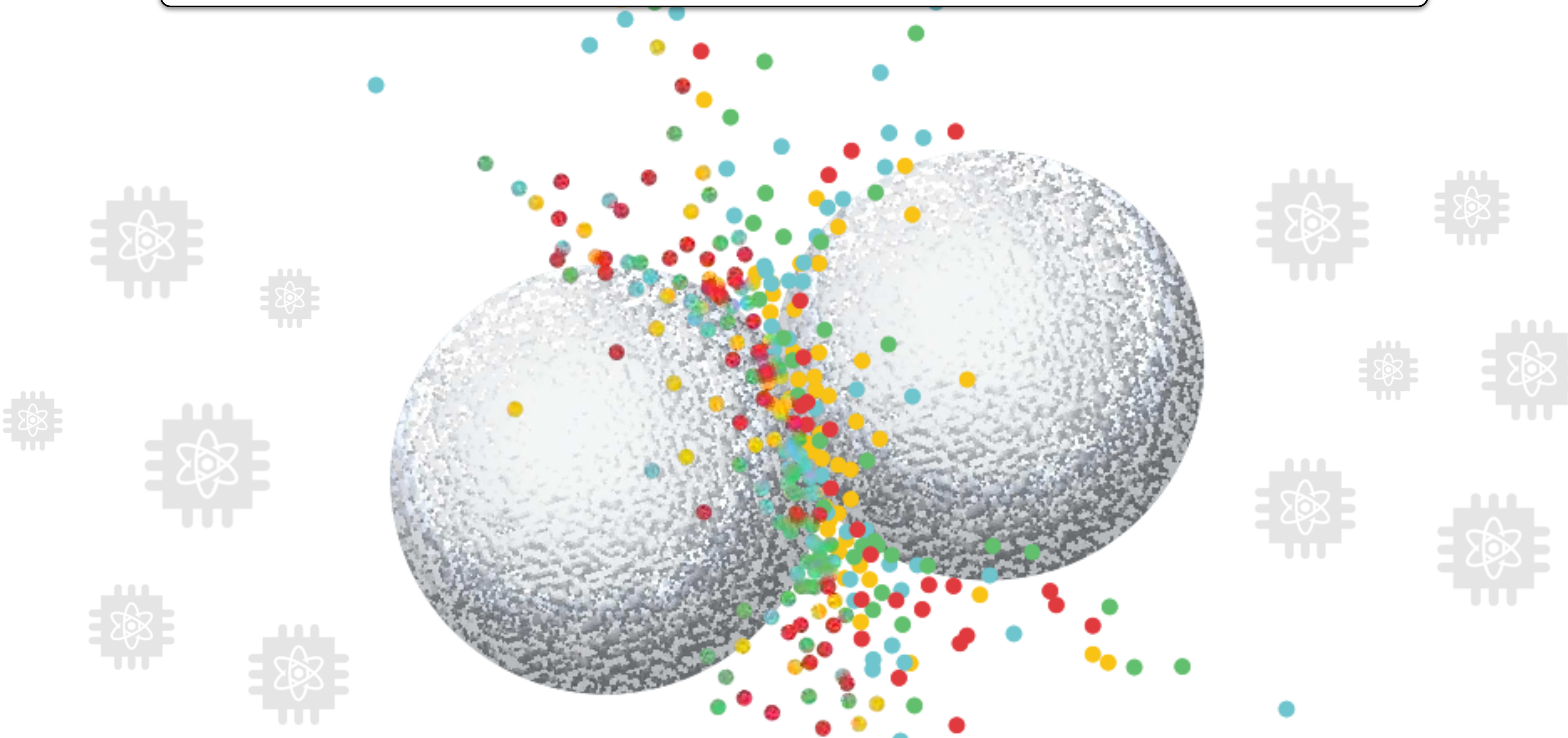
QUANTUM COMPUTATION OF LATTICE GAUGE THEORIES (PART III)

ZOHREH DAVOUDI
University of Maryland, College Park

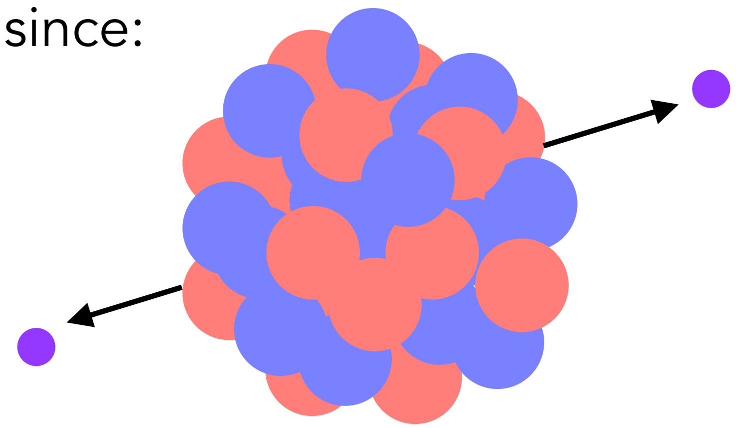


DTP-TALENT COURSE ON QUANTUM COMPUTING FOR NUCLEAR PHYSICS
ECT*, TRENTO, ITALY
JUNE 2025

WHAT ARE CLASSICALLY INTRACTABLE PROBLEMS IN NUCLEAR PHYSICS?

LIMITS OF CLASSICAL SIMULATIONS OF QUANTUM SYSTEMS IN NP/HEP

i) First-principles simulations of nuclei are hard since:



- The complexity of systems grows factorially with the number of quarks.
- There is a severe signal-to-noise degradation in Euclidean Monte Carlo simulations.
- Excitation energies of large nuclei are tiny compared to the QCD scale.

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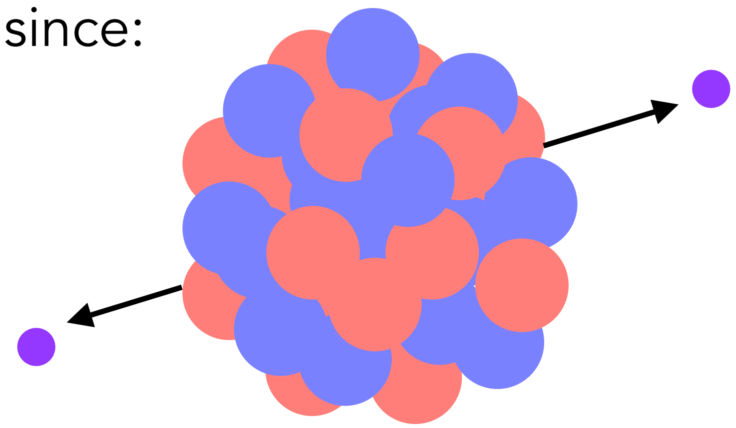

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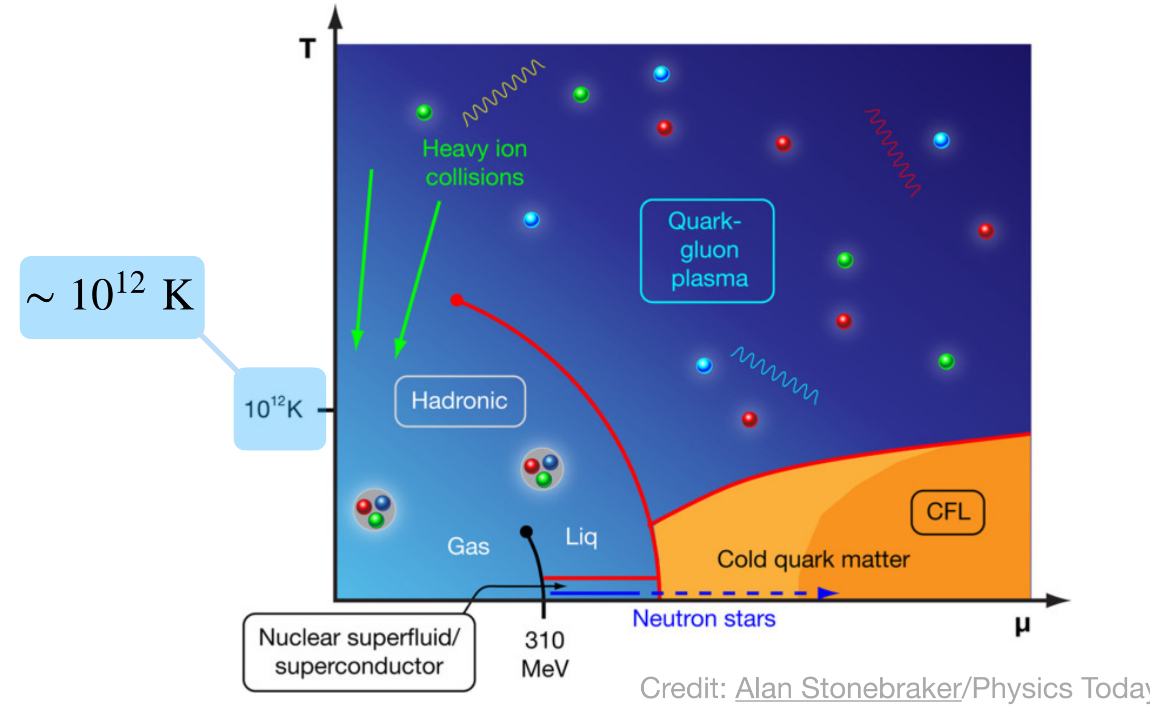
ii) Studies of dense matter, phase diagram of strong interactions not yet fully feasible.



Credit: Alan Stonebraker/Physics Today

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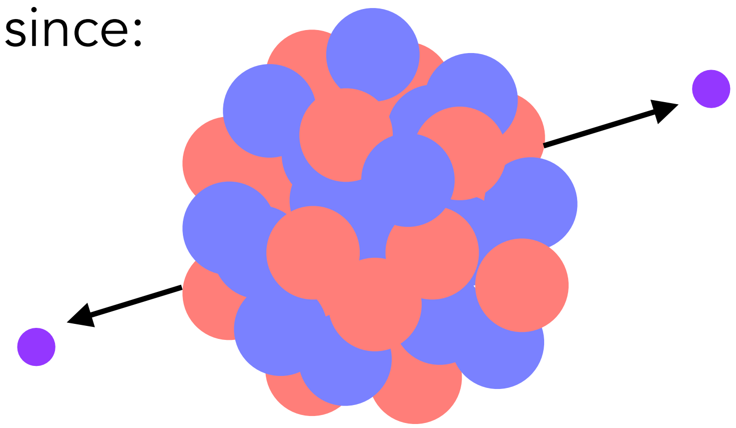

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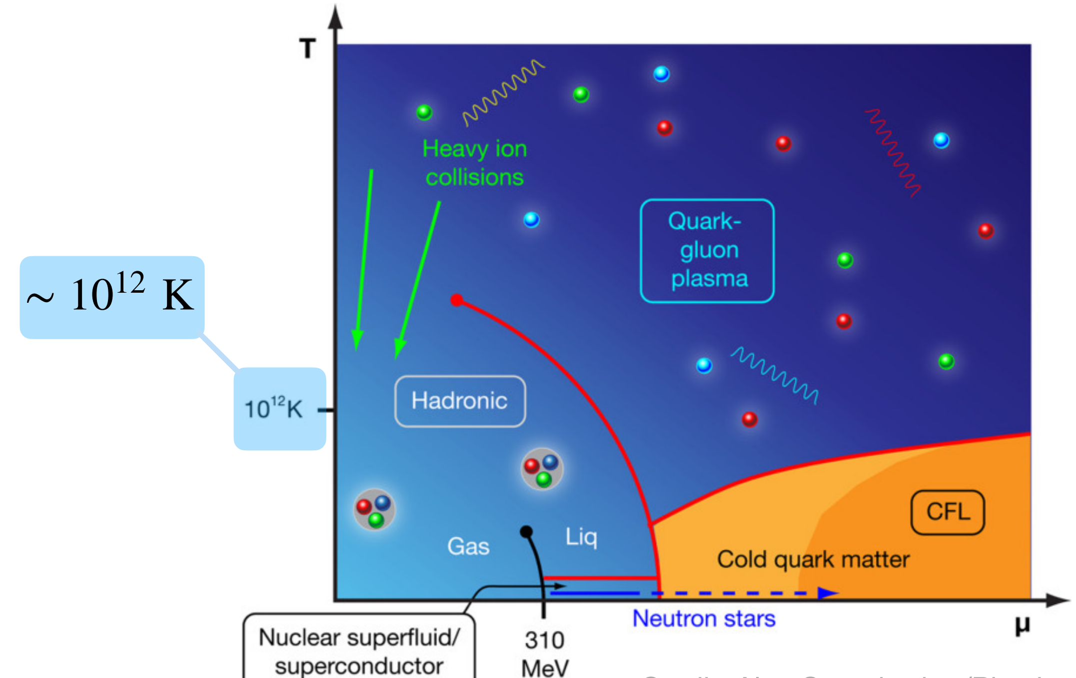

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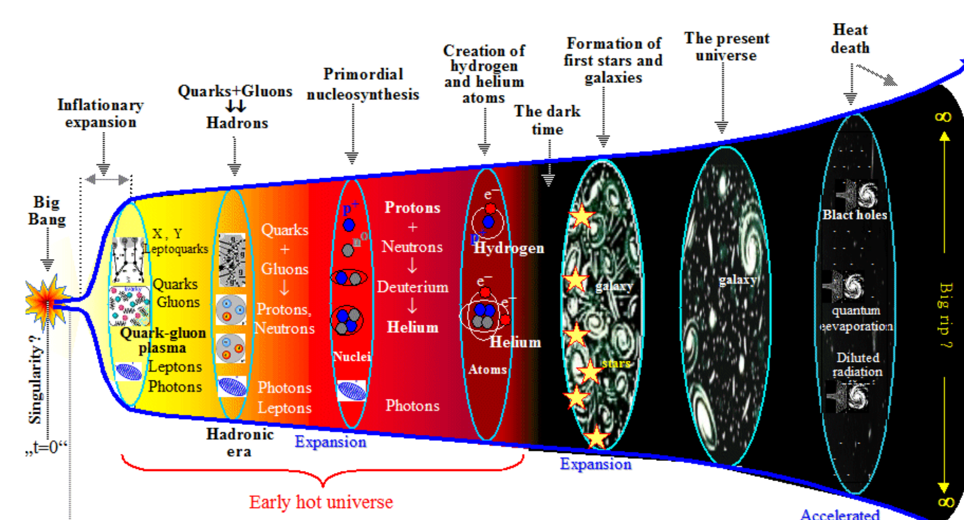
iii) Real-time dynamics of matter, dynamical response functions, transport properties, structure functions, not fully accessible.



Credit: https://astronuclphysics.info

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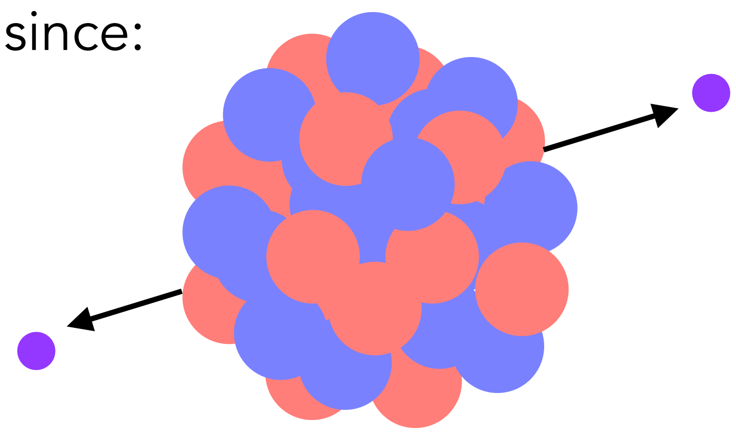

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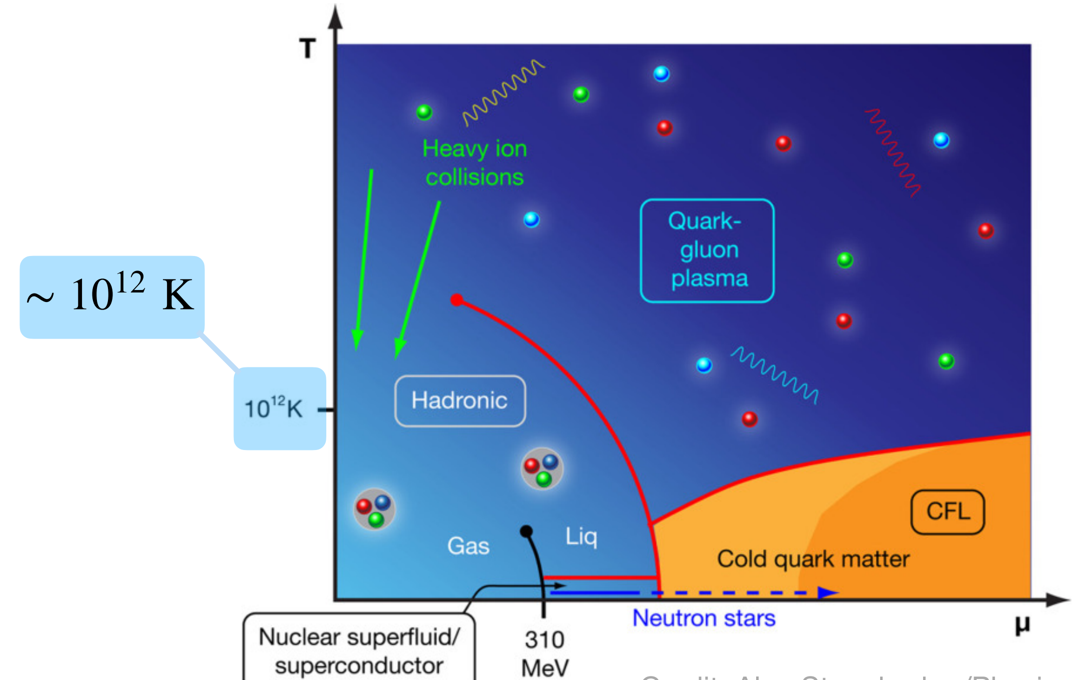

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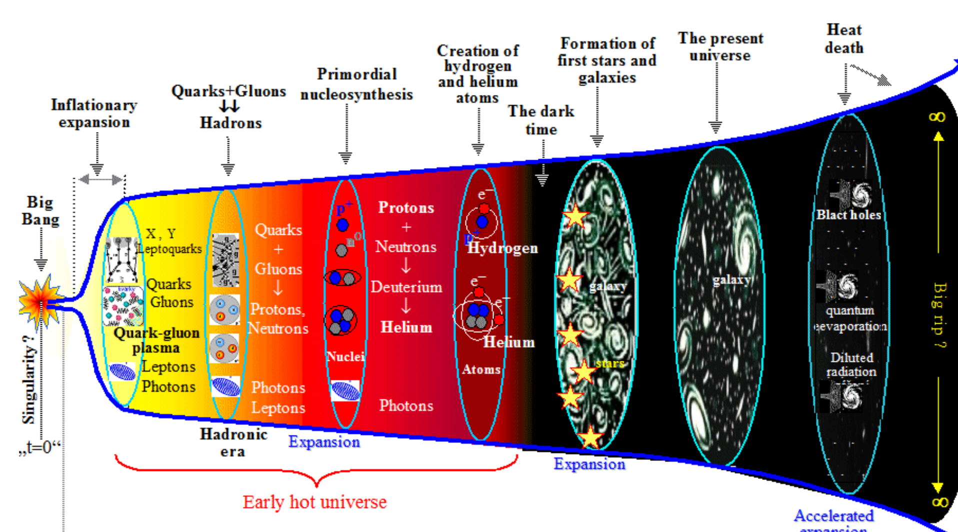
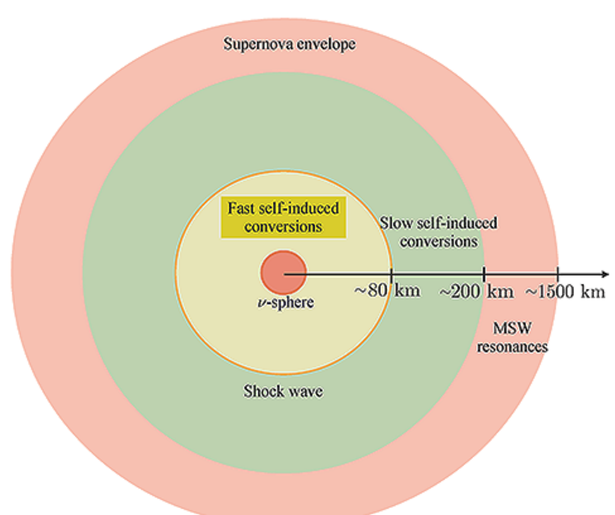


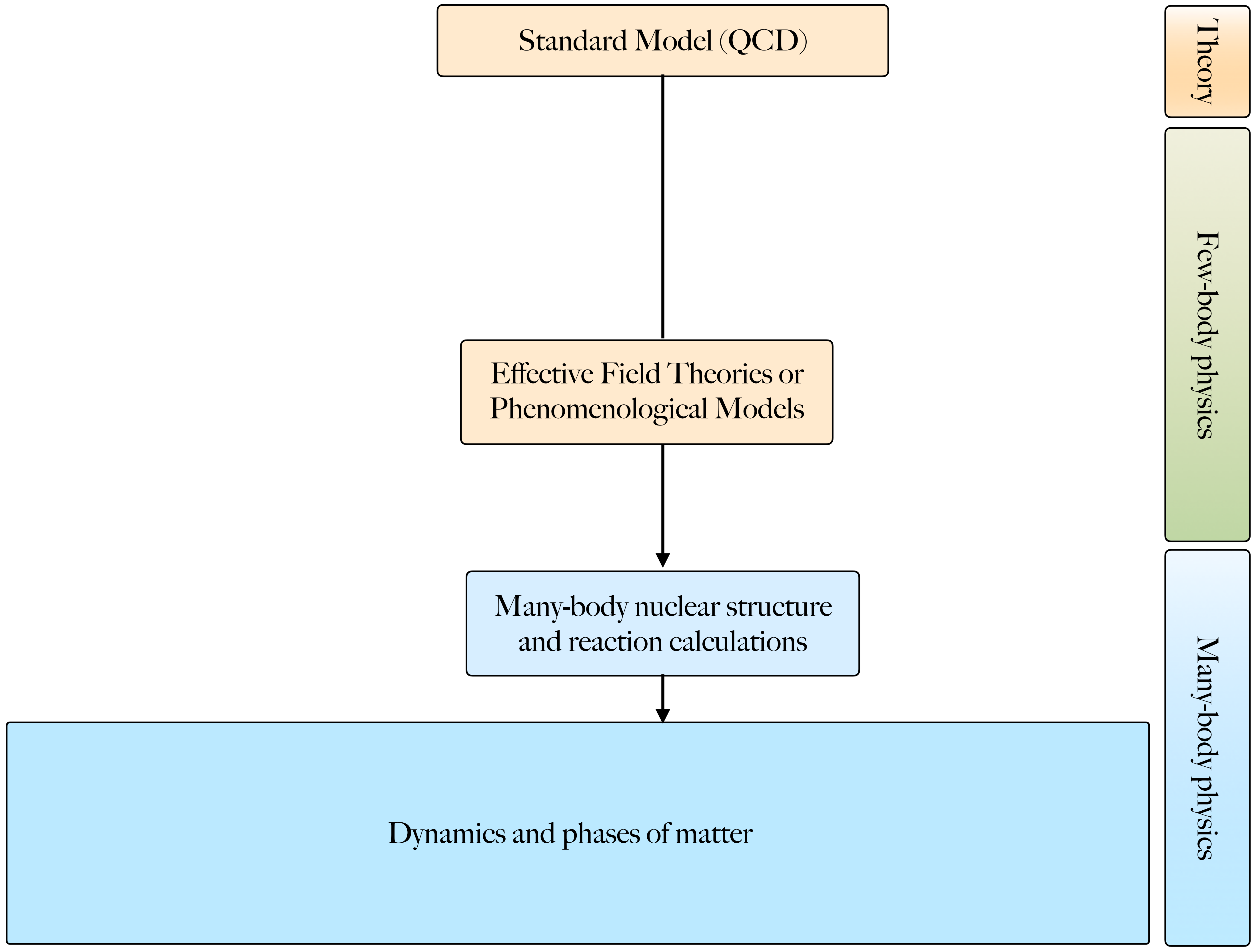
Credit: https://astronuclphysics.info

iv) Accurately predicting the role of neutrinos in dense astrophysical environments and supernovae evolution is challenging.

