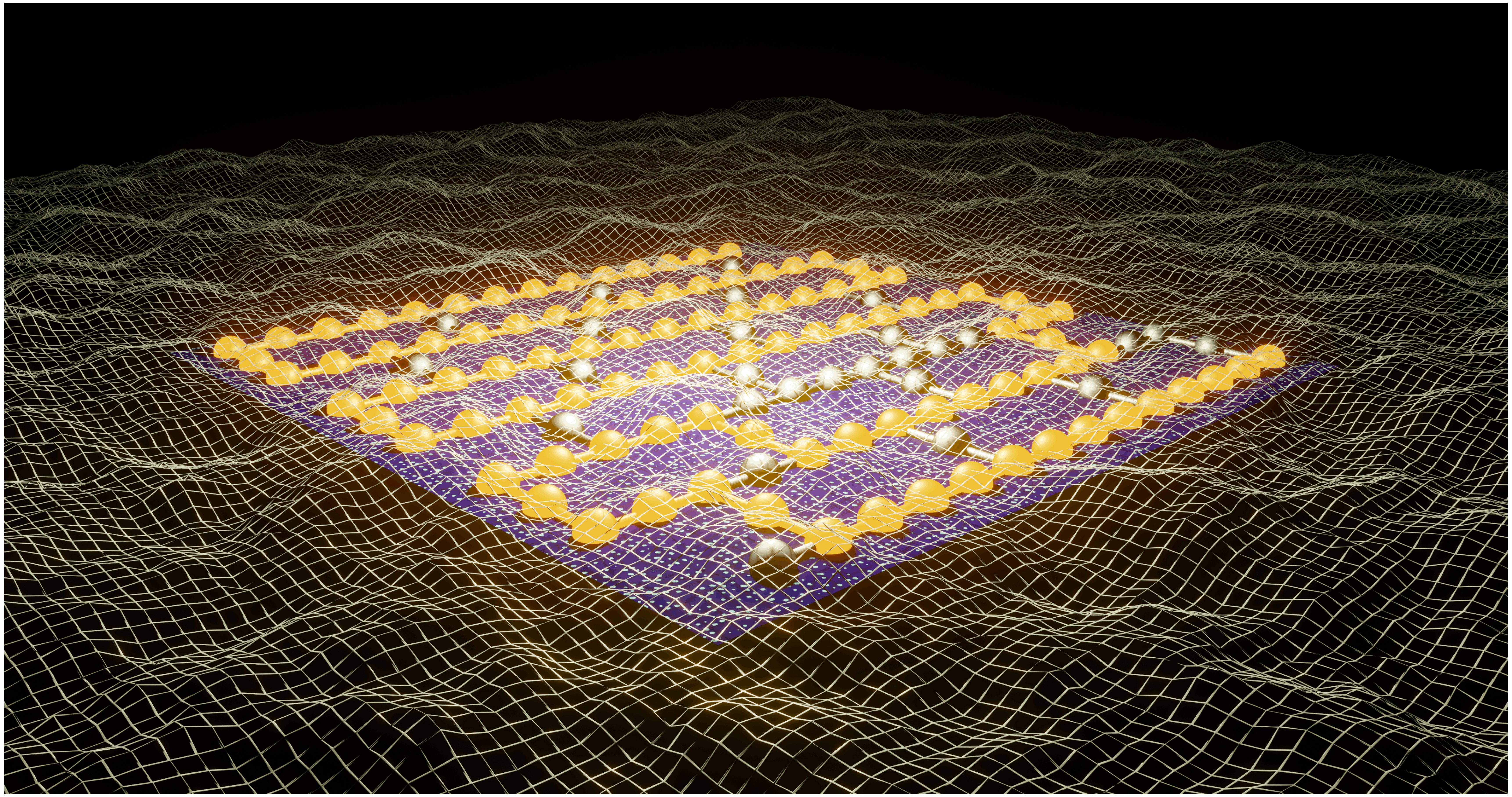
Simulations of hadron dynamics on a quantum computer



Roland C. Farrell

QTI-TH Forum 5/30/24

IQuS NTG

UNIVERSITÄT BERN

I will discuss work done in collaboration with


Marc Illa


Anthony Ciavarella


Martin Savage

Details can be found in:

PRX QUANTUM **5,** 020315 (2024)

Scalable Circuits for Preparing Ground States on Digital Quantum Computers: The Schwinger Model Vacuum on 100 Qubits

Roland C. Farrell,* Marc Illa,† Anthony N. Ciavarella,‡ and Martin J. Savage§
InQubator for Quantum Simulation (IQuS), Department of Physics, University of Washington, Seattle, Washington 98195, USA

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PRX Quantum 5, 020315

Quantum Simulations of Hadron Dynamics in the Schwinger Model using 112 Qubits

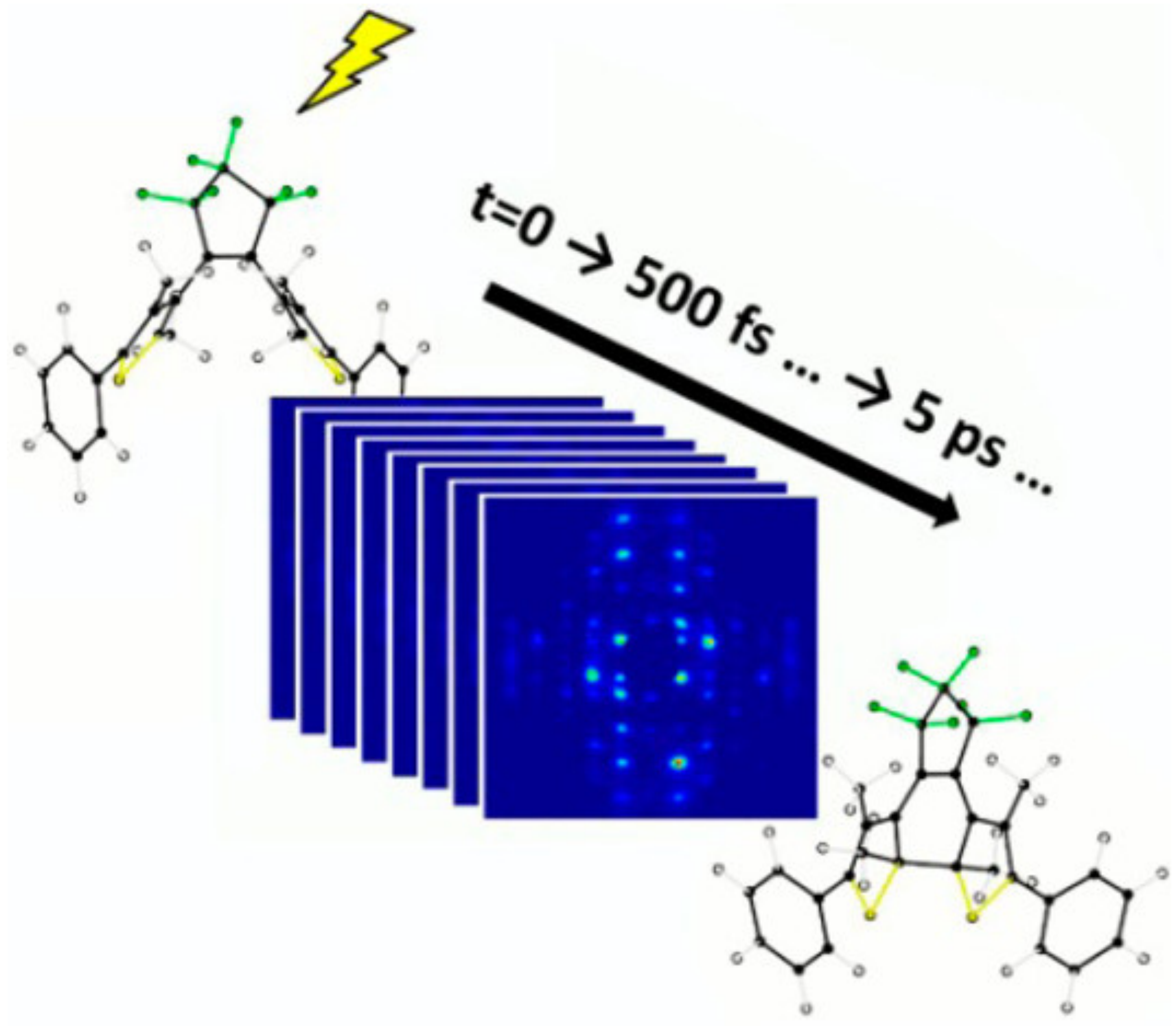
Roland C. Farrell,[1,*] Marc Illa,[1,†] Anthony N. Ciavarella,[1,2,‡] and Martin J. Savage[1,§]
[1] *InQubator for Quantum Simulation (IQuS), Department of Physics, University of Washington, Seattle, WA 98195, USA.*
[2] *Physics Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
(Dated: January 17, 2024)

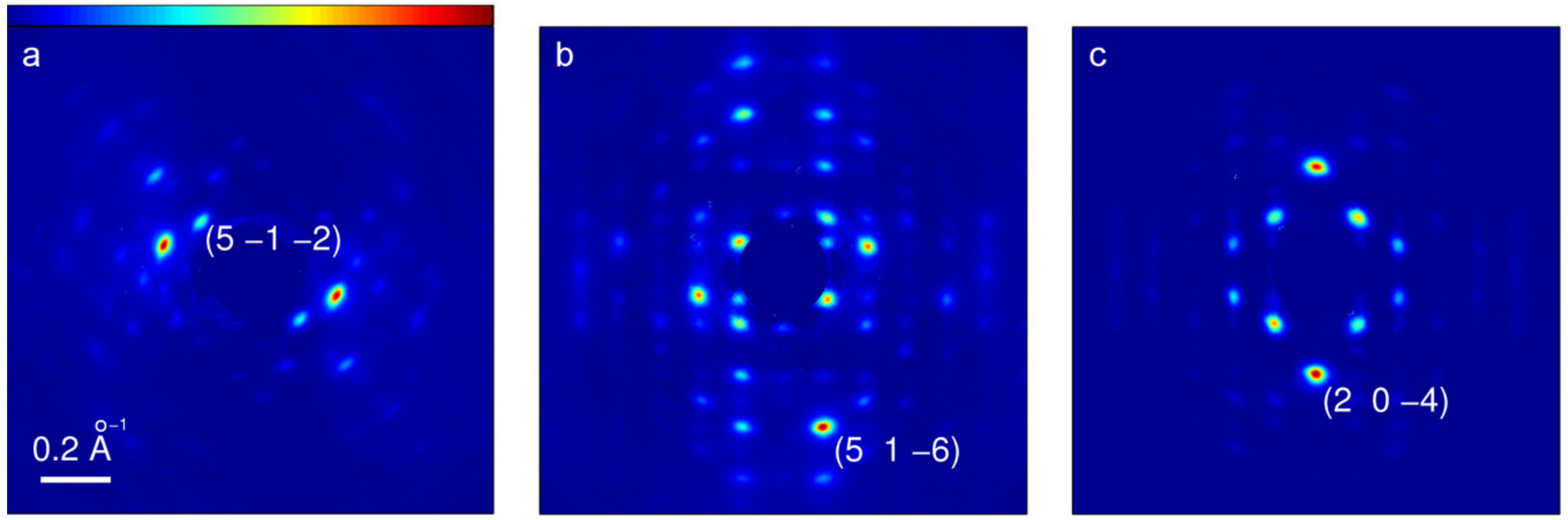
ArXiv: 2401.08044

Outline

1. Motivation and background
2. Mapping electrons and photons to qubits
3. Preparing hadrons on a quantum computer
4. Time evolving hadron on a quantum computer

Probing reactions in real-time

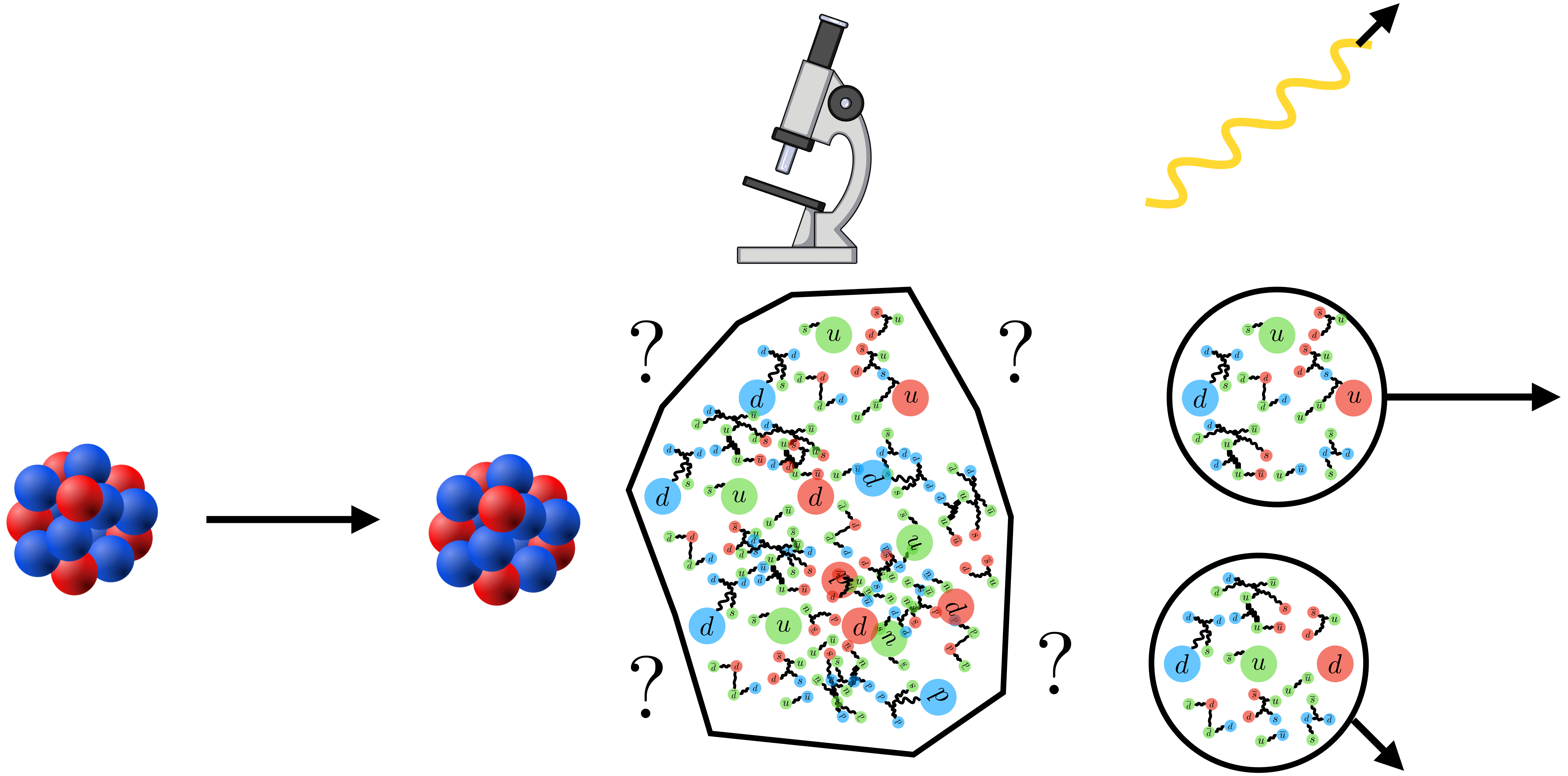




J. Phys. Chem. B 2013, 117, 49, 15894-15902

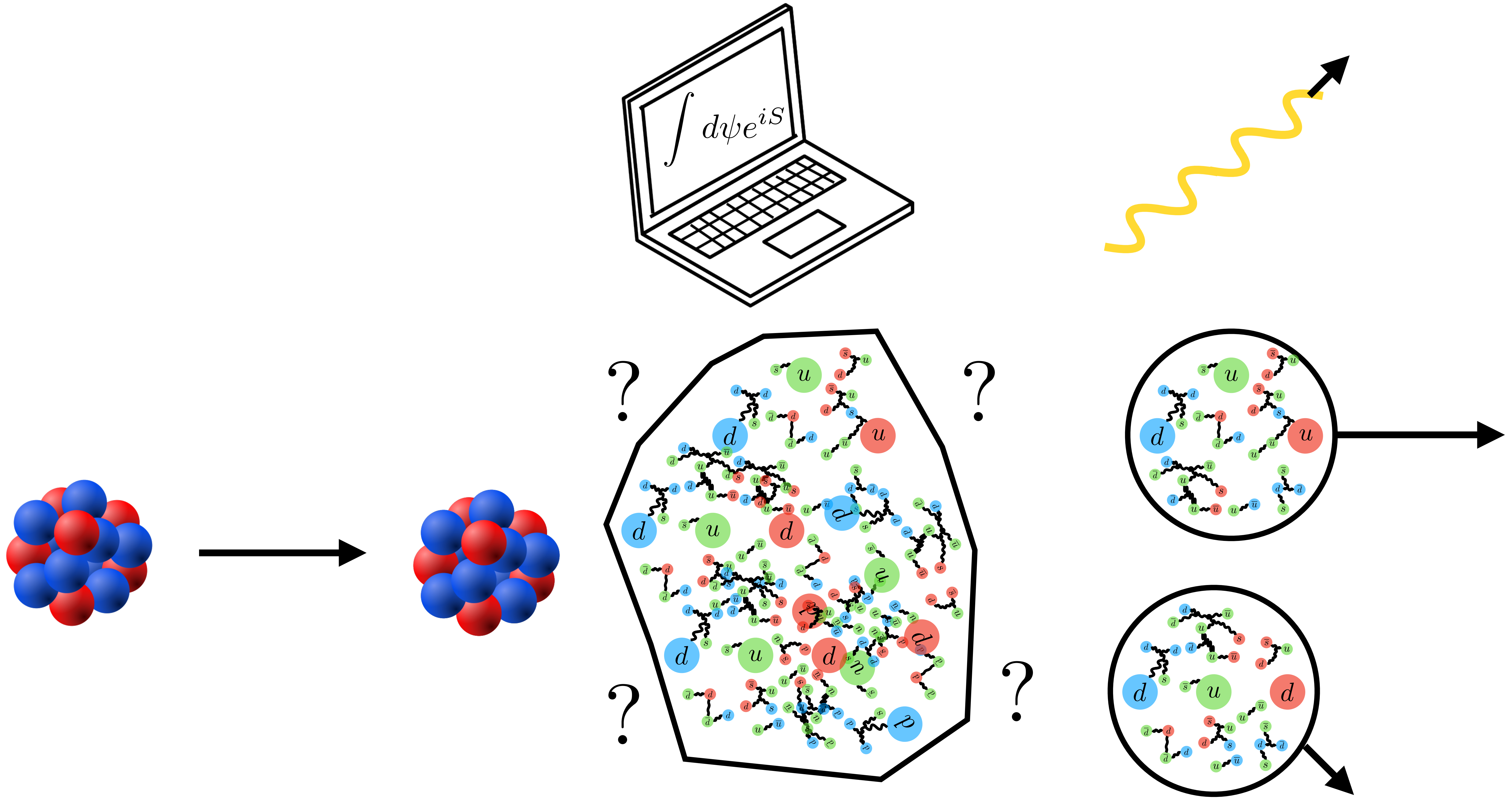
Femtosecond electron diffraction has revealed how molecules re-arrange

Probing reactions in real-time



Hadronic processes are difficult to dissect experimentally

Probing reactions in real-time



Accessible through simulations

Lattice QCD on classical computers

$$Z_E = \int d\psi d\psi^\dagger dA_\mu \, e^{-S_E}$$ ✓

Lattice QCD has been very successful calculating static quantities

Lattice QCD on classical computers

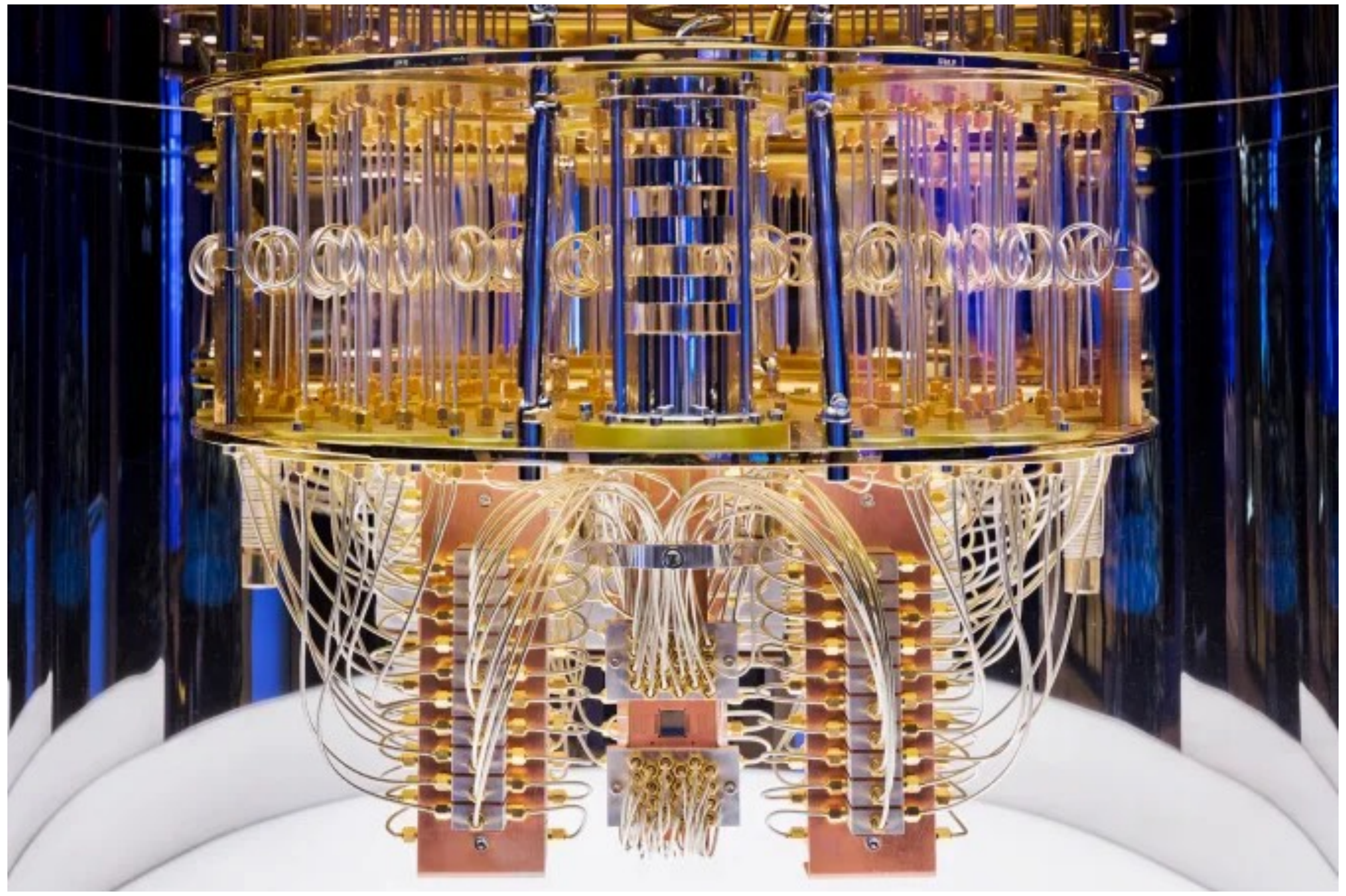
$$Z_E = \int d\psi d\psi^\dagger dA_\mu \, e^{-S_E}$$

Lattice QCD has been very successful calculating static quantities

$$Z = \int d\psi d\psi^\dagger dA_\mu e^{iS}$$

Simulations in Minkowski space encounter the “sign problem”

