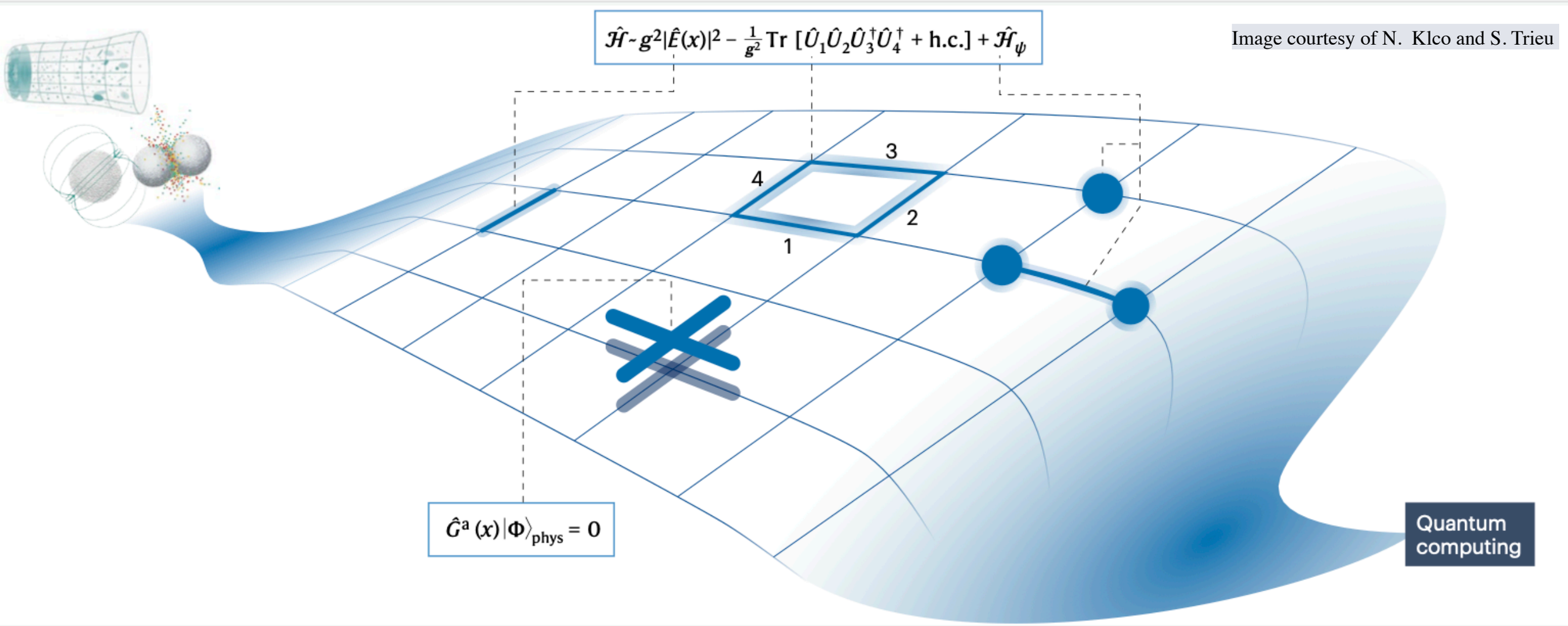
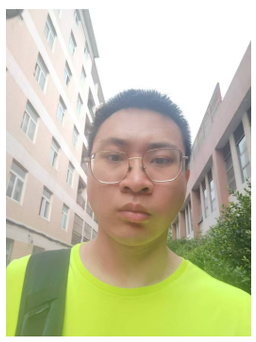


Image courtesy of N. Klco and S. Trieu

在量子计算机上研究强相互作用演化

May. 05, 2025@中国科学院大学物院线上论坛



Y.-L. Wang

Y. Luo

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Chinese Academy of Sciences

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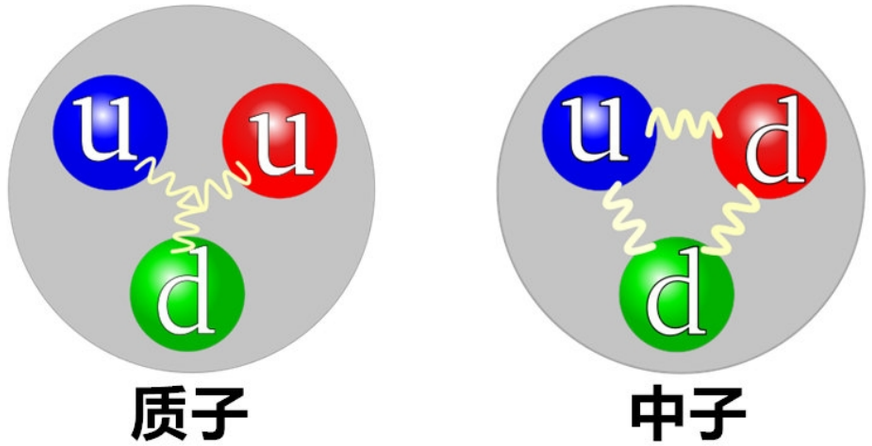
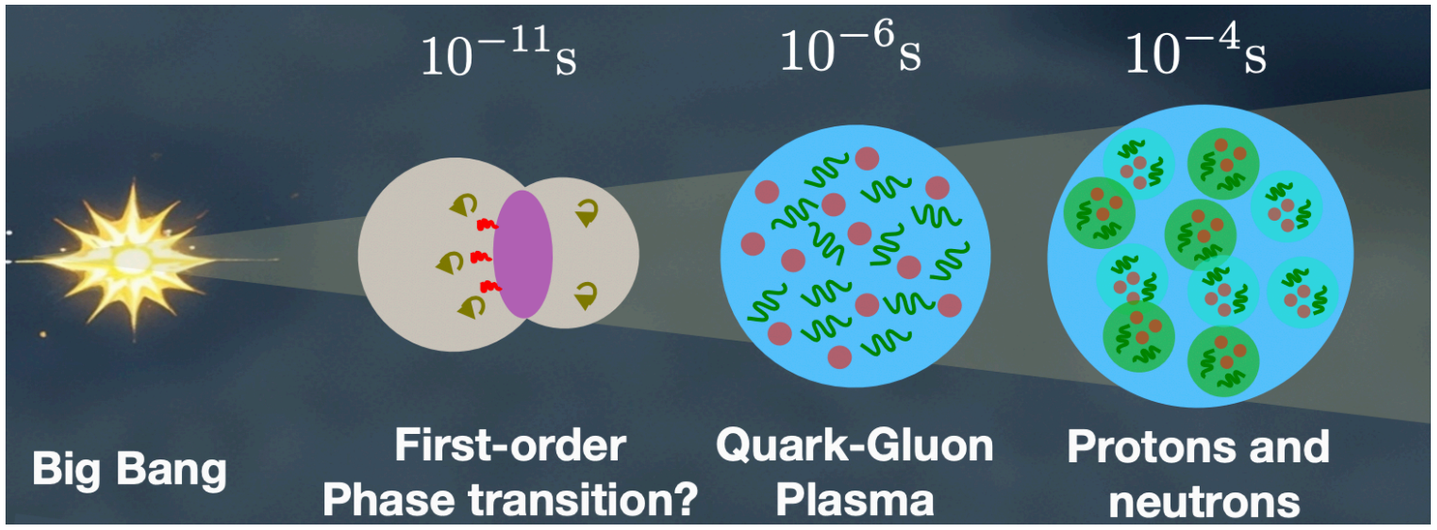
强相互作用及其演化

