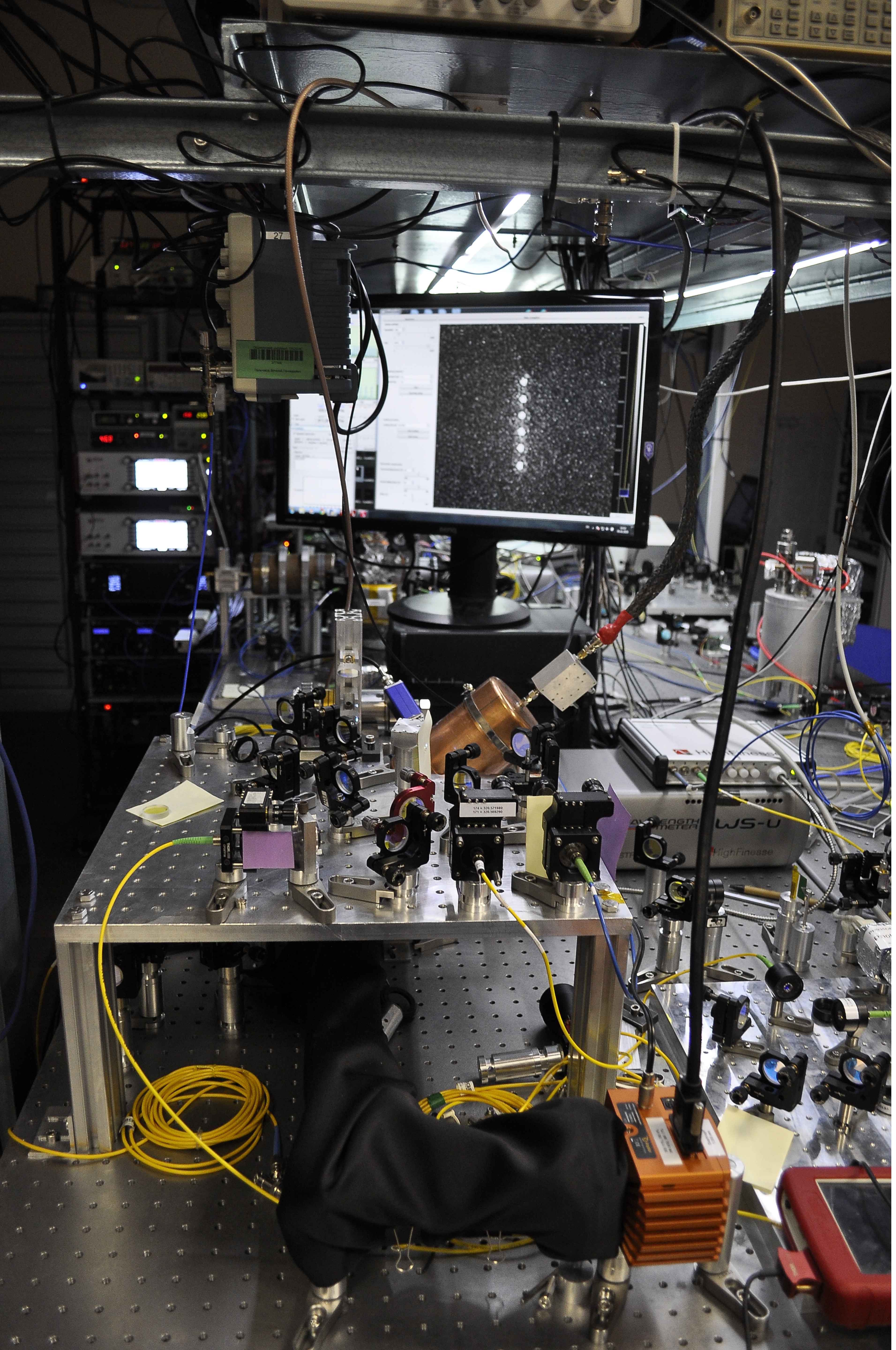


MIPT
MOSCOW INSTITUTE OF PHYSICS AND TECHNOLOGY

LEADING RESEARCH CENTER ON
QUANTUM COMPUTING

RQC

Quantum computing with multilevel quantum systems (qudits)

Aleksey Fedorov
Russian Quantum Center

Theory: E. Kiktenko (RQC), A. Nikolaeva (RQC & MIPT), I. Luchnikov.

Experiment: Blatt group (IQOQI), P. Xu (Wuhan).

Collaboration: Man’ko group (Lebedev Physics Institute), G.V. Shlyapnikov (RQC & LPTMS), A. Lvovsky (Oxford & RQC), D. Abanin (UniGe & RQC).

LRC collaboration: Kolachevskiy group (Lebedev Physics Institute), Biamonte group (Skoltech), Bogdanov group (FTI)

Russian Quantum Center (Former Location @ Skolkovo)

Founded in 2010;
Active stage started in 2012.

2021:
14 scientific groups, 12 laboratories;
200+ researchers and engineers;
Average age — 34 years;
2 Nobel prize winners in boards.

Russian Quantum Center
(Current Location @ Skolkovo Innovations City)

Today's talk

Quantum technologies: "Between hype and hope"

- Basic principles.
- Potential applications: computing, communications, and sensing/metrology.

Brief overview of quantum computing

- Digital quantum computing model.
- Quantum algorithms.

Quantum computing with qudits.

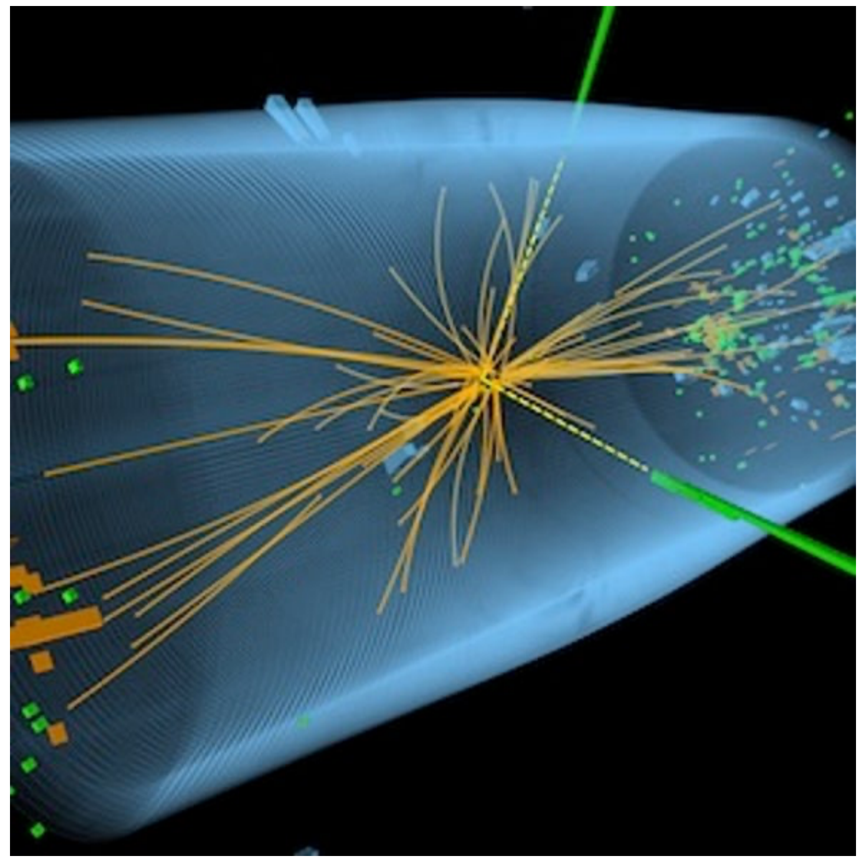
- Decomposition of multiqubit gates.
- Qudit-based quantum algorithms.

+ Open quantum systems analysis.

Quantum technologies: “Between hype and hope”

‘Quantum computing’s trapped between hype and hope

Frontiers of Nature: Big questions about our Universe

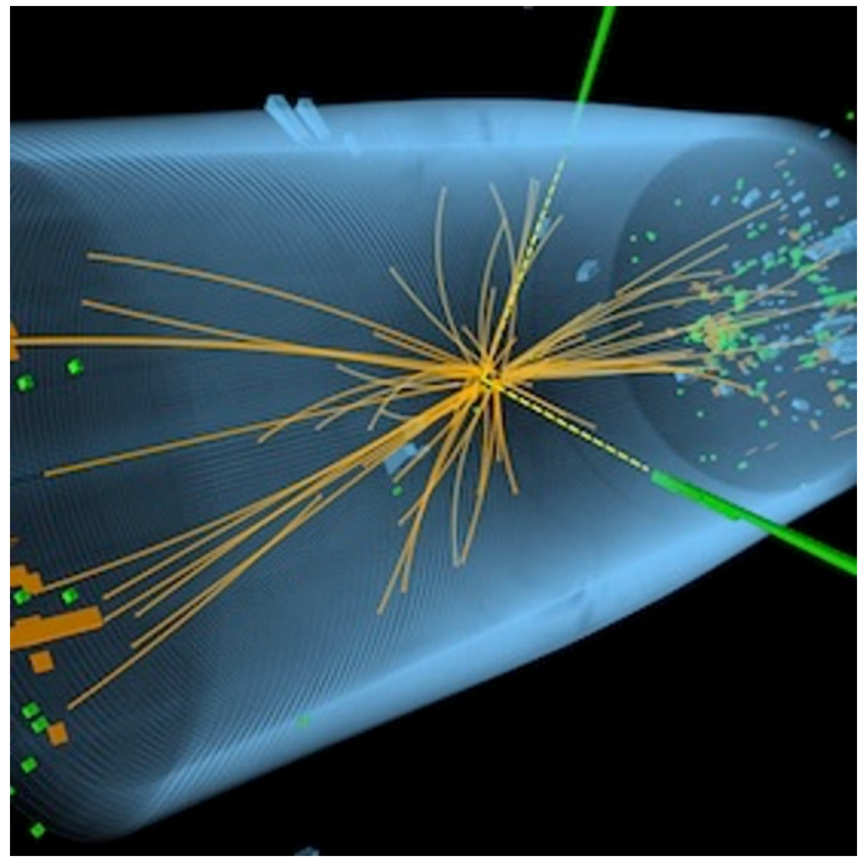
Short distances	Long distances
	
Higgs mechanism	Large-scale structure
Supersymmetry	Dark matter
Quantum gravity	Dark energy

Distance

J. Preskill, Entanglement Frontier, arXiv:1203.5813 (2012)

Frontiers of Nature: Big questions about our Universe

Short distances



Higgs mechanism

Supersymmetry

Quantum gravity

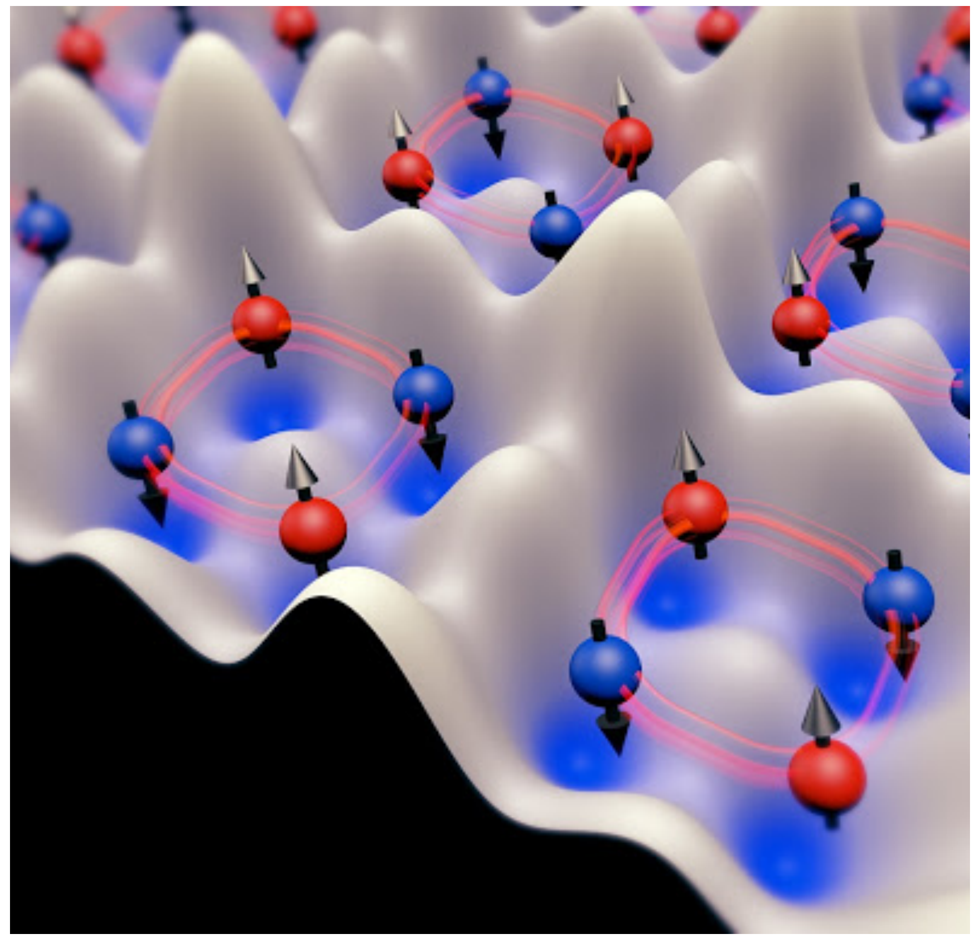
Long distances

Large-scale structure

Dark matter

Dark energy

Complexity



'More is different'

Many-body entanglement

<u>Quantum technologies</u>

Complexity

More Is Different

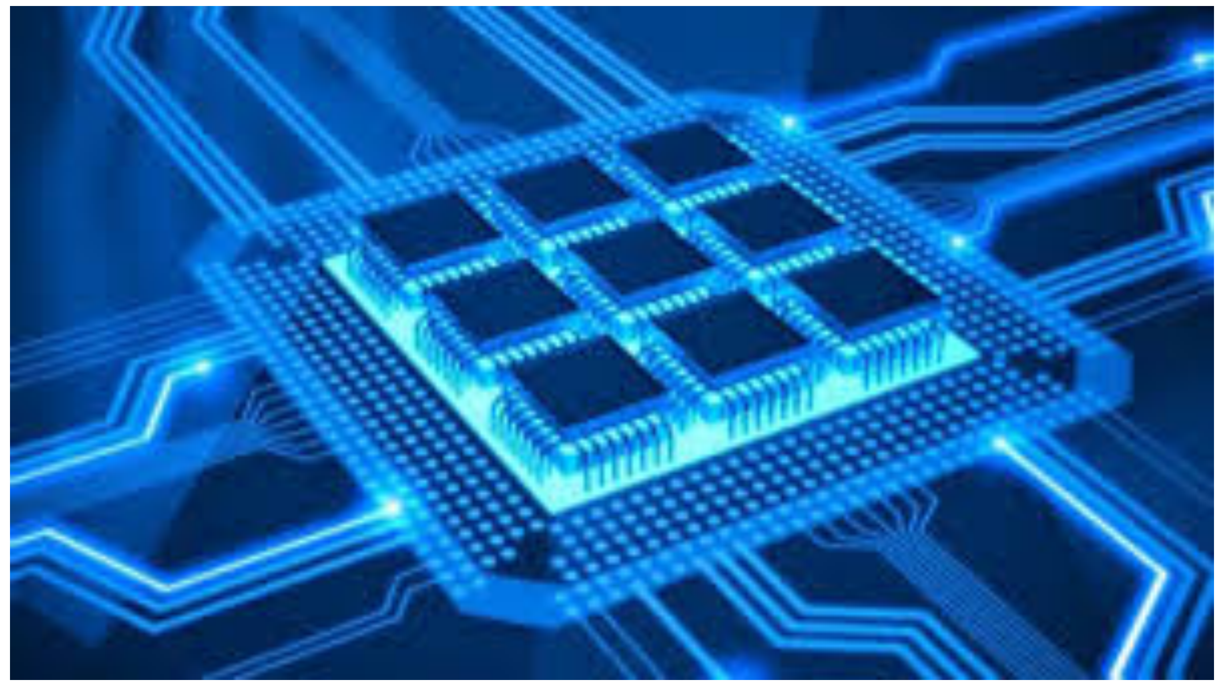
Broken symmetry and the nature of the hierarchical structure of science.

P. W. Anderson

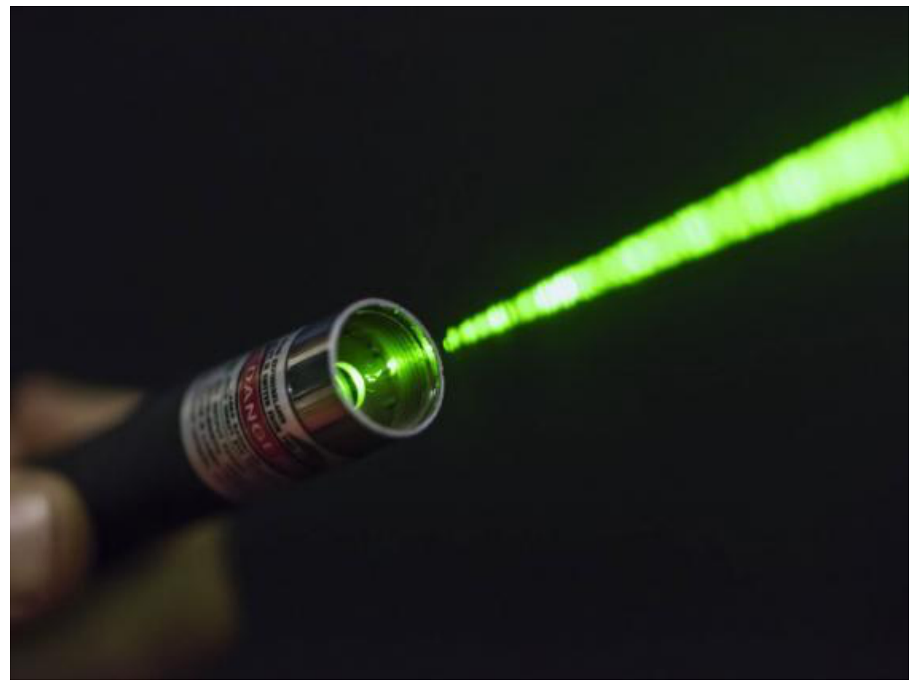
J. Preskill, Entanglement Frontier, arXiv:1203.5813 (2012)

Modern quantum technologies: Controlling quantum phenomena

First quantum revolution:
Collective quantum phenomena

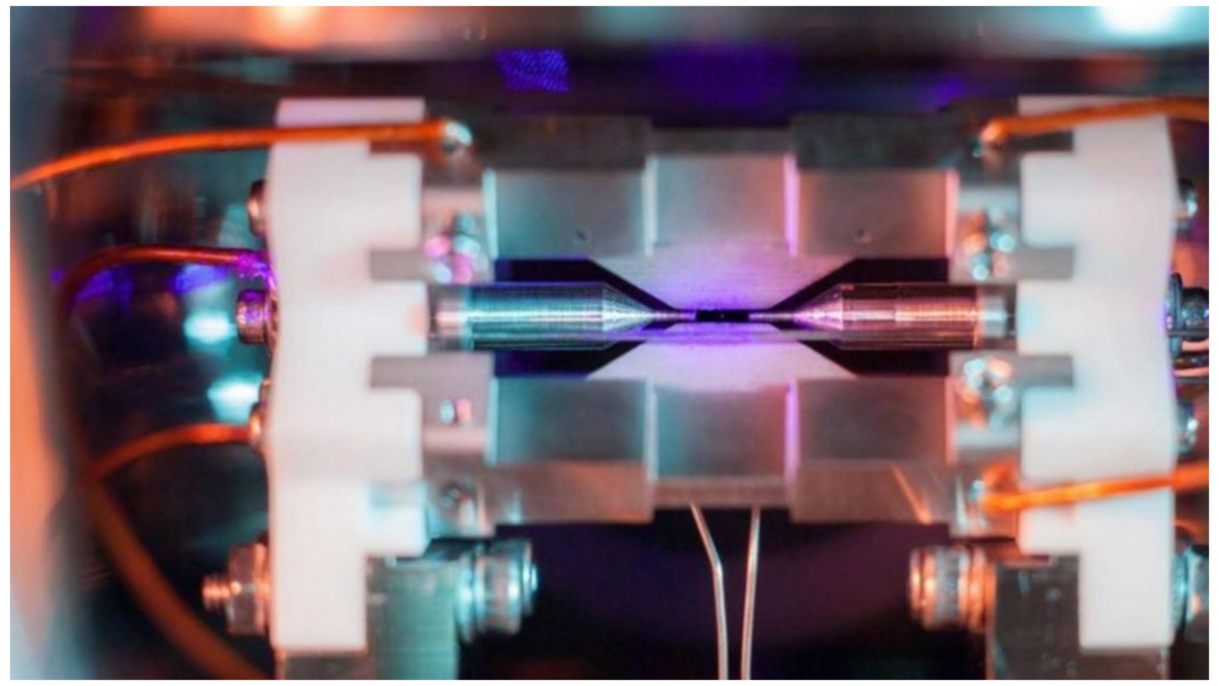


Transistors



Lasers

Second quantum revolution:
Individual quantum phenomena



Single ions, atoms, photons,
and etc

‘Modern quantum technologies’:
individual quantum effects play a
crucial role

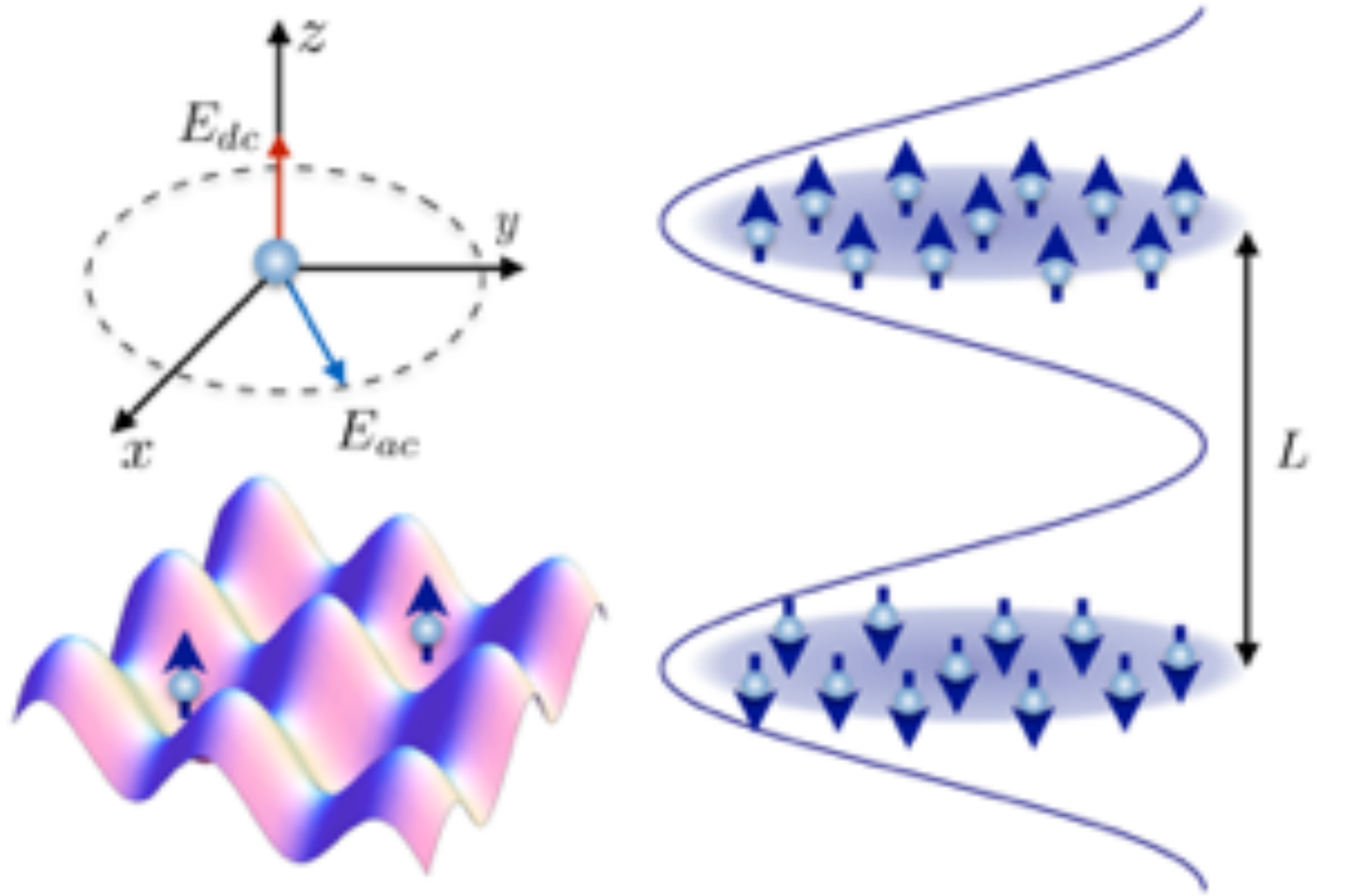
Goals of quantum technologies

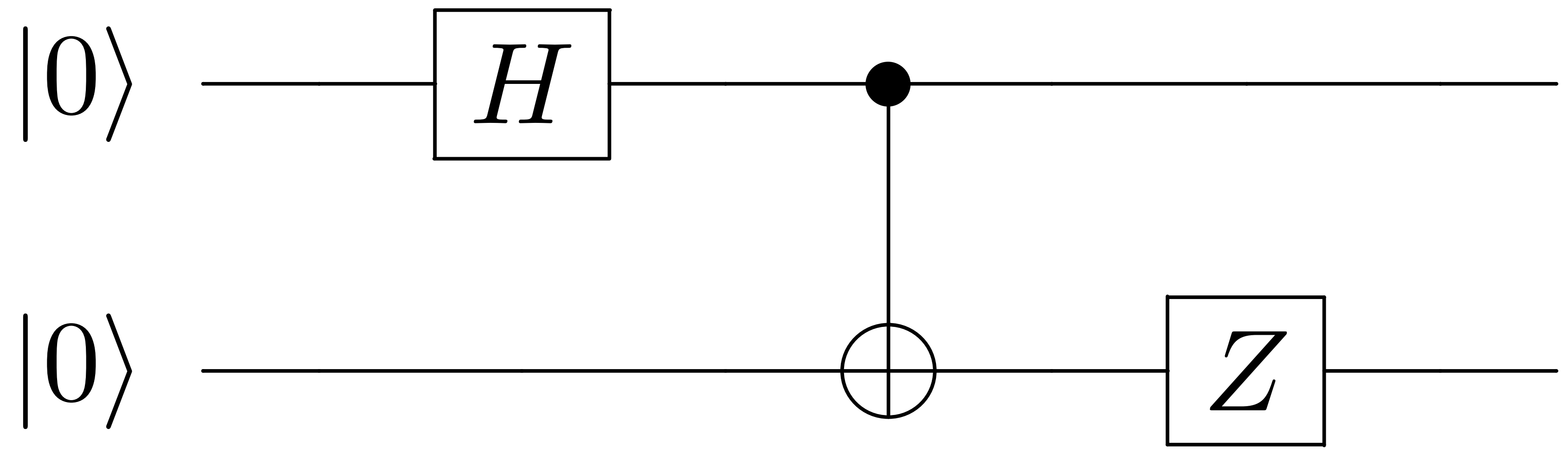
<u>What?</u>

- Isolating and controlling (simple) quantum objects.
- Building complex quantum systems from them.

<u>Why?</u>

- Study new physics with ‘engineered’ many-body systems.
    - Creating and probing new exotic phases of matter.
- Explore new applications.
    - Quantum computing & simulation.
    - Quantum communications.
    - Quantum sensing & metrology.





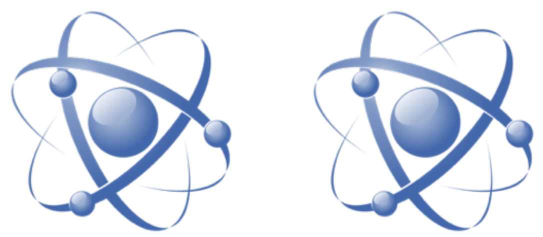
Basic building blocks of quantum technologies

Quantum systems,
e.g. two-level atom
(polarization of
photons, …)

1. Making quantum superposition.

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

2. Making entangled states of quantum systems.

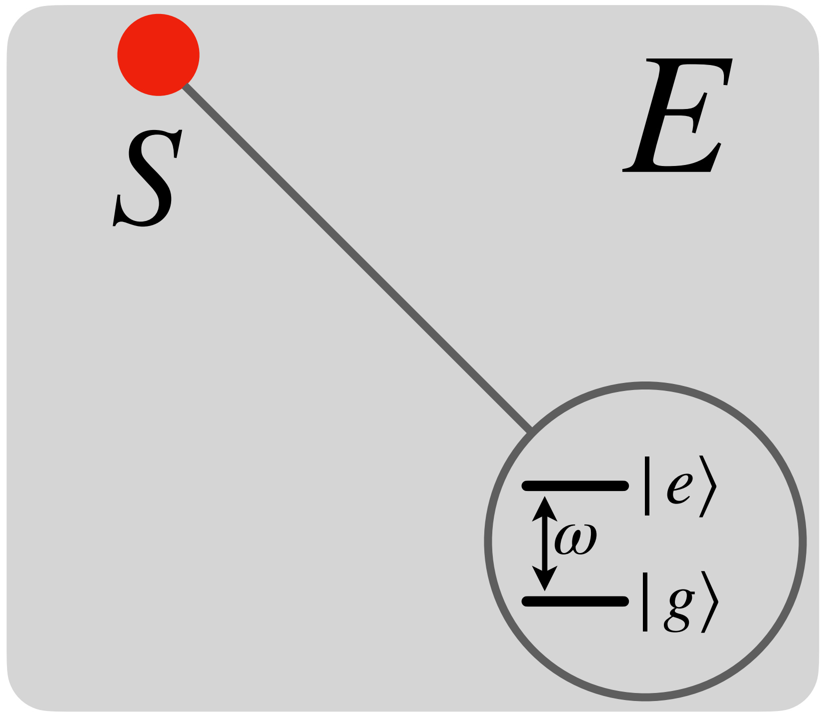


$$|\psi\rangle = \frac{1}{\sqrt{2}}\left[|0\rangle_A|0\rangle_B + |1\rangle_A|1\rangle_B\right]$$

3. No-cloning theorem.

$$\cancel{C|\psi\rangle \to C|\psi\rangle|\psi\rangle}$$

4. Protecting quantum effects from decoherence.



Potentail applications

<u>Quantum computing</u>

- Building a new generation of computing devices based on principles of quantum physics (e.g. superposition, entanglement, tunnelling, etc). Conjecture is that such computing devices are able to solve computational problems, which are beyond the capabilities of classical devices (simulation, prime factorization,…).

<u>Quantum communications (and quantum random number generators)</u>

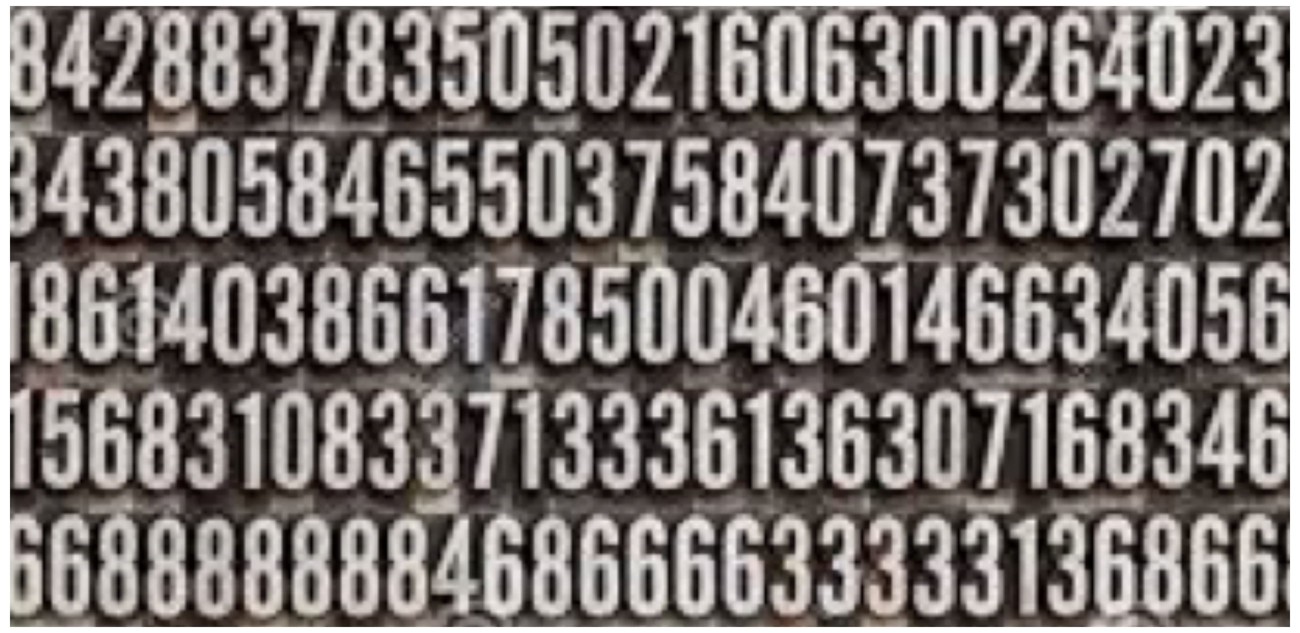
- Encoding information using states of individual quantum systems (e.g. single photons) and transmit them. Fundamental postulates of quantum physics guarantee that it is impossible to extract information without introducing errors. A perfect system for distributing cryptographic keys.

<u>Quantum sensing and metrology</u>

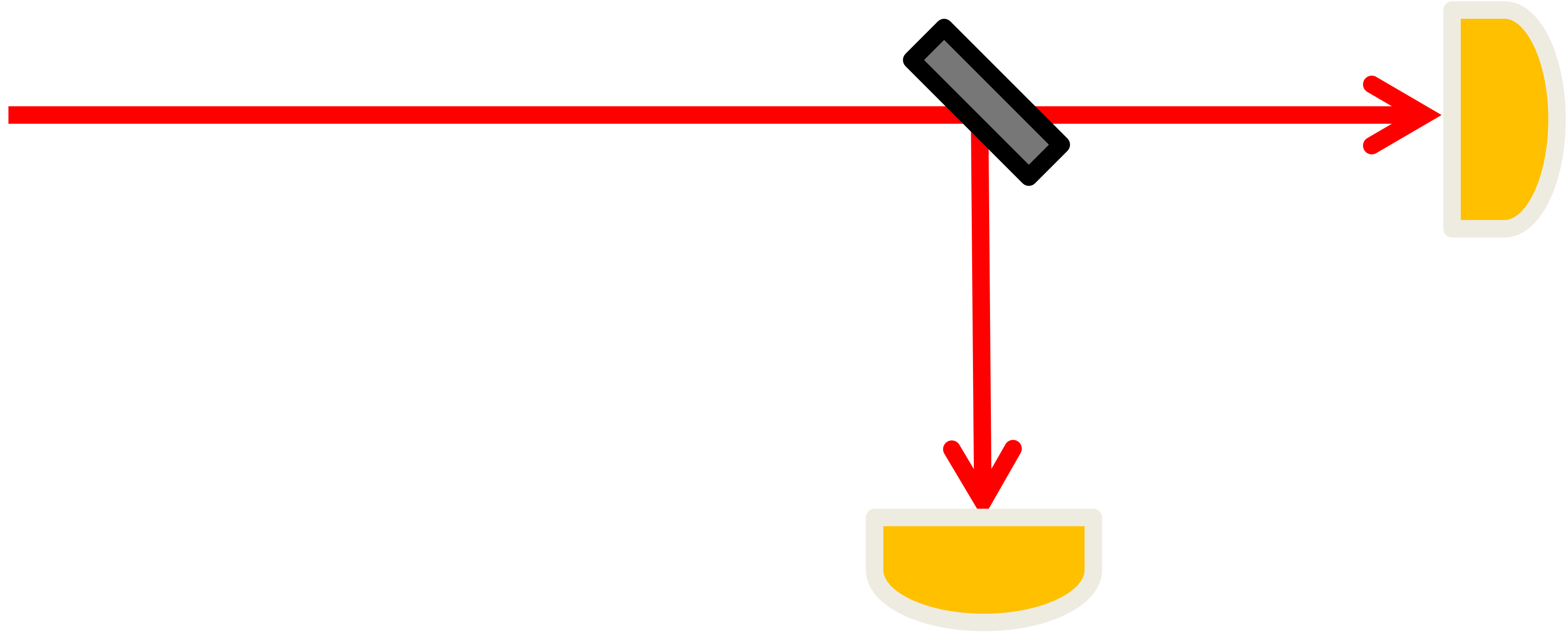
- Using sensitivity of quantum systems to extract perturbation in order to measure weak fields (e.g. magnetic sensors or quantum clocks).

Example: Quantum random number generator

- First-principles calculations (Monte-Carlo).
- Information security and cryptography.
- E-commerce.
- Lotteries and online casinos.



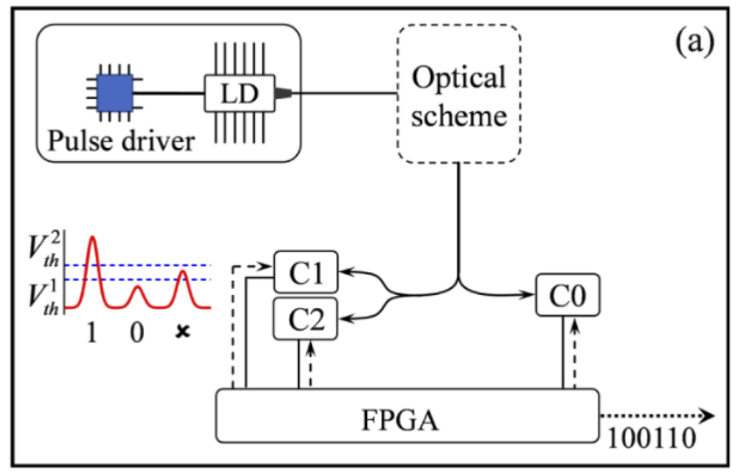
Source of photons



Detector “1”

Detector “0”

Russia



World

Brief introduction to quantum computing

Quantum computing: Brief history

Irreversibility and Heat Generation in the Computing Process

The Thermodynamics of Computation—a Review

Charles H. Bennett

IBM Watson Research Center, Yorktown Heights, New York 10598

Received May 8, 1981

Logical Reversibility of Computation*

Quantum Mechanical Computers[1]

Richard P. Feynman[2]

1. INTRODUCTION

This work is a part of an effort to analyze the physical limitations of computers due to the laws of physics. For example, Bennett[(1)] has made a careful study of the free energy dissipation that must accompany computation. He found it to be virtually zero. He suggested to me the question of the limitations due to quantum mechanics and the uncertainty principle. I have found that, aside from the obvious limitation to size if the working parts are to be made of atoms, there is no fundamental limit from these sources either.

Ю. И. МАНИН

ВЫЧИСЛИМОЕ И НЕВЫЧИСЛИМОЕ

Quantum Mechanical Hamiltonian Models of Turing Machines

Paul Benioff[1]

Simulating Physics with Computers

Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

Quantum theory, the Church–Turing principle and the universal quantum computer

By D. Deutsch

Department of Astrophysics, South Parks Road, Oxford OX1 3RQ, U.K.

(*Communicated by R. Penrose, F.R.S. – Received* 13 *July* 1984)

Volume 48, Number 4 PHYSICAL REVIEW LETTERS 25 January 1982

Is There a Fundamental Bound on the Rate at Which Information Can Be Processed?

