Continuous-variable quantum computing: scalable designs and fault tolerance

Nicolas C Menicucci

RMIT
UNIVERSITY

CENTRE FOR
QUANTUM COMPUTATION &
COMMUNICATION TECHNOLOGY
AUSTRALIAN RESEARCH COUNCIL CENTRE OF EXCELLENCE

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RIT Jul 2020
(Comic sans forever!)

My group

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What is Computation?

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abstract:

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input
(information)

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(information)

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physical:

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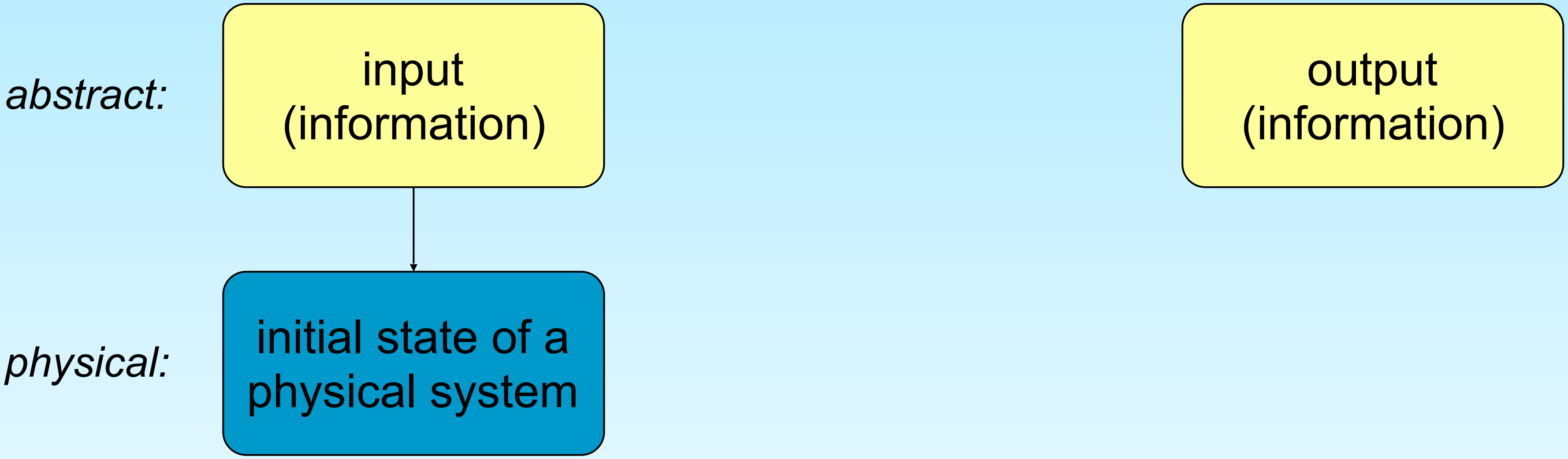

abstract:

input
(information)

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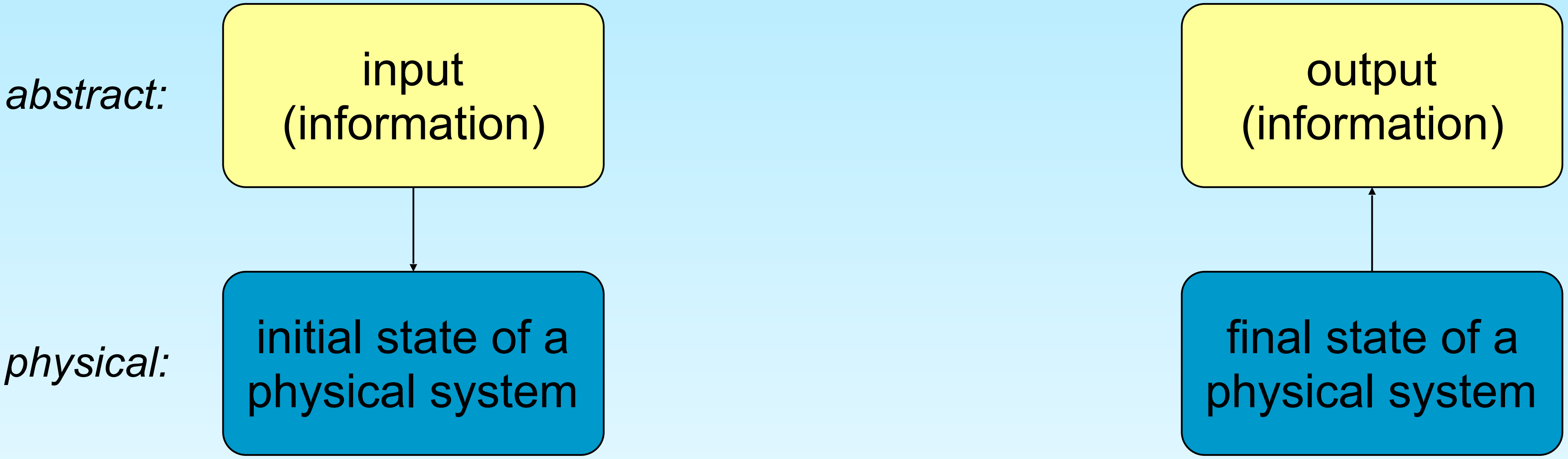
physical:

initial state of a physical system

What is Computation?



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initial state of a physical system

final state of a physical system

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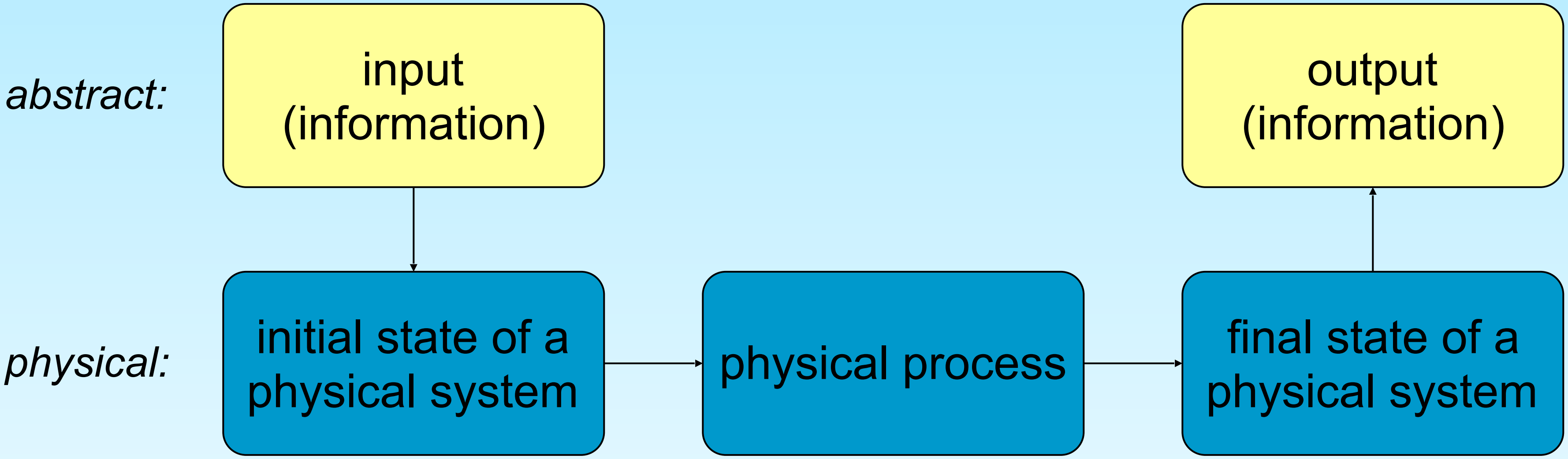

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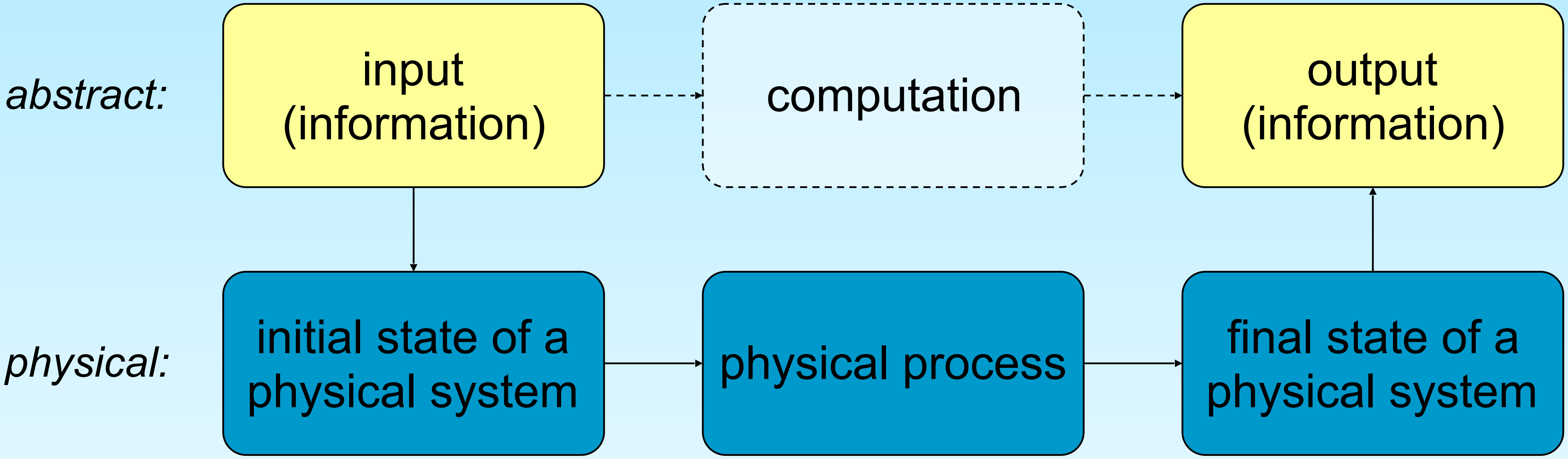

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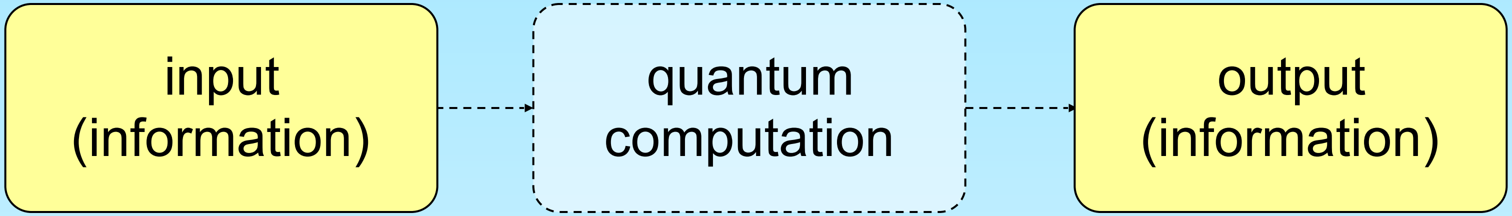
Qubits and CVs

Qubits and CVs



input (information)

quantum computation

output (information)

Qubits and CVs

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quantum computation

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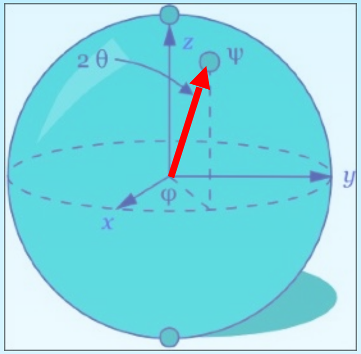
Qubits



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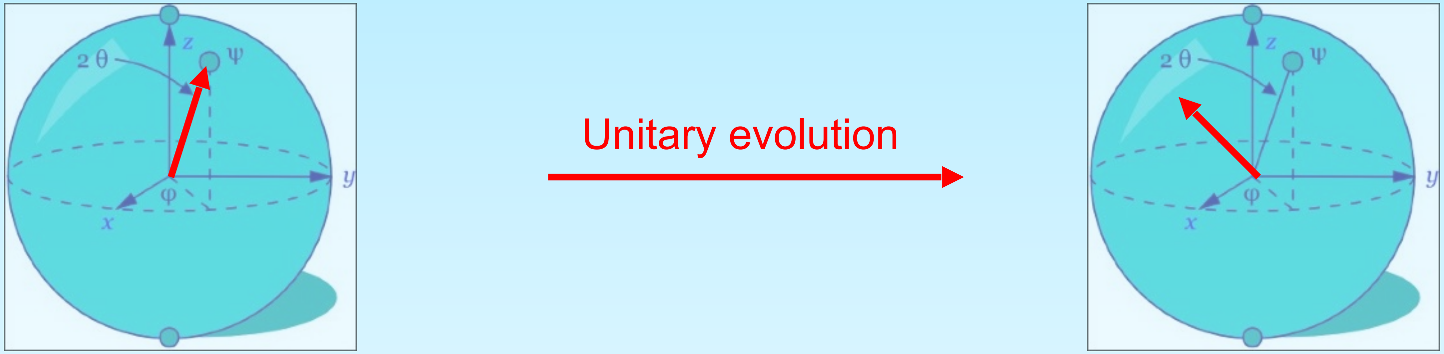
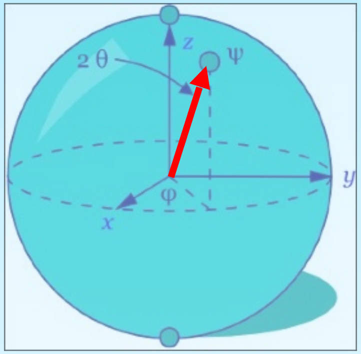


Unitary evolution

Qubits and CVs

input (information) → quantum computation → output (information)

Qubits



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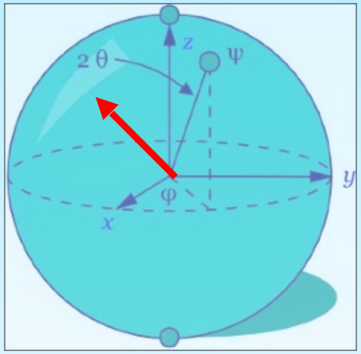
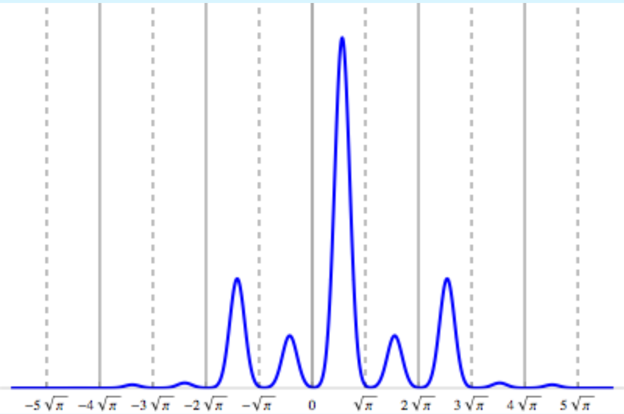


CVs



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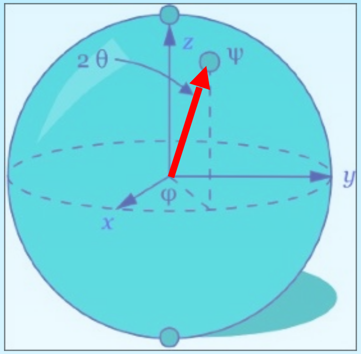
Qubits



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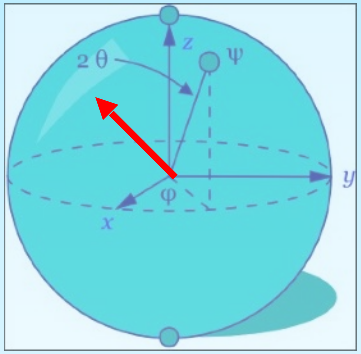

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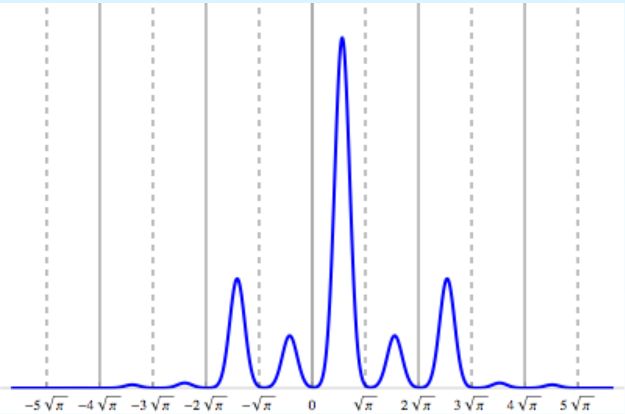

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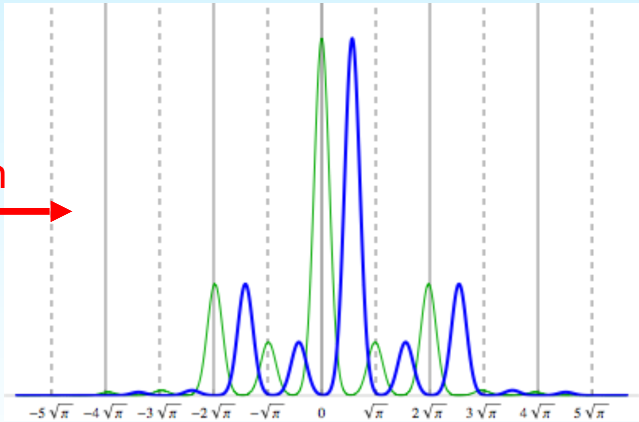

Cluster states

Teleportation “Lite”

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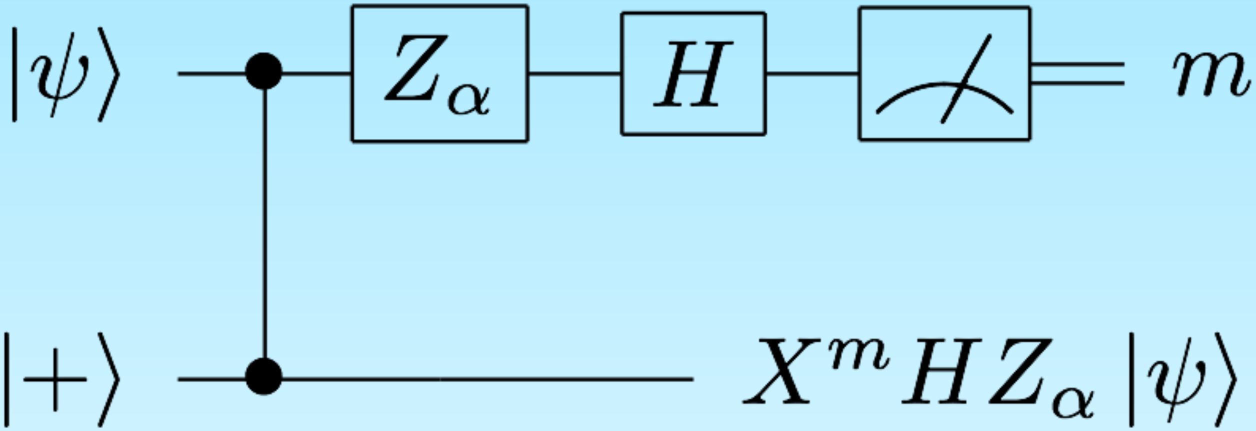

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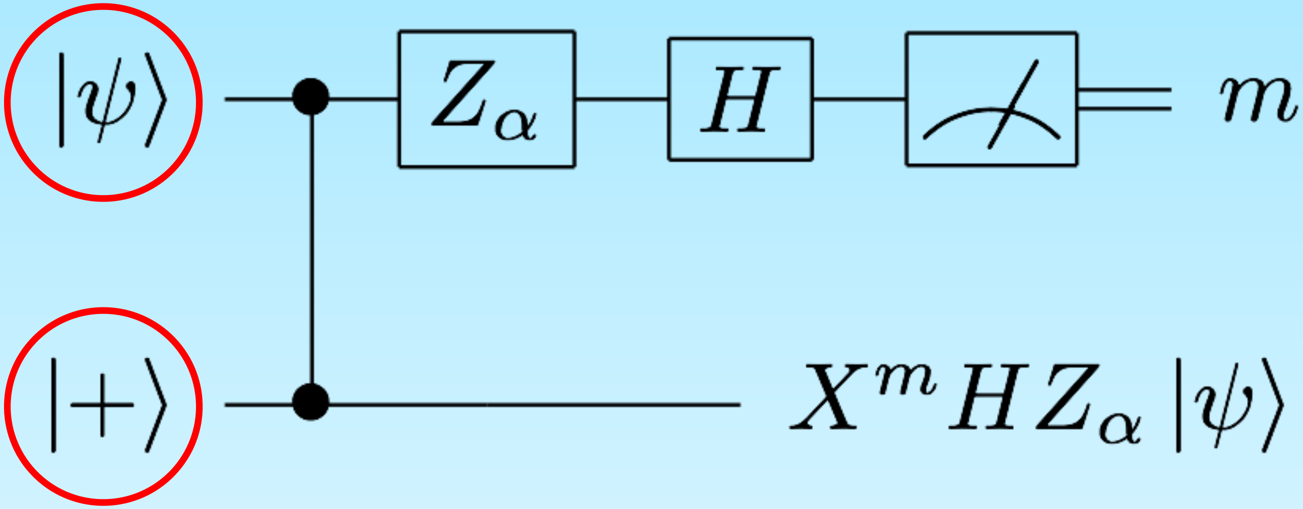

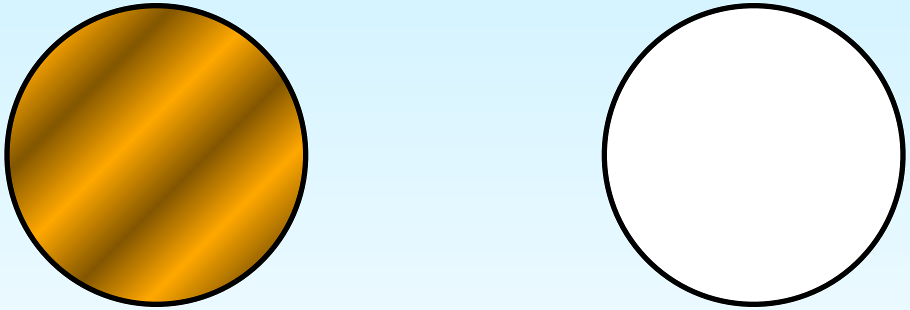

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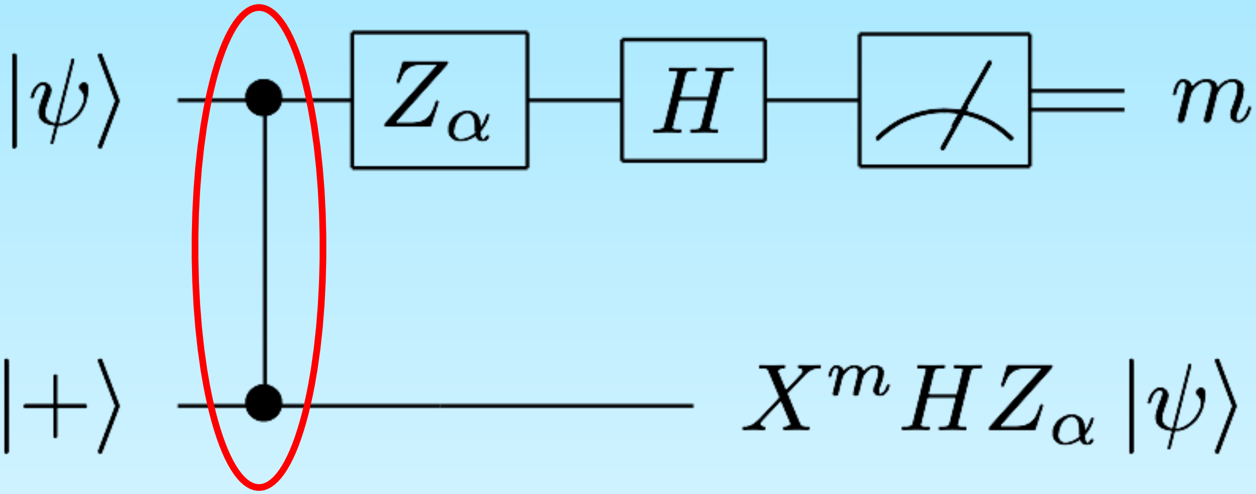

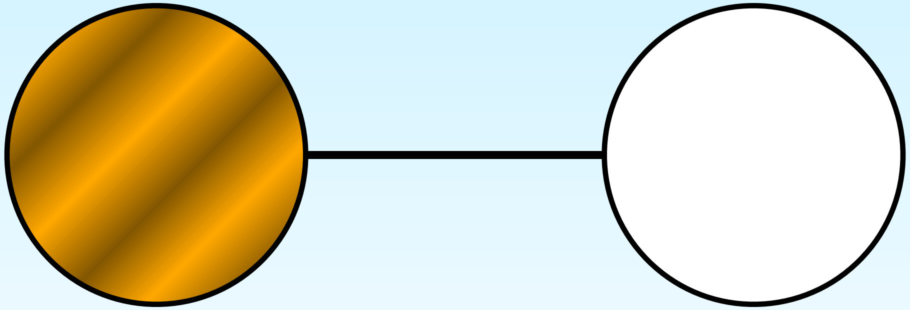

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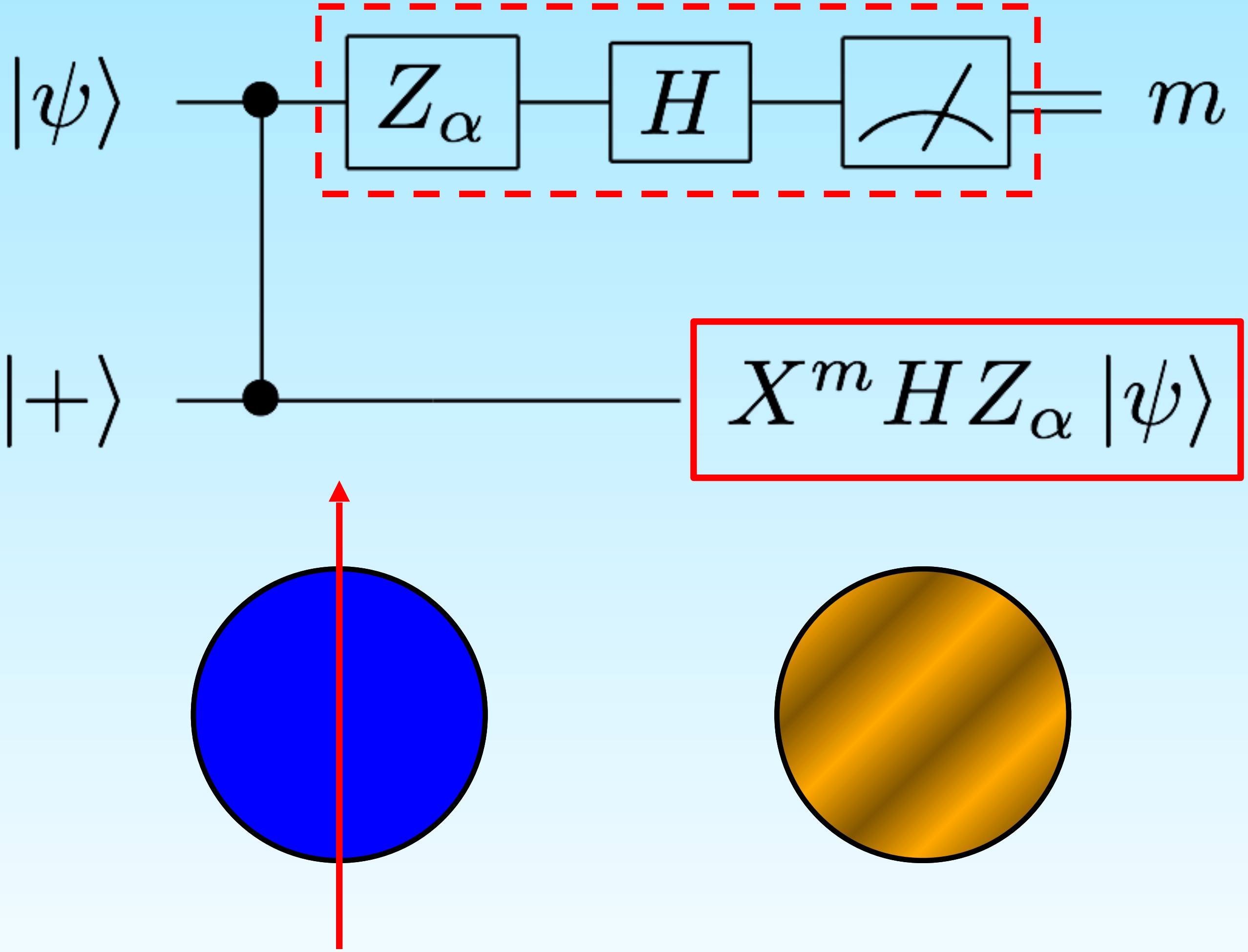

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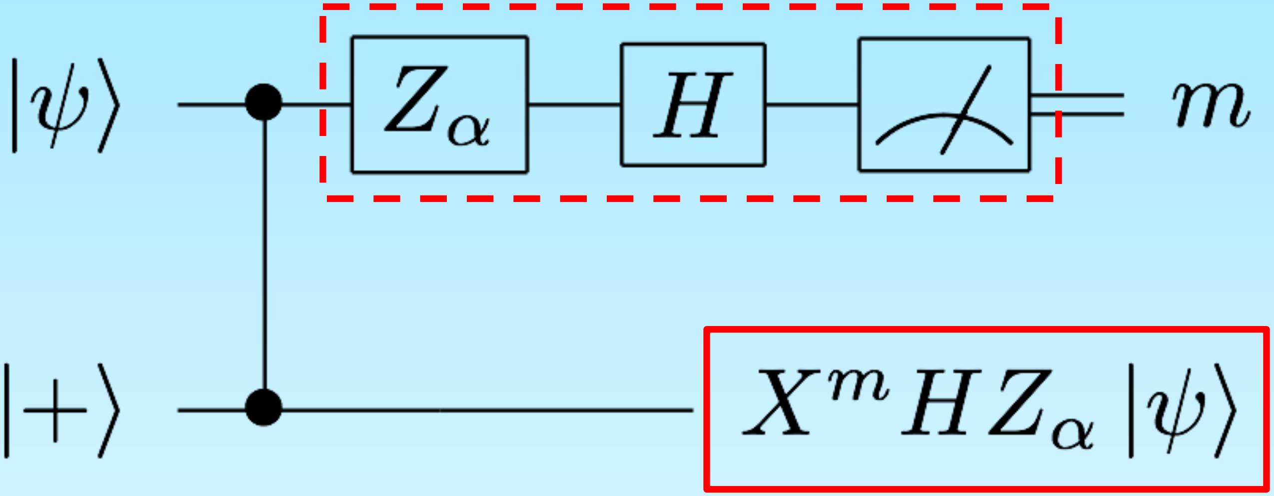

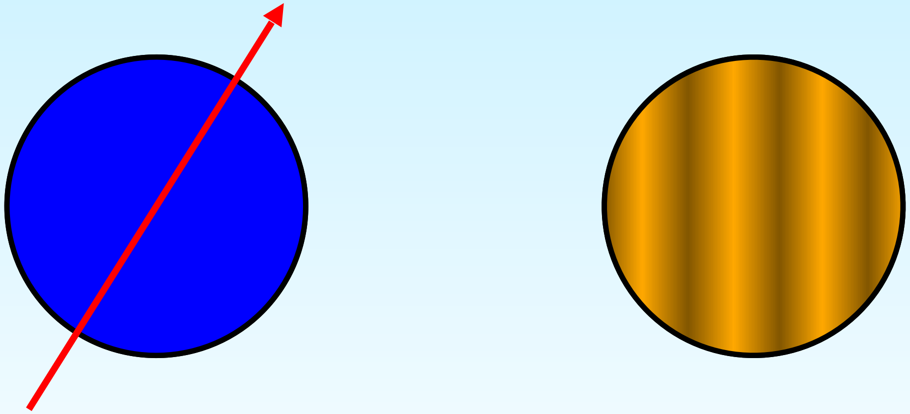

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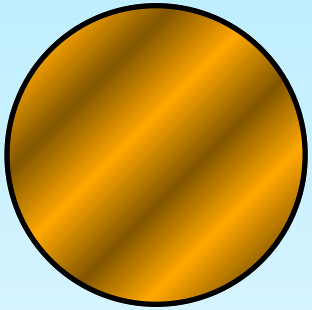

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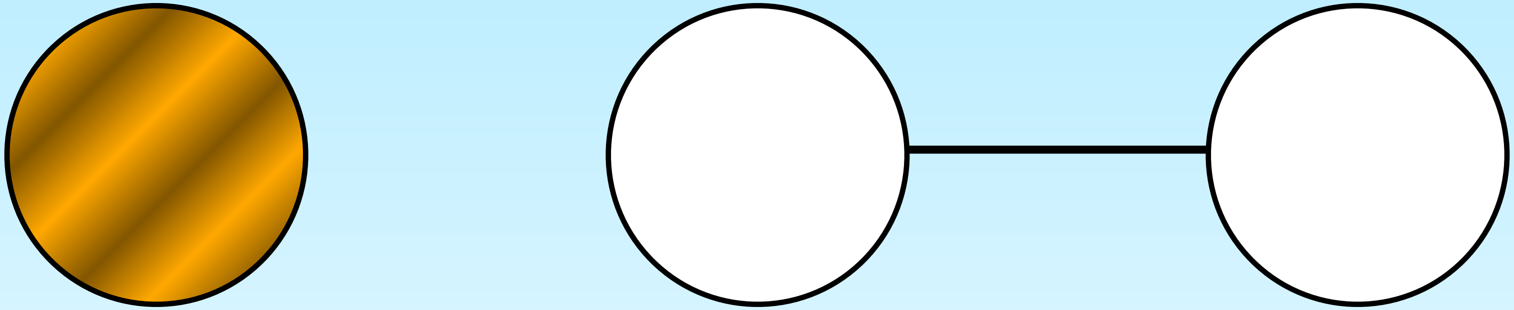

