1-D Steps Toward Digital Quantum Simulations of Standard Model Physics

- some of our recent results

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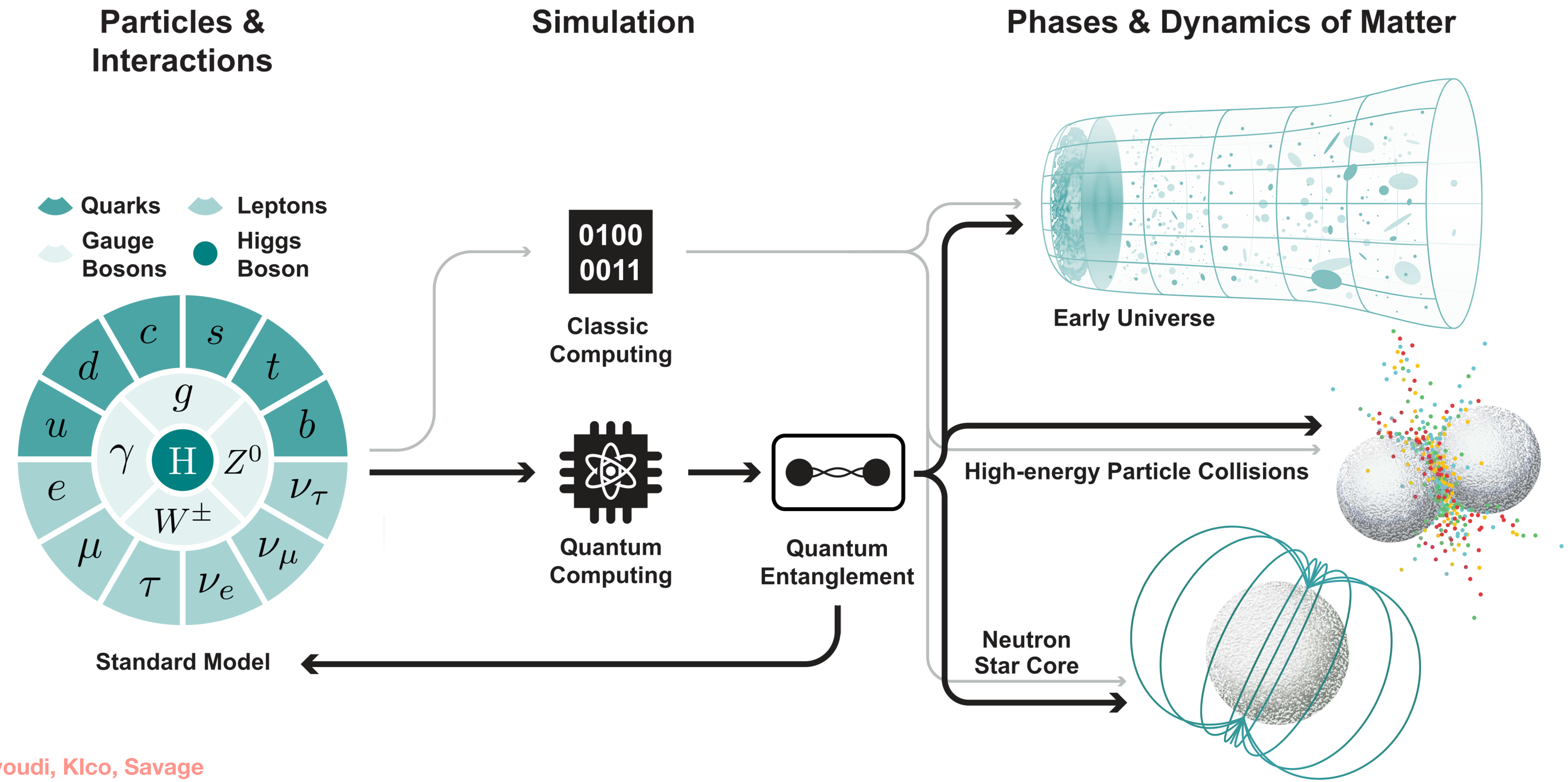
June 6, 2023

Simulating Physics with Computers

Richard P. Feynman

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

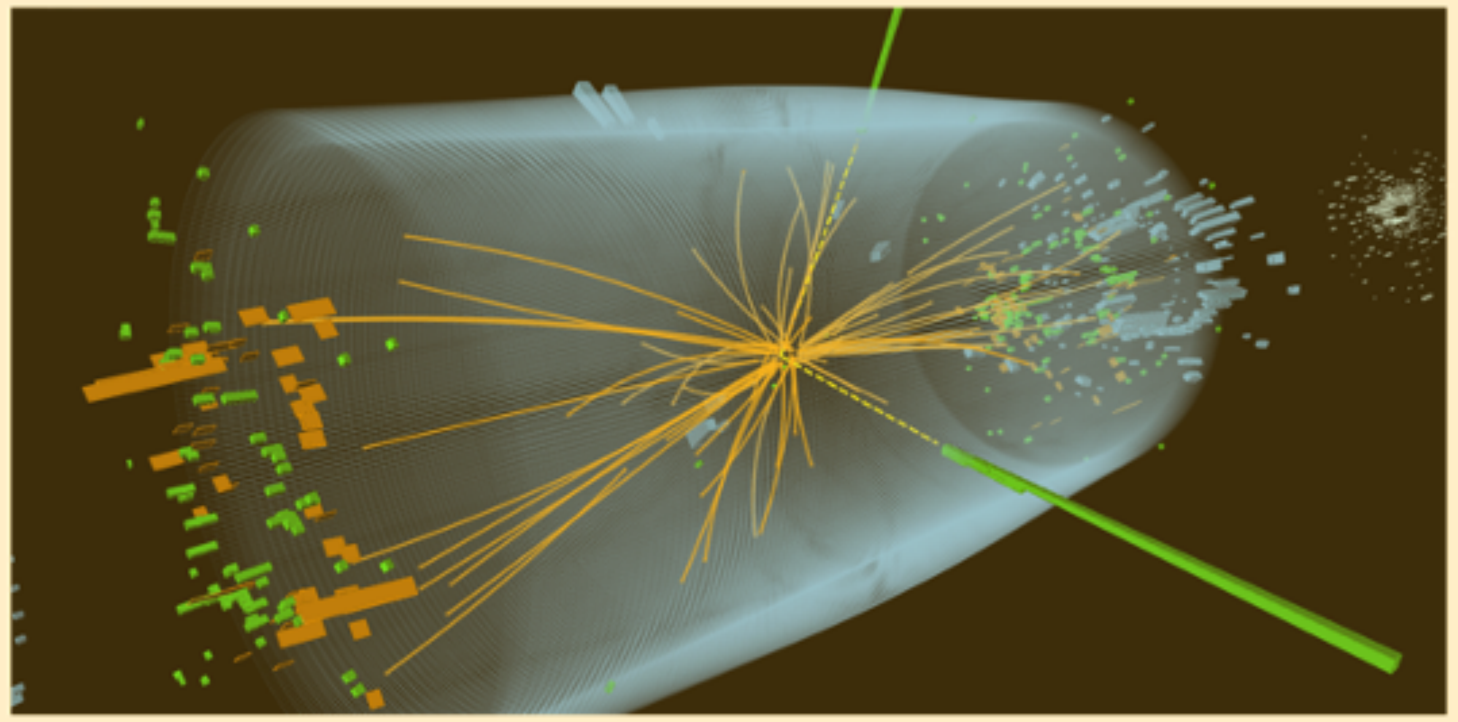
Received May 7, 1981



Bauer, Davoudi, Klco, Savage

Simulation Objectives for the Standard Model and Beyond

Gauge Theories and Descendent Effective Field Theories and Models



Real-time dynamics
particle production, fragmentation
vacuum and in medium

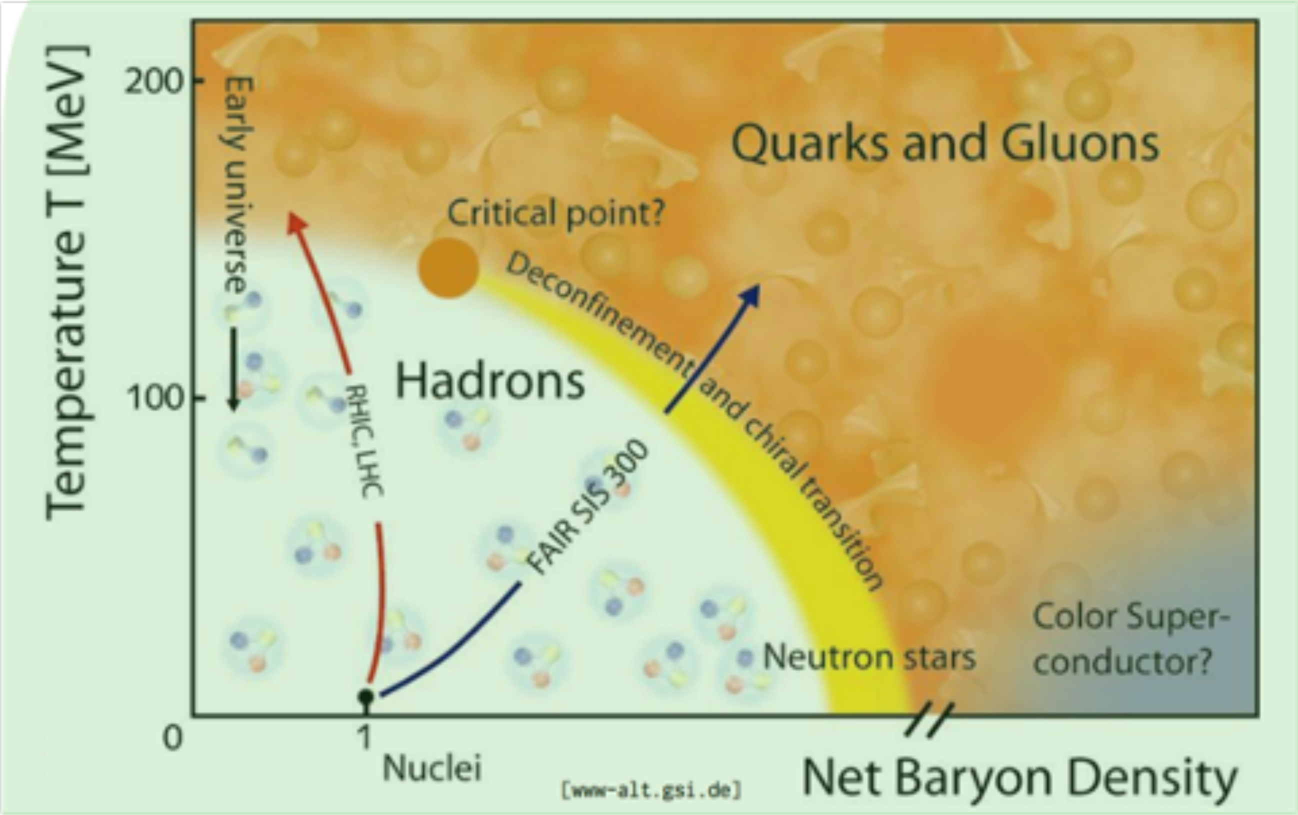
Low-energy reactions

Electroweak processes (e.g., nu-A)

Neutrino dynamics

Matter-antimatter asymmetry

BQP

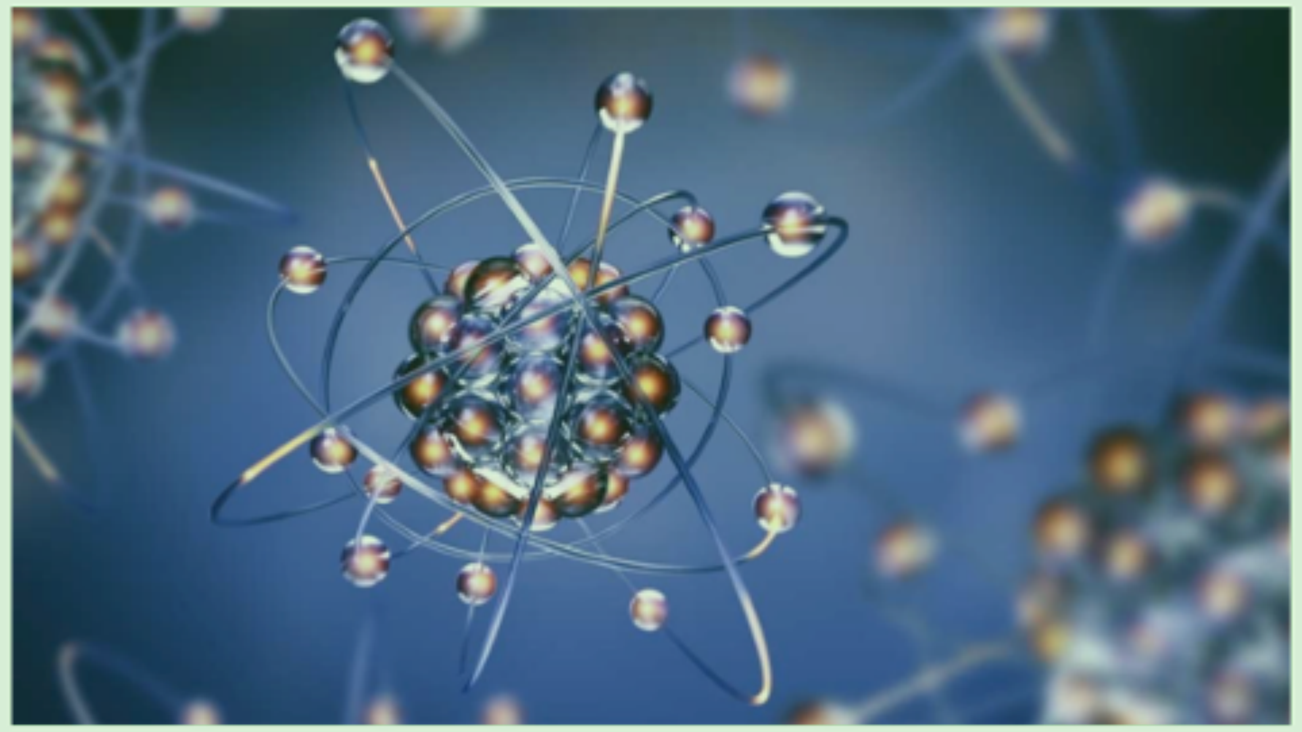


Equation of state of dense
hot matter and dynamics
viscosity, etc

Conquering some "sign problems"