David Deutsch

Astrophysics Department, Oxford University, Oxford OX1 3RQ, England, and Center for Theoretical Physics, University of Texas at Austin, Austin, Texas 78712

(Received 29 September 1981)

It is shown that the laws of physics impose no fundamental bound on the rate at which information can be processed. Recent claims that quantum effects impose such bounds are discussed and shown to be erroneous.

RESEARCH ARTICLES

Universal Quantum Simulators

Seth Lloyd

Feynman's 1982 conjecture, that quantum computers can be programmed to simulate any local quantum system, is shown to be correct.

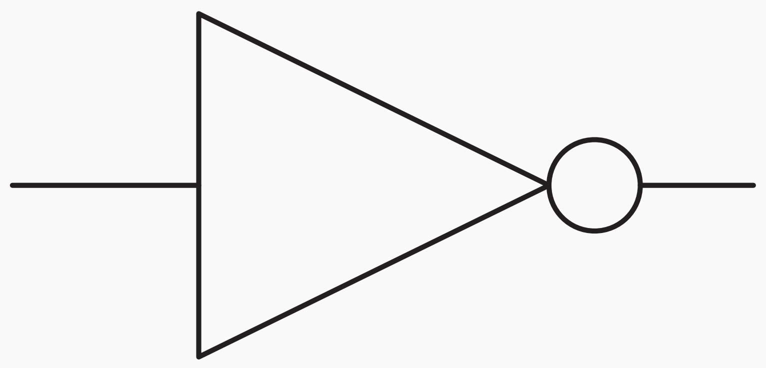
C. Bennet during his talk on the International Conference on Quantum Technologies in Moscow (July, 2019)

Computing: classical vs. quantum

Classical computing:

Basic unit: bit = 0 **or** 1

Computing process:
logical operation under bits

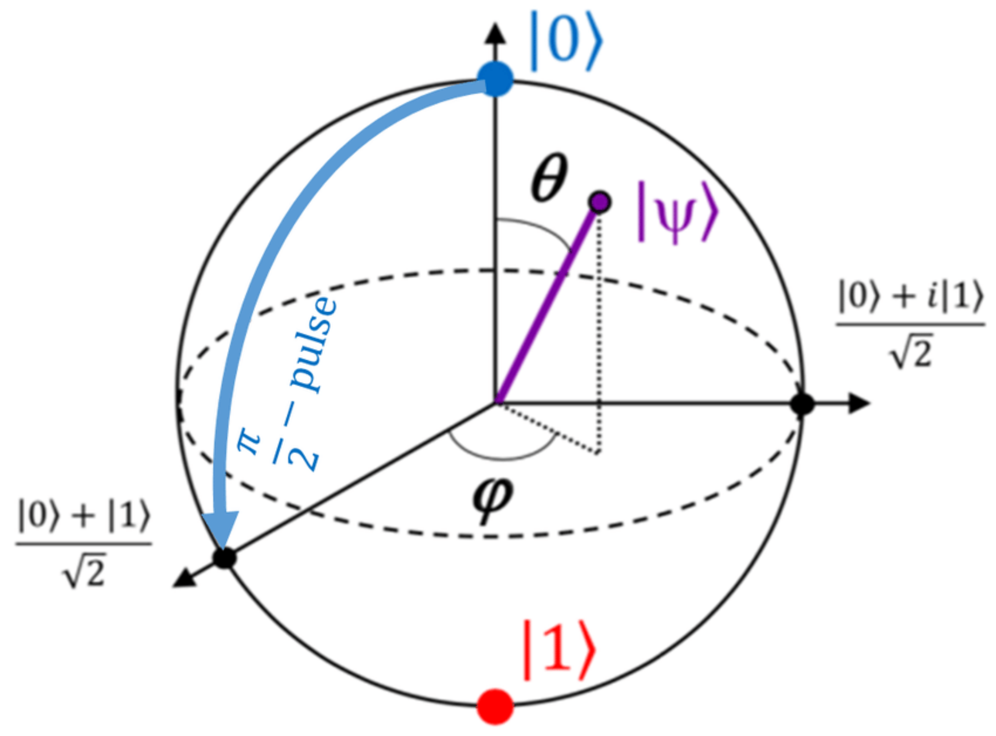


Input	Output
I	F
0	1
1	0

Quantum computing:

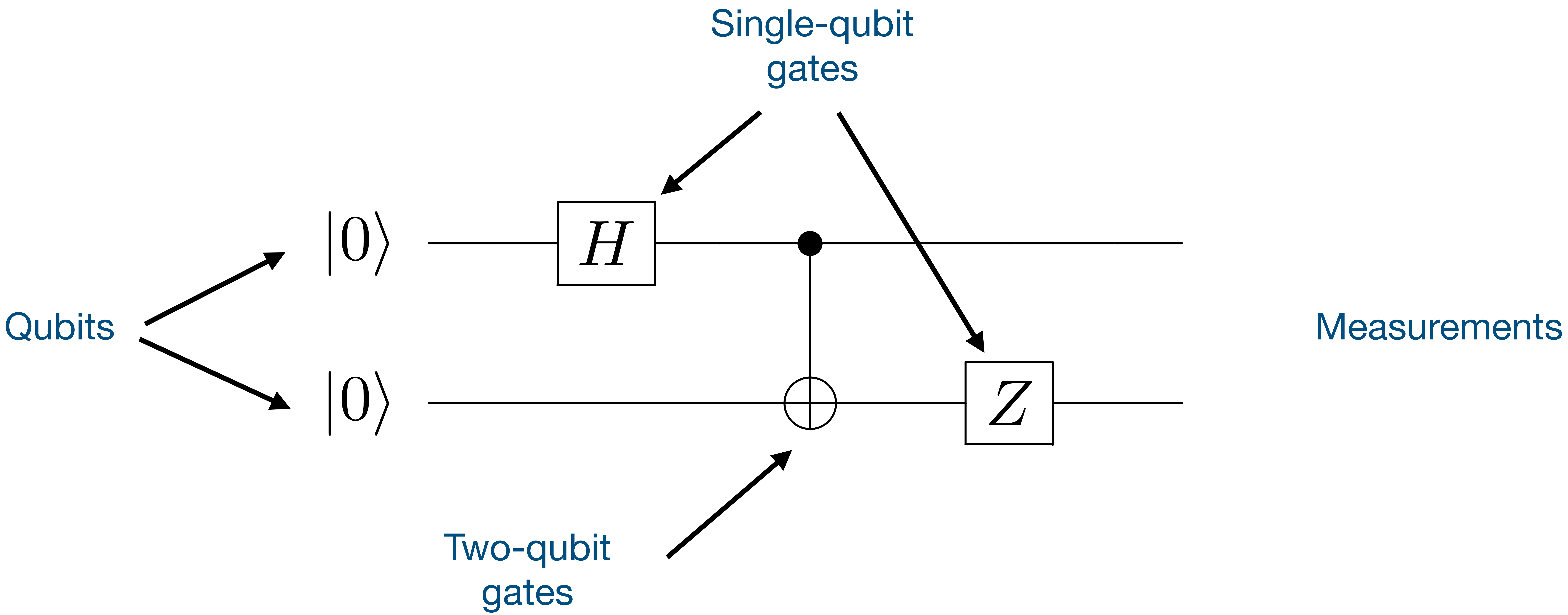
Basic unit: qubit = 0 **and** 1

Computing process:
logical operation under qubits



$$|\psi\rangle = cos\frac{\theta}{2}|0\rangle + e^{i\varphi}sin\frac{\theta}{2}|1\rangle$$

Quantum computing models: Digital quantum computer



Increase the computational volume of a quantum computer: (i) increasing the number of qubits, (ii) increasing the quality of quantum operations, (iii) controlling interactions with the environment (exclude errors)

Quantum gates

Single-qubit gates:

A unitary that acts on a small number of qubits (say, at most 3) is often called a gate, in analogy to classical logic gates like AND, OR, and NOT.
Examples: The Pauli matrices I, X, Y, Z.

Two-qubit gates:

Example: controlled-not gate CNOT.

Universal set of gates:

Theorem: any unitary transformation on any number of qubits can be decomposed as a product of 1- and 2-qubit gates.

Question: What do we need to have in the universal set of quantum gates?

Universal set of quantum gates

Definition 1 *An **instruction set** $\mathcal{G}$ for a d-dimensional qudit is a* finite *set of quantum gates satisfying:*

1. *All gates $g \in \mathcal{G}$ are in $SU(d)$, that is, they are unitary and have determinant 1.*

2. *For each $g \in \mathcal{G}$ the inverse operation $g^\dagger$ is also in $\mathcal{G}$.*

3. *$\mathcal{G}$ is a universal set for $SU(d)$, i.e., the group generated by $\mathcal{G}$ is dense in $SU(d)$. This means that given any quantum gate $U \in SU(d)$ and any accuracy $\epsilon > 0$ there exists a product $S \equiv g_1 \ldots g_m$ of gates from $\mathcal{G}$ which is an ϵ-approximation to U.*

Theorem 1 (Solovay-Kitaev) *Let $\mathcal{G}$ be an instruction set for $SU(d)$, and let a desired accuracy $\epsilon > 0$ be given. There is a constant c such that for any $U \in SU(d)$ there exists a finite sequence S of gates from $\mathcal{G}$ of length $O(\log^c(1/\epsilon))$ and such that $d(U, S) < \epsilon$.*

The Solovay-Kitaev (SK) theorem is one of the most important fundamental results in the theory of quantum computation. In its simplest form the SK theorem shows that, roughly speaking, if a set of single-qubit quantum gates generates a dense subset of $SU(2)$, then that set is guaranteed to fill $SU(2)$ *quickly*, i.e., it is possible to obtain good approximations to any desired gate using surprisingly short sequences of gates from the given generating set.

Universal set of quantum gates

1. We need to generate a superposition of quantum states.

Universal set of quantum gates

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But superposition is not enough. The reason is simply that an unentangled pure state of n qubits can be always written as:

$$(\alpha_1|0\rangle + \beta_1|1\rangle) \otimes (\alpha_2|0\rangle + \beta_2|1\rangle) \otimes \cdots \otimes (\alpha_n|0\rangle + \beta_n|1\rangle).$$

Such a state requires only 2n amplitudes, so we can store the state efficiently.

Universal set of quantum gates

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Such a state requires only 2n amplitudes, so we can store the state efficiently.

2. We need to create entanglement.

$$\sum_{x \epsilon \{0,1\}^n} \alpha_x |x\rangle$$

This state requires only 2^N amplitudes, so we cannot store the state efficiently. Superposition and entanglement allows accessing exponentially large computation spaces.

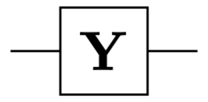
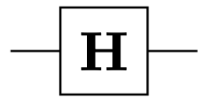
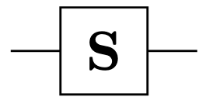
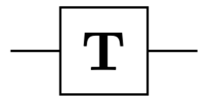
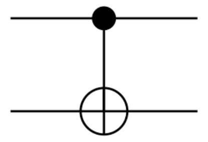
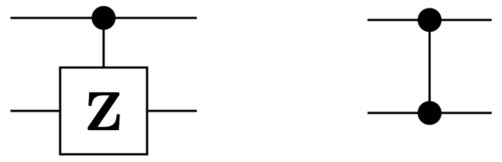
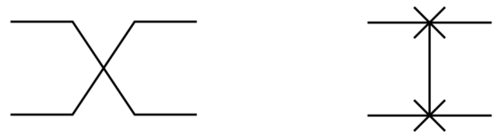
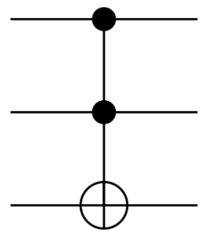
Access to the exponentially large computational space

No known classical algorithm can simulate a quantum computer. But perhaps the most persuasive argument we have that quantum computing is powerful is simply that we don't know how to simulate a quantum computer using a digital computer; that remains true even after many decades of effort by physicists to find better ways to simulate quantum systems.

Qubits	Memory	Time for one gate operation
10	16 kByte	microseconds on a watch
20	16 MByte	milliseconds on smartphone
30	16 GByte	seconds on laptop
40	16 TByte	minutes on supercomputer
50	16 PByte	hours on top supercomputer
60	16 EByte	long long time
80	size of visible universe	age of the universe

J. Preskill, Quantum computing in the NISQ era and beyond, Quantum. 2, p. 79 (2018).

Quantum gates

Operator	Gate(s)	Matrix
Pauli-X (X)		$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$
Pauli-Y (Y)		$\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$
Pauli-Z (Z)		$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$
Hadamard (H)		$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$
Phase (S, P)		$\begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}$
$\pi/8$ (T)		$\begin{bmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{bmatrix}$
Controlled Not (CNOT, CX)		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$
Controlled Z (CZ)		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$
SWAP		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$
Toffoli (CCNOT, CCX, TOFF)		$\begin{bmatrix} 1&0&0&0&0&0&0&0 \\ 0&1&0&0&0&0&0&0 \\ 0&0&1&0&0&0&0&0 \\ 0&0&0&1&0&0&0&0 \\ 0&0&0&0&1&0&0&0 \\ 0&0&0&0&0&1&0&0 \\ 0&0&0&0&0&0&0&1 \\ 0&0&0&0&0&0&1&0 \end{bmatrix}$

Superposition

Entanglement

Is it enough for quantum computing?

Universal set of quantum gates

3. Real vs. imaginary gates.

The set {Hadamard, CNOT} is getting closer to universality, as it's capable of creating entangled superposition states. But it's still not there, as can be seen from the fact that the cNOT and Hadamard matrices have real entries only. So composing them could never give us a unitary transformation like

$$\begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}$$

Let us then take {Haramard, CNOT, Phase}, they can generate superposition, and entanglement, and amplitudes that are not real.

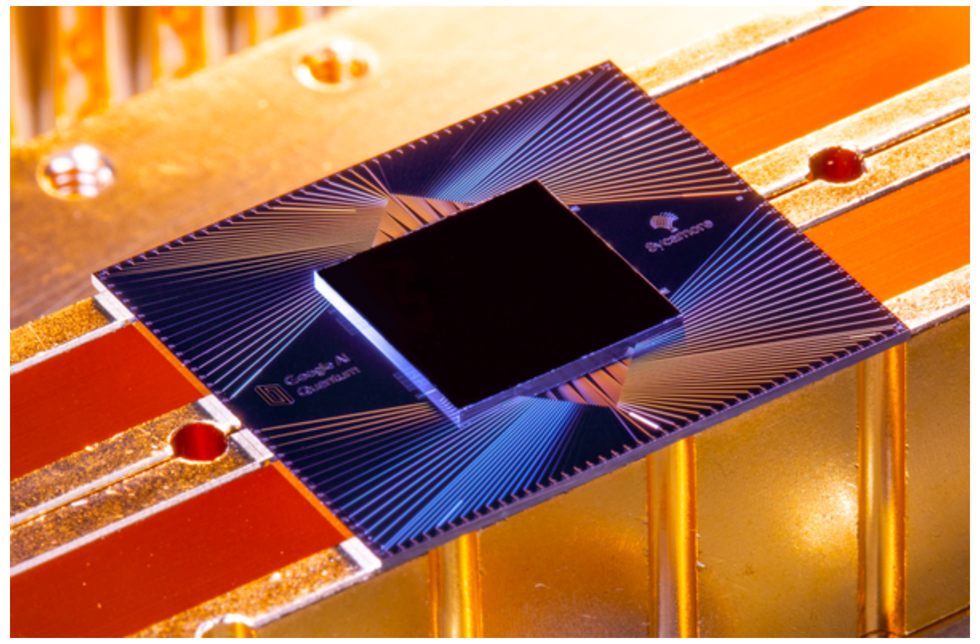
4. Non-trivial observation: {Haramard, CNOT, Phase} is not universal in the view of the Gottesman-Knill Theorem since these gates are stabilzers.

But {CNOT, R(pi/8), Phase} is the universal set of gates

Given a pure quantum state $|\psi\rangle$, we say a unitary matrix U stabilizes $|\psi\rangle$ if $|\psi\rangle$ is an eigenvector of U with eigenvalue 1, or equivalently if $U|\psi\rangle=|\psi\rangle$ where we do not ignore global phase. To illustrate, the following table lists the Pauli matrices and their opposites, together with the unique one-qubit states that they stabilize:

Quantum hardware

1. Superconductors

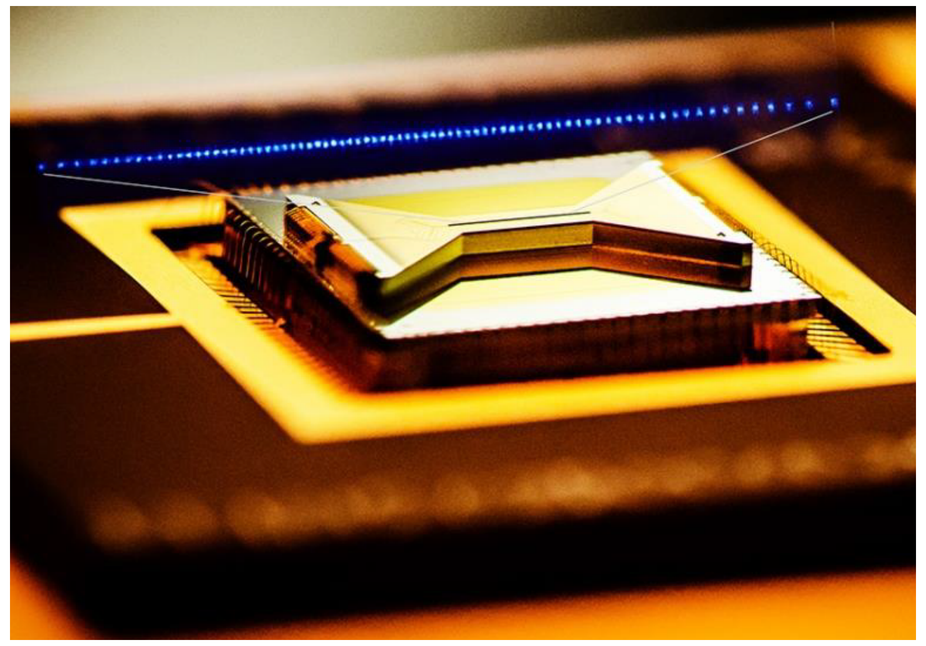


Google

IBM

rigetti

2. Trapped ions

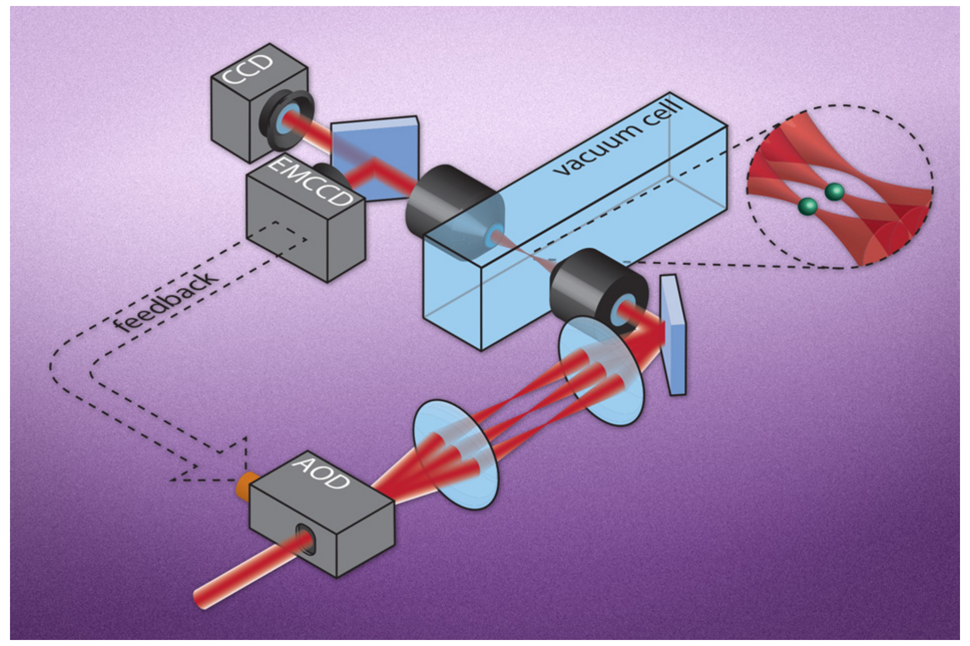


IONQ

AQT

Honeywell

3. Rydberg atoms

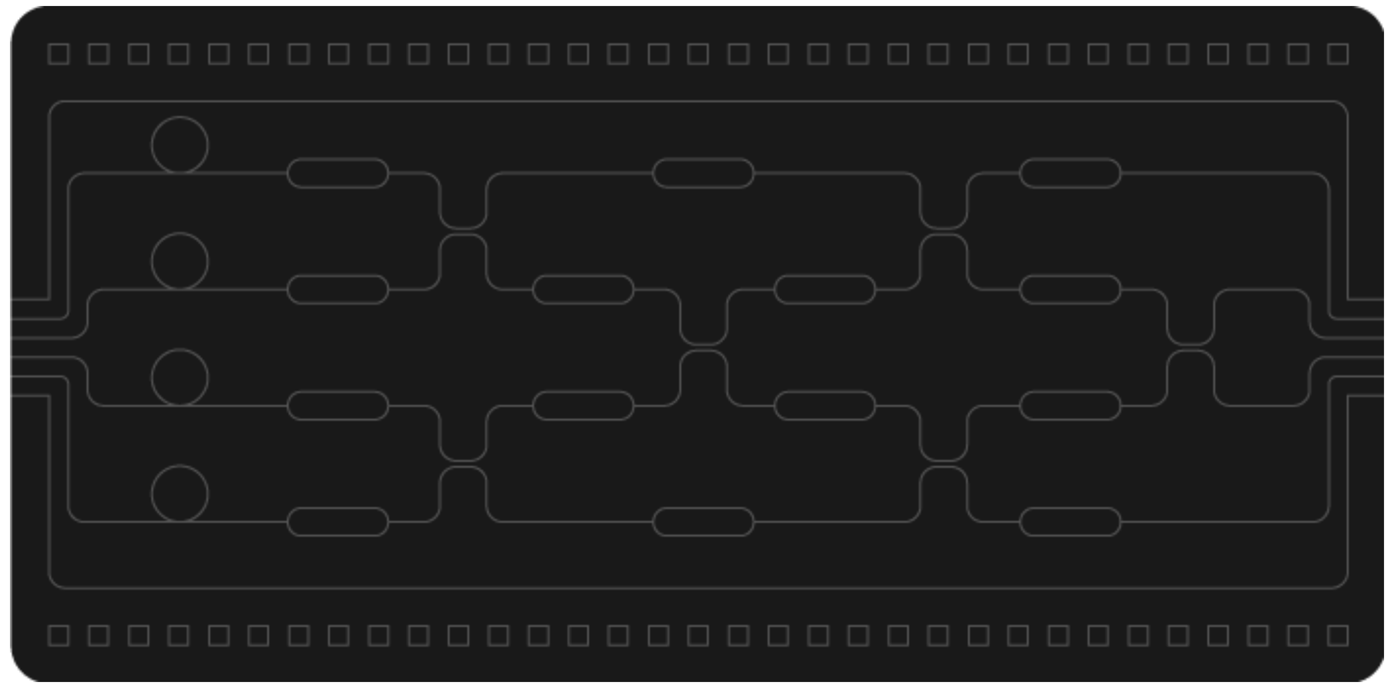


QuEra

PASQAL

ColdQuanta

4. Silicon photonics

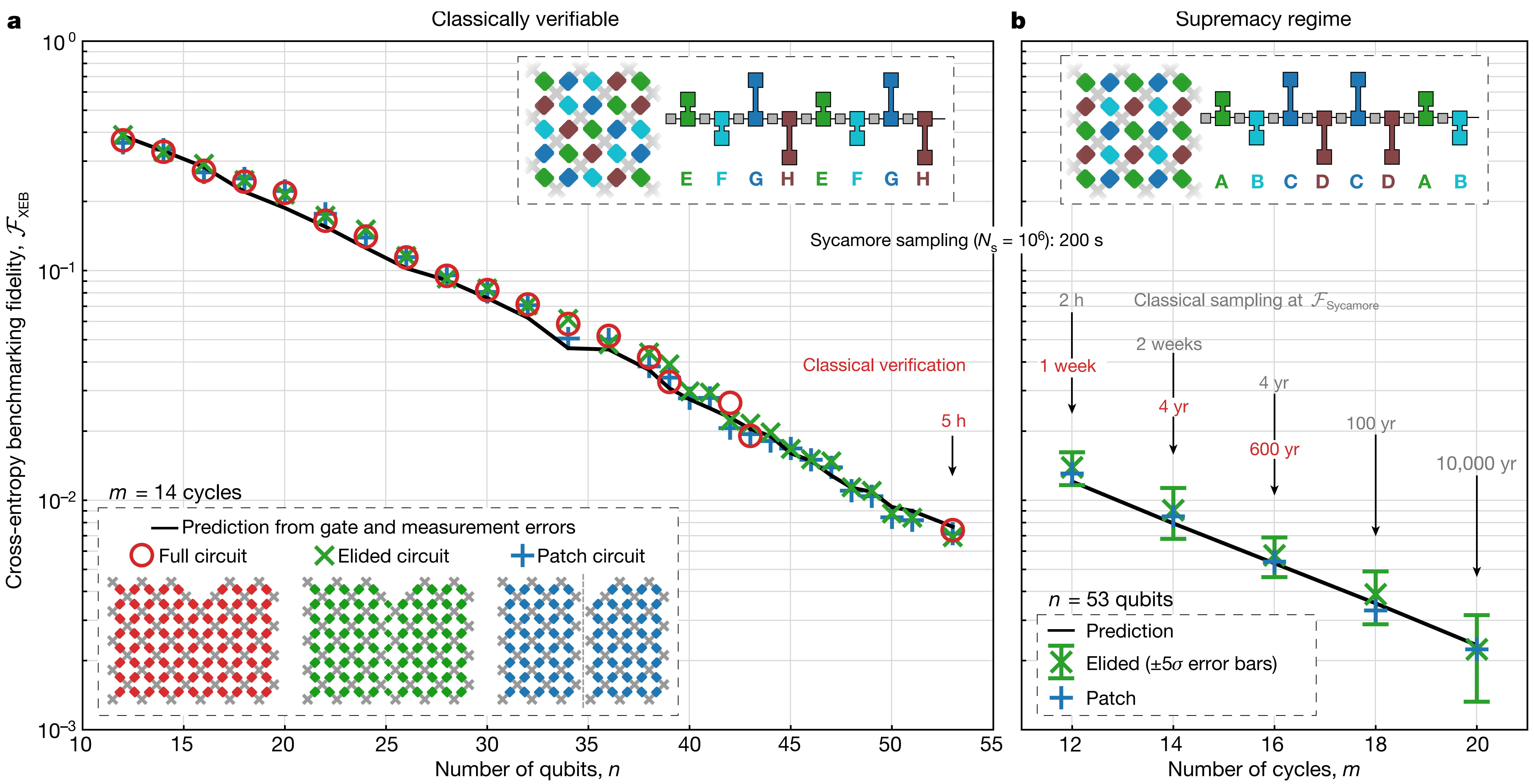


XANADU

PsiQuantum

+ ~10 alternative platforms: semiconductors, color centres, quantum dots, graphene, polaritons,..

Quantum hardware

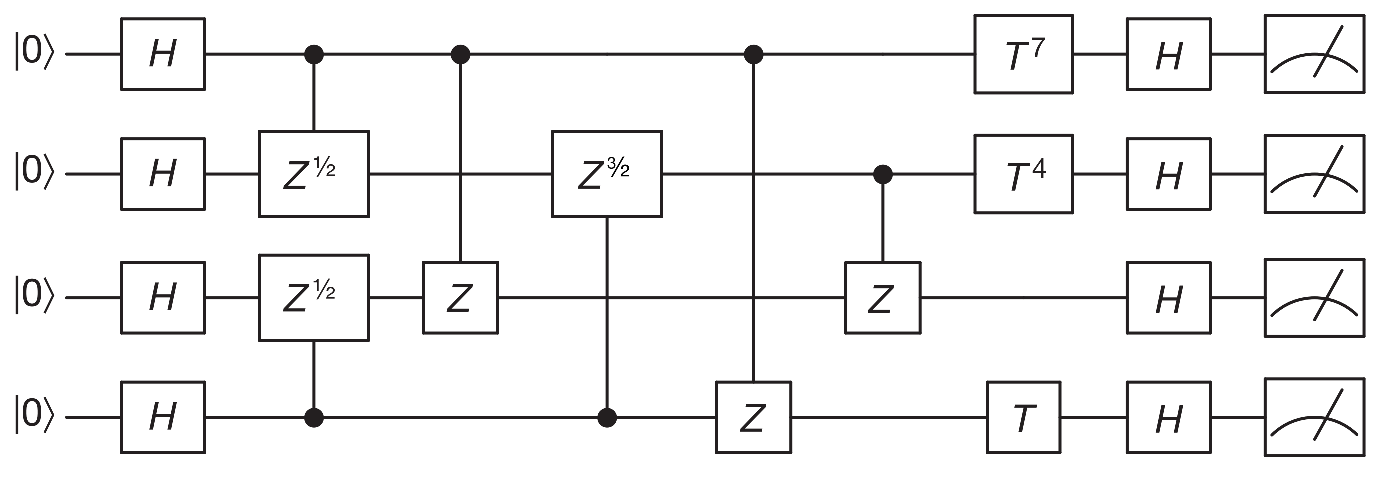


"Our Sycamore processor takes about 200 seconds to sample one instance of a quantum circuit a million times —our benchmarks currently indicate that the equivalent task for a state-of-the-art classical supercomputer would take approximately 10,000 years".

BOX 2

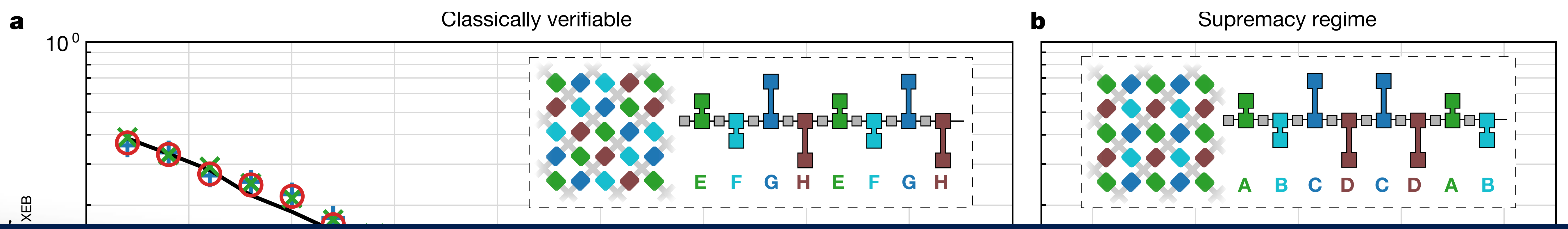
Random quantum circuits

Unlike boson sampling, some quantum-supremacy proposals remain within the standard quantum circuit model. In the model of commuting quantum circuits[10] known as IQP (instantaneous quantum polynomial-time), one considers circuits made up of gates that all commute, and in particular are all diagonal in the X basis; see Box 2 Figure below. Although these diagonal gates may act on the same qubit many times, as they all commute, in principle they could be applied simultaneously. The computational task is to sample from the distribution on measurement outcomes for a random circuit of this form, given a fixed input state. Such circuits are both potentially easier to implement than general quantum circuits and have appealing theoretical properties that make them simpler to analyse[11,18]. However, this very simplicity may make them easier to simulate classically too. Of course, one need not be restricted to commuting circuits to demonstrate supremacy. The quantum-AI group at Google has recently suggested an experiment based on superconducting qubits and non-commuting gates[12]. The proposal is to sample from the output distributions of random quantum circuits, of depth around 25, on a system of around 49 qubits arranged in a 2D square lattice structure (see Fig. 1). It has been suggested[12] that this should be hard to simulate, based on (a) the absence of any known simulation requiring less than a petabyte of storage, (b) IQP-style theoretical arguments[18] suggesting that larger versions of this system should be asymptotically hard to simulate, and (c) numerical evidence[12] that such circuits have properties that we would expect in hard-to-simulate distributions. If this experiment were successful, it would come very close to being out of reach of current classical simulation (or validation, for that matter) using current hardware and algorithms.



Box 2 Figure | Example of an IQP circuit. Between two columns of Hadamard gates (H) is a collection of diagonal gates (T and controlled-$\sqrt{Z}$). Although these diagonal gates may act on the same qubit many times they all commute, so in principle could be applied simultaneously.

Quantum hardware



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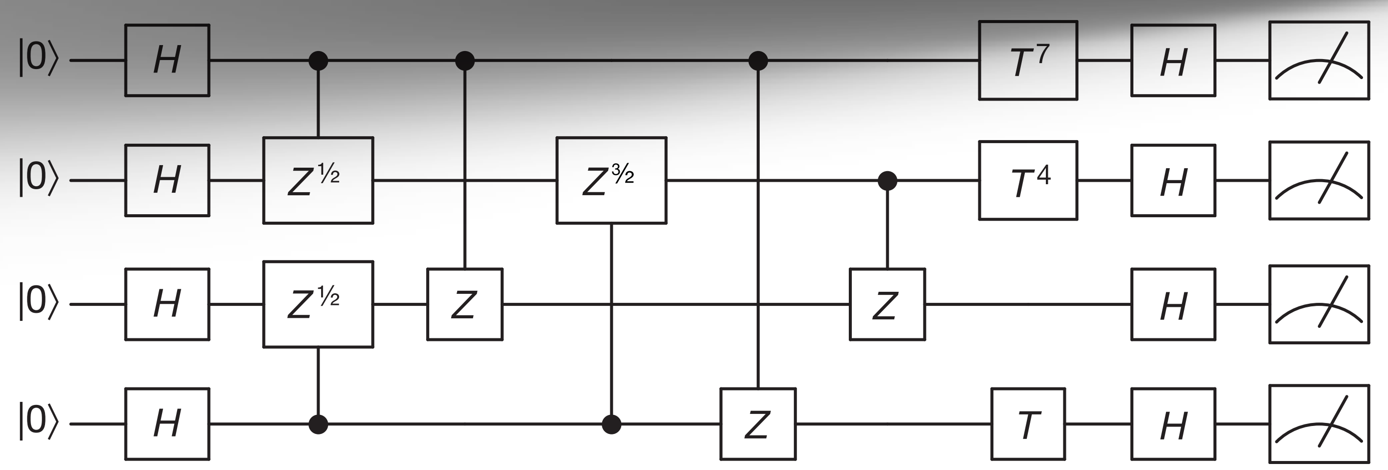
IBM:10’000 years can be reduced to several days
Alibaba: 10’000 years are reduced to 20 days
Chinese Academy of Science: only 5 days are needed

Let us wait!

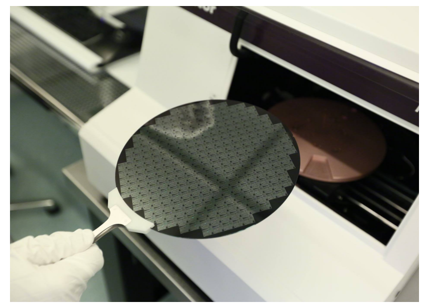
“Our Sycamore processor takes about 200 seconds to sample one instance of a quantum circuit a million times —our benchmarks currently indicate that the equivalent task for a state-of-the-art classical supercomputer would take approximately 10,000 years”.

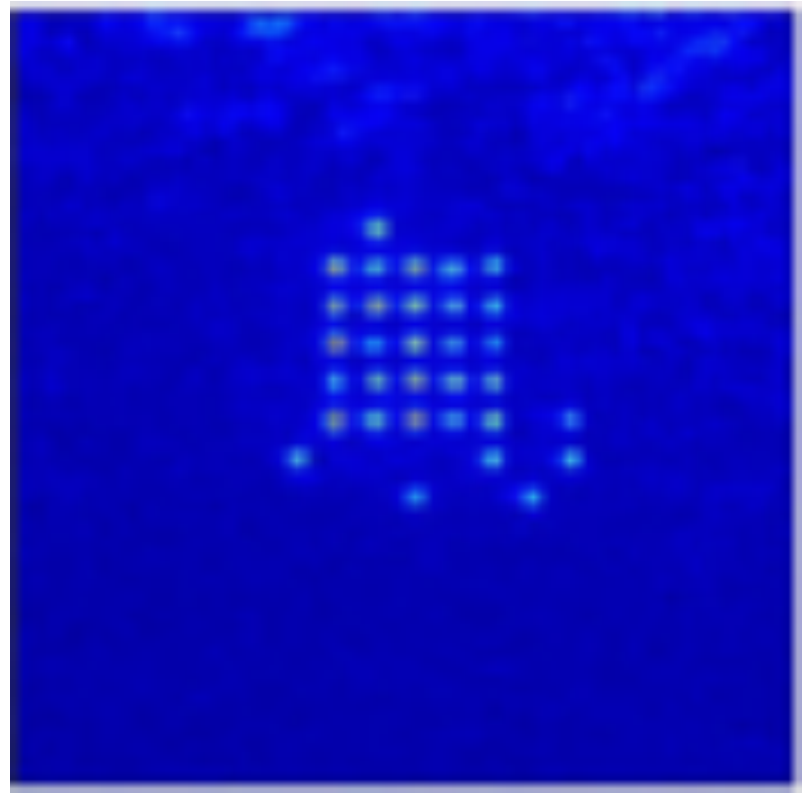


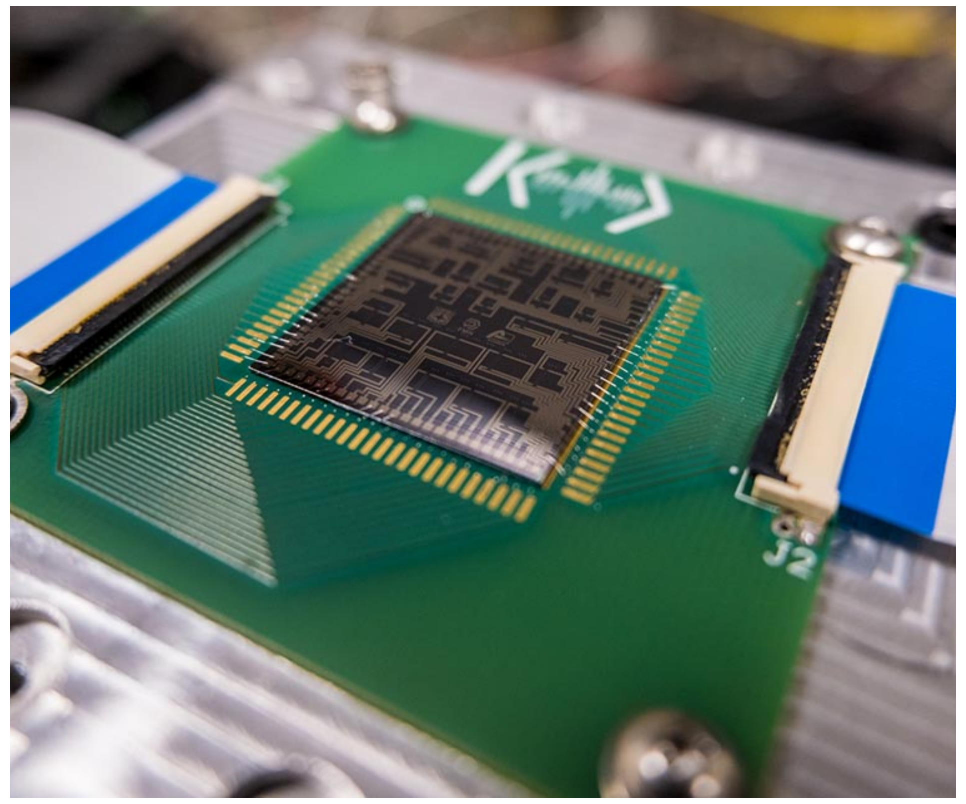
Box 2 Figure | Example of an IQP circuit. Between two columns of Hadamard gates (H) is a collection of diagonal gates (T and controlled-$\sqrt{Z}$). Although these diagonal gates may act on the same qubit many times they all commute, so in principle could be applied simultaneously.

