

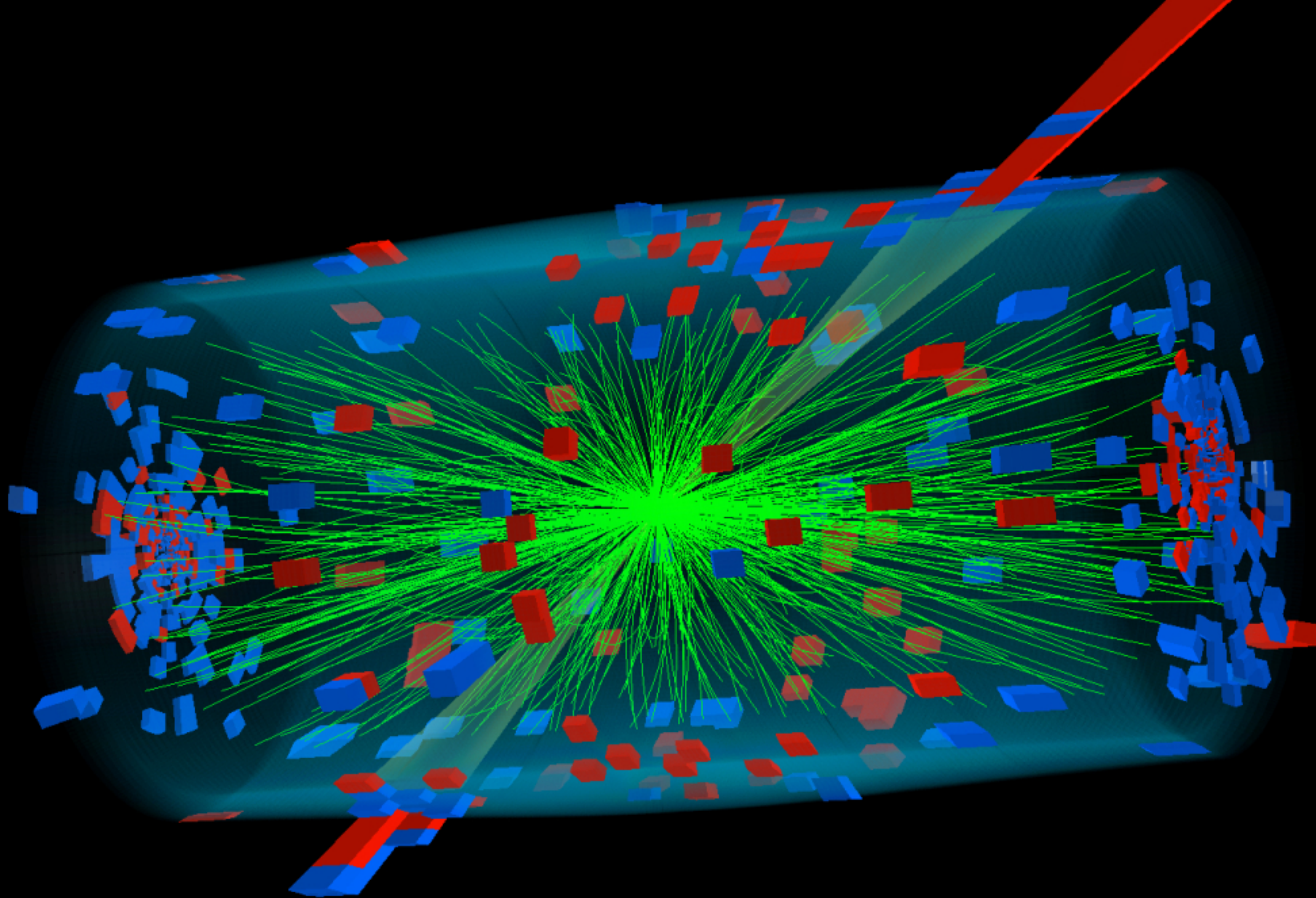
Quantum Computers: A new tool for lattice calculations

Christian Bauer
Physics Division LBNL

Christian Bauer

Quantum computers, A new tool for lattice calculations





CMS Run/Event 262548/458269

Experiment

Theory

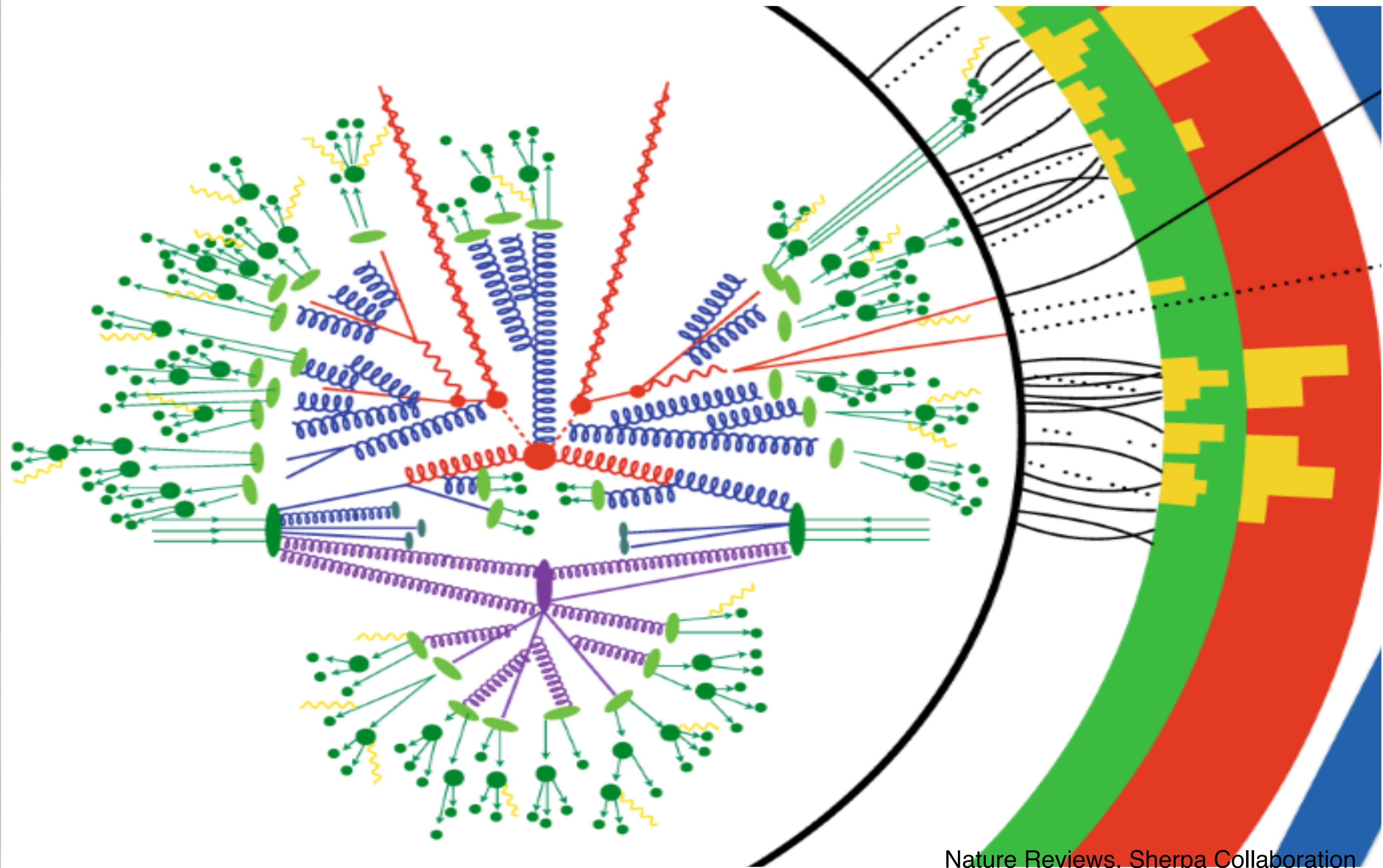
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Quantum computers, A new tool for lattice calculations

Experiment

Simulation

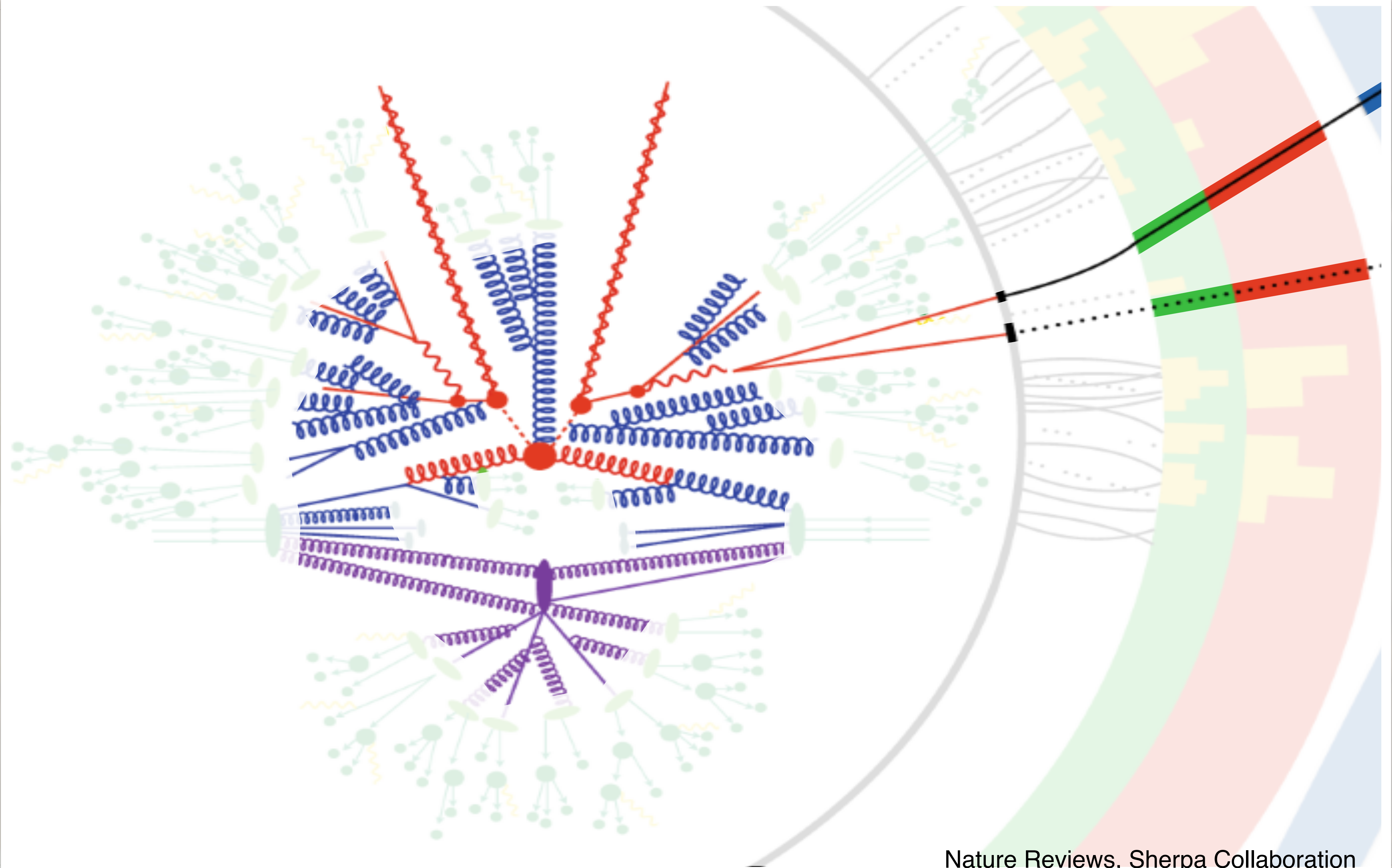
Theory



Nature Reviews, Sherpa Collaboration

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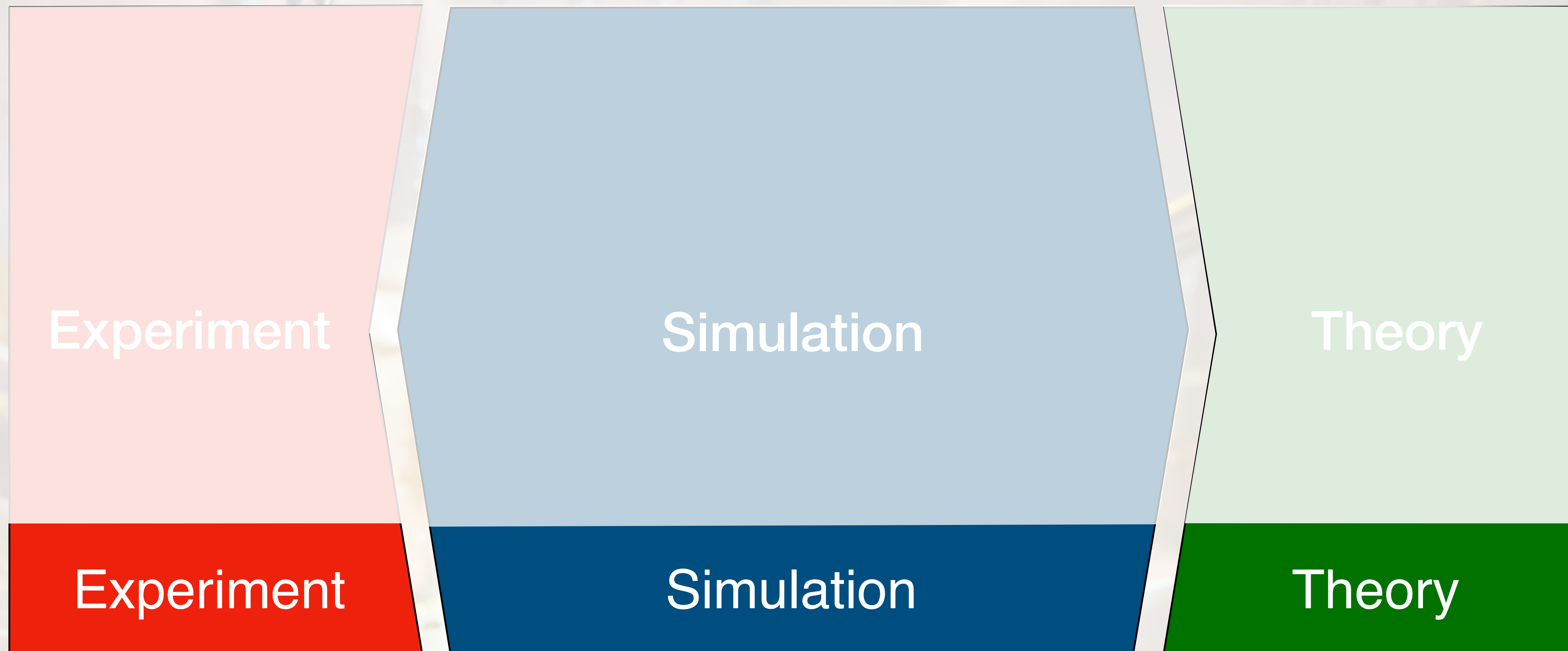
Quantum computers, A new tool for lattice calculations



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Quantum computers, A new tool for lattice calculations



How can we compute non-perturbative properties?

