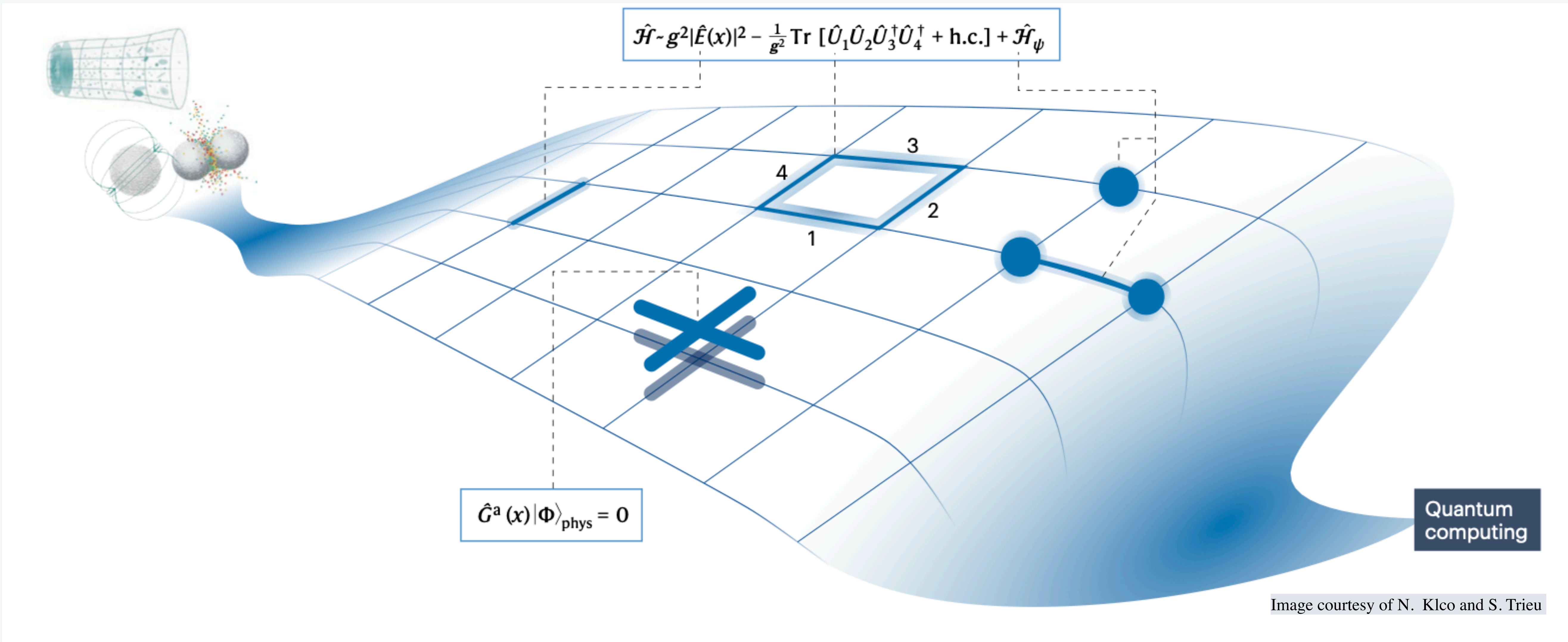


HEP Opportunities in the Quantum Computing Era

第28届LHC Mini-Workshop

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

PDF uncertainty becomes a bottleneck for hadron colliders

non-perturbative physics

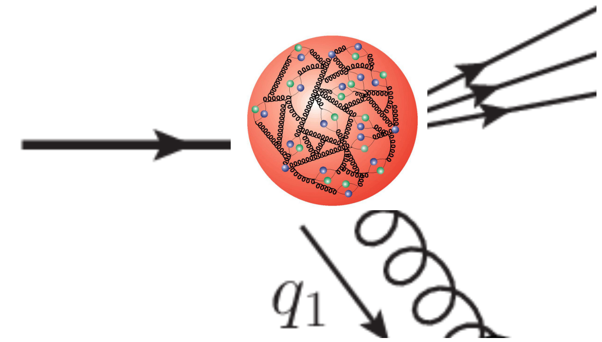
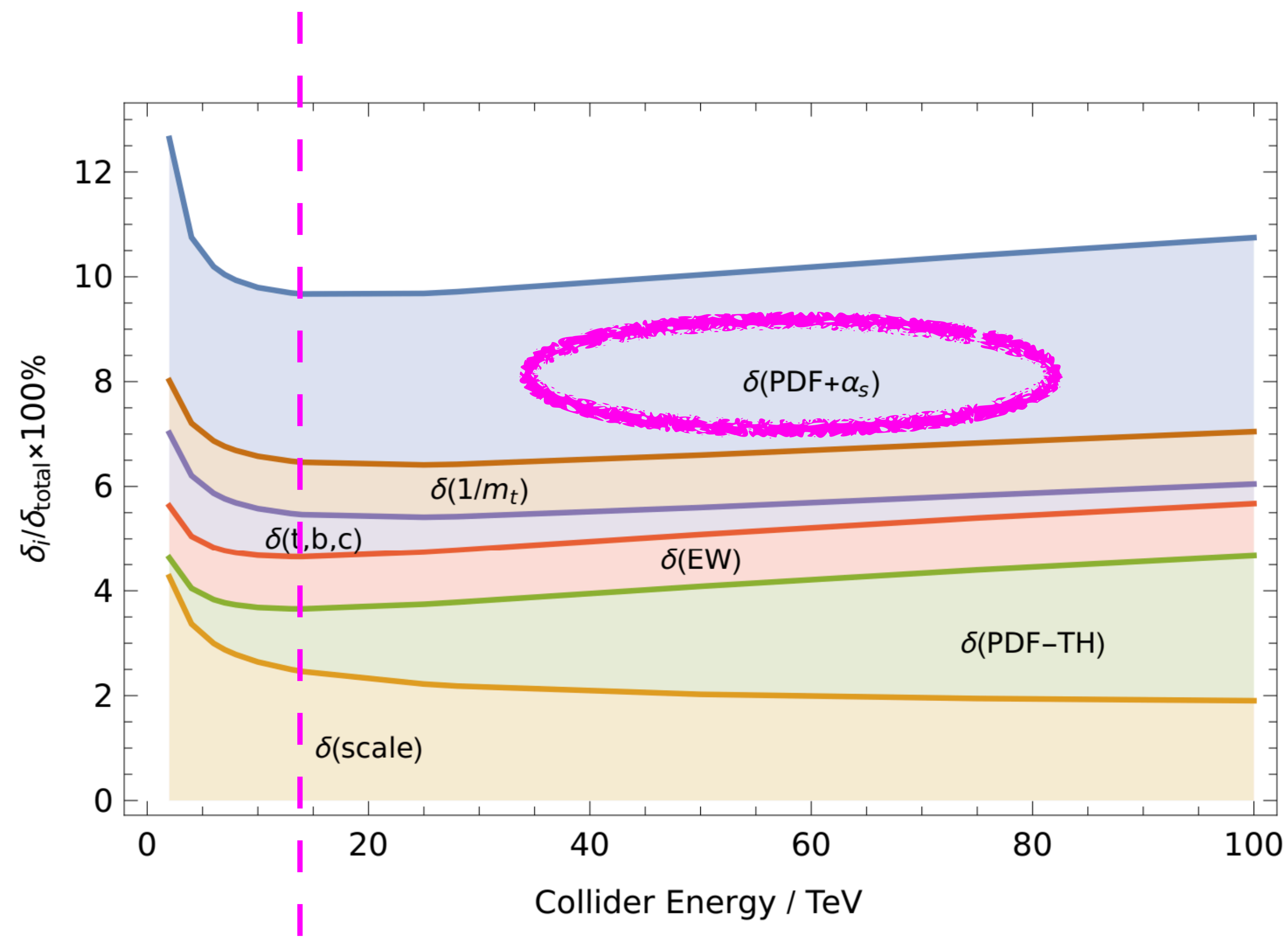


Table 2. Uncertainties on the combined M_W result.

Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4

[CDF Collaboration et al., Science 376, 170–176 (2022)]

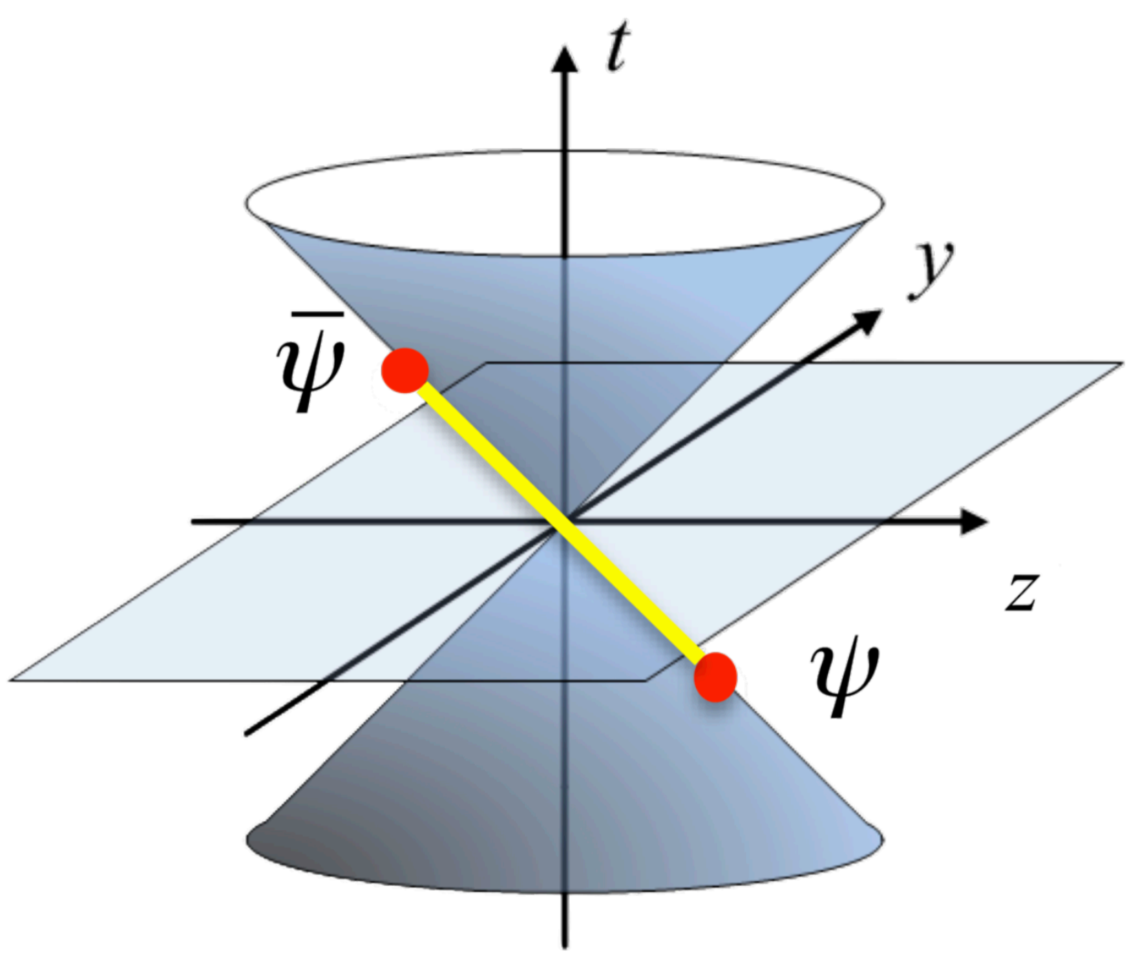


F. Dulat, et al, arXiv:1802.00827
M. Cepeda, et al, arXiv:1902.00134

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"

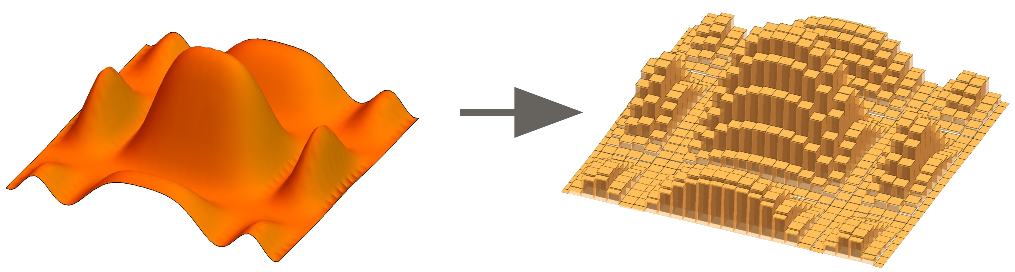
configuration space $\mathcal{C}$ is exponentially large in system size

system size N_V : number of lattice sites

第一性原理计算

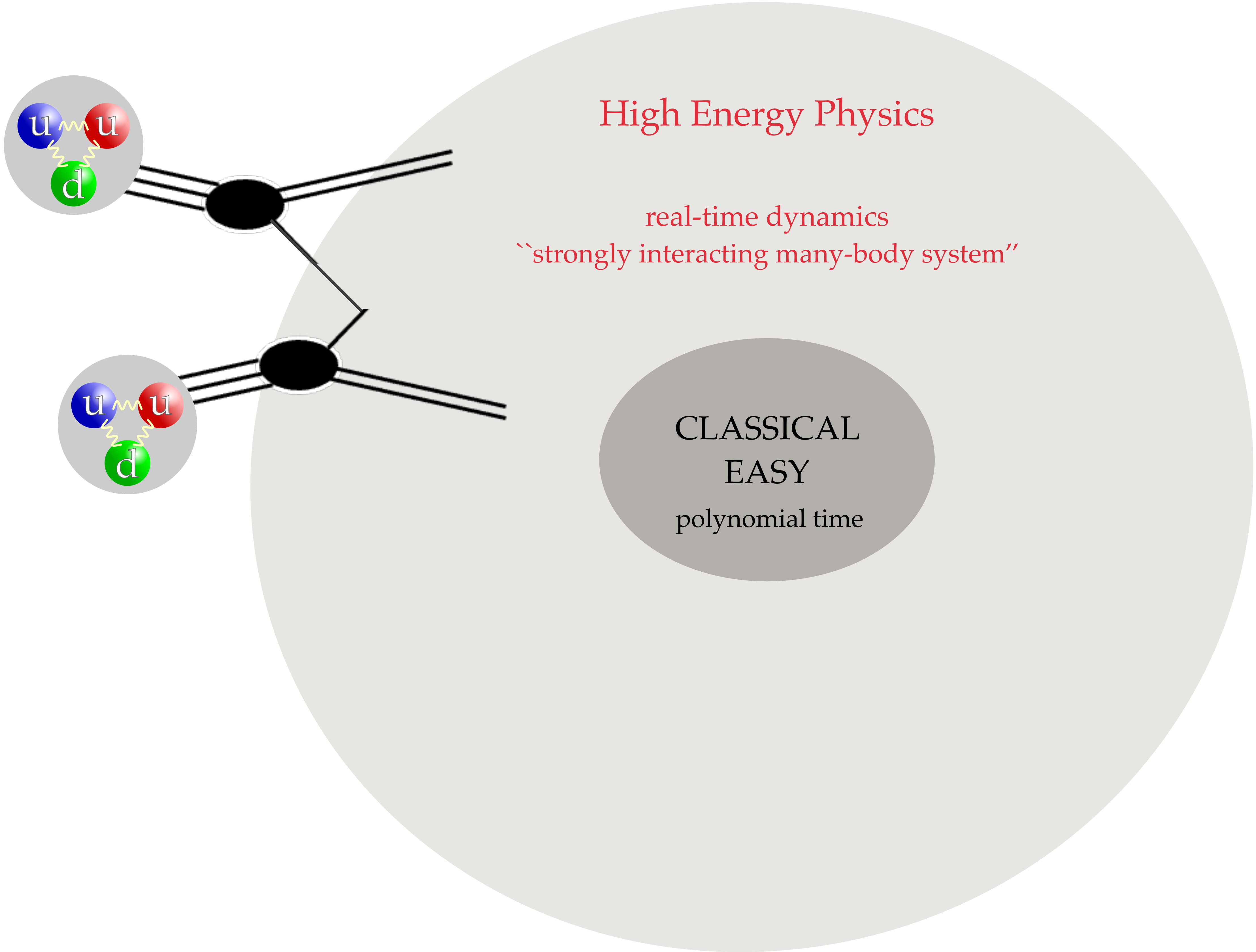
Lattice QCD - Real Time

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



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

exponentially large number
of classical bits in system size



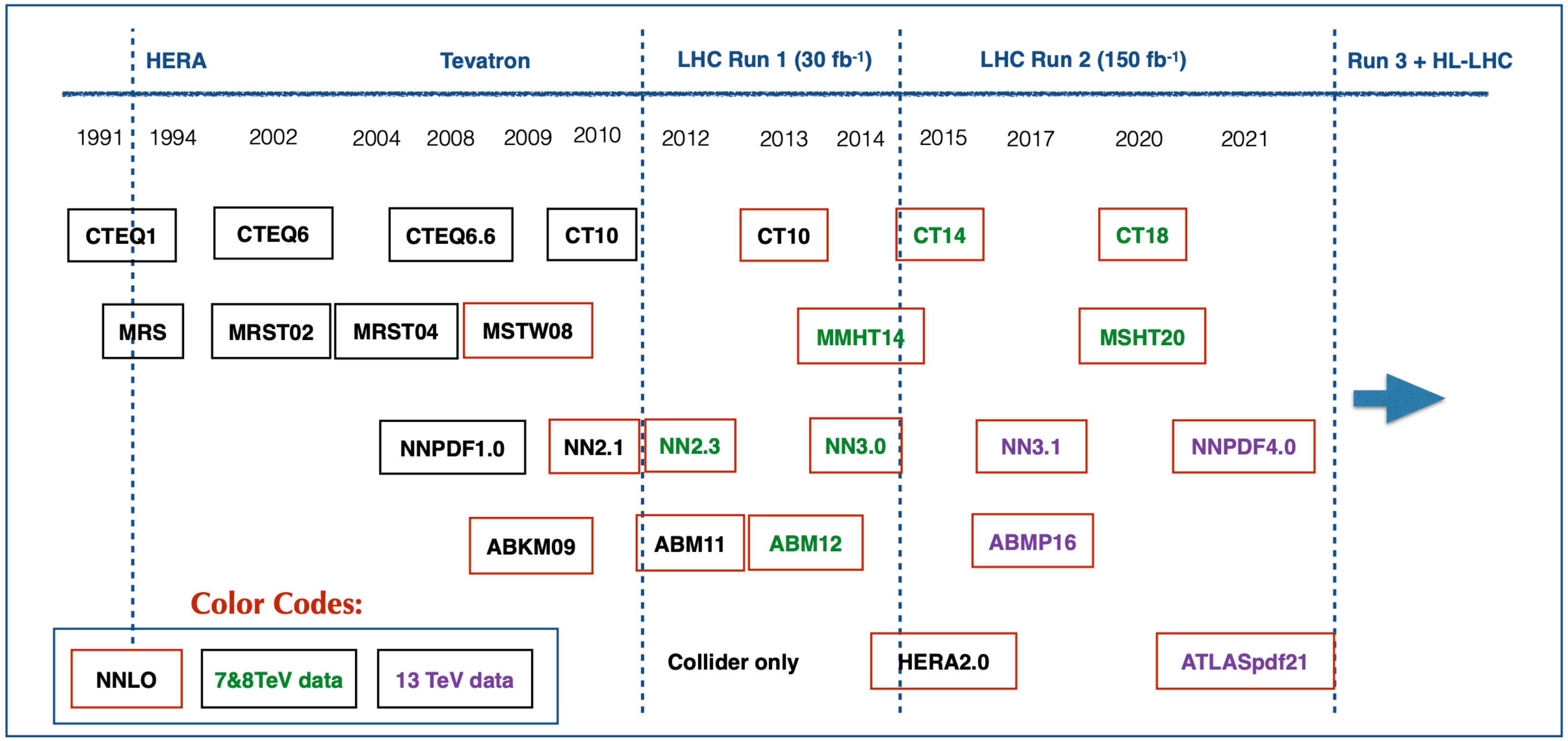
PDF cannot be solved with classical resources in polynomial time,
beyond ``classical easy''

How to determine PDF?