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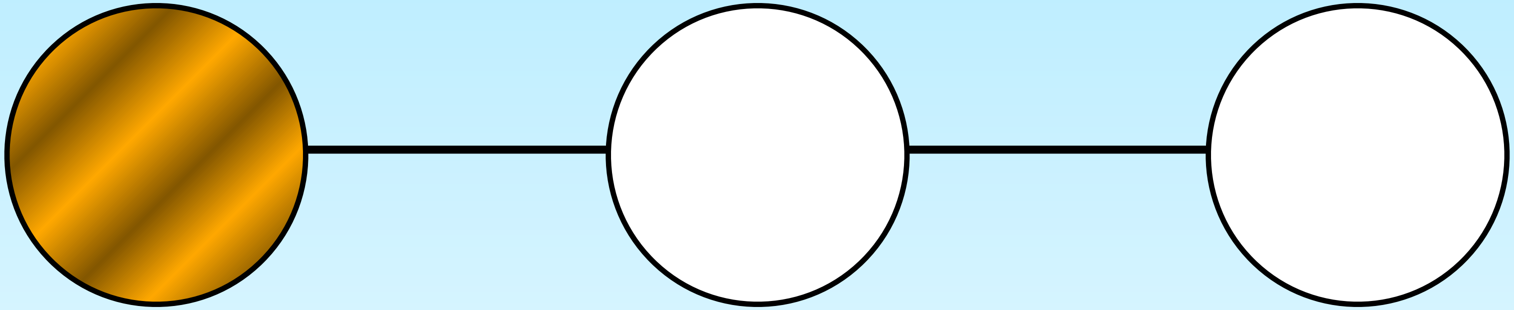

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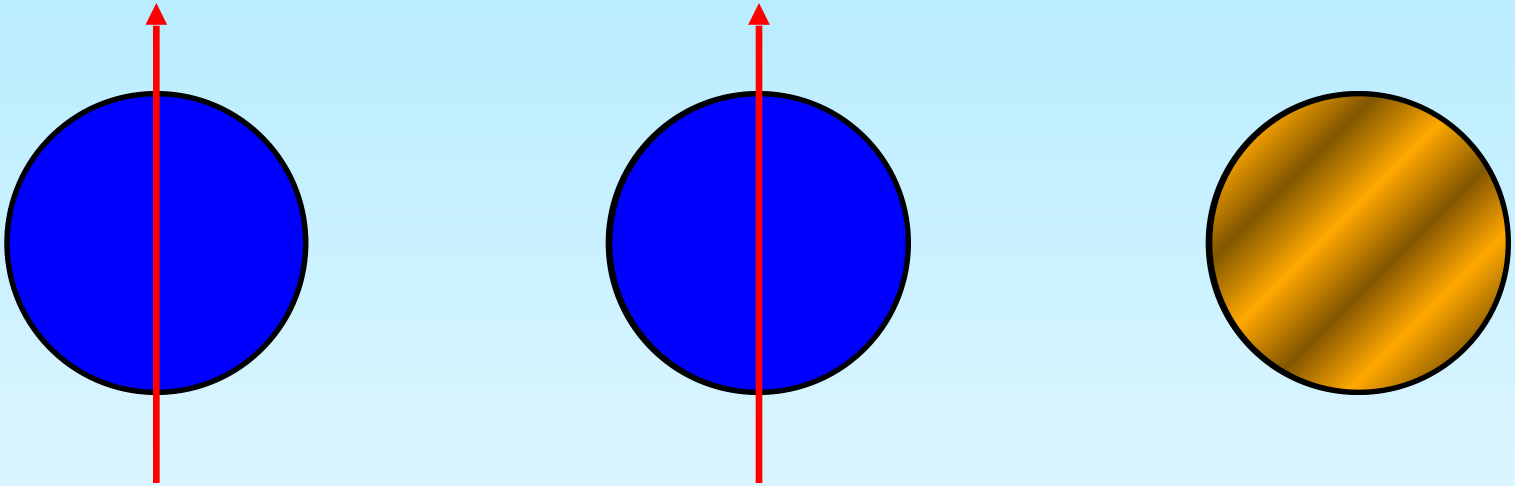

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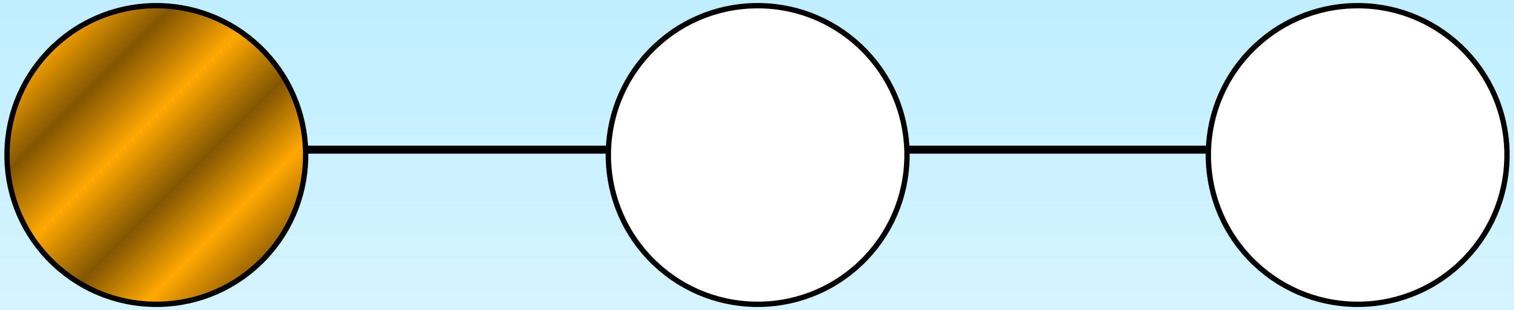
Teleportation



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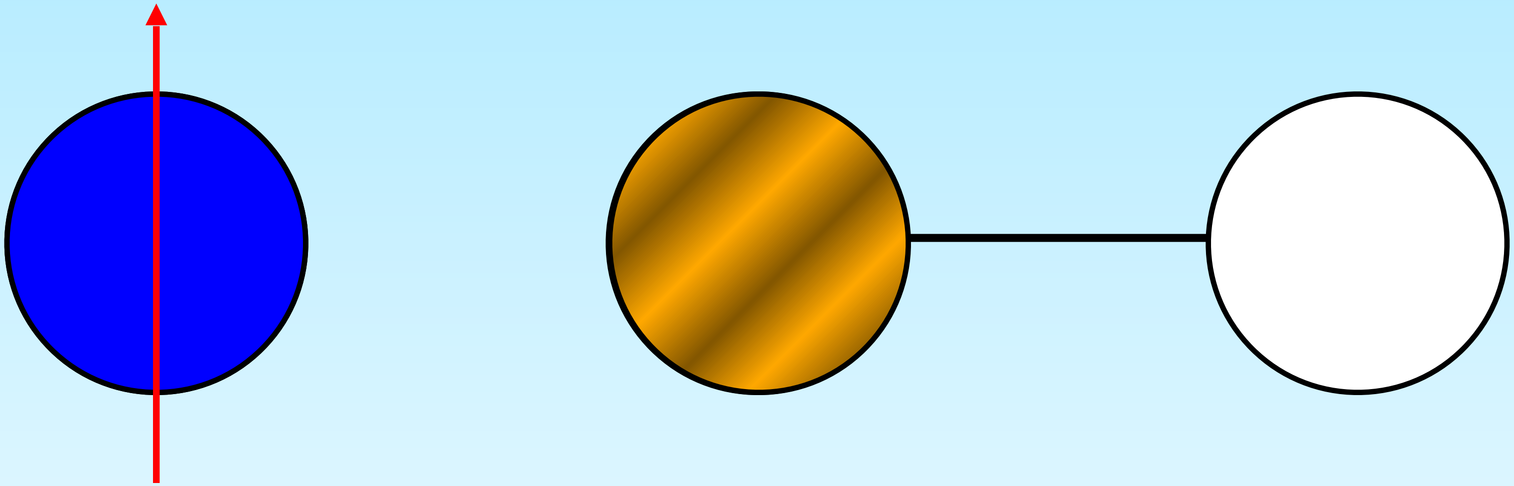

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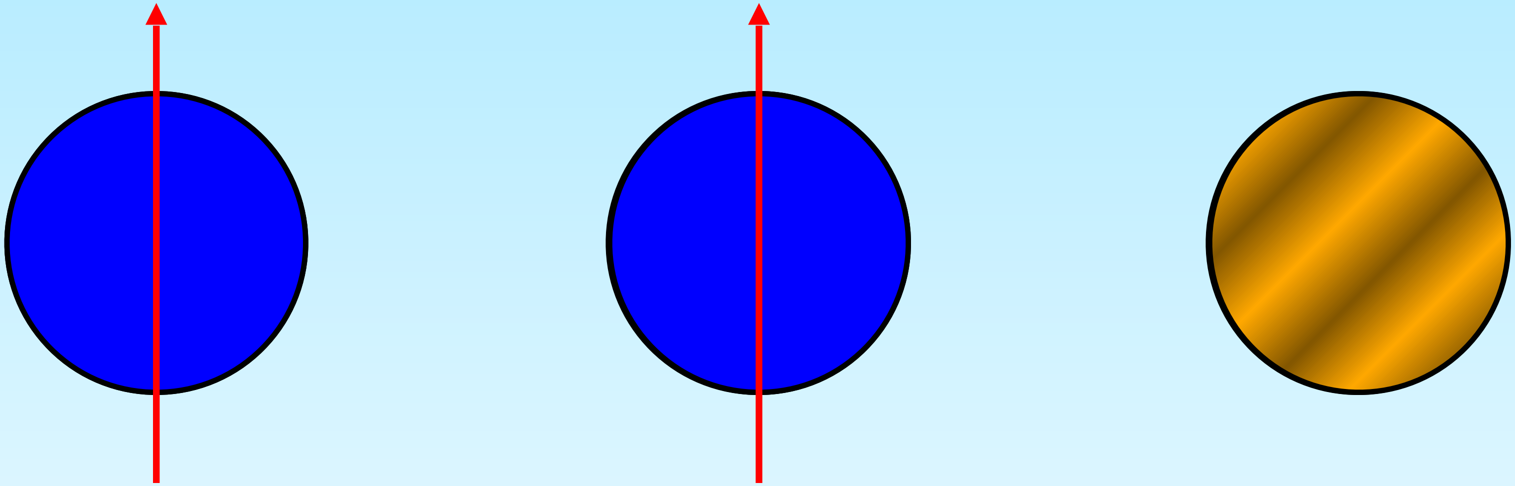

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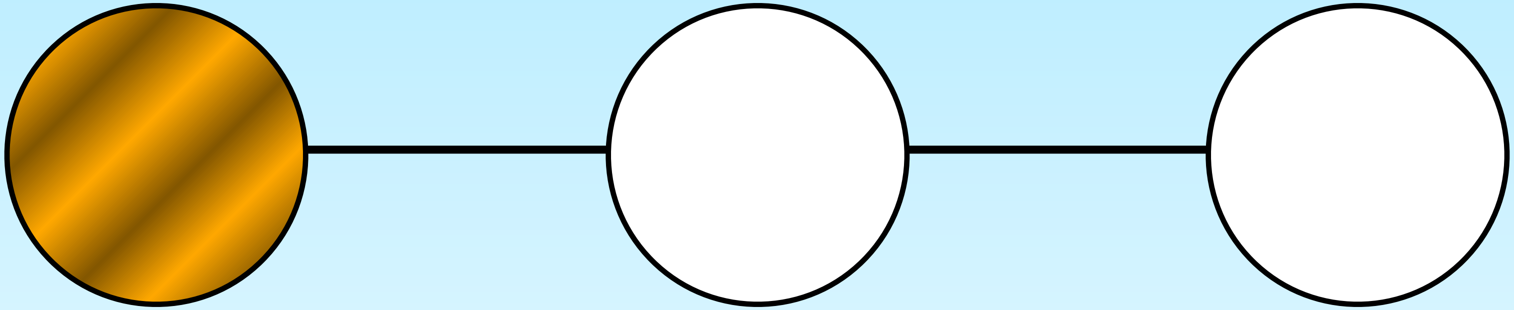

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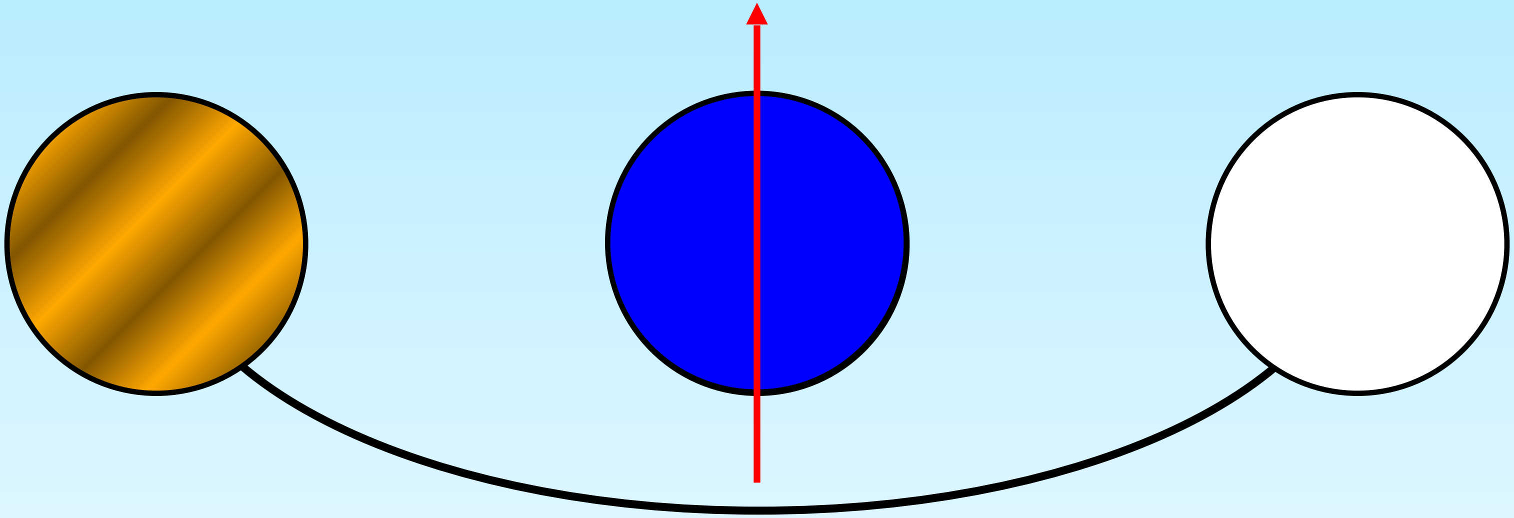

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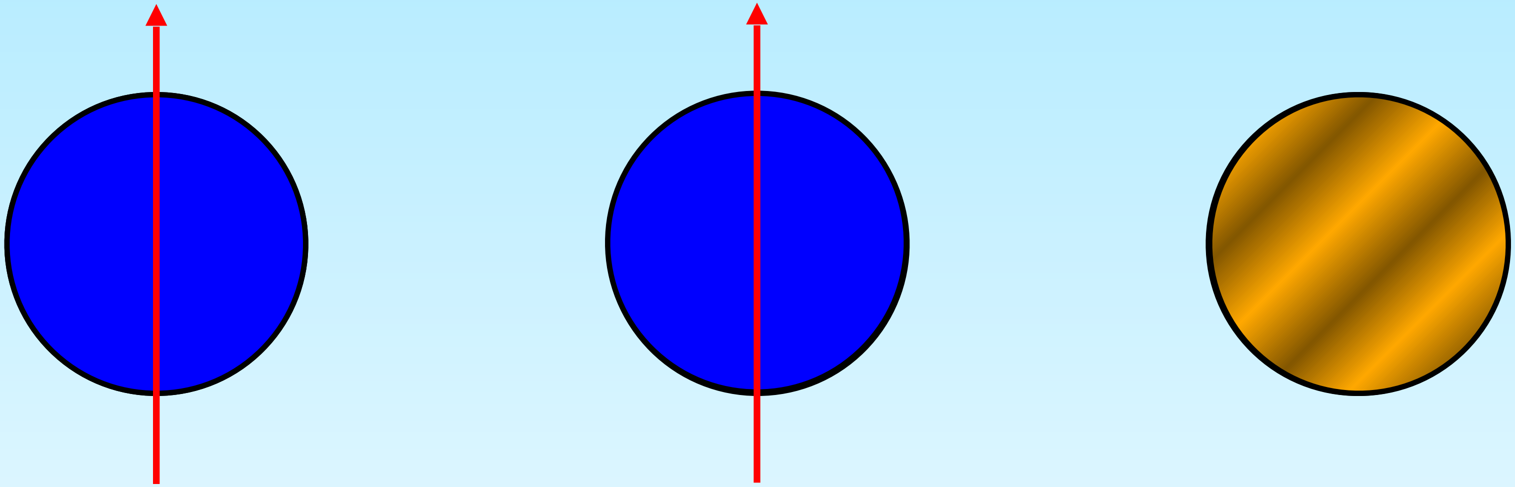

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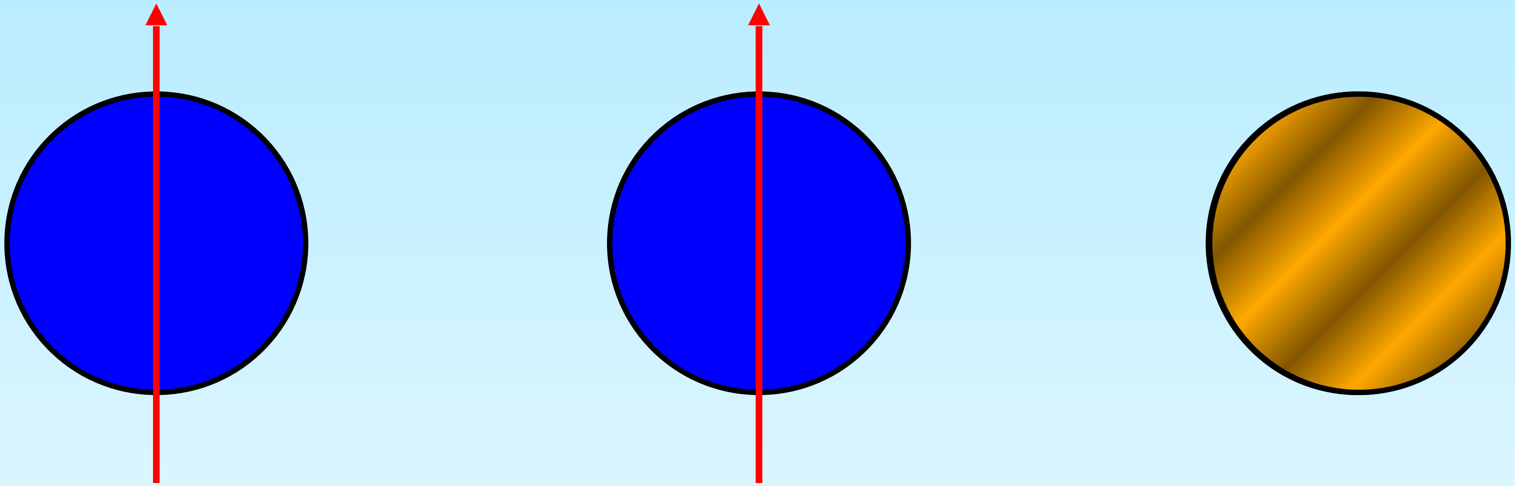

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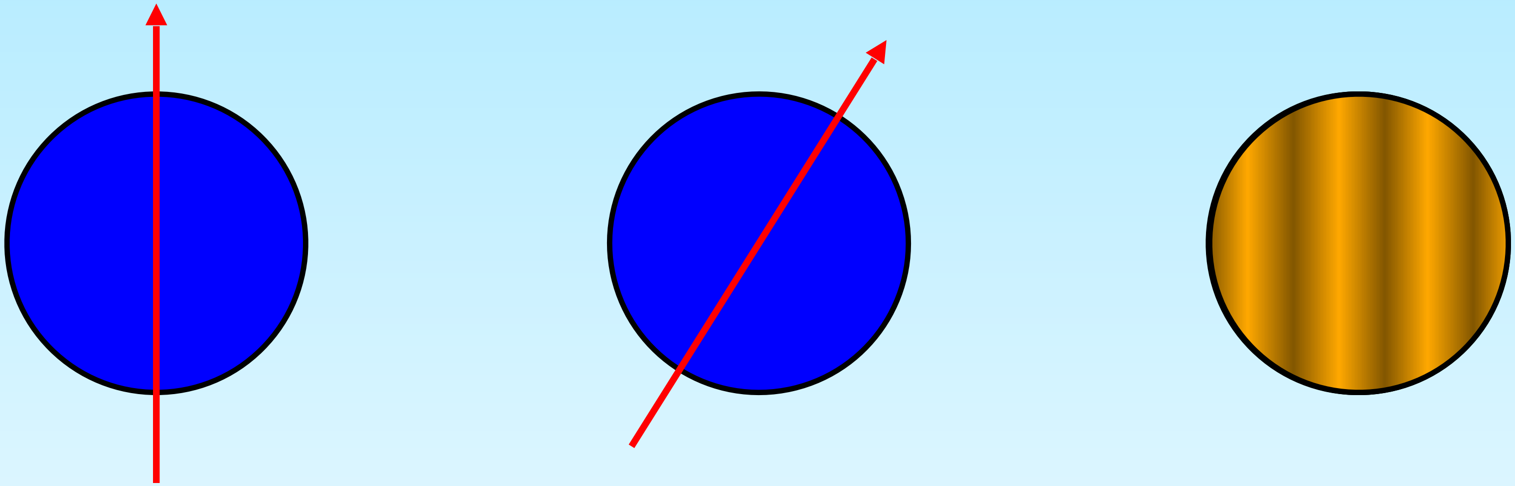

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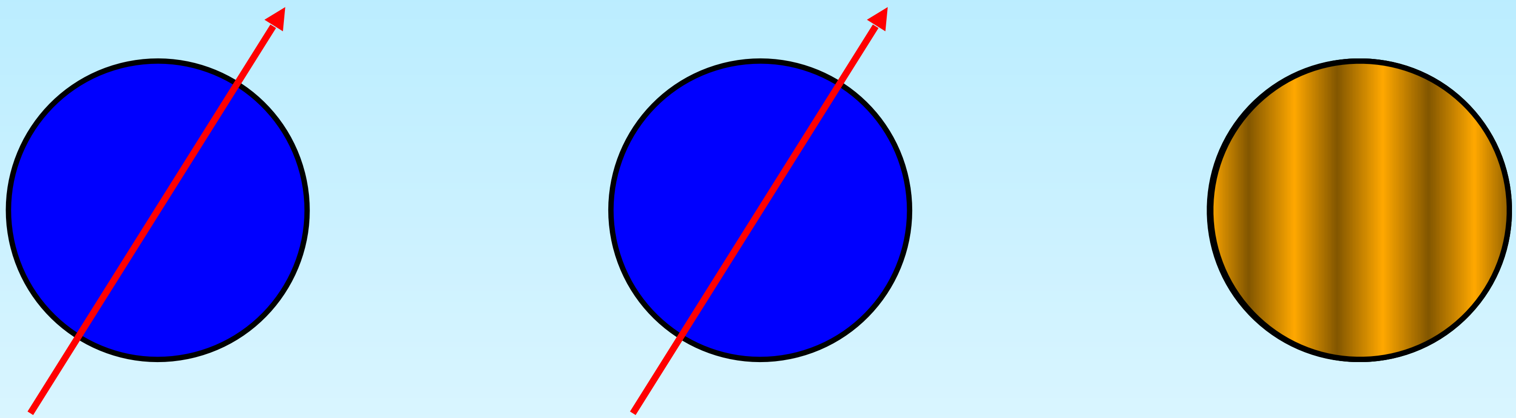
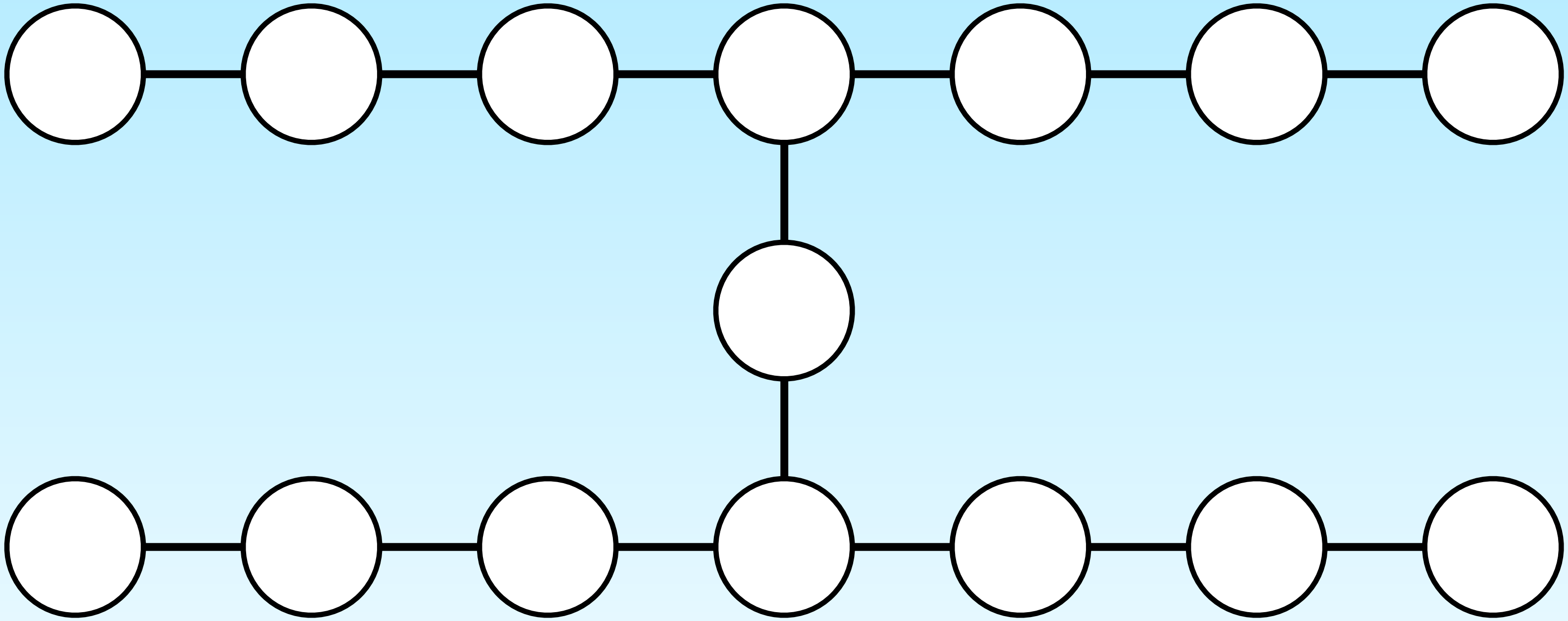


Teleportation Network



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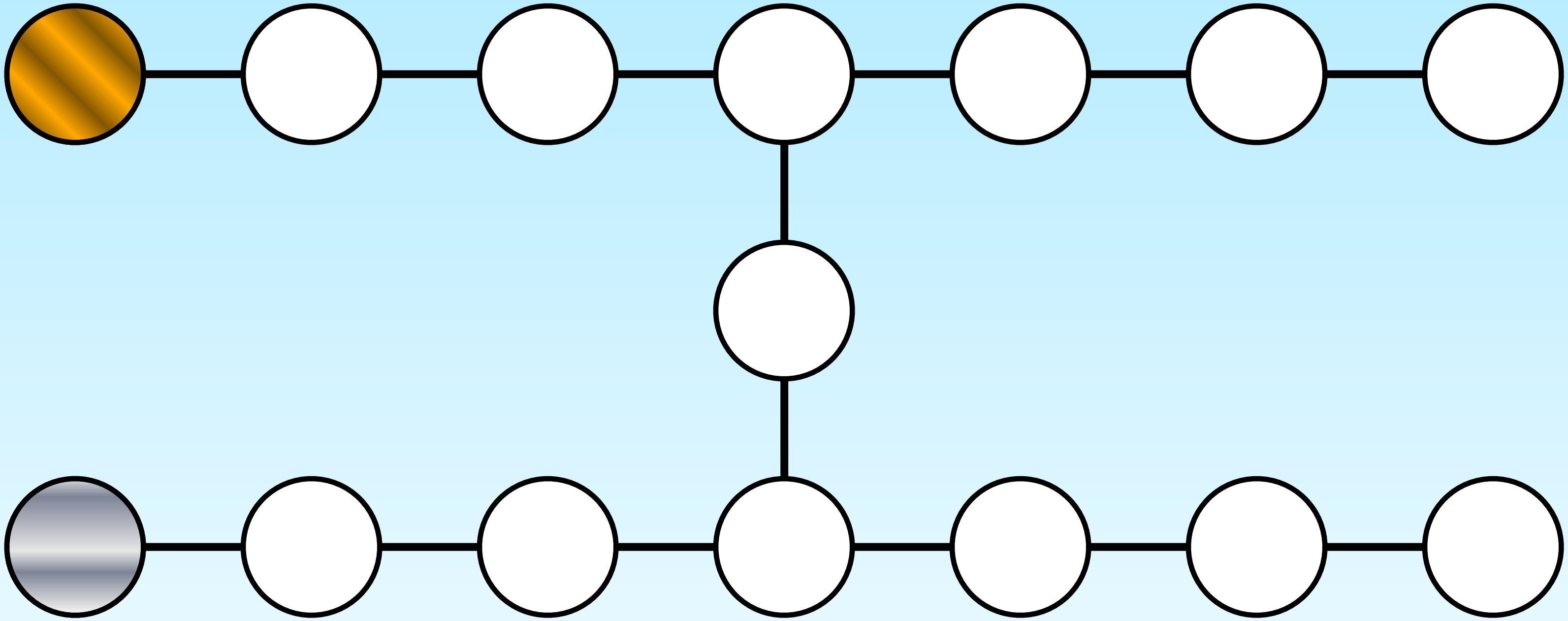

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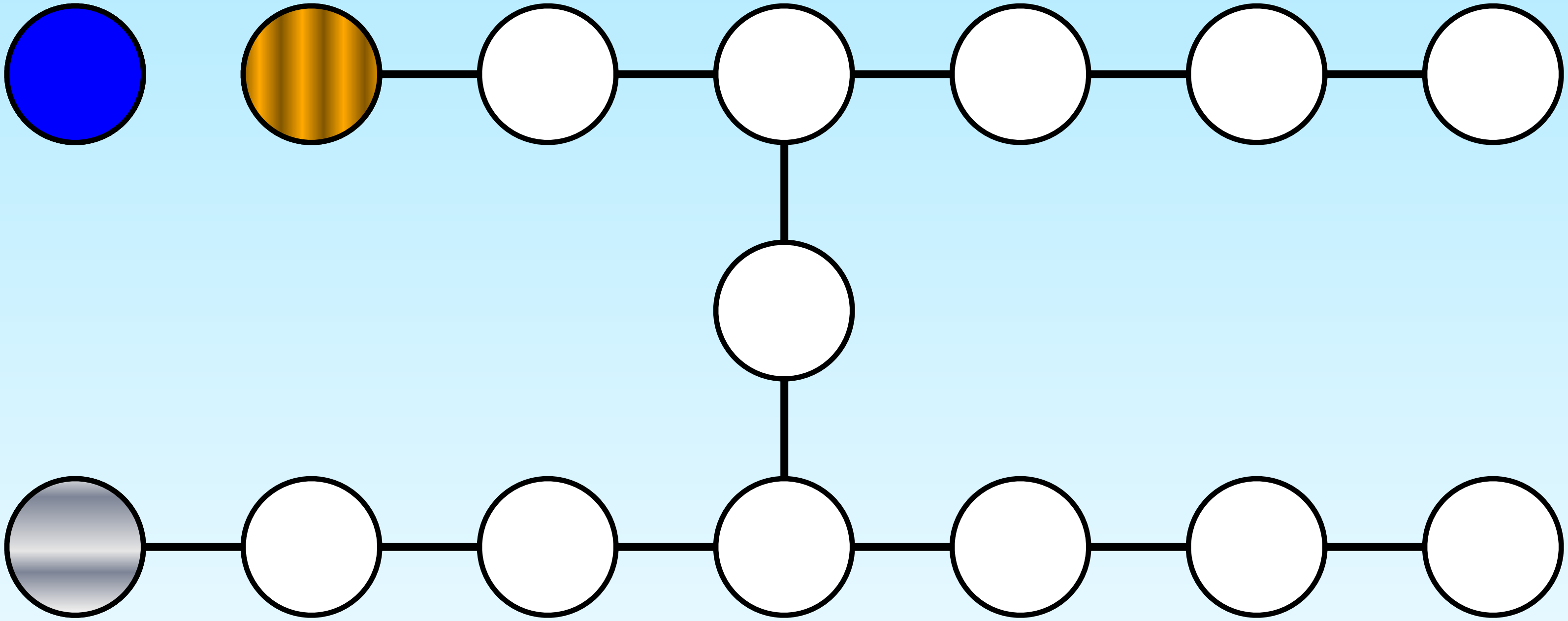

