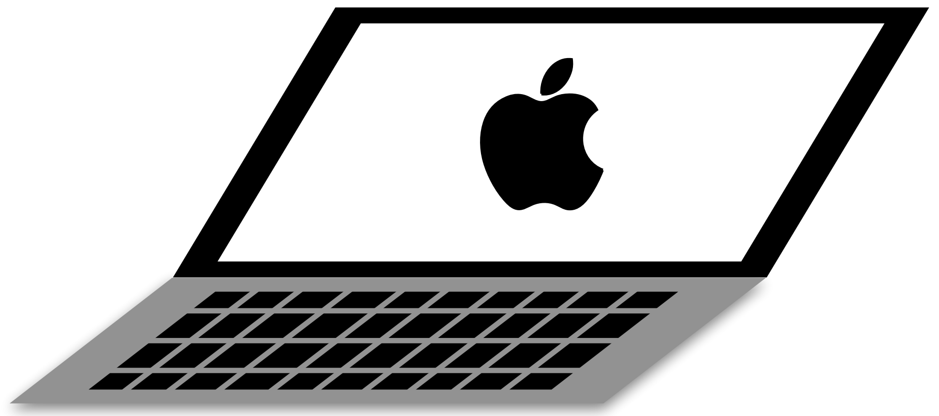
Quantum simulation is a motivating application for large-scale quantum computers. Quantum simulation of quantum field theories involves challenges of regularization, renormalization and gauge symmetry. The light front provides a particularly appealing approach for quantum simulation, allowing techniques developed in other fields to be reused. I will give an introduction to our work in quantum simulation of the yukawa model and early results on QCD, and discuss the prospects for large-scale calculations in the future.

Light Front Calculations on Quantum Computers

Peter Love
Physics and Astronomy, Tufts University (Until July 1)
Brookhaven National Laboratory (Until July 1)
From July 1: Physics & Computer Science, University of Toronto
QMatter Inc.

Simulating Many-Body Quantum Mechanics



$$H|\psi\rangle = E|\psi\rangle$$

Bottleneck:

$$|\psi\rangle \in \mathcal{H};\ \dim(\mathcal{H}) = \mathcal{O}\Big(\exp(\text{n particles})\Big)$$

Classically either:

Exponential memory: Store $O(2^n)$ complex amplitudes in classical memory

Or:

Exponential time: Add up $O(2^n)$ amplitudes of separate paths

Quantum Bits

Two states, zero and one

What makes a good qubit? Choose a system
1) Where you can make a two outcome measurement really well.
2) Where the system is highly mature experimentally.
3) Good control, but weak coupling to environment.

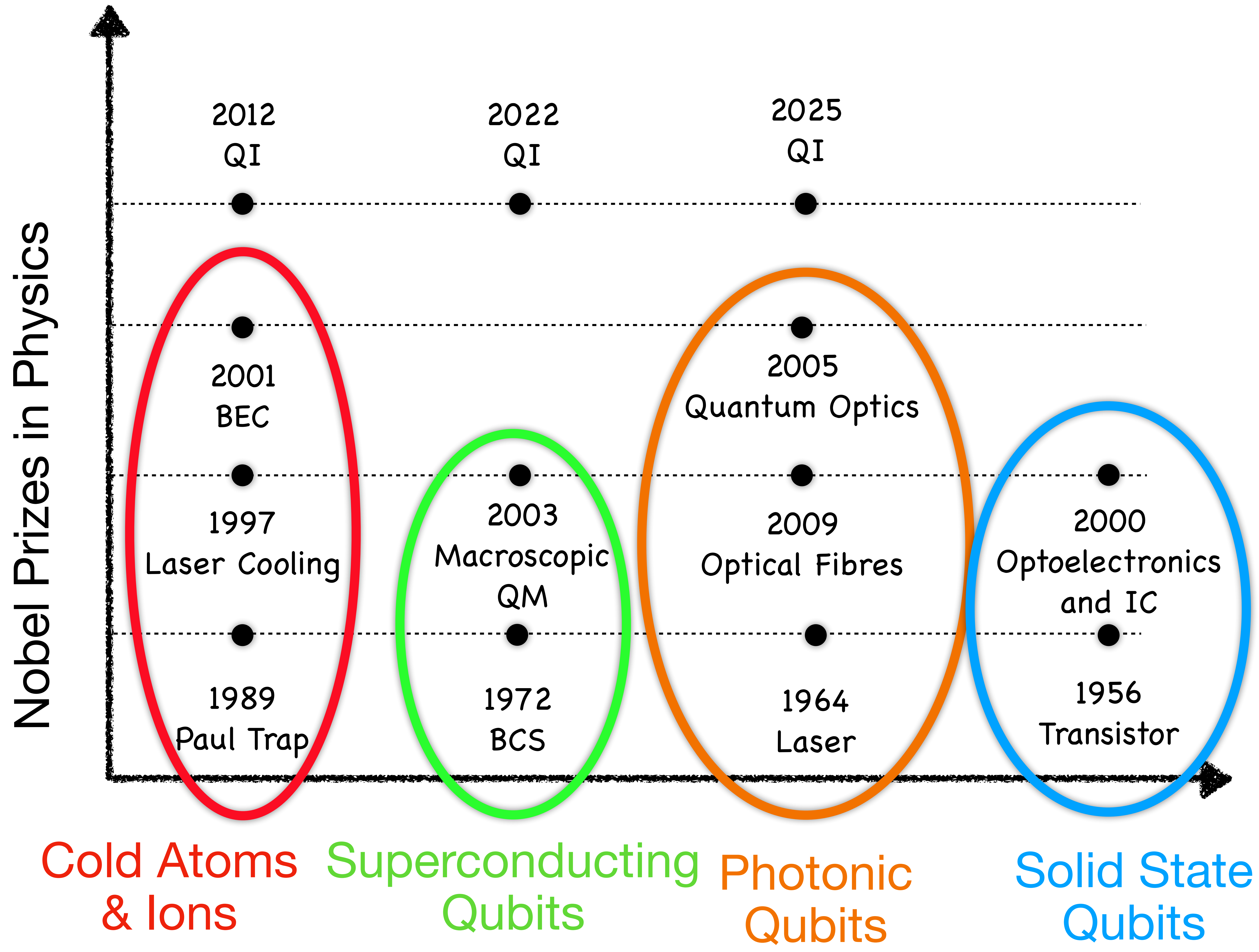
Qubit state: $\begin{pmatrix} \langle 0 | \psi \rangle \\ \langle 1 | \psi \rangle \end{pmatrix}$

Born's rule: $P(0) = |\langle 0 | \psi \rangle|^2$

$P(1) = |\langle 1 | \psi \rangle|^2$

"Partly a thing,
and partly our knowledge of a thing"

Experimental Implementation



Google AI Quantum

IBM

Microsoft

XANADU

QUANTINUUM

Oratomic

ALICE & BOB

IQM

QuEra

QUANTUM MACHINES

Many Quantum Bits

Hilbert space is tensor product of individual qubit Hilbert spaces

n-Qubit Hilbert space: $\mathscr{H} = \mathscr{H}_1 \otimes \mathscr{H}_2 \otimes \ldots \otimes \mathscr{H}_n$

Completely separable states: $|\psi\rangle = |\psi_1\rangle \otimes |\psi_2\rangle \otimes \ldots \otimes |\psi_n\rangle$

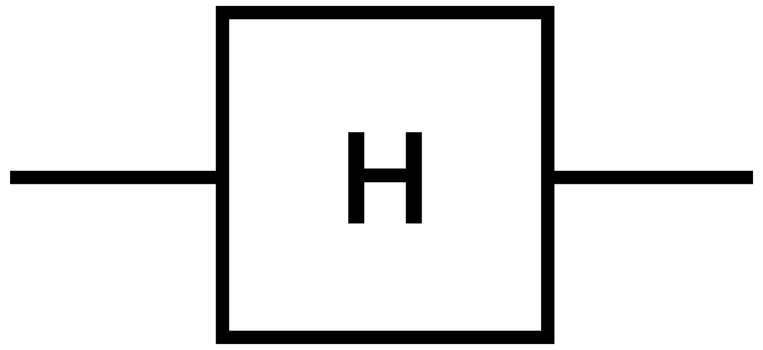
If a state is not completely separable it is entangled.

Partially entangled state: $|\psi\rangle = |\psi_{1234}\rangle \otimes \ldots |\psi_{n-1\rangle} \otimes |\psi_n\rangle$

Globally entangled state: $|\psi\rangle = |\psi_{1234\ldots n}\rangle$

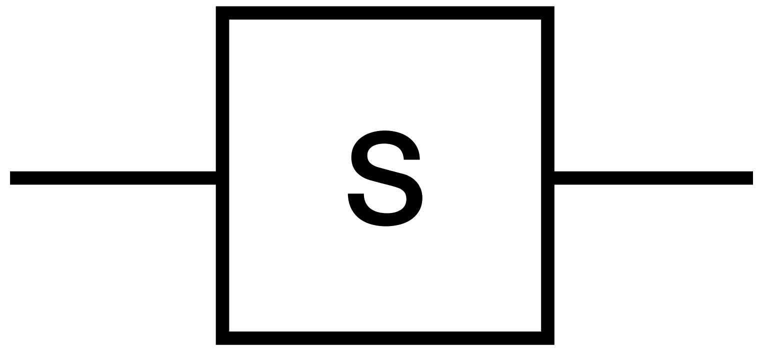
Quantum Gates: Universal Gate Set

Hadamard



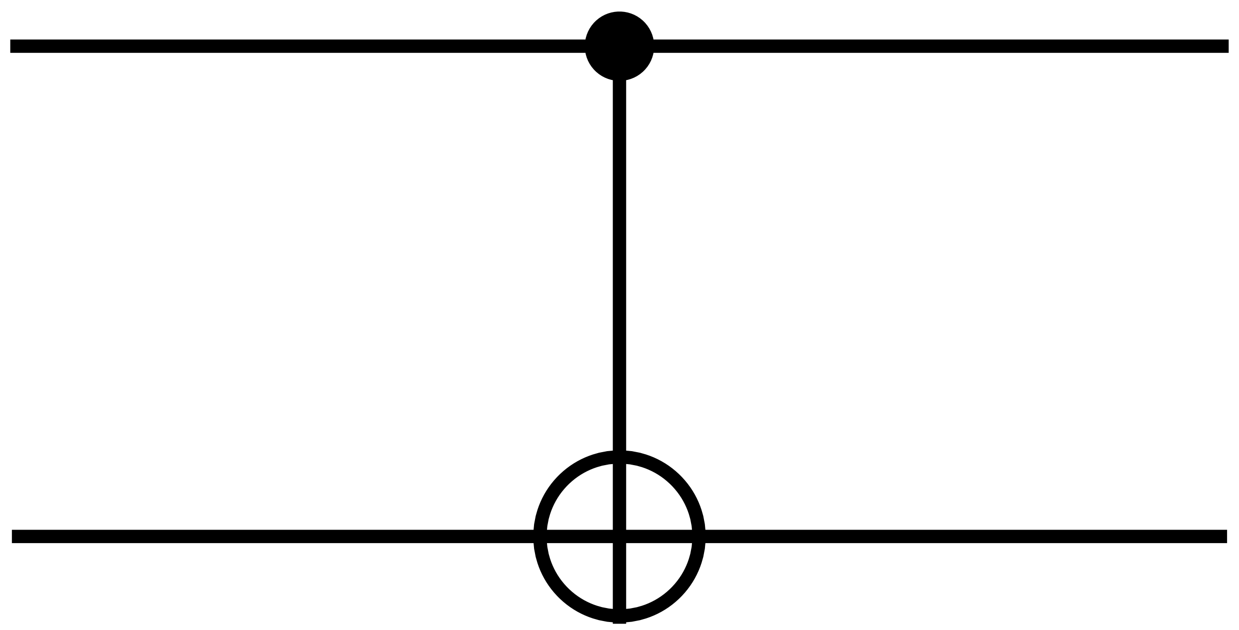
$$\begin{pmatrix} \langle 0 | \psi(t) \rangle \\ \langle 1 | \psi(t) \rangle \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \begin{pmatrix} \langle 0 | \psi(0) \rangle \\ \langle 1 | \psi(0) \rangle \end{pmatrix}$$

S-gate



$$\begin{pmatrix} \langle 0 | \psi(t) \rangle \\ \langle 1 | \psi(t) \rangle \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & i \end{pmatrix} \begin{pmatrix} \langle 0 | \psi(0) \rangle \\ \langle 1 | \psi(0) \rangle \end{pmatrix}$$

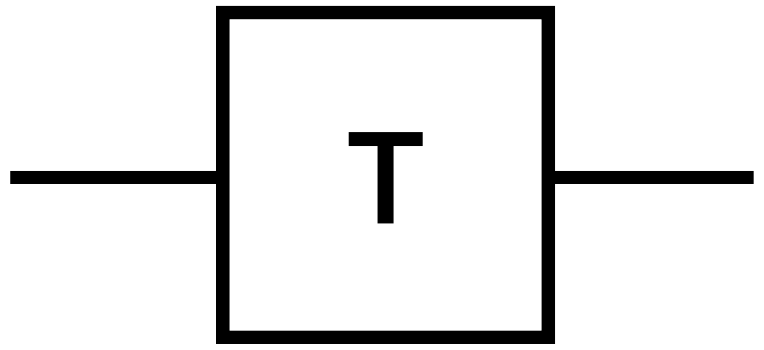
CNOT



$$\begin{pmatrix} \langle 00 | \psi(t) \rangle \\ \langle 01 | \psi(t) \rangle \\ \langle 10 | \psi(t) \rangle \\ \langle 11 | \psi(t) \rangle \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} \langle 00 | \psi(0) \rangle \\ \langle 01 | \psi(0) \rangle \\ \langle 10 | \psi(0) \rangle \\ \langle 11 | \psi(0) \rangle \end{pmatrix}$$

Clifford Gates

T-gate

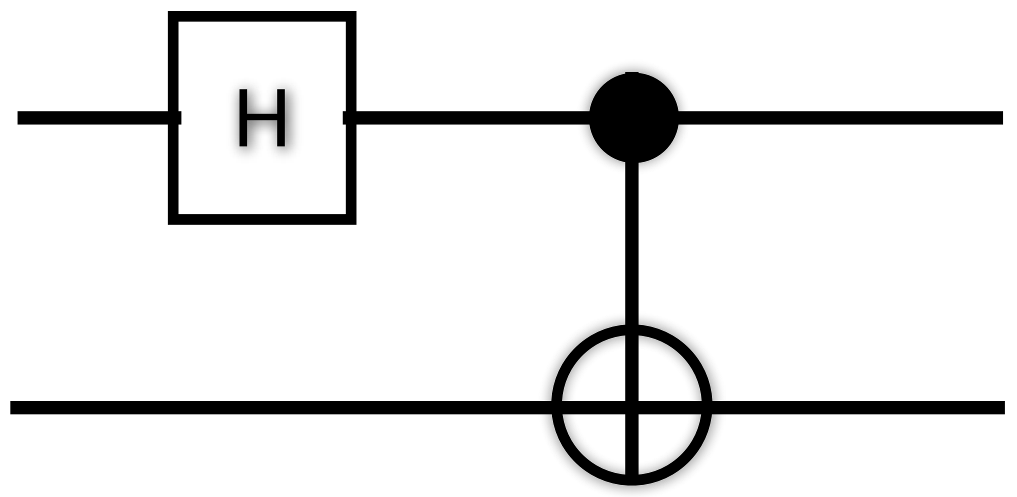


$$\begin{pmatrix} \langle 0 | \psi(t) \rangle \\ \langle 1 | \psi(t) \rangle \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & \sqrt{i} \end{pmatrix} \begin{pmatrix} \langle 0 | \psi(0) \rangle \\ \langle 1 | \psi(0) \rangle \end{pmatrix}$$

Quantum Circuit Model

Quantum Circuit: a single qubit is denoted by a line

Complex circuits - many lines, many gates



$|0\rangle$

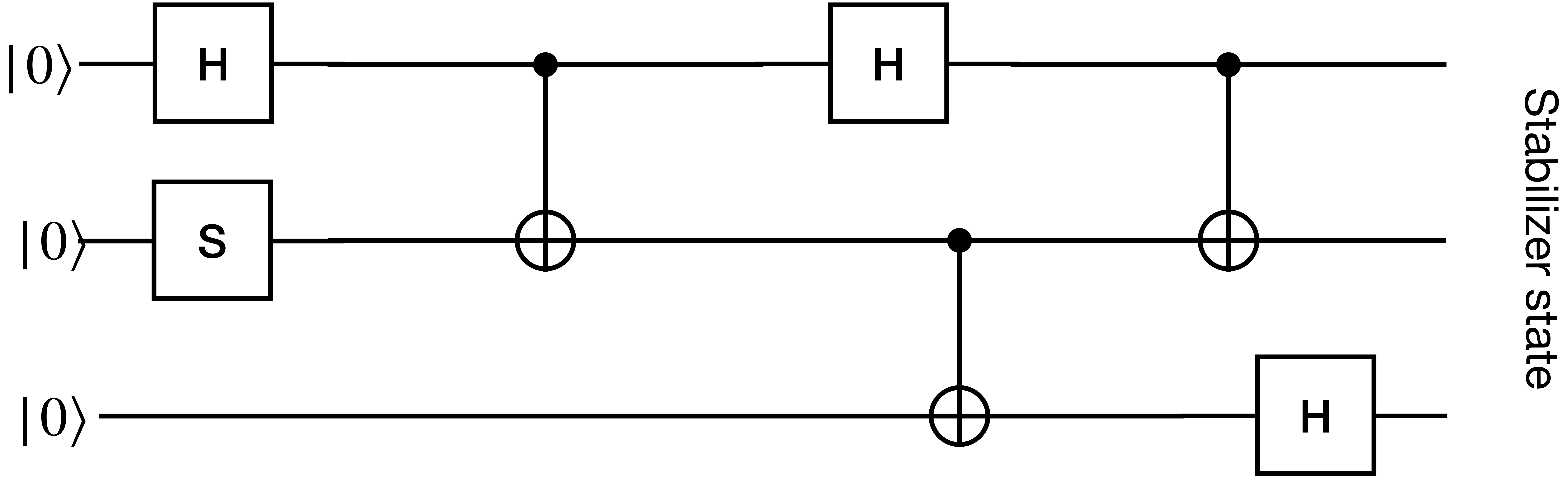
$|0\rangle$

$\frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$

Can denote a register with n qubits

n qubits

Clifford Circuits and Stabilizer States



From all zeros state Clifford gates only produce stabilizer states.