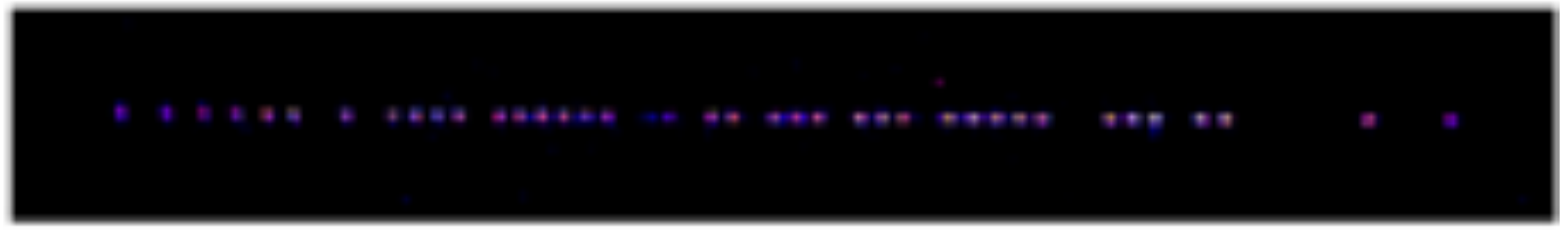
Quantum hardware

Increase the computational volume of a quantum computer: (i) increasing the number of qubits, (ii) increasing the quality of quantum operations, (iii) controlling interactions with the environment









Various physical platforms

(i) Superconducting circuits / MISiS & RQC & BMSTU & ISSP RAS & MIPT & VNIAA …

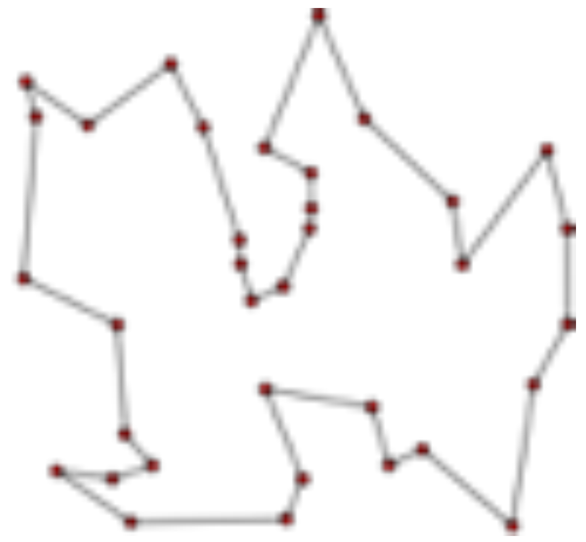
(ii) Neutral atoms / QTC MSU & ISP RAS

(iii) Optical qubits / QTC MSU & BMSTU

(iv) Ions / Lebedev Institute & RQC

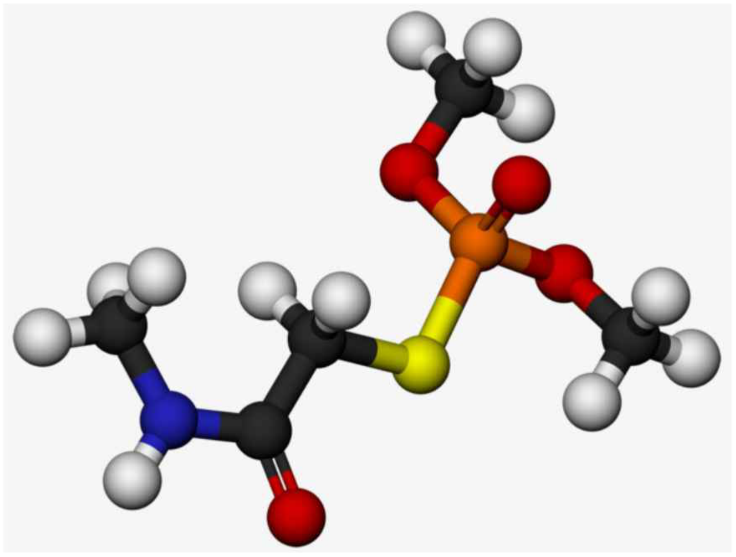
Quantum computing: Applications

Optimization



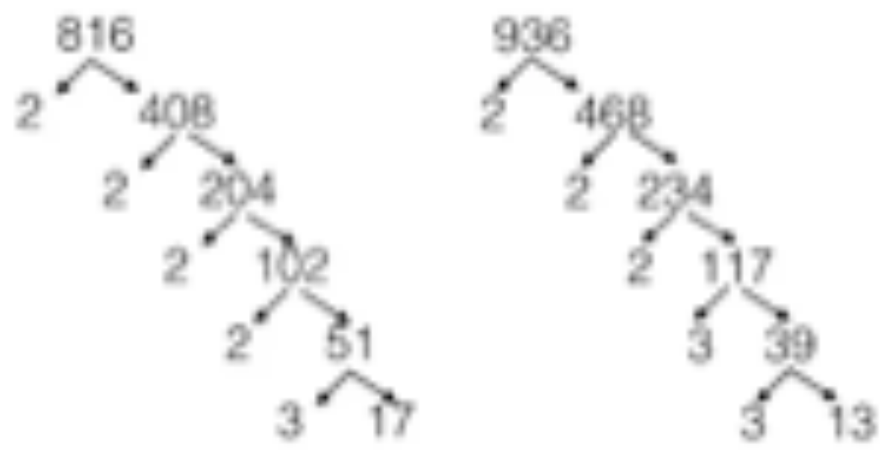
- Logistics
- Finance
- Job scheduling
- Machine learning
- …

Simulation



- Chemistry
- Biophysics
- Materials
- Drugs
- …

Factroization

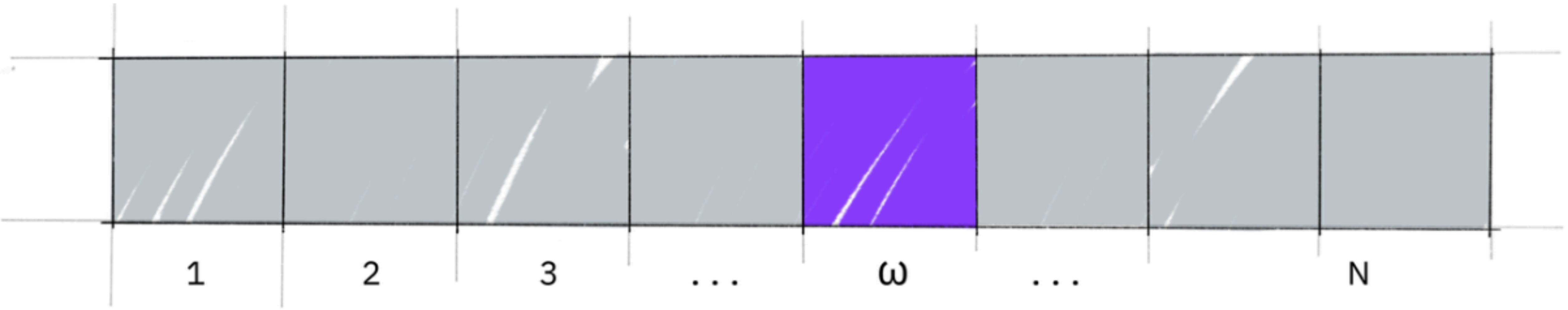


- Cryptoanalysis

Grover's algorithm

Unstructured Search

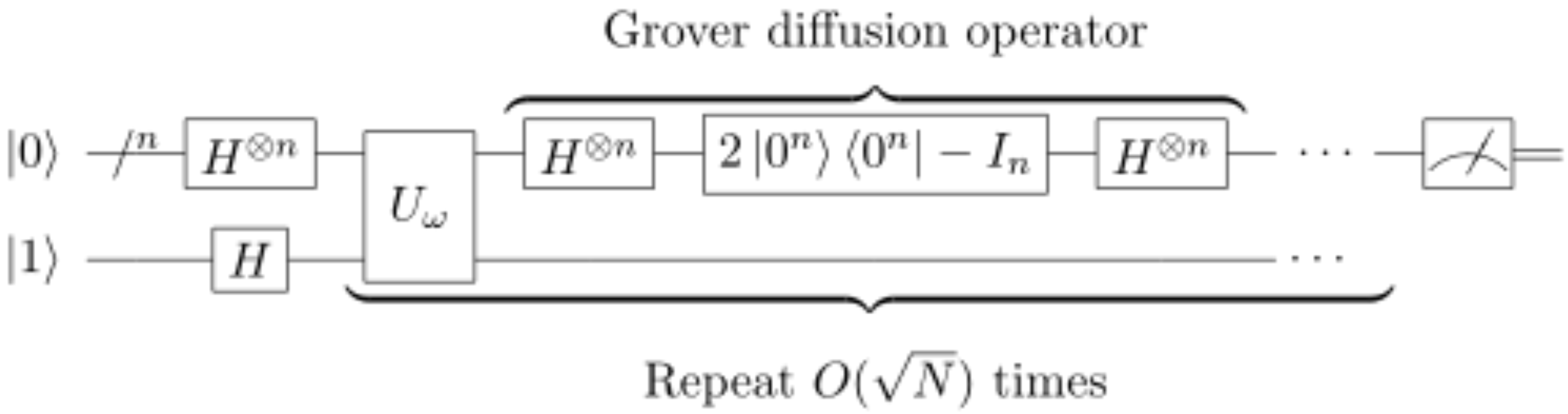
Suppose you are given a large list of N items. Among these items there is one item with a unique property that we wish to locate; we will call this one the winner w. Think of each item in the list as a box of a particular color. Say all items in the list are gray except the winner w, which is purple.

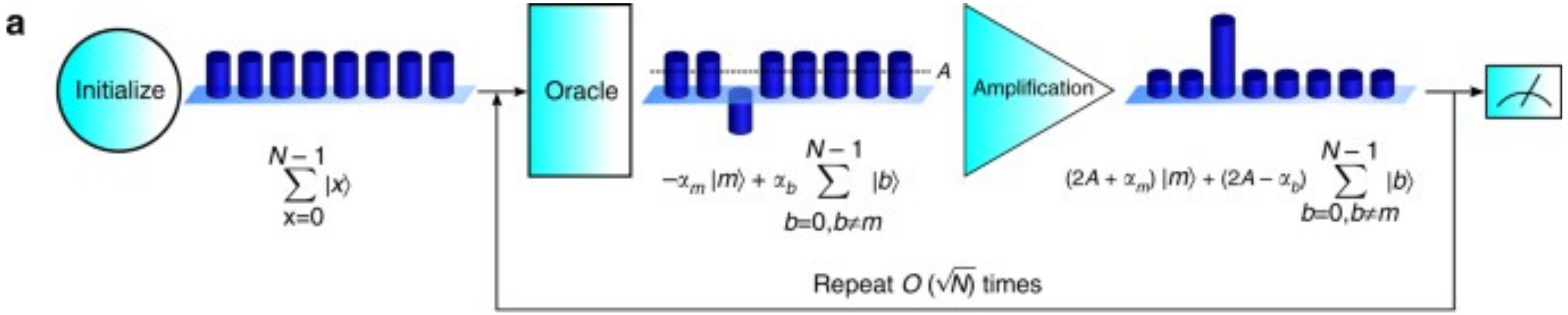


To find the purple box — the marked item — using classical computation, one would have to check on average N/2 of these boxes. On a quantum computer, however, we can find the marked item in roughly √N steps with Grover's algorithm. A quadratic speedup is indeed a substantial time-saver for finding marked items in long lists. Additionally, the algorithm does not use the list's internal structure, which makes it generic; this is why it immediately provides a quadratic quantum speed-up for many classical problems.

https://qiskit.org/textbook/ch-algorithms/grover.html

Grover's algorithm





https://qiskit.org/textbook/ch-algorithms/grover.html

Quantum computing with qudits

Quantum computing with ion qubits / qudits

LEADING RESEARCH CENTER ON
QUANTUM
COMPUTING

Goal: Building a small-scale quantum computers based on ions with online access (2020-2022)

RQC

ФЕДЕРАЛЬНОЕ ГОСУДАРСТВЕННОЕ БЮДЖЕТНОЕ УЧРЕЖДЕНИЕ НАУКИ
Физический институт имени П.Н.Лебедева Российской академии наук
Ф И А Н

Skoltech
Skolkovo Institute of Science and Technology

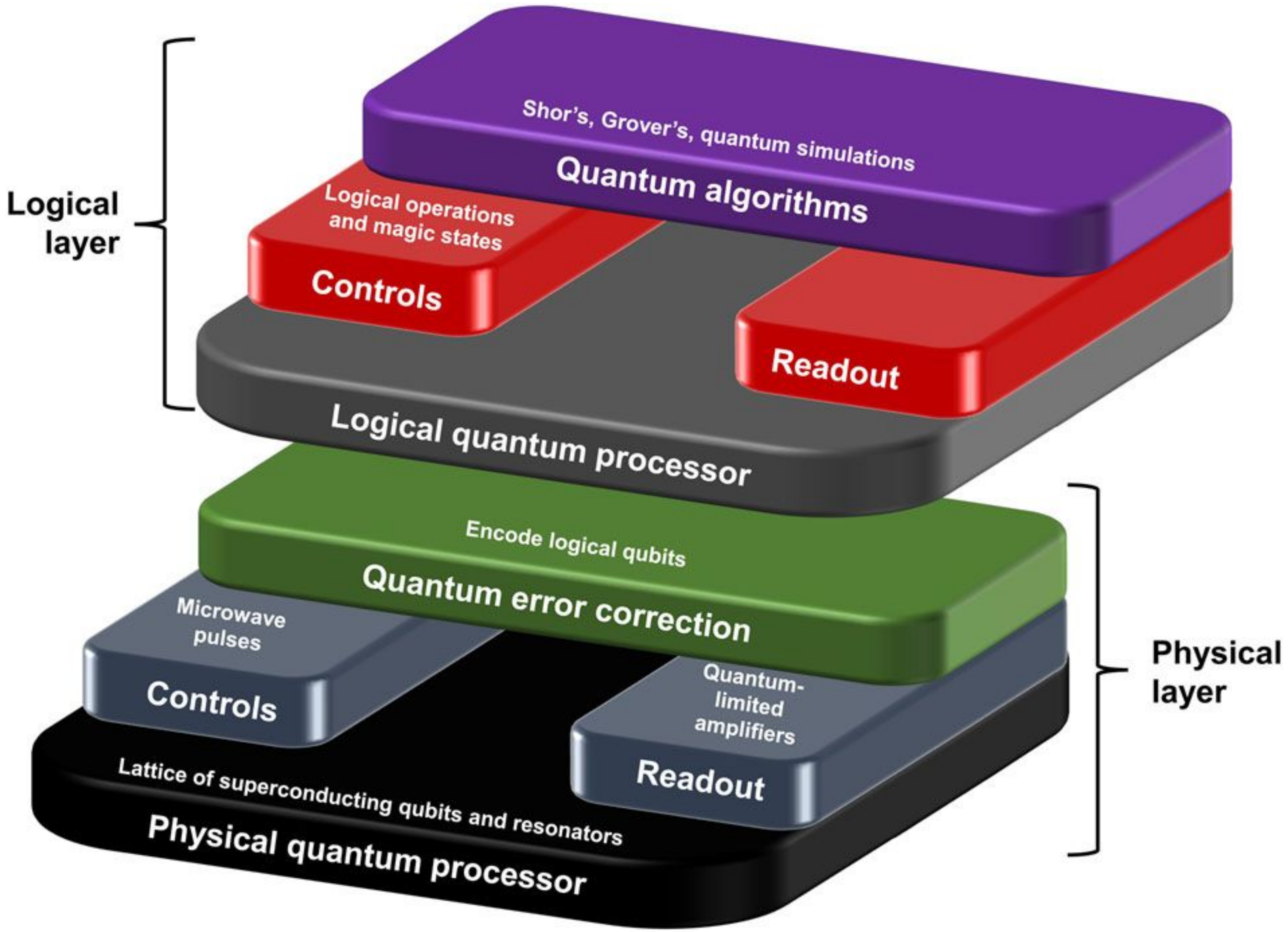
ФТИАН
имени К.А. Валиева

Experiments & Theory, Software

Quantum algorithms

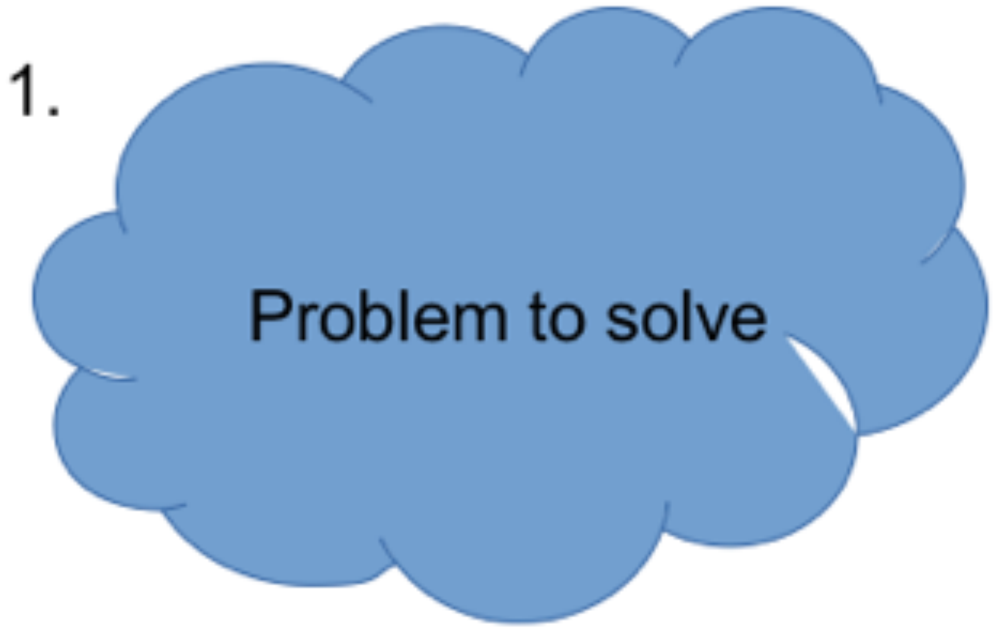
Quantum tomography

Quantum software



Quantum processors require compilers

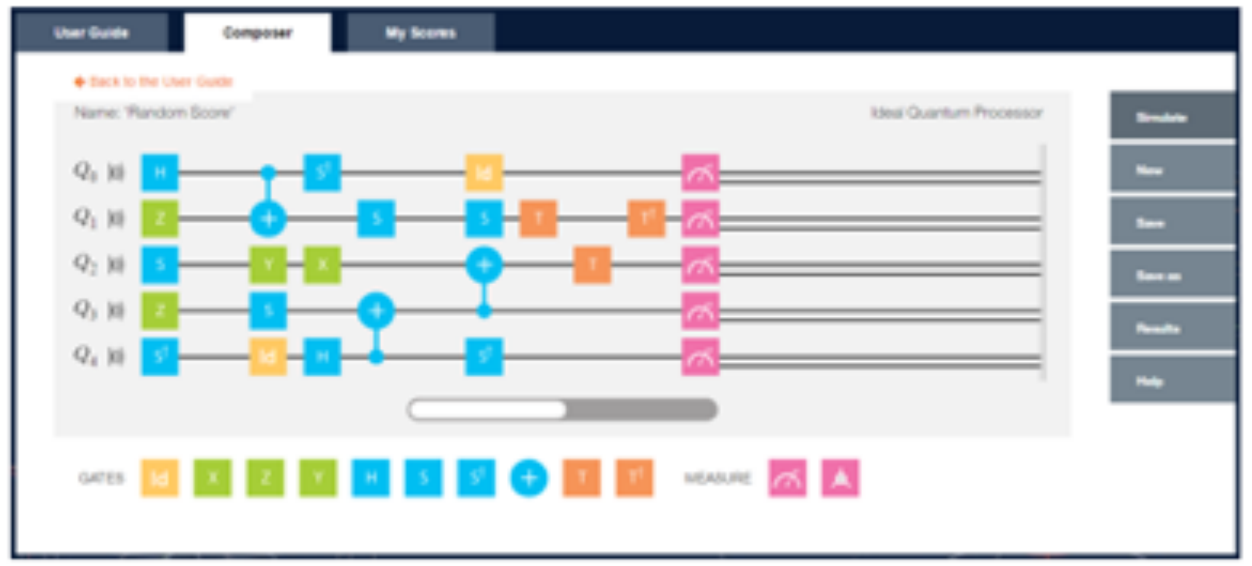
1.



* similar to compilation in classical computing (e.g. compile C++ code)

2.

Quantum circuit for idealized hardware

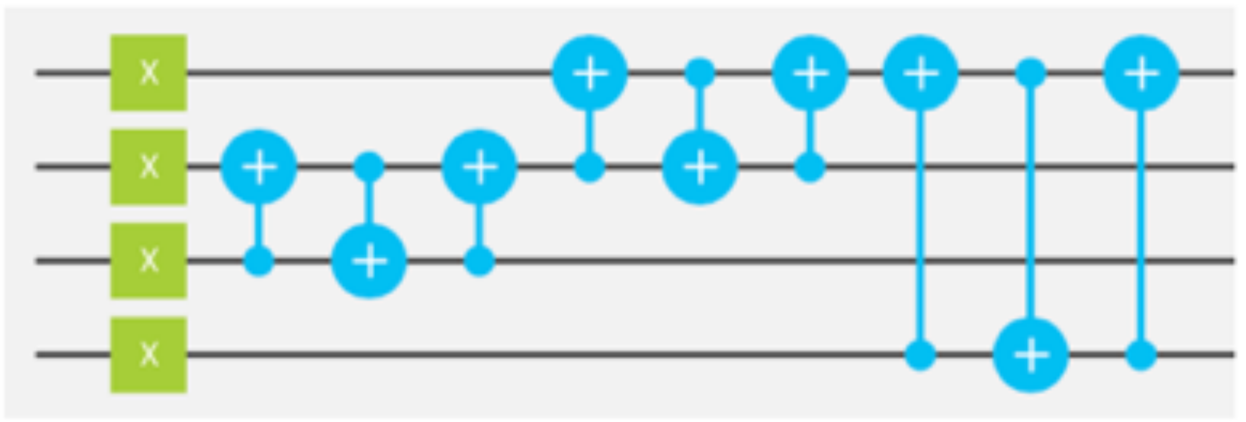


* example generated with Qiskit/QASM Editor/Composer to portray a quantum circuit for an ideal quantum processor

Compile

Quantum circuit for real hardware

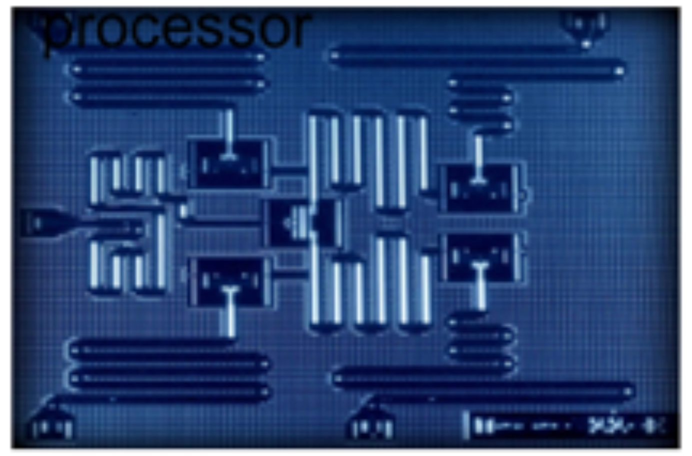
3.



* subject to hardware constraints
* adds additional gates (swap) to satisfy the hardware constraints

4.

Quantum processor



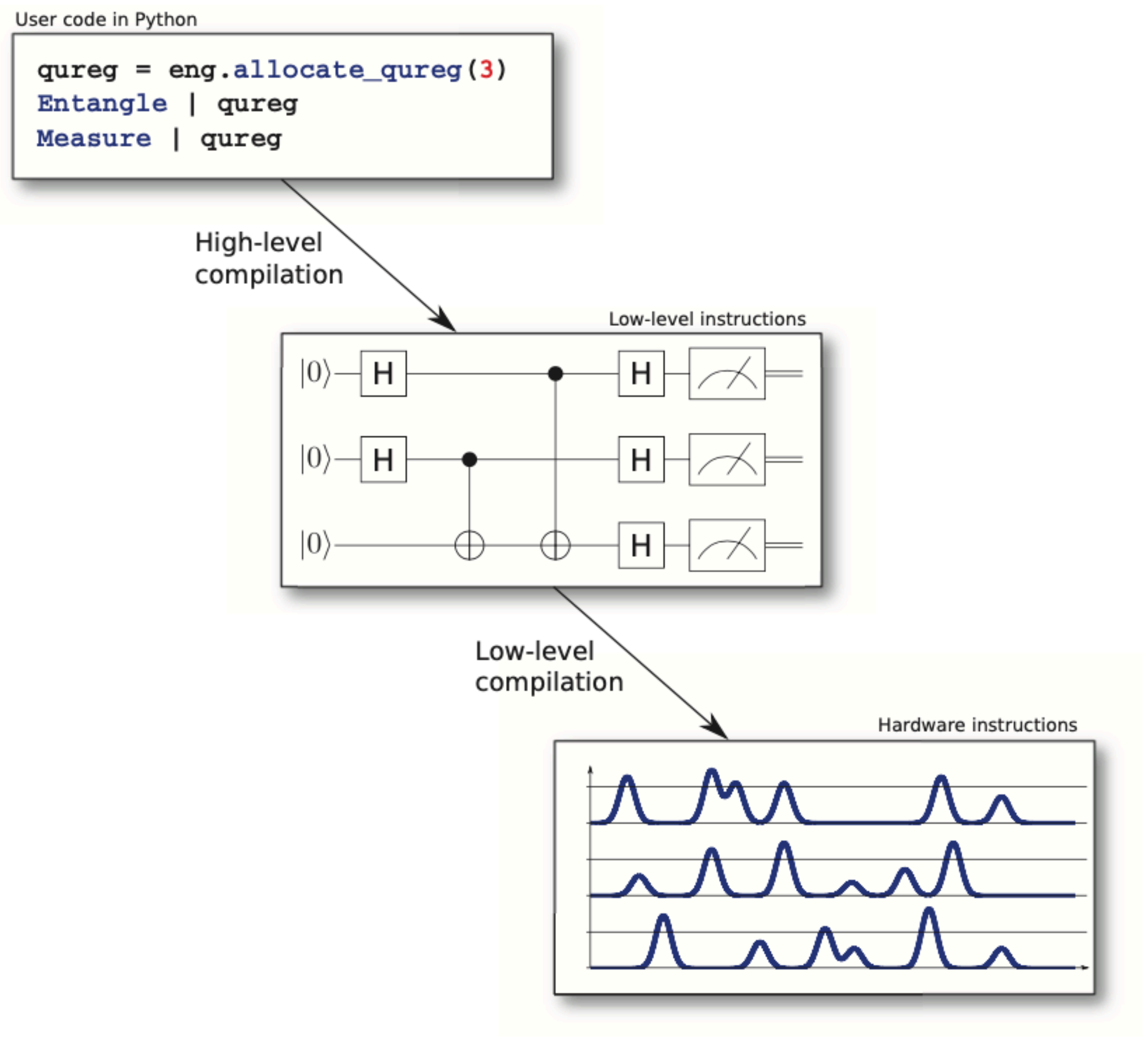
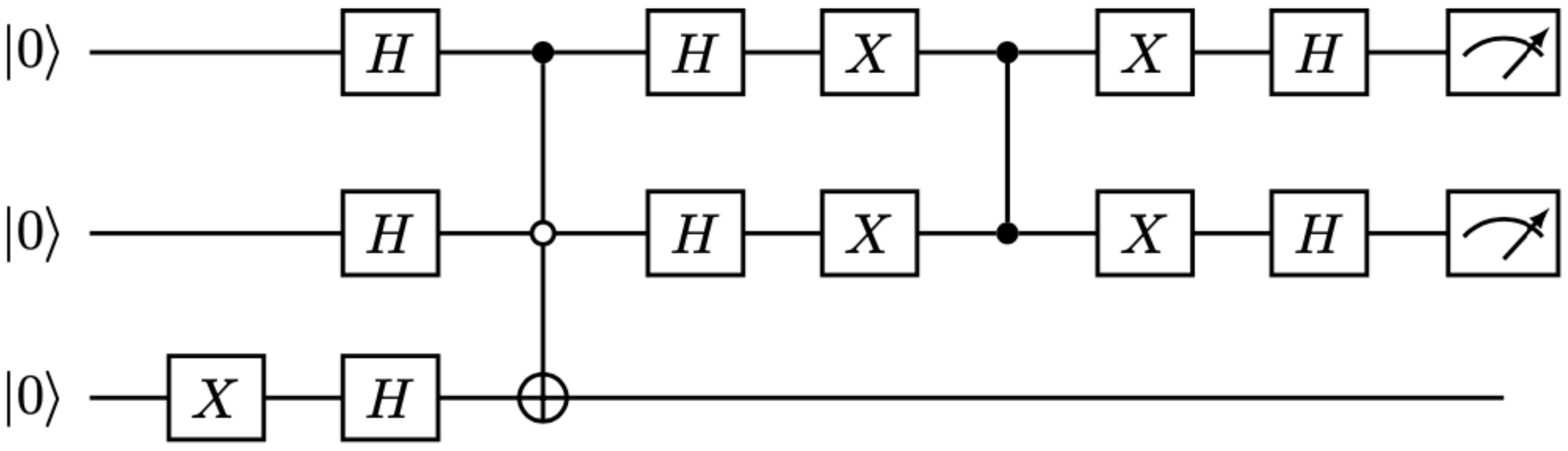


Figure 1: High-level picture of what a compiler does: It transforms the high-level user code to gate sequences satisfying the constraints dictated by the target hardware (supported gate set, connectivity, ...) while optimizing the circuit. The resulting low-level instructions are then translated to, e.g., pulse sequences.

Compiler optimization is important for saving quantum resources

Grover's algorithm

1. What we receive the quantum circuit from end-user:



Initialization of qubits

Pauli X-gate

$$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

Hadamard gate creates superposition

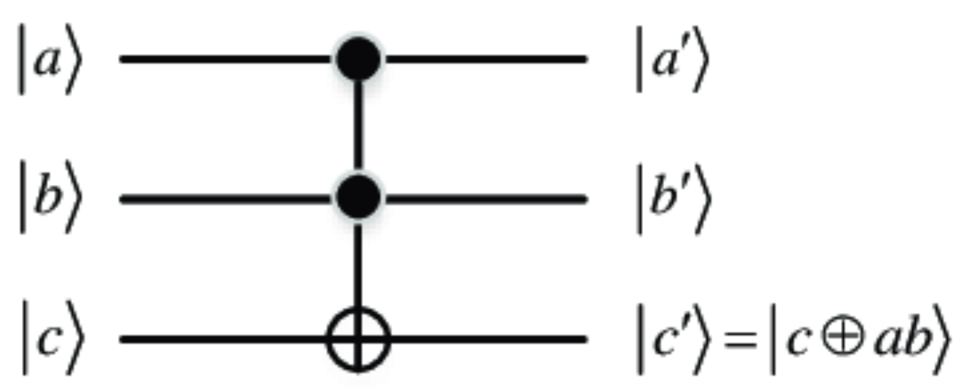
Multiqubit Toffoli gate

Measurements

Toffoli gate

Multiqubit Toffoli gate

Inputs a	b	c	Ouputs a'	b'	c'
0	0	0	0	0	0
0	0	1	0	0	1
0	1	0	0	1	0
0	1	1	0	1	1
1	0	0	1	0	0
1	0	1	1	0	1
1	1	0	1	1	1
1	1	1	1	1	0



How to factor 2048 bit RSA integers in 8 hours using 20 million noisy qubits

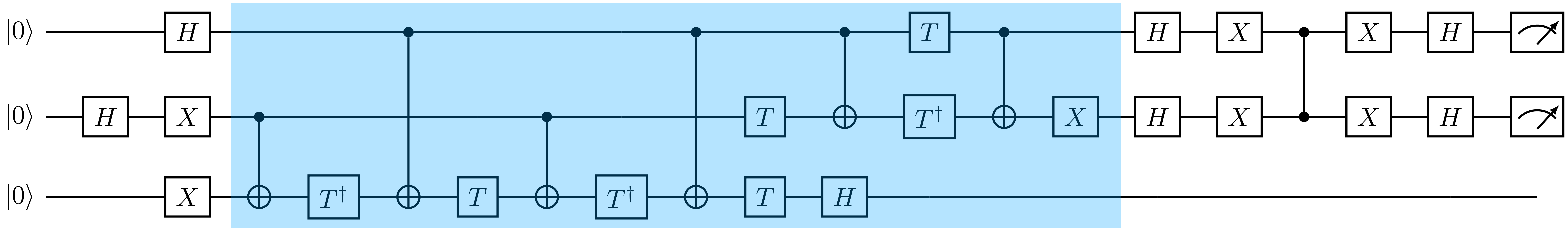
Craig Gidney[1,*] and Martin Ekerå[2]
[1] *Google Inc., Santa Barbara, California 93117, USA*
[2] *KTH Royal Institute of Technology, SE-100 44 Stockholm, Sweden*
Swedish NCSA, Swedish Armed Forces, SE-107 85 Stockholm, Sweden
(Dated: December 6, 2019)

We significantly reduce the cost of factoring integers and computing discrete logarithms in finite fields on a quantum computer by combining techniques from Shor 1994, Griffiths-Niu 1996, Zalka 2006, Fowler 2012, Ekerå-Håstad 2017, Ekerå 2017, Ekerå 2018, Gidney-Fowler 2019, Gidney 2019. We estimate the approximate cost of our construction using plausible physical assumptions for large-scale superconducting qubit platforms: a planar grid of qubits with nearest-neighbor connectivity, a characteristic physical gate error rate of 10^{-3}, a surface code cycle time of 1 microsecond, and a reaction time of 10 microseconds. We account for factors that are normally ignored such as noise, the need to make repeated attempts, and the spacetime layout of the computation. When factoring 2048 bit RSA integers, our construction's spacetime volume is a hundredfold less than comparable estimates from earlier works (Fowler et al. 2012, Gheorghiu et al. 2019). In the abstract circuit model (which ignores overheads from distillation, routing, and error correction) our construction uses $3n + 0.002n \lg n$ logical qubits, $0.3n^3 + 0.0005n^3 \lg n$ Toffolis, and $500n^2 + n^2 \lg n$ measurement depth to factor n-bit RSA integers. We quantify the cryptographic implications of our work, both for RSA and for schemes based on the DLP in finite fields.

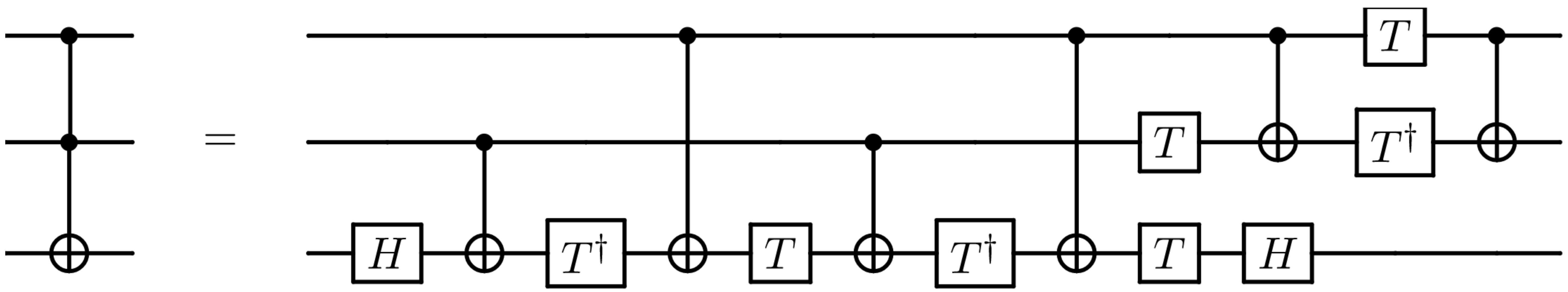
Problem: Decomposition of multiqubit gates on the set of single-qubit and two-qubit gates

Grover's algorithm

2. What we can do on the hardware-agnostic level:



Standard decomposition of the Toffoli gate: 6 CNOTs.

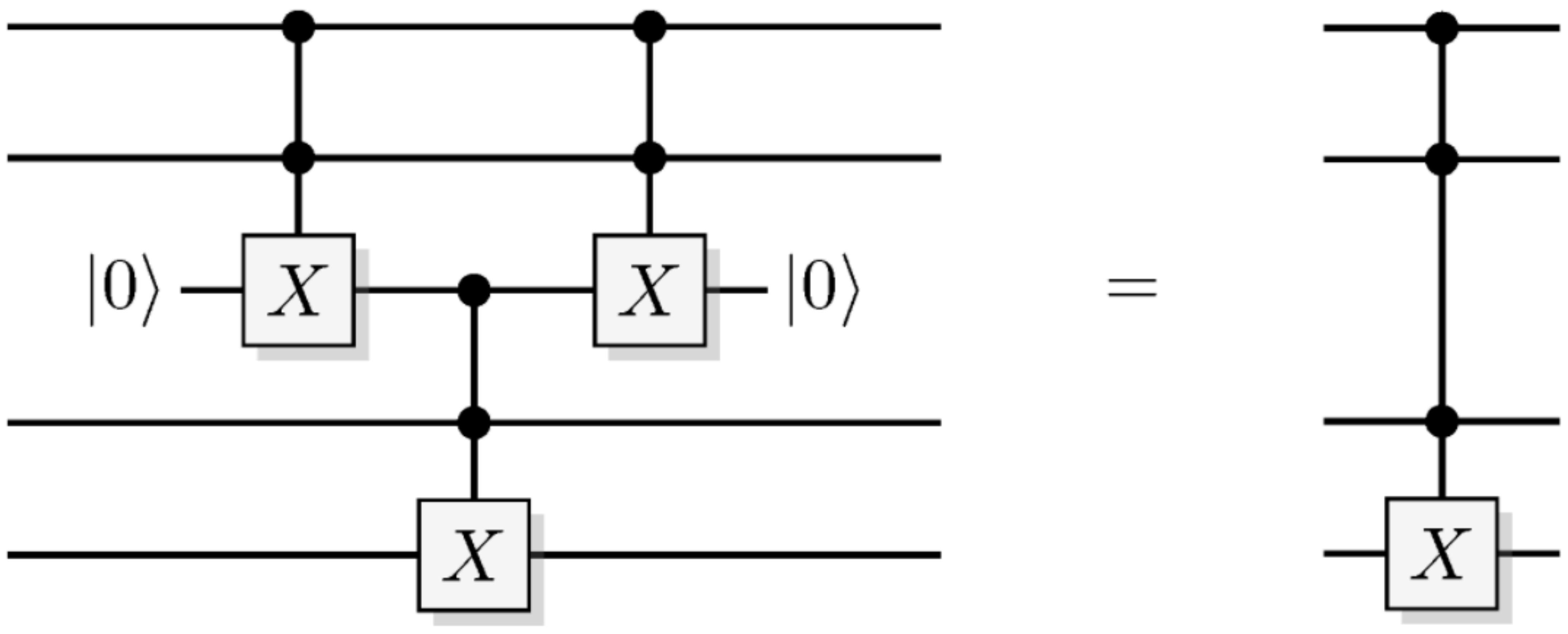


What about n-qubit Toffoli gates?

