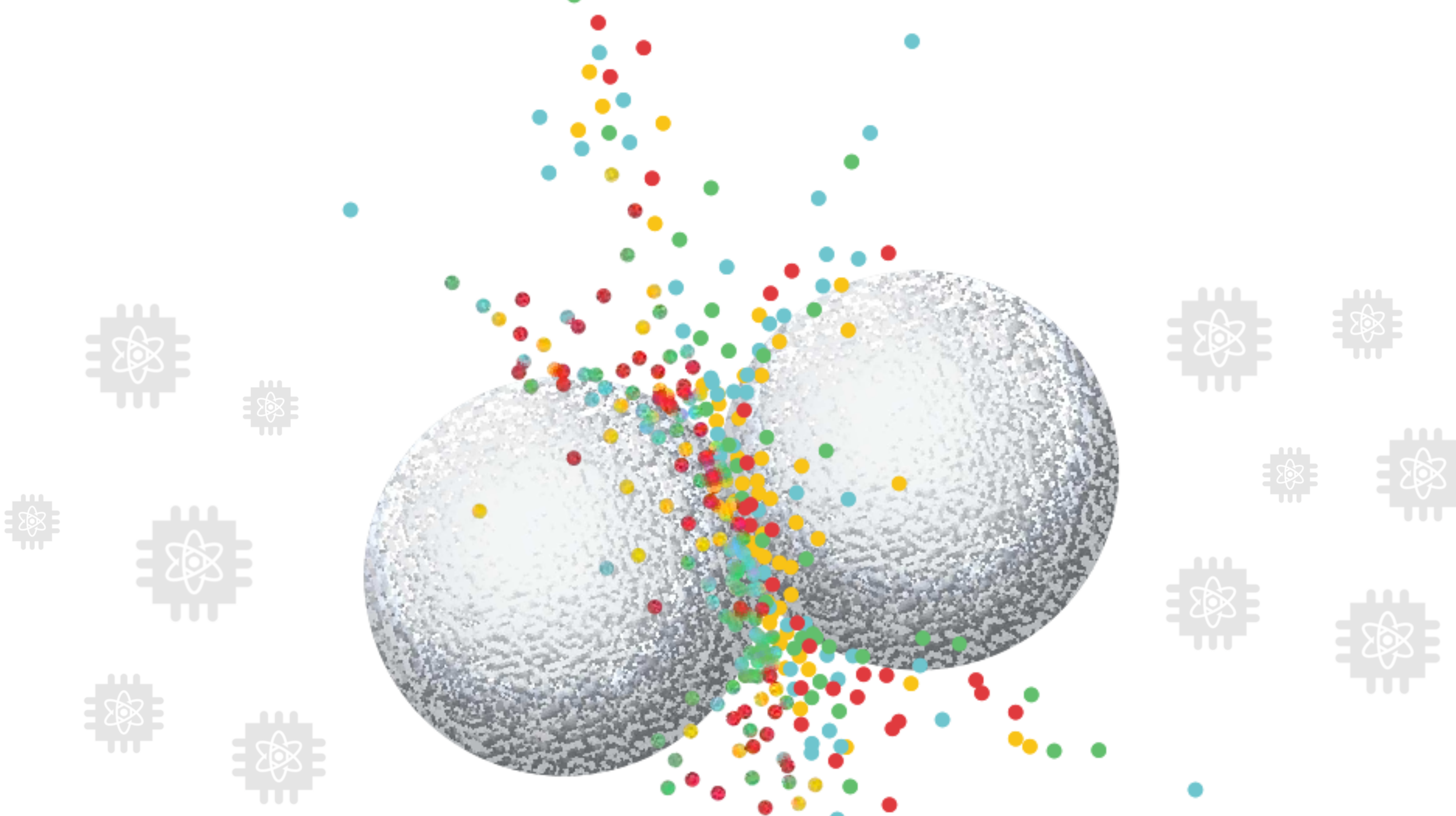


Hadrons and Hadron Interactions in QCD 2024 (HHIQCD 2024)
October-November 2024

Toward Quantum Simulating the Strong Force

Zohreh Davoudi
University of Maryland, College Park

JOINT CENTER FOR QUANTUM INFORMATION AND COMPUTER SCIENCE

MCFP MARYLAND CENTER for Fundamental Physics

Institute for Robust Quantum Simulation

Credit:
D. Dominguez/CERN

THE ORGANIZERS ASKED ME TO GIVE A REVIEW TALK…
BUT SHOULD I GO WITH A MORE FOCUSED PHYSICS TALK?

THE ORGANIZERS ASKED ME TO GIVE A REVIEW TALK…
BUT SHOULD I GO WITH A MORE FOCUSED PHYSICS TALK?

i) Quantum-thermodynamics framework for non-equilibrium processes in gauge theories (and thermalization probing)

ZD, Jarzynski, Mueller, Oruganti, Powers, and Yunger Halpern, accepted to PRL, arXiv:2404.02965 [quant-ph].
ZD, Jarzynski, Mueller, Oruganti, Powers, and Yunger Halpern, manuscript in progress (2024).
Mueller, Wang, Katz, ZD, Cetina, arXiv:2408.00069 [quant-ph].

ii) High-energy scattering of quarks and mesons in simple confining models: simulation and phenomenology

Belyansky, Whitsitt, Mueller, Fahimniya, Bennewitz, ZD, Gorshkov, Phys. Rev. Lett. 132, 091903 (2024).
Bennewitz, Ware, Schuckert, Lerose, Surace, Belyansky, Morong, Luo, De, Collins, Katz, Monroe, ZD, and Gorhskov, arXiv:2403.07061 [quant-ph].

iii) String breaking and charge-formation dynamics in adiabatic and diabatic real-time processes: phenomenology and experiment

De, Lerose, Luo, Surace, Schuckert, Bennewitz, Ware, Morong, Collins, ZD, Gorshkov, Katz, Monroe, arXiv:2410.13815 [quant-ph].
Surace, Lerose, Katz, Bennewitz, Schuckert, Luo, De, Ware, Monroe, ZD, and Gorshkov, manuscript in progress (2024).
Luo, Surace, De, Lerose, Bennewitz, Ware, Schuckert, ZD, Gorshkov, Katz, Monroe, manuscript in progress (2024).

THE ORGANIZERS ASKED ME TO GIVE A REVIEW TALK…
BUT SHOULD I GO WITH A MORE FOCUSED PHYSICS TALK?

i) Quantum-thermodynamics framework for non-equilibrium processes in gauge theories (and thermalization probing)

ZD, Jarzynski, Mueller, Oruganti, Powers, and Yunger Halpern, accepted to PRL, arXiv:2404.02965 [quant-ph].
ZD, Jarzynski, Mueller, Oruganti, Powers, and Yunger Halpern, manuscript in progress (2024).
Mueller, Wang, Katz, ZD, Cetina, arXiv:2408.00069 [quant-ph].

ii) High-energy scattering of quarks and mesons in simple confining models: simulation and phenomenology

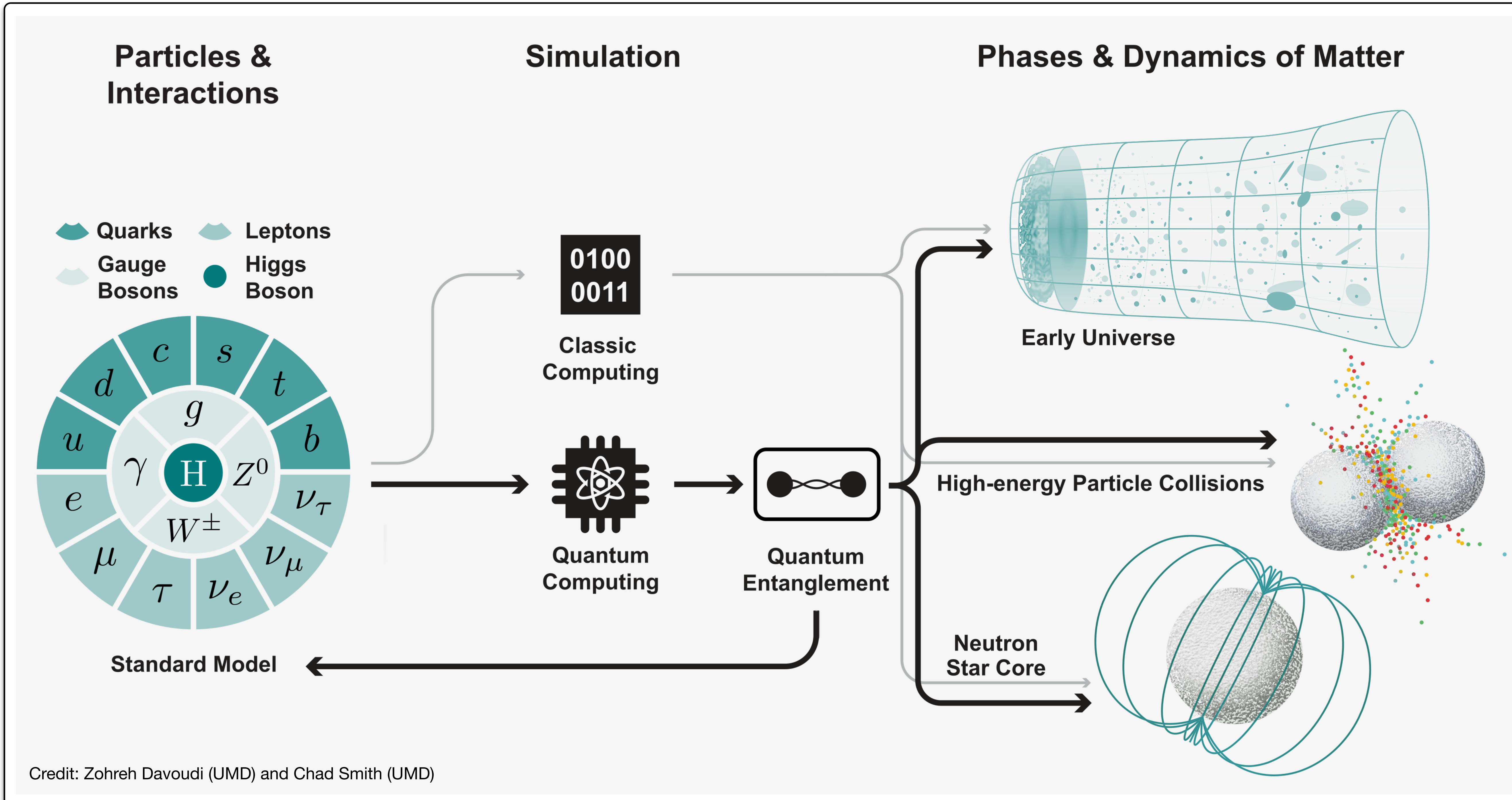
Belyansky, Whitsitt, Mueller, Fahimniya, Bennewitz, ZD, Gorshkov, Phys. Rev. Lett. 132, 091903 (2024).
Bennewitz, Ware, Schuckert, Lerose, Surace, Belyansky, Morong, Luo, De, Collins, Katz, Monroe, ZD, and Gorhskov, arXiv:2403.07061 [quant-ph].

iii) String breaking and charge-formation dynamics in adiabatic and diabatic real-time processes: phenomenology and experiment

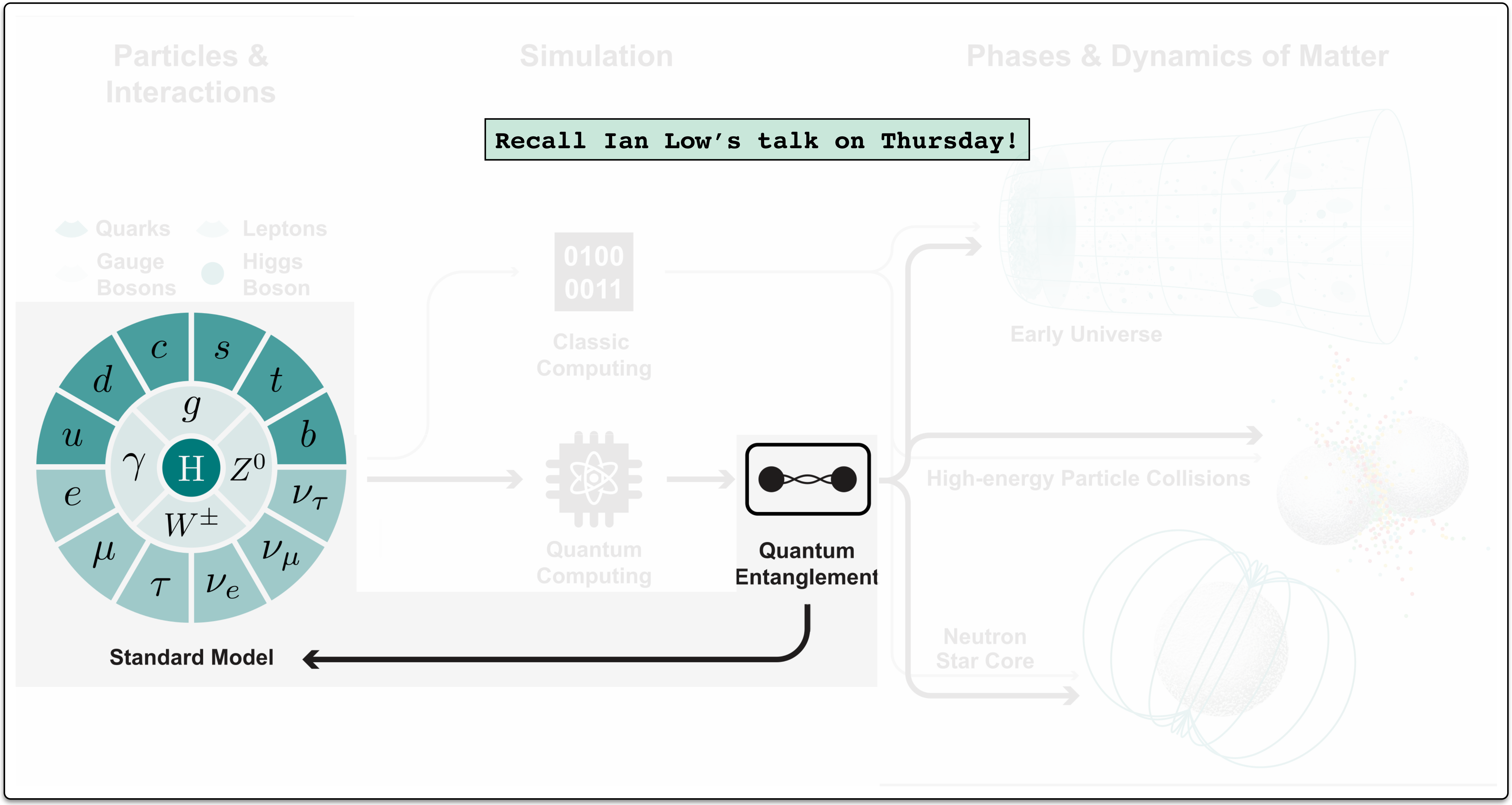
De, Lerose, Luo, Surace, Schuckert, Bennewitz, Ware, Morong, Collins, ZD, Gorshkov, Katz, Monroe, arXiv:2410.13815 [quant-ph].
Surace, Lerose, Katz, Bennewitz, Schuckert, Luo, De, Ware, Monroe, ZD, and Gorshkov, manuscript in progress (2024).
Luo, Surace, De, Lerose, Bennewitz, Ware, Schuckert, ZD, Gorshkov, Katz, Monroe, manuscript in progress (2024).

NO! I WILL STICK TO THE PLAN!

THE OVERVIEW OF TALK IN ONE PICTURE…



Bauer, ZD, Klco, and Savage, Quantum simulation of fundamental particles and forces, *Nature Rev. Phys.* 5 (2023) 7, 420-432.



Bauer, ZD, Klco, and Savage, Quantum simulation of fundamental particles and forces, *Nature Rev. Phys.* 5 (2023) 7, 420-432.

A LITTLE BACKGROUND…

QCD ON A CHIP!

534 Nuclear Instruments and Methods in Physics Research 222 (1984) 534–539
North-Holland, Amsterdam

HARDWARE MATRIX MULTIPLIER / ACCUMULATOR FOR LATTICE GAUGE THEORY CALCULATIONS *

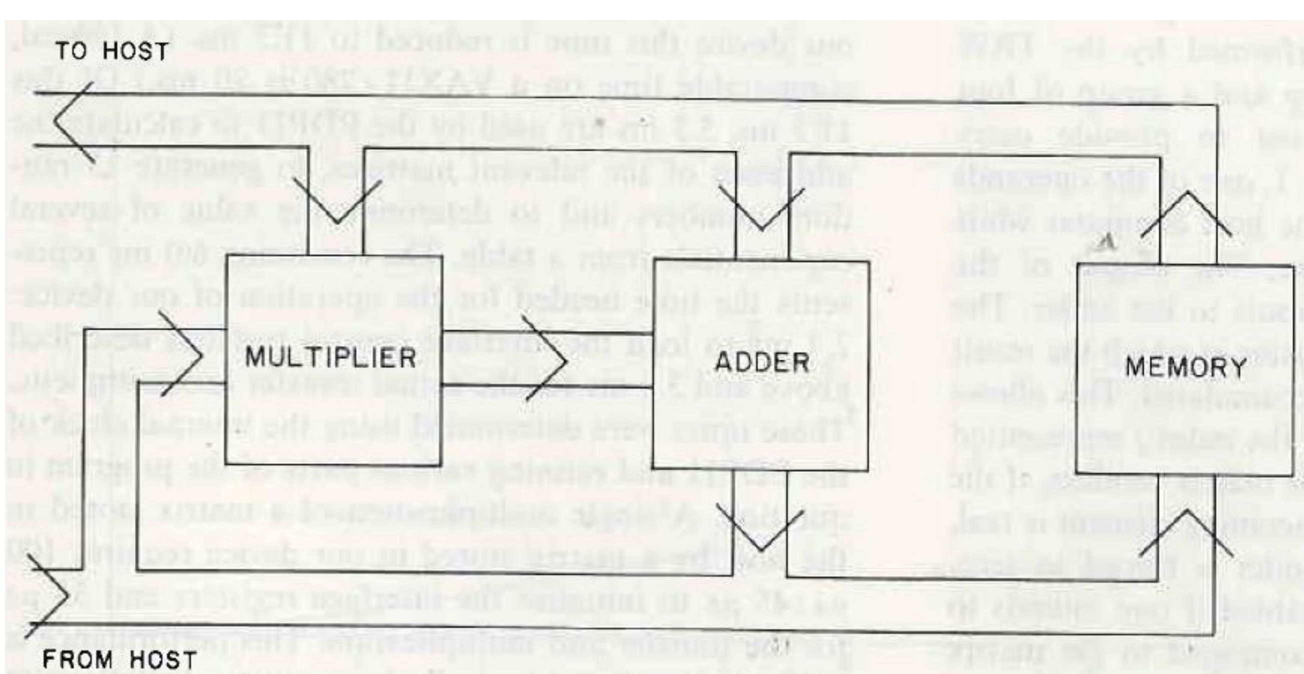
Norman H. CHRIST and Anthony E. TERRANO

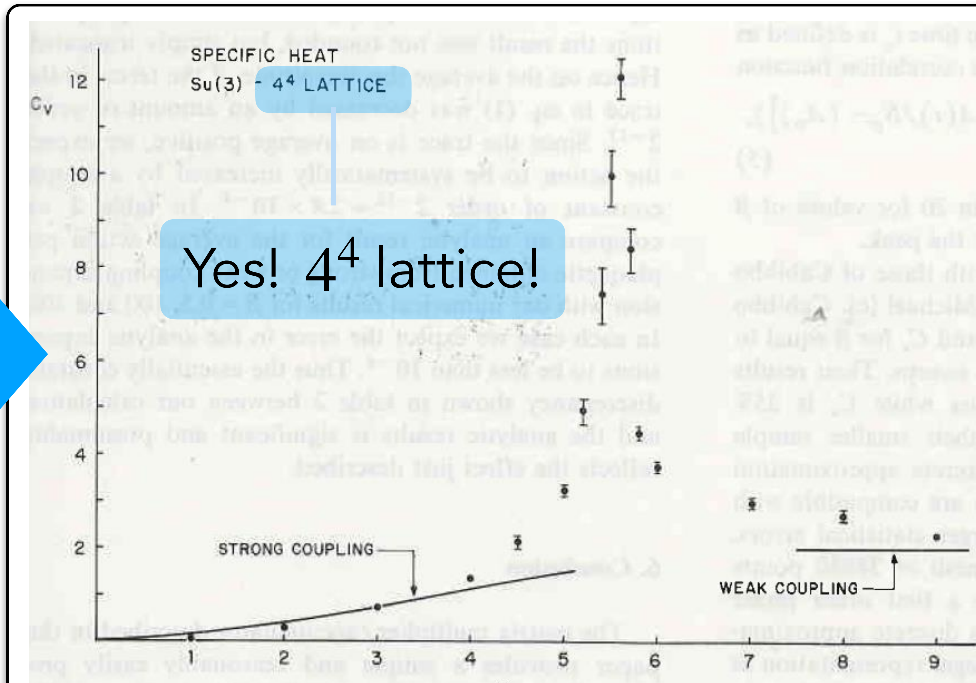
Columbia University, New York, NY 10027, USA

Received 30 September 1983

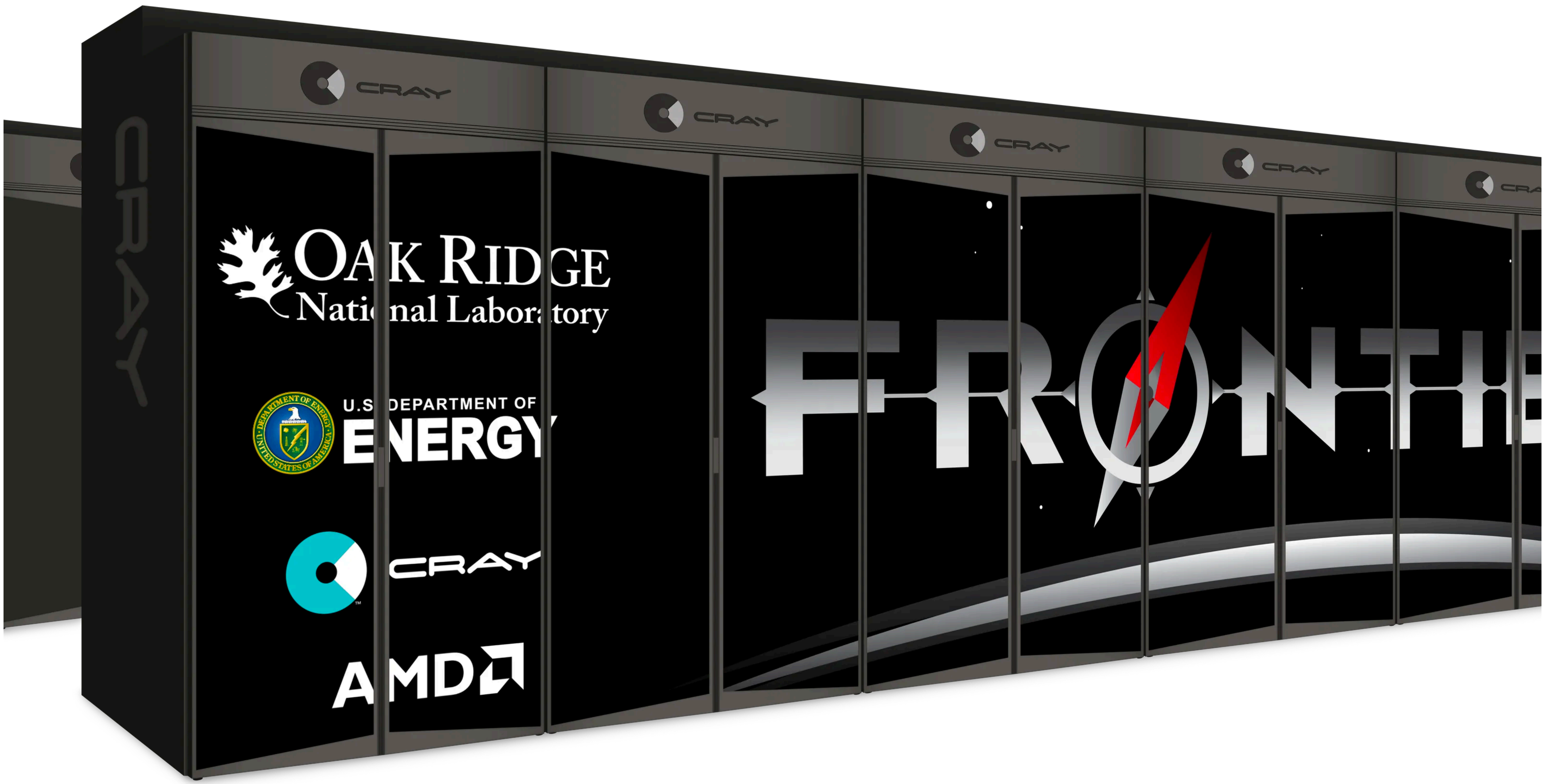
~40 years ago!

10^{10} times or more slower than current supercomputers!
Only few Kbytes of memory!





WITH MANY REMARKABLE THEORY, ALGORITHM, AND CO-DESIGN EFFORTS TO WORK AND HAVING ACCESS TO HUNDREDS OF MILLION CPU HOURS (OR COMPARABLE GPU HOURS) ON THE LARGEST SUPERCOMPUTERS IN AROUND THE WORLD LED TO MANY IMPRESSIVE RESULTS.



Frontier supercomputer, Oak Ridge National Laboratory, USA

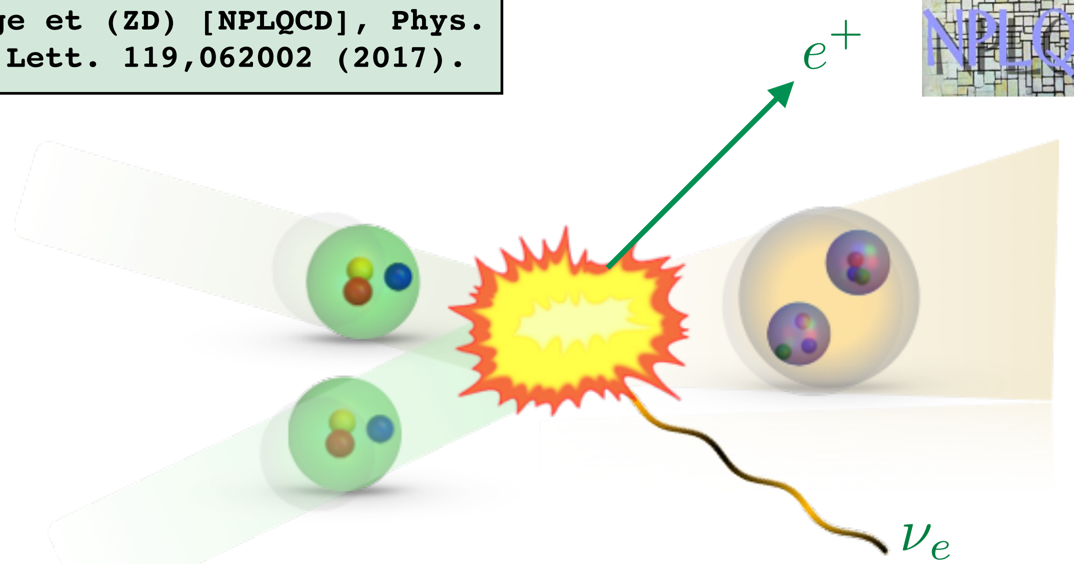
LATTICE QCD IS SUPPORTING A MULTI-BILLION DOLLAR EXPERIMENTAL PROGRAM IN NP (HEP)!

Based on slide content courtesy of Martin Savage.

TWO EXAMPLES: REACTIONS OF NUCLEONS

Proton-proton fusion

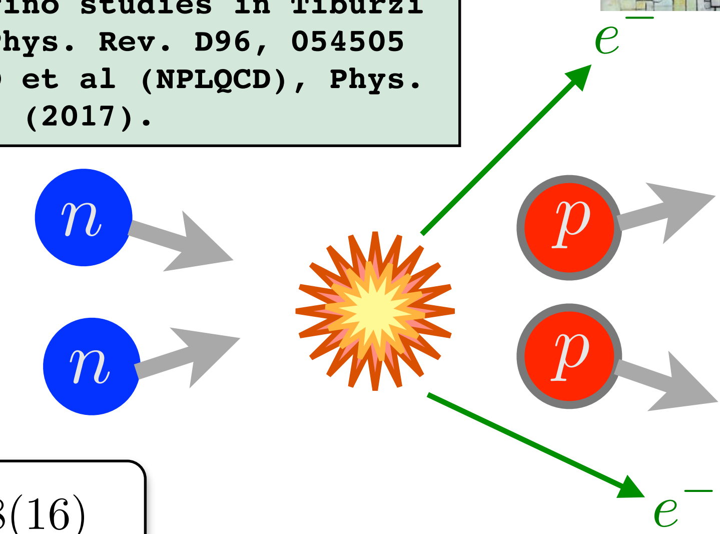
Savage et (ZD) [NPLQCD], Phys. Rev. Lett. 119,062002 (2017).



$$L_{1,A} = 3.9(0.1)(1.0)(0.3)(0.9)\ \mathrm{fm}^3 \quad @\ \mu = m_\pi^{\mathrm{phys.}} = 140\ \mathrm{MeV}$$

Neutrinoless double-β decay

ZD, Detmold, Fu, Grebe, Jay, Murphy, Oare, Shanahan, Wagman, arXiv:2402.09362 [hep-lat]. See also our two-neutrino studies in Tiburzi et al (ZD) (NPLQCD), Phys. Rev. D96, 054505 (2017)and Shanahan, ZD et al (NPLQCD), Phys. Rev. Lett. 119, 062003 (2017).



$$a^2 \mathcal{A}^{nn\to pp} = 0.078(16)$$
$$@\ m_\pi = 806\ \mathrm{MeV}$$

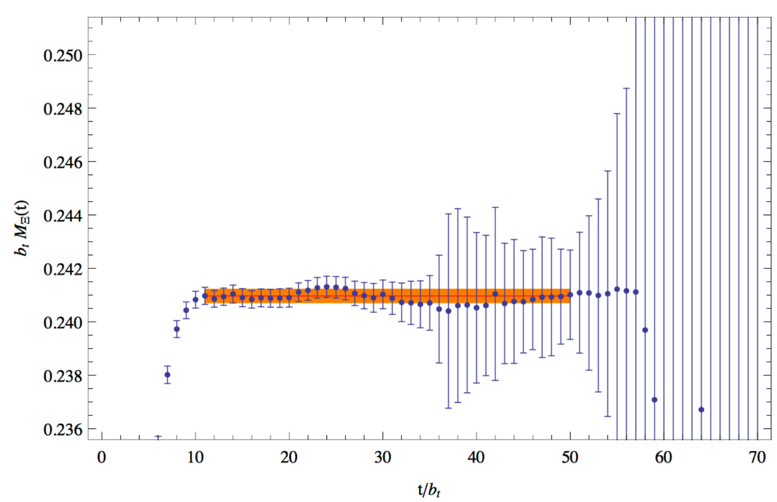
For a review see: ZD, Detmold, Orginos, Parreño, Savage, Shanahan, Wagman, *Phys. Rept.* 900, 1-74 (2021).

DOES THIS MEAN WE ARE ALL SET?
…WELL, UNFORTUNATELY NOT!

THREE FEATURES MAKE LATTICE QCD CALCULATIONS OF NUCLEI HARD:

i) The complexity of systems grows factorially with the number of quarks.

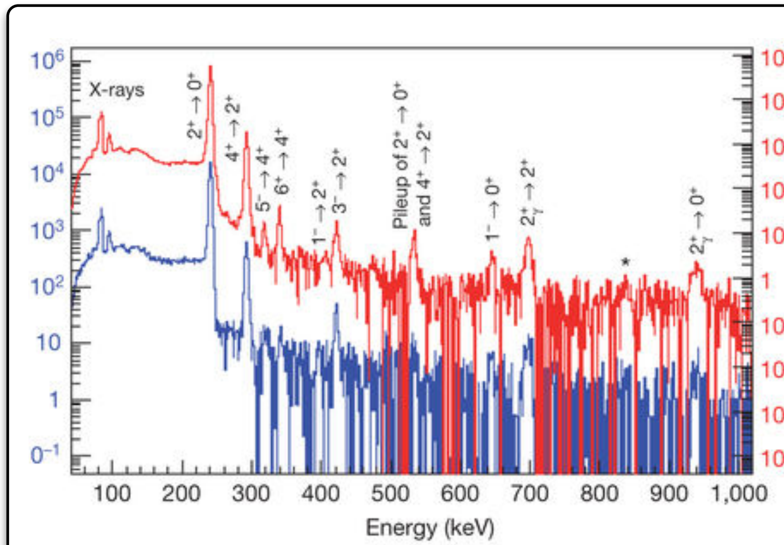
Detmold and Orginos (2013)
Detmold and Savage (2010)
Doi and Endres (2013)



ii) There is a severe signal-to-noise degradation.

