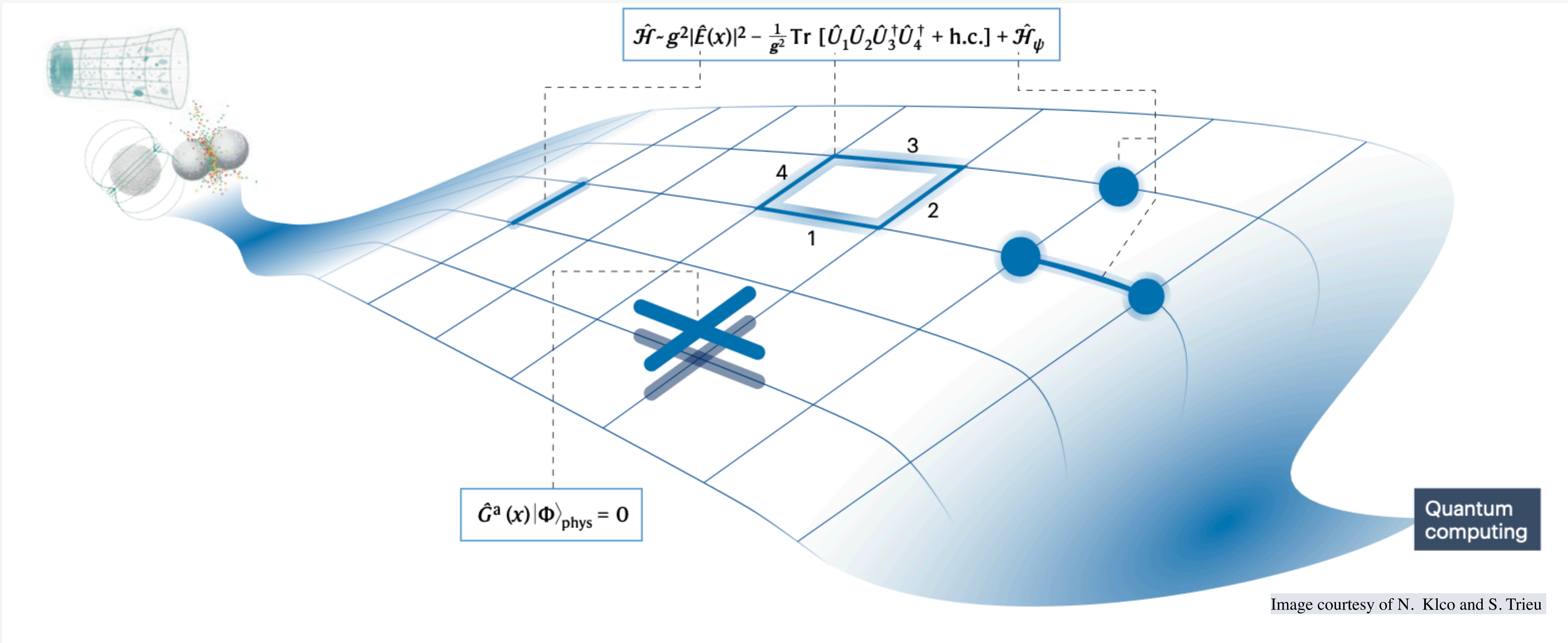


Quantum Simulations for Lattice QCD

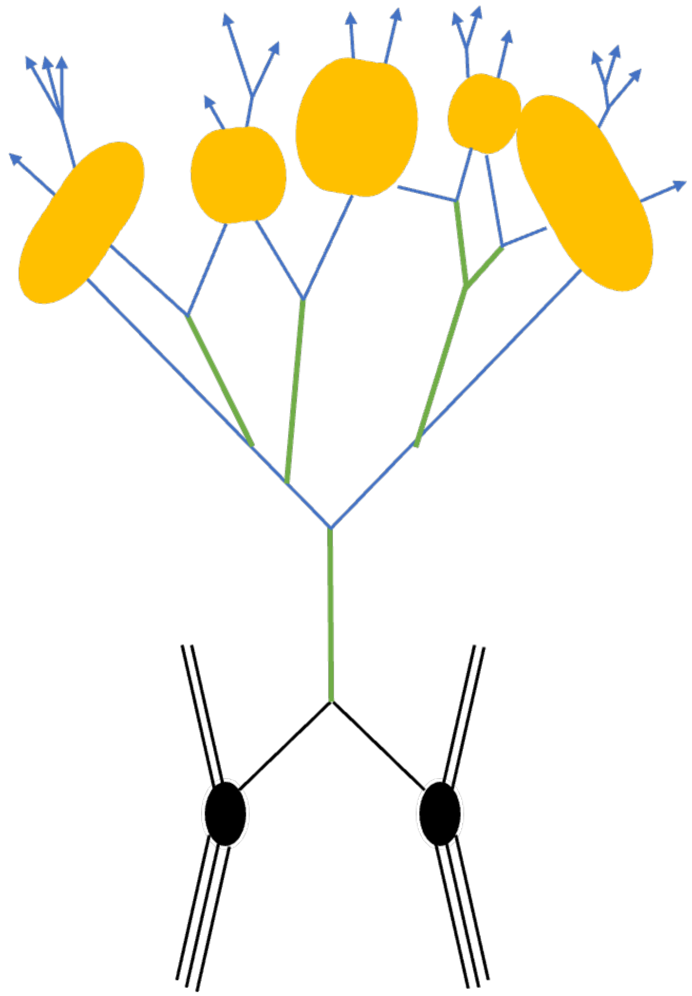
第十四届全国粒子物理学术会议

中国科学技术大学
University of Science and Technology of China

Ying-Ying Li (李英英)