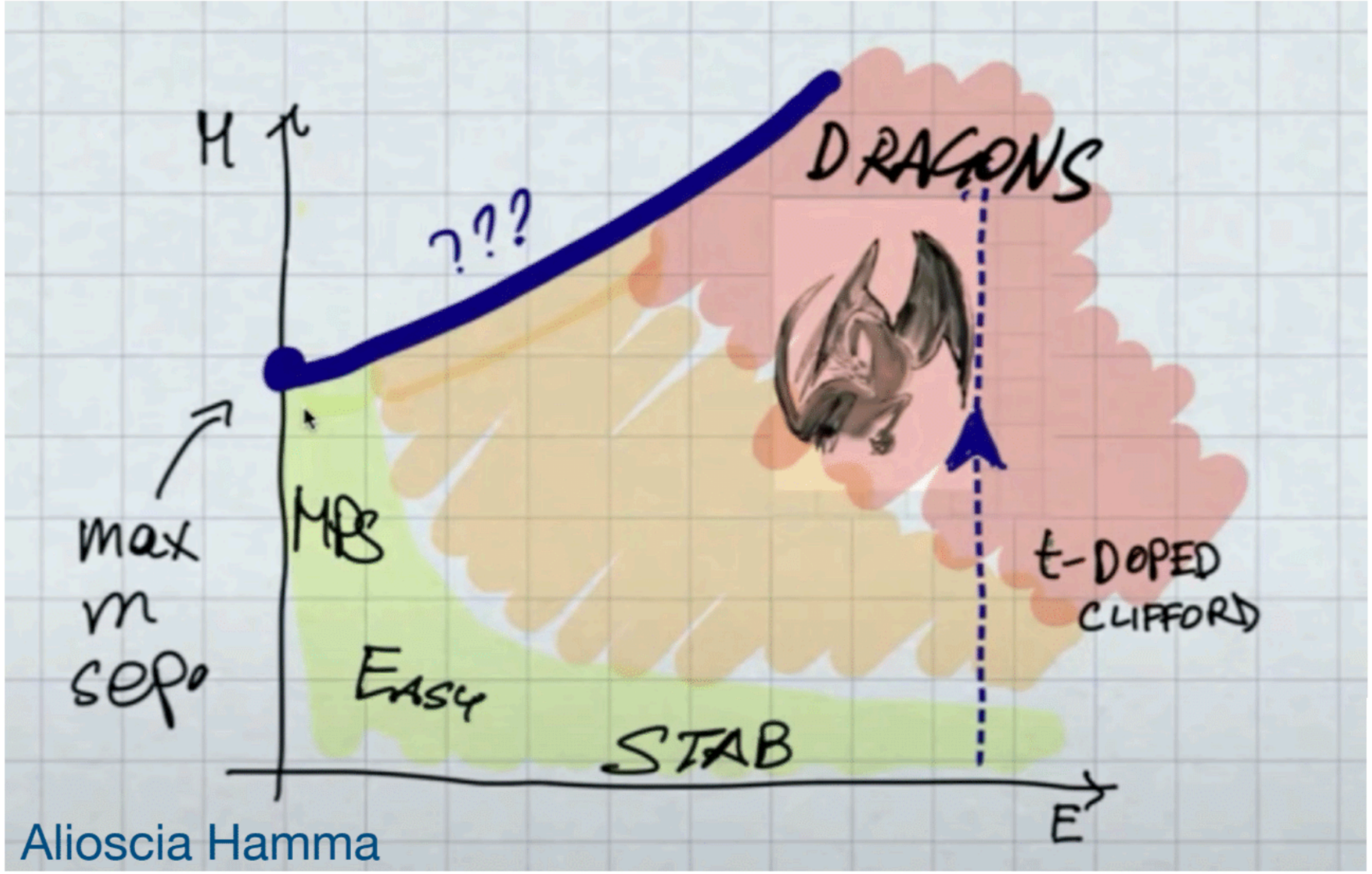
These circuits can be simulated efficiently classically

Circuits with T gates can be simulated with cost exponential only in number of T gates

Stabilizers entangled, but lack “magic”

Magic: Stabilizer Renyi Entropies

Magic



Entanglement

Form probability distribution:

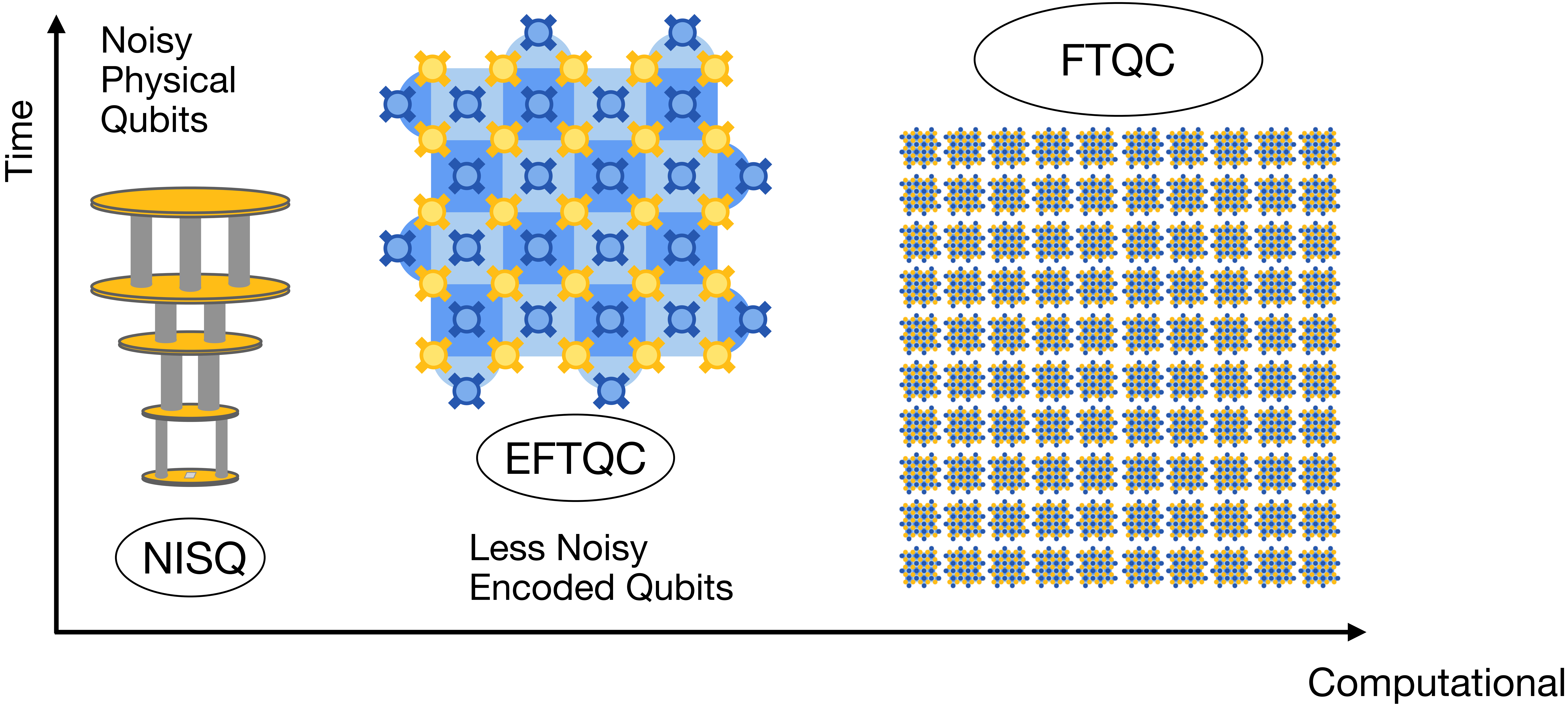
$$V_k(|\psi\rangle) = \frac{\langle\psi|P_k|\psi\rangle}{2^n}$$

Probability of P_k in $|\psi\rangle$

Renyi entropies of V are measures of magic

Leone, L., Oliviero, S.F. and Hamma, A., 2022. Stabilizer rényi entropy. Physical Review Letters, 128(5), p.050402.

Quantum Computing Timeline



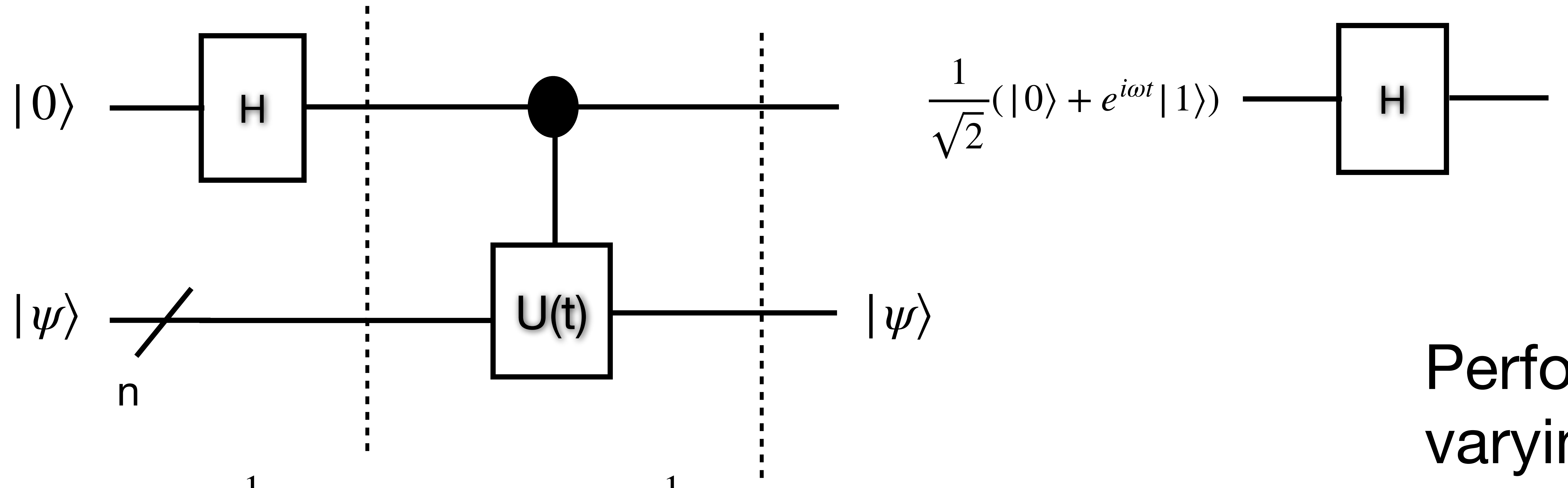
T-gates are the most difficult gates in many quantum error correction schemes

Task: Determining energy eigenvalues

Prepare an energy eigenstate, an eigenstate of $U(t) = \exp(-itH)$:

$$|\psi\rangle : U(t)|\psi\rangle = e^{i\omega t}|\psi\rangle$$

Perform controlled time evolution with U(t)



$$\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)|\psi\rangle$$

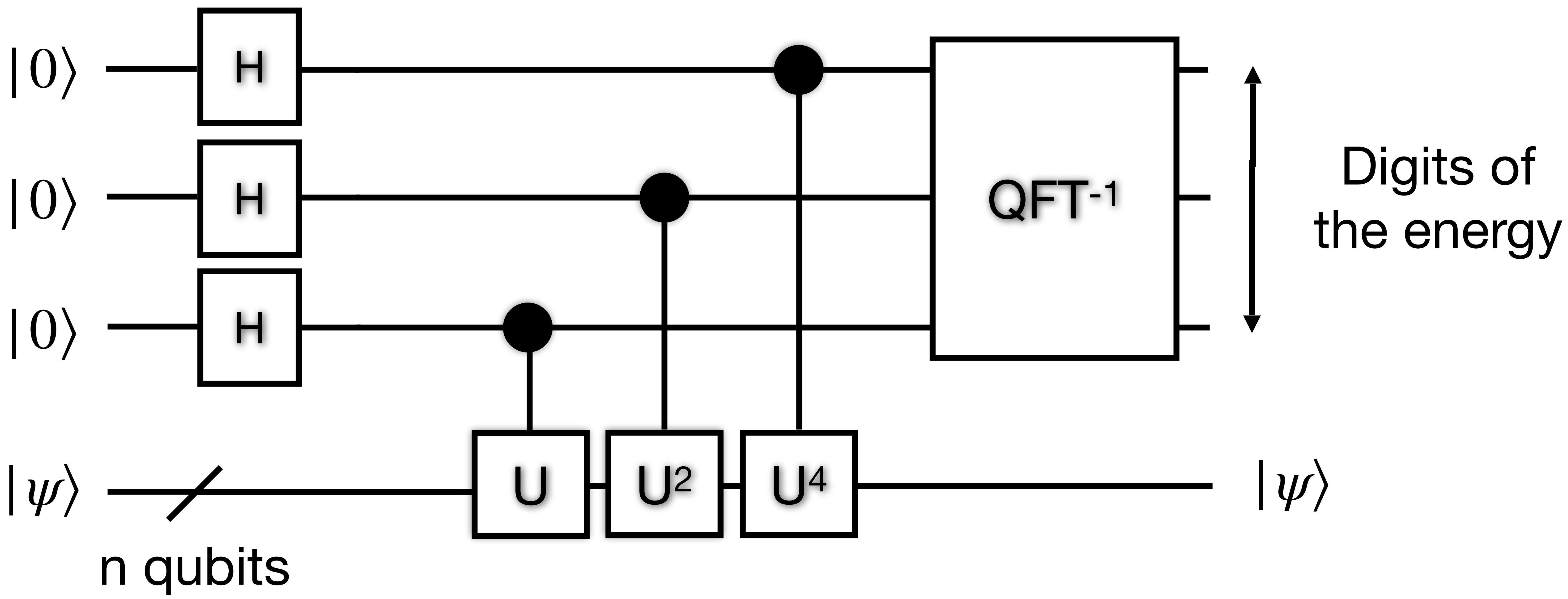
$$\frac{1}{\sqrt{2}}(|0\rangle|\psi\rangle + e^{i\omega t}|1\rangle|\psi\rangle)$$

$$\frac{1}{\sqrt{2}}(|0\rangle + e^{i\omega t}|1\rangle)$$

$$e^{i\omega t/2}(\cos \omega t/2\,|0\rangle + \sin \omega t/2\,|1\rangle)$$

Perform many experiments varying t: determine frequency by FT on classical data

Phase estimation



Do the FT on the quantum computer

Challenge 1: **Simulation of time evolution** (U) controls accuracy

Challenge 2: **State preparation.** Overlap of $|\psi\rangle$ and true ground state gives success probability