Ancilla qubits

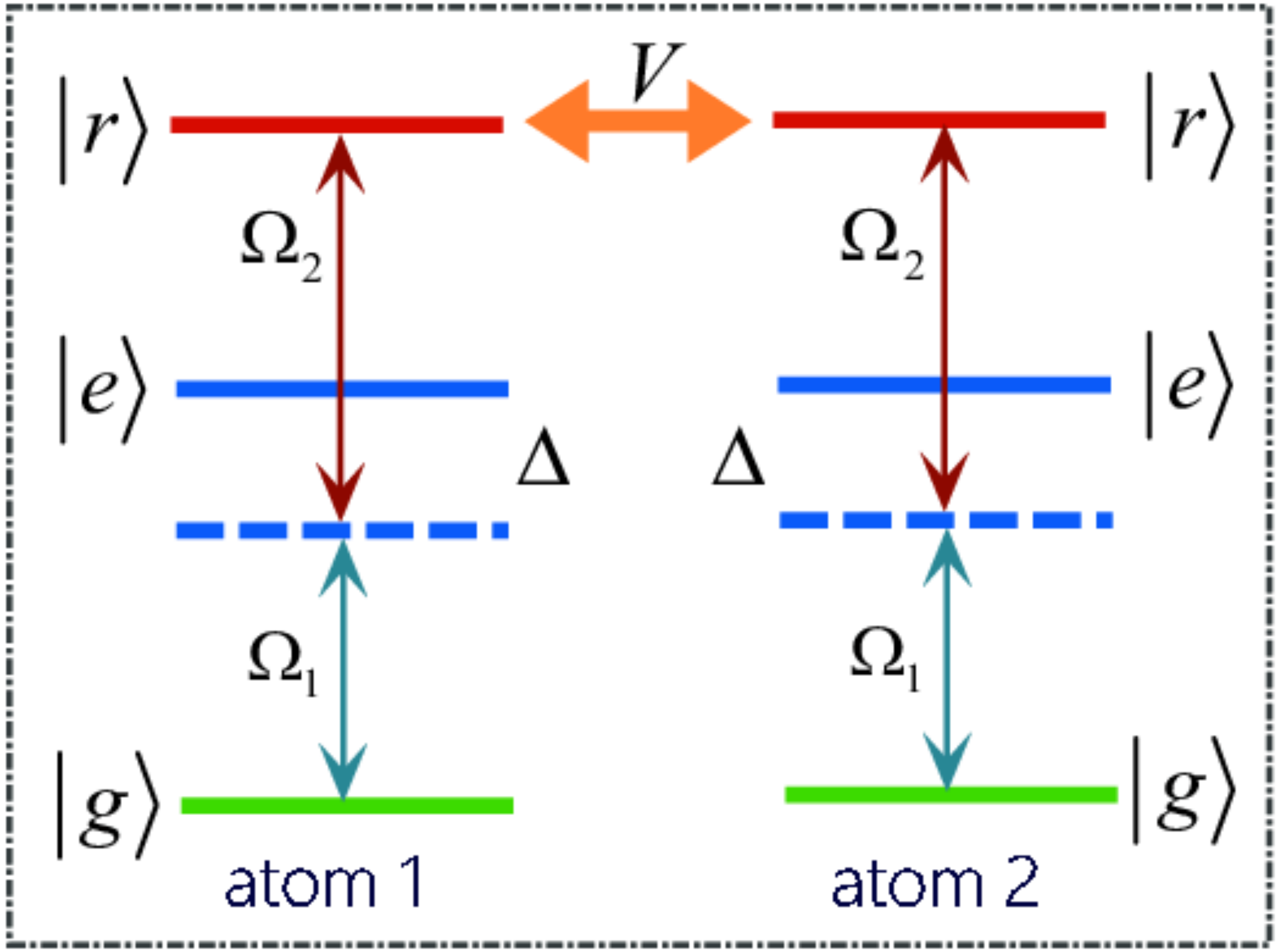
The decomposition of an n-qubit Toffoli can be achieved using Toffoli gates and clean ancilla qubits

«Clean ancilla»



Realistic quantum systems have more than two levels

Example: Quantum information processing with Rydberg atoms



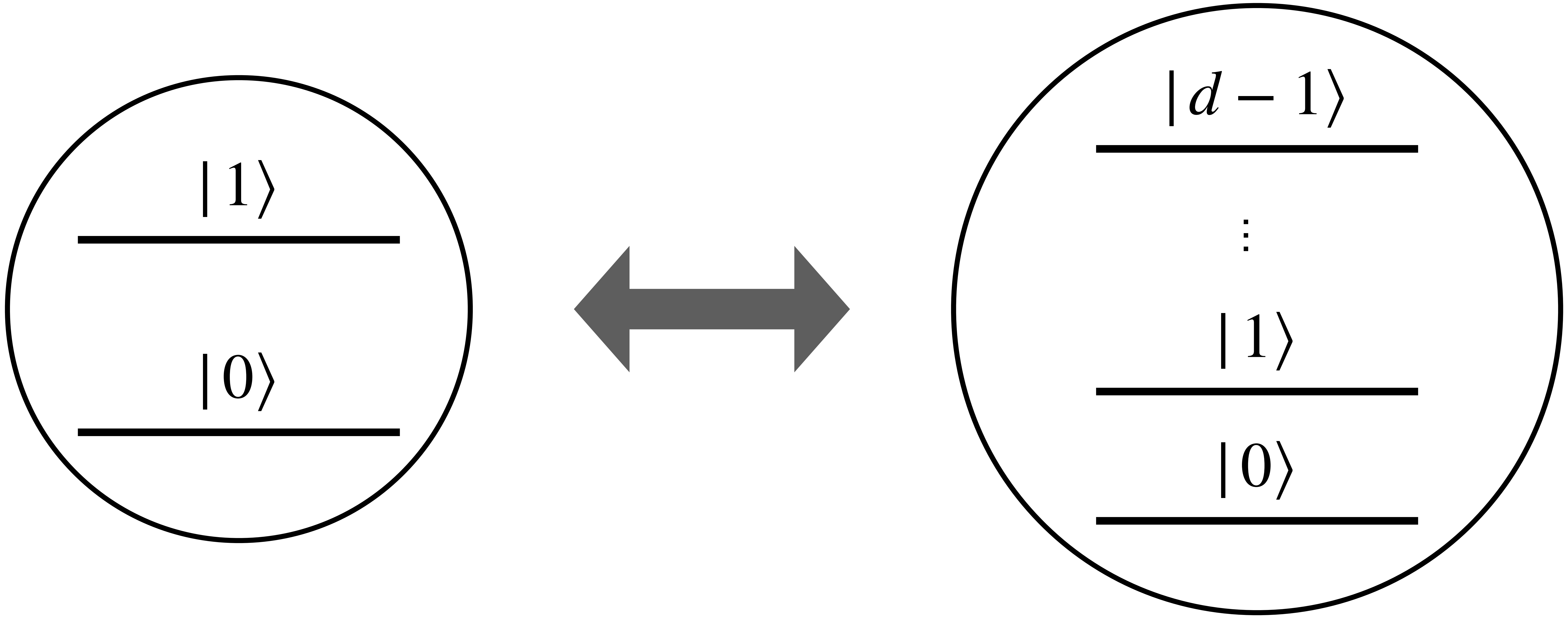
- Hydrogen-like atom
- High principal *(n)* quantum number
- Large dipole-dipole interaction between Rydberg atoms

$$V = \frac{\mu_1 \cdot \mu_2 - 3(\mu_1 \cdot \hat{R})(\mu_2 \cdot \hat{R})}{R^3}$$

$$\mu \propto n^2$$

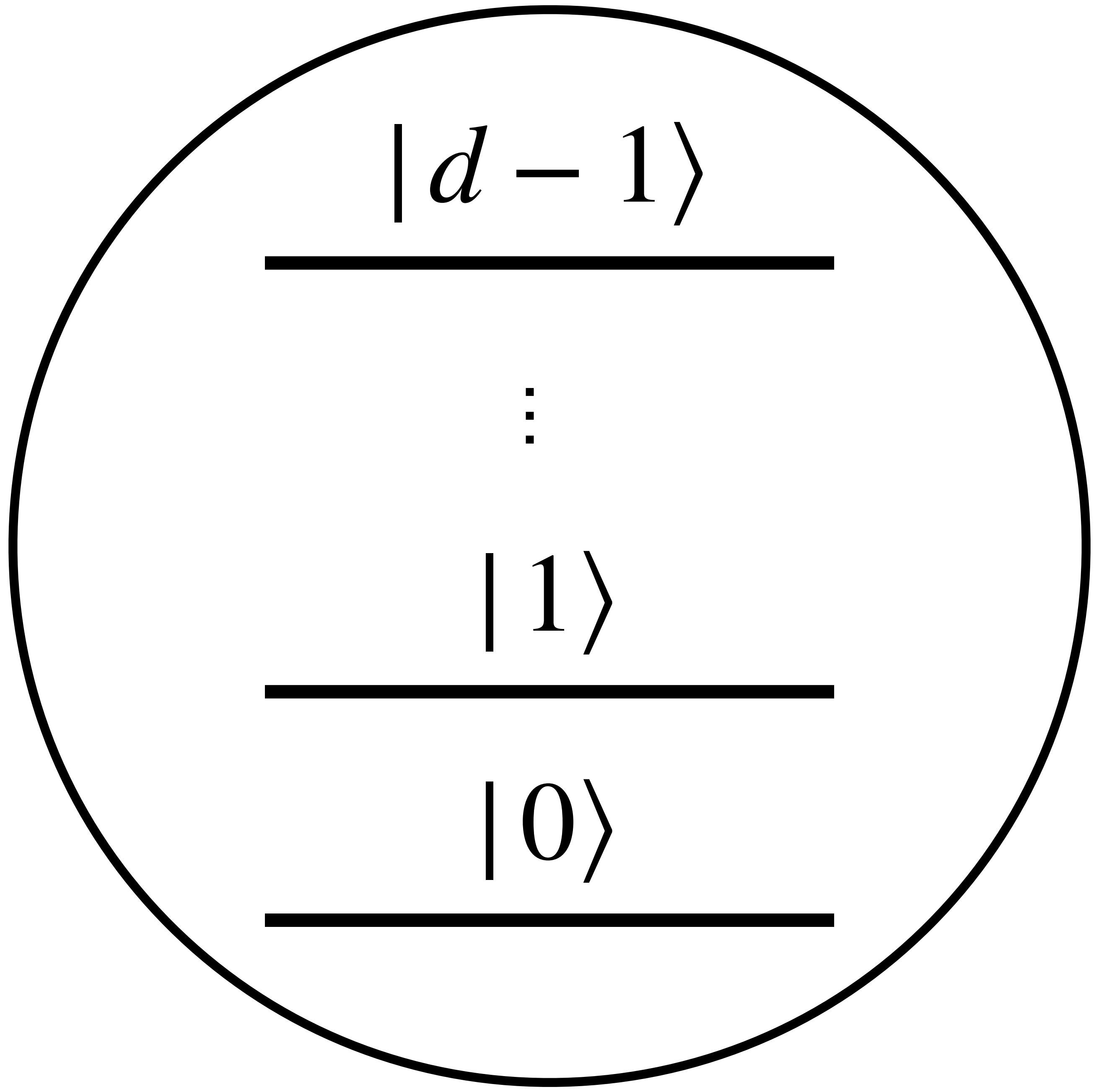
- Dipole blockade

From qubits to qudits



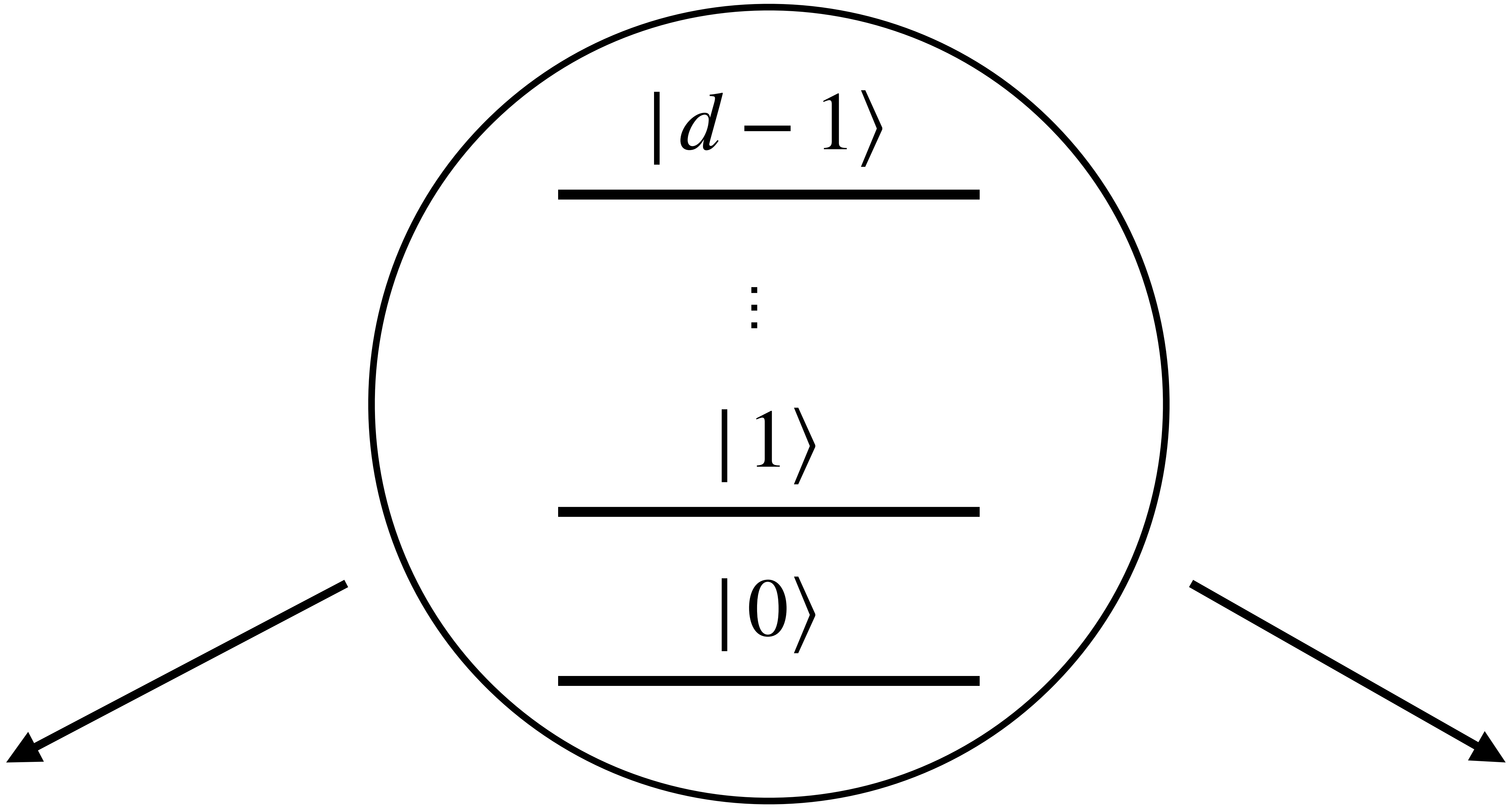
For a review, see M. Erhard, R. Fickler, M. Krenn, and A. Zeilinger, Twisted photons: New quantum perspectives in high dimensions, Light: Sci. Appl. 7, 17146 (2018); Many works: X. Wang, B.C. Sanders, and D. W. Berry, Entangling power and operator entanglement in qudit systems, Phys. Rev. A 67, 042323 (2003); A. B. Klimov, R. Guzmán, J.C. Retamal, and C. Saavedra, Qutrit quantum computer with trapped ions, Phys. Rev. A 67, 062313 (2003); T. C. Ralph, K. J. Resch, and A. Gilchrist, Efficient Toffoli gates using qudits, Phys. Rev. A 75, 022313 (2007); S. S. Ivanov, H. S. Tonchev, and N. V. Vitanov, Time-efficient implementation of quantum search with qudits, Phys. Rev. A 85, 062321 (2012) and many other theoretical and experimental works.

From qubits to qudits



Is it possible to make more efficient implementation of quantum algorithms with qudits?
Is it possible to reduce the number of two-qubit operations?
Is it possible to increase the total fidelity?

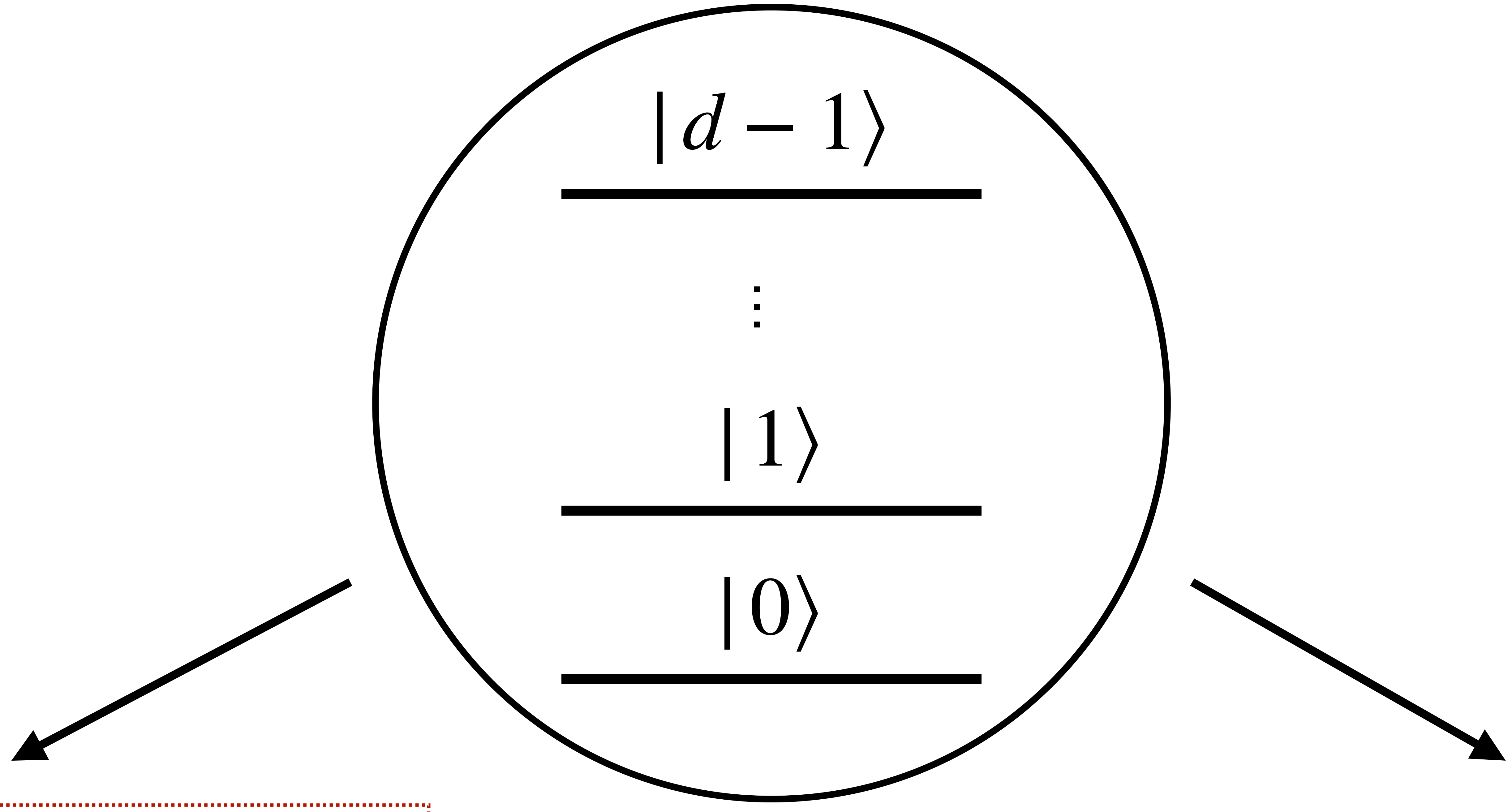
From qubits to qudits



Approach #1.
High-dimensional quantum systems can be decomposed on a set of qubits

Approach #2.
Additional levels can be used instead of ancilla qubits

From qubits to qudits



Approach #1.
High-dimensional quantum systems can be decomposed on a set of qubits

Approach #2.
Additional levels can be used instead of ancilla qubits

Decomposition of qubits to qudits

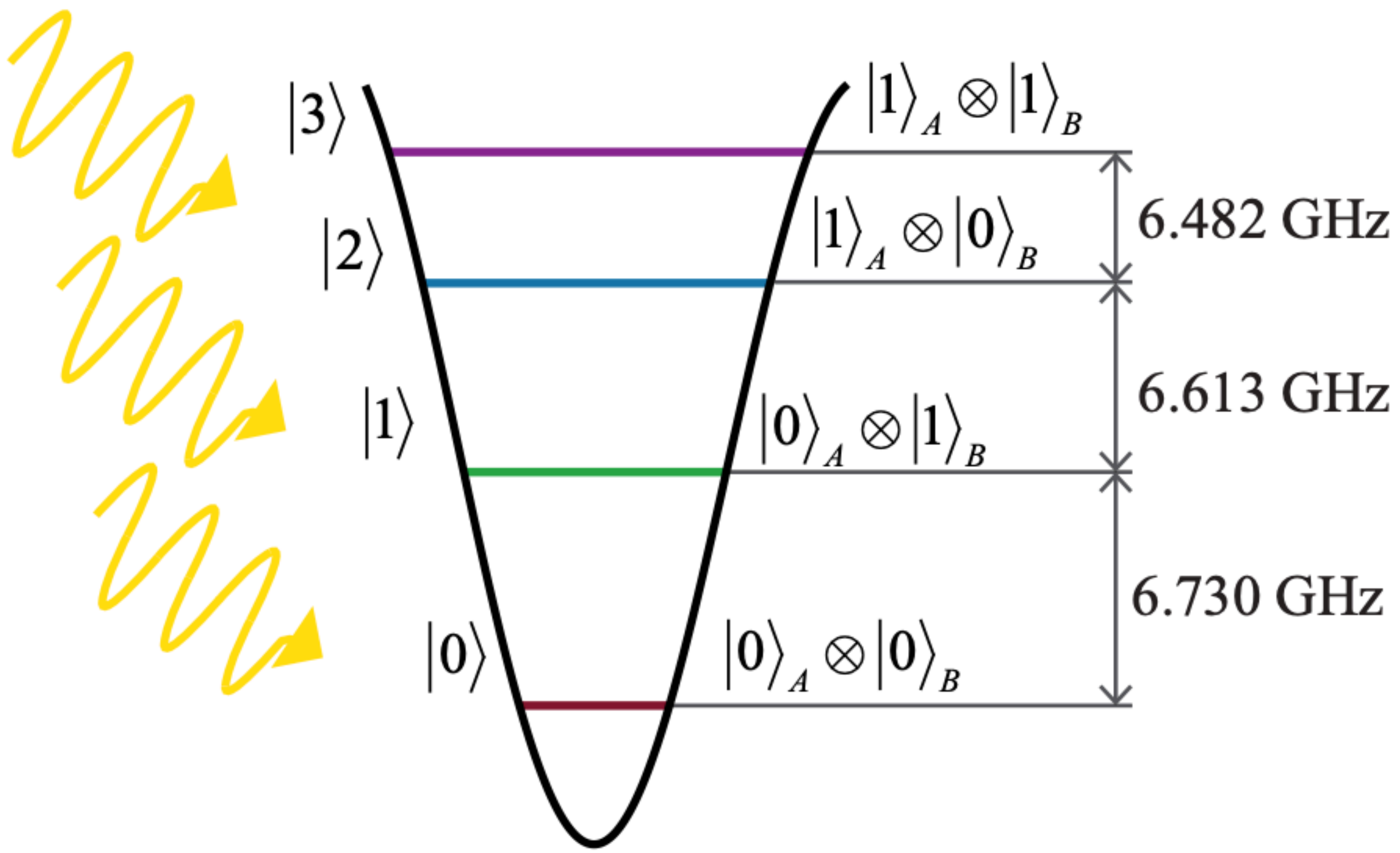
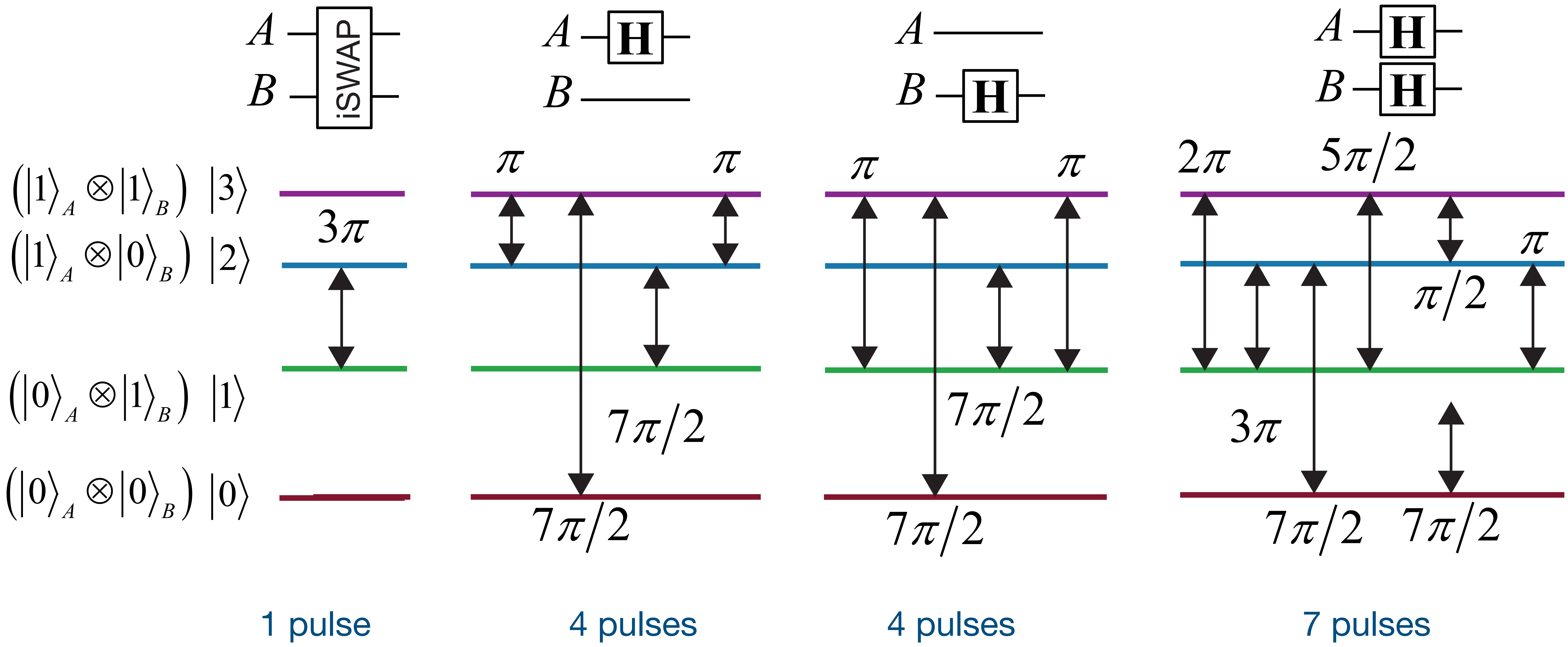


FIG. 1. Isomorphic correspondence between a qudit state with d=4 and a two-qubit system. Transition frequencies between levels correspond to the multilevel superconducting circuit investigated in Ref. [61].

E. Svetitsky, H. Suchowski, R. Resh, Y. Shalibo, J.M. Martinis, and N. Katz, Nat. Comm. 5, 5617 (2014)

Realization of gates with ‘virtual’ qubits

Single-qubit and two-qubit quantum gates are realizable, e.g. universal gate set

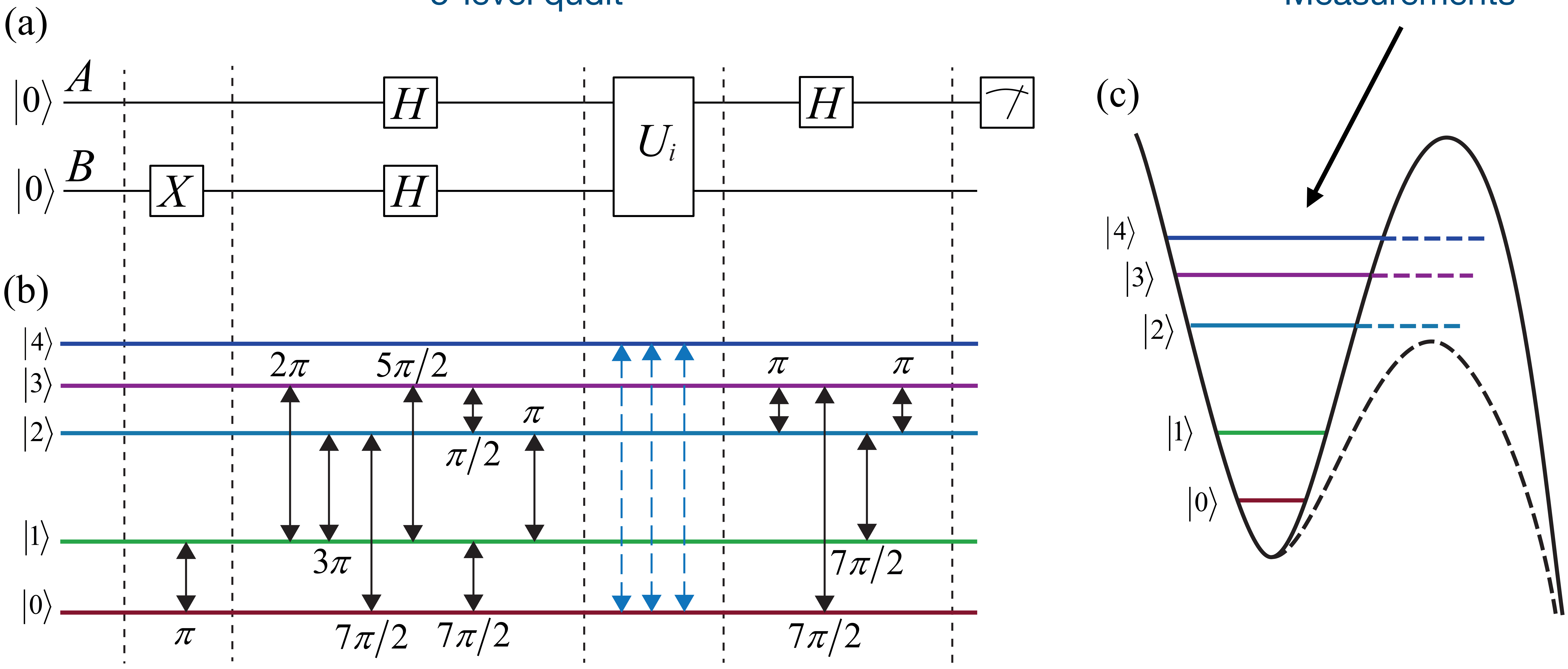


E.O. Kiktenko, A.K. Fedorov, O.V. Man’ko, V.I. Man’ko, Phys. Rev. A 91, 042312 (2015).

Deutsch algorithm using single qudit

5-level qudit

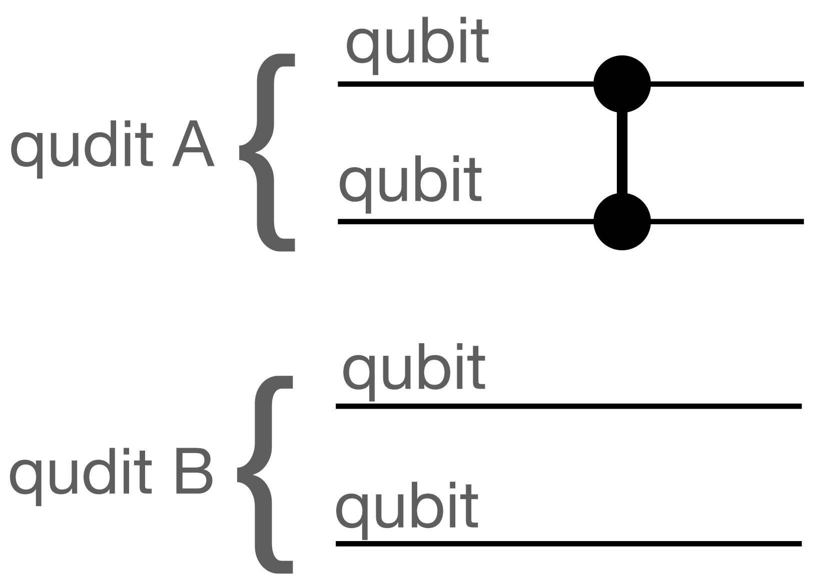
Measurements



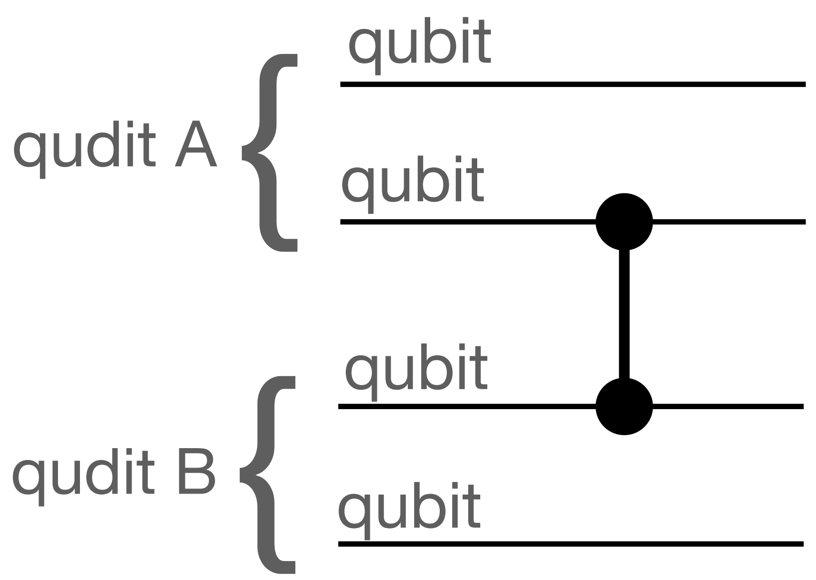
E.O. Kiktenko, A.K. Fedorov, A.A. Strakhov, V.I. Man'ko, Phys. Lett. A 379, 1409 (2015).