Lattice QCD on quantum computers



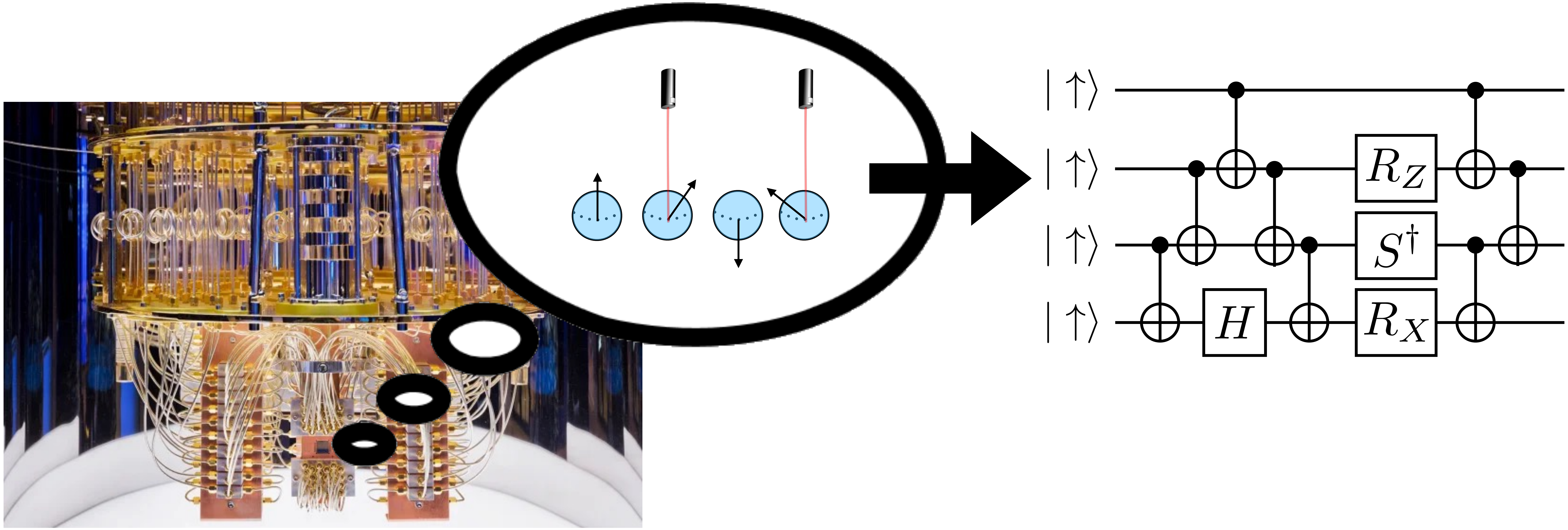
Quantum mechanics naturally evolves in Minkowski space

$$U(t) = e^{-i\hat{H}_{\rm QCD}t} \quad \checkmark$$

Emulate QCD on a system of highly controllable qubits

IBM Research, Flickr

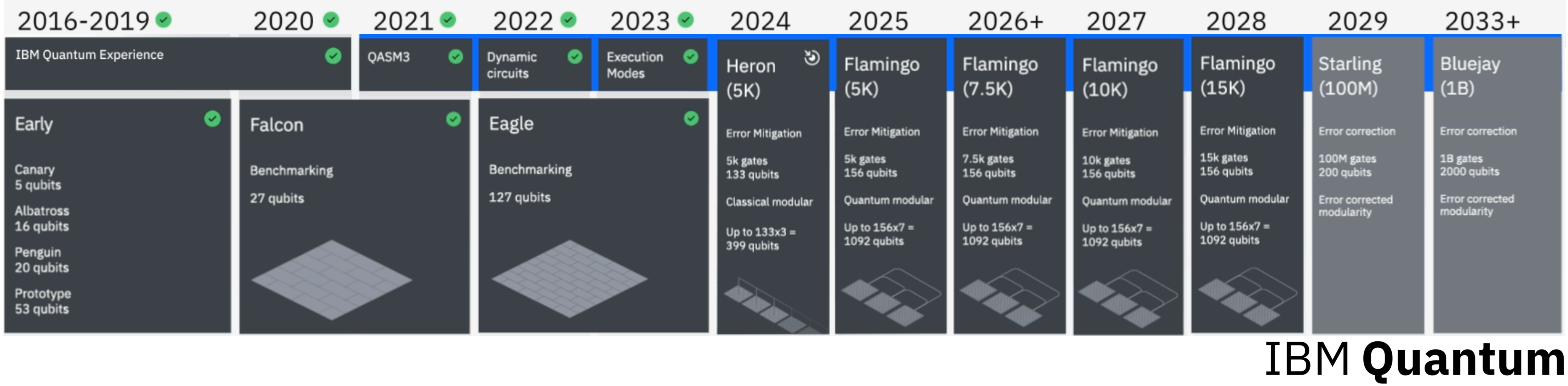
A quantum computer is a highly controllable quantum system



More gates = more device errors

IBM Research, Flickr

Quantum computers are rapidly improving!



Quantum computers are rapidly improving!

IBM **Quantum**

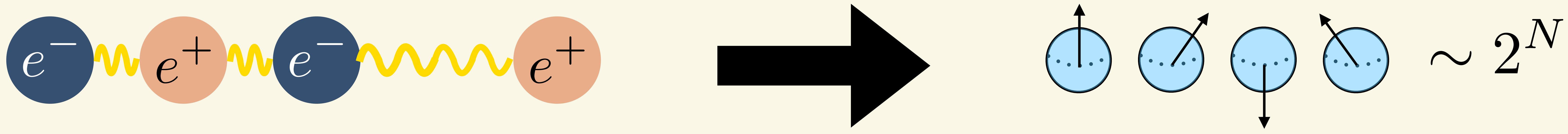
Towards QCD, I will discuss work on the Schwinger model

- QED in 1+1D: also a confining gauge theory with “hadrons”

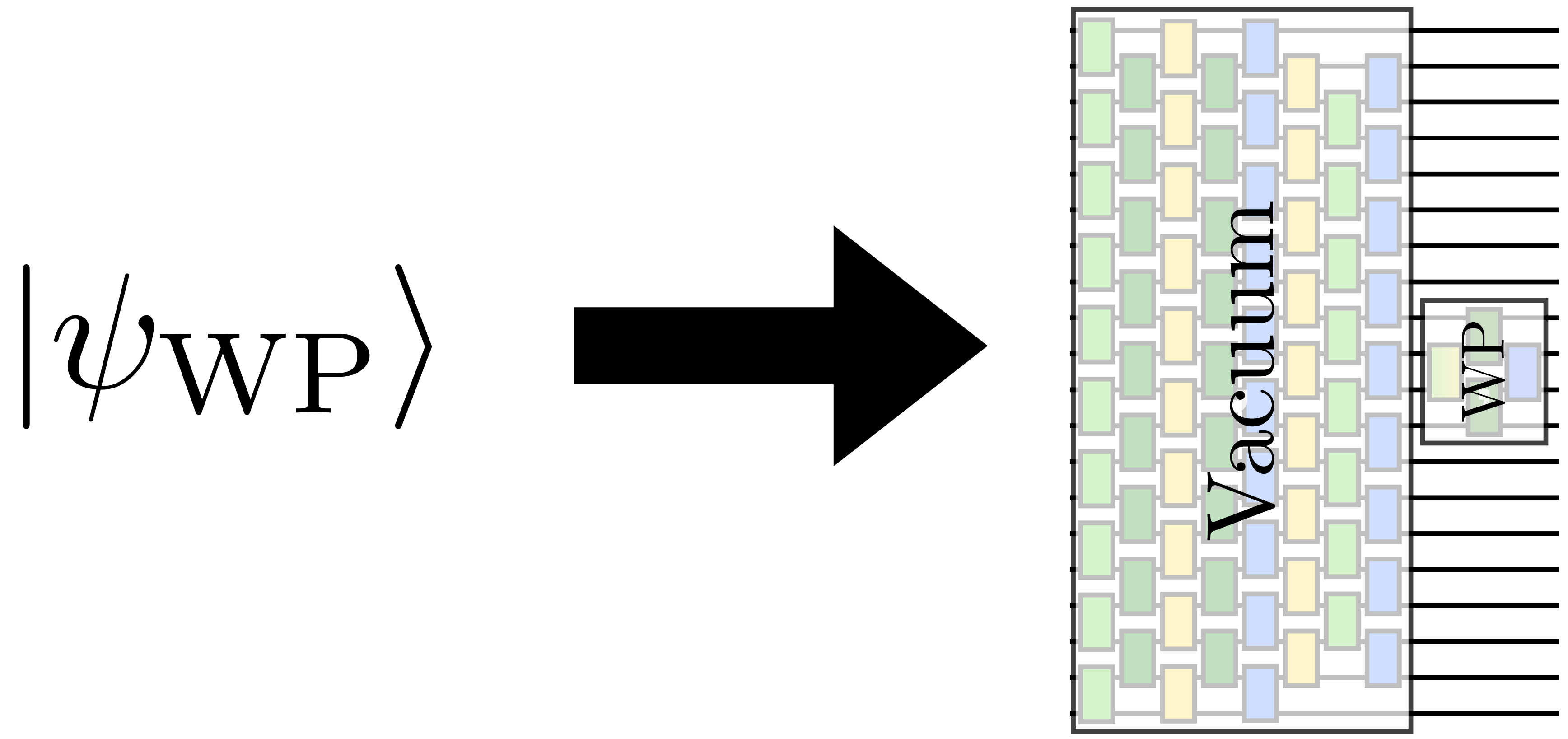
Atas et. al *Nat Commun* **12**, 6499 (2021)
Surace et. al Phys. Rev. X **10**, 021041
Kokail et. al *Nature* **569**, 355–360 (2019)
Klco et. al Phys. Rev. A **98**, 032331
Ciavarella et. al Phys. Rev. D **103**, 094501
Martinez et. al *Nature* **534**, 516–519 (2016)

Goal: to simulate hadron dynamics on a quantum computer

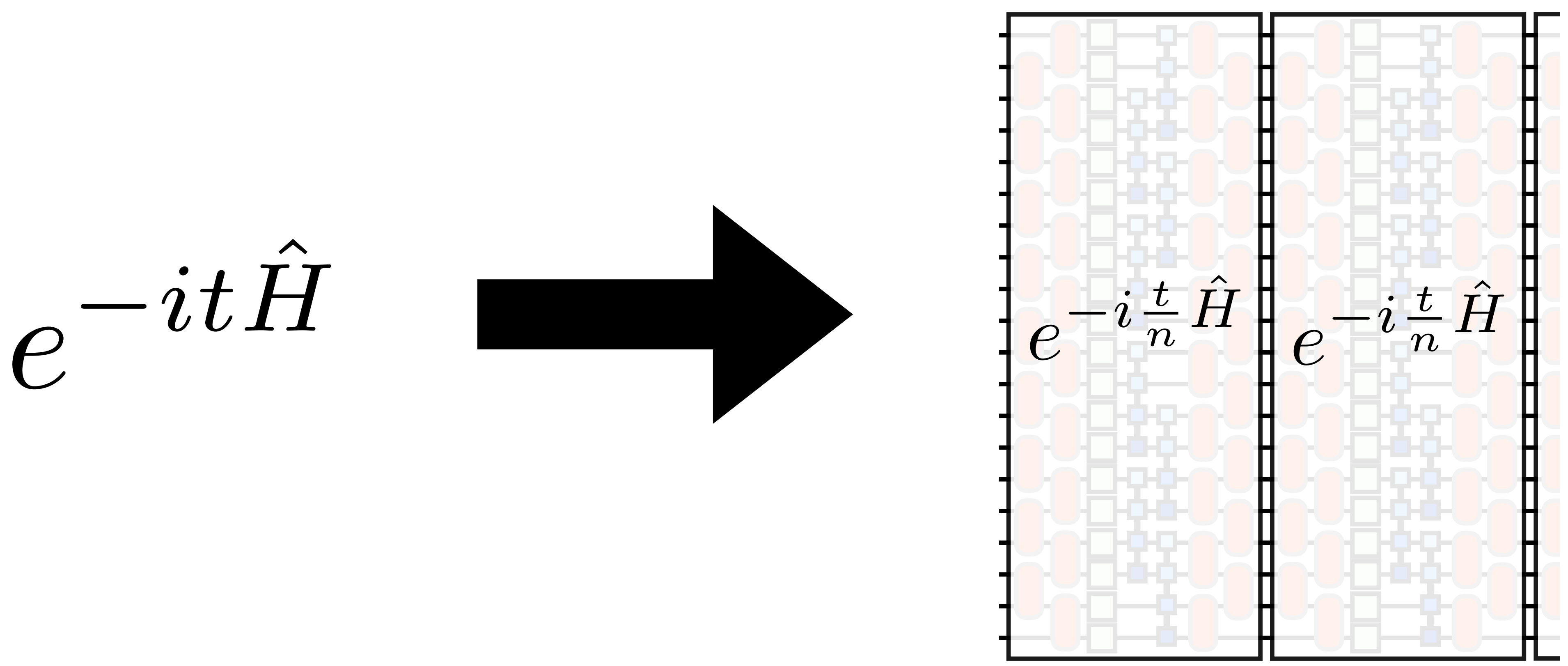
0. Map the Hilbert space onto qubits



1. Prepare the initial state

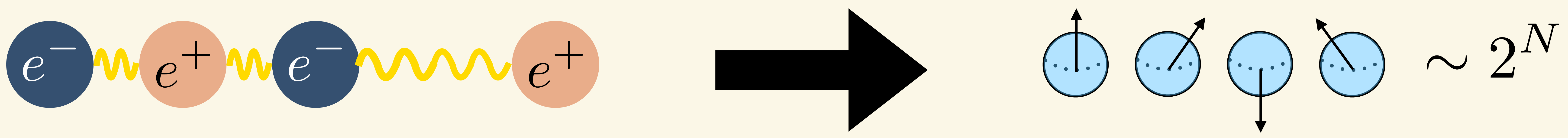


2. Time evolve



Goal: to simulate hadron dynamics on a quantum computer

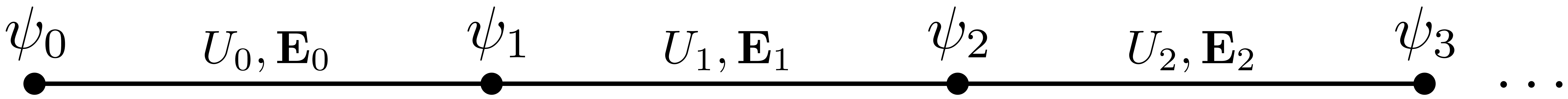
0. Map the Hilbert space onto qubits



1. Prepare the initial state

2. Time evolve

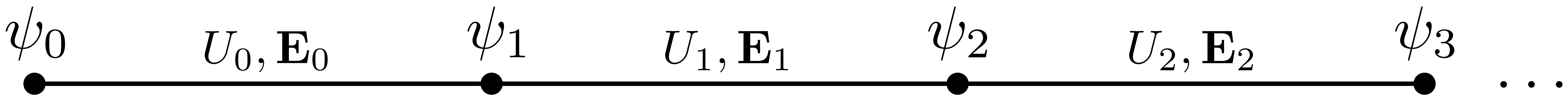
The Schwinger model on a staggered lattice



$$\hat{H}_{\mathrm{KS}} = m \sum_{n=0}^{N-1} (-1)^n \psi_n^\dagger \psi_n + \frac{1}{2} \sum_{n=0}^{N-2} \left(\psi_n^\dagger U_n \psi_{n+1} + \mathrm{h.c.} \right) + \frac{g^2}{2} \sum_{n=0}^{N-2} |\mathbf{E}_n|^2$$

Lattice of size N with electrons (positrons) on even (odd) numbered sites

The Schwinger model on a staggered lattice



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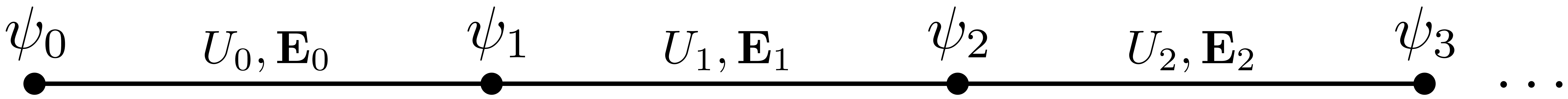
Mass — Kinetic “hopping” — Electric

Lattice of size N with electrons (positrons) on even (odd) numbered sites

The Schwinger model on a staggered lattice



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Mass — Kinetic “hopping” — Electric

In 1+1D the photon is not dynamical and can be removed

The Schwinger model on a staggered lattice

$$\hat{H}_{\text{KS}} = m \sum_{n=0}^{N-1} (-1)^n \psi_n^\dagger \psi_n + \frac{1}{2} \sum_{n=0}^{N-2} \left(\psi_n^\dagger \psi_{n+1} + \text{h.c.} \right) + \frac{g^2}{2} \sum_{n=0}^{N-2} \left(\sum_{m \leq n} \hat{Q}_m \right)^2$$

No parallel transporter

Coulomb potential

A lattice of N interacting electrons and positrons

Mapping to qubits with the JW transformation $\psi_n^\dagger = \prod_{i<n} (-\sigma_i^z)\,\sigma_n^+$

$$\hat{H} \;=\; \frac{m}{2}\sum_{n=0}^{N-1}(-1)^n \hat{Z}_n \;+\; \frac{1}{2}\sum_{n=0}^{N-2}\left(\hat{\sigma}_n^+\hat{\sigma}_{n+1}^- + \mathrm{h.c.}\right) \;+\; \frac{g^2}{2}\sum_{n=0}^{N-2}\left(\sum_{m\le n}\hat{Q}_m\right)^2 , \qquad \hat{Q}_k = -\frac{1}{2}(\hat{Z}_k + (-1)^k)$$

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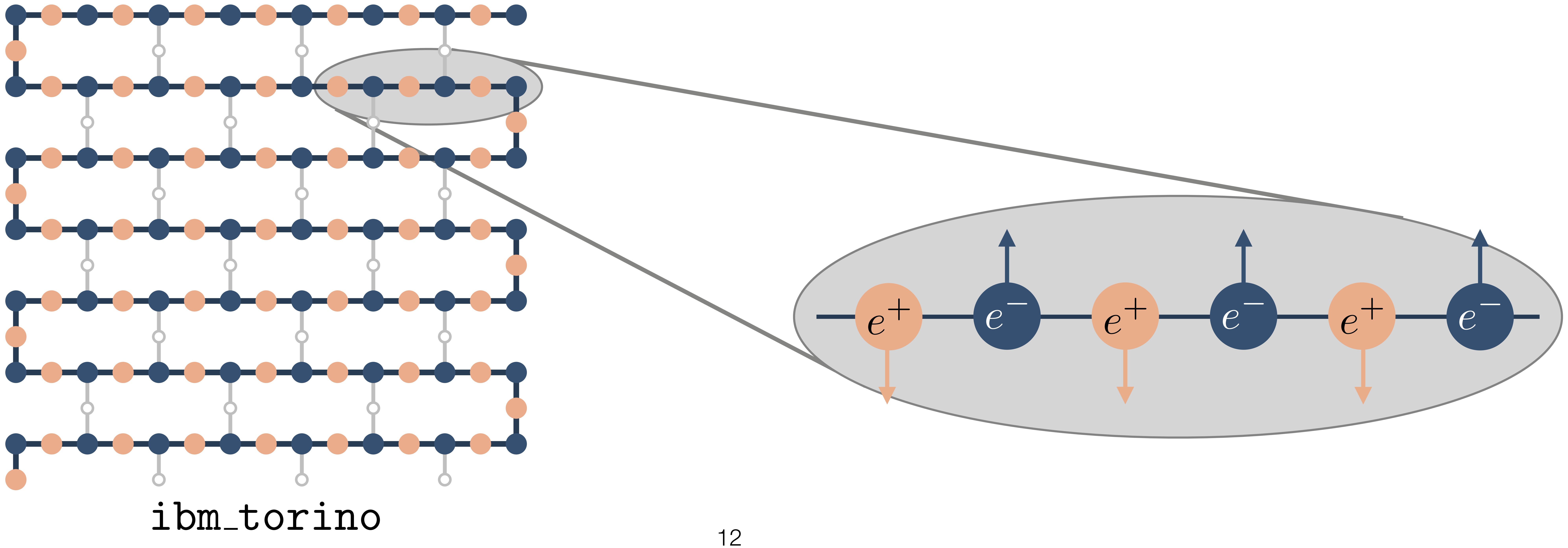


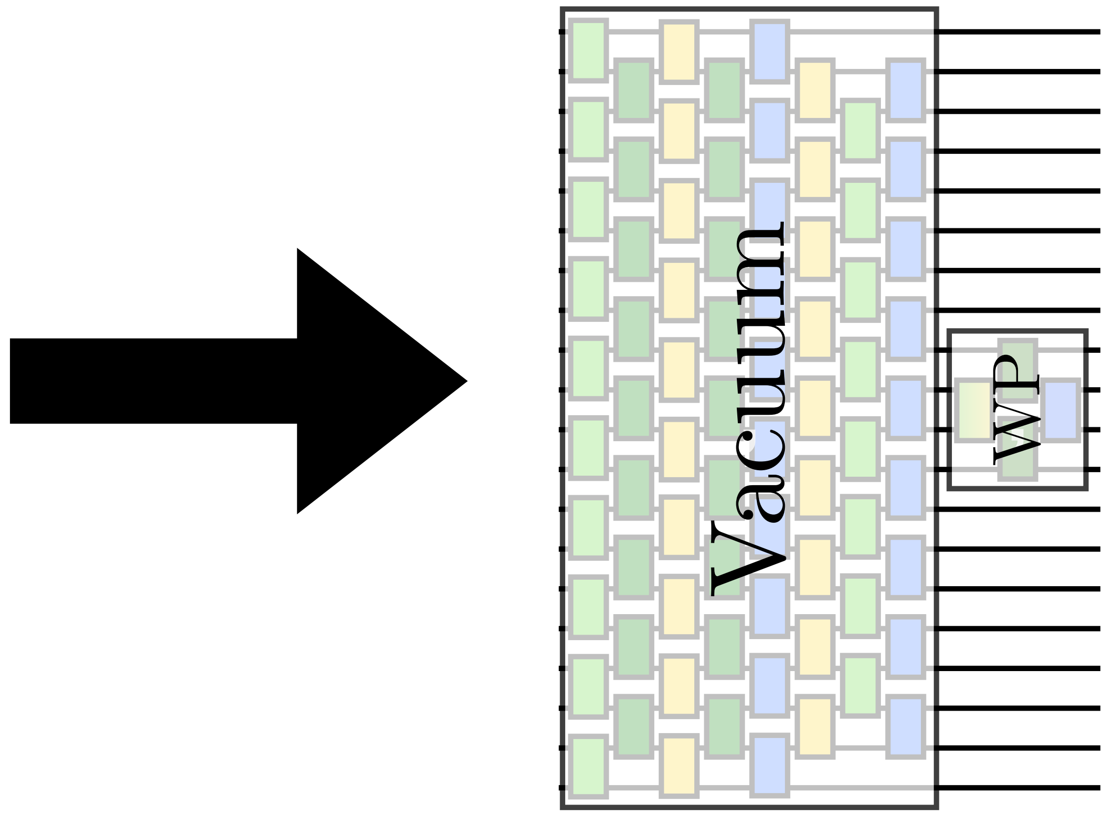
Goal: to simulate hadron dynamics on a quantum computer

