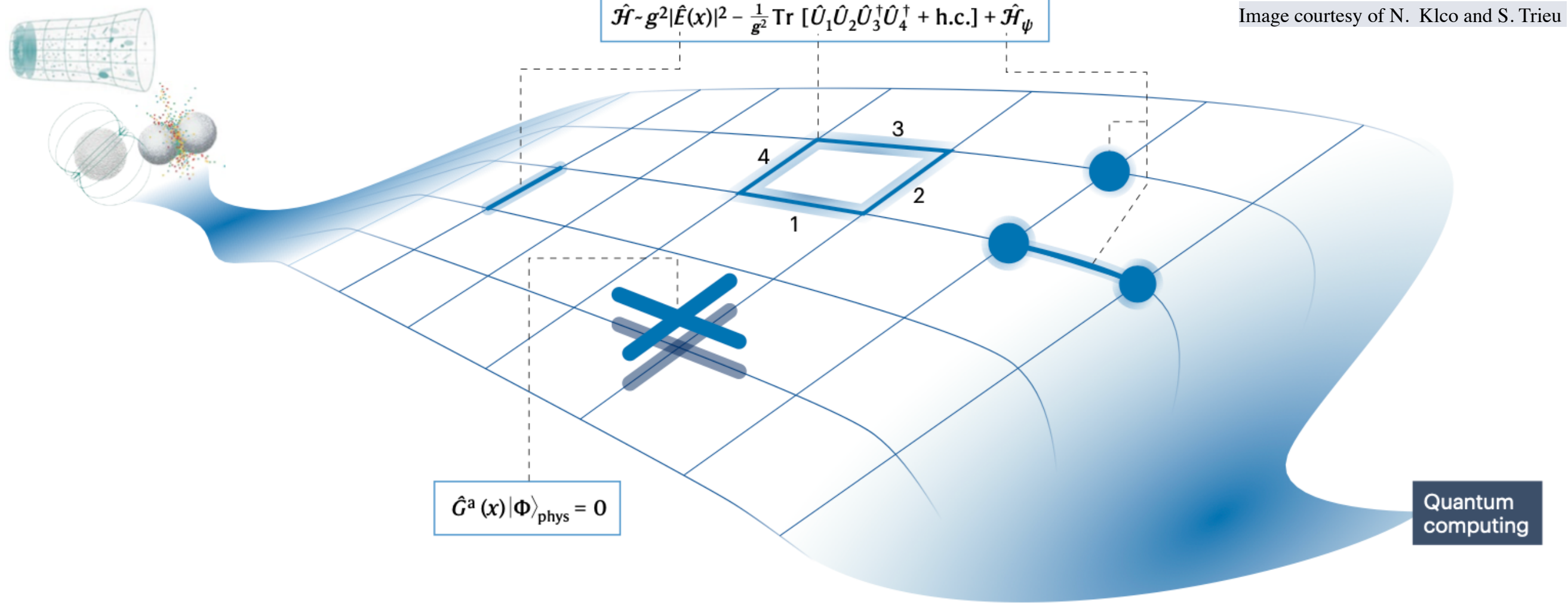
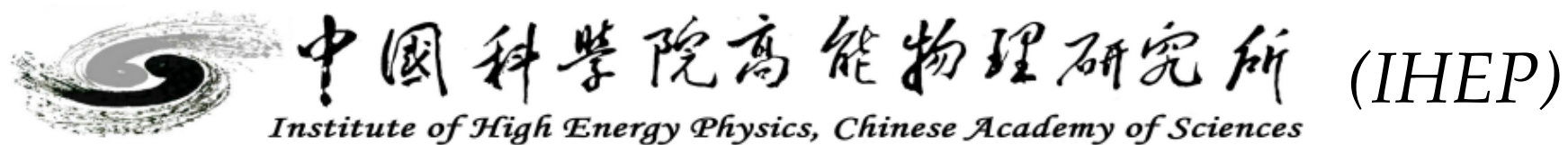




量子计算在 高能物理中的应用

Ying-Ying Li (李英英)



[Carena, Lamm,YYL, Liu, arXiv:2402.16780]

[Carena, YYL, Ou, Singh, arXiv: 2412.10365]

[Cao, Hou,YYL, Liu, Song, Zhang, Zhang, Zhao, arXiv:2505.06347]

第三届有道
真论研讨会

质子-质子对撞机上的物质演化

簇射和强子化

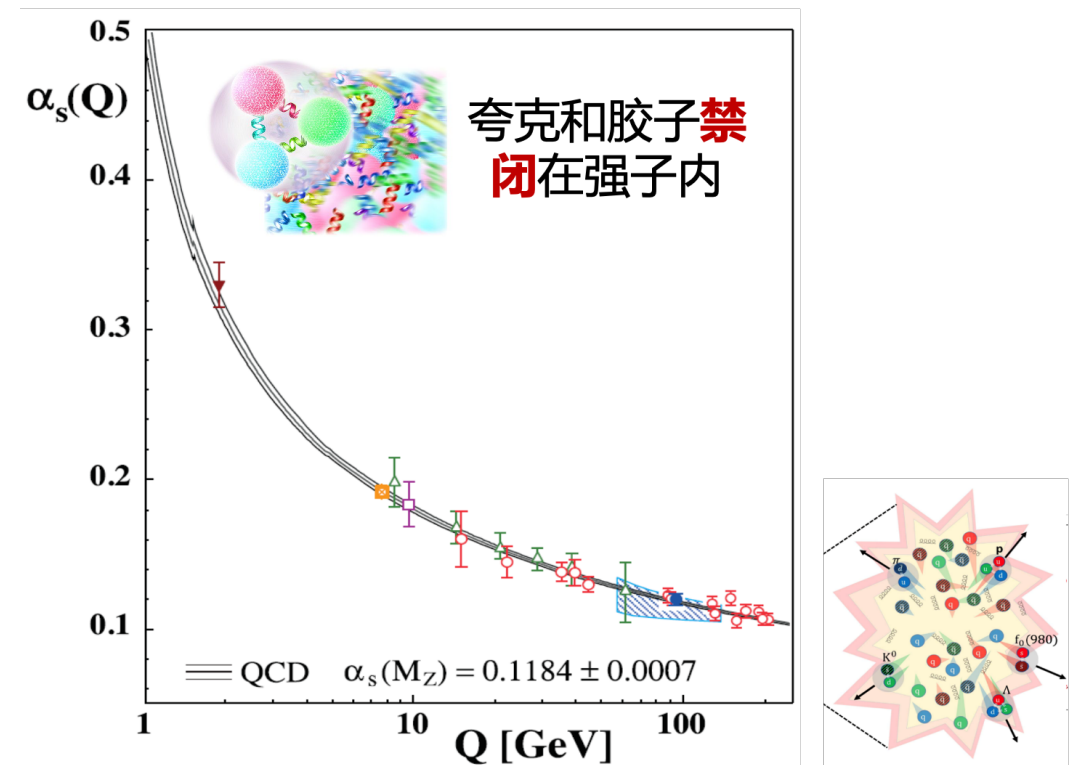
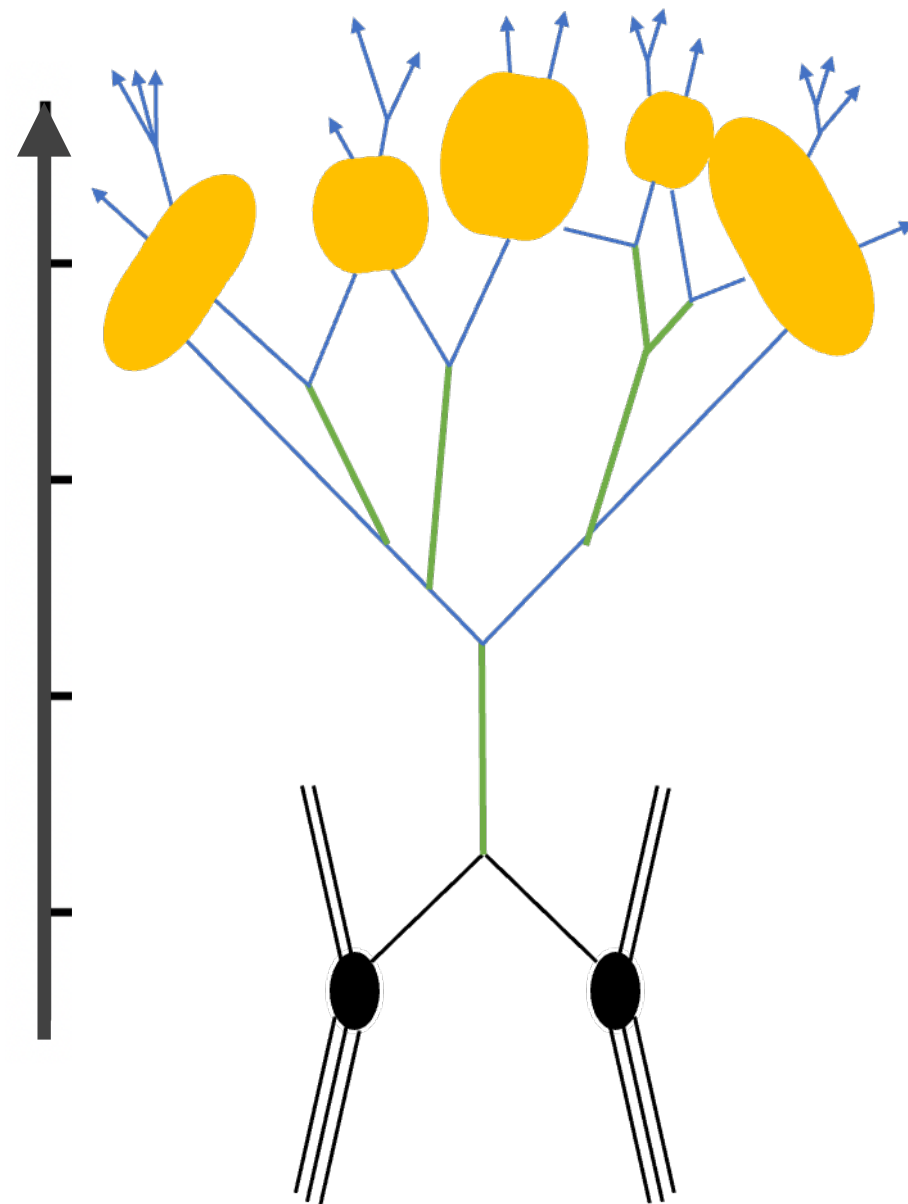
GeV

$n \sim 10^3$

TeV

PDF

~~



Nobel Prize in Physics 2004

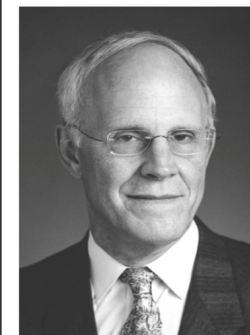


Photo from the Nobel Foundation archive.
David J. Gross



Photo from the Nobel Foundation archive.
H. David Politzer



Photo from the Nobel Foundation archive.
Frank Wilczek

理论上的突破性发现 – 渐进自由
(1973)

非微扰区域

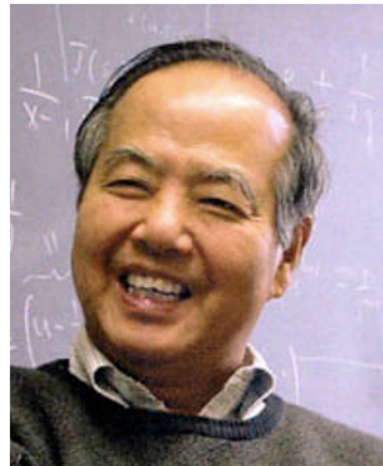
Nuclear Physics A538 (1992) 3c-14c
North-Holland, Amsterdam

NUCLEAR
PHYSICS A

MISSING SYMMETRIES, UNSEEN QUARKS
AND THE PHYSICAL VACUUM

T. D. Lee

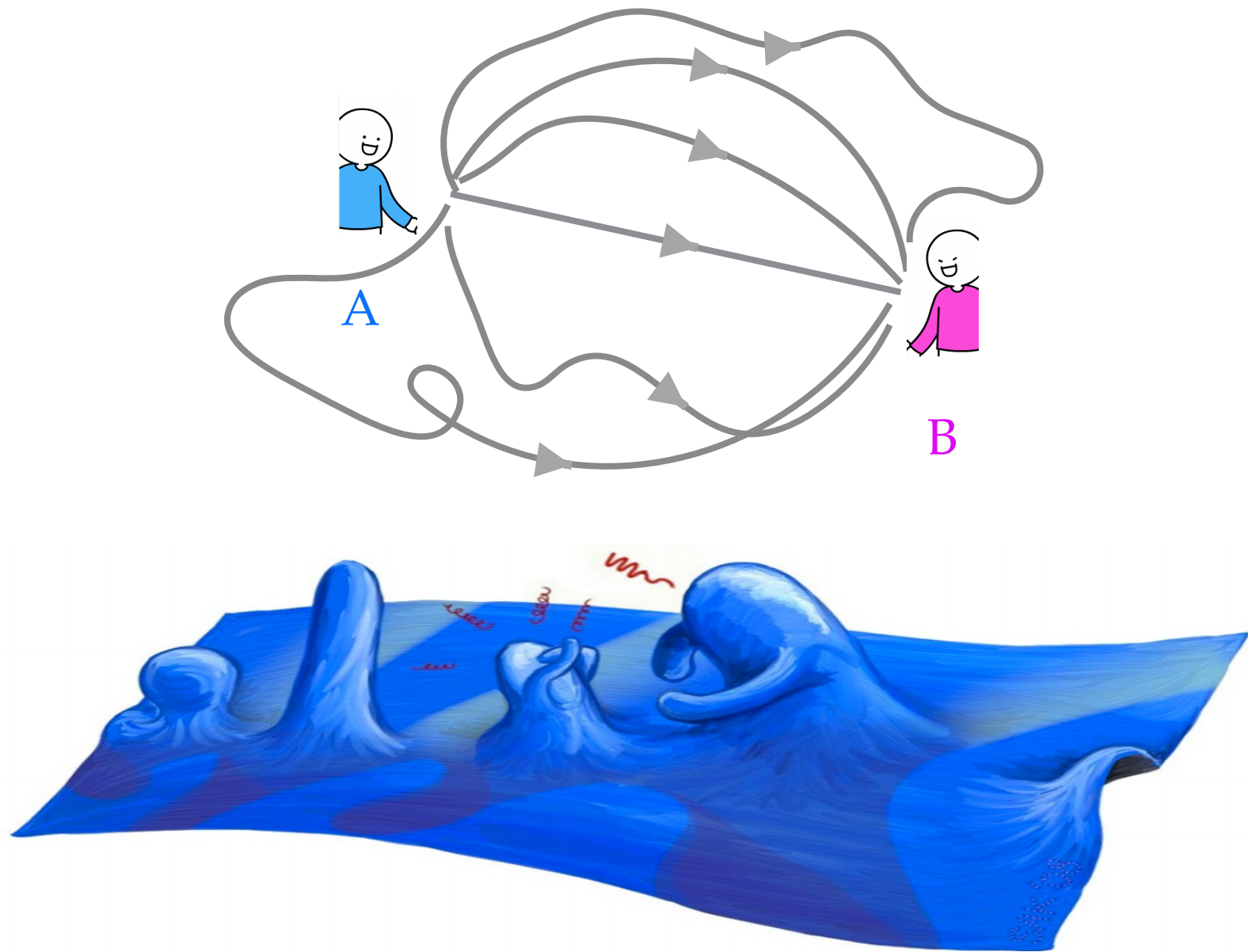
Columbia University, New York, N.Y. 10027