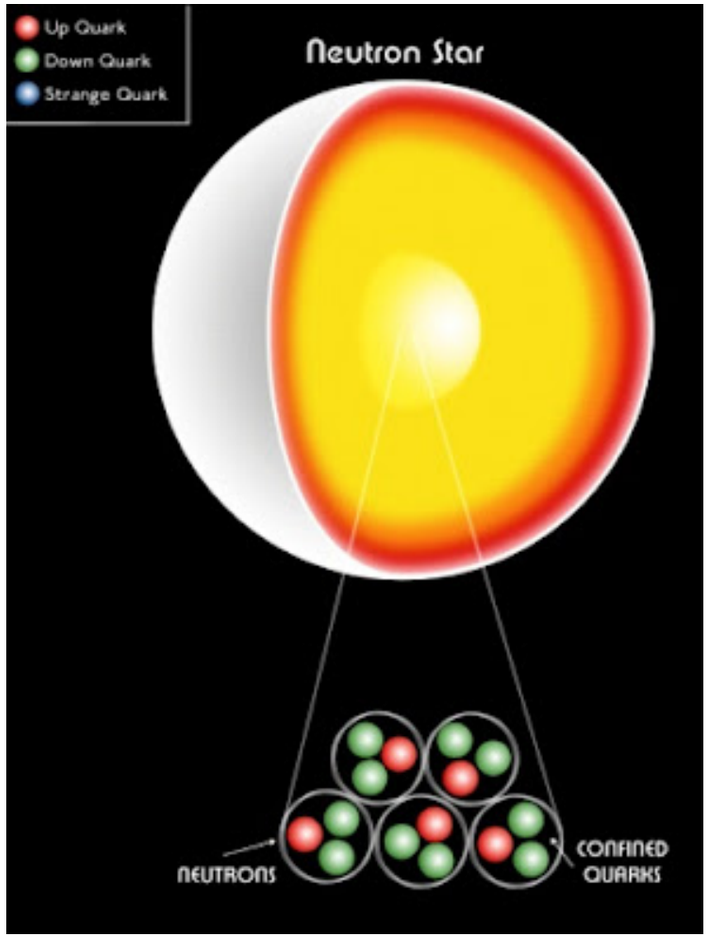
强相互作用：夸克和胶子



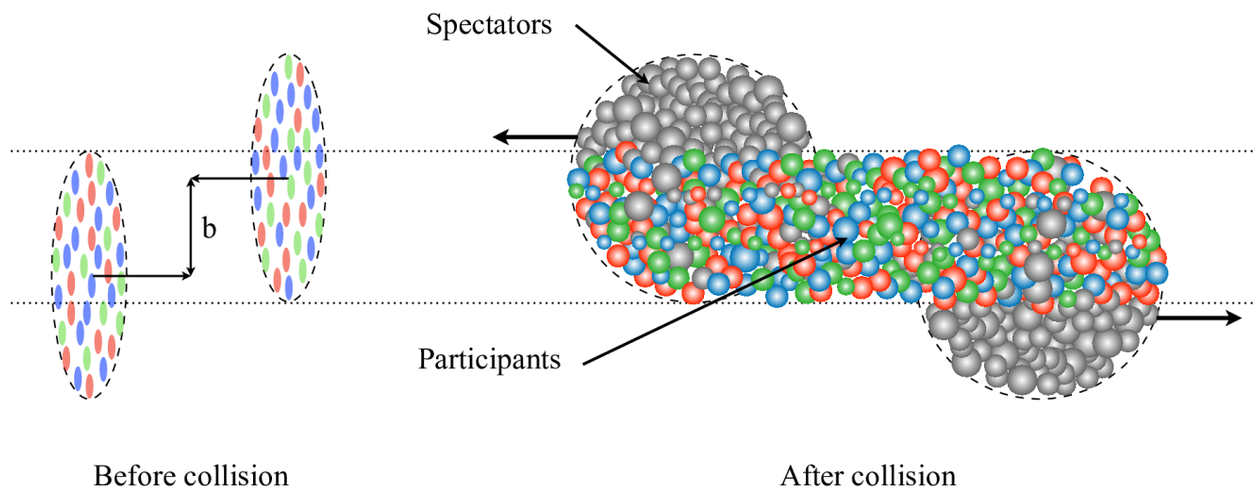
强相互作用及其演化

早期宇宙中的强相互作用物质演化

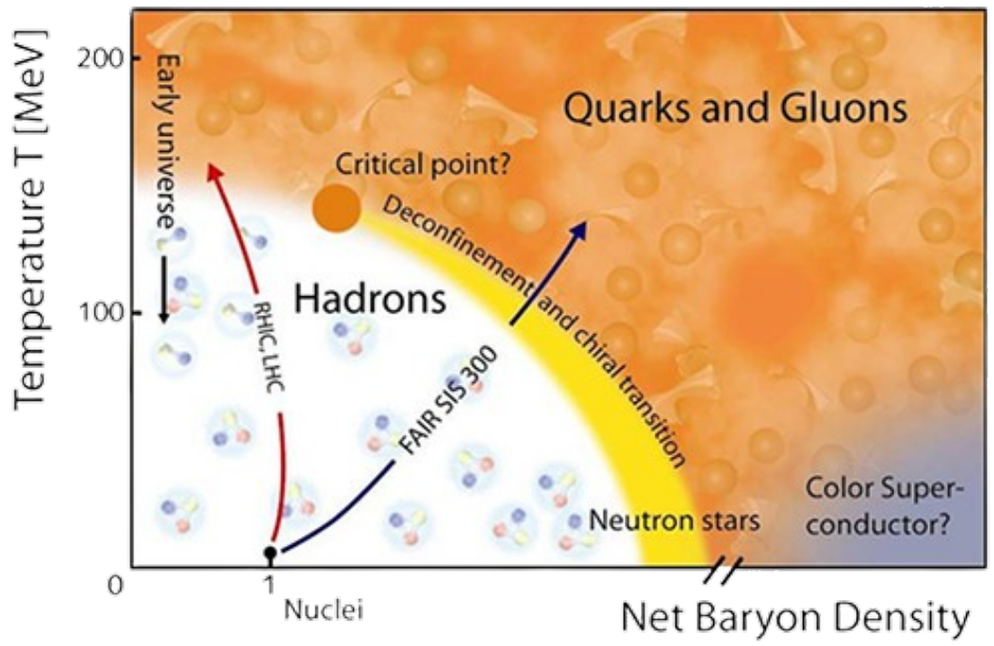




重离子碰撞中的强相互作用物质演化

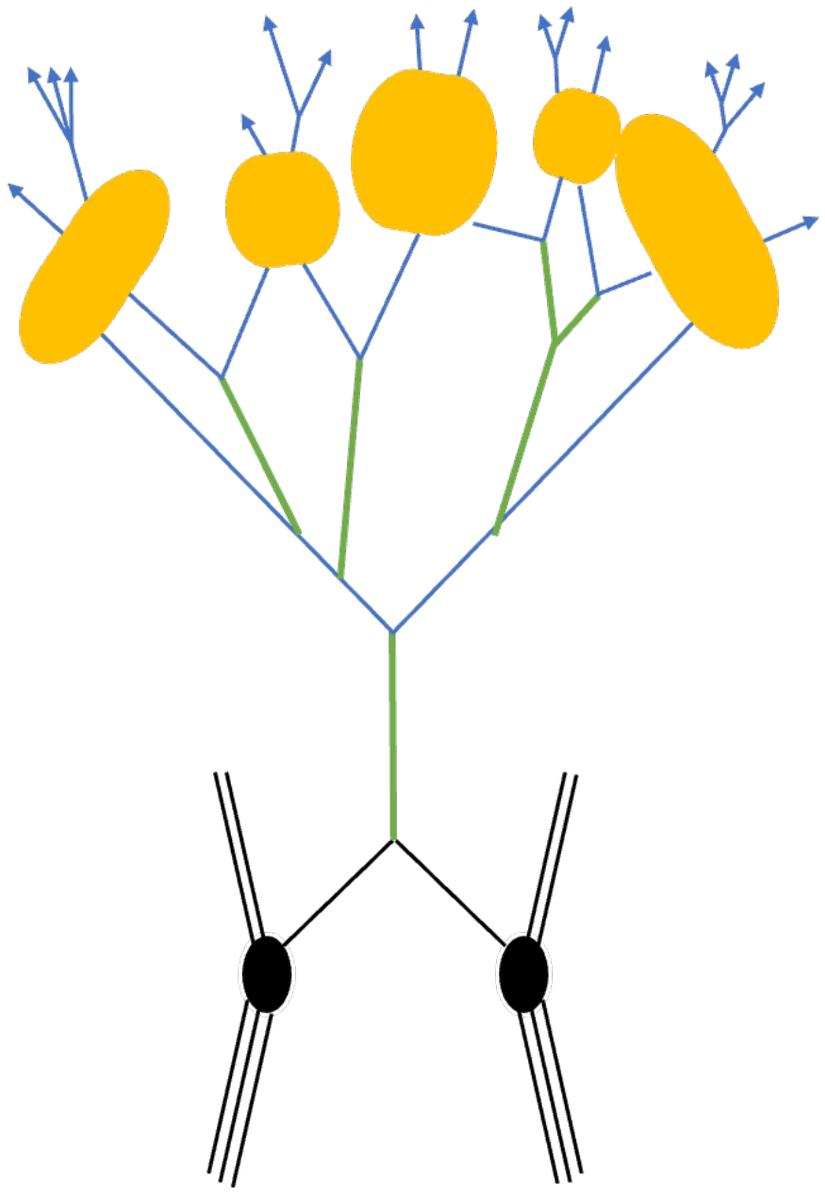


有效温有限密强相互作用物质的相图结构



强相互作用及其演化

质子对撞机上的强相互作用物质演化



部分子簇射和强子化

GeV

$n \sim 10^3$

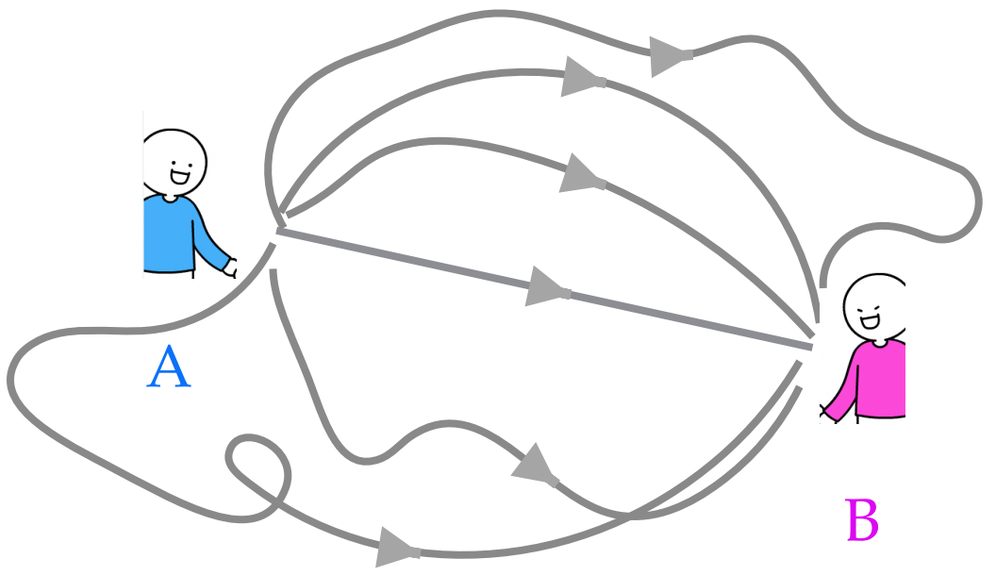
TeV

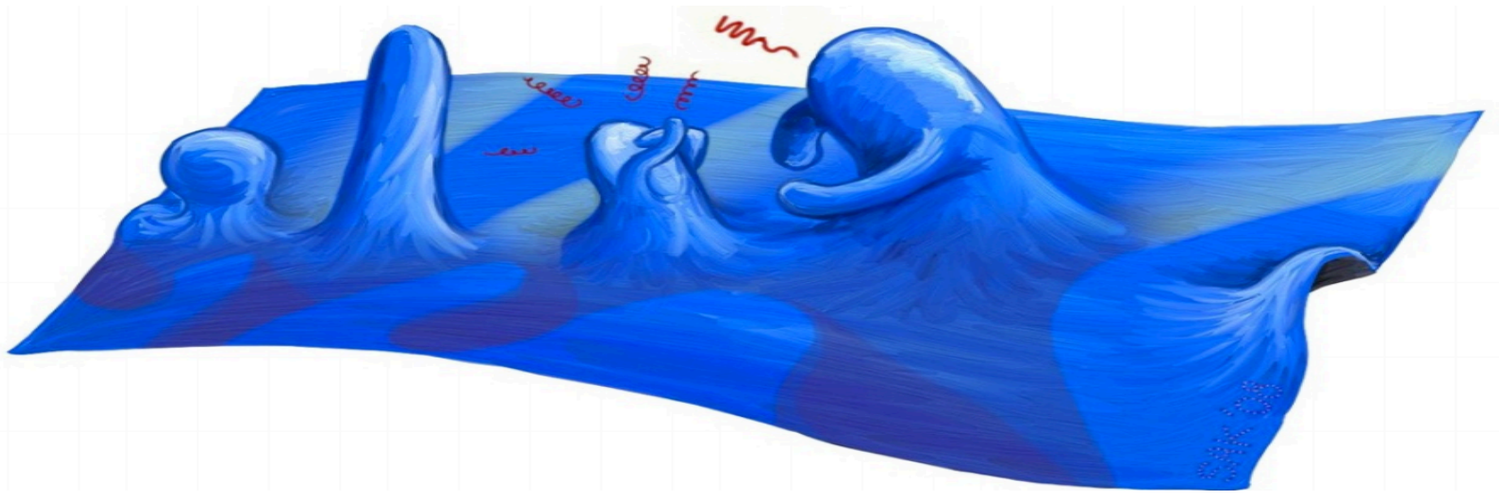
~~ PDF （部分子分布函数）

相互作用强度在非微扰区域

强相互作用物质演化的模拟

Relativistic Quantum Mechanics → Quantum Field Theory (QFT)