yingyingli@ustc.edu.cn

Strong Force - QCD



Parton Shower and Hadronization: non-perturbative

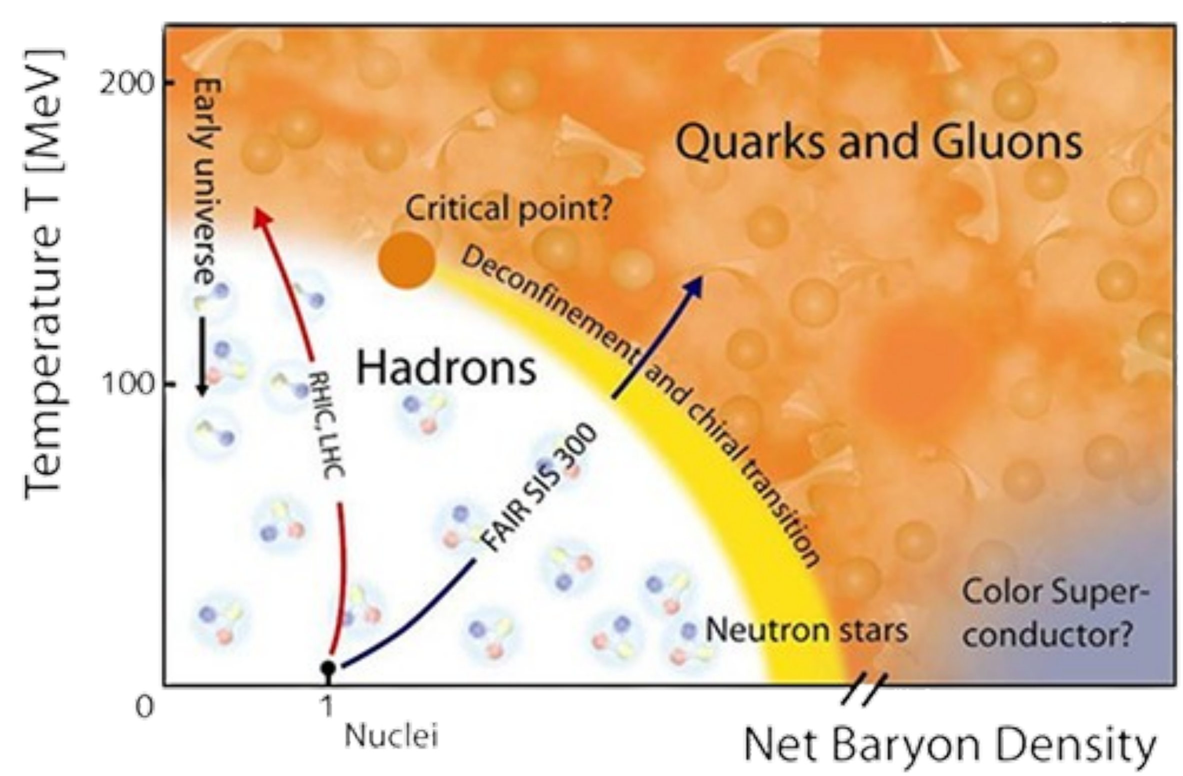
GeV

$n \sim 10^3$

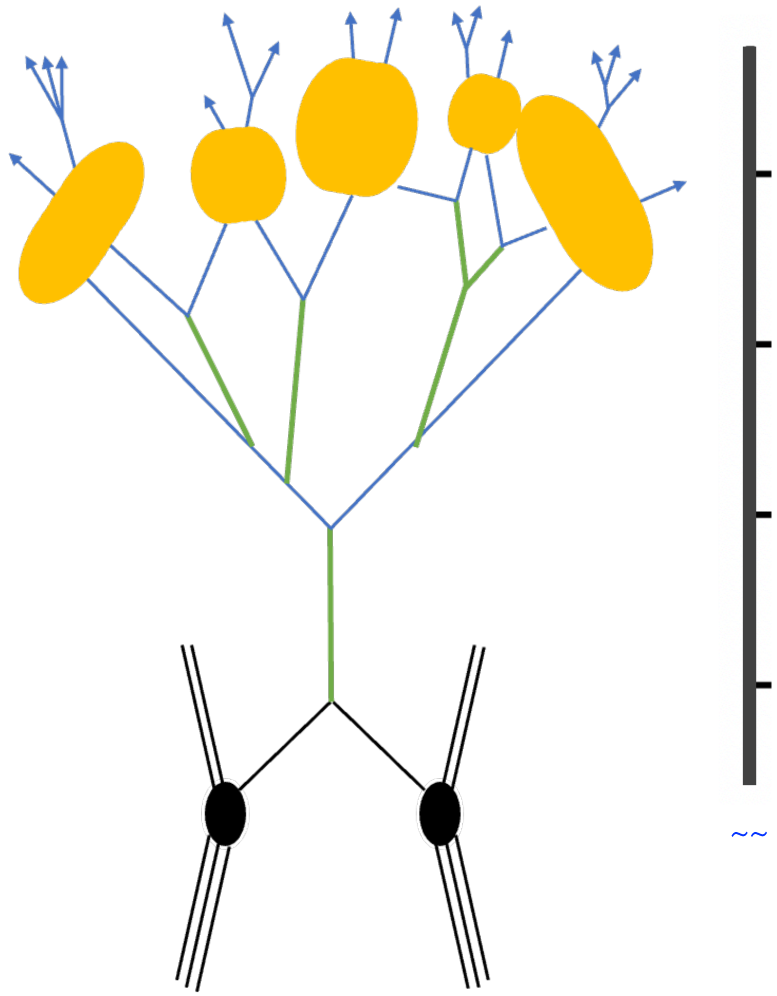
TeV

PDF: non-perturbative

Phases at finite temperature and finite density



Strong Force - QCD



Parton Shower and Hadronization:
non-perturbative

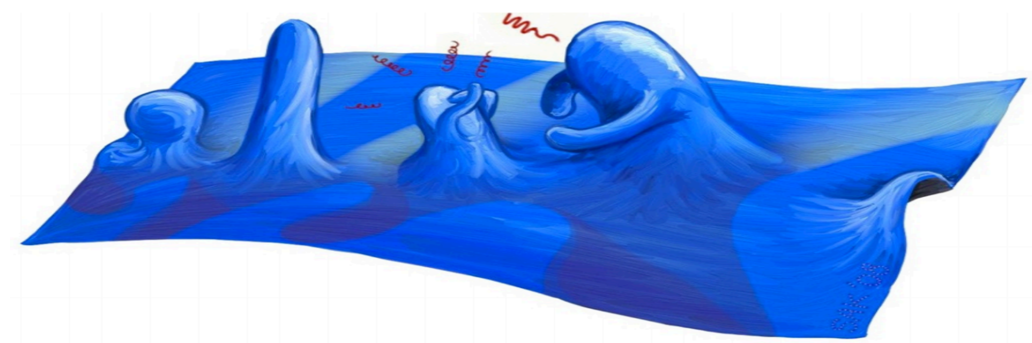
GeV

$n \sim 10^3$

TeV

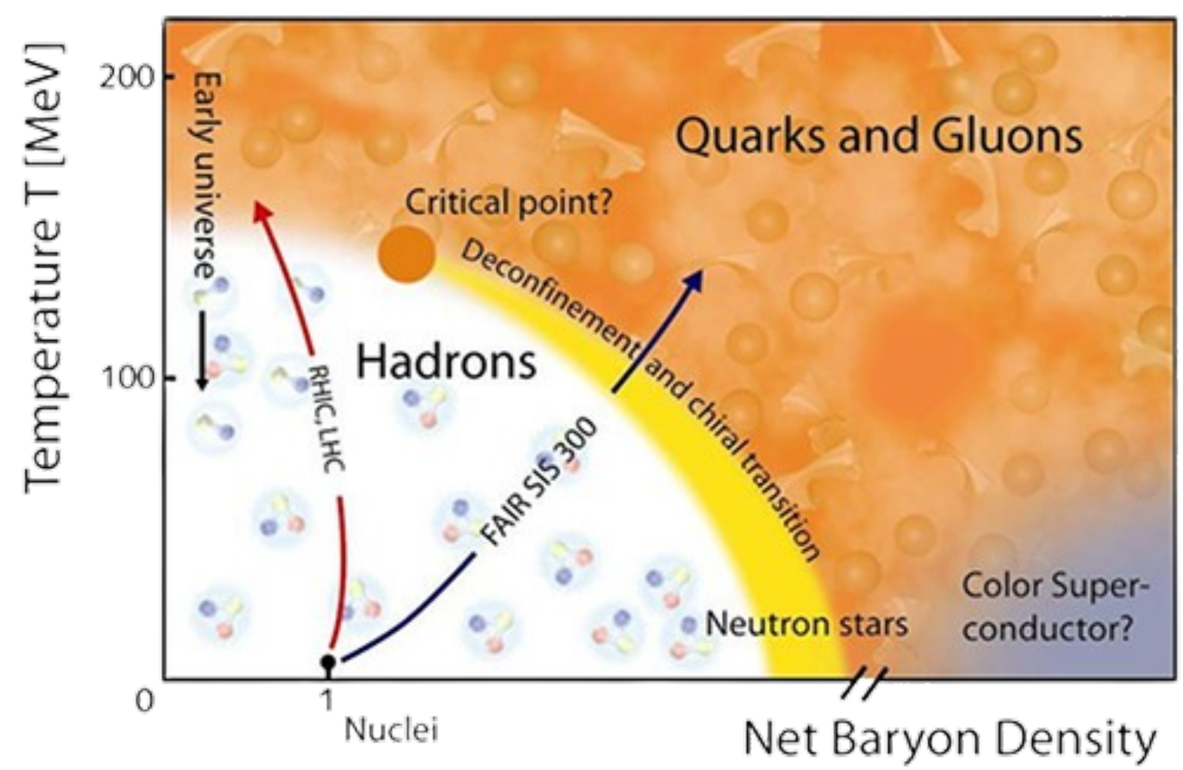
PDF: non-perturbative

第一性原理计算



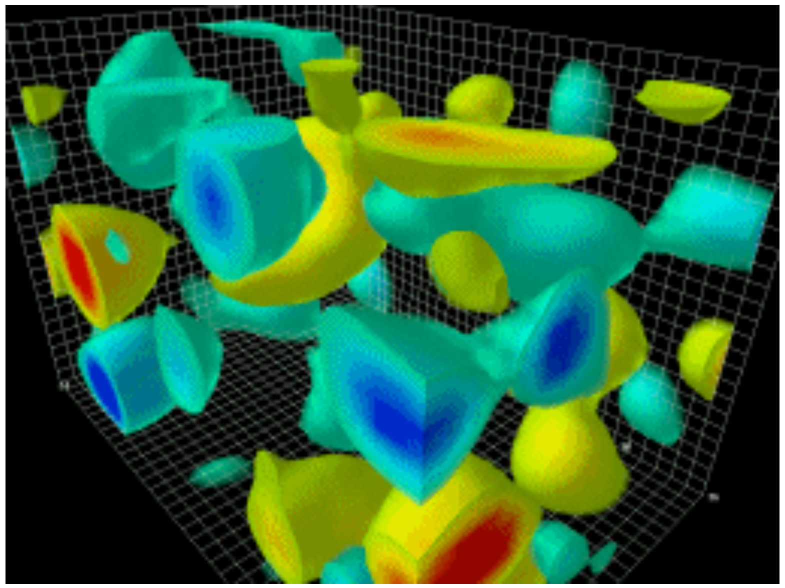
path integral on the background of field configurations

Phases at finite temperature and finite density



第一性原理计算 - Lattice QCD

Euclidean Spacetime



field configurations

$\mathcal{C}$ on lattice

Monte Carlo sampling of lattice field configurations

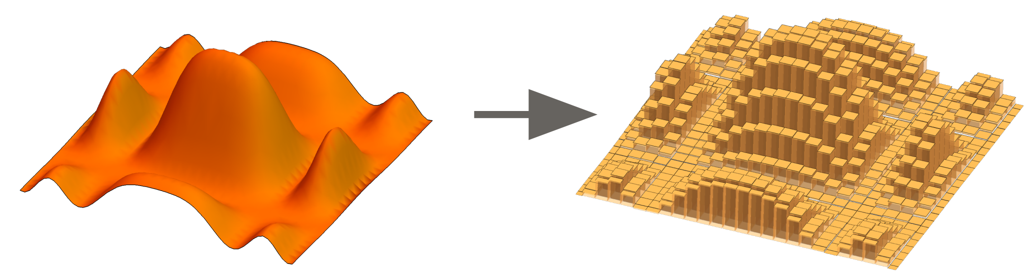
$W(\mathcal{C}) \sim \exp(-S(\mathcal{C}))$

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

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

第一性原理计算 —— Real Time

``a computing system with qubits”

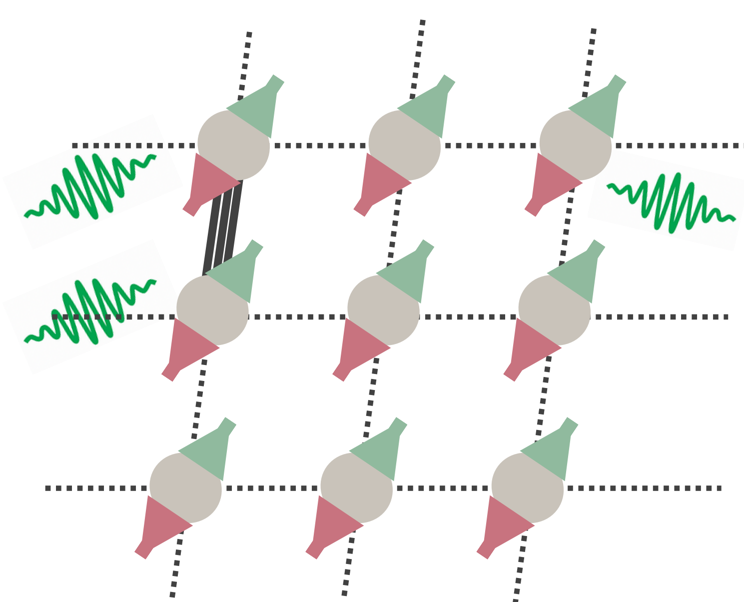
R. P. Feynman - 1982

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

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

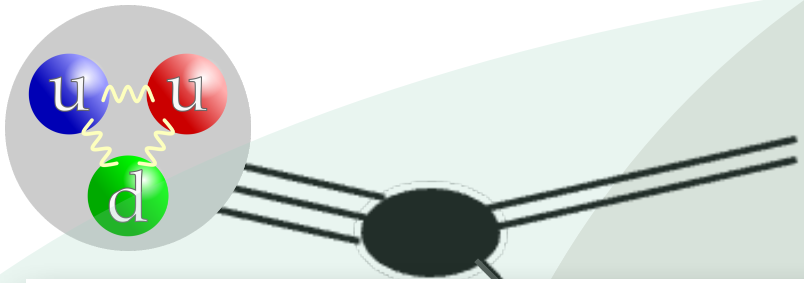
The number of qubits required is a polynomial function of the system size

