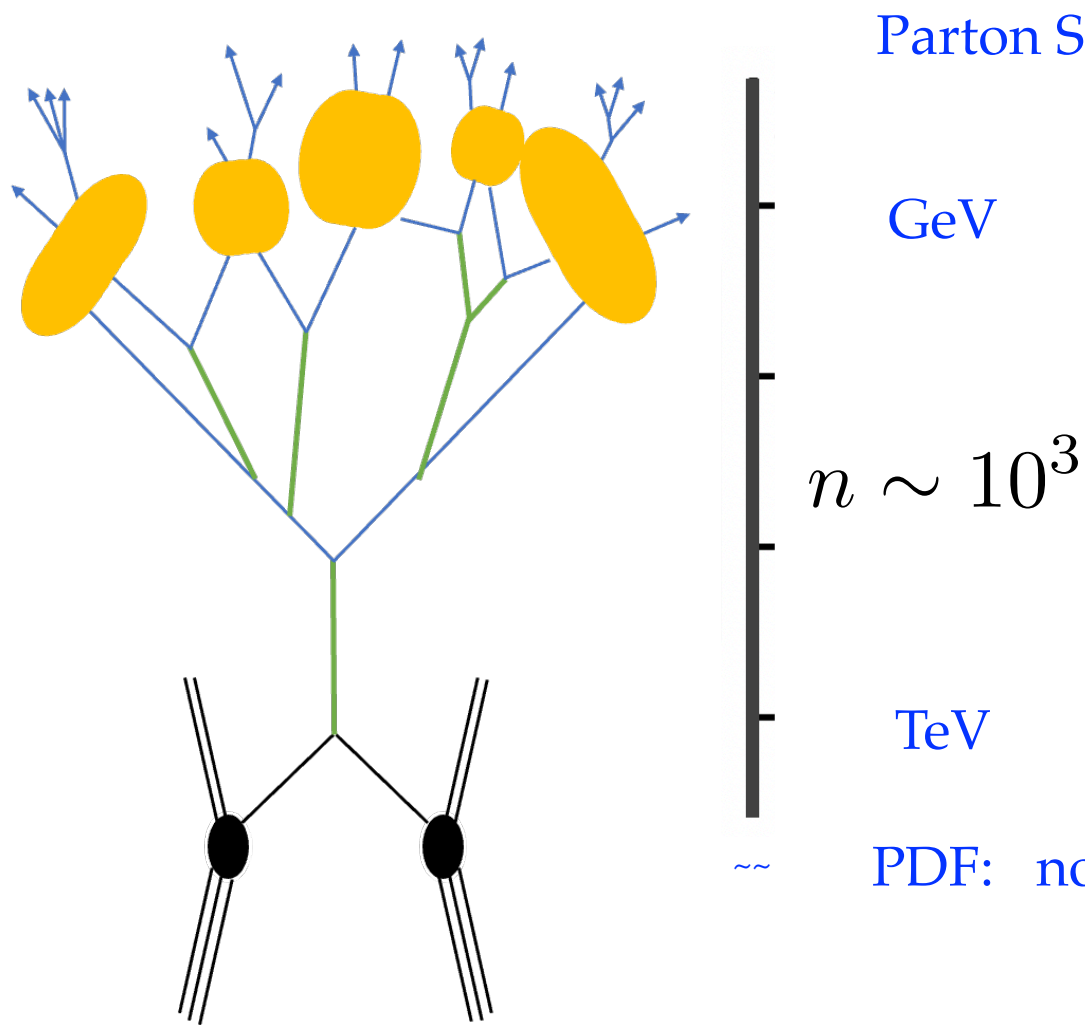


Quantum Simulations for Lattice QCD

第十四届全国粒子物理学术会议

Strong Force - QCD



Parton Shower and Hadronization:
non-perturbative

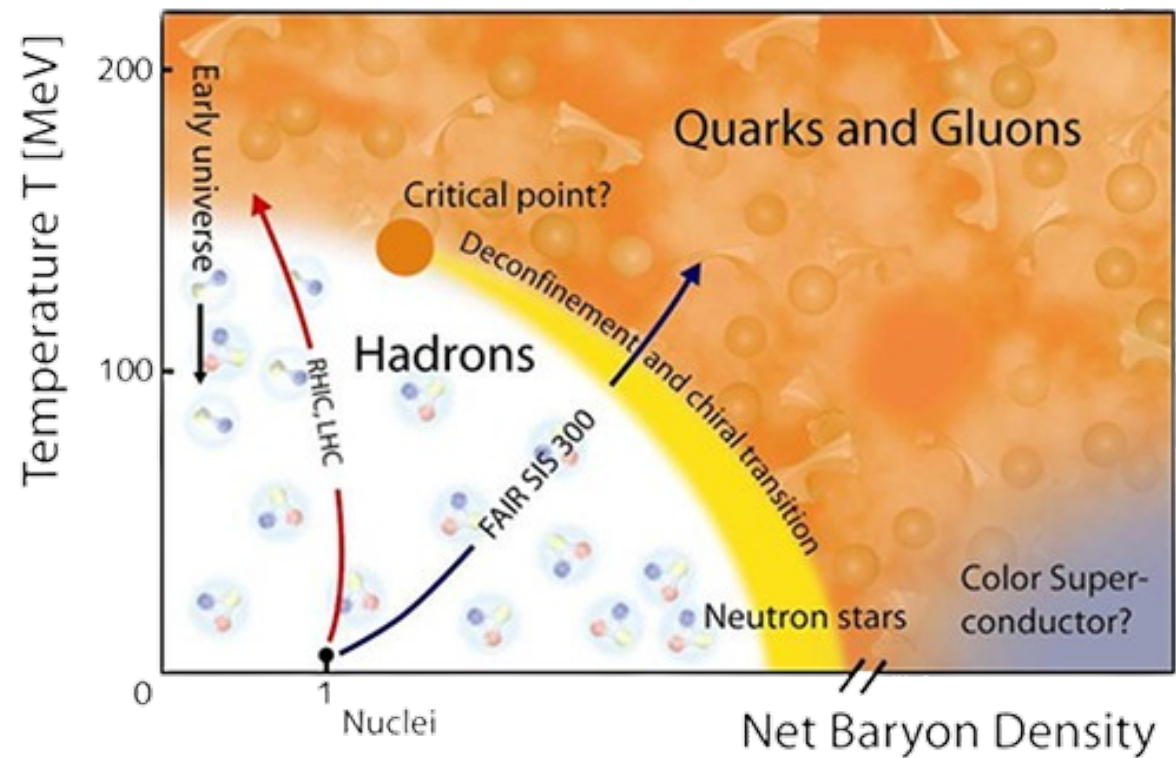
GeV

$n \sim 10^3$

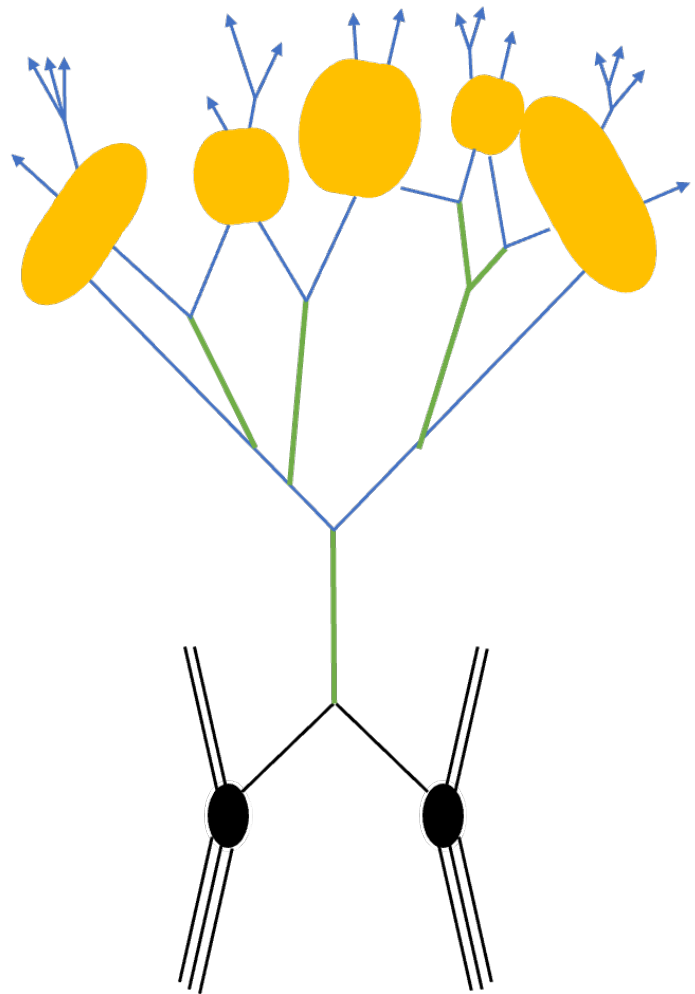
TeV

PDF: non-perturbative

Phases at finite
temperature and finite
density



Strong Force - QCD



Parton Shower and Hadronization:
non-perturbative

GeV

$n \sim 10^3$

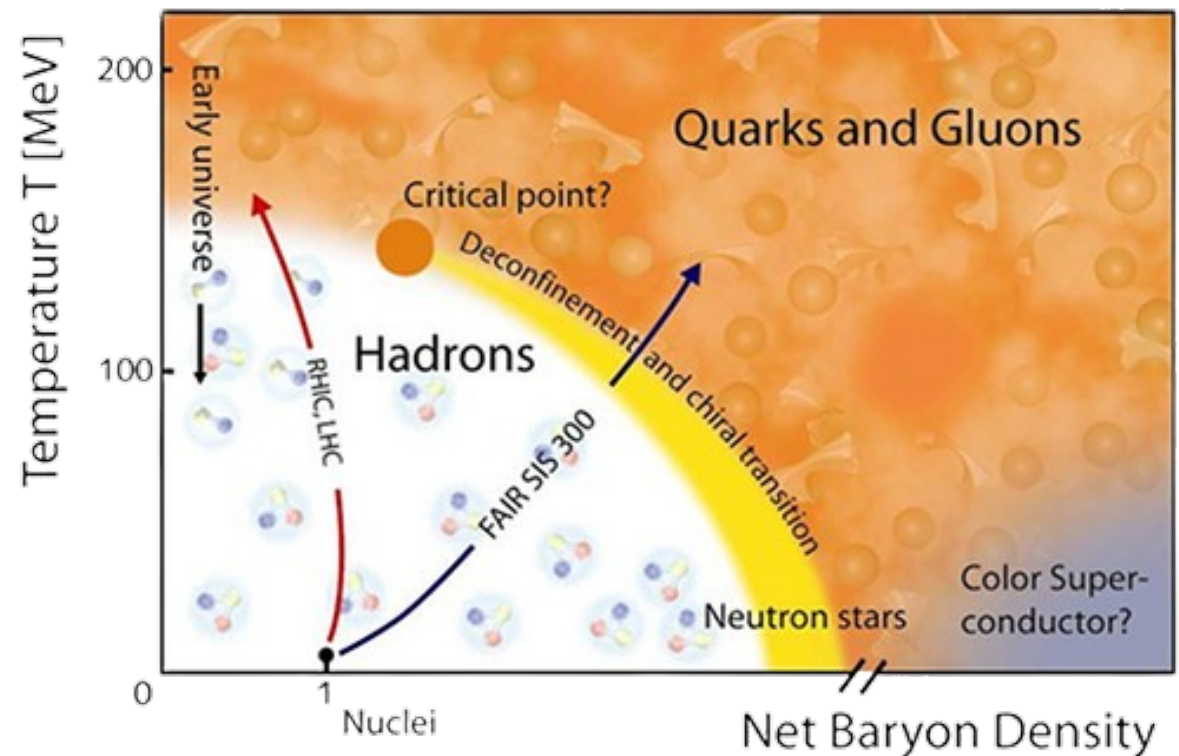
TeV

PDF: non-perturbative

Phases at finite
temperature and finite
density

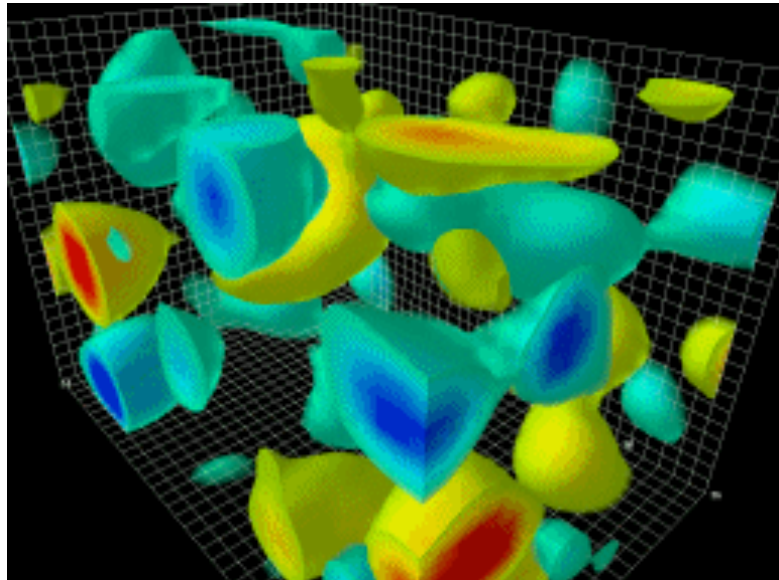
第一性原理计算

path integral on the background
of field configurations



第一性原理计算 - Lattice QCD

Euclidean Spacetime



field configurations
 \mathcal{C} on lattice

Monte Carlo
sampling of lattice
field configurations

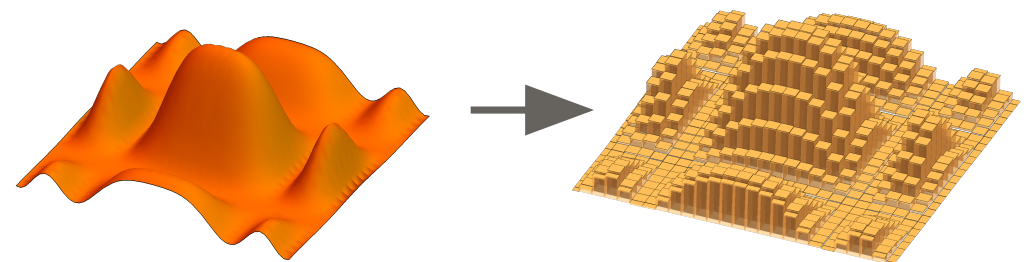
$$W(\mathcal{C}) \sim \exp(-S(\mathcal{C}))$$

$$\langle O \rangle = \frac{\sum_{\mathcal{C}} O(\mathcal{C}) W(\mathcal{C})}{\sum_{\mathcal{C}} W(\mathcal{C})}$$

Real Time

complex $S(\mathcal{C})$

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



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

exponentially large number
of classical bits in system size

“a computing system with qubits”

R. P. Feynman - 1982

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