禁闭是如何发生的？
二十世纪末物理学的疑难问题

非微扰量子场论 — 格点QCD

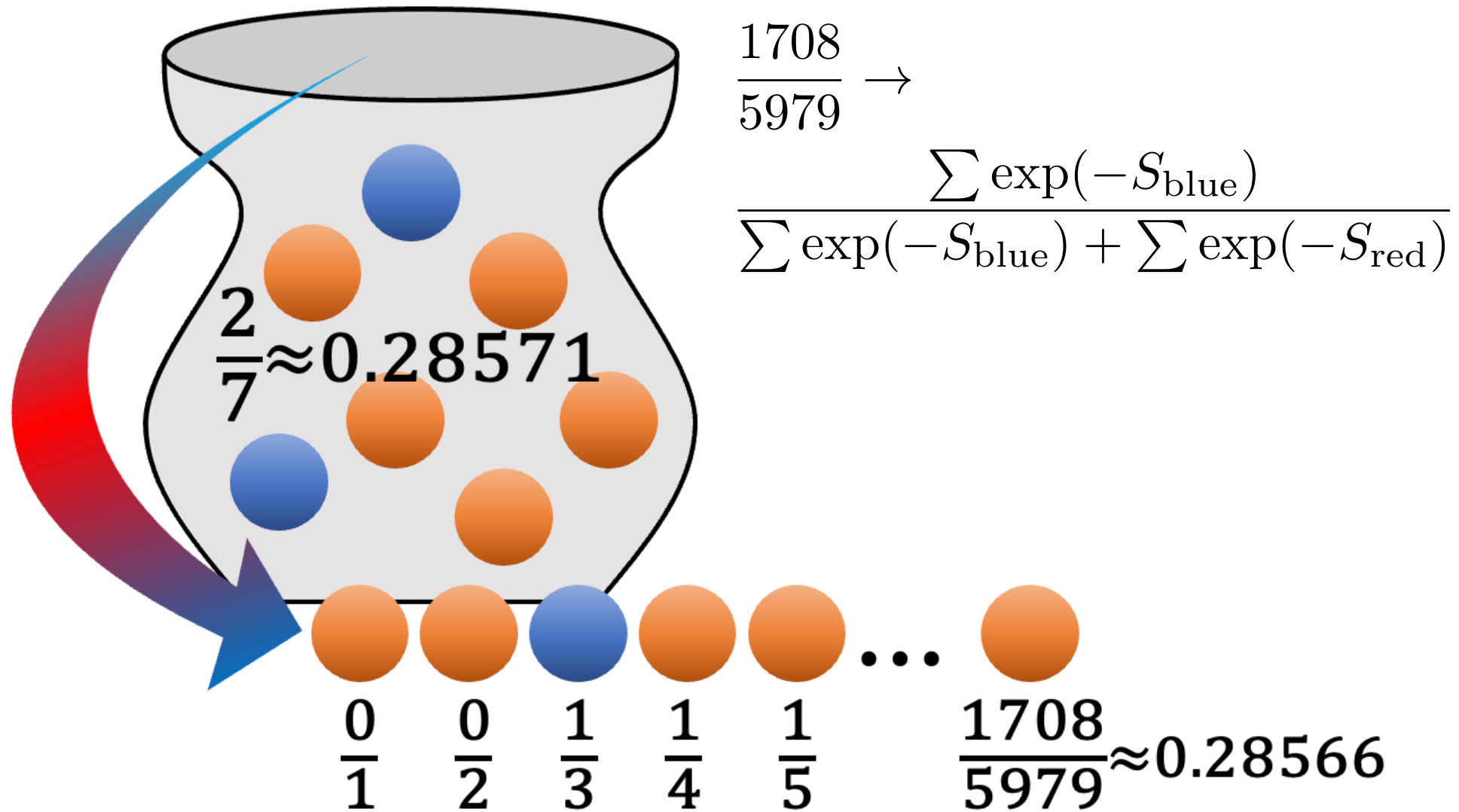
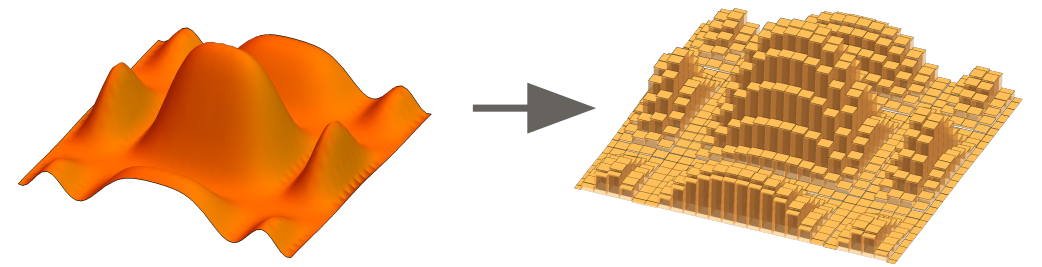
Relativistic Quantum Mechanics $\longrightarrow$ Quantum Field Theory (QFT)



对量子涨落的所有可能路径进行积分

格点QCD - 经典方法

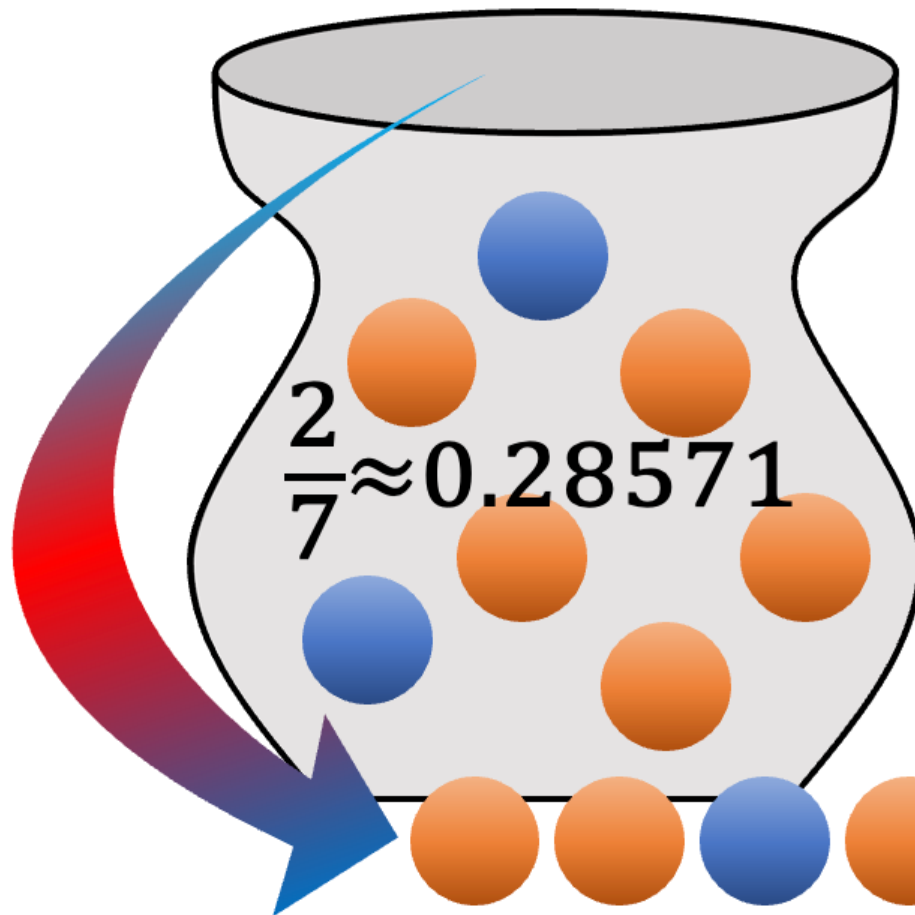
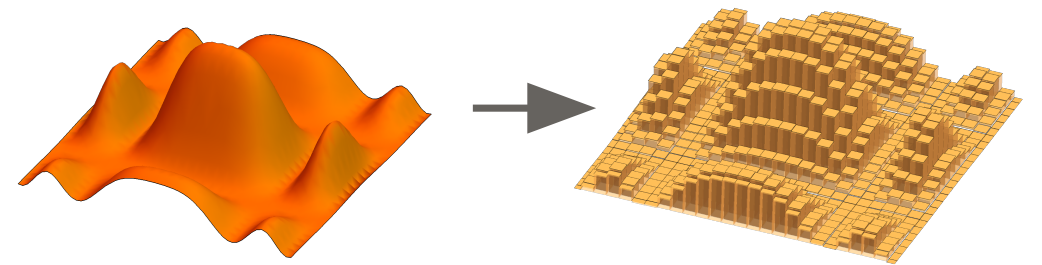
欧氏时空非微扰格点计算
(蒙特卡罗方法)



蓝球和红球的权重: $W(\mathcal{C}) \sim \exp(-S_{\mathcal{C}})$

格点QCD - 经典方法

欧氏时空非微扰格点计算
(蒙特卡罗方法)



$$\frac{1708}{5979} \rightarrow \frac{\sum \exp(-S_{\text{blue}})}{\sum \exp(-S_{\text{blue}}) + \sum \exp(-S_{\text{red}})}$$

如果 S_C 是虚数呢?

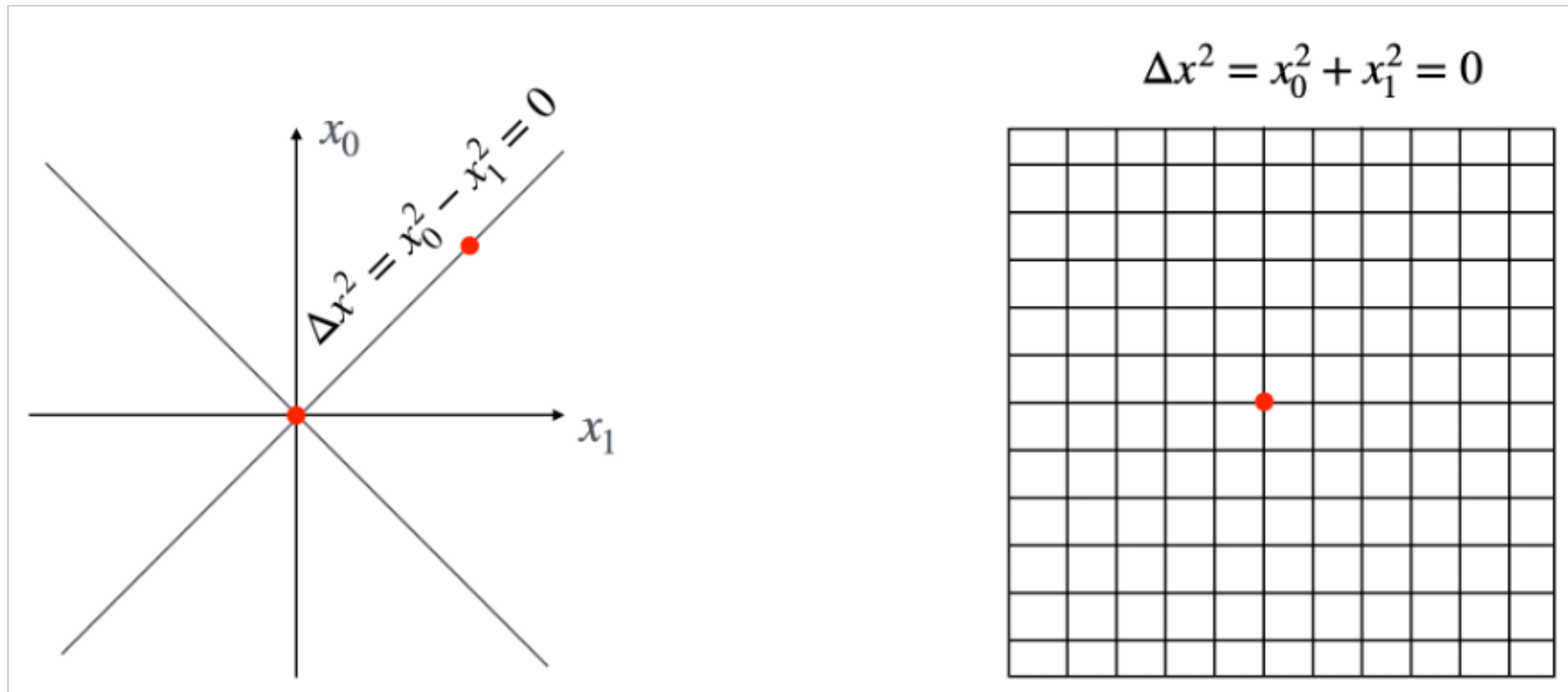
$$\frac{0}{1} \quad \frac{0}{2} \quad \frac{1}{3} \quad \frac{1}{4} \quad \frac{1}{5} \quad \dots \quad \frac{1708}{5979} \approx 0.28566$$

蓝球和红球的权重: $W(C) \sim \exp(-S_C)$

格点QCD - 经典方法

$$f_{q/h}(x) = \int \frac{dz}{4\pi} e^{-ixM_h z} \times \langle h | e^{iHt} \bar{\psi}(0, -z) e^{-iHt} \gamma^+ \psi(0, 0) | h \rangle$$

