Title: Simulating one-dimensional quantum chromodynamics on a quantum computer: Real-time evolutions of tetra- and pentaquarks

Speakers: Christine Muschik

Collection: Quantum Simulators of Fundamental Physics

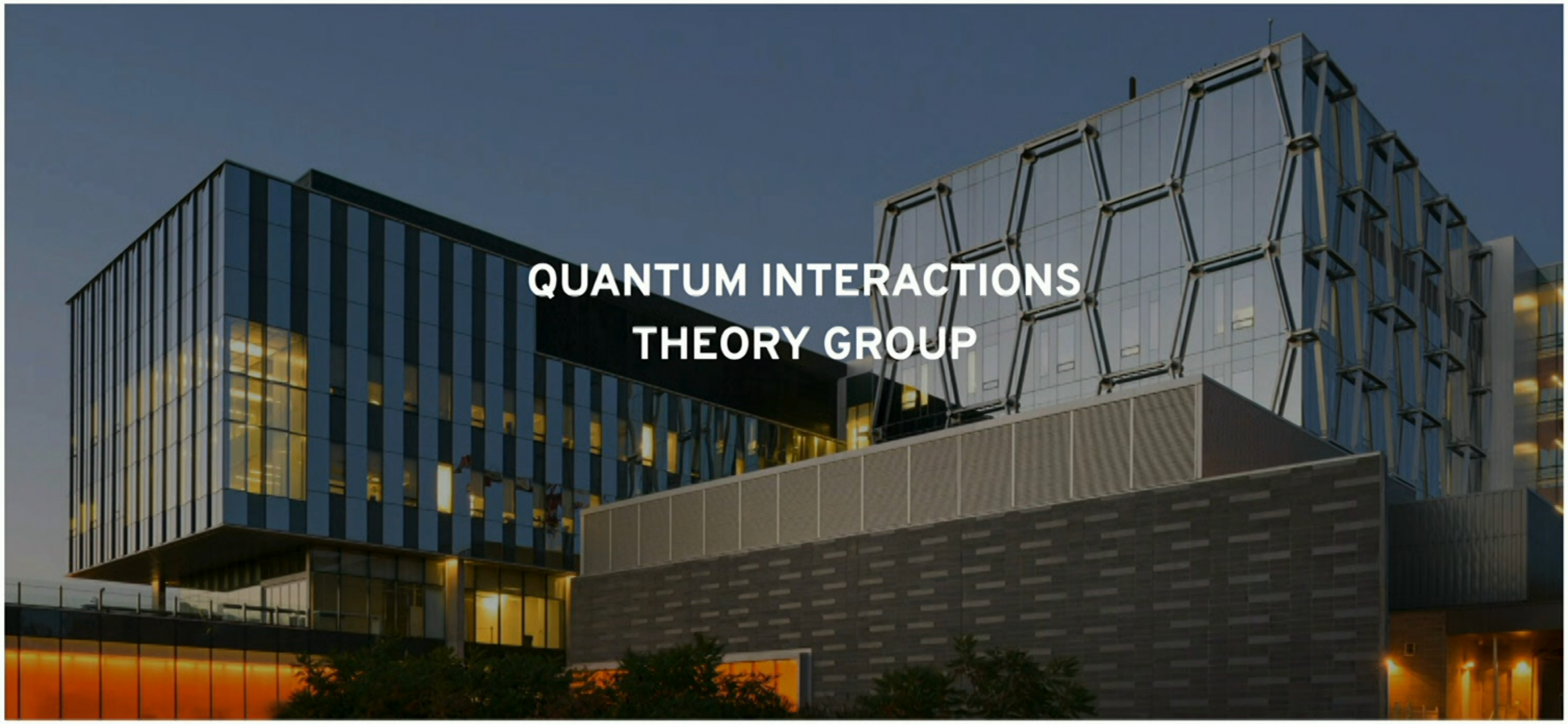
Date: June 05, 2023 - 10:30 AM

URL: https://pirsa.org/23060002

Abstract: ZOOM: https://pitp.zoom.us/j/95722860808?pwd=REYwSDdiK3pFamRJcjJwOW5FV1RPZz09

Teaching quantum computers to simulate particle physics

Christine Muschik



UNIVERSITY OF WATERLOO

IQC Institute for Quantum Computing

PERIMETER INSTITUTE

Quantum Simulation for particle physics

Numerical Simulations of Quantum Systems

Fundamental laws → Complex simulations → **Answers to our questions**

Condensed matter physics

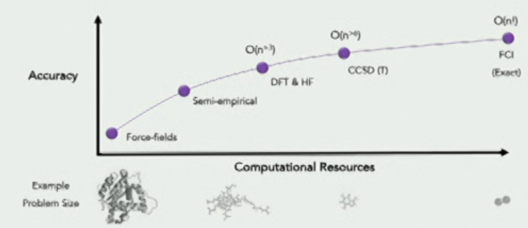
Material science:
Can we predict and design
solids with certain properties?
npj Computational Materials 6, 85 (2020).

Numerical Simulations of Quantum Systems

Fundamental laws → Complex simulations → **Answers to our questions**

Quantum chemistry

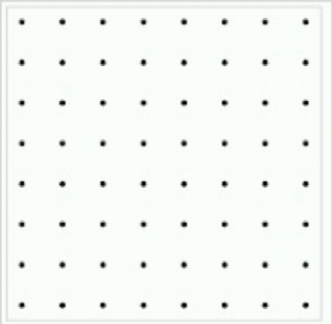
Drug design:
Which types molecules have the desired properties?



Simulating the peniccilin molecule to chemical accuracy requires a computer of the size of the visible universe (Cambride Quantum)

Traditional lattice gauge theory

Discretize space and time → Path integral formalism → Monte Carlo Methods



$$\langle \mathcal{O} \rangle = \int \mathcal{D}_{\text{Fields}} \mathcal{O} e^{-S} / \int \mathcal{D}_{\text{Fields}} e^{-S}$$

Immensely successful classical approach, despite the quantumness of the problem!