Hamiltonian Simulation

Goal Estimate λ :

$$H|\lambda\rangle = \lambda|\lambda\rangle$$

Problem

$$H^\dagger = H \text{ but } H^\dagger H \neq \mathbb{I}$$

$$\implies H \neq U_n \dots U_1 U_0$$

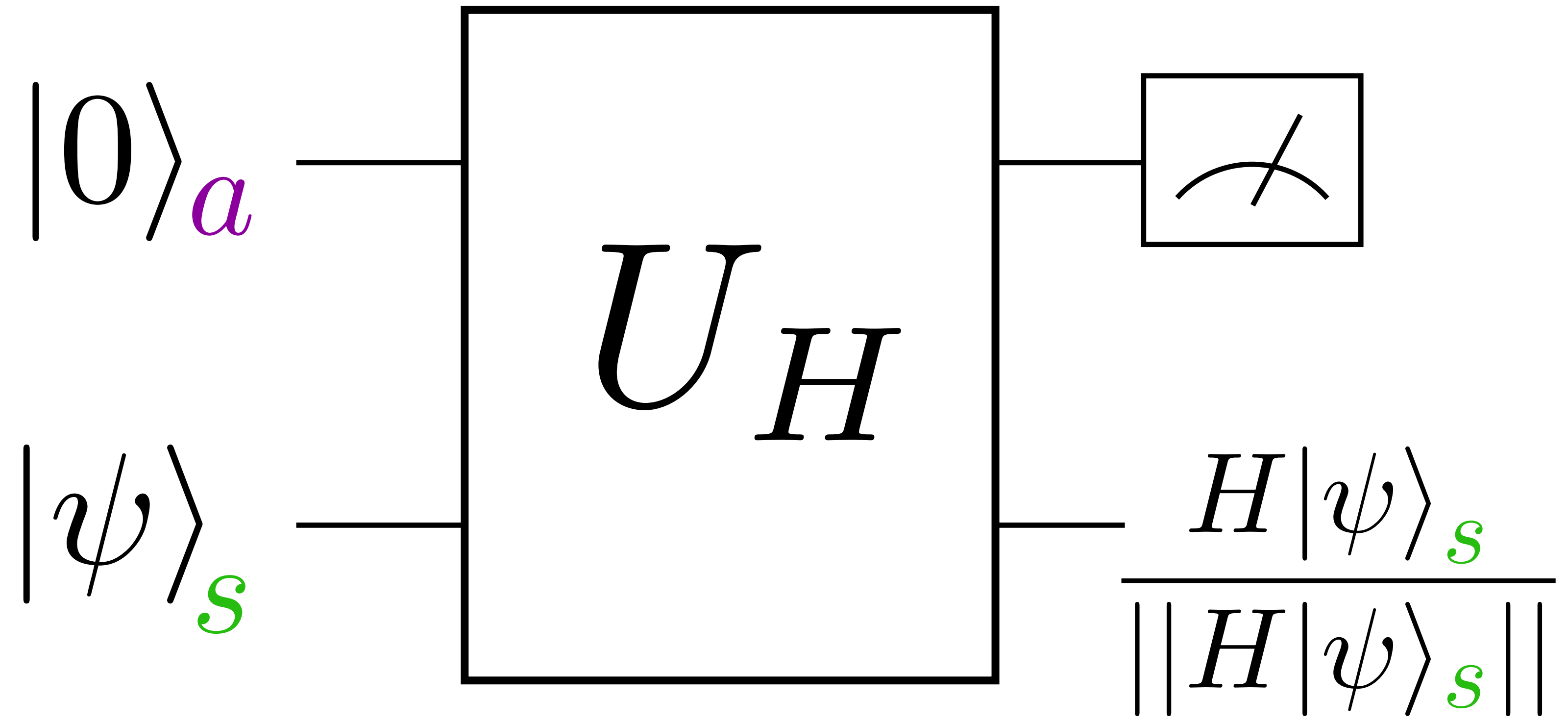
Solution Encode $H \to U_H$ such that

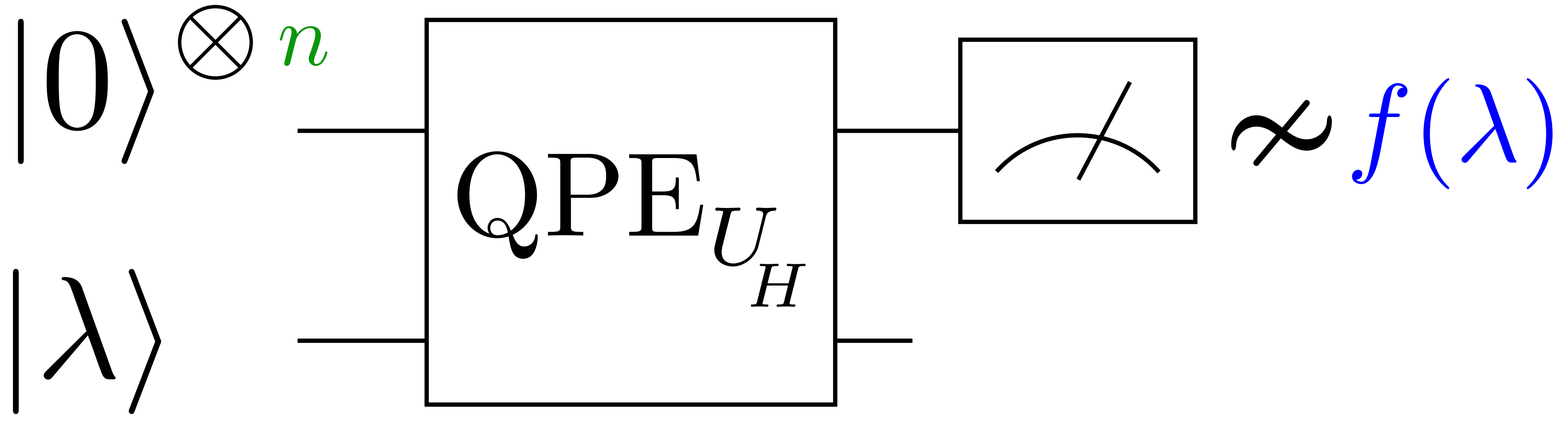
(a) $U_H = U_n \dots U_1 U_0$

(b) $\text{spectrum}(U_H) = f\Big(\text{spectrum}(H)\Big)$

Example: Block Encoding (circa 2013)

$$H \to U_H = \begin{pmatrix} H/\alpha & \star \\ \star & \star \end{pmatrix}$$

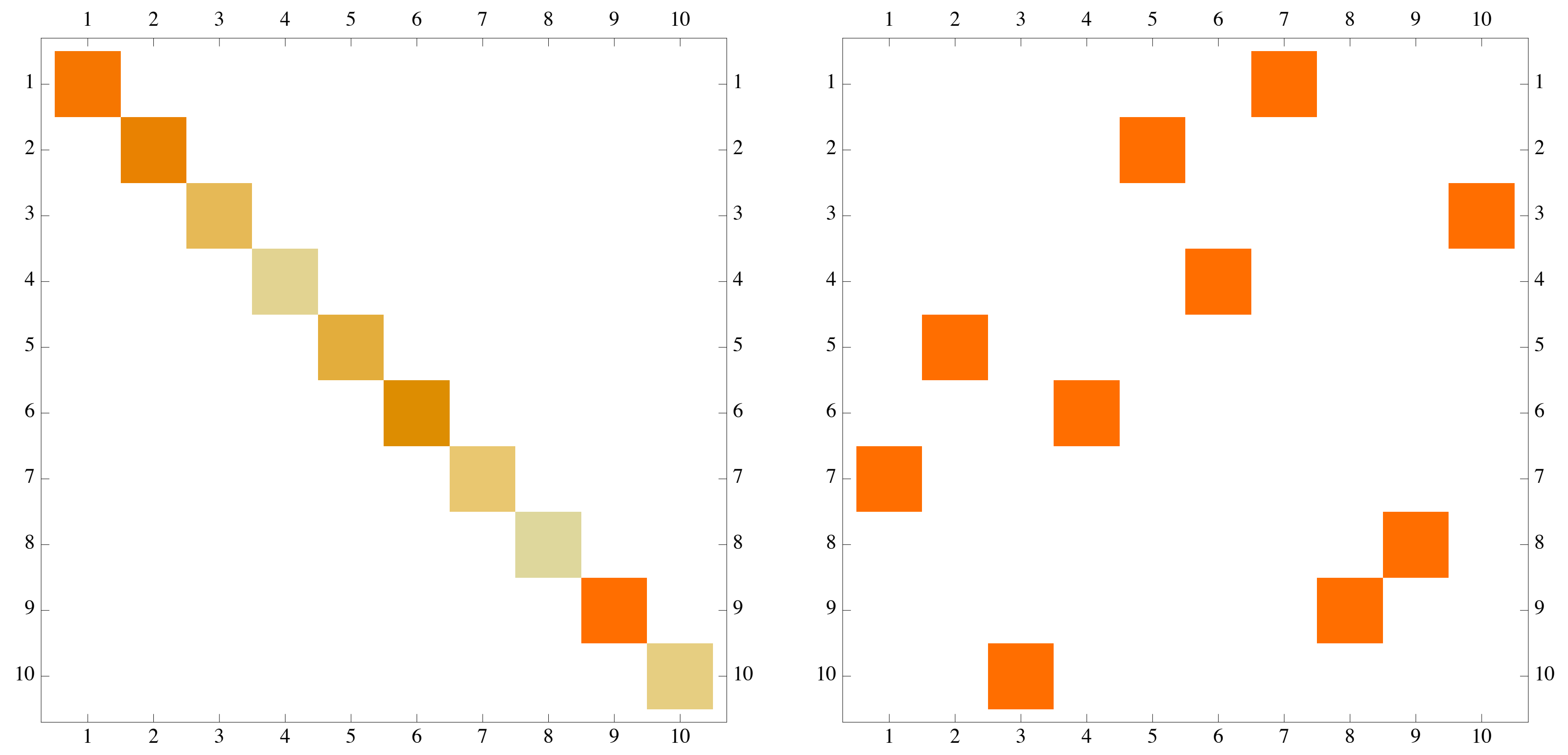




Two classes of quantum simulatable Hamiltonians

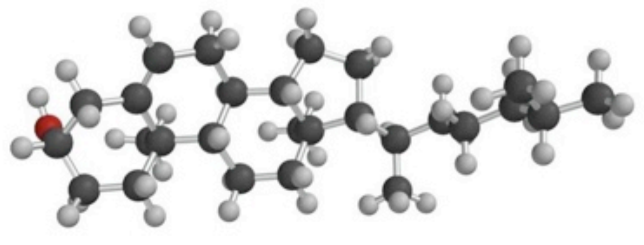
Direct Mappings: Hamiltonian is local (and hence sparse)

Compact Mappings: Hamiltonian is sparse (but not local)

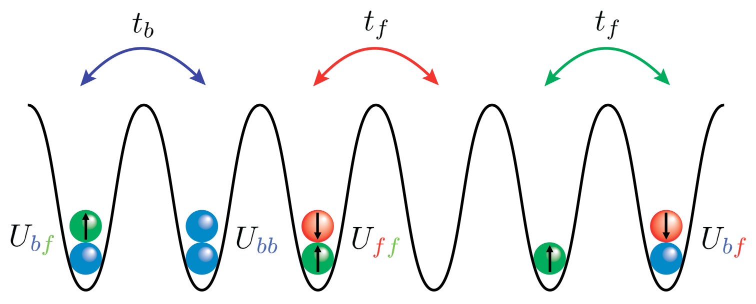


Quantum simulation algorithms exist for both classes

A Quantum Computer for Chemistry?



c cholesterol

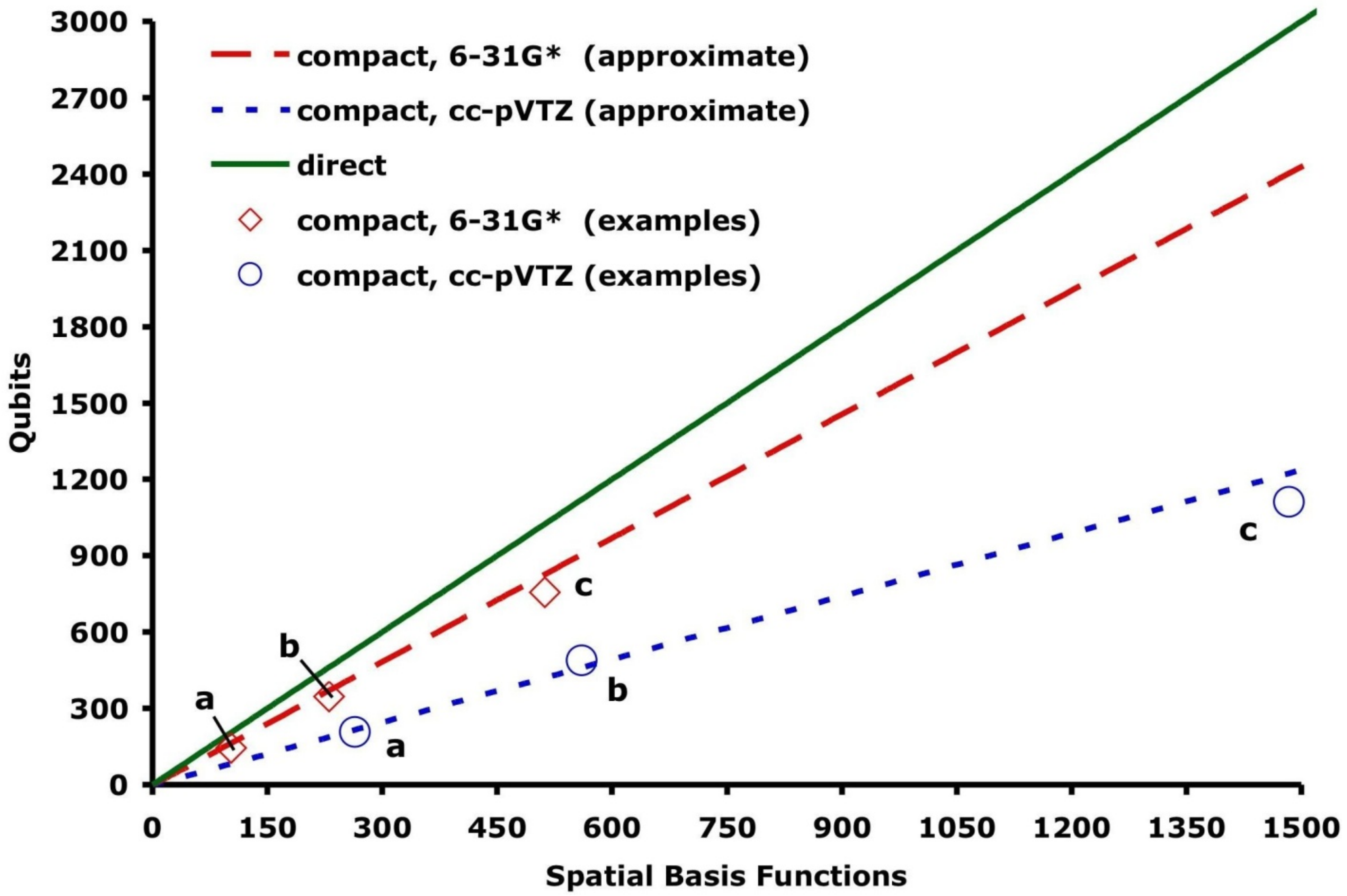


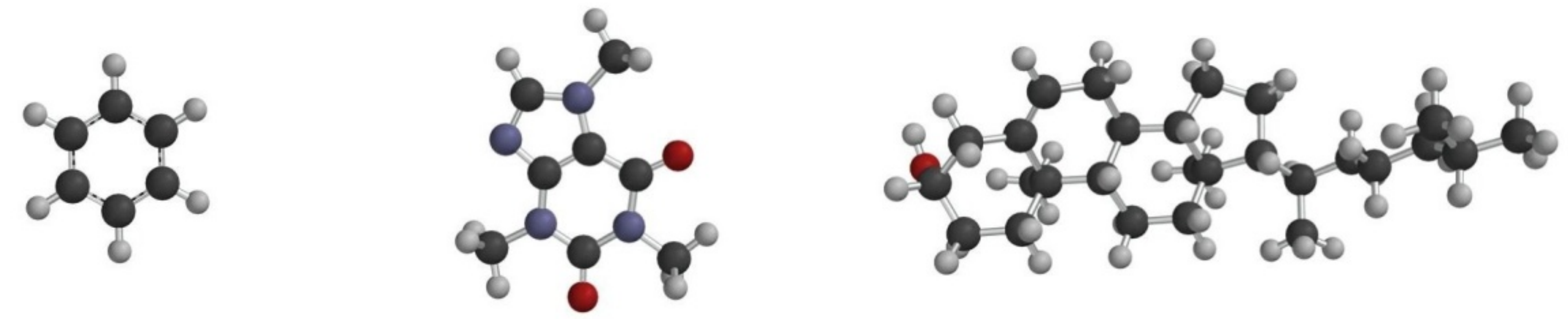
Map fermions to Qubits

State preparation

Phase estimation

E=??