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Quantum computers, A new tool for lattice calculations

Lattice Gauge Theory relies on Feynman's path integral formulation, which sums over all possible “paths” or configurations weighted by the action

$$\langle \Omega | O | \Omega \rangle =$$

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$$\langle \Omega | O | \Omega \rangle = \lim_{\beta \rightarrow \infty} \sum_n e^{-\beta E_n} \langle n | O | n \rangle = \lim_{\beta \rightarrow \infty} \text{Tr} [e^{-\beta H} O]$$

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$$\langle \phi_0 | e^{-\beta H} | \phi_0 \rangle = \int d\phi_1 \dots d\phi_{N-1} \prod_{k=0}^{N-1} \langle \phi_{k+1} | e^{-\epsilon H} | \phi_k \rangle = \mathcal{N} e^{-\epsilon S_E} \quad (\phi_0 = \phi_N)$$

Creutz ('83)

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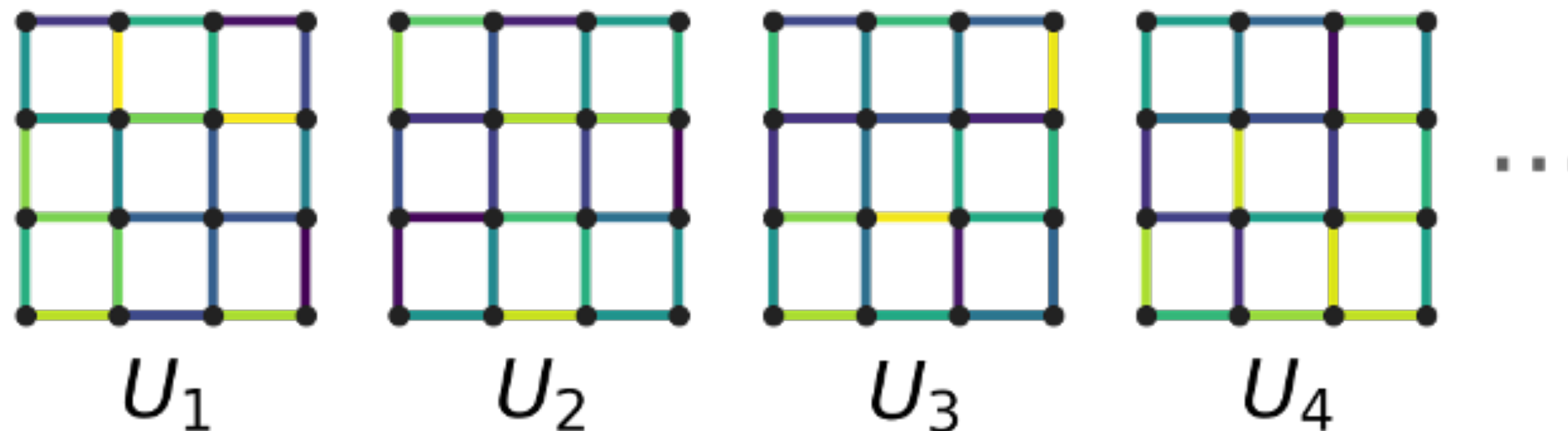
Putting it together

$$\langle \Omega | O | \Omega \rangle = \int \mathcal{D}\phi O[\phi] e^{-S_E[\phi]}$$

Lattice Gauge Theory relies on Feynman's path integral formulation, which sums over all possible “paths” or configurations weighted by the action

$$\langle \Omega | O | \Omega \rangle = \frac{\int \mathcal{D}\phi O[\phi] e^{-S_E[\phi]}}{\int \mathcal{D}\phi e^{-S_E[\phi]}}$$

Computed by Monte Carlo:
Generate field configurations, calculate $O[\phi]e^{-S_E[\phi]}$ and average



Lattice Gauge Theory relies on Feynman's path integral formulation, which sums over all possible “paths” or configurations weighted by the action

$$\langle \Omega | O | \Omega \rangle = \frac{\int \mathcal{D}\phi O[\phi] e^{-S_E[\phi]}}{\int \mathcal{D}\phi e^{-S_E[\phi]}}$$

Tremendously successful, and what most of this conference is about

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Tremendously successful, and what most of this conference is about

- Compute vacuum expectation values (operators create excitations)
- Calculations performed in Euclidean space
- Action needs to be real to maintain positive integrand } (no sign problem)
- Typically, can not deal with non-local light-like observables
- Can not deal with complex actions (finite density)
- Can not deal with dynamics

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How can we handle such observables?

Lattice Gauge Theory relies on Feynman's path integral formulation, which sums over all possible “paths” or configurations weighted by the action

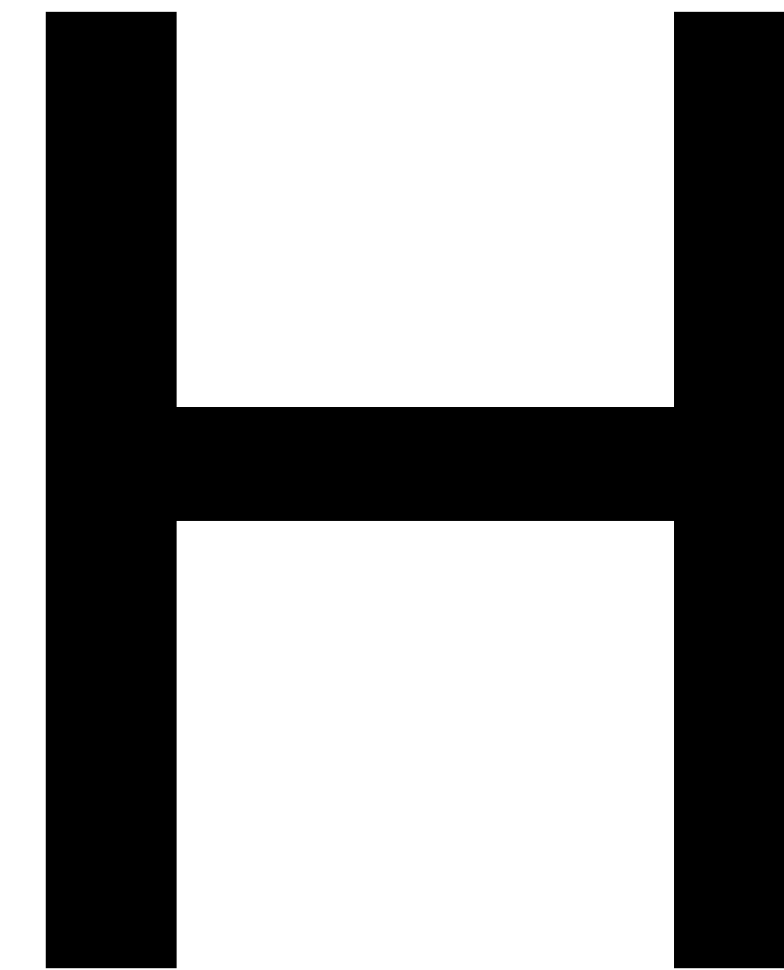
Compute directly expectation value squared of operator in given state

$$|\langle \Psi | O | \Psi \rangle|^2$$

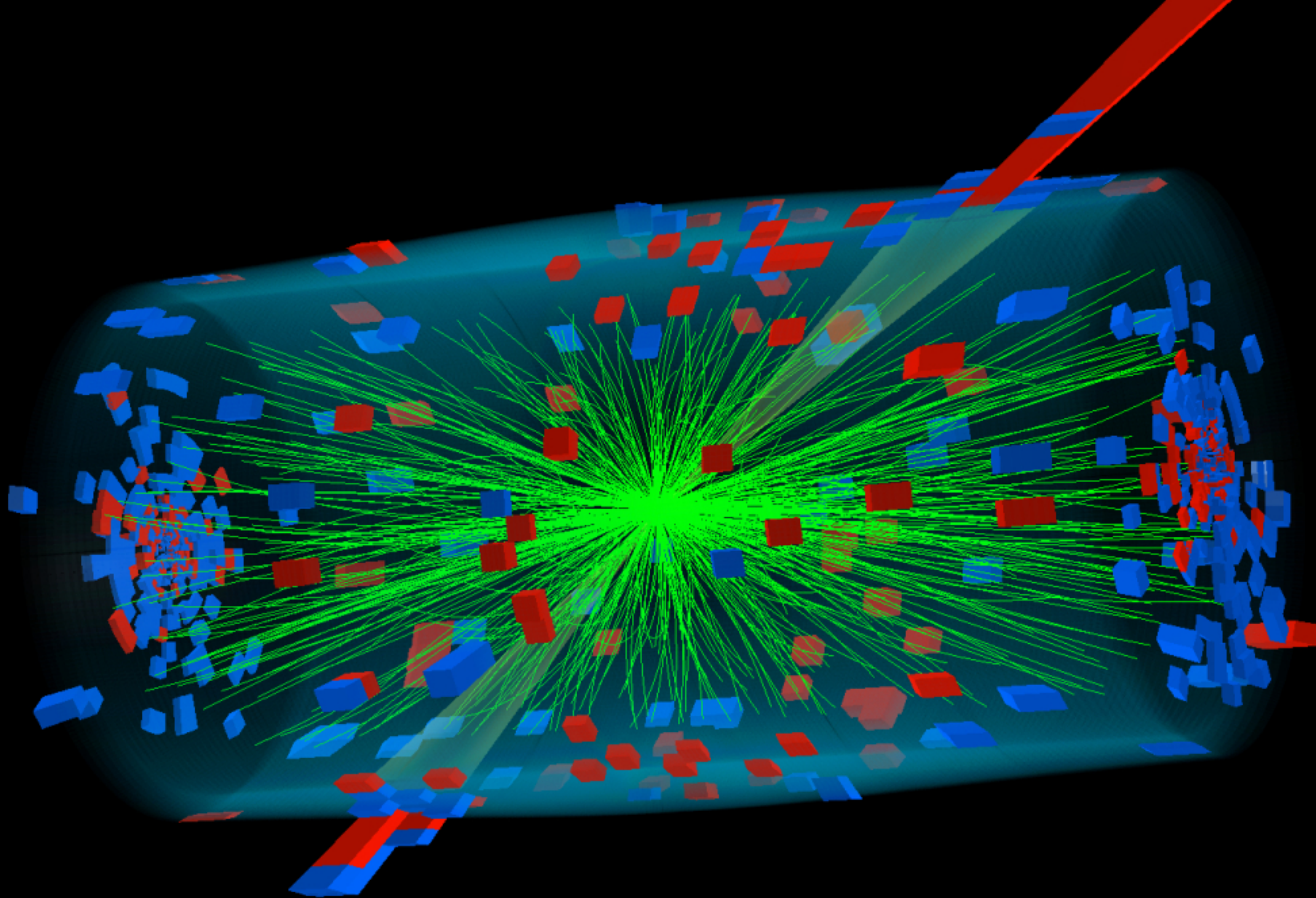
or probability that given initial state evolves into particular final state

$$|\langle \Psi(t_f) | U(t_i, t_f) | \Psi(t_i) \rangle|^2$$

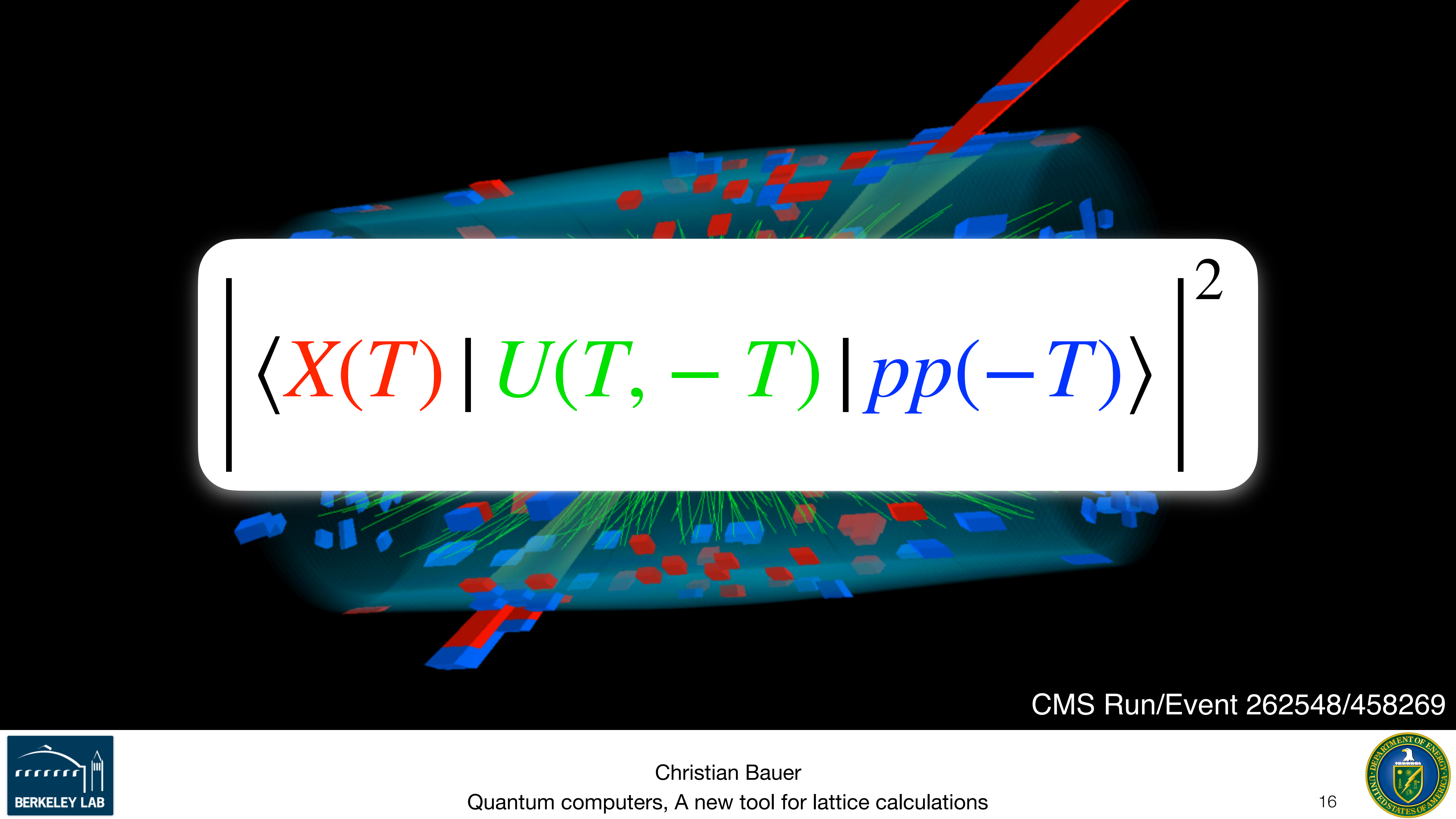
This requires working with the Hamiltonian, rather than the action.