PDF:光锥上的关联函数 — 闵氏时空问题



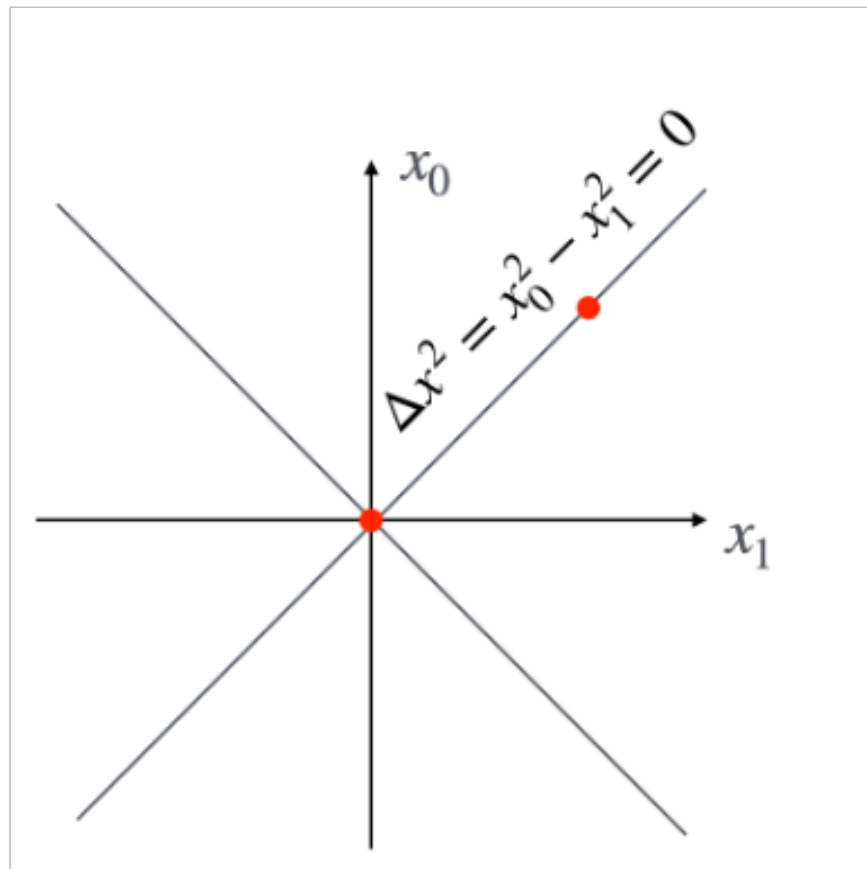
闵氏空间：类光

欧式空间：类空

格点QCD - 经典方法

$$f_{q/h}(x) = \int \frac{dz}{4\pi} e^{-ixM_h z} \times \langle h | e^{iHt} \bar{\psi}(0, -z) e^{-iHt} \gamma^+ \psi(0, 0) | h \rangle$$

PDF: 光锥上的关联函数 — 闵氏时空问题



闵氏空间：类光

$$\int \mathcal{D}\phi e^{iS}$$

complex $S(\mathcal{C})$

蒙特卡罗采样
“符号问题”

configuration space $\mathcal{C}$ is
exponentially large in system size

system size N_V : number of lattice sites

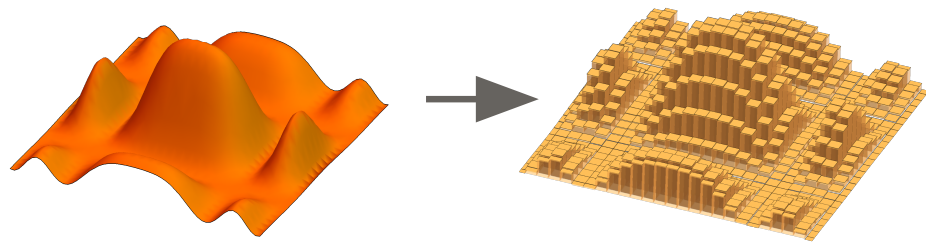
格点QCD - 量子计算方法

量子场论

实时空非微扰计算-量子模拟

格点非微扰计算 — 闵氏时空

$$\int \mathcal{D}\phi e^{iS} = \langle x | e^{-iHt} | y \rangle$$



$$\dim H \propto |G|^{N_V}$$

所需经典比特数: $N_b \propto |G|^{N_V}$
(*CLASSICAL HARD*)

From 1970s Phys. Rev. D 11, 395 (1975) KS Hamiltonian



1982



所需量子比特数: $N_q \propto N_V \log |G|$
(*QUANTUM EASY*)

Simulating Physics with Computers

Richard P. Feynman

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

Received May 7, 1981

...nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy...

格点QCD - 量子计算方法

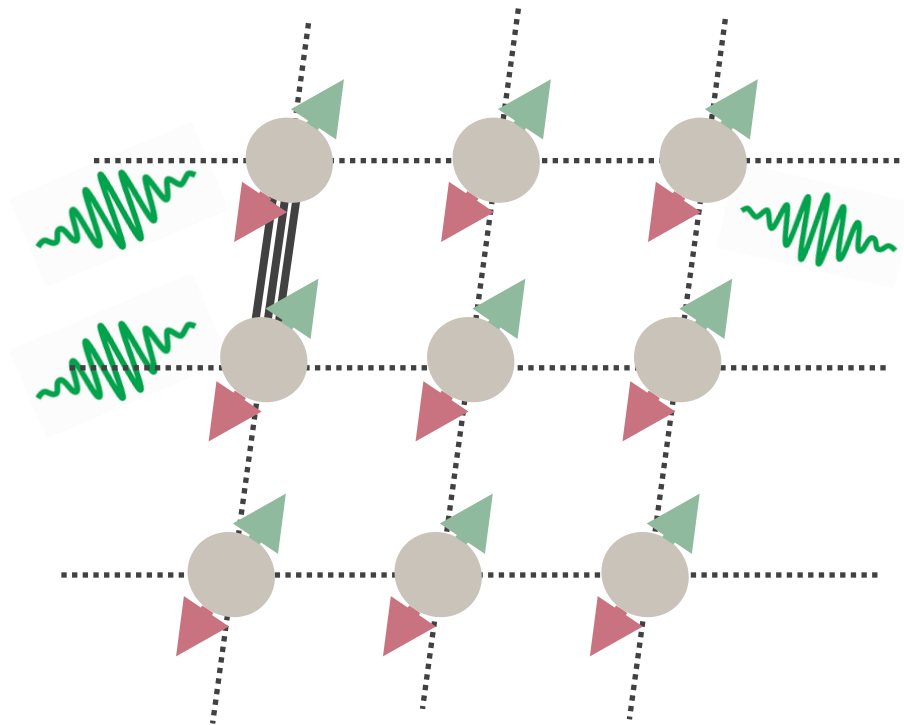


1996 - Seth Lloyd: efficient simulation of **LOCAL** Hamiltonians

Universal Quantum Simulators

Seth Lloyd

Feynman's 1982 conjecture, that quantum computers can be programmed to simulate any local quantum system, is shown to be correct.



$$N(\text{wavy line}) \propto N_q^m$$

Polynomial Time Complexity

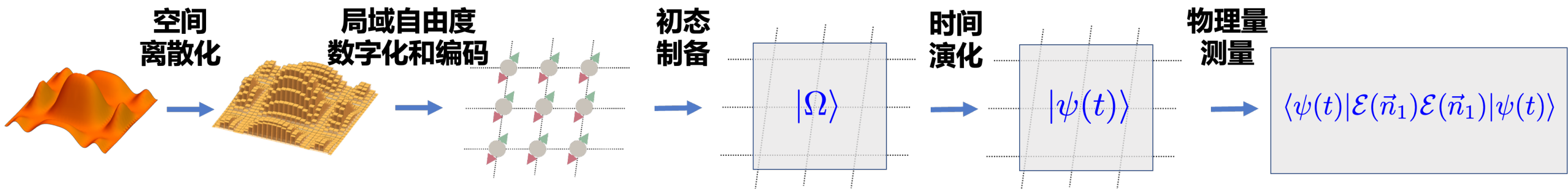
格点QCD - 量子计算方法



1996 - Seth Lloyd: efficient simulation of **LOCAL** Hamiltonians



[Jordan, Lee, Preskill, 2011]



时间复杂度为多项式形式的**标量场**量子模拟方法

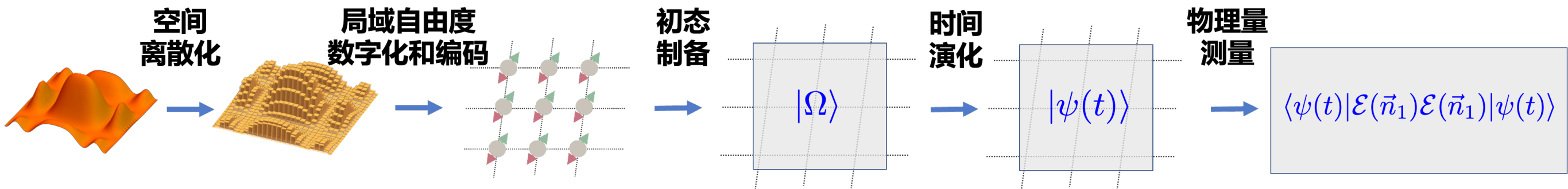
格点QCD - 量子计算方法



1996 - Seth Lloyd: efficient simulation of **LOCAL** Hamiltonians



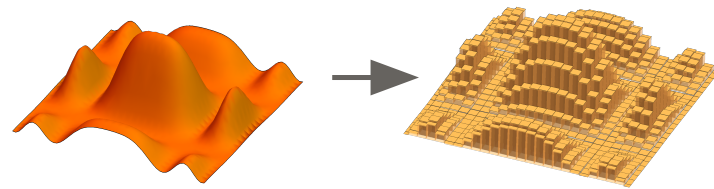
[Jordan, Lee, Preskill, 2011]



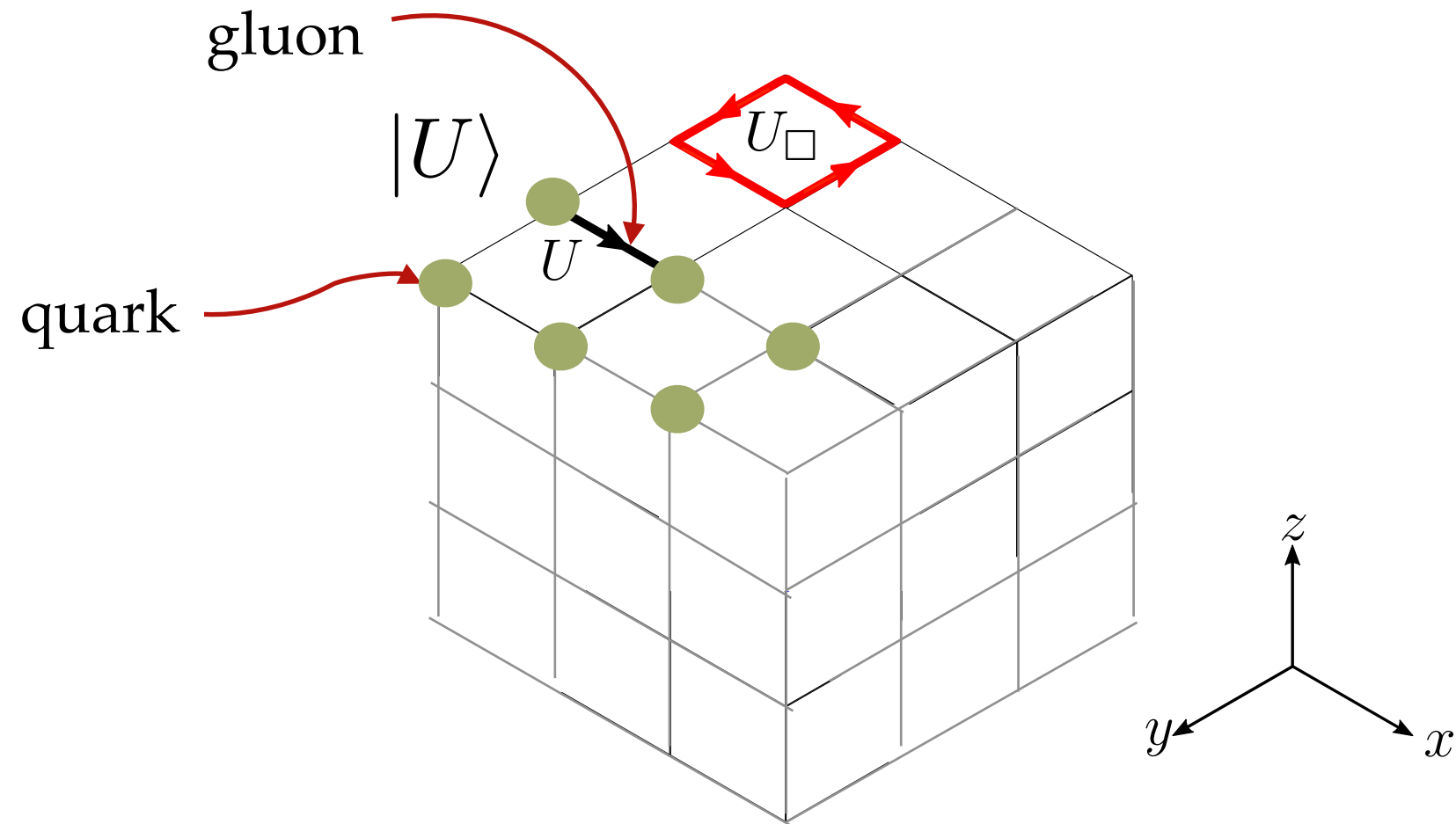
时间复杂度为多项式形式的**标量场**量子模拟方法

Q: 非阿贝尔规范场和费米子场量子模拟方法是什么?