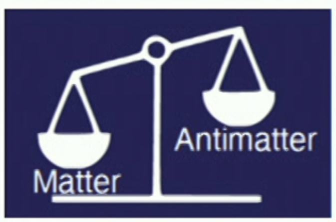
See for example FLAG review 2021

DOE High Energy Physics Exascales Requirement Review

Inaccessible to traditional lattice gauge theory

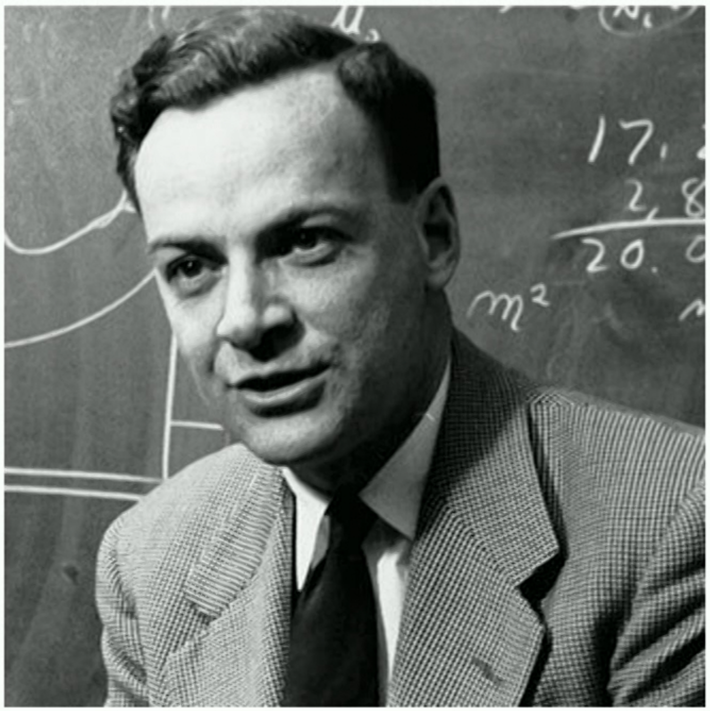
Afflicted by sign problems

Topological terms	Real time evolutions	Chemical potentials
Fundamental symmetries	Dynamical processes	High matter density



"Nature is quantum, goddamn it!

So if we want to simulate it, we need a quantum computer."



Richard Feynman

Quantum simulations of gauge theories for particle physics

2005 | 2011 | 2016 | Now

Early theory proposals

Early review: U. J. Wiese, Annalen der Physik 525, 777 (2013).

Earliest Visionaries:
Jordan, Lee, Preskill, Science (2012).
Cirac, Zohar, Reznik, Wiese, Zoller, Lewenstein and others…

Exp. demonstration of a digital quantum simulation of a lattice gauge theory

[Nature 534, 516 (2016)]

More exciting experiments

Review: Bañuls, M. et al. Simulating Lattice Gauge Theories within Quantum Technologies. Eur. Phys. J. D 74, 165 (2020).

Highly active field

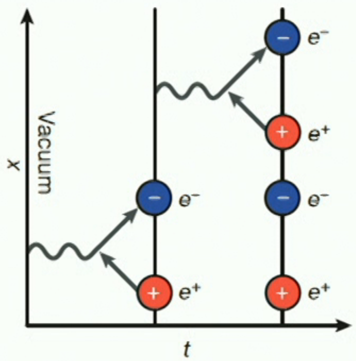
- dedicated conferences
- dedicated funding schemes
- special issues

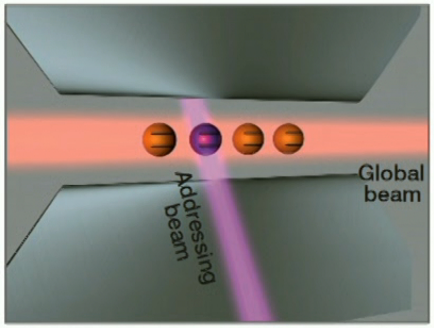
Real-time dynamics of lattice gauge theories with a few-qubit quantum computer

Esteban A. Martinez, Christine A. Muschik, Philipp Schindler, Daniel Nigg, Alexander Erhard,
Markus Heyl, Philipp Hauke, Marcello Dalmonte, Thomas Monz, Peter Zoller & Rainer Blatt

Nature **534**, 516–519 (2016)

- Trapped ion quantum computer
- Quantum simulation of 1D-QED
- Real-time dynamics of electron-positron pair creation.





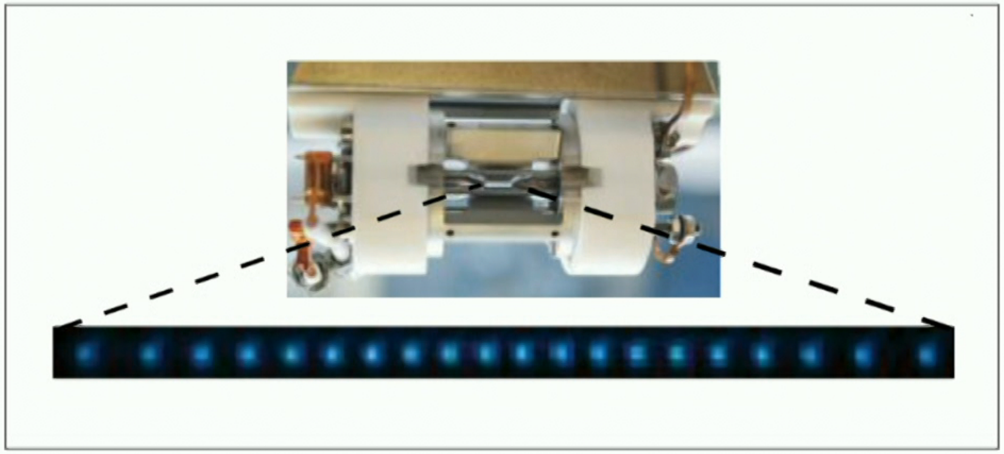
Theory + Experiment (in "Top 10 breakthroughs in physics 2016)

Self-verifying variational quantum simulation of lattice models

C. Kokail, C. Maier, R. van Bijnen, T. Brydges, M. K. Joshi, P. Jurcevic, C. A. Muschik, P. Silvi, R. Blatt, C. F. Roos & P. Zoller

Nature **569**, 355–360 (2019)

- VQE on trapped ion quantum simulator
- Application = 1D-QED



Describing stable matter as we know it requires non-Abelian gauge theories

Gauge Theories

Abelian

Gauge singlets involve as much matter as antimatter

Non-Abelian

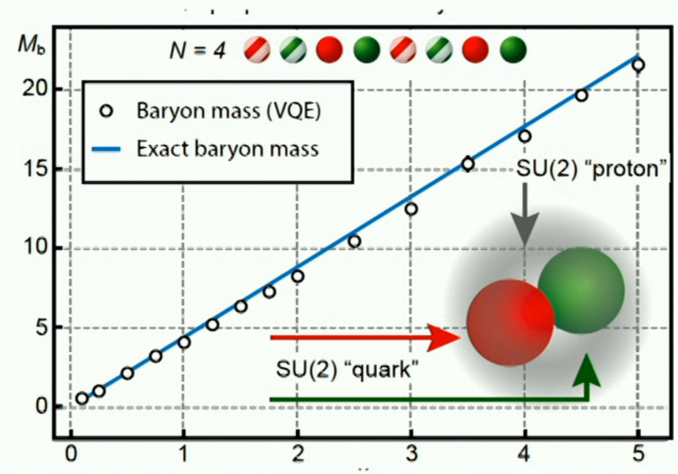
Gauge singlets can be built from matter only