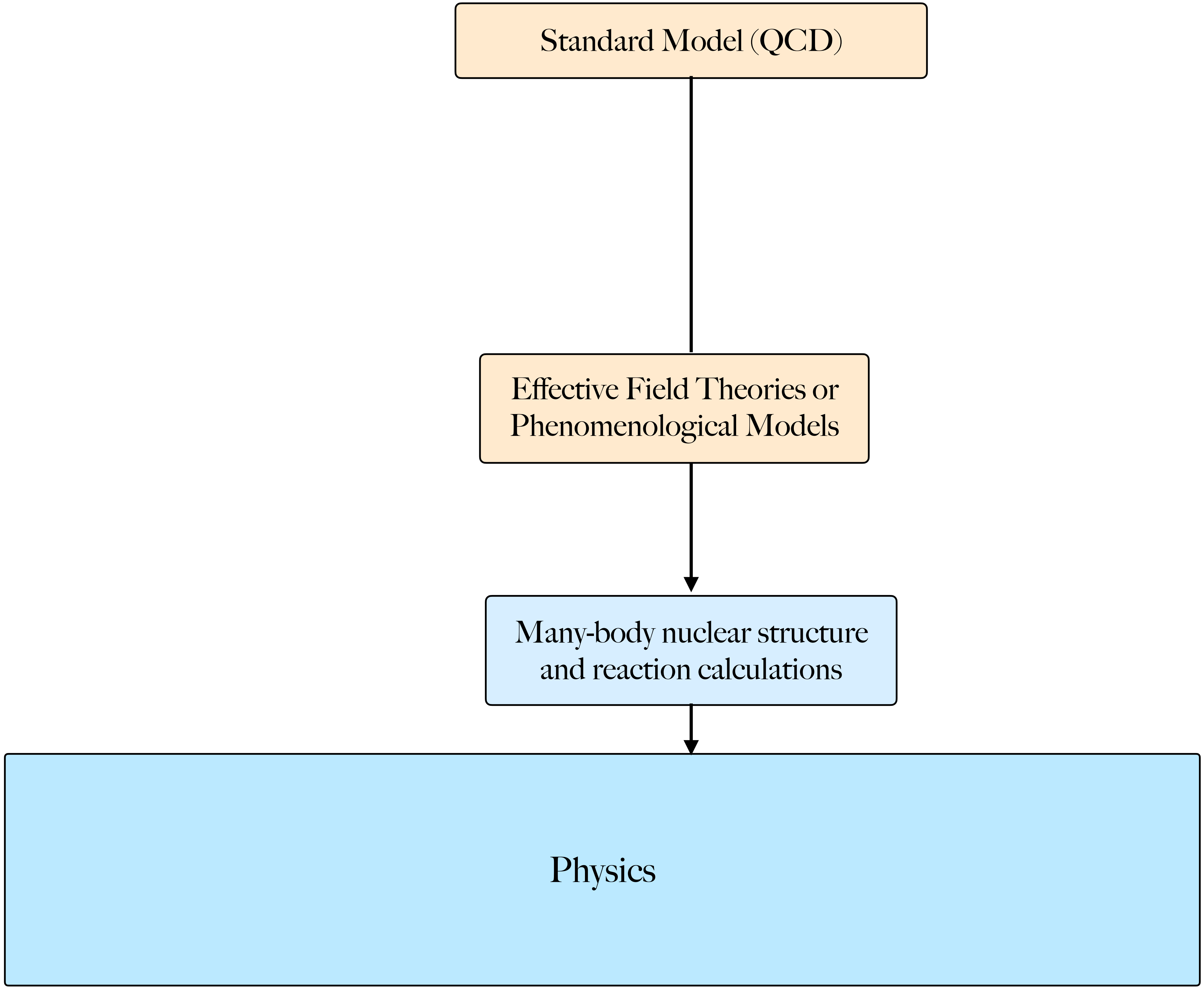
Paris (1984) and Lepage (1989)
Wagman and Savage (2017, 2018)

iii) Excitation energies of nuclei are much smaller than the QCD scale.



Beane at al (NPLQCD) (2009)
Beane, Detmold, Orginos, Savage (2011)
ZD (2018)
Briceno, Dudek and Young (2018)

A NUCLEAR PHYSICS ROADMAP



ADDITIONALLY THE SIGN PROBLEM FORBIDS:

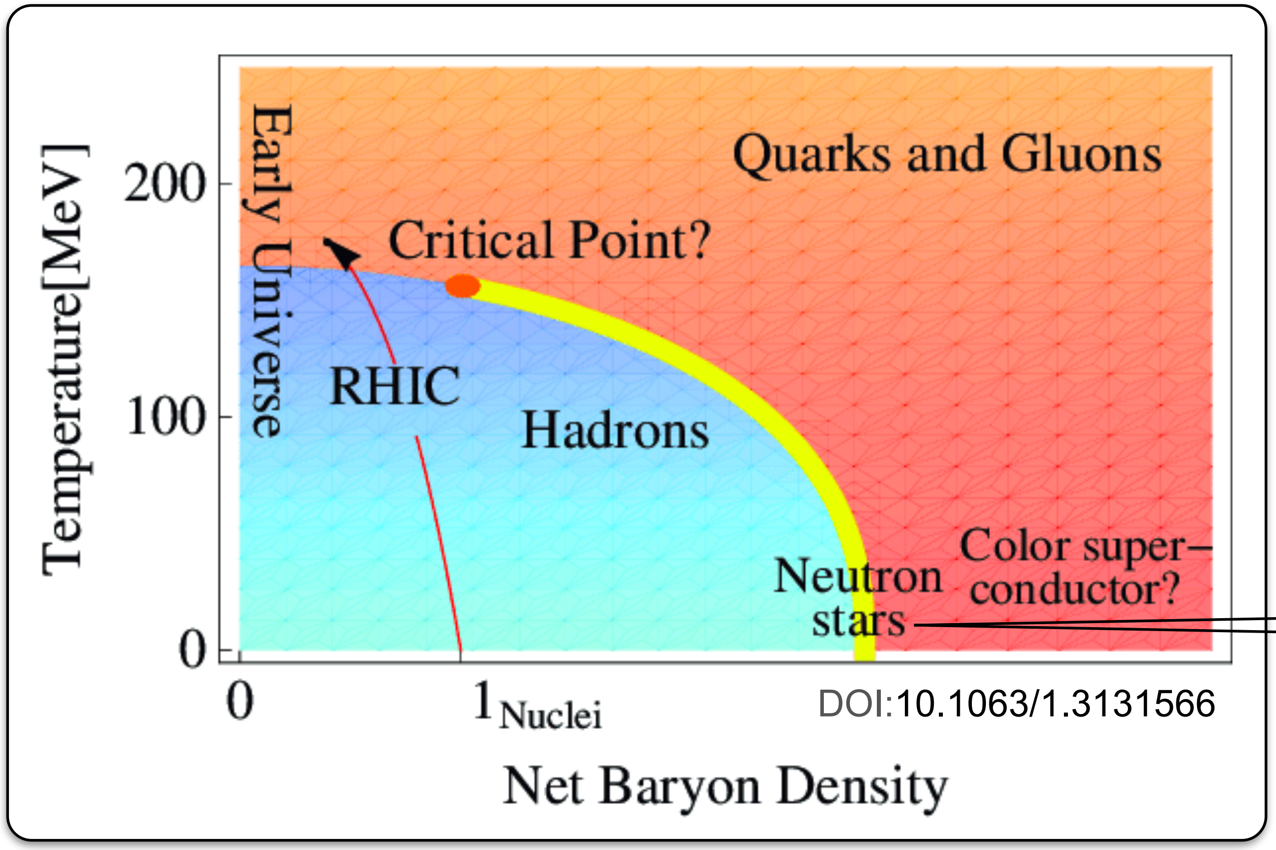
i) Studies of nuclear isotopes, dense matter, and phase diagram of QCD…both with lattice QCD and with *ab initio* nuclear many-body methods.

Path integral formulation:

$$e^{-S[U,q,\bar{q}]}$$

with a complex action:

$$\mathcal{L}_{\mathrm{QCD}} \to \mathcal{L}_{\mathrm{QCD}} - i\mu \sum_f \bar{q}_f \gamma^0 q_f$$



ADDITIONALLY THE SIGN PROBLEM FORBIDS:

ii) Real-time dynamics of matter in heavy-ion collisions or after Big Bang…

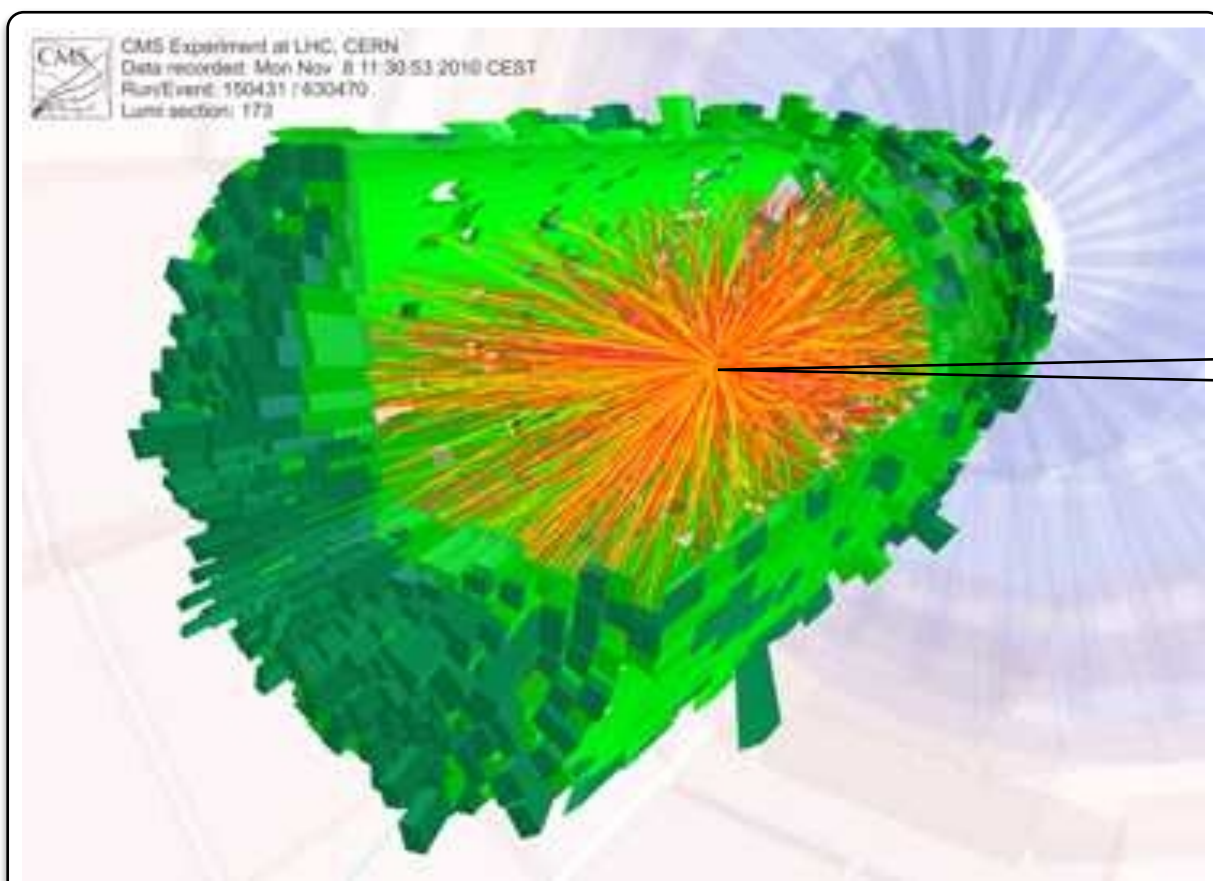
…and a wealth of dynamical response functions, transport properties, hadron distribution functions, and non-equilibrium physics of QCD.

Path integral formulation:

$$e^{iS[U,q,\bar{q}]}$$

Hamiltonian evolution:

$$U(t) = e^{-iHt}$$



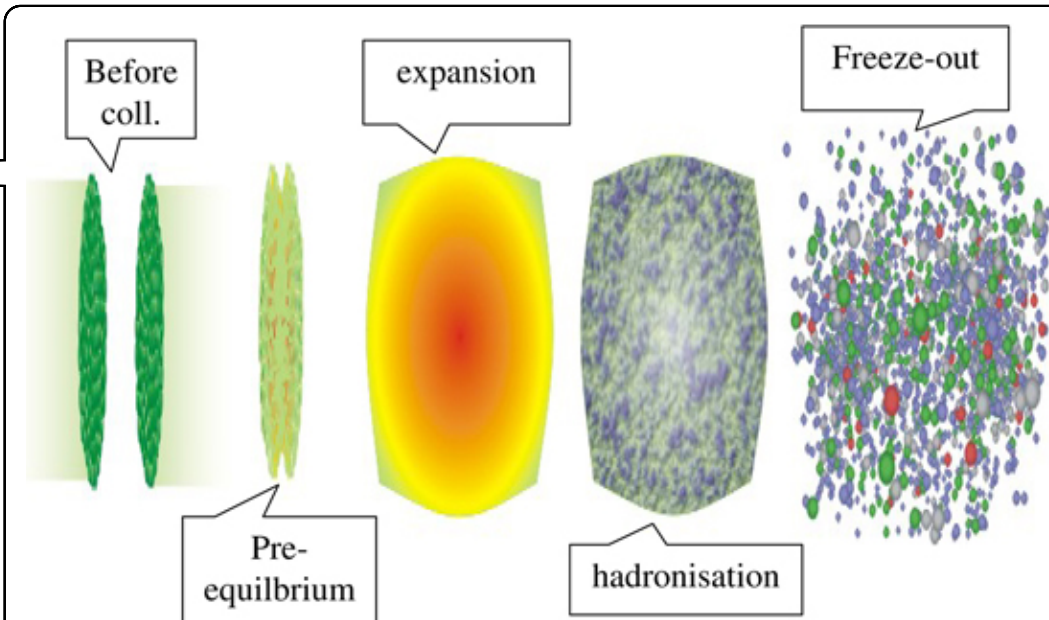


Image credit: Chaudhuri, Advances in High Energy Physics, vol. 2013,\.

ADDITIONALLY THE SIGN PROBLEM FORBIDS:

ii) Real-time dynamics of matter in heavy-ion collisions or after Big Bang…

…and a wealth of dynamical response functions, transport properties, hadron distribution functions, and non-equilibrium physics of QCD.

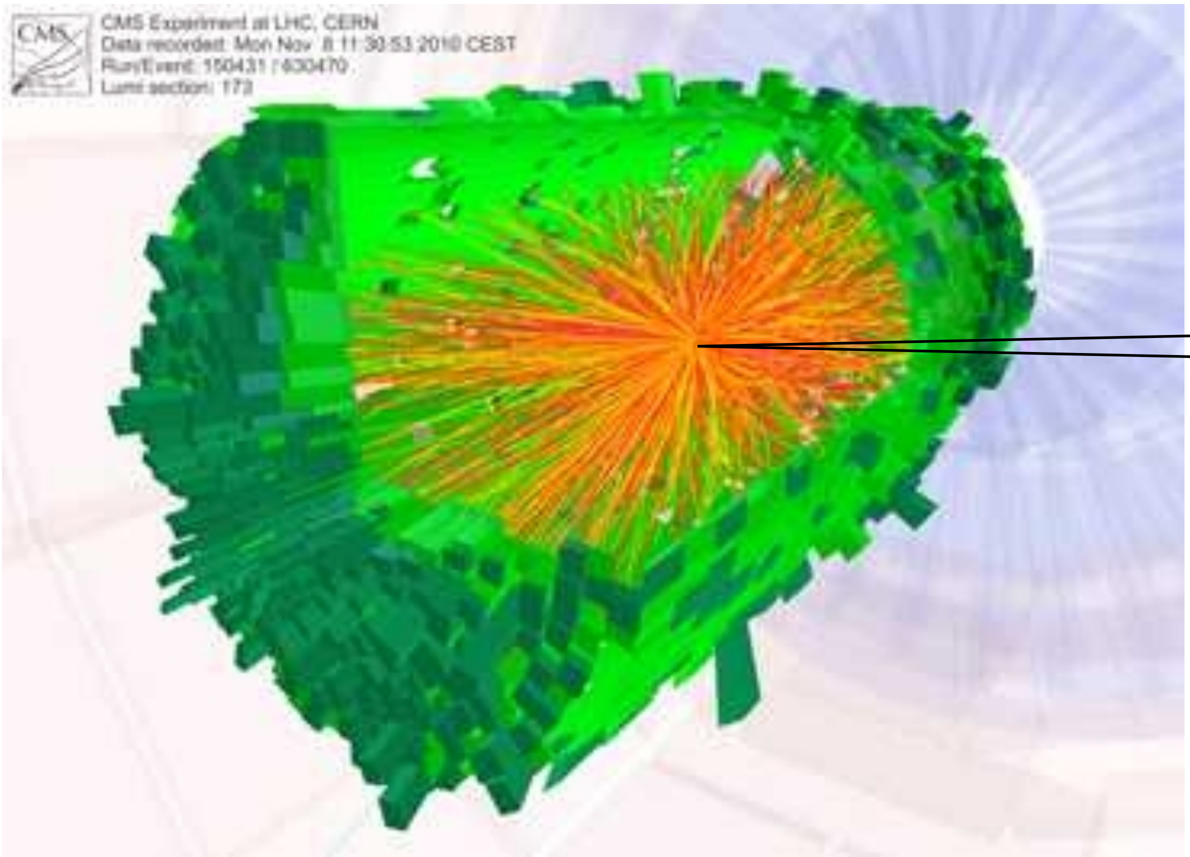
Path integral formulation:

$$e^{iS[U,q,\bar{q}]}$$

Hamiltonian evolution:

$$U(t) = e^{-iHt}$$

Tensor-network methods are suitable but still limited! See Patrick's Emonts's talk later!



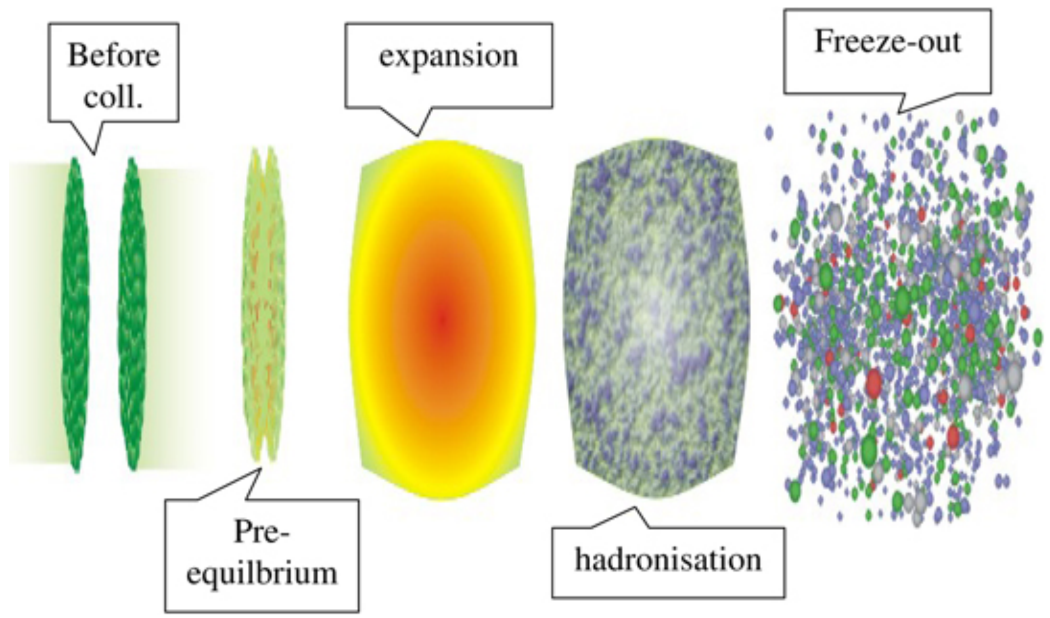


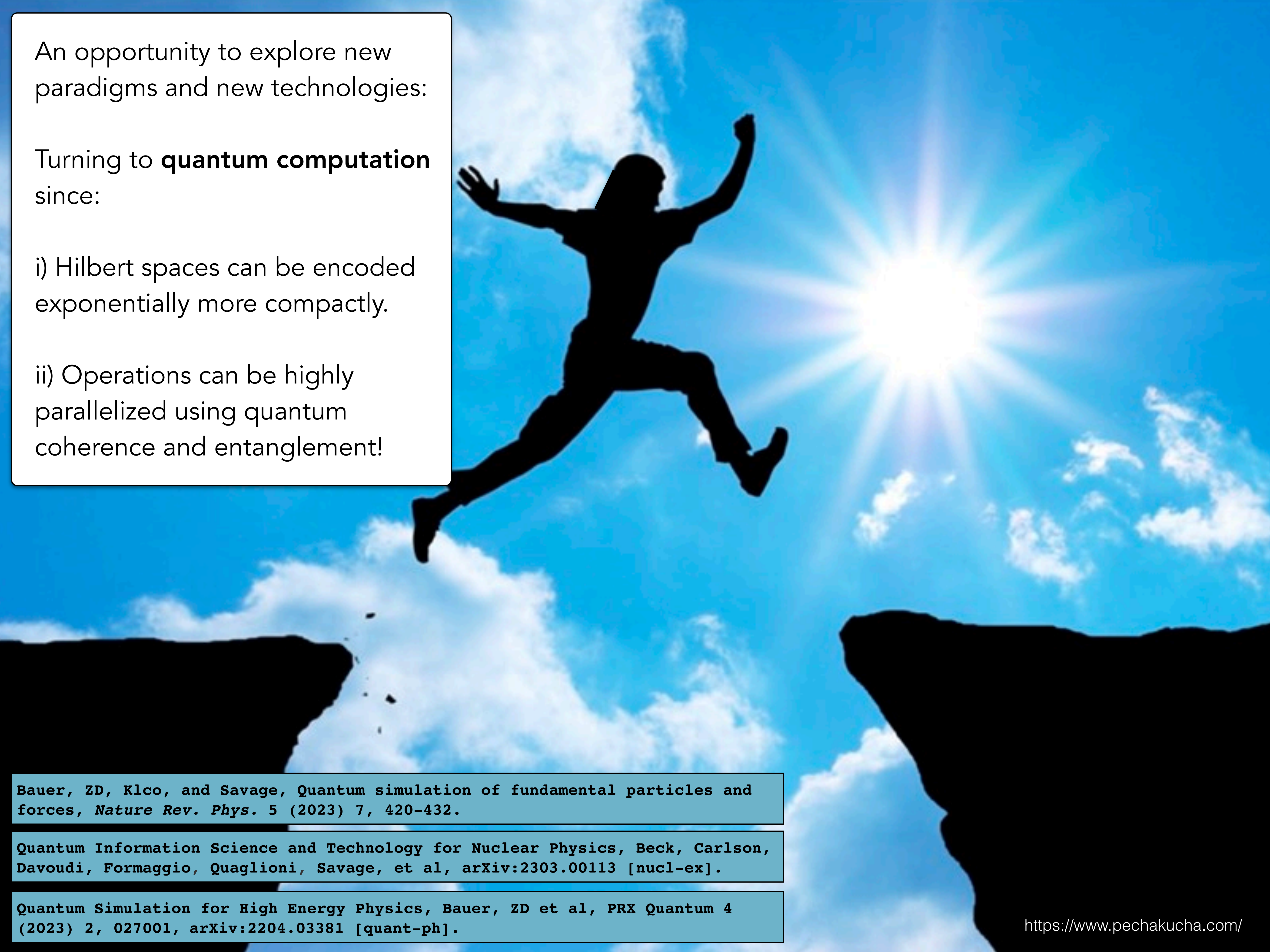
Image credit: Chaudhuri, Advances in High Energy Physics, vol. 2013,\.

An opportunity to explore new paradigms and new technologies:

Turning to **quantum computation** since:

i) Hilbert spaces can be encoded exponentially more compactly.

ii) Operations can be highly parallelized using quantum coherence and entanglement!

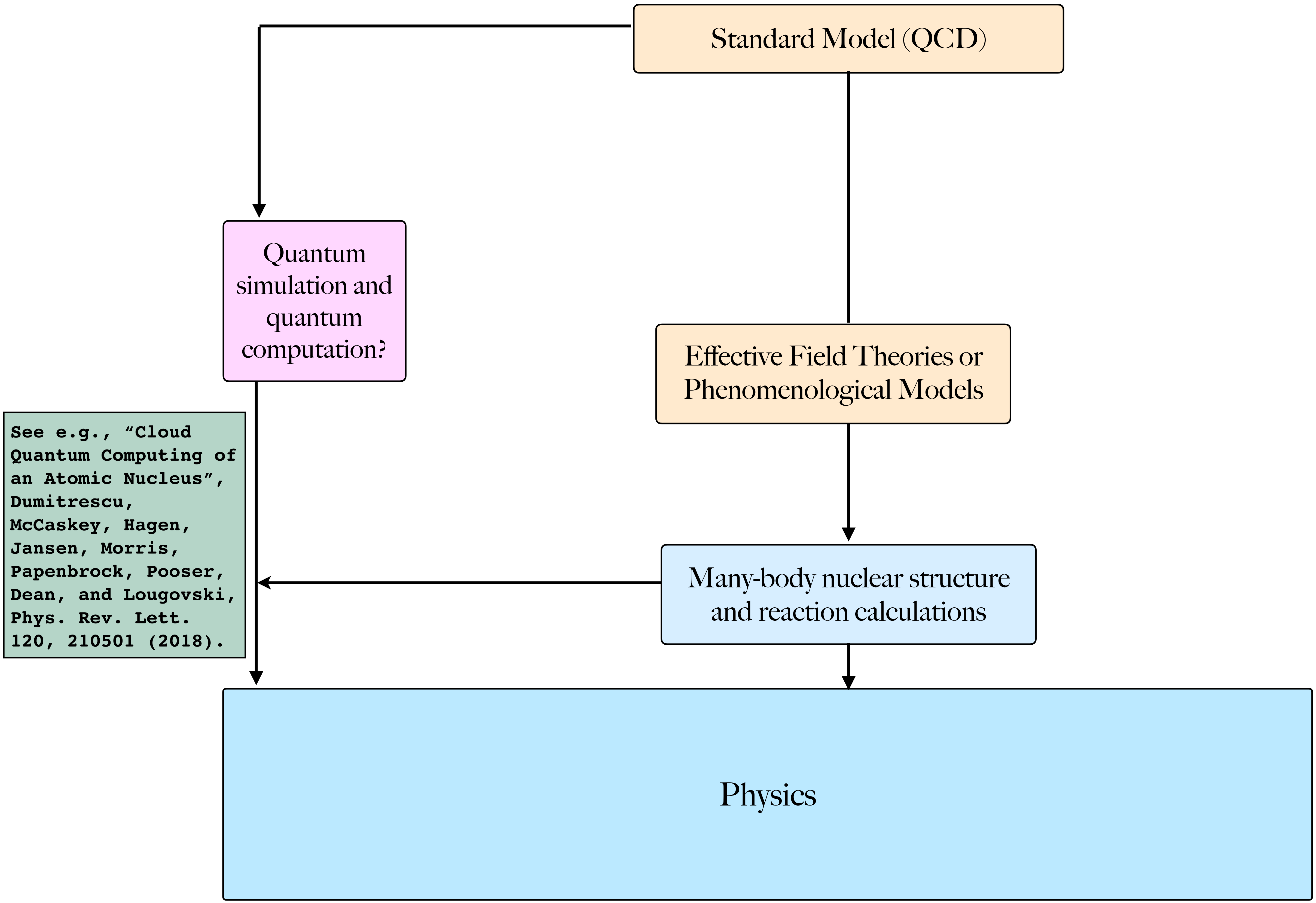


Bauer, ZD, Klco, and Savage, Quantum simulation of fundamental particles and forces, *Nature Rev. Phys.* 5 (2023) 7, 420-432.

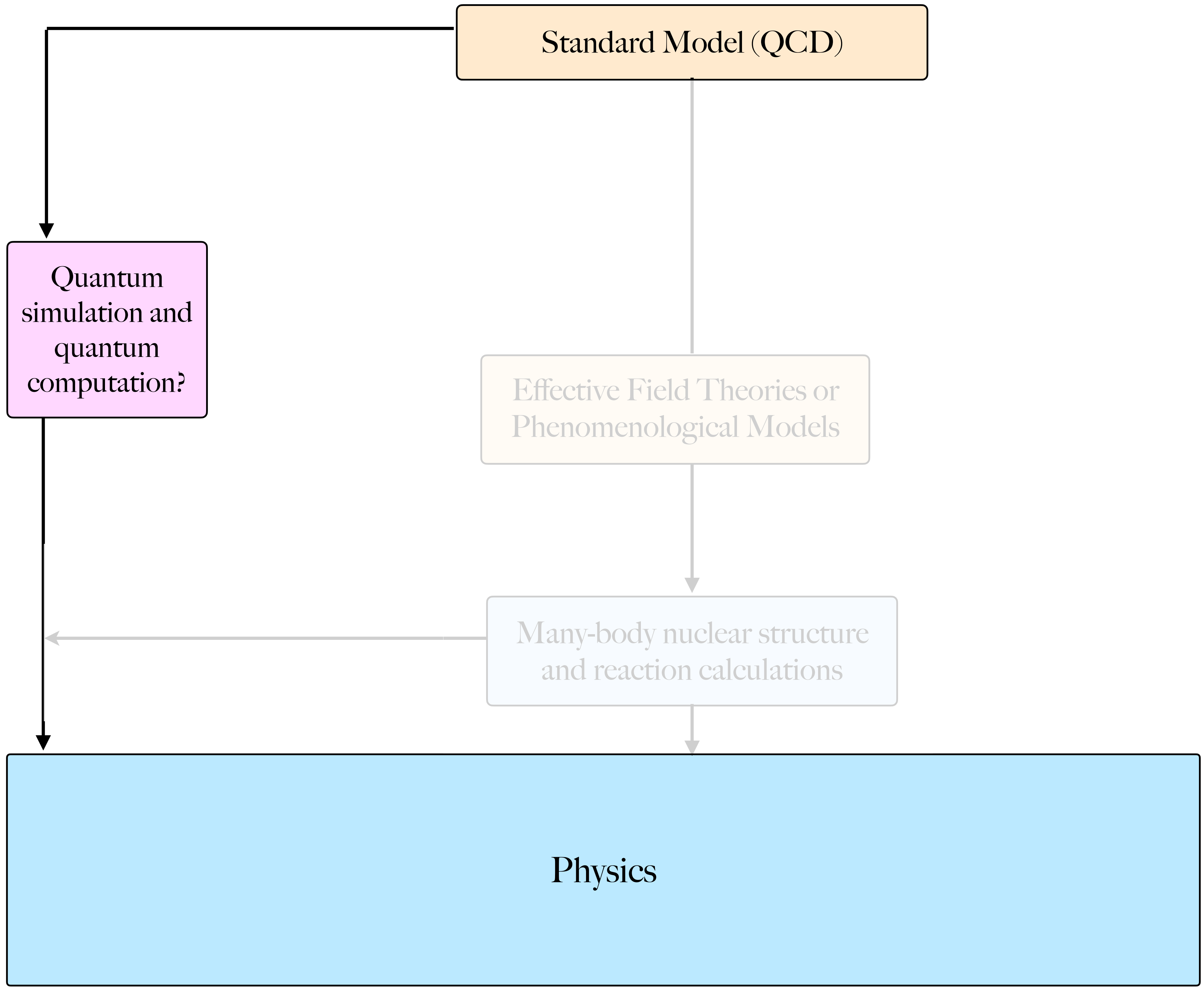
Quantum Information Science and Technology for Nuclear Physics, Beck, Carlson, Davoudi, Formaggio, Quaglioni, Savage, et al, arXiv:2303.00113 [nucl-ex].

Quantum Simulation for High Energy Physics, Bauer, ZD et al, PRX Quantum 4 (2023) 2, 027001, arXiv:2204.03381 [quant-ph].

