quantum simulation of lattice field theories

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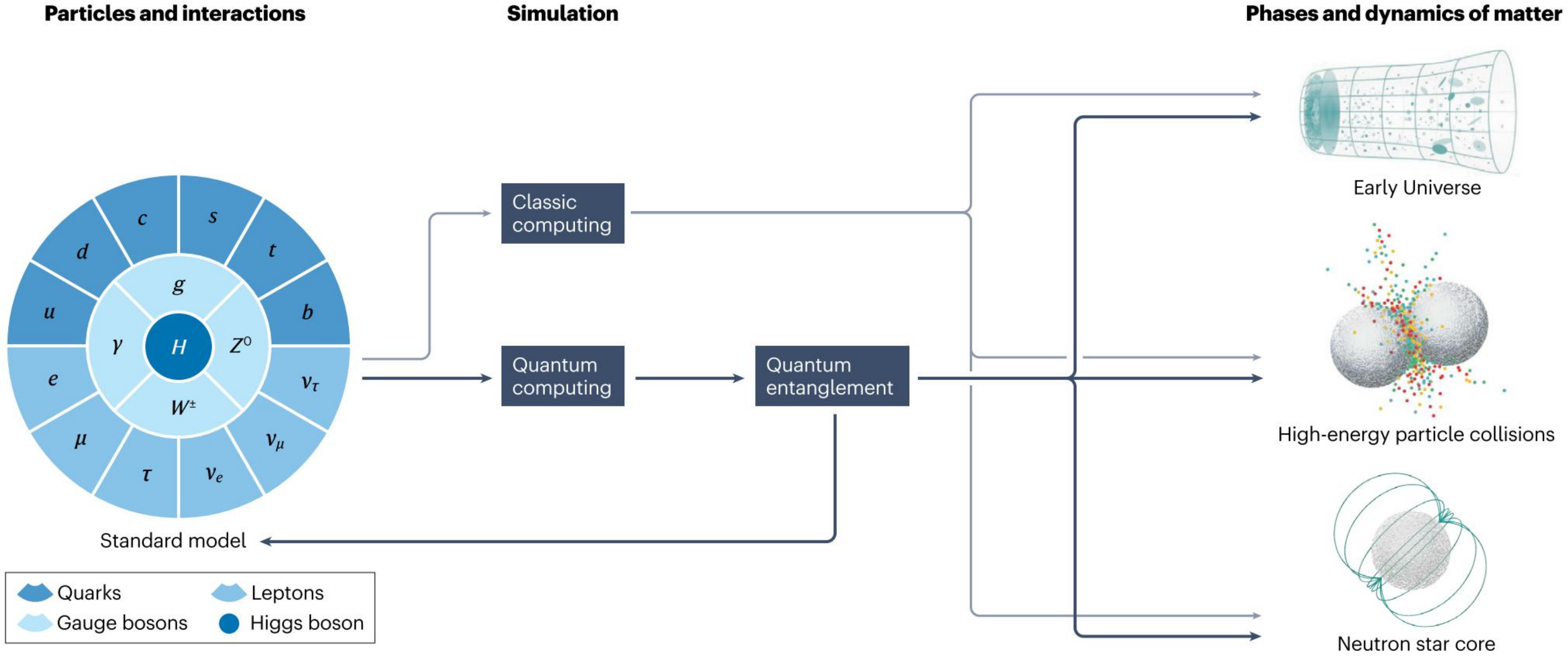
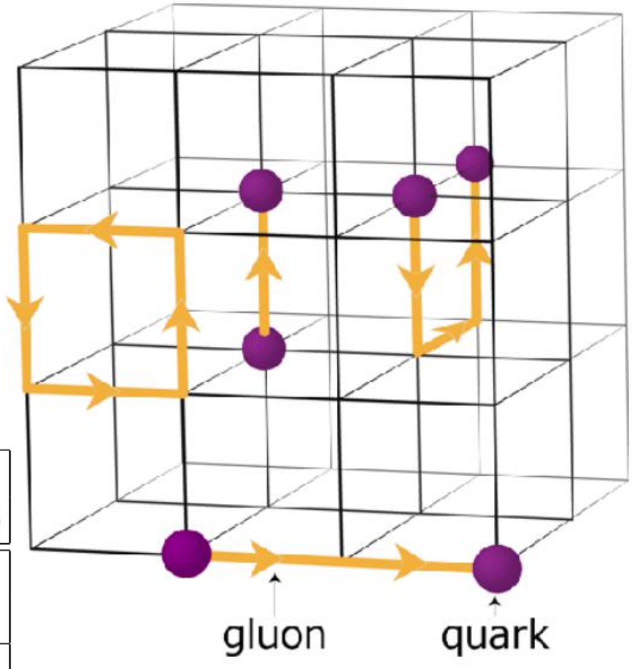
Classical and Quantum Computing of Standard Model



