - Relatively easy to do experimentally
- One non-Gaussian measurement is additionally needed for universality
  - Photon counting (harder)

Practical Preparation Method #1

- In-line squeezing (C_Z gate) can be replaced with an appropriate beam splitter network*
  - In general, $O(N^2)$ optical elements needed
  - One squeezer for each mode
  - Entanglement between *spatial* modes



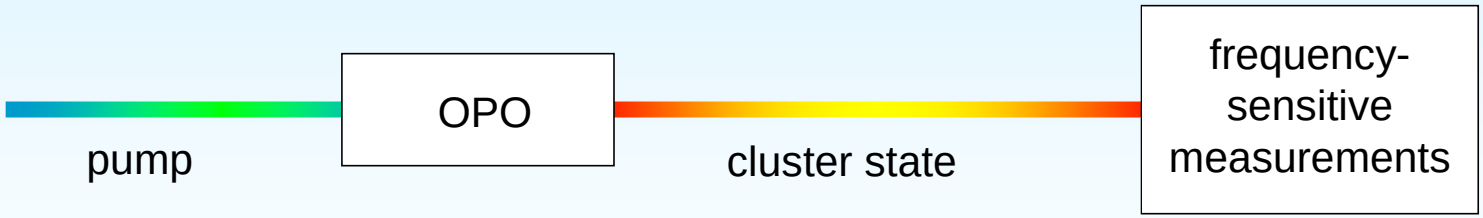
* P. van Loock, C. Weedbrook, M. Gu, PRA **76**, 032321 (2007)

Practical Preparation Method #1

- Advantages
  - Easy to do proof-of-principle experiments now
  - 4-mode CV cluster-state QC demonstrated
  - Passive beamsplitters replace active C_Z gates
- Disadvantages
  - N squeezers
  - Stable interferometer with $O(N^2)$ beamsplitters
  - Coherence of entire state must be maintained during measurements
  - N is fixed for a given setup

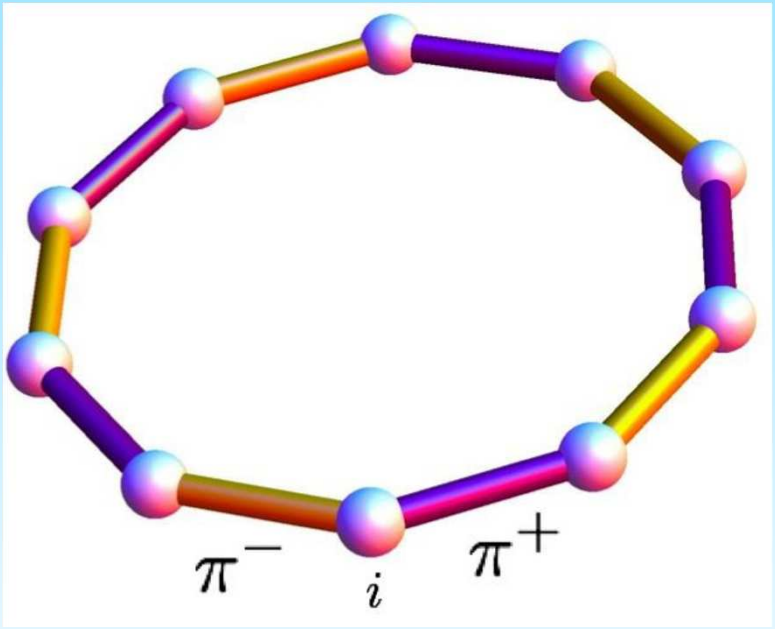
Practical Preparation Method #2

- All squeezing and interference can be performed within a *single* crystal*
  - In general, $O(N^2)$ couplings needed
  - Single pump, single output beam
  - Entanglement between *frequency* modes



* NCM, S. Flammia, H. Zaidi, O. Pfister, PRA **76**, 010302(R) (2007)

Single-OPO Cluster States



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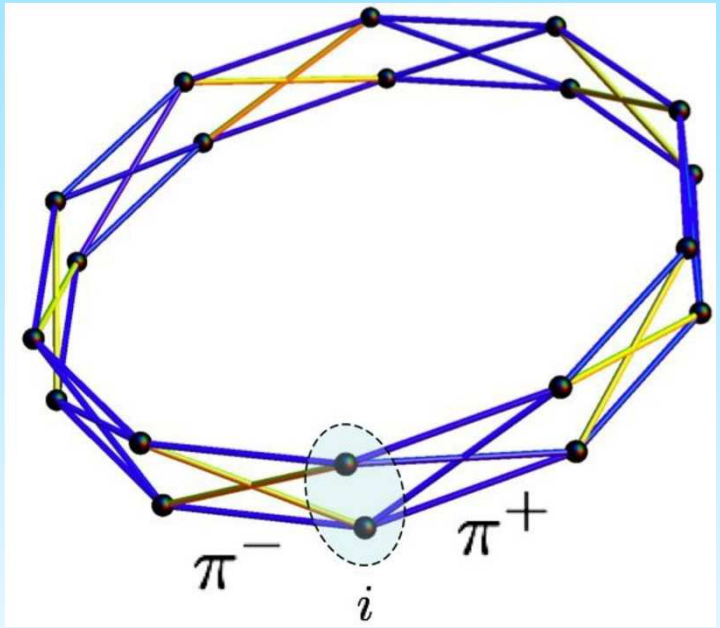
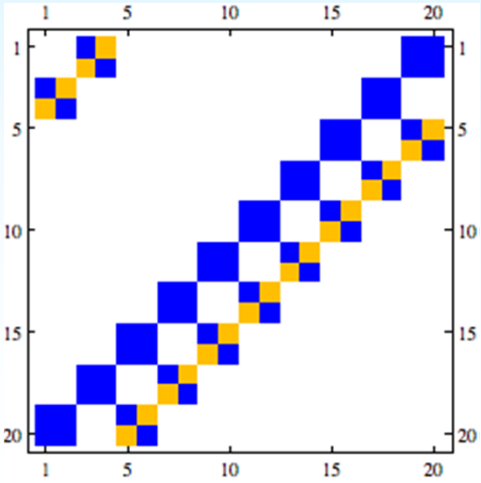
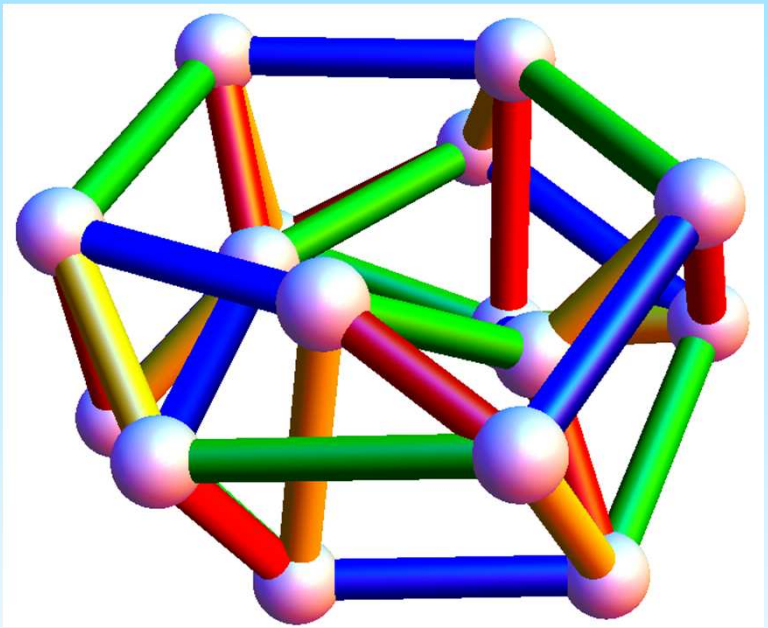


