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Quantum computing QCD for hadron structure and dynamics

Zohreh Davoudi
University of Maryland, College Park

MARYLAND CENTER for Fundamental Physics

JOINT CENTER FOR QUANTUM INFORMATION AND COMPUTER SCIENCE

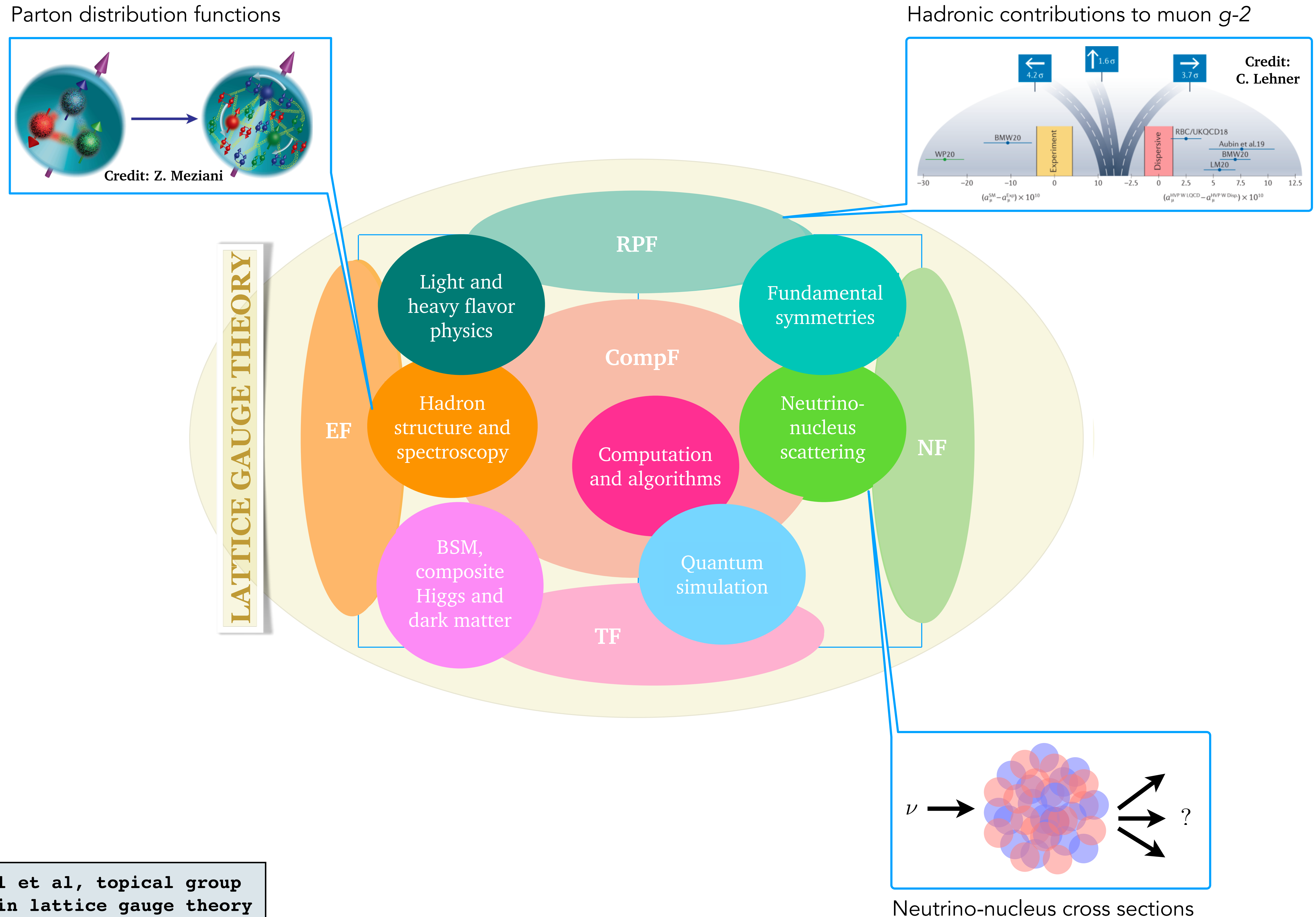
Institute for Robust Quantum Simulation

[PART I]
WHY QUANTUM COMPUTING FOR THE NP/QCD/HEP RESEARCH?

LATTICE QCD HAS CARRIED OUT A SUCCESSFUL PROGRAM THAT SUPPORTS A BROAD EXPERIMENTAL PROGRAM IN NP…

Slide content courtesy of Martin Savage.

… AND IN HEP, WITH MANY CRITICAL RESULTS STARTING TO EMERGE (e.g., MUON g-2).

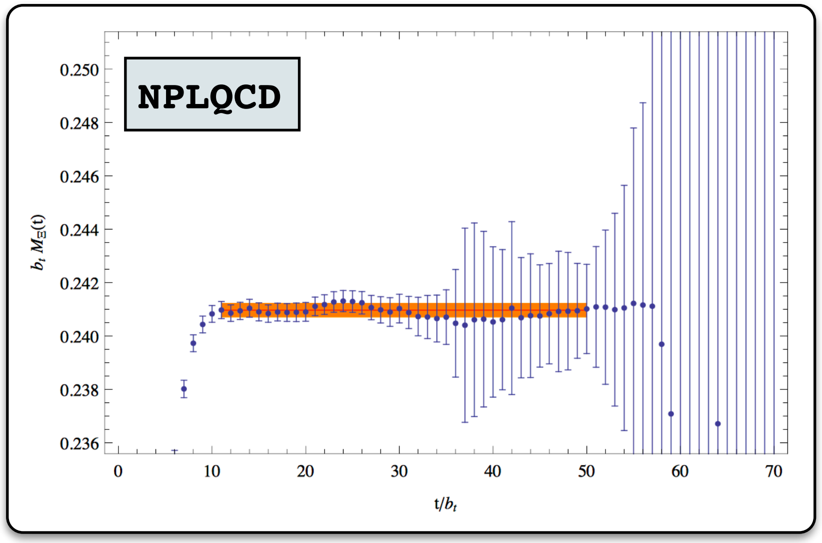


ZD, Neil et al, topical group report in lattice gauge theory arXiv:2209.10758 [hep-lat].

Does this mean we are all set?
…Well, unfortunately not!

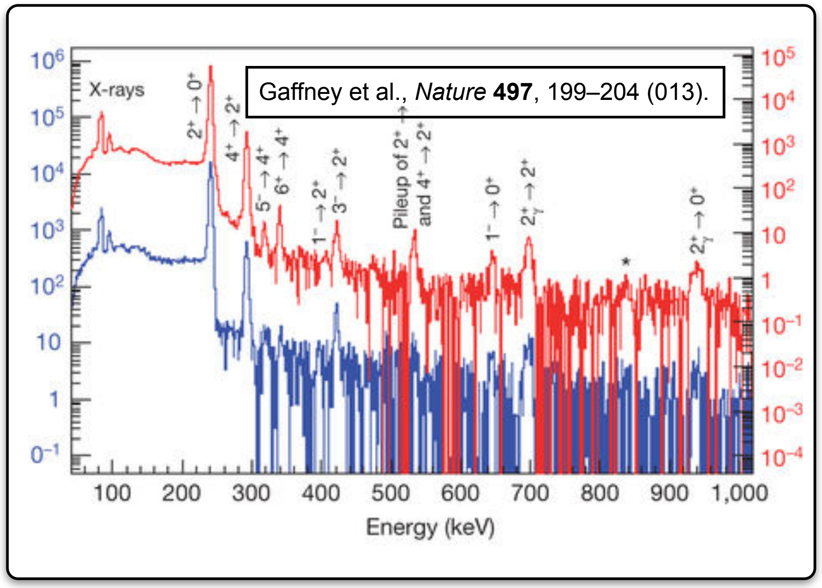
THREE FEATURES MAKE LATTICE QCD CALCULATIONS OF NUCLEI HARD:

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



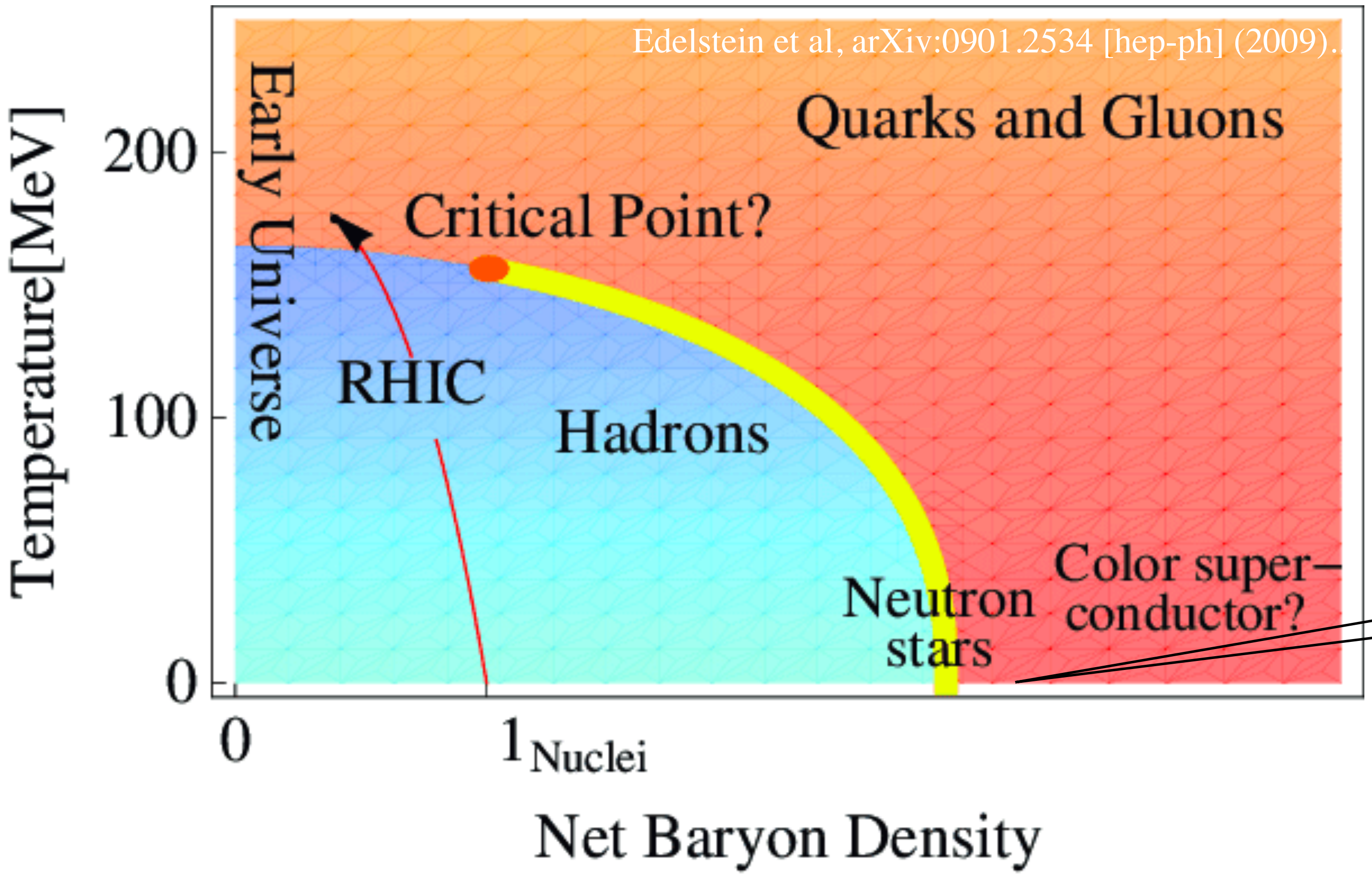
ii) There is a severe signal-to-noise degradation in Euclidean nuclear correlators.

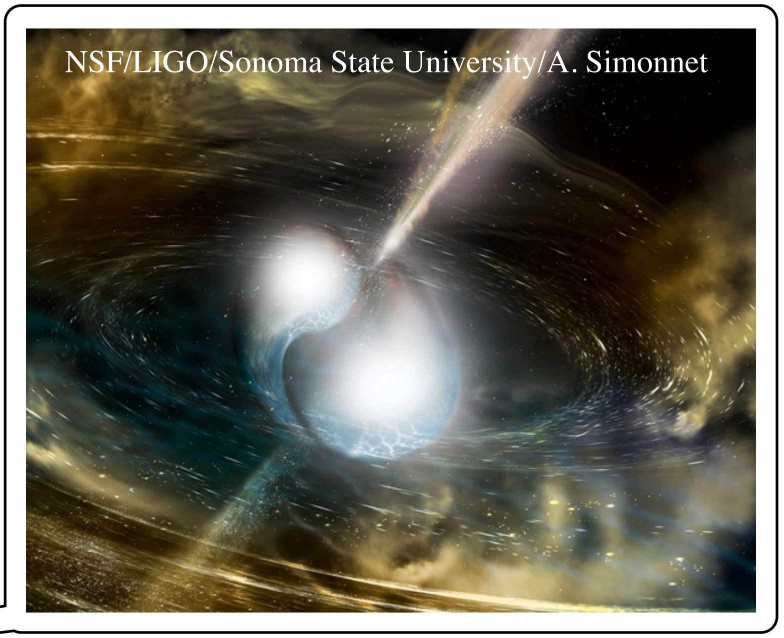
iii) Excitation energies of nuclei are much smaller than the QCD scale.



ADDITIONALLY THE SIGN PROBLEM FORBIDS:

i) Studies dense matter such as interior of neutron stars and phase diagram of QCD





Path integral formulation…

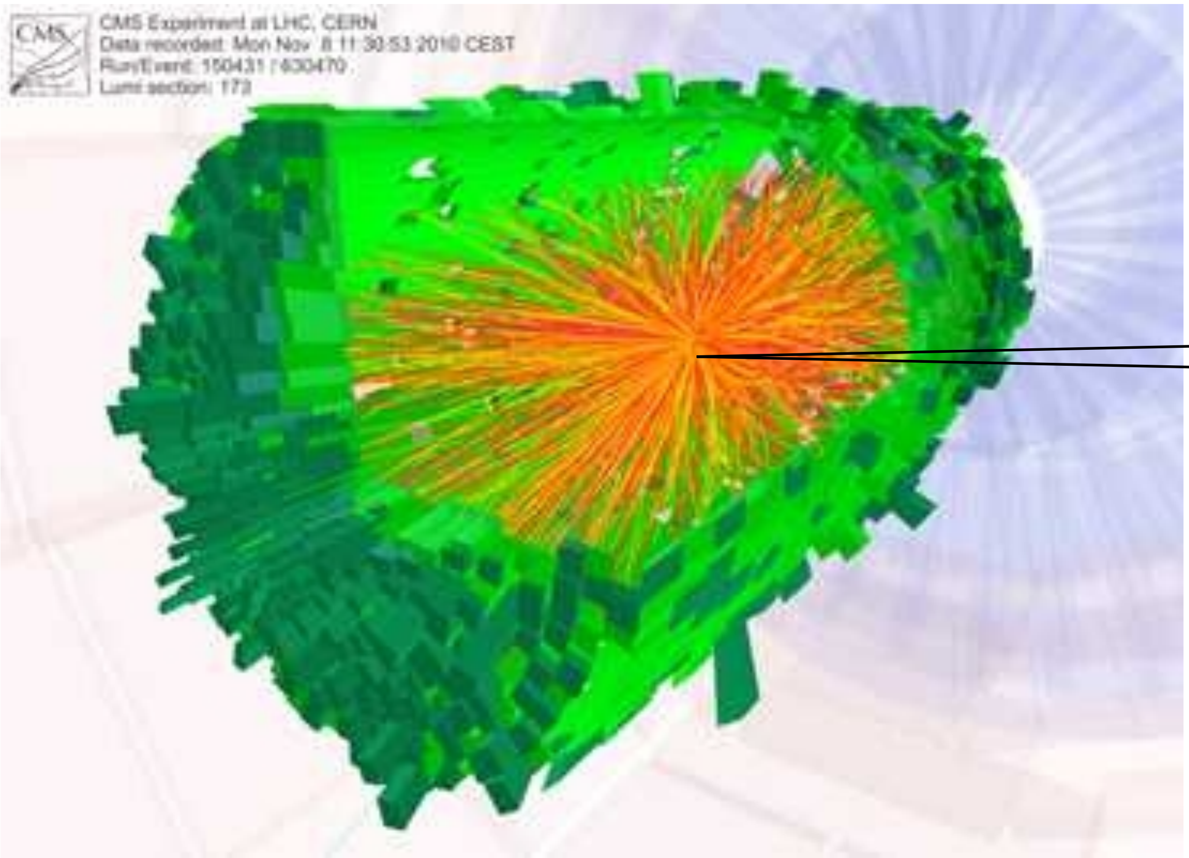
$$e^{-S[U,q,\bar{q}]}$$

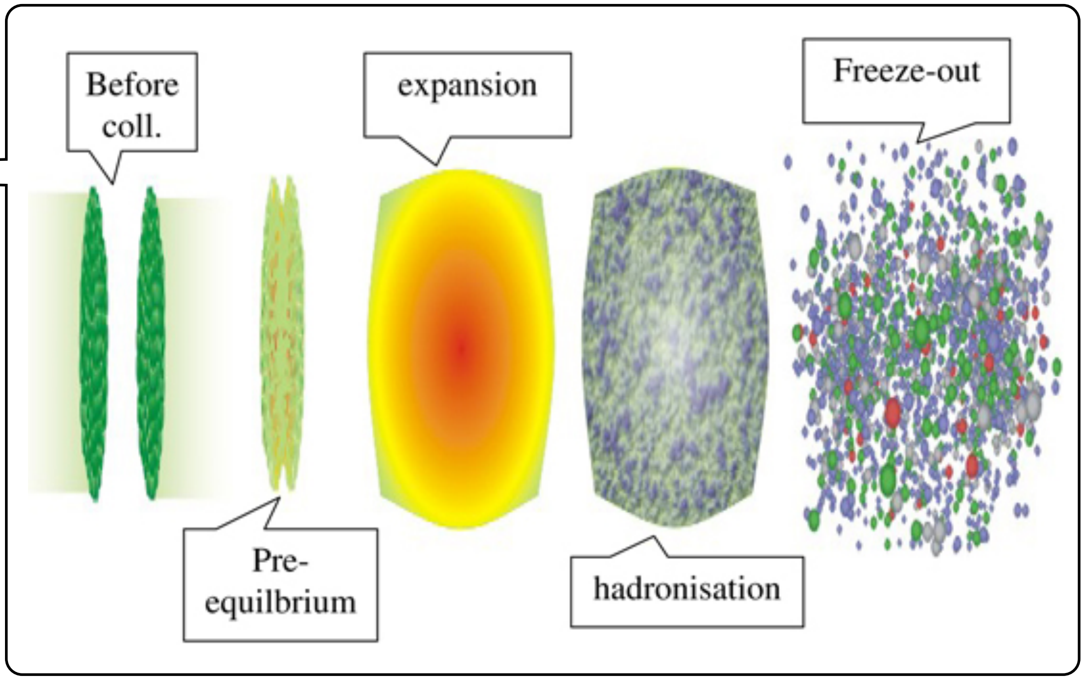
…with a complex action:

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

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, parton distribution functions, and non-equilibrium physics of QCD.

