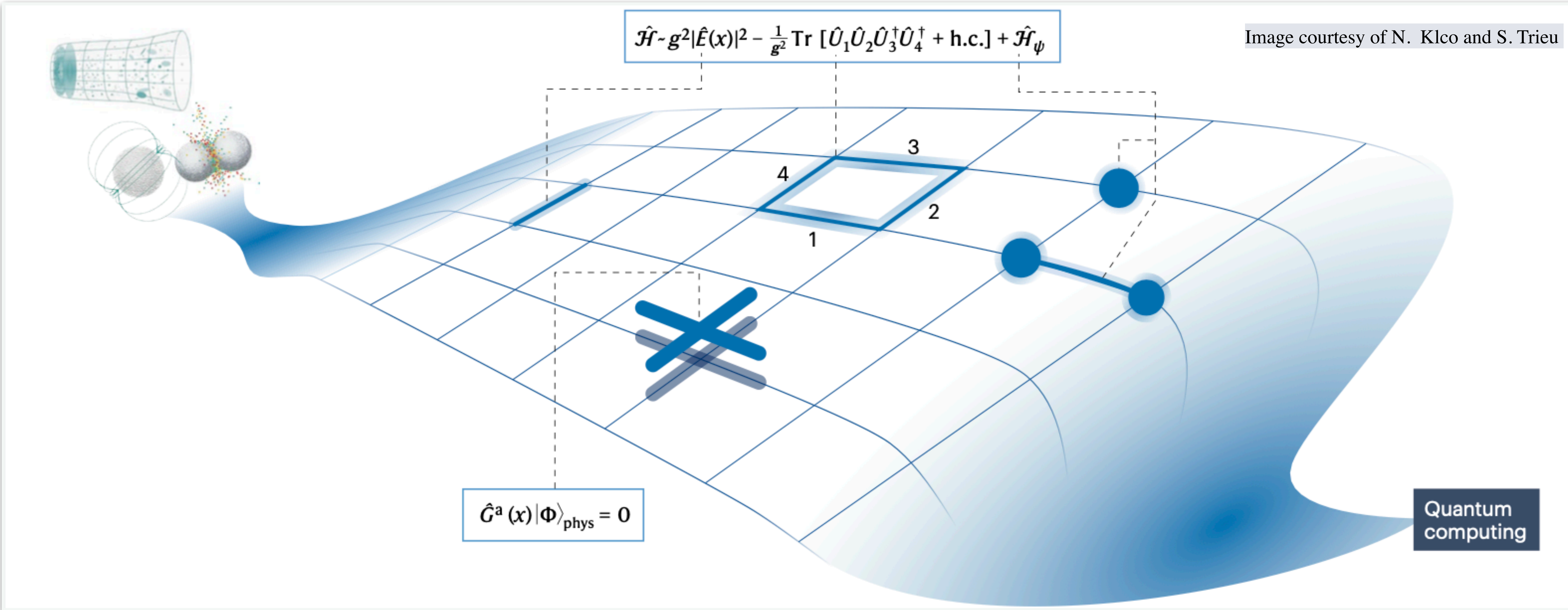


量子计算在高能物理中的应用

Ying-Ying Li (李英英)

中国科学院高能物理研究所 (IHEP)
Institute of High Energy Physics, Chinese Academy of Sciences

[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

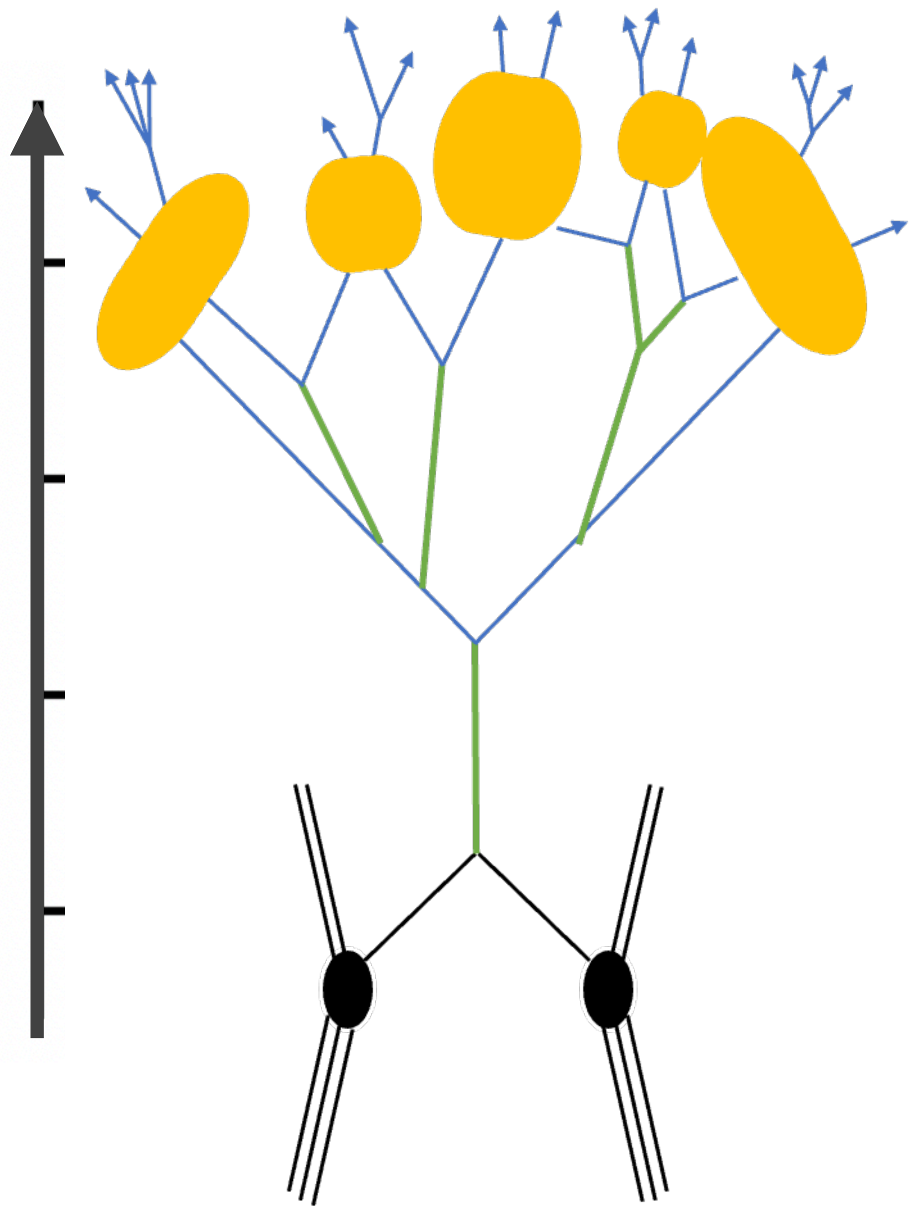
簇射和强子化

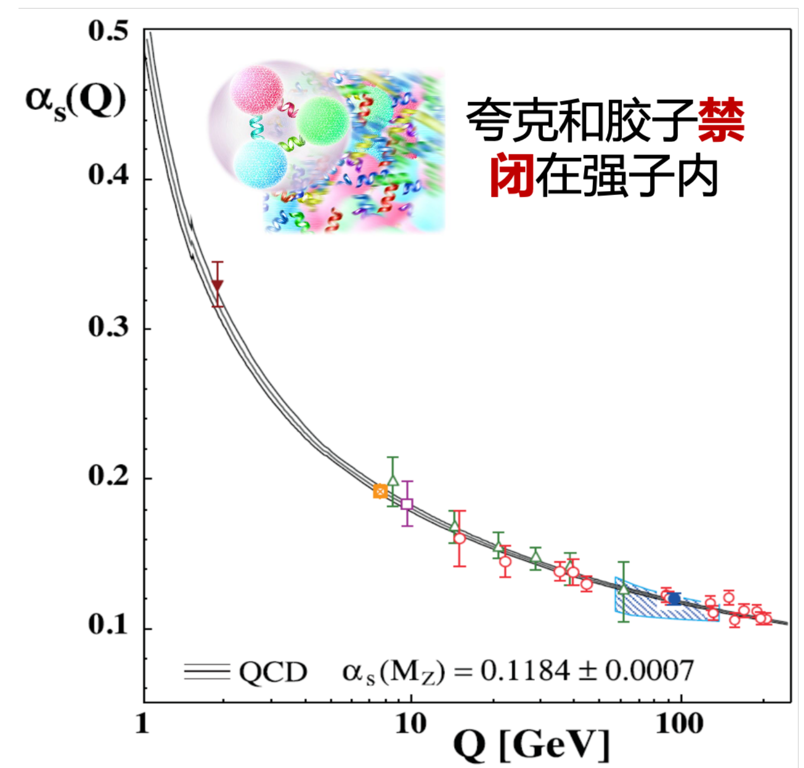
GeV

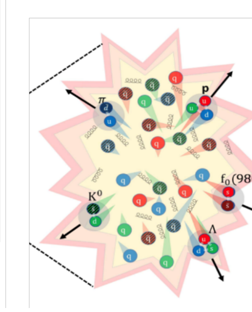
$n \sim 10^3$

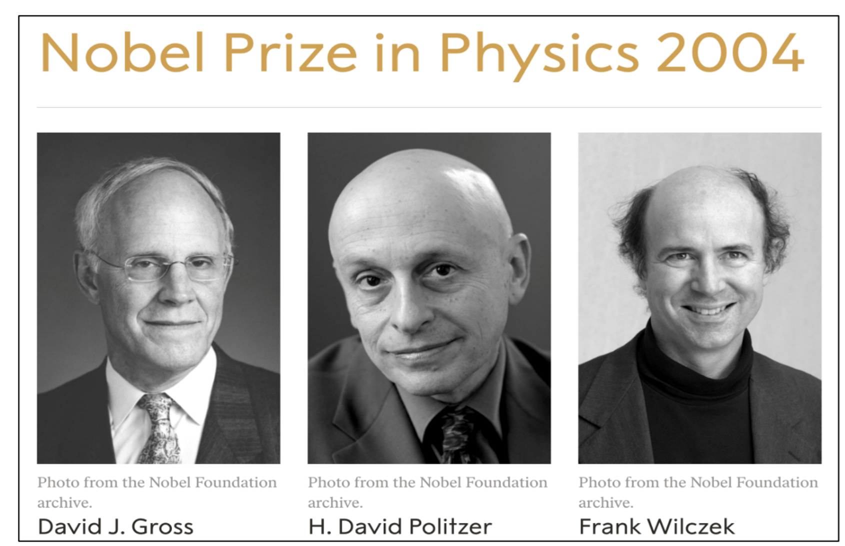
TeV

~~ PDF









理论上的突破性发现 – 渐进自由
（1973）

非微扰区域

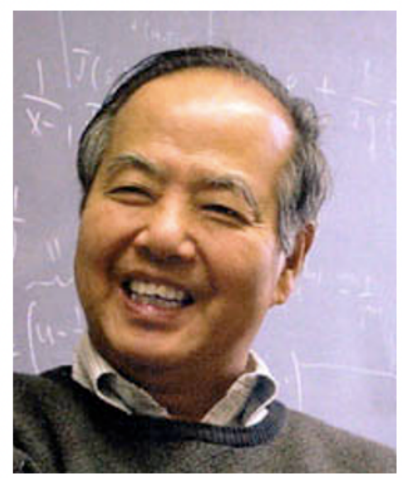
Nuclear Physics A538 (1992) 3c-14c
North-Holland, Amsterdam