3 pump frequencies
(polarized)



Single-OPO Cluster States



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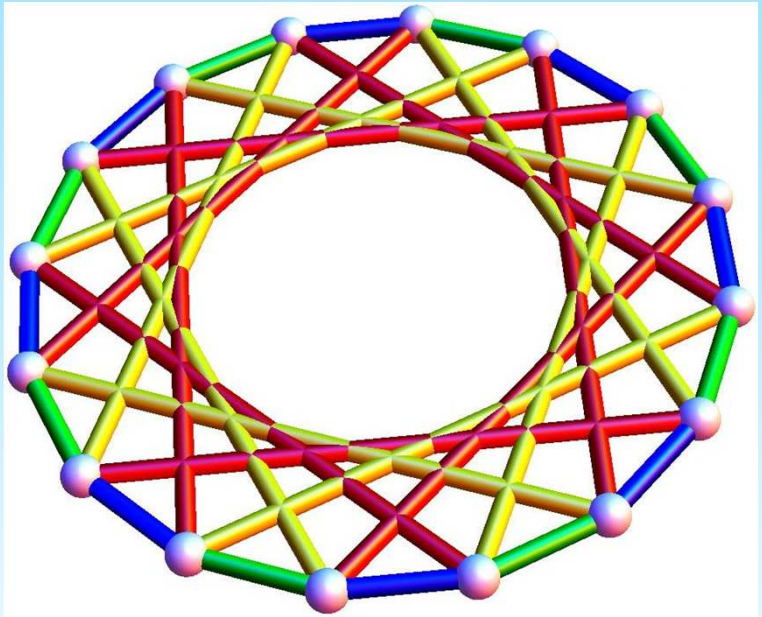
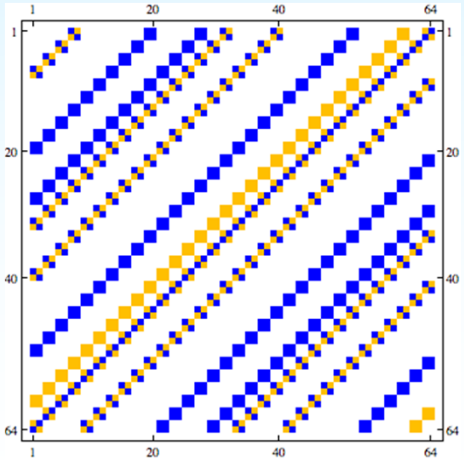


15 pump frequencies
(polarized)



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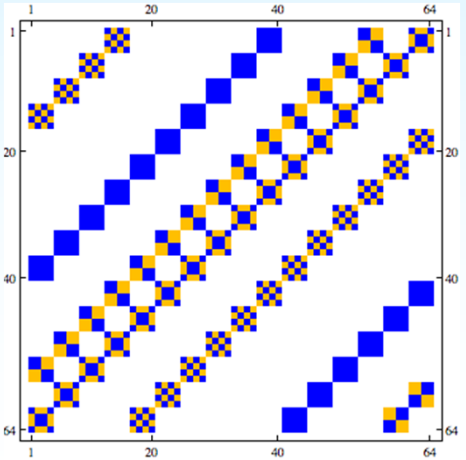
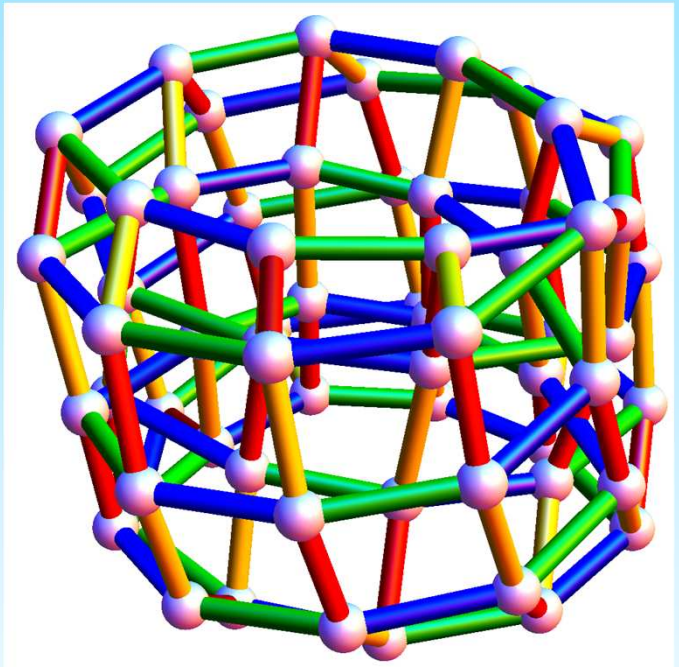


Single-OPO Cluster States



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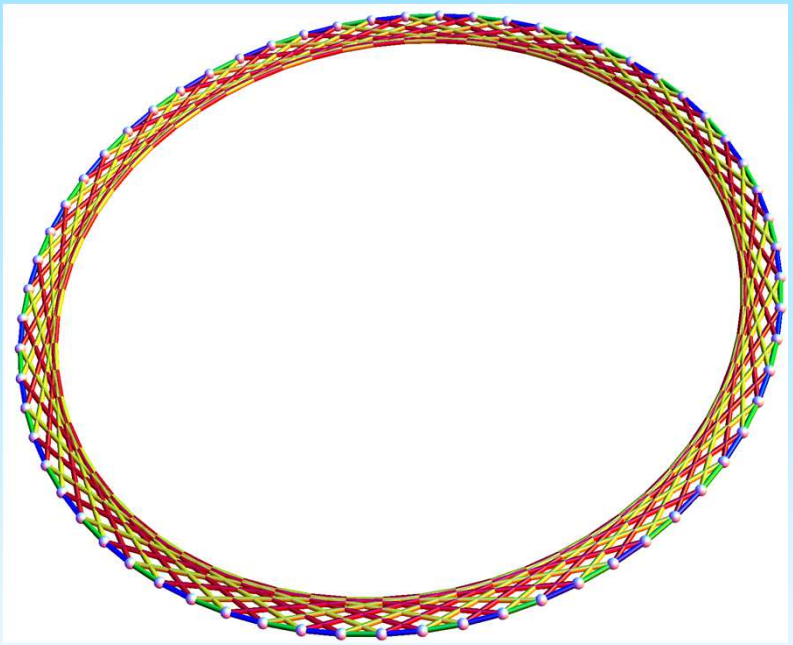

15 pump frequencies
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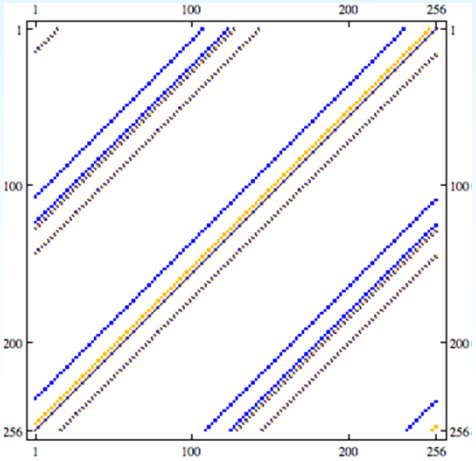