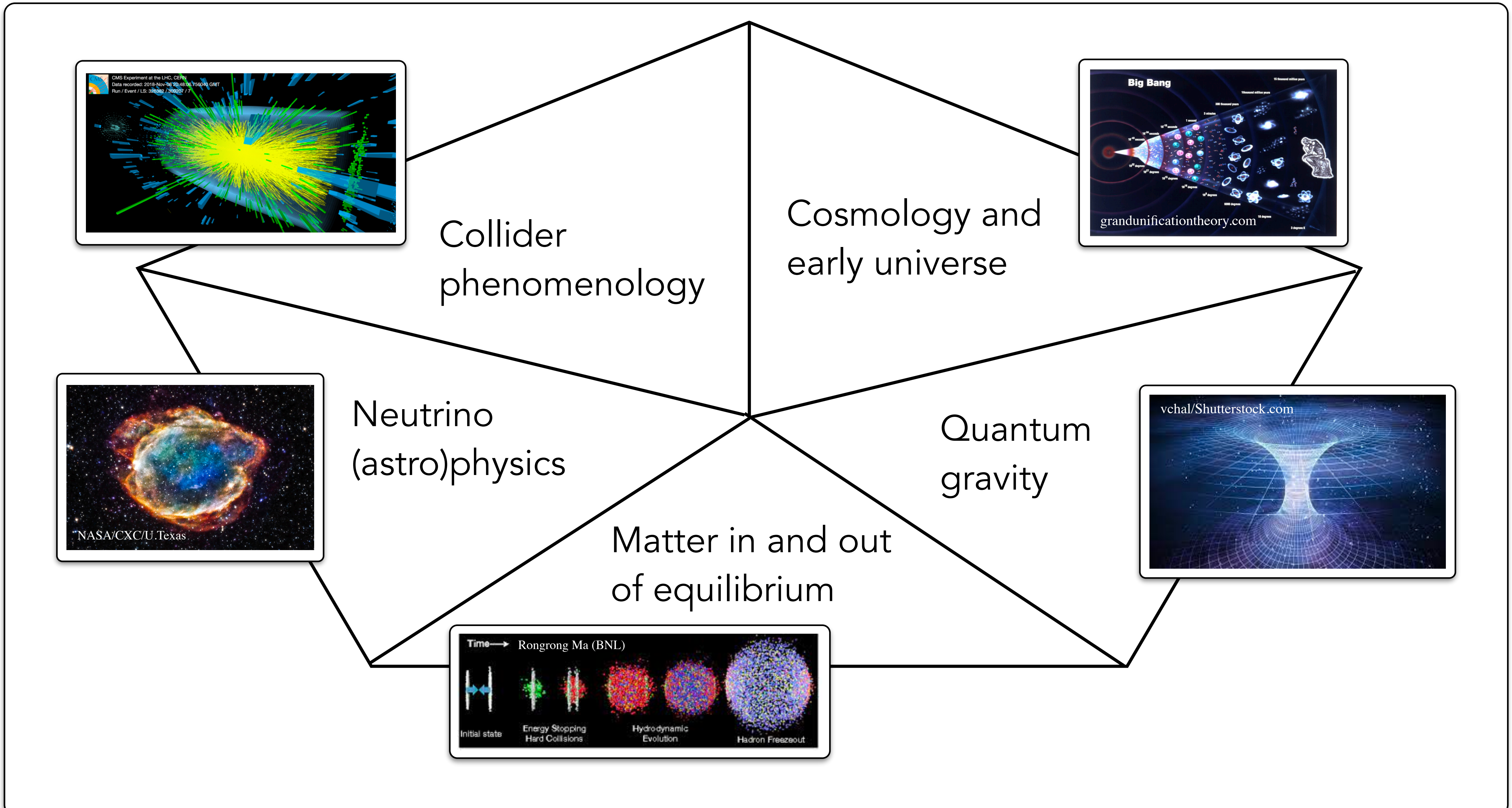
Path integral formulation:

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

Hamiltonian evolution:

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

PLUS MANY INTRACTABLE QUESTIONS IN HIGH ENERGY PHYSICS AS WELL…



Quantum Simulation for High Energy Physics, Bauer, ZD et al, PRX Quantum 4 (2023) 2, 027001.

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

An opportunity to explore new paradigms and new technologies:

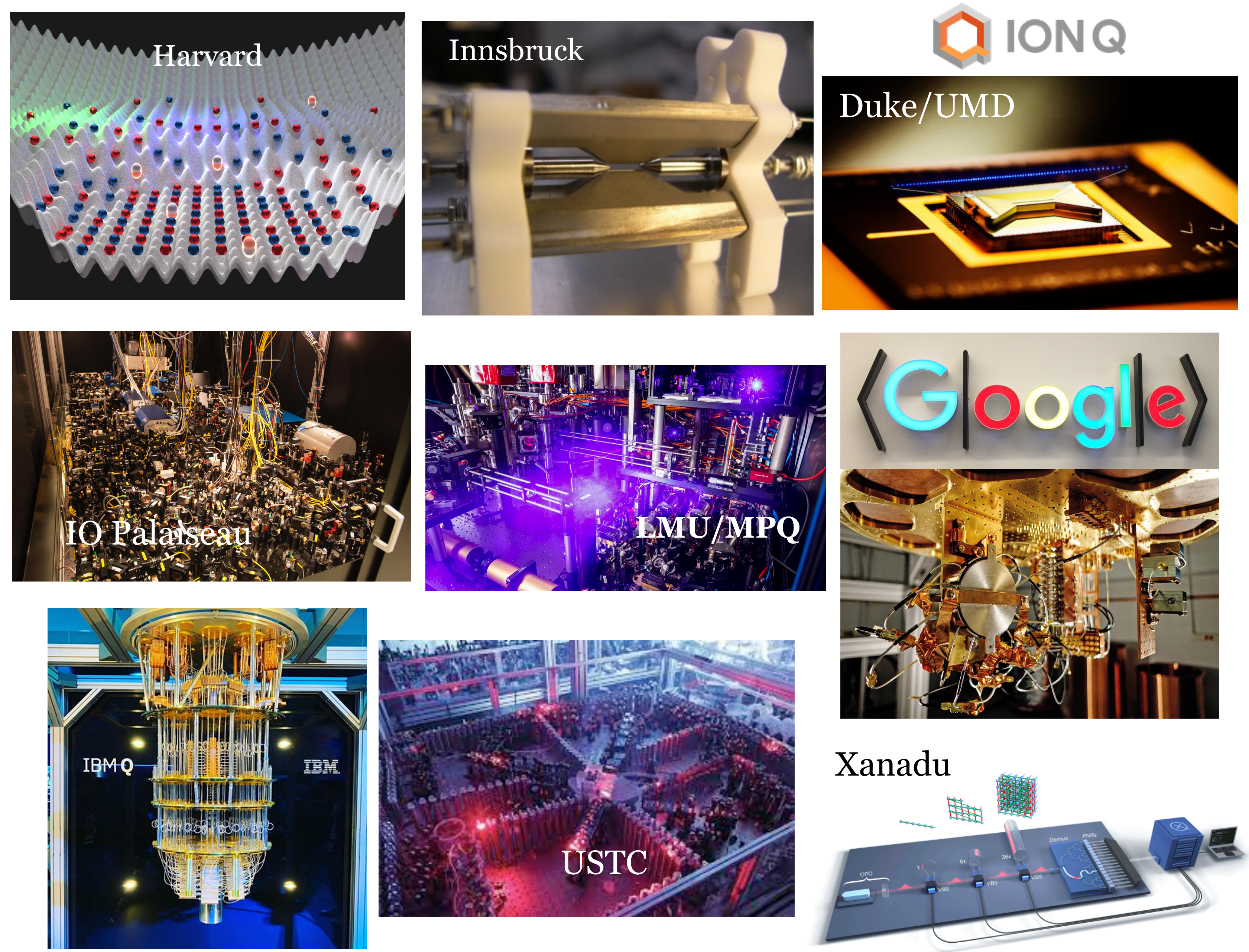
Turning to **quantum computation** since:

i) Hilbert spaces can be encoded exponentially more compactly.

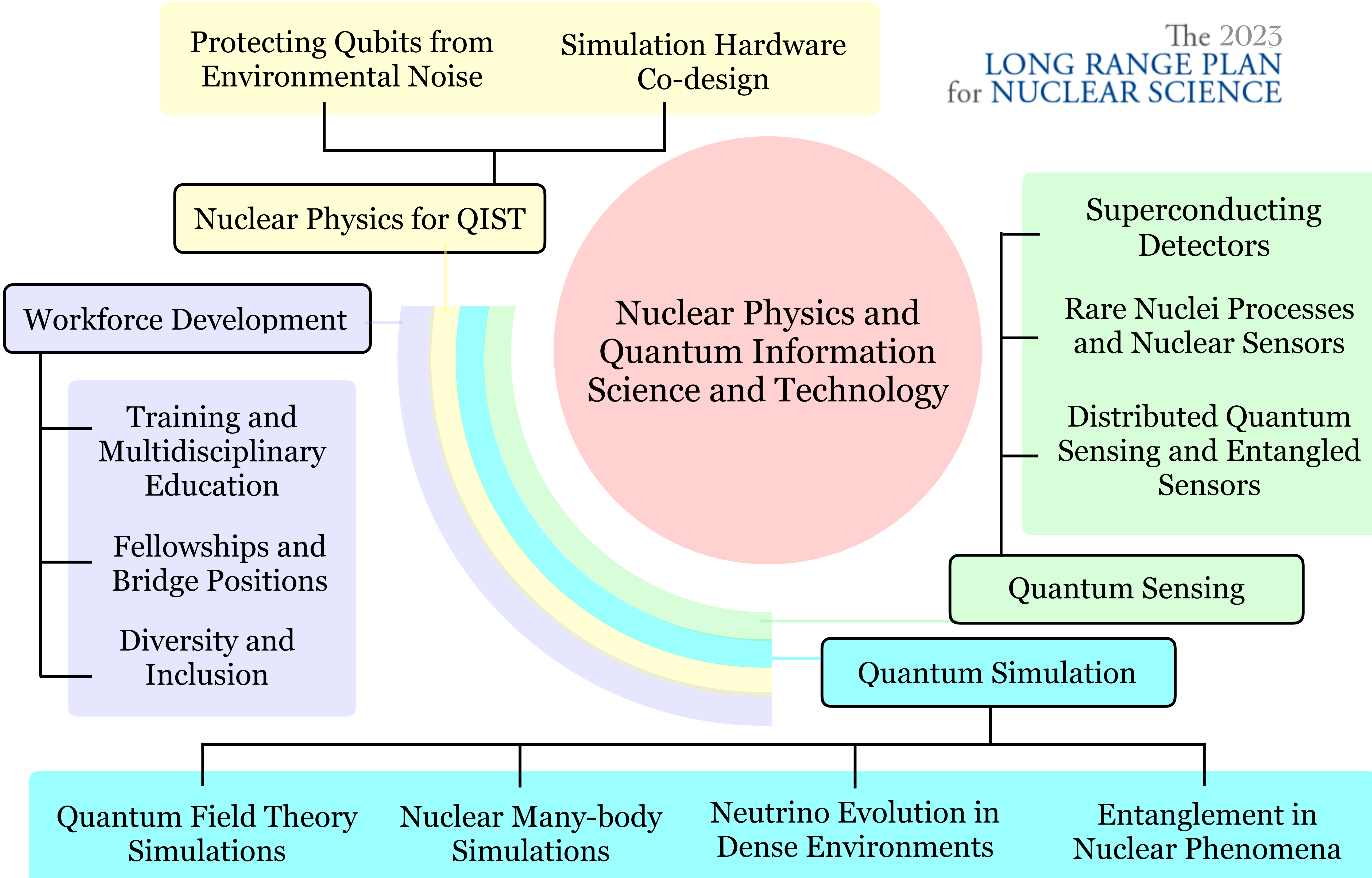
ii) Operations can be highly parallelized using quantum coherence and entanglement!

A RANGE OF QUANTUM SIMULATORS 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)
- Laser-cooled polar molecules
- Optical quantum computing



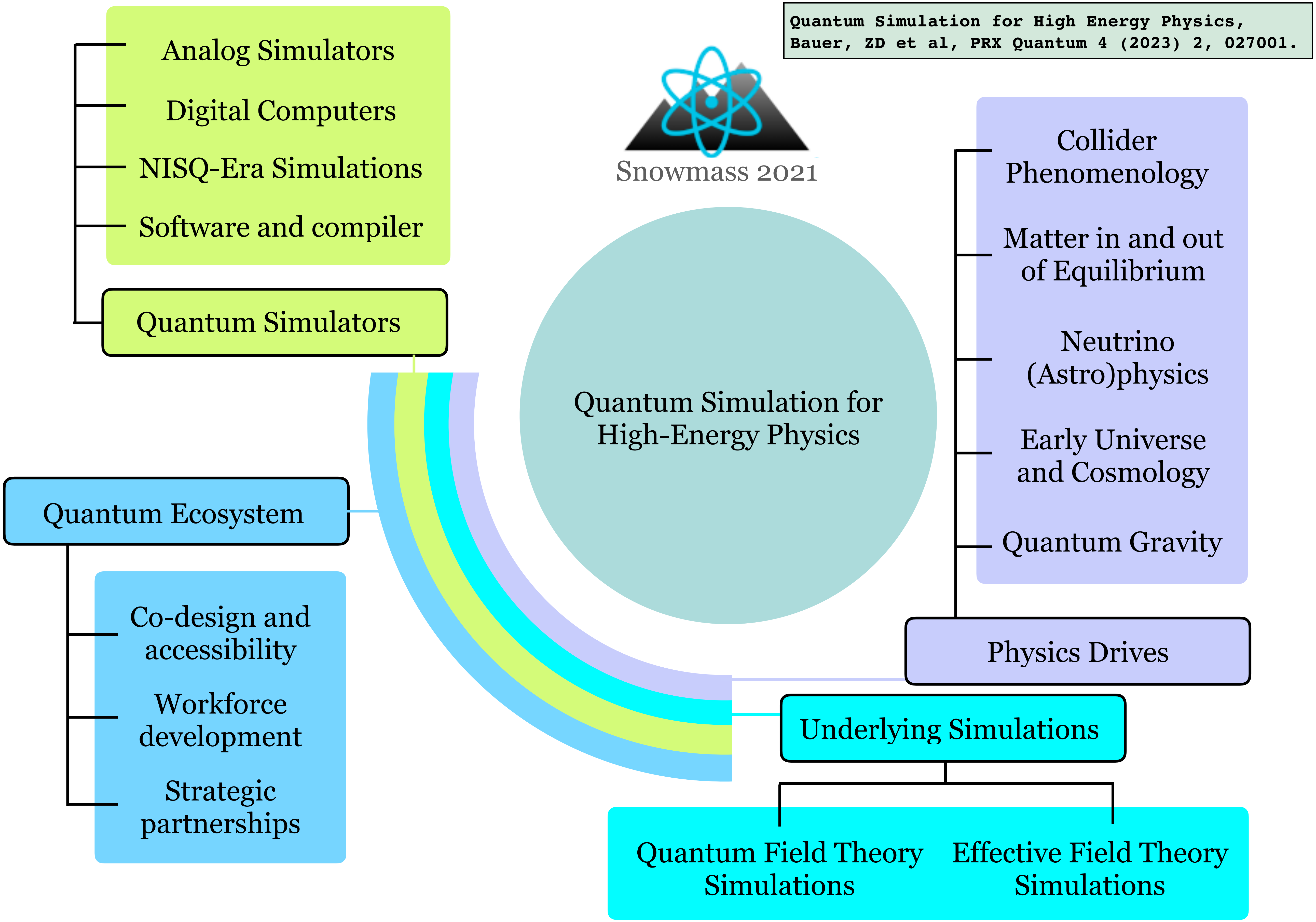
THE ROLE OF QUANTUM SIMULATION IN NUCLEAR-PHYSICS STUDIED IN THE LONG RANGE PLAN 2023.



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

THE ROLE OF QUANTUM SIMULATION IN HIGH ENERGY PHYSICS STUDIED IN THE SNOWMASS 2021(2).

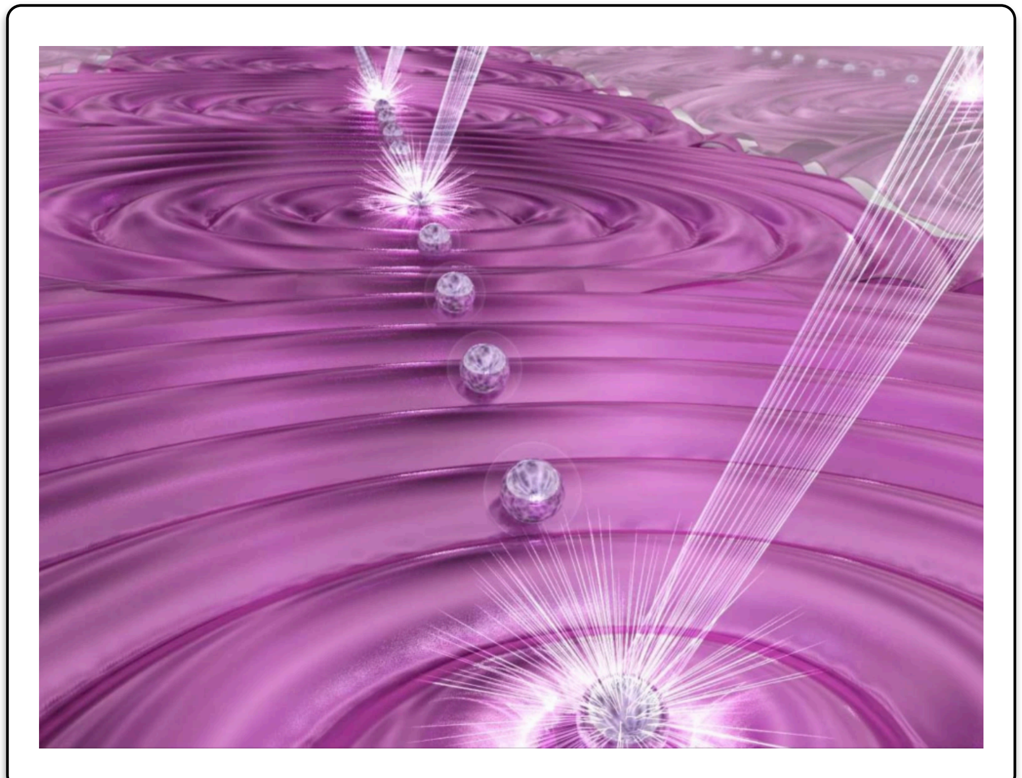
Quantum Simulation for High Energy Physics, Bauer, ZD et al, PRX Quantum 4 (2023) 2, 027001.