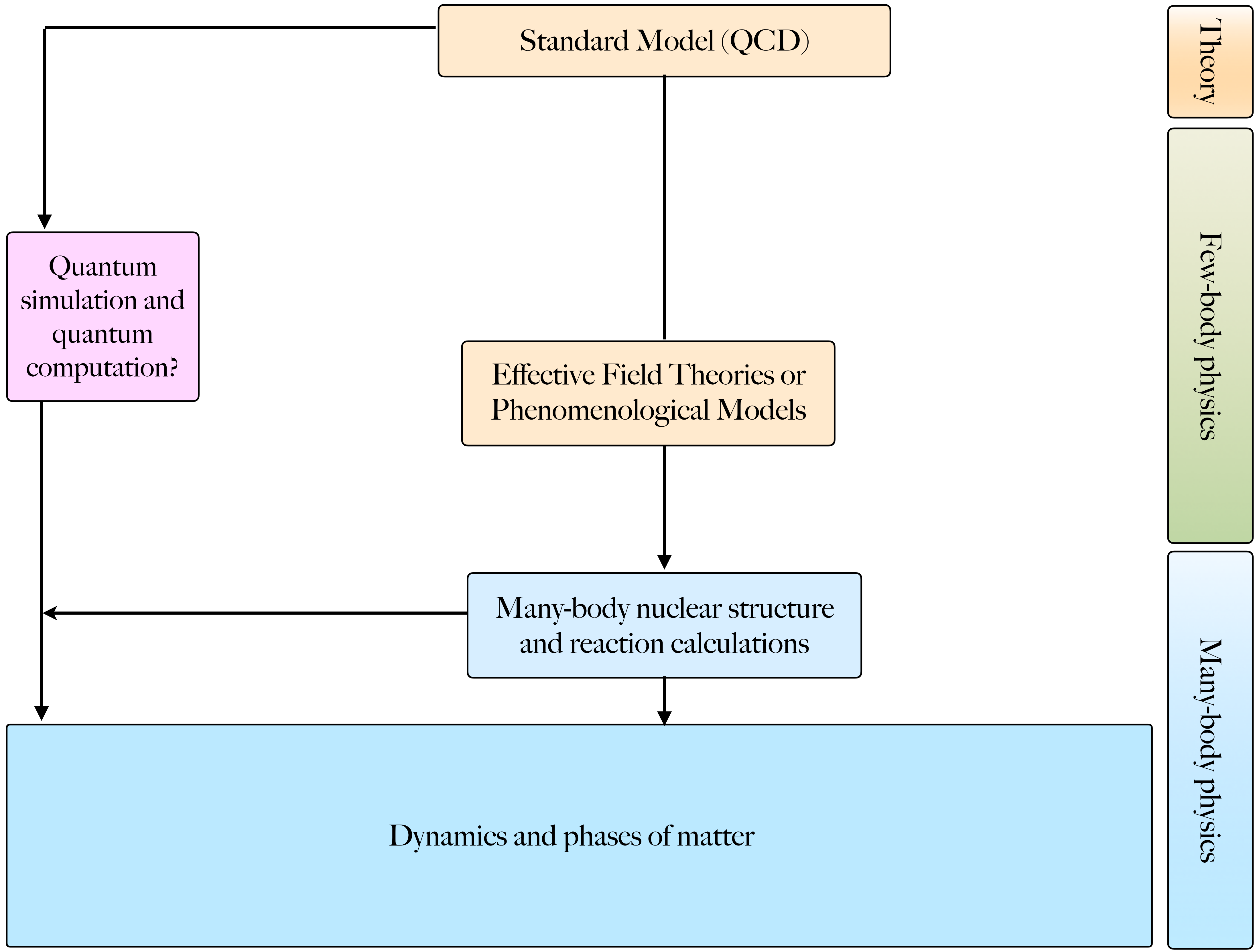


Credit: Armstrong et al /INT/UW

A NUCLEAR/PARTICLE PHYSICS ROADMAP



A NUCLEAR/PARTICLE PHYSICS ROADMAP FOR LEVERAGING QUANTUM TECHNOLOGIES



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

SO HOW MUCH DOES IT COST TO QUANTUM COMPUTE QCD DYNAMICS?

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

Science 336, 6085 1130-1133 (2012).

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

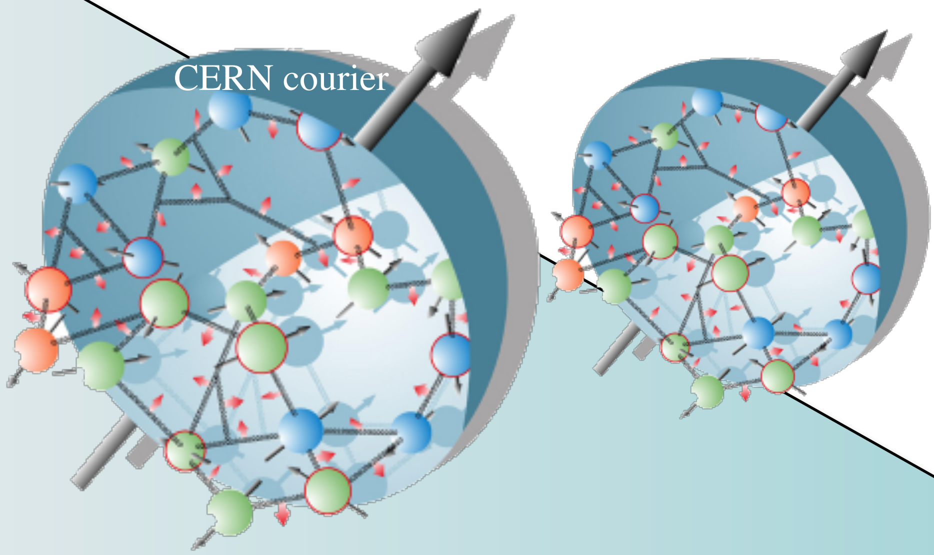
Byrnes and Yamamoto, Phys.Rev. A73 (2006) 022328.
Shaw, Lougovski, Stryker, Wiebe, Quantum 4, 306 (2020).
Ciavarella, Klco, and Savage, Phys. Rev. D 103, 094501 (2021).
Kan and Nam, arXiv:2107.12769 [quant-ph].
Lamm, Lawrence, and Yamauchi, *Phys.Rev.D* 100 (2019) 3, 034518.
Paulson *et al, PRX Quantum* 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, PRX Quantum 5:040347 (2024).
Lamm et al, arXiv:2405.12890 [hep-lat].

Second-order product formula
Non-local fermion encoding

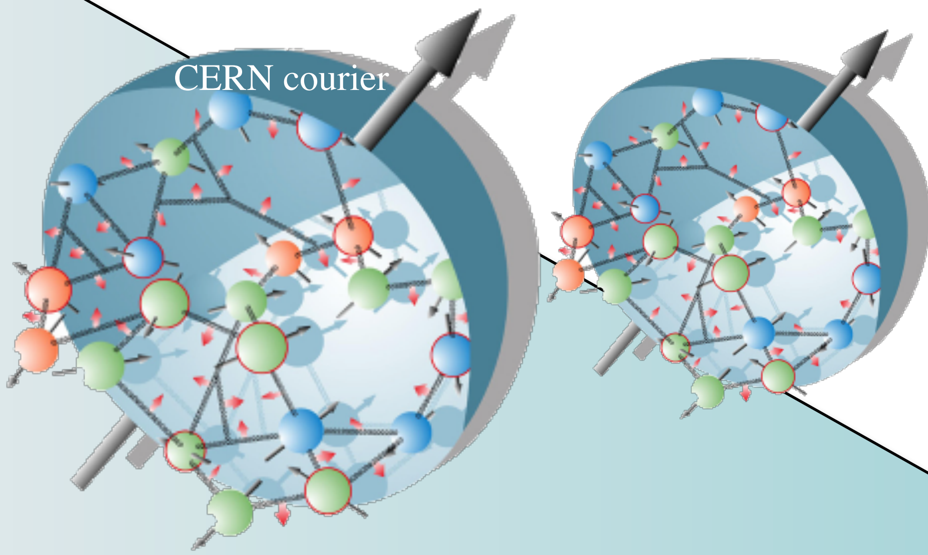
$O(10^{53})$ T gates

Kan, Nam (2021)

Time evolving under QCD in a $10 \times 10 \times 10$ lattice at fixed parameters with error 10^{-3} (10^{10} qubits).



Starting from the Standard Model



$O(10^{53})$ T gates

Kan, Nam (2021)

$O(10^{39})$ T gates

ZD, Stryker (2025)

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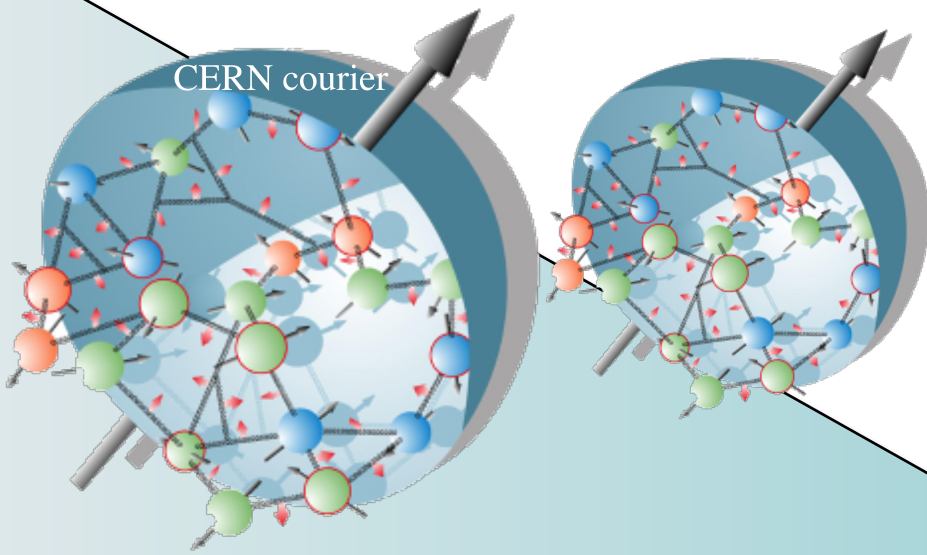
Second-order product formula (better term decomposition)

Non-local fermion encoding

Starting from the Standard Model



Starting from the Standard Model

$O(10^{53})$ T gates

`Kan, Nam (2021)`

⇩

$O(10^{39})$ T gates

`ZD, Stryker (2025)`

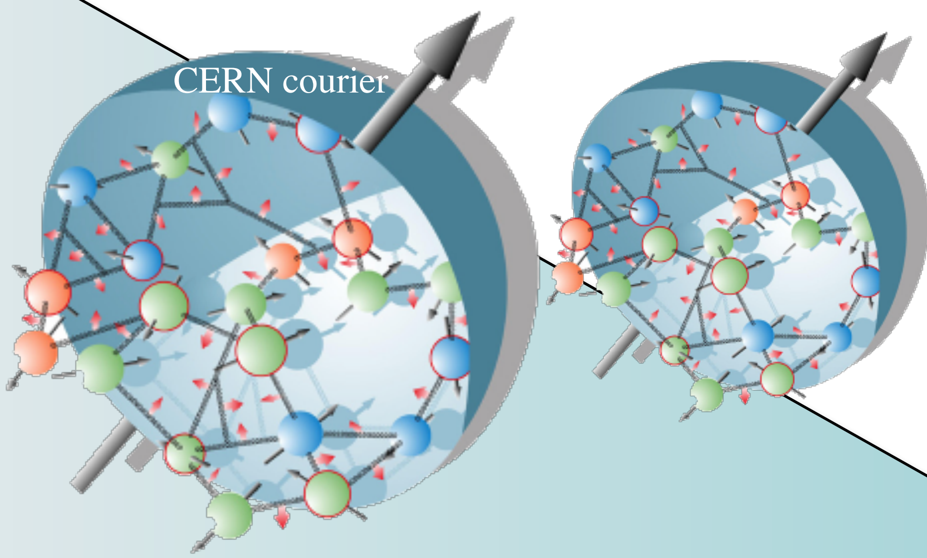
⇩

$O(10^{28})$ T gates

`Rhodes, Kreshchuk, Pathak (2024)`

Time evolving under QCD in a $10 \times 10 \times 10$ lattice at fixed parameters with error 10^{-3} (10^{10} qubits).

Near-optimal time-evolution algorithms
Local fermion encoding



Starting from the Standard Model

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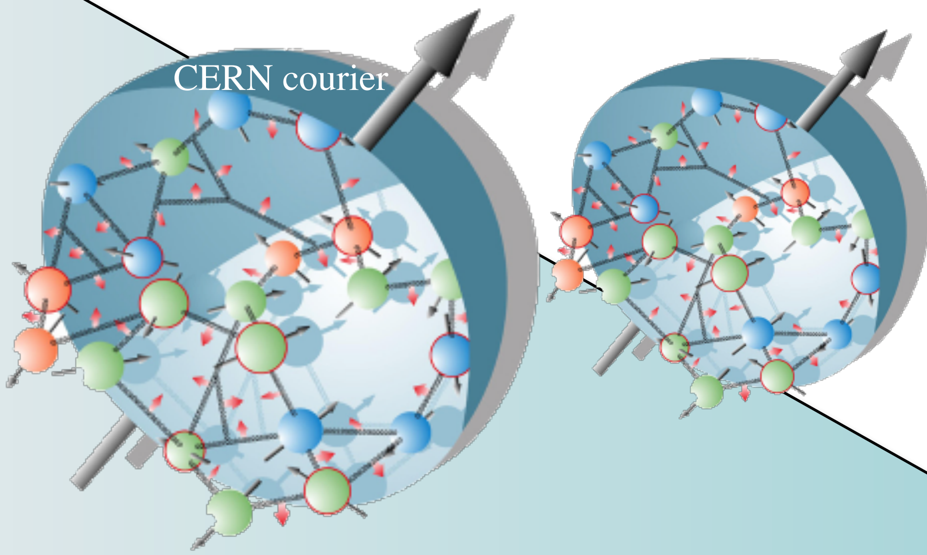


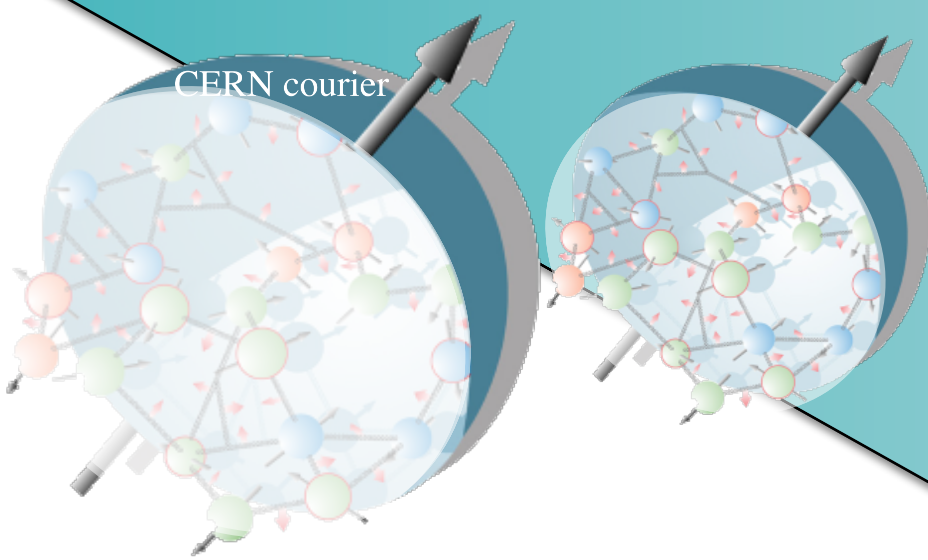
Starting from the Standard Model

Classically:

$\mathcal{O}(10^{18})$ floating-point operations per second

$\mathcal{O}(10^{15})$ bytes of memory

HOW MUCH DOES IT COST TO
INSTEAD QUANTUM COMPUTE
NUCLEAR EFFECTIVE FIELD THEORIES?



Starting from the nuclear Hamiltonian

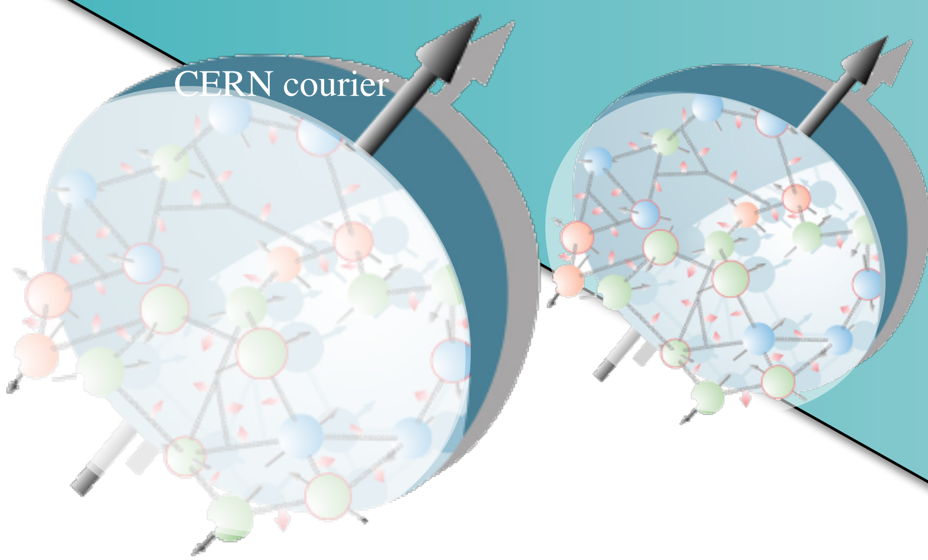
Time evolving an A=40 nucleus under pionless EFT in a $10 \times 10 \times 10$ lattice at fixed parameters with error 10^{-1} (10^4 qubits).

$O(10^{11})$ CNOT depth

Roggero, Li, Carlson, Gupta, Perdue (2020)

Second-order product formula
Non-local fermion encoding

Starting from the nuclear Hamiltonian



Second-order product formula (better error bounds)
Local fermion encoding

$O(10^7)$ CNOT depth

`Watson, Bringewatt, Shaw, Childs, Gorshkov, ZD (2023)`

⇧

$O(10^{11})$ CNOT depth

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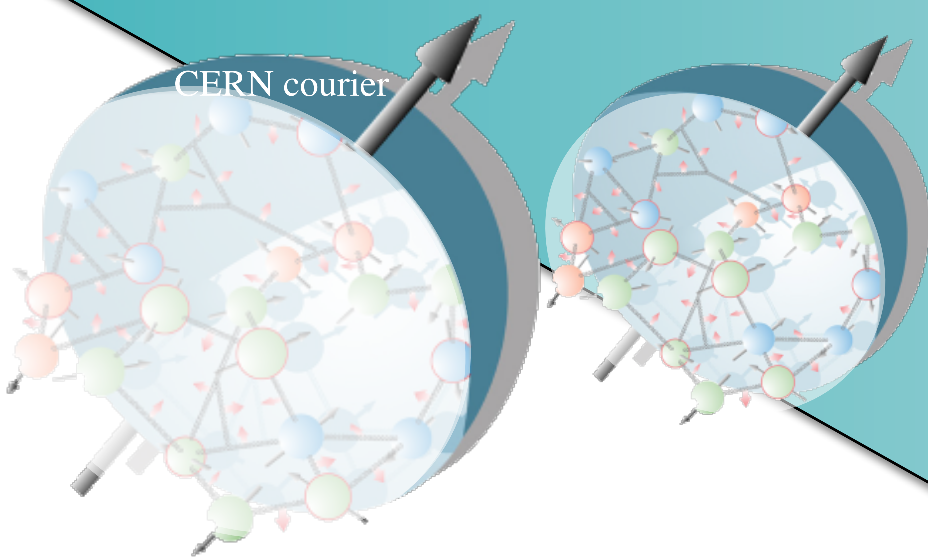

?

$\Uparrow$

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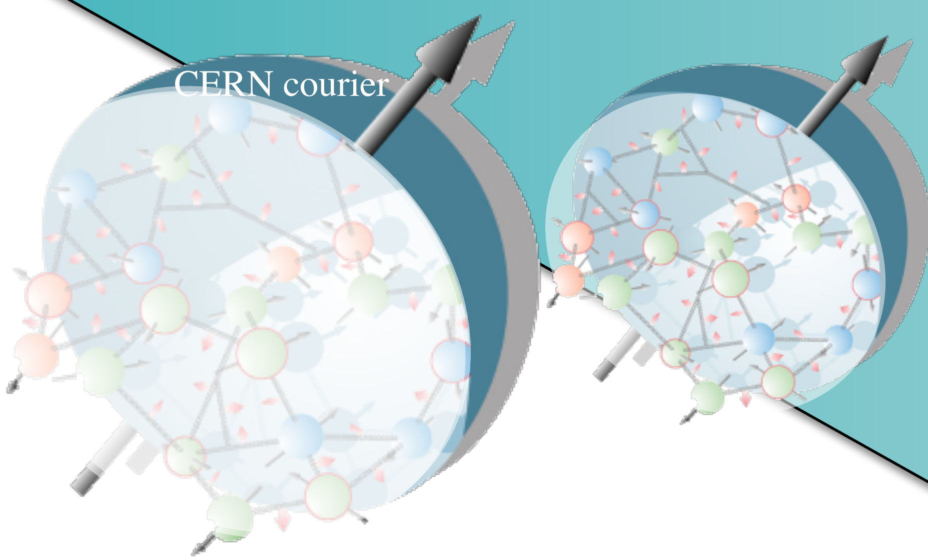


?