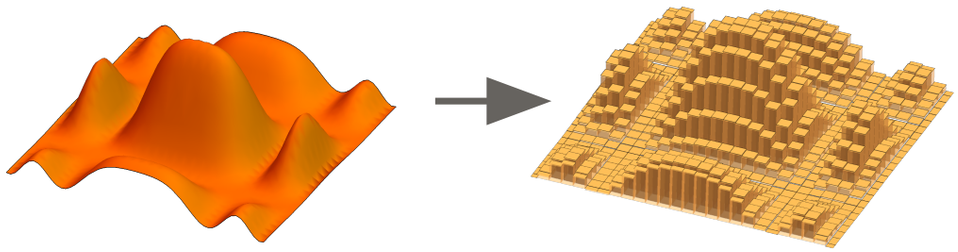


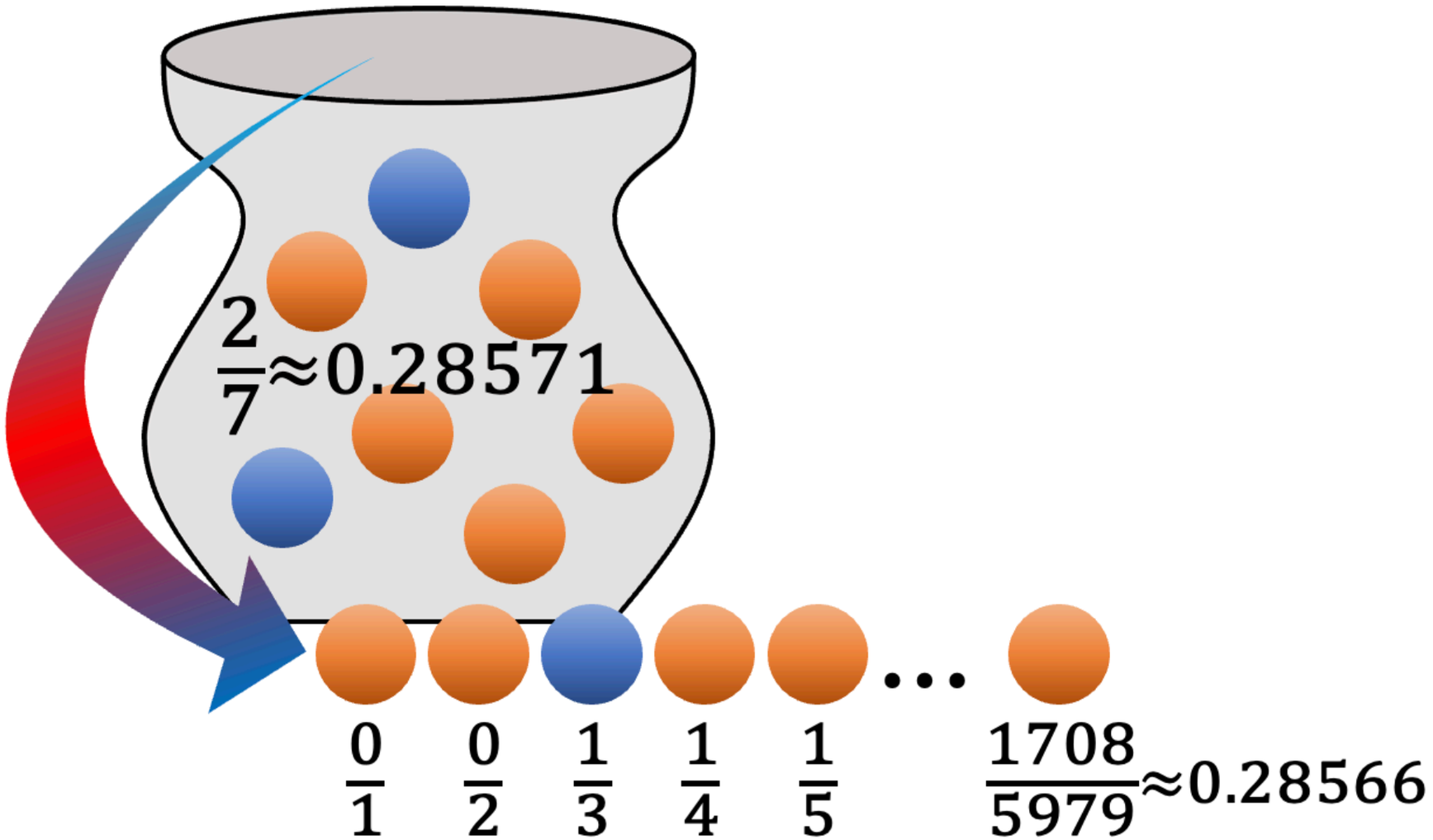


在量子场背景上作路径积分

格点QCD - 经典方法

欧氏时空非微扰格点计算
(蒙特卡罗方法)





格点QCD - 经典方法

欧氏时空非微扰格点计算
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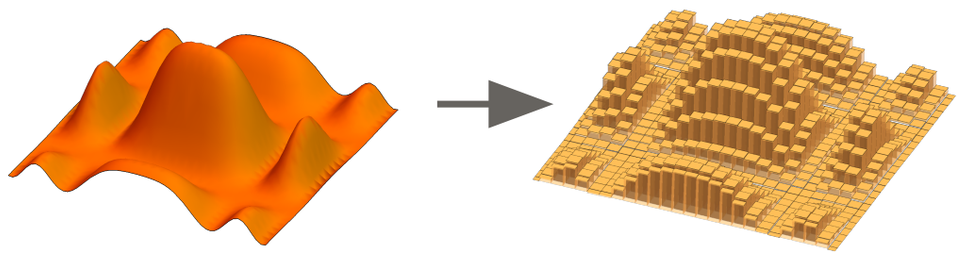
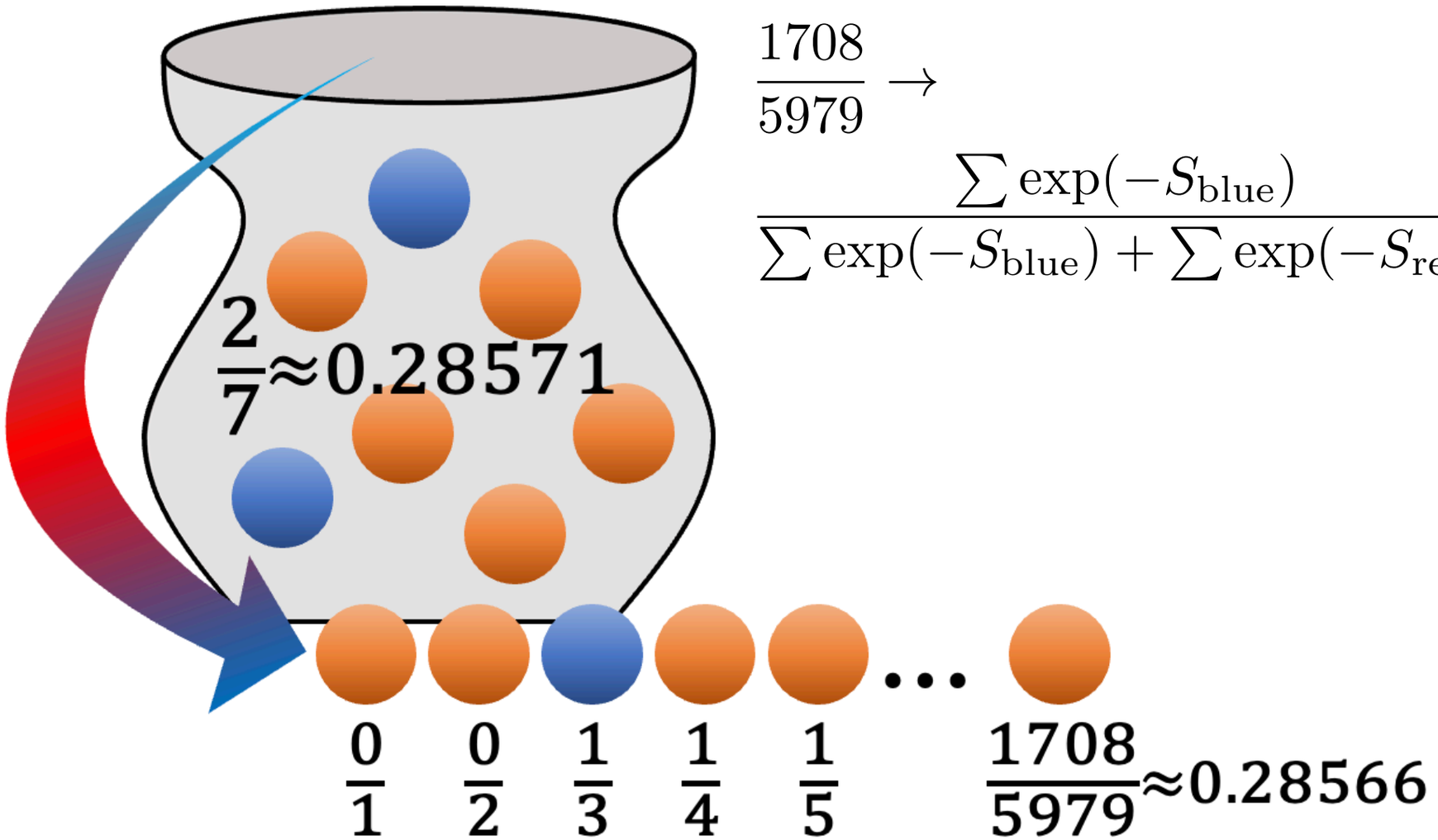