The early universe

Supernova/Neutron stars



Precision structure and interactions
of nuclei

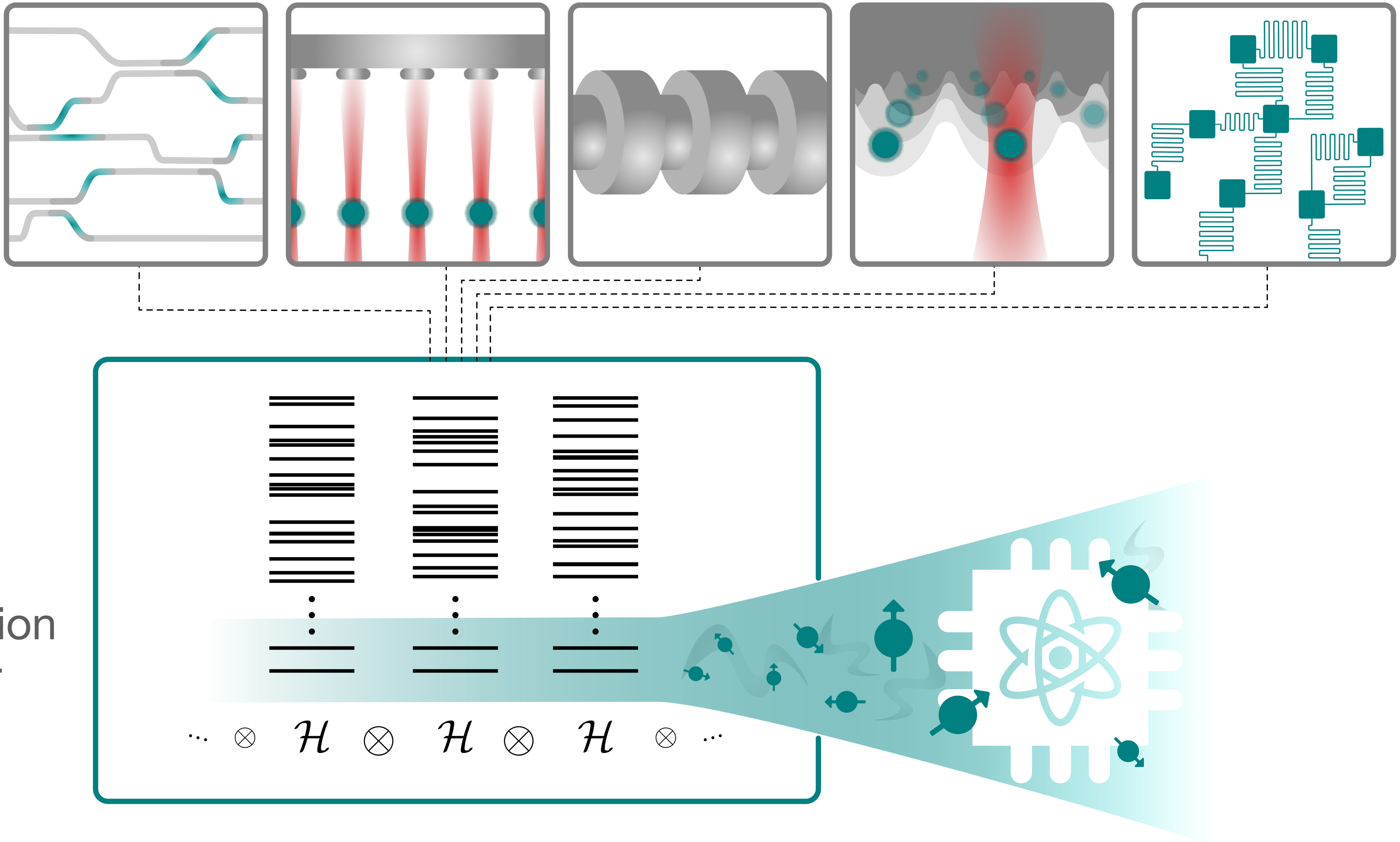
Many-body systems

Rare processes, double-beta decay

QMA

– symmetries

Physical Systems in Multi-Hilbert Space, Hybrid Devices



Map scalar, fermion and vector systems

Optimize for target observables

Minimize time-to-solution within a specified error

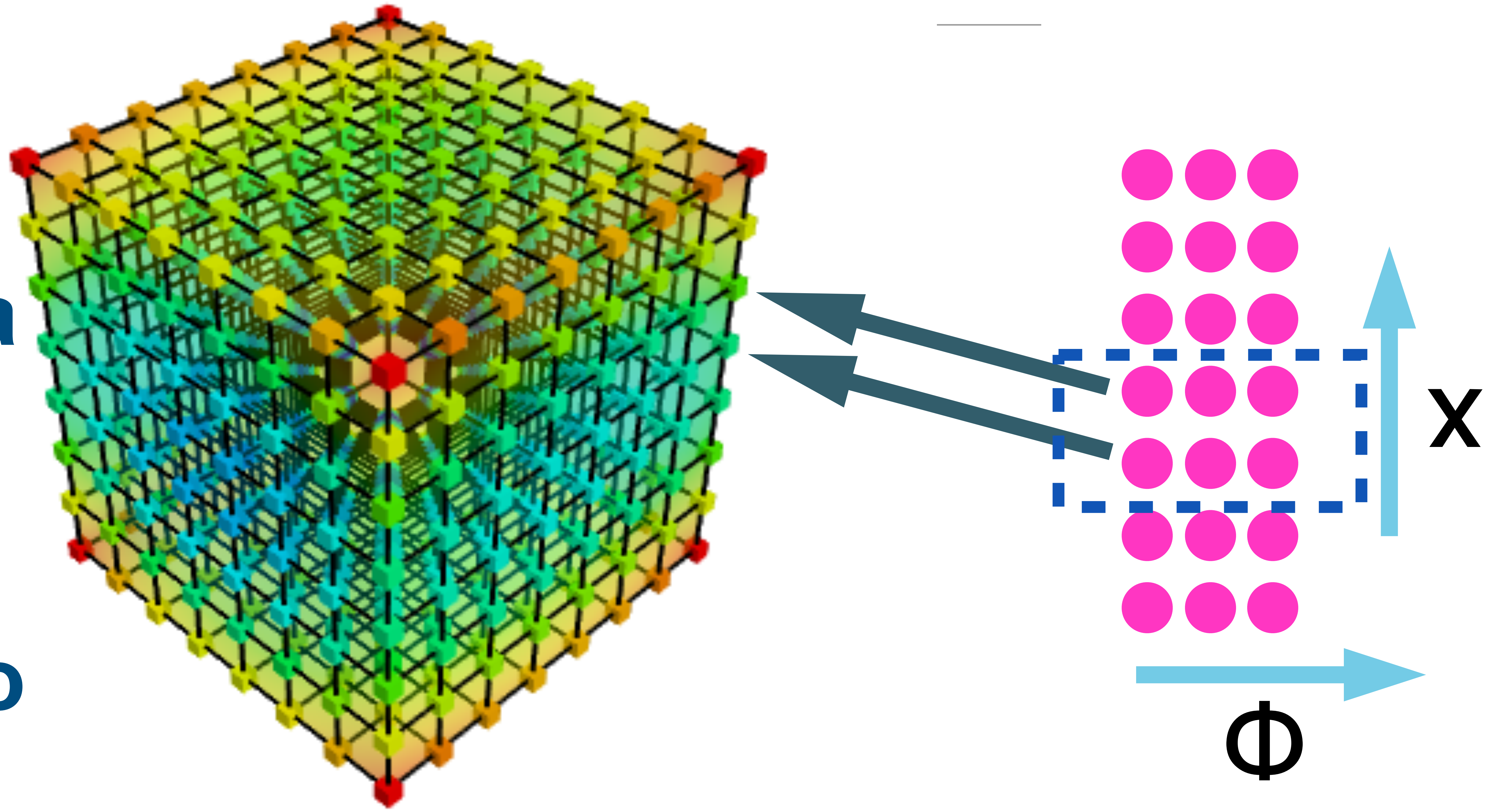
Bauer, Davoudi, Klco, Savage

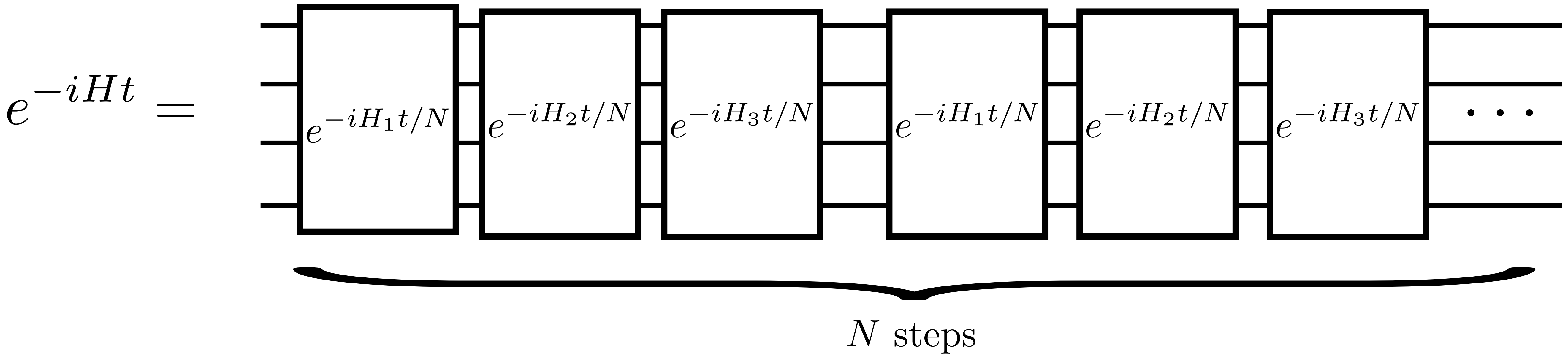
Digital To-Do List for Quantum Chromodynamics

1. **Map quarks and gluons on a quantum register of qubits, qutrits, …**

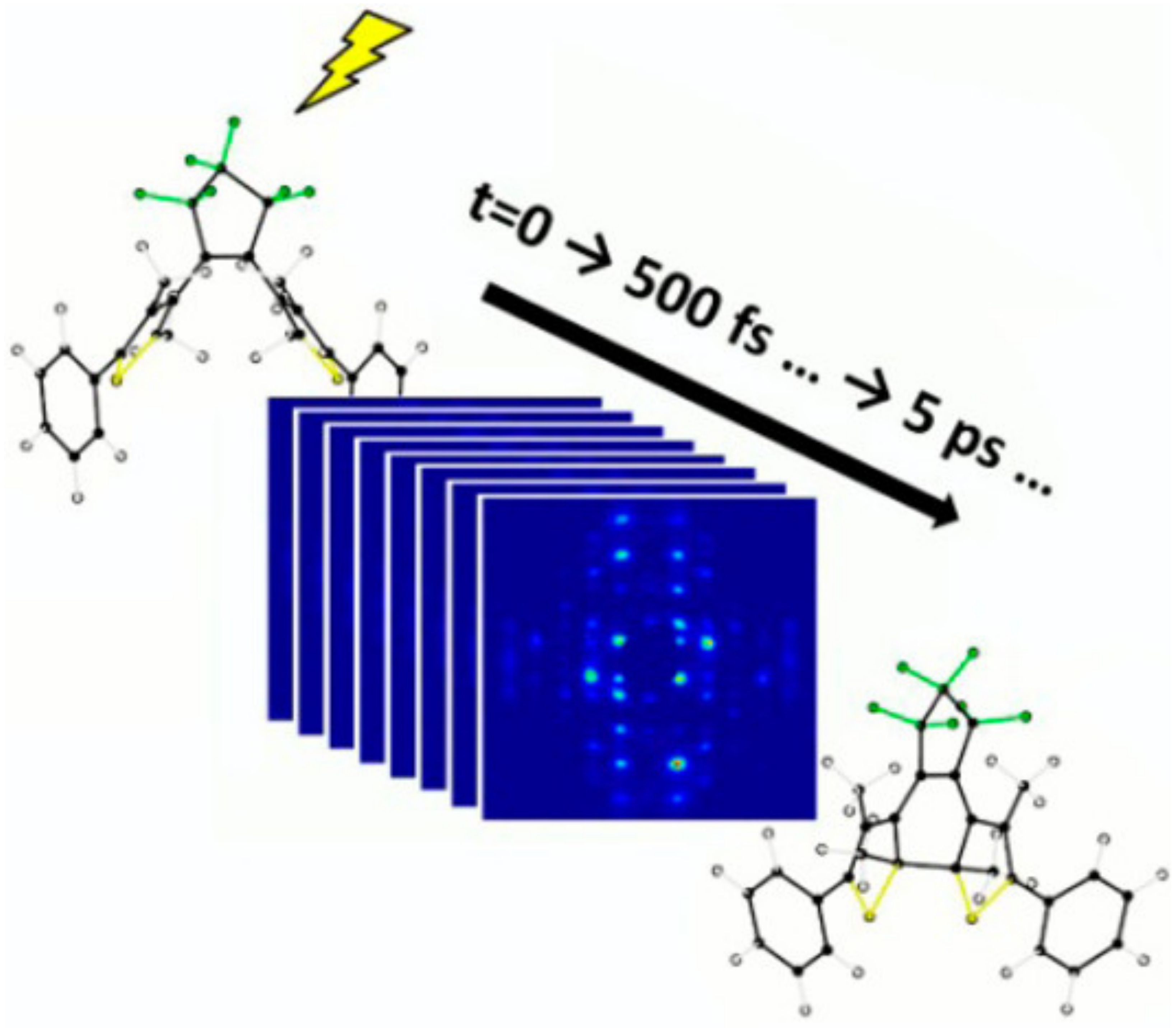
2. **Develop unitary operators to evolve initial wavefunctions forward in time**

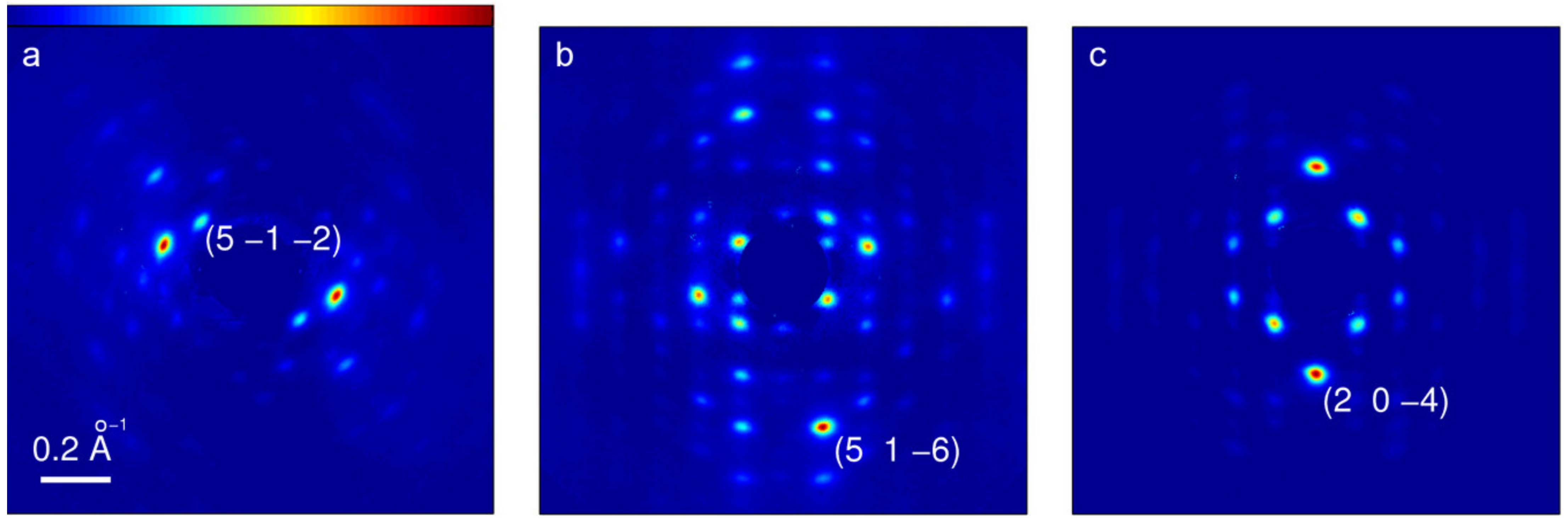
3. **Develop observables**





Real-Time Dynamics and Improved modeling of Reaction Pathways





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

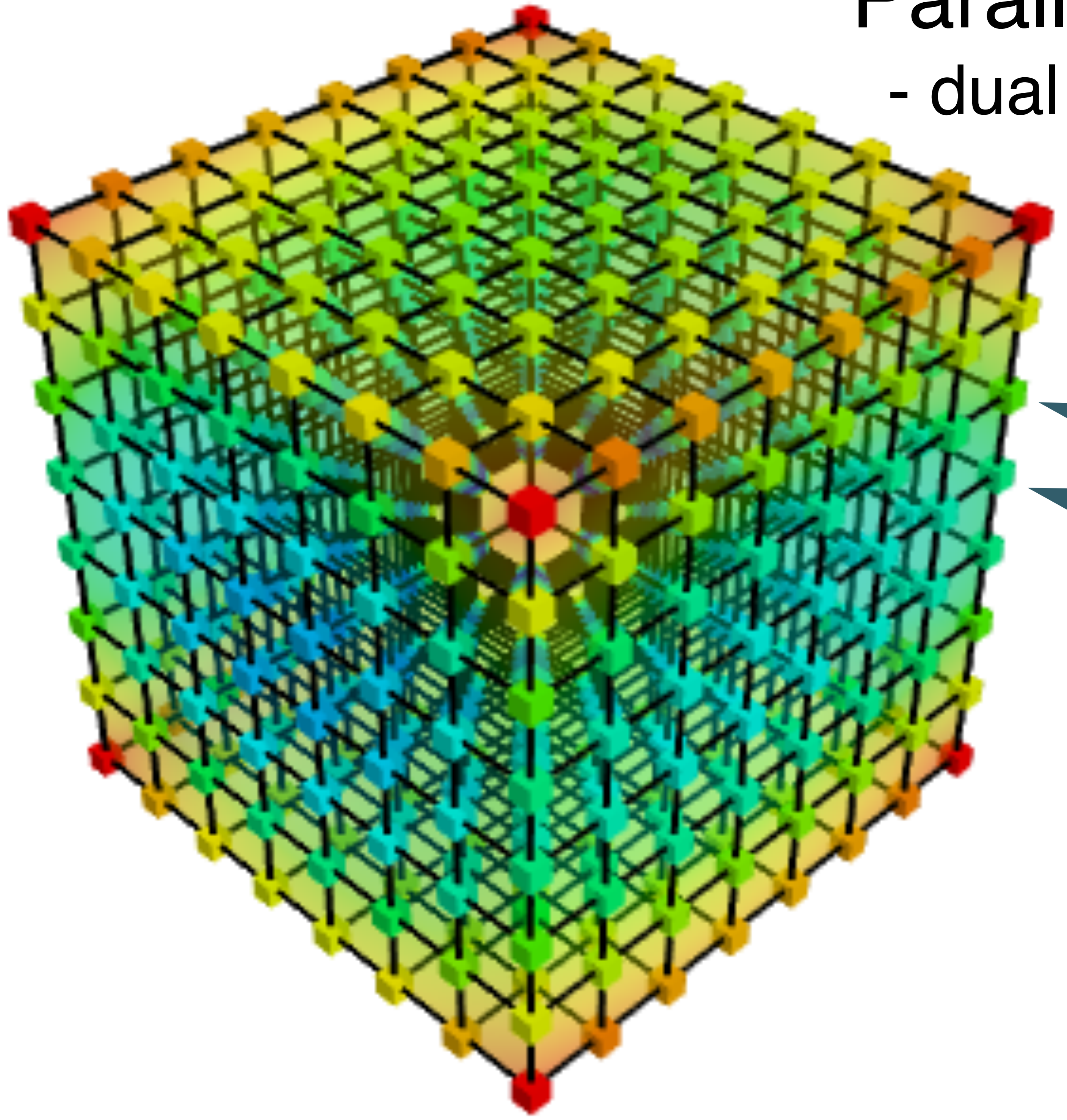
Femto-second chemistry reveals reaction mechanisms
Quantum simulations will reveal the reactions pathways of QCD

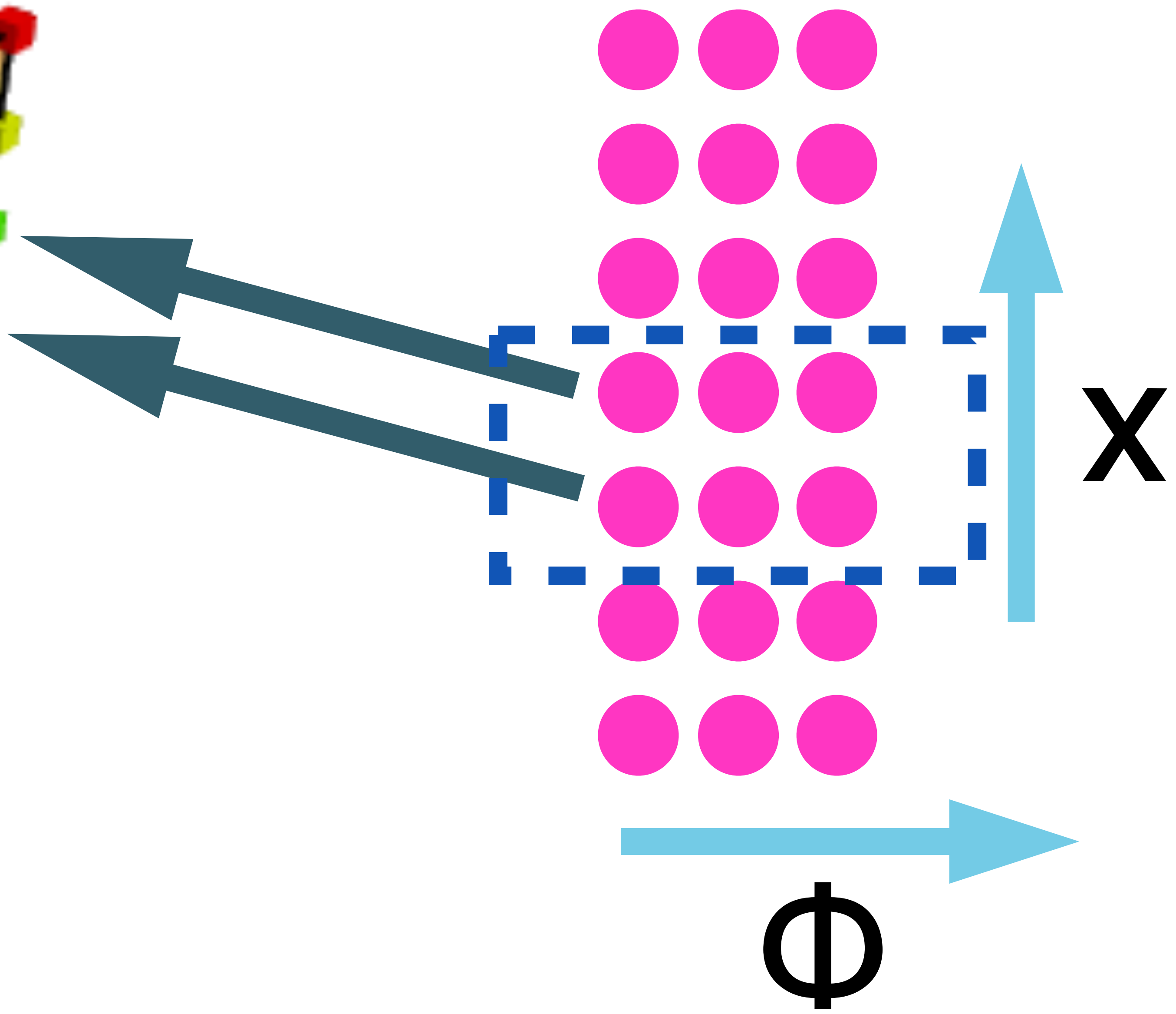
Gold-Standard for QFT
Can entanglement be used more strategically?