0. Map the Hilbert space onto qubits

✓

1. Prepare the initial state

$$|\psi_{\mathrm{WP}}\rangle$$



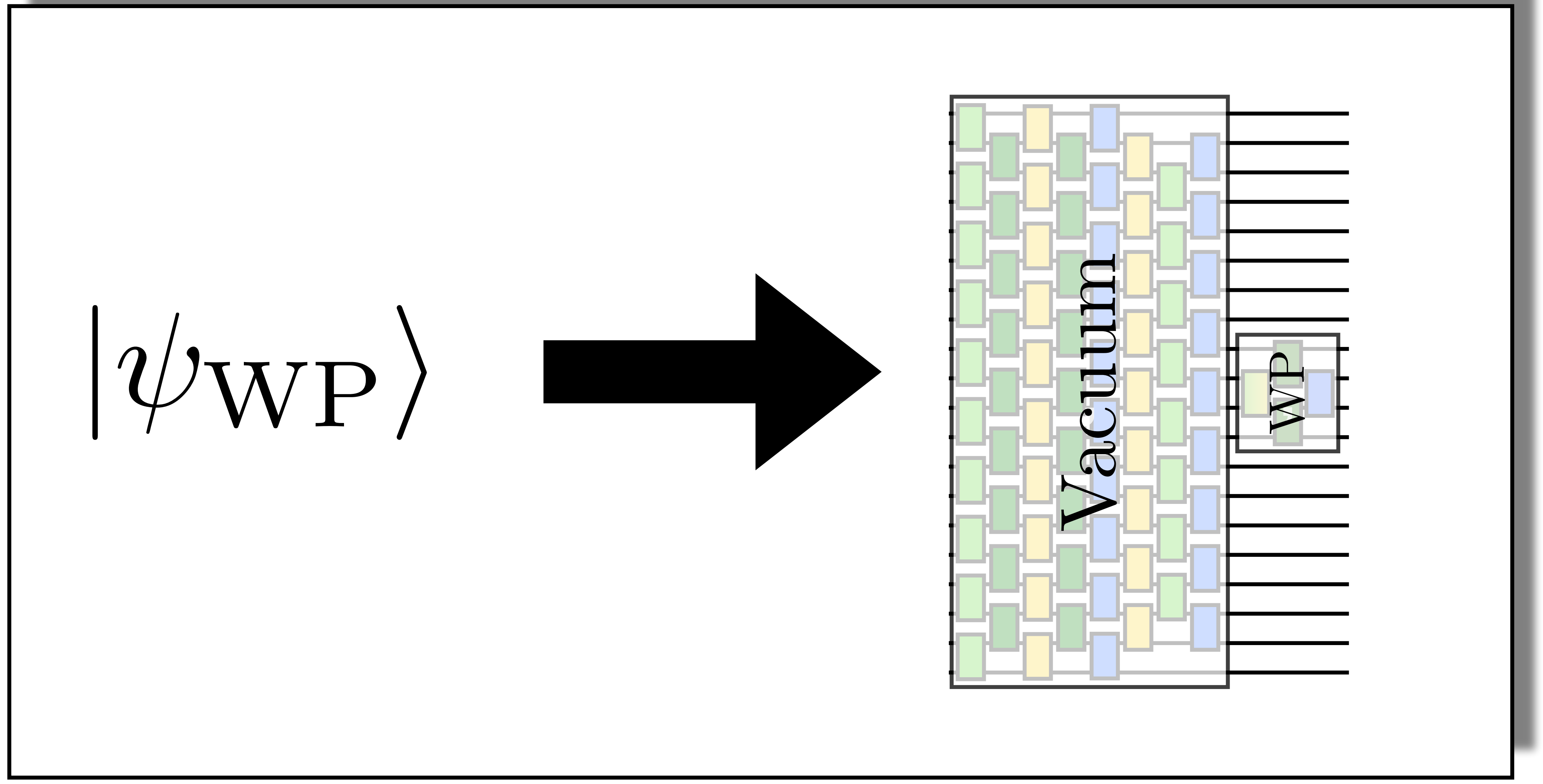
2. Time evolve

$$e^{-it\hat{H}}$$

Goal: prepare a hadron wavepacket

1. Prepare the interacting vacuum

2. Excite a hadron wave packet on top of the vacuum

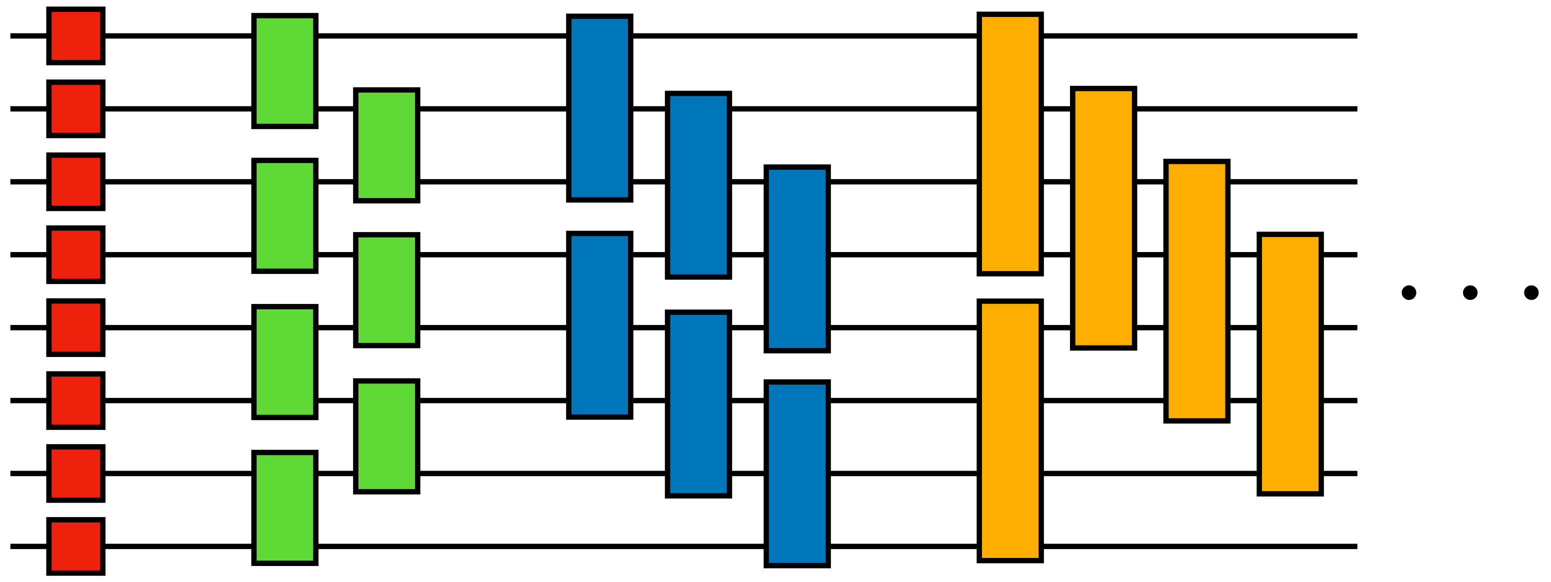


Important features of the vacuum

Translational and CP symmetry → Circuits are repeated across the lattice

$$\langle \hat{Q}_n \rangle = (-1)^d \langle \hat{Q}_{n+d} \rangle$$

$$|\psi_{\text{vac}}\rangle_{N=8} = \cdots$$



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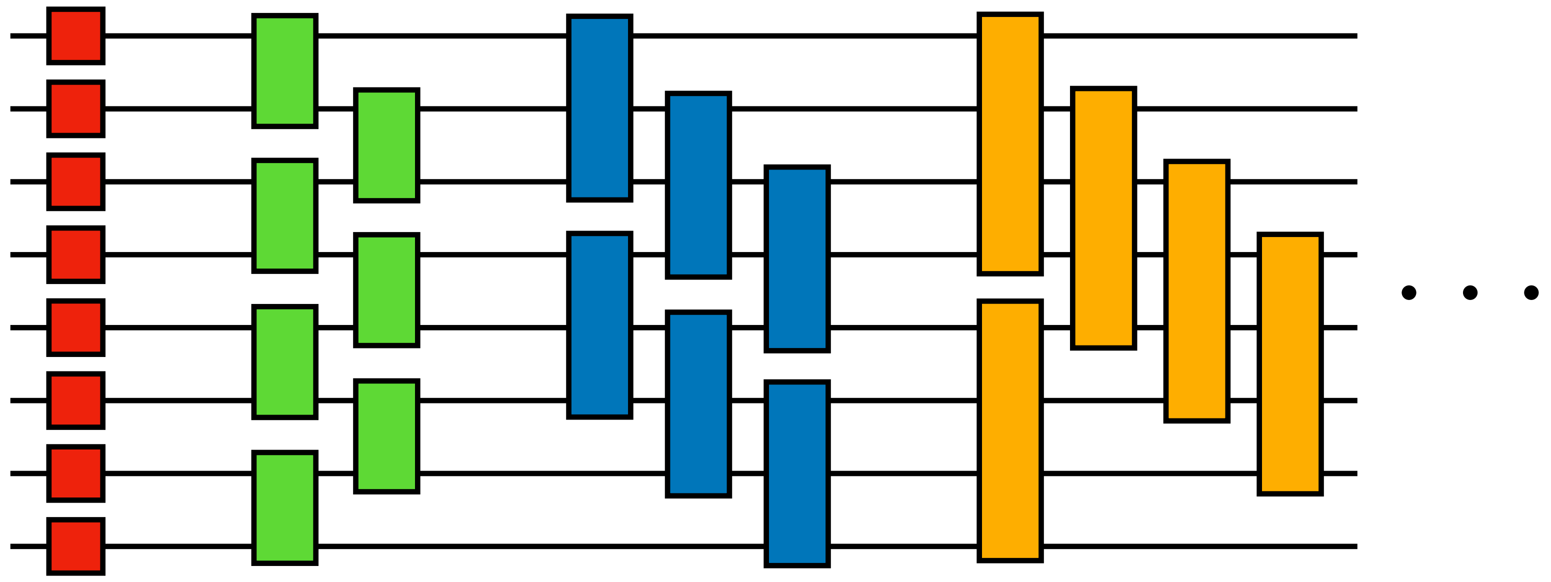
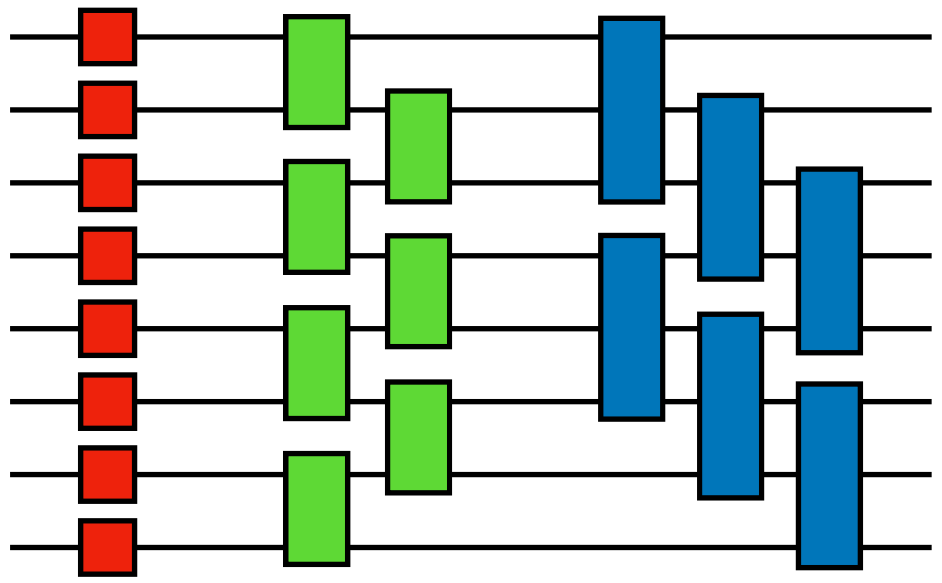


Spectrum is gapped → Circuits have structure over $\sim m_{\mathrm{hadron}}^{-1}$ sites

$$\langle \hat{Q}_n \hat{Q}_{n+d} \rangle_c \sim e^{-d\, m_{\mathrm{hadron}}}$$

$$|\psi_{\mathrm{vac}}\rangle_{N=8} \approx $$

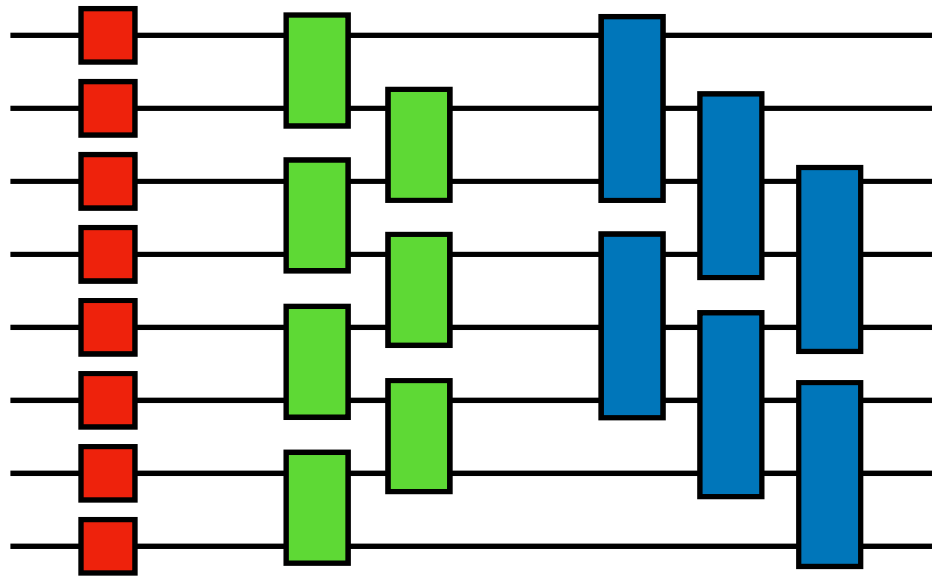


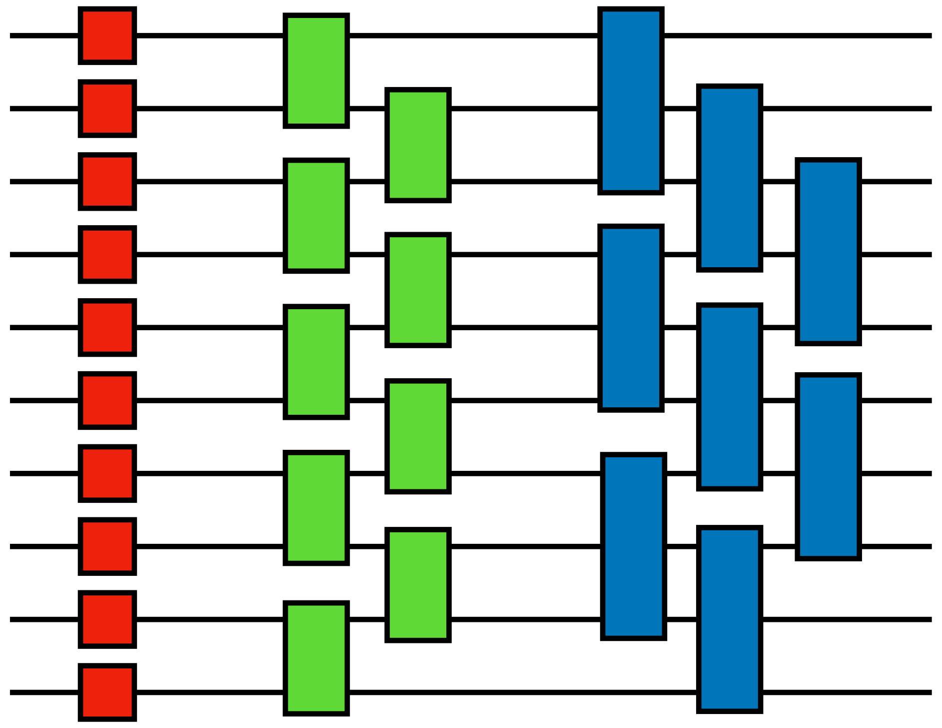
Important features of the vacuum

Translational and CP symmetry → Circuits are repeated across the lattice

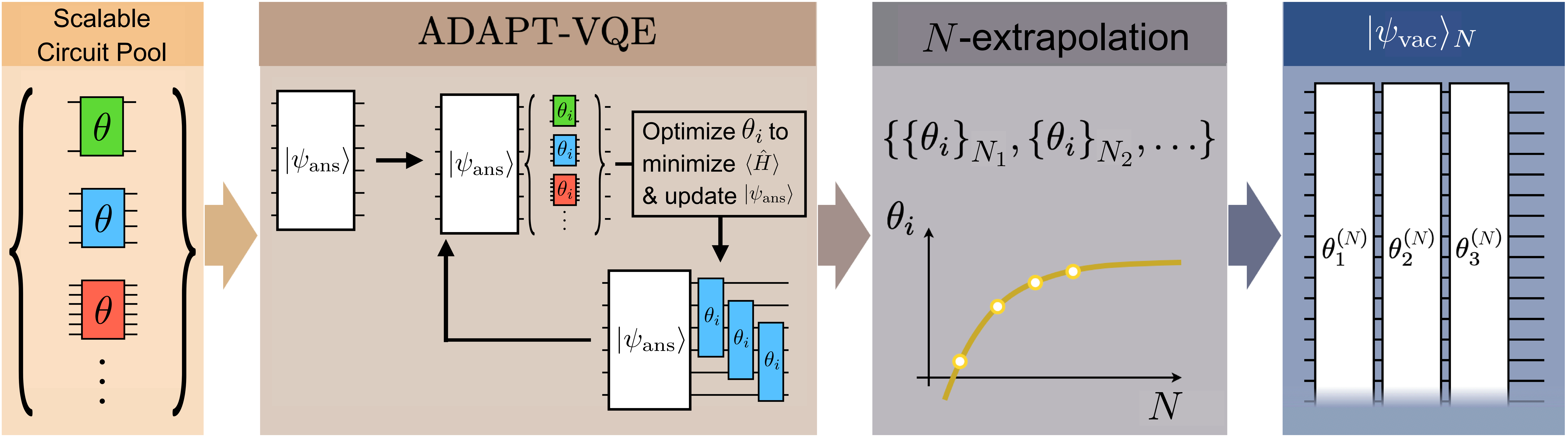
Spectrum is gapped → Circuits structure converges in N

$$\langle \hat{Q}_n \hat{Q}_{n+d} \rangle_{N=8} = \langle \hat{Q}_n \hat{Q}_{n+d} \rangle_{N=10} + \mathcal{O}(e^{-N m_{\text{hadron}}})$$

$|\psi_{\text{vac}}\rangle_{N=8} \approx$ 

$|\psi_{\text{vac}}\rangle_{N=10} \approx$ 

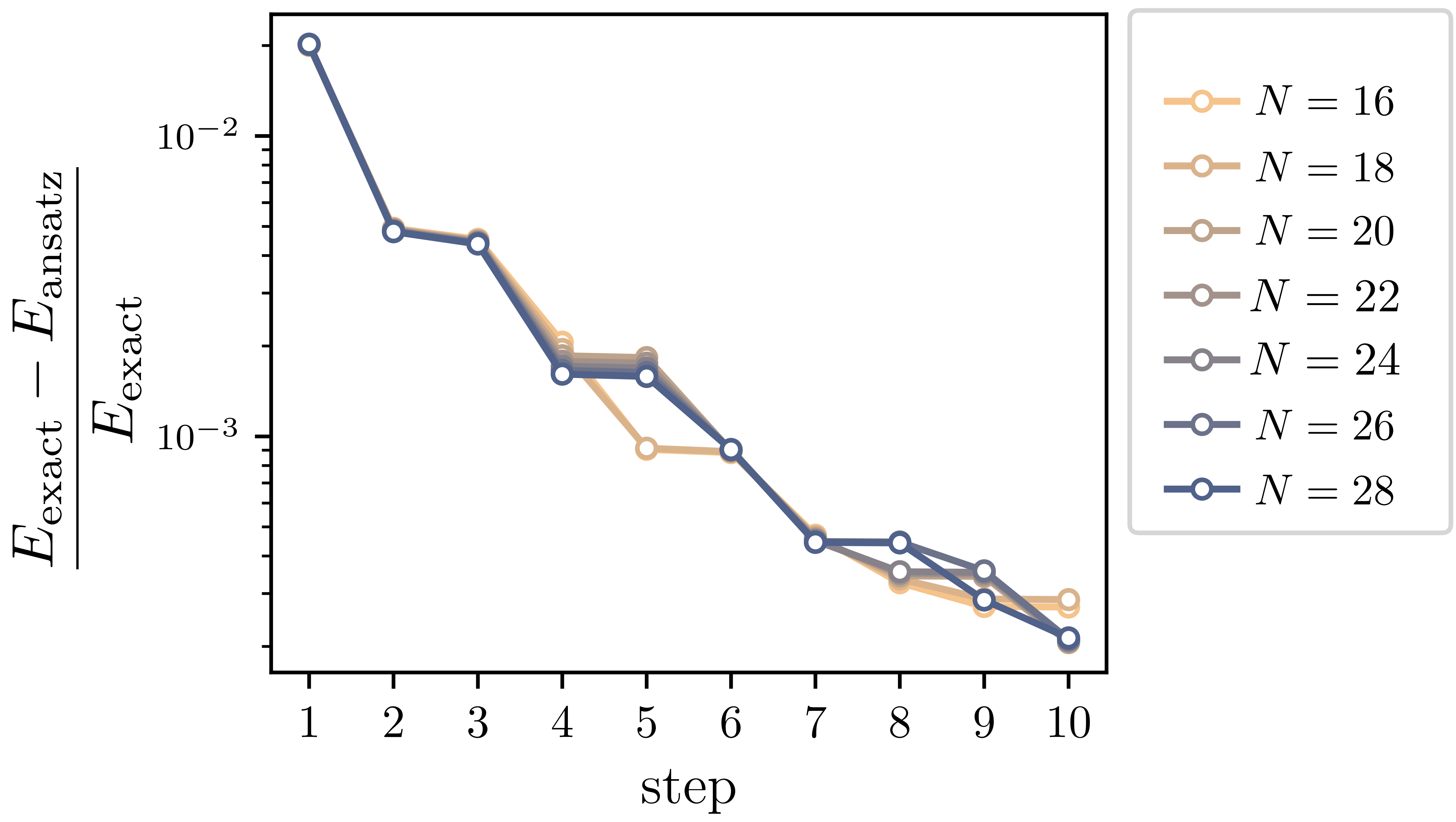
The SC-ADAPT-VQE state preparation algorithm

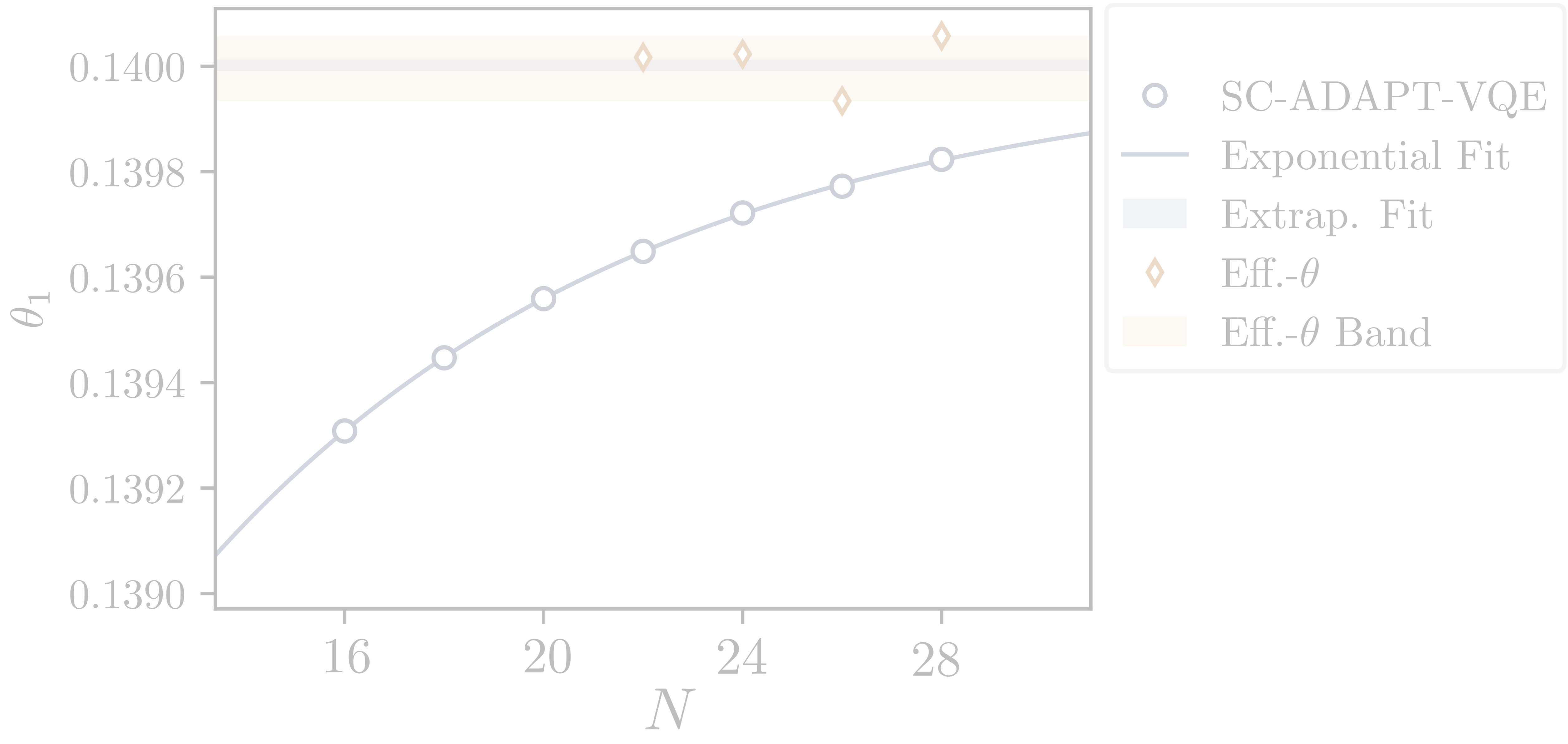


θ_i and θ_i are found by variational minimizing $E = \langle \hat{H} \rangle$ on classical computers.