1996 - Seth LIoyd: efficient simulation of LOCAL Hamiltonians



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

QUANTUM EASY



High Energy Physics

real-time dynamics
finite density

QUANTUM HARD

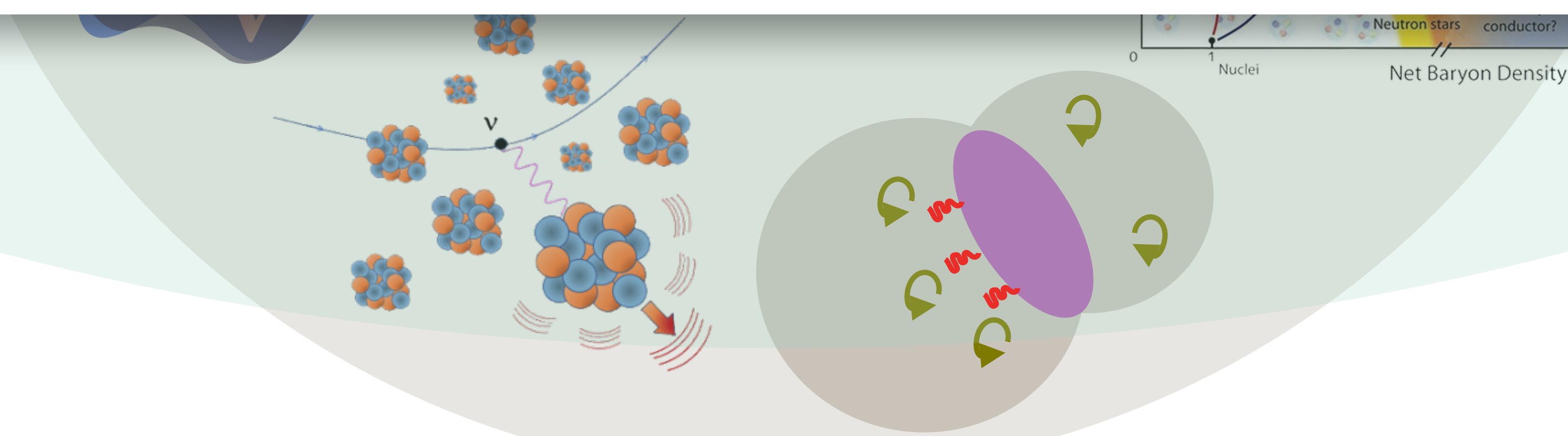
e.g. traveling salesmen problem

[*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 Zorzetti[5]

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



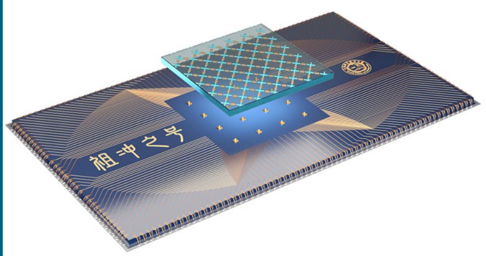
Problems in HEP that are beyond classical easy but are ``QUANTUM EASY”

Quantum Computing

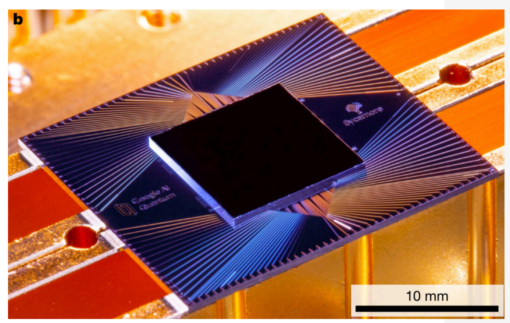
Now - Noisy Intermediate Scale Quantum (NISQ) era