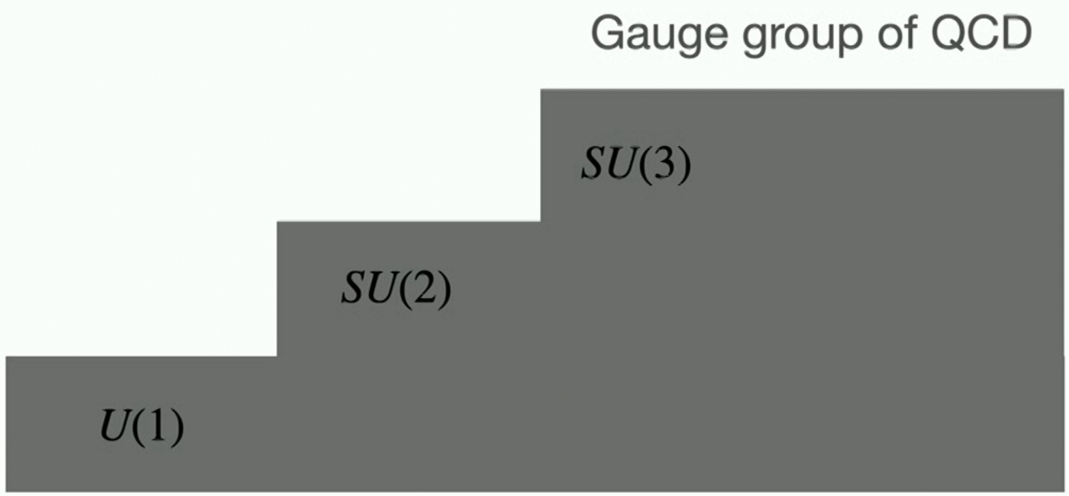
SU(2) hadrons on a quantum computer via a variational approach

Yasar Y. Atas, Jinglei Zhang, Randy Lewis, Amin Jahanpour, Jan F. Haase & Christine A. Muschik

Nature Communications **12**, Article number: 6499 (2021)

- Superconducting quantum simulator (IBM)
- Quantum simulation of 1D-SU(2)




Gauge group of QCD
SU(3)
SU(2)
U(1)

arXiv > quant-ph > arXiv:2207.03473

[Submitted on 7 Jul 2022]

Real-time evolution of SU(3) hadrons on a quantum computer

Yasar Y. Atas, Jan F. Haase, Jinglei Zhang, Victor Wei, Sieglinde M.-L. Pfaendler, Randy Lewis, Christine A. Muschik

The theory of quarks and gluons - quantum chromodynamics - has been known for decades. Yet it is not fully understood. A recent example is the discovery of tetraquarks that led to a new research field. To address the many unsolved questions of the standard model, nonperturbative calculations are crucial. Quantum computers could simulate problems for which traditional QCD methods are inapplicable, such as real-time evolutions. We take a key step in exploring this possibility by performing a real-time evolution of tetraquark physics in one-dimensional SU(3) gauge theory on a superconducting quantum computer. Our experiment represents a first quantum computation involving quarks with three colour degrees of freedom, i.e. with the gauge group of QCD.

Simulating 1D-QCD on a quantum computer

Theory + Experiment:
- Tetraquarks
- Real-time evolution

Simulate quarks with three colours, i.e. the gauge group of QCD

Simulating 1D-QCD on a quantum computer

Related work:

Preparations for Quantum Simulations of Quantum Chromodynamics in 1+1 Dimensions: (I) Axial Gauge

Roland C. Farrell, Ivan A. Chernyshev, Sarah J. M. Powell, Nikita A. Zemlevskiy, Marc Illa, Martin J. Savage

Tools necessary for quantum simulations of $1+1$ dimensional quantum chromodynamics are developed. When formulated in axial gauge and with two flavors of quarks, this system requires 12 qubits per spatial site with the gauge fields included via non-local interactions. Classical computations and D-Wave's quantum annealer Advantage are used to determine the hadronic spectrum, enabling a decomposition of the masses and a study of quark entanglement. Color edge states confined within a screening length of the end of the lattice are found. IBM's 7-qubit quantum computers, ibmq_jakarta and ibm_perth, are used to compute dynamics from the trivial vacuum in one-flavor QCD with one spatial site. More generally, the Hamiltonian and quantum circuits for time evolution of $1+1$ dimensional $SU(N_c)$ gauge theory with N_f flavors of quarks are developed, and the resource requirements for large-scale quantum simulations are estimated.

M. Savage,
University of Washington

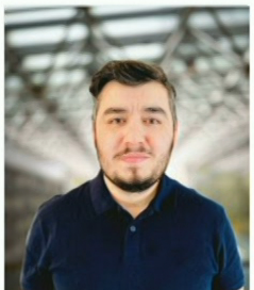
Experimental demonstration of color neutral objects (gauge singlets/color singlets).

Color neutral states of SU(3): invariant under arbitrary rotations in color space

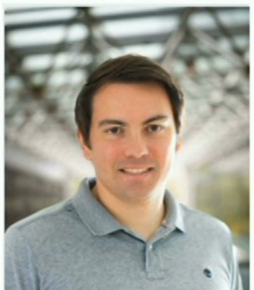
Involve all the color charges available in the theory i.e. red, green, and blue (and their anticolors).
In contrast to Abelian quantum electrodynamics (QED), where a singlet state involves electron-positron pairs only.

Color singlet states are the relevant physical states,
→ important step towards the understanding, description and prediction of more complex and realistic experiments