Circuits are systematically scaled and executed on a quantum computer

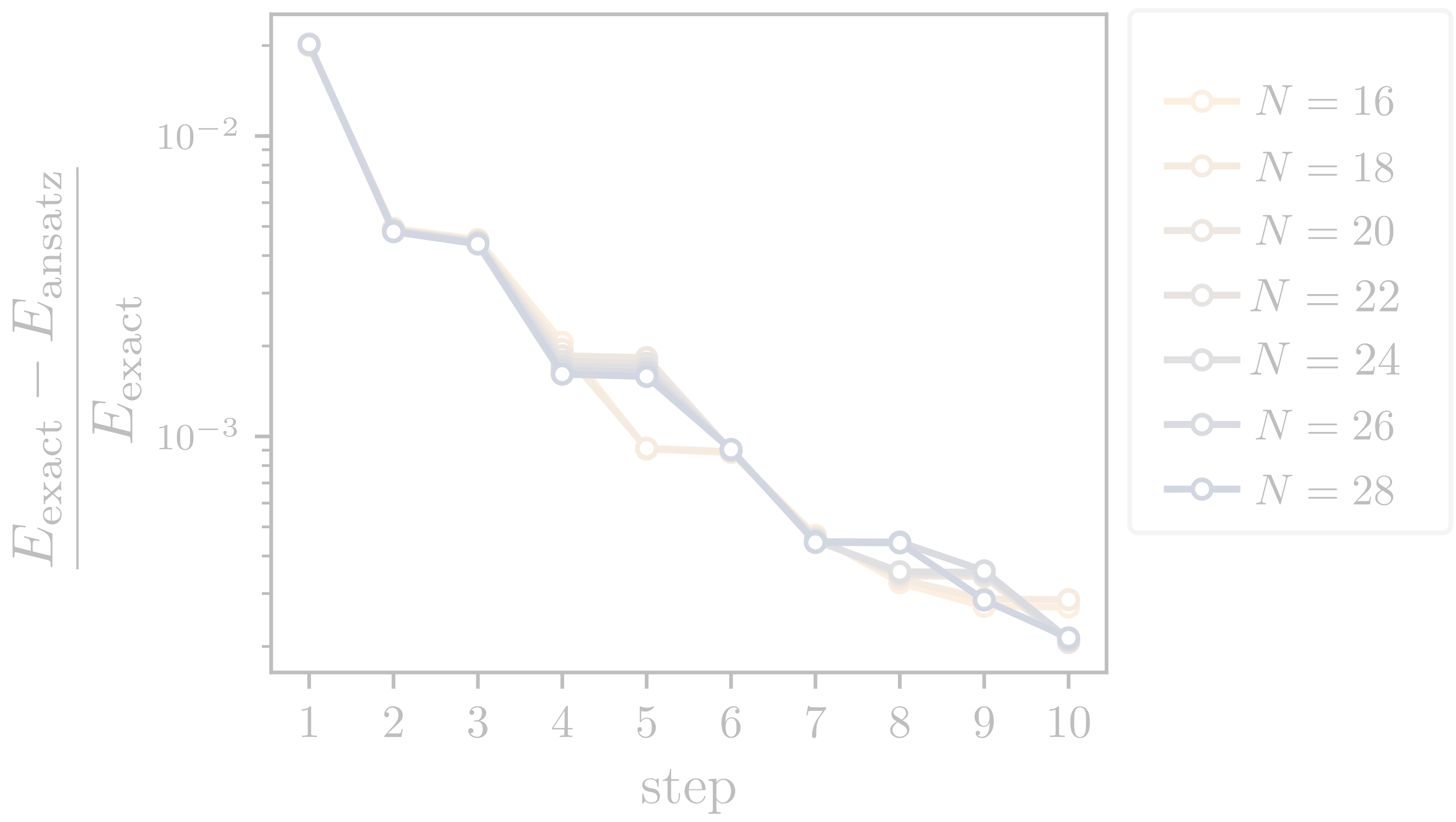
Vacuum preparation circuits found for $N \leq 28$ using classical computers

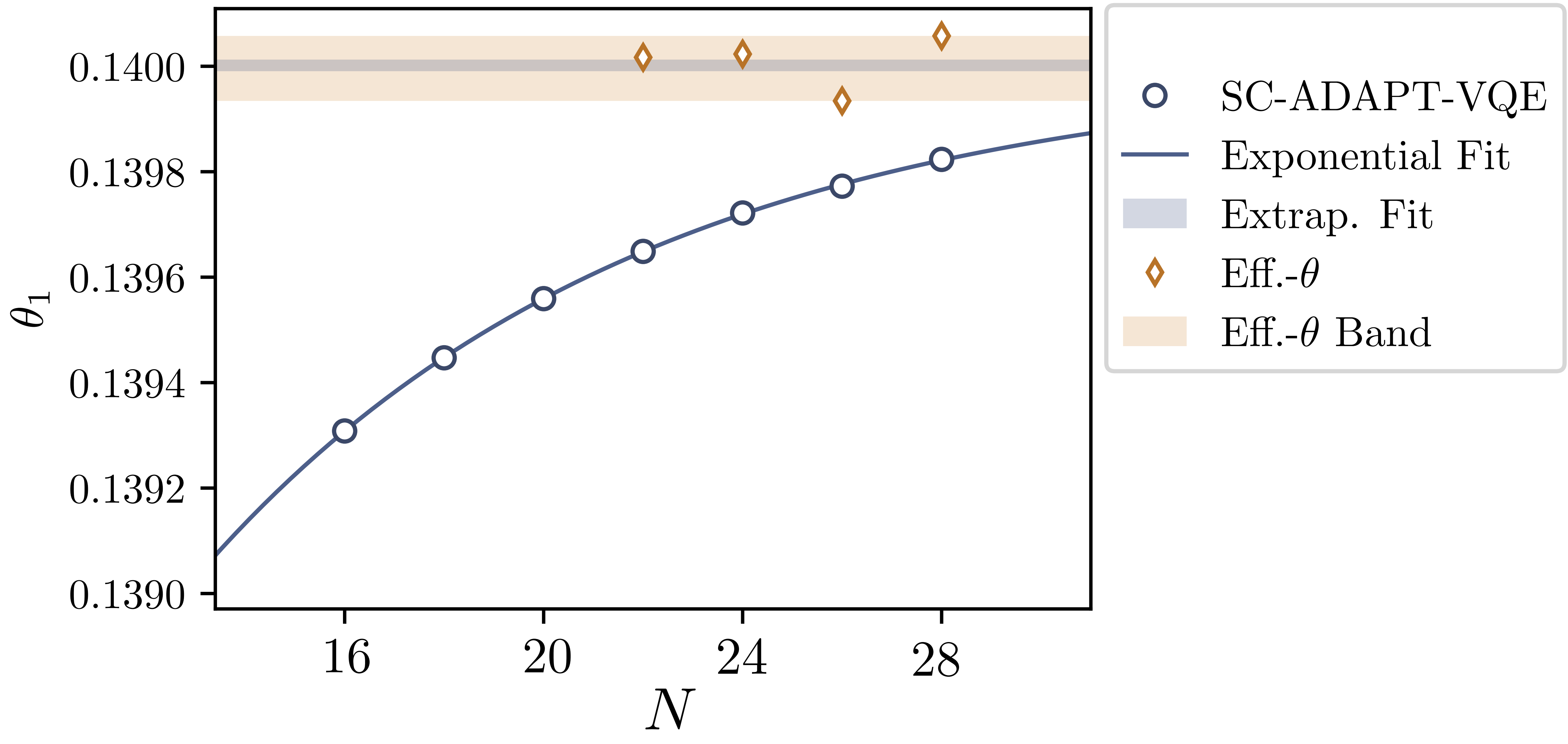




Energy converges exponentially as larger correlations are added

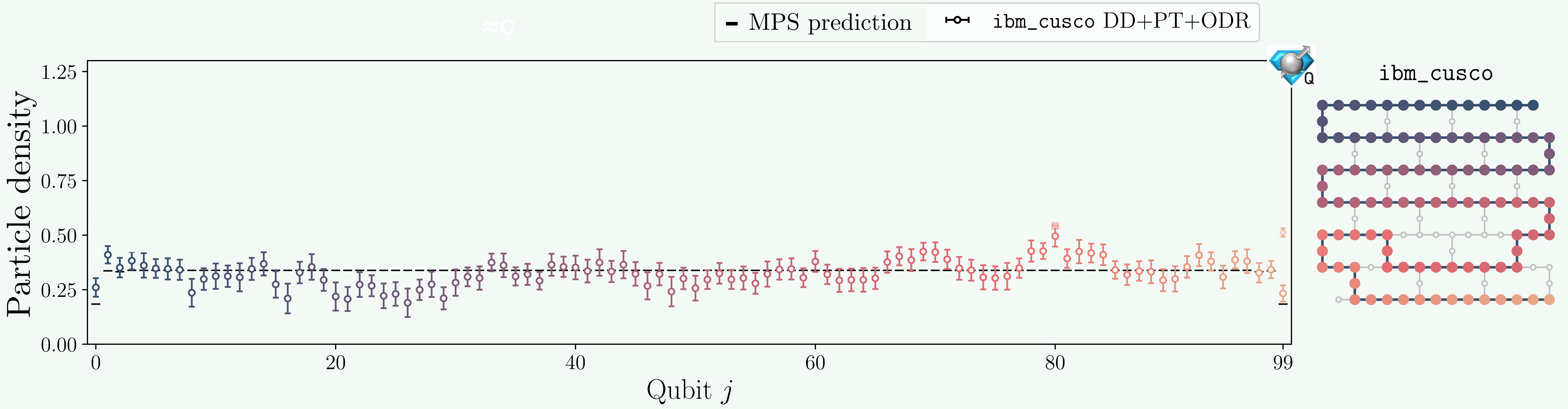
Vacuum preparation circuits found for $N \leq 28$ using <u>classical</u> computers





Vacuum preparation circuit structure converges exponentially in N

Results from IBM's quantum computer



Vacuum preparation circuits were scaled to $N = 100$ and run on ibm_cusco

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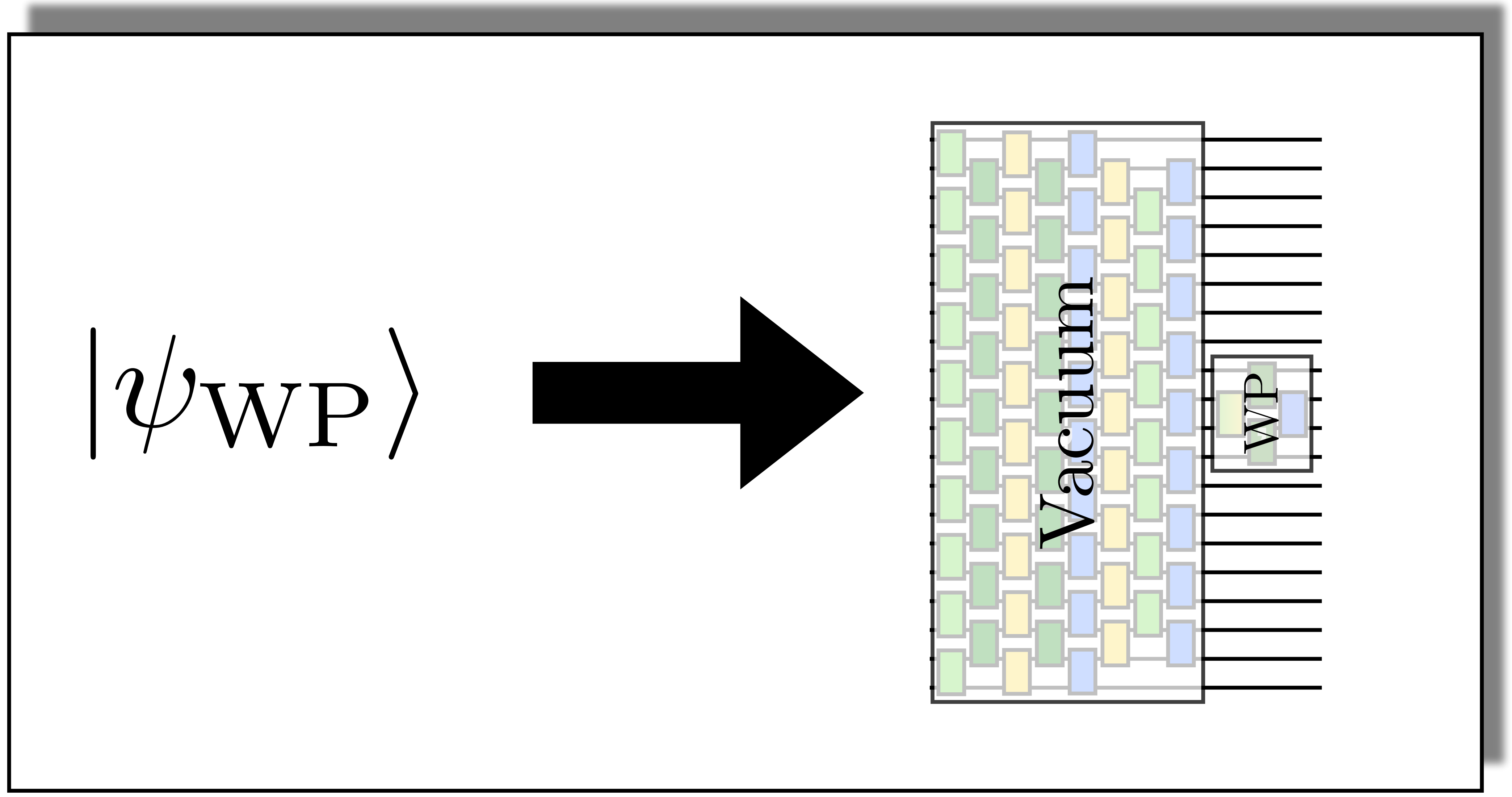
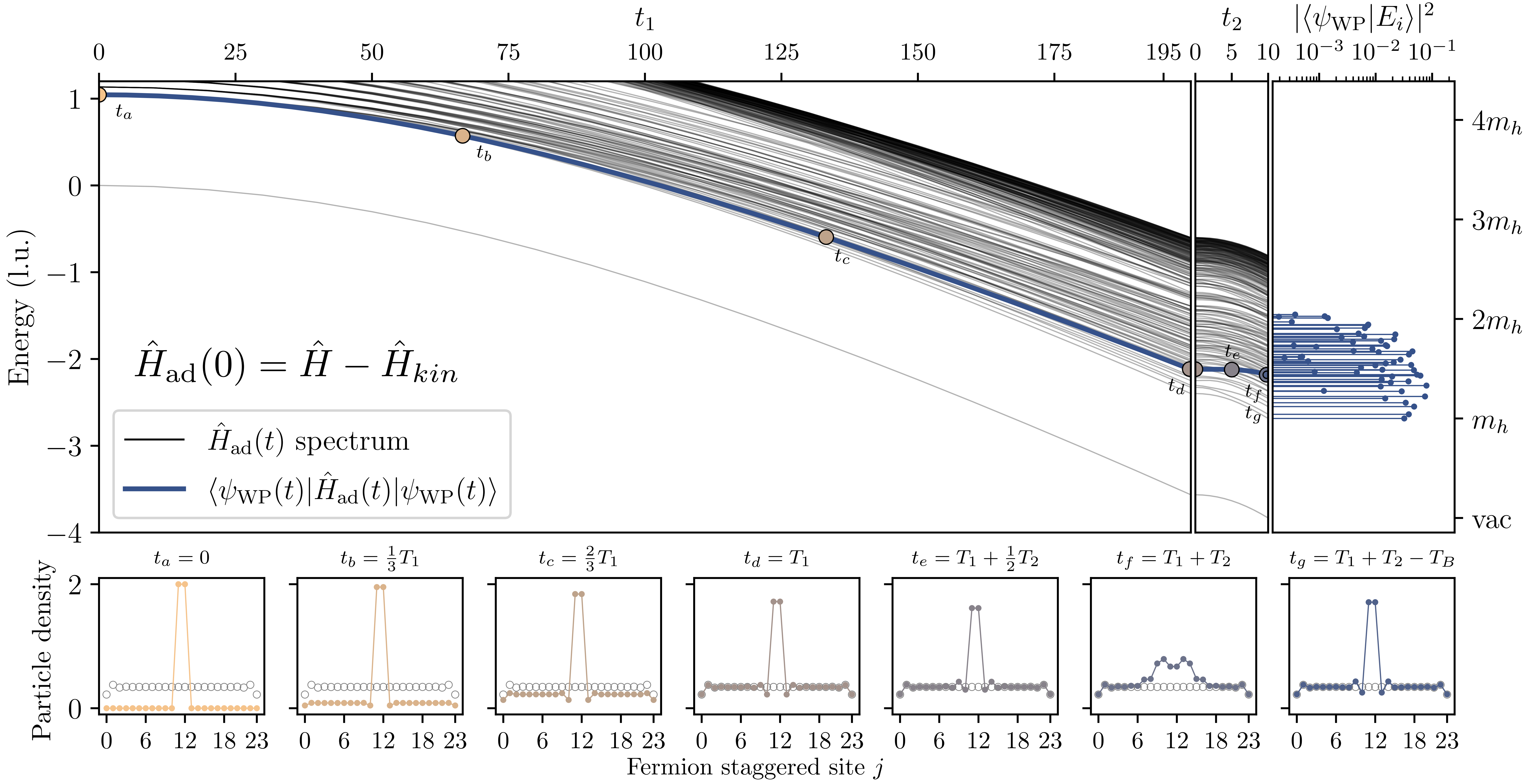
Goal: prepare a hadron wavepacket

1. Prepare the interacting vacuum ✓

2. Excite a hadron wave packet on top of the vacuum



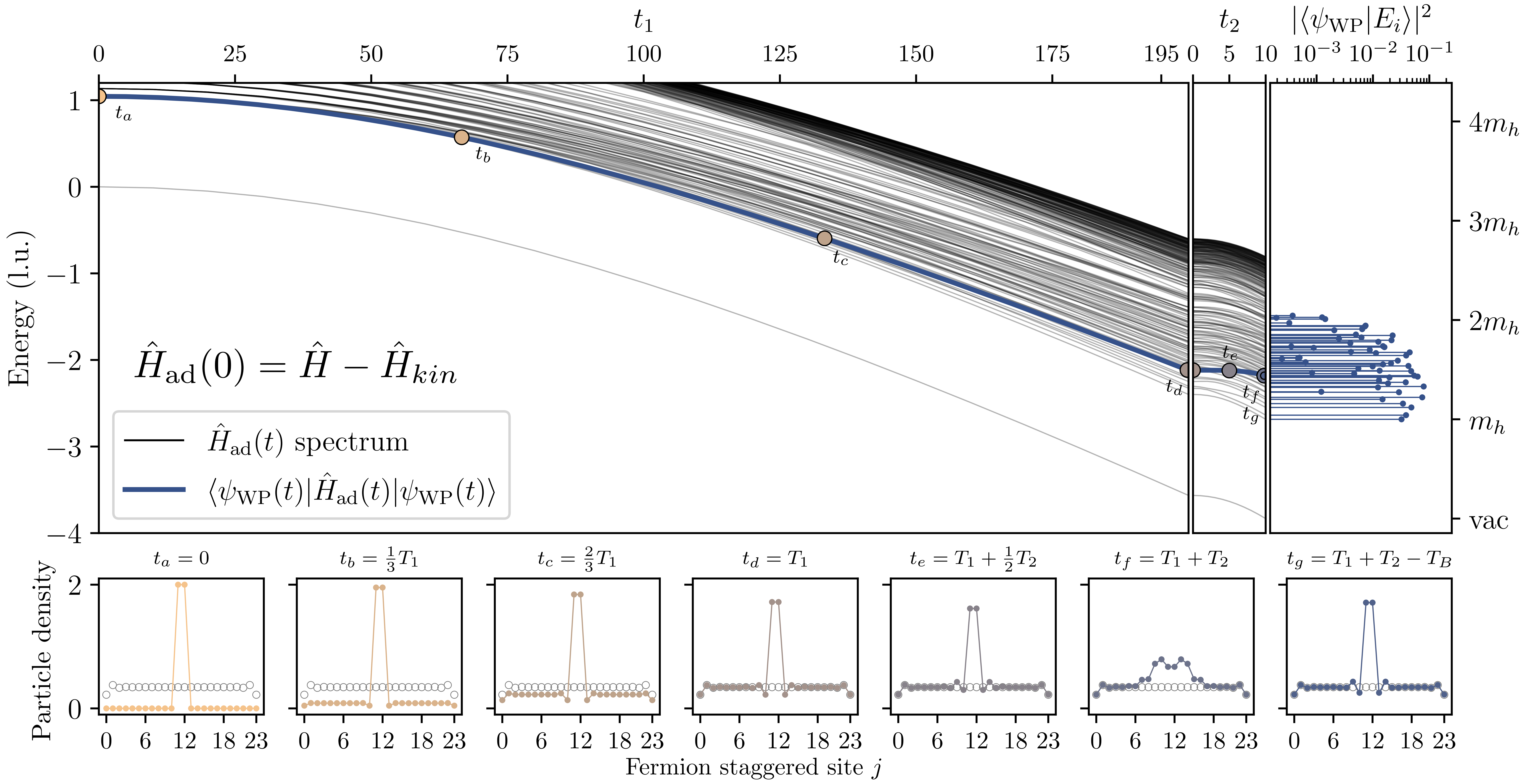
Adiabatic state preparation



A hadronic wave packet can be prepared by adiabatically turning on $\hat{H}_{kin}$