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

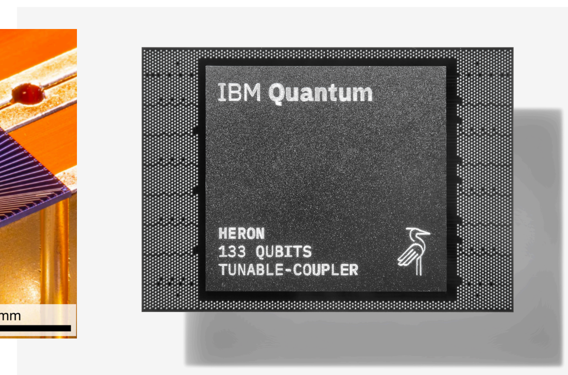
superconducting processor



176 qubits



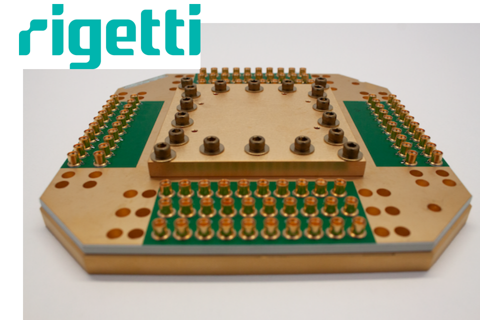
54 qubits



1121 qubits
access to 156 qubits

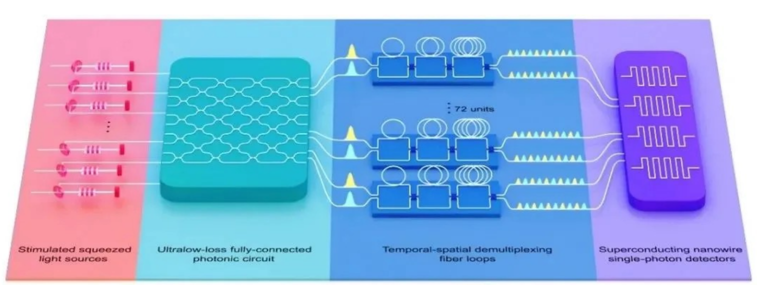
multi-chip quantum processor

rigetti



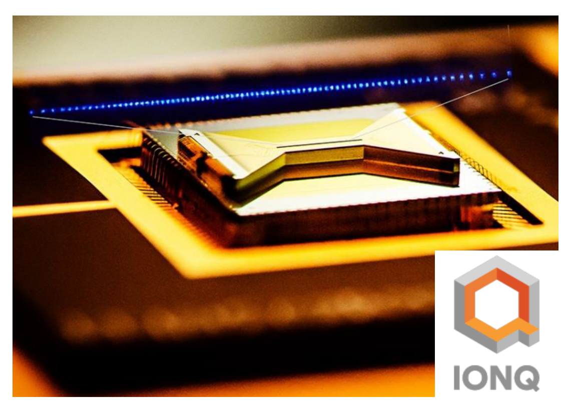
80 qubits

photon qubits



Jiuzhang - 255 qubits

trapped ion qubits

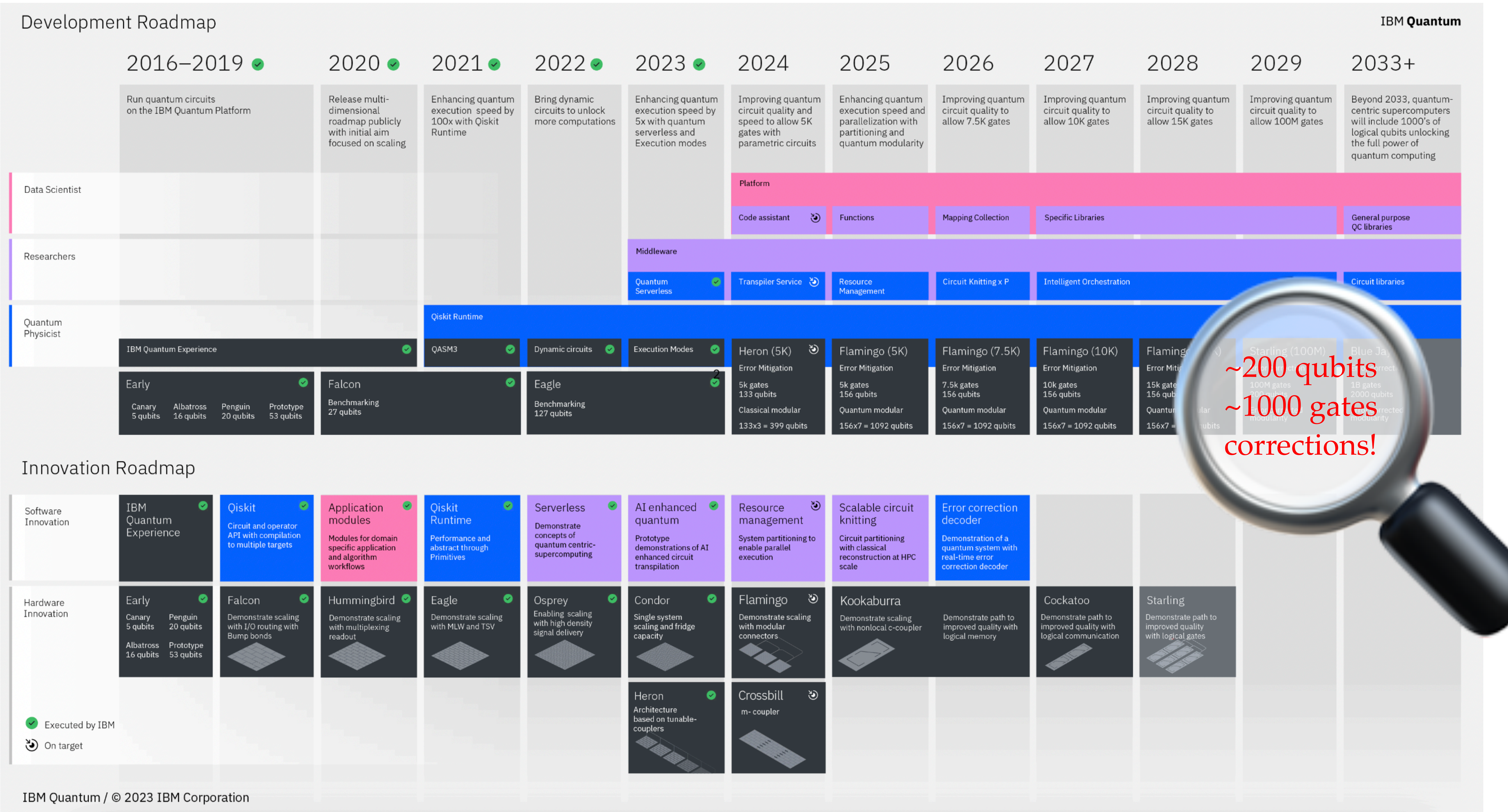


22 qubits

48 logical qubits

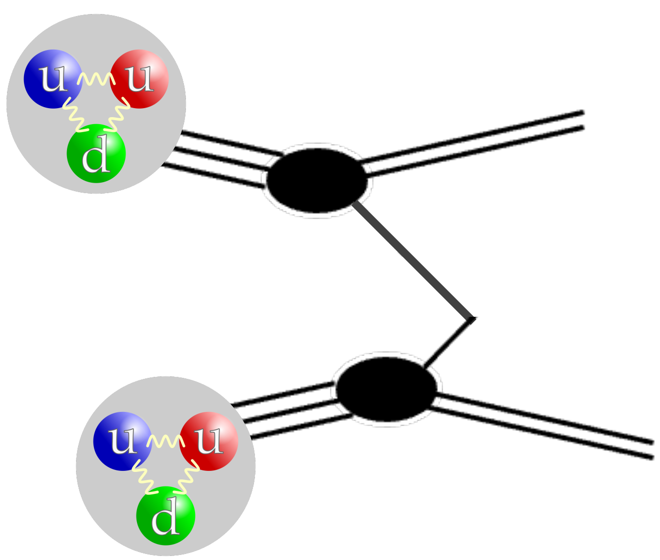
Quantum Computing

Next decades



Quantum Computing for HEP

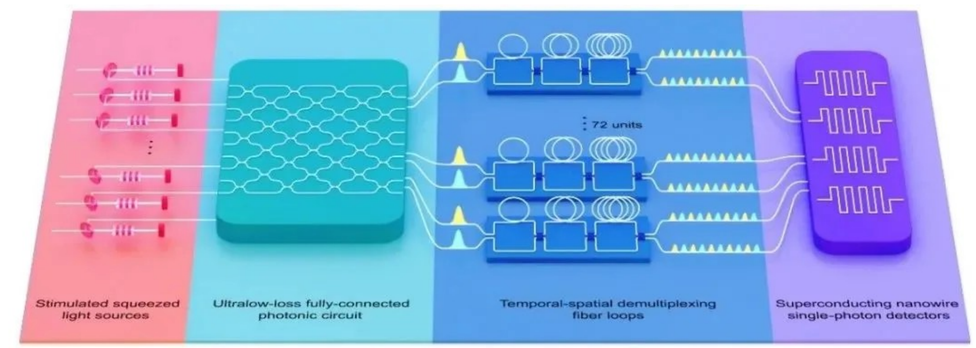
$$\int \mathcal{D}\phi e^{iS} = \langle x| \, e^{-iHt} \, |y\rangle$$

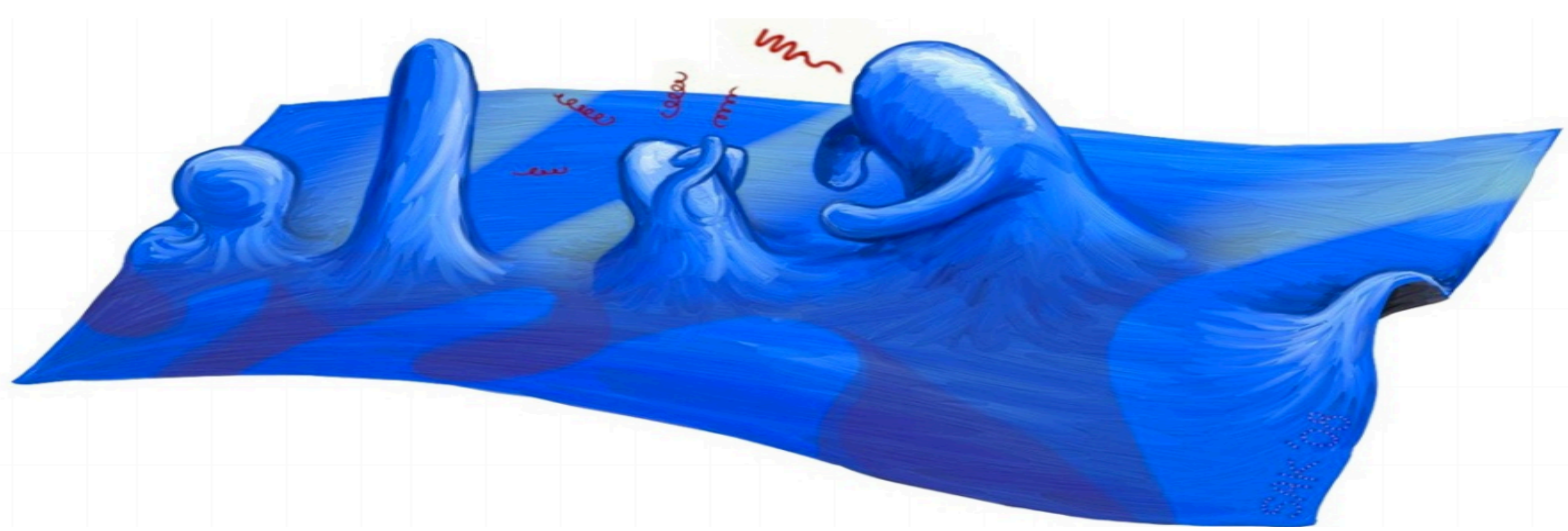


mapping

DOF to qubits

time evolution
to quantum gates





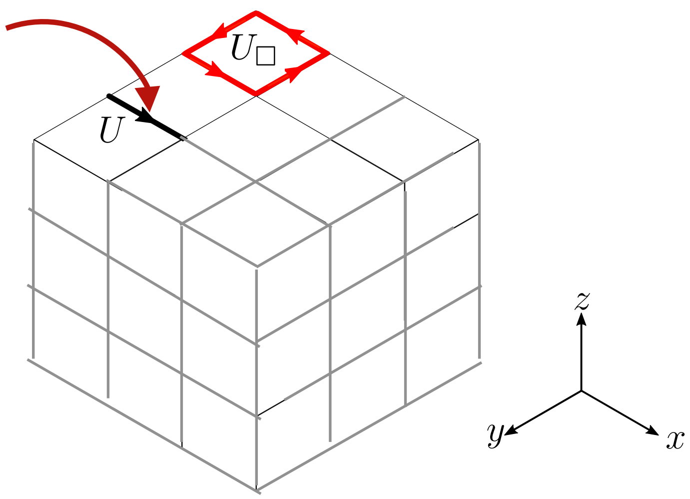
non-trivial vacuum,
composite initial state,
bosonic and fermionic DOF,
symmetries, …

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

infinities in QFT

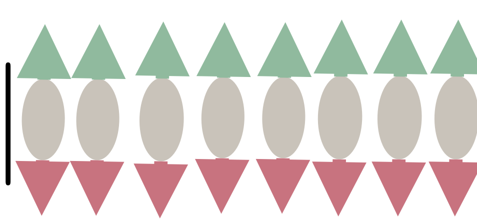
gluon

group element basis $|U\rangle$



block product encoding: BT, BI

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

$|U\rangle = |$  $\rangle$

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

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

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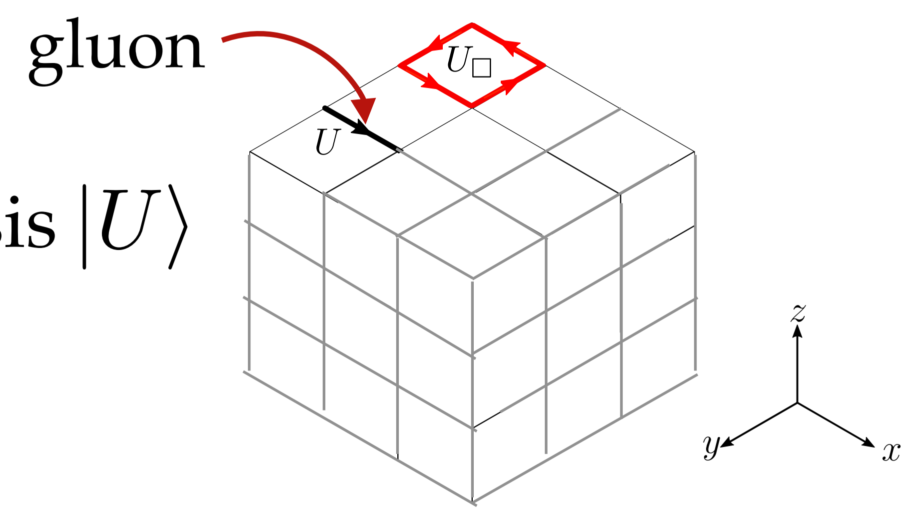

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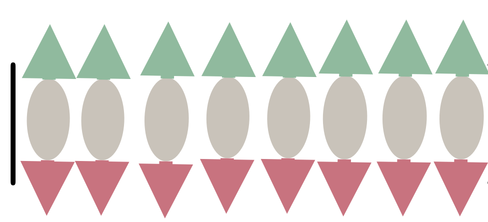
$|U\rangle = |$  $\rangle$