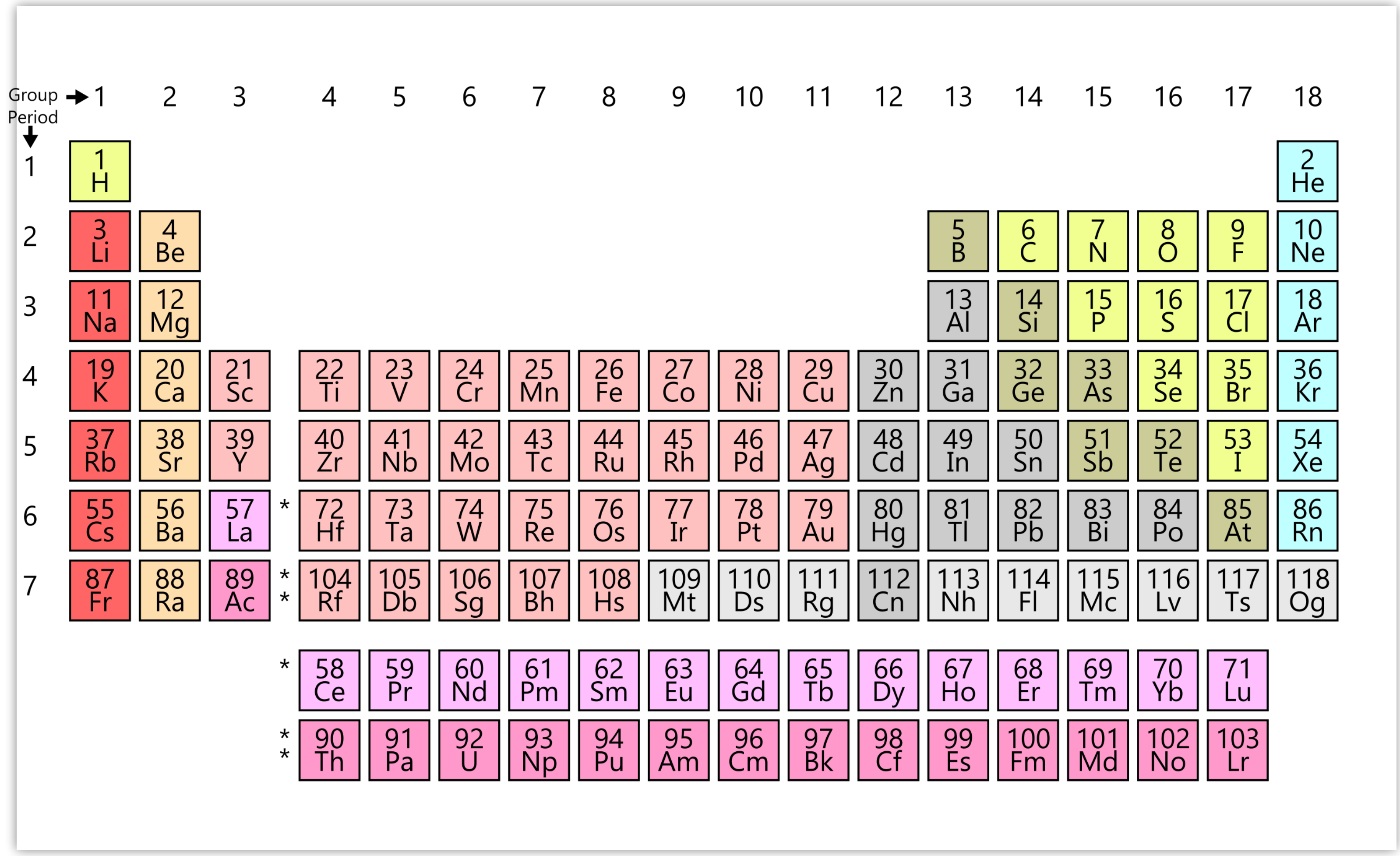
a benzene b caffeine c cholesterol

Key point: number of qubits ~ number of orbitals.

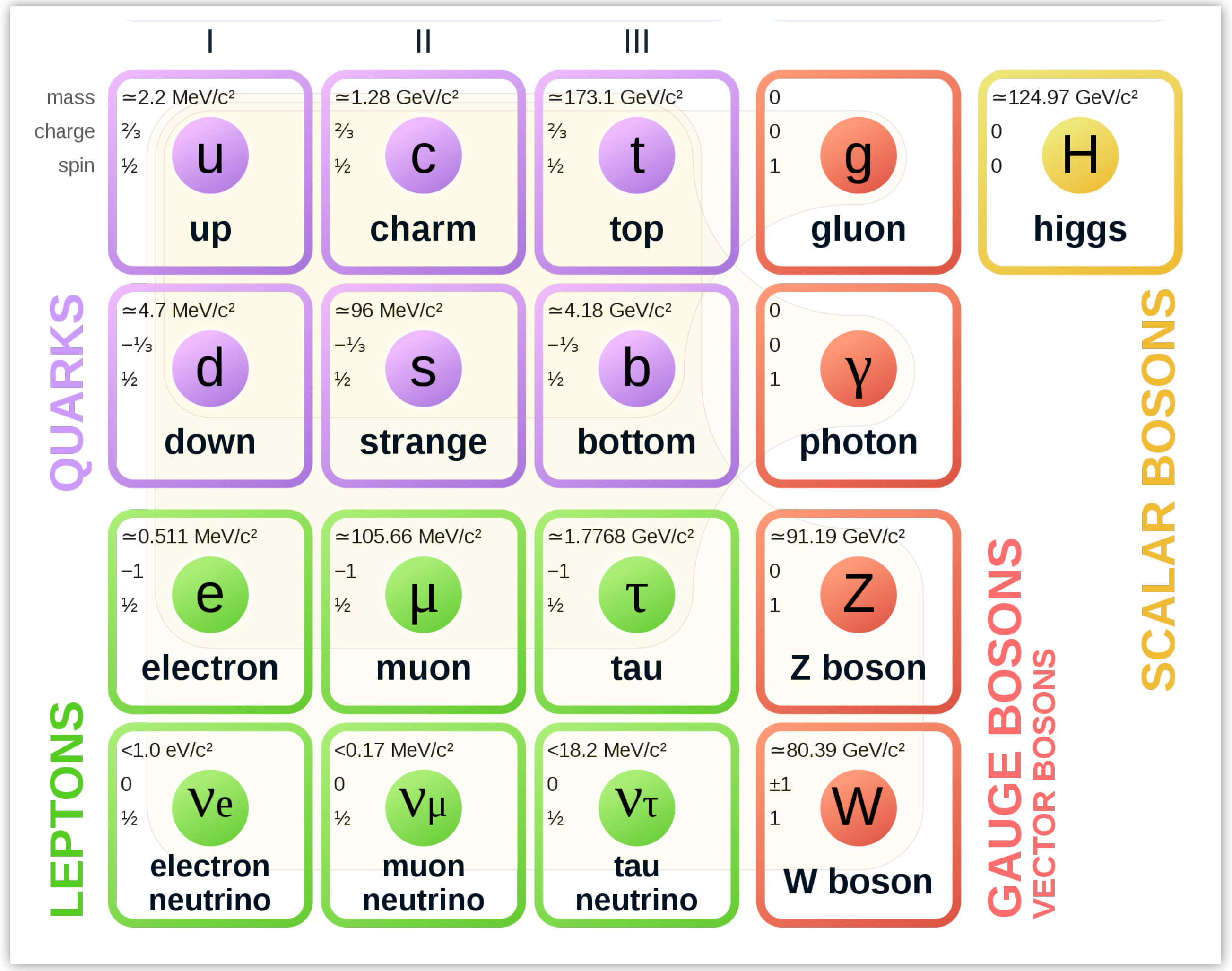
Hard problems for hundreds of qubits (orbitals)

Simulated Quantum Computation of Molecular Energies, Alan Aspuru-Guzik, Anthony Dutoi, Peter J. Love, Martin Head-Gordon, Science, 309, 5741, (2005)

Comparing Quantum Chemistry to Quantum Field Theory



Why lattices not orbitals?



Compact Basis representations

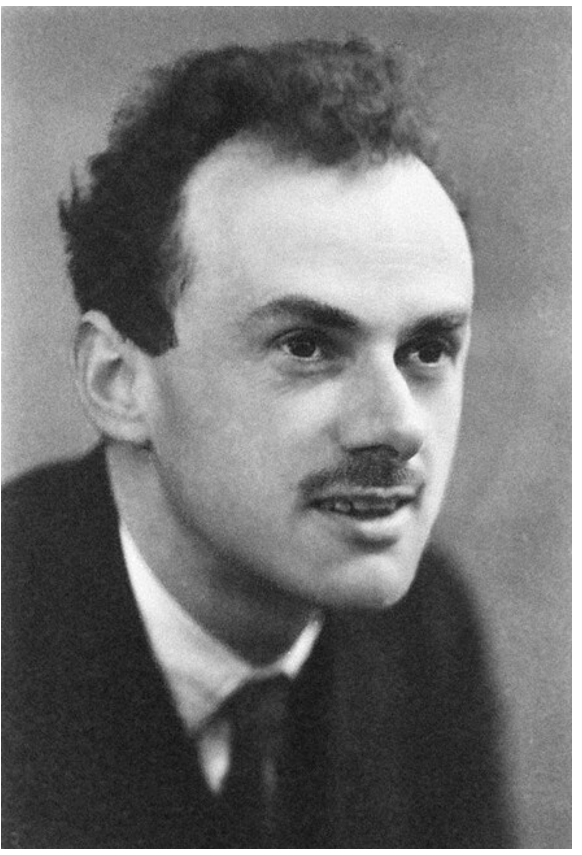
Lattices

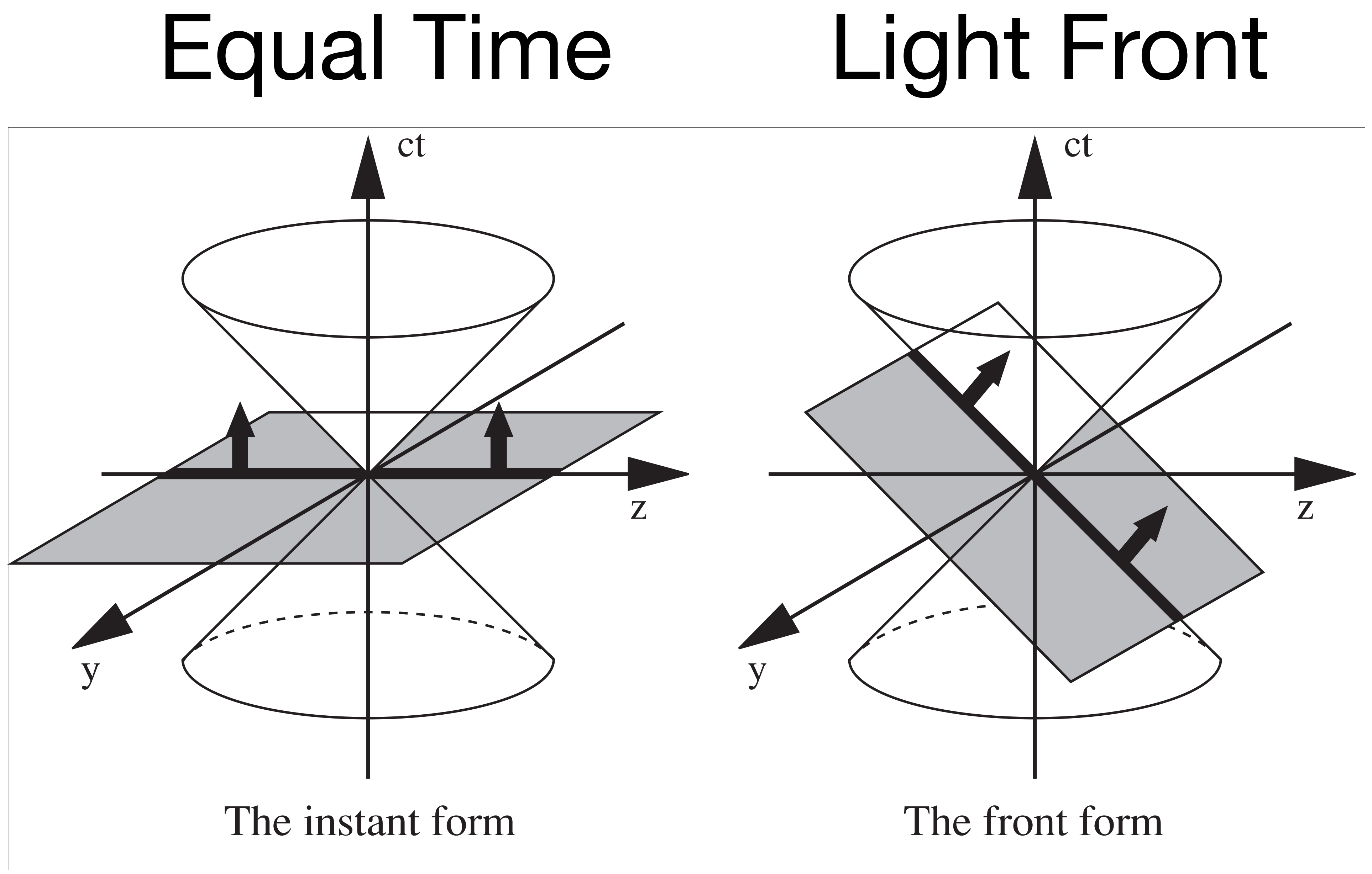
Static quantities of interest

Renormalization!

Ken Wilson, Nuclear Physics B-Proceedings Supplements, 17:82–92, 1990.

Light Front Field theory on quantum computers





Hamiltonian formulation as required by quantum simulation.

Basis of momentum orbitals (DLCQ) or symmetry adapted functions (BLFQ).