Scalability of the qudit approach: Two-qudit example with CZ

$$|11\rangle \rightarrow -|11\rangle$$
$$|xy\rangle \rightarrow |xy\rangle \text{ for } xy \neq 1$$

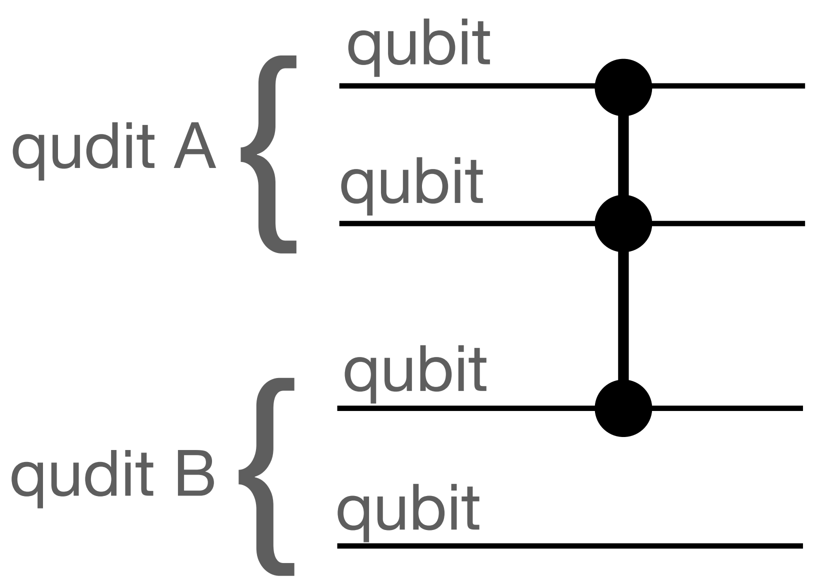


0 two-quidit operations
VS
1 two-qubit operation



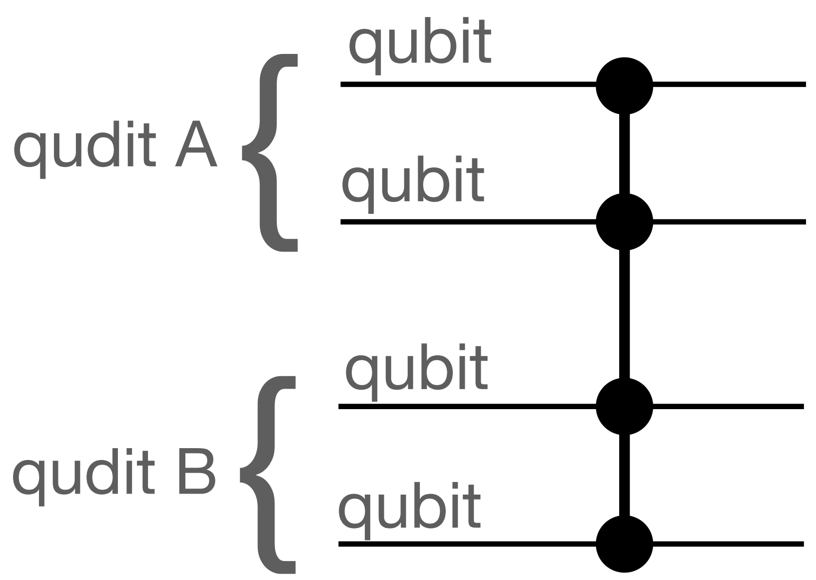
$$|01\rangle_A|10\rangle_B \rightarrow -|01\rangle_A|10\rangle_B$$
$$|01\rangle_A|11\rangle_B \rightarrow -|01\rangle_A|11\rangle_B$$
$$|11\rangle_A|10\rangle_B \rightarrow -|11\rangle_A|10\rangle_B$$
$$|11\rangle_A|11\rangle_B \rightarrow -|11\rangle_A|11\rangle_B$$

4 two-quidit operations
VS
1 two-qubit operation



$$|11\rangle_A|10\rangle_B \rightarrow -|11\rangle_A|10\rangle_B$$
$$|11\rangle_A|11\rangle_B \rightarrow -|11\rangle_A|11\rangle_B$$

2 two-quidit operations
VS
6 two-qubit operations

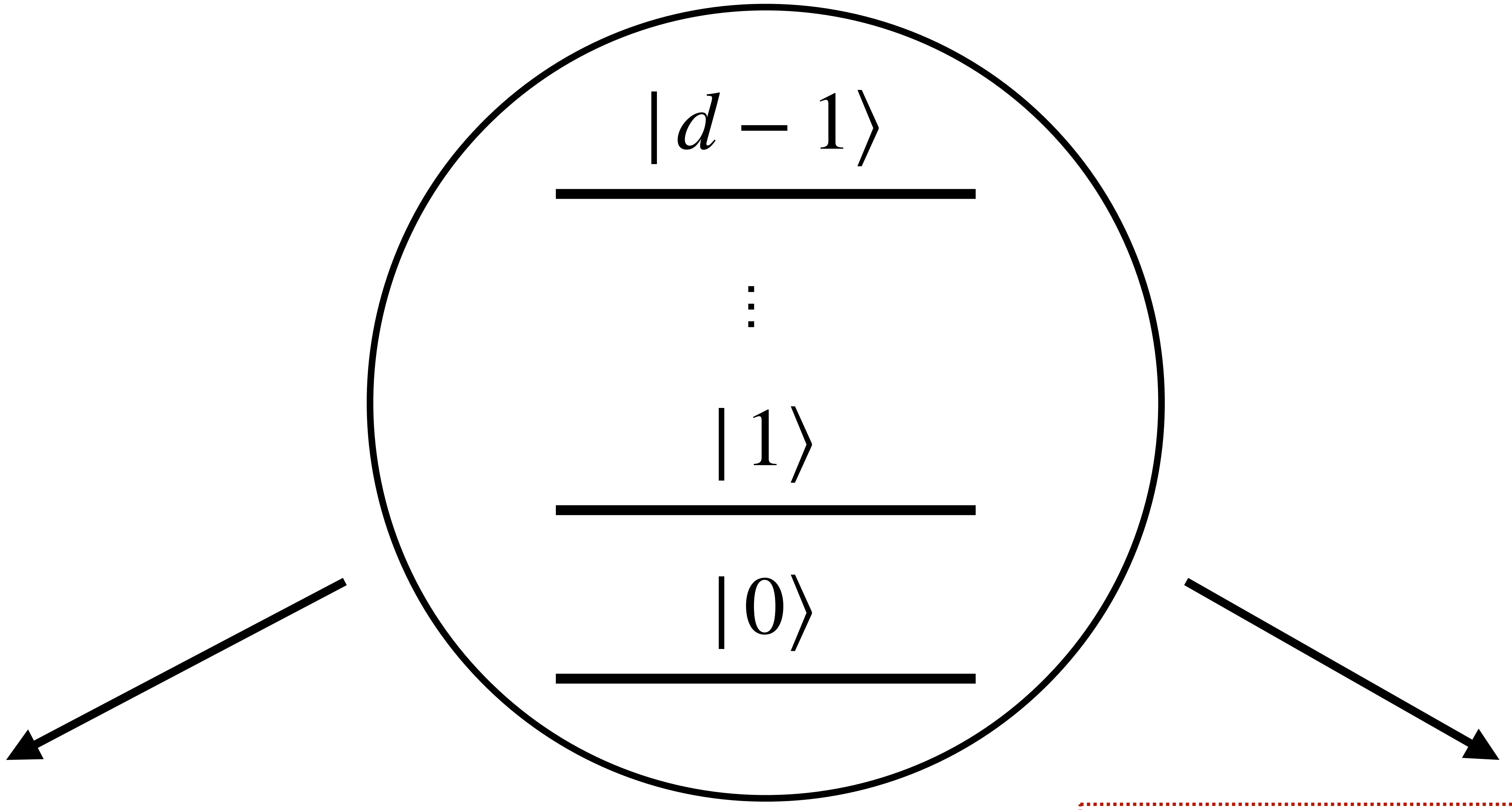


$$|11\rangle_A|11\rangle_B \rightarrow -|11\rangle_A|11\rangle_B$$

1 two-quidit operation
VS
26 two-qubit operation

The number of two-particle operations can be reduced significantly! But not always…

From qubits to qudits

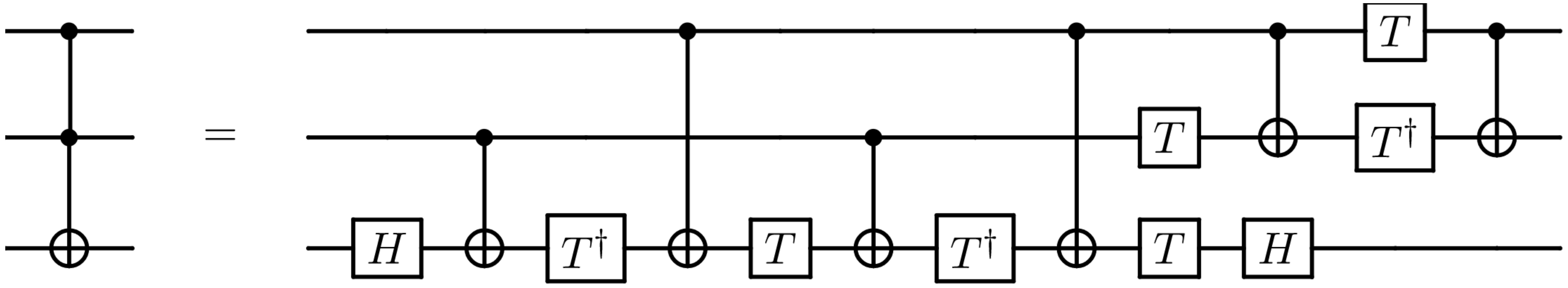


Approach #1.
High-dimensional quantum systems can be decomposed on a set of qubits

Approach #2.
Additional levels can be used instead of ancilla qubits

Ancilla qubits

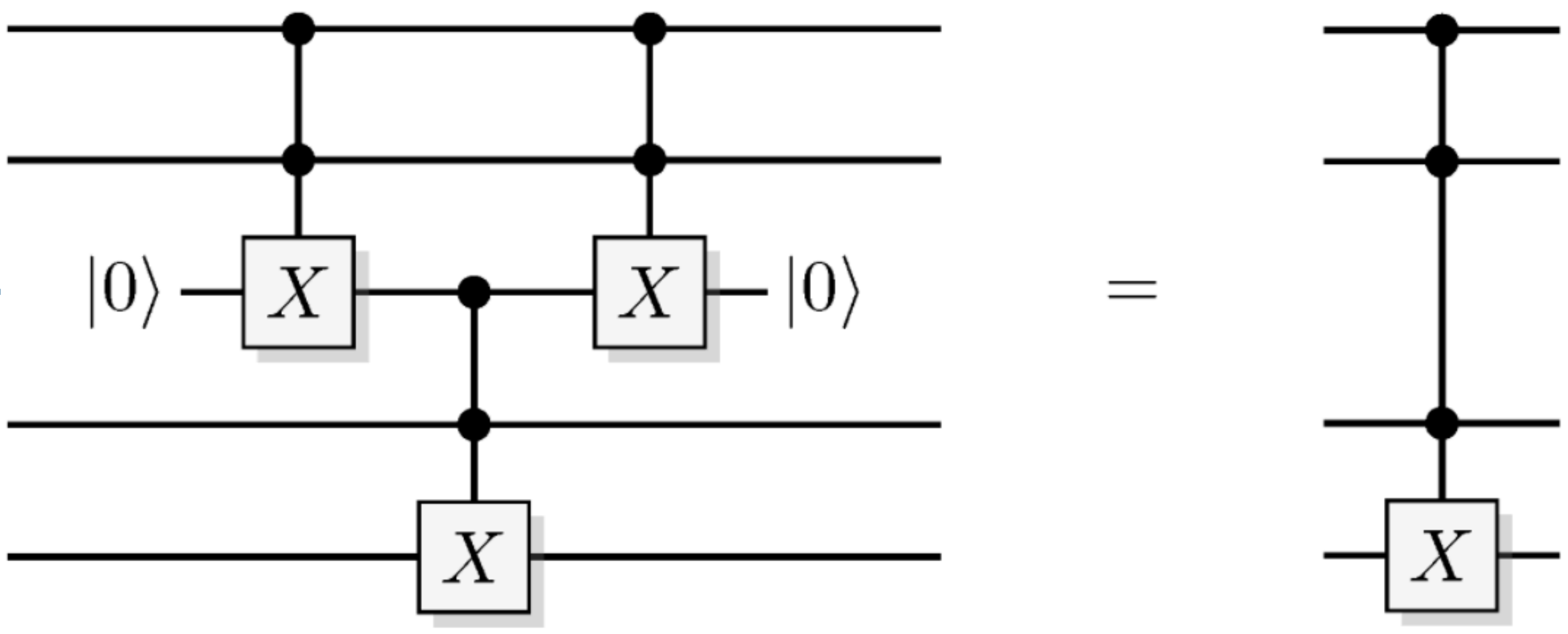
Standard way for the decomposition of multiqubit gates. Toffoli gate:



$$T = \begin{bmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{bmatrix}$$

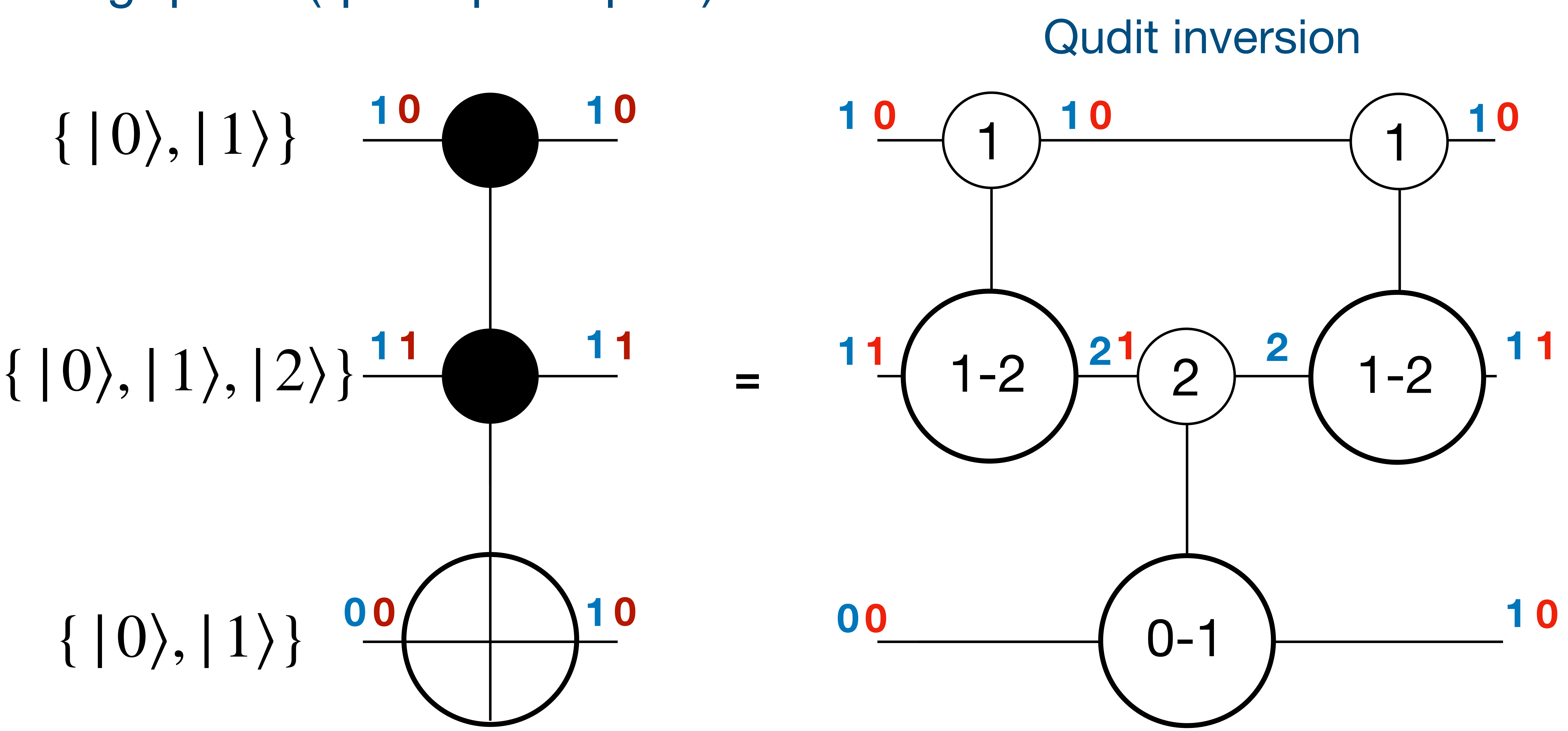
The decomposition of an n-qubit Toffoli can be achieved using Toffoli gates and clean ancilla qubits

«Clean ancilla»



From additional qubits to additional levels

Toffoli gate using qudits (qubit-qutrit-qubit):



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Realization of efficient quantum gates with a superconducting qubit-qutrit circuit

Received: 15 January 2019
Accepted: 8 August 2019
Published online: 16 September 2019

T. Bækkegaard[1], L. B. Kristensen[1], N. J. S. Loft[1], C. K. Andersen[2], D. Petrosyan[3] & N. T. Zinner[1,4]

Building a quantum computer is a daunting challenge since it requires good control but also good isolation from the environment to minimize decoherence. It is therefore important to realize quantum gates efficiently, using as few operations as possible, to reduce the amount of required control and operation time and thus improve the quantum state coherence. Here we propose a superconducting circuit for implementing a tunable system consisting of a qutrit coupled to two qubits. This system can efficiently accomplish various quantum information tasks, including generation of entanglement of the two qubits and conditional three-qubit quantum gates, such as the Toffoli and Fredkin gates. Furthermore, the system realizes a conditional geometric gate which may be used for holonomic (non-adiabatic) quantum computing. The efficiency, robustness and universality of the presented circuit makes it a promising candidate to serve as a building block for larger networks capable of performing involved quantum computational tasks.

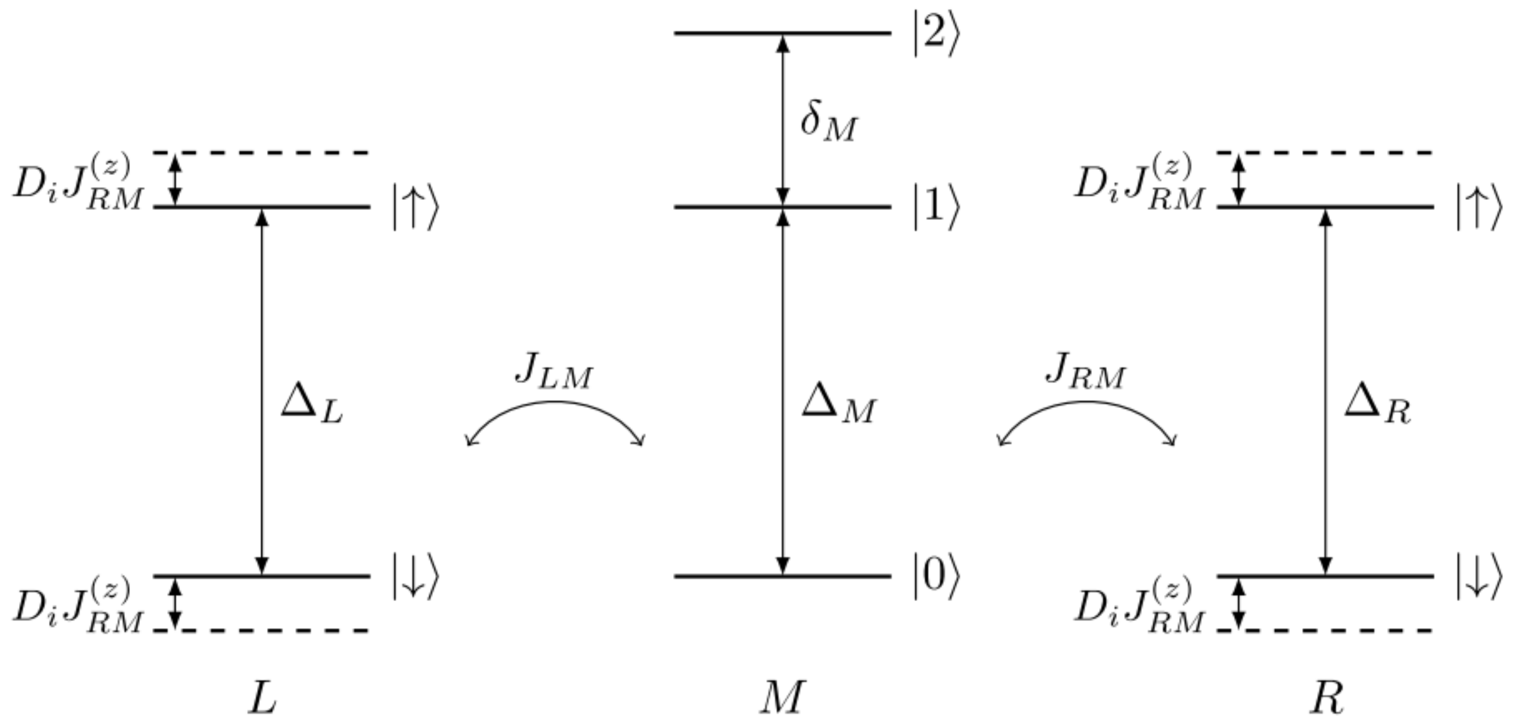


Figure 2. Energy diagram of the system of two qubits (left, L, and right, R) and a qutrit (middle, M) described by the Hamiltonian in Equation (1). Also shown are the exchange couplings $J_{\alpha M}$ and state-dependent energy shifts $J_{\alpha M}^{(z)}$ of (1). D_i depend on the state of the qutrit $|i\rangle$, with, $D_0 = 0$, and typically, $D_1 \gtrsim 2$ and $D_2 \lesssim 4$.

LETTER

doi:10.1038/nature10713

Implementation of a Toffoli gate with superconducting circuits

A. Fedorov[1], L. Steffen[1], M. Baur[1], M. P. da Silva[2,3] & A. Wallraff[1]

coherence. Here we implement a Toffoli gate with three superconducting transmon qubits coupled to a microwave resonator. By exploiting the third energy level of the transmon qubits, we have significantly reduced the number of elementary gates needed for the implementation of the Toffoli gate, relative to that required in theoretical proposals using only two-level systems.

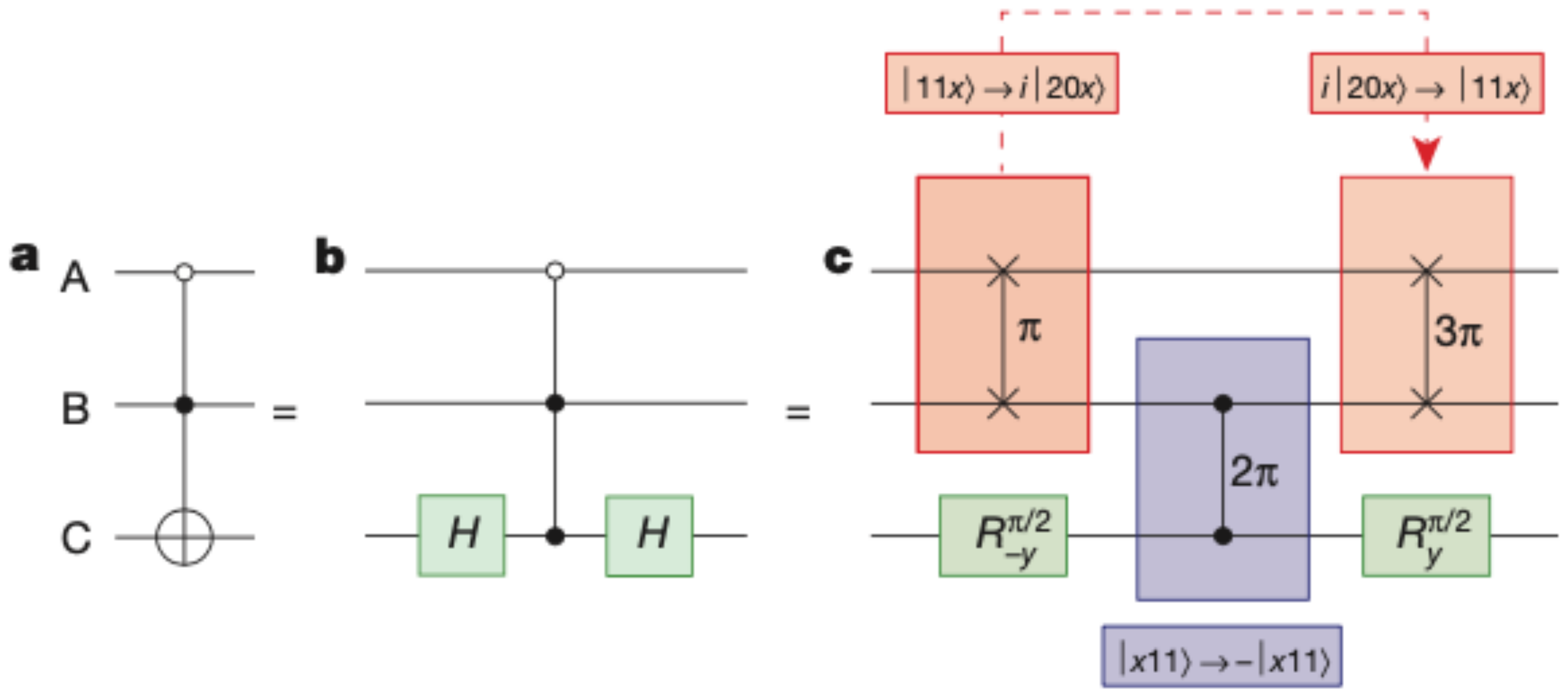
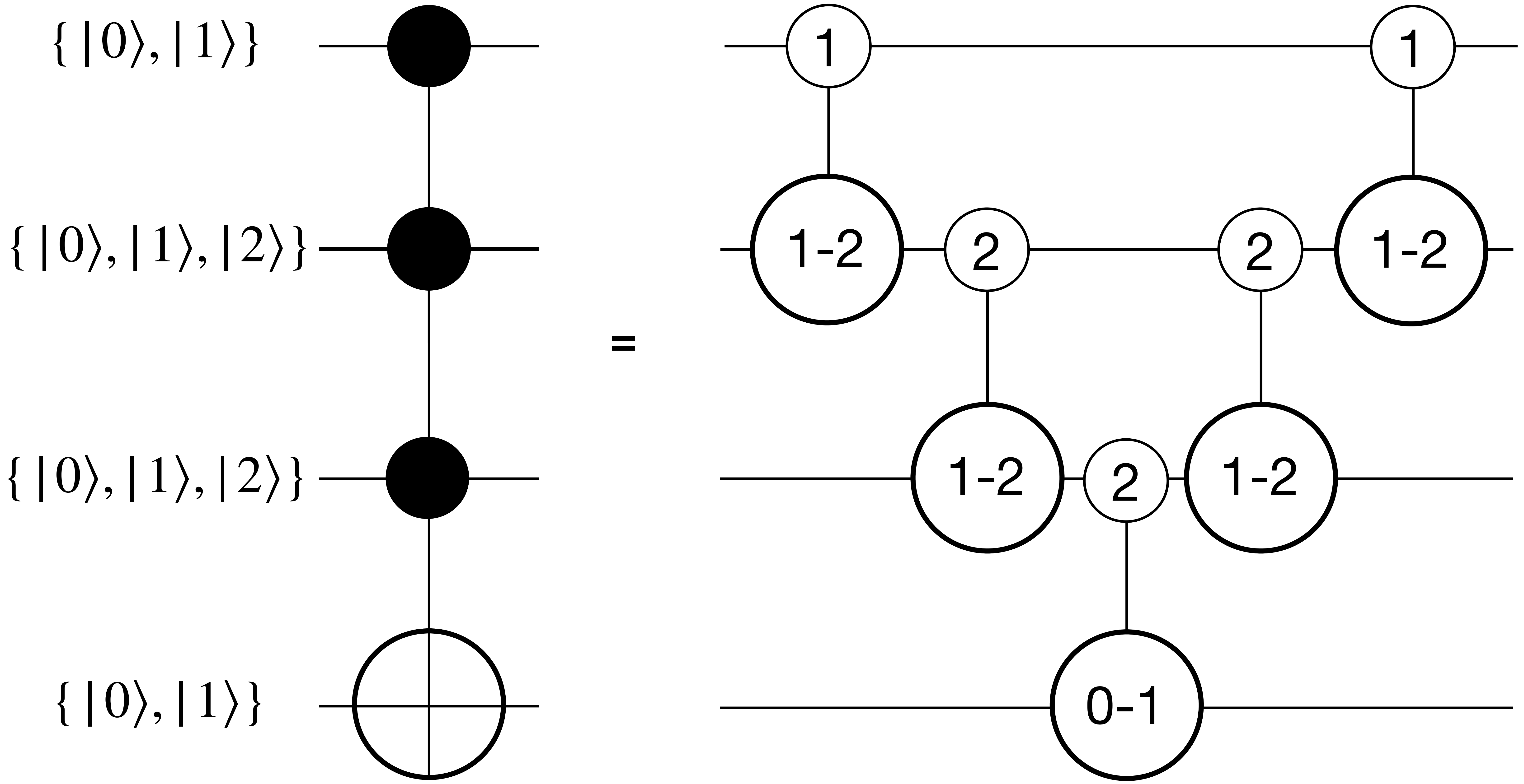


FIG. 1. **Circuit diagram of the Toffoli gate. a,** A NOT-operation (⊕) is applied to qubit C if the control qubits (A and B) are in the ground (○) and excited state (●) respectively. **b,** The Toffoli gate can be decomposed into a CCPHASE gate sandwiched between Hadamard gates (**H**) applied to qubit C. **c,** The CCPHASE gate is implemented as a sequence of a qubit-qutrit gate, a two-qubit gate and a second qubit-qutrit gate. Each of these gates is realized by tuning the $|11\rangle$ state into resonance with $|20\rangle$ for a $\{\pi, 2\pi, 3\pi\}$ coherent rotation respectively. For the Toffoli gate, the Hadamard gates are replaced with $\pm\pi/2$ rotations about the y axis (represented by $R_{\pm y}^{\pi/2}$). **d,** Pulse sequence used for the implementation of the Toffoli gate. During the preparation (I), resonant microwave pulses are applied to the qubits on the corresponding gate lines. The Toffoli gate (II) is implemented with three flux pulses and resonant microwave pulses (colour coded as in **c**). The measurement (III) consists of microwave pulses that turn the qubit states to the desired measurement axis, and a subsequent microwave pulse applied to the resonator is used to perform a joint dispersive read-out.

Generalization: 4-qubit Toffoli gate

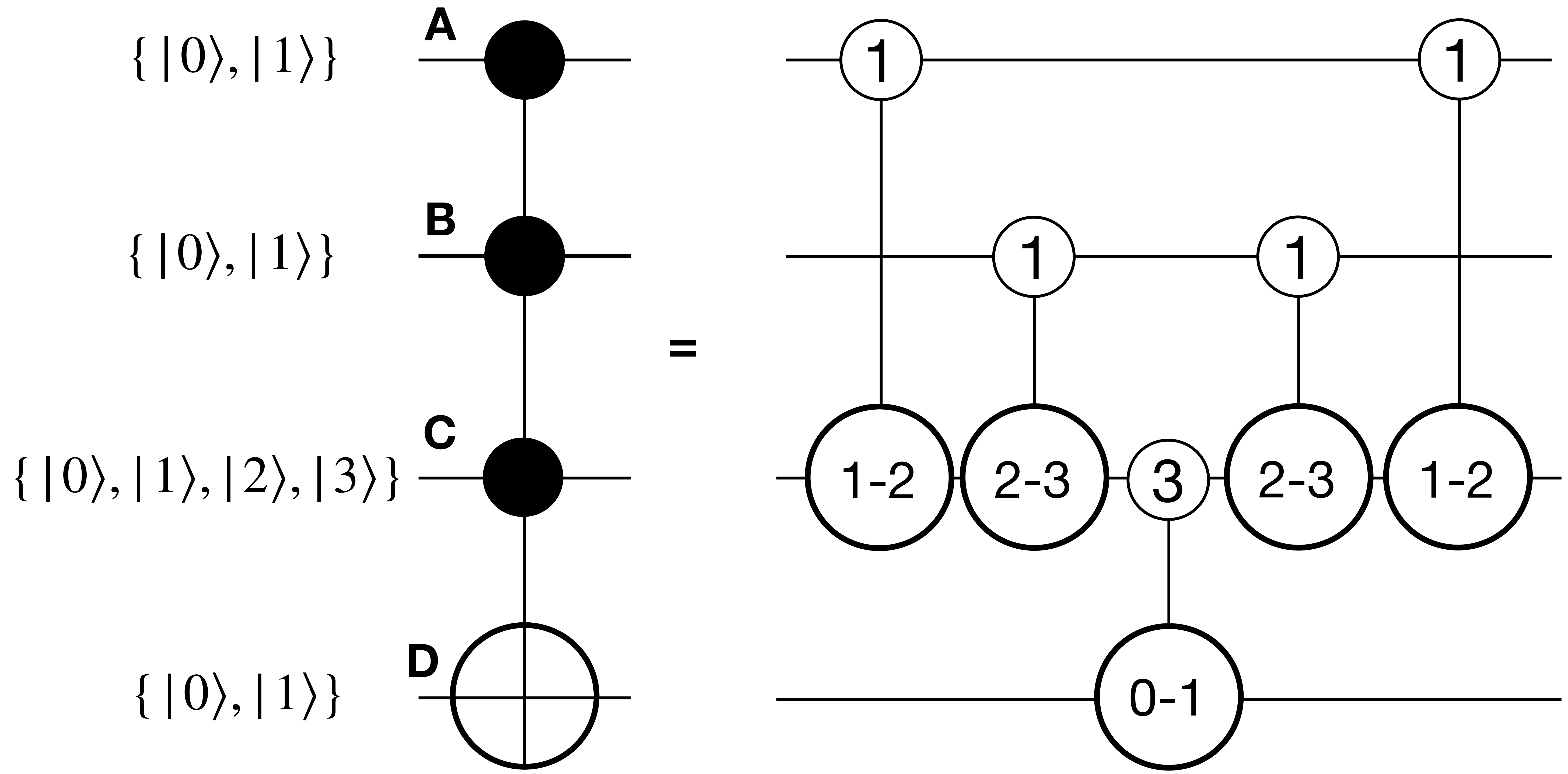


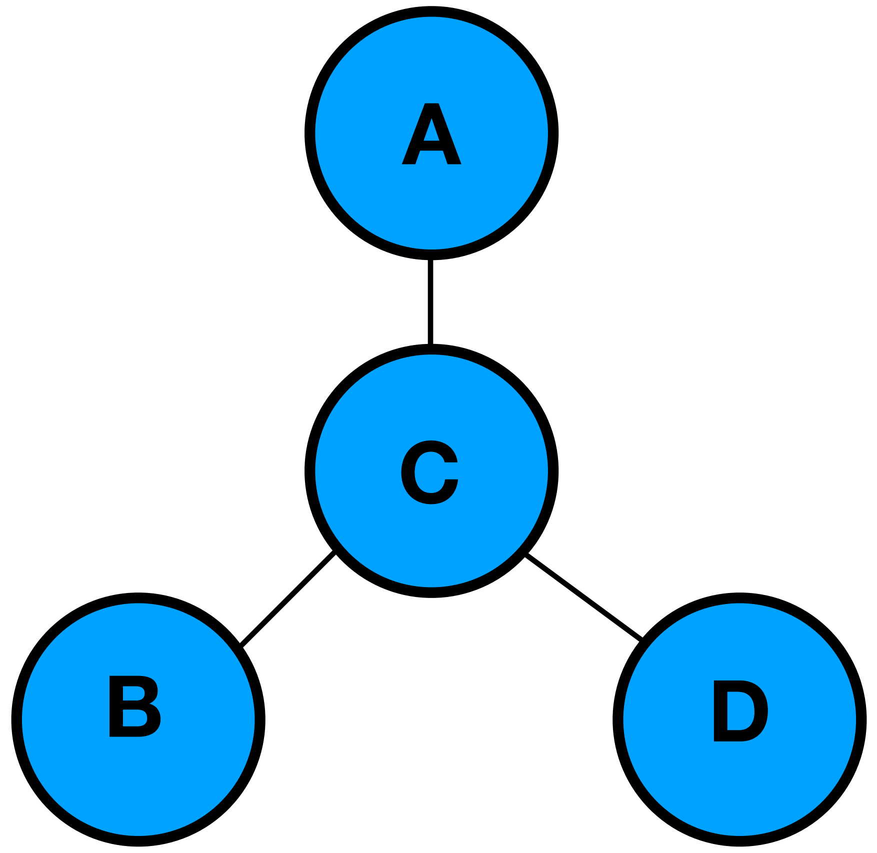
4 qubit Toffoli = {2 qubits + 2 qutrit} + 5 gen. CNOTs + linear topology

N qubit Toffoli = {2 qubits + (N - 2) qutrit} + (2N - 3) gen. CNOTs + linear topology

Generalization: n-qubit Toffoli gate

The same scaling in other topologies, but we need to increase the number of levels





N qubit Toffoli = {(N - 1) qubits + N-level qudit} + (2N - 3) gen. CNOTs + star topology

nature physics

ARTICLES

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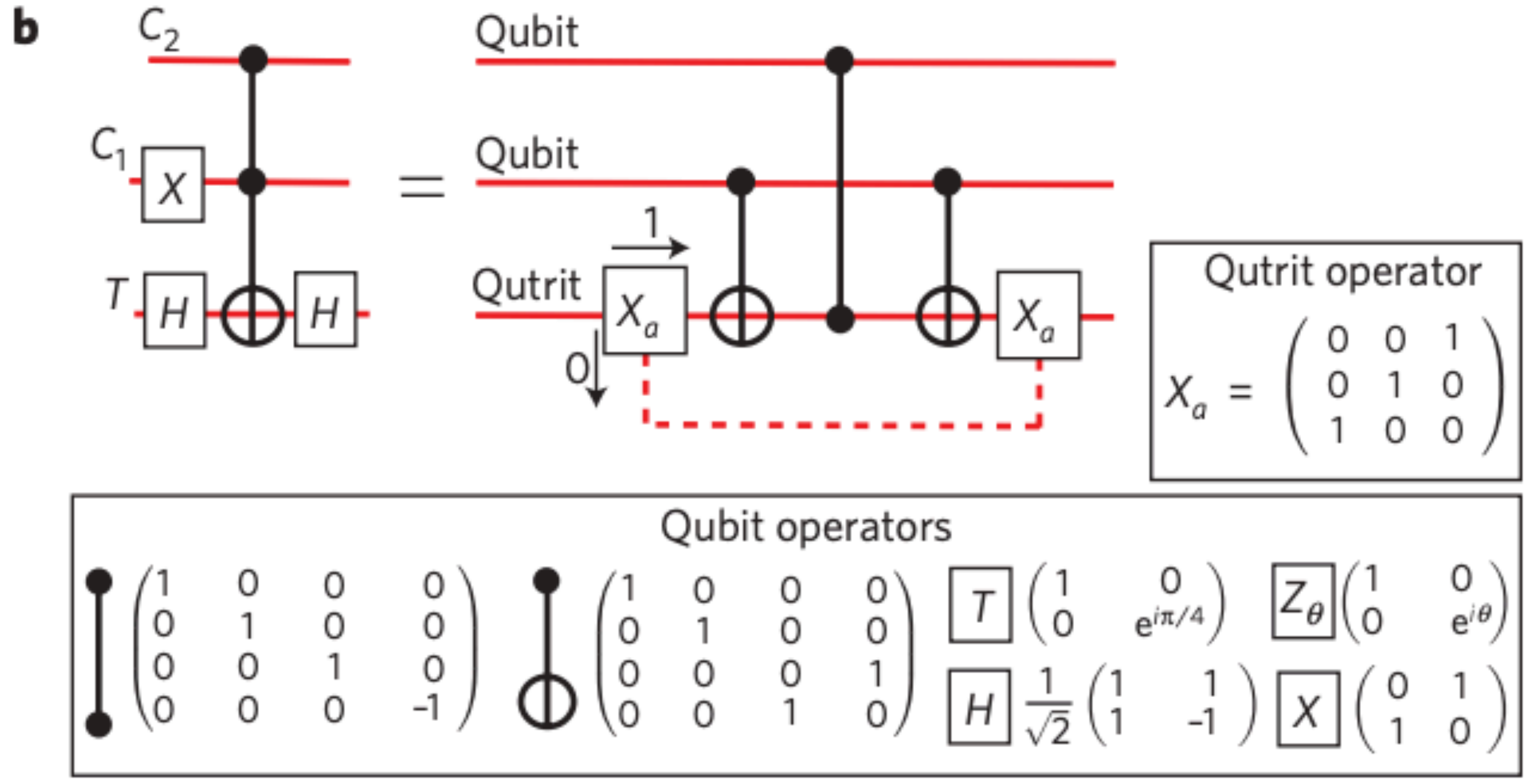
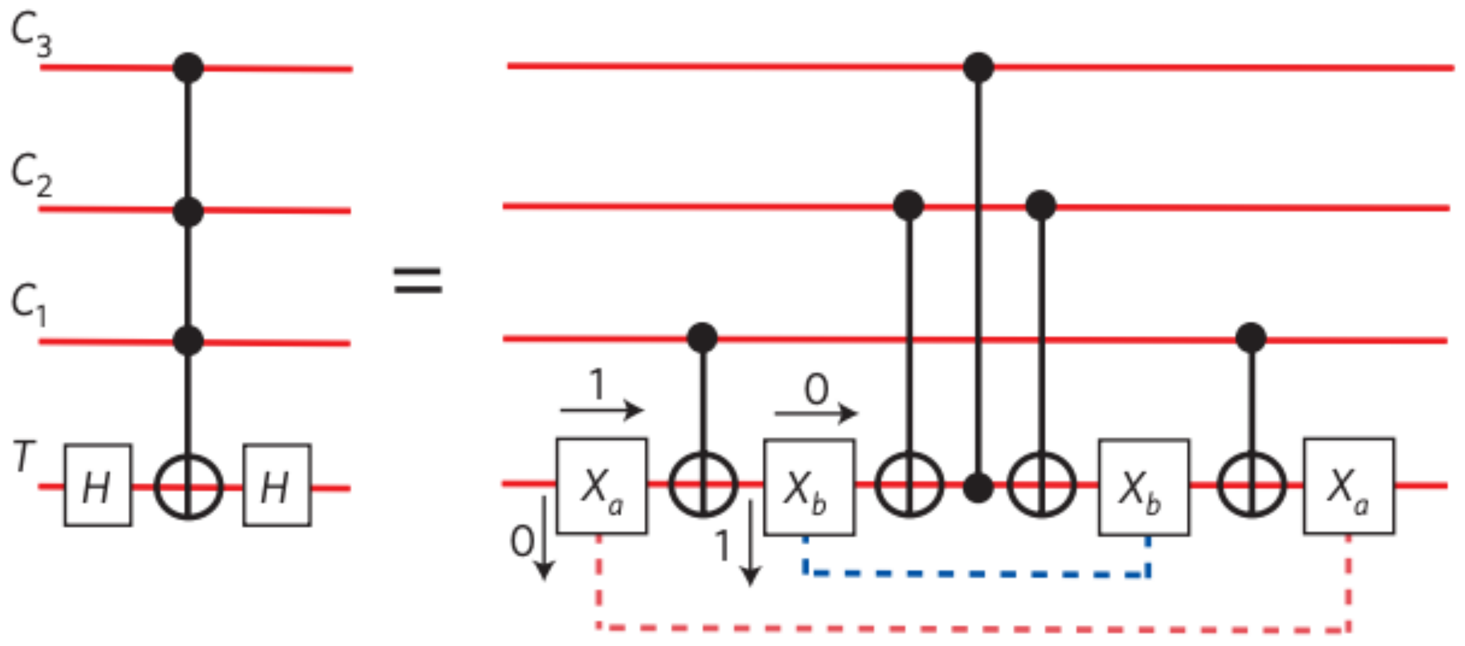
Simplifying quantum logic using higher-dimensional Hilbert spaces

Benjamin P. Lanyon[1]*, Marco Barbieri[1], Marcelo P. Almeida[1], Thomas Jennewein[1,2], Timothy C. Ralph[1], Kevin J. Resch[1,3], Geoff J. Pryde[1,4], Jeremy L. O'Brien[1,5], Alexei Gilchrist[1,6] and Andrew G. White[1]

Quantum computation promises to solve fundamental, yet otherwise intractable, problems across a range of active fields of research. Recently, universal quantum logic-gate sets—the elemental building blocks for a quantum computer—have been demonstrated in several physical architectures. A serious obstacle to a full-scale implementation is the large number of these gates required to build even small quantum circuits. Here, we present and demonstrate a general technique that harnesses multi-level information carriers to significantly reduce this number, enabling the construction of key quantum circuits with existing technology. We present implementations of two key quantum circuits: the three-qubit Toffoli gate and the general two-qubit controlled-unitary gate. Although our experiment is carried out in a photonic architecture, the technique is independent of the particular physical encoding of quantum information, and has the potential for wider application.