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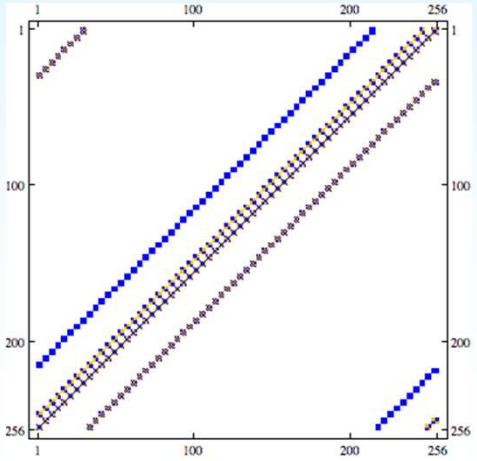
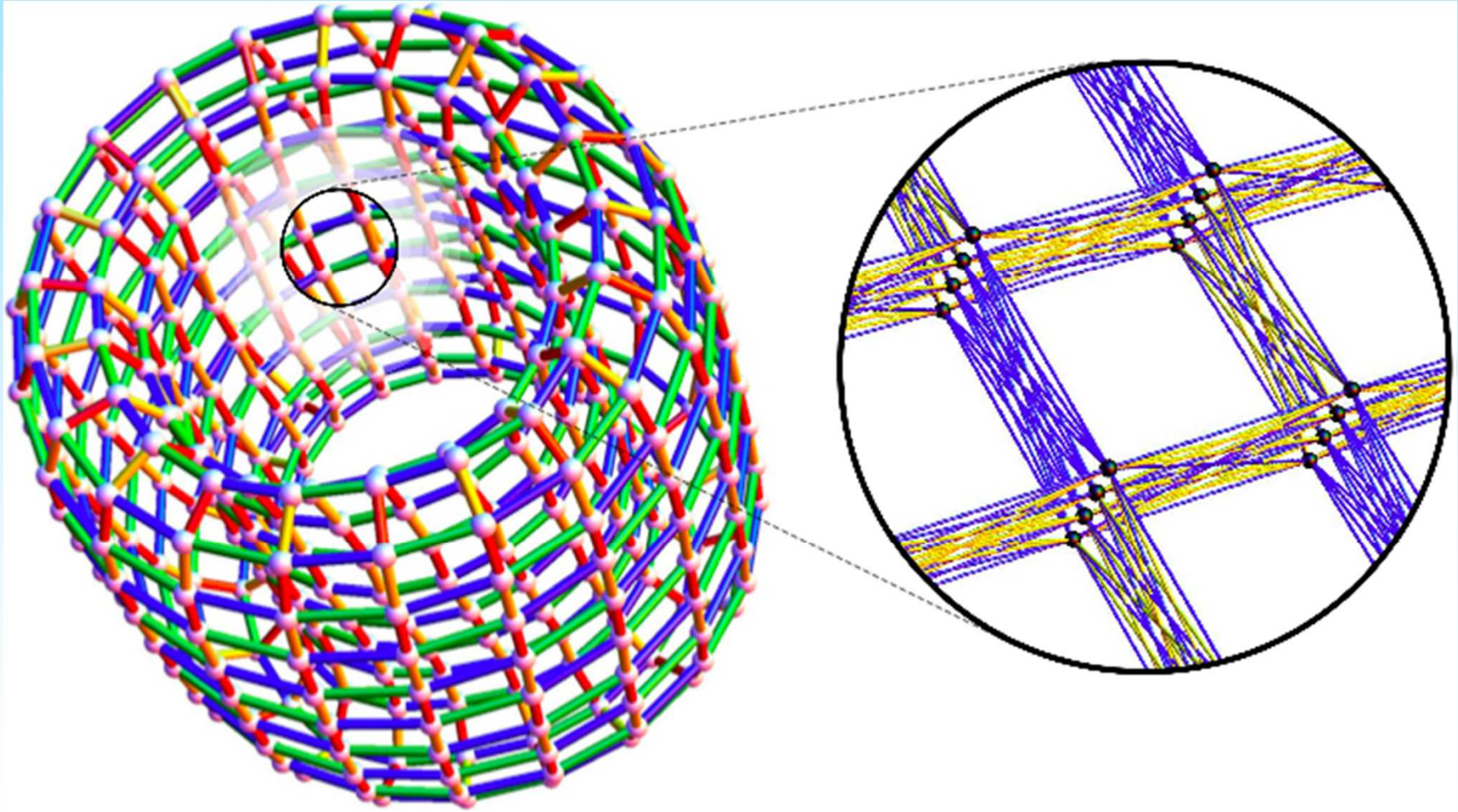


Practical Preparation Method #2

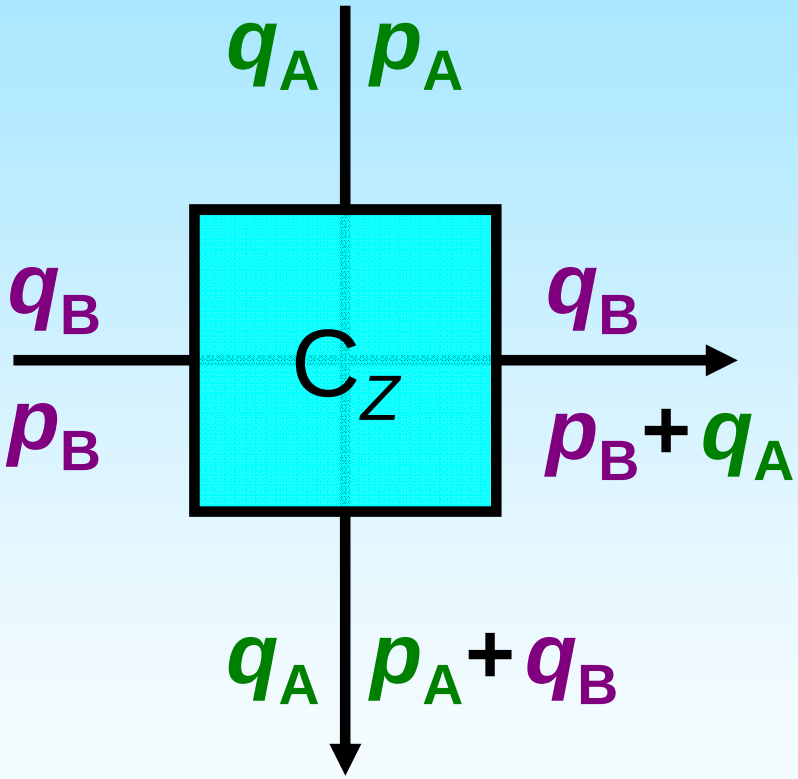


NCM, S. Flammia, O. Pfister, PRL **101**, 130501 (2008)
S. Flammia, NCM, O. Pfister, J. Phys. B **42**, 114009 (2009)