A NUCLEAR PHYSICS ROADMAP FOR LEVERAGING QUANTUM TECHNOLOGIES

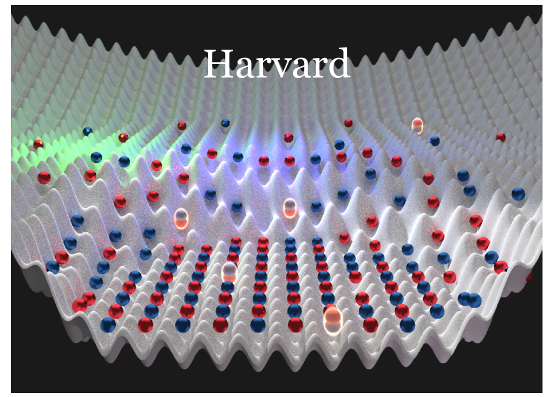


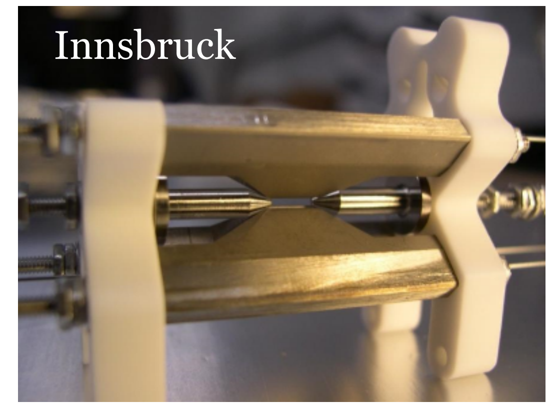
A NUCLEAR PHYSICS ROADMAP FOR LEVERAGING QUANTUM TECHNOLOGIES



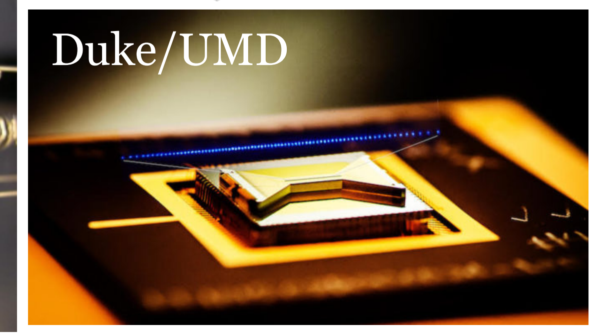
A RANGE OF QUANTUM SIMULATORS/COMPUTERS WITH VARING CAPACITY AND CAPABILITY

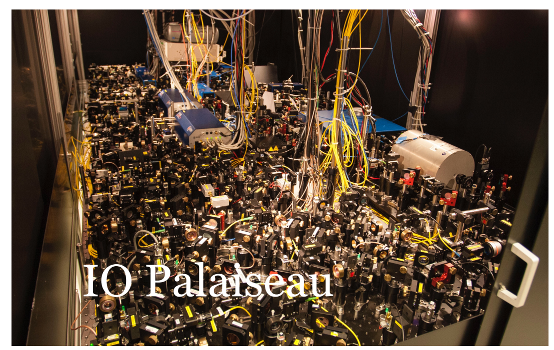
- Atomic systems (trapped ions, cold atoms, Rydbergs)
- Condensed matter systems (superconducting circuits, dopants in semiconductors such as in Silicon, NV centers in diamond)
- Optical quantum computing

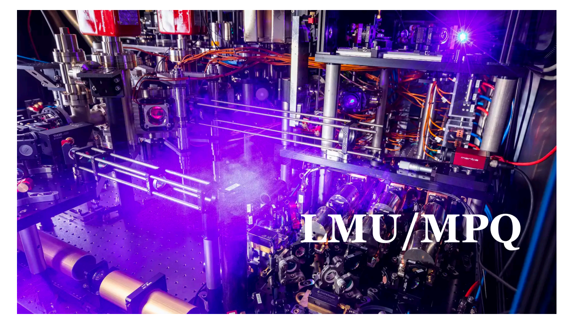


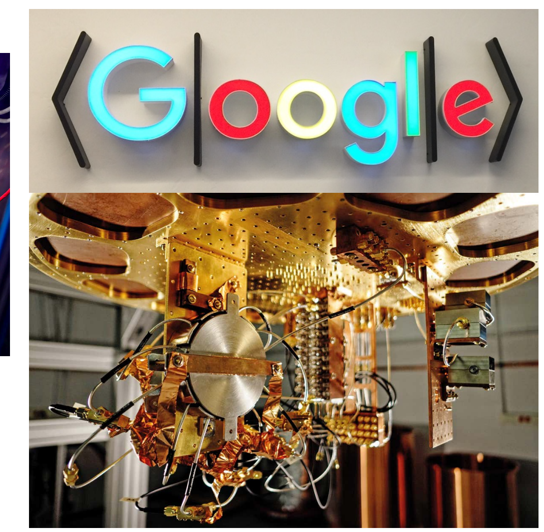


IONQ

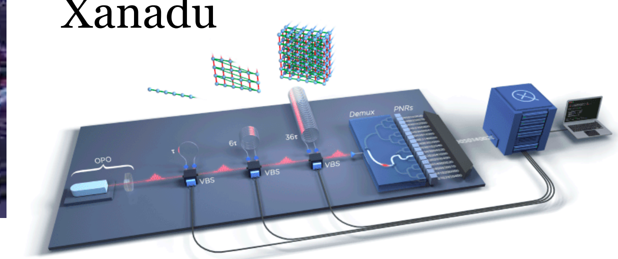








Xanadu



WHERE DO COMMERCIAL-GRADE SYSTEMS STAND TODAY…AND TOMORROW?

IONQ

	Performance	Scale
Now	• 99.6% 2QG Native Fidelity • 600 μs 2GQ Speed	36 qubits
2025	• >99.9% 2QG Native Fidelity • 99.999% 2QG Logical Fidelity • 300 μs 2GQ Speed	100 qubits
2026+	• >99.95% 2QG Native Fidelity • 99.9999% 2QG Logical Fidelity • 300 μs 2GQ Speed	1,000+ qubits

WHERE DO COMMERCIAL-GRADE SYSTEMS STAND TODAY…AND TOMORROW?

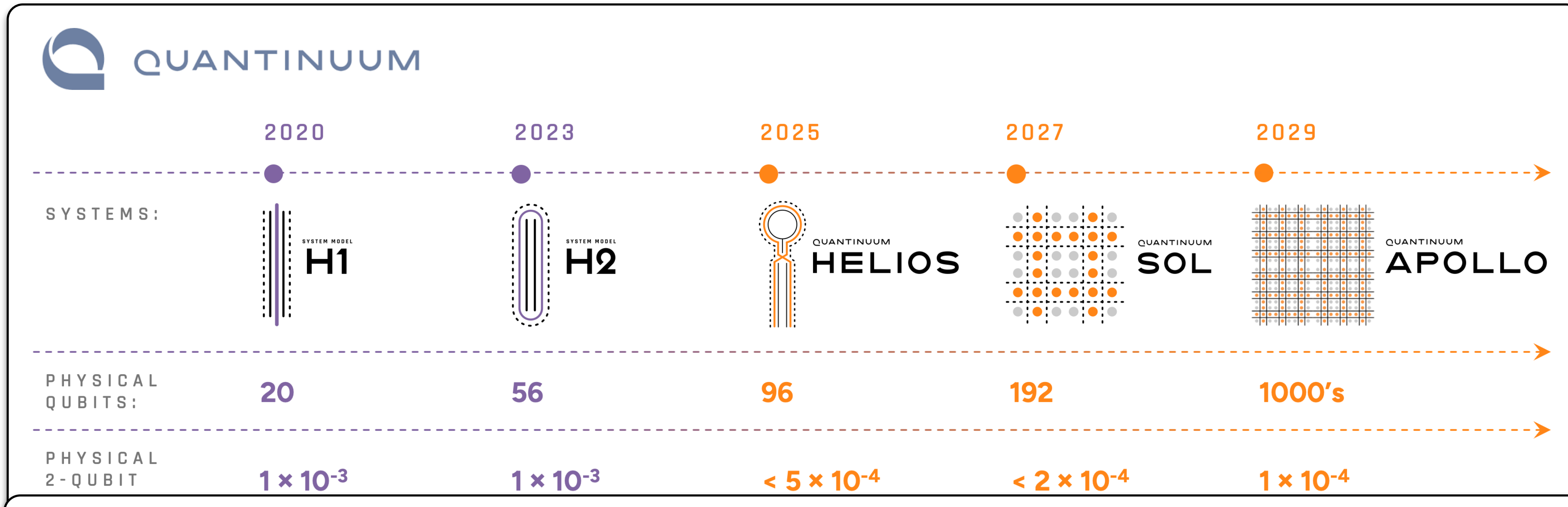
QUANTINUUM

	2020	2023	2025	2027	2029
SYSTEMS:	SYSTEM MODEL H1	SYSTEM MODEL H2	QUANTINUUM HELIOS	QUANTINUUM SOL	QUANTINUUM APOLLO
PHYSICAL QUBITS:	20	56	96	192	1000's
PHYSICAL 2-QUBIT GATE ERROR:	1×10^{-3}	1×10^{-3}	$< 5 \times 10^{-4}$	$< 2 \times 10^{-4}$	1×10^{-4}
LOGICAL QUBITS:		> 12	~ 50	~ 100	100's
LOGICAL ERROR RATES:		1×10^{-3}	$< 10^{-4}$	$\sim 10^{-5}$	1×10^{-5} to 1×10^{-10}*

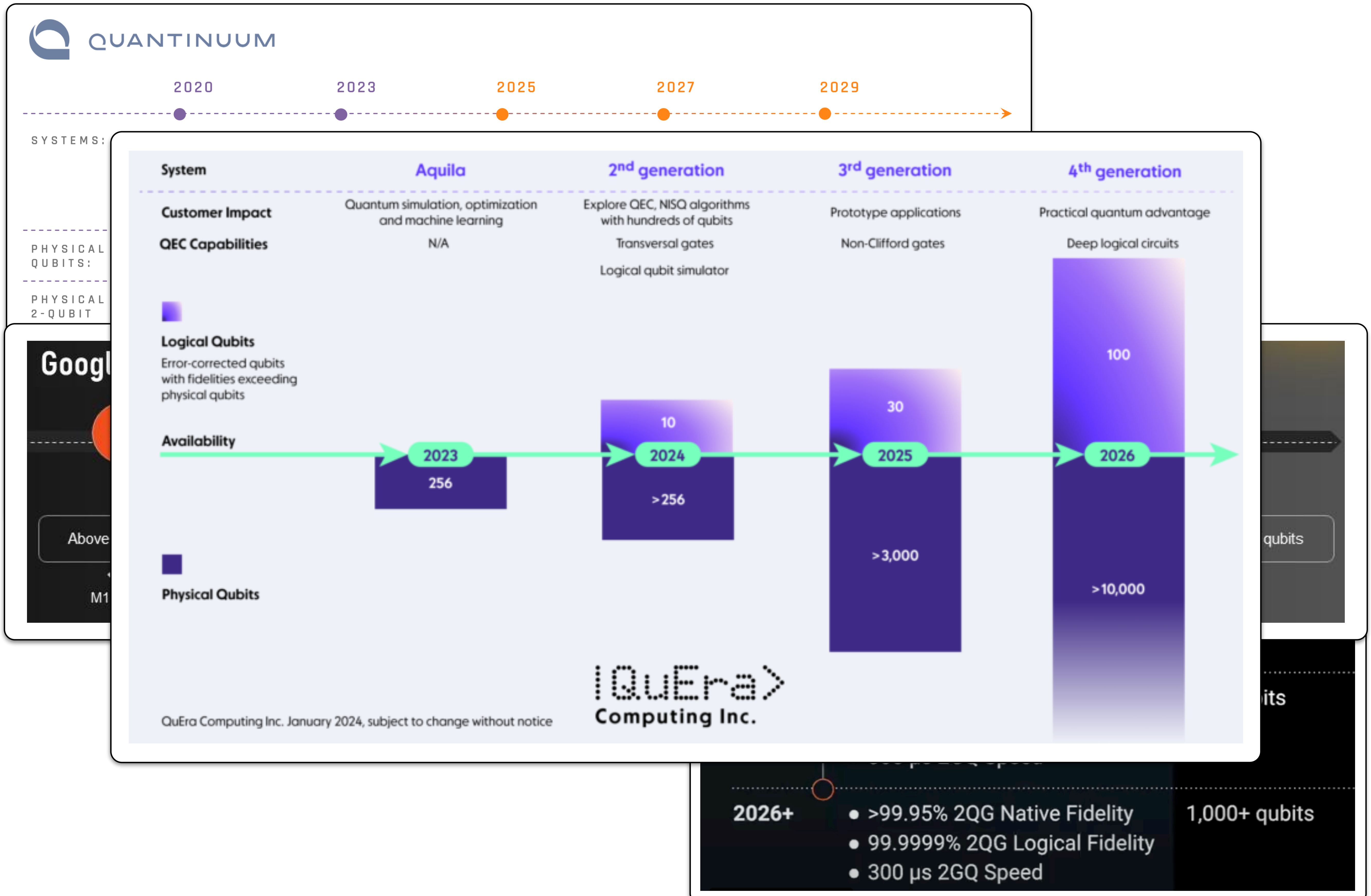
*analysis based on recent literature in new, novel error correcting codes predict that error could be as low as 1E-10 in Apollo (ref: arXiv:2403.16054, arXiv:2308.07915)

	Performance	Scale
Now	• 99.6% 2QG Native Fidelity • 600 µs 2GQ Speed	36 qubits
2025	• >99.9% 2QG Native Fidelity • 99.999% 2QG Logical Fidelity • 300 µs 2GQ Speed	100 qubits
2026+	• >99.95% 2QG Native Fidelity • 99.9999% 2QG Logical Fidelity • 300 µs 2GQ Speed	1,000+ qubits

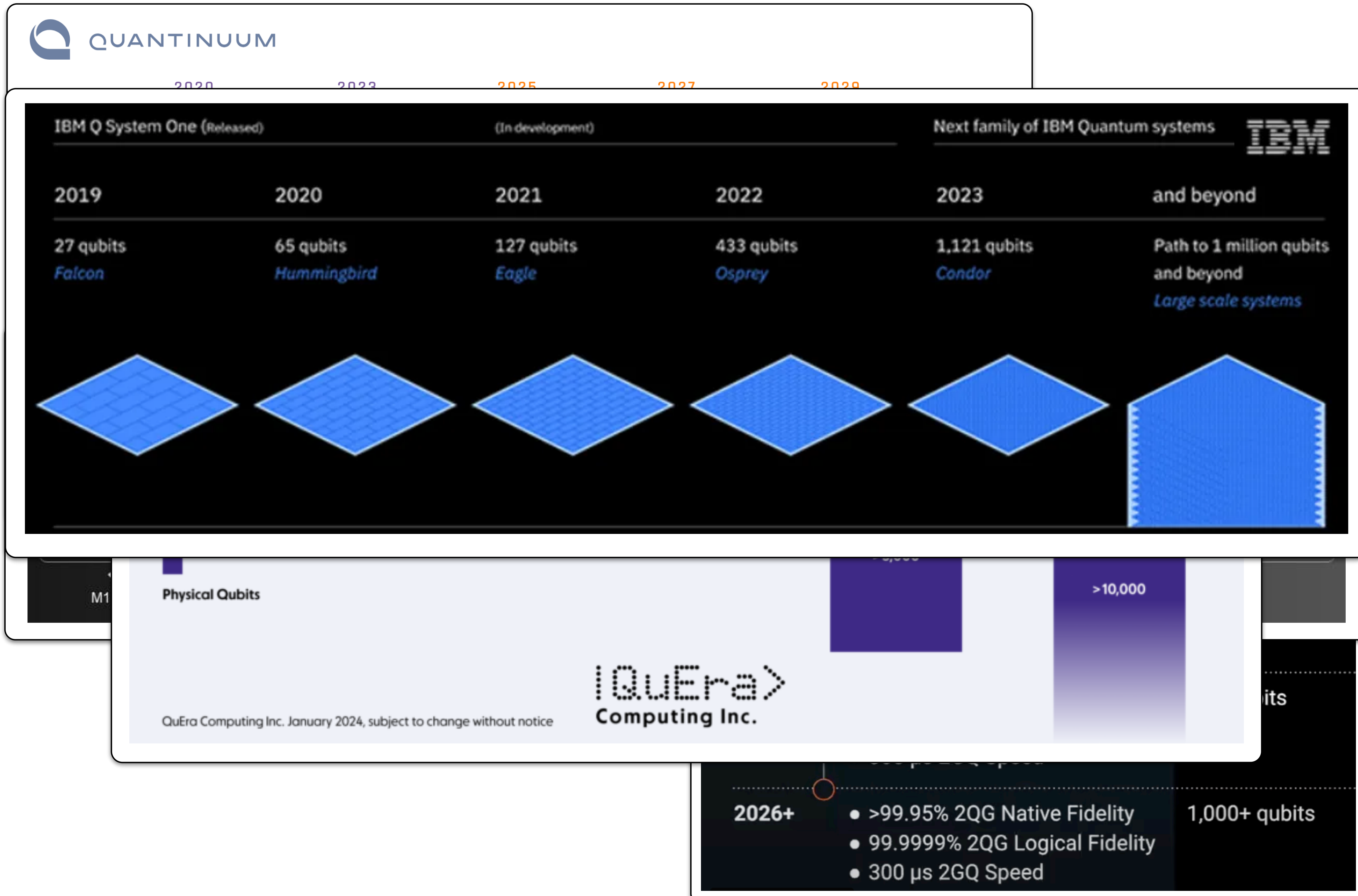
WHERE DO COMMERCIAL-GRADE SYSTEMS STAND TODAY…AND TOMORROW?



WHERE DO COMMERCIAL-GRADE SYSTEMS STAND TODAY…AND TOMORROW?



WHERE DO COMMERCIAL-GRADE SYSTEMS STAND TODAY…AND TOMORROW?



QUANTUM SIMULATION AND QUANTUM-COMPUTING BASICS

i) Quantum-simulation steps: A brief introduction

ii) Various modes of quantum simulation: Digital, analog, hybrid

iii) Digital-quantum-simulations basics:

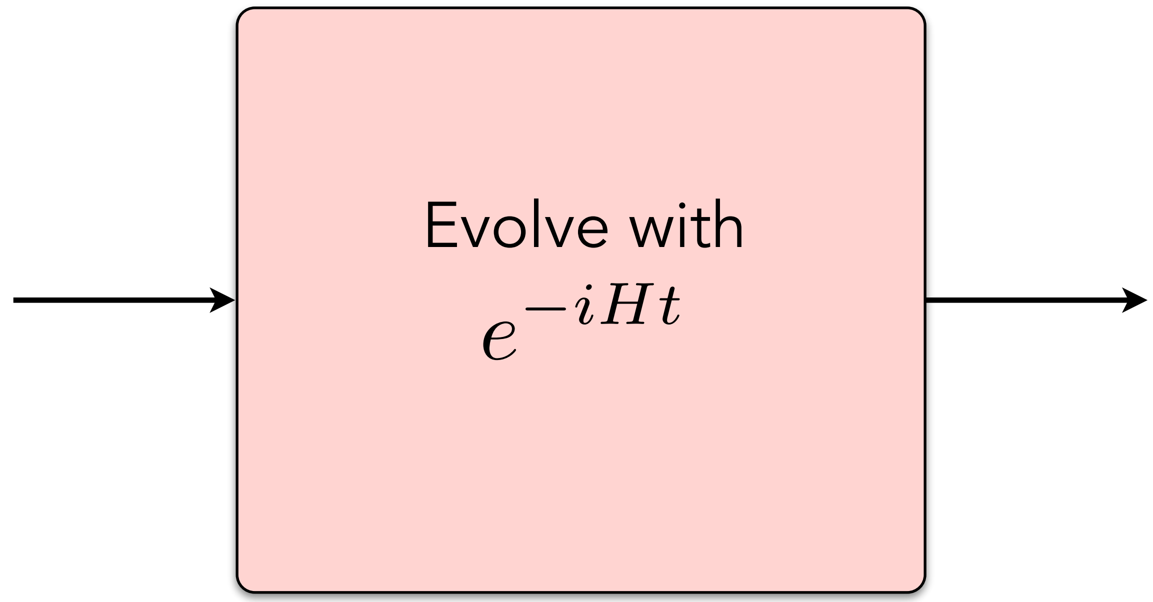
- qubits and gates
- Encoding fermions and bosons onto qubits
- State-preparation strategies
- Time evolution (via product formulas)
- Measurement strategies and observables

ON A QUANTUM COMPUTING MACHINE, WE CAN IN PRINCIPLE:

Prepare the initial state →

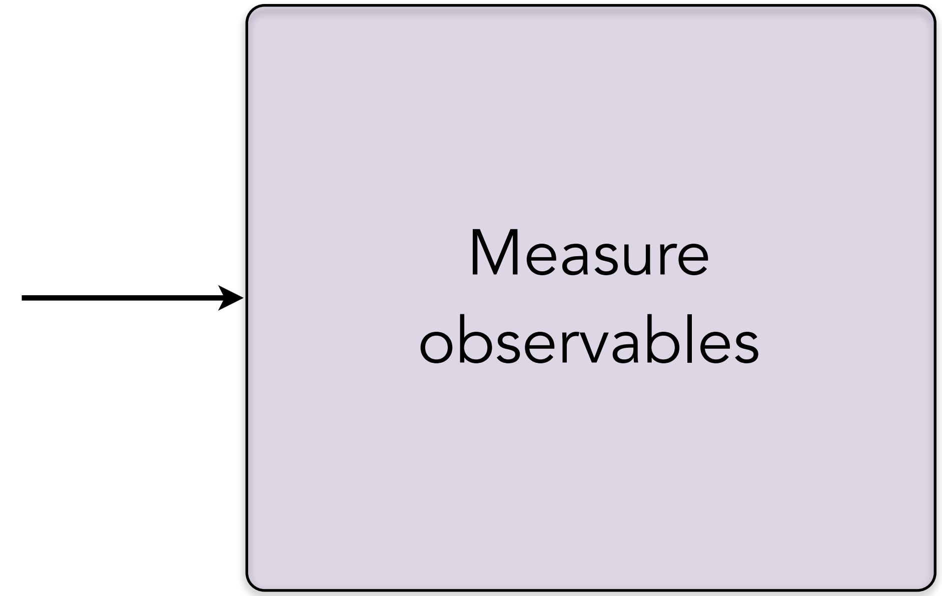
- Nontrivial specially in strongly-interacting theories like quantum chromodynamics (QCD).
- Thermal states possible.

ON A QUANTUM COMPUTING MACHINE, WE CAN IN PRINCIPLE:



- Depends on the mode of the simulator.
- The choice of formulation and basis states impacts the implementation.

ON A QUANTUM COMPUTING MACHINE, WE CAN IN PRINCIPLE:



- May require non-trivial circuits given the observable
- Exponentially large number of amplitudes to be measured. Efficient but approximate protocols are being developed.

CAN WE COMBINE THIS WITH CLASSICAL COMPUTING?

QUANTUM SUBPROCESS

Prepare the initial state → Evolve with e^{-iHt} → Measure observables

?

Conventional lattice QCD

?

QUANTUM SIMULATION AND QUANTUM-COMPUTING BASICS

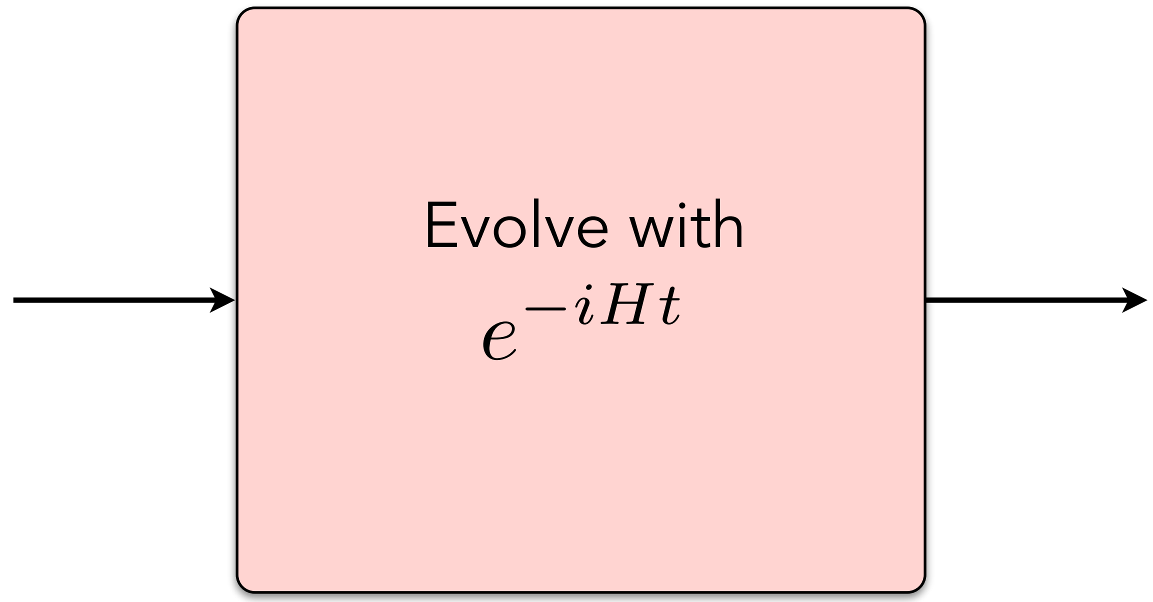
i) Quantum-simulation steps: A brief introduction

ii) Various modes of quantum simulation: Digital, analog, hybrid

iii) Digital-quantum-simulations basics:

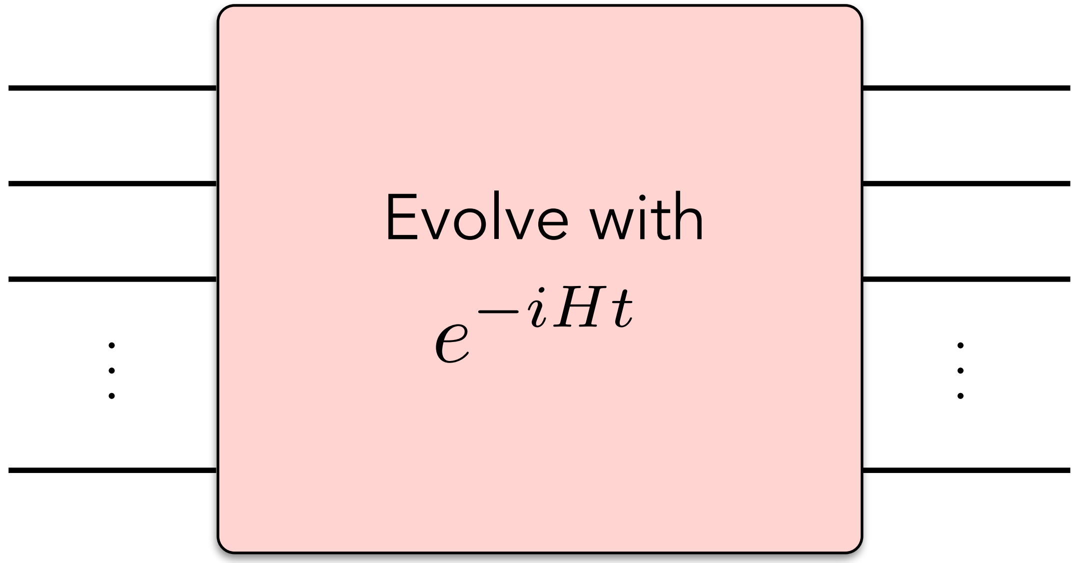
- qubits and gates
- Encoding fermions and bosons onto qubits
- State-preparation strategies
- Time evolution (via product formulas)
- Measurement strategies and observables

THIS LECTURE CONCERNS PRIMARILY TIME EVOLUTION.



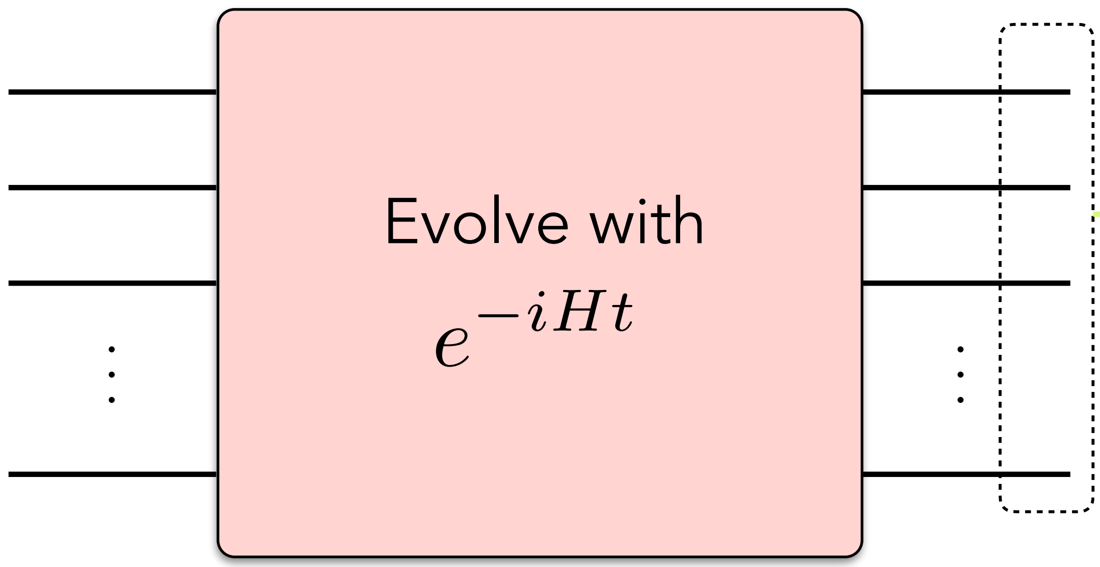
DIFFERENT APPROACHES TO QUANTUM SIMULATION

Analog



DIFFERENT APPROACHES TO QUANTUM SIMULATION

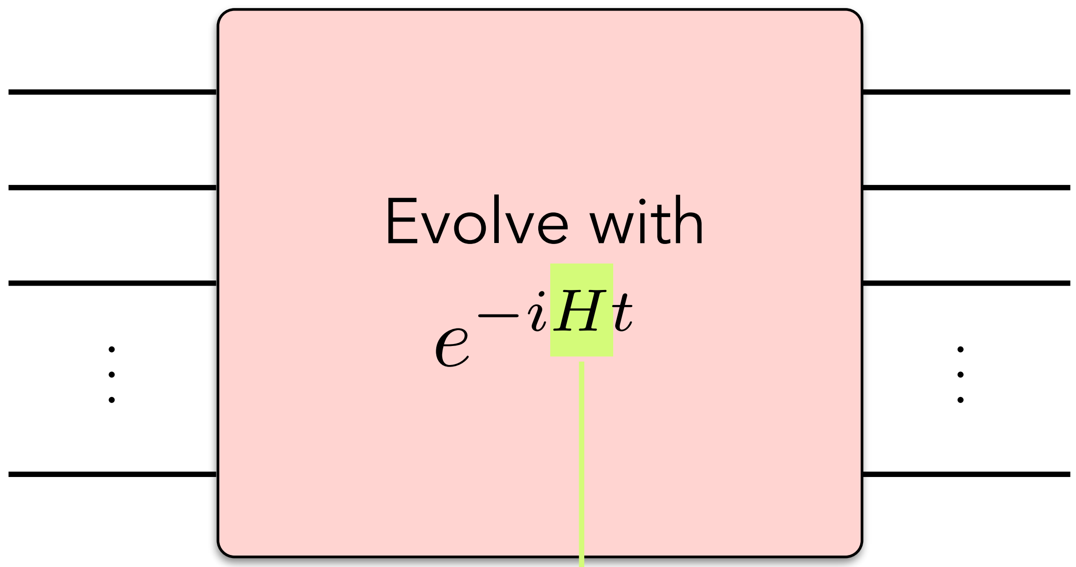
Analog



Degrees of freedom in the simulator: fermions, bosons, spins (of various dimensions), etc.

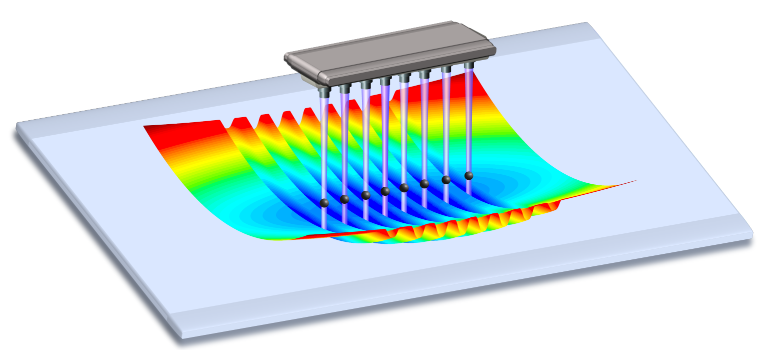
DIFFERENT APPROACHES TO QUANTUM SIMULATION

Analog

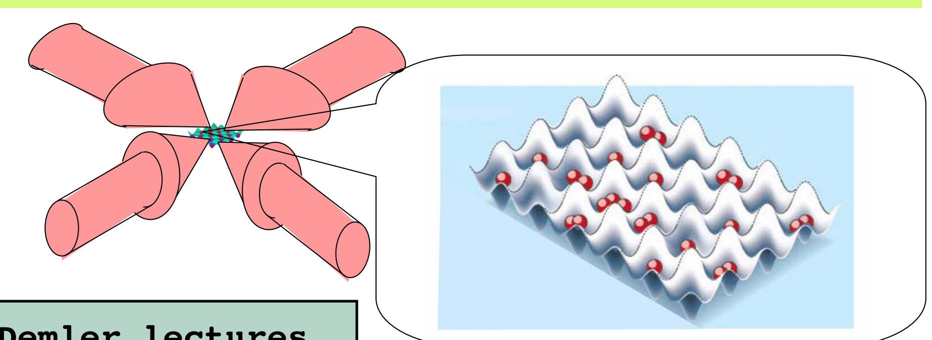


The engineered simulator Hamiltonian that mimics the Hamiltonian of target system.

Some of the leading analog simulators are: cold-atoms in optical lattices, Rydberg atoms with optical tweezers, trapped ions, superconducting circuits (including when coupled to photonics systems), etc.