Second quantized representation

$$x^\mu = \left(x^+, x^-, \vec{x}^\perp\right)$$

$$\boxed{H_{LC}\,|\psi\rangle = M^2\,|\psi\rangle}$$

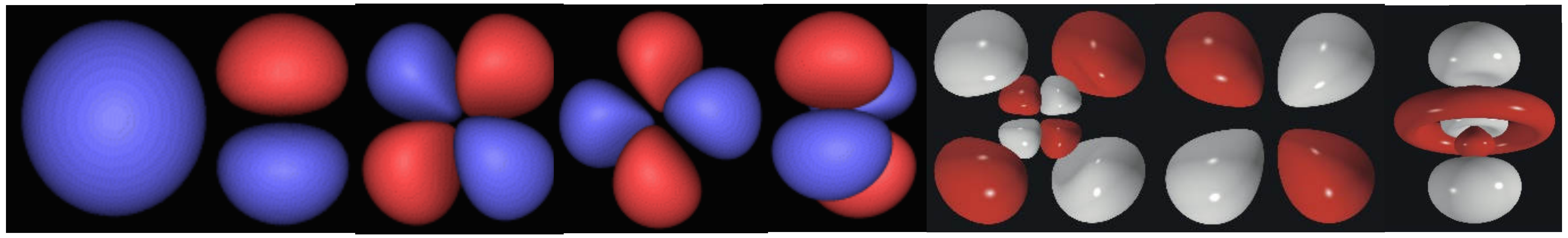
Adapted from: Quantum chromodynamics and other field theories on the light cone, Stanley J. Brodsky, Hans-Christian Pauli, Stephen S. Pinsky, Physics Reports, Volume 301, Issues 4–6, 1 August 1998, Pages 299-486

From Fermions to qubits

Direct Mapping: Orbital occupancy maps to qubit state

n orbitals

n qubits



$= |10000011\rangle$

(1, 0, 0, 0, 0, 0, 1, 1)

Single qubit creation and annihilation operators are $Q^{+} = |1\rangle\langle 0|, Q^{-} = |0\rangle\langle 1|$

But want operators that obey fermionic commutation relations

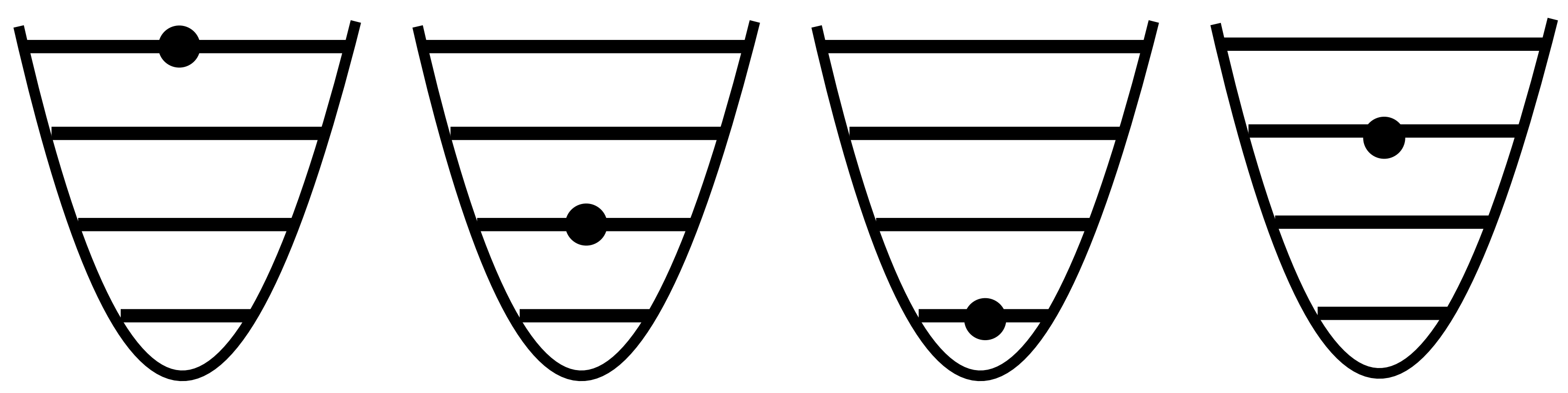
Jordan-Wigner mapping 1928:

$$a_j = Q_j^- \otimes Z_j Z_{j+1} \ldots Z_n, \qquad a_j^\dagger = Q_j^+ \otimes Z_j Z_{j+1} \ldots Z_n$$

Many new fermion mappings since 2012

From Bosons to qubits

Direct Mapping: Orbital occupancy maps to qubit state: cutoff Λ



(3, 1, 0, 2)

(11, 01, 00, 10) $= |11010010\rangle$

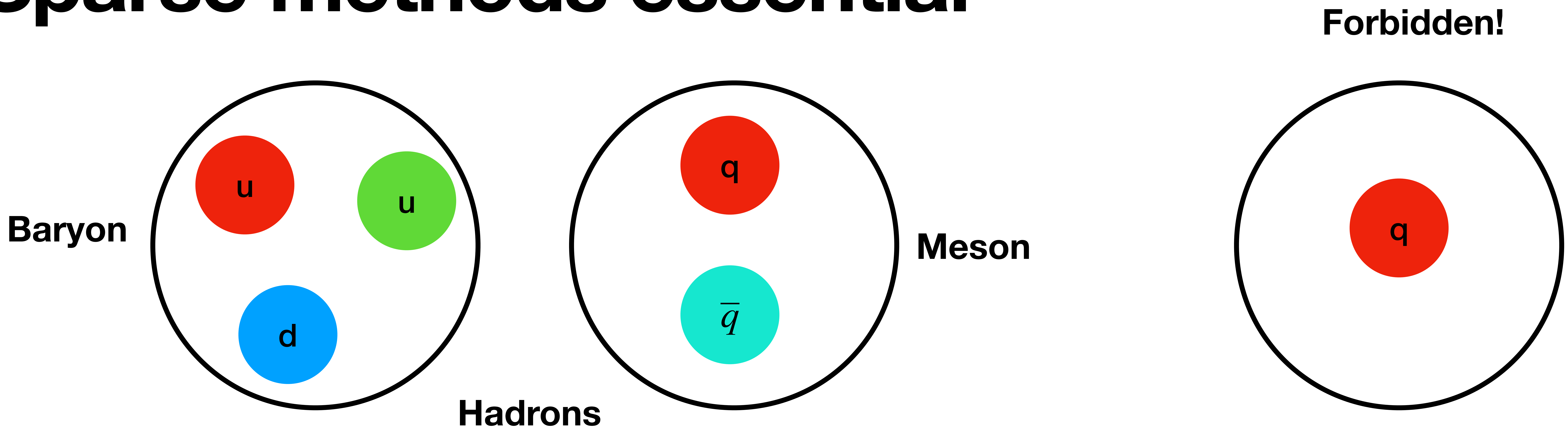
Many choices of occupancy encoding: unary, gray code, binary.

Creation and annihilation operators: $\sqrt{n+1}\,|n+1\rangle\langle n|, \sqrt{n}\,|n-1\rangle\langle n|$

No exact mapping of bosons commutation relations.

Cutoff induces error in algebra when occupancy=cutoff.

Sparse methods essential



Confinement: Physical states are colorless: no free quarks.

Matrix elements between unphysical states diverge.

Only include physical states in simulation: sparse methods.

Hamiltonian Simulation

Goal Estimate λ :

$$H|\lambda\rangle = \lambda|\lambda\rangle$$

Solution Encode $H \rightarrow U_H$ such that

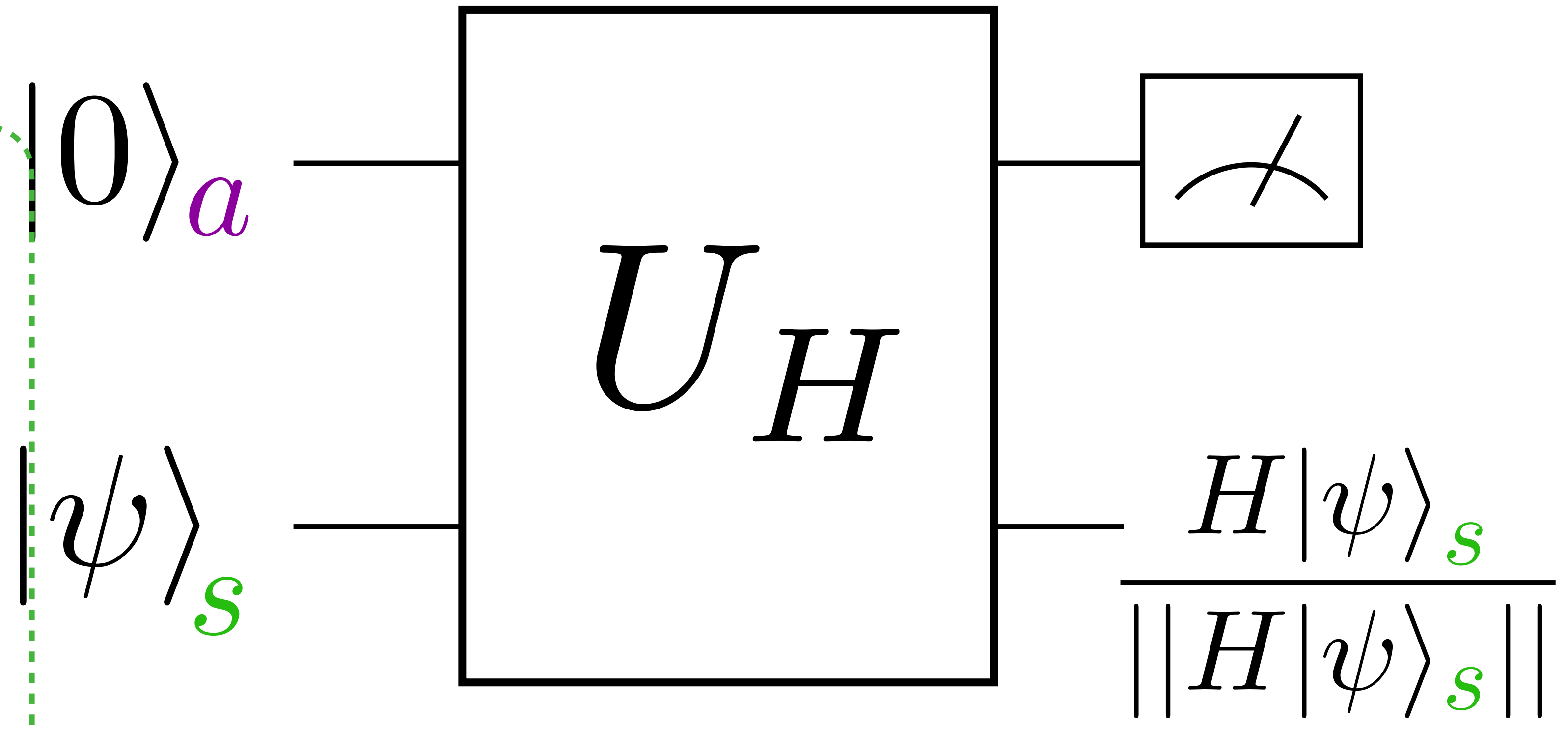
(a) $U_H = U_n \dots U_1 U_0$

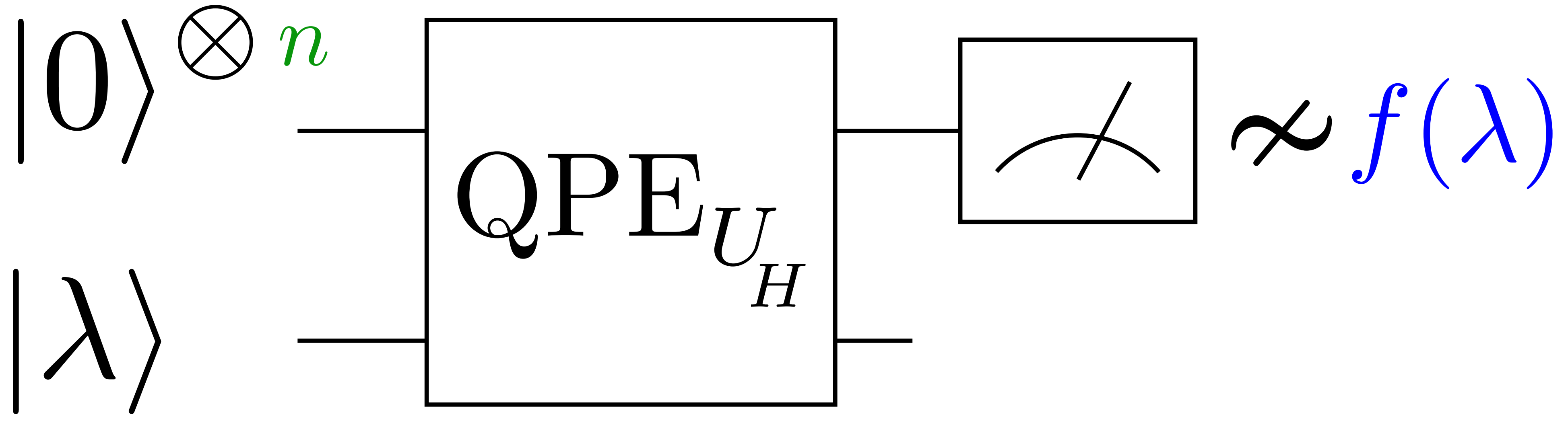
(b) $\text{spectrum}(U_H) = f\Big(\text{spectrum}(H)\Big)$

LOBE: Ladder Operator Block Encoding.
Block encode terms in second quantized Hamiltonian directly.

Example: Block Encoding (circa 2013)

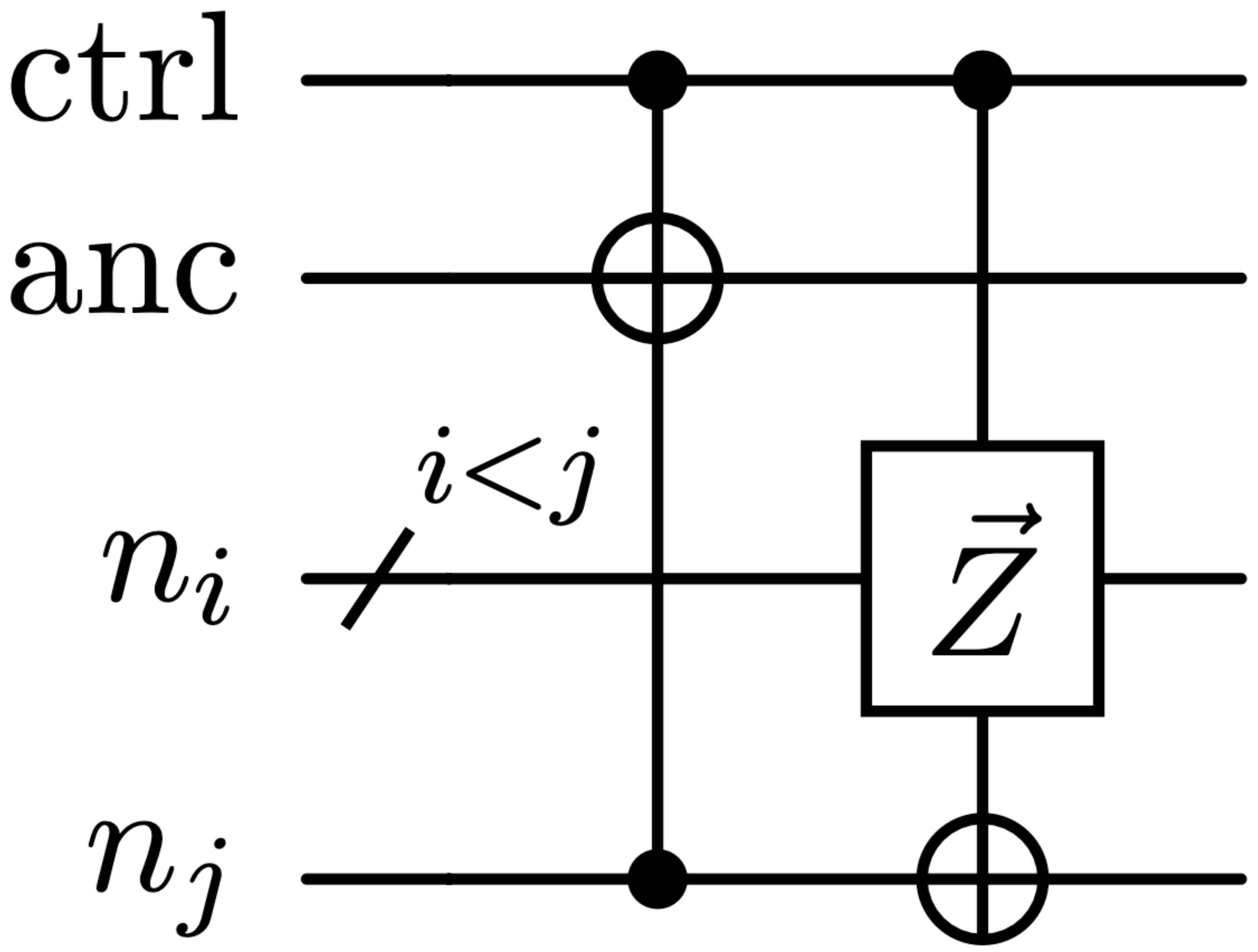
$$H \rightarrow U_H = \begin{pmatrix} H/\alpha & \star \\ \star & \star \end{pmatrix}$$