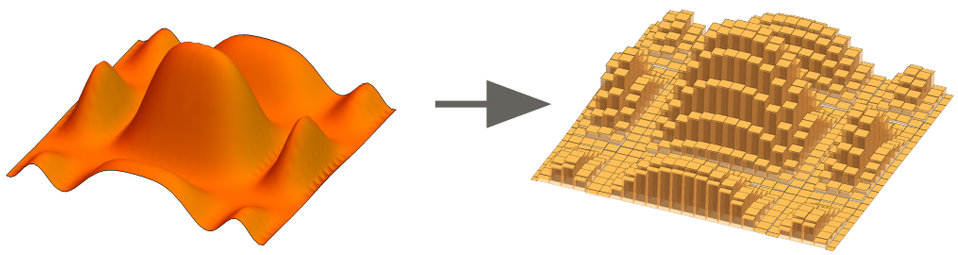


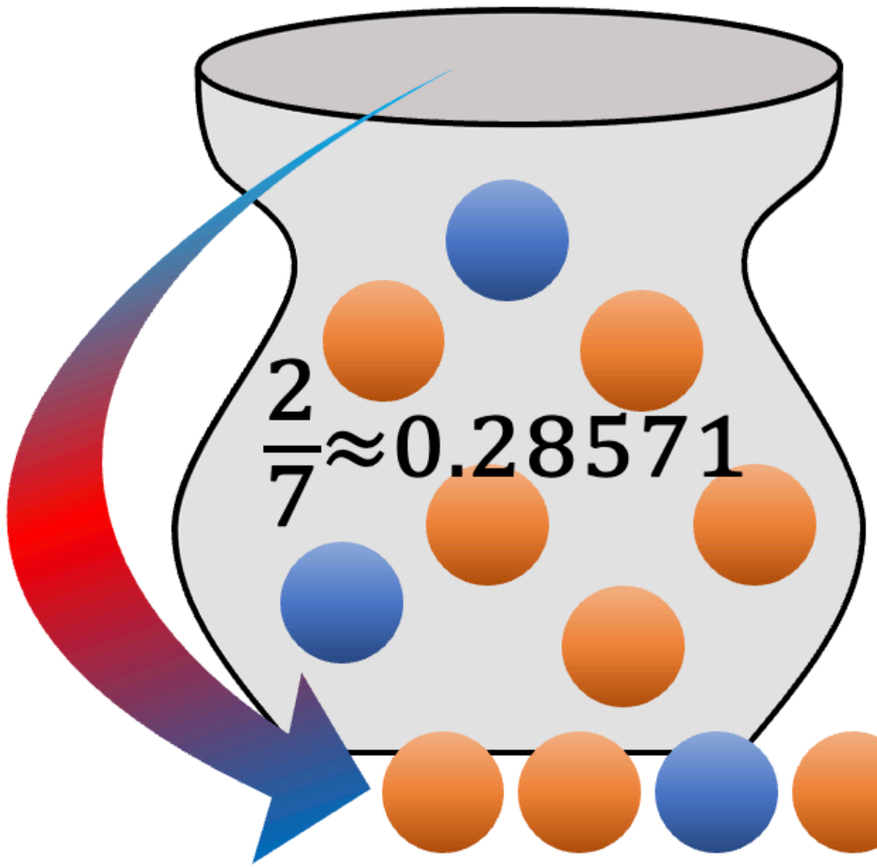
$$\frac{1708}{5979} \rightarrow \frac{\sum \exp(-S_{\text{blue}})}{\sum \exp(-S_{\text{blue}}) + \sum \exp(-S_{\text{red}})}$$

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

格点QCD - 经典方法

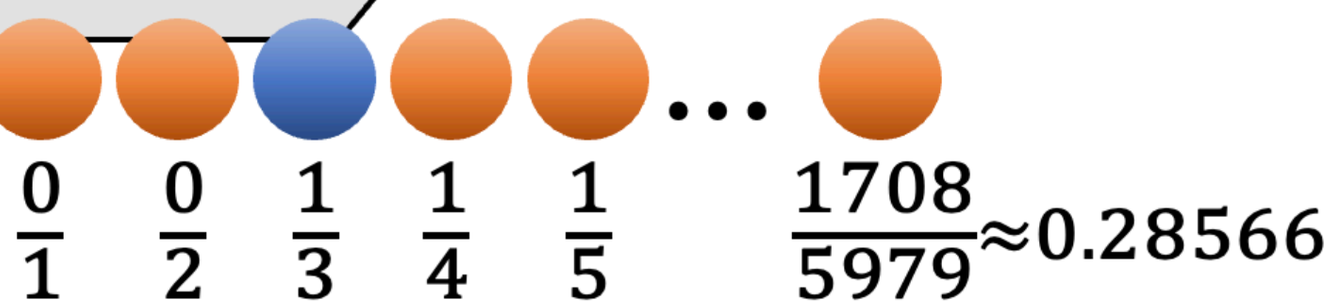
欧氏时空非微扰格点计算
(蒙特卡罗方法)





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

如果 S_C 是虚数呢?

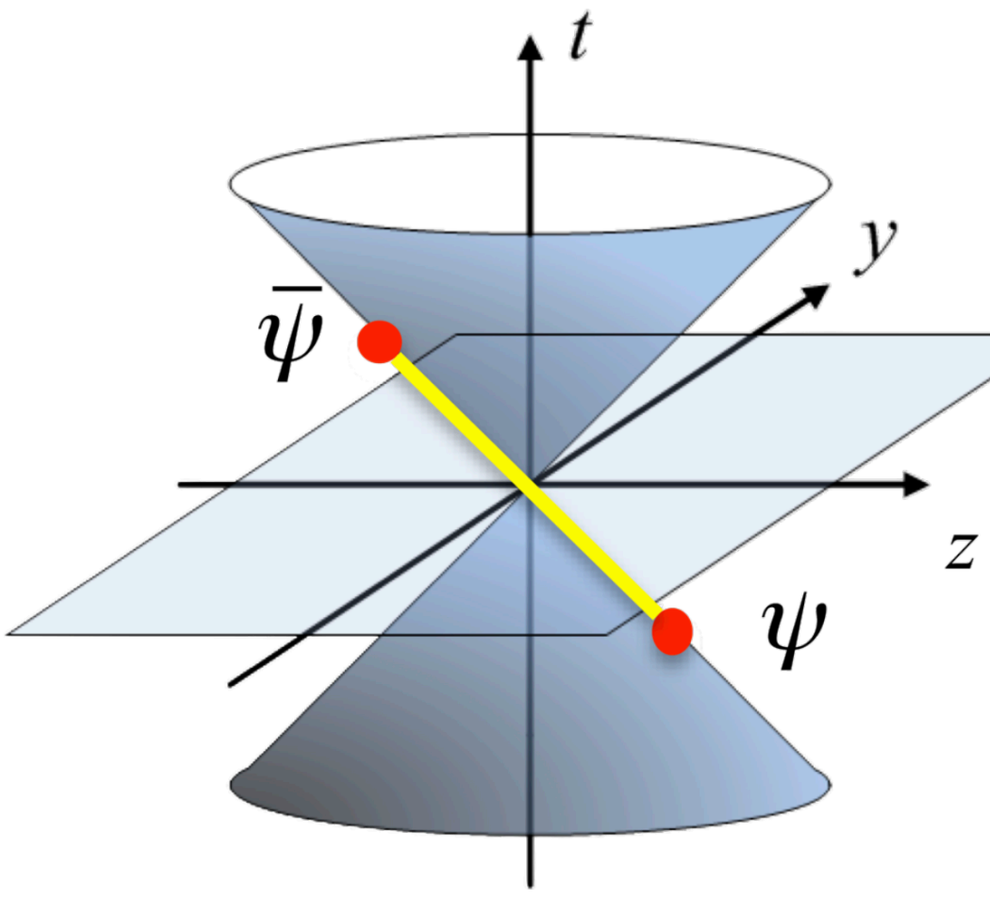


蓝球和红球的权重: $W(\mathcal{C}) \sim \exp(-S_{\mathcal{C}})$

格点QCD - 经典方法

欧氏时空非微扰格点计算面临挑战

PDF:光锥上的关联函数 — 闵氏时空问题



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

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

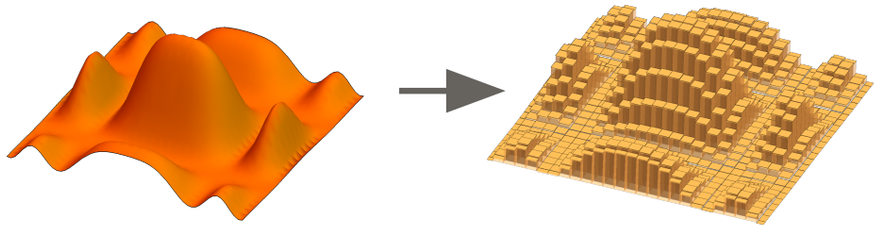
实时动态过程, 非平衡过程, ...

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

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



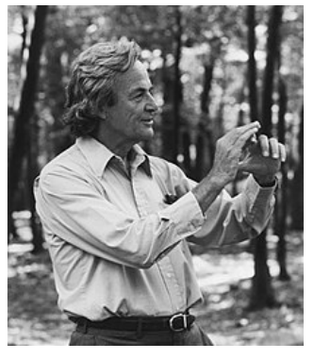
$$\dim H \propto |G|^{N_V}$$

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

"nature isn't classical"



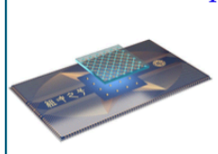
所需量子比特数: $N_q \propto N_V \log |G|$

(*QUANTUM EASY*)

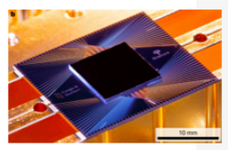
Now - Noisy Intermediate Scale Quantum (NISQ) era

more than 50 well controlled qubits, not error-corrected yet

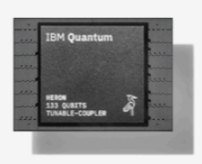
superconducting processor



176 qubits



54 qubits

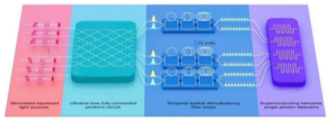


1121 qubits
access to 133 qubits

multi-chip quantum processor

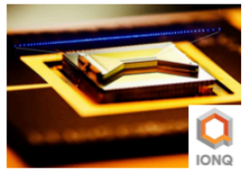
80 qubits

photon qubits



Jiuzhang - 255 qubits

trapped ion qubits



22 qubits

48 logical qubits

量子计算机上的强相互作用演化研究

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

[Jordan, Lee, Preskill, 2011]