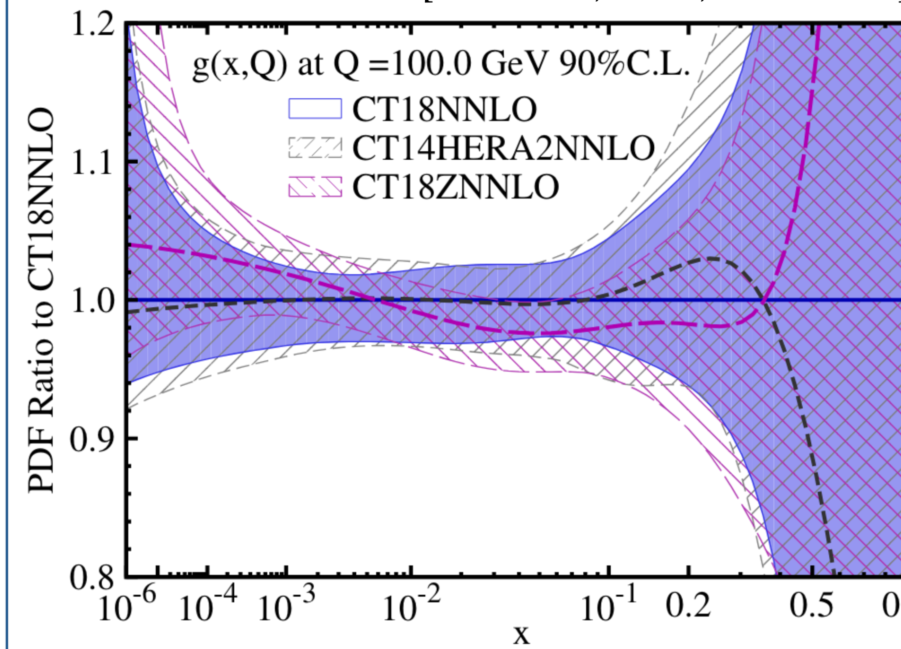
- Fitting to data

large uncertainties

[J. Gao, DIS2022]



[Hou et al., CT18, 1912.10053]



- Lattice QCD: Quasi-PDF from LaMET [X. Ji, PRL. 110, (2013), 262002] hard for p > 3GeV

$$\mathcal{O}\left(\frac{\Lambda^2_{QCD}}{x^2p^2}, \frac{\Lambda^2_{QCD}}{(1-x)^2p^2}, \frac{m_N^2}{p^2}\right)$$

- Quantum Computing

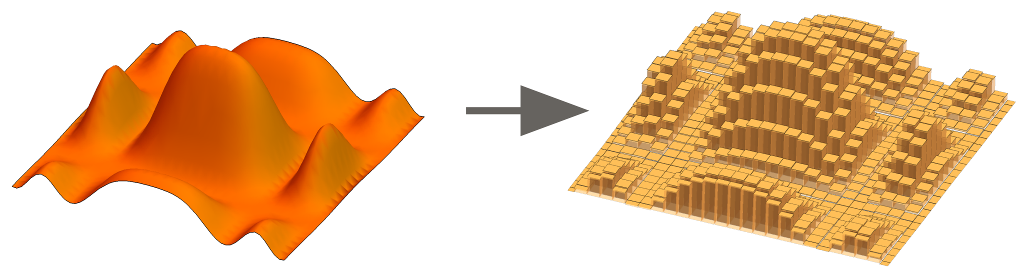
``a computing system with qubits" R. P. Feynman - 1982

第一性原理计算

"a computing system with qubits"

R. P. Feynman - 1982

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



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

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

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

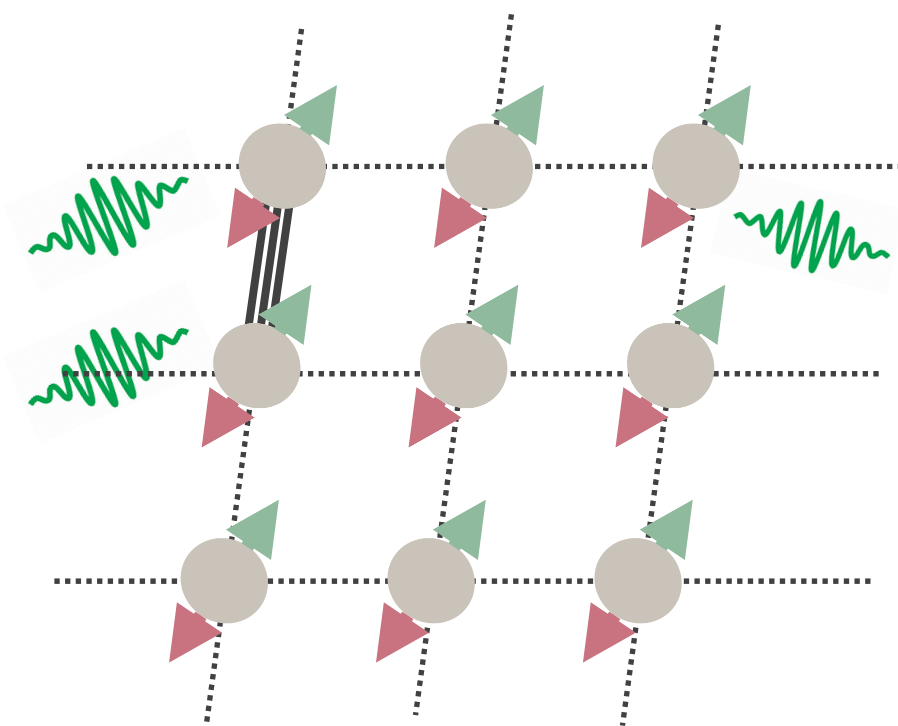
Quantum Computing

1996 - Seth LIoyd: efficient simulation of LOCAL Hamiltonians

Universal Quantum Simulators

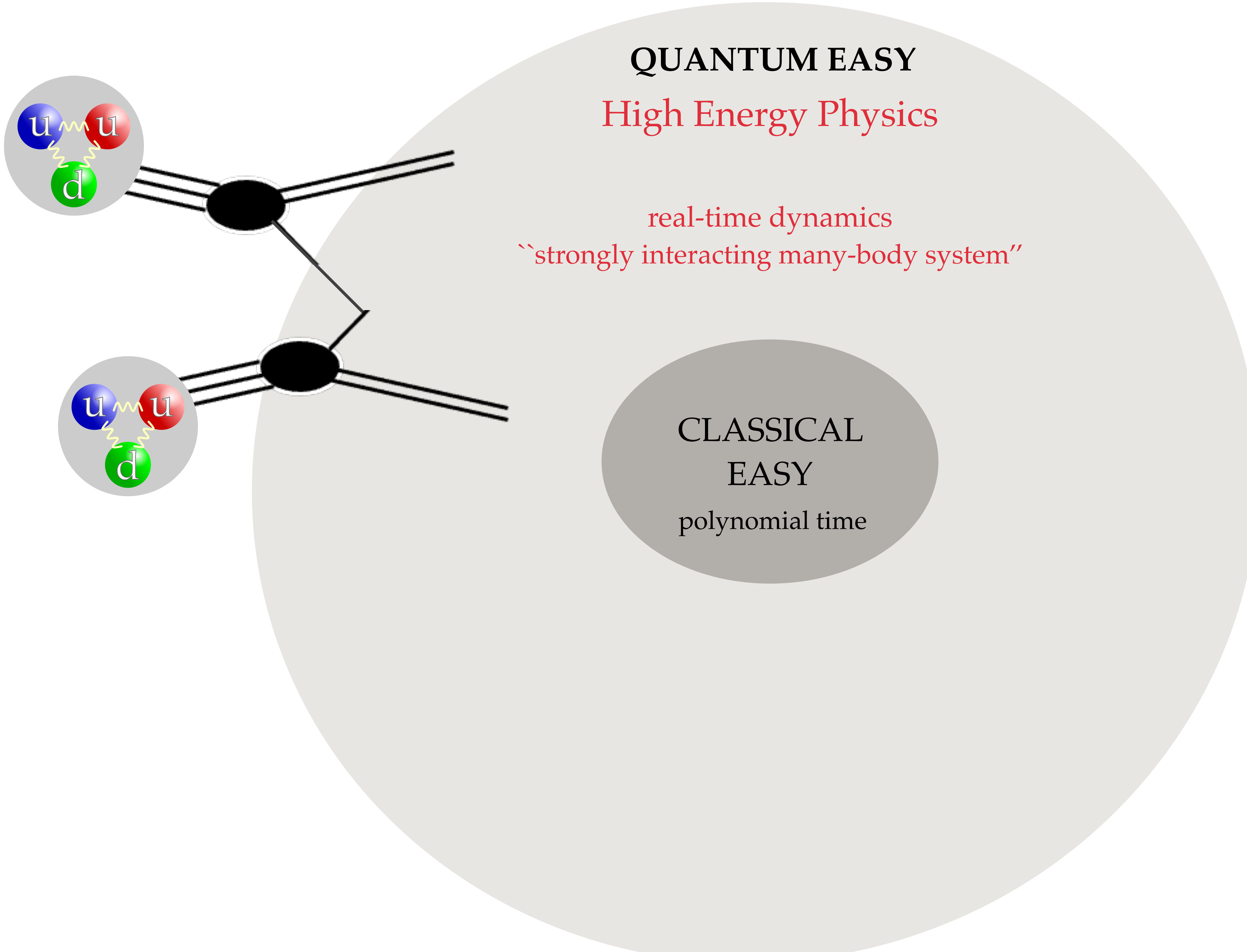
Seth Lloyd

Feynman's 1982 conjecture, that quantum computers can be programmed to simulate any local quantum system, is shown to be correct.



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

The number of operations required is also a polynomial function of the system size



PDF should be able to be solved with quantum resources in polynomial time
``QUANTUM EASY''

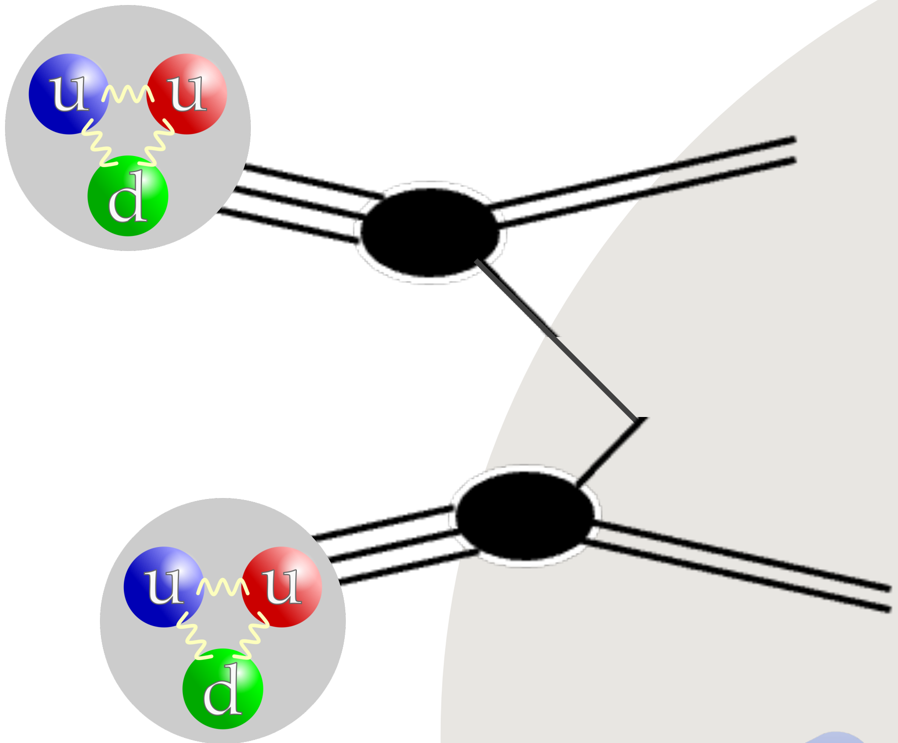
QUANTUM EASY

High Energy Physics

real-time dynamics
finite density
quantum interference
out-of equilibrium
``strongly interacting many-body system''

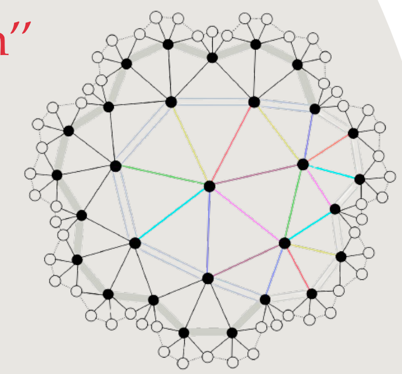
QUANTUM HARD

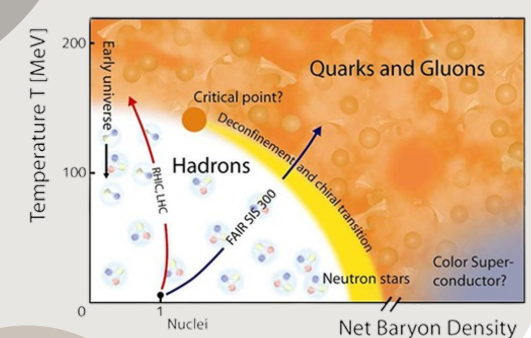
e.g. traveling salesmen problem

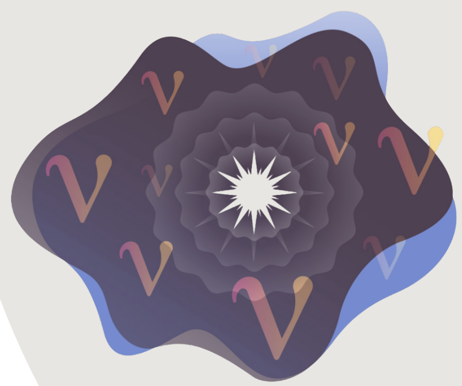


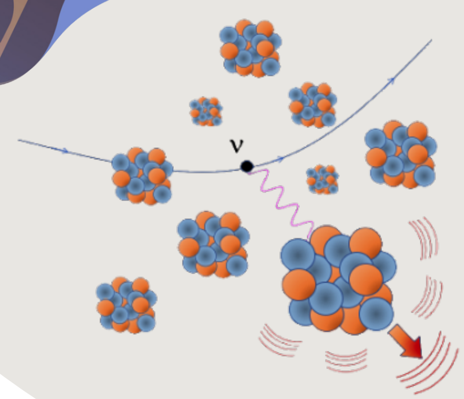
CLASSICAL EASY

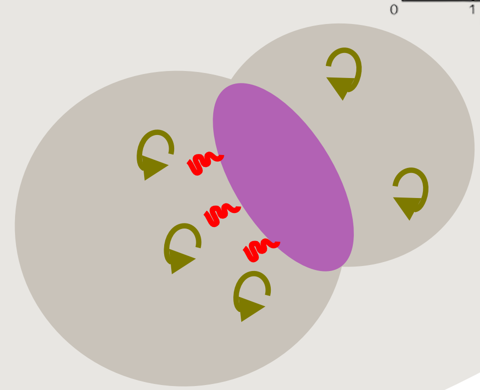
polynomial time











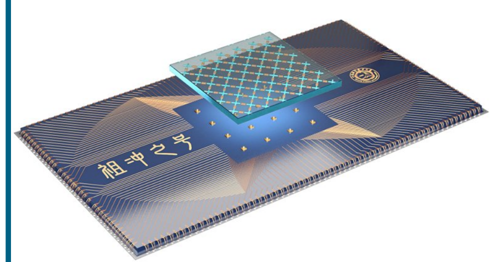
Problems in HEP that are beyond classical easy but are ``QUANTUM EASY''

Quantum Computing

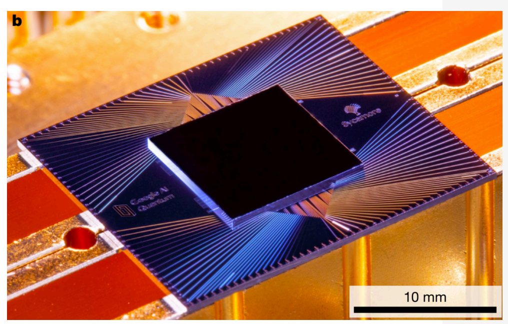
Now - Noisy Intermediate Scale Quantum (NISQ) era