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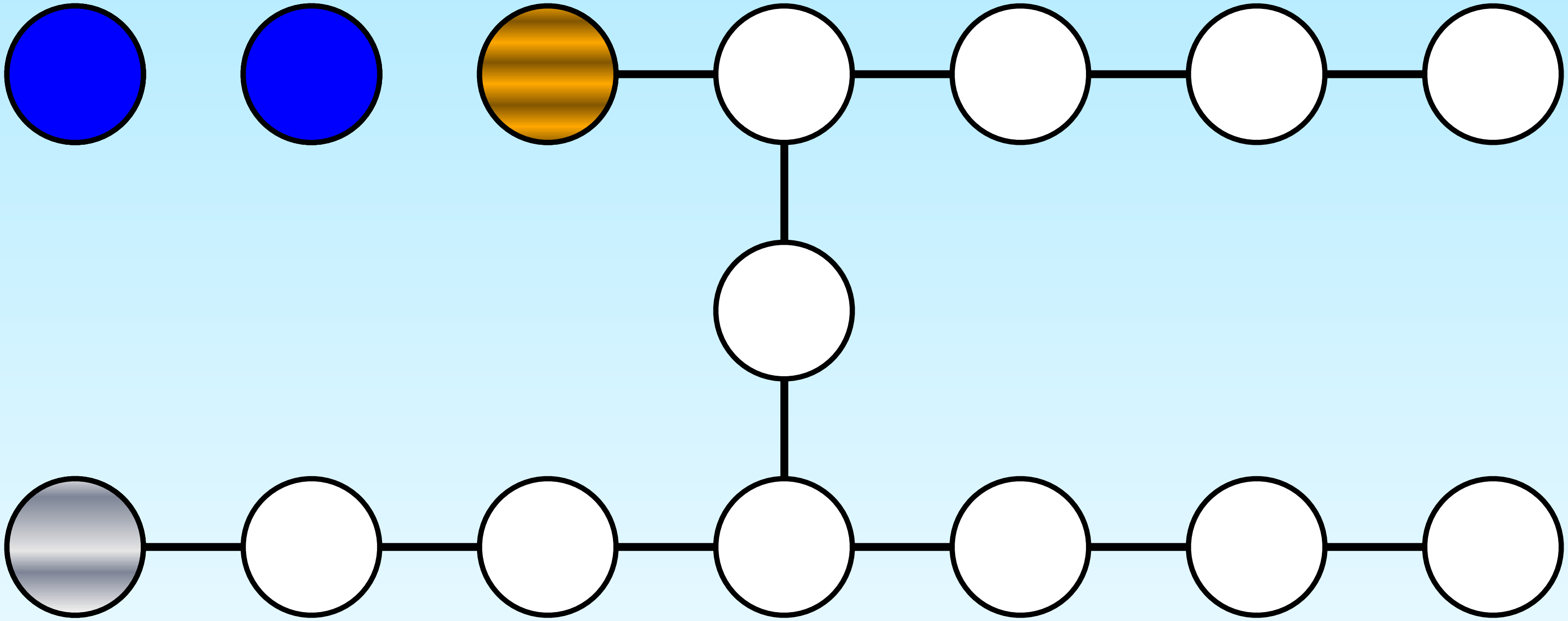

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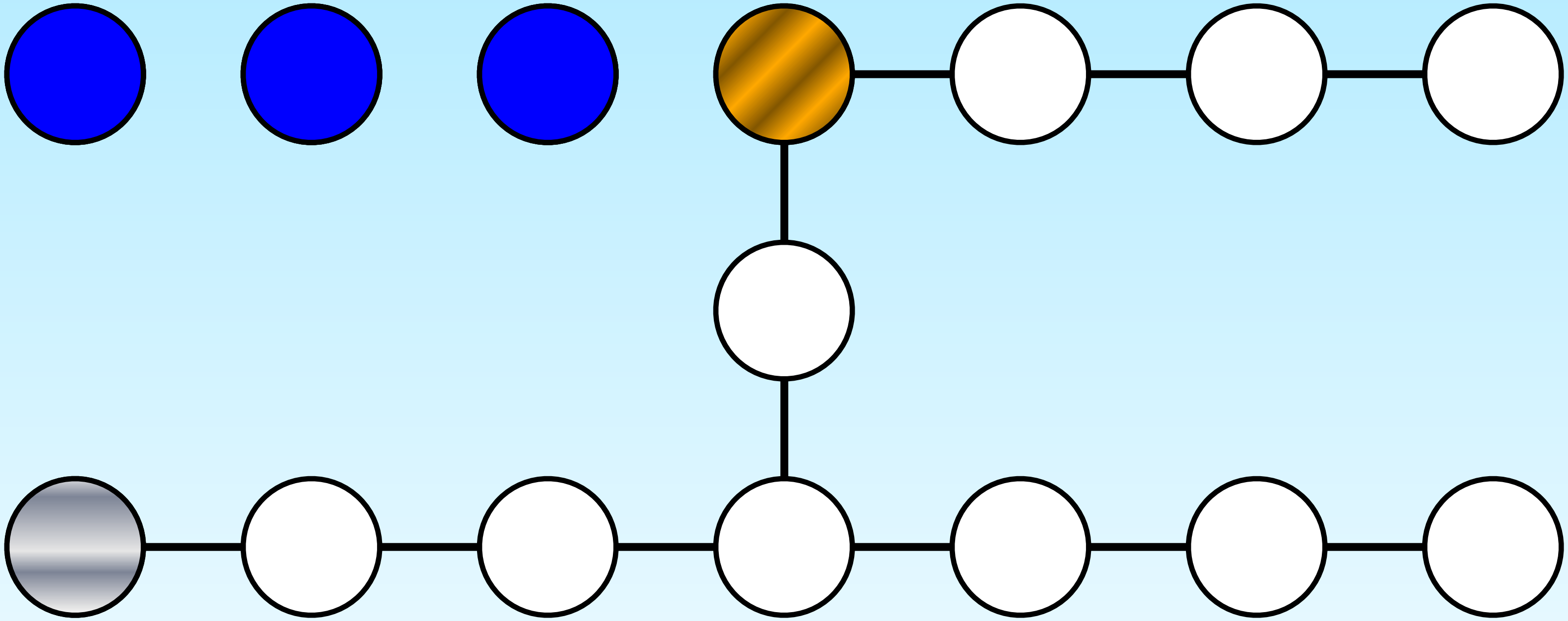

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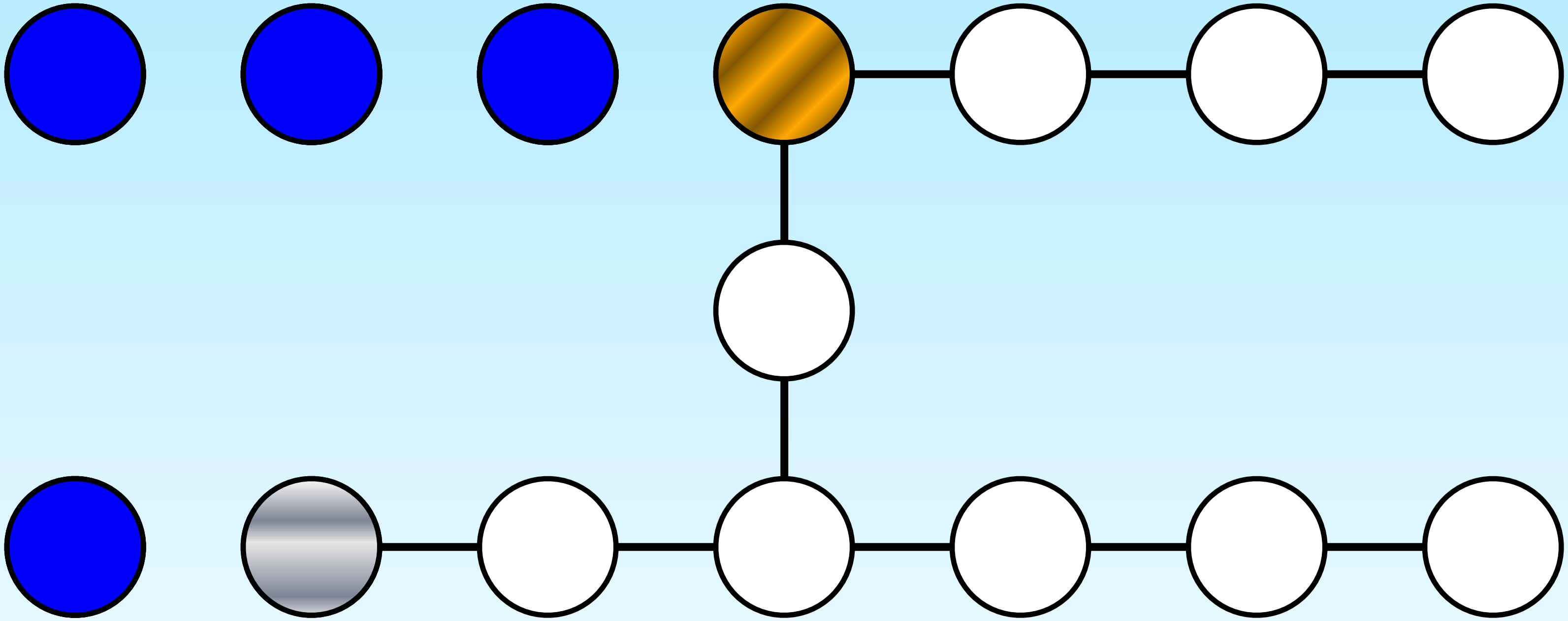

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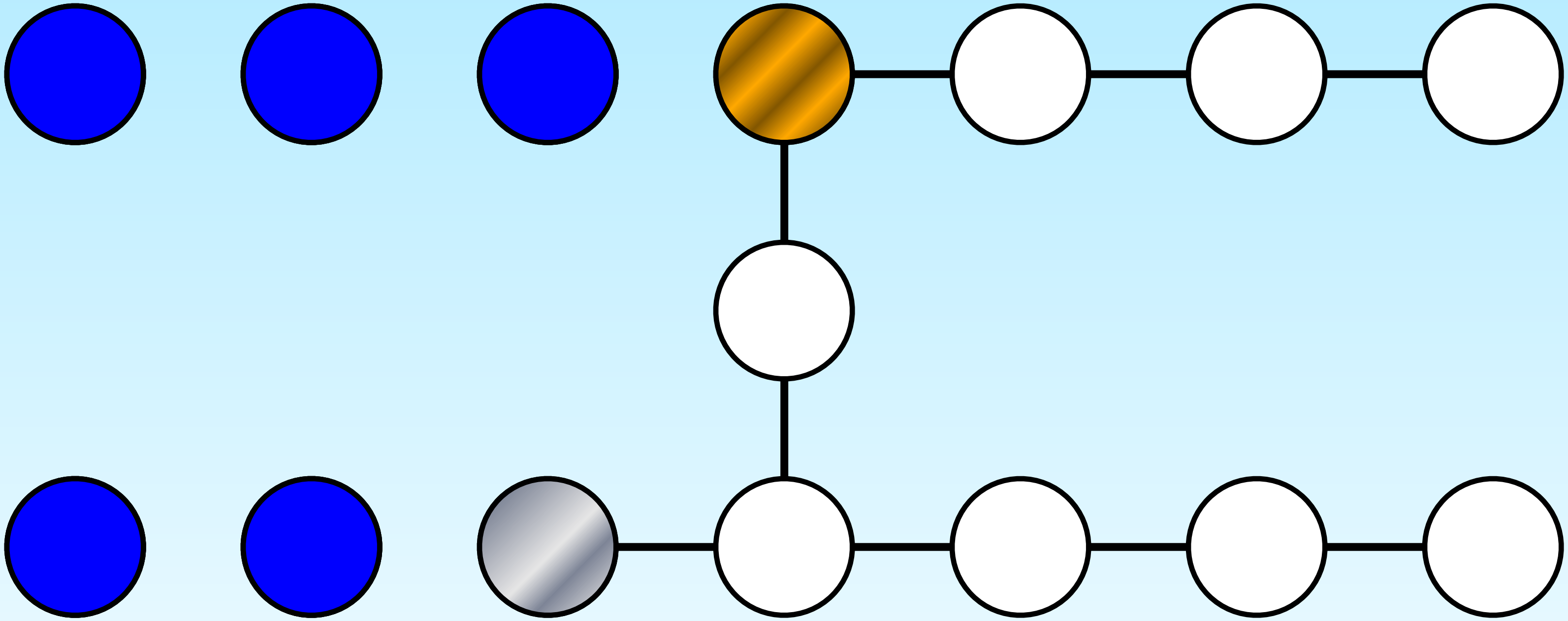

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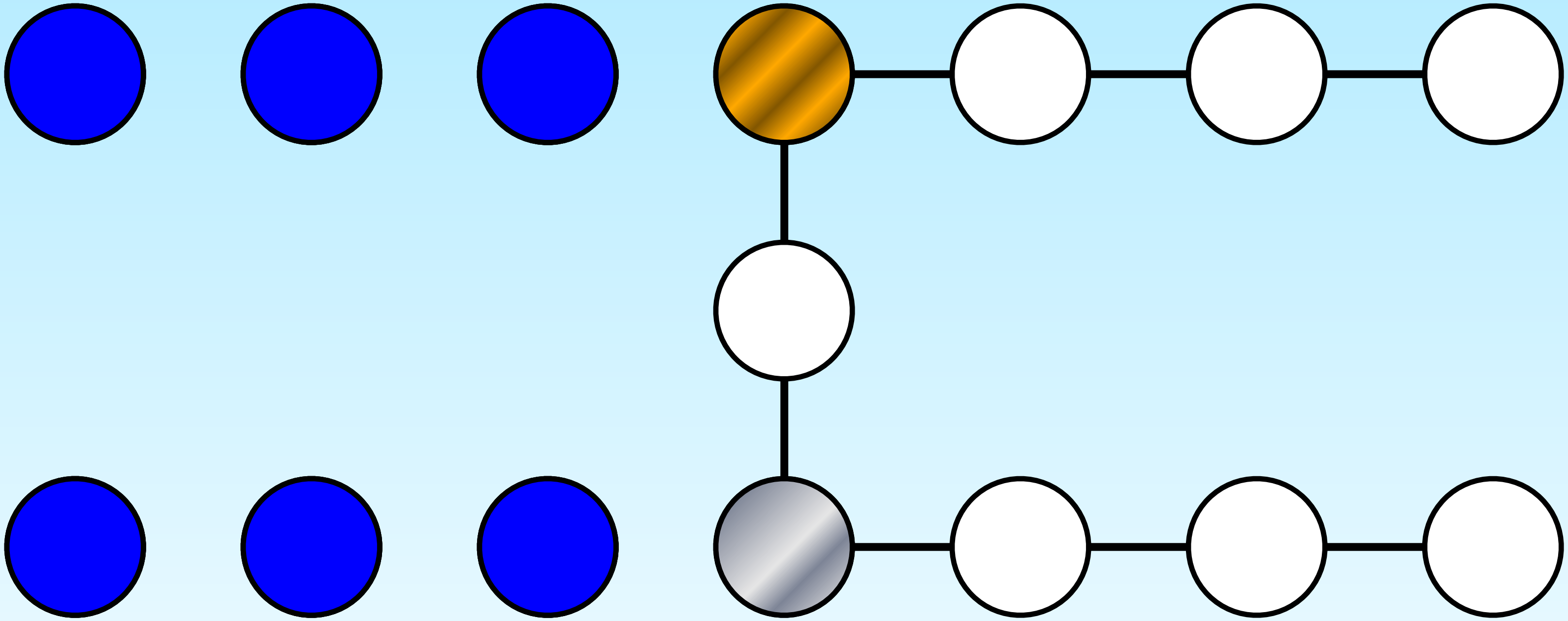

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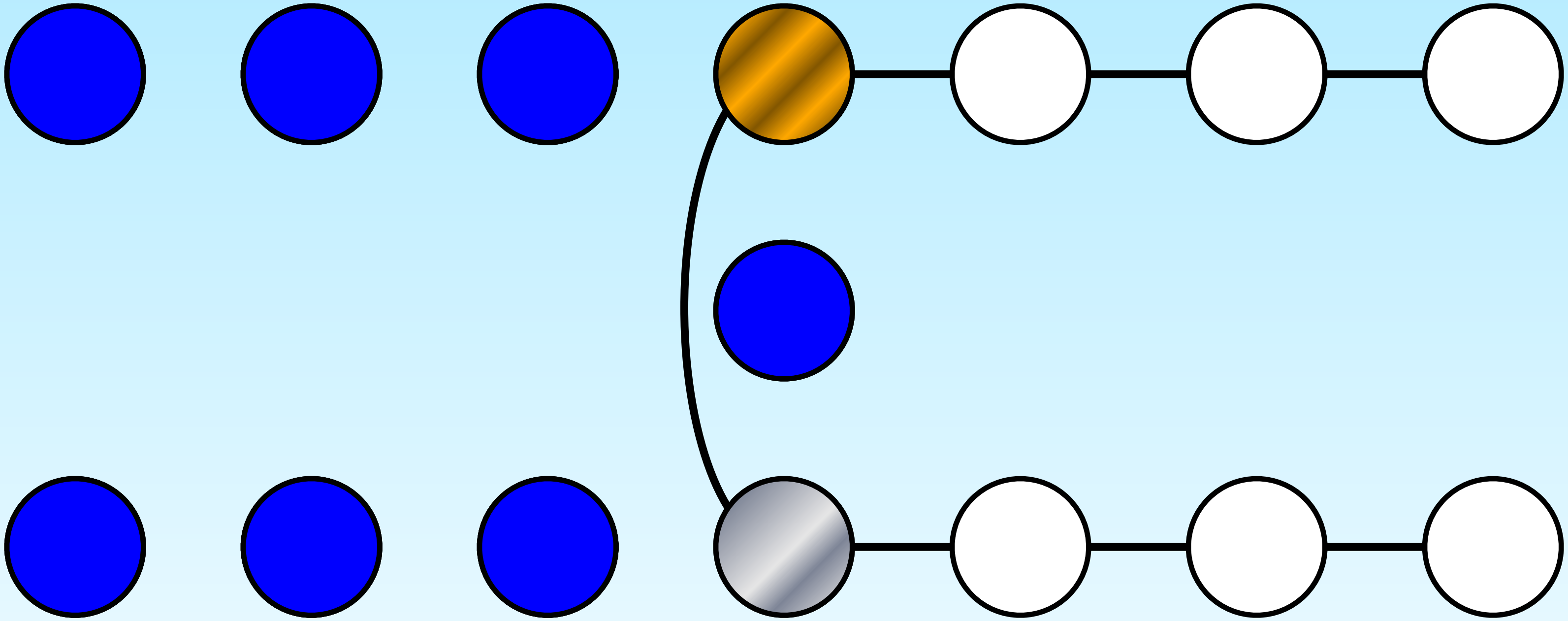

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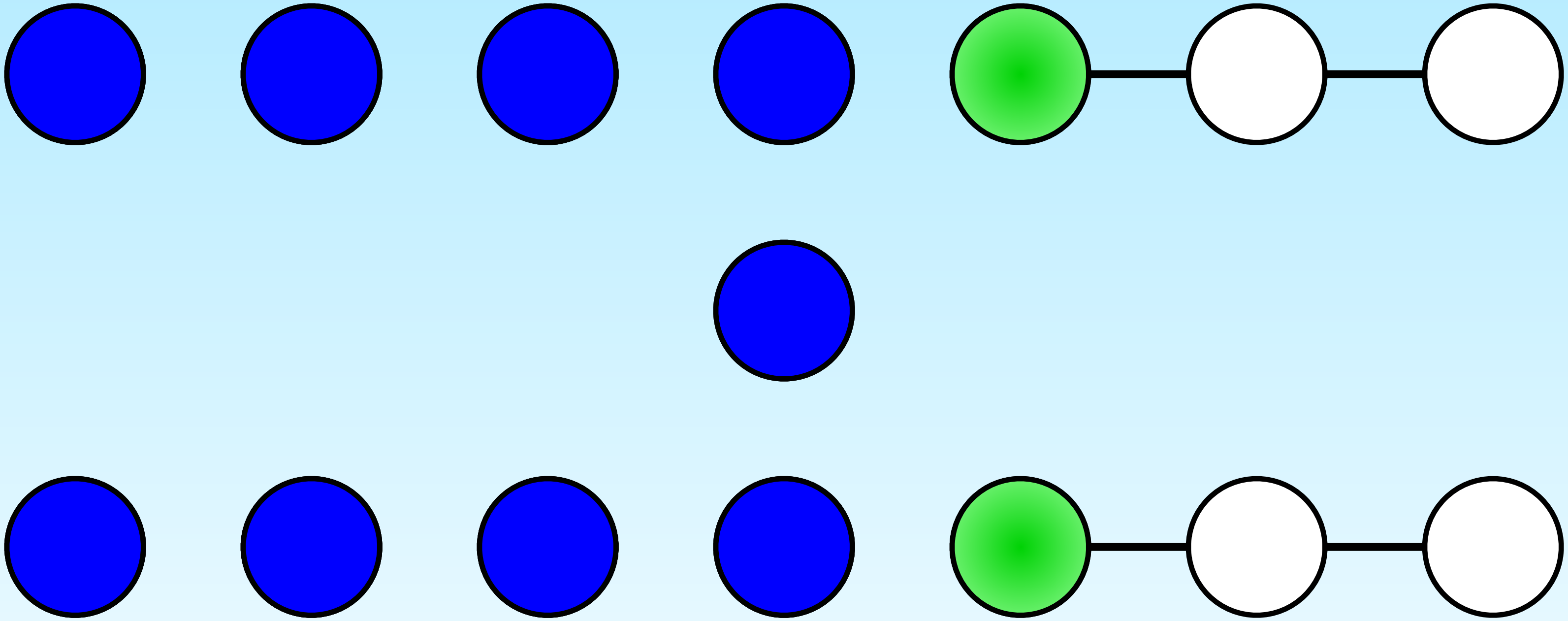

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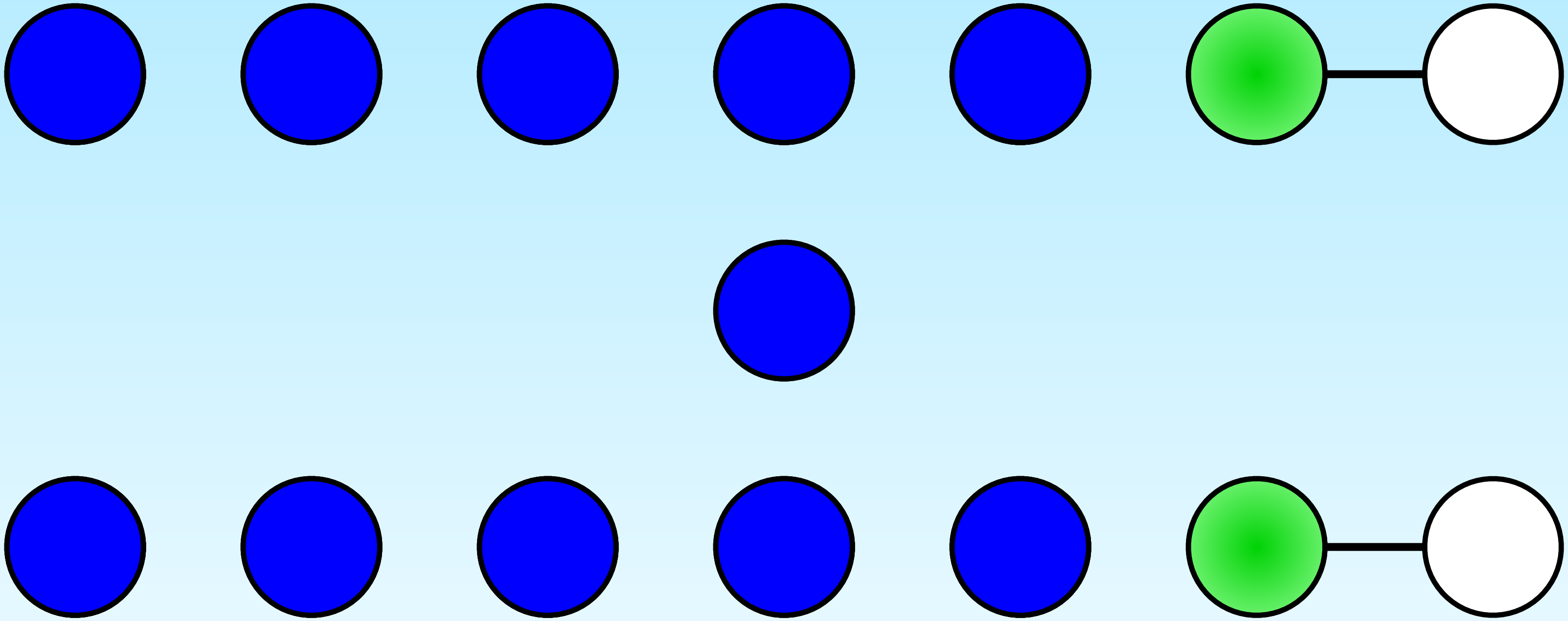

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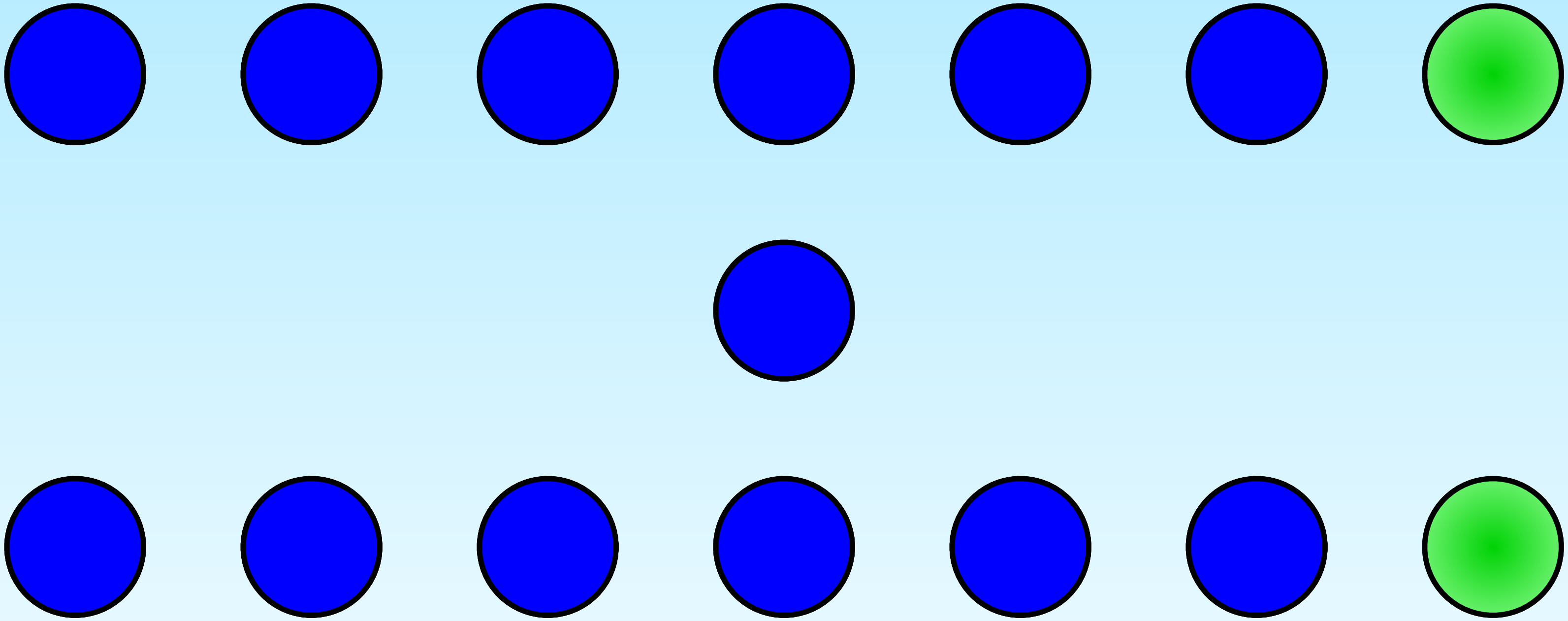
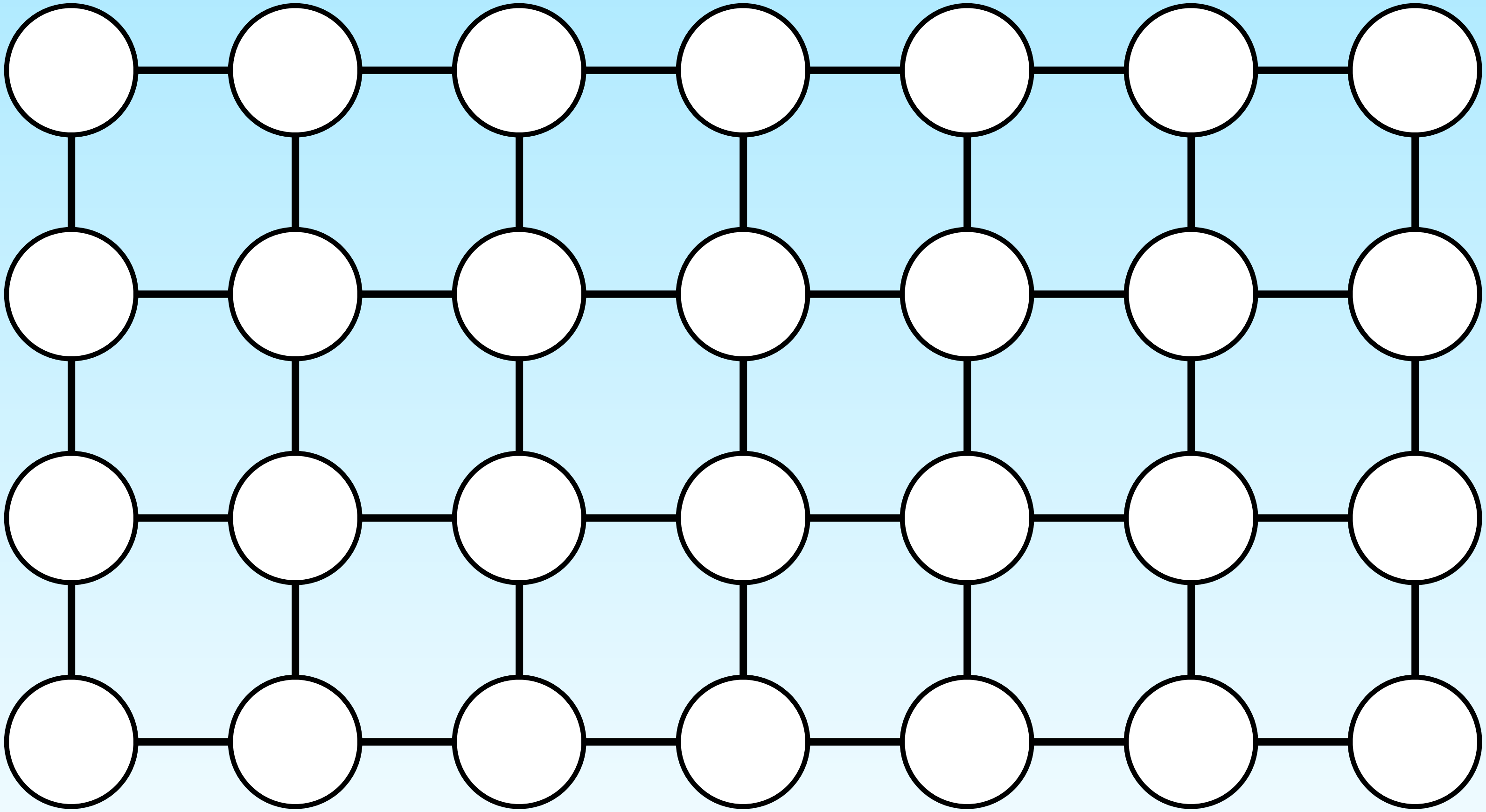