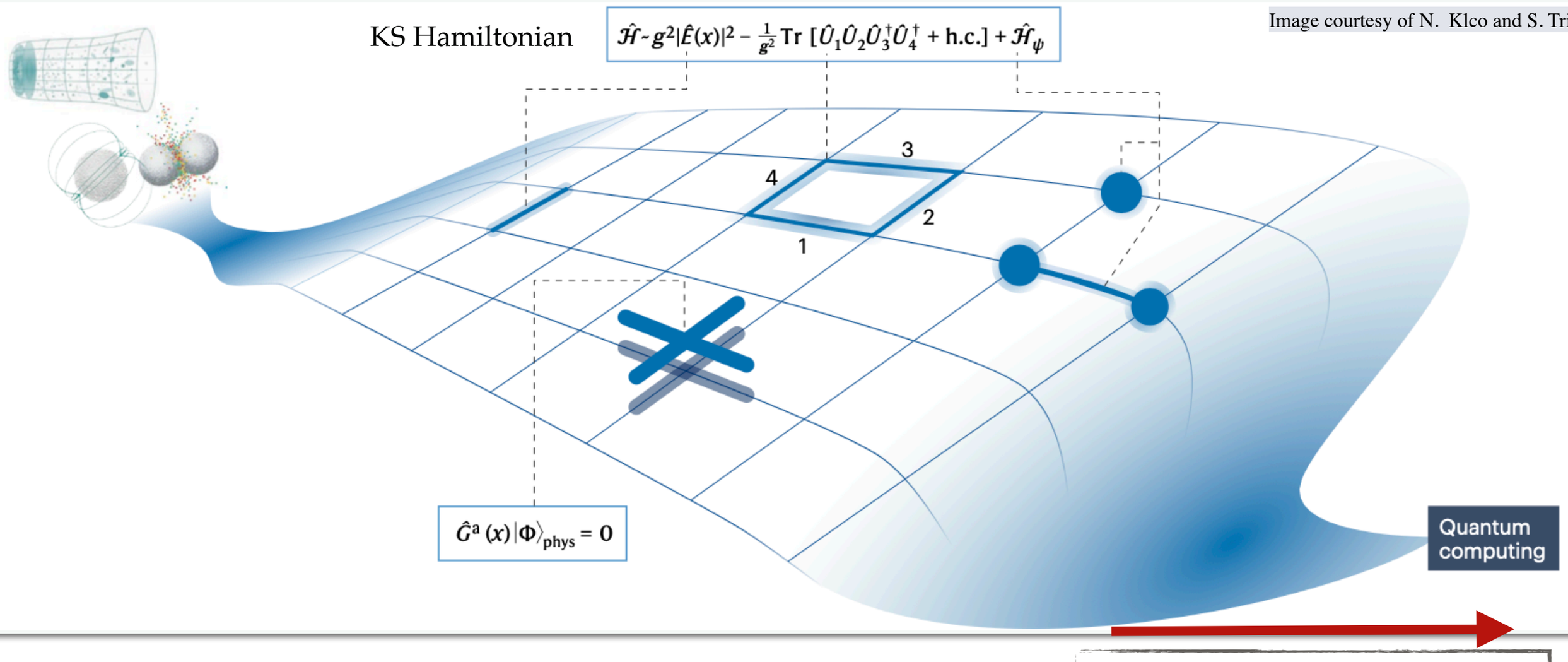


Image courtesy of N. Klco and S. Trieu

Discretization 离散化

Digitization 数字化

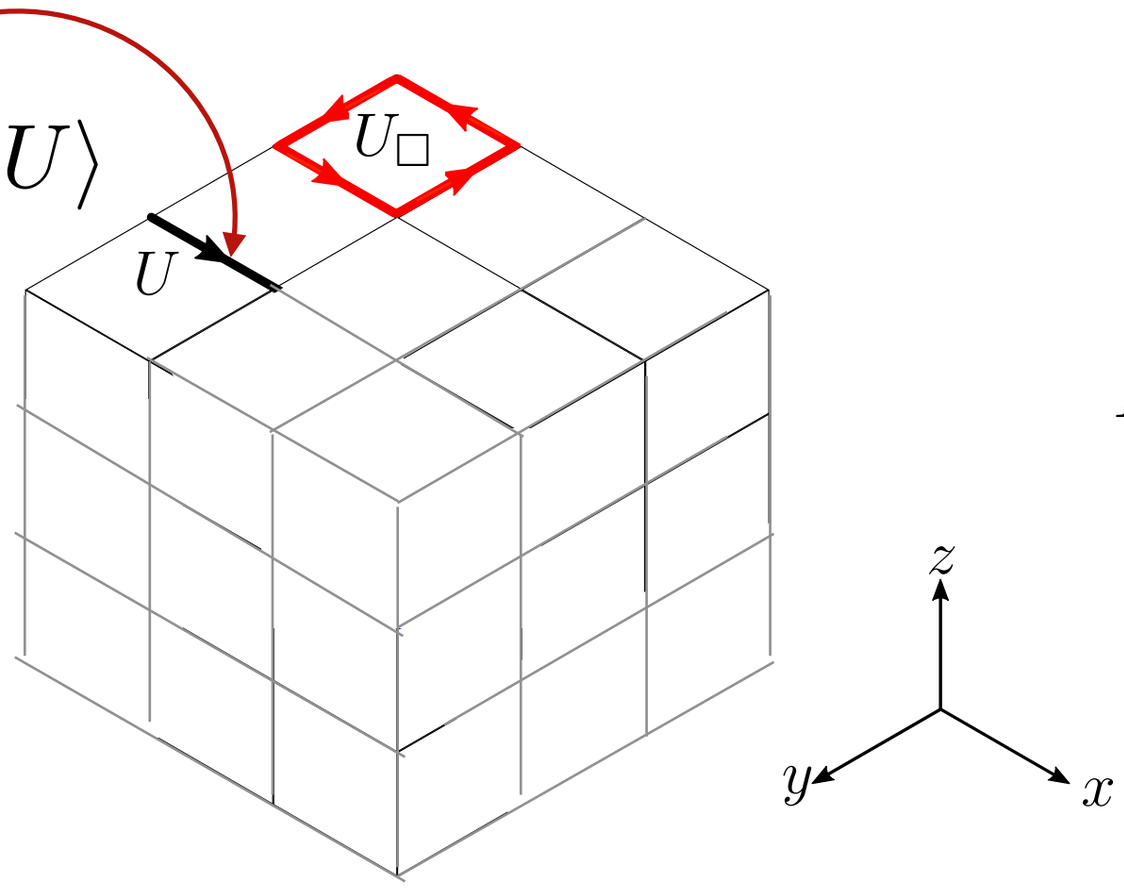
Initialization 初态制备

Gauge field and quark field DOF to qubits

Propagation 时间演化

Evaluation 测量

Error mitigation/corrections 误差缓解和纠错



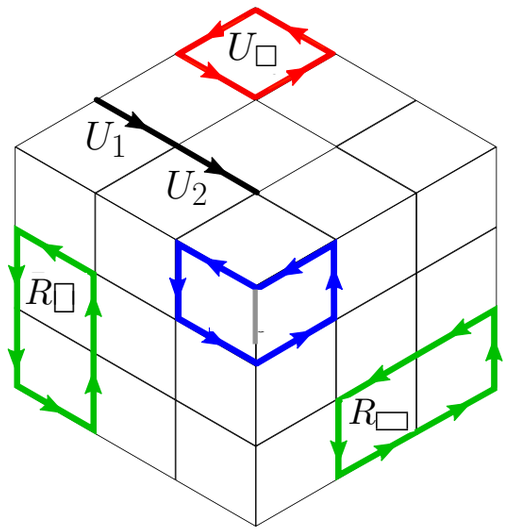
规范不变的哈密顿量

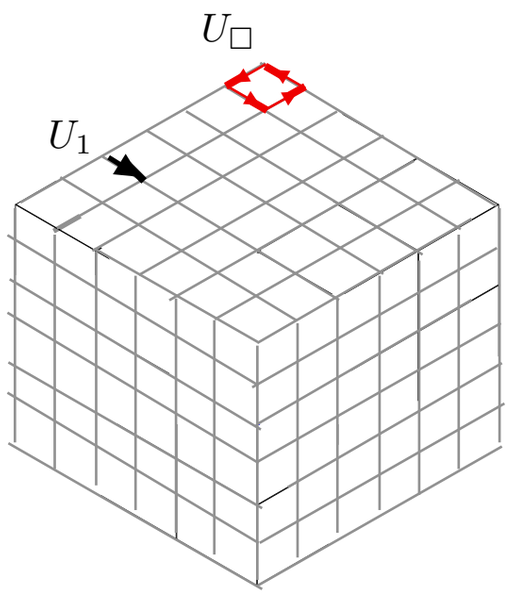
KS Hamiltonian [Phys. Rev. D 11, 395 (1975)]

$$H_{KS} = \sum \left(\underset{K_L}{\rightarrow\!\!-} + \underset{U_\square}{\square} \right)$$

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

$$K_{2L} = E_i(\mathbf{x})U_i(\mathbf{x})E_i(\mathbf{x}+a\mathbf{i})U_i^\dagger(\mathbf{x})$$





[Carena, Lamm,**YYL**, Liu, PRL. **129**, 051601]

改进哈密顿量

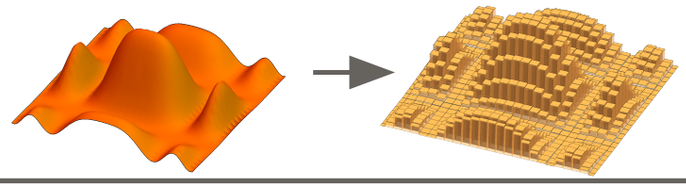
$$H_I = \sum \Big(K_L + K_{2L} + U_\square + R_\square + R_{\square\!\!\square} \Big)$$

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

$$N_q \sim \left(\frac{L}{a}\right)^d$$

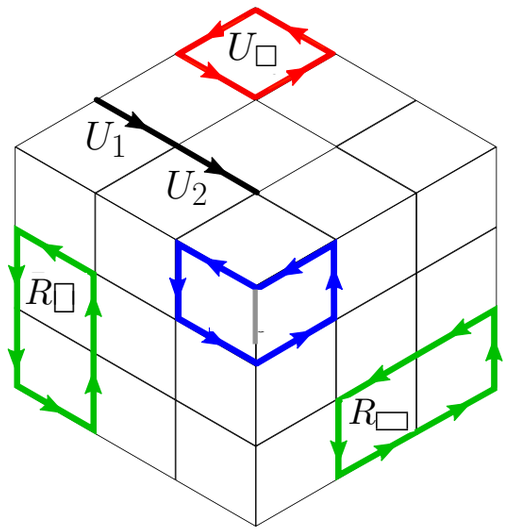
相同误差水平下，有效降低量子比特数以及演化所需的时间片数目

Discretization



infinities in QFT

$$K_{2L} = E_i(\mathbf{x})U_i(\mathbf{x})E_i(\mathbf{x}+a\mathbf{i})U_i^\dagger(\mathbf{x})$$



