用于核多体系统研究的量子计算理论与方法发展

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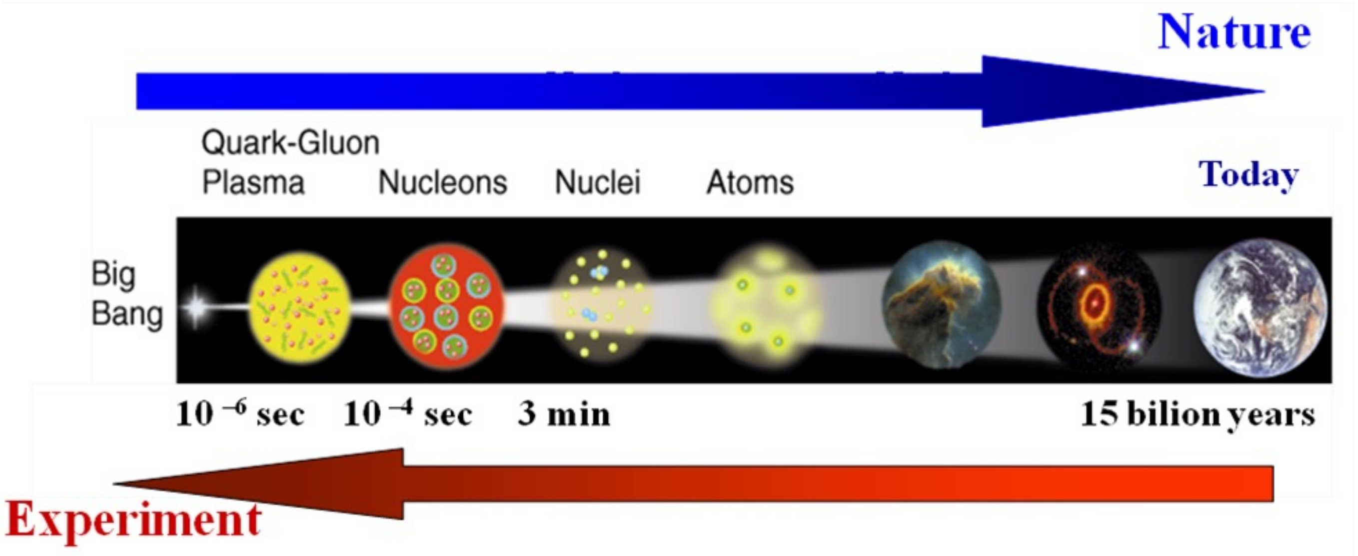
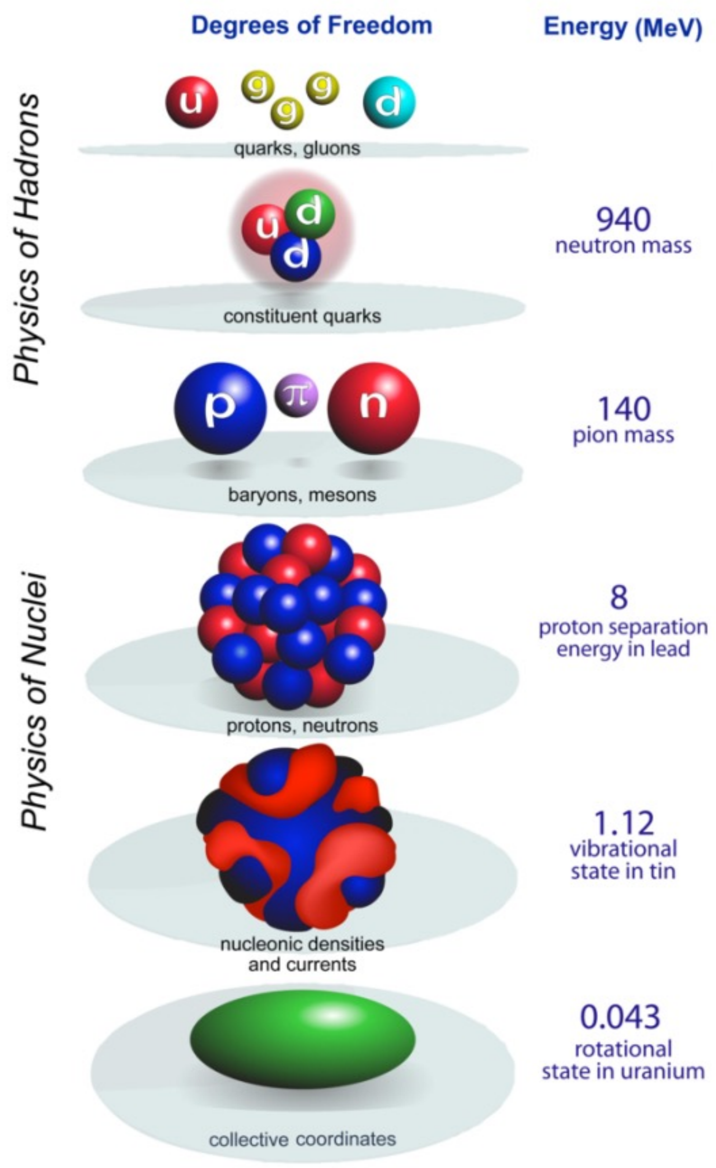
核多体理论从头计算研究中的重大挑战与困难

- **重大挑战**：基于**最基本的自由度**来刻画**各个能标尺度**下的**核多体系统**

- **困难**：随着**粒子数的增加**，量子多体系统**态矢量**的数目呈**指数级增长**。



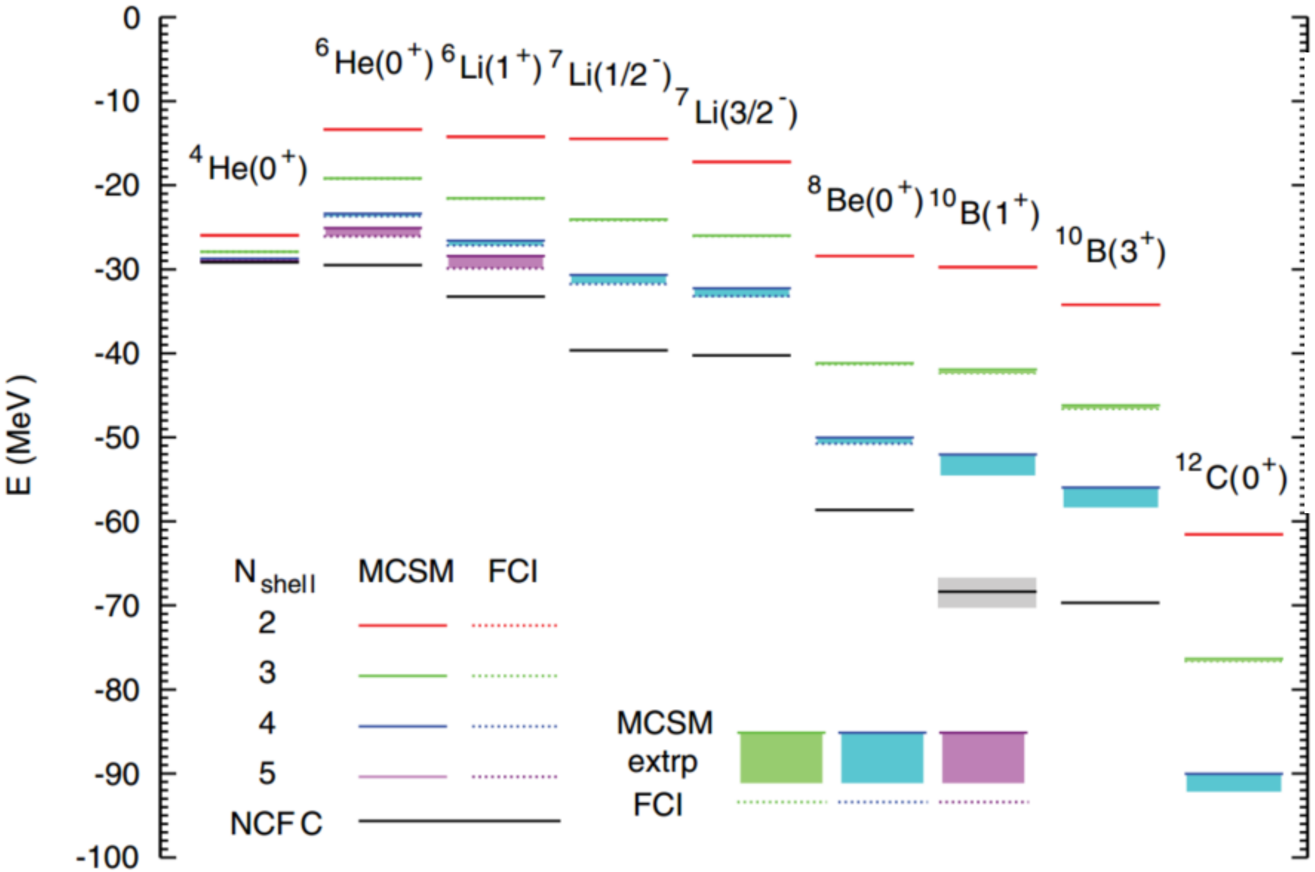


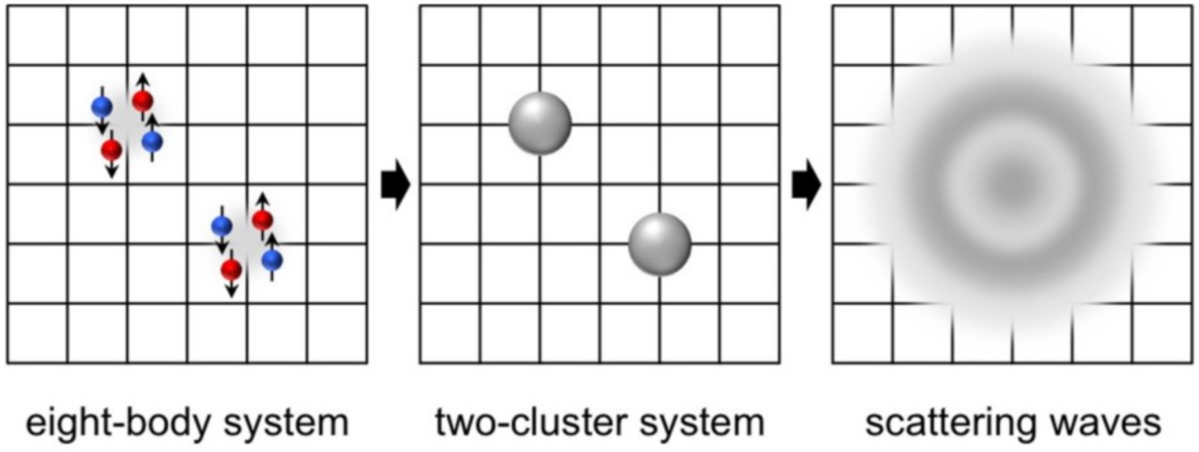
多核子系统结构与动力学的从头计算

$$H_A = T_{\mathrm{rel}} + V = \sum_{i<j}^{A} \frac{(\vec{p}_i - \vec{p}_j)^2}{2m_N A} + V_{\mathrm{NN}} + V_{\mathrm{NNN}} + \cdots$$

结构计算

散射模拟





$\alpha\alpha$ scattering

[PHYSICAL REVIEW C **86** 054301 (2012)]

[Nature **528** 111 (2015)]

多核子系统从头计算所需计算资源的指数级增长

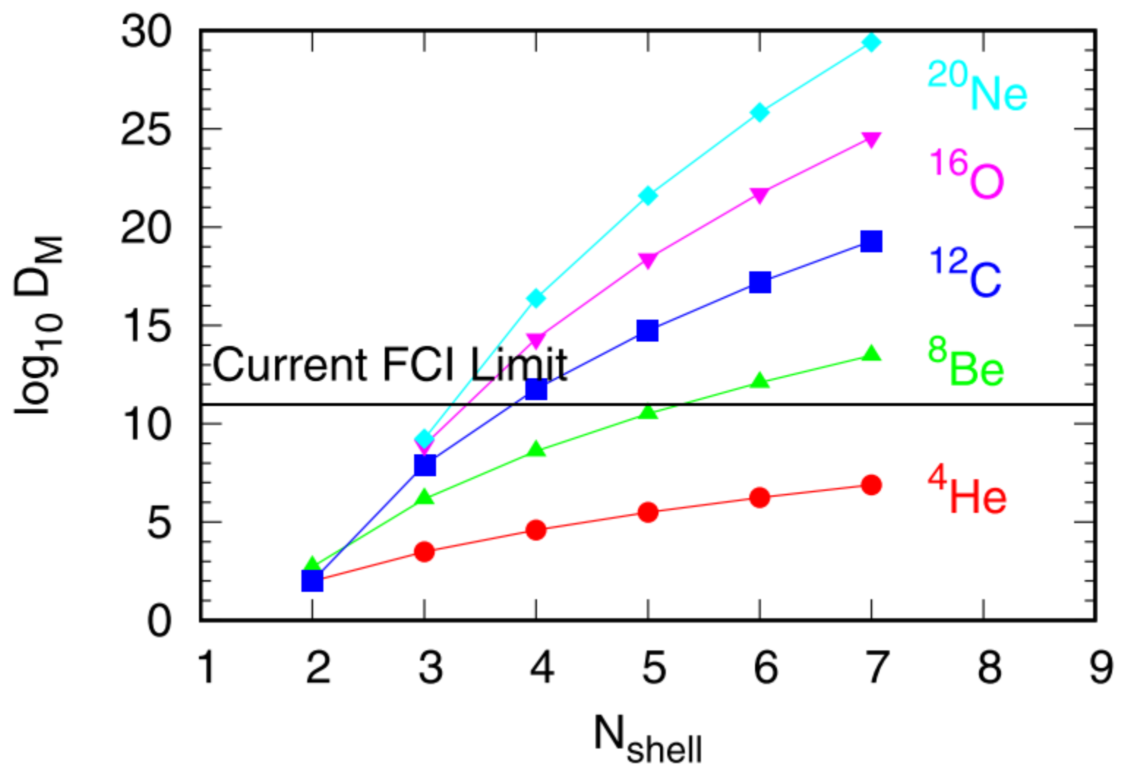


FIG. 1. *M*-scheme dimensions D_M for light nuclei examined in this work as a function of basis space N_{shell}. The horizontal black line indicates the approximate limit of the dimension for full configuration interaction (FCI) calculations using the Lanczos diagonalization method.