Jordan, Lee, Preskill

Scalar field theory is BQP-complete

Parallelizes easily at the circuit level
- dual layer application per Trotter step





Could it be done better ?
Can entanglement be used strategically?

Double exponential convergence of field digitization
- Nyquist-Shannon - JLP, FNAL, UW
- QFT and exact conjugate-momentum space operator

Lattice Gauge Field Theories and the Standard Model

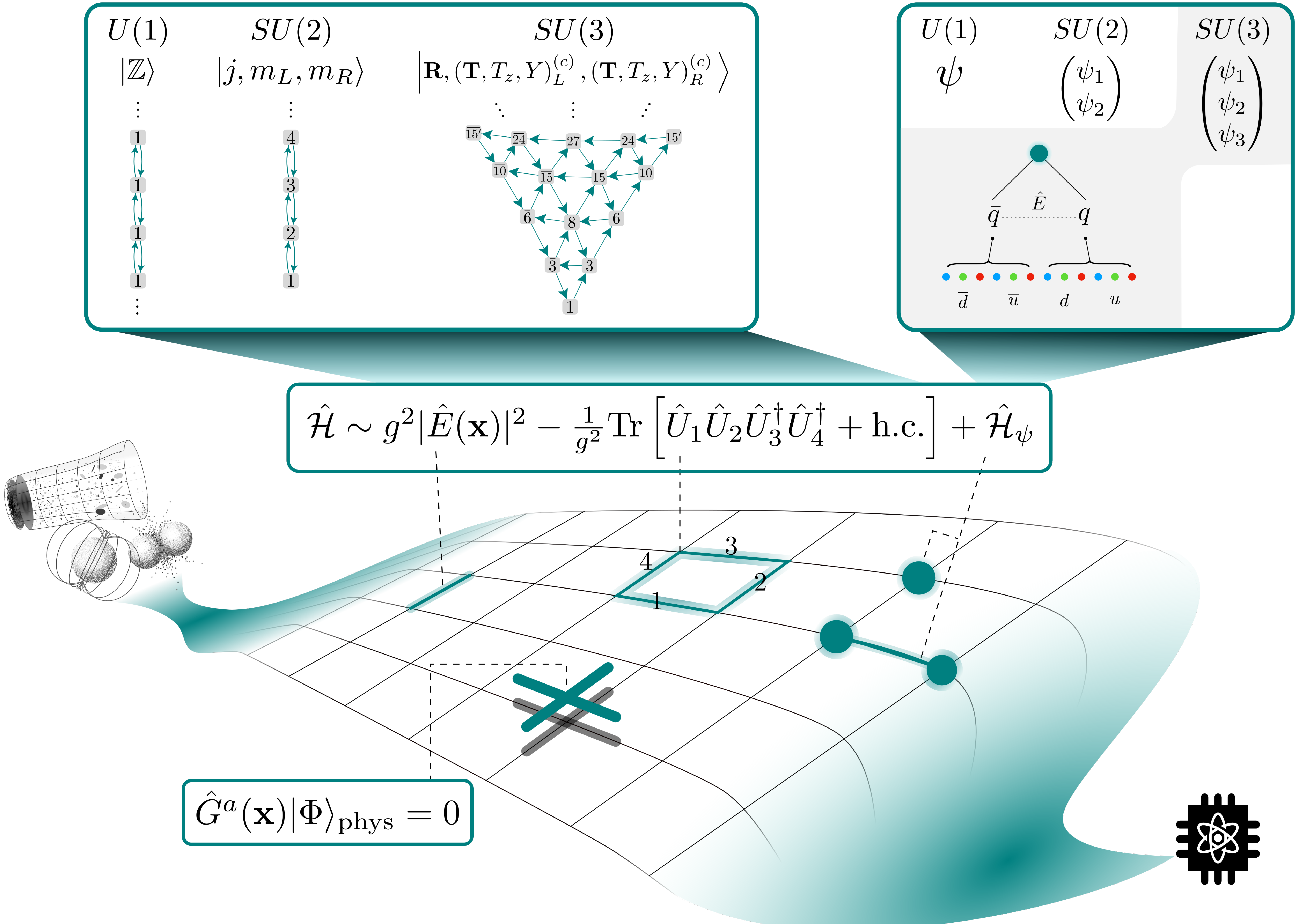
Hamiltonian: Kogut-Susskind
1970’s

Yang-Mills: Byrnes-Yamamoto
2005

SU(N): Zohar et al
(2013)

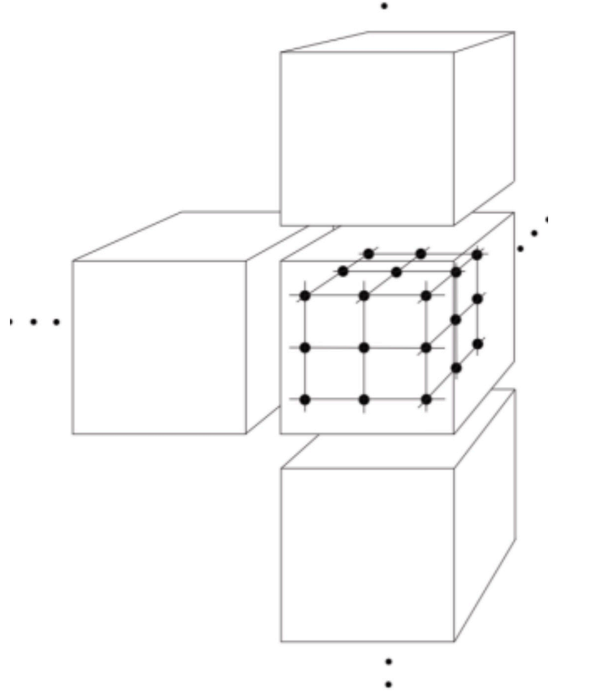
QLM: Banerjee et al
Tagliacozzo et al
(2013)

First Quantum Simulation:
Innesbruck, 4 Trapped Ions
(2016)



Bauer, Davoudi, Klco, Savage

Yang-Mills
Byrnes-Yamamoto — Kogut-Susskind



Many valid ways to distribute fields in the UV with same IR physics
e.g., Kogut-Susskind basis = electric basis

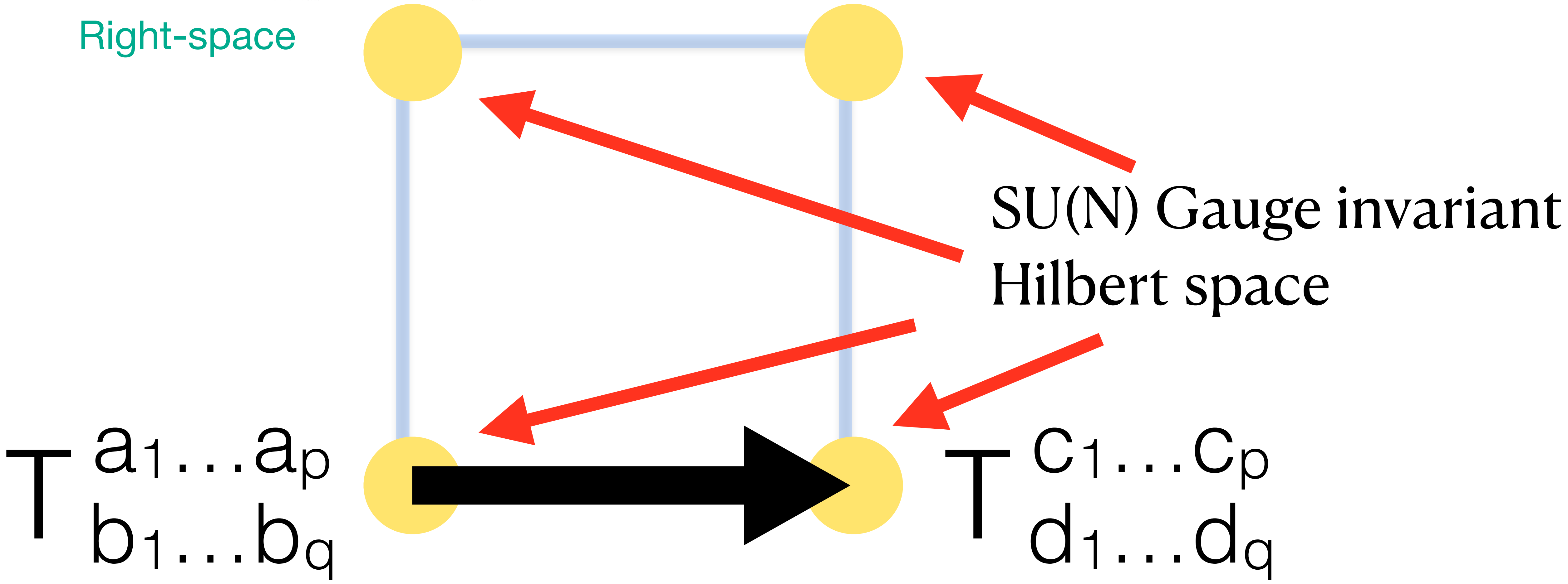
$$\hat{H} = \frac{g^2}{2}\sum_{\text{links}} \hat{E}^2 - \frac{1}{2g^2}\sum_{\Box}\left(\hat{\Box} + \hat{\Box}^\dagger\right)$$

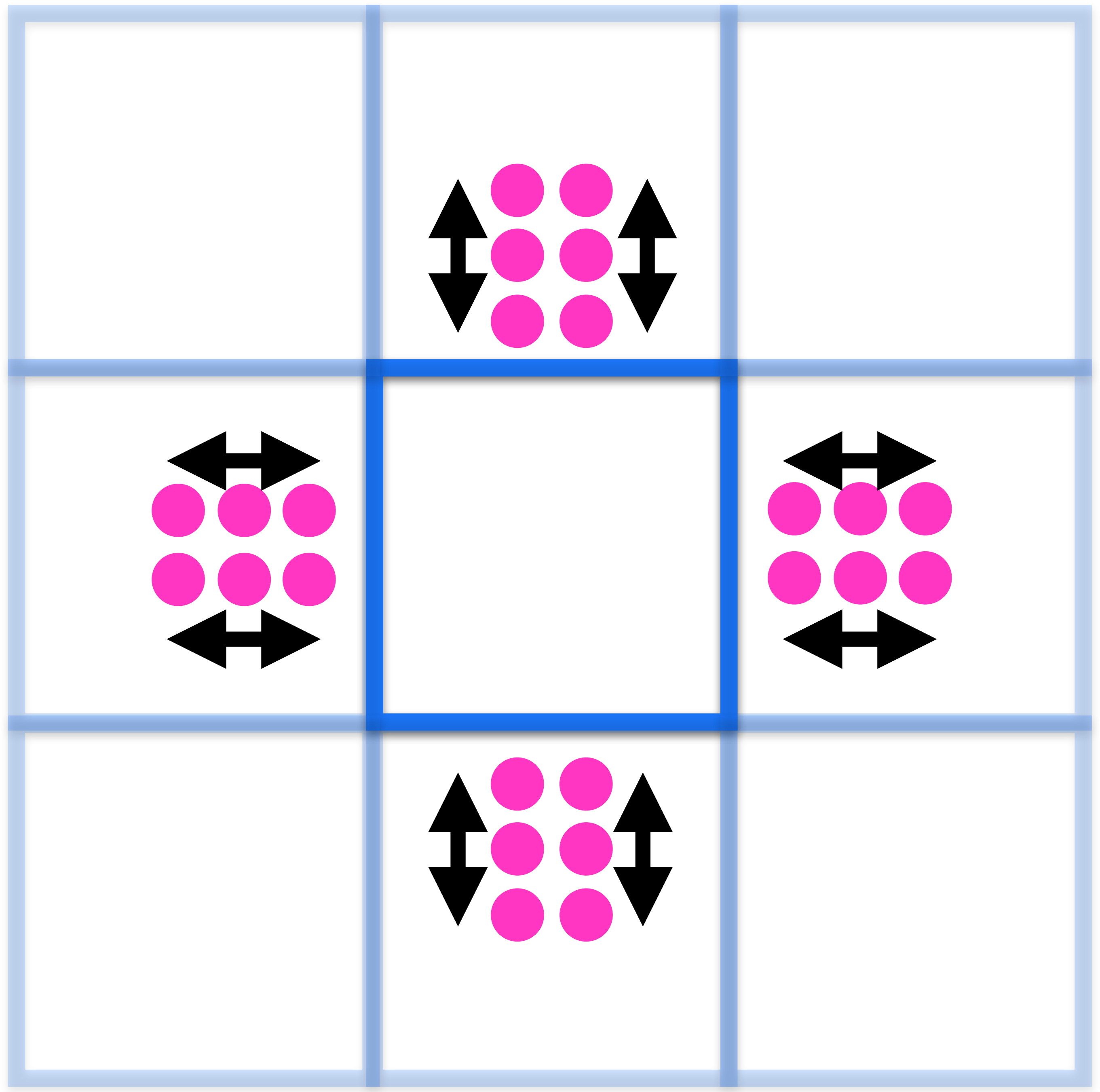
Electric Field Casimir operator

$|p, q, T_L, T_L^z, Y_L, T_R, T_R^z, Y_R\rangle$

Left-space　　Right-space

Magnetic Field operator
Off-diagonal on electric basis





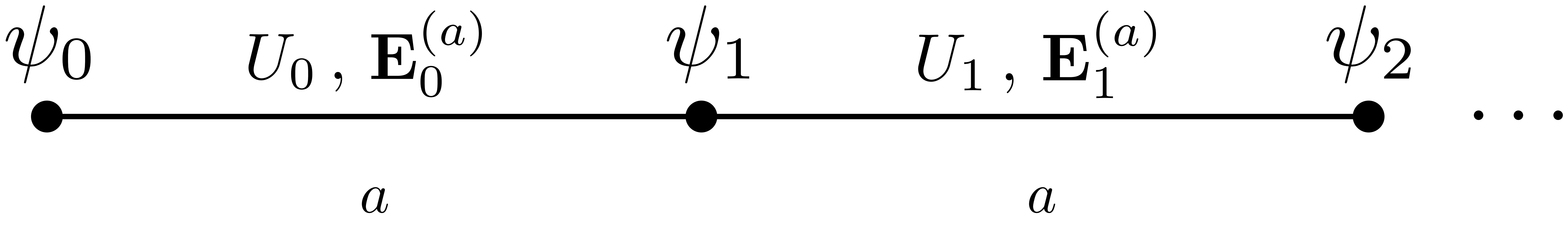
Truncate in Casimir
= dimensionality of irrep

Continuum limit

Lattice Hamiltonian for two-flavor QCD in 1+1D
A_0=0 Weyl Gauge

Lattice spacing = a

Formal : Banuls, Cirac, Jansen, ….