Discretization



infinities in QFT



Gauge invariant Hamiltonian
in terms of gluon field operators
(second quantization)

KS Hamiltonian Phys. Rev. D 11, 395 (1975)

$$H_{KS} = \sum \left(\underbrace{\longrightarrow}_{K_L} + \underbrace{\square}_{U_{\square}} + \underbrace{\bullet \longrightarrow \bullet}_{\psi_i^\dagger U_{ij} \psi_j} + \underbrace{\bullet \bullet}_{m \psi_i^\dagger \psi_i} \right)$$

$$H_{KS} \xrightarrow{a \rightarrow 0} H = \int dx (E^2 + B^2)$$

Digitization

数字化-非阿贝尔规范场：对称性

infinities in field variables

Formulations & bases: examples

Kogut-Susskind Formulation

- Irrep / angular momentum basis: *Byrnes, Yamamoto, Zohar, Burrell, et al*
- Group-element basis: *Carena, Lamm, YYL, Liu, Zohar, et al.*
- Mixed basis: *Bauer, D'Andrea, Freytsis, Grabowska*
- Large N truncations: *Bauer, Ciavarella*
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Casimir variables: *Klco, Savage, Stryker, Ciavarella*

Schwinger boson formulations: *Mathur, Anishetty, Raychowdhury, et al*

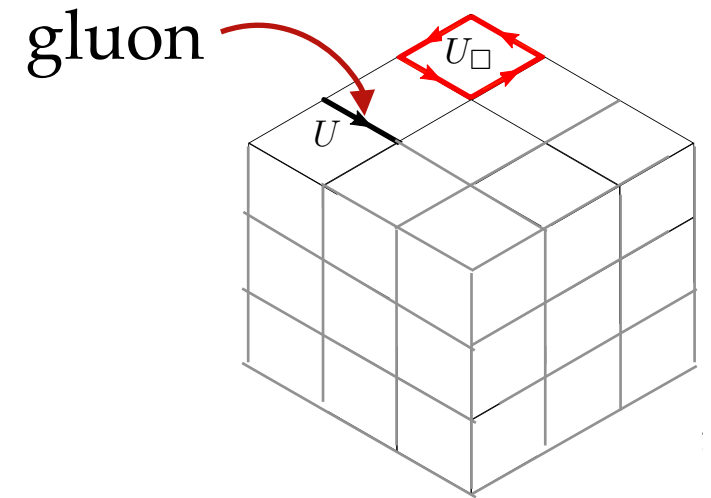
Loop-string-hadron formulation: *Raychowdhury, Stryker, Davoudi, Kadam, et al.*

Qubit models: *Chandrasekhara, Singh, et al.*

Dual/rotor formulations: *Kaplan, Stryker, Haase, et al.*

q-deformed Kogut-Susskind: *Zache, Zoller et al*

Dual/rotor formulations: *Kaplan, Stryker, Haase, Dellantonio, et al.*



Theory developments and algorithms are still in very early stages, vibrant research directions

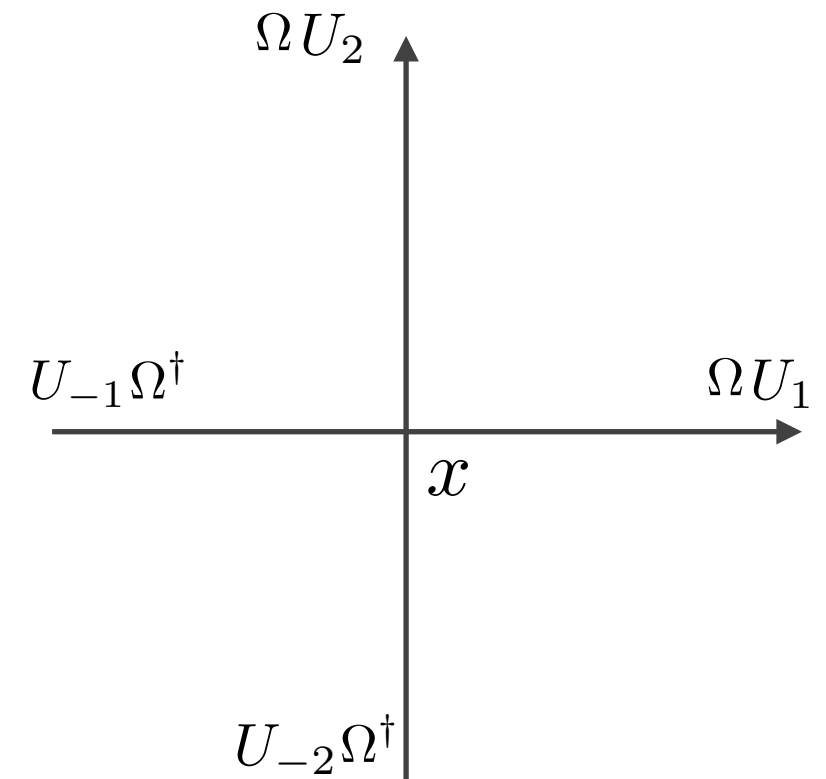
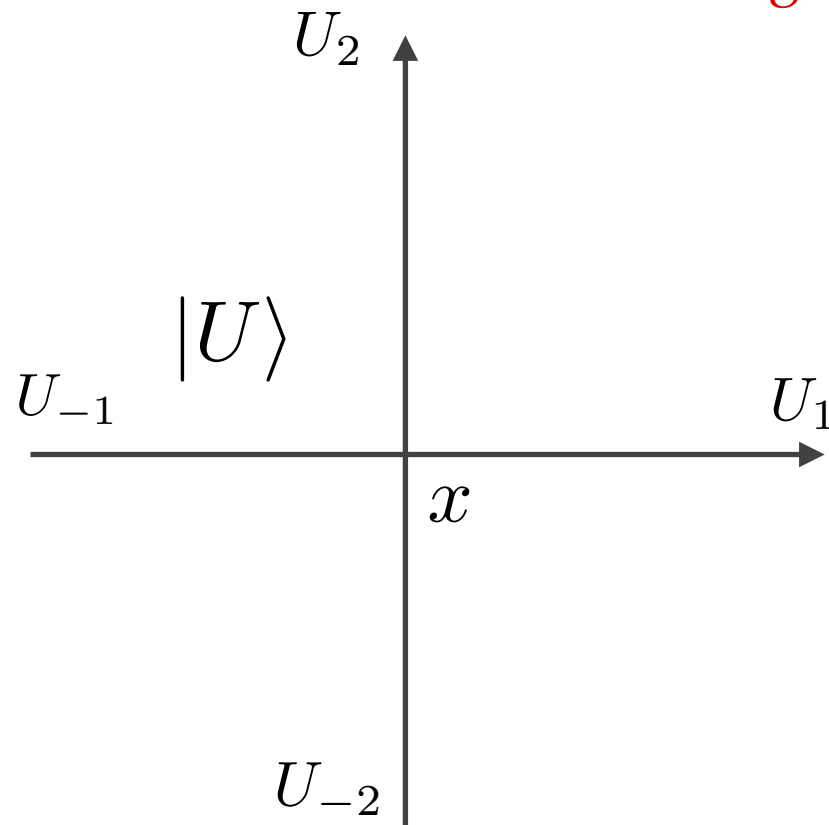
Digitization

$$|q\rangle^N \rightarrow |G\rangle$$

infinities in QFT

$$\hat{\Theta}_\Omega(x) = \exp(i\phi(\Omega)\hat{G}^a(x))$$

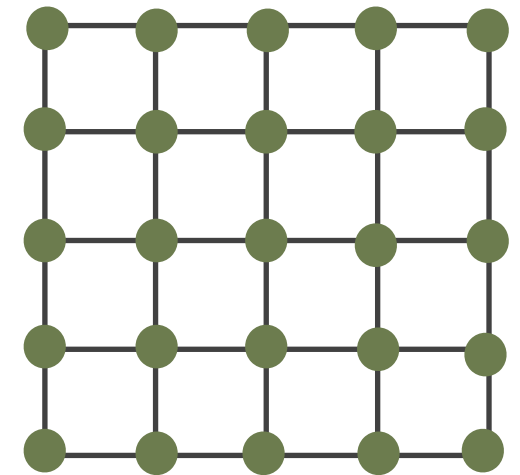
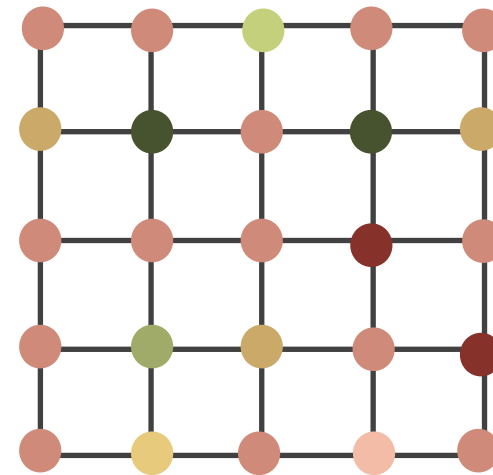
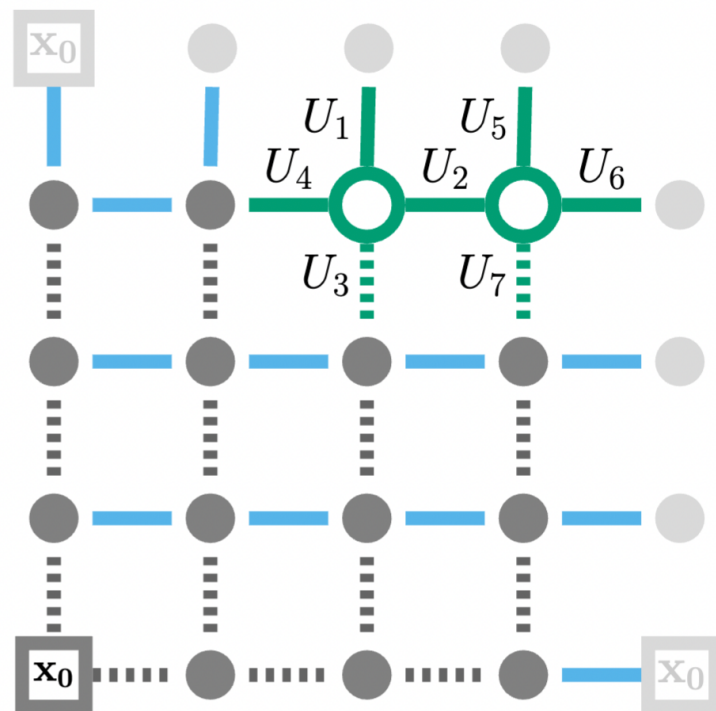
$\xrightarrow{\text{gauge transformation}}$



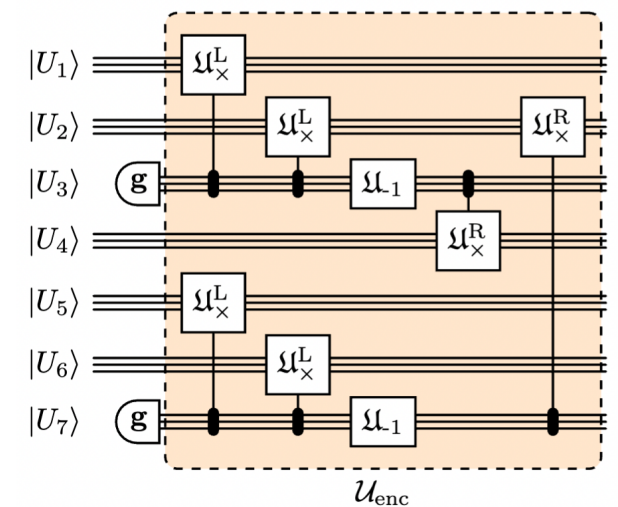
gauge equivalent states

$$\hat{\Theta}_\Omega(x) |U_{-1}U_1U_{-2}U_2\rangle = |U'_{-1}U'_1U'_{-2}U'_2\rangle$$

How to do gauge fixing...



Prepare gauge-invariant states
(gauge fixing)

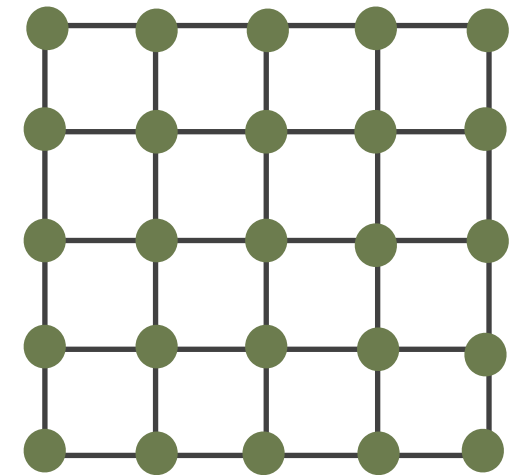
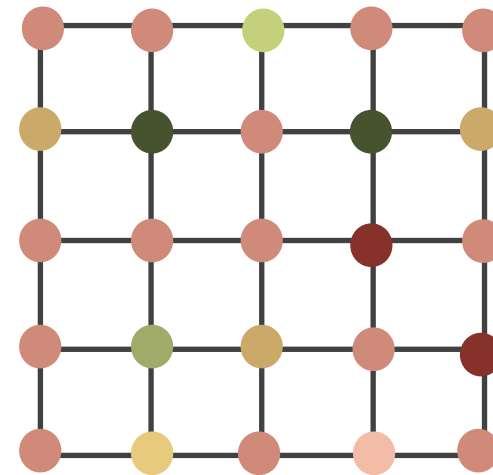
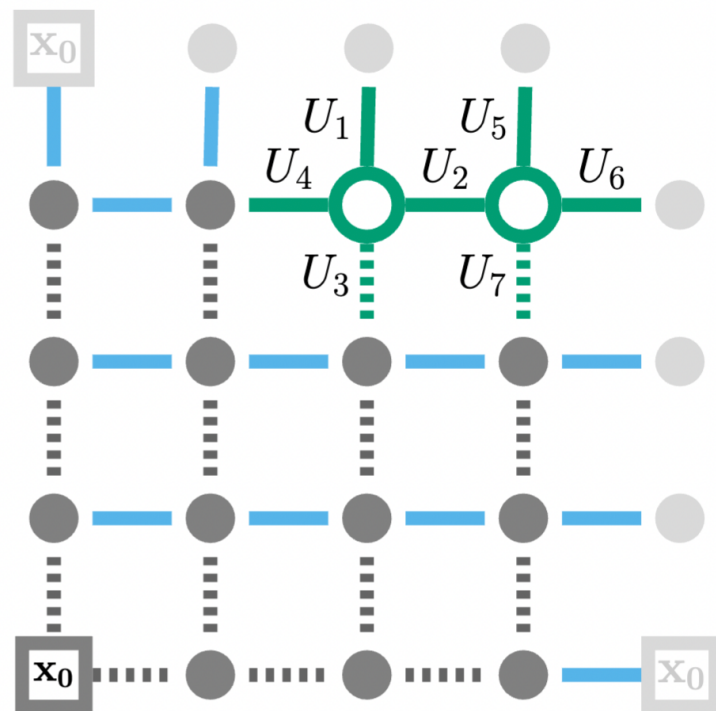