Hamiltonian worked out by Kogut, Susskind
Relationship to action shown by Creutz



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$$\left| \langle X(T) | U(T, -T) | pp(-T) \rangle \right|^2$$

CMS Run/Event 262548/458269

Instead of doing Monte-Carlo simulation of path integral, can try to do time evolution using Schrödinger equation

$$\left| \langle X(T) | U(T, -T) | pp(-T) \rangle \right|^2$$

All elements in this expression in terms of fields $\phi(x)$

Both position x and field $\phi(x)$ are continuous

Discretizing position x and digitizing field value $\phi(x)$ turn continuous (QFT) problem into discrete (QM) problem

Leads to Hamiltonian Lattice Gauge Theory

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Quantum computers, A new tool for lattice calculations

Basic idea is to map the infinite Hilbert space of QFT on a finite dimensional HS making this a QM problem

$$\left| \langle X(T) | U(T, -T) | pp(-T) \rangle \right|^2$$

3 basic steps:

1. Create an initial state vector at time (-T) of two proton wave packets
2. Evolve this state forward in time from to time T using the Hamiltonian of the full interacting field theory
3. Perform a measurement of the state

The complexity of this calculation is unfortunately still the same as for a Monte-Carlo simulation of a problem with a sign problem

Classical computer	
nL=2	10^5
nL=3	10^18
nL=4	10^43
nL=5	10^83
nL=6	10^150

Quantum Algorithms for Quantum Field Theories

Stephen P. Jordan,^{1*} Keith S. M. Lee,² John Preskill³

Quantum field theory reconciles quantum mechanics and special relativity, and plays a central role in many areas of physics. We developed a quantum algorithm to compute relativistic scattering probabilities in a massive quantum field theory with quartic self-interactions (ϕ^4 theory) in spacetime of four and fewer dimensions. Its **run time is polynomial** in the number of particles, their energy, and the desired precision, and applies at both weak and strong coupling. In the strong-coupling and high-precision regimes, our quantum algorithm **achieves exponential speedup over the fastest known classical algorithm.**

Science 336 (2012) 1130

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Quantum computers therefore put first principles calculations of scattering cross sections (and other observables) in the realm of possibility

	Classical computer	Quantum Computer
nL=2	10^5	10^1
nL=3	10^{18}	10^1
nL=4	10^{43}	10^2
nL=5	10^{83}	10^2
nL=6	10^{150}	10^2



There are several steps that need to be implemented for a successful simulation of HEP simulations

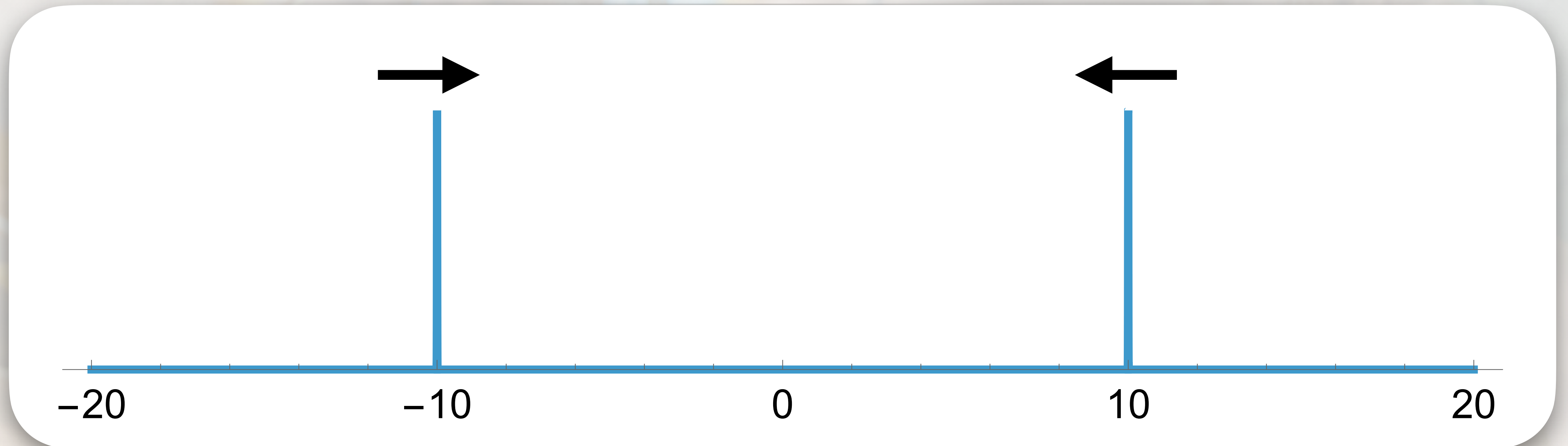
- Setting up initial state
- Obtaining time-evolution operator
- Measuring interesting observables

There are several steps that need to be implemented for a successful simulation of HEP simulations

- Setting up initial state
- Obtaining time-evolution operator
- Measuring interesting observables

Setting up an initial state is the first step of any simulation, and is difficult since even initial state is not known perturbatively

For problem discussed, need two wave packets of protons



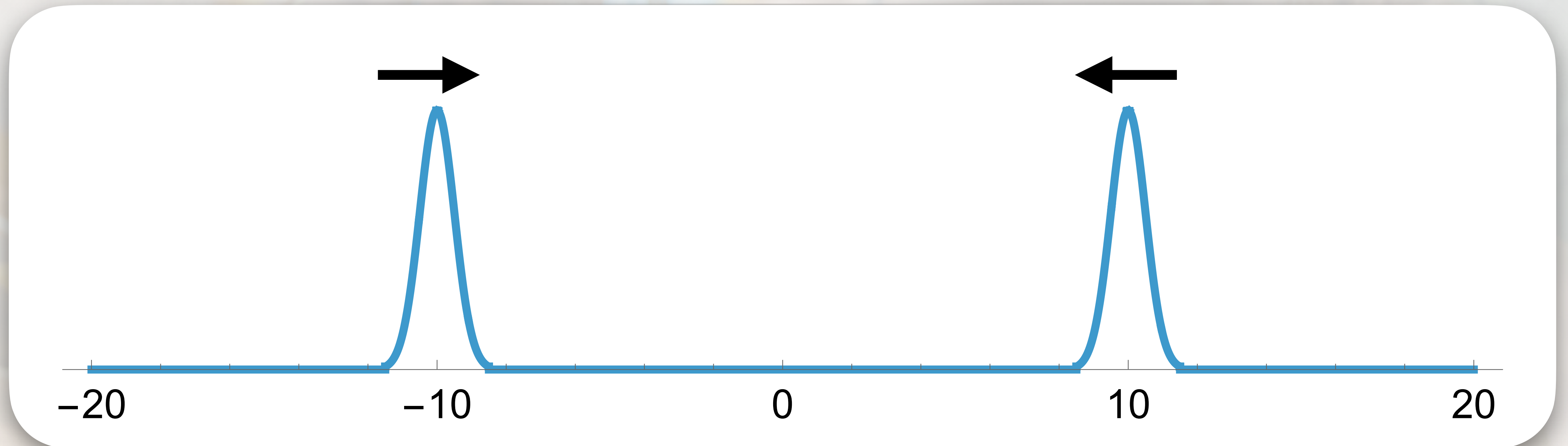
Need wave packets in interacting theory

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Adiabatic

Create wave packet in free theory and adiabatically turn on interactions

Can be made exact in principle

Very expensive in practice

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Variationally

Find an approximate circuit to produce initial state through variational ansatz

Has some systematic uncertainties

Very efficient to implement

Most techniques nowadays use some form of variational algorithm to determine the initial state

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, WA 98195, USA.*

(Dated: April 23, 2024)

The vacuum of the lattice Schwinger model is prepared on up to 100 qubits of IBM's **Eagle**-processor quantum computers. A new algorithm to prepare the ground state of a gapped translationally-invariant system on a quantum computer is presented, which we call Scalable Circuits ADAPT-VQE (SC-ADAPT-VQE). This algorithm uses the exponential decay of correlations between distant regions of the ground state, together with ADAPT-VQE, to construct quantum circuits for state preparation that can be scaled to arbitrarily large systems. These scalable circuits can be determined using classical computers, avoiding the challenging task of optimizing parameterized circuits on a quantum computer. SC-ADAPT-VQE is applied to the Schwinger model, and shown to be systematically improvable, with an accuracy that converges exponentially with circuit depth. Both the structure of the circuits and the deviations of prepared wavefunctions are found to become independent of the number of spatial sites, L . This allows for a controlled extrapolation of the circuits, determined using small or modest-sized systems, to arbitrarily large L . The circuits for the Schwinger model are determined on lattices up to $L = 14$ (28 qubits) with the `qiskit` classical simulator, and subsequently scaled up to prepare the $L = 50$ (100 qubits) vacuum on IBM's 127 superconducting-qubit quantum computers `ibm_brisbane` and `ibm_cusco`. After introducing an improved error-mitigation technique, which we call Operator Decoherence Renormalization, the chiral condensate and charge-charge correlators obtained from the quantum computers are found to be in good agreement with classical Matrix Product State simulations.

arXiv: 2308.04481

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Roland C. Farrell ^{*}, Marc

InQubator for Q
University

The vacuum of the lattice Schwinger quantum computers. A new algorithm invariant system on a quantum computer (SC-ADAPT-VQE). This algorithm regions of the ground state, together preparation that can be scaled determined using classical computers on a quantum computer. SC-ADAPT-VQE systematically improvable, with the structure of the circuits are independent of the number of qubits. The circuits, determined using small-scale simulations of the Schwinger model are determined using a quantum simulator, and subsequently scaled to larger systems. SC-ADAPT-VQE superconducting-qubit quantum computer proved error-mitigation techniques for the condensate and charge-charge correlation functions in good agreement with classical Monte Carlo results.

Scattering wave packets of hadrons in gauge theories: Preparation on a quantum computer

Zohreh Davoudi^{1,2,3,4,5}, Chung-Chun Hsieh^{1,2}, and Saurabh V. Kadam⁶

arXiv: 2402.00840

¹Department of Physics, University of Maryland, College Park, MD 20742 USA

²Maryland Center for Fundamental Physics, University of Maryland, College Park, MD 20742, USA

³Joint Center for Quantum Information and Computer Science, National Institute of Standards and Technology (NIST) and University of Maryland, College Park, MD 20742 USA

⁴The NSF Institute for Robust Quantum Simulation, University of Maryland, College Park, Maryland 20742, USA

⁵National Quantum Laboratory (QLab), University of Maryland, College Park, MD 20742 USA

⁶ InQubator for Quantum Simulation (IQuS), Department of Physics, University of Washington, Seattle, WA 98195, USA



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

Roland C. Farrell ^{*}, Marc Illa [†], Nikita A. Zemlevskiy [‡], and John Preskill [§]

InQubator for Quantum Simulation
University of Washington

The vacuum of the lattice Schwinger model is prepared on digital quantum computers. A new algorithm, SC-ADAPT-VQE, prepares an invariant system on a quantum computer. This algorithm finds regions of the ground state, together with a variational preparation that can be scaled to larger systems. SC-ADAPT-VQE is systematically improvable, with the structure of the circuits independent of the number of qubits. The circuits, determined using small-scale simulations of the Schwinger model are determined on a quantum simulator, and subsequently scaled to a superconducting-qubit quantum computer. The algorithm is proven error-mitigation technique for the condensate and charge-charge correlation functions in good agreement with classical Monte Carlo results.

Scattering wave packets of hadrons in gauge theories: Preparation on a quantum computer

Zohreh Davoudi^{1,2,3,4,5,6}

- ¹Department of Physics, University of Maryland
- ²Maryland Center for Functional Materials Research, University of Maryland
- ³Joint Center for Quantum Information and Computer Science (NIST) and University of Maryland
- ⁴The NSF Institute for Quantum Science and Technology, USA
- ⁵National Quantum Laboratory, USA
- ⁶InQubator for Quantum Simulation, University of Washington, 98195, USA

Digital quantum simulations of scattering in quantum field theories using W states

Roland C. Farrell ^{1,2,*}, Nikita A. Zemlevskiy ^{3,†}, Marc Illa ^{3,‡} and John Preskill ^{1,2,4,§}

¹*Institute for Quantum Information and Matter, California Institute of Technology*

²*Department of Physics, California Institute of Technology*

³*InQubator for Quantum Simulation (IQuS), Department of Physics, University of Washington*

⁴*AWS Center for Quantum Computing*

(Dated: May 7, 2025)

High-energy particle collisions can convert energy into matter through the inelastic production of new particles. Quantum computers are an ideal platform for simulating the out-of-equilibrium dynamics of the collision and the formation of the subsequent many-particle state. In this work, evidence for inelastic particle production is observed in one-dimensional Ising field theory using IBM's quantum computers. The scattering experiment is performed on 100 qubits of `ibm.marrakesh` and uses up to 6,412 two-qubit gates to access the post-collision dynamics. Integral to these simulations is a new quantum algorithm for preparing the initial state (wavepackets) of a quantum field theory scattering simulation. This method efficiently prepares wavepackets by extending recent protocols for creating W states with mid-circuit measurement and feedforward. The required circuit depth is independent of wavepacket size and spatial dimension, representing a superexponential improvement over previous methods. Our wavepacket preparation algorithm can be applied to a wide range of lattice models and is demonstrated in one-dimensional Ising field theory, scalar field theory, the Schwinger model, and two-dimensional Ising field theory.