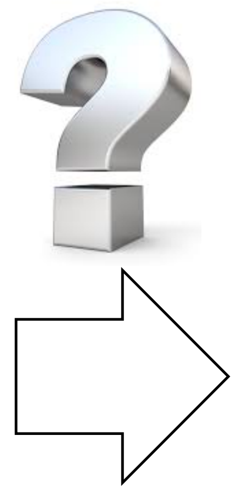
[PART II]
WHAT HAS TO BE DEVELOPED IN THE COMING YEARS?

QUANTUM SIMULATION OF QUANTUM CHROMODYNAMICS (QCD)?

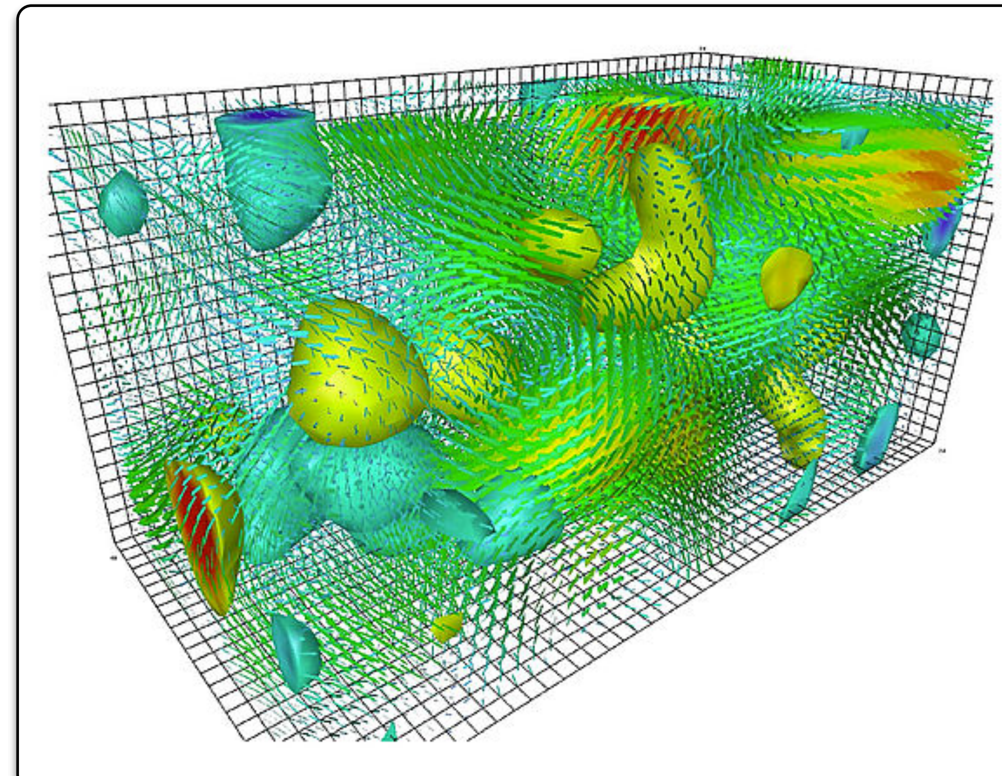
A controlled quantum system



CREDIT: EMILY EDWARDS, UNIVERSITY OF MARYLAND



Strong-interaction physics



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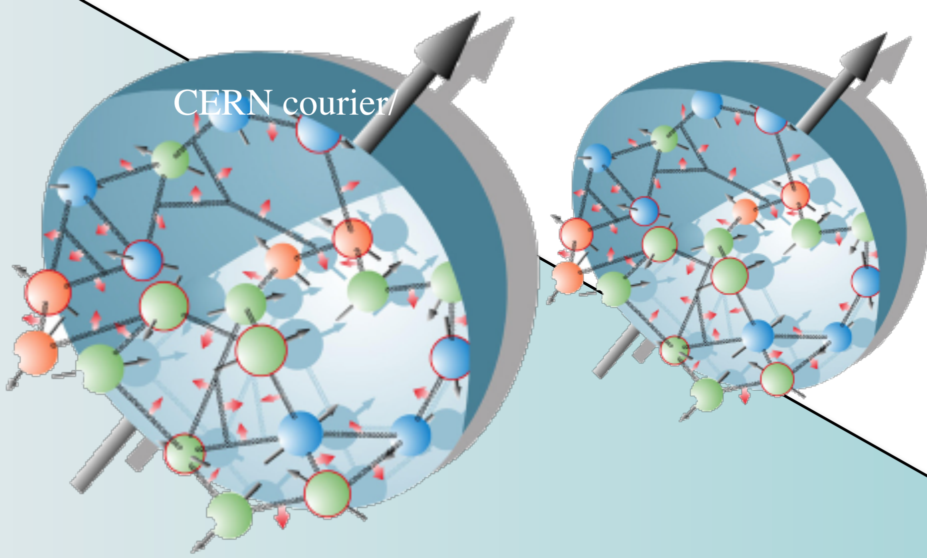
UNIQUE FEATURES OF QUANTUM SIMULATION OF QUANTUM FIELD THEORIES

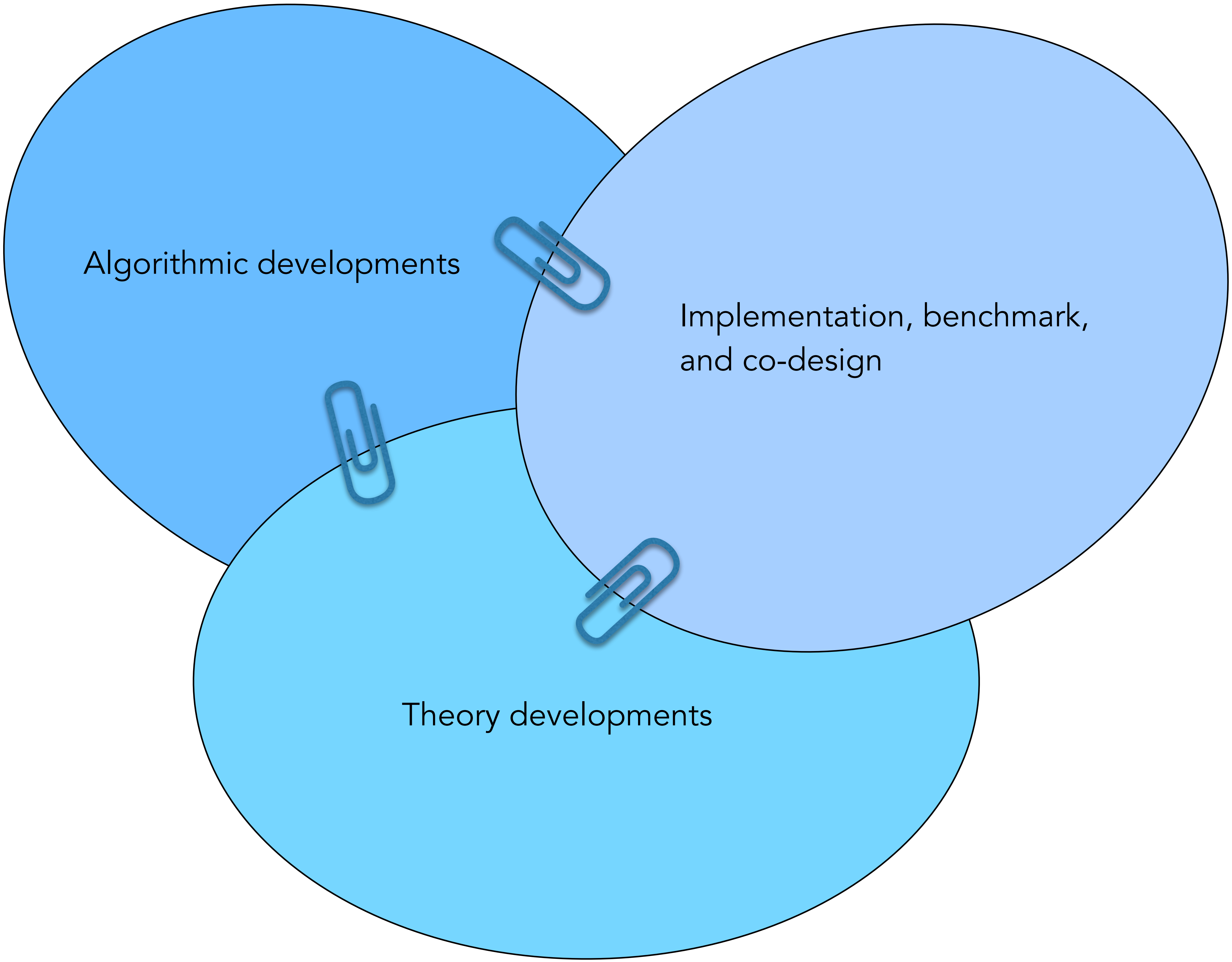


Starting from the Standard Model

Both bosonic and fermionic DOF are dynamical and coupled, exhibit both global and local (gauge) symmetries, relativistic hence particle number not conserved, vacuum state nontrivial in strongly interacting theories.

Attempts to cast QFT problems in a language closer to quantum chemistry and NR simulations: Kreshchuk, Kirby, Goldstein, Beauchemin, Love, arXiv:2002.04016 [quant-ph], Kreshchuk, Jia, Kirby, Goldstein, Vary, Love, Entropy 2021, 23, 597, Liu, Xin, arXiv:2004.13234 [hep-th], Barata , Mueller, Tarasov, Venugopalan (2020)

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



How to formulate QCD 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.

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

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

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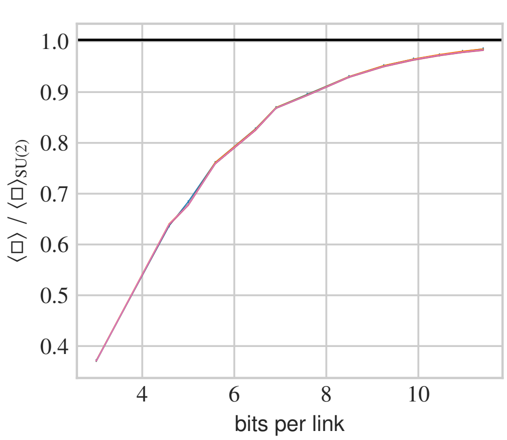
Fermion hopping term | Fermion mass | Energy of color electric field | Energy of color magnetic field

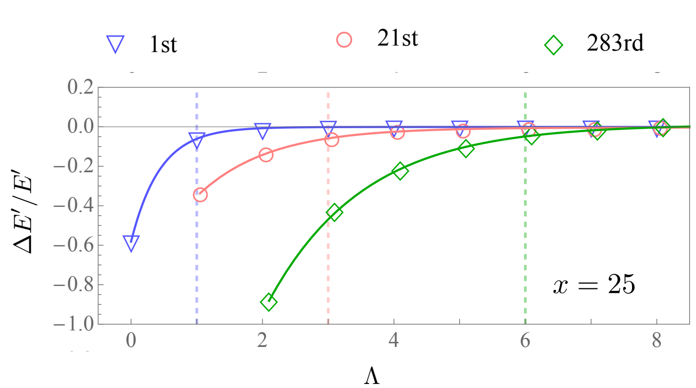
See also Tong, Albert, McClean, Preskill, and Su (2021) and Ciavarella (2023).

Gauge-field truncation

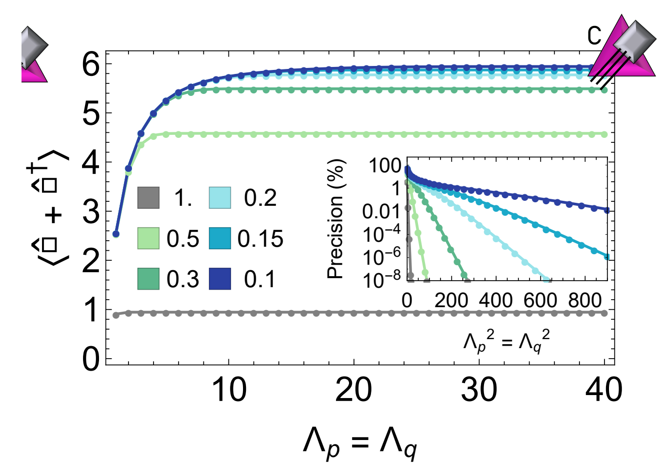
SU(2) pure gauge in 3+1 D in the U basis



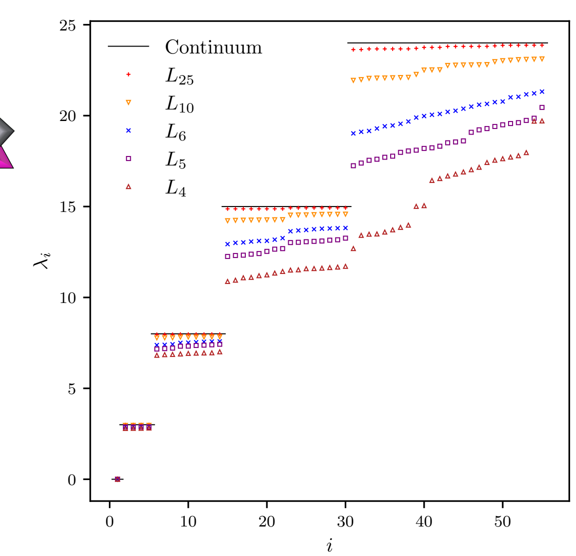
SU(2) with matter in 1+1 D in the E basis



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**.

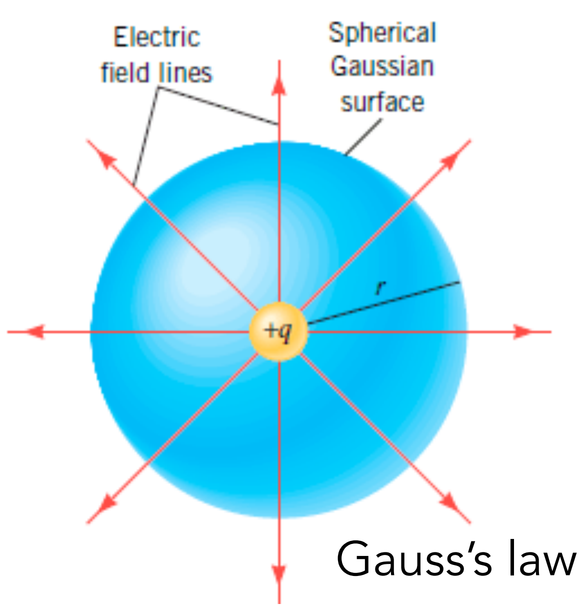
$$H^{(\mathrm{KS})} = H_I^{(\mathrm{KS})} + H_E^{(\mathrm{KS})} + H_M^{(\mathrm{KS})} + H_B^{(\mathrm{KS})}$$

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

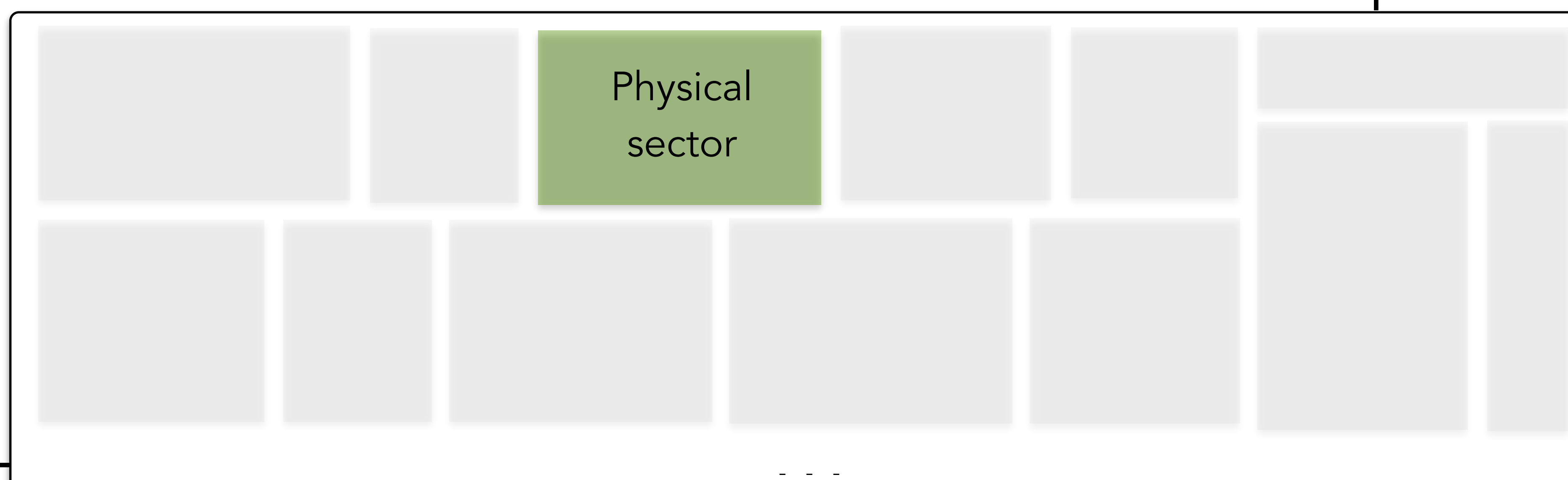
Generator of infinitesimal gauge transformation

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

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



Gauss's law



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

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Fermion hopping term | Fermion mass | Energy of color electric field | 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, BUT 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.