Digitization

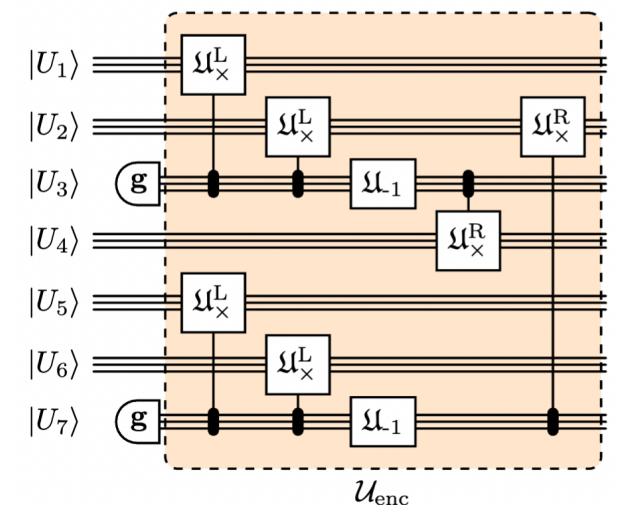
$$|q\rangle^N \rightarrow |G\rangle$$

infinities in QFT

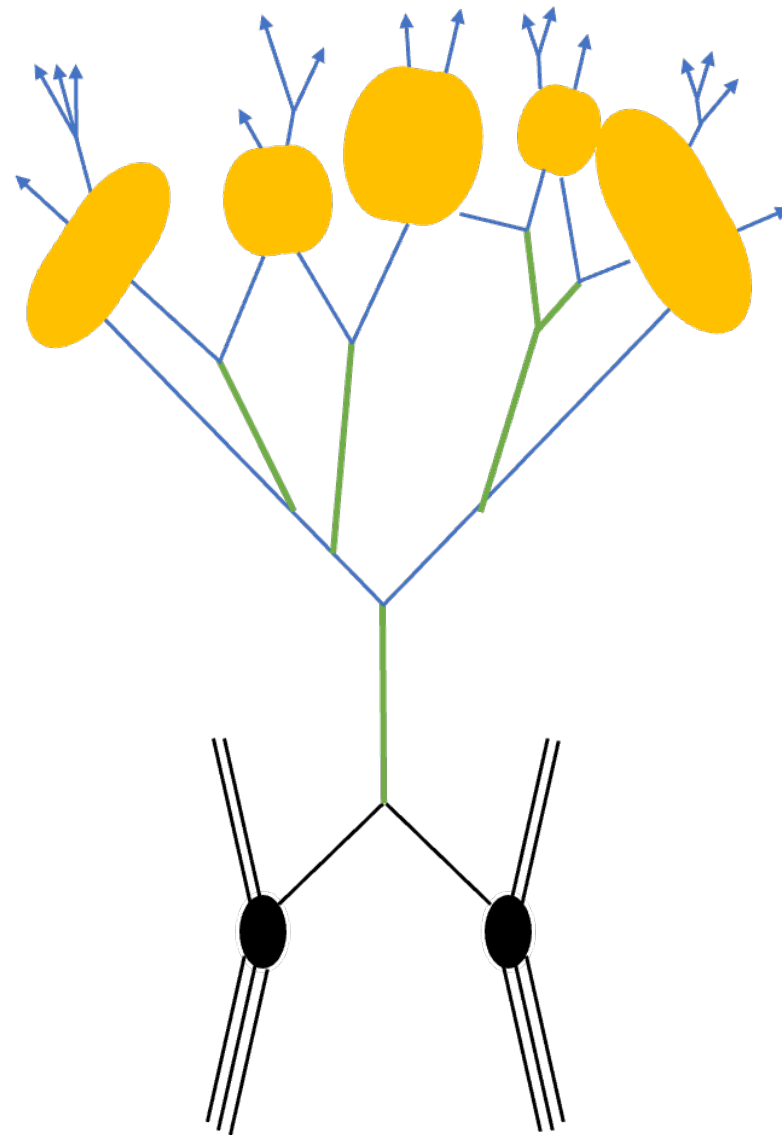
How to do gauge fixing...



Prepare gauge-invariant states
(gauge fixing)

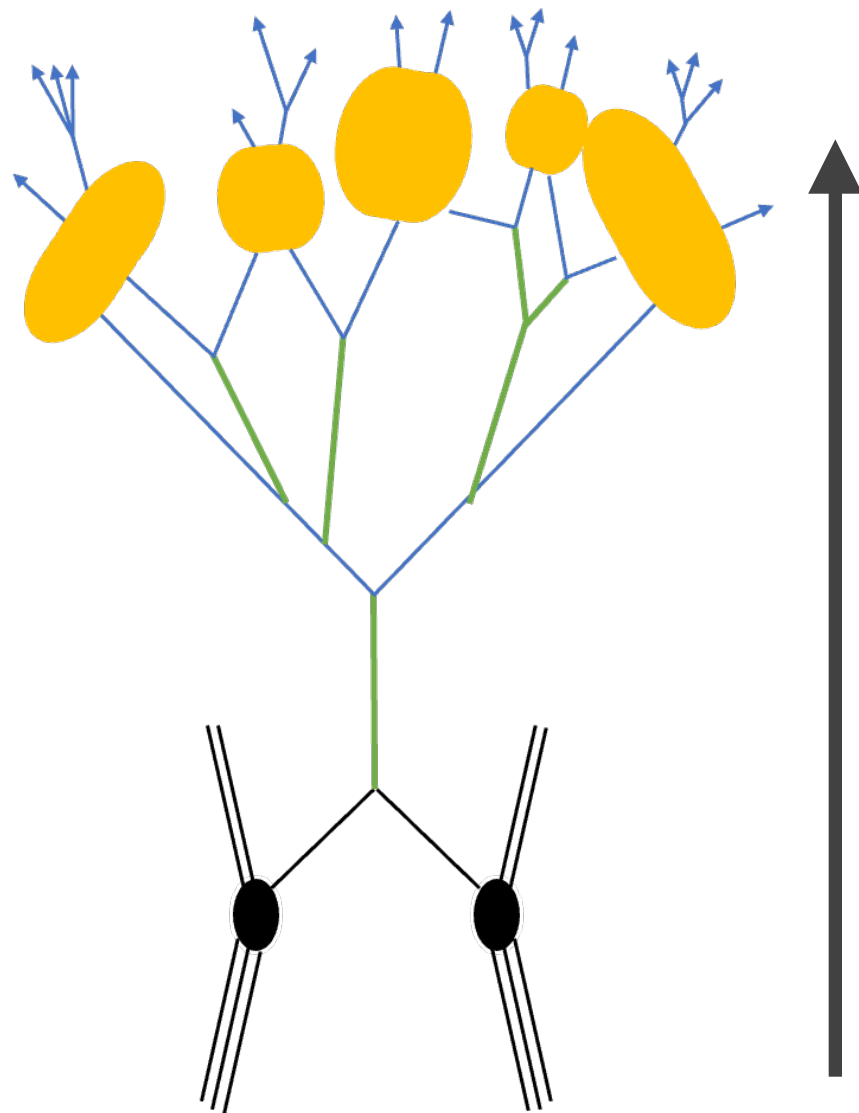


Initial State Preparation $\mathcal{U} |G\rangle^L \rightarrow |\psi_0\rangle$



*How to prepare proton states from
quarks and gluons? Inverse problem of PDF!!*

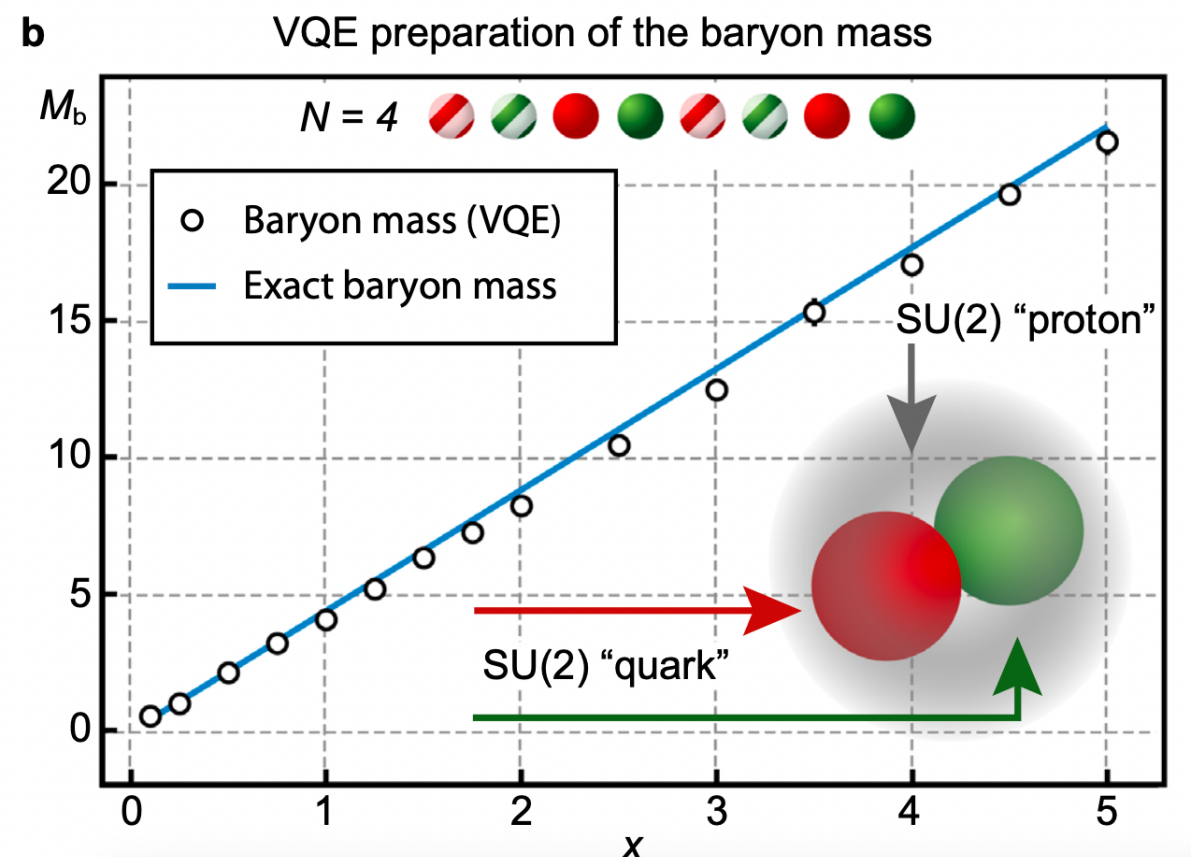
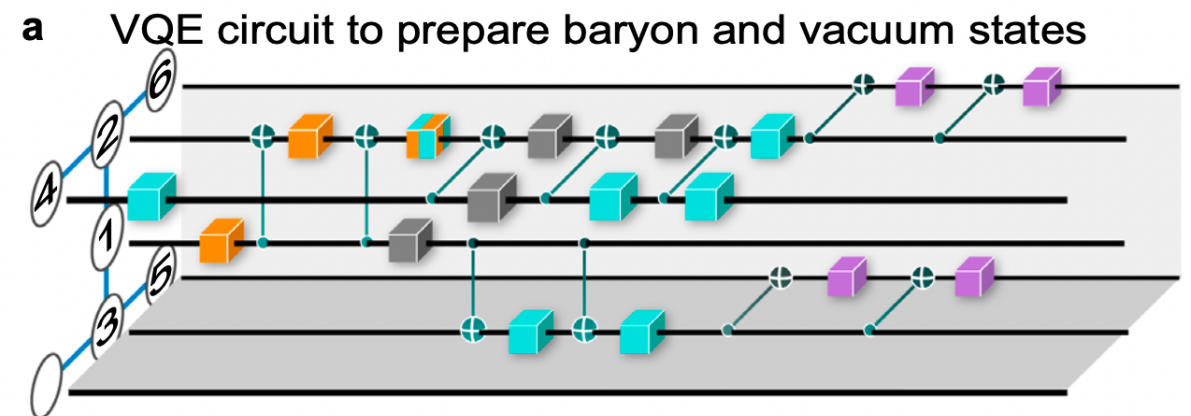
Initial State Preparation $\mathcal{U} |G\rangle^L \rightarrow |\psi_0\rangle$



How to prepare proton states from quarks and gluons?