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

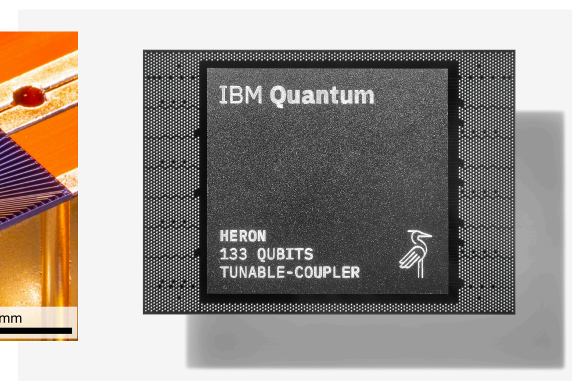
superconducting processor



176 qubits



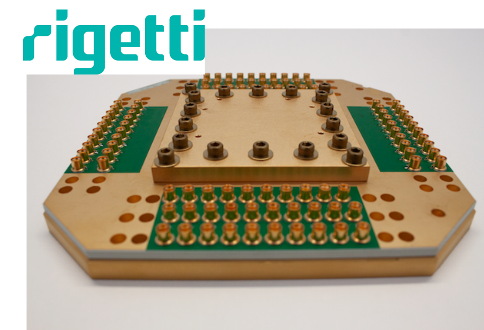
54 qubits



1121 qubits

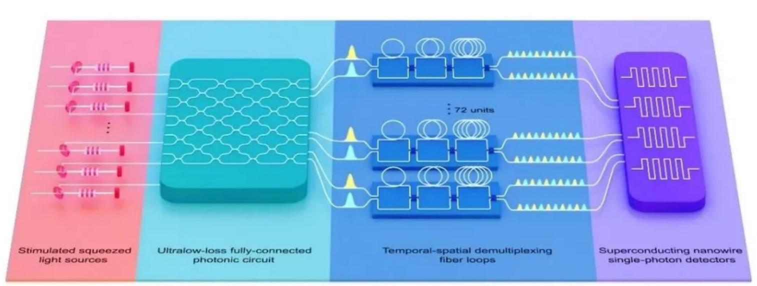
access to 133 qubits

multi-chip quantum processor



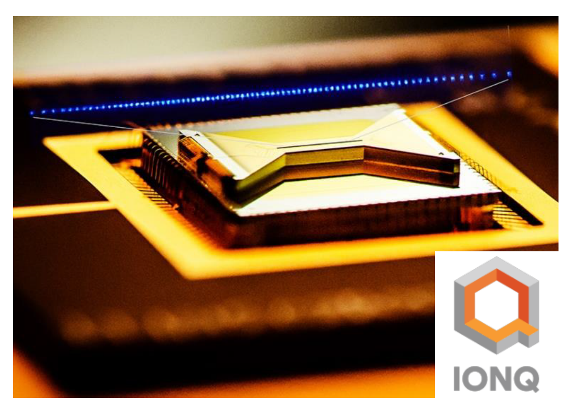
80 qubits

photon qubits



Jiuzhang - 255 qubits

trapped ion qubits

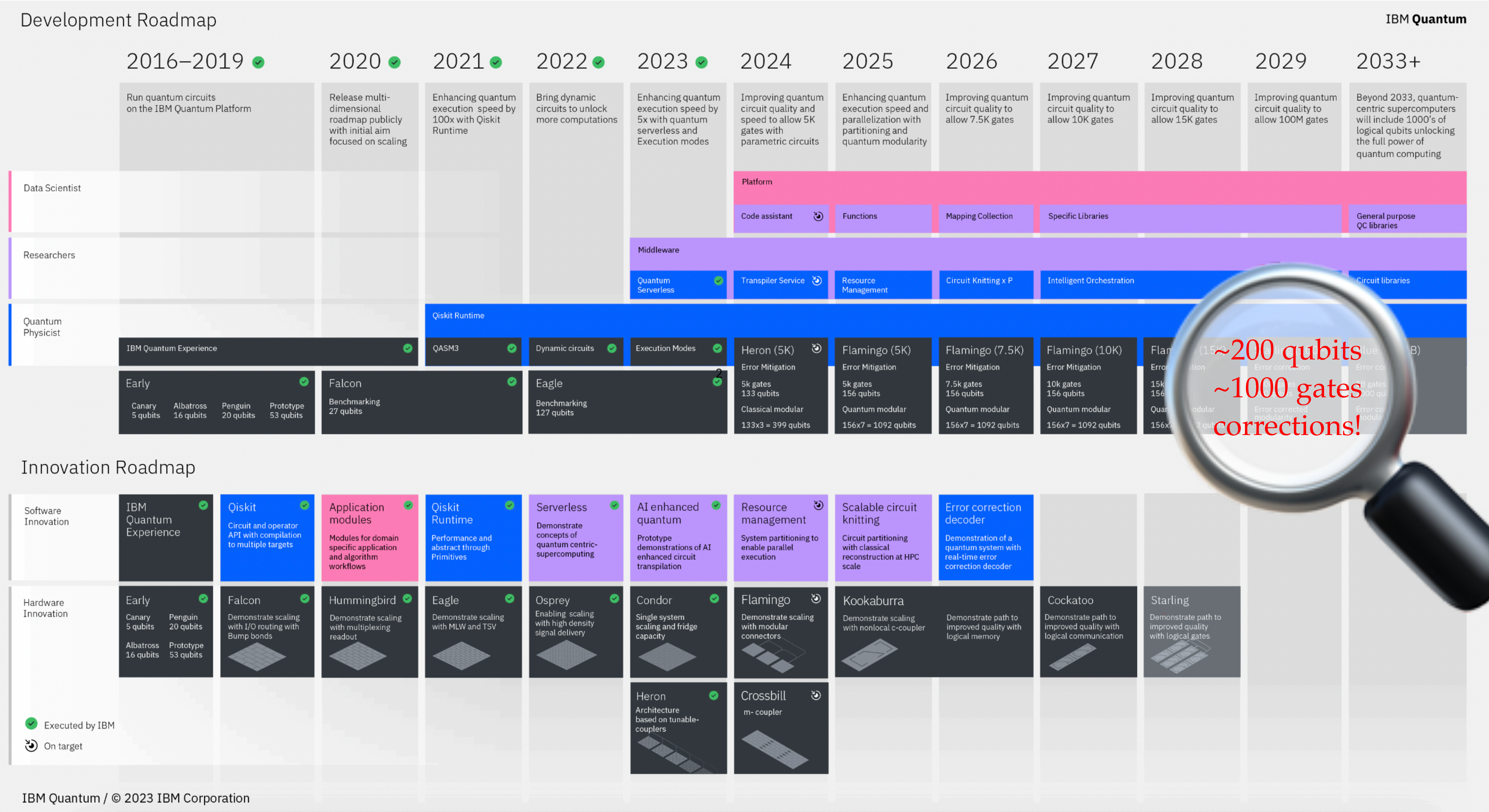


22 qubits

48 logical qubits

Quantum Computing

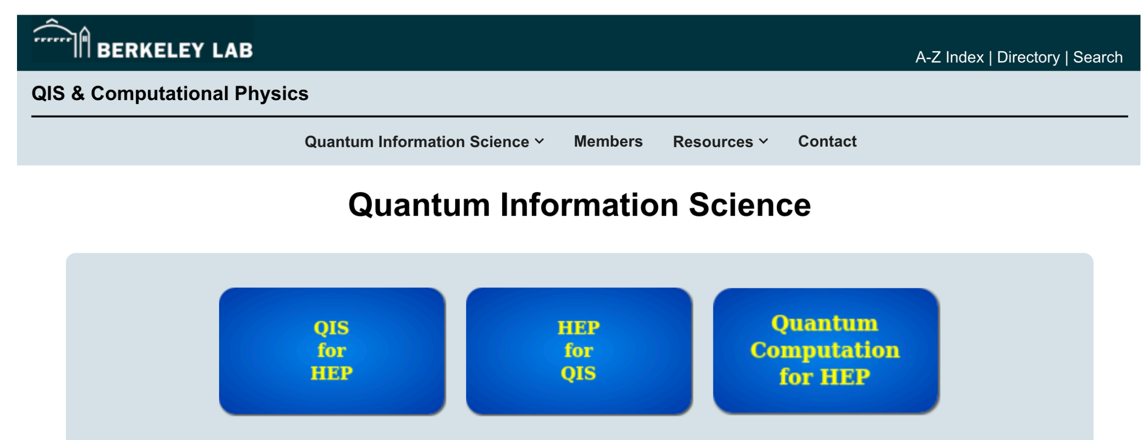
Next decades



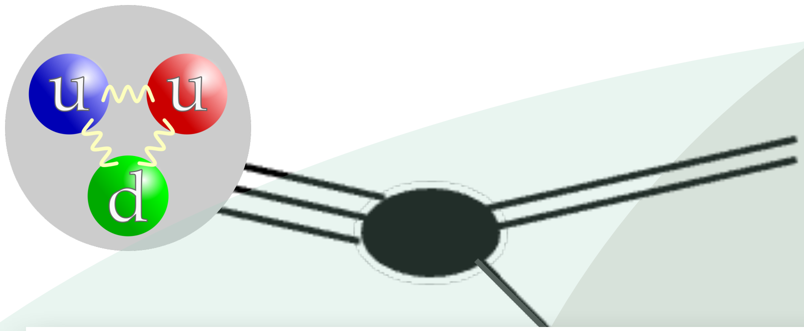
Quantum Computing for HEP

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 EASY

High Energy Physics

real-time dynamics
finite density
quantum interference

QUANTUM HARD

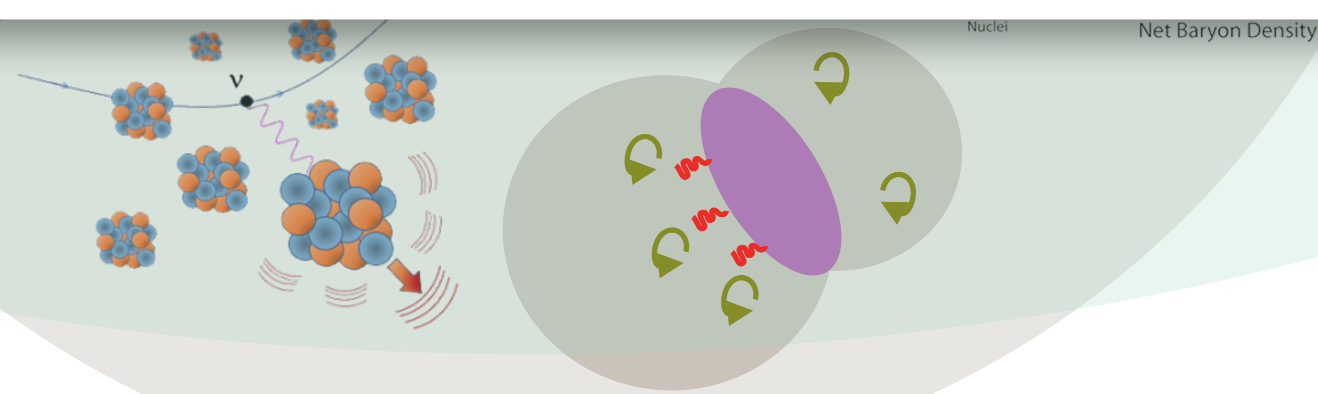
e.g. traveling salesmen problem

[*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



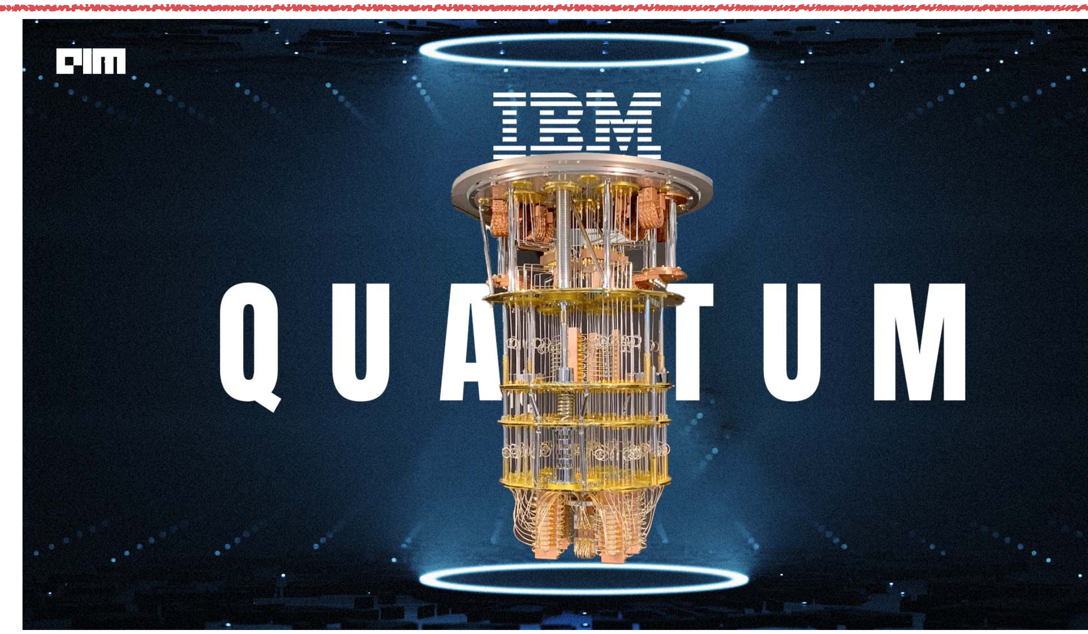
Problems in HEP that are beyond classical easy but are ``QUANTUM EASY”

Quantum Computing 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”



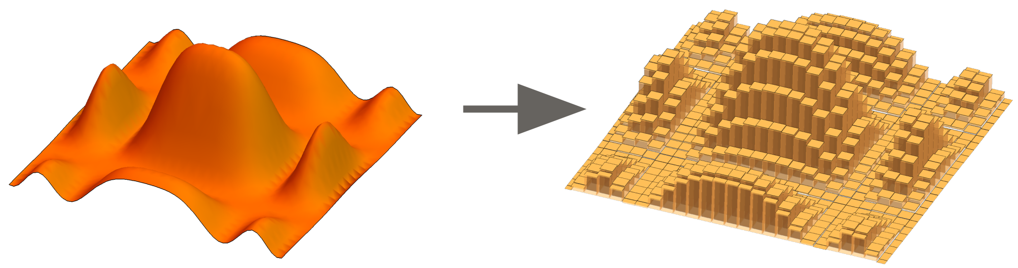
… chart future for use of quantum computing in particle physics

Quantum Computing for HEP

[Jordan, Lee, Preskill, 2011]