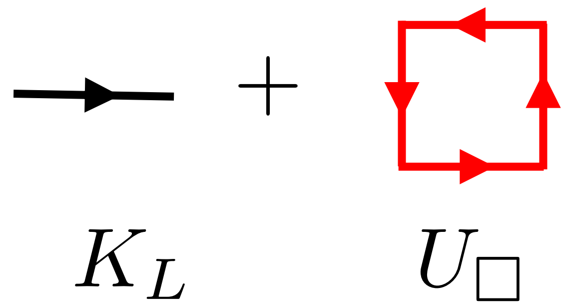
[Lamm, **YYL**, Shu, Wang, Bin, arXiv:2405.12890]

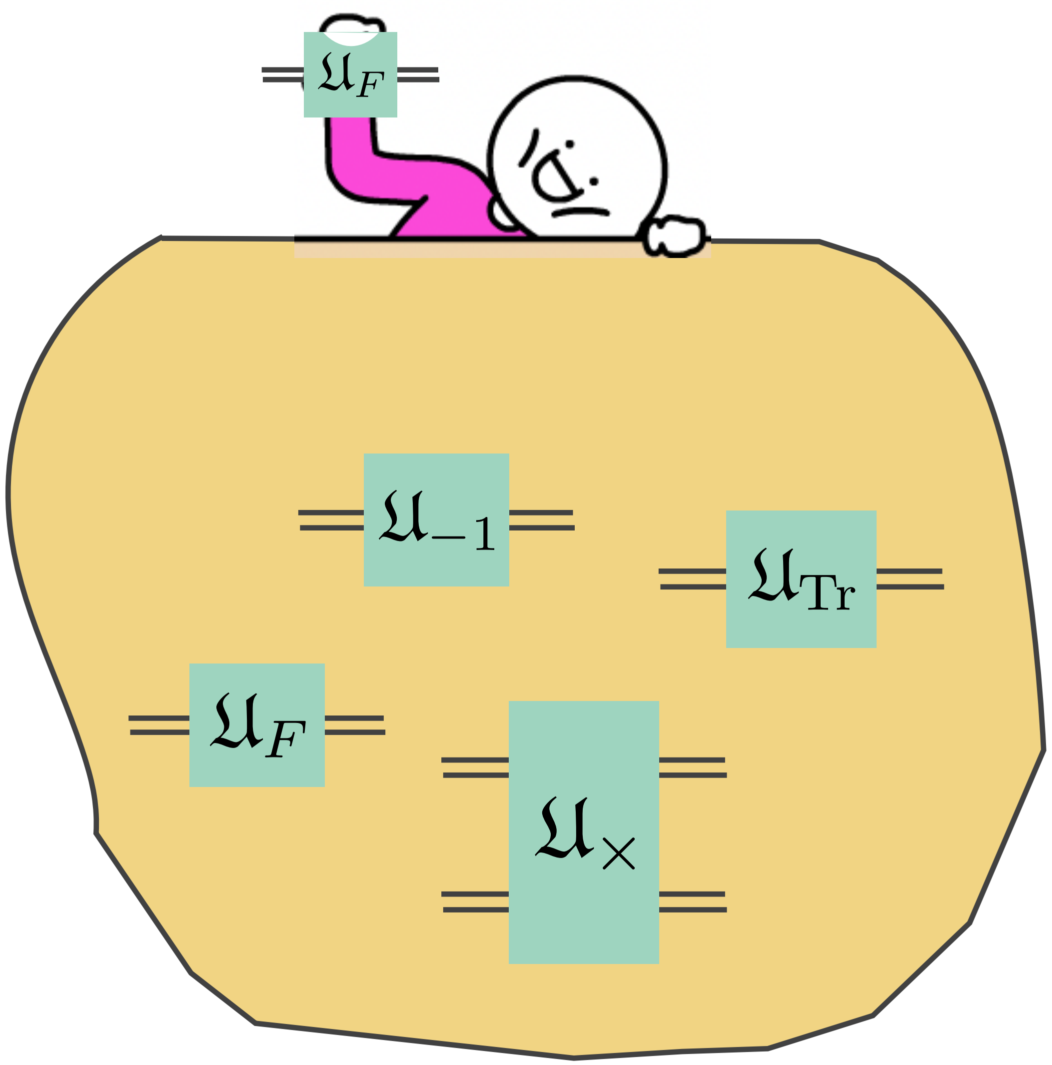
qudit system?

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

$G-$register : $|U\rangle$ ══

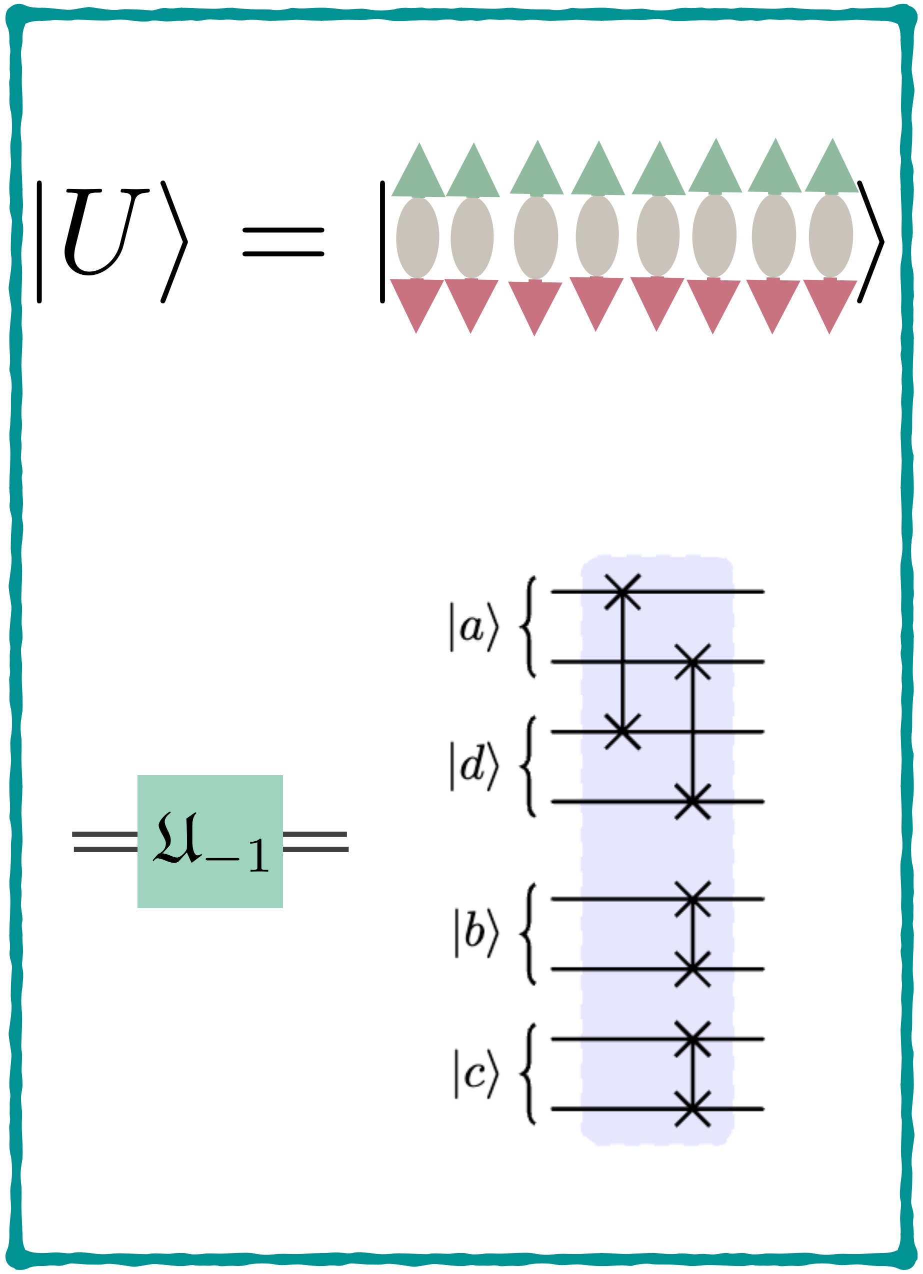
$$H_{KS} = \sum \left(\quad + \quad \right)$$