Staggered Lattice of size $2L$ with (anti)quarks on (odd) even numbered sites

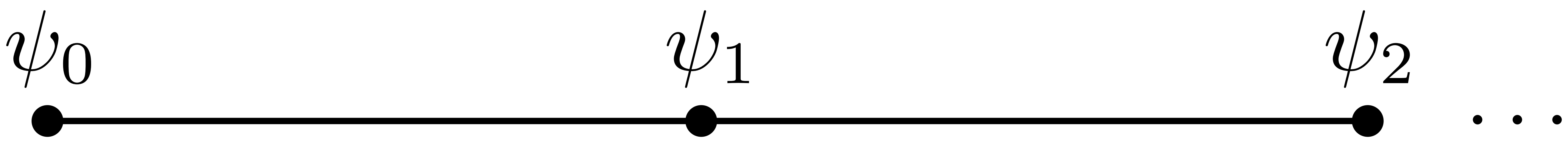
$$H_{\mathrm{KS}} = \sum_{f=u,d}\left[\frac{1}{2a}\sum_{n=0}^{2L-2}\left(\psi_n^{(f)\dagger}U_n\psi_{n+1}^{(f)}\ +\ \mathrm{h.c.}\right) + m_f\sum_{n=0}^{2L-1}(-1)^n\psi_n^{(f)\dagger}\psi_n^{(f)}\right] + \frac{ag^2}{2}\sum_{n=0}^{2L-2}\sum_{a=1}^{8}|\mathbf{E}_n^{(a)}|^2$$

Quark Kinetic Term (Hopping) | Quark Mass Term | Chromo-electric energy

Explicit degrees of freedom (qubits) for gauge fields
- locally constrained by Gauss's law

Lattice Hamiltonian for two-flavor QCD in 1+1D
A_x=0 Axial Gauge

$$V_{\rm QCD} \sim g^2 \sum_{a=1}^{8} Q_0^{(a)} Q_2^{(a)}$$



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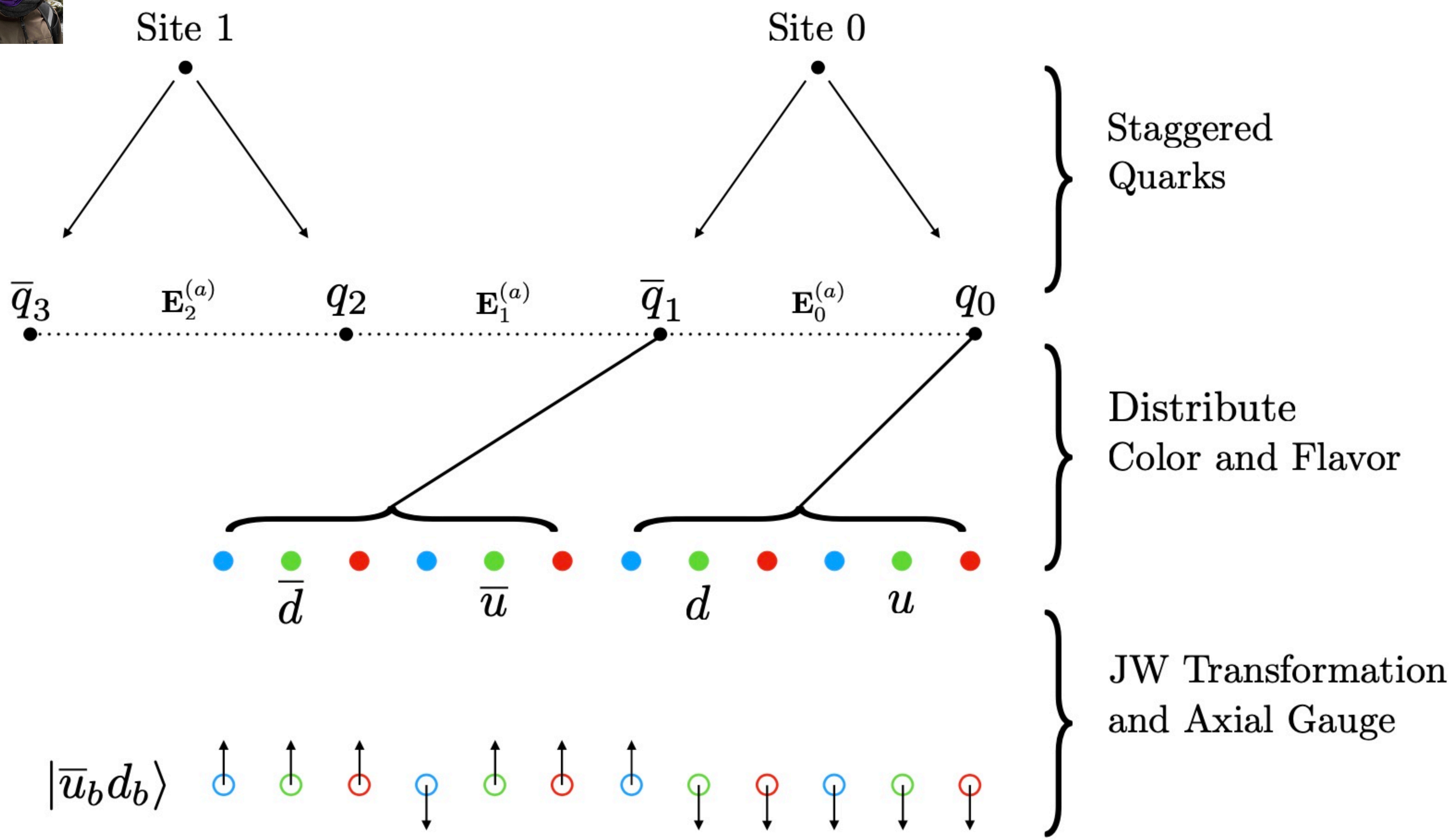
Quark Kinetic Term (Hopping) | Quark Mass Term | Chromo-electric energy

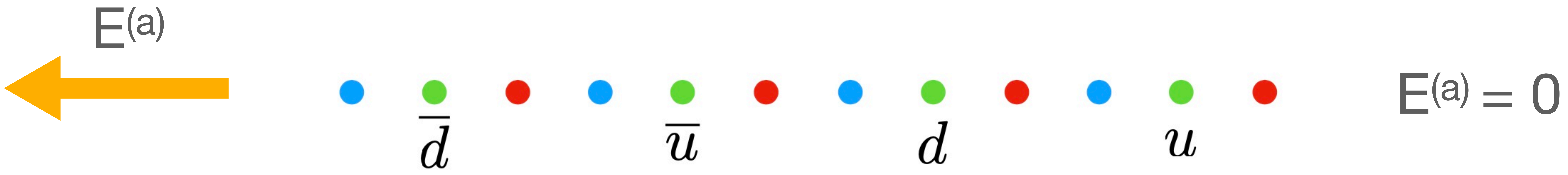
$Q^{(a)}$ have diagonal and also off-diagonal action in color space

Entangles in color space - distinct from QED

Simulations using IBM's Quantum Computers
1+1D QCD



Color Edge States

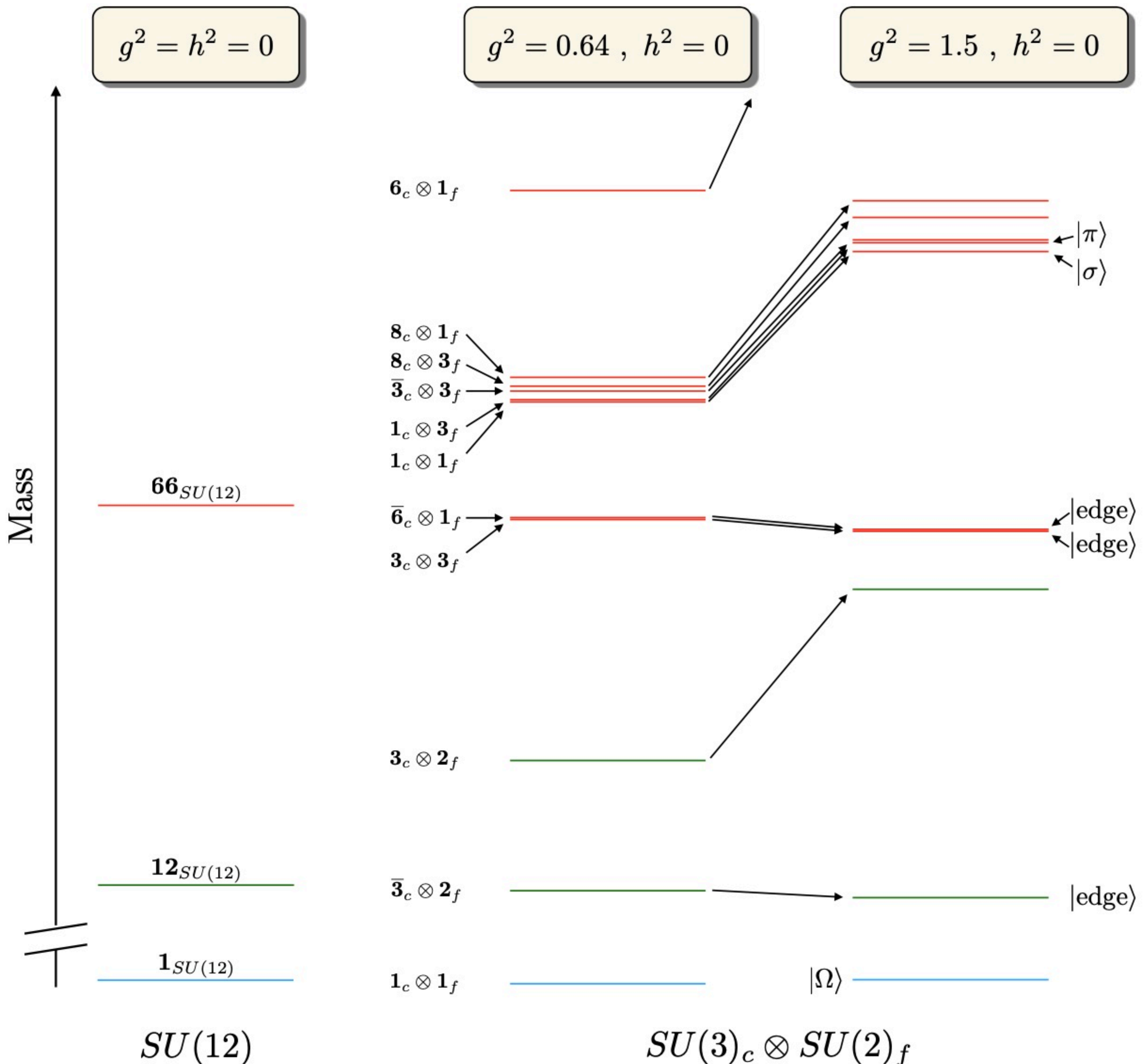


OBCs support color-edge states

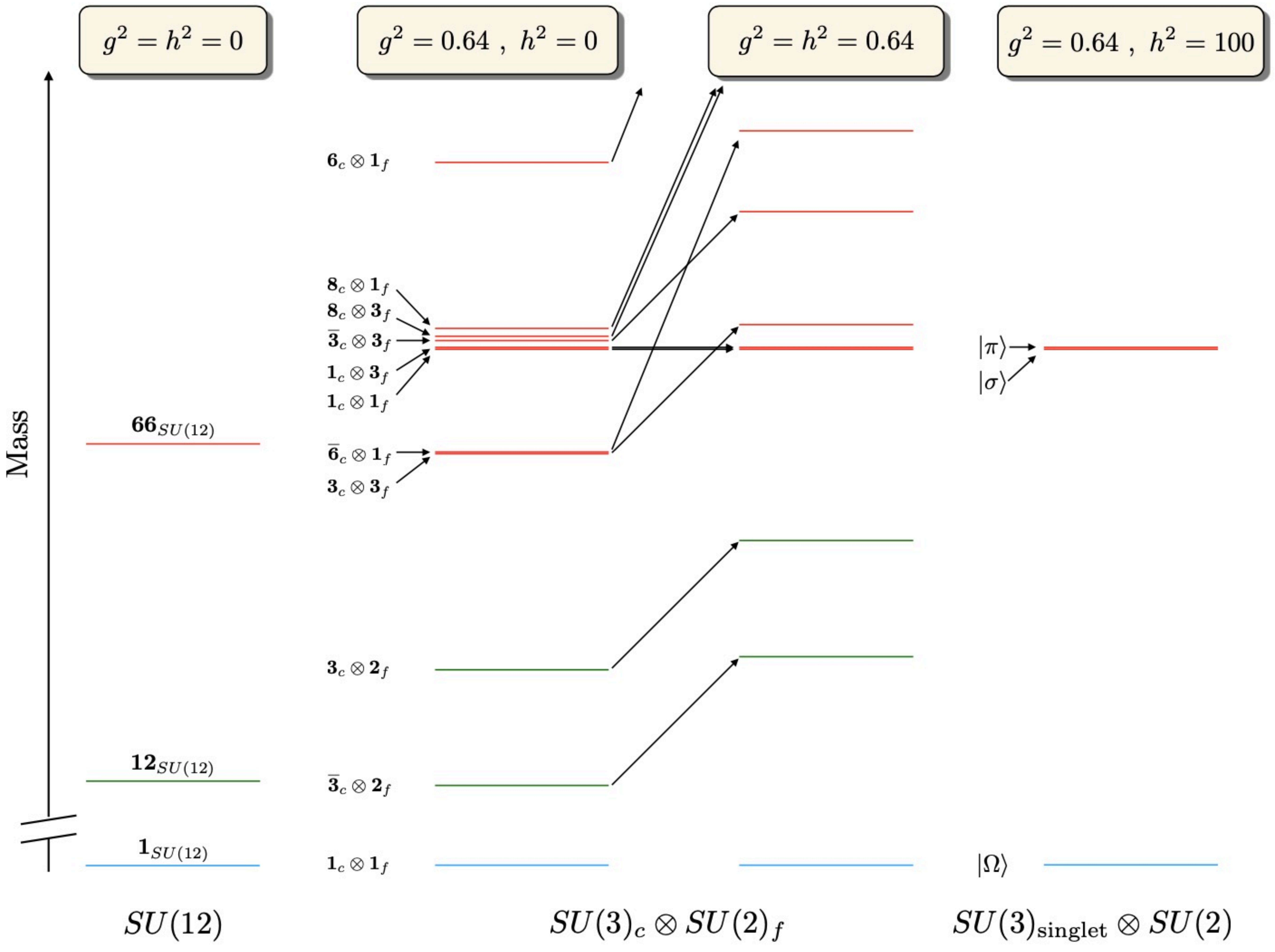
$$H_1 = \frac{h^2}{2} \sum_{n=0}^{2L-1} \left(\sum_{f=0}^{1} Q_{n,f}^{(a)} Q_{n,f}^{(a)} + 2Q_{n,0}^{(a)} Q_{n,1}^{(a)} \right) + h^2 \sum_{n=0}^{2L-2} \sum_{m=n+1}^{2L-1} \sum_{f=0}^{1} \sum_{f'=0}^{1} Q_{n,f}^{(a)} Q_{m,f'}^{(a)}$$