[Phys. Rev. C **104** 054315 (2021)]

N_{shell}	$N_{sp}/2$ (for n or p)
1	2
2	8
3	20
4	40
5	70
6	112
7	168
8	240
9	330
10	440

$N_{shell} = 4$:

- 单粒子基矢数目: $2\times40 = 80$
- 多体哈密顿矩阵维度(^{12}C): $\sim 10^{12}$
- 非零两体矩阵元数目:

  ~ several copies of 2308

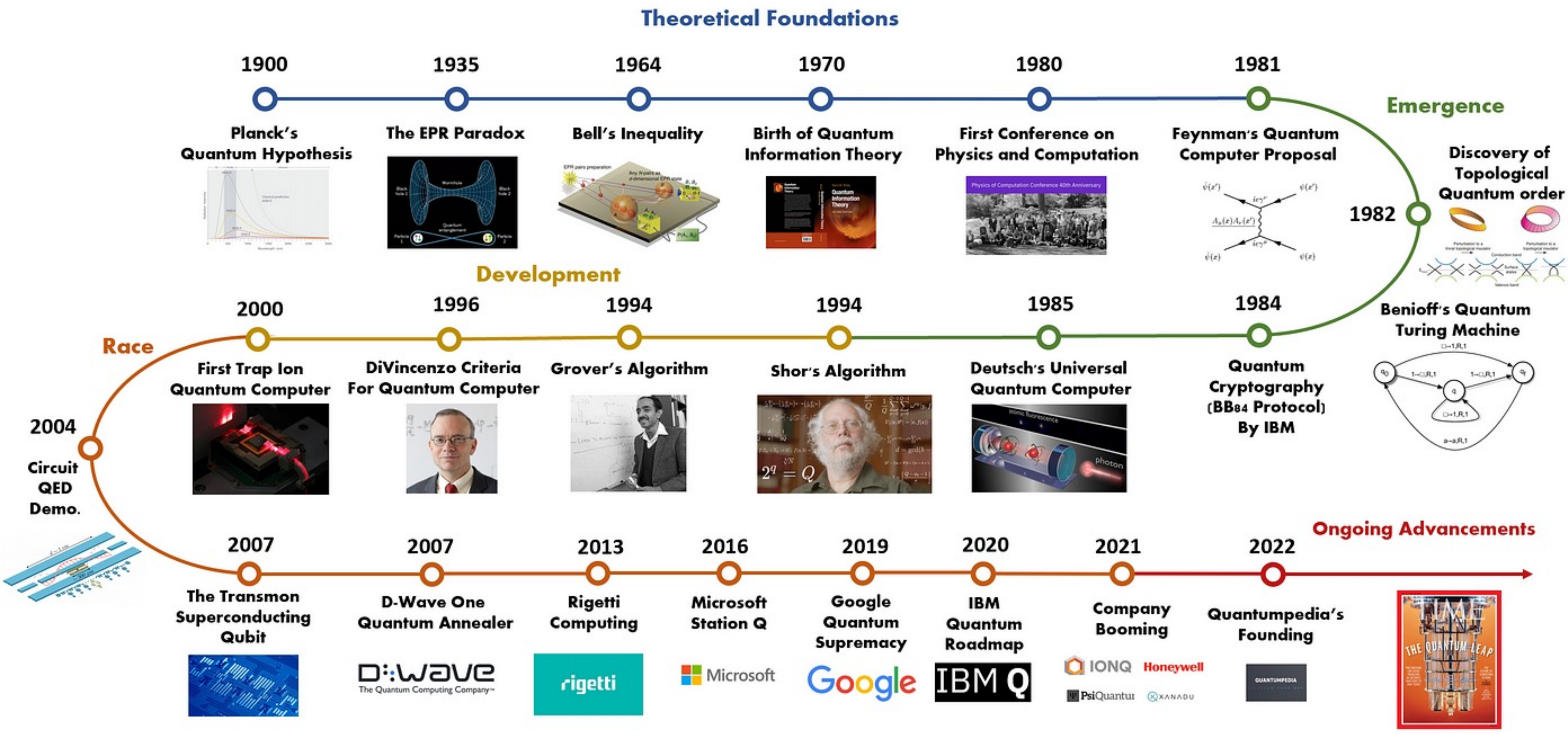
量子计算机有望改变游戏规则

"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."

"自然界不是经典的，该死！如果你想要对自然进行模拟，最好让它是量子力学的。天哪，这真是一个奇妙的问题，因为它看起来一点也不容易。"

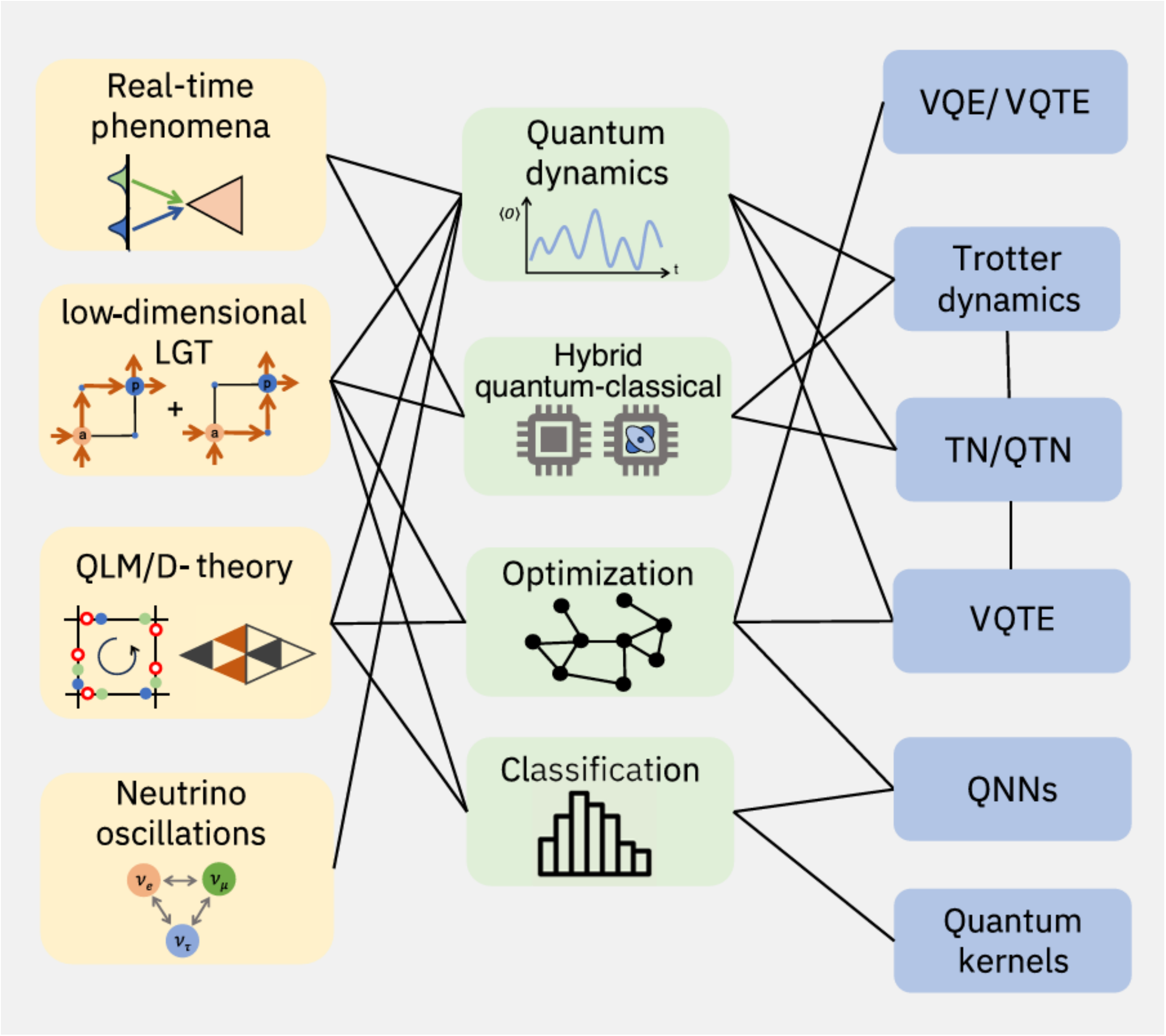
[R. P. Feynman, Int. J. Theor. Phys. 21, 467 (1982)]

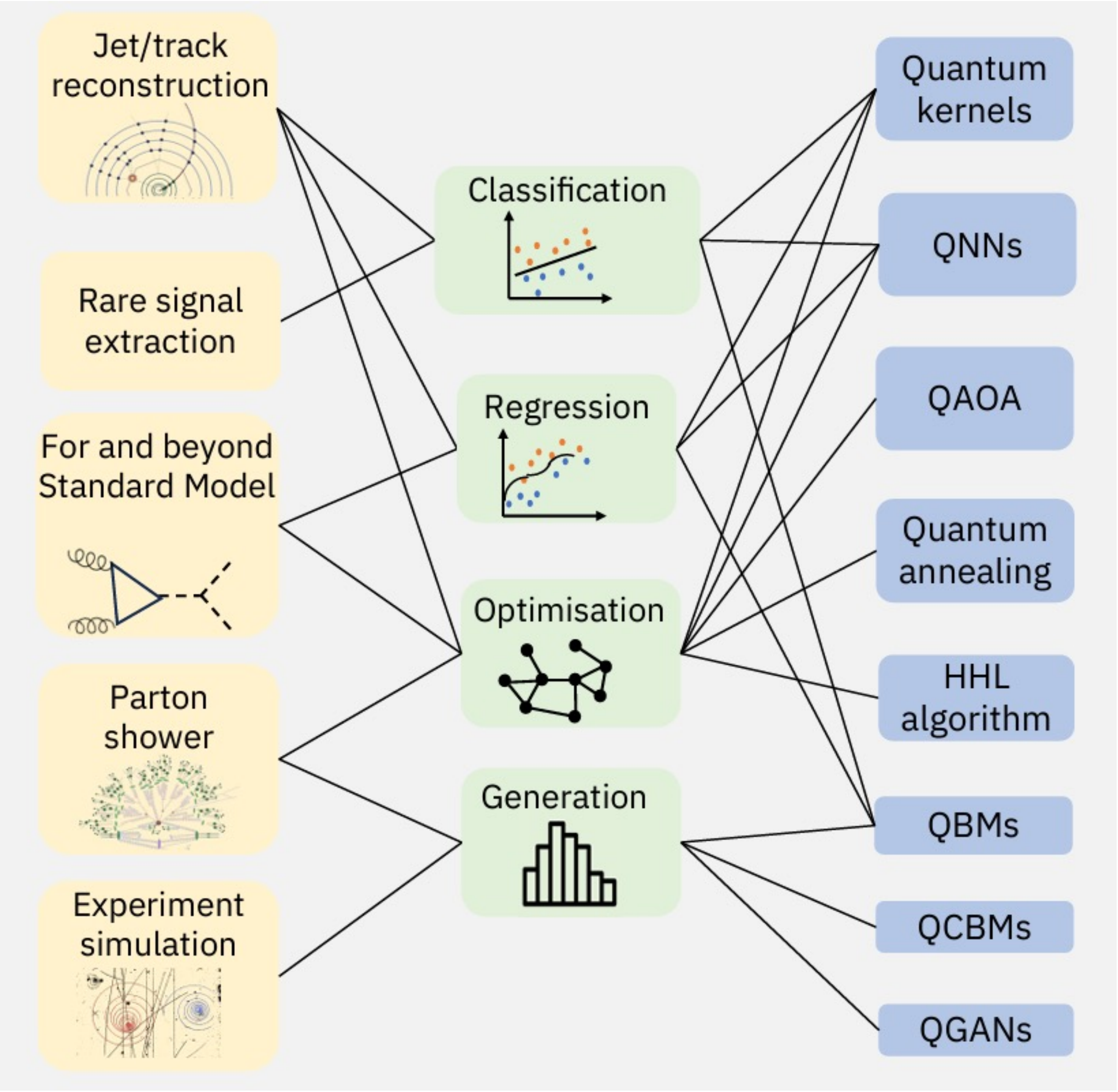
历史回顾：量子计算技术



[Figure credit: quantumpedia.uk]