$$N_q \propto N_V \log |G|$$

The number of qubits required is a polynomial function of the system size

“a computing system with qubits”

R. P. Feynman - 1982

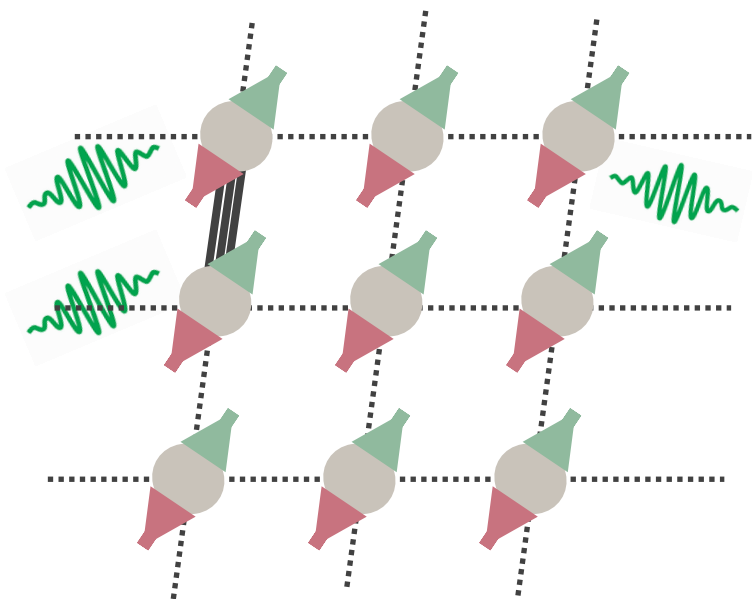
$$\dim H \propto |G|^{N_V}$$

$$N_q \propto N_V \log |G|$$

The number of qubits required is a polynomial function of the system size



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



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

QUANTUM EASY

High Energy Physics

real-time dynamics
finite density

QUANTUM HARD

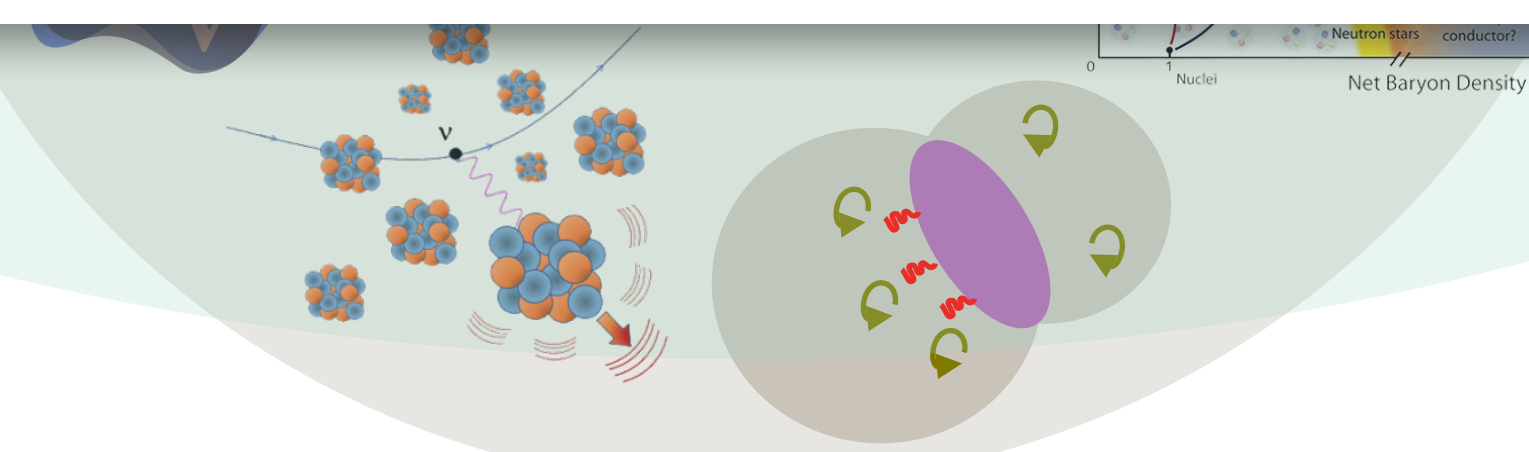
e.g. traveling salesmen
problem

[PRX Quantum 4 (2023) 2, 027001]

Quantum Simulation for High Energy Physics

Christian W. Bauer,^{1, a} Zohreh Davoudi,^{2, b} A. Baha Balantekin,³ Tanmoy Bhattacharya,⁴
Marcela Carena,^{5, 6, 7, 8} Wibe A. de Jong,¹ Patrick Draper,⁹ Aida El-Khadra,⁹
Nate Gemelke,¹⁰ Masanori Hanada,¹¹ Dmitri Kharzeev,^{12, 13} Henry Lamm,⁵
Ying-Ying Li,⁵ Junyu Liu,^{14, 15} Mikhail Lukin,¹⁶ Yannick Meurice,¹⁷
Christopher Monroe,^{18, 19, 20, 21} Benjamin Nachman,¹ Guido Pagano,²² John Preskill,²³
Enrico Rinaldi,^{24, 25, 26} Alessandro Roggero,^{27, 28} David I. Santiago,^{29, 30}
Martin J. Savage,³¹ Irfan Siddiqi,^{29, 30, 32} George Siopsis,³³ David Van Zanten,⁵
Nathan Wiebe,^{34, 35} Yukari Yamauchi,² Kübra Yeter-Aydeniz,³⁶ and Silvia Zorzetti⁵