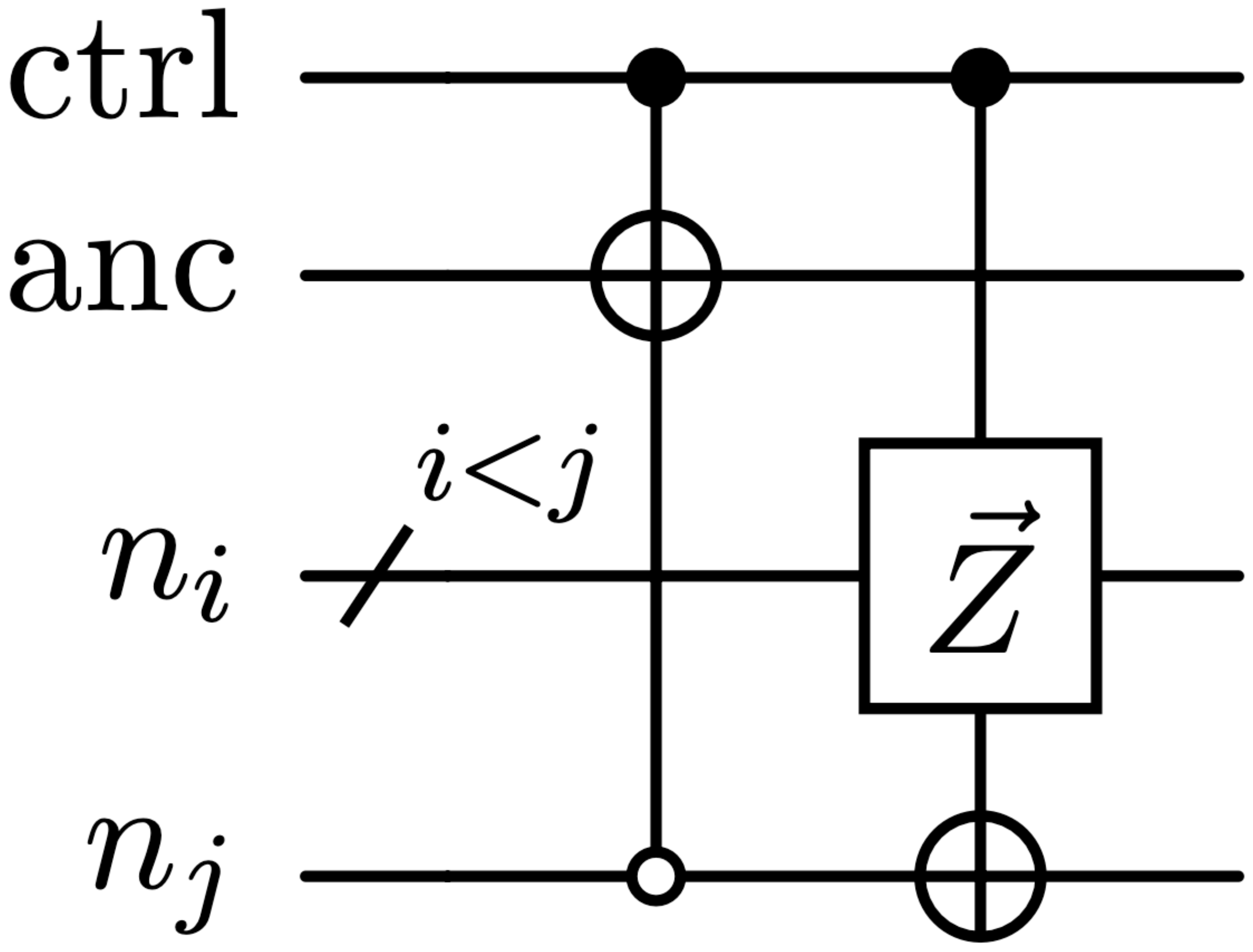
Fermionic Creation Operator

$$H = b^\dagger$$



Fermionic Annihilation Operator

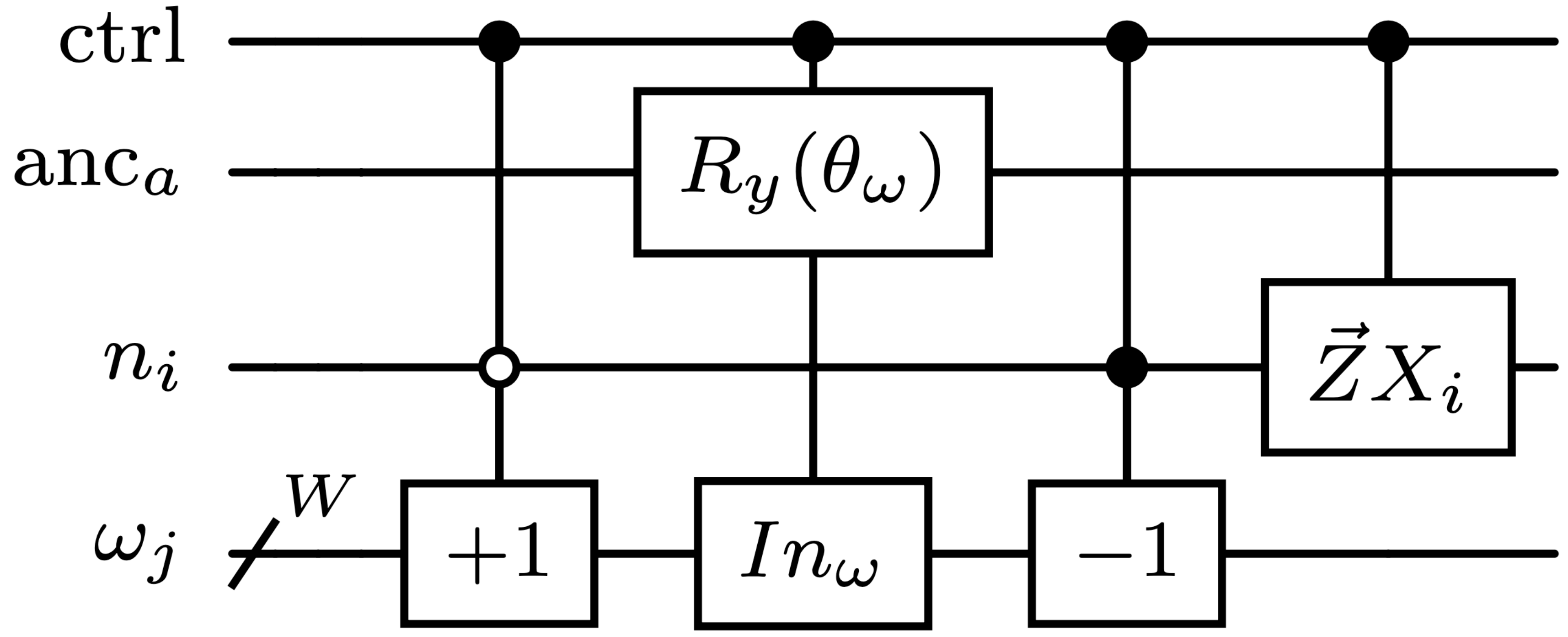
$$H = b$$



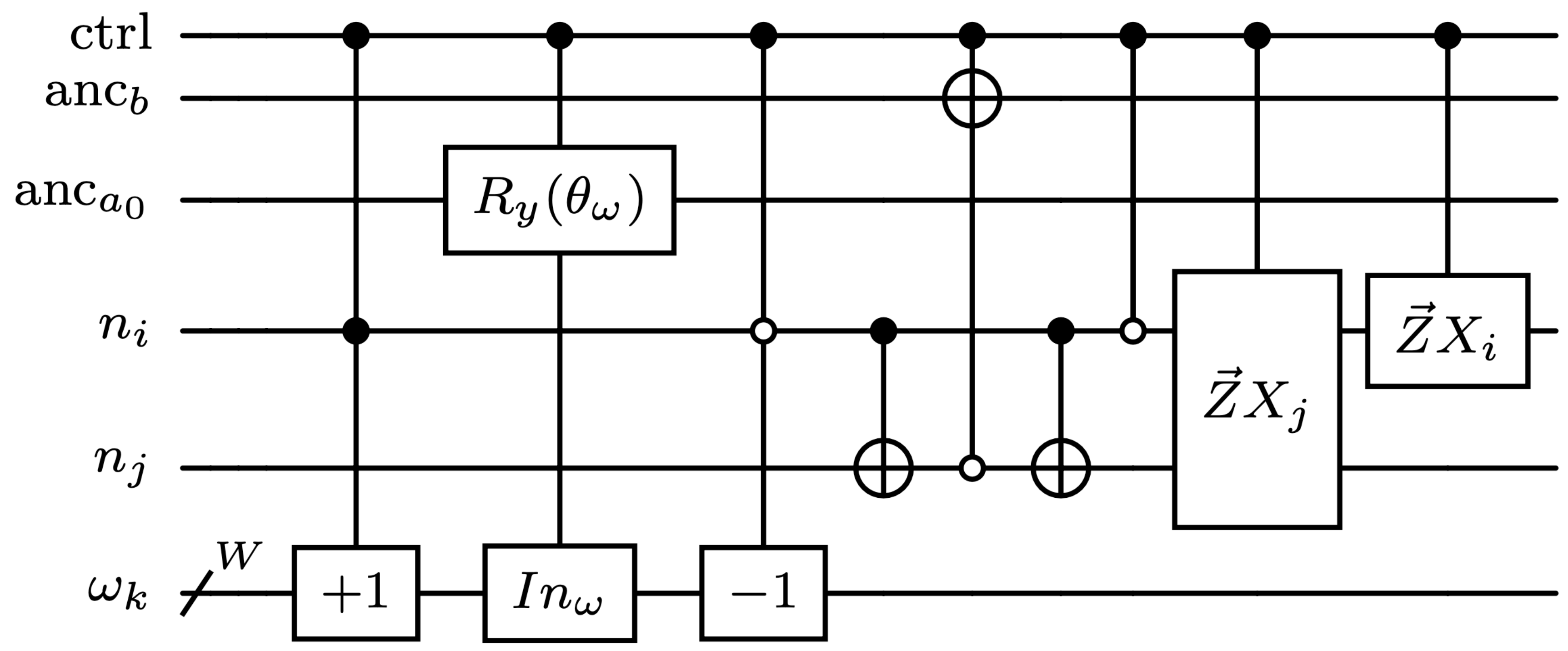
Simon et al. Quantum (2025)

Interactions between Fermions and Bosons

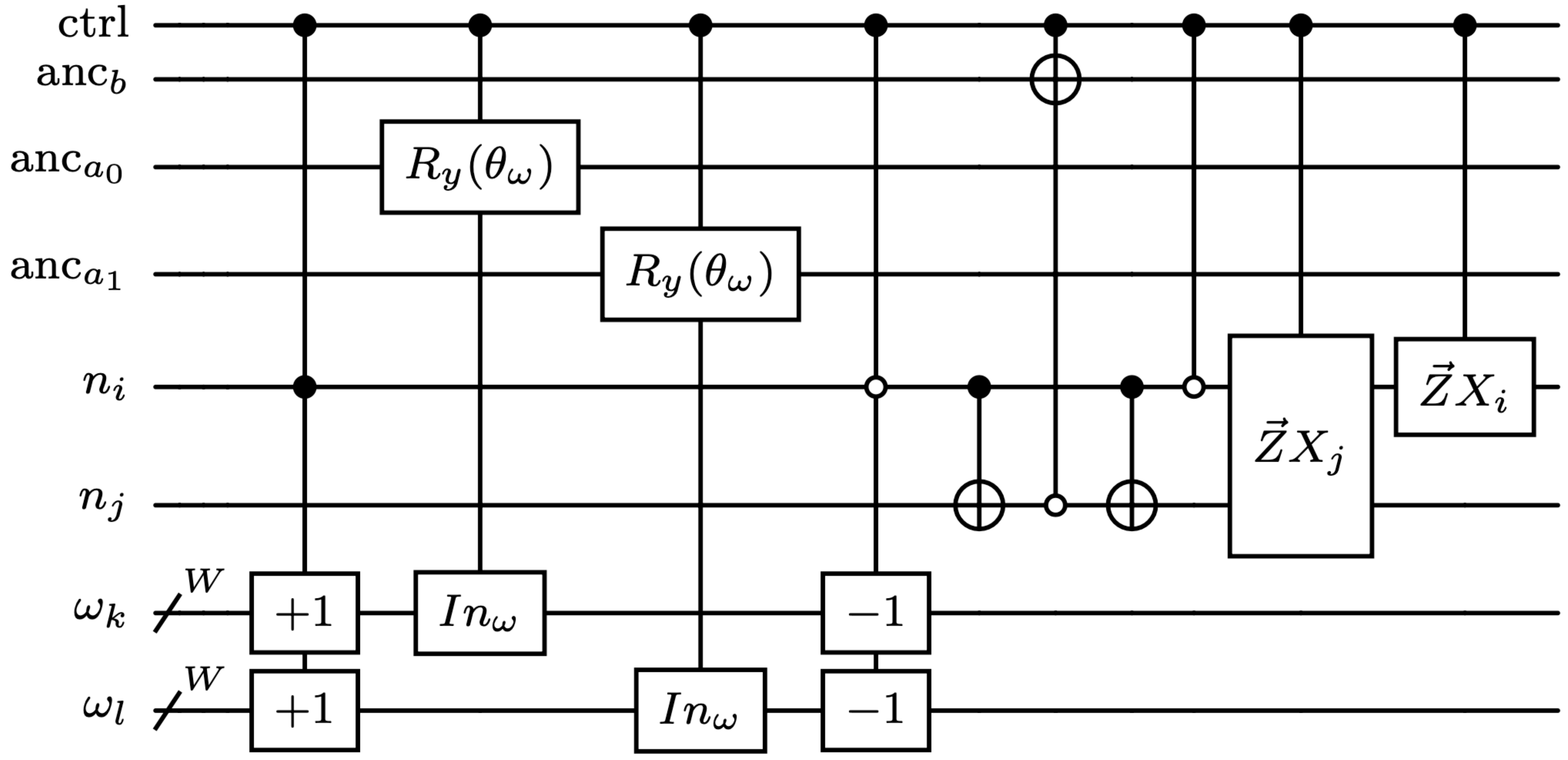
$$H = b_i^\dagger a_j^\dagger + a_j b_i$$



$$H = b_i^\dagger b_j^\dagger a_k + a_k^\dagger b_j b_i$$



$$H = b_i^\dagger b_j^\dagger a_k a_l + a_l^\dagger a_k^\dagger b_j b_i$$



Simon et al. Quantum (2025)

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PAPERS PERSPECTIVES

Ladder Operator Block-Encoding

William A. Simon, Carter M. Gustin, Kamil Serafin, Alexis Ralli, Gary R. Goldstein, and Peter J. Love

Department of Physics and Astronomy, Tufts University, Medford, MA 02155, USA

Published:	2025-12-22, volume 9, page 1953
Editor:	Di Fang
Eprint:	arXiv:2503.11641v5
Doi:	https://doi.org/10.22331/q-2025-12-22-1953
Citation:	Quantum 9, 1953 (2025).

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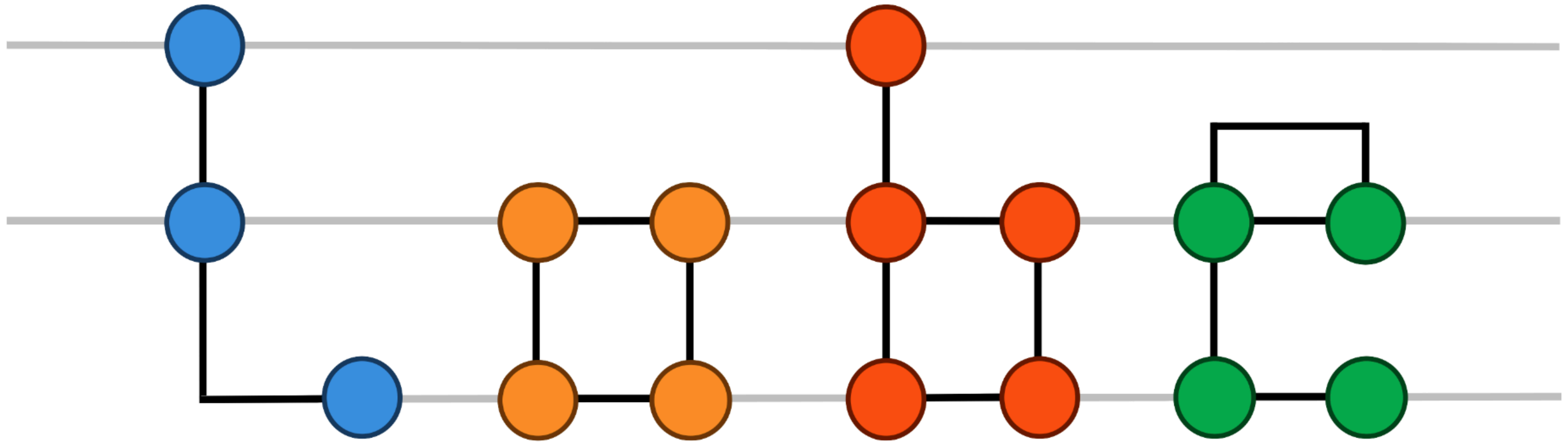
Ladder Operator Block Encoding (LOBE)



This repository serves as a library to generate quantum circuits that create Block Encodings of second-quantized operators written in terms of creation and annihilation (ladder) operators.