arXiv: 2505.03111

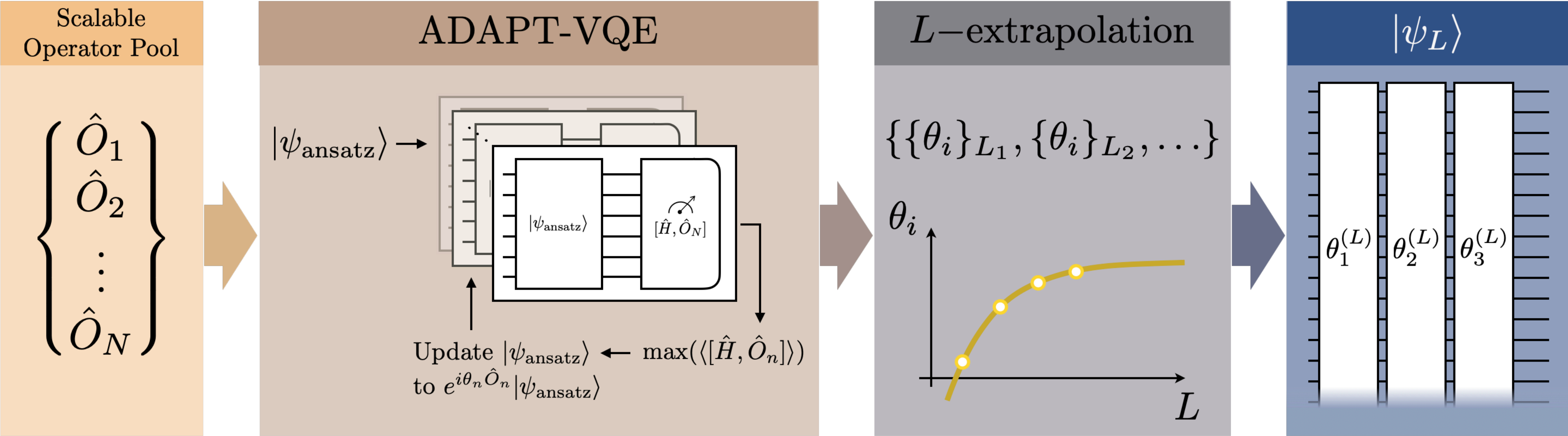
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Quantum computers, A new tool for lattice calculations



Most techniques nowadays use some form of variational algorithm to determine the initial state

Creating a ground state is best done variationally



Farrell, Illa, Ciavarella, Savage('23)

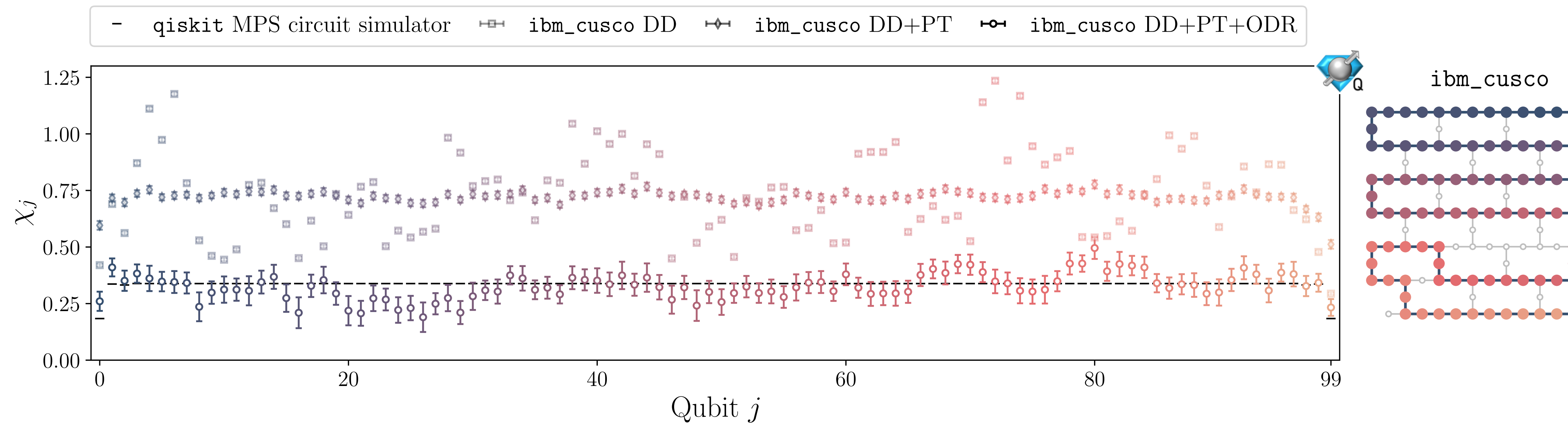
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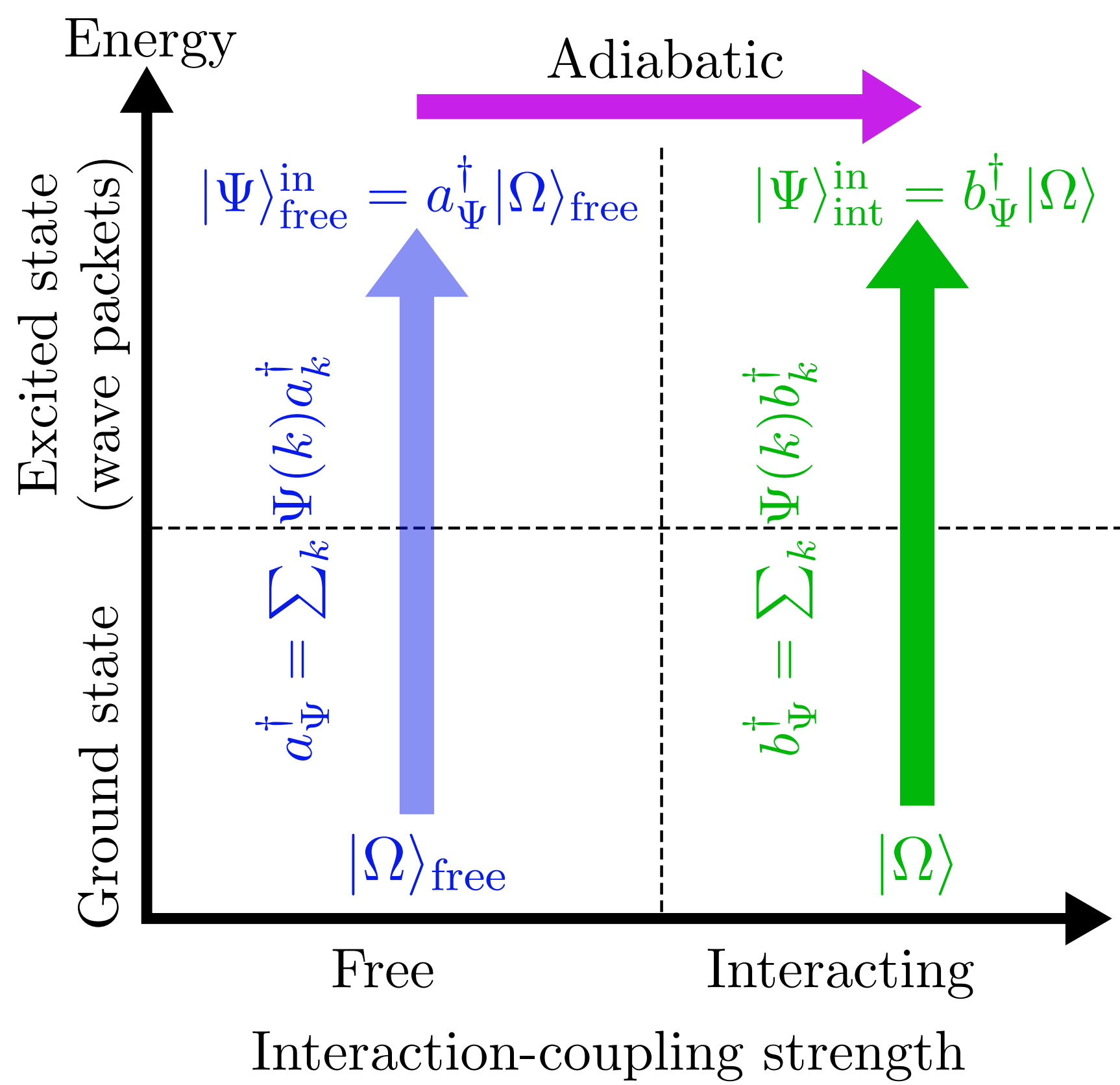
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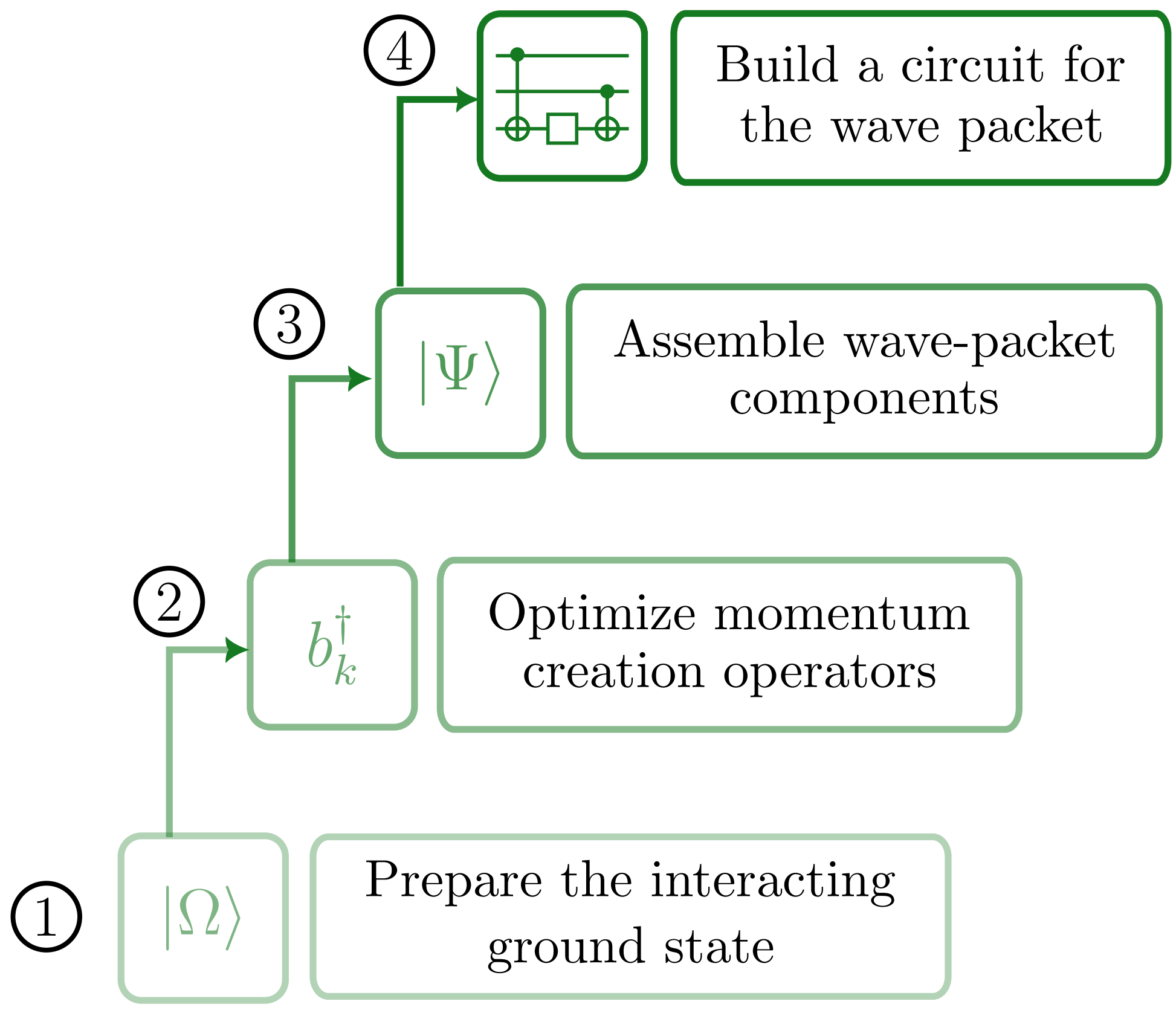


Most techniques nowadays use some form of variational algorithm to determine the initial state