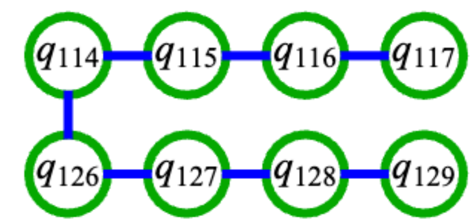


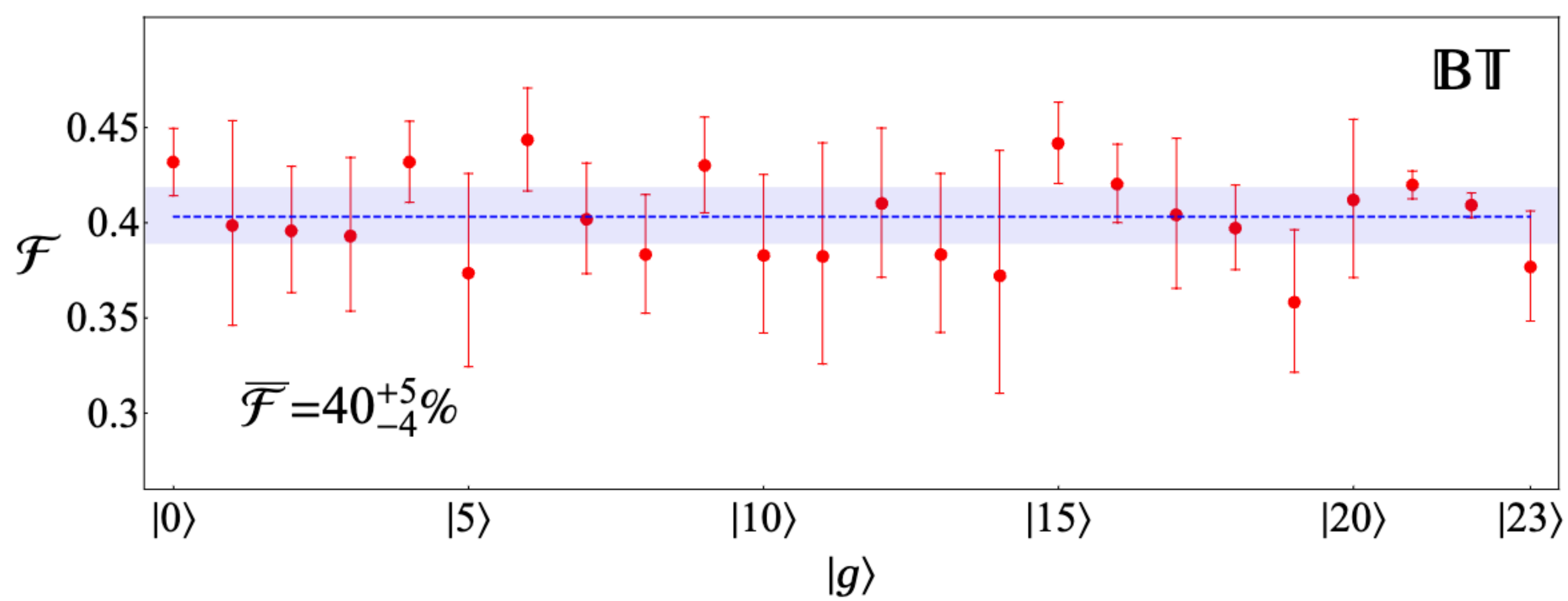
$$\mathcal{U}(t) = e^{-iH_{KS}t}$$
$$\approx \left[e^{-i\delta t K_L} e^{-i\delta t U_\square}\right]^{t/\delta t}$$

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



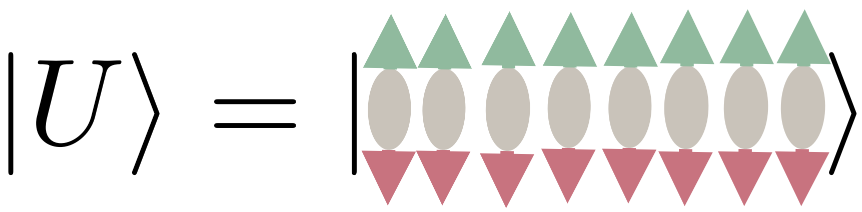
Quafu quantum cloud computing cluster

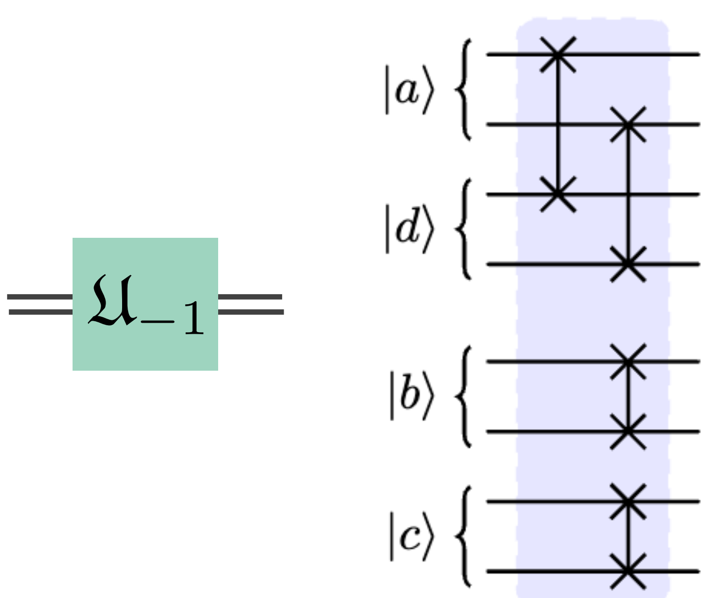




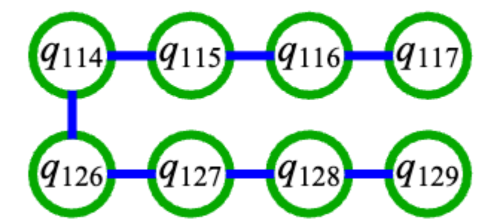
[Lamm, **YYL**, Shu, Wang, Bin, arXiv:2405.12890]

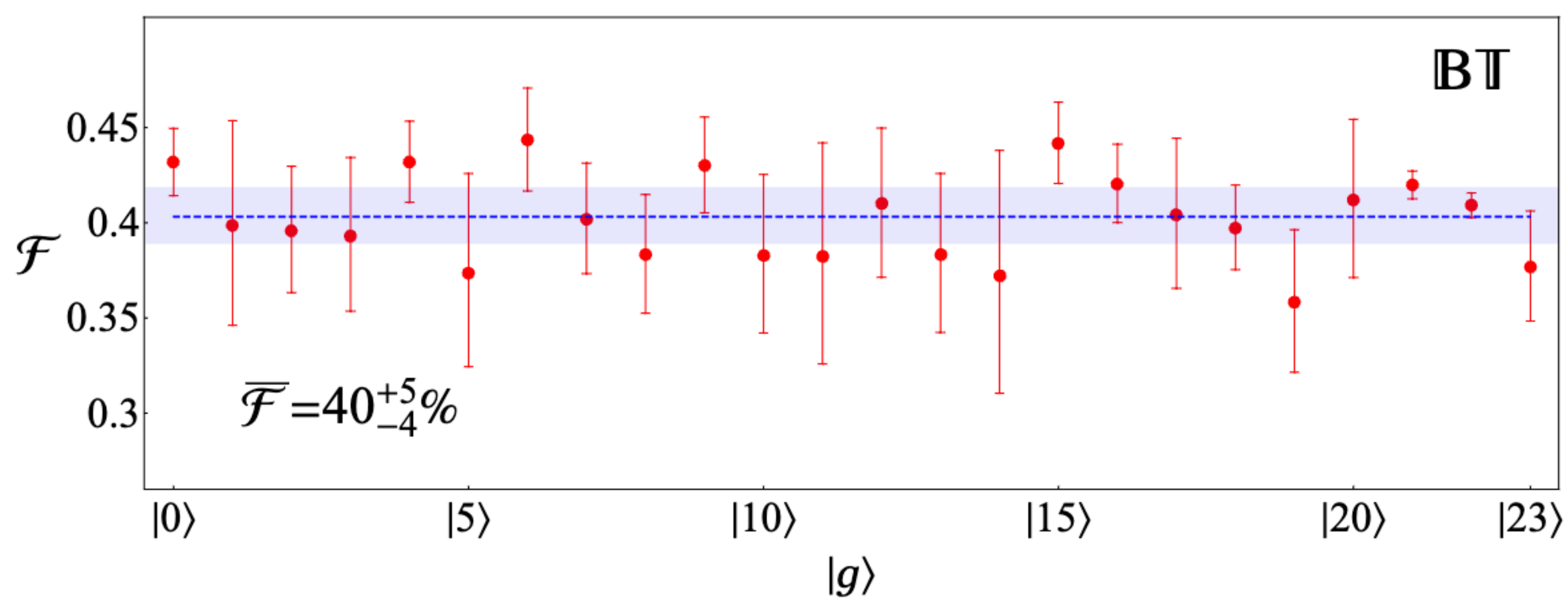
Propagation $\mathcal{U}\,|\psi_0\rangle \rightarrow |\psi(t)\rangle$





optimization?





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

Now - Noisy Intermediate Scale Quantum (NISQ) era

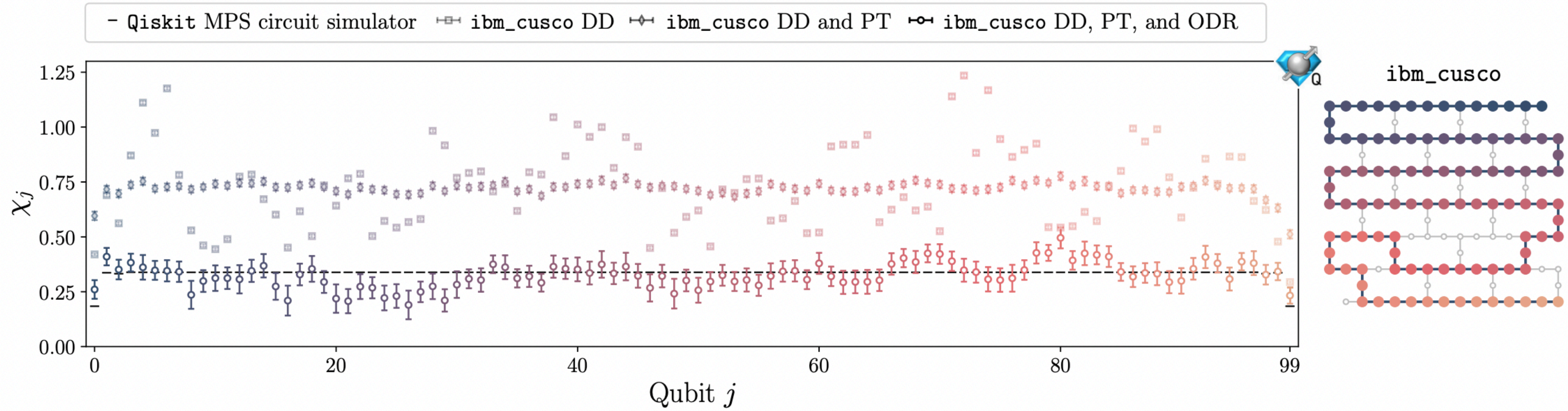
more than 50 well controlled qubits, not error-corrected yet

Physics Benchmarks

Physics Benchmarks for Quantum Computing

$1+1d$ Schwinger Model — Chiral condensate

$$\mathcal{L} = \overline{\psi}\left(i\not{D} - m_{\psi}\right)\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$



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

"Quantum potential for first-principle calculations!"