⇧

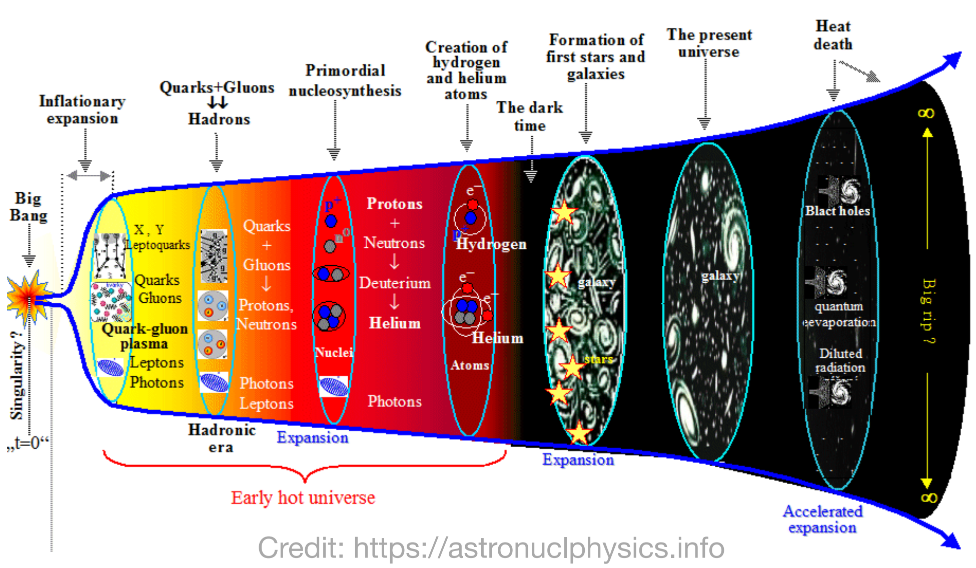
$O(10^{20})$ CNOT depth

Watson, Bringewatt, Shaw, Childs, Gorshkov, ZD (2023)

Time evolving an A=40 nucleus under LO chiral EFT in a $10 \times 10 \times 10$ lattice at fixed parameters with error 10^{-1} (10^4 qubits).

EXAMPLES OF PROGRESS IN REAL-TIME NONEQUILIBRIUM EXPLORATIONS WITH QUANTUM COMPUTERS

Evolution of matter?

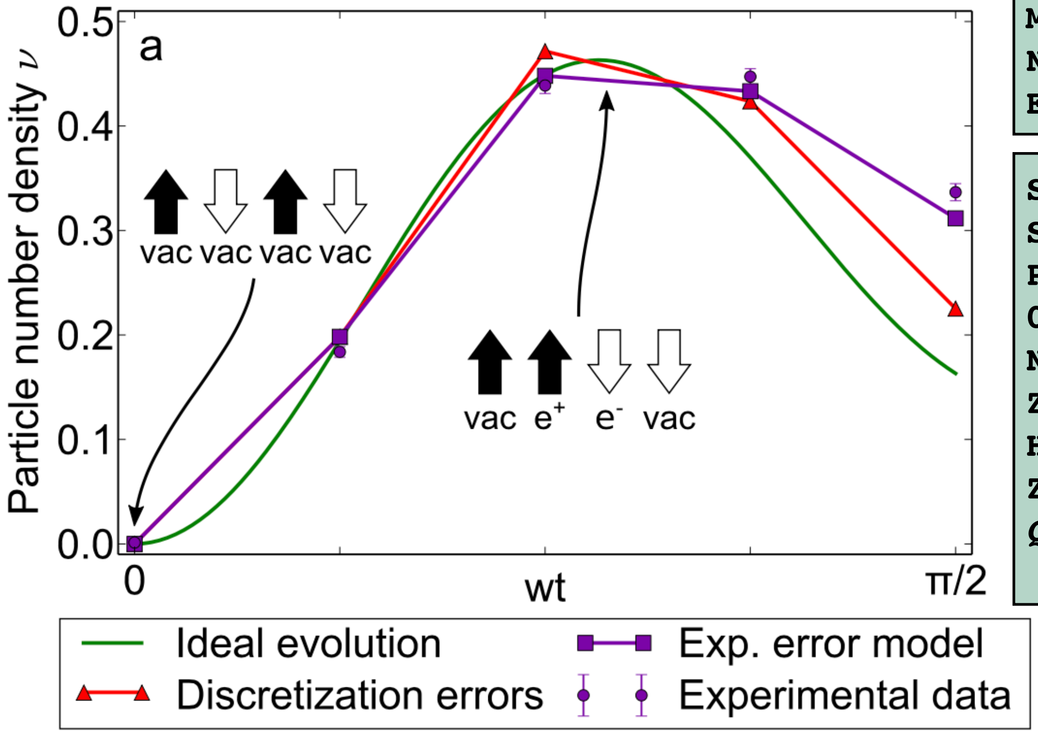


Credit: https://astronuclphysics.info

REAL-TIME EVOLUTION AND QUENCH DYNAMICS IN LATTICE GAUGE THEORIES

universität innsbruck

Real-time dynamic of lattice Schwinger model



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

See also: Klco, Savage, et al, Phys. Rev. A 98, 032331 (2018), Nguyen, Tran, Zhu, Green, Huerta Alderete, ZD, Linke, *PRX Quantum* 3 (2022) 2, 020324.

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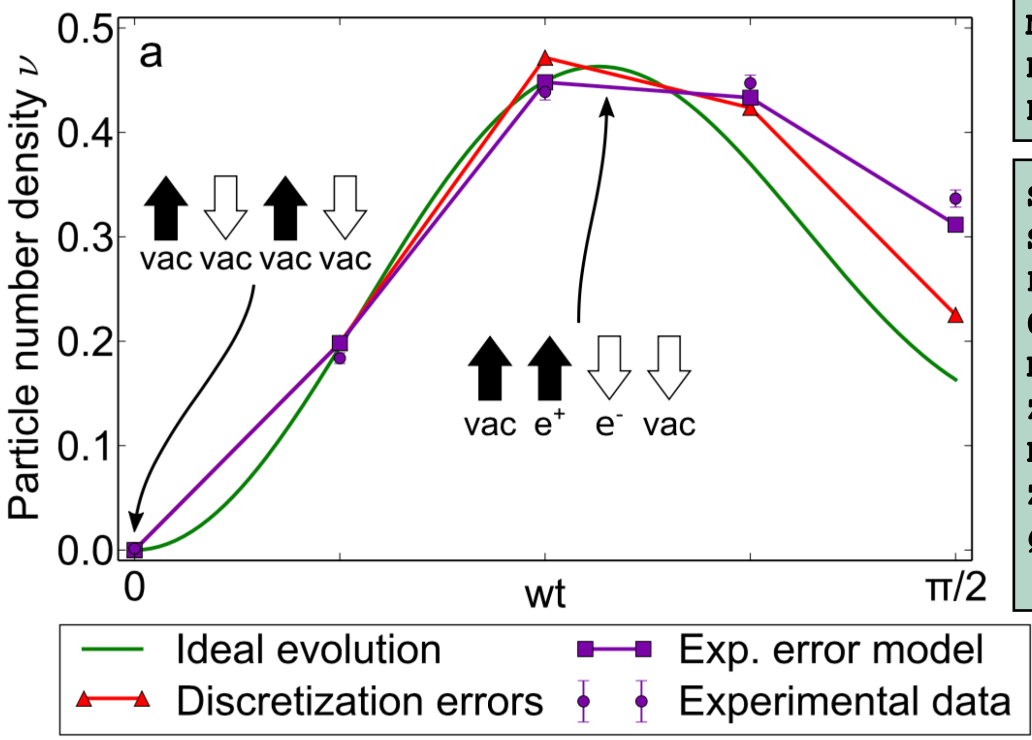

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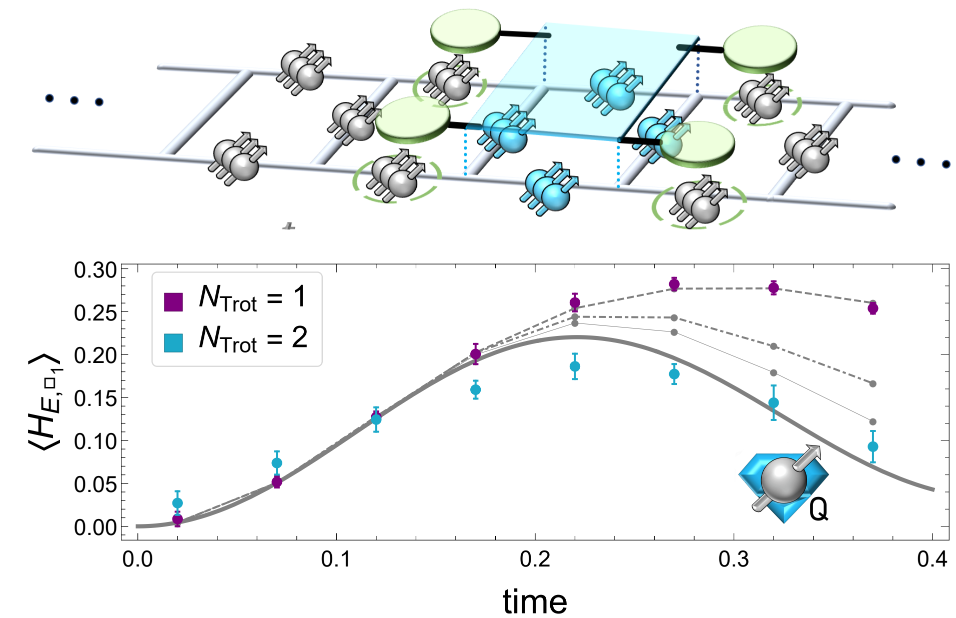
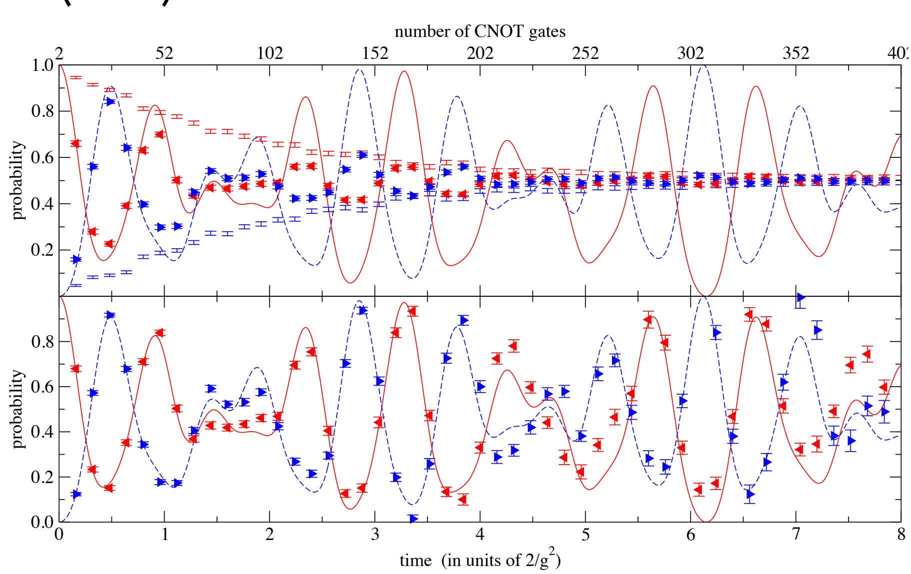
Real-time dynamic of pure (2+1)D SU(2) with global irreps



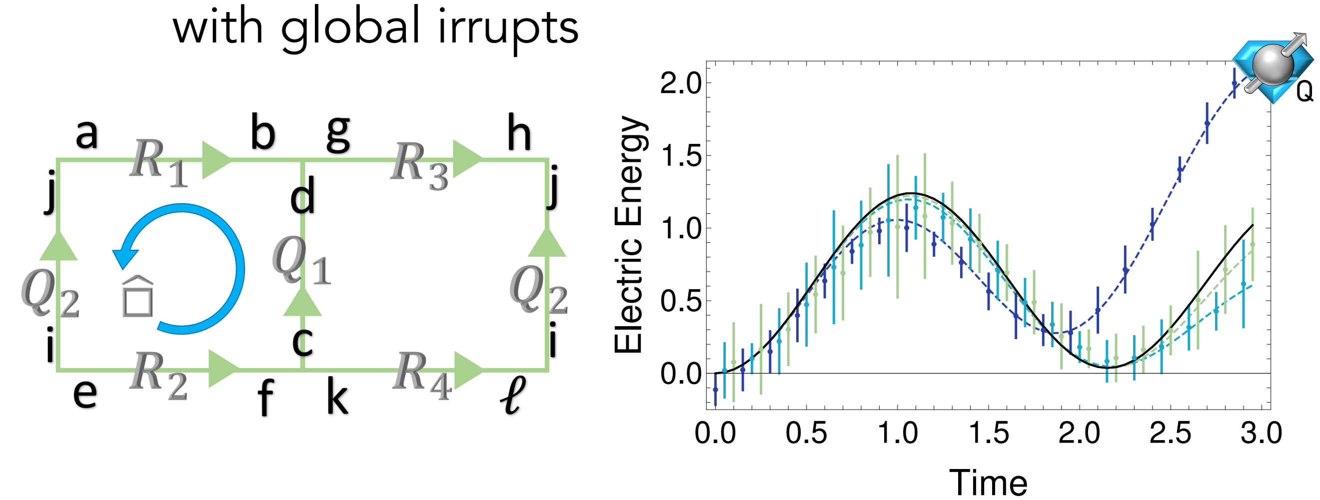
Klco, Savage, and Stryker, Phys. Rev. D 101, 074512 (2020).

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

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



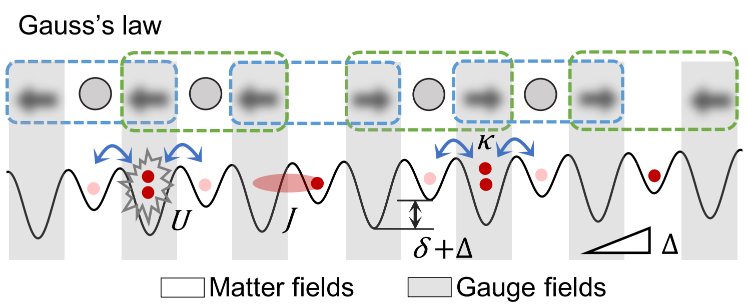
Real-time dynamic of pure (2+1)D SU(3) with global irrupts



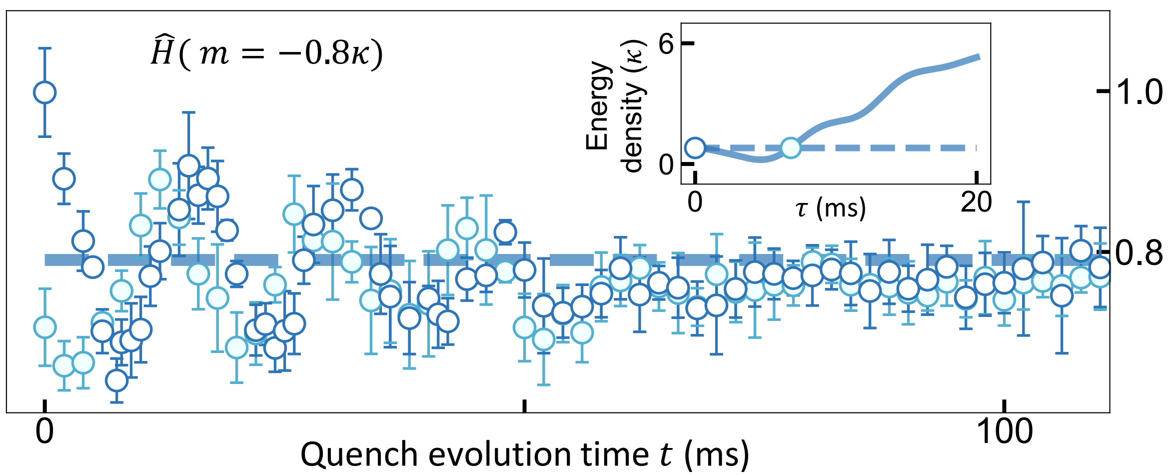
Ciavarella, Klco, and Savage, Phys. Rev. D 103, 094501 (2021).

THERMALIZATION AND NON-EQUILIBRIUM PROPERTIES

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



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



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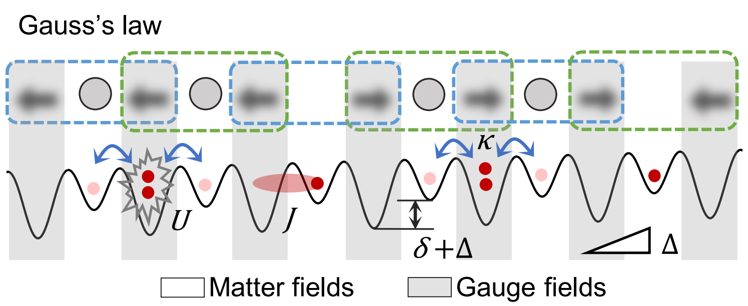

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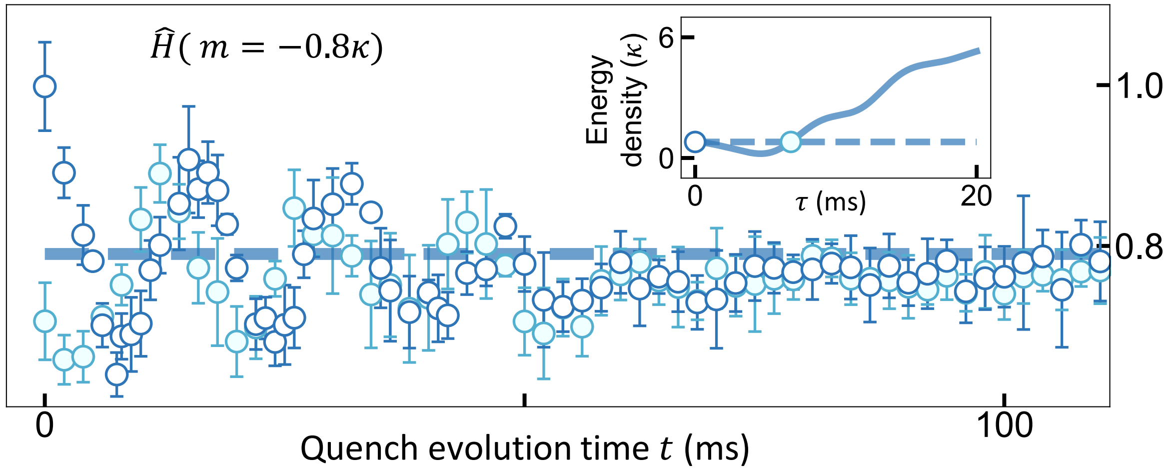
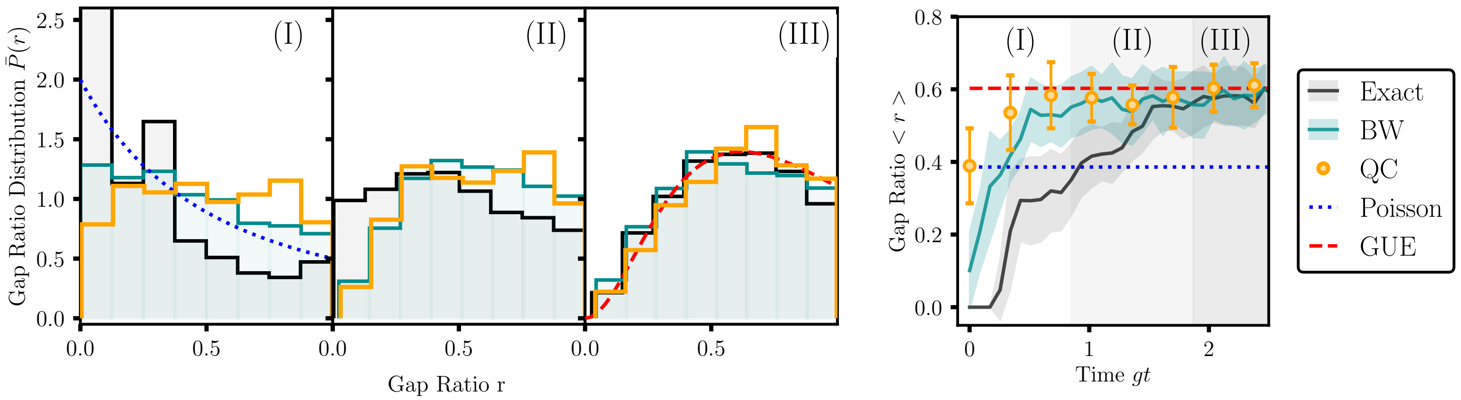


Stages of thermalization dynamics of Z_2 LGT in (2+1)D from entanglement spectrum



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

Experimental demonstration with trapped ions:

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

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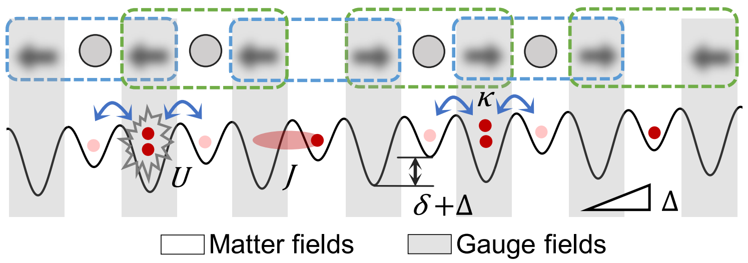