Several new ideas have improved variational techniques significantly



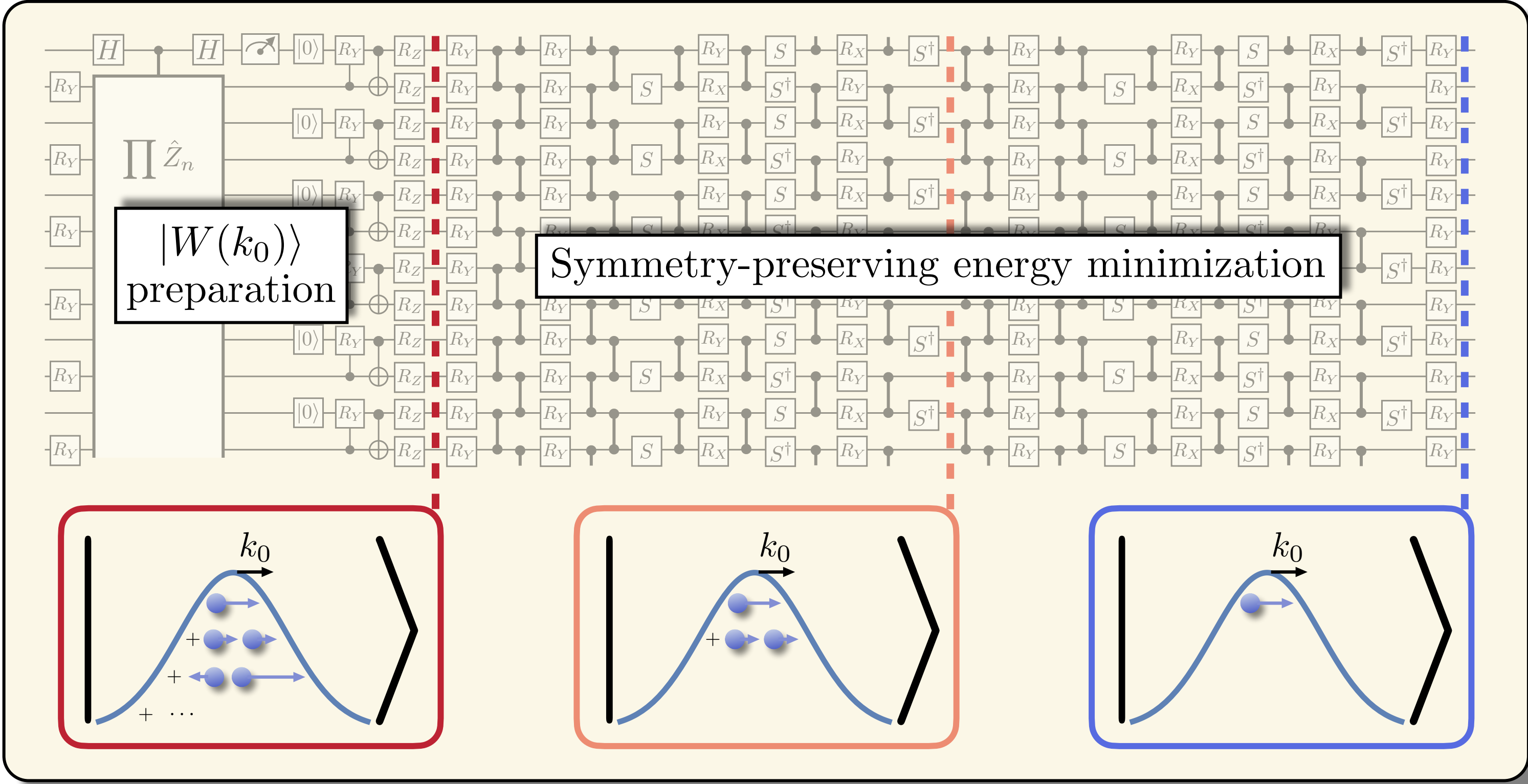
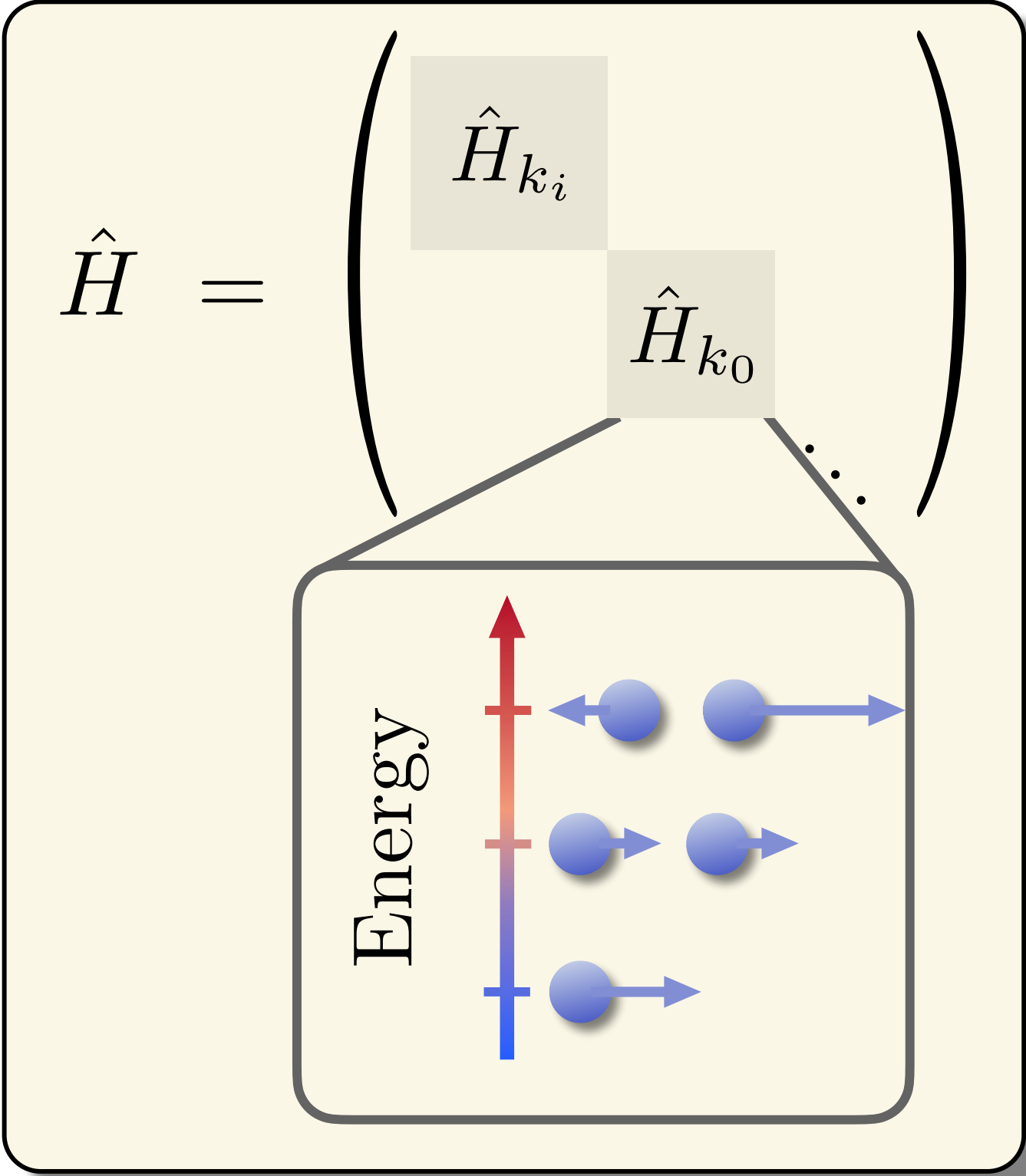
(a)



(b)

Most techniques nowadays use some form of variational algorithm to determine the initial state

Several new ideas have improved variational techniques significantly



Farrell, Zemlevskiy, Illa, Preskill ('25)

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Quantum computers, A new tool for lattice calculations

There are several steps that need to be implemented for a successful simulation of HEP simulations

- Setting up initial state
- Obtaining time-evolution operator
- Measuring interesting observables

There are many different parts of the theory that need to be worked out when formulating a Hamiltonian lattice gauge theory

1. How to formulate a lattice theory that reproduces $SU(3)$ in the limit of vanishing lattice spacing
 - Whether to add any additional expansions in the theory
2. What basis to choose for the Hilbert space
3. How to truncate the theory (how to choose a discrete set of field values)

Goal is a Hamiltonian Lattice theory that reproduces QCD in continuum limit

A Trailhead for Quantum Simulation of SU(3) Yang-Mills Lattice Gauge Theory in the Local Multiplet Basis

Anthony Ciavarella,^{1,*} Natalie Klco,^{2,†} and Martin J. Savage^{1,‡}

¹*InQubator for Quantum Simulation (IQUS), Department of Physics,
University of Washington, Seattle, WA 98195, USA*

²*Institute for Quantum Information and Matter (IQIM) and Walter Burke Institute for Theoretical Physics,
California Institute of Technology, Pasadena CA 91125, USA*

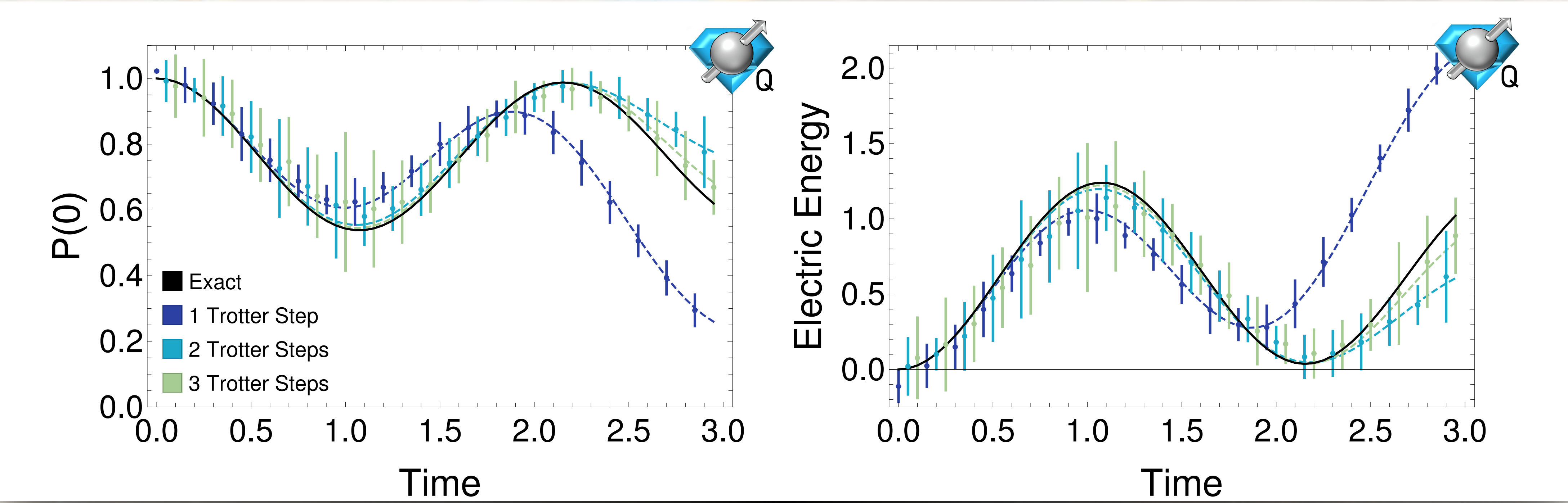
(Dated: February 23, 2021 - 1:41)

arXiv:2101.10227v2
Phys.Rev.D 103 (2021) 9

Worked out all details, provided efficient quantum algorithms and got results from hardware

Paper presented above was first (and essentially still only one) that could do real SU(3) calculations on quantum hardware

Results could be obtained on a 2x1 lattice



We very recently realized that adding an additional expansion can lead to dramatic simplifications in the lattice theory

1. How to formulate a lattice theory that reproduces $SU(3)$ in the limit of vanishing lattice spacing
 - Whether to add any additional expansions in the theory
2. What basis to choose for the Hilbert space
3. How to truncate the theory (how to choose a discrete set of field values)
4. ...

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PHYSICAL REVIEW LETTERS **133**, 111901 (2024)

arXiv: 2402.10265v4

**Quantum Simulation of SU(3) Lattice Yang-Mills Theory
at Leading Order in Large- N_c Expansion**

Anthony N. Ciavarella^{1,*} and Christian W. Bauer^{1,2,†}

¹*Physics Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

²*Department of Physics, University of California, Berkeley, Berkeley, California 94720, USA*

 (Received 28 February 2024; revised 26 July 2024; accepted 5 August 2024; published 9 September 2024)

Quantum simulations of the dynamics of QCD have been limited by the complexities of mapping the continuous gauge fields onto quantum computers. By parametrizing the gauge invariant Hilbert space in terms of plaquette degrees of freedom, we show how the Hilbert space and interactions can be expanded in inverse powers of N_c . At leading order in this expansion, the Hamiltonian simplifies dramatically, both in the required size of the Hilbert space as well as the type of interactions involved. Adding a truncation of the resulting Hilbert space in terms of local energy states we give explicit constructions that allow simple representations of SU(3) gauge fields on qubits and qutrits. This formulation allows a simulation of the real time dynamics of a SU(3) lattice gauge theory on a 5×5 and 8×8 lattice on `ibm_torino` with a CNOT depth of 113.



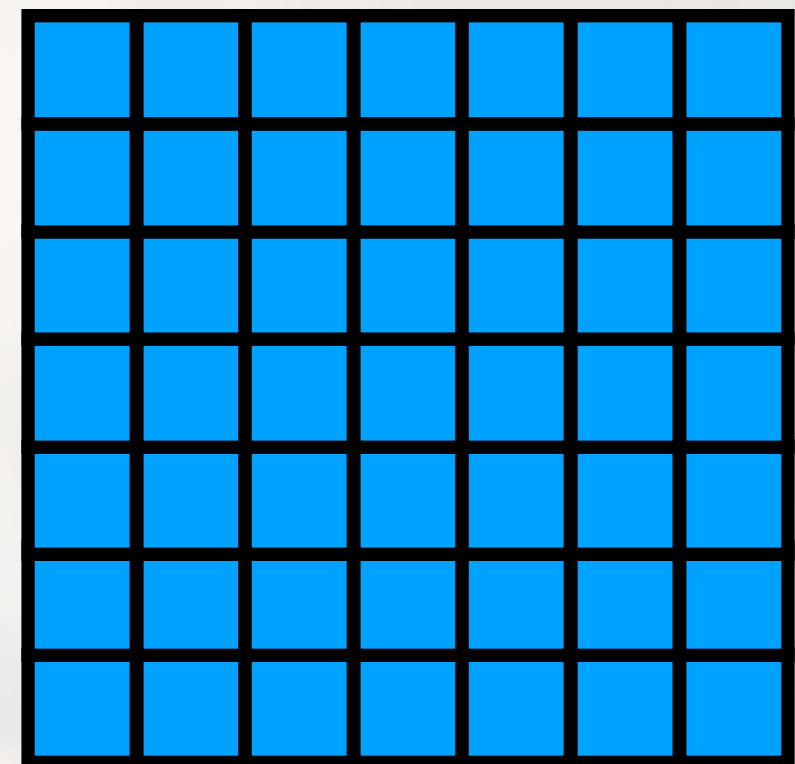
One can now work out the Hamiltonians, and obtain a relatively simple result, which can be represented by a single qubit per plaquette

$$\hat{H} = \sum_p \left(\frac{8}{3}g^2 - \frac{1}{2g^2} \right) \hat{P}_{1,p} - \frac{1}{\sqrt{2}g^2} \hat{P}_{0,p+x} \hat{P}_{0,p-x} \hat{P}_{0,p+y} \hat{P}_{0,p-y} \hat{X}_p$$