Simon et al. Quantum (2025)

Canonical Hamiltonian Light-Front Simulation

PHYSICAL REVIEW A **105**, 032418 (2022)

Quantum simulation of quantum field theory in the light-front formulation

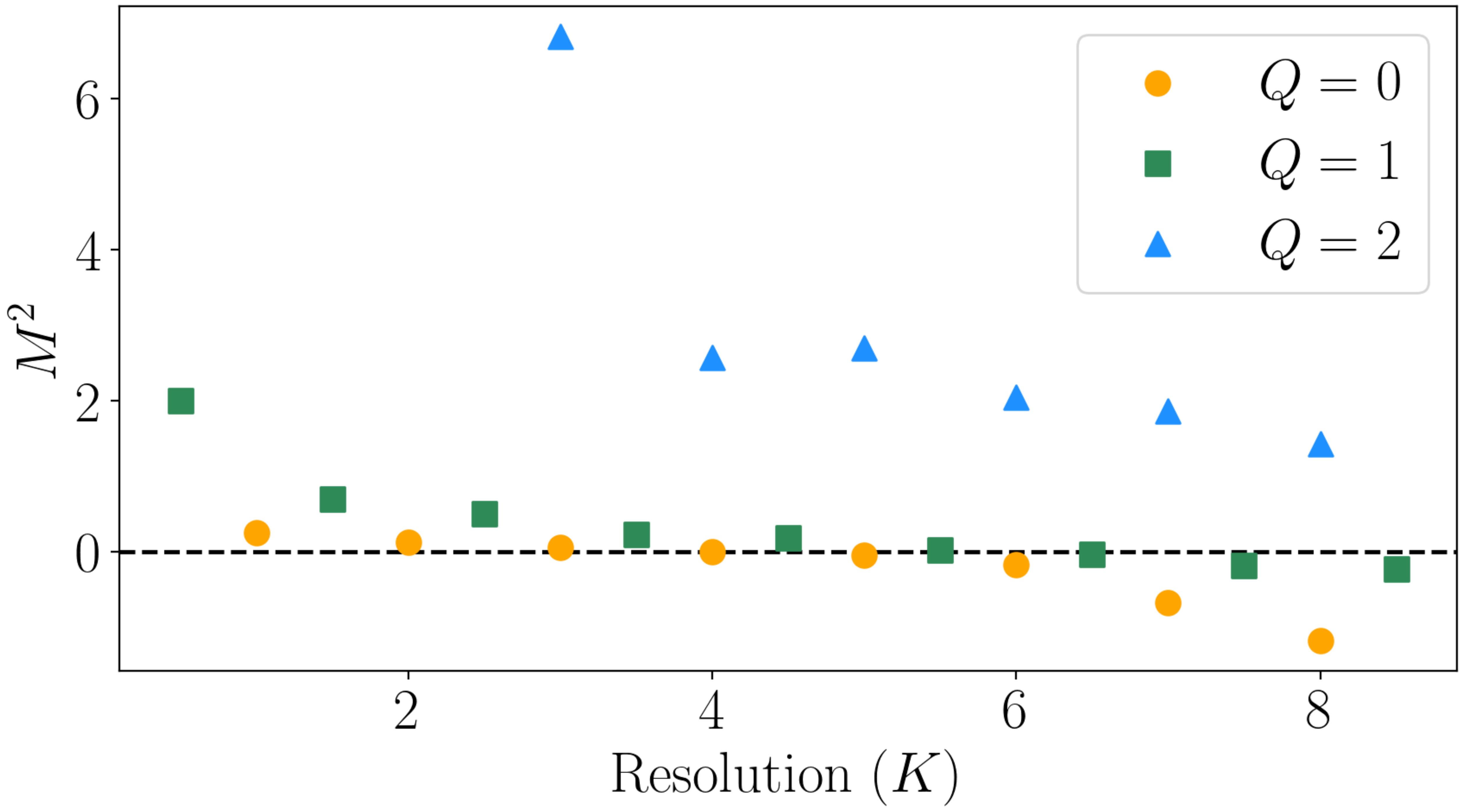
Michael Kreshchuk,[1] William M. Kirby,[1] Gary Goldstein,[1] Hugo Beauchemin,[1] and Peter J. Love[1,2,*]

1+1D Yukawa Model

Momentum orbitals

Fock space basis:

$$\{\,|f\rangle, |\bar{f}\rangle, |b\rangle, |ff\rangle, |ffb\rangle, \ldots\}$$



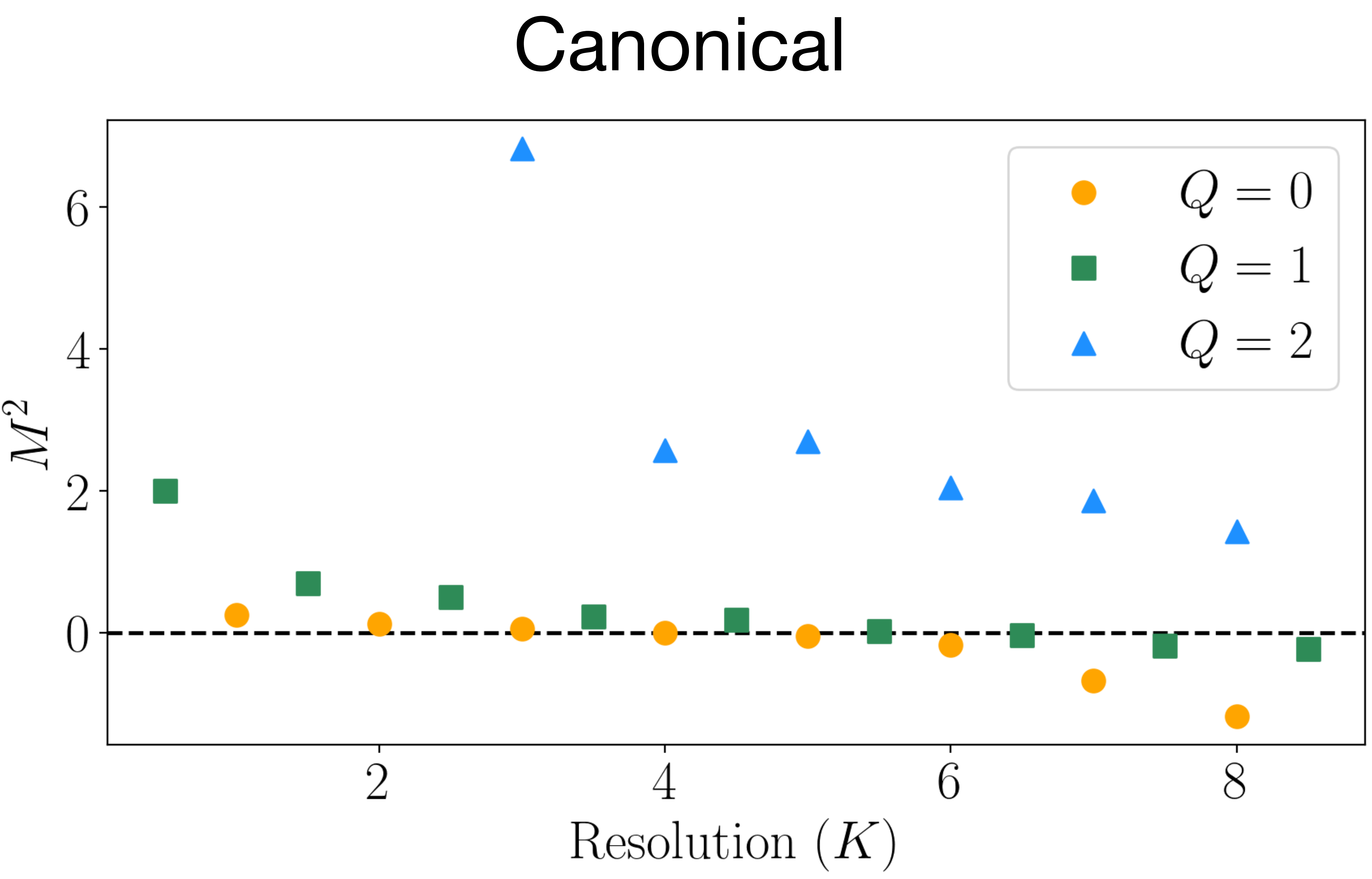
Canonical Hamiltonian poorly defined -divergences cause negative mass^2 values.

PHYSICAL REVIEW D **112,** 096003 (2025)

Second-order renormalized Hamiltonian of Yukawa theory

Kamil Serafin,* Carter M. Gustin, and Peter J. Love†
Department of Physics and Astronomy, Tufts University, Medford, Massachusetts 02155, USA

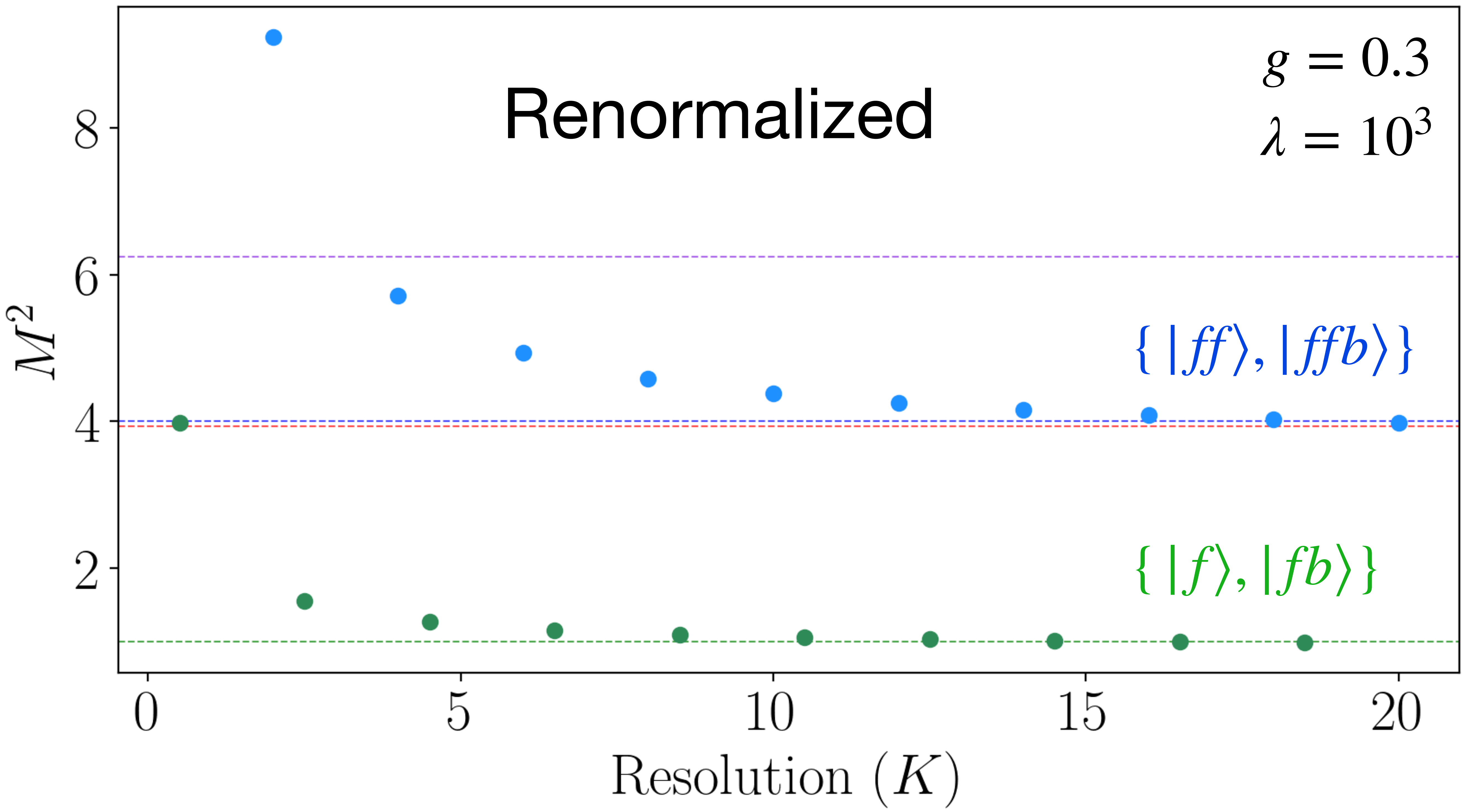
(Received 6 August 2025; accepted 23 September 2025; published 4 November 2025)



PHYSICAL REVIEW D **113,** 016018 (2026)

Renormalized Yukawa Hamiltonian: Spectrum, parton distribution functions, and resource estimates for quantum simulation

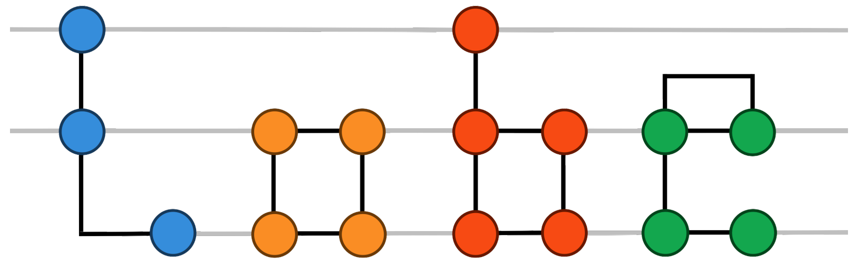
Carter M. Gustin,[1,*] Kamil Serafin,[1] William A. Simon,[1] Alexis Ralli,[1] Gary R. Goldstein,[1] and Peter J. Love[1,2]
[1]*Department of Physics and Astronomy, Tufts University, Medford, Massachusetts 02155, USA*
[2]*Brookhaven National Laboratory, Upton, New York 11973, USA*

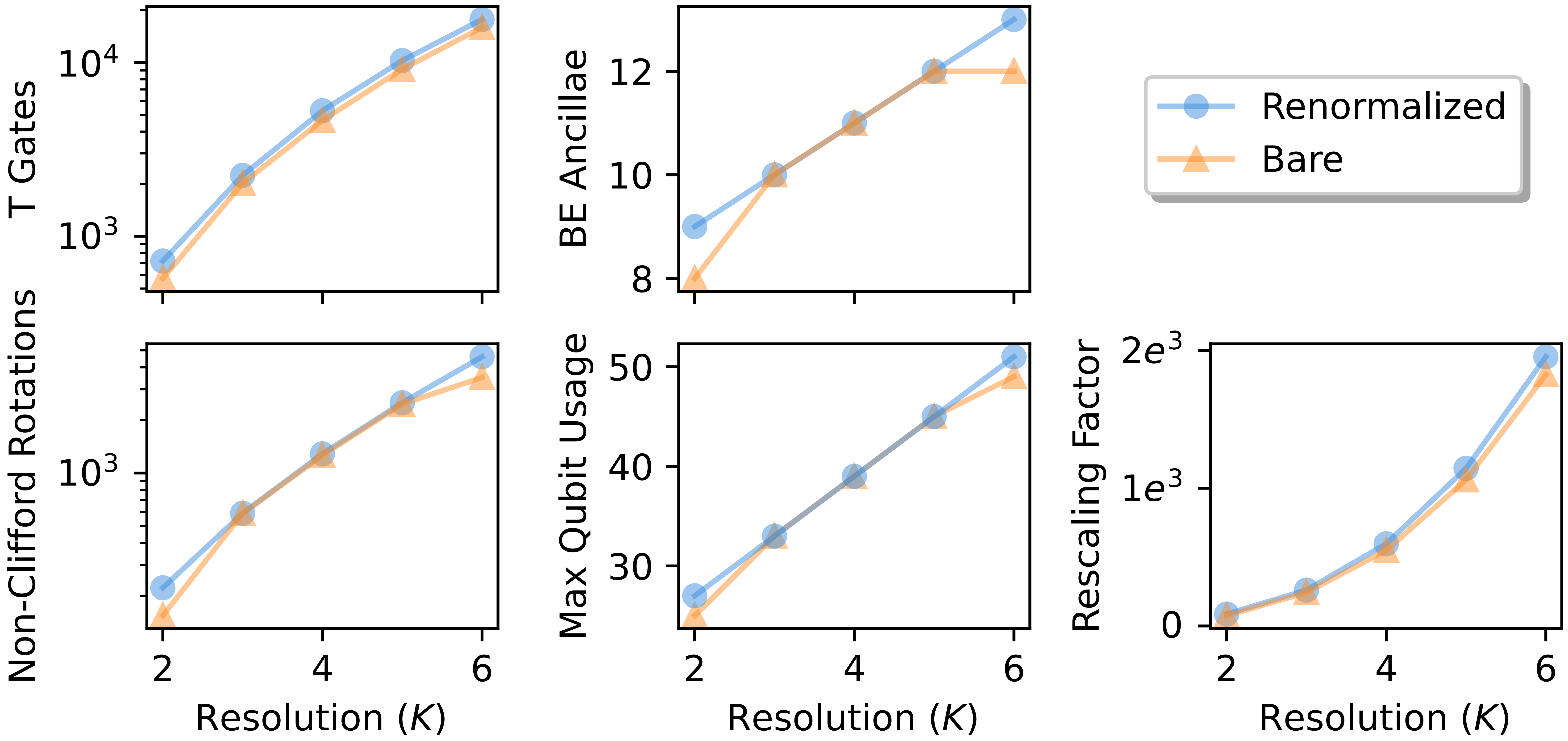


The continuum limit of the renormalized spectrum: Yukawa

Quantum resources for renormalized simulation: Yukawa Theory

Simulation resources do not diverge under renormalization.