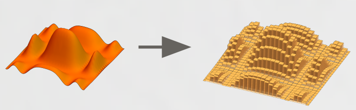
(2030s) narrow down the framework with

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

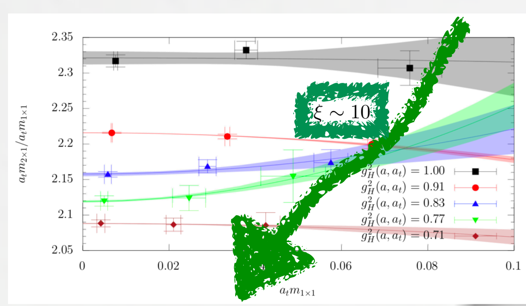
HEP case calculations for experiments

various methods

2030s -



$$|q\rangle^N \to |G\rangle$$
$$\downarrow$$
$$\mathcal{U}\,|G\rangle^L \to |\psi_0\rangle$$
$$\downarrow$$
$$\mathcal{U}\,|\psi_0\rangle \to |\psi(t)\rangle$$
$$\downarrow$$
$$\langle \mathcal{O} \rangle$$



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

2020 -

2011-

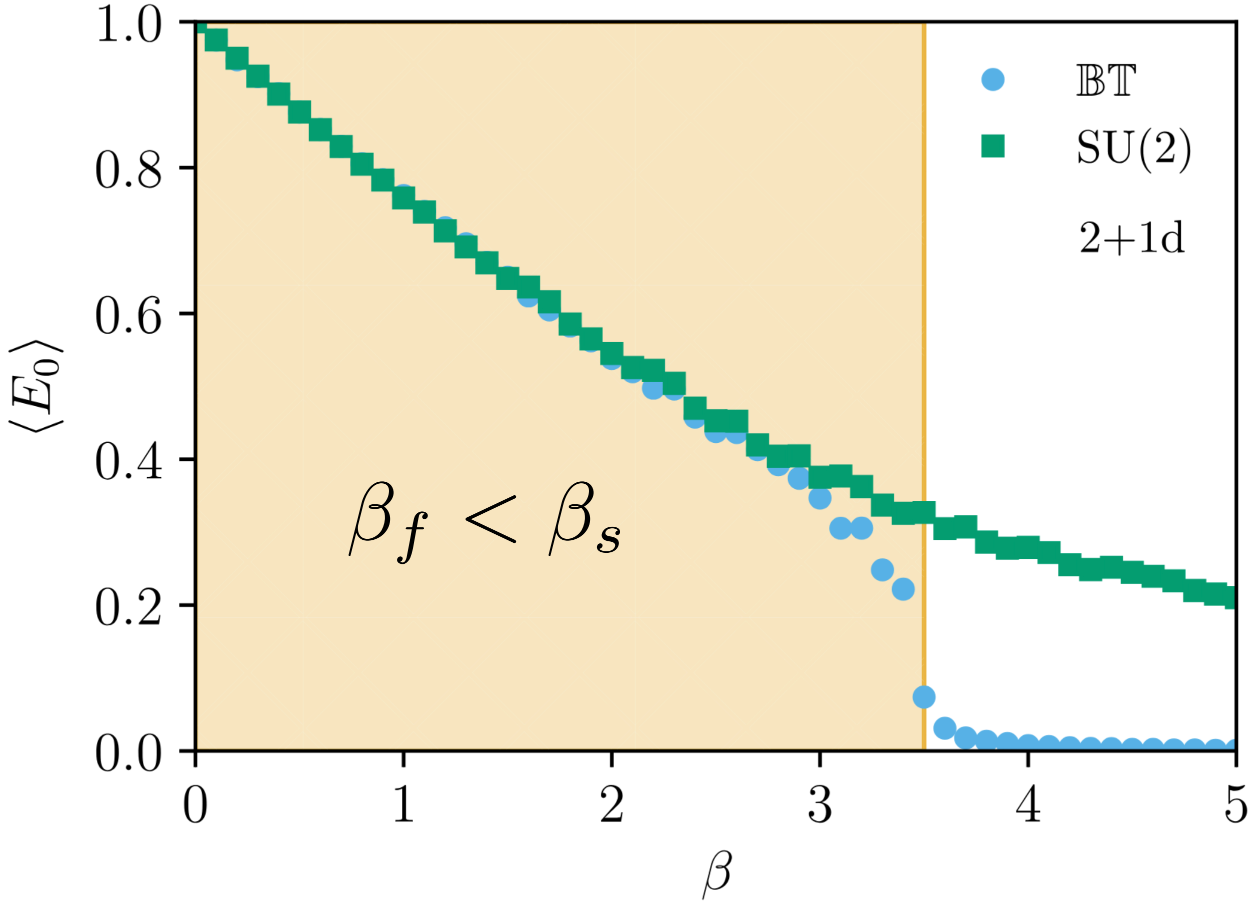
Thank you

BACK UP

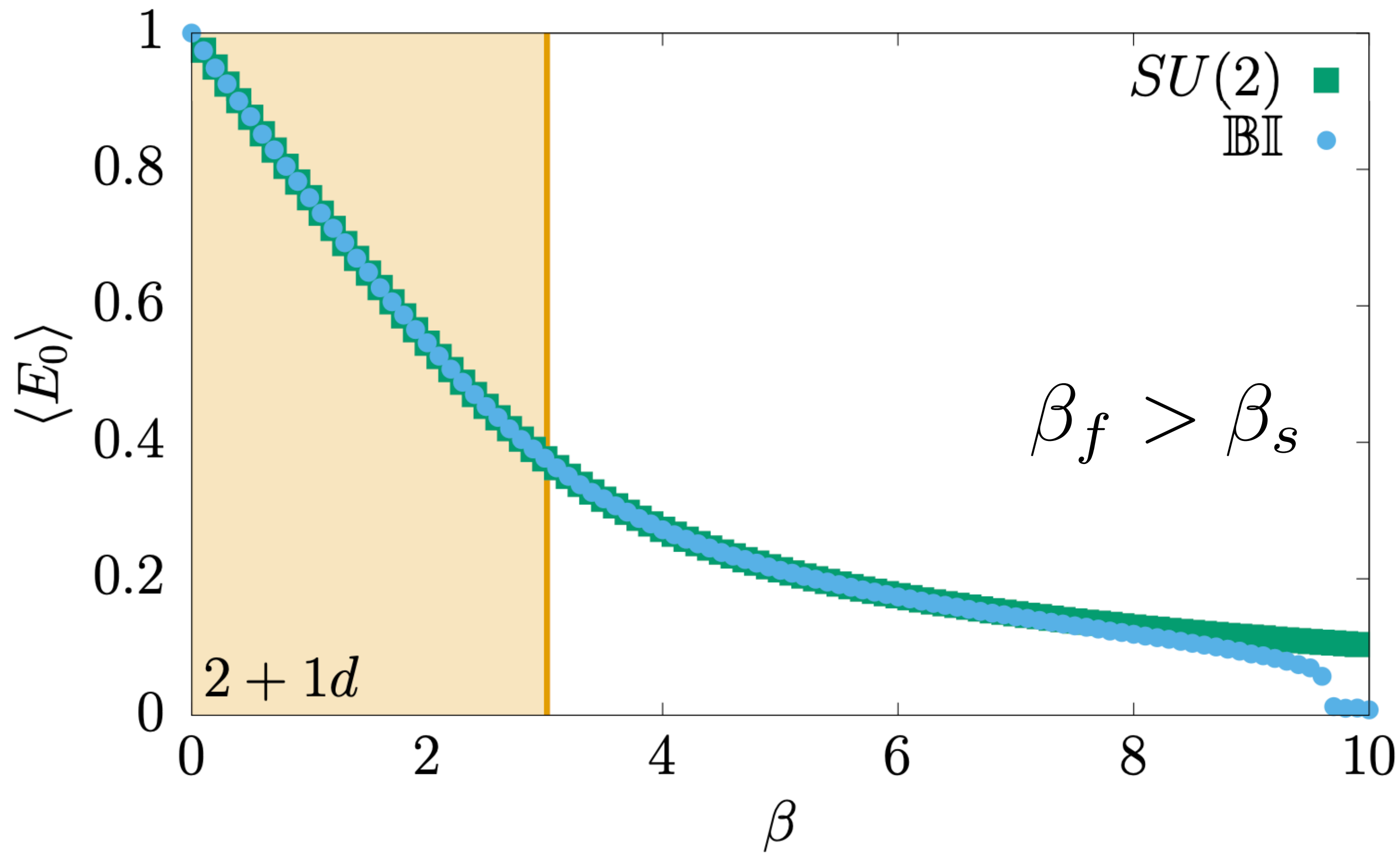
Digitization $|q\rangle^N \to |G\rangle$

infinities in QFT

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



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

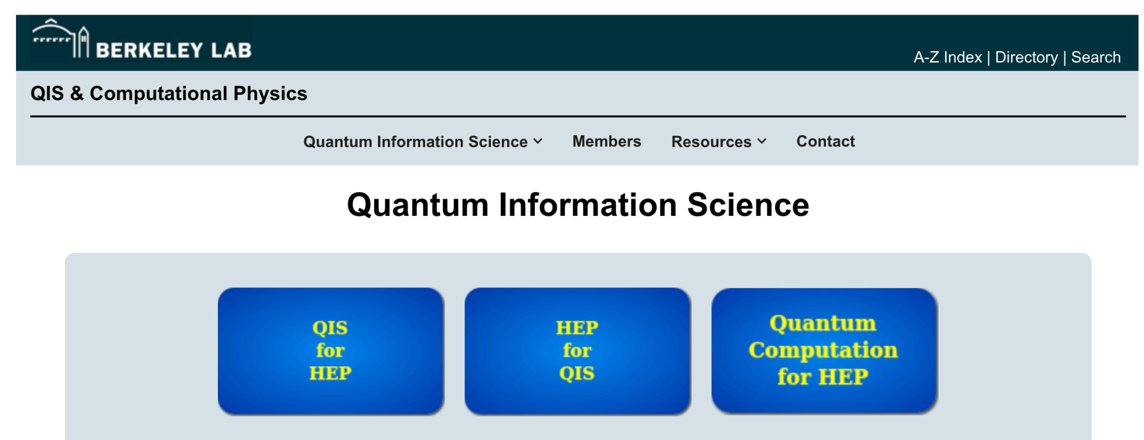


In the Scaling Regime: significantly reduces the errors in simulating SU(2) physics