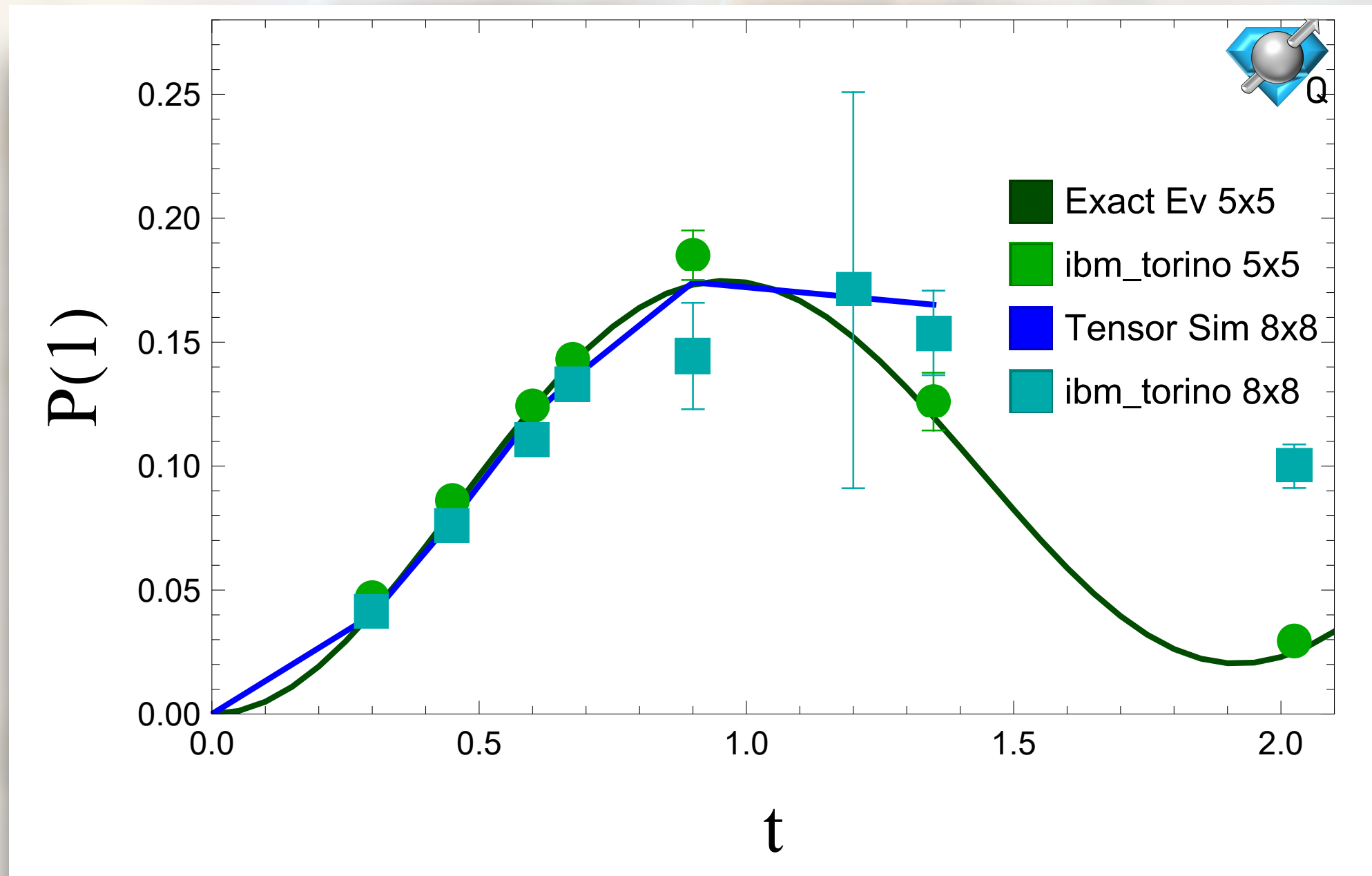
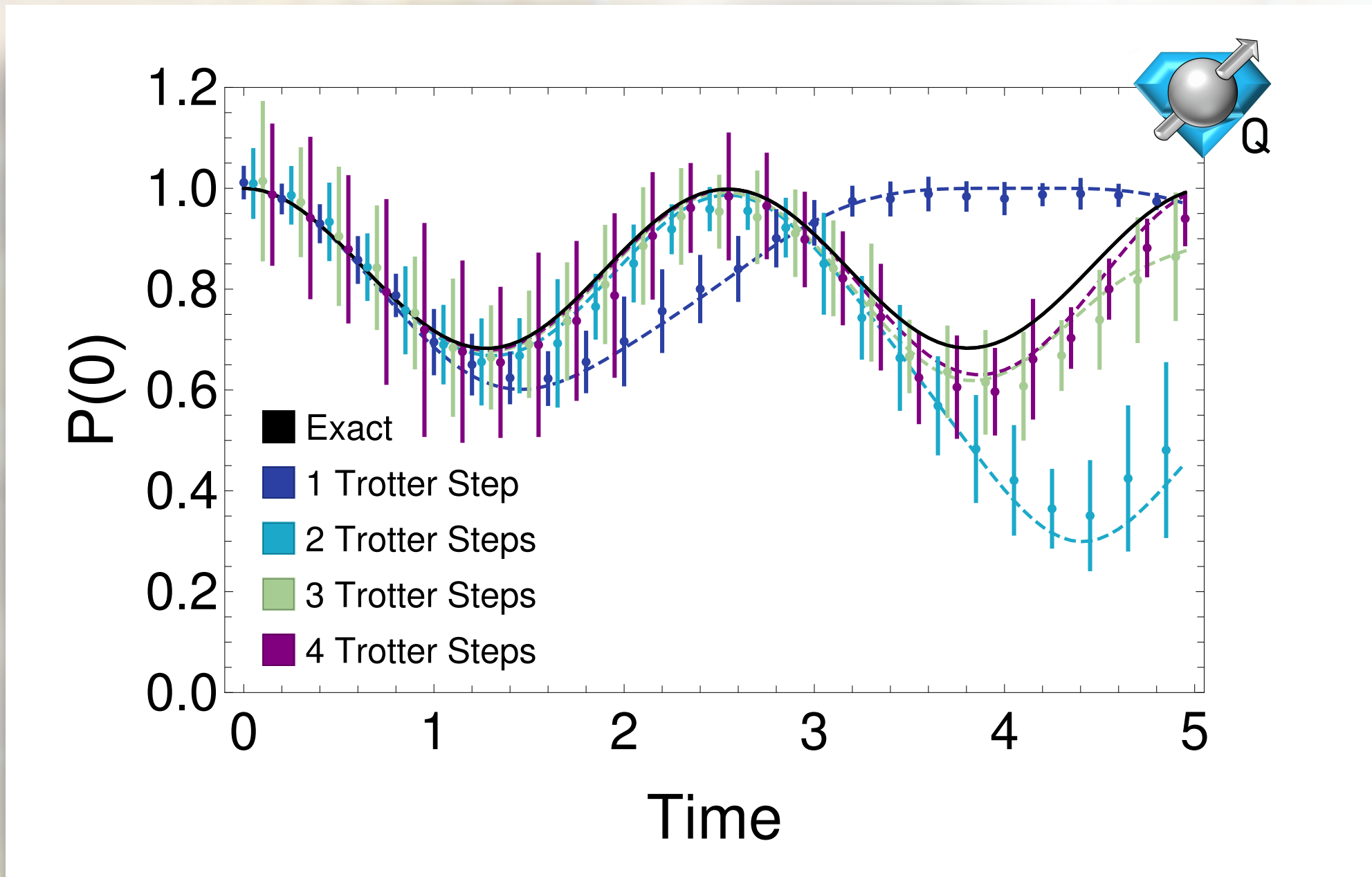
A $1/N_c$ expansion in QCD is quite standard in many classical applications. Can it help in quantum simulation?



Trailhead for quantum simulation of SU(3)
Yang-Mills lattice gauge theory in the local
multiplet basis,
2101.10227



Quantum Simulation of SU(3)
Lattice Yang Mills Theory at
Leading Order in Large N,
2402.10265



Recently extended these results to include $1/N_c$ corrections, as well as include higher truncations in the Hilbert space

Efficient Truncations of $SU(N_c)$ Lattice Gauge Theory for Quantum Simulation

Anthony N. Ciavarella ^{1,*} Ivan M. Burbano ^{1,2,3,†} and Christian W. Bauer ^{1,2,‡}

¹*Physics Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

²*Department of Physics, University of California, Berkeley, Berkeley, CA 94720*

³*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

(Dated: March 18, 2025)

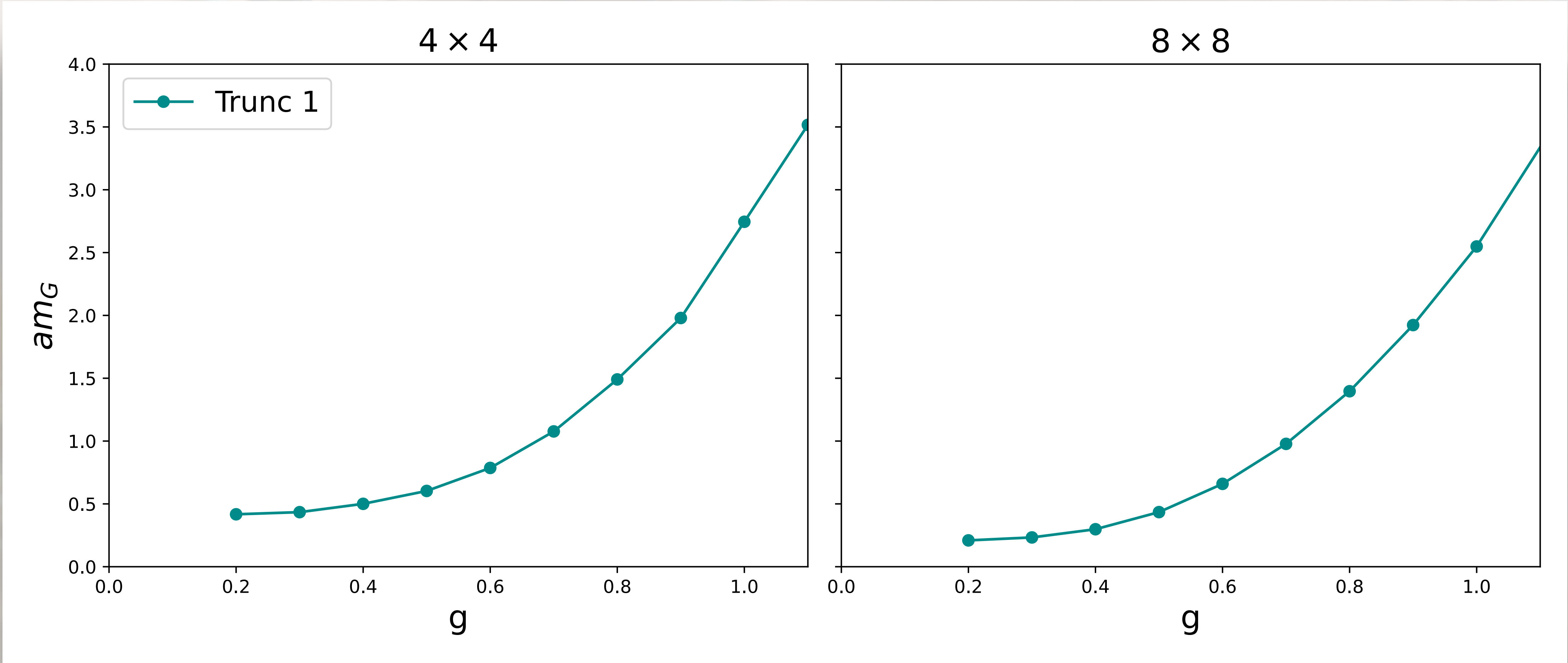
Quantum simulations of lattice gauge theories offer the potential to directly study the non-perturbative dynamics of quantum chromodynamics, but naive analyses suggest that they require large computational resources. Large N_c expansions are performed to order $1/N_c$ to simplify the Hamiltonian of pure $SU(N_c)$ lattice gauge theories. A reformulation of the electric basis is introduced with a truncation strategy based on the construction of local Krylov subspaces with plaquette operators. Numerical simulations show that these truncated Hamiltonians are consistent with traditional lattice calculations at relatively small couplings. It is shown that the computational resources required for quantum simulation of time evolution generated by these Hamiltonians is 17 – 19 orders of magnitude smaller than previous approaches.

arXiv: 2503.11888v1

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Quantum computers, A new tool for lattice calculations

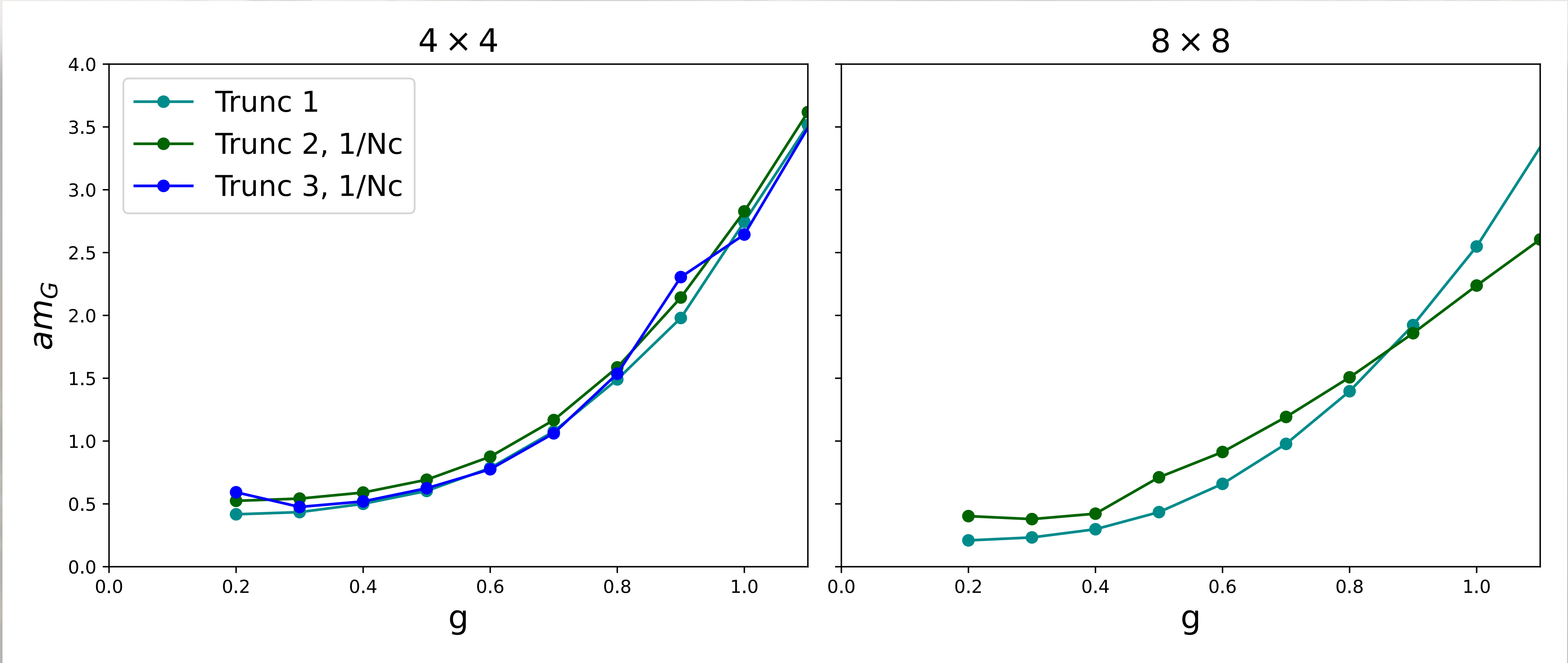
Using tensor network simulation calculated glueball mass as a function of coupling constant. Found unexpectedly good convergence down to small values of g