Practical Preparation Method #2

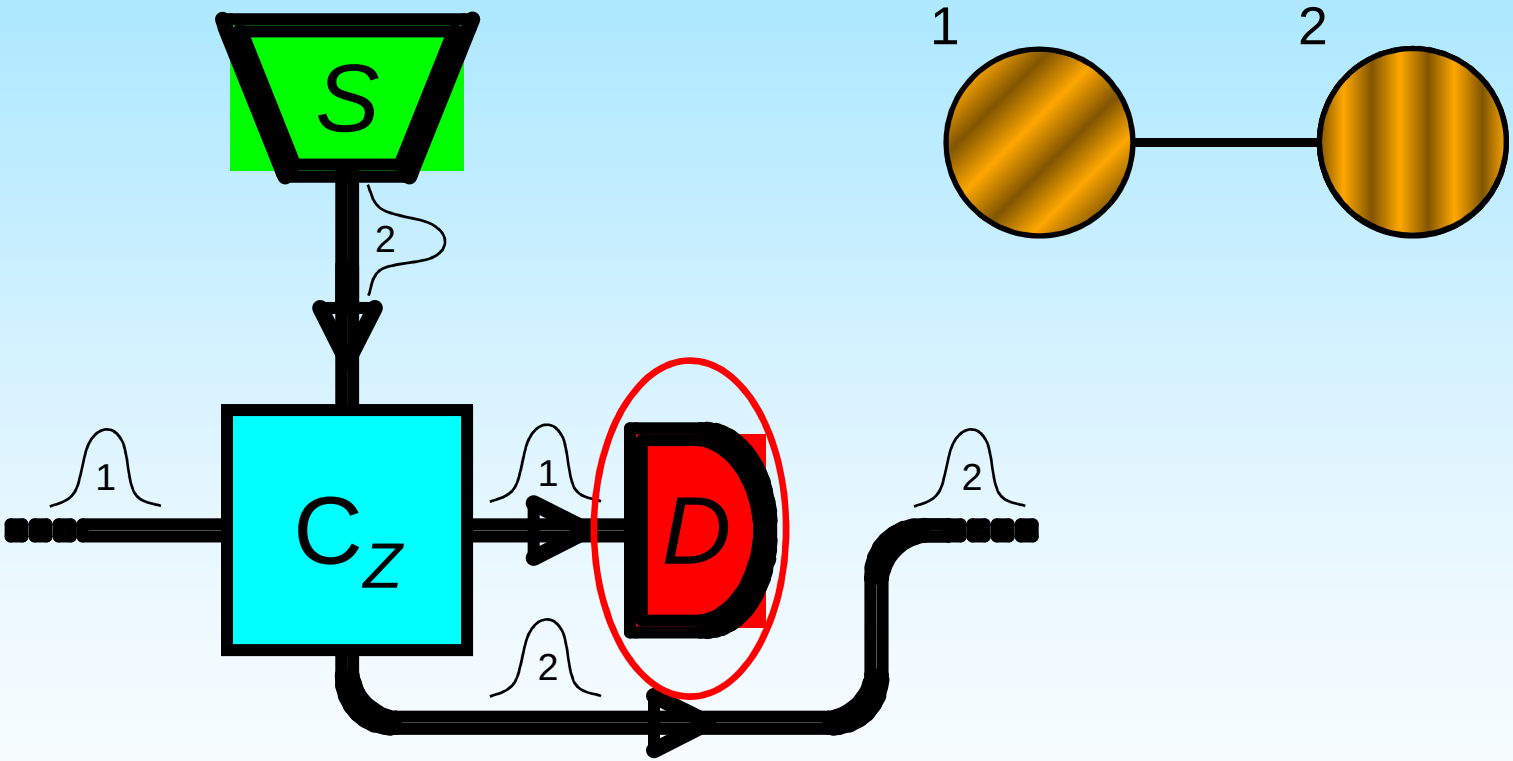
- Advantages:
  - Single OPO does everything at once
  - Scalability over thousands of modes
  - Exactly 15 pump frequencies, regardless of size
  - Nonlinear crystal already exists (PPKTP)
  - Experiments underway
- Disadvantages
  - Finite (albeit large) scaling
  - Frequency-sensitive measurements
  - Coherence of entire state must be maintained during measurements
  - *N* is fixed for a given setup

C_Z Gate

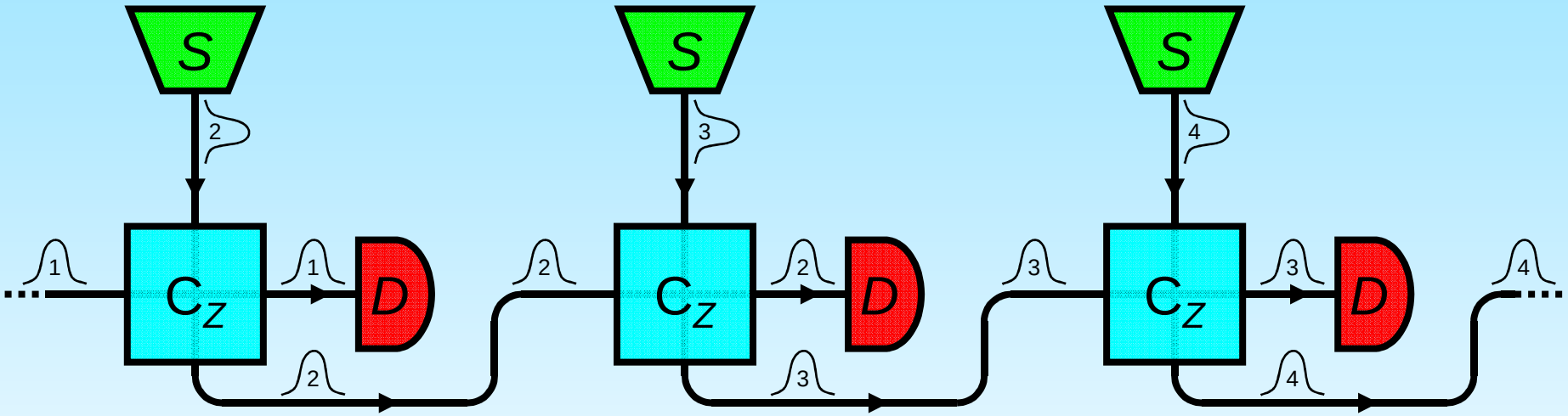


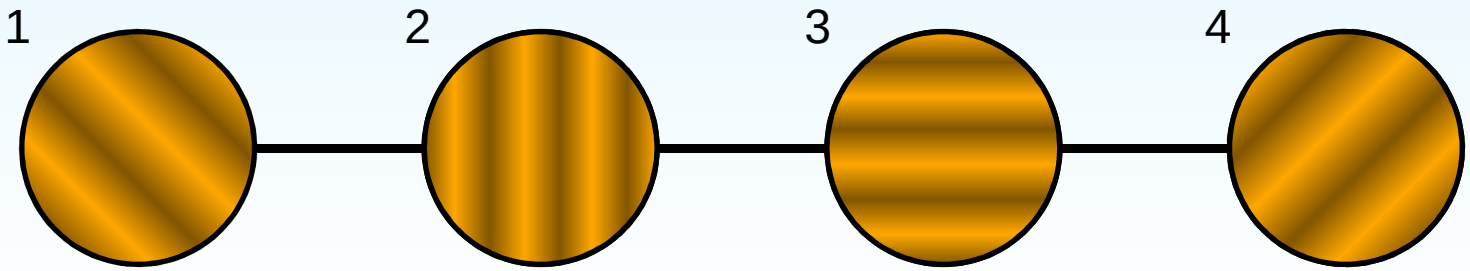
- Quantum nondemolition (QND) interaction
- Information about *q* is copied onto *p* of other mode
- Entangling gate
- Better initial squeezing in *p* results in more entanglement
- Hard to implement