NUCLEAR PHYSICS A

MISSING SYMMETRIES, UNSEEN QUARKS AND THE PHYSICAL VACUUM

T. D. Lee

Columbia University, New York, N.Y. 10027

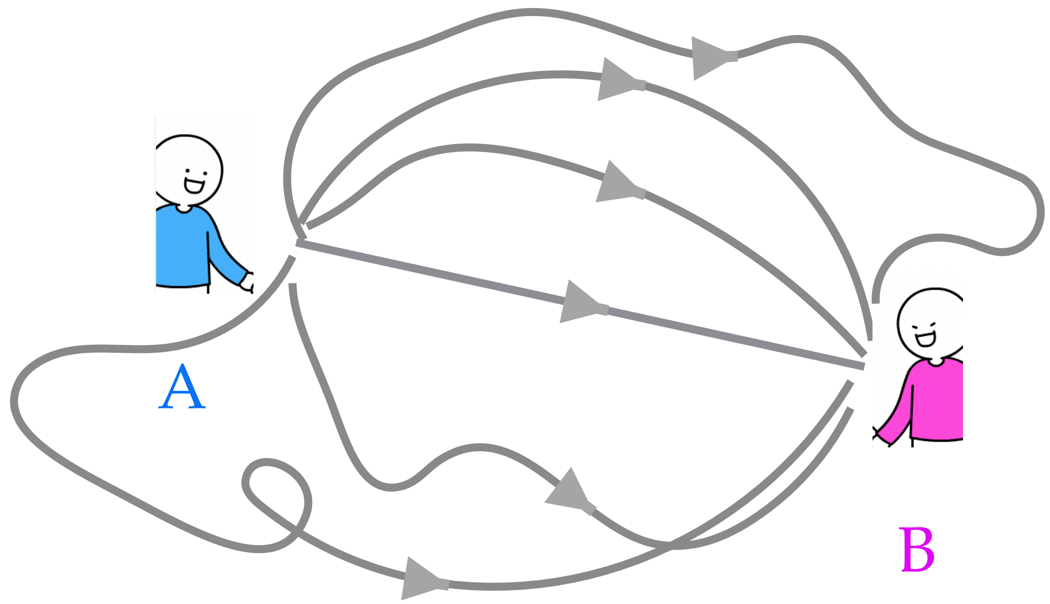


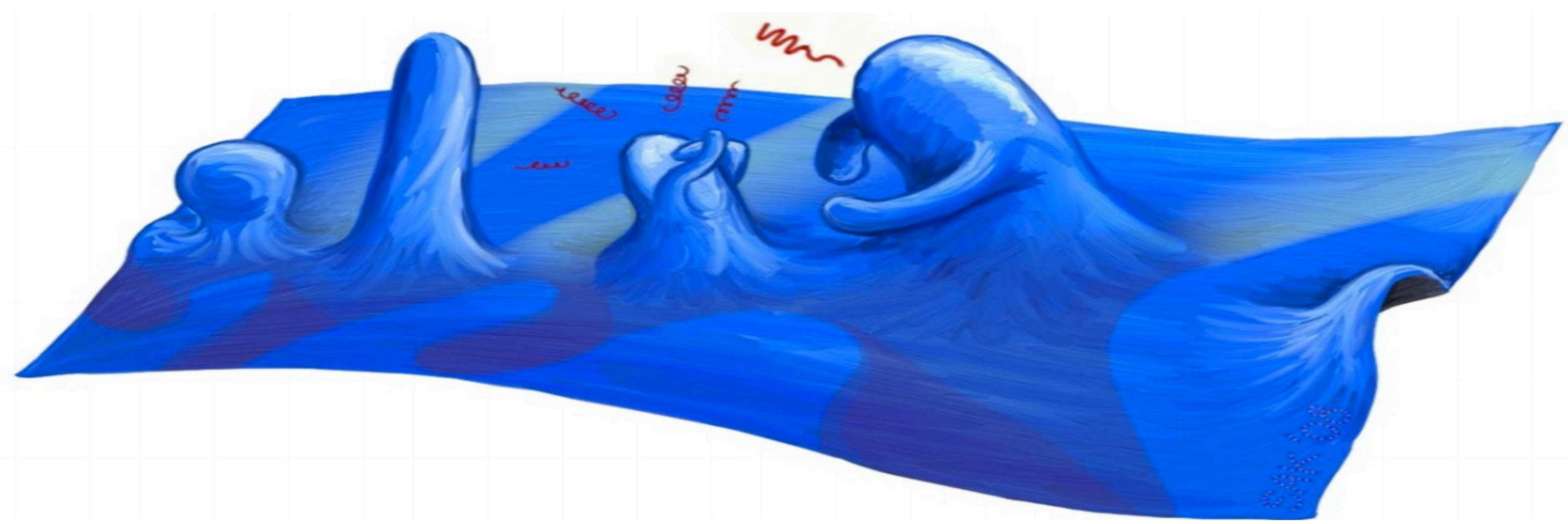
禁闭是如何发生的？

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 → Quantum Field Theory (QFT)

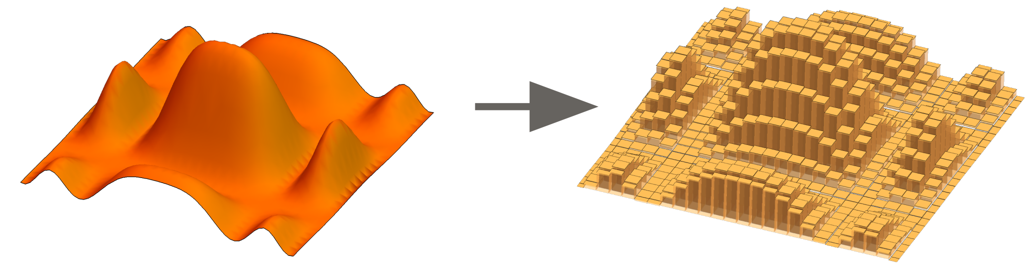


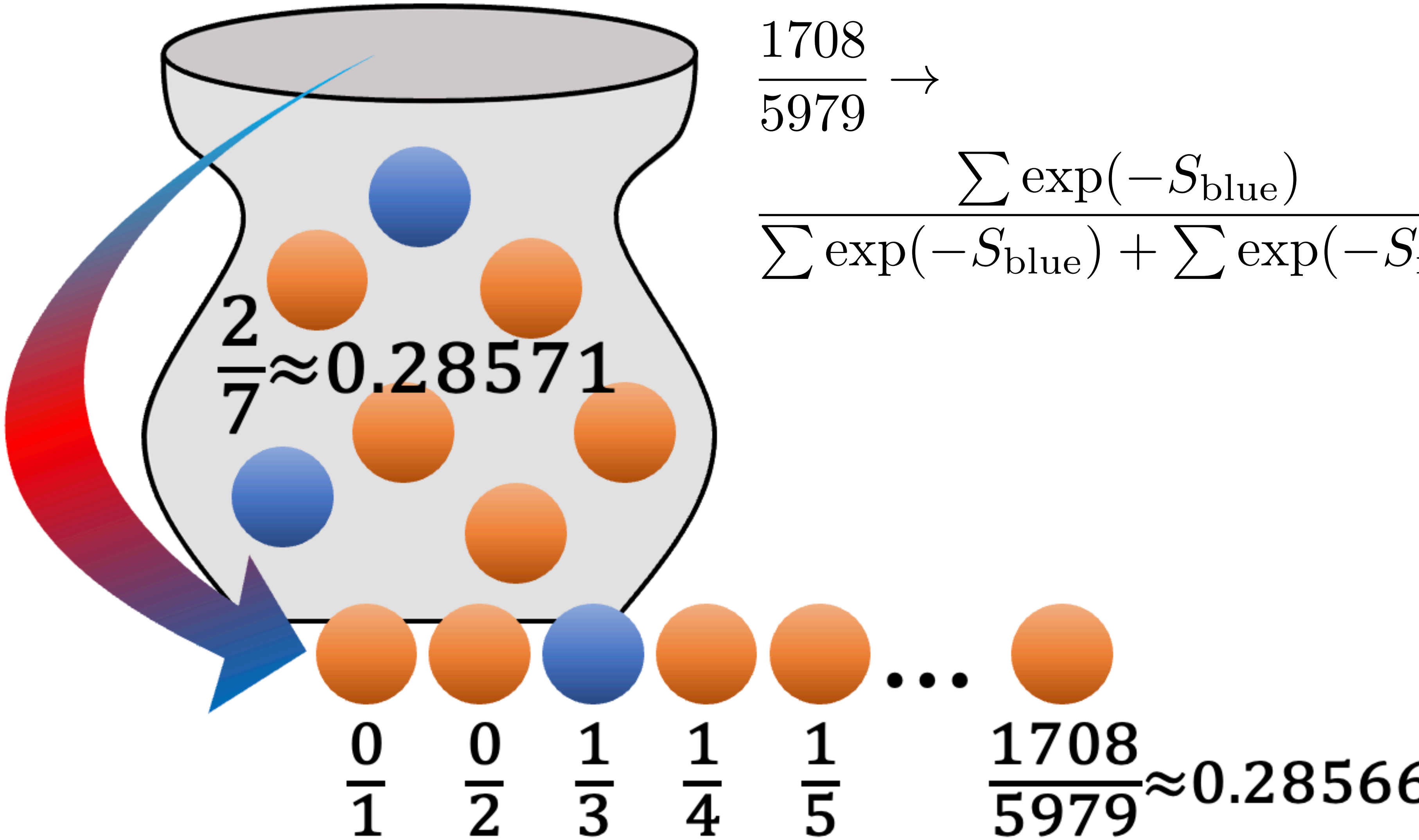


对量子涨落的所有可能路径进行积分

格点QCD - 经典方法

欧氏时空非微扰格点计算
(蒙特卡罗方法)





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

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

格点QCD - 经典方法

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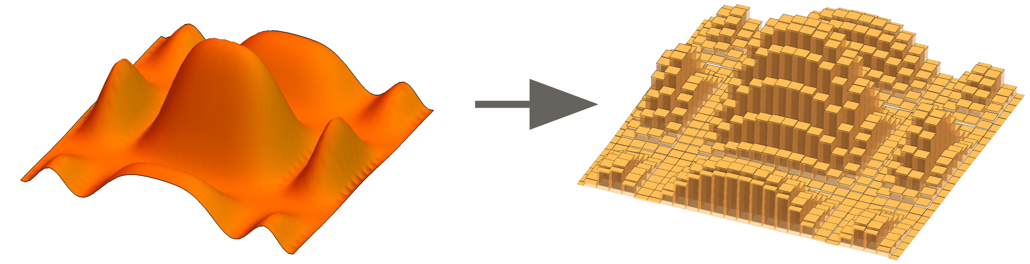
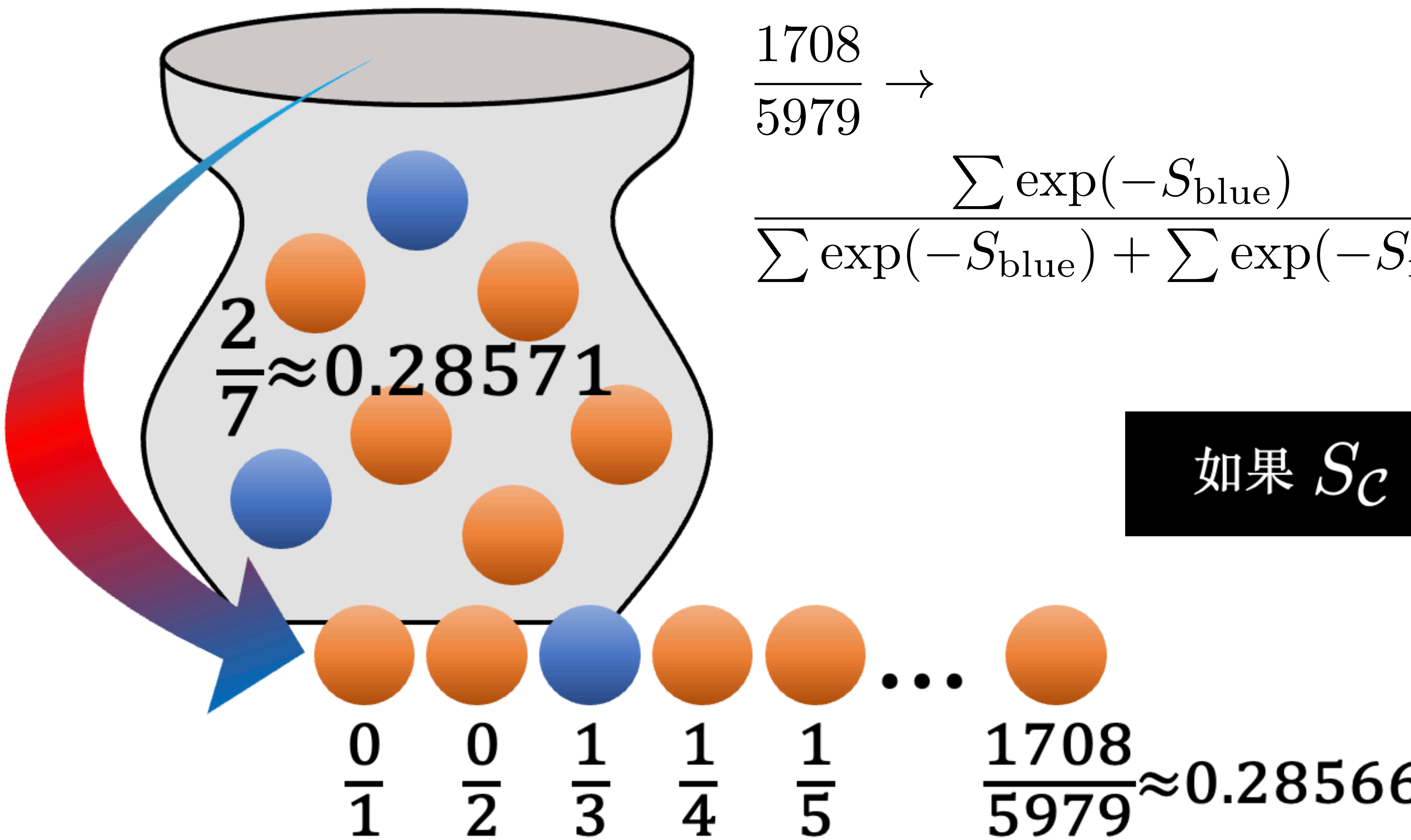


$$\frac{1708}{5979} \to \frac{\sum \exp(-S_{\rm blue})}{\sum \exp(-S_{\rm blue}) + \sum \exp(-S_{\rm red})}$$



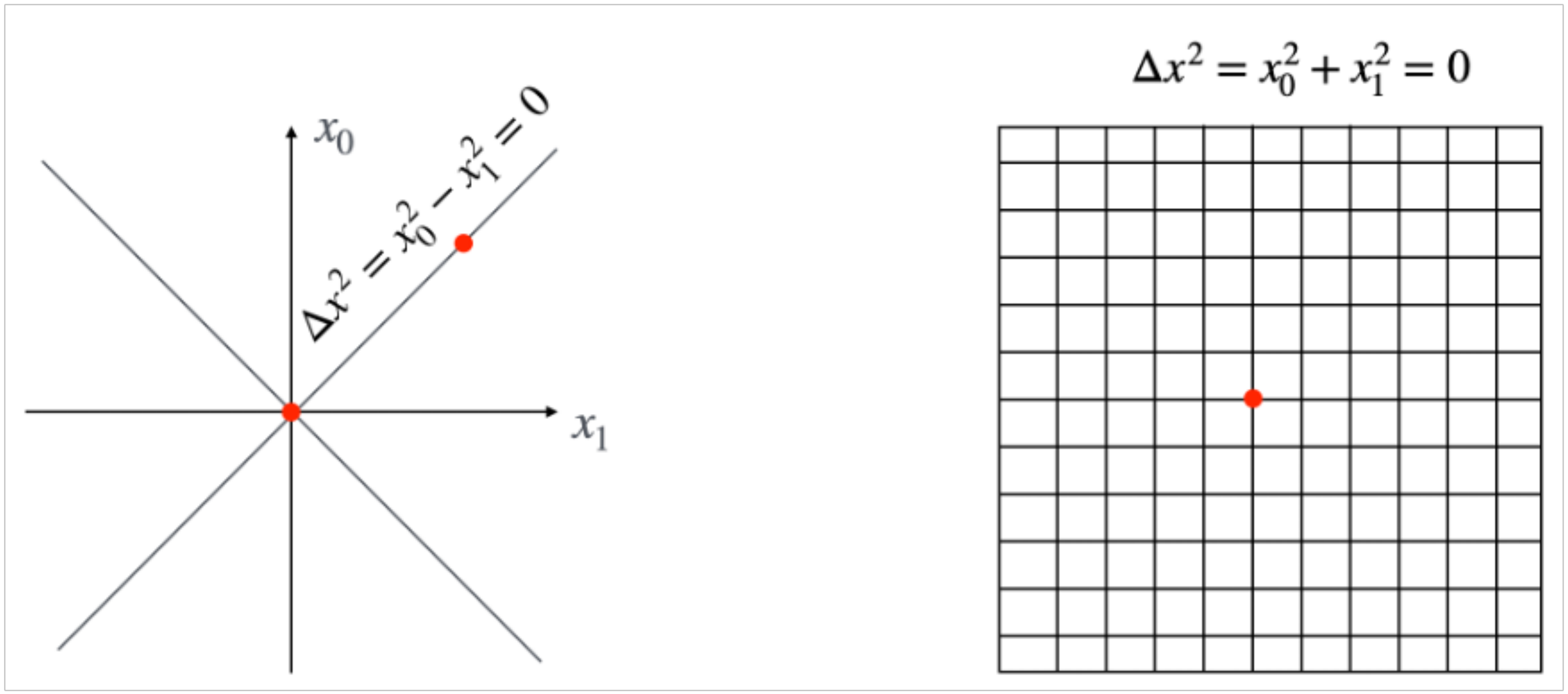
如果 $S_{\mathcal{C}}$ 是虚数呢?