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

Discretization



infinities in space

Carena, Lamm, YYL, Liu, Gustafson, Water,…

Digitization

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

infinities in field variables

Bauer, Davoudi, Gustafson, Meurice, Lamm, YYL, Savage,…

Initialization

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

ground/thermal/bound state prep

Karsen, Davoudi, Lawrence, YYL, Xu, Liu, Xing…

Propagation

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

efficiency of time evolutions

Davoudi, Gustafson, YYL, Stryker, Wang, Zohar…

Evaluation

$$\langle \mathcal{O} \rangle$$

parton distribution function,

Lamm, Liu, Yamauchi, Xing…

Error mitigation/corrections

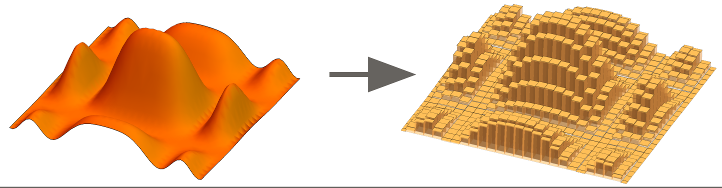
gauge symmetry for error corrections

Bauer, Carena, Halimeh, Lamm, YYL,…

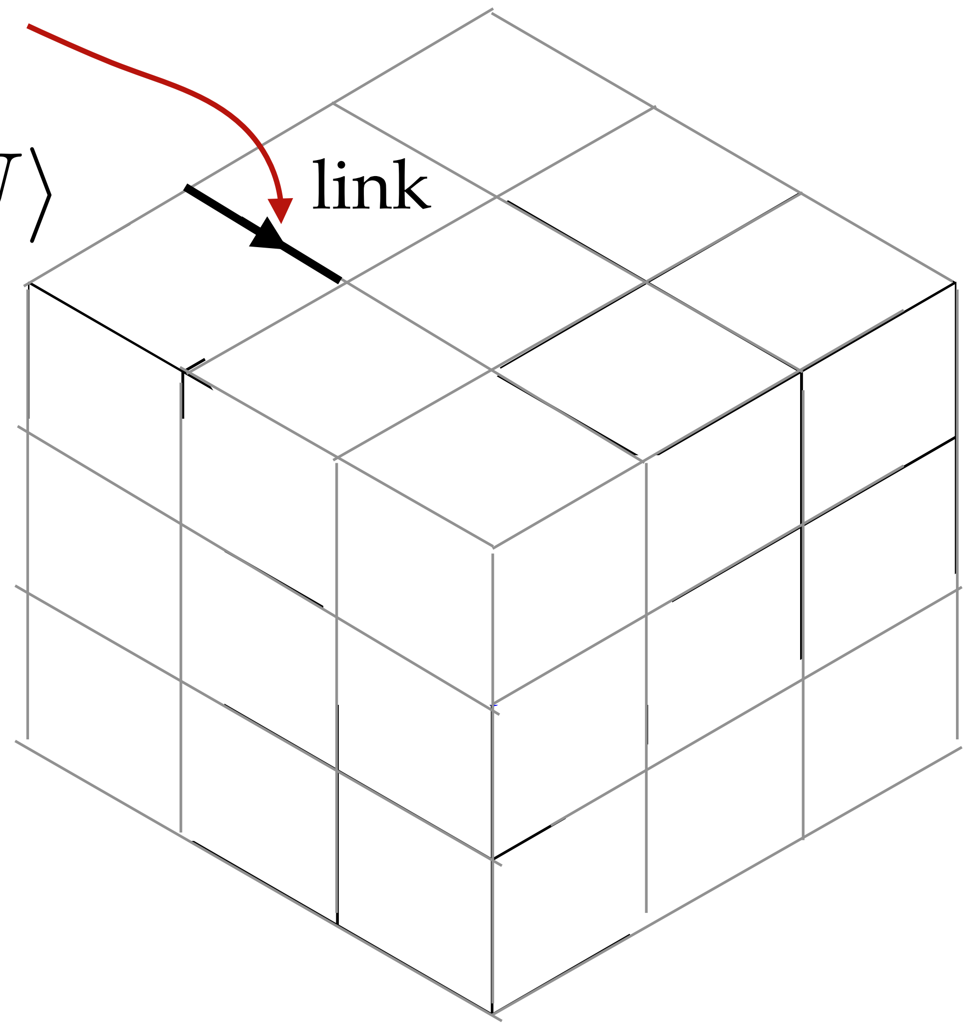
Discretization

infinities in space

Discretization



infinities in QFT

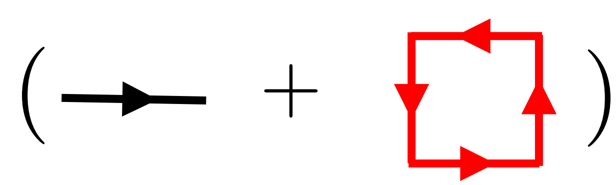


group element basis $|U\rangle$

spatial dimension d

lattice spacing a

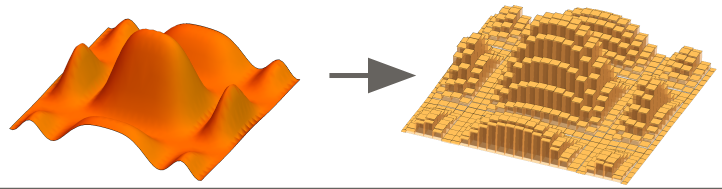
$H_{KS} = \sum$



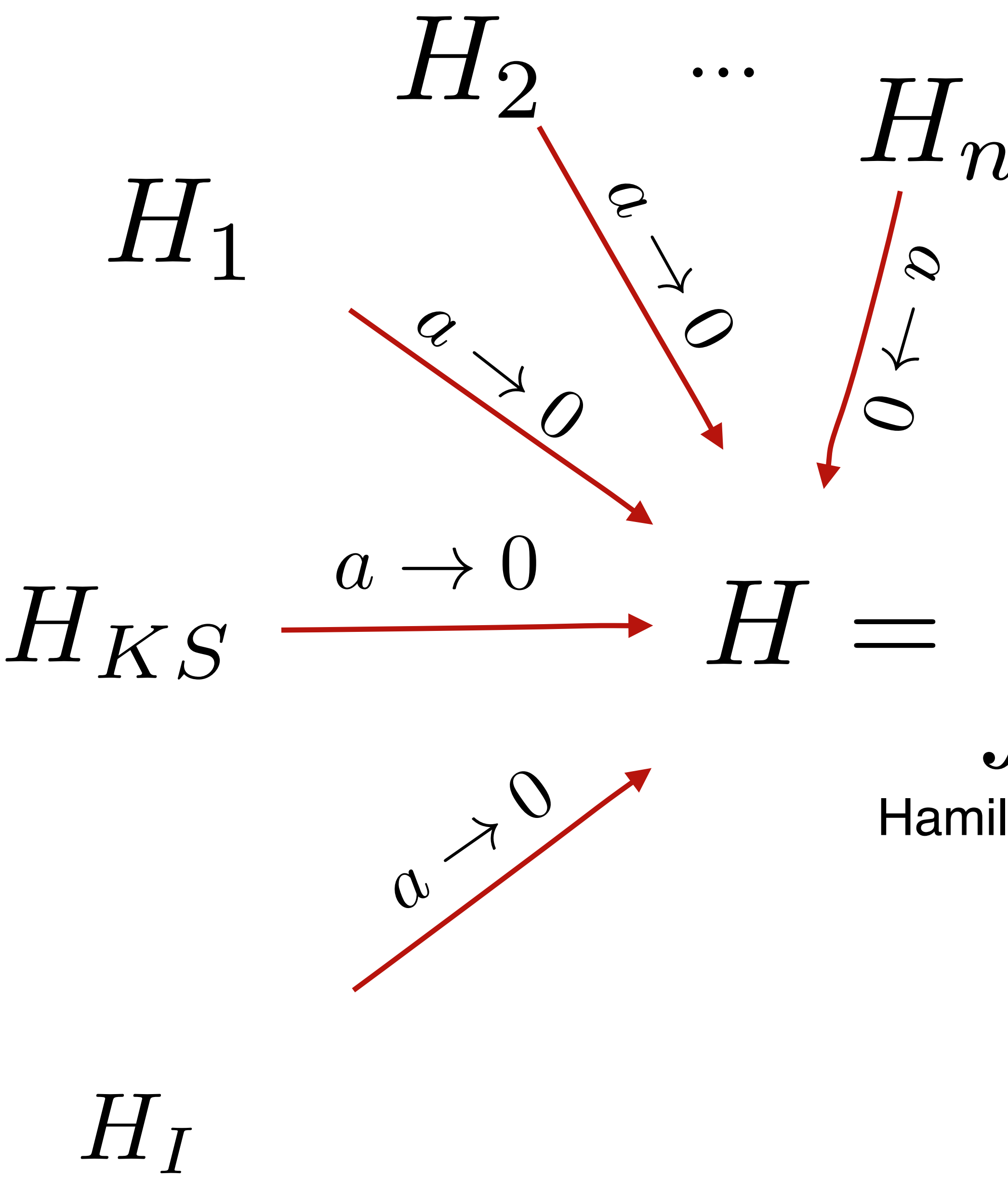
E^2 — electric energy

$U_\square$ — magnetic energy

Discretization

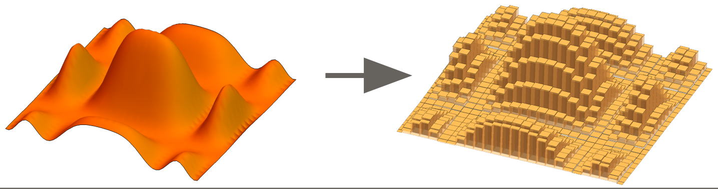


infinities in QFT

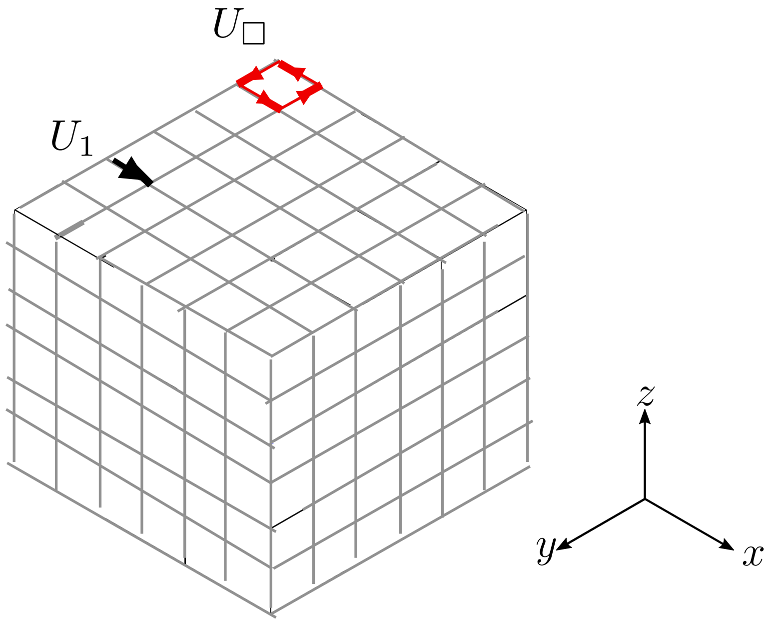


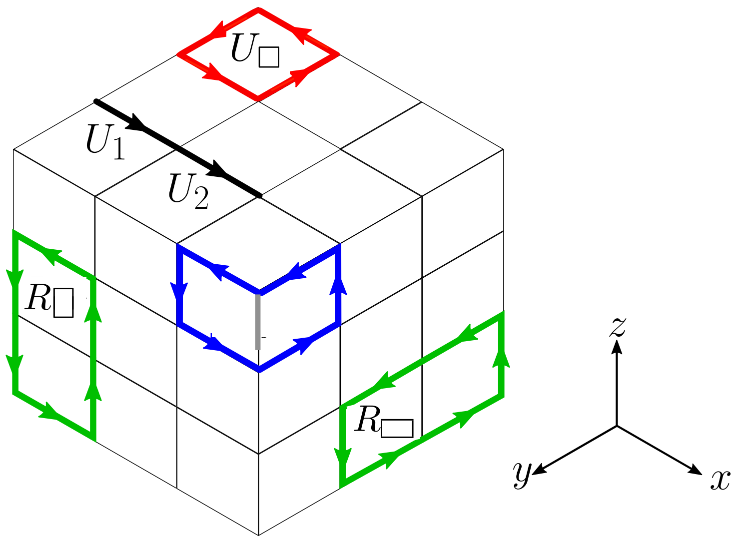
$$H = \int dx (E^2 + B^2)$$

Hamiltonian in continuous space



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





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

The number of qubits, also trotter steps needed can be reduced

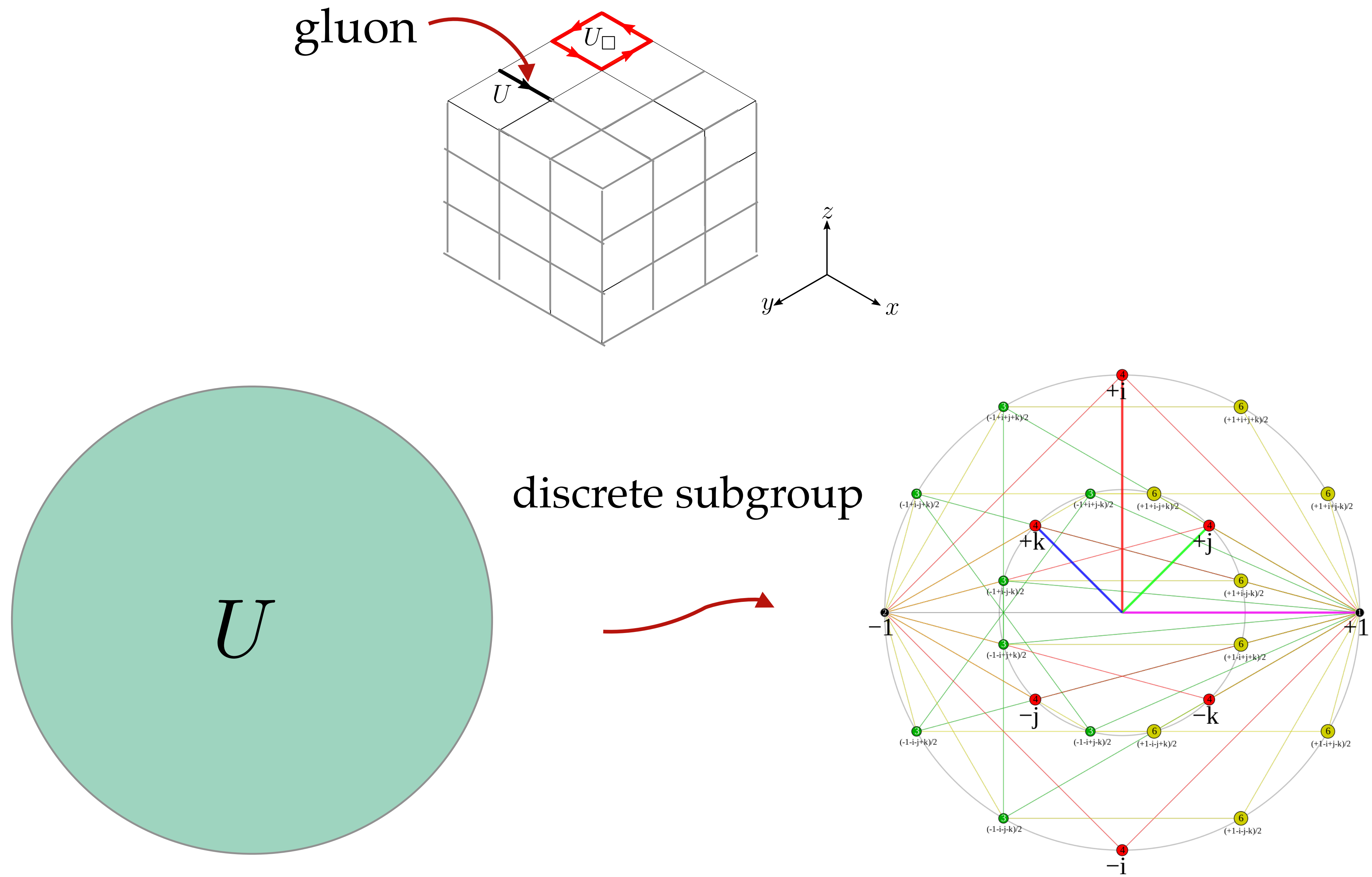
[Carena, Lamm,**YYL**, Liu, PRL. **129**, 051601]

Digitization

infinities in field variables

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

infinities in QFT

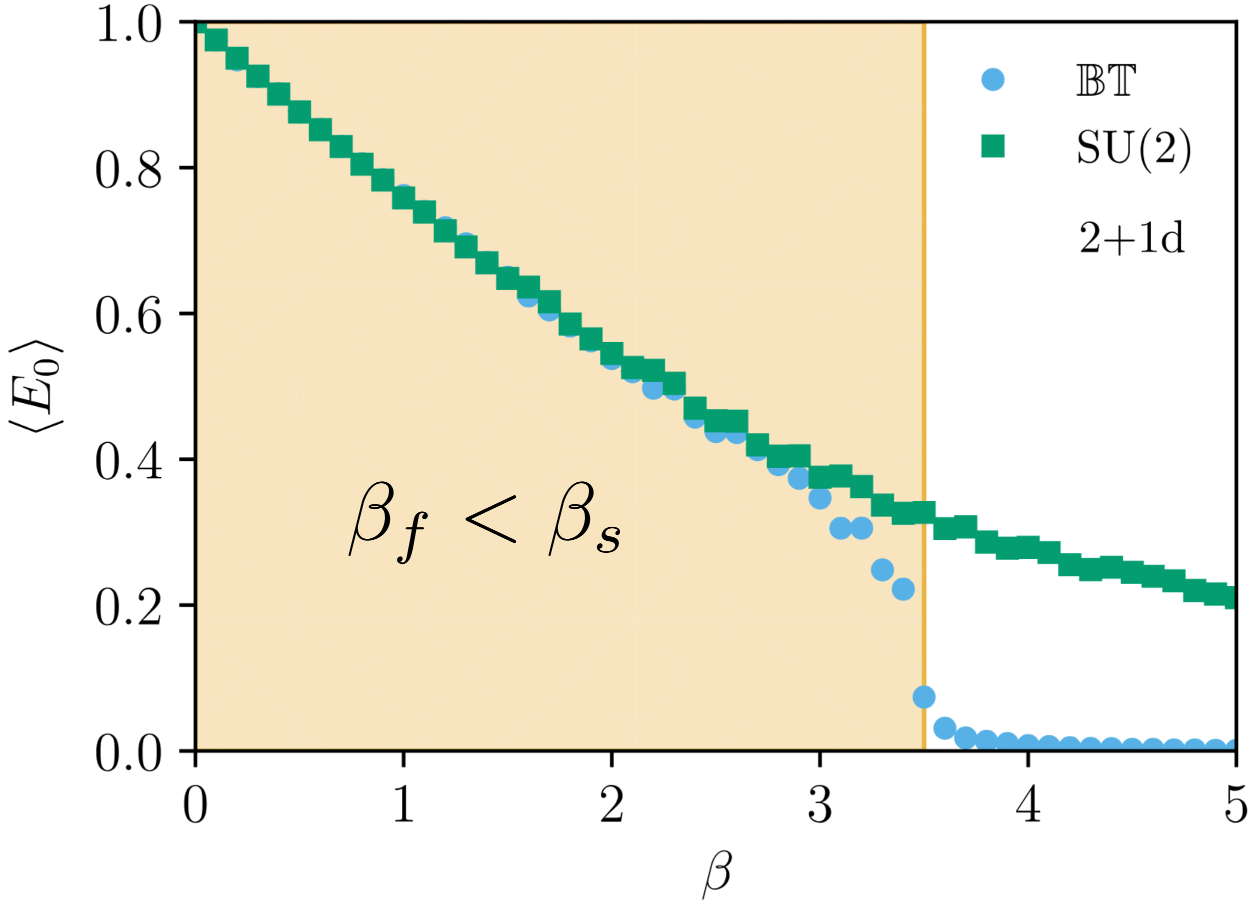


continuous field variables

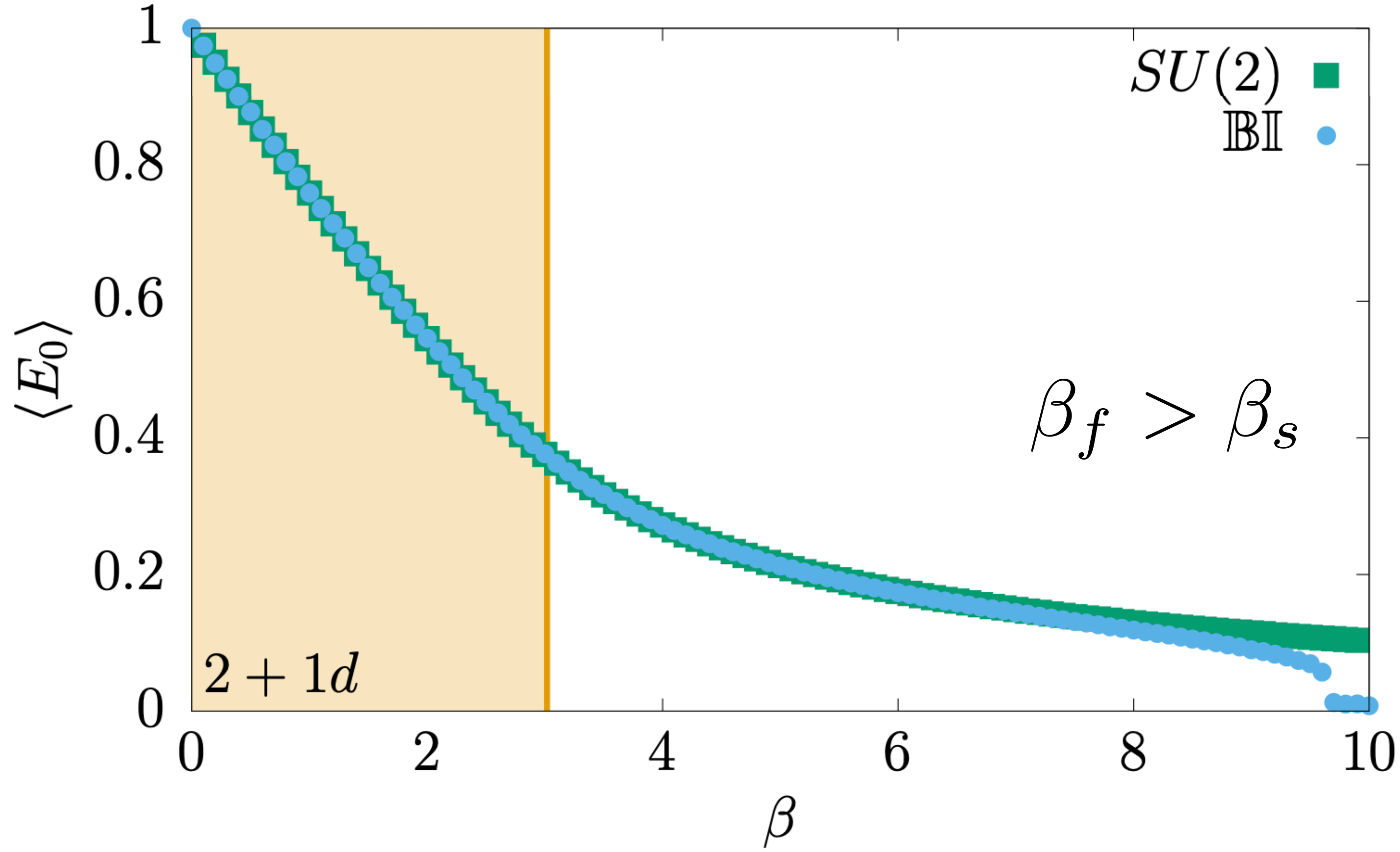
$G-$register : $|U\rangle$

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

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



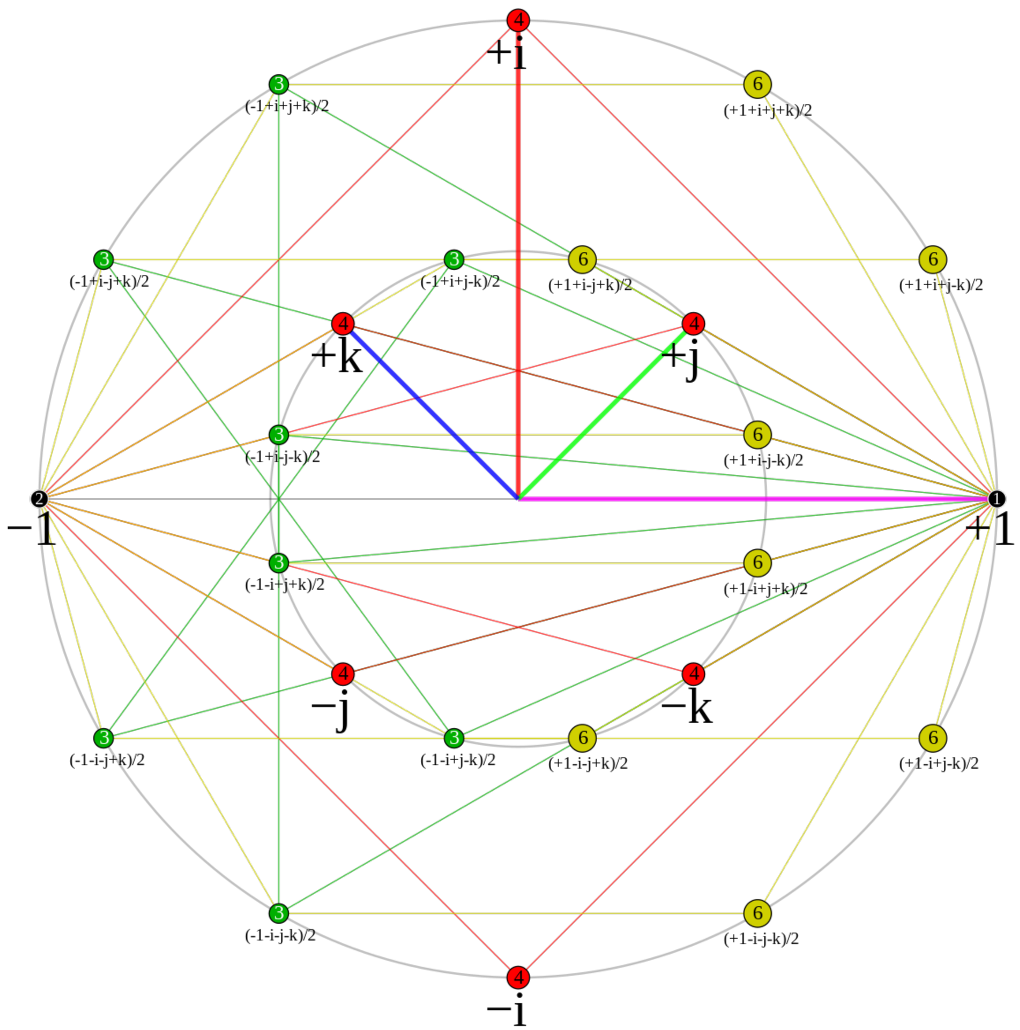
[Lamm, **YYL**, Shu, Wang, Bin, arXiv:2405.12890]



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

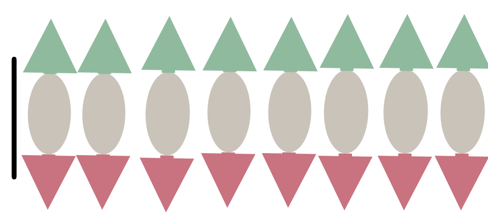
Digitization $\quad |q\rangle^N \to |G\rangle$

infinities in QFT



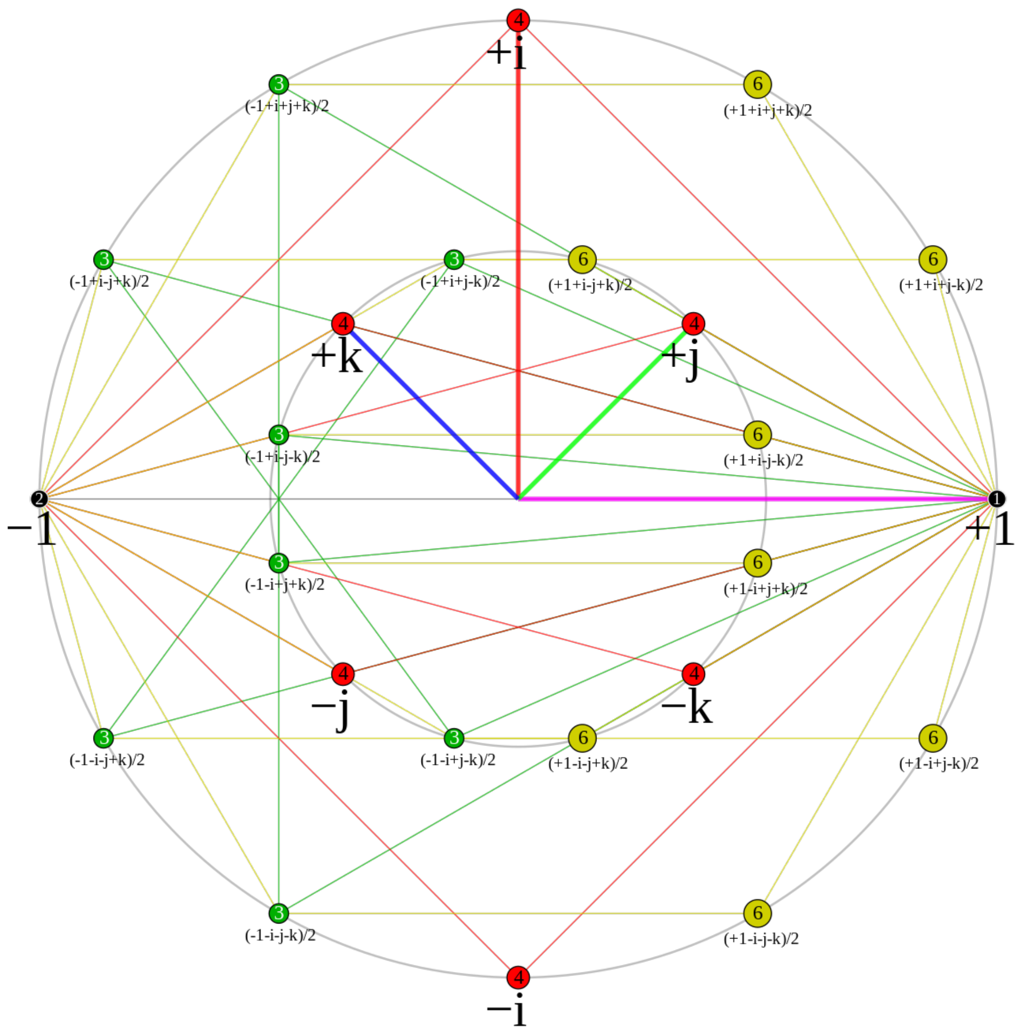
block product encoding: BT, BI

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

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

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

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



block product encoding: BT, BI

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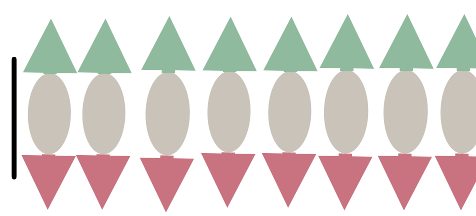
$|U\rangle = |$  $\rangle$

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

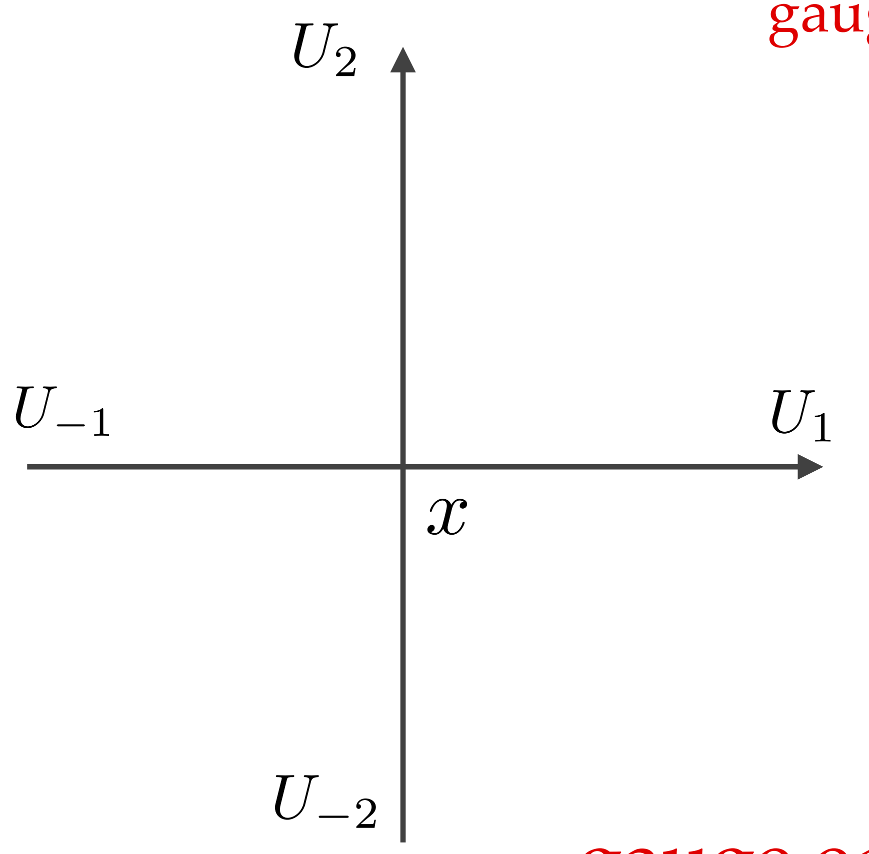
qudit system?