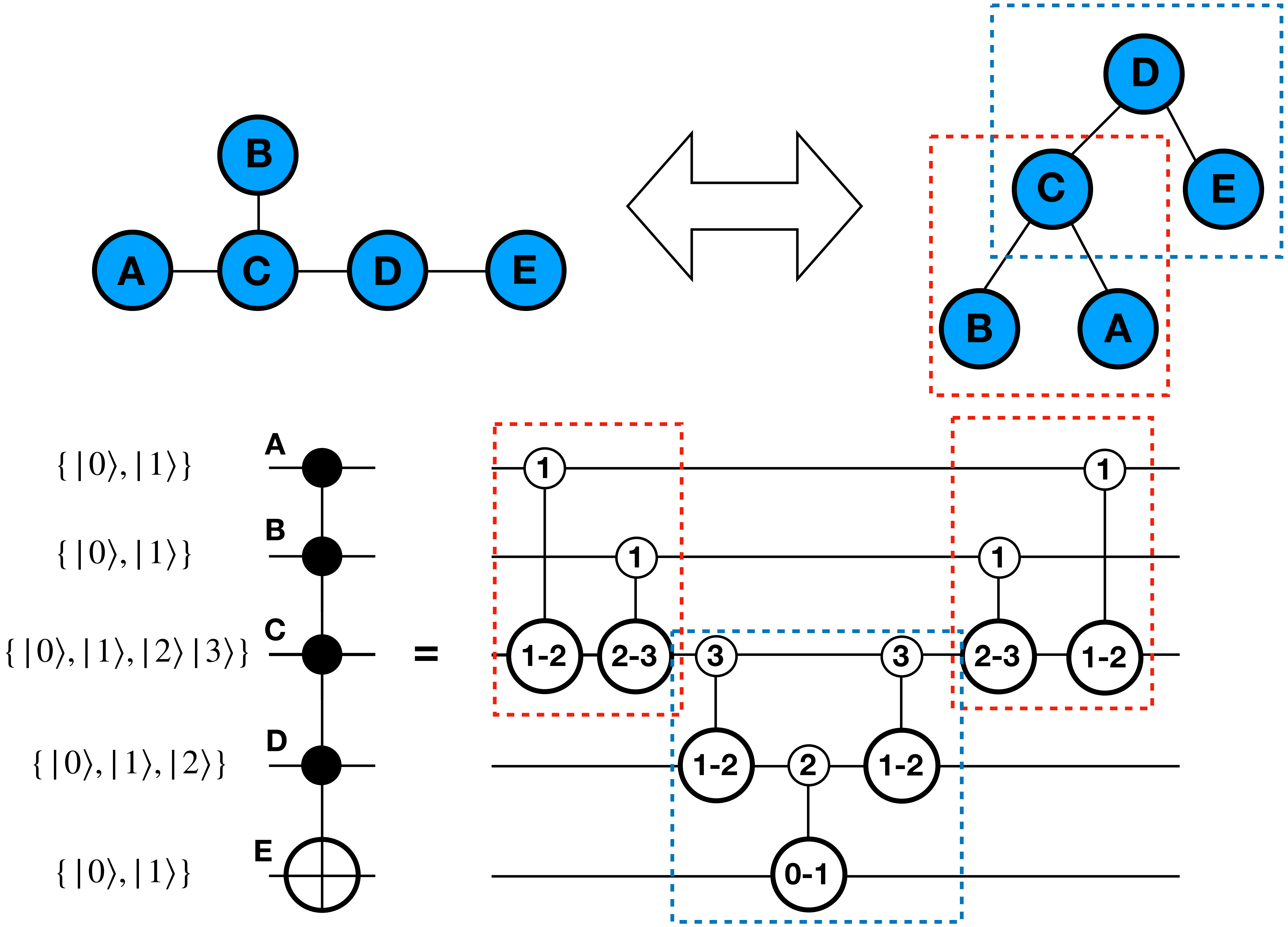
Scalability of the approach: we need to increase the number of levels





Generalization: n-qubit Toffoli gate

Generalization for other topologies saves the scaling



If {# of levels in qudit $\geq$ # connections + 1} then N-qubit Toffoli = (2N - 3) gen. CNOTs

PHYSICAL REVIEW A **101**, 022304 (2020)

Scalable quantum computing with qudits on a graph

E. O. Kiktenko,[1,2,3] A. S. Nikolaeva,[1,3] Peng Xu,[4,5] G. V. Shlyapnikov,[1,3,6,7,8] and A. K. Fedorov[1,3]

# of levels in qudit ≥ # of connections + 1

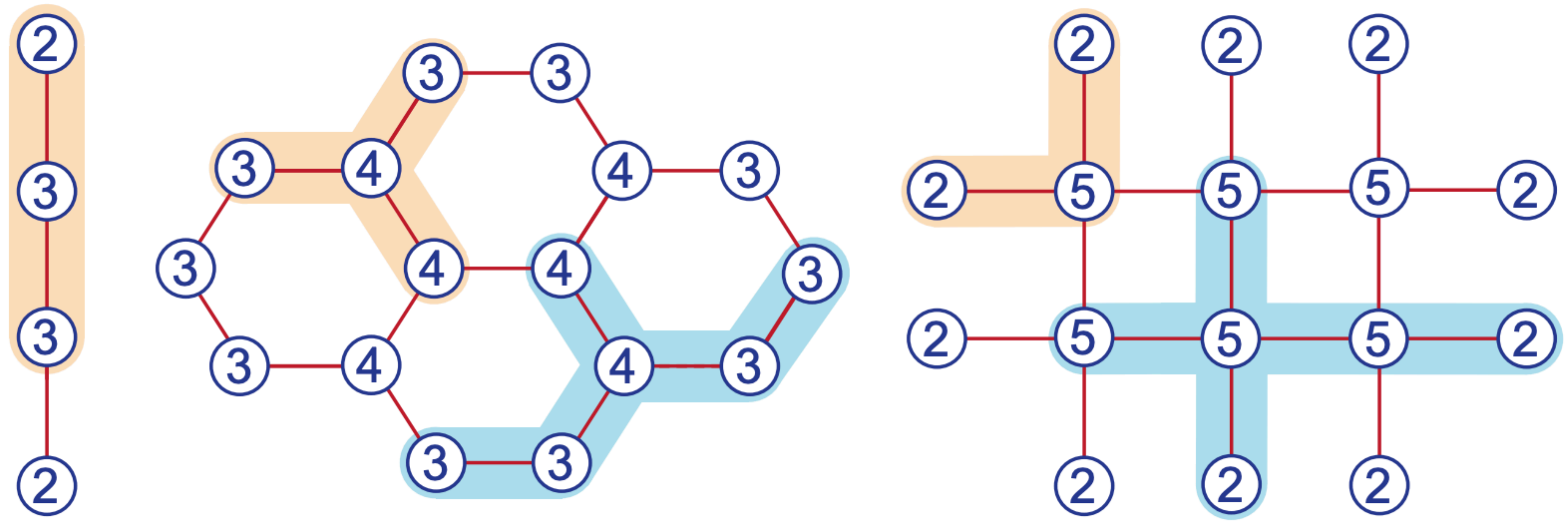
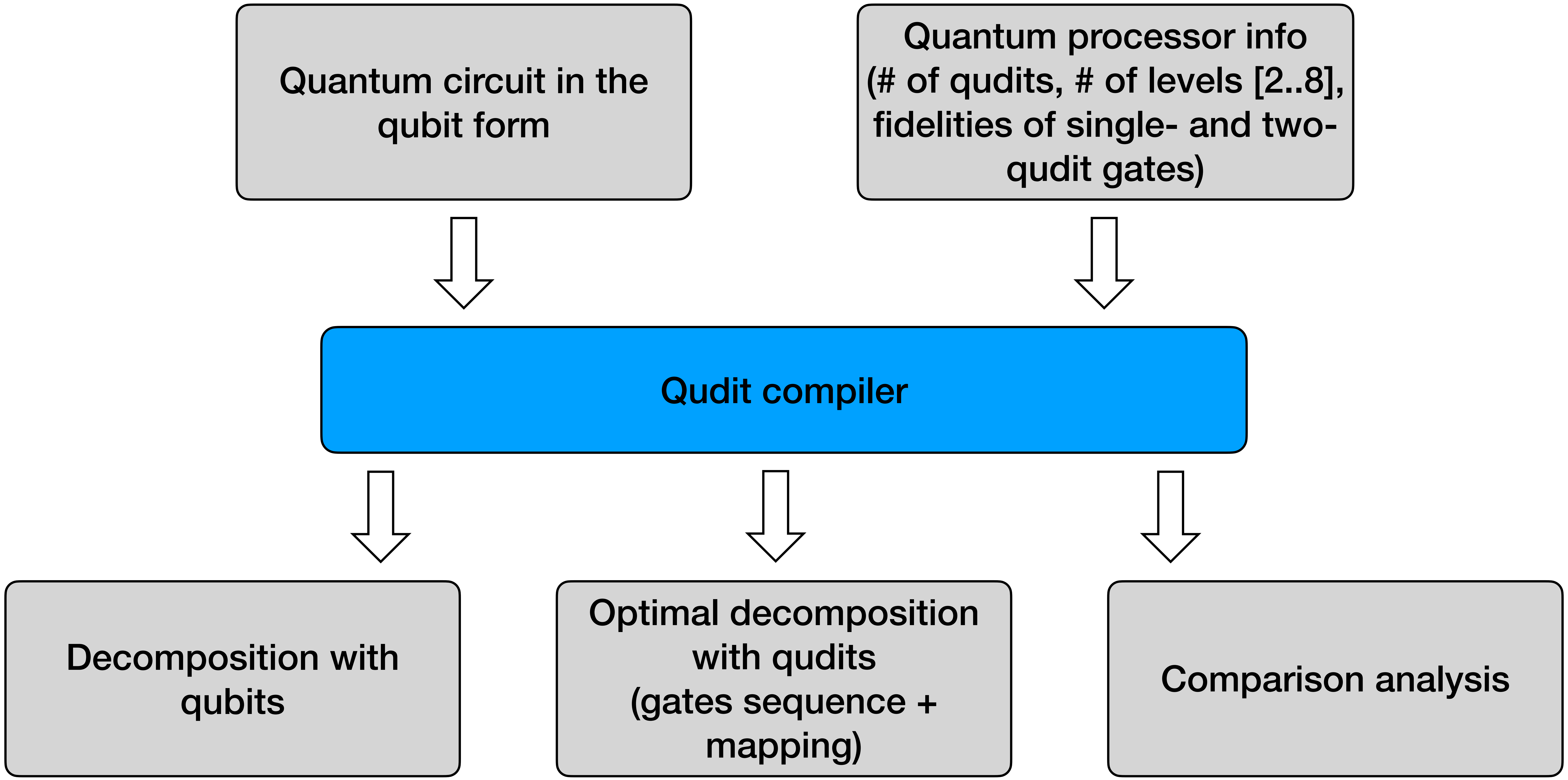


Figure 1. Illustration of various multi-qudit and qubit-qudit schemes for quantum computing that provides reduction in the number of operations for the realization of the Toffoli gate and reduces the depth of the corresponding circuit. We note that if condition (3) holds for a whole system, then it is also fulfilled for *any* its acyclic-connected subsystem (highlighted).

connection within the subgraph plays a role (not connectivity)

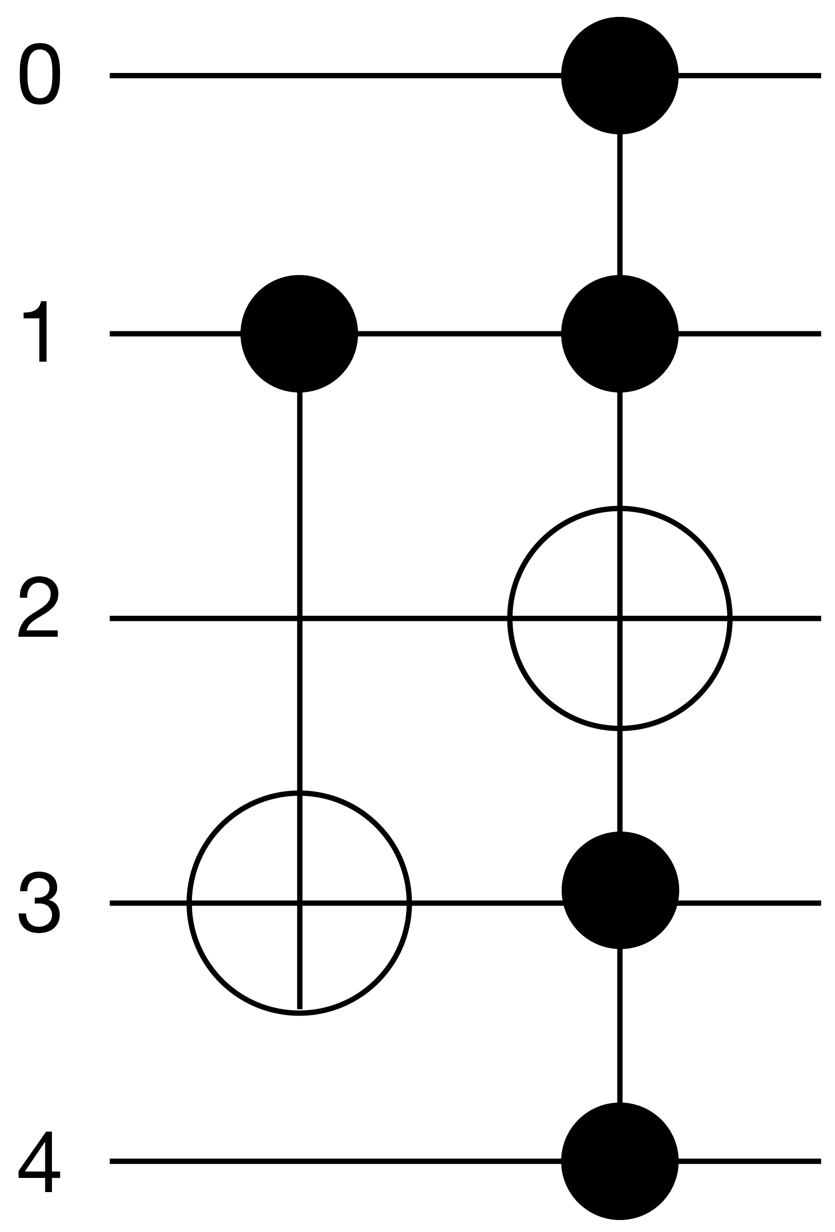
Qudit compiler for ion-based quantum processor



Qudit compiler for ion-based quantum processor

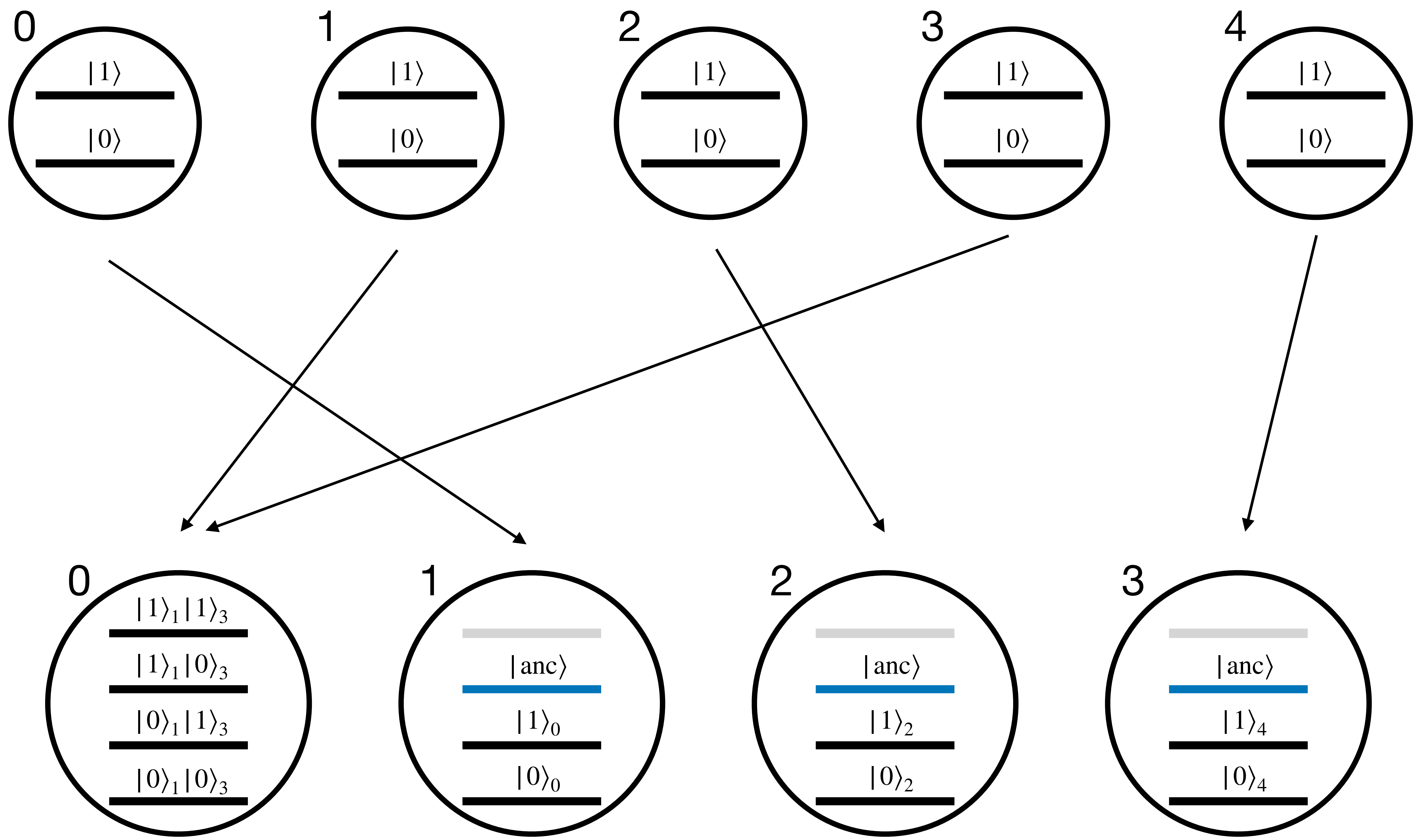
We consider the full set of mappings and optimize the total fidelity

<u>Input circuit</u>



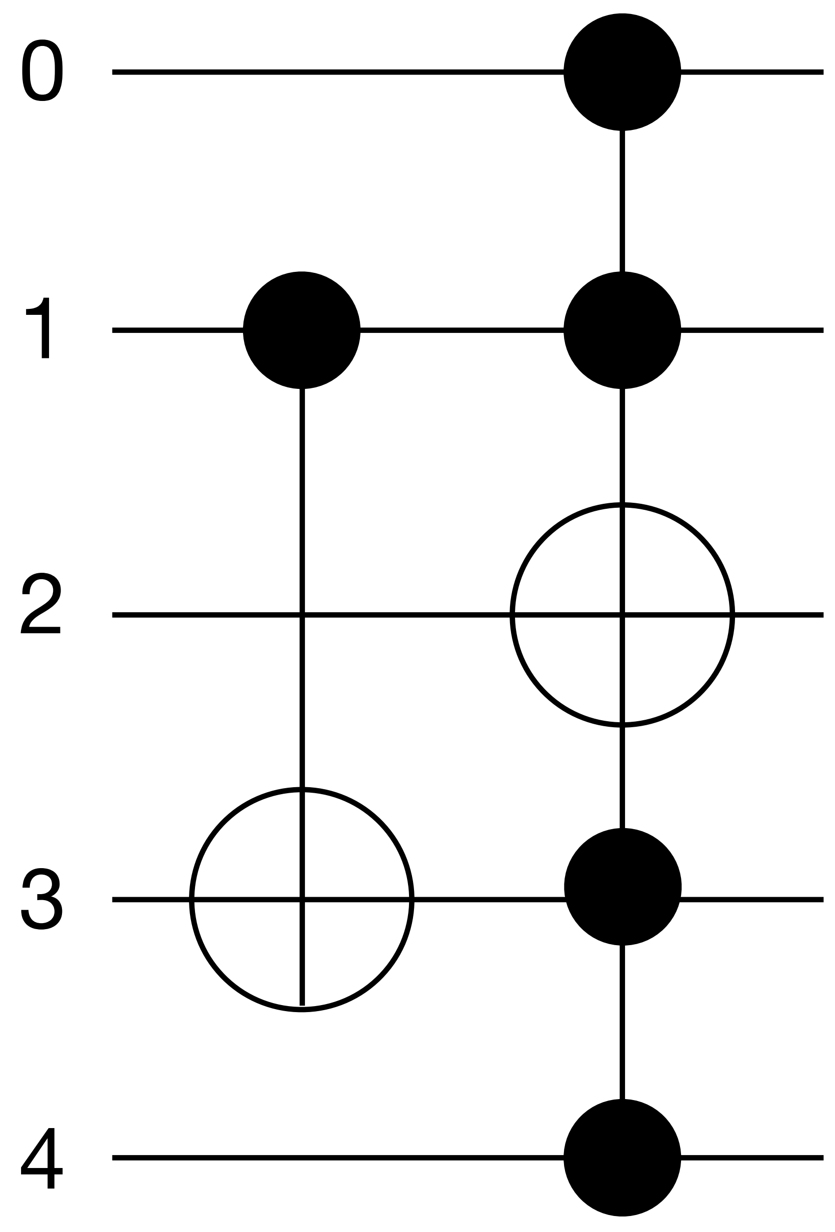
4 level quantum systems

<u>Possible mappings</u>



Qudit compiler for ion-based quantum processor

Input circuit




```
------------------
Input circuit info
------------------
Number of employed qubits: 5
Total number of gates: 2
Number of single-qubit gates: 0
Number of two-qubit gates: 1
> CNOT: 1
Number of n-controlled gates with n > 1
> 2-qubit controlled unitary:  0
> 3-qubit controlled unitary:  0
> 4-qubit controlled unitary:  1

----------------------------------------------
Results for circuit implementation with qubits
----------------------------------------------
Number of employed ions: 5
Number of single-ion operations: 118
Number of two-ion operations: 77
Fidelity: 0.17
Fidelity is below critical value: True

------------------------------------------------------
Results for circuit implementation with qudits (d = 4)
------------------------------------------------------
Number of employed ions: 4
Number of single-ion operations: 23 (80% improvement compared to the qubit implementation)
Number of two-ion operations: 5 (93% improvement compared to the qubit implementation)
Fidelity: 0.86 (417% improvement compared to the qubit implementation)
Fidelity is below critical value: False
Optimal qubits-to-qudits mapping: [[1, 3], [0], [2], [4]]
```