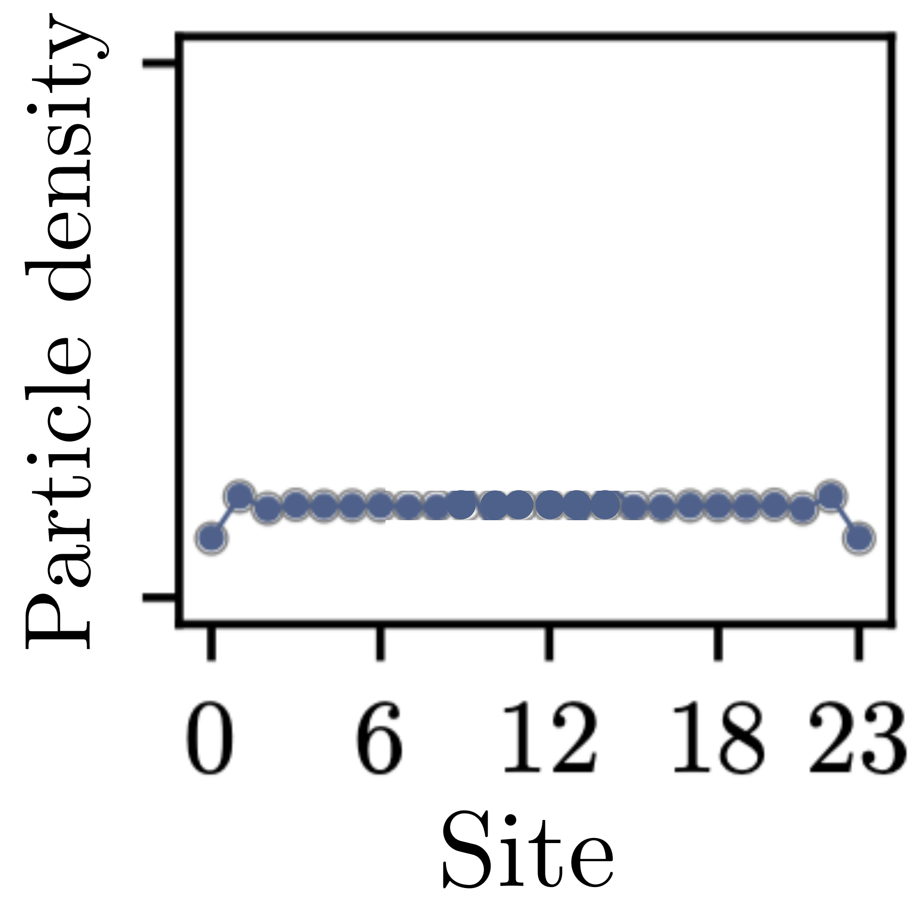
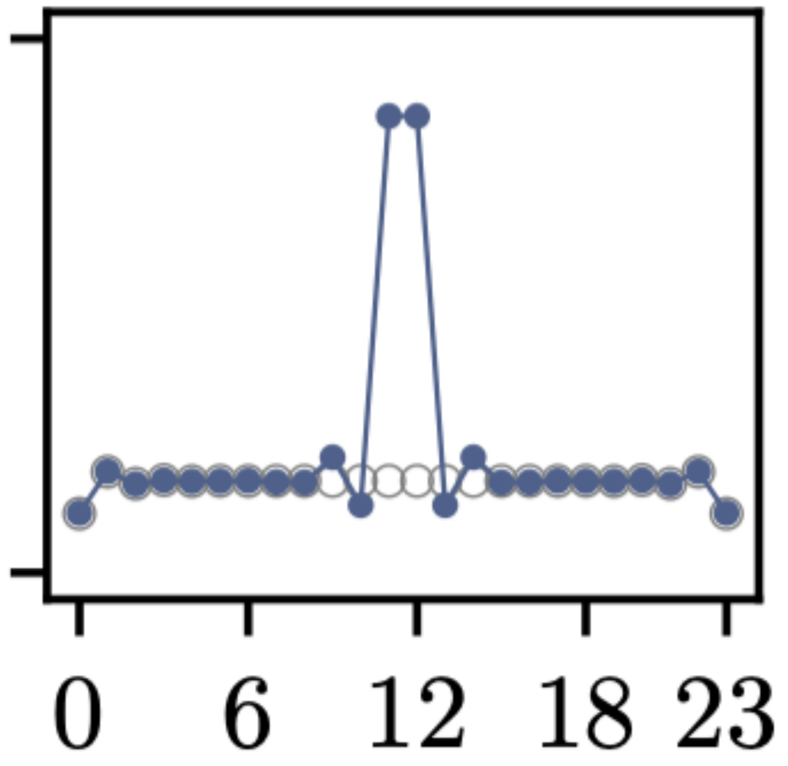
Adiabatic JLP procedure: Quantum Inf. Comput. 14, 1014 (2014)

Adiabatic state preparation



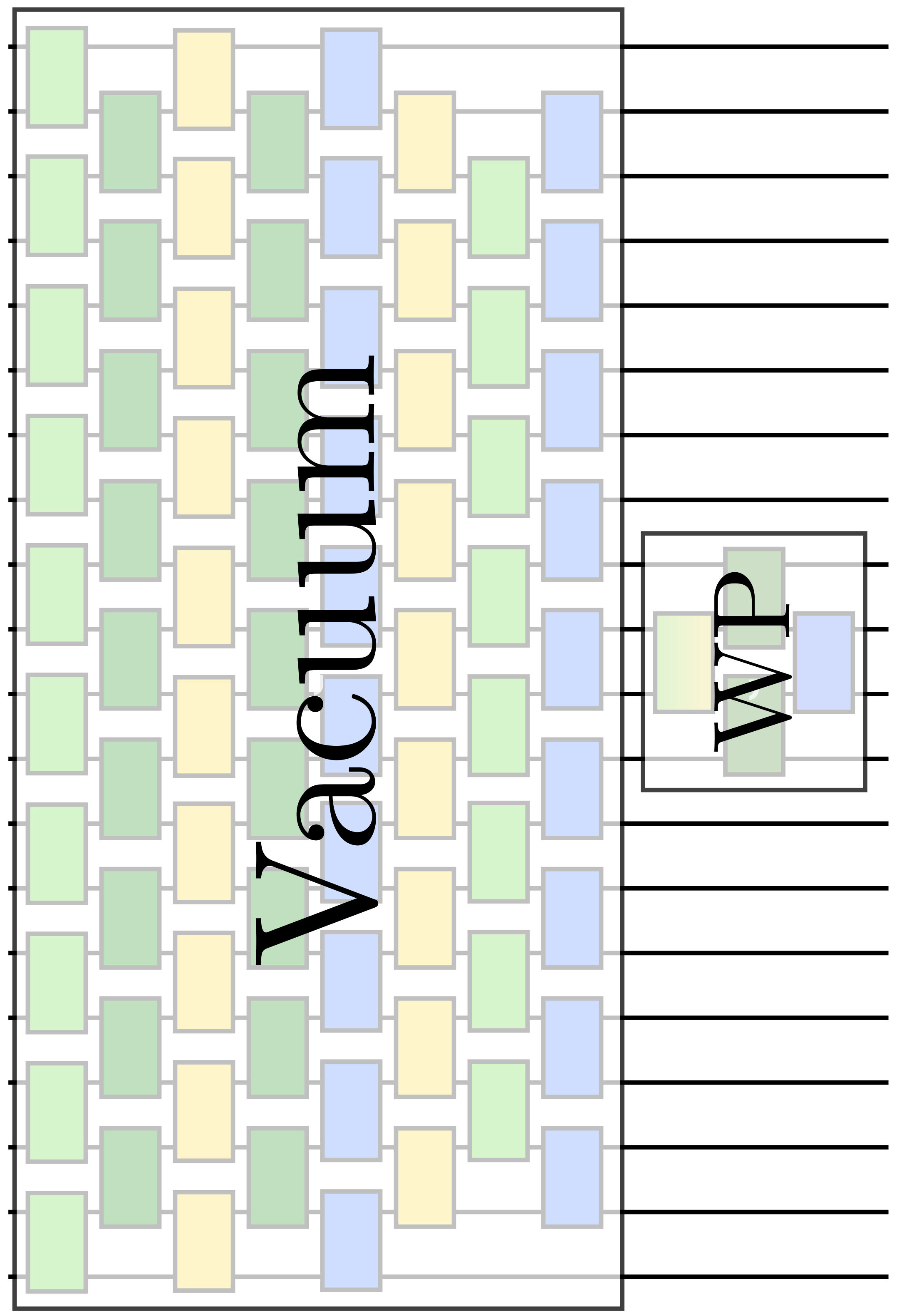
Adiabatic preparation circuits require too many gates: use SC-ADAPT-VQE

SC-ADAPT-VQE for preparing hadron wave packets

	Vacuum	Wave packet
Variationally minimize	$E = \langle \psi_{\text{ansatz}} \vert \hat{H} \vert \psi_{\text{ansatz}} \rangle$	$\mathcal{I} = 1 - \vert \langle \psi_{\text{ansatz}} \vert \psi_{\text{WP}} \rangle \vert^2$
Scalability	Translational symmetry 	Localized 

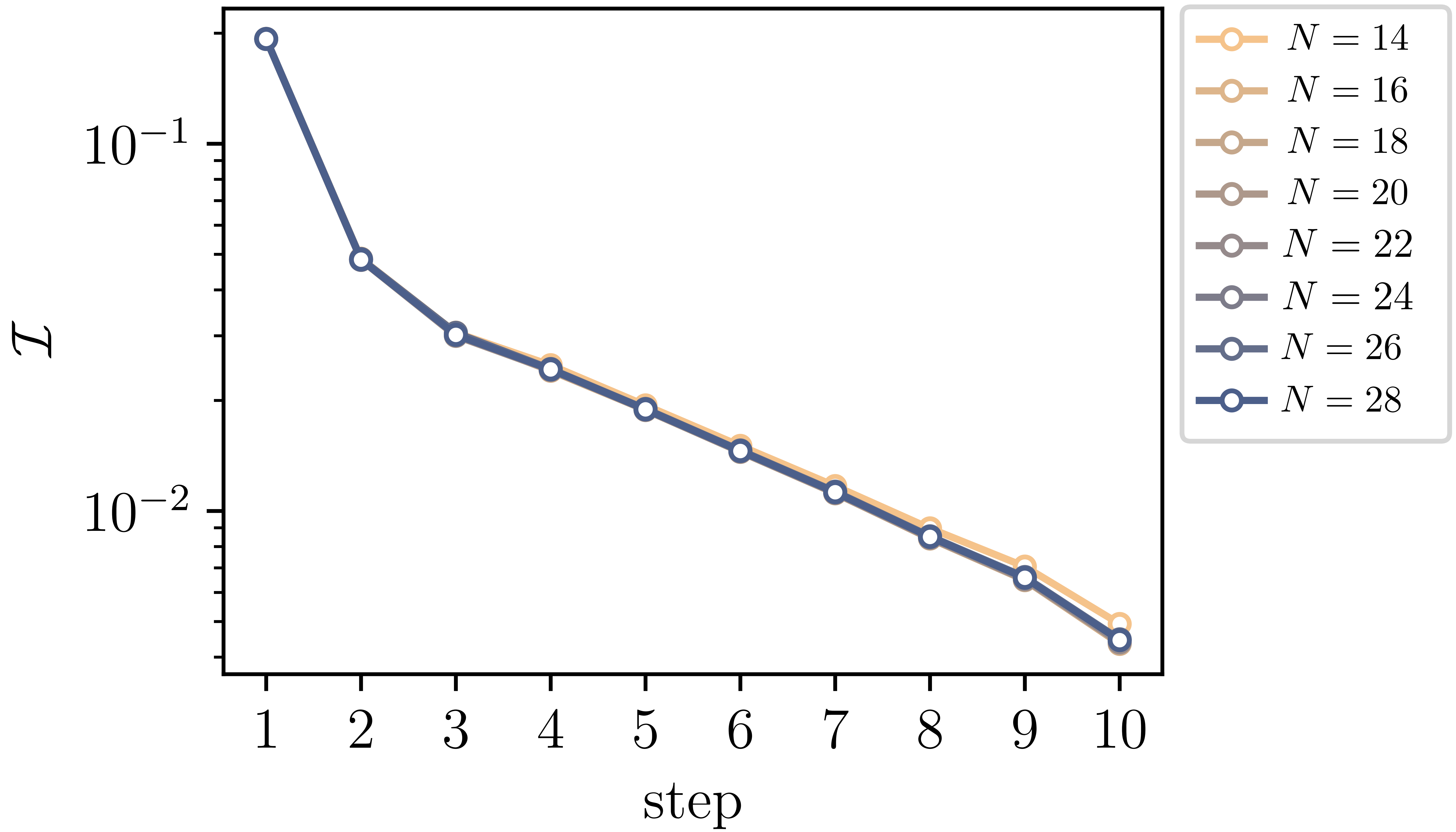
Localized circuits maximize overlap with the adiabatically prepared wave packet

SC-ADAPT-VQE for preparing hadron wave packets



SC-ADAPT-VQE wave packet is built on top of the vacuum

SC-ADAPT-VQE for preparing hadron wave packets



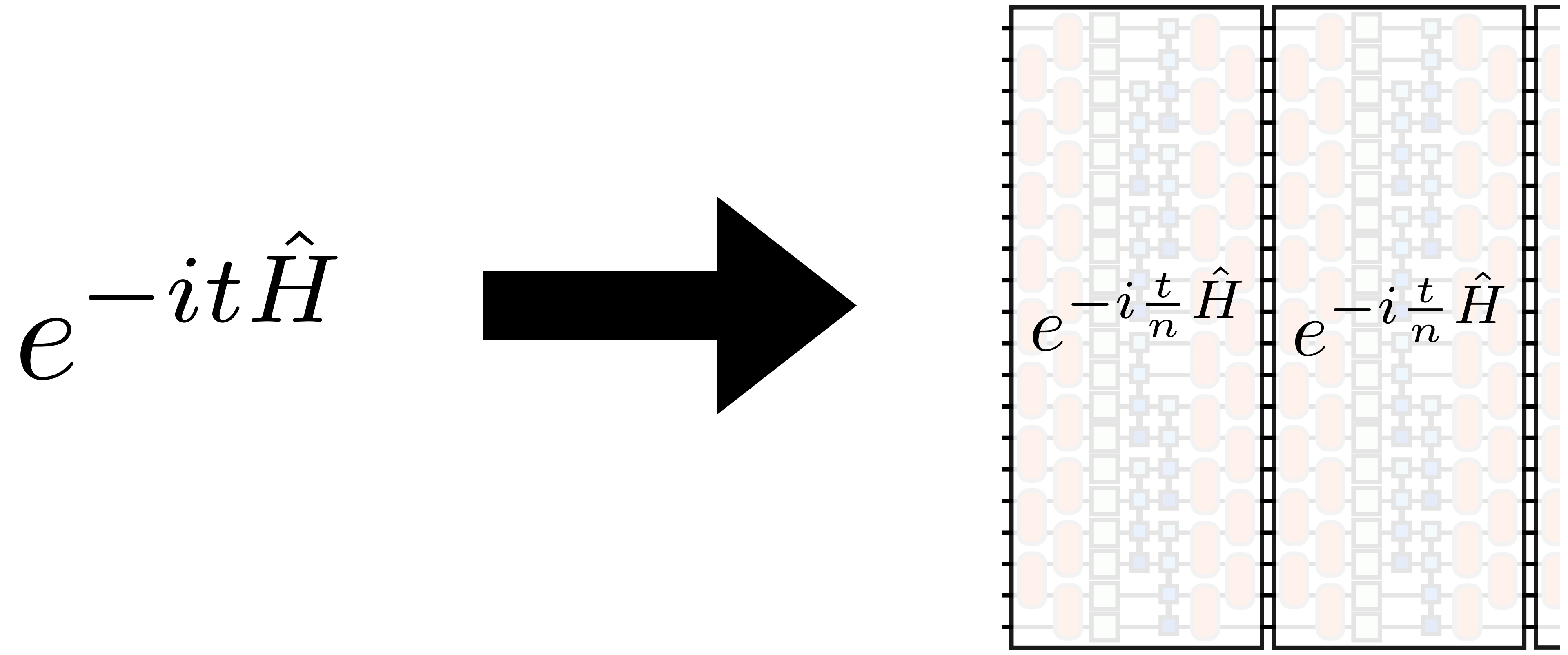
Infidelity decreases exponentially as larger correlations are added

Goal: to simulate hadron dynamics on a quantum computer

0. Map the Hilbert space onto qubits

1. Prepare the initial state

2. Time evolve



Trotterized time evolution

$$\hat{H} = \underbrace{\frac{m}{2}\sum_{n=0}^{N-1}(-1)^n \hat{Z}_n}_{\hat{H}_m} + \underbrace{\frac{1}{2}\sum_{n=0}^{N-2}\left(\hat{\sigma}_n^+\hat{\sigma}_{n+1}^- + \text{h.c.}\right)}_{\hat{H}_{kin}} + \underbrace{\frac{g^2}{2}\sum_{n=0}^{N-2}\left(\sum_{m\leq n}\hat{Q}_m\right)^2}_{\hat{H}_{el}}$$

Trotterized time evolution

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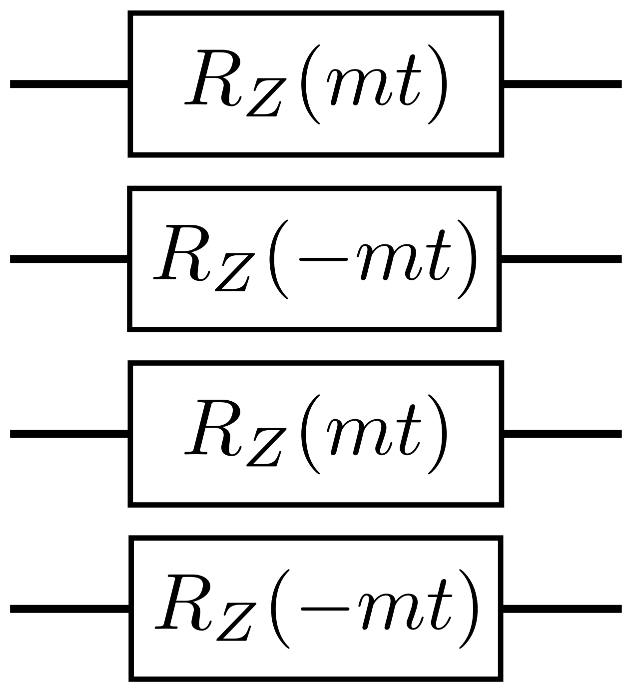
$$e^{-it\hat{H}_m} = \prod_{n=0}^{N-1} e^{-it\frac{m}{2}(-1)^n\hat{Z}_n}$$

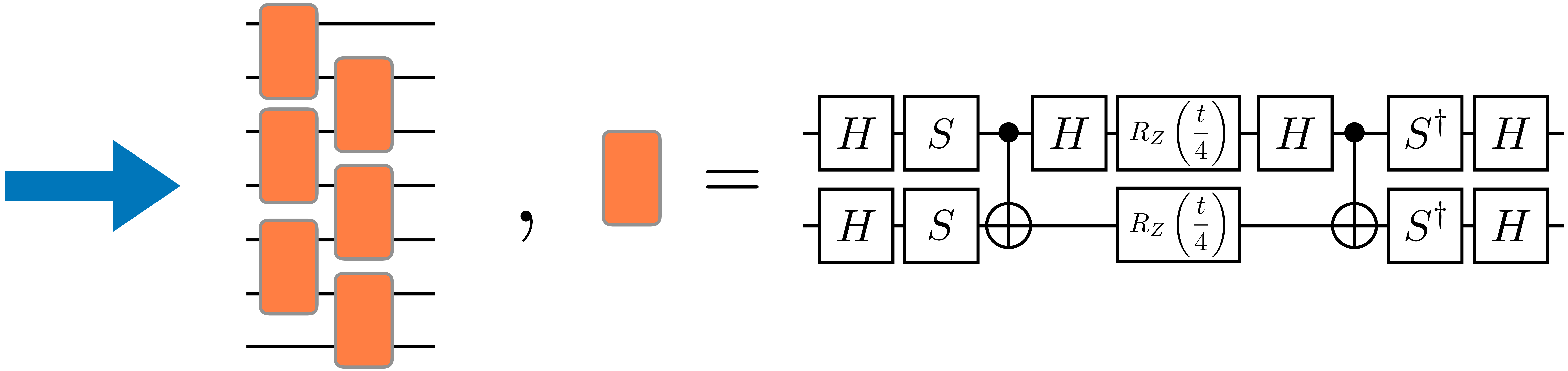


$e^{-it\hat{H}_m}$ requires only single-qubit gates

Trotterized time evolution

$$\hat{H} = \underbrace{\frac{m}{2}\sum_{n=0}^{N-1}(-1)^n \hat{Z}_n}_{\hat{H}_m} + \underbrace{\frac{1}{2}\sum_{n=0}^{N-2}\left(\hat{\sigma}_n^+\hat{\sigma}_{n+1}^- + \text{h.c.}\right)}_{\hat{H}_{kin}} + \underbrace{\frac{g^2}{2}\sum_{n=0}^{N-2}\left(\sum_{m\le n}\hat{Q}_m\right)^2}_{\hat{H}_{el}}$$

$e^{-it\hat{H}_{kin}}$



$e^{-it\hat{H}_{kin}}$ requires $N-2$ two-qubit gates

Trotterized time evolution

$$\hat{H} = \underbrace{\frac{m}{2}\sum_{n=0}^{N-1}(-1)^n \hat{Z}_n}_{\hat{H}_m} + \underbrace{\frac{1}{2}\sum_{n=0}^{N-2}\left(\hat{\sigma}_n^+\hat{\sigma}_{n+1}^- + \text{h.c.}\right)}_{\hat{H}_{kin}} + \underbrace{\frac{g^2}{2}\sum_{n=0}^{N-2}\left[\sum_{m\leq n}\left(\hat{Z}_m + (-1)^m\hat{I}\right)\right]^2}_{\hat{H}_{el}}$$

$\hat{H}_{el}$ has $\hat{Z}\hat{Z}$ between all pairs of qubits: $\mathcal{O}(N^2)$ two-qubit gates ✗

Trotterized time evolution

$$\hat{H} = \underbrace{\frac{m}{2}\sum_{n=0}^{N-1}(-1)^n \hat{Z}_n}_{\hat{H}_m} + \underbrace{\frac{1}{2}\sum_{n=0}^{N-2}\left(\hat{\sigma}_n^+\hat{\sigma}_{n+1}^- + \text{h.c.}\right)}_{\hat{H}_{kin}} + \underbrace{\frac{g^2}{2}\sum_{n=0}^{N-2}\left[\sum_{m\leq n}\left(\hat{Z}_m + (-1)^m\hat{I}\right)\right]^2}_{\hat{H}_{el}}$$

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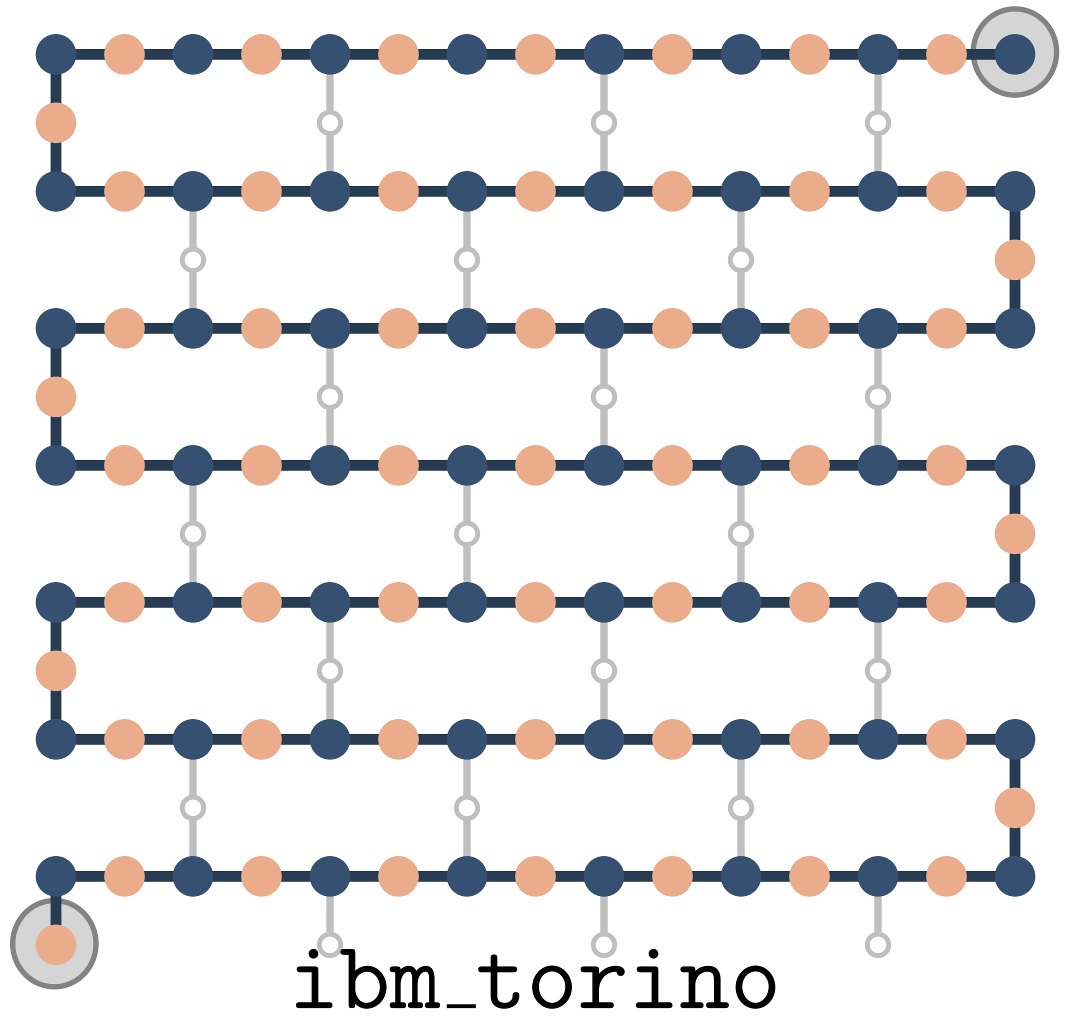
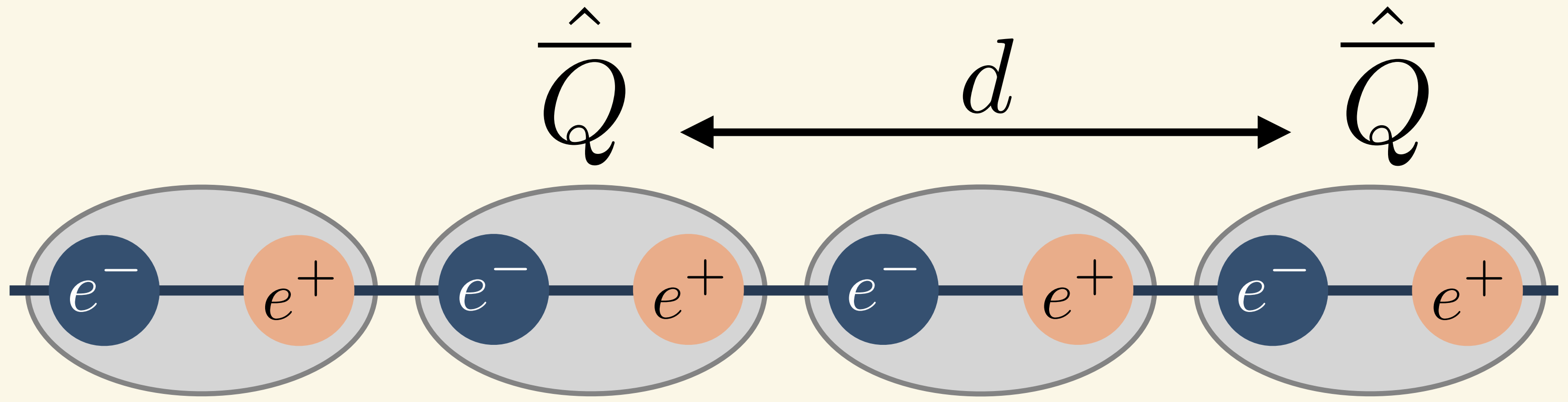