C. Bauer, et.al, Nature Rev. Phys. 5 (2023)

First Principle Computing of Standard Model

- **Lattice Field Theory: quantum field theory on the discrete space-time lattice**
- **Lattice QCD**
  - numerical **Monte Carlo** method

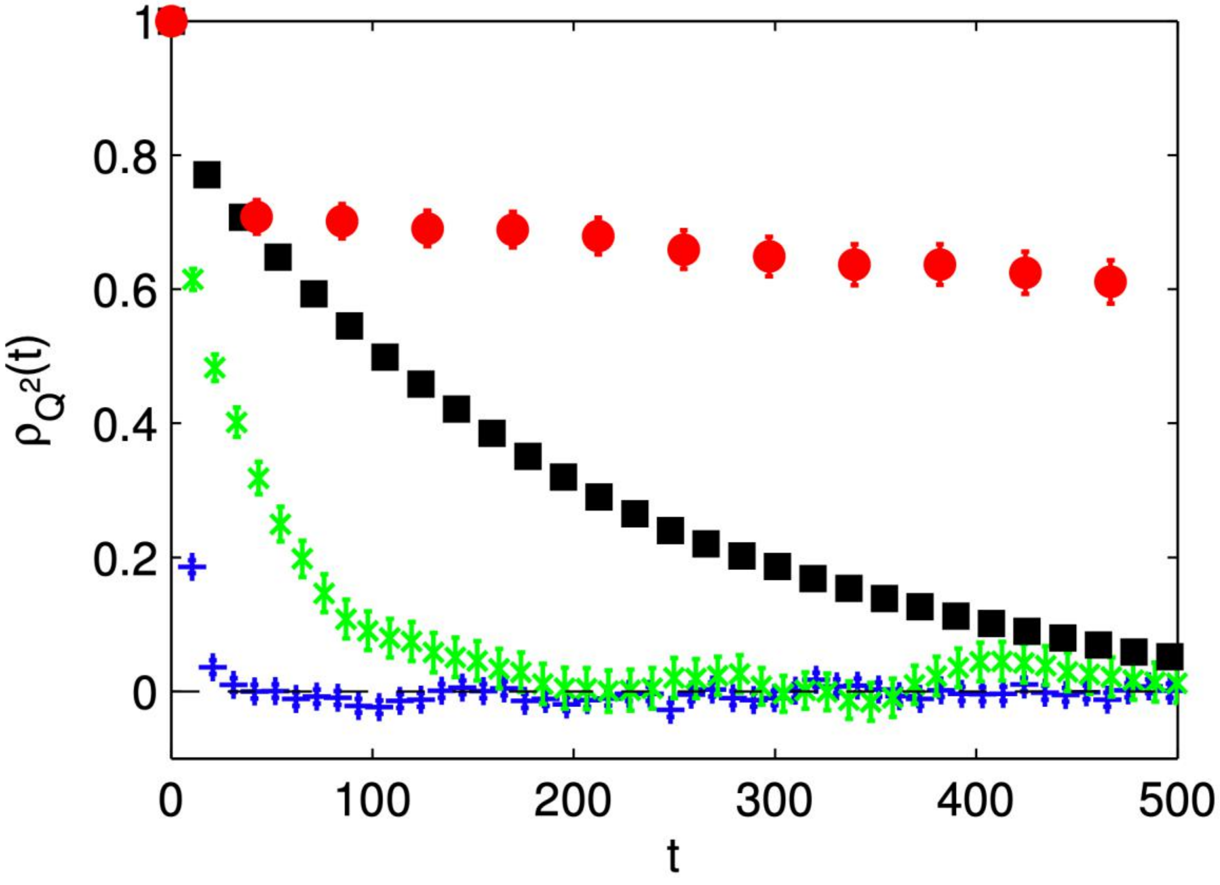


Computational Task	Current Usage	2025 Usage	Current Storage (Disk)	2025 Storage (Disk)	2025 Network Requirements (WAN)
Accelerator Modeling	~ 10M – 100M core-hrs/yr	~ 10G – 100G core-hrs/yr			
Computational Cosmology	~ 100M – 1G core-hrs/yr	~ 100G – 1000G core-hrs/yr	~10PB	>100PB	300Gb/s (burst)
Lattice QCD	~1G core-hrs/yr	~ 100G – 1000G core-hrs/yr	~1PB	>10PB	
Theory	~ 1M – 10M core-hrs/yr	~ 100M – 1G core-hrs/yr			
Cosmic Frontier Experiments	~ 10M – 100M core-hrs/yr	~ 1G – 10G core-hrs/yr	~1PB	10 – 100PB	
Energy Frontier Experiments	~ 100M core-hrs/yr	~ 10G – 100G core-hrs/yr	~1PB	>100PB	300Gb/s
Intensity Frontier Experiments	~ 10M core-hrs/yr	~ 100M – 1G core-hrs/yr	~1PB	10 – 100PB	300Gb/s