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

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

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

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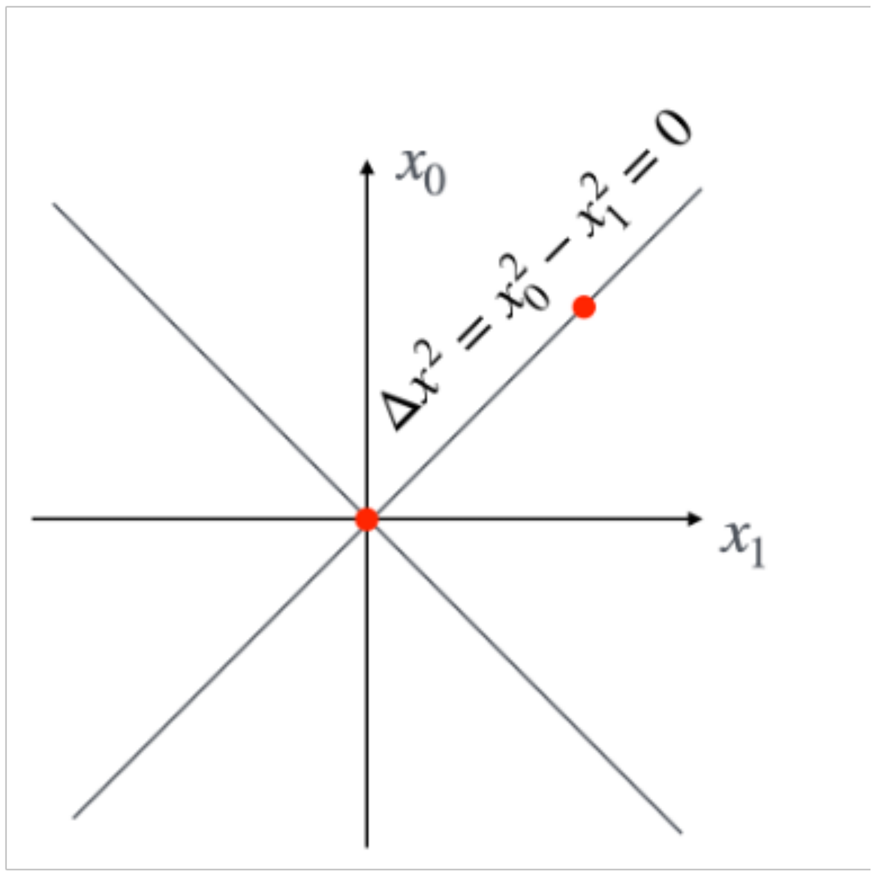


闵氏空间：类光

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

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

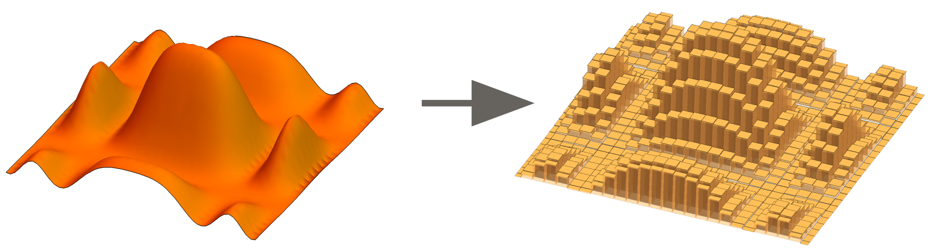
格点QCD - 量子计算方法

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...

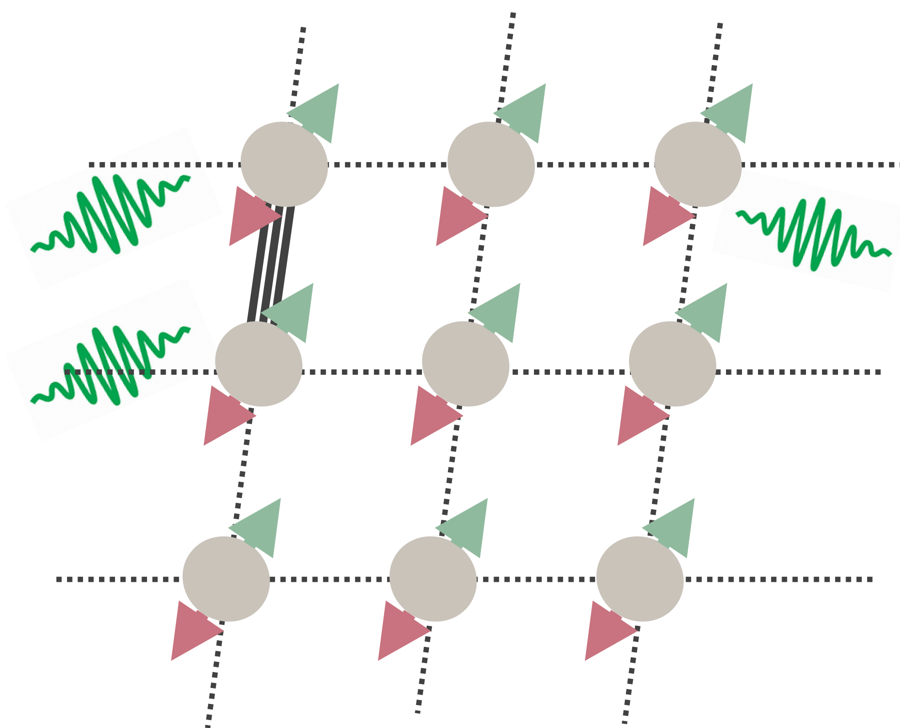
格点QCD - 量子计算方法

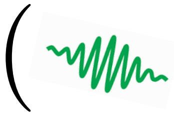
- 1996 - Seth LIoyd: efficient simulation of LOCAL Hamiltonians

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.



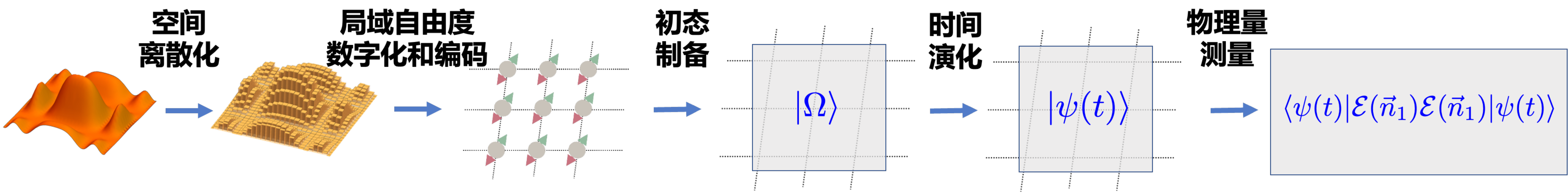
$N($  $) \propto N_q^m$

Polynomial Time Complexity

格点QCD - 量子计算方法

- 1996 - Seth LIoyd: efficient simulation of LOCAL Hamiltonians

- [Jordan, Lee, Preskill, 2011]

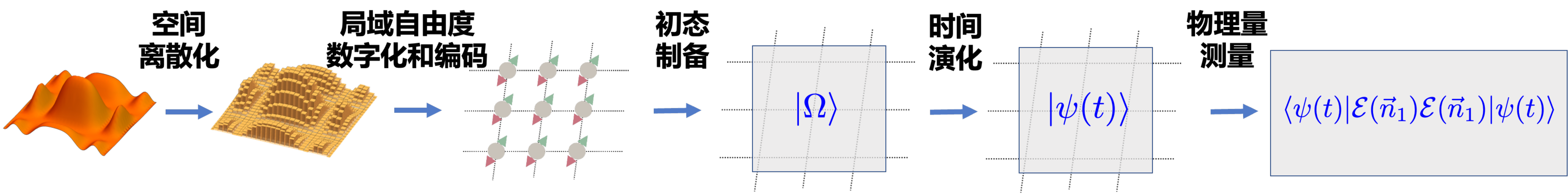


时间复杂度为多项式形式的标量场量子模拟方法

格点QCD - 量子计算方法

- 1996 - Seth LIoyd: efficient simulation of LOCAL Hamiltonians

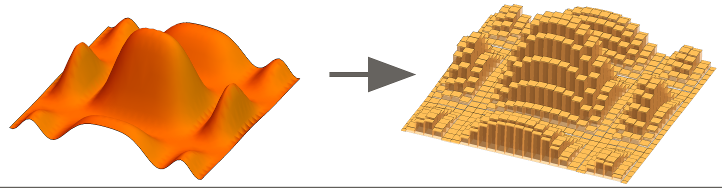
- [Jordan, Lee, Preskill, 2011]