Low-Lying Spectra

The Low-lying Spectrum for $L = 1$

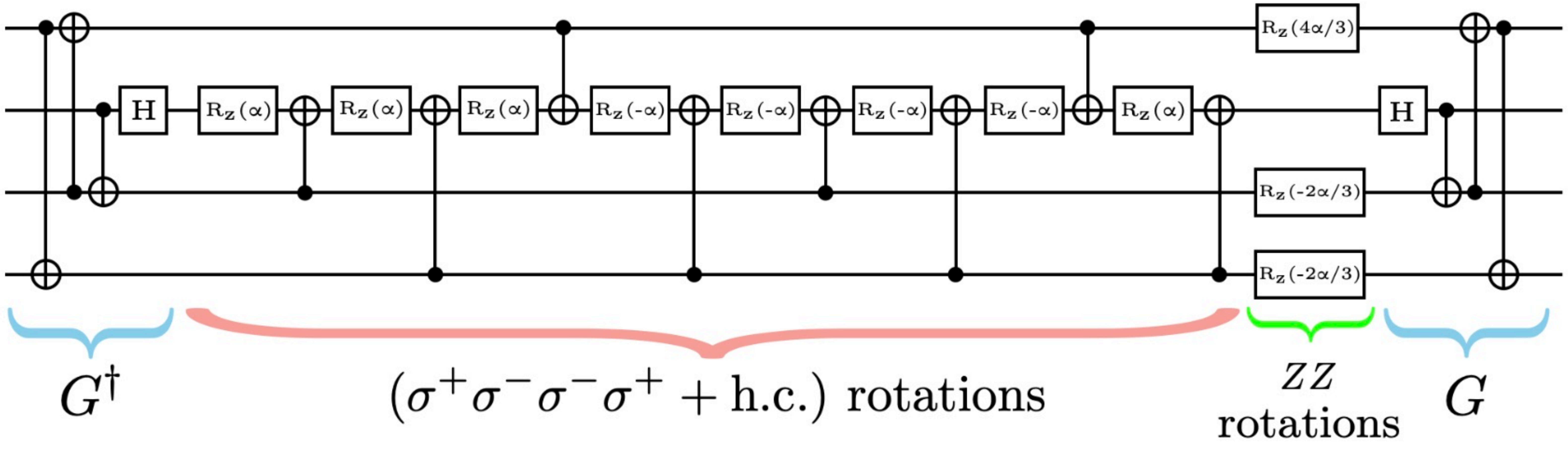


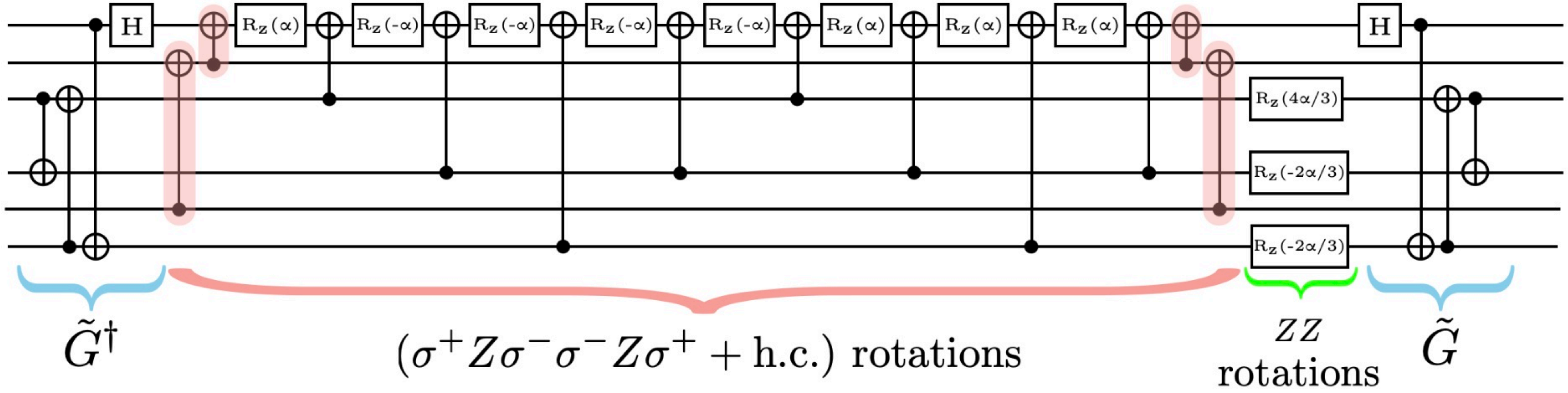
The Low-lying Spectrum for $L = 1$



Simulations using IBM's Quantum Computers
1-site, 3 colors, 1 flavor: m=g=L=1

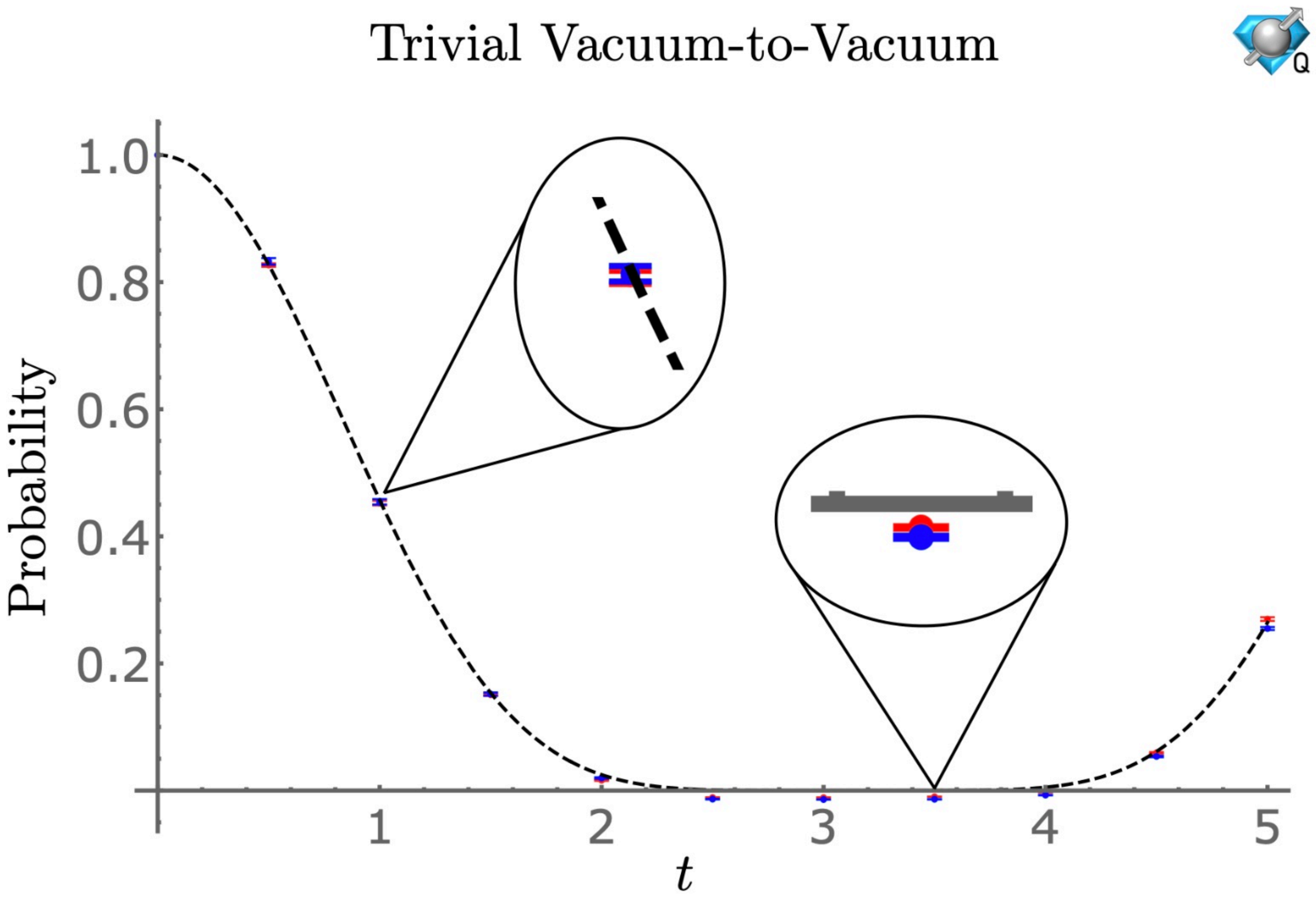
Circuits to implement Trotterized Gauge term





Simulations using IBM's Quantum Computers
1-site, 3 colors, 1 flavor: m=g=L=1

IBM 7 qubit Perth and Jakarta



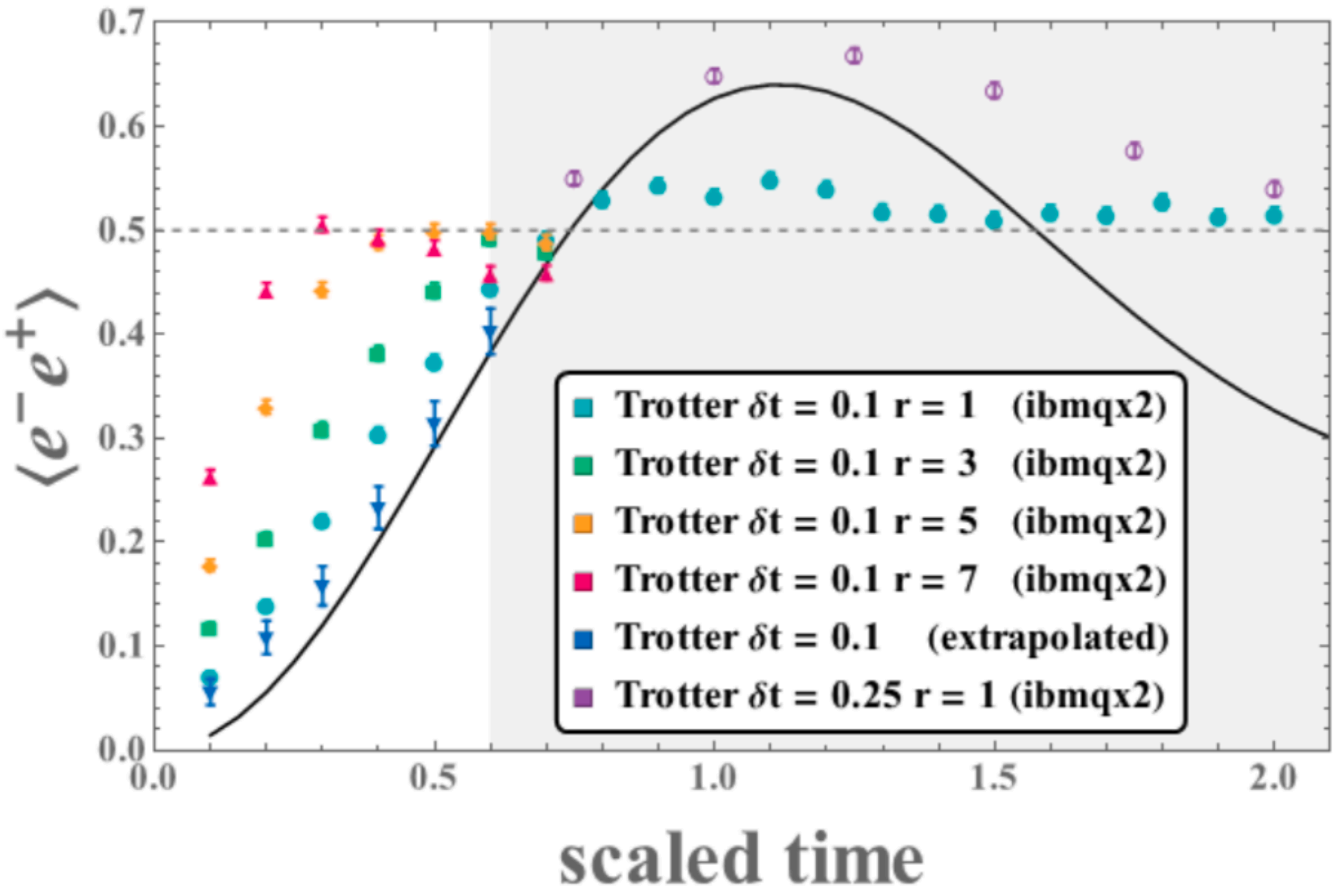
34 CNOTs per step
447 Pauli-Twirled circuits
1000 shots per circuits

Dynamic Decoupling
Pauli-Twirling
Post selection
De-coherence renormalization

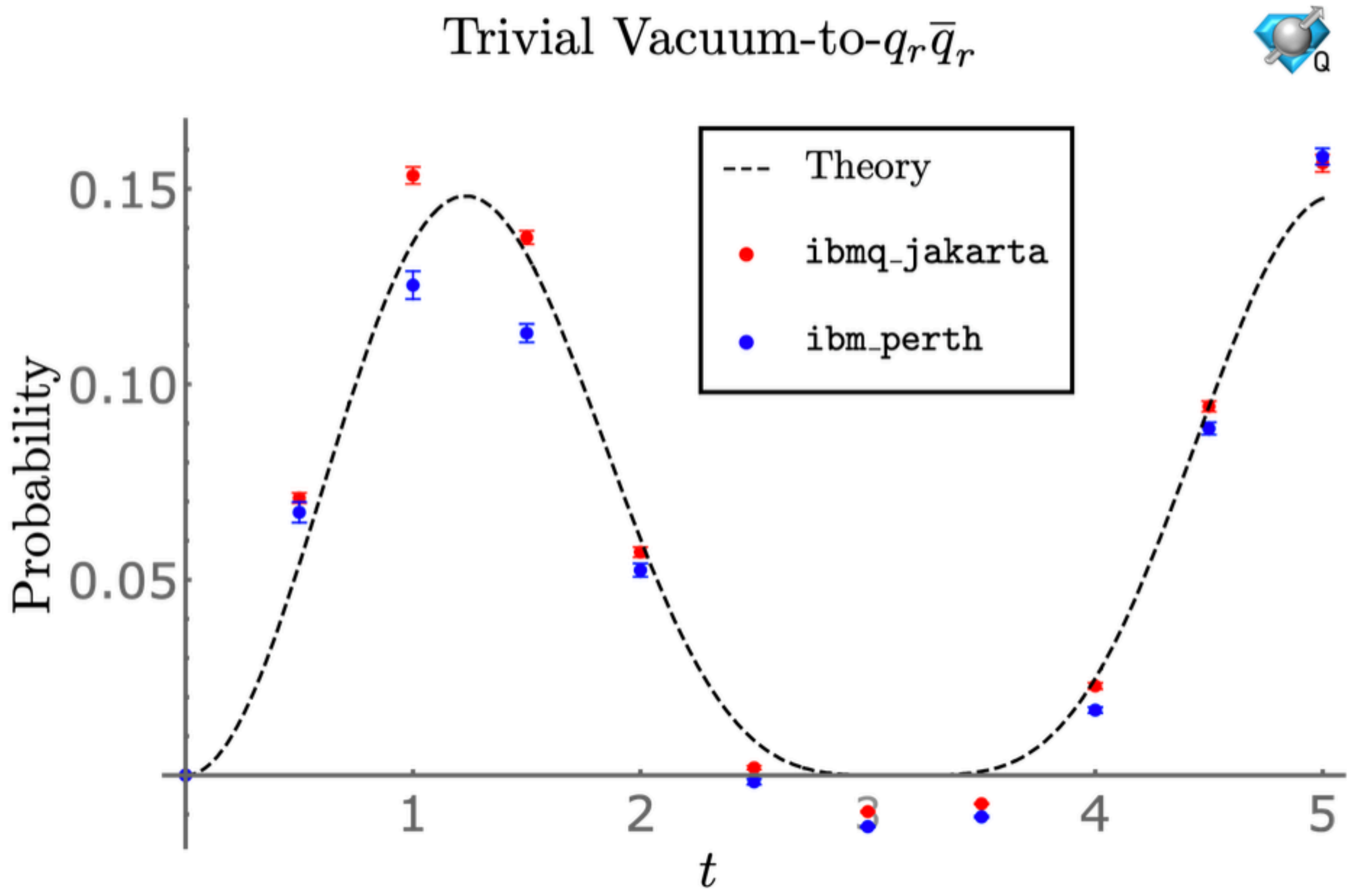
Number of CNOT gates for one Trotter step of $SU(3)$			
L	$N_f = 1$	$N_f = 2$	$N_f = 3$
1	30	114	242
2	228	878	1,940
5	1,926	7,586	16,970
10	8,436	33,486	75,140
100	912,216	3,646,086	8,201,600

The Difference 5 Years Makes

2017-8



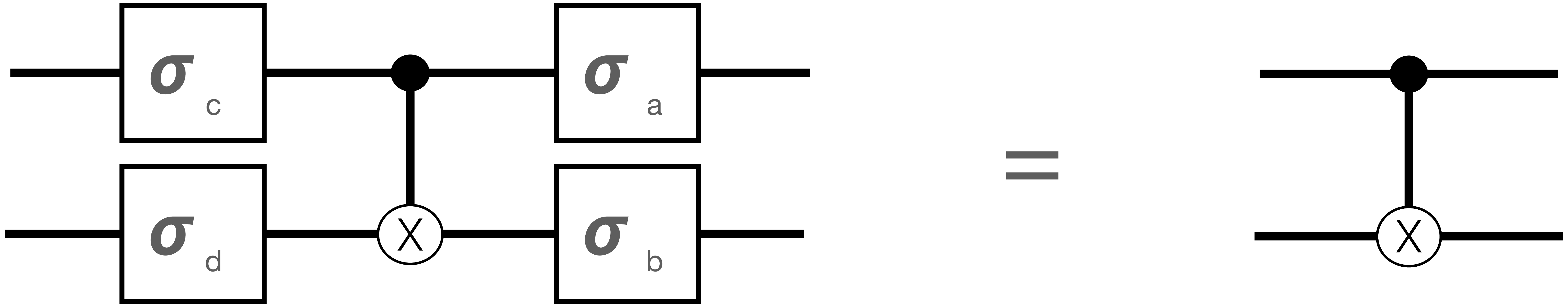
2022



Error Mitigation - NISQ-Life

IBM

Pauli-Twirling



Coherent errors from errors on control and target transformed to incoherent, averaged over all channels

Mitigating depolarizing noise on quantum computers with noise-estimation circuits

Miroslav Urbanek,[1,*] Benjamin Nachman,[2] Vincent R. Pascuzzi,[2]
Andre He,[2,†] Christian W. Bauer,[2] and Wibe A. de Jong[1,‡]

Self-mitigating Trotter circuits for SU(2) lattice gauge theory on a quantum computer

Sarmed A Rahman, Randy Lewis, Emanuele Mendicelli, and Sarah Powell
Department of Physics and Astronomy, York University, Toronto, Ontario, Canada, M3J 1P3

(Dated: May 18, 2022)

Post-Selection

Device Hilbert space >>> Physical Hilbert space
Select only members of measurement ensemble entirely in Physical space
Eliminates order-p errors.

Decoherence Renormalization
The Difference 1 Year Can Make!

Self-mitigating Trotter circuits for SU(2) lattice gauge theory on a quantum computer

Sarmed A Rahman, Randy Lewis, Emanuele Mendicelli, and Sarah Powell

Department of Physics and Astronomy, York University, Toronto, Ontario, Canada, M3J 1P3

(Dated: May 2022. Updated: October 2022.)