ASCR/HEP Exascale Report [arXiv:1603.09303]

Why Quantum Simulation of Lattice Field Theory

1) 临界慢化问题（critical slowing down）



ALPHA Collaboration, *Nucl.Phys.B* 845 (2011) 93-119

- 格点场论需要取连续极限（格距$a \to 0$）
- Markov Chain Monte Carlo方法天然具有自关联性
- **critical slowing down：** $a \to 0, \ \tau_{\text{int}} \to \infty$
- **计算时间指数增加**

Why Quantum Simulation of Lattice Field Theory

2) 符号问题（sign problem）

$$\langle O \rangle = \int DU \; O(U) \; e^{-S}$$

S is real → Monte Carlo method

S is complex → Sign problem

- ☑ Hadron spectroscopy
- ☑ Hadron structure
- ☑ Finite temperature phase transition
- ☑ Standard model precision test
- ☑ …

- ✗ Strong CP violation
- ✗ Quark gluon plasma
- ✗ Finite density QCD phase transition
- ✗ Properties of neutron star
- ✗ …

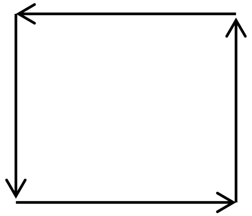
Quantum Simulation of Quantum Link Model

- Lattice QCD cannot be simulated on current quantum computers (need millions of fault tolerant qubits and quantum gates)
- The Hilbert space of quantum link model is **finite**
- We investigated the Z2 quantum link model

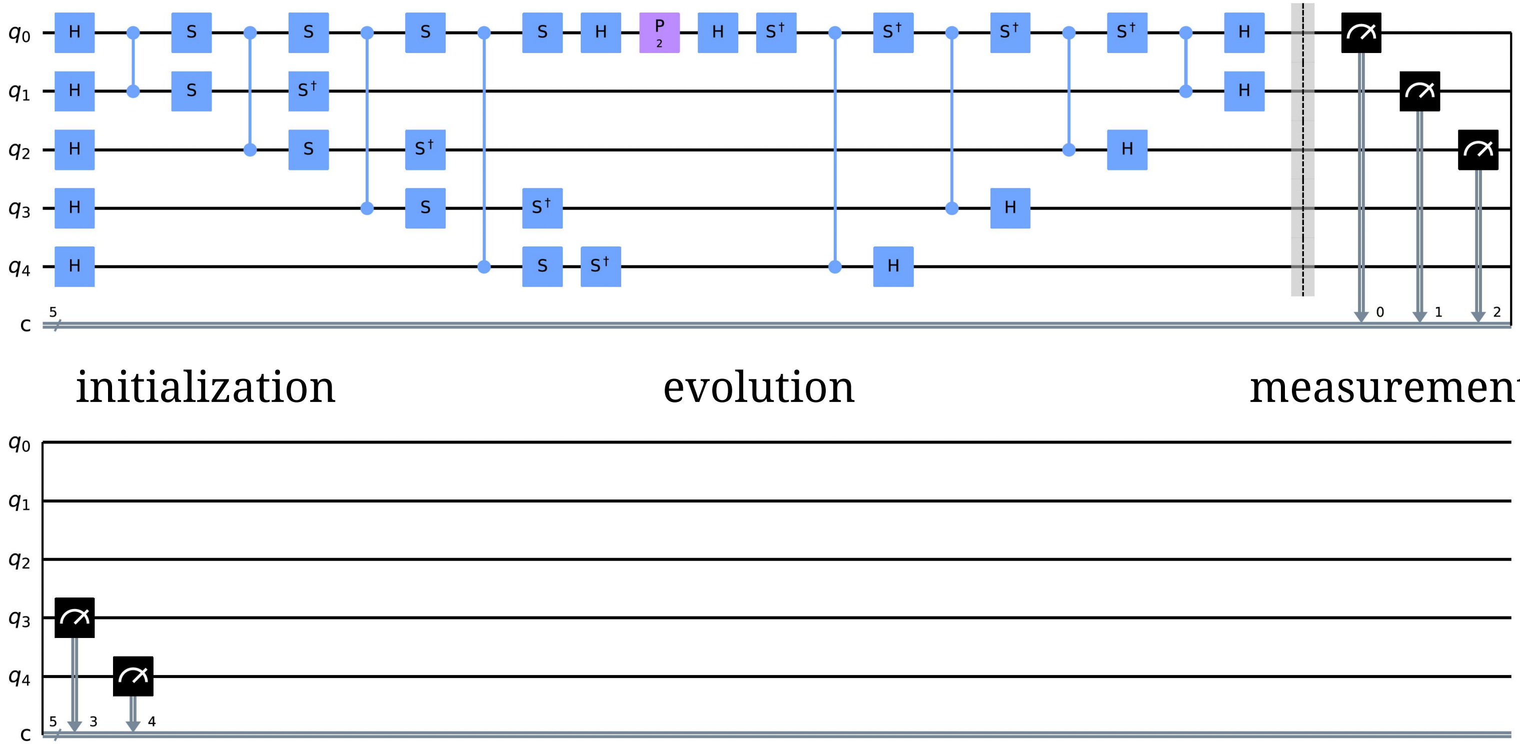
$$H = -g \sum_{\square} U_{\square} - \Gamma \sum_{i} S_i^x \, ,$$