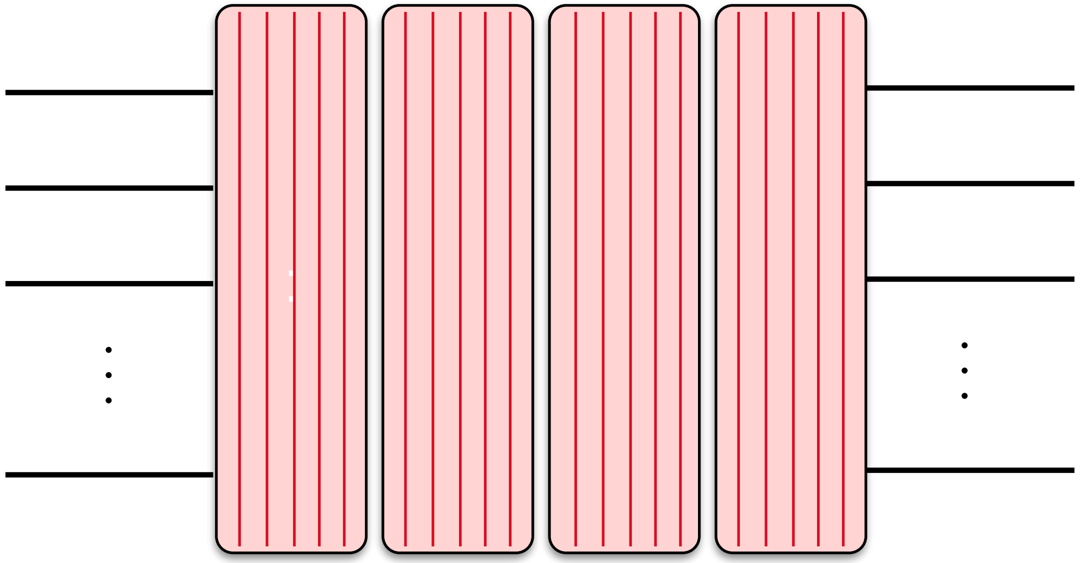
CREDIT: ANDREW SHAW, UNIVERSITY OF MARYLAND



Eugene Demler lectures, Harvard University.

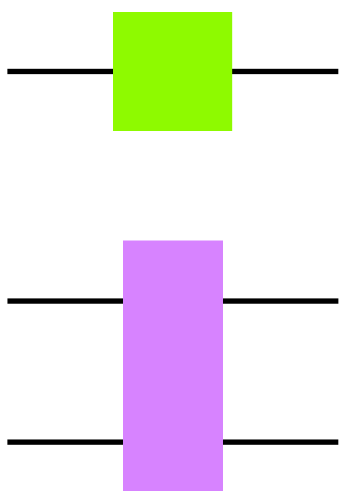
DIFFERENT APPROACHES TO QUANTUM SIMULATION

Digital

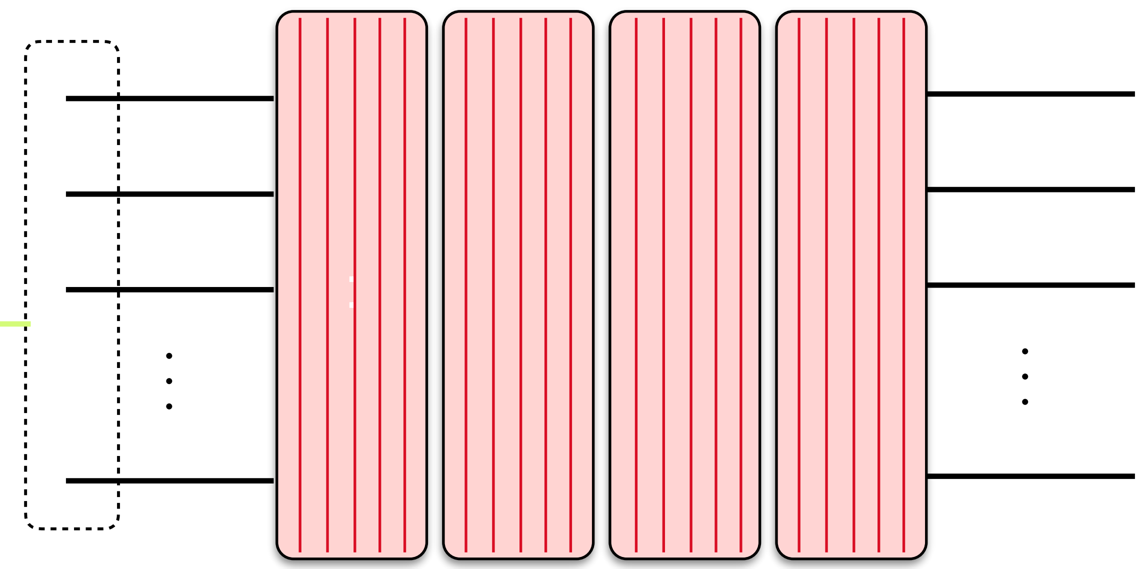


DIFFERENT APPROACHES TO QUANTUM SIMULATION

Digital



Only qubits as DOF. Only universal single- and two-qubit operations allowed.



DIFFERENT APPROACHES TO QUANTUM SIMULATION

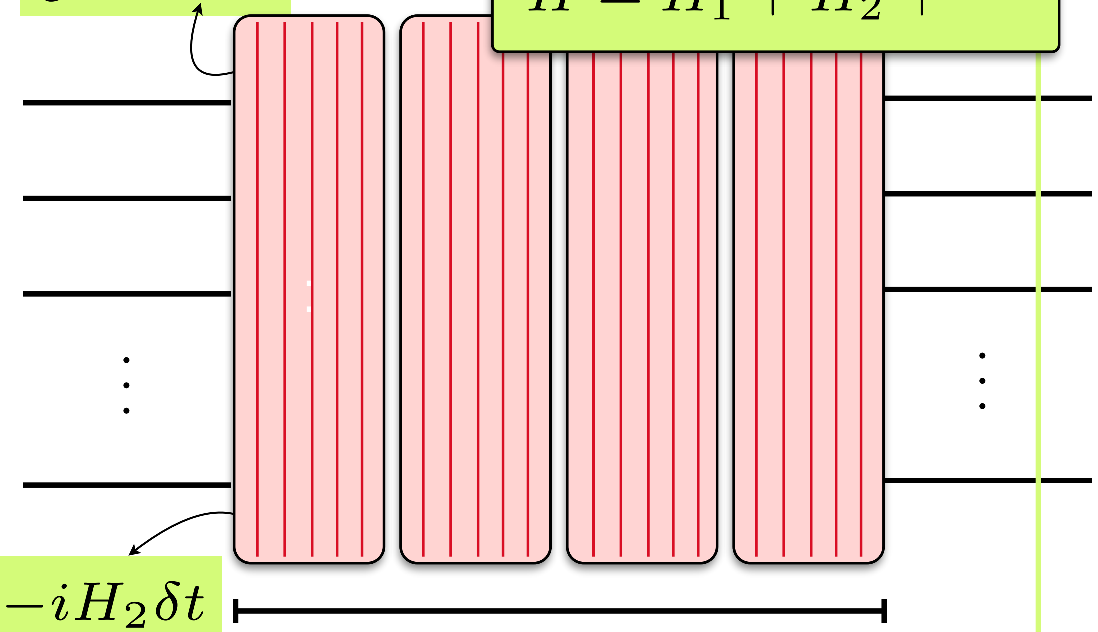
Example of a digital scheme:

Digital

$e^{-iH_1 \delta t}$

$H = H_1 + H_2 + \cdots$

Each of these can now potentially be decomposed to a universal set of single and two-qubit gates.



$e^{-iH_2 \delta t}$

$t = N_T \delta t$

Trotter-Suzuki expansion:

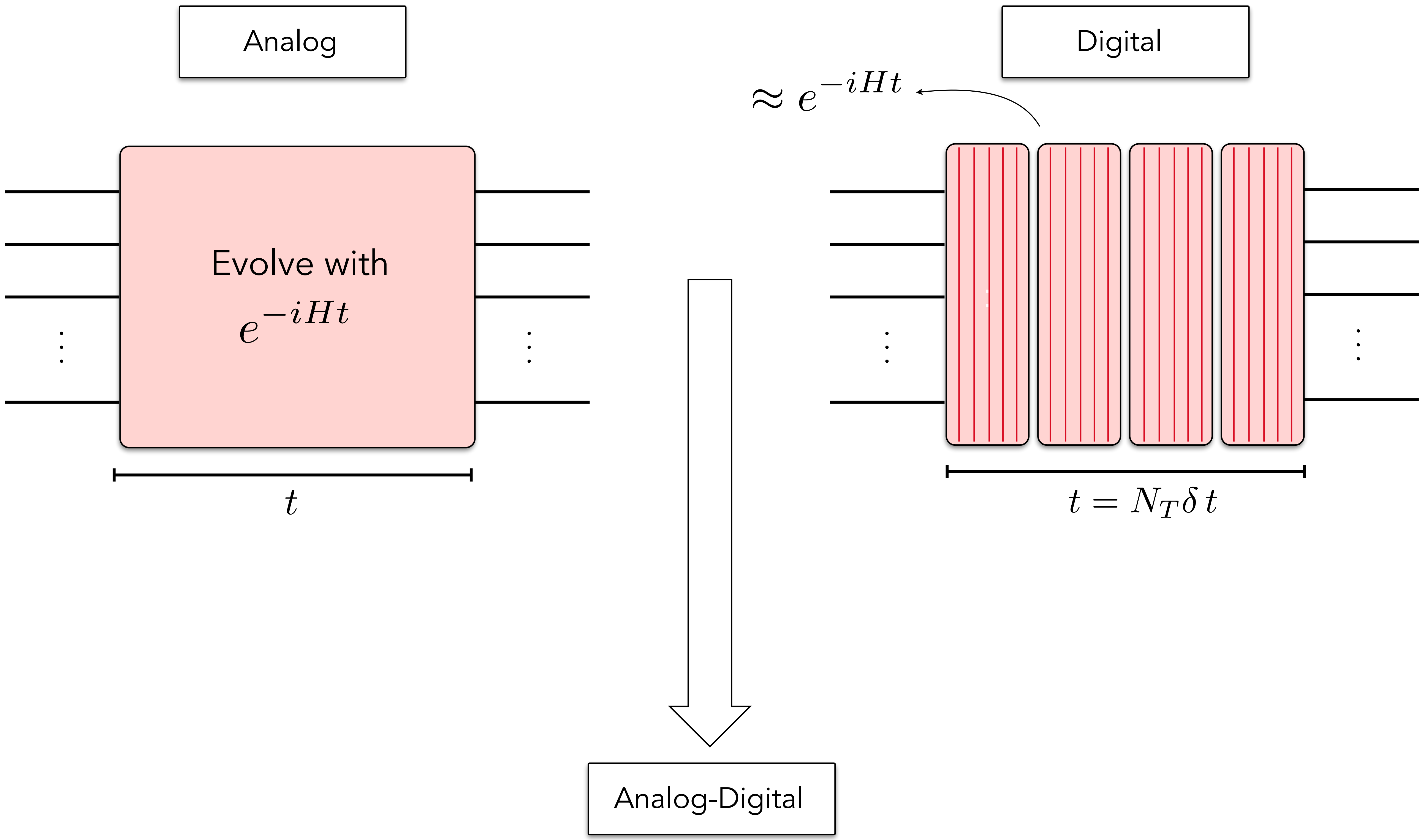
$$e^{-i(H_1+H_2+\cdots)t} = \left[e^{-iH_1\delta t} e^{-iH_2 \delta t} \cdots\right]^{t/\delta t} + \mathcal{O}((\delta t)^2)$$

Other digitalization schemes also exist.

…other methods exist too.

Andrew Childs lectures on Quantum Simulation, University of Maryland.

DIFFERENT APPROACHES TO QUANTUM SIMULATION



QUANTUM SIMULATION AND QUANTUM-COMPUTING BASICS

i) Quantum-simulation steps: A brief introduction

ii) Various modes of quantum simulation: Digital, analog, hybrid

iii) Digital-quantum-simulations basics:

- qubits and gates
- Encoding fermions and bosons onto qubits
- State-preparation strategies
- Time evolution (via product formulas)
- Measurement strategies and observables

**A textbook of extreme popularity:
Nielson and Chuang, Quantum Computation and Quantum Information.
But some of the newer notions not there.**

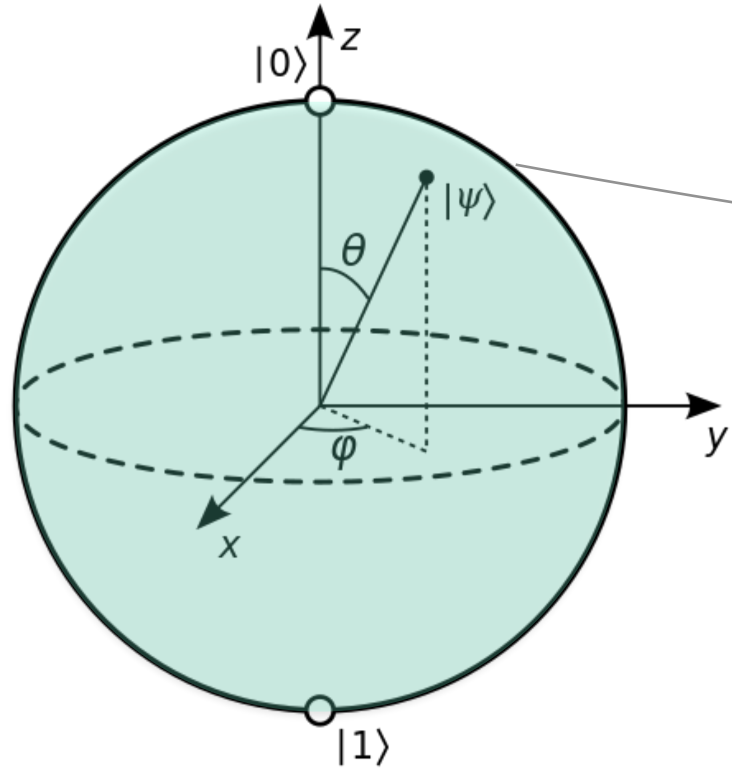
QUANTUM SIMULATION AND QUANTUM-COMPUTING BASICS

i) Quantum-simulation steps: A brief introduction

ii) Various modes of quantum simulation: Digital, analog, hybrid

iii) Digital-quantum-simulations basics:

- qubits and gates
- Encoding fermions and bosons onto qubits
- State-preparation strategies
- Time evolution (via product formulas)
- Measurement strategies and observables



State of a single qubit: $|\psi\rangle = a|0\rangle + b|1\rangle \equiv a\begin{pmatrix}1\\0\end{pmatrix} + b\begin{pmatrix}0\\1\end{pmatrix}$

$$\equiv \cos(\theta/2)|0\rangle + ie^{i\phi}\sin(\theta/2)|1\rangle$$

State of two qubits: $|\psi\rangle = a|00\rangle + b|01\rangle + c|10\rangle + d|11\rangle$

$$\equiv a\begin{pmatrix}1\\0\\0\\0\end{pmatrix} + b\begin{pmatrix}0\\1\\0\\0\end{pmatrix} + c\begin{pmatrix}0\\0\\1\\0\end{pmatrix} + d\begin{pmatrix}0\\0\\0\\1\end{pmatrix}$$

(Examples of) quantum logic gates

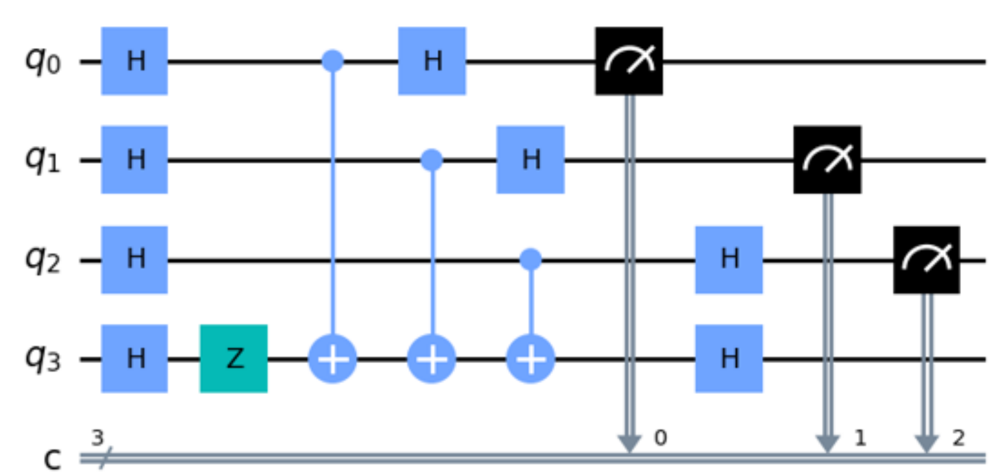
Operator	Gate(s)	Matrix
Pauli-X (X)	X	$\begin{bmatrix}0 & 1\\1 & 0\end{bmatrix}$
Pauli-Y (Y)	Y	$\begin{bmatrix}0 & -i\\i & 0\end{bmatrix}$
Pauli-Z (Z)	Z	$\begin{bmatrix}1 & 0\\0 & -1\end{bmatrix}$
Hadamard (H)	H	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$
Phase (S, P)	S	$\begin{bmatrix}1 & 0\\0 & i\end{bmatrix}$
$\pi/8$ (T)	T	$\begin{bmatrix}1 & 0\\0 & e^{i\pi/4}\end{bmatrix}$
Controlled Not (CNOT, CX)		$\begin{bmatrix}1 & 0 & 0 & 0\\0 & 1 & 0 & 0\\0 & 0 & 0 & 1\\0 & 0 & 1 & 0\end{bmatrix}$

Any unitary on a finite number of qubits can be approximated *efficiently* by a finite sequence of a universal gate set. `Solovay (1995) and Kitaev (1997).`

Two common choices for these gate sets are:

- $R^x(\theta) = e^{-i\theta\sigma^x/2}$, $R^y(\theta) = e^{-i\theta\sigma^y/2}$, $R^z(\theta) = e^{-i\theta\sigma^z/2}$, $P_\phi = \begin{pmatrix}1 & 0\\0 & e^{i\phi}\end{pmatrix}$, CNOT
- H, S, CNOT, T (S not strictly needed but more economical.)

Example of) a quantum circuit:



QUANTUM SIMULATION AND QUANTUM-COMPUTING BASICS

i) Quantum-simulation steps: A brief introduction
ii) Various modes of quantum simulation: Digital, analog, hybrid
iii) Digital-quantum-simulations basics:

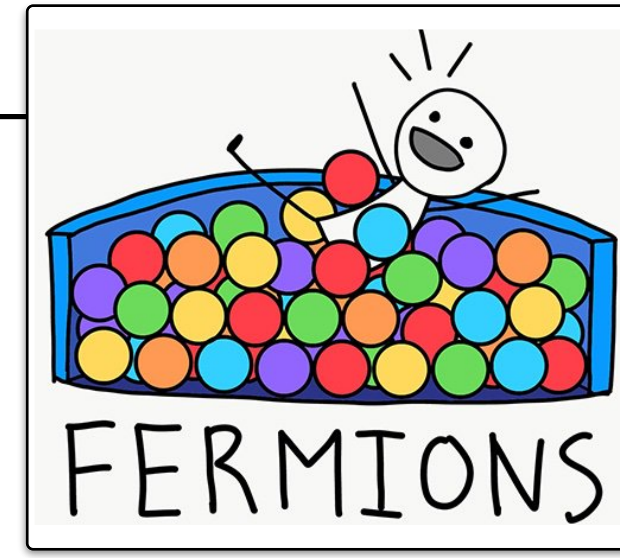
- qubits and gates
- Encoding fermions and bosons onto qubits
- State-preparation strategies
- Time evolution (via product formulas)
- Measurement strategies and observables

Fermions are **finite-dimensional** locally but obey **Fermi statistics**. Mapping a fermionic Hamiltonian into a qubit Hamiltonian can be done:

- using one qubit per fermion but at the cost of non-local qubit interactions using Jordan-Wigner transformation:

$$\psi_i = \Big(\prod_{j<i} \sigma_j^z\Big)\sigma_i^+, \quad \psi_i^\dagger = \Big(\prod_{j<i} \sigma_j^z\Big)\sigma_i^-$$

- using more than one qubit per fermion to assist retaining any existing locality in the original fermionic Hamiltonian (e.g. Verstrate-Cirac, compact, superfast encodings).

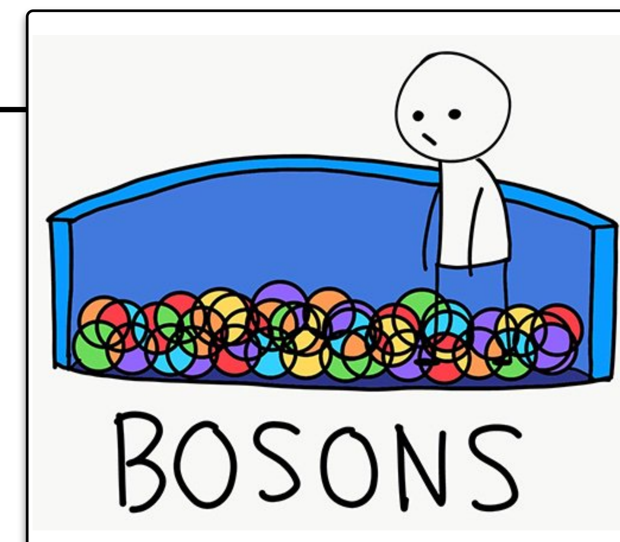


Bosons are **infinite-dimensional** locally but obey **Bose statistics**. Mapping a bosonic Hamiltonian into a qubit Hamiltonian can be done, e.g.,

- using binary encoding, requiring $\eta = \log(\Lambda + 1)$ qubits per boson, where Λ is the cutoff on boson occupation per site:

$$\hat{N}_p\,|p\rangle = p\,|p\rangle \text{ where } |p\rangle = \otimes_{j=0}^{\eta-1}\,|p_j\rangle \text{ with } p = \sum_{j=0}^{\eta-1} 2^j p_j$$

- using unary encoding, requiring Λ qubits per boson.



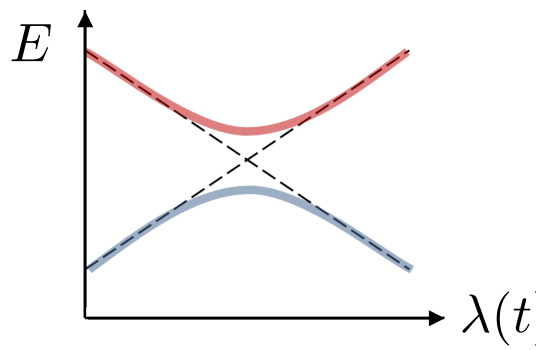
QUANTUM SIMULATION AND QUANTUM-COMPUTING BASICS

i) Quantum-simulation steps: A brief introduction
ii) Various modes of quantum simulation: Digital, analog, hybrid
iii) Digital-quantum-simulations basics:

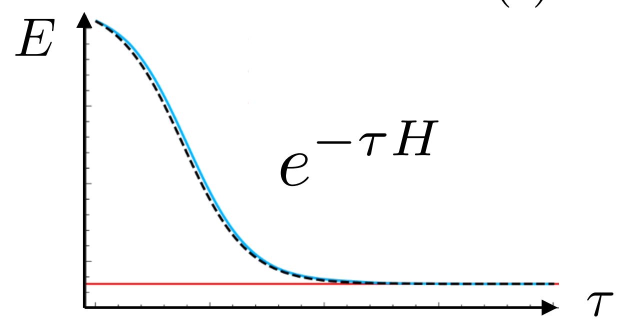
- qubits and gates
- Encoding fermions and bosons onto qubits
- State-preparation strategies
- Time evolution (via product formulas)
- Measurement strategies and observables

EXAMPLES OF (GROUND-)STATE PREPARATION METHODS

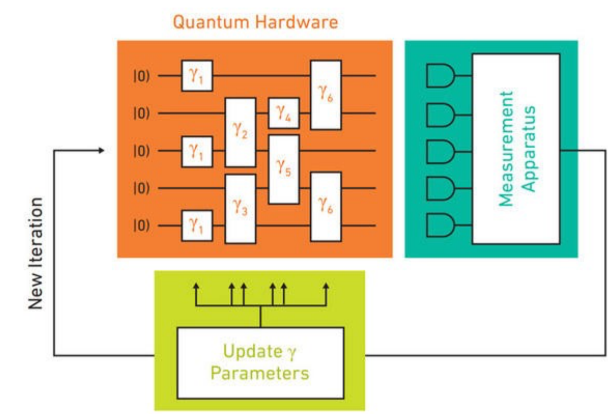
- **Adiabatic state preparation:** Prepare the ground state of a simple Hamiltonian, then adiabatically turn the Hamiltonian to that of the target Hamiltonian. Requires a non-closing energy gap.



- **Imaginary time evolution:** Start with an easily prepared state and evolve with imaginary time operator to settle in the ground state. Require implementing non-unitary operator which can be costly.



- **Variational quantum eigensolver (VQE):** Use the variational principle of quantum mechanic and classical processing to minimize the energy of a non-trivial ansatz wavefunction generated by a quantum circuit. The optimized circuit corresponding to the minimum energy generates an approximation to ground-state wavefunction. Can fail if stuck in local minima manifolds or manifolds with exponentially small gradients in qubit number.



- **Classically computed states:** Use classical computing such as Monte Carlo or Tensor Networks to learn the state or features of the state when possible, for a direct implementation of the state as a quantum circuit, or as close enough state to the ground state as a starting point of the above algorithms so to achieve more efficient implementations.

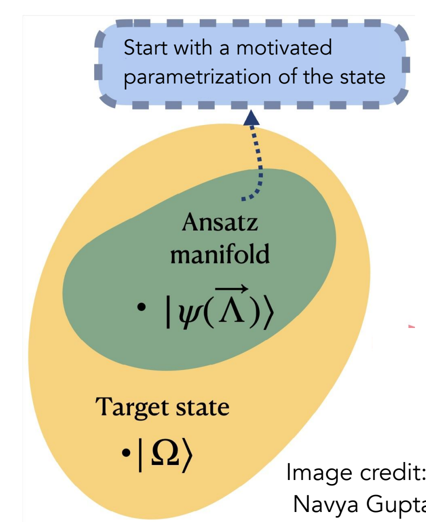


Image credit: Navya Gupta (UMD)

OUTLINE OF PART II:
QUANTUM SIMULATION AND QUANTUM-COMPUTING BASICS

i) Quantum-simulation steps: A brief introduction
ii) Various modes of quantum simulation: Digital, analog, hybrid
iii) Digital-quantum-simulations basics:

- qubits and gates
- Encoding fermions and bosons onto qubits
- State-preparation strategies
- Time evolution (via product formulas)
- Measurement strategies and observables

(IMPROVED) THEORY OF PRODUCT FORMULAS

Consider the Hamiltonian $$H = \sum_{i=1}^{\Gamma} H_i$$

First-order product formula

$$V_1(t) = e^{-itH_1} e^{-itH_2} \cdots e^{-itH_\Gamma}$$

is bounded by:

$$\|V_1(t) - e^{-itH}\| \leq \frac{t^2}{2} \sum_{i=1}^{\Gamma} \left\| \left[\sum_{j=i+1}^{\Gamma} H_j, H_i \right] \right\|$$

Second-order formula

$$V_2(t) = (e^{-itH_\Gamma/2} \cdots e^{-itH_2/2} e^{-itH_1/2})(e^{-itH_1/2} e^{-itH_2/2} \cdots e^{-itH_\Gamma/2})$$

is bounded by:

$$\|V_2(t) - e^{-itH}\| \leq \frac{t^3}{12} \sum_{i=1}^{\Gamma} \left\| \left[\sum_{k=i+1}^{\Gamma} H_k, \left[\sum_{j=i+1}^{\Gamma} H_j, H_i \right] \right] \right\| + \frac{t^3}{24} \sum_{i=1}^{\Gamma} \left\| \left[H_i, \left[H_i, \sum_{j=i+1}^{\Gamma} H_j \right] \right] \right\|$$

A general bound also exist, see: `Childs, Su, Tran, Wiebe, Zhu, Phys. Rev. X 11, 011020 (2021).`

OUTLINE OF PART II:
QUANTUM SIMULATION AND QUANTUM-COMPUTING BASICS

i) Quantum-simulation steps: A brief introduction
ii) Various modes of quantum simulation: Digital, analog, hybrid
iii) Digital-quantum-simulations basics:

- qubits and gates
- Encoding fermions and bosons onto qubits
- State-preparation strategies
- Time evolution (via product formulas)
- Measurement strategies and observables

EXAMPLES OF ACCESSIBLE OBSERVABLES

One can measure the following quantities to learn properties of the outcome state. Some of these can be measured directly in the computational basis, but others need a change of basis or other dedicated quantum circuits to access them.

- Energy and momentum, particle and charge (both locally and globally)
- Various correlation functions (both static and dynamical)
- Asymptotic S-matrix elements (assuming asymptotic final states are reached and overlap with a specified final state is desired)
- Entanglement measures such as entanglement spectrum (which can signal thermalization or lack of) using efficient ansatze.

Fidelities and full state tomography are hard as they demand exponentially large number of measurements.

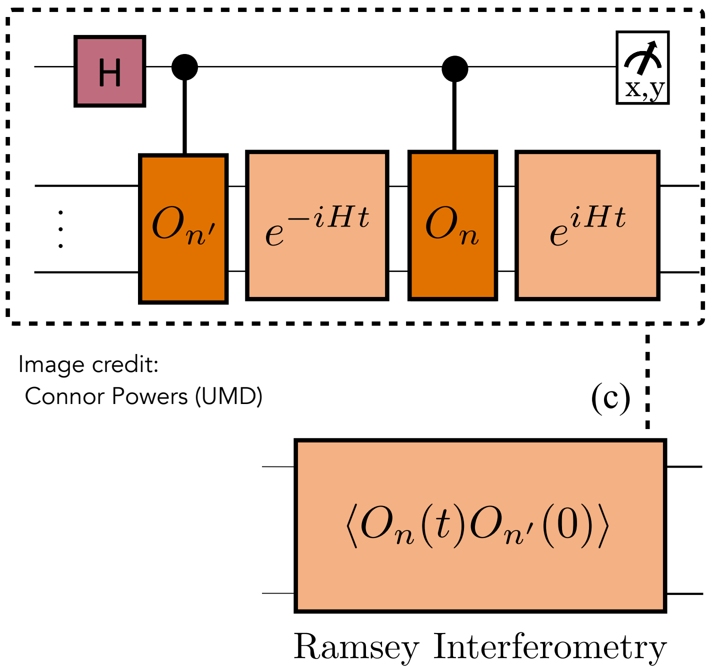


Image credit:
Connor Powers (UMD)

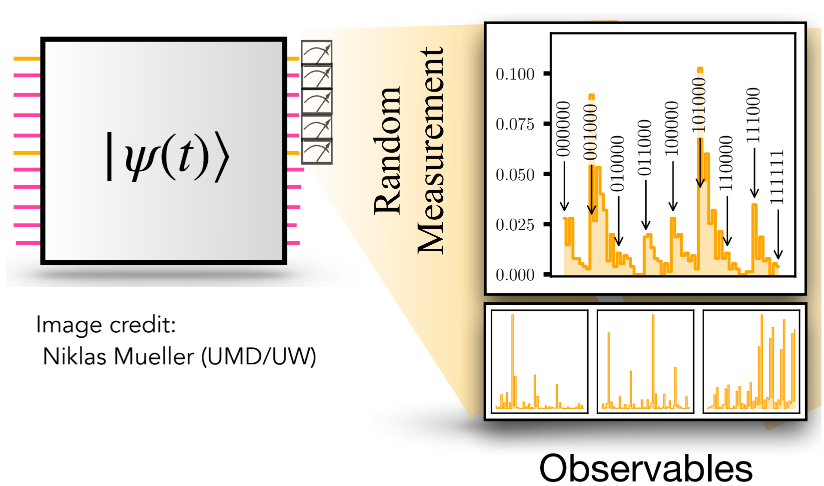
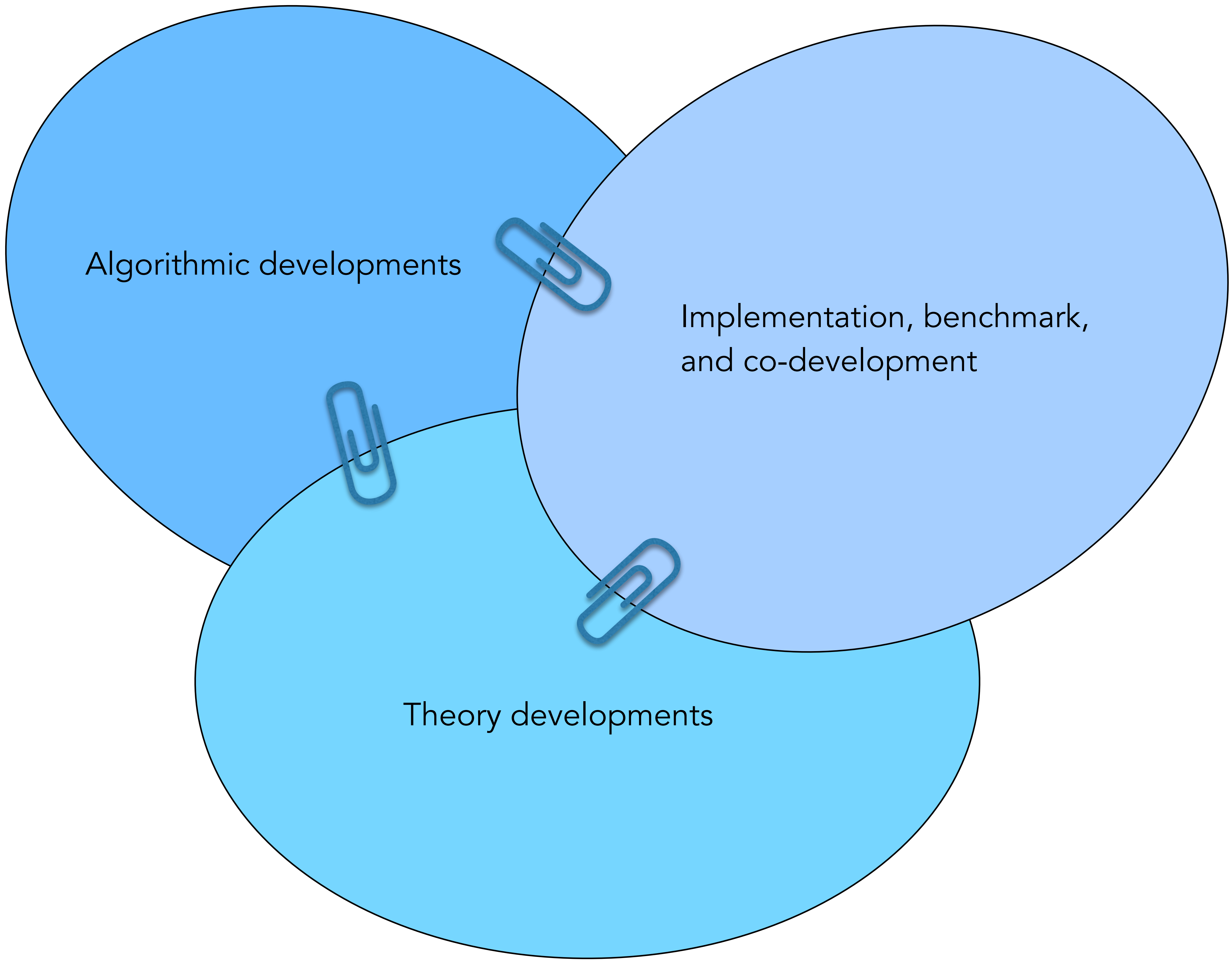


Image credit:
Niklas Mueller (UMD/UW)

SO WHERE DO WE START? WHAT ARE THE QUESTIONS TO ADDRESS? WHAT DO WE NEED TO DEVELOP?