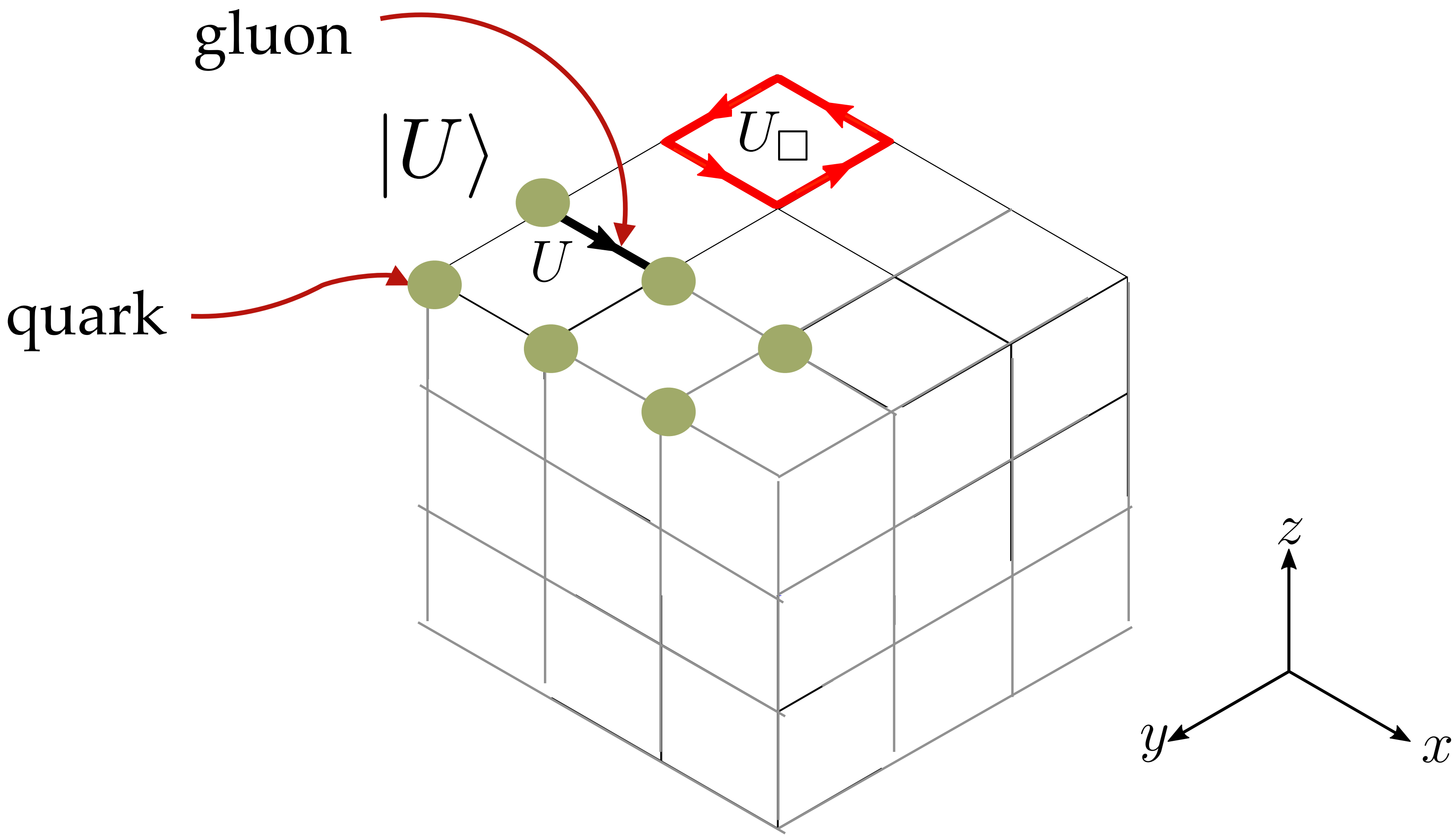
时间复杂度为多项式形式的标量场量子模拟方法

Q: 非阿贝尔规范场和费米子场量子模拟方法是什么？

Discretization

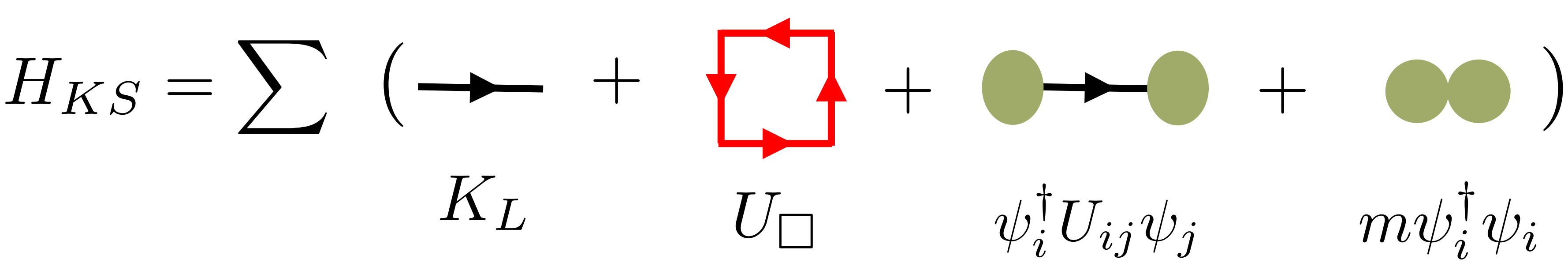


infinities in QFT



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

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

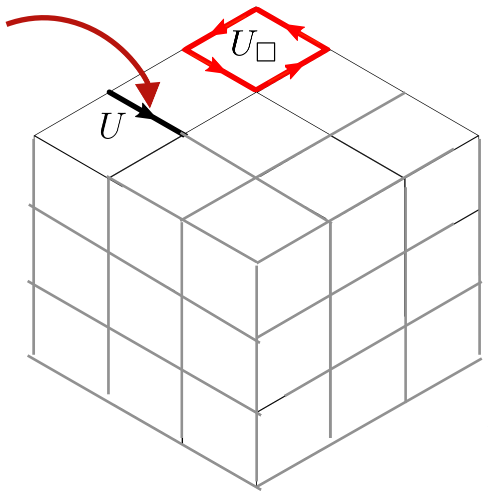


$$H_{KS} \xrightarrow{a \to 0} H = \int dx (E^2 + B^2)$$

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*

— Continuous-Variable quantum computing: *Abel, Spannowsky, Williams, et al.*

***Gauge magnets*/Quantum link models:** *Wiese, Chandrasekhara, et al.*

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.*

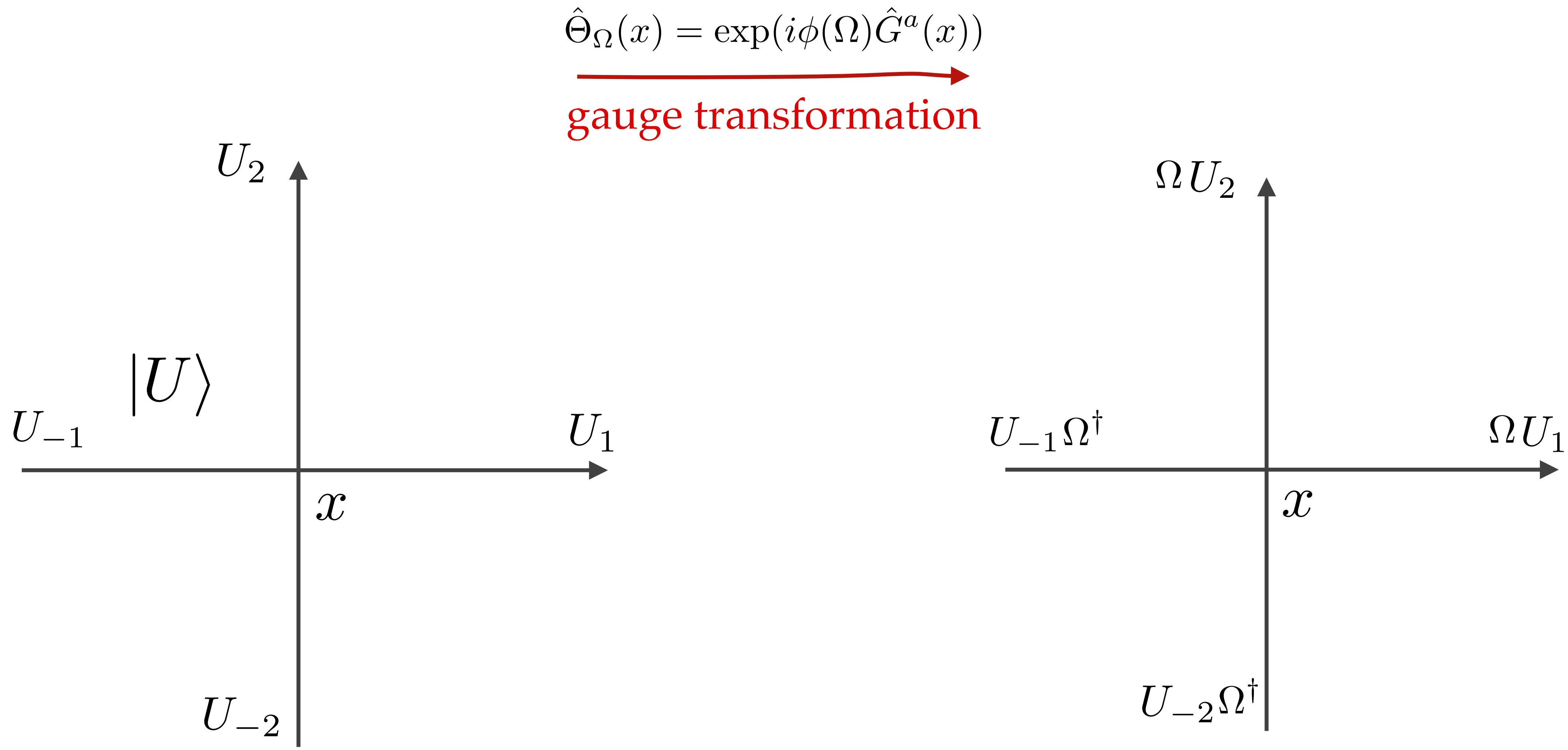
Dual/rotor formulations: *Kaplan, Stryker, Haase, et al.*

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

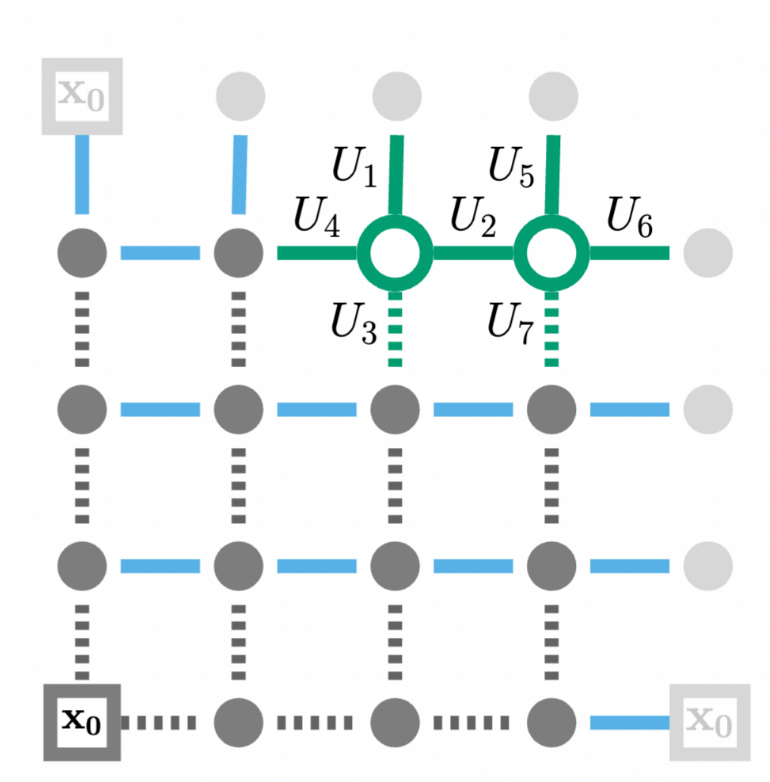
Digitization $|q\rangle^N \to |G\rangle$ infinities in QFT

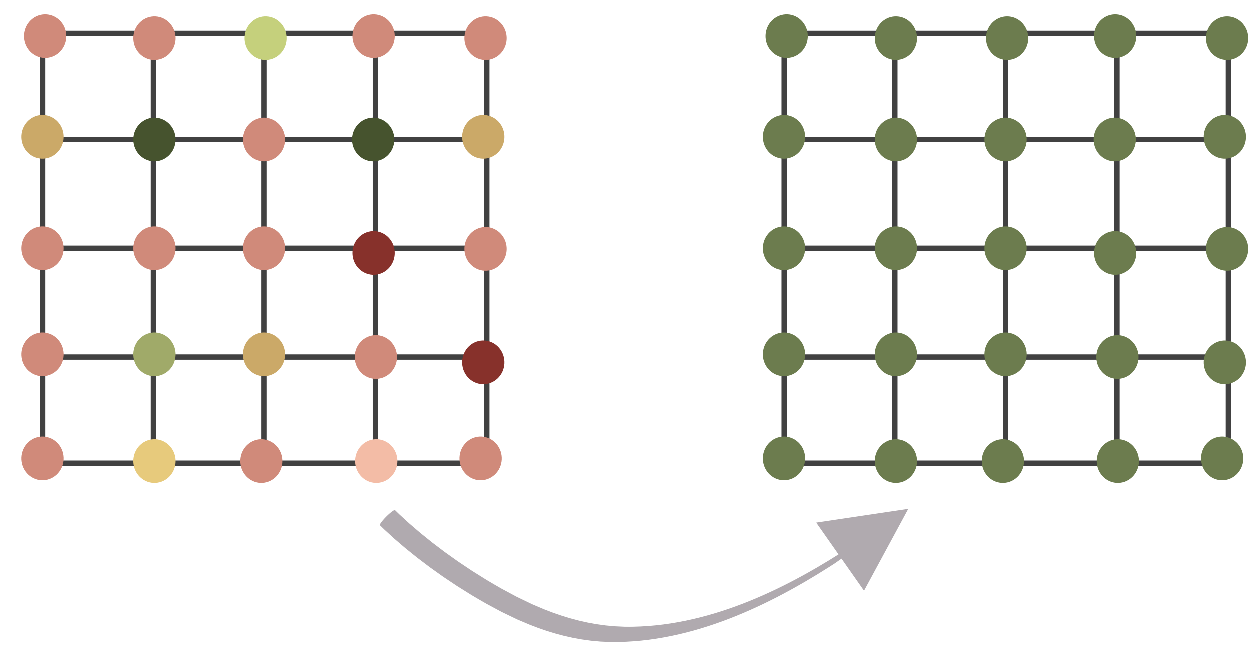


gauge equivalent states

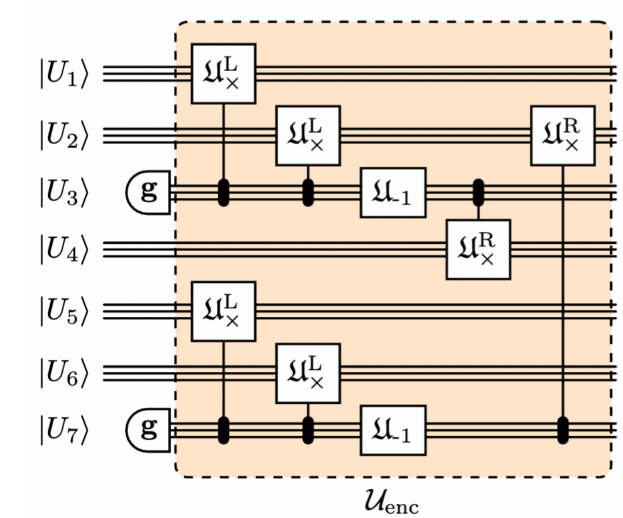
$$\hat{\Theta}_\Omega(x)\,|U_{-1}U_1U_{-2}U_2\rangle = \left|U'_{-1}U'_1U'_{-2}U'_2\right\rangle$$

How to do gauge fixing…





Prepare gauge-invariant states (gauge fixing)



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

Digitization $|q\rangle^N \rightarrow |G\rangle$ infinities in QFT

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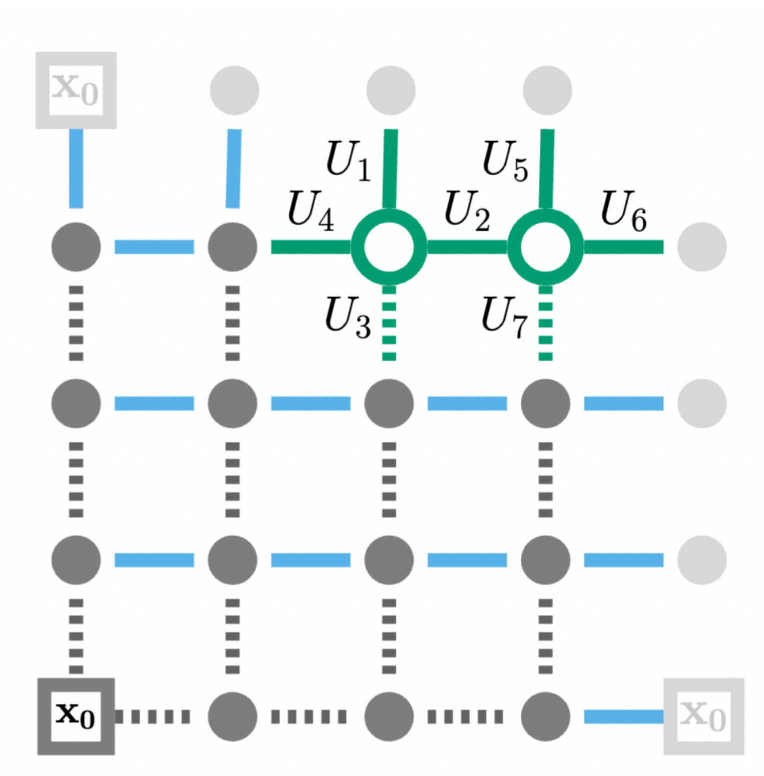