- Collider Phenomenology
- Matter in and out of Equilibrium
- Neutrino (Astro)physics
- Early Universe and Cosmology
- Quantum Gravity



Problems in HEP that are beyond classical easy but are
“QUANTUM EASY”

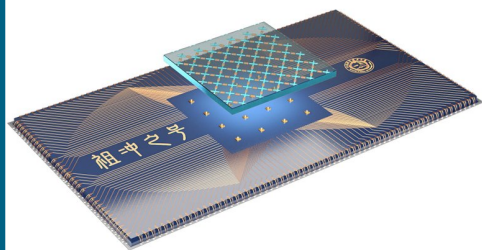
Quantum Computing



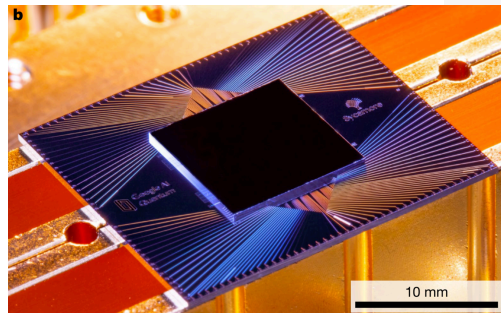
Now - Noisy Intermediate Scale Quantum (NISQ) era

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

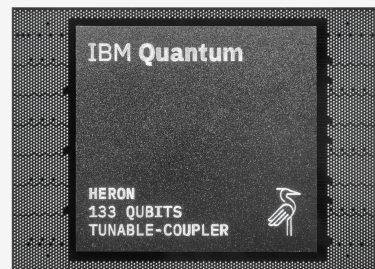
superconducting processor



176 qubits



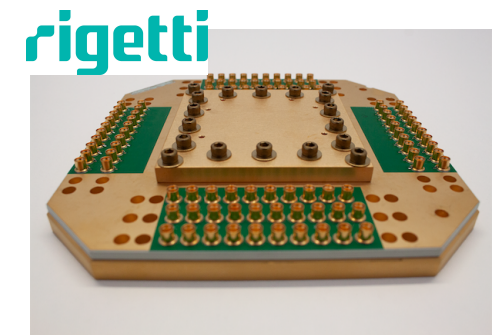
54 qubits



1121 qubits

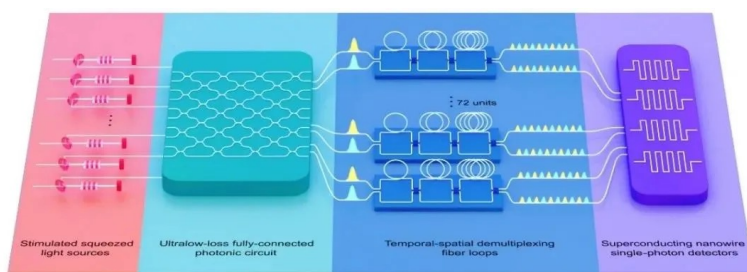
access to 156 qubits

multi-chip quantum processor



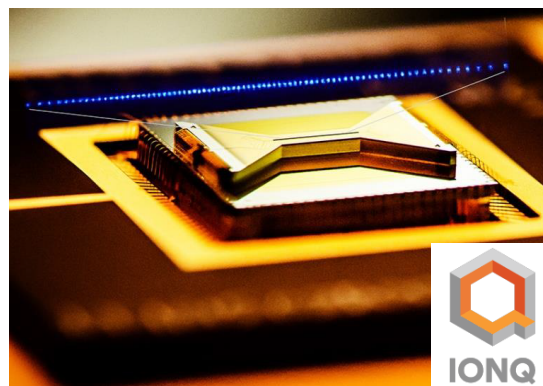
80 qubits

photon qubits



Jiuzhang - 255 qubits

trapped ion qubits



22 qubits

48 logical qubits



Quantum Computing

Next decades

Development Roadmap

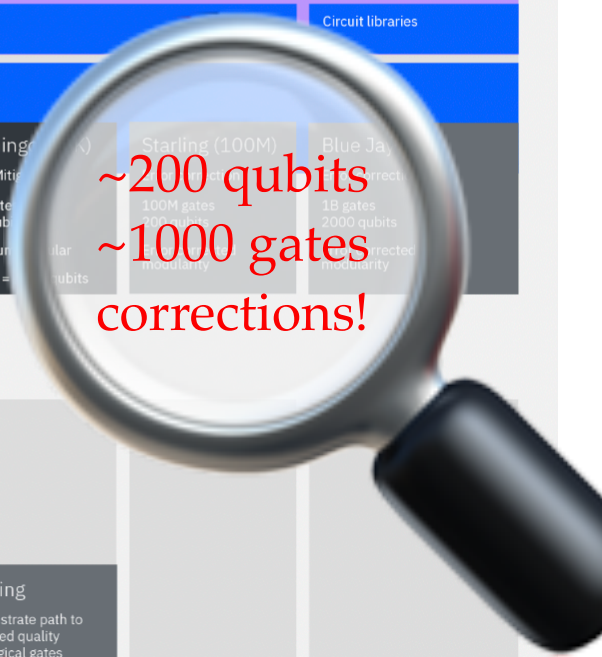
IBM Quantum

	2016–2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2033+
Overall Progress	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 Physicist			Qiskit Runtime									
Hardware Milestones	IBM Quantum Experience	QASM3	Dynamic circuits	Execution Modes	Heron (5K)	Flamingo (5K)	Flamingo (7.5K)	Flamingo (10K)	Flamingo (15K)	Starling (100M)	Blue Jay	
Qubit Count	Early: Canary (5), Albatross (16), Penguin (20), Prototype (53)	Falcon (27)	Eagle (127)		5k gates, 133 qubits	5k gates, 156 qubits	7.5k gates, 156 qubits	10k gates, 156 qubits	15k gates, 156 qubits	100M gates, 2000 qubits	1B gates, 2000 qubits	
Gate Count					133x3 = 399 gates	156x7 = 1092 gates	156x7 = 1092 gates	156x7 = 1092 gates	156x7 = 1092 gates	~200 qubits, ~1000 gates corrections!		

Innovation Roadmap

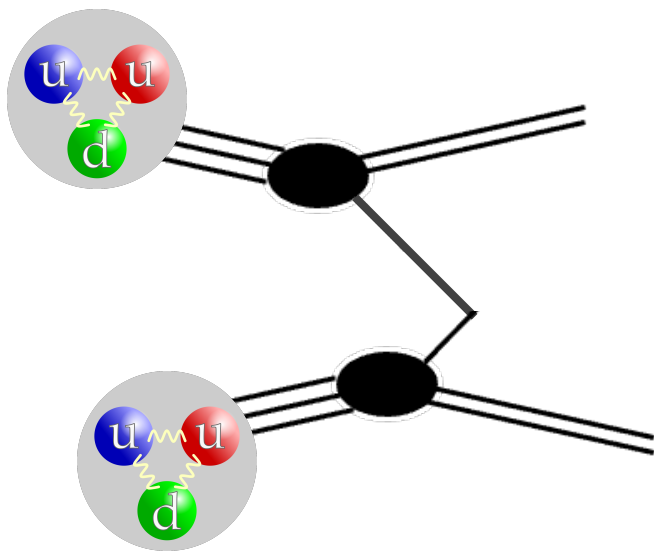
	2016–2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2033+
Software Innovation	IBM Quantum Experience	Qiskit	Application modules	Qiskit Runtime	Serverless	AI enhanced quantum	Resource management	Scalable circuit knitting	Error correction decoder			
Hardware Innovation	Early	Falcon	Hummingbird	Eagle	Osprey	Condor	Flamingo	Kookaburra	Cockatoo	Starling		
Hardware Milestones	Canary (5), Albatross (16), Penguin (20), Prototype (53)	Demonstrate scaling with I/O routing with Bump bonds	Demonstrate scaling with multiplexing readout	Demonstrate scaling with MLW and TSV	Enabling scaling with high density signal delivery	Single system scaling and fridge capacity	Demonstrate scaling with modular connectors	Demonstrate scaling with nonlocal c-coupler	Demonstrate path to improved quality with logical communication	Demonstrate path to improved quality with logical gates	Demonstrate path to improved quality with logical gates	
Hardware Milestones						Heron Architecture based on tunable-couplers	Crossbill m-coupler					

IBM Quantum / © 2023 IBM Corporation



Quantum Computing for HEP

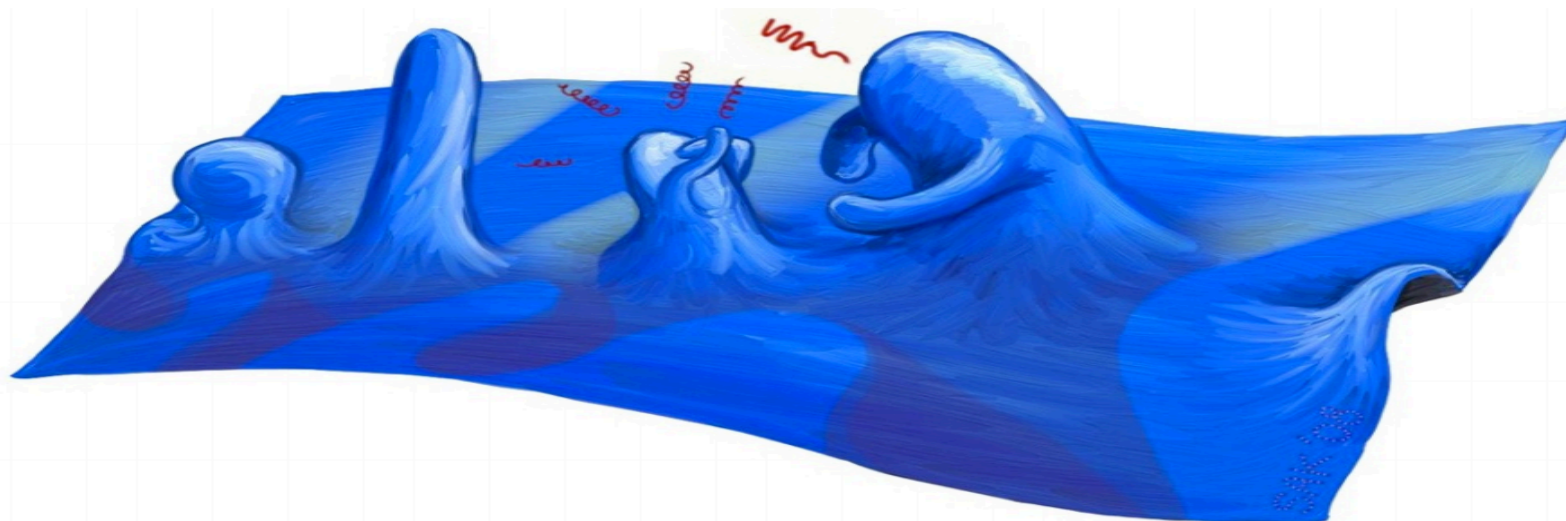
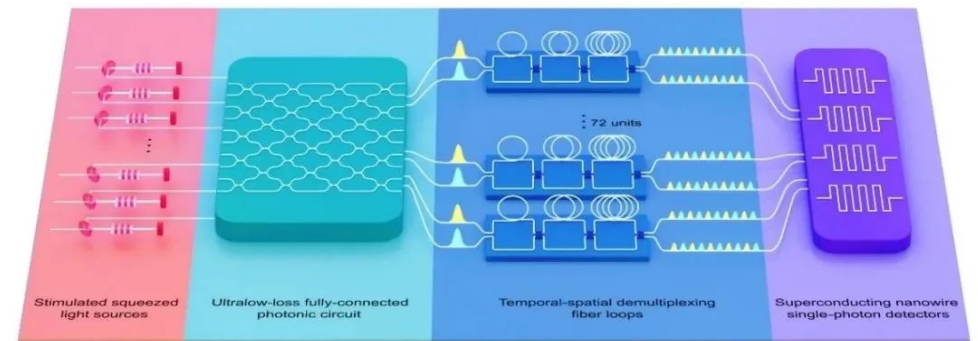
$$\int \mathcal{D}\phi e^{iS} = \langle x | e^{-iHt} | y \rangle$$