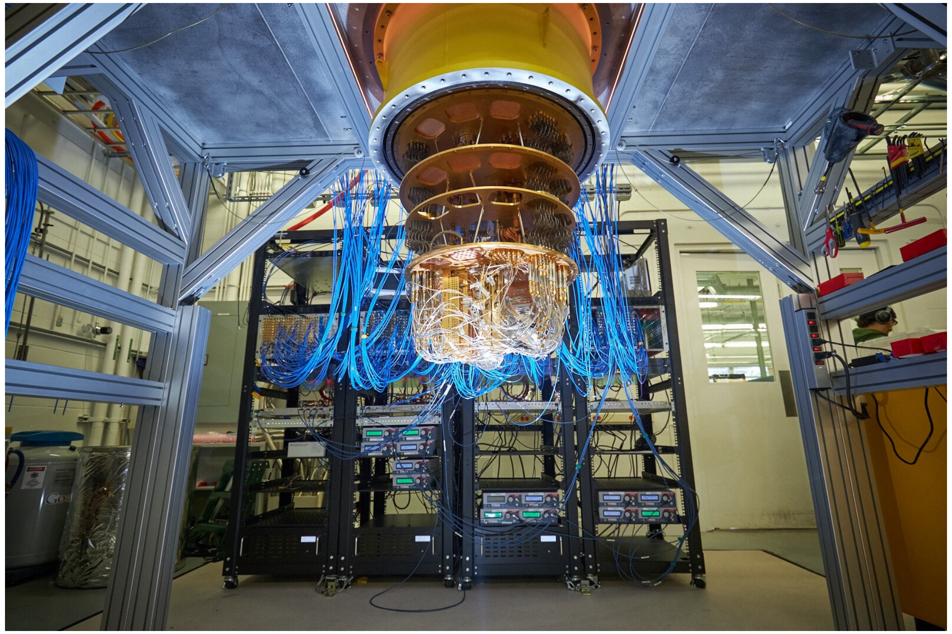
量子计算技术的前沿推进：核物理理论与实验

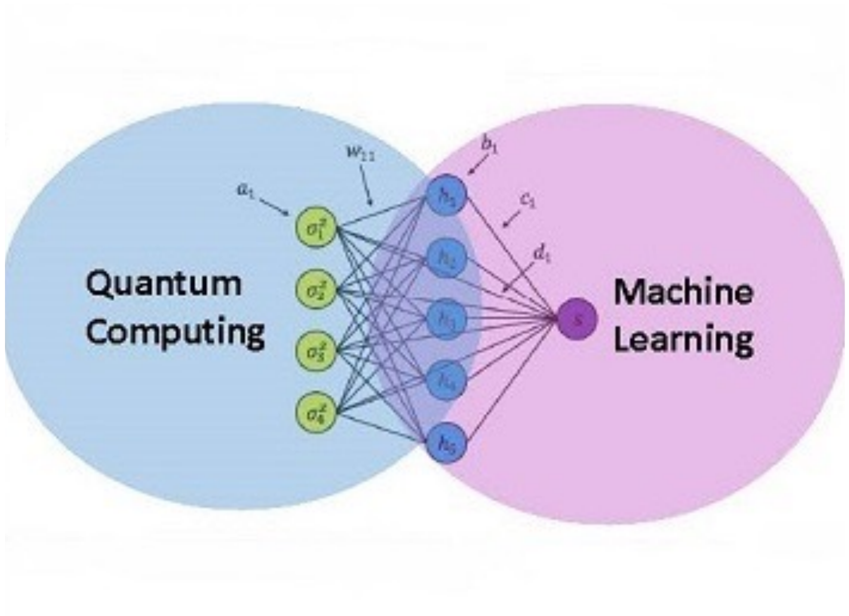


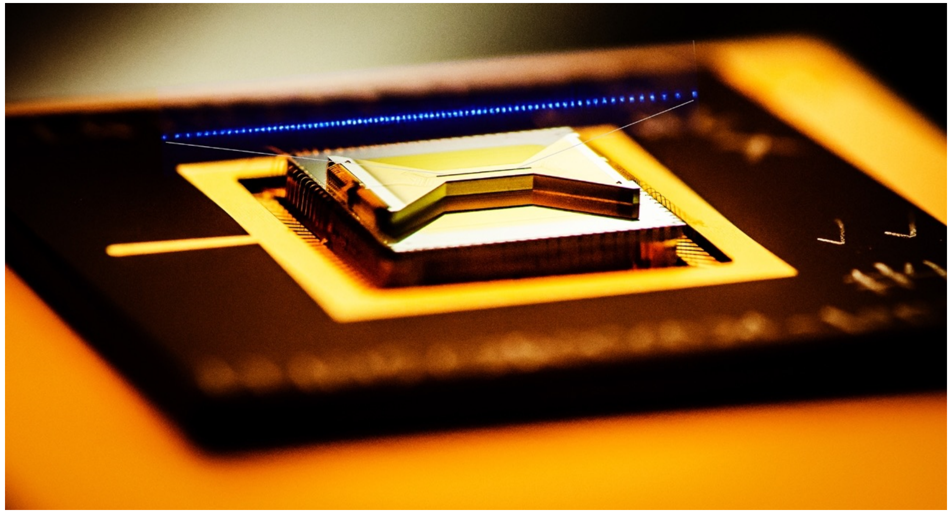


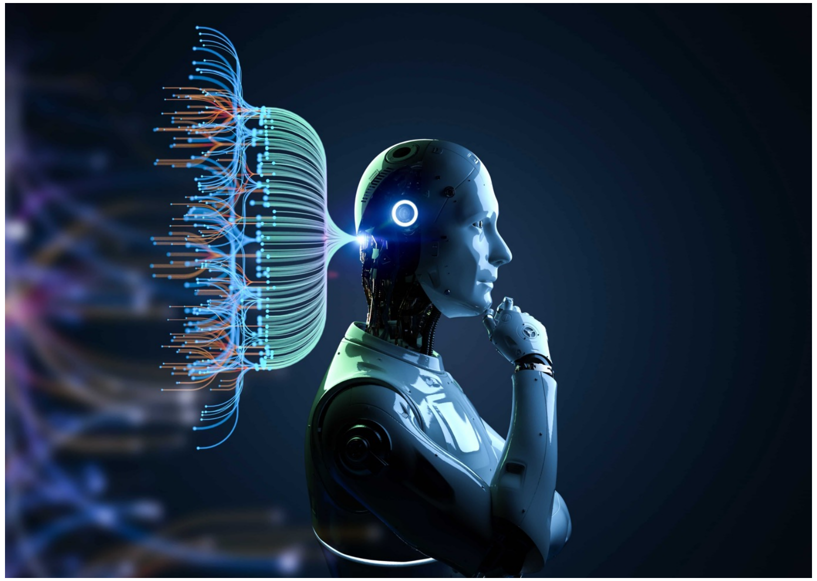
[PRX QUANTUM 5, 037001 (2024)]

不断发展中量子计算前沿研究

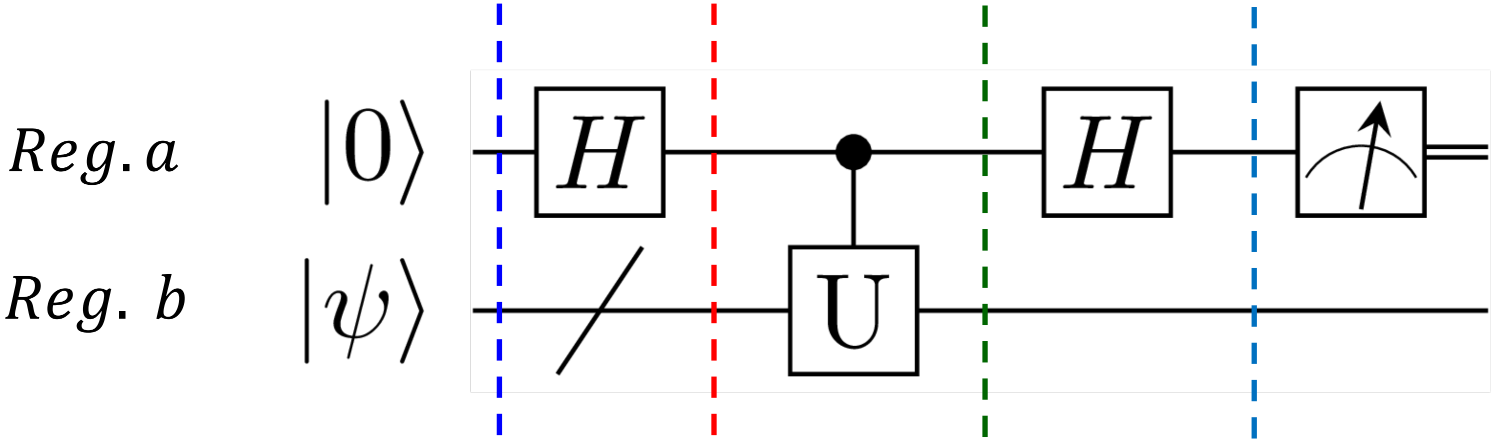








量子计算：基本逻辑



$$|0\rangle_a|\psi\rangle_b$$

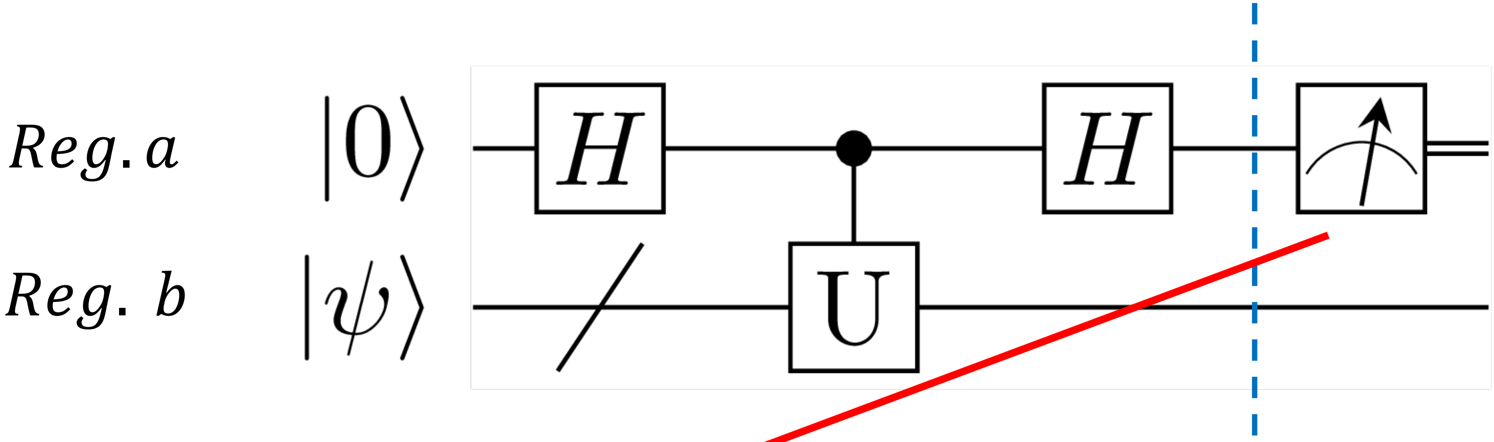
$$\frac{1}{\sqrt{2}}(|0\rangle_a + |1\rangle_a)|\psi\rangle_b$$

$$\frac{1}{\sqrt{2}}|0\rangle_a|\psi\rangle_b + \frac{1}{\sqrt{2}}|1\rangle_a\boldsymbol{U}|\psi\rangle_b$$

$$\frac{1}{2}|0\rangle_a(I + \boldsymbol{U})|\psi\rangle_b + \frac{1}{2}|1\rangle_a(I - \boldsymbol{U})|\psi\rangle_b$$

- 利用可控量子系统及其可控操作，实现具有特定性质的波函数制备

量子计算：基本逻辑



$$\frac{1}{2}|0\rangle_a(I+\boldsymbol{U})|\psi\rangle_b+\frac{1}{2}|1\rangle_a(I-\boldsymbol{U})|\psi\rangle_b$$

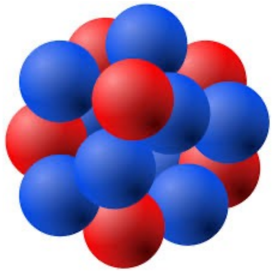
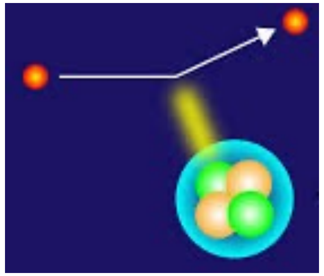
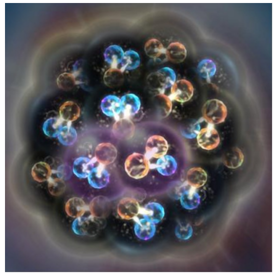
$$\begin{cases} P(|0\rangle_a)=\frac{1}{4}\langle\psi|\,(I+U^\dagger)(I+U)|\psi\rangle \\ P(|1\rangle_a)=\frac{1}{4}\langle\psi|\,(I-U^\dagger)(I-U)|\psi\rangle \end{cases}$$

$$\boxed{P\big(|0\rangle_a\big)-P\big(|1\rangle_a\big)=\frac{1}{2}\langle\psi|\,\big(U^\dagger+U\big)|\psi\rangle=\boldsymbol{Re}\langle\boldsymbol{\psi}|\boldsymbol{U}|\boldsymbol{\psi}\rangle}$$

注：
- 有类似的制备、测量手段得到 $\boldsymbol{Im}\langle\boldsymbol{\psi}|\boldsymbol{U}|\boldsymbol{\psi}\rangle$
- 进而通过量子计算手段得到期望值 $\langle\boldsymbol{\psi}|\boldsymbol{U}|\boldsymbol{\psi}\rangle$

- 利用可控量子系统及其可控操作，实现具有特定性质的波函数制备

总体思路：如何使用量子计算解决多体问题？

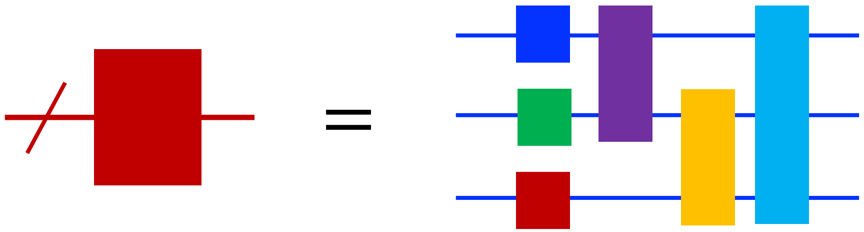
构建多体系统哈密顿量$\boldsymbol{H}$

$f(H)$ (如：e^{-iHt}, $\frac{1}{E-H}$)