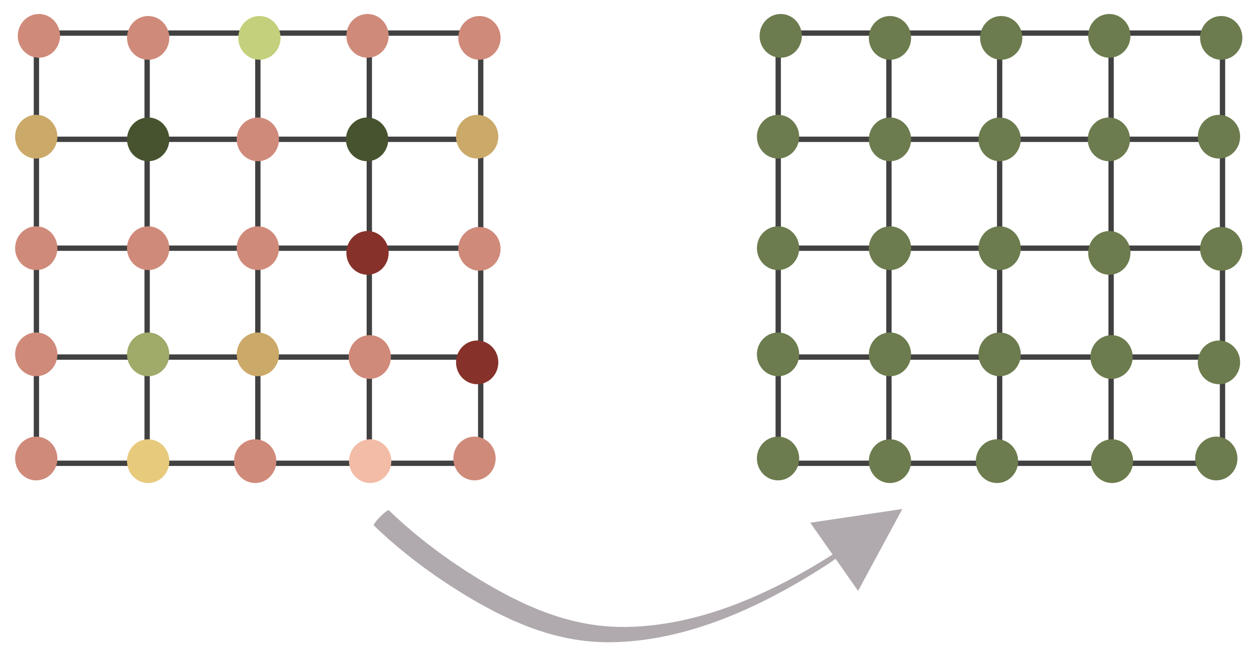

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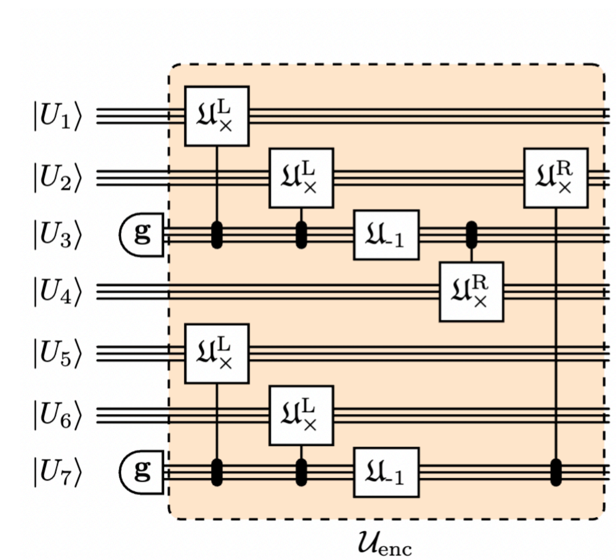
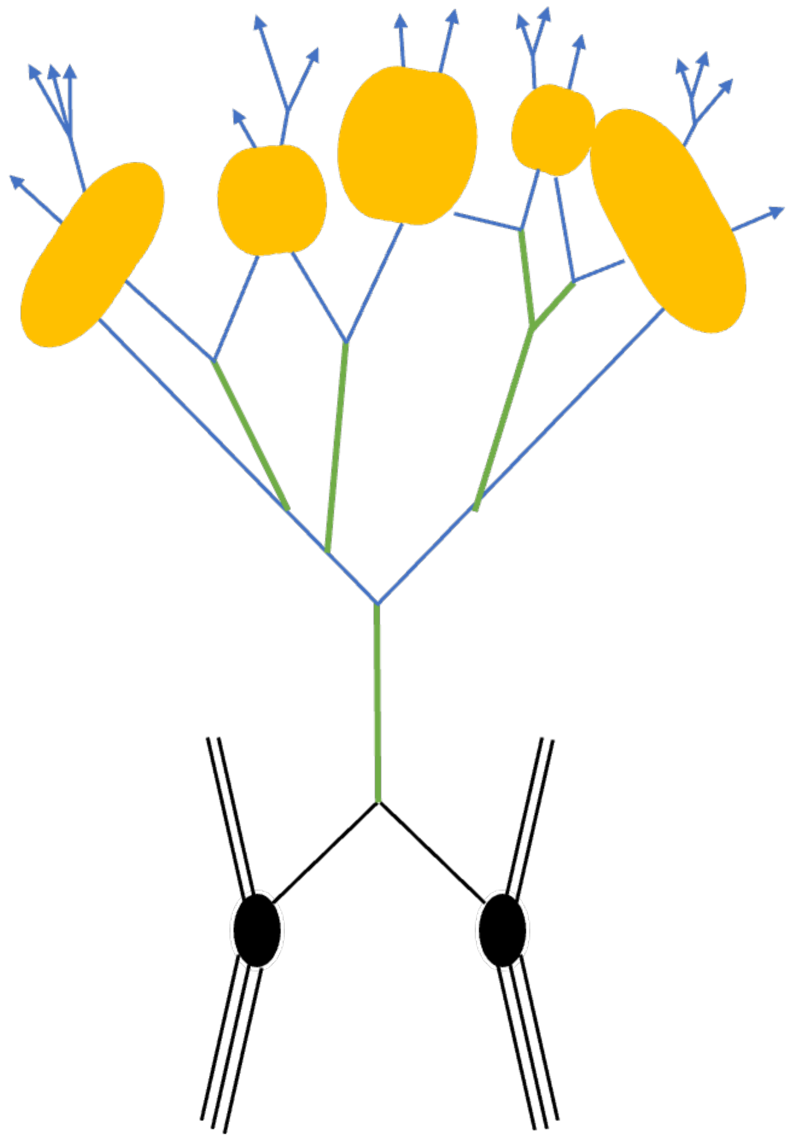


[Carena, Lamm, **YYL**, Liu, arXiv:2402.16780]

for other digitization methods?

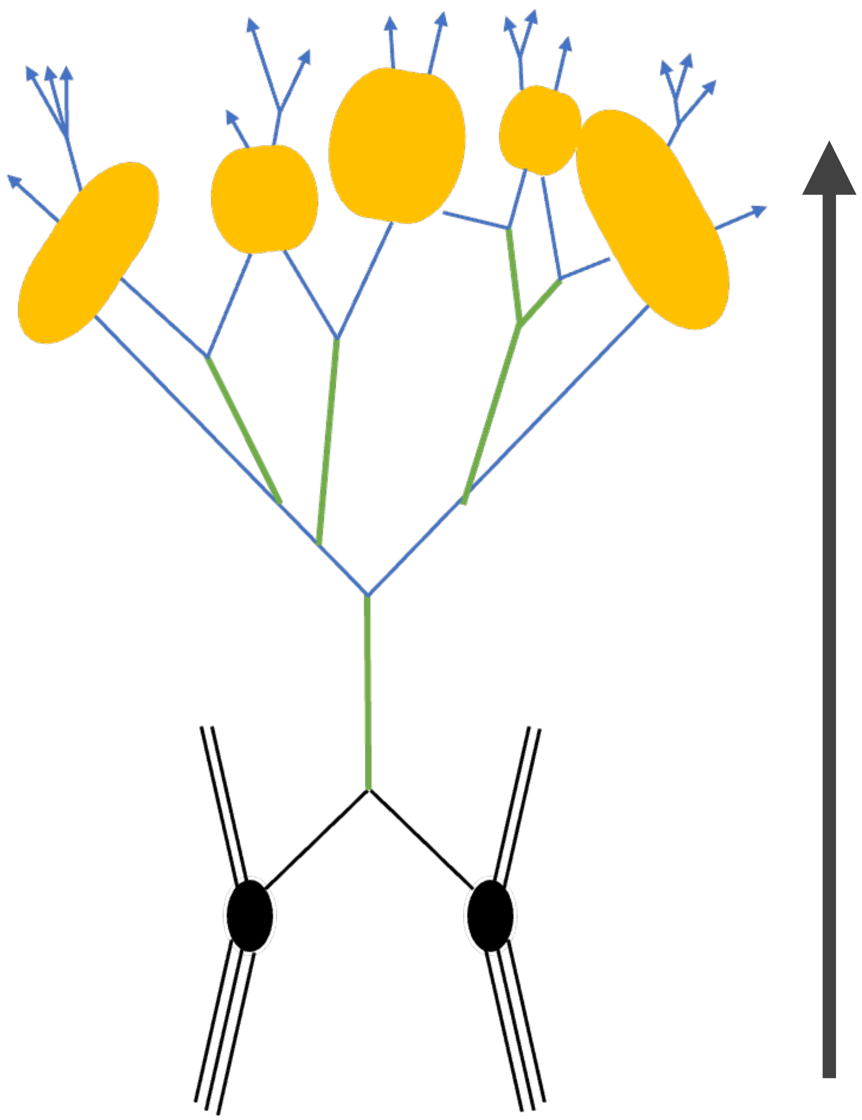
Initial State Preparation $\mathcal{U}\,|G\rangle^L \to |\psi_0\rangle$



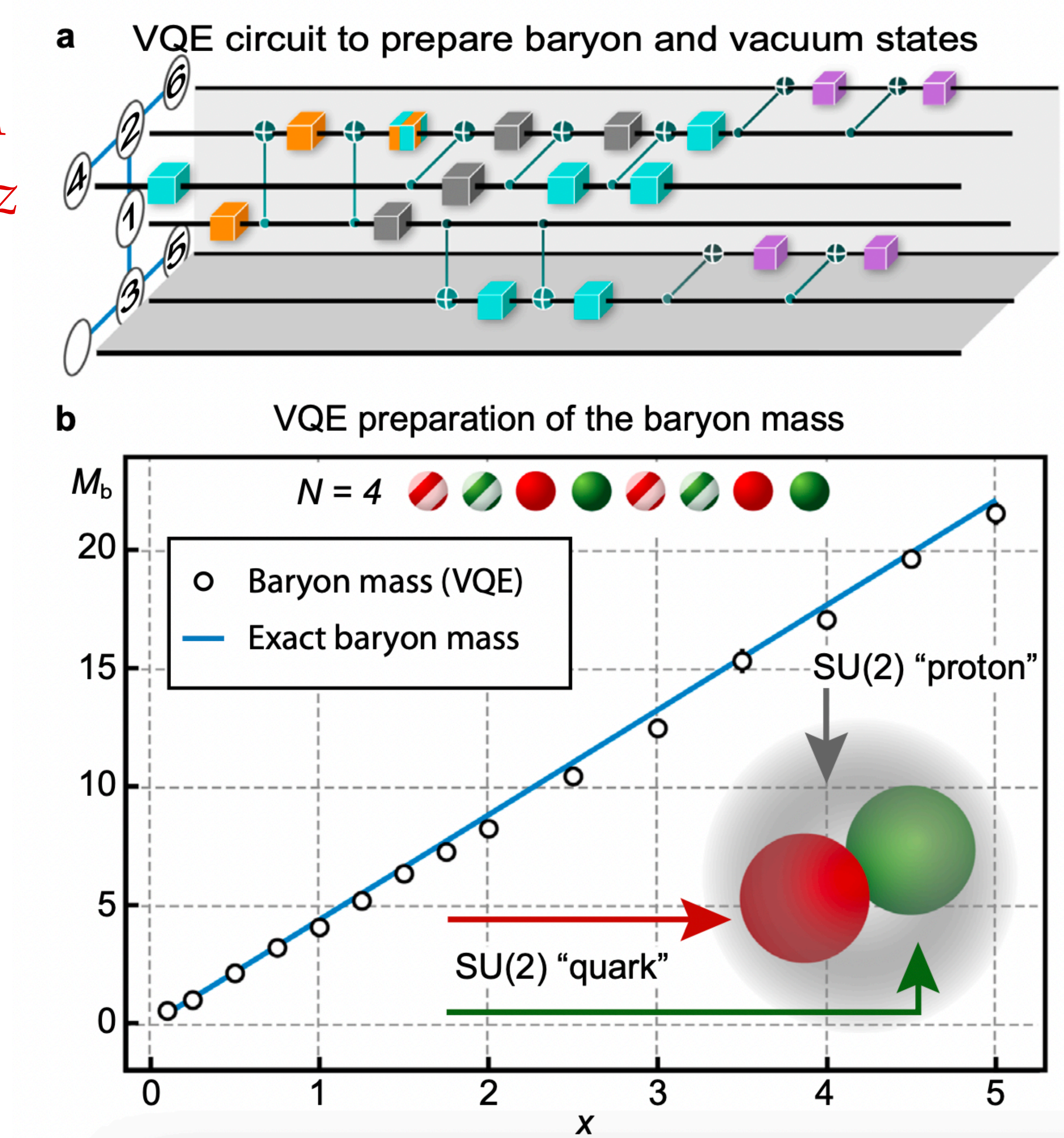
How to prepare proton states from quarks and gluons? Inverse problem of PDF!!