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

Bosonic basis
Cirac and Zohar

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

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

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

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?
- Should we develop gauge-invariant simulation algorithms?
- How do we do state preparation and compute observables like scattering amplitudes?

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?

Implementation, benchmark, and co-design

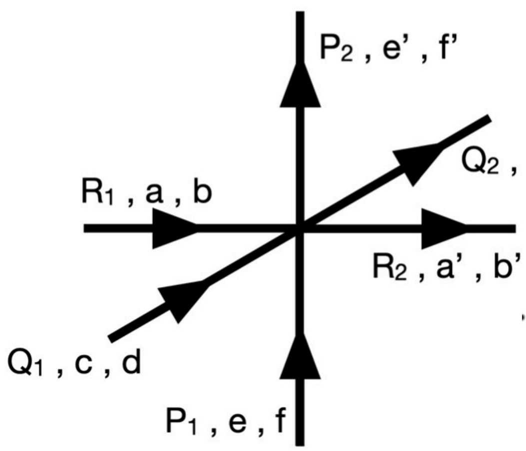
What is the capability limit of the hardware for gauge-theory simulations so far?

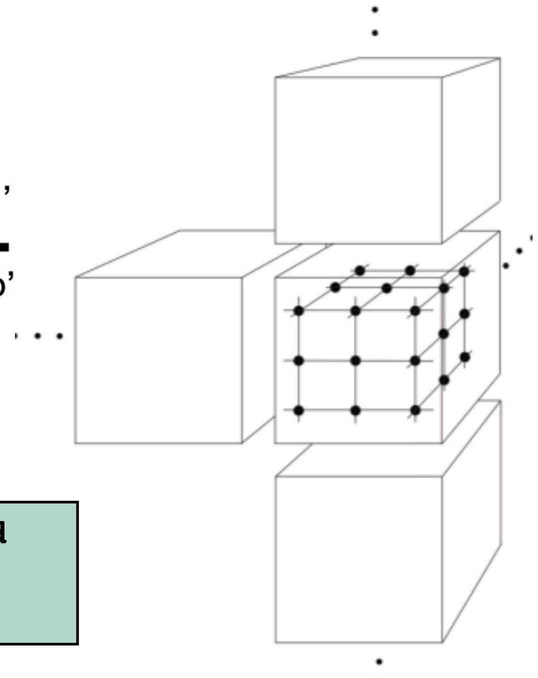
What is the nature of noise in hardware and how can it best be mitigated?

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

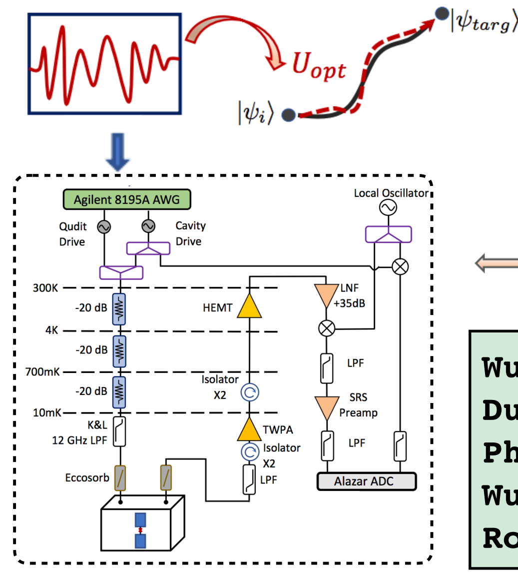
Can digital and analog ideas be combined to facilitate simulations of field theories?

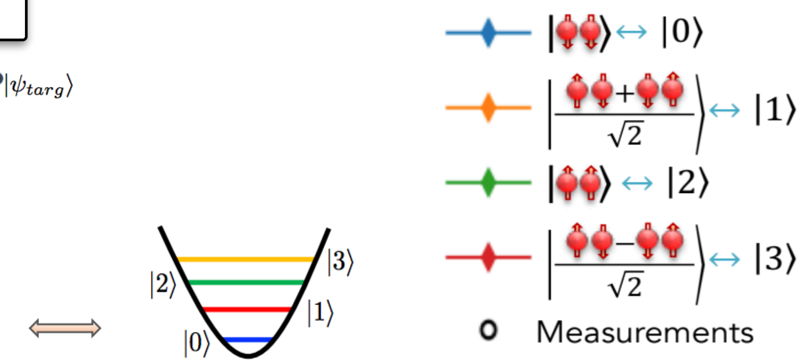
SOME CO-DESIGN EXAMPLES: MULTI-DIMENSIONAL LOCAL HILBERT SPACES AND MULTI-MODE INTERACTIONS



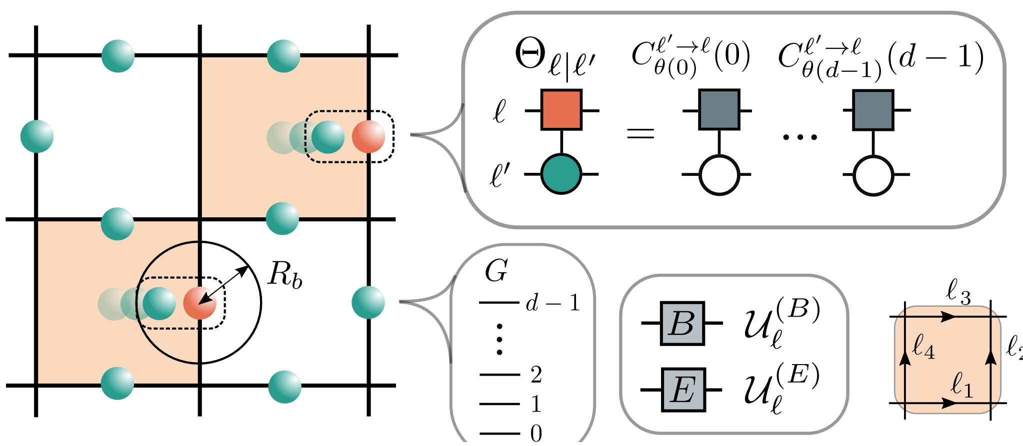


Ciavarella, Klco, and Savage, Phys. Rev. D 103, 094501 (2021).

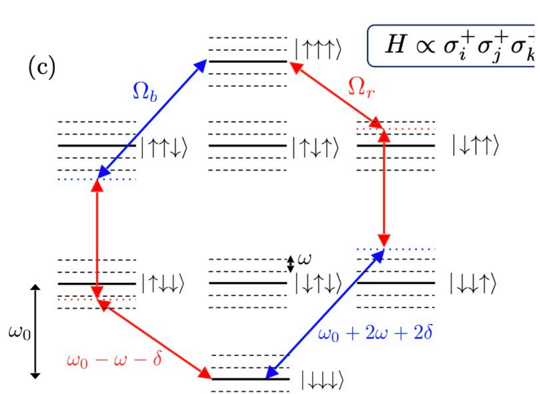


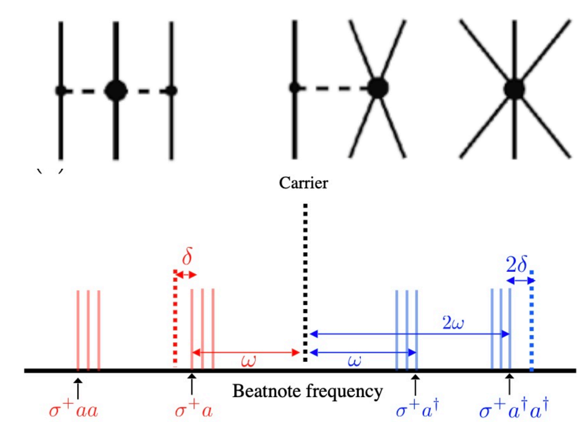


Wu, Tomarken, Petersson, Martinez, Rosen, DuBois arXiv:2005.13165, Holland et al., Phys. Rev. A 101, 062307 (2020) Wu, Wendt, Kravvaris, Ormand, DuBois, Rosen, Pederiva, and Quaglioni (2020).



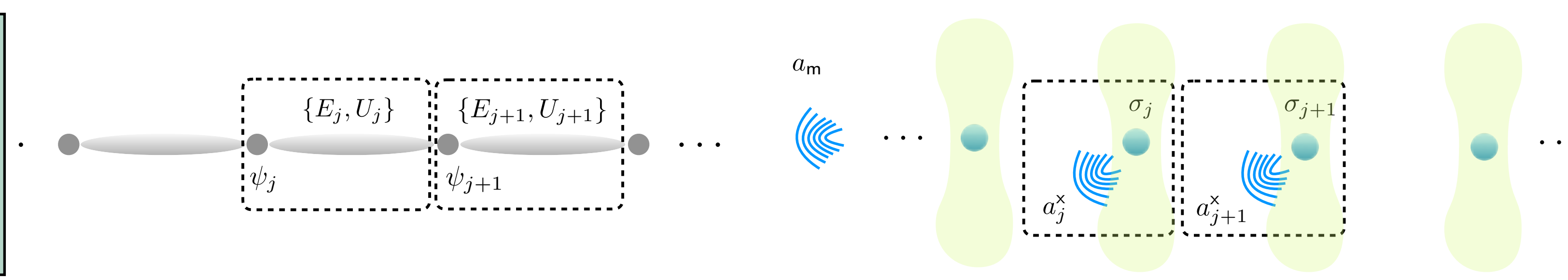
González-Cuadra, Zache, Carrasco, Kraus, Zoller, arXiv:2203.15541 [quant-ph].





Andrade, ZD, Grass, Hafezi, Pagano, Seif, arXiv:2108.01022 [quant-ph], Bermudez et al, Pays.Rev.A79, 060303 R (2009), Katz, Centina, Monroe, arXiv:2202.04230 [quant-ph].

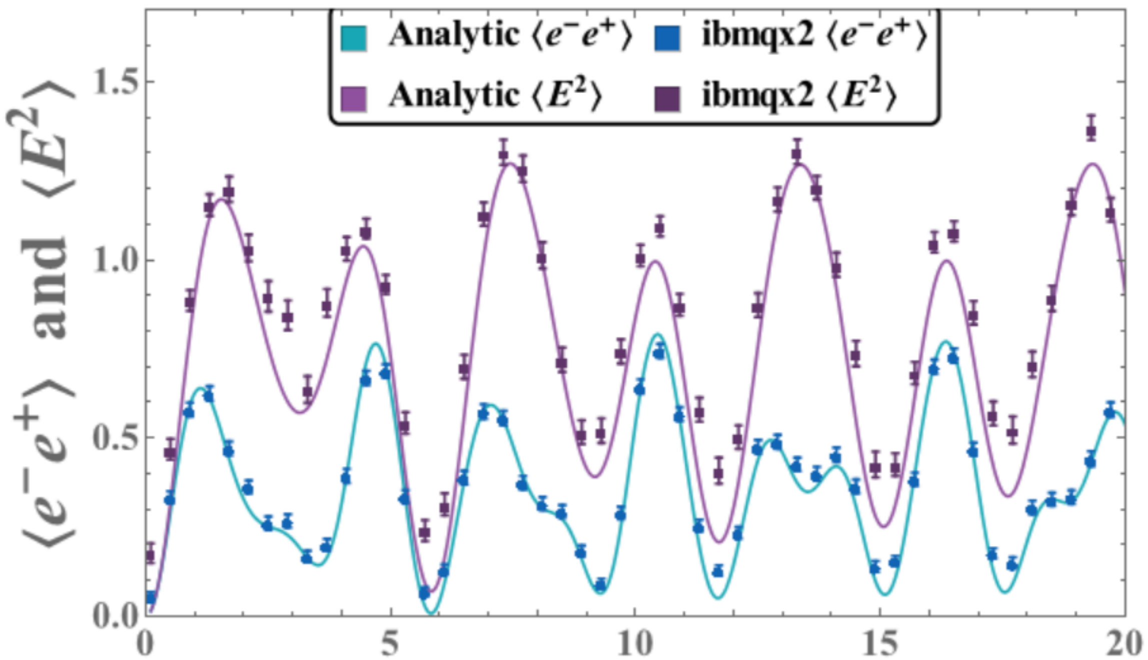
ZD, Linke, Pagano, Phys. Rev. Research 3, 043072 (2021). See also Casanova et al, Phys. Rev. Lett. 108, 190502 (2012), Lamata et al, EPJ Quant. Technol. 1, 9 (2014), and Mezzacapo et al, Phys. Rev. lett. 109, 200501 (2012).



[PART III]
EXAMPLES SHOWCASING PROGRESS IN A RANGE OF QCD-INSPIRED PROBLEMS…

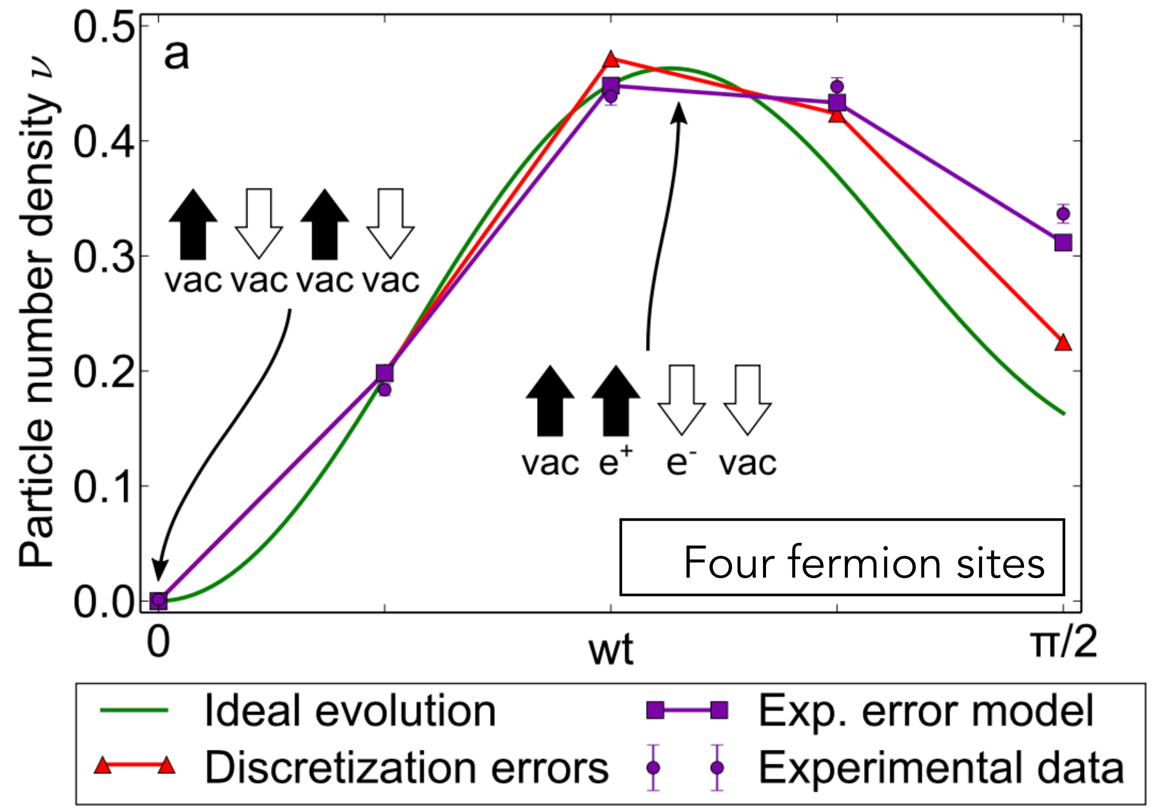
REAL-TIME EVOLUTION AND QUENCH DYNAMICS IN ABELIAN LGTs

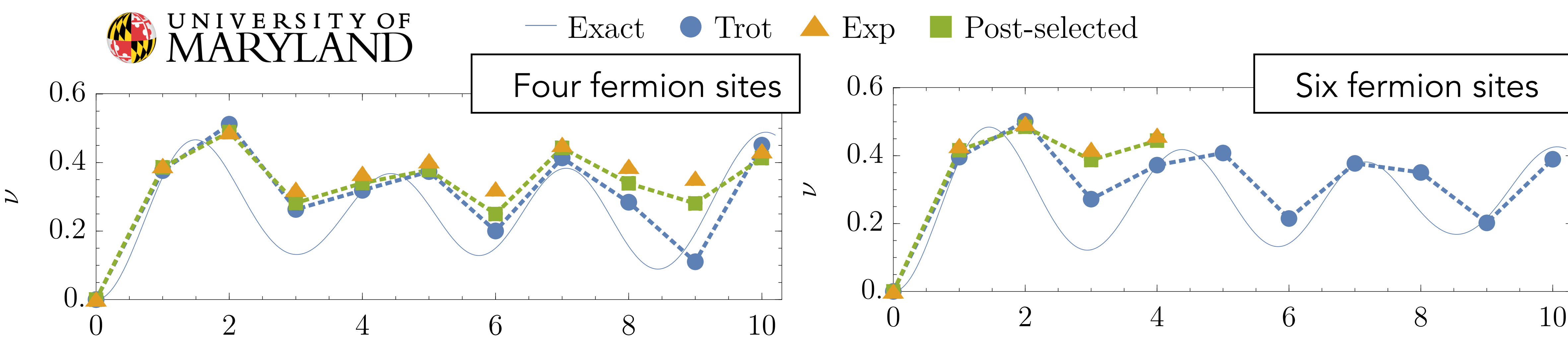
Klco, Savage, et al, Phys. Rev. A 98, 032331 (2018).