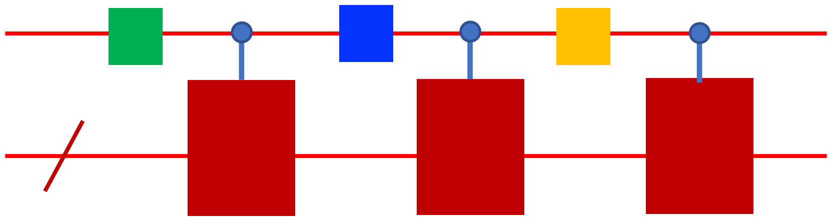
结构性质
（如：能谱）

动力学
（如：散射）

问题1：哈密顿量的线路表示？



问题2：哈密顿量函数的线路表示？



问题3：高效、精确的量子计算模拟？

如：算法、量子门复杂度、时间效率、误差、噪声控制、测量等

问题1：如何获得多体系统哈密顿量的线路表示？

经典计算策略：量子多体系统的能量本征值计算

Step 1: 构建多体系统哈密顿量

$$H = T + V_{int}$$

Step 2: 选择基矢集（结合物理与现实性考量，一般为单粒子基矢）

$$\{|\psi_\alpha\rangle\}$$

Step 3: 构建多体系统的哈密顿量矩阵。其矩阵元为

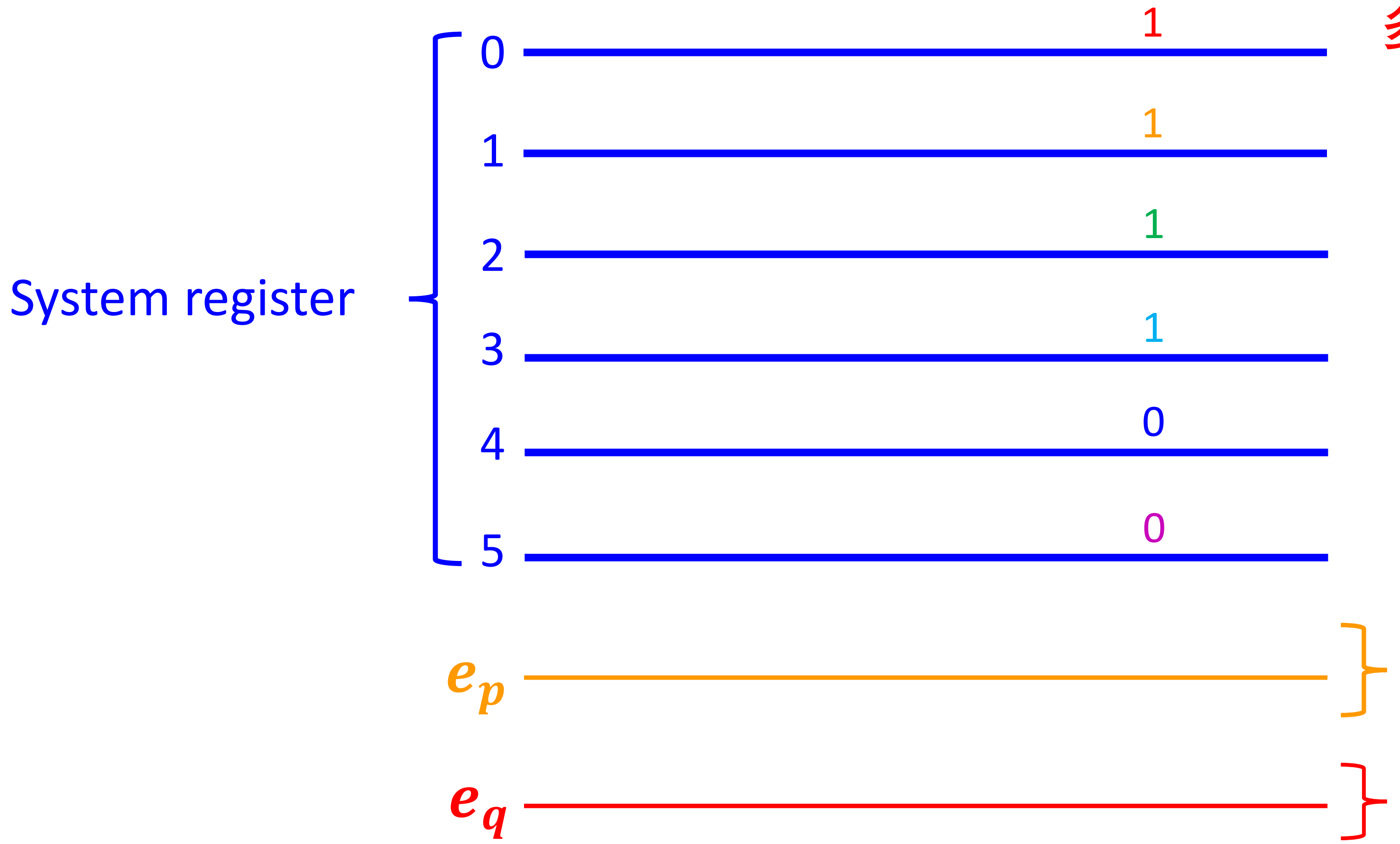
$$\{\langle\psi_\alpha|H|\psi_\beta\rangle\}$$

Step 4: 哈密顿矩阵

$$\begin{bmatrix} \langle\psi_1|H|\psi_1\rangle & \cdots & \langle\psi_1|H|\psi_N\rangle \\ \vdots & \ddots & \vdots \\ \langle\psi_N|H|\psi_1\rangle & \cdots & \langle\psi_N|H|\psi_N\rangle \end{bmatrix}$$

量子计算策略：元素一

- 单费米子基的直接编码



多费米子态编码方案：

以二进制字符串编码的Fock态

e.g.,

$$|\mathcal{F}\rangle = a_0^\dagger a_1^\dagger a_2^\dagger a_3^\dagger |0\rangle$$

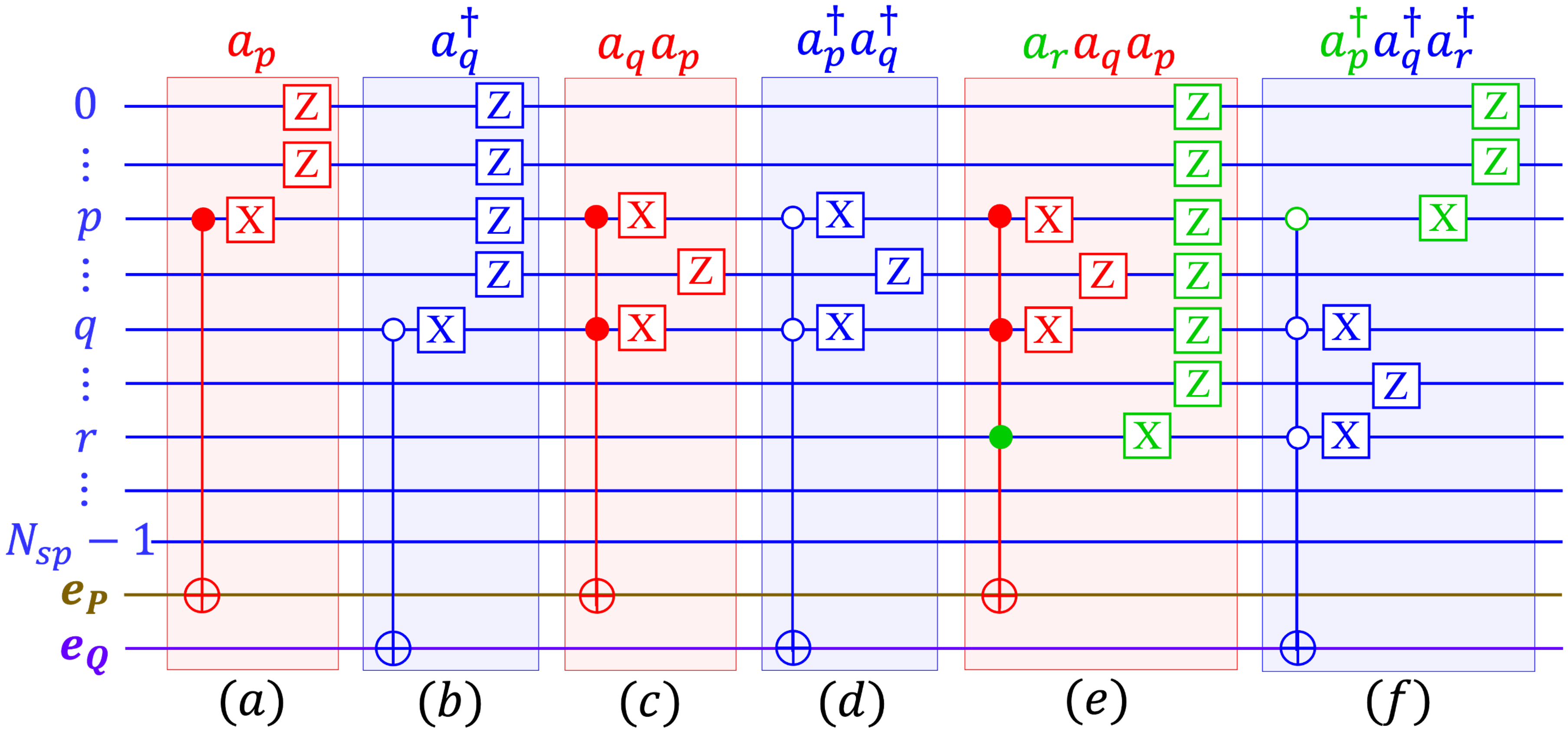
$$|\mathcal{F}\rangle \rightarrow |111100\rangle_{sys}$$

Flagging errors of annihil'n op.'s

Flagging errors of creat'n op.'s

量子计算策略：元素二

- 费米子算符的新型线路表示

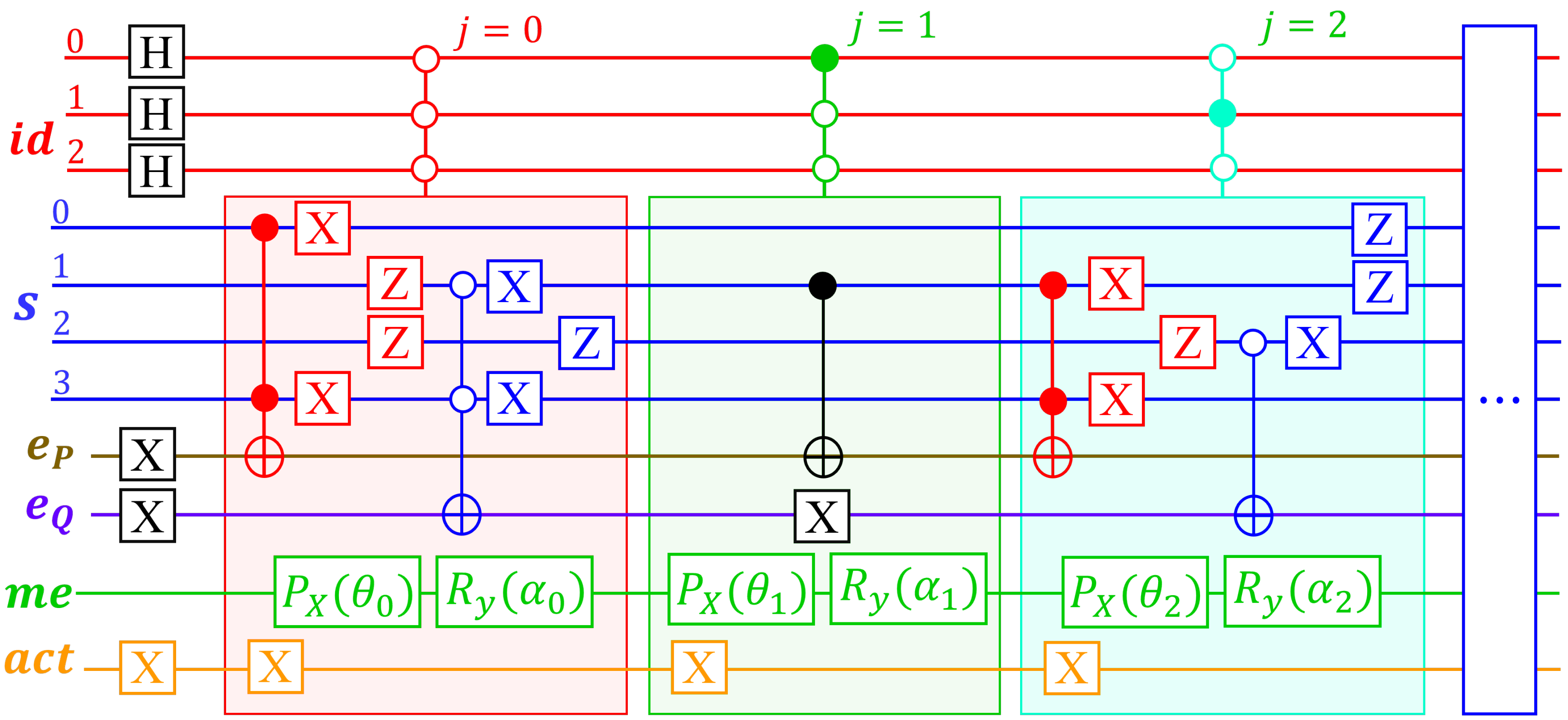


- 类似于标准**全组态相互作用**（FCI）计算中的“**布尔掩码**”（Boolean masking）思想
- 与Jordan-Wigner变换对比，无需复杂的算符预编译

[**WD** et al., arXiv: 2505.19906]

量子计算策略：元素三

○ 多体系统哈密顿量算符的线路表象设计 [WD et al., arXiv: 2505.19906]



$$H_x = \rho_0 e^{i\theta_0} a_1^\dagger a_3^\dagger a_3 a_0 + \rho_1 e^{i\theta_1} a_1^\dagger a_1 + \rho_2 e^{i\theta_2} a_2^\dagger a_3 a_1 + \cdots$$