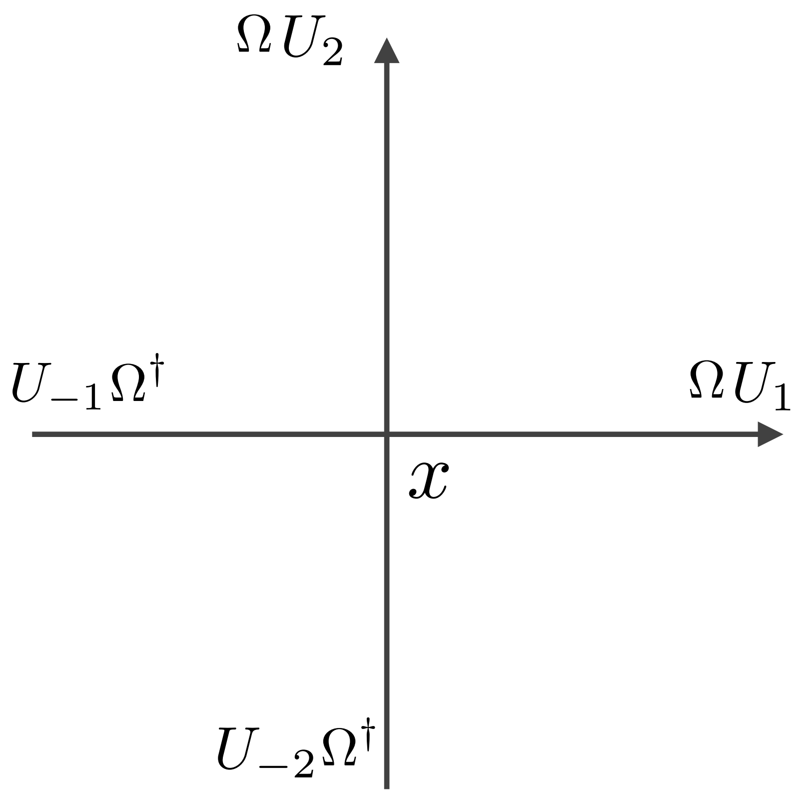
Digitization $|q\rangle^N \to |G\rangle$

infinities in QFT

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

gauge transformation





gauge equivalent states

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

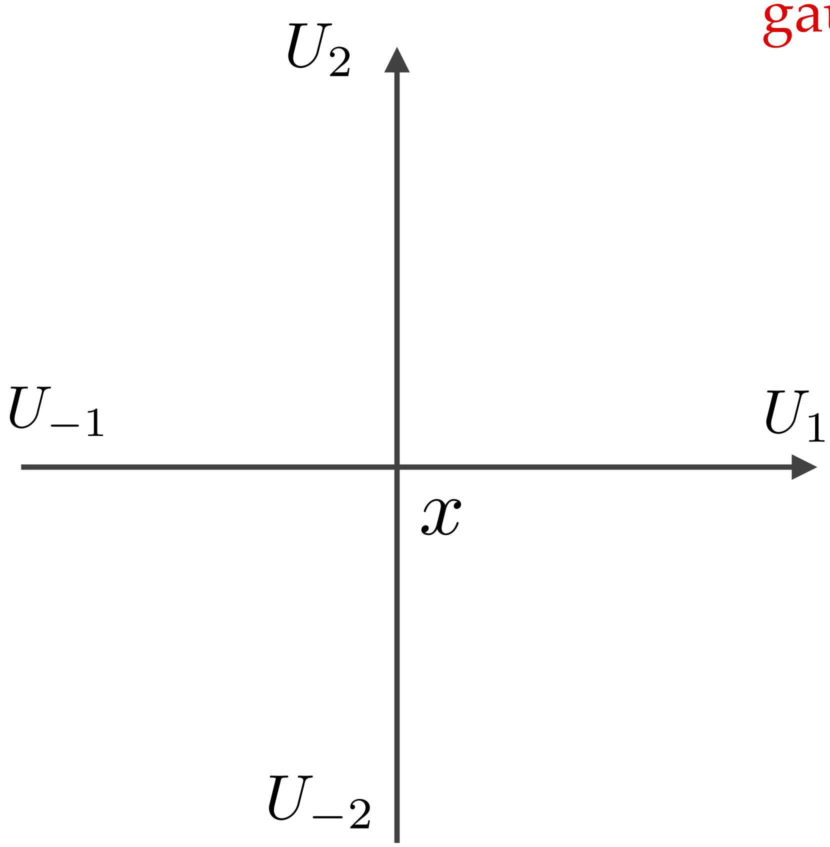
Carena, Lamm, **YYL**, Liu, arXiv:2402.16780

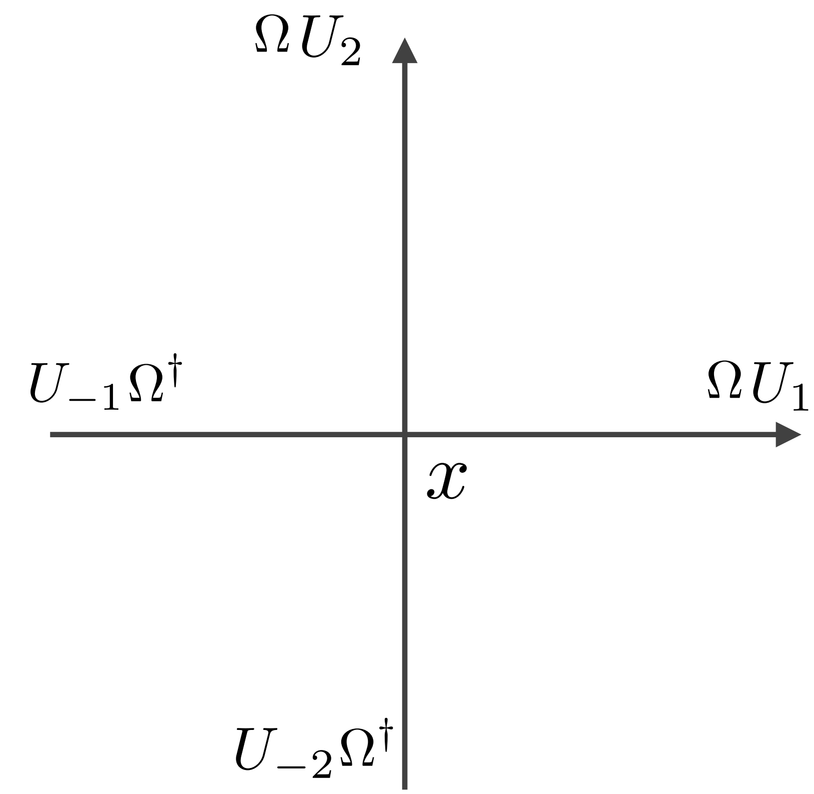
Digitization $|q\rangle^N \to |G\rangle$

infinities in QFT

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

gauge transformation





gauge equivalent states

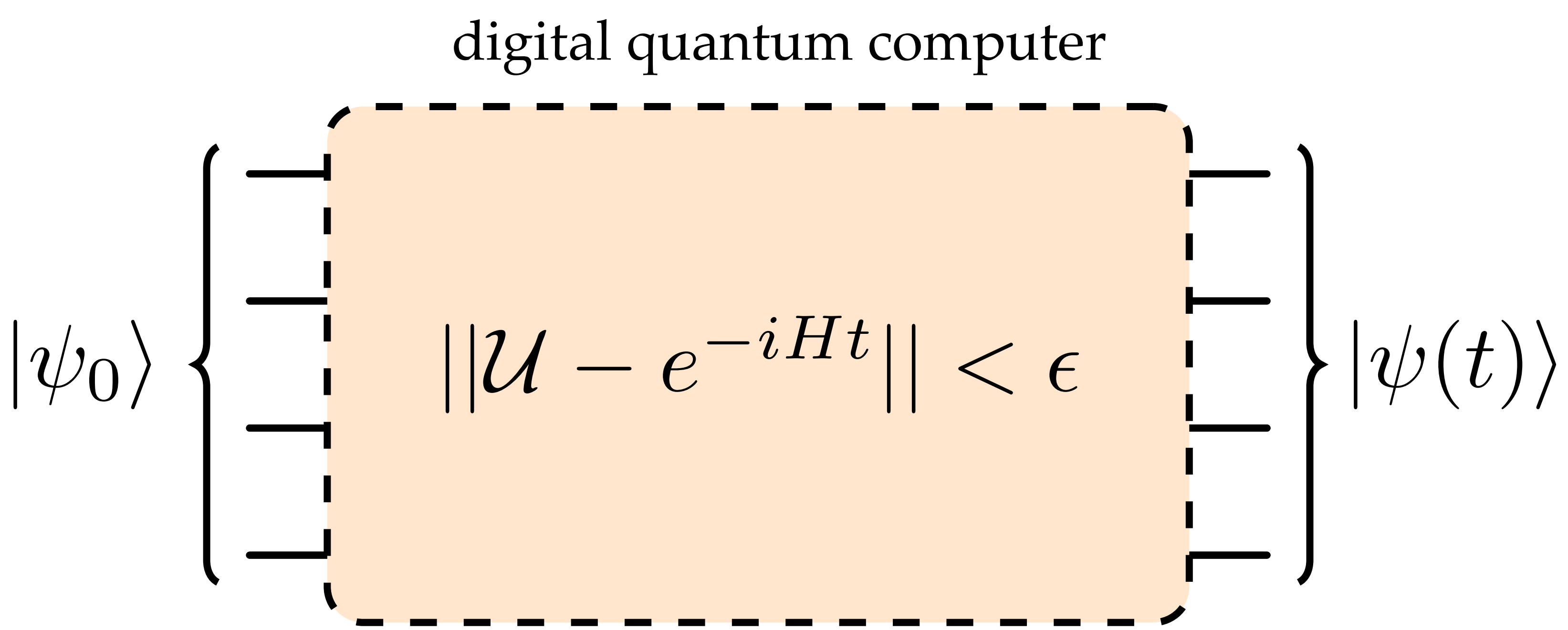
$$\hat{\Theta}_\Omega(x)\,|U_{-1}U_1U_{-2}U_2\rangle = \left|U'_{-1}U'_1U'_{-2}U'_2\right\rangle$$

error corrections:

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

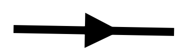
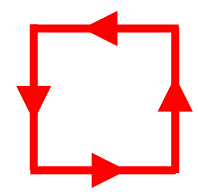
Carena, Lamm, **YYL**, Liu, arXiv:2402.16780

Propagation

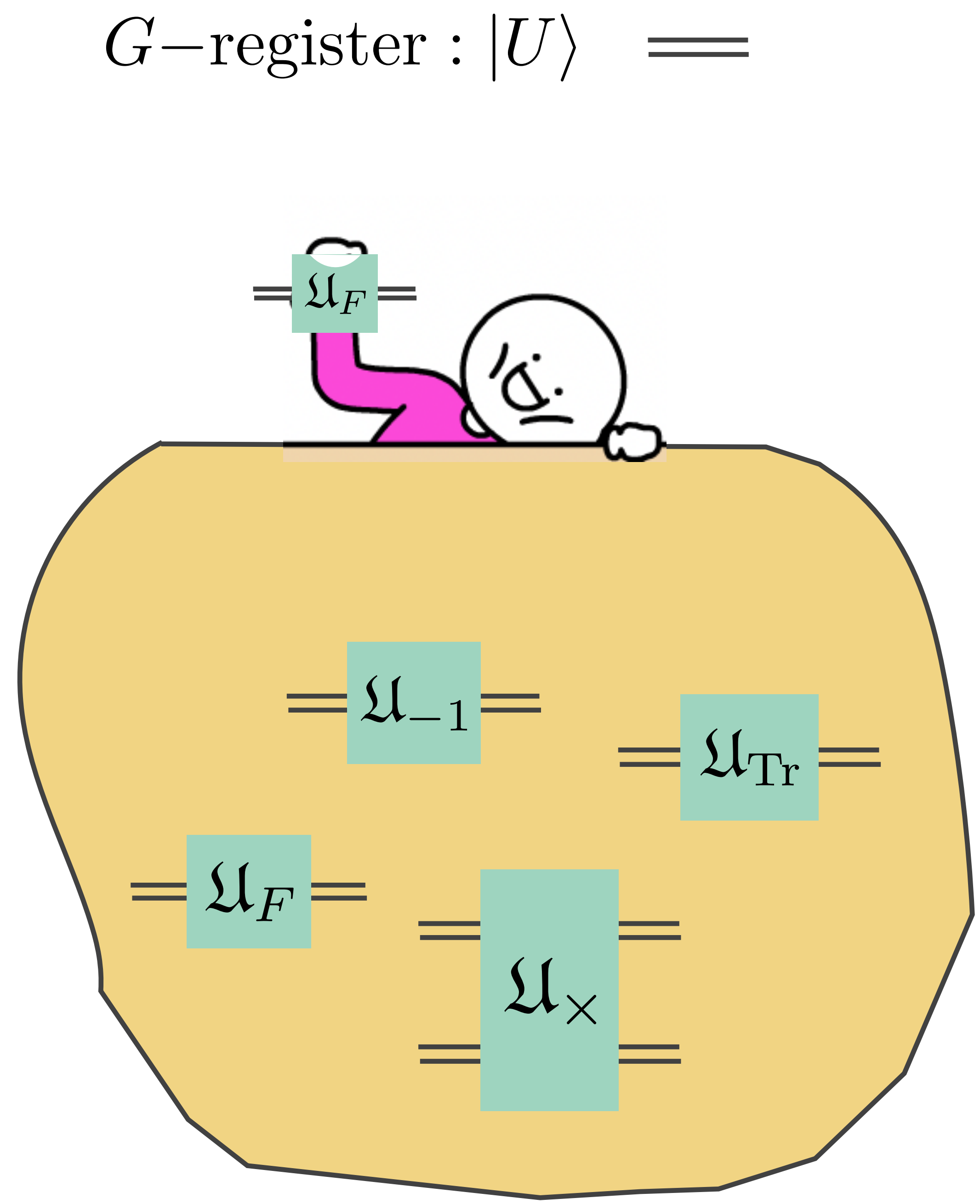


time-evolution while keep the gauge redundancies

Propagation $\quad \mathcal{U}\left|\psi_0\right\rangle \to \left|\psi(t)\right\rangle$

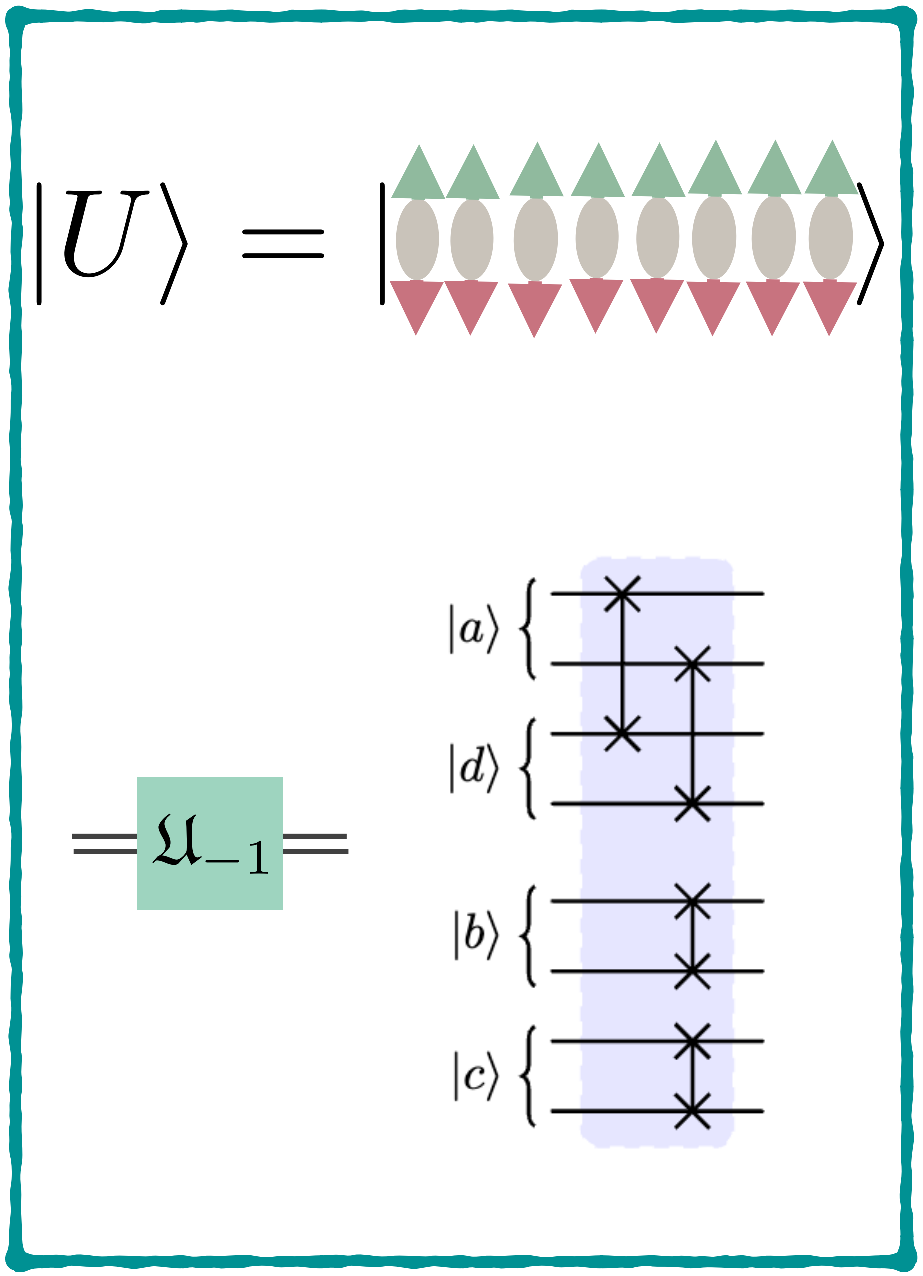
$$H_{KS} = \sum \Big($$  $$+$$  $$\Big)$$

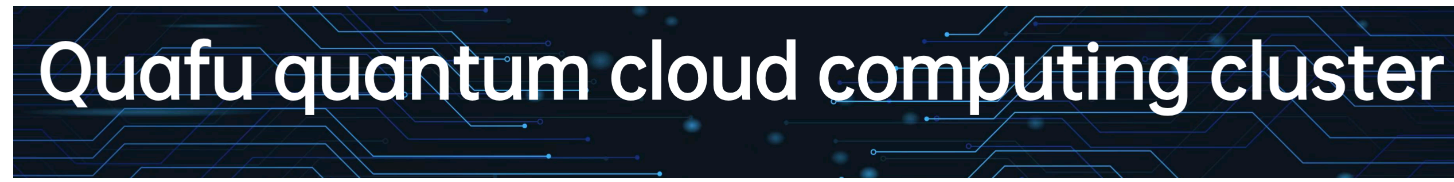
$$K_L \qquad\qquad U_\square$$

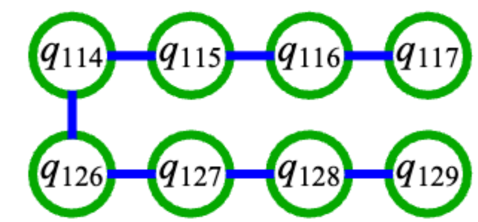


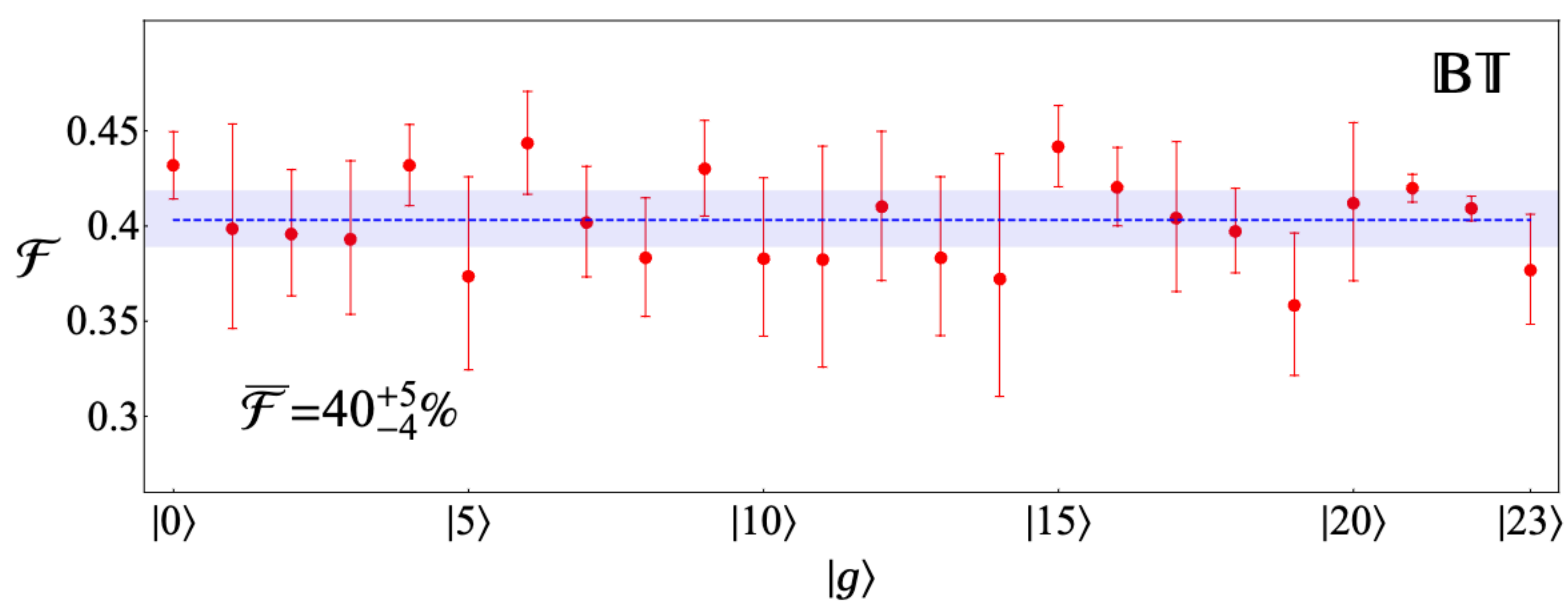
$$\mathcal{U}(t) = e^{-iH_{KS}t}$$
$$\approx \left[e^{-i\delta t K_L} e^{-i\delta t U_\square}\right]^{t/\delta t}$$