Cluster State



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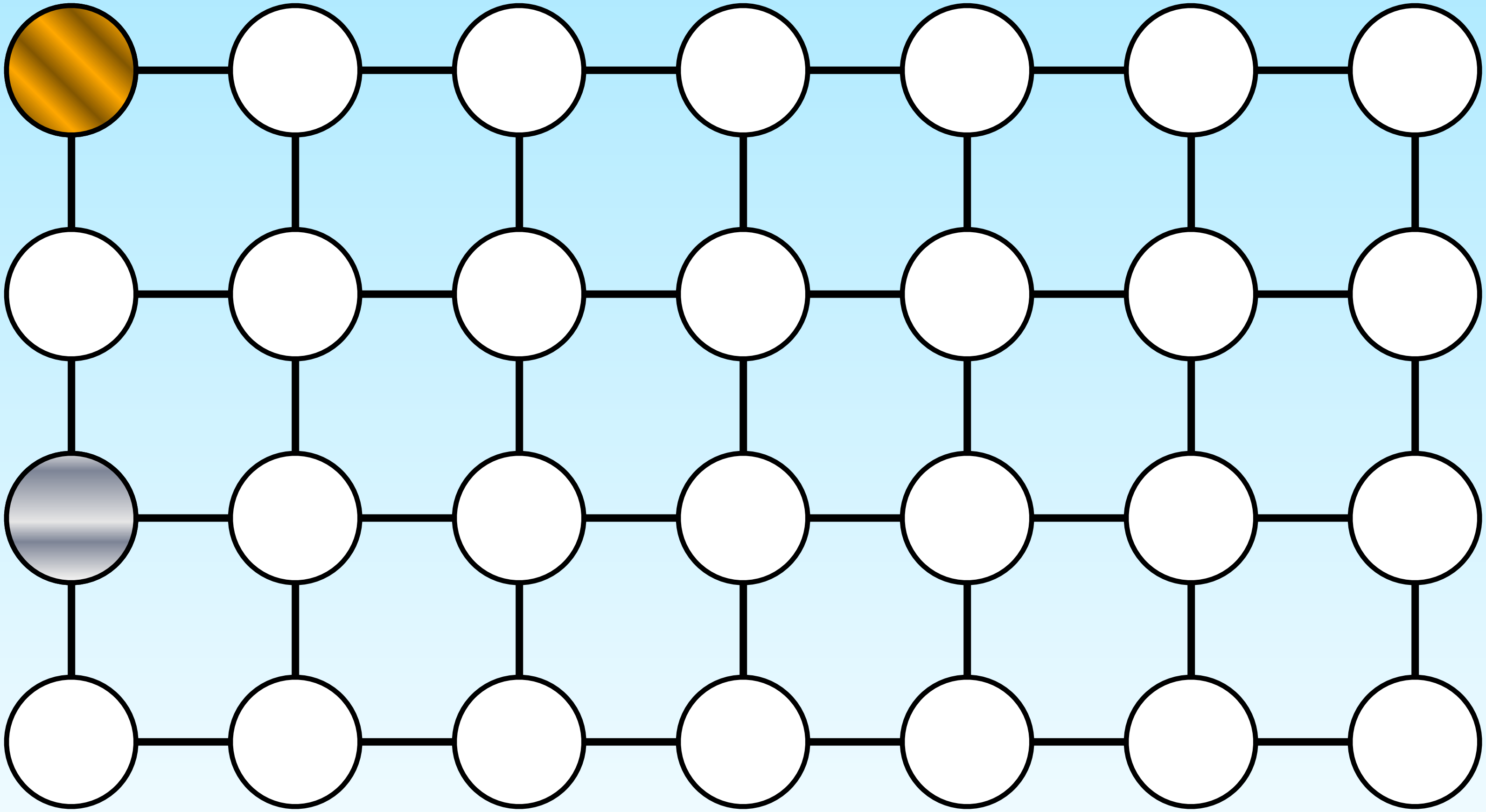

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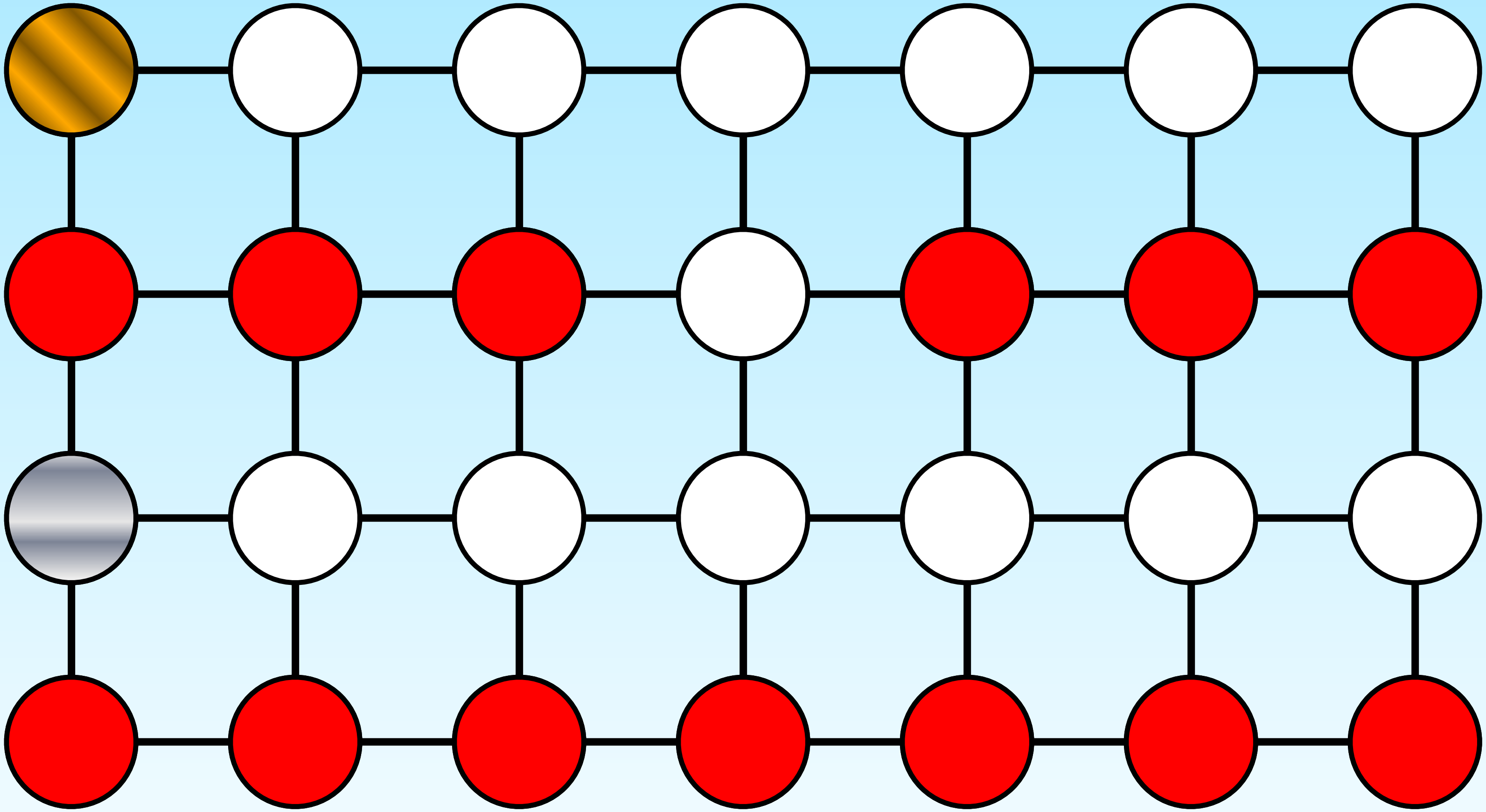

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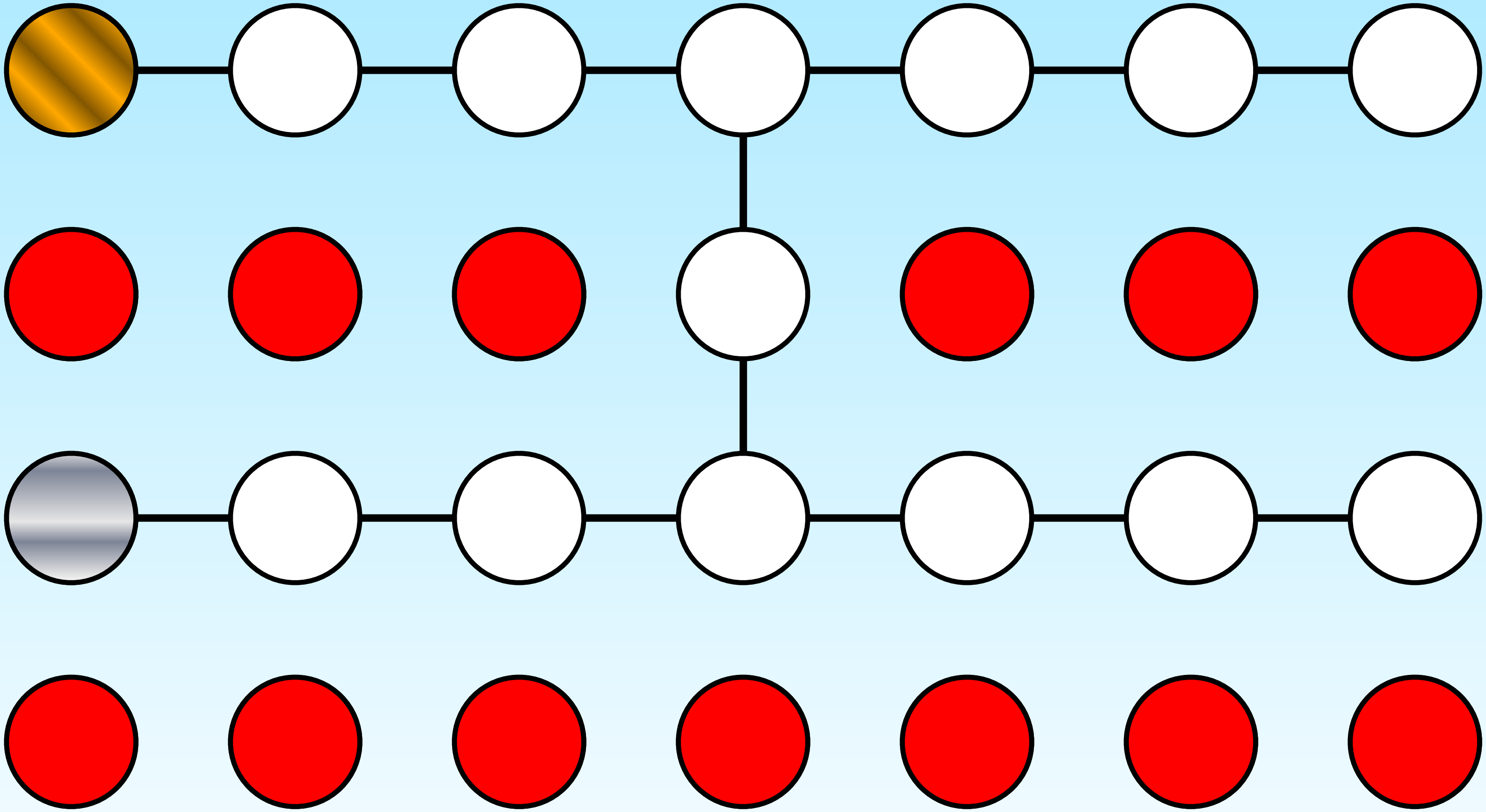

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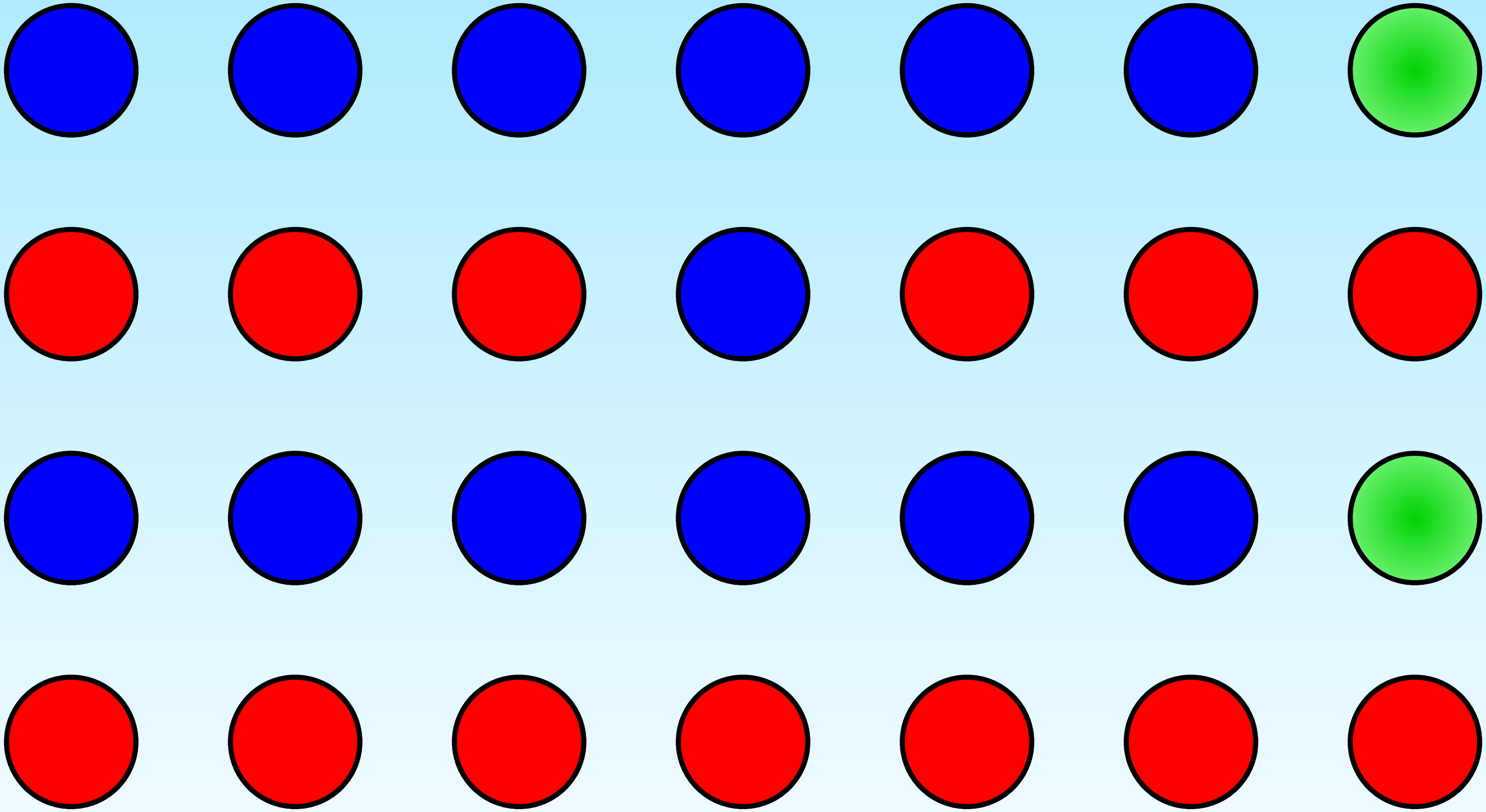

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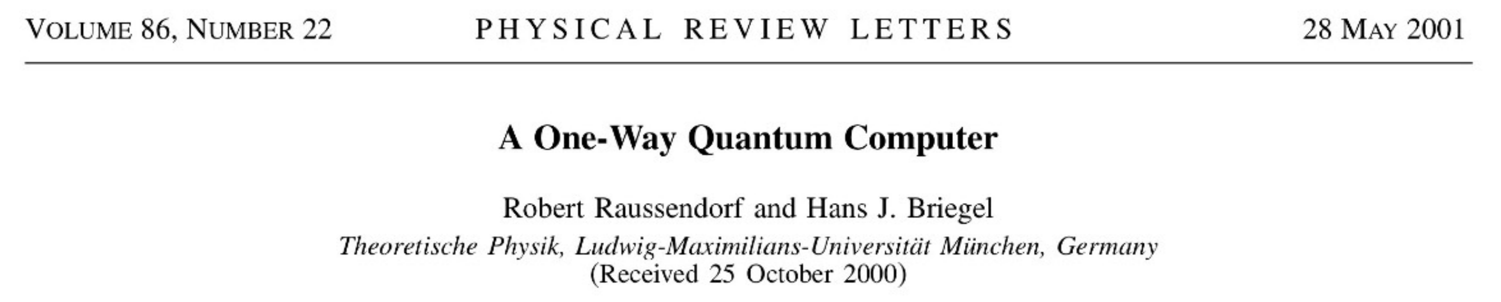

VOLUME 86, NUMBER 22 PHYSICAL REVIEW LETTERS 28 MAY 2001

A One-Way Quantum Computer

Robert Raussendorf and Hans J. Briegel
Theoretische Physik, Ludwig-Maximilians-Universität München, Germany

(Received 25 October 2000)

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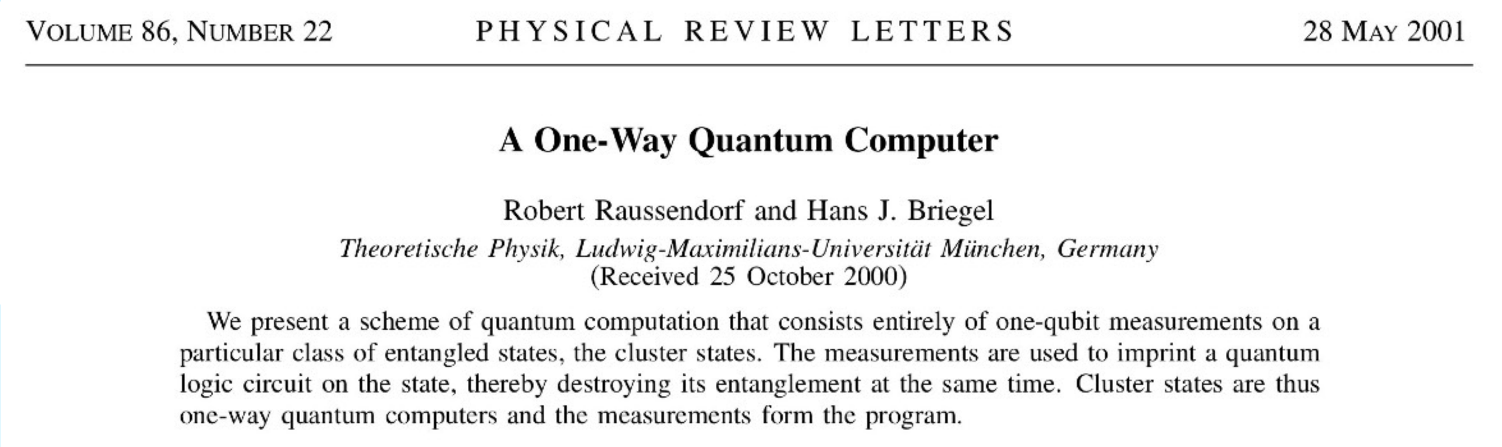

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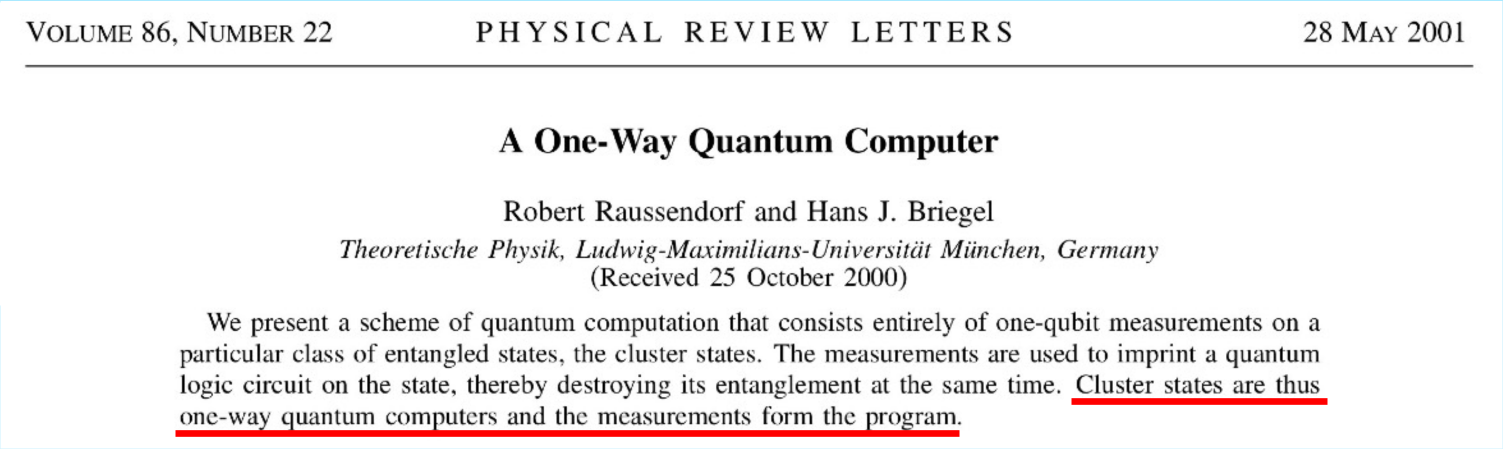
Cluster state



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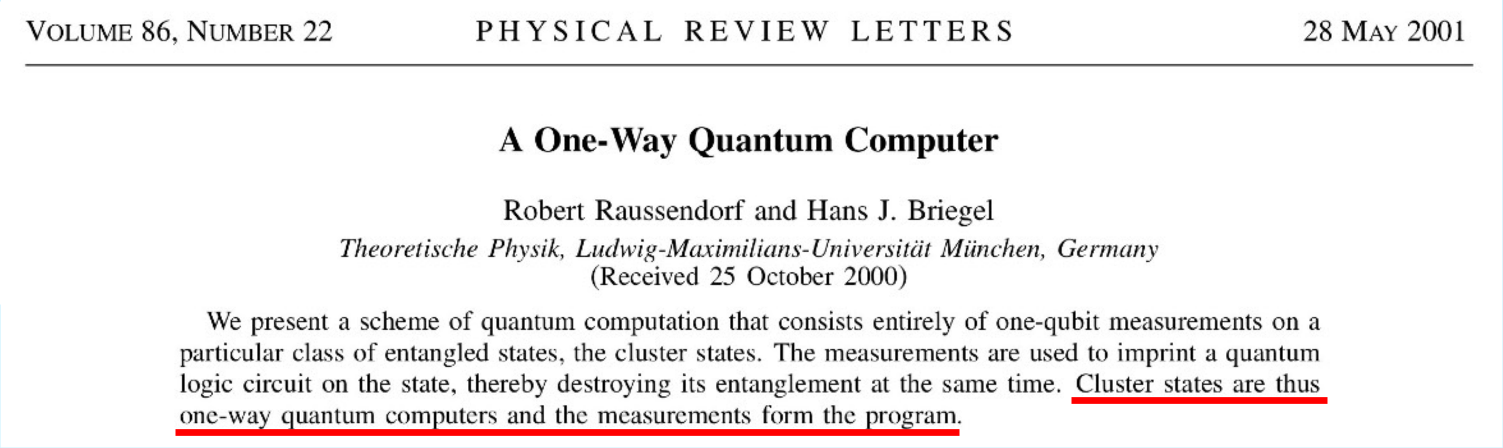

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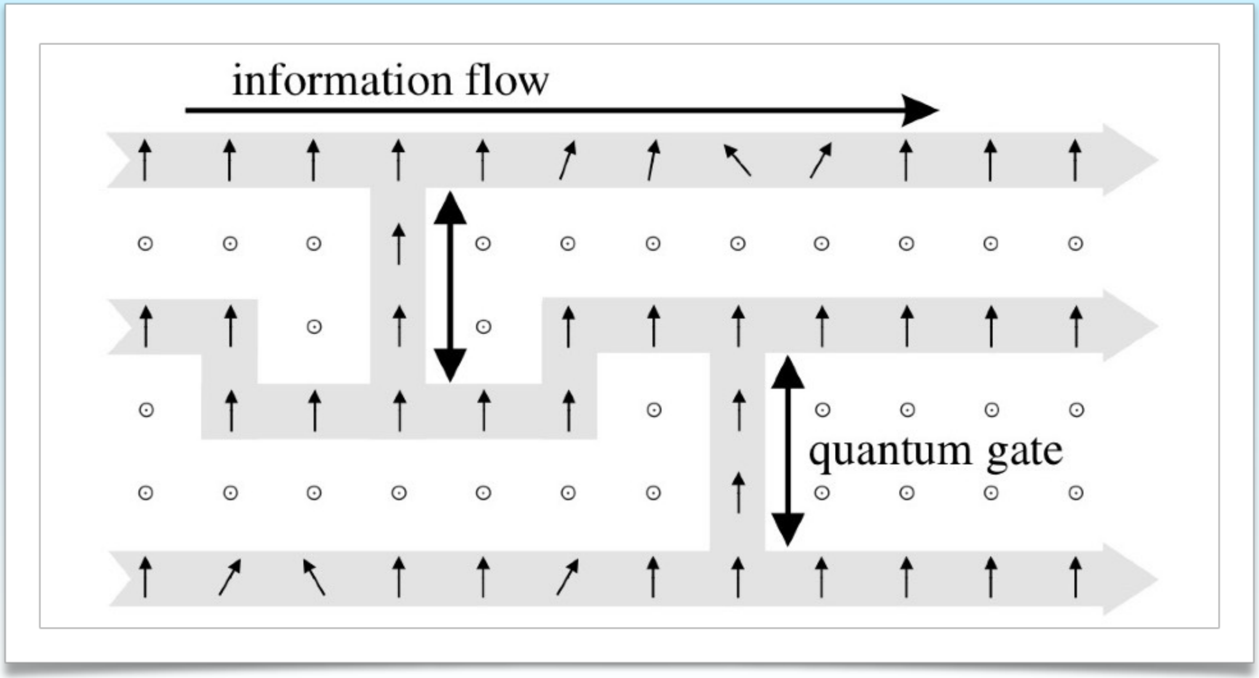

Why bother with CVs?

CVs: Advantages

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  - huge scaling potential
- Fundamental
  - avoid premature optimisation
    (i.e., why should we restrict to photonic qubits?)
- Both together
  - more options for practical tasks (e.g., quantum cryptography, cluster states)
  - "hybrid" schemes: CV technology helps to manipulate photonic quantum states

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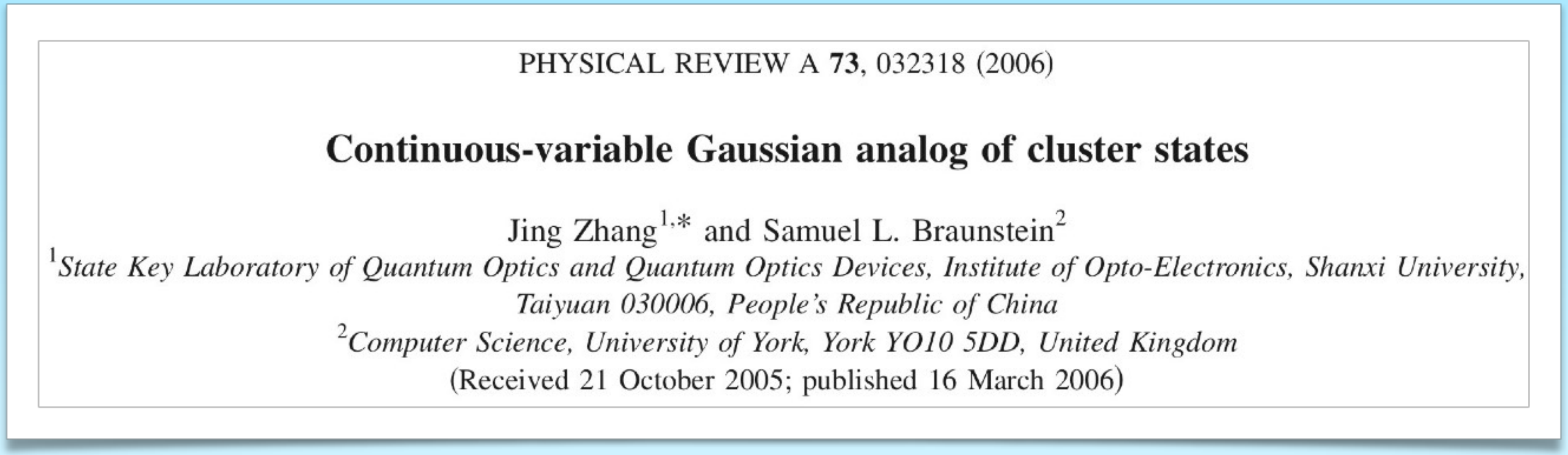
- Both together
  - must do extra work to employ existing algorithms
  - smaller literature, fewer optimised experimental platforms

CV cluster states

CV cluster states



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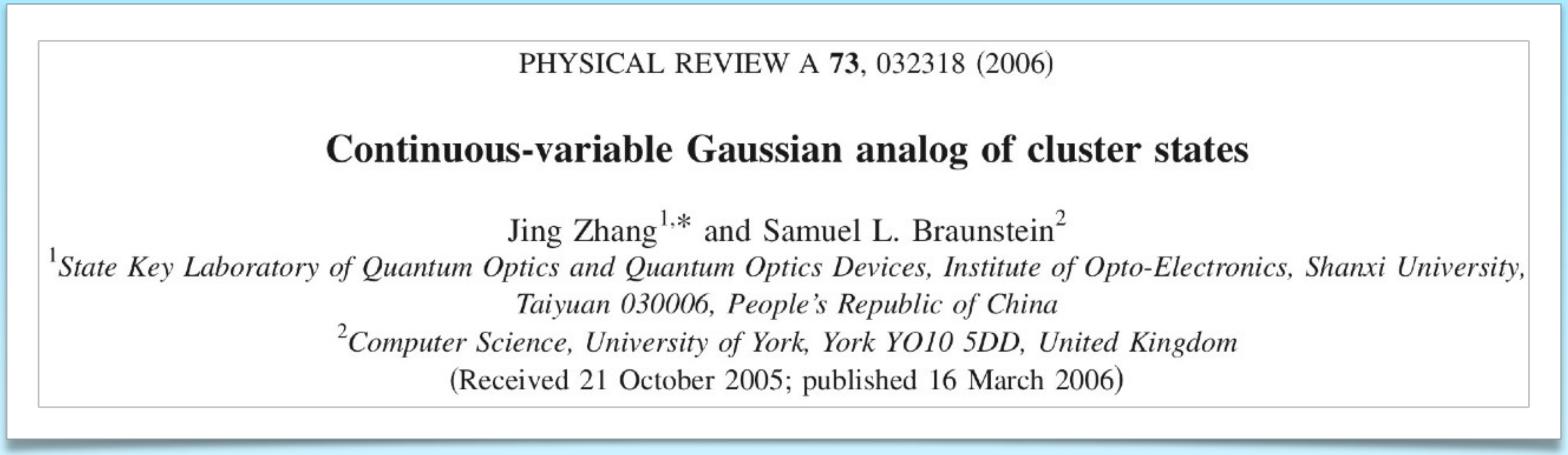
Continuous-variable Gaussian analog of cluster states

Jing Zhang[1,*] and Samuel L. Braunstein[2]
[1]*State Key Laboratory of Quantum Optics and Quantum Optics Devices, Institute of Opto-Electronics, Shanxi University, Taiyuan 030006, People's Republic of China*
[2]*Computer Science, University of York, York YO10 5DD, United Kingdom*

(Received 21 October 2005; published 16 March 2006)

CV cluster states



PHYSICAL REVIEW A **73**, 032318 (2006)

Continuous-variable Gaussian analog of cluster states

Jing Zhang[1,*] and Samuel L. Braunstein[2]
[1]*State Key Laboratory of Quantum Optics and Quantum Optics Devices, Institute of Opto-Electronics, Shanxi University, Taiyuan 030006, People's Republic of China*
[2]*Computer Science, University of York, York YO10 5DD, United Kingdom*

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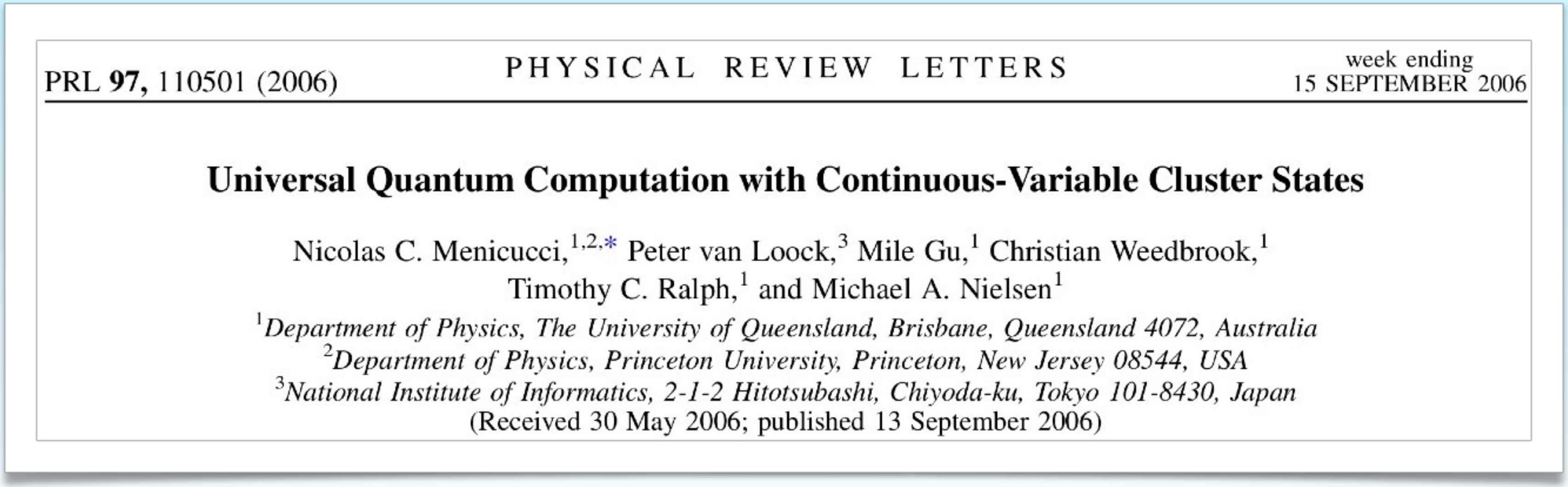


PRL **97,** 110501 (2006) PHYSICAL REVIEW LETTERS week ending 15 SEPTEMBER 2006

Universal Quantum Computation with Continuous-Variable Cluster States

Nicolas C. Menicucci,[1,2,*] Peter van Loock,[3] Mile Gu,[1] Christian Weedbrook,[1]
Timothy C. Ralph,[1] and Michael A. Nielsen[1]
[1]*Department of Physics, The University of Queensland, Brisbane, Queensland 4072, Australia*
[2]*Department of Physics, Princeton University, Princeton, New Jersey 08544, USA*
[3]*National Institute of Informatics, 2-1-2 Hitotsubashi, Chiyoda-ku, Tokyo 101-8430, Japan*