$j = 0 \mapsto 000$ $j = 1 \mapsto 001$ $j = 2 \mapsto 010$

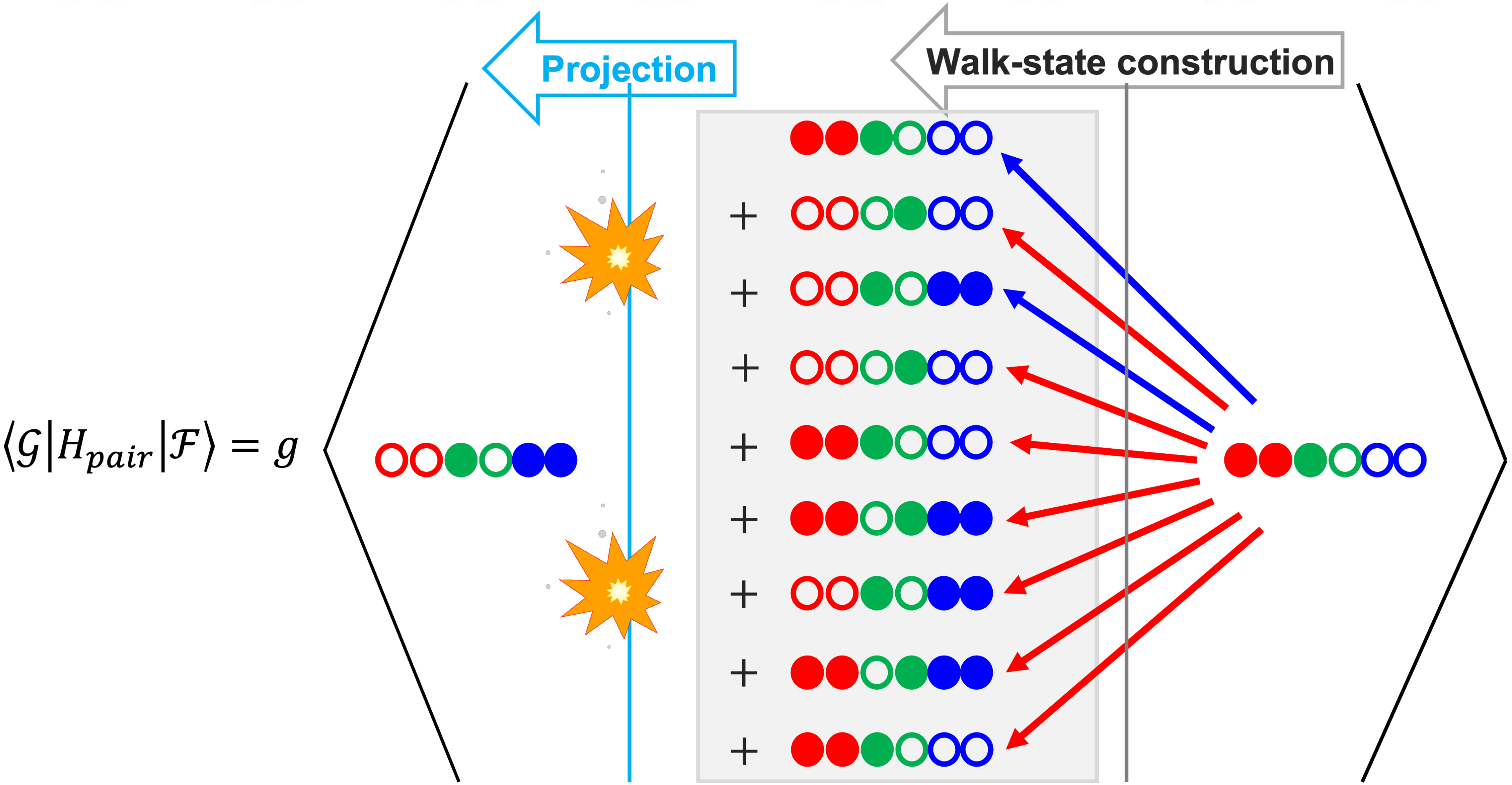
与“标准”方法（如 Jordan-Wigner + Linear Combination of Unitaries）相比，本方法

- 无需Jordan-Wigner的预编译
- 无需复杂的Oracle （如Prepare Oracle in LCU）设计

量子计算策略：元素四

- 采用量子步行计算多体系统哈密顿量矩阵元

$$H_{\text{pair}} = g\Big[\underbrace{a_0^\dagger a_1^\dagger a_1 a_0}_{i=0} + \underbrace{a_2^\dagger a_3^\dagger a_1 a_0}_{i=1} + \underbrace{a_4^\dagger a_5^\dagger a_1 a_0}_{i=2} + \underbrace{a_0^\dagger a_1^\dagger a_3 a_2}_{i=3} + \underbrace{a_2^\dagger a_3^\dagger a_3 a_2}_{i=4} + \underbrace{a_4^\dagger a_5^\dagger a_3 a_2}_{i=5} + \underbrace{a_0^\dagger a_1^\dagger a_5 a_4}_{i=6} + \underbrace{a_2^\dagger a_3^\dagger a_5 a_4}_{i=7} + \underbrace{a_4^\dagger a_5^\dagger a_5 a_4}_{i=8}\Big]$$



基于量子步行的新型多费米子体系哈密顿量输入方案

- 一般的多体费米子系统哈密顿量

$$\boldsymbol{H}=\sum_{j}\langle p_j q_j \cdots r_j|H|u_j v_j \cdots w_j\rangle a^{\dagger}_{p_j} a^{\dagger}_{q_j} \cdots a^{\dagger}_{r_j} a_{w_j} \cdots a_{v_j} a_{u_j}$$

- 基于H以及Fock态$|\mathcal{F}\rangle$, $|\mathcal{G}\rangle$ 构建的量子行走态
  - $$\mathscr{T}_f\,|\mathcal{F}\rangle_s \otimes |0\rangle_a = \frac{1}{\sqrt{\mathcal{B}}}\sum_{j=0}^{\mathcal{B}-1} \xi_{\mathcal{F},j} e^{i\beta_j}\,|j\rangle_{id}\,|\mathcal{F}_j\rangle_s\,|y^{P}_{\mathcal{F},j}\rangle_{e_P}\,|y^{Q}_{\mathcal{F},j}\rangle_{e_Q}\,|\rho_j\rangle_{me}\,|v_j\rangle_{act}$$
  - $$\mathscr{T}_b\,|\mathcal{G}\rangle_s \otimes |0\rangle_a = \frac{1}{\sqrt{\mathcal{B}}}\sum_{k=0}^{\mathcal{B}-1} |k\rangle_{id}\,|\mathcal{G}\rangle_s\,|0\rangle_{e_P}\,|0\rangle_{e_Q}\,|0\rangle_{me}\,|0\rangle_{act}$$

[**WD** and Vary, PLB 866, 139548 (2025)]
[**WD** and Vary, PRA 108, 052614 (2023)]
[**WD** et al., arXiv: 2505.19906]

- H的块编码（block encoding）输入方法

$$\boxed{(\langle\mathcal{G}|_s \otimes \langle 0|_a)\mathscr{T}_b^{\dagger}\mathscr{T}_f(|\mathcal{F}\rangle_s \otimes |0\rangle_a) = \frac{1}{\mathcal{B}\Xi}\langle\mathcal{G}|H|\mathcal{F}\rangle} \Rightarrow \boxed{\text{Input form}}$$

玻色子算符的新型线路表示

➢ Boson operators

$$a_k |k^{r_k}\rangle = \sqrt{r_k}\,|k^{r_k-1}\rangle$$

$$a_k^\dagger |k^{r_k}\rangle = \sqrt{r_k+1}\,|k^{r_k+1}\rangle$$

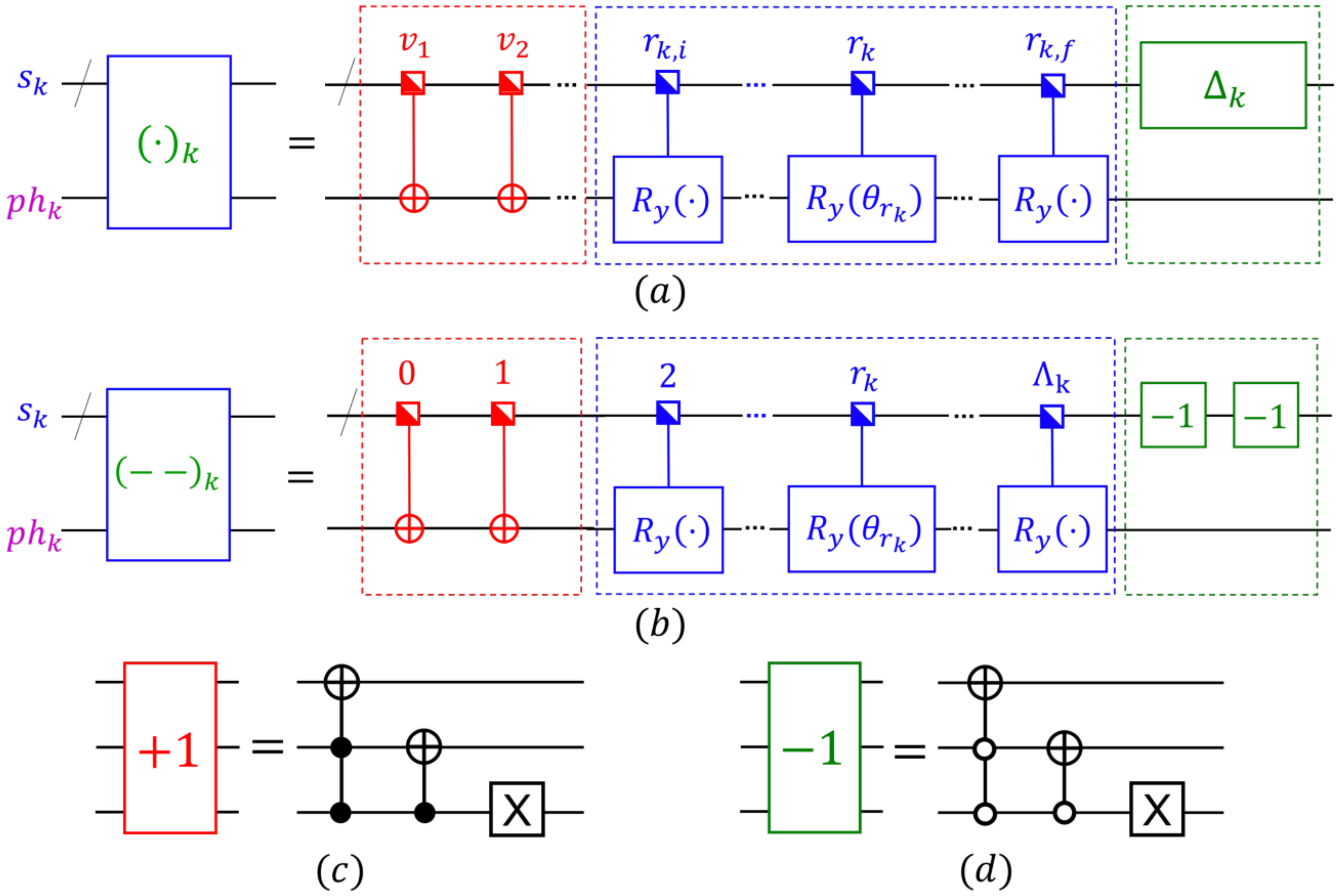
➢ Commutation relations

$$[a_m, a_n^\dagger] = \delta_{m,n}$$

$$[a_m, a_n] = [a_m^\dagger, a_n^\dagger] = 0,$$

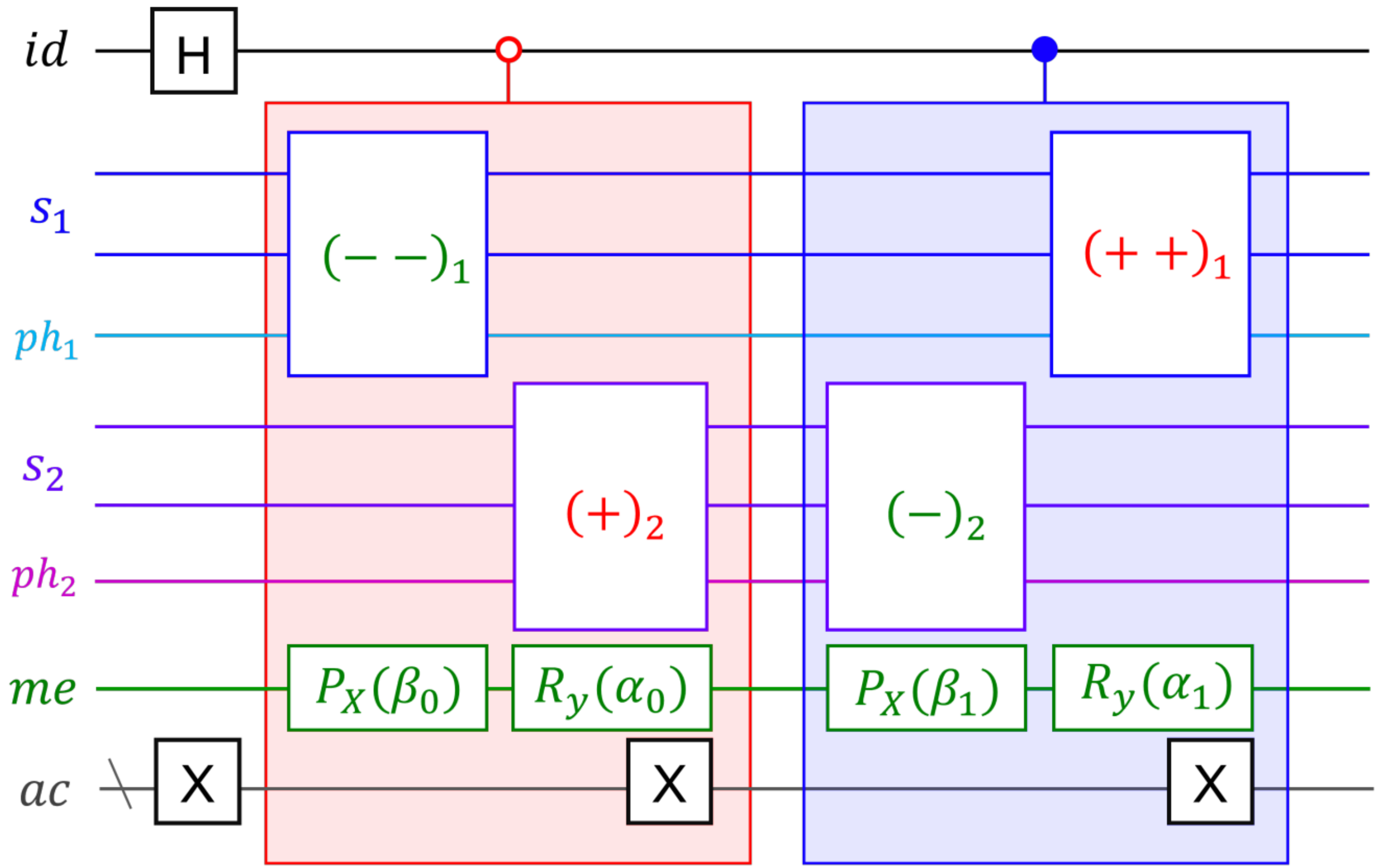
➢ Normalized state

$$|k^{r_k}\rangle = \frac{1}{\sqrt{r_k!}}(a_k^\dagger)^{r_k}\,|k^0\rangle$$



[WD and Vary, PRD 111, 016013 (2025)]