QUANTUM SIMULATION OF QUANTUM FIELD THEORIES: A MULTI-PRONG EFFORT



How to formulate Standard Model field theories in the Hamiltonian language?

What are the efficient formulations? Which bases will be most optimal toward the continuum limit?

How to preserve the symmetries? How much should we care to retain gauge invariance?

How to quantify systematics such as finite volume, discretization, boson truncation, time digitization, etc?

Theory developments

HAMILTONIAN FORMULATION OF U(1) AND SU(N) LATTICE GAUGE THEORIES

An infinite-dimensional Hilbert space that needs to be truncated. There are also (local) Gauss's law constraints.

$$H^{(\mathrm{KS})} = H_I^{(\mathrm{KS})} + H_E^{(\mathrm{KS})} + H_M^{(\mathrm{KS})} + H_B^{(\mathrm{KS})}$$

Fermion hopping term | Energy of color electric field | Fermion mass | Energy of color magnetic field

Kogut and Susskind (1970s).

HAMILTONIAN FORMULATION OF U(1) AND SU(N) LATTICE GAUGE THEORIES

An **infinite-dimensional Hilbert space** that needs to be truncated. There are also (local) Gauss's law constraints.

$$H^{(\mathrm{KS})} = H_I^{(\mathrm{KS})} + H_E^{(\mathrm{KS})} + H_M^{(\mathrm{KS})} + H_B^{(\mathrm{KS})}$$

$H_I^{(\mathrm{KS})}$	$H_E^{(\mathrm{KS})}$	$H_M^{(\mathrm{KS})}$	$H_B^{(\mathrm{KS})}$
Fermion hopping term	Energy of color electric field	Fermion mass	Energy of color magnetic field

Conjugate variable pairs: electric field (E) and gauge link (U). Spectrum of E is discrete but unbound, while spectrum of U is bounded but continuous.

HAMILTONIAN FORMULATION OF U(1) AND SU(N) LATTICE GAUGE THEORIES

An **infinite-dimensional Hilbert space** that needs to be truncated. There are also (local) Gauss's law constraints.

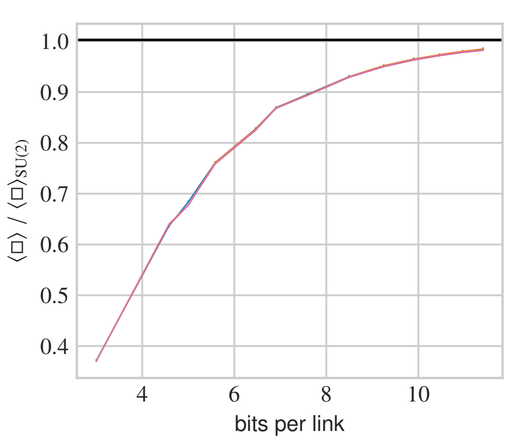
$$H^{(\mathrm{KS})} = H_I^{(\mathrm{KS})} + H_E^{(\mathrm{KS})} + H_M^{(\mathrm{KS})} + H_B^{(\mathrm{KS})}$$

Fermion hopping term | Energy of color electric field | Fermion mass | Energy of color magnetic field

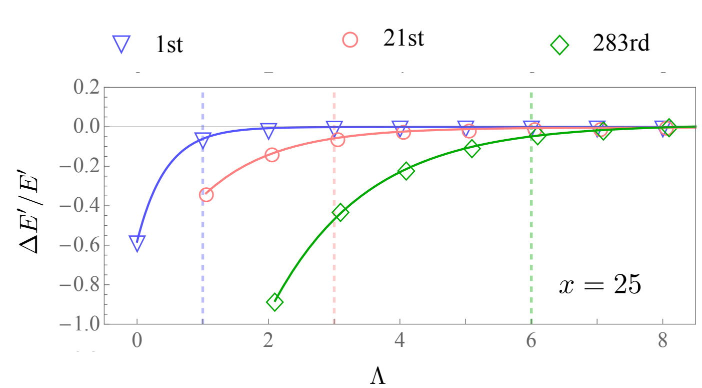
See also Tong, Albert, McClean, Preskill, and Su (2021) and Ciavarella (2023).

Gauge-field truncation

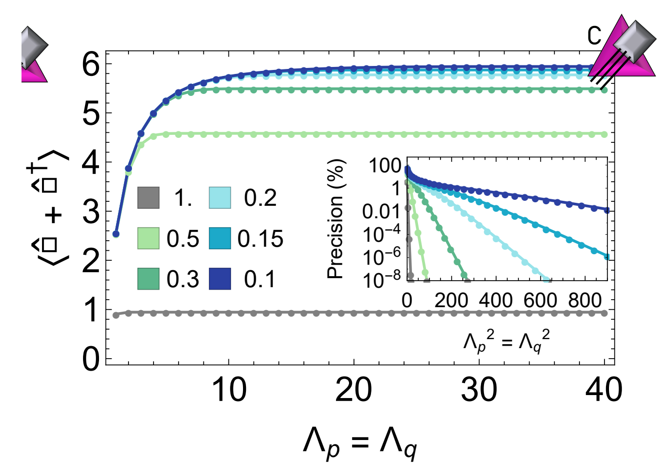
SU(2) pure gauge in 3+1 D in the U basis



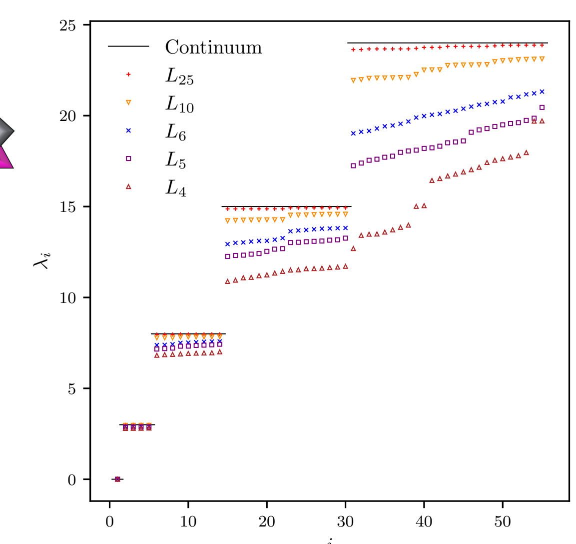
SU(2) with matter in 1+1 D in the E basis



SU(3) pure gauge in 2+1 D in the E basis



SU(2) pure gauge in the U basis



Hackett et al, Phys. Rev. A 99, 062341 (2019).

ZD, Raychowdhury, and Shaw, Phys. Rev. D 104, 074505 (2021).

iavarella, Klco, and Savage, Phys. Rev. D 103, 094501 (2021).

Jakobs et al, arXiv:2304.02322 [hep-lat] (2021).

HAMILTONIAN FORMULATION OF U(1) AND SU(N) LATTICE GAUGE THEORIES

An infinite-dimensional Hilbert space that needs to be truncated. There are also **(local) Gauss's law constraints**.

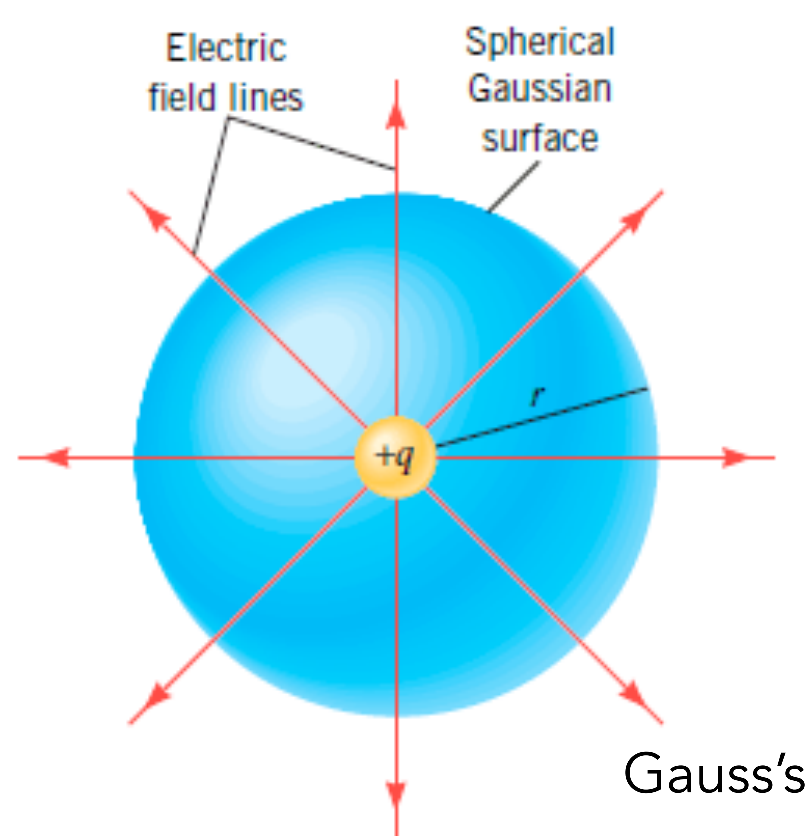
$$H^{(\mathrm{KS})} = H_I^{(\mathrm{KS})} + H_E^{(\mathrm{KS})} + H_M^{(\mathrm{KS})} + H_B^{(\mathrm{KS})}$$

$H_I^{(\mathrm{KS})}$	$H_E^{(\mathrm{KS})}$	$H_M^{(\mathrm{KS})}$	$H_B^{(\mathrm{KS})}$
Fermion hopping term	Energy of color electric field	Fermion mass	Energy of color magnetic field

Generator of infinitesimal gauge transformation

$$[G_r^a, H] = 0$$

$$G_r^a |\psi\rangle_{\mathrm{phys.}} = 0$$



Gauss's law

HAMILTONIAN FORMULATION OF U(1) AND SU(N) LATTICE GAUGE THEORIES

An infinite-dimensional Hilbert space that needs to be truncated. There are also **(local) Gauss's law constraints**.

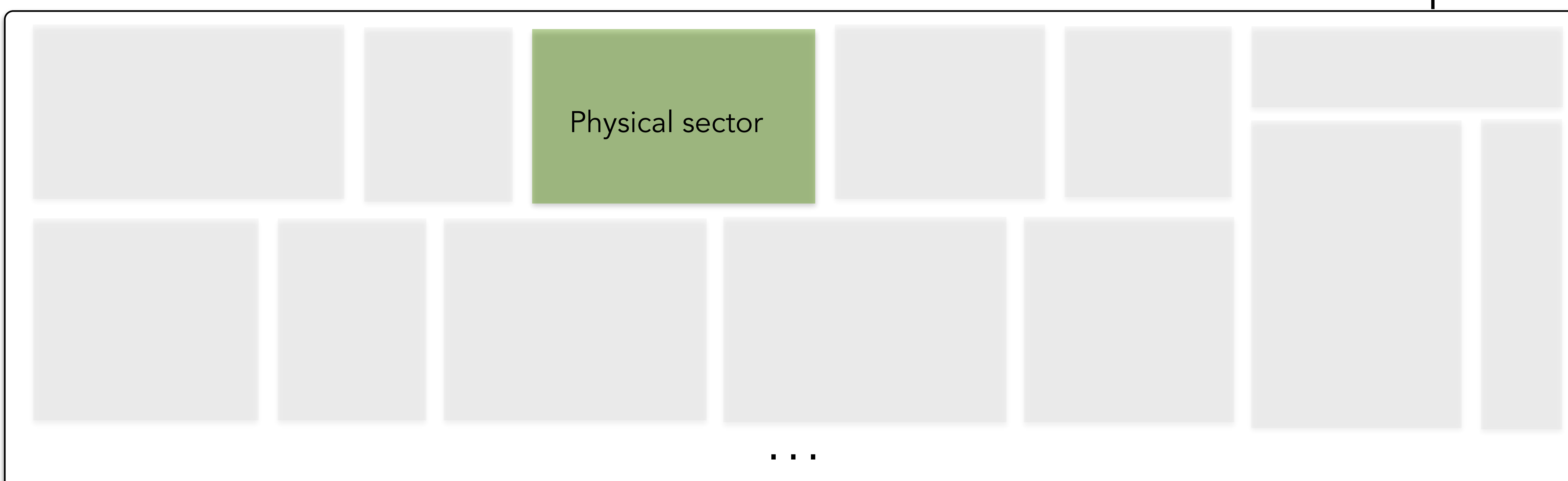
$$H^{(\mathrm{KS})} = H_I^{(\mathrm{KS})} + H_E^{(\mathrm{KS})} + H_M^{(\mathrm{KS})} + H_B^{(\mathrm{KS})}$$

Fermion hopping term | Energy of color electric field | Fermion mass | Energy of color magnetic field

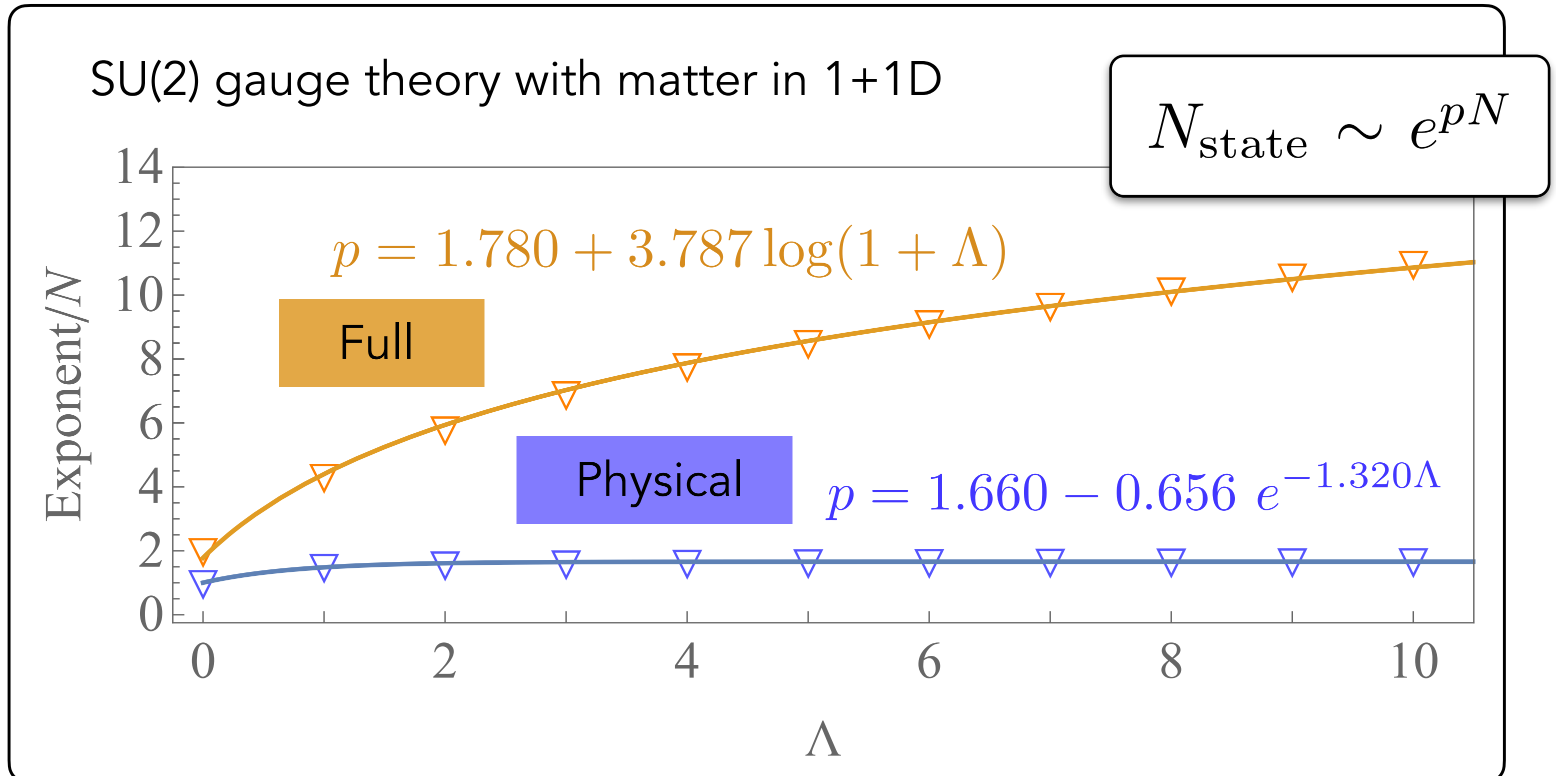
Generator of infinitesimal gauge transformation

$$[G_r^a, H] = 0$$

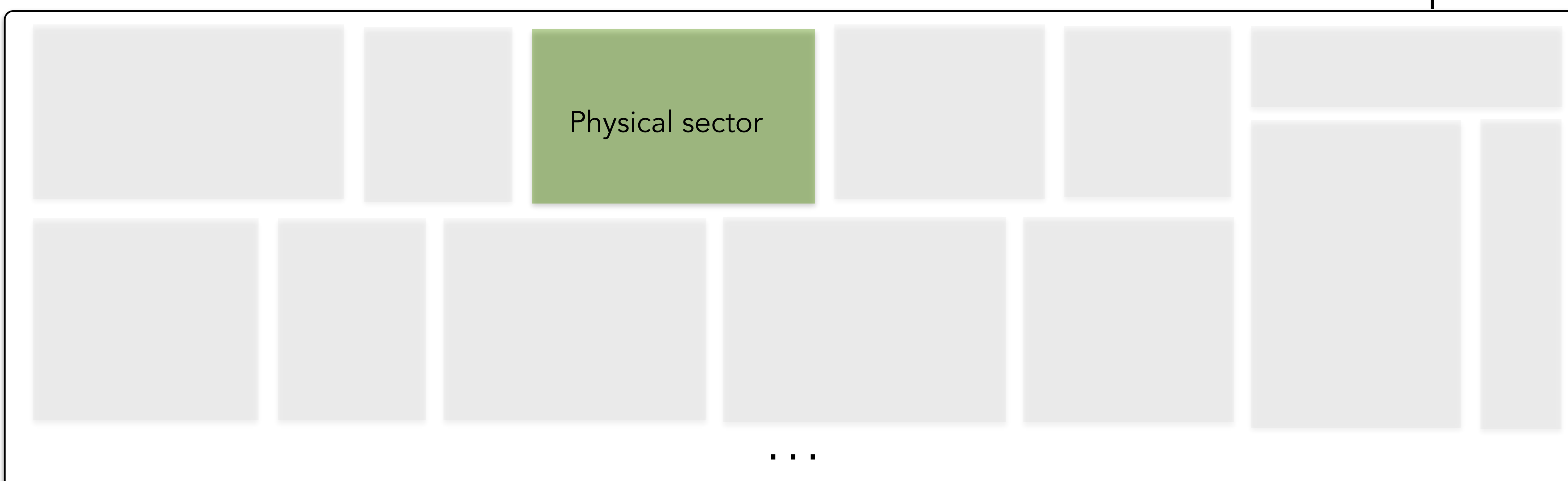
$$G_r^a |\psi\rangle_{\mathrm{phys.}} = 0$$



HAMILTONIAN FORMULATION OF U(1) AND SU(N) LATTICE GAUGE THEORIES



ZD, Raychowdhury, and Shaw, Phys. Rev. D 104, 074505, arXiv:2009.11802 [hep-lat]



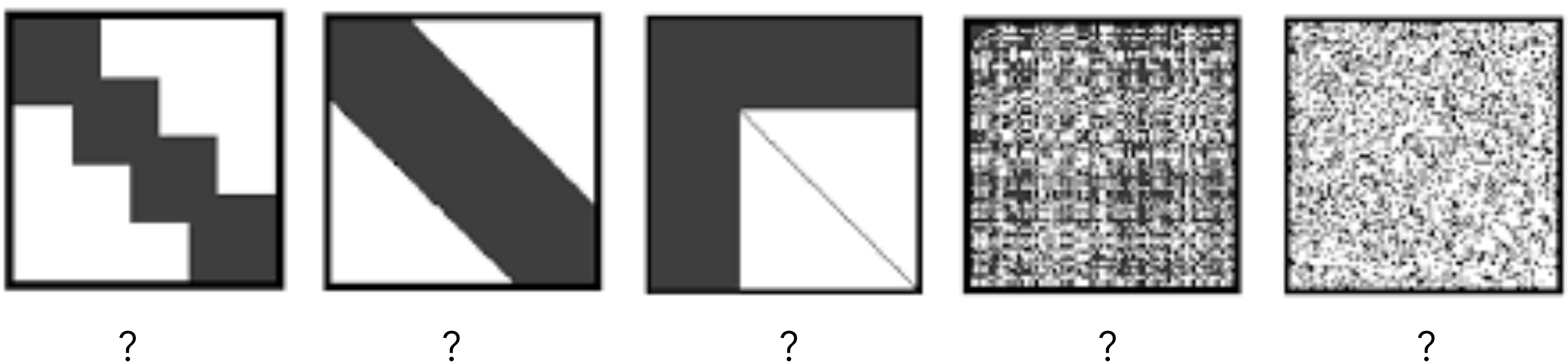
HAMILTONIAN FORMULATION OF U(1) AND SU(N) LATTICE GAUGE THEORIES

An infinite-dimensional Hilbert space that needs to be truncated. There are also (local) Gauss's law constraints.

$$H^{(\mathrm{KS})} = H_I^{(\mathrm{KS})} + H_E^{(\mathrm{KS})} + H_M^{(\mathrm{KS})} + H_B^{(\mathrm{KS})}$$

$H_I^{(\mathrm{KS})}$	$H_E^{(\mathrm{KS})}$	$H_M^{(\mathrm{KS})}$	$H_B^{(\mathrm{KS})}$
Fermion hopping term	Energy of color electric field	Fermion mass	Energy of color magnetic field

The **choice of basis** matters! It dictates which Hamiltonian term is naturally diagonal, how complex the rest of the terms are, and what level of truncation is needed.



MANY HAMILTONIAN FORMULATIONS OF GAUGE THEORIES EXIST, WHICH ONE TO PICK?

Gauge-field theories (Abelian and non-Abelian):

Group-element representation
Zohar et al; Lamm et al; Jansen, Urbach, et al.

Prepotential formulation
Mathur, Raychowdhury et al

Loop-String-Hadron basis
Raychowdhury, Stryker, Kadam

Link models, qubitization
Chandrasekharan, Wiese et al; Alexandru, Bedaque, et al; Hersch et al, Banerjee, Marinkowich, et al.

Fermionic basis
Hamer et al; Martinez et al; Banuls et al

Bosonic basis
Cirac and Zohar

Local irreducible representations
Byrnes and Yamamoto; Ciavarella, Klco, and Savage

Light-front quantization Kreshchuk, Love, Goldstien, Vary et al

Manifold lattices
Buser et al

Dual plaquette (magnetic) basis
Bender, Zohar et al; Kaplan and Styker; Unmuth-Yockey; Hasse et al; Jansen, Muschik et al; Bauer and Grabowska

Spin-dual representation
Mathur et al

Scalar field theory

Field basis
Jordan, Lee, and Preskill

Wavelet basis
Bagherimehrab, Sanders, et al.

Continuous-variable basis
Pooser, Siopsis et al

Harmonic-oscillator basis
Klco and Savage

Single-particle basis
Barata , Mueller, Tarasov, and Venugopalan.

Algorithmic developments
[Digital]

Near- and far-term algorithms with bounded errors and resource requirement for gauge theories?

Can given formulation/encoding reduce qubit and gate resources?

Can we develop gauge-invariant simulation algorithms?

How do we do state preparation and compute observables like scattering amplitudes?

Algorithmic developments [Digital]

- Near- and far-term algorithms with bounded errors and resource requirement for gauge theories?
- Can given formulation/encoding reduce qubit and gate resources?
- Can we develop gauge-invariant simulation algorithms?
- How do we do state preparation and compute observables like scattering amplitudes?

Algorithms for simulating quantum field theories started from pioneering work of Jordan, Lee, Preskill.

Algorithmic progress for U(1), SU(2), and SU(3) quantum field theories include:

Shaw, Lougovski, Stryker, Wiebe, Quantum 4, 306 (2020).
Ciavarella, Klco, and Savage, Phys. Rev. D 103, 094501 (2021).
Kan and Nam, arXiv:2107.12769 [quant-ph].
Lamm, Lawrence, and Yamauchi, *Phys.Rev.D* 100 (2019) 3, 034518.
Paulson *et al, PRX Quantum* 2 (2021) 030334.
Murairi, Cervia, Kumar, Bedaque, Alexandru, arXiv:2208.11789 [hep-lat].
ZD, Shaw, and Stryker, Quantum 7, 1213 (2023).
Sakamoto, Morisaki, Haruna, Itou, Fujii, Mitarai, Quantum 8, 1474 (2024).
M. Rhodes, M. Kreshchuk, S. Pathak, arXiv:2405.10416 [quant-ph].
Lamm et al, arXiv:2405.12890 [hep-lat].

How many qubits and gates are required to achieve accuracy ϵ in a given observables? Are there algorithms that scale optimally?

What about the ultimate theory for us?

Quantum Chromodynamics, a SU(3) LGT in 3+1 coupled to 6 flavors of quarks

What about the ultimate theory for us?
Quantum Chromodynamics, a SU(3) LGT in 3+1 coupled to 6 flavors of quarks

		10^3 lattice at fixed paramts.
Kan and Nam:	Kogut and Susskind in E basis, no Gauss-law implementation *a priori* Evaluates matrix elements quantumly Uses product formulas. Breaks all bosonic ladder ops. to even/odd space	$O(10^{50})$ T gates
ZD and Stryker:	Kogut and Susskind in E basis, no Gauss-law implementation *a priori* Evaluates matrix elements quantumly Uses PFs. Breaks only some of the bosonic ladder ops. to even/odd space	PRELIMINARY $O(10^{30})$ T gates
Rhodes, Kreshchuk, Pathak	Kogut and Susskind in E basis, no Gauss-law implementation a priori Uses QROM to access matrix elements evaluated classically Uses block encoding of time evolution. No even-odd breaking.	$O(10^{25})$ T gates
Ciavarella, Klco, Savage:	Kogut and Susskind in E basis, some Gauss-law implementation *a priori* Uses controlled operations to access matrix elements evaluated classically Not a full algorithm in 3+1 D with error analysis	-
Lamm et al:	Kogut and Susskind in U basis, no Gauss-law implementation *a priori* Matrix elements simple (no Clebsch–Gordan coeff. in this basis) Uses block encoding, no full error analysis for SU(3) subgroups yet	- [For SU(2), $O(10^{13})$ T gates]

How far can we continue to improve? Will this problem become reasonably doable in the fault-tolerant era?

Algorithmic developments
[Digital]

- Near- and far-term algorithms with bounded errors and resource requirement for gauge theories?
- Can given formulation/encoding reduce qubit and gate resources?
- Can we develop gauge-invariant simulation algorithms?
- How do we do state preparation and compute observables like scattering amplitudes?

Vacuum and hadronic states?

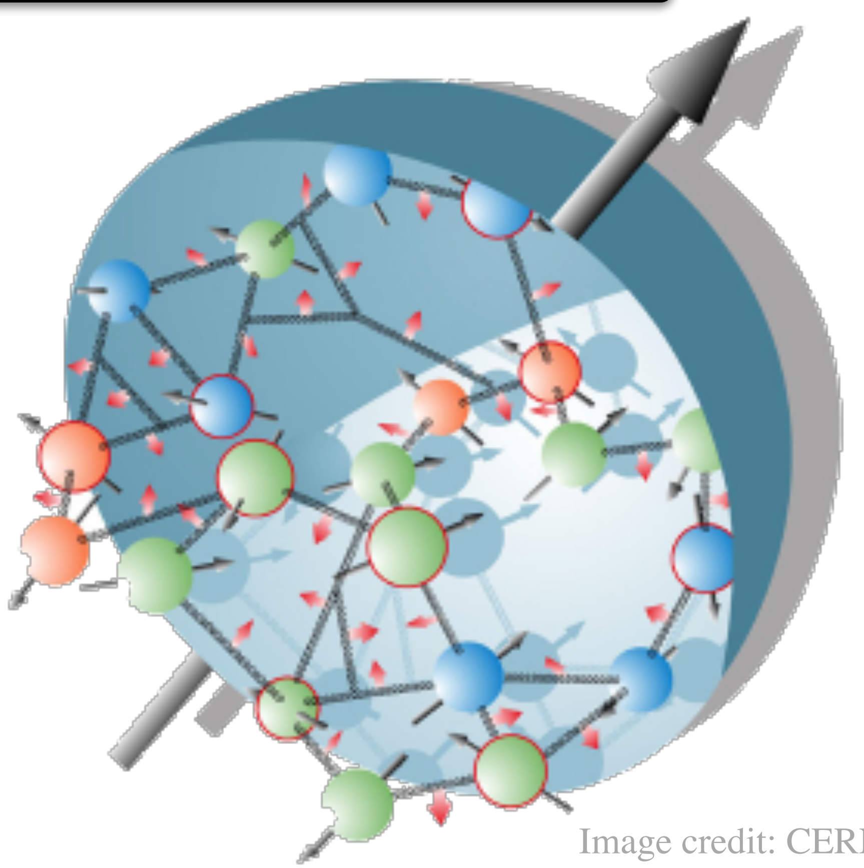
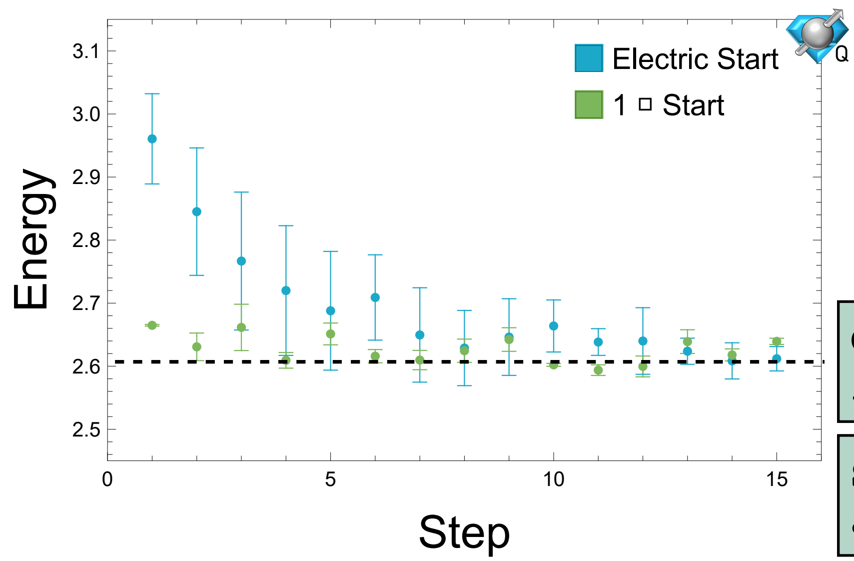
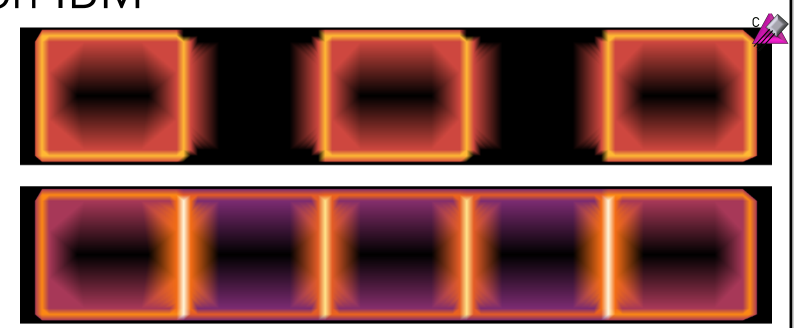


Image credit: CERN courier

VACCUM AND HADRONIC STATE PREPARATION AND SPECTROSCOPY IN GAUGE THEORIES

Variational state preparation of the vacuum state for a two plaquette system in pure SU(2) LGT on IBM

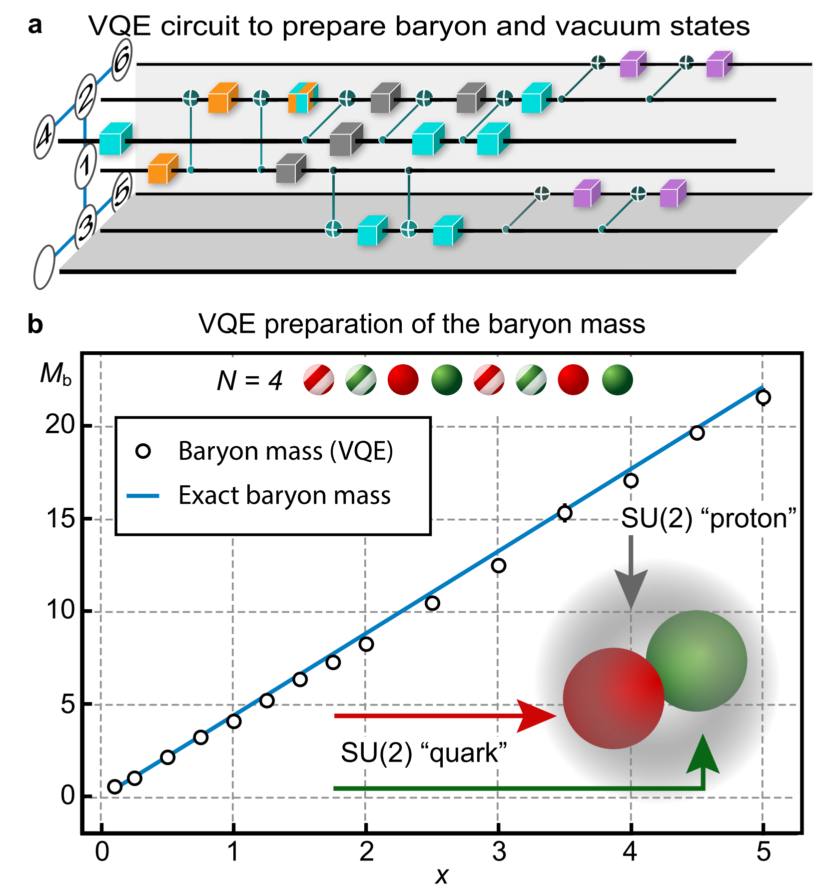




Ciavarella and Chernyshev, *Phys.Rev.D* 105 (2022) 7, 074504.