(Received 30 May 2006; published 13 September 2006)

Optical implementation

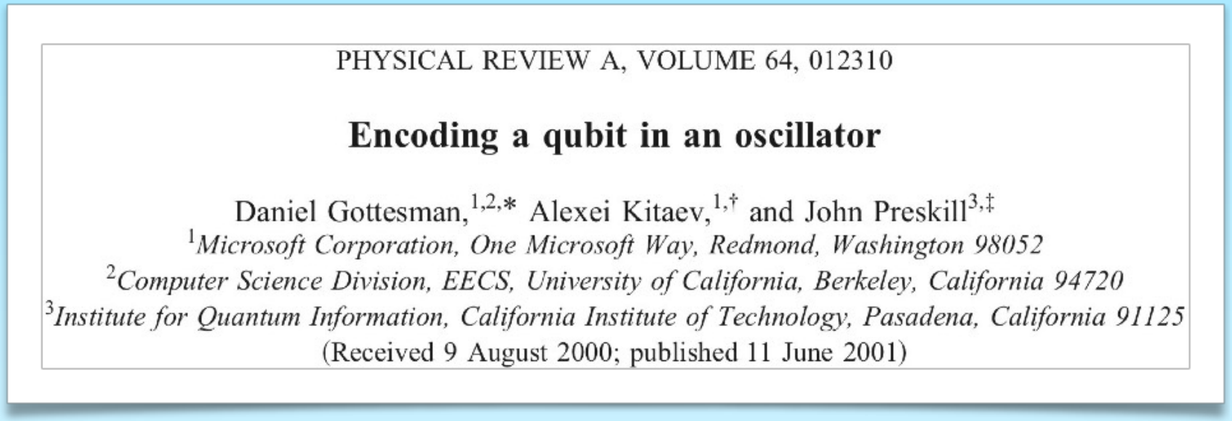
- Continuous quantum variables
  - Computational basis: eigenstates of $q = (a + a^\dagger)/\sqrt{2}$
  - Conjugate basis: eigenstates of $p = -i(a - a^\dagger)/\sqrt{2}$
- Advantages of CV (over qubit) cluster states
  - Deterministic generation
  - Scalable to huge sizes
- Problem: ideal CV cluster states are infinitely squeezed (infinite energy)
  - Finite squeezing → additive Gaussian noise
  - Fault tolerance possible with encoded qubits (GKP)

Computation with ideal states

- Single-mode projective measurements are sufficient for universal QC
- Homodyne detection (quadrature measurements) enables all Gaussian unitaries
  - Relatively easy to do experimentally
  - Very low noise
- Photon counting enables the rest
  - Less efficient, but technology rapidly improving
- Still have to handle intrinsic noise…

Fault tolerance

Encoded qubits



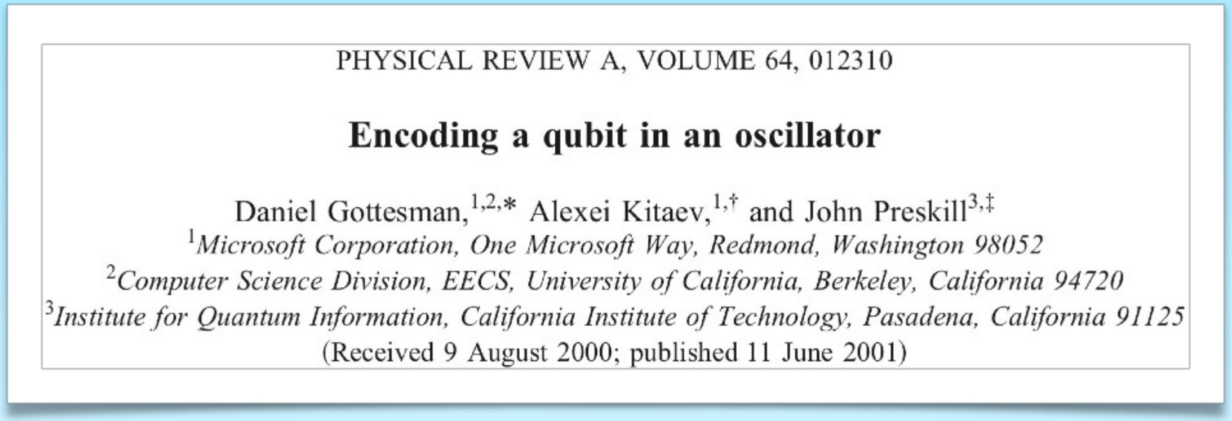
PHYSICAL REVIEW A, VOLUME 64, 012310

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)

Encoded qubits



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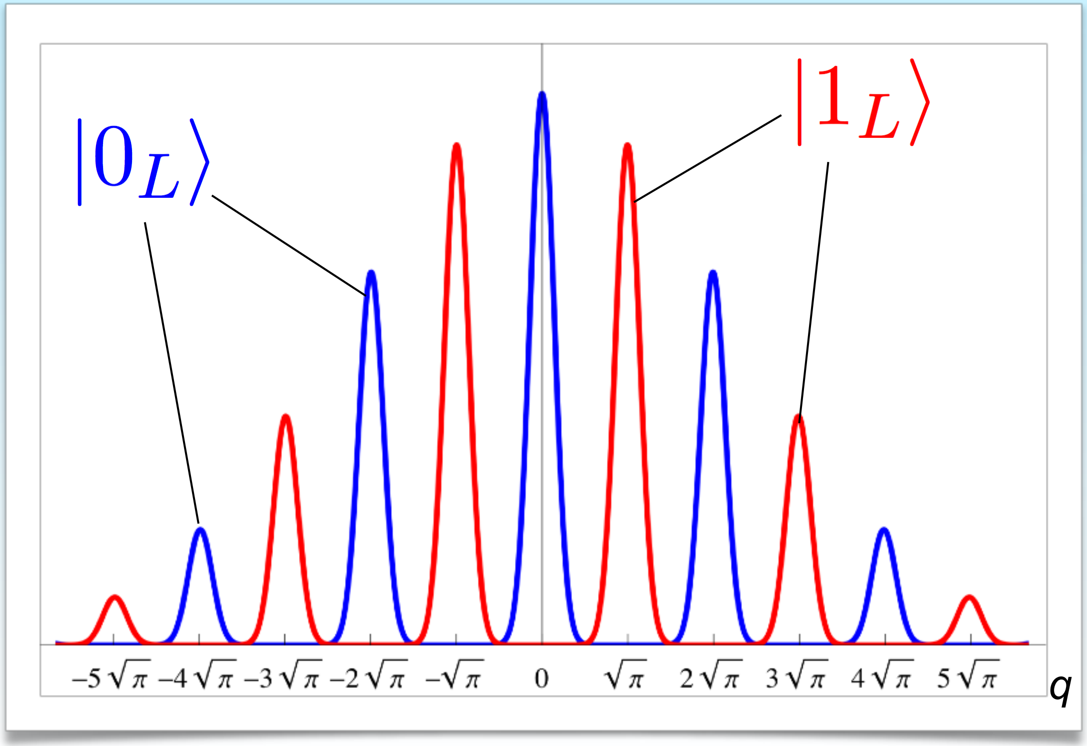
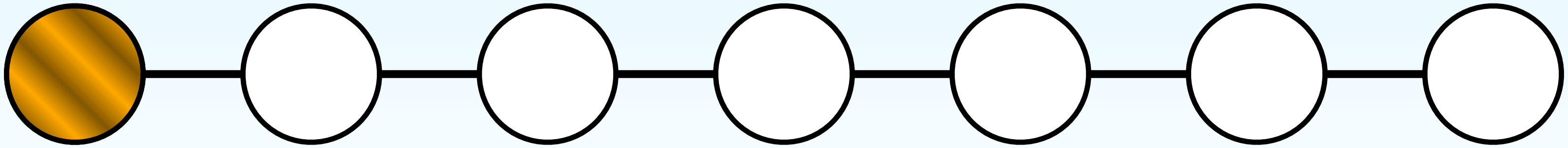
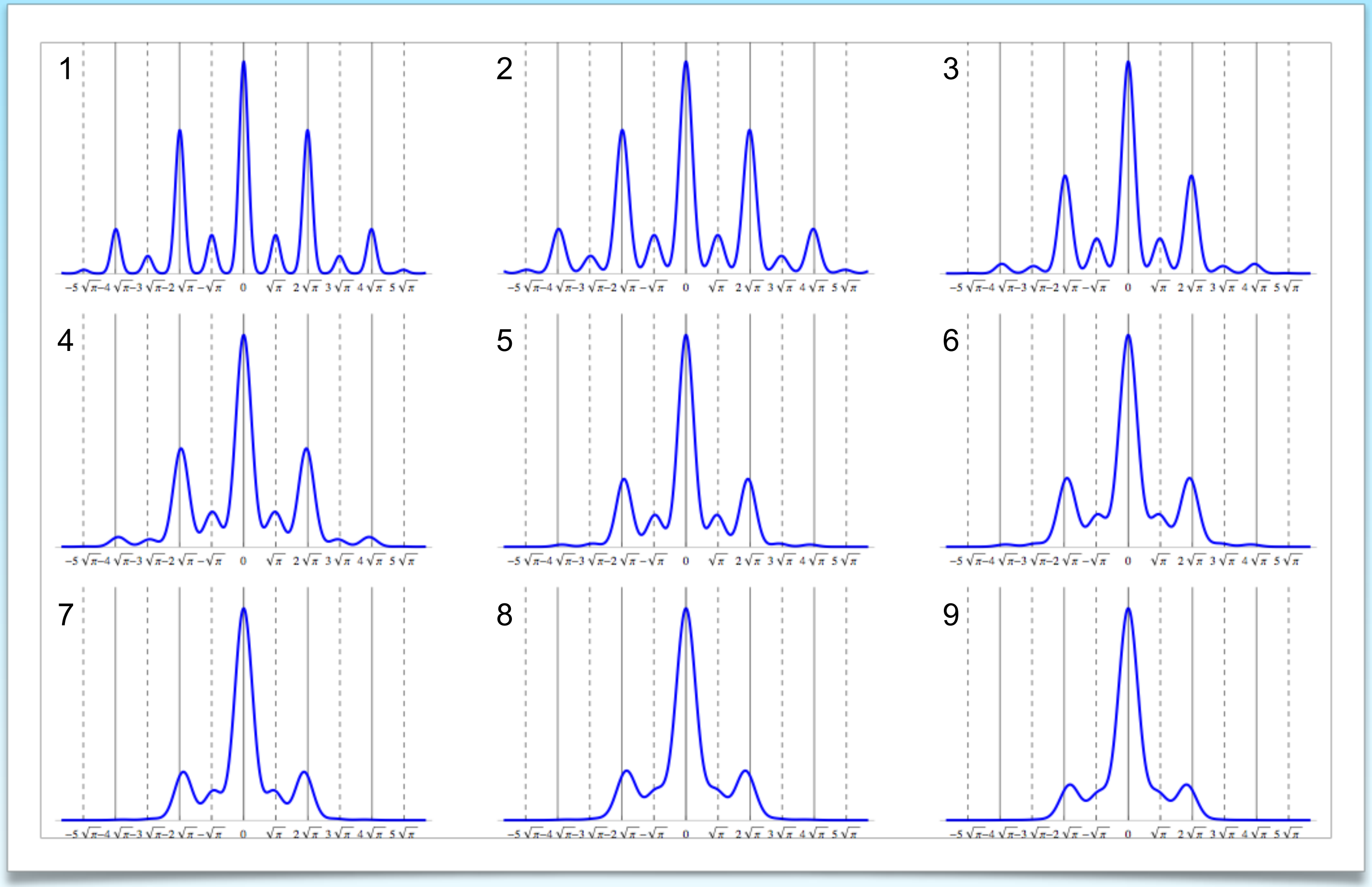


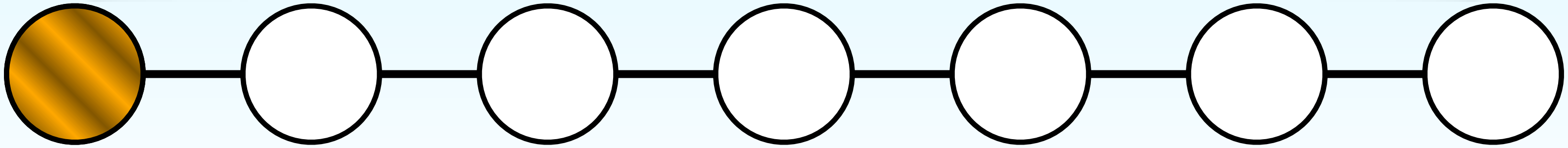
Noise process



Information flow →

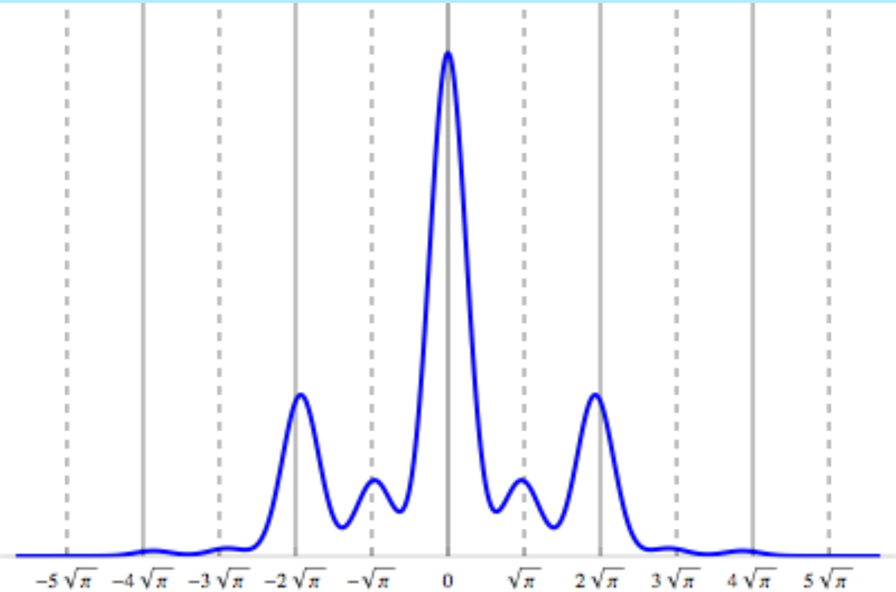
Noise process





Information flow →

Projecting to qubit-level errors



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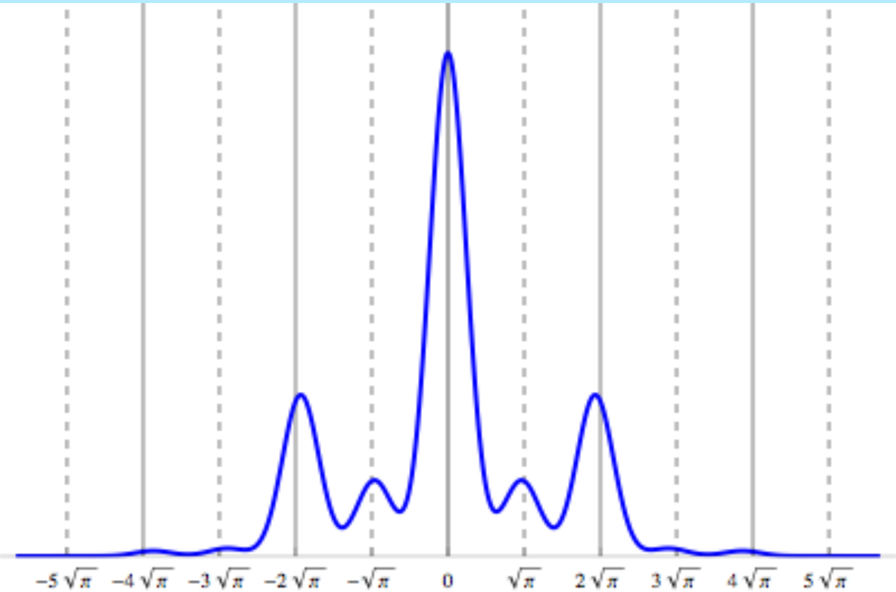

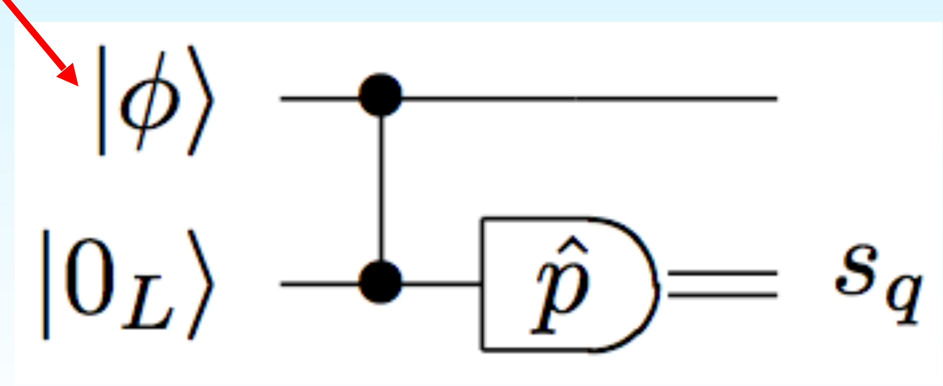

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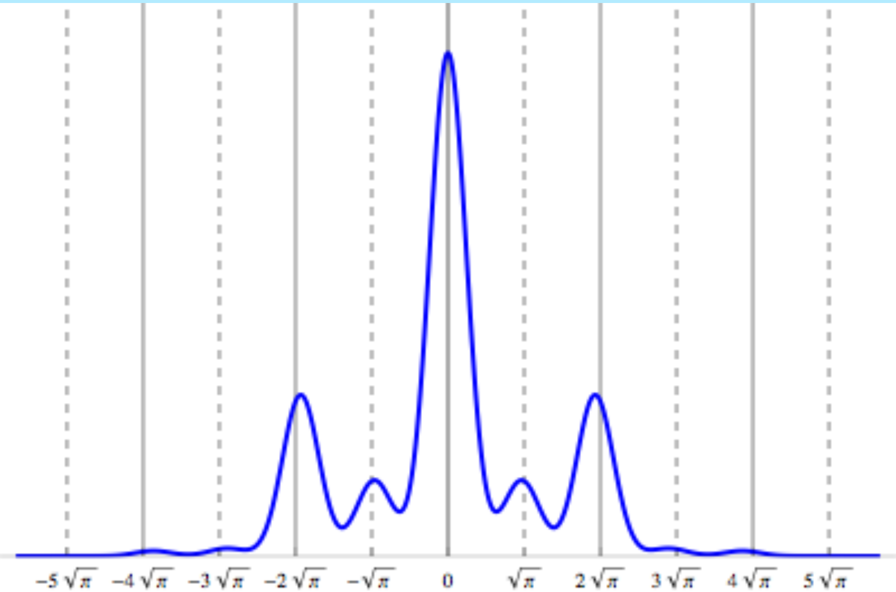

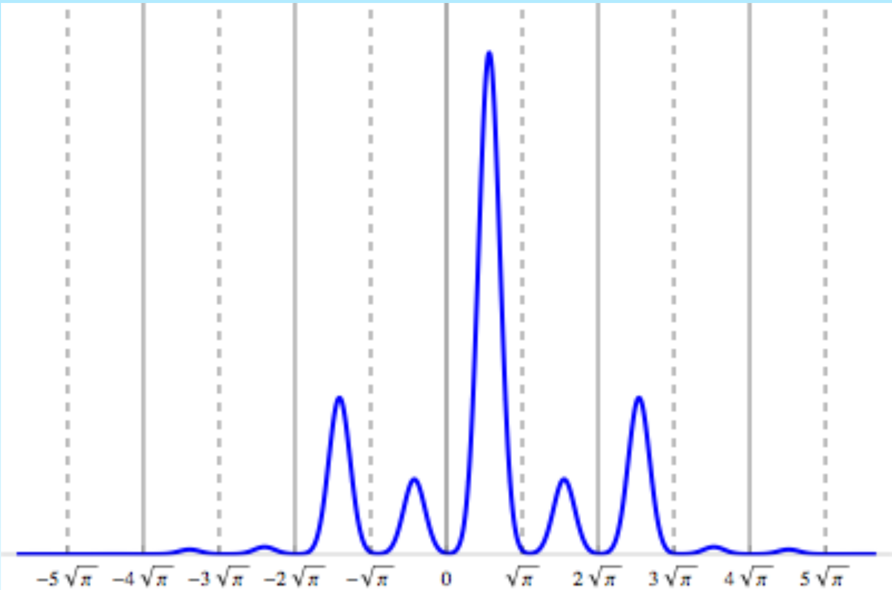

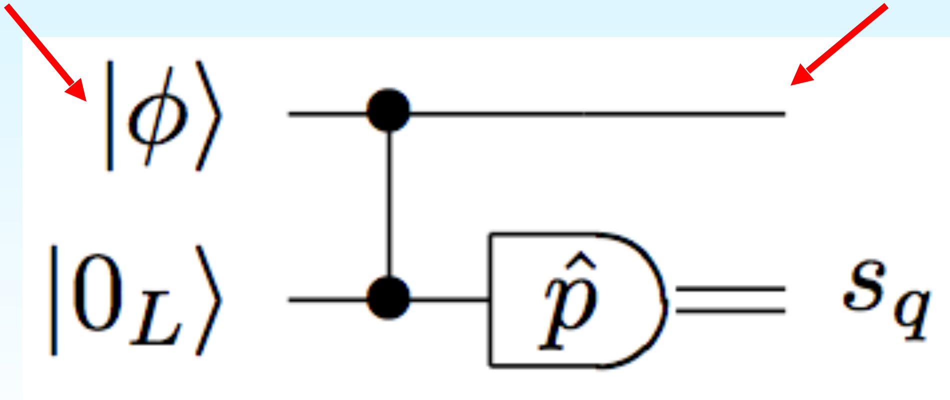

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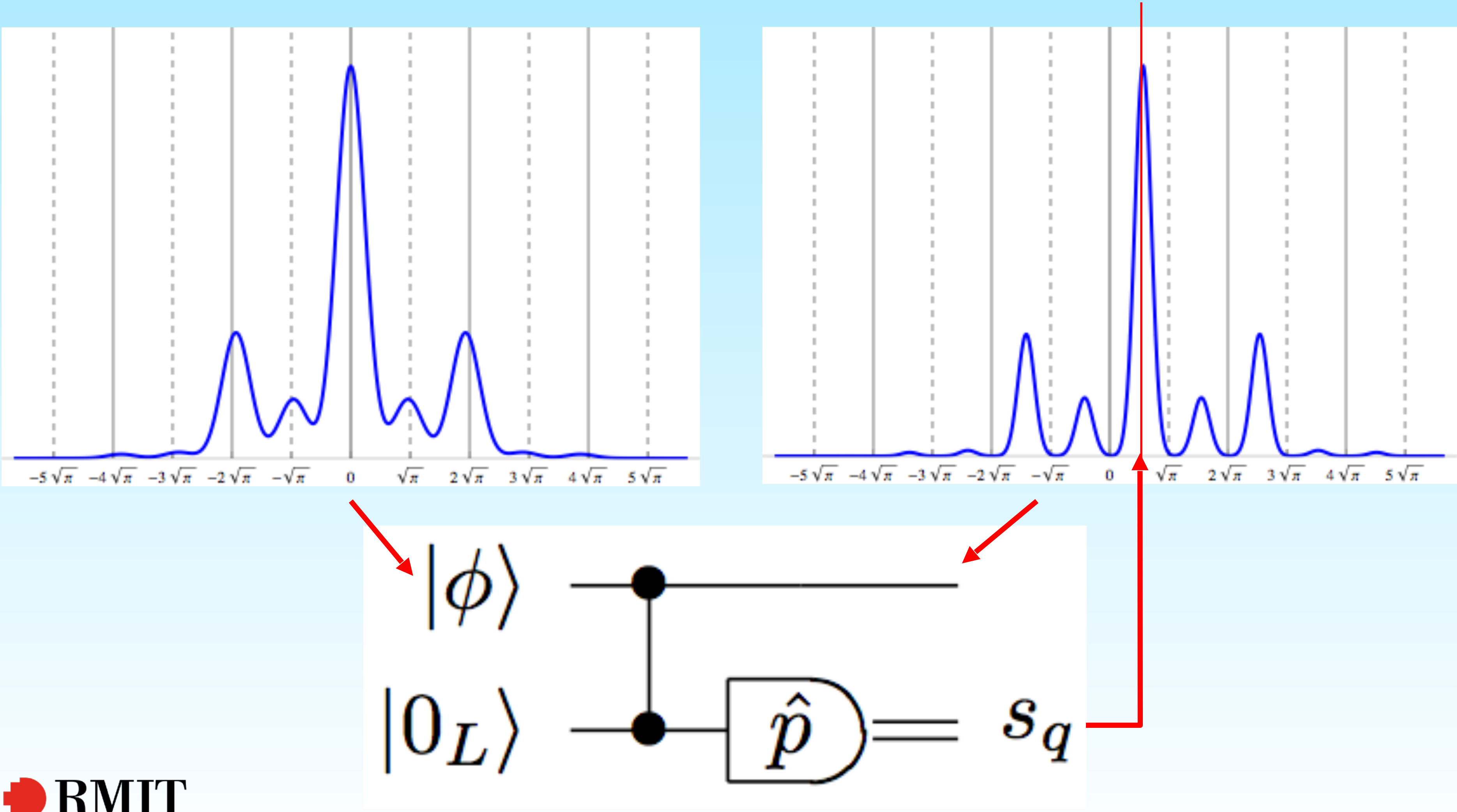

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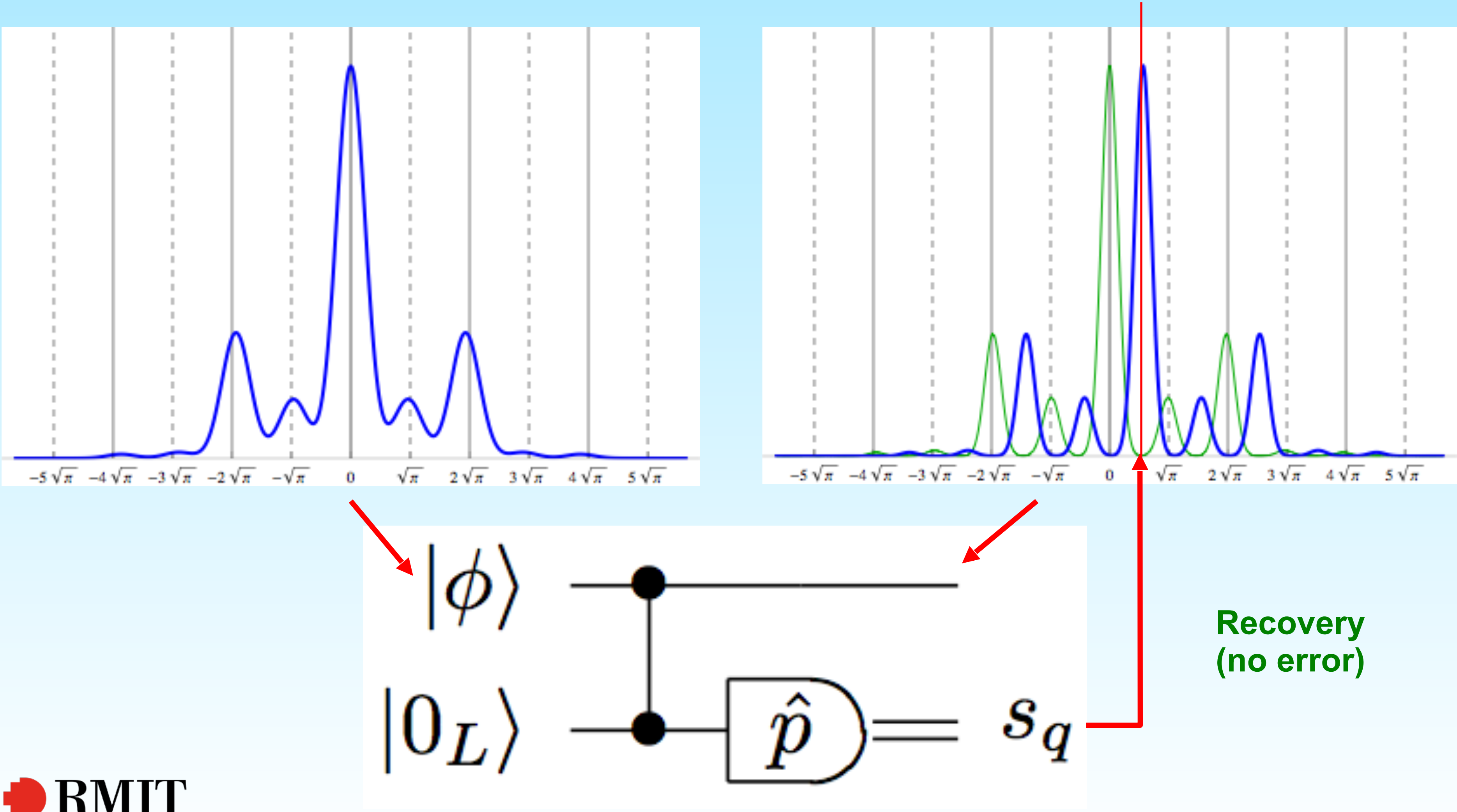
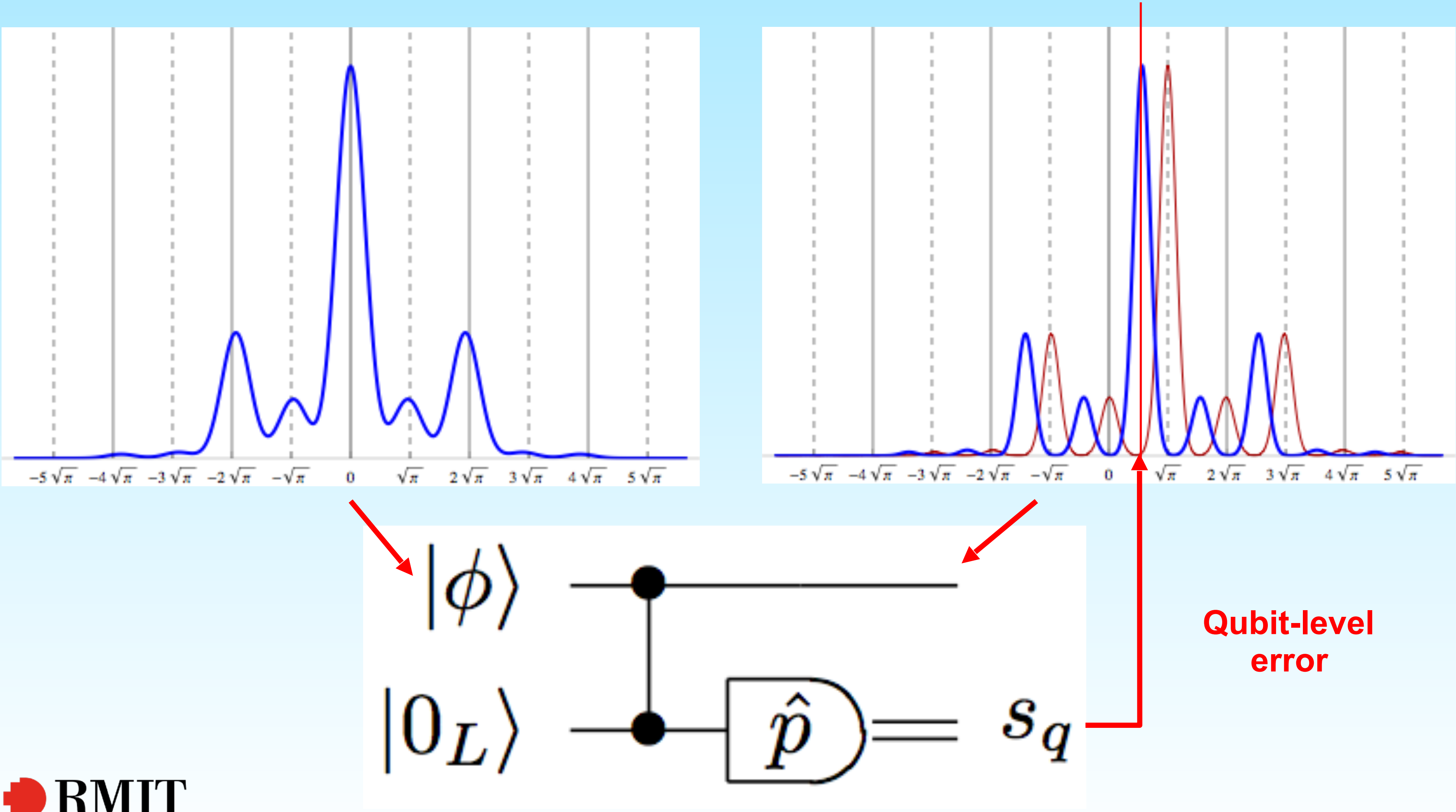


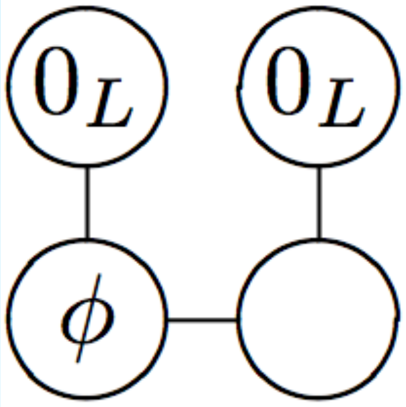
Recovery (no error)