Overhead for long-range gates:

$\mathcal{O}(N^2)$ circuit depth

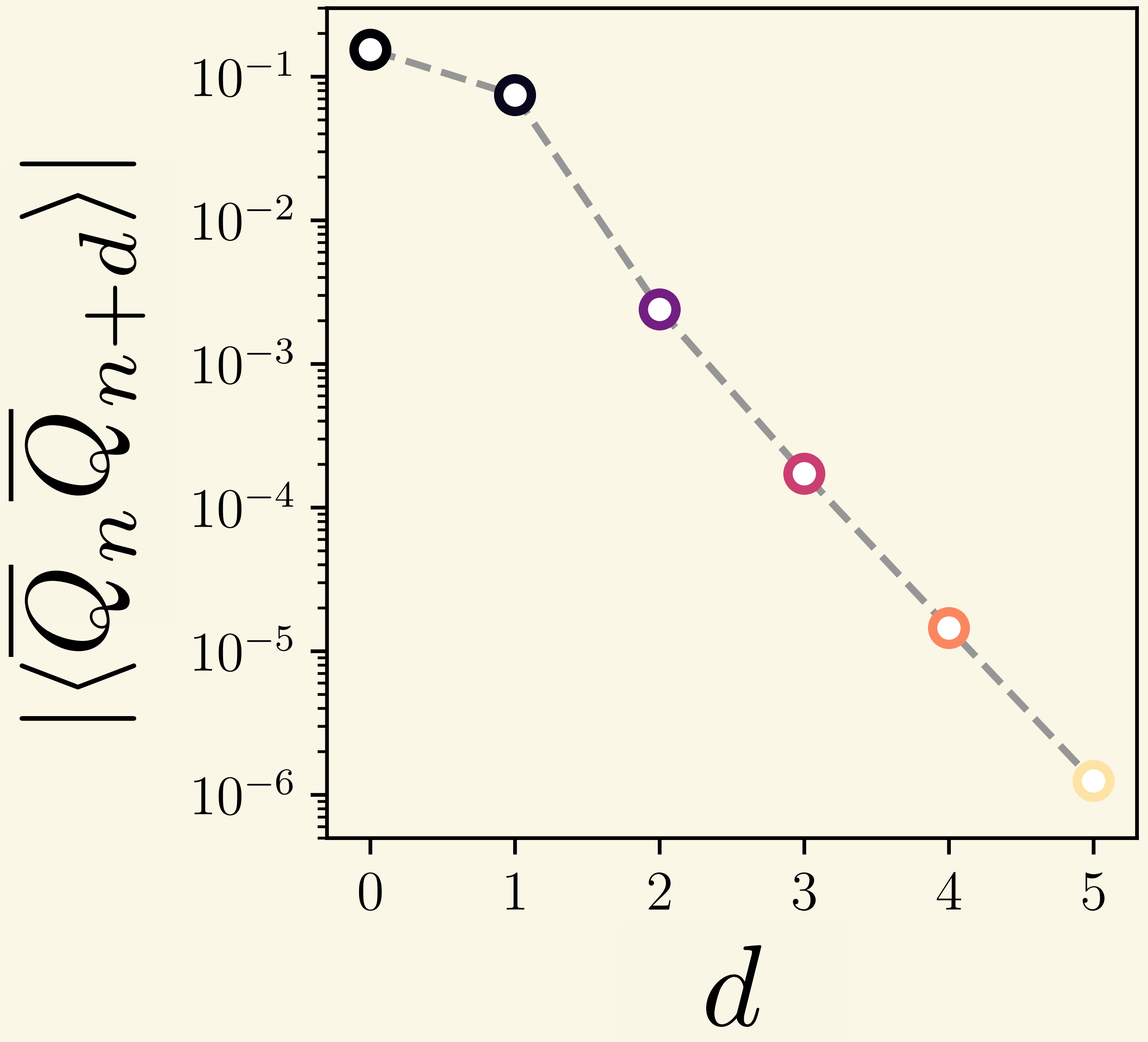
Effective electric interaction

Confinement screens charges; interaction effectively short-ranged



$$\hat{\bar{Q}}_n = \hat{Q}_{2n} + \hat{Q}_{2n+1}$$

$$\hat{\delta}_n = \hat{Q}_{2n} - \hat{Q}_{2n+1}$$



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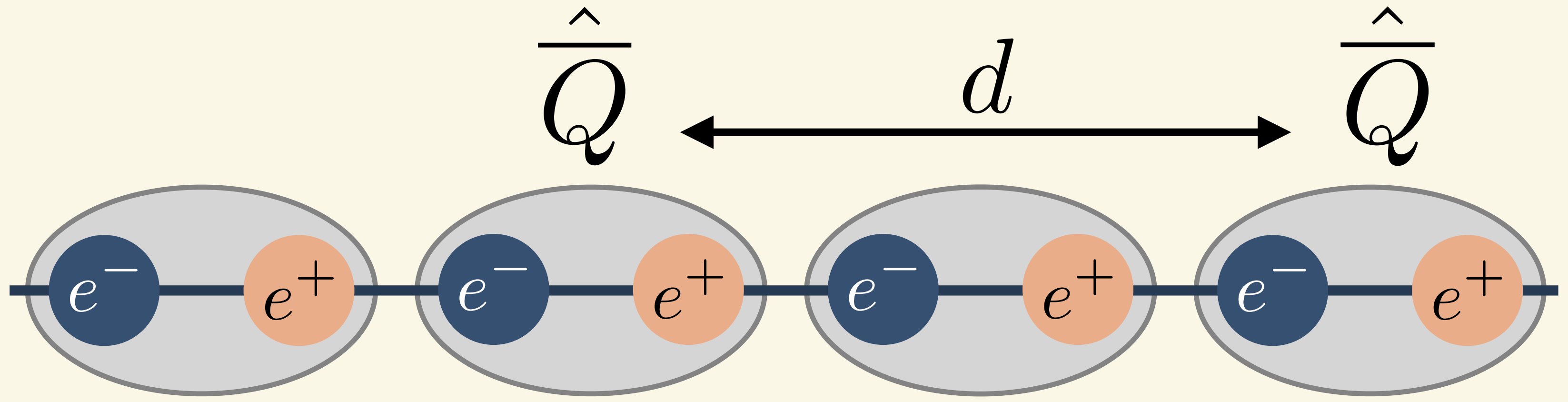

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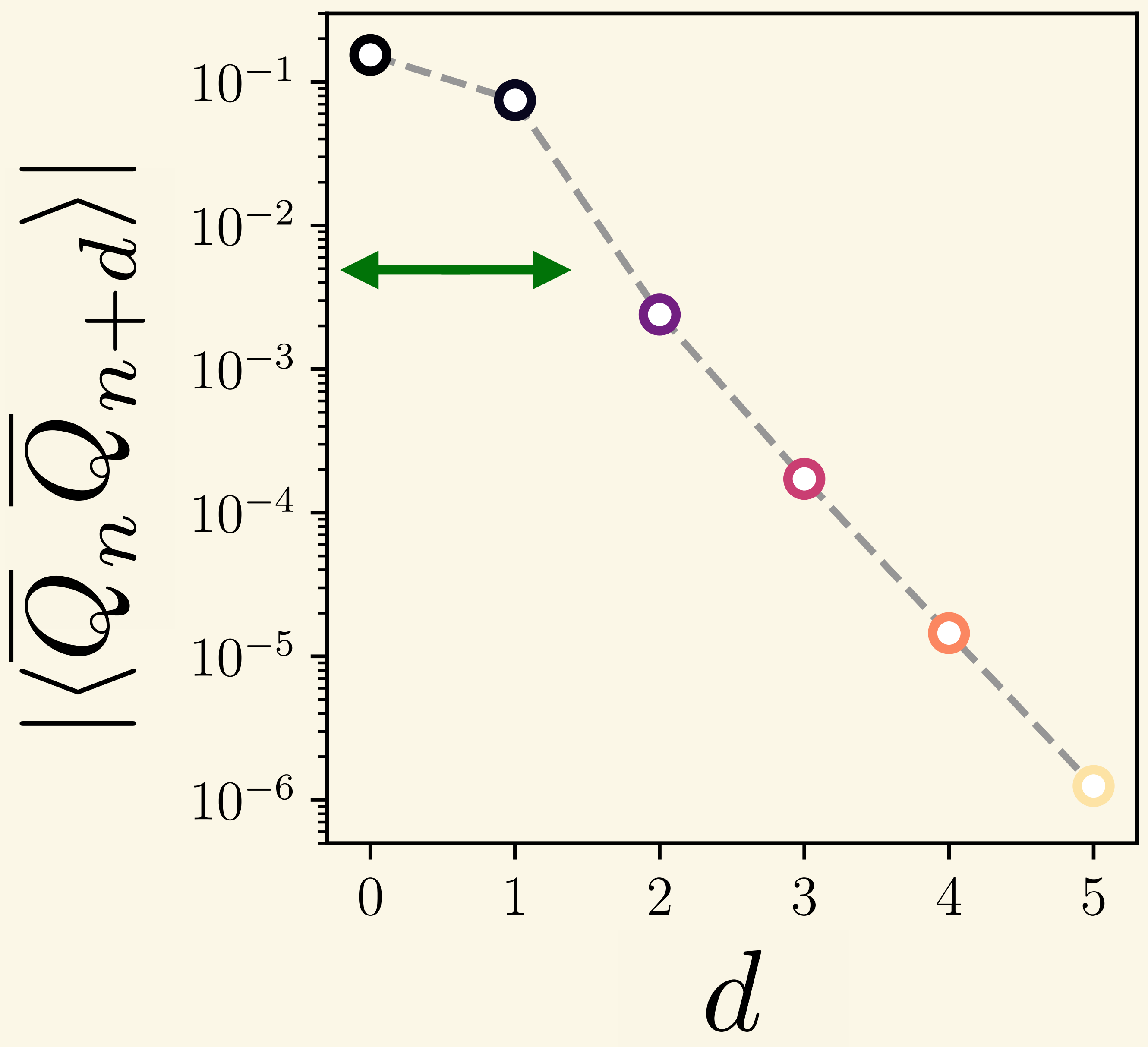

Truncate interactions beyond the confinement length $\sim m_{\text{hadron}}^{-1}$

Truncating the interaction beyond $\bar{\lambda}$ spatial sites

$$\hat{H}_{el}(\overline{\lambda}) = \frac{g^2}{2}\Bigg\{\sum_{n=0}^{\frac{N}{4}-1}\Bigg[\left(\frac{N}{2}-\frac{5}{4}-2n\right)\hat{\overline{Q}}_n^2+\frac{1}{2}\hat{\overline{Q}}_n\hat{\delta}_n+\frac{1}{4}\hat{\delta}_n^2+\left(\frac{3}{4}+2n\right)\hat{\overline{Q}}_{\frac{N}{4}+n}^2-\frac{1}{2}\hat{\overline{Q}}_{\frac{N}{4}+n}\hat{\delta}_{\frac{N}{4}+n}+\frac{1}{4}\hat{\delta}_{\frac{N}{4}+n}^2\Bigg]$$
$$+\,2\sum_{n=0}^{\frac{N}{4}-2}\sum_{m=n+1}^{\min(\frac{N}{4}-1,n+\bar{\lambda})}\Bigg[(\frac{N}{2}-1-2m)\,\hat{\overline{Q}}_n\hat{\overline{Q}}_m+\frac{1}{2}\hat{\overline{Q}}_n\hat{\delta}_m+(1+2n)\,\hat{\overline{Q}}_{\frac{N}{4}+n}\hat{\overline{Q}}_{\frac{N}{4}+m}-\frac{1}{2}\hat{\overline{Q}}_{\frac{N}{4}+m}\hat{\delta}_{\frac{N}{4}+n}\Bigg]\Bigg\}$$

Truncating the interaction beyond $\bar{\lambda}$ spatial sites

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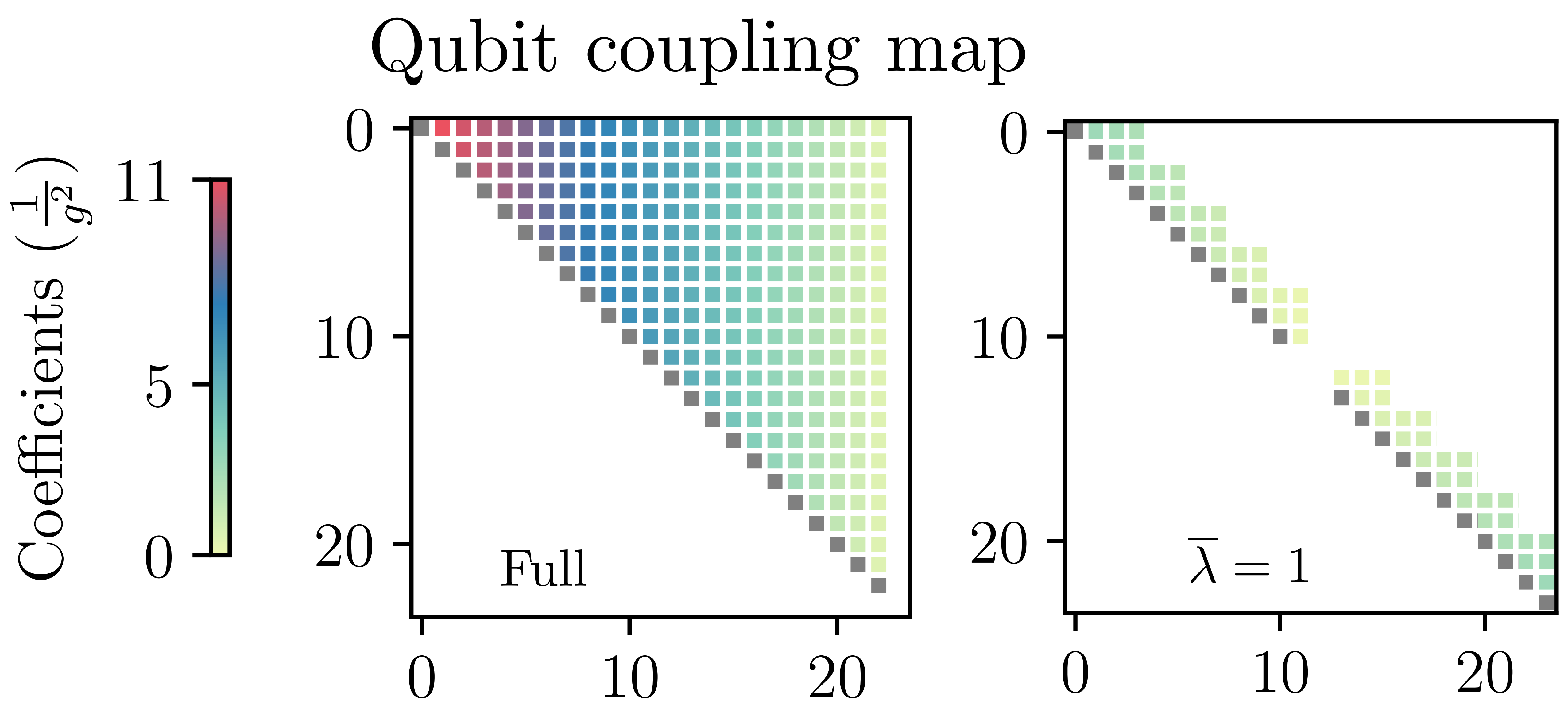
$$+2\sum_{n=0}^{\frac{N}{4}-2}\sum_{m=n+1}^{\min(\frac{N}{4}-1,n+\bar{\lambda})}\Bigg[(\frac{N}{2}-1-2m)\hat{\bar{Q}}_n\hat{\bar{Q}}_m+\frac{1}{2}\hat{\bar{Q}}_n\hat{\delta}_m+(1+2n)\hat{\bar{Q}}_{\frac{N}{4}+n}\hat{\bar{Q}}_{\frac{N}{4}+m}-\frac{1}{2}\hat{\bar{Q}}_{\frac{N}{4}+m}\hat{\delta}_{\frac{N}{4}+n}\Bigg]\Bigg\}$$



$e^{-it\hat{H}_{el}(\bar{\lambda})}$ requires $\mathcal{O}(\bar{\lambda}N)$ two-qubit gates

Truncating the interaction beyond $\bar{\lambda}$ spatial sites

$$\hat{H}_{el}(\bar{\lambda}) = \frac{g^2}{2}\Bigg\{\sum_{n=0}^{\frac{N}{4}-1}\Bigg[\left(\frac{N}{2}-\frac{5}{4}-2n\right)\hat{Q}_n^2+\frac{1}{2}\hat{Q}_n\hat{\delta}_n+\frac{1}{4}\hat{\delta}_n^2+\left(\frac{3}{4}+2n\right)\hat{Q}_{\frac{N}{4}+n}^2-\frac{1}{2}\hat{Q}_{\frac{N}{4}+n}\hat{\delta}_{\frac{N}{4}+n}+\frac{1}{4}\hat{\delta}_{\frac{N}{4}+n}^2\Bigg]$$
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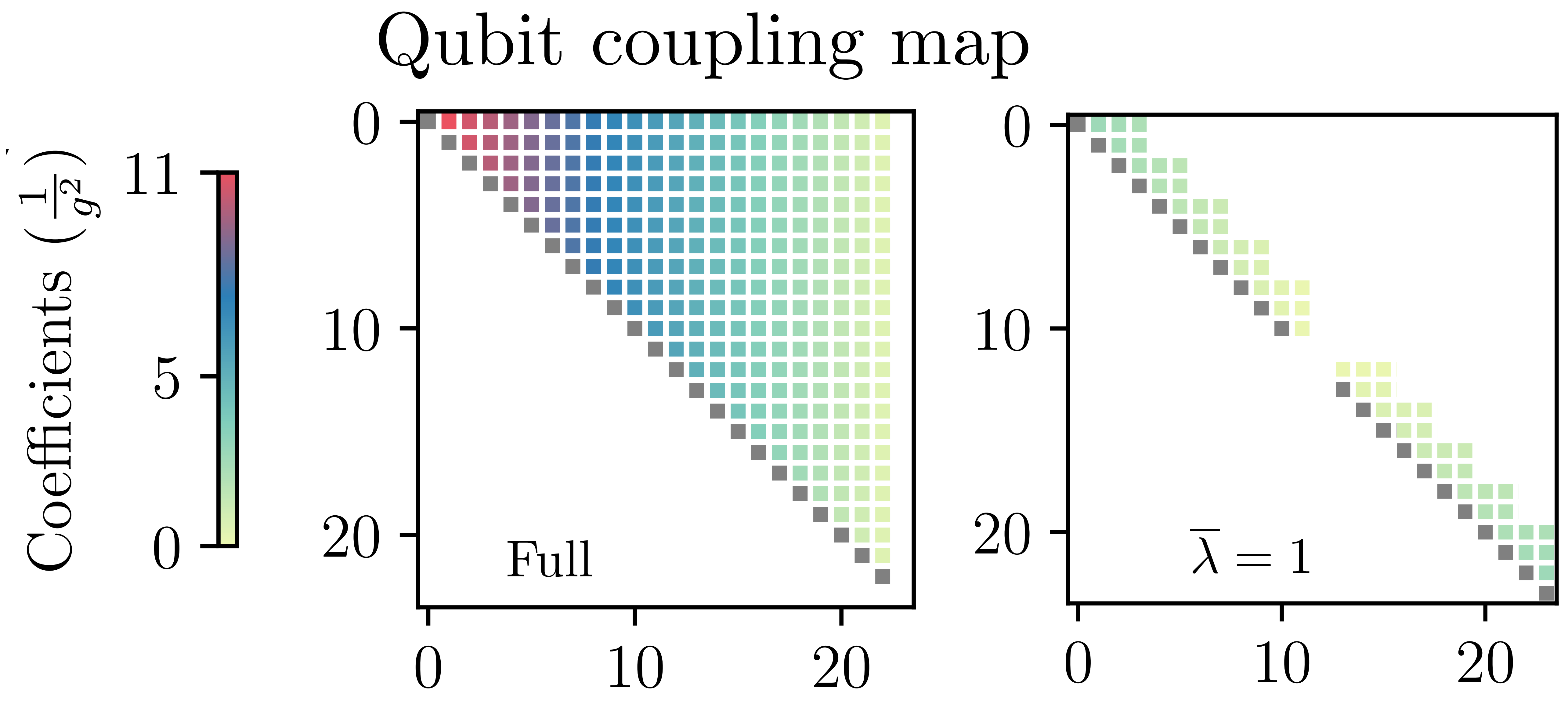
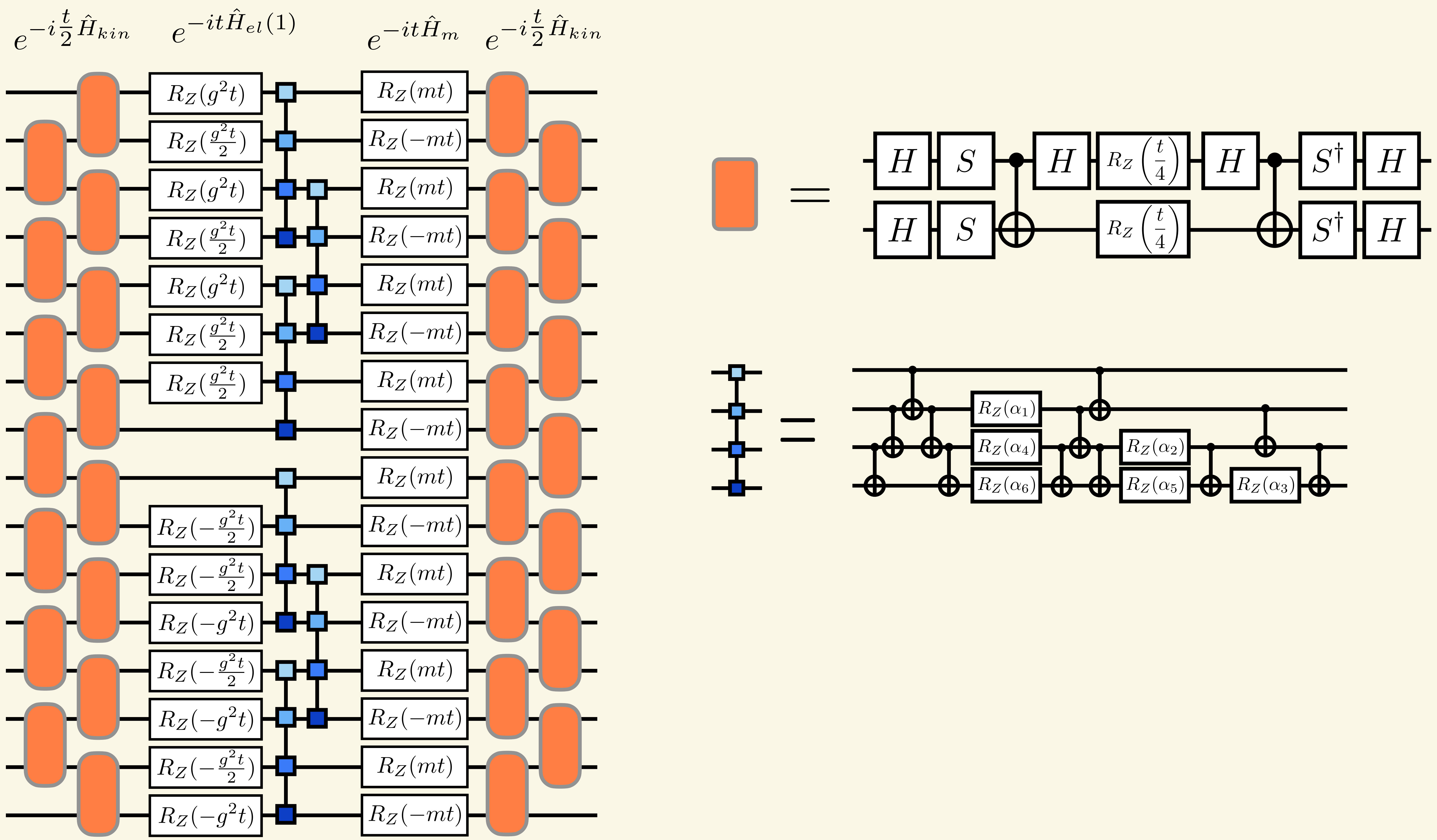