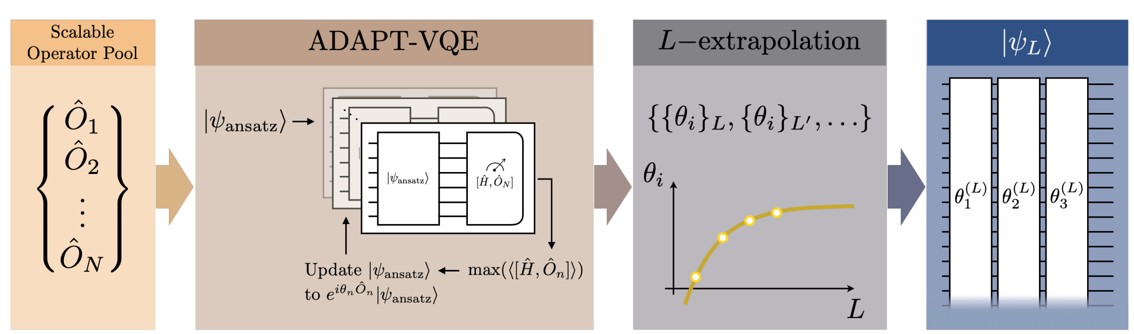
See also: Gustafson et al, arXiv:2408.12641 [quant-ph].

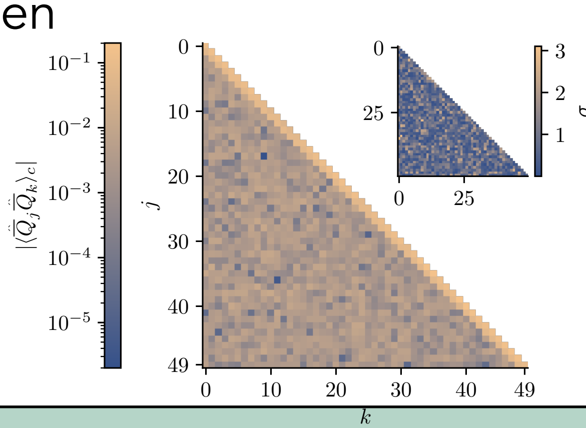
Low-lying spectrum of SU(2) with matter in 1+1 D on IBM

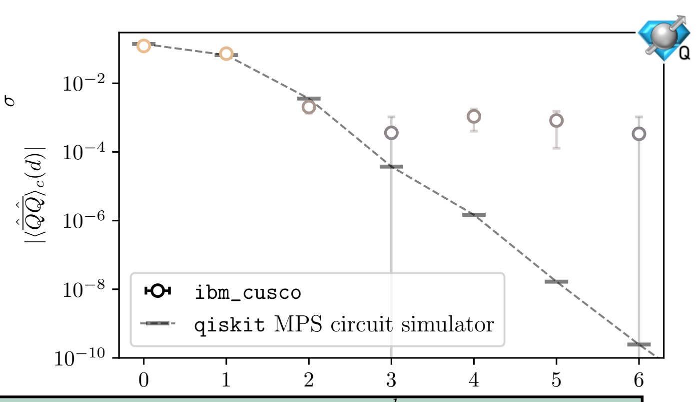


Atas et al, Nature Communications 12, 6499 (2021). SU(3) example: Atas et al: arXiv:2207.03473 [quant-ph].

Schwinger model vacuum on a 100 qubits IBM system: Connected correlation functions between spatial charges





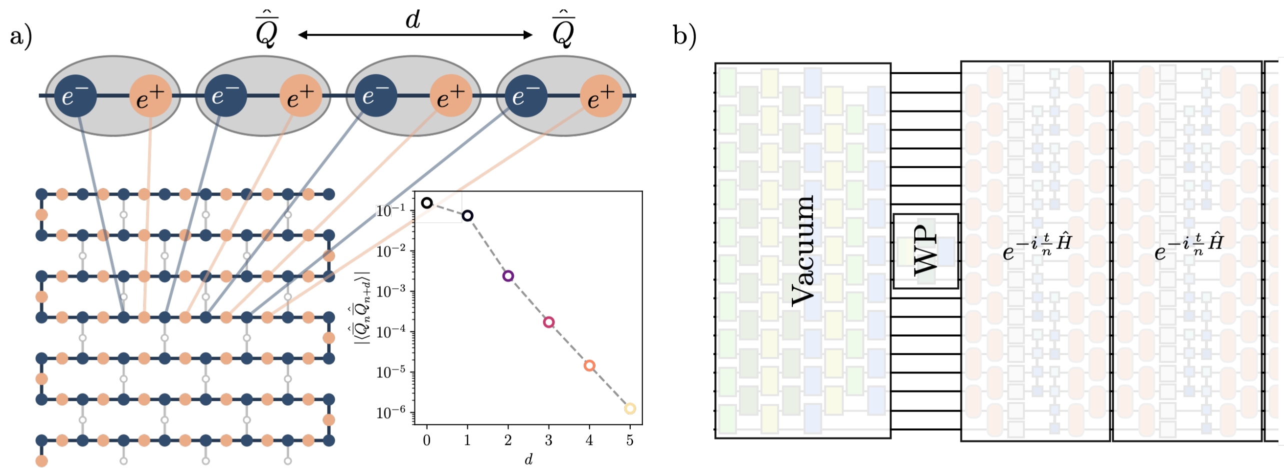


Farrell, Illa, Ciavarella, Savage, arXiv:2308.04481 [quant-ph].

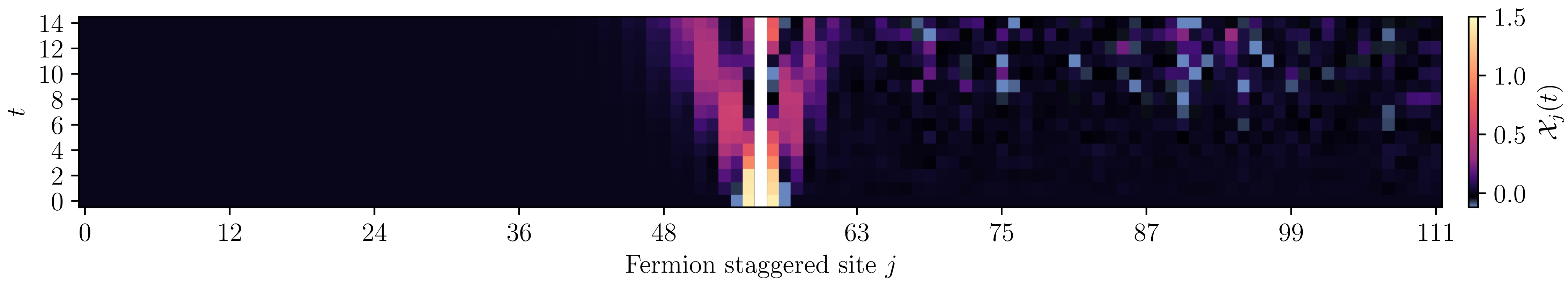
Hamiltonian methods in general: Itou, Matsumoto, Tanizaki, arXiv:2307.16655 [hep-lat]. See also studies on D-wave annealers: Rahman et al, Phys. Rev. D 104, 034501 (2021), Illa and Savage, arXiv:2202.12340 [quant-ph], Farrel et al, arXiv:2207.01731 [quant-ph]. Digital approaches: Kane, Gomes, and Kreshchuk, arXiv:2310.13757 [quant-ph].

FIRST STEPS TOWARD HADRONIC WAVEPACKETS FOR COLLISION PROCESSES

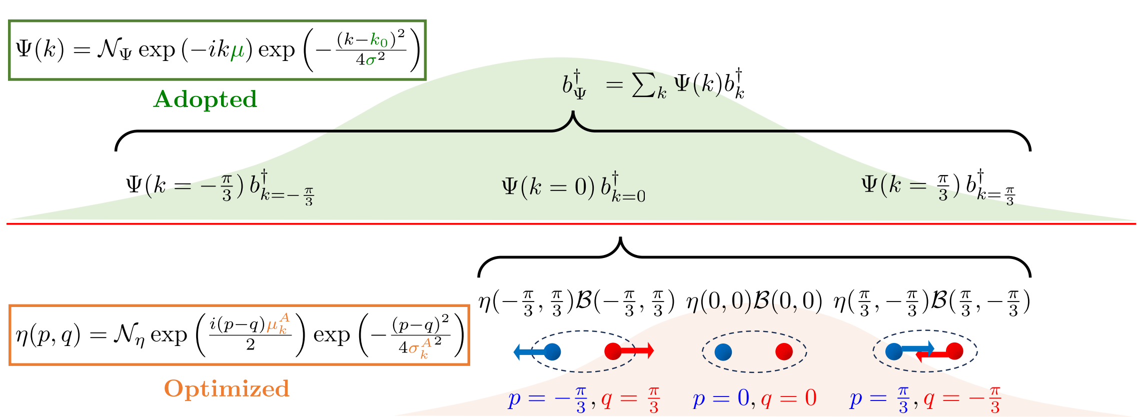
Hadron wave packet evolution in the Schwinger model (112 staggered sites with IBM with noise mitigation):

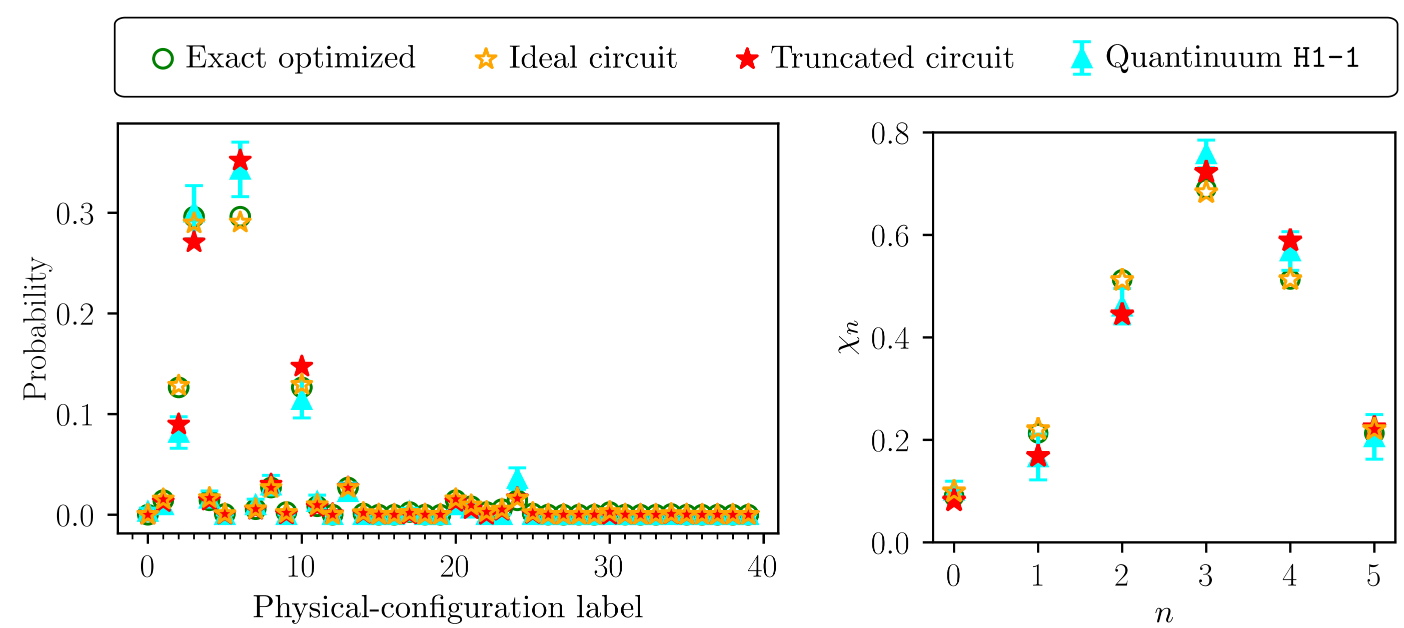


Farrell, Illa, Ciavarella, Savage, arXiv:2401.08044 [quant-ph].



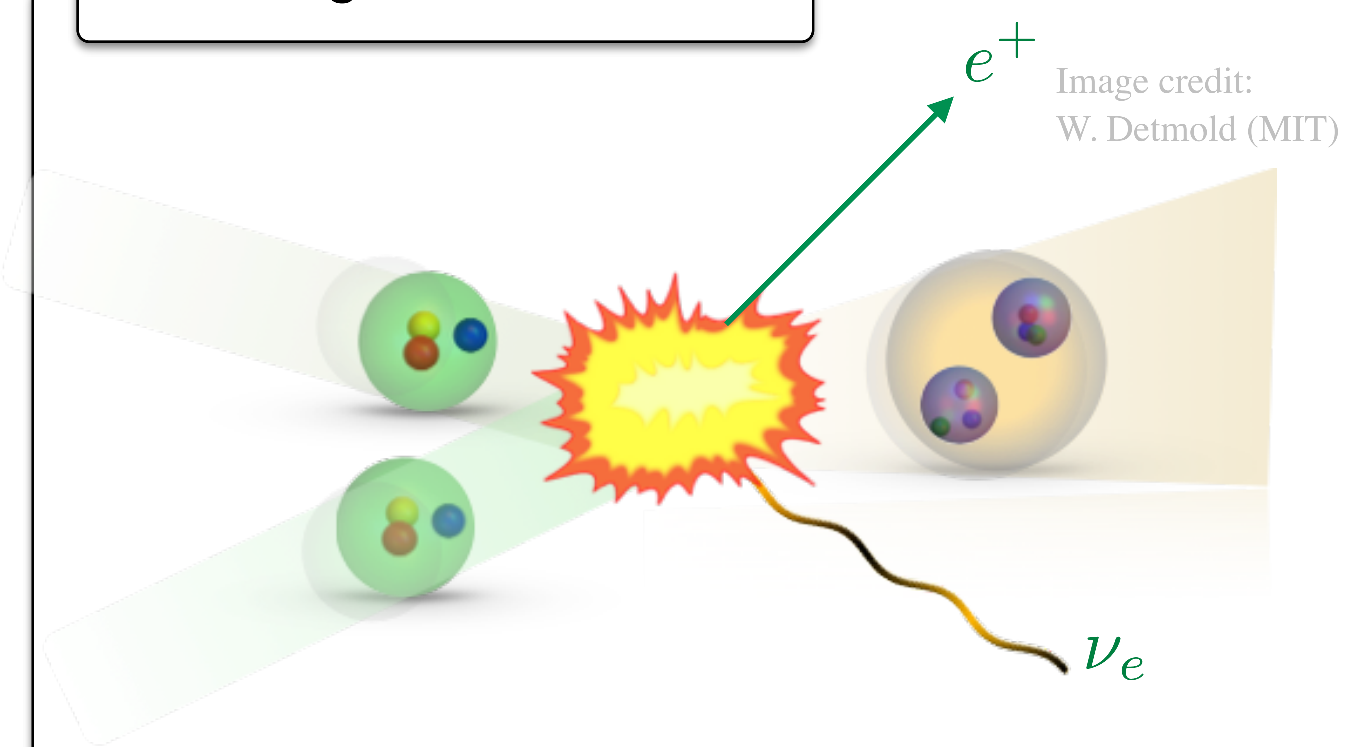
Hadron wavepacket in the Z_2 gauge theory (12 staggered sites with Quantinuum, minimal noise mitigation):





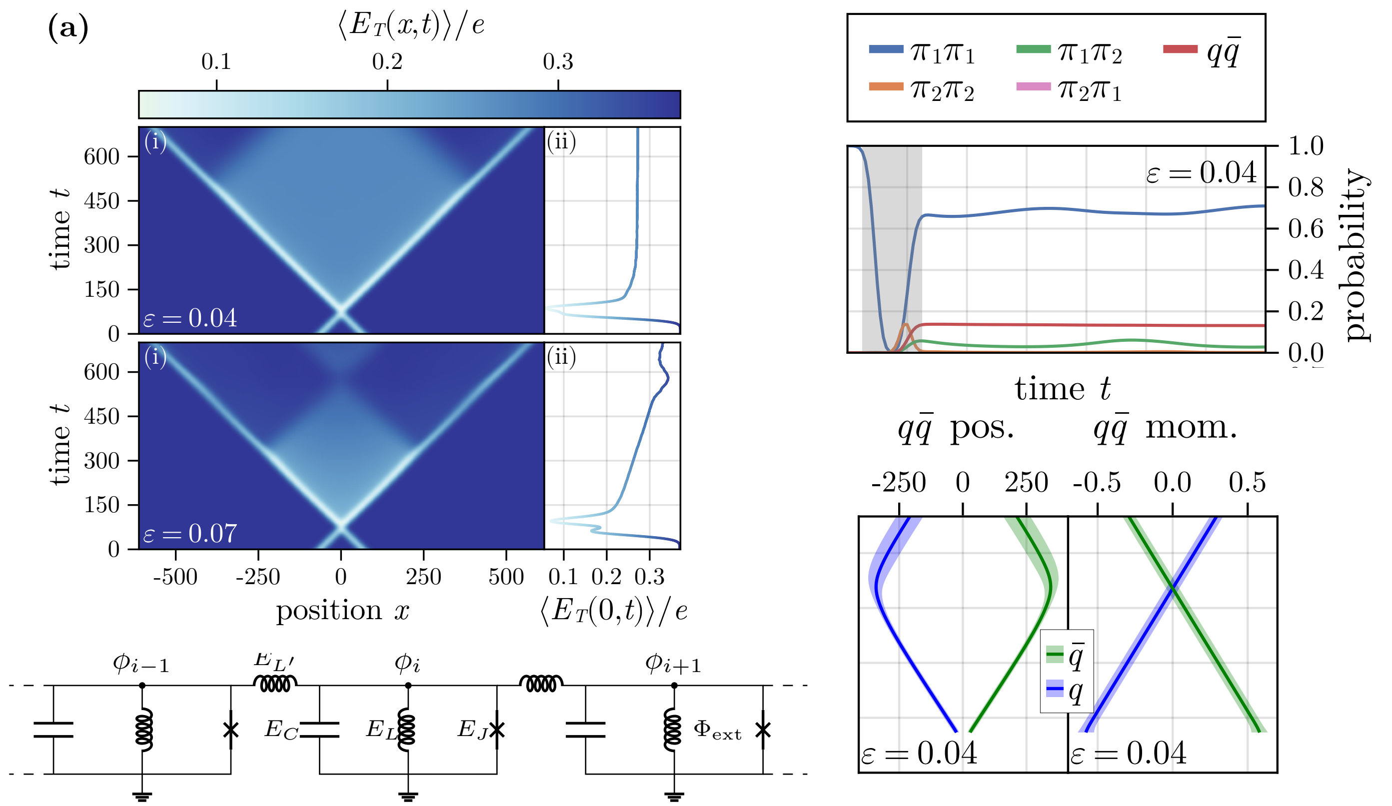
ZD, Hsieh, and Kadam, arXiv:2402.00840 [quant-ph].

Scattering and transitions?



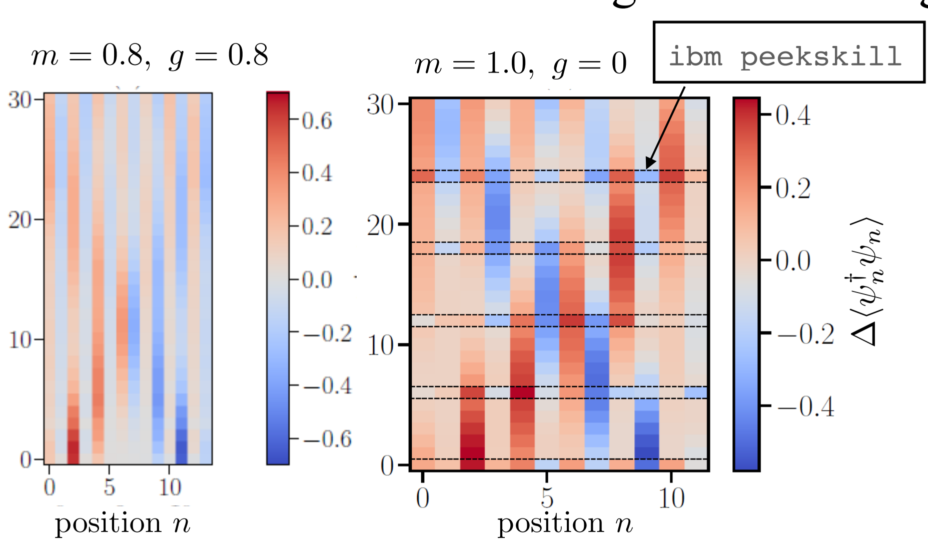
FIRST STEPS TOWARD COLLISION/REACTION PROCESSES

High-Energy collision of quarks and hadrons in the Schwinger model: From tensor networks to circuit QED



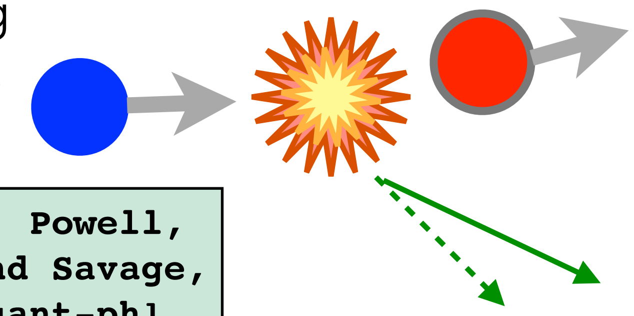
Belyansky, Whitsitt, Mueller, Fahimniya, Bennewitz, ZD, and Gorshkov, arXiv:2307.02522 [quant-ph].

Fermion-antifermion scattering in the Thirring model in (1+1)D

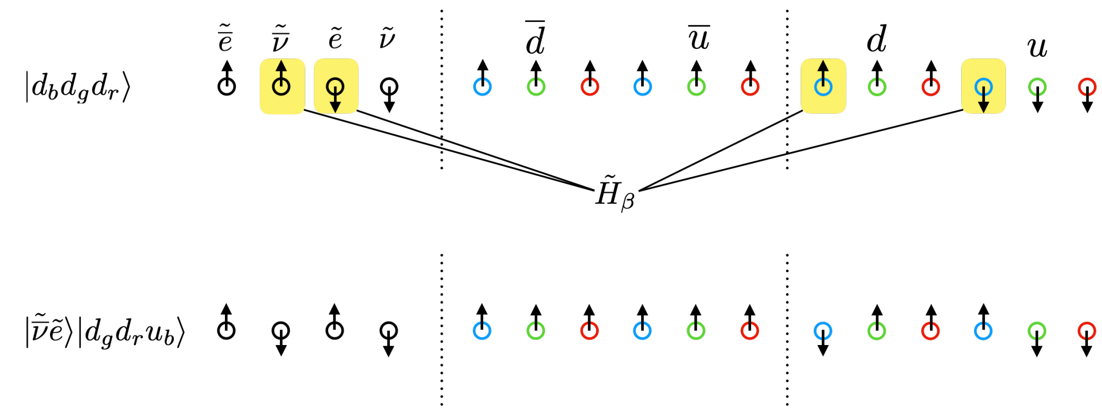


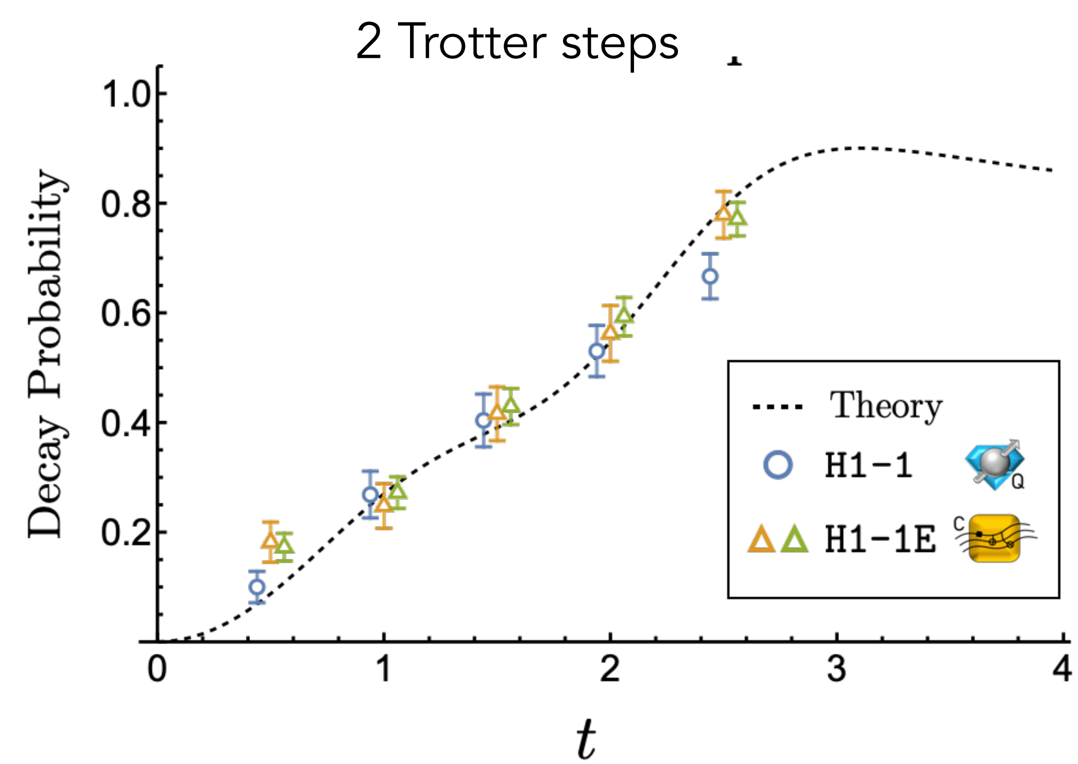
Chai, Crippa, Jansen, Kühn, Pascuzzi, Tacchino, Tavernelli, arXiv:2312.02272 [quant-ph].

Quantum computing β decay in 1+1 QCD

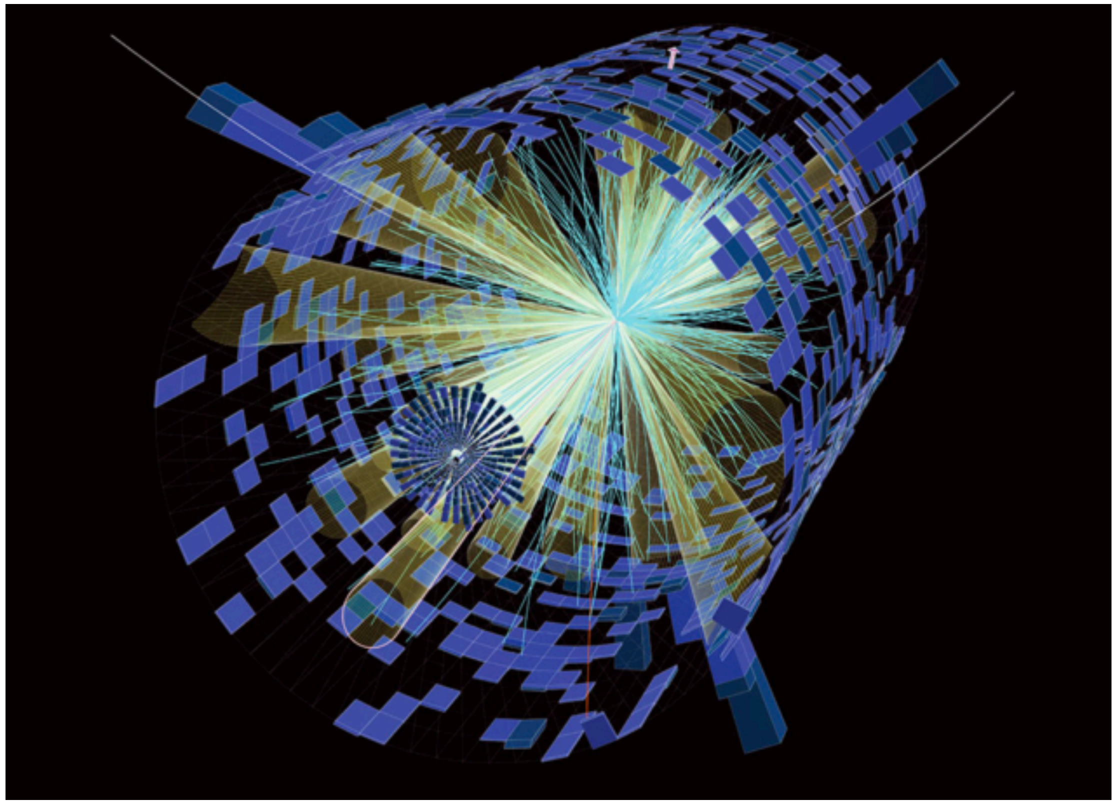


Farrell, Chernyshev, Powell, Zemlevskiy, Illa, and Savage, arXiv:2209.10781 [quant-ph].





LHC Physics?