Projecting to qubit-level errors



Qubit-level error

Noisy qubit-level Clifford gates



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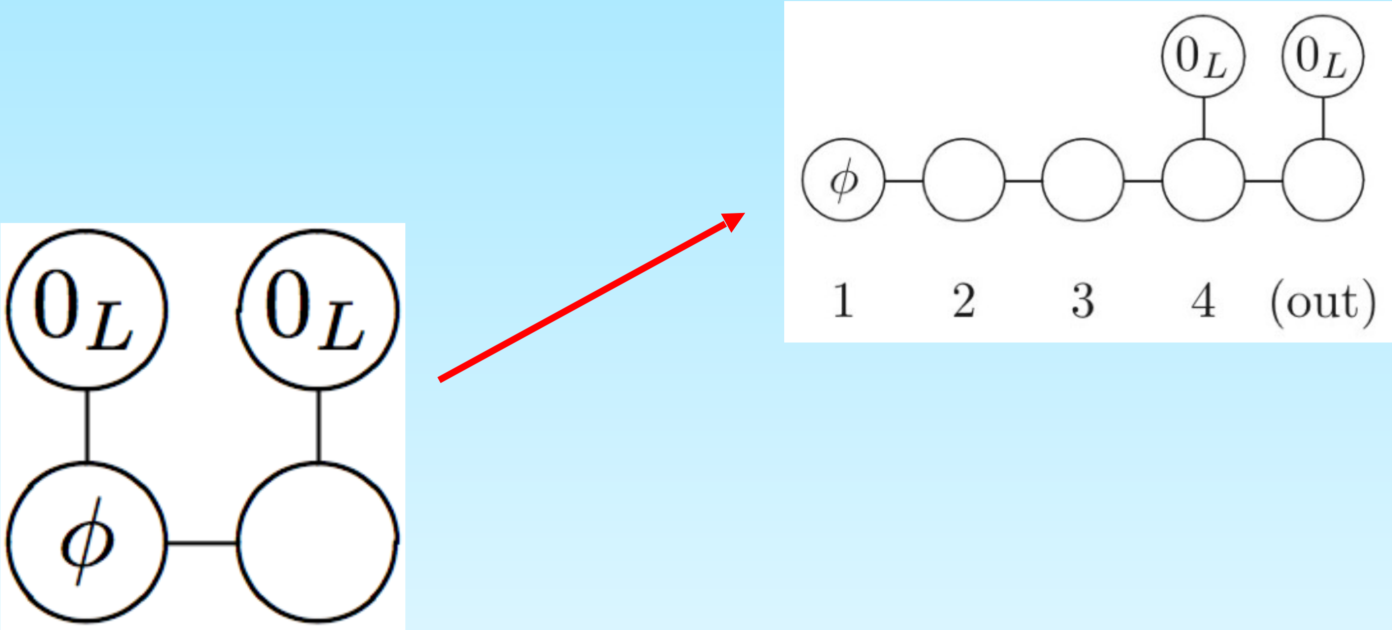

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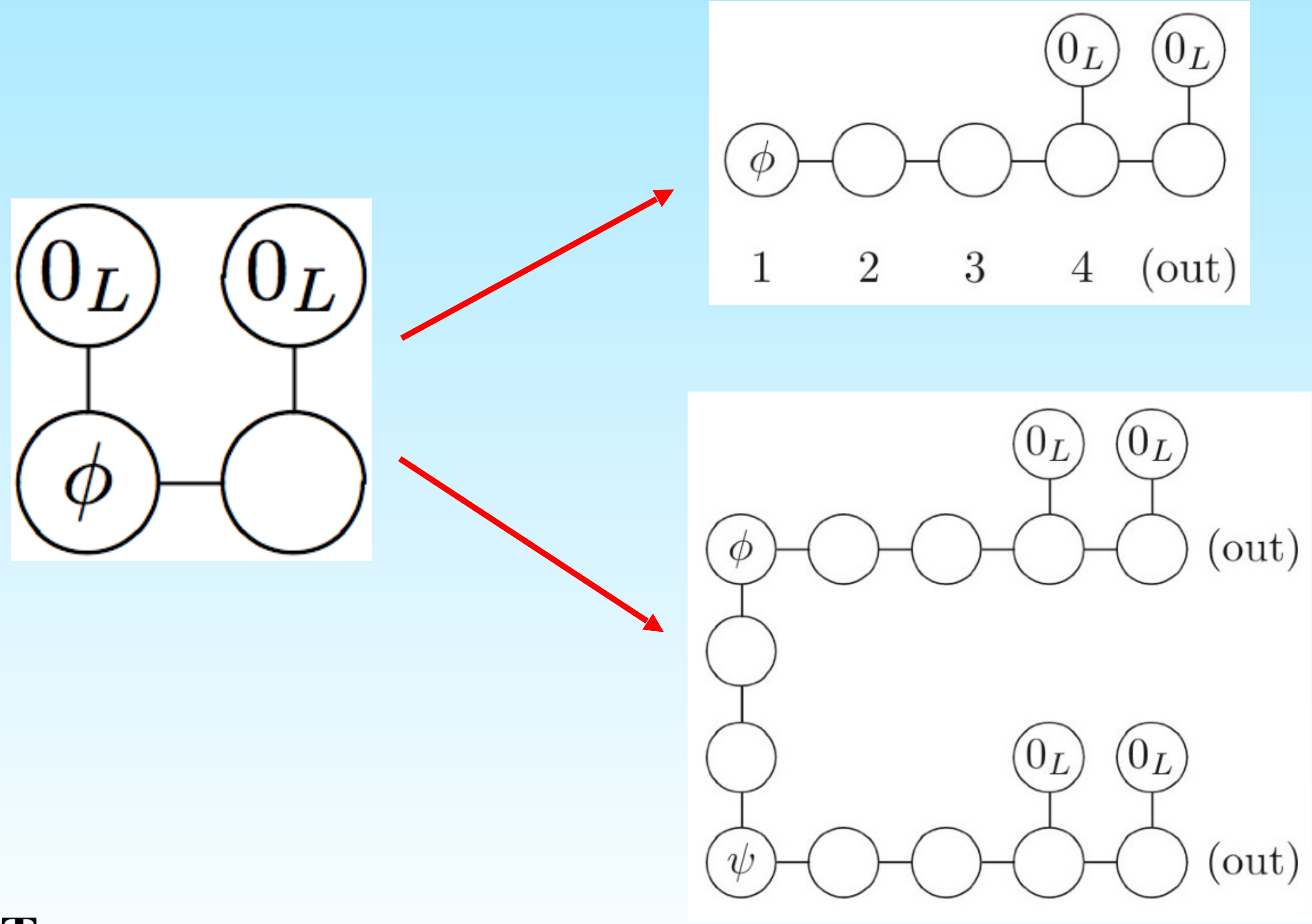

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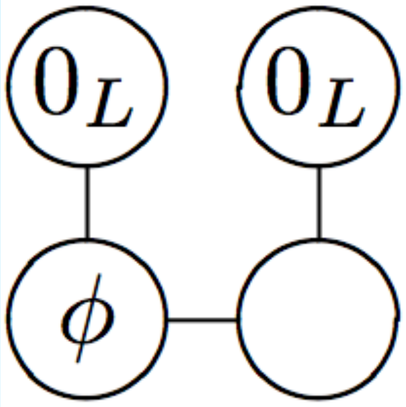
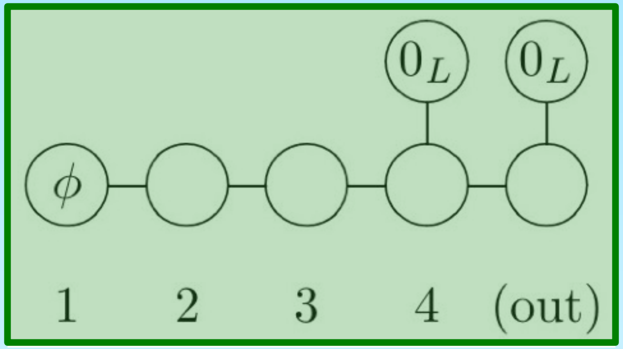
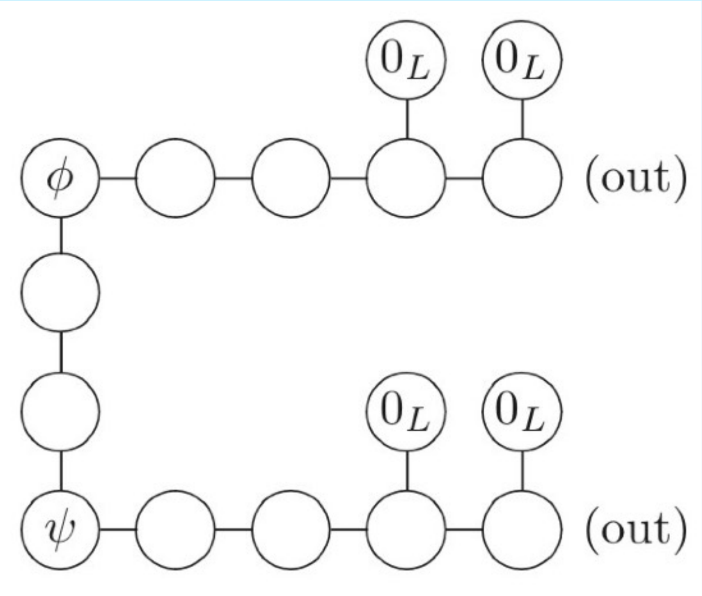


Noisy
1-qubit
Clifford
gate





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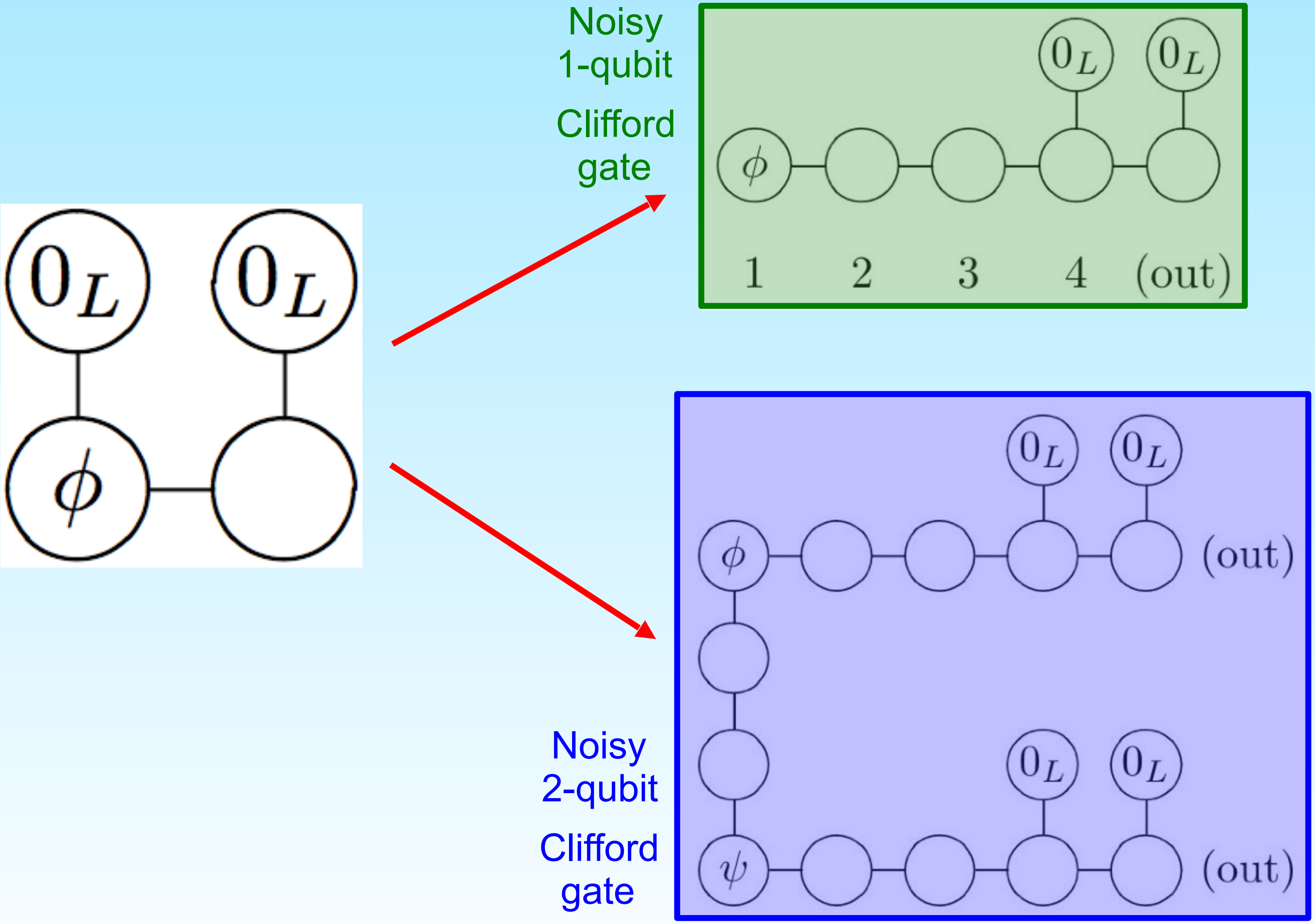

Noisy
1-qubit
Clifford
gate

Noisy
2-qubit
Clifford
gate

Fault tolerance

- Homodyne detection implements (faulty) qubit gates
- Use qubit-level quantum error correction to reduce errors (well established)
- Fault tolerance

  (initial error < threshold) →

  (arbitrarily low error in final computation)

Fault tolerance

High squeezing ⇒ low Gaussian noise ⇒ low rate of Pauli errors

Fault tolerance

How high?

High squeezing ⇒ low Gaussian noise ⇒ low rate of Pauli errors

Fault tolerance

How high?

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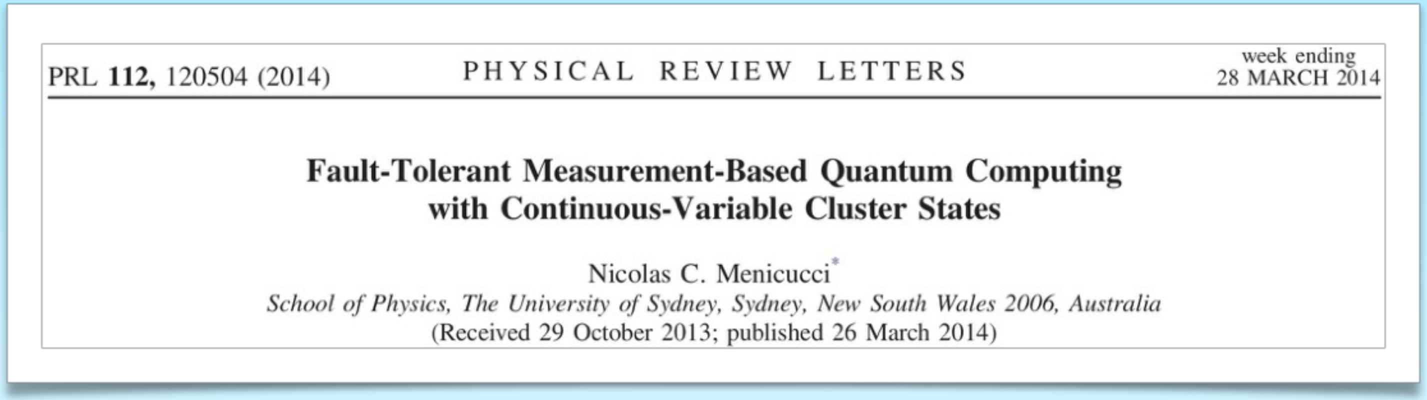


PRL **112,** 120504 (2014) PHYSICAL REVIEW LETTERS week ending 28 MARCH 2014

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

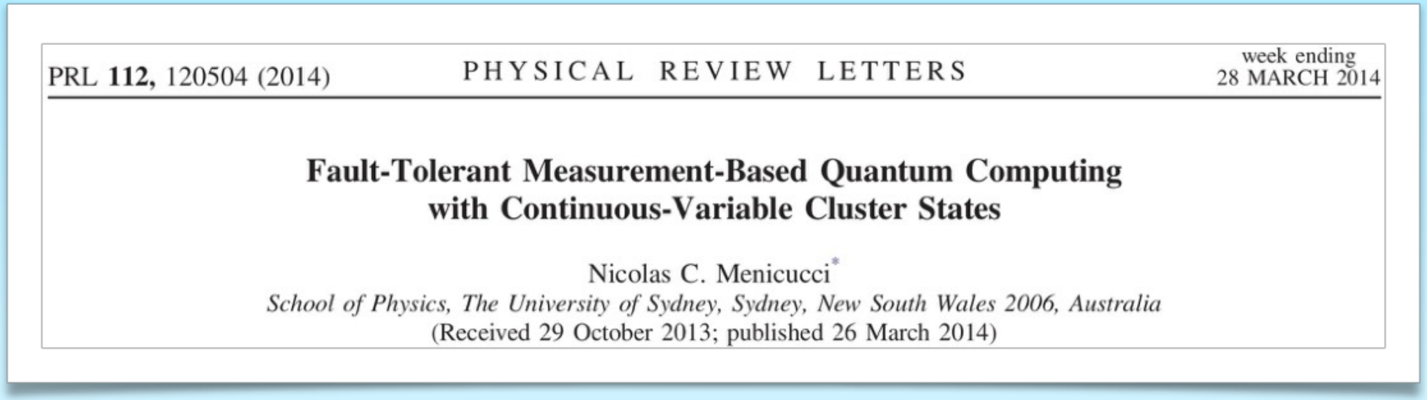
Nicolas C. Menicucci*
School of Physics, The University of Sydney, Sydney, New South Wales 2006, Australia

(Received 29 October 2013; published 26 March 2014)

Fault tolerance

How high?

High squeezing ⇒ low Gaussian noise ⇒ low rate of Pauli errors



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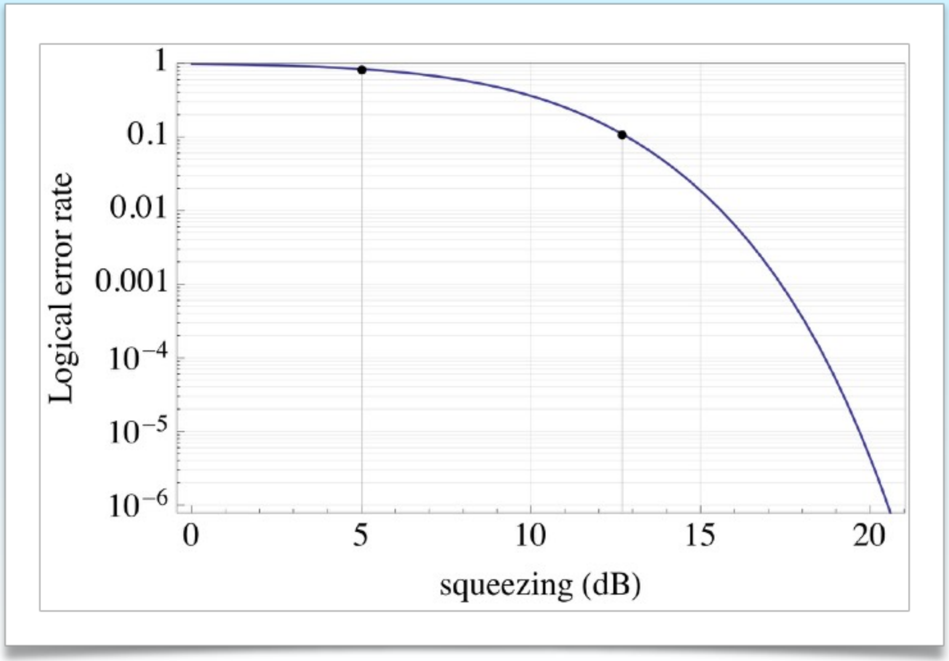

Fault-tolerant squeezing threshold ≤ 20.5 dB

RMIT UNIVERSITY

Resources sufficient for FT QC

- CV cluster state with sufficient squeezing: "railroad tracks"
- GKP qubits with sufficient squeezing: "train cars" carrying the discrete quantum information
- Homodyne detection = Gaussian unitaries: "switches" to guide the info & measurement
- Non-Clifford resource: photon counting, cubic-phase gate, cubic phase state

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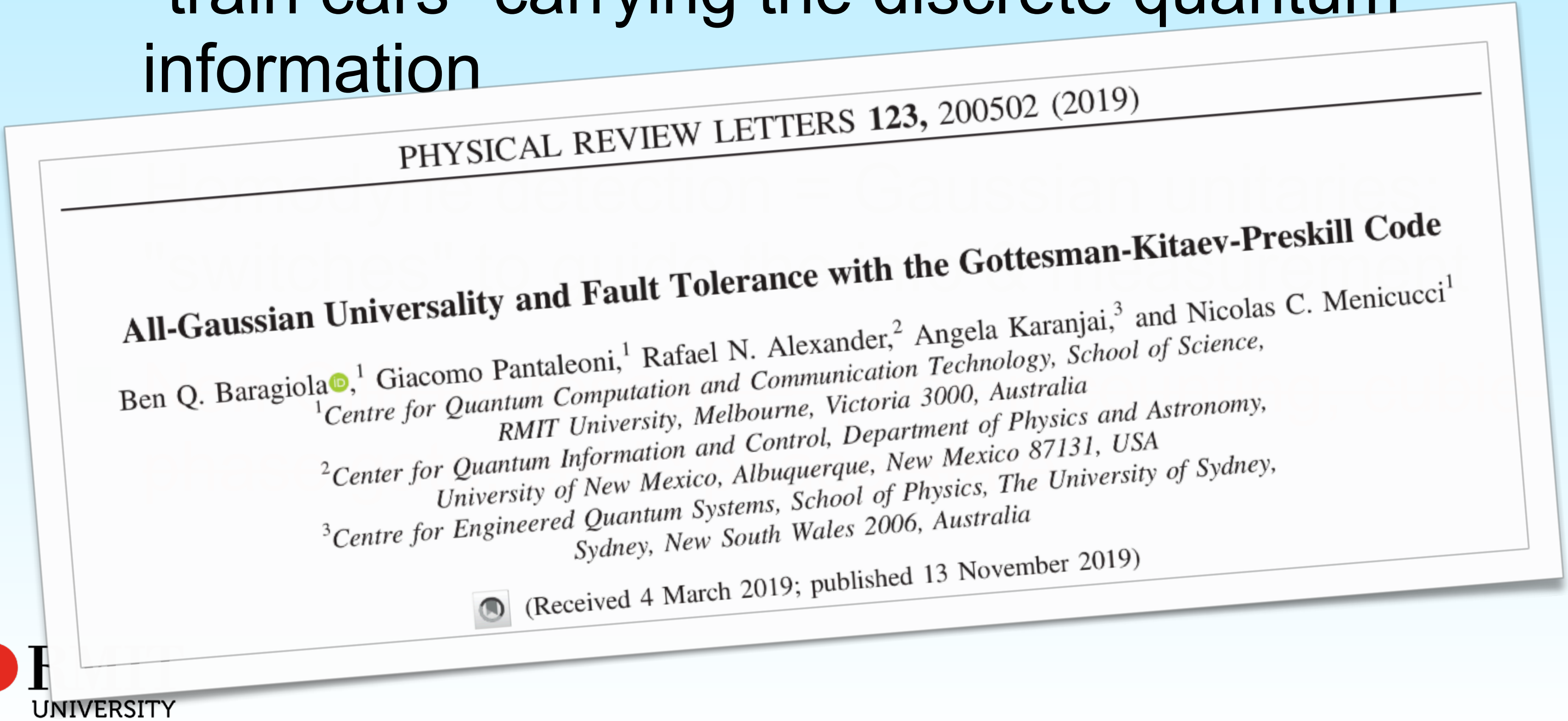

PHYSICAL REVIEW LETTERS **123,** 200502 (2019)

All-Gaussian Universality and Fault Tolerance with the Gottesman-Kitaev-Preskill Code

Ben Q. Baragiola,[1] Giacomo Pantaleoni,[1] Rafael N. Alexander,[2] Angela Karanjai,[3] 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, Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico 87131, USA*

[3]*Centre for Engineered Quantum Systems, School of Physics, The University of Sydney, Sydney, New South Wales 2006, Australia*

(Received 4 March 2019; published 13 November 2019)

RMIT UNIVERSITY

Resources sufficient for FT QC

- CV cluster state with sufficient squeezing: "railroad tracks"
- GKP qubits with sufficient squeezing: "train cars" carrying the discrete quantum information
- Homodyne detection = Gaussian unitaries: "switches" to guide the info & measurement
- Vacuum state! (or heterodyne detection)

Experimental GKP states

Encoding a qubit in a trapped-ion mechanical oscillator

C. Flühmann[1]*, T. L. Nguyen[1], M. Marinelli[1], V. Negnevitsky[1], K. Mehta[1] & J. P. Home[1]*

Nature **566**, 513–517(2019)

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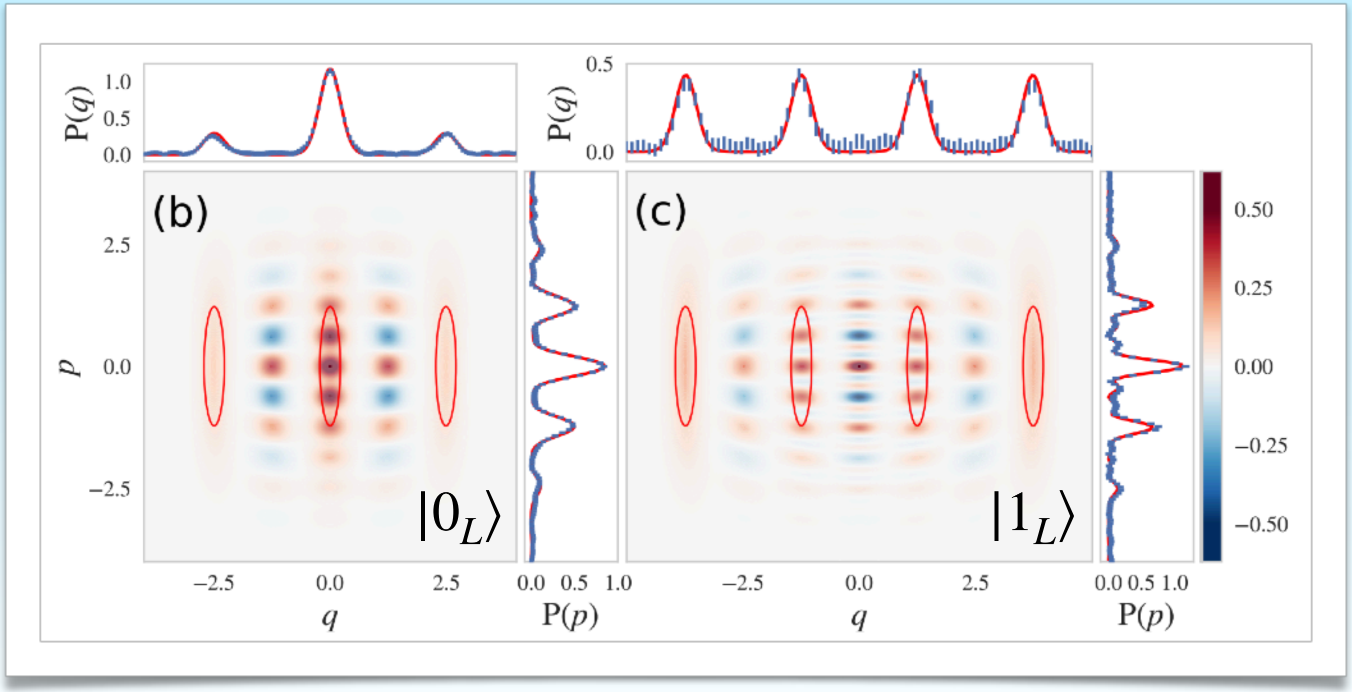
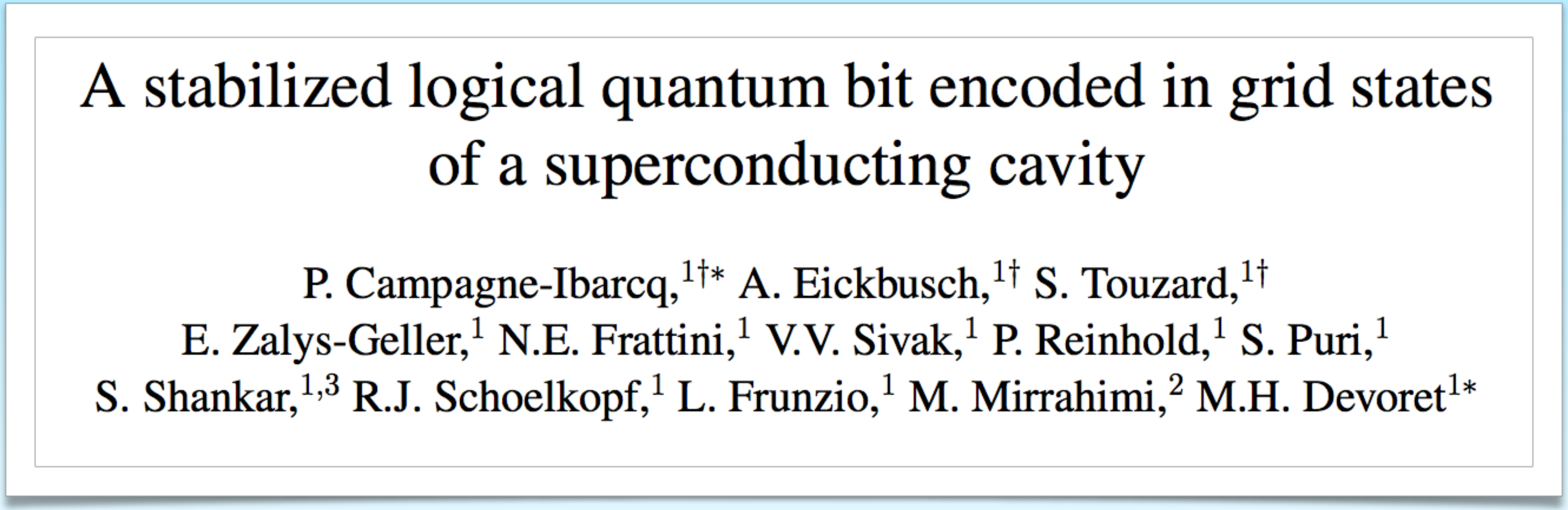


Experimental GKP states



A stabilized logical quantum bit encoded in grid states of a superconducting cavity

P. Campagne-Ibarcq,[1†*] A. Eickbusch,[1†] S. Touzard,[1†]
E. Zalys-Geller,[1] N.E. Frattini,[1] V.V. Sivak,[1] P. Reinhold,[1] S. Puri,[1]
S. Shankar,[1,3] R.J. Schoelkopf,[1] L. Frunzio,[1] M. Mirrahimi,[2] M.H. Devoret[1*]

arXiv:1907.12487

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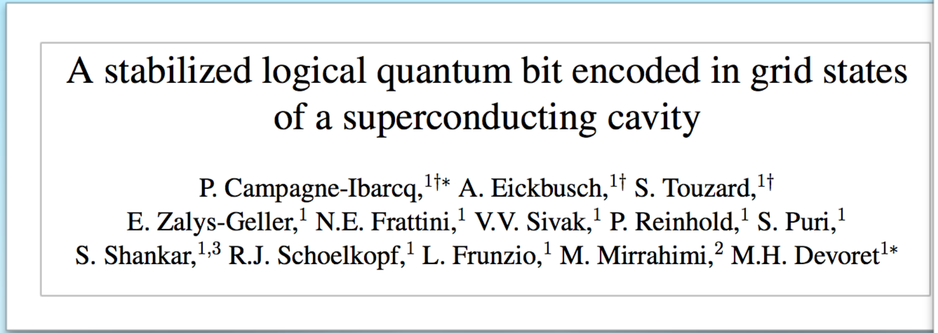

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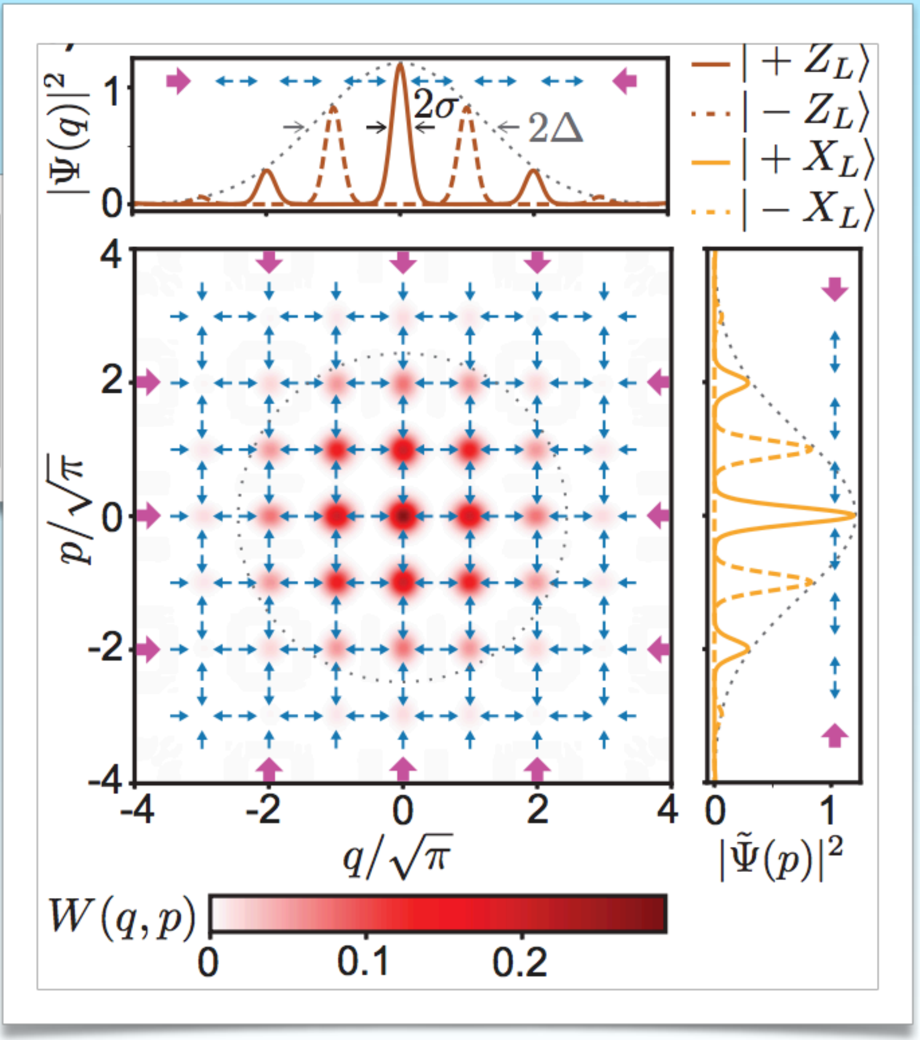

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Making CV cluster states

Linear optics

- Inline squeezing (C_Z gate) can be replaced with offline squeezing + interferometer*

Linear optics

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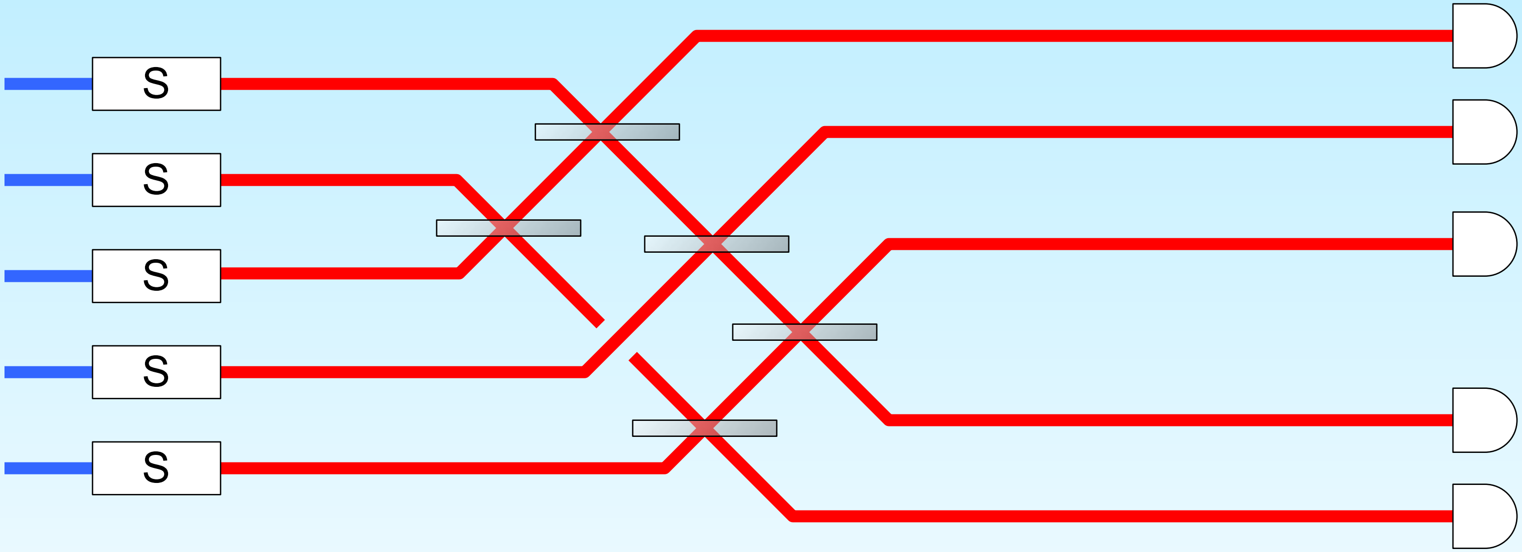

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* P. van Loock, C. Weedbrook, M. Gu, PRA **76**, 032321 (2007)

How can we make
scalable resource states?