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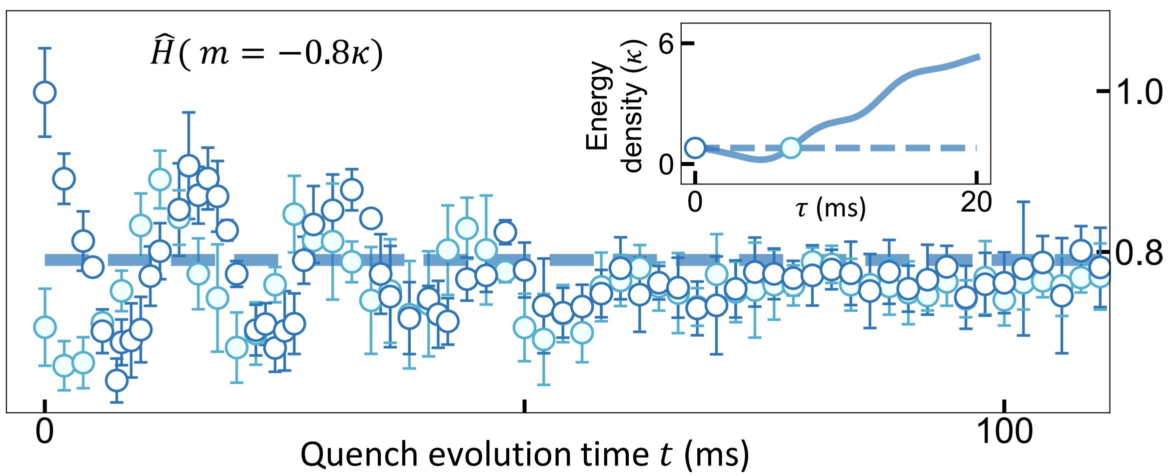
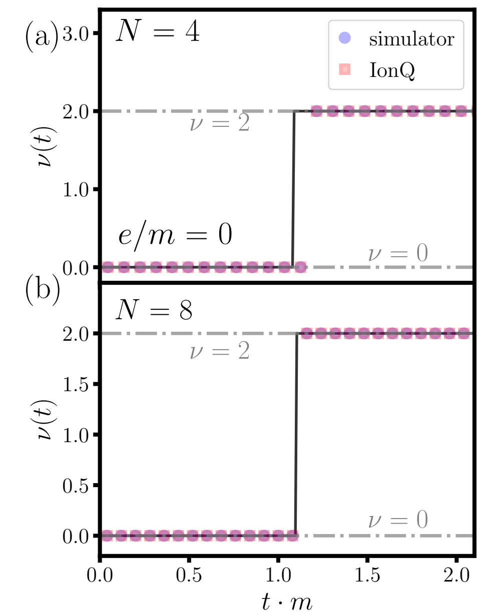
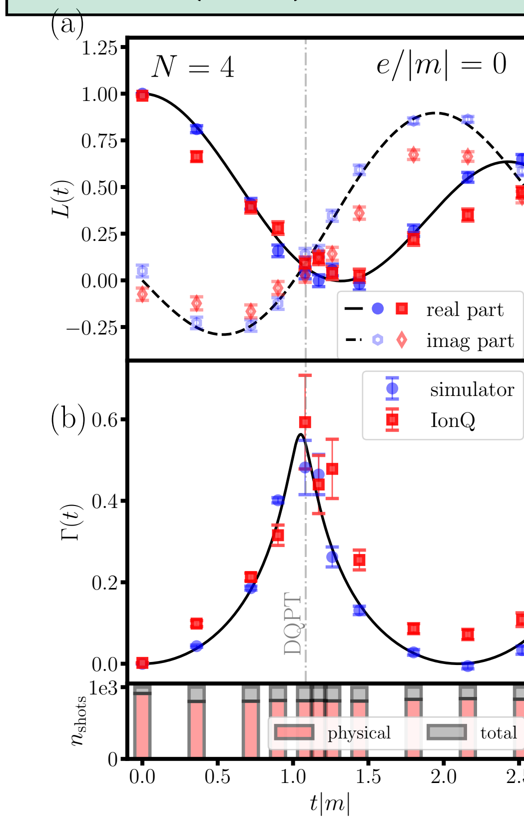


A dynamical phase transition and topological order in lattice Schwinger model

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.

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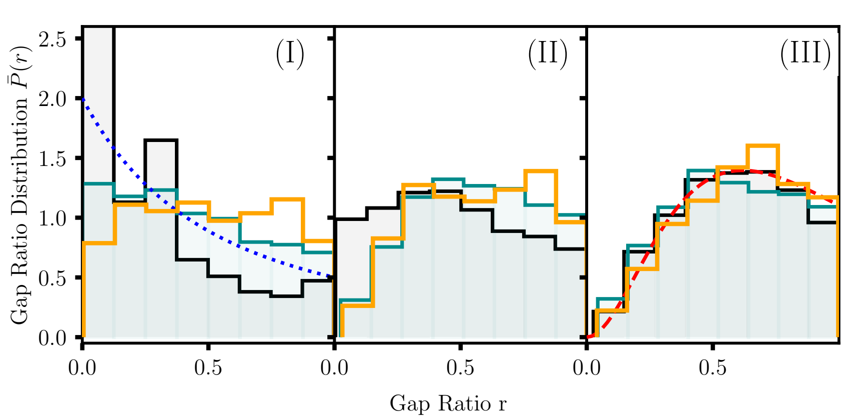

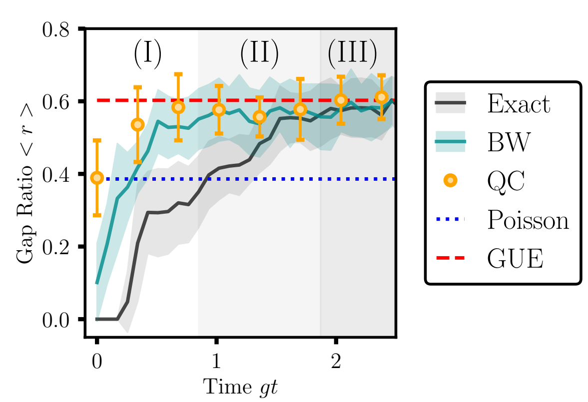

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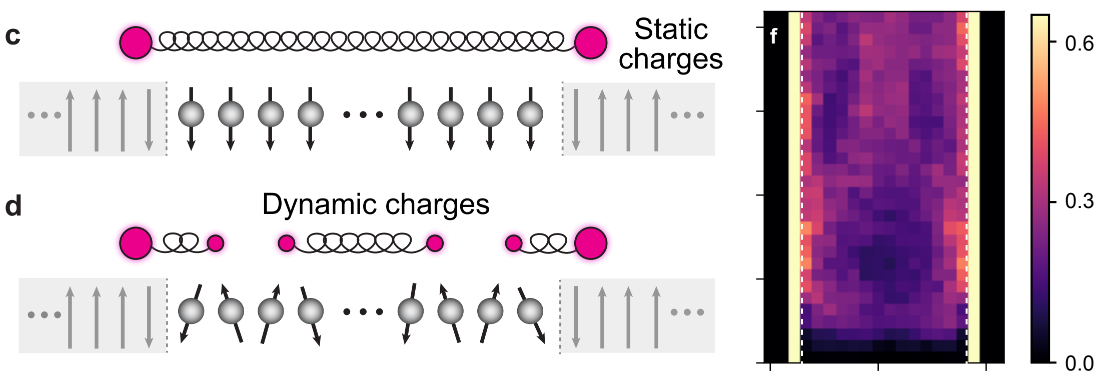
STRING BREAKING, BUBBLE NUCLEATION, AND PARTICLE PRODUCTION

String breaking in an Ising model (a Z_2 gauge theory) using a trapped-ion simulator:

De et al (ZD), arXiv:2410.13815 [quant-ph].



See aslo Luo et al (ZD), arXiv:2505.09607 [quant-ph], Alexandru et al, arXiv:2504.13760 [hep-lat].

False-vacuum decay in an Ising model (a Z_2 gauge theory) with a D-wave quantum annealer:

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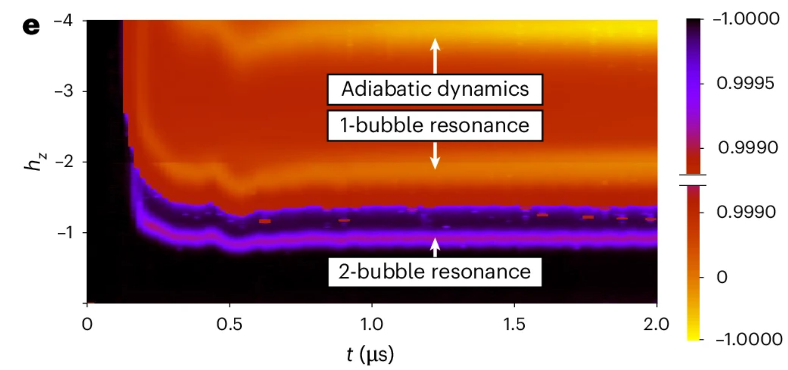

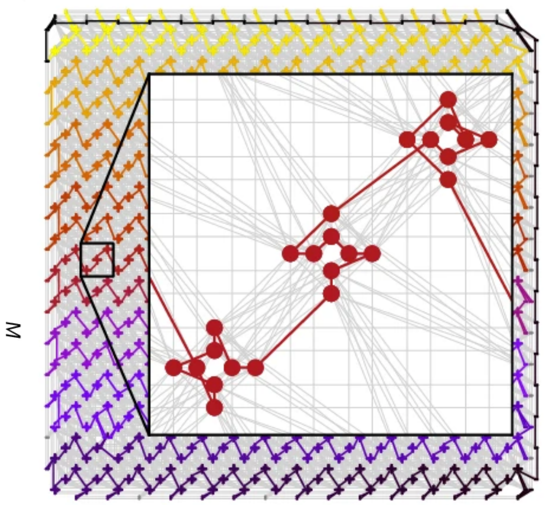

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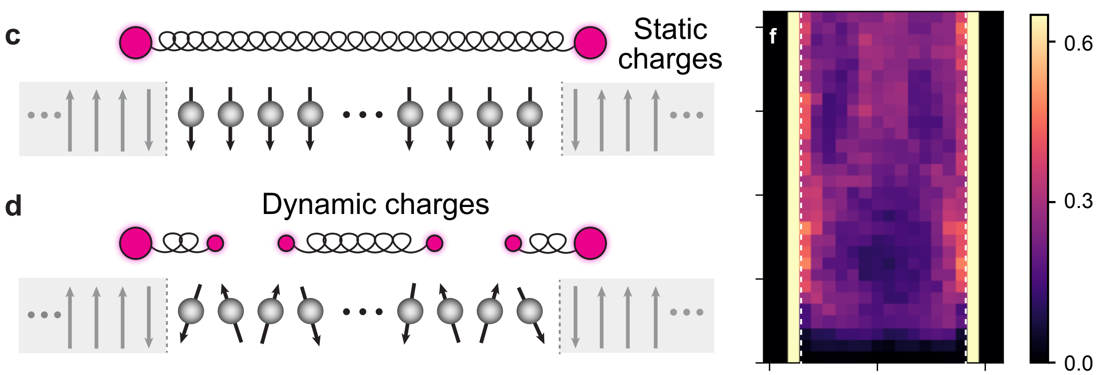

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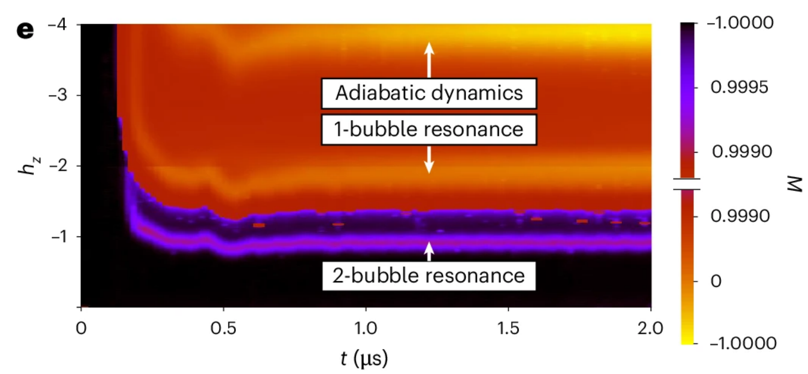

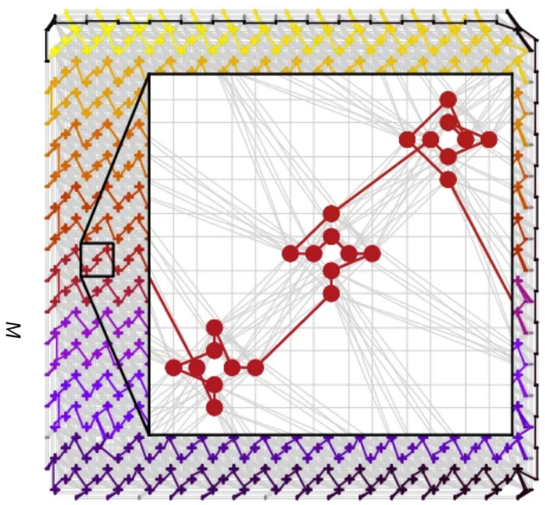

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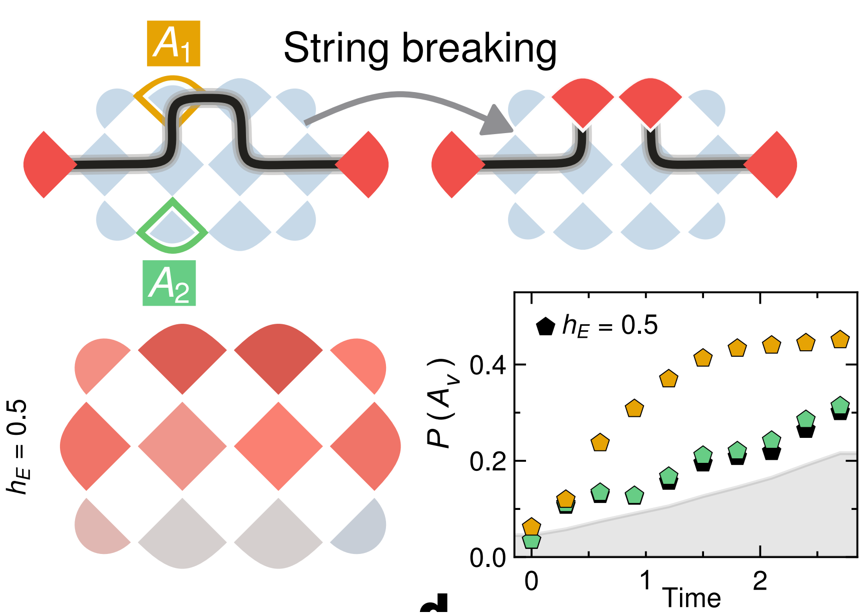
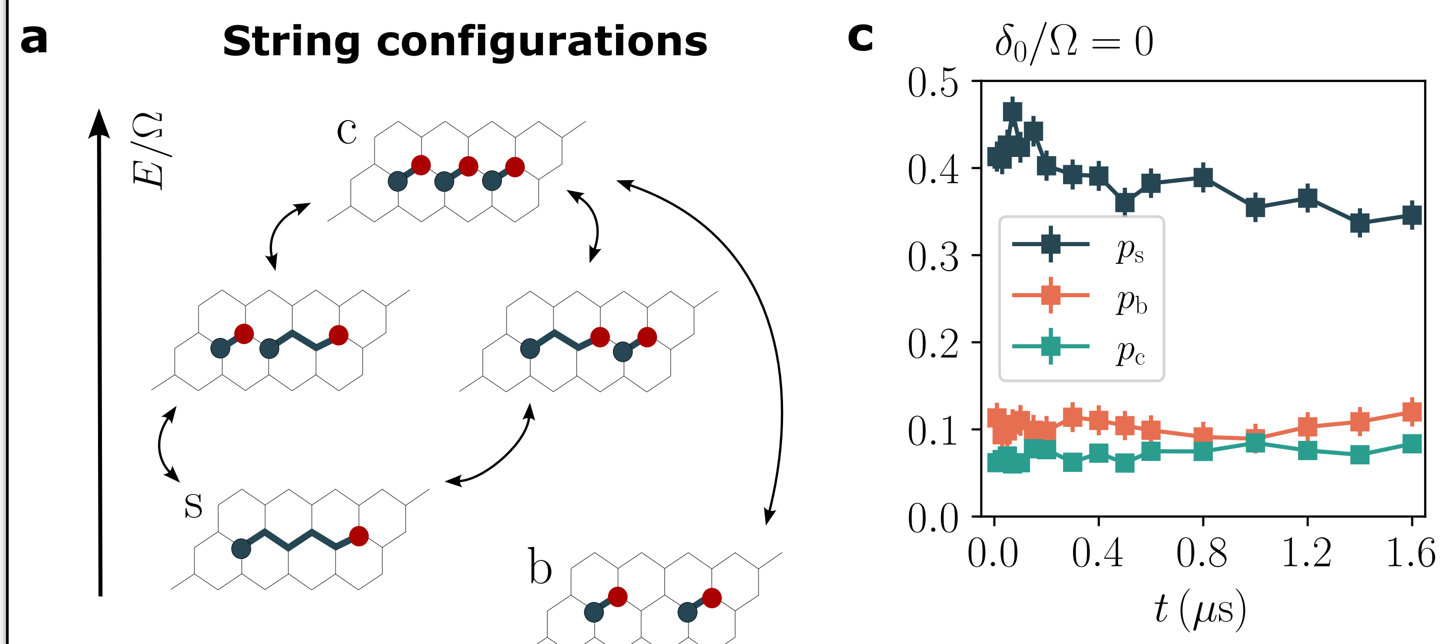
String breaking in a (2+1)D Z_2 gauge theory with a superconducting quantum processor:

Cochran et al, arXiv:2409.17142 [quant-ph].



String breaking in (2+1)D U(1) quantum link model with a Rydberg-array simulator:



Gonzalez-Cuadra et al, arXiv:2410.16558 [quant-ph].

Vacuum and hadronic states?

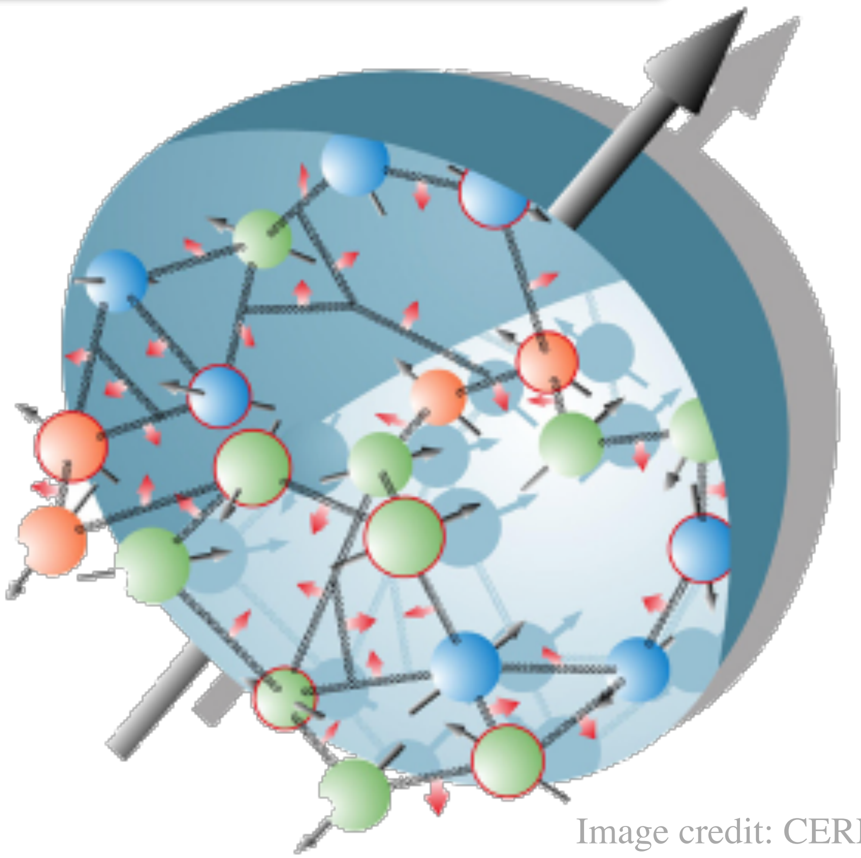
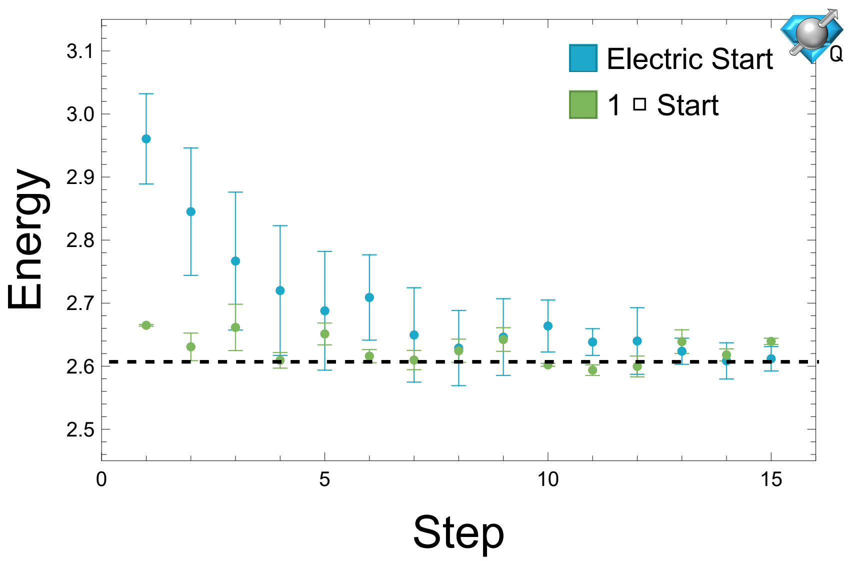
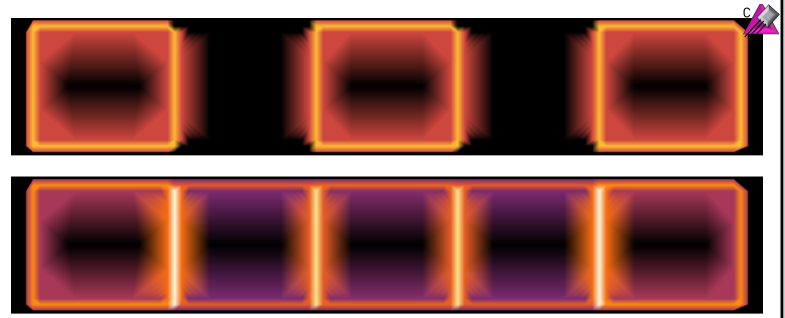


Image credit: CERN courier

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

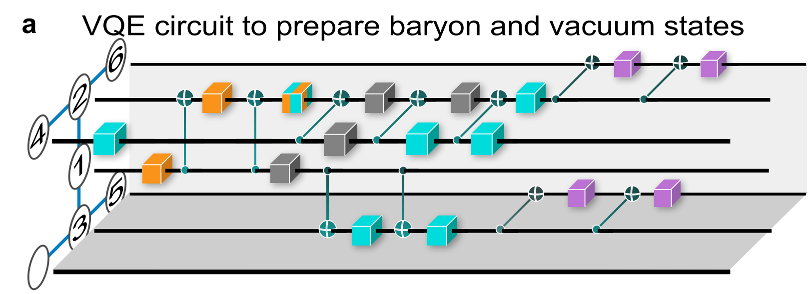


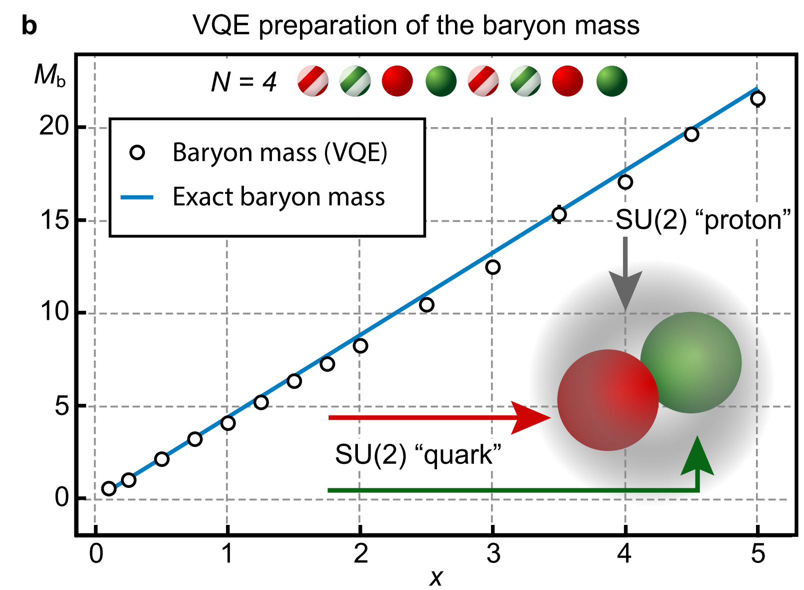


Ciavarella and Chernyshev, *Phys.Rev.D* 105 (2022) 7, 074504.