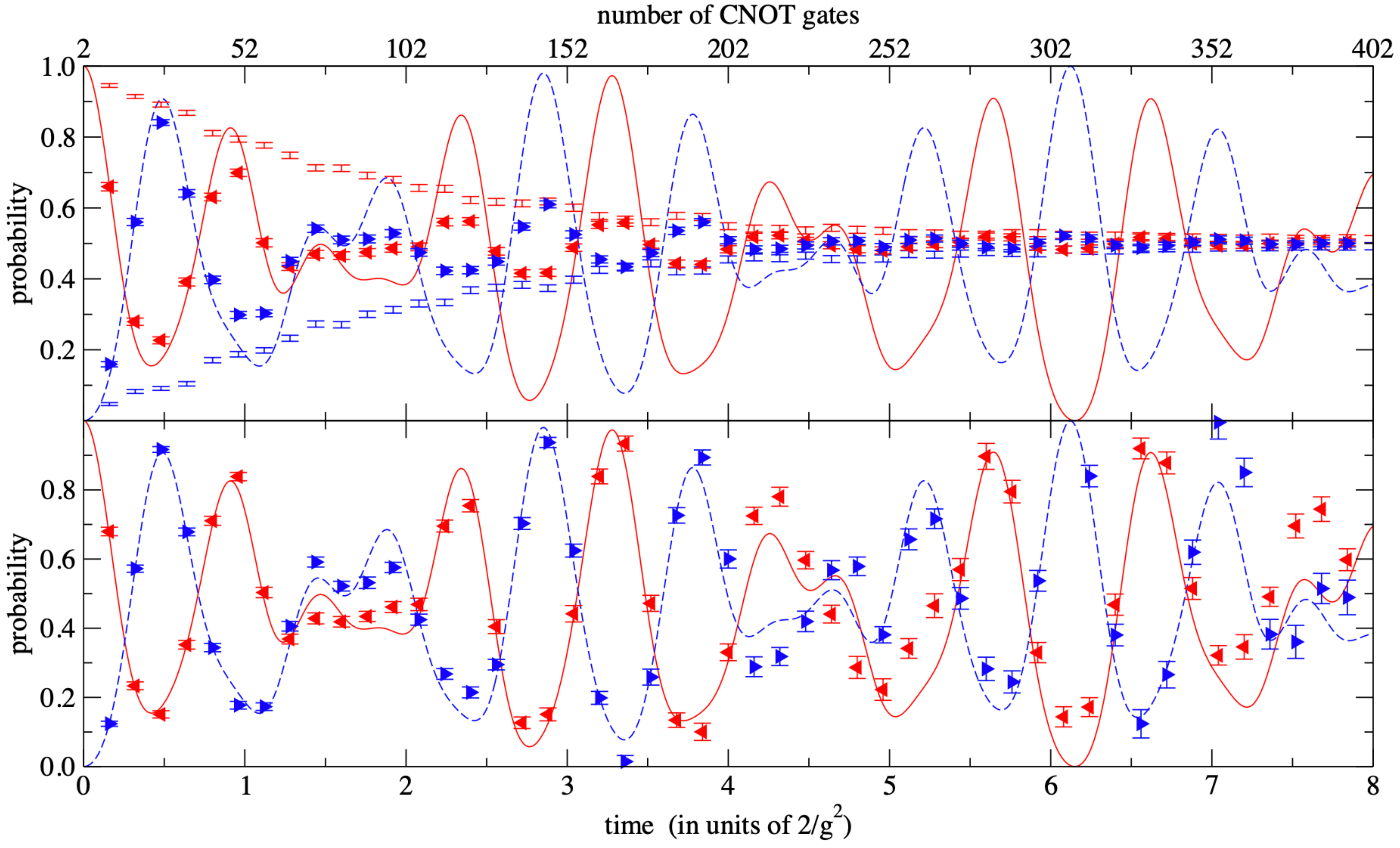
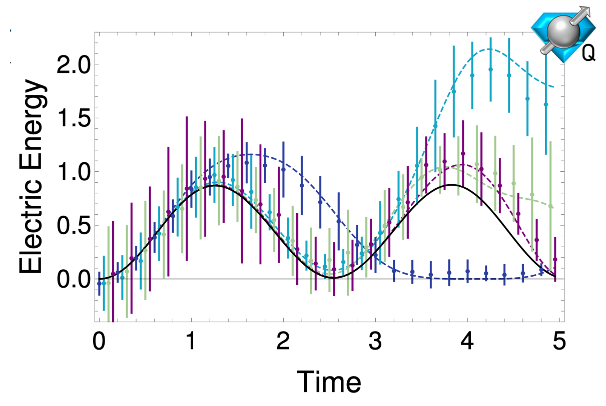
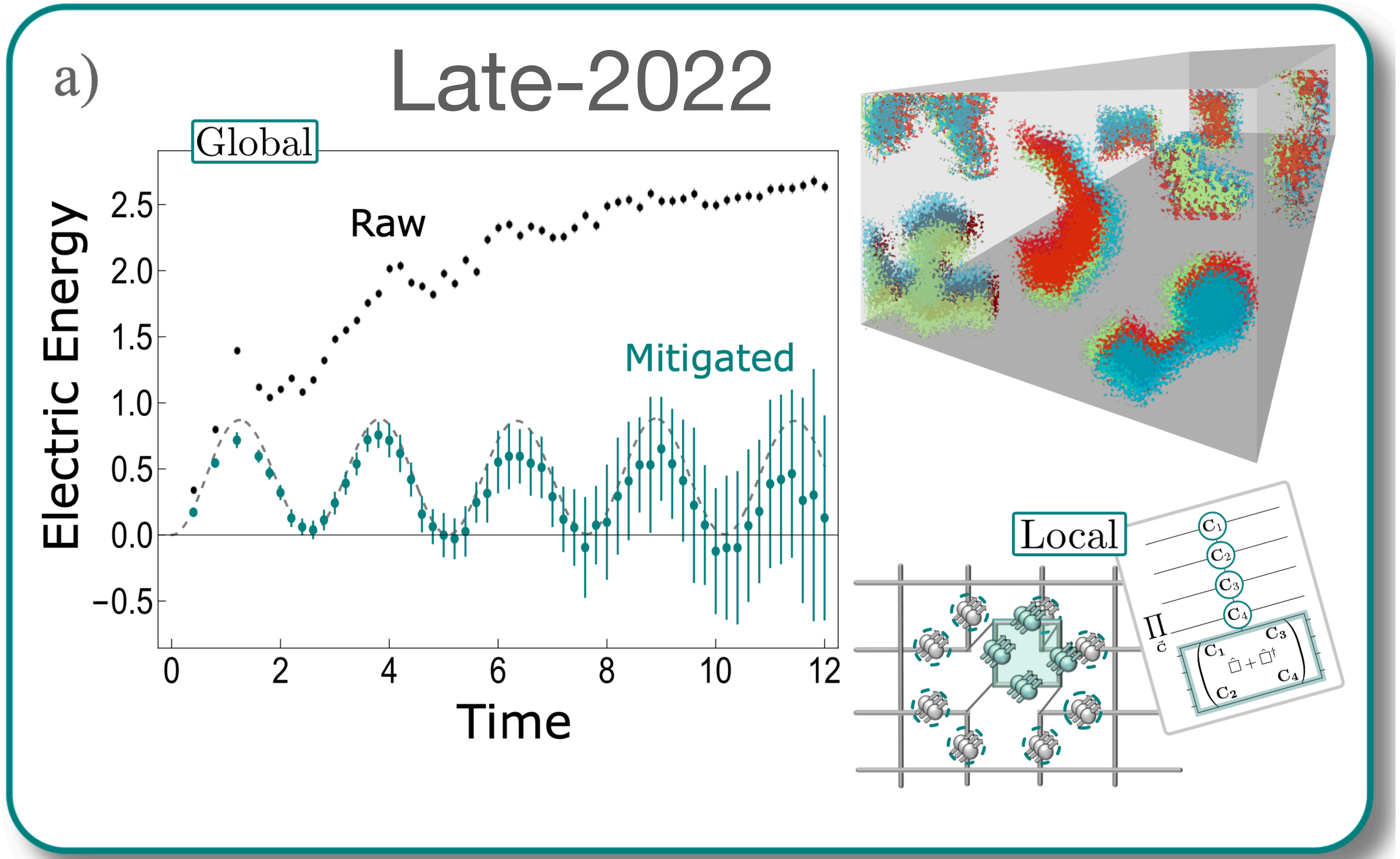


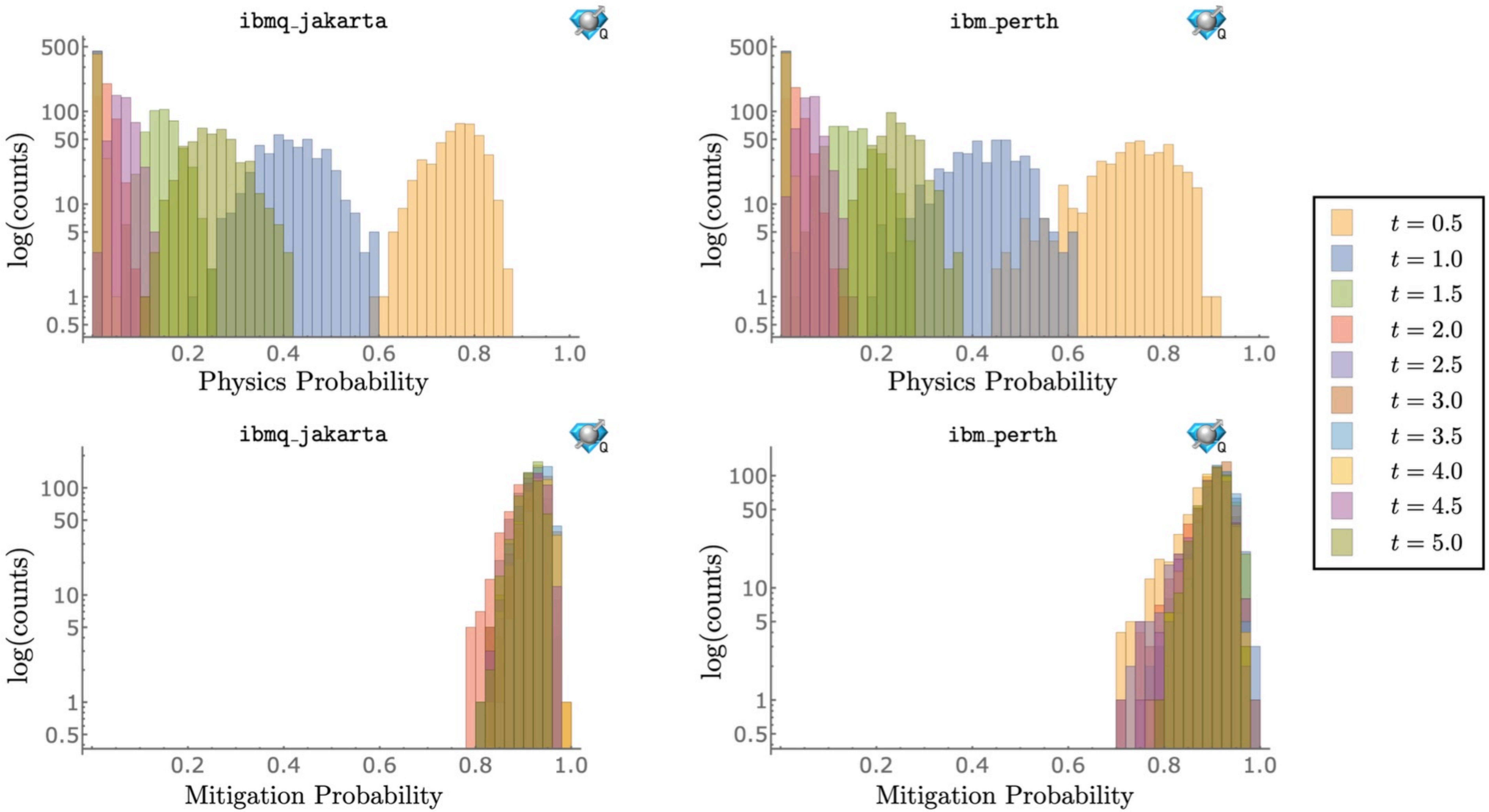
FIG. 3. Time evolution by self-mitigation on a two-plaquette lattice from the initial state of Fig. 1 with gauge coupling $x = 2.0$ and time step $dt = 0.08$. In both panels, the red solid (blue dashed) curve is the exact probability of the left (right) plaquette being measured to have $j = \frac{1}{2}$. **Upper panel:** The red left-pointing (blue right-pointing) triangles are the physics data computed from the `ibm_lagos` quantum processor. The red (blue) error bars without symbols are the mitigation data computed on `ibm_lagos` from the same circuit but with half the steps forward in time and then half backward in time. **Lower panel:** The triangles are the physics results obtained by applying Eq. (8) to the data from the upper panel.



Early-2022

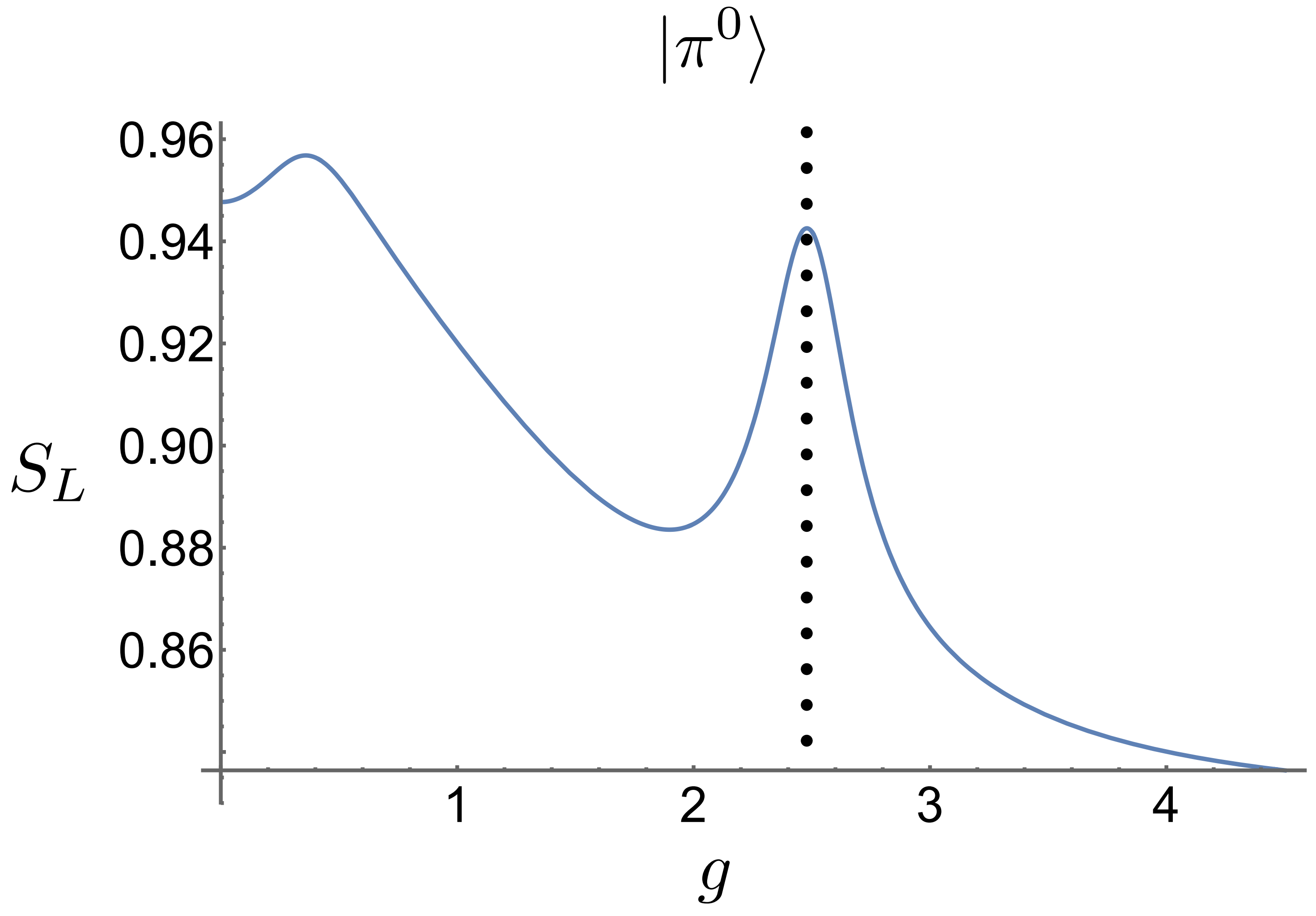


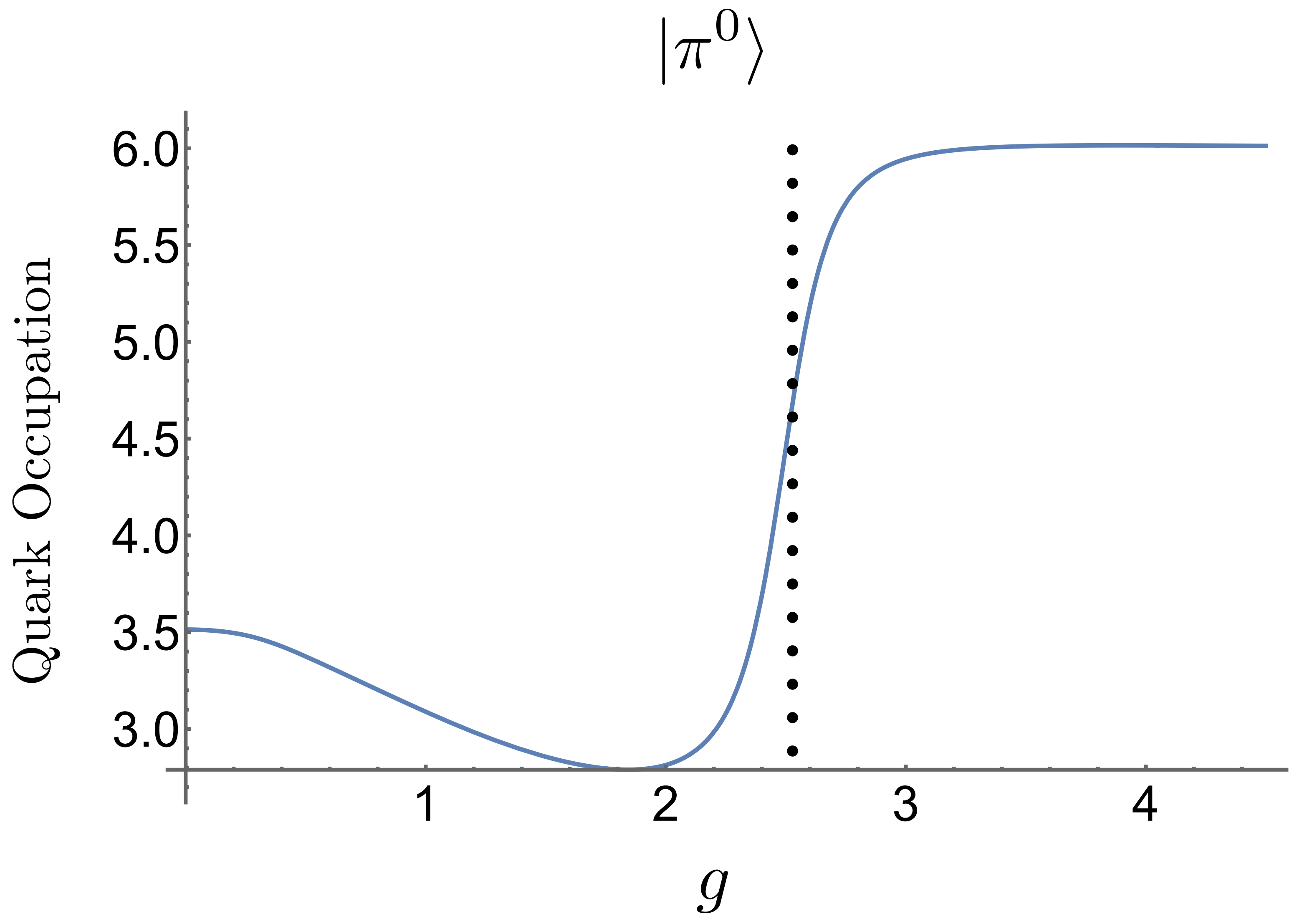
Twirling and Decoherence Mitigation



Entanglement structure in the mesons for $L = 2$

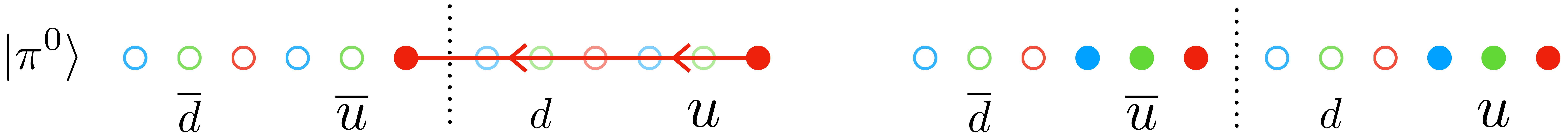
$$S_L = 1 - \mathrm{Tr}\left[\rho_q^2\right]$$