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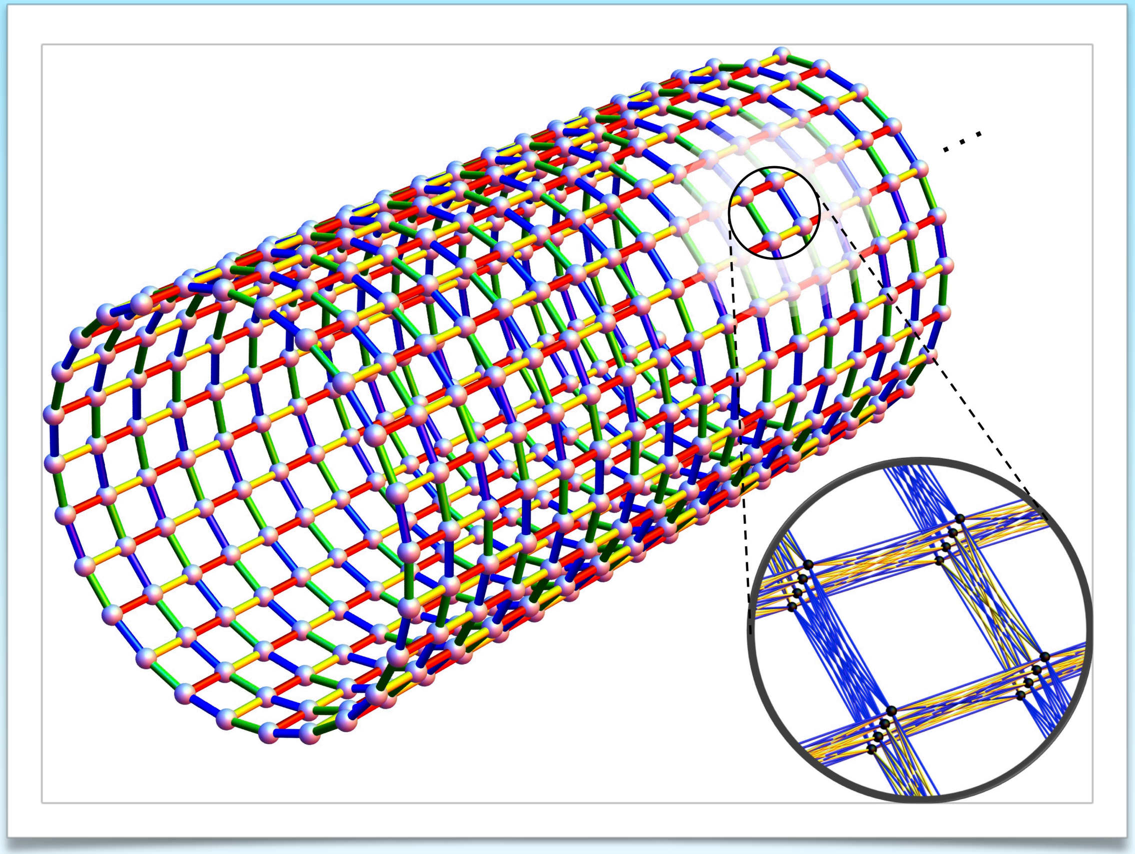
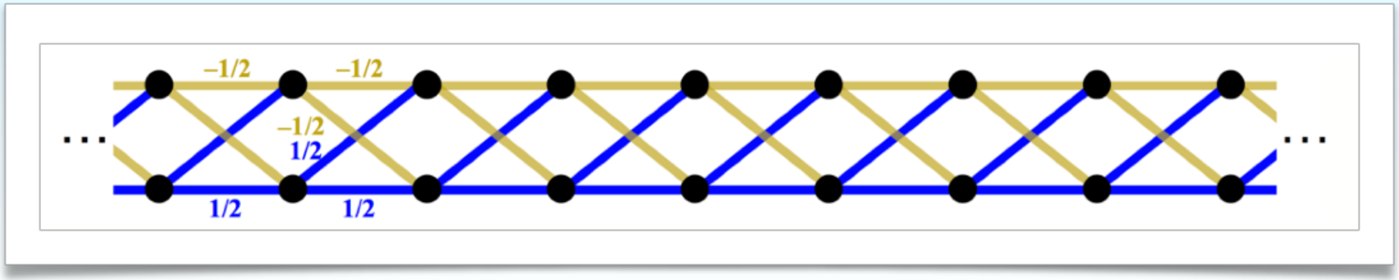
Macronode-based cluster states

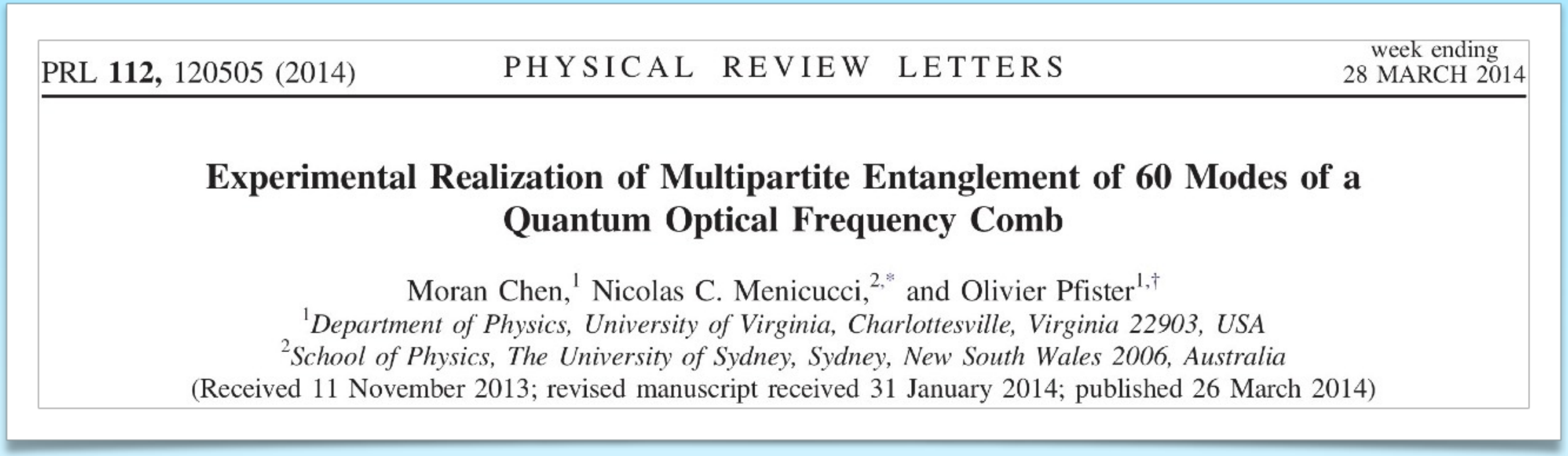


Temporal or frequency modes



Frequency-mode cluster states

Frequency-mode cluster states



PRL **112,** 120505 (2014) PHYSICAL REVIEW LETTERS week ending 28 MARCH 2014

Experimental Realization of Multipartite Entanglement of 60 Modes of a Quantum Optical Frequency Comb

Moran Chen,[1] Nicolas C. Menicucci,[2,*] and Olivier Pfister[1,†]
[1]*Department of Physics, University of Virginia, Charlottesville, Virginia 22903, USA*
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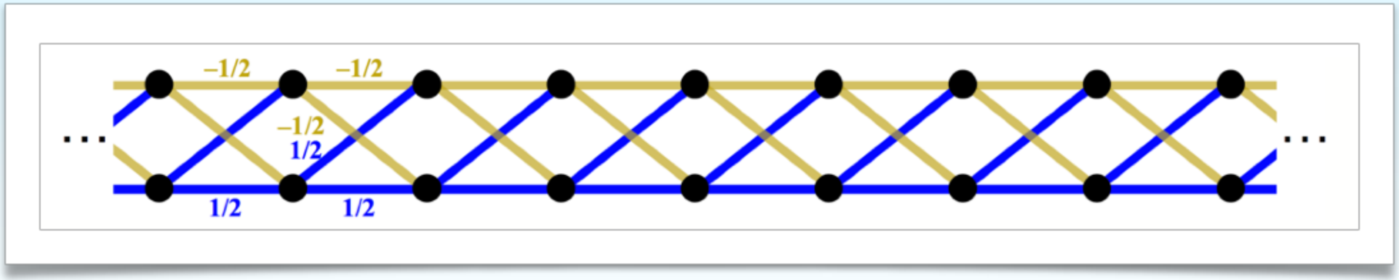
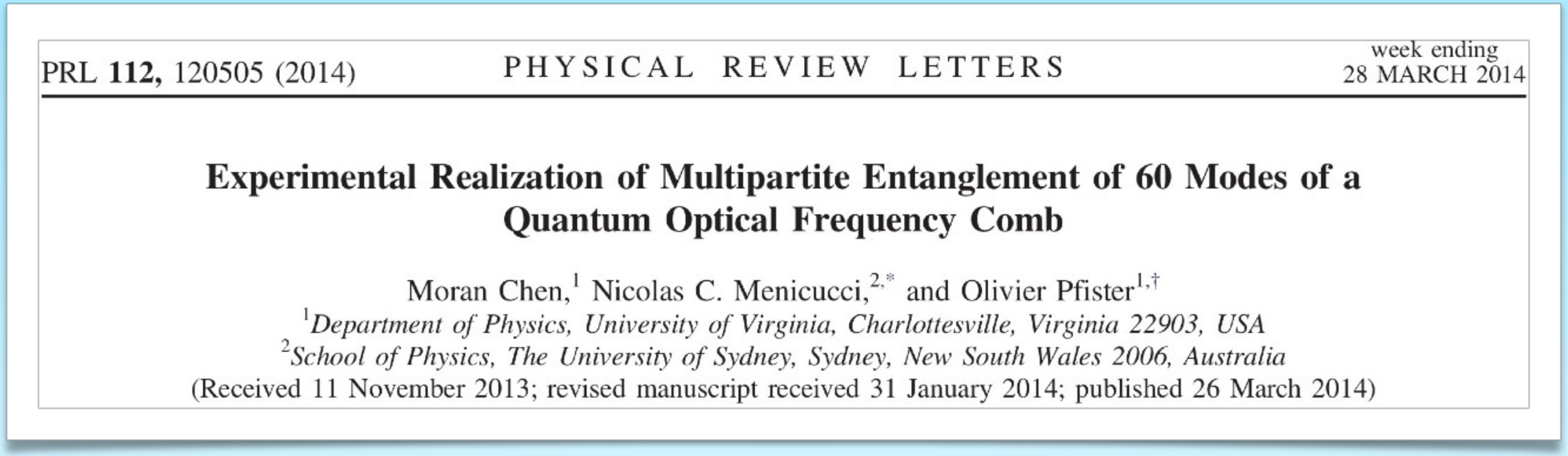
(Received 11 November 2013; revised manuscript received 31 January 2014; published 26 March 2014)



Frequency-mode cluster states



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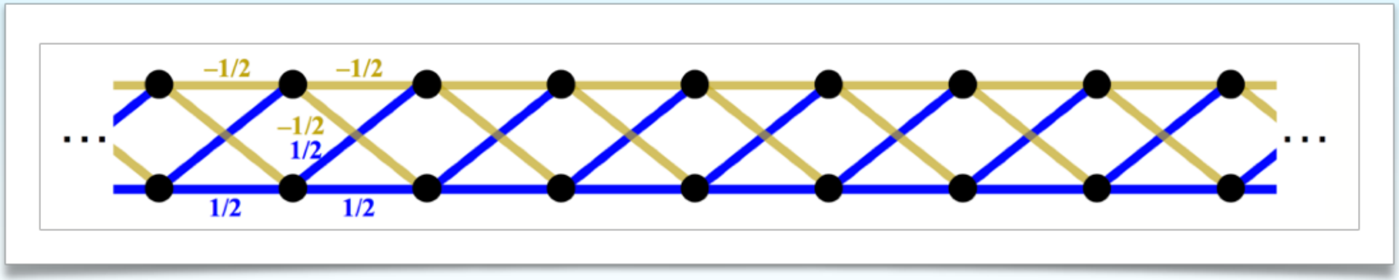
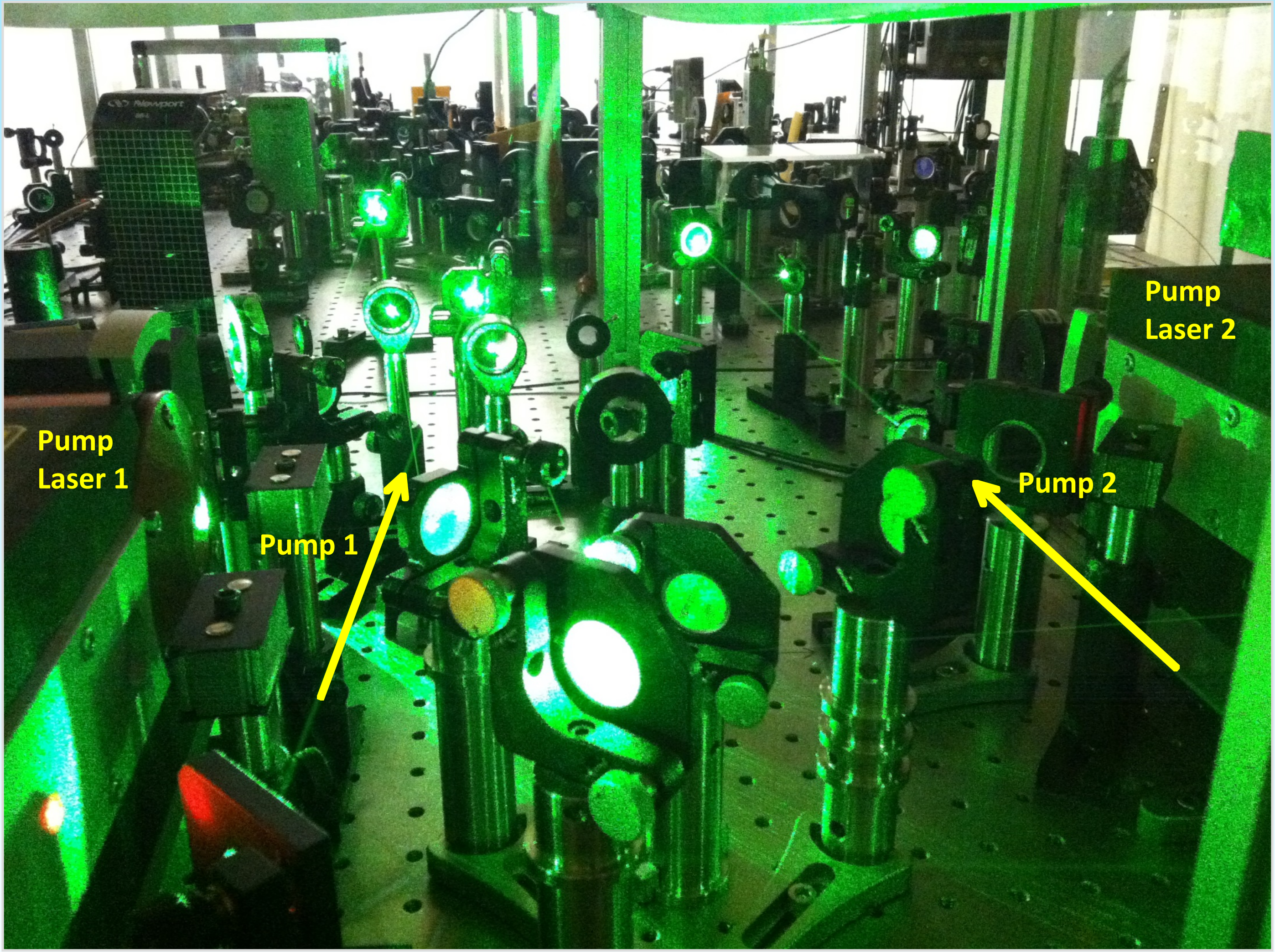
60-mode linear cluster state



Frequency-mode cluster state (wire)



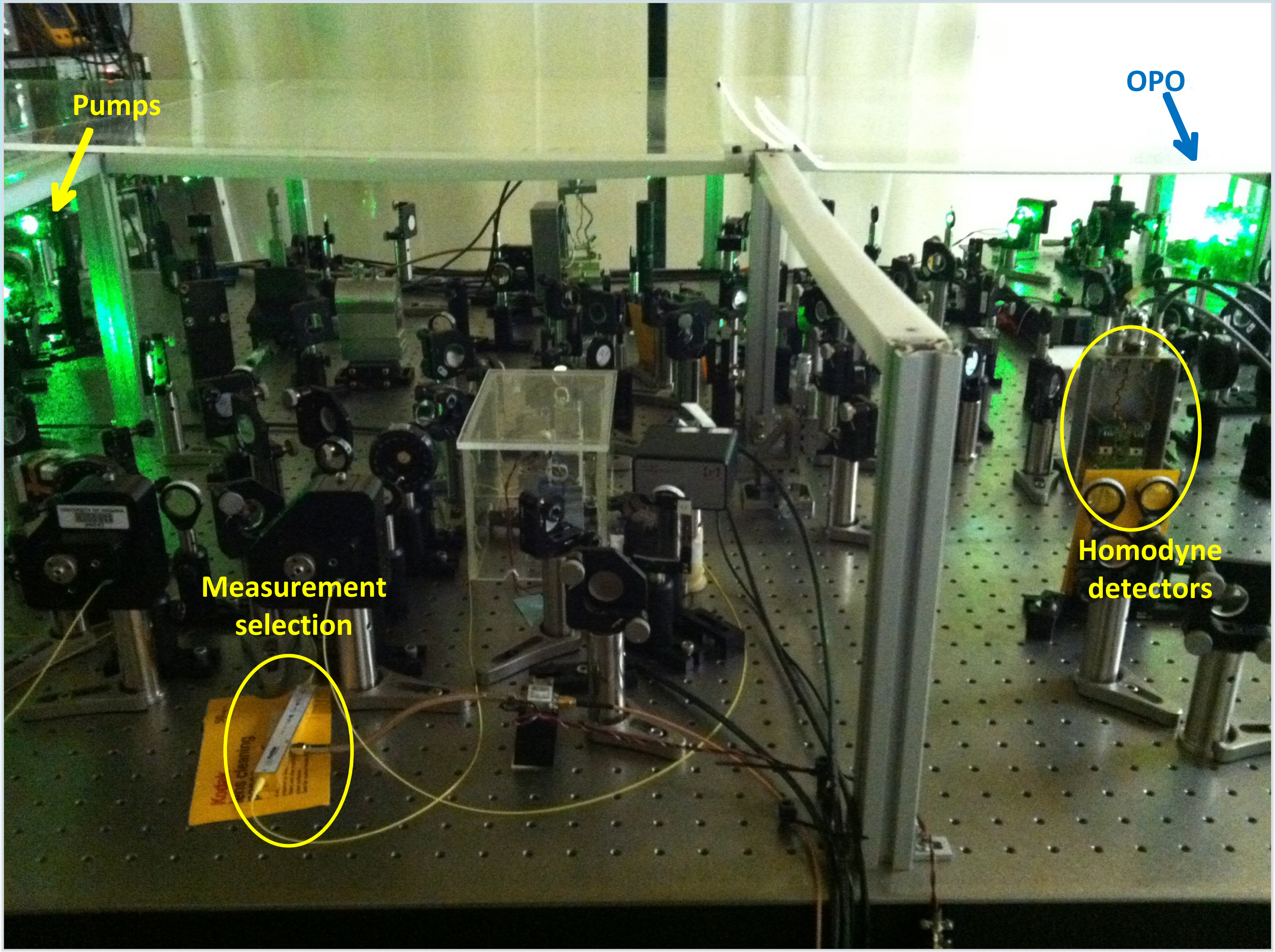

pump

OPO

cluster state

frequency-sensitive measurements

Frequency-mode cluster state (wire)



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cluster state

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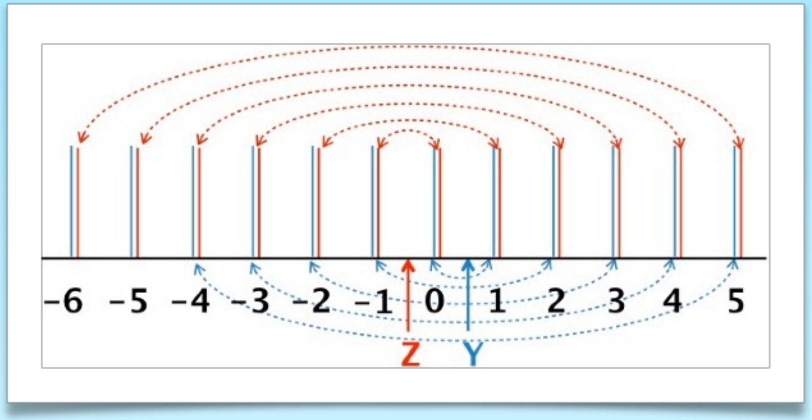

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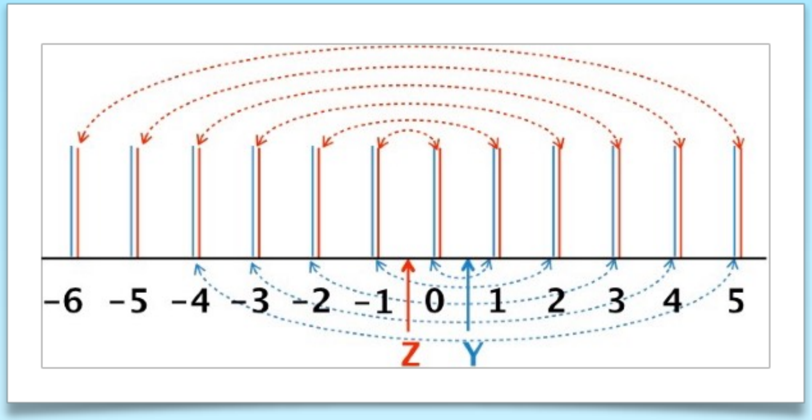
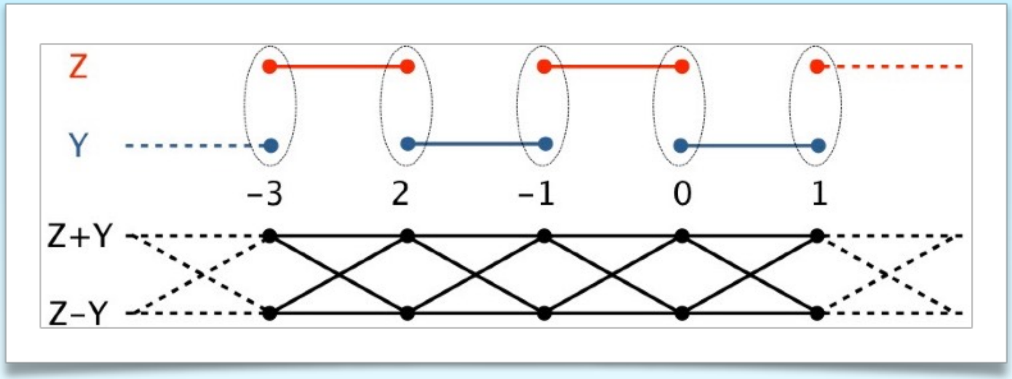
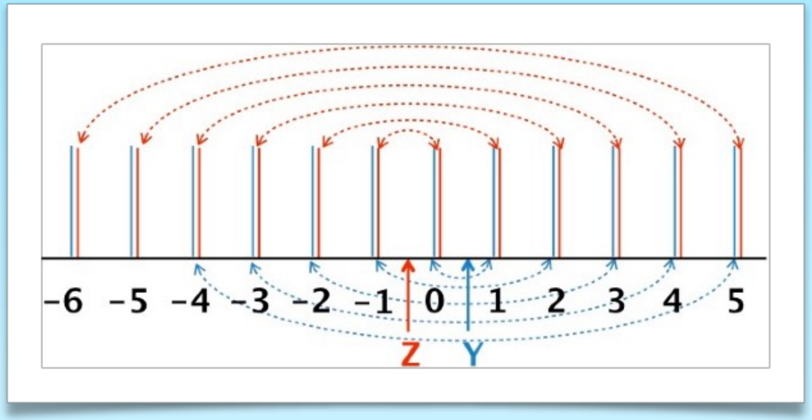
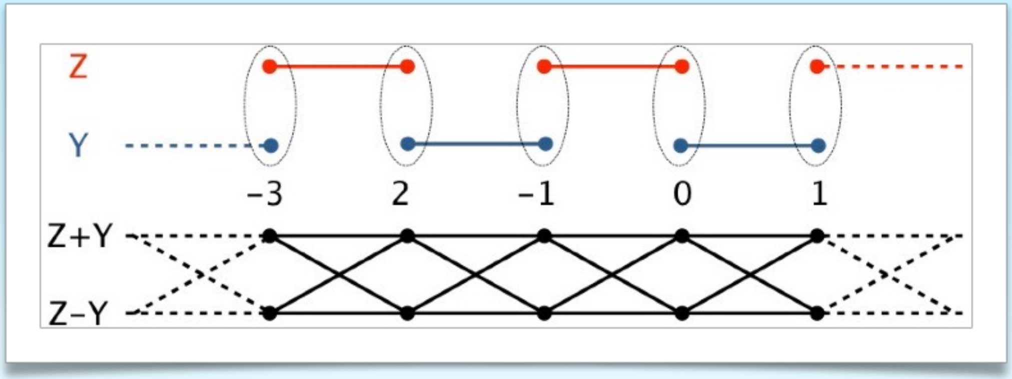




Frequency-mode cluster state (wire)

equivalent





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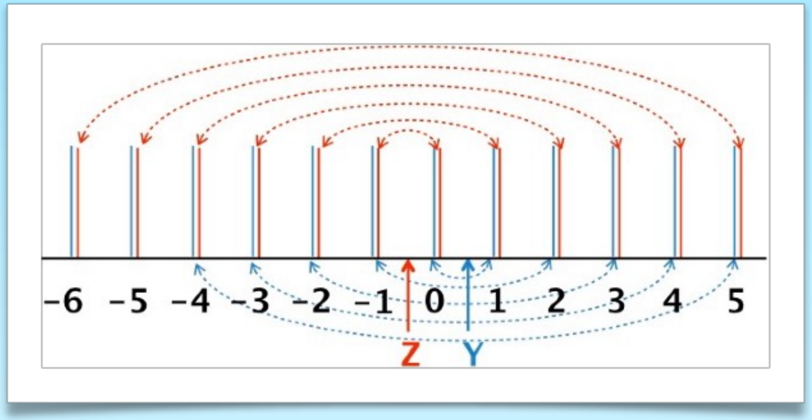
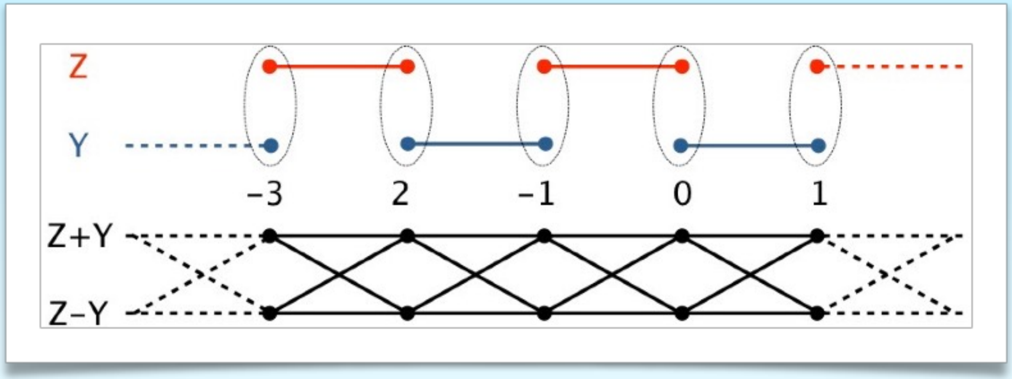
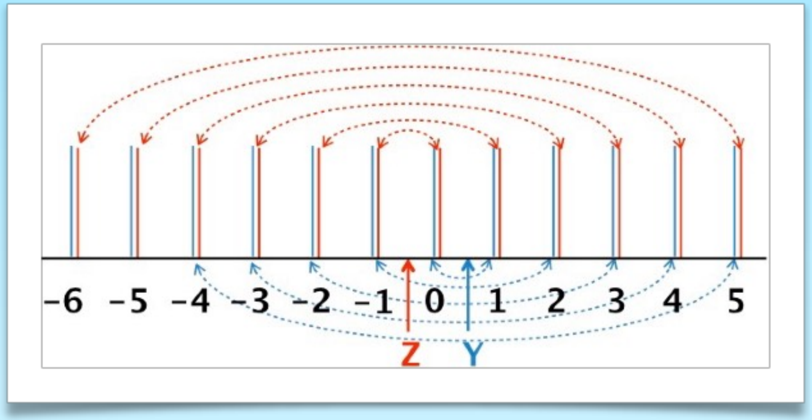