Teleportation "Lite" Using C_Z Gate

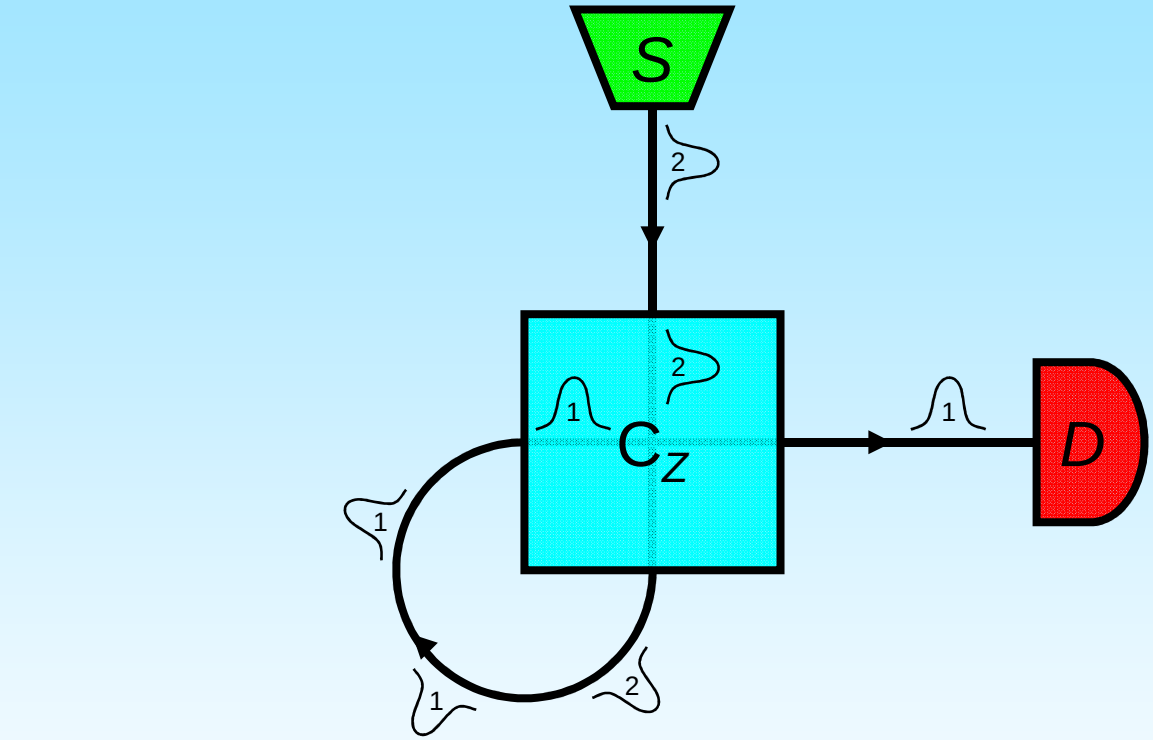


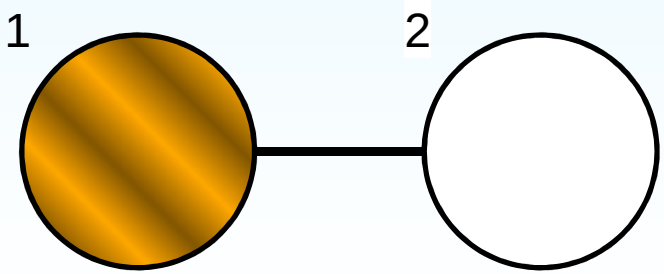
Quantum Wire Using Many C_Z's



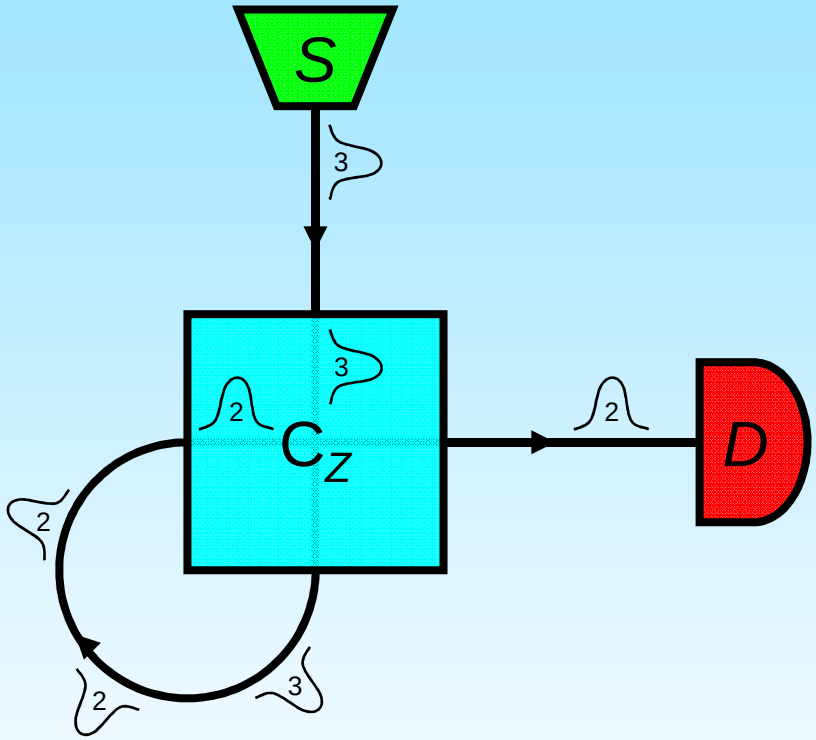


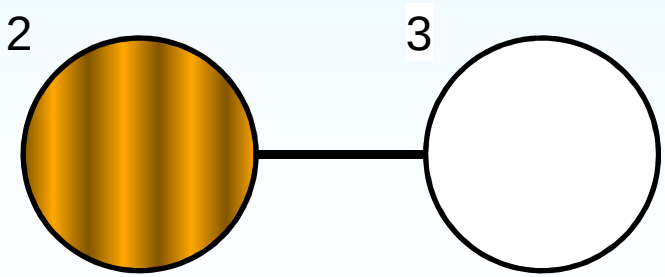
Quantum Wire Using One C_Z Gate





Quantum Wire Using One C_Z Gate





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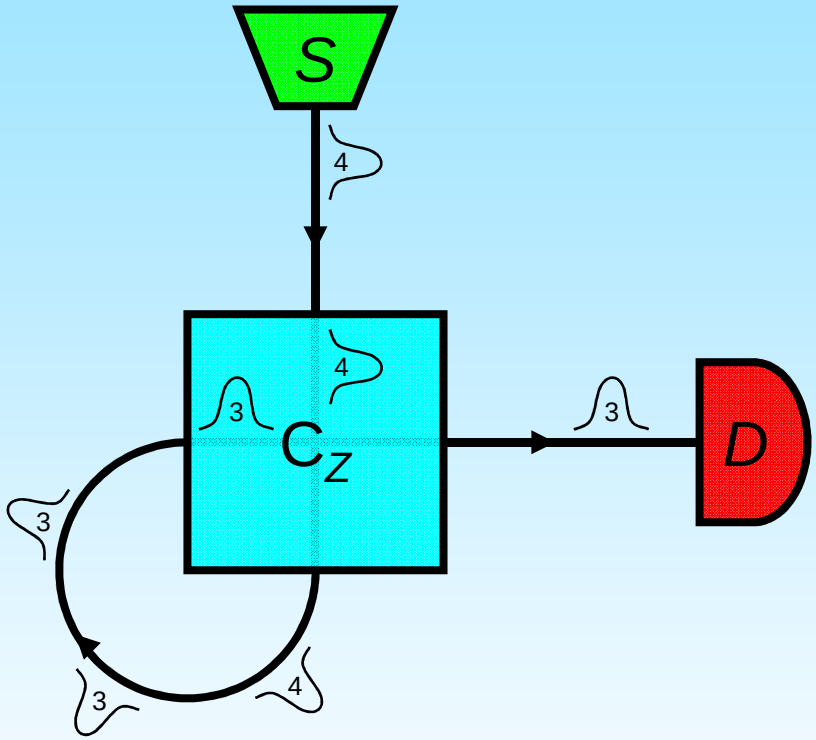