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

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





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

**For Hamiltonian spectroscopy methods in general, see: 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].
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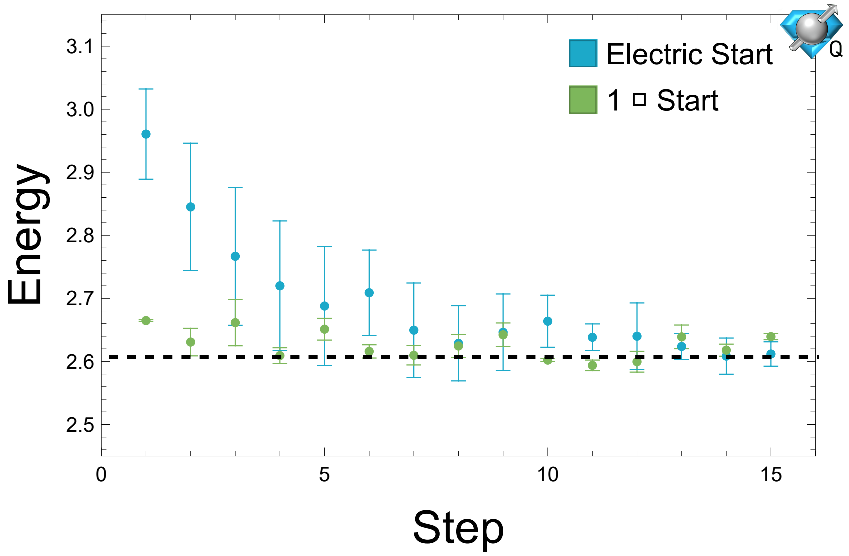

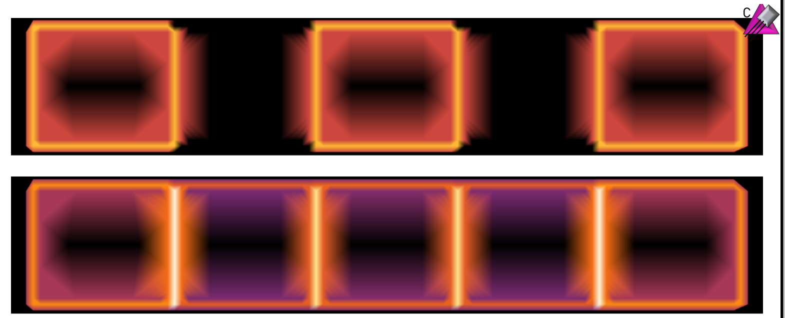

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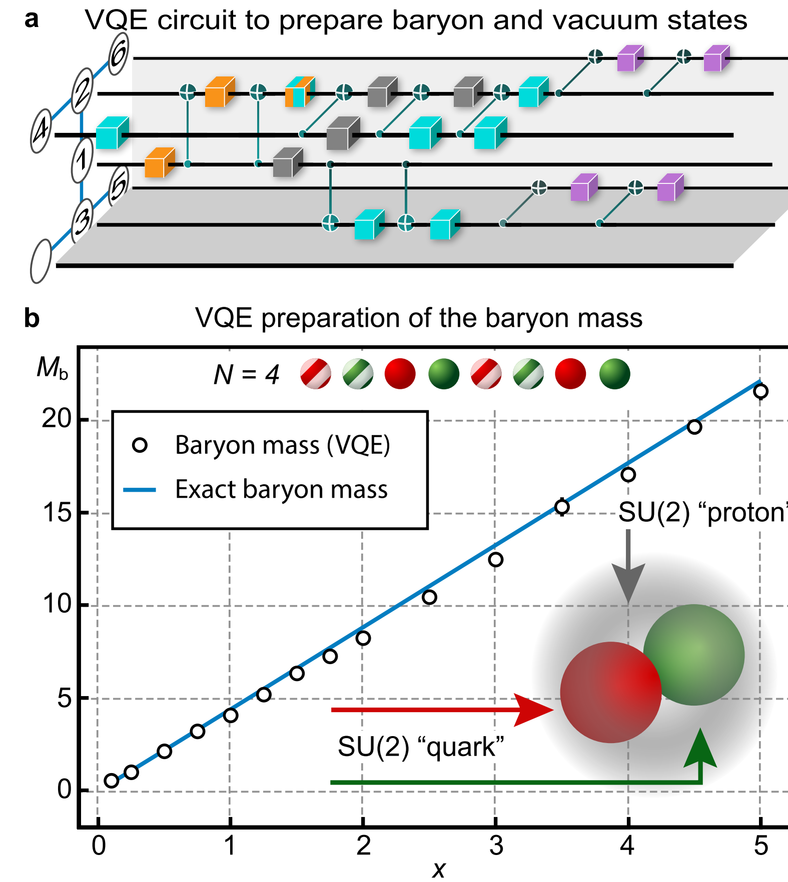

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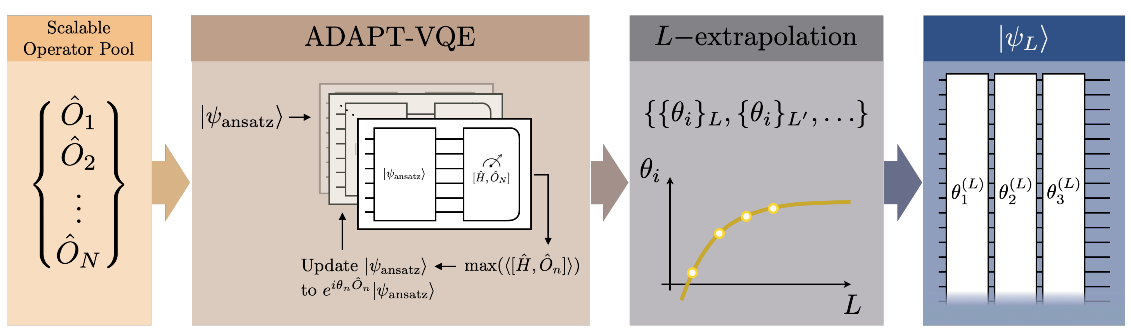
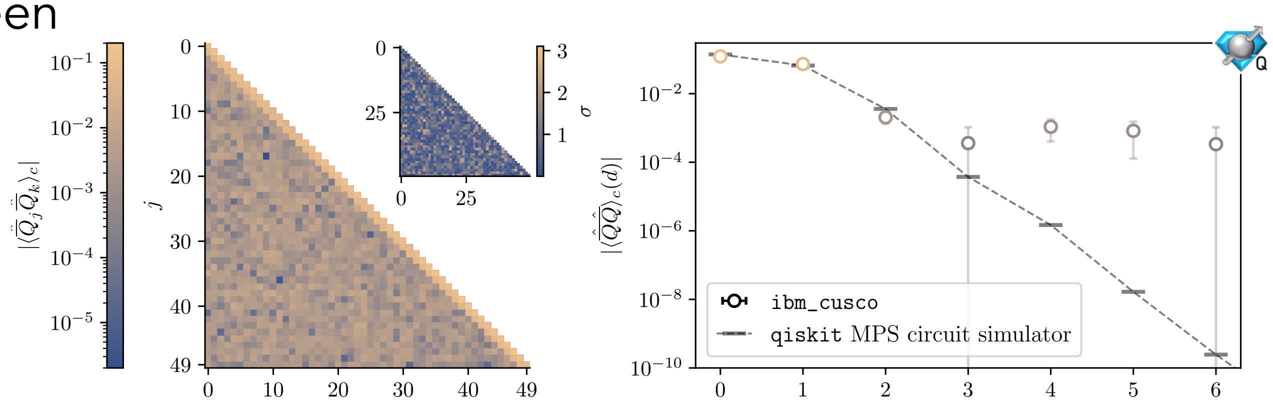
Schwinger model vacuum on a 100 qubits IBM system: Connected correlation functions between spatial charges





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

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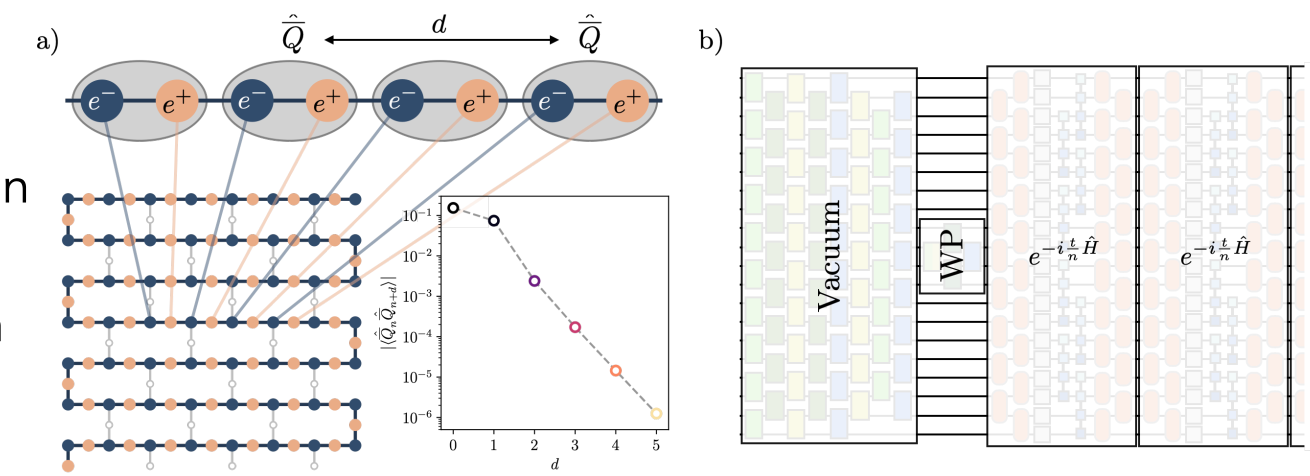
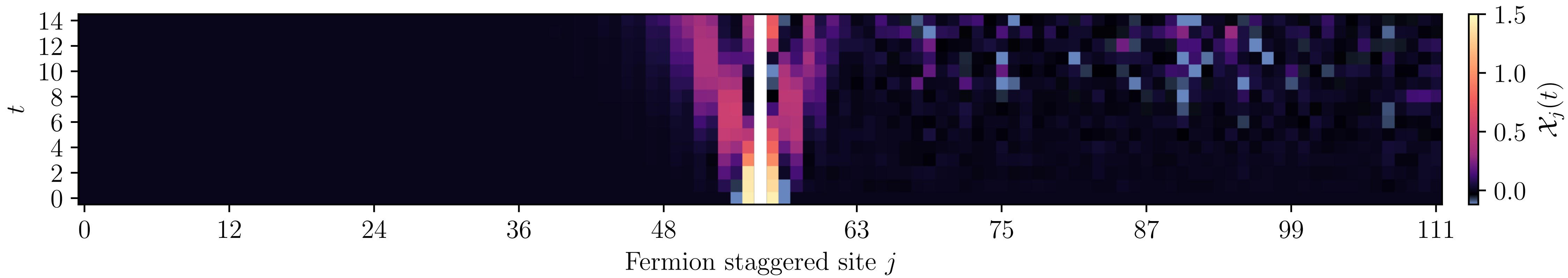
FIRST STEPS TOWARD HADRONIC WAVE PACKETS FOR COLLISION PROCESSES

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



Farrell, Illa, Ciavarella, Savage, Phys.Rev.D 109 (2024) 11, 114510.



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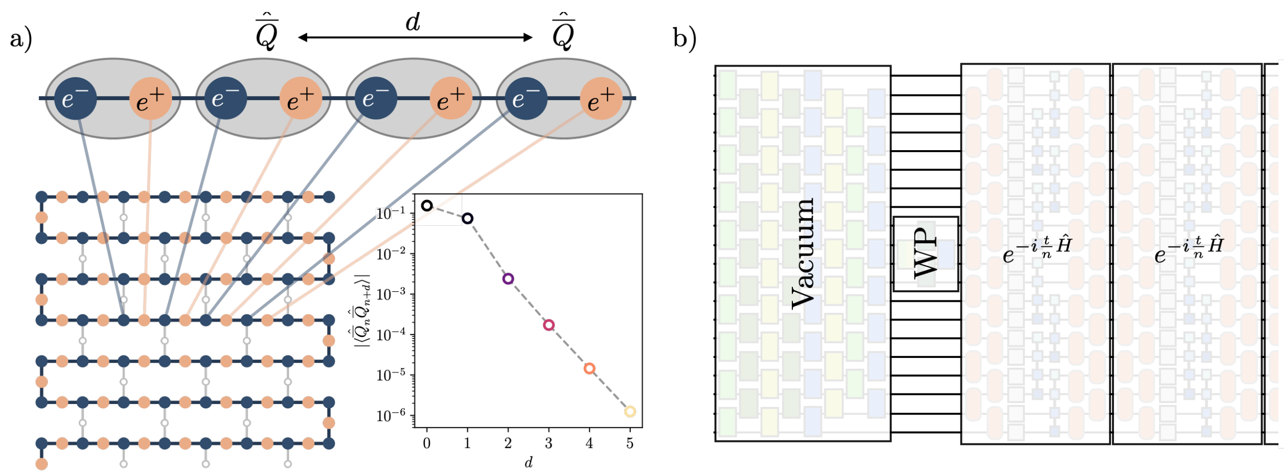

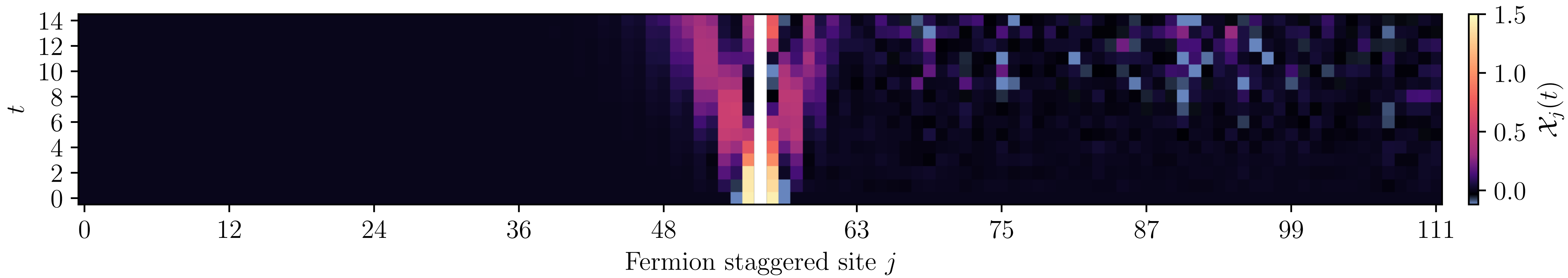

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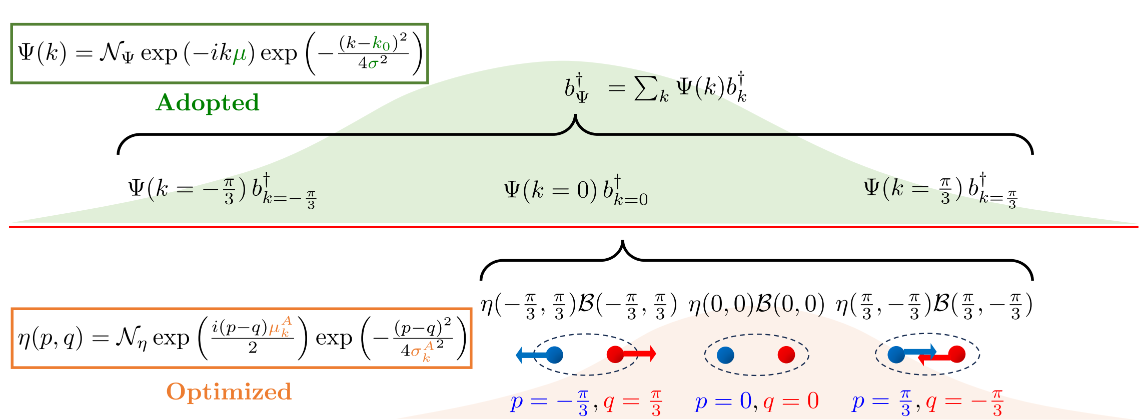
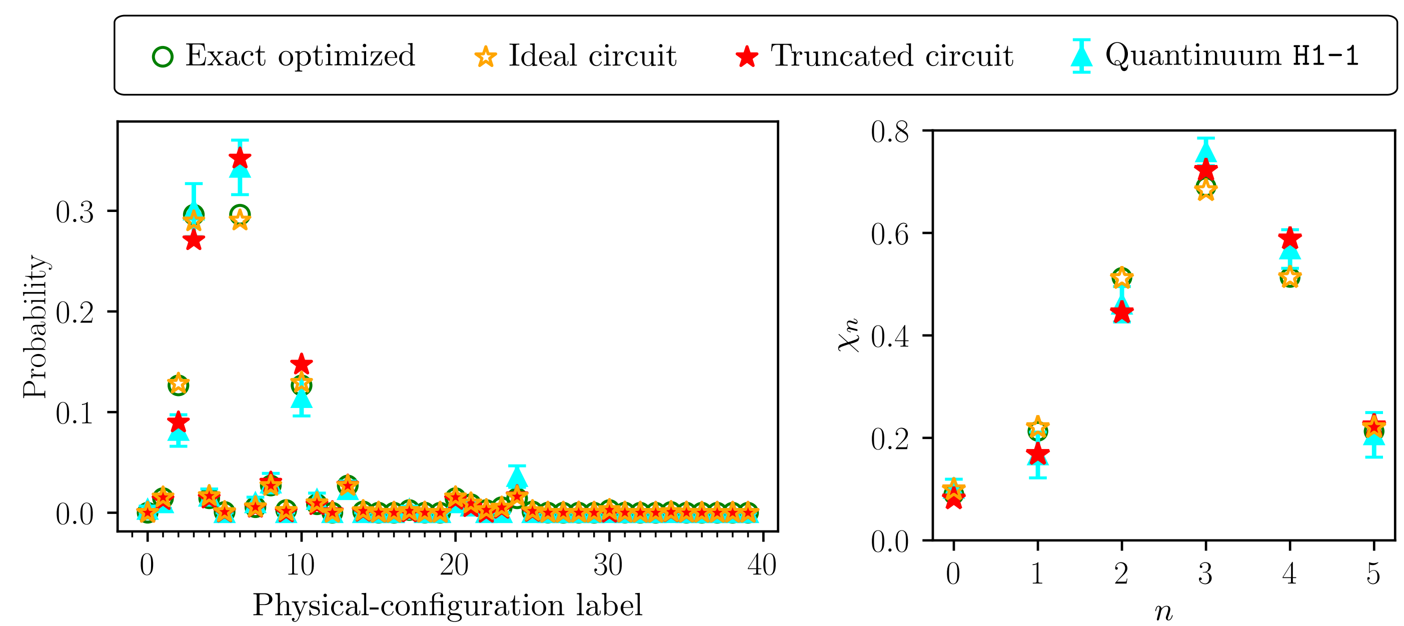
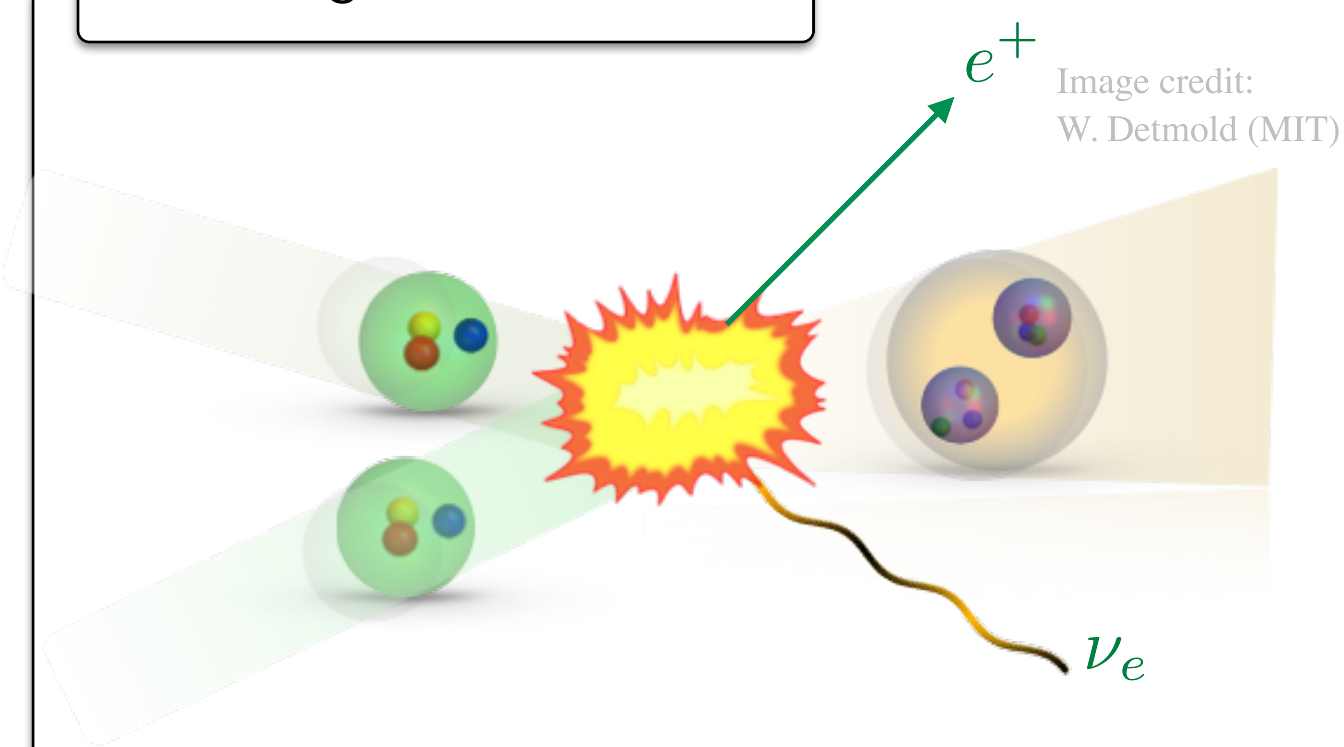
Hadron wave packet in the Z_2 gauge theory (12 staggered sites with Quantinuum, minimal noise mitigation):