基于量子步行的新型多玻色子体系哈密顿量输入方案



$$H_x = \rho_0 e^{i\beta_0} b_2^\dagger b_1 b_1 + \rho_1 e^{i\beta_1} b_1^\dagger b_1^\dagger b_2$$

$j = 0 \mapsto 0$ $\quad j = 1 \mapsto 1$

Block-encoding a many-boson Hamiltonian

$$(\langle\mathcal{G}|_s \otimes \langle 0|_a)\mathcal{T}_2^\dagger \mathcal{T}_1(|\mathcal{F}\rangle_s \otimes |0\rangle_a) = \frac{1}{\mathcal{D}\Xi}\langle\mathcal{G}|H|\mathcal{F}\rangle$$

[**WD** and Vary, PRD 111, 016013 (2025)]

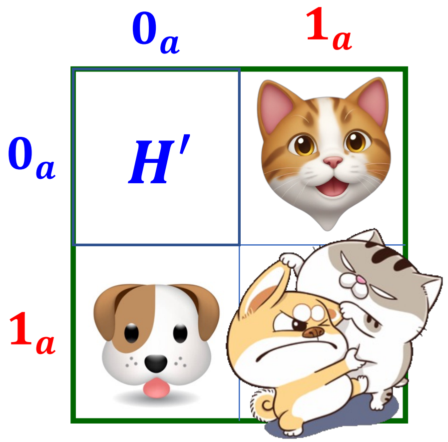
Q2. 哈密顿量函数的量子线路？

关于多体哈密顿量的切比雪夫多项式

- 哈密顿量$H' = H/(\mathcal{D}\Lambda)$的量子线路输入

$$(\langle \mathcal{G}|_s \otimes \langle 0|_a)\boxed{\mathcal{T}_b^\dagger S \mathcal{T}_f}(|\mathcal{F}\rangle_s \otimes |0\rangle_a) = \frac{1}{\mathcal{D}\Lambda}\langle \mathcal{G}|\boxed{H}|\mathcal{F}\rangle$$

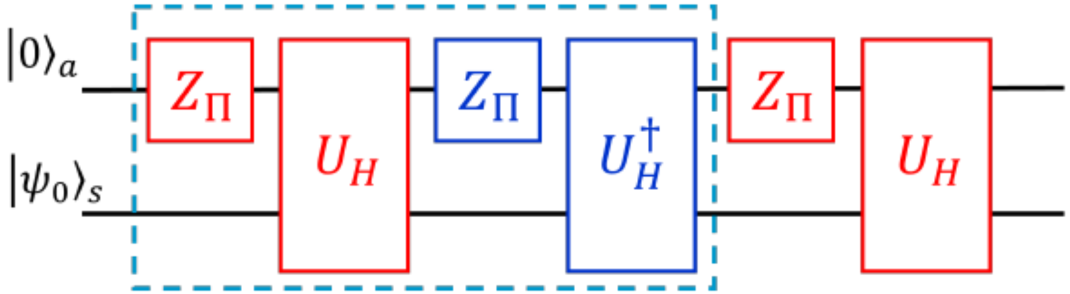
$$\hookrightarrow \quad U_H \equiv \mathcal{T}_b^\dagger S \mathcal{T}_f$$



- 多体哈密顿量的切比雪夫多项式
  - Even order: $\langle \psi_0|\boxed{T_{2k}(H')}|\psi_0\rangle = (\langle \psi_0|_s \otimes \langle 0|_a)\boxed{(U_H^\dagger Z_\Pi U_H Z_\Pi)^k}(|\psi_0\rangle_s \otimes |0\rangle_a)$
  - Odd order: $\langle \psi_0|\boxed{T_{2k+1}(H')}|\psi_0\rangle = (\langle \psi_0|_s \otimes \langle 0|_a)\boxed{[U_H Z_\Pi (U_H^\dagger Z_\Pi U_H Z_\Pi)^k]}(|\psi_0\rangle_s \otimes |0\rangle_a)$

with $Z_\Pi \equiv (2|0\rangle_a\langle 0|_a - \mathbb{I}_a) \otimes \mathbb{I}_s$

- 例子： $T_3(H')$的量子线路



$\Rightarrow \sim T_3(H')|\psi_0\rangle_s \otimes |\cdot\rangle_a$

[**WD** and Vary, PLB 866 139548 (2025)]

[Low and Chuang, PRL 118, 010501 (2017)]

Q3. 高效、高精度的量子计算算法？

Hybrid framework for structure calculations

- 选定一个pivot $|\psi_0\rangle$，可以根据$T_k(H')$ 生成Krylov 基矢集合

$$\{|\psi_i\rangle = T_k(H')\,|\psi_0\rangle\,|k = 0, 1, 2, \cdots, \mathcal{K} - 1\}$$

- Krylov 基矢中的矩阵元

$$H'_{ij} = \langle\psi_i|H'|\psi_j\rangle = \langle\psi_0|T_i(H')H'T_j(H')|\psi_0\rangle$$

$$\Omega_{ij} = \langle\psi_i|\psi_j\rangle = \langle\psi_0|T_i(H')T_j(H')|\psi_0\rangle$$

$$T_1(H') = H'$$

$$T_i(x)T_j(x) = \frac{1}{2}\left(T_{i+j}(x) + T_{|i-j|}(x)\right)$$

$$H'_{ij} = \frac{1}{4}\left(\langle T_{i+j+1}(H')\rangle_0 + \langle T_{|i+j-1|}(H')\rangle_0 + \langle T_{|i-j+1|}(H')\rangle_0 + \langle T_{|i-j-1|}(H')\rangle_0\right)$$

$$\Omega_{ij} = \frac{1}{2}\left(\langle T_{i+j}(H')\rangle_0 + \langle T_{|i-j|}(H')\rangle_0\right).$$

- 量子-经典结合算法SA-QKSD

[**WD** and Vary, PLB 866 139548 (2025)]

[Kirby, et al., Quantum 7, 1018 (2023)]

Quantum computing

$\langle T_k(H')\rangle_0 \equiv \langle\psi_0|T_k(H')|\psi_0\rangle$ ⇒

Classical calculations

$\{H'_{ij}\}$ **and** $\{\Omega_{ij}\}$ ⇒ $H'\,|\Psi\rangle = \lambda\Omega\,|\Psi\rangle$ ⇒ $\{\lambda_i\}$

应用：^{42}Ca, ^{44}Ca, 以及 ^{46}Ca的能谱计算

- 核子间的相互作用：配对-四极-四极模型

$$H_A = g\left[-\sum_{\alpha,\beta} s_\alpha s_\beta a^\dagger_\alpha a^\dagger_{\bar{\alpha}} a_{\bar{\beta}} a_\beta + \chi \sum_{\alpha<\beta}\sum_{\gamma<\delta}\sum_{\mu=-2}^{2} \langle\alpha|r^2 Y_{2\mu}(\Omega_{\hat{r}})|\gamma\rangle\langle\beta|r^2 Y^*_{2\mu}(\Omega_{\hat{r}})|\delta\rangle a^\dagger_\alpha a^\dagger_\beta a_\delta a_\gamma\right]$$

- 基矢空间

	SP basis (qubit)	n	l	$2j$	$2m_j$	2τ
$0f_{7/2}$	**0**	0	3	7	$+7$	-1
	1	0	3	7	-7	-1
	2	0	3	7	$+5$	-1
	3	0	3	7	-5	-1
	4	0	3	7	$+3$	-1
	5	0	3	7	-3	-1
	6	0	3	7	$+1$	-1
	7	0	3	7	-1	-1

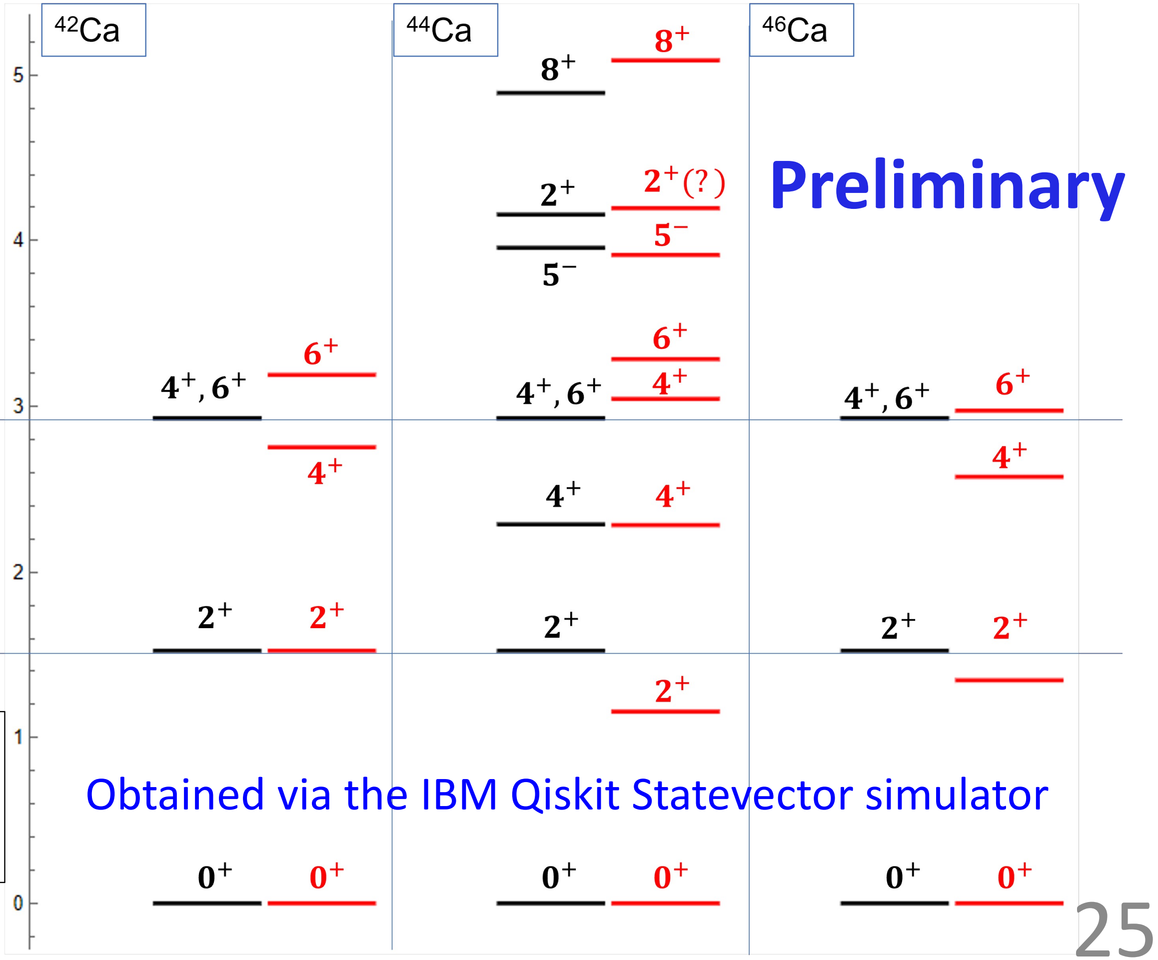
Color coding:
Theory
Experiment

See numerical values in the tables

4^+, 2.92714 MeV

2^+, 1.52471 MeV

The ratio and absolute values of the two levels in ^{42}Ca are used to fit the parameters g and χ



[WD and Vary, PLB 866, 139548 (2025)]

量子-经典混合框架计算格林函数与谱函数

- **格林函数**

$$G(E) = -i\int_{-\infty}^{\infty} \exp[iEt]\exp[-iHt]\,dt$$

$$\Downarrow \quad \exp[-iHt] = \sum_{n=0}^{\infty}(-i)^n(2-\delta_{n,0})J_n(t)T_n(H)$$

$$\langle\psi_{\rm out}|G(E_p)|\psi_{\rm in}\rangle = -i\pi\left[\sum_{\tau=0}^{N-1} e^{2\pi i p\tau/N}\sum_{n=0}^{n_{\max}(\tau)}(-i)^n(2-\delta_{n,0})J_n(\pi\tau)\langle\psi_{\rm out}|T_n(H)|\psi_{\rm in}\rangle\right]$$