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



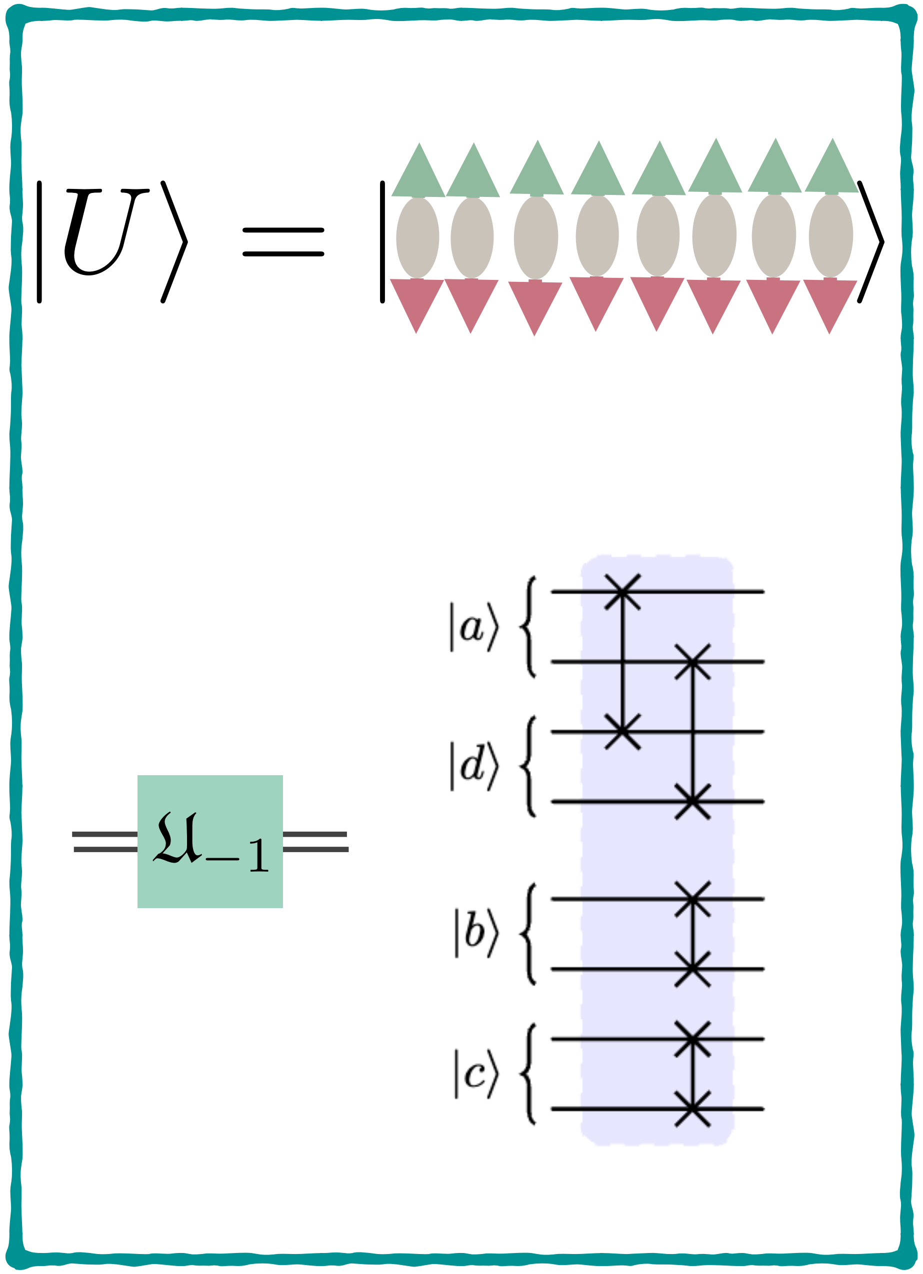


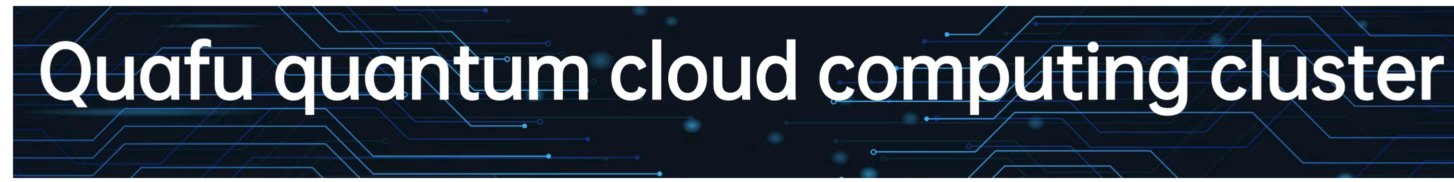


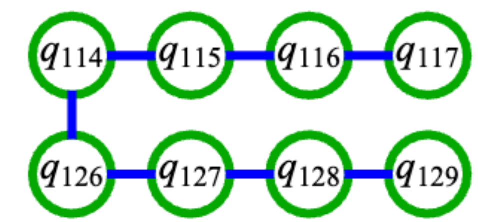


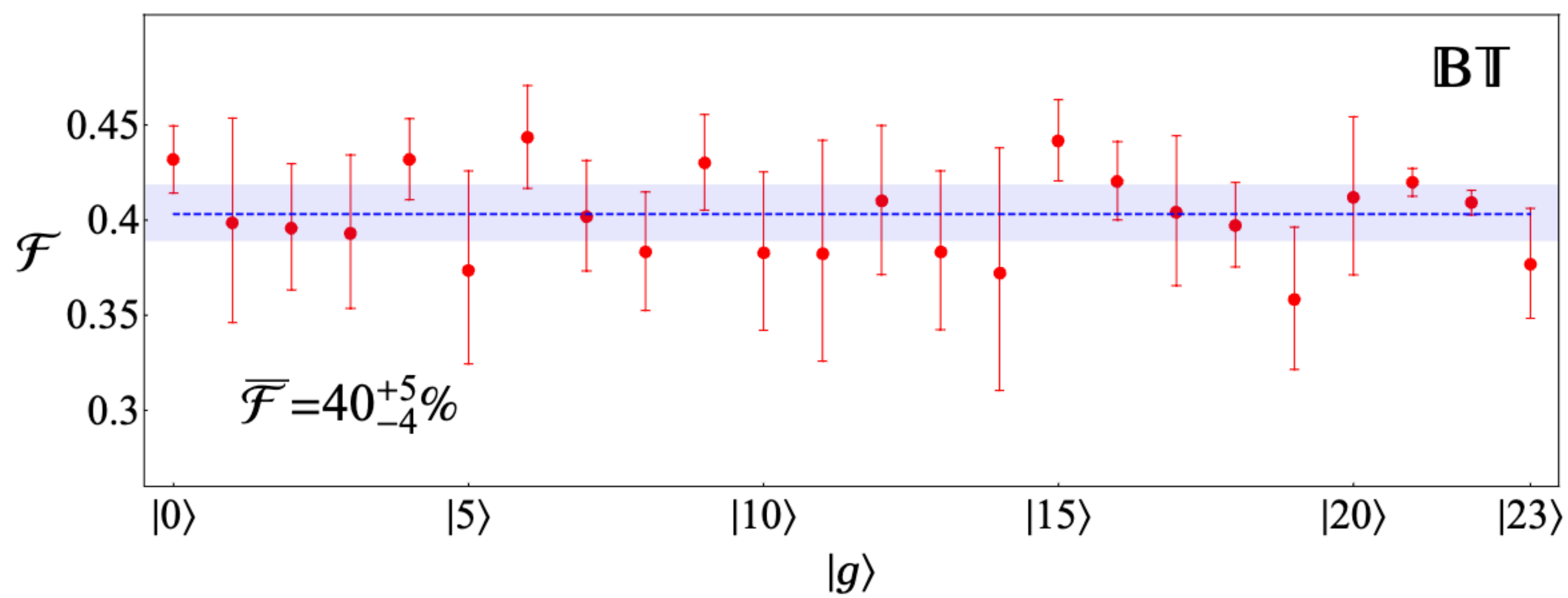
[Lamm, **YYL**, Shu, Wang, Bin, arXiv:2405.12890]

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





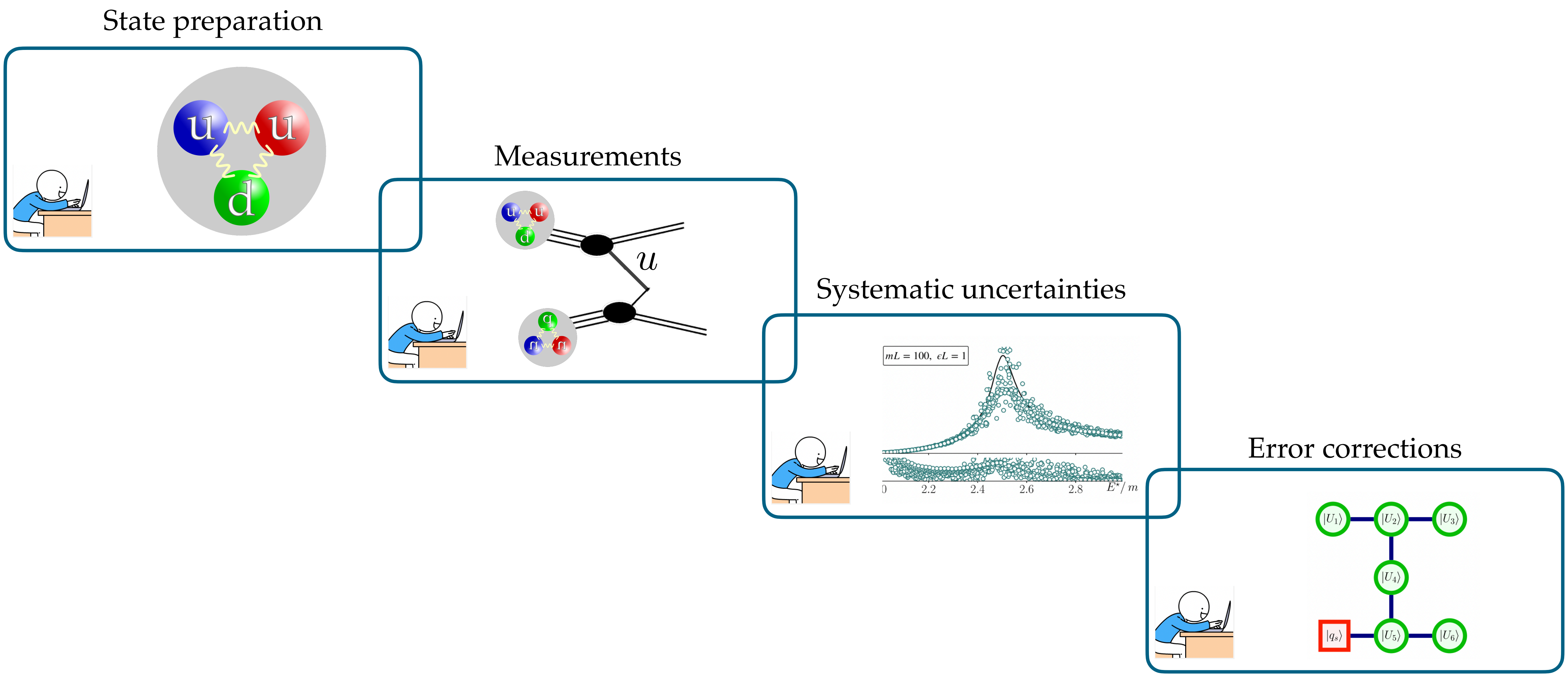




optimization?

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

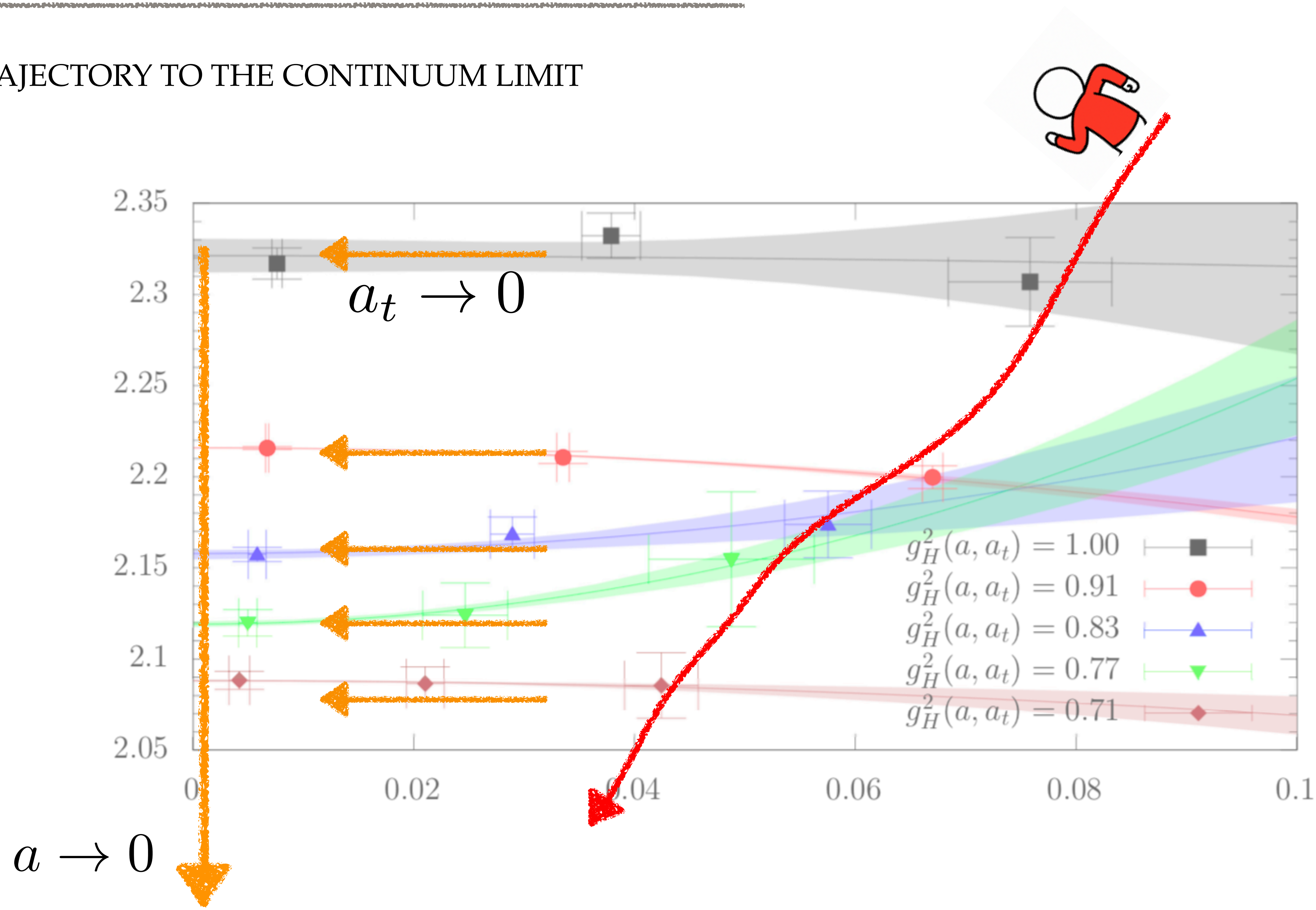
To reach the observables — How to do…



and reach the continuum limit

To reach observables in the continuum limit

TRAJECTORY TO THE CONTINUUM LIMIT



continuous
space-time limit

[Carena, Lamm, **YYL**, Liu, PRD. **104**, 094519]

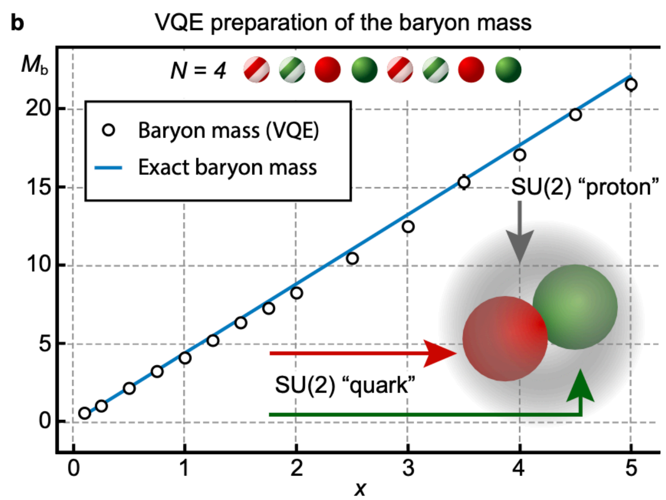
Now - Noisy Intermediate Scale Quantum (NISQ) era

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

Physics Benchmarks

Physics Benchmarks for Quantum Computing

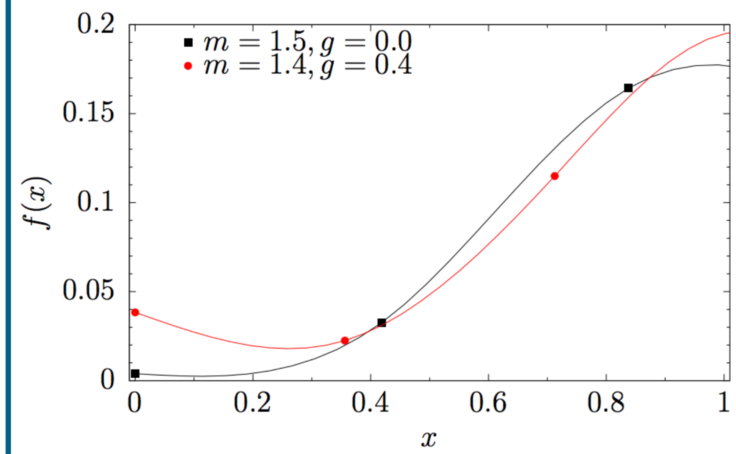
proton state preparation



Atas et al, Nat Commun 12, 6499 (2021)

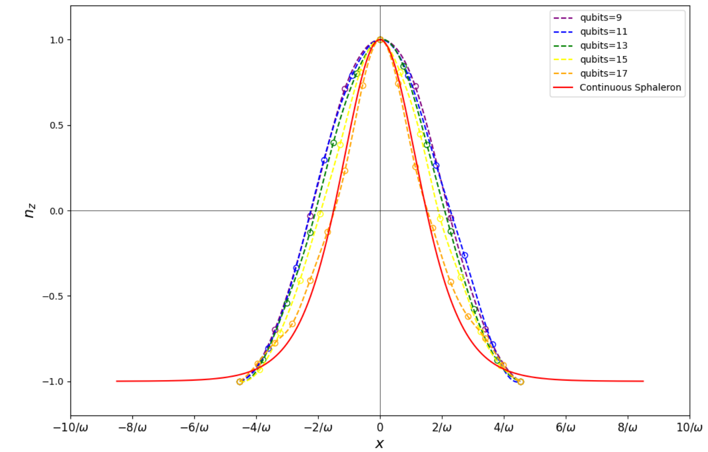
PDF

$$\langle\Psi|\mathcal{O}(t)\mathcal{O}(0)|\Psi\rangle = \frac{\partial}{\partial\epsilon_t}\frac{\partial}{\partial\epsilon_0}\langle\Psi|e^{-iHt}e^{-i\mathcal{O}\epsilon_t}e^{iHt}e^{i\mathcal{O}\epsilon_0}|\Psi\rangle$$