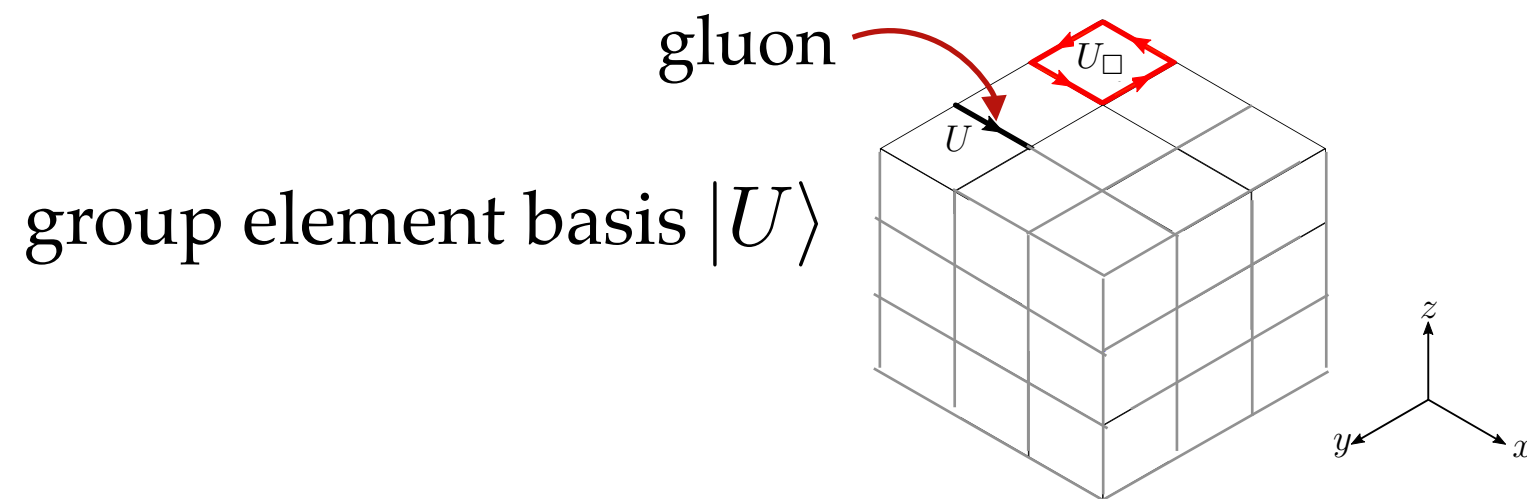
mapping

DOF to qubits

time evolution
to quantum gates



non-trivial vacuum,
composite initial state,
bosonic and fermionic DOF,
symmetries, ...



block product encoding: BT, BI

$$U = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \mid a, b, c, d \in \mathbf{F}_3, ad - bc \equiv 1 \pmod{3} \right\}$$

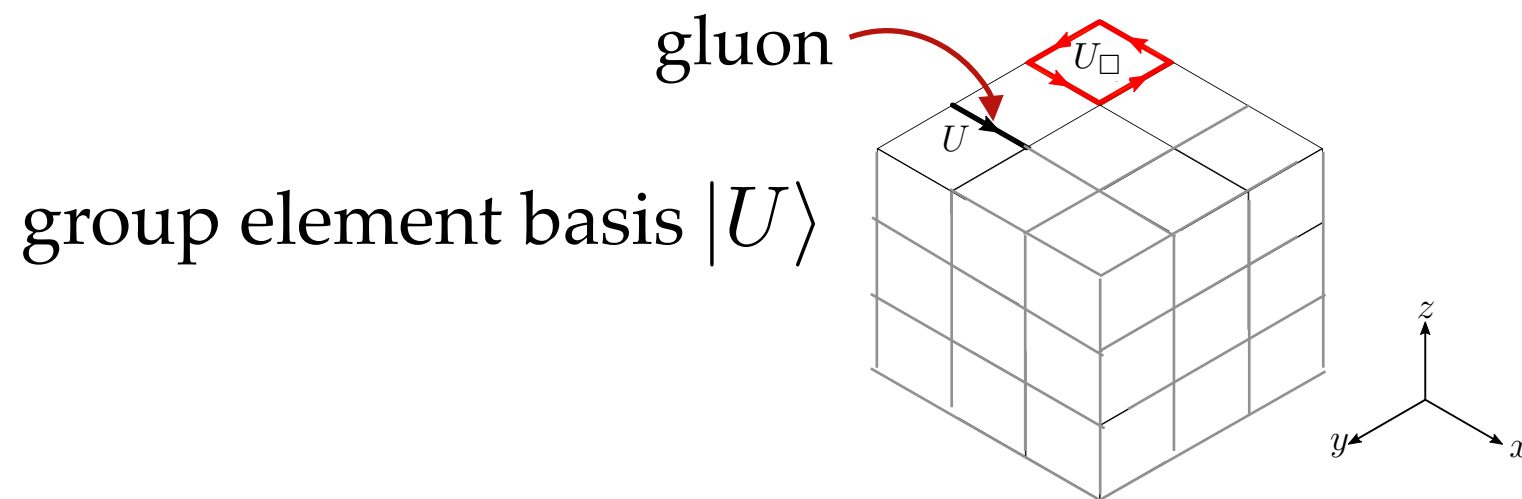
$$|U\rangle = \left| \begin{array}{cccccccc} \blacktriangle & \blacktriangle & \blacktriangle & \blacktriangle & \blacktriangle & \blacktriangle & \blacktriangle & \blacktriangle \\ \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \\ \blacktriangledown & \blacktriangledown & \blacktriangledown & \blacktriangledown & \blacktriangledown & \blacktriangledown & \blacktriangledown & \blacktriangledown \end{array} \right\rangle$$

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

Digitization

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

infinities in QFT



block product encoding: BT, BI

$$U = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \mid a, b, c, d \in \mathbf{F}_3, ad - bc \equiv 1 \pmod{3} \right\}$$

$$|U\rangle = \left| \begin{array}{cccccccc} \blacktriangle & \blacktriangle & \blacktriangle & \blacktriangle & \blacktriangle & \blacktriangle & \blacktriangle & \blacktriangle \\ \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \\ \blacktriangledown & \blacktriangledown & \blacktriangledown & \blacktriangledown & \blacktriangledown & \blacktriangledown & \blacktriangledown & \blacktriangledown \end{array} \right\rangle$$

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

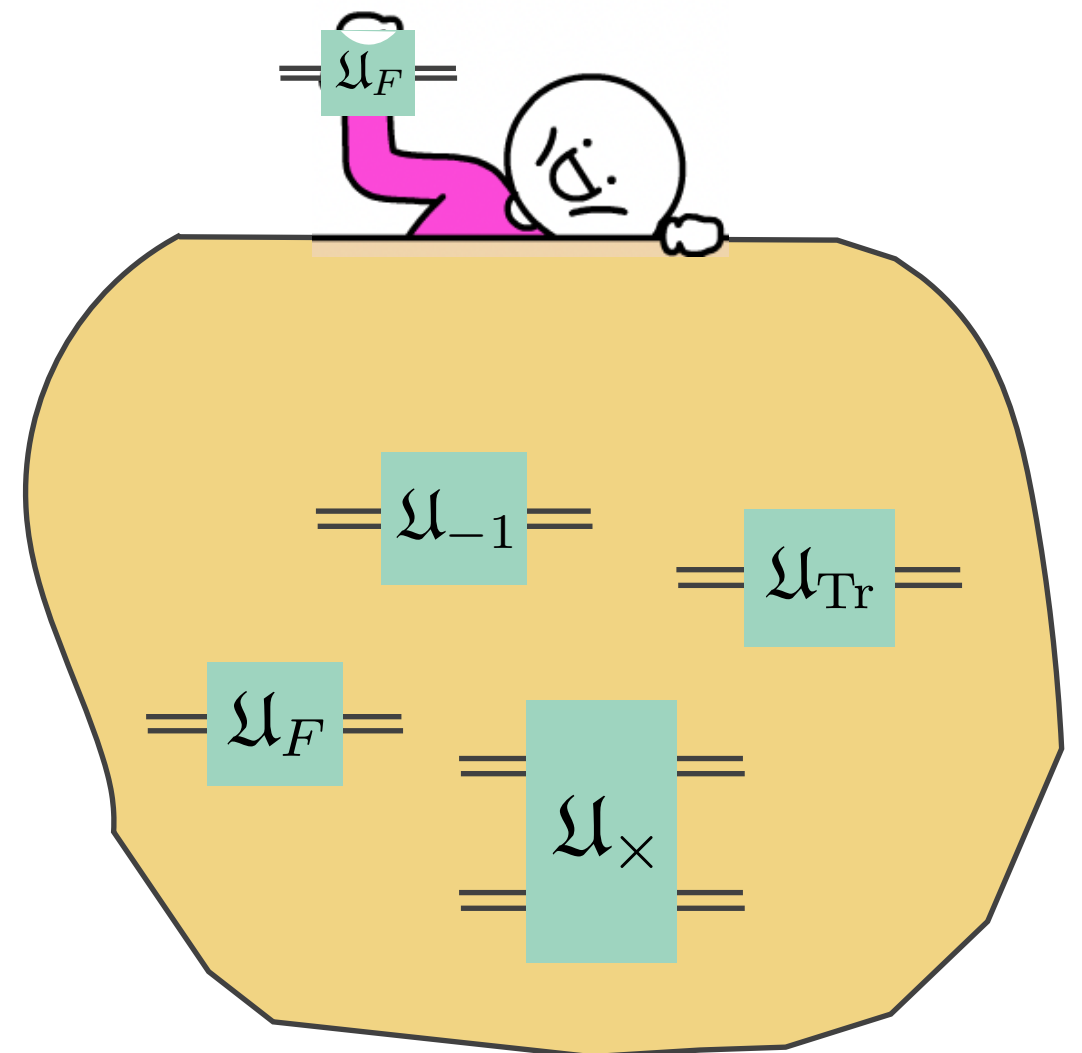
qudit system?