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

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





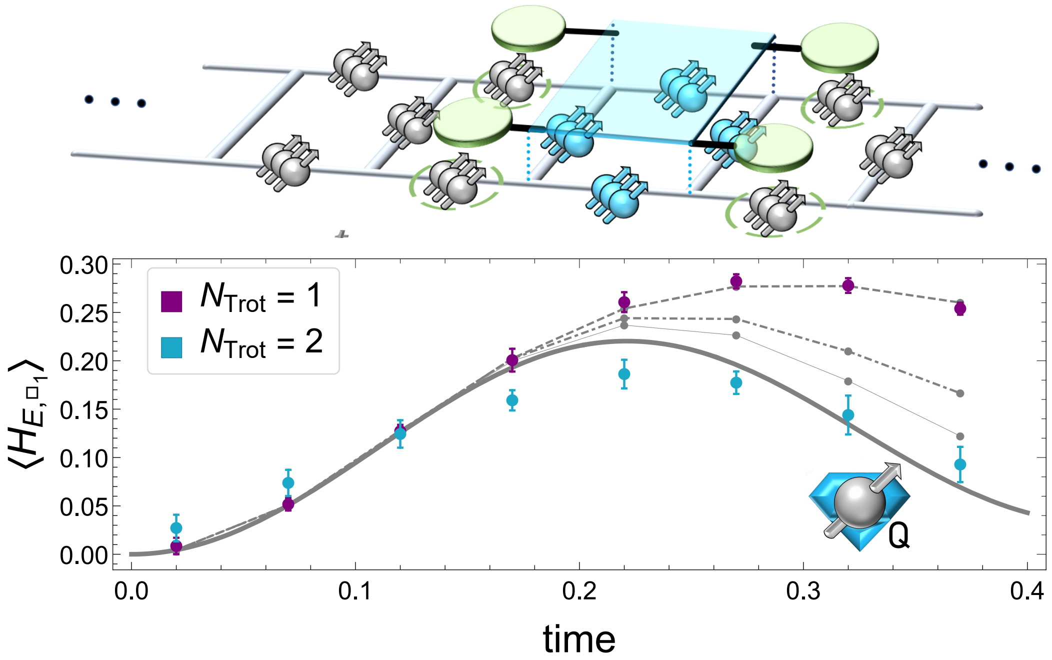
80 entangling gates!

Nguyen, Tran, Zhu, Green, Huerta Alderete, ZD, Linke, *PRX Quantum* 3 (2022) 2, 020324.

90 entangling gates!

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

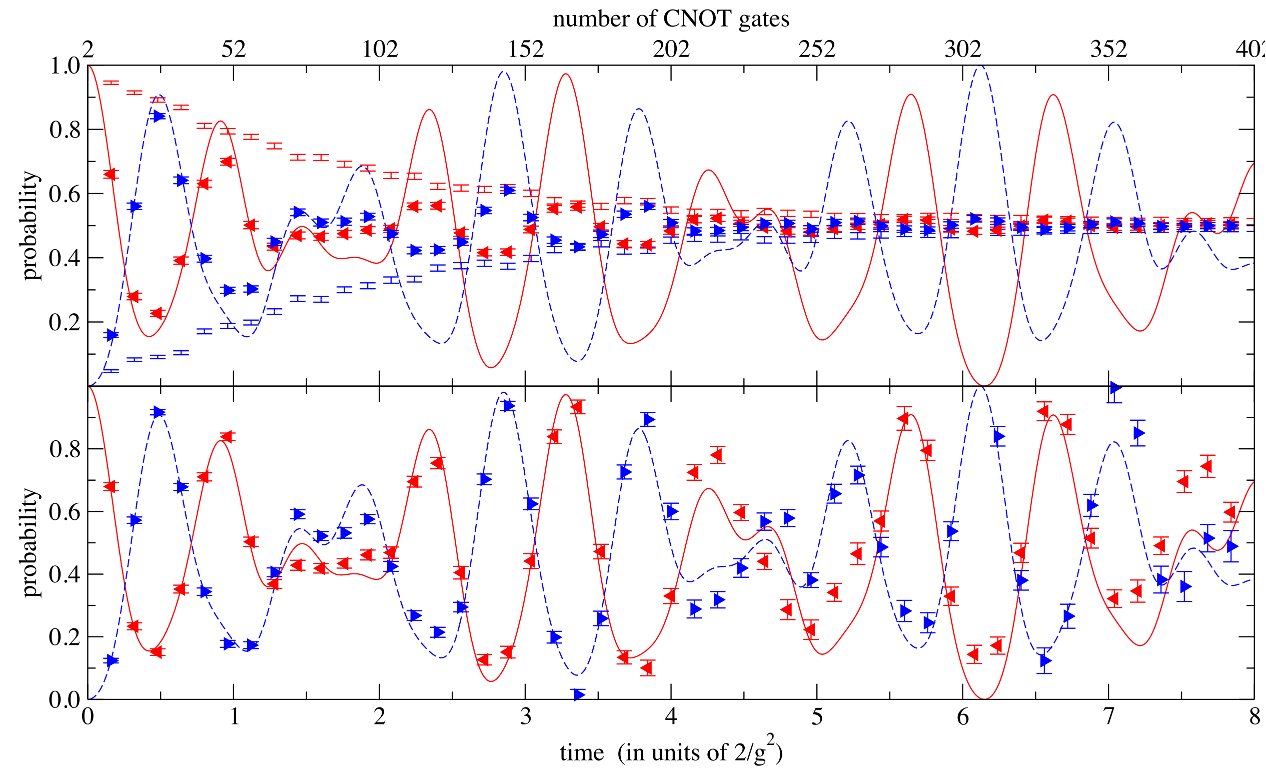
Real-time dynamic of pure SU(2) with global irreps on IBM

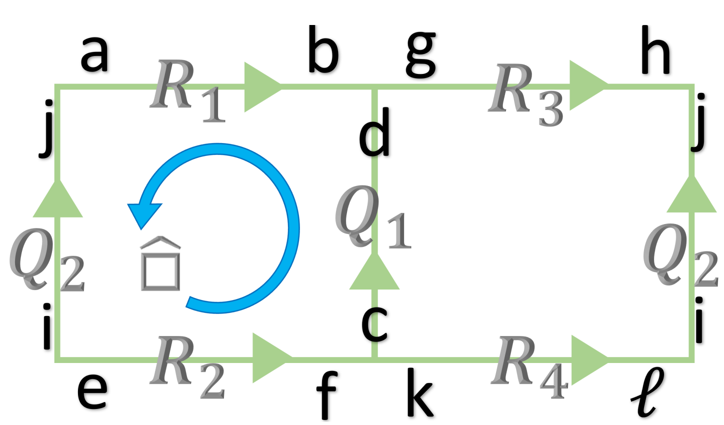


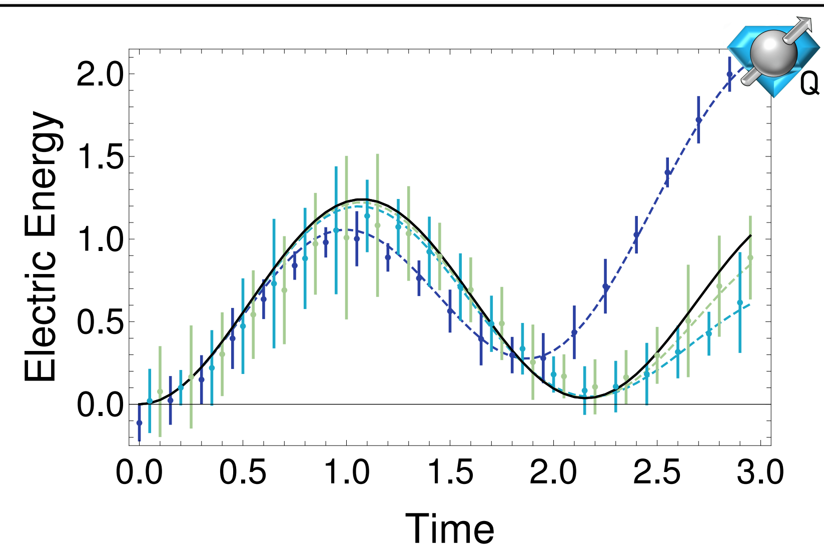
Klco, Savage, and Stryker, Phys. Rev. D 101, 074512 (2020).

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).





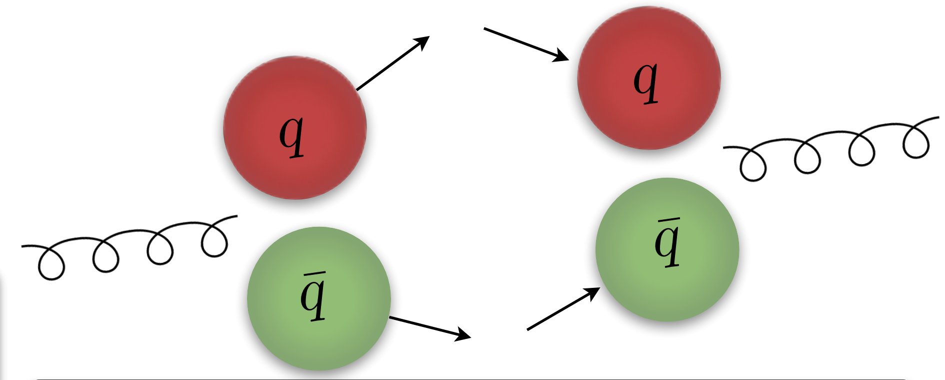


Real-time dynamic of pure SU(3) with global irrupts on IBM

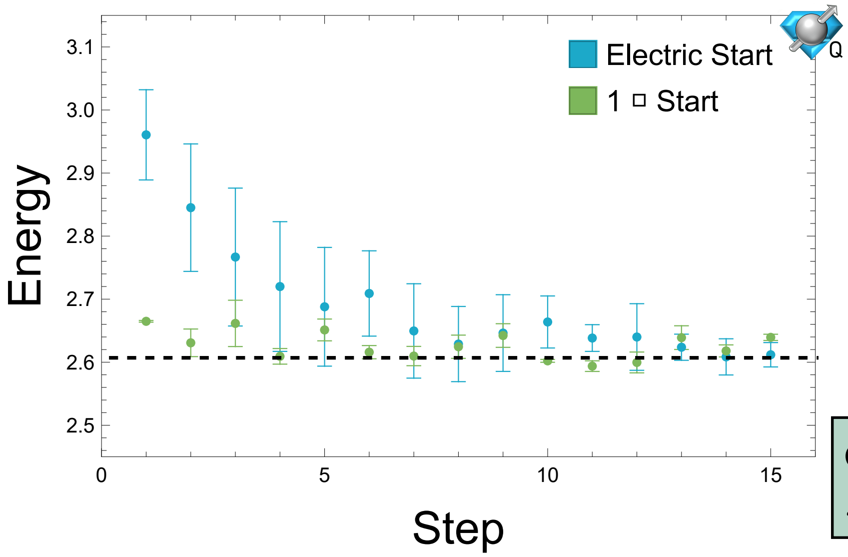
Ciavarella, Klco, and Savage, Phys. Rev. D 103, 094501 (2021).

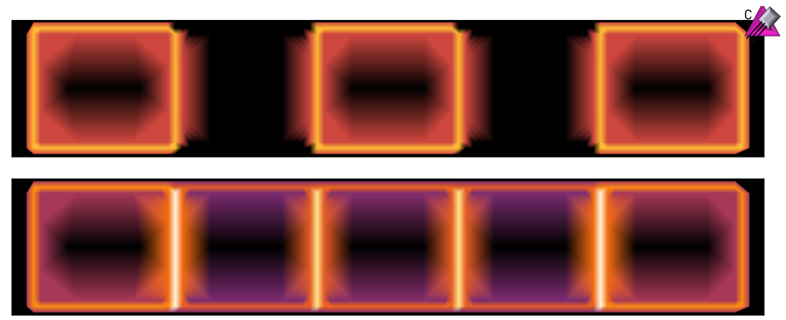
See also studies on D-wave annealers: Rahman et al, Phys. Rev. D 104, 034501 (2021), Illa and Savage, arXiv:2202.12340 [quant-ph], Farrel et al, arXiv:2207.01731 [quant-ph].

VACCUM AND HADRONIC STATE PREPARATION AND SPECTROSCOPY IN LGTS



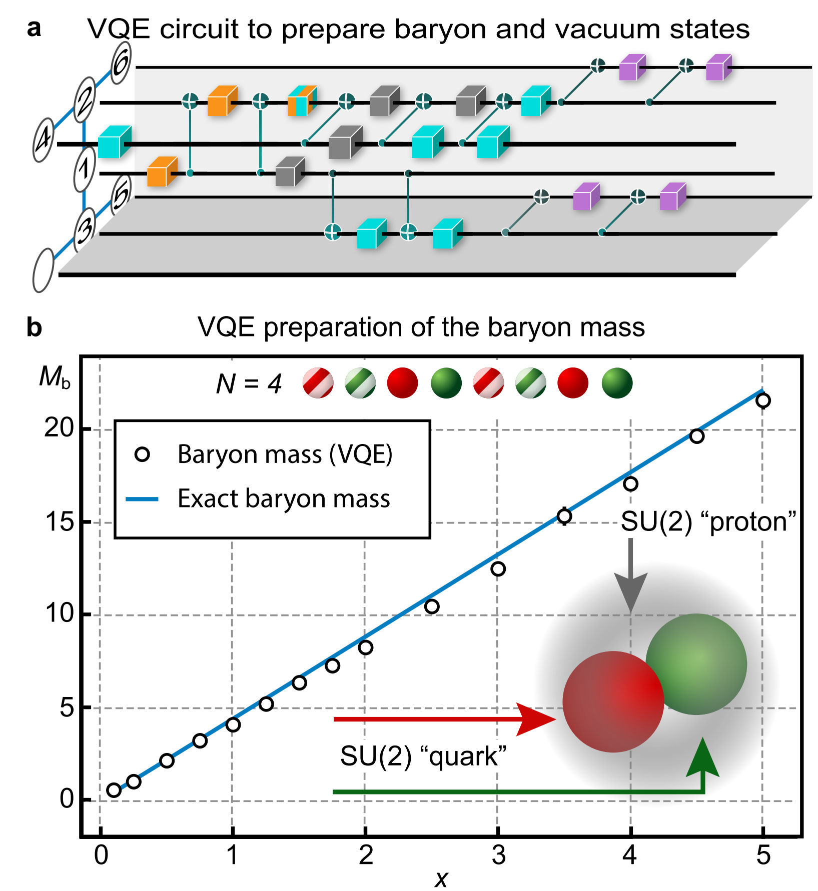
Variational state preparation of the vacuum state for a two plaquette system in pure SU(2) LGT on IBM





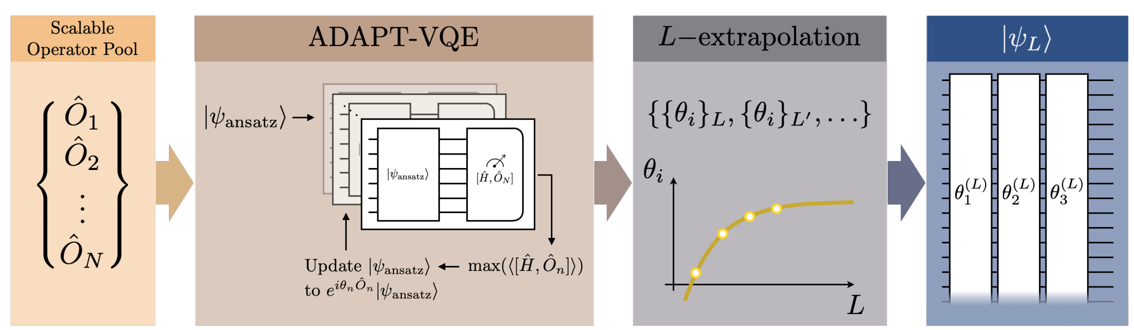
Ciavarella and Chernyshev, *Phys.Rev.D* 105 (2022) 7, 074504.

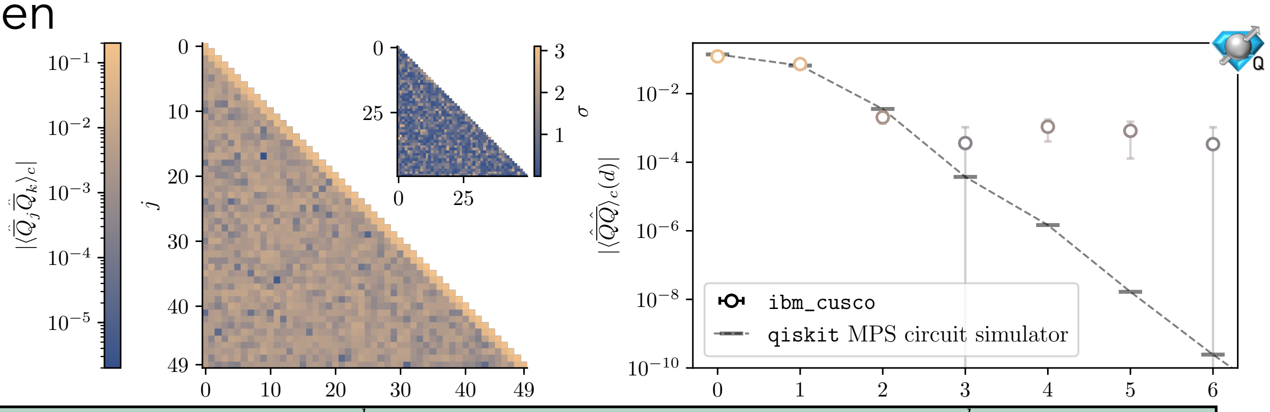
Low-lying spectrum of SU(2) with matter in 1+1 D on IBM



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

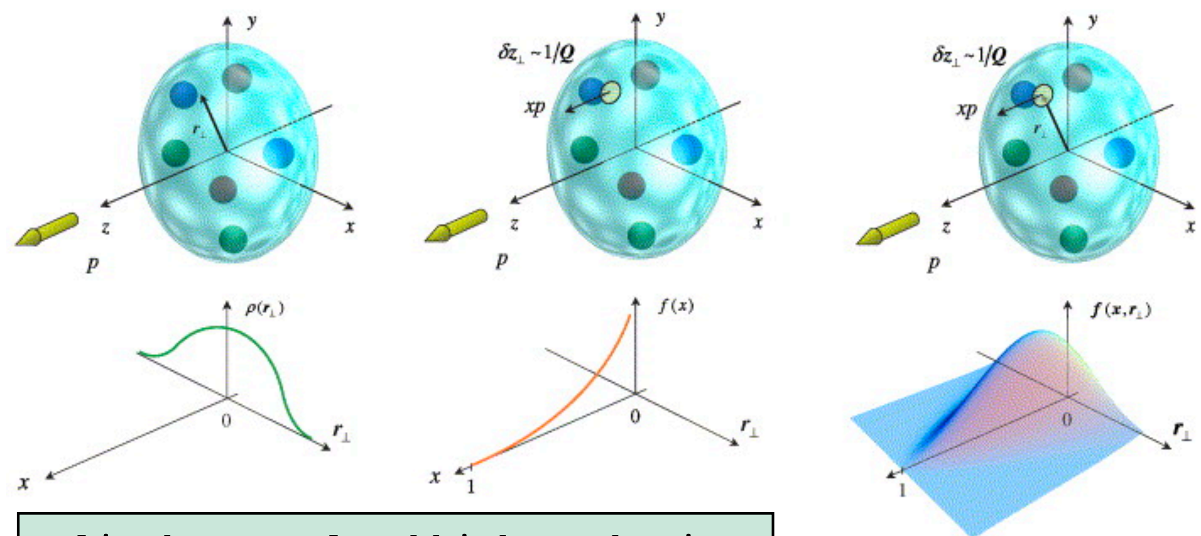




Farrell, Illa, Ciavarella, Savage, arXiv:2308.04481 [quant-ph].