*VQA
ansatz*

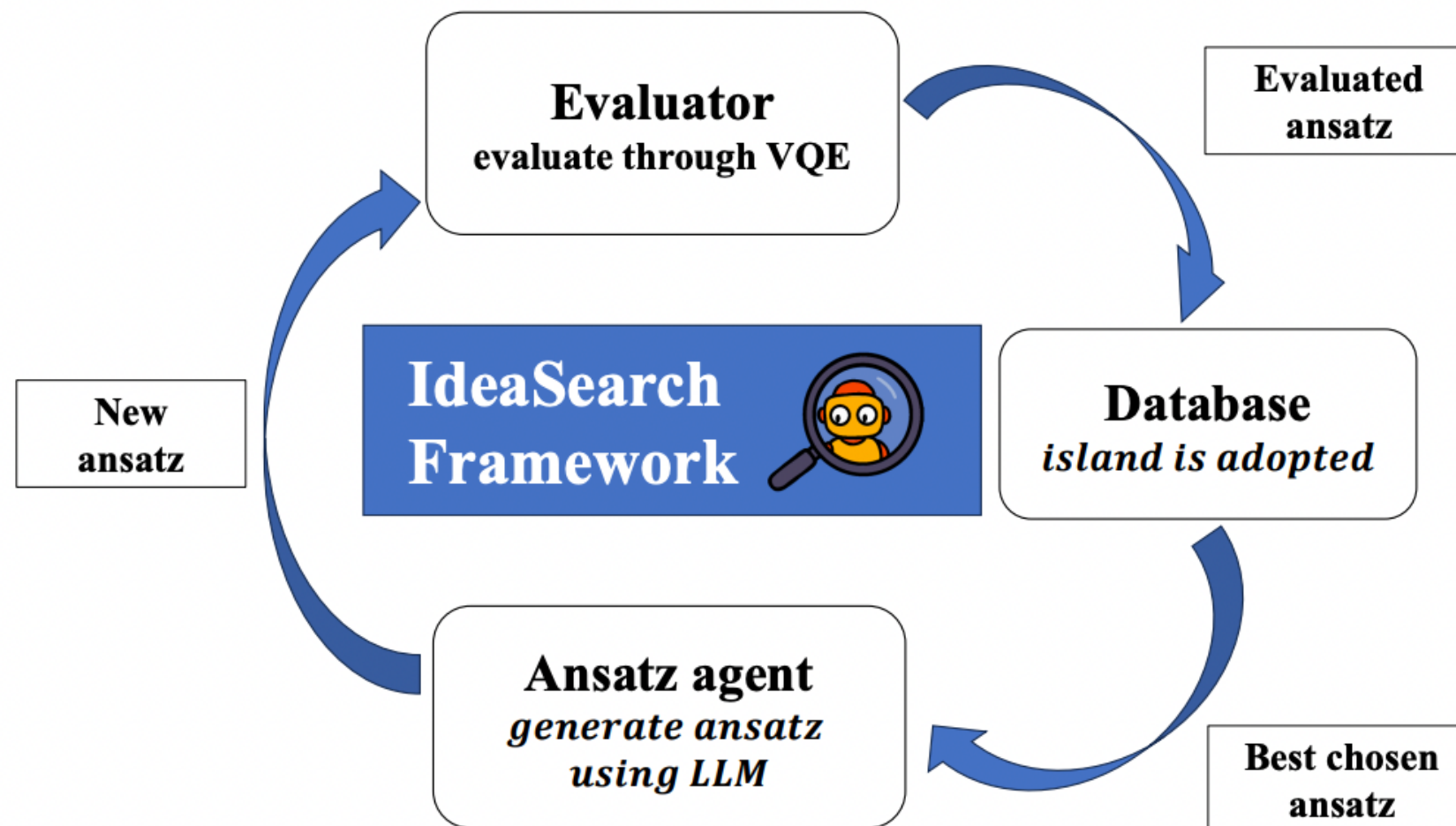
*ground state for the sector with $B = 1$
Variational Quantum Algorithms (VQA)*



Initial State Preparation $\mathcal{U} |G\rangle^L \rightarrow |\psi_0\rangle$

*LLM Helps to find
proper VQA
ansatz from scratch*

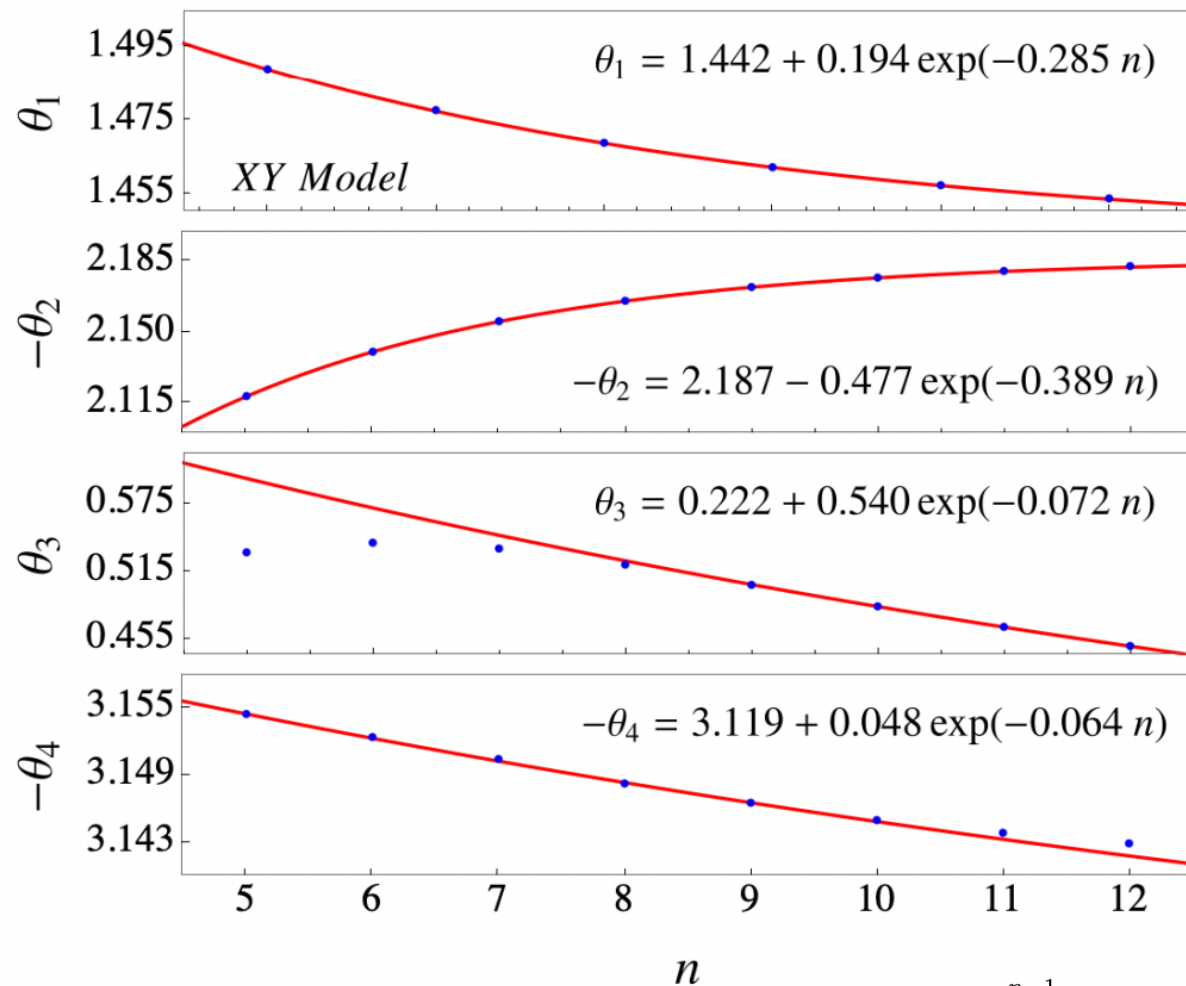
scalability



Initial State Preparation $\mathcal{U} |G\rangle^L \rightarrow |\psi_0\rangle$

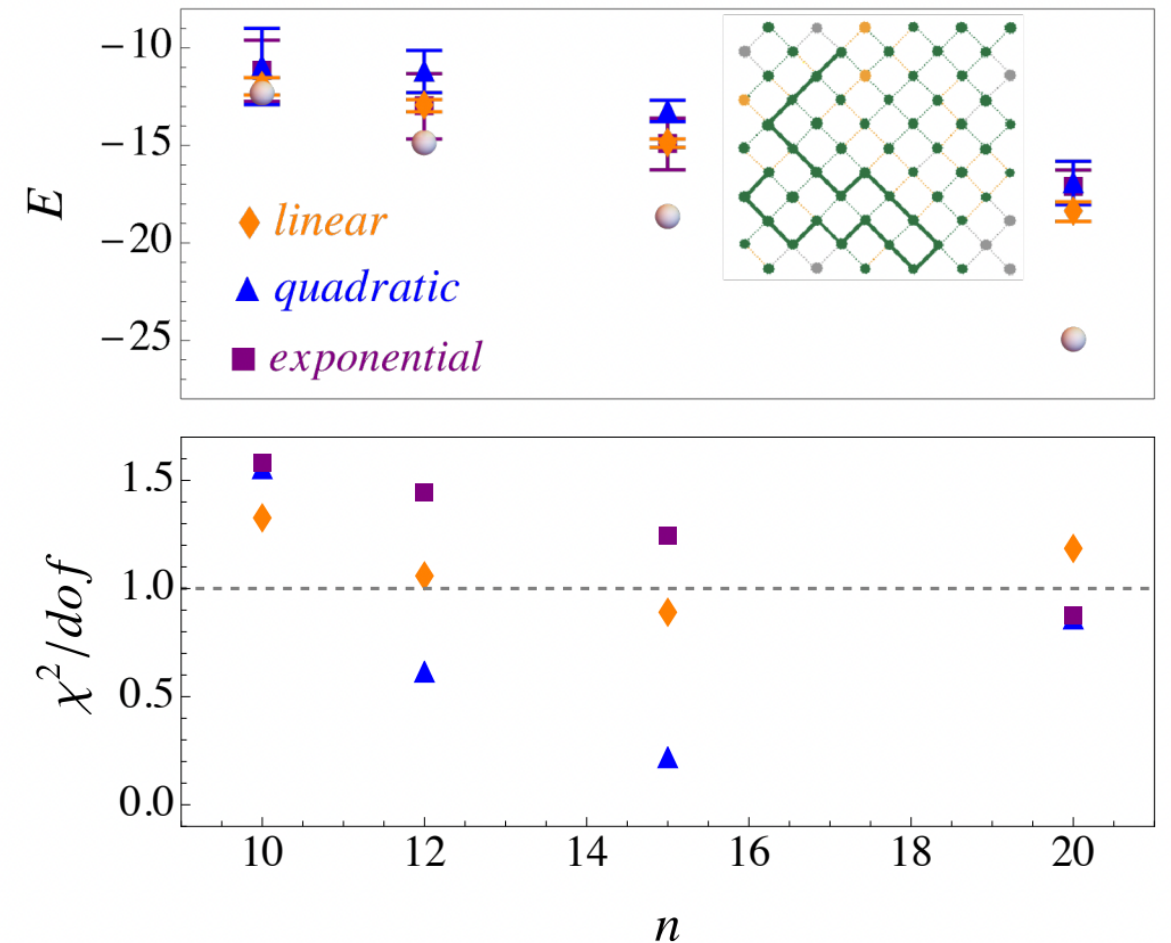
*LLM Helps to find
proper VQA
ansatz from scratch*

scalability



$$H_{XY} = \sum_i^{n-1} \left(\frac{1+\gamma}{2} \sigma_i^x \sigma_{i+1}^x + \frac{1-\gamma}{2} \sigma_i^y \sigma_{i+1}^y \right) + g_z \sum_i \sigma_i^z$$

Practicality in the NISQ era



Initial State Preparation $\mathcal{U} |G\rangle^L \rightarrow |\psi_0\rangle$

*LLM Helps to find
proper VQA
ansatz from scratch*

scalability

arXiv > quant-ph > arXiv:2505.06347

Search...
Help | Adv...

Quantum Physics
[Submitted on 9 May 2025 (v1), last revised 13 Nov 2025 (this version, v2)]

Scalable Quantum State Preparation via Large-Language-Model-Driven Discovery

Qing-Hong Cao, Zong-Yue Hou, Ying-Ying Li, Xiaohui Liu, Zhuo-Yang Song, Liang-Qi Zhang, Shutao Zhang, Ke Zhao

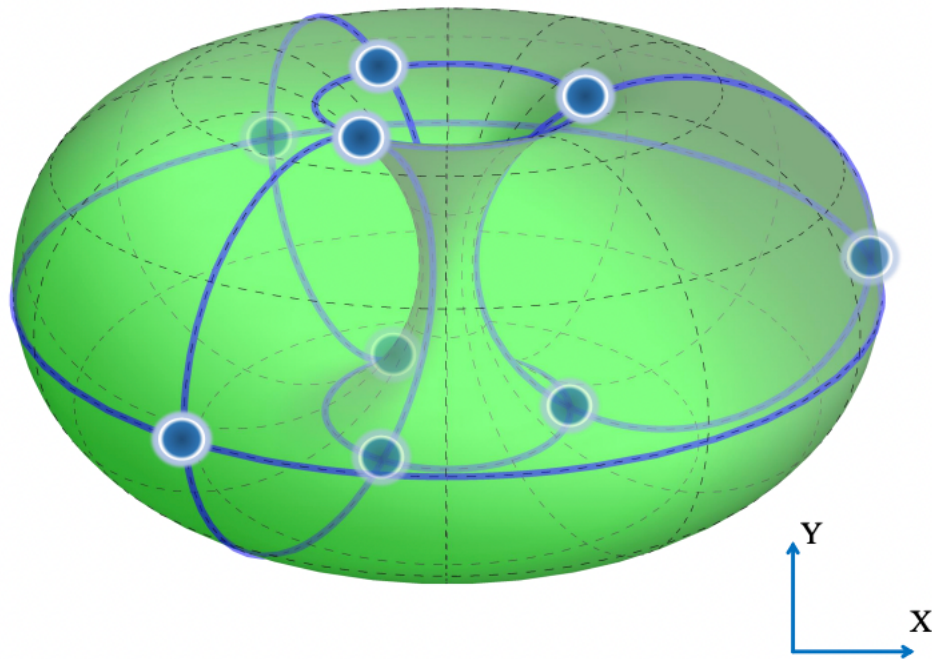
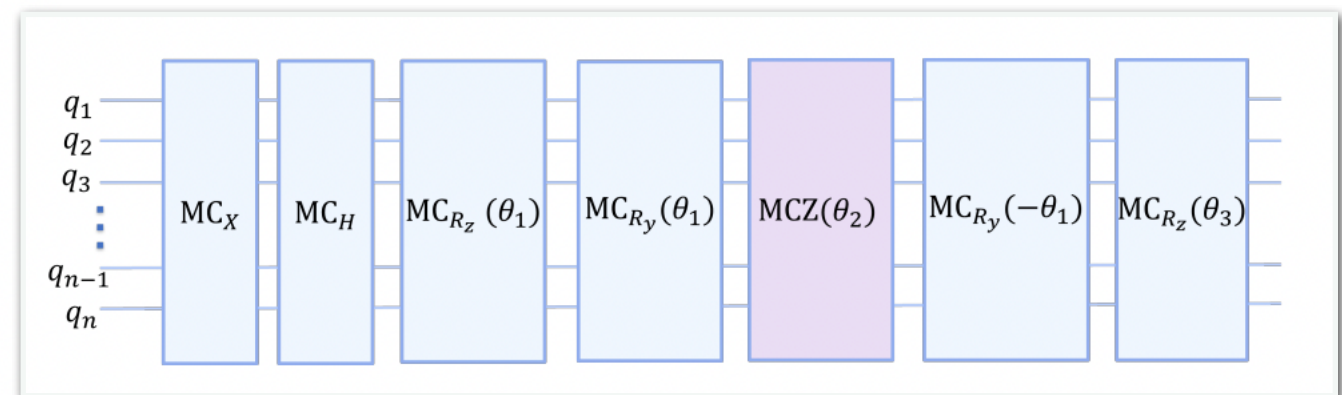


FIG. 5: The geometry of the two-qubit meta-circuit $\text{MCZ}(\theta)$ for the 2+1d scalar field theory.