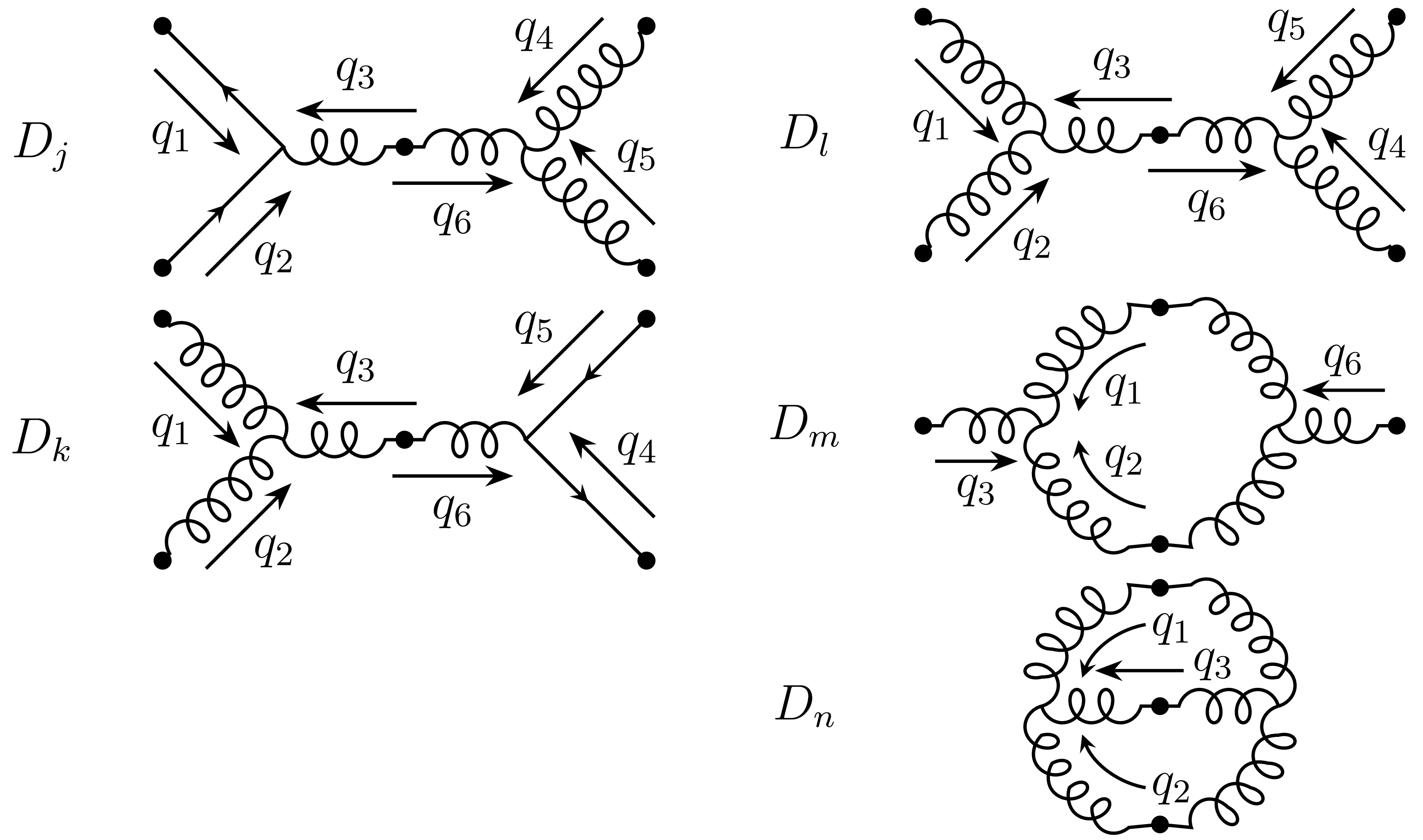


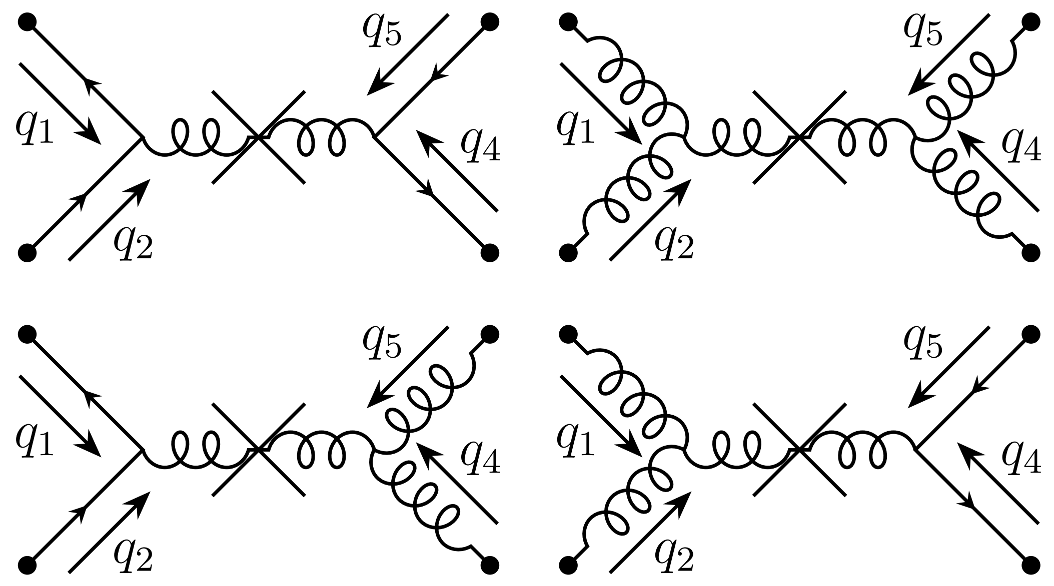
Renormalized Second Order Hamiltonian for QCD

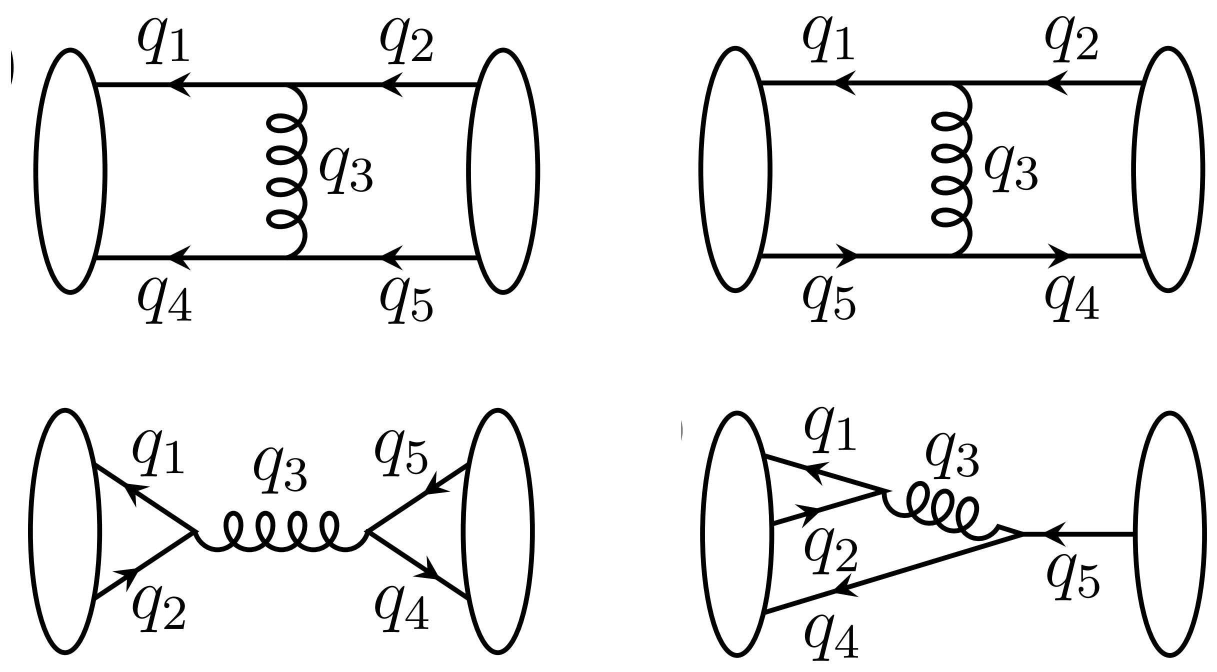
Second-order effective renormalized Hamiltonian of Quantum Chromodynamics

Kamil Serafin, Carter M. Gustin, and Peter J. Love*
Department of Physics and Astronomy,
Tufts University, Medford, Massachusetts 02155, USA

arXiv:2606.24699 [hep-ph]

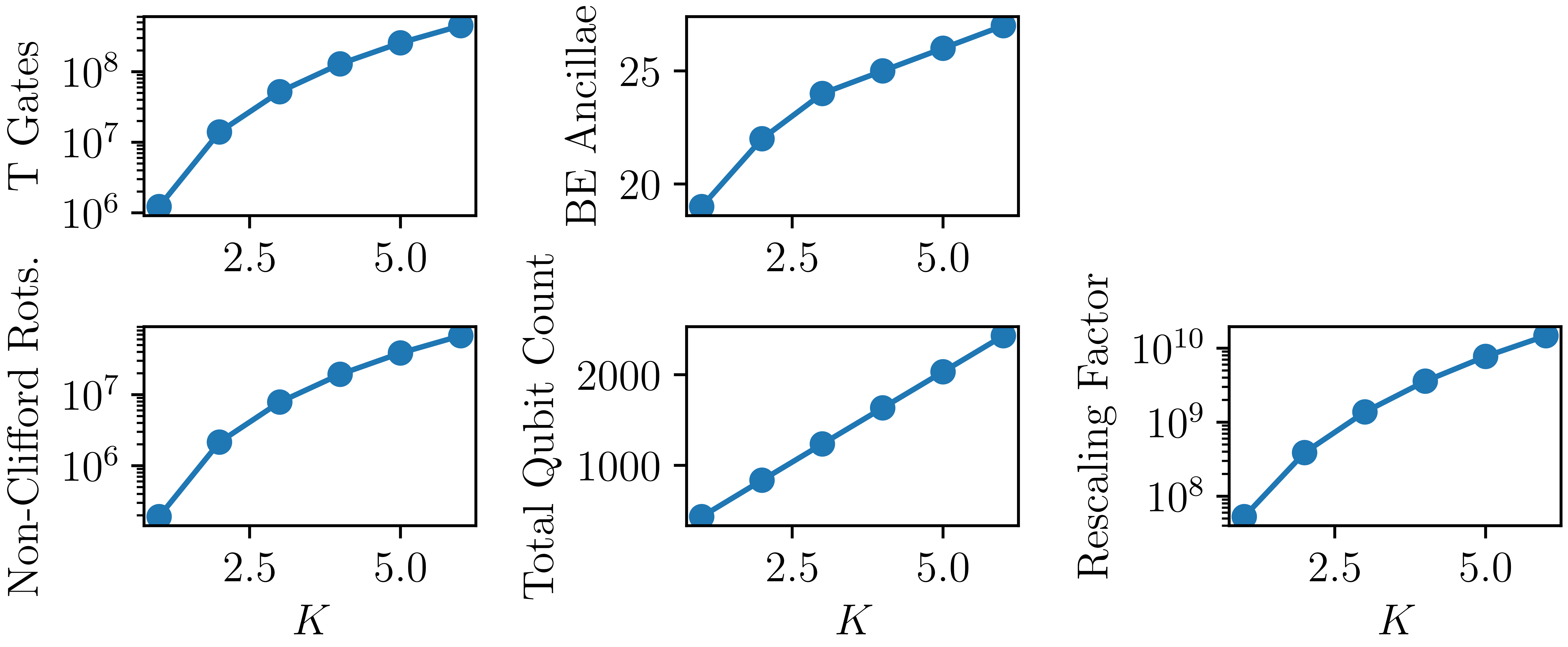






Quantum resources for renormalized simulation: QCD

Simulation resources do not diverge under renormalization.



Quantum Simulation of QCD Results in Context

	Number of T gates	Number of qubits
Kan, Nam (2021) ArXiV □	$\mathcal{O}(10^{55})$	$\mathcal{O}(10^{8})$
Davoudi, Stryker (2025) APS DNP □	$\mathcal{O}(10^{39})$	—
Rhodes, Kreshchuk, Pathak (2024) Phys. Rev. D □	$\mathcal{O}(10^{28})$	$\mathcal{O}(10^{10})$
Gustin et. al (preliminary, pessimistic) △	$\mathcal{O}(10^{24})$	$\mathcal{O}(10^{5})$

□ Time Evolution, 10^3 lattice (position space) △ Eigenstate estimation, 10^3 lattice (momentum space)

Quantum software for resource estmation

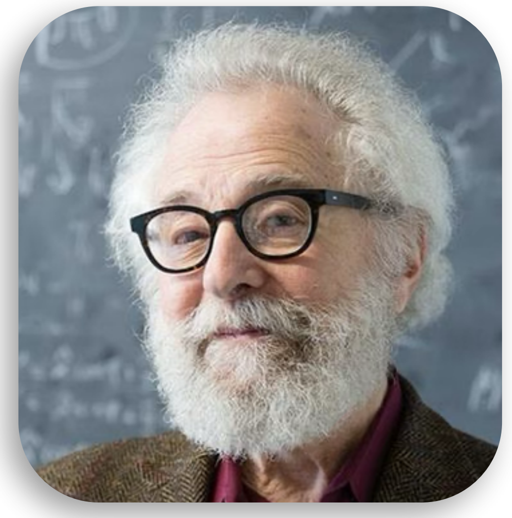
Open Particle: like Open Fermion but with bosons too.

Describe and renormalize second quantized Hamiltonians by RGPEP

Lobe: Ladder Operator Block Encoding (arXiv:2503.11641)

Generate block encodings of second quantized Hamiltonians

Conclusions

- Front form of QFT of interest for quantum simulation.
- Renormalized Hamiltonians obtained within the front form of QFT via RGPEP.
- Resource estimates improving but still much to do (SOS methods next).
- Specific estimates for observable computation to come.
- Classical simulations of RGPEP QCD Hamiltonian also interesting!

Thanks!

NuHaQ (esp James Vary)

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Open Particle