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].

HADRON STRUCTURE, PARTON DISTRIBUTION FUNCTIONS, HADRONIZATION



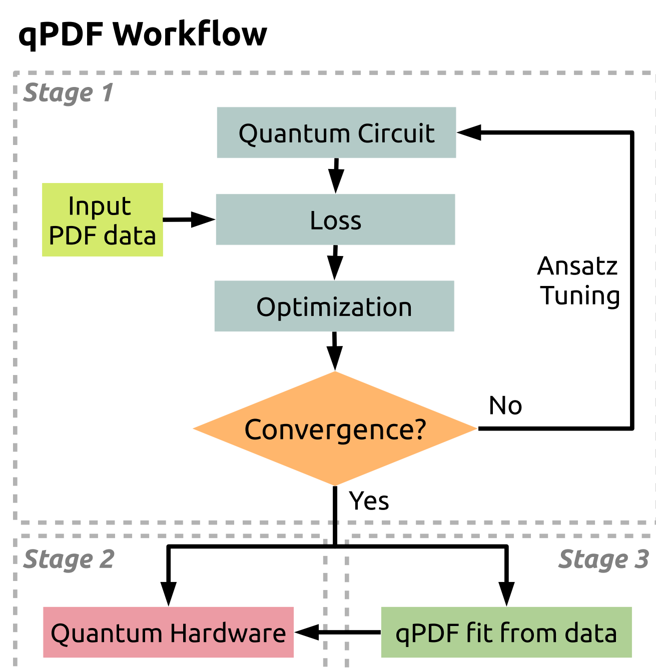
Belitskya, Radyushkinbc, Physics Reports 418 (2005), 1-387.

Either calculate PDFs directly since non-equal time amplitudes are possible on quantum computers…

Mueller, Tarasov, and Raju Venugopalan, PRD 102, 016007 (2020), Lamm, Lawrence, and Yamauchi, Phys. Rev. Res. 2, 013272 (2020), Echevarria, Egusquiza, Rico, and G Schnell, PRD 104, 014512 (2021).

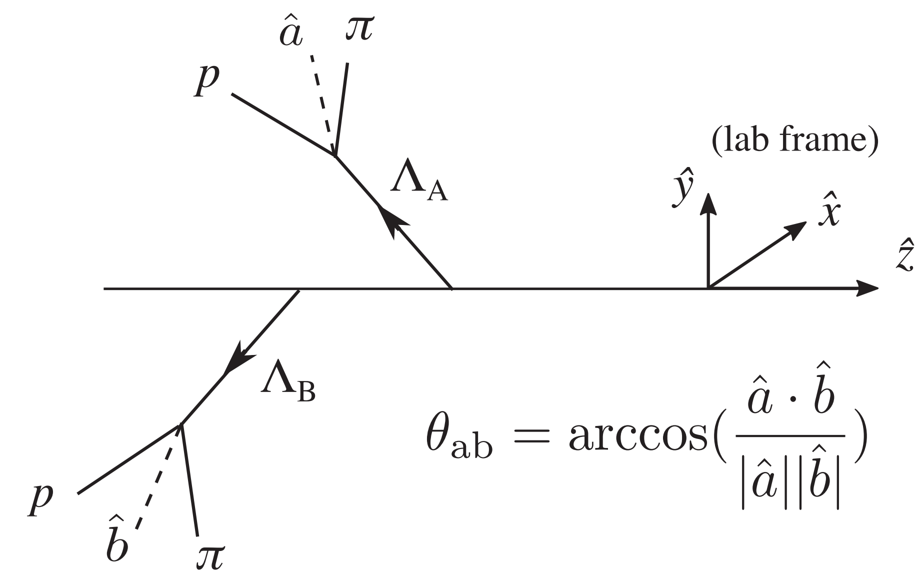
…or expedite global fitting of PDFs with variational quantum eigensolvers…

Perez-Salinas, Cruz-Martinez, Alhajri, and Carrazza , PRD 103, 034027 (2021), Qian, Basili, Pal, Luecke, and Vary, arXiv:2112.01927 (2021).



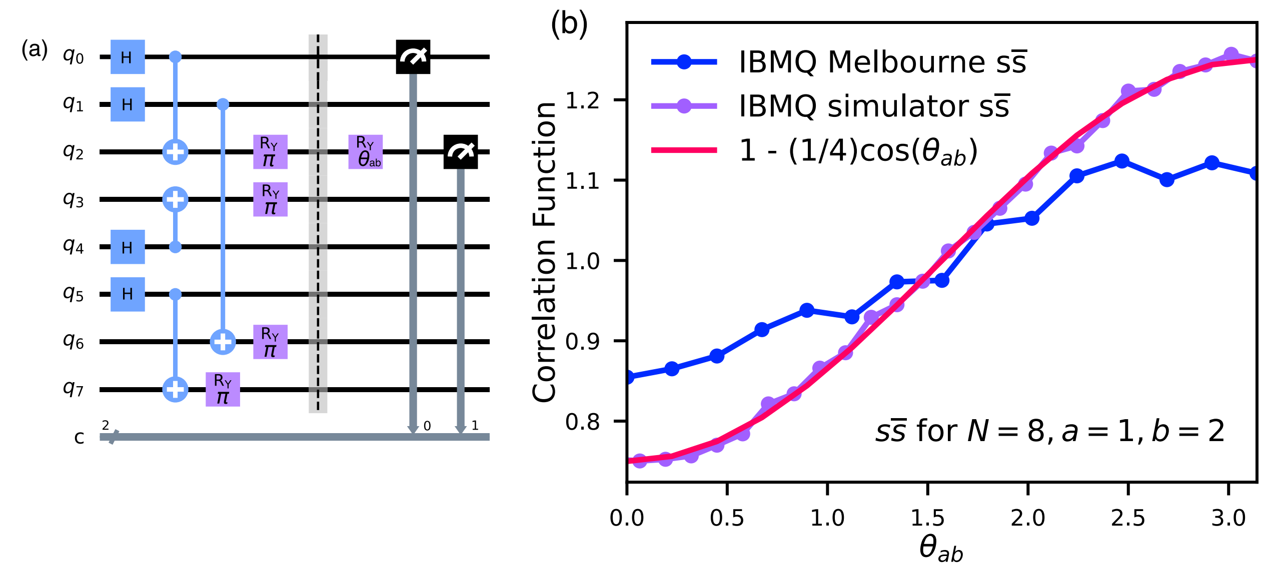
Λ and $\bar{\Lambda}$ spin correlations provide novel insights into quantum features of many-body parton dynamics.

ep or *pp* collisions



$$\theta_{ab} = \arccos\left(\frac{\hat{a}\cdot\hat{b}}{|\hat{a}||\hat{b}|}\right)$$

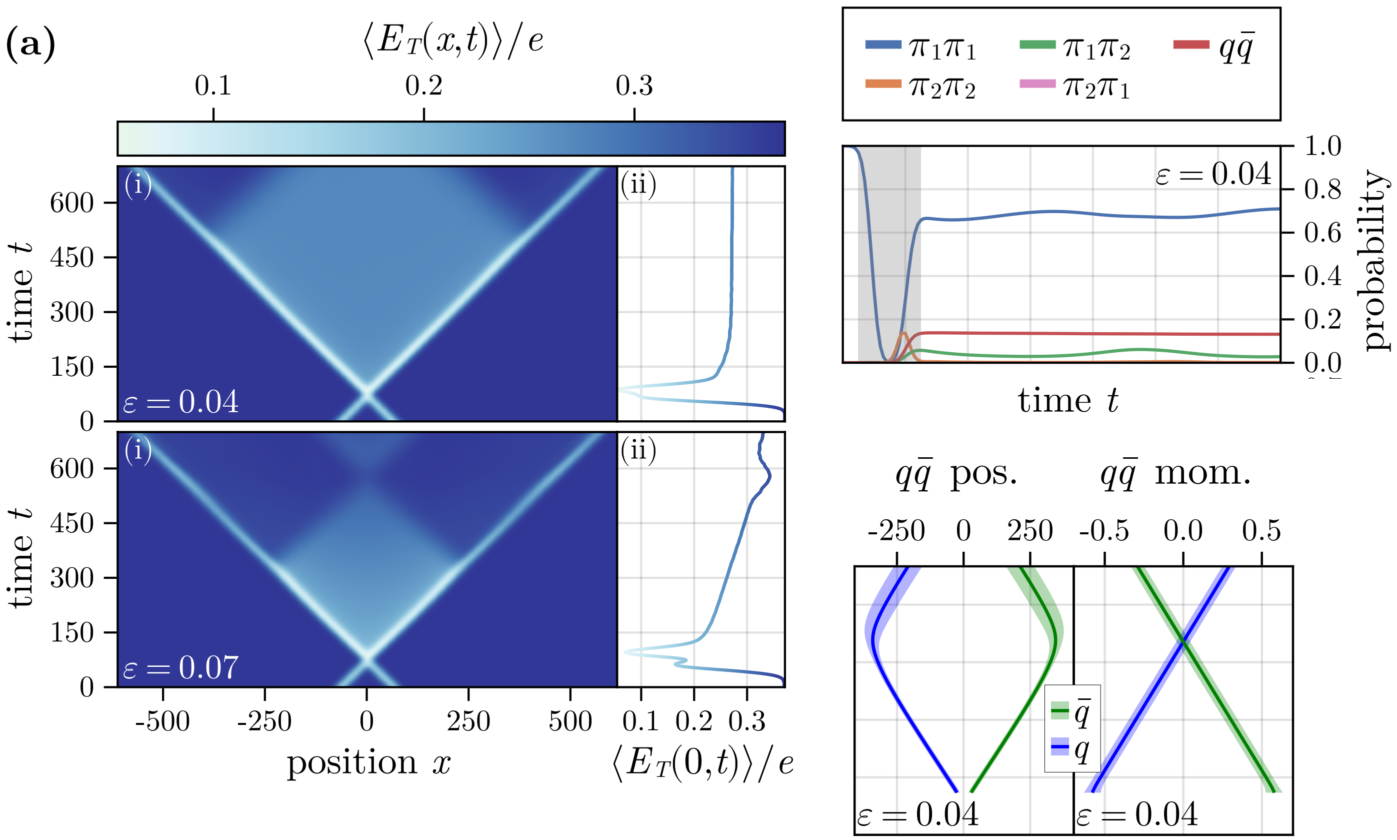
Quantum simulating a simple model of hadronization originating from QCD strings:

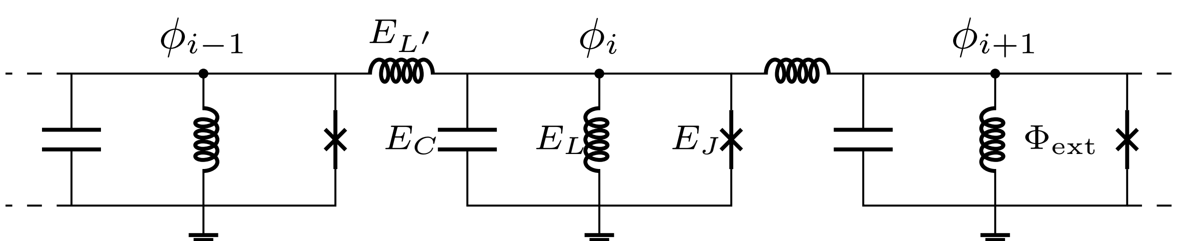


Gong, Parida, Tu, and Venugopalan, *Phys.Rev.D* 106 (2022) 3, L031501. See also: Barata, Gong, Venugopalan, arXiv:2308.13596 [hep-ph].

FIRST STEPS TOWARD COLLISION/REACTION PROCESSES

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

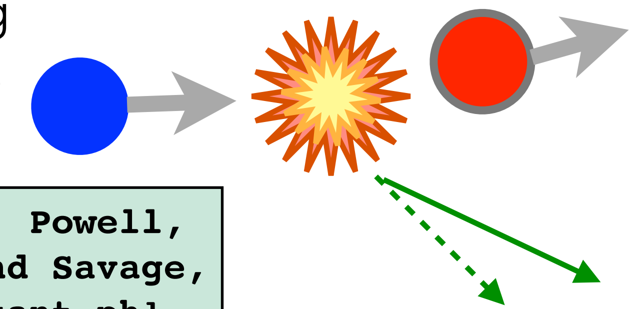




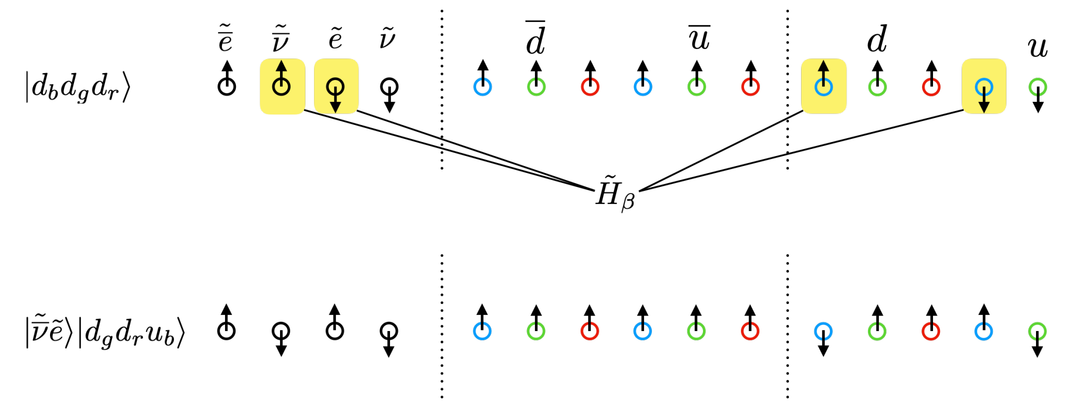
Belyansky, Whitsitt, Mueller, Fahimniya, Bennewitz, ZD, and Gorshkov, arXiv:2307.02522 [quant-ph].

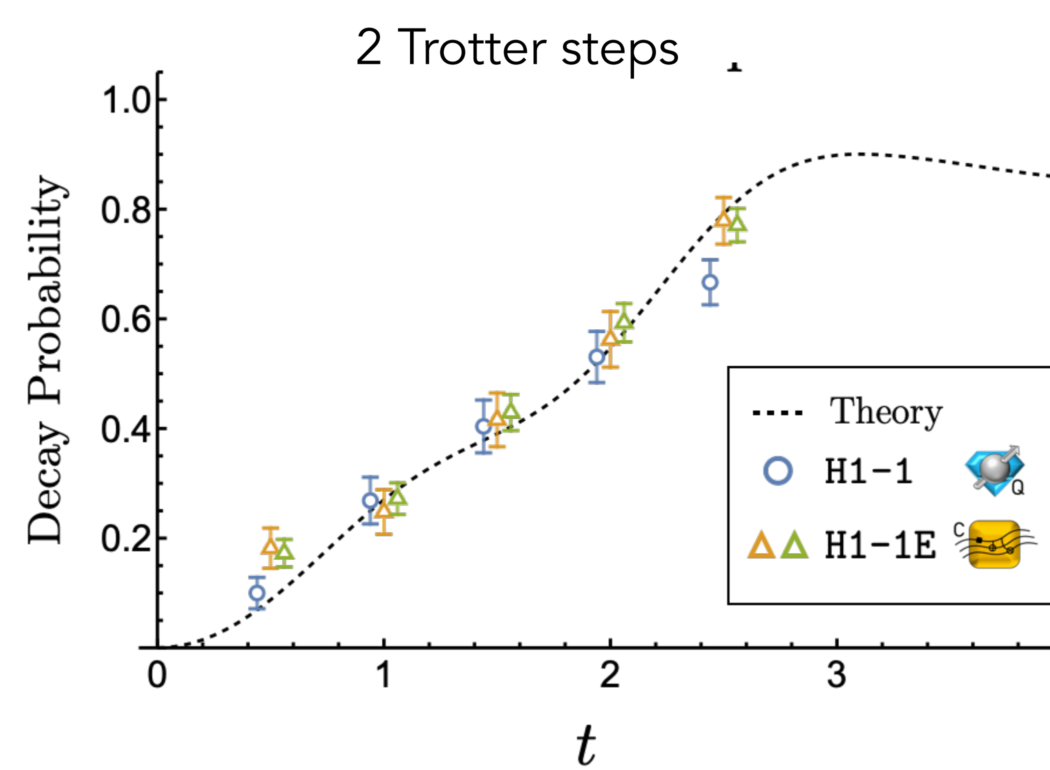
See also Ashley Milsted, Liu, John Preskill, and Vidal, PRX Quantum 3 (2022) 2, 020316, and Rigobello, Notarnicola, Magnifico, and Montangero, Phys. Rev. D 104, 114501 (2021).