Metric	LLM Ansatz	Tentative Ansatz
Circuit Depth	24	72
Number of Parameters	3	6
E_{VQE}	8.794	8.771
Fidelity	0.941	0.947

Initial State Preparation $\mathcal{U} |G\rangle^L \rightarrow |\psi_0\rangle$

*LLM Helps to find
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ansatz from scratch*

scalability

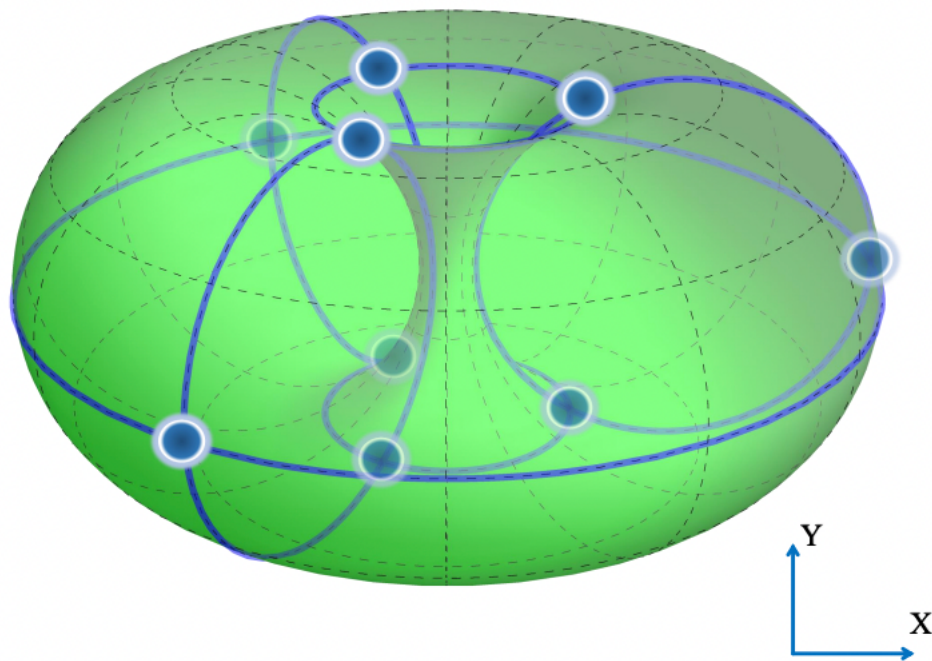
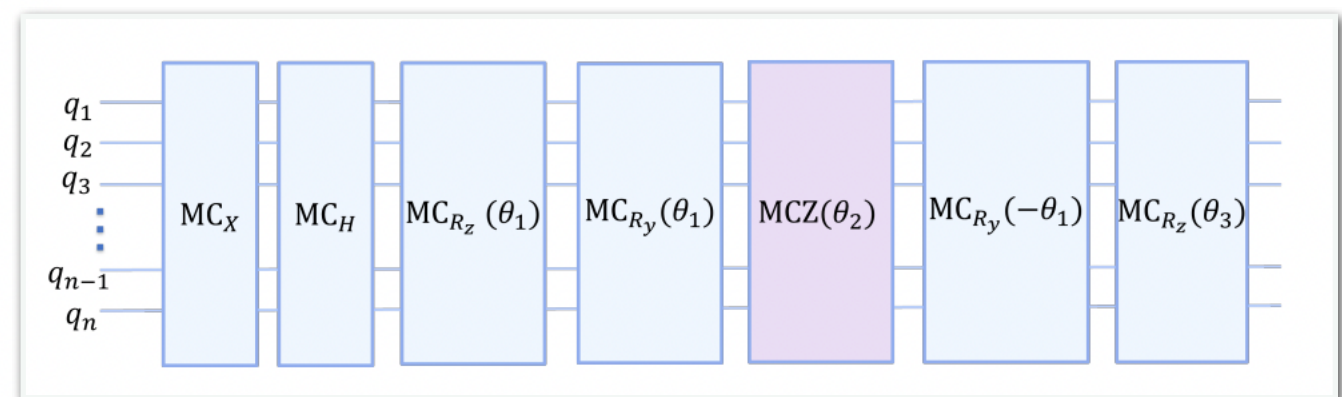


FIG. 5: The geometry of the two-qubit meta-circuit $\text{MCZ}(\theta)$ for the 2+1d scalar field theory.



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Extending to 2+1d non-Abelian gauge theories?

Digitization

数字化-费米子场：对易关系

费米子场：反对易关系

$$\{c_i, c_j^\dagger\} = \delta_{ij}, \quad \{c_i, c_j\} = \{c_i^\dagger, c_j^\dagger\} = 0,$$

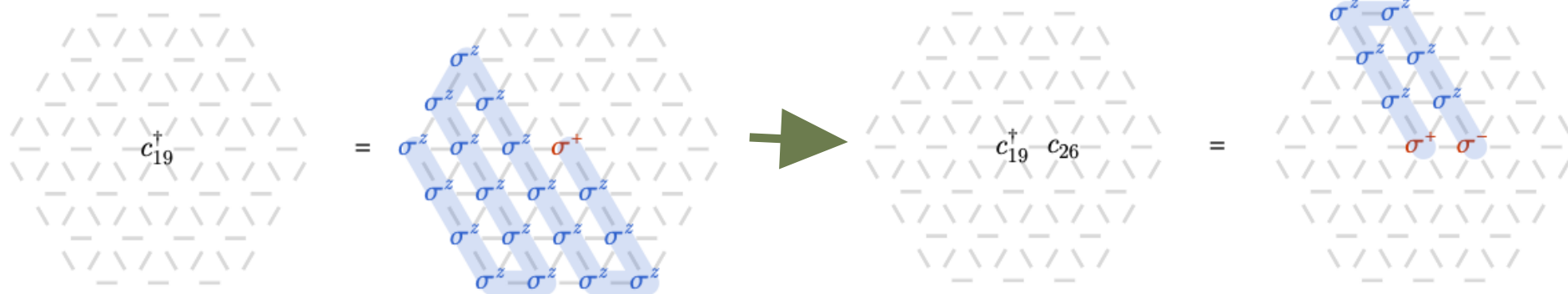
泡利算符：对易关系

$$[\hat{\sigma}_i^+, \hat{\sigma}_j^-] = \delta_{ij} \hat{\sigma}_i^z, \quad [\hat{\sigma}_i^z, \hat{\sigma}_j^\pm] = \pm 2\delta_{ij} \hat{\sigma}_i^\pm$$

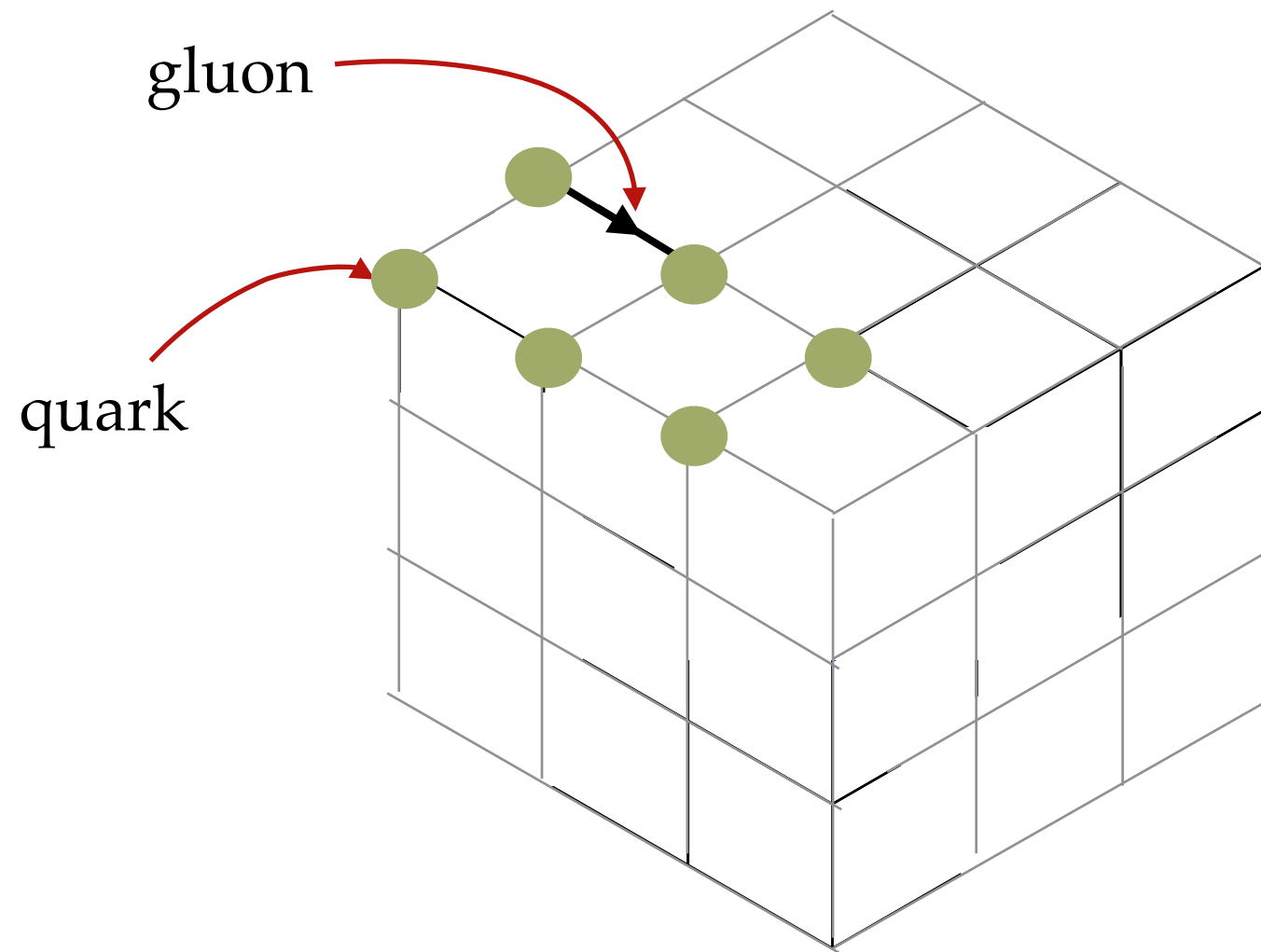
JW变换

$$c_i = \left(\prod_{j < i} \hat{\sigma}_j^z \right) \hat{\sigma}_i^+$$
$$c_i^\dagger = \left(\prod_{j < i} \hat{\sigma}_j^z \right) \hat{\sigma}_i^-$$

高维时空非局域相互作用



非微扰QCD计算量子比特资源估计



spatial dimension d

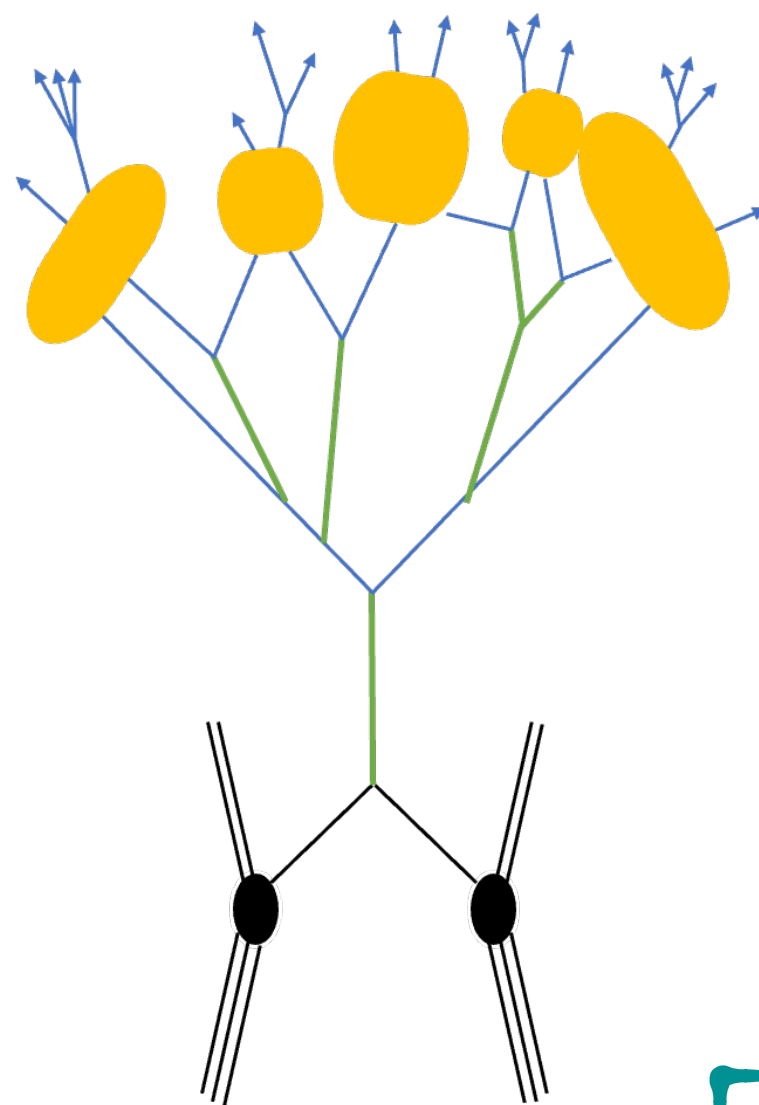
lattice spacing a

$$(na)^{-1} \lesssim E \lesssim a^{-1}$$

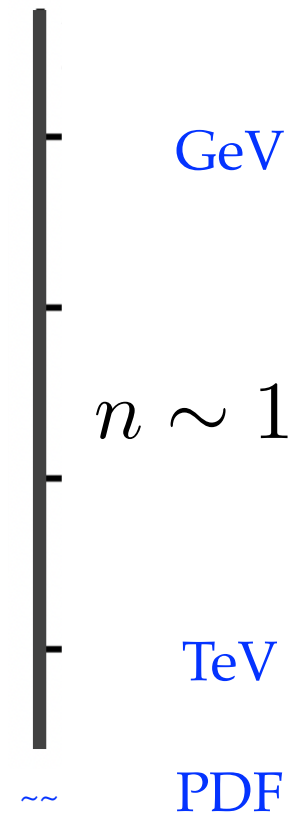
$$\begin{aligned} n_{\text{qubits}} &\sim (n_{\text{gluon}} + n_{\text{quark}}) \times n^d \\ &\sim f \times n^d \end{aligned}$$