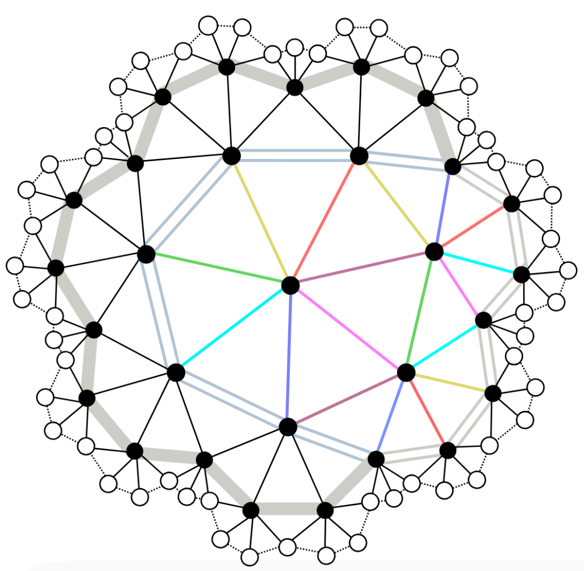
Lamm, et al., T. Li, et al,

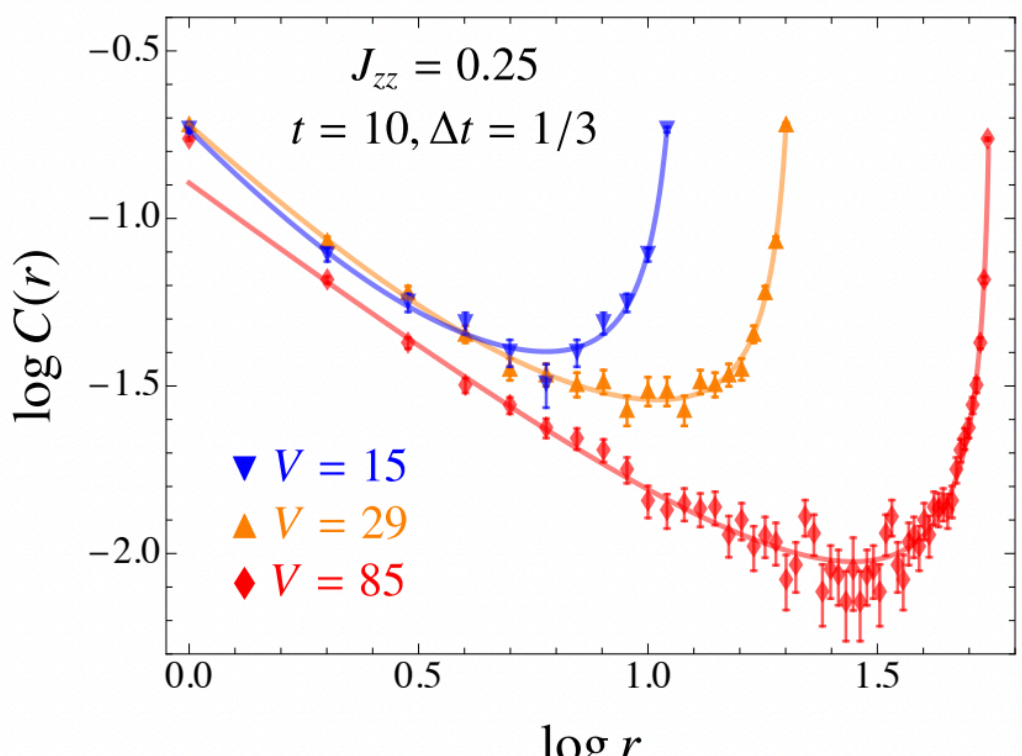
topological objects preparation



Huang, **YYL**, Liu, Wang, Zhang, in preparation

Holography

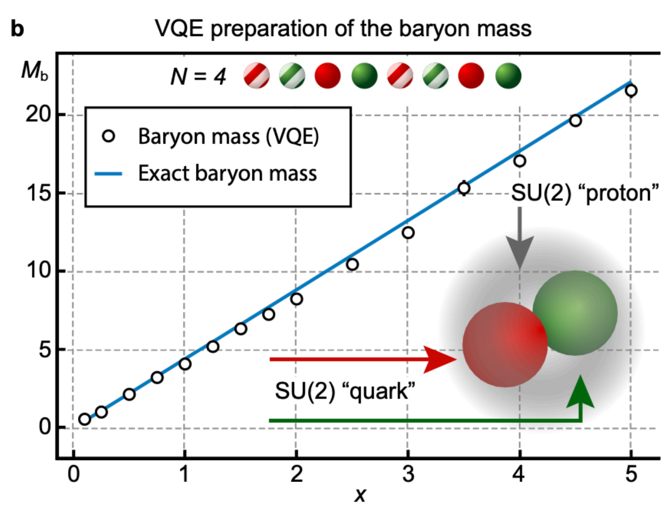




[**YYL,** Sajid, Unmuth-Yockey, arXiv:2312.10544]

Physics Benchmarks for Quantum Computing

proton state preparation



Atas et al, Nat Commun 12, 6499 (2021)

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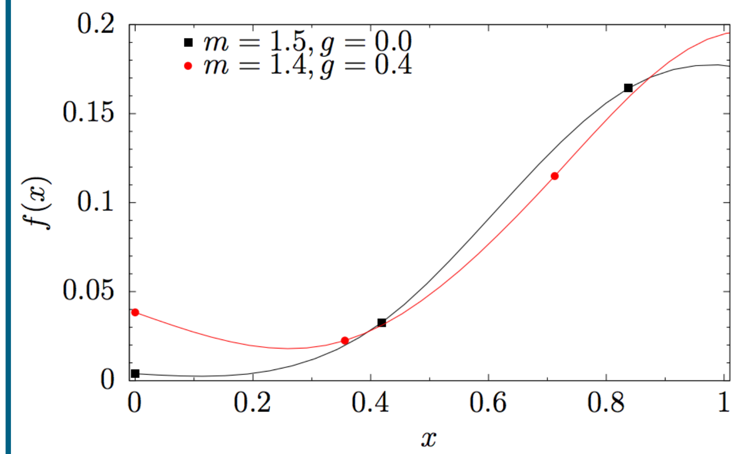
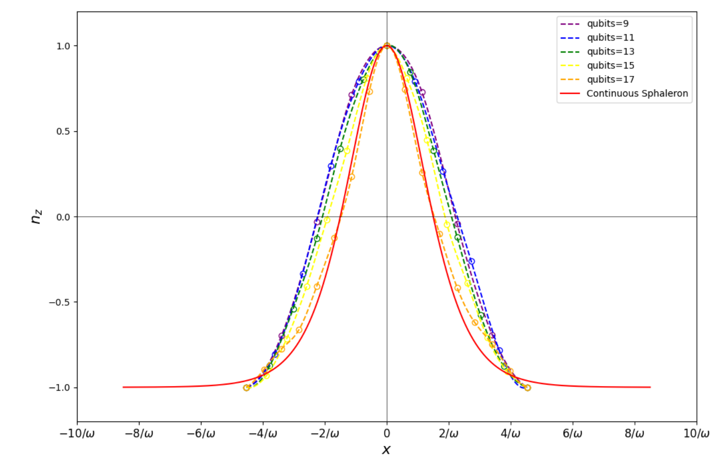
$$\langle\Psi|\mathcal{O}(t)\mathcal{O}(0)|\Psi\rangle = \frac{\partial}{\partial\epsilon_t}\frac{\partial}{\partial\epsilon_0}\langle\Psi|e^{-iHt}e^{-i\mathcal{O}\epsilon_t}e^{iHt}e^{i\mathcal{O}\epsilon_0}|\Psi\rangle$$



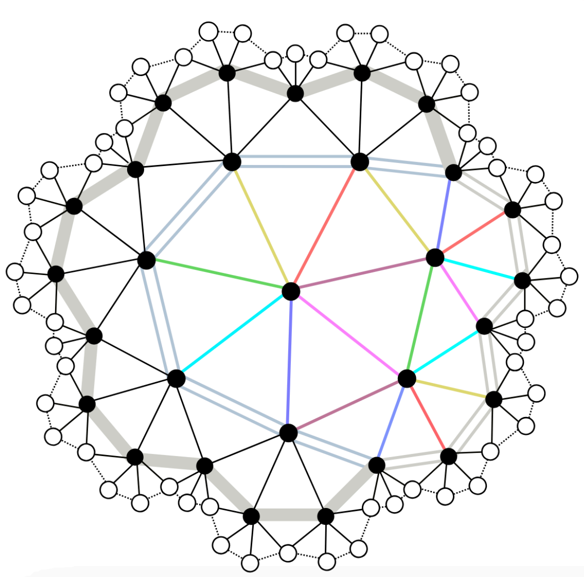
Lamm, et al., T. Li, et al,

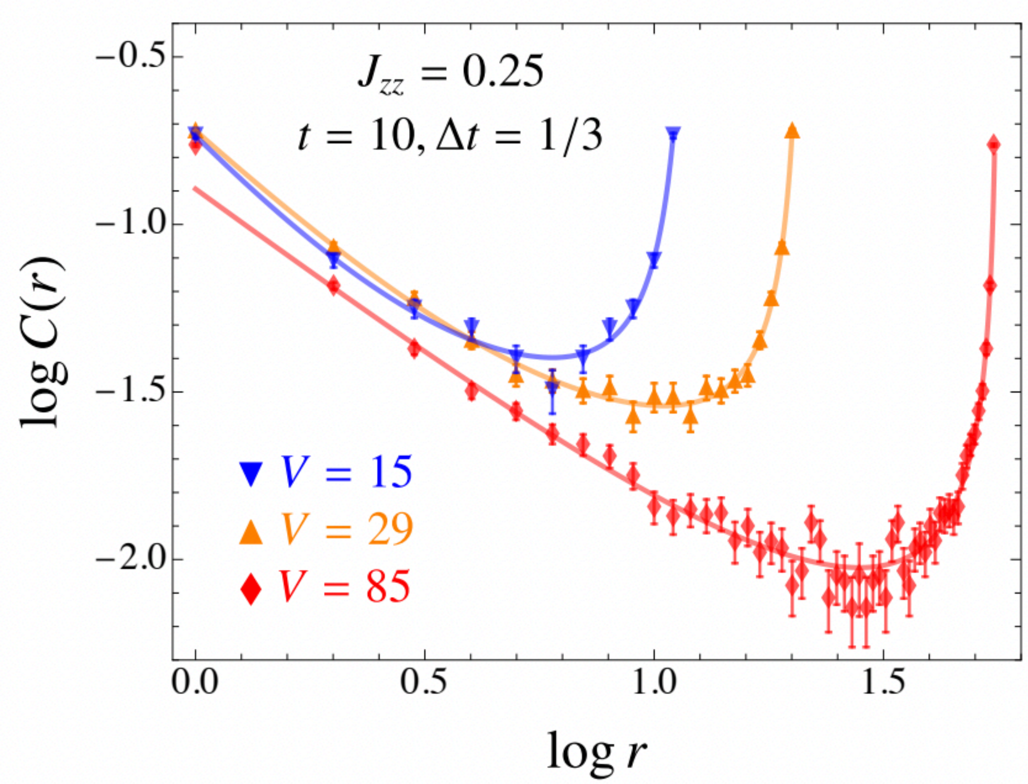
topological objects preparation



Huang, **YYL**, Liu, Wang, Zhang,
in preparation

Holography





[**YYL,** Sajid, Unmuth-Yockey, arXiv:2312.10544]

entanglement entropy?

"Quantum potential for first-principle calculations!"

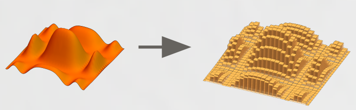
(2030s) narrow down the framework with

- 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

2030s -

various methods



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

↓

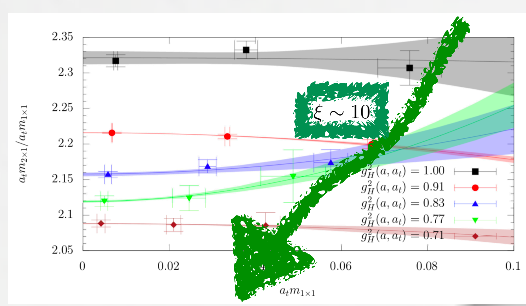
$\mathcal{U}\,|G\rangle^L \rightarrow |\psi_0\rangle$

↓

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

↓

$\langle \mathcal{O} \rangle$



2020 -

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

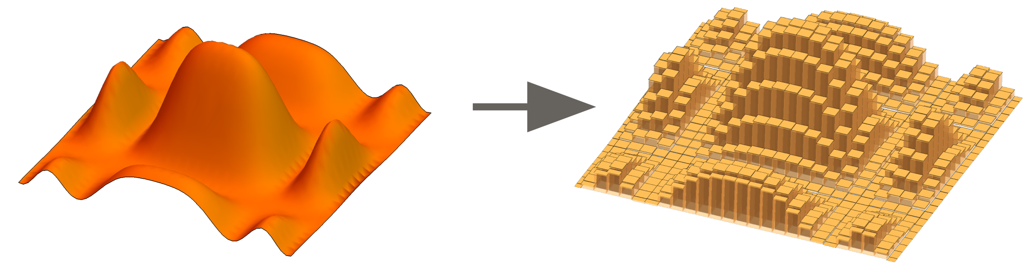
2011-

Thank you

BACK UP

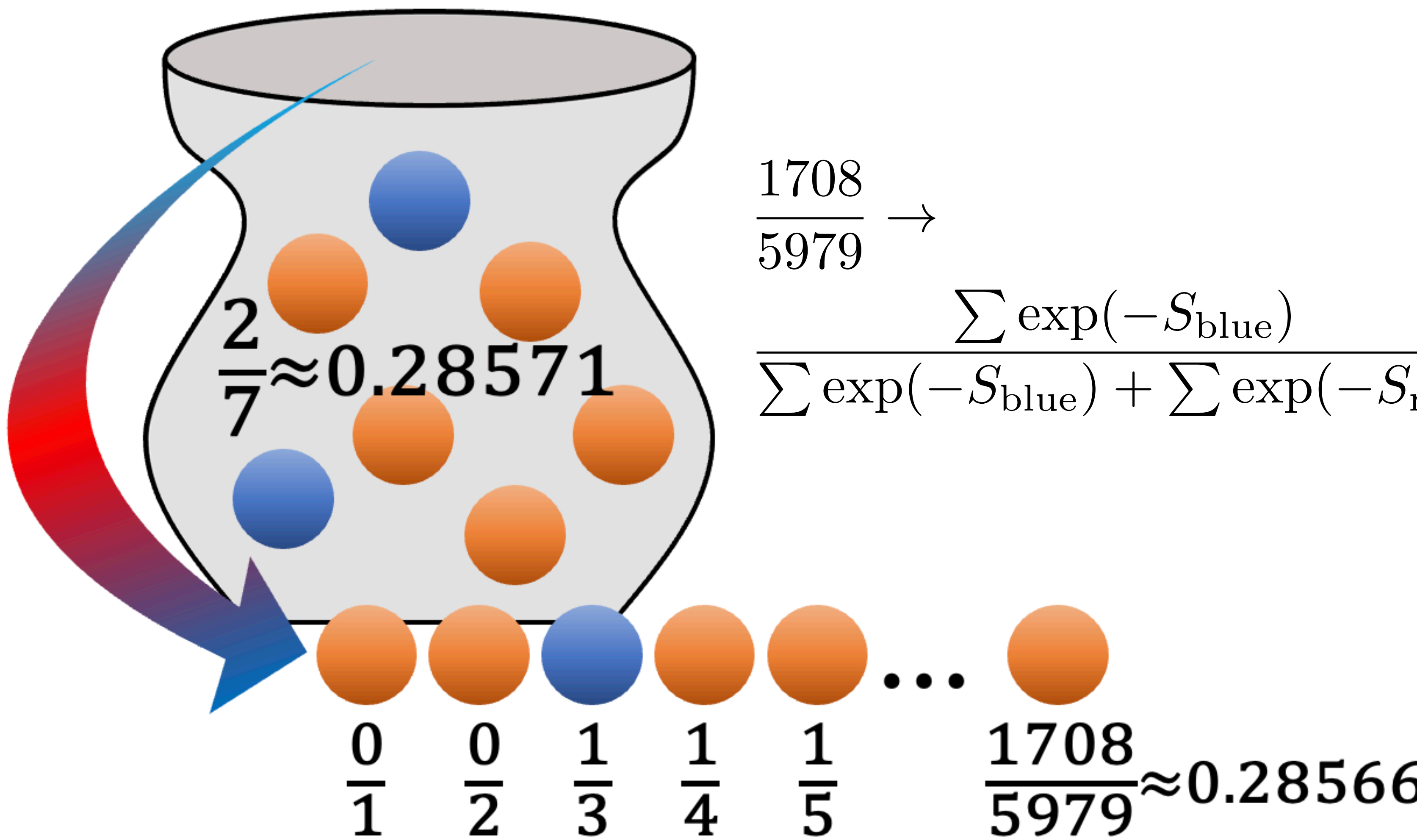
first-principle calculations of
non-perturbative physics

Lattice QCD



Path integral in Euclidean spacetime → Monte Carlo sampling of lattice field configurations

"Sign problem" if action is complex-valued



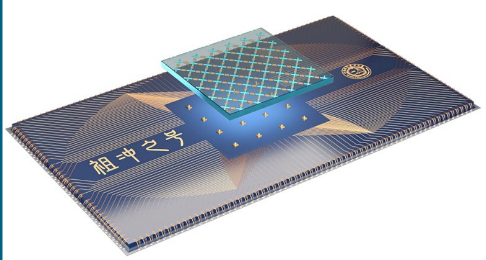
$$\frac{1708}{5979} \to \frac{\sum \exp(-S_{\text{blue}})}{\sum \exp(-S_{\text{blue}}) + \sum \exp(-S_{\text{red}})}$$

Quantum Computing

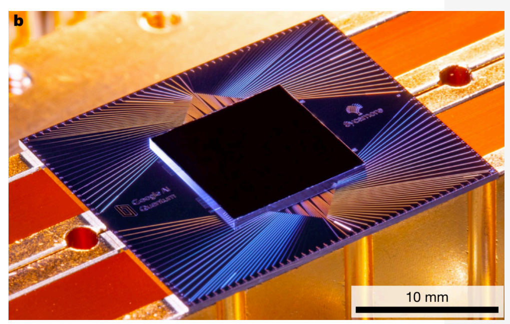
- Now - Noisy Intermediate Scale Quantum (NISQ) era