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

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



VQA ansatz



How to prepare proton states from quarks and gluons?

Nature Communications 12, Article number: 6499 (2021) | Cite this article

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

LLM Helps to find proper VQA ansatz from scratch

scalability

arXiv > quant-ph > arXiv:2505.06347

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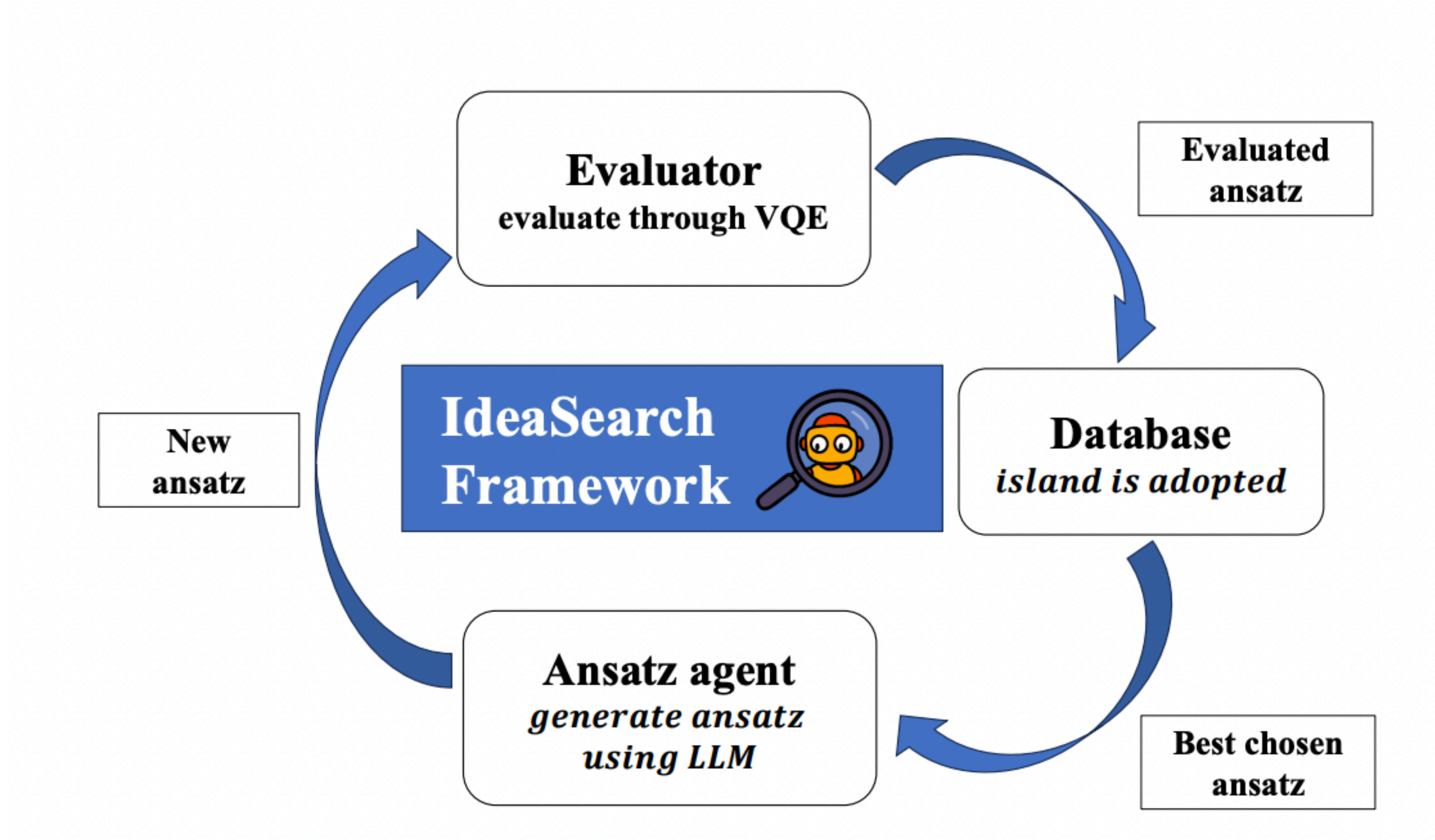
Quantum Physics

[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



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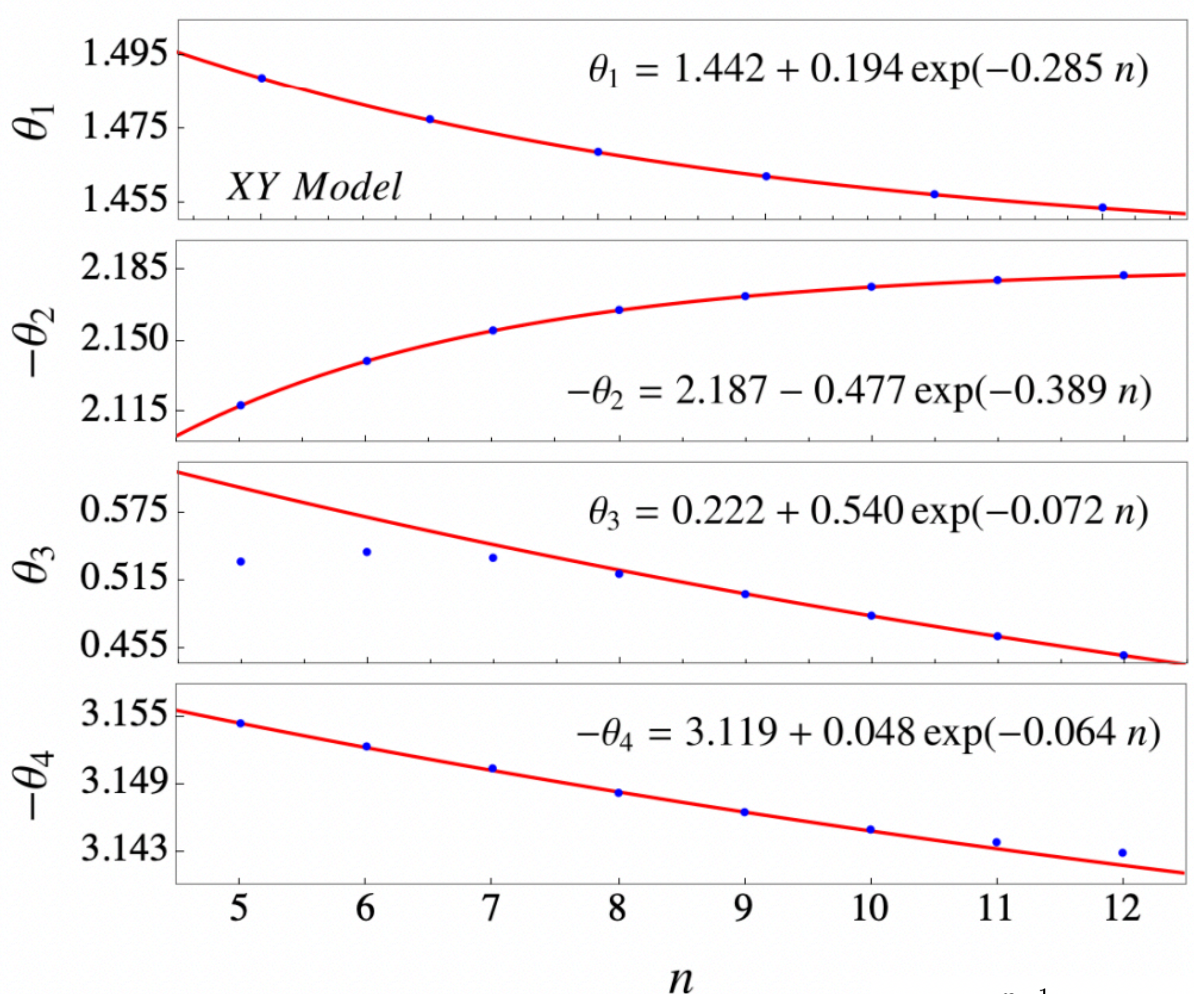
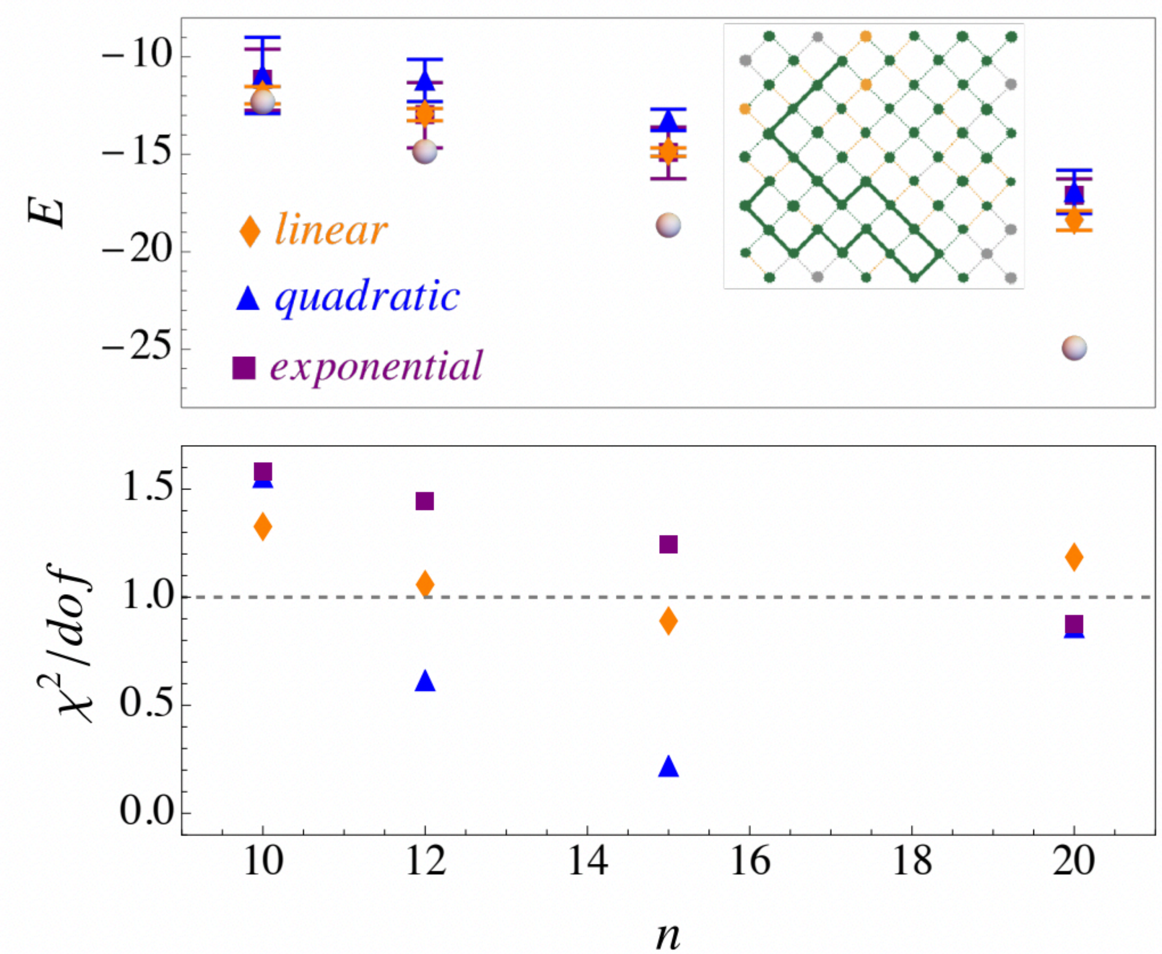


Practicality in the NISQ era



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

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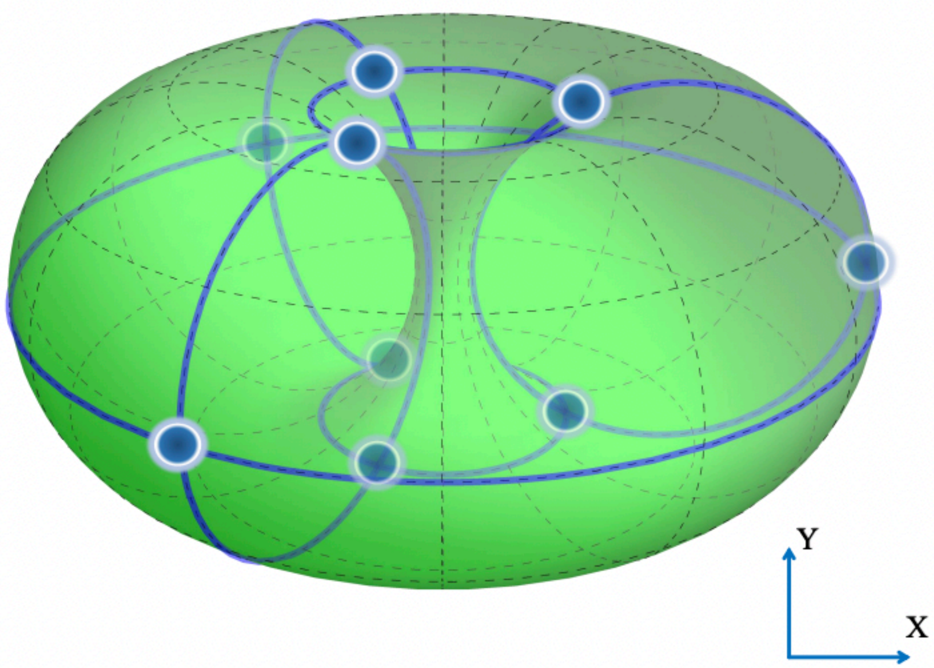
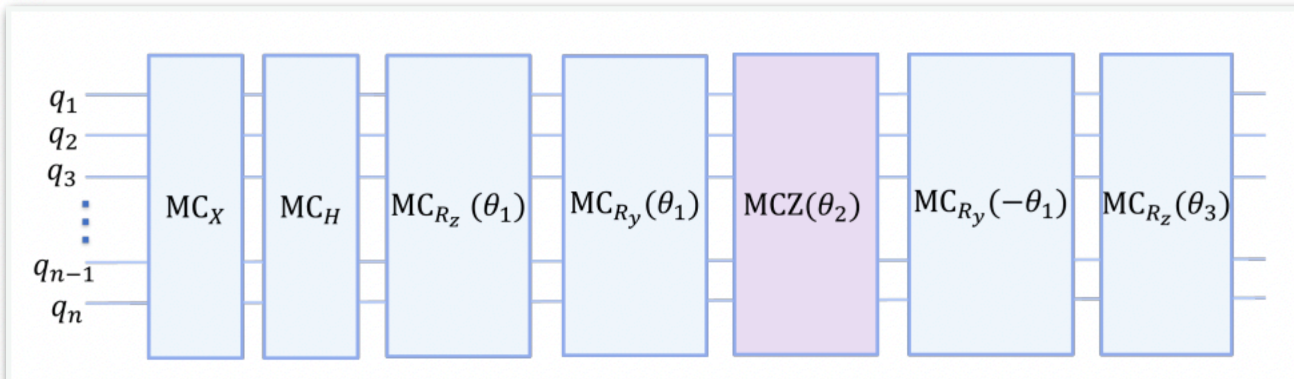


FIG. 5: The geometry of the two-qubit meta-circuit MCZ(θ) for the 2+1d scalar field theory.