•规范场的哈密顿量

infinities in QFT



Energy Scales



$$n \sim 10^3$$

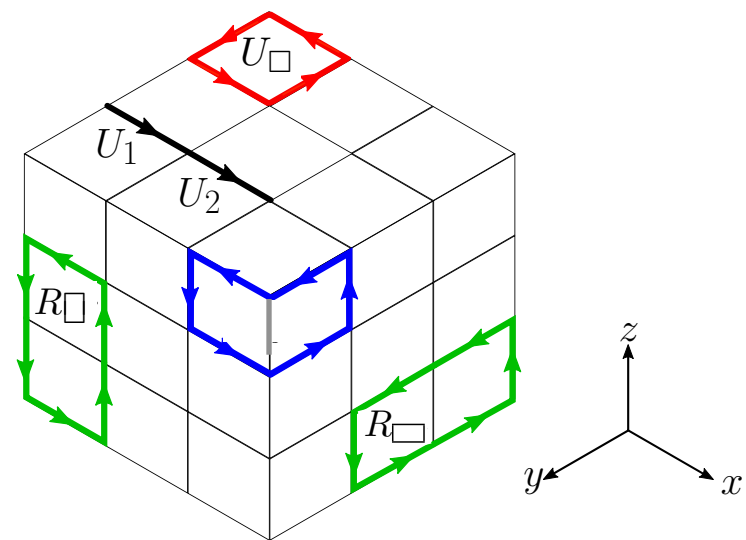
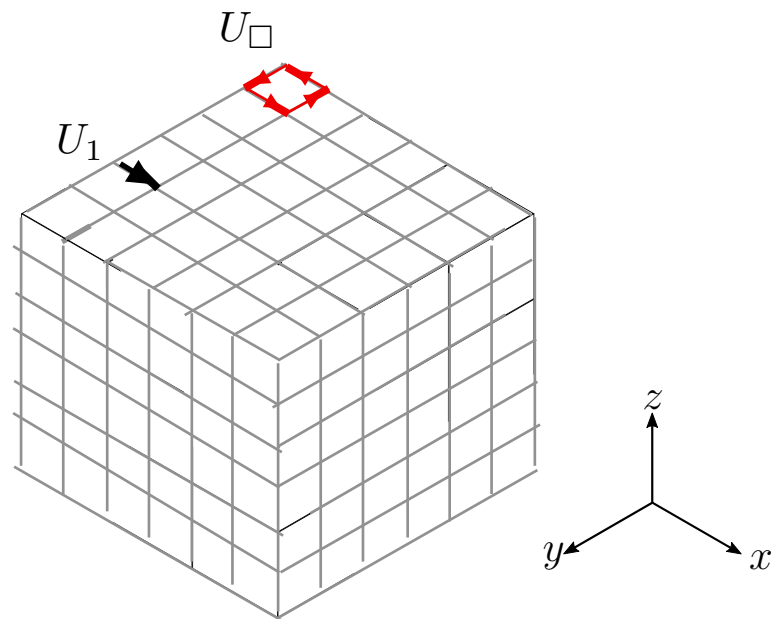
$$n_{\text{qubits}} \sim f \times n^d$$

non-perturbative regime

$$100\text{MeV} \lesssim E \lesssim \text{GeV}$$

$$n_q \sim f \times 1000$$

$$| \langle H_{KS}(a) - H \rangle | \sim | \langle H_I(2a) - H \rangle | ?$$



improved Hamiltonian

non-perturbative regime

$$100\text{MeV} \lesssim E \lesssim \text{GeV}$$

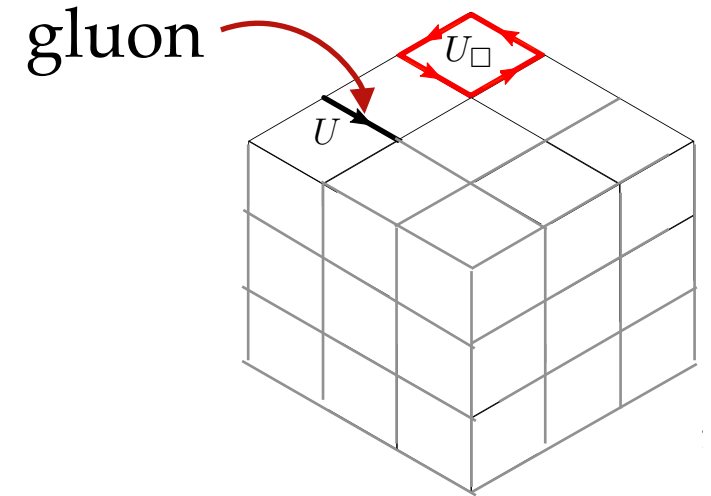
$$n_q \sim f \times 125$$

Digitization

数字化

infinities in field variables

How large is f



Formulations & bases: examples

Kogut-Susskind Formulation

- Irrep / angular momentum basis: *Byrnes, Yamamoto, Zohar, Burrell, et al*
- Group-element basis: *Carena, Lamm, YYL, Liu, Zohar, et al.*
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Loop-string-hadron formulation: *Raychowdhury, Stryker, Davoudi, Kadam, et al.*

Qubit models: *Chandrasekhara, Singh, et al.*

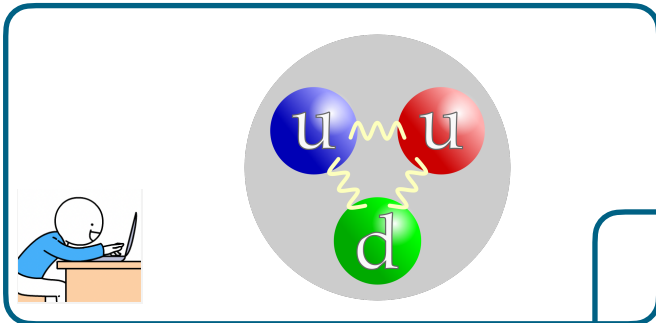
Dual/rotor formulations: *Kaplan, Stryker, Haase, et al.*

q-deformed Kogut-Susskind: *Zache, Zoller et al*

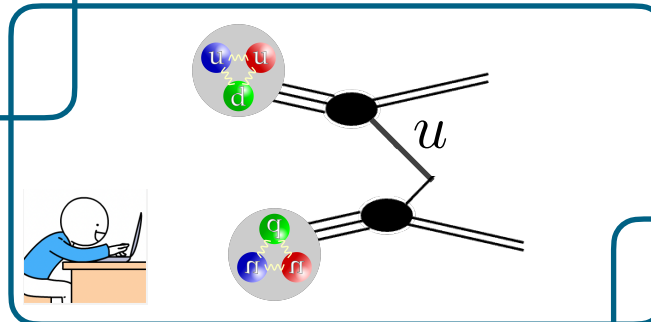
Dual/rotor formulations: *Kaplan, Stryker, Haase, Dellantonio, et al.*

Theory developments and algorithms are still in very early stages, vibrant research directions

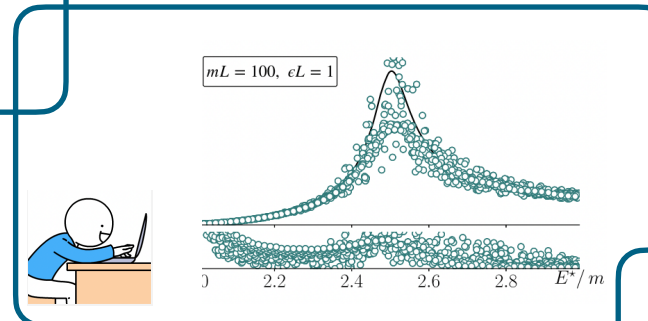
State preparation



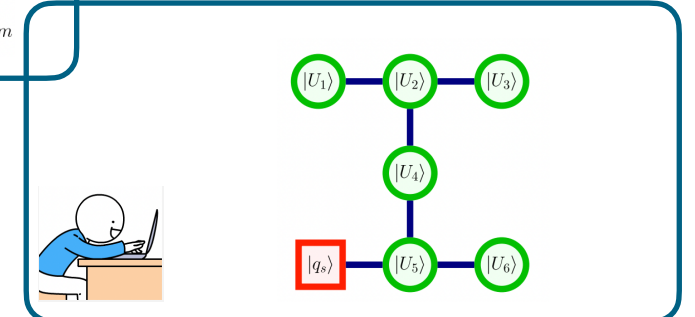
Measurements



Systematic uncertainties



Error corrections



To be continued:

非微扰QCD计算量子线路深度估计

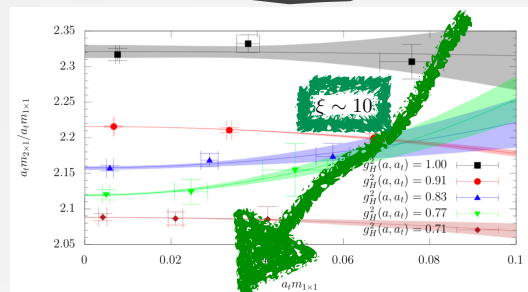
Where are we?

“We need time, so start now”

(2030s) narrow down the framework with

- systematic studies of errors from digitization
 - hardware co-design
 - improving algorithms
 - benchmark studies
 - ...
- phase diagrams with spontaneous symmetry breaking, and for improved H
 - qudits for blocking encodings and the redundancies
 - efficient quantum circuits based on qudits
 - HEP case calculations for experiments

various methods



2030s -



“also told you...”

S. P. Jordan,
K. S. M. Lee,
J. Preskill



2011-



2020 -



Next decades

Development Roadmap

IBM Quantum

	2016–2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2033+
	Run quantum circuits on the IBM Quantum Platform	Release multi-dimensional roadmap publicly with initial aim focused on scaling	Enhancing quantum execution speed by 100x with Qiskit Runtime	Bring dynamic circuits to unlock more computations	Enhancing quantum execution speed by 5x with quantum serverless and Execution modes	Improving quantum circuit quality and speed to allow 5K gates with parametric circuits	Enhancing quantum execution speed and parallelization with partitioning and quantum modularity	Improving quantum circuit quality to allow 7.5K gates	Improving quantum circuit quality to allow 10K gates	Improving quantum circuit quality to allow 15K gates	Improving quantum circuit quality to allow 100M gates	Beyond 2033, quantum-centric supercomputers will include 1000's of logical qubits unlocking the full power of quantum computing
Data Scientist						Platform						
						Code assistant	Functions	Mapping Collection	Specific Libraries			General purpose QC libraries
Researchers					Middleware							
					Quantum Serverless	Transpiler Service	Resource Management	Circuit Knitting x P	Intelligent Orchestration			Circuit libraries
Quantum Physicist			Qiskit Runtime									
	IBM Quantum Experience		QASM3	Dynamic circuits	Execution Modes	Heron (5K) Error Mitigation 5k gates 133 qubits Classical modular 133x3 = 399 qubits	Flamingo (5K) Error Mitigation 5k gates 156 qubits Quantum modular 156x7 = 1092 qubits	Flamingo (7.5K) Error Mitigation 7.5k gates 156 qubits Quantum modular 156x7 = 1092 qubits	Flamingo (10K) Error Mitigation 10k gates 156 qubits Quantum modular 156x7 = 1092 qubits	Flamingo (15K) Error Mitigation 15k gates 156 qubits Quantum modular 156x7 = 1092 qubits	Flamingo (100M) Error Mitigation 100M gates 156 qubits Quantum modular 156x7 = 1092 qubits	Flamingo (100M) Error Mitigation 100M gates 156 qubits Quantum modular 156x7 = 1092 qubits
	Early Canary 5 qubits Albatross 16 qubits Penguin 20 qubits Prototype 53 qubits	Falcon Benchmarking 27 qubits		Eagle Benchmarking 127 qubits								

~200 qubits
~1000 gates
corrections!

Innovation Roadmap

Software Innovation	IBM Quantum Experience	Qiskit Circuit and operator API with compilation to multiple targets	Application modules Modules for domain specific application and algorithm workflows	Qiskit Runtime Performance and abstract through Primitives	Serverless Demonstrate concepts of quantum-centric supercomputing	AI enhanced quantum Prototype demonstrations of AI enhanced circuit transpilation	Resource management System partitioning to enable parallel execution	Scalable circuit knitting Circuit partitioning with classical reconstruction at HPC scale	Error correction decoder Demonstration of a quantum system with real-time error correction decoder		
Hardware Innovation	Early Canary 5 qubits Albatross 16 qubits Penguin 20 qubits Prototype 53 qubits	Falcon Demonstrate scaling with I/O routing with Bump bonds	Hummingbird Demonstrate scaling with multiplexing readout	Eagle Demonstrate scaling with MLW and TSV	Osprey Enabling scaling with high density signal delivery	Condor Single system scaling and fridge capacity	Flamingo Demonstrate scaling with modular connectors	Kookaburra Demonstrate scaling with nonlocal c-coupler	Cockatoo Demonstrate path to improved quality with logical communication	Starling Demonstrate path to improved quality with logical gates	
						Heron Architecture based on tunable-couplers	Crossbill m-coupler				

✓ Executed by IBM

🕒 On target

Benchmarks

Parton Shower [Nachman, Provasoli, Bauer, arXiv:1904.03196]

$$\mathcal{L} = \bar{f}_1(i\not{\partial} + m_1)f_1 + \bar{f}_2(i\not{\partial} + m_2)f_2 + (\partial_\mu\phi)^2 \\ + g_1\bar{f}_1f_1\phi + g_2\bar{f}_2f_2\phi + g_{12}[\bar{f}_1f_2 + \bar{f}_2f_1]\phi$$