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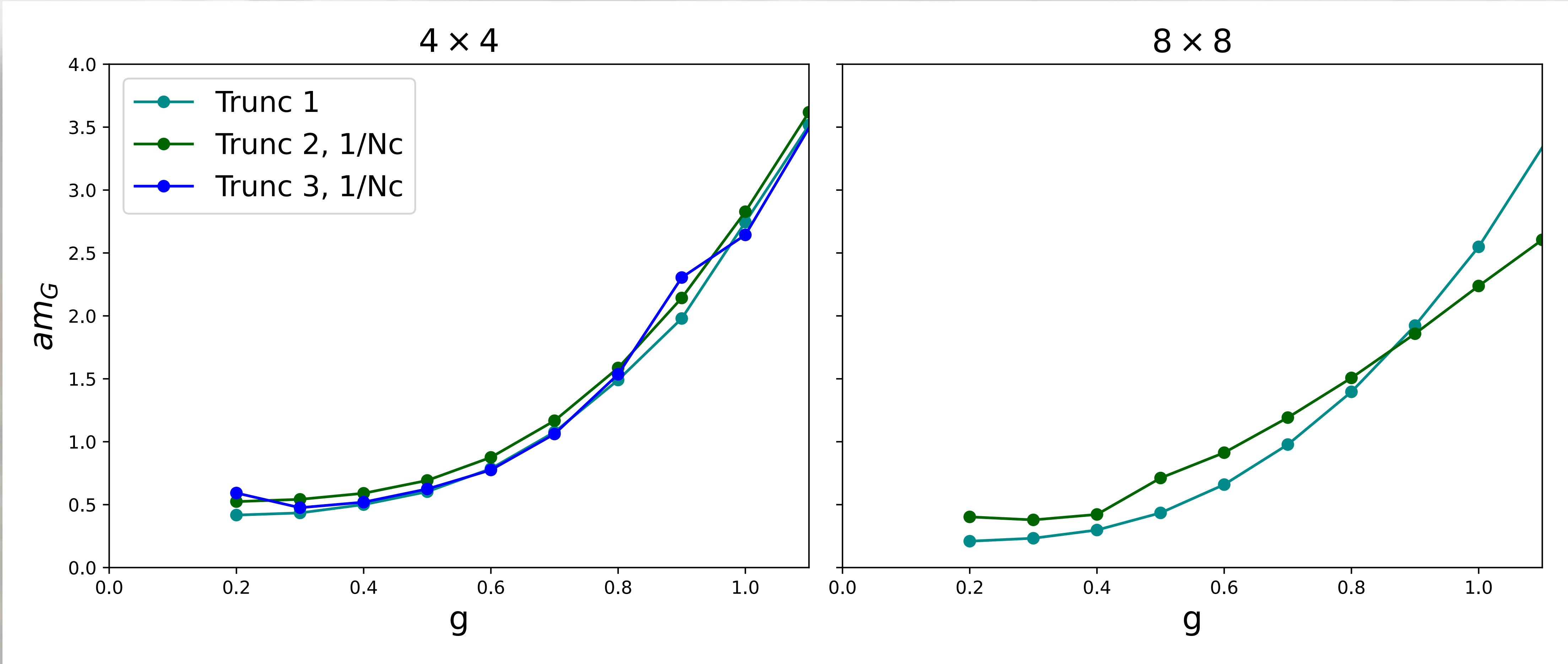
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Quantum computers, A new tool for lattice calculations

Using tensor network simulation calculated glueball mass as a function of coupling constant. Found unexpectedly good convergence down to small values of g

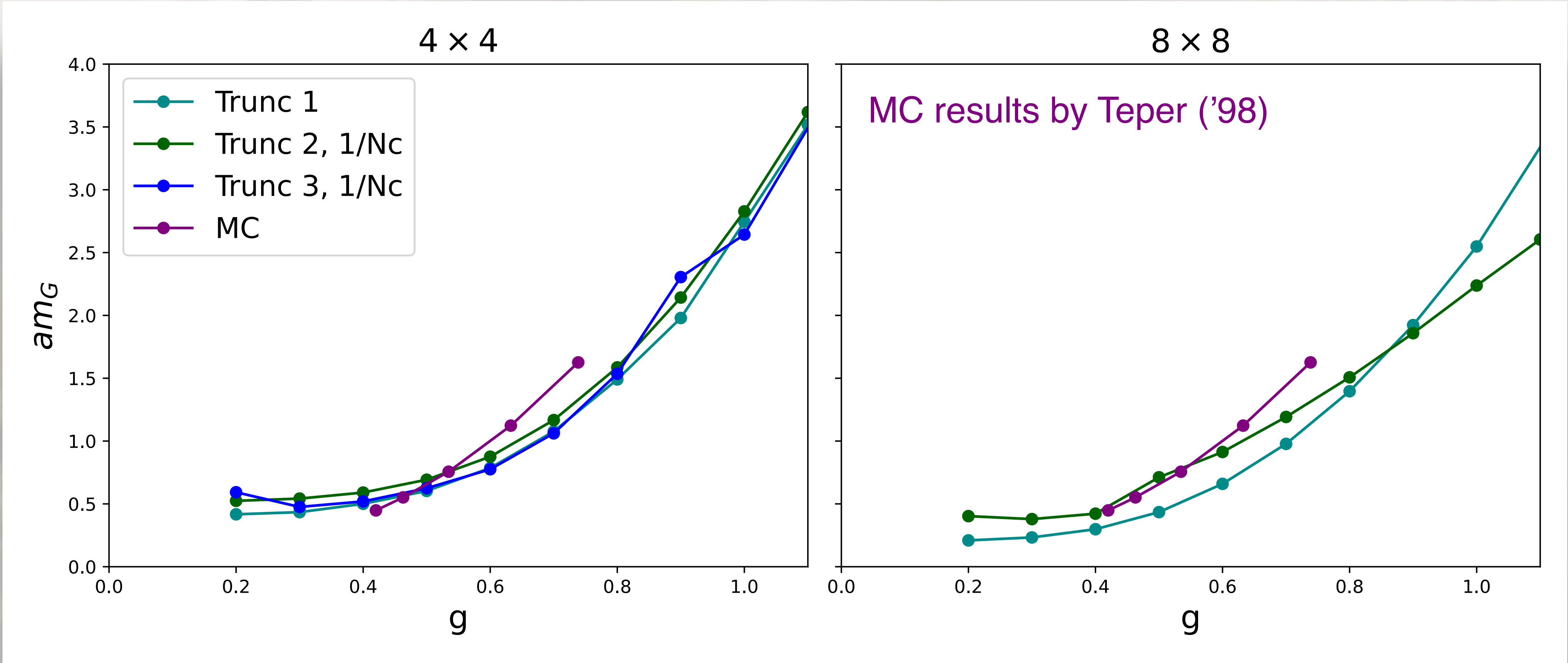


Unexpectedly good convergence and small $1/N_c$ effects.

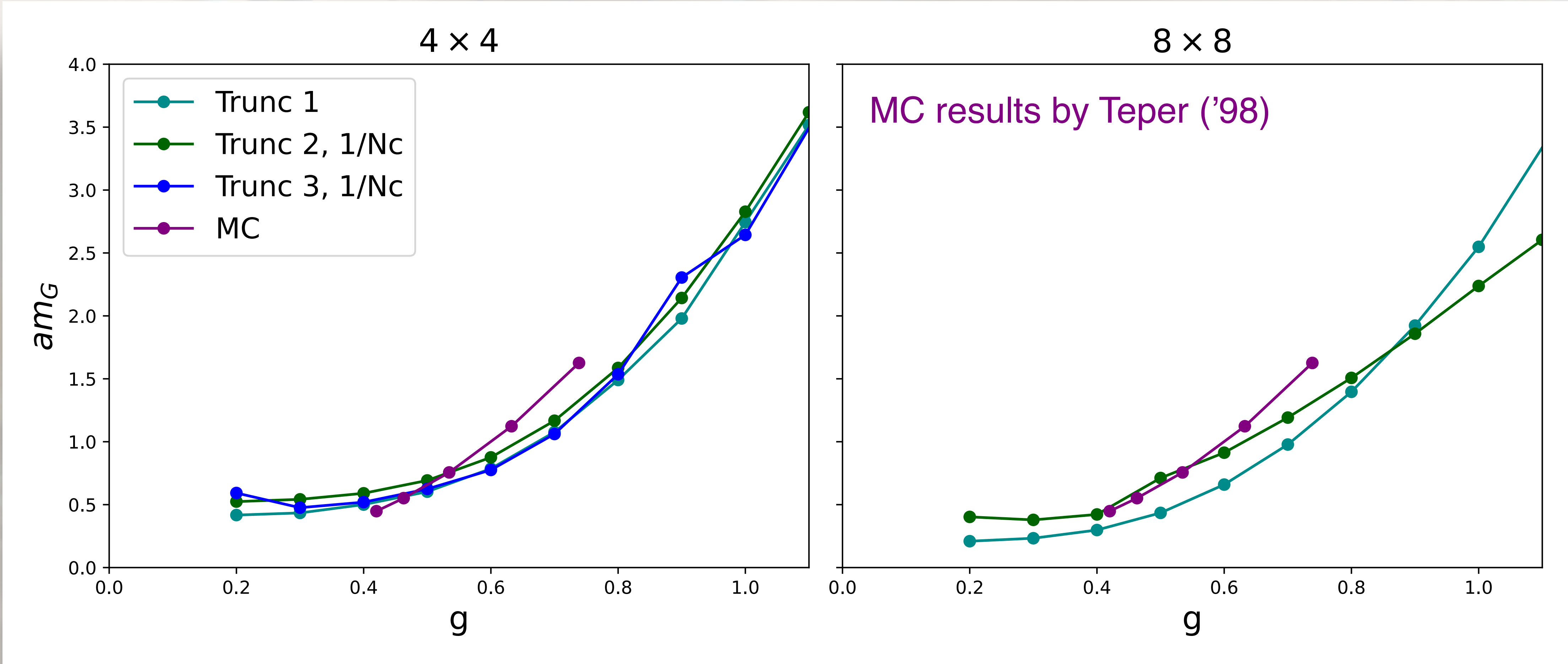
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Surprisingly good agreement with results from traditional MC calculation

Recently, worked out Hamiltonian in $1/N_c$ expansion including fermionic degrees of freedom, getting a big step closer to QCD

Large N_c Truncations for $SU(N_c)$ Lattice Yang-Mills Theory with Fermions

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Quantum simulations of quantum chromodynamics (QCD) require a representation of gauge fields and fermions on the finitely many degrees of freedom available on a quantum computer. We introduce a truncation of lattice QCD coupled to staggered fermions that includes (i) a local Krylov truncation that generates allowed basis states; (ii) a maximum allowed electric energy per link; (iii) a limit on the number of fermions per site; and (iv) a truncation in the large N_c scaling of Hamiltonian matrix elements. Explicit truncated Hamiltonians for $1 + 1D$ and $2 + 1D$ lattices are given, and numerical simulations of string-breaking dynamics are performed.

There are several steps that need to be implemented for a successful simulation of HEP simulations

- Setting up initial state
- Obtaining time-evolution operator
- Measuring interesting observables

The Quantum Complexity of String Breaking in the Schwinger Model

Sebastian Grieninger ^{1,*} Martin J. Savage ^{1,†} and Nikita A. Zemlevskiy ^{1,‡}

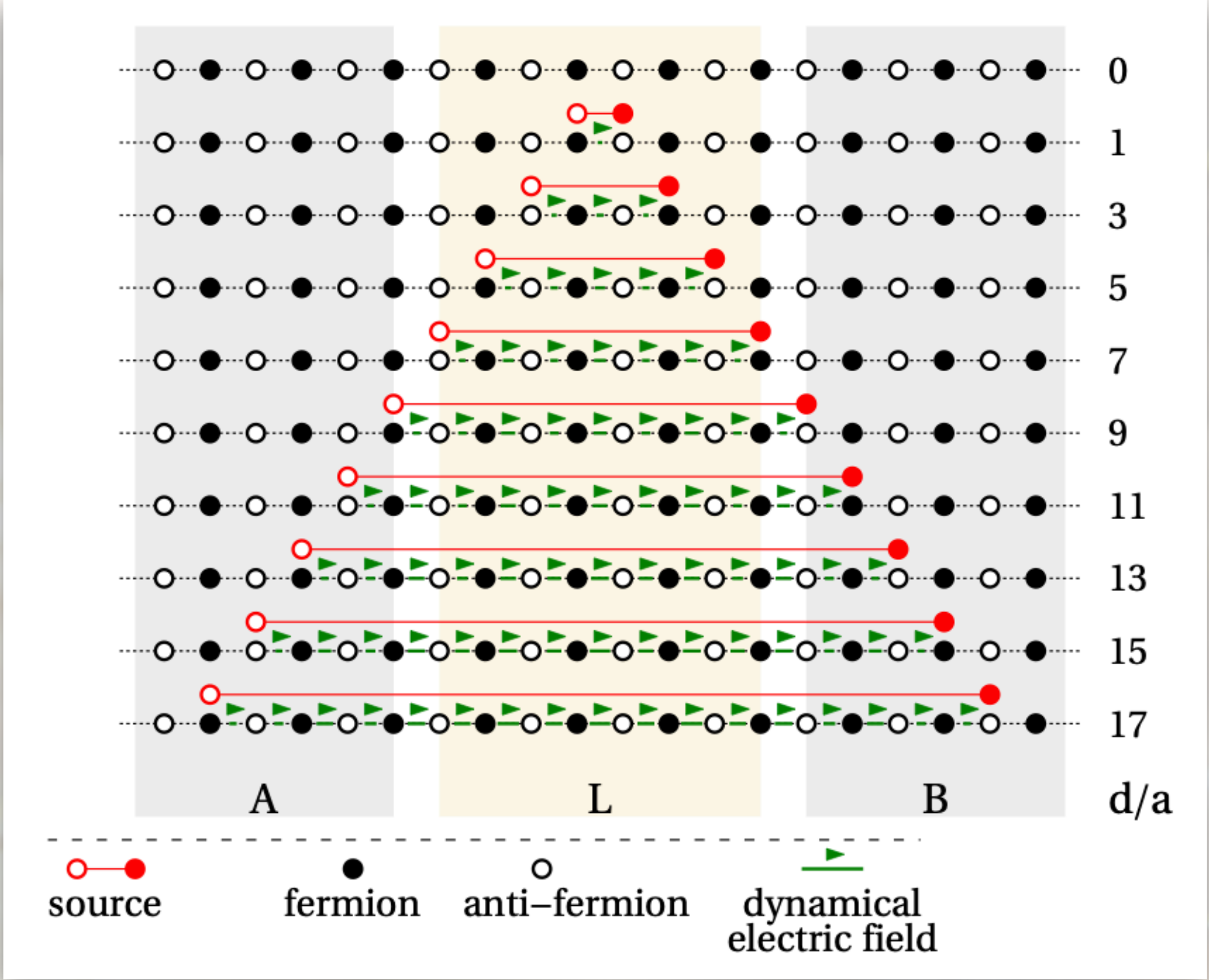
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University of Washington, Seattle, WA 98195, USA*

(Dated: April 15, 2026)

String breaking, the process by which flux tubes fragment into hadronic states, is a hallmark of confinement in strongly-interacting quantum field theories. A suite of quantum complexity measures is examined using Matrix Product States to characterize the string breaking process in the 1+1D Schwinger model. We demonstrate the presence of nonlocal quantum correlations along the string that may affect fragmentation dynamics, and show that entanglement and magic offer complementary perspectives on string formation and breaking beyond conventional observables.