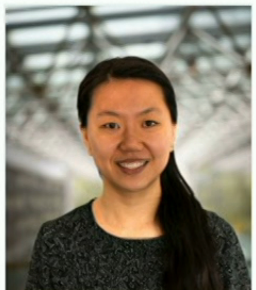
Simulating 1D-QCD on a quantum computer



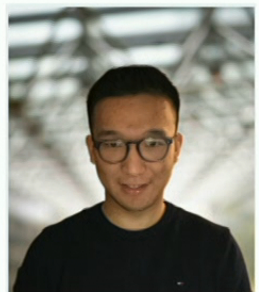
YASAR ATAS
IQC



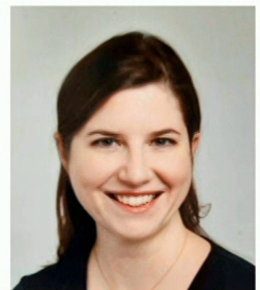
JAN FRIEDRICH HAASE
IQC



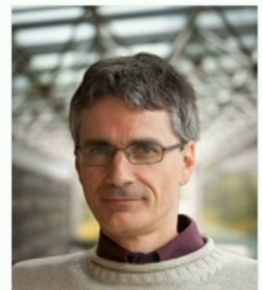
JINGLEI ZHANG
IQC



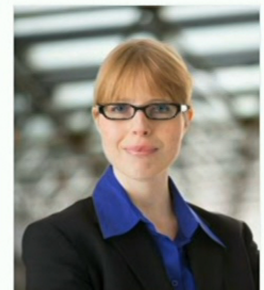
VICTOR WEI
IQC



SIEGLINDE PFÄNDLER
IBM



RANDY LEWIS
YORK

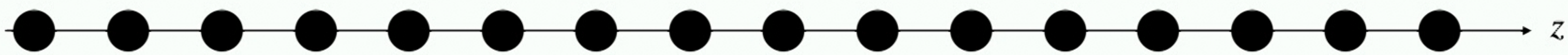


CHRISTINE MUSCHIK
IQC

Lattice QCD

in one dimension

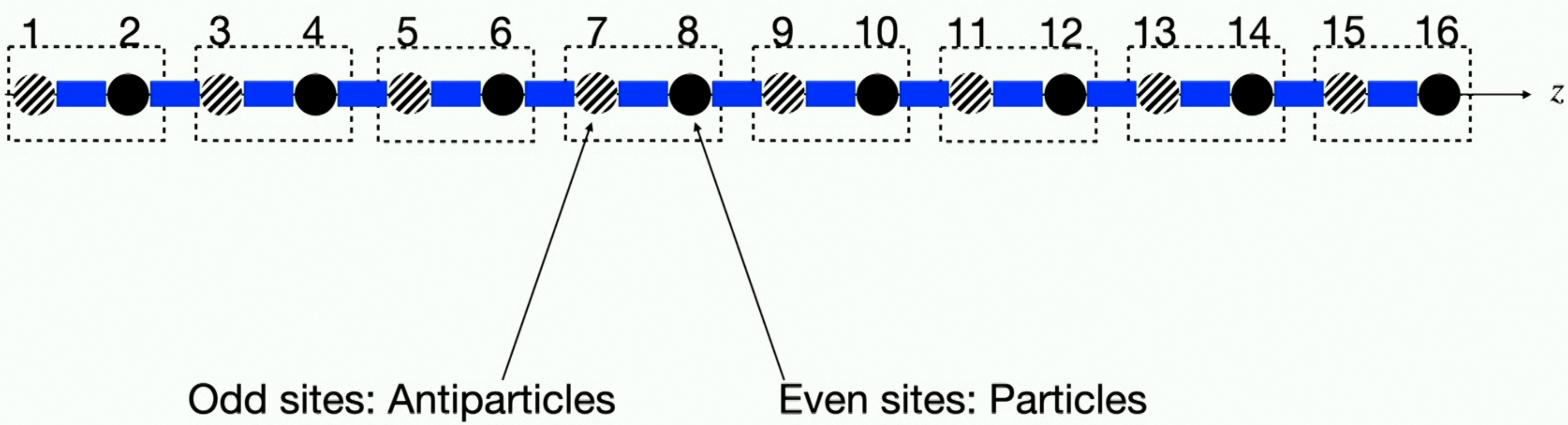
Lattice QCD
in one dimension



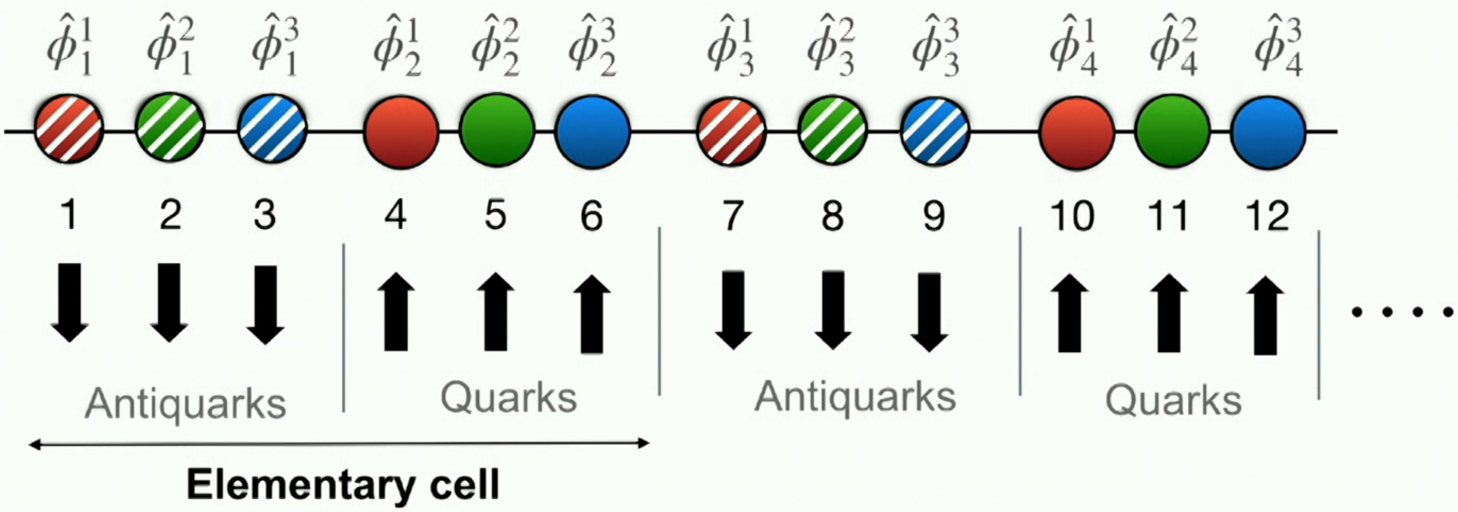
Lattice QCD
in one dimension

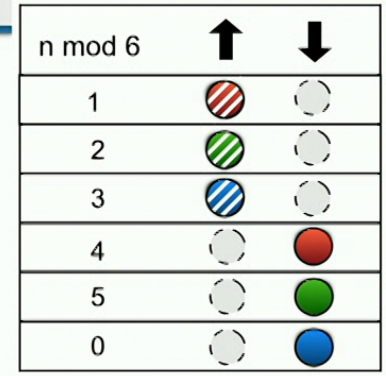
Matter: on vertices
Gauge fields: on links