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 $\mathcal{U}\,|G\rangle^{L} \rightarrow |\psi_0\rangle$

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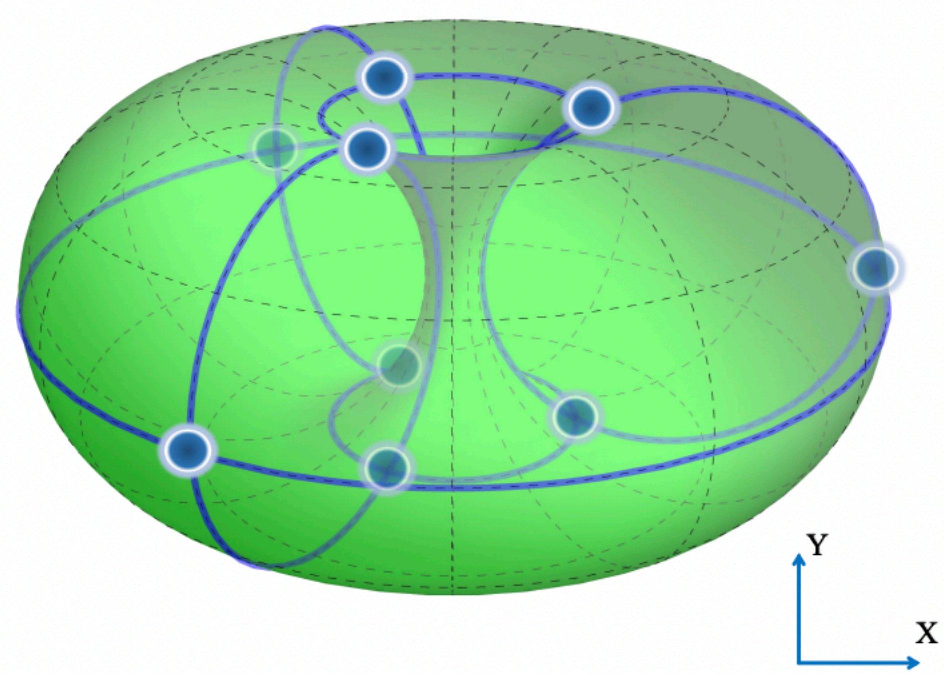

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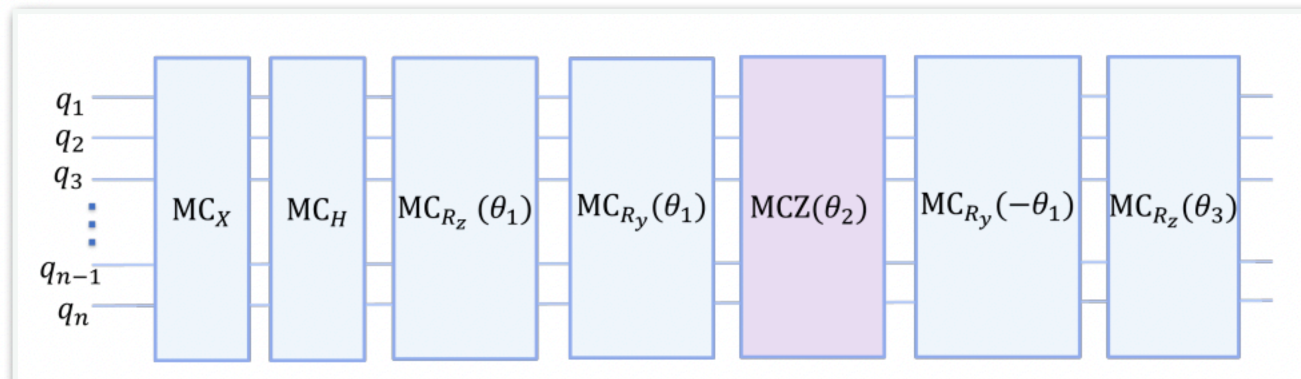

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Circuit Depth	24	72
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Extending to 2+1d non-Abelian gauge theories?

Digitization

数字化-费米子场：对易关系

费米子场：反对易关系

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

泡利算符：对易关系

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

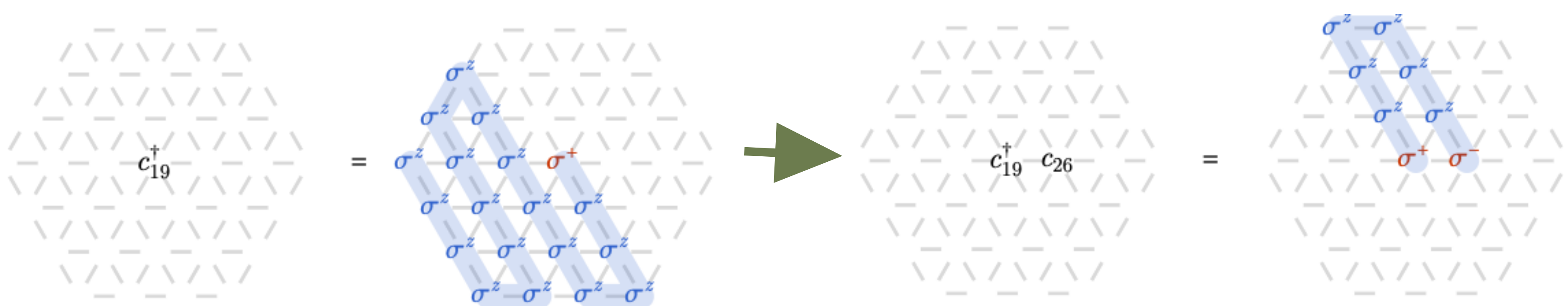
JW变换

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

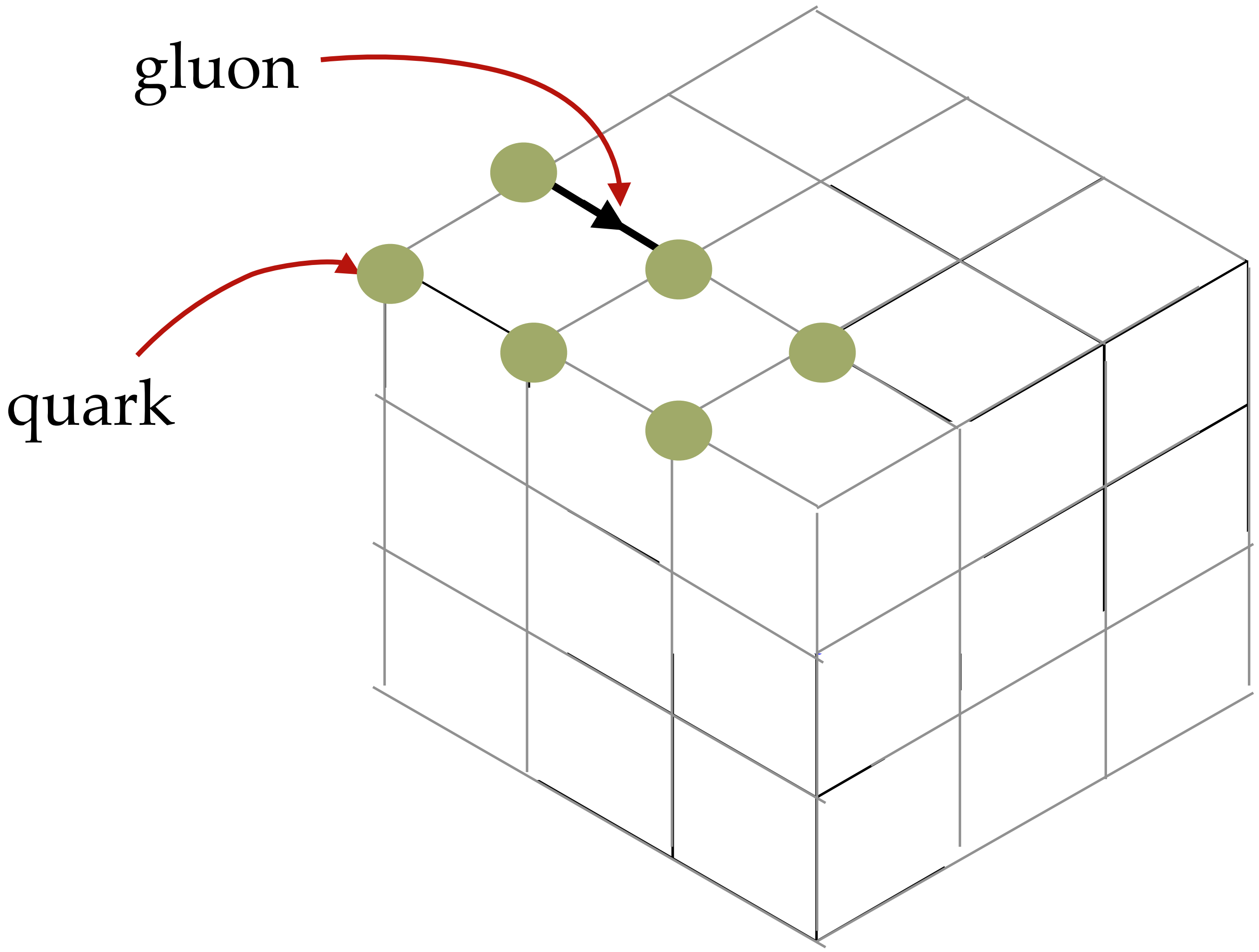
$$c_i^\dagger = \left(\prod_{j<i} \hat{\sigma}_j^z\right)\hat{\sigma}_i^-$$

高维时空非局域相互作用

[Everett You, UCSD]



非微扰QCD计算量子比特资源估计



spatial dimension d

lattice spacing a

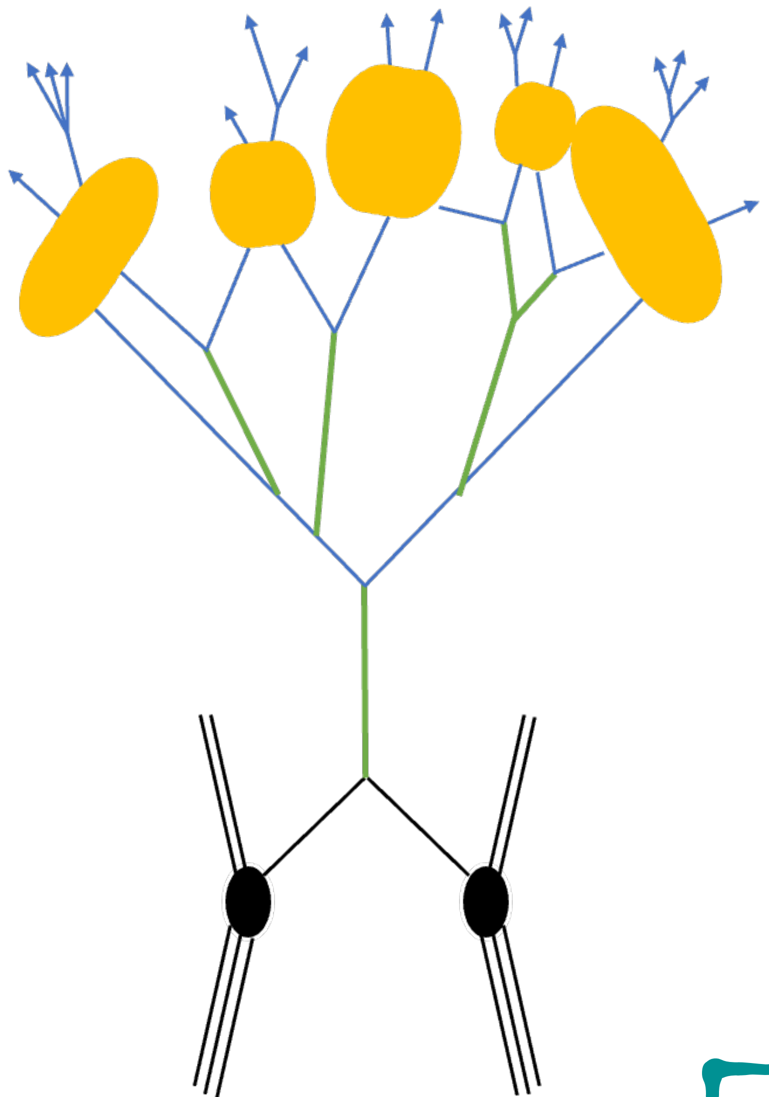
$$(na)^{-1} \lesssim E \lesssim a^{-1}$$