$\bar{\lambda}=1$ will be used

$e^{-it\hat{H}_{el}(\bar{\lambda})}$ requires $\mathcal{O}(\bar{\lambda}N)$ two-qubit gates

Trotterized time evolution

$$e^{-it\hat{H}} \approx$$



One second order Trotter step with the $\bar{\lambda} = 1$ truncated electric interaction

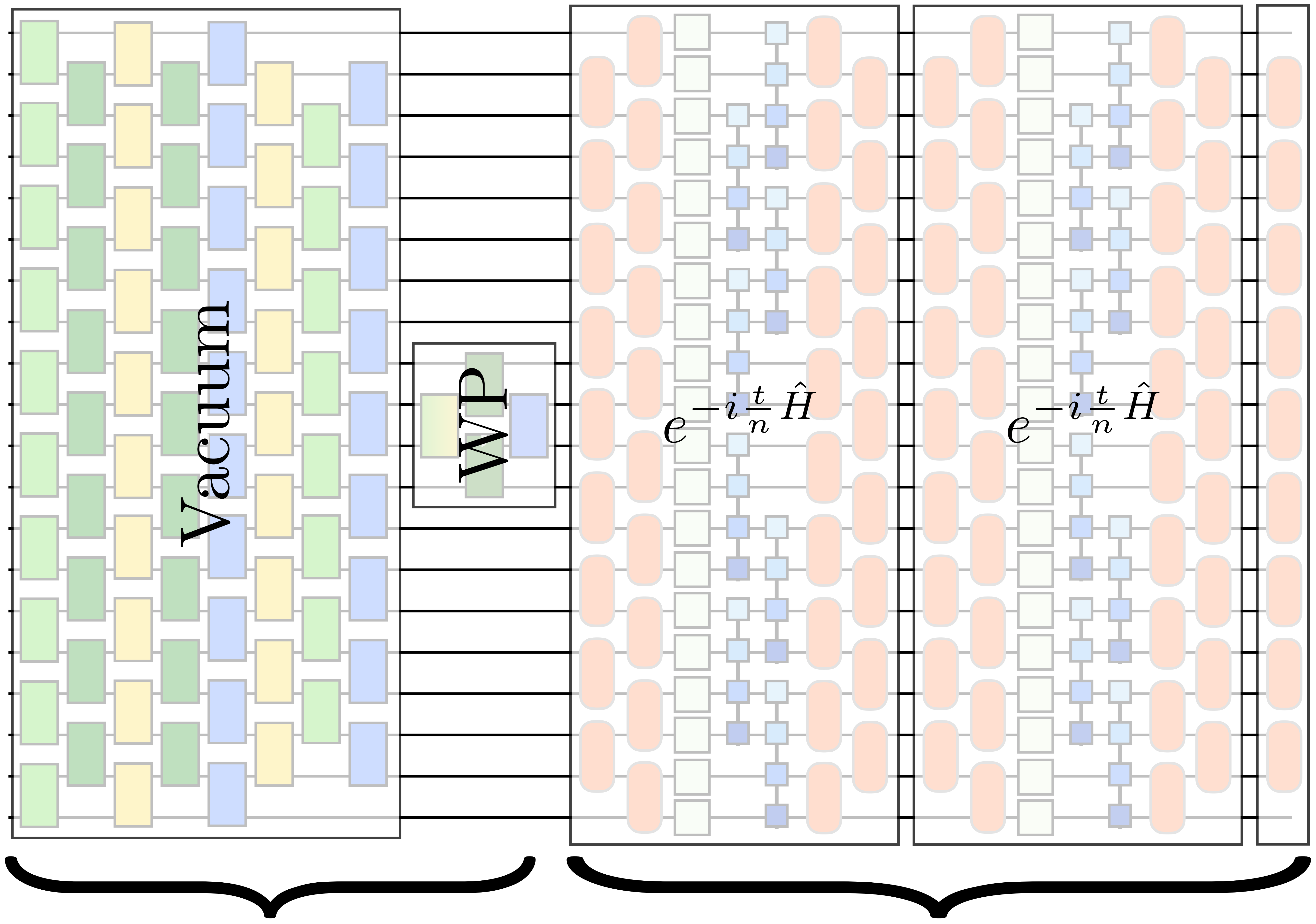
Goal: to simulate hadron dynamics on a quantum computer

0. Map the Hilbert space onto qubits

1. Prepare the initial state

2. Time evolve

Quantum circuits for simulating hadron dynamics



Hadron wave packet prepared with SC-ADAPT-VQE

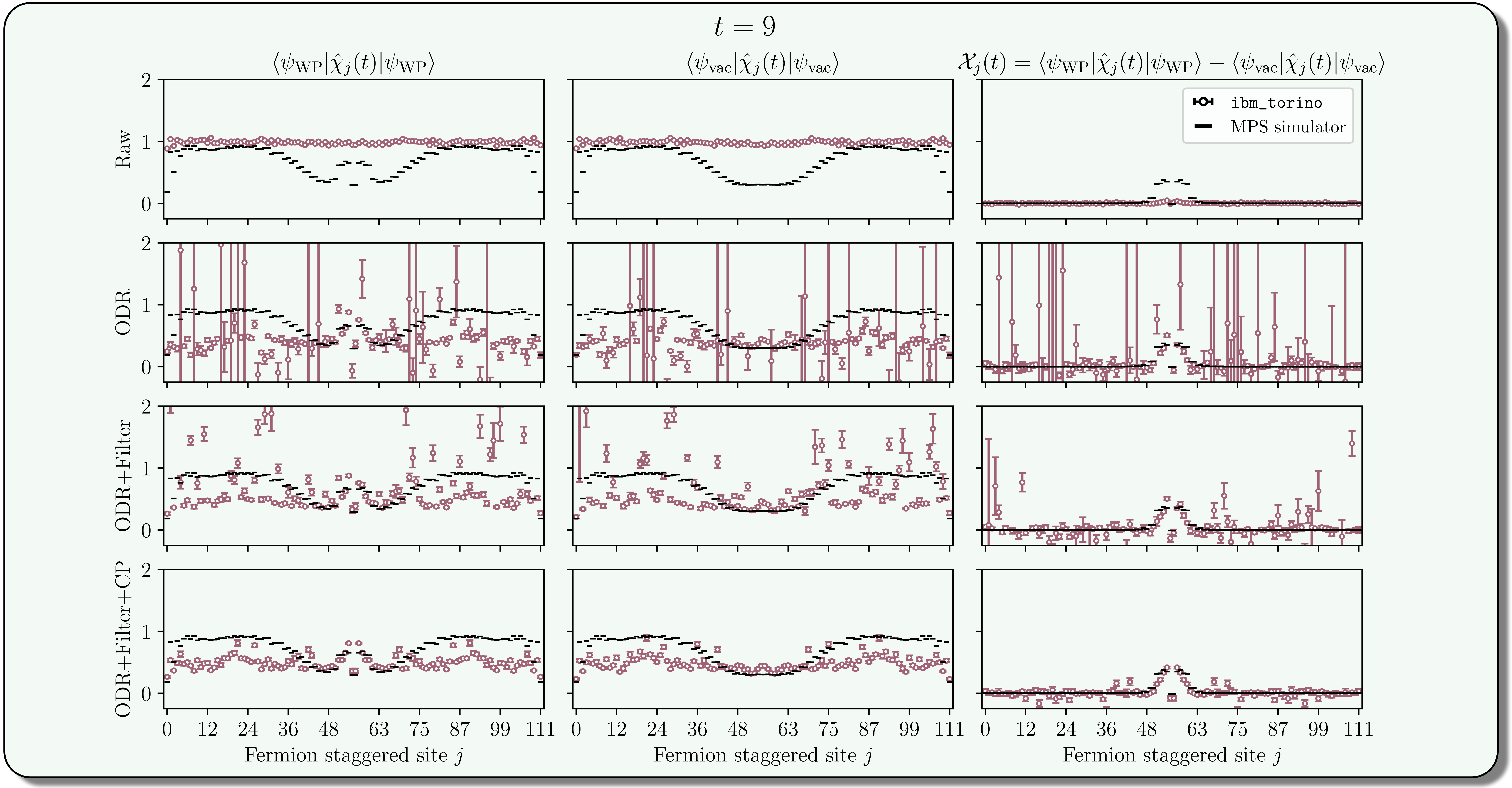
Trotterized time evolution with $\overline{\lambda} = 1$ truncated interaction

Results from IBM's quantum computer

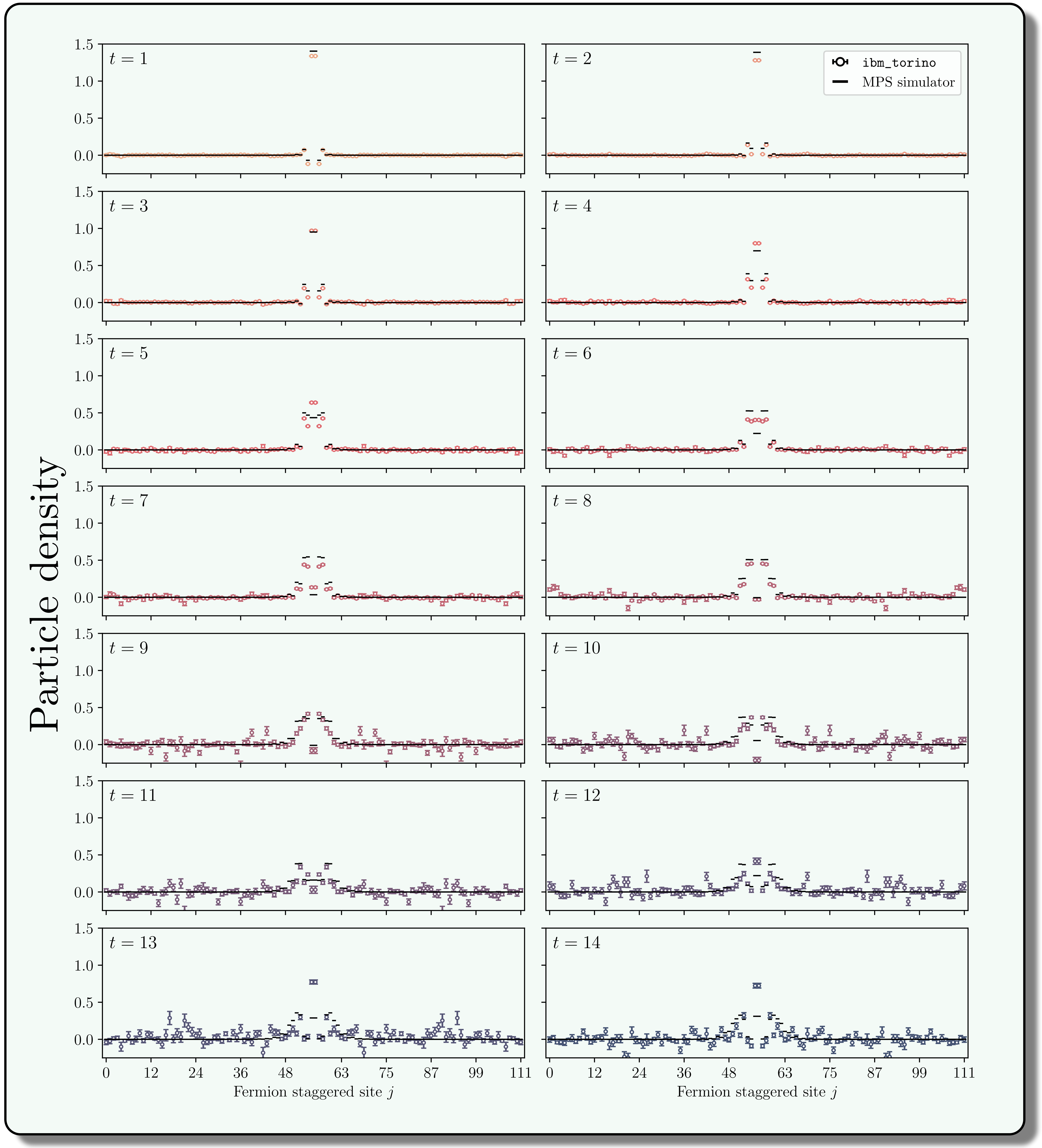
- Reflection symmetric in the absence of device errors
- Hadron propagation clearly identified

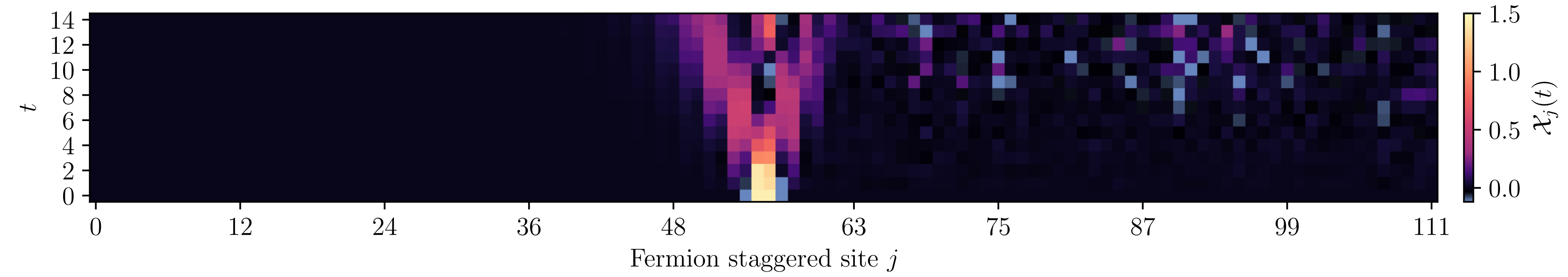
Results from IBM's quantum computer

t	N_T	# of CNOTs (per t)	CNOT depth (per t)	Executed CNOTs ($\times 10^9$)	Total # of shots ($\times 10^6$)
1 & 2	2	2,746	70	$4 \times 2 \times 10.5$	$4 \times 2 \times 3.8$
3 & 4	4	4,598	120	$4 \times 2 \times 17.7$	$4 \times 2 \times 3.8$
5 & 6	6	6,450	170	$4 \times 2 \times 24.8$	$4 \times 2 \times 3.8$
7 & 8	8	8,302	220	$4 \times 2 \times 31.9$	$4 \times 2 \times 3.8$
9 & 10	10	10,154	270	$4 \times 2 \times 13.0$	$4 \times 2 \times 1.3$
11 & 12	12	12,006	320	$4 \times 2 \times 15.4$	$4 \times 2 \times 1.3$
13 & 14	14	13,858	370	$4 \times 2 \times 17.7$	$4 \times 2 \times 1.3$
Totals				1.05×10^{12}	1.54×10^{8}



Error mitigation essential to extract a signal!

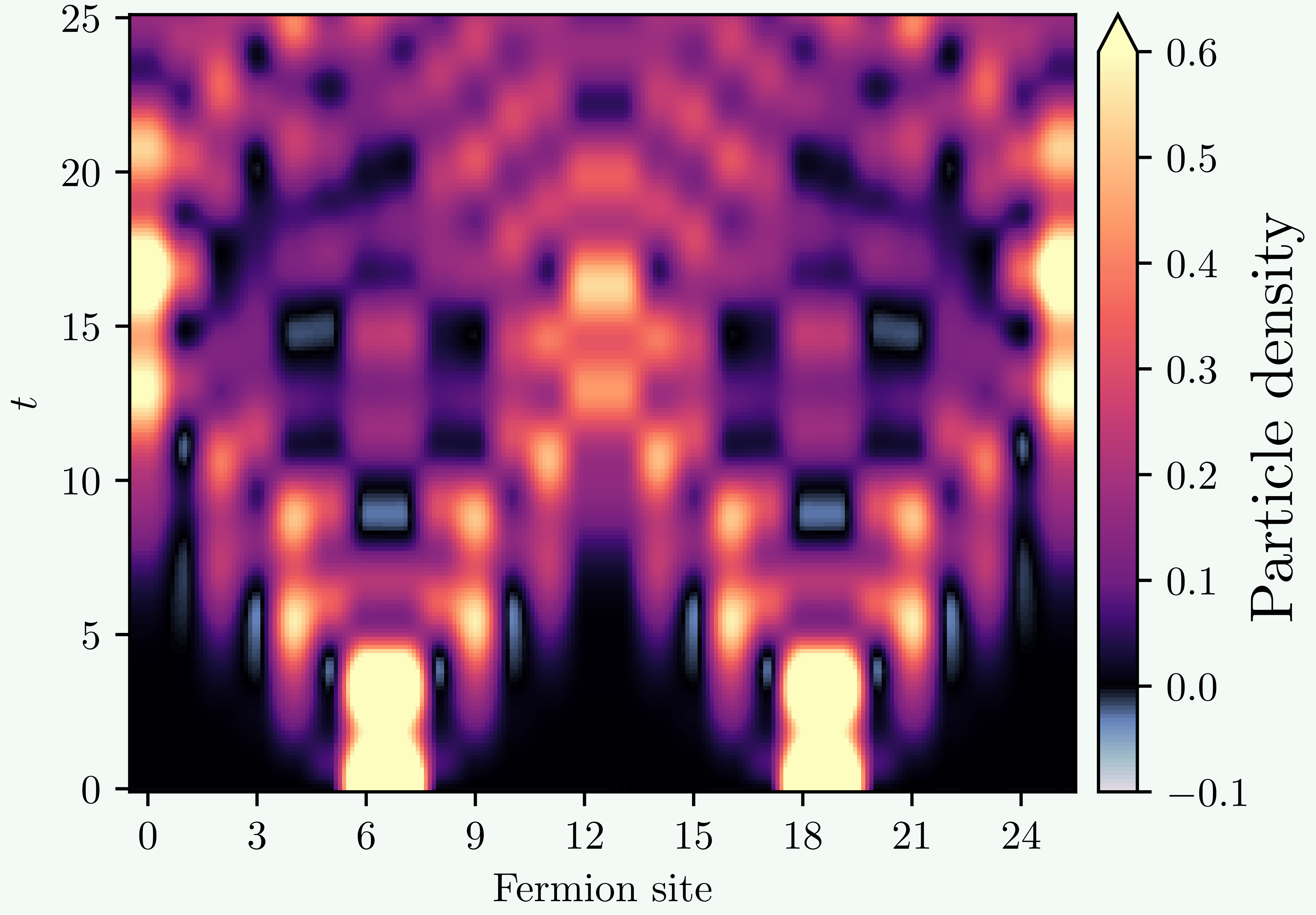




- Qualitative agreement with MPS
- Systematic error around the wave packet

Looking toward the (immediate) future

Hadron collisions

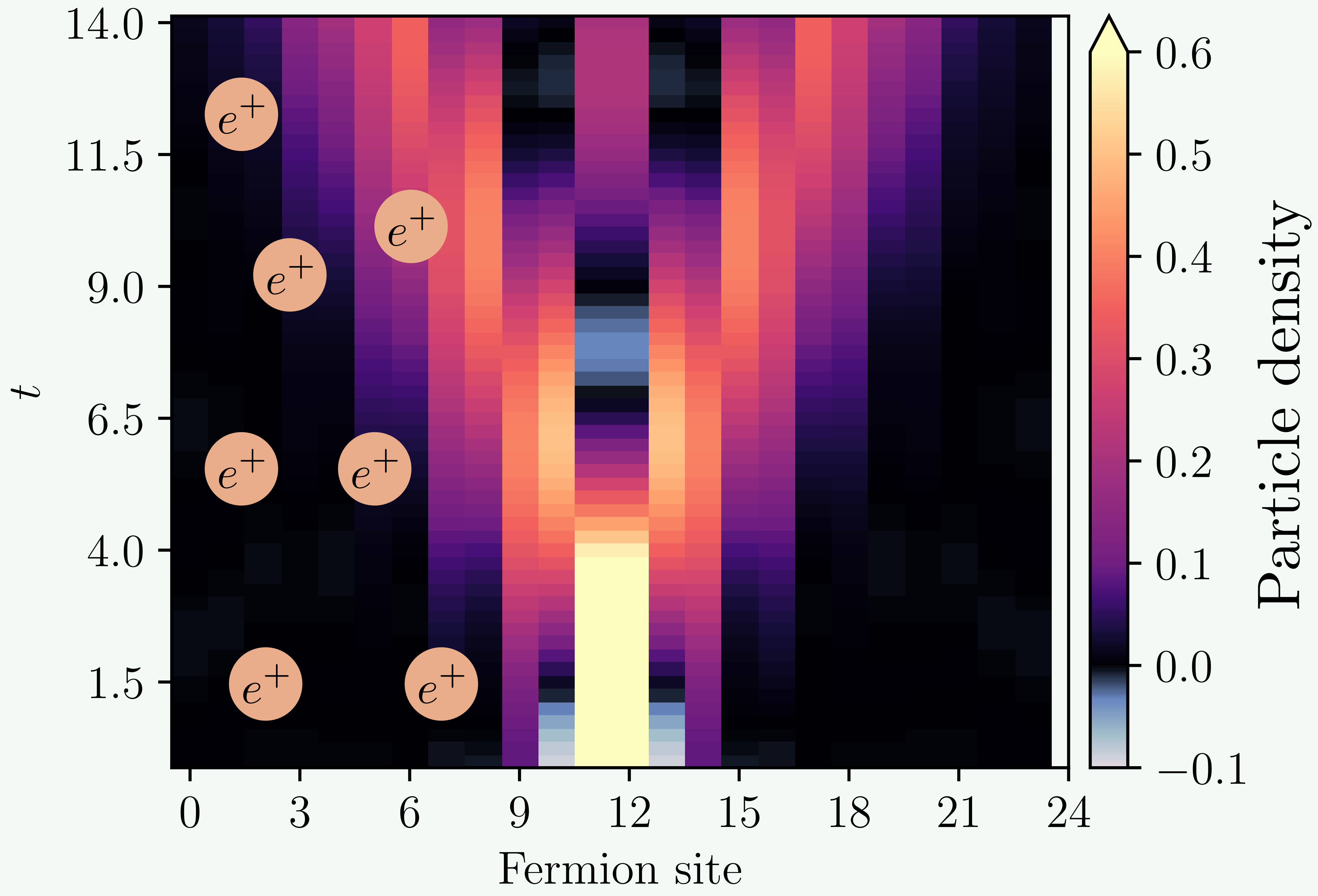


Real-time scattering in the lattice Schwinger model

Irene Papaefstathiou,[1,2] Johannes Knolle,[3,2,4] and Mari Carmen Bañuls[1,2]

arxiv.org/abs/2402.18429

In-medium effects



Steps Toward Quantum Simulations of Hadronization and Energy-Loss in Dense Matter