Qudit compiler for ion-based quantum processor

We combine two approaches: we use the first qudit as a set of two qubits and additional levels of other qudits as ancillas

```
==========================================================================================================
      ┐                    ┌              ┐                                ┌              ┐
 0. 0.│                    │1.  0.  0.  0.│                                │1.  0.  0.  0.│
 0. 1.│───@[4]─────────────│0.  0.  0.  1.│────────────────────────────────│0.  0.  0.  1.│──────────────
 1. 0.│   │                │0.  0.  1.  0.│                                │0.  0.  1.  0.│
 0. 0.│   │                │0.  1.  0.  0.│                                │0.  1.  0.  0.│
      ┘   │                └              ┘                                └              ┘
          │
          │                ┌                                          ┐
          │                │ 0.5+0.5j -0.5-0.5j  0. +0.j    0. +0.j   │
──────────@[4]─────────────│ 0.5+0.5j  0.5+0.5j  0. +0.j    0. +0.j   │───@[4]──────────────────────────
                           │ 0.  +0.j  0.  +0.j  1. +0.j    0. +0.j   │   │
                           │ 0.  +0.j  0.  +0.j  0. +0.j    1. +0.j   │   │
                           └                                          ┘   │
                                                                          │       ┌                                                  ┐
                                                                          │       │ 0.707+0.j  0.707+0.j  0.    +0.j  0.    +0.j│
──────────────────────────────────────────────────────────────────────────@[4]────│ 0.707+0.j -0.707+0.j  0.    +0.j  0.    +0.j│─
                                                                                  │ 0.    +0.j 0.    +0.j 1.    +0.j  0.    +0.j│
                                                                                  │ 0.    +0.j 0.    +0.j 0.    +0.j  1.    +0.j│
                                                                                  └                                                  ┘

──────────────────────────────────────────────────────────────────────────────────────────────────────────
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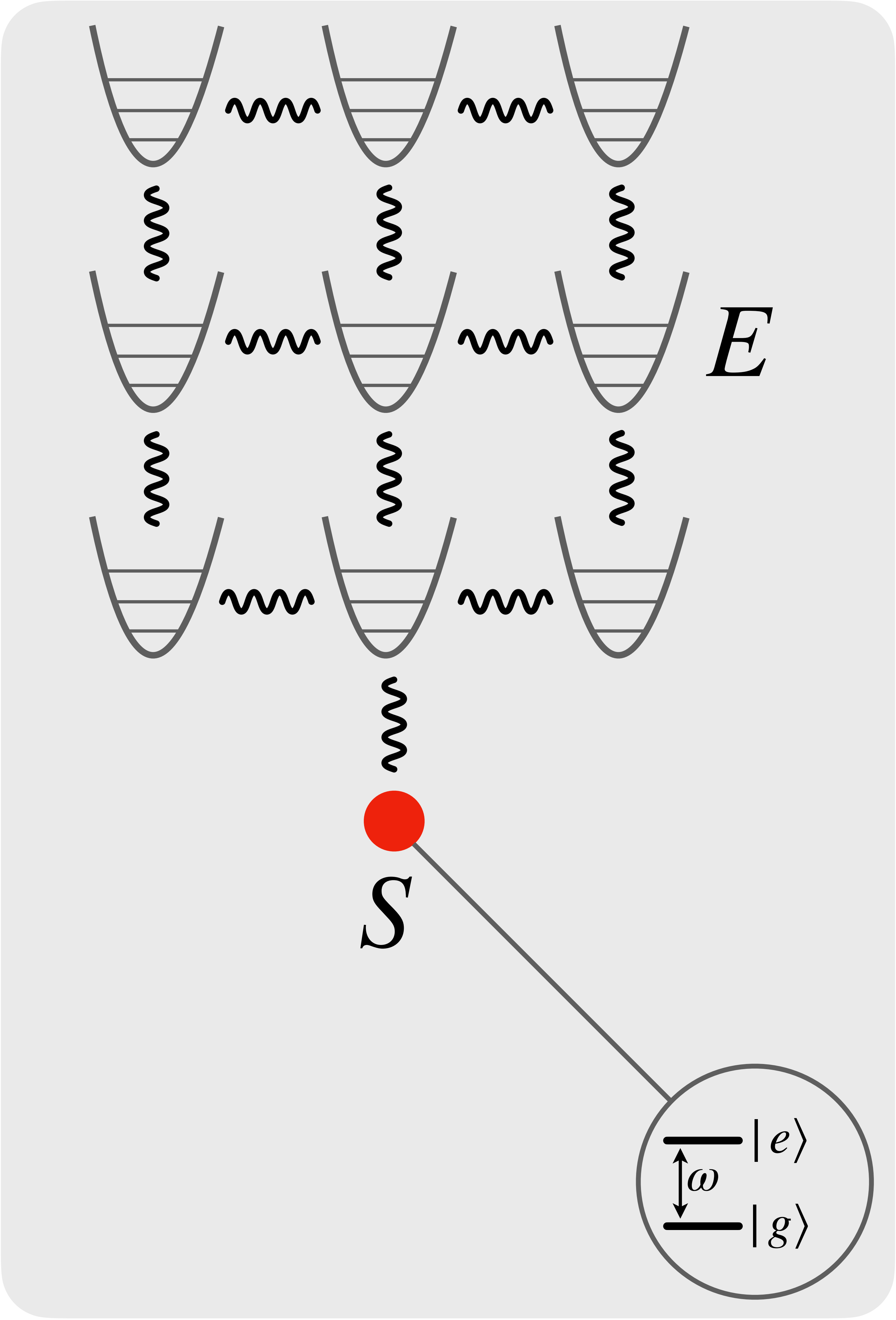
Open quantum systems

Theory of open quantum systems

The unified framework of open quantum systems theory is aimed to analyze non-equilibrium dynamical effects of quantum physics. One of the goals is to make a prediction of the dynamics.



Non-Markovianity, i.e. effects of memory, are among the most challenging problems

Evolution equation

$$\partial_t \rho(t) = \frac{1}{i}[H, \rho(t)]$$

Hard to solve (curse of dimensionality)

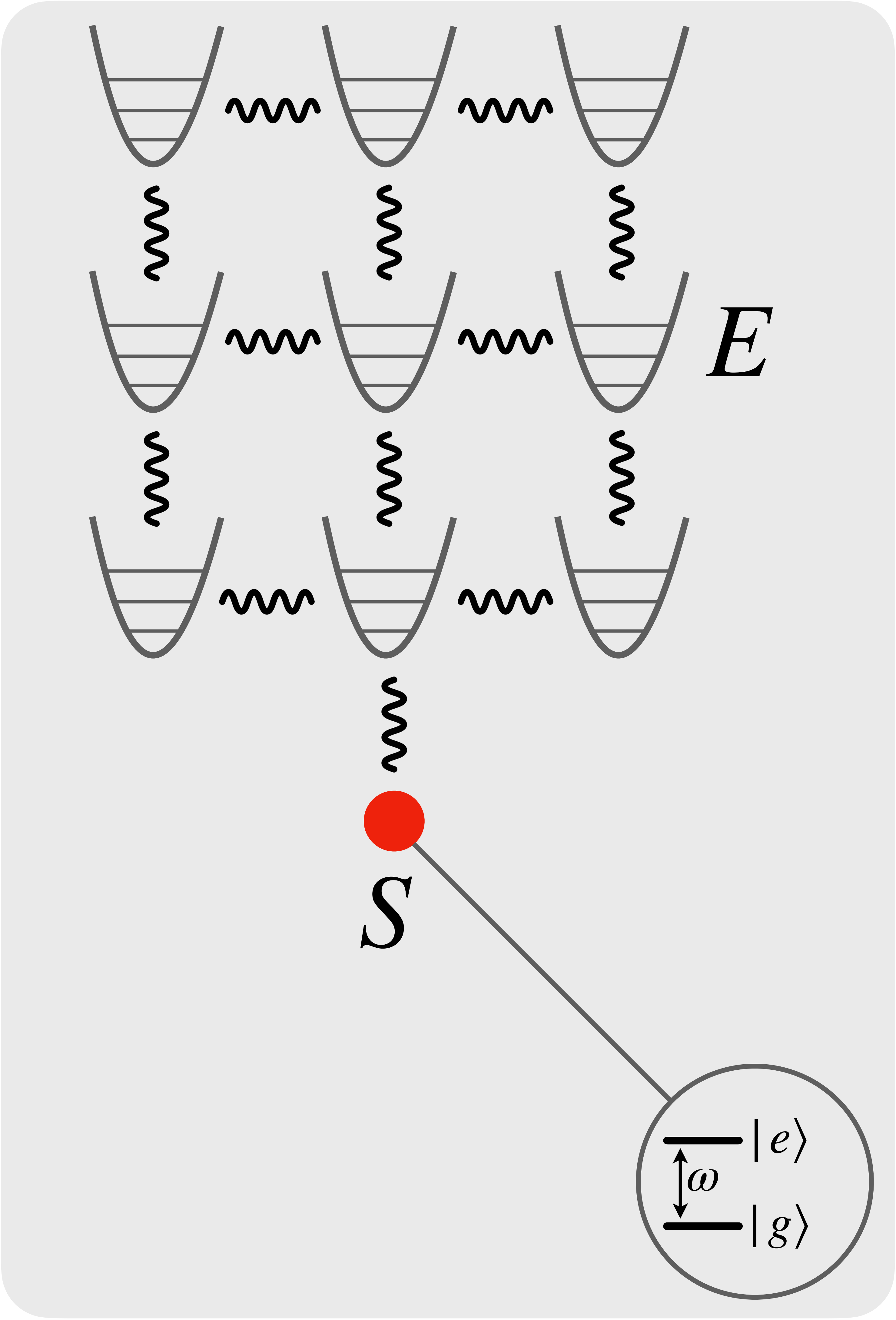
Time-convolution called the Nakajima-Zwanzig equation

$$\partial_t \rho_S(t) = \int_0^t d\tau K(\tau) \rho_S(t-\tau)$$

Hard to derive (the exact derivation is of the same complexity as solving dynamics equation)

Theory of open quantum systems

The unified framework of open quantum systems theory is aimed to analyze non-equilibrium dynamical effects of quantum physics. One of the goals is to make a prediction of the dynamics.



- The class of problems that can be understood analytically is limited to several exceptional situations.

- Many different approaches are suggested (non-Markovian quantum state diffusion, the hierarchical equations of motion, the time-evolving matrix product operators, the dressed quantum trajectories, the Dirac-Frenkel time-dependent variational approach, etc.), but they have many limitations.

- Moreover, in realistic experimental conditions the joint Hamiltonian of system and environment is often unknown.

A possible solution: to use a data-driven approach (learning non-Markovian dynamics).

Advantages: can be based on experimentally observed data.

Disadvantages: “black-box” approaches (no physical insights about the system), scalability, convergence, and model selection.

Learning non-Markovian dynamics

	Convergence to the optimal solution with guaranties	Interpretability	Automatic model selection	Scalability
One can learn NZ equation from data	✓	✗	✗	✓
One can train RNN (or other models) to predict quantum trajectories from data	✗	✗	✗	✓
One can train Markovian embedding of non-Markovian quantum dynamics from data using non-convex optimization	✗	✓	✗	+/−

- One can learn NZ equation from data

  J. Cerrillo and J. Cao, Non-Markovian dynamical maps: numerical processing of open quantum trajectories. Phys. Rev. Lett. 112, 110401 (2014).

- One can train RNN (or other models) to predict quantum trajectories from data

  L. Banchi, E. Grant, A. Rocchetto, and S. Severini, Modelling non-markovian quantum processes with recurrent neural networks, New J. Phys. 20, 123030 (2018).

- One can train Markovian embedding of non-Markovian quantum dynamics from data using non-convex optimization

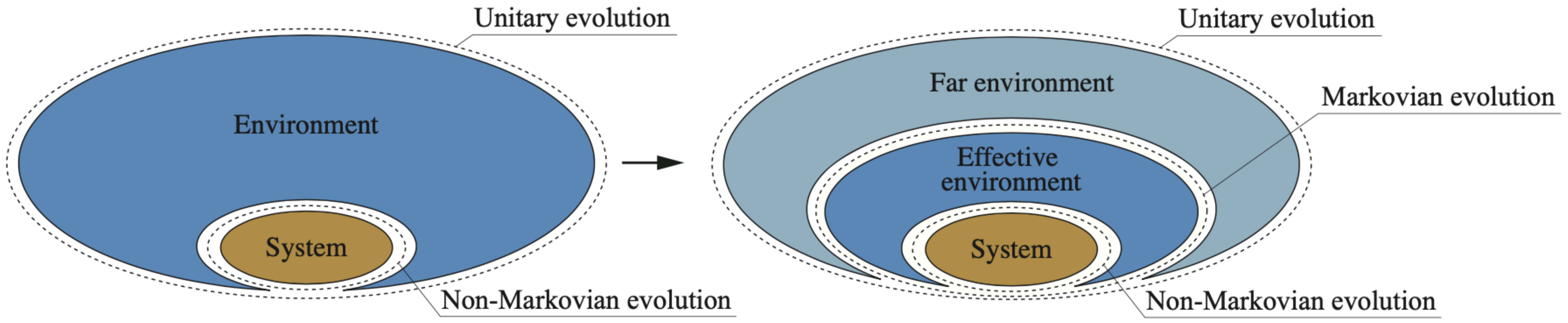
  I.A. Luchnikov, S.V. Vintskevich, D.A. Grigoriev, and S.N. Filippov, Machine learning non-Markovian quantum dynamics, Phys. Rev. Lett. 124, 140502 (2020).

  C. Guo, K. Modi, and D. Poletti, Tensor-network-based machine learning of non-Markovian quantum processes, Phys. Rev. A 102, 062414 (2020).

The concept of Markovian embedding

Markovian embedding

- **Idea**: Embedding the non-Markovian system dynamics into a Markovian dynamics of the system and the effective environment of a finite dimension.
- Environment induces the system's non-Markovian dynamics as a two-component system consisting of effective and far environments.



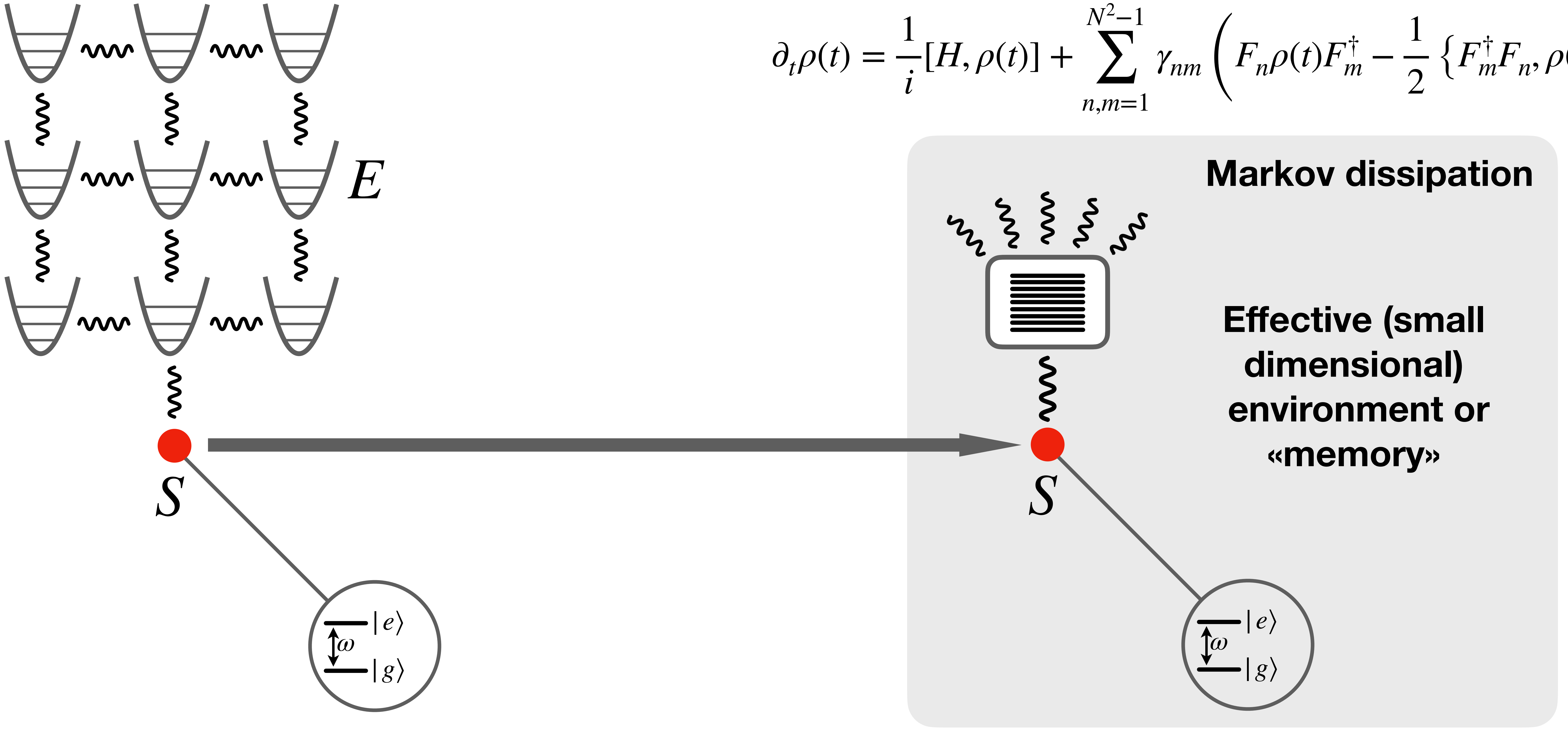
Environment is split into two parts: The finite-dimensional effective environment, which is responsible for memory effects in the system's dynamics, and the remaining far environment responsible for dissipation.

Features of Markovian embedding

- Markovian embedding is not just a “black box” model of open quantum dynamics; it provides insights both about the system’s properties and its environment.

- Markovian embedding can be reconstructed having only information about the non-Markovian dynamics of a system, which is accessible in realistic experimental conditions.

$$\partial_t \rho(t) = \frac{1}{i}[H, \rho(t)] + \sum_{n,m=1}^{N^2-1} \gamma_{nm} \left(F_n \rho(t) F_m^\dagger - \frac{1}{2} \left\{ F_m^\dagger F_n, \rho(t) \right\} \right)$$



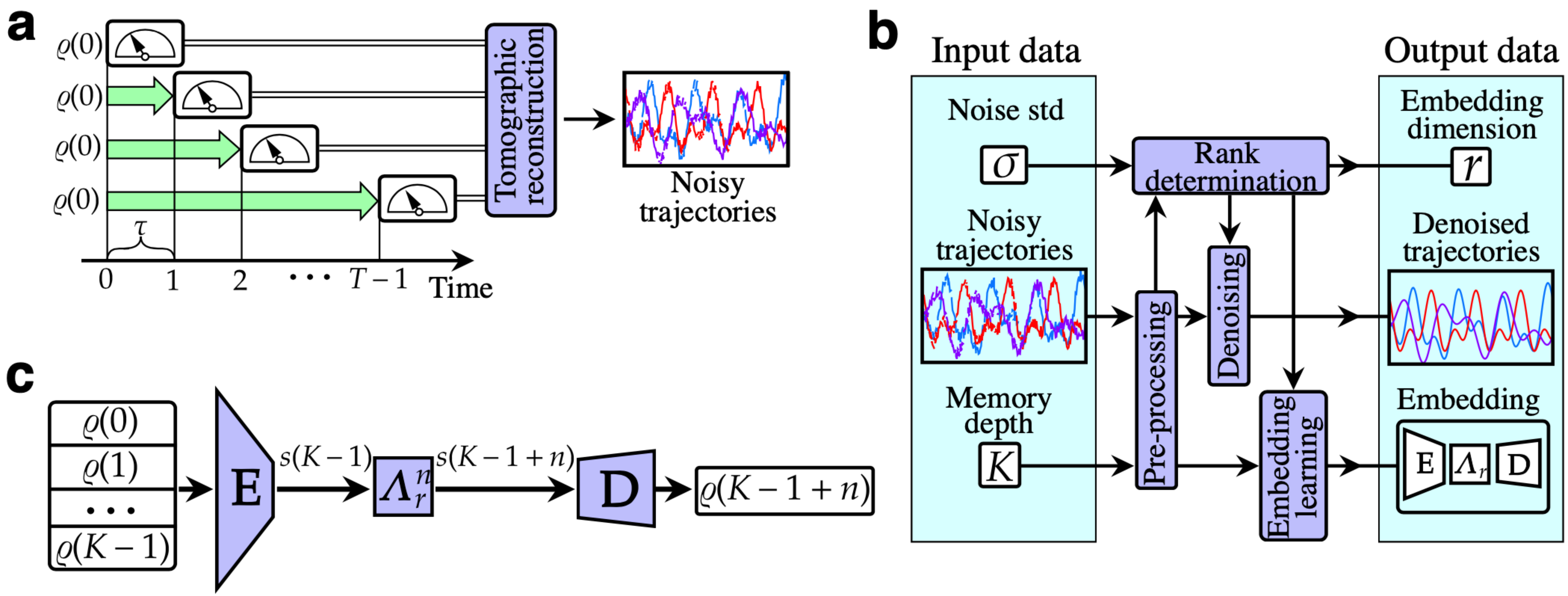
Our goal

Idea: The system and the effective environment instantiate a Markovian embedding, and their collective dynamics is dissipative and Markovian. We would like to base our method on:

- experimentally accessible data;
- linear machine learning methods (scalable, data efficient and admit the exact solution);

Convergence to the optimal solution with guaranties	Interpretability	Automatic model selection	Scalability
Linear machine learning methods, matrix decompositions	The concept of Markovian embedding	Choosing the simplest possible model that captures relevant physics	Linear machine learning methods

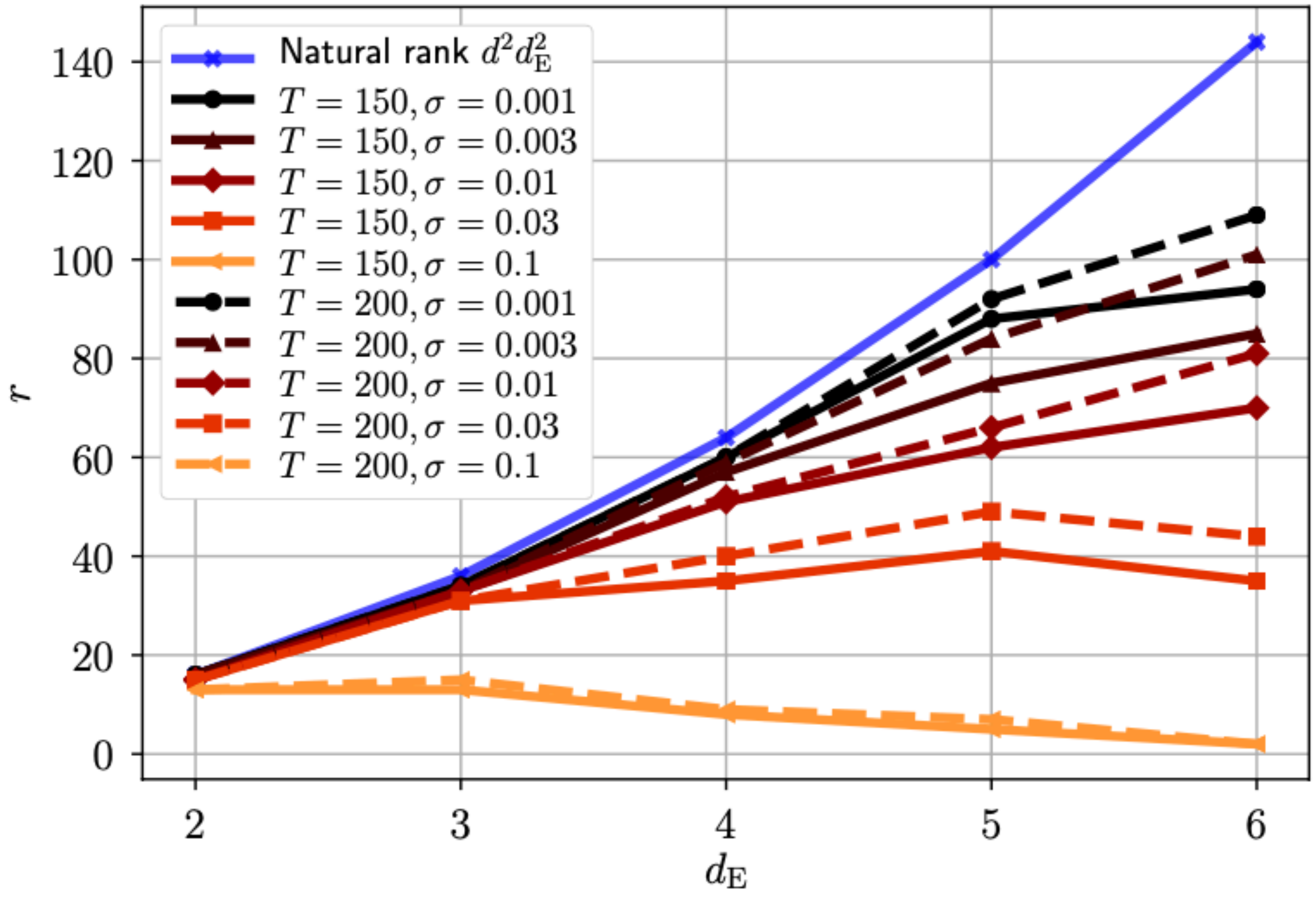
Probing non-Markovian dynamics: General scheme



a) Extraction of quantum trajectories via quantum tomography of system states at discrete time moments. b) Main building blocks of the input data processing and connections between blocks. c) Dynamics prediction based on the reconstructed Markovian embedding.

Predicted Markovian embedding minimal dimension

Qubit with a finite dimensional environment; we sample at random a quantum dynamical semigroup generator in the GKSL form. We simulate noise appearing during data acquisition of trajectories.



The method works correctly and predicts the irregular non-Markovian dynamics of a qubit

Predicted Markovian embedding minimal dimension

Qubit with a finite dimensional environment; we sample at random a quantum dynamical semigroup generator in the GKSL form. We simulate noise appearing during data acquisition of trajectories.

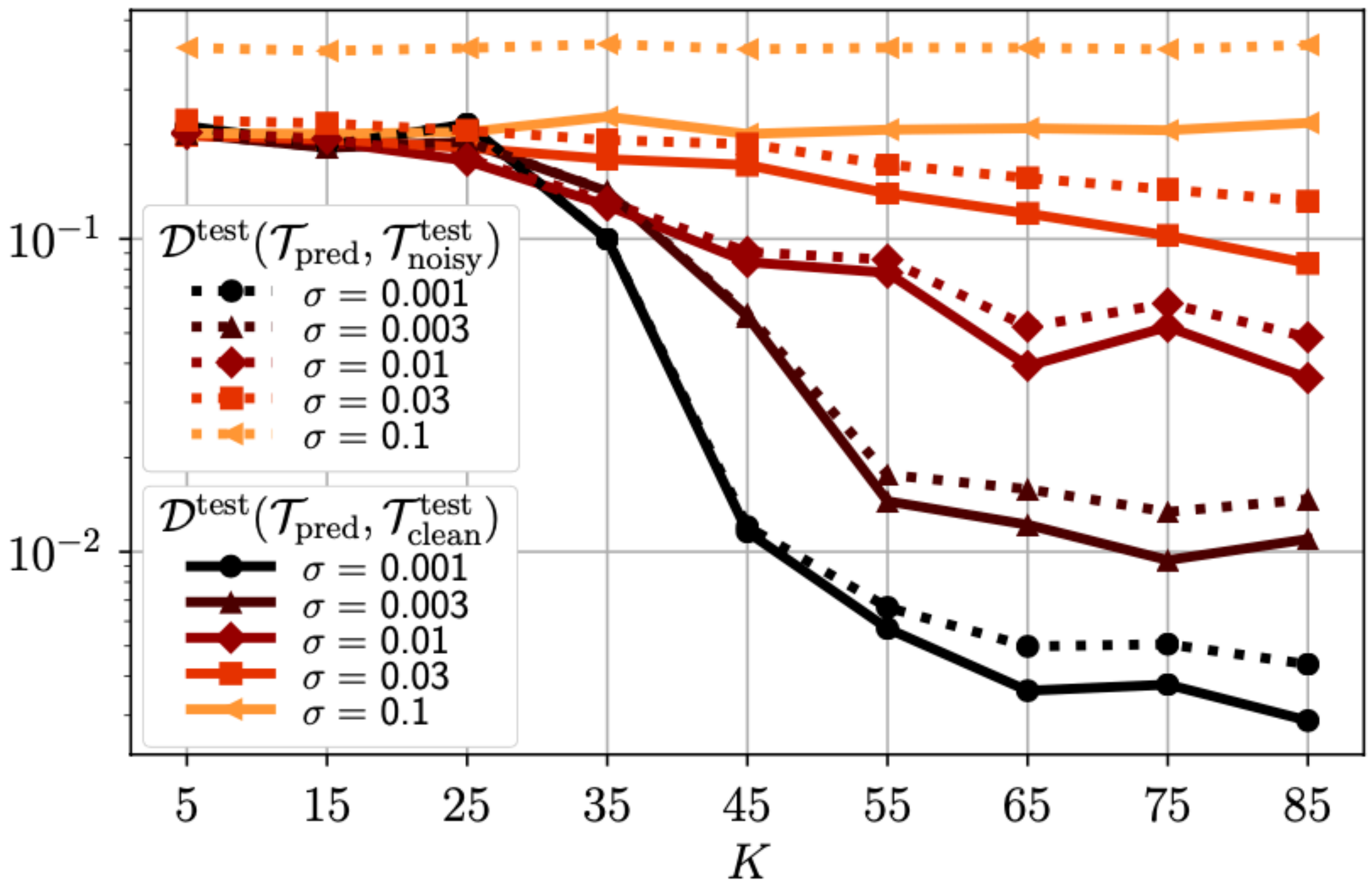
	$\sigma = 10^{-1}$		$\sigma = 10^{-2}$		$\sigma = 10^{-3}$	
	$T = 150$	$T = 200$	$T = 150$	$T = 200$	$T = 150$	$T = 200$
$d_\mathrm{E} = 2$	**2**	**2**	**2**	**2**	**2**	**2**
$d_\mathrm{E} = 3$	2	2	**3**	**3**	**3**	**3**
$d_\mathrm{E} = 4$	2	2	**4**	**4**	**4**	**4**
$d_\mathrm{E} = 5$	2	2	4	**5**	**5**	**5**
$d_\mathrm{E} = 6$	1	1	5	5	5	**6**

TABLE I: Reconstructed effective dimensions of the environment $d_\mathrm{E}^\mathrm{eff}$ for data sets of different length and noise levels. Cases where $d_\mathrm{E}^\mathrm{eff} = d_\mathrm{E}$ are shown in bold font.

Selection of the memory depth hyperparemeter

Qubit with a finite dimensional environment; we sample at random a quantum dynamical semigroup generator in the GKSL form. We simulate noise appearing during data acquisition of trajectories.

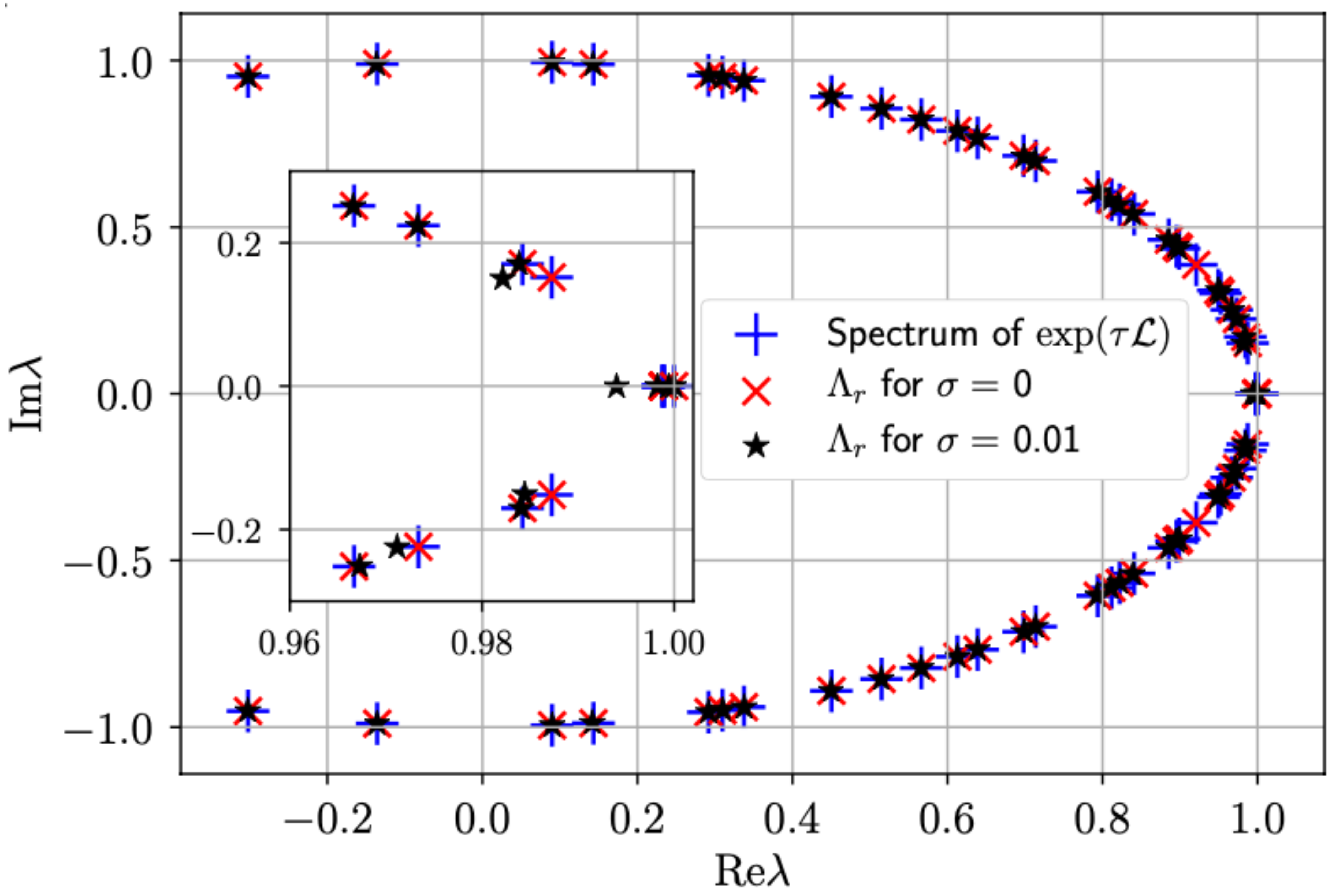
$$\mathcal{D}^{\text{test}}(\mathcal{T}_1, \mathcal{T}_2) = \frac{1}{T-K} \sum_{k=K}^{T-1} \|\varrho_1(k) - \varrho_2(k)\|_1,$$



'Saturation' value of K: starting from which the accuracy of prediction is mainly determined by the noise level

Reconstructing eigenfrequencies of the joint system

Qubit with a finite dimensional environment; we sample at random a quantum dynamical semigroup generator in the GKSL form. We simulate noise appearing during data acquisition of trajectories.

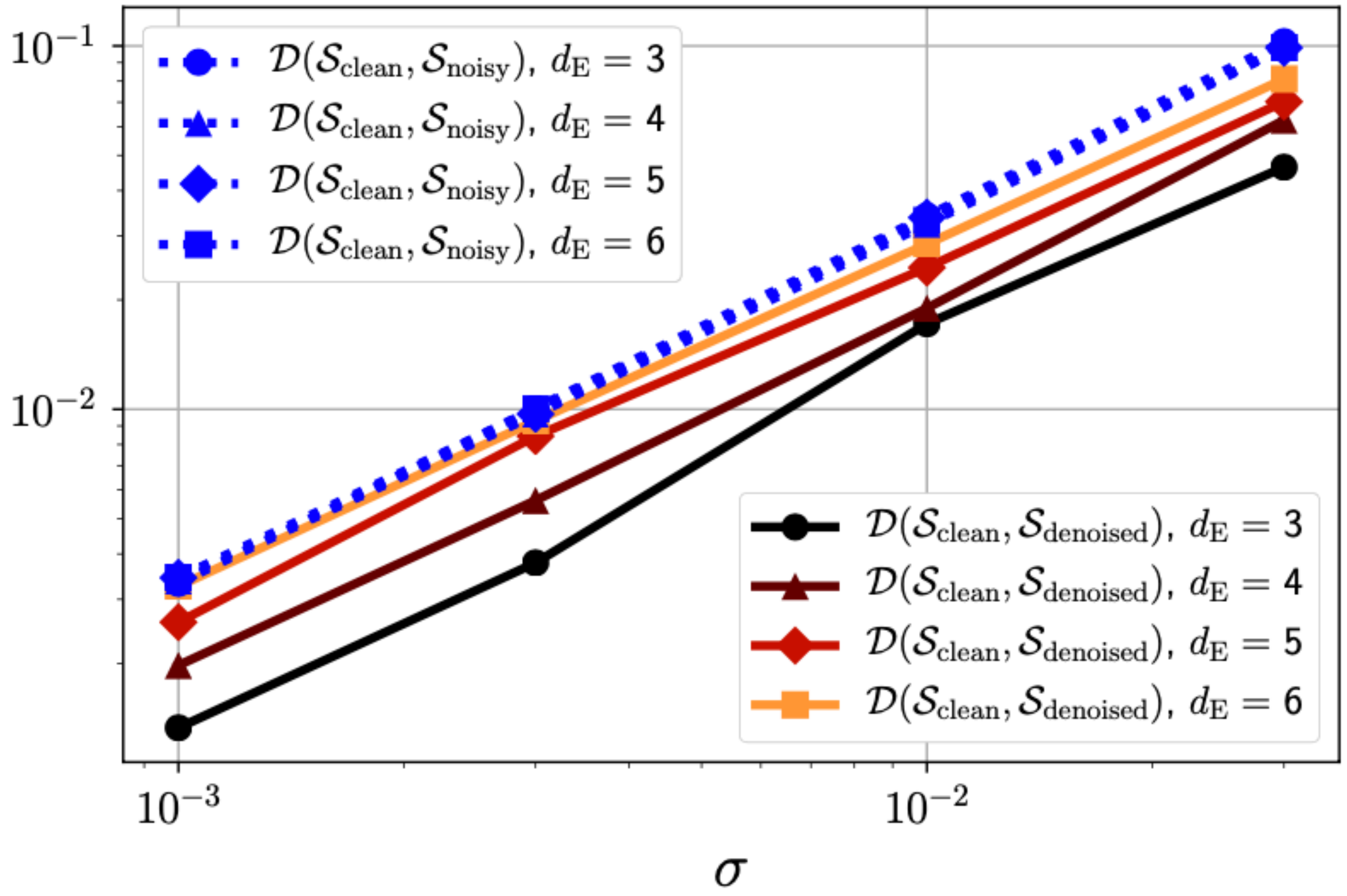


A perfect coincidence in the case without noise; in the presence of noise, we see that the approach provides valuable information about eigenfrequencies.

Quality of deniosing

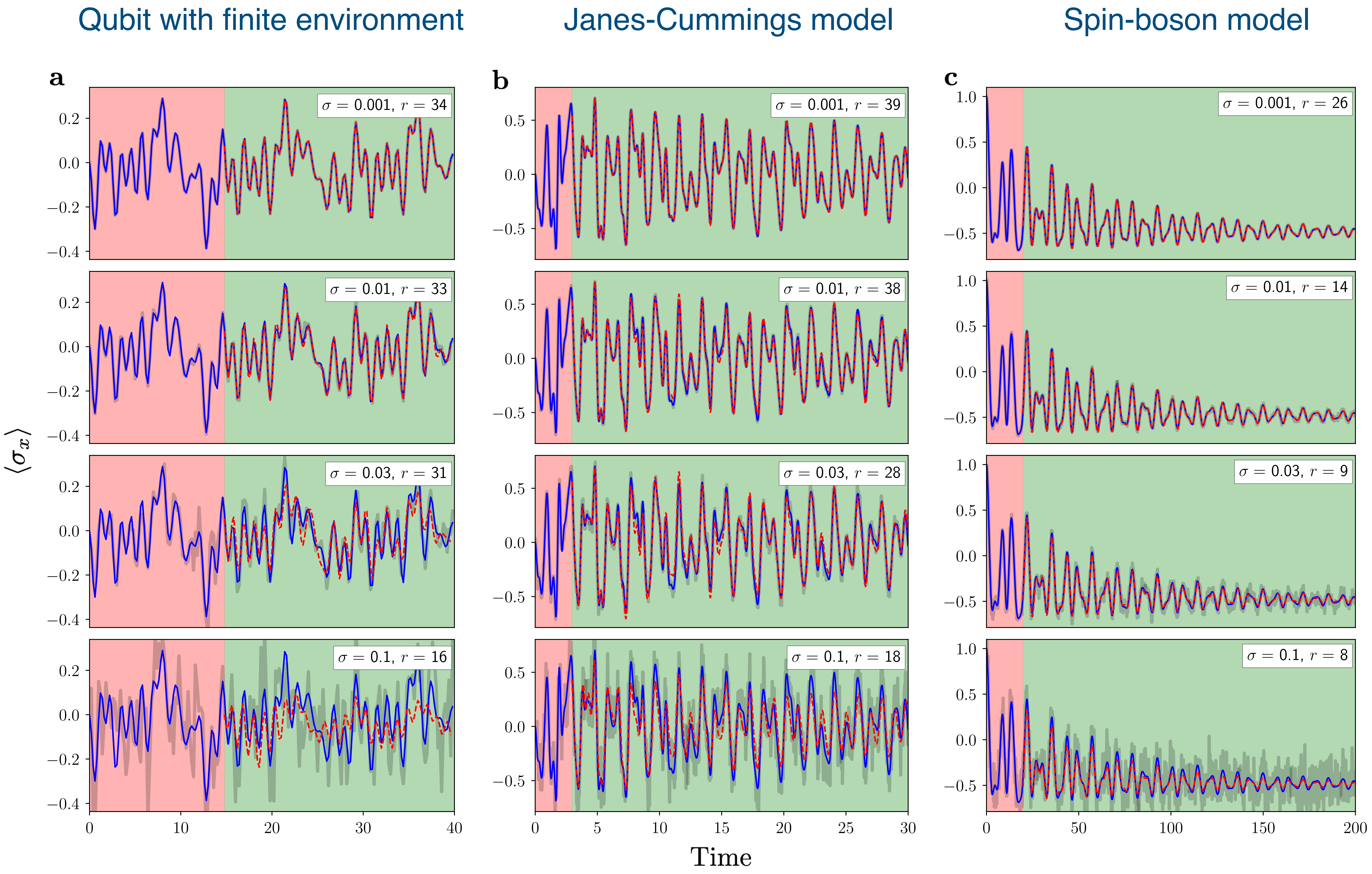
Qubit with a finite dimensional environment; we sample at random a quantum dynamical semigroup generator in the GKSL form. We simulate noise appearing during data acquisition of trajectories.

$$\mathcal{D}(\mathcal{S}_1, \mathcal{S}_2) = \frac{1}{LT} \sum_{l=1}^{L} \sum_{k=0}^{T-1} \|\varrho_1^{(l)}(k) - \varrho_2^{(l)}(k)\|_1,$$



As a valuable by-product of the rank estimation we obtain the denoised version of a data set.

Dynamics prediction and denoising for various models



Quantum simulation: Lattice models

Cold atoms meet lattice gauge theory

Monika Aidelsburger[1,2], Luca Barbiero[3], Alejandro Bermudez[4], Titas Chanda[5], Alexandre Dauphin[3], Daniel González-Cuadra[3], Przemysław R. Grzybowski[6], Simon Hands[7], Fred Jendrzejewski[8], Johannes Jünemann[9], Gediminas Juzeliunas[10], Valentin Kasper[3], Angelo Piga[3], Shi-Ju Ran[11], Matteo Rizzi[12,13], Gérman Sierra[14], Luca Tagliacozzo[15], Emanuele Tirrito[16], Torsten V. Zache[17,18], Jakub Zakrzewski[5], Erez Zohar[19], Maciej Lewenstein[3,201]

The central idea of this review is to consider quantum field theory models relevant for particle physics and replace the fermionic matter in these models by a bosonic one. This is mostly motivated by the fact that bosons are more "accessible" and easier to manipulate for experimentalists, but this "substitution" also leads to new physics and novel phenomena. It allows us to gain new information about among other things confinement and the dynamics of the deconfinement transition. We will thus consider bosons in dynamical lattices corresponding to the bosonic Schwinger or Z_2 Bose-Hubbard models. Another central idea of this review concerns atomic simulators of paradigmatic models of particle physics theory such as the Creutz-Hubbard ladder, or Gross-Neveu-Wilson and Wilson-Hubbard models. Finally, we will briefly describe our efforts to design experimentally friendly simulators of these and other models relevant for particle physics.

Quantum simulation: Quantum machine learning

Quantum Machine Learning in High Energy Physics

Wen Guan[1], **Gabriel Perdue**[2], **Arthur Pesah**[3], **Maria Schuld**[4], **Koji Terashi**[5], **Sofia Vallecorsa**[6], **Jean-Roch Vlimant**[7]

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[2] Fermi National Accelerator Laboratory, Fermilab Quantum Institute, PO Box 500, Batavia, IL, USA 60510-0500
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[4] University of KwaZulu-Natal School of Chemistry and Physics, Durban, ZA 4000
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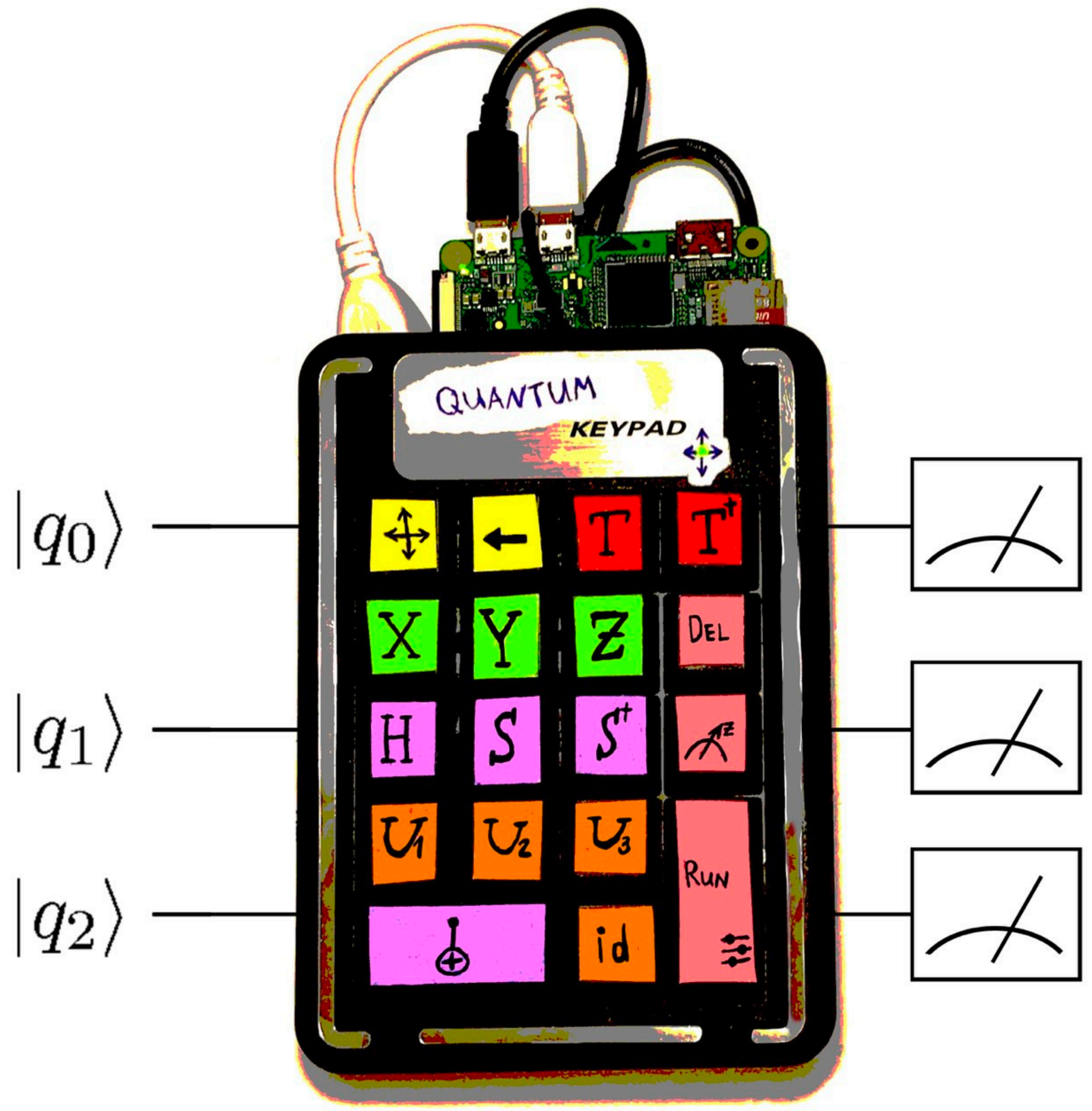
May 2020

Abstract. Machine learning has been used in high energy physics for a long time, primarily at the analysis level with supervised classification. Quantum computing was postulated in the early 1980s as way to perform computations that would not be tractable with a classical computer. With the advent of noisy intermediate-scale quantum computing devices, more quantum algorithms are being developed with the aim at exploiting the capacity of the hardware for machine learning applications. An interesting question is whether there are ways to apply quantum machine learning to High Energy Physics. This paper reviews the first generation of ideas that use quantum machine learning on problems in high energy physics and provide an outlook on future applications.

5.1. Quantum Graph Neural Networks for particle track reconstruction