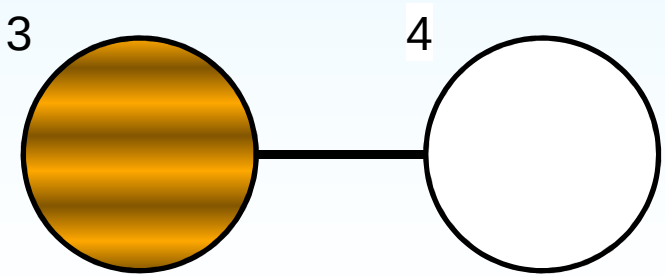

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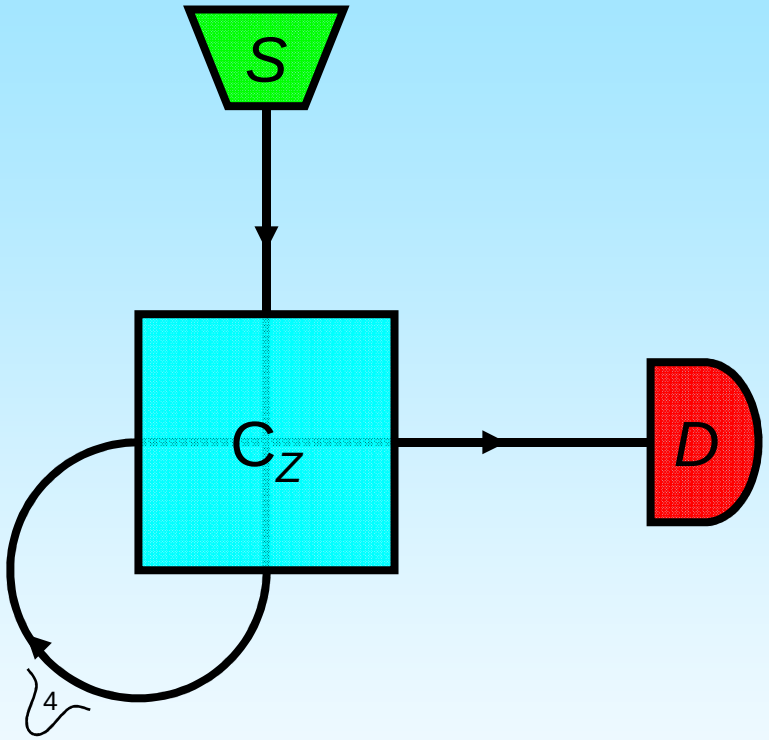
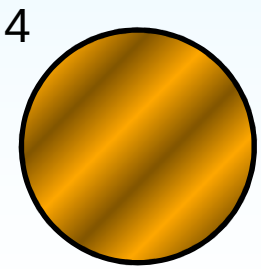
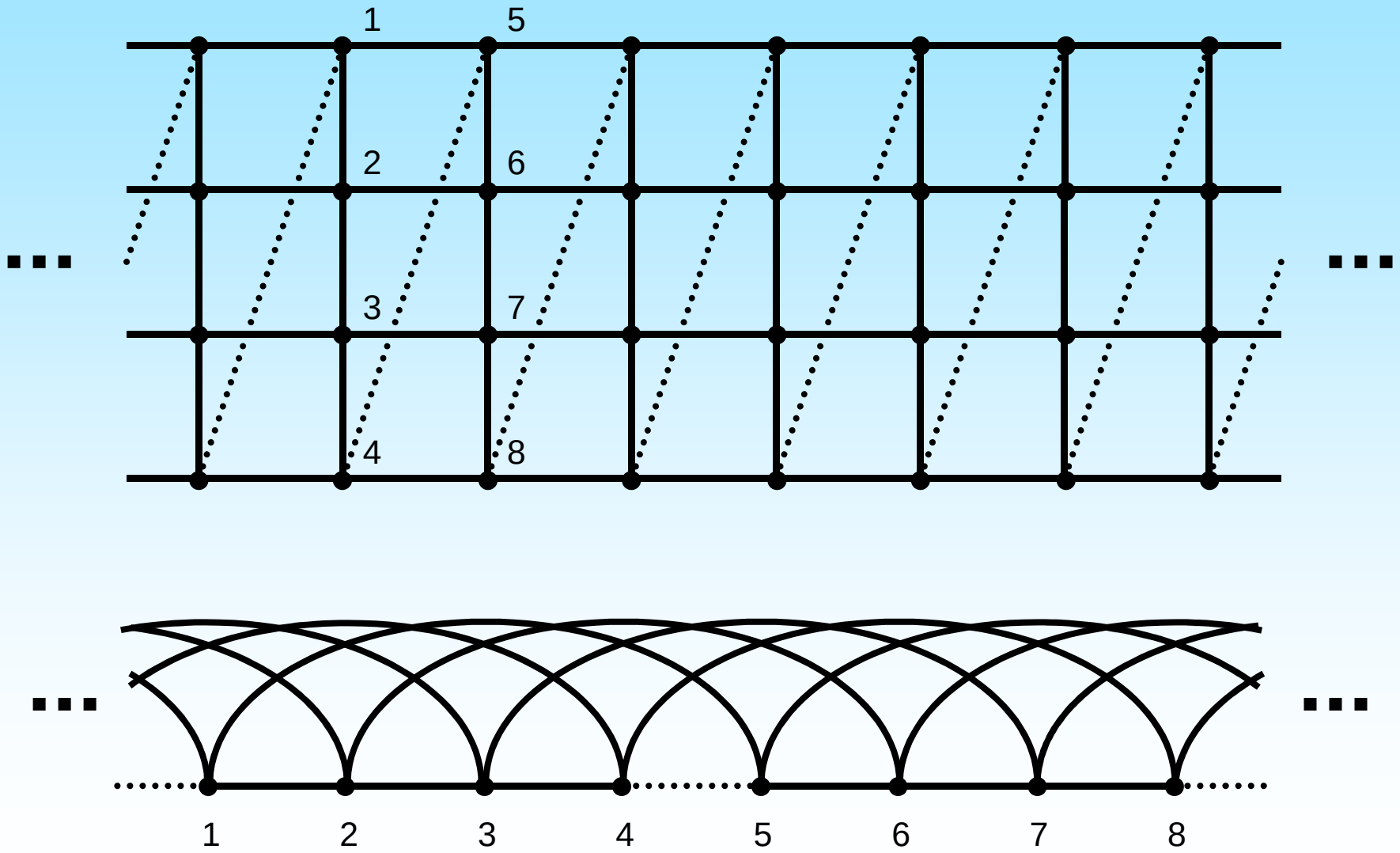
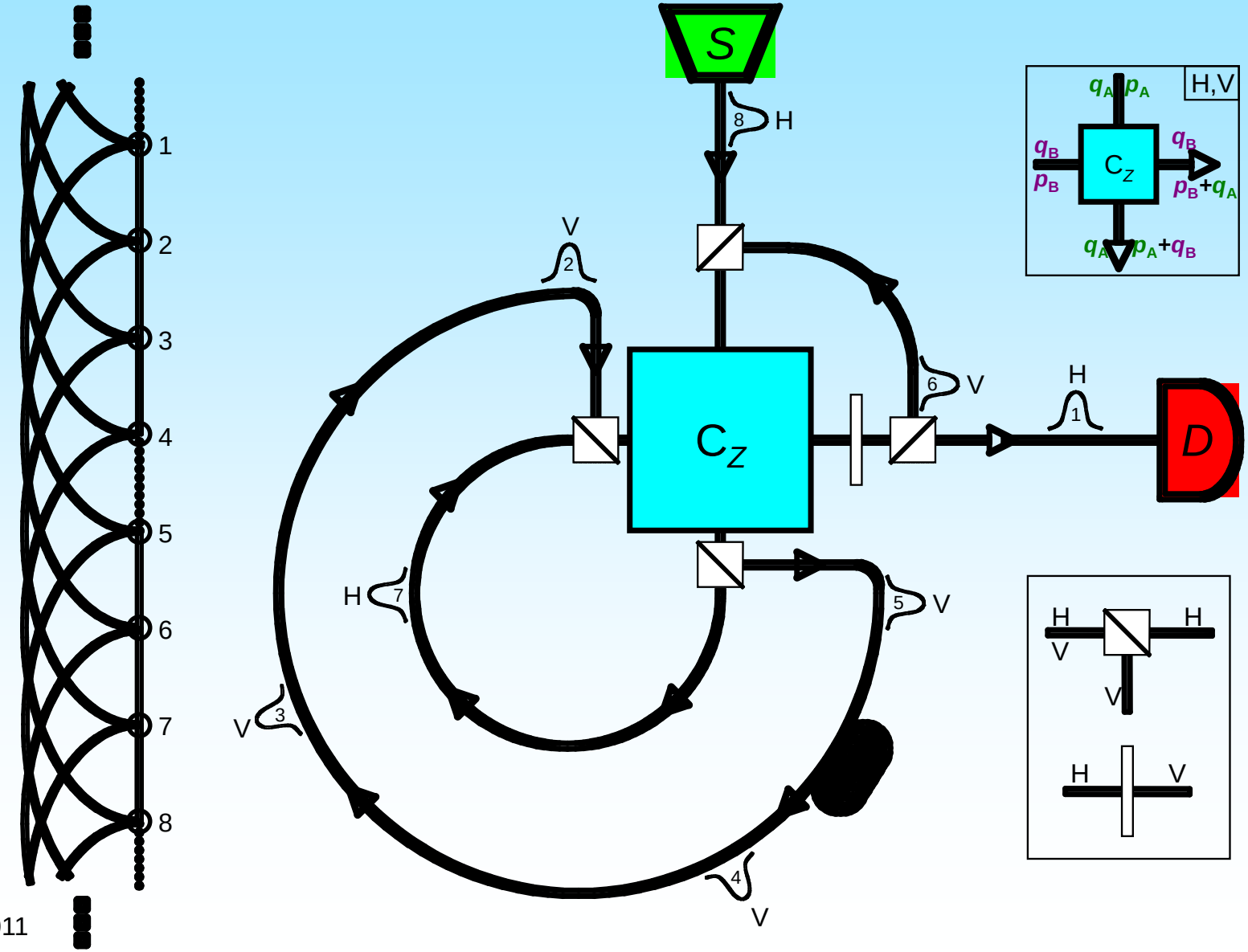