Quantum Computing for HEP

Brookhaven
Argonne
Oak Ridge
LBNL
Fermilab

1 **(h) Quantum Information Science for High Energy Physics Research**



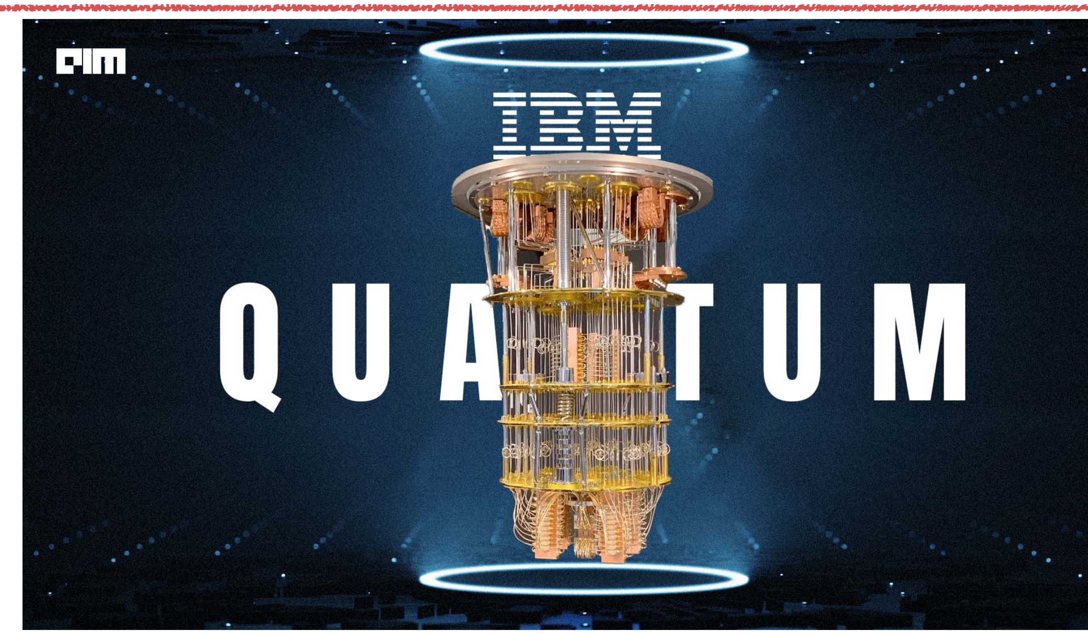
HEP-QIS QuantISED program is aligned with the ``Science First'' driver for the national QIS program

Quantum Computing for HEP

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.

DESY. QUANTUM | Center for Quantum Technology and Applications

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

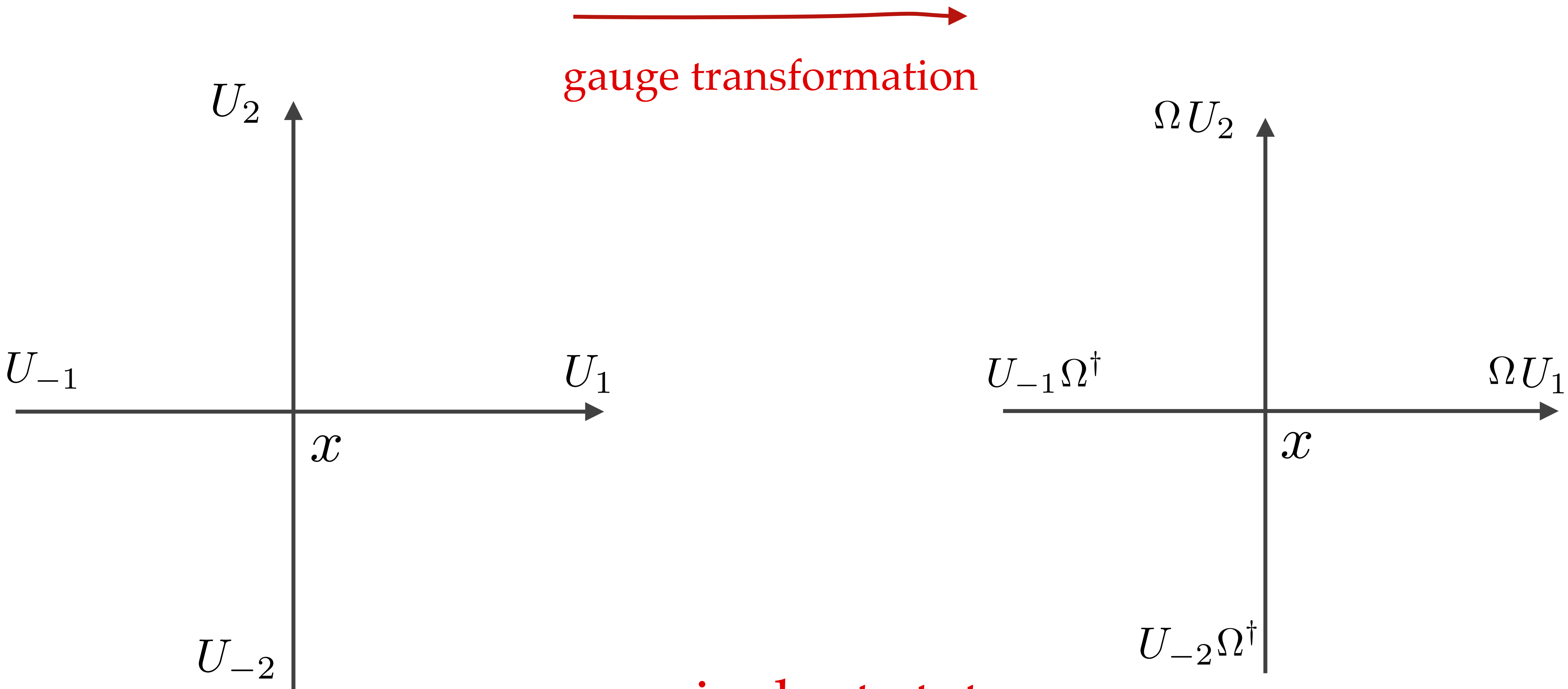


… chart future for use of quantum computing in particle physics

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

infinities in QFT

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



gauge equivalent states

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

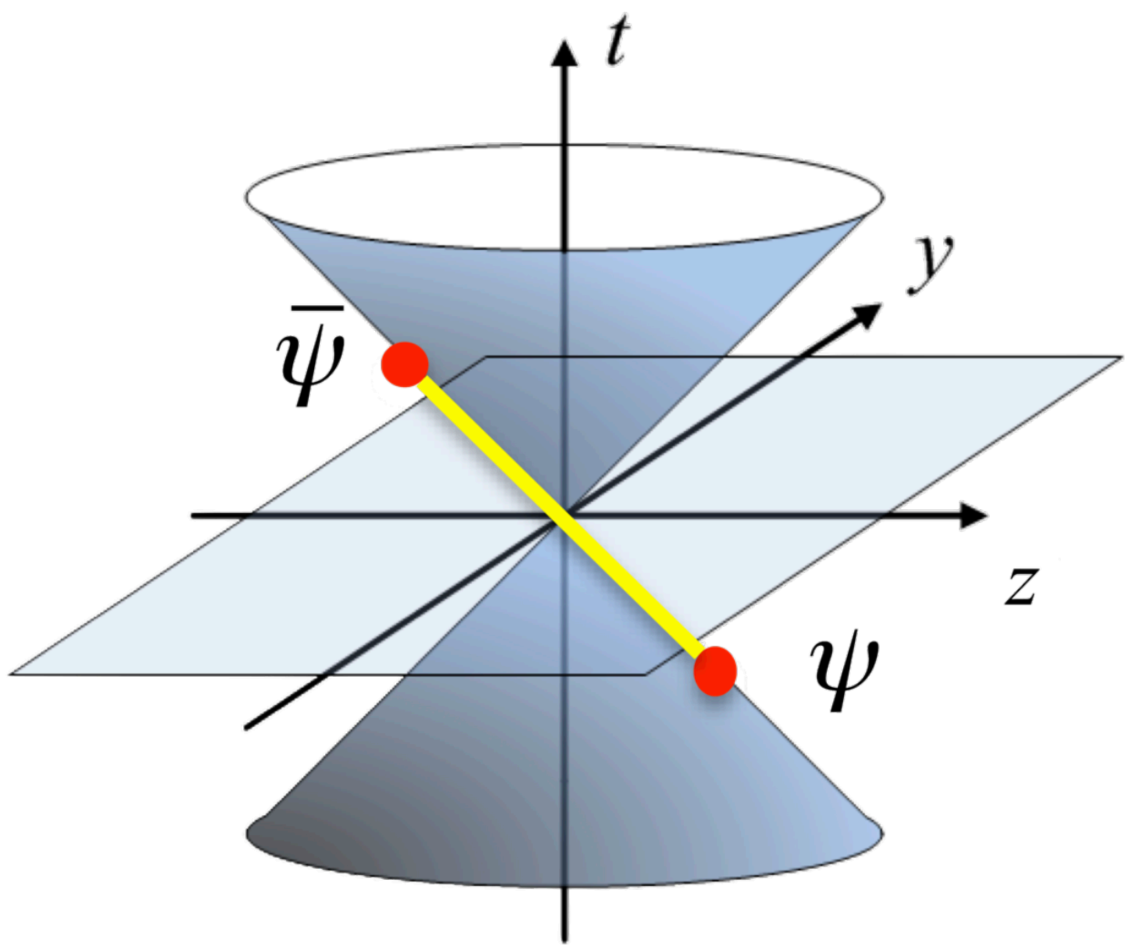
error corrections:

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

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

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