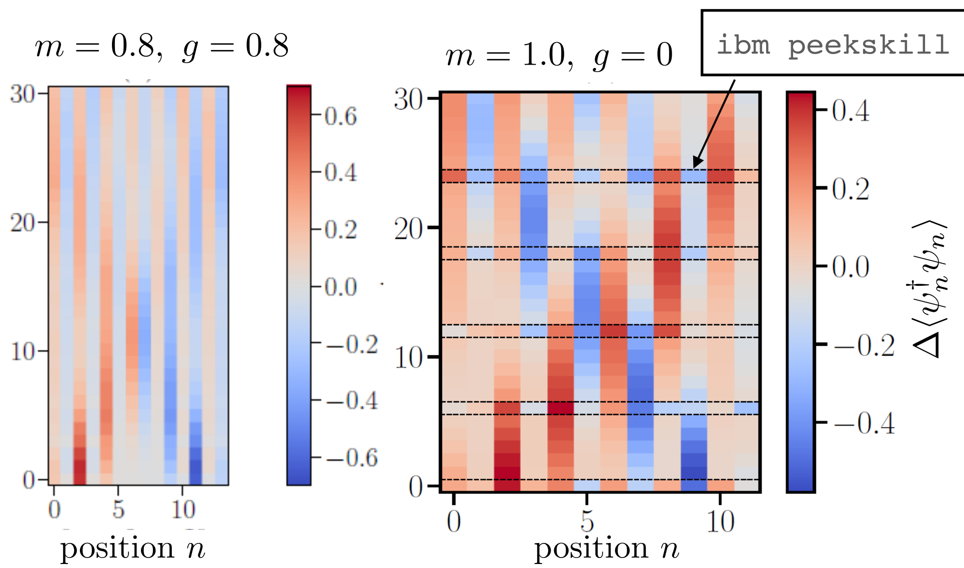
ZD, Hsieh, and Kadam, Quantum 8, 1520 (2024).

Scattering and transitions?



FIRST STEPS TOWARD COLLISION/REACTION PROCESSES

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

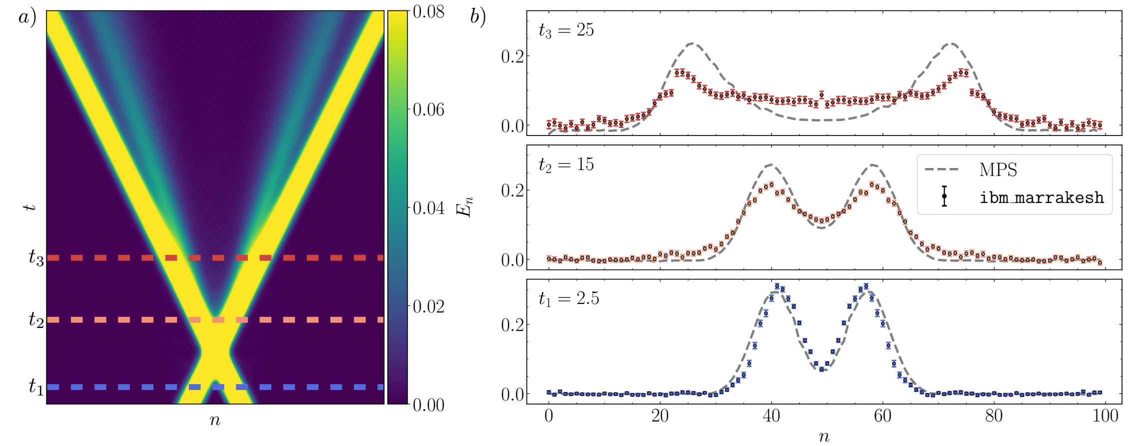


Chai, Crippa, Jansen, Kühn, Pascuzzi, Tacchino, Tavernelli, Quantum 9, 1638 (2025).

See also Chai, Guo, Kuhn, arXiv:2505.21240 [quant-ph].

Scattering in (1+1)D Ising field theory

Farrell, Zemlevskiy, Illa, Preskill, arXiv:2505.03111 [quant-ph].



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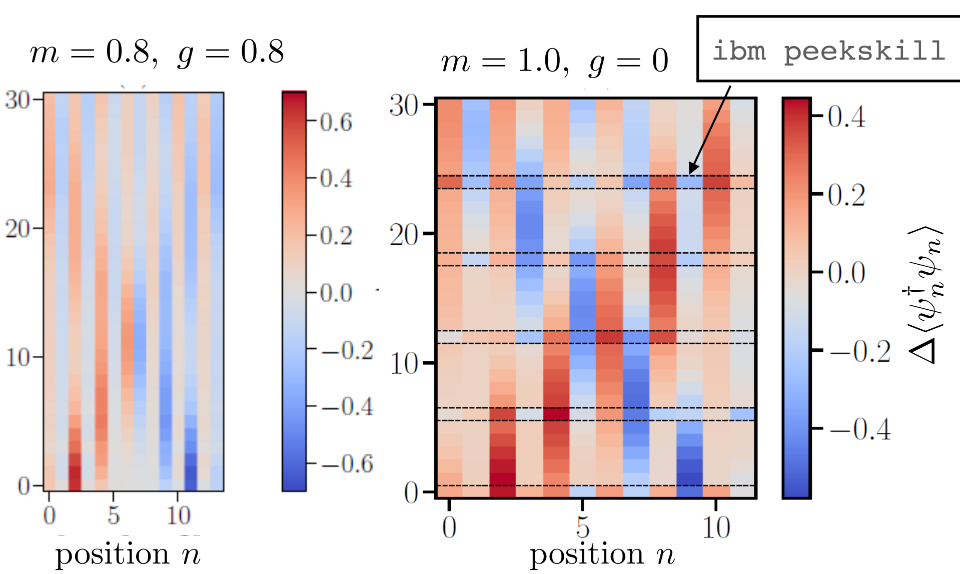

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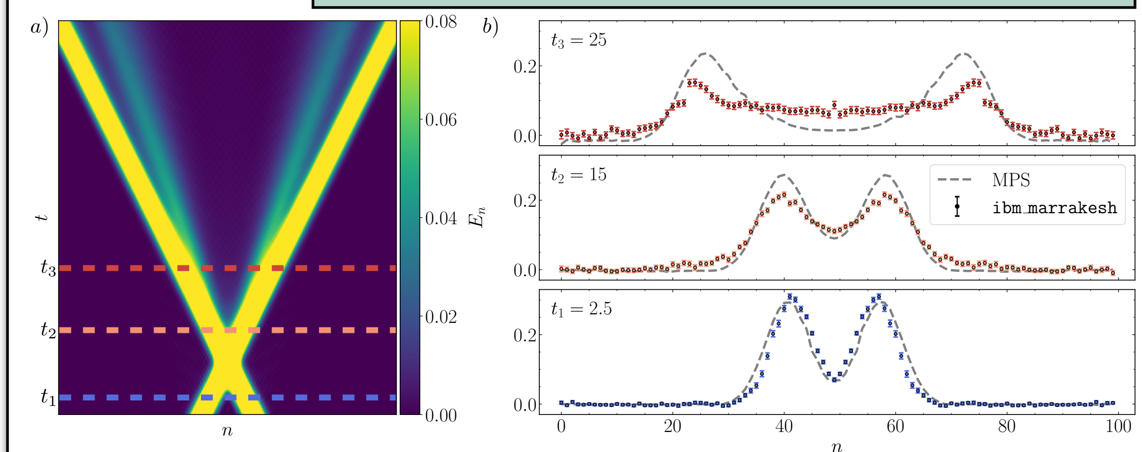

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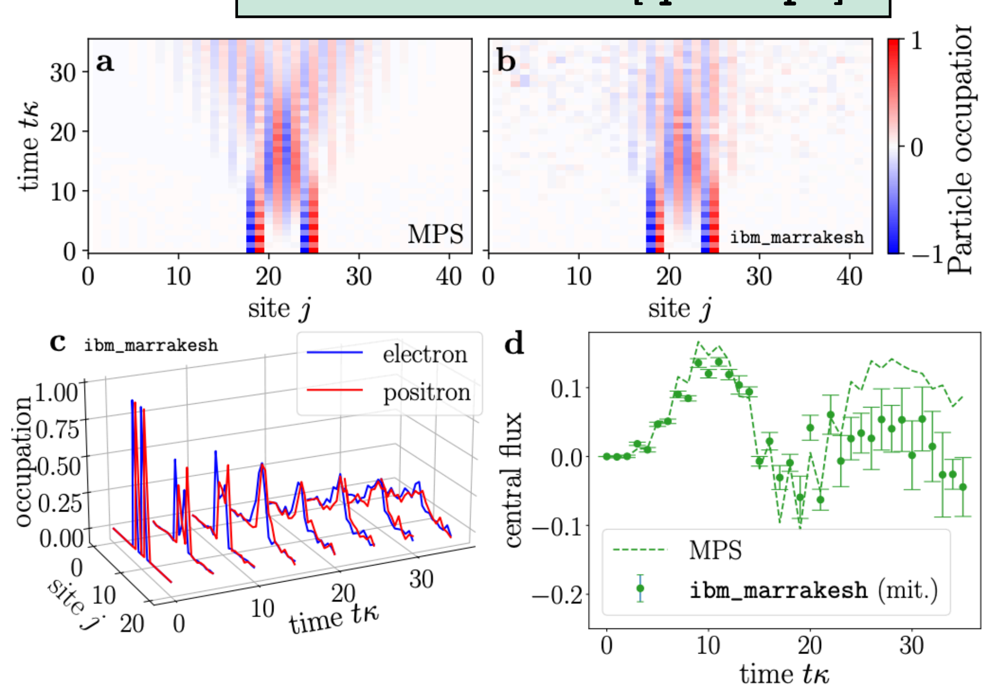
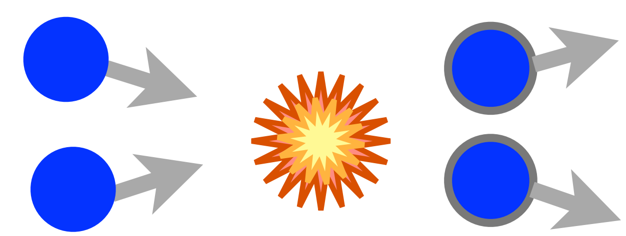
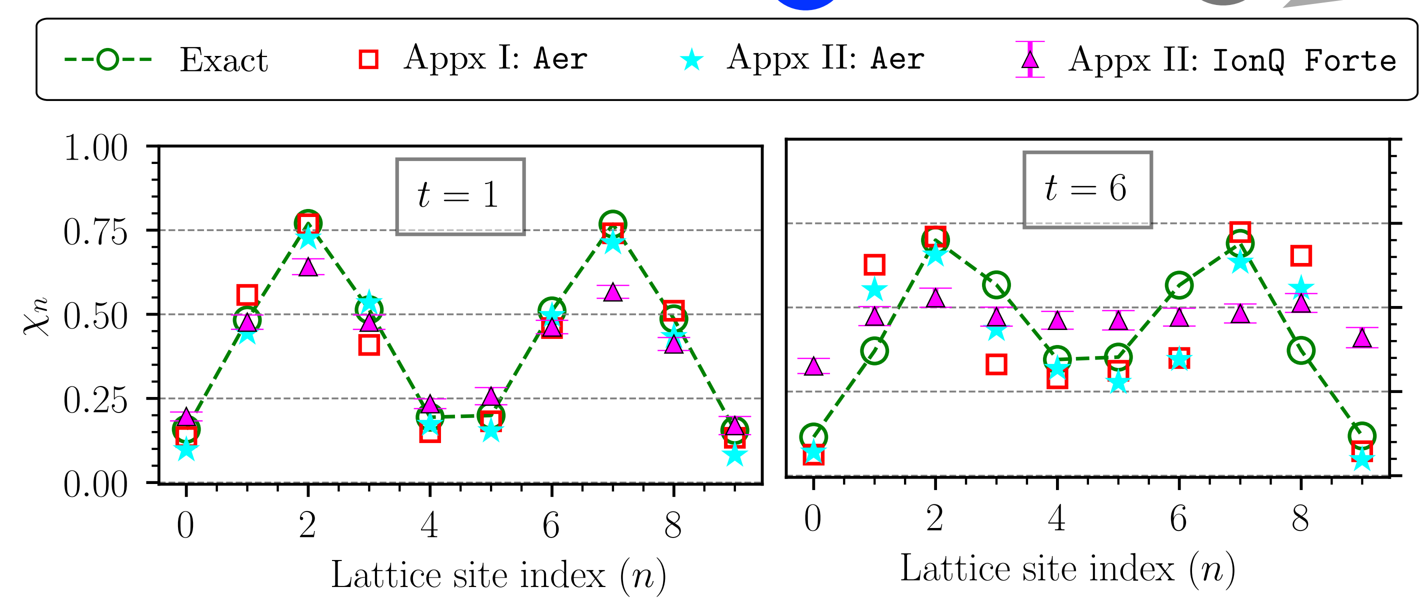
Hadron scattering in a (1+1)D U(1) quantum link model

Schuhmacher, Su, Osborne, Gandon, Halimeh, Tavernelli, arXiv:2505.20387 [quant-ph].



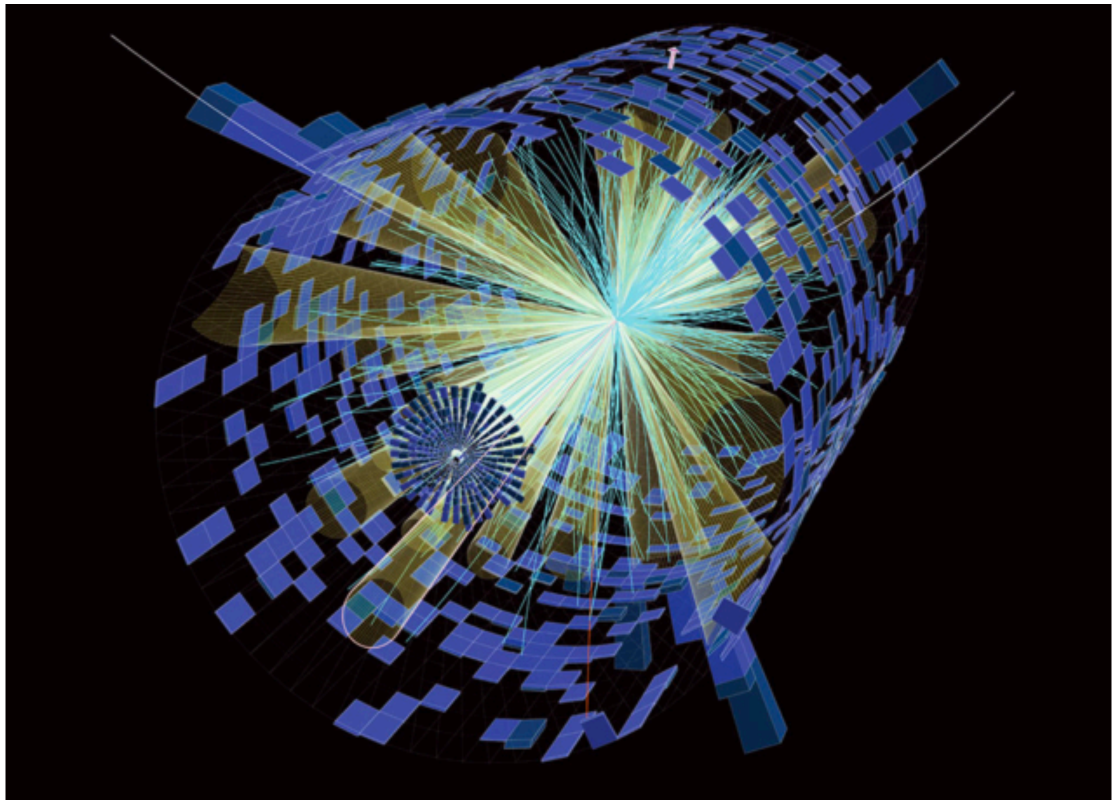
Hadron scattering in (1+1)D Z_2 gauge theory





ZD, Hsieh, Kadam, arXiv:2505.20408 [quant-ph].

Physics of Large Hadron Collider?

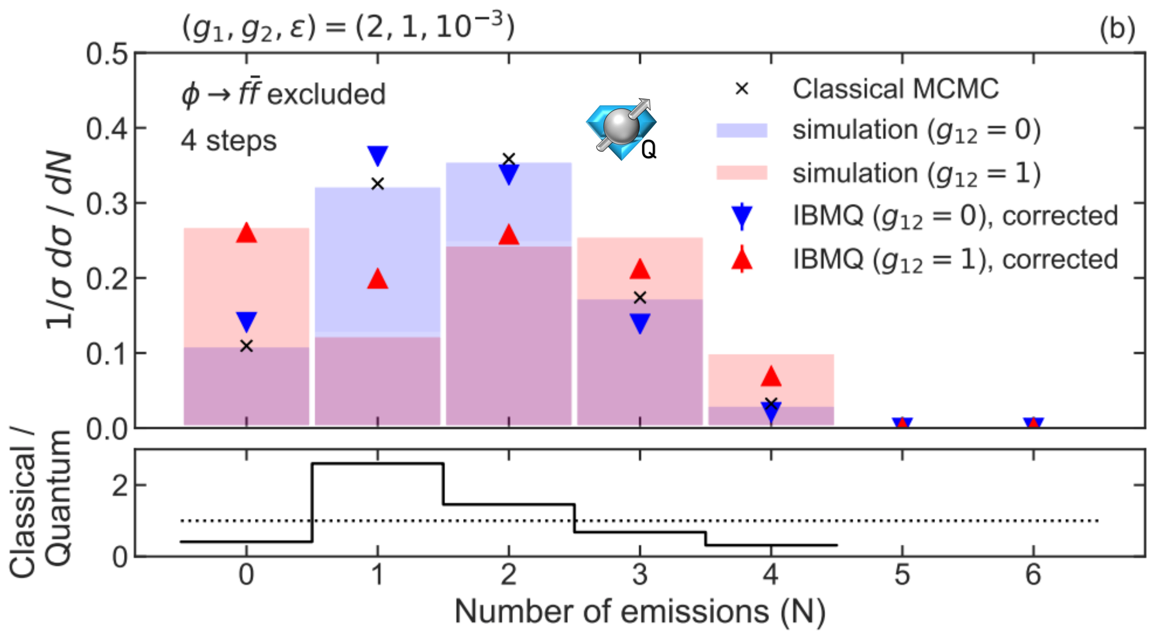


Credit: CERN

ALGORITHMS RELEVANT TO THE PARTON SHOWER/JETS/PDFS

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).