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

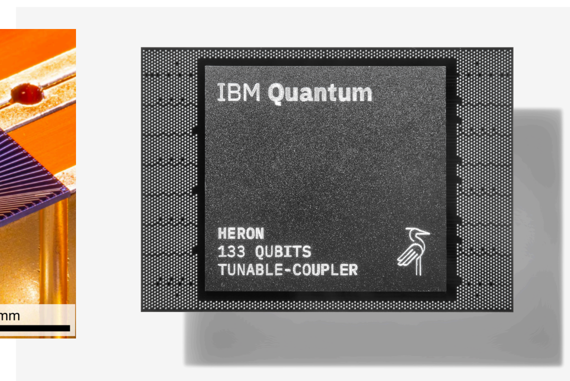
superconducting processor



176 qubits

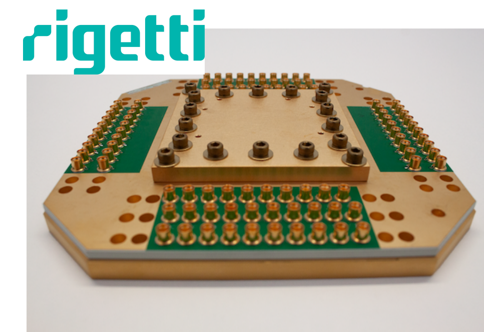


54 qubits



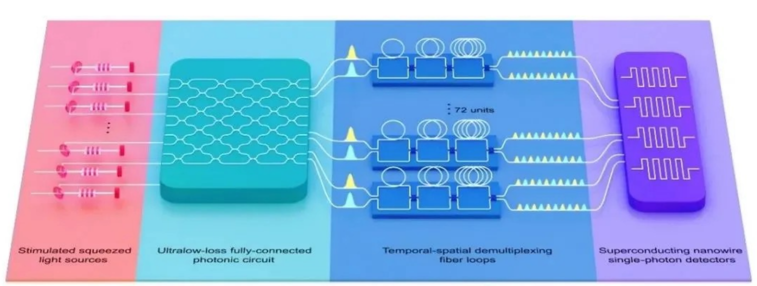
1121 qubits
access to 133 qubits

multi-chip quantum processor



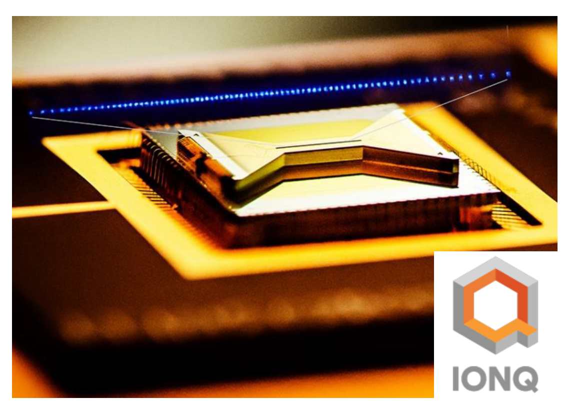
80 qubits

photon qubits



Jiuzhang - 255 qubits

trapped ion qubits

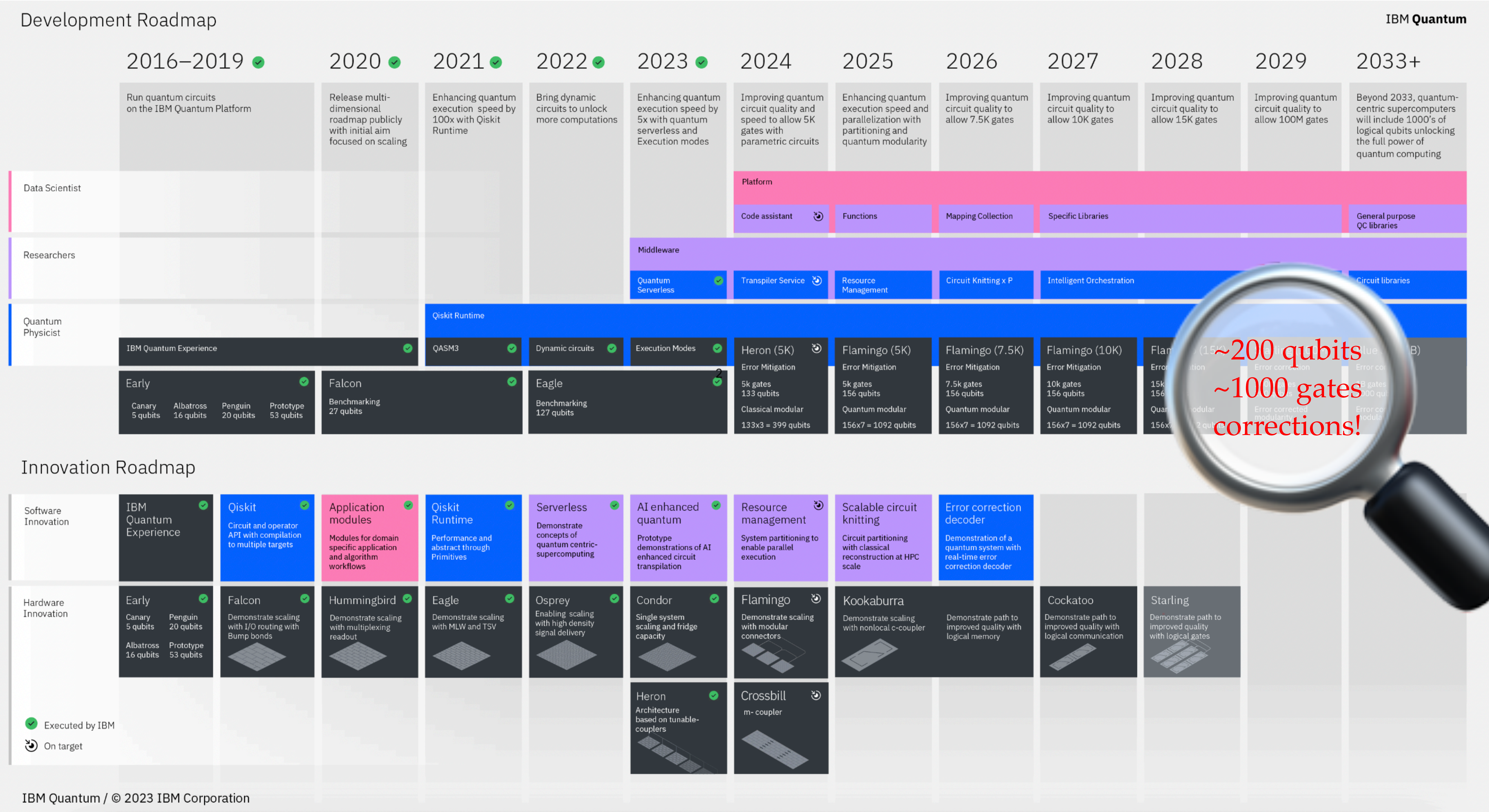


22 qubits

48 logical qubits

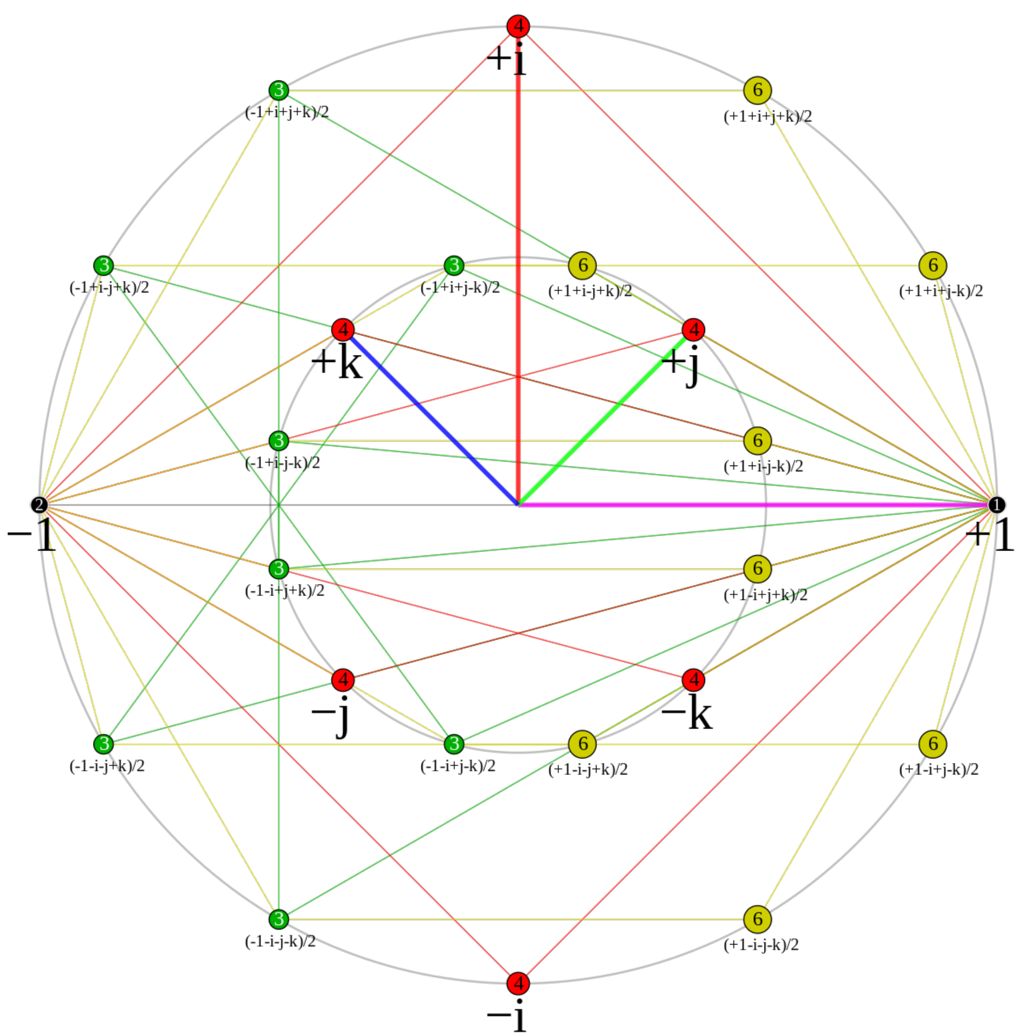
Quantum Computing

Next decades



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

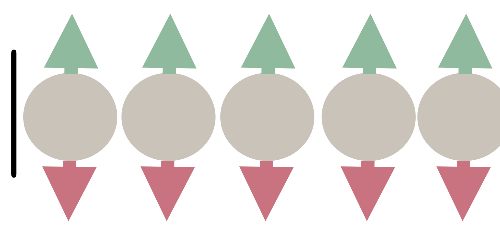
infinities in QFT



ordered product encoding: BT

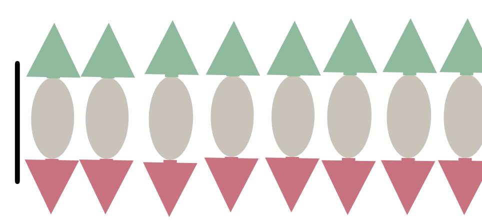
$$U = (-1)^m \mathbf{i}^n \mathbf{j}^o \mathbf{l}^{p+2q}$$

binary variables : m, n, o, p, q

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

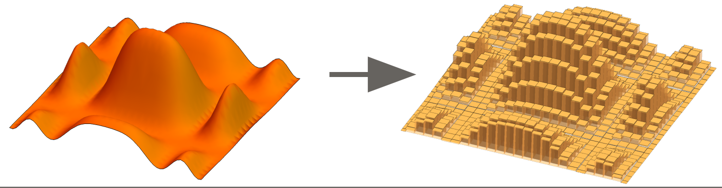
block product encoding: BT, BI

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

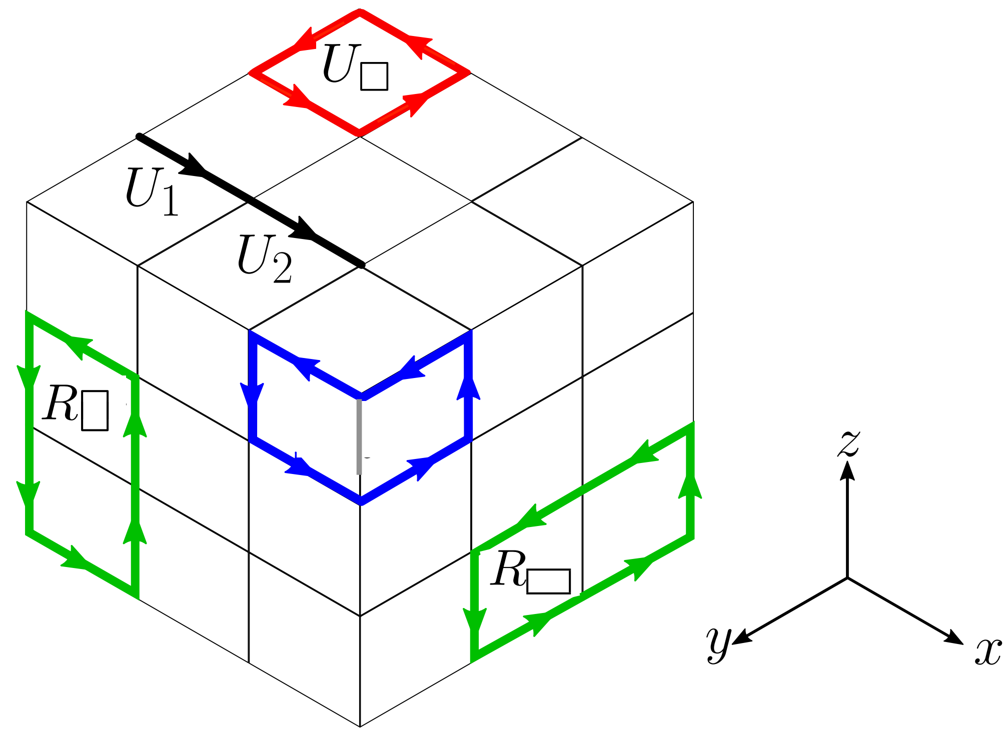
$$|U\rangle = |$$  $$\rangle$$

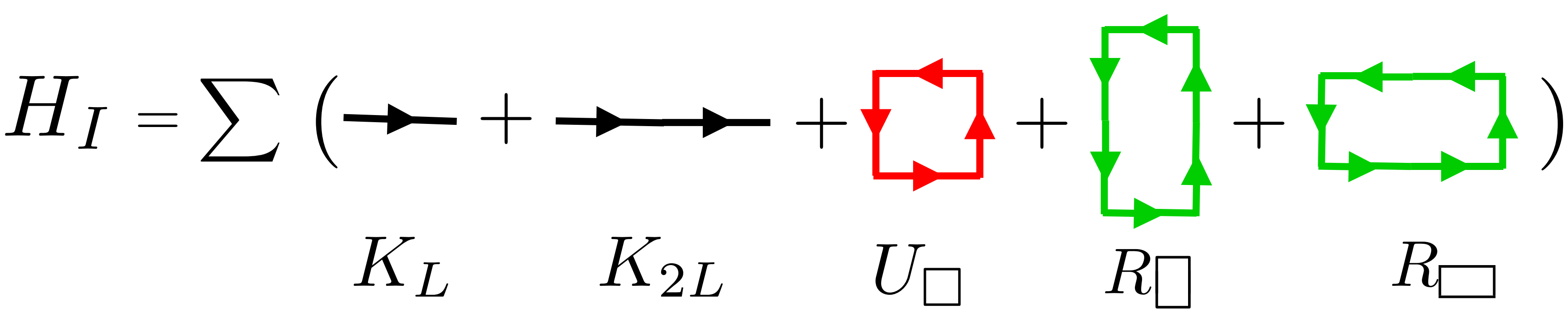
[Lamm, **YYL**, Shu, Wang, Bin, arXiv:2405.12890]

Discretization



infinities in QFT





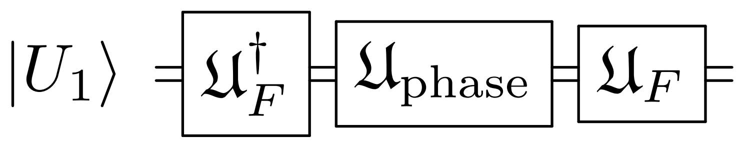
improved gauge invariant Hamiltonian

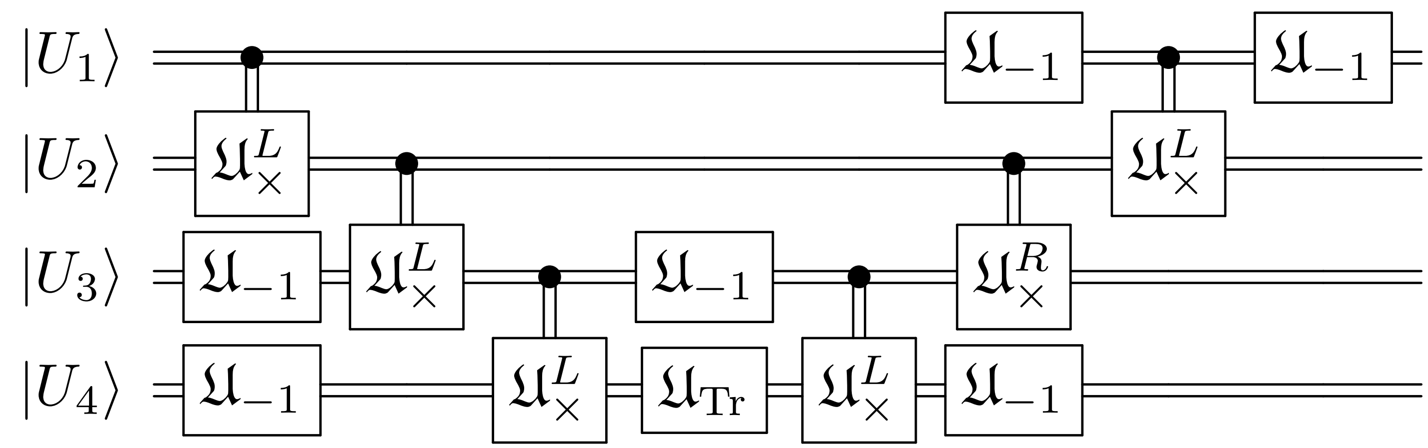
[Carena, Lamm, **YYL**, Liu, PRL. **129**, 051601]

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

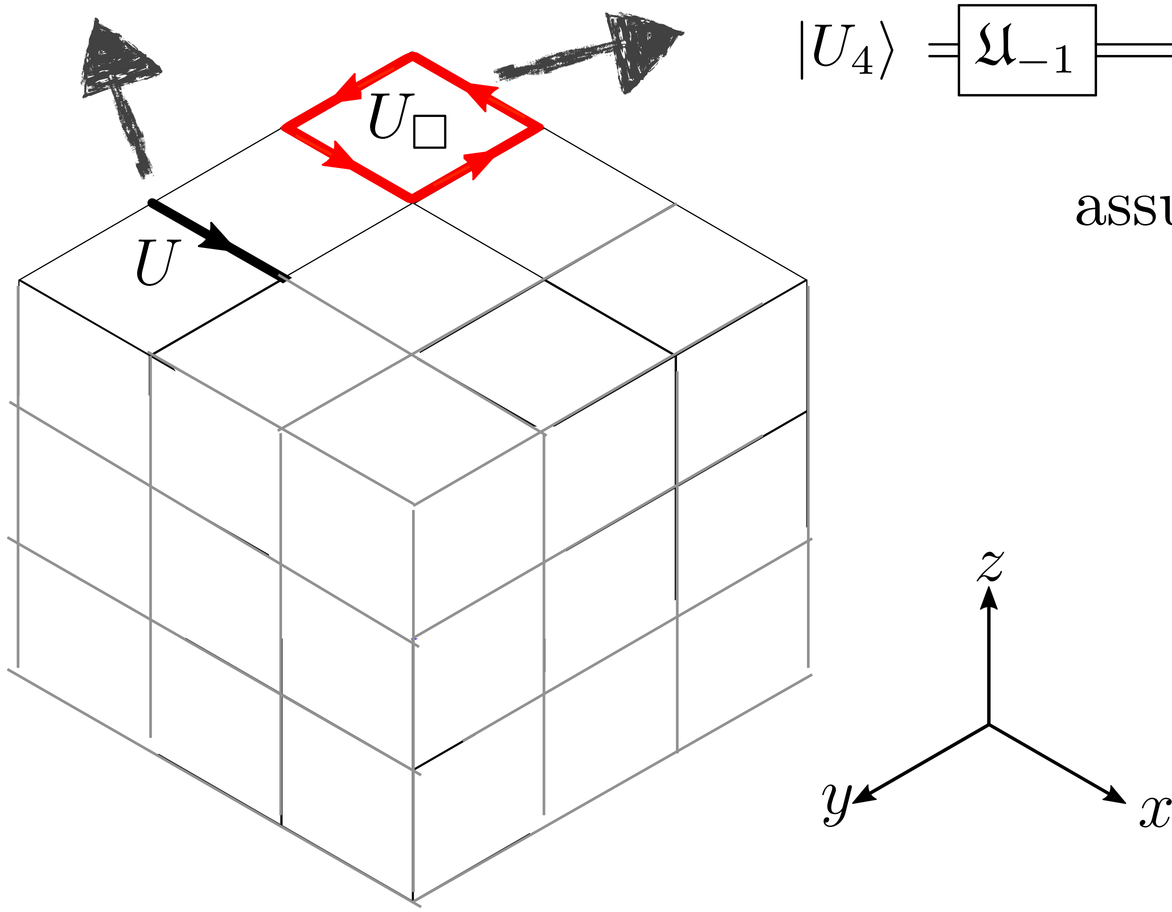
$$e^{-i\delta t U_{\square}}$$

$$e^{-i\delta t K_L}$$



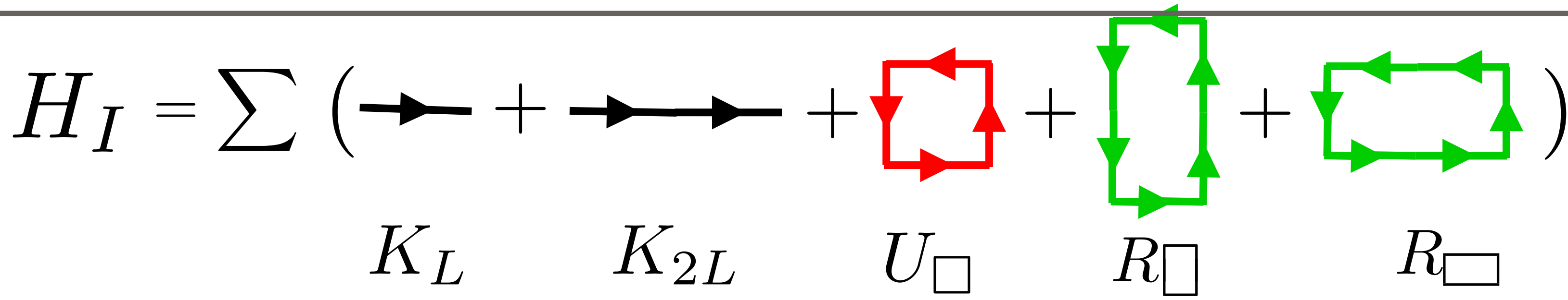


assuming linear register connectivity

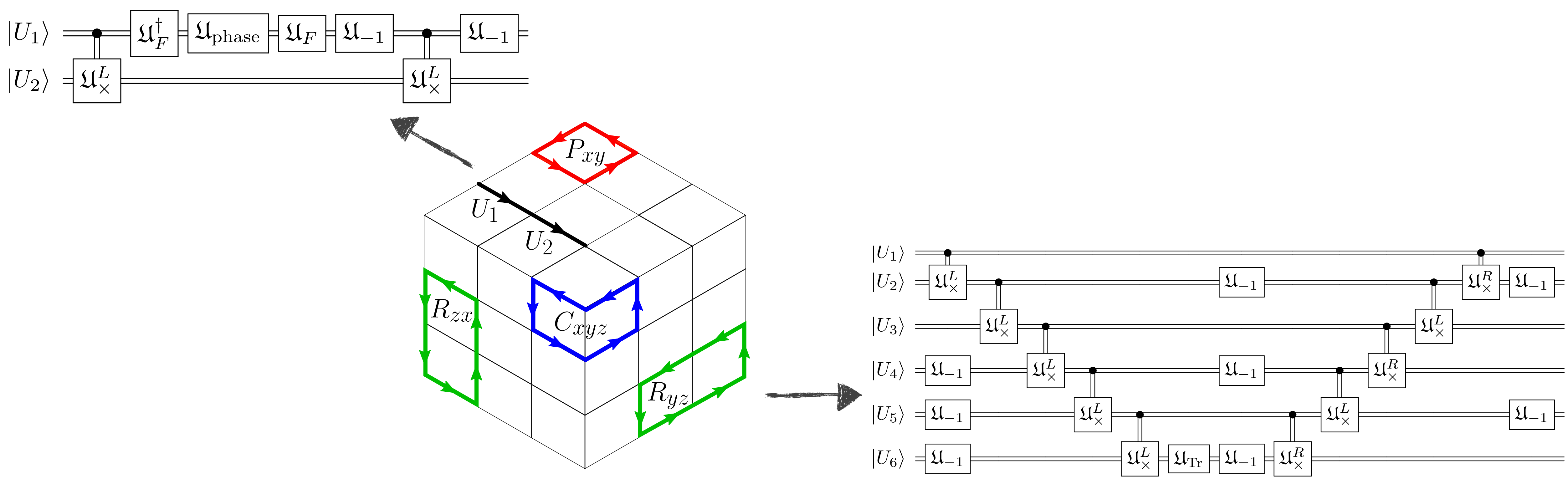


[Carena, Lamm,**YYL**, Liu, PRL. **129**, 051601]

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



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



For the discrete subgroups, will H_I improve the convergence to continuous group?

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