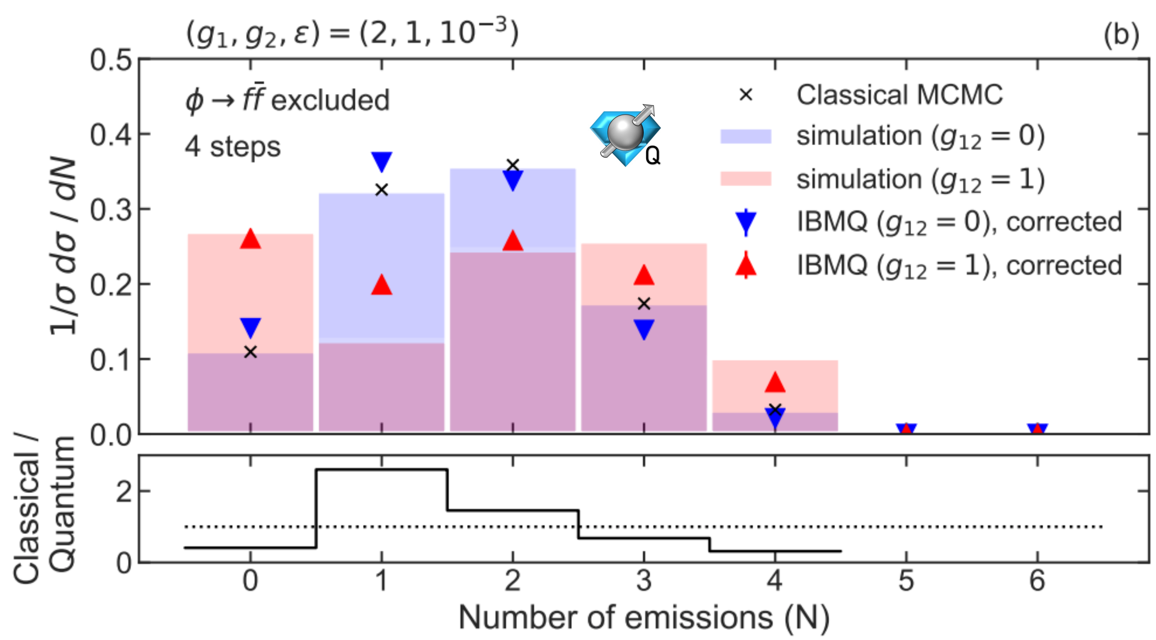


Credit: CERN

ALGORITHMS RELEVANT TO THE LHC PHYSICS

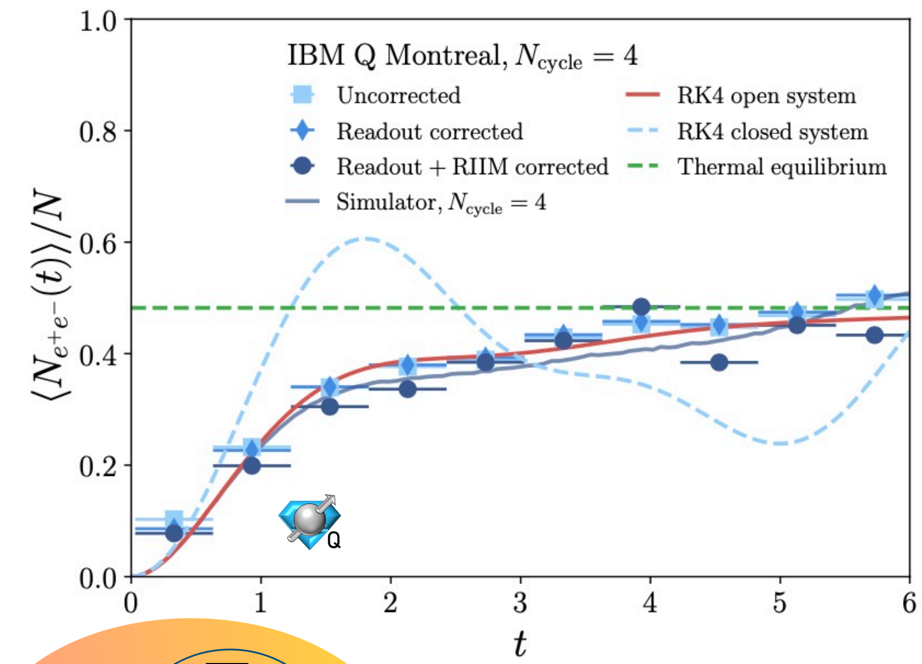
A polynomial-time quantum final-state shower algorithm that models the effects of intermediate spin states similar to those present in electroweak showers.

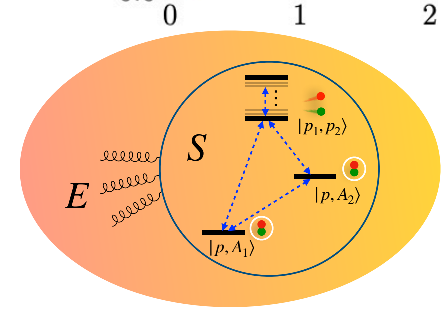
Nachman, Provasoli, and Bauer‡, *Phys. Rev. Lett.* 126 (2021) 6, 062001.



See also Bepari, Malik, Spannowsky, Williams, Phys. Rev. D 103, 076020 (2021), Williams, Malik, Spannowsky, Bepari, Phys. Rev. D 106 (2022) 056002, Gustafson, Prestel, Spannowsky, Williams, J. High Energ. Phys. 2022, 35 (2022).

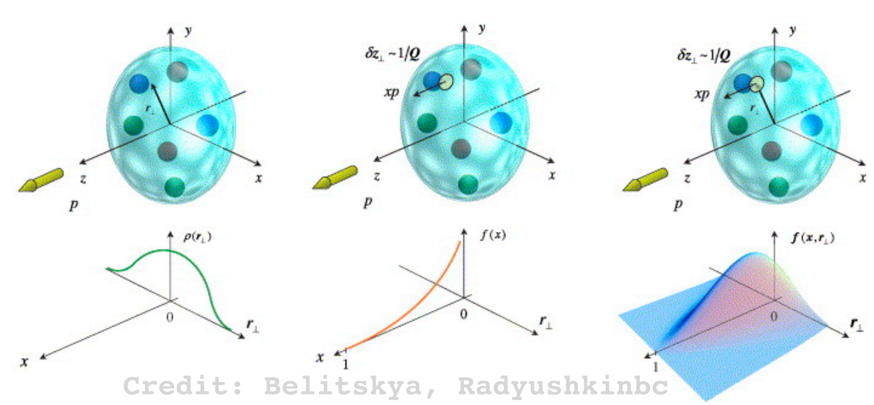
Open quantum system dynamics:
$q\bar{q}$ moving in medium





$q\bar{q}$ moving in medium

de Jong, Metcal, Mulligan, Ploskon, Ringer, and, Yao, *Phys.Rev.D* 104 (2021) 5, 051501. See also Lee, Mulligan, Ringer, Yao, arXiv:2308.03878 [quant-ph].

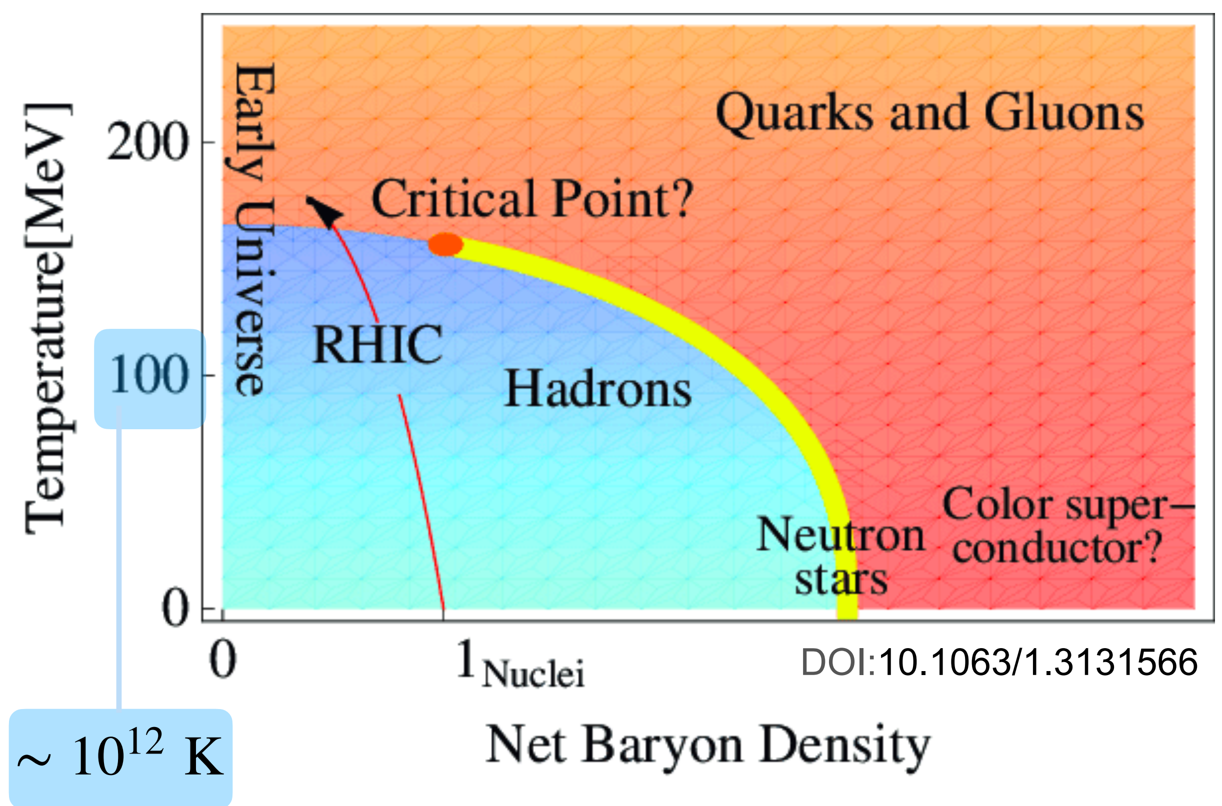


Credit: Belitskya, Radyushkinbc

Distribution functions and first attempts at fragmentation functions from non-equal time amplitudes:

Mueller, Tarasov, and Raju Venugopalan, PRD 102, 016007 (2020), Lamm, Lawrence, and Yamauchi, Phys. Rev. Res. 2, 013272 (2020), Echevarria, Egusquiza, Rico, and Schnell, PRD 104, 014512 (2021), Gustin, Goldstein arXiv:2211.07826 [hep-th], Li, Xing, Zhang, arXiv:2406.05683 [hep-ph].

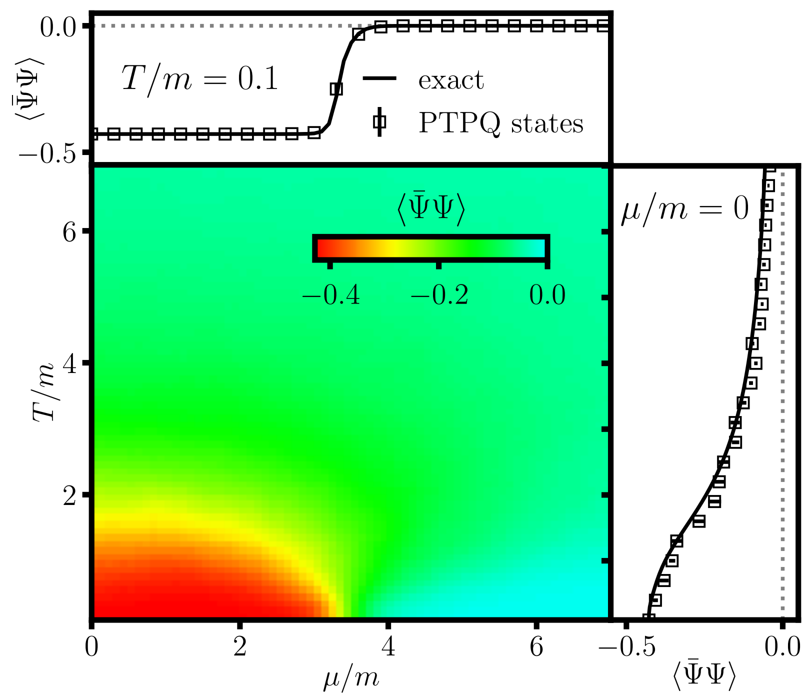
Phase diagram of QCD?



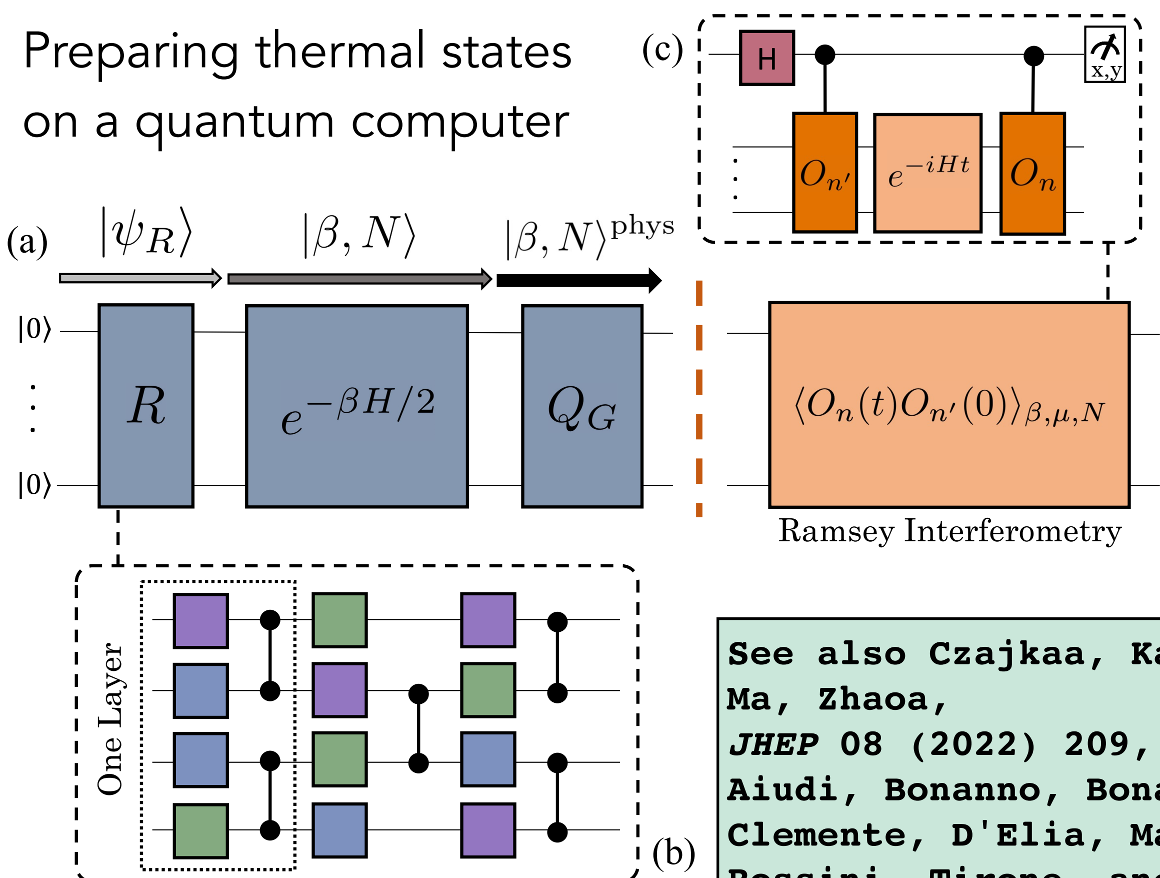
FINITE TEMPERATURE AND FINTIE DENSITY PHASE DIAGRAM, QGP TRANSPORT

Phase diagram of Z_2^{1+1} with fermions

Toward Quantum Phase Computing Phase Diagrams of Gauge Theories with Thermal Pure Quantum States, ZD, Mueller, Powers, Phys. Rev. Lett. 131 (2023) 8, 081901.



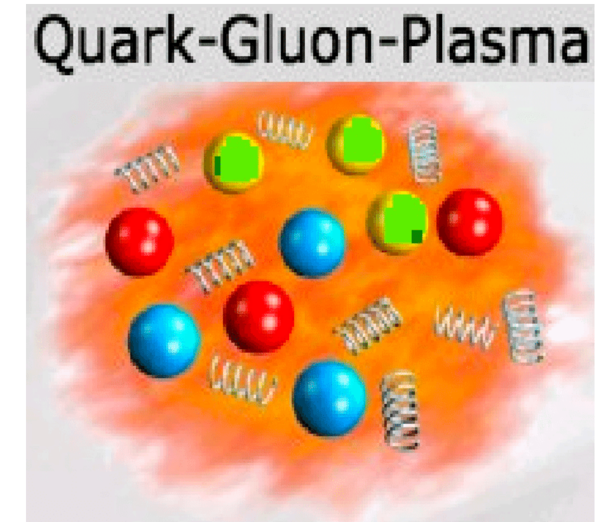
Preparing thermal states on a quantum computer



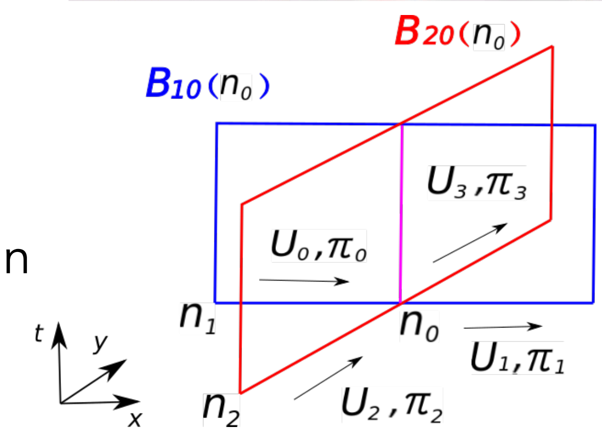
See also Czajkaa, Kang, Ma, Zhaoa, *JHEP* 08 (2022) 209, and Aiudi, Bonanno, Bonati, Clemente, D'Elia, Maio, Rossini, Tirone, and Zambello, arXiv:2308.01279 [quant-ph].

Transport coefficients from real-time correlators of energy momentum tensor

Cohen, Lamm, Lawrence, and Yamauchi, Phys. Rev. D 104, 094514 (2021).

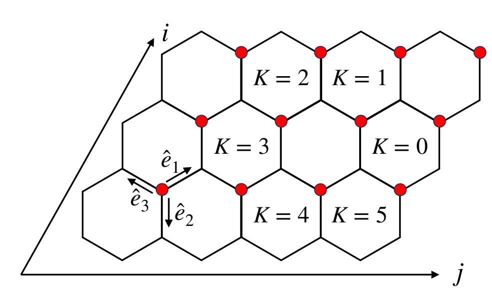


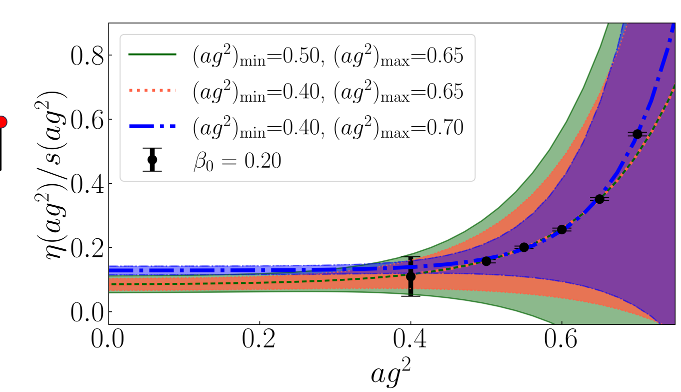
How to define energy-momentum tensor in Hamiltonian formulation



Shear viscosity in SU(2) LGT in 2+1 D with $j_{max} = 1/2$

Turro, Ciavarella, Yao, Phys. Rev. D 109, 114511 (2024).





See also: Farrell, Illa, Savage, arXiv:2405.06620 [quant-ph].

Evolution of matter?

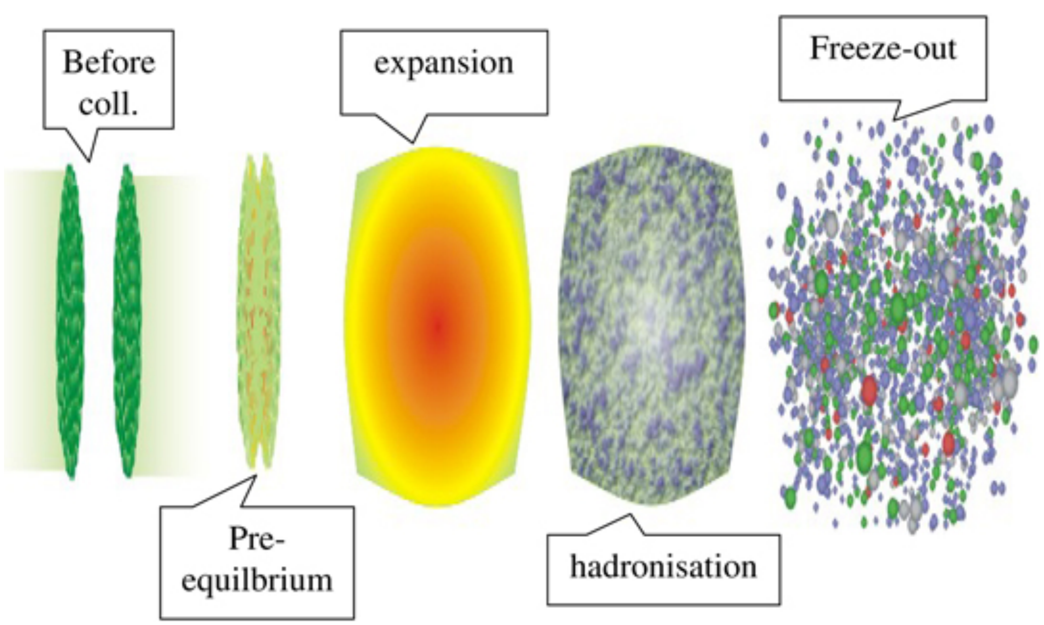
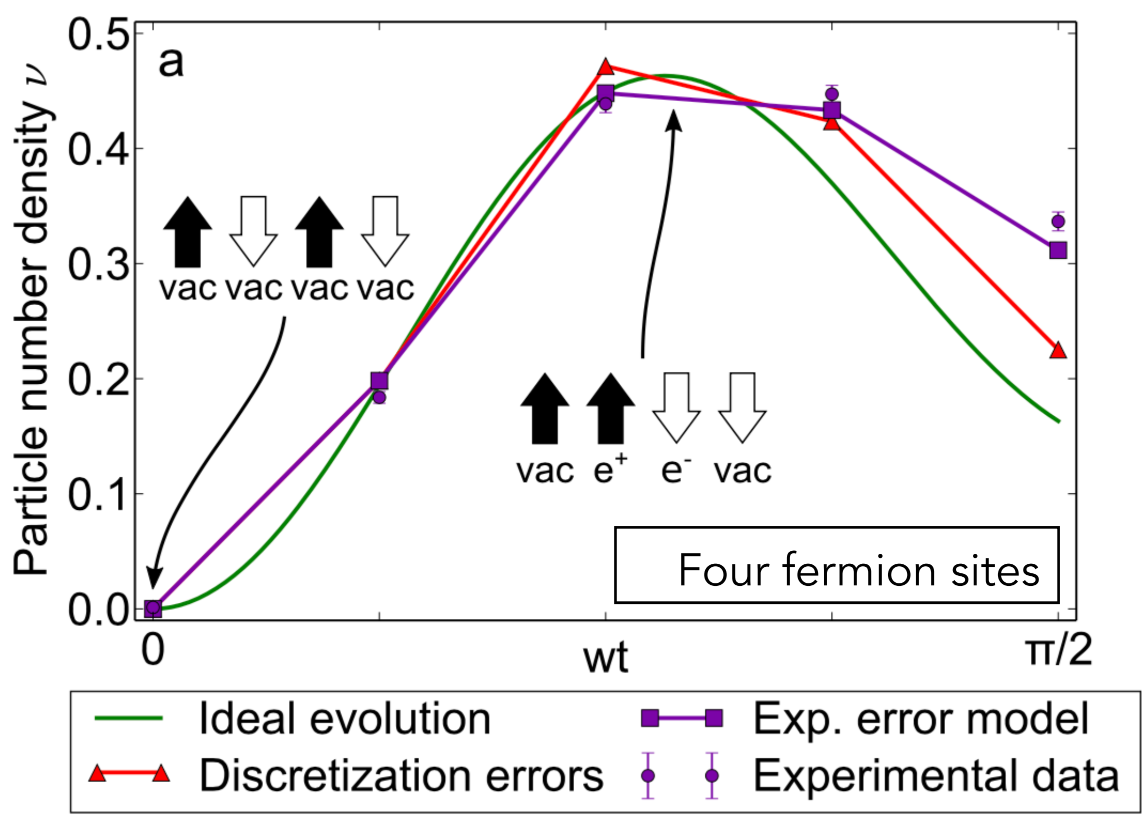


Image credit: Chaudhuri, Advances in High Energy Physics, vol. 2013,\.

REAL-TIME EVOLUTION AND QUENCH DYNAMICS IN ABELIAN LGTs

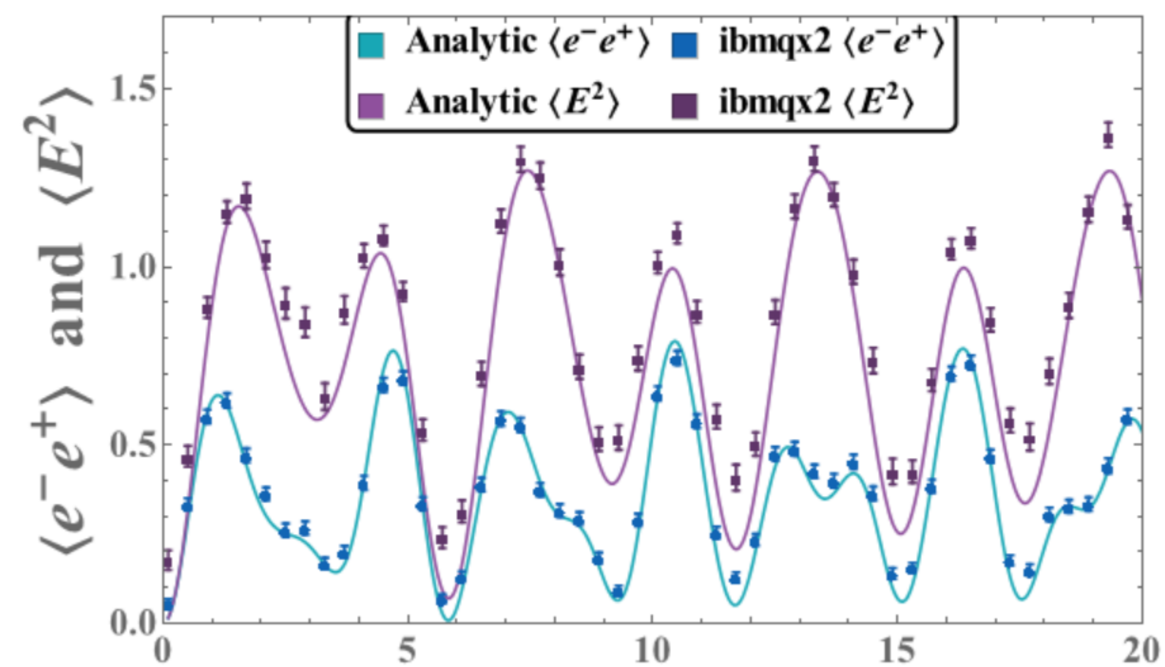
universität innsbruck

Martinez et al, Nature 534, 516 EP (2016).



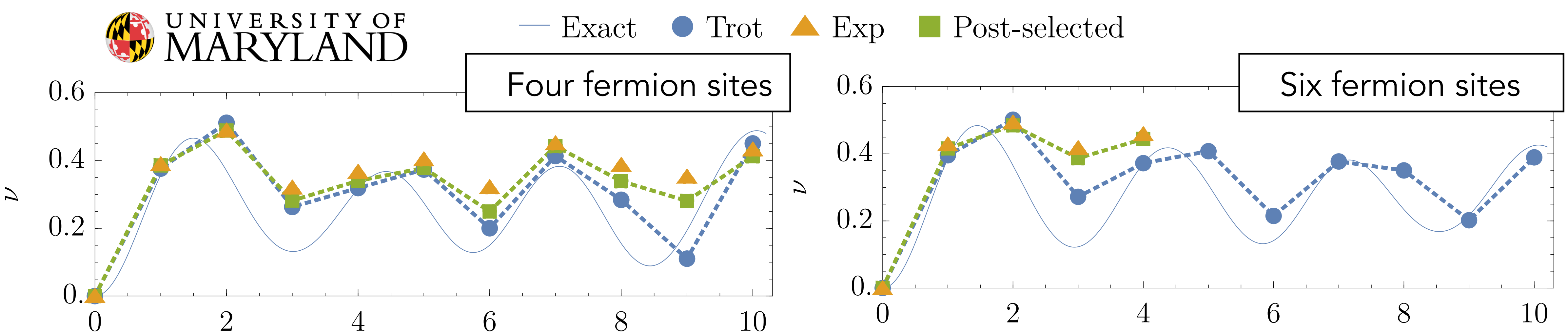
Klco, Savage, et al, Phys. Rev. A 98, 032331 (2018).

INSTITUTE for NUCLEAR THEORY — OAK RIDGE National Laboratory — IBM



Not the spin formulation: a 2-qubit reduction of 4-qubit simulation.

UNIVERSITY OF MARYLAND

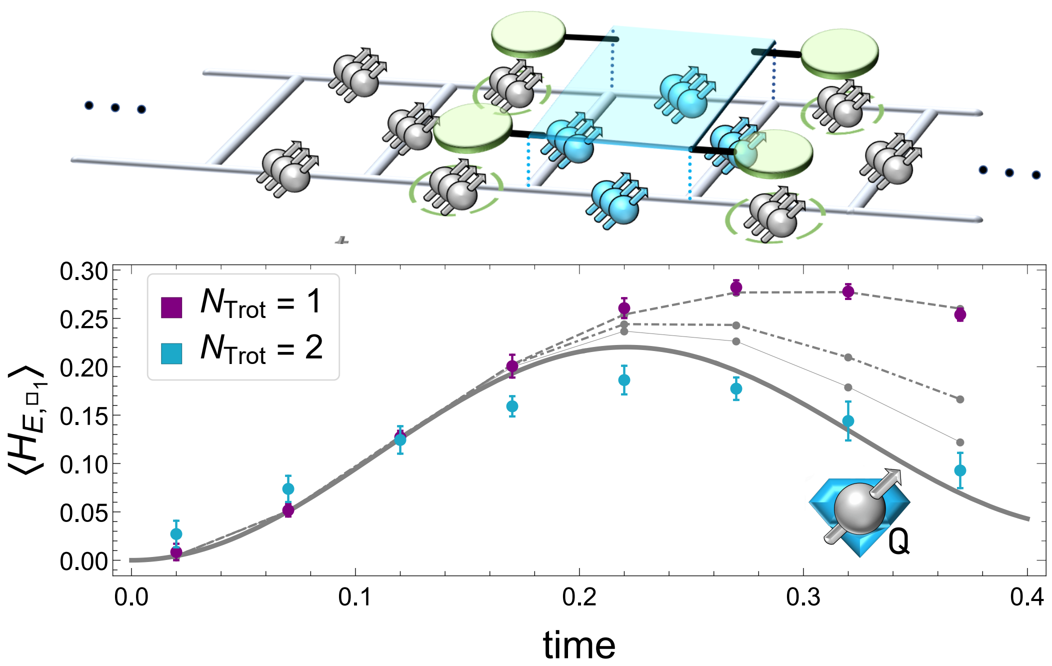


80 entangling gates!

90 entangling gates!