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

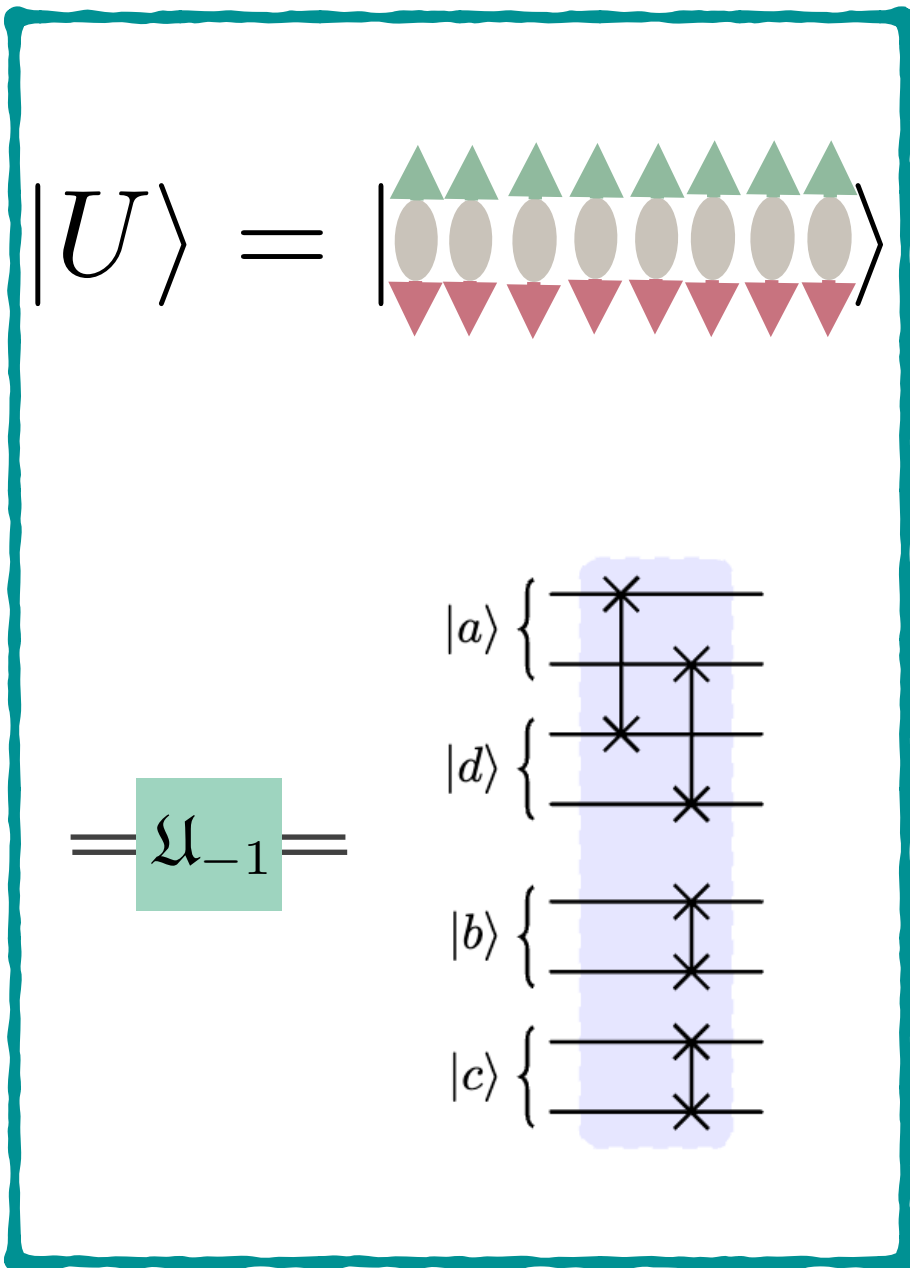
$$H_{KS} = \sum \left(\begin{array}{c} \longrightarrow \\ K_L \end{array} + \begin{array}{c} \square \\ U_{\square} \end{array} \right)$$

$$\begin{aligned} \mathcal{U}(t) &= e^{-iH_{KS}t} \\ &\approx \left[e^{-i\delta t K_L} e^{-i\delta t U_{\square}} \right]^{t/\delta t} \end{aligned}$$

G-register : $|U\rangle =$

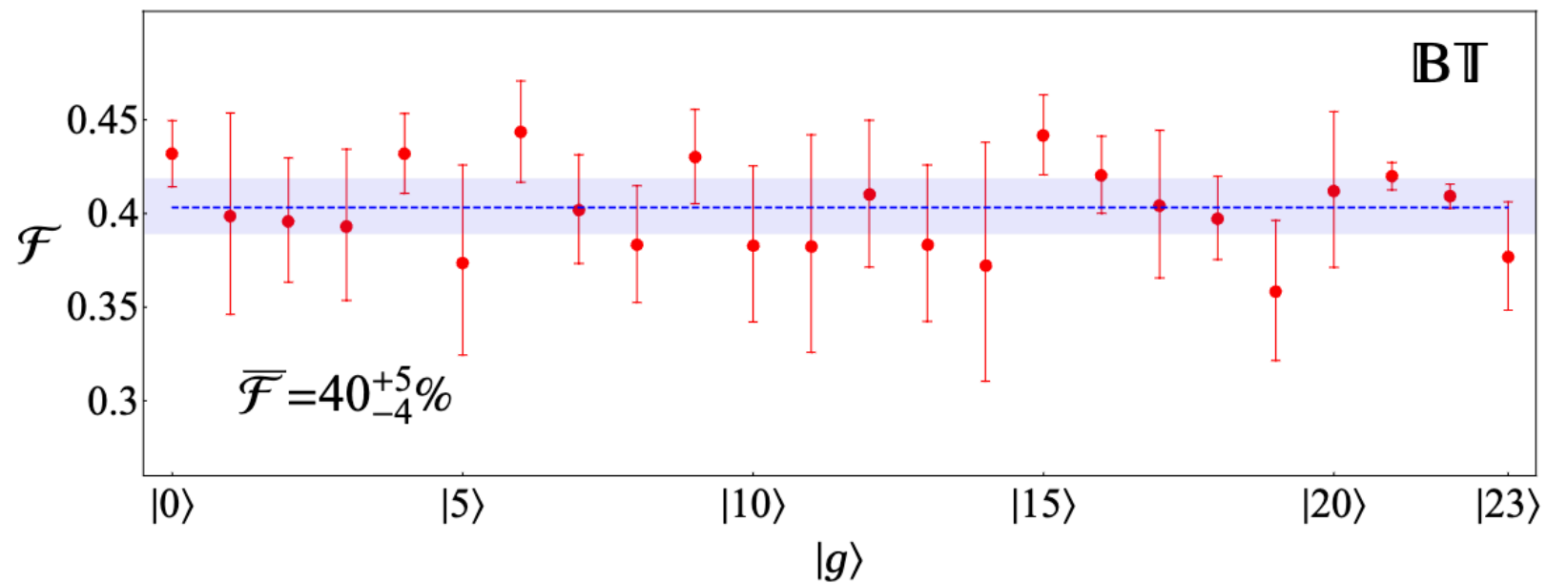
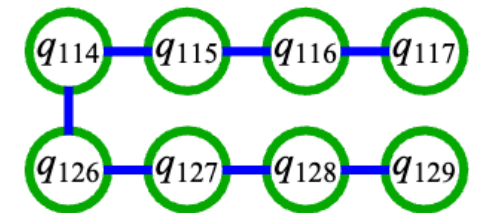