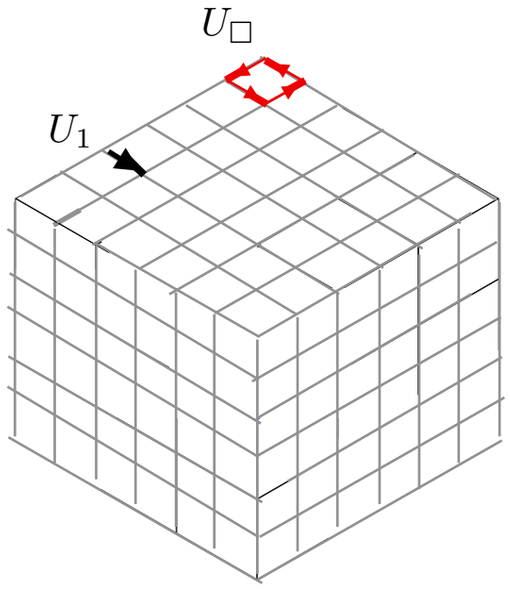
改进哈密顿量

$$H_I = \sum \Big(+ + + + \Big)$$

K_L K_{2L} $U_\square$ $R_\square$ $R_{\square\!\!\square}$

量子线路

$$\langle U_1', U_2' | \mathcal{U}_{K_{2L}} | U_1, U_2 \rangle = \delta_{U_1' U_2', U_1 U_2} \langle U_1' | e^{i\theta K_{L_1}} | U_1 \rangle$$



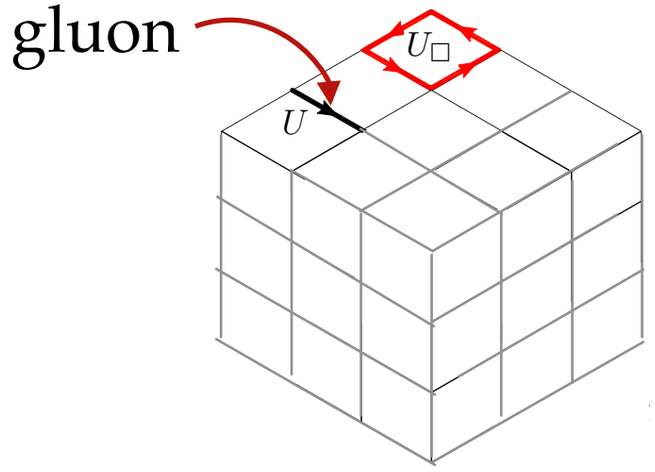
群元素乘积不变!

Thus can be reduced to the matrix elements of the one-link kinetic term

[Carena, Lamm,**YYL**, Liu, PRL. **129**, 051601]

Digitization

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

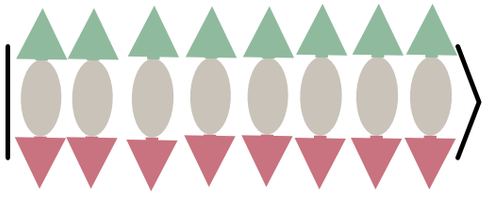
infinities in QFT

discrete subgroup

$$|U\rangle = \left\{ \begin{pmatrix} \alpha & -\overline{\beta} \\ \beta & \overline{\alpha} \end{pmatrix} : \ \alpha, \beta \in \mathbb{C}, |\alpha|^2 + |\beta|^2 = 1 \right\} \rightsquigarrow |U\rangle = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \middle| a, b, c, d \in \mathbf{F}_3, ad - bc \equiv 1 \pmod 3 \right\}$$

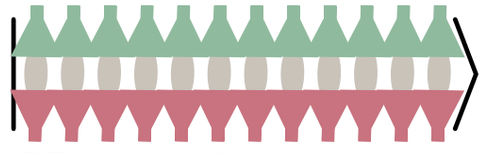
3-sphere

block product encoding: BT

$$|U\rangle = |$$ 

block product encoding: BI

$$|U\rangle = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \middle| a, b, c, d \in \mathbf{F}_5, ad - bc \equiv 1 \bmod(5) \right\}$$

$$|U\rangle = |$$ 

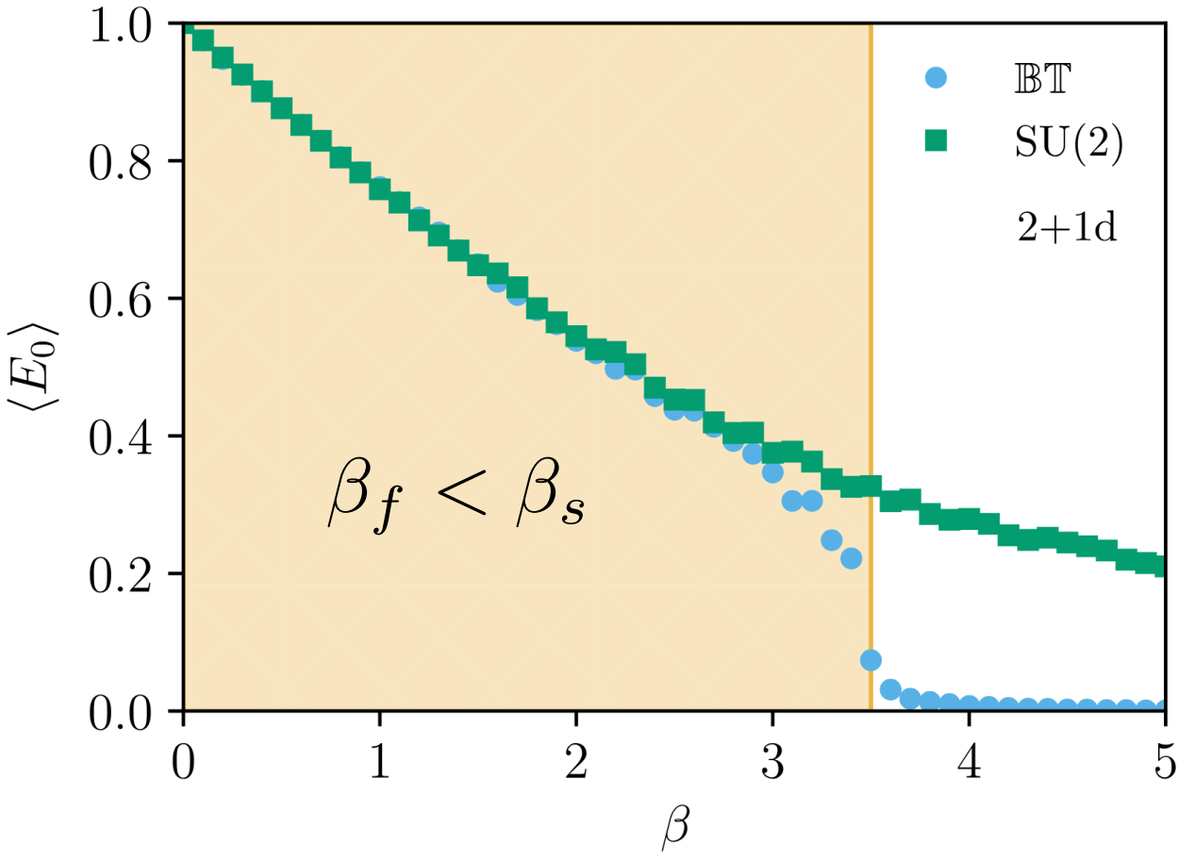
qudit?

[Lamm,**YYL**, Shu, Wang, Bin, arXiv:2405.12890]

- quantum algorithms developed for its time evolutions

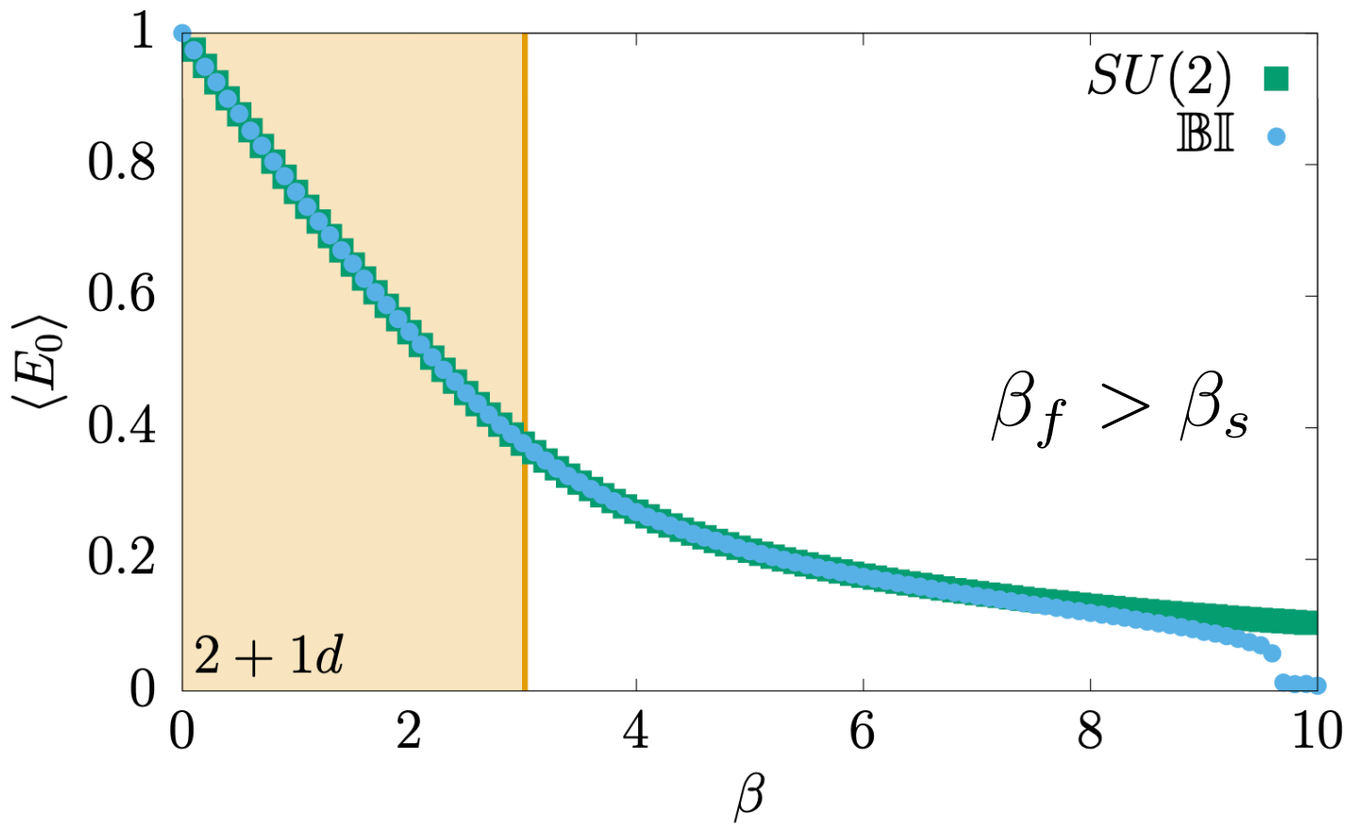
Digitization $|q\rangle^N \to |G\rangle$ infinities in QFT

[Gustafson, Lamm, Lovelace, Mush, PRD **106**, 114501]



如何系统低量化/降低误差?