Lattice QCD
in one dimension

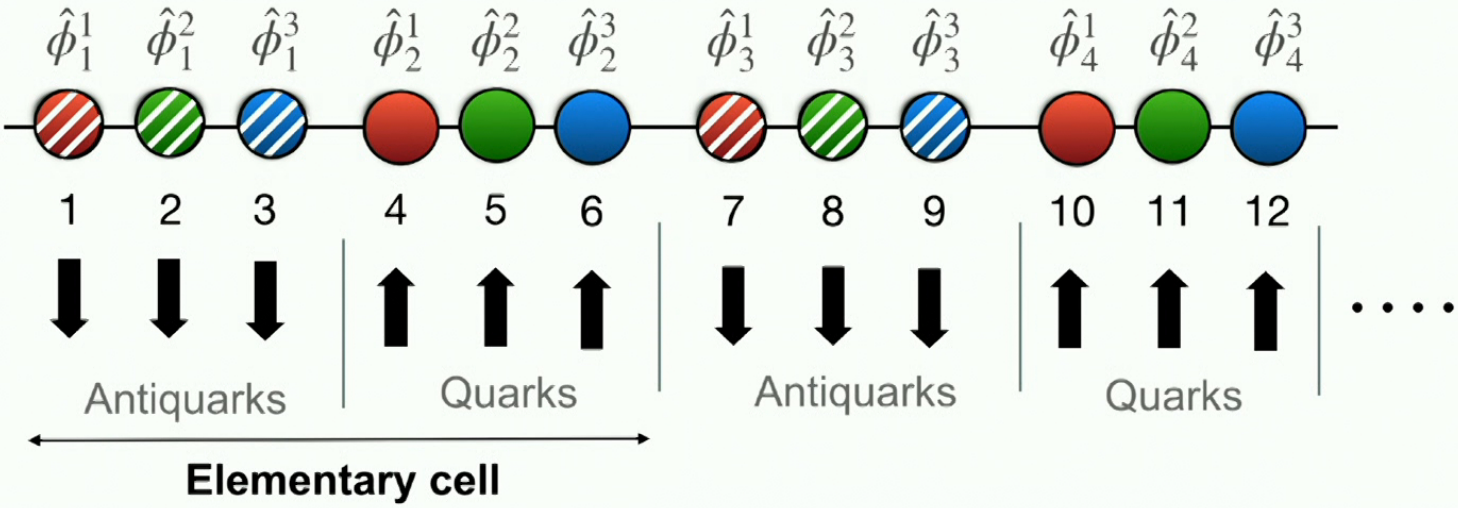


Lattice QCD
in one dimension





Lattice QCD
in one dimension



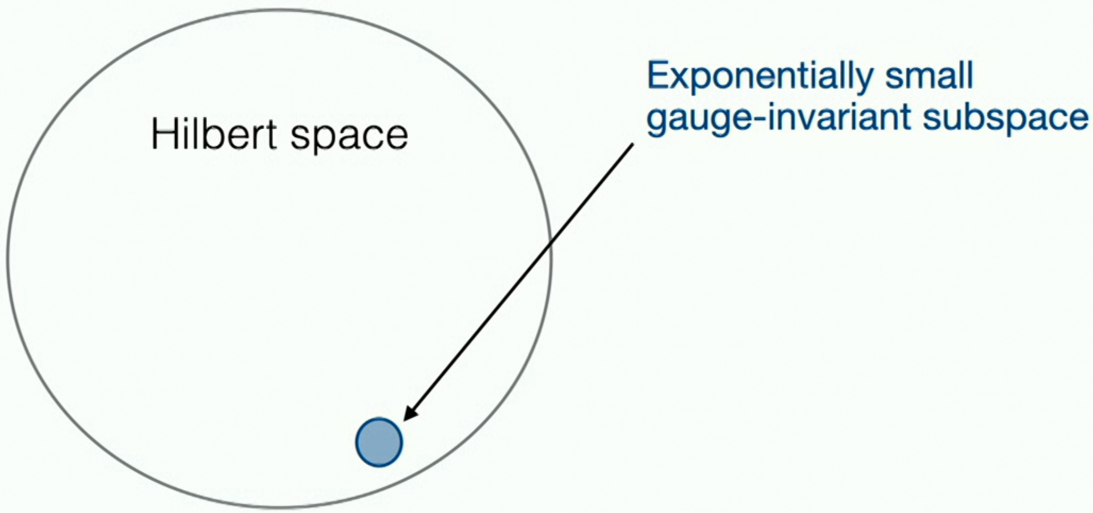
Lattice QCD
in one dimension

Open boundary conditions → gauge fields can be eliminated by a gauge transformation*

- Hamiltonian description in terms of matter fields only
- Resource-efficient approach for quantum simulations
- Colour-electric fields contribute
- Colour-electric fields can be accessed in the simulation

*Zohar, E. & Cirac, J. I. Eliminating fermionic matter fields in lattice gauge theories. Phys. Rev. B 98, 075119 (2018).

Resource-efficient encoding of gauge theories



Quantum 5, 393 (2021), PRX Quantum 2, 030334 (2021).

Lattice QCD

in one dimension

$$\hat{H} = \hat{H}_{kin} + \tilde{m}\hat{H}_m + \frac{1}{2x}\hat{H}_e$$

Lattice QCD
in one dimension

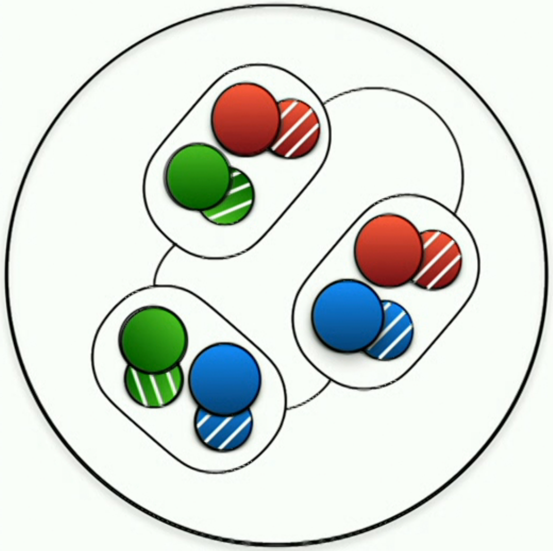
$$\hat{H} = \hat{H}_{kin} + \tilde{m}\hat{H}_m + \frac{1}{2x}\hat{H}_e$$

$$\hat{H}_{kin} = \frac{1}{2}\sum_{n=1}^{N-1}(-1)^n \left(\hat{\sigma}^+_{3n-2}\hat{\sigma}^z_{3n-1}\hat{\sigma}^z_{3n}\hat{\sigma}^-_{3n+1} - \hat{\sigma}^+_{3n-1}\hat{\sigma}^z_{3n}\hat{\sigma}^z_{3n+1}\hat{\sigma}^-_{3n+2} + \hat{\sigma}^+_{3n}\hat{\sigma}^z_{3n+1}\hat{\sigma}^z_{3n+2}\hat{\sigma}^-_{3n+3} + \mathrm{H.\,c.}\right)$$

$$\hat{H}_m = \frac{1}{2}\sum_{n=1}^{N}\left[(-1)^n\left(\hat{\sigma}^z_{3n-2} + \hat{\sigma}^z_{3n-1} + \hat{\sigma}^z_{3n}\right) + 3\right]$$

$$\hat{H}_e = \sum_{n=1}^{N-1}\left(\sum_{m\leqslant n}\hat{\mathbf{Q}}_m\right)^2$$