CV Cluster State Using One C_Z



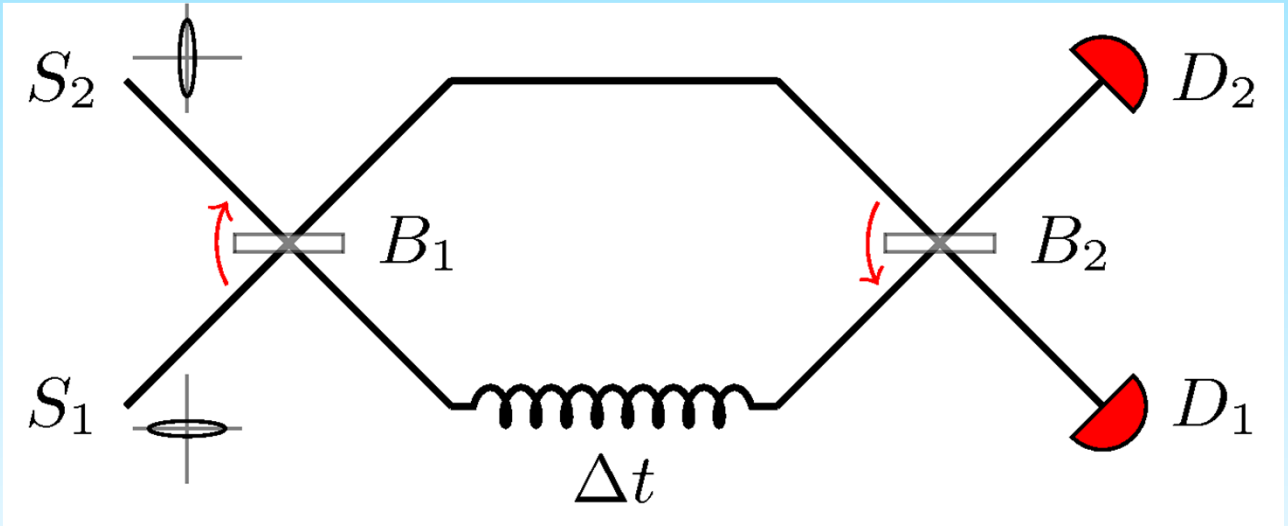
CV Cluster State Using One C_Z

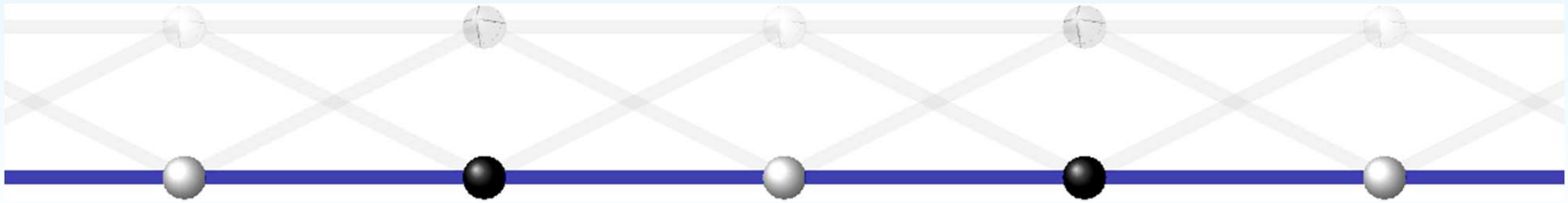


Temporal-Mode CV Cluster States

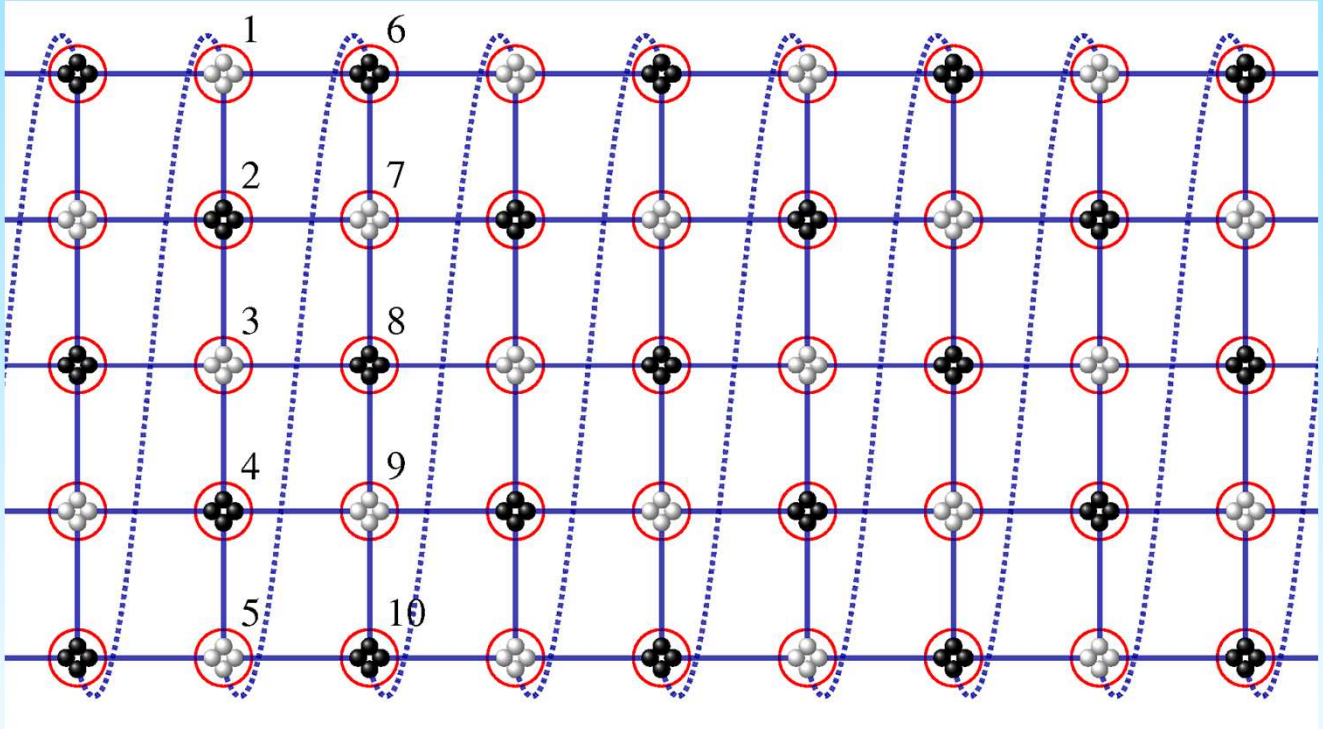
- Advantages:
  - Only one squeezer, C_Z gate, homodyne detector, and photon counter required
    - Just need to perfect one of each
    - Modematching and phaselocking only once
  - Grow-as-you-go
    - Robust against decoherence
    - Easy to add rows to the lattice
    - Extensible in time
- Disadvantages
  - C_Z gates are experimentally challenging