Propagation $\mathcal{U} |\psi_0\rangle \rightarrow |\psi(t)\rangle$



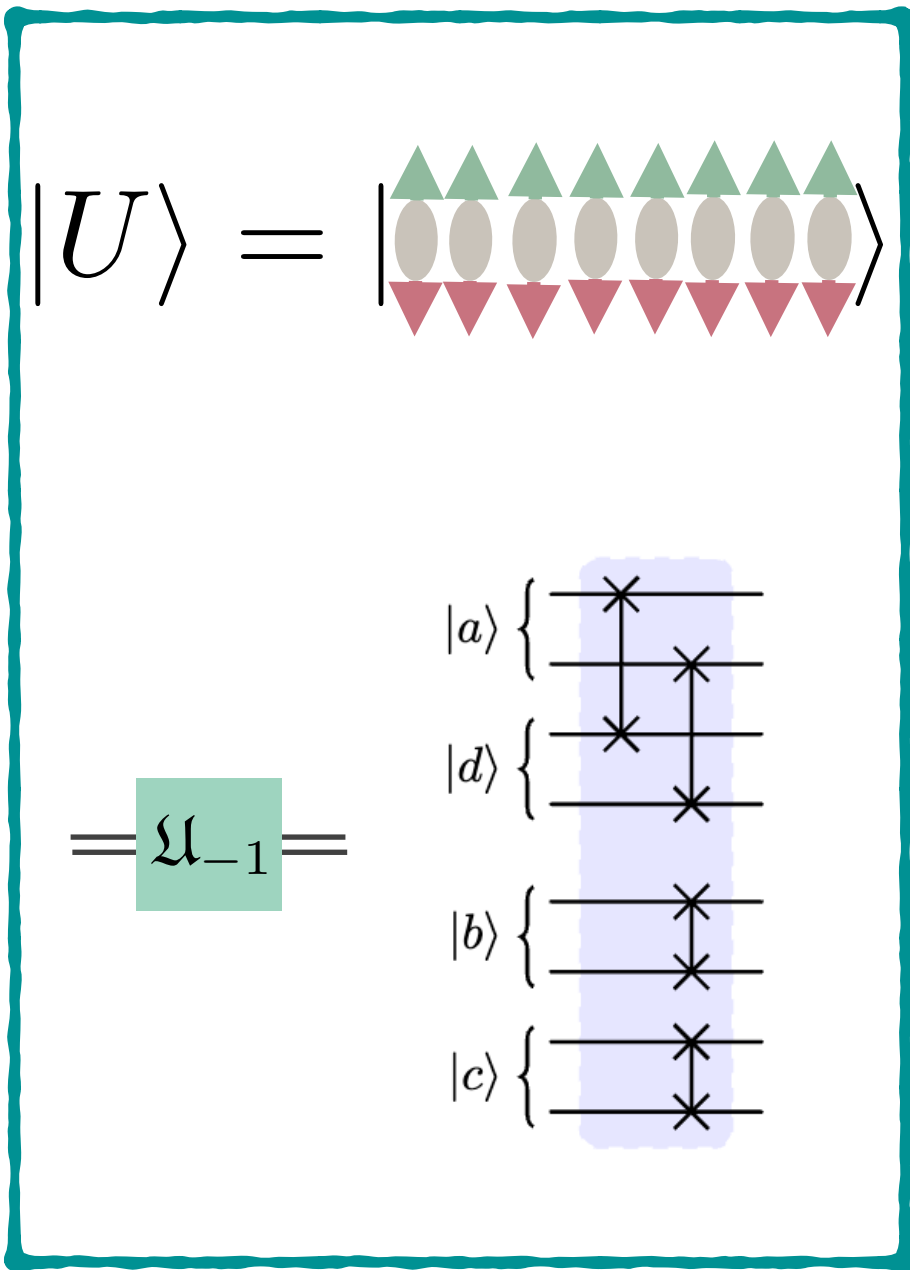
Quafu quantum cloud computing cluster

芯片名称	Baiwang	系统状态	Maintenance
芯片版本	V3	队列任务数	24
可用比特数	136	错误率	$3e-3$ (1-qubit)
			$5.4e-2$ (2-qubit)



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

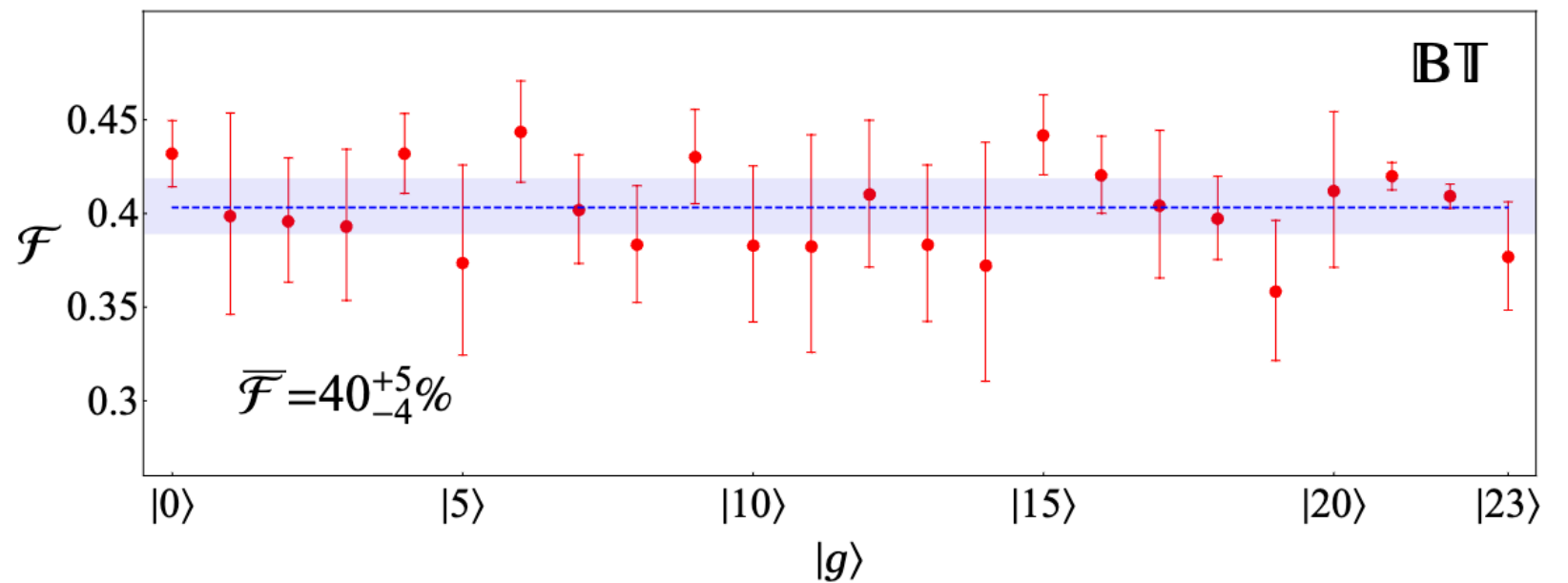
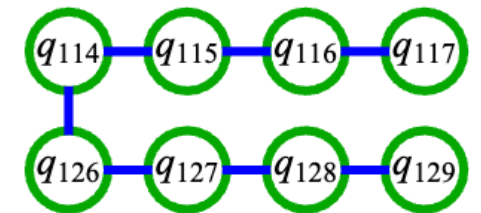
Propagation $\mathcal{U} |\psi_0\rangle \rightarrow |\psi(t)\rangle$



optimization?

Quafu quantum cloud computing cluster

芯片名称	Baiwang	系统状态	Maintenance
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[Lamm,YYL, Shu, Wang, Bin, arXiv:2405.12890]



Now - Noisy Intermediate Scale Quantum (NISQ) era

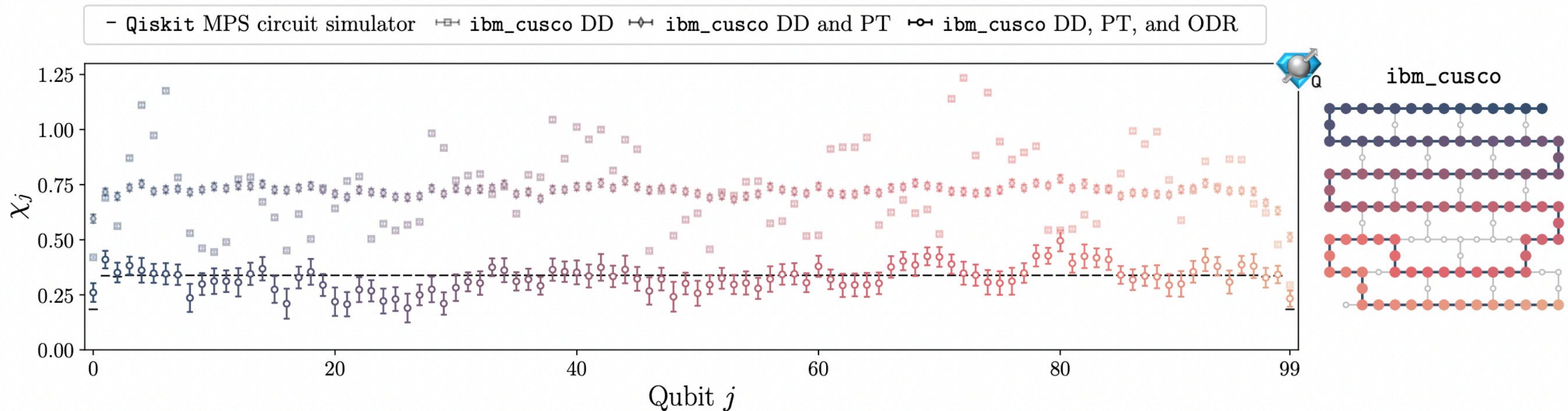
more than 50 well controlled qubits, not error-corrected yet

Physics Benchmarks

Physics Benchmarks for Quantum Computing

1 + 1d Schwinger Model — Chiral condensate

$$\mathcal{L} = \bar{\psi} (i\mathcal{D} - m_{\psi}) \psi - \frac{1}{4} F^{\mu\nu} F_{\mu\nu}$$



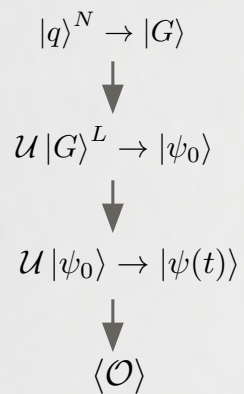
[Roland C. Farrell, et al., PRX Quantum 5, 020315]

“Quantum potential for first-principle calculations!”

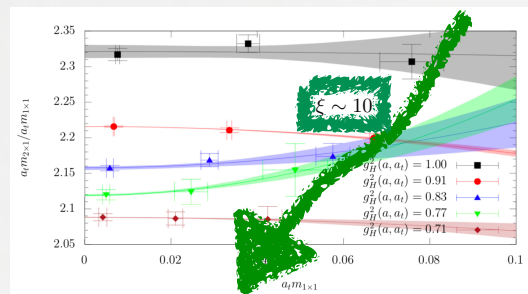
(2030s) narrow down the framework with

- improving algorithms — efficient Fourier transformations
- theoretical studies of uncertainties — phase diagrams for improved H
- hardware co-design — qudits for blocking encodings
- benchmark studies
- ...