Tetraquark



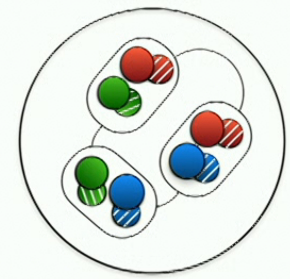
Lattice QCD
in one dimension

$$\hat{H} = \hat{H}_{kin} + \tilde{m}\hat{H}_m + \frac{1}{2x}\hat{H}_e$$

$$\tilde{m} = am \text{ and } x = 1/g^2a^2$$

Strong coupling limit: $\tilde{m} \to \infty$ and $x \to 0$

Tetraquark
in the strong coupling limit

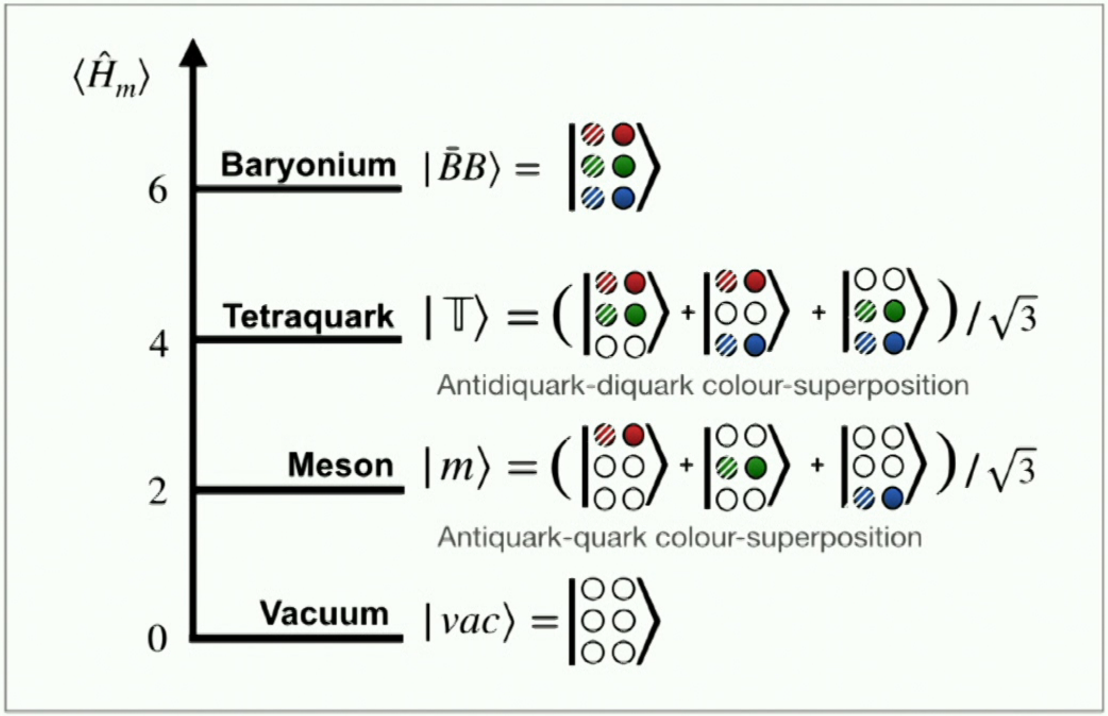


$$|\mathbb{T}\rangle = \Big($$  $$\Big)/\sqrt{3}$$

$$|\mathbb{T}\rangle = \frac{1}{\sqrt{3}}\big(|\uparrow\,\uparrow\,\downarrow\rangle|\downarrow\,\downarrow\,\uparrow\rangle + |\uparrow\,\downarrow\,\uparrow\rangle|\downarrow\,\uparrow\,\downarrow\rangle + |\downarrow\,\uparrow\,\uparrow\rangle|\uparrow\,\downarrow\,\downarrow\rangle\big)$$

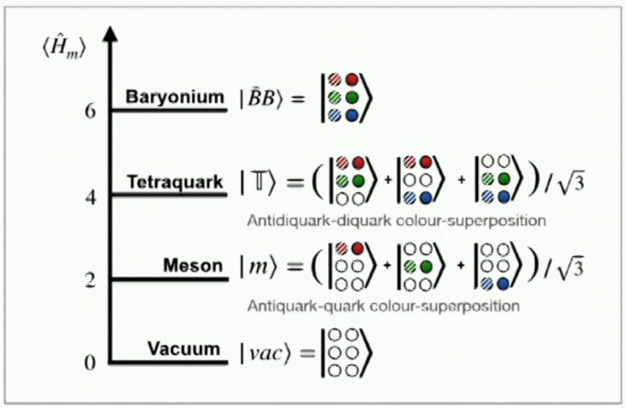
n mod 6	⬆	⬇
1		
2		
3		
4		
5		
0		

Basis states in the strong coupling limit in the B=0 subsector

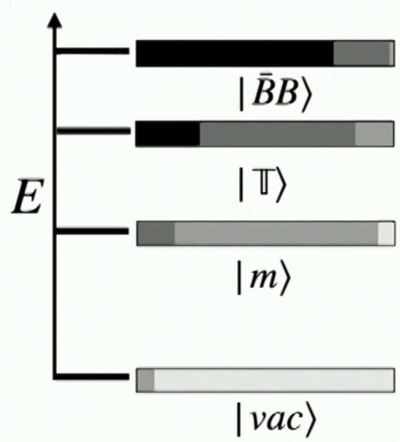


Energy Spectrum

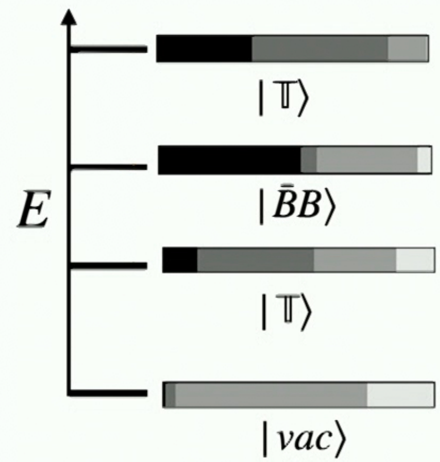
$\tilde{m} \to \infty$ and $x \to 0$



$\tilde{m} = 1.2,\ x = 0.8$



$\tilde{m} = 0.45,\ x = 0.8$



$|\bar{B}B\rangle$ $|\mathbb{T}\rangle$ $|m\rangle$ $|vac\rangle$

Quantum time evolution

Trotter protocol

- Up to 8 trotter steps (~80 gates)
- Reduction to 3 qubits
- Observe mean particle number versus time

Experiment

- IBM quantum computer
- Error self-mitigation using randomised compiling

Quantum time evolution

Trotter protocol

- Up to 8 trotter steps (~80 gates)
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Experiment