Roland C. Farrell,[1,2,*] Marc Illa,[1,†] and Martin J. Savage[1,‡]

arxiv.org/abs/2405.06620

Summary

- Quantum simulations of fundamental physics are promising candidates for a “quantum advantage”
- Informed by <u>symmetries</u> and <u>hierarchies in length scales</u>, we developed efficient quantum simulation protocols for the Schwinger model
- Prepared a hadron wave packet and time evolved it on `ibm_torino`
- One of the most complex digital quantum simulations ever performed: up to 13,858 two-qubit gates over 112 qubits. 154 million measurements
- Error mitigation essential to extracting a signal

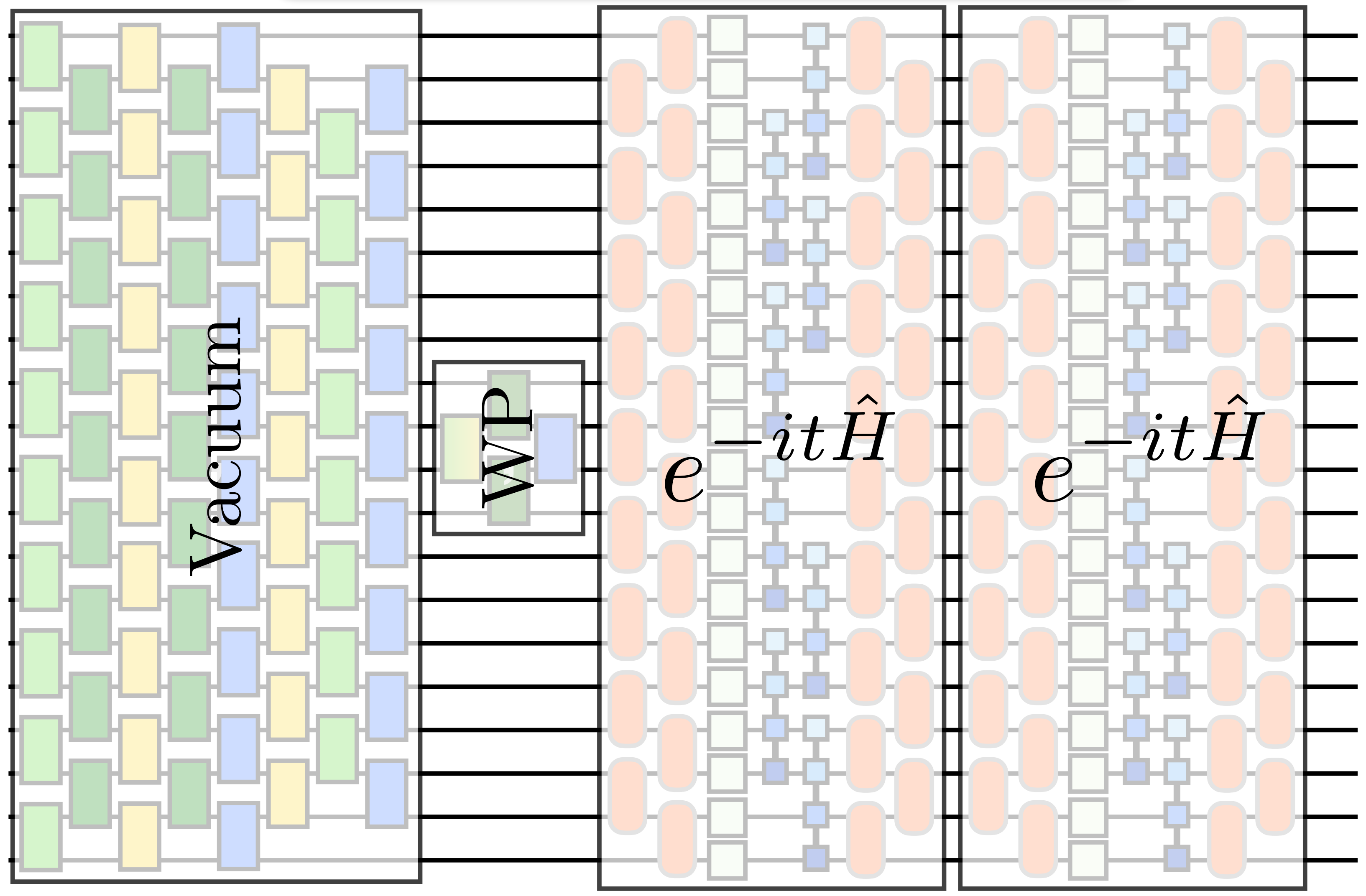
Thanks for listening!

IQuS InQubator for Quantum Simulation

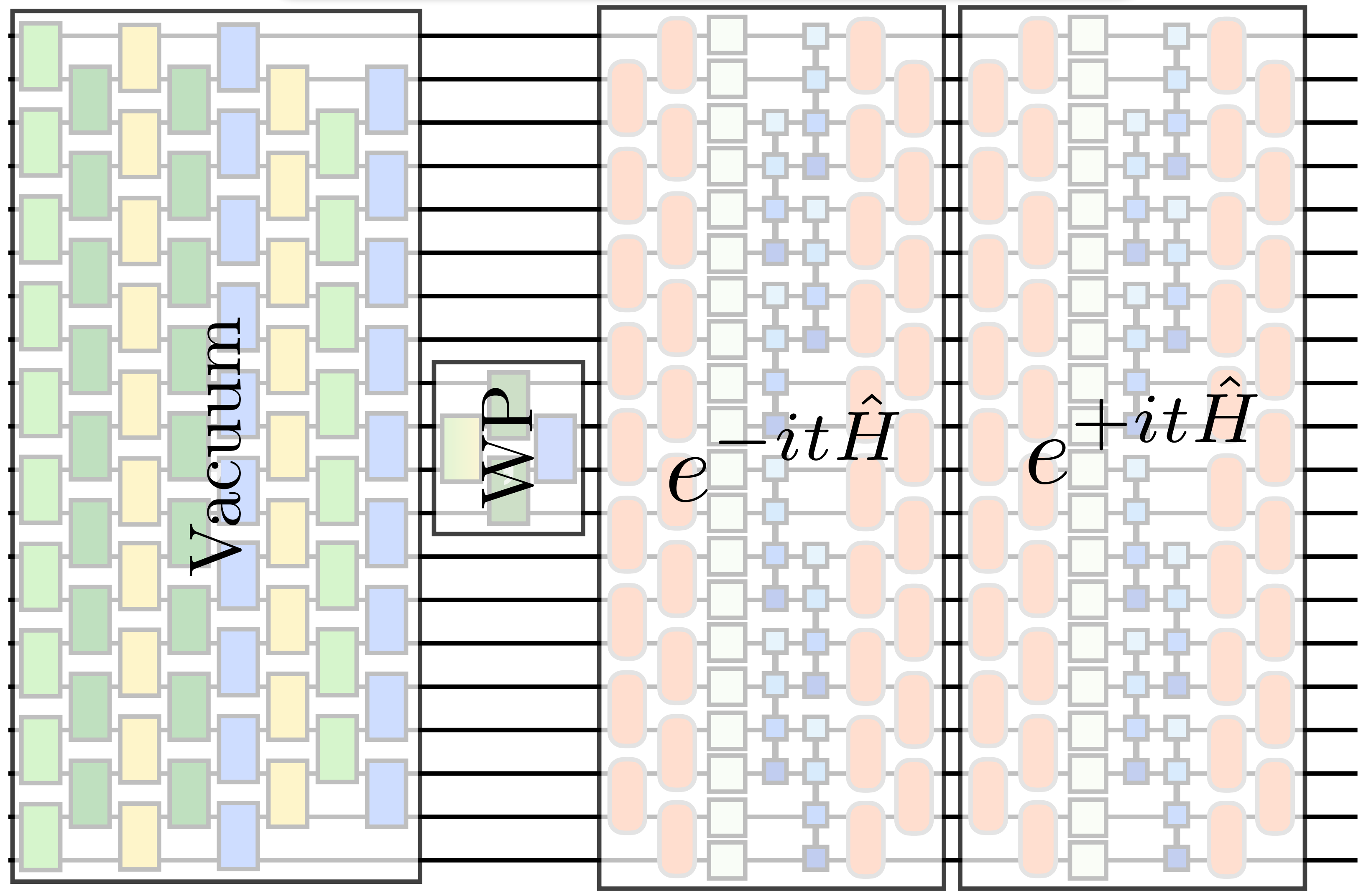
UW Nuclear Theory Group

IBM Quantum

Physics circuit

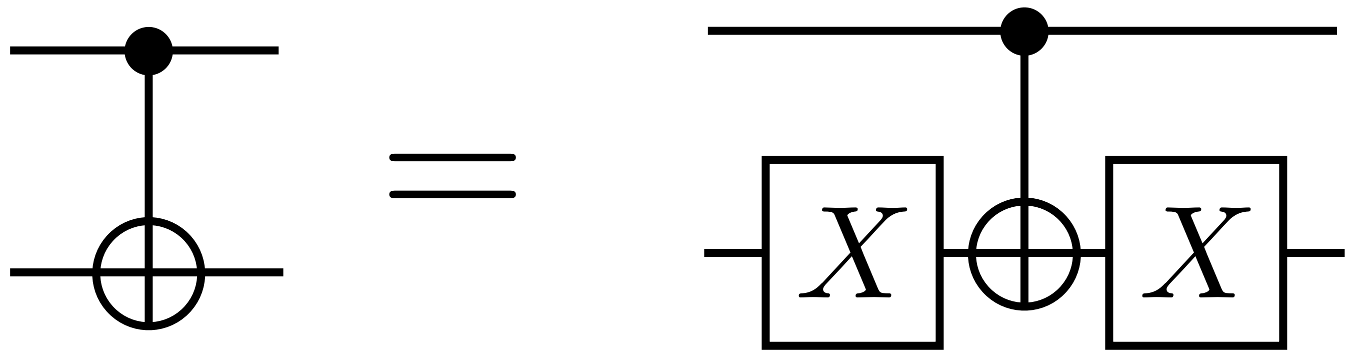


Mitigation circuit

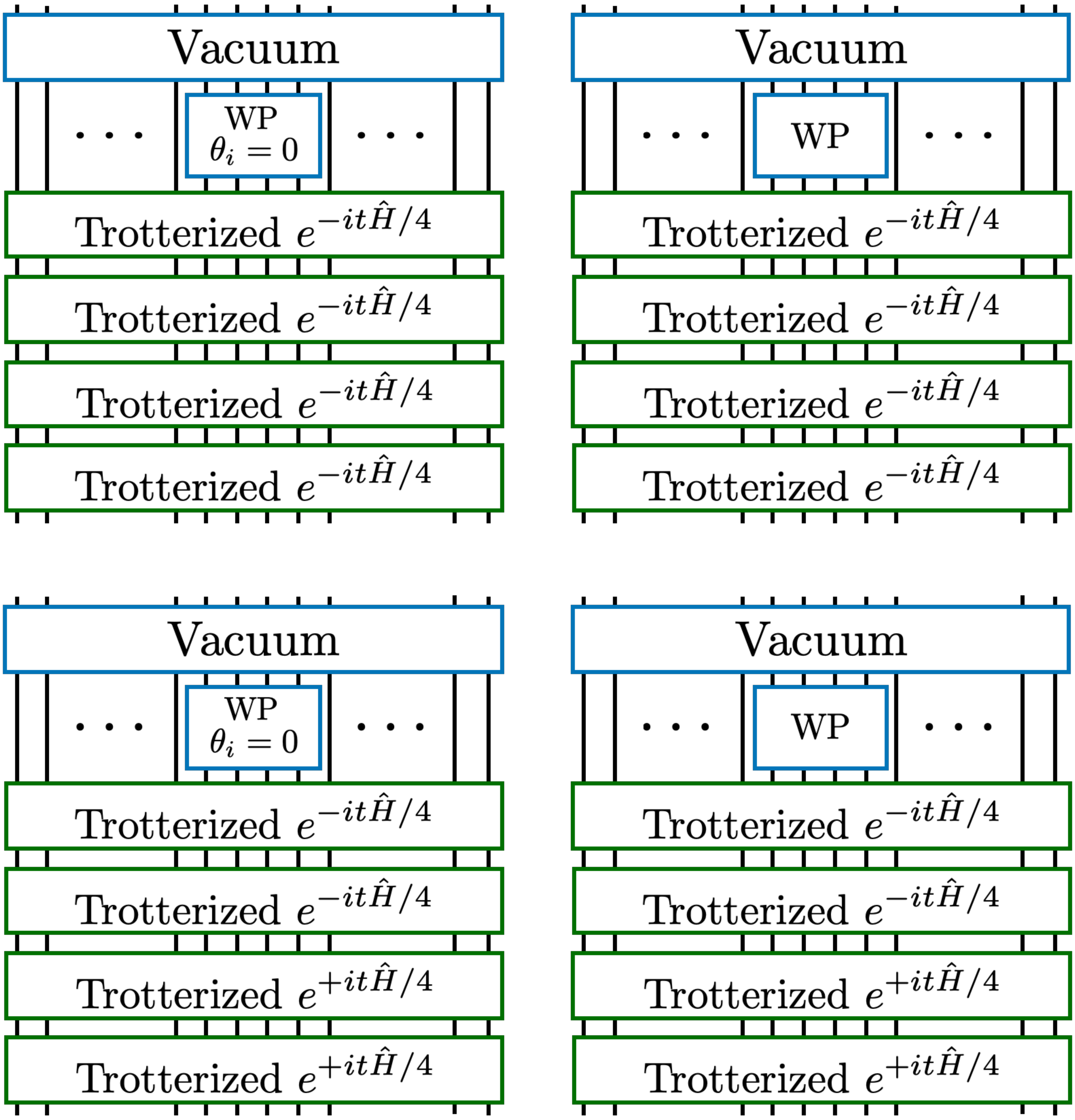


$$\left.\frac{\langle\hat{Z}\rangle_{\text{measured}}}{\langle\hat{Z}\rangle_{\text{expected}}}\right|_{\text{physics}} = \left.\frac{\langle\hat{Z}\rangle_{\text{measured}}}{\langle\hat{Z}\rangle_{\text{expected}}}\right|_{\text{mitigation}}$$

Pauli twirling



Solve for $\langle\hat{Z}\rangle_{\text{expected}}$



Vacuum
WP
$\theta_i = 0$
Trotterized $e^{-it\hat{H}/4}$
Trotterized $e^{-it\hat{H}/4}$
Trotterized $e^{-it\hat{H}/4}$
Trotterized $e^{-it\hat{H}/4}$
Vacuum
WP
Trotterized $e^{-it\hat{H}/4}$
Trotterized $e^{-it\hat{H}/4}$
Trotterized $e^{-it\hat{H}/4}$
Trotterized $e^{-it\hat{H}/4}$
Vacuum
WP
$\theta_i = 0$
Trotterized $e^{-it\hat{H}/4}$
Trotterized $e^{-it\hat{H}/4}$
Trotterized $e^{+it\hat{H}/4}$
Trotterized $e^{+it\hat{H}/4}$
Vacuum
WP
Trotterized $e^{-it\hat{H}/4}$
Trotterized $e^{-it\hat{H}/4}$
Trotterized $e^{+it\hat{H}/4}$
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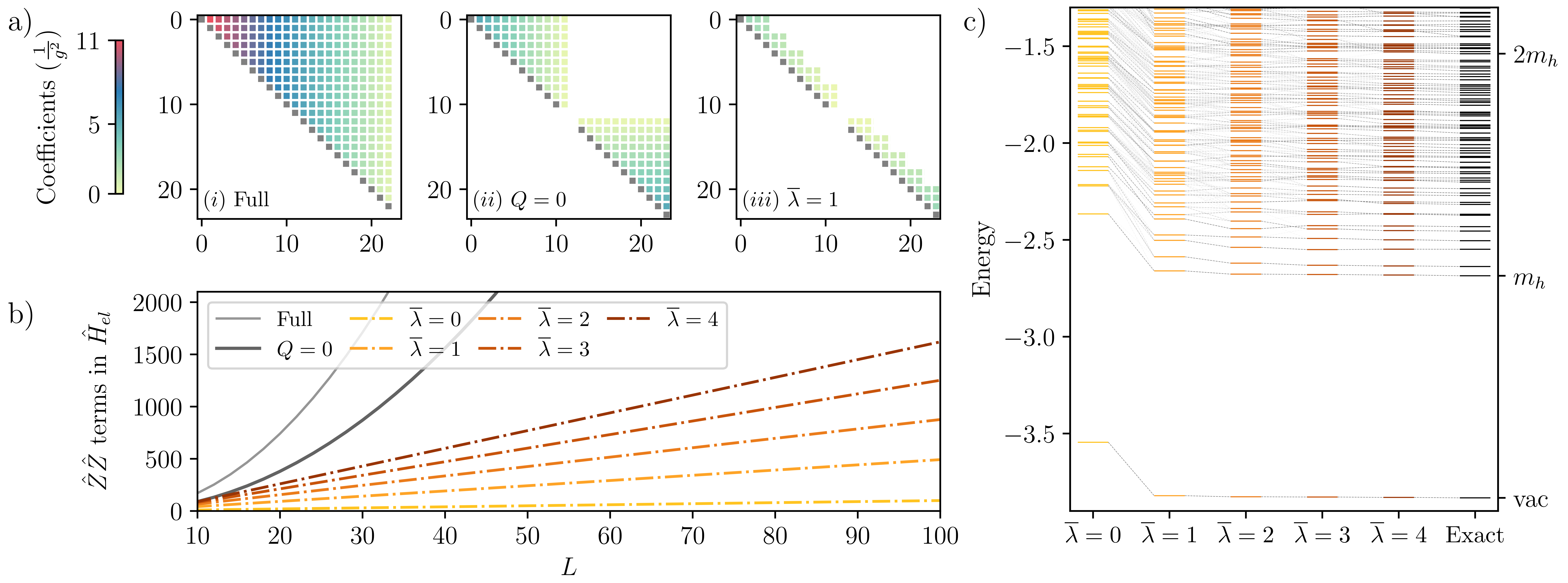
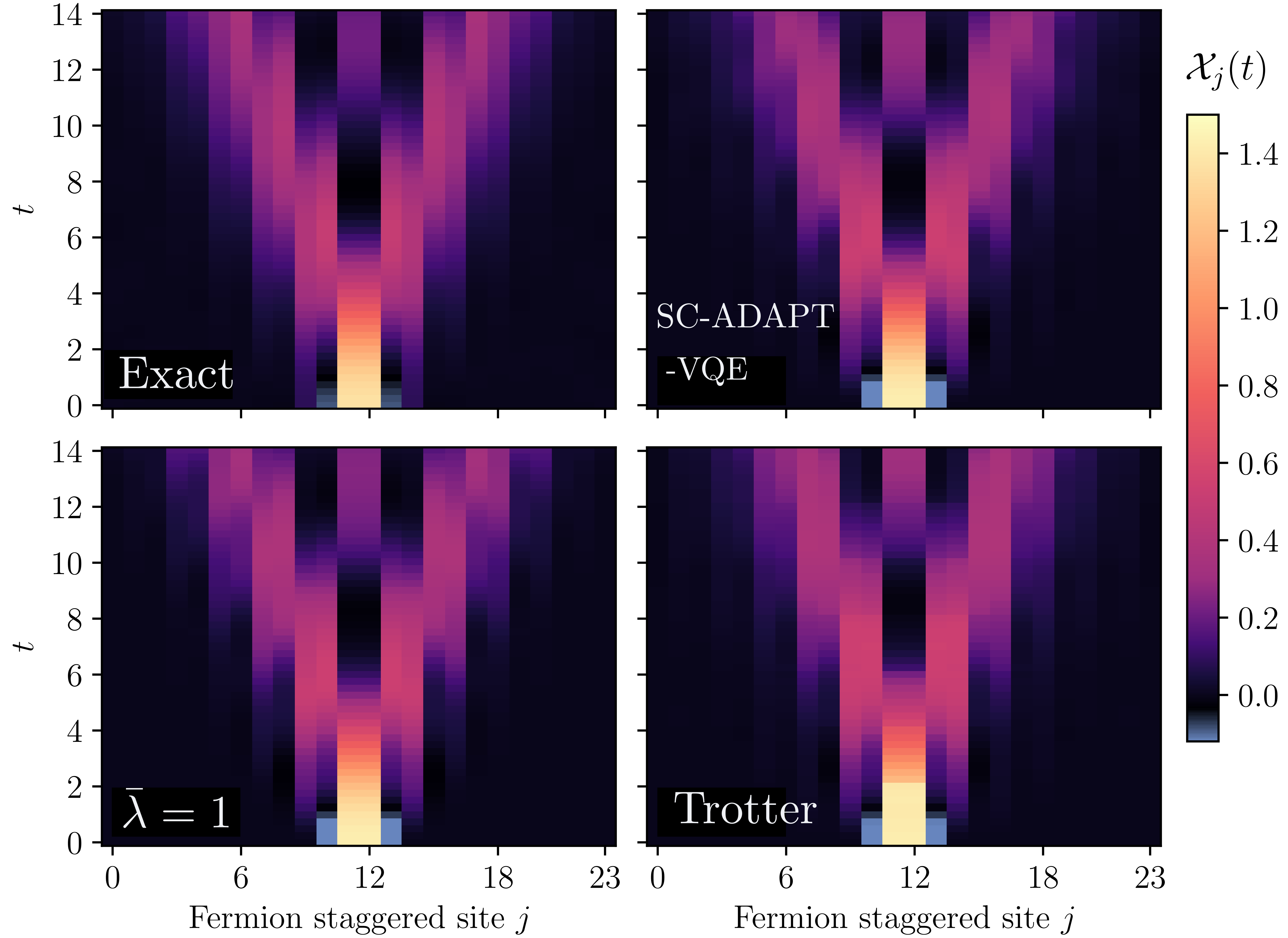

a)
Coefficients $(\frac{1}{g^2})$
11
5
0
(i) Full
(ii) $Q = 0$
(iii) $\overline{\lambda} = 1$
b)
$\hat{Z}\hat{Z}$ terms in $\hat{H}_{el}$
Full
$Q = 0$
$\overline{\lambda} = 0$
$\overline{\lambda} = 1$
$\overline{\lambda} = 2$
$\overline{\lambda} = 3$
$\overline{\lambda} = 4$
L
c)
Energy
$2m_h$
m_h
vac
Exact

Effective electric interaction

Quantify errors on $N = 24$ system that can be done exactly



10^1
10^{-1}
10^{-3}
10^{-5}
Δ_i
10 30 50 70 90 110 130 150 170 190
Bond dimension i
10^1
10^0
10^{-1}
Time (h)
qiskit-CPU
cuQuantum-GPU
10 30 50 70 90 110 130 150 170 190
Bond dimension
$t = 0$
$t = 1$
$t = 2$
$t = 3$
$t = 4$
$t = 5$
$t = 6$
$t = 7$
$t = 8$
$t = 9$
$t = 10$
$t = 11$
$t = 12$
$t = 13$
$t = 14$