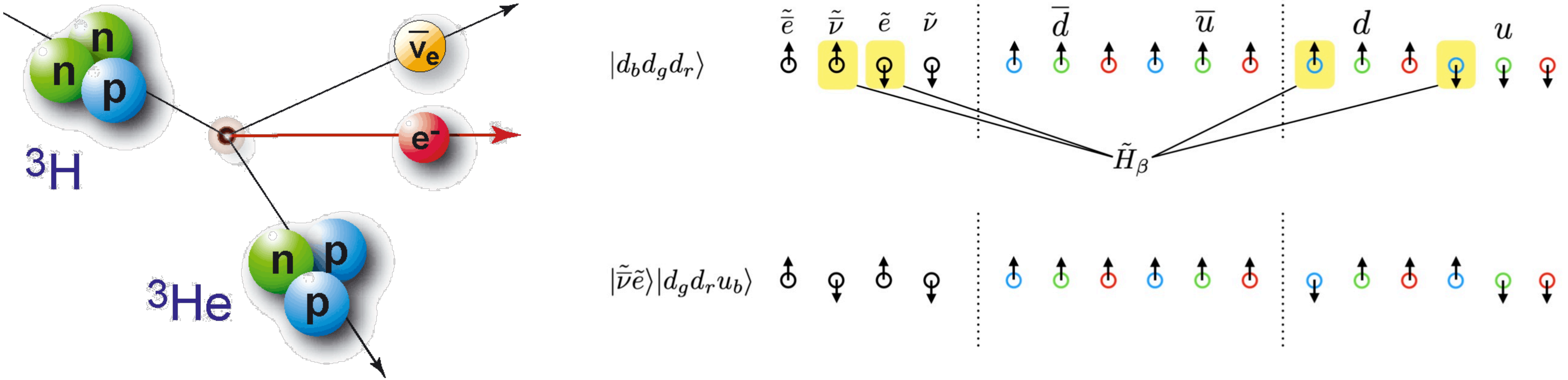
Peak in entanglement coincides with transition from quark-antiquark to baryon-anti-baryon structure

$g \lesssim 2.5$ $\qquad\qquad$ $g \gtrsim 2.5$



Balance between mass and gauge-field energies

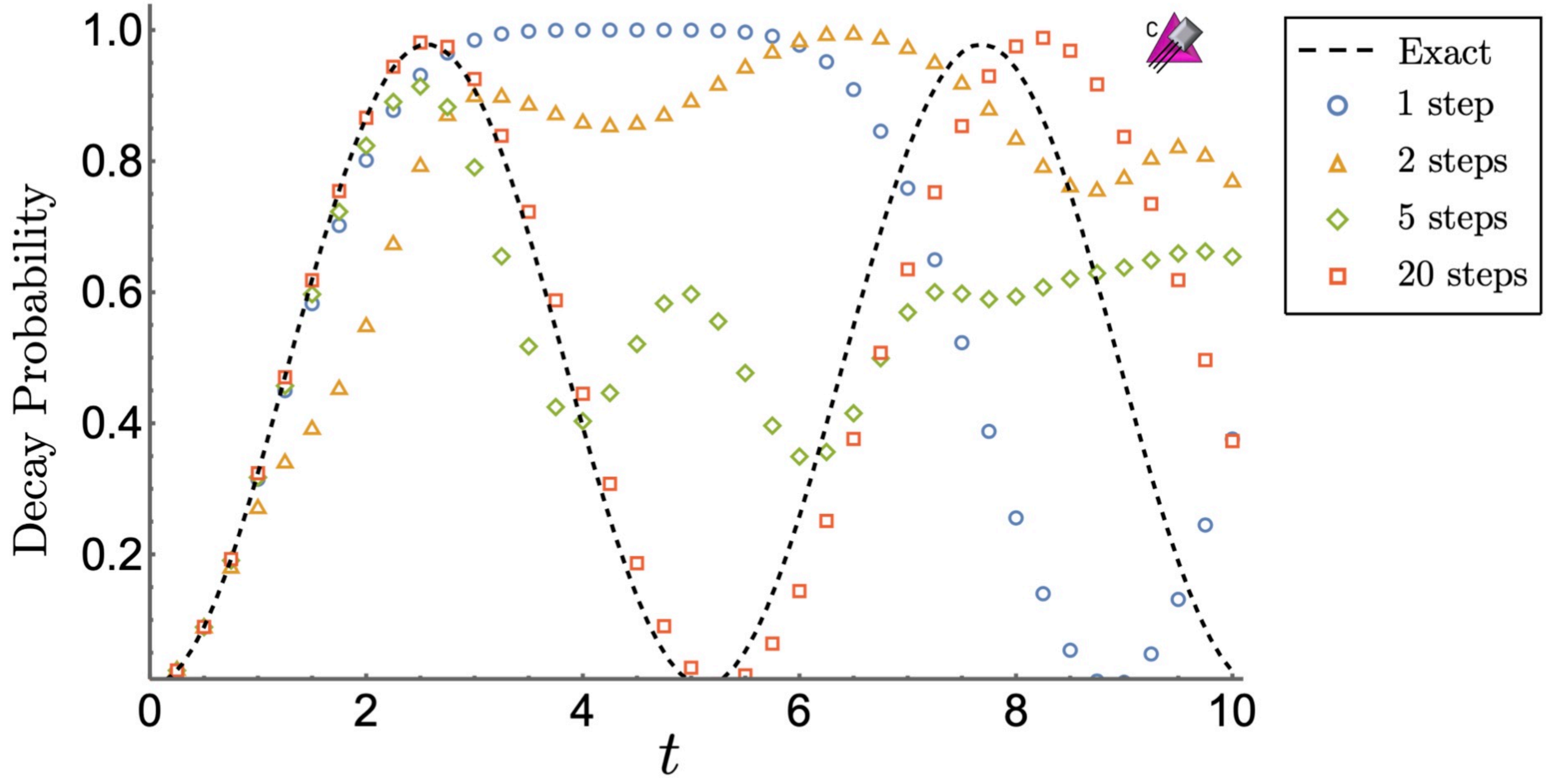
Semileptonic Weak Decays : L=1, Nf=2



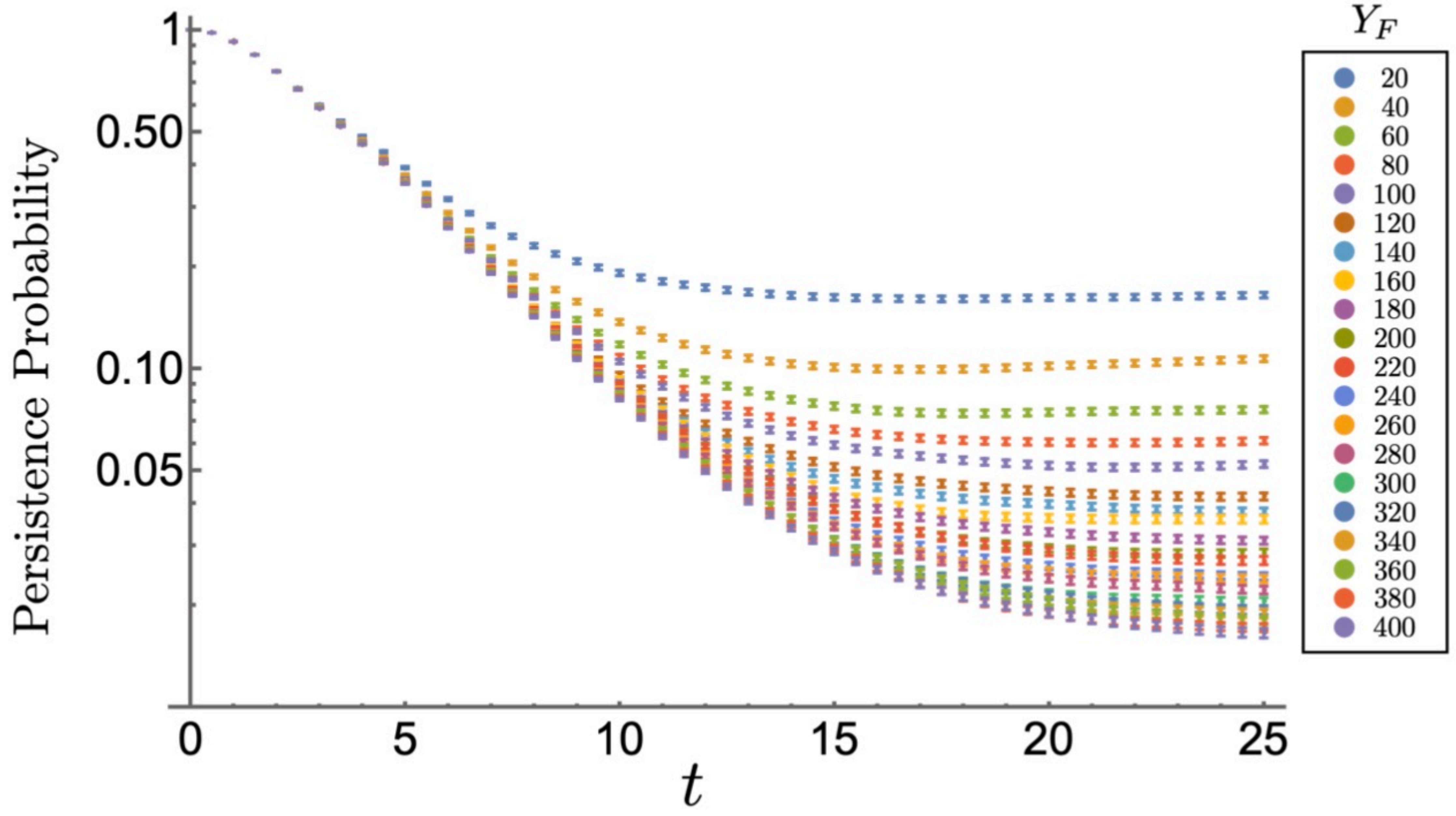
nQ=16 qubit JW mapping, with leptons at *the end* of the site.

— 6 quarks, 6 antiquarks and 4 leptons and anti-leptons

Semileptonic Decays : Expectations —Recovering Real-Time Exponential-Decay



One available final state



Y_F available final states

Semileptonic Decays : Real-time Baryon Decay Quantum Simulation using Quantinuum, 16-qubits

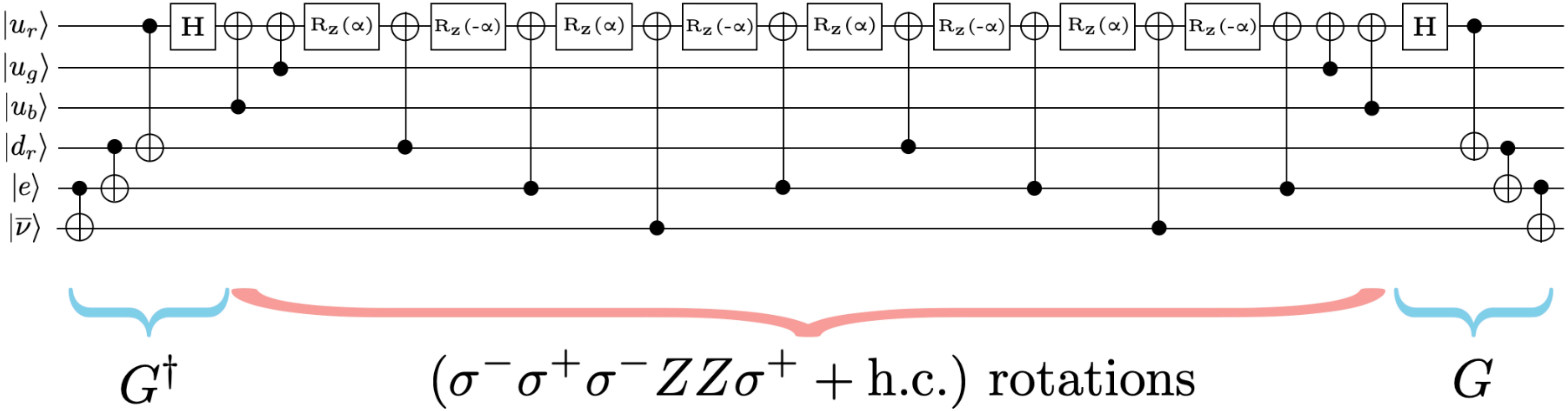
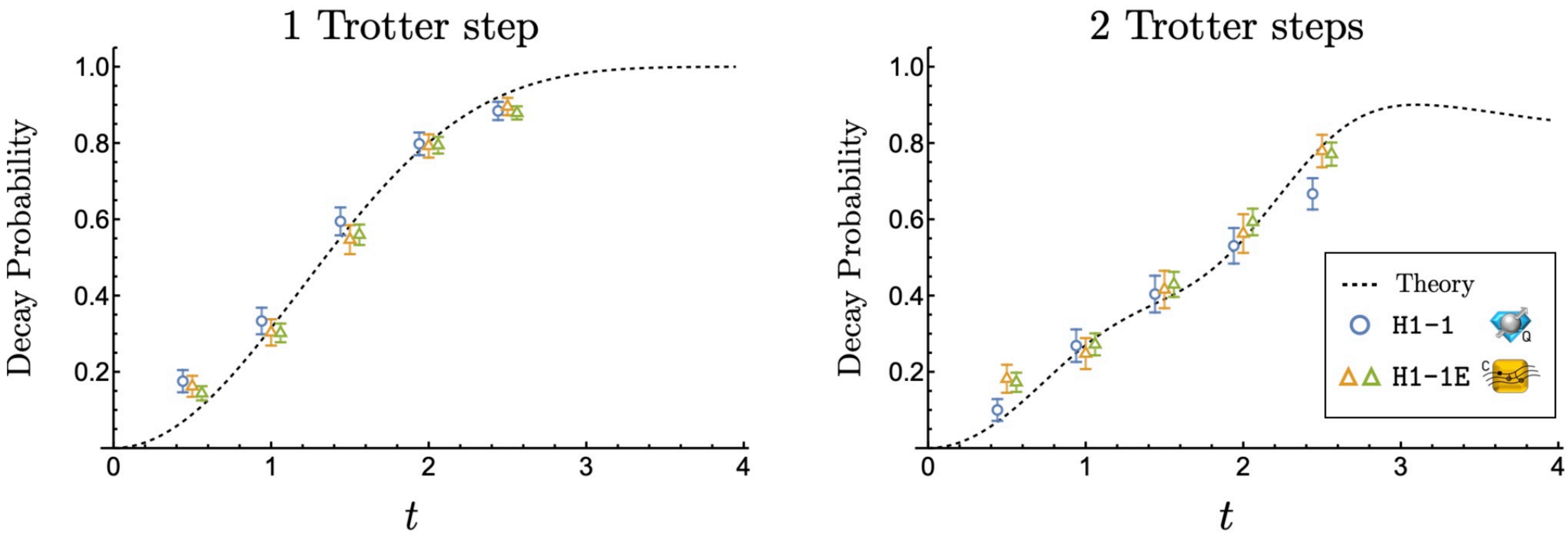


FIG. 9. A quantum circuit that provides the time evolution associated with the $\sigma^-_{\overline{\nu}}\sigma^+_e\sigma^-_{d,r}Z_{u,b}Z_{u,g}\sigma^+_{u,r}$ operator in the β-decay Hamiltonian, with $\alpha = \sqrt{2}Gt/8$.