REAL-TIME EVOLUTION AND QUENCH DYNAMICS IN NON-ABELIAN LGTs

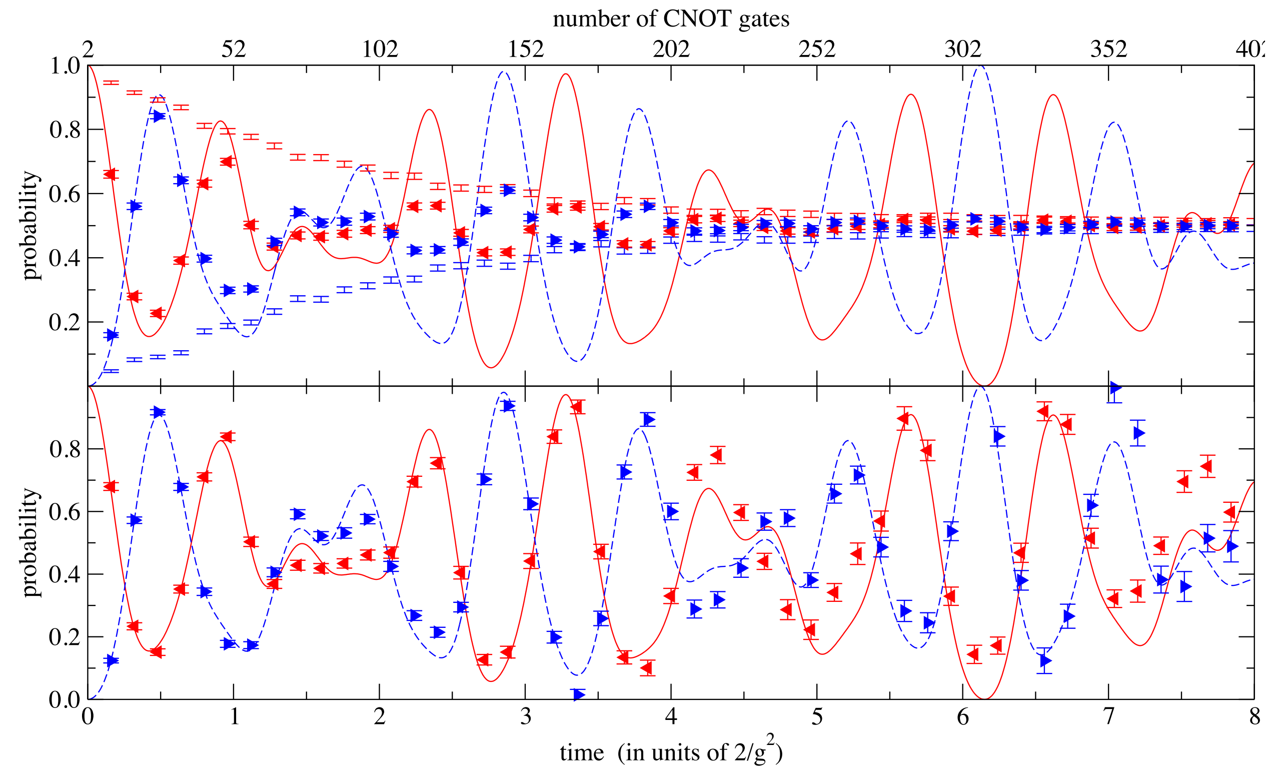
Real-time dynamic of pure SU(2) with global irreps on IBM

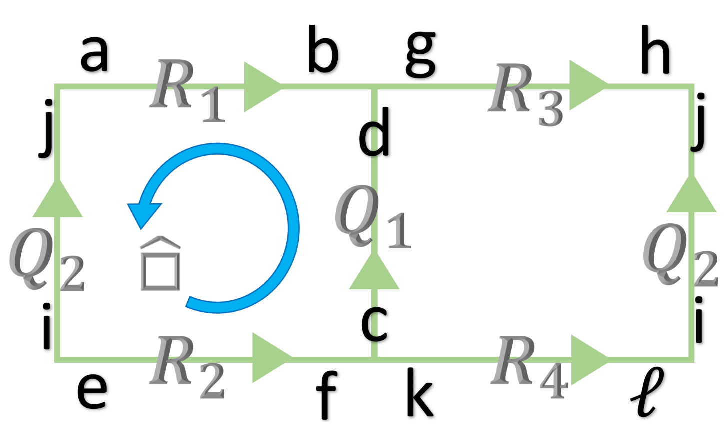


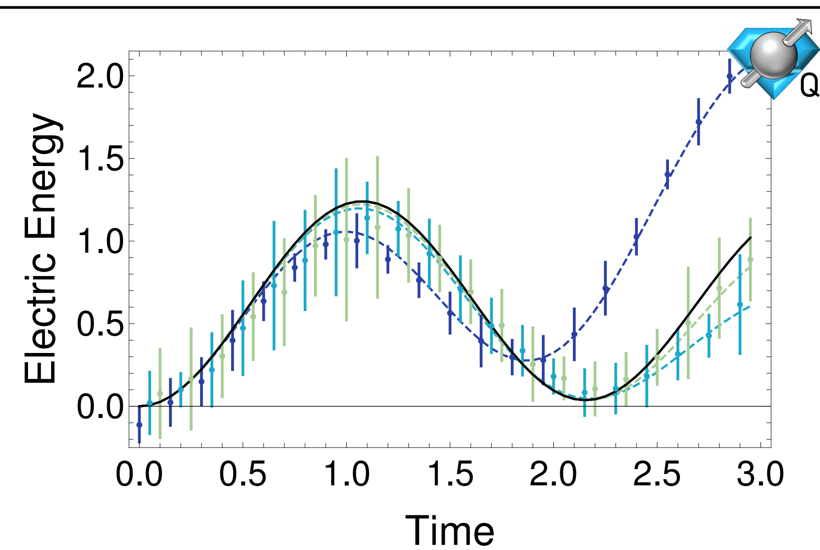
Klco, Savage, and Stryker, Phys. Rev. D 101, 074512 (2020).

Self-mitigating Trotter circuits for pure SU(2) LGT in 2+1 D on IBM

Rahman, Lewis, Mendicelli, Powell, *Phys. Rev. D 106, 074502 (2022).*







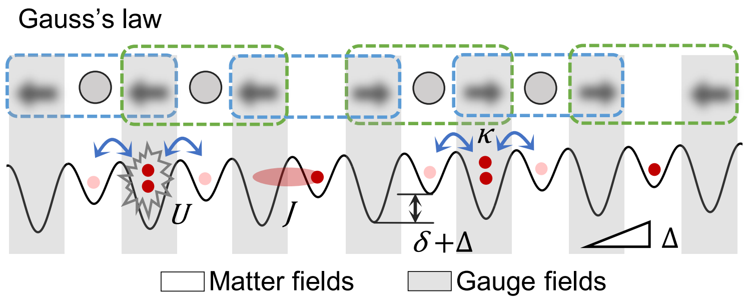
Real-time dynamic of pure SU(3) with global irrupts on IBM

Ciavarella, Klco, and Savage, Phys. Rev. D 103, 094501 (2021).

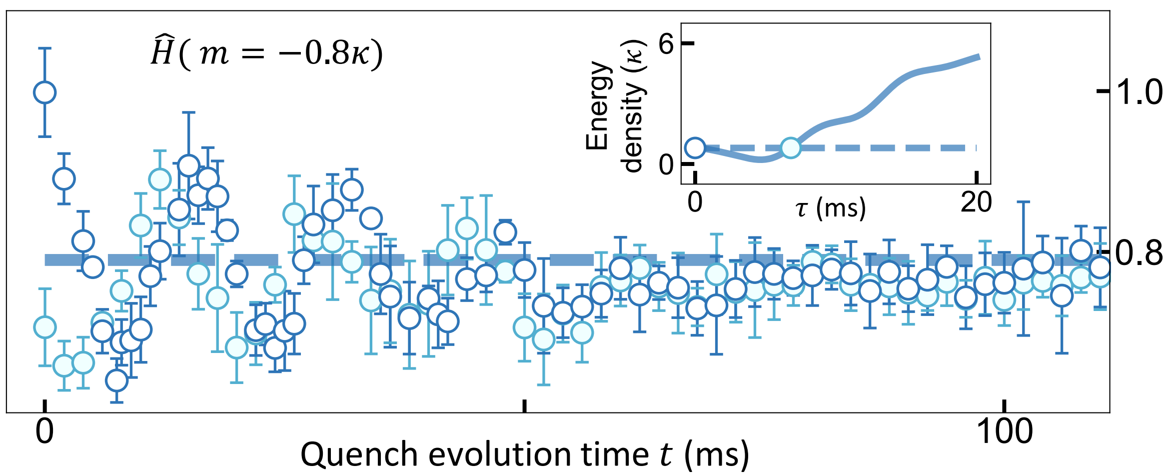
See also studies on D-wave annealers: Rahman et al, Phys. Rev. D 104, 034501 (2021), Illa and Savage, arXiv:2202.12340 [quant-ph], Farrel et al, arXiv:2207.01731 [quant-ph].

THERMALIZATION AND NON-EQUILIBRIUM PROPERTIES

Thermalization dynamics of U(1) Quantum Link Model in a 71-site analog simulator

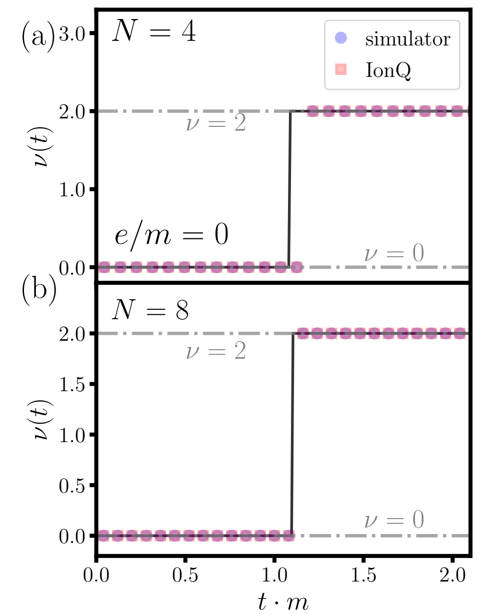


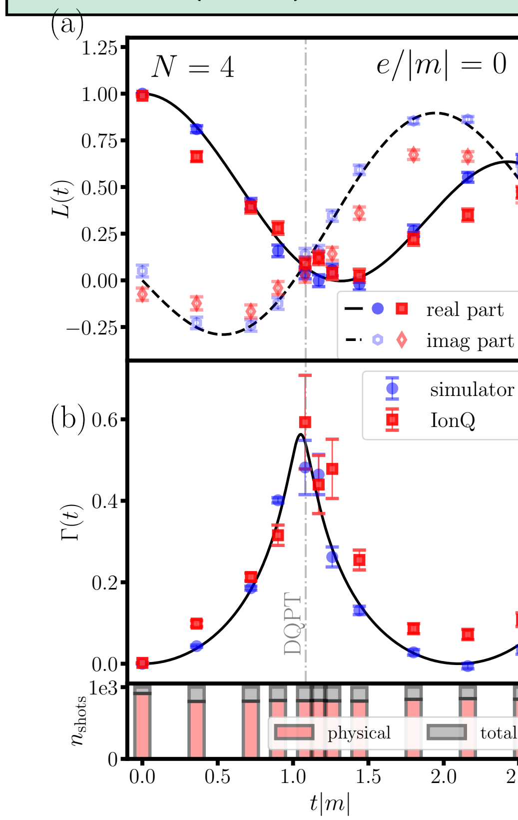
Zhou et al, *Science* 377 (2022) 6603.



A dynamical phase transition and topological order in lattice Schwinger model with IonQ quantum computer:

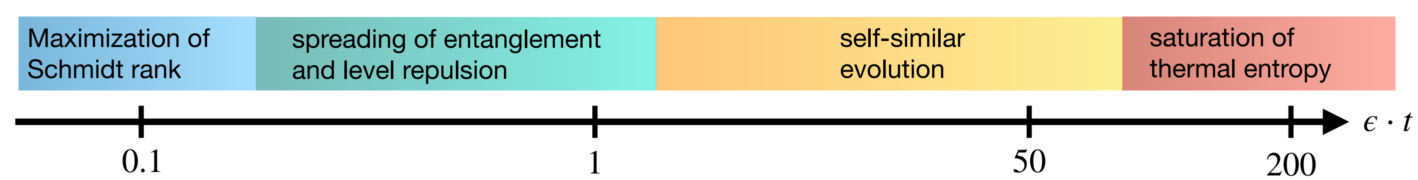
For other quantum PTs see: Thompson and Siopsis, Quant. Inf. Proc. 22 (2023) 11, 396, and Quant. Sci. Tech. 7 (2022) 3, 035001.

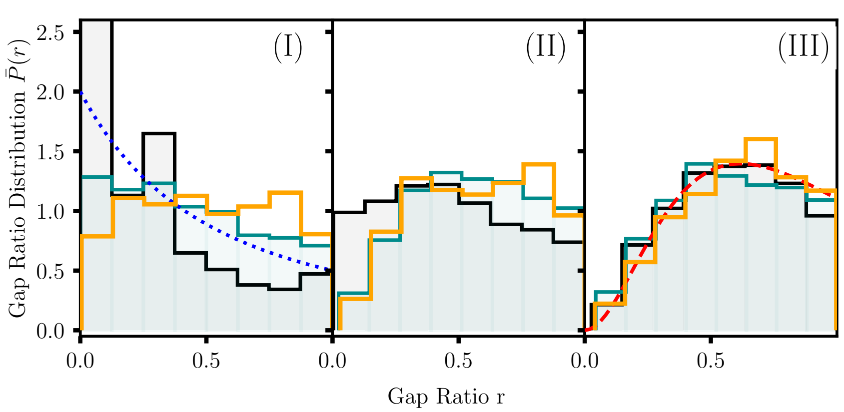


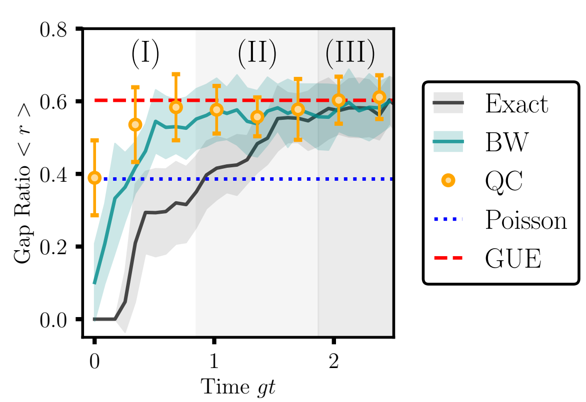


Mueller, Carolan, Connelly, ZD, Dumitrescu, Yeter-Aydeniz, PRX Quantum 4 (2023) 3.

Stages of thermalization dynamics of Z2 LGT in 2+1 D from entanglement spectrum







Mueller, Zache, Ott, Phys. Rev. Lett. 129, 011601 (2022).

Experimental demonstration with trapped ions:

Mueller, Wang, Katz, ZD, Cetina, arXiv:2408.00069 [quant-ph].

Algorithmic developments
[Analog]

Can practical proposals for current hardware be developed?

Can we simulate higher-dimensional gauge theories?

Can non-Abelian gauge theories be realized in an analog simulator?

Can we robustly bound the errors in the analog simulation? What quantities are more robust to errors?

Many pioneering work. Not covering for the sake of time!

Implementation, benchmark, and co-development

- What is the capability limit of the hardware for gauge-theory simulations so far?
- What is the nature of noise in hardware and how can it best be mitigated?
- Can we co-develop dedicated systems for gauge-theory simulations?
- Can digital and analog ideas be combined to facilitate simulations of field theories?

Implementation, benchmark, and co-development

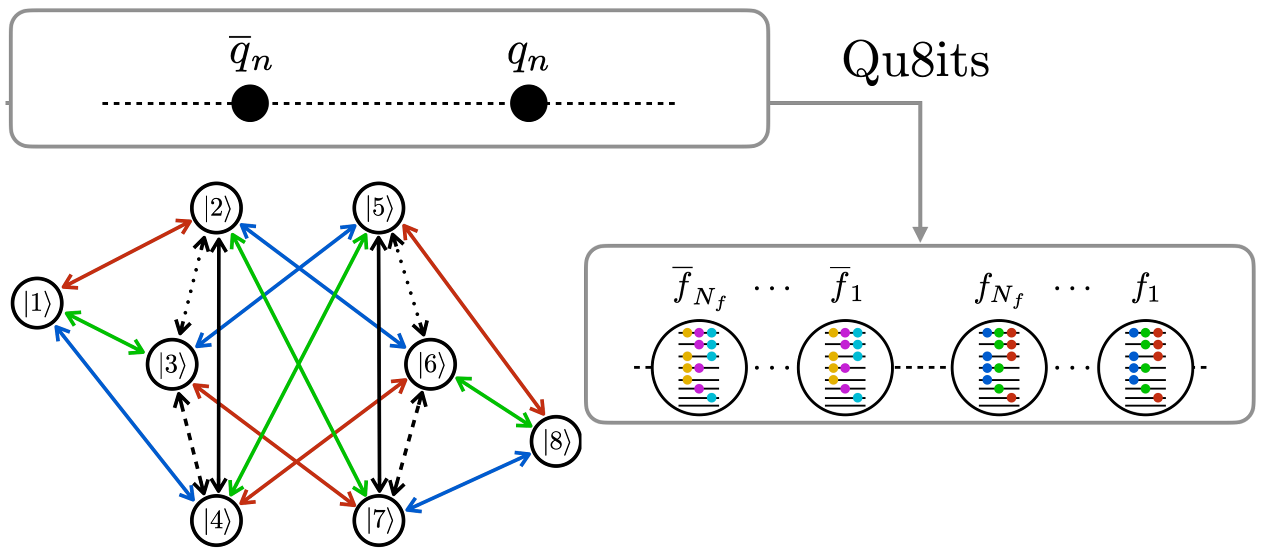
What is the capability limit of the hardware for gauge-theory simulations so far?

What is the nature of noise in hardware and how can it best be mitigated?

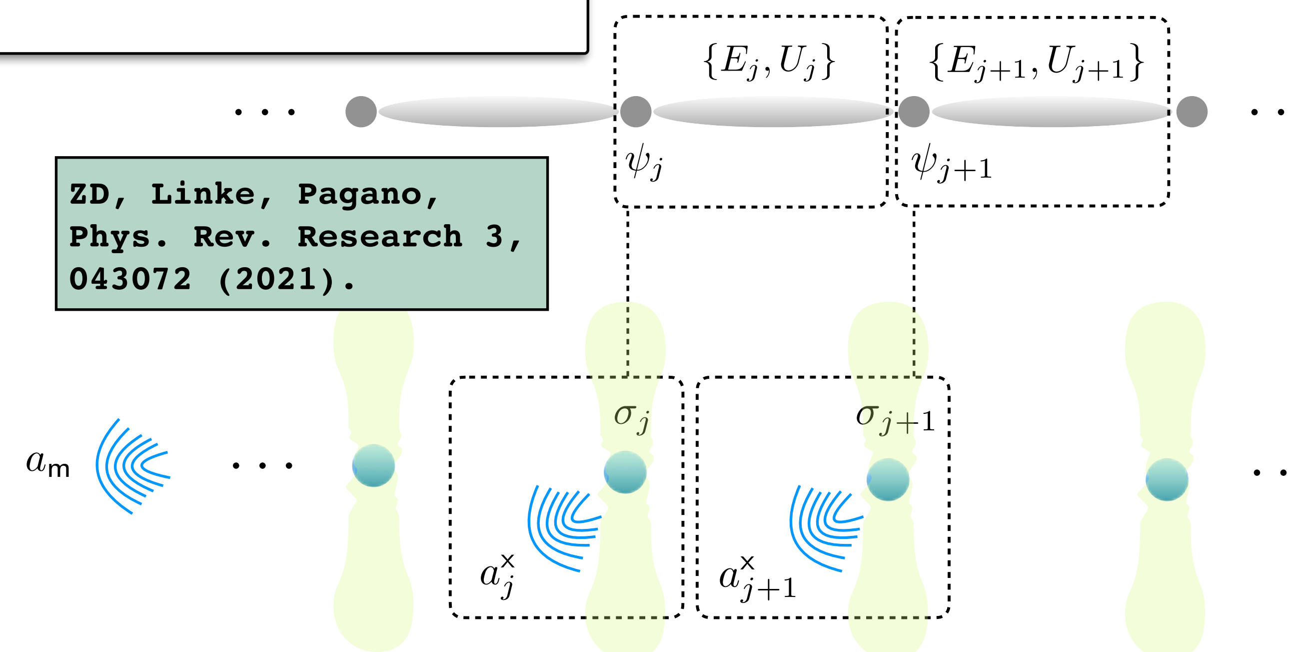
Can we co-develop dedicated systems for gauge-theory simulations?

Can digital and analog ideas be combined to facilitate simulations of field theories?

SOME CO-DESIGN EXAMPLES: LEVERAGING MULTI-DIMENSIONAL LOCAL HILBERT SPACES AND MULTI-MODE INTERACTIONS



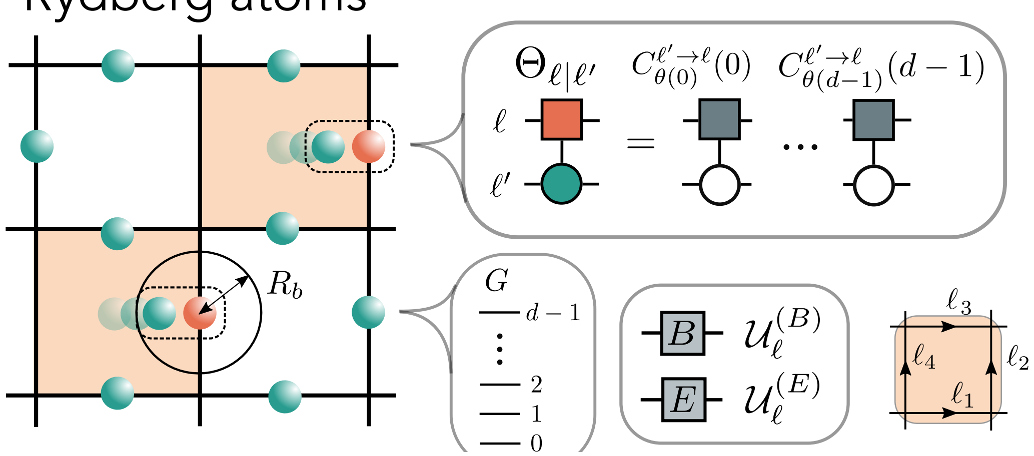
Illa, Robin, Savage, arXiv:2403.14537 [quant-ph].



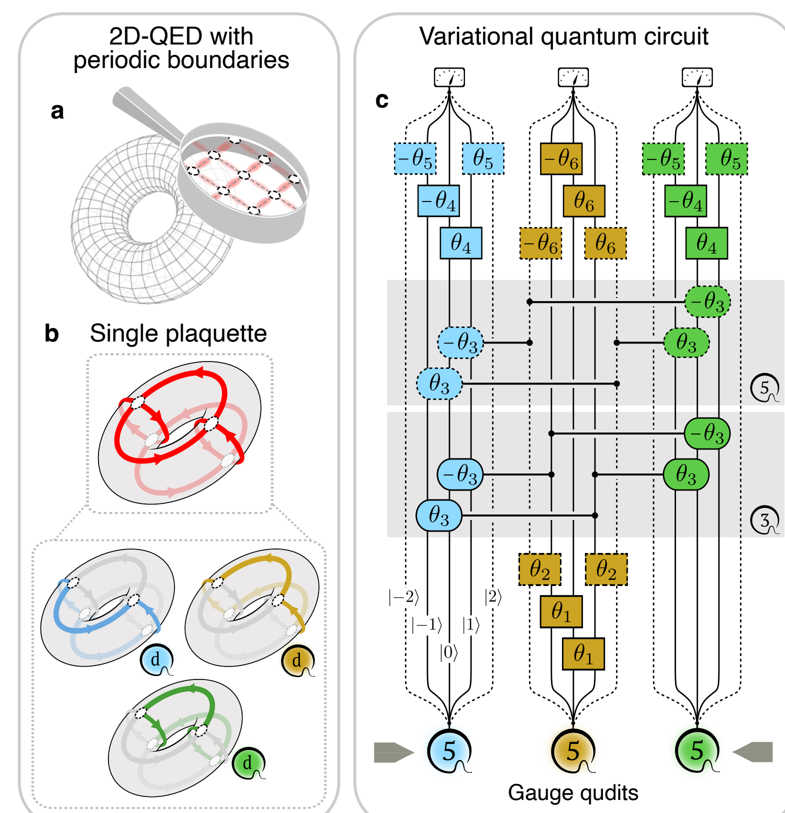
ZD, Linke, Pagano, Phys. Rev. Research 3, 043072 (2021).

Ion-phonon systems

Rydberg atoms



González-Cuadra, Zache, Carrasco, Kraus, Zoller, arXiv:2203.15541 [quant-ph].

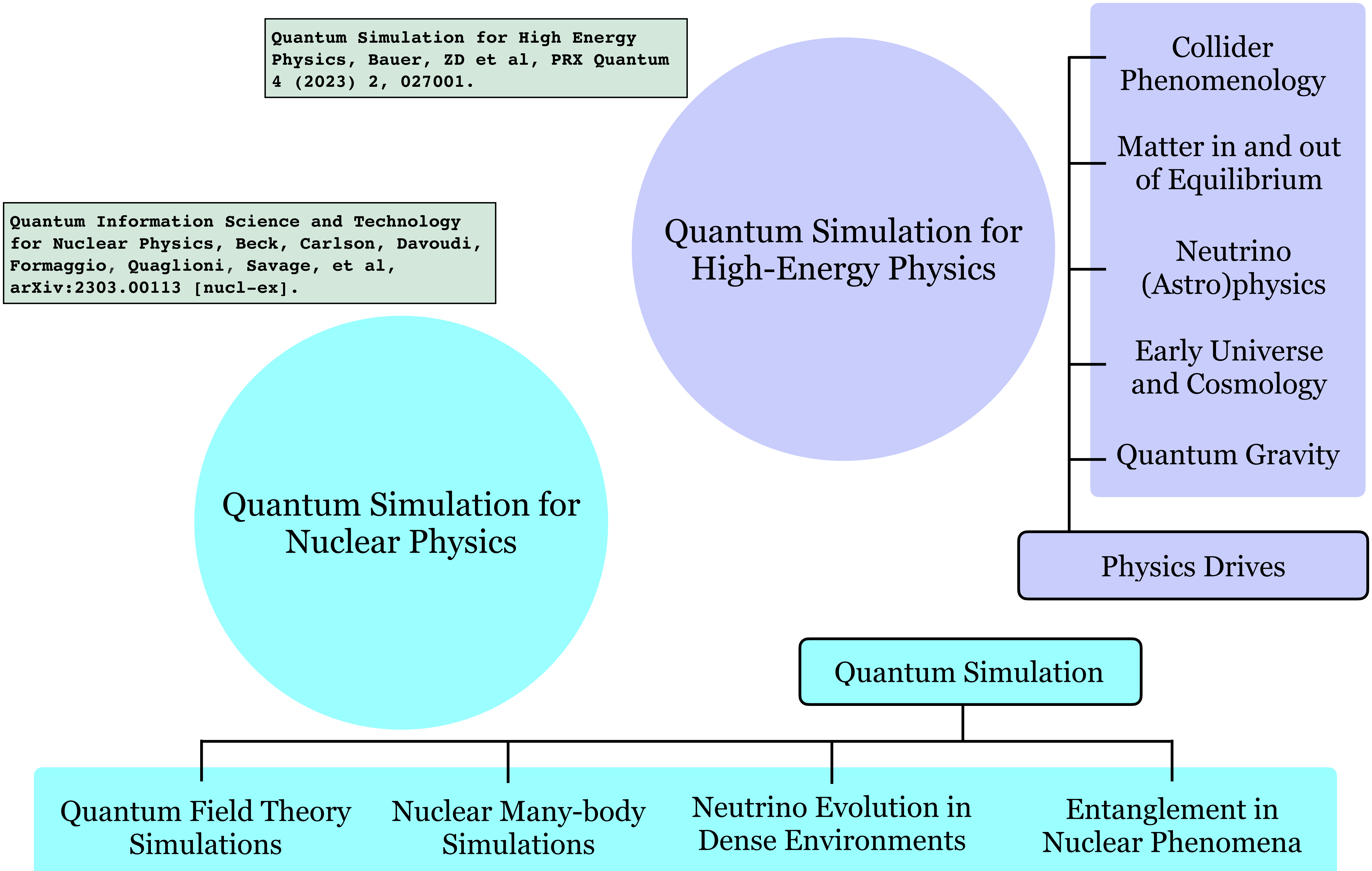


Ion qudits

Meth, Haase, Zhang, Edmunds, Postler, Jena, Steiner, Dellantonio, Blatt, Zoller, Monz, Schindler, Muschik, and Ringbauer, arXiv:2310.12110 [quant-ph].

FINAL WORD…

QUANTUM SIMULATION OF FUNDAMENTAL INTERACTIONS HAS THE PROMISE OF ADDRESSING A RANGE OF COMPUTATIONALLY INTRACTABLE PROBLEMS IN HEP AND NP.



COLLABORATORS I HAVE BEEN ENJOYING WORKING WITH IN THE NPLQCD COLLABORATION:

Silas Beane (F) @UW
Emmanuel Chang
William Detmold (F) @MIT
Anthony Grebe (P) @Fermilab
Marc Illa (P) @UW/IQuS
Kostas Orginos (F) @William & Mary/JLab
Assumpta Parreno (F) @Barcelona

Robert Perry (P) @MIT
Martin Savage (F) @UW/IQuS
Phiala Shanahan (F) @MIT
Brian Tiburzi (F) @CUNY
Michael Wagman (F) @Fermilab
Frank Winter (F) @JLab

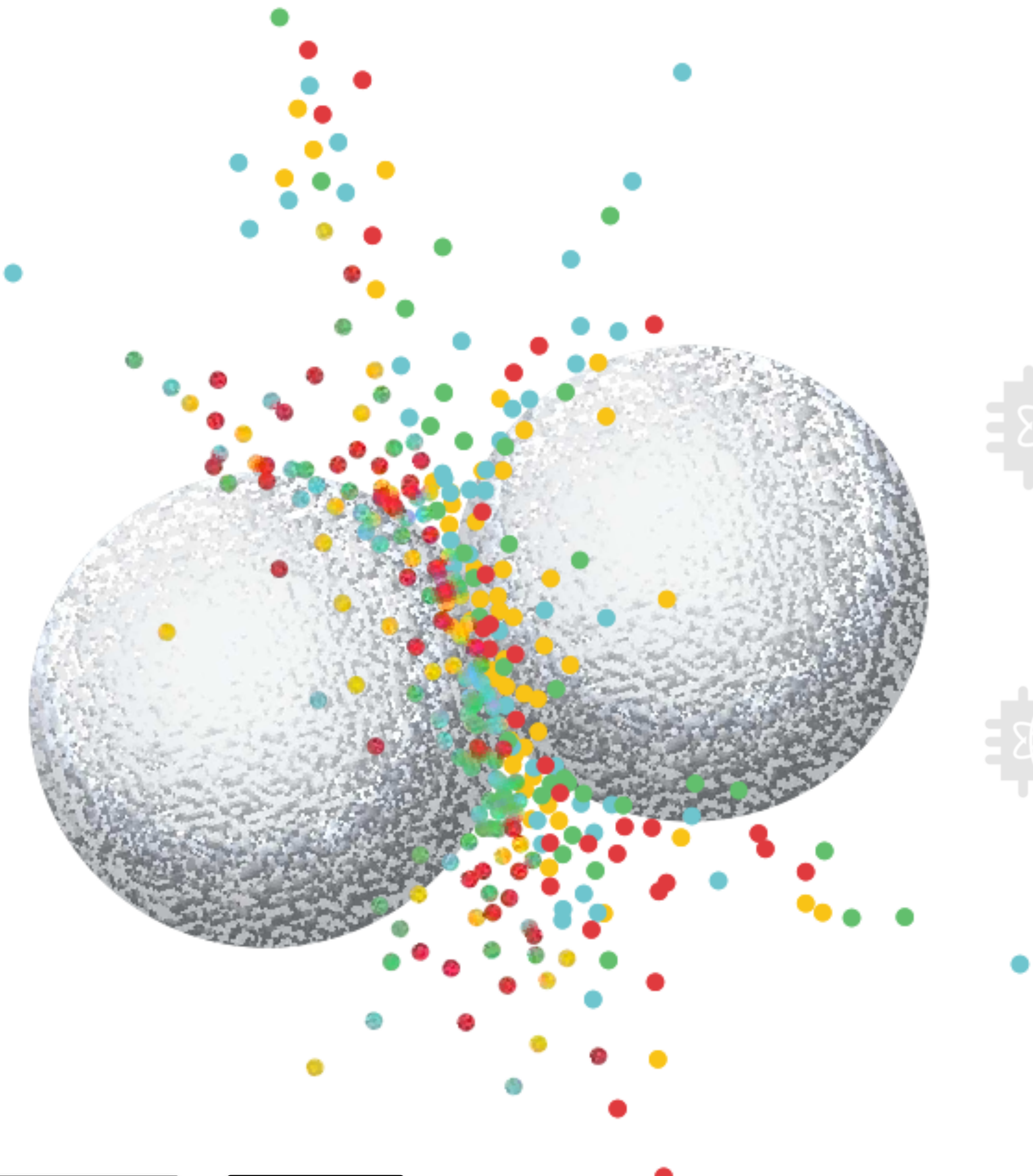
COLLABORATORS I HAVE BEEN ENJOYING WORKING WITH IN THE QUANTUM LAND:

Barbara Abdrade (S) @Barcelona
Ron Belyansky (P) @U Chicago
Elizabeth Bennewitz (S) @UMD
Jocob Bringewatt (S) @UMD
Joseph Carolan (S) @UMD
Marko Cetina (F) @Duke
Andrew Childs (F) @UMD
Kate Collins (S) @UMD
Andrew Connelly (former S) @NCSU
Eleanor Crane (P) @MIT
Arinjoy De (S) @Duke
Eugene Dumitrescu (Staff) @ORNL
Ali Fahimniya (P) @UMD
Alexey Gorshkov (F) @UMD/NIST
Tobias Grass (RF) @Barcelona
Alaina Green (F) @UMD/NIST
Michael Gullans (F) @UMD/NIST
* Navya Gupta (S) @UMD
Mohammad Hafezi (F) @UMD
* Chung-Chun Hsieh (S) @UMD
Ali Izadi Rad (S) @UMD
Christopher Jarzynski (F) @UMD
* Saurabh Kadam (P) @IQuS/UW
Or Katz (P) @Duke
Alessio Lerose (P) @Geneva

Norbert Linke (F) @Duke
De Luo (S) @Duke
Christopher Monroe (F) @Duke
Will Morong (former P) @UMD
* Niklas Mueller (RF) @IQuS/UW
Gautam Nambir (S) @UMD
Nhung Nguyen (Staff) @Quantinuum
Greeshma Oruganti (S) @UMD
Guido Pagano (F) @Rice
* Connor Powers (S) @UMD
Ali Rad (S) @UMD
* Indrakshi Raychowdhury (F) @BIST
Alexander Schuckert (P) @UMD
* Alexander Shaw (S) formerly @UMD
* Andrew Shaw (S) formerly @UMD
* Jesse Stryker (P) @LBNL
Federica Surace (P) @Caltech
Minh Tran (Staff) @IBM
Brayden Ware (P) @UMD
Christopher White (P) @UMD
James Watson (P) @UMD
Seth Whitsitt (P) @UMD
* Vinay Vikramaditya (S) @UMD
Kubra. Yeter-Aydeniz (MITRE Inc.)
Nicole Yunger Halpern (F) @UMD/NIST

Asterisk denotes group members (past and current).

THANK YOU



U.S. DEPARTMENT OF ENERGY | Office of Science
Alfred P. Sloan Foundation
Joint Center for Quantum Information and Computer Science
SIMONS FOUNDATION
RIKEN
NSF | Institute for Robust Quantum Simulation
PERIMETER INSTITUTE
MCFP MARYLAND CENTER for Fundamental Physics
USQCD