- **谱函数**

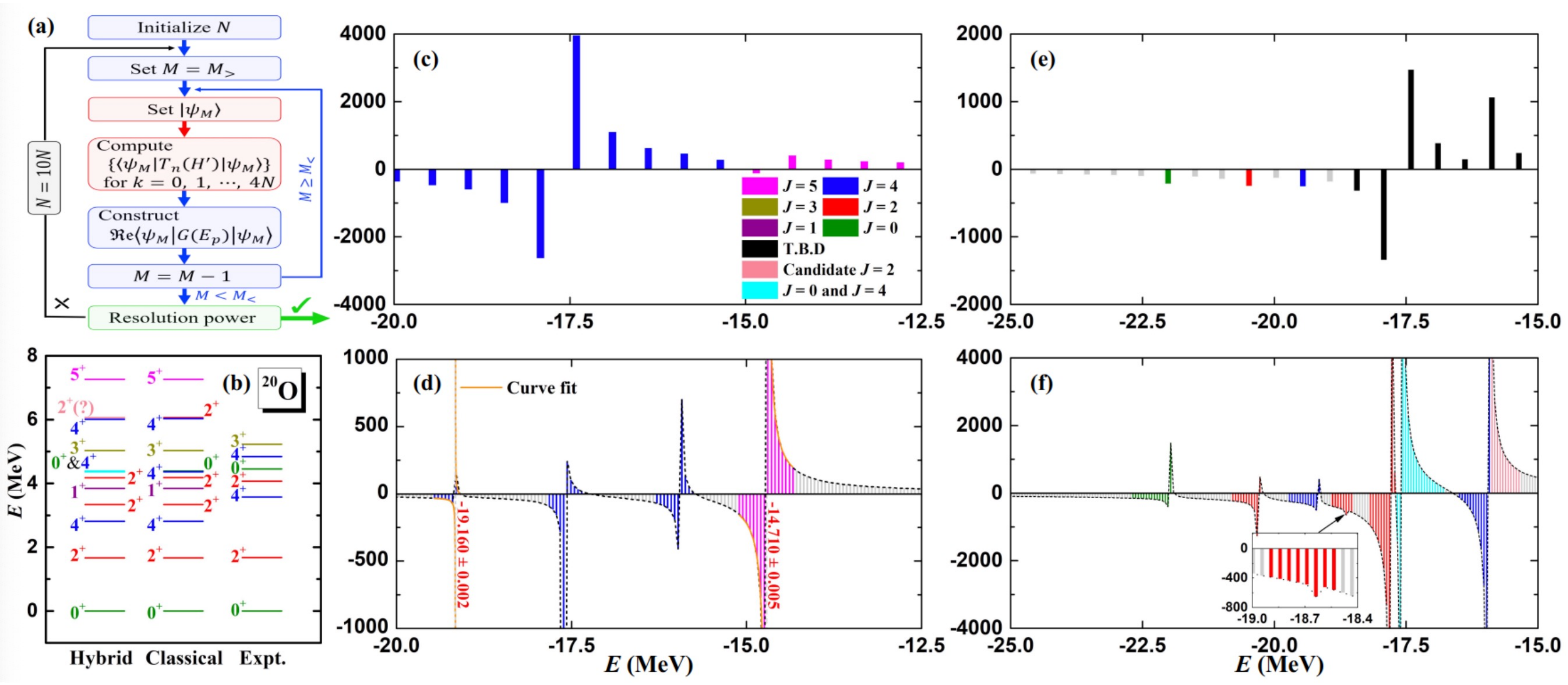
$$F_\psi(E_p) \equiv \mathfrak{Re}\langle\psi|G(E_p)|\psi\rangle$$

- **量子-经典混合框架**

[**WD** et al., arXiv: 2505.19906]

Quantum computing	$\Rightarrow$	Classical calculations
$\langle T_k(H')\rangle_0 \equiv \langle\psi_0\|T_k(H')\|\psi_0\rangle$		$\langle\psi_{out}\|G(E_p)\|\psi_{in}\rangle$ and $F_\psi(E_p) = Re\langle\psi\|G(E_p)\|\psi\rangle$

应用：^{20}O的全束缚态能谱计算

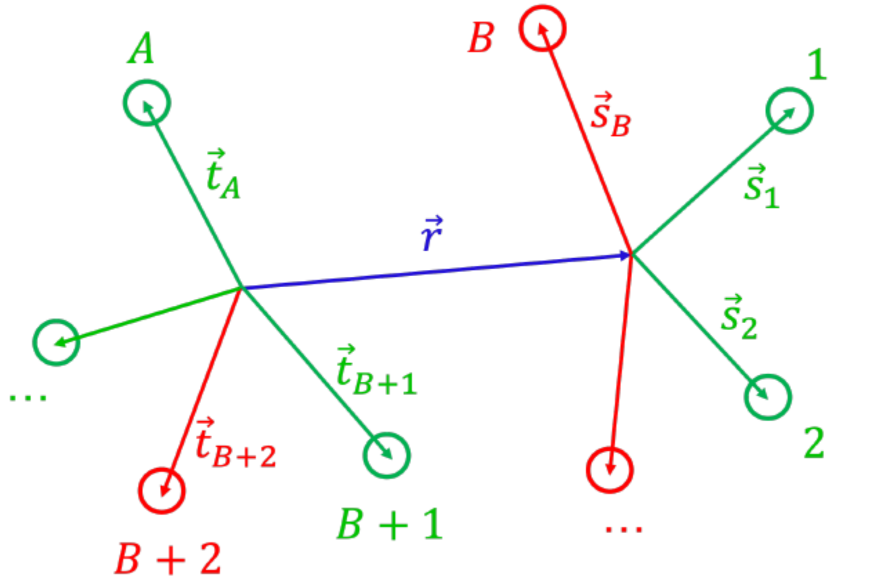


[**WD** et al., arXiv: 2505.19906]

近期进展：用于低能和高能核体系动力学研究的量子算法

开发了核弹性散射相移的理论以及量子算法

- 核$\mathcal{X}$包含$(A-B)$个核子；核$\mathcal{Y}$包含B个核子
- 问题：量子计算机计算原子核$\mathcal{X}$与核$\mathcal{Y}$弹性散射相移？



$$H_A(\omega) = \underbrace{\frac{1}{2Am}\sum_{i<j}^{A}(\vec{p}_i-\vec{p}_j)^2 + \sum_{i<j}^{A} V_{ij}}_{H_{\mathrm{sc},A}} + \underbrace{\frac{1}{2A}m\omega^2\sum_{i<j}^{A}(\vec{r}_i-\vec{r}_j)^2}_{\mathcal{V}_{\mathrm{HO}}^{\mathrm{rel}}(\omega)}$$

无约束散射系统哈密顿量　　核子间引入谐振子势

Idea: 弹性散射相移与核素间相对运动能量$E_n(\omega\to 0)$解析关联

- 开发了新的核多体弹性散射理论

A-nucleon system in HO trap

$H_A(\omega)$
$= H_{\mathrm{sc},A} + \mathcal{V}_{\mathrm{HO}}^{\mathrm{rel}}(\omega)$
$= H_{\mathrm{rel}}(\omega) + H_{\mathcal{X}'}(\omega) + H_{\mathcal{Y}'}(\omega)$

$A1$ →

Quantum eigensolver

$H_A(\omega) \Rightarrow \{E_{tot,i}(\omega)\}$
$H_{\mathcal{X}'}(\omega) \Rightarrow E_{\mathcal{X}',gs}(\omega)$
$H_{\mathcal{Y}'}(\omega) \Rightarrow E_{\mathcal{Y}',gs}(\omega)$

$B1$ ↓　　$A2$ ↓

Inter-nucleus motion in HO trap

$H_{\mathrm{rel}}(\omega) = T_{\mathrm{rel}} + V_{\mathrm{HO}}(\omega) + V_{\mathrm{int}}$

$B2$ →

Eigenenergies of $H_{\mathrm{rel}}(\omega)$

$\{E_{\mathrm{rel},i}(\omega)\}$

$C1$ ↓

Extrapolation via the MERE formula for $\boldsymbol{\delta_l}$

General applications:
$A1 \to A2 \to C1$
This work with limited problems:
$B1 \to B2 \to C1$

[Peiyan Wang, WD,* et al. PRC 109, 6 (2024)]
[T. Busch et al., Found. Phys. 28, 549 (1998)]

开发了核弹性散射相移的理论以及量子算法

$$H_{sc} = T_{rel} + V_{int}$$

使用外加谐振子势将散射态离散化

$$H_{obj}(\omega) = H_{sc} + \frac{1}{2}\mu\omega^2 r^2$$

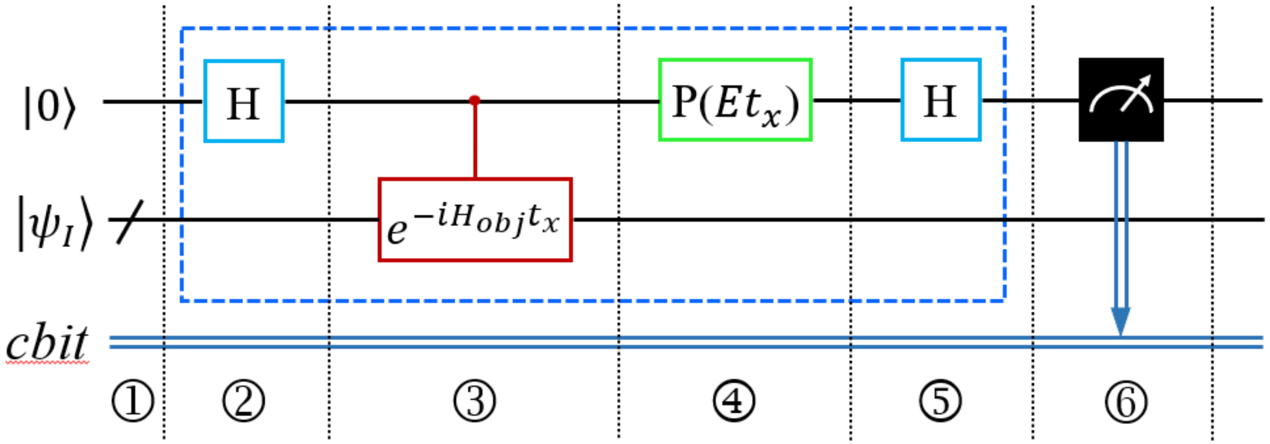
Rodeo量子算法计算本征值

$$E_n = E_n(\omega)$$

使用经典计算机外推

$$\delta = \delta(\omega)|_{\omega\to 0}$$

碰撞系统弹性散射相移



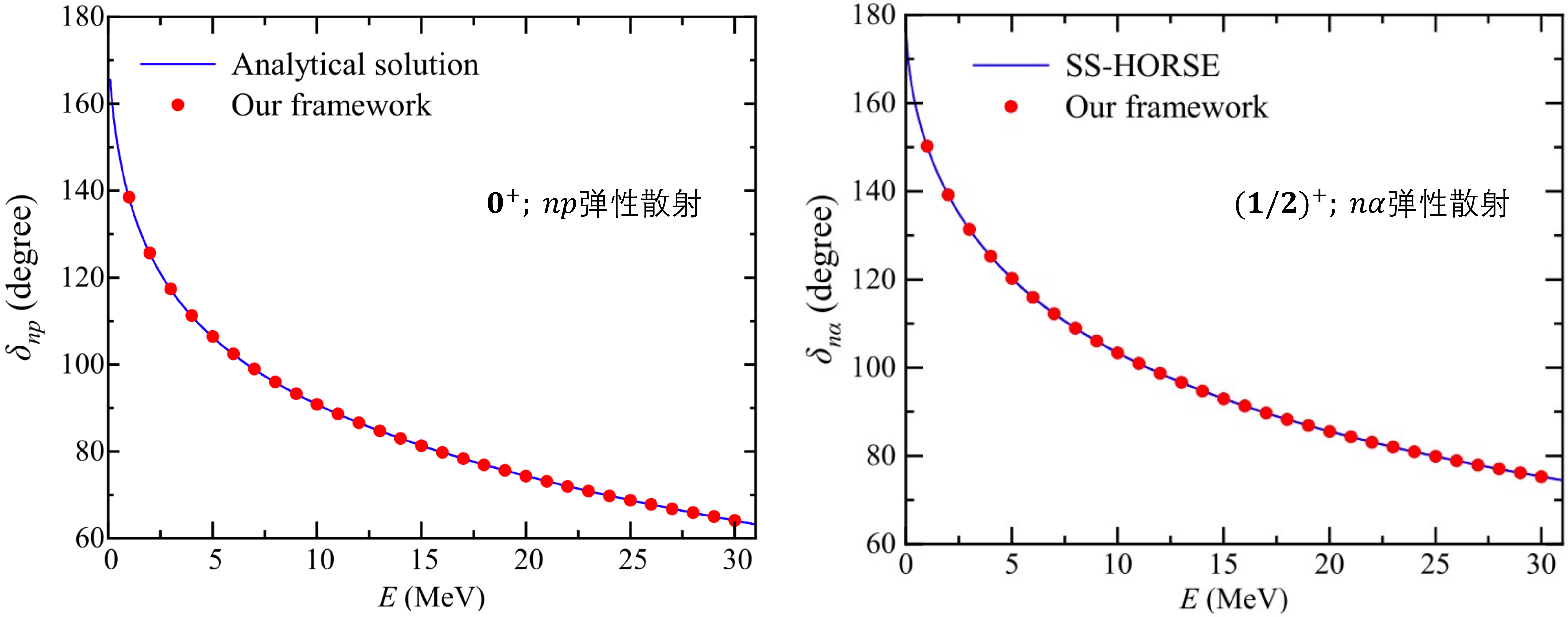
The probability of the measurement 0 for m-th state:

$$P(|0\rangle,|\phi_m\rangle) = \frac{1}{4}|c_m|^2\left|1+e^{i(E-E_m)t_1}\right|^2 = |c_m|^2\left|\cos\left(\frac{E-E_m}{2}t_1\right)\right|^2$$

$$p^{2l+1}cot\delta_l(p) = (-1)^{l+1}\,(4\mu\omega)^{l+\frac{1}{2}}\frac{\Gamma(\frac{2l+3}{4}-\frac{\varepsilon}{2})}{\Gamma(\frac{1-2l}{4}-\frac{\varepsilon}{2})}, \varepsilon = \frac{E}{\omega}, p = \sqrt{\mu E}$$

[Peiyan Wang, WD,* et al. PRC 109, 6 (2024)]
[T. Busch et al., Found. Phys. 28, 549 (1998)]
[K. Choi, D. Lee et al., PRL 127, 040505 (2021)]

核弹性散射相移的量子算法的应用



[Peiyan Wang, **WD,*** et al. PRC 109, 6 (2024)]

开发了QCD系统含时演化的高效精确的量子算法

模型问题: a quark scattered by the background color field generated by a heavy nucleus.