HEP case calculations for experiments



various methods



2030s -

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



2020 -



2011-

Thank you

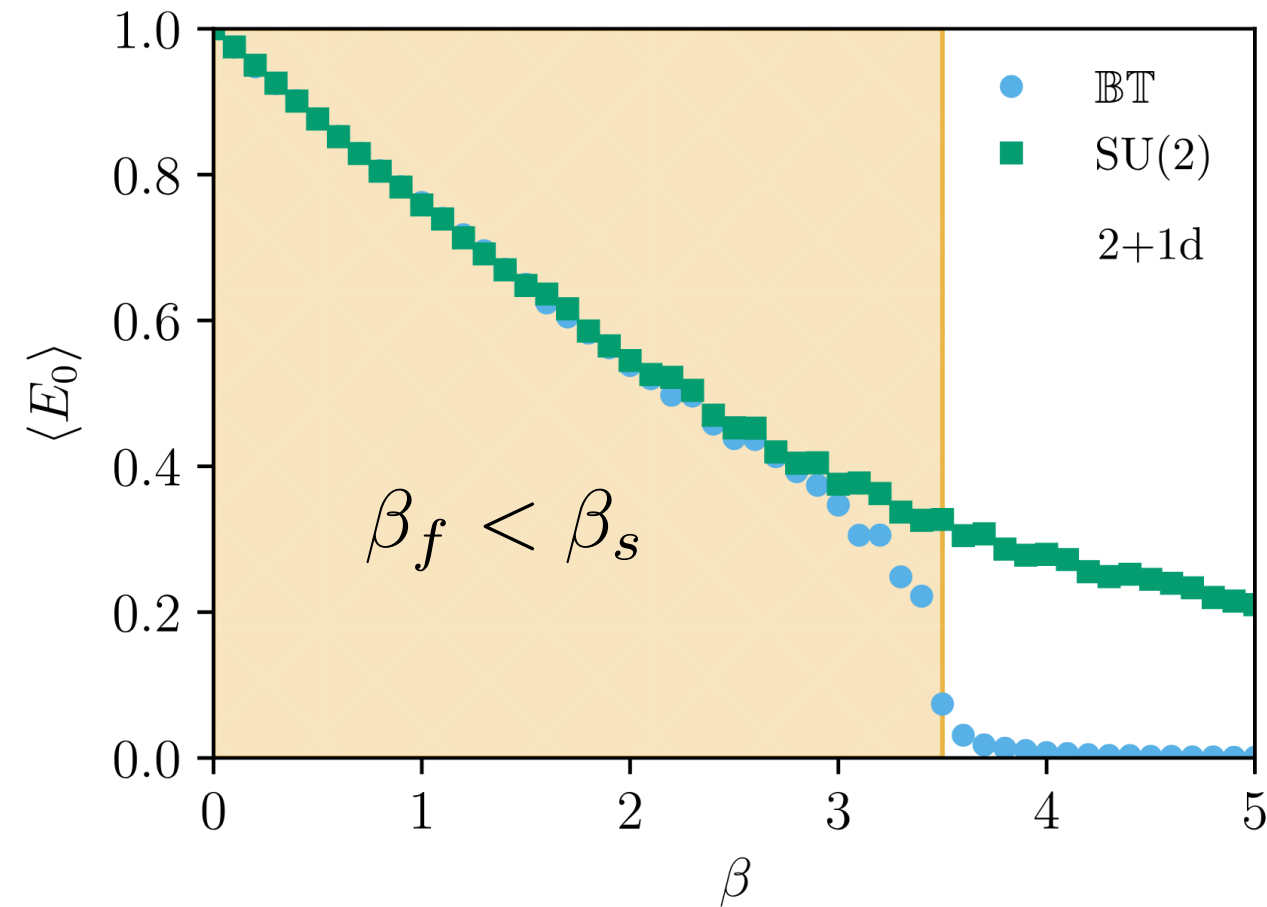
BACK UP

Digitization

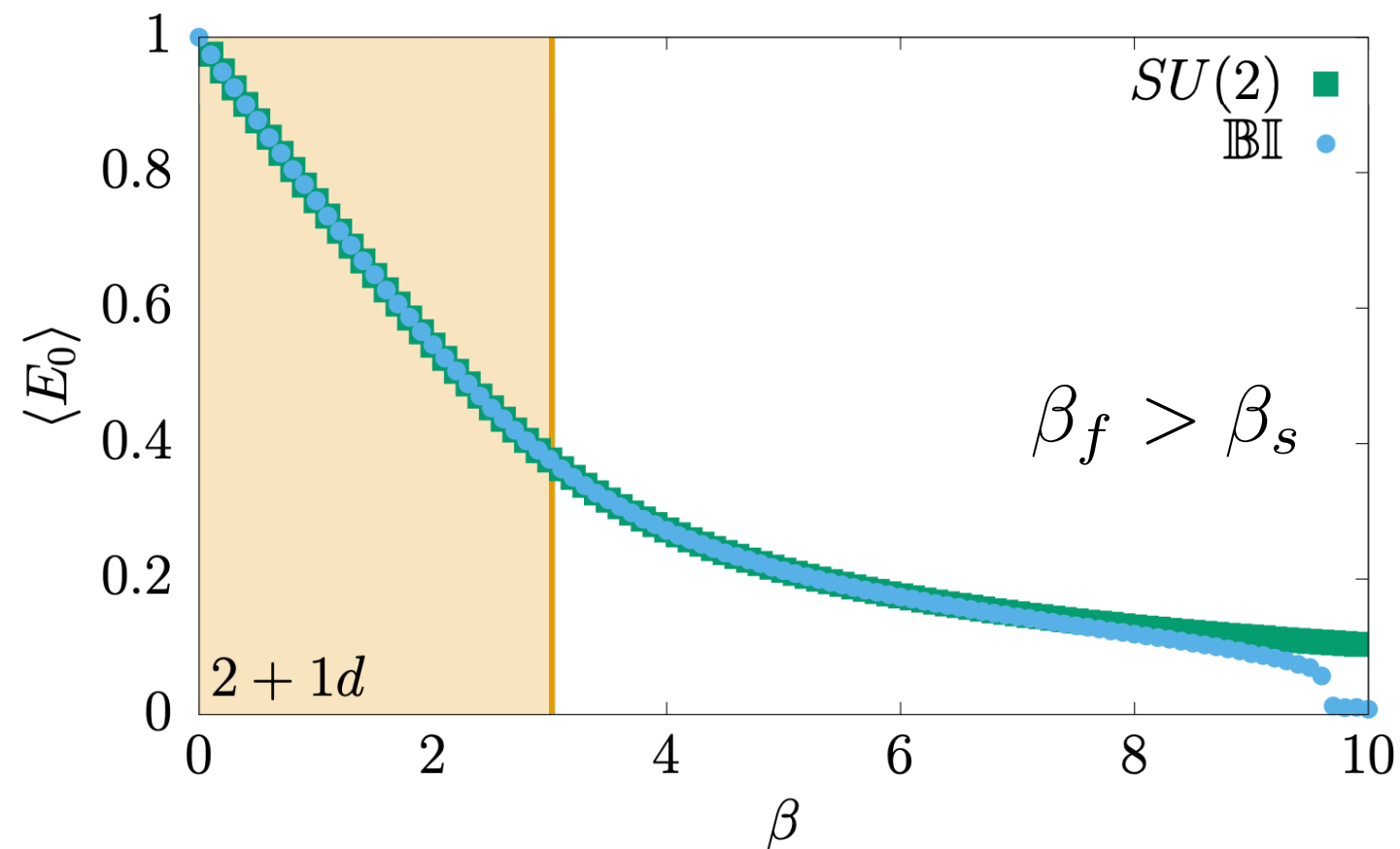
$$|q\rangle^N \rightarrow |G\rangle$$

infinities in QFT

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



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



In the Scaling Regime:
significantly reduces the errors in
simulating SU(2) physics

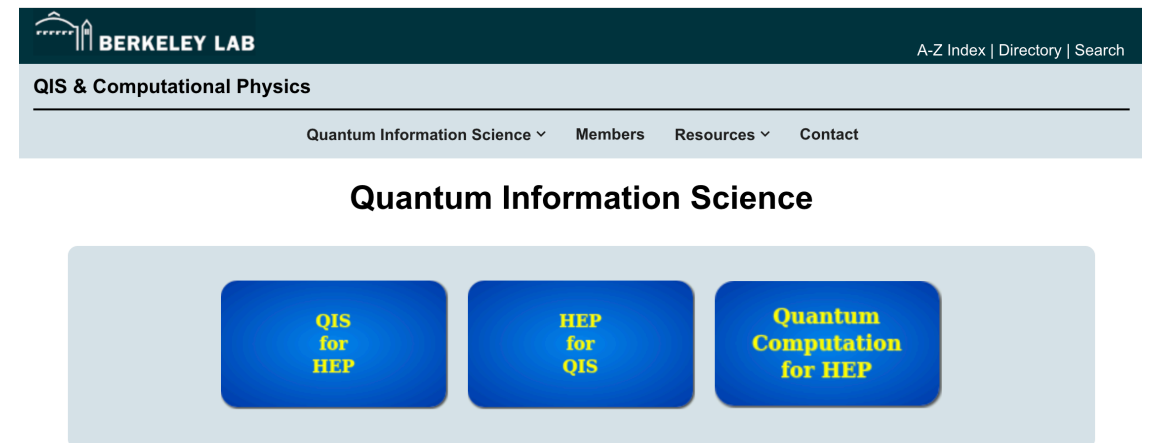
Quantum Computing for HEP



Brookhaven
Argonne
Oak Ridge
LBNL
Fermilab

1

(h) Quantum Information Science for High Energy Physics Research



HEP-QIS QuantISED program is aligned with the “Science First” driver for the national QIS program