$$n_{\text{qubits}} \sim (n_{\text{gluon}} + n_{\text{quark}}) \times n^d$$

$$\sim f \times n^d$$

• 规范场的哈密顿量

infinities in QFT



Energy Scales

GeV

$n \sim 10^3$

TeV

PDF

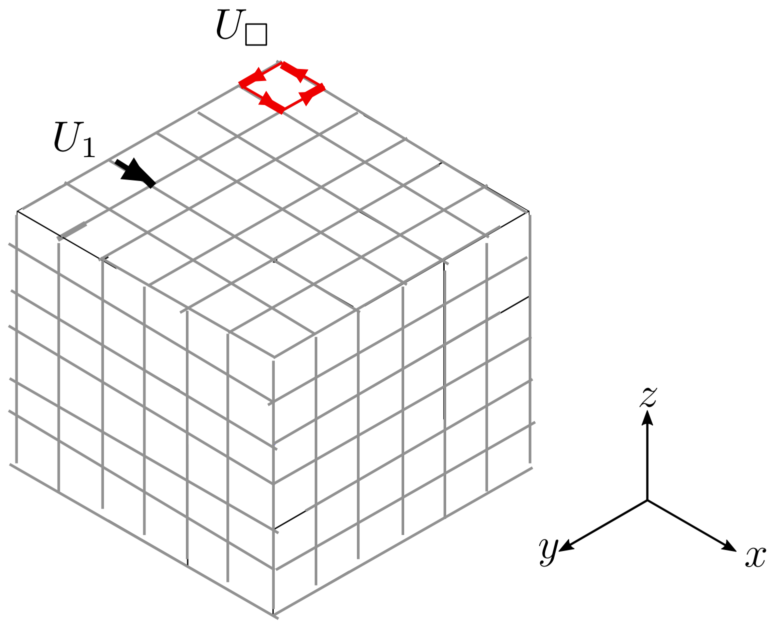
$$n_{\text{qubits}} \sim f \times n^d$$

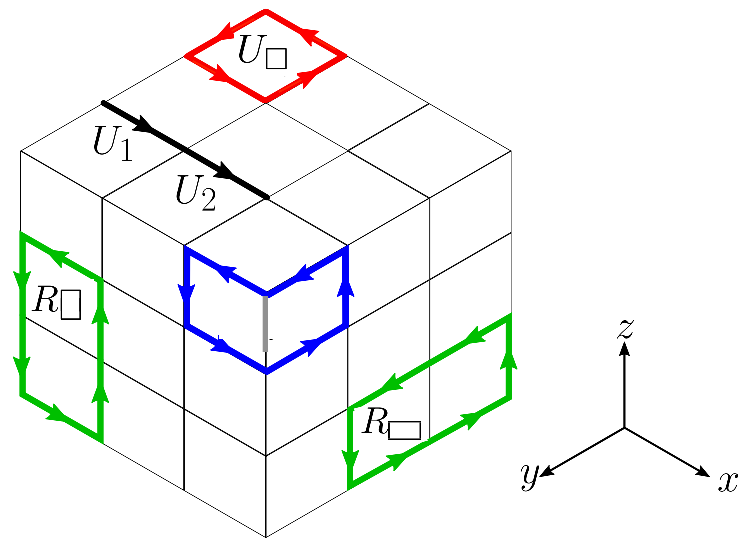
non-perturbative regime

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

$$n_q \sim f \times 1000$$

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





improved Hamiltonian

non-perturbative regime

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

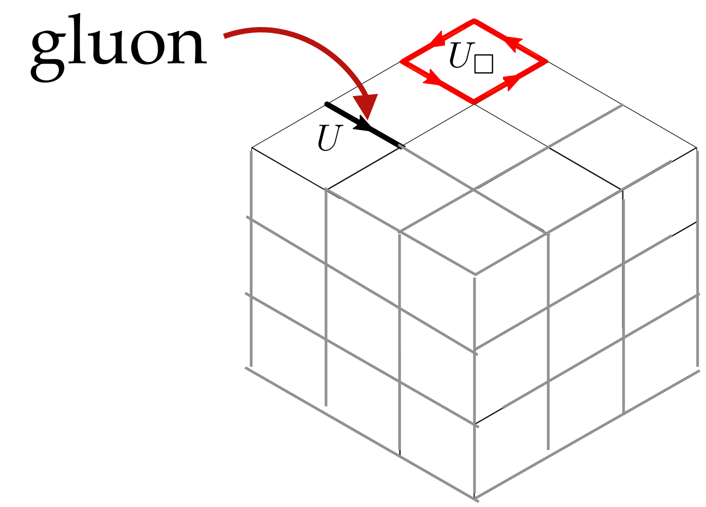
$$n_q \sim f \times 125$$

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.*

— Mixed basis: *Bauer, D'Andrea, Freytsis, Grabowska*

— Large N truncations: *Bauer, Ciavarella*

— Continuous-Variable quantum computing: *Abel, Spannowsky, Williams, et al.*

***Gauge magnets*/Quantum link models:** *Wiese, Chandrasekhara, et al.*

Casimir variables: *Klco, Savage, Stryker, Ciavarella*

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

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

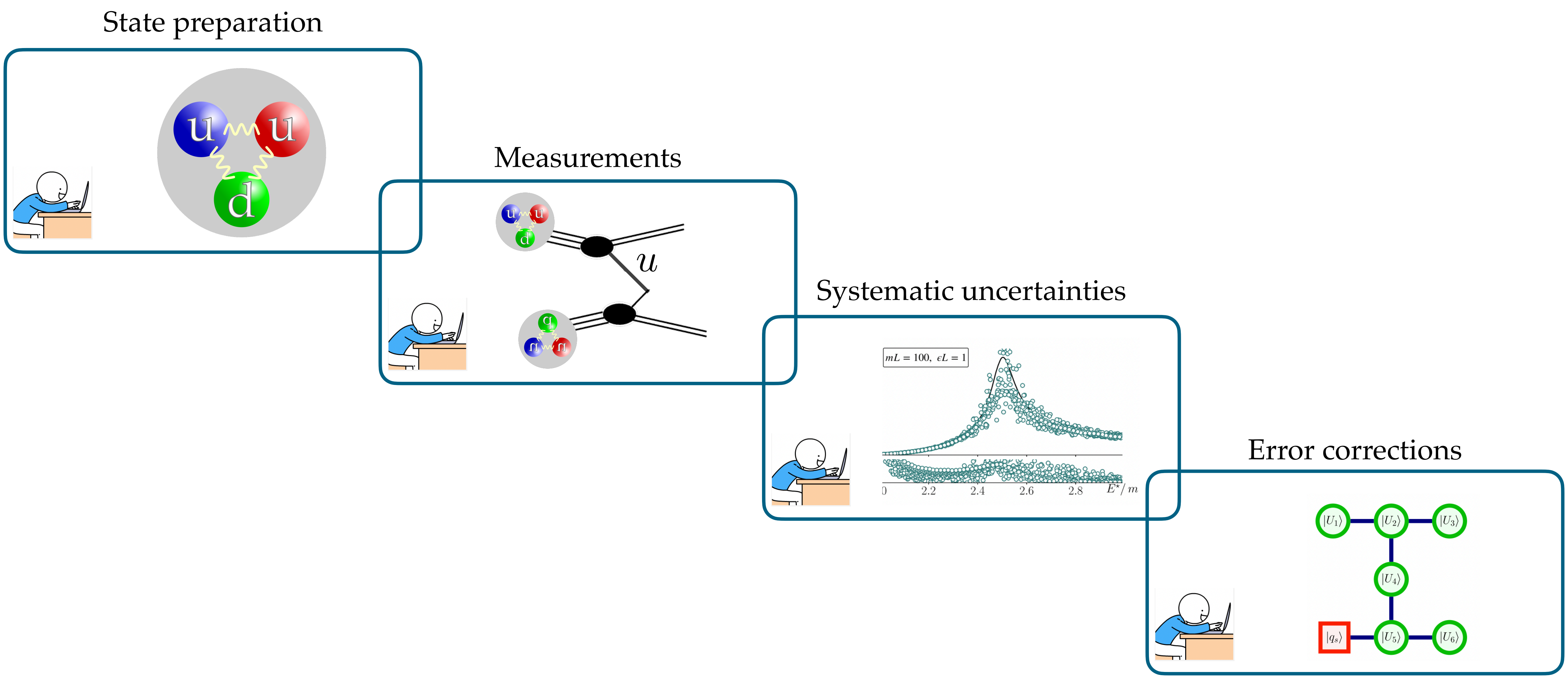
Qubit models: *Chandrasekhara, Singh, et al.*

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



To be continued:

非微扰QCD计算量子线路深度估计

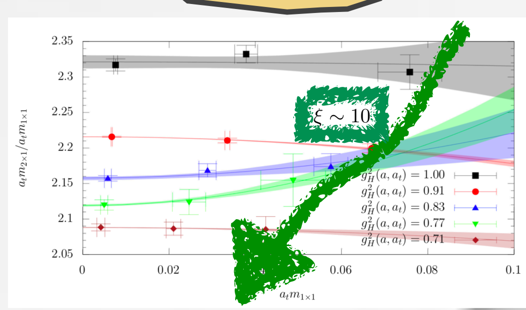
Where are we?

"We need time, so start now"

(2030s) narrow down the framework with

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

various methods



2030s -

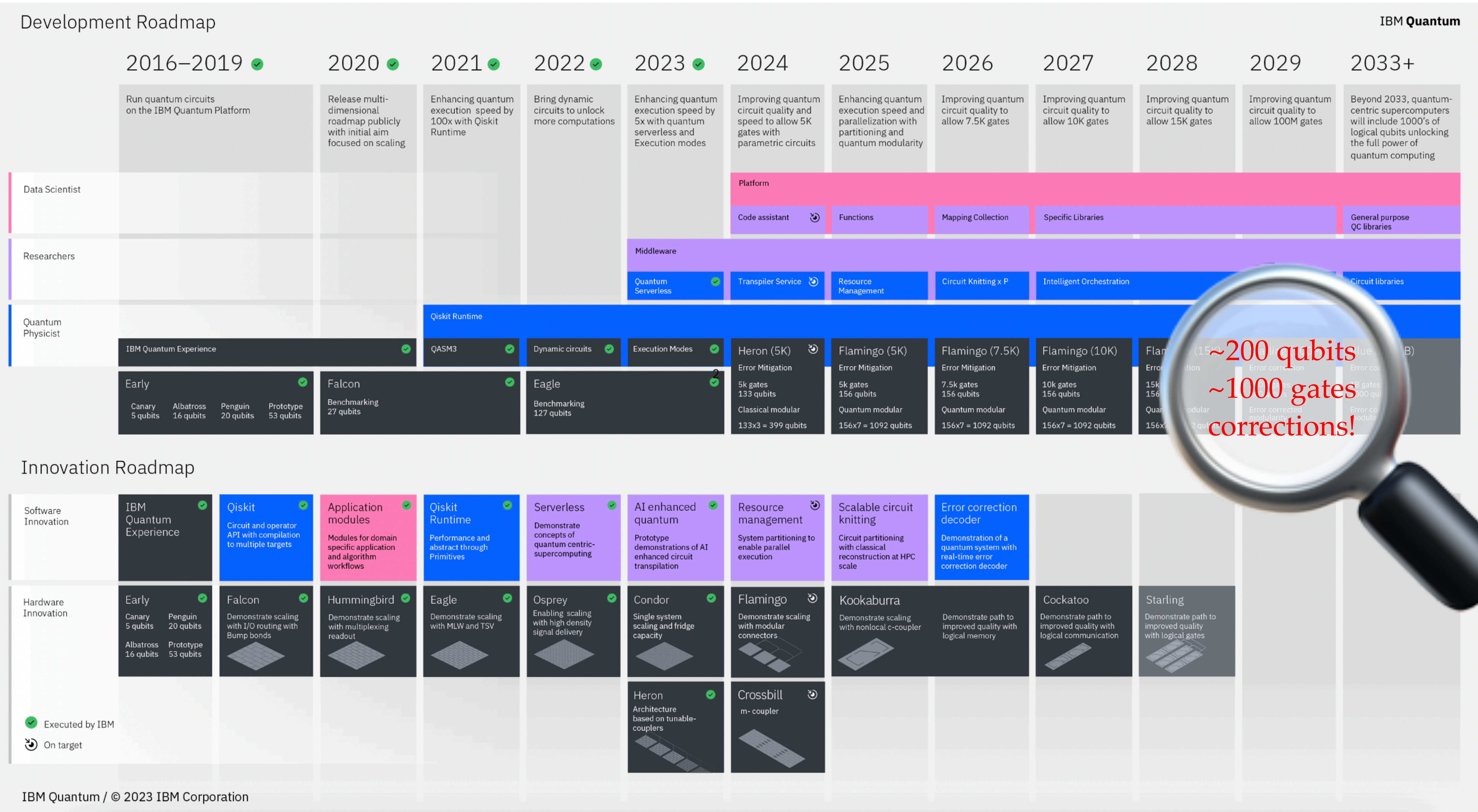
``also told you…"

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

2020 -

2011-

Next decades



Benchmarks

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

$$\mathcal{L} = \bar{f}_1(i\partial\!\!\!/ + m_1)f_1 + \bar{f}_2(i\partial\!\!\!/ + m_2)f_2 + (\partial_\mu\phi)^2$$
$$+ g_1\bar{f}_1 f_1\phi + g_2\bar{f}_2 f_2\phi + g_{12}\left[\bar{f}_1 f_2 + \bar{f}_2 f_1\right]\phi$$