Quantum computing β decay in 1+1 QCD



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

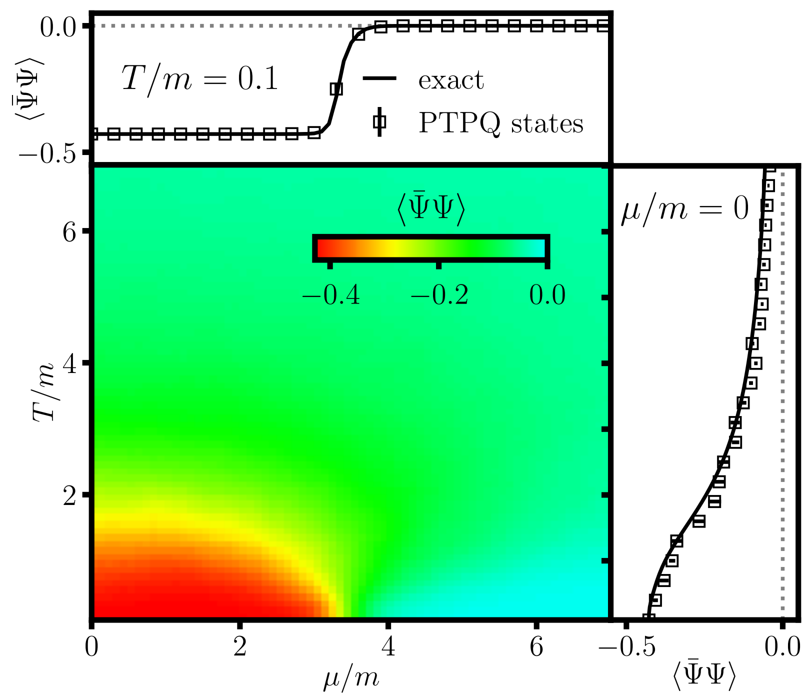




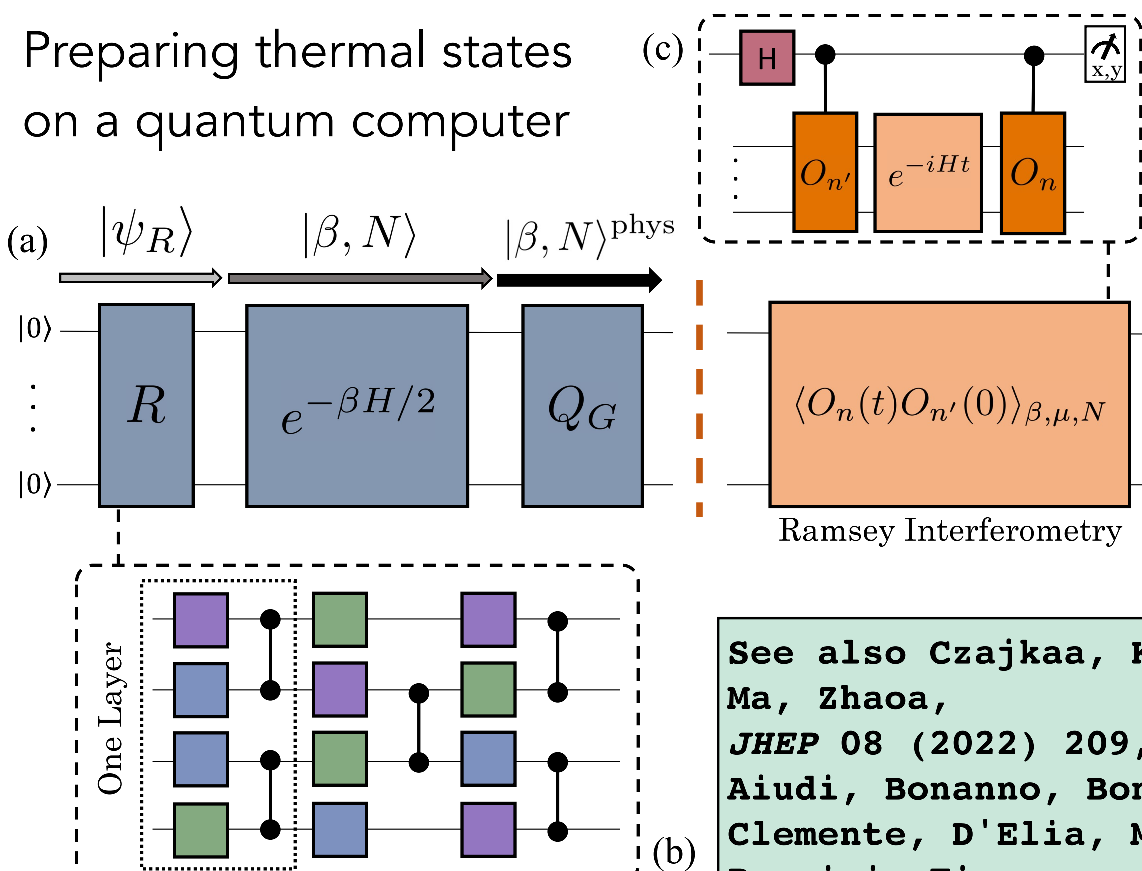
FINITE TEMPERATURE AND FINTIE DENSITY PHASE DIAGRAM, QGP TRANSPORT

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

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



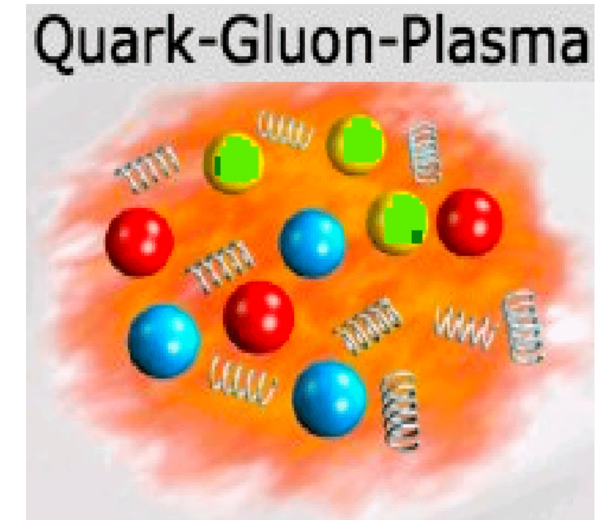
Preparing thermal states on a quantum computer



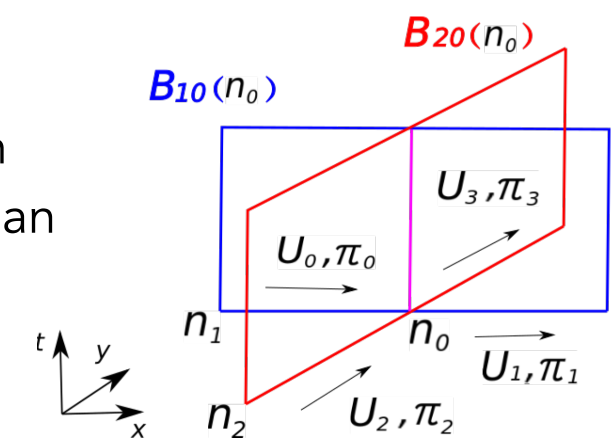
See also Czajkaa, Kang, Ma, Zhaoa, *JHEP* 08 (2022) 209, and Aiudi, Bonanno, Bonati, Clemente, D'Elia, Maio, Rossini, Tirone, and Zambello, arXiv:2308.01279 [quant-ph].

Transport coefficients from real-time correlators of energy momentum tensor

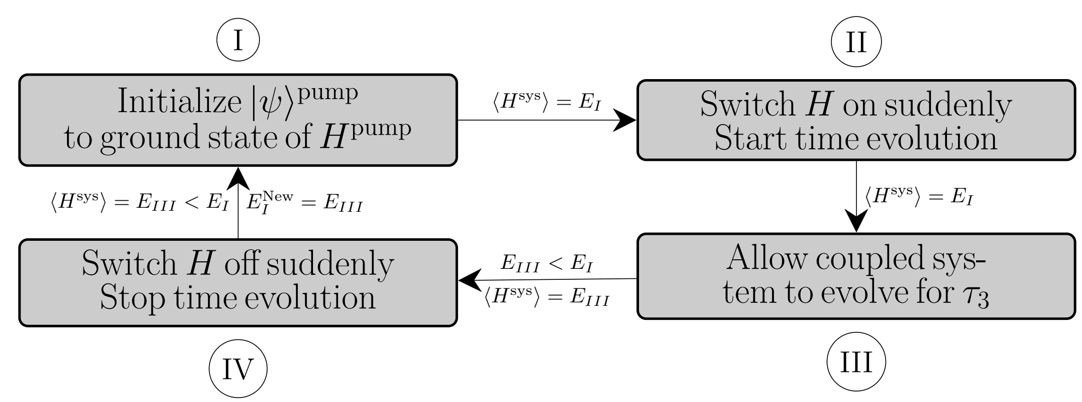
Cohen, Lamm, Lawrence, and Yamauchi, Phys. Rev. D 104, 094514 (2021).



How to define energy-momentum tensor in Hamiltonian formulation



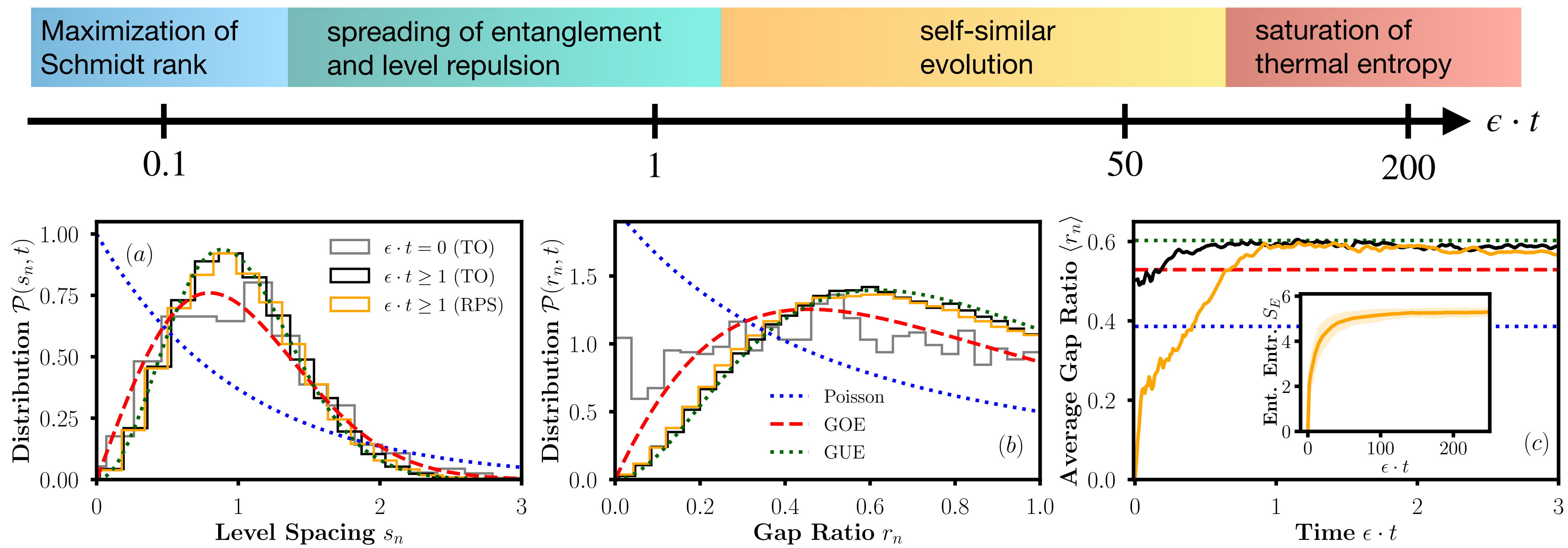
How to prepare a proton state? [Generally not developed sufficiently.]



EMERGING UNDERSTANDING OF THERMALIZATION IN SIMPLE GAUGE THEORIES

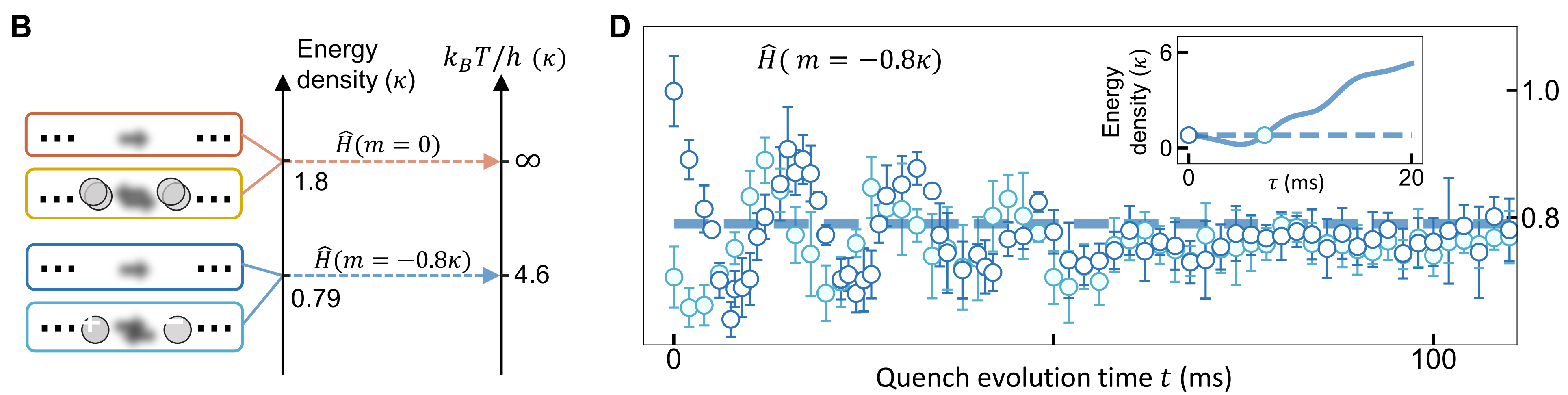
Numerical study of Z_2 LGT in 2+1 D

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



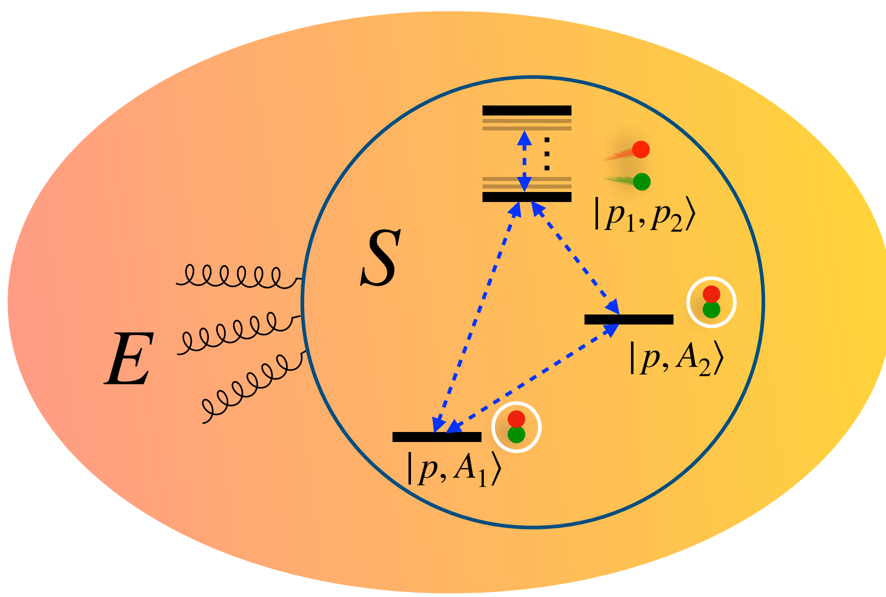
Quantum Link Model in a 70-site analog simulator

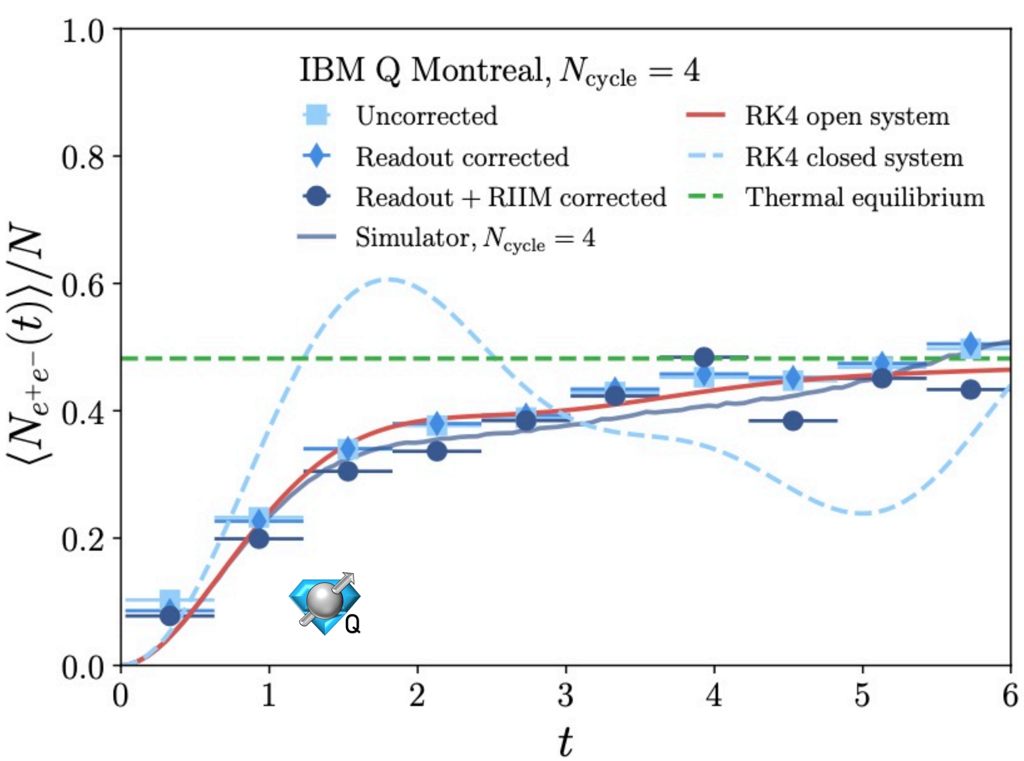
***Zhou et al, Science* 377 (2022) 6603.**



OPEN QUANTUM SYSTEMS AND NON-EQUILIBRIUM PROPERTIES

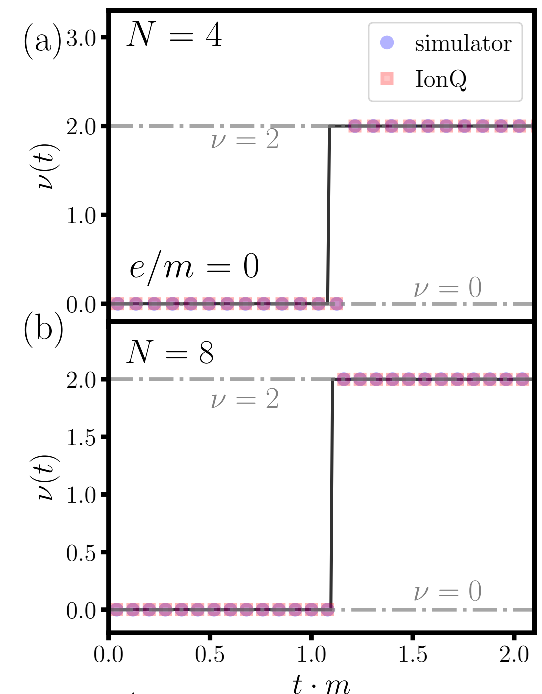
Open quantum system dynamics: $q\bar{q}$ moving in medium