[Lamm,**YYL**, Shu, Wang, Bin, arXiv:2405.12890]

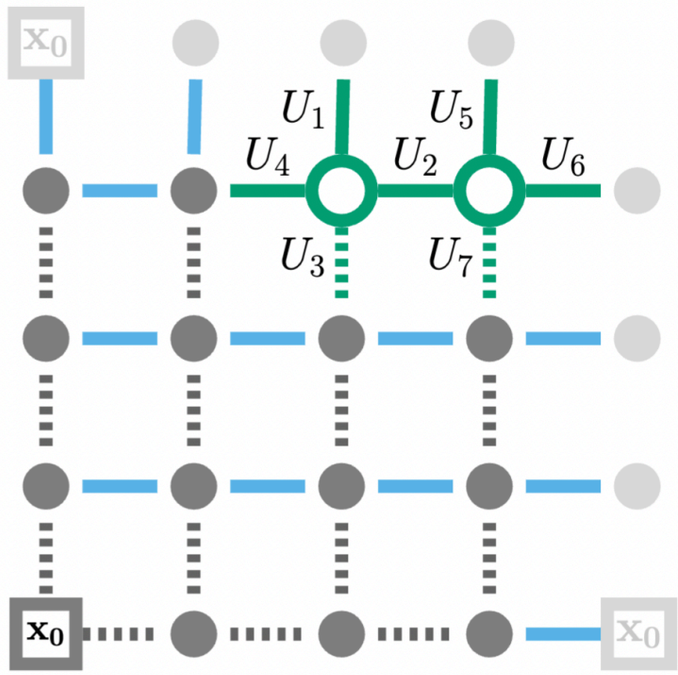


在可外推区域:

有效降低SU(2)理论计算的误差

Digitization $|q\rangle^N \to |G\rangle$

infinities in QFT



规范对称性意味着冗余，我们是否在量子模拟过程中保留规范冗余?

$$\mathcal{H}_{\text{full}} = \text{span}(\{|U\rangle, U \in G\})^{\otimes N_L}$$

$$\hat{\Theta}_\Omega(x)\,|U_1U_2U_3U_4\rangle = |U_1'U_2'U_3'U_4'\rangle$$

gauge redundant

gauge invariant

$$\hat{\Theta}_\Omega(x)\,|\psi_{\text{phys}}\rangle = |\psi_{\text{phys}}\rangle$$

$$\hat{G}^a(x)\,|\psi_{\text{phys}}\rangle = 0 \quad \text{(Gauss's law)}$$

$$\mathcal{H}_{\text{inv}} = \text{span}(\{|U\rangle, U \in G\})^{\otimes N_L - N_V + 1}$$

Digitization $|q\rangle^N \to |G\rangle$

infinities in QFT

去掉规范冗余的哈密顿量会是非局域的

$$\mathcal{H}_{\text{full}} = \text{span}(\{|U\rangle, U \in G\})^{\otimes N_L}$$

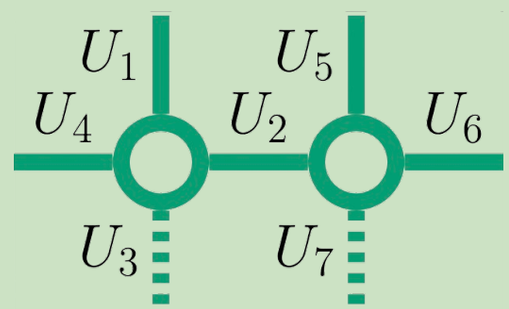
$$H_{KS} = \sum \left(\underset{K_L}{\rightarrow\!\!-} + \underset{U_\square}{\square} \right)$$

$$\mathcal{H}_{\text{inv}} = \text{span}(\{|U\rangle, U \in G\})^{\otimes N_L - N_V + 1}$$

$$\hat{\Theta}_\Omega(x) |\psi_{\text{phys}}\rangle = |\psi_{\text{phys}}\rangle$$

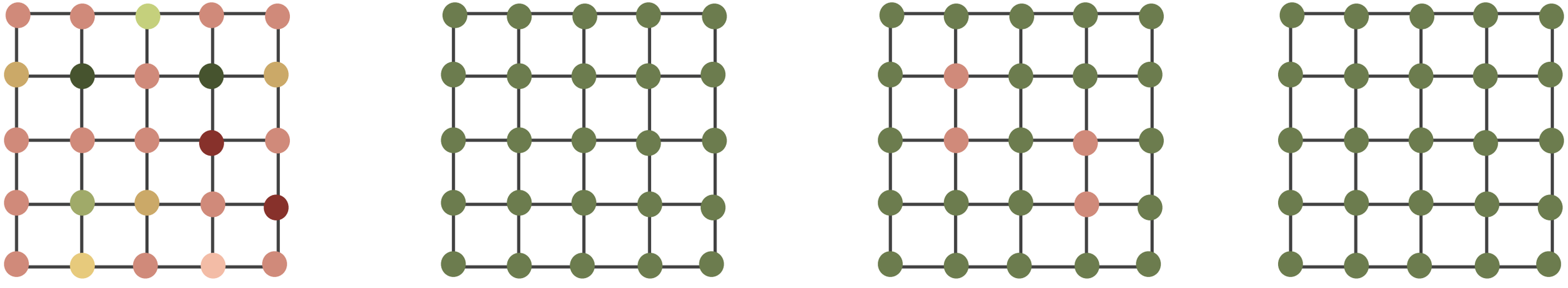
$$H_{KS} = \sum \left(\underset{K_L}{\rightarrow\!\!-} + \underset{U_\square}{\square} \right)$$

kinetic terms for U_3, U_7
depend on other links



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

如果保留规范冗余…

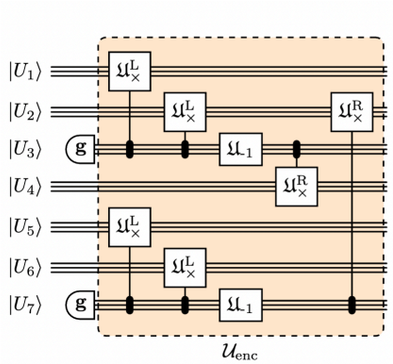


制备规范不变的初态

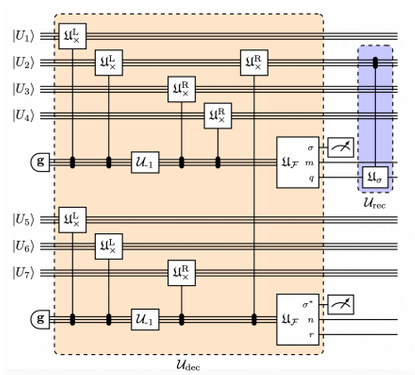
时间演化中会有量子噪声

测量高斯定理并恢复规范不变性

KL condition



$$\mathcal{U}(t) = e^{-iH_{KS}t}$$

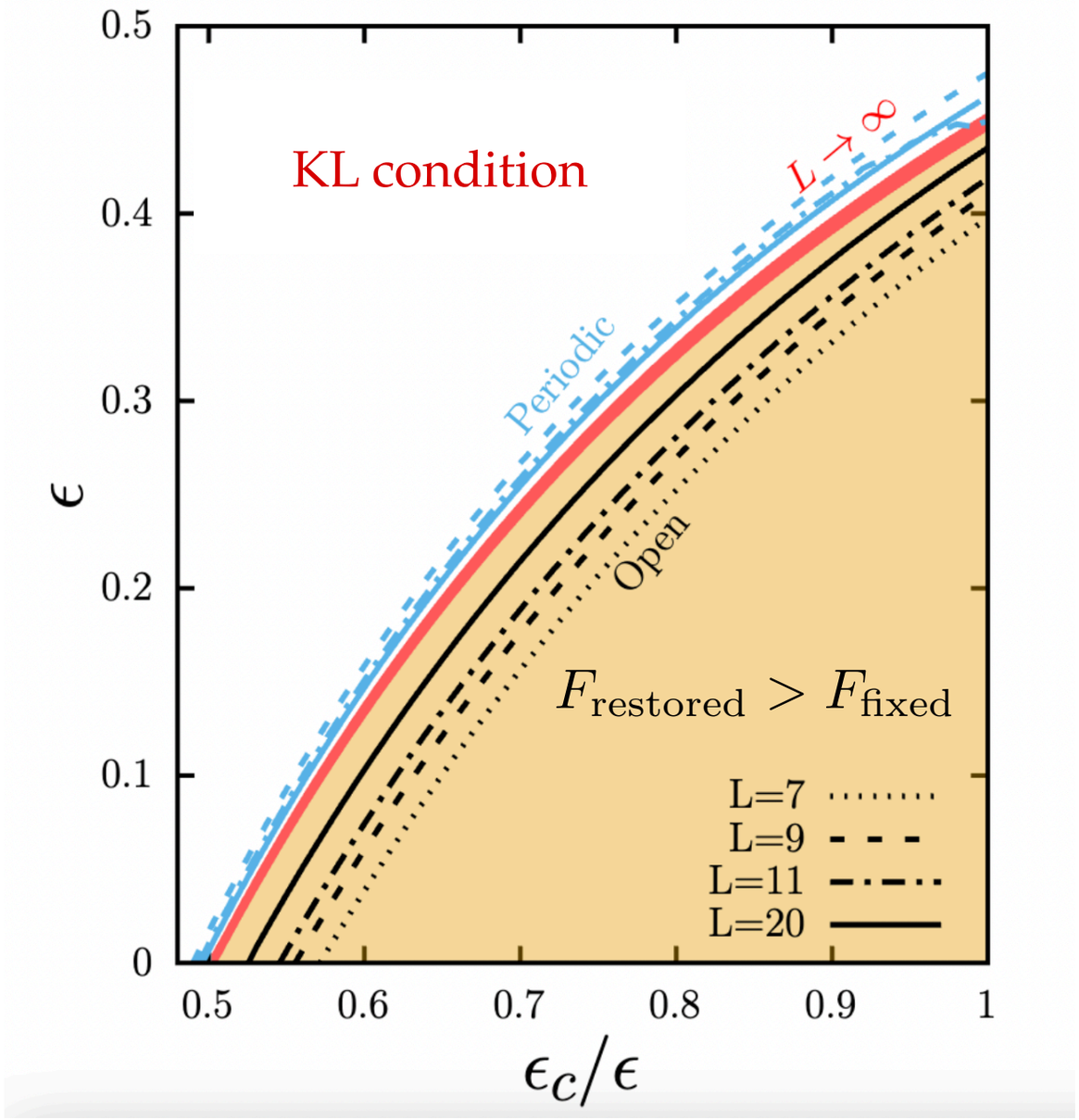


[Carena, Lamm,**YYL**, Liu, arXiv:2402.16780]