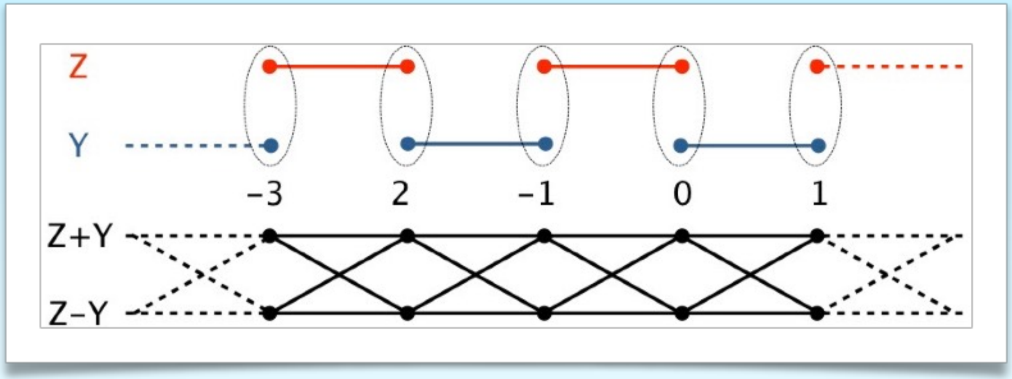


60 modes addressable

Frequency-mode cluster state (wire)

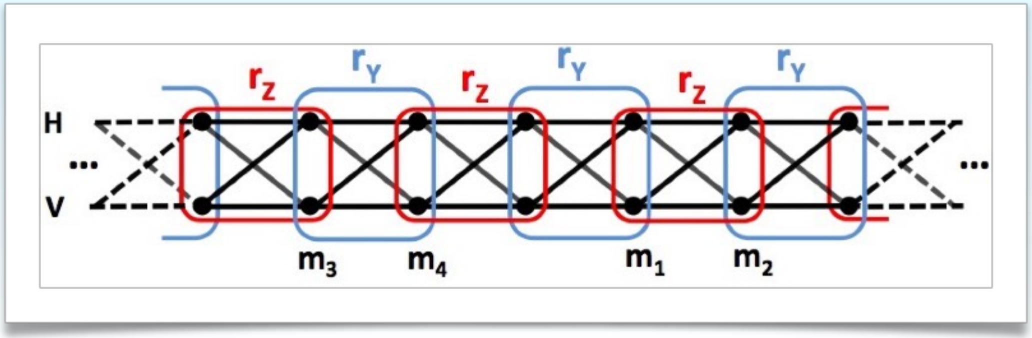
equivalent





60 modes addressable

after polarization rotation

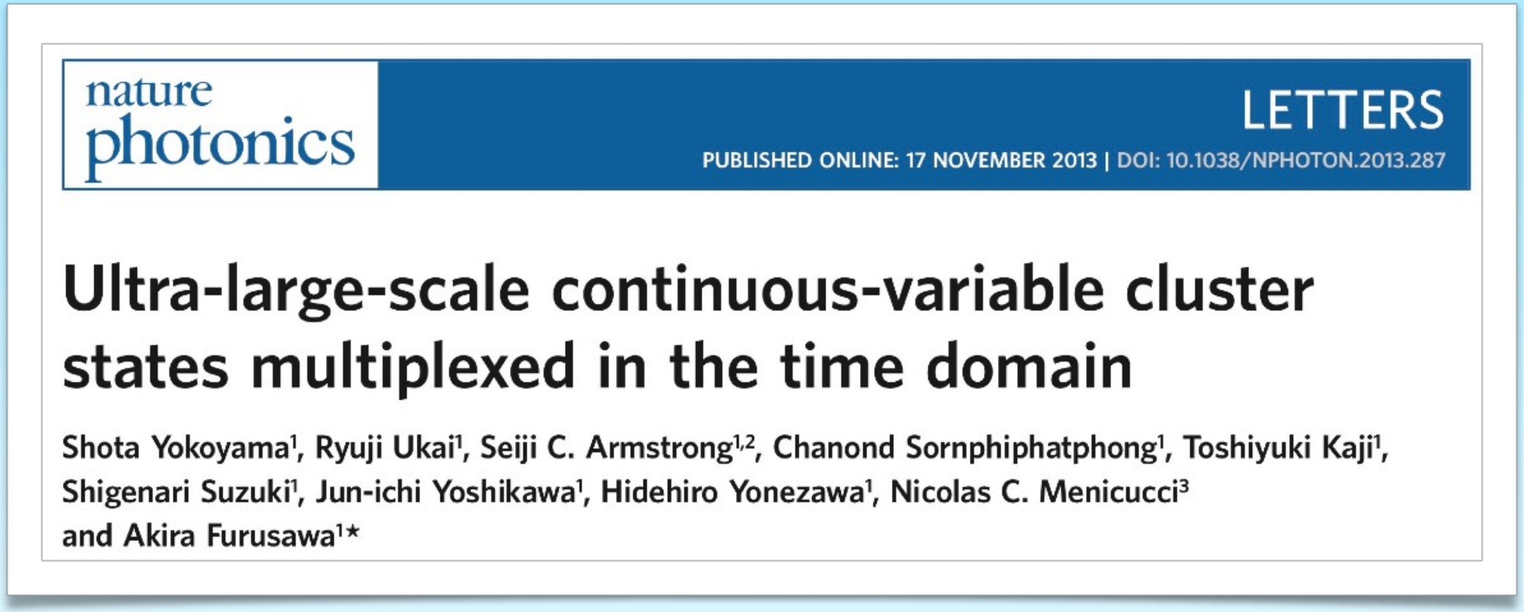


(verification)

Temporal-mode cluster states

Temporal-mode cluster states

Temporal-mode cluster states



nature photonics

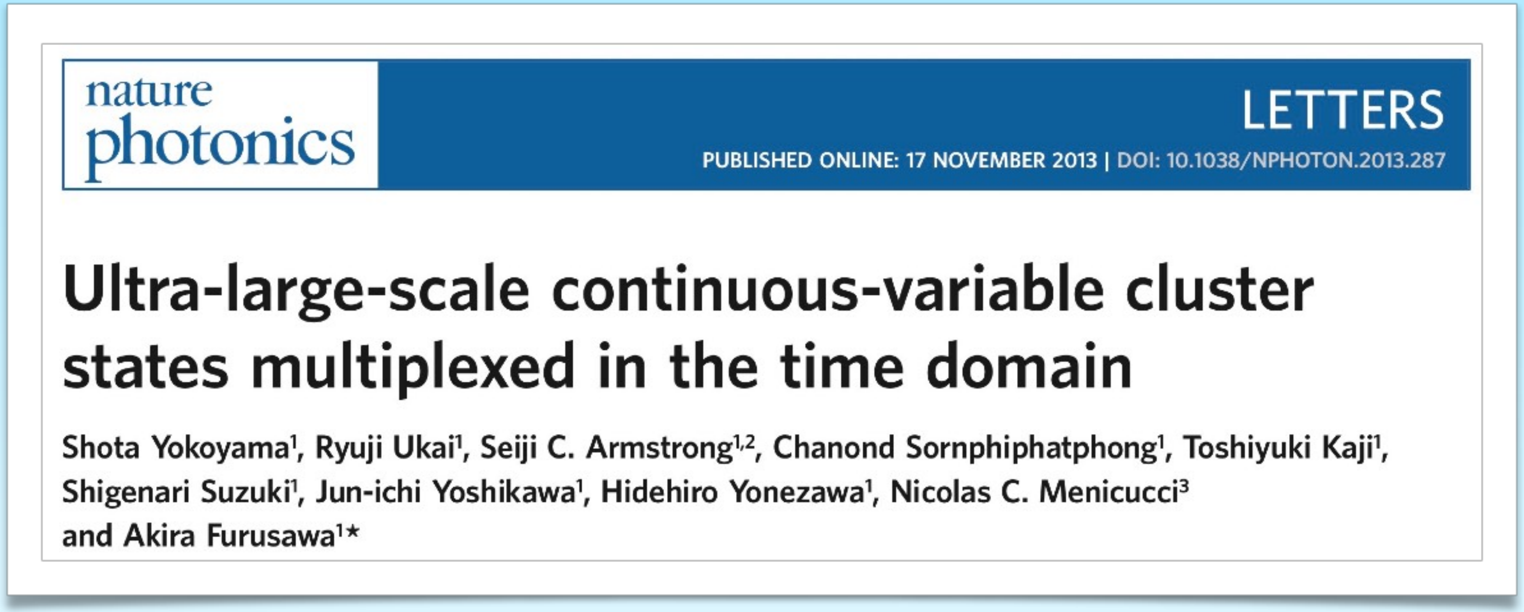
LETTERS

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

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]*

Temporal-mode cluster states



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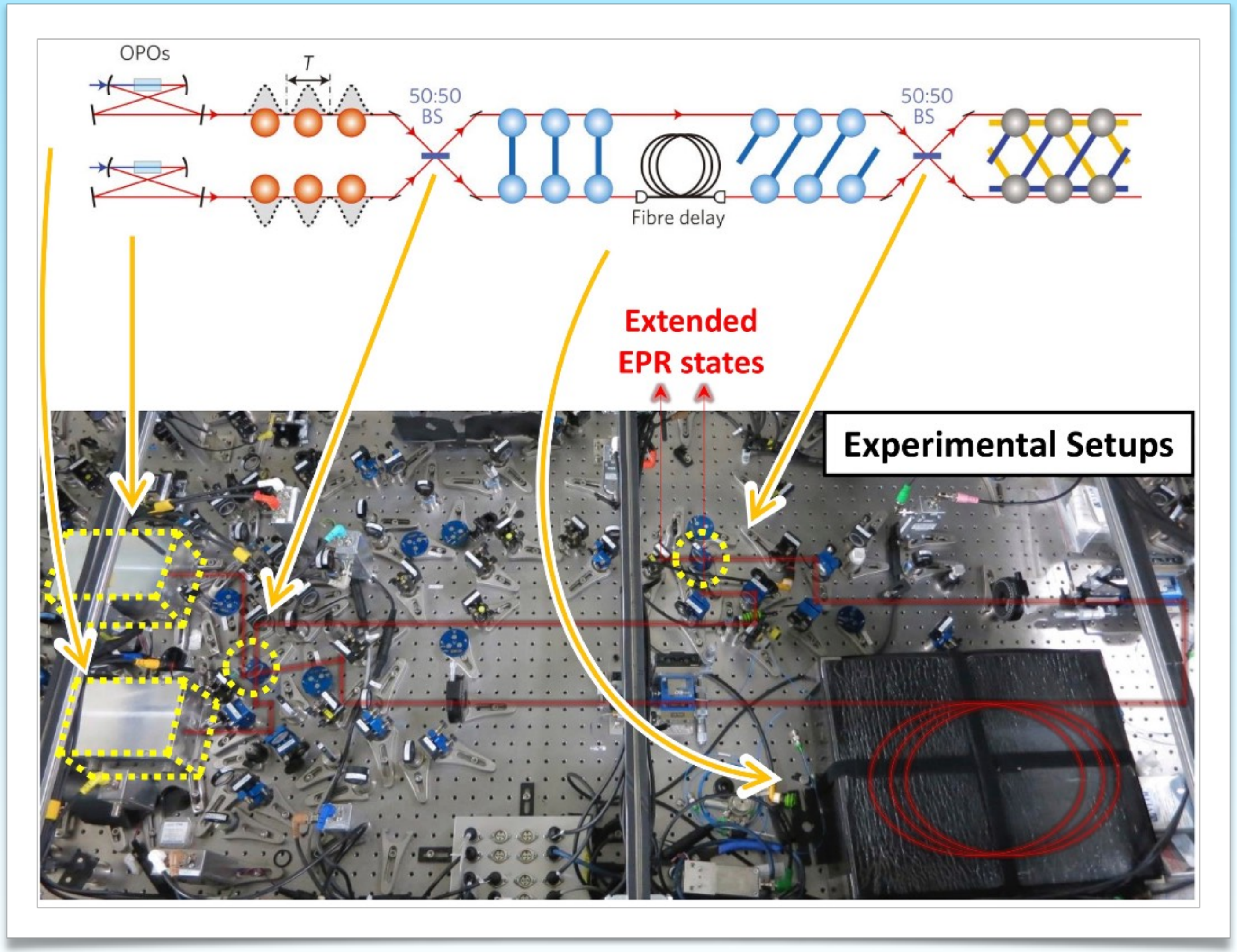
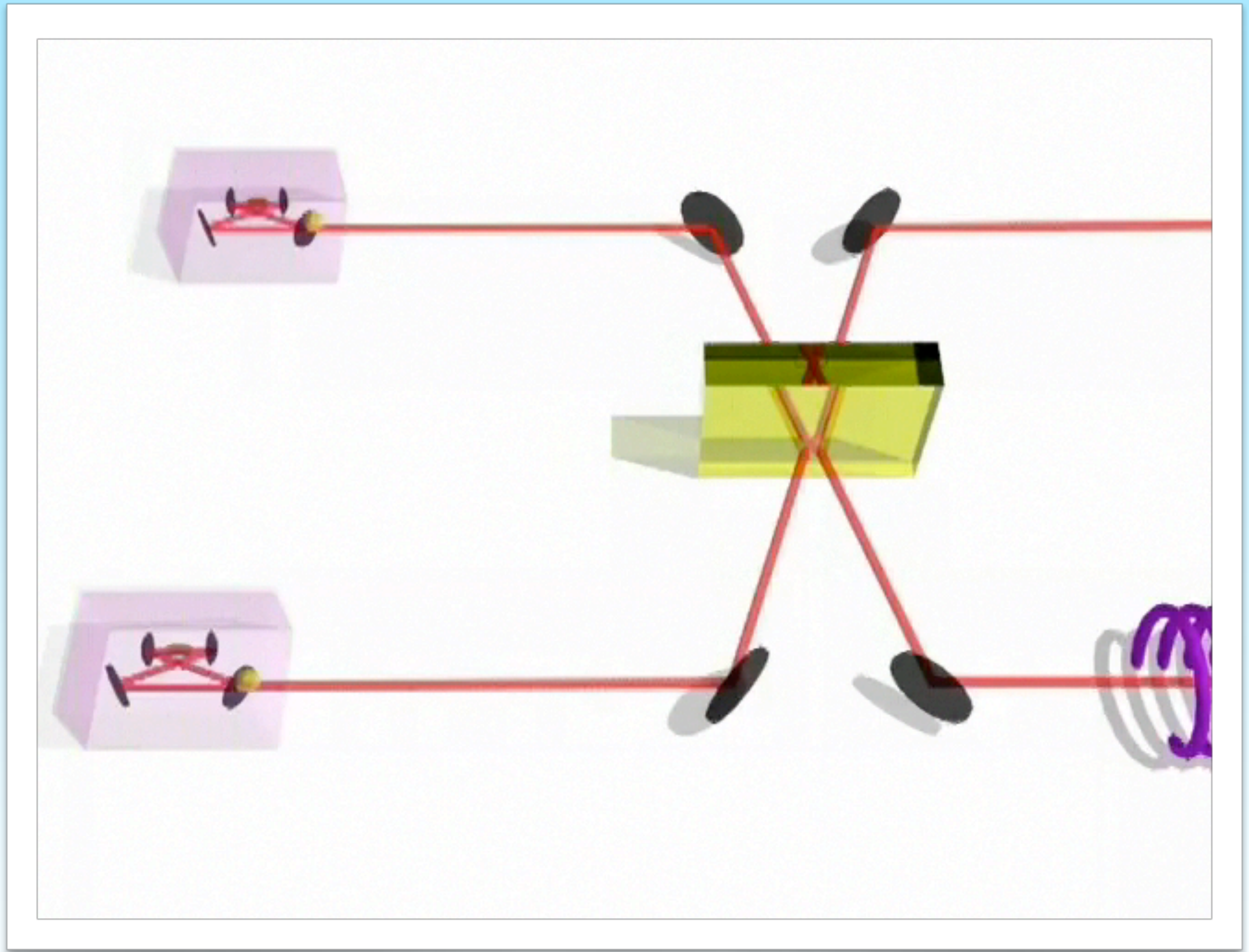
10,000-mode linear cluster state

Temporal-mode cluster states



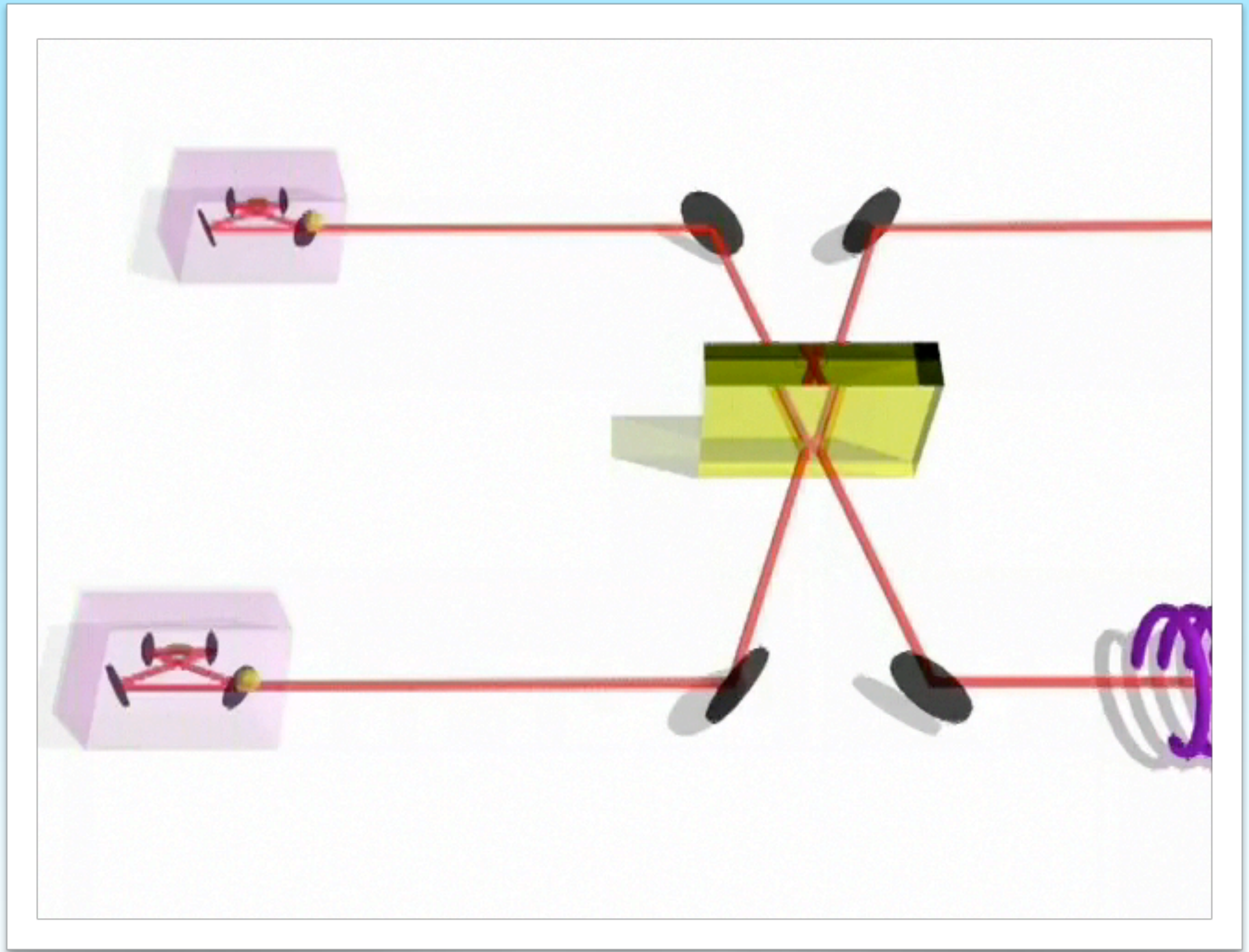
Temporal-mode cluster states



Animation by Seiji Armstrong

(available online at https://youtu.be/gor29QIP9Ls)

Temporal-mode cluster states



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Temporal-mode cluster states

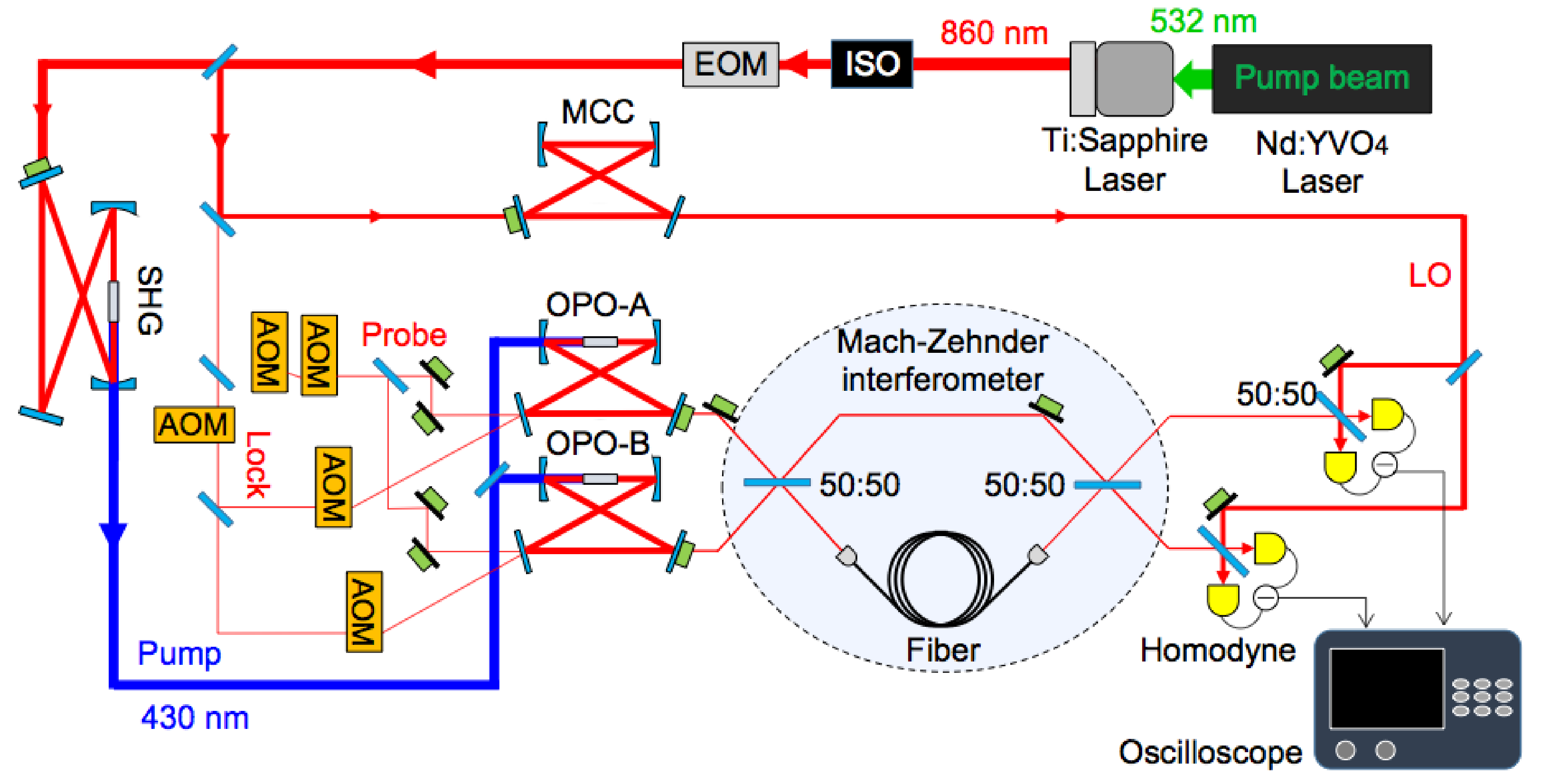

Fig. S4. Experimental setup.

Temporal-mode cluster states

APL PHOTONICS **1**, 060801 (2016)

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]

Temporal-mode cluster states

APL PHOTONICS **1**, 060801 (2016)

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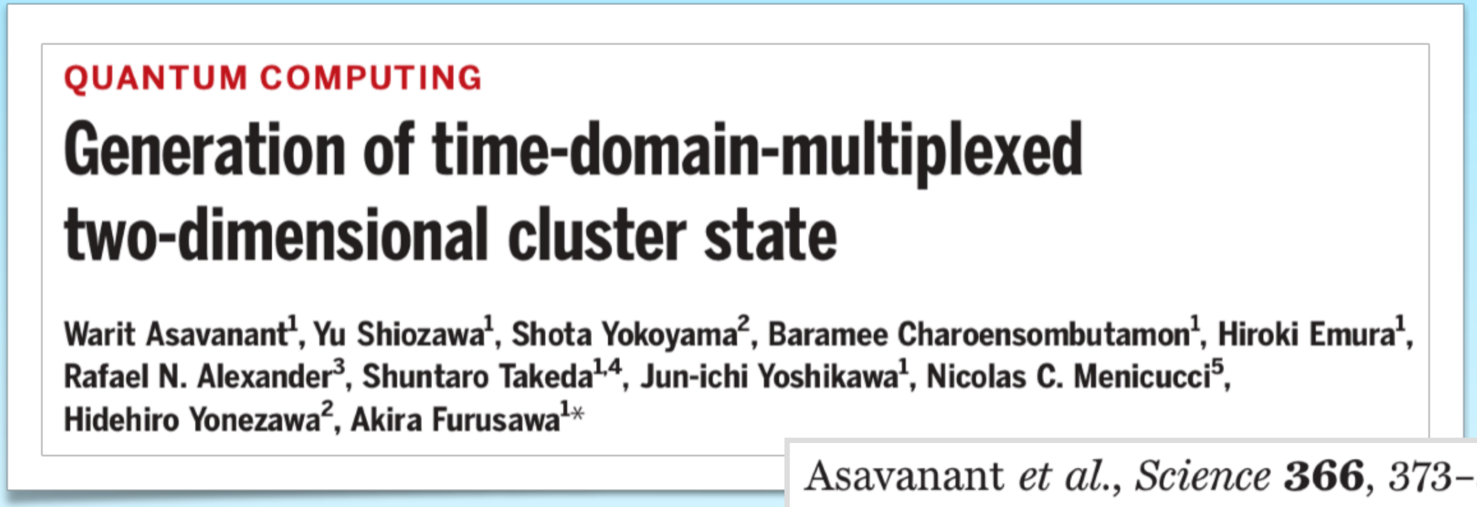
and Akira Furusawa[1,a]

1-million-mode linear cluster state!

Temporal-mode cluster states



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]*

Asavanant *et al.*, *Science* **366**, 373–376 (2019)

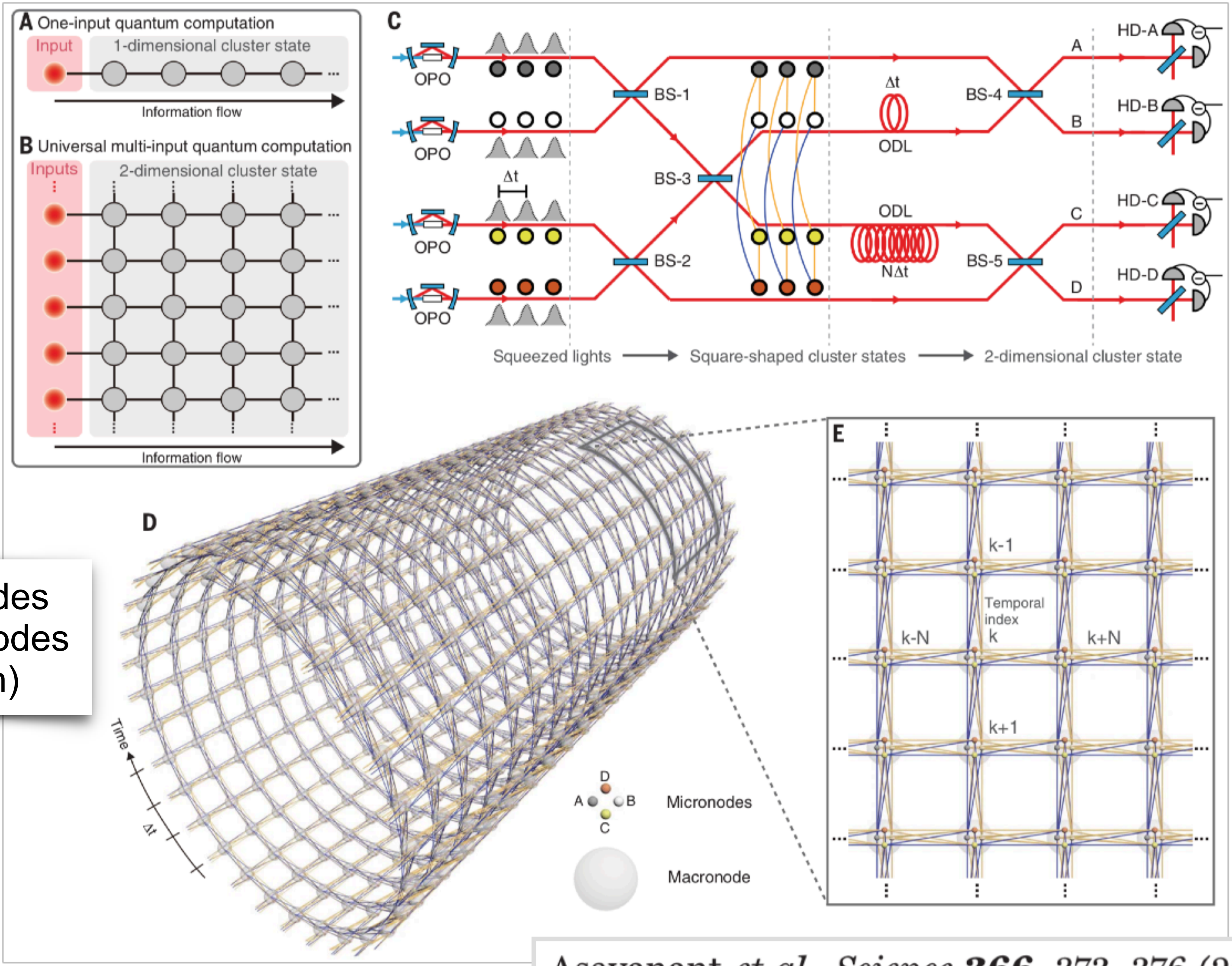
QUANTUM COMPUTING

Deterministic generation of a two-dimensional cluster state

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

Larsen *et al.*, *Science* **366**, 369–372 (2019)

Temporal-mode cluster states

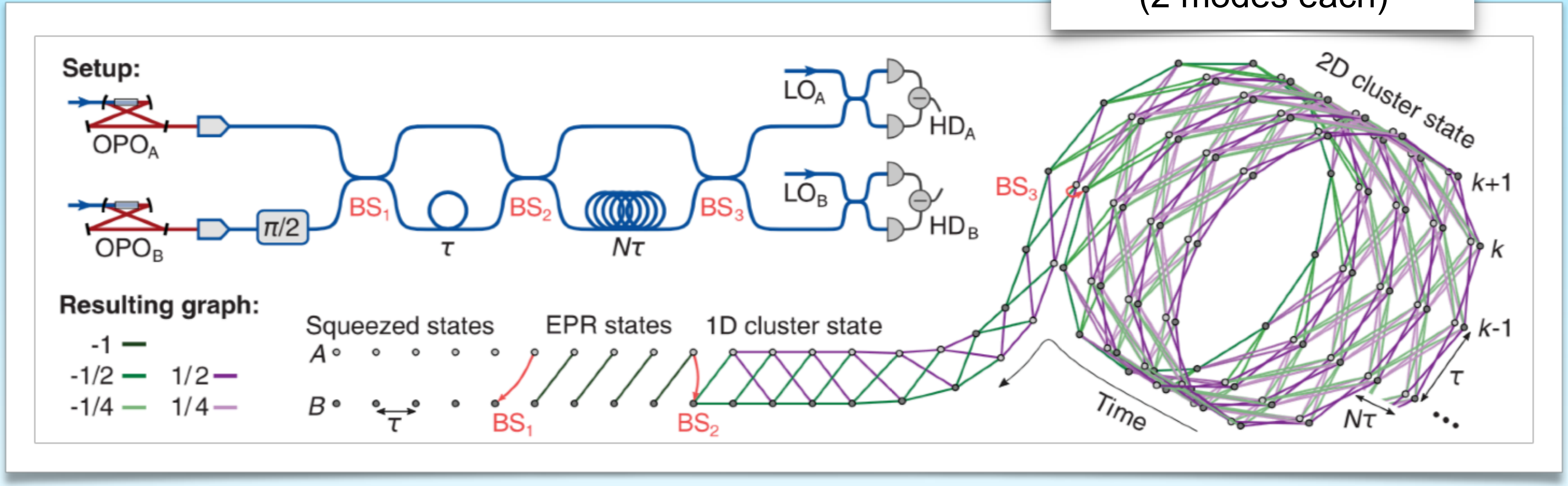


24,800 total modes
5 x 1240 macronodes
(4 modes each)

Asavanant *et al.*, *Science* **366**, 373–376 (2019)

Temporal-mode cluster states

30,000 total modes
12 x 1250 macronodes
(2 modes each)



Larsen *et al.*, *Science* **366**, 369–372 (2019)

Other proposed approaches

- Frequency-temporal modes
  - like musical tones: one frequency for some period of time
  - frequency adds an extra lattice dimension
- Frequency-spatial modes
  - frequency-encoded linear states in different beams woven together
- Three-dimensional lattice topologies

Conclusion

Conclusion

- CV cluster states
  - Enable measurement-based quantum computation using continuous variables
  - Fault tolerance is possible
- GKP qubits
  - Enable fault tolerance with CV cluster states
  - All-Gaussian gate set (only known bosonic code with this feature!)
  - Achieved in trapped ions and circuit QED
- Macronode-based methods are scalable
  - 1D CV cluster state (wire): frequency and temporal modes achieved
  - 2D CV cluster state (universal): temporal modes achieved
  - 3D and higher-dimensional lattices possible
  - Millions of modes achieved
  - Need to improve squeezing (~4.5 dB, need >10 dB)