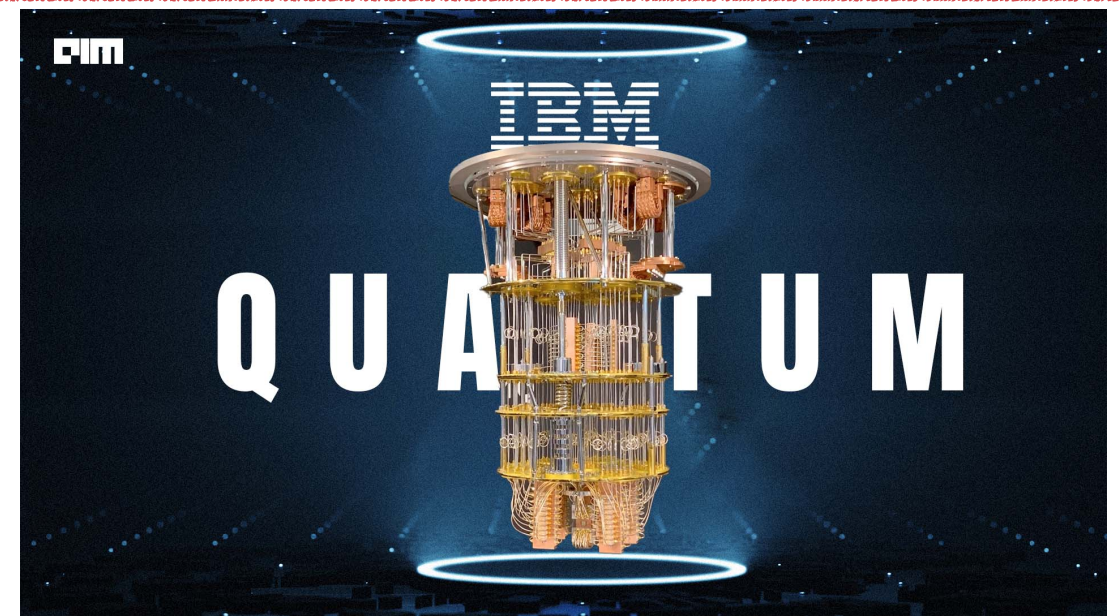
Quantum Computing for HEP

CERN Quantum Technology Initiative Accelerating Quantum Technology Research and Applications

2. **Quantum simulation and information processing:** Applications to QCD1 (Quantum Chromo Dynamics), non-perturbative dynamics using lattice QFT and more, map of quantum field theories onto quantum devices, use of well-controlled quantum systems to simulate or reproduce the behaviour of less accessible many-body quantum phenomena, noise and error control by investigations of Hilbert-space truncation mitigations.



“offers the fascinating opportunity to solve problems which are extremely hard or even impossible to address on conventional computers”



... chart future for use of quantum computing in particle physics

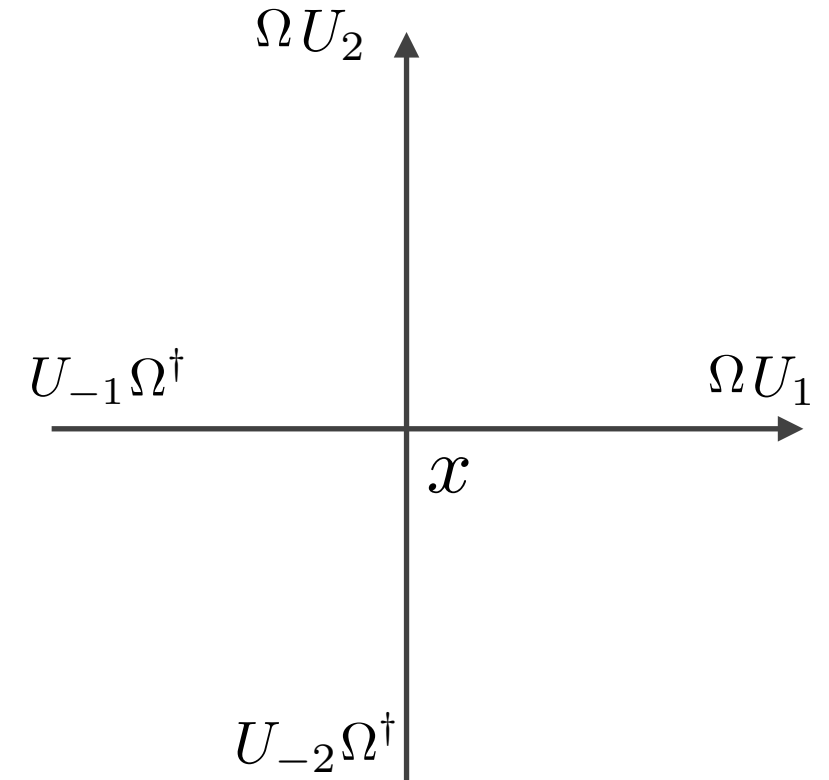
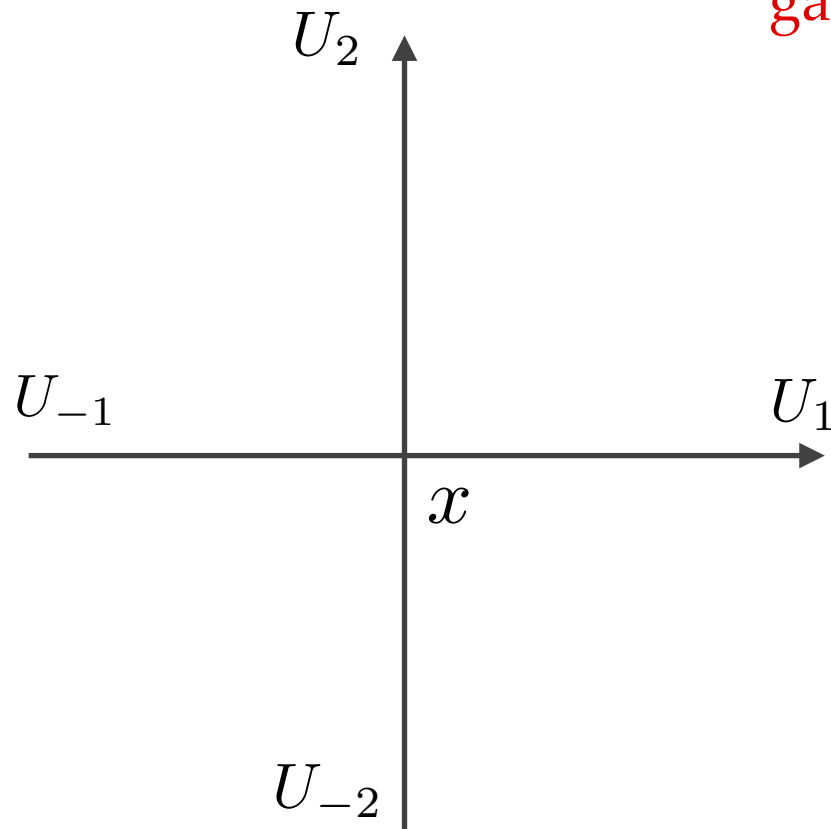
Digitization

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

infinities in QFT

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

gauge transformation



gauge equivalent states

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

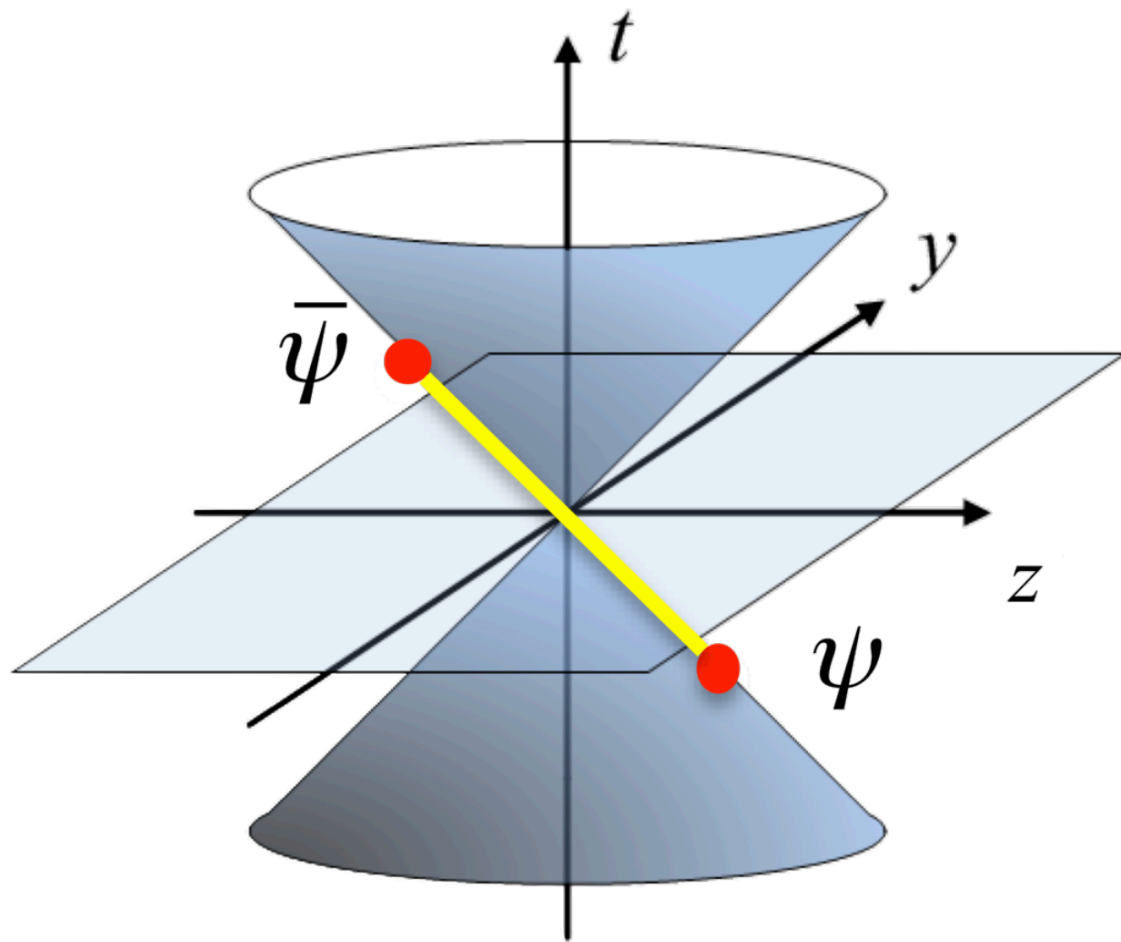
error corrections:

- circuits constructed for general groups,
- error thresholds derived as guidelines to keep gauge redundancies

Lattice QCD - Euclidean Spacetime

PDF: light-cone correlators

intrinsically Minkowski problem



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

complex $S(\mathcal{C})$

Monte Carlo Sampling
“Sign Problem”

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

system size N_V : number of lattice sites