方法开发: time-dependent basis light-front quantization (tBLFQ) on quantum computer.

Fock-sector 截断: $|q\rangle = a|\tilde{q}\rangle + \cancel{b|\tilde{q}g\rangle + \cdots}$

散射系统的运动方程（光前）： $i\dfrac{\partial}{\partial x^+}|\psi;x^+\rangle = \dfrac{1}{2}\boldsymbol{P}^-|\psi;x^+\rangle$

含时演化算符: $\boldsymbol{U} = \mathcal{T}\exp\left\{-\dfrac{i}{2}\int_0^{x^+}\boldsymbol{P}^-(s)\,ds\right\}$

散射系统的光前哈密顿量:

$$\boldsymbol{P}^- = \int dx^- d^2x_\perp \left\{\frac{1}{2}\overline{\Psi}\gamma^+\frac{m^2-\nabla_\perp^2}{i\partial^+}\Psi + g\overline{\Psi}\gamma^\mu T^a\Psi\mathcal{A}_\mu^a\right\}$$
$$= \boldsymbol{P}^-_{\mathrm{QCD}}\left(\boldsymbol{k}^\perp\right) + \boldsymbol{V}\left(x^+, \boldsymbol{x}^\perp, c\right).$$

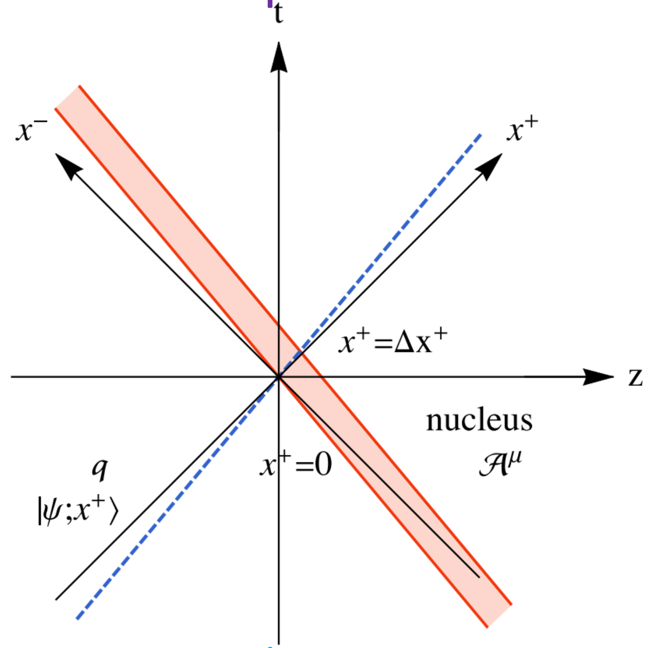
McLerran-Venugopalan模型
用以描述背景场作用

动量基矢表象

$$\boxed{\boldsymbol{P}^- = \boldsymbol{P}^-_{\mathrm{QCD}}\left(\boldsymbol{k}^\perp\right) + \mathcal{F}^\dagger\boldsymbol{V}\left(x^+, \boldsymbol{k}^\perp, c\right)\mathcal{F}}$$

量子模拟

1. 哈密顿量输入
2. 初态准备
3. 含时演化
4. 测量



[Meijian Li, et al., PRD 101, 076016 (2020)]
[McLerran, et al., PRD 50, 2225 (1994)]

量子算法: Truncated Taylor series (TTS)

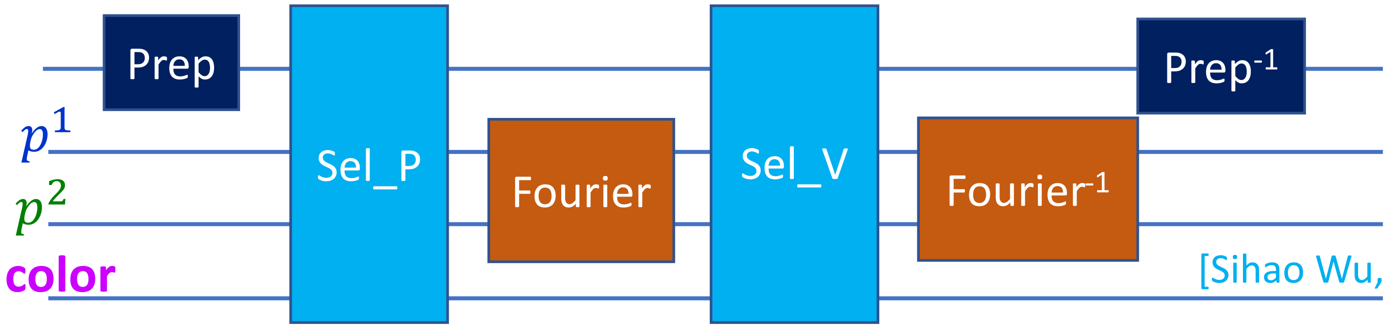
[Berry, et al., PRL 114, 090502 (2015)]

$$P^- = P^-_{\rm QCD} + \mathcal{F}^\dagger V \mathcal{F} = \sum_{l=1}^{L} \alpha_l H_l$$

时间演化算符

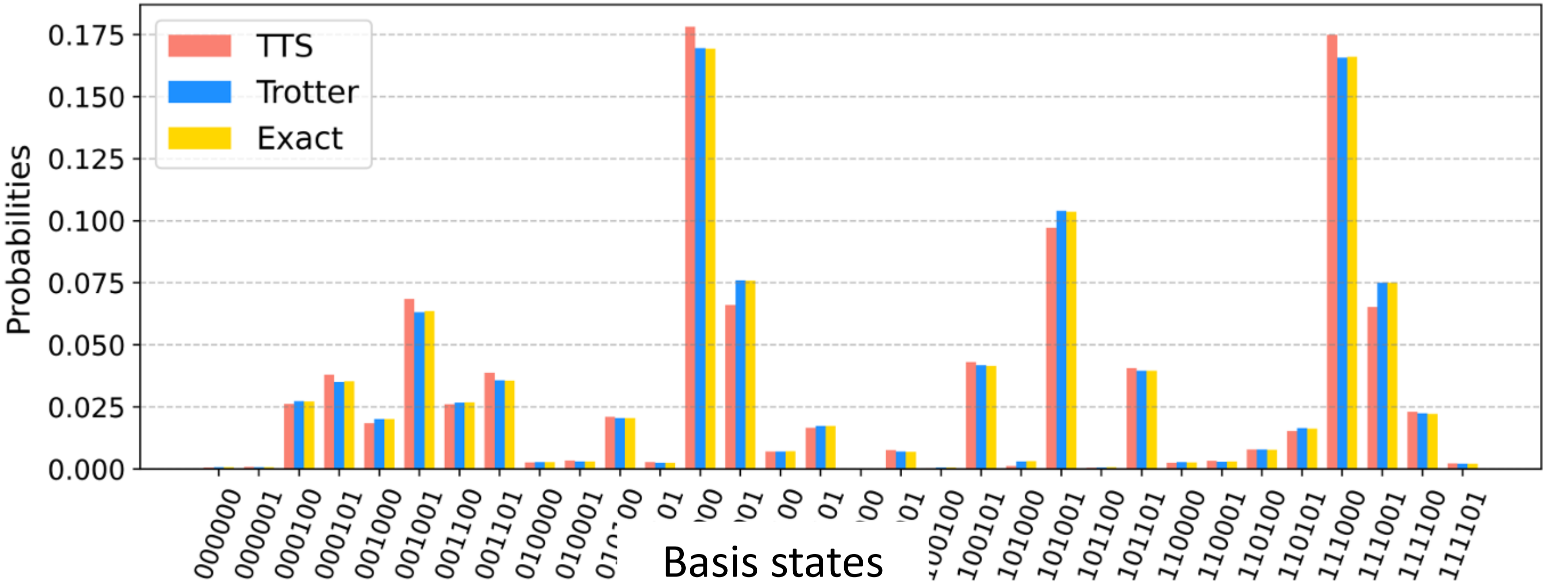
$$U_r \approx \sum_{k=0}^{K} \sum_{\ell_1,\ldots,\ell_k=1}^{L} \frac{(-it/r)^k}{k!} \alpha_{\ell_1} \cdots \alpha_{\ell_k} H_{\ell_1} \cdots H_{\ell_k}$$

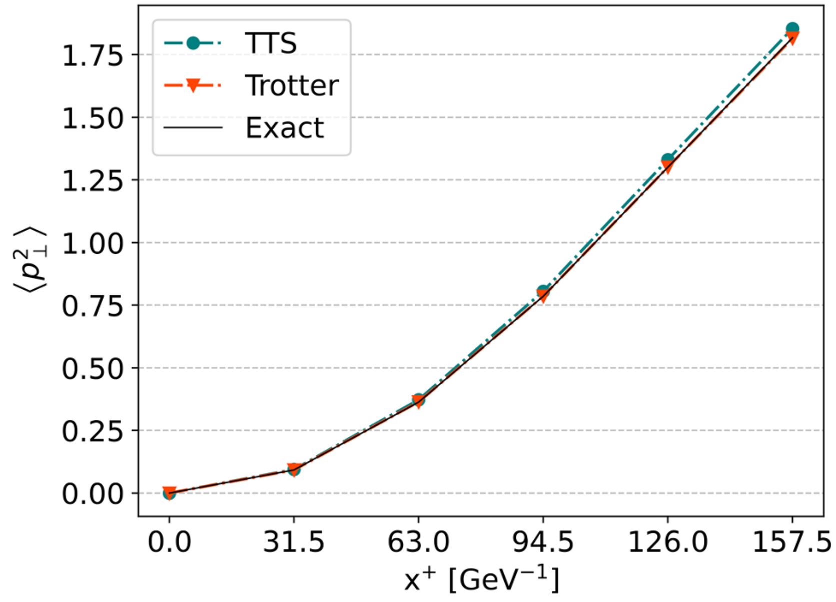
量子线路结构



[Sihao Wu, **WD,*** et al., PRD 110, 056044]

散射动力学的量子模拟



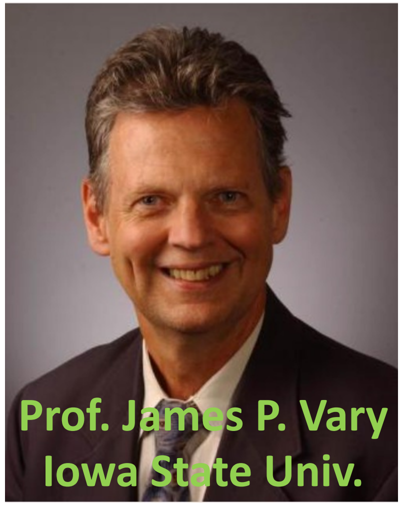


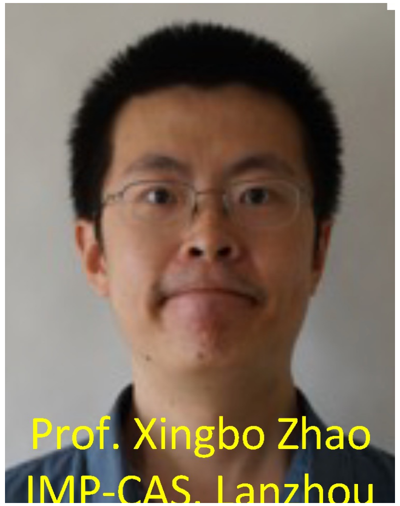
Transverse momentum broadening

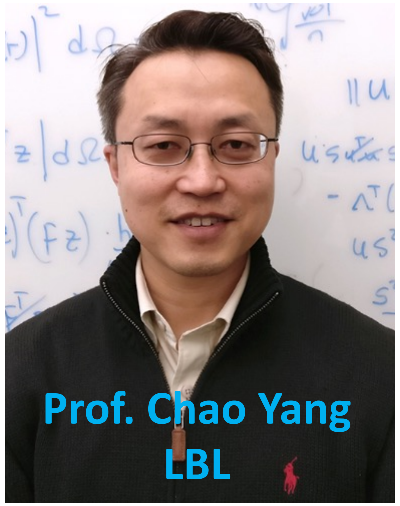
总结

- 核多体问题的从头计算对经典计算机具有极大挑战性。量子计算有望更高效解决此类问题。
- 在本报告中，我们介绍了适用于量子多体系统哈密顿量的量子线路设计方案。
- 基于这些哈密顿量输入方案，我们设计了多种量子算法计算多体系统结构和动力学。
- 我们还介绍了在低能和高能核散射量子算法开发方面的最新进展。
- 下一步，我们计划优化哈密顿量输入模型，并开发高效量子算法，以在近期及未来的量子硬件上开展量子多体结构与动力学的从头计算研究。
- Stay tuned.

Team members







Thank you!