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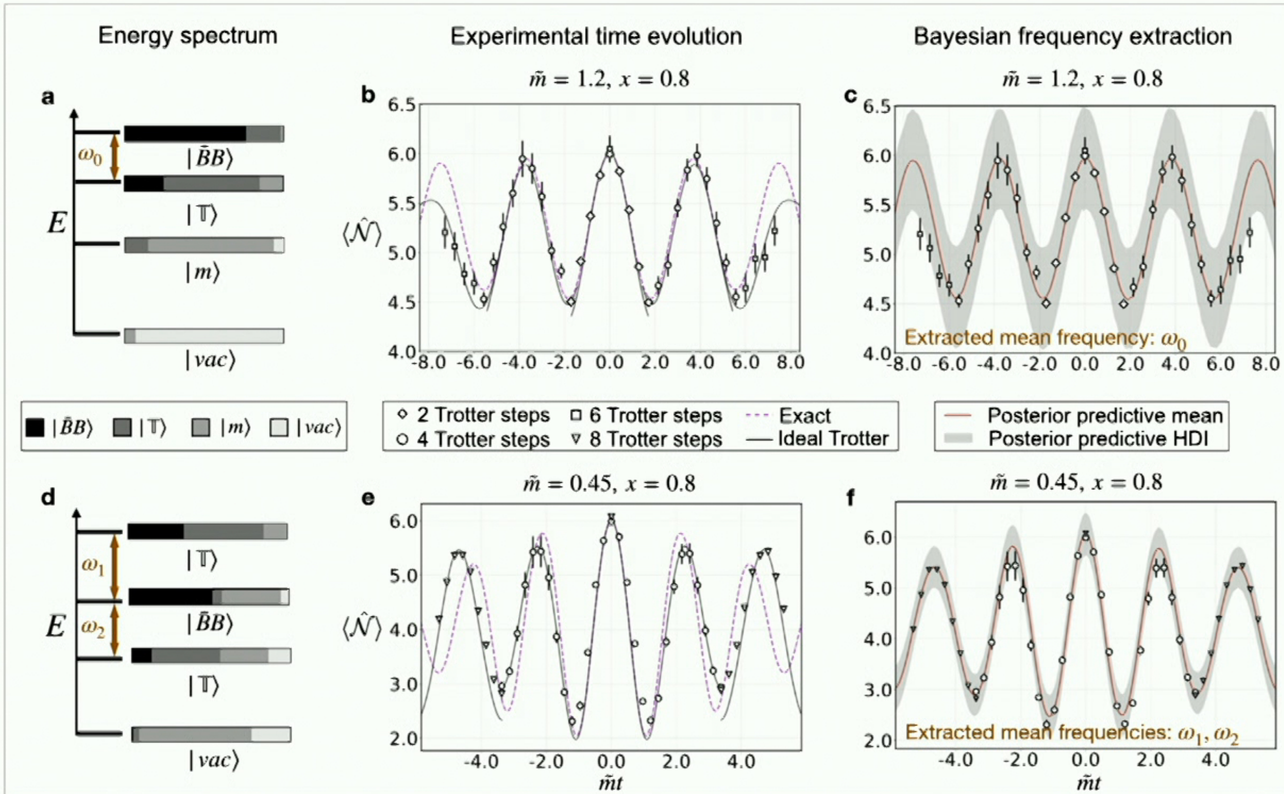
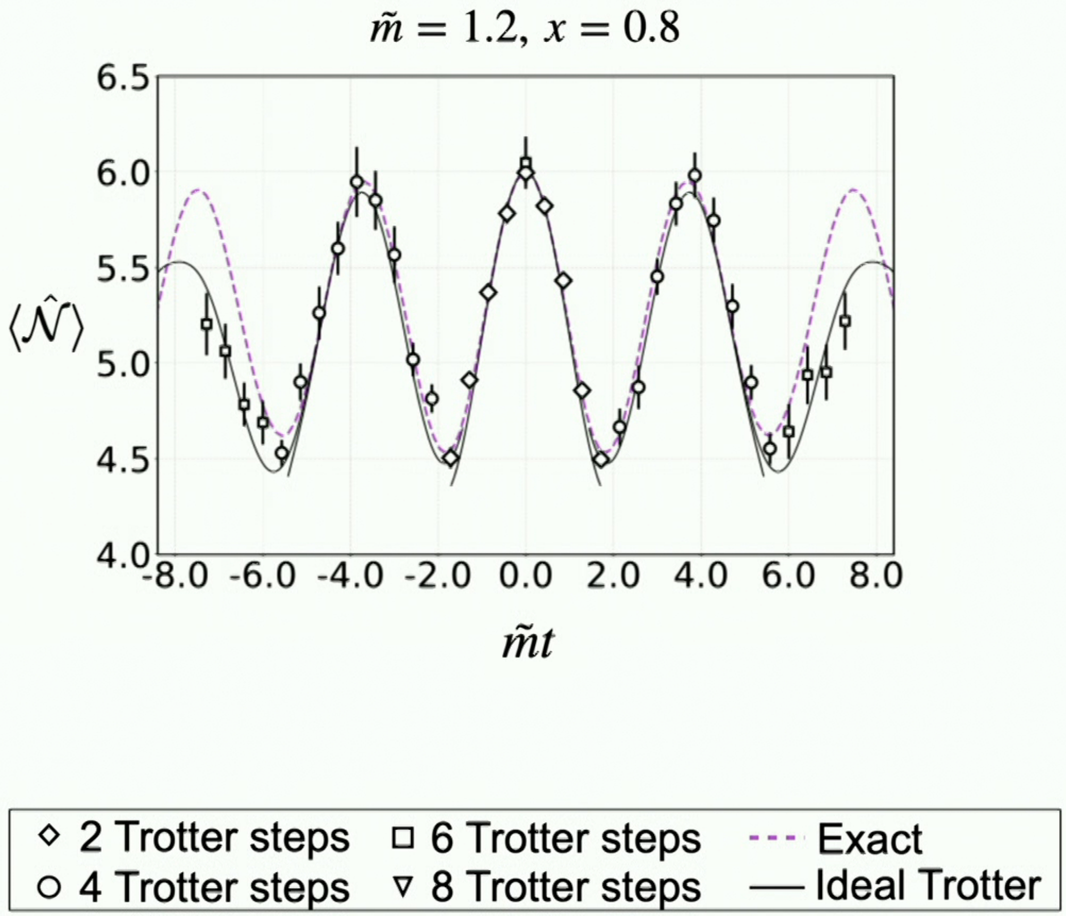
Results