Schwinger model (QED in 1+1D) is often studied theory that exhibit string breaking and confinement, and can be used to understand quantum nature of strings

Setup: obtain ground state of system with static charges and study string that (does or does not) form

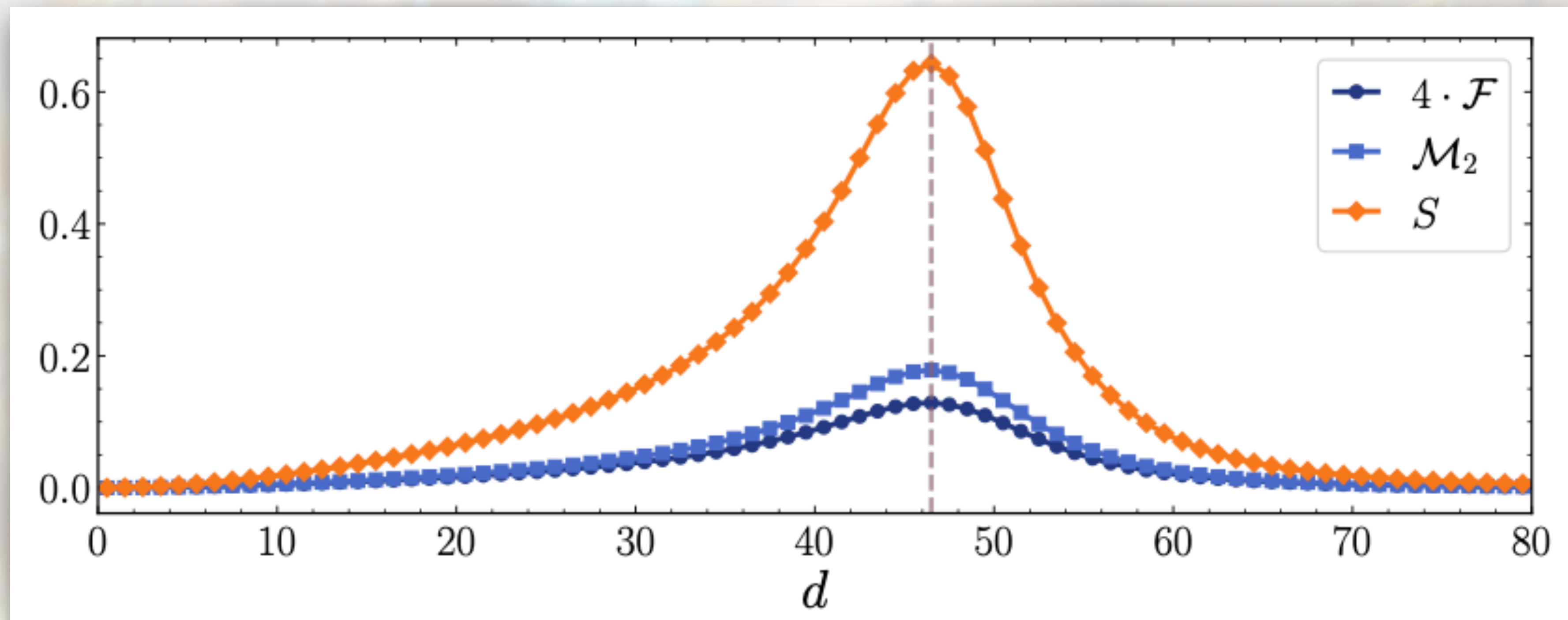


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Quantum correlations in the string start to build up, but are gone once only have isolated hadrons

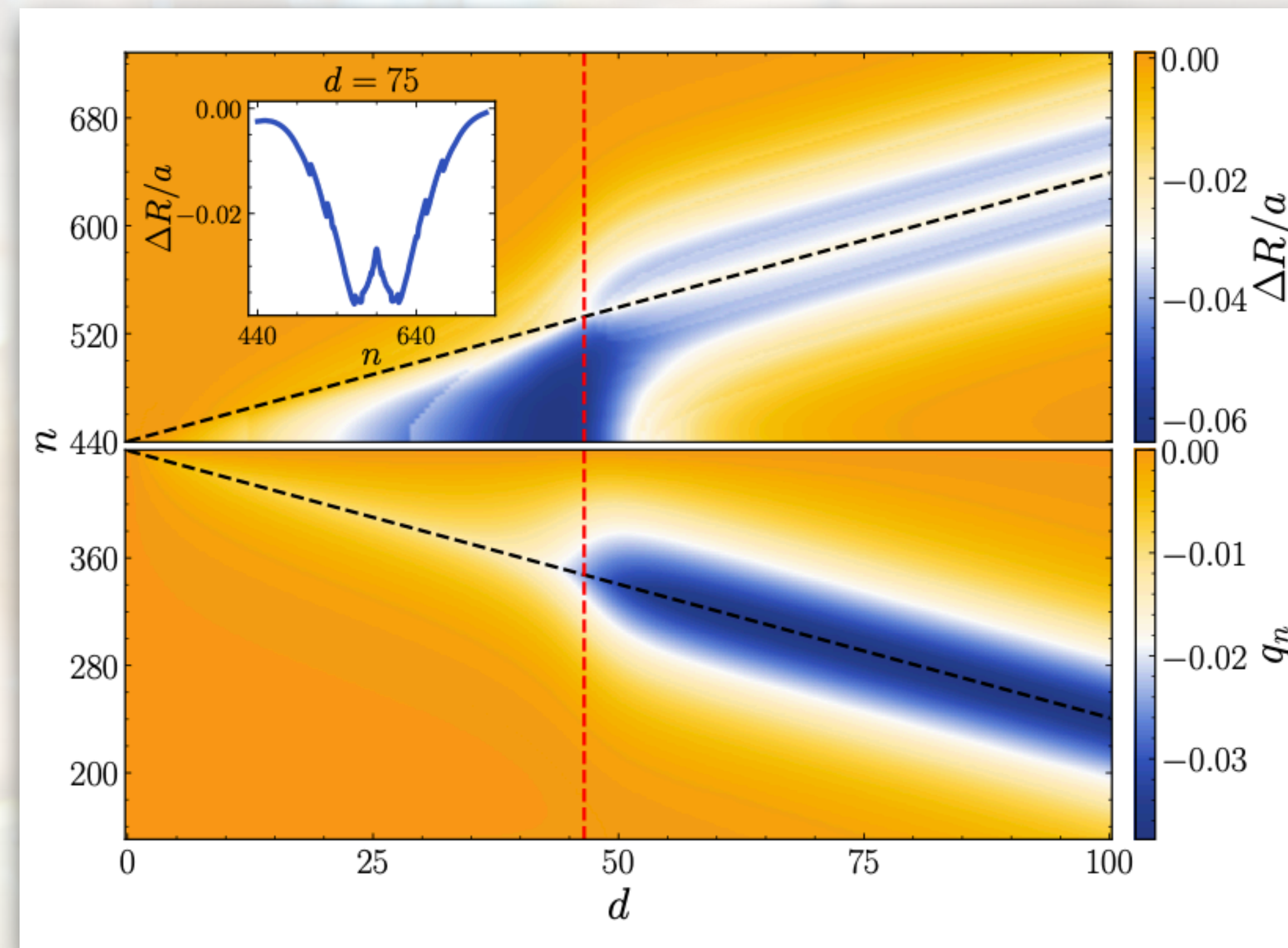


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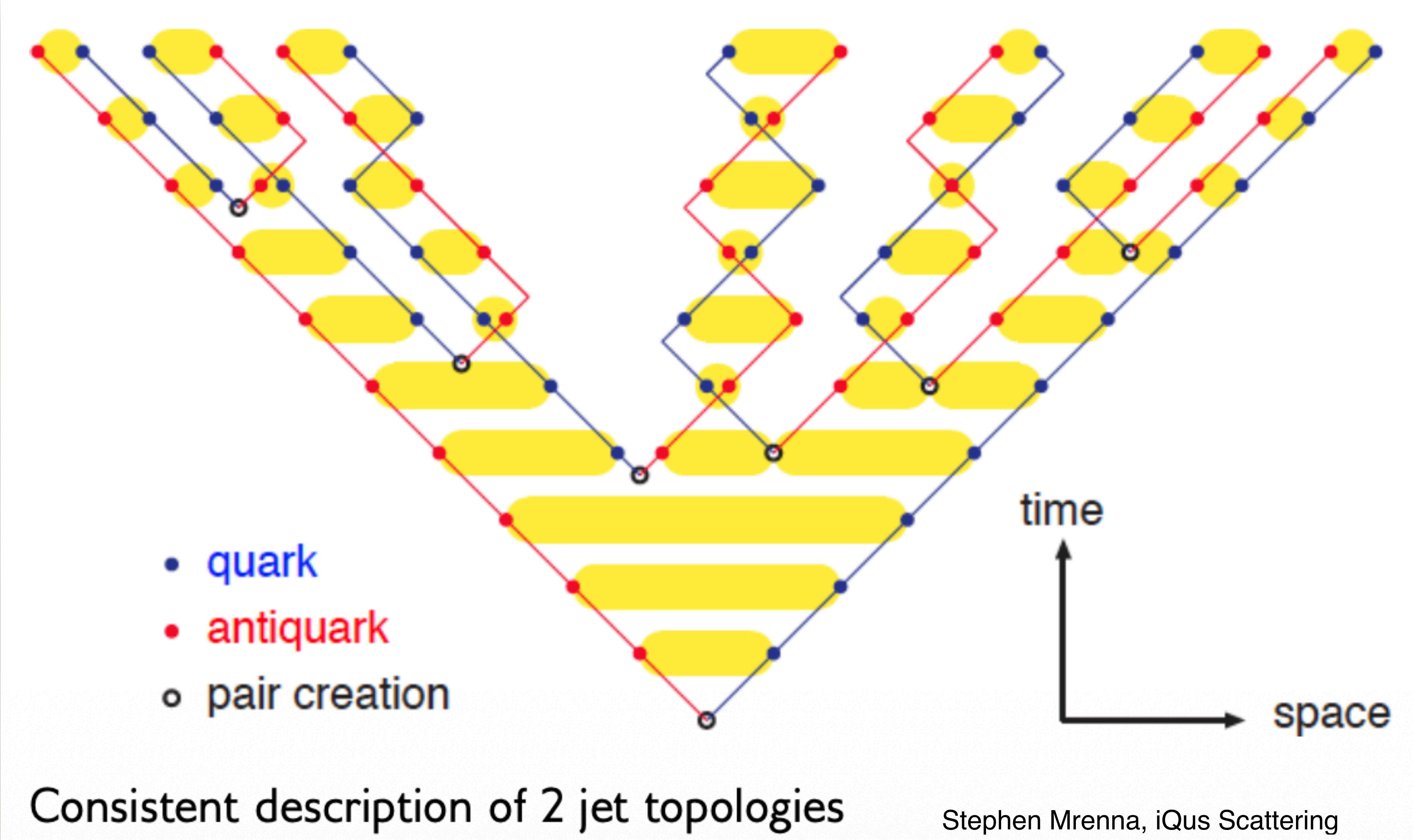
These quantum correlations are such that they are not simulatable using classical techniques (they have large amount of magic)



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Hadronization is currently described by simple classical models based on a probabilistic description of string breaking



Schwinger model (QED in 1+1D) is often studied theory that exhibit string breaking and confinement, and can be used to understand quantum nature of strings

Testing Hadronization Models with Near-Term Quantum Hardware

Principal Investigator

Christian W. Bauer, Senior Scientist

Senior / Key Personnel

LBNL: Christian Bauer (Senior Scientist)

University of Washington: Martin Savage (Professor of Physics)

Hypothesis: Near-term quantum hardware can be used to simulate the dynamics of hadronization and fragmentation in QCD and make predictions for exclusive particle level observables, similar to those that can be obtained with parton shower algorithms. The hypothesis further states that these predictions can be made with controlled systematic uncertainties small enough to use these simulations to test and possibly improve hadronization models used in current event generators. Finally, similar predictions are possible for confining gauge theories different from QCD, in particular those that might describe hadronization in strongly interacting dark sector models.

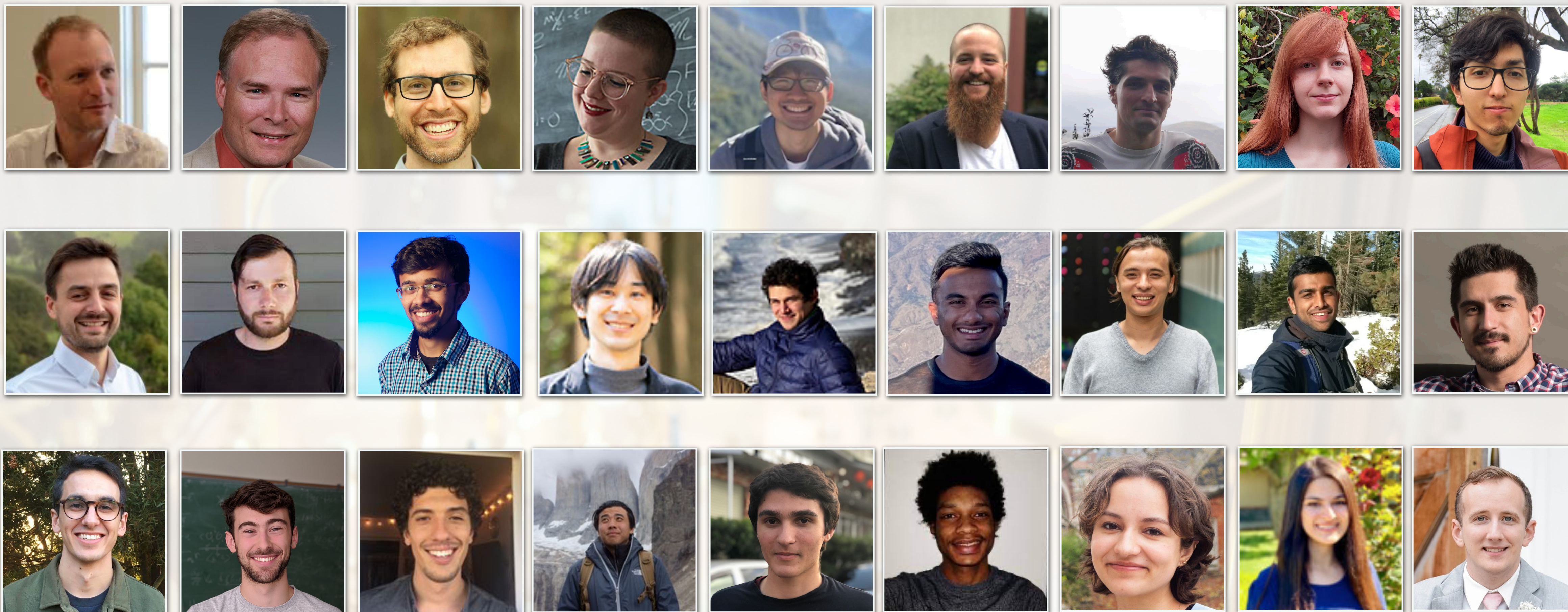
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There are many outstanding problems that are both interesting theoretically and can make significant impact

- ◆ Formulate more efficient or accurate Hamiltonians
- ◆ Develop protocols for systematic uncertainties (truncation, finite lattice spacing, lattice volume, trotter errors etc)
- ◆ Think about best ways to utilize new tool to advance our scientific goals
- ◆ All of you have right skills to make strong contributions to this exciting field

Talk to me if you are interested in joining



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