- quantum algorithms to correct errors for general gauge theories

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

2d lattice

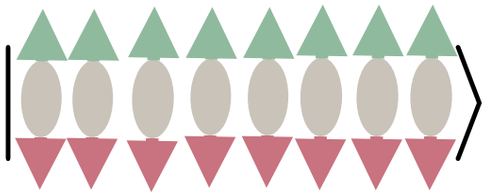


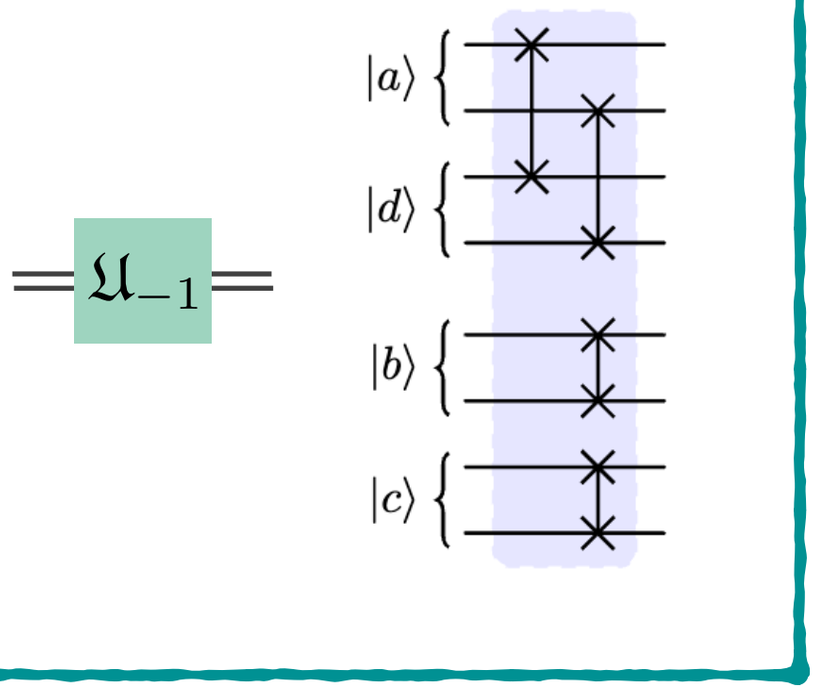
- 在一定的噪声阈值以下，保留规范冗余可以保持更高的保真度。

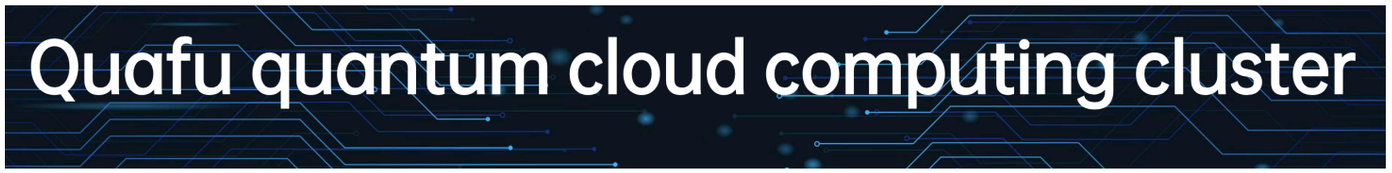
用于强相互作用物质演化的研究

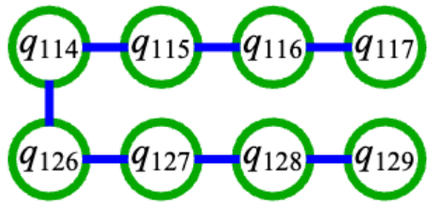
[Carena, Lamm,**YYL**, Liu, arXiv:2402.16780]

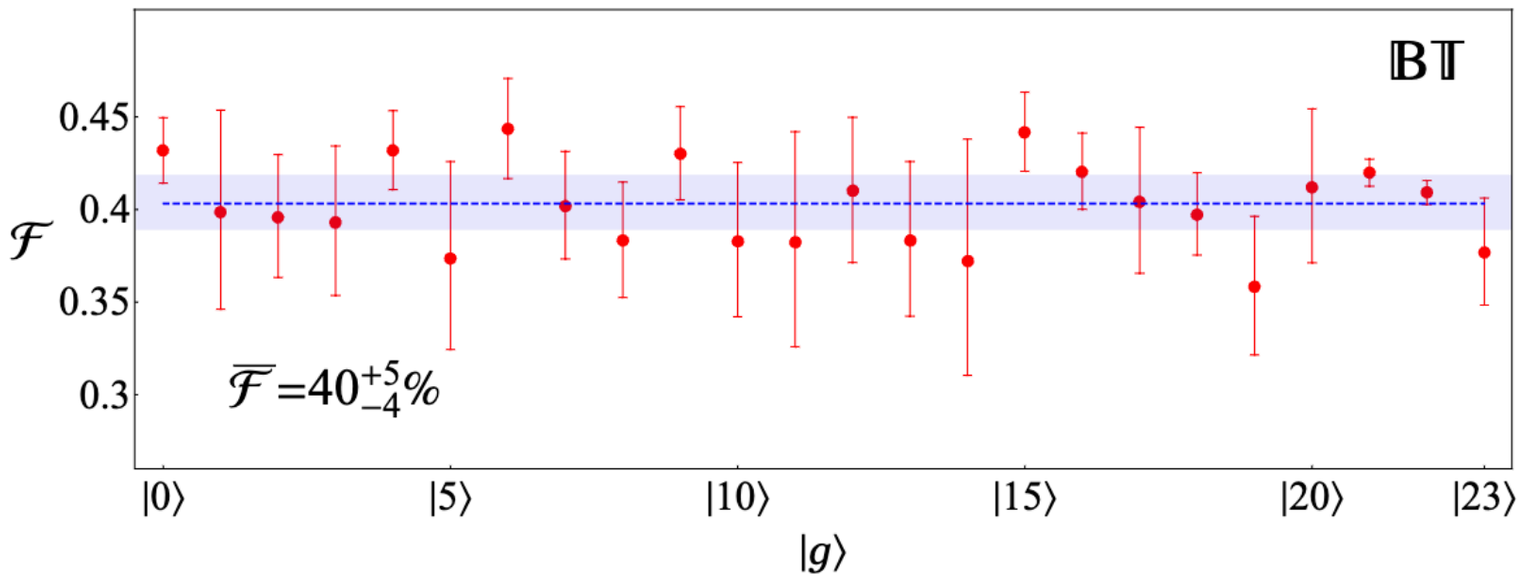
Propagation $\mathcal{U}\,|\psi_0\rangle \to |\psi(t)\rangle$

$|U\rangle =$ 





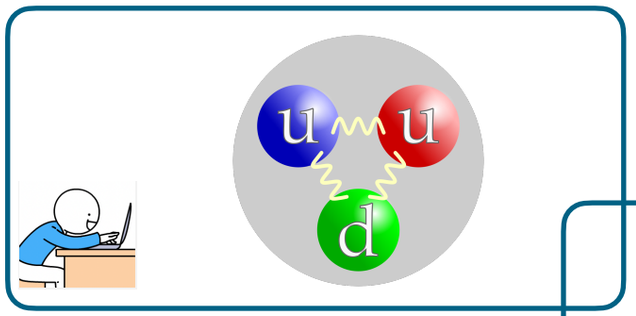




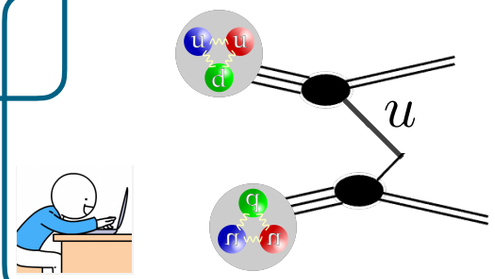
[Lamm,**YYL**, Shu, Wang, Bin, arXiv:2405.12890]

To reach the observables — How to do…

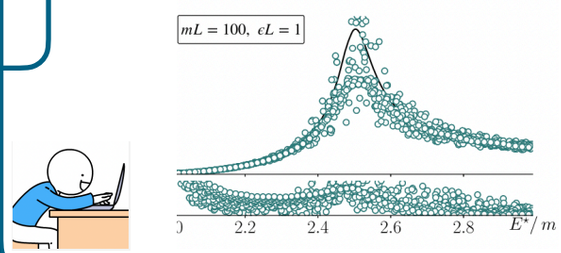
State preparation



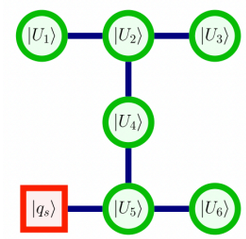
Measurements



Systematic uncertainties



Error corrections

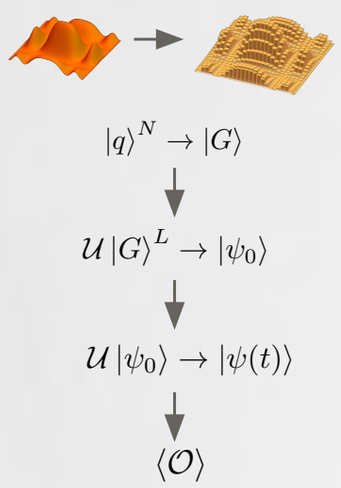


and reach the continuum limit

“Quantum potential for first-principle calculations!”

(2030s) narrow down the framework with

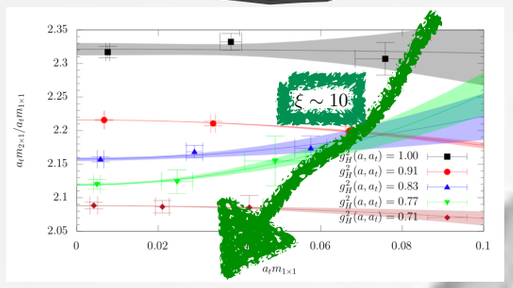
- systematic studies of errors from digitization —— phase diagrams with spontaneous symmetry breaking, and for improved H
- hardware co-design —— qudits for blocking encodings and the redundancies
- improving algorithms —— efficient quantum circuits based on qudits
- benchmark studies —— HEP case calculations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



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

2011-

various methods



2020 -

2030s -

Thank you

BACK UP