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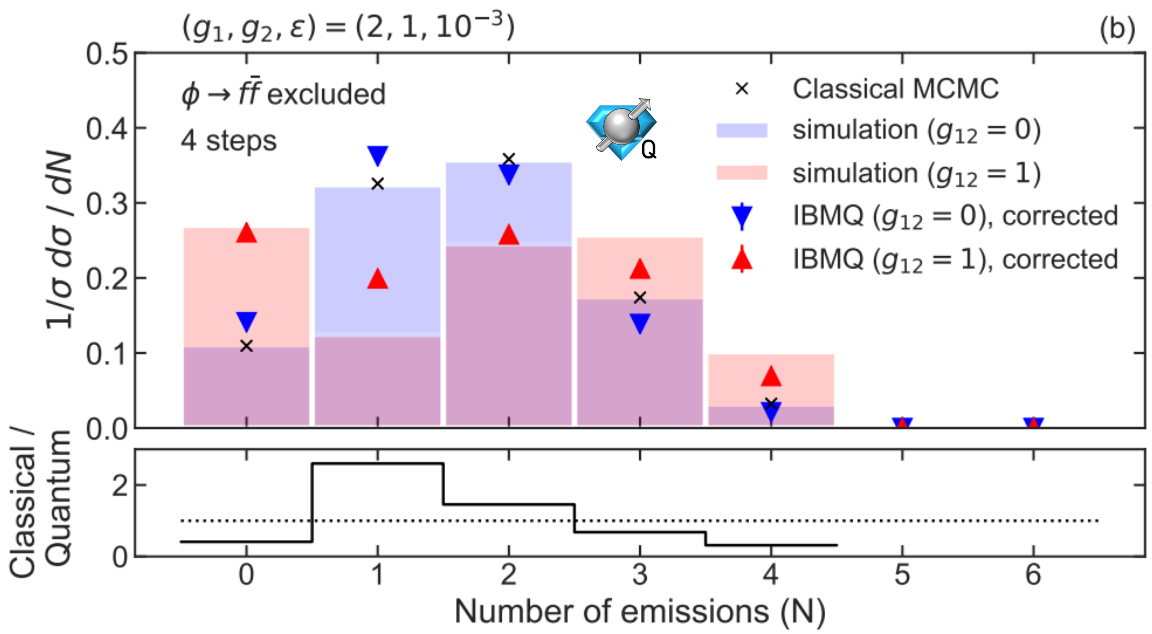

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A quantum algorithm for tracing the evolution of a multi-particle jet probe in the presence of a medium described as a stochastic color field:

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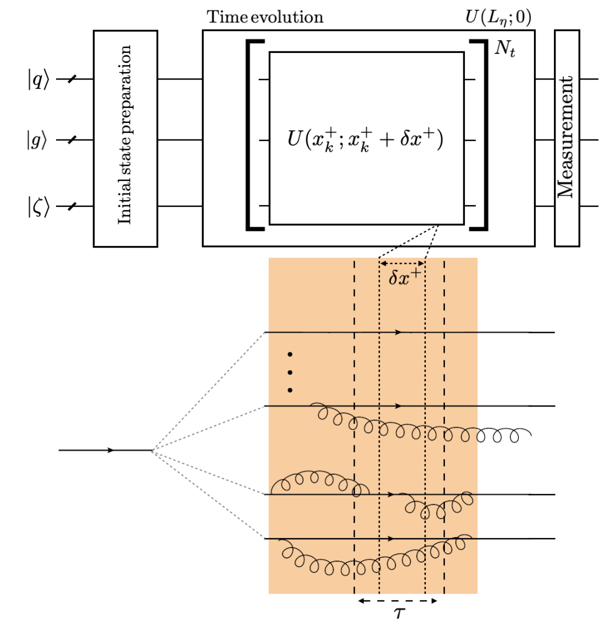

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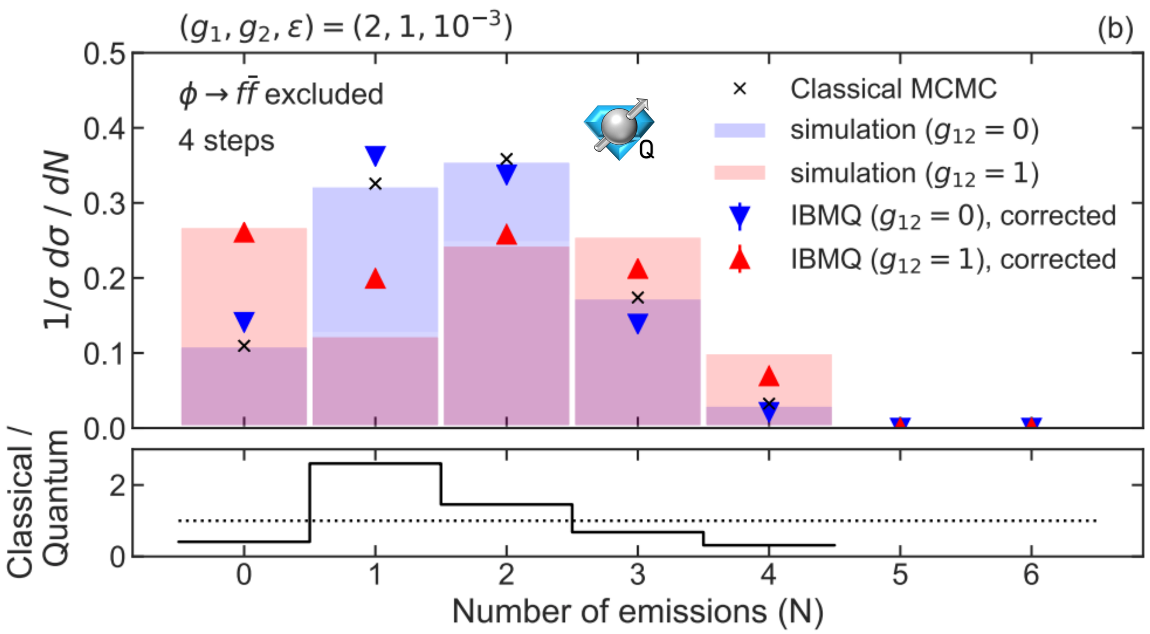

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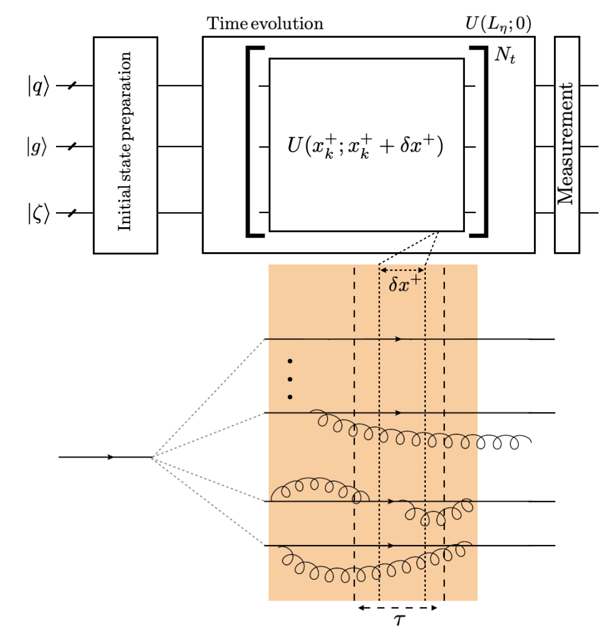
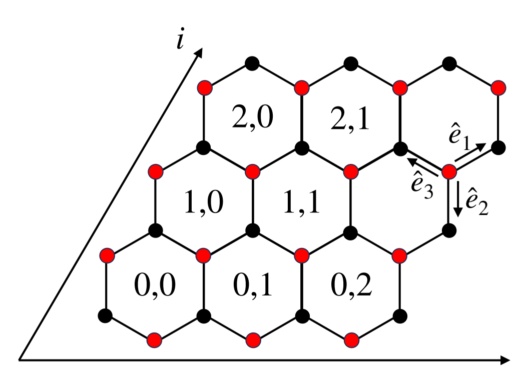
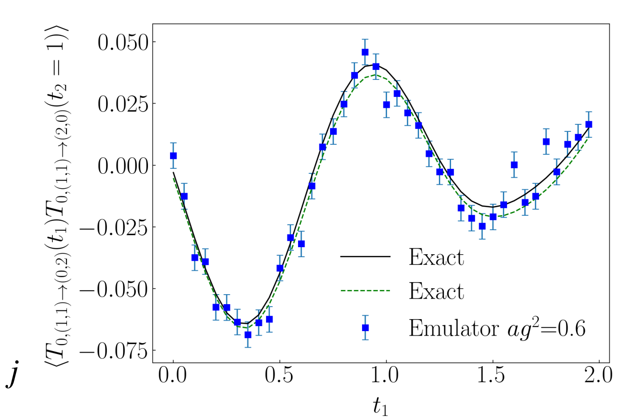


Energy-energy correlators in (2+1) SU(2) LGT ultimately useful in studies of jet substructure:

Kyle Lee, Francesco Turro, Xiaojun Yao, Phys. Rev. D 111, 054514 (2025).





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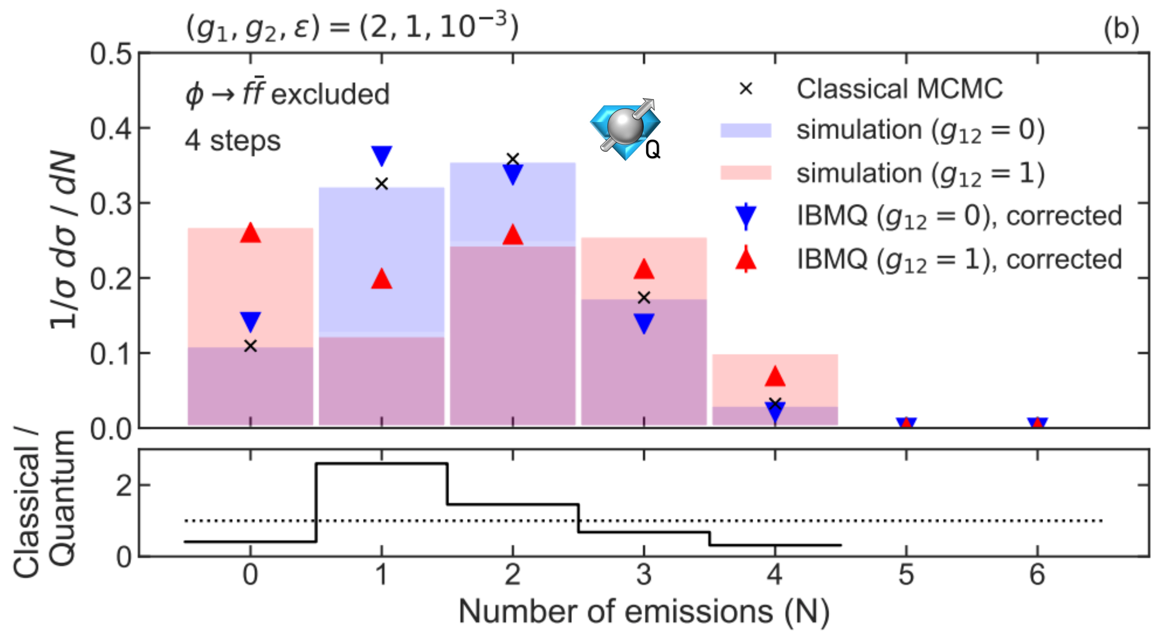

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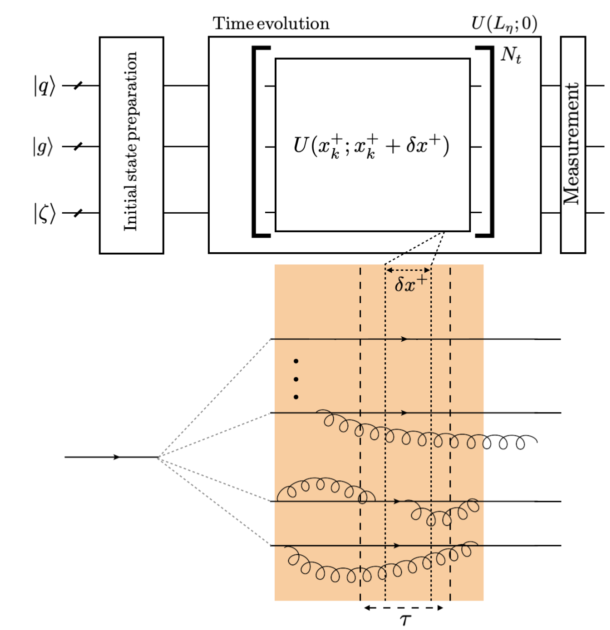

Distribution functions and first attempts at fragmentation functions from non-equal time amplitudes:

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].

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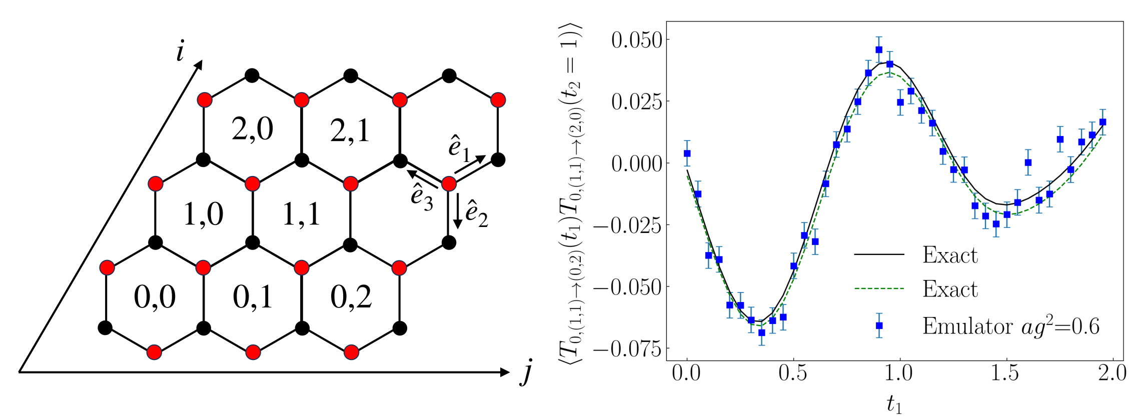
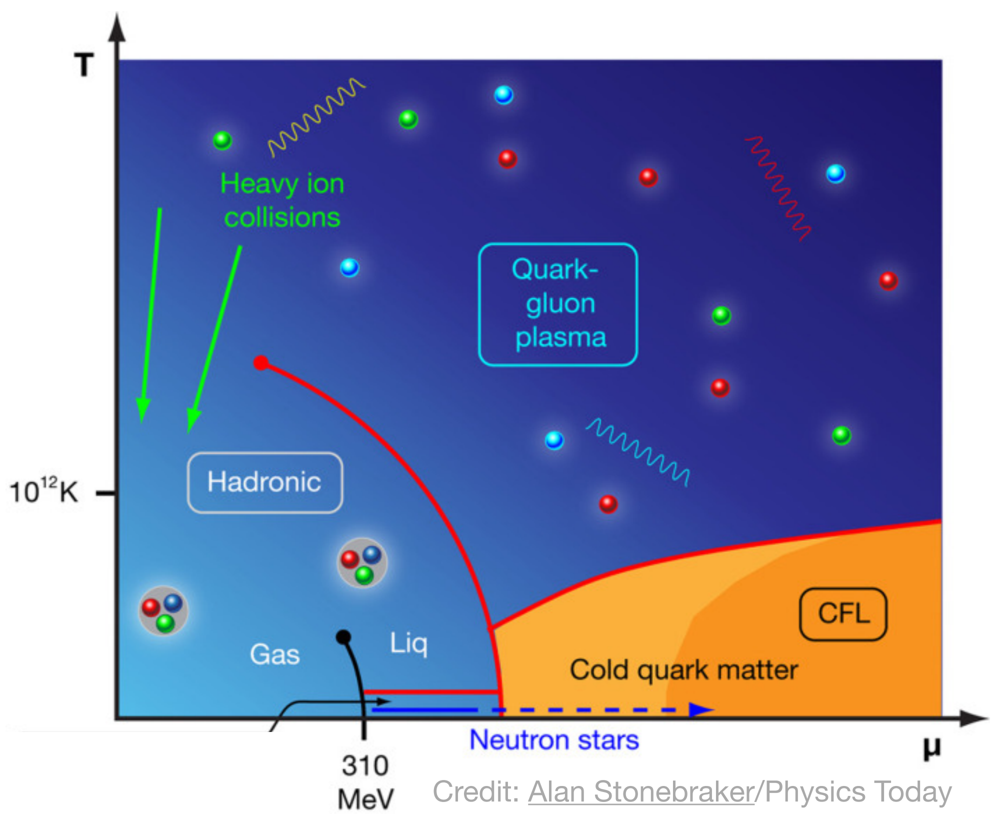


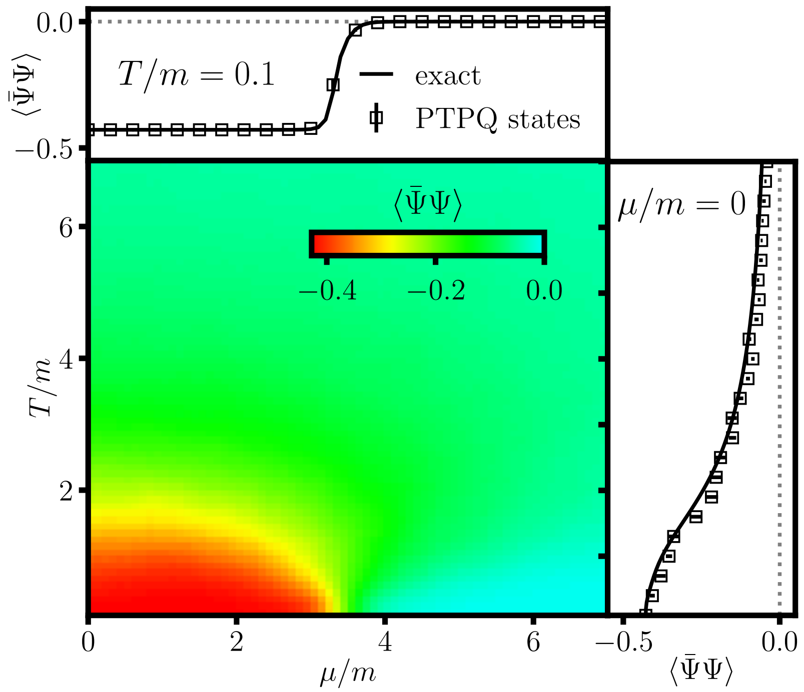
Phase diagram of matter under strong interactions?



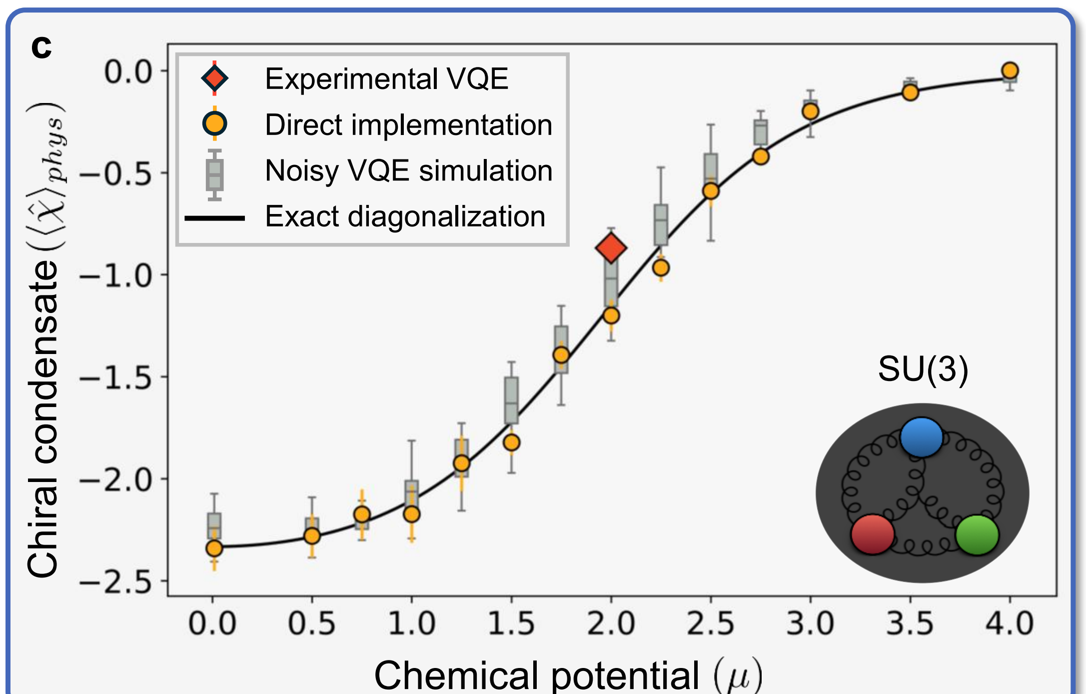
FINITE-TEMPERATURE AND FINTIE-DENSITY PHASE DIAGRAM, TRANSPORT

Phase diagram of (1+1)D Z_2 with fermions

ZD, Mueller, Powers, Phys. Rev. Lett. 131 (2023) 8, 081901.



Phase diagram of QCD in (1+1)D using a trapped-ion quantum computer



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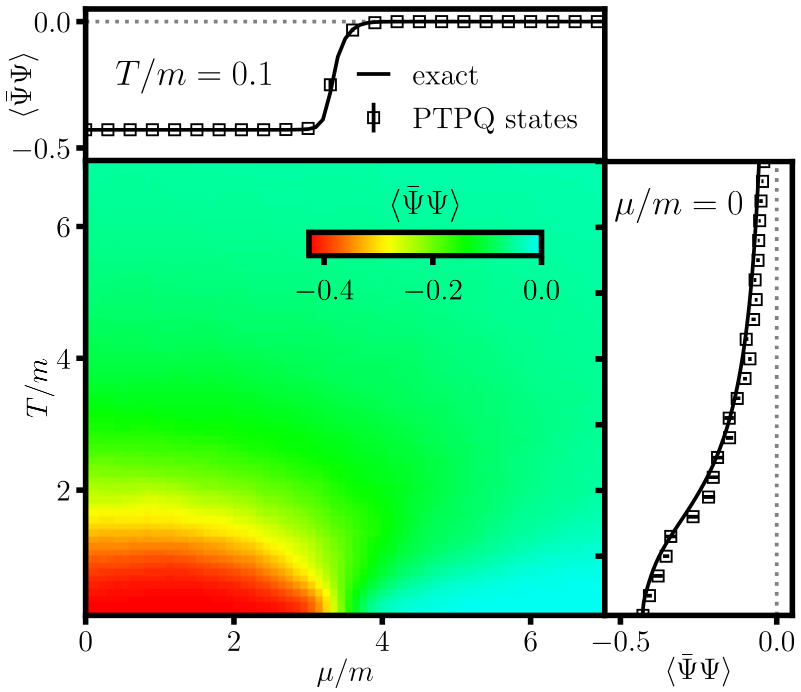
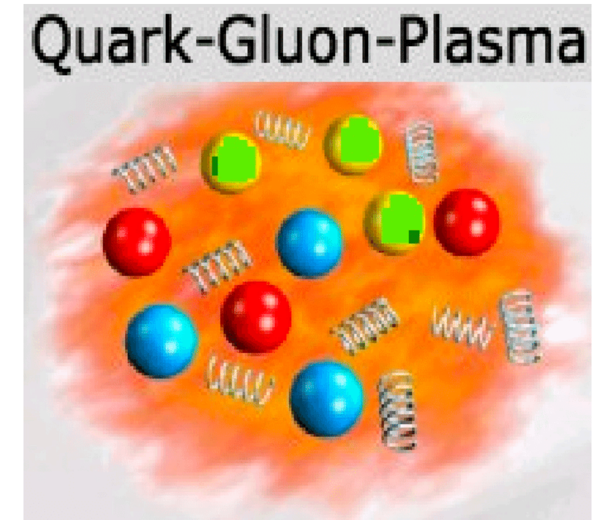
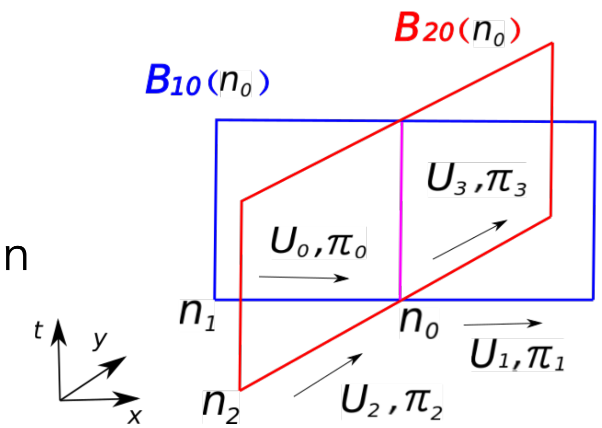