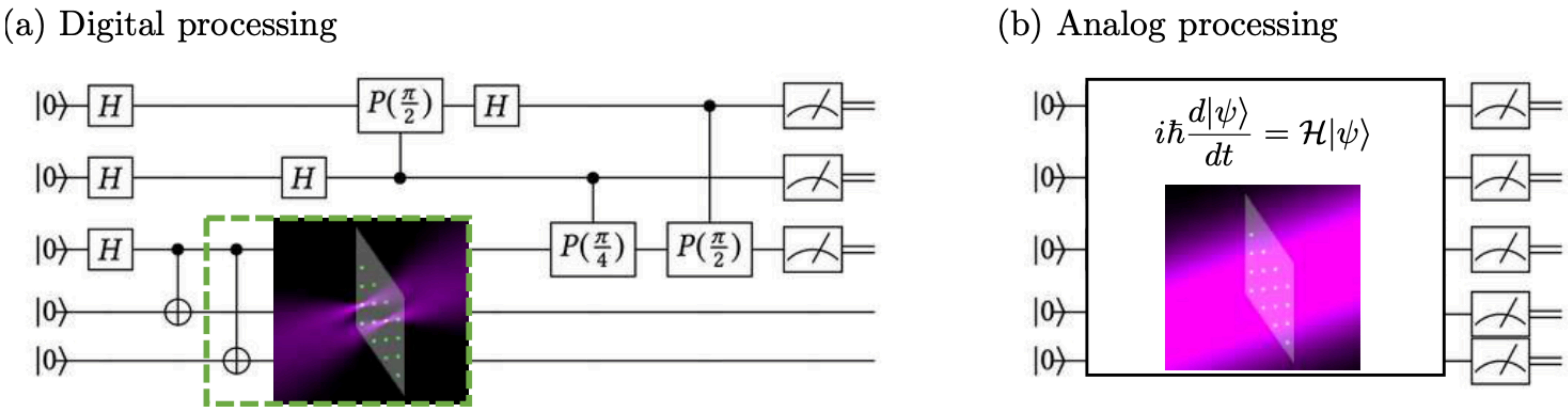
5.2. Classification Using Variational Quantum Circuits

Thank you for your attention!



Invitation to publish in EPJ QT

Quantum computing models: Digital quantum computer

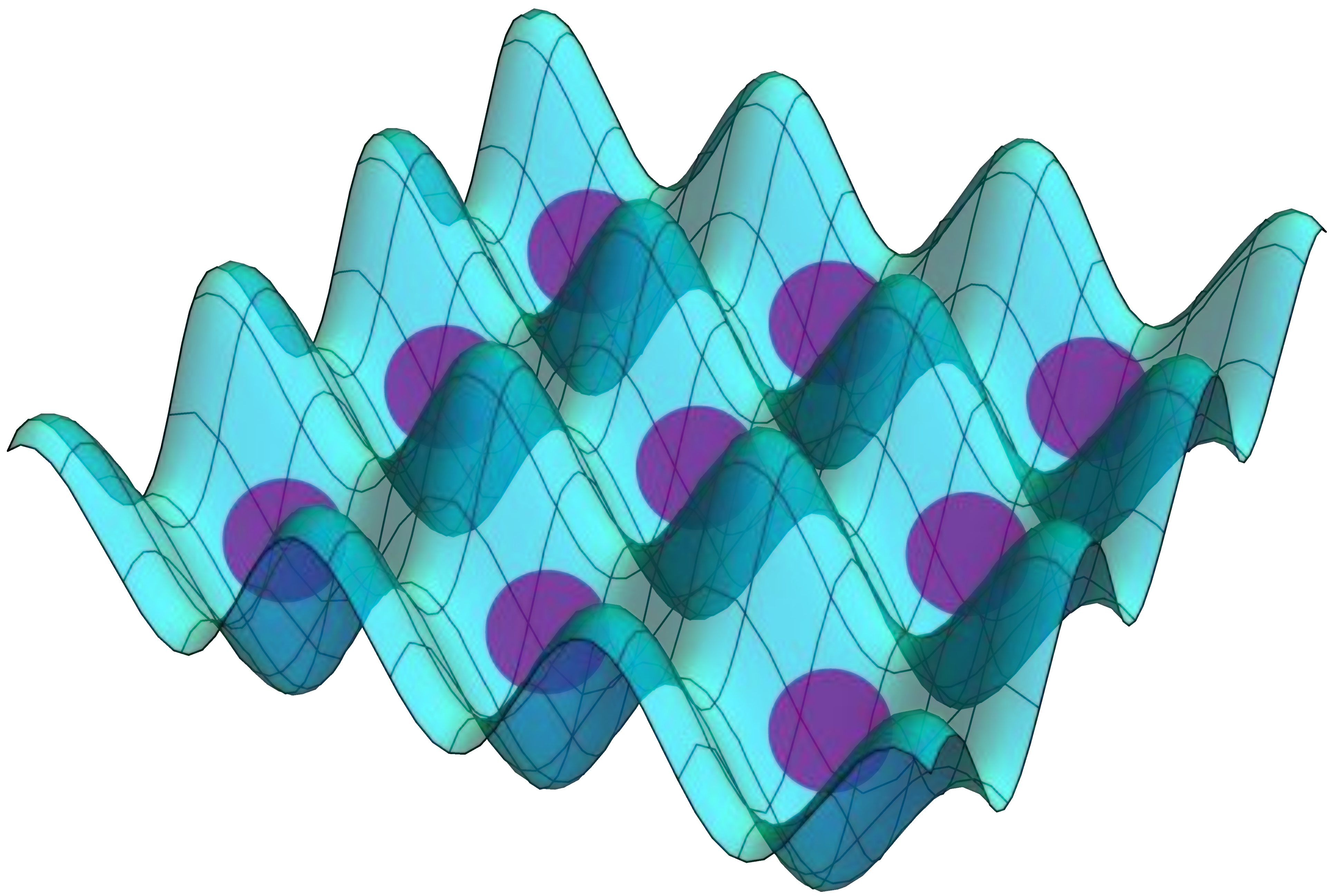


SIAM REVIEW
Vol. 50, No. 4, pp. 755–787

Adiabatic Quantum Computation Is Equivalent to Standard Quantum Computation*

Dorit Aharonov†
Wim van Dam‡
Julia Kempe§
Zeph Landau¶
Seth Lloyd‖
Oded Regev§

Quantum simulation: (Bose-)Hubbard model



$$\hat{H} = \sum_{i=1}^{N} \frac{p_i^2}{2m} + V(x_i) + \sum_{j \neq i} \frac{1}{2} U(x_i - x_j),$$

$$U(x_i - x_j) = \frac{4\pi\hbar^2 a_s}{m} \delta(x_i - x_j).$$

$$\hat{H} = \sum_i \epsilon_i \hat{b}_i^\dagger \hat{b}_i - \sum_{<i,j>} t_{i,j} \hat{b}_i^\dagger \hat{b}_j + U_0 \sum_i \hat{n}_i(\hat{n}_i - 1).$$

Quantum simulation: (Bose-)Hubbard model

Quantum phase transition from a superfluid to a Mott insulator in a gas of ultracold atoms

Markus Greiner*, Olaf Mandel*, Tilman Esslinger†, Theodor W. Hänsch* & Immanuel Bloch*

* *Sektion Physik, Ludwig-Maximilians-Universität, Schellingstrasse 4/III, D-80799 Munich, Germany, and Max-Planck-Institut für Quantenoptik, D-85748 Garching, Germany*

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Quantum simulation: ‘Higgs’ mode

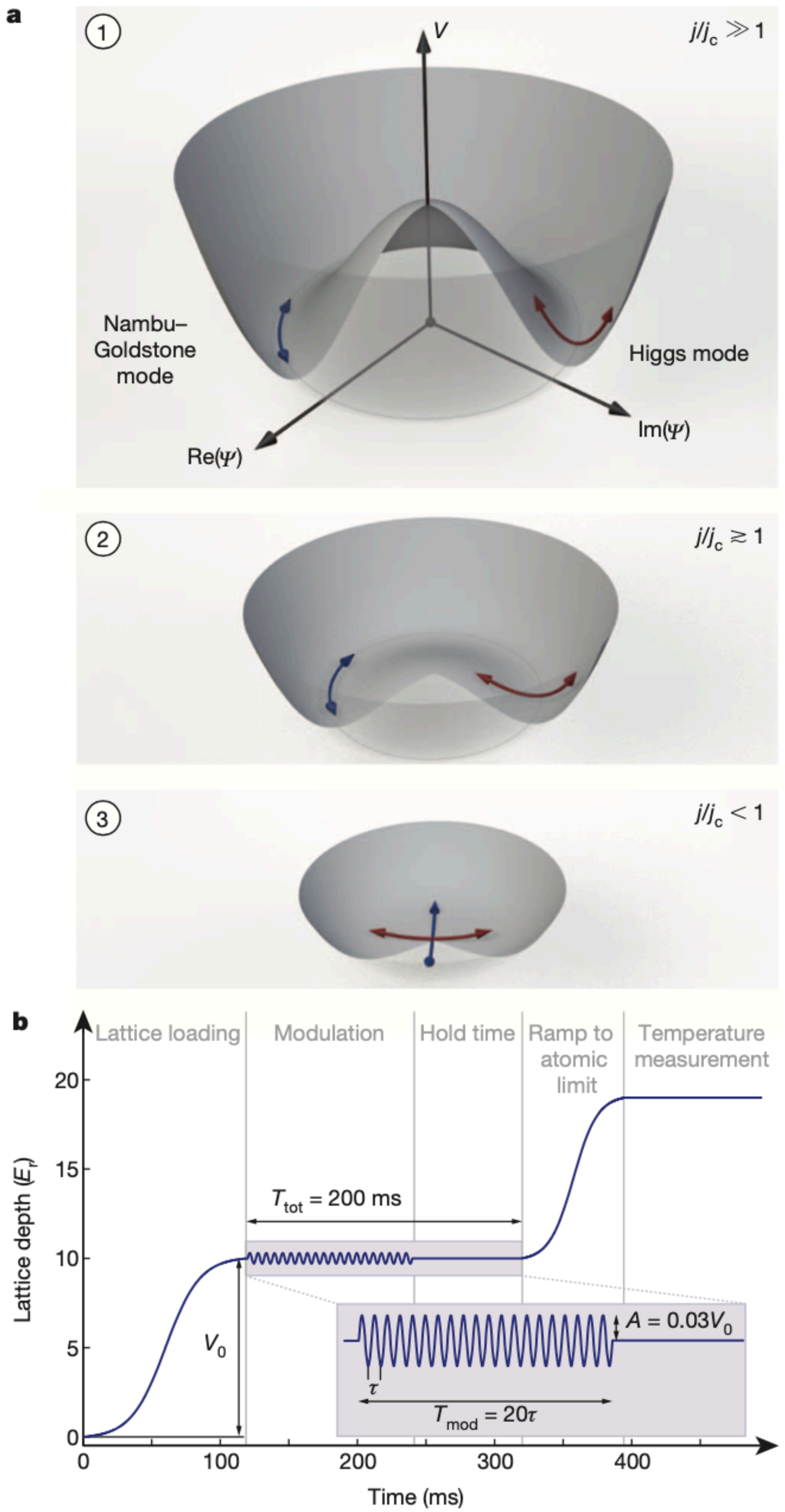
LETTER

doi:10.1038/nature11255

The ‘Higgs’ amplitude mode at the two-dimensional superfluid/Mott insulator transition

Manuel Endres[1], Takeshi Fukuhara[1], David Pekker[2], Marc Cheneau[1], Peter Schauß[1], Christian Gross[1], Eugene Demler[3], Stefan Kuhr[1,4] & Immanuel Bloch[1,5]

Spontaneous symmetry breaking plays a key role in our understanding of nature. In relativistic quantum field theory, a broken continuous symmetry leads to the emergence of two types of fundamental excitation: massless Nambu–Goldstone modes and a massive ‘Higgs’ amplitude mode. An excitation of Higgs type is of crucial importance in the standard model of elementary particle physics[1], and also appears as a fundamental collective mode in quantum many-body systems[2]. Whether such a mode exists in low-dimensional systems as a resonance-like feature, or whether it becomes overdamped through coupling to Nambu–Goldstone modes, has been a subject of debate[2–9]. Here we experimentally find and study a Higgs mode in a two-dimensional neutral superfluid close to a quantum phase transition to a Mott insulating phase. We unambiguously identify the mode by observing the expected reduction in frequency of the onset of spectral response when approaching the transition point. In this regime, our system is described by an effective relativistic field theory with a two-component quantum field[2,7], which constitutes a minimal model for spontaneous breaking of a continuous symmetry. Additionally, all microscopic parameters of our system are known from first principles and the resolution of our measurement allows us to detect excited states of the many-body system at the level of individual quasiparticles. This allows for an in-depth study of Higgs excitations that also addresses the consequences of the reduced dimensionality and confinement of the system. Our work constitutes a step towards exploring emergent relativistic models with ultracold atomic gases.



Quantum simulation: 'Higgs' mode

LETTER

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The 'Higgs' amplitude mode at the two-dimensional superfluid/Mott insulator transition

Manuel Endres[1], Takeshi Fukuhara[1], David Pekker[2], Marc Cheneau[1], Peter Schauß[1], Christian Gross[1], Eugene Demler[3], Stefan Kuhr[1,4] & Immanuel Bloch[1,5]

Spontaneous symmetry breaking plays a key role in our understanding of nature. In relativistic quantum field theory, a broken continuous symmetry leads to the emergence of two types of fundamental excitation: massless Nambu–Goldstone modes and a massive 'Higgs' amplitude mode. An excitation of Higgs type is of crucial importance in the standard model of elementary particle physics[1], and also appears as a fundamental collective mode in quantum many-body systems[2]. Whether such a mode exists in low-dimensional systems as a resonance-like feature, or whether it becomes overdamped through coupling to Nambu–Goldstone modes, has been a subject of debate[2–9]. Here we experimentally find and study a Higgs mode in a two-dimensional neutral superfluid close to a quantum phase transition to a Mott insulating phase. We unambiguously identify the mode by observing the expected reduction in frequency of the onset of spectral response when approaching the transition point. In this regime, our system is described by an effective relativistic field theory with a two-component quantum field[2,7], which constitutes a minimal model for spontaneous breaking of a continuous symmetry. Additionally, all microscopic parameters of our system are known from first principles and the resolution of our measurement allows us to detect excited states of the many-body system at the level of individual quasiparticles. This allows for an in-depth study of Higgs excitations that also addresses the consequences of the reduced dimensionality and confinement of the system. Our work constitutes a step towards exploring emergent relativistic models with ultracold atomic gases.

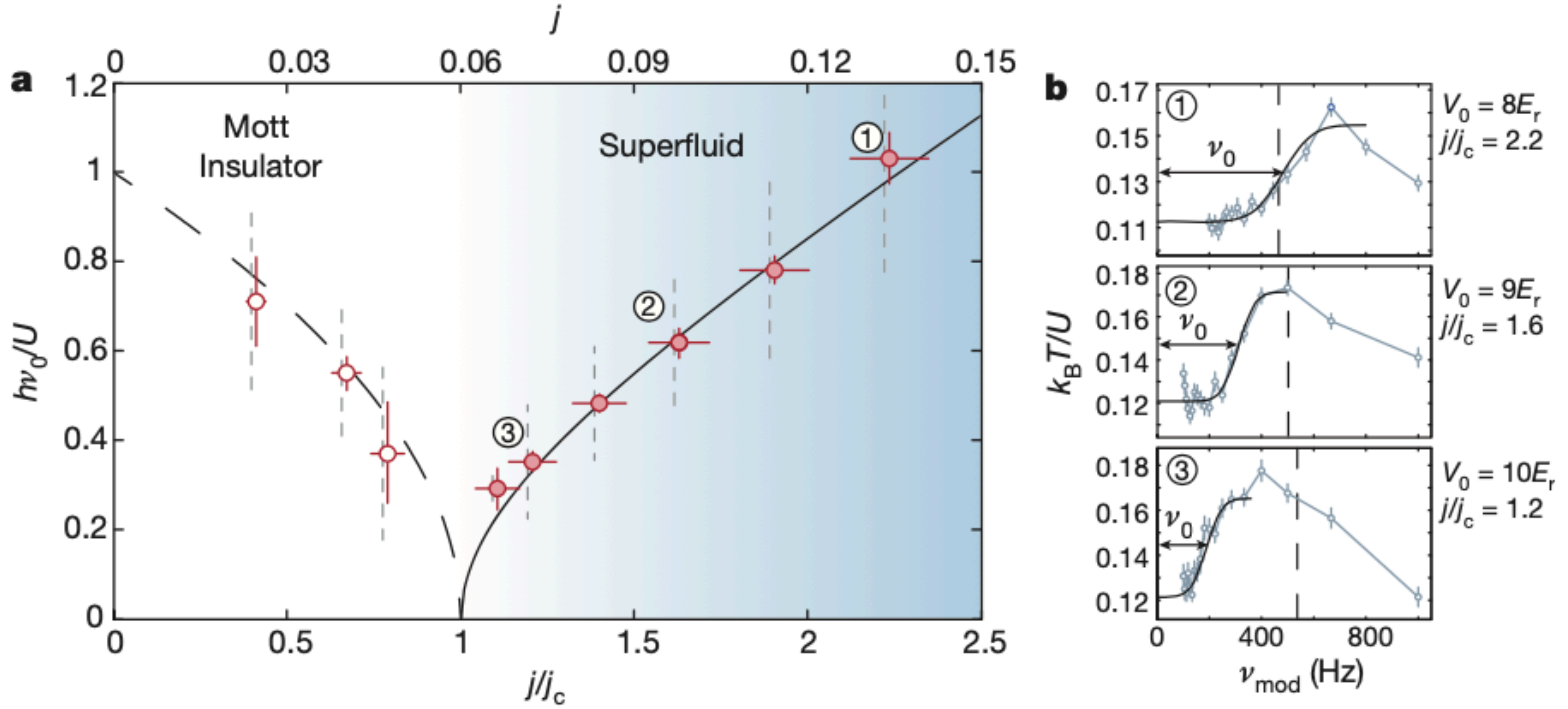

Figure 2 | Softening of the Higgs mode. a, The fitted gap values $h\nu_0/U$ (circles) show a characteristic softening close to the critical point in quantitative agreement with analytic predictions for the Higgs and the Mott gap (solid line and dashed line, respectively; see text). Horizontal and vertical error bars denote the experimental uncertainty of the lattice depths and the fit error for the centre frequency of the error function, respectively (Methods). Vertical dashed lines denote the widths of the fitted error function and characterize the sharpness of the spectral onset. The blue shading highlights the superfluid region. **b**, Temperature response to lattice modulation (circles and connecting blue line) and fit with an error function (solid black line) for the three different points labelled in **a**. As the coupling j approaches the critical value j_c, the change in the gap values to lower frequencies is clearly visible (from panel 1 to panel 3). Vertical dashed lines mark the frequency U/h corresponding to the on-site interaction. Each data point results from an average of the temperatures over ~50 experimental runs. Error bars, s.e.m.

Quantum simulation: Lattice models

ARTICLE

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Self-verifying variational quantum simulation of lattice models

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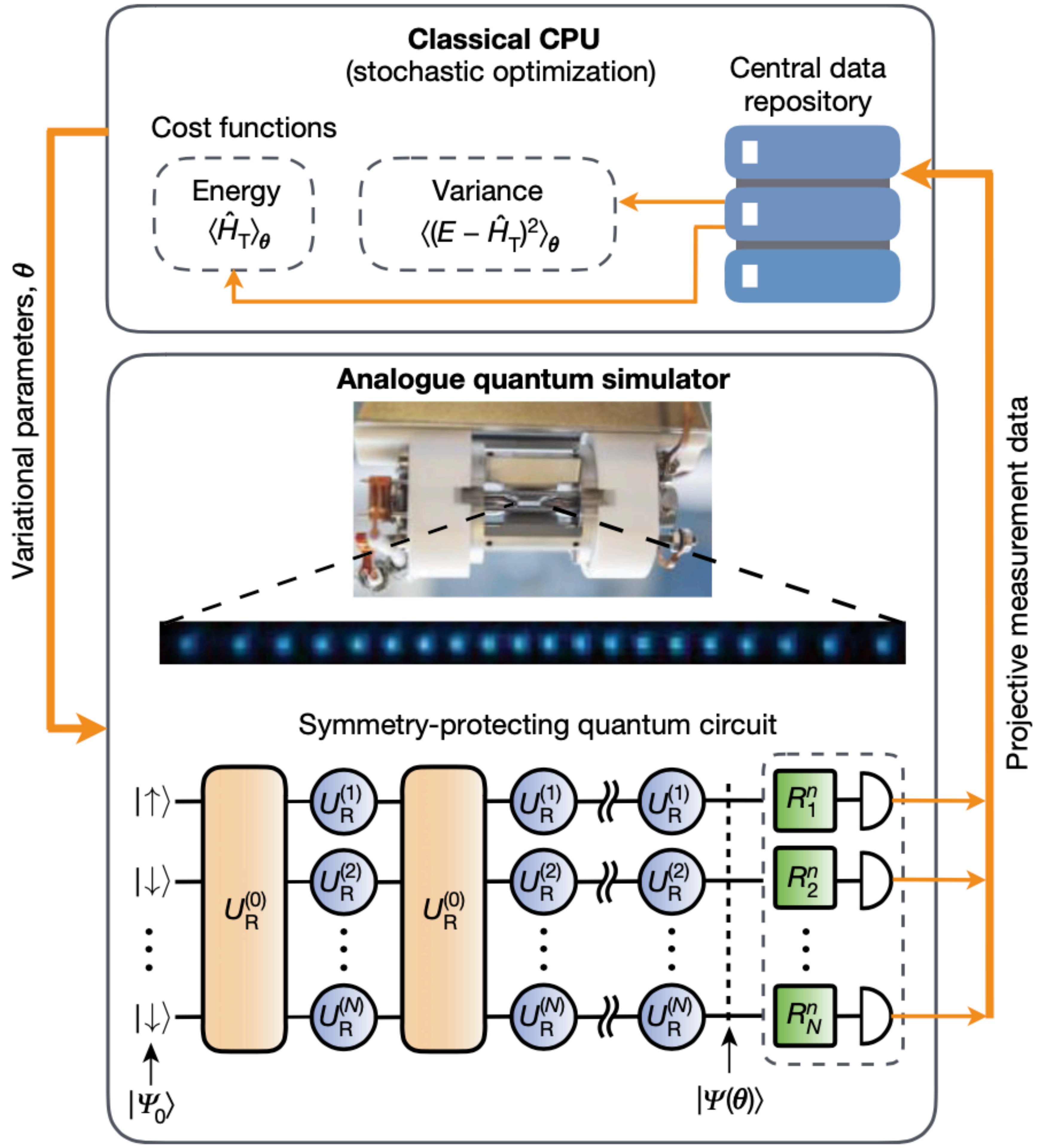
$$\hat{H}_{\mathrm{T}} = w \sum_{j=1}^{N-1} [\hat{\sigma}_j^+ \hat{\sigma}_{j+1}^- + \mathrm{H.c.}] + \frac{m}{2} \sum_{j=1}^{N} (-1)^j \hat{\sigma}_j^z + \bar{g} \sum_{j=1}^{N} \hat{L}_j^2$$



Quantum simulation: Lattice models

Cold atoms meet lattice gauge theory

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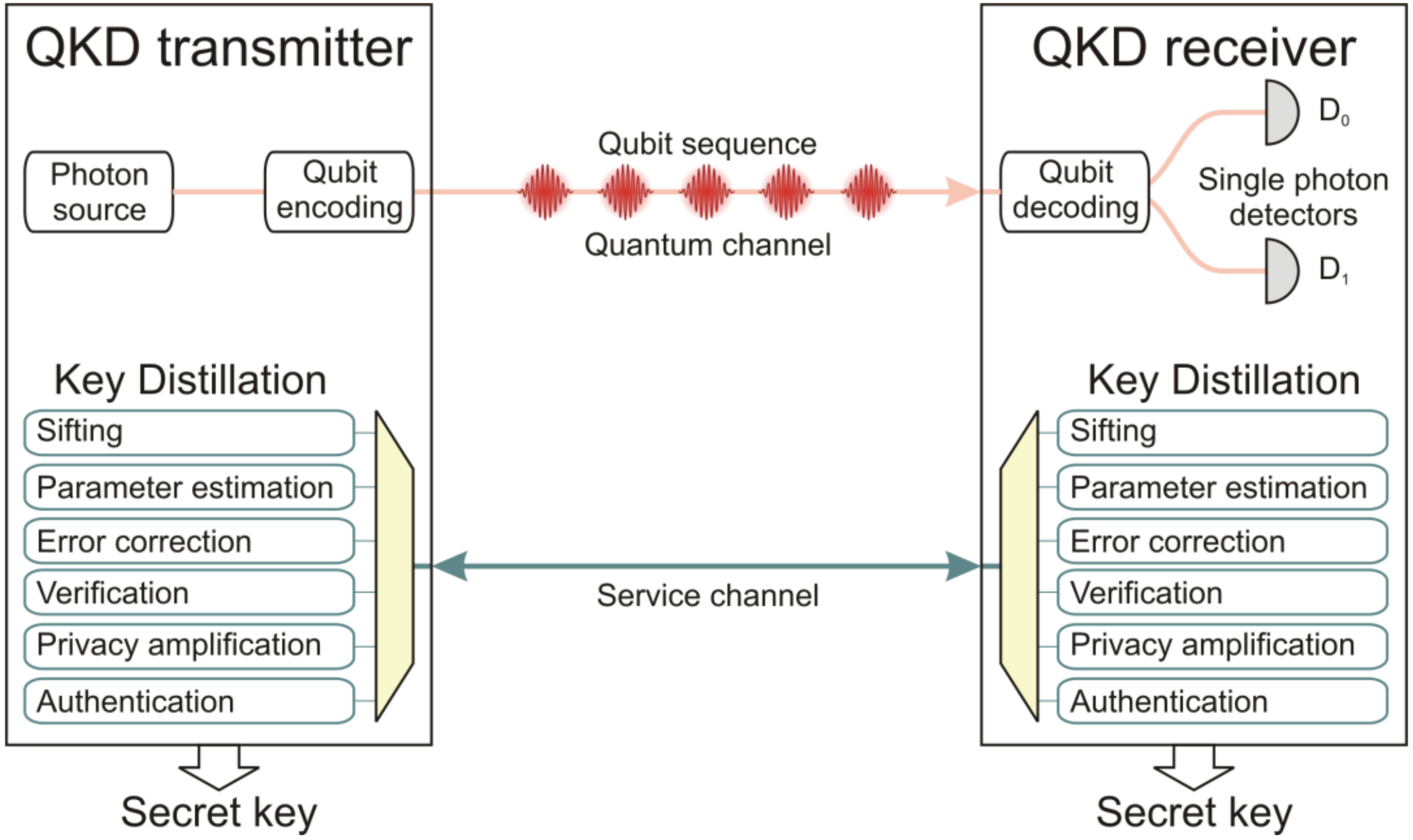
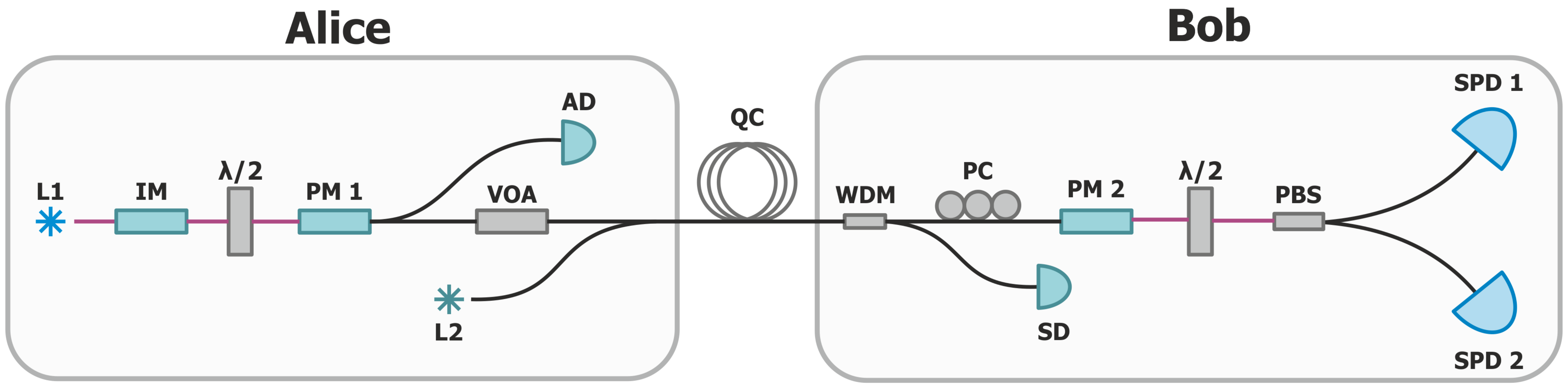
The central idea of this review is to consider quantum field theory models relevant for particle physics and replace the fermionic matter in these models by a bosonic one. This is mostly motivated by the fact that bosons are more "accessible" and easier to manipulate for experimentalists, but this "substitution" also leads to new physics and novel phenomena. It allows us to gain new information about among other things confinement and the dynamics of the deconfinement transition. We will thus consider bosons in dynamical lattices corresponding to the bosonic Schwinger or Z_2 Bose-Hubbard models. Another central idea of this review concerns atomic simulators of paradigmatic models of particle physics theory such as the Creutz-Hubbard ladder, or Gross-Neveu-Wilson and Wilson-Hubbard models. Finally, we will briefly describe our efforts to design experimentally friendly simulators of these and other models relevant for particle physics.

Example: Quantum communications



- One cannot take a measurement without perturbing the system.
- One cannot determine simultaneously the position and the momentum of a particle with arbitrarily high accuracy (Heisenberg uncertainty principle).
- One cannot duplicate an unknown quantum state (No-cloning theorem).
- One cannot simultaneously measure the polarization of a photon in the vertical-horizontal basis and simultaneously in the diagonal basis -> BB84.

Example: Quantum communications

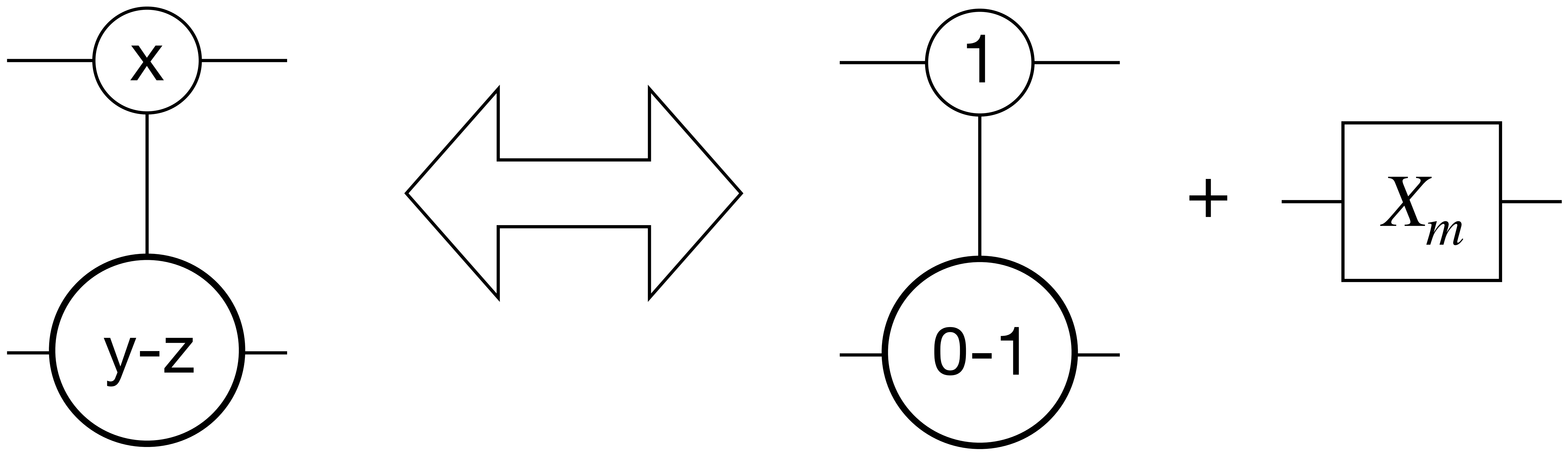


Parameters	Laboratory conditions	Urban conditions
L	25.5 km	30.6 km
Attn	4.8 dB	11.7 dB
QBER	1.6%	5.1%
R_{rec}	3.2 kbit/s	1.5 kbit/s

Table I. **Implementation parameters and experimental results on realization of the plug-and-play scheme with the BB84 protocol**. Results of operating of the developed setup in laboratory and urban conditions, where L is the length of the communication channel and Attn is the total attenuation. The generation rate R_{rec} is for keys after information reconciliation.

Experimental prospectives

Required set of two-qudit gate can be obtained from the one particular two-qudit gate and the single-qudit gate



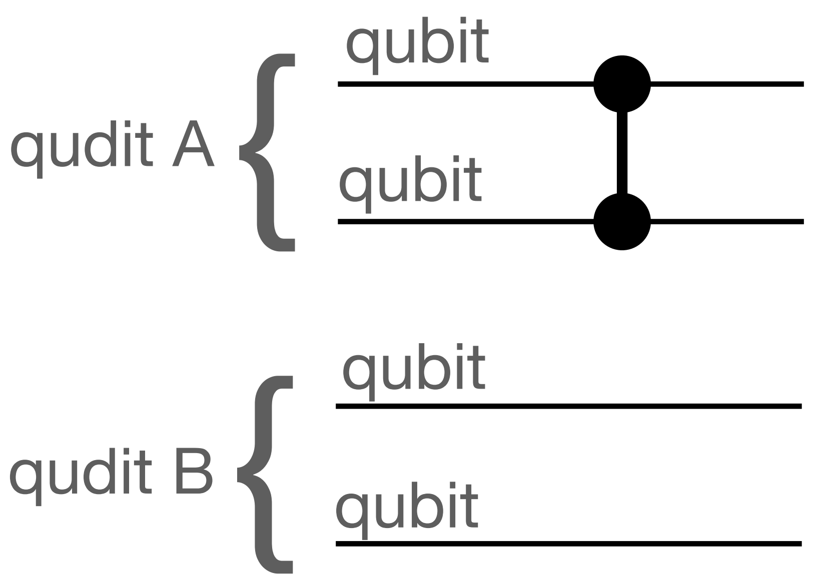
$$X_m = |0\rangle\langle m| + |m\rangle\langle 0| + \{\mathbf{I} - |0\rangle\langle 0| - |1\rangle\langle 1|\}$$

In experiment we have some concrete ('native') two-qubit gate, so the scheme works for experimentally relevant cases

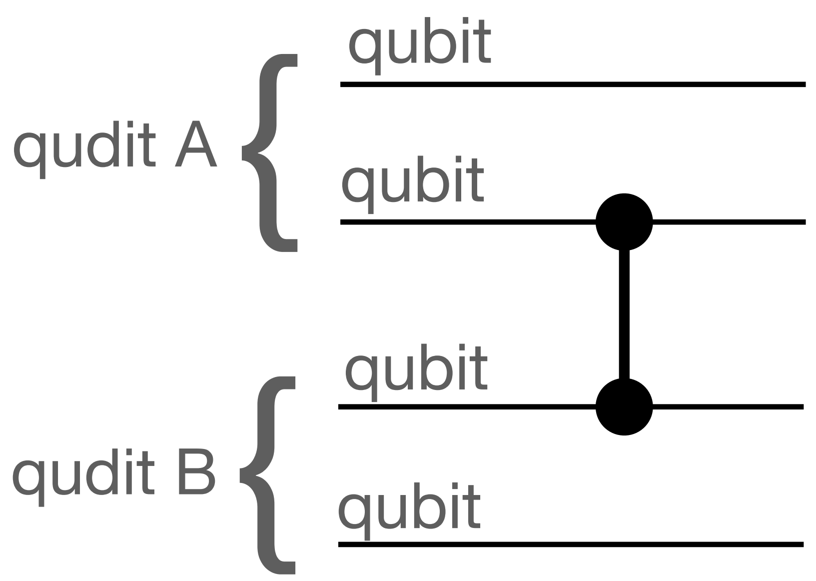
Scalability of the qudit approach: Two-qudit example with CZ

$$|11\rangle \rightarrow -|11\rangle$$

$$|xy\rangle \rightarrow |xy\rangle \text{ for } xy \neq 1$$



0 two-quidit operations
VS
1 two-qubit operation



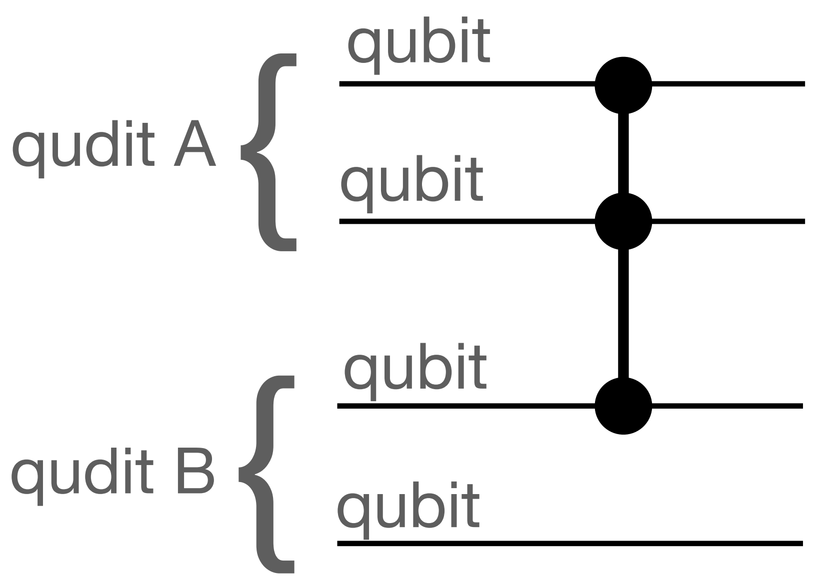
$$|01\rangle_A|10\rangle_B \rightarrow -|01\rangle_A|10\rangle_B$$

$$|01\rangle_A|11\rangle_B \rightarrow -|01\rangle_A|11\rangle_B$$

$$|11\rangle_A|10\rangle_B \rightarrow -|11\rangle_A|10\rangle_B$$

$$|11\rangle_A|11\rangle_B \rightarrow -|11\rangle_A|11\rangle_B$$

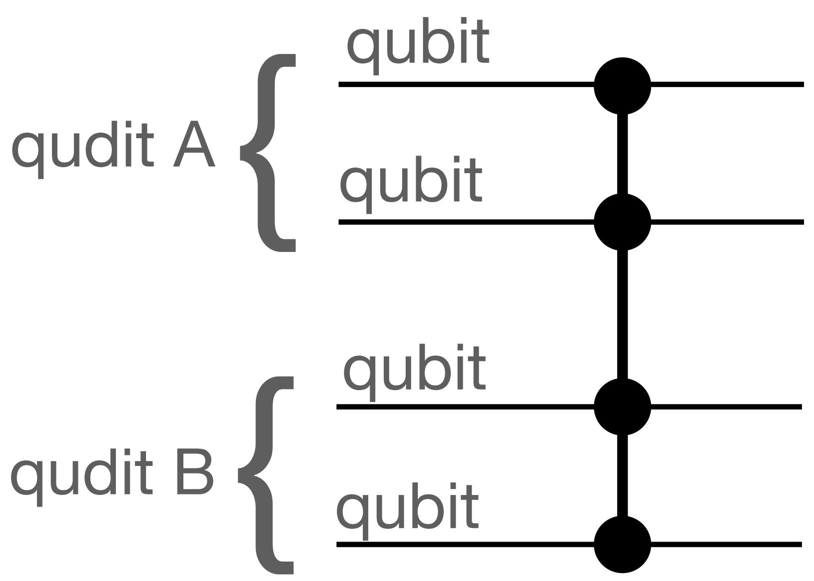
4 two-quidit operations
VS
1 two-qubit operation



$$|11\rangle_A|10\rangle_B \rightarrow -|11\rangle_A|10\rangle_B$$

$$|11\rangle_A|11\rangle_B \rightarrow -|11\rangle_A|11\rangle_B$$

2 two-quidit operations
VS
6 two-qubit operations



$$|11\rangle_A|11\rangle_B \rightarrow -|11\rangle_A|11\rangle_B$$

1 two-quidit operation
VS
26 two-qubit operation

The number of two-particle operations can be reduced significantly! But not always…

Realization of gates with ‘virtual’ qubits

Elementary gates for quantum computation

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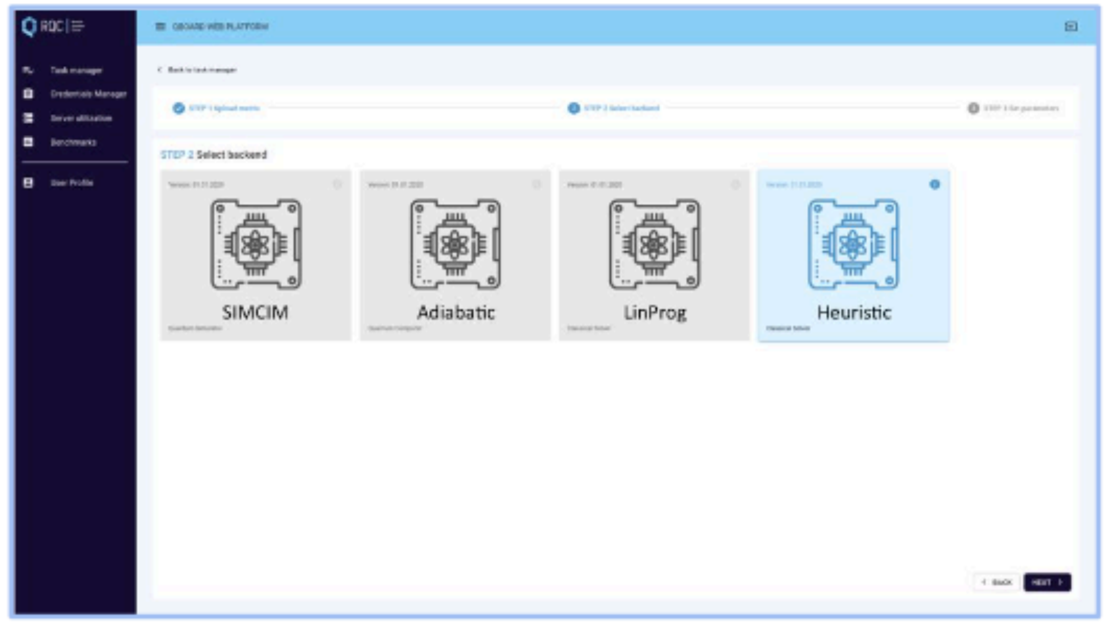
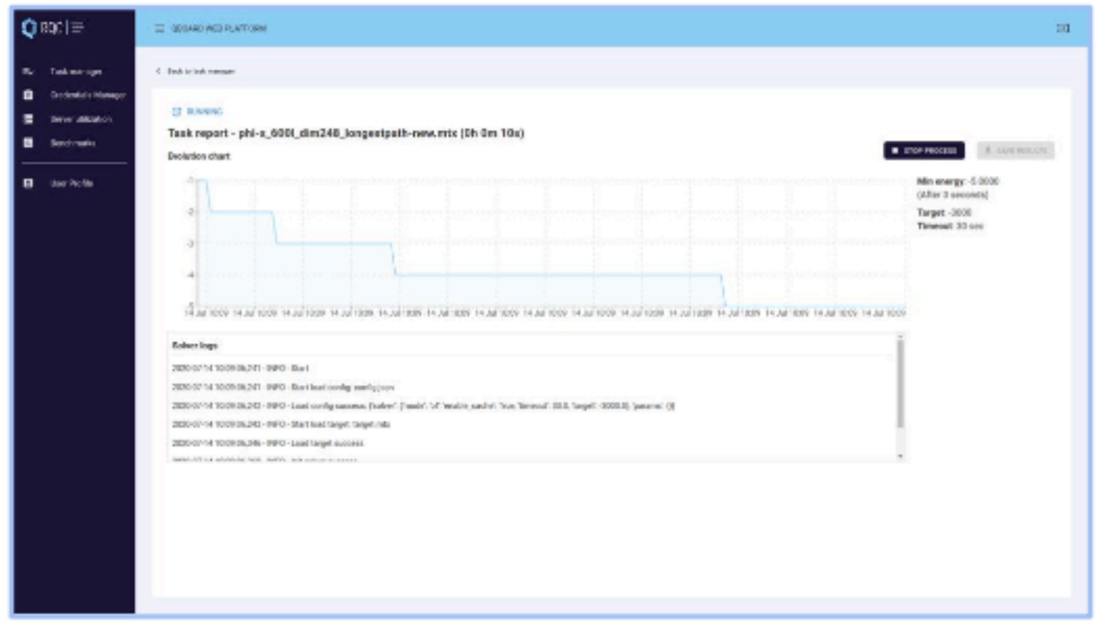
Abstract

We show that a set of gates that consists of all one-bit quantum gates (U(2)) and the two-bit exclusive-or gate (that maps Boolean values (x, y) to $(x, x \oplus y)$) is universal in the sense that all unitary operations on arbitrarily many bits n ($\mathrm{U}(2^n)$) can be expressed as compositions of these gates. We investigate the number of the above gates required to implement other gates, such as generalized Deutsch-Toffoli gates, that apply a specific U(2) transformation to one input bit if and only if the logical AND of all remaining input bits is satisfied. These gates play a central role in many proposed constructions of quantum computational networks. We derive upper and lower bounds on the exact number of elementary gates required to build up a variety of two- and three-bit quantum gates, the asymptotic number required for n-bit Deutsch-Toffoli gates, and make some observations about the number required for arbitrary n-bit unitary operations.

PACS numbers: 03.65.Ca, 07.05.Bx, 02.70.Rw, 89.80.+h

Quantum optimization platform: QBoard





QBoard — cloud-based quantum computing platform

The unified cloud platform for solving industrial problems on turnkey quantum computers (from setup to final result).
Learn more

qboard.tech

TRL: 6-7

SimCIM — quantum computing emulator (quantum-inspired algorithms)

The use of this emulator allows an early assessment of the applicability and potential benefits of using a quantum computer, as well as solving combinatorial problems that are not available for traditional computational methods.
Learn more

TRL: 7-8

Financial sector	Material Design	Telecom	Nuclear industry	Energy sector	Biomed	Consulting
Portfolio optimization and risk modelling based on quantum and quantum-inspired algorithms	Quantum chemistry and simulation of advanced materials based on quantum-enhanced machine learning	Optimizing 5G network topology with asymptotic speedup	Scheduling maintenance intervals for nuclear reactors	Solving optimization problems of the oil & gas sector	DNA analysis and genome assembly based on quantum-inspired algorithms	2 consulting projects completed

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