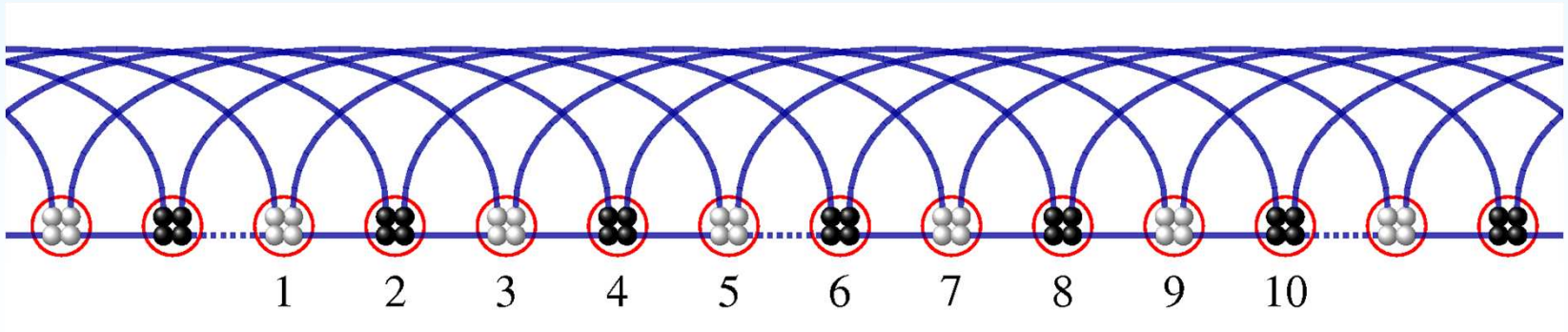
Temporal-Mode GPEPS





Temporal-Mode GPEPS





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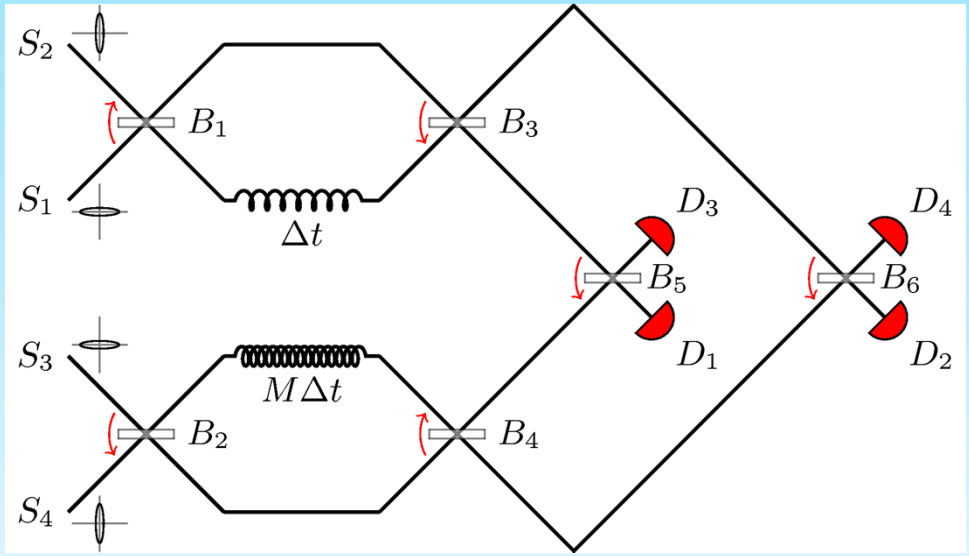

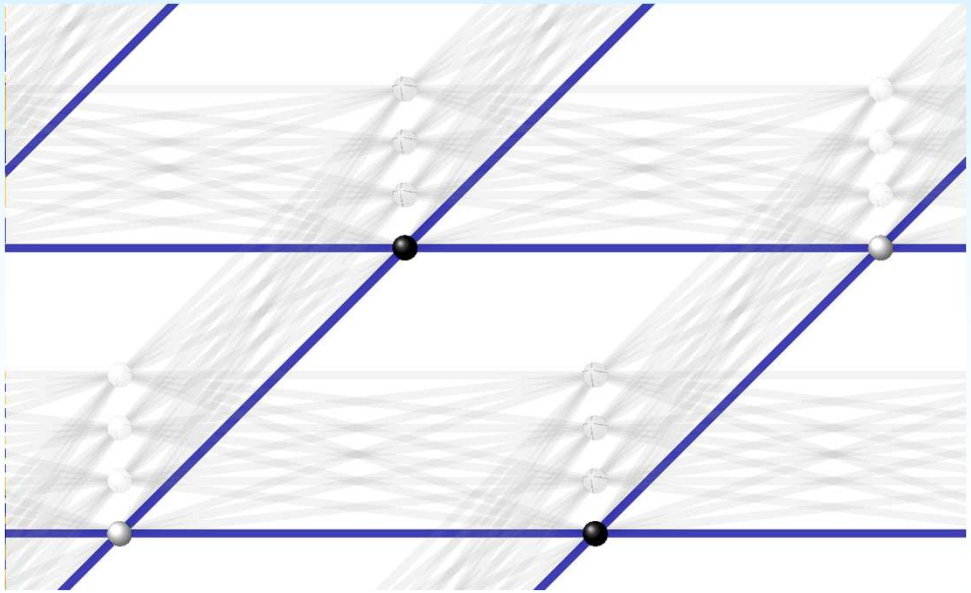

Conclusion

- CV cluster states allow for measurement-based quantum computation using continuous variables
- Optical schemes
  - Squeezers + C_Z gates (spatial)
  - Squeezers + beamsplitters (spatial)
  - Single OPO (frequency)
  - One squeezer + one C_Z gate (temporal)
  - Four squeezers + six beamsplitters (temporal)
- Thank you