Transport coefficients from real-time correlators of energy momentum tensor

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



How to define energy-momentum tensor in Hamiltonian formulation



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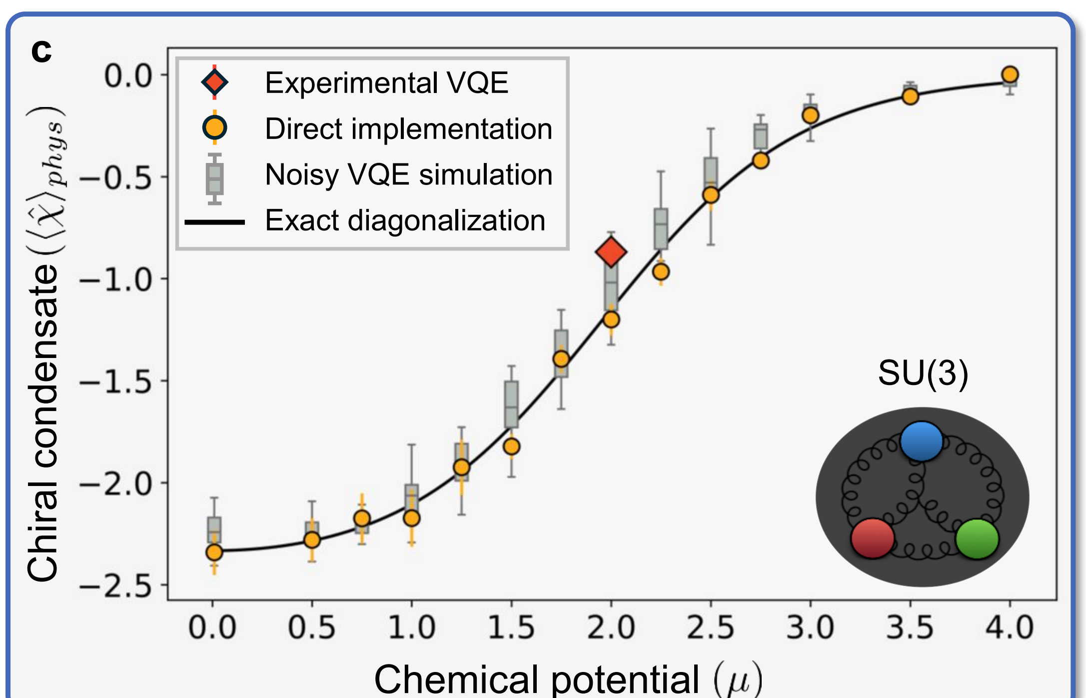

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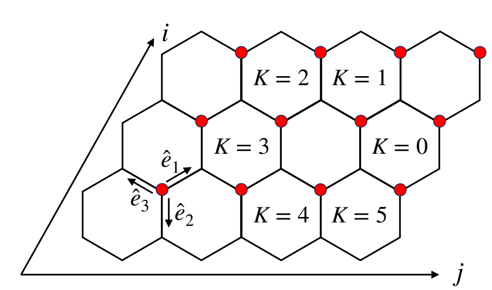
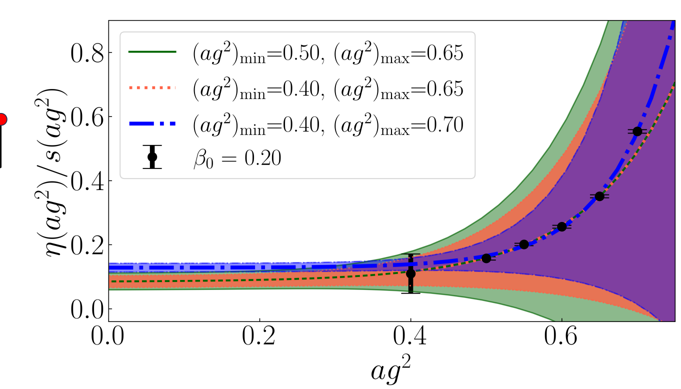
Shear viscosity in SU(2) LGT in 2+1 D with $j_{\max} = 1/2$

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



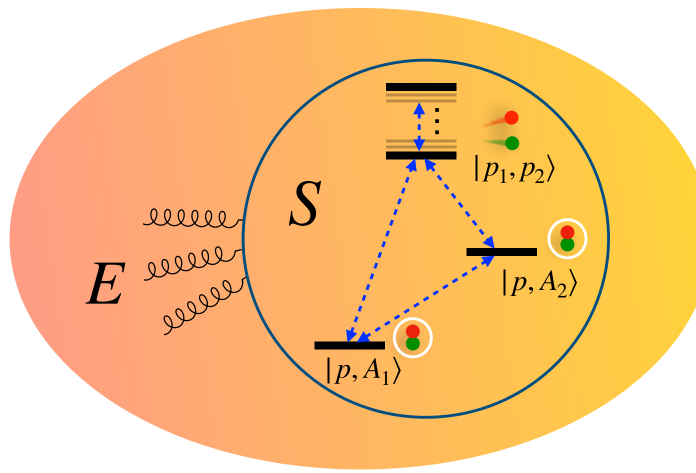


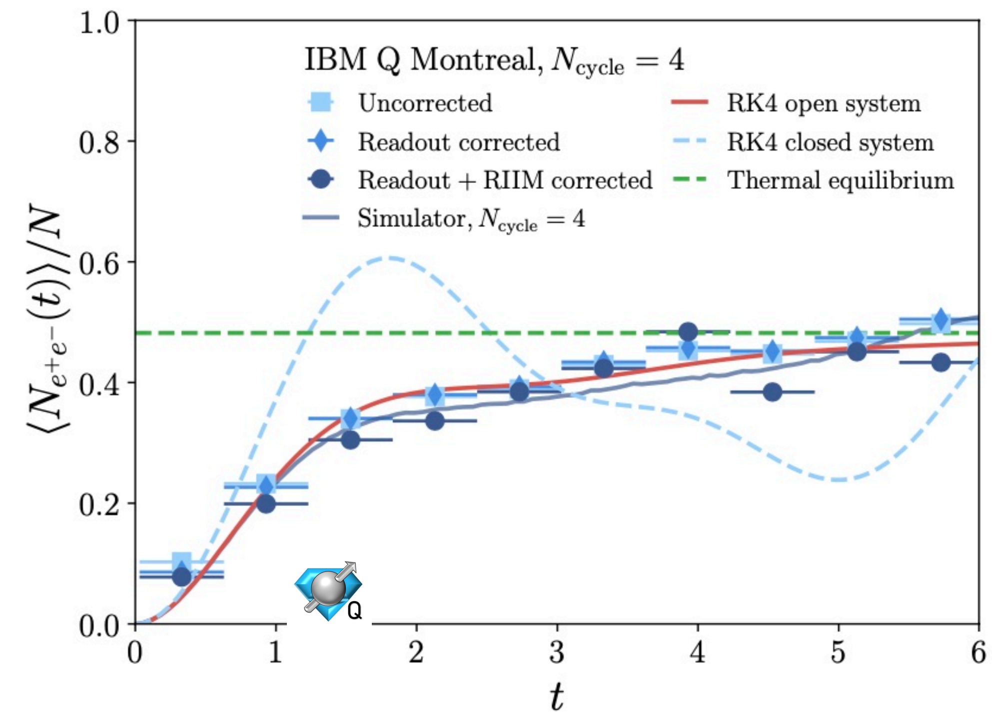
See also: Farrell, Illa, Savage, Phys.Rev.C 111 (2025) 1, 015202.

PROBING STRONGLY-INTERACTING DENSE MATTER WITH HEAVY QUARKS

Open quantum system dynamics: $q\bar{q}$ moving in medium
(Schwinger model in the medium of scalar fields)

de Jong, Metcal, Mulligan, Ploskon, Ringer, and, Yao, *Phys.Rev.D* 104 (2021) 5, 051501. See also Lee, Mulligan, Ringer, Yao, Phys.Rev.D 108, 094518 (2023).

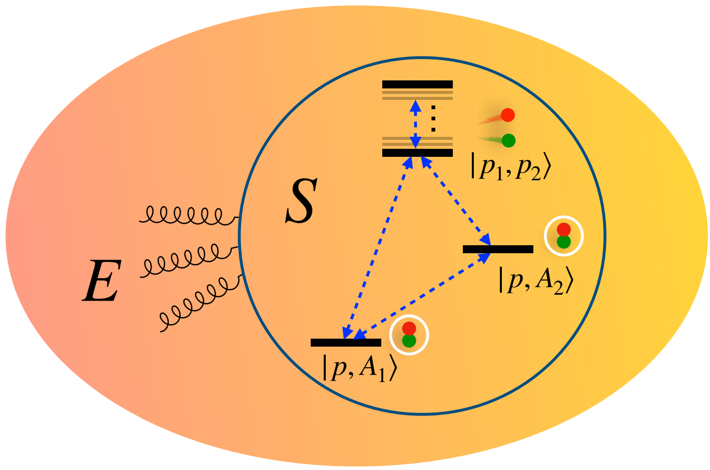


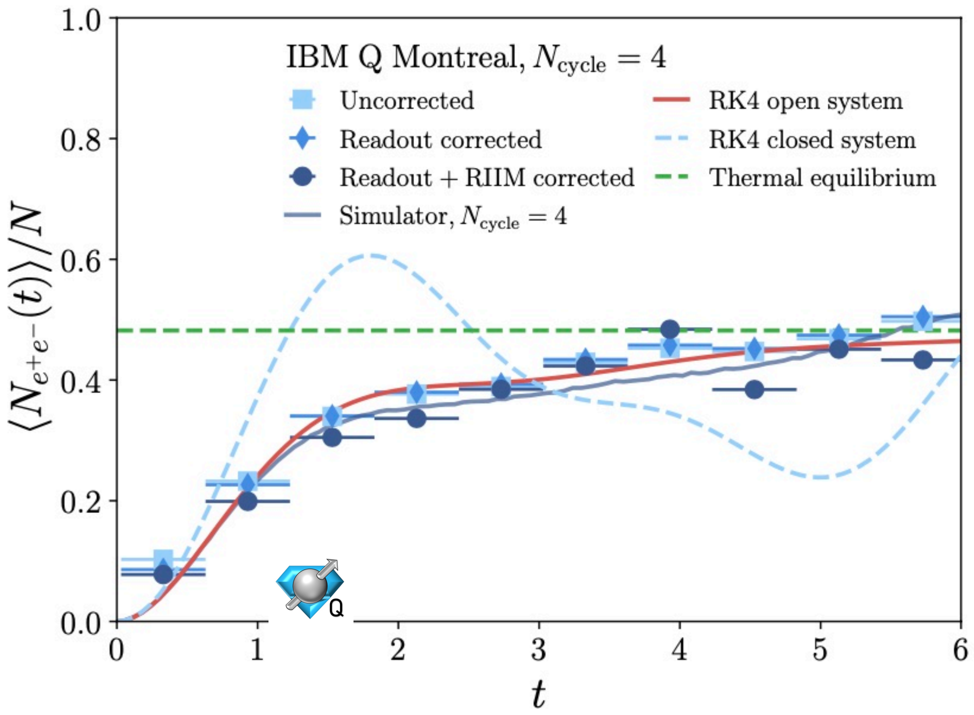


PROBING STRONGLY-INTERACTING DENSE MATTER WITH HEAVY QUARKS

Open quantum system dynamics: $q\bar{q}$ moving in medium (Schwinger model in the medium of scalar fields)

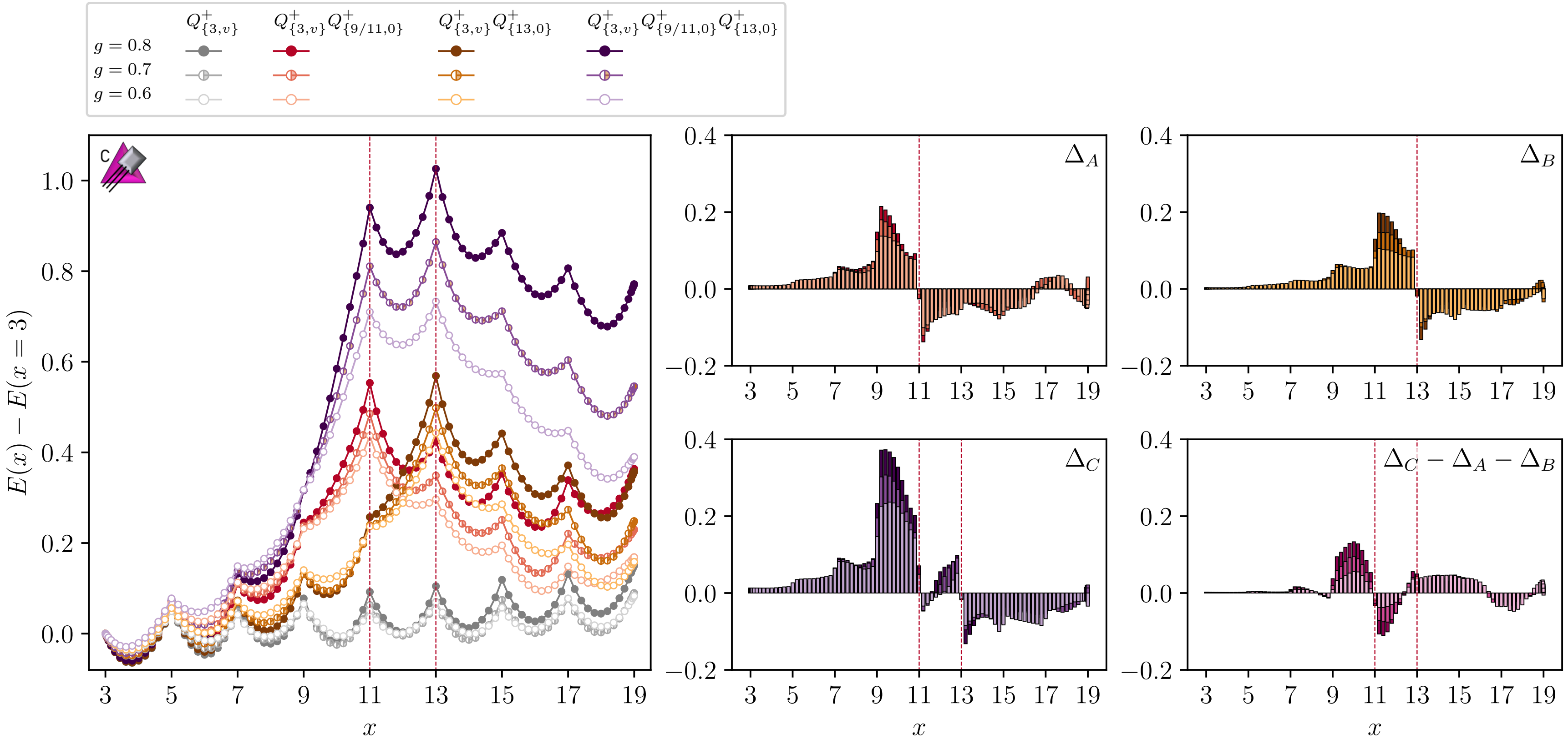
de Jong, Metcal, Mulligan, Ploskon, Ringer, and, Yao, *Phys.Rev.D* 104 (2021) 5, 051501. See also Lee, Mulligan, Ringer, Yao, Phys.Rev.D 108, 094518 (2023).



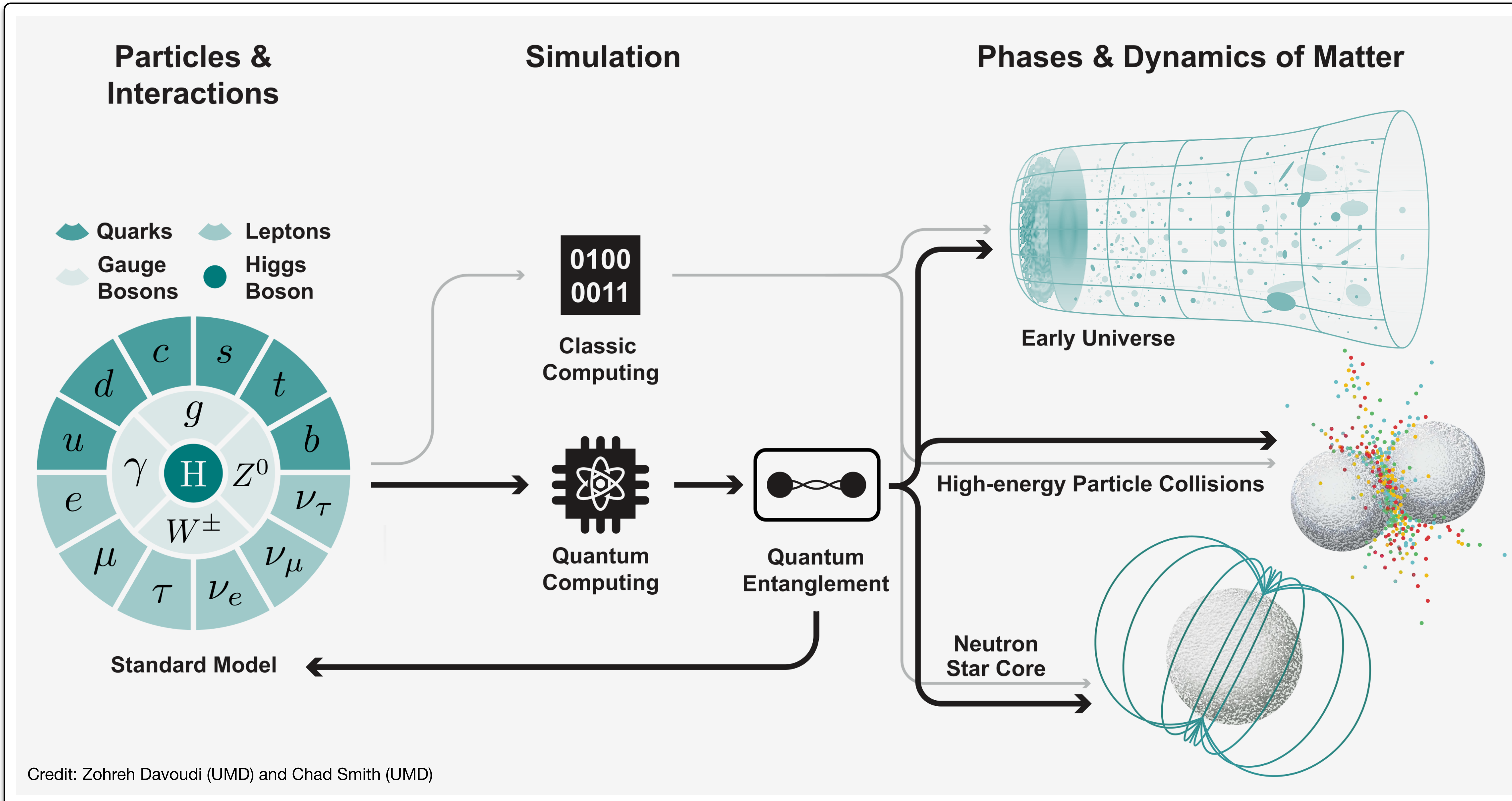


Closed quantum system dynamics of a heavy charge moving in the background of heavy and light charges in the Schwinger model:

Farrell, Illa, Savage, Phys.Rev.C 111 (2025) 1, 015202.

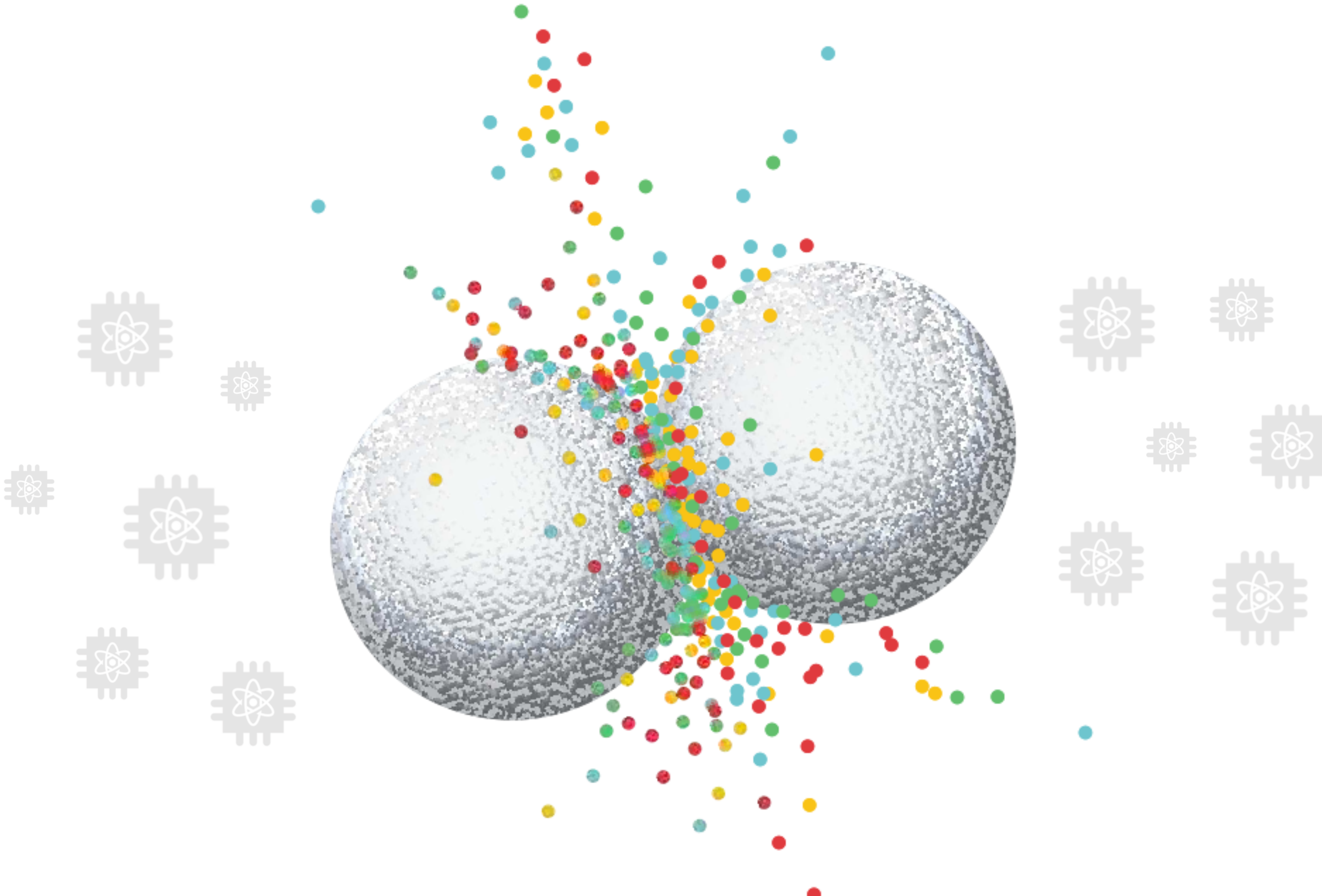


FINAL WORD…



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

THANK YOU



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