$$U_{\square} = S^z_{r,\mu} S^z_{r+\mu,\nu} S^z_{r+\nu,\mu} S^z_{r,\nu} \, .$$

Hamiltonian



plaquette



5 qubits Z2 quantum link model

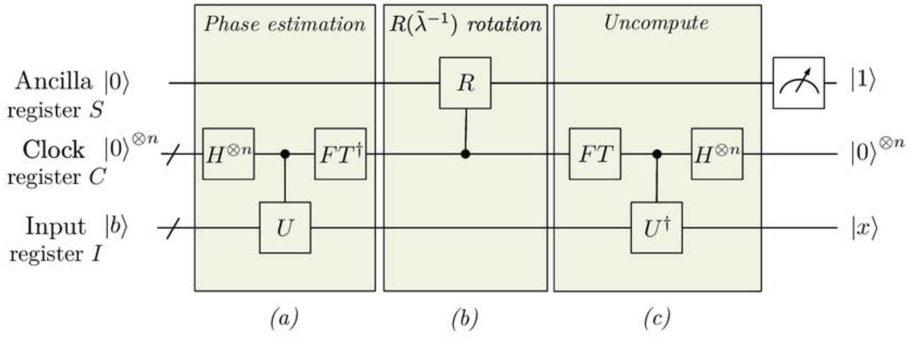
Hybrid Quantum Classical Simulation

$$\langle O \rangle = \frac{1}{Z} \int \mathscr{D}U O'[U] \det M \, e^{-S_g}$$

Solve Mx=b

Hybrid Monte Carlo algorithm: most time consuming part in classical computing (~80%)

- use HHL(Harrow-Hassidim-Lloyd) algorithm to solve linear equation Mx=b
- quantum speedup: O(N) v.s. O(log(N)) (e.g. Conjugate Gradient)
- detM on the quantum computer, others on the classical computer (hybrid quantum classical)



- work in progress with 龙沛洵

HiQuArC Project

- HiQuArC (**Hi**gh performance, **Qu**antum, and **Ar**tificial intelligence **C**omputing)
- developing a software package for lattice field theory simulation

HiQuArC

CuFT

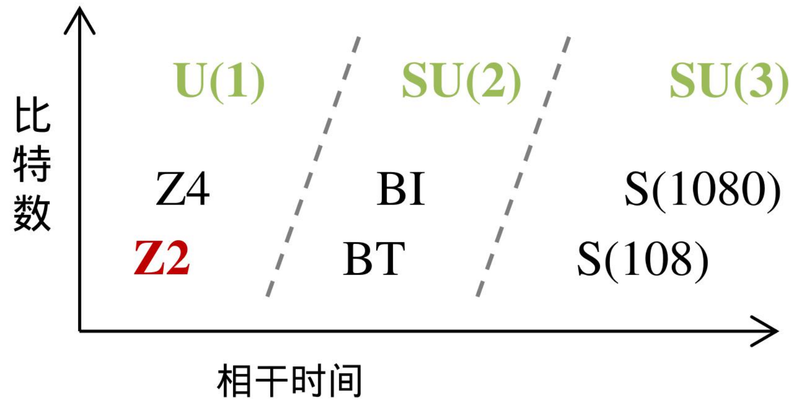
Classical high performance simulation based on Monte Carlo method

QuFT

Quantum simulation with quantum simulator and real hardware

MLFT

Lattice field theory simulation based on machine learning



verification — CuPy

quantum simulation — Qiskit, PENNYLANE

sampling — PyTorch

Summary and outlook

- Quantum simulation of simple toy model of lattice field theory is feasible on current NISQ quantum computers
- Hybrid quantum classical simulation method using HHL algorihm is working in progress
- HiQuArC project
    - Goal: developing a quantum simulation package for lattice field theories
    - three components
        - CuFT: classical high performance computing with Monte Carlo
        - QuFT: quantum simulation with quantum circuit model
        - MLFT: sampling field configuration with machine learning method
    - can serve as a SDK for quantum computing platform