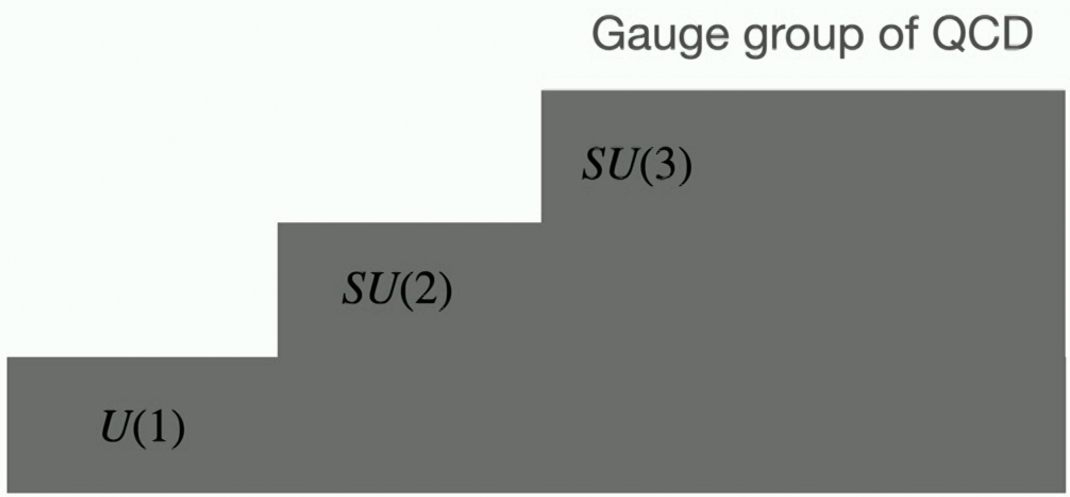


Energy spectrum
Experimental time evolution
Bayesian frequency extraction
a
b
c
$\tilde{m} = 1.2,\ x = 0.8$
$\tilde{m} = 1.2,\ x = 0.8$
$|\bar{B}B\rangle$
$|\mathbb{T}\rangle$
$|m\rangle$
$|vac\rangle$
ω_0
E
$\langle\hat{\mathcal{N}}\rangle$
Extracted mean frequency: ω_0
$|\bar{B}B\rangle$ $|\mathbb{T}\rangle$ $|m\rangle$ $|vac\rangle$
2 Trotter steps
4 Trotter steps
6 Trotter steps
8 Trotter steps
Exact
Ideal Trotter
Posterior predictive mean
Posterior predictive HDI
d
e
f
$\tilde{m} = 0.45,\ x = 0.8$
$\tilde{m} = 0.45,\ x = 0.8$
ω_1
ω_2
Extracted mean frequencies: ω_1, ω_2
$\tilde{m}t$


$\tilde{m} = 1.2,\ x = 0.8$
$\langle \hat{\mathcal{N}} \rangle$
$\tilde{m}t$
6.5
6.0
5.5
5.0
4.5
4.0
-8.0 -6.0 -4.0 -2.0 0.0 2.0 4.0 6.0 8.0
2 Trotter steps
4 Trotter steps
6 Trotter steps
8 Trotter steps
Exact
Ideal Trotter

Summary

- Time evolutions cannot be accessed with traditional lattice gauge theory
- Develop quantum protocols to simulate fundamental particle interactions



Experimental demonstration of color neutral objects (gauge singlets/color singlets).

Color neutral states of SU(3): invariant under arbitrary rotations in color space

Involve all the color charges available in the theory i.e. red, green, and blue (and their anticolors).
In contrast to Abelian quantum electrodynamics (QED), where a singlet state involves electron-positron pairs only.

Color singlet states are the relevant physical states,
→ important step towards the understanding, description and prediction of more complex and realistic experiments

Next steps

- More flavours
- Higher dimensions: 2D* and 3D
- Time evolutions of physical dynamical processes

*Quantum 5, 393 (2021), PRX Quantum 2, 030334 (2021).

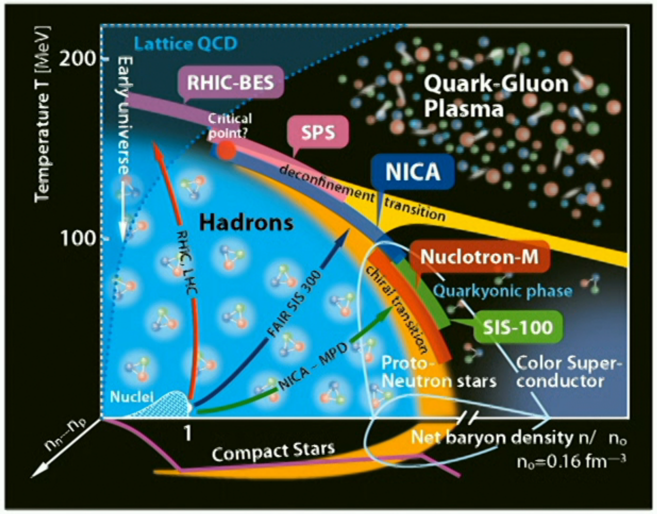
Outlook

Vast problem classes in particle physics are insurmountable for traditional approaches, (but not for quantum computers!)

Examples:

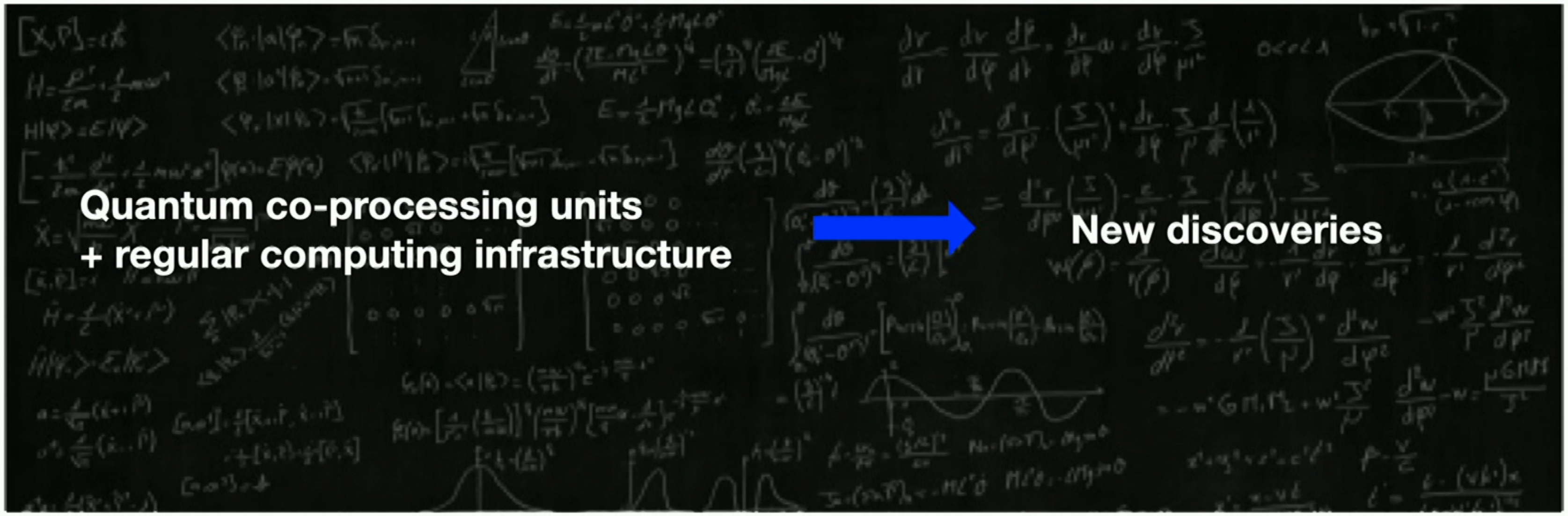
Real-time evolutions

High matter density



- Particle physics
- Nuclear physics
- Cosmology
- Astrophysics
- Condensed matter physics

Quantum enhanced scientific computing




Unexplored territory ahead