Semileptonic Decays : Real-time Baryon Decay Quantum Simulation using Quantinuum, 16-qubits



1-step: 59 ZZ

2-steps: 212 ZZ gates

Resource Requirements

For 1 Trotter step

L	# of qubits	CNOTs	
5	80	9,874	2.5K
10	160	38,074	10K
50	800	926,074	25K
100	1600	3,692,074	900K

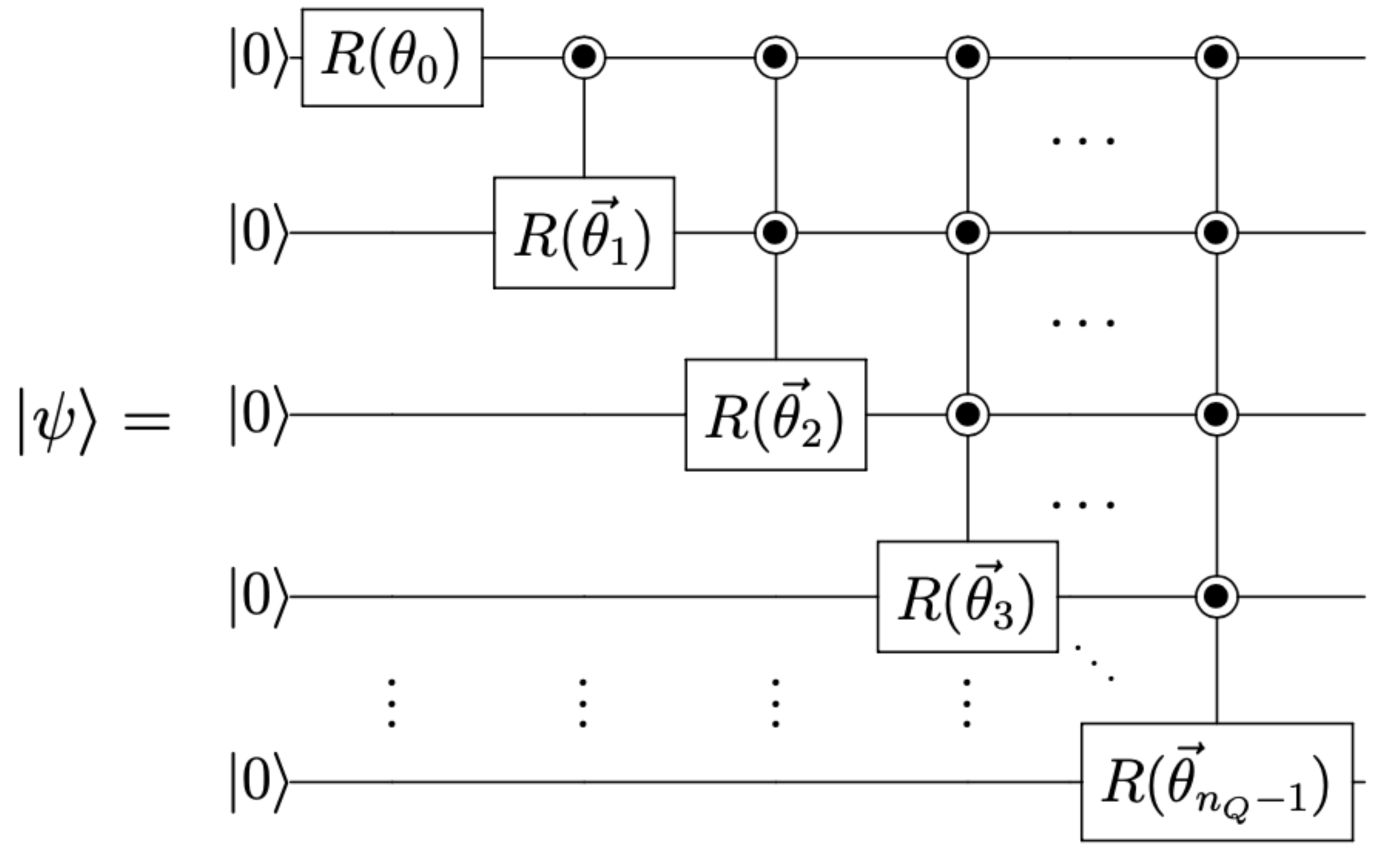
$$H_{\text{glue}} \sim L^2$$

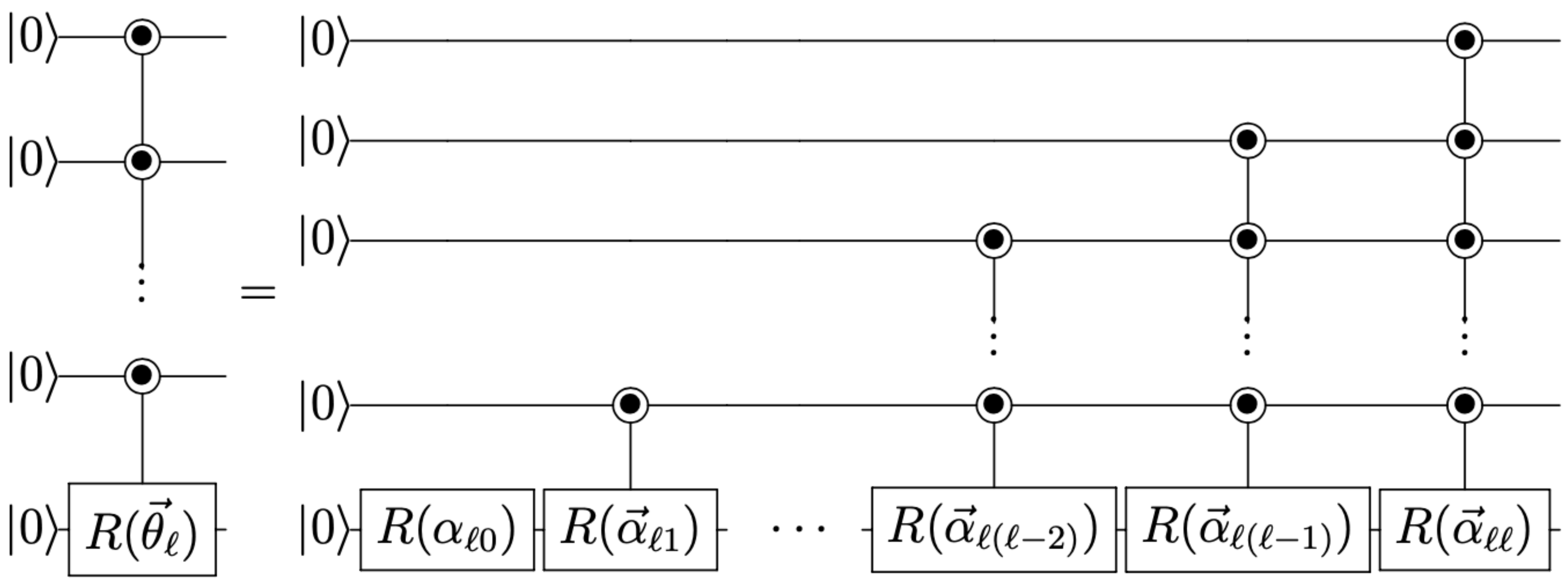
- BUT this is too naive — in reality it will be ~ L R, i.e. much fewer gates
- R = confinement scale (an emergent scale in the simulation)
- Now consistent with Feynman's criterion for simulation

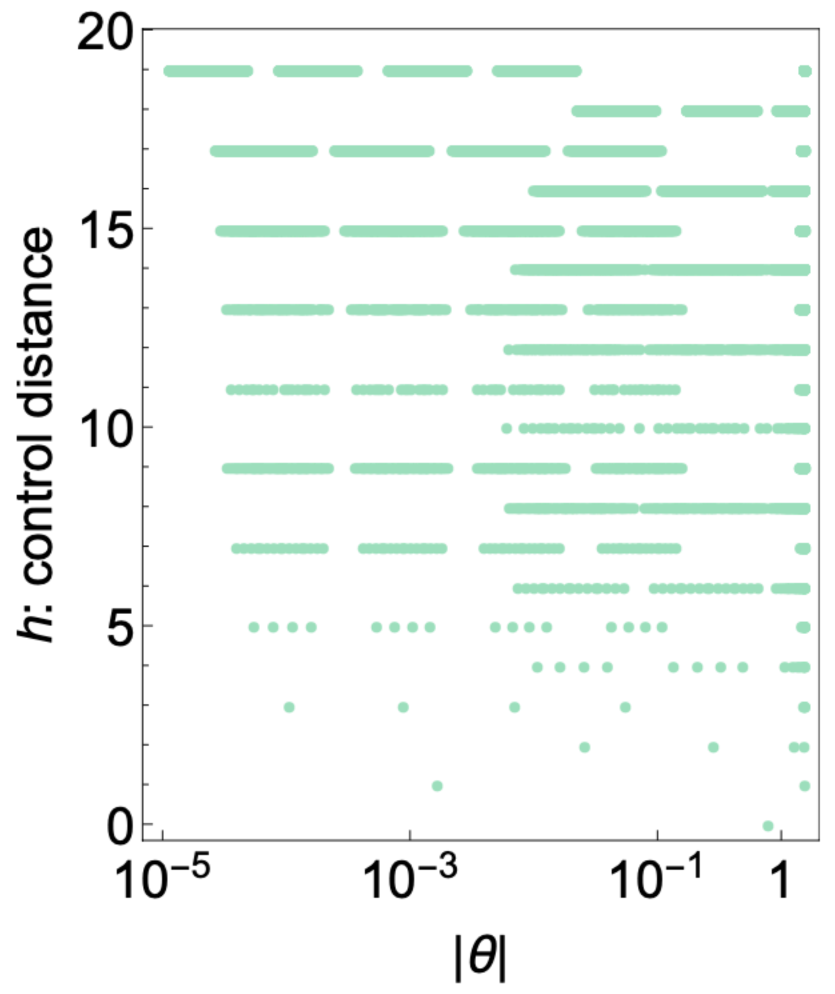
State Preparation with Localizable or Physics-Aware Quantum Circuits

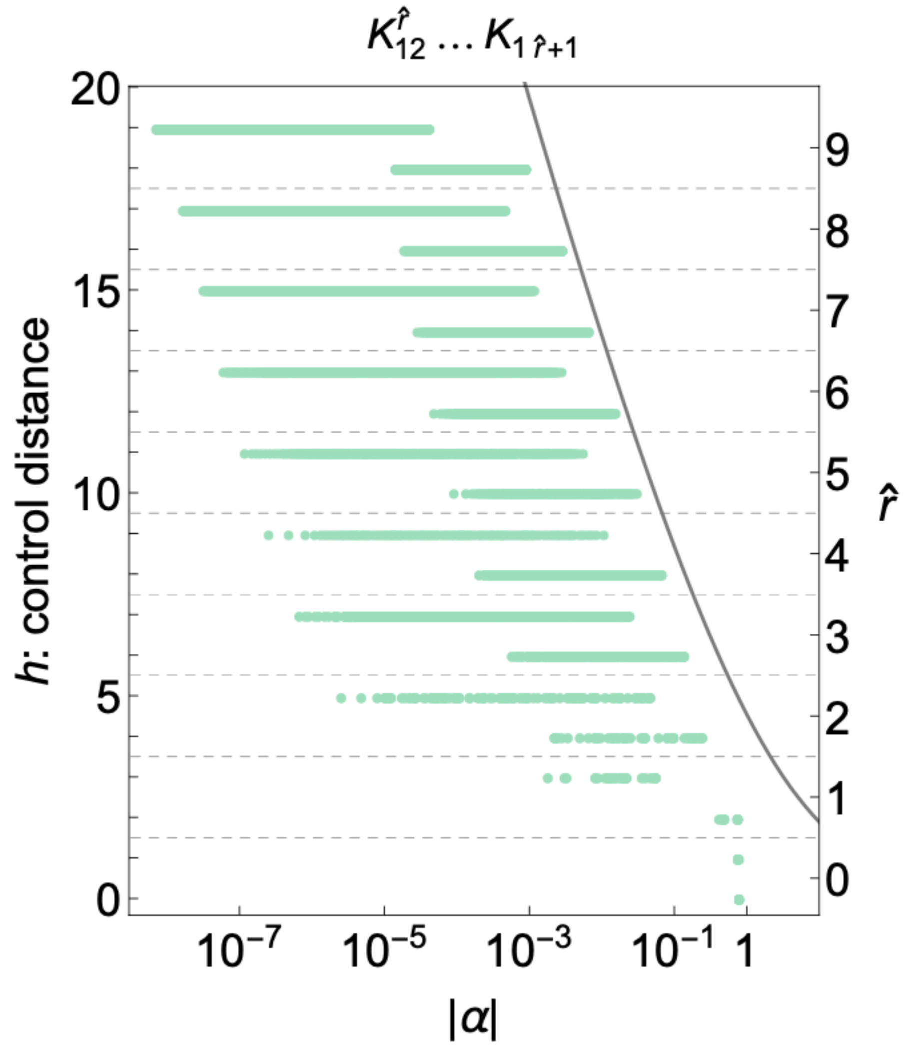
Systematically Localizable Operators for Quantum Simulations of Quantum Field Theories

Natalie Klco* and Martin J. Savage†









Correlation length allows for fixed-point angles to be determined exponentially well with small-scale simulations

Doublers are less of a problem

From discussions with Anthony Ciavarella

One d-dim Kogut-Susskind fermion has 2^d-1 doublers

4+0 D : 1 fermion -> 16 massless fermions, 4 tastes of 4 component Dirac spinors

3+1D: 1 fermion -> 8 massless fermions, 2 tastes of 4 component Dirac spinors

Some of the Challenges

- Quantum Volume in Simulations and Errors
- Designing quantum circuits that scale efficiently
- (Sufficient) Access to devices - TI Vs SC
- 2+1D cold-atom systems
- Integration of HPC and Quantum algorithms
- Can quantum simulations crack chiral gauge theories ?

A High-Level Comment and a Conjecture

We are likely missing an important ingredient so far:

- all of the “power” of computation - the gates - are being applied at the scale of the lattice spacing
- this becomes increasingly disparate from the scale of physics in the continuum limit
- Seek physics and circuit scalings to move away from the UV

I conjecture that efficient digital quantum circuits exist for Standard Model lattice field theory simulations where the gate-structure, or power, is dominantly focused at the scale of the physics/observable(s). i.e. EFTs can manifest at the quantum circuit level.

Summary

- Near-term : Great progress toward dynamic properties of matter from the Standard Model
  - 1+1D heading toward 2+1D
- Advances in computers and simulators
- Quantum simulations of Standard-Model physics face challenges

FIN

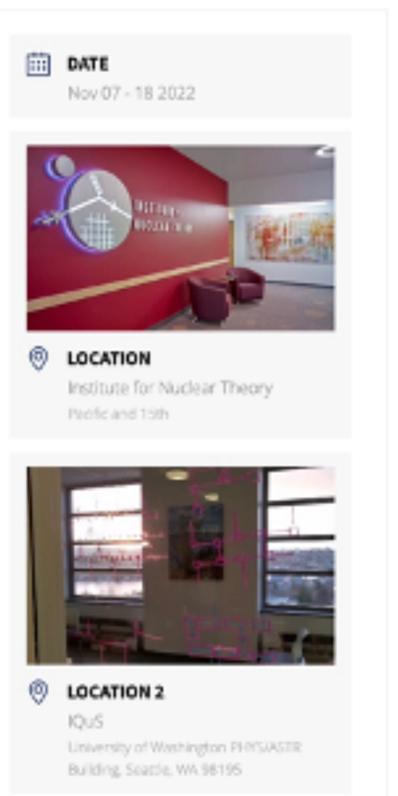
Recent IQuS Workshops – 2022

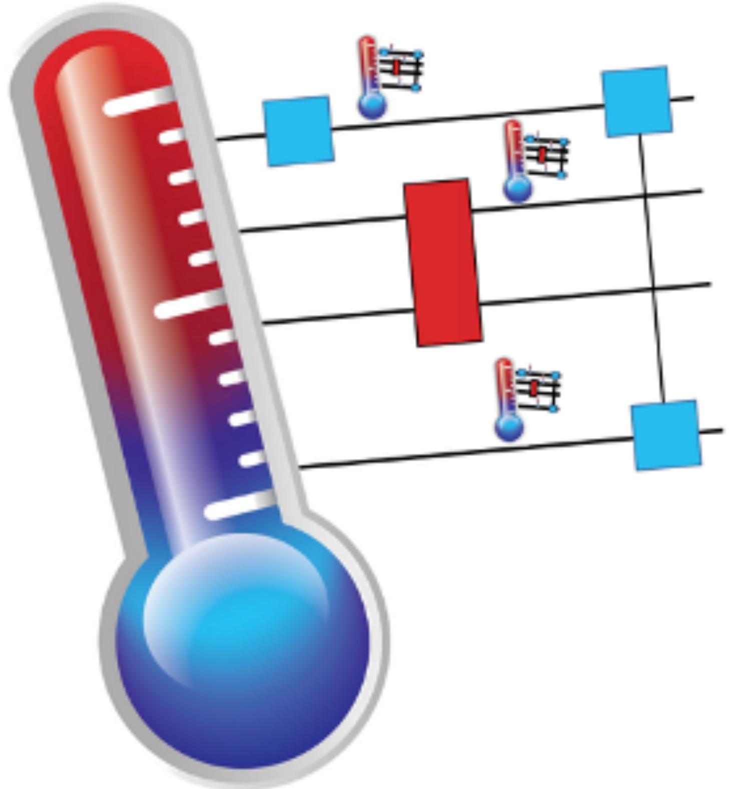
Next-Generation Computing for Nuclear Physics
August 2022

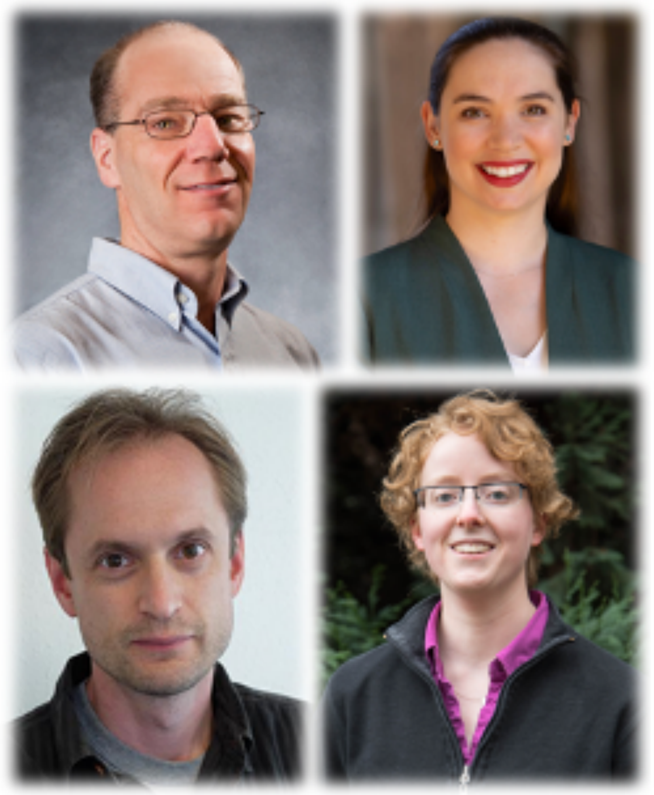
At the Interface of Quantum Sensors and Quantum Simulations (22-3b)

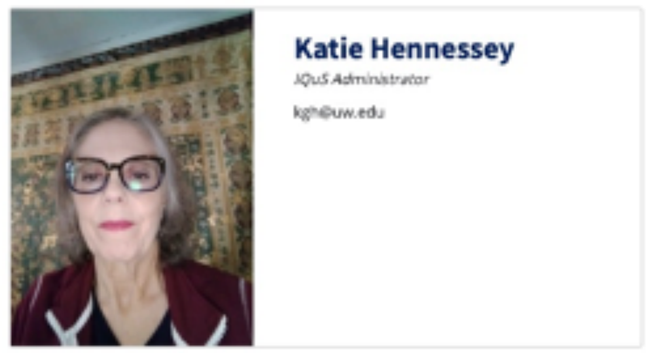
IQuS InQubator for Quantum Simulation

Organizers: Doug Beck (UIUC), Natalie Klco (Caltech), Crystal Noel (UMD) and Joel Ullom (NIST)









Thank you !!

https://iqus.uw.edu/events/iqus-workshop-22-3b/