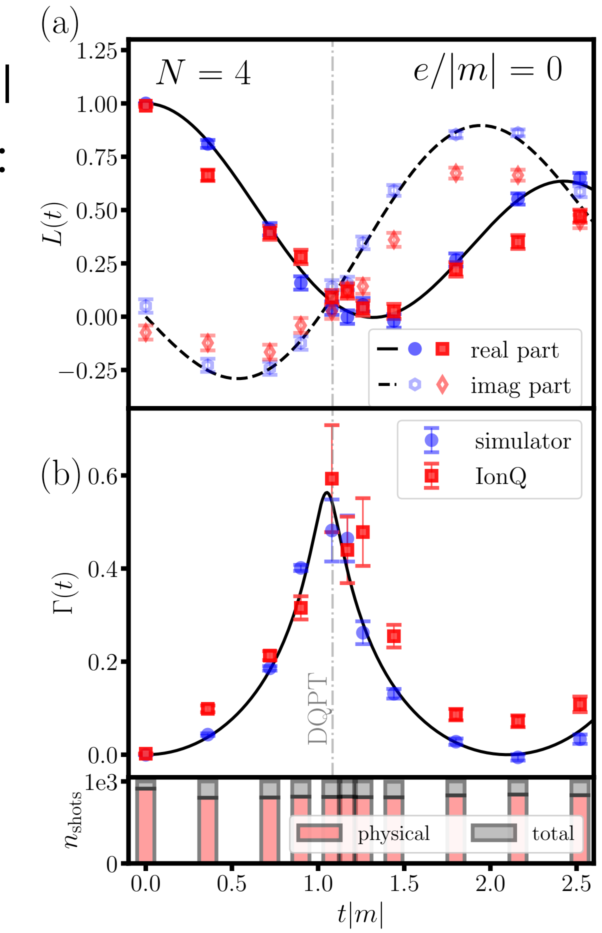




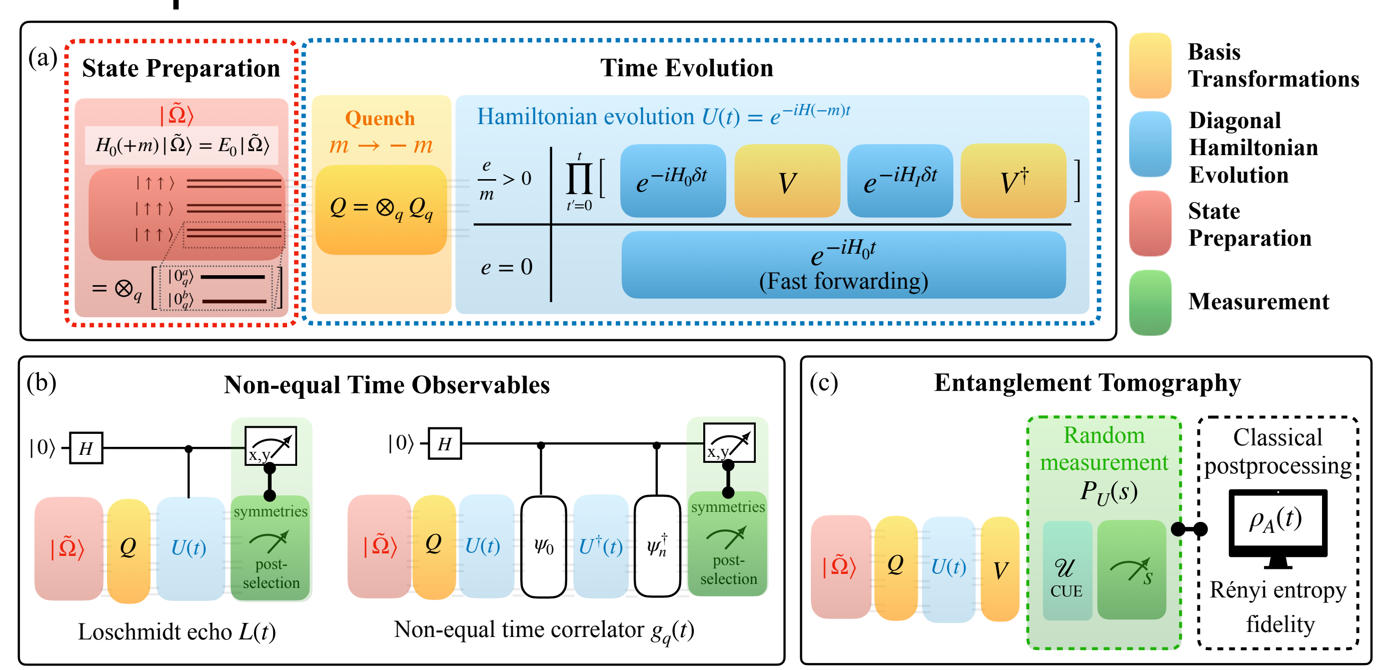
de Jong, Metcalf, Mulligan, Ploskon, Ringer, and, Yao, *Phys.Rev.D* 104 (2021) 5, 051501. See also Lee, Mulligan, Ringer, Yao, arXiv:2308.03878 [quant-ph].

A dynamical quantum phase transition in the Schwinger model with an IonQ quantum computer:



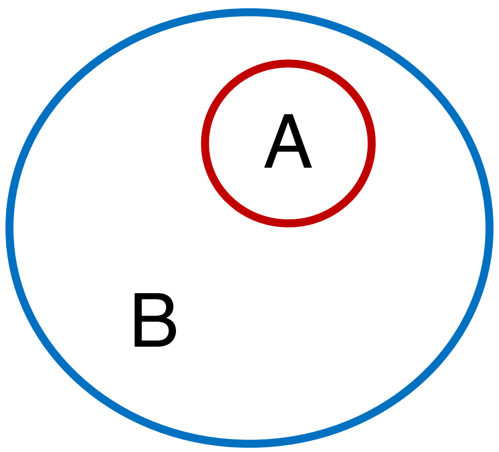


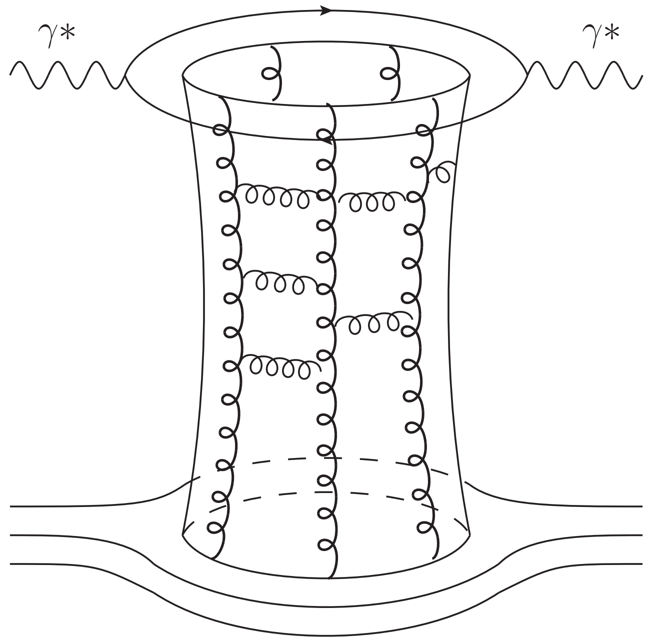
Mueller, Carolan, Connelly, ZD, Dumitrescu, Yeter-Aydeniz, PRX Quantum 4 (2023) 3.



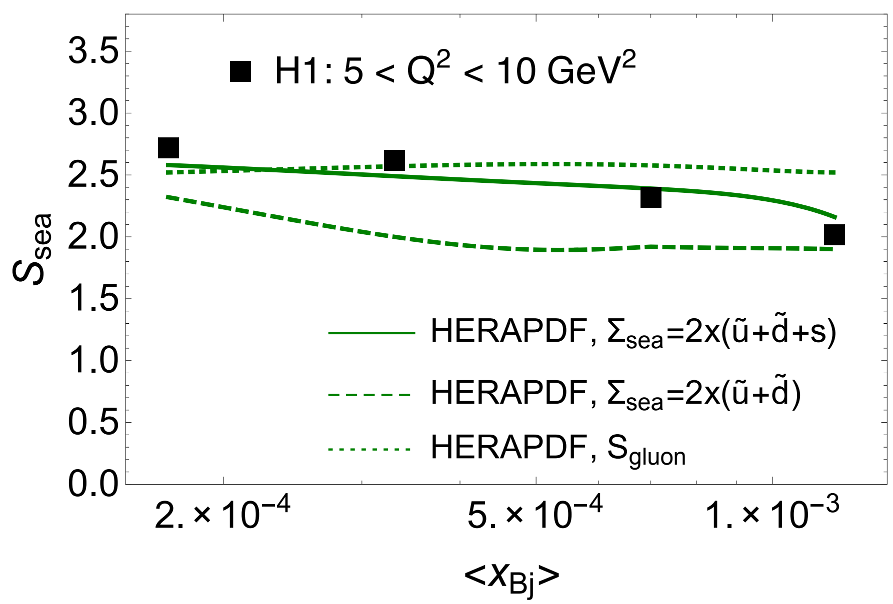
QUANTUM ENTANGLEMENT IN HIGH- AND LOW-ENERGY NUCLEAR PHYSICS

Deep inelastic scattering as a probe of entanglement?



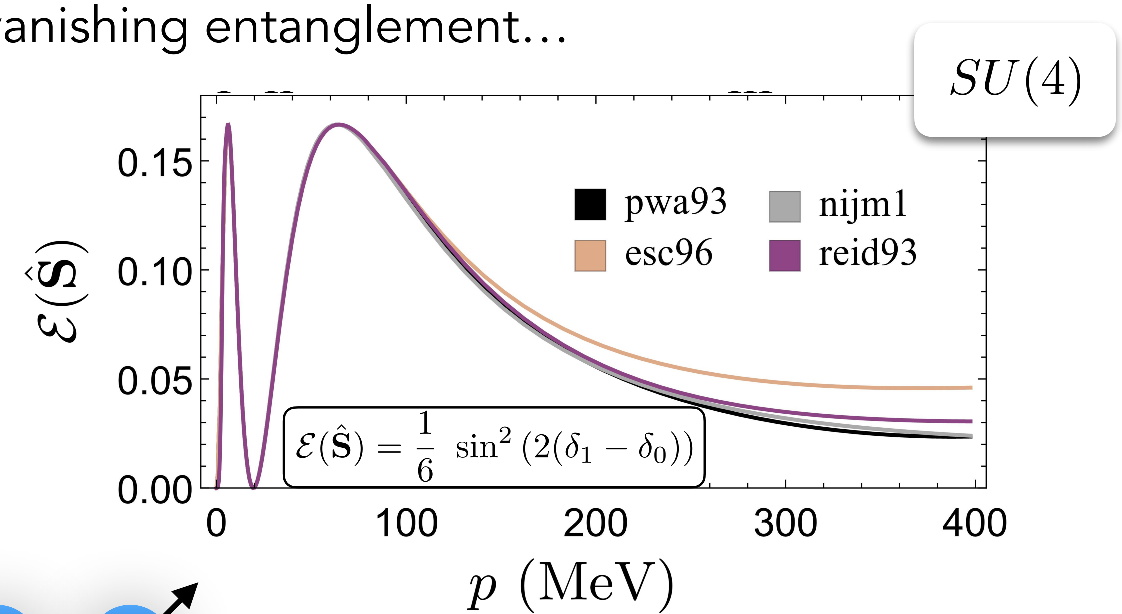


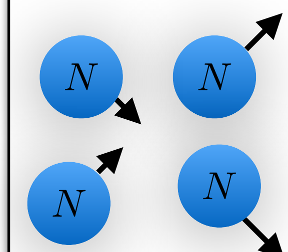
Entropy of hadrons derived from PDFs can be related to entanglement entropy.



Kharzeev and Levin,, Phys. Rev. D 95, 114008 (2017), Zhang, Hao, Kharzeev, and Korepin, Phys. Rev. D 105, 014002 (2022).

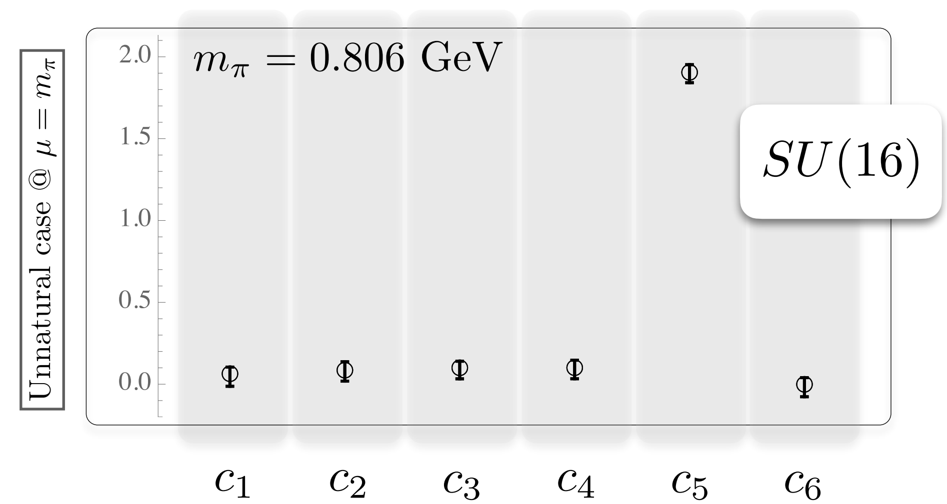
NN interactions at low energies are consistent with vanishing entanglement…

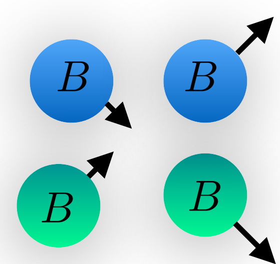




Beane, Kaplan, Klco and Savage, Phys. Rev. Lett. 122, 102001 (2019), see also Liu, Low, Mehen, Phys. Rev. C 107 (2023) 2, 025204.

…as are low-energy BB interactions as obtained with lattice QCD.

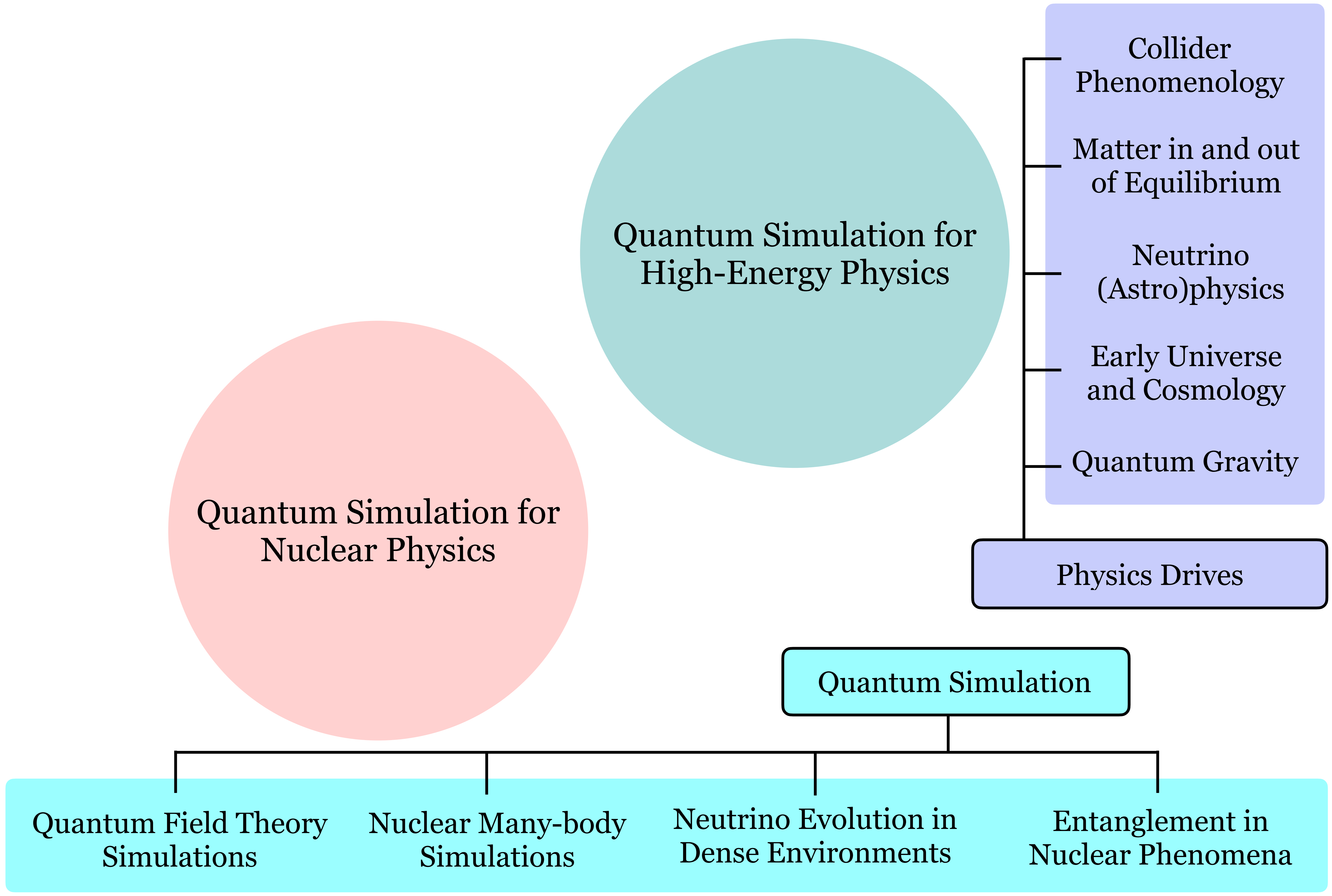




Wagman, Winter, Chang, ZD, Detmold, Orginos, Savage, Shanahan (NPLQCD),Phys. Rev. D 96, 114510 (2017)

SUMMARY

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



THANK YOU